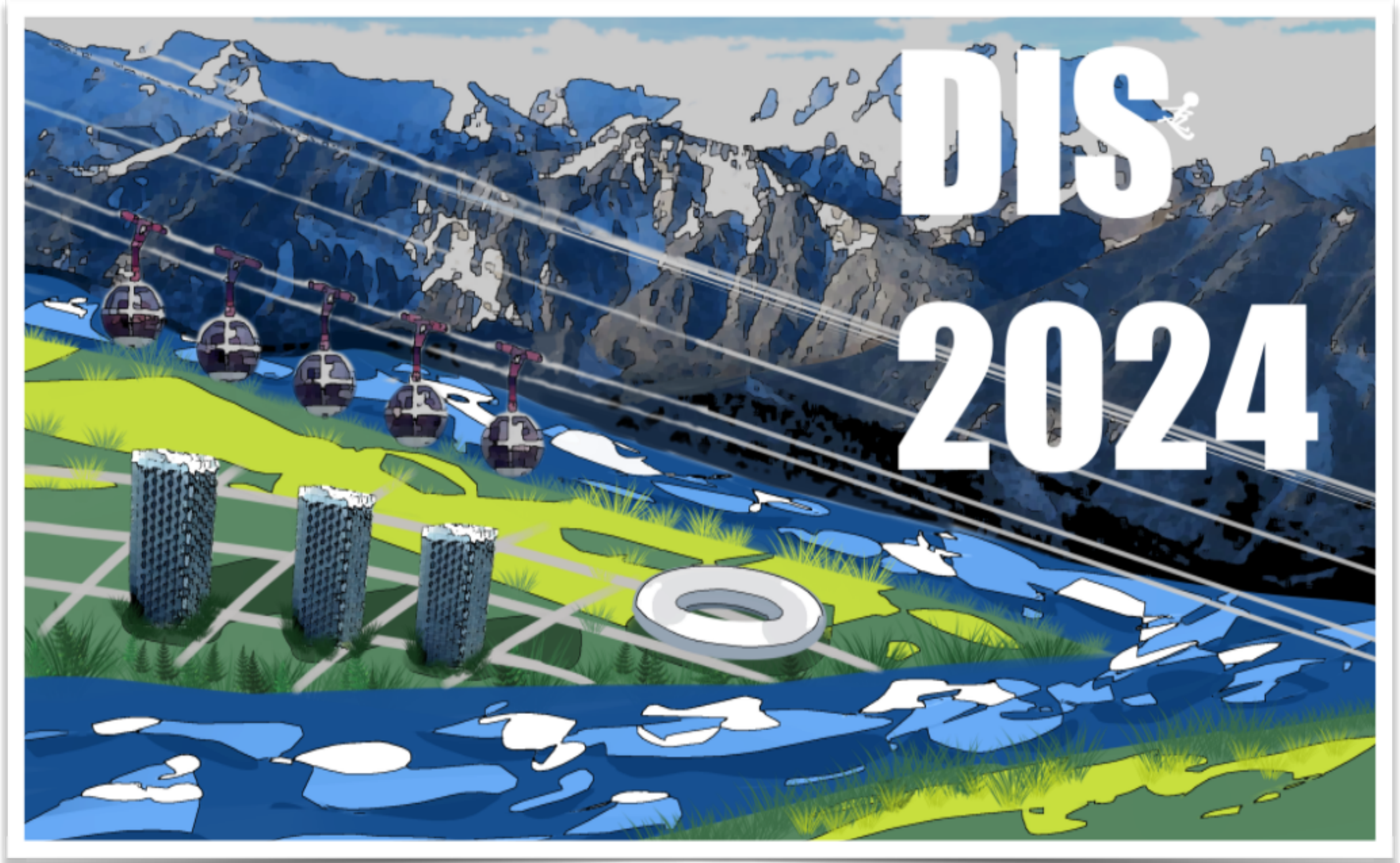
HIGGS PRODUCTION AT NLL ACCURACY IN THE BFKL APPROACH

Francesco Giovanni Celiberto, UAH Madrid

In collaboration with: L. Delle Rose, M. Fucilla, G. Gatto, D.Yu. Ivanov, M.M.A. Mohammed, A. Papa

Grenoble



2024, April 9th

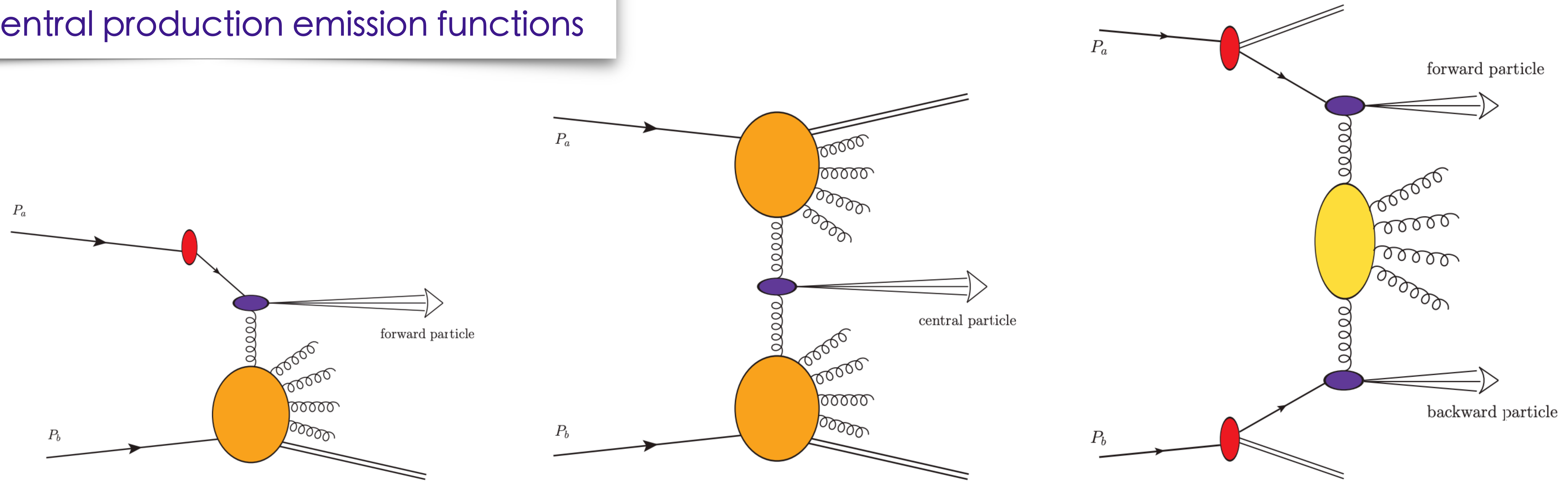
Madrid UAH

talento cm Programa de atracción de talento investigador Comunidad de Madrid

ANIVERSARIO PATRIMONIO MUNDIAL

High-energy factorization at a glance

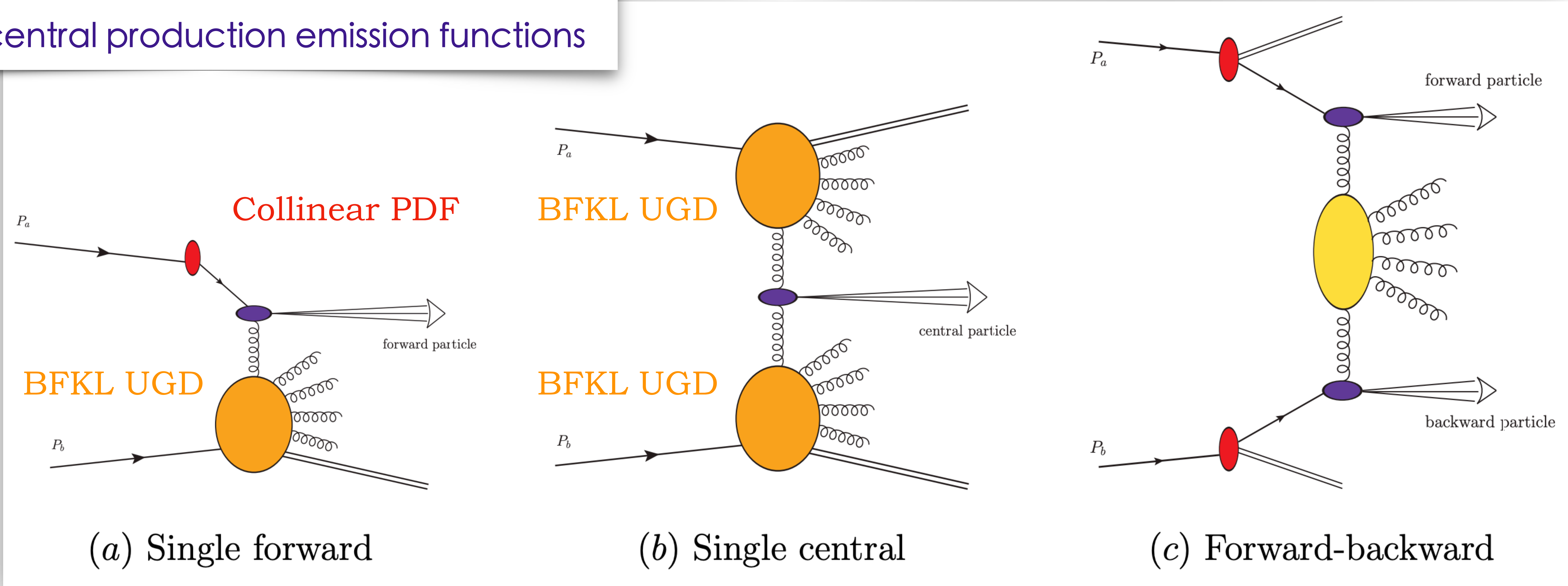
Singly/double off-shell coefficient functions
Forward/central production emission functions



(a) Single forward (b) Single central (c) Forward-backward

High-energy factorization at a glance

Singly/double off-shell coefficient functions
Forward/central production emission functions

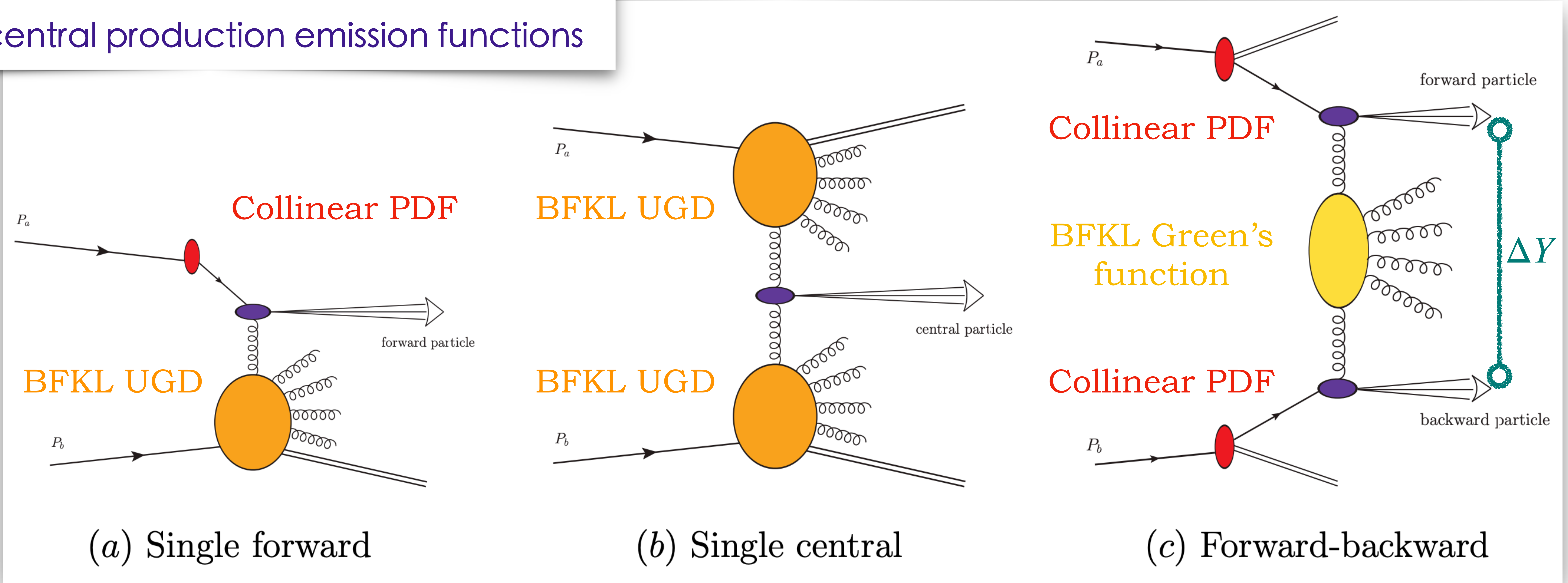


Fast q/g + small-x g	gg induced
Hybrid factorization	High-energy factorization
BFKL + Threshold	BFKL or small-x improved PDFs

🔗 [M. Bonvini, S. Marzani (2018)]

High-energy factorization at a glance

Singly/double off-shell coefficient functions
Forward/central production emission functions

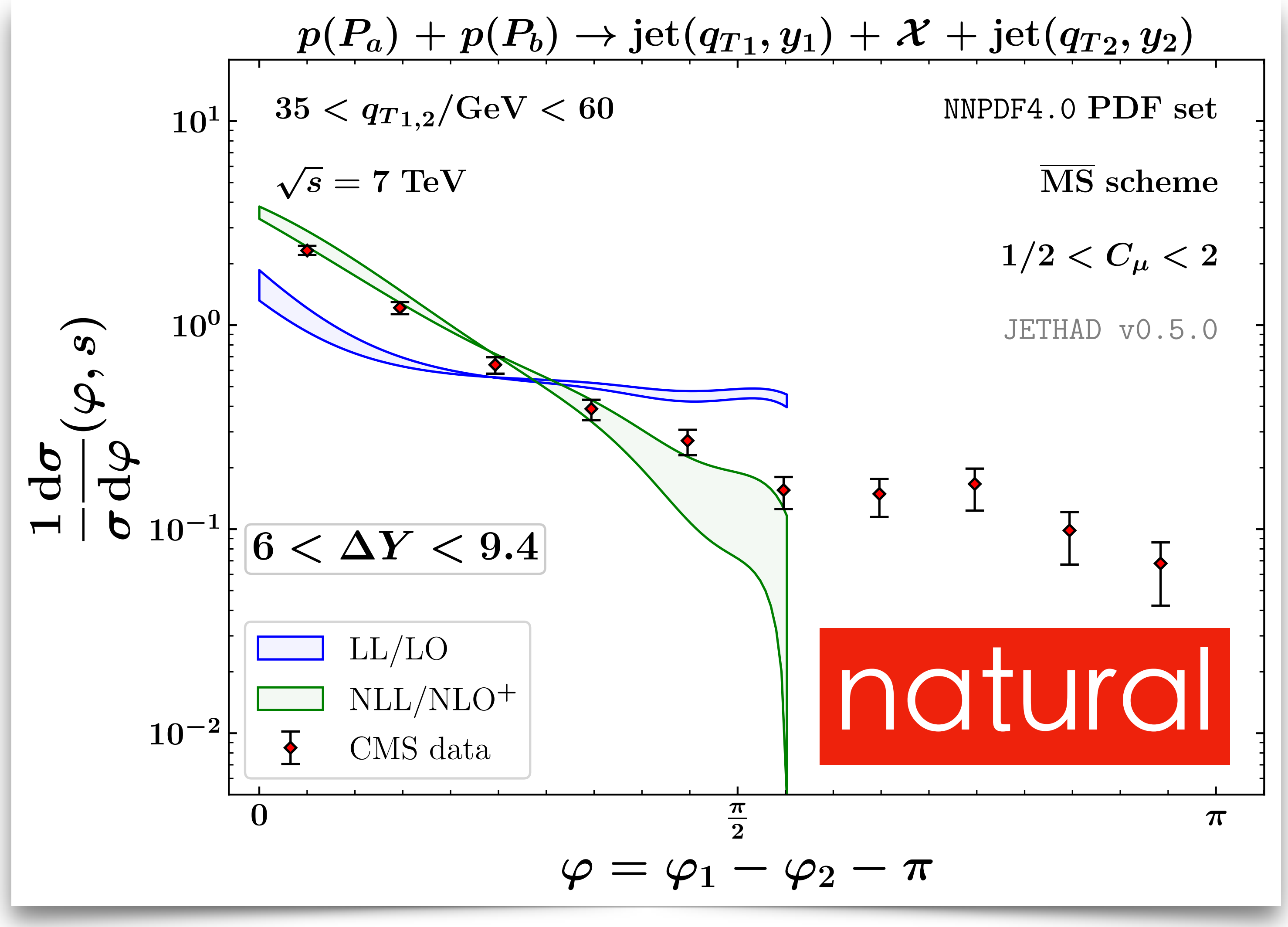


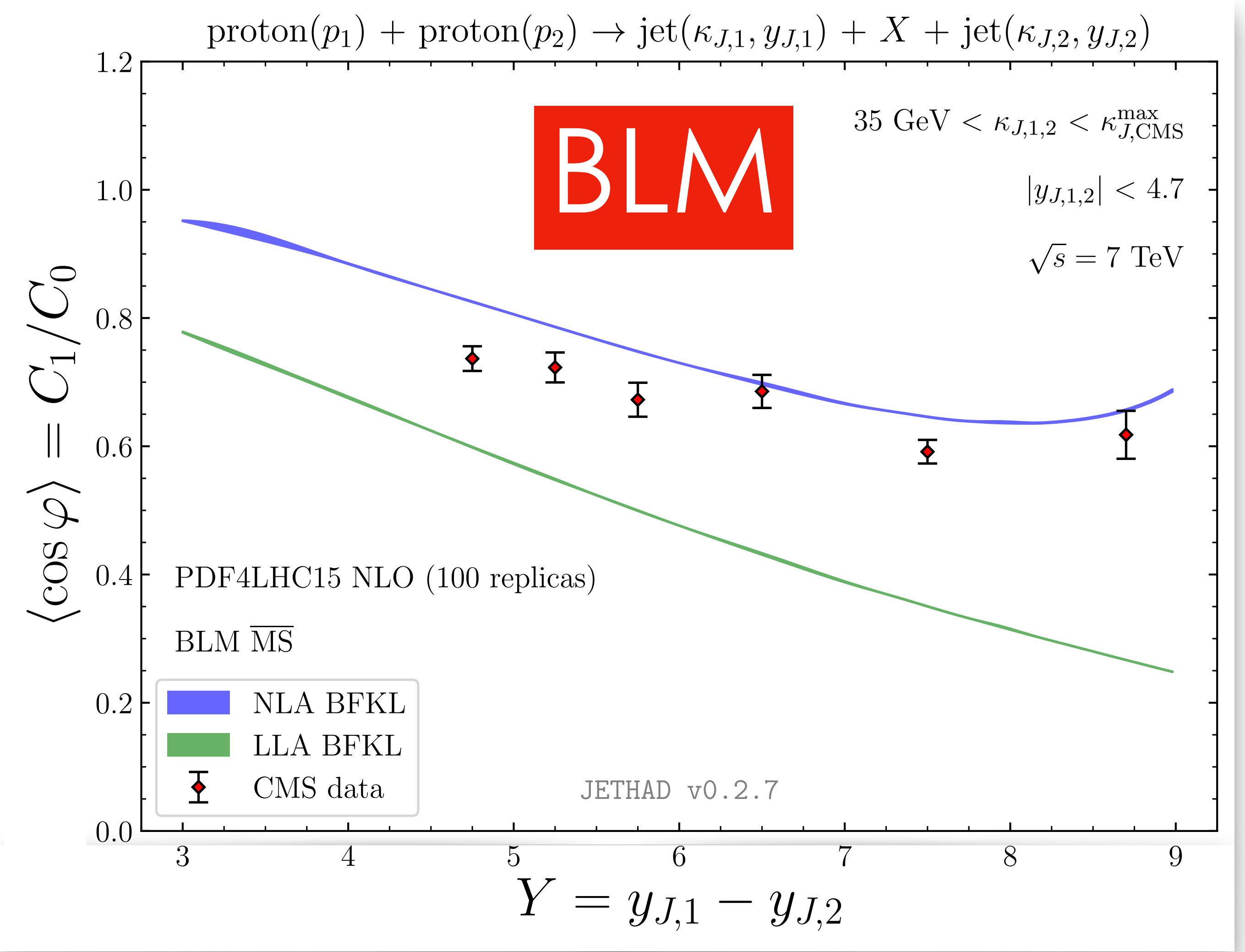
Single forward	Single central	Forward-backward
Fast q/g + small-x g	gg induced	Large rapidity distances, $\Delta Y \gg 1$
Hybrid factorization	High-energy factorization	High energies, moderate x
BFKL + Threshold	BFKL or small-x improved PDFs	PDFs + t-channel BFKL (NLL/NLO HyF)
	🔗 [M. Bonvini, S. Marzani (2018)]	Imbalance logs ← back-to-back

Mueller-Navelet jets @LHC & resummation instabilities

- BLM scales, theory vs experiment: CMS @7TeV with symmetric p_T-ranges ✓
- Strong manifestation of higher-order instabilities via scale variation (¡!)
- ¡ At natural scales: NLL/LL ratio large, no agreement with data, unphysical values !

[CMS Collaboration, JHEP 08 (2016) 139]
[B. Ducloué et al., Phys. Rev. Lett. 112 (2014) 082003]
[F. Caporale et al., Eur. Phys. J. C 74 (2014) 10, 3084]



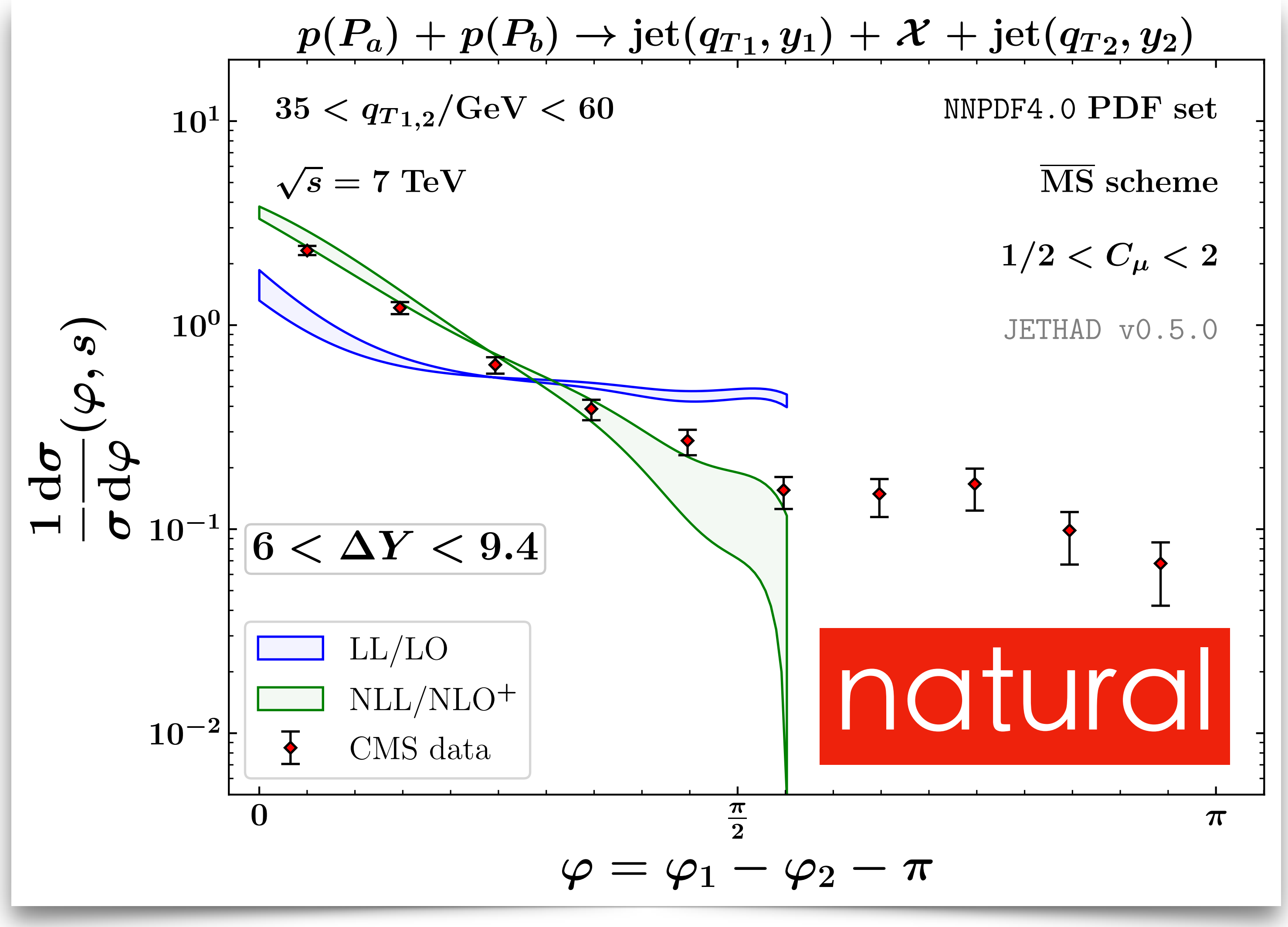


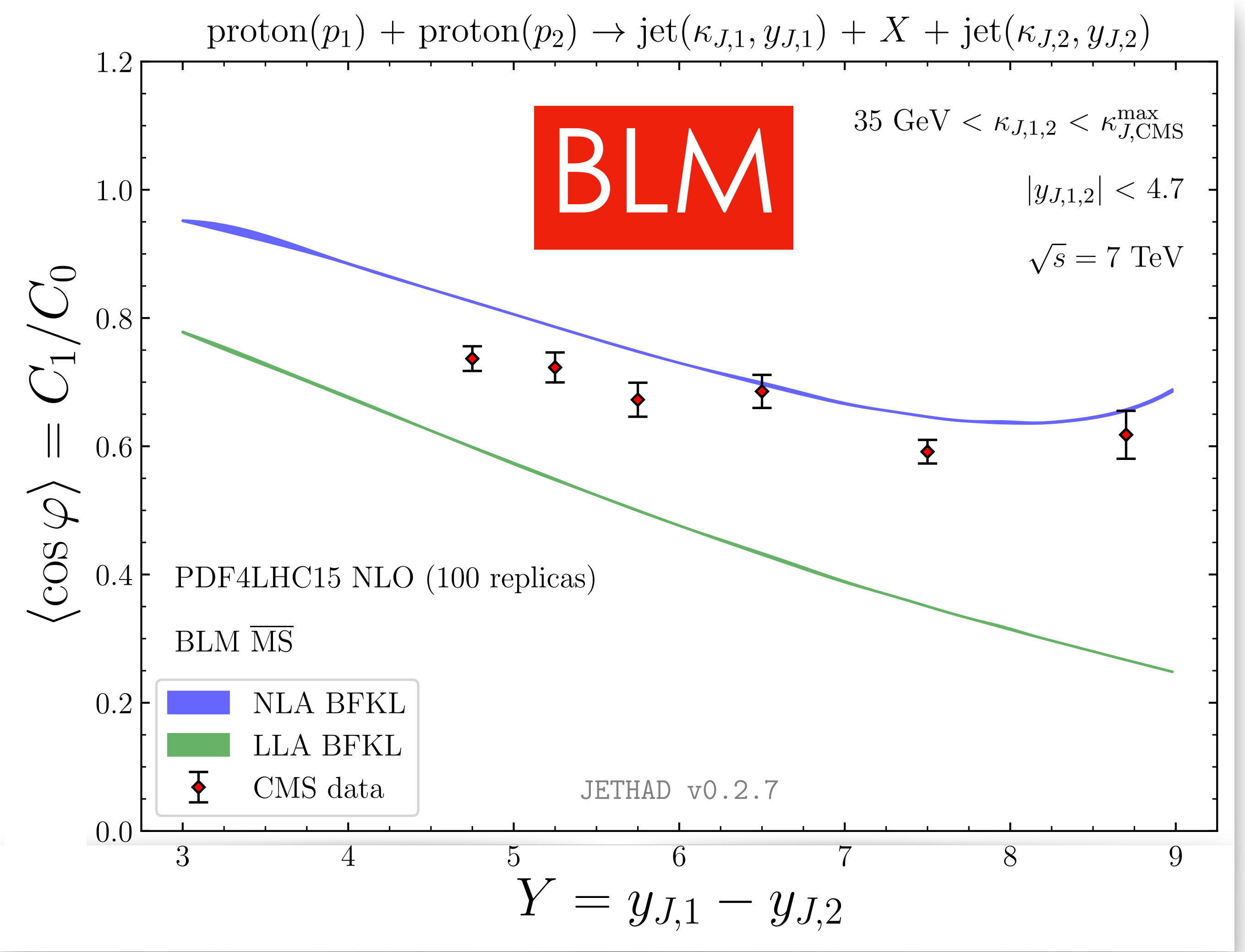
(left figure) [F. G. C., A. Papa, Phys. Rev. D 106 (2022) 11, 114004]
(right figure) [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]

Mueller-Navelet jets @LHC & resummation instabilities

- BLM scales, theory vs experiment: CMS @7TeV with symmetric p_T-ranges ✓
- Strong manifestation of higher-order instabilities via scale variation (¡!)
- ¡ At natural scales: NLL/LL ratio large, no agreement with data, unphysical values !

[CMS Collaboration, JHEP 08 (2016) 139]
[B. Ducloué et al., Phys. Rev. Lett. 112 (2014) 082003]
[F. Caporale et al., Eur. Phys. J. C 74 (2014) 10, 3084]





(left figure) [F. G. C., A. Papa, Phys. Rev. D 106 (2022) 11, 114004]
(right figure) [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]

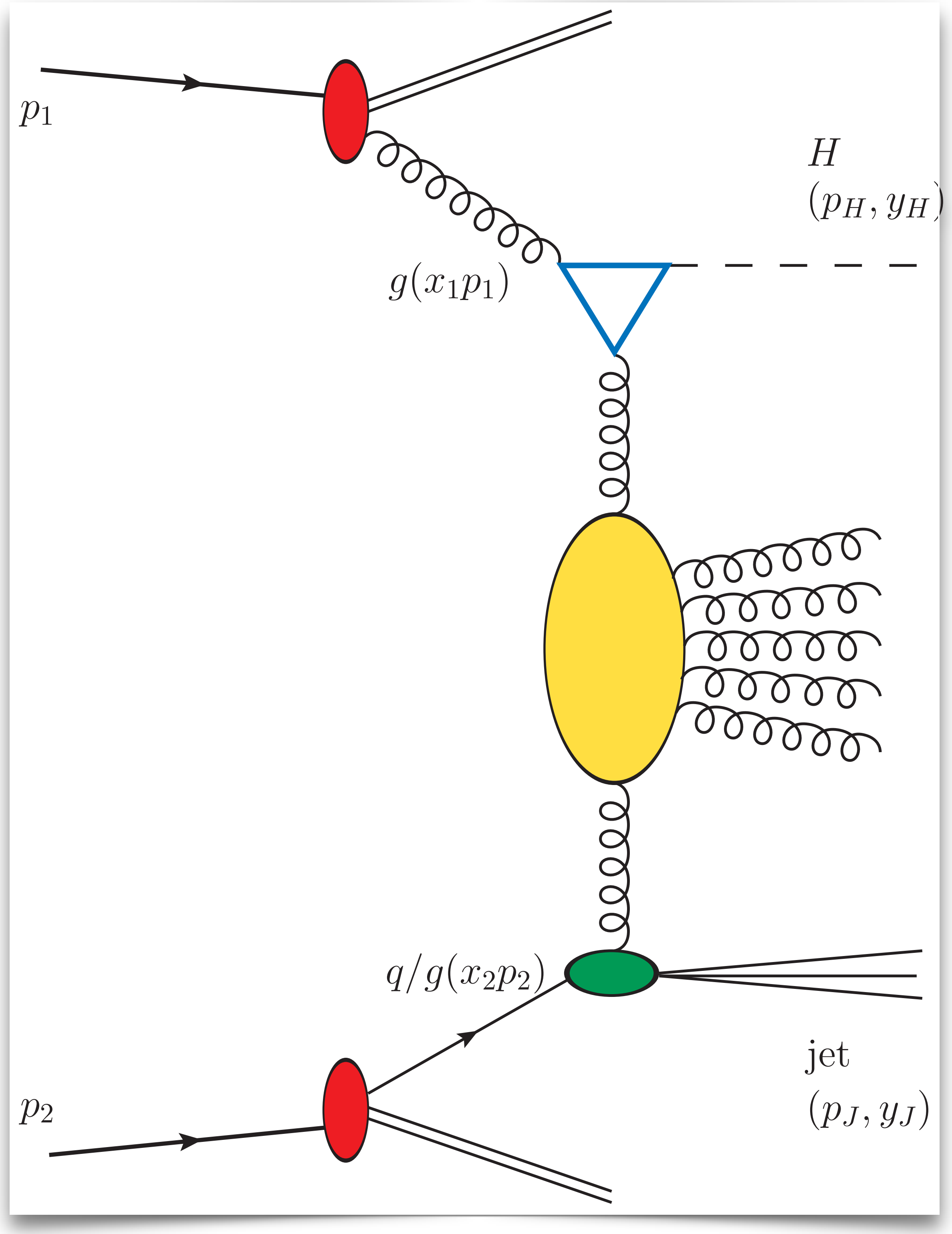
- $\mu_R^{\text{BLM}} \gg \mu_R^{\text{nat.}} \Rightarrow d\sigma^{\text{BLM}}/d\sigma^{\text{nat.}} \sim 10^{-(1\div 2)}$ ⇒ precision studies hampered ✗
- Unsuccessful scale optimization → processes featuring natural stability (¿?)

From Mueller-Navelet to Higgs and heavy flavor

Pheno path: hunt for channels leading to a NLL stabilization pattern at natural scales (¡!)

HIGGS BOSON

Stabilizers ⇔ large Higgs transverse masses



(Higgs + jet, NLL/NLO*) 🔗 [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

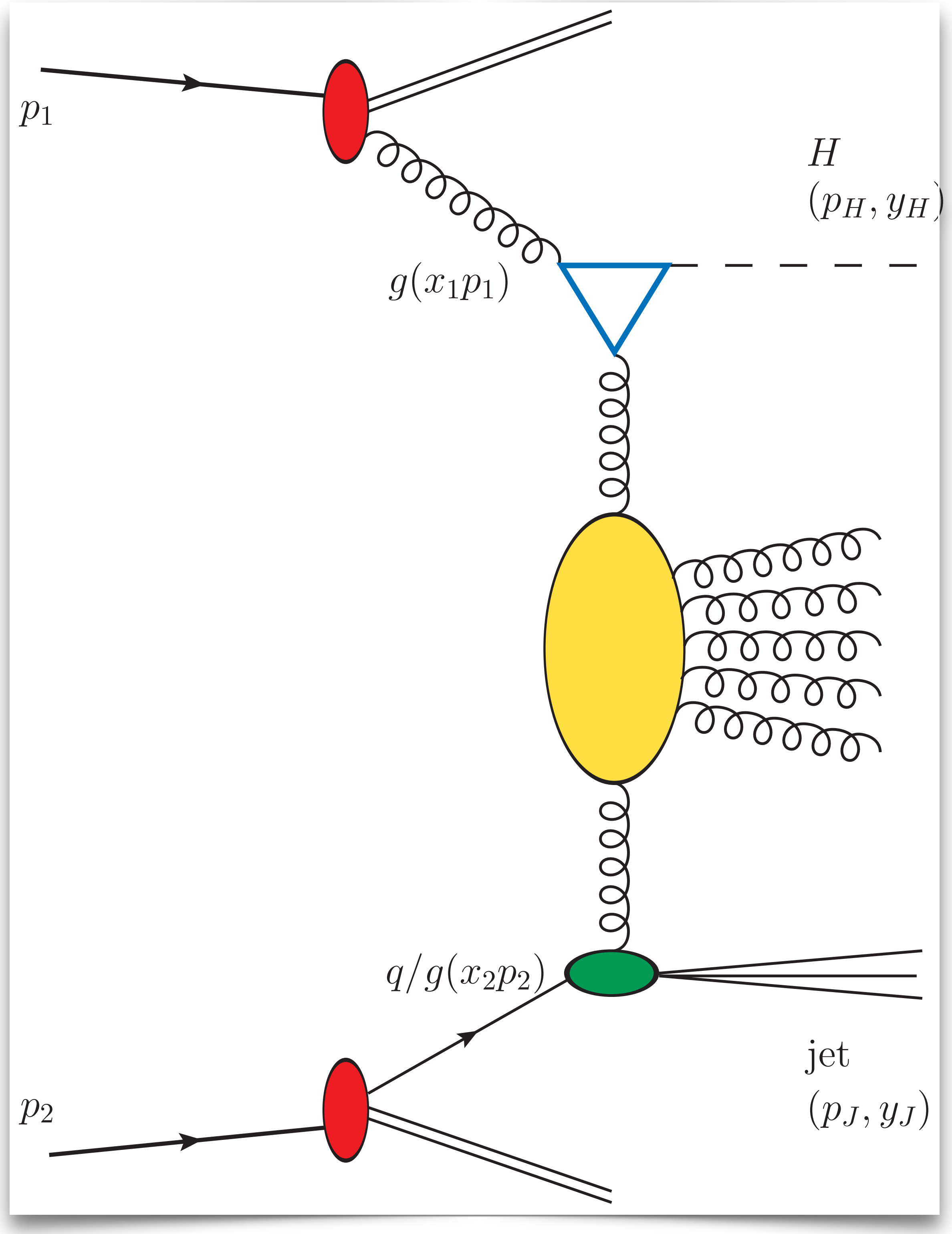
(NLO Higgs impact factor) 🔗 [F. G. C., M. Fucilla et al., JHEP 08 (2022) 092]

From Mueller-Navelet to Higgs and heavy flavor

Pheno path: hunt for channels leading to a NLL stabilization pattern at natural scales (¡!)

Higgs boson

Stabilizers ⇔ large Higgs transverse masses

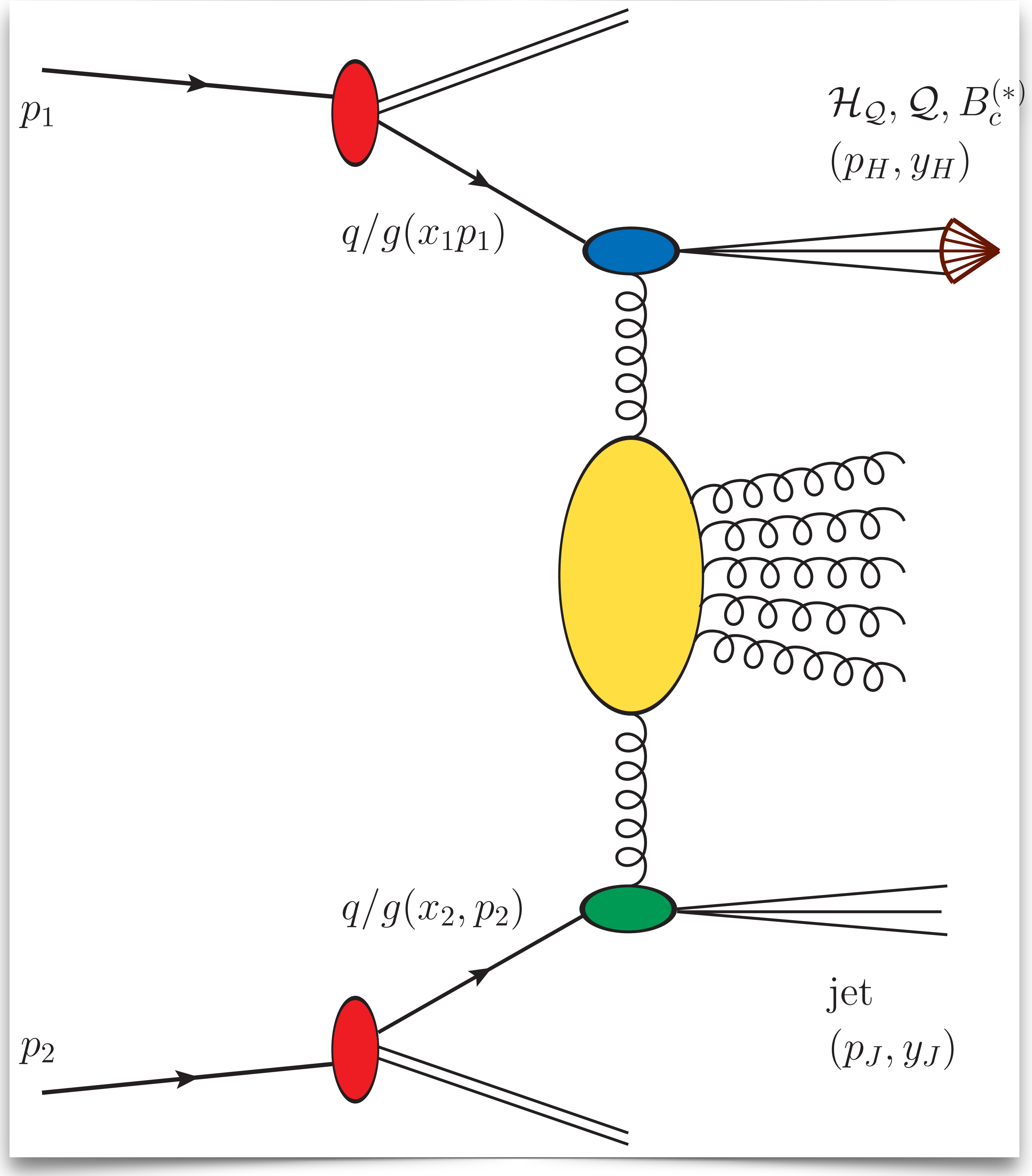


(Higgs + jet, NLL/NLO*) 🔗 [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

(NLO Higgs impact factor) 🔗 [F. G. C., M. Fucilla et al., JHEP 08 (2022) 092]

Heavy flavor at large p_T

Stabilizers ⇔ gluon fragmentation channels



($\Lambda_c^\pm$ baryons, NLL/NLO) 🔗 [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

(J/ψ or Υ, NLL/NLO) 🔗 [F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

($B_c^\pm(^1S_0)$ or $B_c^{*\pm}(^3S_1)$, NLL/NLO) 🔗 [F. G. C., Phys. Lett. B 835 (2022) 137554]

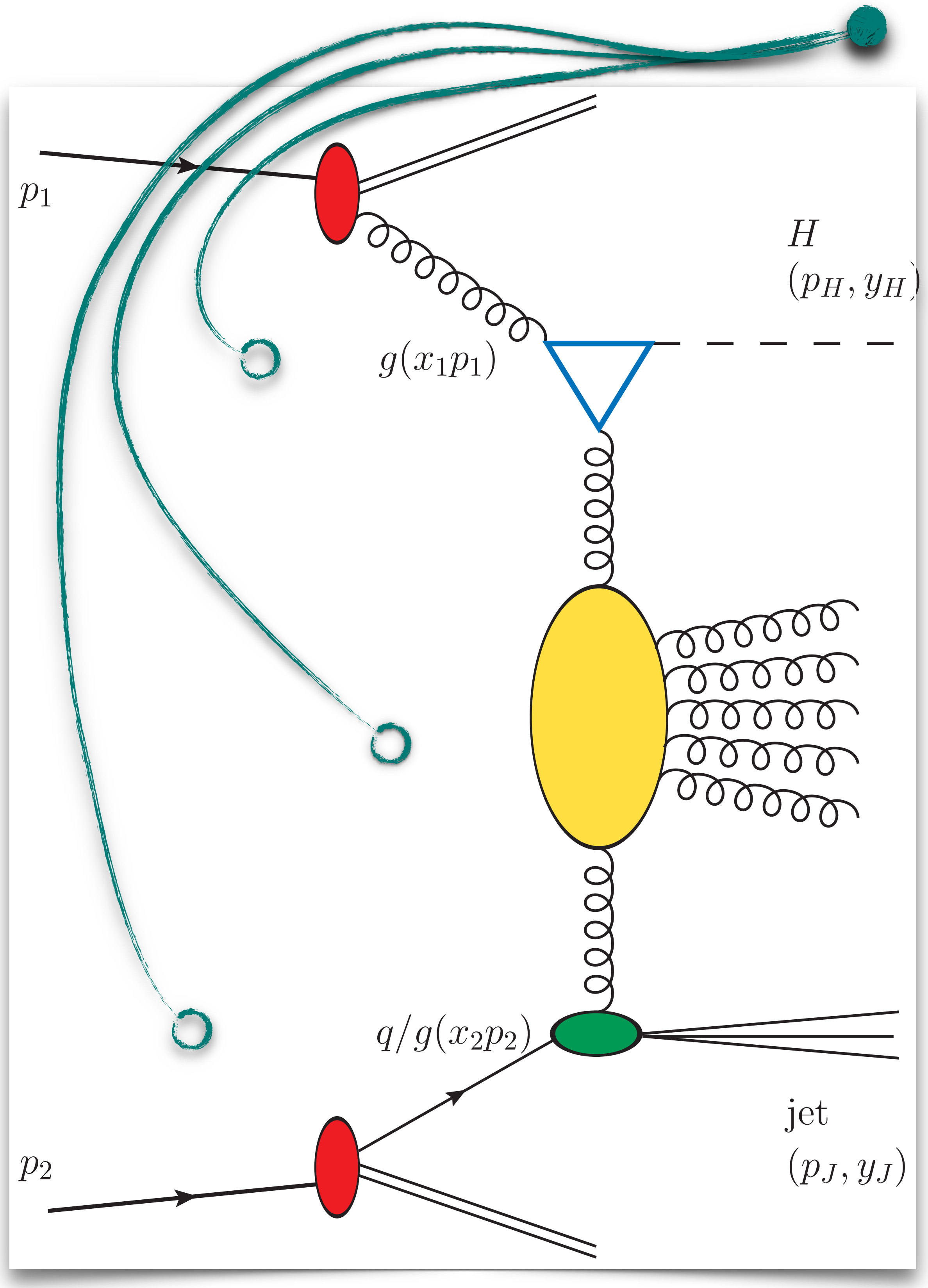
From Mueller-Navelet to Higgs and heavy flavor

Pheno path: hunt for channels leading to a NLL stabilization pattern at natural scales (¡!)

Higgs boson

Stabilizers ⇔ large Higgs transverse masses

$\mu_{F,R} \sim M_{H,\perp}$



NLO* = LO + NLO^RGE

NLL

NLO* = LO + NLO^RGE

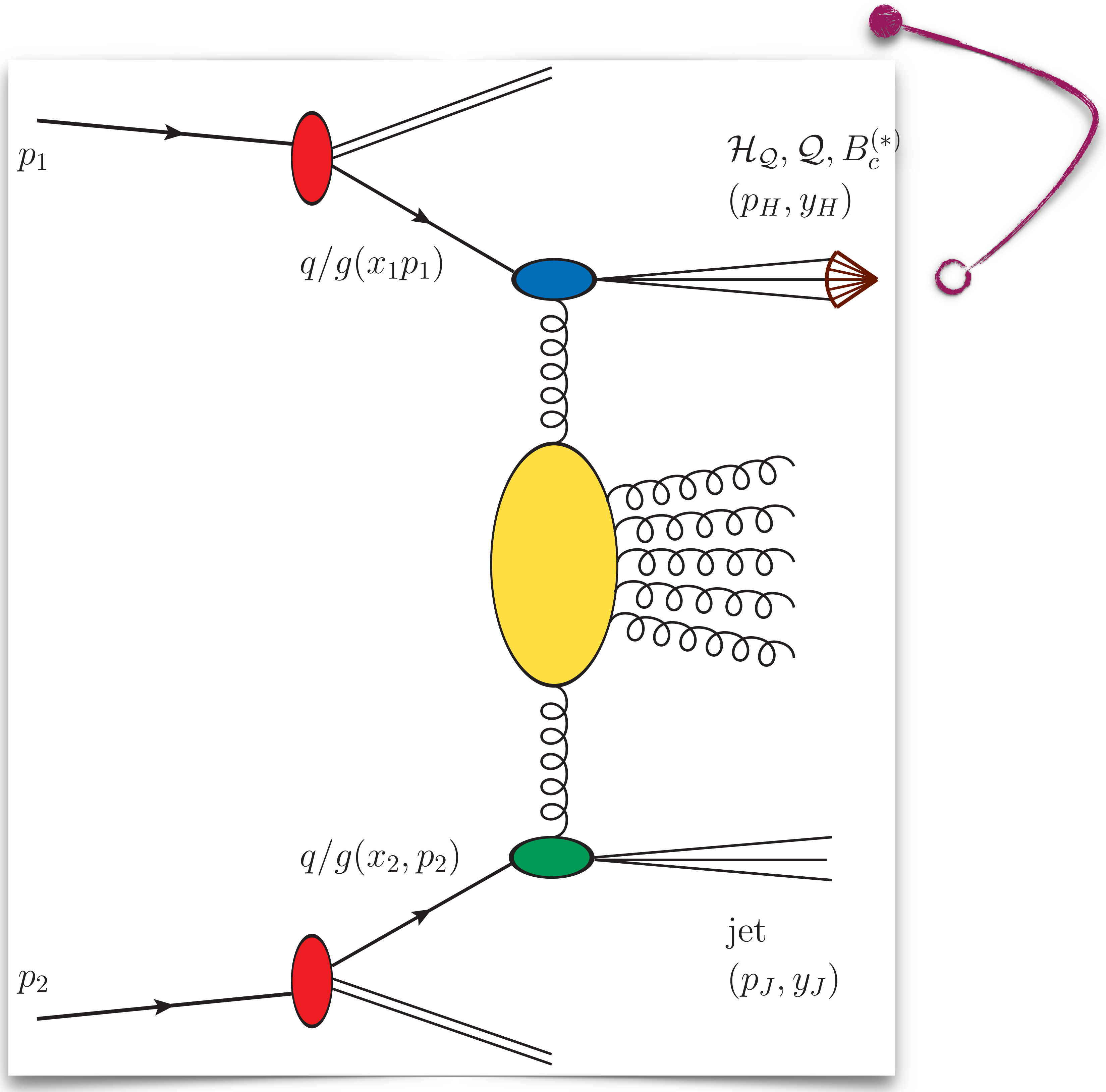
Heavy flavor at large p_T

Stabilizers ⇔ gluon fragmentation channels

NLO(+)

NLL

NLO(+)



(Higgs + jet, NLL/NLO*) [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

(NLO Higgs impact factor) [F. G. C., M. Fucilla et al., JHEP 08 (2022) 092]

($\Lambda_c^\pm$ baryons, NLL/NLO) [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

(J/ψ or Υ, NLL/NLO) [F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

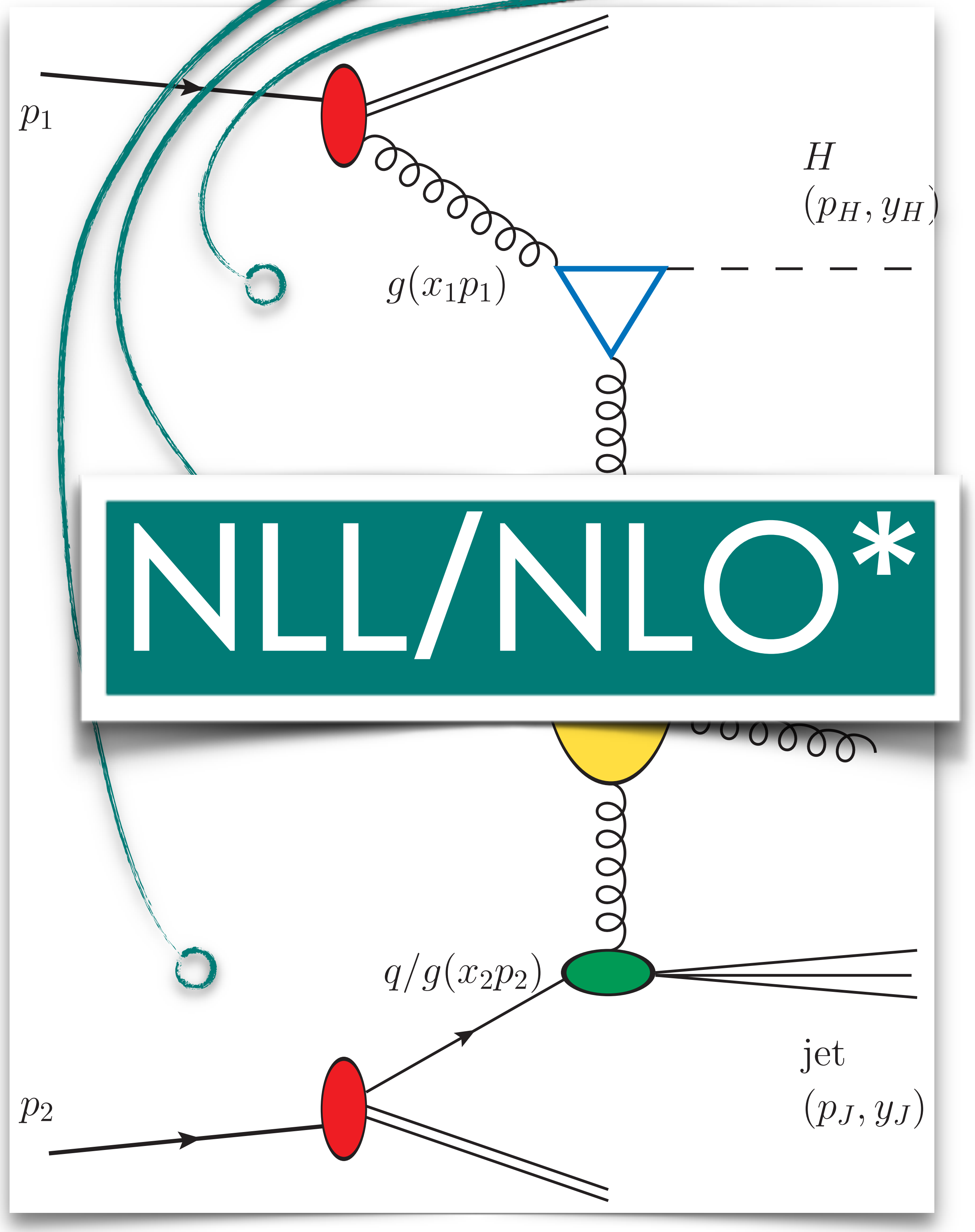
($B_c^\pm(^1S_0)$ or $B_c^{*\pm}(^3S_1)$, NLL/NLO) [F. G. C., Phys. Lett. B 835 (2022) 137554]

From Mueller-Navelet to Higgs and heavy flavor

Pheno path: hunt for channels leading to a NLL stabilization pattern at natural scales (¡!)

Higgs boson

Stabilizers ⇔ large Higgs transverse masses



NLL/NLO*

$\mu_{F,R} \sim M_{H,\perp}$

NLO*

= LO + NLO[RGE]

NLL

NLO*

= LO + NLO[RGE]

(Higgs + jet, NLL/NLO*) 🔗 [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

(NLO Higgs impact factor) 🔗 [F. G. C., M. Fucilla et al., JHEP 08 (2022) 092]

Heavy flavor at large p_T

Stabilizers ⇔ gluon fragmentation channels

NLO(+)

NLL

NLO(+)

($\Lambda_c^\pm$ baryons, NLL/NLO) 🔗 [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

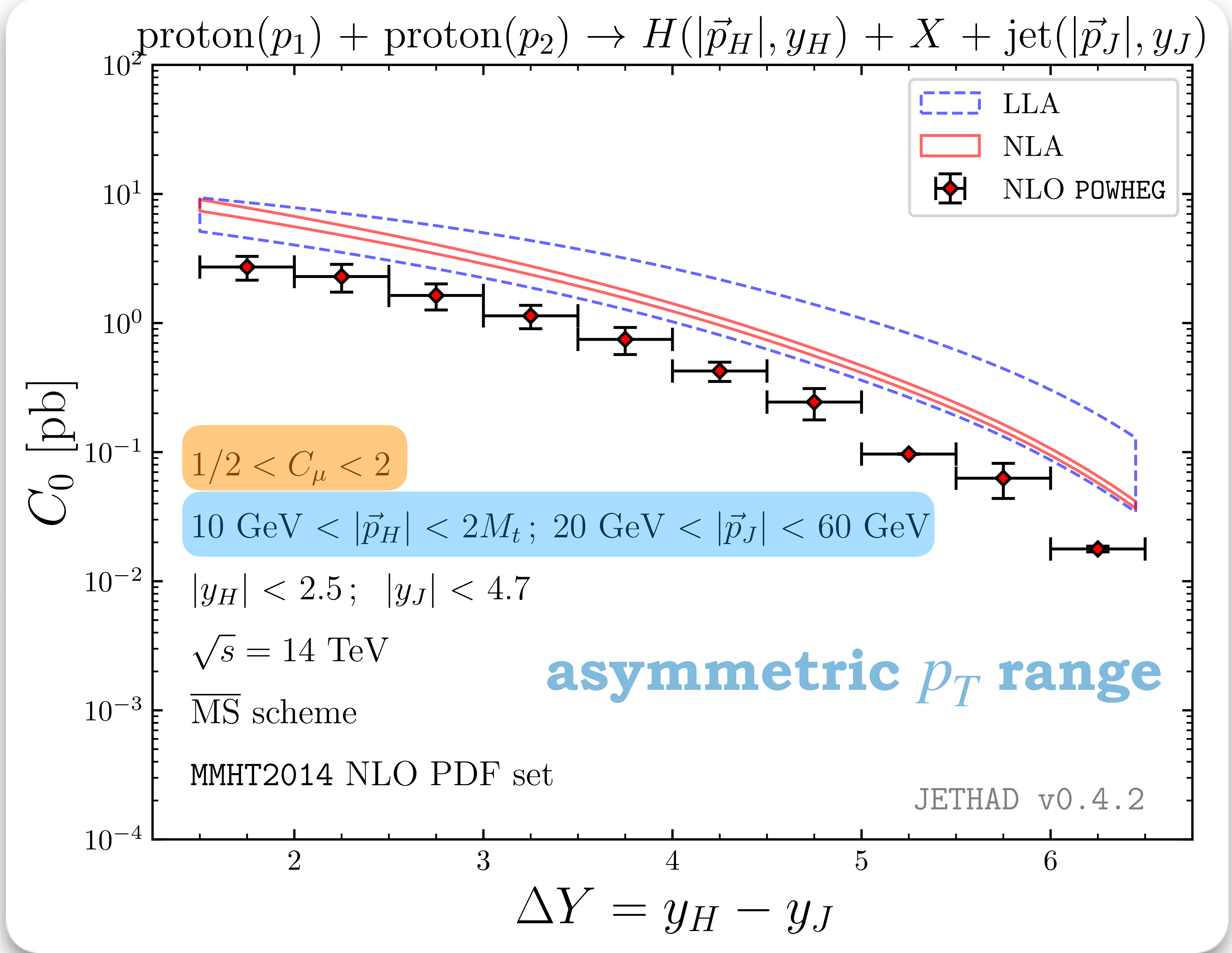
(J/ψ or Υ, NLL/NLO) 🔗 [F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

($B_c^\pm(^1S_0)$ or $B_c^{*\pm}(^3S_1)$, NLL/NLO) 🔗 [F. G. C., Phys. Lett. B 835 (2022) 137554]

Higgs + jet: ΔY-spectrum

$$\mathcal{C}_n(\Delta Y, s) = \int_{p_H^{\min}}^{p_H^{\max}} d|\vec{p}_H| \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_H^{\min}}^{y_H^{\max}} dy_H \int_{y_J^{\min}}^{y_J^{\max}} dy_J \, \delta\left(y_H - y_J - \Delta Y\right) \mathcal{C}_n$$

natural scales



[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

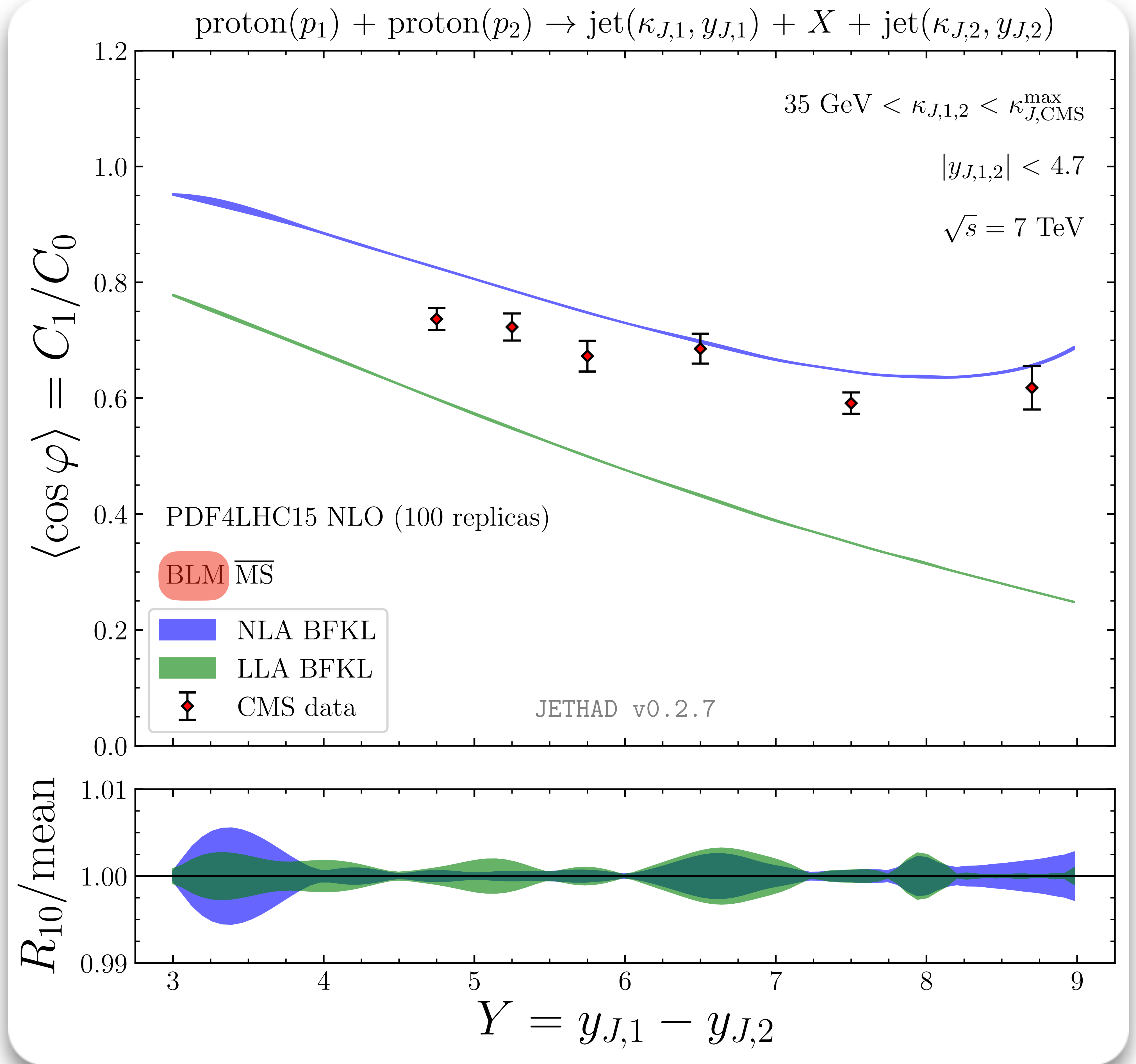
Higgs + jet: Angular correlations

$$R_{n0}(\Delta Y, s) = C_n/C_0 \equiv \langle \cos n\varphi \rangle$$

Mueller-Navelet jets

[B. Ducloué, L. Szymanowski, S. Wallon, Phys.Rev.Lett. 112 (2014) 082003]

(figure below) [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]



[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

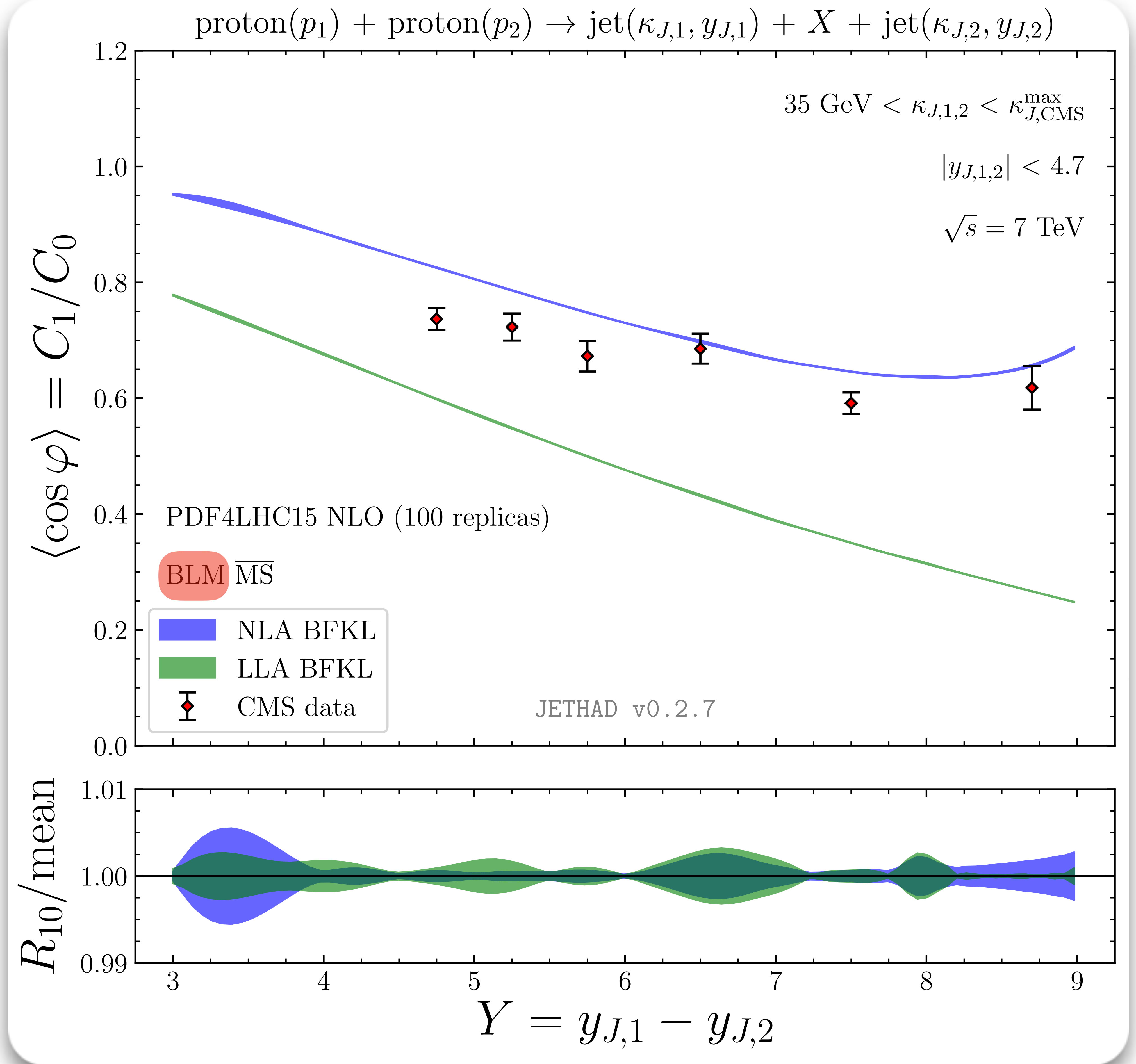
Higgs + jet: Angular correlations

$$R_{n0}(\Delta Y, s) = C_n/C_0 \equiv \langle \cos n\varphi \rangle$$

Mueller-Navelet jets

[B. Ducloué, L. Szymanowski, S. Wallon, Phys.Rev.Lett. 112 (2014) 082003]

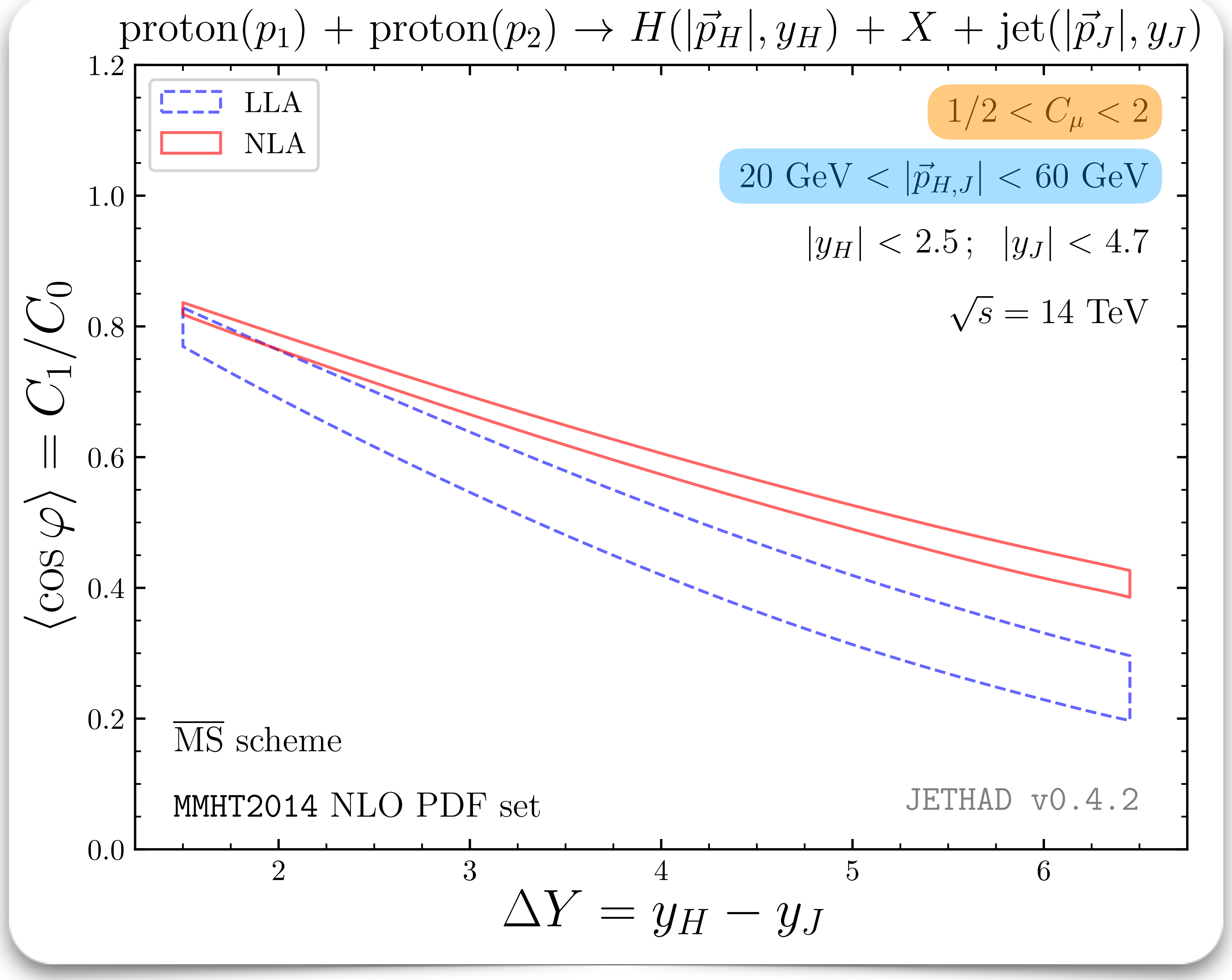
(figure below) [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]



Higgs + jet

(figure below) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 4, 293]

(NLO Higgs impact factor) [F. G. C. et al., under review (2022)]



