EIC, HL-LHC, forward physics

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AdT

Comunidad de Madrid

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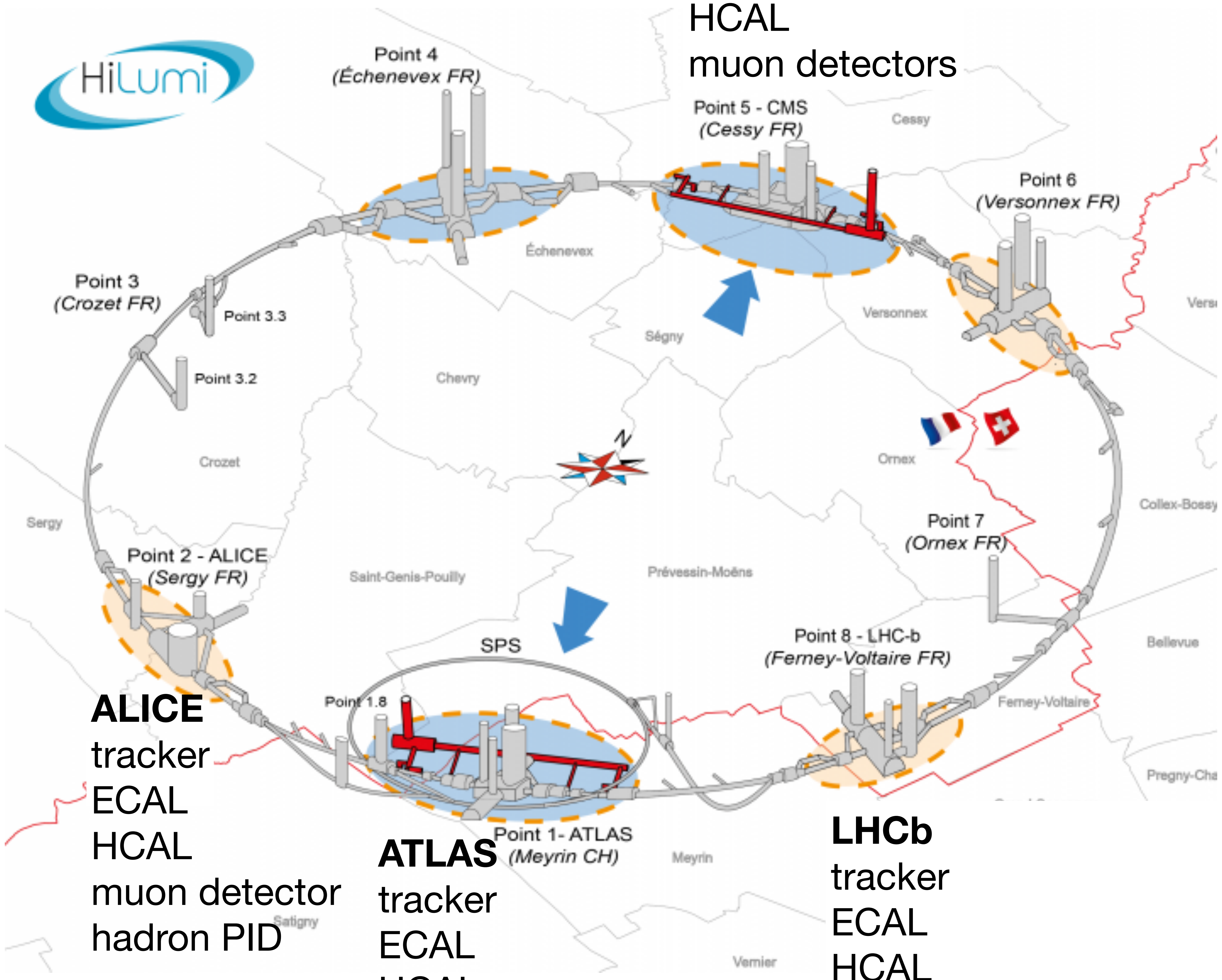
The high-lumi LHC

CMS
tracker
ECAL
HCAL
muon detectors



ALICE
tracker
ECAL
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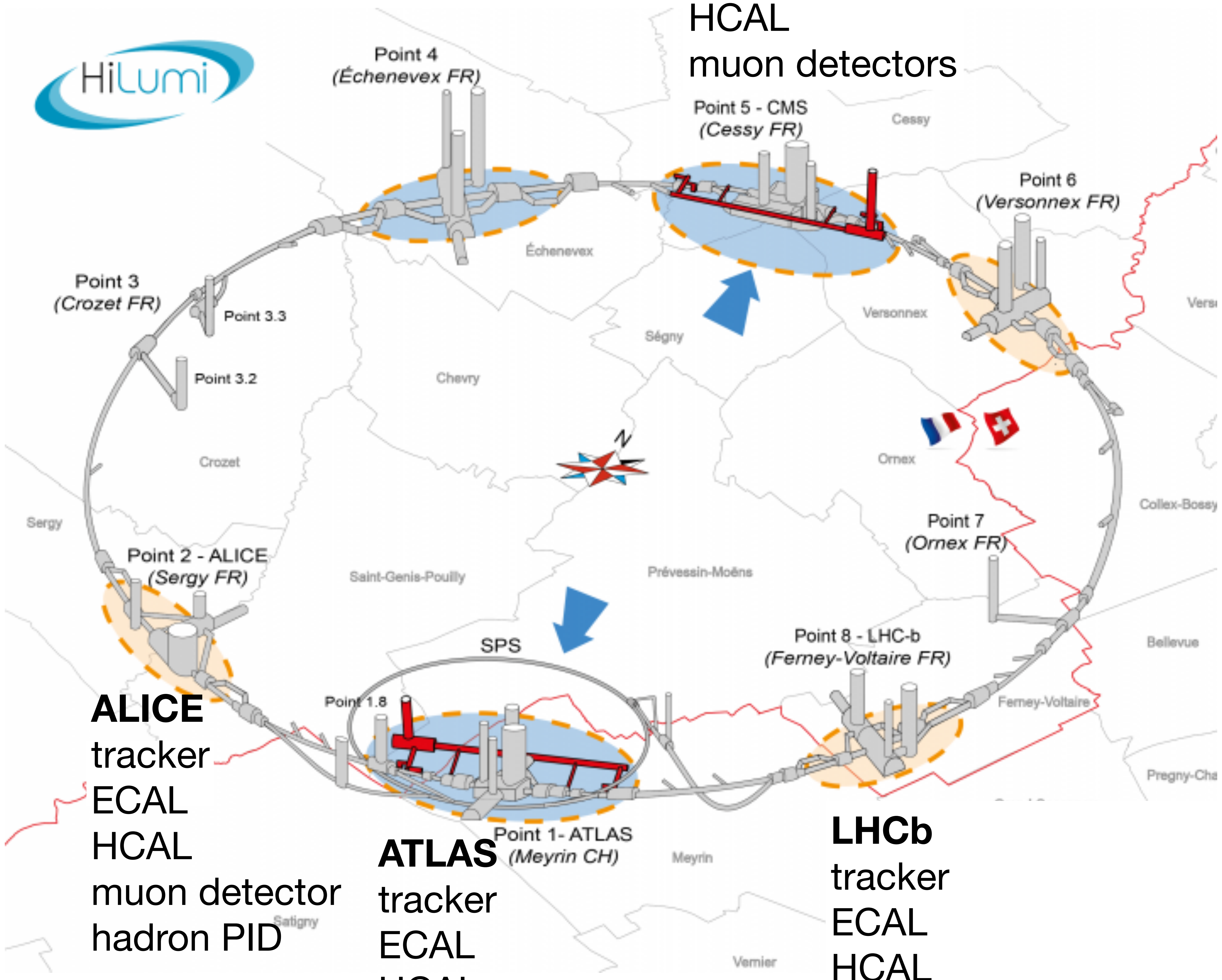
muon detector
hadron PID

ATLAS
tracker
ECAL
HCAL
muon detector

LHCb
tracker
ECAL
HCAL
muon detector
hadron PID

The high-lumi LHC

A. Dainese et al., CERN Yellow Reports: Vol. 7 (2019)



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pp collisions

$\sqrt{s} = 14$ TeV

ATLAS/CMS $\mathscr{L} : 5 \cdot 10^{34}$ cm^{-2} s^{-1} $\rightarrow \mathscr{L}_{\text{int}} : 3000$ fb^{-1}

LHCb $\mathscr{L} : 2 \cdot 10^{33}/2 \cdot 10^{34}$ cm^{-2} s^{-1} $\rightarrow \mathscr{L}_{\text{int}} : 300$ fb^{-1}

PbPb collisions

$\sqrt{s_{NN}} = 5.5$ TeV

ALICE/ATLAS/CMS RUN4: $\mathscr{L}_{\text{int}} : 6.8$ nb^{-1}

LHCb RUN4: $\mathscr{L}_{\text{int}} : 1.0$ nb^{-1}

pPb collisions

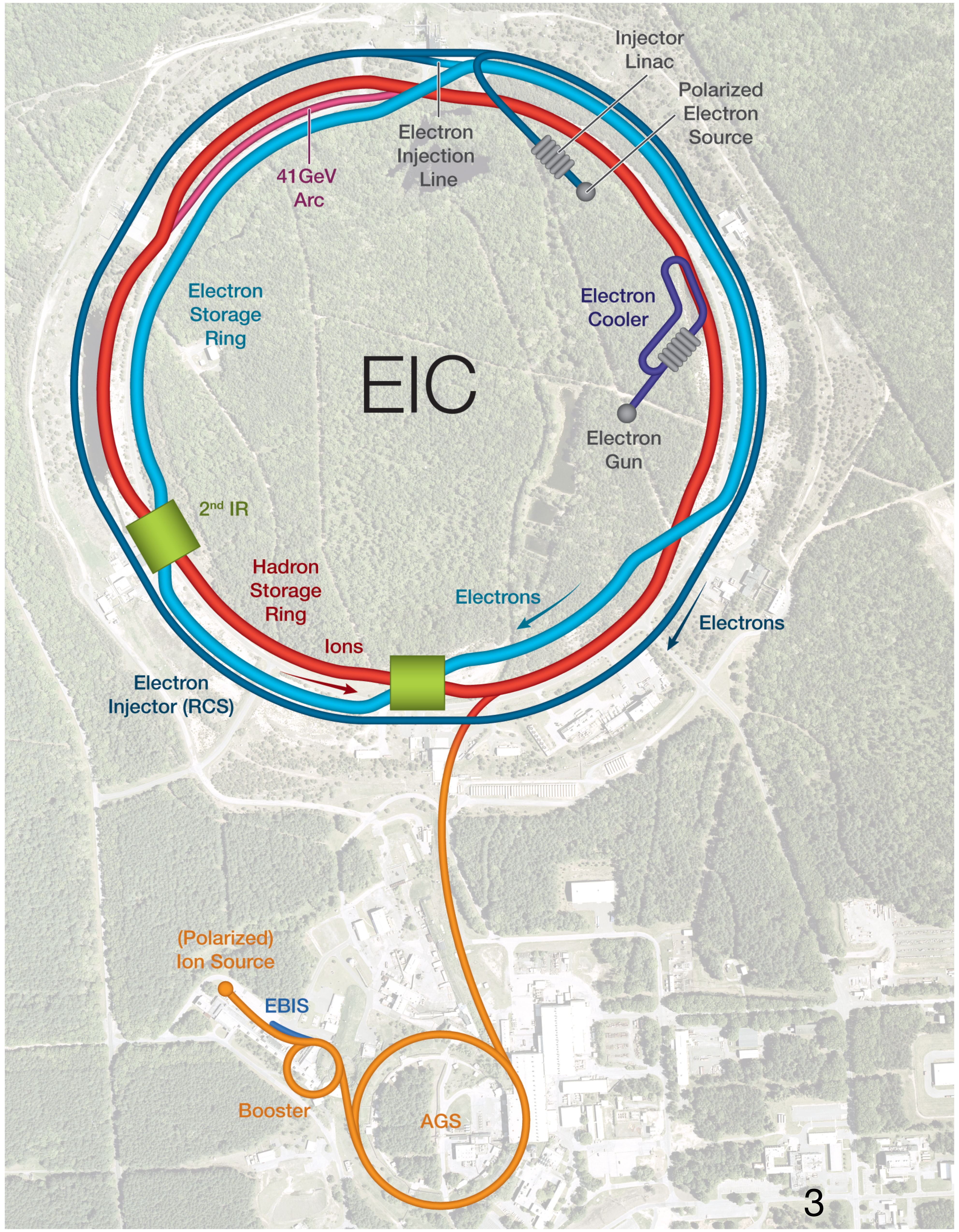
$\sqrt{s_{NN}} = 8.8$ TeV

ATLAS/CMS RUN4: $\mathscr{L}_{\text{int}} : 0.6$ pb^{-1}

ALICE/LHCb RUN4: $\mathscr{L}_{\text{int}} : 0.3$ pb^{-1}

Also pO and OO runs and possibly other intermediate-mass nuclei such as Ar-Ar

The electron-ion collider



- Based on RHIC:
  - use existing hadron storage ring
    energy: 41–275 GeV
  - add electron storage ring in RHIC tunnel
    energy: 5–18 GeV

$\rightarrow \sqrt{s} = 29 - 141$ GeV

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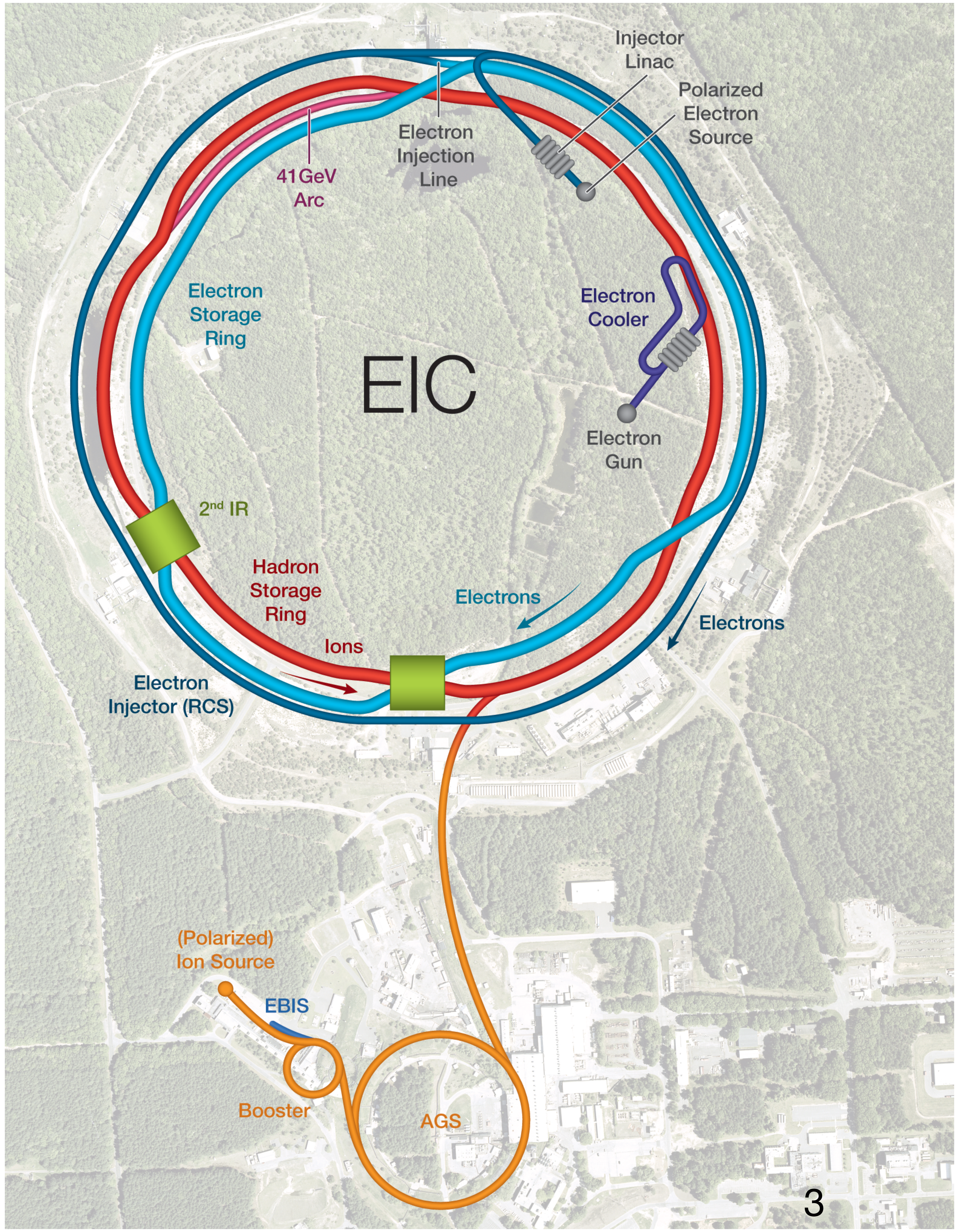

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  ~ 70% polarisation

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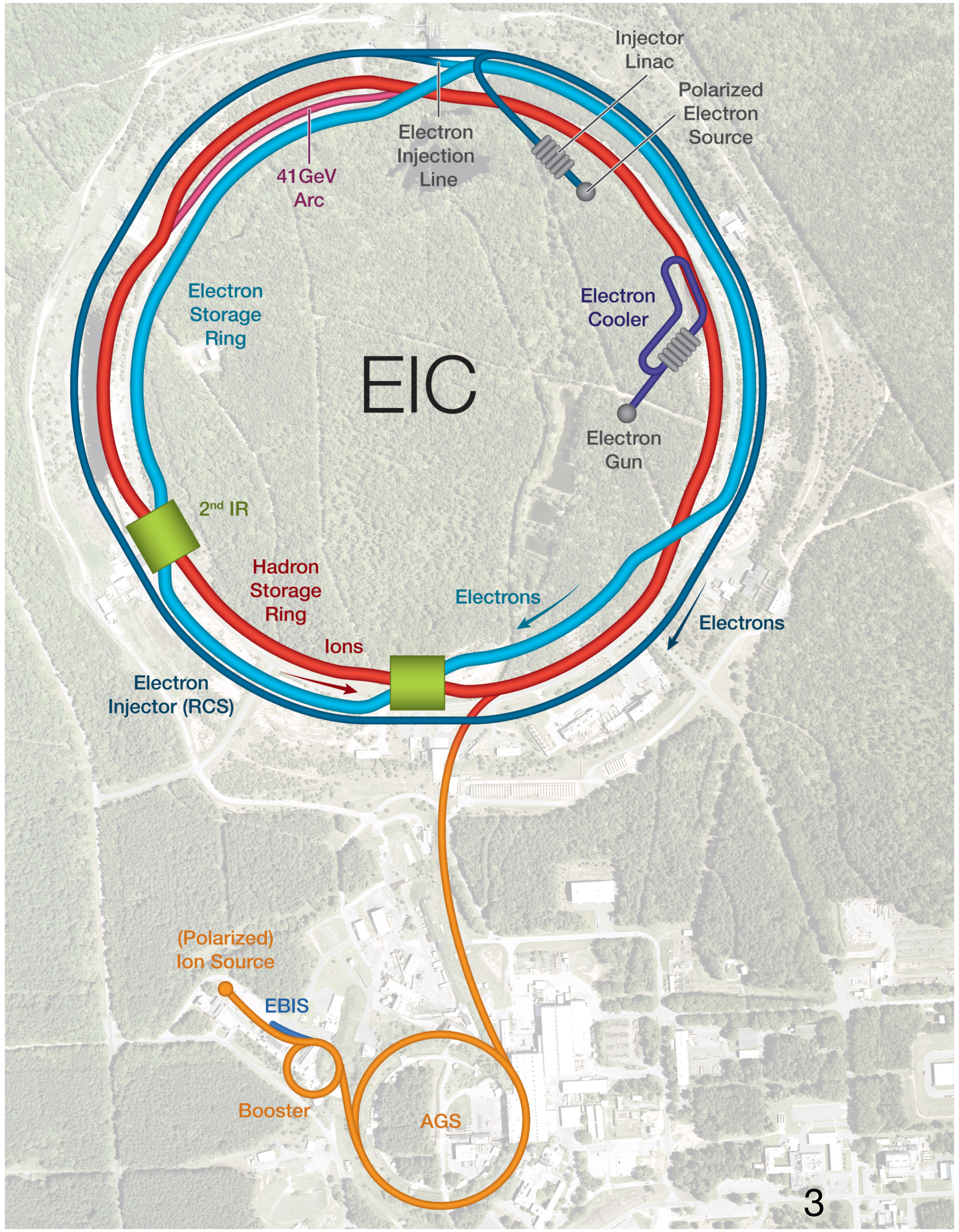

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  $\leftrightarrow \mathscr{L}_{\text{int}} = 10 - 100$ fb^{-1}/year

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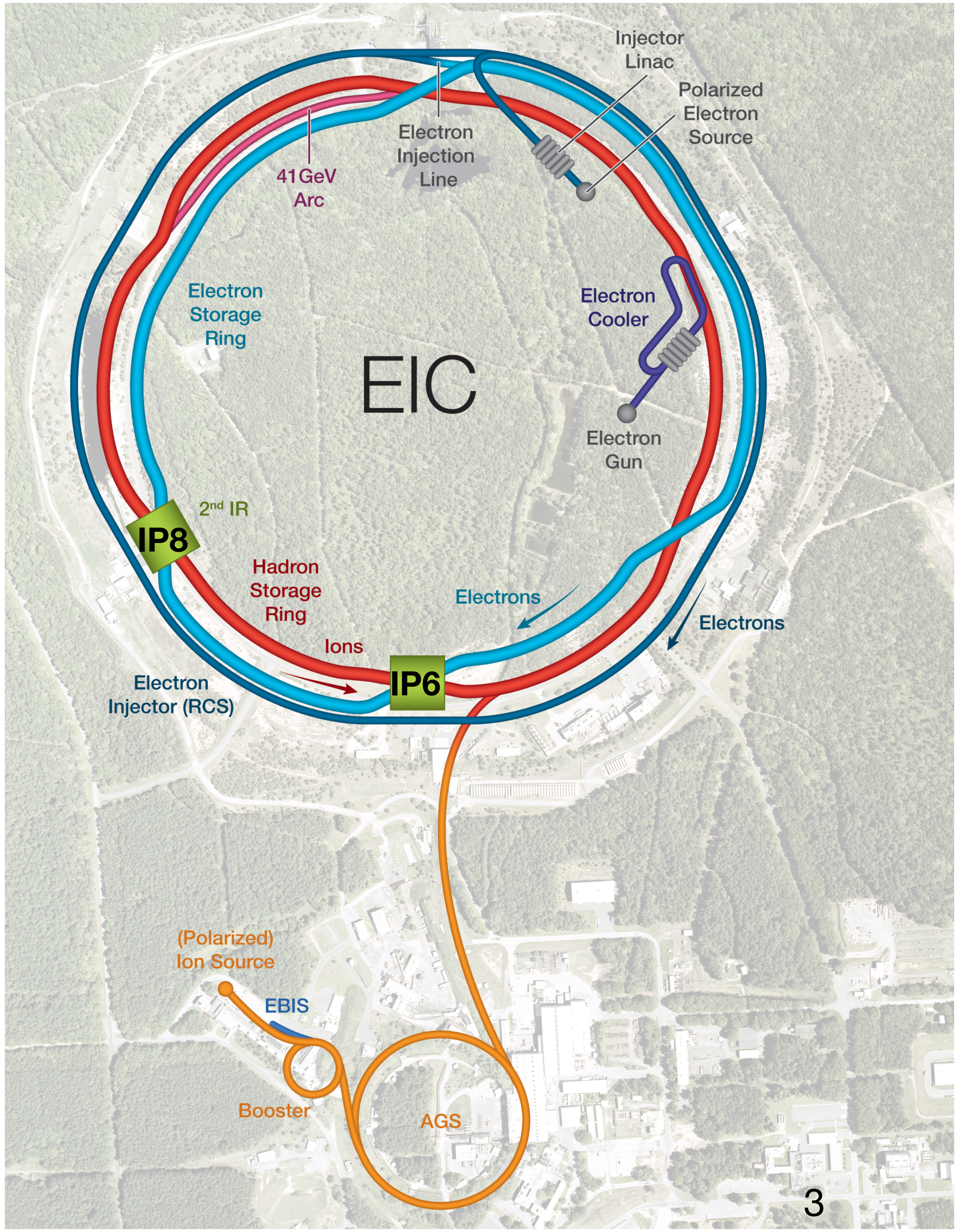

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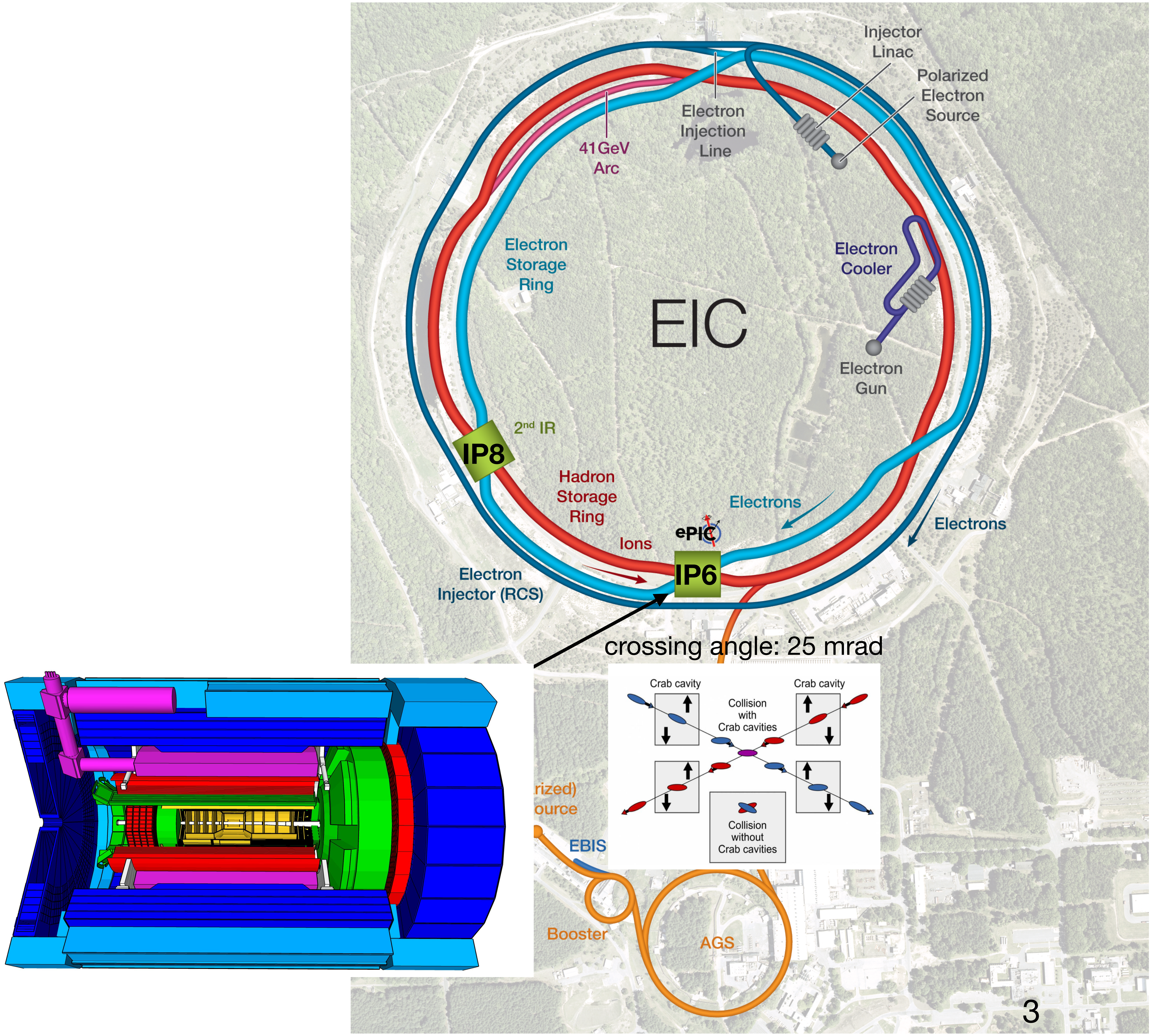

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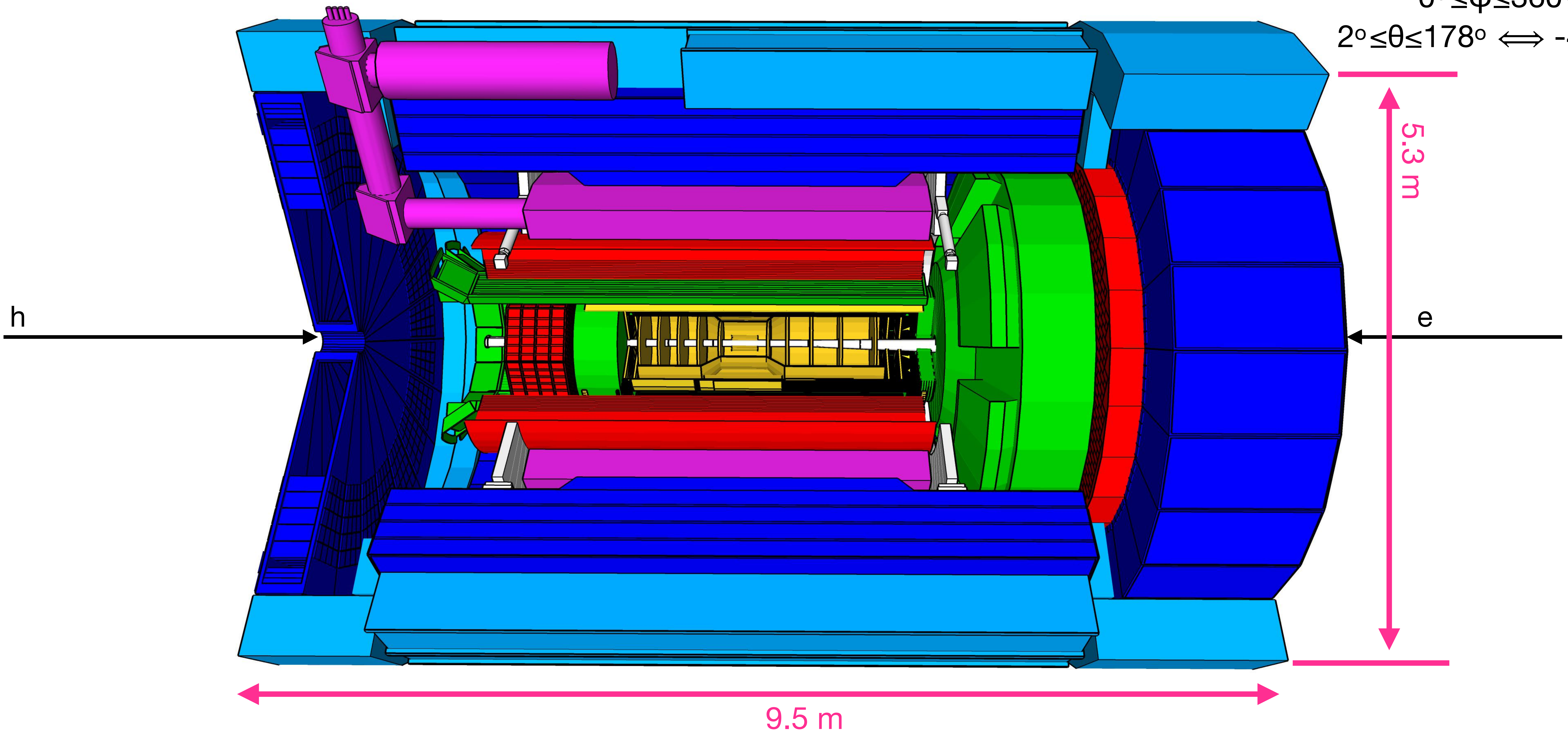
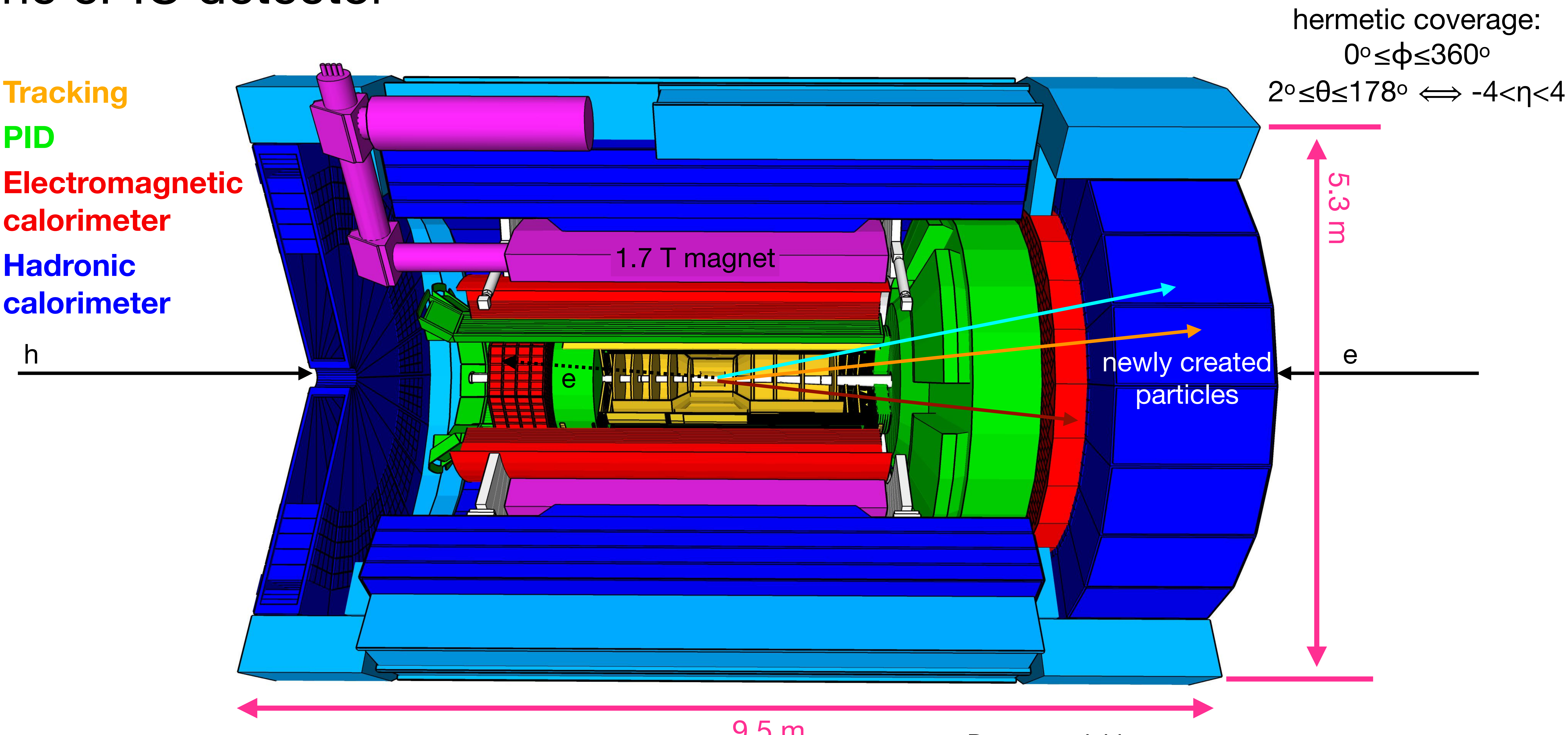
The ePIC detector

hermetic coverage:
0°≤ϕ≤360°
2°≤θ≤178° ⟺ -4<η<4



The ePIC detector

- Tracking
- PID
- Electromagnetic calorimeter
- Hadronic calorimeter



Data acquisition:
no trigger; all collision data is digitised
with strong zero-suppression at front-end electronics