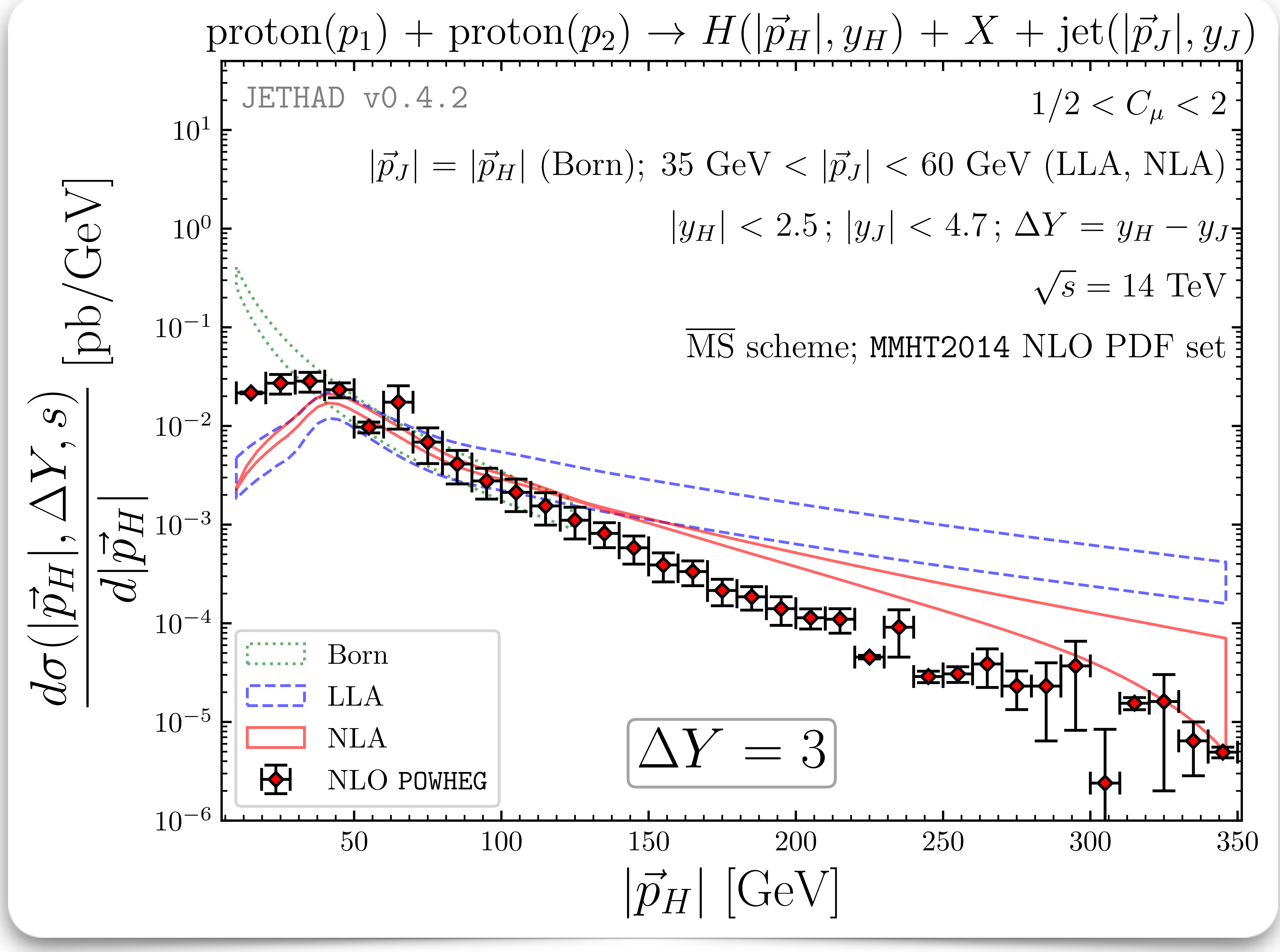
natural scales

symmetric p_T range

[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

Higgs + jet: Transverse-momentum spectrum

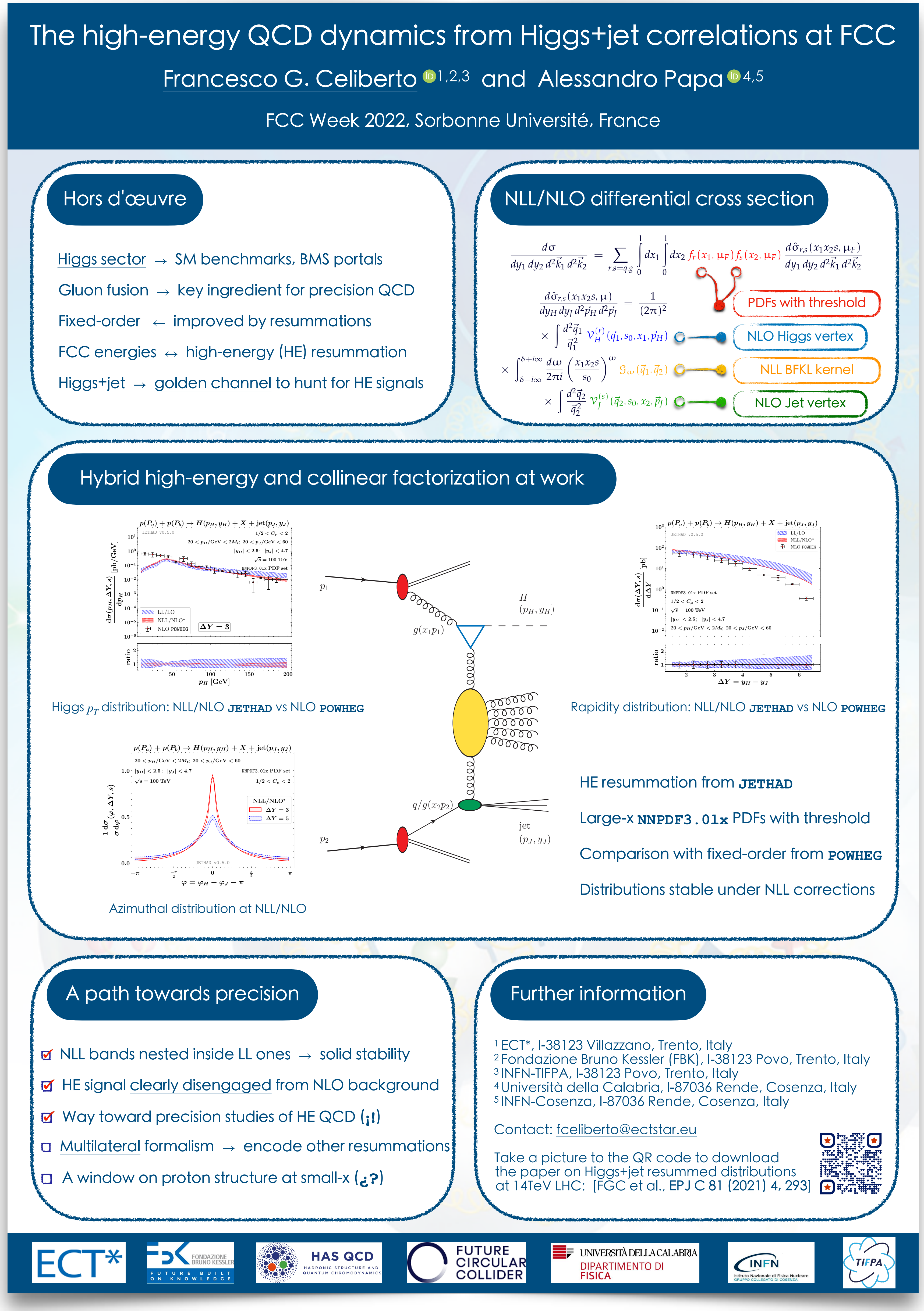
$$\frac{d\sigma(|\vec{p}_H|, \Delta Y, s)}{d|\vec{p}_H| d\Delta Y} = \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_H^{\min}}^{y_H^{\max}} dy_H \int_{y_J^{\min}}^{y_J^{\max}} dy_J \, \delta\left(y_H - y_J - \Delta Y\right) \mathcal{C}_0$$



- HE resummation from JETHAD
- Comparison with fixed-order POWHEG
- Distributions stable under NLL corrections

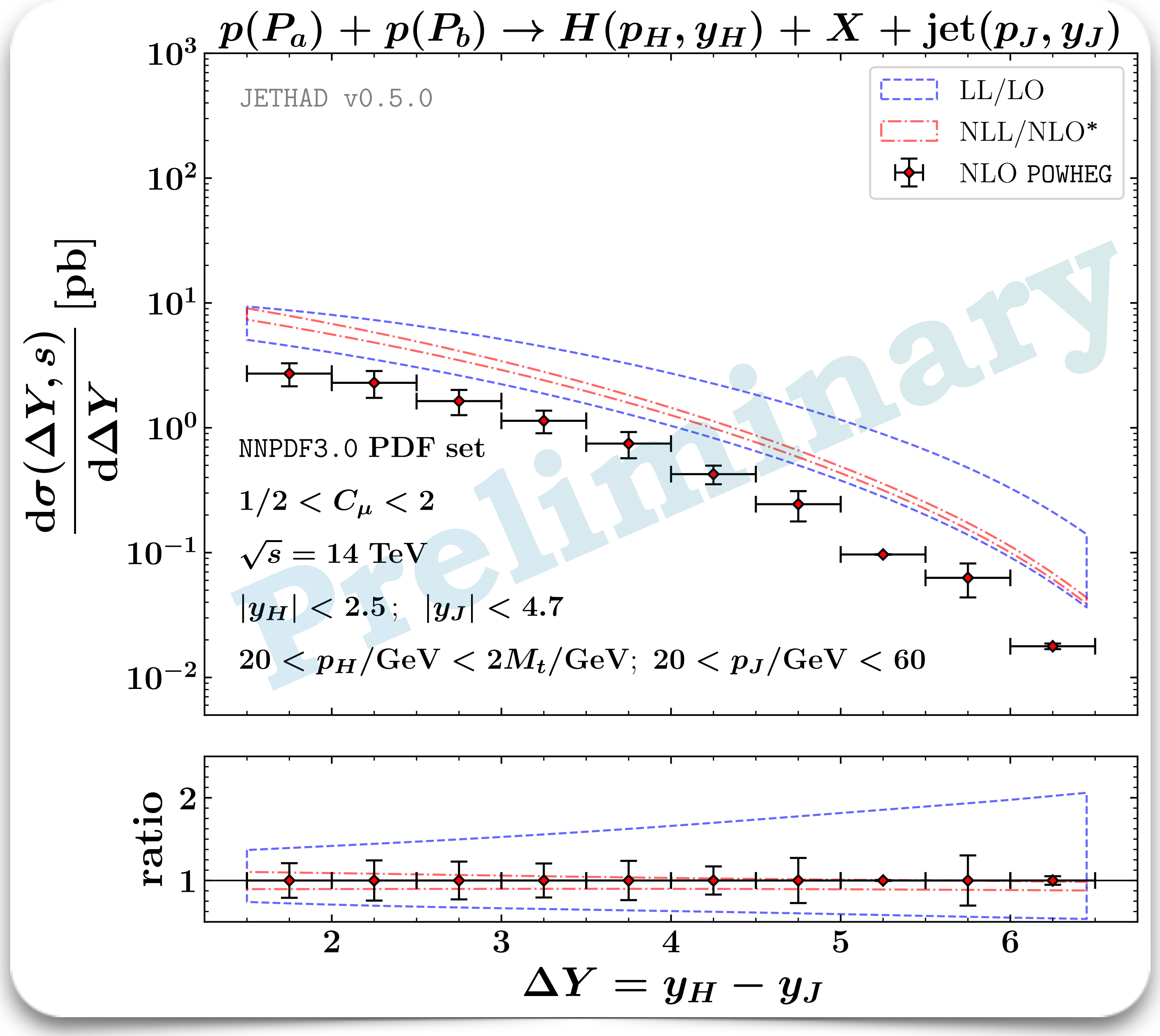
[F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

Higgs + jet: Highlights from the FCC Week 2022

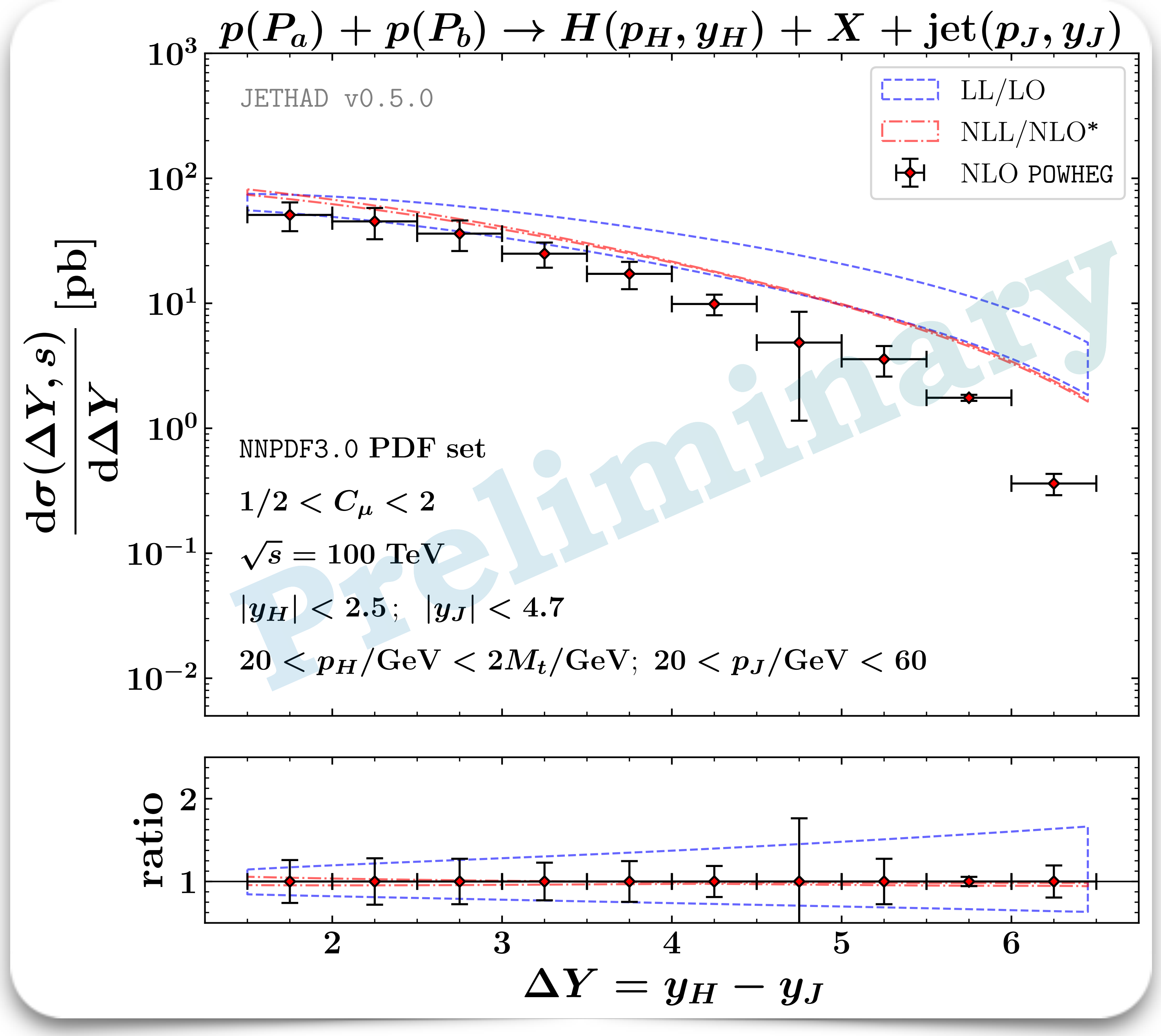


$$C_n(\Delta Y, s) = \int_{p_H^{\rm min}}^{p_H^{\rm max}} d|\vec{p}_H| \int_{p_J^{\rm min}}^{p_J^{\rm max}} d|\vec{p}_J| \int_{y_H^{\rm min}}^{y_H^{\rm max}} dy_H \int_{y_J^{\rm min}}^{y_J^{\rm max}} dy_J\, \delta\left(y_H - y_J - \Delta Y\right) \mathcal{C}_n$$

Rapidity distribution: NLL/NLO* JETHAD vs NLO POWHEG



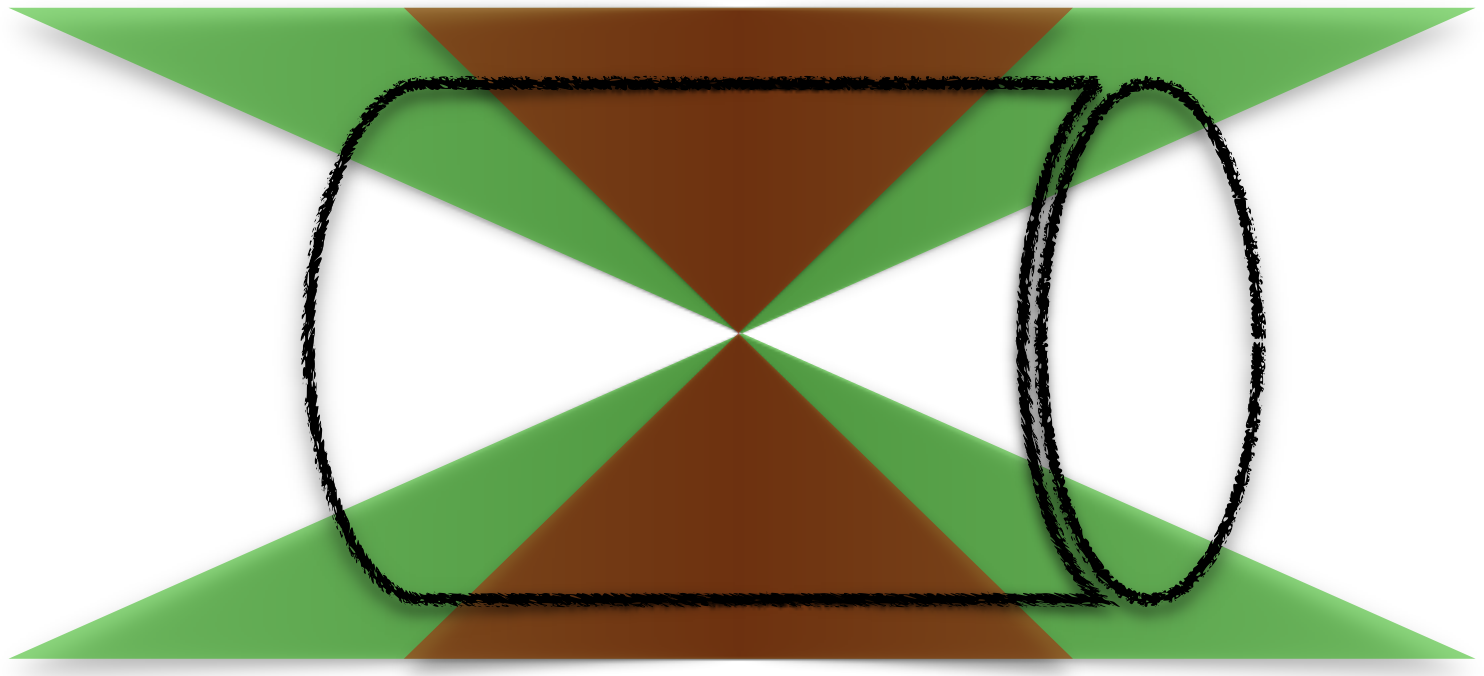
14 TeV LHC



100 TeV FCC

High-energy QCD at new-gen Forward Facilities

Forward + backward CMS detections: Mueller-Navelet, hadron-jet, di-hadron



$|y_{\rm jet}| < 4.7$

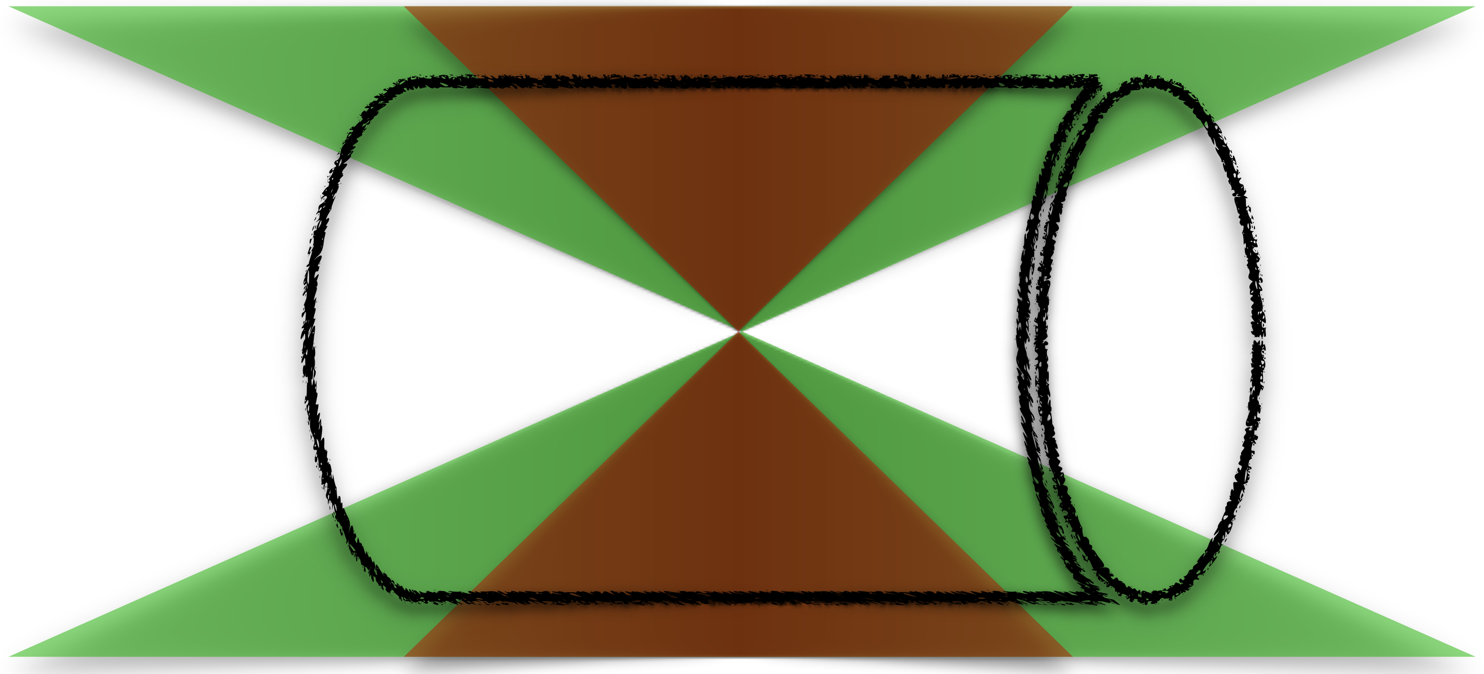
barrel + endcap

$|y_{\rm hadron}| < 2.4$

barrel

High-energy QCD at new-gen Forward Facilities

- Forward + backward CMS detections: Mueller-Navelet, hadron-jet, di-hadron



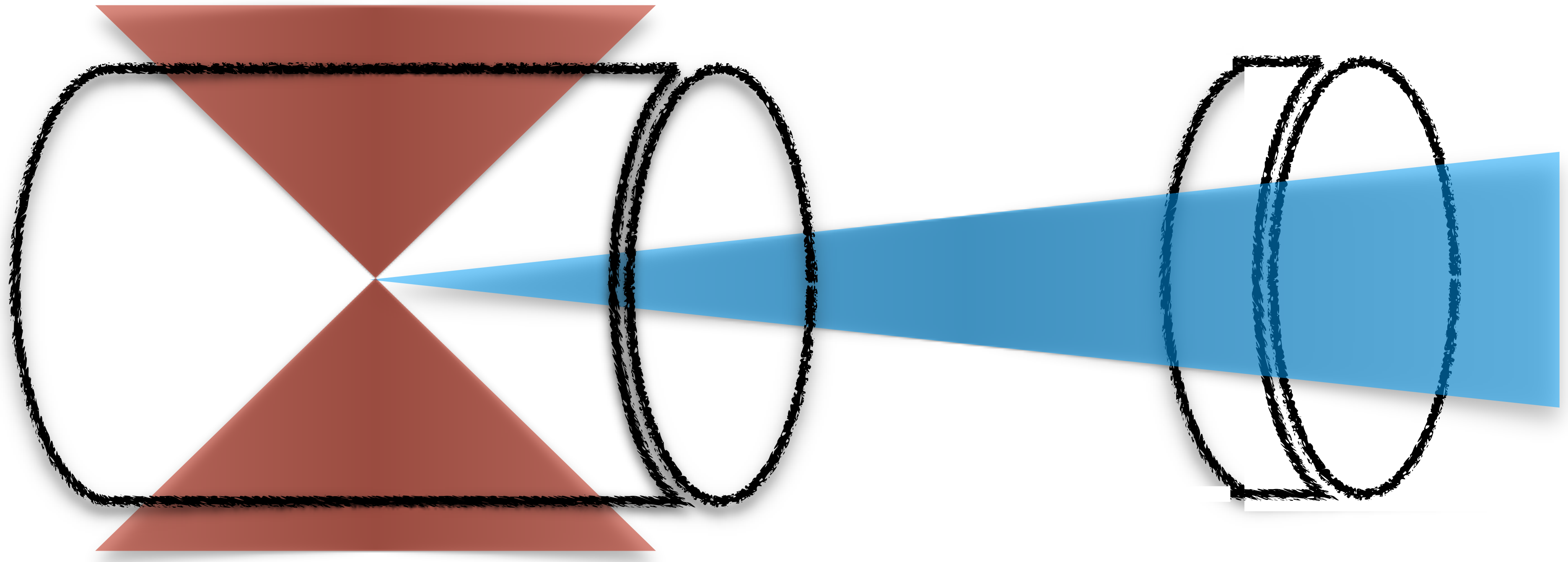
$|y_{\rm jet}| < 4.7$

barrel + endcap

$|y_{\rm hadron}| < 2.4$

barrel

- Ultra-forward FPF + central ATLAS detections: single-charmed hadrons + Higgs



$5 < |y_{D^*, \Lambda_c}| < 7$

FPF

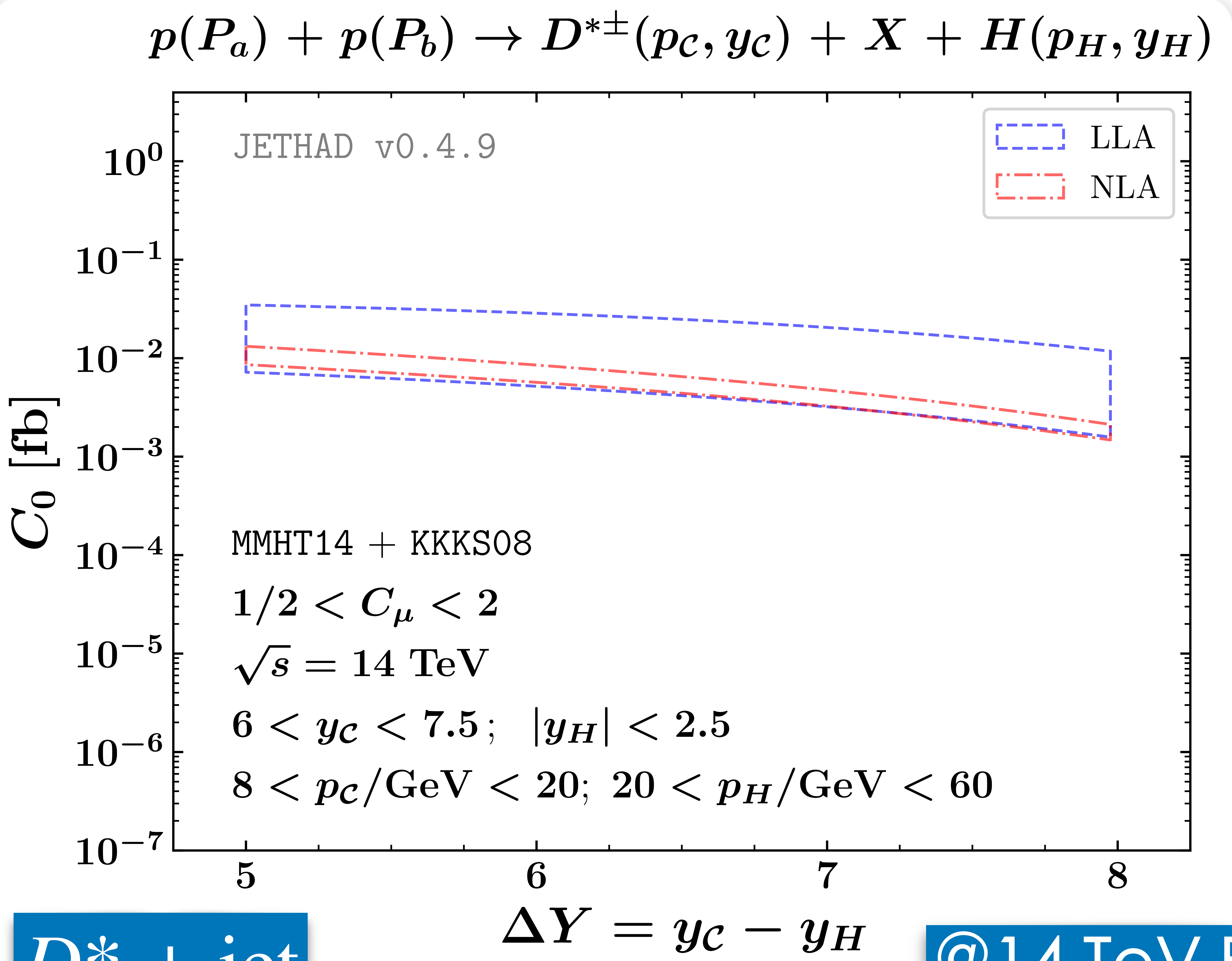
$|y_{\rm Higgs}| < 2.5$

ATLAS barrel

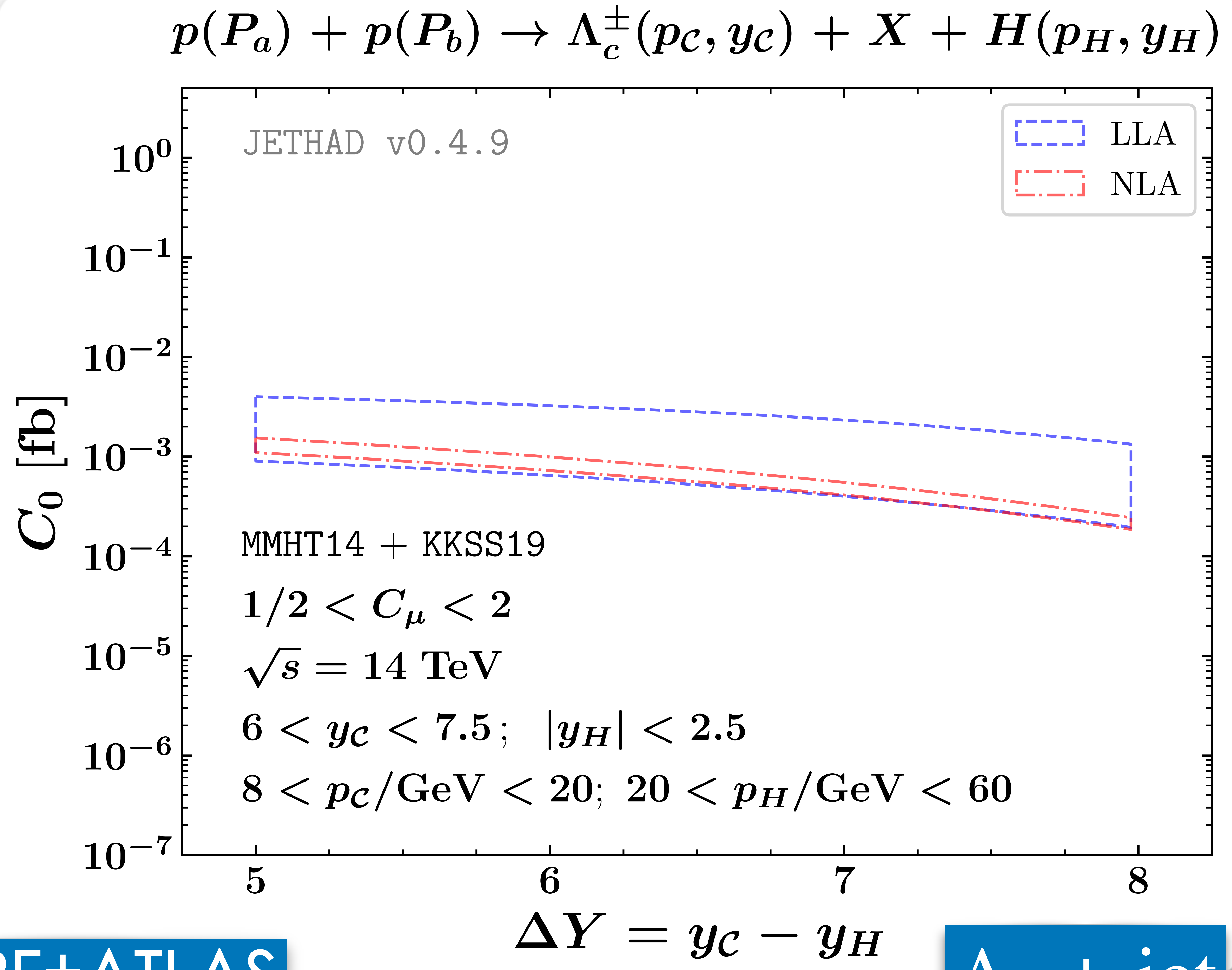
(charm + Higgs) 🔗 [F. G. C. et al., Phys. Rev. D 105 (2022) 11, 114056]

(light mesons + heavy flavor) 🔗 [F. G. C., Phys. Rev. D 105 (2022) 11, 114008]

Ultraforward charm + Higgs: ΔY-spectrum



D^* + jet

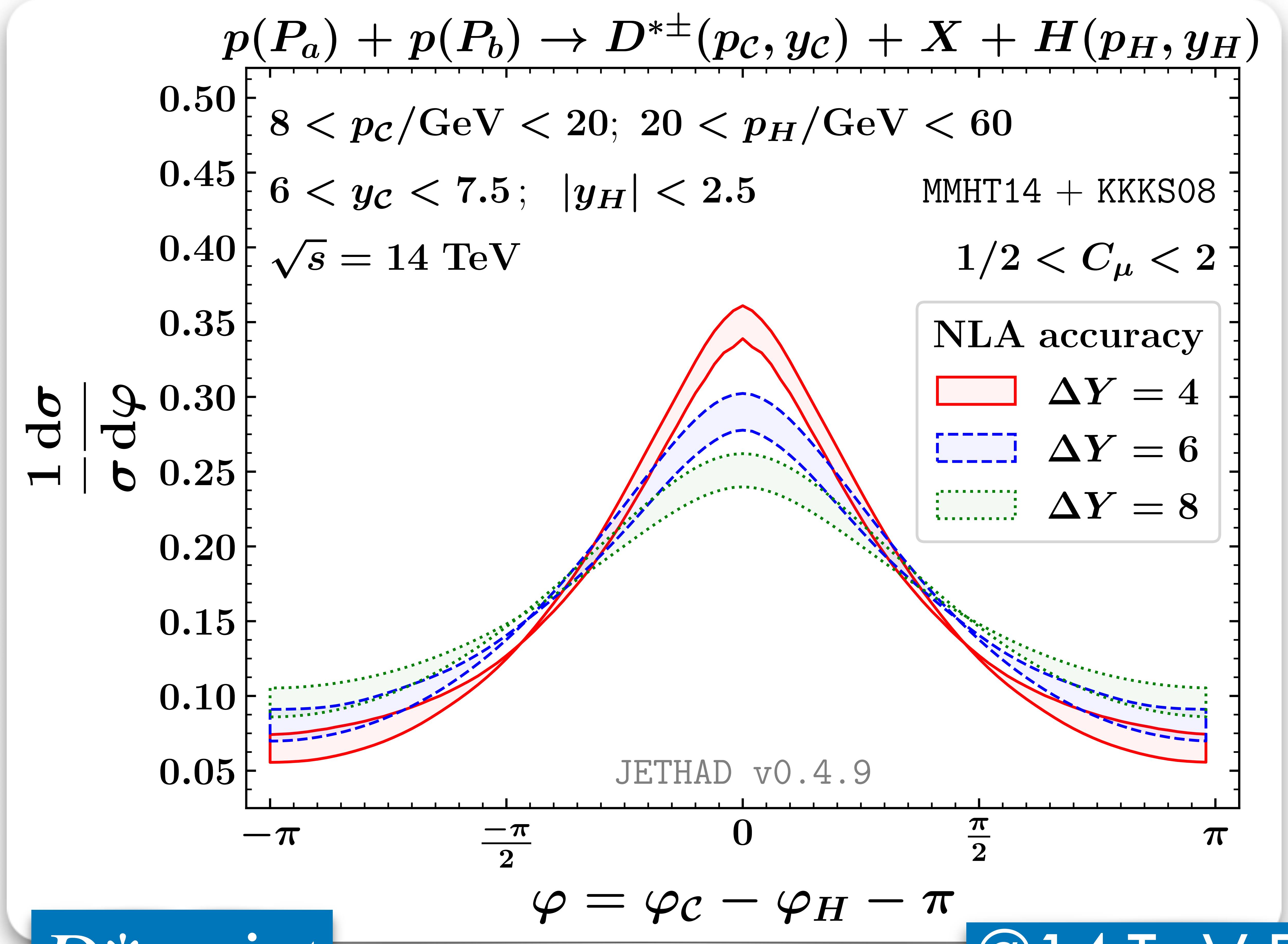


@14 TeV FPF+ATLAS

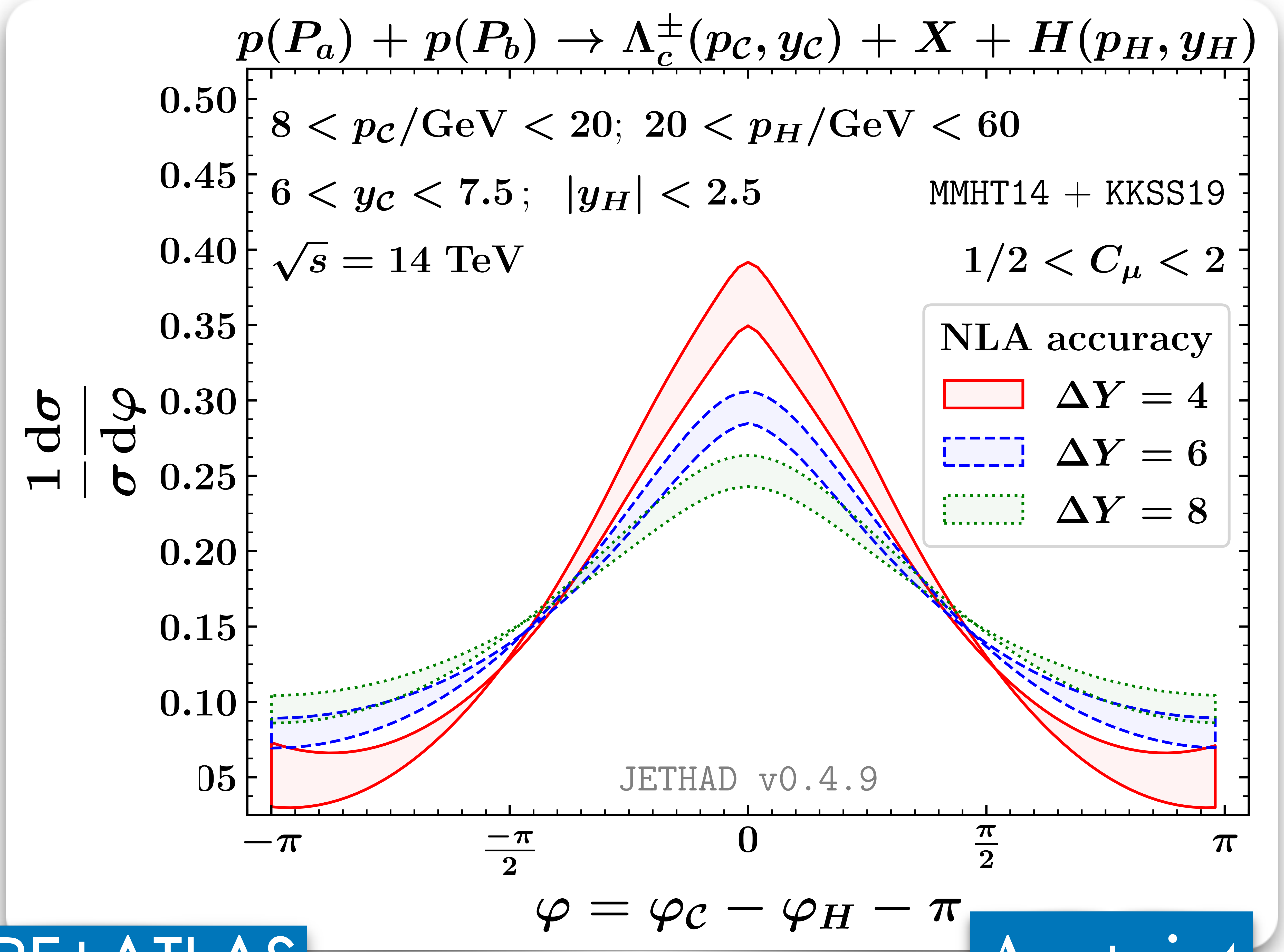
Λ_c + jet

[F. G. C., M. Fucilla, M. M. A. Mohammed, A. Papa, Phys. Rev. D 105 (2022) 11, 114056]

Ultraforward charm + Higgs: Azimuthal multiplicity



$D^* + \text{jet}$



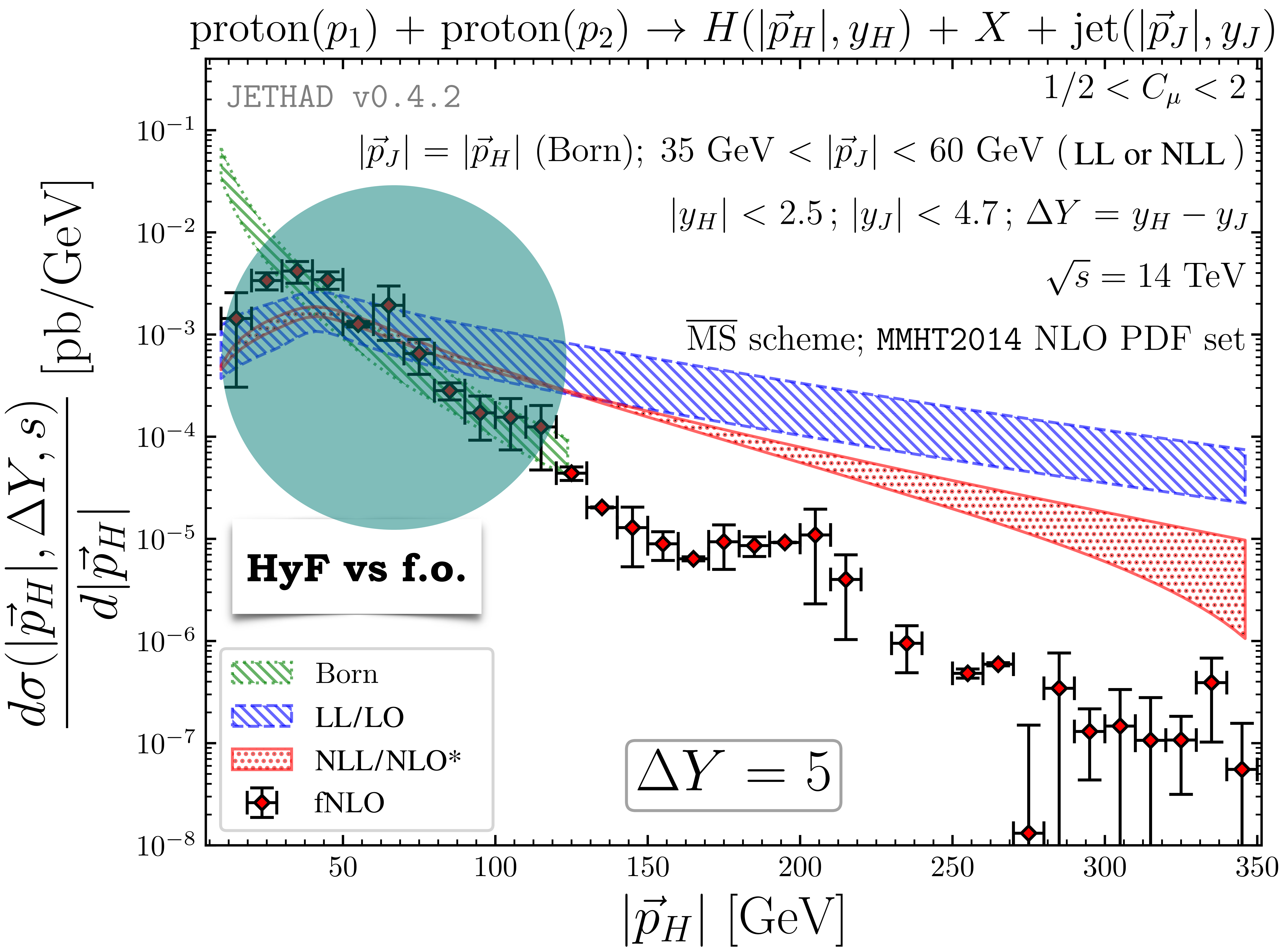
@14 TeV FPF+ATLAS

$\Lambda_c + \text{jet}$

[F. G. C., M. Fucilla, M. M. A. Mohammed, A. Papa, Phys. Rev. D 105 (2022) 11, 114056]

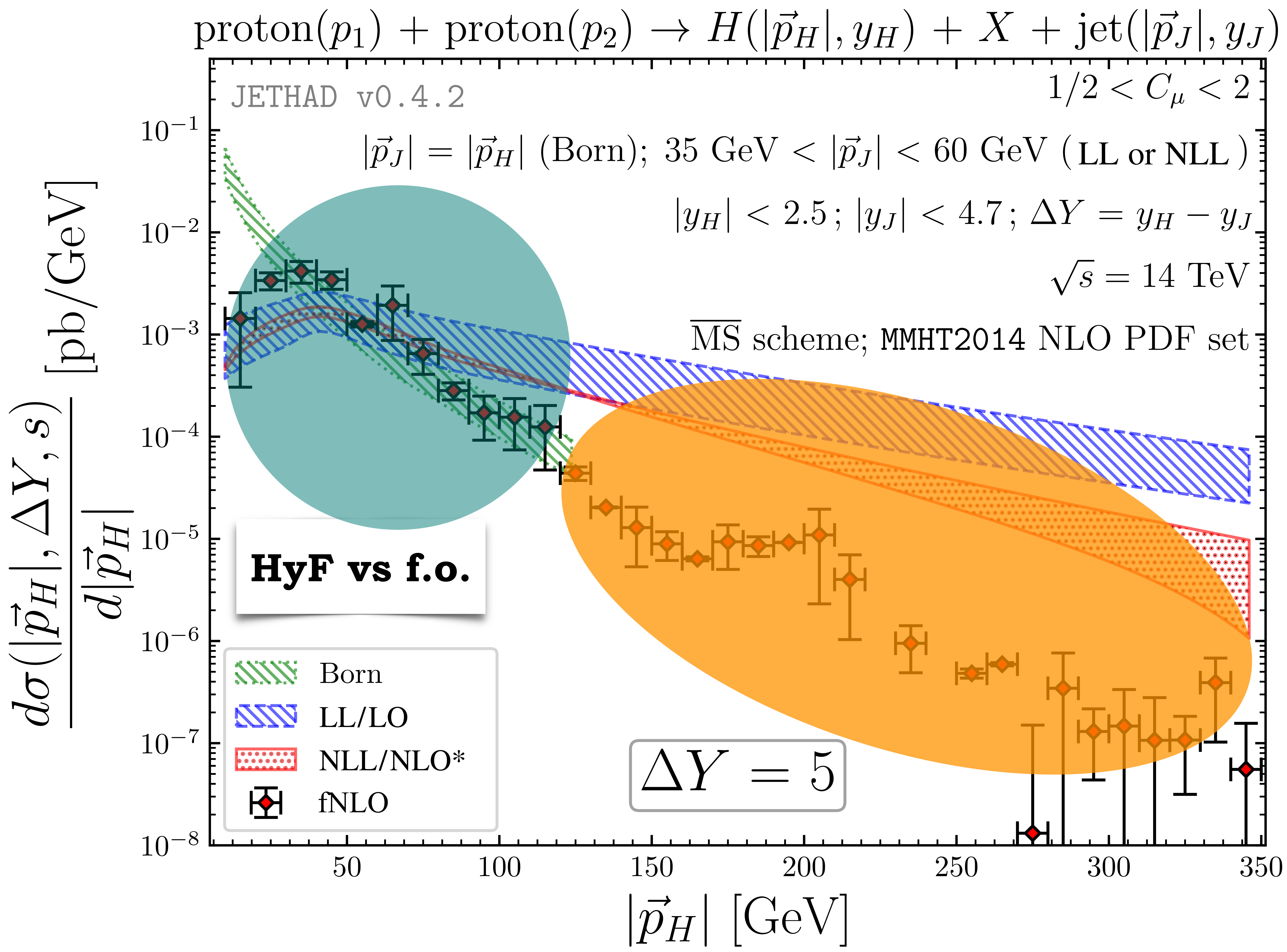
ALTERNATIVE CONCLUSIONS

(Higgs + jet, NLL/NLO* HyF) 🔗 [F. G. C., D Yu. Ivanov, M, M. A. Mohammed, A. Papa, Eur. Phys. J. C (2021) 8, 780]



¡ **Precision corrections** *expected*

(Higgs + jet, NLL/NLO* HyF) 🔗 [F. G. C., D Yu. Ivanov, M, M. A. Mohammed, A. Papa, Eur. Phys. J. C (2021) 8, 780]



¡ **Precision corrections** *expected*, but **HyF** *predicts* **large deviations** from **f.o.** !

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

JETHAD Method → NLL/NLO Additive Matching (analytic: BFKL kernel + coefficient functions)

$$\underbrace{\mathrm{d}\sigma^{\rm NLL/NLO^{-}}(\Delta Y, \varphi, s)} \;=\; \underbrace{\underbrace{\mathrm{d}\sigma^{\rm NLO}(\Delta Y, \varphi, s)}_{\textbf{NLO}\ \text{fixed order}}}_{\textbf{NLO}\ \texttt{POWHEG}\ \text{w/o PS}} \;+\; \mathrm{d}\sigma^{\rm NLL^{-}}(\Delta Y, \varphi, s) \;-\; \Delta\mathrm{d}\sigma^{\rm NLL/NLO^{-}}(\Delta Y, \varphi, s)$$

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

JETHAD Method → NLL/NLO Additive Matching (analytic: BFKL kernel + coefficient functions)

$$\underbrace{\mathrm{d}\sigma^{\mathrm{NLL/NLO^-}}(\Delta Y, \varphi, s)} = \underbrace{\underbrace{\mathrm{d}\sigma^{\mathrm{NLO}}(\Delta Y, \varphi, s)}_{\textbf{NLO}\ \text{fixed order}}}_{\textbf{NLO}\ \texttt{POWHEG}\ \text{w/o PS}} + \underbrace{\mathrm{d}\sigma^{\mathrm{NLL^-}}(\Delta Y, \varphi, s)}_{\textbf{NLL}^{-}\ \textbf{resum}\ \text{(HyF)}} - \Delta\mathrm{d}\sigma^{\mathrm{NLL/NLO^-}}(\Delta Y, \varphi, s)$$

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

JETHAD Method → NLL/NLO Additive Matching (analytic: BFKL kernel + coefficient functions)

$$\underbrace{d\sigma^{\text{NLL/NLO}^-}(\Delta Y, \varphi, s)} = \underbrace{\underbrace{d\sigma^{\text{NLO}}(\Delta Y, \varphi, s)}_{\textbf{NLO}\ \text{fixed order}}}_{\textbf{NLO}\ \texttt{POWHEG}\ \text{w/o PS}} + \underbrace{\underbrace{d\sigma^{\text{NLL}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^-\ \textbf{resum}\ \text{(HyF)}} - \underbrace{\Delta d\sigma^{\text{NLL/NLO}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^-\ \textbf{expanded}\ \text{at NLO}}}_{\textbf{NLL}^-\ \texttt{JETHAD}\ \text{w/o NLO}^-\ \text{double counting}}$$

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

JETHAD Method → NLL/NLO Additive Matching (analytic: BFKL kernel + coefficient functions)

$$\underbrace{\underbrace{d\sigma^{\mathrm{NLL/NLO}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL/NLO}^-\ \text{matched}}}_{\text{NLO POWHEG} \oplus \text{NLL}^- \text{ JETHAD}} = \underbrace{\underbrace{d\sigma^{\mathrm{NLO}}(\Delta Y, \varphi, s)}_{\textbf{NLO}\ \text{fixed order}}}_{\text{NLO POWHEG w/o PS}} + \underbrace{\underbrace{d\sigma^{\mathrm{NLL}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^-\ \textbf{resum}\ (\text{HyF})} - \underbrace{\Delta d\sigma^{\mathrm{NLL/NLO}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^-\ \textbf{expanded}\ \text{at NLO}}}_{\text{NLL}^- \text{ JETHAD w/o NLO}^- \text{ double counting}}$$

HELL + ggHiggs

$N^3LL_{lx}/LL_{sx}/N^3LO$

Inclusive Higgs

[M. Bonvini, S. Marzani (2018)]

HEJ framework

NLL_{sx}^-/NLO

Higgs + jet(s)

[J. R. Andersen et al. (2022)]

RadISH + MCFM-8.3

$NNLL_{TM}/NLO$

Higgs + jet

[P.F. Monni et al. (2020)]

(NLO Higgs) [F. G. C., M. Fucilla, D.Yu. Ivanov, M.M.A. Mohammed, A. Papa, JHEP 08 (2022) 092]

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

JETHAD Method → NLL/NLO Additive Matching (analytic: BFKL kernel + coefficient functions)

$$\underbrace{\underbrace{\mathrm{d}\sigma^{\mathrm{NLL/NLO}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL/NLO}^- \text{ matched}}}_{\text{NLO POWHEG} \,\oplus\, \text{NLL}^- \text{ JETHAD}} = \underbrace{\underbrace{\mathrm{d}\sigma^{\mathrm{NLO}}(\Delta Y, \varphi, s)}_{\textbf{NLO} \text{ fixed order}}}_{\text{NLO POWHEG w/o PS}} + \underbrace{\underbrace{\mathrm{d}\sigma^{\mathrm{NLL}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^- \textbf{ resum} \text{ (HyF)}} - \underbrace{\Delta\mathrm{d}\sigma^{\mathrm{NLL/NLO}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^- \textbf{ expanded} \text{ at NLO}}}_{\text{NLL}^- \text{ JETHAD w/o NLO}^- \text{ double counting}}$$

Higgs + jet at NLL/NLO from POWHEG + JETHAD

🔗 [My talk in the EW Session (WG3)]

(NLO Higgs) 🔗 [F. G. C., M. Fucilla, D.Yu. Ivanov, M.M.A. Mohammed, A. Papa, JHEP 08 (2022) 092]

Matching NLL to NLO with JETHAD

¡ **Precision corrections** *expected* ⇔ *need* for an accurate NLL-to-NLO **Matching procedure** !

JETHAD Method → NLL/NLO Additive Matching (analytic: BFKL kernel + coefficient functions)

$$\underbrace{\underbrace{d\sigma^{\text{NLL/NLO}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL/NLO}^- \text{ matched}}}_{\textbf{NLO}\ \texttt{POWHEG} \oplus \textbf{NLL}^-\ \texttt{JETHAD}} = \underbrace{\underbrace{d\sigma^{\text{NLO}}(\Delta Y, \varphi, s)}_{\textbf{NLO} \text{ fixed order}}}_{\textbf{NLO}\ \texttt{POWHEG}\ \text{w/o PS}} + \underbrace{\underbrace{d\sigma^{\text{NLL}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^- \textbf{ resum} \text{ (HyF)}} - \underbrace{\Delta d\sigma^{\text{NLL/NLO}^-}(\Delta Y, \varphi, s)}_{\textbf{NLL}^- \textbf{ expanded} \text{ at NLO}}}_{\textbf{NLL}^-\ \texttt{JETHAD}\ \text{w/o NLO}^- \text{ double counting}}$$

Higgs + jet at NLL/NLO
from
POWHEG + JETHAD

[My talk in the EW Session (WG3)]

¡ Thanks for the attention !

(NLO Higgs) [F. G. C., M. Fucilla, D.Yu. Ivanov, M.M.A. Mohammed, A. Papa, JHEP 08 (2022) 092]

EXTRAS

Higgs production from LHC to FCC

PHYSICAL REVIEW LETTERS **120,** 202003 (2018)

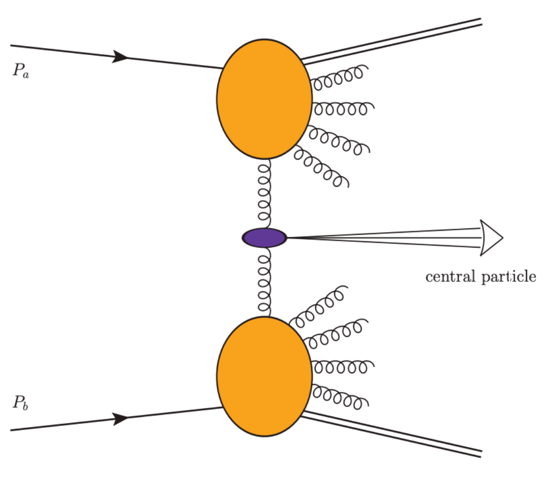
Double Resummation for Higgs Production

Marco Bonvini[1,*] and Simone Marzani[2,†]
[1]INFN, Sezione di Roma 1, Piazzale Aldo Moro 5, 00185 Roma, Italy
[2]Dipartimento di Fisica, Università di Genova and INFN, Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy

(Received 26 February 2018; published 16 May 2018)

We present the first double-resummed prediction of the inclusive cross section for the main Higgs production channel in proton-proton collisions, namely, gluon fusion. Our calculation incorporates to all orders in perturbation theory two distinct towers of logarithmic corrections which are enhanced, respectively, at threshold, i.e., large x, and in the high-energy limit, i.e., small x. Large-x logarithms are resummed to next-to-next-to-next-to-leading logarithmic accuracy, while small-x ones to leading logarithmic accuracy. The double-resummed cross section is furthermore matched to the state-of-the-art fixed-order prediction at next-to-next-to-next-to-leading accuracy. We find that double resummation corrects the Higgs production rate by 2% at the currently explored center-of-mass energy of 13 TeV and its impact reaches 10% at future circular colliders at 100 TeV.

DOI: 10.1103/PhysRevLett.120.202003



(b) Single central

High-energy resummation (BFKL) ⇒ PDFs at small-x

Altarelli-Ball-Forte to stabilize the $\mathrm{NLL_{sx}}$ BFKL kernel

$\mathrm{N^3LL_{lx}}$/$\mathrm{LL_{sx}}$/$\mathrm{N^3LO}$ rapidity-inclusive coefficient functions

$$C_{ij}(x,\alpha_s) = C^{\rm fo}_{ij}(x,\alpha_s) + \Delta C^{\rm lx}_{ij}(x,\alpha_s) + \Delta C^{\rm sx}_{ij}(x,\alpha_s)$$

Backup

Higgs production from LHC to FCC

PHYSICAL REVIEW LETTERS **120,** 202003 (2018)

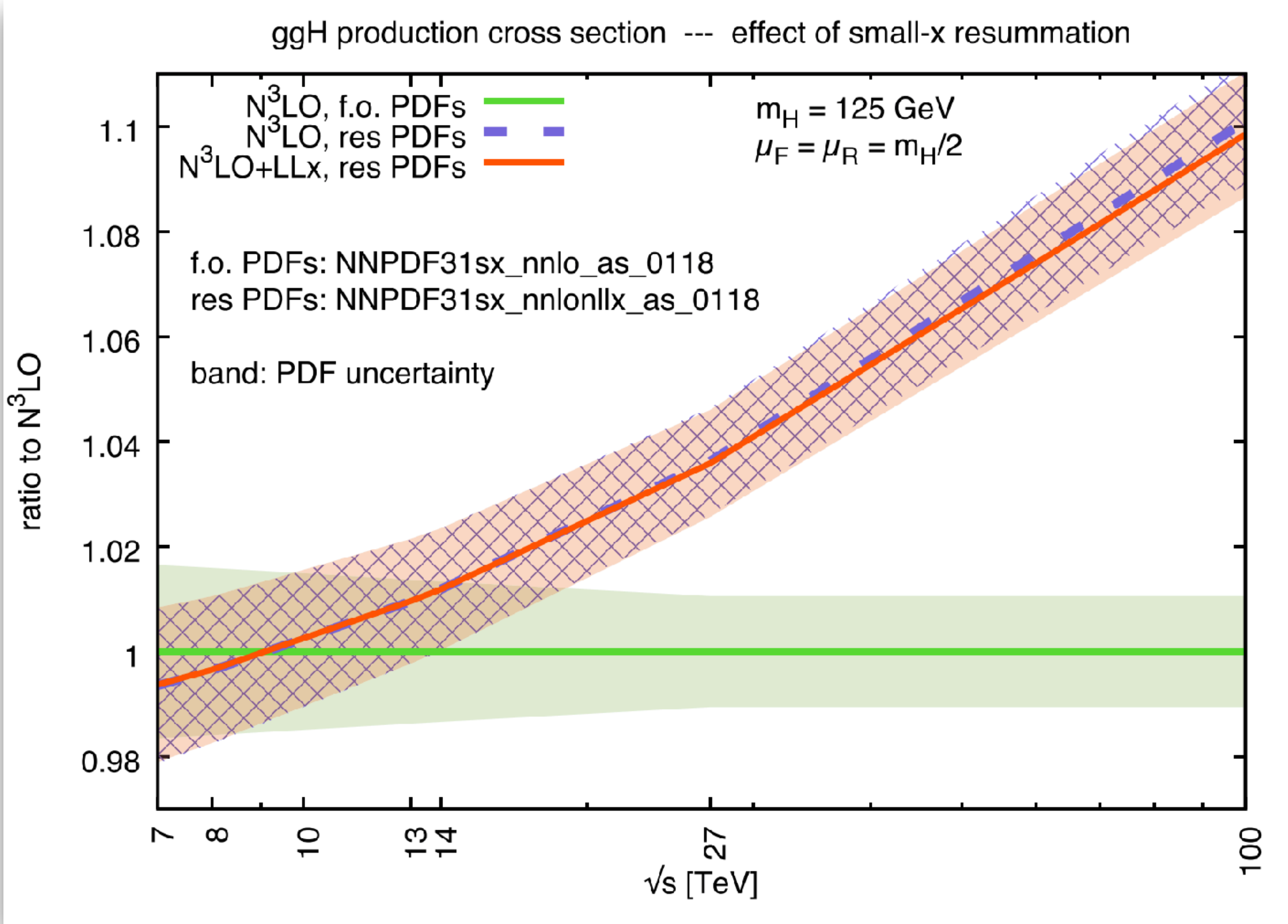
Double Resummation for Higgs Production

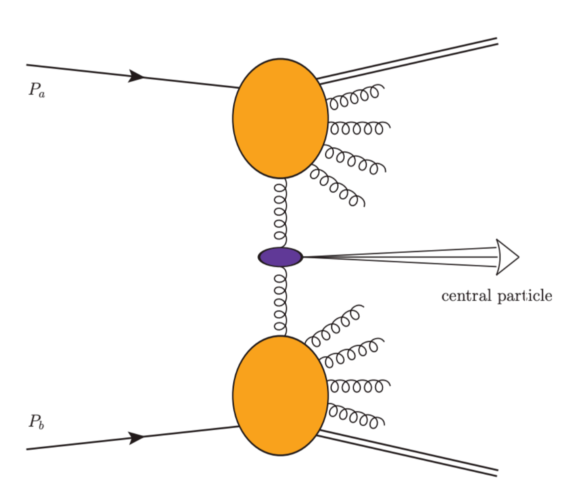
Marco Bonvini[1,*] and Simone Marzani[2,†]
[1]*INFN, Sezione di Roma 1, Piazzale Aldo Moro 5, 00185 Roma, Italy*
[2]*Dipartimento di Fisica, Università di Genova and INFN, Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy*

(Received 26 February 2018; published 16 May 2018)

We present the first double-resummed prediction of the inclusive cross section for the main Higgs production channel in proton-proton collisions, namely, gluon fusion. Our calculation incorporates to all orders in perturbation theory two distinct towers of logarithmic corrections which are enhanced, respectively, at threshold, i.e., large x, and in the high-energy limit, i.e., small x. Large-x logarithms are resummed to next-to-next-to-next-to-leading logarithmic accuracy, while small-x ones to leading logarithmic accuracy. The double-resummed cross section is furthermore matched to the state-of-the-art fixed-order prediction at next-to-next-to-next-to-leading accuracy. We find that double resummation corrects the Higgs production rate by 2% at the currently explored center-of-mass energy of 13 TeV and its impact reaches 10% at future circular colliders at 100 TeV.

DOI: 10.1103/PhysRevLett.120.202003





(*b*) Single central

High-energy resummation (BFKL) ⇒ PDFs at small-x

Altarelli-Ball-Forte to stabilize the $\mathrm{NLL_{sx}}$ BFKL kernel

$\mathrm{N^3LL_{lx}}$/$\mathrm{LL_{sx}}$/$\mathrm{N^3LO}$ rapidity-inclusive coefficient functions

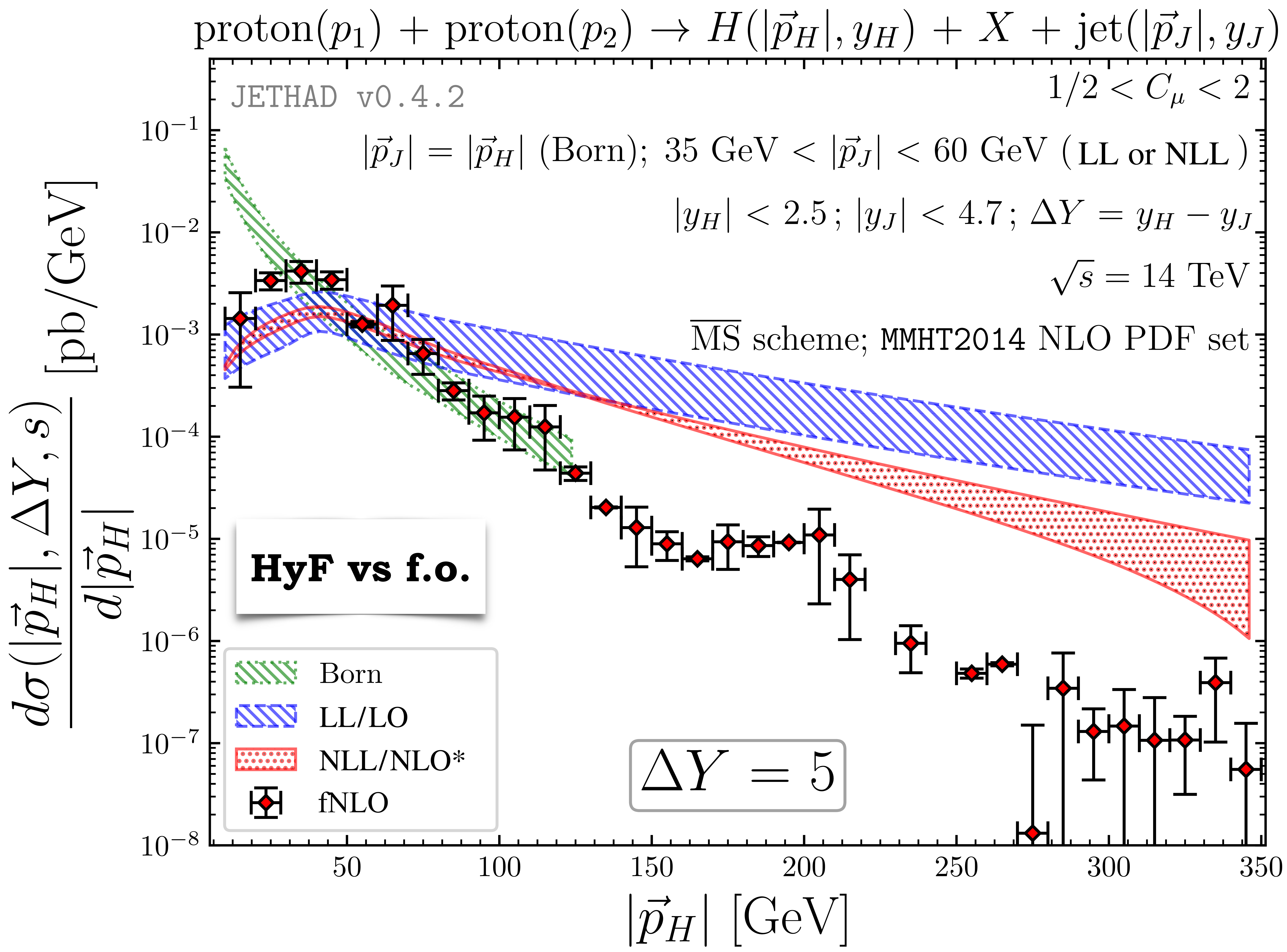
(¡!) 100 TeV EW physics ⇔ small-x physics!