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0°≤ϕ≤360°
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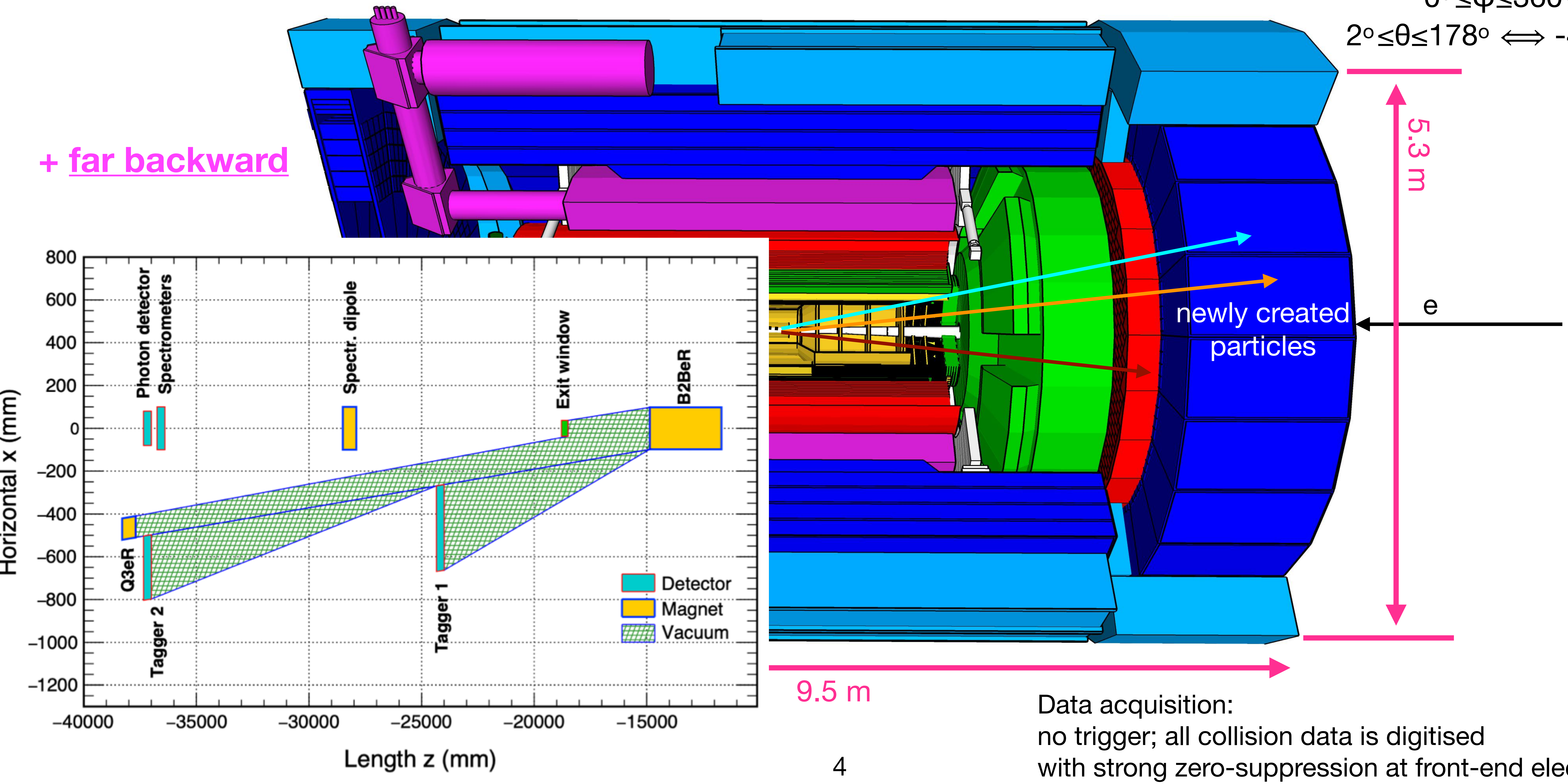
+ far backward



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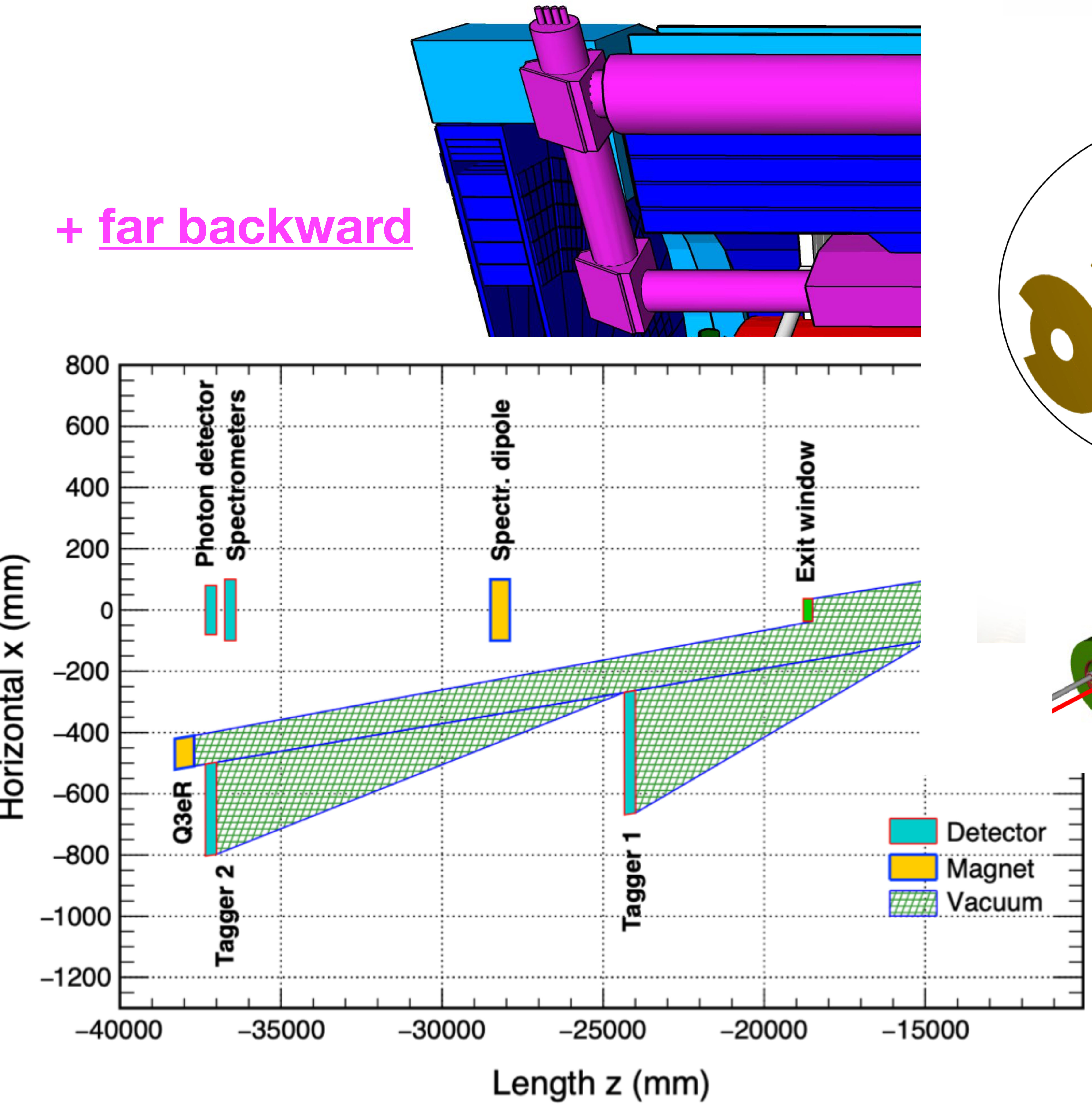
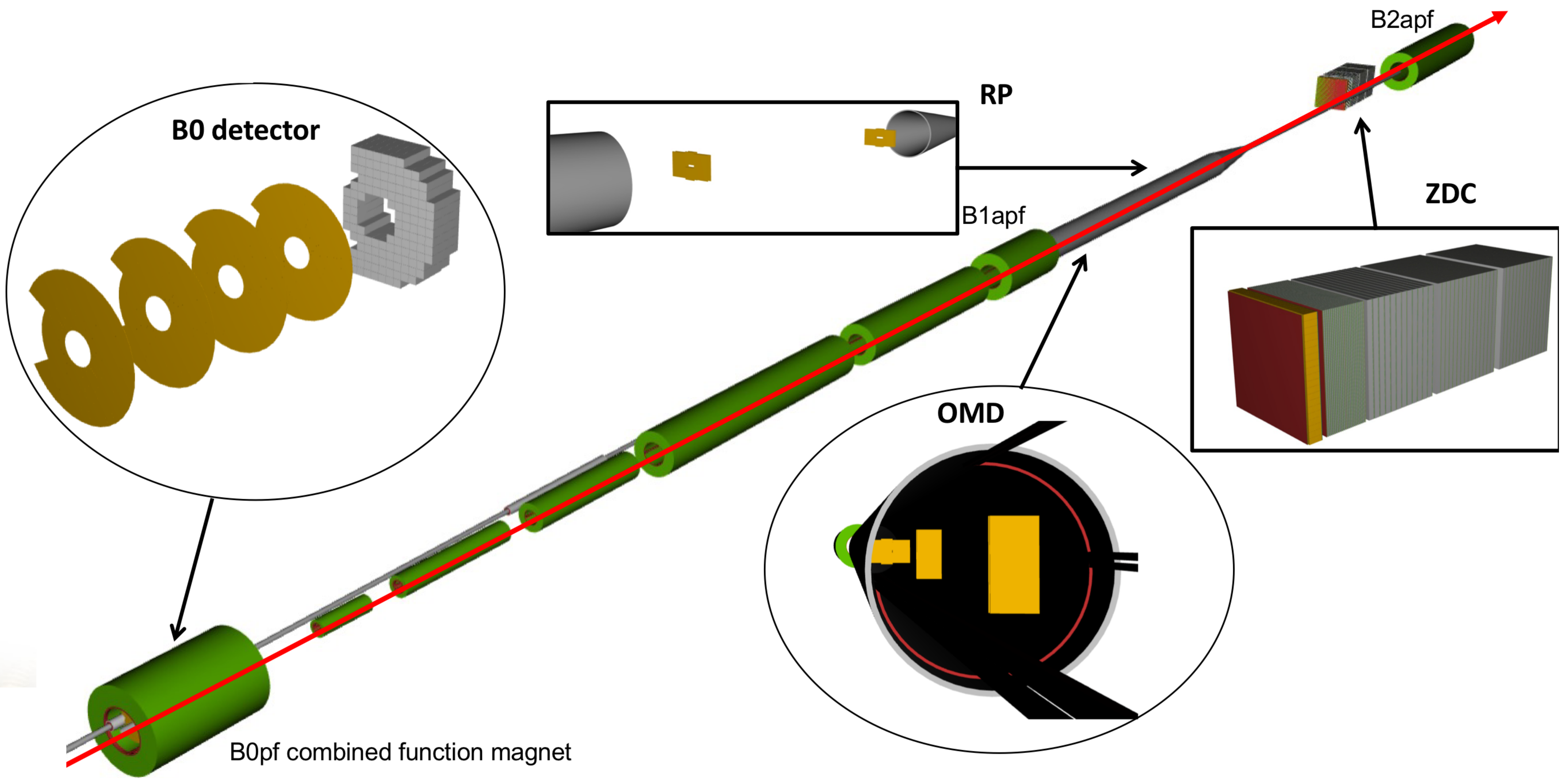
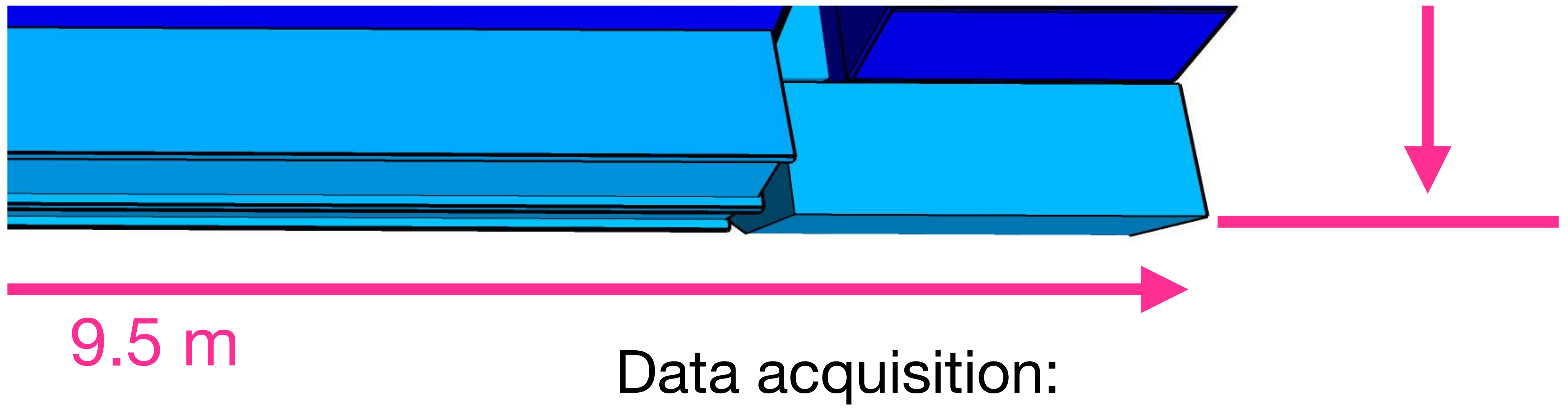


+ far forward





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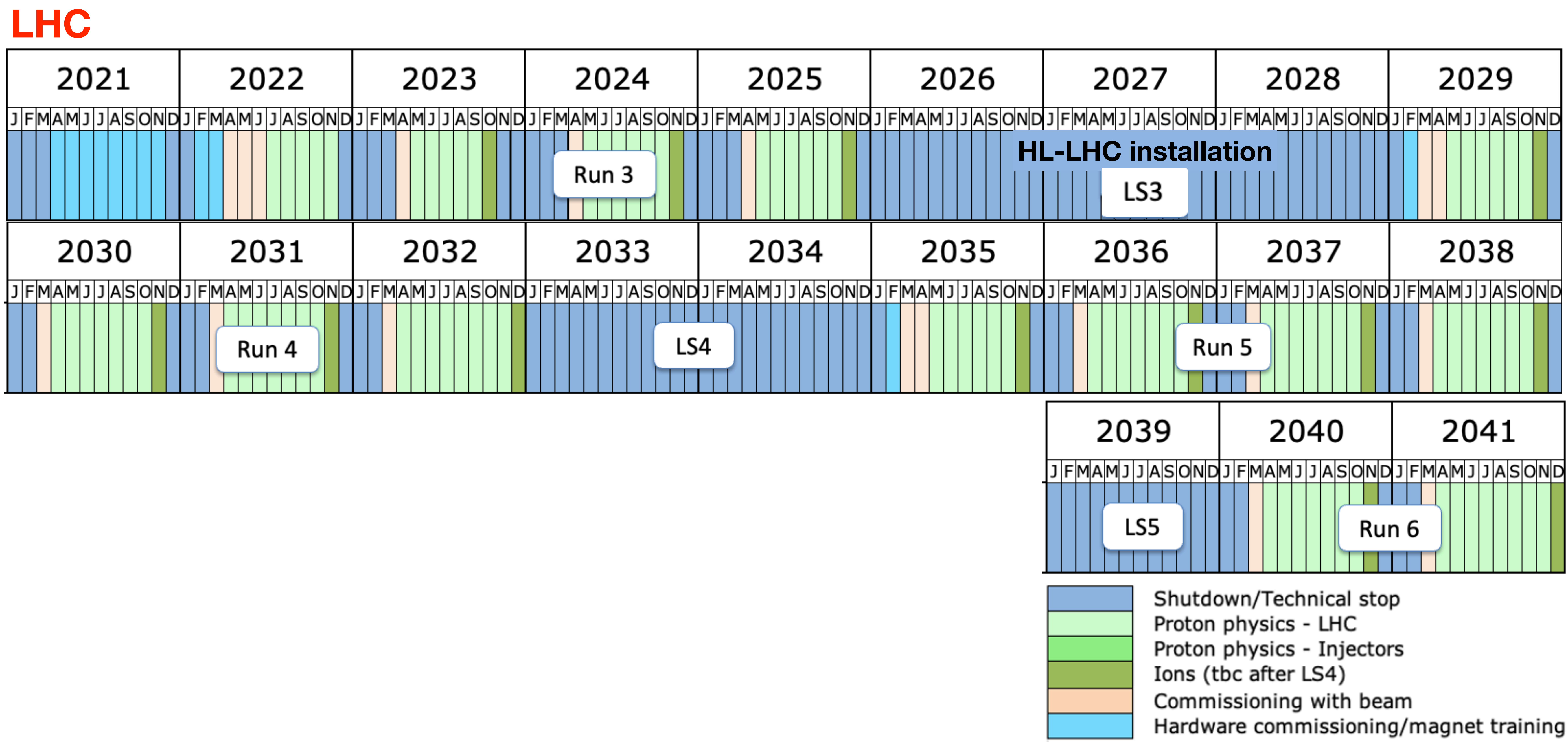
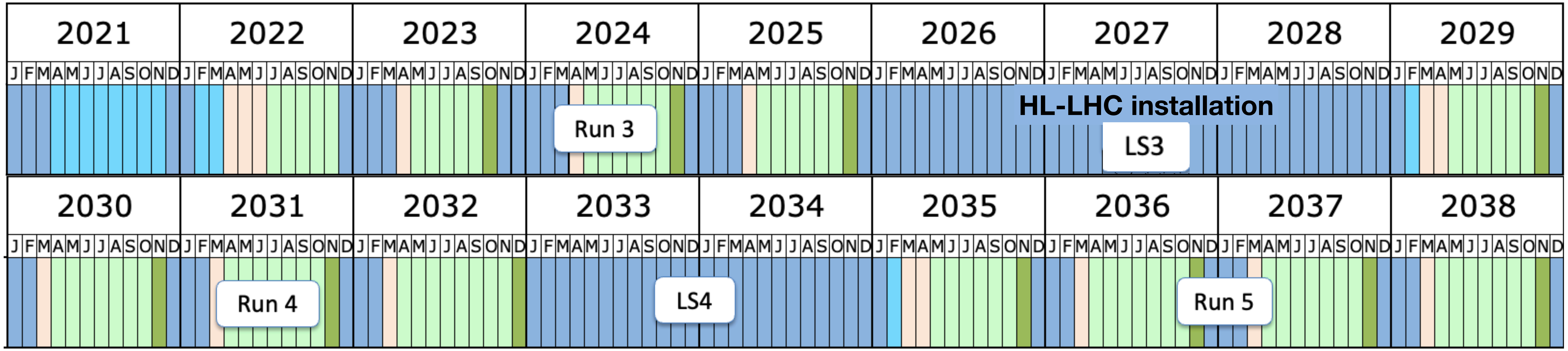
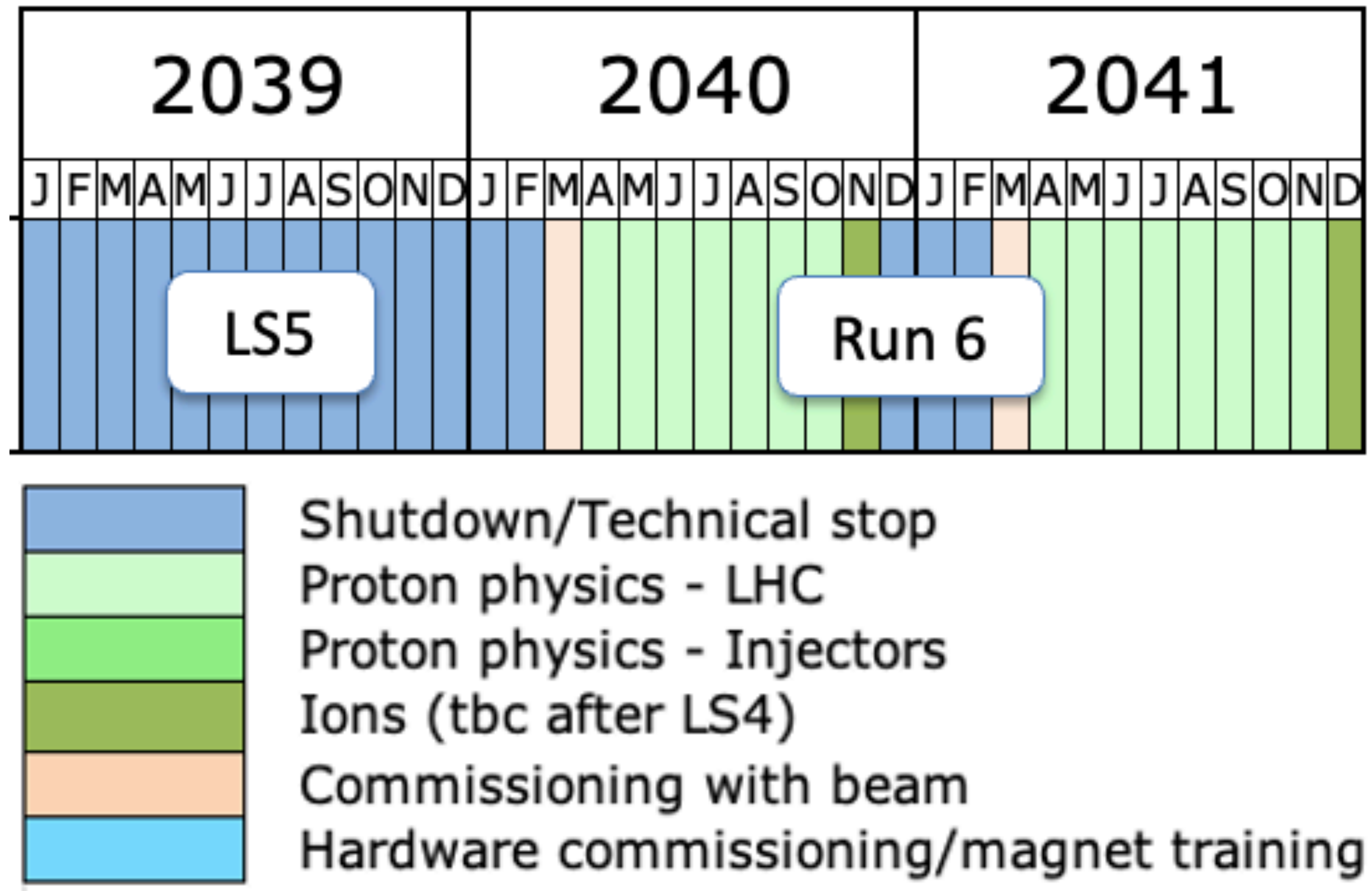
Timelines


LHC
2021
2022
2023
2024
2025
2026
2027
2028
2029
Run 3
HL-LHC installation
LS3
2030
2031
2032
2033
2034
2035
2036
2037
2038
Run 4
LS4
Run 5
2039
2040
2041
LS5
Run 6
Shutdown/Technical stop
Proton physics - LHC
Proton physics - Injectors
Ions (tbc after LS4)
Commissioning with beam
Hardware commissioning/magnet training

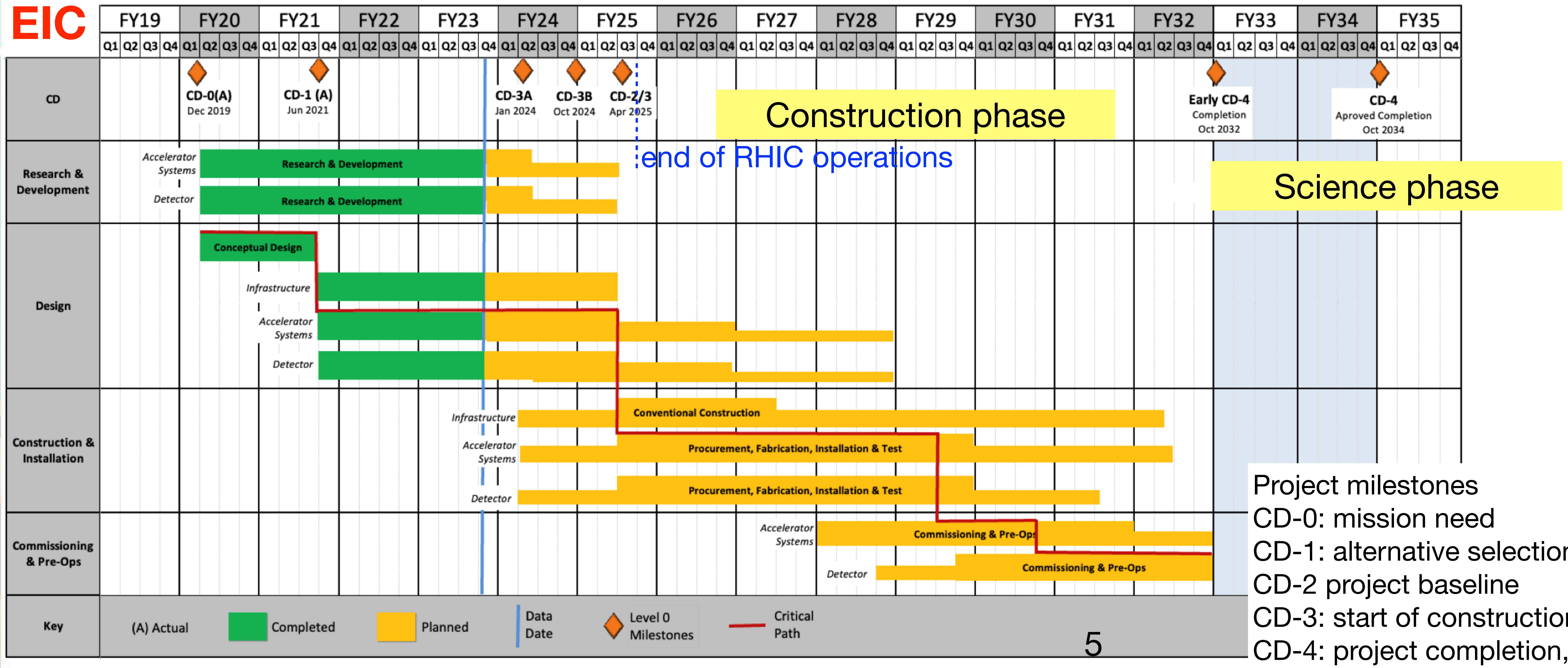
Timelines

LHC



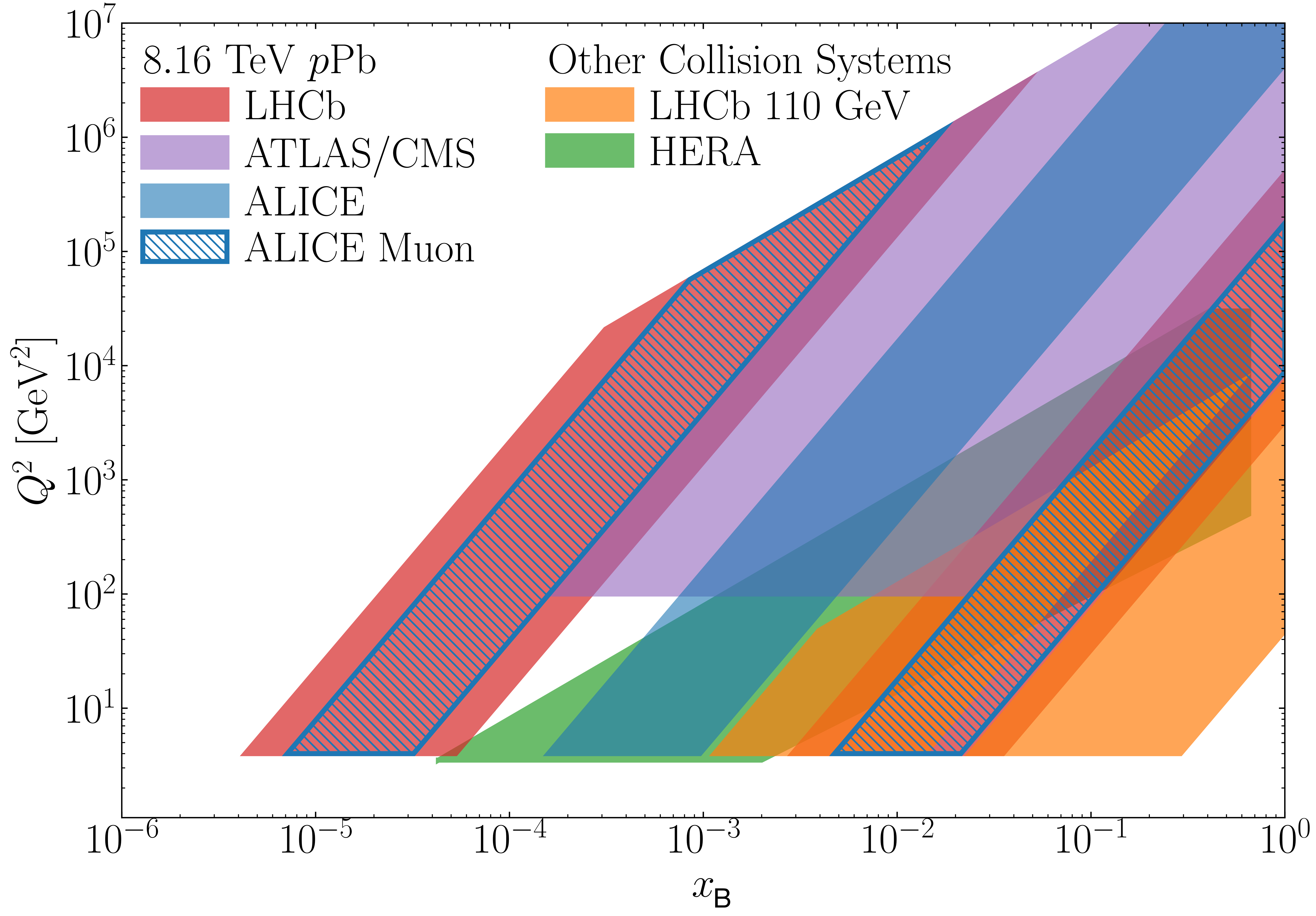


EIC



Project milestones
CD-0: mission need
CD-1: alternative selection, cost range
CD-2 project baseline
CD-3: start of construction
CD-4: project completion, start of operation

Kinematic coverage



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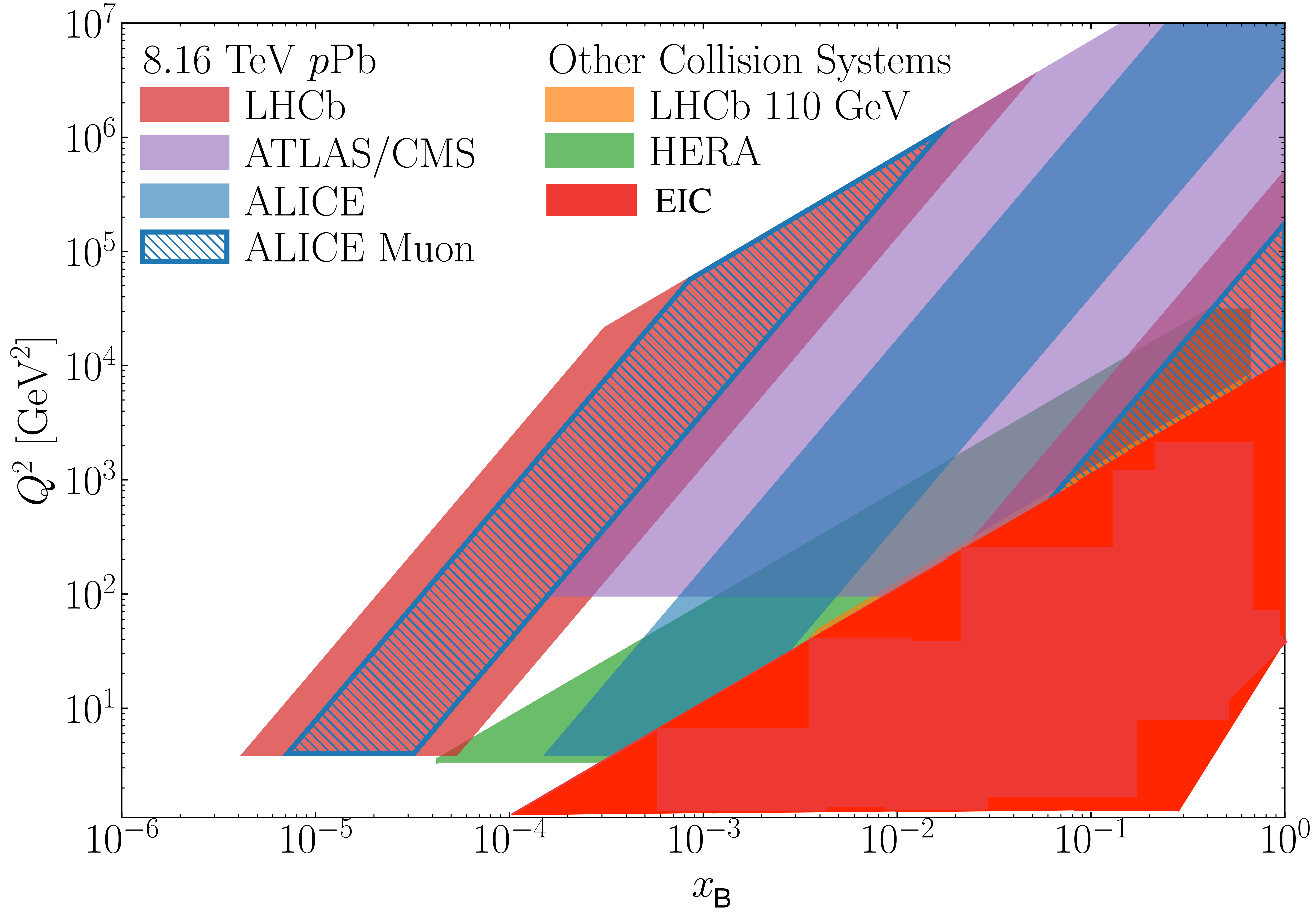