(¿?) Can LHC physics be BFKL physics?

$$C_{ij}(x,\alpha_s) = C^{\mathrm{fo}}_{ij}(x,\alpha_s) + \Delta C^{\mathrm{lx}}_{ij}(x,\alpha_s) + \Delta C^{\mathrm{sx}}_{ij}(x,\alpha_s)$$

Backup

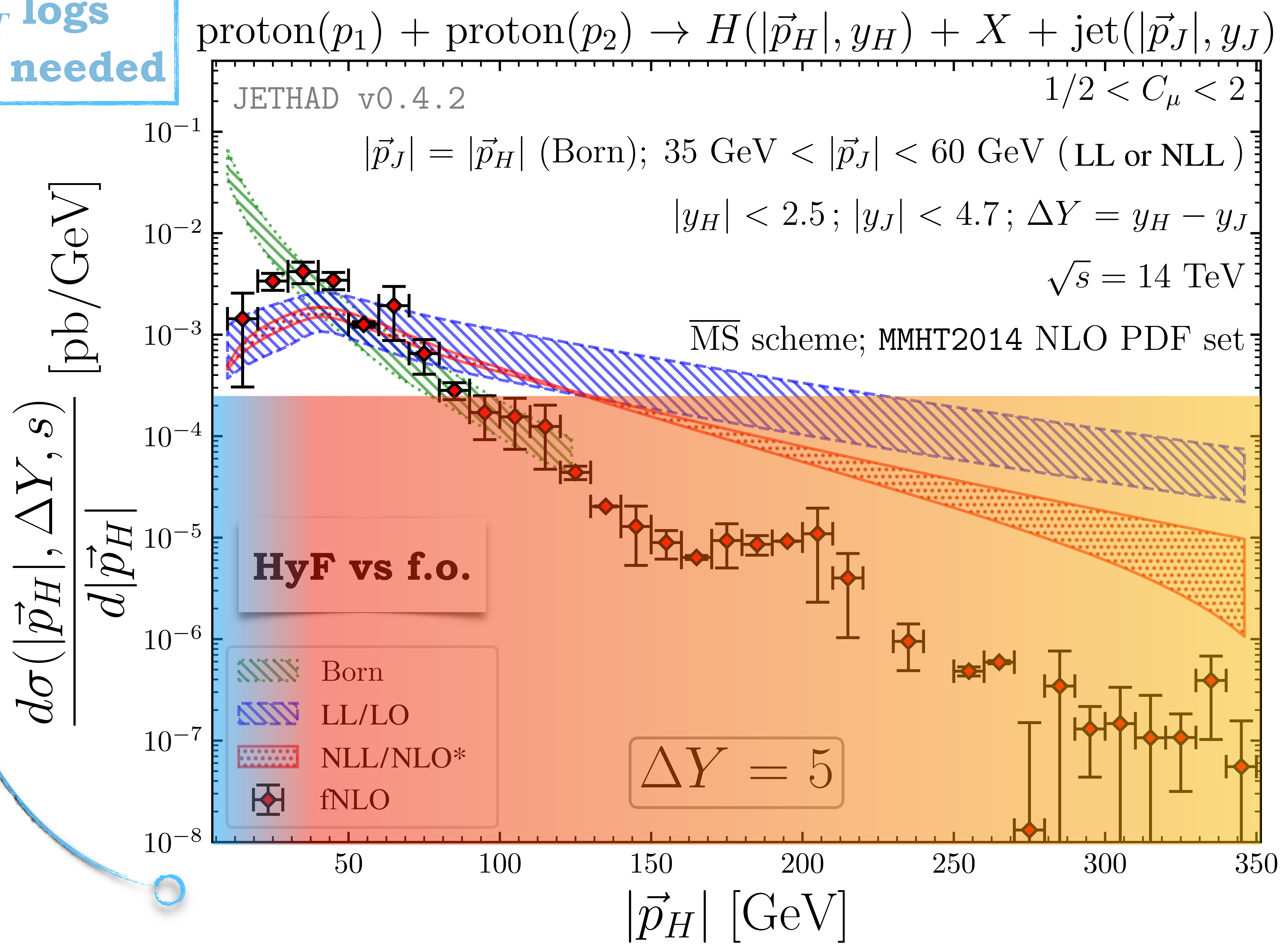
Backup



(Higgs + jet, NLL/NLO* HyF) 🔗 [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

large p_T logs
p_T-resum. needed

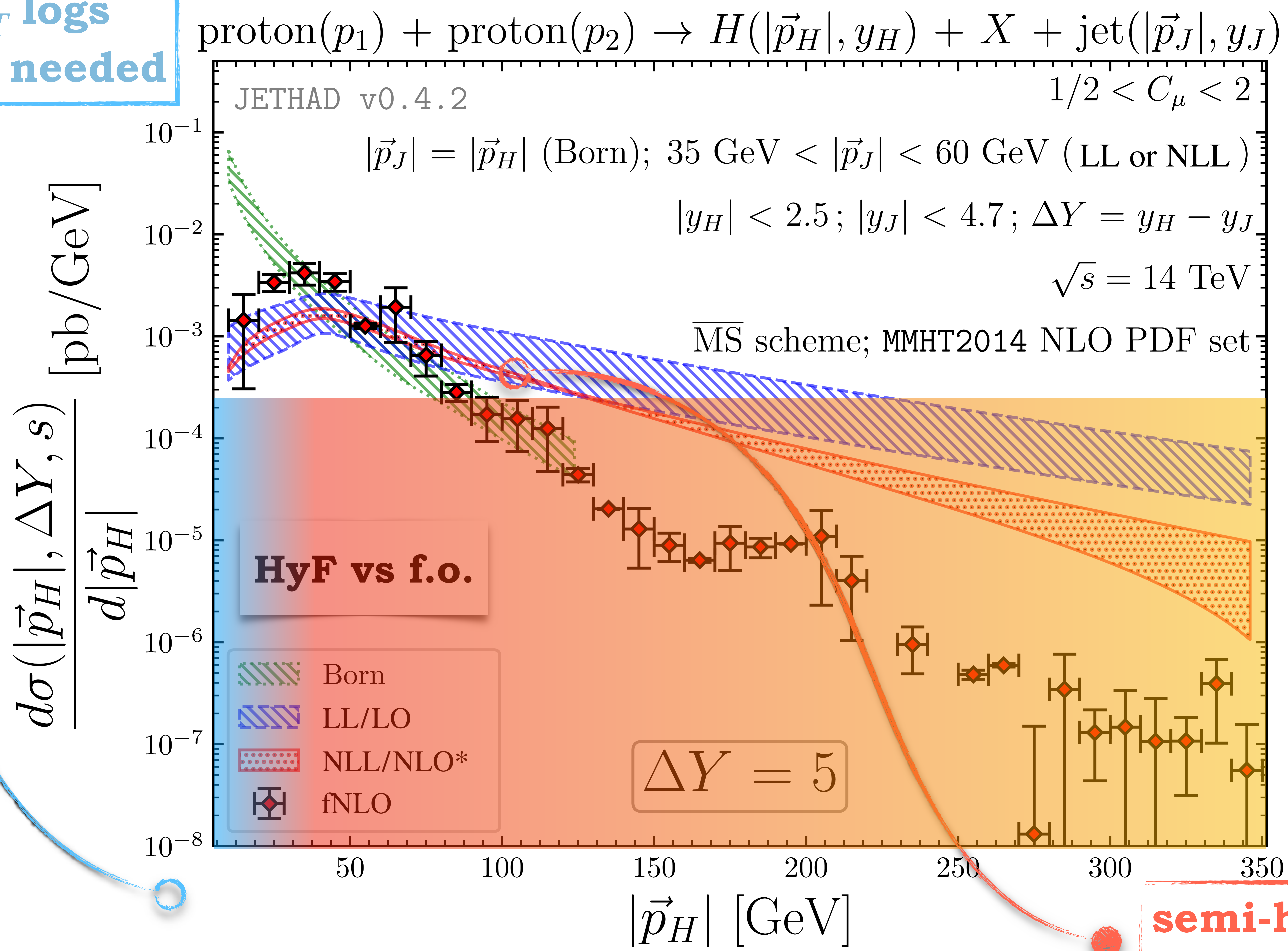
Backup



(Higgs + jet, NLL/NLO* HyF) [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

large p_T logs
p_T-resum. needed

Backup



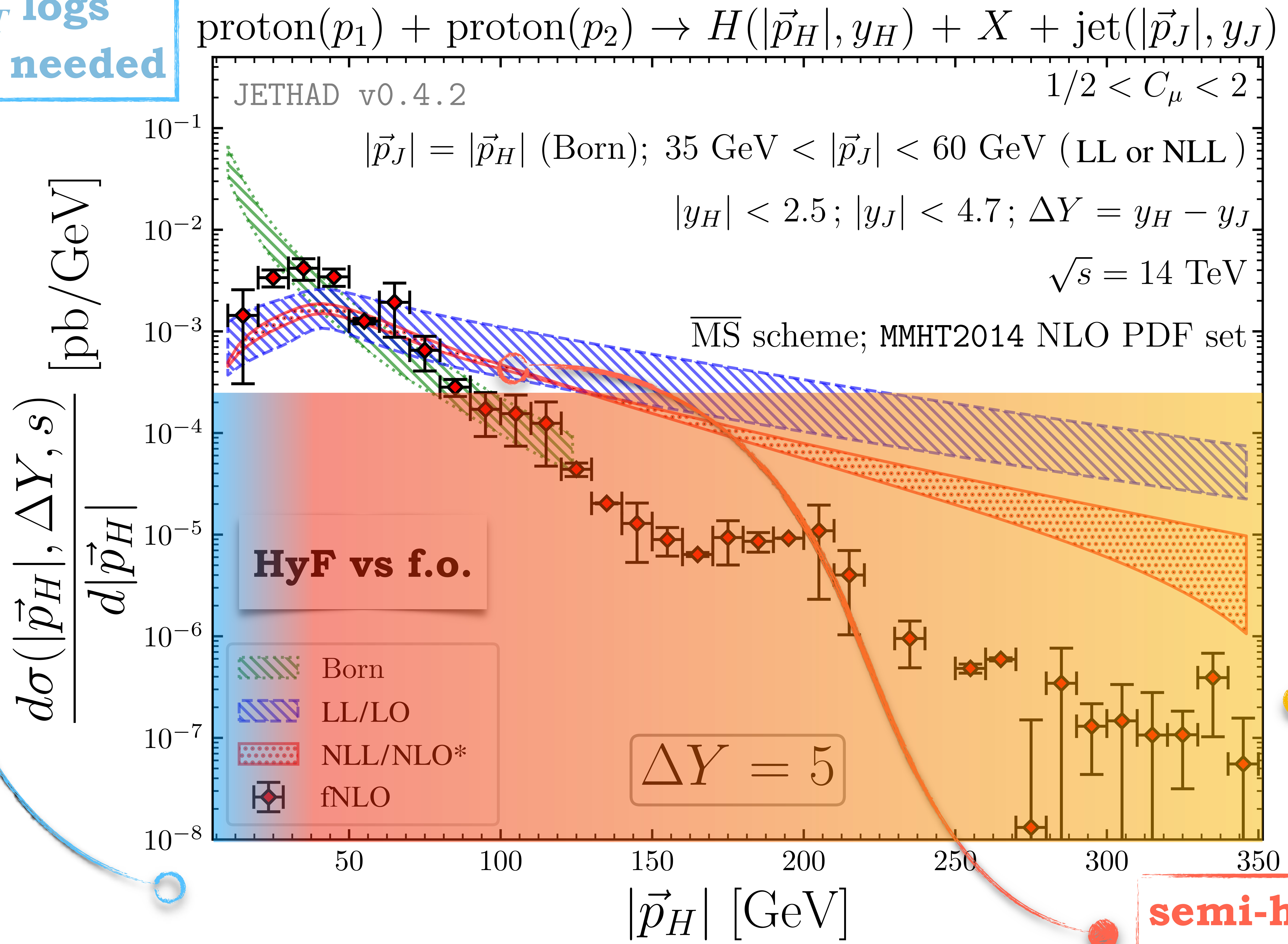
semi-hard regime
BFKL expected

(Higgs + jet, NLL/NLO* HyF) [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

Backup

large p_T logs
p_T-resum. needed

DGLAP-type + large-x threshold logs → BFKL decoupling



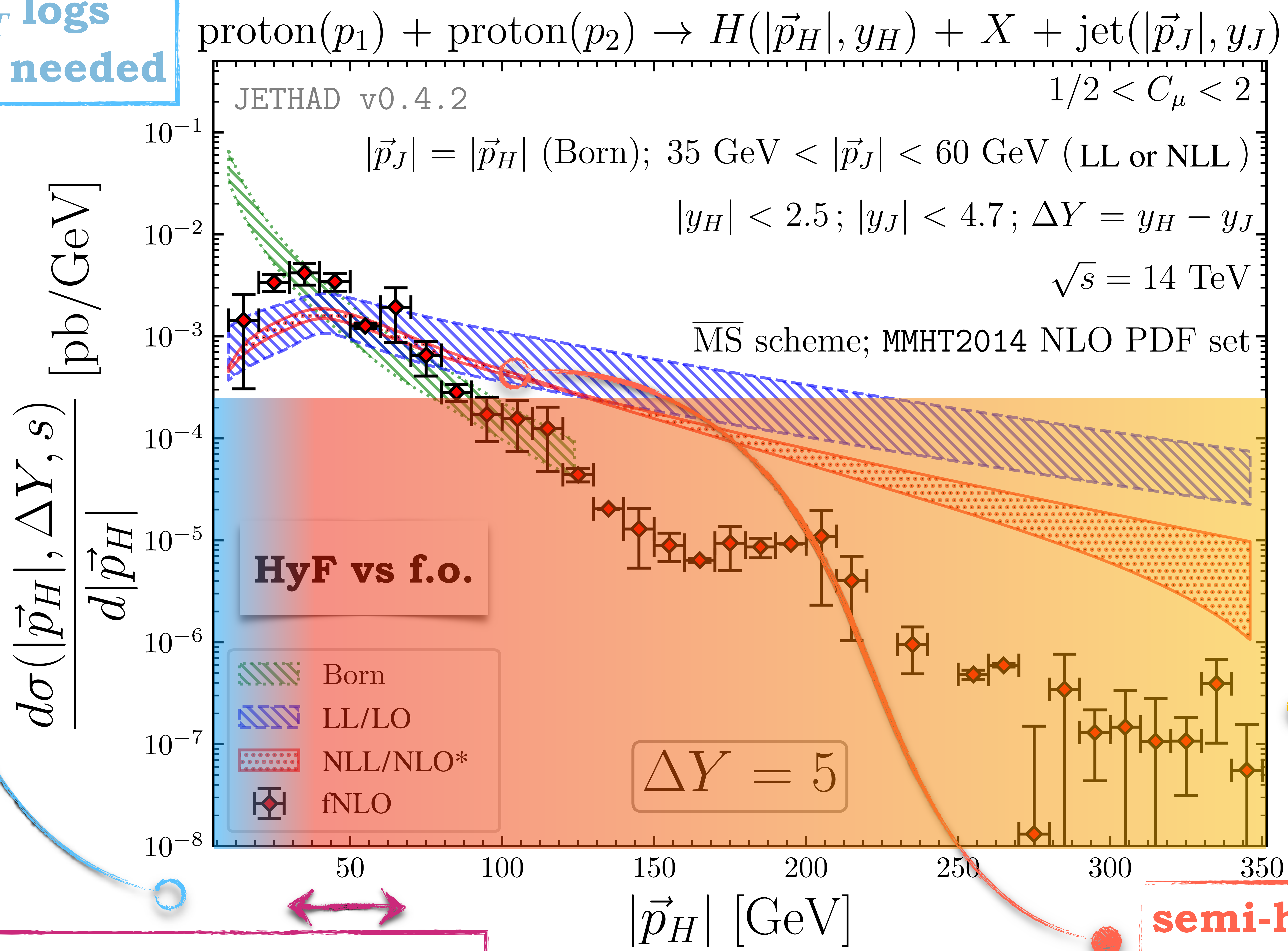
semi-hard regime
BFKL expected

(Higgs + jet, NLL/NLO* HyF) 🔗 [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

DGLAP-type + large-x threshold logs → BFKL decoupling

large p_T logs
p_T-resum. needed

Backup



almost back-to-back emissions
large imbalance double logs

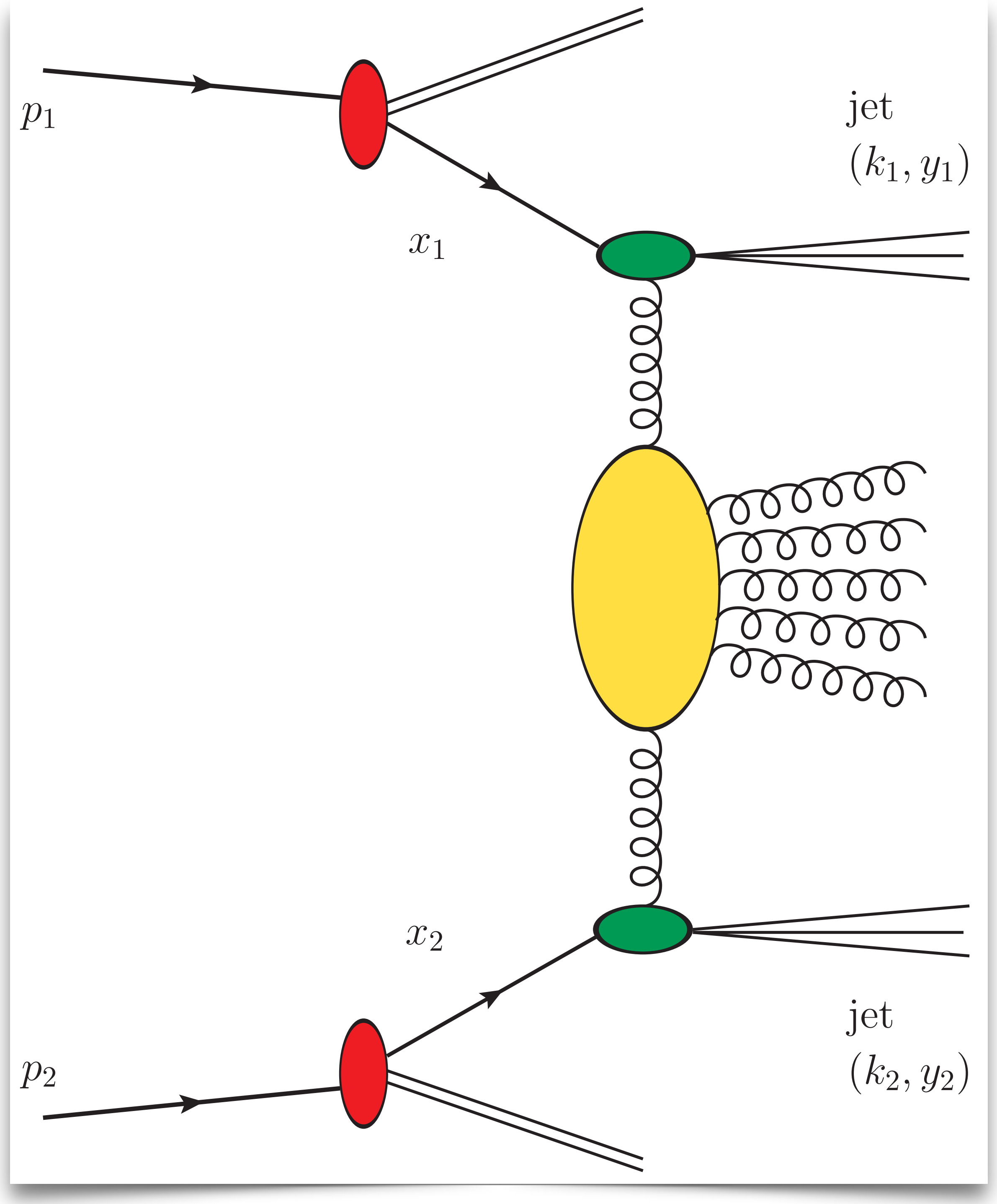
semi-hard regime
BFKL expected

(Higgs + jet, NLL/NLO* HyF) [F. G. C. et al., Eur. Phys. J. C (2021) 8, 780]

Mueller-Navelet jets @LHC & resummation instabilities

- Inclusive hadroproduction of two jets with high p_T and large rapidity separation, ΔY
- Moderate x (collinear PDFs), but t-channel p_T (BFKL resummation) $\Rightarrow$ hybrid factorization (HyF)

$$\frac{d\sigma}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2} = \sum_{r,s=q,g} \int_0^1 dx_1 \int_0^1 dx_2\, f_r(x_1,\mu_F)\, f_s(x_2,\mu_F)\, \frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu_F)}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2}$$



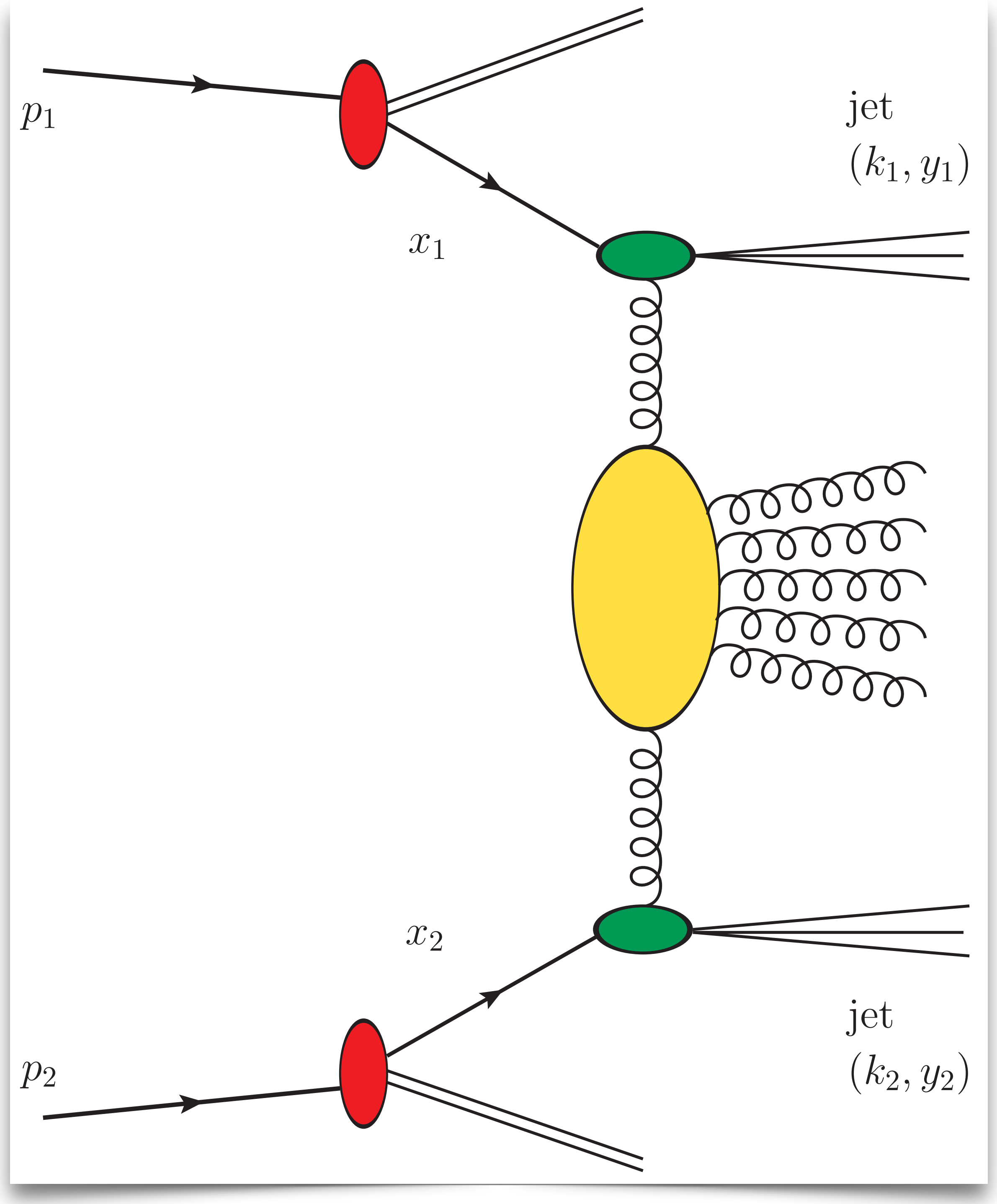
Backup

Mueller-Navelet jets @LHC & resummation instabilities

- Inclusive hadroproduction of two jets with high p_T and large rapidity separation, ΔY
- Moderate x (collinear PDFs), but t-channel p_T (BFKL resummation) $\Rightarrow$ hybrid factorization (HyF)

$$\frac{d\sigma}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2} = \sum_{r,s=q,g} \int_0^1 dx_1 \int_0^1 dx_2\, f_r(x_1, \mu_F)\, f_s(x_2, \mu_F)\, \frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu_F)}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2}$$

jet vertices (off-shell coefficient functions)



$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2} = \frac{1}{(2\pi)^2}$$

NLO(+) $$\times \int \frac{d^2\vec{q}_1}{\vec{q}_1^{\,2}}\, \mathcal{V}_J^{(r)}(\vec{q}_1, s_0, x_1, \vec{k}_1)$$

NLL $$\times \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{x_1 x_2 s}{s_0}\right)^{\omega} \mathcal{G}_\omega(\vec{q}_1, \vec{q}_2)$$

NLO(+) $$\times \int \frac{d^2\vec{q}_2}{\vec{q}_2^{\,2}}\, \mathcal{V}_J^{(s)}(\vec{q}_2, s_0, x_2, \vec{k}_2)$$

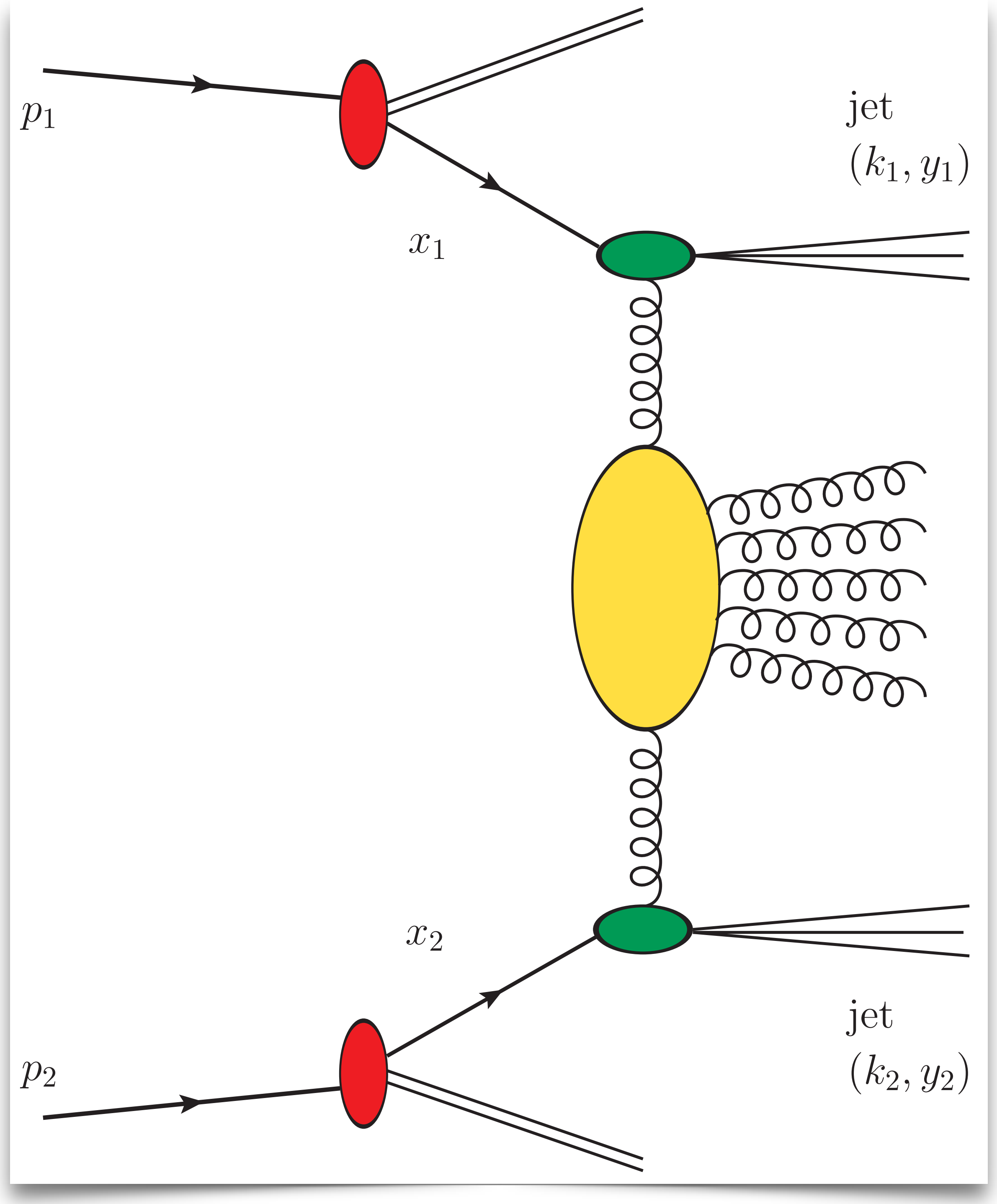
BFKL Green's function

Backup

Mueller-Navelet jets @LHC & resummation instabilities

- Inclusive hadroproduction of two jets with high p_T and large rapidity separation, ΔY
- Moderate x (collinear PDFs), but t-channel p_T (BFKL resummation) ⇒ hybrid factorization (HyF)

$$\frac{d\sigma}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2} = \sum_{r,s=q,g} \int_0^1 dx_1 \int_0^1 dx_2\, f_r(x_1,\mu_F)\, f_s(x_2,\mu_F)\, \frac{d\hat{\sigma}_{r,s}(x_1 x_2 s,\mu_F)}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2}$$



$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s,\mu)}{dy_1\, dy_2\, d^2\vec{k}_1\, d^2\vec{k}_2} = \frac{1}{(2\pi)^2}$$

NLO(+) $$\times \int \frac{d^2\vec{q}_1}{\vec{q}_1^{\,2}}\, \mathcal{V}_J^{(r)}(\vec{q}_1, s_0, x_1, \vec{k}_1)$$

NLL $$\times \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{x_1 x_2 s}{s_0}\right)^{\omega} \mathcal{G}_\omega(\vec{q}_1, \vec{q}_2)$$

NLO(+) $$\times \int \frac{d^2\vec{q}_2}{\vec{q}_2^{\,2}}\, \mathcal{V}_J^{(s)}(\vec{q}_2, s_0, x_2, \vec{k}_2)$$

jet vertices (off-shell coefficient functions)

BFKL Green's function

- NLL/LL instabilities + NLO missing threshold ⇒ precision studies hampered

Backup

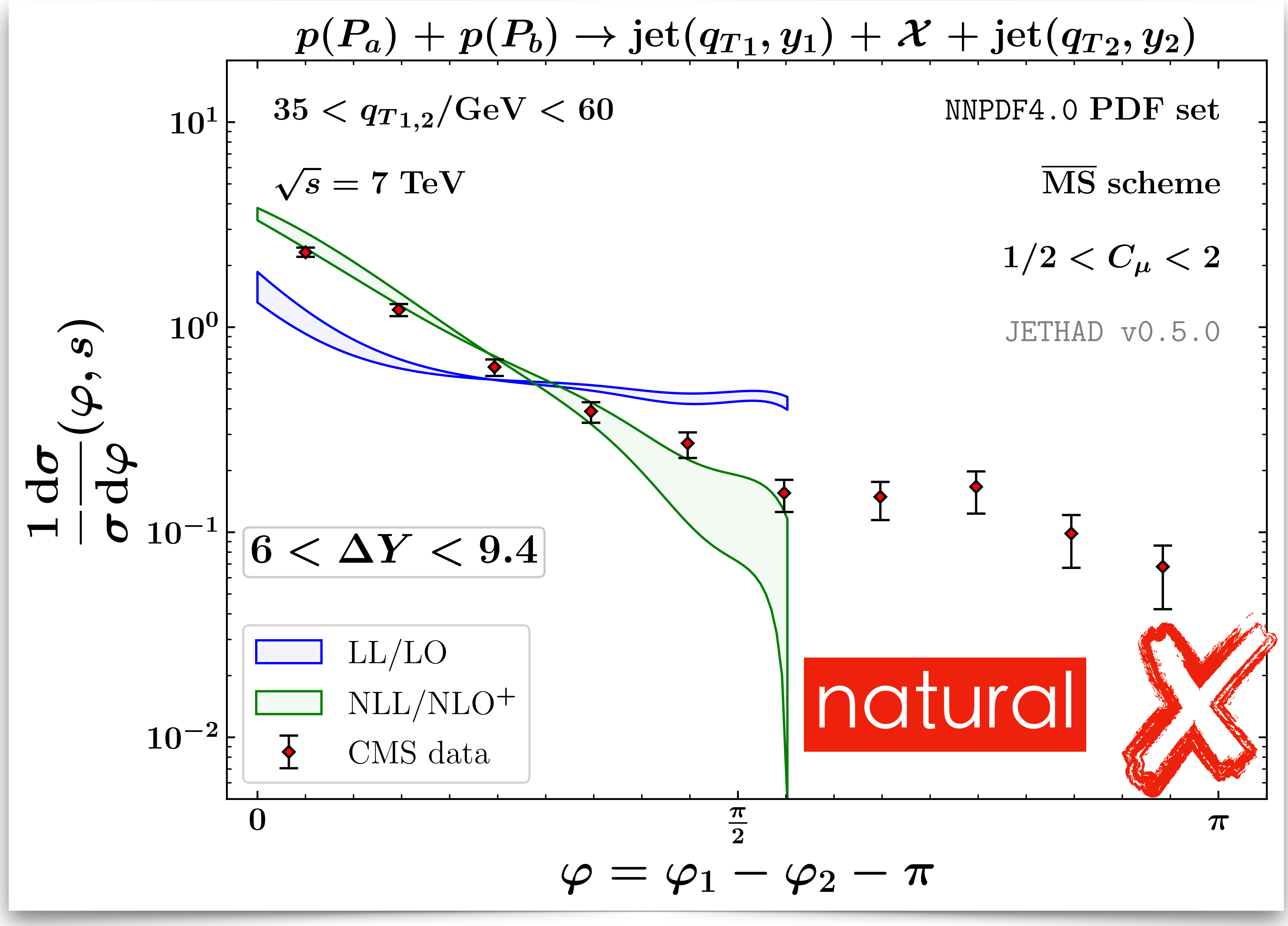
Azimuthal-angle multiplicity

$$\frac{1}{\sigma}\frac{d\sigma(\Delta Y, s)}{d\varphi} = \frac{1}{2\pi}\left\{1 + 2\sum_{n=1}^{\infty}\cos(n\varphi)\langle\cos(n\varphi)\rangle\right\}$$

MUELLER-NAVELET JETS

[B. Ducloué, L. Szymanowski, S. Wallon, Phys. Rev. Lett. 112 (2014) 082003]

(figure below) [F. G. C., A. Papa, Phys. Rev. D 106 (2022) 11, 114004]



Backup

Azimuthal-angle multiplicity

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma(\Delta Y, s)}{\mathrm{d}\varphi} = \frac{1}{2\pi}\left\{1 + 2\sum_{n=1}^{\infty}\cos(n\varphi)\langle\cos(n\varphi)\rangle\right\}$$

MUELLER-NAVELET JETS

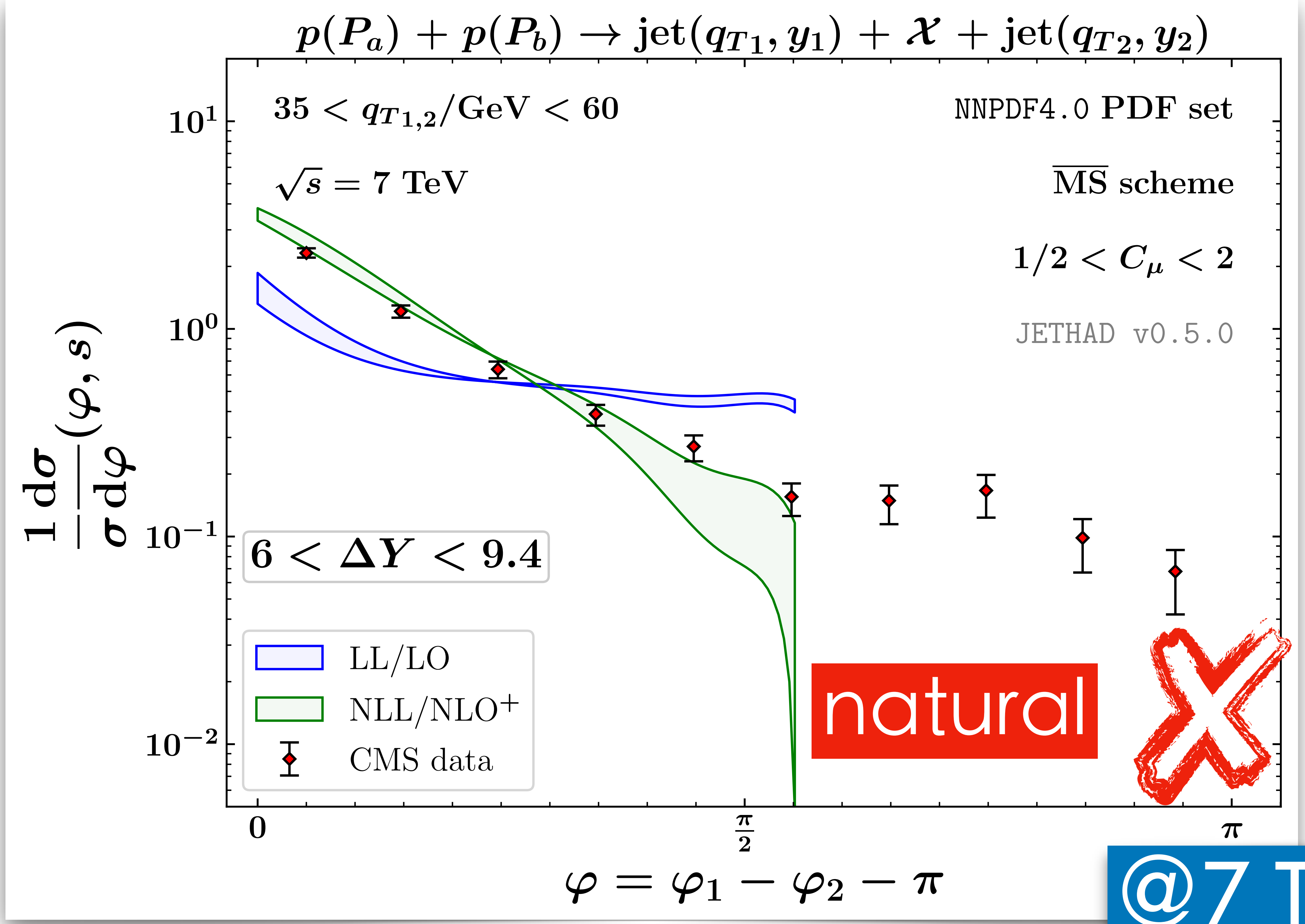
🔗 [B. Ducloué, L. Szymanowski, S. Wallon, Phys. Rev. Lett. 112 (2014) 082003]

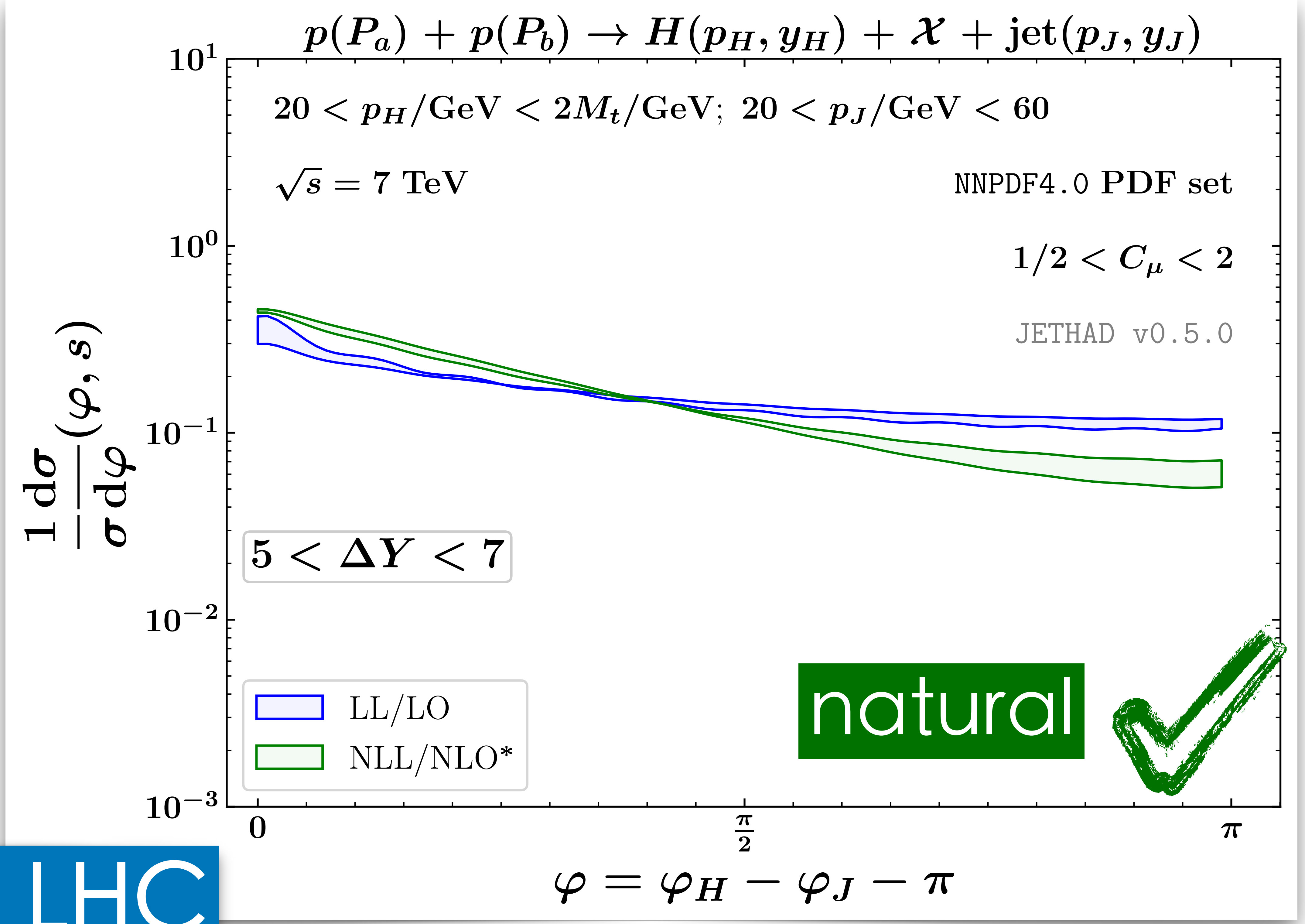
(figure below) 🔗 [F. G. C., A. Papa, Phys. Rev. D 106 (2022) 11, 114004]

HIGGS + JET

(figure below) 🔗 [F. G. C. et al., Eur. Phys. J. C 81 (2021) 4, 293]

(NLO Higgs coefficient function) 🔗 [F. G. C. et al., JHEP 08 (2022) 092]





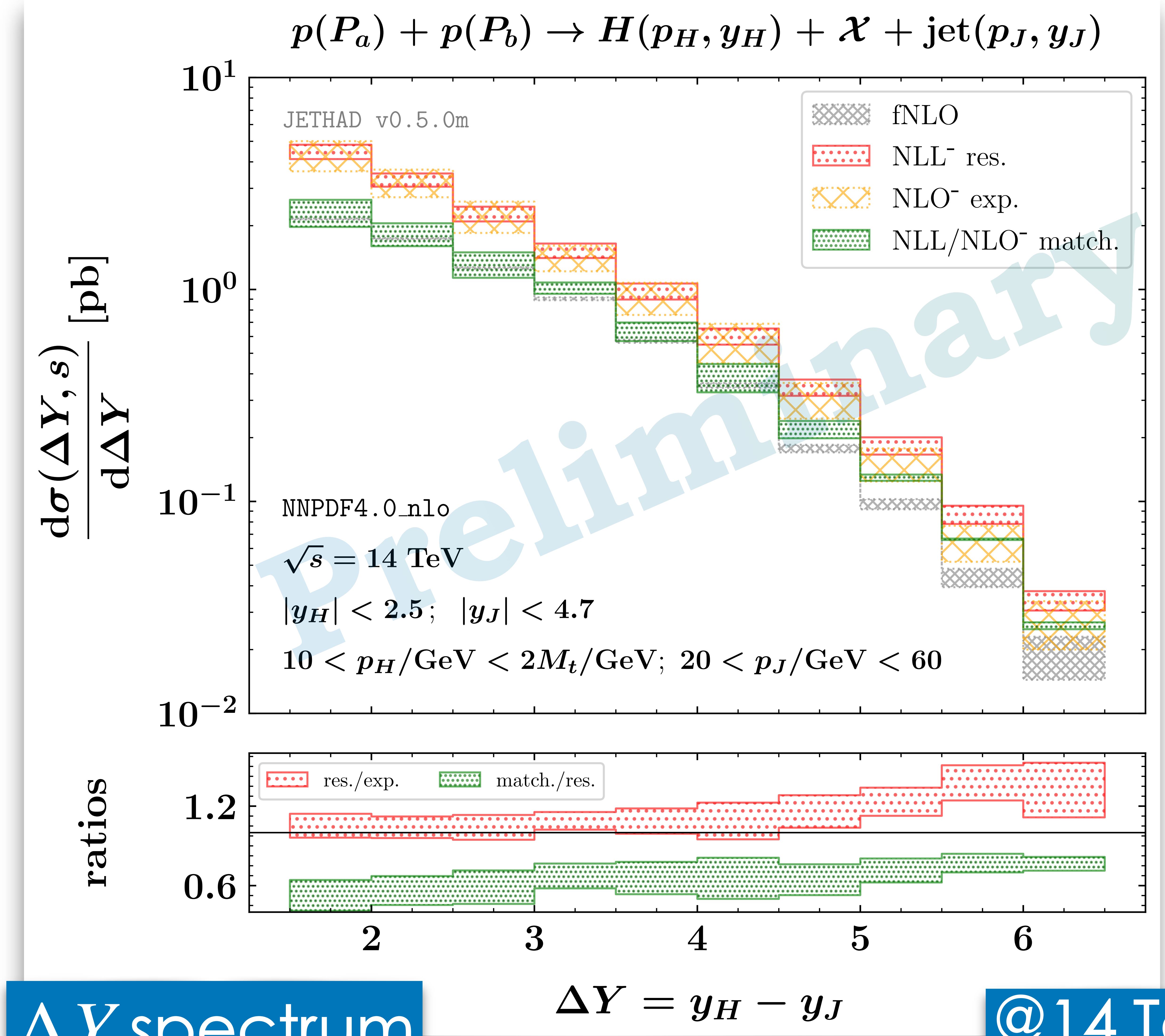
@7 TeV LHC

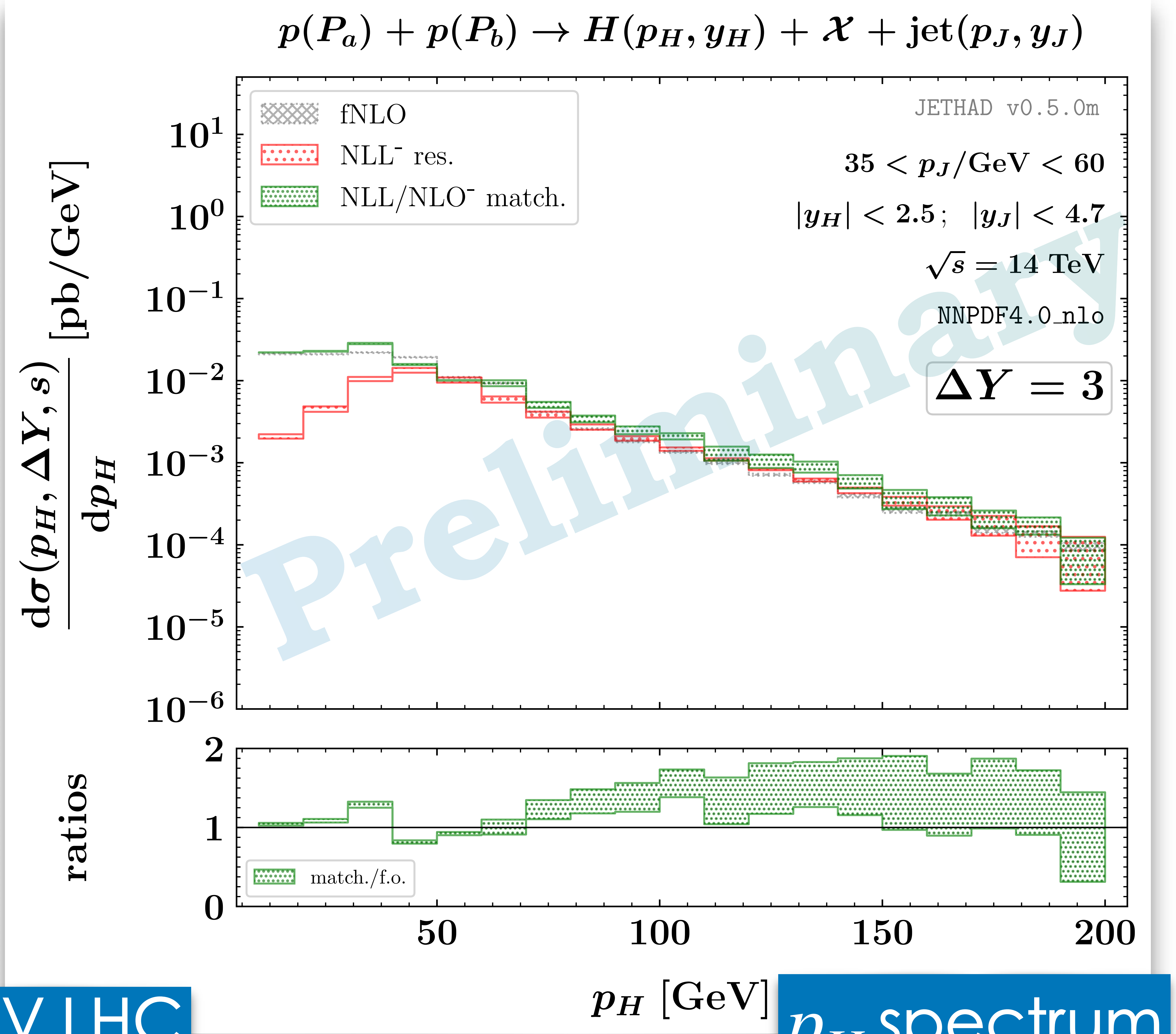
Backup

Hybrid factorization via the JETHAD code python + F

🔗 [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]. 🔗 [F. G. C. , Phys. Rev. D 105 (2022) 11, 114008]

The Higgs + jet spectrum from POWHEG + JETHAD





ΔY spectrum

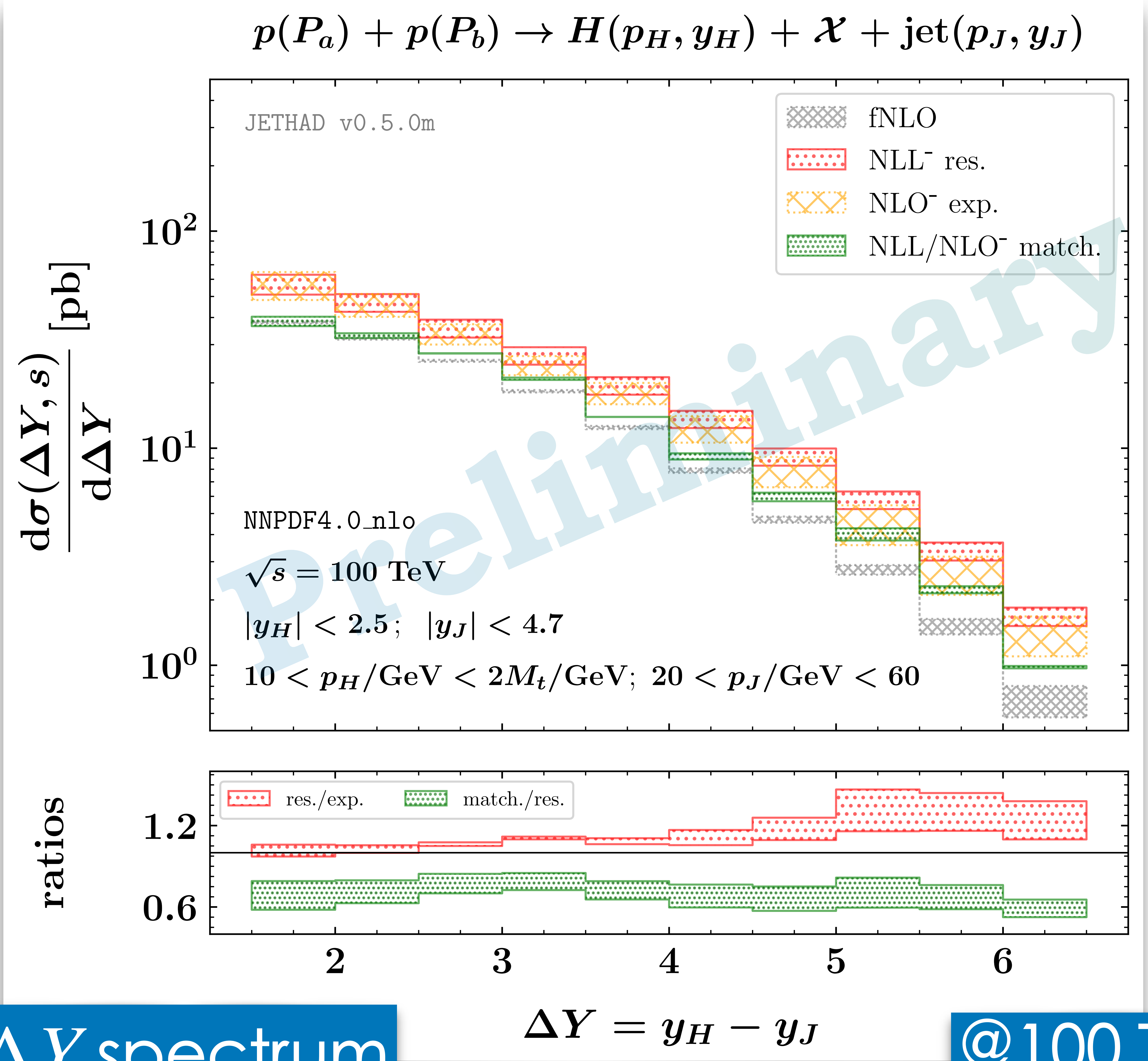
@14 TeV LHC

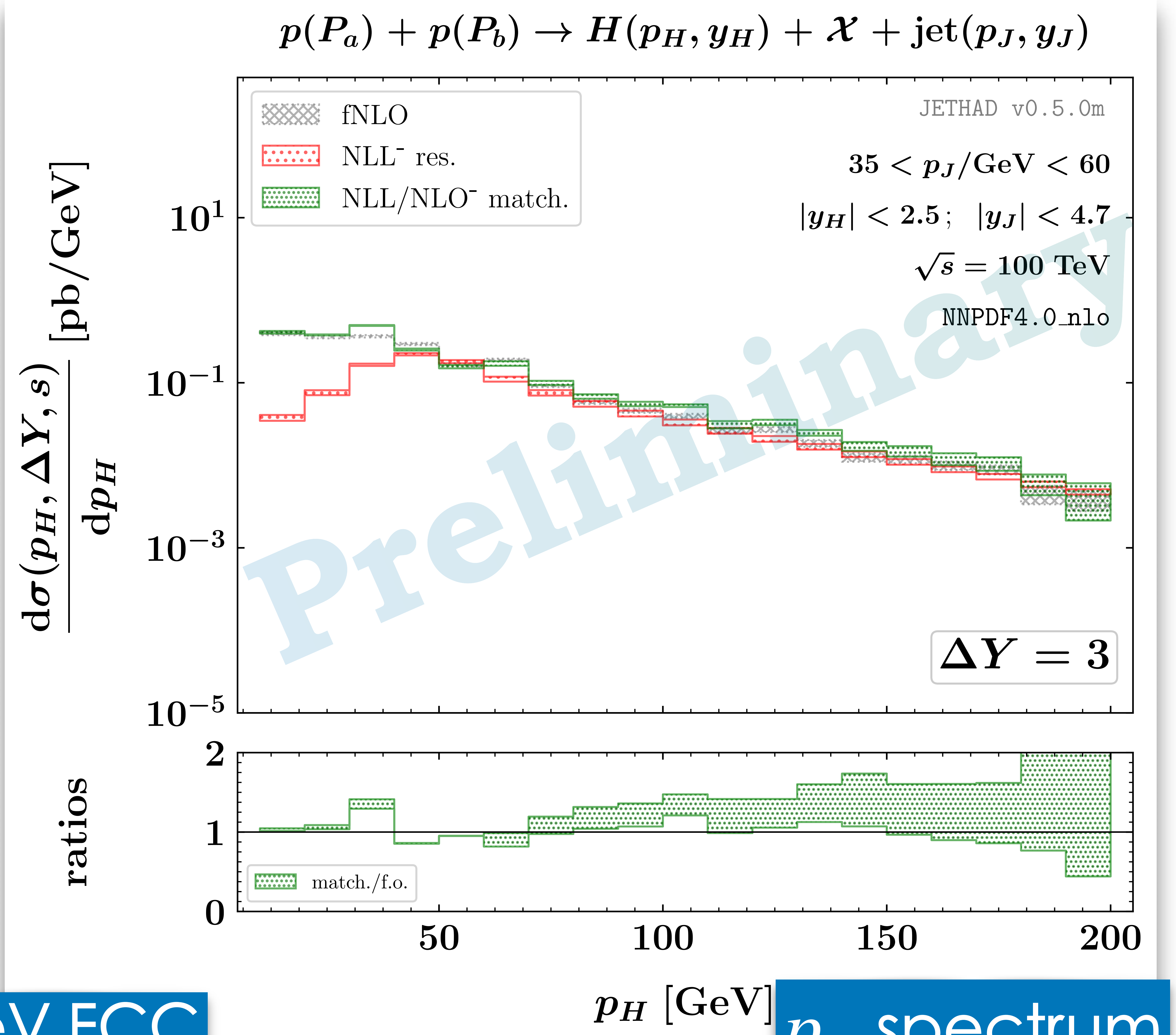
p_H spectrum

Backup

NLL matched to NLO fixed-order POWHEG + JETHAD (in progress)

The Higgs + jet spectrum from POWHEG + JETHAD





ΔY spectrum

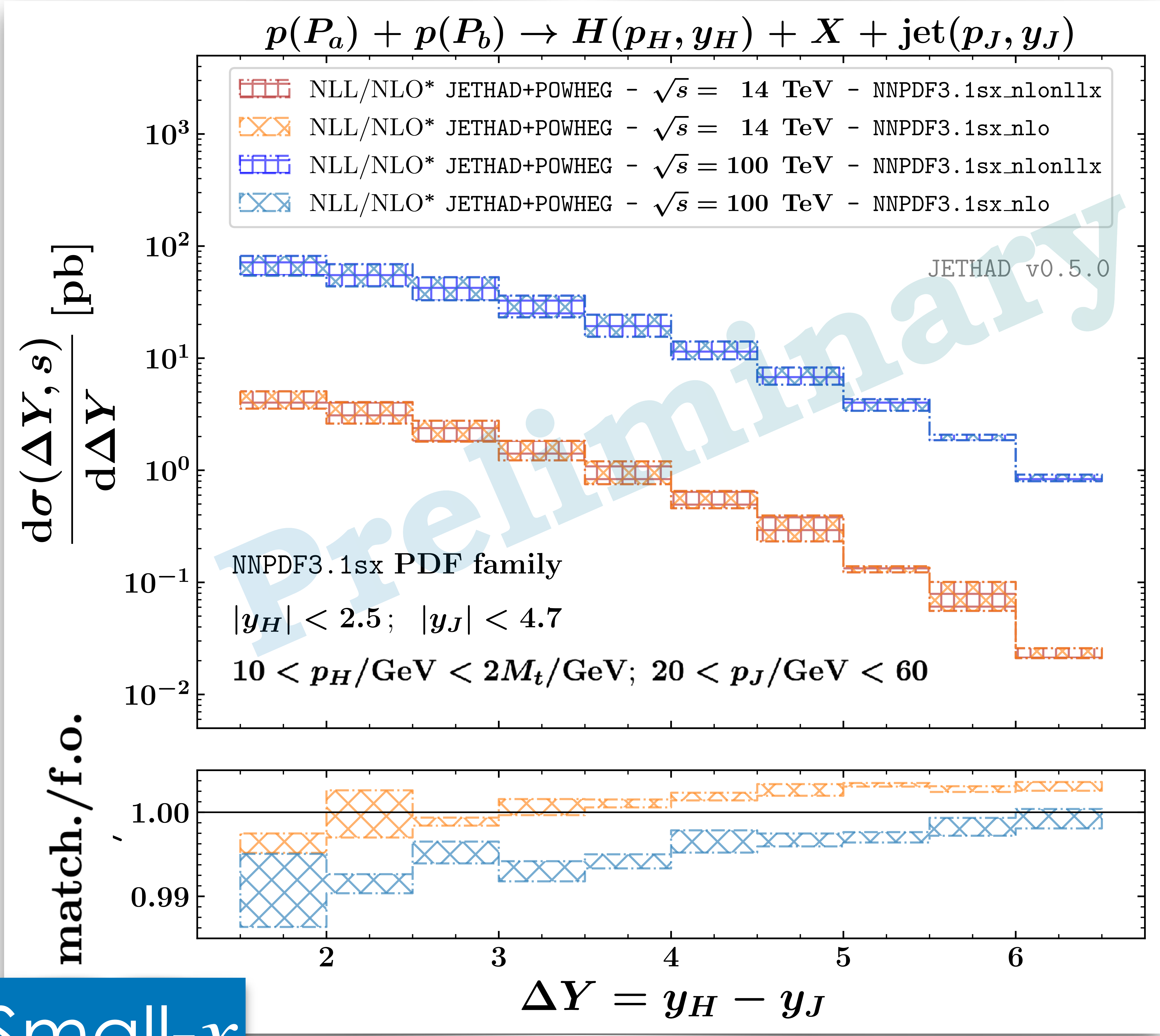
@100 TeV FCC

p_H spectrum

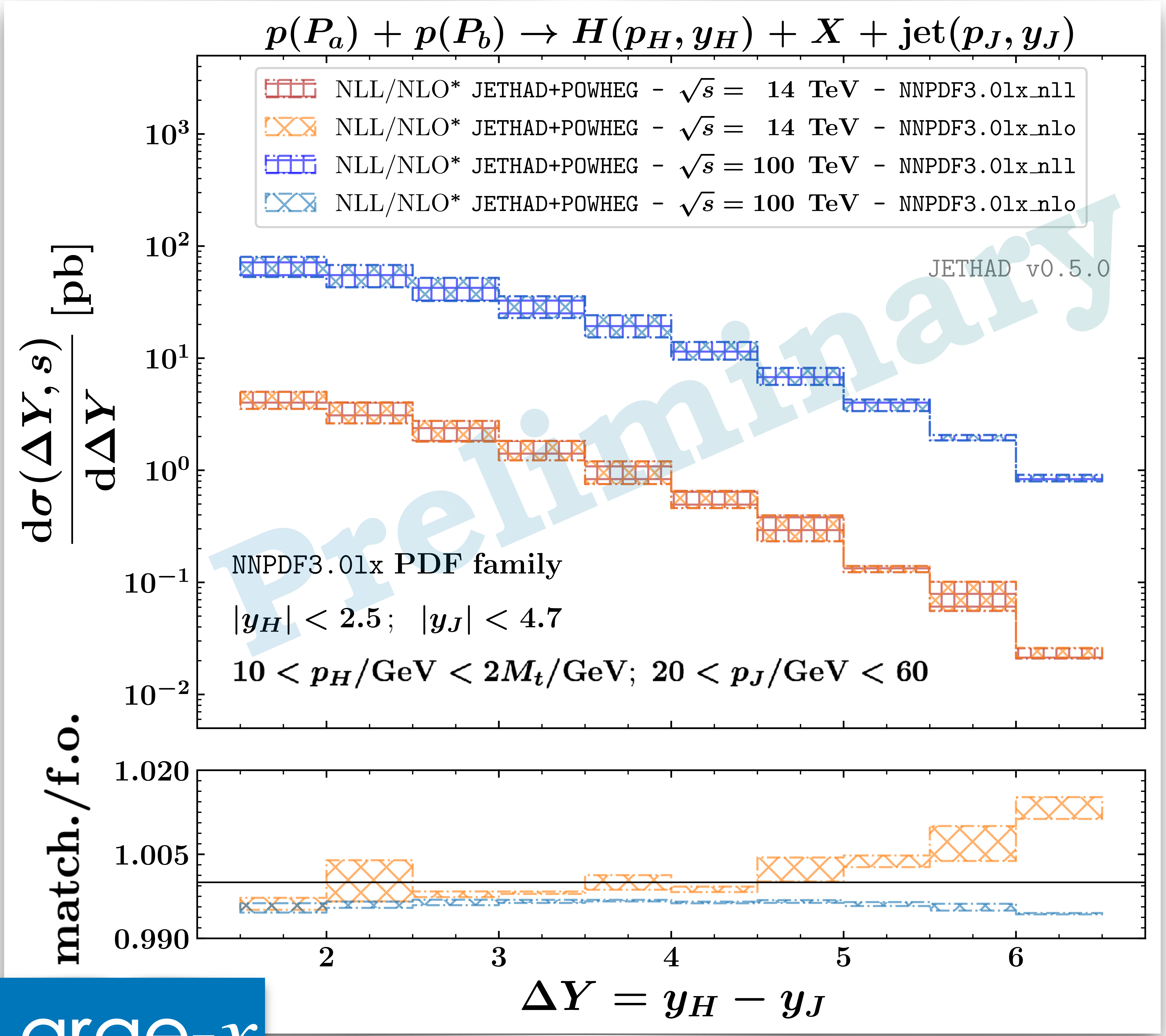
Backup

NLL matched to NLO fixed-order JETHAD + POWHEG (in progress)