Impact of HL-LHC on determination of PDFs

A. Dainese et al., CERN Yellow Reports: Vol. 7 (2019)

Predictions based on

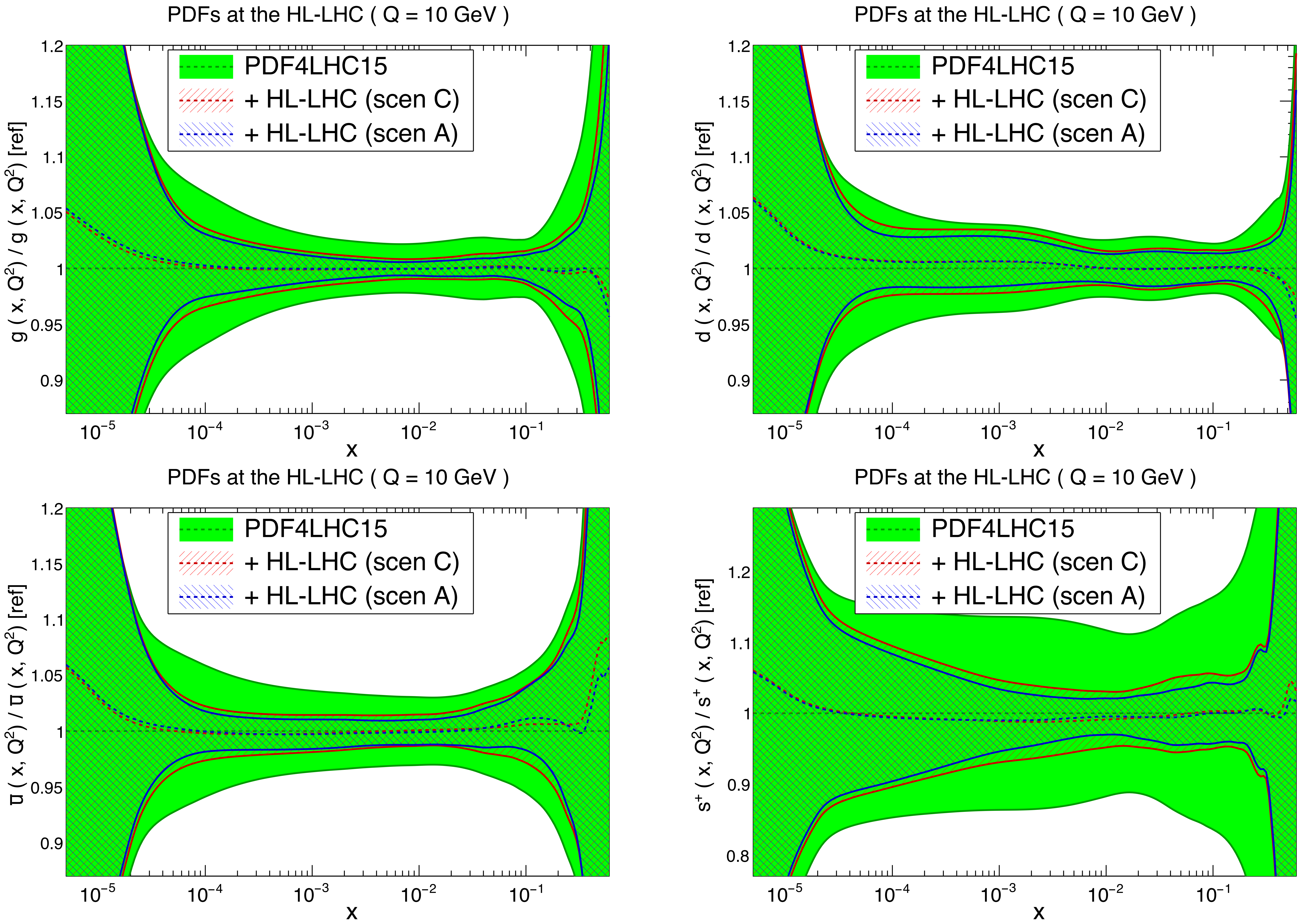
$\mathscr{L} = 3$ ab^{-1} for ATLAS and CMS

$\mathscr{L} = 0.3$ ab^{-1} for LHCb

at $\sqrt{s} = 14$

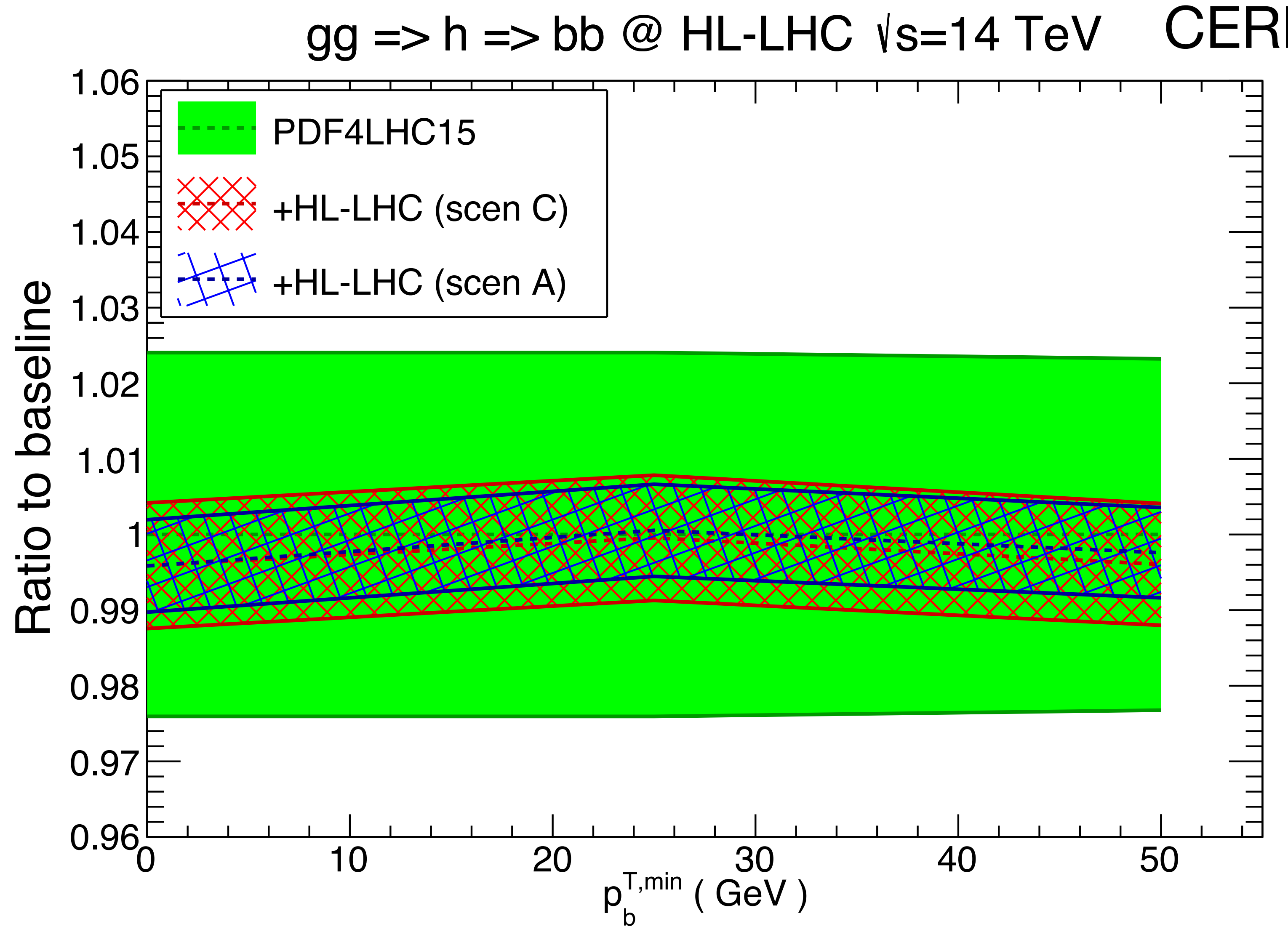
Limited amount of considered processes:

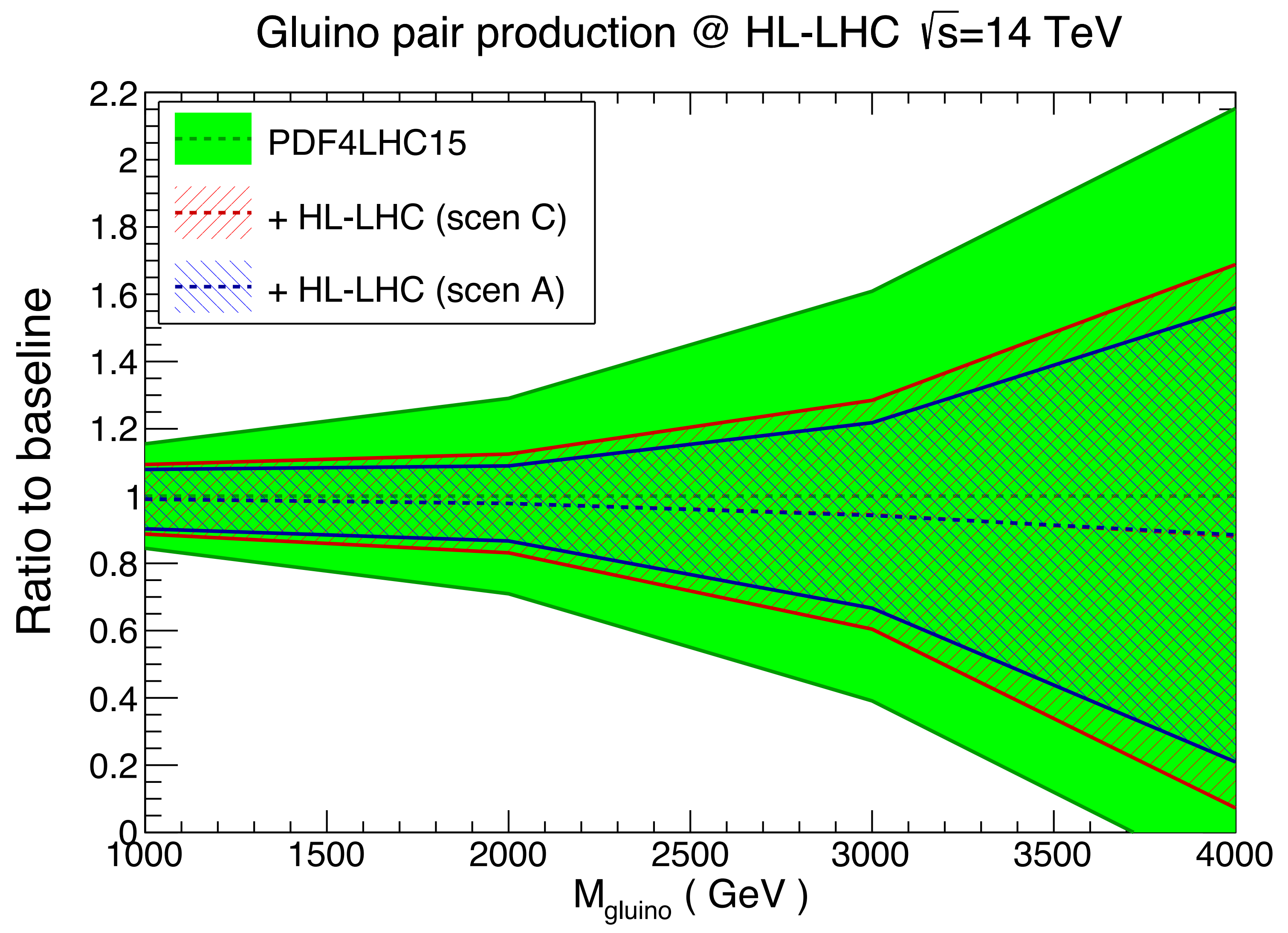
- high-mass Drell-Yan
- top-quark pair production
- (high-pT) Z
- W(+charm quark)
- isolated photons
- inclusive jet production

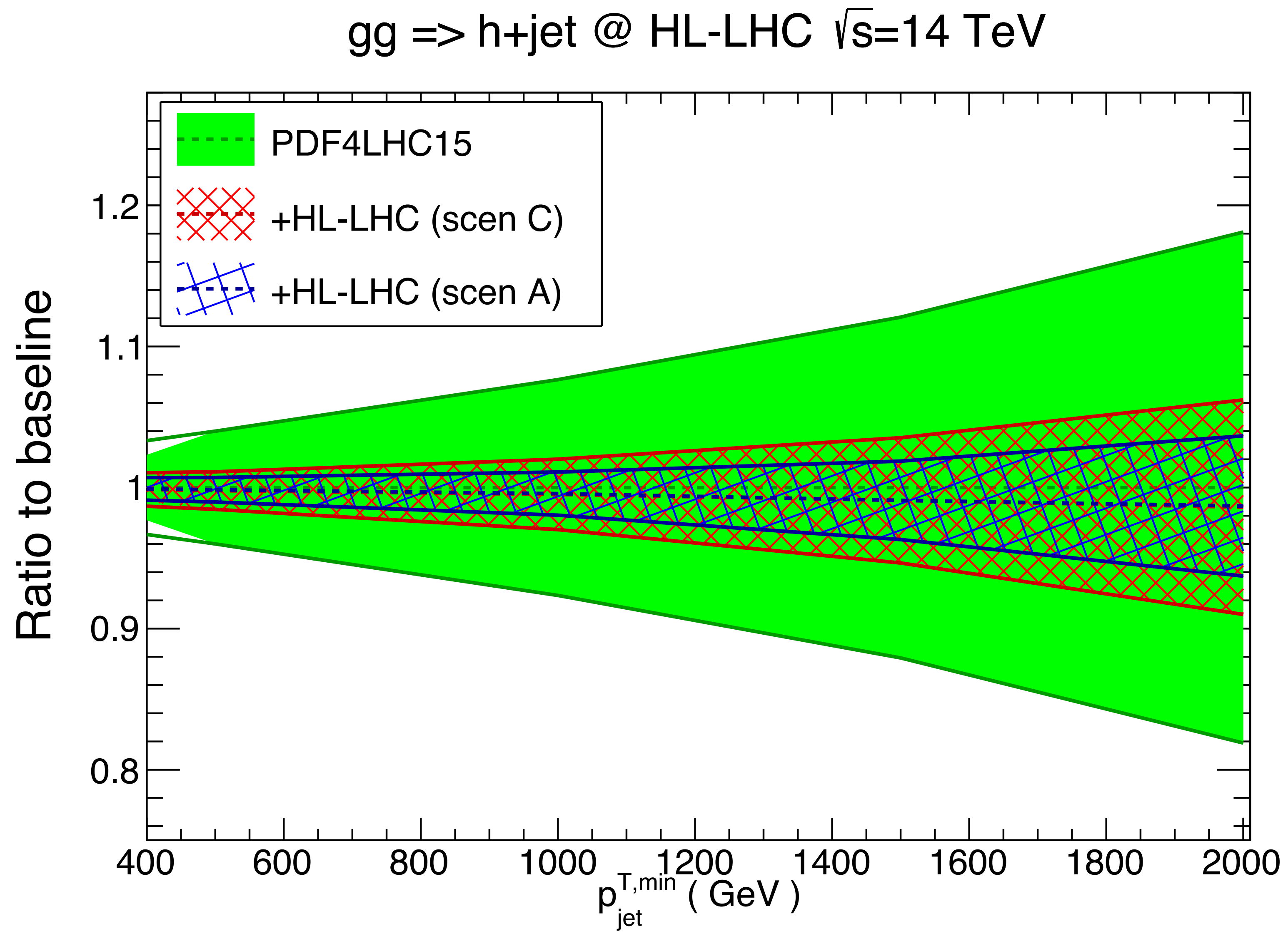


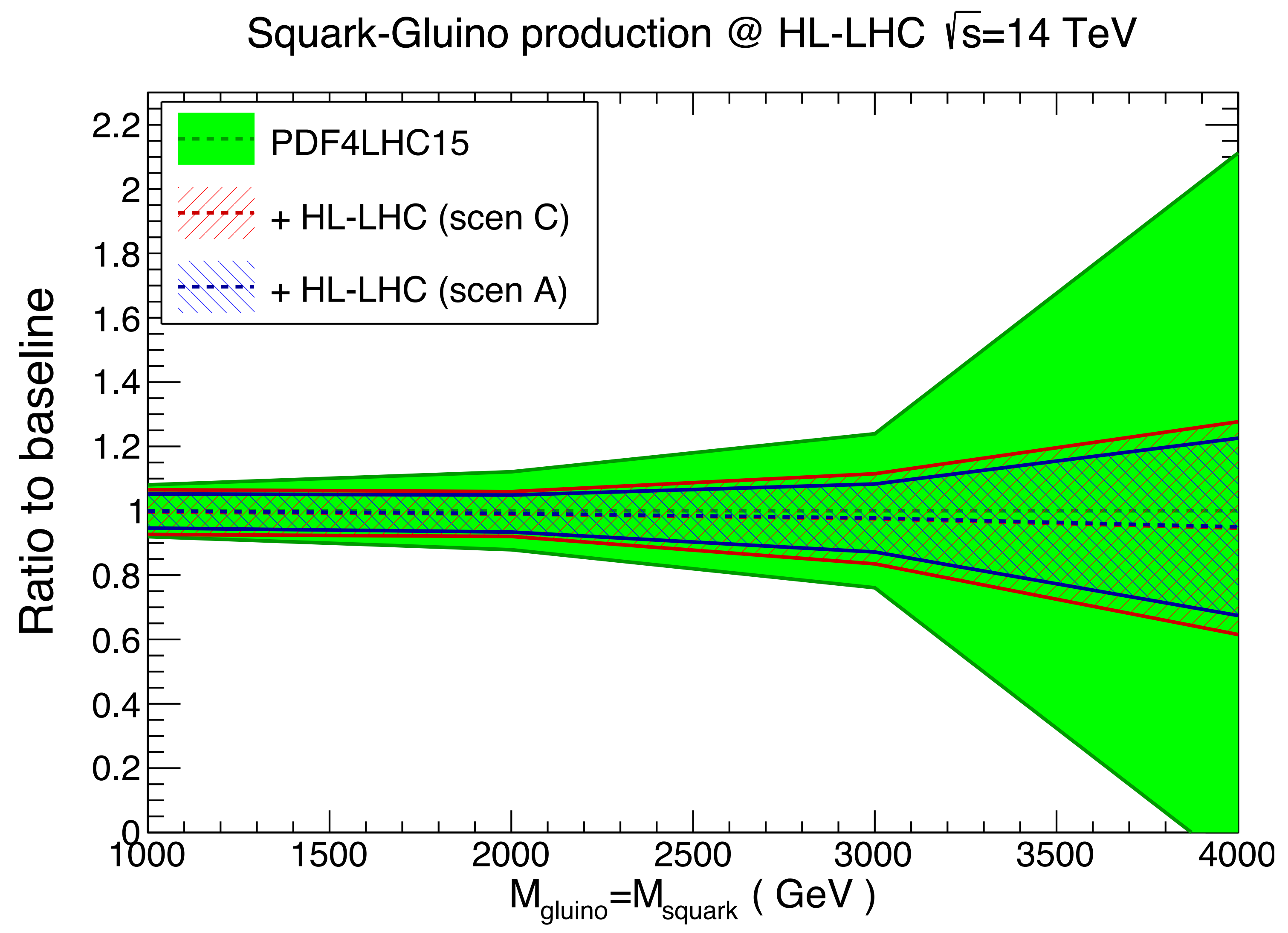
Impact of HL-LHC PDFs on Higgs production and BSM searches

A. Dainese et al.,
CERN Yellow Reports: Vol. 7 (2019)









Impact of EIC on determination of PDFs

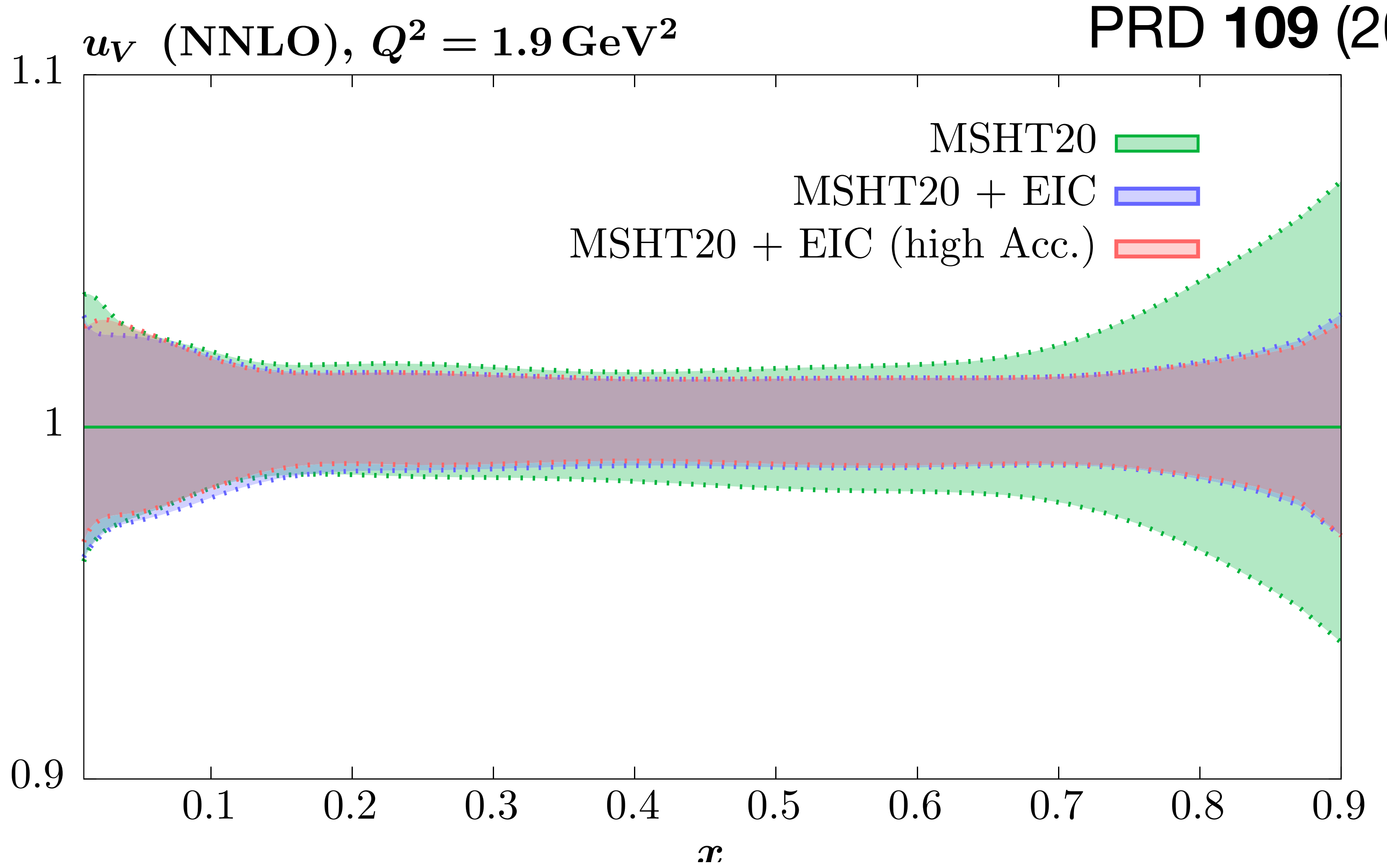
Inclusive e^-p data only

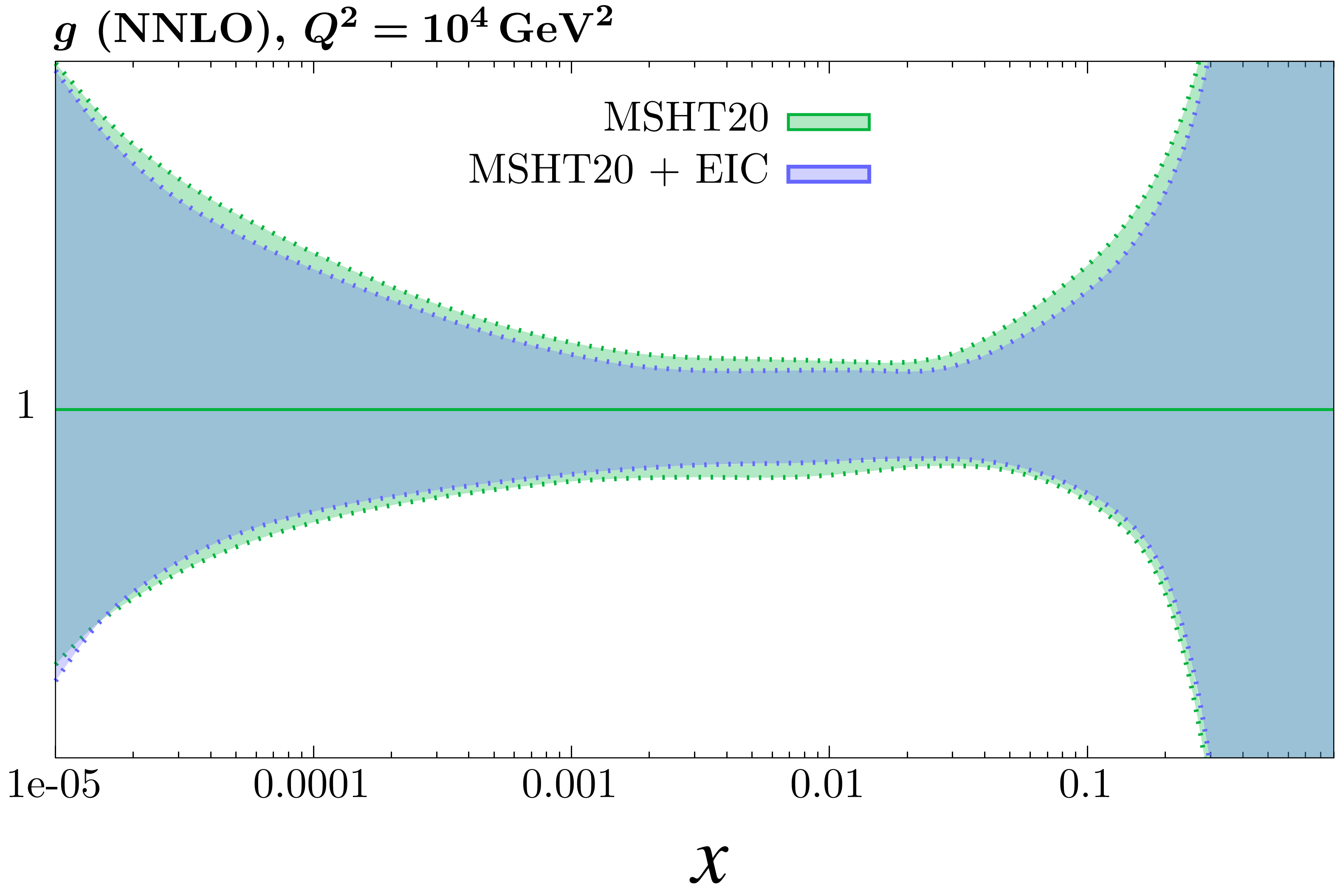
E_{ep}: 18x275, 10x275, 10x100
5x100, 5x41

$\mathscr{L}$: 1 year of data collection for each E_{ep}

Global fits

N. Armesto et al.,
PRD **109** (2024) 054019





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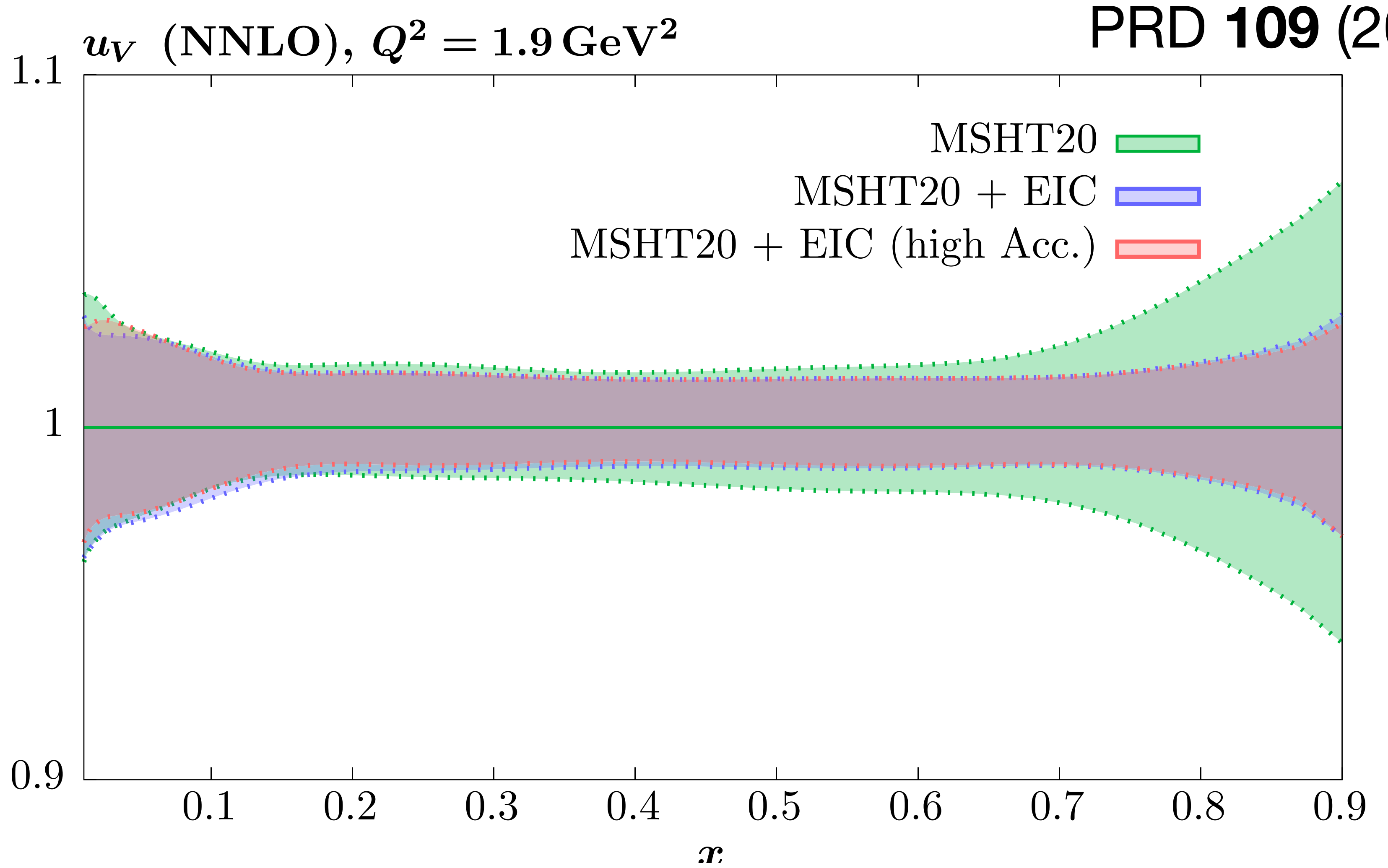
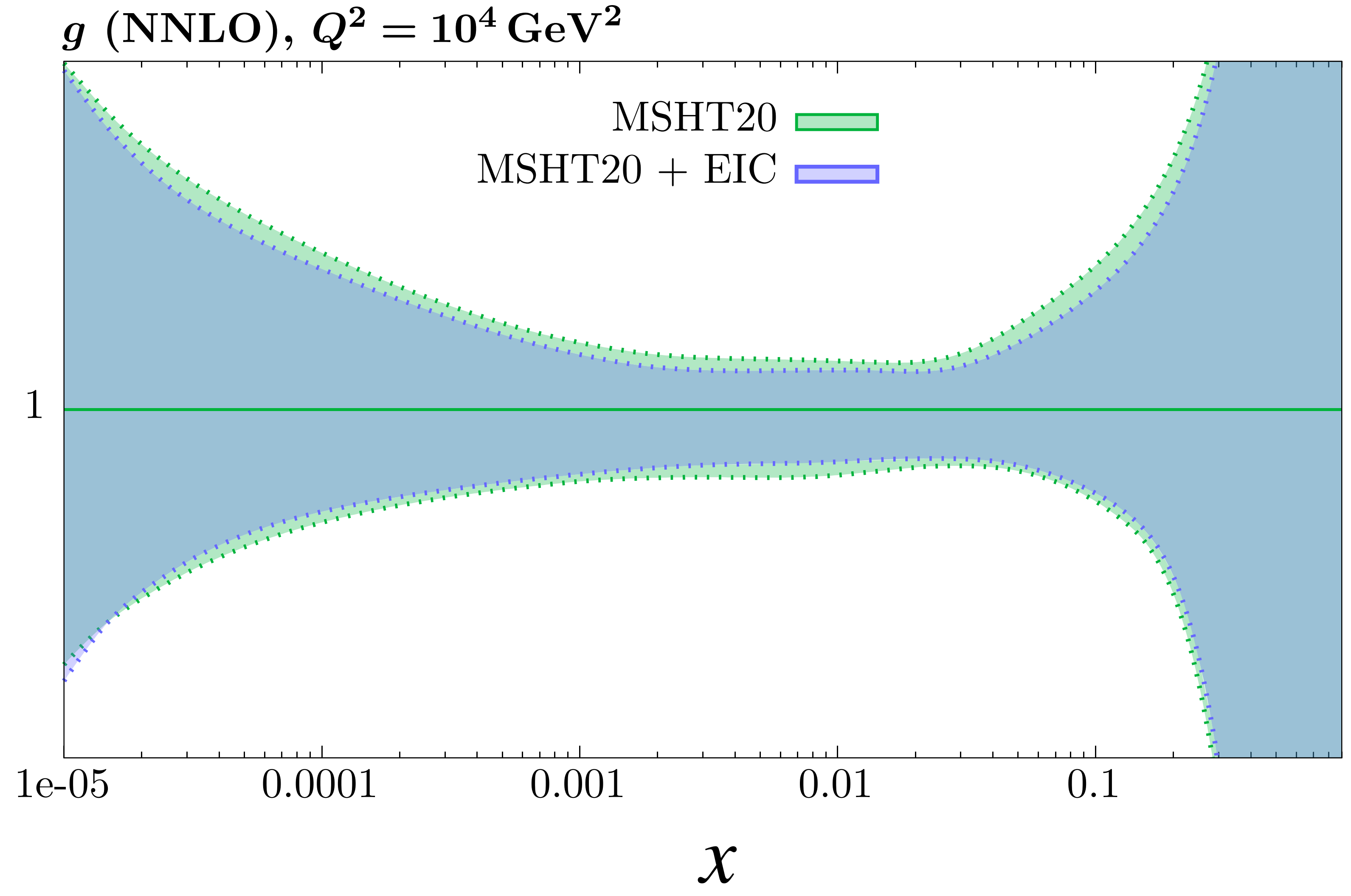
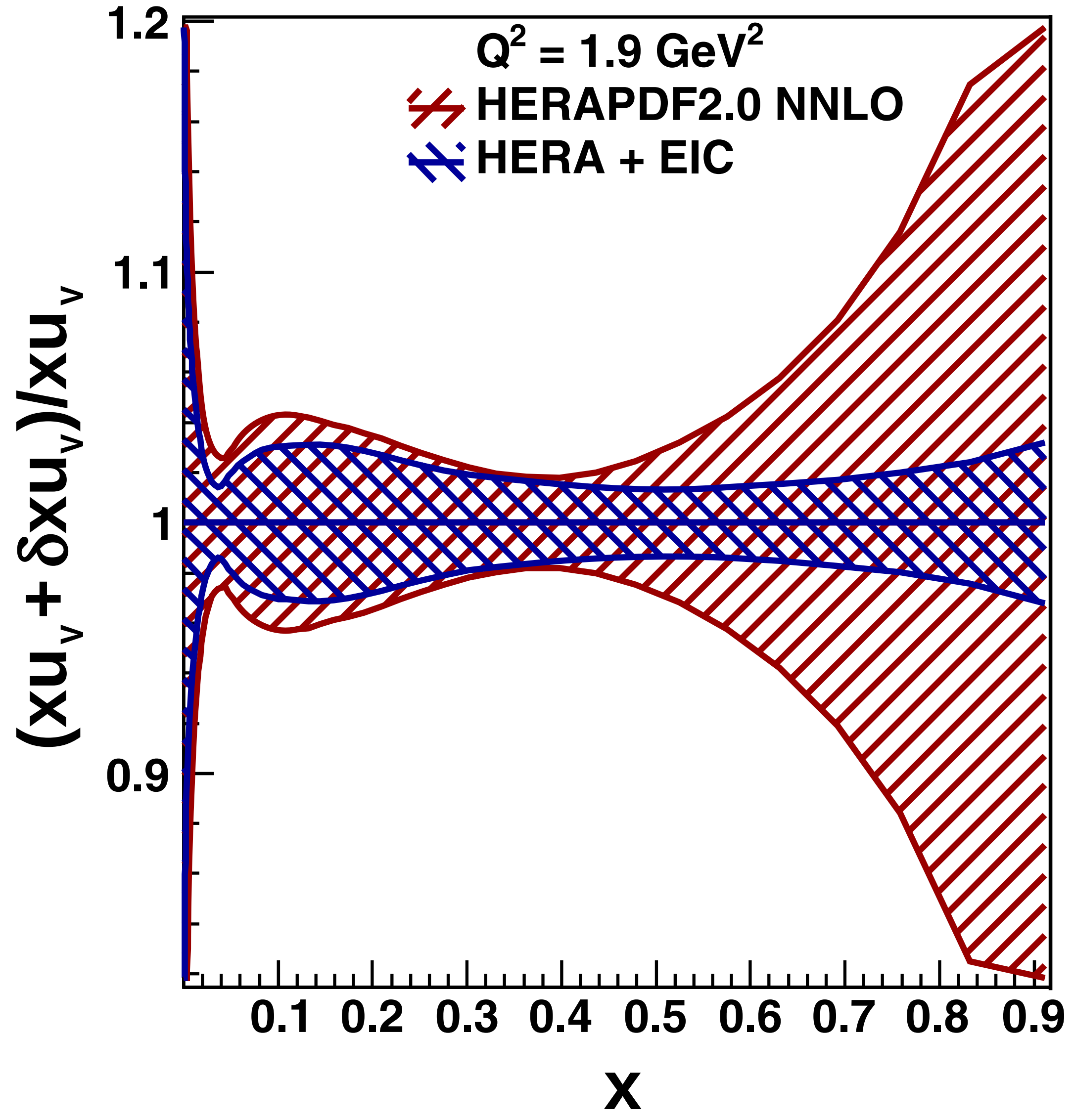
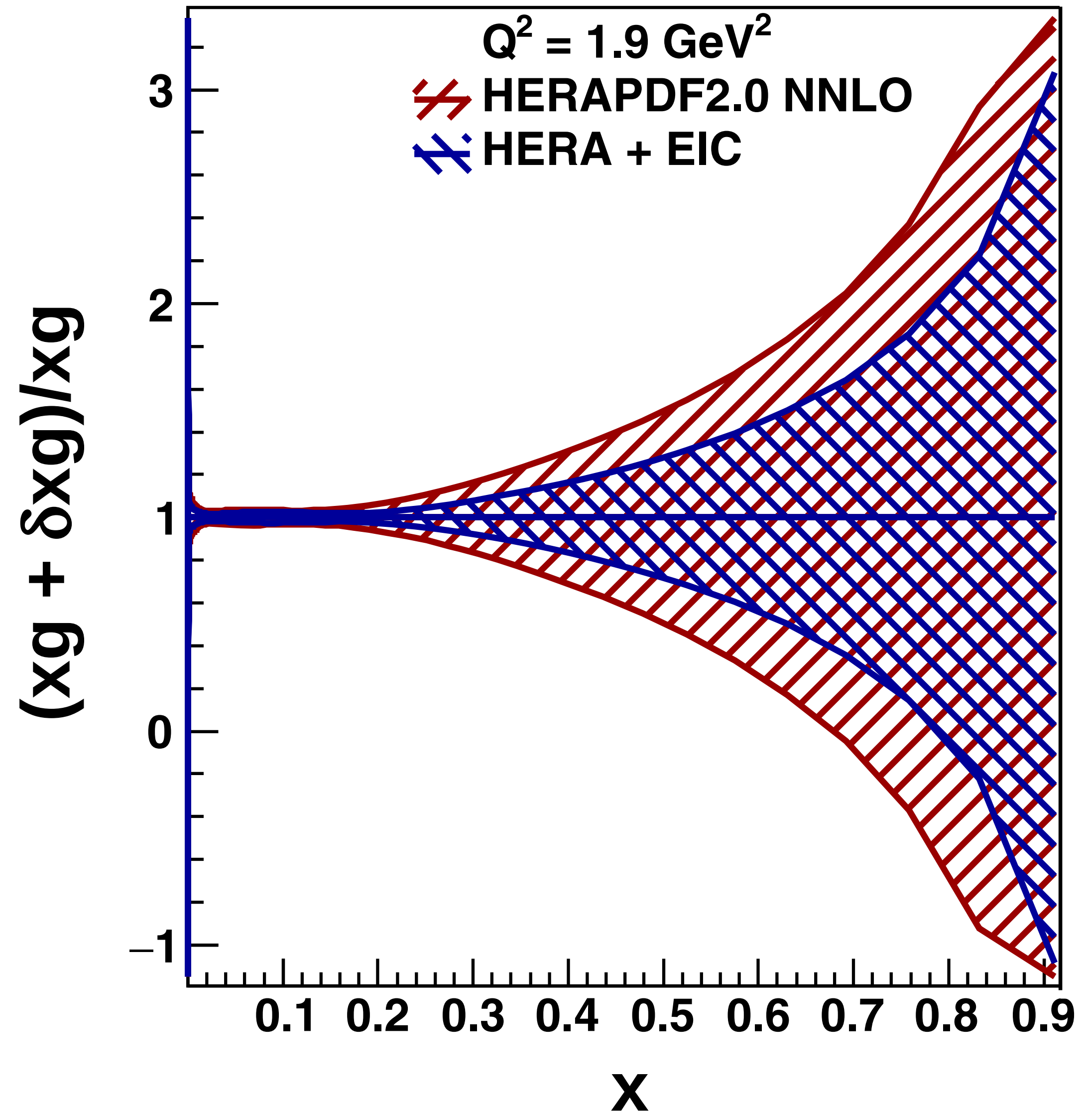