Small-x and large-x enhancement from PDFs



Small-x

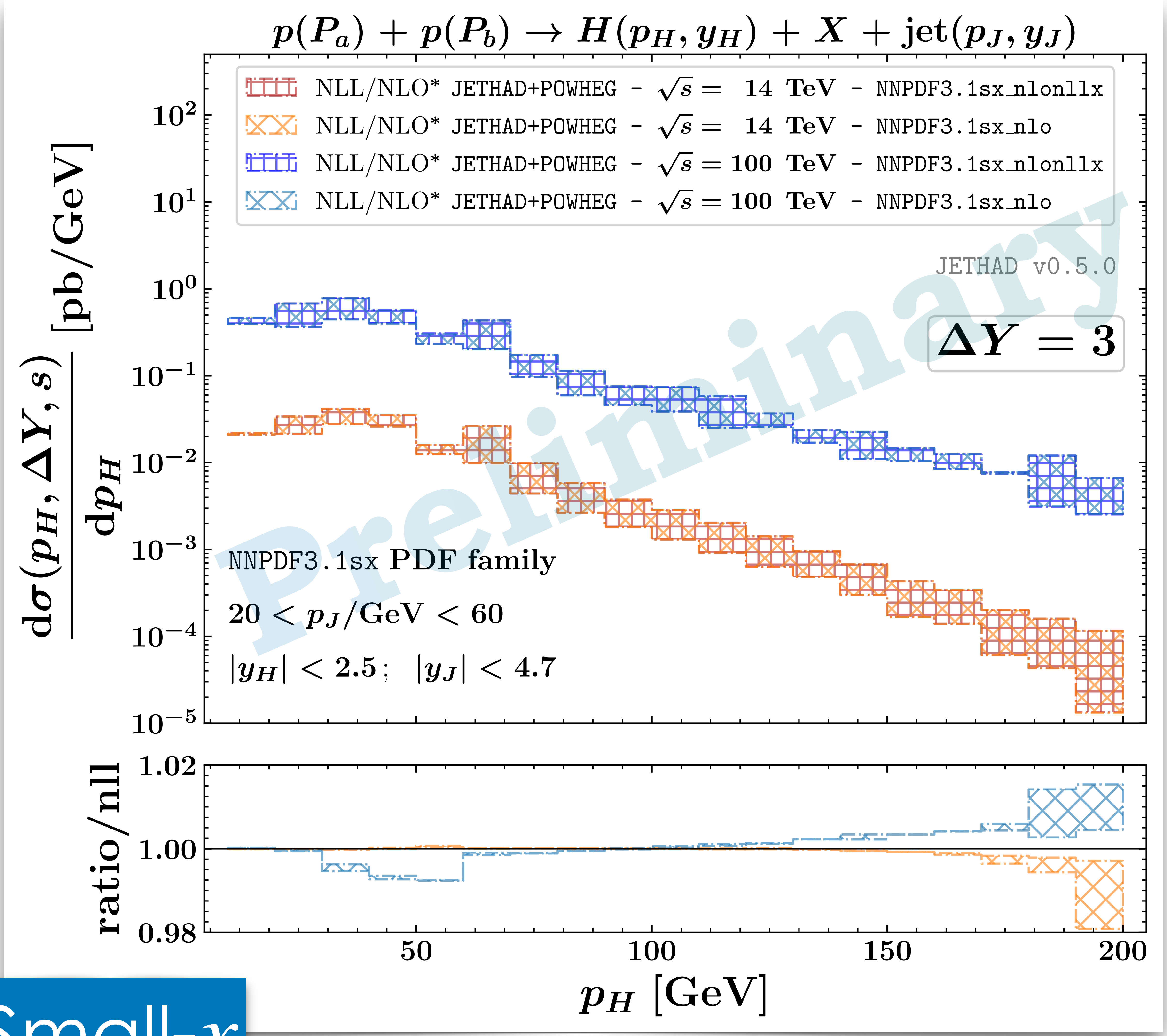


Large-x

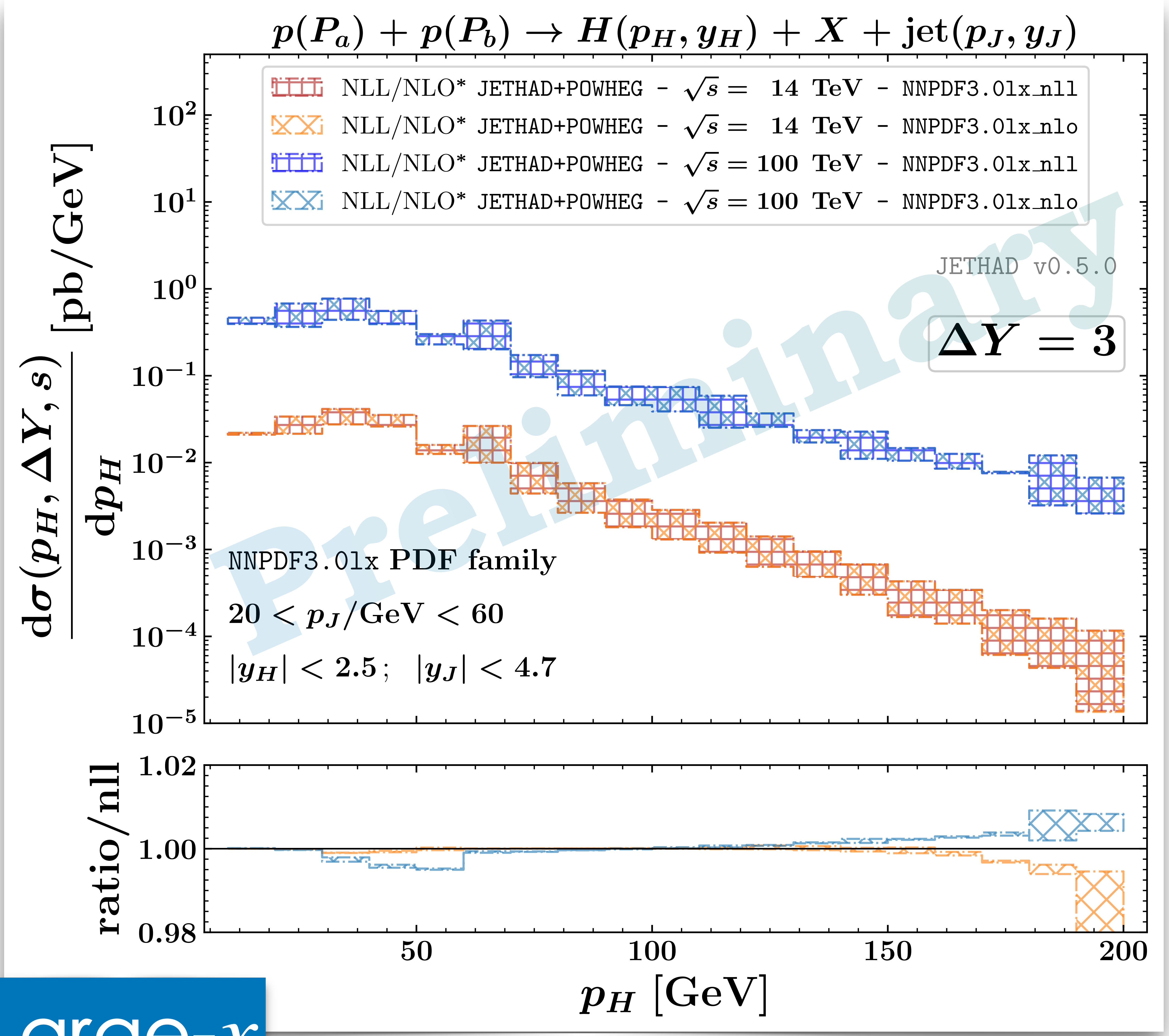
Backup

Impact of large-x threshold logs on NLO emission functions to be gauged

Small-x and large-x enhancement from PDFs



Small-x

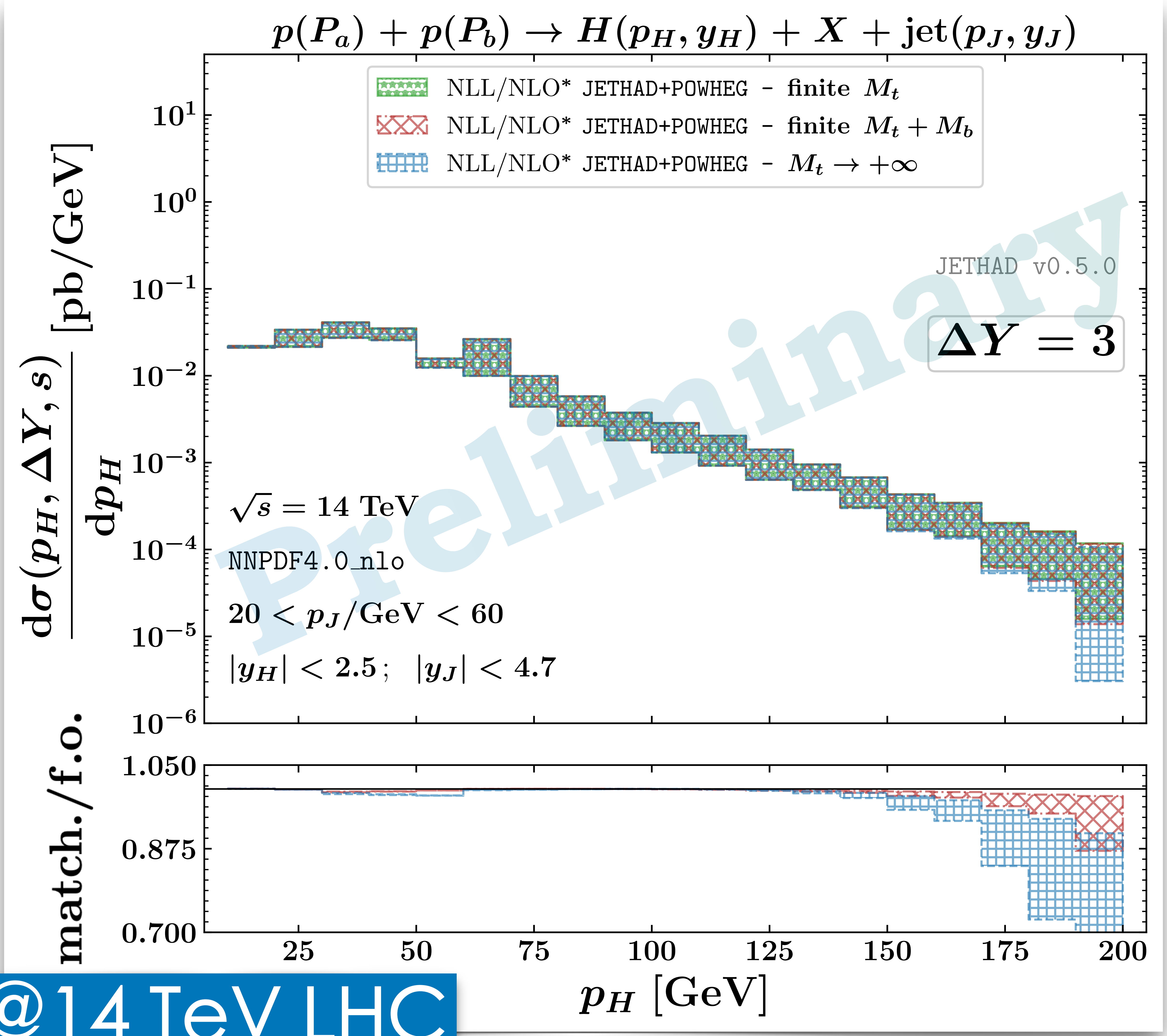


Large-x

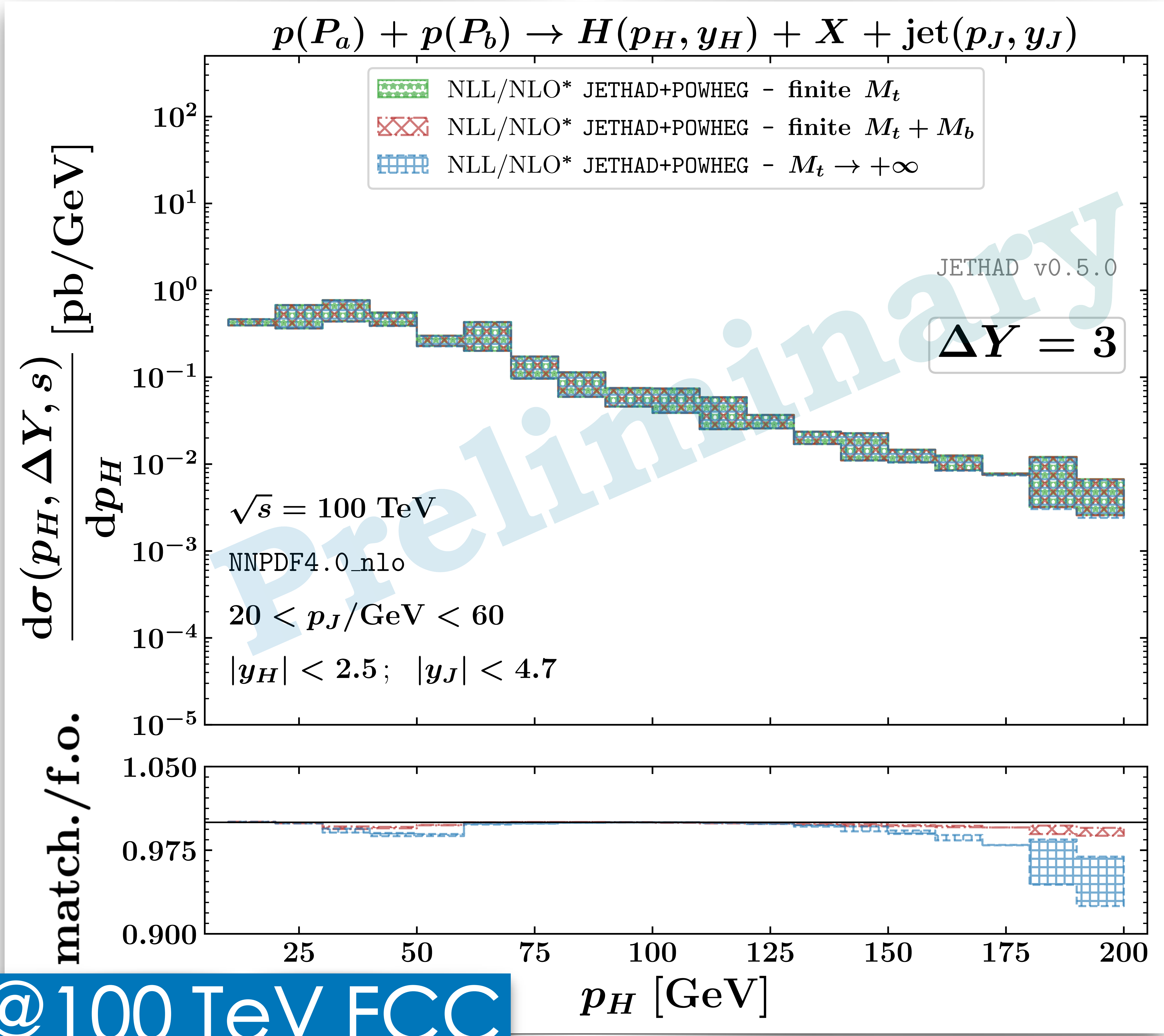
Backup

Impact of large-x threshold logs on NLO emission functions to be gauged

Finite top- and bottom-mass corrections



@14 TeV LHC



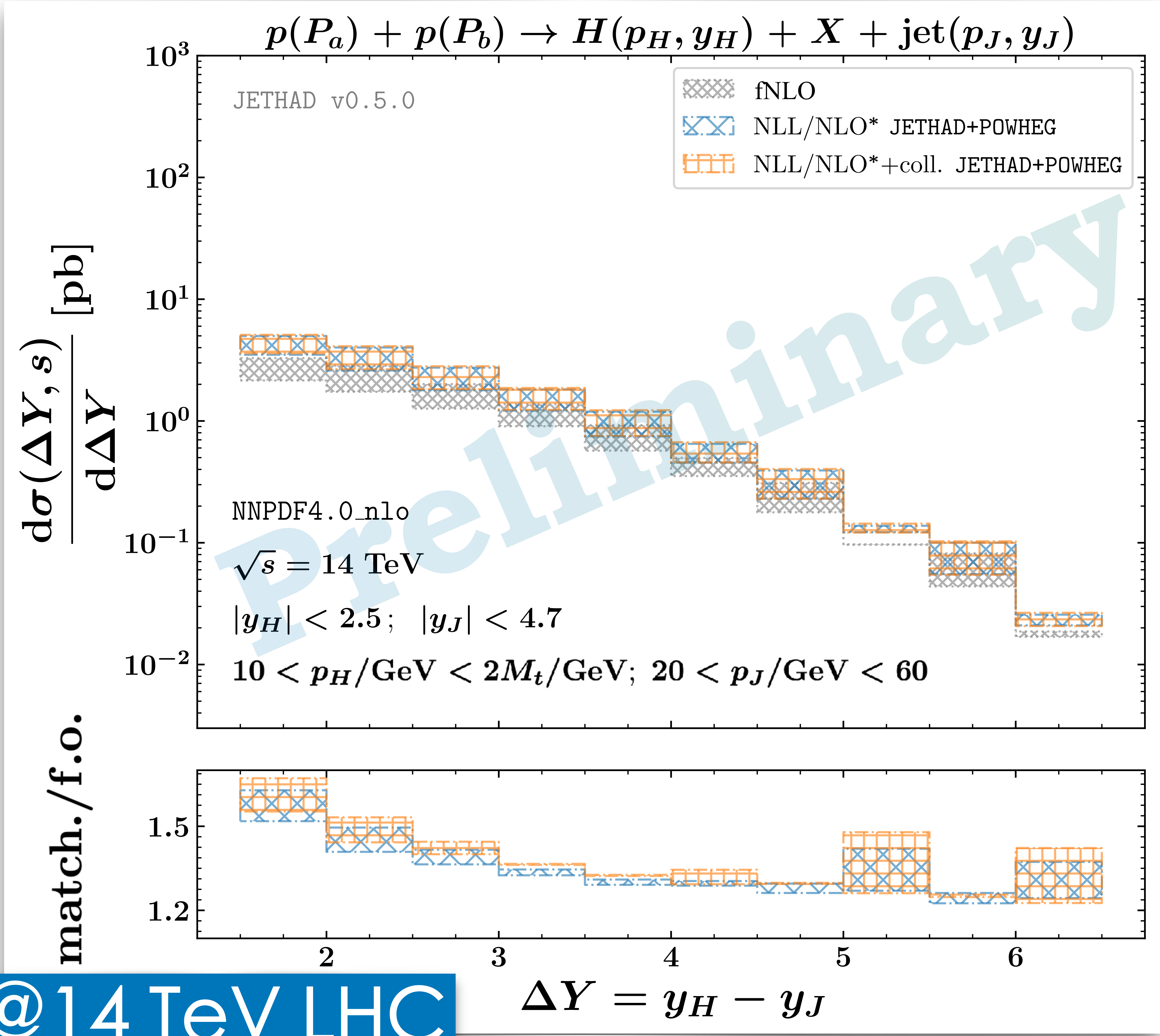
@100 TeV FCC

Backup

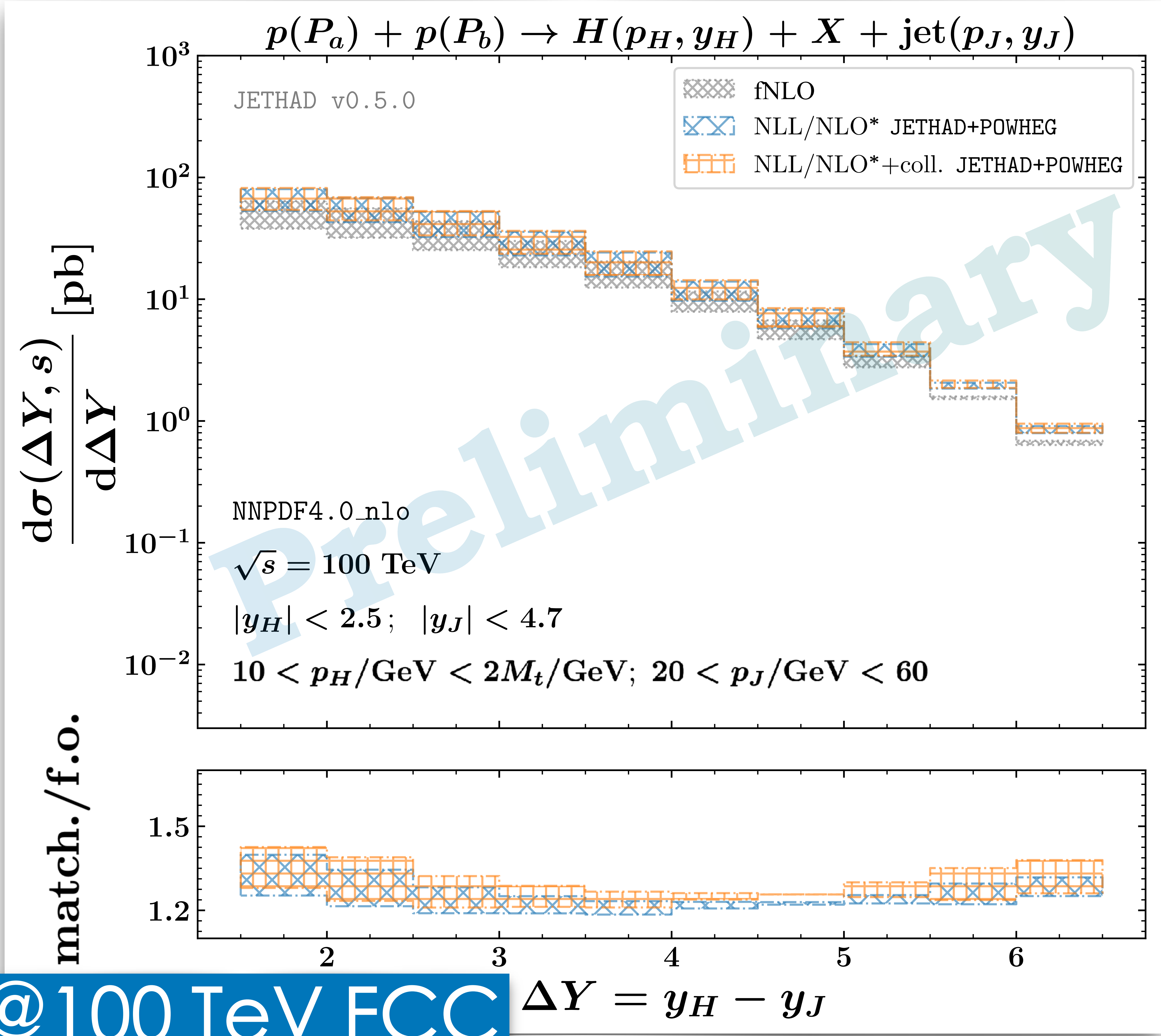
Effect of finite heavy-quark masses on NLO emission fns. to be gauged

Effect of collinear improvement on NLL BFKL kernel

Backup



@14 TeV LHC



@100 TeV FCC

(Collinear improvement) [G.P. Salam, JHEP 07 (1998) 019]; [M. Ciafaloni et al., Phys.Lett.B 587 (2004) 87-94]; [A. Sabio Vera, Nucl.Phys.B 722 (2005) 65-80]

WORK IN PROGRESS Effect of ABF-stabilized kernel to be gauged

The JETHAD technology

High-energy resummation

Hunting BFKL

in semi-hard reactions

Mueller-Navelet, light hadrons

ERIS super-module

$$\alpha_s \ln(s) \lesssim 1$$

JETHAD

v0.5.0m

python + F

🔗 [Eur. Phys. J. C 81 (2021) 8, 691]

🔗 [Phys. Rev. D 105 (2022) 11, 114008]

Backup

The JETHAD technology

High-energy resummation

Hunting BFKL

in semi-hard reactions

Mueller-Navelet, light hadrons

ERIS super-module

$$\alpha_s \ln(s) \lesssim 1$$

ERIS, 𝕯υναμις super-modules

Higgs + jet, weak bosons

High-energy resummation

Matching NLL/NLO

In Higgs + jet at the LHC

JETHAD

v0.5.0m

python + F

🔗 [Eur. Phys. J. C 81 (2021) 8, 691]

🔗 [Phys. Rev. D 105 (2022) 11, 114008]

Backup

The JETHAD technology

High-energy resummation

Hunting BFKL

in semi-hard reactions

Mueller-Navelet, light hadrons

ERIS super-module

$$\alpha_s \ln(s) \lesssim 1$$

ERIS, 𝔇υναμις super-modules

Higgs + jet, weak bosons

High-energy resummation

Matching NLL/NLO

In Higgs + jet at the LHC

JETHAD

v0.5.0m

python + F

[Eur. Phys. J. C 81 (2021) 8, 691]

[Phys. Rev. D 105 (2022) 11, 114008]

Backup

Forward Drell-Yan, onium, Higgs

LExA, HATHOR super-modules

Proton structure

Small-x UGD

Gluon TMD PDFs

The JETHAD technology

High-energy resummation

Hunting BFKL

in semi-hard reactions

Mueller-Navelet, light hadrons

ERIS super-module

$$\alpha_s \ln(s) \lesssim 1$$

ERIS, Δναμις super-modules

Higgs + jet, weak bosons

High-energy resummation

Matching NLL/NLO

In Higgs + jet at the LHC

JETHAD

v0.5.0m

python + F

WORK IN PROGRESS

Quarkonium studies

from low to high p_T

NRFF1.0 onium FFs

Vectors & pseudoscalars

JETHAD + DGLAP evolution operators

Forward Drell-Yan, onium, Higgs

LExA, HATHOR super-modules

Proton structure

Small-x UGD

Gluon TMD PDFs

[Eur. Phys. J. C 81 (2021) 8, 691]

[Phys. Rev. D 105 (2022) 11, 114008]

Backup

The JETHAD technology

High-energy resummation
Hunting BFKL
in semi-hard reactions

Mueller-Navelet, light hadrons
ERIS super-module

Quarkonium studies
from low to high p_T
NRFF1.0 onium FFs

Vectors & pseudoscalars
JETHAD + DGLAP evolution operators

WORK IN PROGRESS

$$\alpha_s \ln(s) \lesssim 1$$

JETHAD
v0.5.0m

python + F

ERIS, Δυναμις super-modules
Higgs + jet, weak bosons

High-energy resummation
Matching NLL/NLO
In Higgs + jet at the LHC

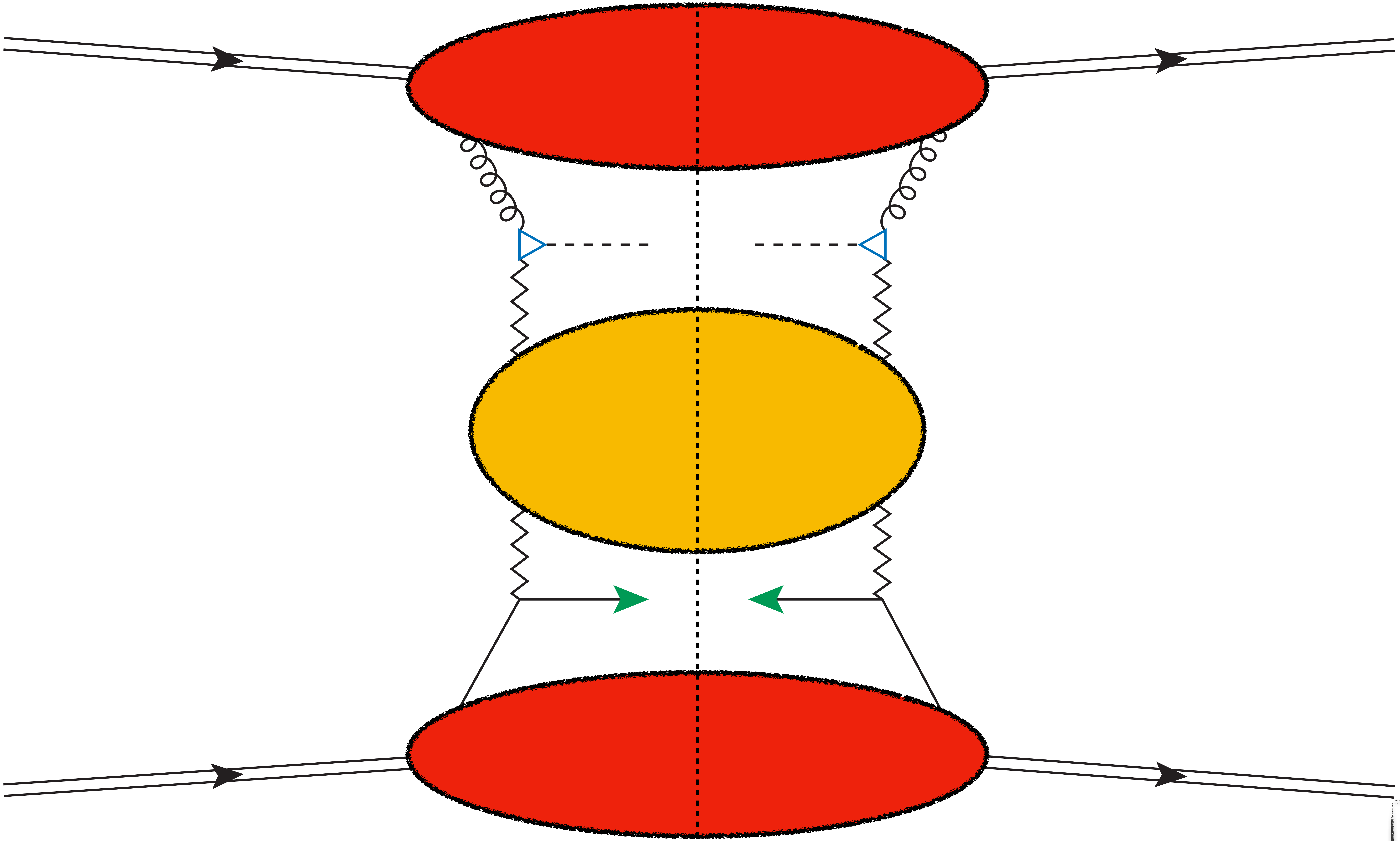
Forward Drell-Yan, onium, Higgs
LExA, HATHOR super-modules

Proton structure
Small-x UGD
Gluon TMD PDFs

[Eur. Phys. J. C 81 (2021) 8, 691]
[Phys. Rev. D 105 (2022) 11, 114008]

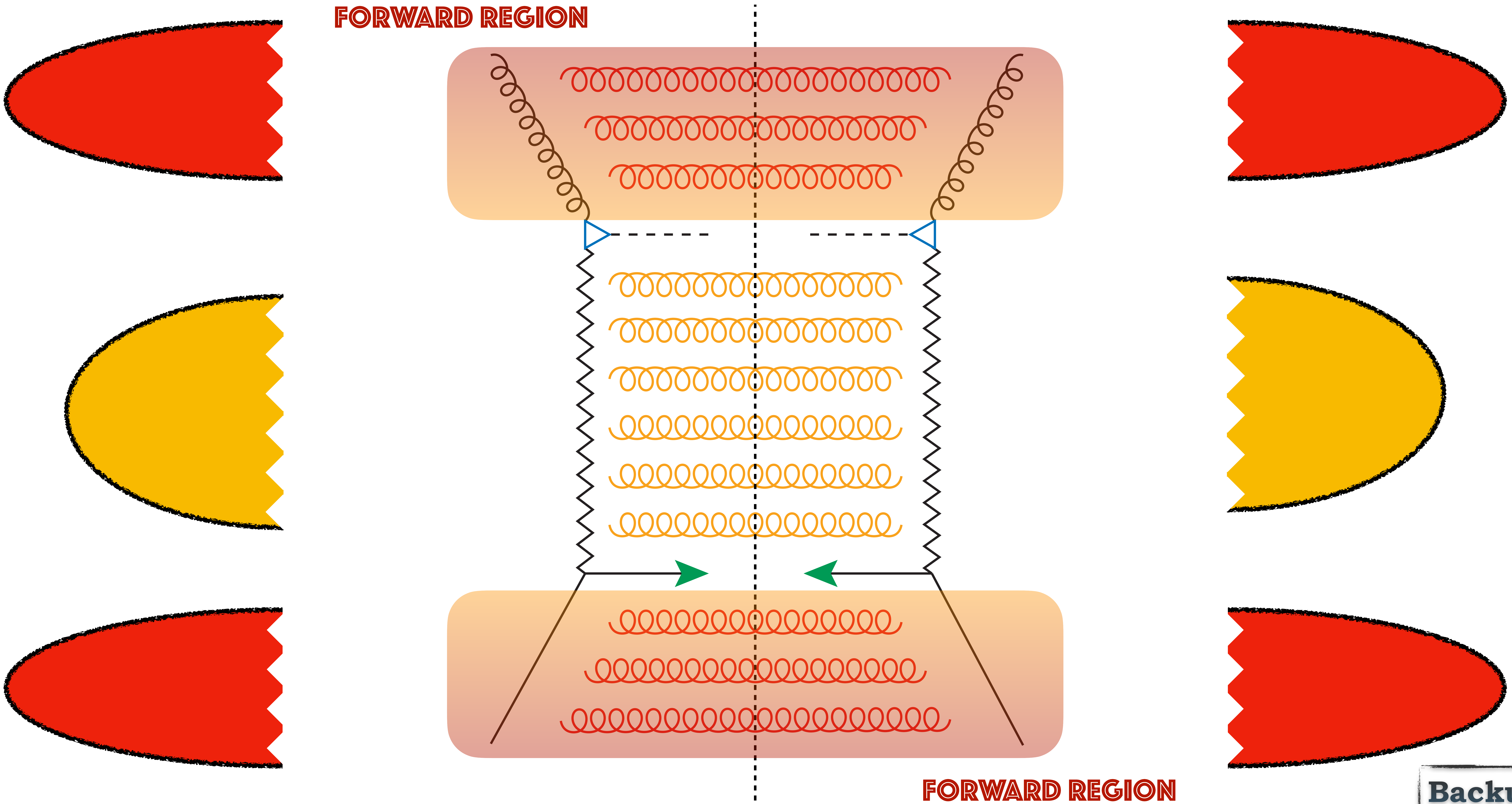
Backup

Anatomy of Higgs + jet in hybrid factorization (HyF)



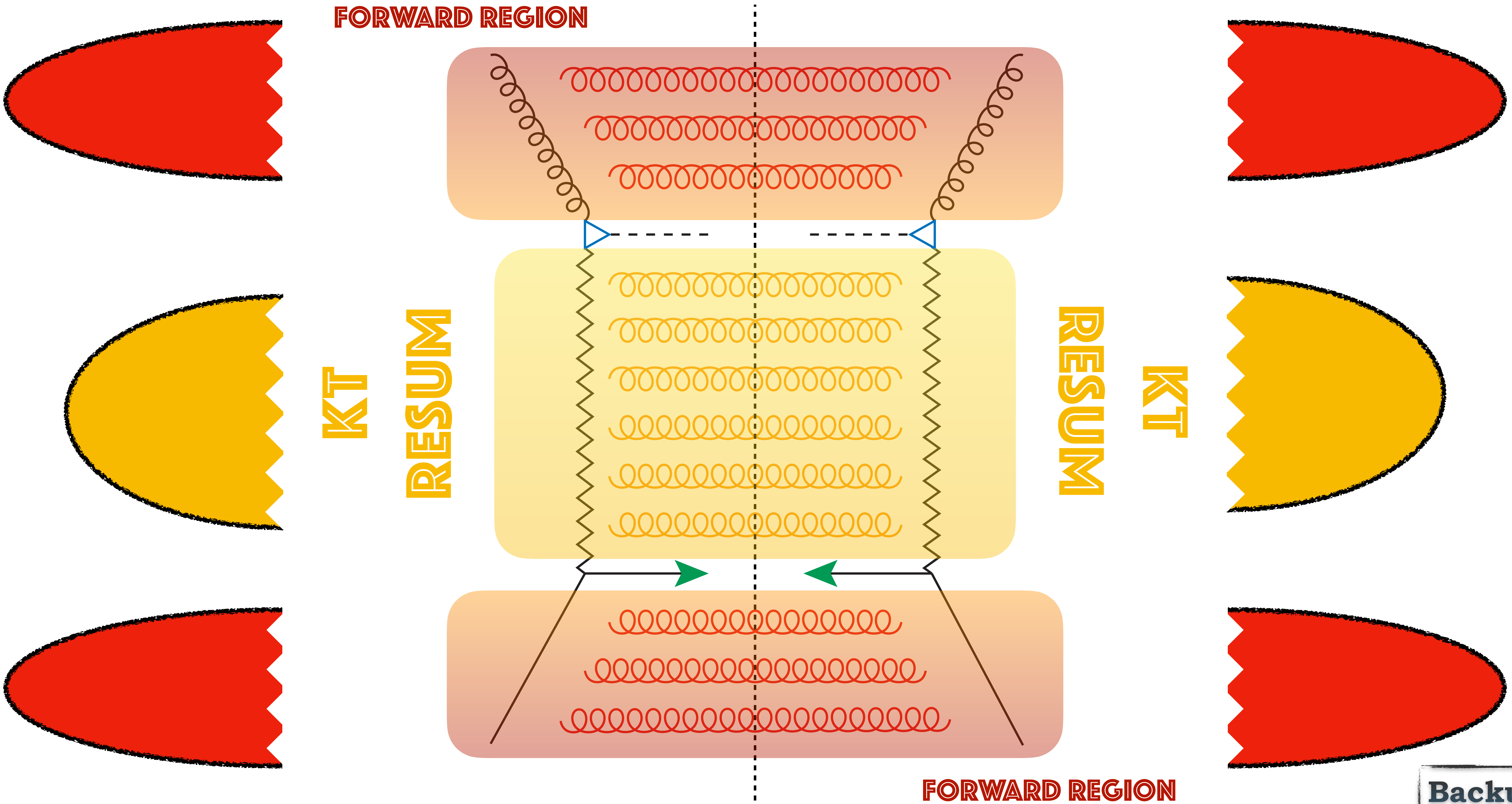
Backup

Anatomy of Higgs + jet in hybrid factorization (HyF)



Backup

Anatomy of Higgs + jet in hybrid factorization (HyF)



Backup

Ultraforward charm + Higgs production @14 TeV FPF+ATLAS

High-energy QCD in ultraforward directions

Backup

Physics Reports 968 (2022) 1–50

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

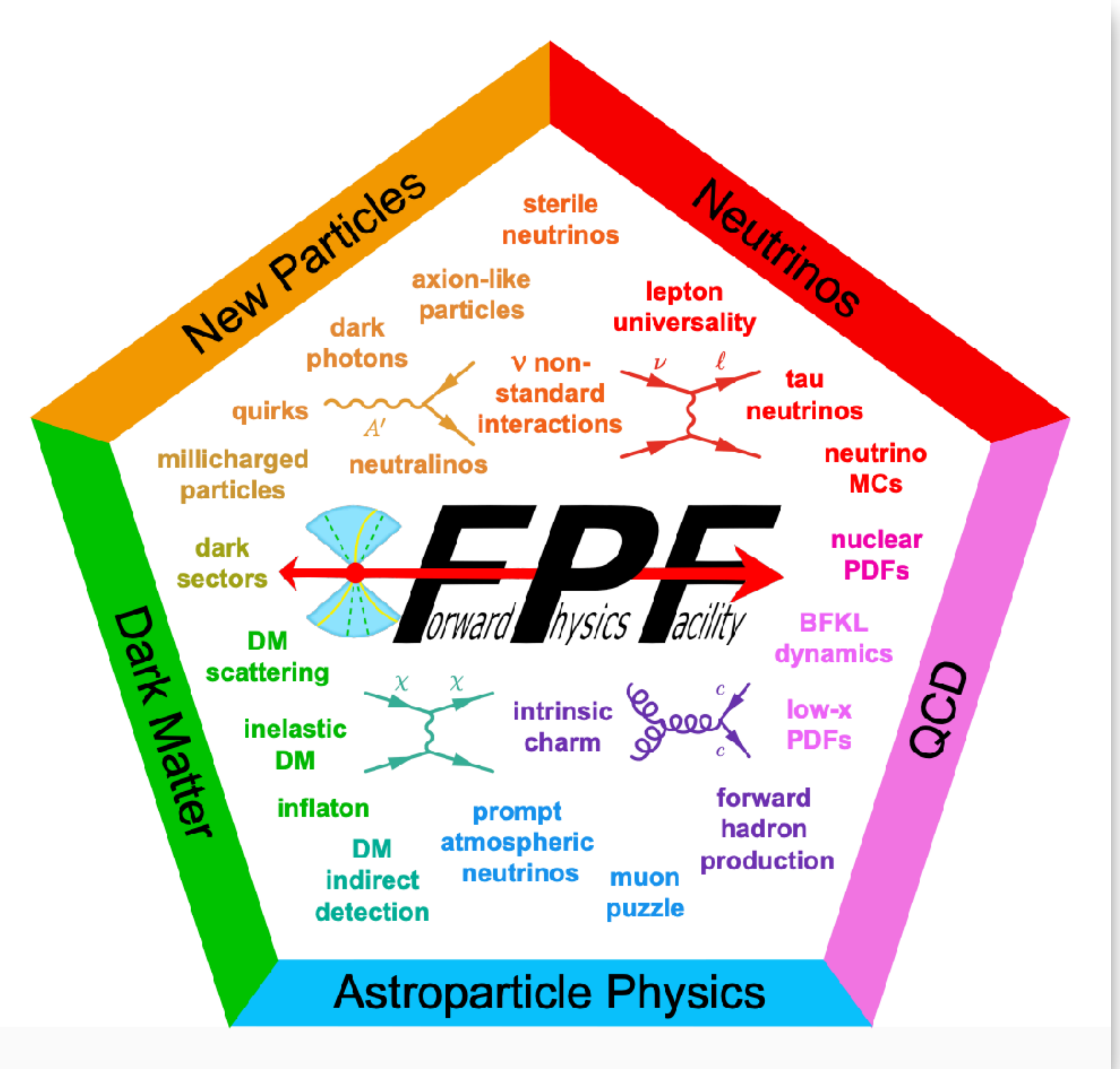
The Forward Physics Facility: Sites, experiments, and physics potential

Luis A. Anchordoqui [1], Akitaka Ariga [2,3], Tomoko Ariga [4], Weidong Bai [5], Kincso Balazs [6], Brian Batell [7], Jamie Boyd [6], Joseph Bramante [8], Mario Campanelli [9], Adrian Carmona [10], Francesco G. Celiberto [11,12,13], Grigorios Chachamis [14], Matthew Citron [15], Giovanni De Lellis [16,17], Albert De Roeck [6], Hans Dembinski [18], Peter B. Denton [19], Antonia Di Crescenzo [16,17,6], Milind V. Diwan [20], Liam Dougherty [21], Herbi K. Dreiner [22], Yong Du [23], Rikard Enberg [24], Yasaman Farzan [25], Jonathan L. Feng [26,*], Max Fieg [26], Patrick Foldenauer [27], Saeid Foroughi-Abari [28], Alexander Friedland [29], Michael Fucilla [30,31], Jonathan Gall [32], Maria Vittoria Garzelli [33,*], Francesco Giuli [34], Victor P. Goncalves [35], Marco Guzzi [36], Francis Halzen [37], Juan Carlos Helo [38,39], Christopher S. Hill [40], Ahmed Ismail [41], Ameen Ismail [42], Richard Jacobsson [6], Sudip Jana [43], Yu Seon Jeong [44], Krzysztof Jodłowski [45], Kevin J. Kelly [46], Felix Kling [29,47,**], Fnu Karan Kumar [20], Zhen Liu [48], Rafał Maciuła [49], Roshan Mammen Abraham [41], Julien Manshanden [33], Josh McFayden [50], Mohammed M.A. Mohammed [30,31], Pavel M. Nadolsky [51], Nobuchika Okada [52], John Osborne [6], Hidetoshi Otono [4], Vishvas Pandey [53,46], Alessandro Papa [30,31], Digesh Raut [54], Mary Hall Reno [55], Filippo Resnati [6], Adam Ritz [28], Juan Rojo [56], Ina Sarcevic [57], Christiane Scherb [58], Holger Schulz [59], Pedro Schwaller [60], Dipan Sengupta [61], Torbjörn Sjöstrand [62], Tyler B. Smith [26], Dennis Soldin [54], Anna Stasto [63], Antoni Szczurek [49], Zahra Tabrizi [64], Sebastian Trojanowski [65,66], Yu-Dai Tsai [26,46], Douglas Tuckler [67], Martin W. Winkler [68], Keping Xie [7], Yue Zhang [67]

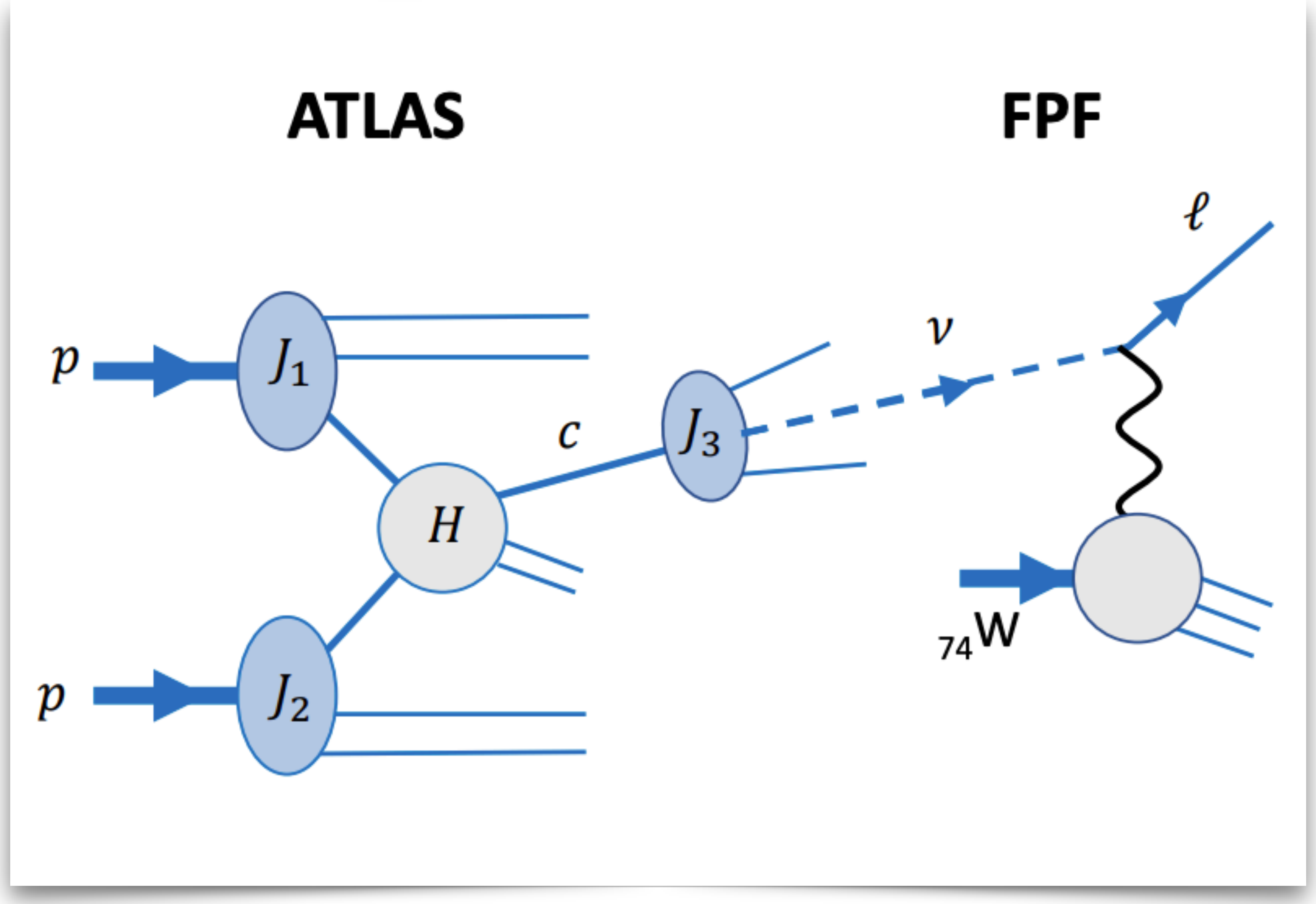
[1] Department of Physics and Astronomy, Lehman College, City University of New York, Bronx, NY 10468, USA
[2] Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
[3] Department of Physics, Chiba University, 1-33 Yayoi-cho Inage-ku, Chiba, 263-8522, Japan
[4] Kyushu University, Nishi-ku, 819-0395 Fukuoka, Japan
[5] Sun Yat-sen University, School of Physics, No. 135, Xingang Xi Road, Guangzhou, 510275, PR China
[6] CERN, CH-1211 Geneva 23, Switzerland
[7] PITT PACC, Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA
[8] Department of Physics, Queen's University, Kingston, ON K7L 2S8, Canada
[9] Department of Physics & Astronomy, University College London, Gower Street, London, WC1E 6BT, United Kingdom
[10] CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, E18071 Granada, Spain
[11] European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), I-38123 Villazzano, Trento, Italy
[12] Fondazione Bruno Kessler (FBK), I-38123 Povo, Trento, Italy
[13] INFN-TIFPA Trento Institute of Fundamental Physics and Applications, I-38123 Povo, Trento, Italy

* Corresponding authors.
** Corresponding author at: Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany.
E-mail addresses: jlf@uci.edu (J.L. Feng), maria.vittoria.garzelli@desy.de (M.V. Garzelli), felix.kling@desy.de (F. Kling).

https://doi.org/10.1016/j.physrep.2022.04.004
0370-1573/© 2022 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).



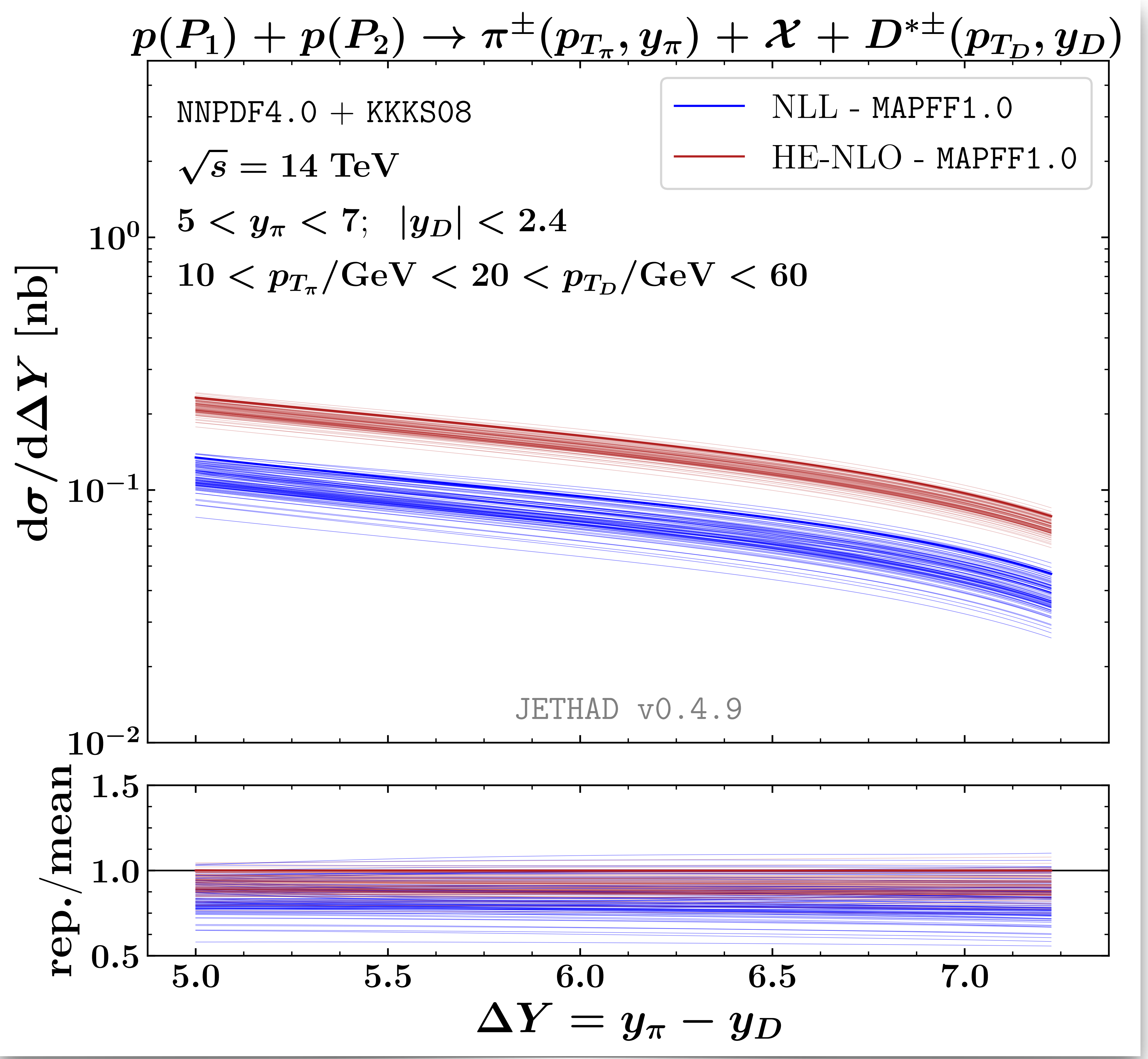
🔗 [FPF Snowmass Whitepaper]



Rapidity distributions @FPF+ATLAS

Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) production

[FPF Snowmass Whitepaper]

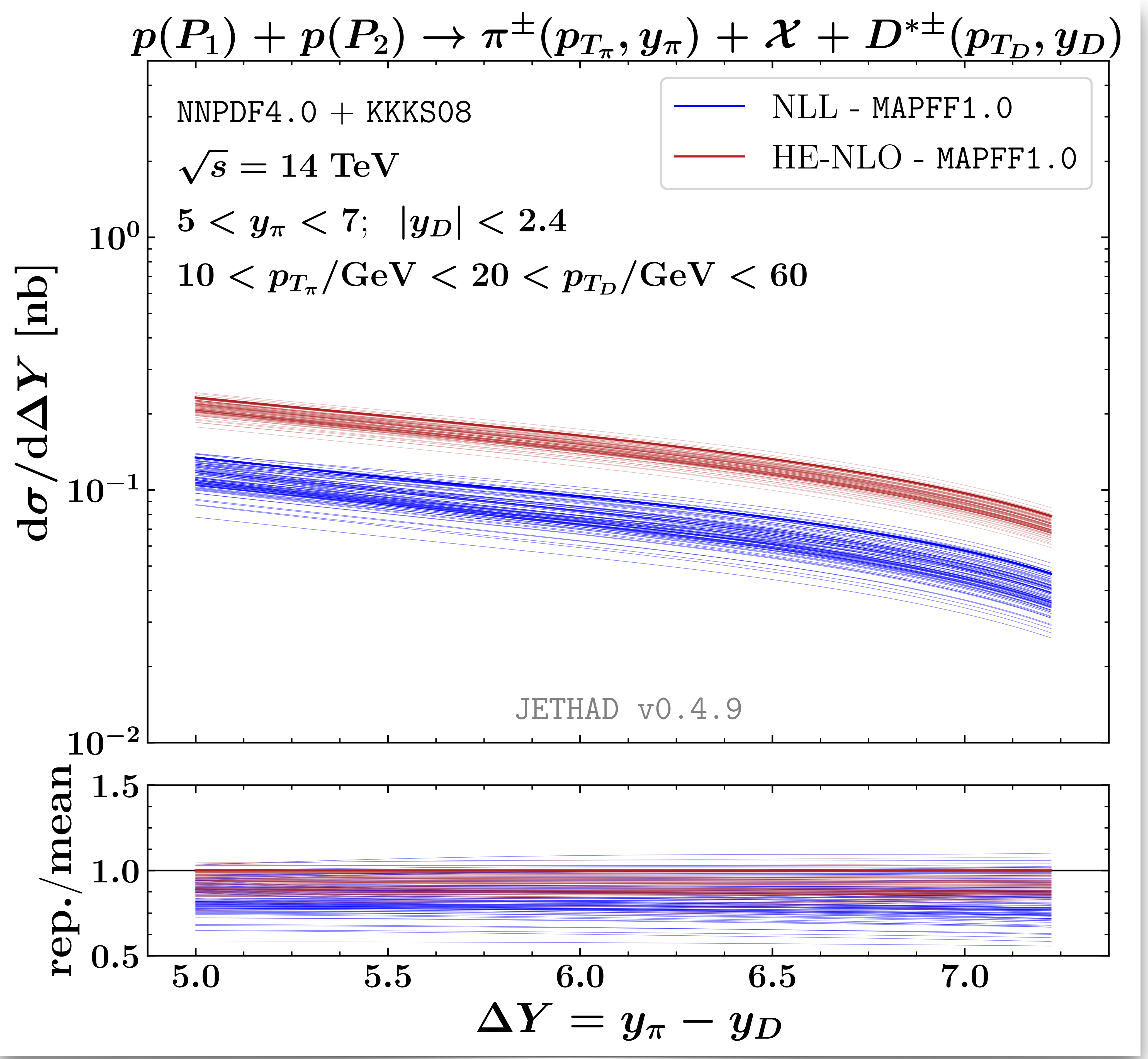


Backup

Rapidity distributions @FPF+ATLAS

Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) production

[FPF Snowmass Whitepaper]



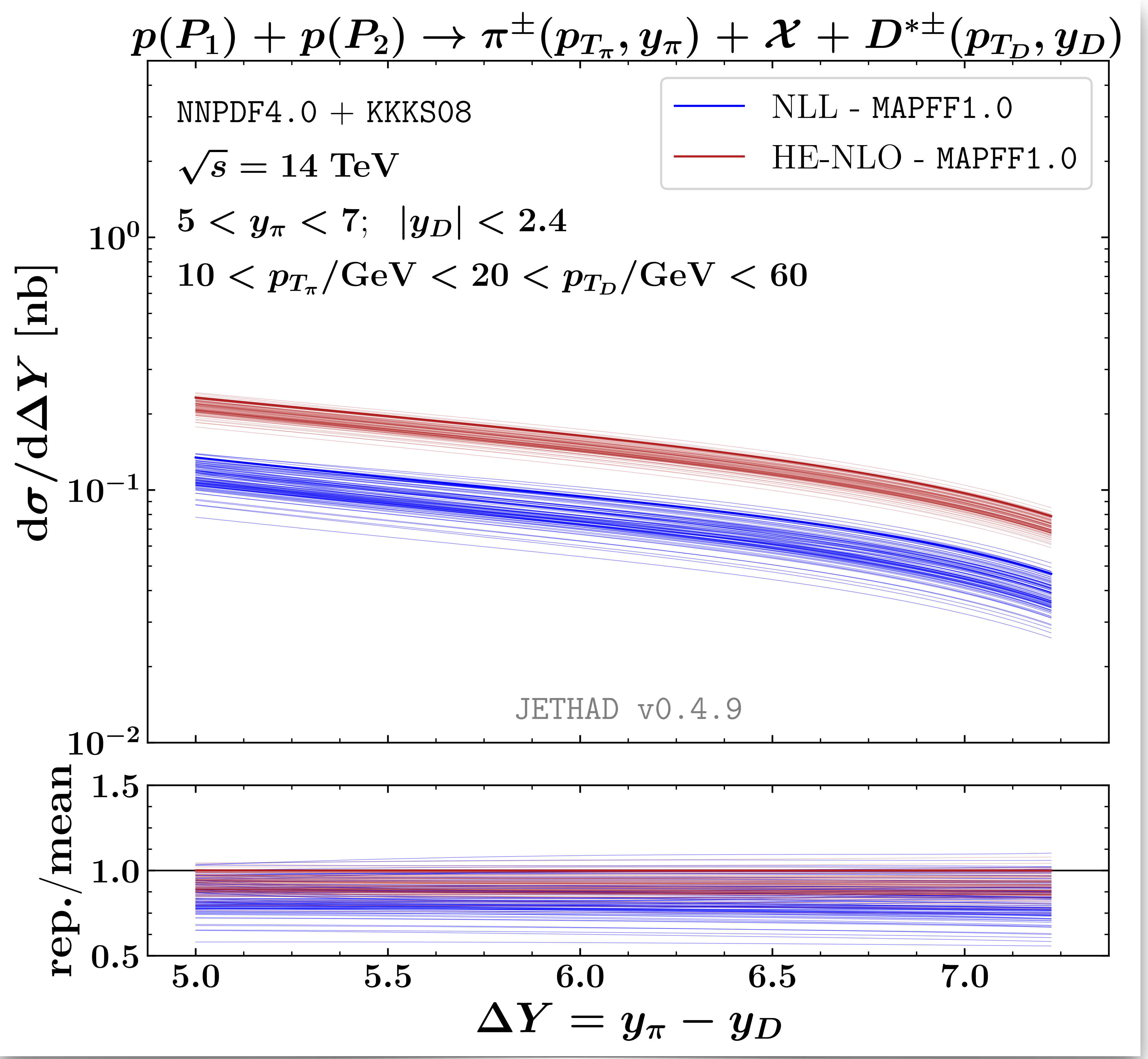
- Impact of collinear FFs on ΔY-distribution
- Replica method at work

Backup

Rapidity distributions @FPF+ATLAS

Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) production

[FPF Snowmass Whitepaper]

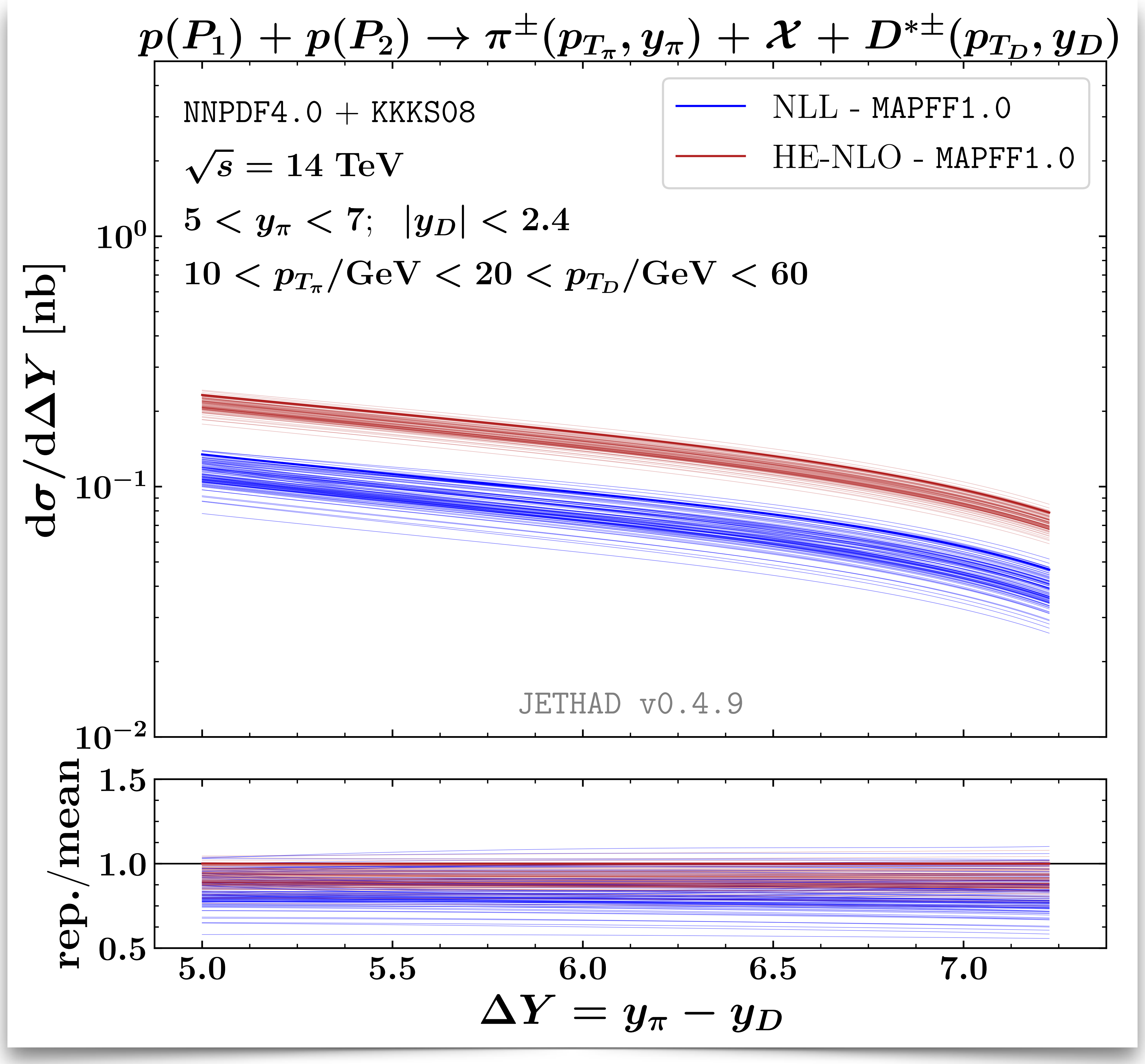


* Impact of collinear FFs on ΔY-distribution
* Replica method at work
* Larger spread of replicas at NLL
* Probe FFs in complementary ranges
  Weight of FF replicas in the same set
  Different sets via functional correlation?
* Complementary studies on FFs

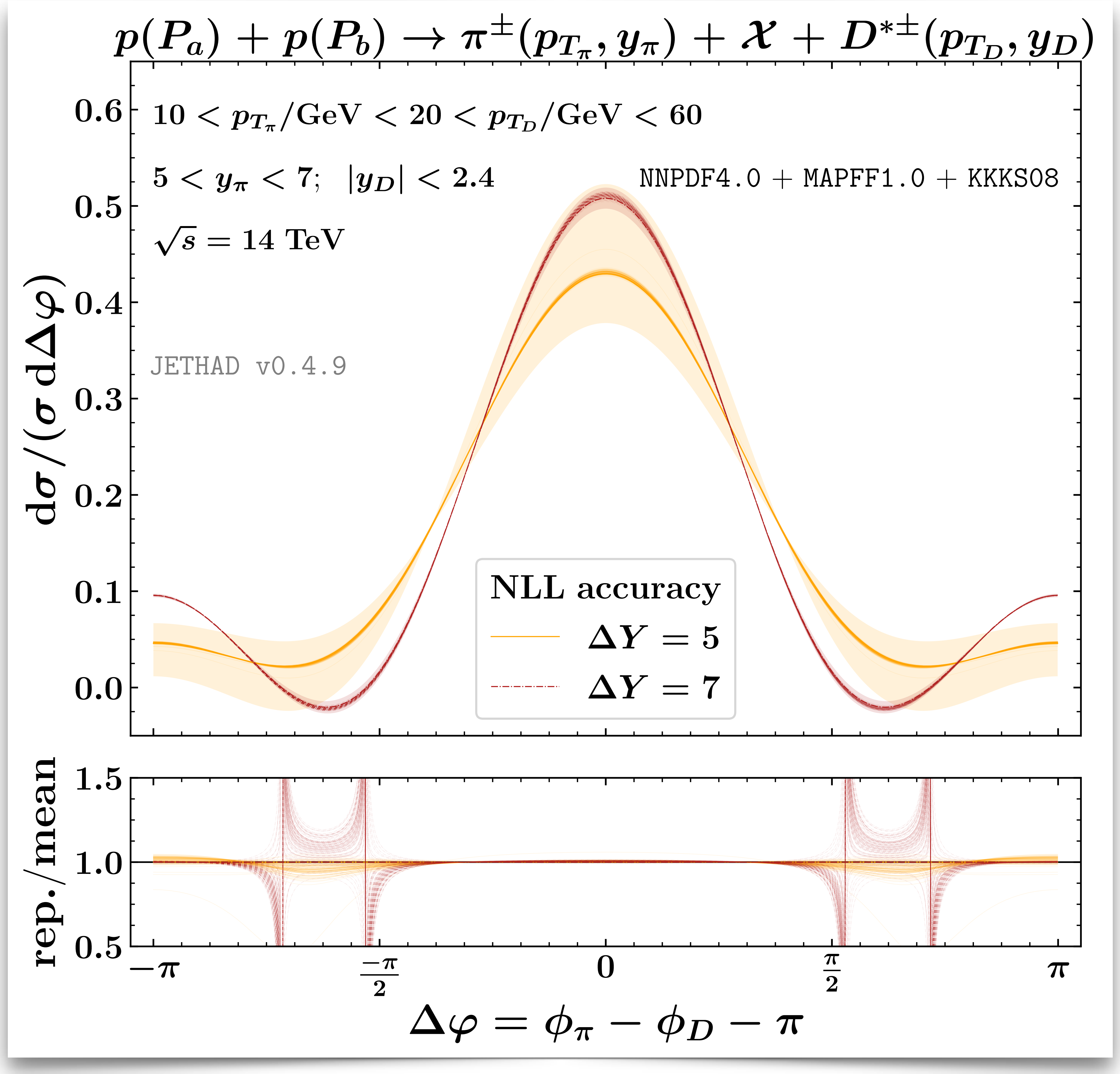
Backup

Rapidity distributions @FPF+ATLAS

Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) ΔY-spectrum



Inclusive $\pi^{\pm}$ (FPF) + $D^{*\pm}$ (ATLAS) $\Delta\varphi$-spectrum



[FPF Snowmass Whitepaper]

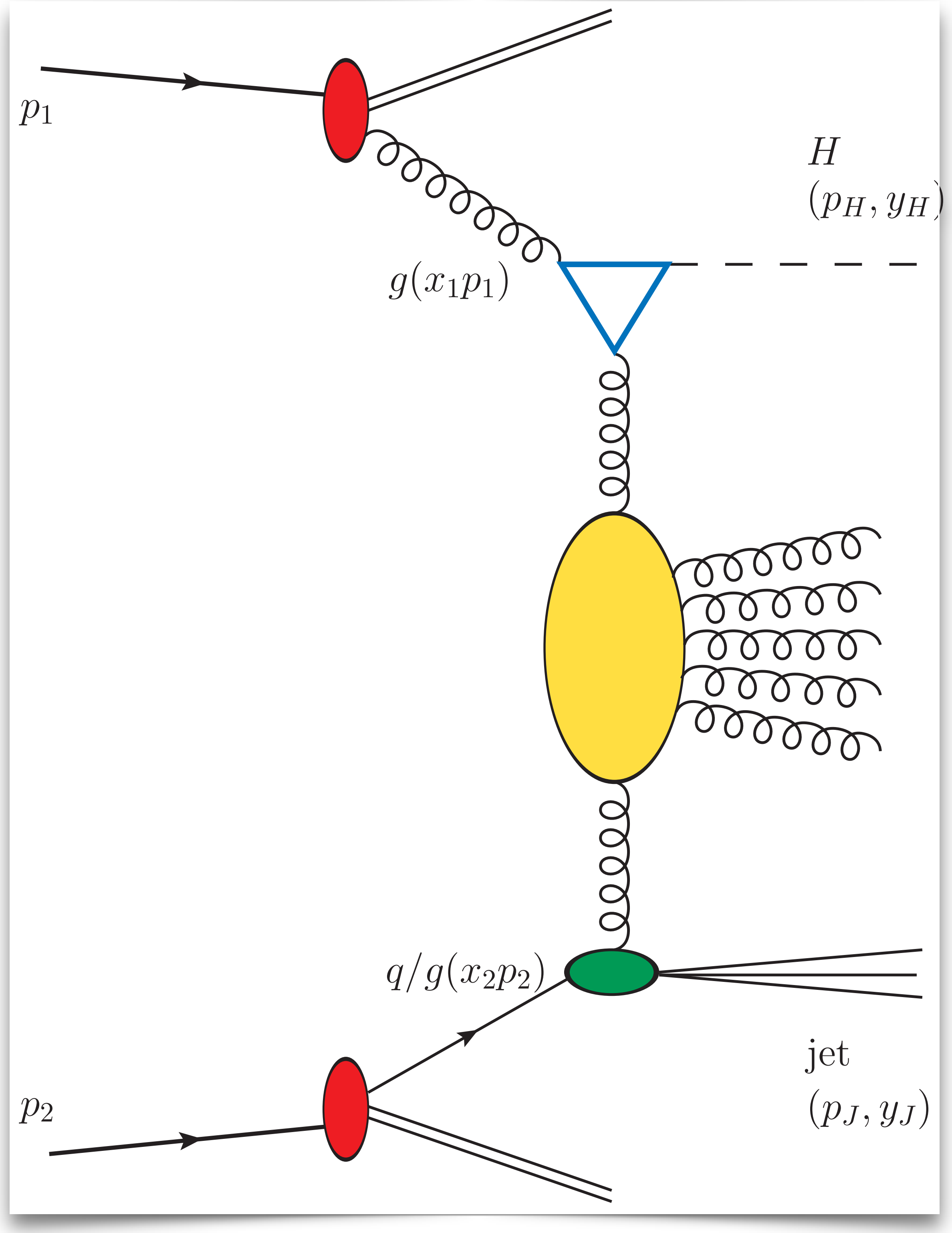
Backup

HIGGS + JET DISTRIBUTIONS

Inclusive Higgs + jet at the LHC

- Inclusive h.p. of a Higgs + jet system with high p_T and large rapidity separation, ΔY
- Large energy scales expected to stabilize the high-energy resummed series

$$\frac{d\sigma}{dx_1 dx_2\, d|\vec{p}_H|\, d|\vec{p}_J| d\varphi_H d\varphi_J} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + \sum_{n=1}^{\infty} 2\cos(n\varphi)\,\mathcal{C}_n\right]$$



$$\varphi = \varphi_H - \varphi_J - \pi$$

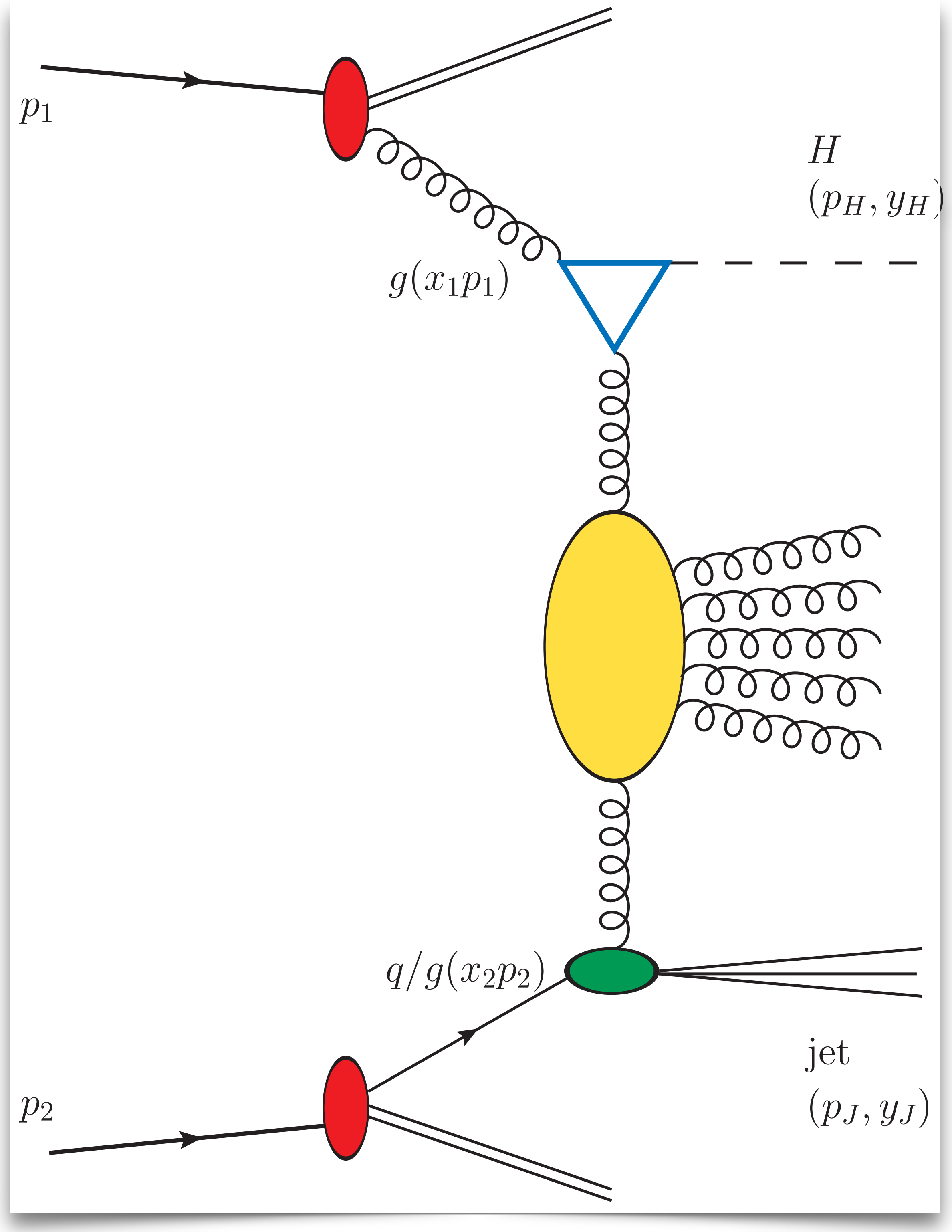
Backup

Inclusive Higgs + jet at the LHC

- Inclusive h.p. of a Higgs + jet system with high p_T and large rapidity separation, ΔY
- Large energy scales expected to stabilize the high-energy resummed series

$$\frac{d\sigma}{dx_1 dx_2\, d|\vec{p}_H|\, d|\vec{p}_J| d\varphi_H d\varphi_J} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + \sum_{n=1}^{\infty} 2\cos(n\varphi)\, \mathcal{C}_n\right]$$

$$\varphi = \varphi_H - \varphi_J - \pi$$



$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_H\, dy_J\, d^2\vec{p}_H\, d^2\vec{p}_J} = \frac{1}{(2\pi)^2}$$

NLO* $$\times \int \frac{d^2\vec{q}_1}{\vec{q}_1^{\,2}}\, \mathcal{V}_H^{(r)}(\vec{q}_1, s_0, x_1, \vec{p}_H)$$

NLL $$\times \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{x_1 x_2 s}{s_0}\right)^{\omega} \mathcal{G}_\omega(\vec{q}_1, \vec{q}_2)$$

NLO* $$\times \int \frac{d^2\vec{q}_2}{\vec{q}_2^{\,2}}\, \mathcal{V}_J^{(s)}(\vec{q}_2, s_0, x_2, \vec{p}_J)$$

Higgs vertex (off-shell coefficient function)

jet vertex (off-shell coefficient function)

BFKL Green's function

Backup

Inclusive Higgs + jet at the LHC

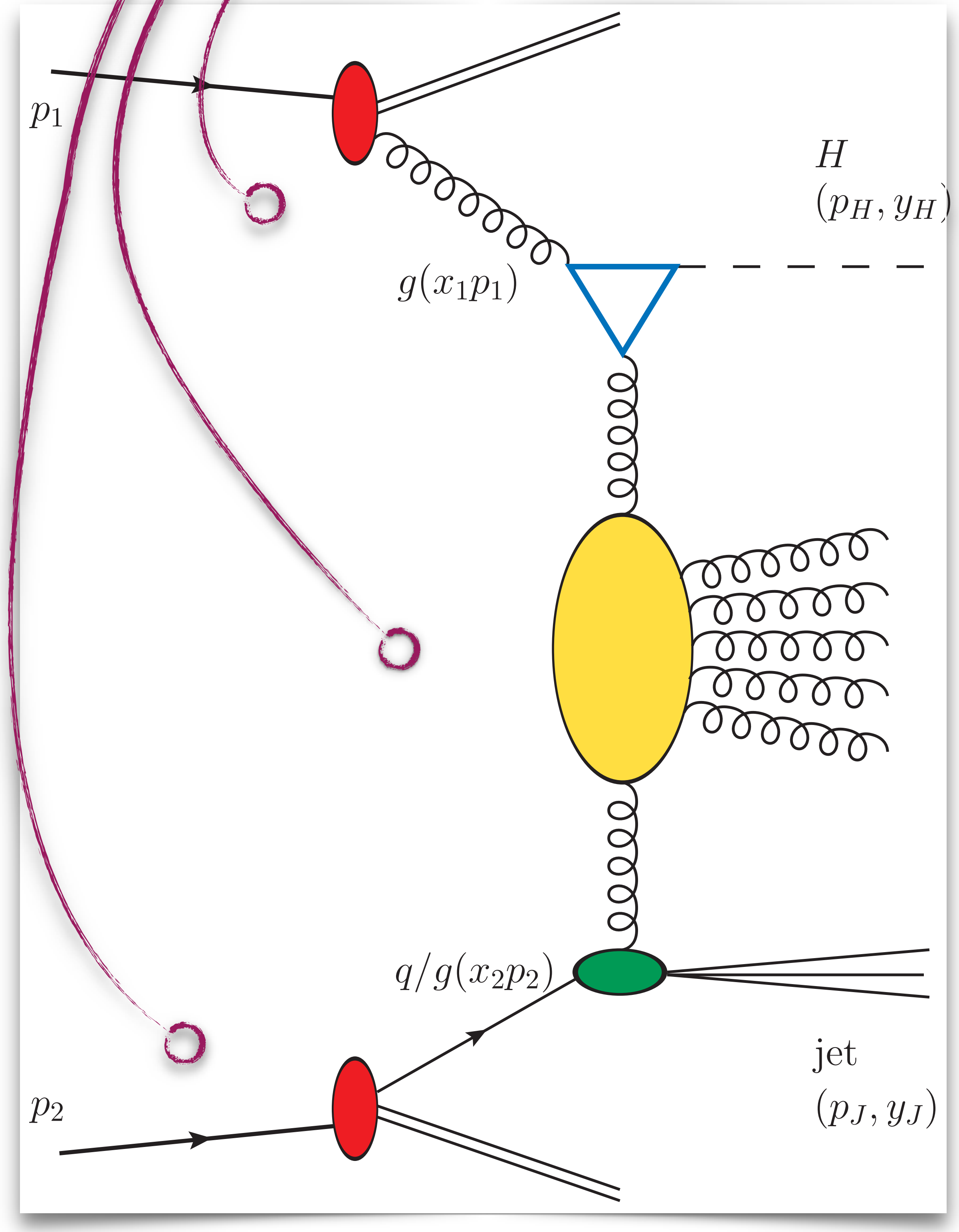
- Inclusive h.p. of a Higgs + jet system with high p_T and large rapidity separation, ΔY
- Large energy scales expected to stabilize the high-energy resummed series

$$\frac{d\sigma}{dx_1 dx_2\, d|\vec{p}_H|\, d|\vec{p}_J| d\varphi_H d\varphi_J} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + \sum_{n=1}^{\infty} 2\cos(n\varphi)\,\mathcal{C}_n\right]$$