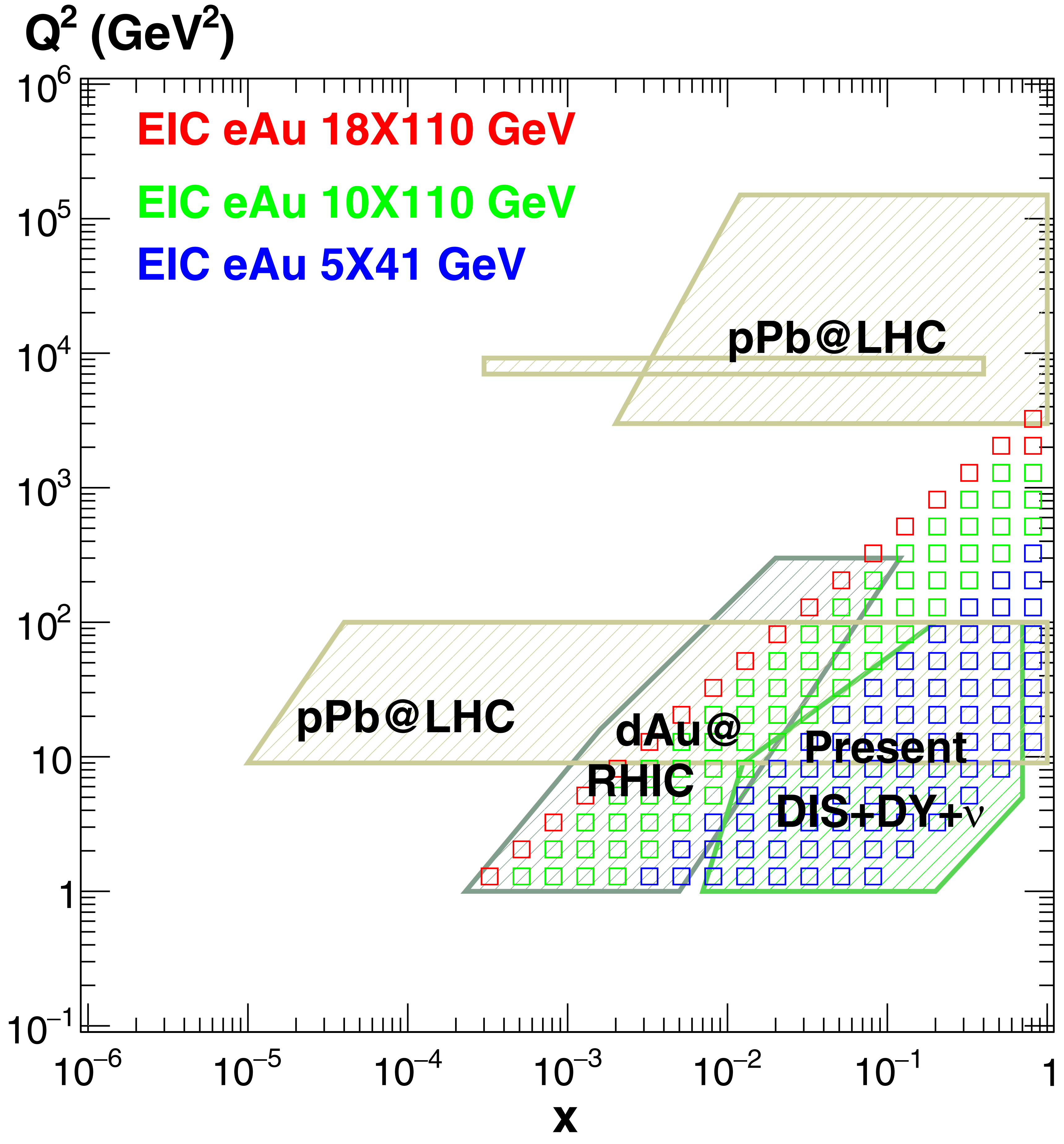


HERA only





Nuclear PDFs at EIC



pPb LHC data: dijet, electro-weak boson, and D-meson

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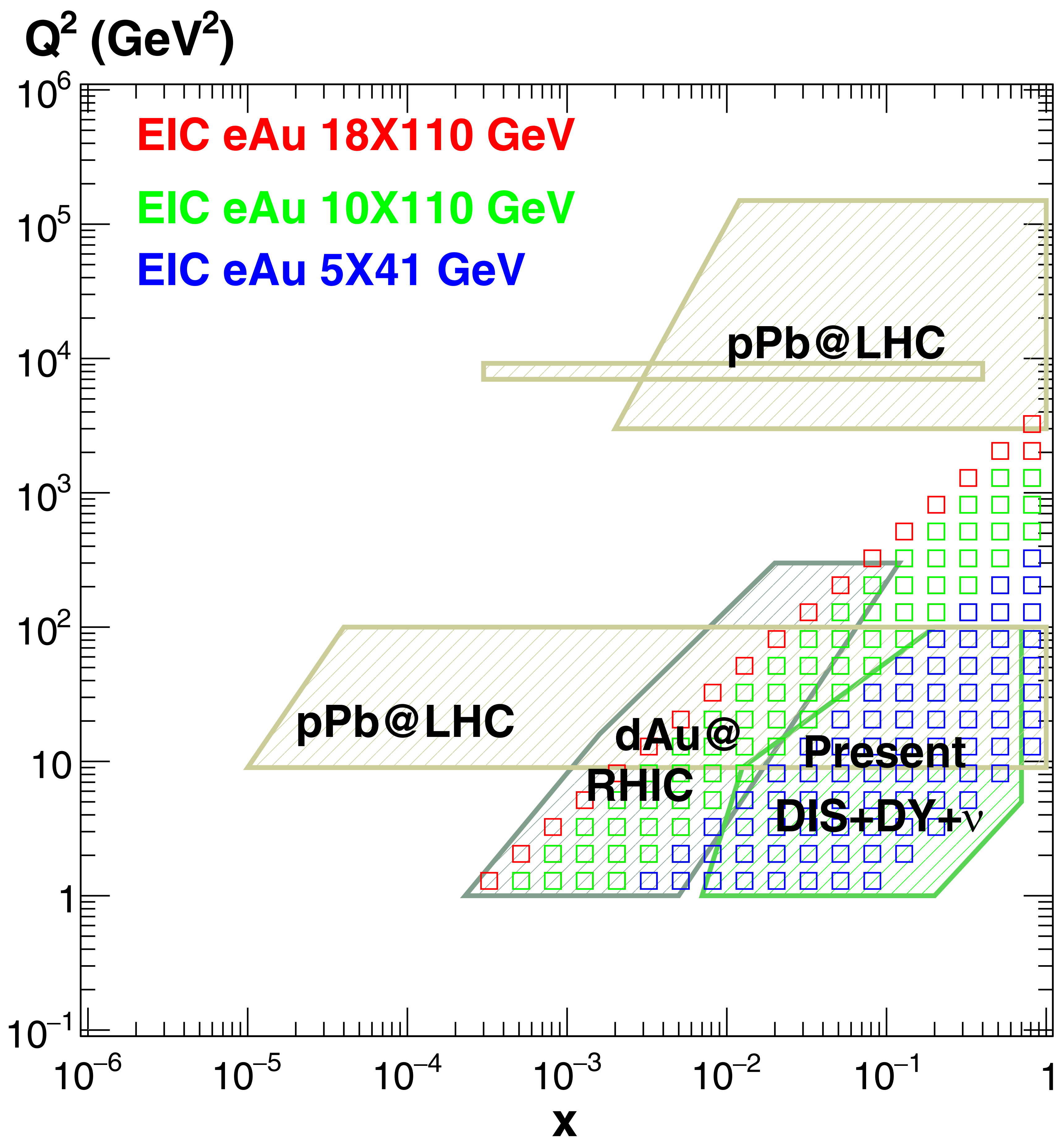

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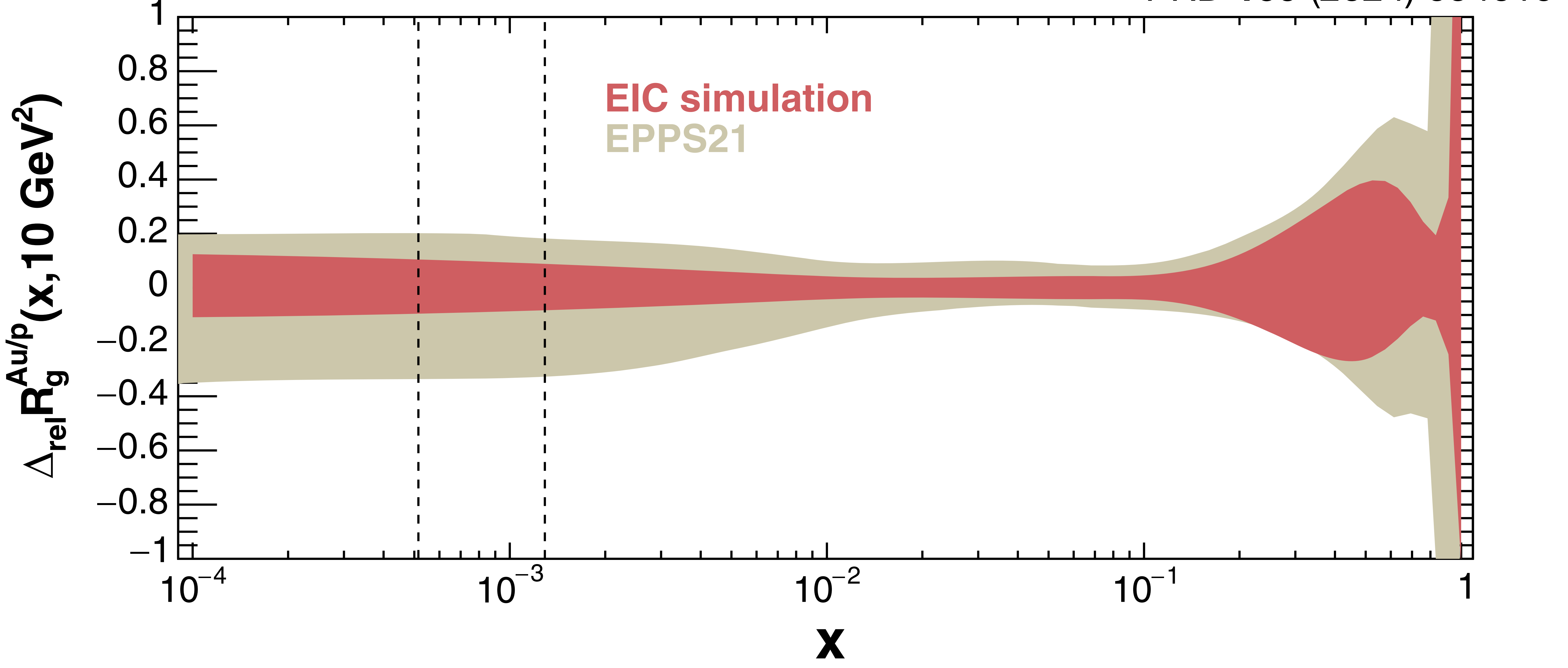
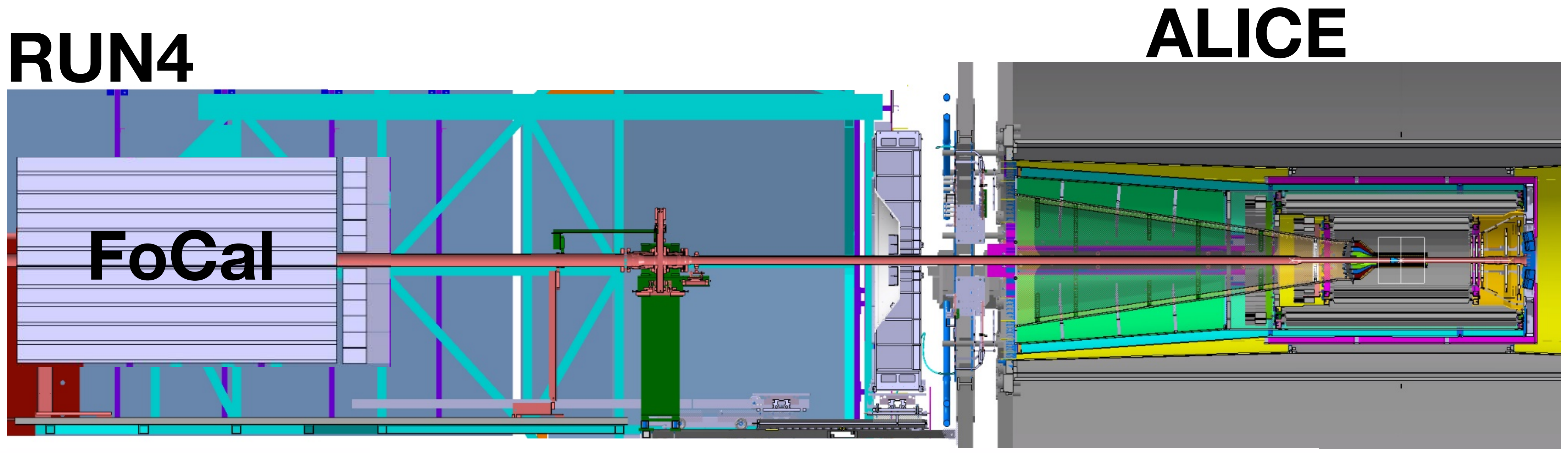


Inclusive e-Au data only:

constrain of nuclear PDF one single nucleus!

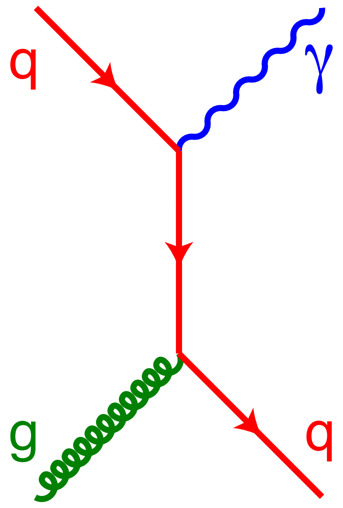
Probing small-x gluon PDFs: Forward Calorimeter (FoCal) at ALICE



EMCal+HCal in $3.4 < \eta < 5.8$

Isolated photons

isolated photons in coincidence with hadrons (π^0):
dominated by quark-gluon Compton scattering



Probe (nuclear) gluon PDFs and saturation in x_B down to 10^{-6}

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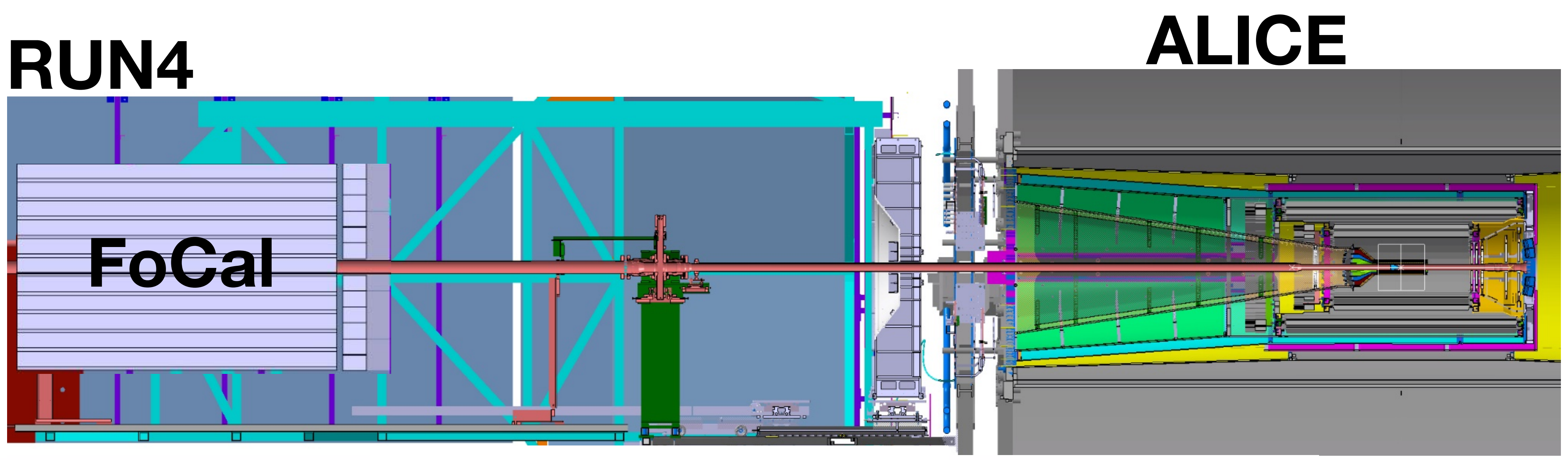

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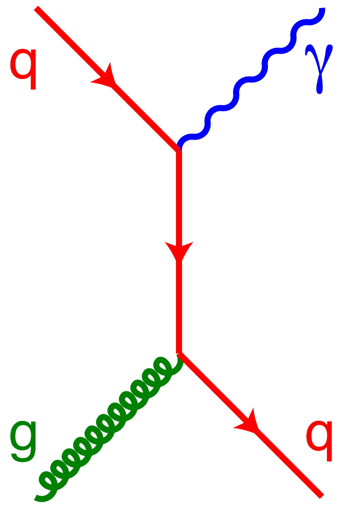

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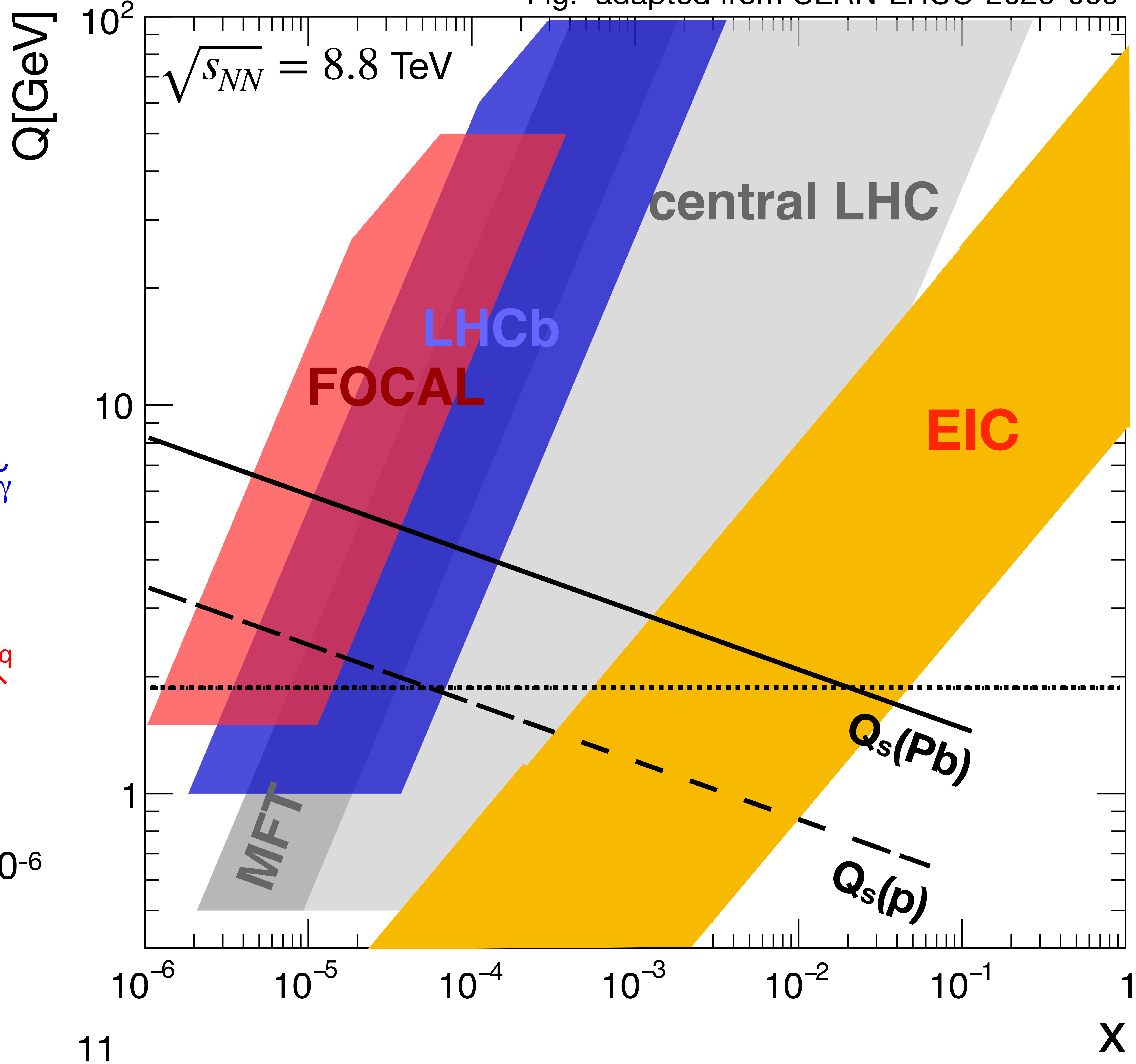
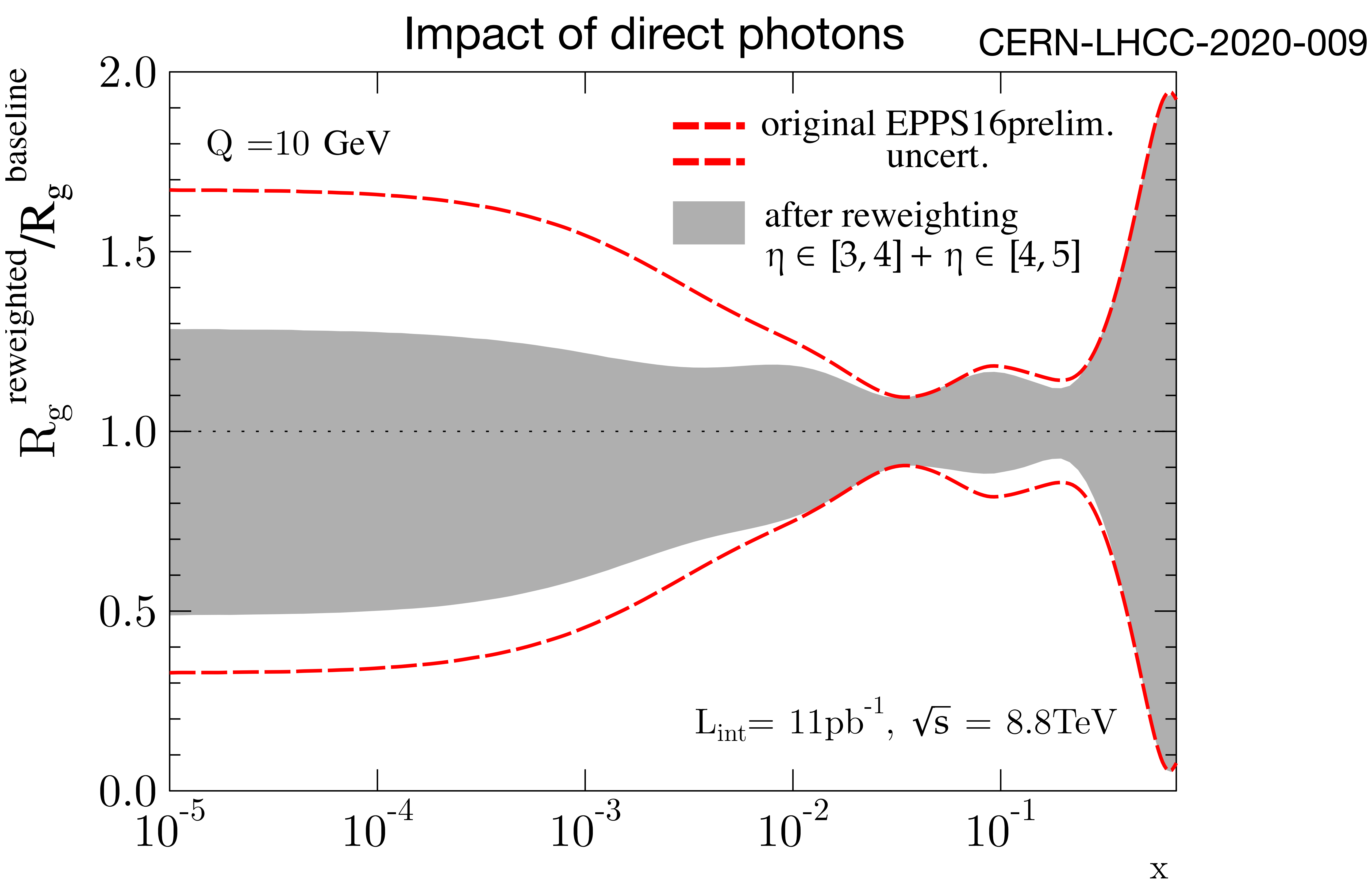
Fig. adapted from CERN-LHCC-2020-009