Higgs vertex (off-shell coefficient function)

jet vertex (off-shell coefficient function)

$$\varphi = \varphi_H - \varphi_J - \pi$$



$\mu_{F,R} \sim M_{H,\perp}$

$\mu_R \sim \sqrt{M_{H,\perp}\, p_J}$

$\mu_{F,R} \sim p_J$

NLO*

NLL

NLO*

$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_H\, dy_J\, d^2\vec{p}_H\, d^2\vec{p}_J} = \frac{1}{(2\pi)^2}$$

$$\times \int \frac{d^2\vec{q}_1}{\vec{q}_1^{\,2}}\, \mathcal{V}_H^{(r)}(\vec{q}_1, s_0, x_1, \vec{p}_H)$$

$$\times \int_{\delta - i\infty}^{\delta + i\infty} \frac{d\omega}{2\pi i} \left(\frac{x_1 x_2 s}{s_0}\right)^{\omega} \mathcal{G}_\omega(\vec{q}_1, \vec{q}_2)$$

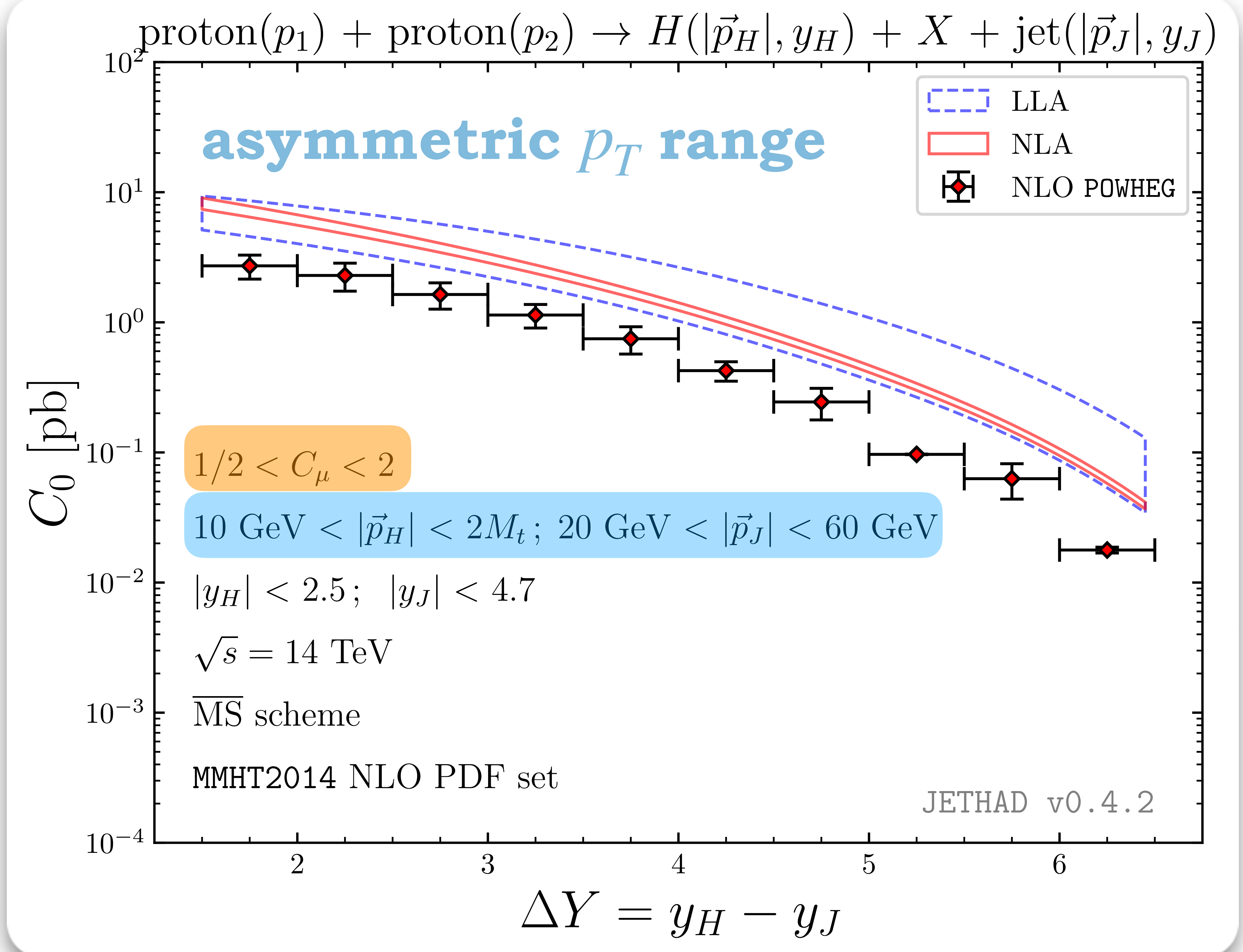
$$\times \int \frac{d^2\vec{q}_2}{\vec{q}_2^{\,2}}\, \mathcal{V}_J^{(s)}(\vec{q}_2, s_0, x_2, \vec{p}_J)$$

BFKL Green's function

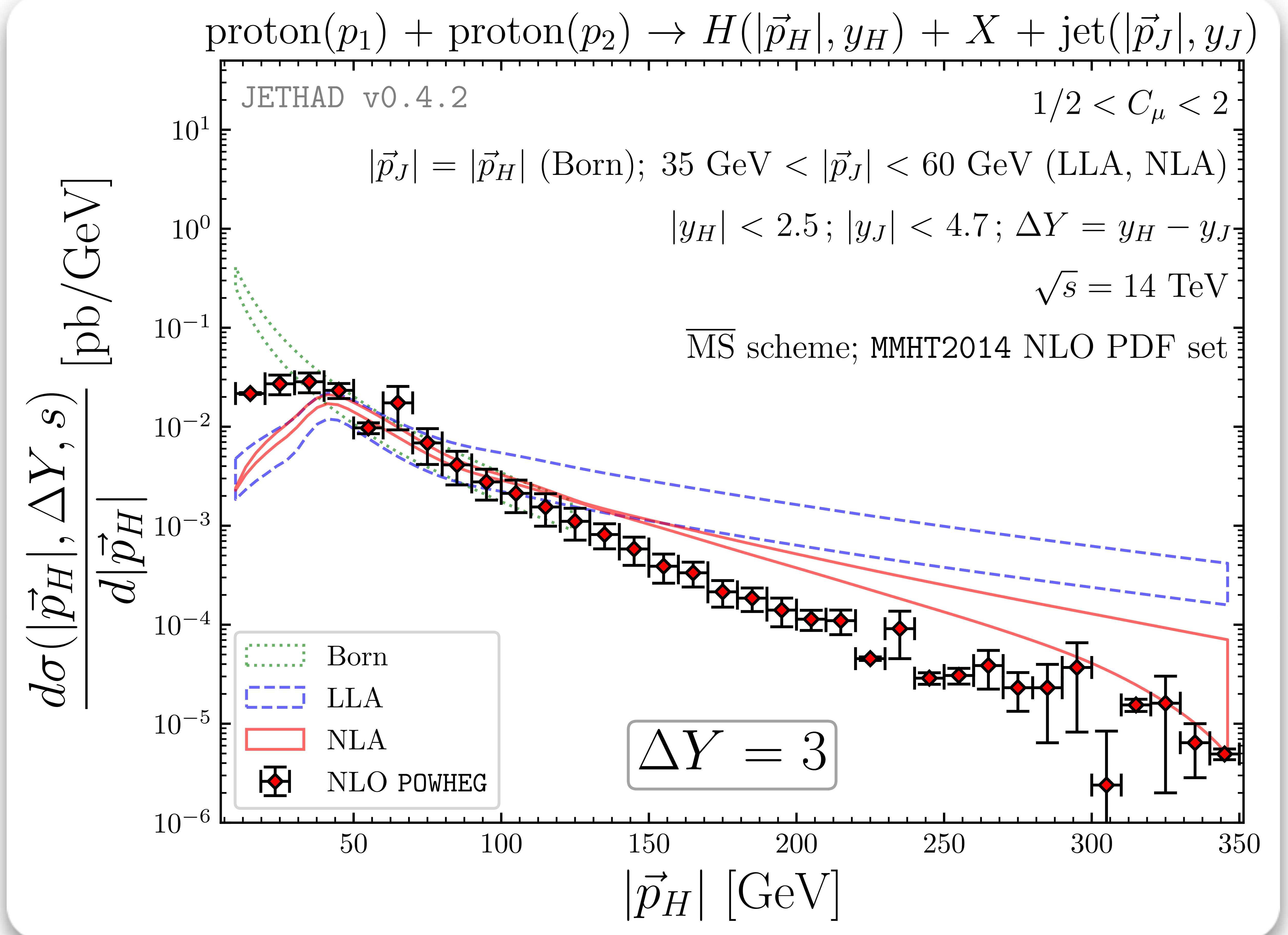
Backup

The Higgs + jet spectrum in hybrid factorization

ΔY spectrum



p_H spectrum



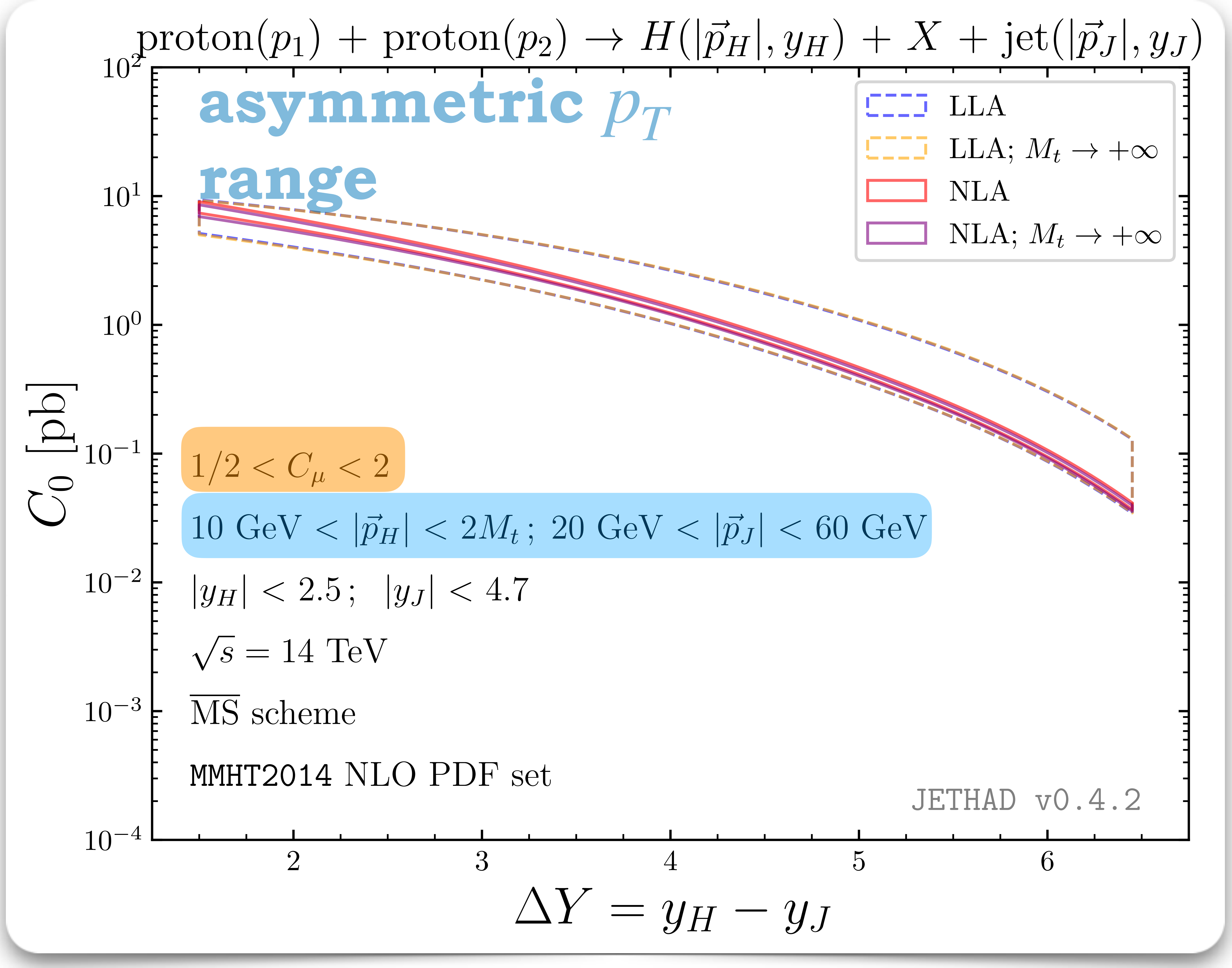
(in this slide) 🔗 [F. G. C. et al., Eur. Phys. J. C 81 (2021) 4, 293]

(JETHAD) 🔗 [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]

Backup

ΔY-distribution in the infinite top-mass limit

$$C_n(\Delta Y, s) = \int_{p_H^{\min}}^{p_H^{\max}} d|\vec{p}_H| \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_H^{\min}}^{y_H^{\max}} dy_H \int_{y_J^{\min}}^{y_J^{\max}} dy_J \, \delta\left(y_H - y_J - \Delta Y\right) \mathcal{C}_n$$



Backup

🔗 [F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

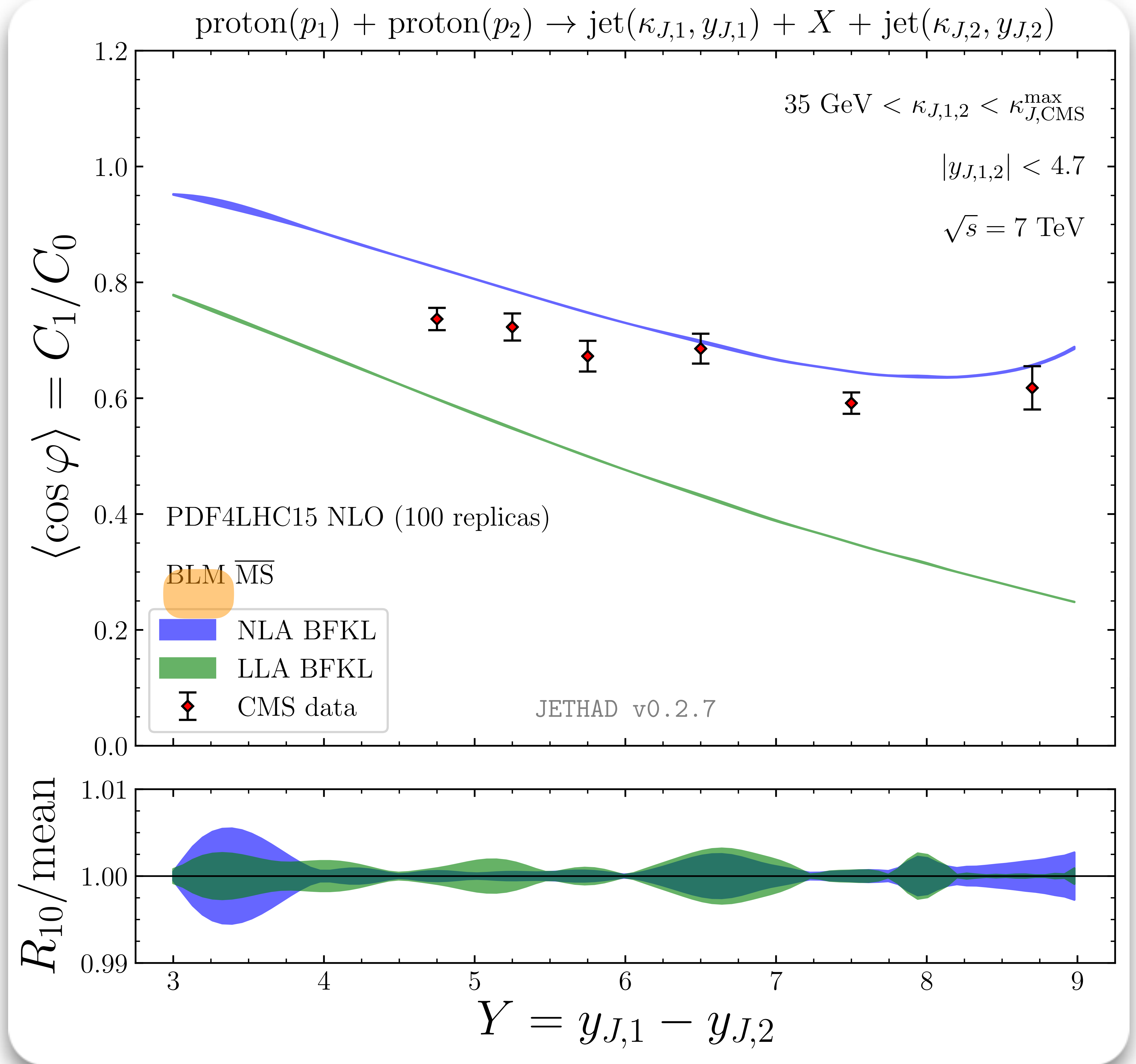
Angular correlations in the infinite top-mass limit

$$R_{n0}(\Delta Y, s) = C_n/C_0 \equiv \langle \cos n\varphi \rangle$$

Mueller-Navelet jets

[B. Ducloué, L. Szymanowski, S. Wallon, Phys.Rev.Lett. 112 (2014) 082003]

(figure below) [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]



Backup

Angular correlations in the infinite top-mass limit

$$R_{n0}(\Delta Y, s) = C_n/C_0 \equiv \langle \cos n\varphi \rangle$$

Mueller-Navelet jets

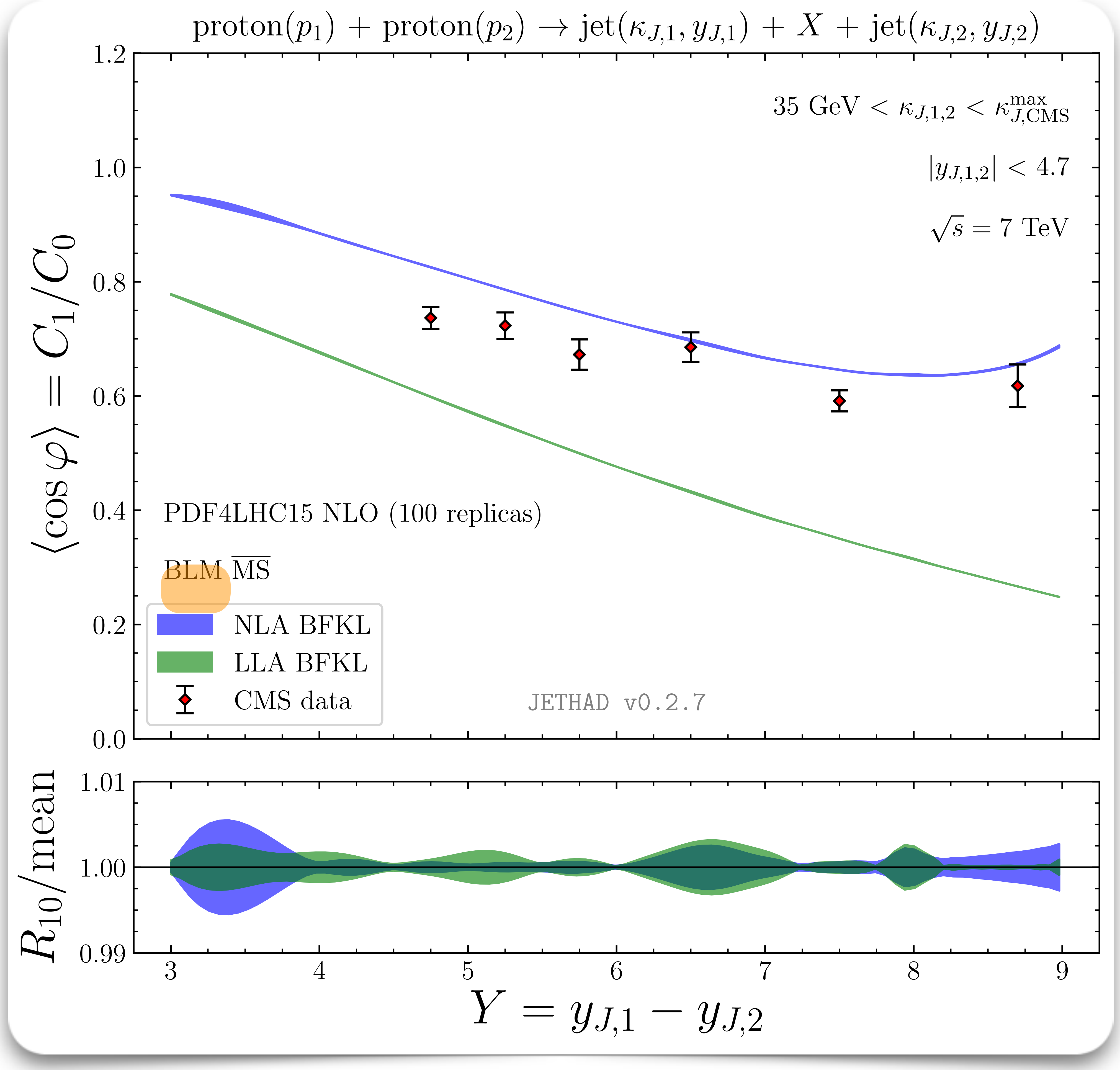
[B. Ducloué, L. Szymanowski, S. Wallon, Phys.Rev.Lett. 112 (2014) 082003]

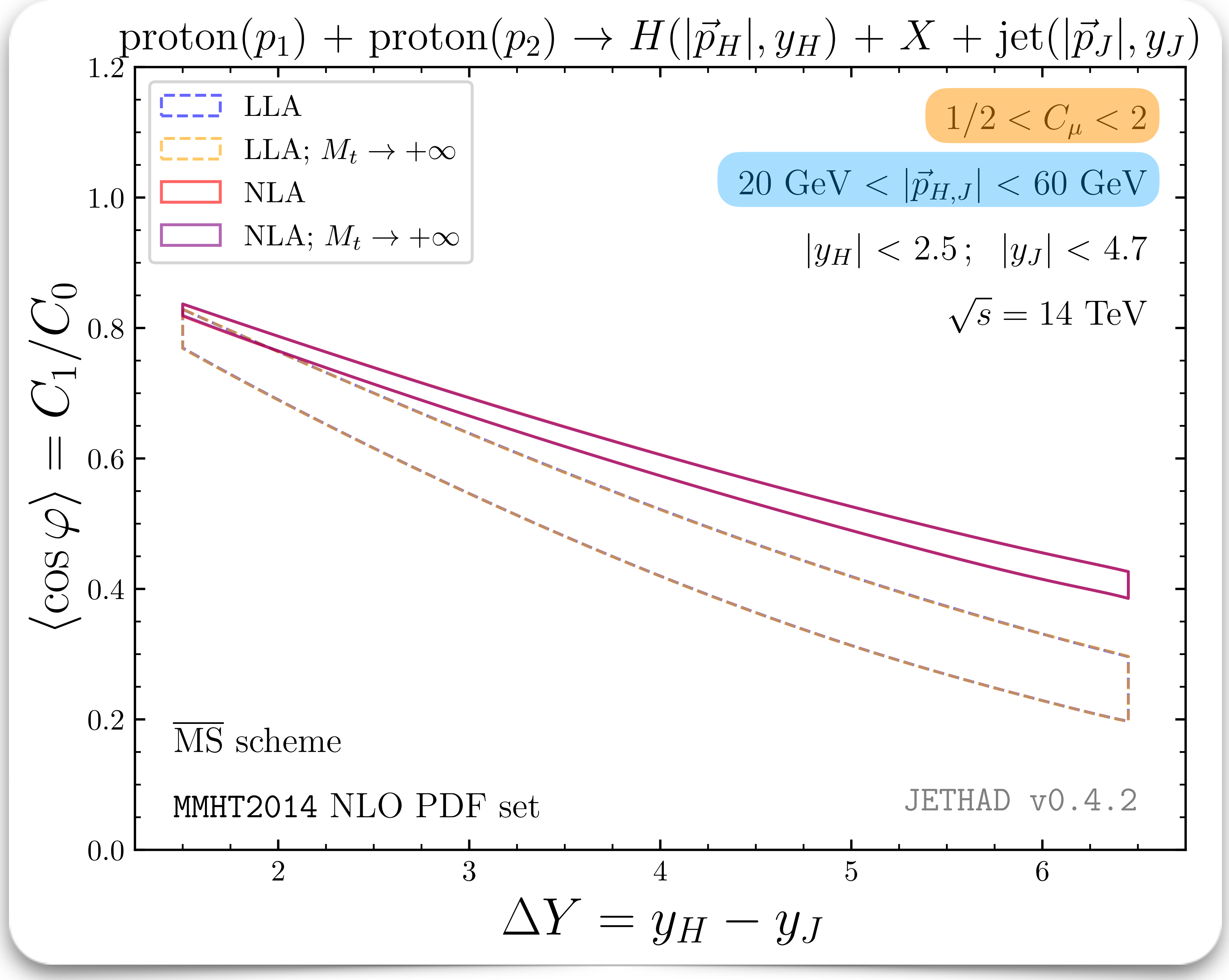
(figure below) [F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]

Higgs + jet

(figure below) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 4, 293]

(NLO Higgs impact factor) [F. G. C. et al., under review (2022)]



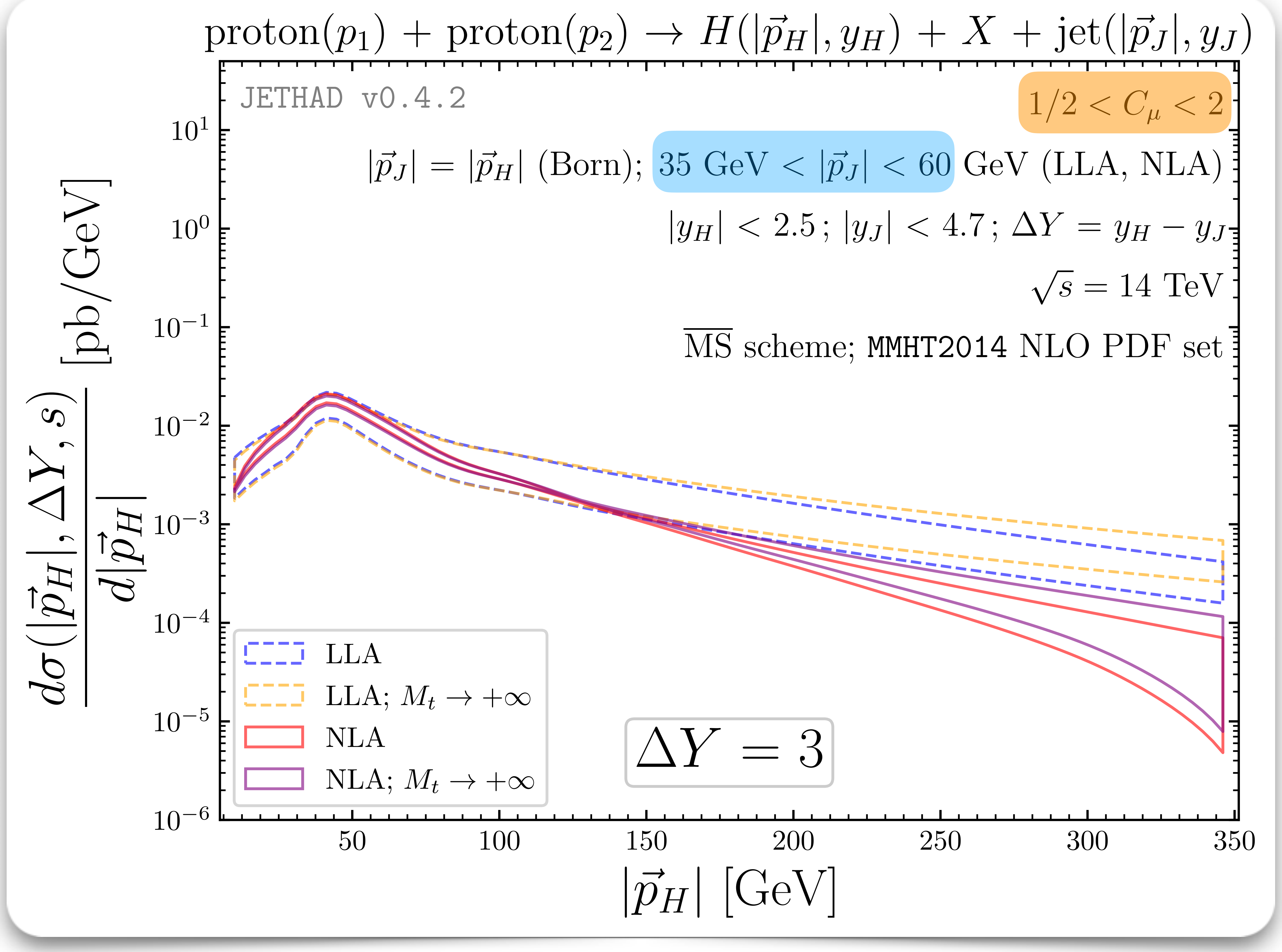


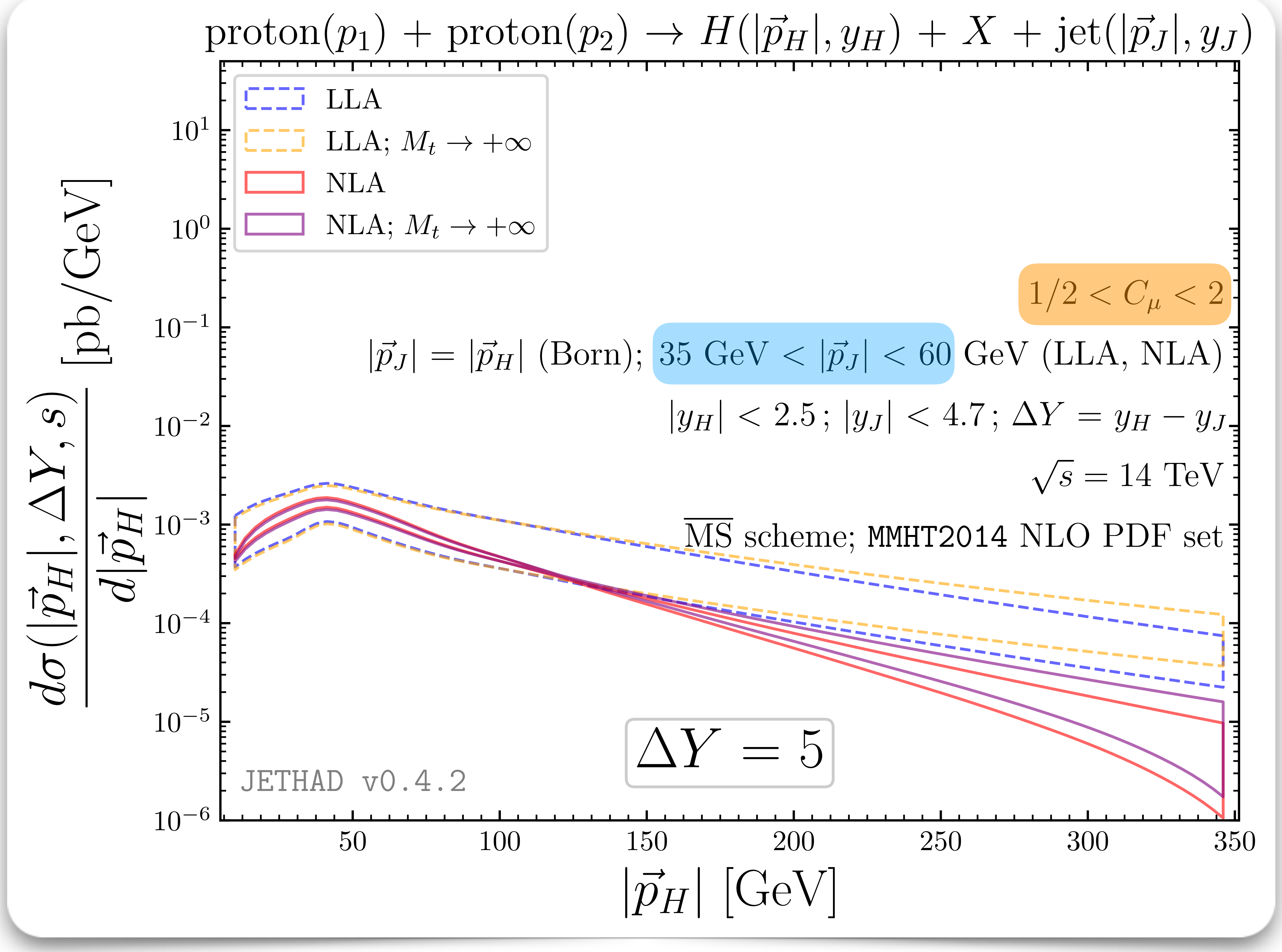
natural scales

symmetric p_T range

Backup

Higgs transverse-momentum distribution for $(M_t \to +\infty)$



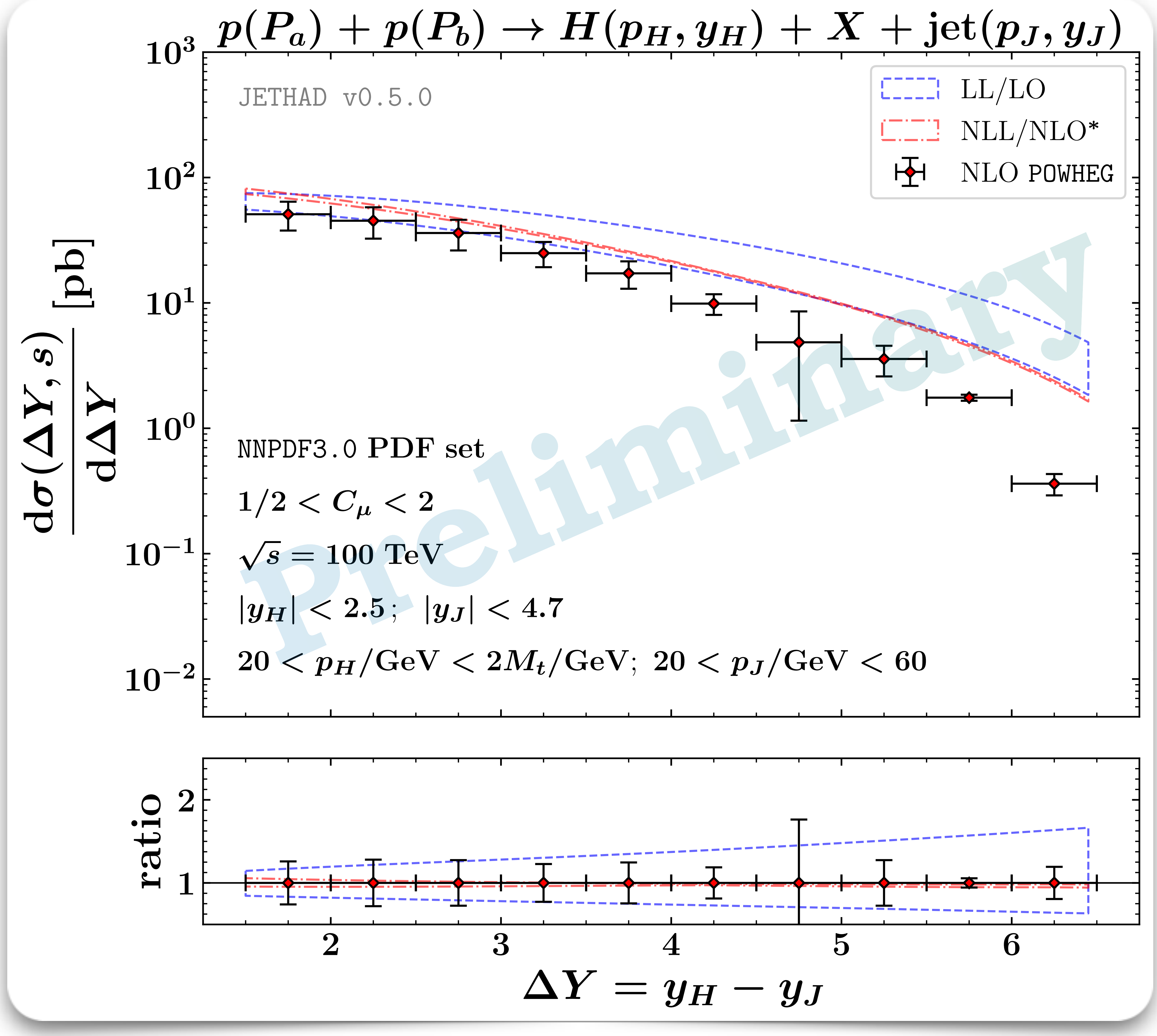


🔗 [F. G. C., D. Yu. Ivanov, M. M. A. Mohammed, A. Papa, Eur. Phys. J. C 81 (2021) 4, 293]

Backup

Higgs + jet at @FCC: small-x enhancement from PDFs

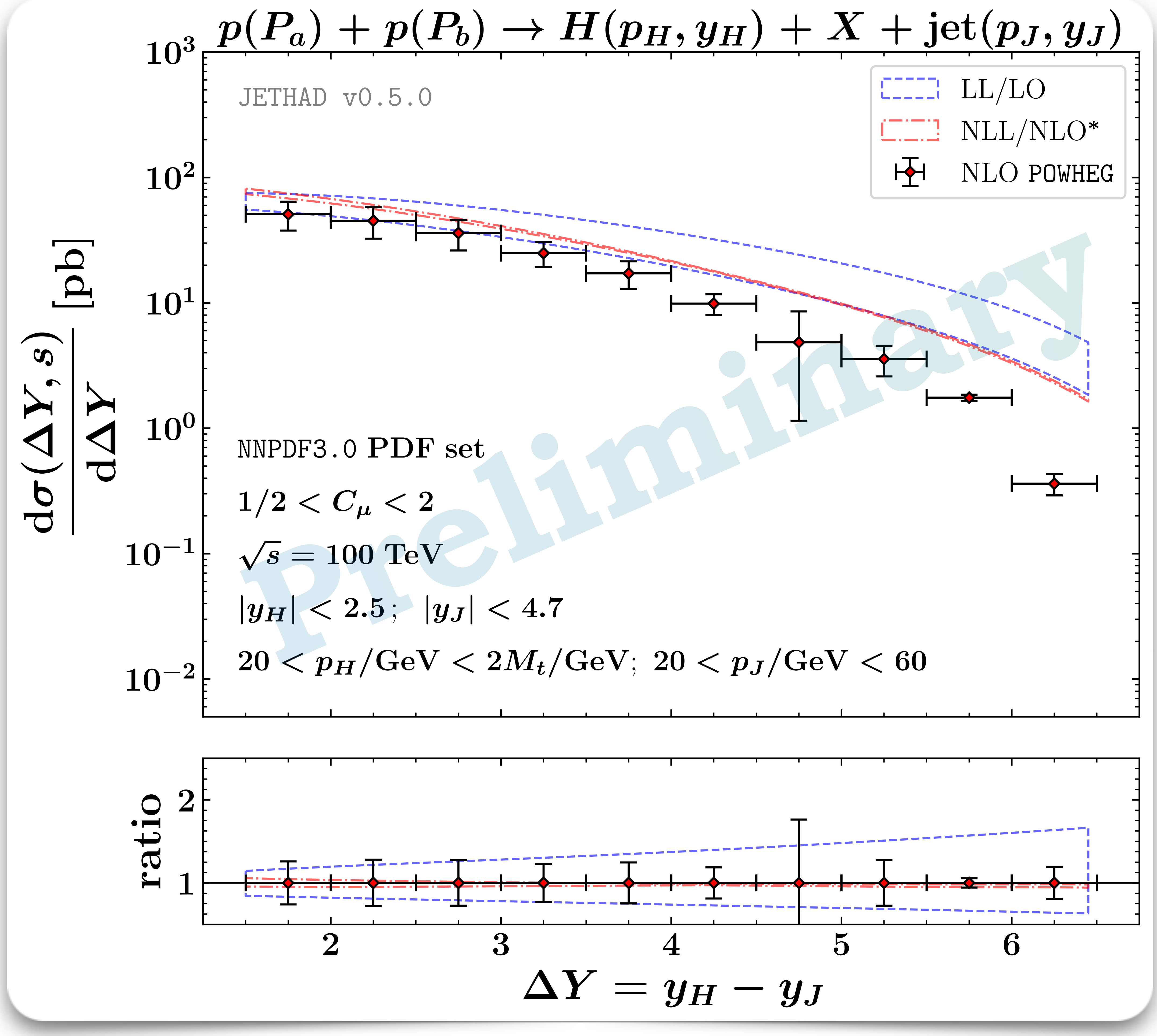
High-energy resummation + **NNPDF3.0**



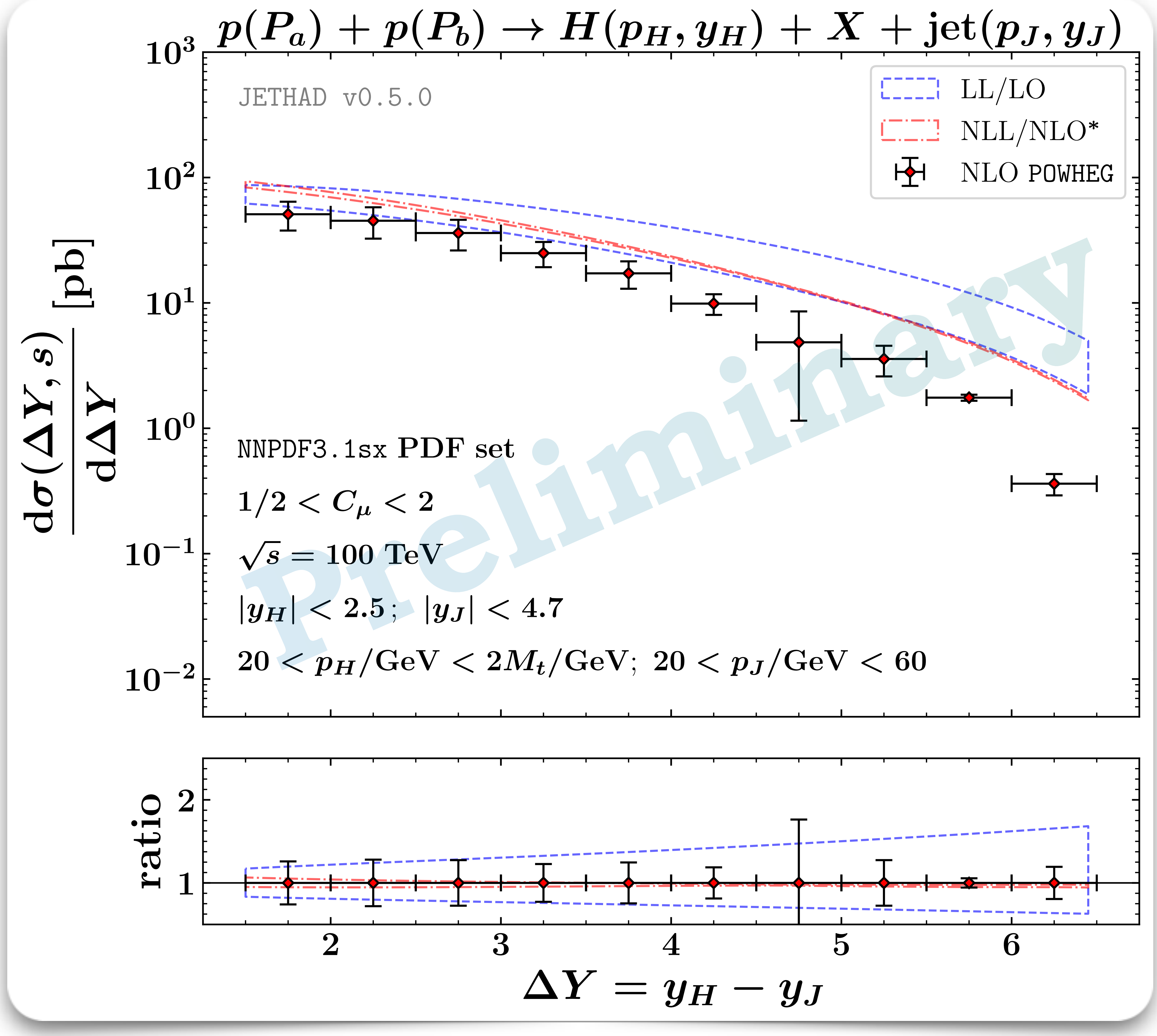
Backup

Higgs + jet at @FCC: small-x enhancement from PDFs

High-energy resummation + **NNPDF3.0**



High-energy resummation + **NNPDF3.1sx**

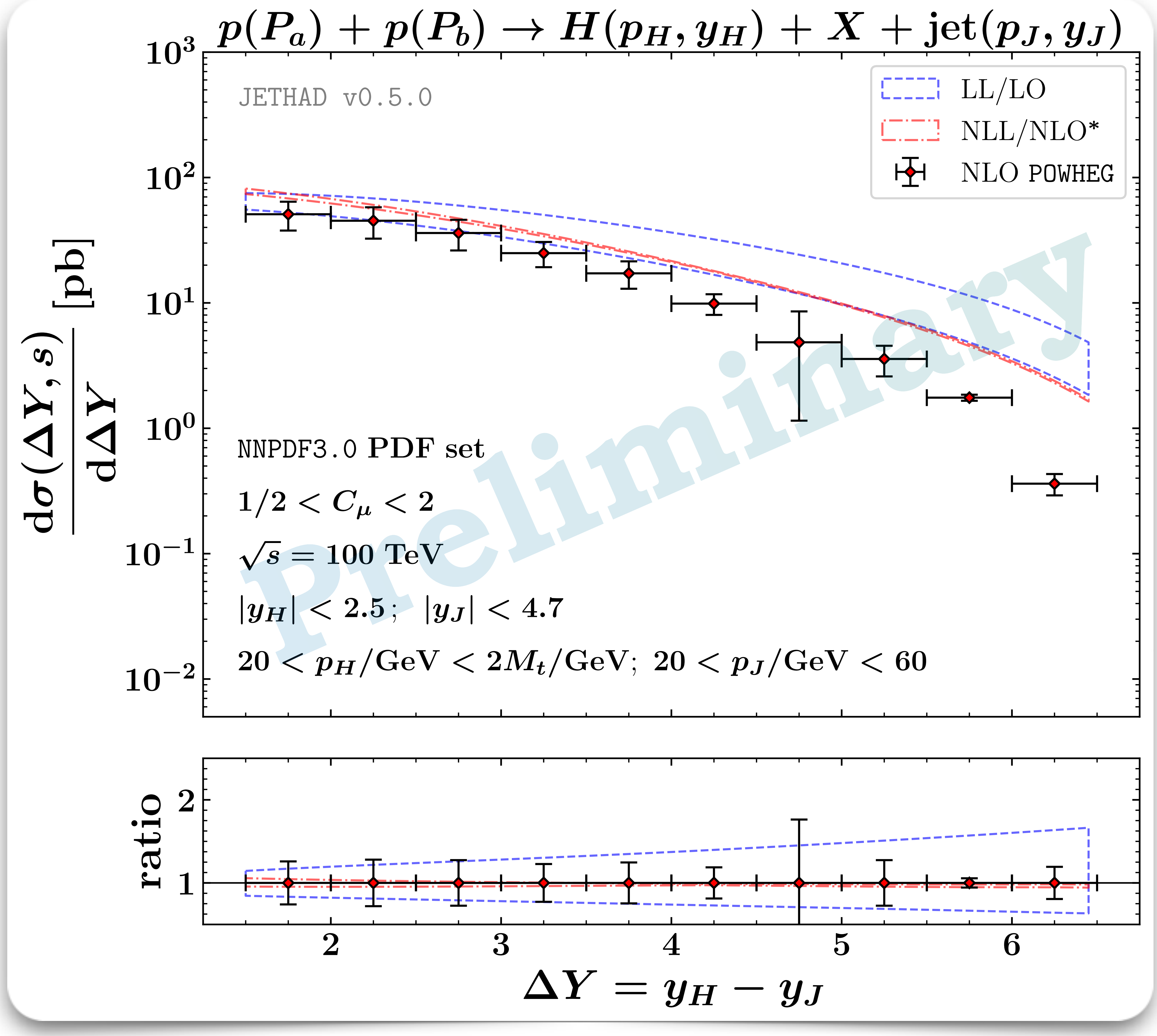


Backup

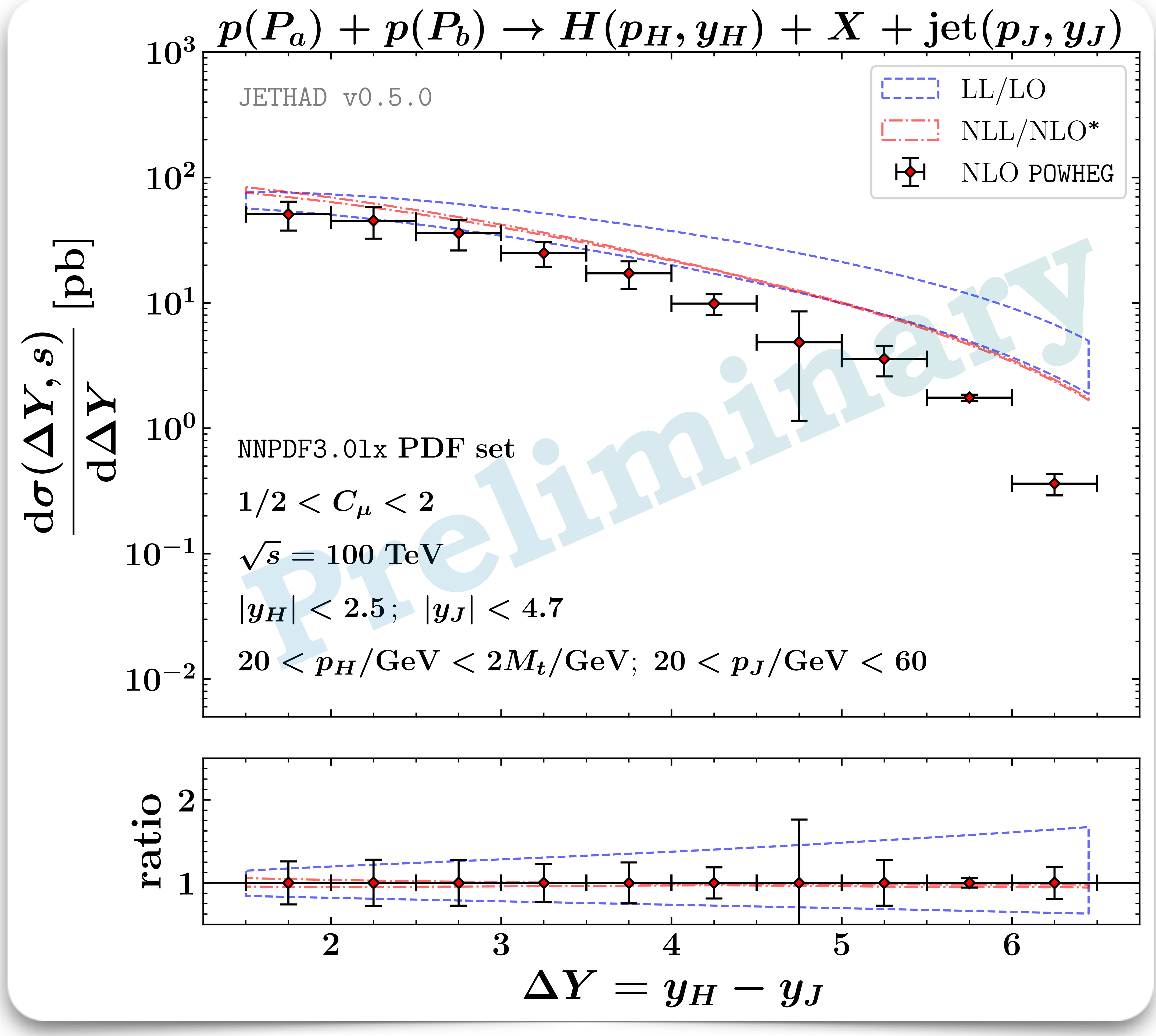
Small-x resummation on PDFs $\Rightarrow$ $+(13.5 \div 2.10)\,\%$ @NLL/NLO*

Higgs + jet at @FCC: large-x enhancement from PDFs

High-energy resummation + **NNPDF3.0**



High-energy resummation + **NNPDF3.01x**



Backup

Threshold resummation on PDFs $\Rightarrow$ $+(10.7 \div 2.15)\,\%$ @NLL/NLO*

HEAVY-LIGHT HADRONS

From Higgs + jet to bound states

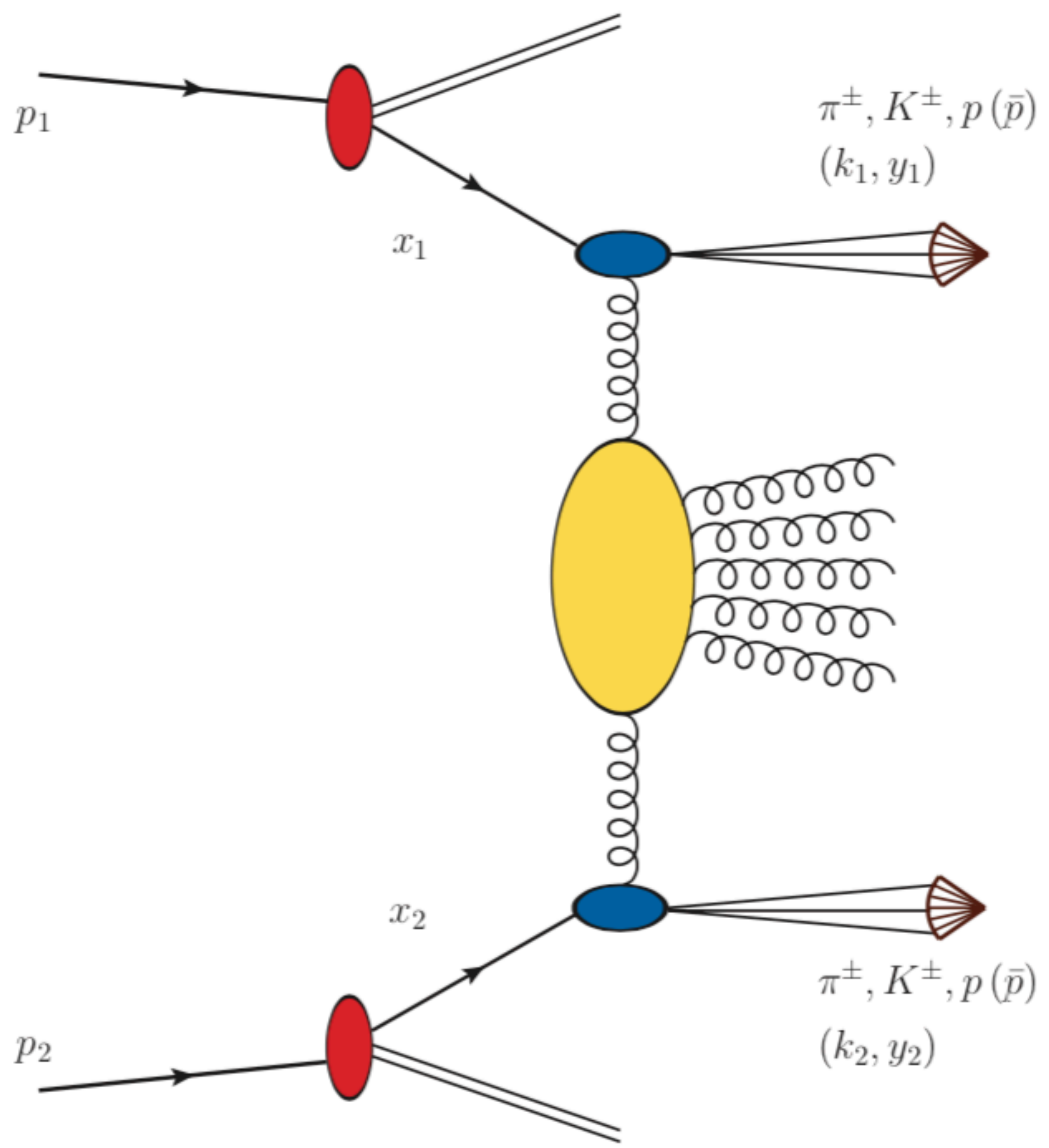
Di-hadron and hadron-jet correlations

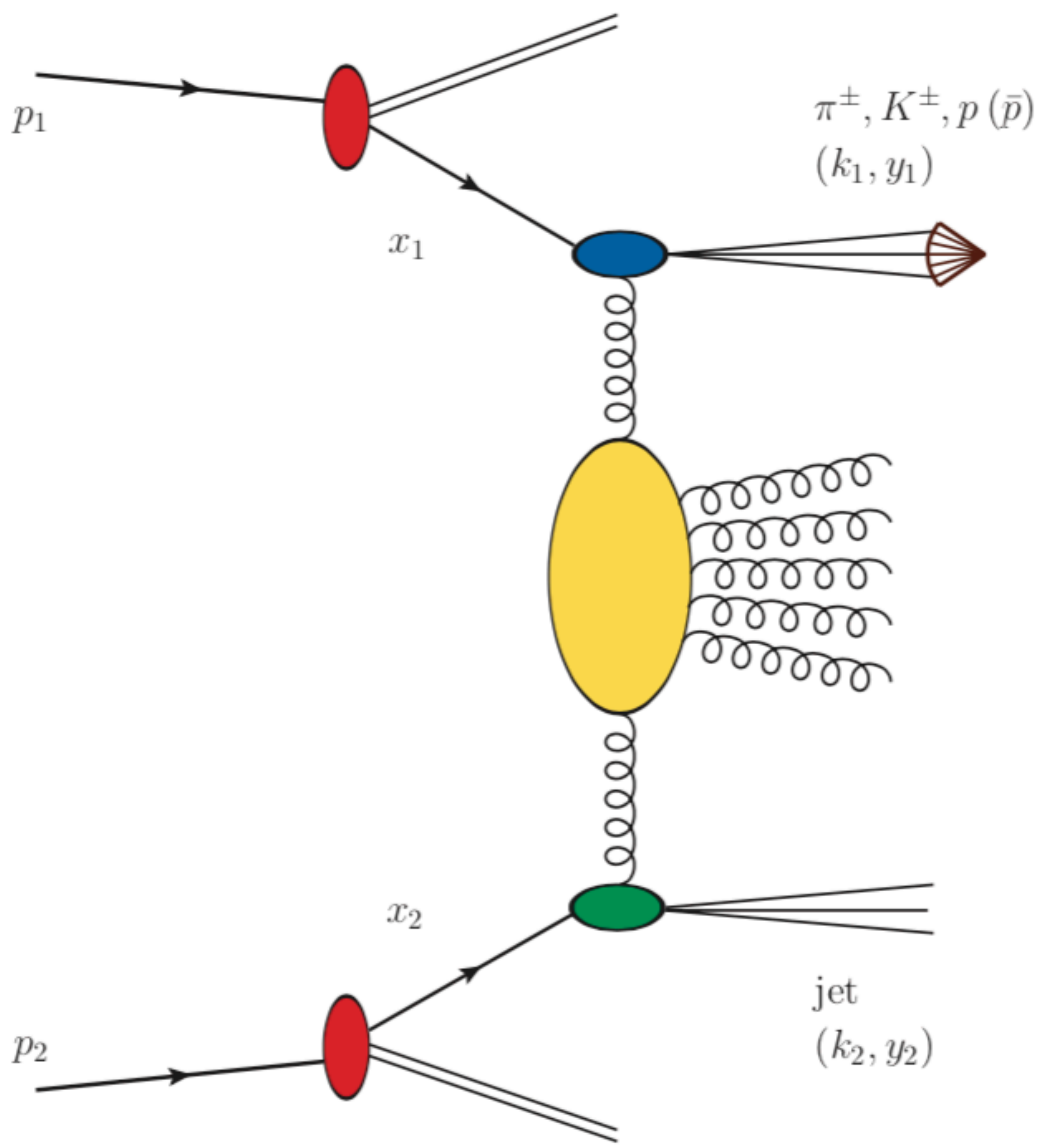
Inclusive di-hadron production

[D.Yu. Ivanov, A. Papa (2012)] (NLO forward-hadron impact factor)
[F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2016, 2017)]

Inclusive hadron-jet production

[A.D. Bolognino, F.G.C., D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2018)]
[F.G.C. (in preparation)]





- ◇ NLO impact factors known $\Rightarrow$ full NLA BFKL analysis feasible
- ◇ PDFs + FFs at work (both), hadrons at smaller rapidities than jets (di-hadron)
- ◇ genuine *asymmetric* cuts in transverse momenta (hadron-jet)

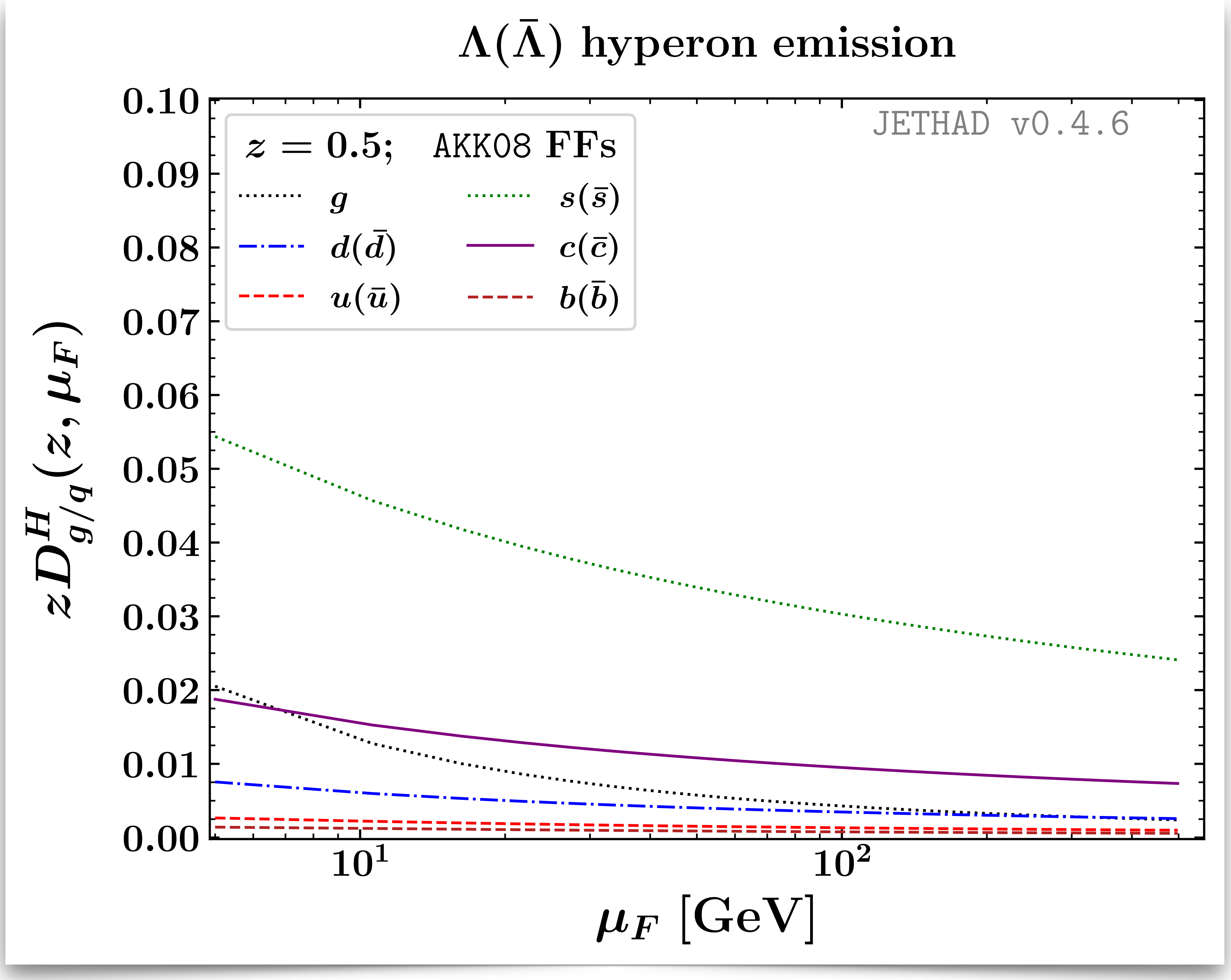
[F. G. C., Eur. Phys. J. C 81 (2021) 8, 691]

Backup

Stabilizing effects of heavy-flavor fragmentation

AKK08 VFNS collinear FFs for Λ hyperon: $|uds\rangle$

[S. Albino et al., Nucl. Phys. B 803 (2008) 42-104]

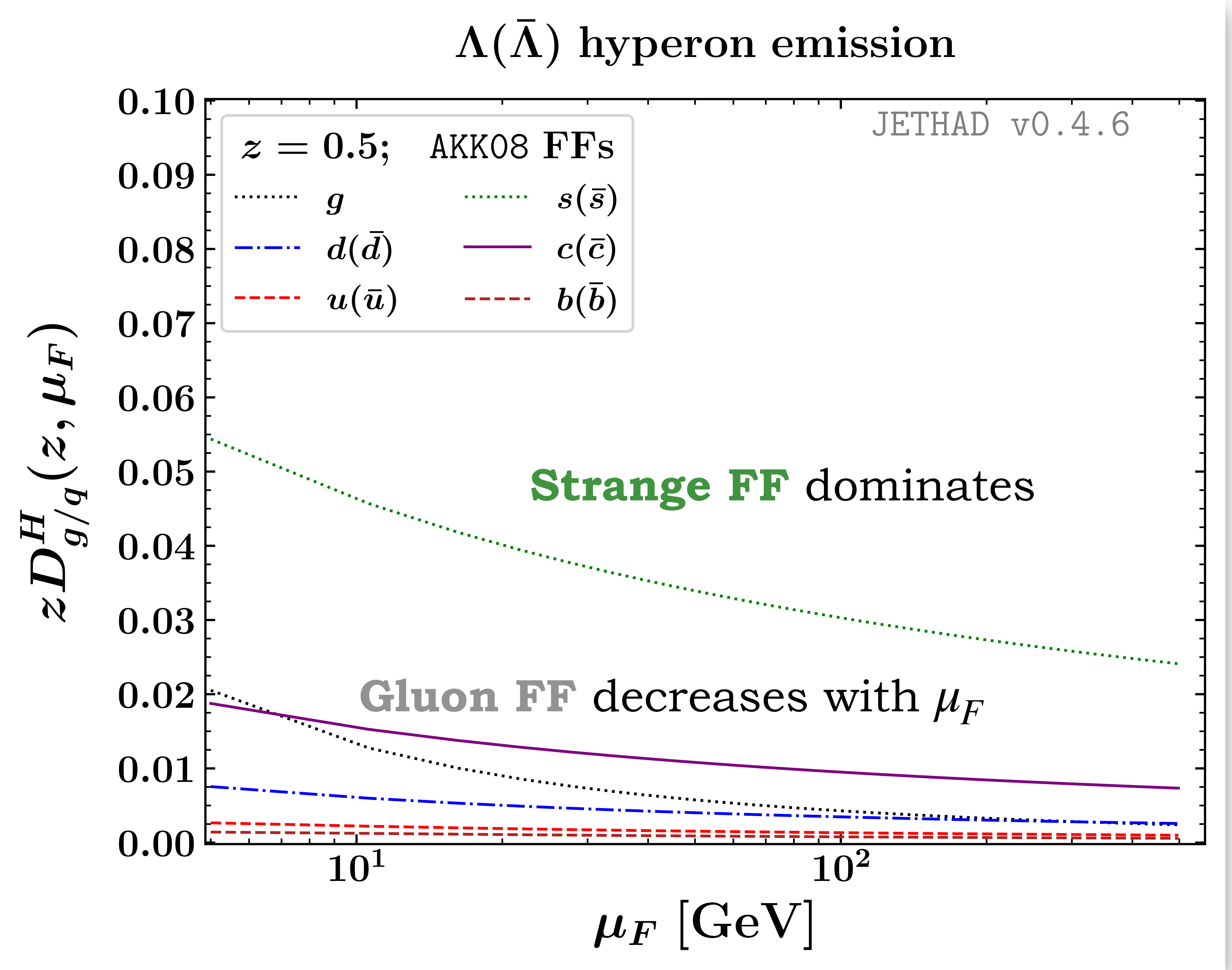


Backup

Stabilizing effects of heavy-flavor fragmentation

AKK08 VFNS collinear FFs for Λ hyperon: $|uds\rangle$

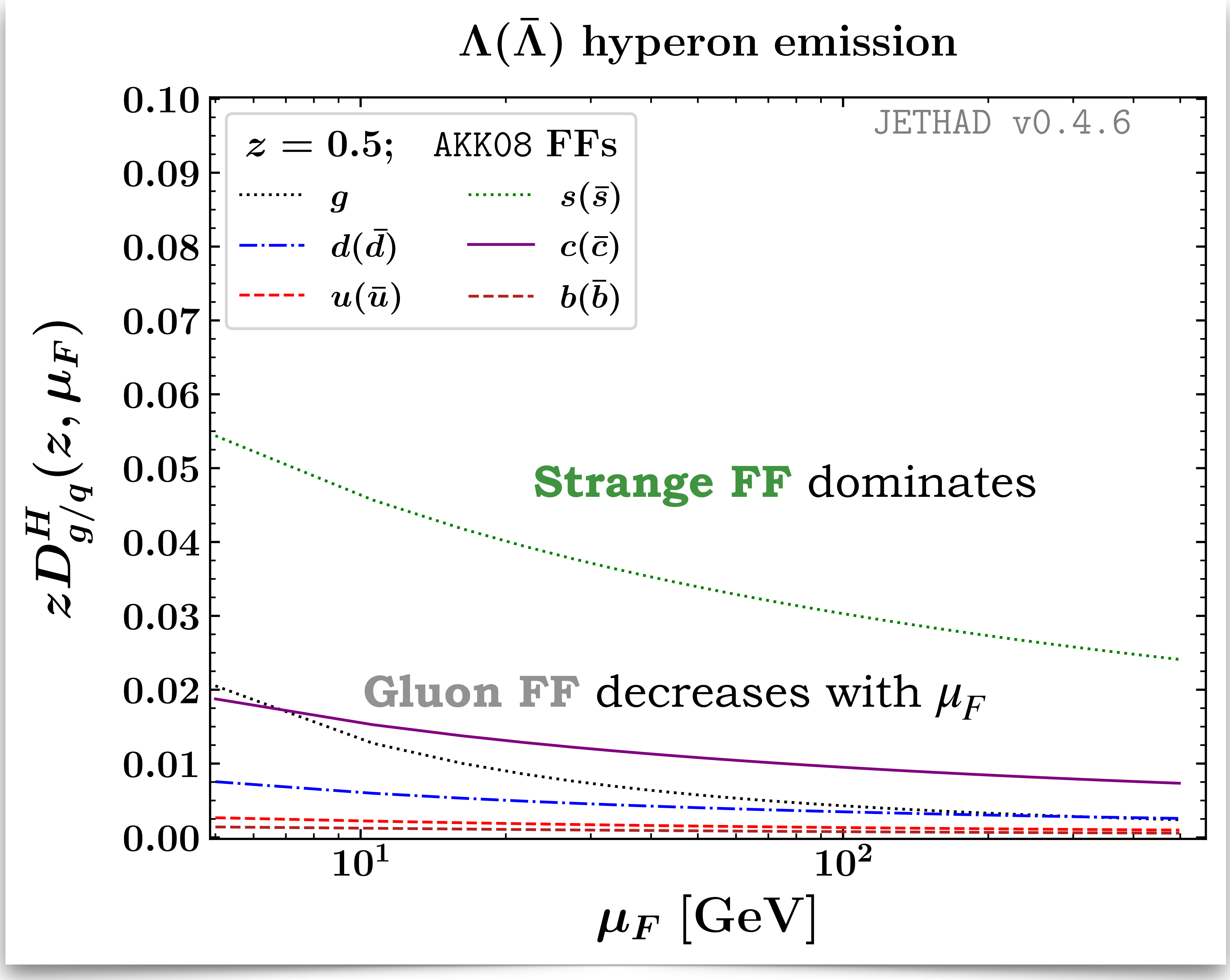
[S. Albino et al., Nucl. Phys. B 803 (2008) 42-104]

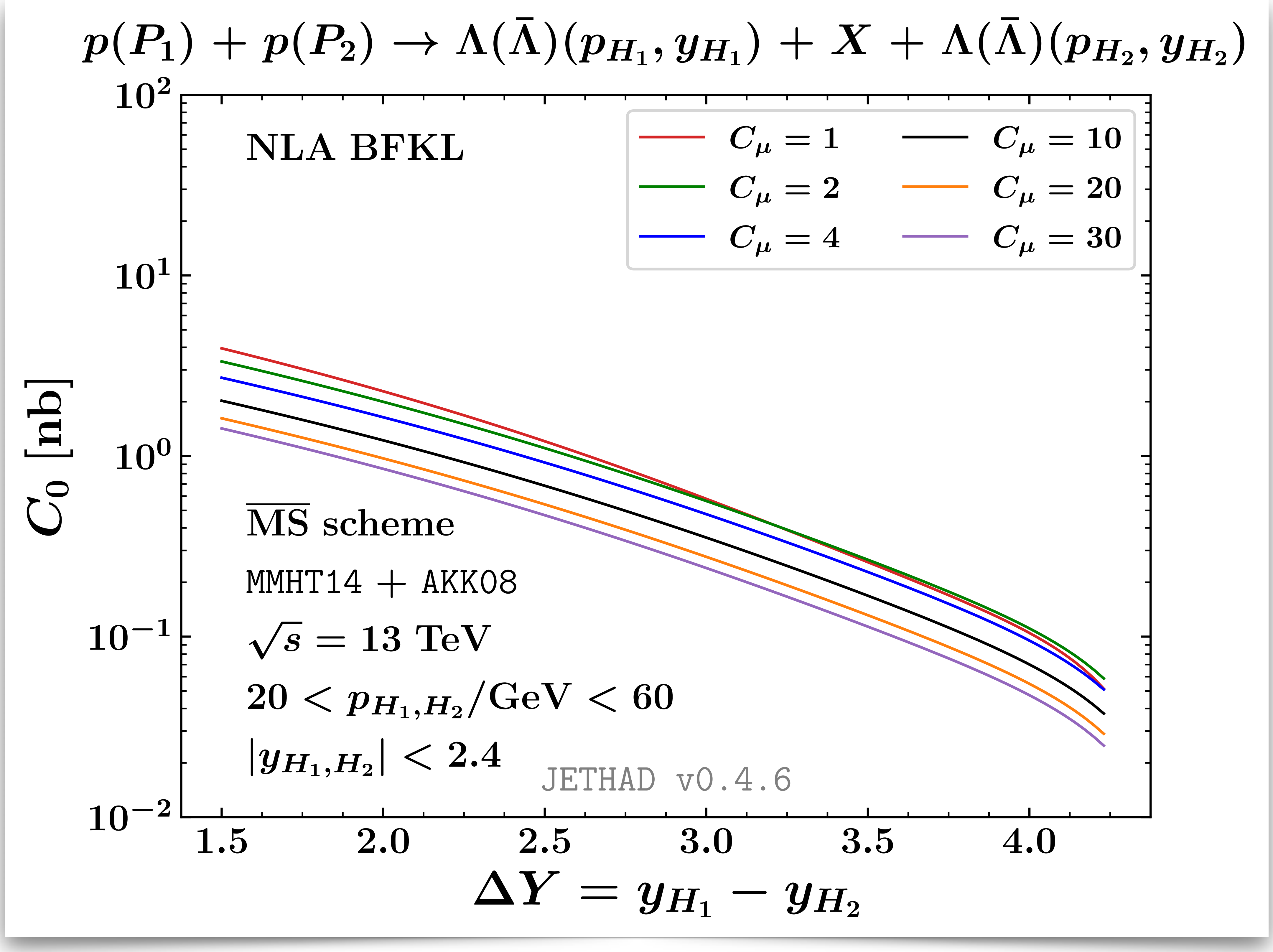


Backup

Stabilizing effects of heavy-flavor fragmentation

- **AKK08** VFNS collinear FFs for Λ hyperon: $|uds\rangle$ [S. Albino et al., Nucl. Phys. B 803 (2008) 42-104]





- Rapidity distribution sensitive to scale variations

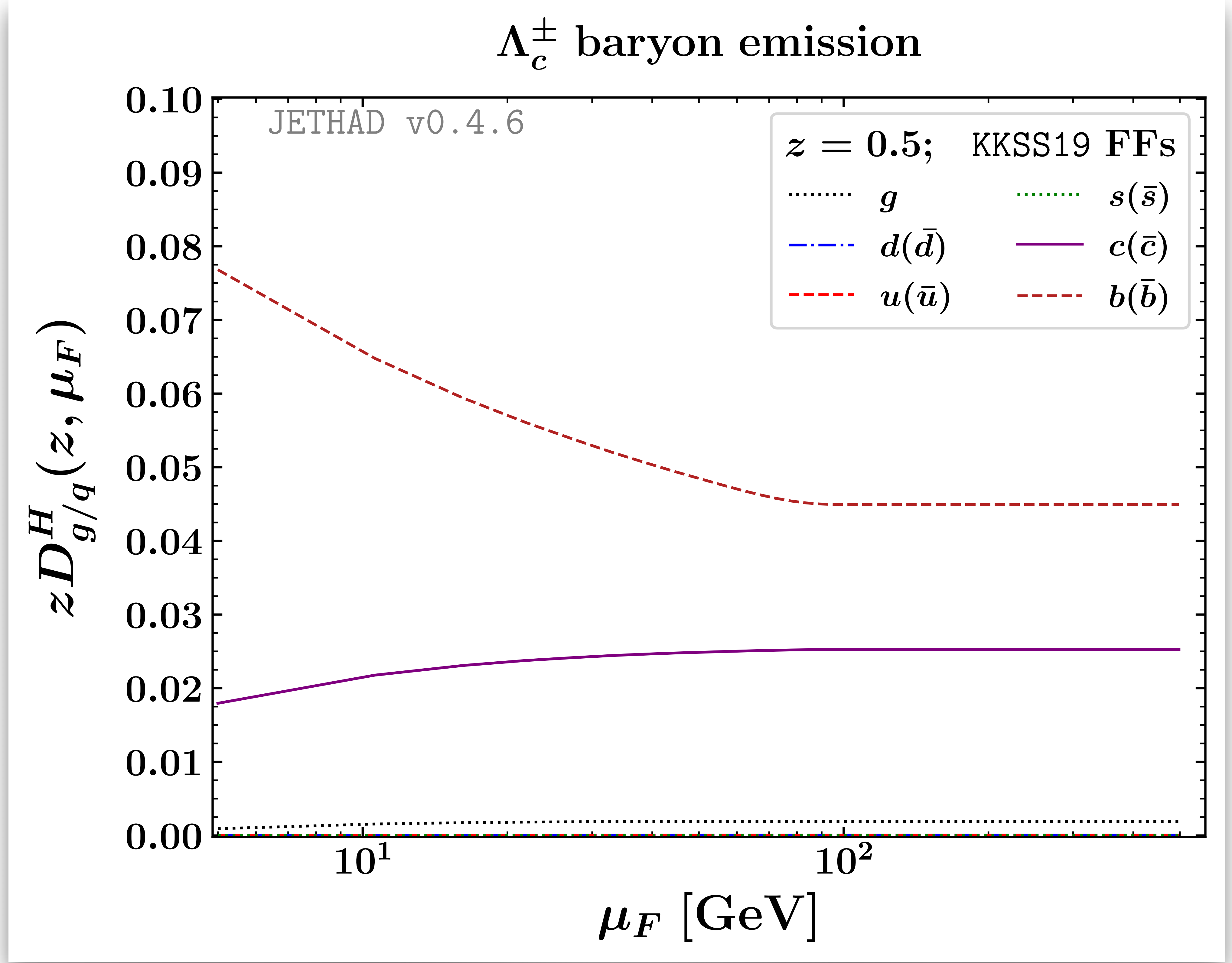
(Λ hyperons) [F. G. C. et al., Phys. Rev. D 102 (2020) 9, 094019]

(cascade Ξ baryons) [F. G. C., Eur. Phys. J. C (in press)]

Backup

Stabilizing effects of heavy-flavor fragmentation

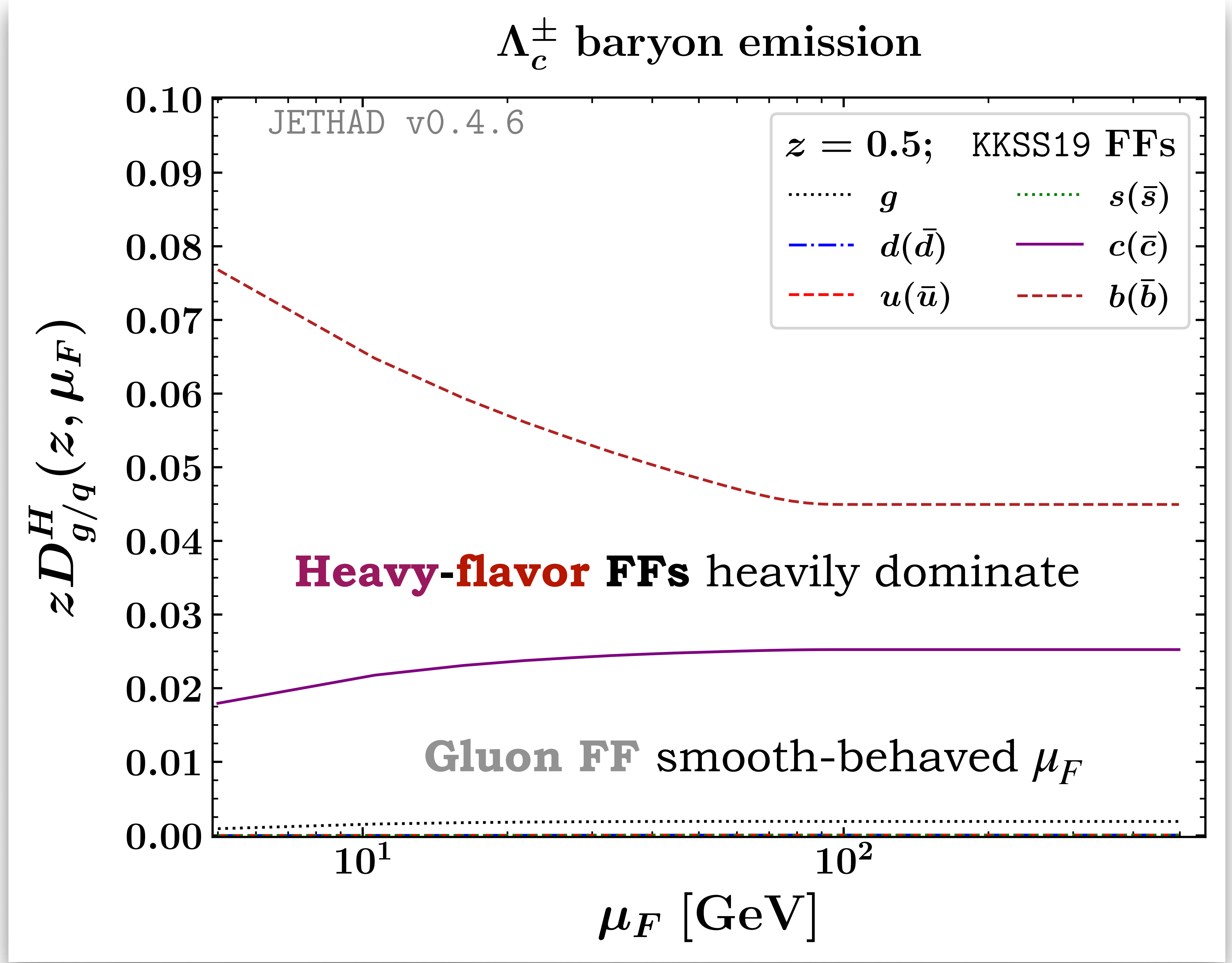
KKSS19 VFNS collinear FFs for Λ_c baryons: $|udc\rangle$ [B. A. Kniehl et al., Phys. Rev. D 101 (2020) 11, 114021]



Backup

Stabilizing effects of heavy-flavor fragmentation

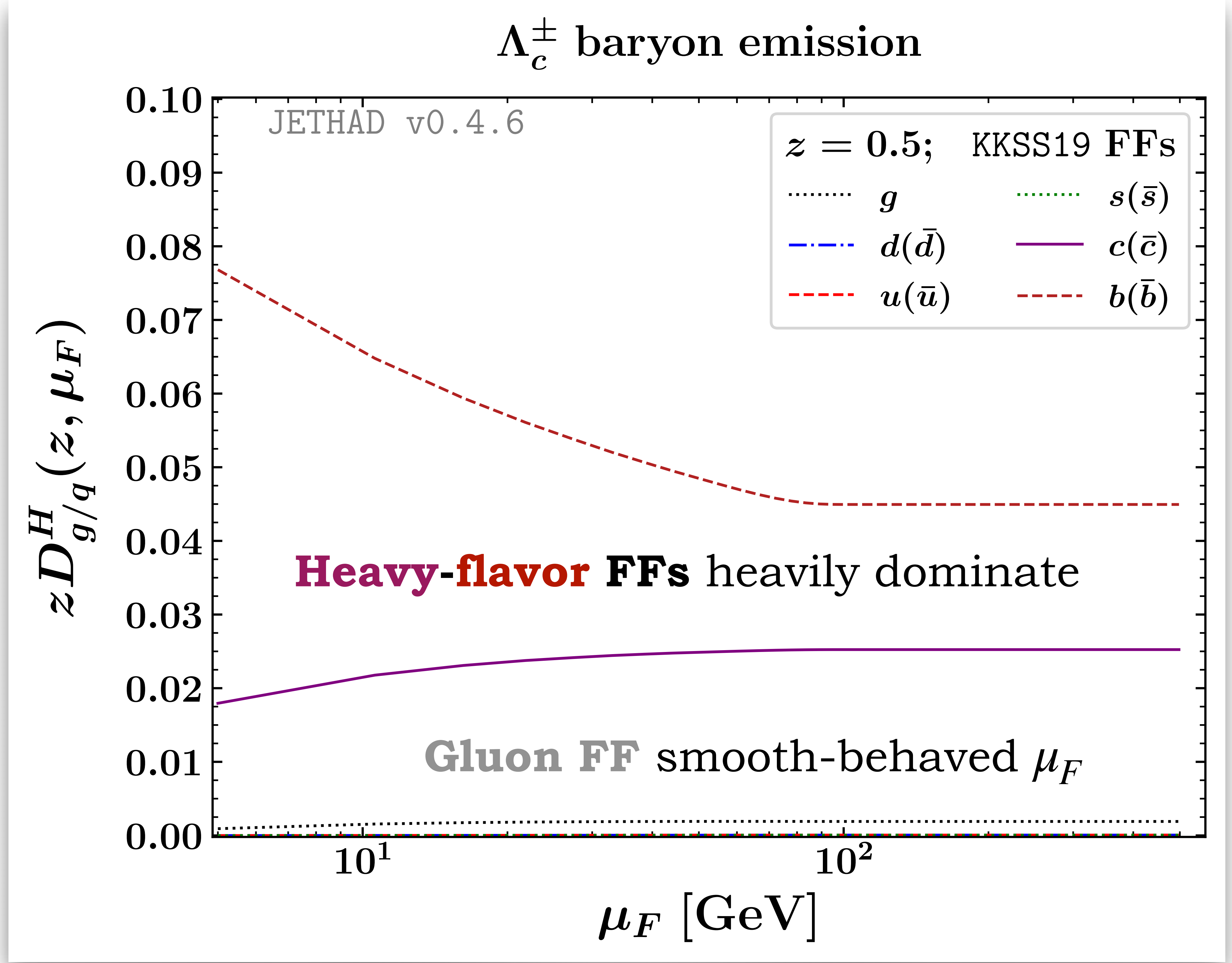
KKSS19 VFNS collinear FFs for Λ_c baryons: $|udc\rangle$ [B. A. Kniehl et al., Phys. Rev. D 101 (2020) 11, 114021]

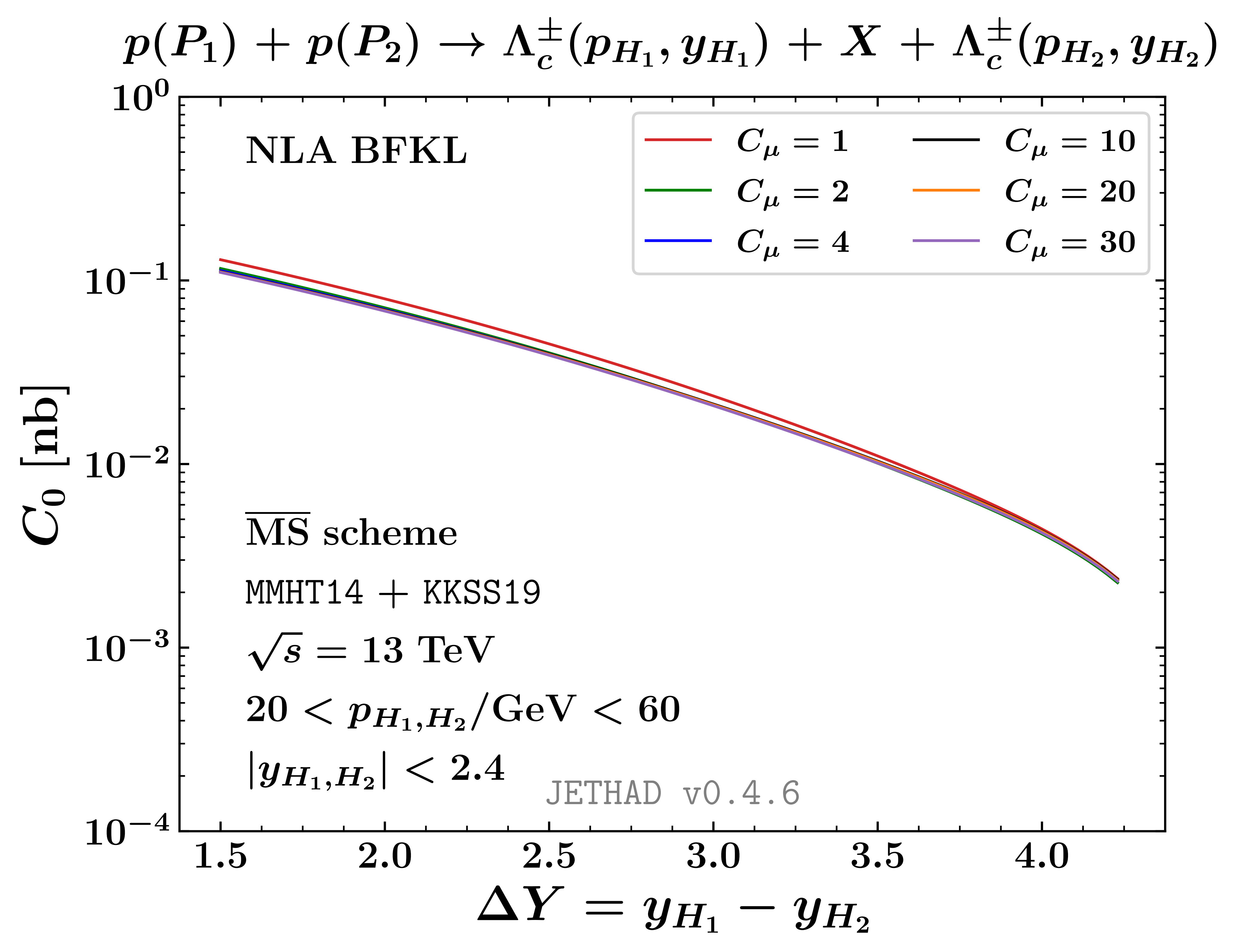


Backup

Stabilizing effects of heavy-flavor fragmentation

- **KKSS19** VFNS collinear FFs for Λ_c baryons: $|udc\rangle$ [B. A. Kniehl et al., Phys. Rev. D 101 (2020) 11, 114021]





- Rapidity distribution stable under scale variations

($B_c^{(*)}$ hadrons) [F. G. C., Phys. Lett. B 835 (2022) 137554]

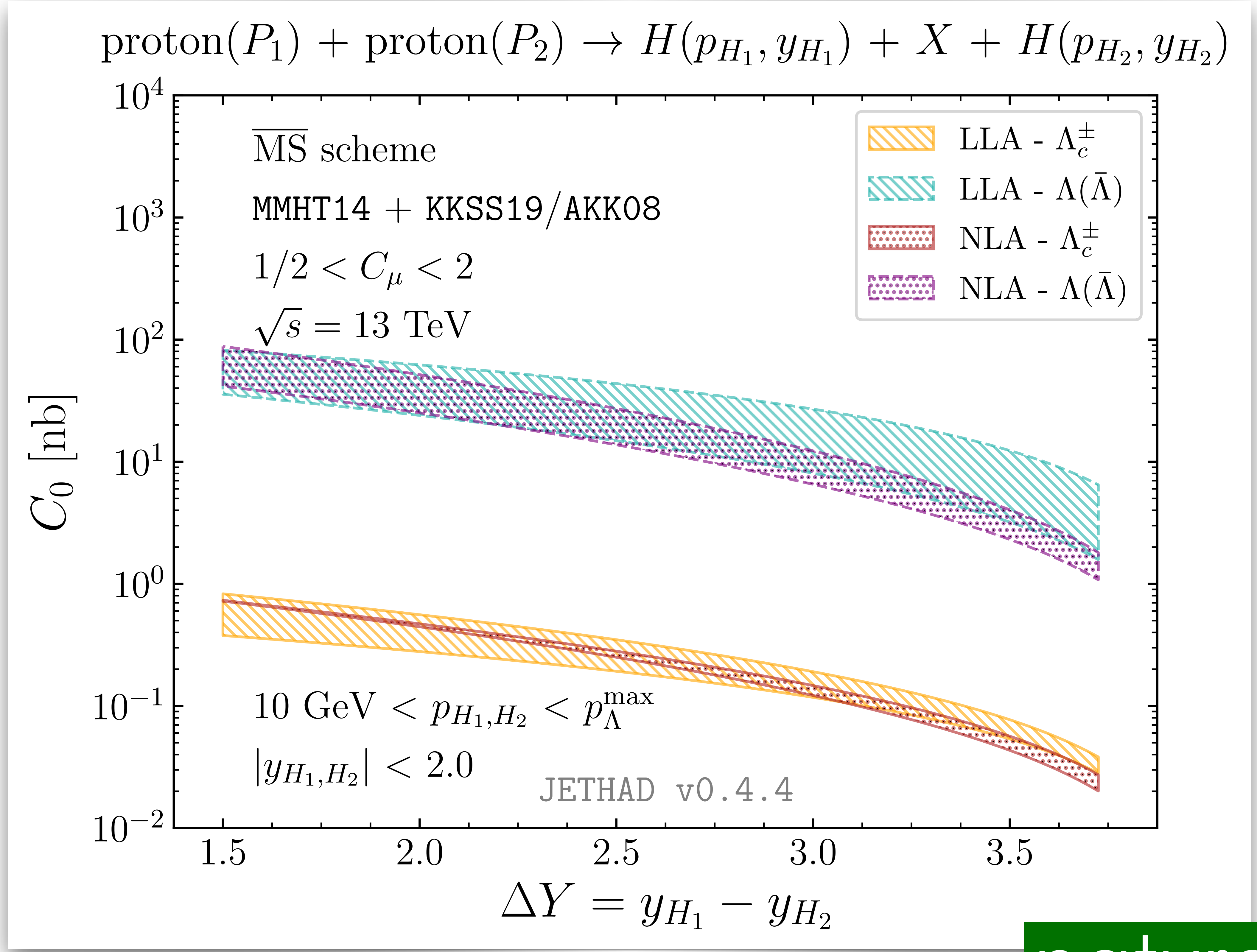
(Λ_c baryons, in this slide) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

(H_b hadrons) [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

Backup

Stability under scale variations & NLL corrections

Hybrid factorization @work: Λ_c baryons $|udc\rangle$ versus Λ hyperons $|uds\rangle$

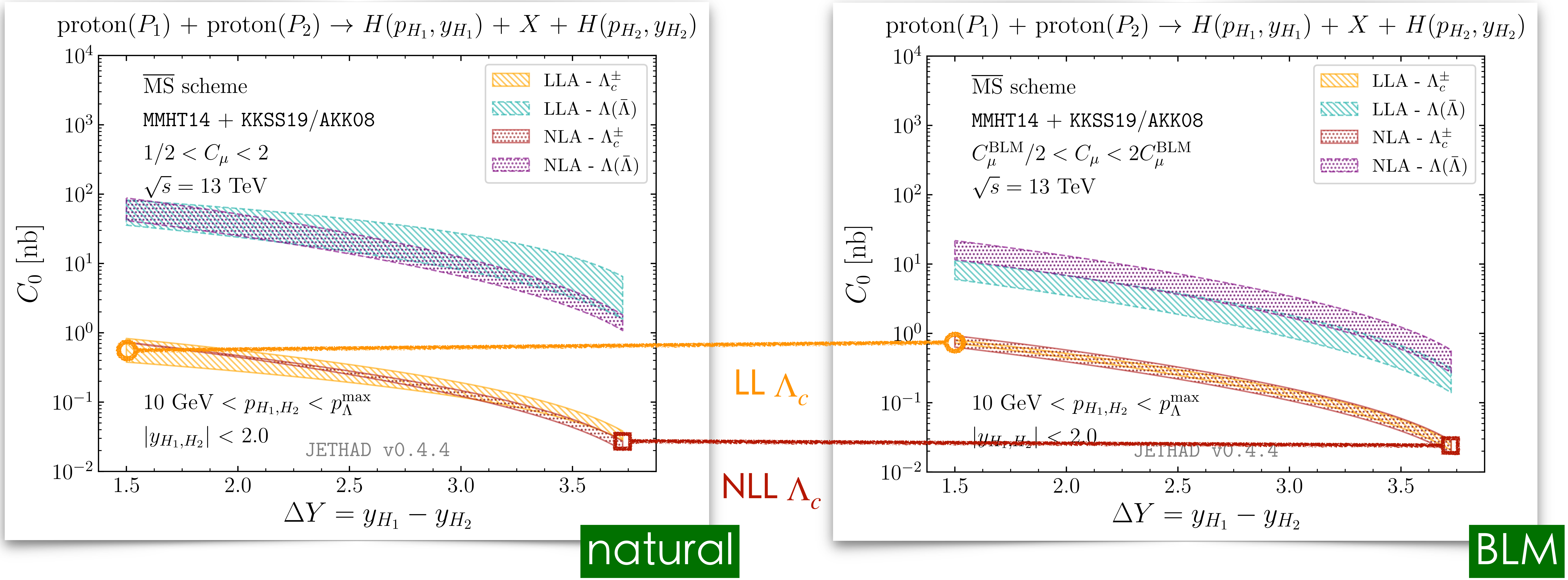


natural

Backup

Stability under scale variations & NLL corrections

Hybrid factorization @work: Λ_c baryons $|udc\rangle$ versus Λ hyperons $|uds\rangle$



NLL corrections: rapidity distribution stable for Λ_c

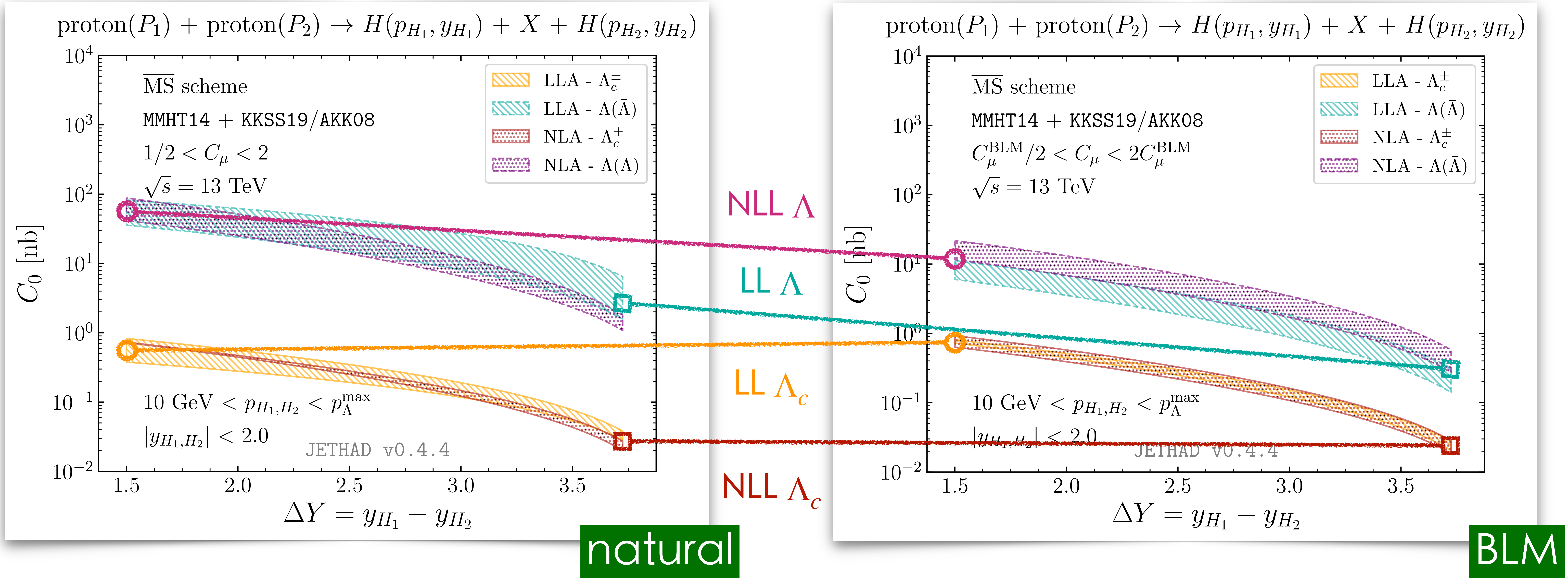
(Λ_c baryons, in this slide) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

(H_b hadrons) [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

Backup

Stability under scale variations & NLL corrections

- Hybrid factorization @work: Λ_c baryons $|udc\rangle$ versus Λ hyperons $|uds\rangle$



- NLL corrections: rapidity distribution stable for Λ_c, loses $\sim 10^1$ magnitude for Λ

(Λ_c baryons, in this slide) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

(H_b hadrons) [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

Backup

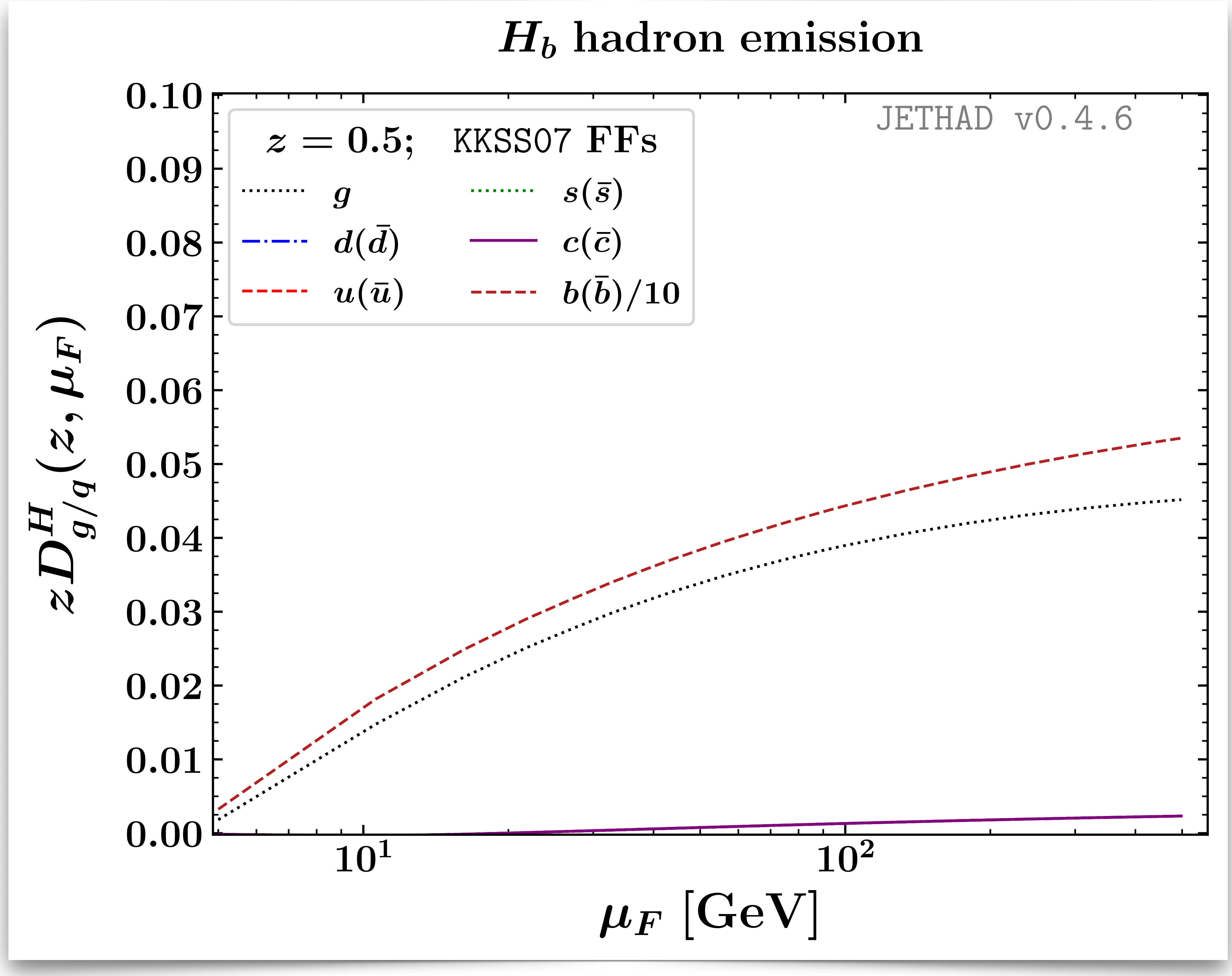
Stabilizing effects of heavy-flavor fragmentation

KKSS07 VFNS collinear FFs for:

$$H_b = B^{\pm}, B^0, B_s^0, \Lambda_b$$

[B. A. Kniehl, H. Spiesberger, Phys. Rev. D 98 (2018) 11, 114010]

[B. A. Kniehl et al., Phys. Rev. D 77 (2008) 11, 014011]



Backup

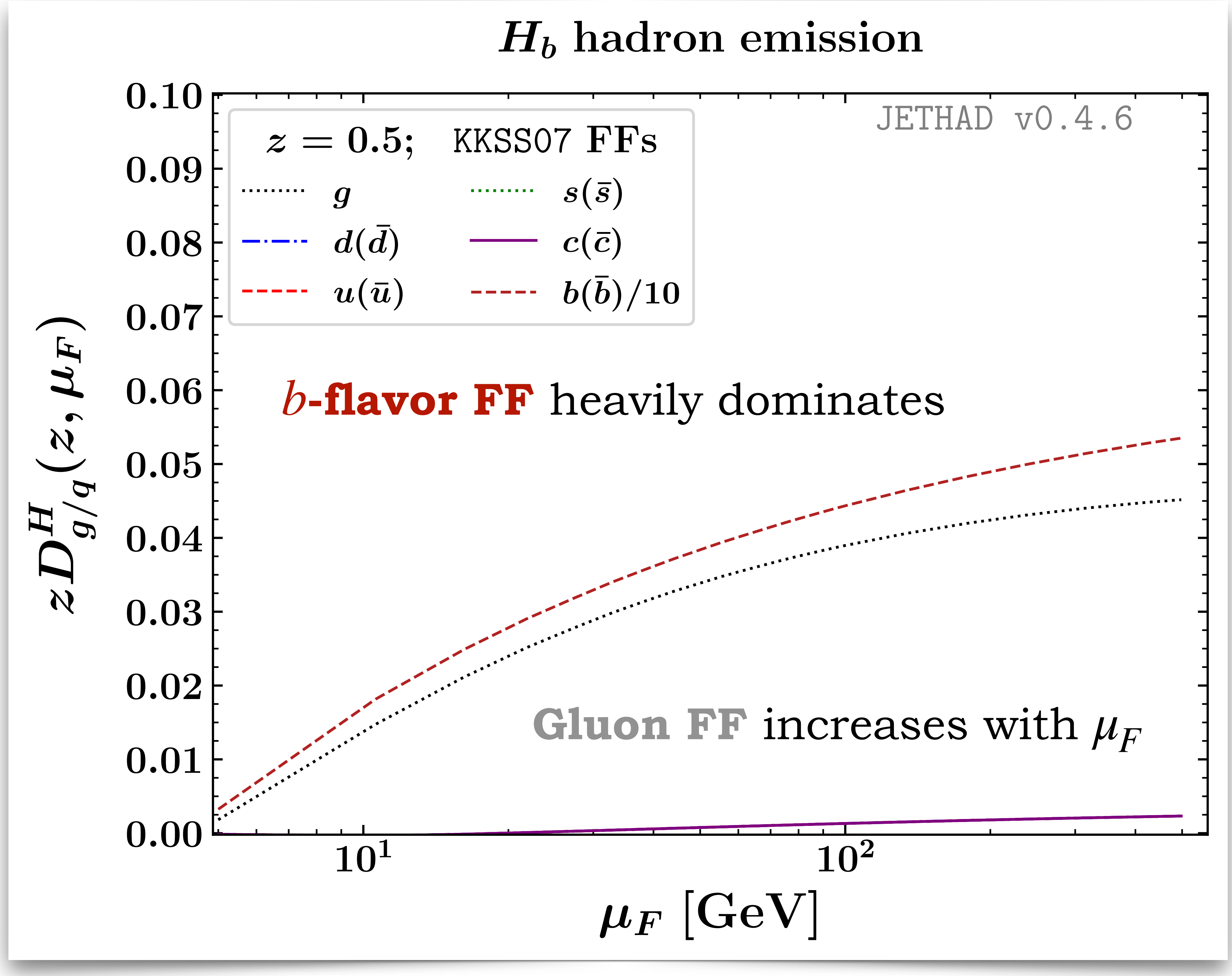
Stabilizing effects of heavy-flavor fragmentation

KKSS07 VFNS collinear FFs for:

$$H_b = B^{\pm}, B^0, B_s^0, \Lambda_b$$

[B. A. Kniehl, H. Spiesberger, Phys. Rev. D 98 (2018) 11, 114010]

[B. A. Kniehl et al., Phys. Rev. D 77 (2008) 11, 014011]



Backup

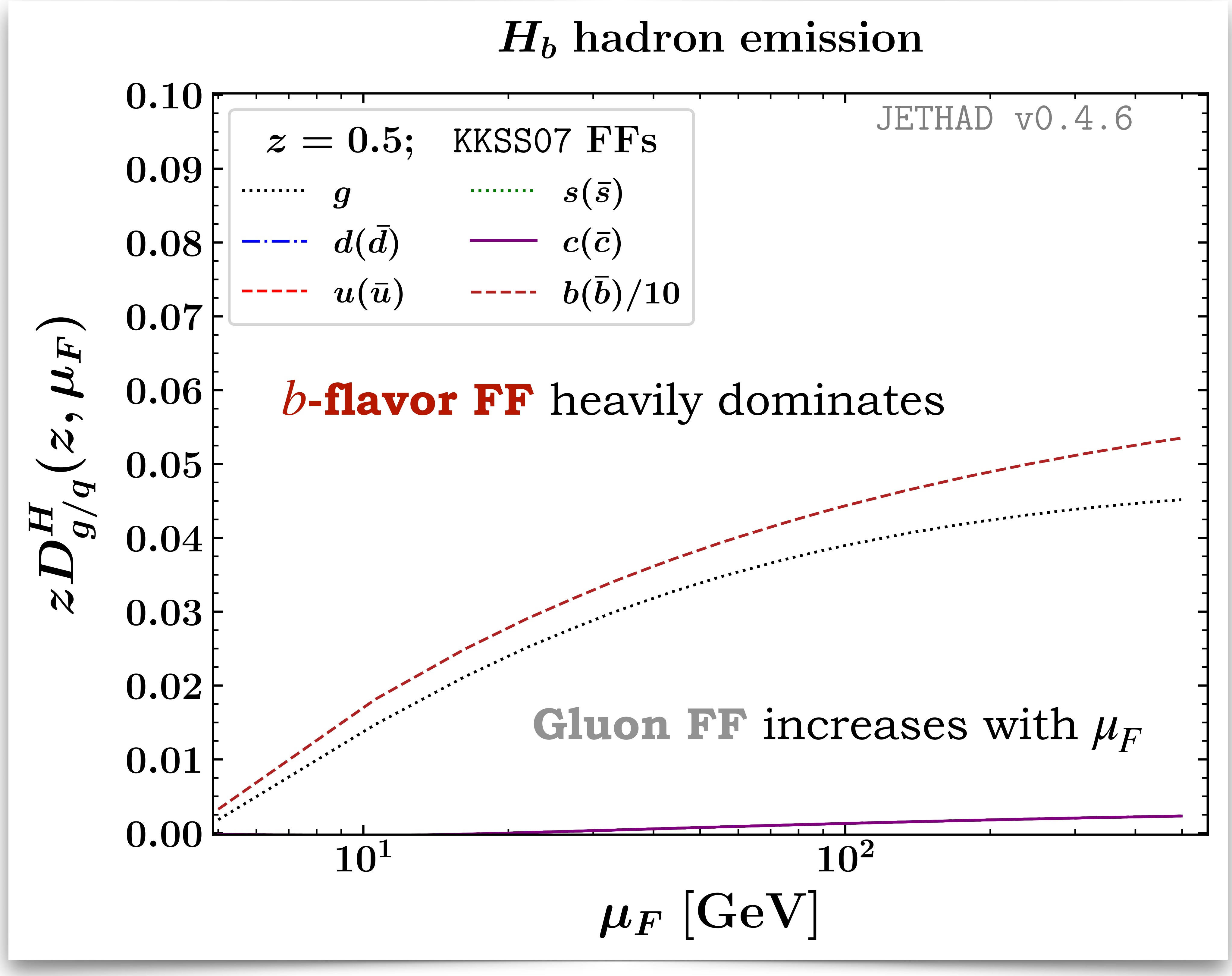
Stabilizing effects of heavy-flavor fragmentation

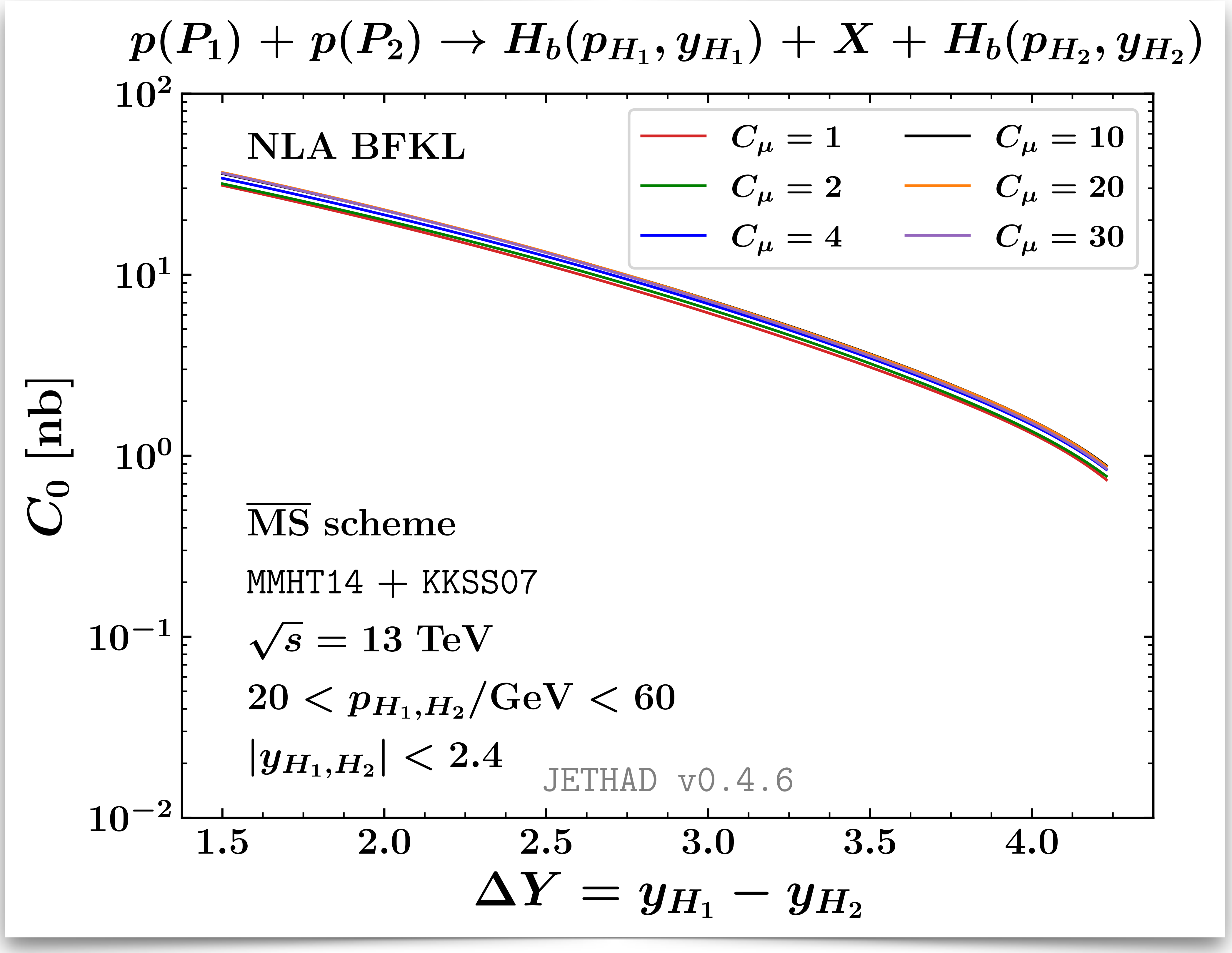
KKSS07 VFNS collinear FFs for:

$$H_b = B^\pm, B^0, B_s^0, \Lambda_b$$

[B. A. Kniehl, H. Spiesberger, Phys. Rev. D 98 (2018) 11, 114010]

[B. A. Kniehl et al., Phys. Rev. D 77 (2008) 11, 014011]





Rapidity distribution very stable under scale variations

(H_b hadrons, in this slide) [F. G. C. et al., Phys. Rev. D 104 (2021) 11, 114007]

(Λ_c baryons) [F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

Backup

Stabilizing effects of heavy-flavor fragmentation

- Stabilization mechanism encoded in the heavy-flavor gluon FF

- Forward-hadron LO impact factor $\Rightarrow$ gluon FF enhanced by gluon PDF in collinear convolution

$$c_\Lambda(n,\nu,|\vec{p}|,x) = 2\sqrt{\frac{C_F}{C_A}}(|\vec{p}|^2)^{i\nu-1/2}\int_x^1 \frac{\mathrm{d}z}{z}\left(\frac{z}{x}\right)^{2i\nu-1}\left[\frac{C_A}{C_F} f_g(z) D_g^\Lambda\left(\frac{x}{z}\right) + \sum_{a=q,\bar{q}} f_a(z) D_a^\Lambda\left(\frac{x}{z}\right)\right]$$

Backup

Stabilizing effects of heavy-flavor fragmentation

- Stabilization mechanism encoded in the heavy-flavor gluon FF

- Forward-hadron LO impact factor $\Rightarrow$ gluon FF enhanced by gluon PDF in collinear convolution

$$c_\Lambda(n,\nu,|\vec{p}|,x) = 2\sqrt{\frac{C_F}{C_A}}(|\vec{p}|^2)^{i\nu-1/2}\int_x^1 \frac{\mathrm{d}z}{z}\left(\frac{z}{x}\right)^{2i\nu-1}\left[\frac{C_A}{C_F} f_g(z) D_g^\Lambda\left(\frac{x}{z}\right) + \sum_{a=q,\bar{q}} f_a(z) D_a^\Lambda\left(\frac{x}{z}\right)\right]$$

- Forward-hadron NLO impact factor $\Rightarrow$ a non-diagonal heavy-flavor channel open...

$$c_1^{(1)}(n,\nu,|\vec{k}_1|,\alpha_1) = 2\sqrt{\frac{C_F}{C_A}}\left(\vec{k}_1^2\right)^{i\nu-\frac{1}{2}}\frac{1}{2\pi}\int_{\alpha_1}^1\frac{dx}{x}\int_{\frac{\alpha_1}{x}}^1\frac{d\zeta}{\zeta}\left(\frac{x\zeta}{\alpha_1}\right)^{2i\nu-1}$$
$$\times\left[\frac{C_A}{C_F} f_g(x) D_g^h\left(\frac{\alpha_1}{x\zeta}\right) C_{gg}(x,\zeta) + \sum_{a=q,\bar{q}} f_a(x) D_a^h\left(\frac{\alpha_1}{x\zeta}\right) C_{qq}(x,\zeta)\right.$$
$$\left. + D_g^h\left(\frac{\alpha_1}{x\zeta}\right)\sum_{a=q,\bar{q}} f_a(x) C_{qg}(x,\zeta) + \frac{C_A}{C_F} f_g(x) \sum_{a=q,\bar{q}} D_a^h\left(\frac{\alpha_1}{x\zeta}\right) C_{gq}(x,\zeta)\right]$$

...but $|C_{gg}| \sim 50 \div 10^4 |C_{gq}|$

Backup

(NLO impact factor) [D. Yu. Ivanov, A. Papa JHEP 07 (2012) 045]

Stabilizing effects of heavy-flavor fragmentation

- Stabilization mechanism encoded in the heavy-flavor gluon FF

- Forward-hadron LO impact factor ⇒ gluon FF enhanced by gluon PDF in collinear convolution

$$c_\Lambda(n,\nu,|\vec p|,x) = 2\sqrt{\frac{C_F}{C_A}}(|\vec p|^2)^{i\nu-1/2}\int_x^1 \frac{\mathrm{d}z}{z}\left(\frac{z}{x}\right)^{2i\nu-1}\left[\frac{C_A}{C_F} f_g(z) D_g^\Lambda\left(\frac{x}{z}\right) + \sum_{a=q,\bar q} f_a(z) D_a^\Lambda\left(\frac{x}{z}\right)\right]$$

- Forward-hadron NLO impact factor ⇒ a non-diagonal heavy-flavor channel open...

$$\begin{aligned} c_1^{(1)}(n,\nu,|\vec k_1|,\alpha_1) &= 2\sqrt{\frac{C_F}{C_A}}\left(\vec k_1^2\right)^{i\nu-\frac{1}{2}}\frac{1}{2\pi}\int_{\alpha_1}^1\frac{dx}{x}\int_{\frac{\alpha_1}{x}}^1\frac{d\zeta}{\zeta}\left(\frac{x\zeta}{\alpha_1}\right)^{2i\nu-1} \\ &\times\left[\frac{C_A}{C_F} f_g(x) D_g^h\left(\frac{\alpha_1}{x\zeta}\right) C_{gg}(x,\zeta) + \sum_{a=q,\bar q} f_a(x) D_a^h\left(\frac{\alpha_1}{x\zeta}\right) C_{qq}(x,\zeta)\right. \\ &+ \left. D_g^h\left(\frac{\alpha_1}{x\zeta}\right)\sum_{a=q,\bar q} f_a(x) C_{qg}(x,\zeta) + \frac{C_A}{C_F} f_g(x) \sum_{a=q,\bar q} D_a^h\left(\frac{\alpha_1}{x\zeta}\right) C_{gq}(x,\zeta)\right] \end{aligned}$$

...but $|C_{gg}| \sim 50 \div 10^4 |C_{gq}|$

- Gluon FF rises with energy ⇒ this compensates PDF and BFKL kernel decreasing behavior

Backup

(NLO impact factor) 🔗 [D. Yu. Ivanov, A. Papa JHEP 07 (2012) 045]

VECTOR QUARKONIA

Is the natural stability robust?

(1) **KKSS07** and **KKSS19** VFNS collinear FFs share the same extraction technology

¿ *Might natural stability be related to the given FF determination(s)* ?

Backup

Is the natural stability robust?

(1) **KKSS07** and **KKSS19** VFNS collinear FFs share the same extraction technology

¿ *Might natural stability be related to the given FF determination(s)* ?

(2) **KKSS07** and **KKSS19** VFNS collinear FFs assume no initial-scale gluon, but evolution-driven

¿ *Might natural stability be artificially generated by this Ansatz* ?

Backup

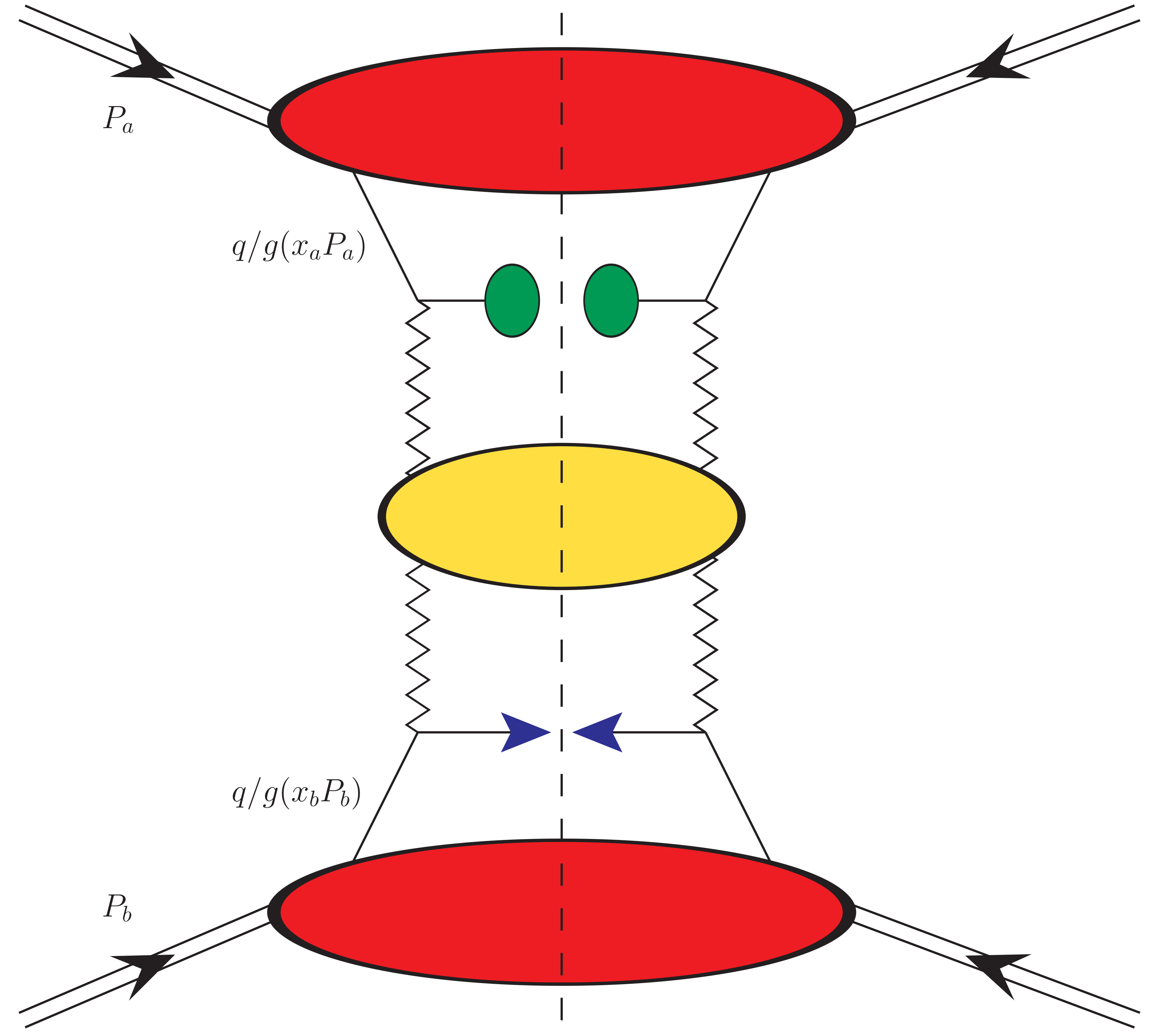
Vector quarkonium from single-parton fragmentation

(1) ¡ *Let us consider J/ψ and Υ at large p_T $\rightarrow$ single-parton* ***fragmentation*** *from* ***NRQCD*** !

Backup

Vector quarkonium from single-parton fragmentation

(1) ¡ *Let us consider J/ψ and Υ at large p_T $\rightarrow$ single-parton **fragmentation** from **NRQCD**!*



2.1 High-energy resummed cross section

The process under investigation is

$$p(P_a) + p(P_b) \rightarrow \mathcal{Q}(p_\mathcal{Q}, y_\mathcal{Q}) + X + \text{jet}(p_J, y_J) \;, \tag{1}$$

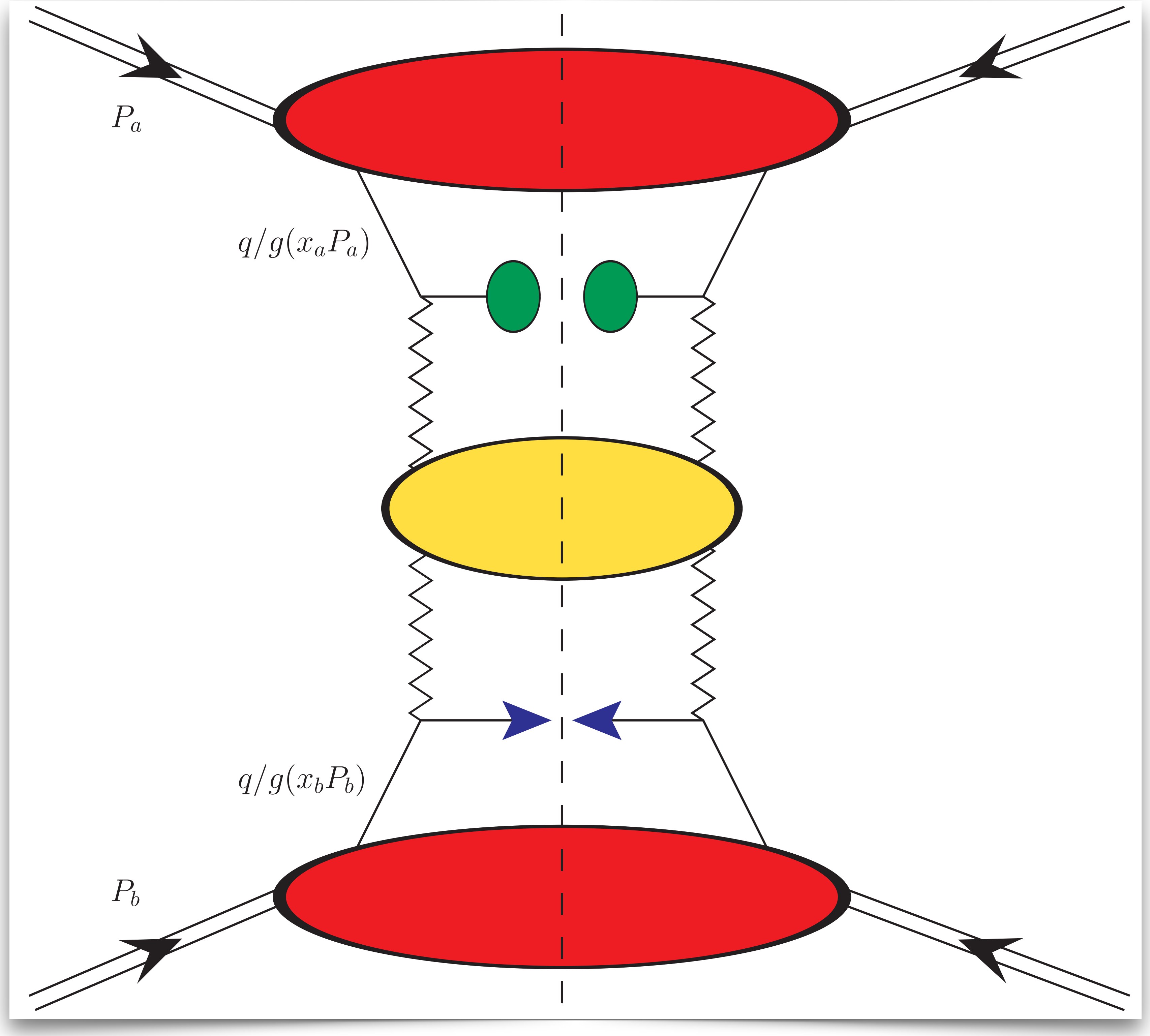
where $p(P_{a,b})$ stands for an initial proton with momentum $P_{a,b}$, $\mathcal{Q}(p_\mathcal{Q}, y_\mathcal{Q})$ is a J/ψ or a Υ emitted with momentum $p_\mathcal{Q}$ and rapidity $y_\mathcal{Q}$, the light jet is tagged with momentum p_J and rapidity y_J, and X denotes all the undetected products of the reaction. High observed transverse momenta, $|\vec{p}_{\mathcal{Q},J}|$, together with a large rapidity separation, $\Delta Y = y_\mathcal{Q} - y_J$, are required conditions to get a diffractive semi-hard configuration in the final state. Furthermore the transverse-momentum ranges need to be enough large to ensure the validity of description of the quarkonium production mechanism in terms of single-parton VFNS collinear fragmentation.

[F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

Backup

Vector quarkonium from single-parton fragmentation

(1) ¡ *Let us consider J/ψ and Υ at large p_T* $\rightarrow$ *single-parton* ***fragmentation*** *from* ***NRQCD*** !



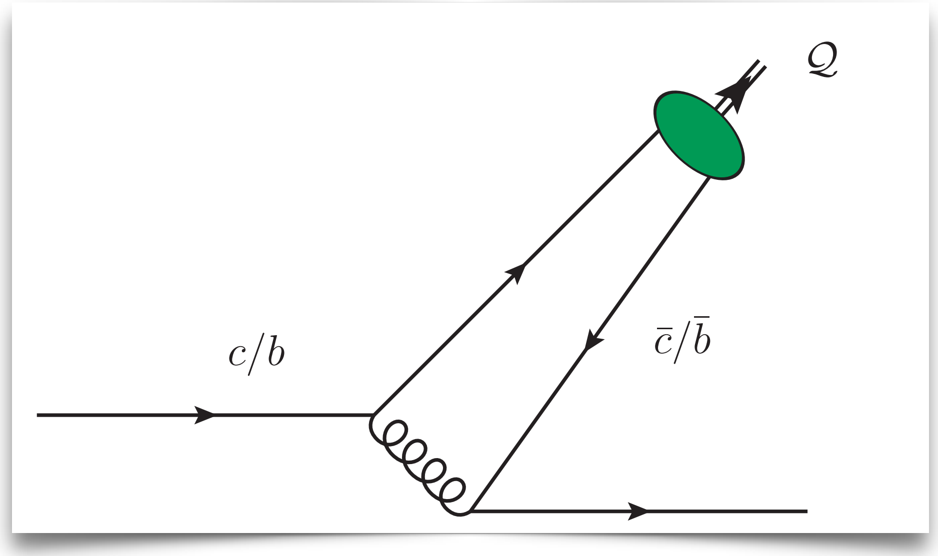
2.1 High-energy resummed cross section

The process under investigation is

$$p(P_a) + p(P_b) \rightarrow \mathcal{Q}(p_\mathcal{Q}, y_\mathcal{Q}) + X + \text{jet}(p_J, y_J) \;, \tag{1}$$

where $p(P_{a,b})$ stands for an initial proton with momentum $P_{a,b}$, $\mathcal{Q}(p_\mathcal{Q}, y_\mathcal{Q})$ is a J/ψ or a Υ emitted with momentum $p_\mathcal{Q}$ and rapidity $y_\mathcal{Q}$, the light jet is tagged with momentum p_J and rapidity y_J, and X denotes all the undetected products of the reaction. High observed transverse momenta, $|\vec{p}_{\mathcal{Q},J}|$, together with a large rapidity separation, $\Delta Y = y_\mathcal{Q} - y_J$, are required conditions to get a diffractive semi-hard configuration in the final state. Furthermore the transverse-momentum ranges need to be enough large to ensure the validity of description of the quarkonium production mechanism in terms of single-parton VFNS collinear fragmentation.