Expected impact of FoCal on gluon PDFs



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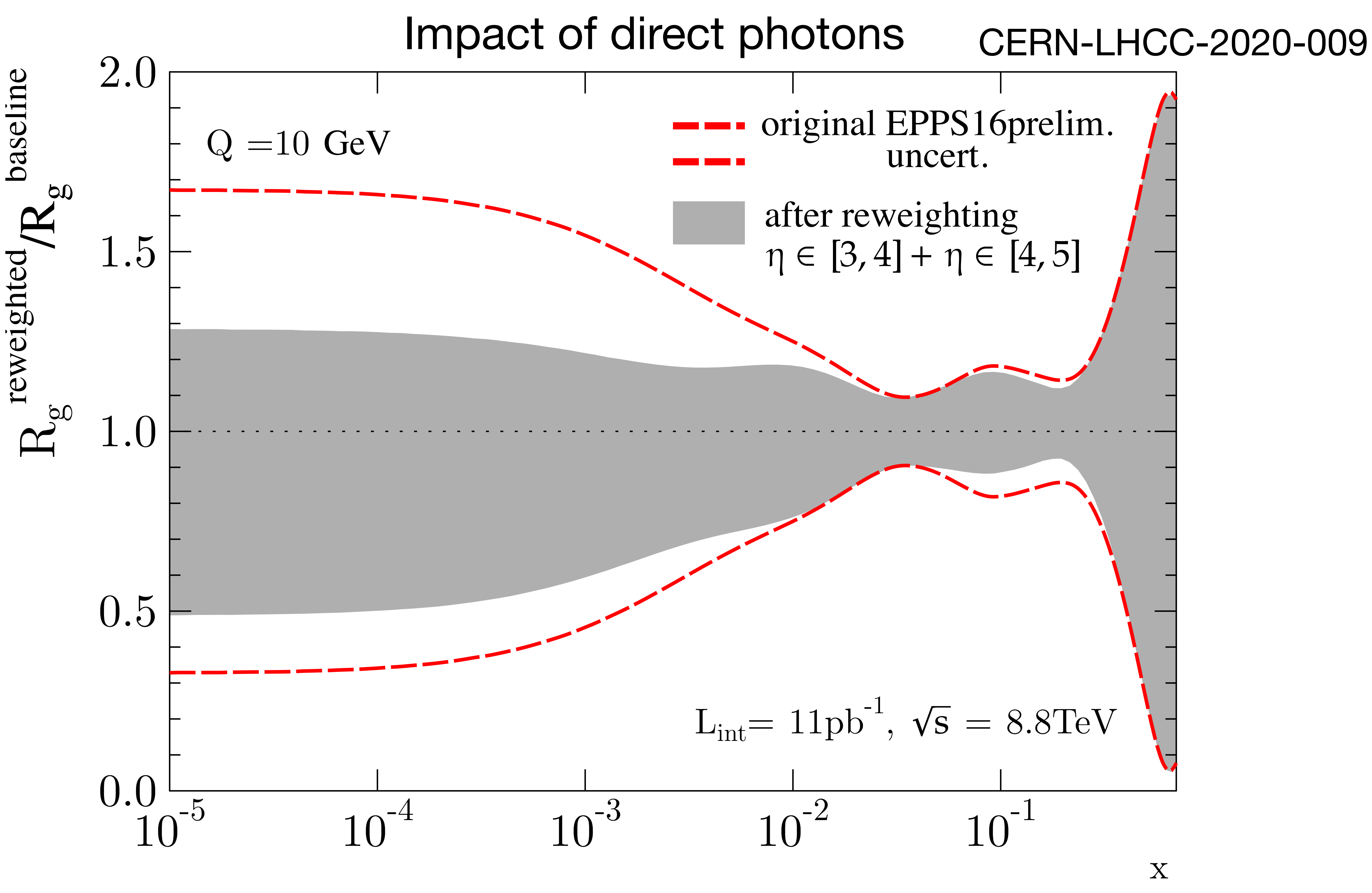
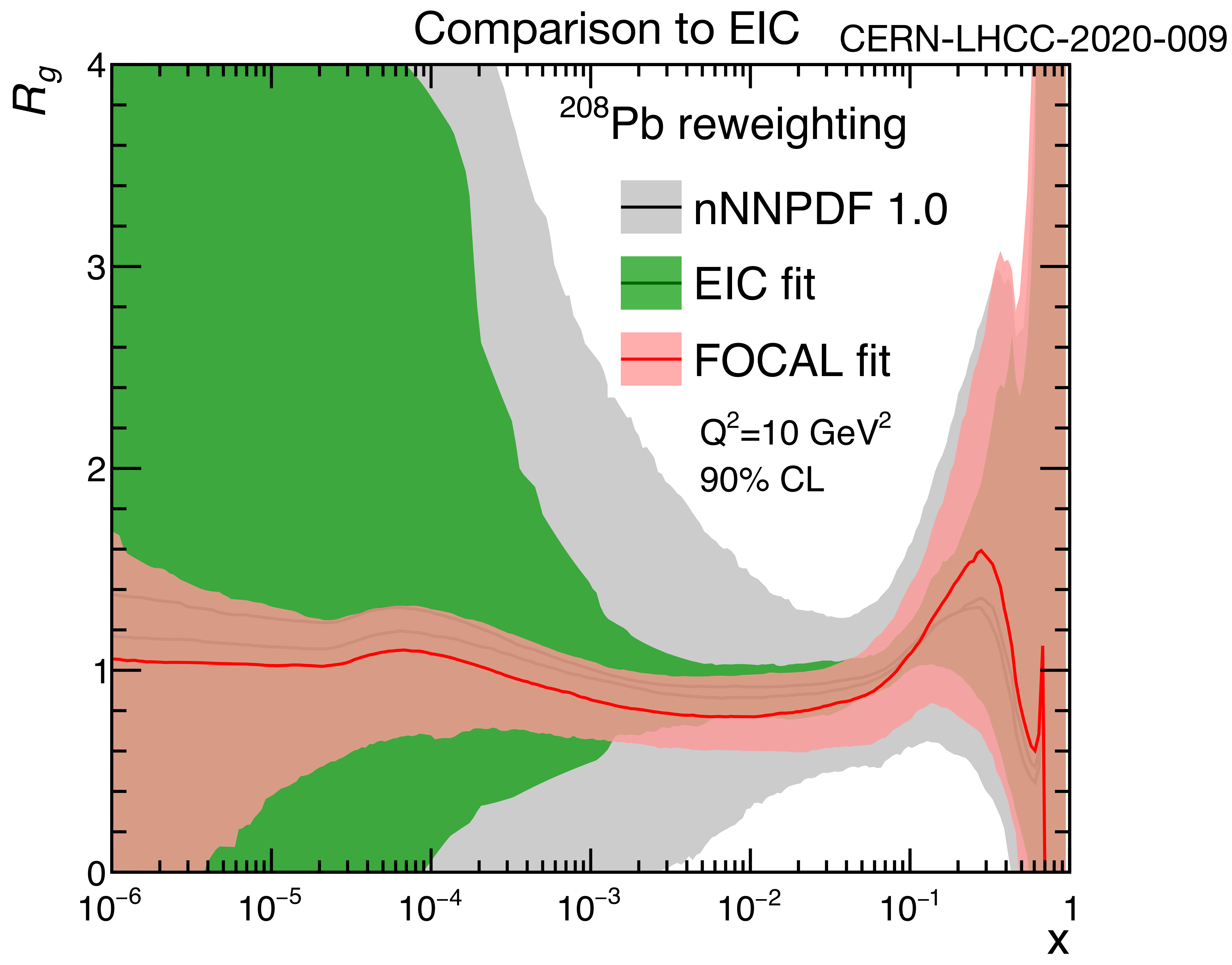
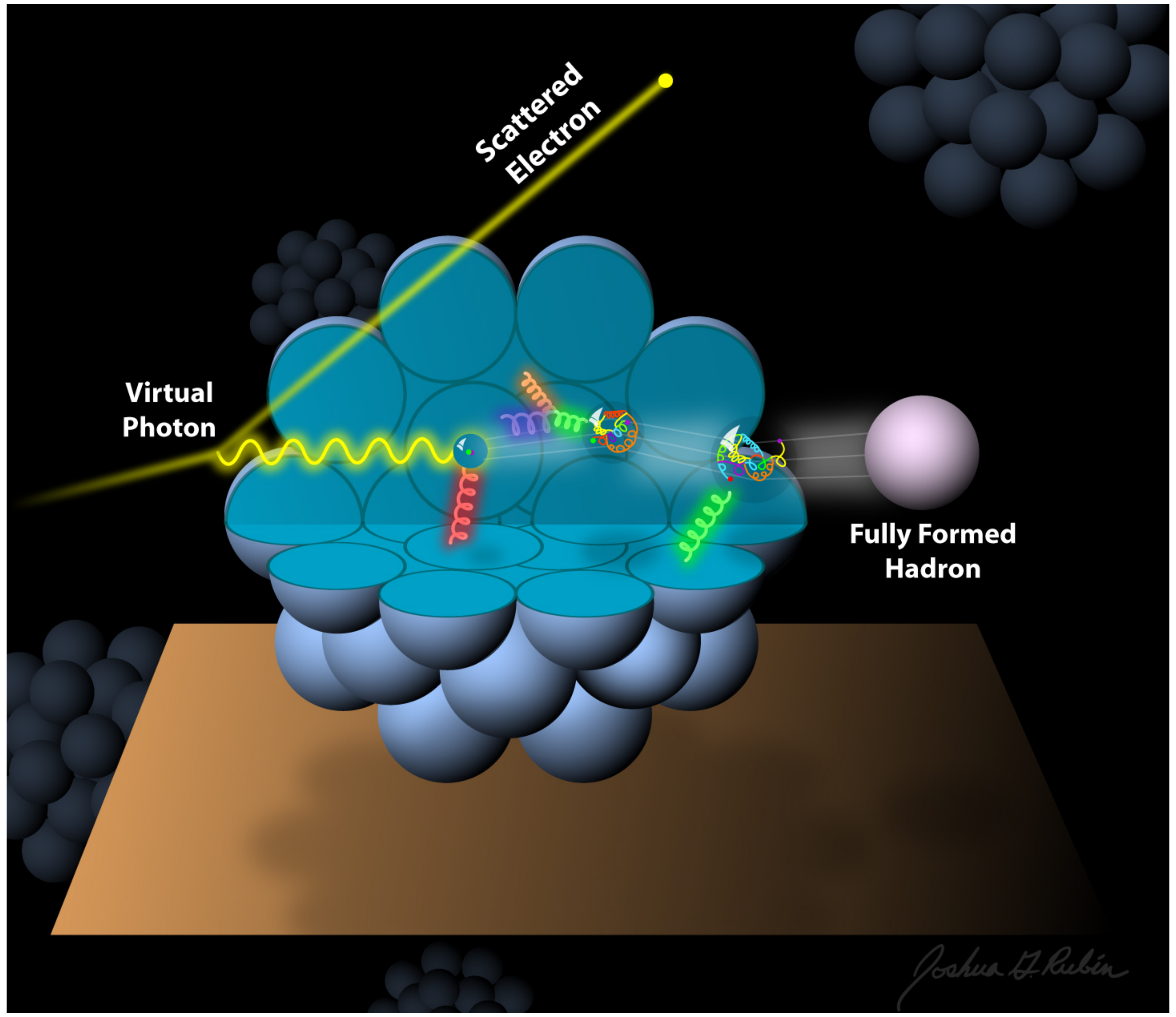




Study of hadronisation



- Energy loss of parton by medium-induced gluon radiation
- Energy loss of (pre-)hadron via absorption and rescattering (small)

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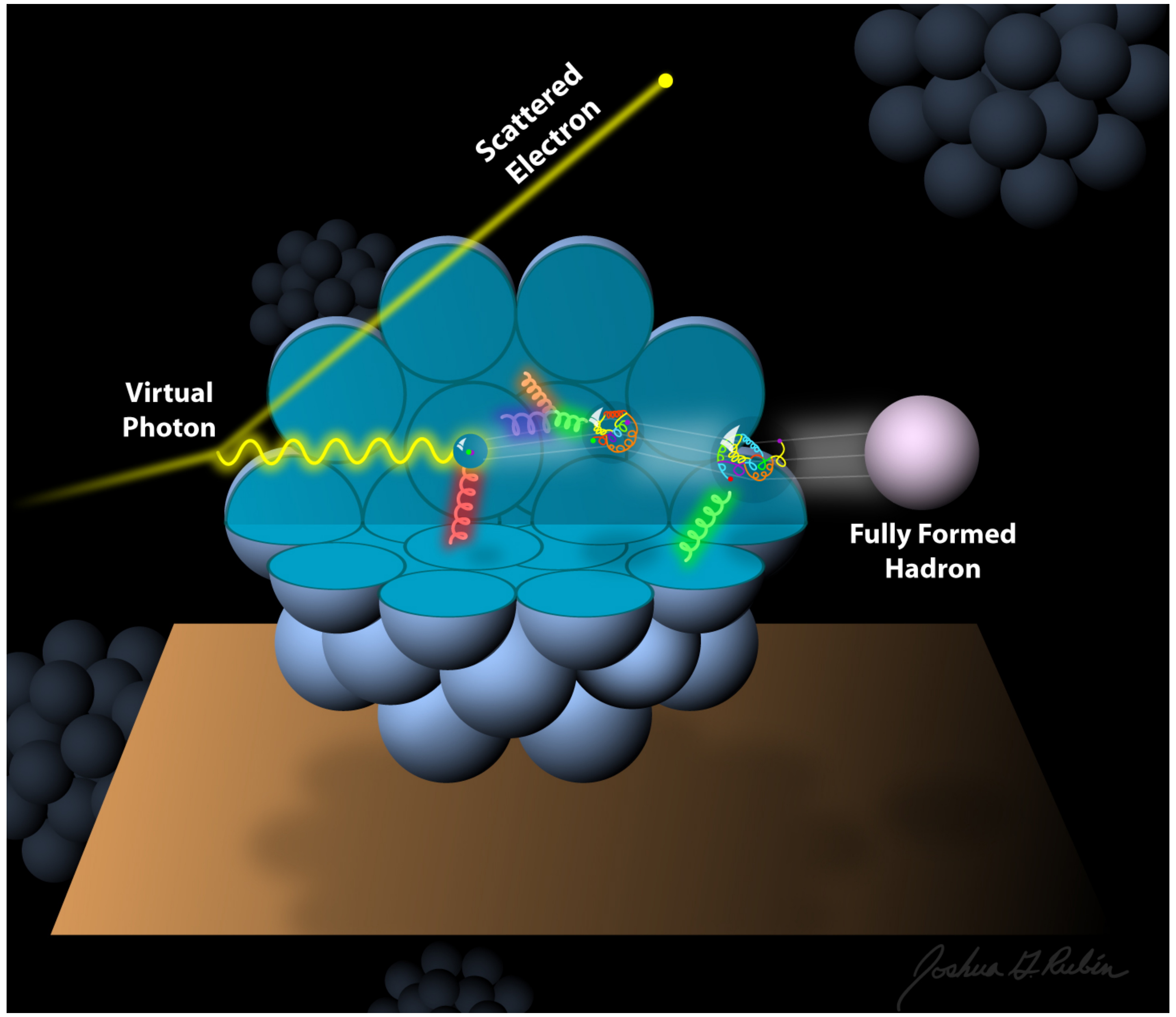

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  ⟶ using variety of nuclei probe space-time evolution of hadron formation

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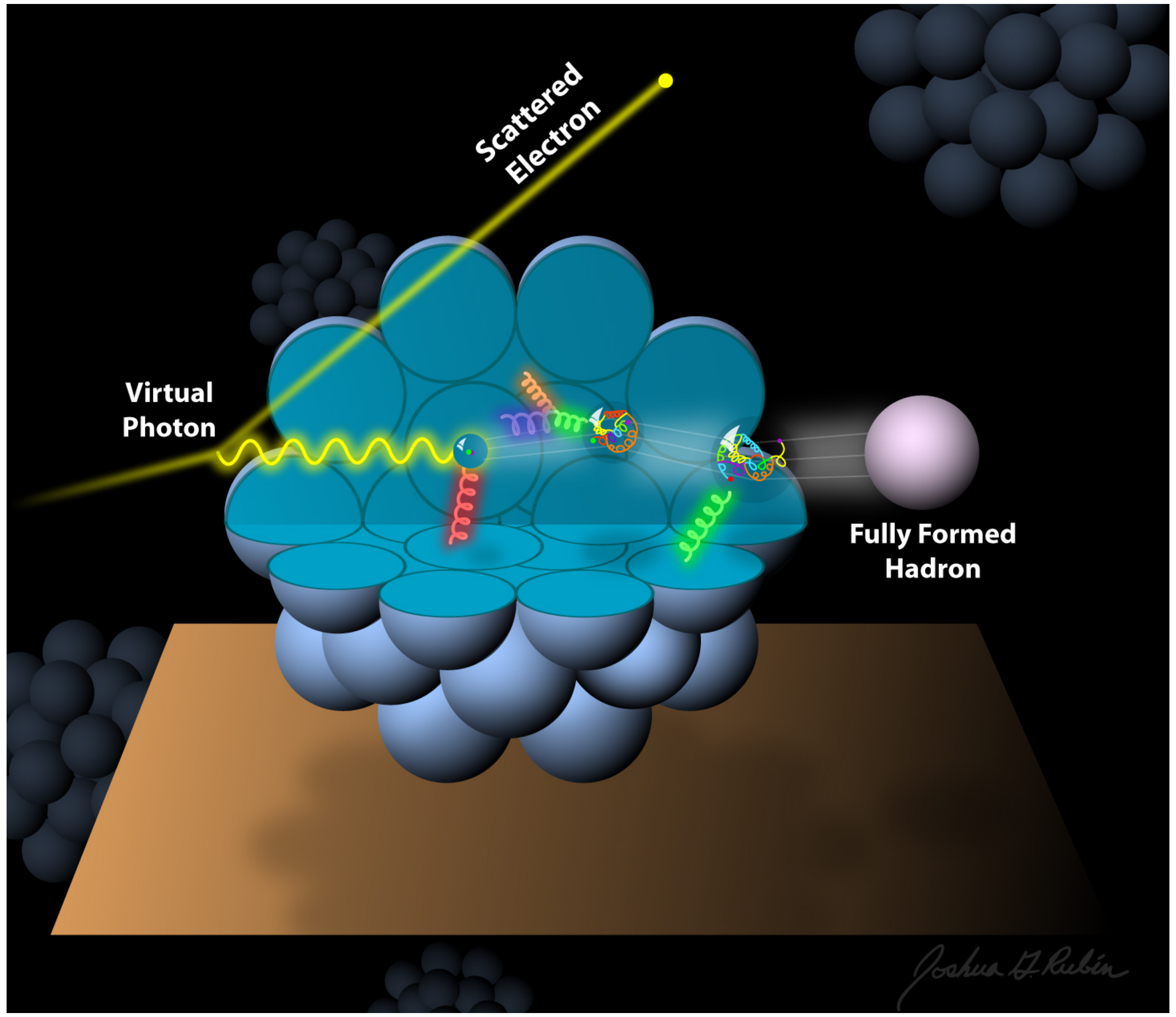

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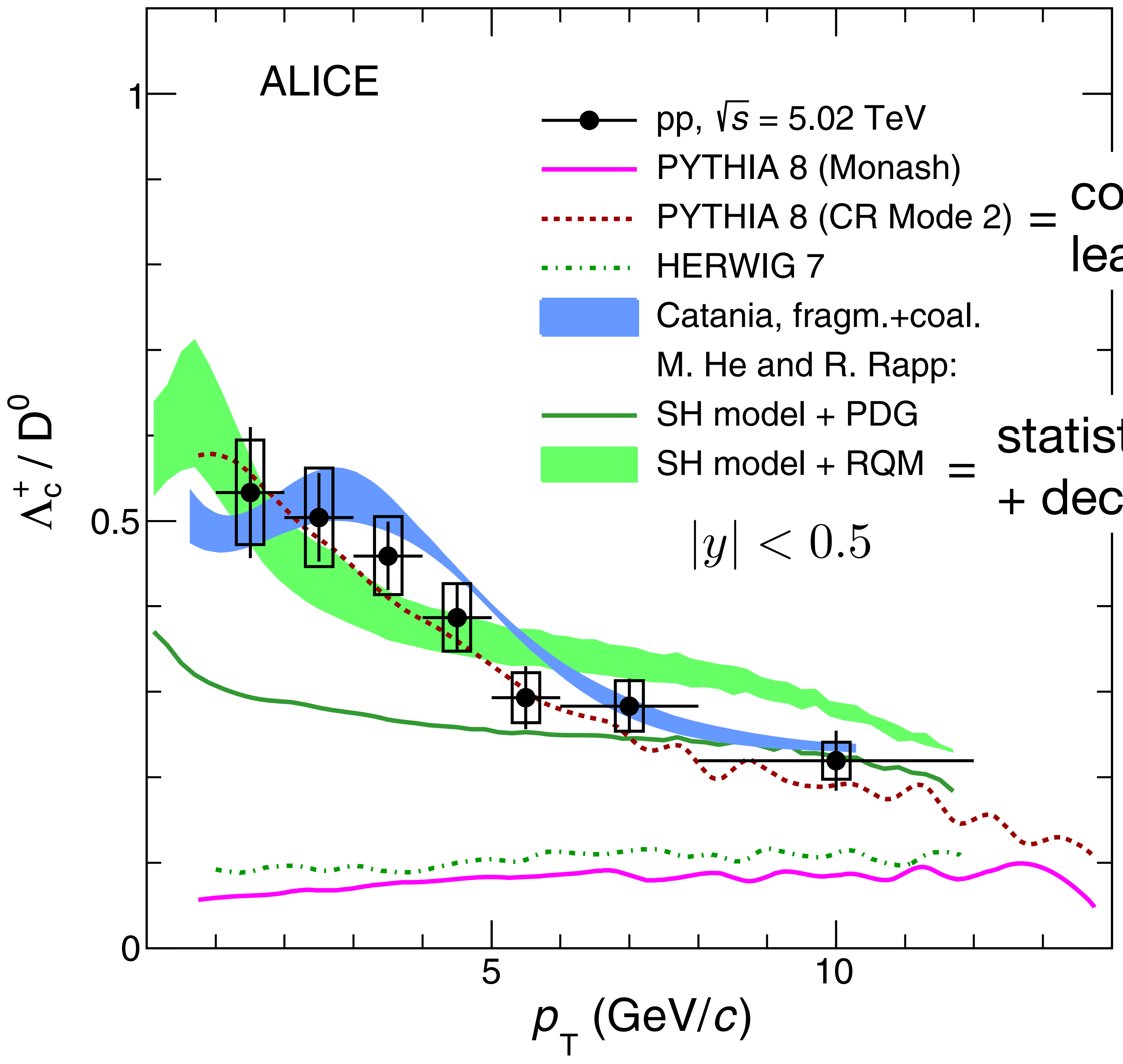
Λ_c^+/D^0

ALICE, Phys. Rev. Lett. **127** (2021) 202301



= colour reconnection beyond the leading-colour approximation

= statistical hadronisation model + decaying excited states

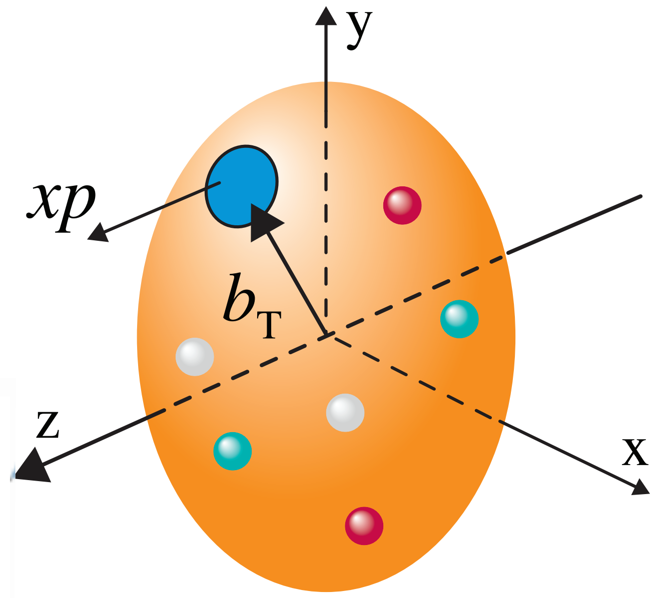
- Decrease with p_T

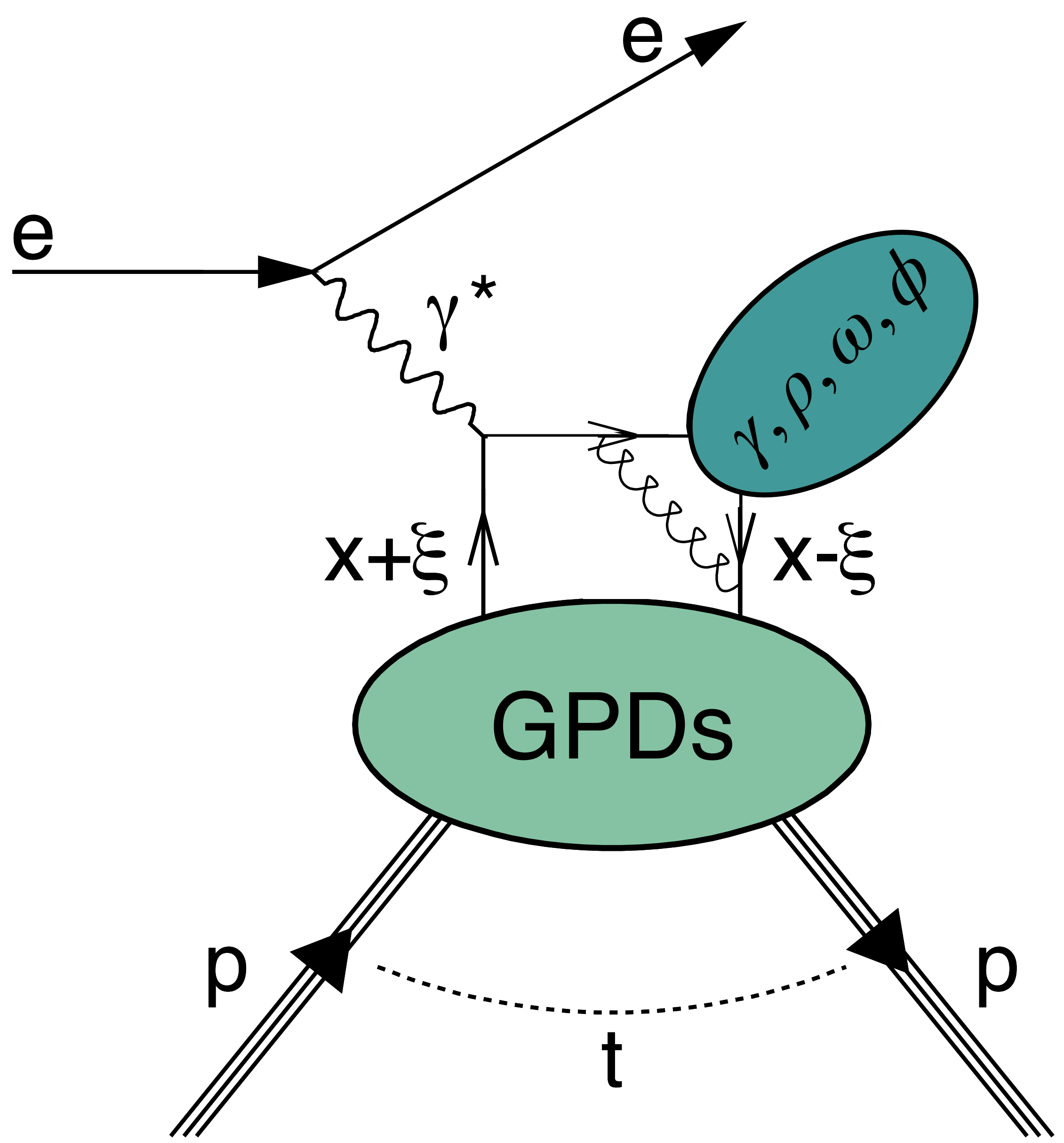
→ suggests difference for meson and baryon formation

- Larger than for e^+e^- and ep measurements

→ suggest additional mechanisms in hadron-hadron collisions

GPDs at the EIC and LHC





Hard exclusive meson production
Hard scale=large Q^2

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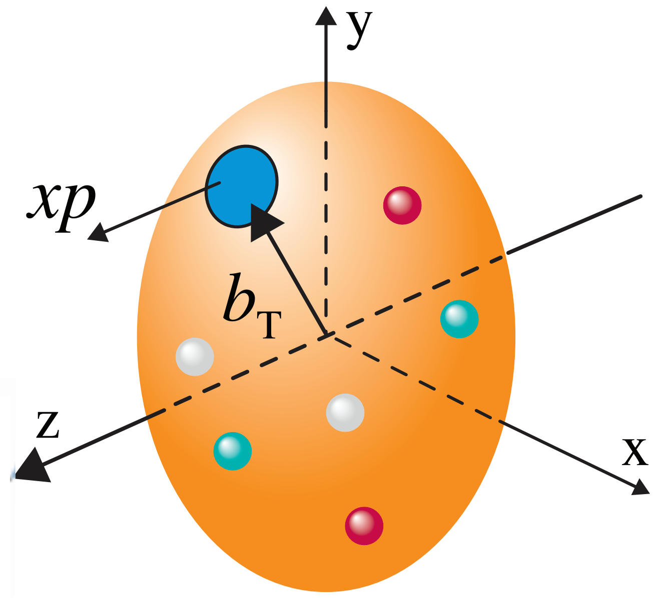

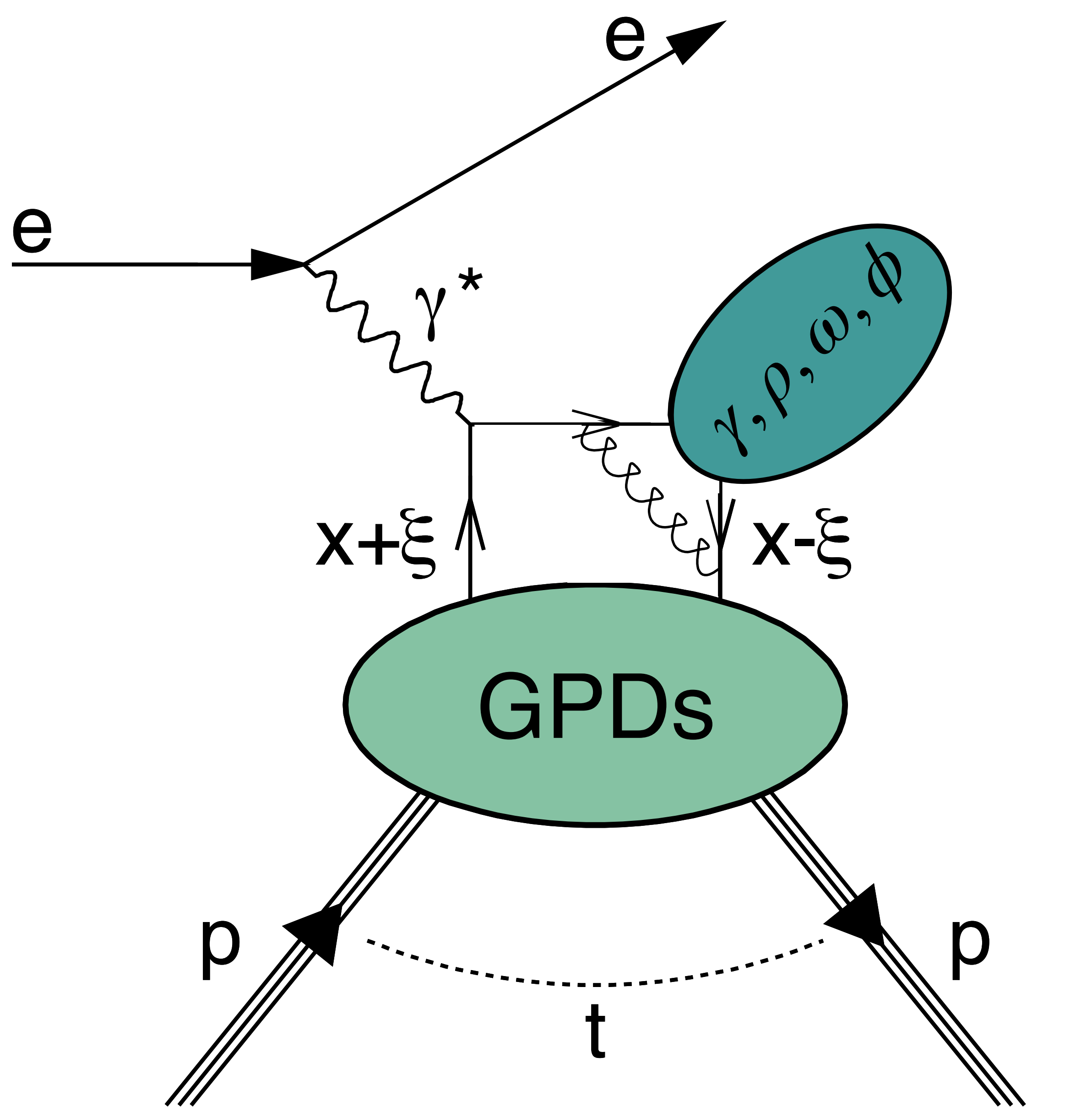

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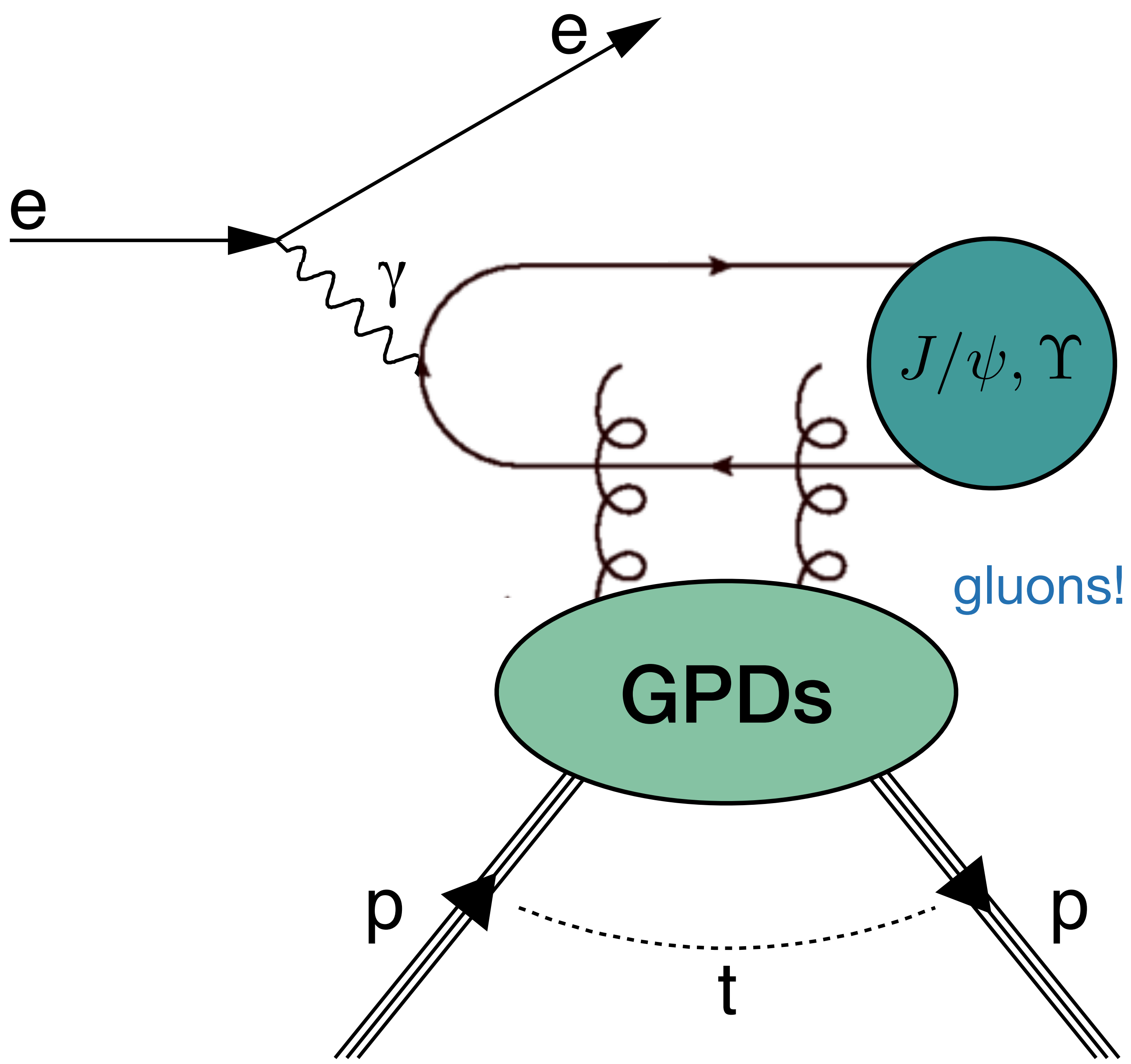
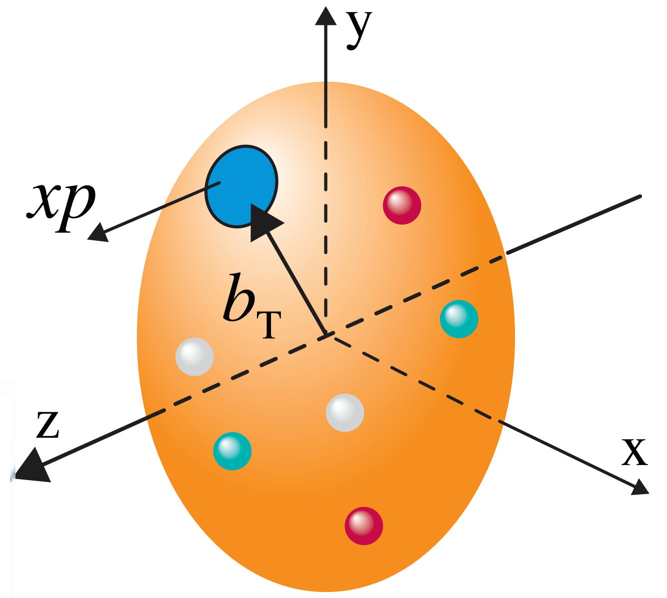
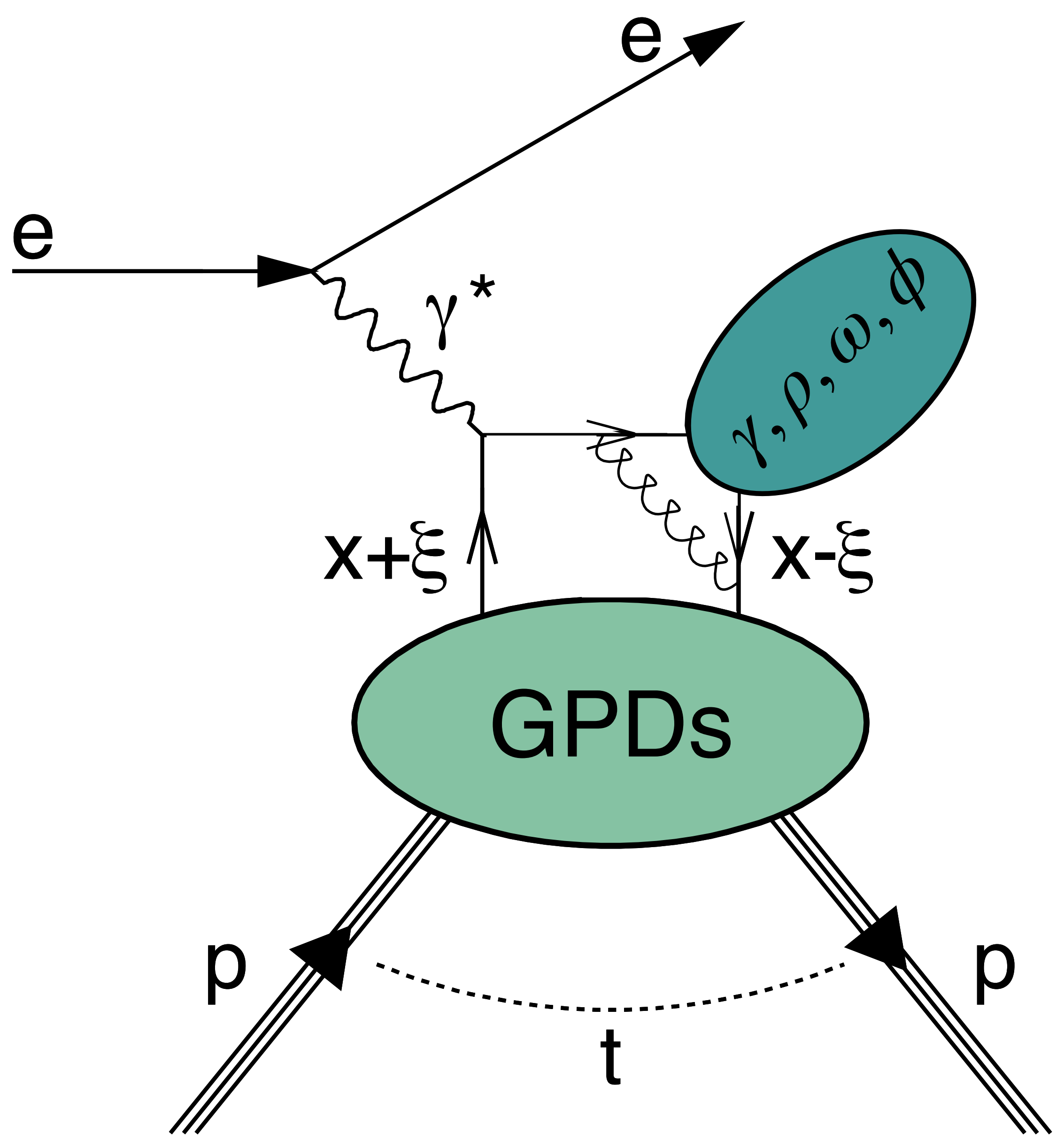