🔗 [F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]



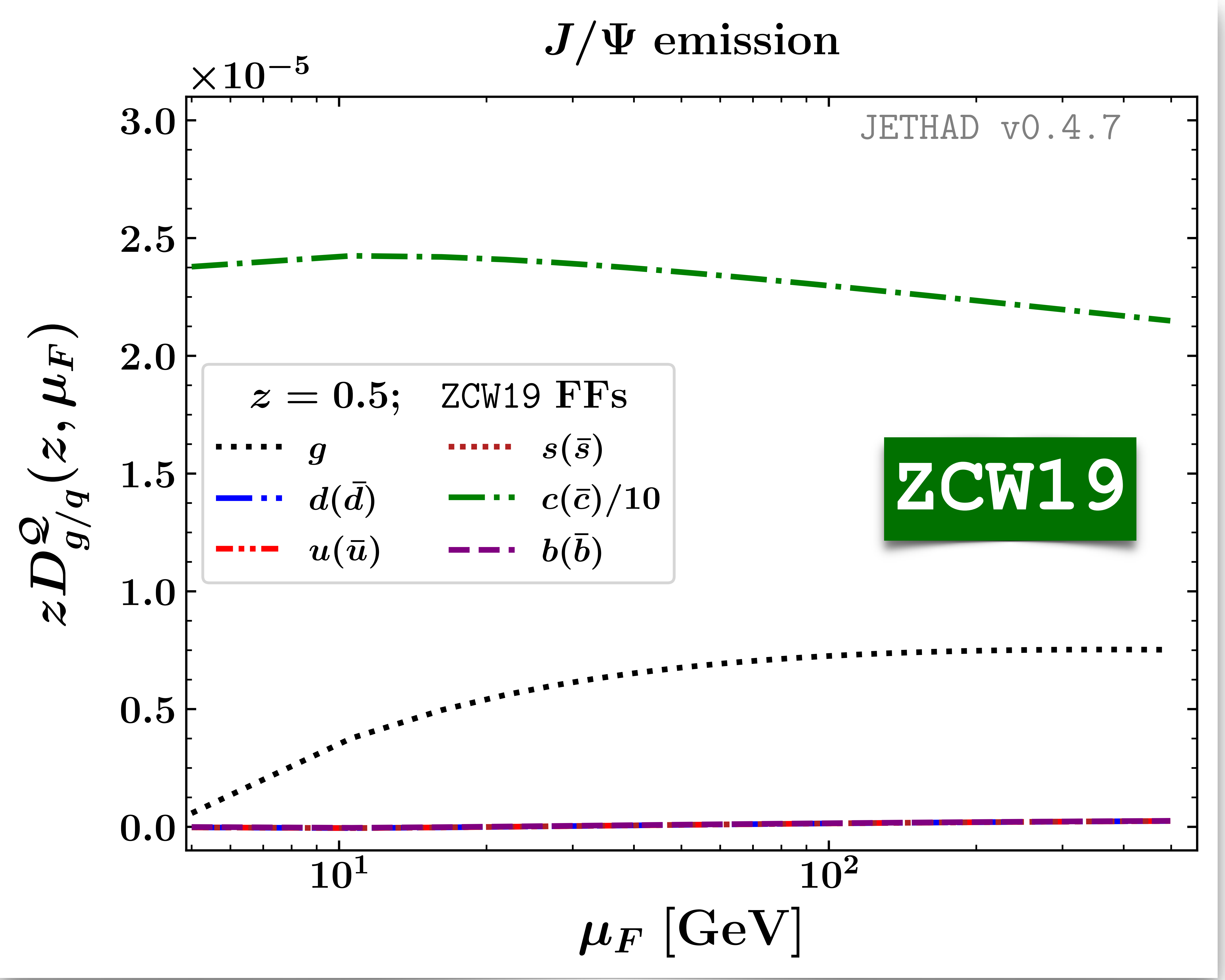
(LO) 🔗 [E. Braaten et al., Phys. Rev. D 48 (1993) 4230-4235]

(NLO) 🔗 [X. Zheng et al., Phys. Rev. D 100 (2019) 1, 014005]

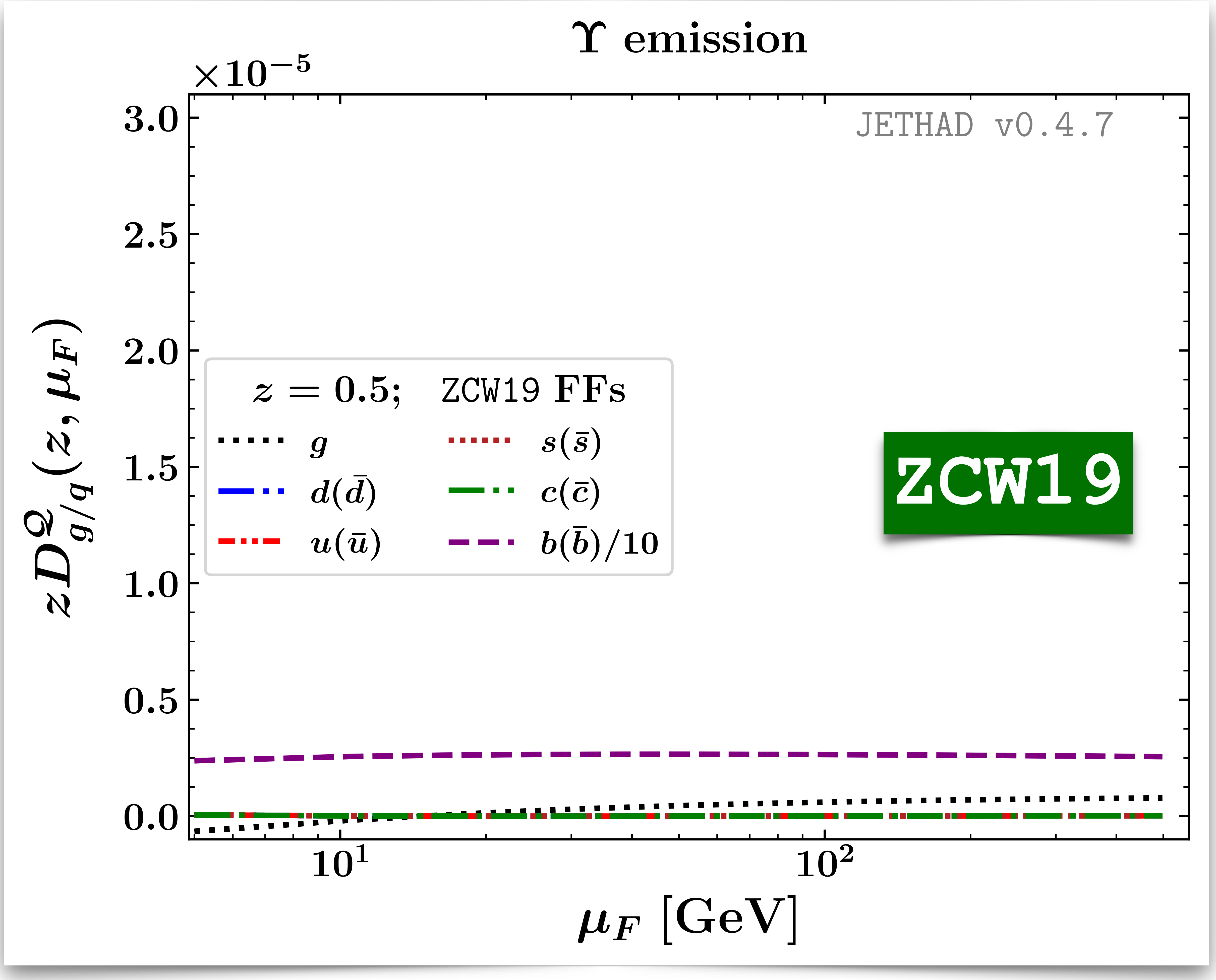
Backup

Vector quarkonium + jet at the LHC

J/ψ collinear FFs



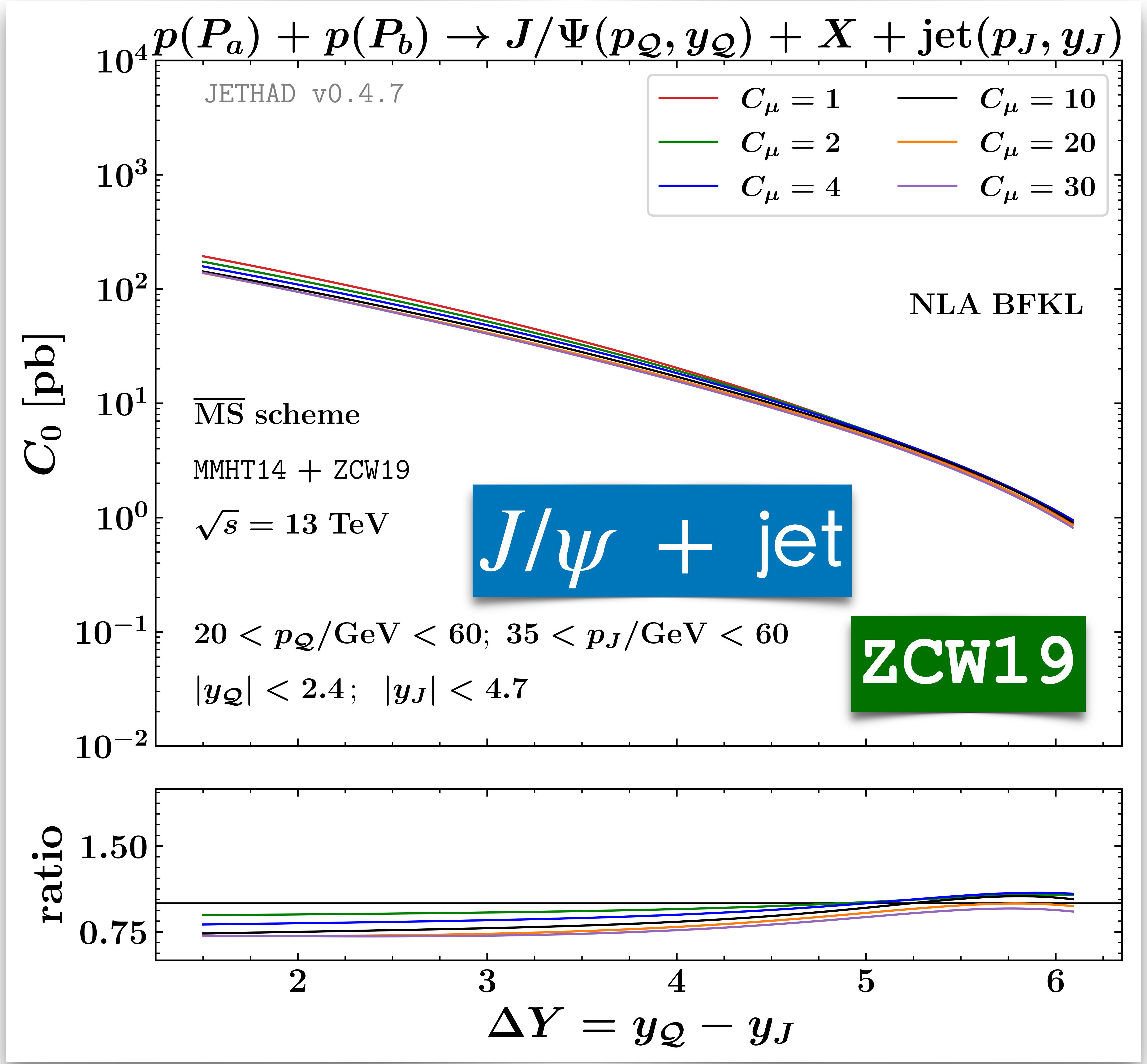
Υ collinear FFs

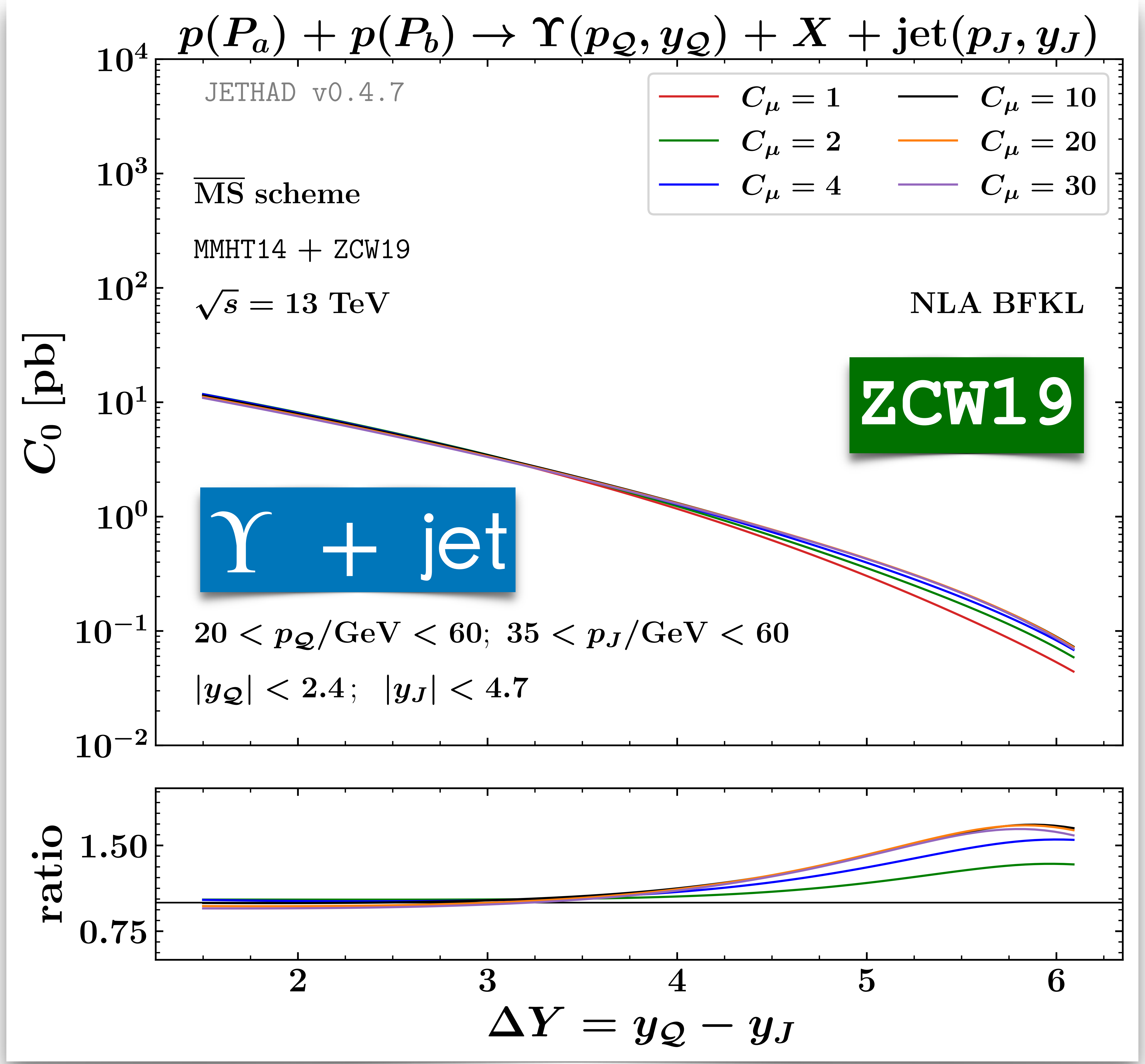


Backup

[F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

Vector quarkonium + jet at the LHC





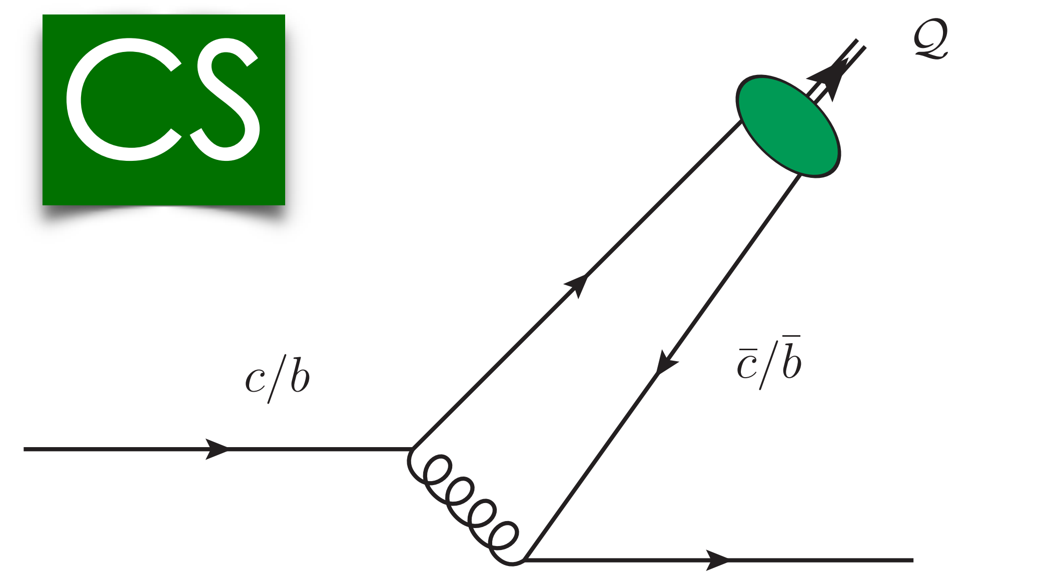
Backup

[F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

Vector quarkonium from single-parton fragmentation

(2) ¡ *Let us consider J/ψ and Υ at large p_T* → *initial-scale* ***heavy-quark*** + ***gluon*** *from* ***NRQCD*** !

CS



$$D_Q^{\mathcal{Q}}(z, \mu_F \equiv \mu_0) = D_Q^{\mathcal{Q},\mathrm{LO}}(z) + \frac{\alpha_s^3(\mu_R)}{m_Q^3} |\mathcal{R}_{\mathcal{Q}}(0)|^2 \, \Gamma^{\mathcal{Q},\mathrm{NLO}}(z)$$

$(Q \to \mathcal{Q}\, Q)$ at $\mu_0 = 3m_Q$

(LO) 🔗 [E. Braaten et al., Phys. Rev. D 48 (1993) 4230-4235]

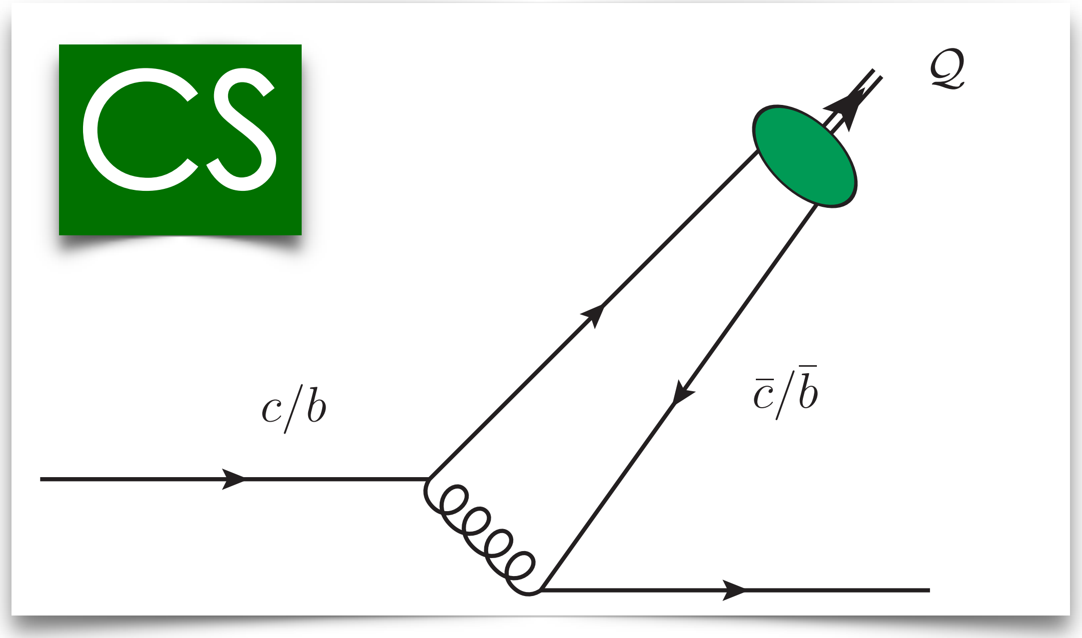
(NLO) 🔗 [X. Zheng et al., Phys. Rev. D 100 (2019) 1, 014005]

🔗 [F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

Backup

Vector quarkonium from single-parton fragmentation

(2) ¡ *Let us consider J/ψ and Υ at large p_T* $\rightarrow$ *initial-scale* ***heavy-quark*** + ***gluon*** *from* ***NRQCD*** !



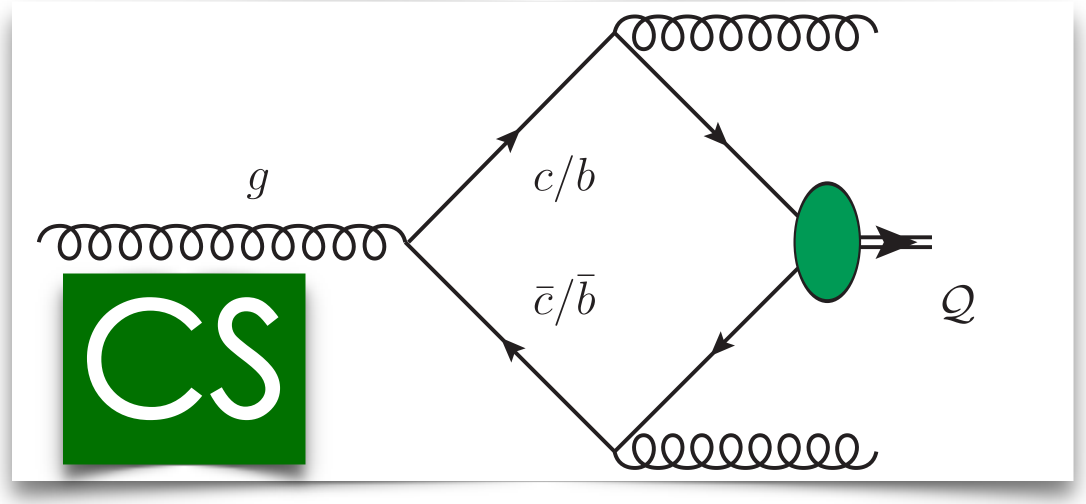
$$D_Q^{\mathcal{Q}}(z, \mu_F \equiv \mu_0) = D_Q^{\mathcal{Q},\mathrm{LO}}(z) + \frac{\alpha_s^3(\mu_R)}{m_Q^3} |\mathcal{R}_{\mathcal{Q}}(0)|^2 \, \Gamma^{\mathcal{Q},\mathrm{NLO}}(z)$$

$(Q \rightarrow \mathcal{Q}\, Q)$ at $\mu_0 = 3m_Q$

(LO) 🔗 [E. Braaten et al., Phys. Rev. D 48 (1993) 4230-4235]

(NLO) 🔗 [X. Zheng et al., Phys. Rev. D 100 (2019) 1, 014005]

+



$$D_g^{\mathcal{Q}}(z, 2m_Q) = \frac{5}{36(2\pi)^2}\alpha_s^3(2m_Q)\frac{|\mathcal{R}_{\mathcal{Q}}(0)|^2}{m_Q^3}\int_0^z \mathrm{d}\xi \int_{(\xi+z^2)/2z}^{(1+\xi)/2} \mathrm{d}\tau \frac{1}{(1-\tau)^2(\tau-\xi)^2(\tau^2-\xi)^2}$$
$$\sum_{i=1}^{2} z^i \left[f_i^{(g)}(\xi,\tau) + g_i^{(g)}(\xi,\tau)\frac{1+\xi-2\tau}{2(\tau-\xi)\sqrt{\tau^2-\xi}} \ln\left(\frac{\tau-\xi+\sqrt{\tau^2-\xi}}{\tau-\xi-\sqrt{\tau^2-\xi}}\right)\right] ,$$

$(Q \rightarrow \mathcal{Q}\, gg)$ at $\mu_0 = 2m_Q$

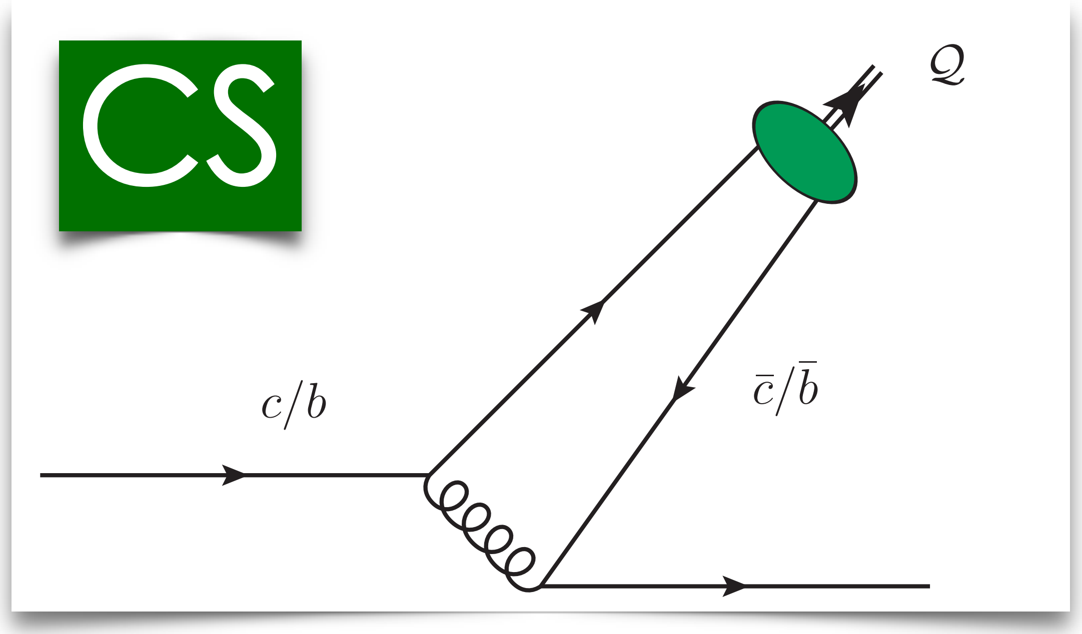
(LO) 🔗 [A. Braaten, T.C Yuan, Phys. Rev. Lett. 71 (1993), 1673]

🔗 [F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

Backup

Vector quarkonium from single-parton fragmentation

(2) ¡ *Let us consider J/ψ and Υ at large p_T* $\rightarrow$ *initial-scale* ***heavy-quark*** + ***gluon*** *from* ***NRQCD*** !



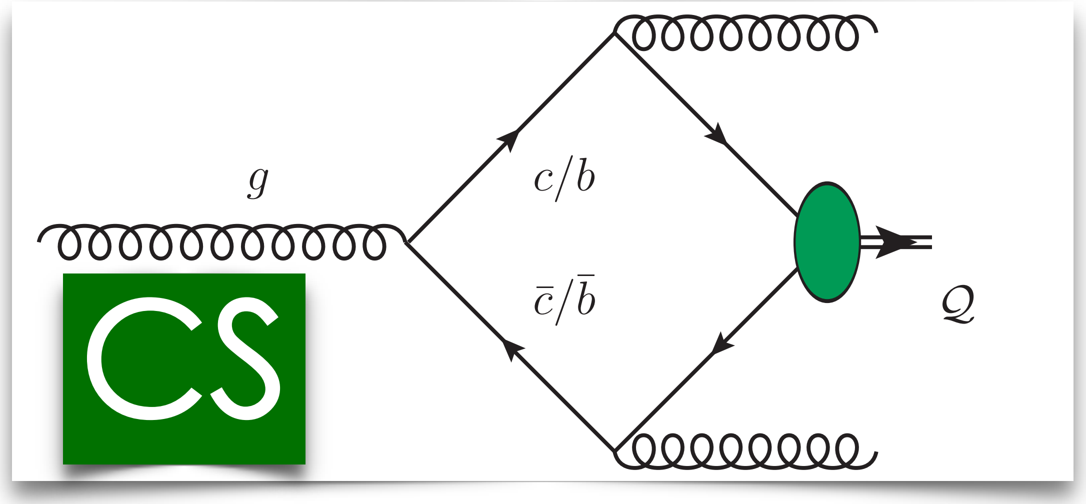
$$D_Q^{\mathcal{Q}}(z, \mu_F \equiv \mu_0) = D_Q^{\mathcal{Q},\mathrm{LO}}(z) + \frac{\alpha_s^3(\mu_R)}{m_Q^3} |\mathcal{R}_{\mathcal{Q}}(0)|^2 \, \Gamma^{\mathcal{Q},\mathrm{NLO}}(z)$$

$(Q \rightarrow \mathcal{Q}\, Q)$ at $\mu_0 = 3 m_Q$

(LO) [E. Braaten et al., Phys. Rev. D 48 (1993) 4230-4235]

(NLO) [X. Zheng et al., Phys. Rev. D 100 (2019) 1, 014005]

+



$$D_g^{\mathcal{Q}}(z, 2m_Q) = \frac{5}{36(2\pi)^2} \alpha_s^3(2m_Q) \frac{|\mathcal{R}_{\mathcal{Q}}(0)|^2}{m_Q^3} \int_0^z \mathrm{d}\xi \int_{(\xi+z^2)/2z}^{(1+\xi)/2} \mathrm{d}\tau \frac{1}{(1-\tau)^2(\tau-\xi)^2(\tau^2-\xi)^2} \sum_{i=1}^{2} z^i \left[f_i^{(g)}(\xi,\tau) + g_i^{(g)}(\xi,\tau) \frac{1+\xi-2\tau}{2(\tau-\xi)\sqrt{\tau^2-\xi}} \ln\left(\frac{\tau-\xi+\sqrt{\tau^2-\xi}}{\tau-\xi-\sqrt{\tau^2-\xi}} \right) \right],$$

$(Q \rightarrow \mathcal{Q}\, gg)$ at $\mu_0 = 2 m_Q$

(LO) [A. Braaten, T.C Yuan, Phys. Rev. Lett. 71 (1993), 1673]

$\otimes$

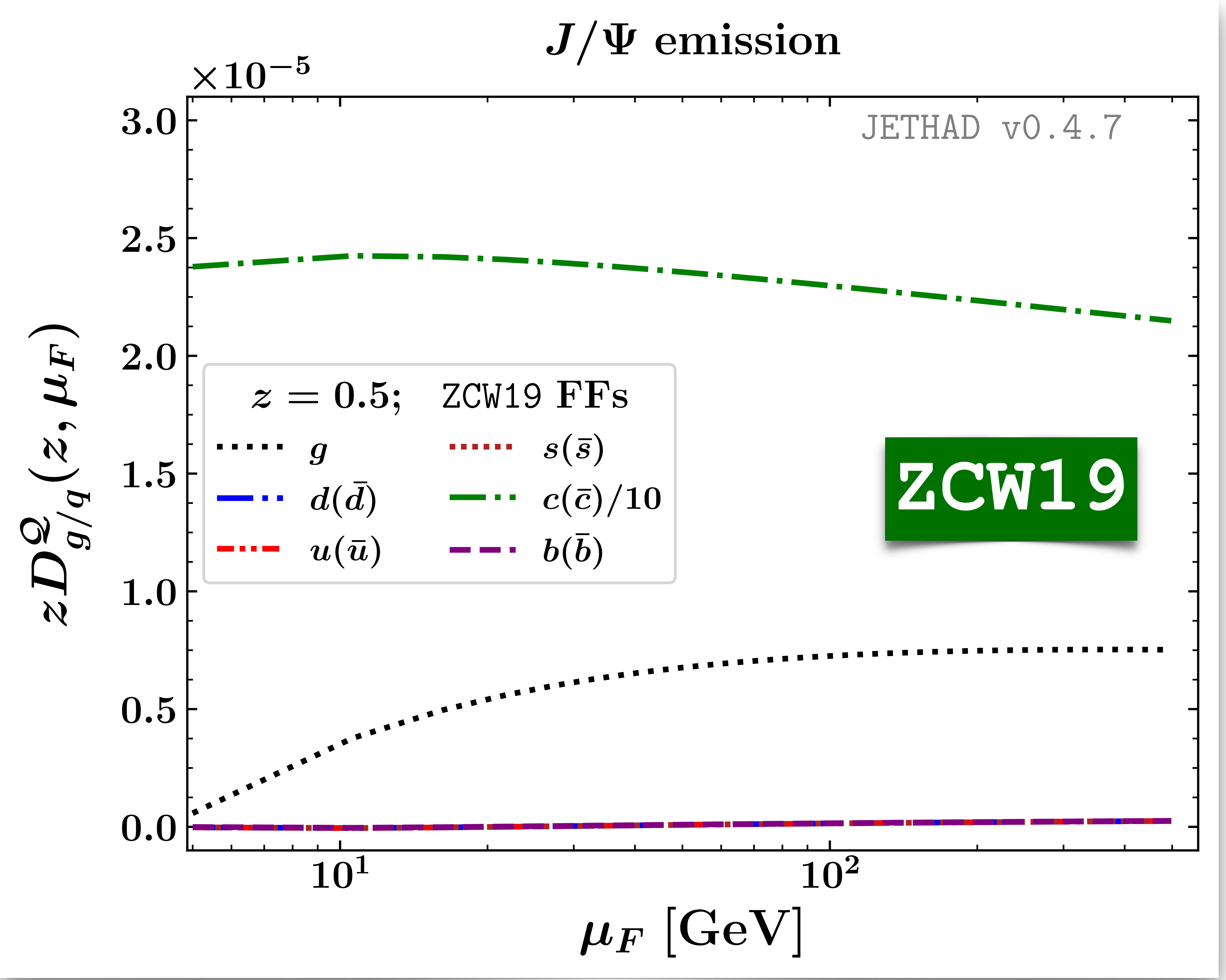
[F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

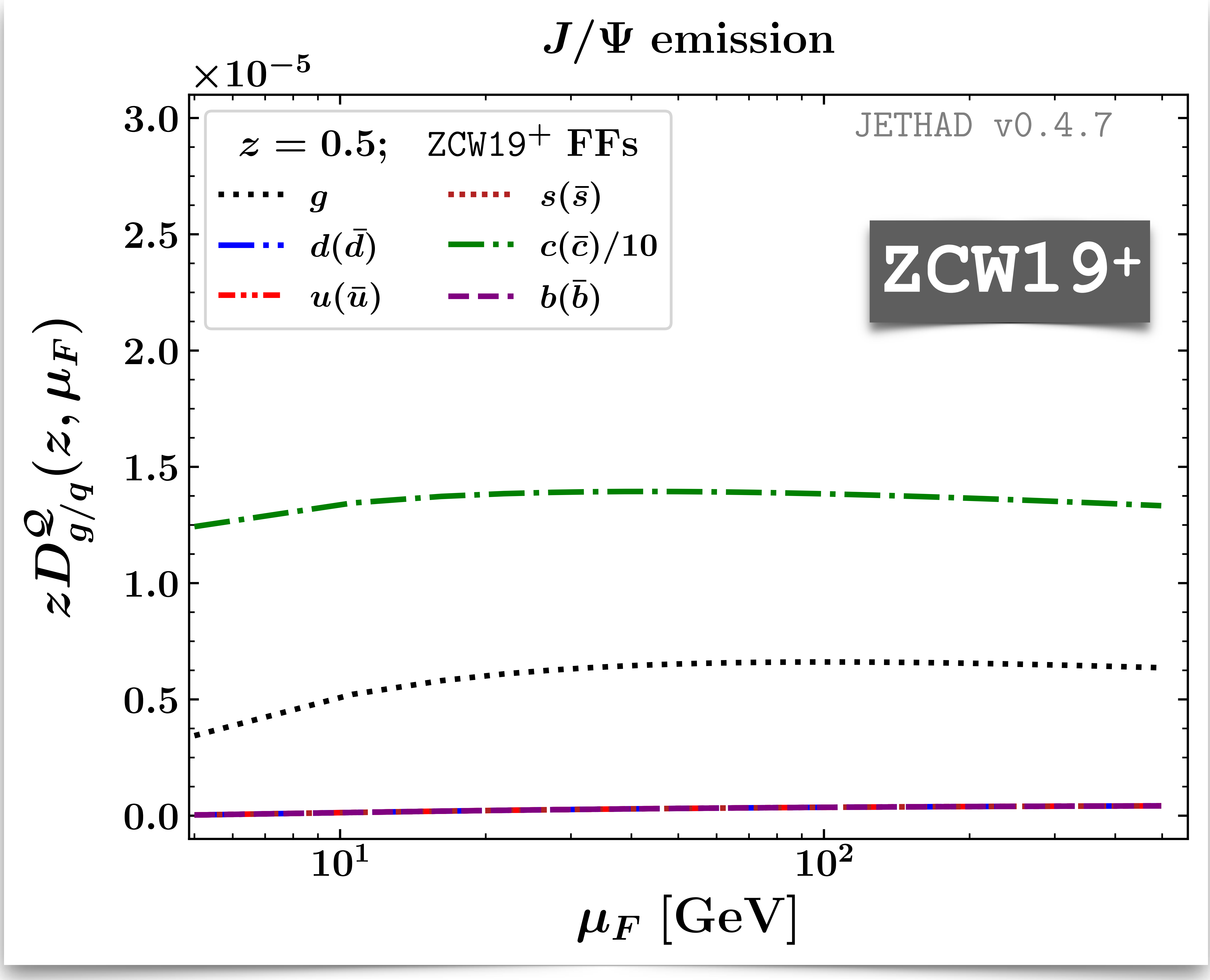
ZCW19+ onium FFs = **APFEL++**

Backup

Vector quarkonium + jet at the LHC

J/ψ collinear FFs



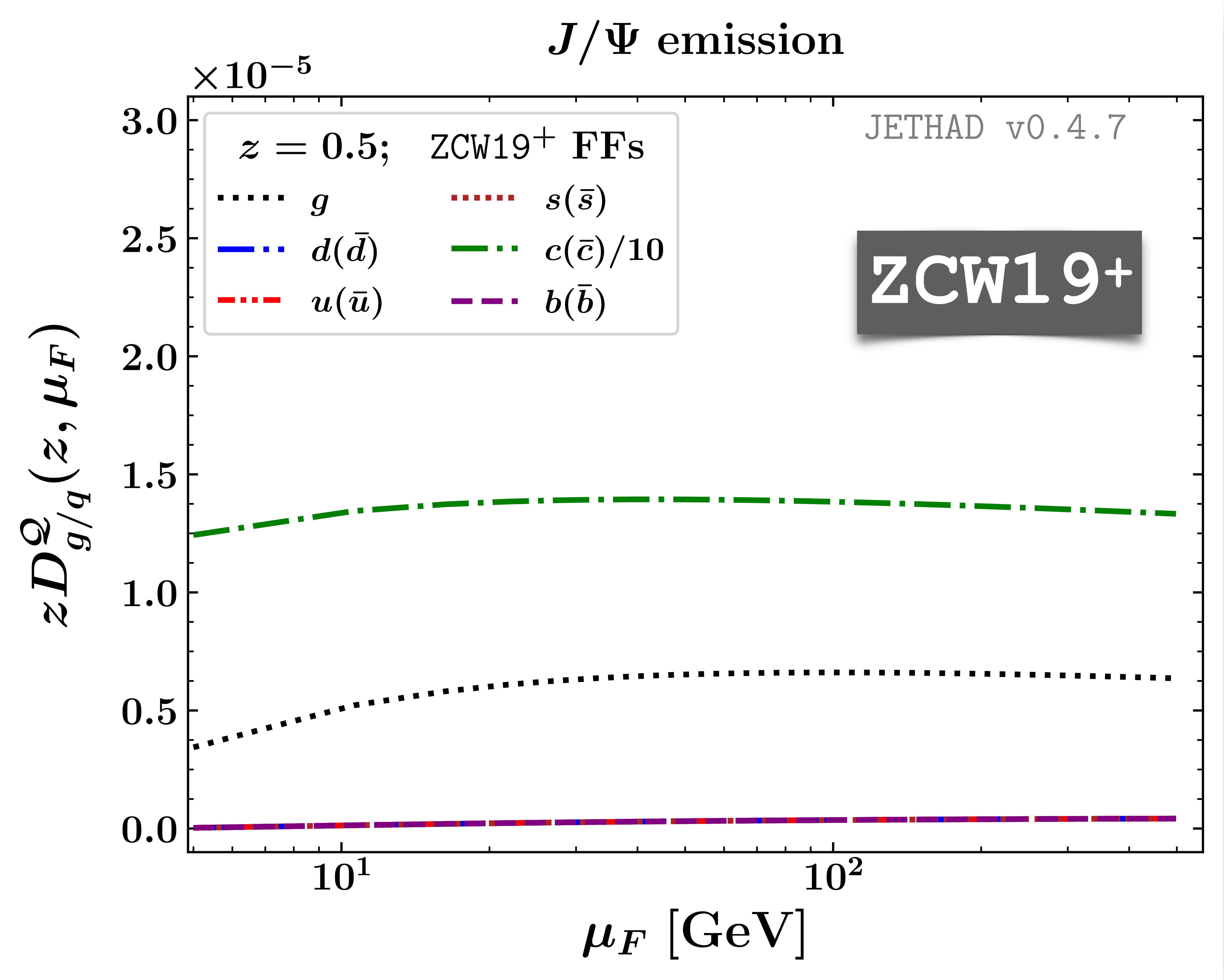


Backup

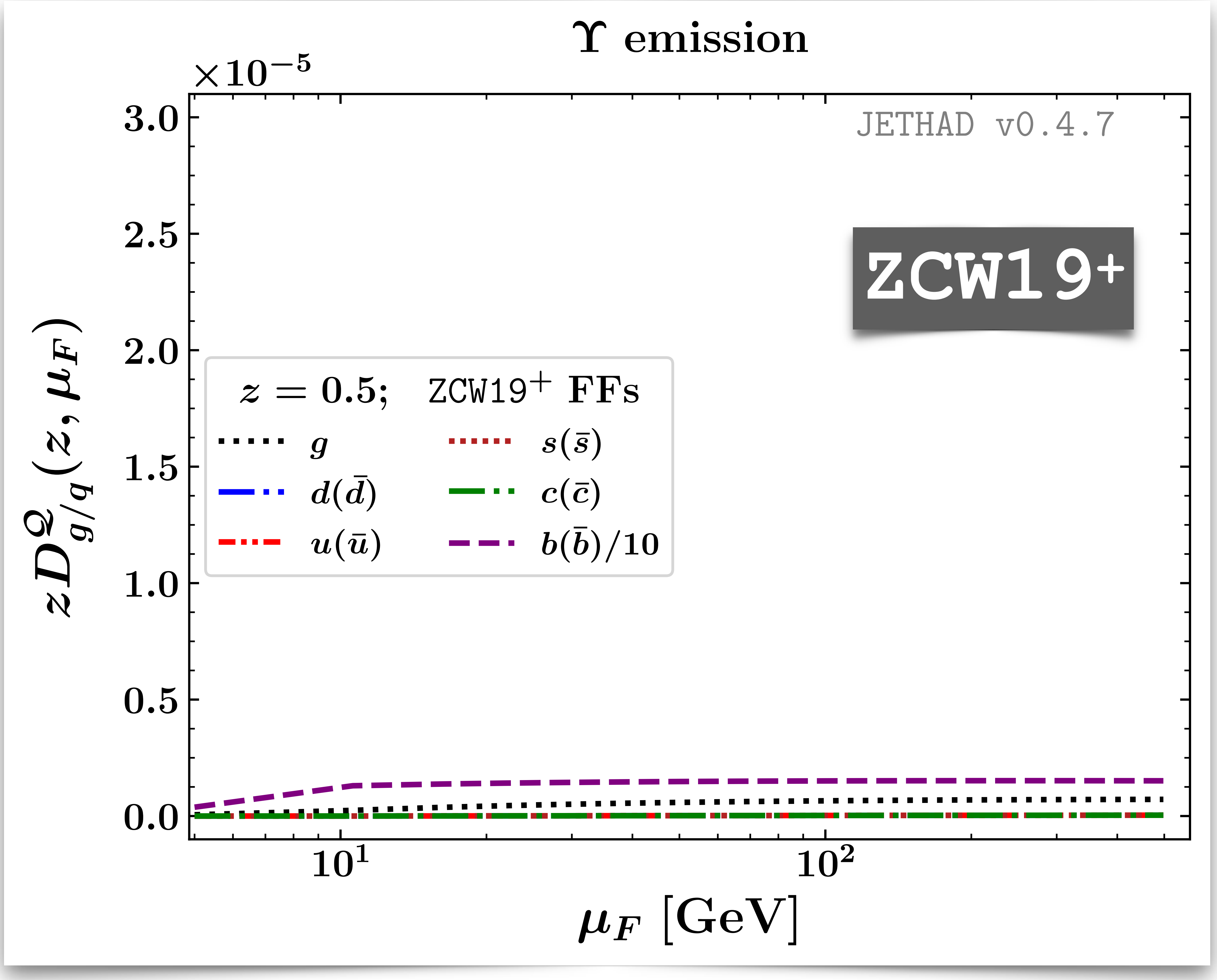
🔗 [F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

Vector quarkonium + jet at the LHC

J/ψ collinear FFs



Υ collinear FFs

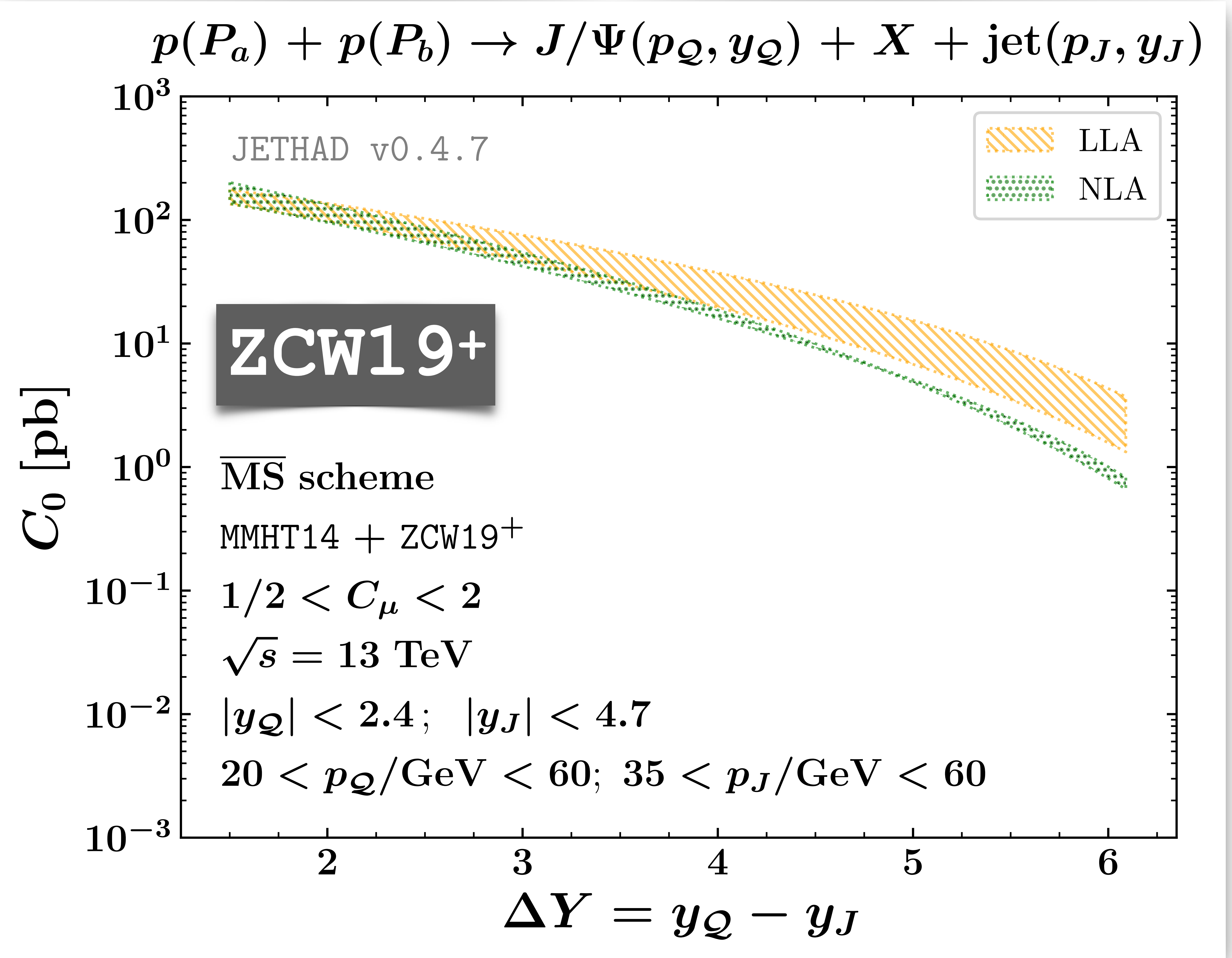


🔗 [F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

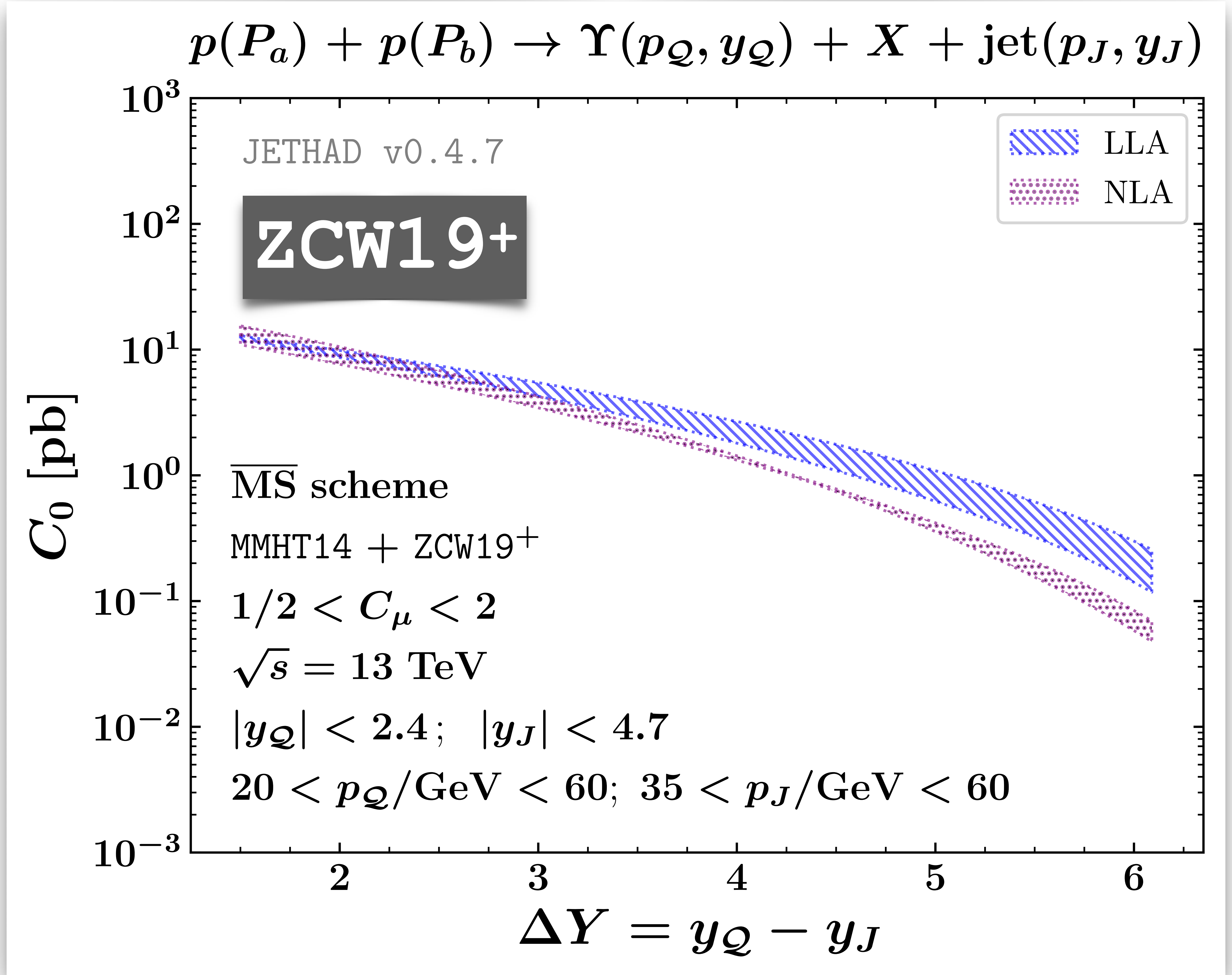
Backup

Vector quarkonium + jet at the LHC

J/ψ + jet



Υ + jet

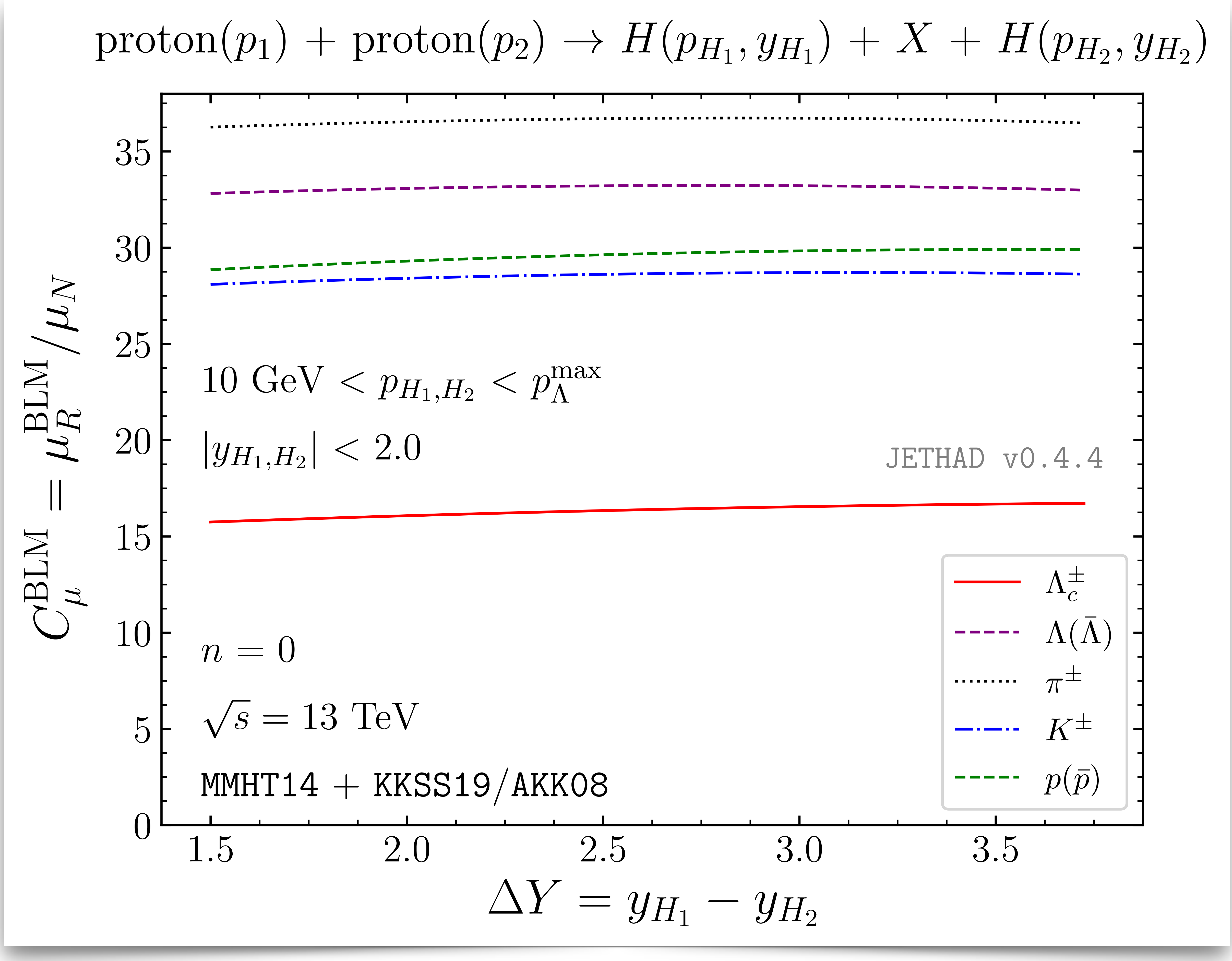


[F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

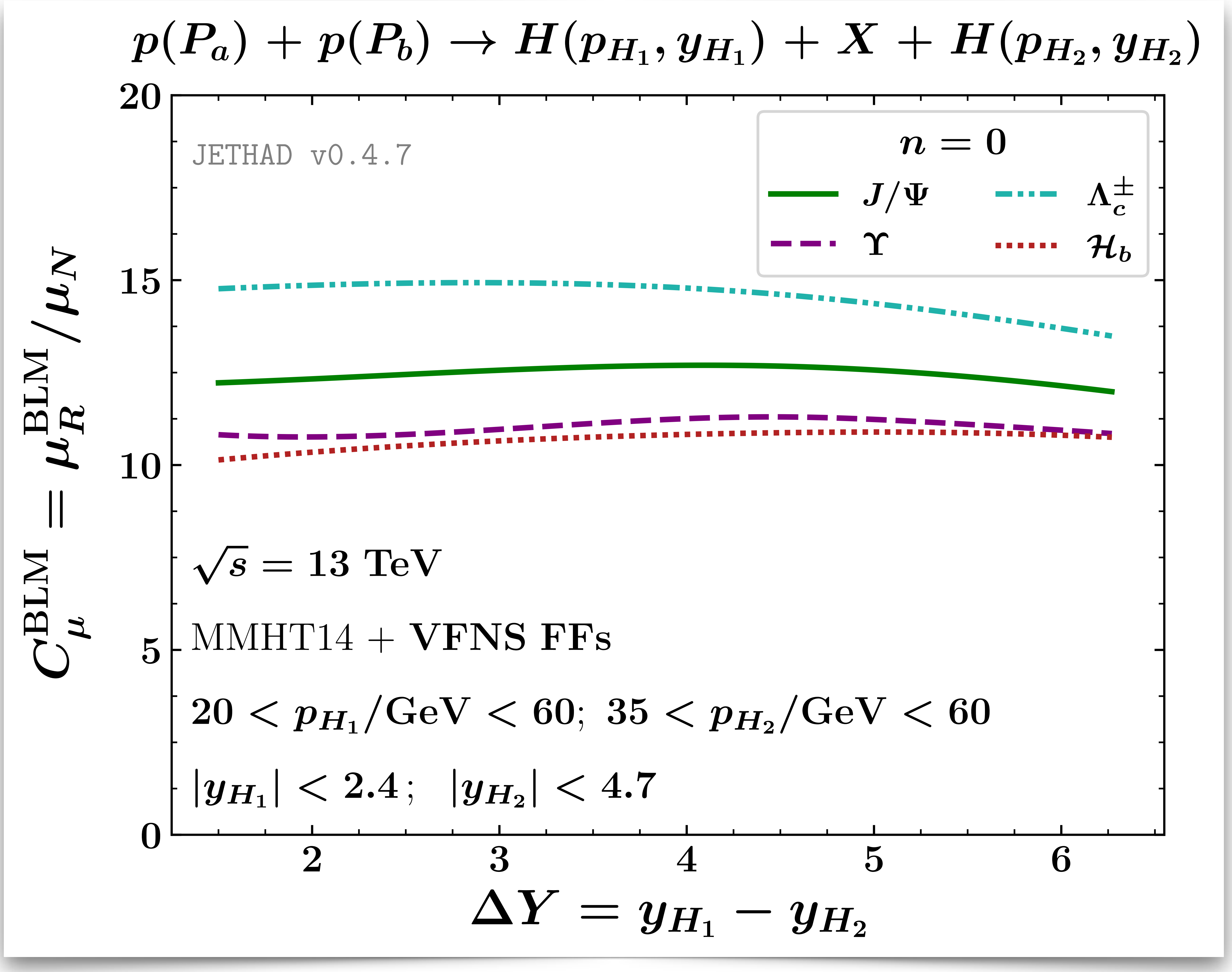
Backup

Heavy flavor at the LHC: BLM scales

Heavy-light hadrons



Vector quarkonia

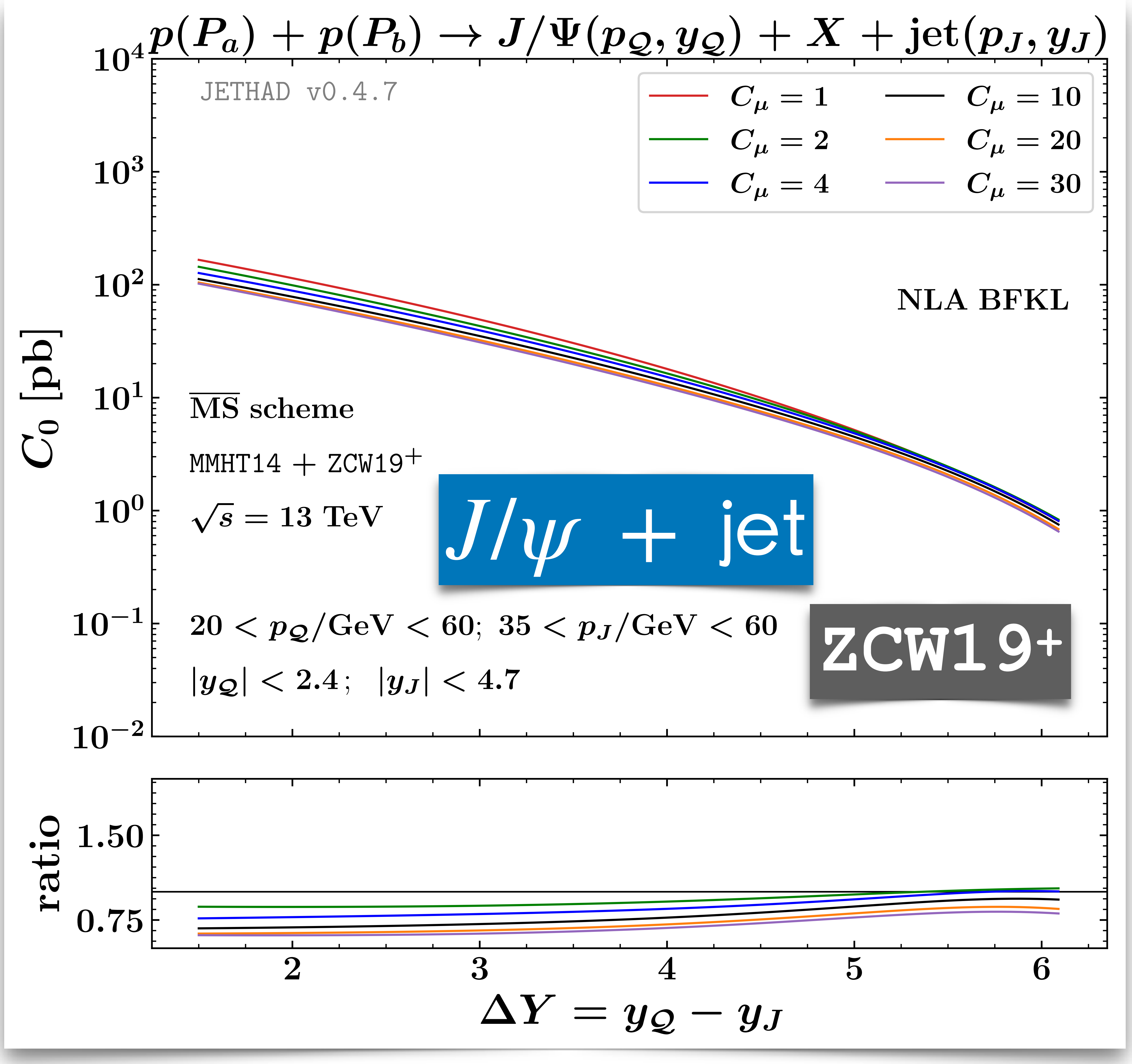


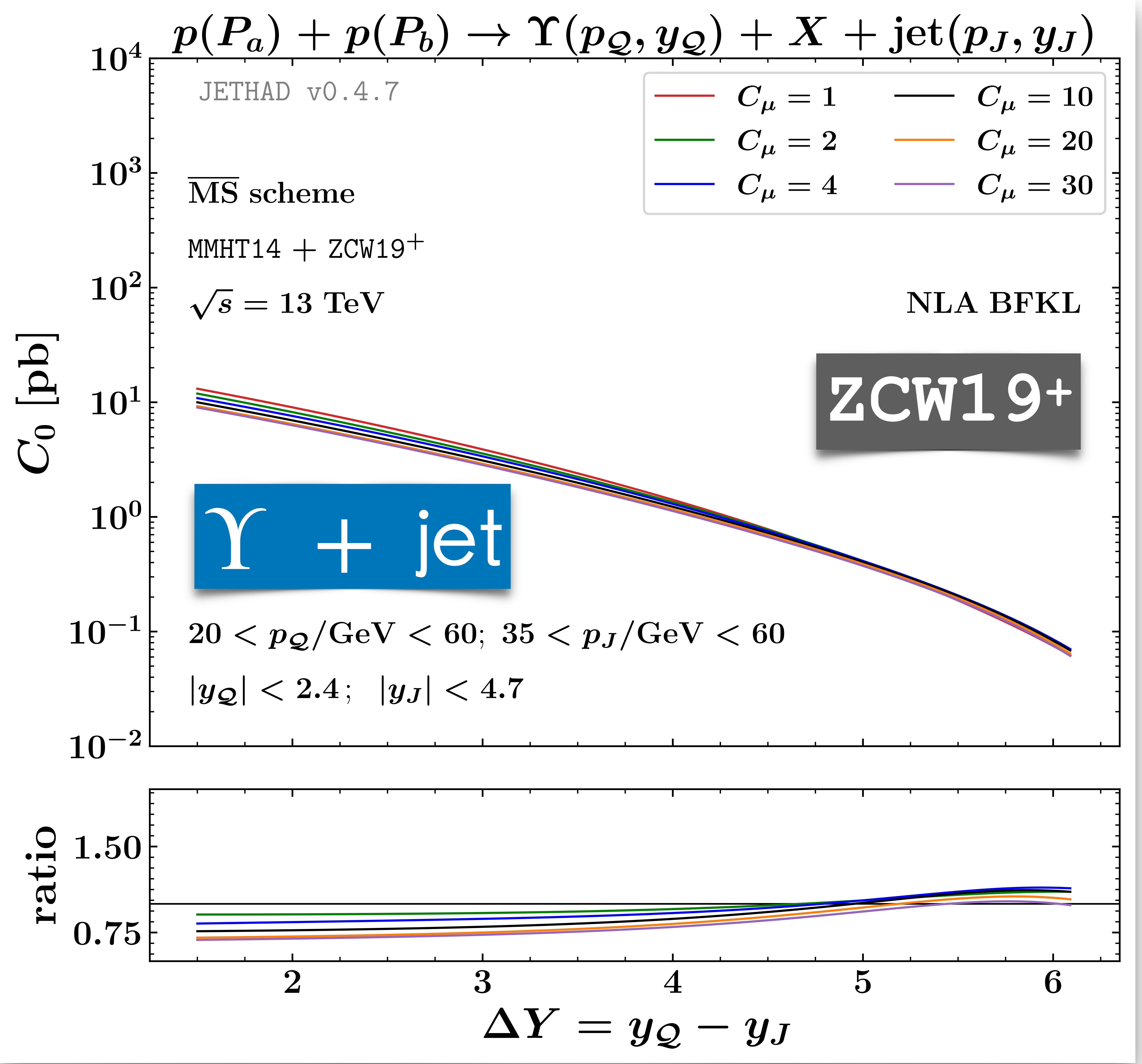
[F. G. C. et al., Eur. Phys. J. C 81 (2021) 8, 780]

Backup

[F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

Vector quarkonium + jet at the LHC





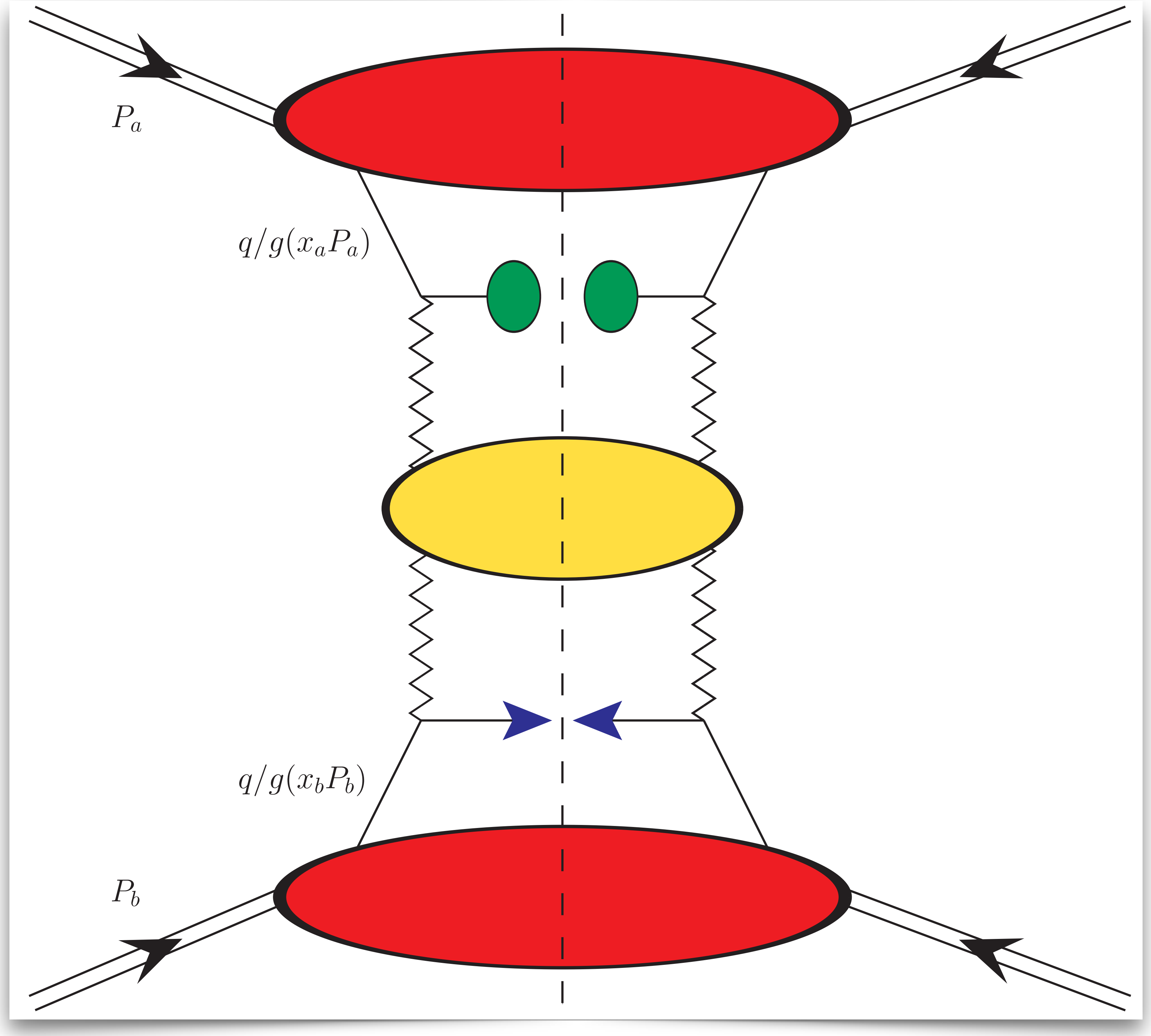
[F. G. C. et al., Eur. Phys. J. C 82 (2022) 10, 929]

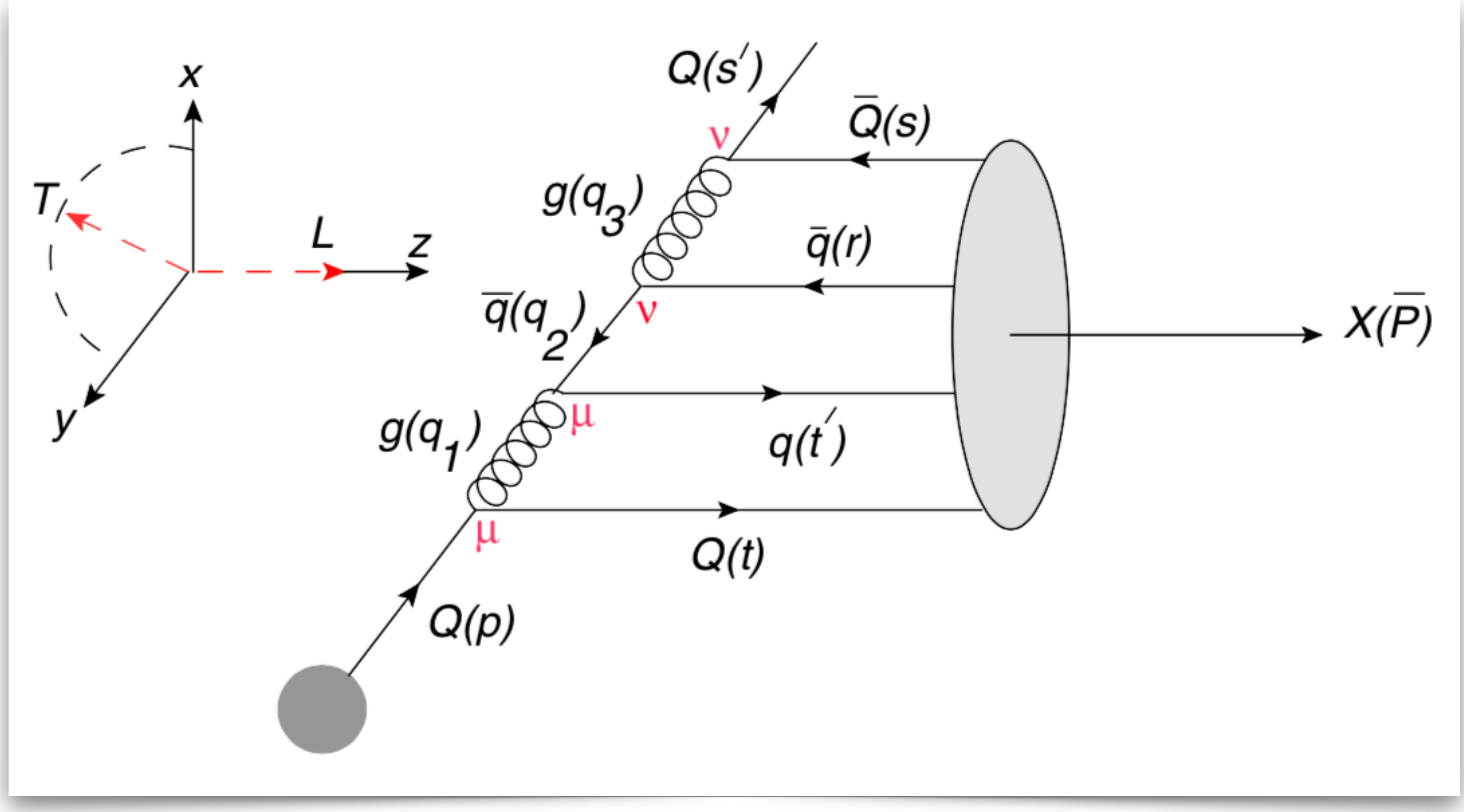
Backup

A HIGH-ENERGY QCD PORTAL TO EXOTIC MATTER

Heavy-light tetraquark from single-parton fragmentation

¡ *Let us consider heavy-light $X_{Qq\bar{Q}\bar{q}}$ tetraquarks at large p_T* $\rightarrow$ *single-parton* ***fragmentation*** !



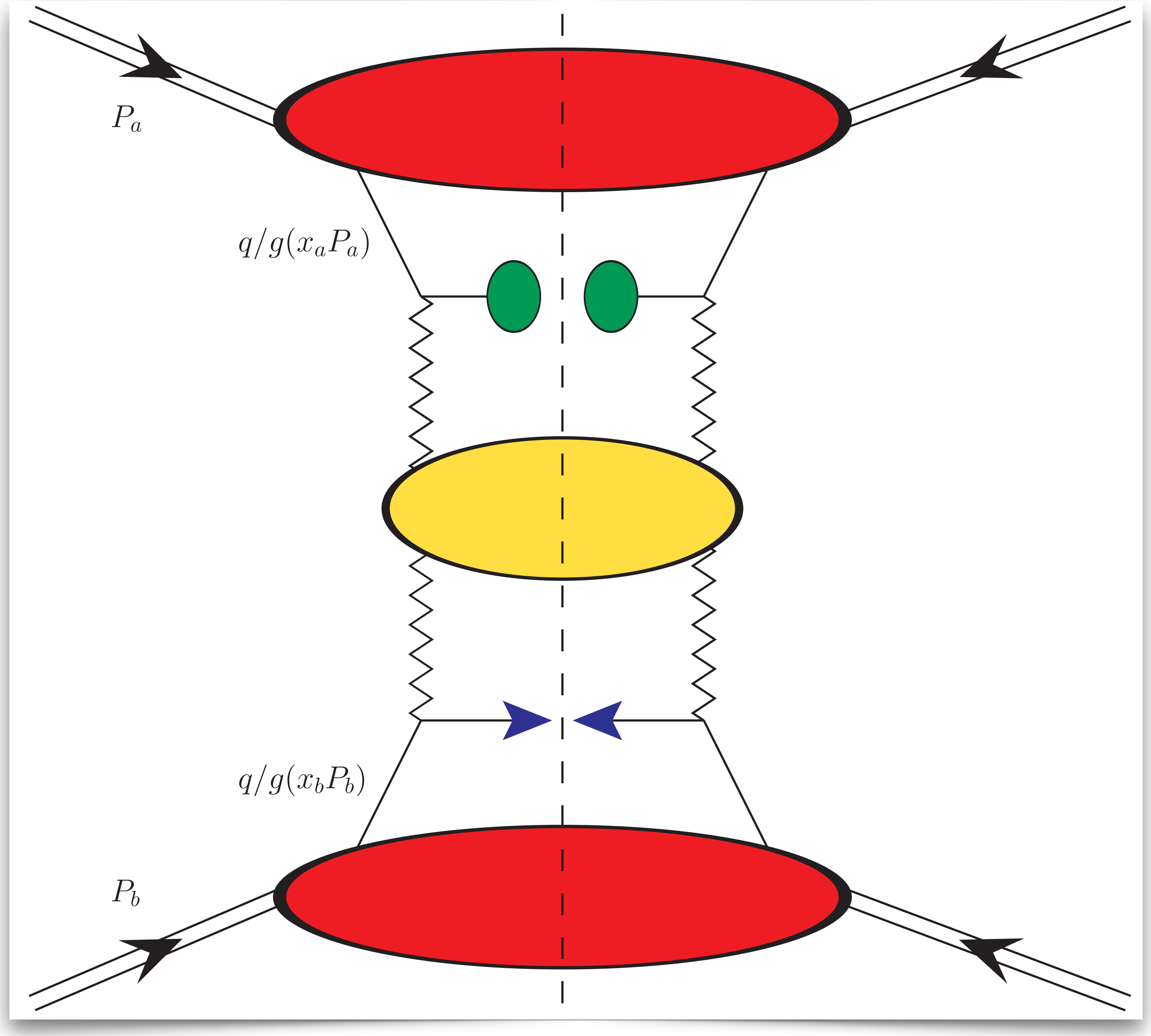


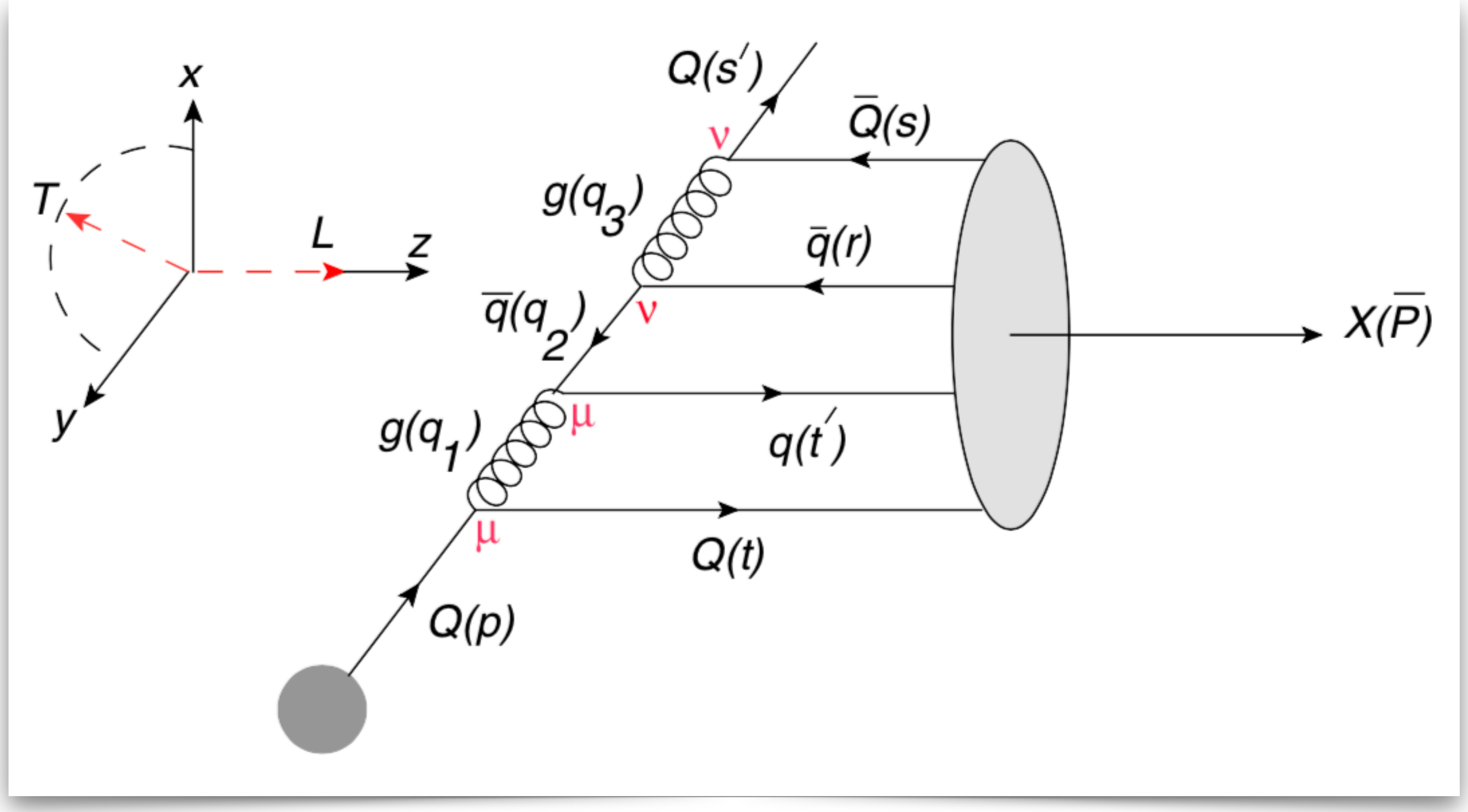
🔗 [F. G. C., A. Papa, to appear in PLB]

Backup

Heavy-light tetraquark from single-parton fragmentation

¡ Let us consider heavy-light $X_{Qq\bar{Q}\bar{q}}$ tetraquarks at large p_T → single-parton ***fragmentation*** *!*





[F. G. C., A. Papa, to appear in PLB]

TQHL1.0 FFs: $(Q \to X_{Qq\bar{Q}\bar{q}}) \otimes$ **APFEL++**

$[\mu_0 = m_X + m_Q]$

S-wave

$$D_Q^X(z,\mu_0) = N \frac{z \times \Sigma_{\rm spin} \Gamma \bar{\Gamma}}{(m_X^2 - 2m_Q^2 + 2p \cdot s')^2}$$
$$= N \frac{z \times \Sigma_{\rm spin} \Gamma \bar{\Gamma}}{[m_X^2 - (m_Q^2 + \langle p_T^2 \rangle)(1 + z - \frac{1}{1-z})]^2}$$

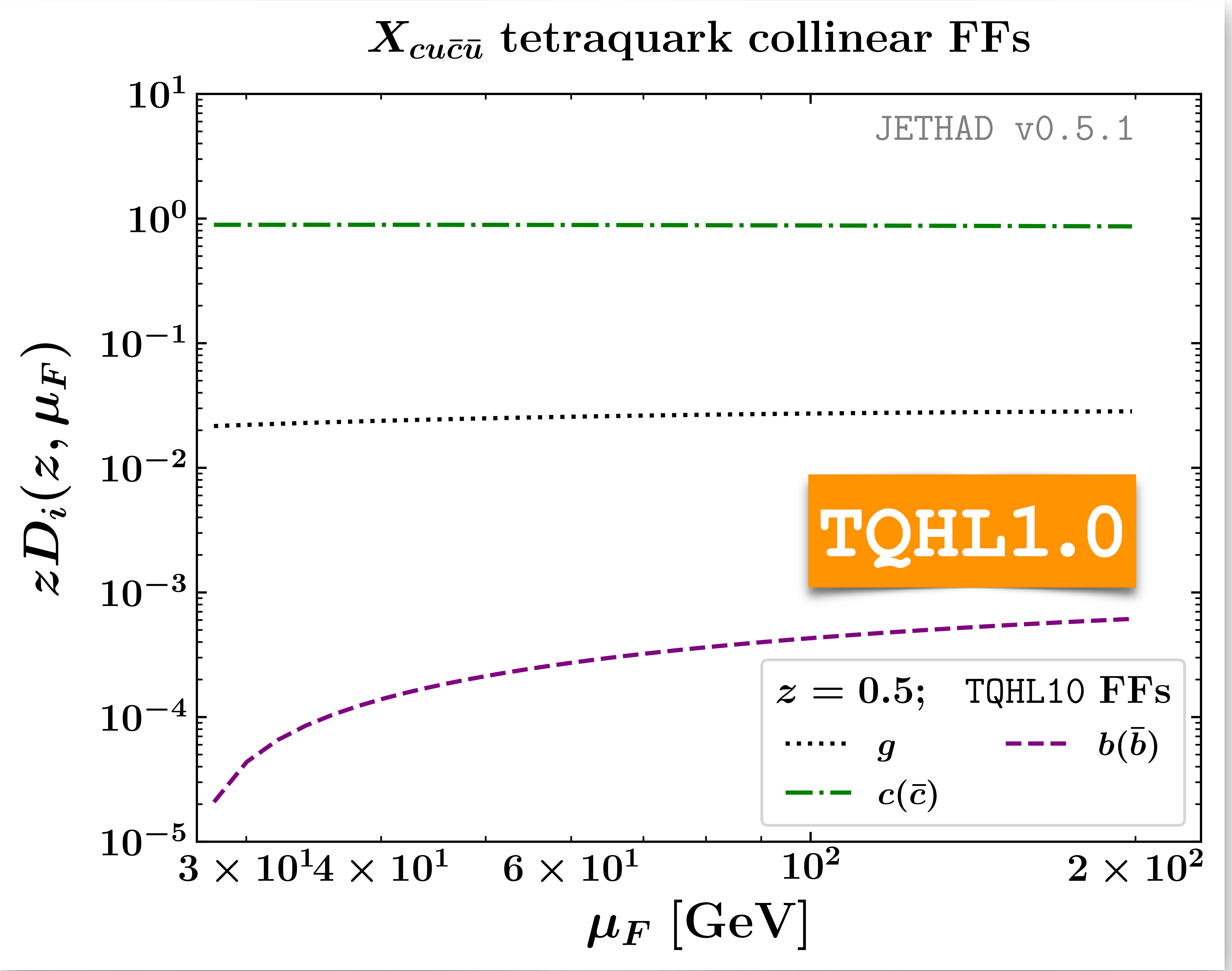
(LO) [S. M. Moosavi Nejad, Phys. Rev. D 05 (2022) 3, 034001]

(framework) [M. Suzuki, Phys. Rev. D 33 (1986) 676]

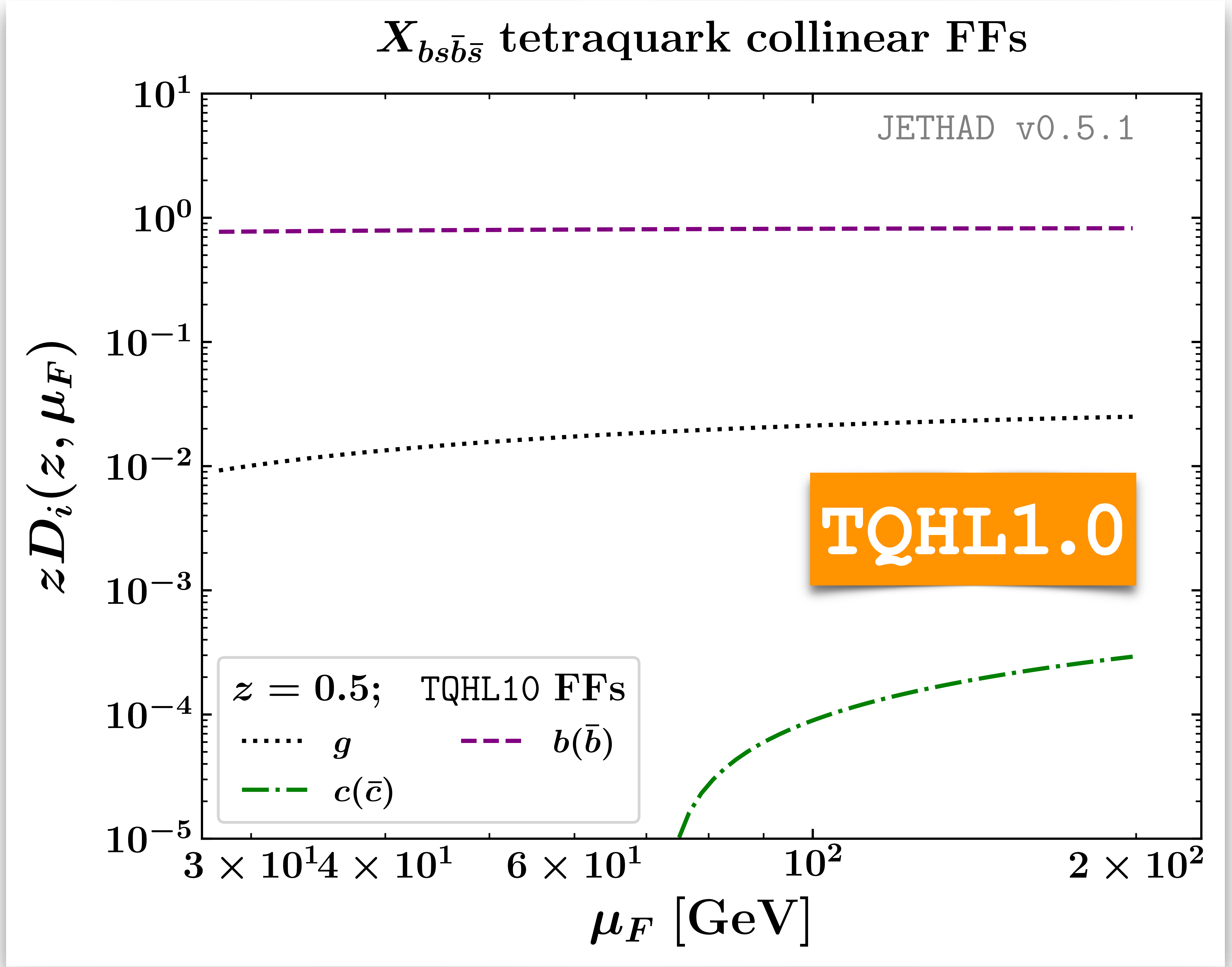
Backup

Heavy-light tetraquarks at the HL-LHC

$X_{cu\bar{c}\bar{u}}$ collinear FFs



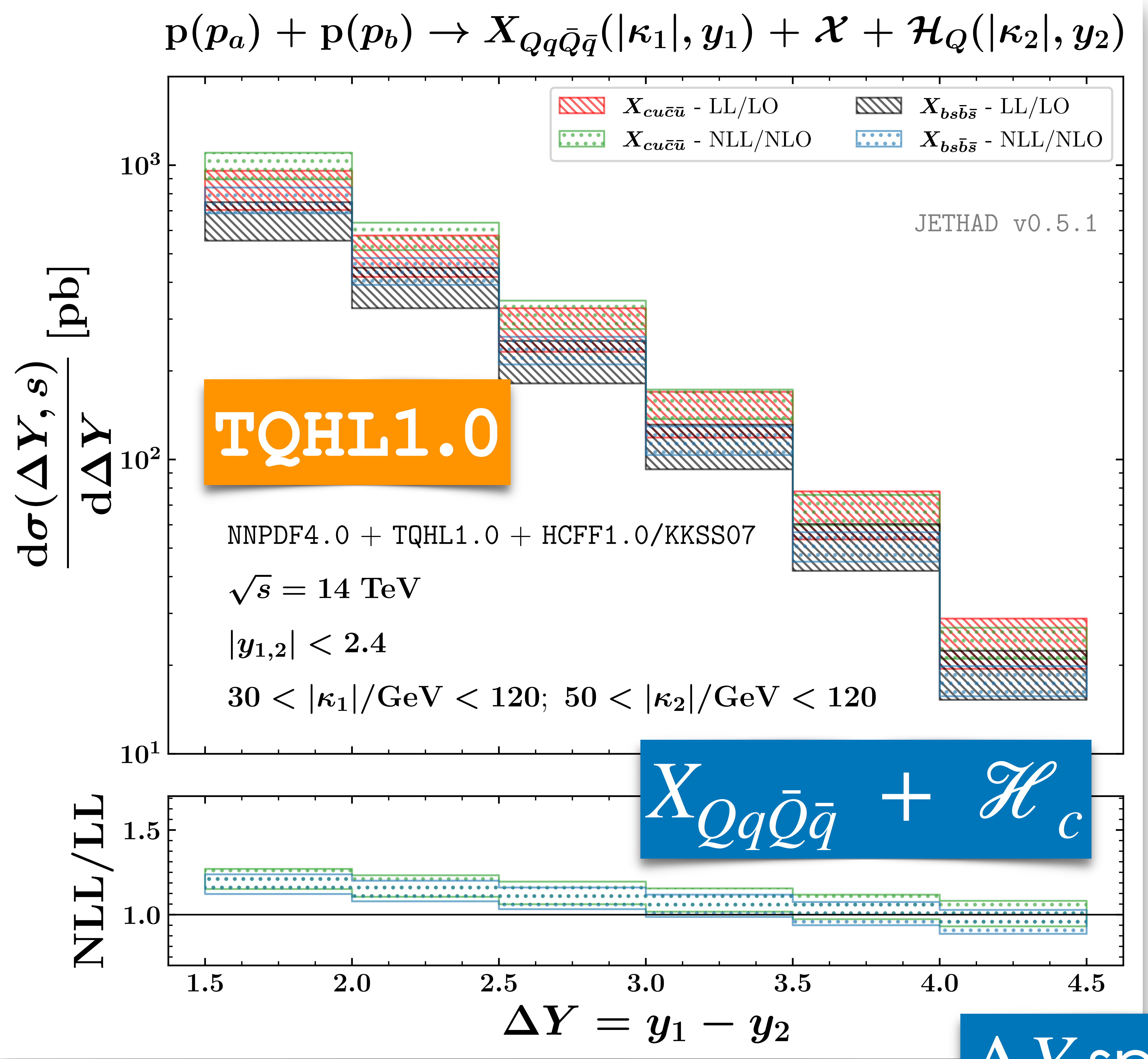
$X_{bs\bar{b}\bar{s}}$ collinear FFs

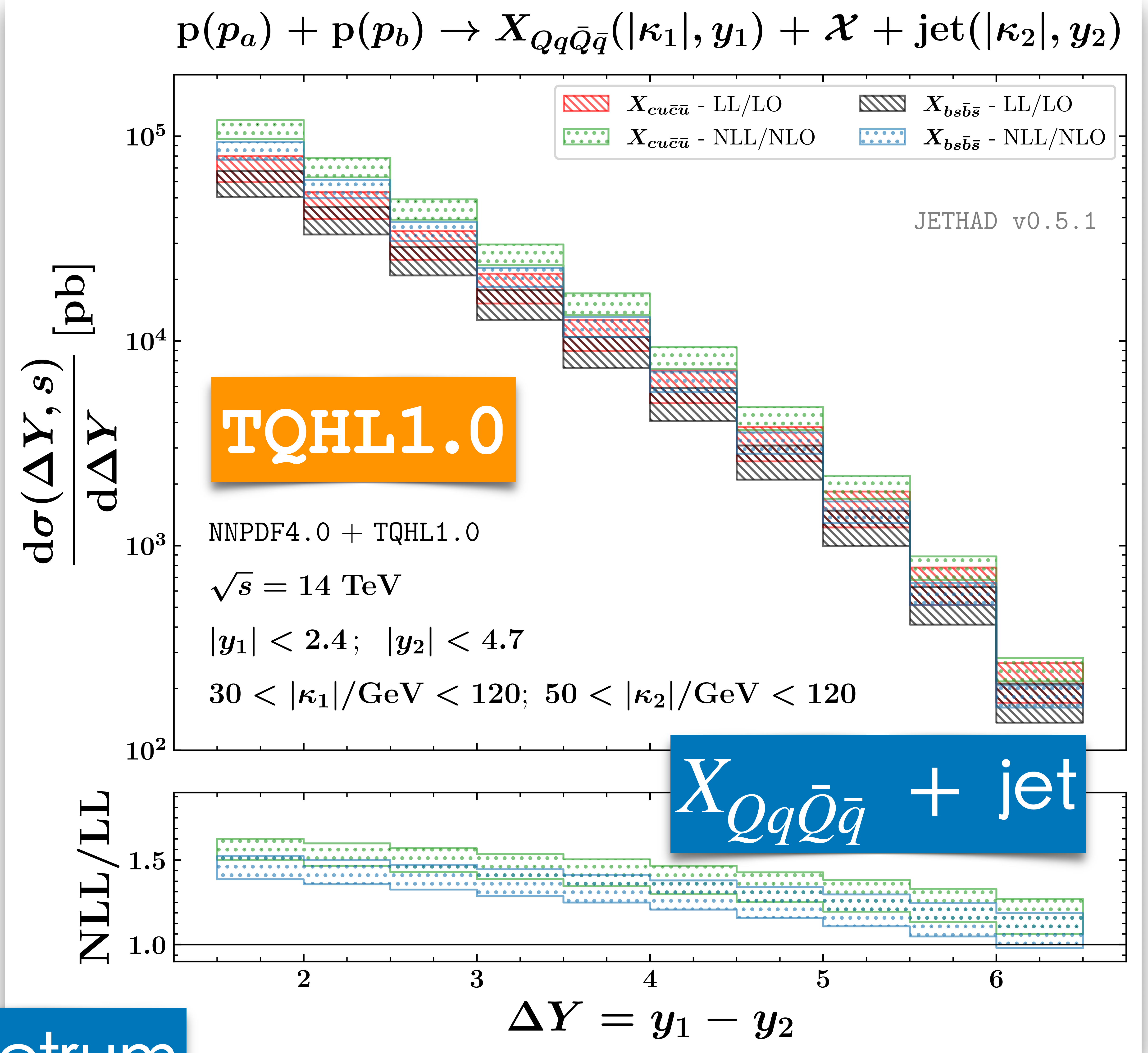


🔗 [F. G. C., A. Papa, to appear in PLB]

Backup

Heavy-light tetraquarks at the HL-LHC



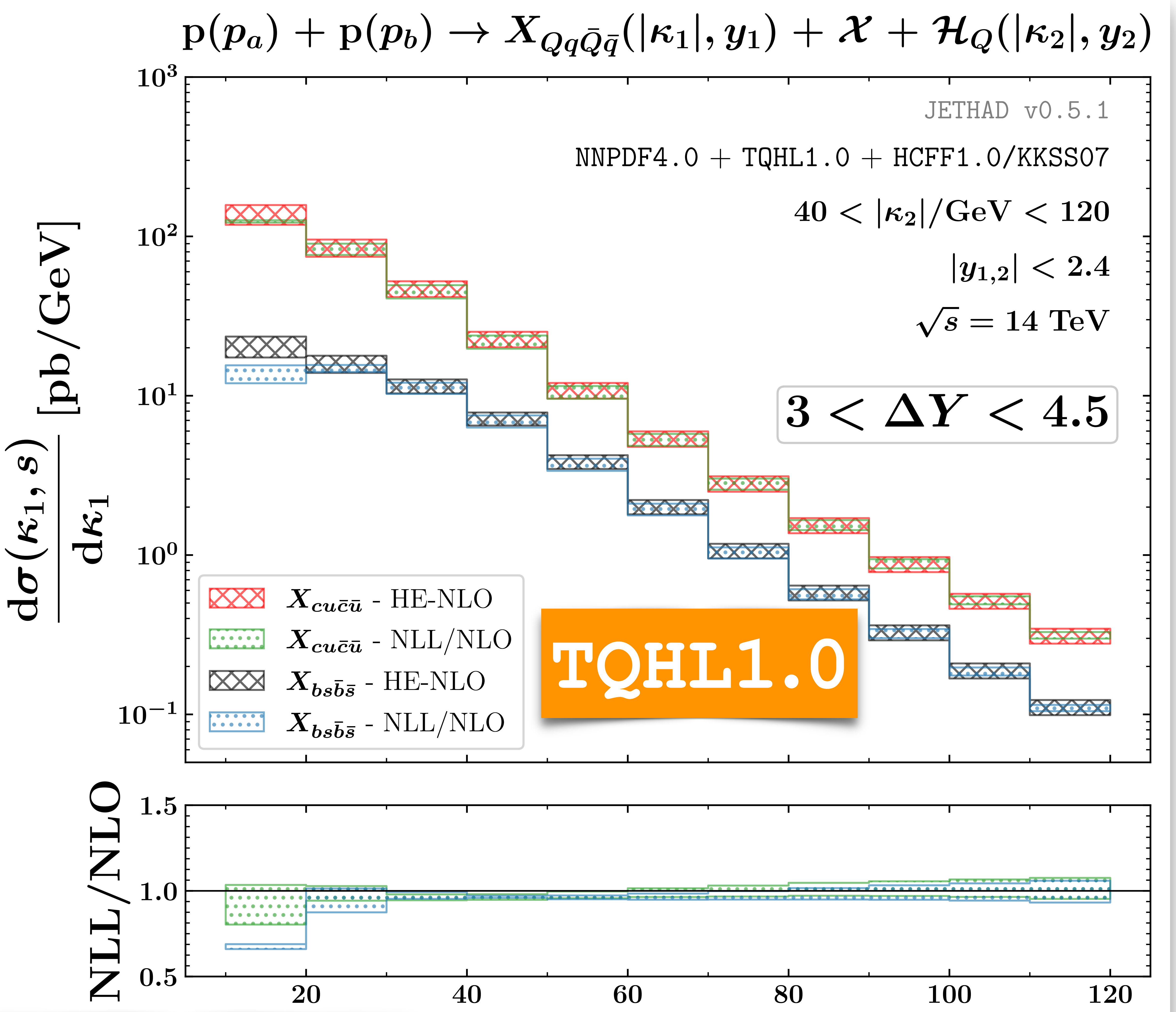


ΔY spectrum

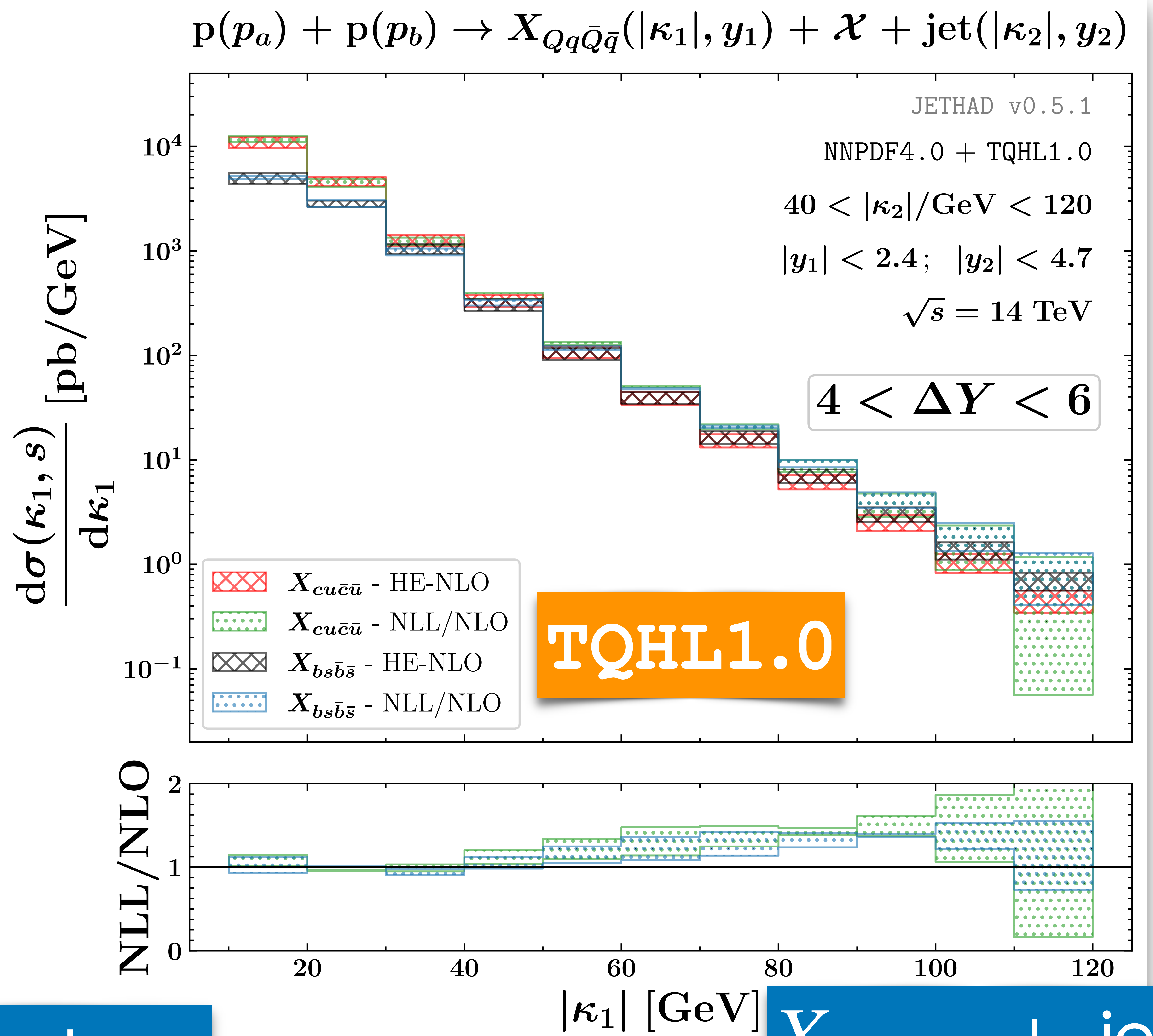
[F. G. C., A. Papa, to appear in PLB]

Backup

Heavy-light tetraquarks at the HL-LHC



$X_{Qq\bar{Q}\bar{q}} + \mathscr{H}_c$



$X_{Qq\bar{Q}\bar{q}}$ + jet

$|\kappa_1|$ spectrum

🔗 [F. G. C., A. Papa, to appear in PLB]

Backup

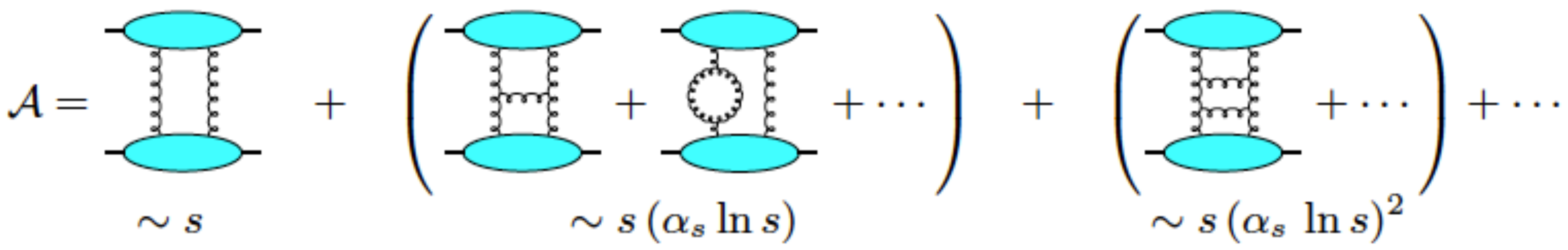
Basics of BFKL

The high-energy resummation

- **BFKL resummation**: [V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975, 1976, 1977); Y.Y. Balitskii, L.N. Lipatov (1978)]

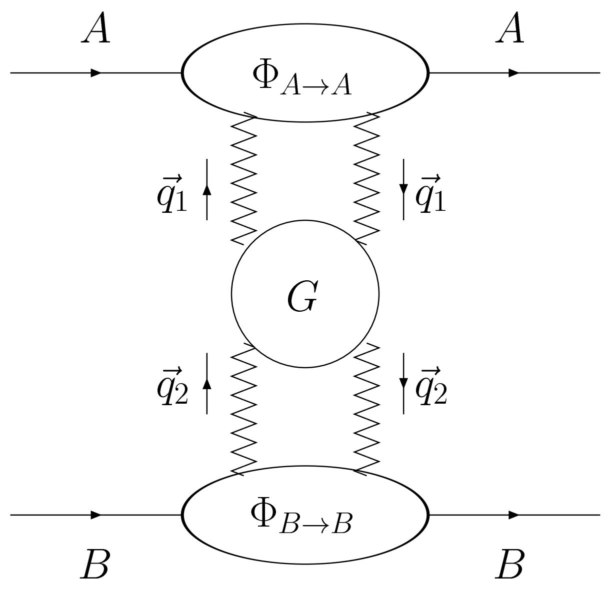
  $\xrightarrow{\text{based on}}$ **gluon Reggeization**

  leading logarithmic approximation (LL): $\alpha_s^n (\ln s)^n$



  next-to-leading logarithmic approximation (NLL): $\alpha_s^{n+1} (\ln s)^n$

Total cross section for $A + B \to X$: $\sigma_{AB}(s) = \frac{\mathcal{I}m_s\{\mathcal{A}_{AB}^{AB}\}}{s} \Leftarrow$ ***optical theorem***



- $\mathcal{I}m_s\,\{\mathcal{A}_{AB}^{AB}\}$ factorization:

  convolution of the **Green's function** of two interacting Reggeized gluons with the **impact factors** of the colliding particles

Green's function is **process-independent**, describes energy dependence and obeys BFKL equation; impact factors are known in the **NLL just for few processes**

Backup

The high-energy resummation

$$\mathrm{Im}_s\,(\mathcal{A}) = \frac{s}{(2\pi)^{D-2}} \int \frac{d^{D-2}q_1}{\vec{q}_1^{\,2}}\, \Phi_A(\vec{q}_1, s_0) \int \frac{d^{D-2}q_2}{\vec{q}_2^{\,2}}\, \Phi_B(-\vec{q}_2, s_0) \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{s_0}\right)^{\omega} G_\omega(\vec{q}_1, \vec{q}_2)$$

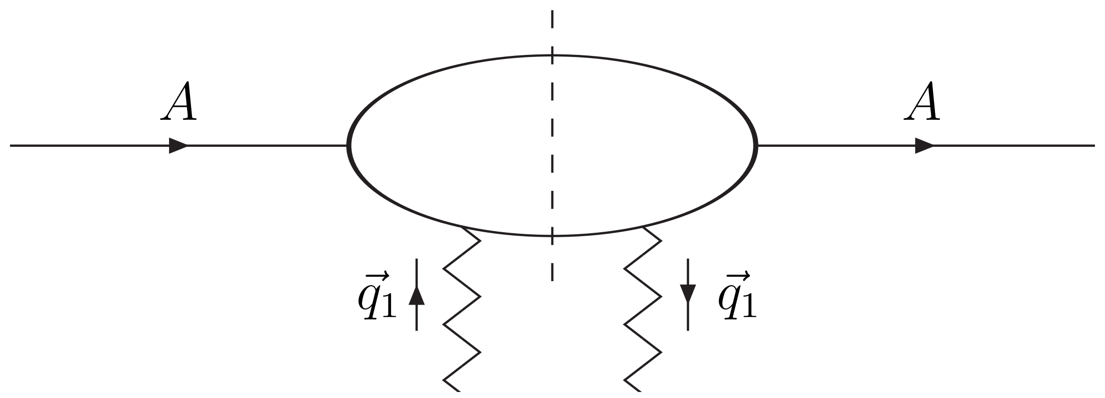
- **Green's function** is **process-independent** and takes care of the **energy dependence**

  $\longrightarrow$ determined through the **BFKL equation**

  [Ya.Ya. Balitskii, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]

- **Impact factors** are **process-dependent** and depend on the hard scale, but not on the energy

  $\longrightarrow$ known in the NLA just for few processes



- <u>Successful tests</u> of NLA BFKL in the **Mueller–Navelet** channel with the advent of the LHC; nevertheless, *new BFKL-sensitive observables* as well as *more exclusive final-state reactions* are needed (**di-hadron**, **hadron-jet**, **heavy-quark pair**, **multi-jet**, production processes,...)

(**MN jets**) [B. Ducloué, L. Szymanowski, S. Wallon (2014); F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2015, 2016)]
(**di-hadron**) [F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2016, 2017)]
(**four-jet**) [F. Caporale, F.G.C., G. Chachamis, A. Sabio Vera (2016)]
(**multi-jet**) F. Caporale, F.G.C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (2016, 2017, 2017)]
(**heavy-quark pair**) [F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2018); A.D. Bolognino, F.G.C., D.Yu. Ivanov, M. Fucilla, A. Papa (2018)]
(**hadron-jet**) [M.M.A. Mohammed, MD thesis (2018); A.D. Bolognino, F.G.C., D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2018)]

Backup

The high-energy resummation

$$\mathrm{Im}_s\left(\mathcal{A}\right) = \frac{s}{(2\pi)^{D-2}} \int \frac{d^{D-2}q_1}{\vec{q}_1^{\,2}} \Phi_A(\vec{q}_1, s_0) \int \frac{d^{D-2}q_2}{\vec{q}_2^{\,2}} \Phi_B(-\vec{q}_2, s_0) \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{s_0}\right)^{\omega} G_\omega(\vec{q}_1, \vec{q}_2)$$

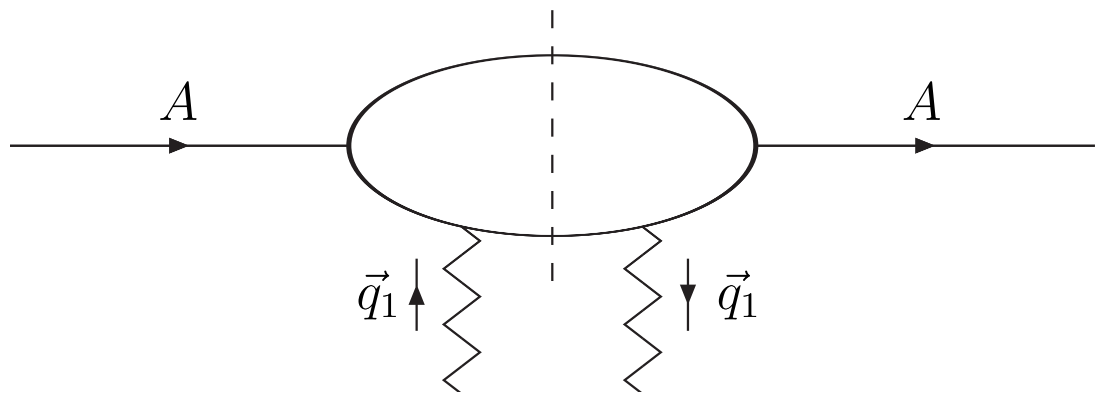
- **Green's function** is **process-independent** and takes care of the **energy dependence**

  $\longrightarrow$ determined through the **BFKL equation**

  [Ya.Ya. Balitskii, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]

- **Impact factors** are **process-dependent** and depend on the hard scale, but not on the energy

  $\longrightarrow$ known in the NLA just for few processes



- Successful tests of NLA BFKL in the **Mueller–Navelet** channel with the advent of the LHC; nevertheless, *new BFKL-sensitive observables* as well as *more exclusive final-state reactions* are needed (**di-hadron**, **hadron-jet**, **heavy-quark pair**, **multi-jet**, production processes,...)

(**MN jets**) [B. Ducloué, L. Szymanowski, S. Wallon (2014); F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2015, 2016)]
(**di-hadron**) [F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2016, 2017)]
(**four-jet**) [F. Caporale, F.G.C., G. Chachamis, A. Sabio Vera (2016)]
(**multi-jet**) F. Caporale, F.G.C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (2016, 2017, 2017)]
(**heavy-quark pair**) [F.G.C., D.Yu. Ivanov, B. Murdaca, A. Papa (2018); A.D. Bolognino, F.G.C., D.Yu. Ivanov, M. Fucilla, A. Papa (2018)]
(**hadron-jet**) [M.M.A. Mohammed, MD thesis (2018); A.D. Bolognino, F.G.C., D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2018)]

¡ NEW ! NLO HIGGS

(κ_T space) 🔗 [M. Hentschinski et al. (2021)]
(κ_T & Mellin) 🔗 [F.G.C. et al. (2022)]

Backup

Gluon Reggeization in perturbative QCD

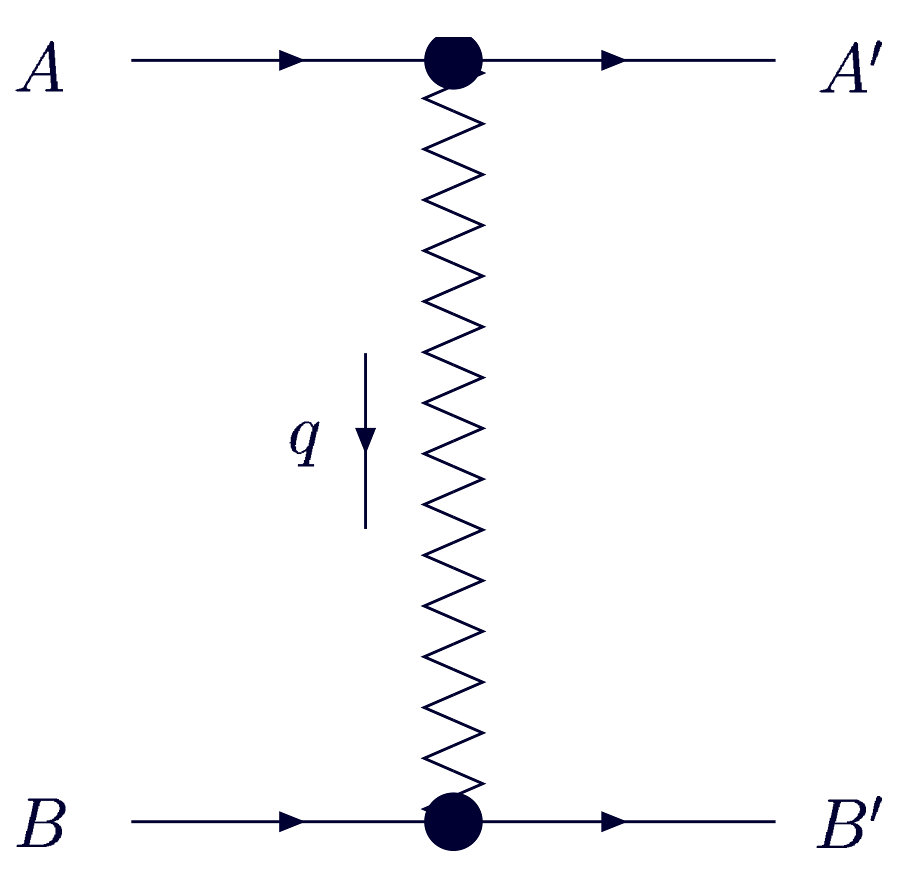
- Gluon quantum numbers in the t-channel: 8^- representation
- Regge limit: $s \simeq -u \to \infty$, t not growing with s

$\to$ amplitudes governed by **gluon Reggeization** $\to$ $D_{\mu\nu} = -i\frac{g_{\mu\nu}}{q^2}\left(\frac{s}{s_0}\right)^{\alpha_g(q^2)-1}$

$\xrightarrow{\text{feature}}$ all-order resummation: **LLA** $[\alpha_s^n(\ln s)^n]$ + **NLA** $[\alpha_s^{n+1}(\ln s)^n]$

$\xrightarrow{\text{consequence}}$ factorization of elastic and real part of inelastic amplitudes

$\xrightarrow{\text{example}}$ Elastic scattering process: $A + B \longrightarrow A' + B'$



$$(\mathcal{A}_8^-)_{AB}^{A'B'} = \Gamma^c_{A'A}\left[\left(\frac{-s}{-t}\right)^{j(t)} - \left(\frac{s}{-t}\right)^{j(t)}\right]\Gamma^c_{B'B}$$

$$j(t) = 1 + \omega(t)\,, \qquad j(0) = 1$$

$\omega(t)$ $\to$ Reggeized gluon trajectory

$\Gamma^c_{A'A} = g\langle A'|T^c|A\rangle\Gamma_{A'A}$ $\to$ PPR vertex

T^c $\to$ fundamental (q) or adjoint (g)

- QCD is the unique SM theory where all elementary particles reggeize
- Possible extensions: N=4 SYM, AdS/CFT,...

The high-energy resummation

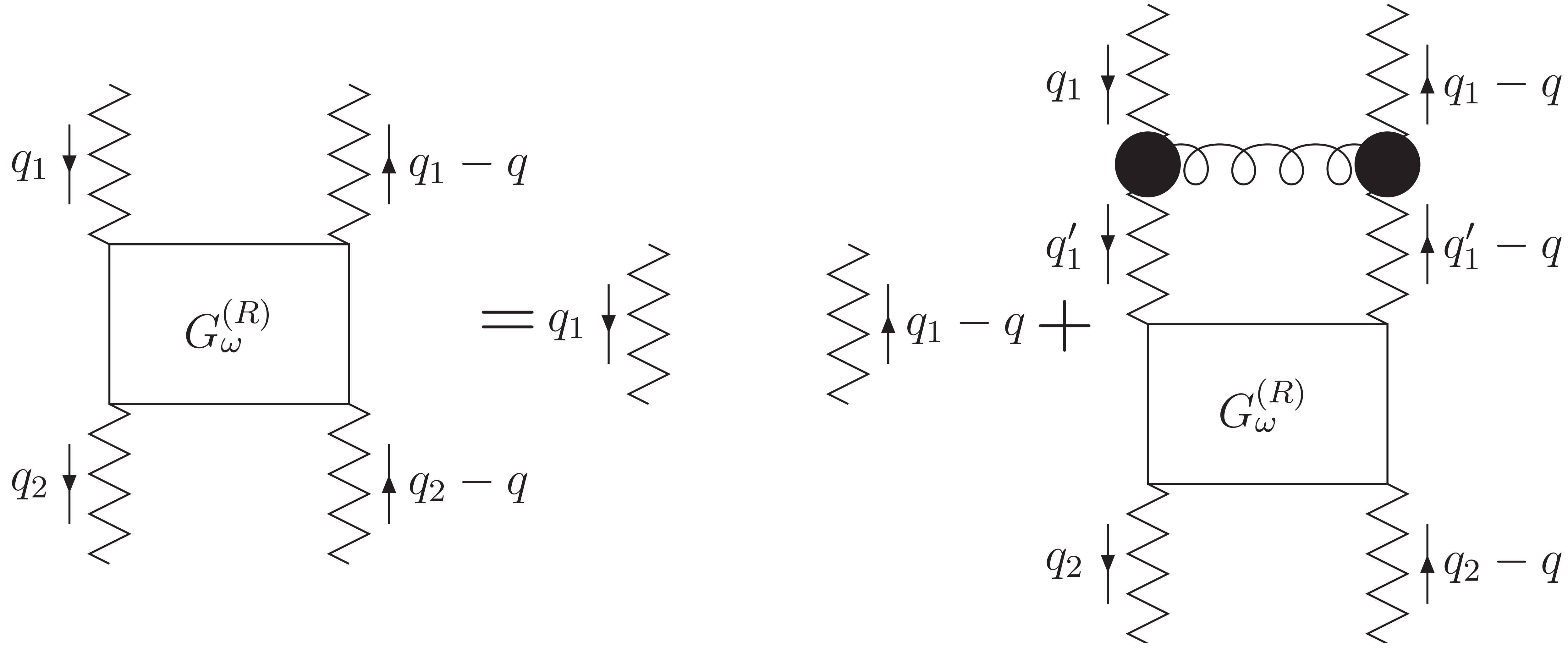
$$\mathcal{I}m_s\{\mathcal{A}\} = \frac{s}{(2\pi)^{D-2}} \int \frac{d^{D-2}q_1}{\vec{q}_1^{\,2}} \Phi_A(\vec{q}_1, s_0) \int \frac{d^{D-2}q_2}{\vec{q}_2^{\,2}} \Phi_B(-\vec{q}_2, s_0) \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{s_0}\right)^{\omega} G_\omega(\vec{q}_1, \vec{q}_2)$$

- **Green's function** is **process-independent** and takes care of the **energy dependence**

  $\longrightarrow$ determined through the **BFKL equation**

  [Ya.Ya. Balitskii, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]

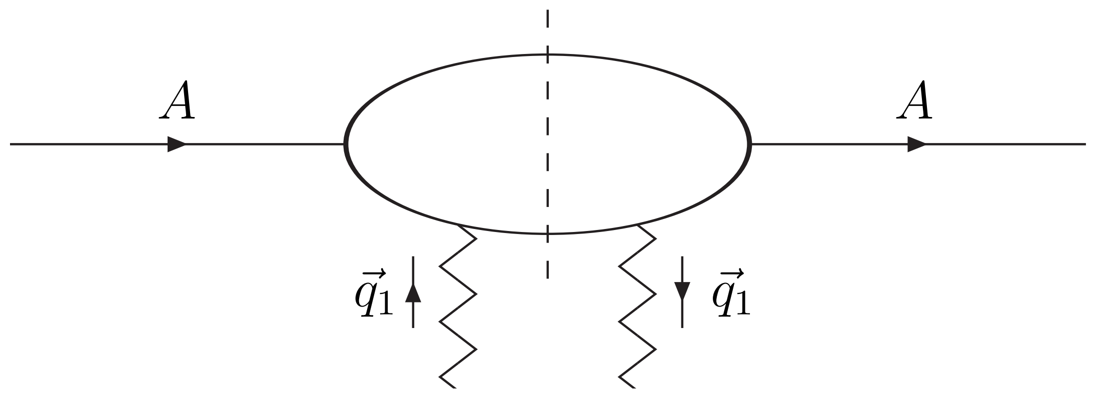
$$\omega\, G_\omega(\vec{q}_1, \vec{q}_2) = \delta^{D-2}(\vec{q}_1 - \vec{q}_2) + \int d^{D-2}q\, K(\vec{q}_1, \vec{q})\, G_\omega(\vec{q}, \vec{q}_1)\,.$$



Backup

The high-energy resummation

- **Impact factors** are **process-dependent** and depend on the hard scale, but not on the energy
  $\longrightarrow$ known in the NLA just for few processes



◇ **colliding partons**

[V.S. Fadin, R. Fiore, M.I. Kotsky, A. Papa (2000)]
[M. Ciafaloni, G. Rodrigo (2000)]

◇ $\gamma^* \longrightarrow V$, with $V = \rho^0,\ \omega,\ \phi$, forward case

[D.Yu. Ivanov, M.I. Kotsky, A. Papa (2004)]

◇ forward jet production

[J. Bartels, D. Colferai, G.P. Vacca (2003)]
(exact IF) [F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa, A. Perri (2012)]
(small-cone IF) [D.Yu. Ivanov, A. Papa (2012)]
(several jet algorithms discussed) [D. Colferai, A. Niccoli (2015)]

◇ forward identified hadron production

[D.Yu. Ivanov, A. Papa (2012)]

◇ $\gamma^* \longrightarrow \gamma^*$

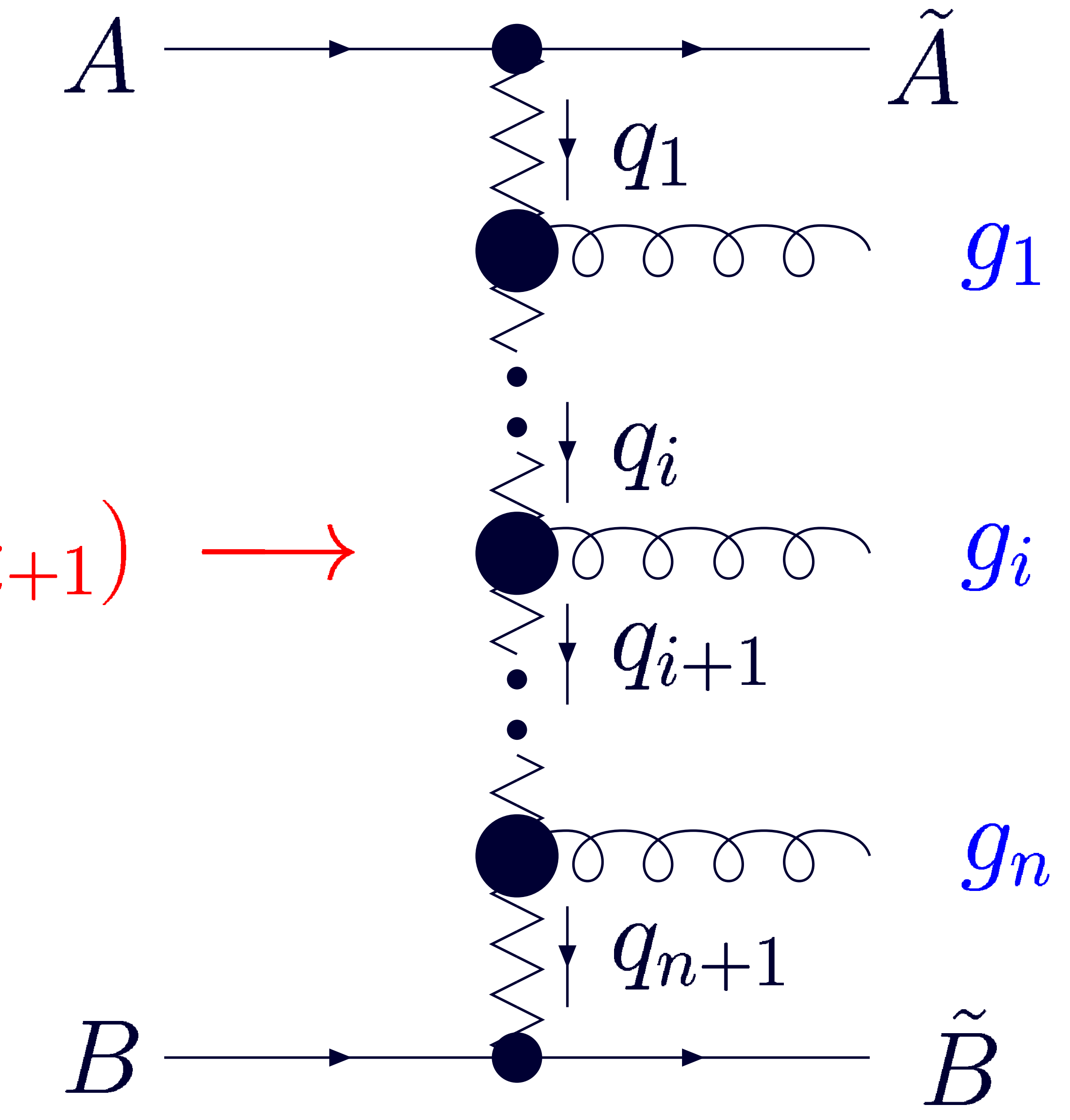
[J. Bartels *et al.* (2001), I. Balitsky, G.A. Chirilli (2011, 2013)]

Backup

The high-energy resummation

BFKL in the LLA (I)

Inelastic scattering process $A + B \;\rightarrow\; \tilde{A} + \tilde{B} + n$ in the LLA



$\gamma^{G_i}_{c_i c_{i+1}}(q_i, q_{i+1}) \longrightarrow$

multi-Regge kinematics

$$\mathrm{Re}\mathcal{A}^{\tilde{A}\tilde{B}+n}_{AB} = 2s\,\Gamma^{c_1}_{\tilde{A}A} \left(\prod_{i=1}^{n} \gamma^{P_i}_{c_i c_{i+1}}(q_i, q_{i+1}) \left(\frac{s_i}{s_R} \right)^{\omega(t_i)} \frac{1}{t_i} \right) \frac{1}{t_{n+1}} \left(\frac{s_{n+1}}{s_R} \right)^{\omega(t_{n+1})} \Gamma^{c_{n+1}}_{\tilde{B}B}$$

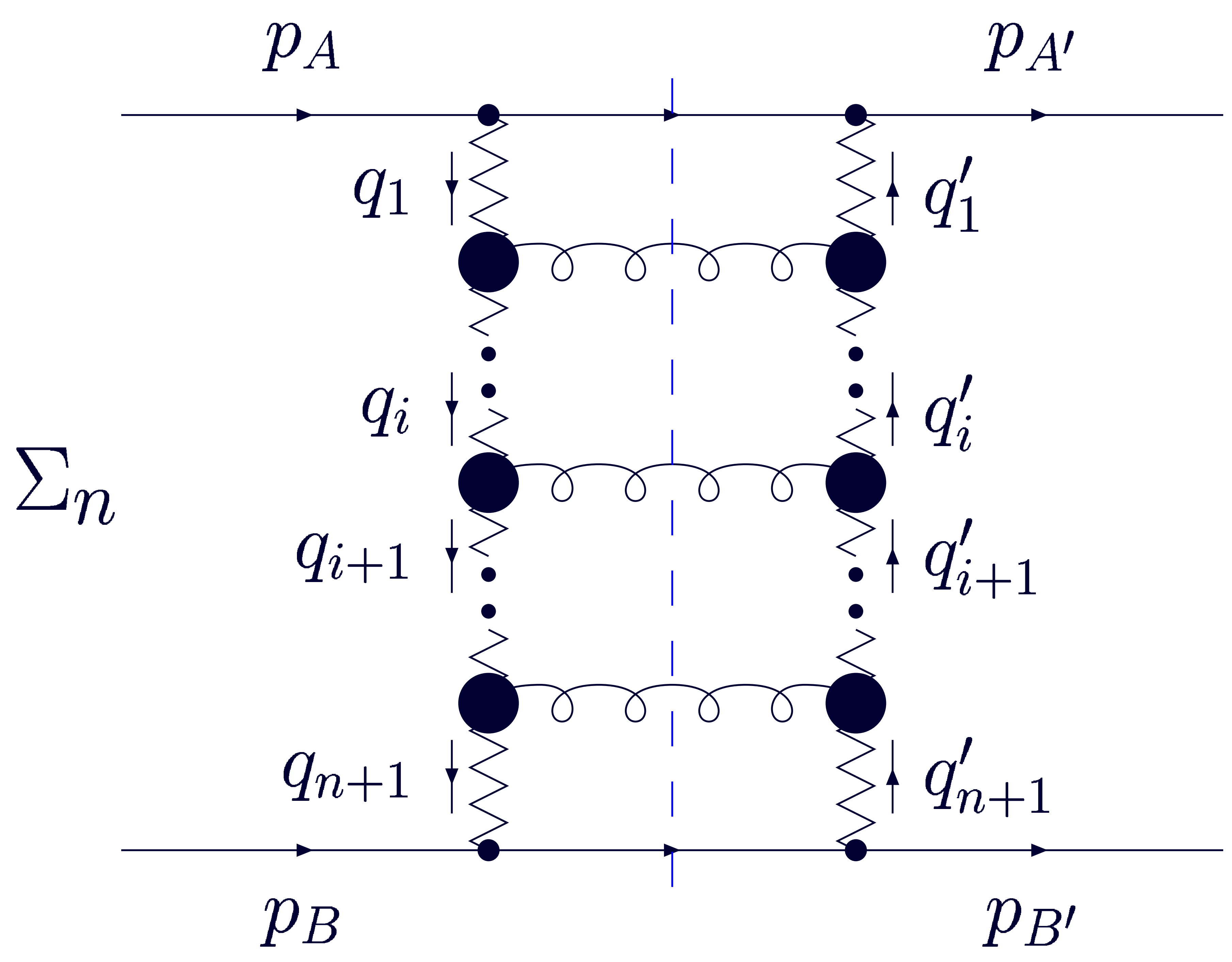
$\gamma^{P_i}_{c_i c_{i+1}}(q_i, q_{i+1}) \;\rightarrow\;$ RRG vertex

$s_R \;\rightarrow\;$ energy scale, irrelevant in the LLA

Backup

BFKL in the LLA (II)

Elastic amplitude $A + B \longrightarrow A' + B'$ in the LLA via s-channel unitarity



$$\mathcal{A}_{AB}^{A'B'} = \sum_{\mathcal{R}} (\mathcal{A}_{\mathcal{R}})_{AB}^{A'B'} \,, \qquad \mathcal{R} = 1 \text{ (singlet)}, \, 8^- \text{ (octet)}, \ldots$$

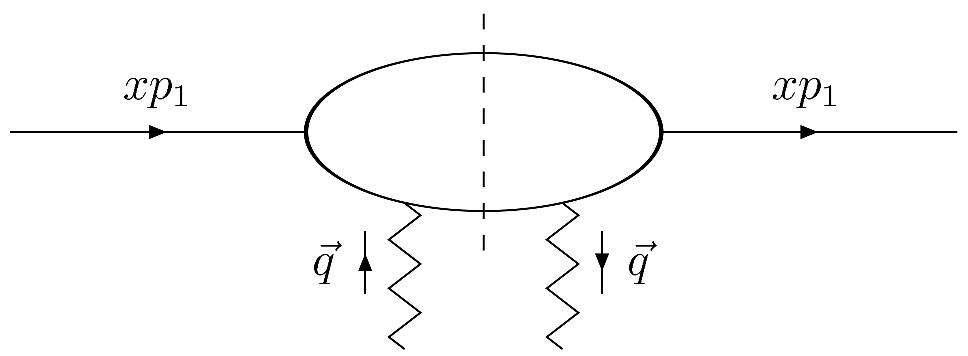
The 8^- color representation is important for the bootstrap, i.e. the consistency between the above amplitude and that with one Reggeized gluon exchange

Backup

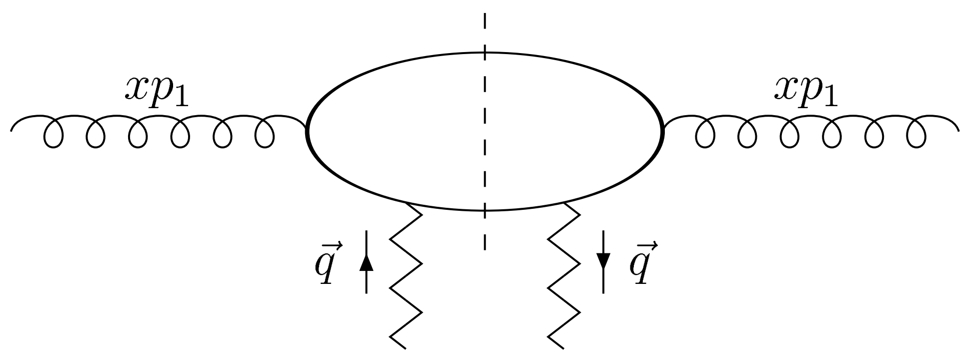
Hybrid factorization at work

Forward-jet impact factor

- take the impact factors for **colliding partons**
  [V.S. Fadin, R. Fiore, M.I. Kotsky, A. Papa (2000)]
  [M. Ciafaloni and G. Rodrigo (2000)]

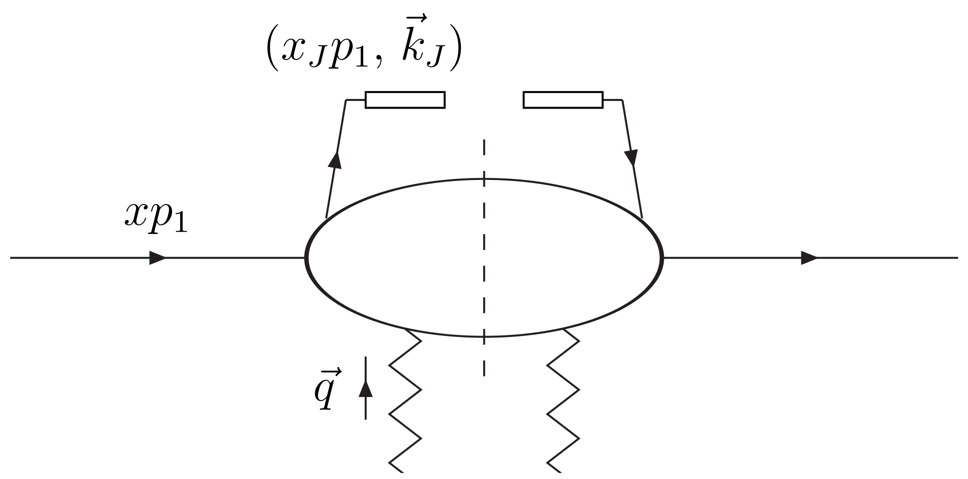


quark vertex

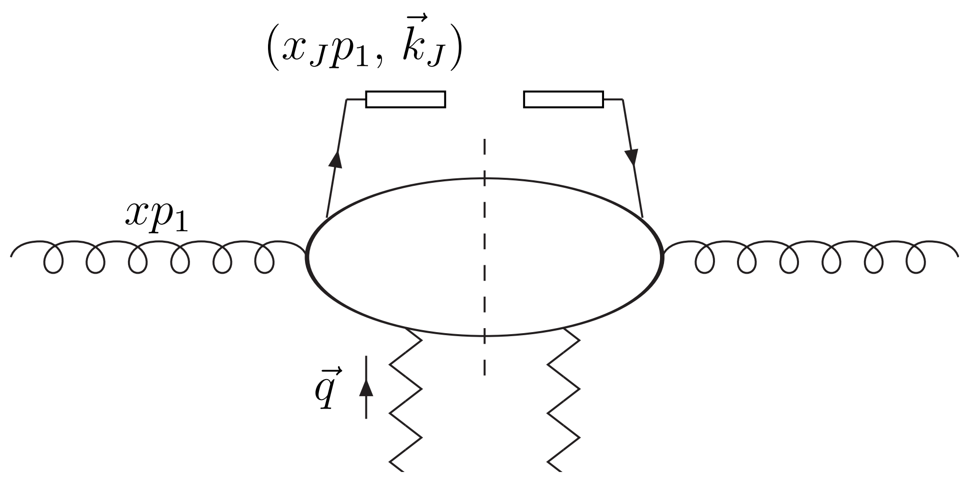


gluon vertex

- "open" one of the integrations over the phase space of the intermediate state to allow one parton to generate the jet



quark jet vertex

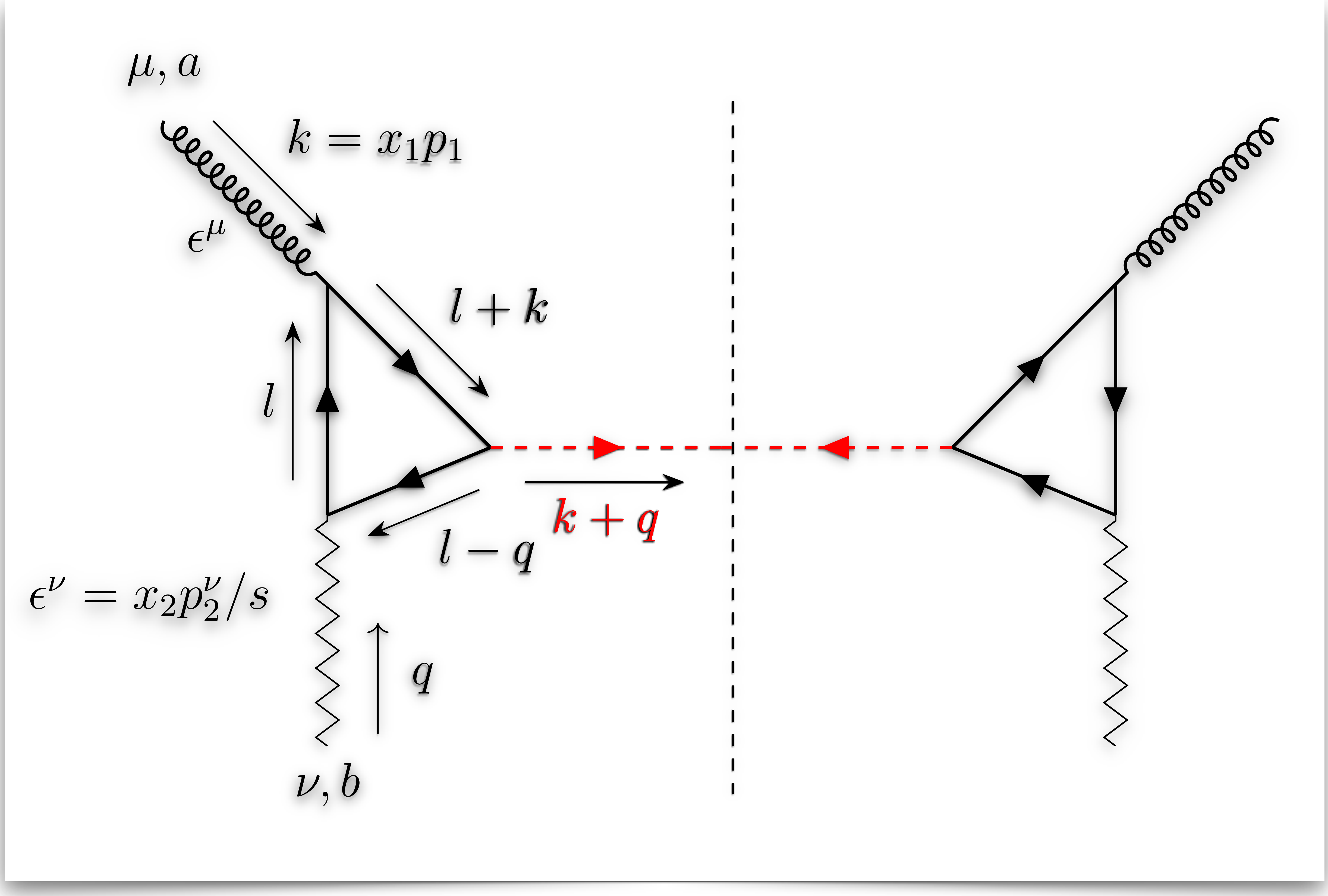


gluon jet vertex

- use QCD collinear factoriz.: $\sum_{s=q,\bar{q}} f_s \otimes$ [quark vertex] $+ f_g \otimes$ [gluon vertex]

Backup

Forward-Higgs LO impact factor



$$\frac{d\Phi_J^{(0)}(\nu, n)}{dx_J d^2\vec{p}_J} = 2\alpha_s \sqrt{\frac{C_F}{C_A}} (\vec{p}_J^{\,2})^{i\nu - 3/2} \left(\frac{C_A}{C_F} f_g(x_J) + \sum_{a=q\bar{q}} f_a(x_J) \right) e^{in\phi_J}$$

Backup

Forward-Higgs NLO-RG impact factor

$$\tilde{c}_H^{(1)}(n,\nu,|\vec{p}_H|,x_H) = c_H(n,\nu,|\vec{p}_H|,x_H)\left\{\frac{\beta_0}{4N_c}\left(2\ln\frac{\mu_{R_1}}{|\vec{p}_H|}+\frac{5}{3}\right)+\frac{\chi\left(n,\nu\right)}{2}\ln\left(\frac{s_0}{M_{H,\perp}^2}\right)\right.$$

$$+\frac{\beta_0}{4N_c}\left(2\ln\frac{\mu_{R_1}}{M_{H,\perp}}\right)$$

$$\left.-\frac{1}{2N_c f_g(x_H,\mu_{F_1})}\ln\frac{\mu_{F_1}^2}{M_{H,\perp}^2}\int_{x_H}^1\frac{dz}{z}\left[P_{gg}(z)f_g\left(\frac{x_H}{z},\mu_{F_1}\right)+\sum_{a=q,\bar{q}}P_{ga}(z)f_a\left(\frac{x_H}{z},\mu_{F_1}\right)\right]\right\}$$

Backup

Forward-jet NLO-RG impact factor

$$\tilde{c}_J^{(1)}(n,\nu,|\vec{p}_J|,x_J) = c_J(n,\nu,|\vec{p}_J|,x_J)\left\{\frac{\beta_0}{4N_c}\left(2\ln\frac{\mu_{R_2}}{|\vec{p}_J|}+\frac{5}{3}\right)+\frac{\chi(n,\nu)}{2}\ln\left(\frac{s_0}{|\vec{p}_J|^2}\right)\right.$$

$$-\frac{1}{2N_c\left(\frac{C_A}{C_F}f_g(x_J,\mu_{F_2})+\sum_{a=q,\bar{q}}f_a(x_J,\mu_{F_2})\right)}\ln\frac{\mu_{F_2}^2}{|\vec{p}_J|^2}$$

$$\times\left(\frac{C_A}{C_F}\int_{x_J}^1\frac{dz}{z}\left[P_{gg}(z)f_g\left(\frac{x_J}{z},\mu_{F_2}\right)+\sum_{a=q,\bar{q}}P_{ga}(z)f_a\left(\frac{x_J}{z},\mu_{F_2}\right)\right]\right.$$

$$\left.\left.+\sum_{a=q,\bar{q}}\int_{x_J}^1\frac{dz}{z}\left[P_{ag}(z)f_g\left(\frac{x_J}{z},\mu_{F_2}\right)+P_{aa}(z)f_a\left(\frac{x_J}{z},\mu_{F_2}\right)\right]\right)\right\}\,.$$

Backup

Inclusive Higgs + jet: NLL/NLO* azimuthal coefficients

$$\mathcal{C}_n = \frac{e^{\Delta Y}}{s} \frac{M_{H,\perp}}{|\vec{p}_H|}$$

$$\times \int_{-\infty}^{+\infty} d\nu \left(\frac{x_J x_H s}{s_0}\right)^{\bar{\alpha}_s(\mu_{R_c})\left\{\chi(n,\nu)+\bar{\alpha}_s(\mu_{R_c})\left[\bar{\chi}(n,\nu)+\frac{\beta_0}{8N_c}\chi(n,\nu)\left[-\chi(n,\nu)+\frac{10}{3}+4\ln\left(\frac{\mu_{R_c}}{\sqrt{\vec{p}_H\vec{p}_J}}\right)\right]\right]\right\}}$$

$$\times \left\{\alpha_s^2(\mu_{R_1}) c_H(n,\nu,|\vec{p}_H|,x_H)\right\} \left\{\alpha_s(\mu_{R_2})[c_J(n,\nu,|\vec{p}_J|,x_J)]^*\right\}$$

$$\times \left\{1 + \bar{\alpha}_s(\mu_{R_1}) \frac{\tilde{c}_H^{(1)}(n,\nu,|\vec{p}_H|,x_H)}{c_H(n,\nu,|\vec{p}_H|,x_H)} + \bar{\alpha}_s(\mu_{R_2}) \left[\frac{\tilde{c}_J^{(1)}(n,\nu,|\vec{p}_J|,x_J)}{c_J(n,\nu,|\vec{p}_J|,x_J)}\right]^*\right\} .$$

Backup