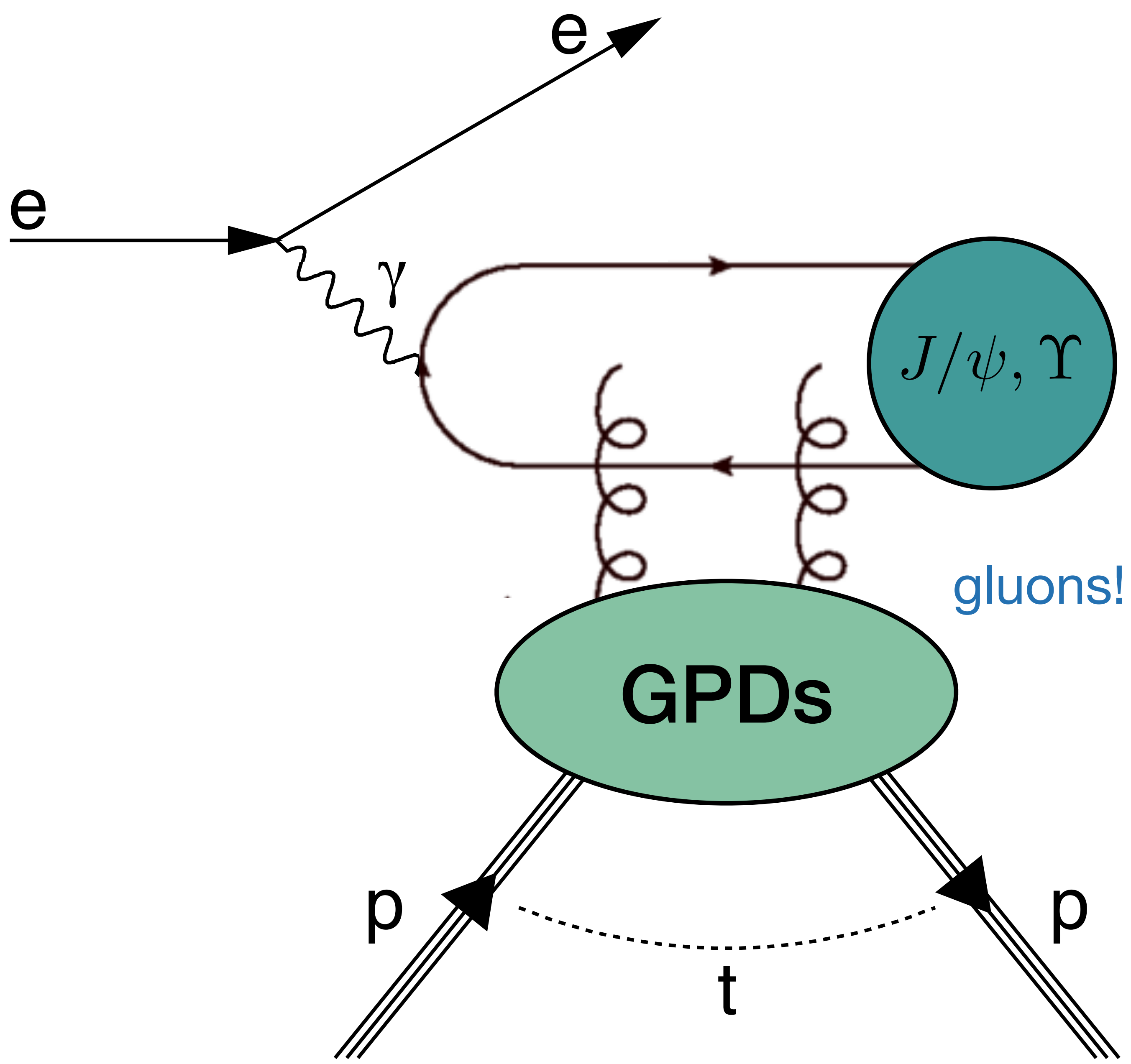
Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

GPDs at the EIC and LHC

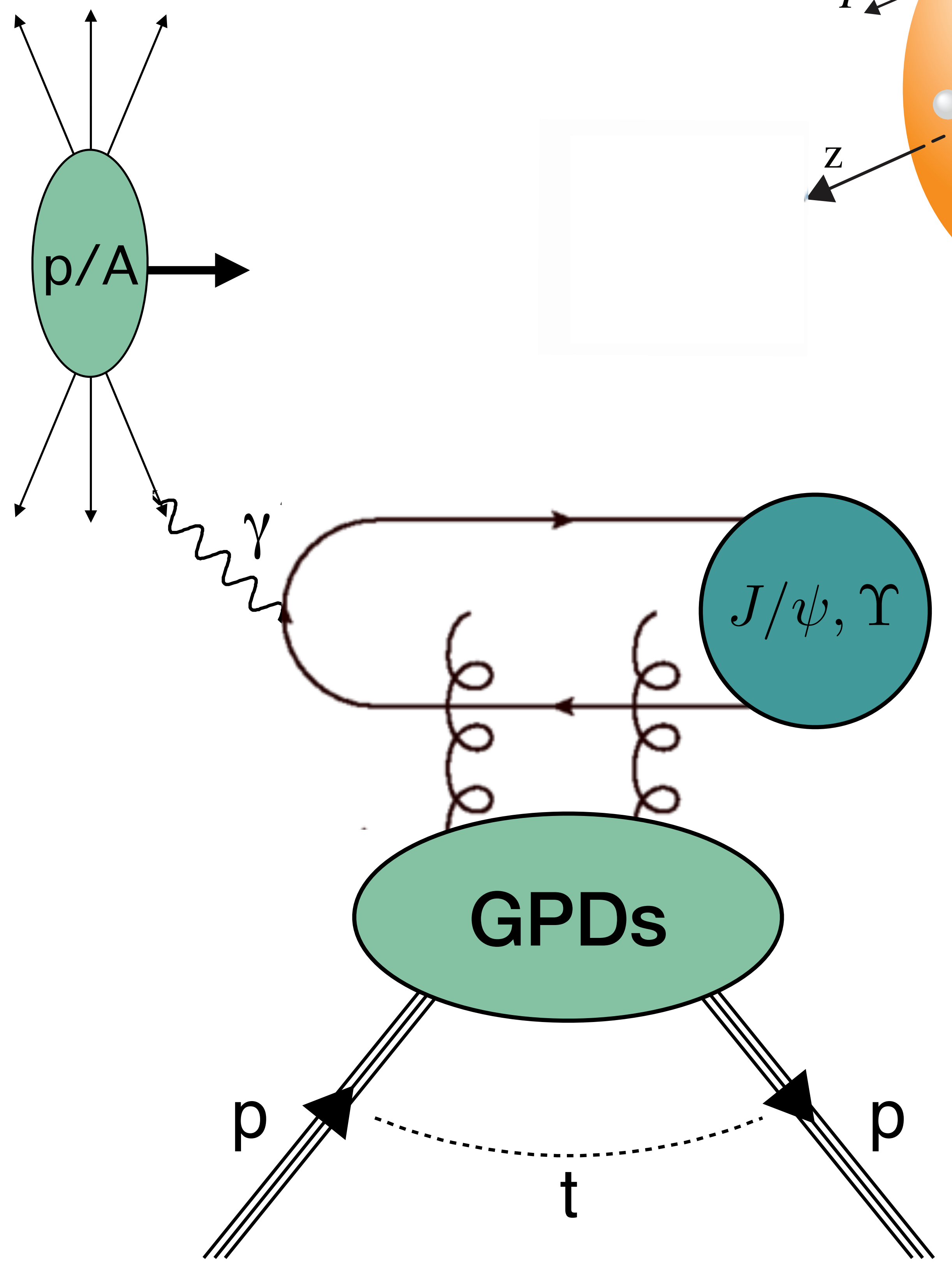




Hard exclusive meson production
Hard scale=large Q^2

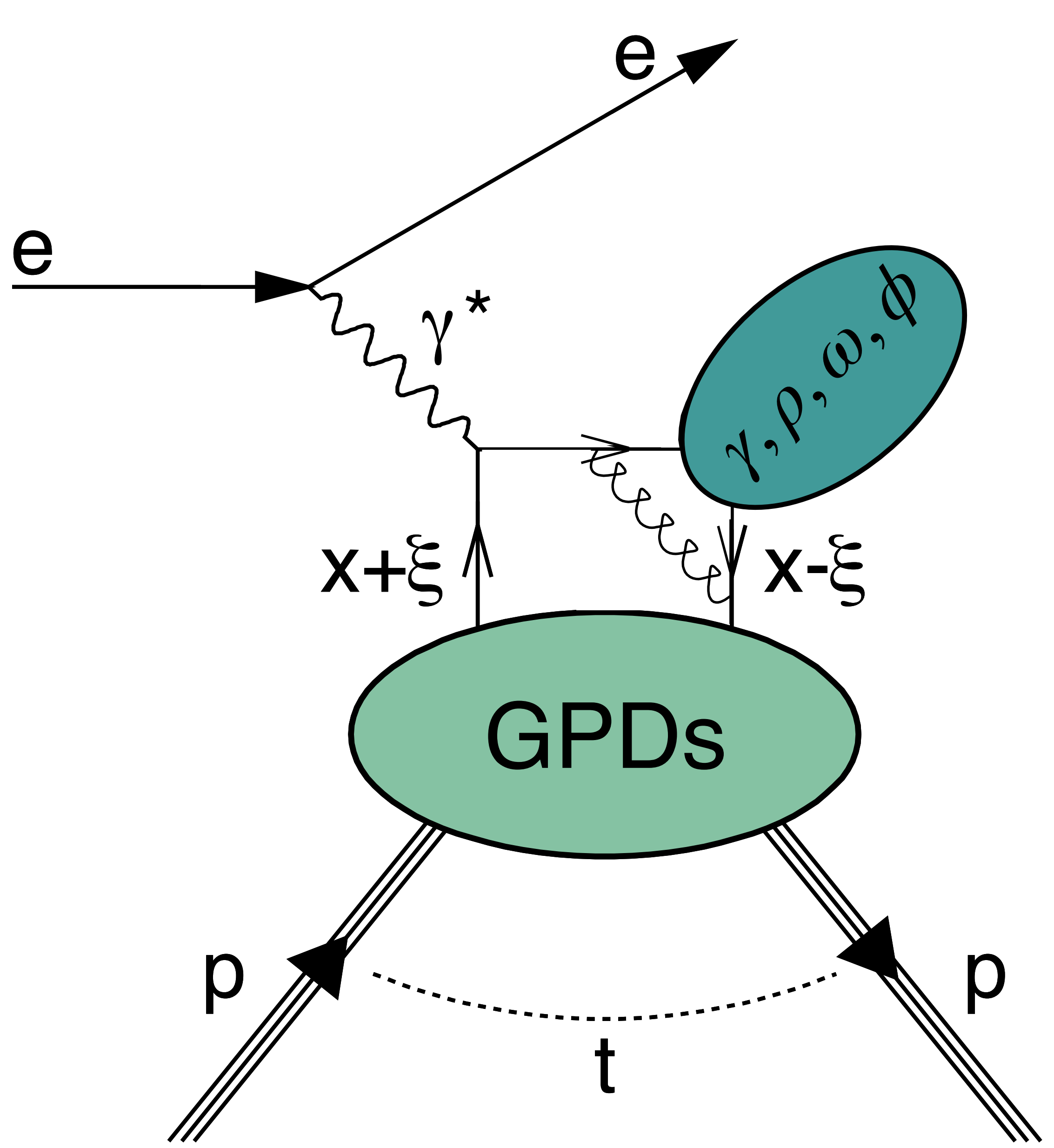


Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass



Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

GPDs at the EIC and LHC



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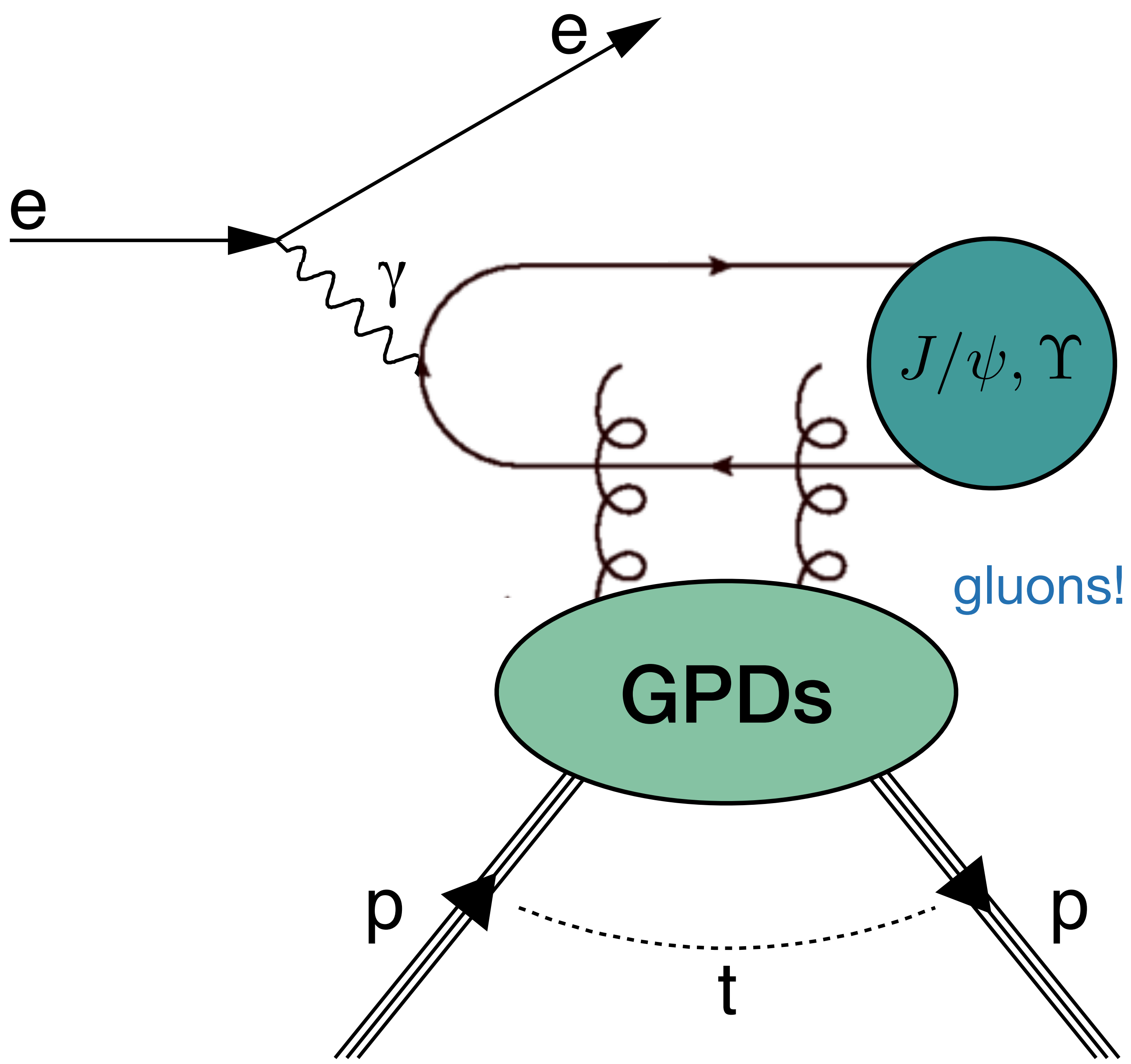

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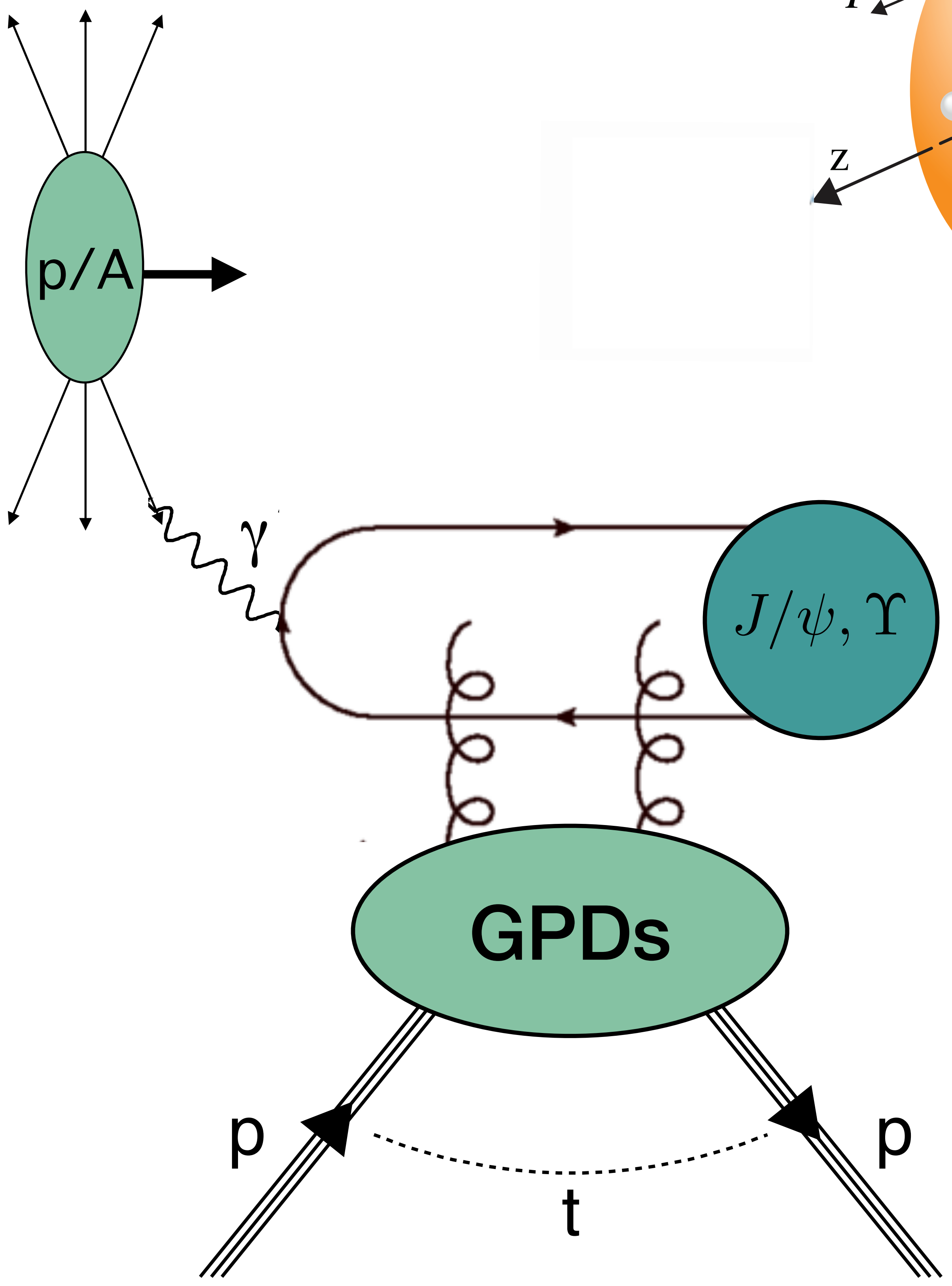
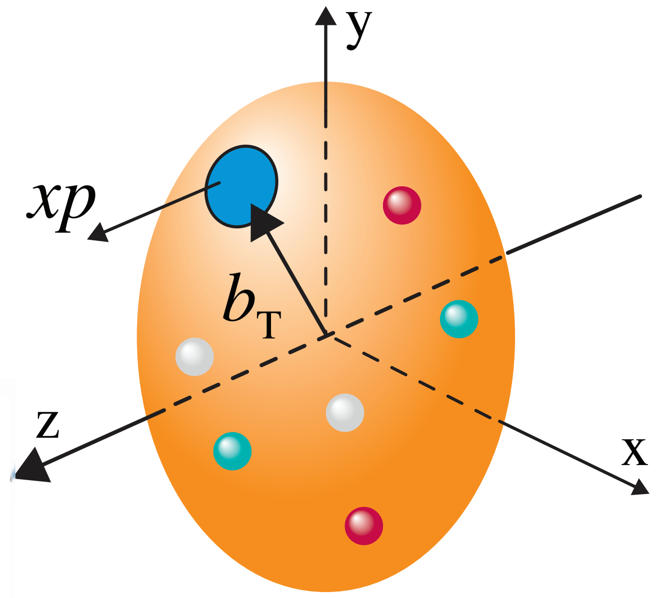
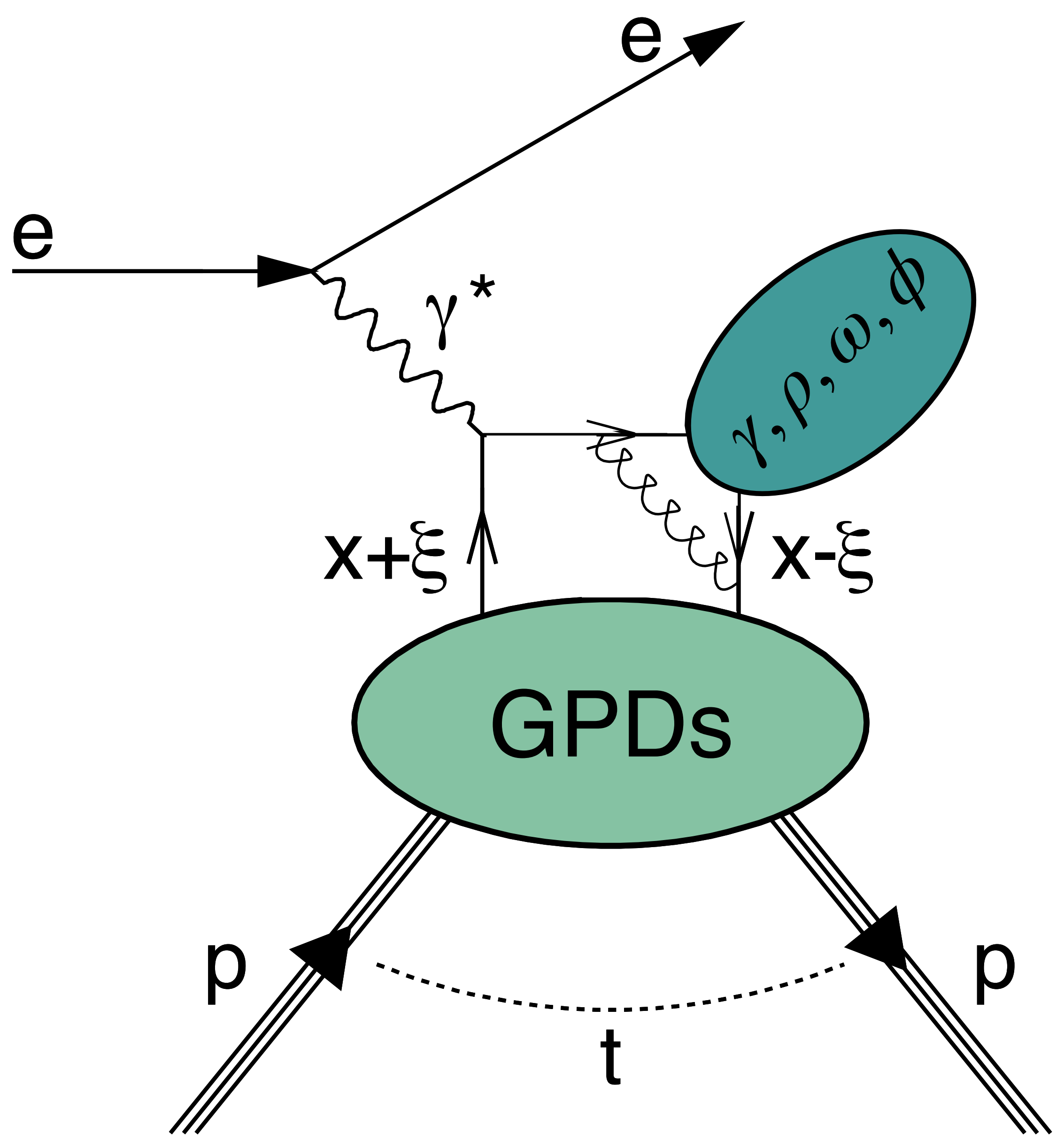


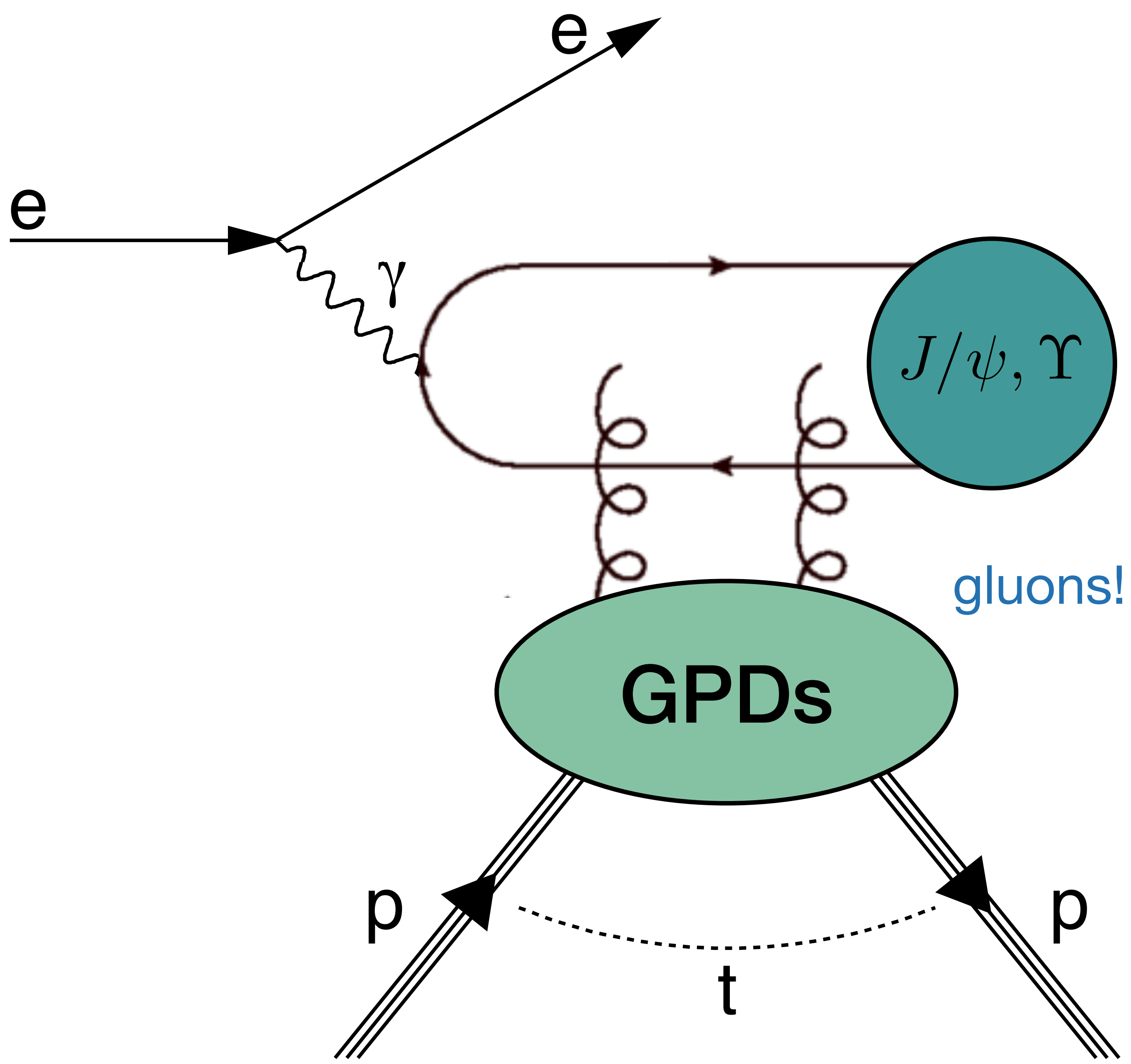


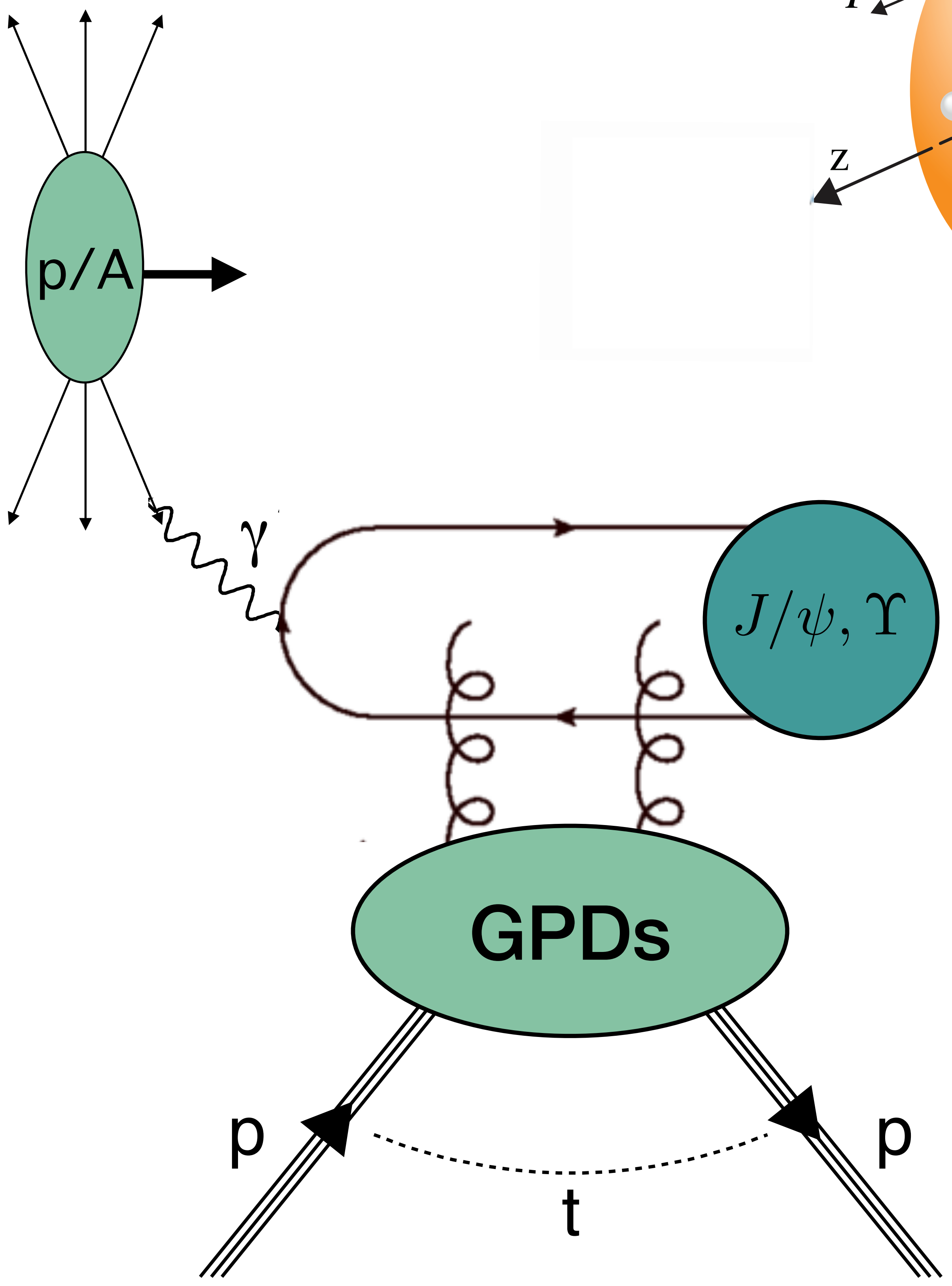
Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

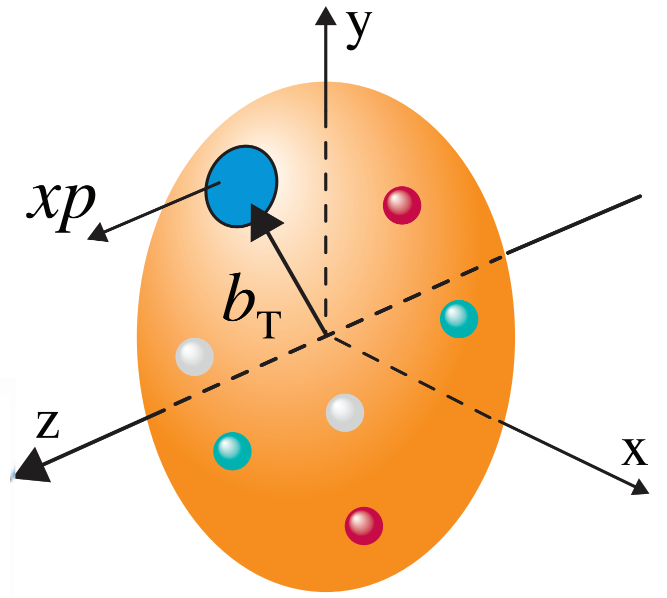
down to $x_B=10^{-4}$ at HERA/EIC

GPDs at the EIC and LHC









Hard exclusive meson production
Hard scale=large Q^2

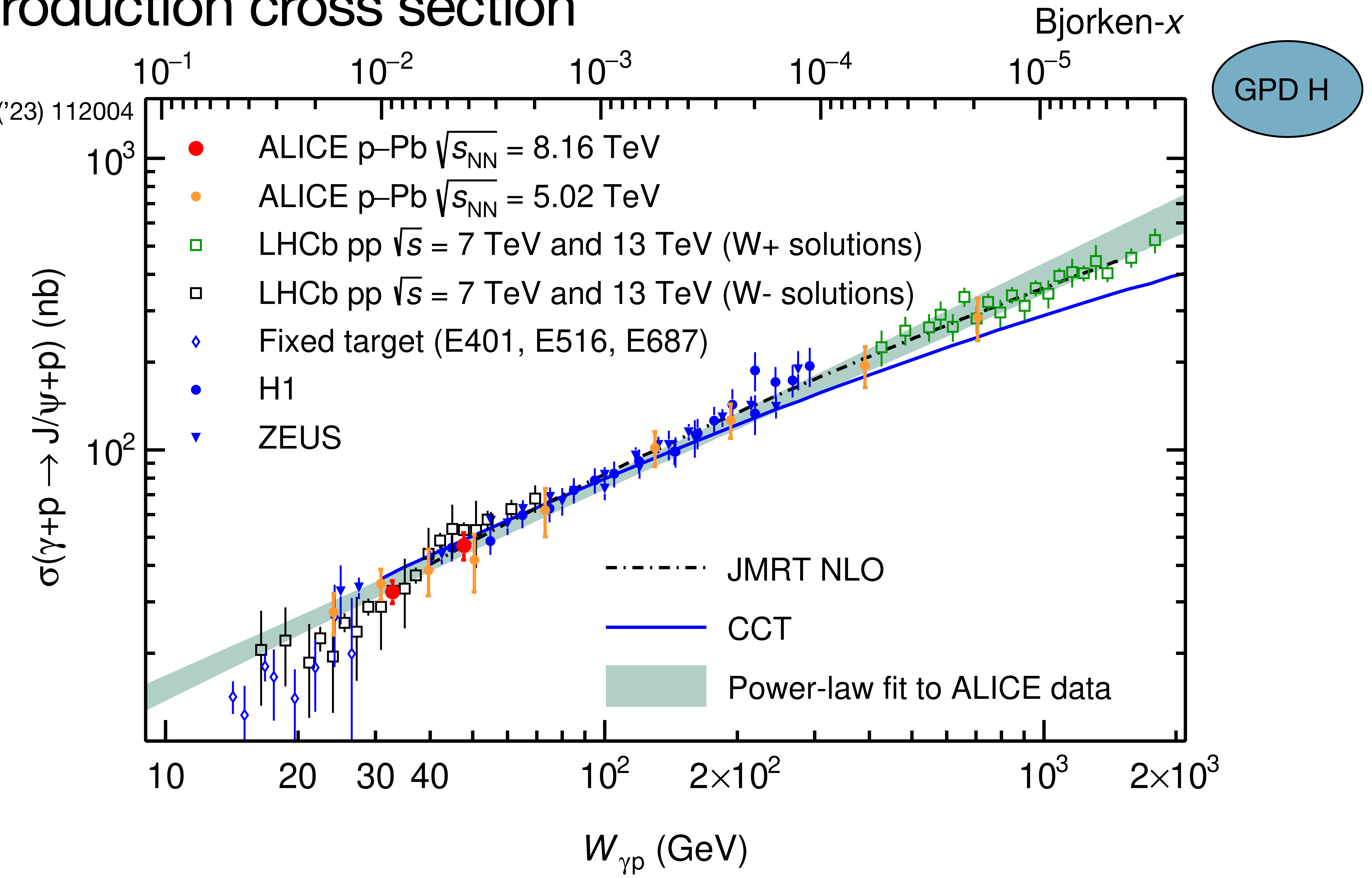
Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

down to $x_B=10^{-4}$ at HERA/EIC

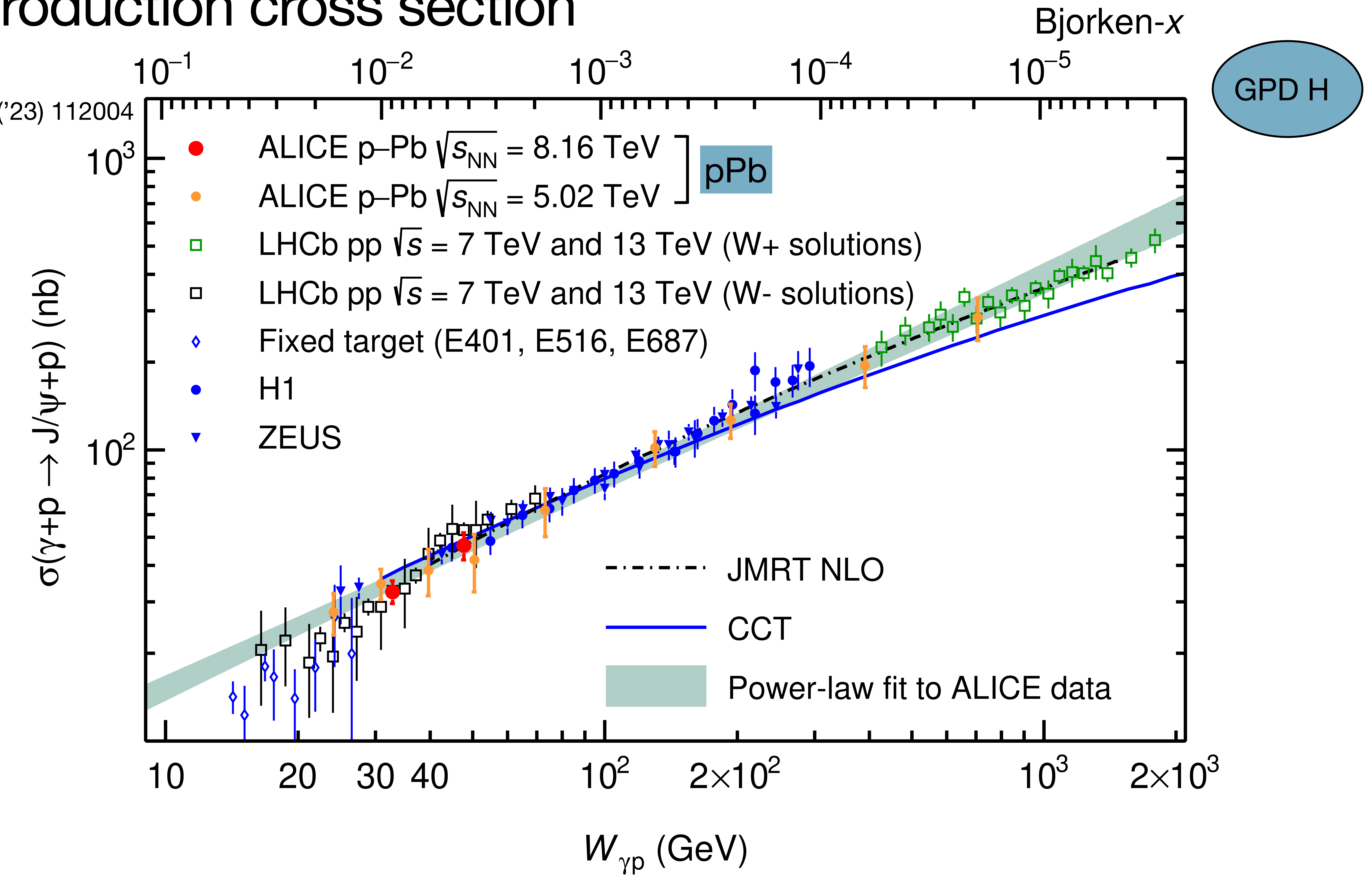
down to $x_B=10^{-6}$ at LHC!

J/ψ photoproduction cross section

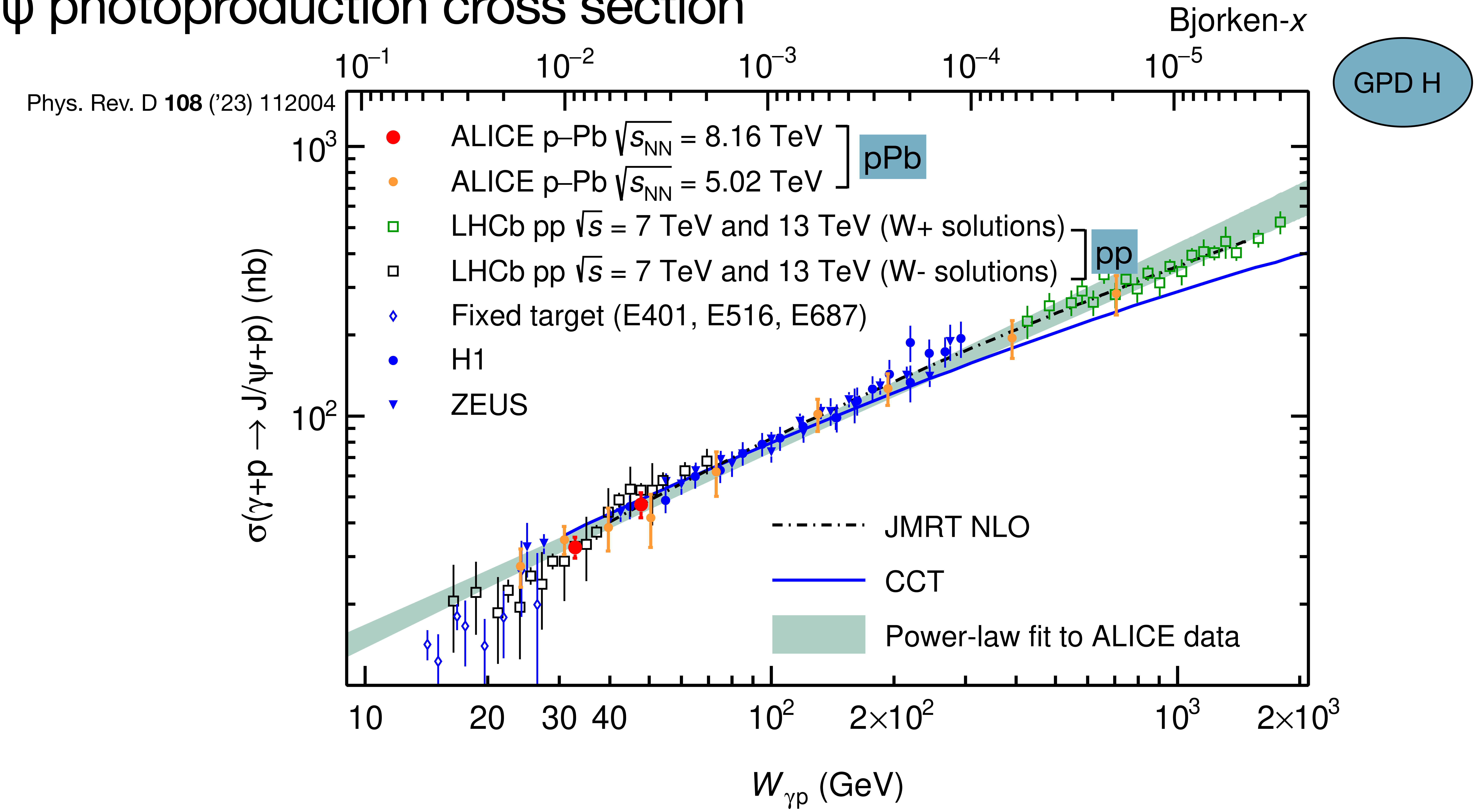


J/ψ photoproduction cross section

Phys. Rev. D **108** ('23) 112004



J/ψ photoproduction cross section



J/ψ photoproduction cross section

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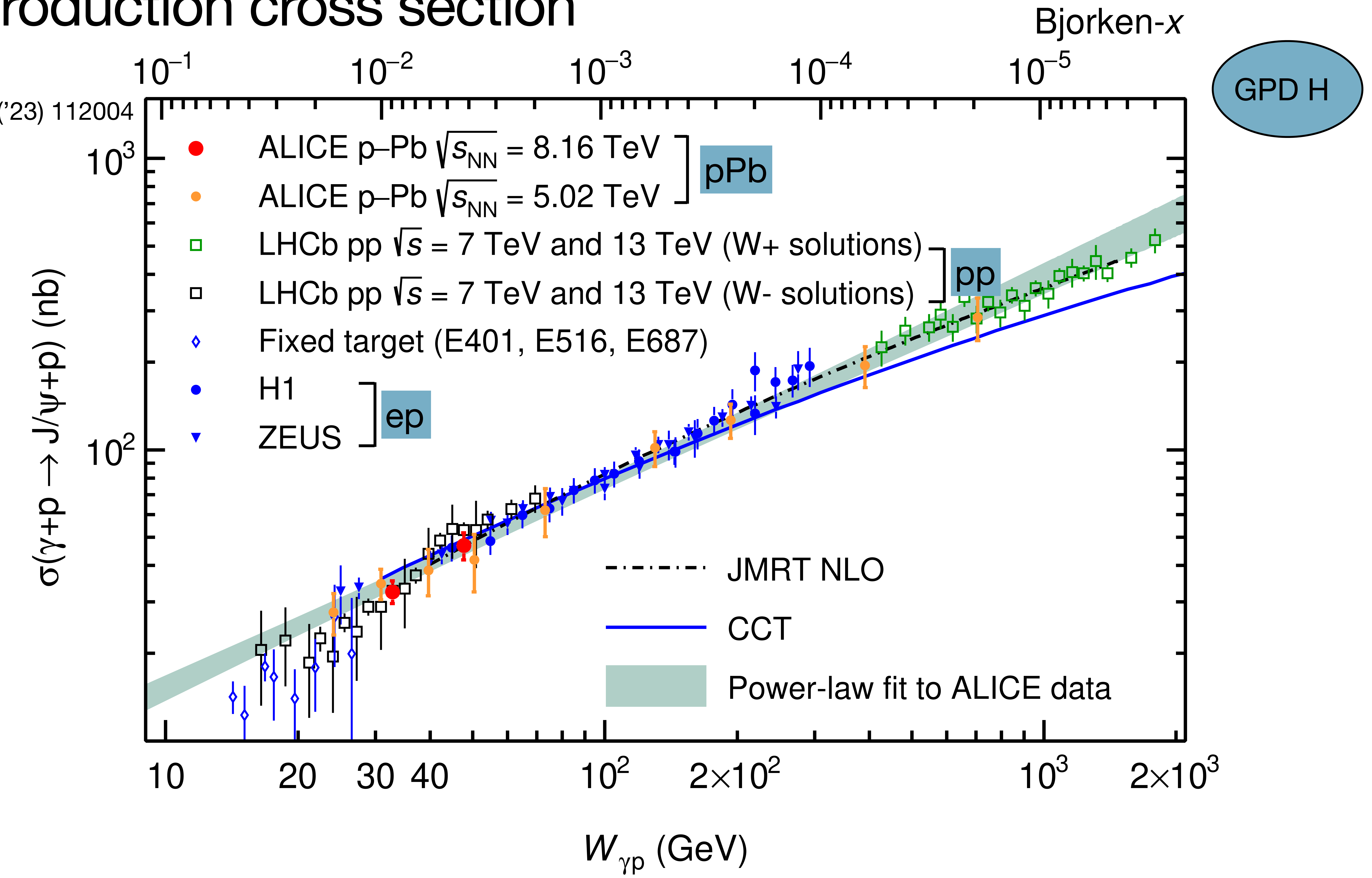

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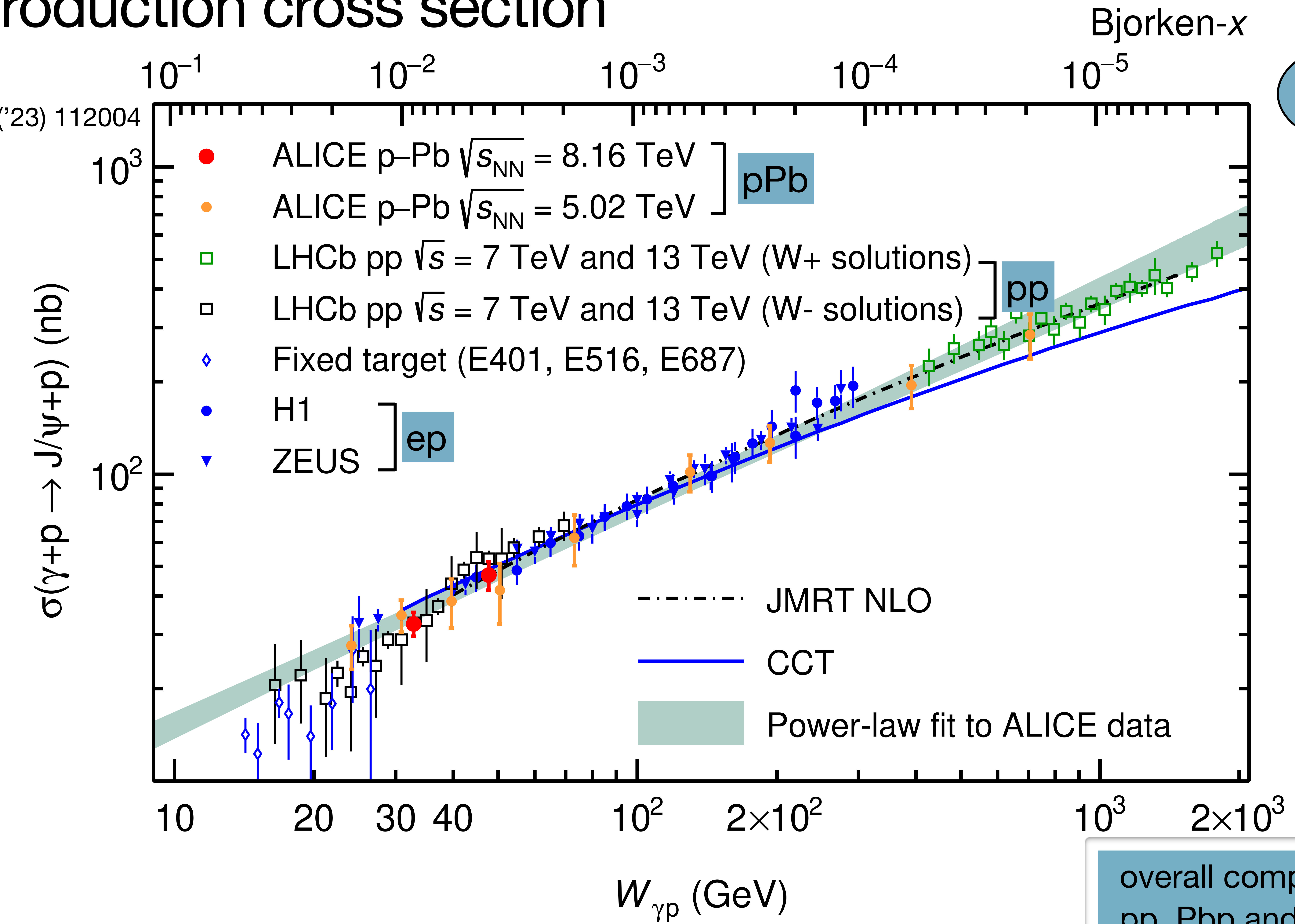
Phys. Rev. D **108** ('23) 112004

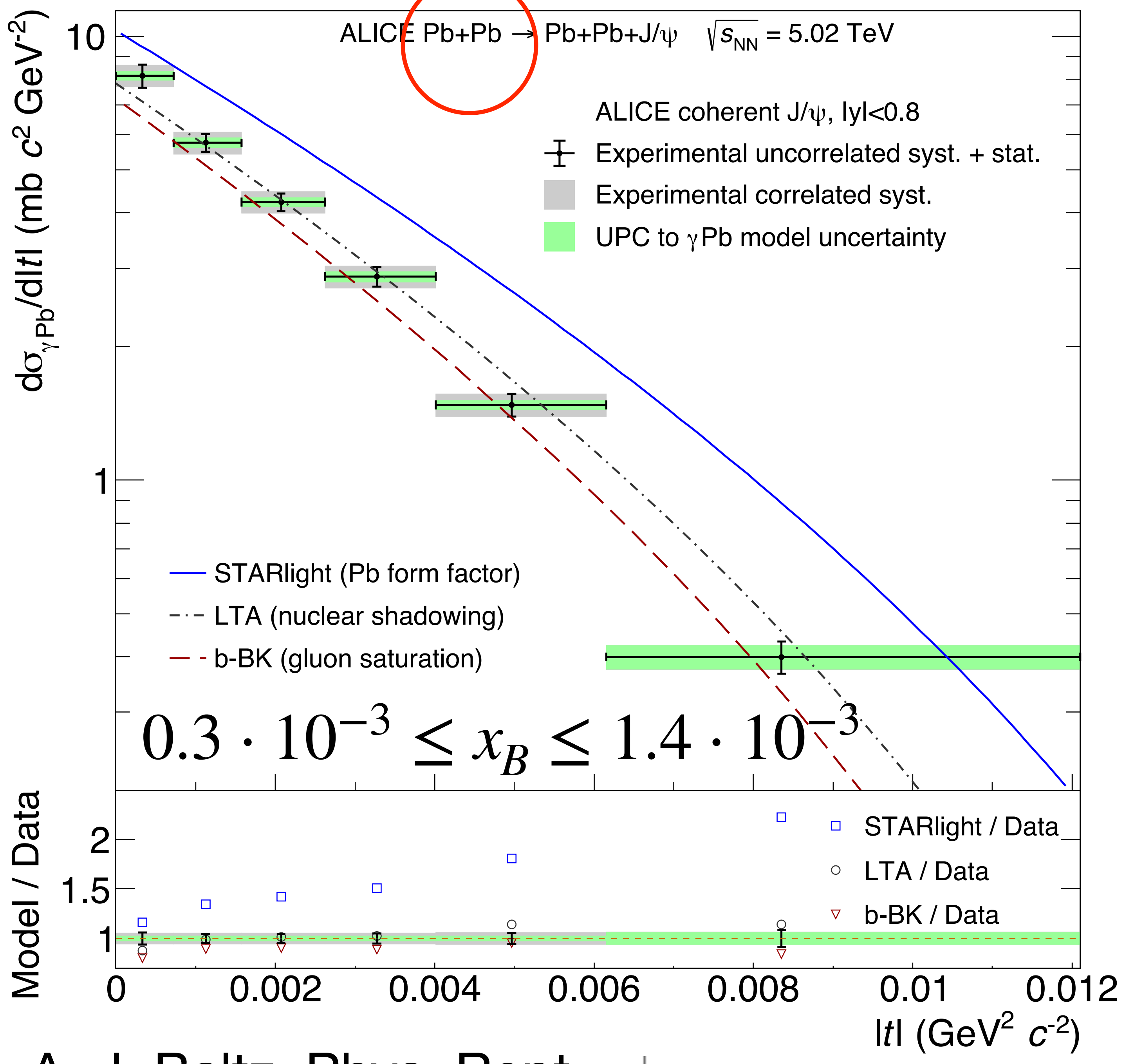


GPD H

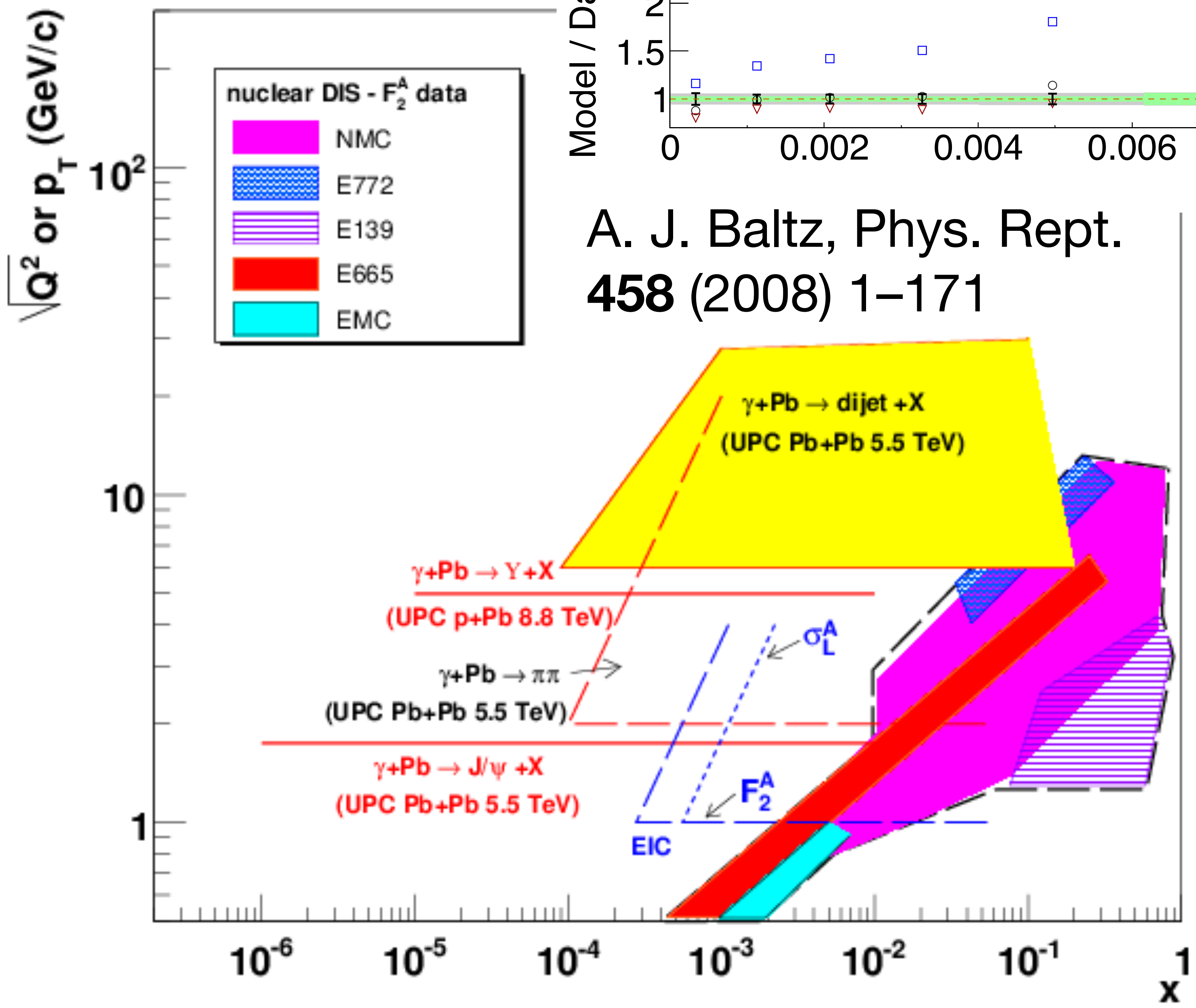
overall compatibility between pp, Pbp and ep data: hint of universality of underlying physics

GPDs at LHC and the EIC

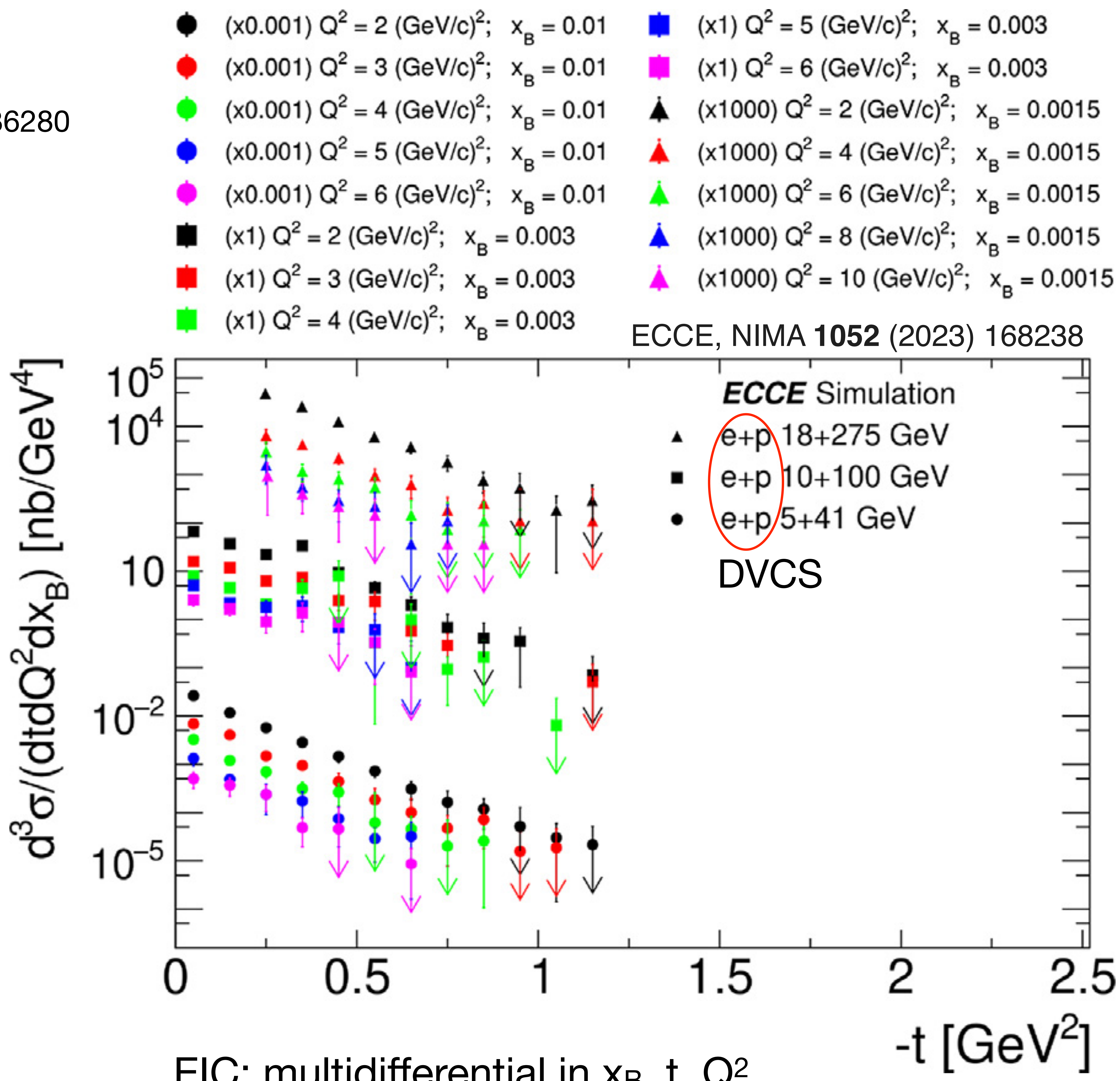
ALICE, Phys. Lett. B **817** (2021) 136280



A. J. Baltz, Phys. Rept. **458** (2008) 1–171



ECCE, NIMA **1052** (2023) 168238



EIC: multidifferential in x_B, t, Q^2
with detection of scattered proton

Polarisation and angles

- for spin-1/2 hadron:

Four parton helicity-conserving twist-2 GPDs

$H(x,\xi,t)$	$E(x,\xi,t)$	parton-spin independent
$\tilde{H}(x,\xi,t)$	$\tilde{E}(x,\xi,t)$	parton-spin dependent
proton helicity non flip	proton helicity flip	

Four parton helicity-flip twist-2 GPDs

$H_T(x,\xi,t)$	$E_T(x,\xi,t)$
$\tilde{H}_T(x,\xi,t)$	$\tilde{E}_T(x,\xi,t)$

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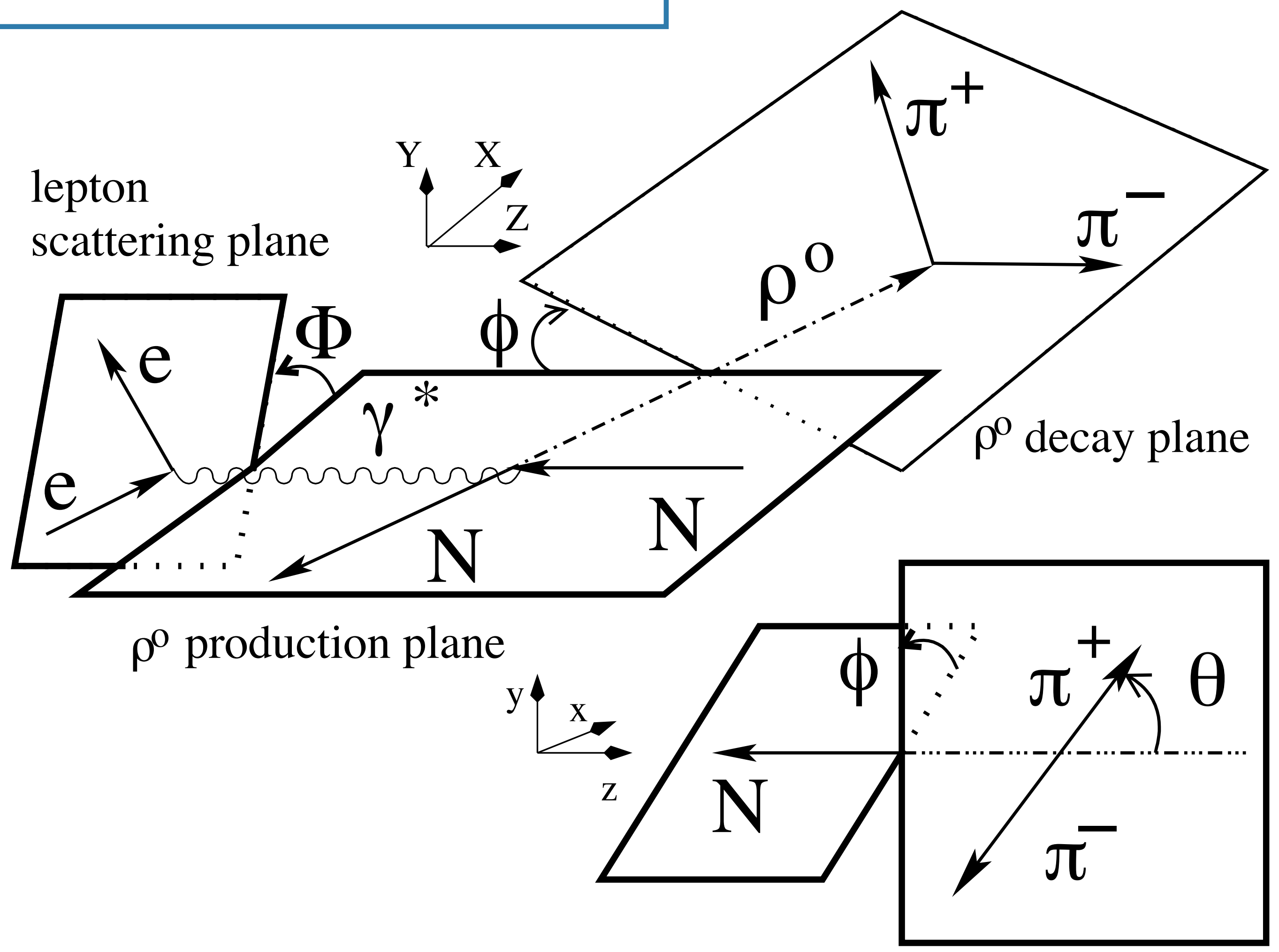
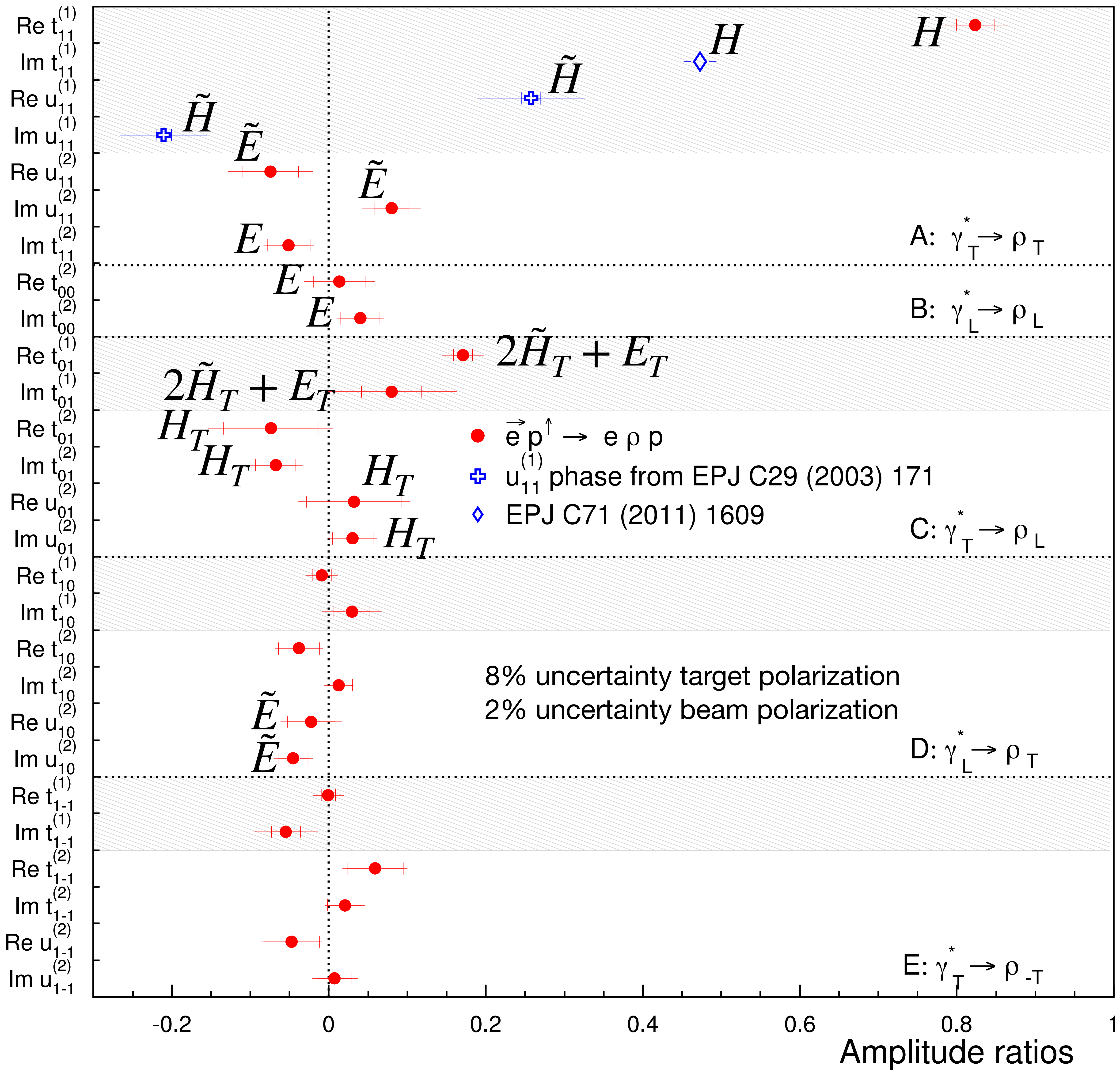


Exclusive ρ on transversely polarised p

Possible at EIC

HERMES, Eur. Phys. J. C **77** (2017) 378



via unpolarised target | via transversely polarised target

Polarisation and angles

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Four parton helicity-conserving twist-2 GPDs

$H(x,\xi,t)$	$E(x,\xi,t)$	parton-spin independent
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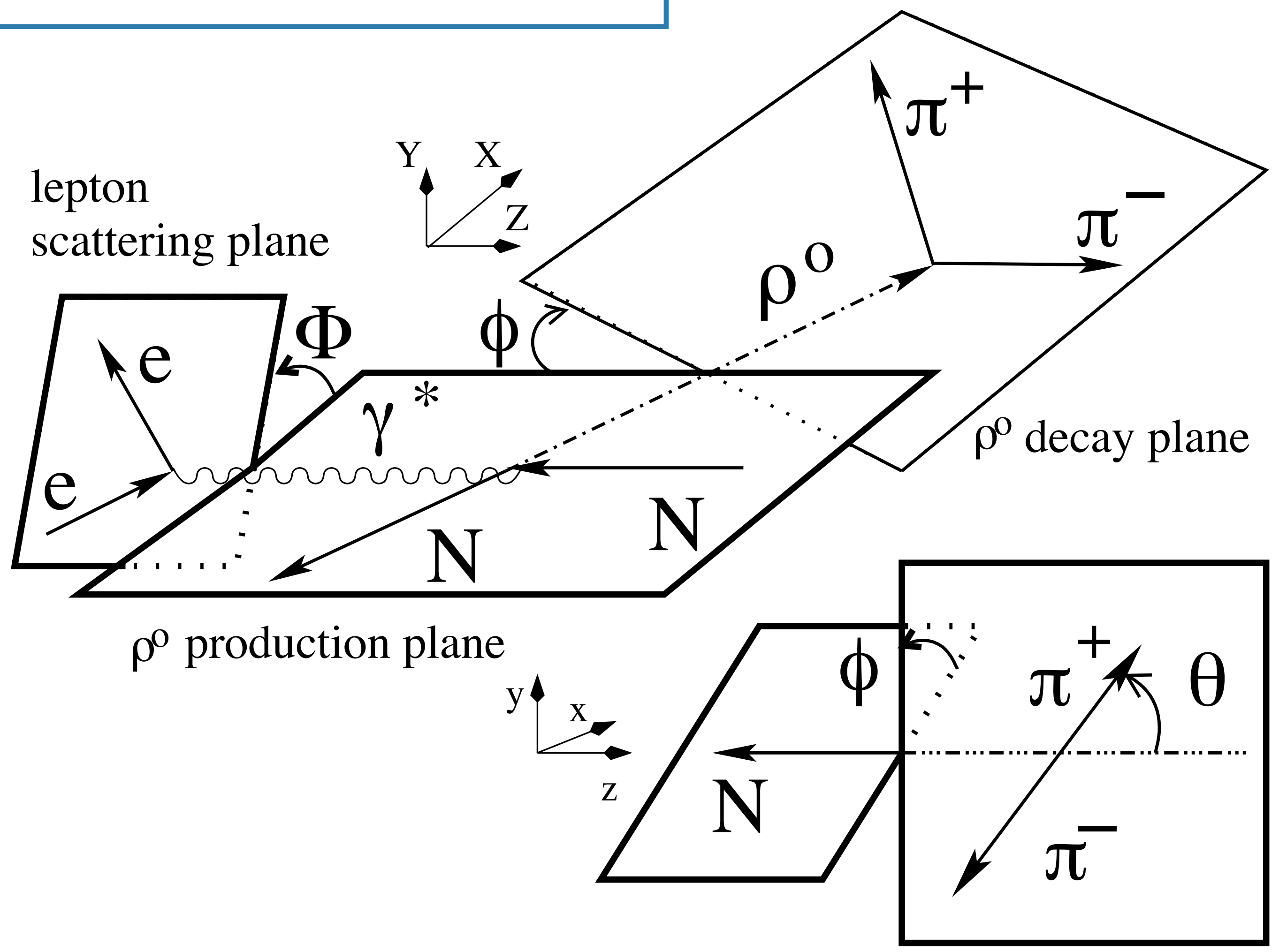

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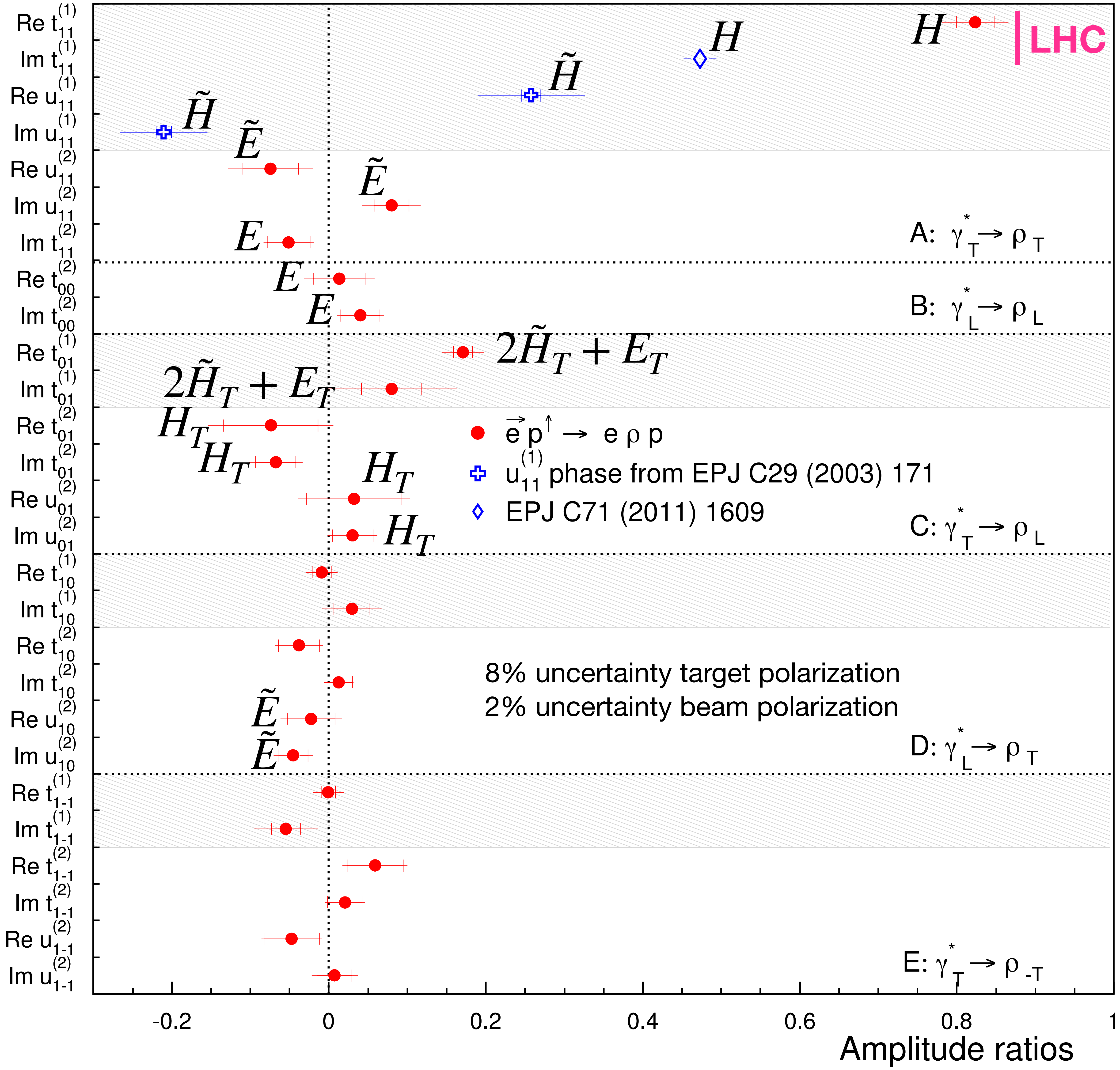

via unpolarised target

via transversely polarised target

Polarisation and angles

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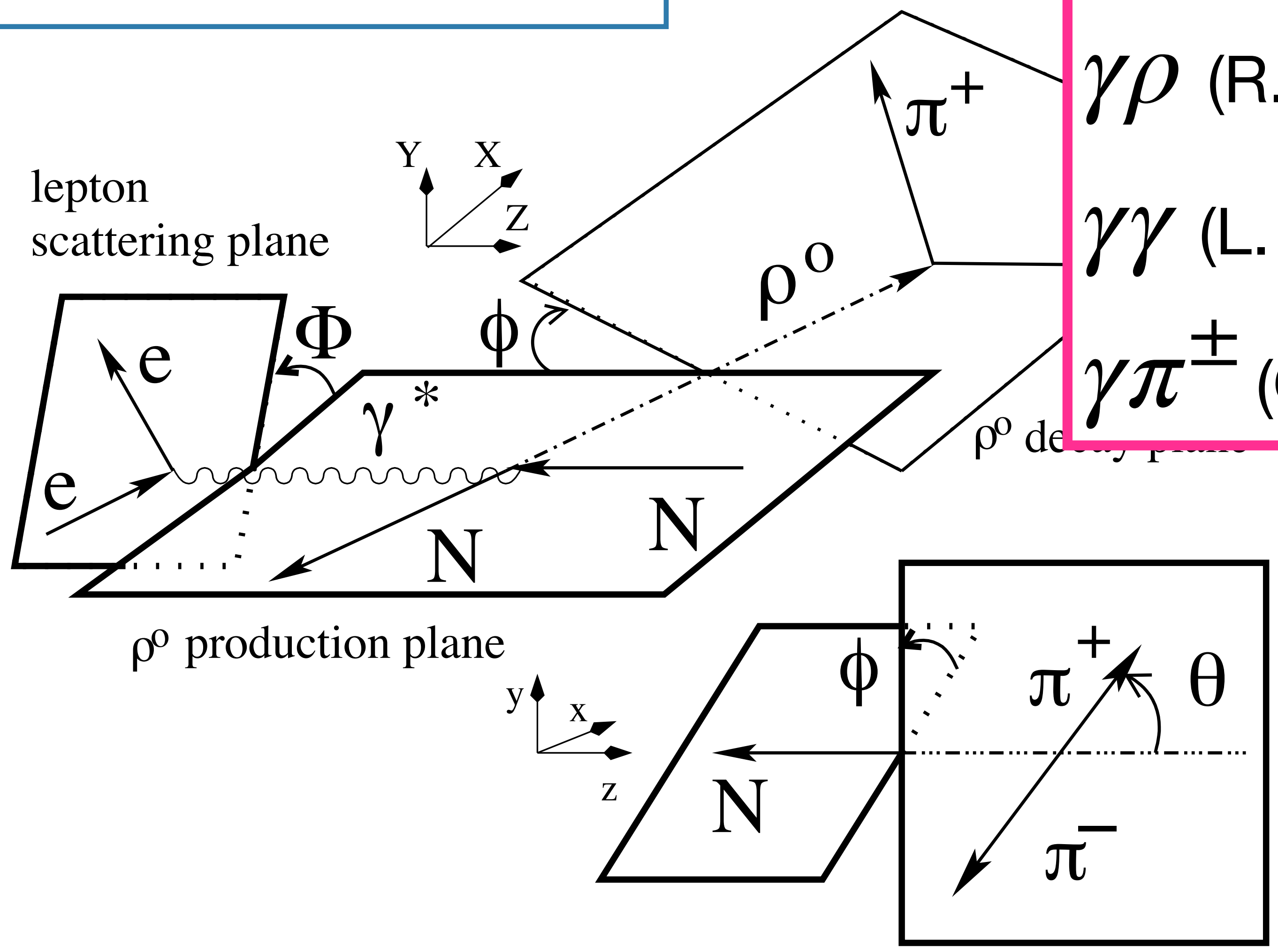

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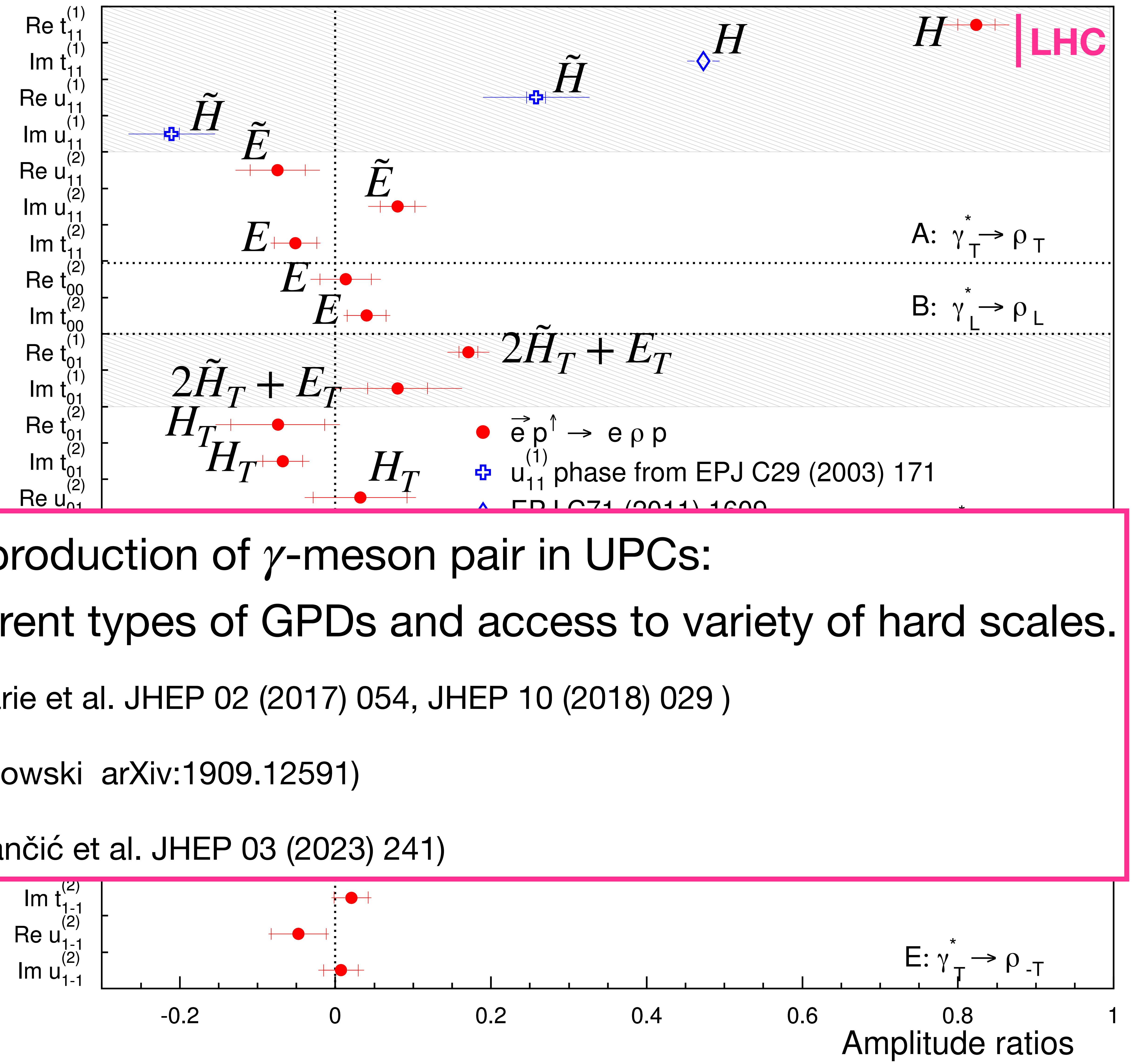


via unpolarised target | via transversely polarised target

Exclusive production of γ-meson pair in UPCs:
probe different types of GPDs and access to variety of hard scales.

$\gamma\rho$ (R. Boussarie et al. JHEP 02 (2017) 054, JHEP 10 (2018) 029)

$\gamma\gamma$ (L. Szymanowski arXiv:1909.12591)

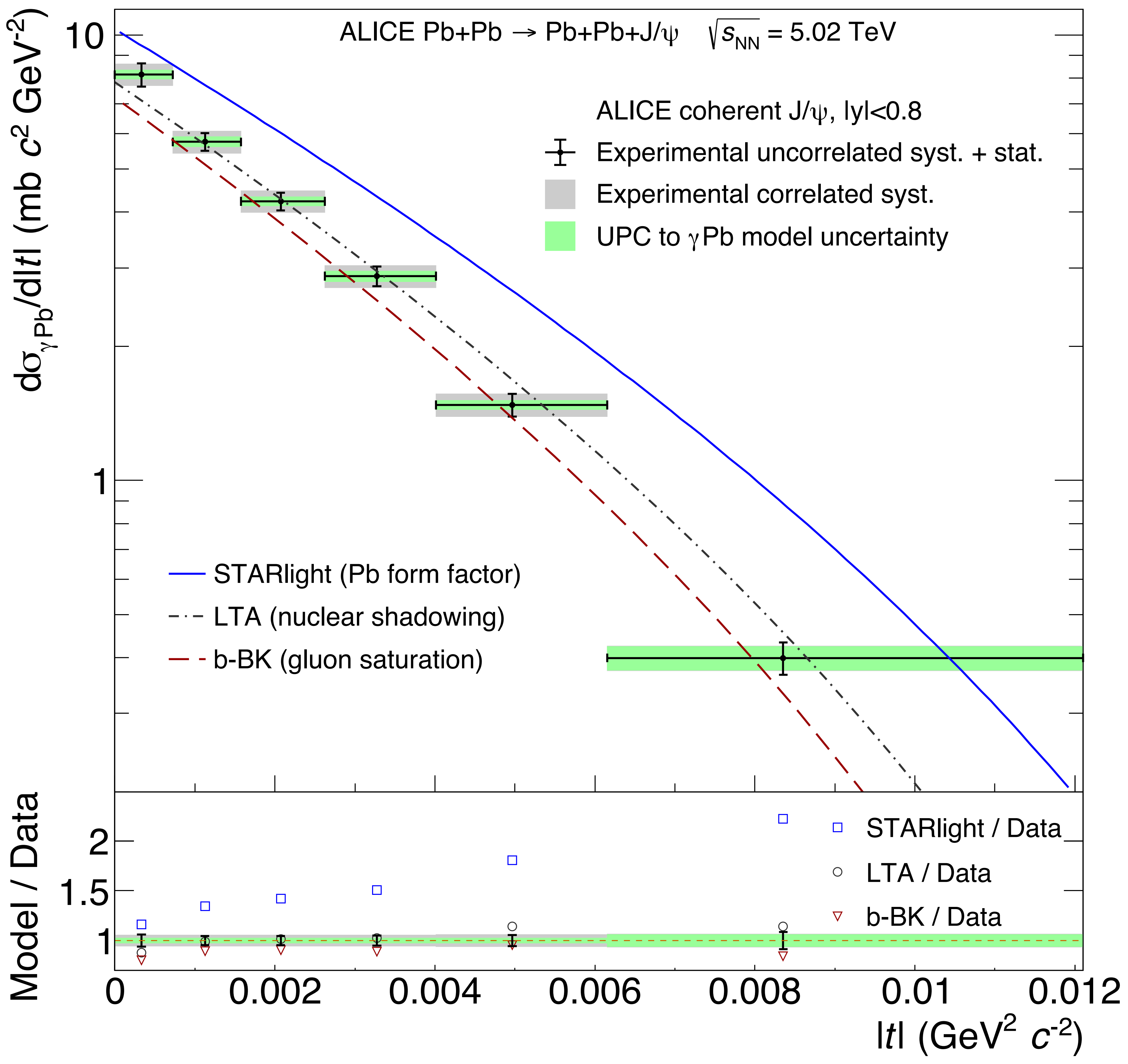
$\gamma\pi^{\pm}$ (G. Duplančić et al. JHEP 03 (2023) 241)

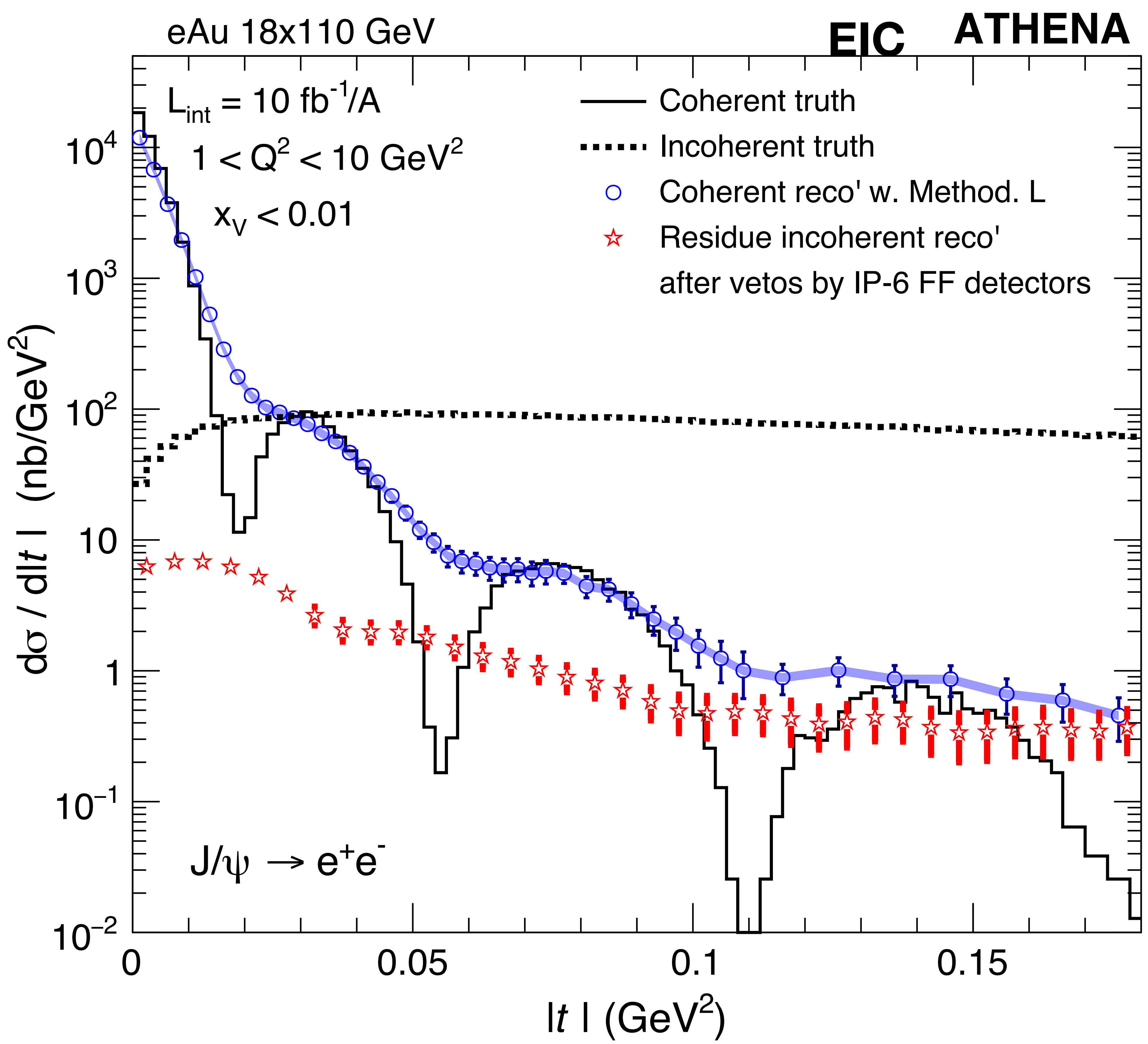
Diffractive measurements on nuclei

→ probe gluon saturation

→ nuclear imaging in position space:

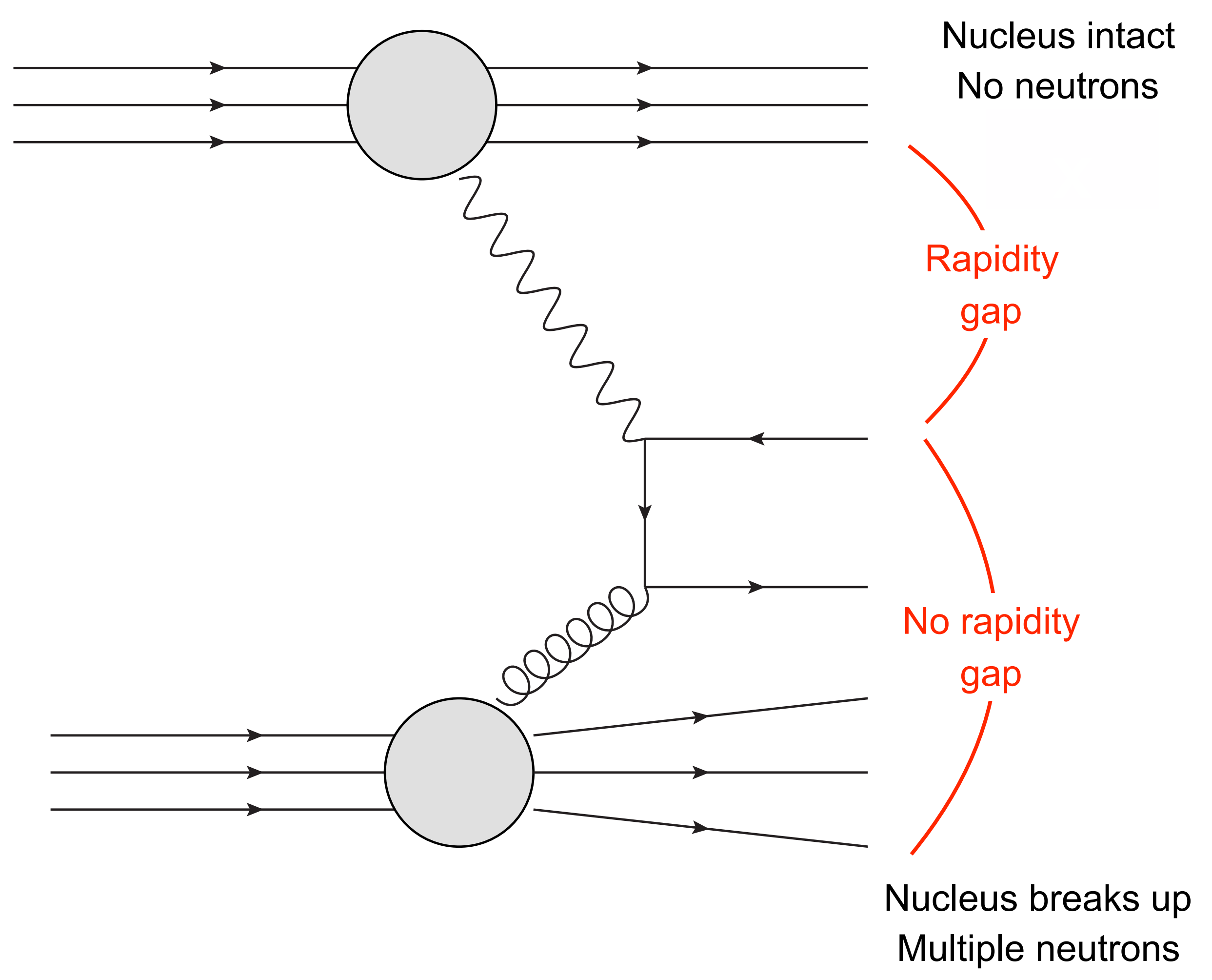
ALICE, Phys. Lett. B **817** (2021) 136280





Inclusive photoproduction at the LHC

Dijets in PbPb collisions



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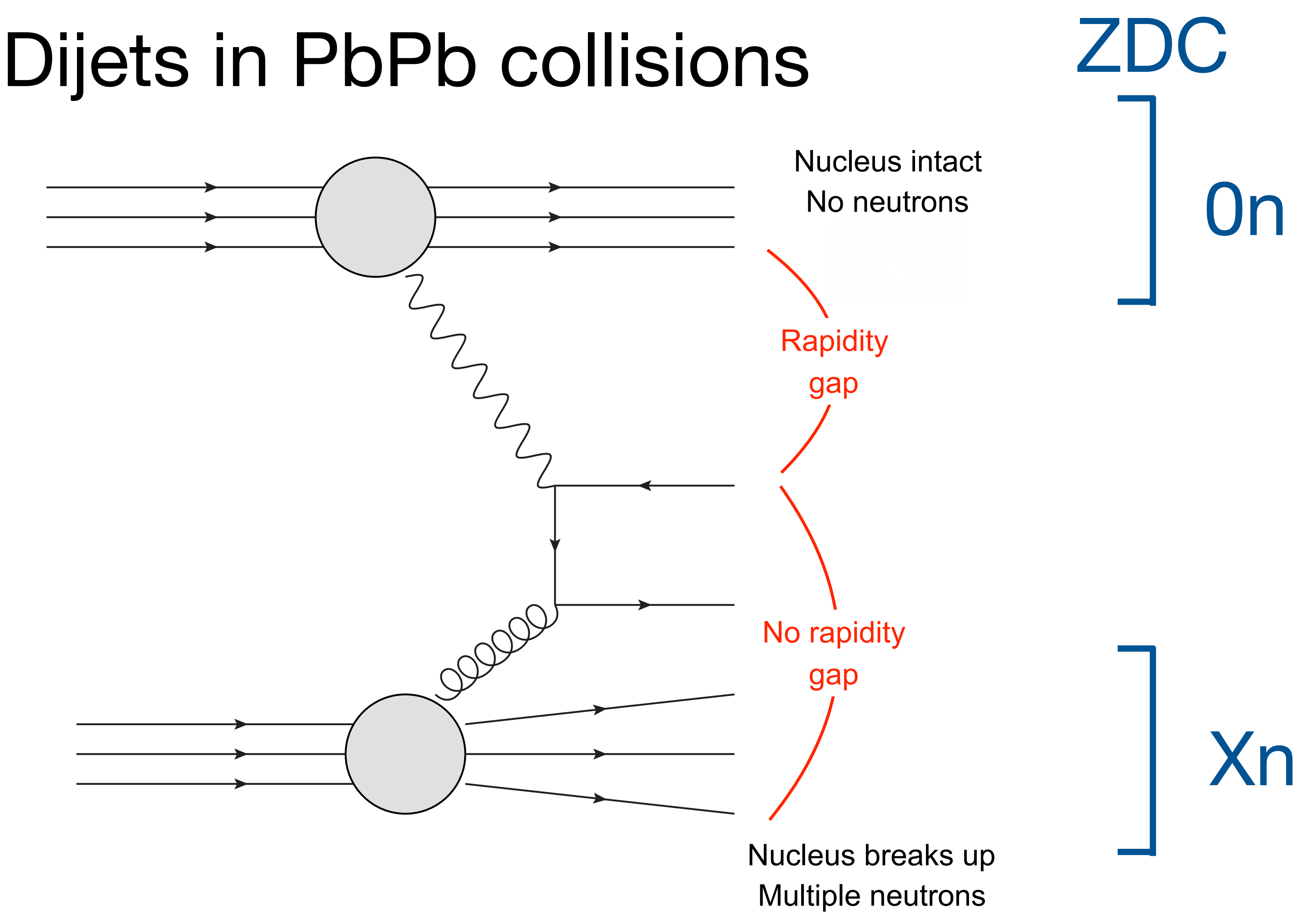
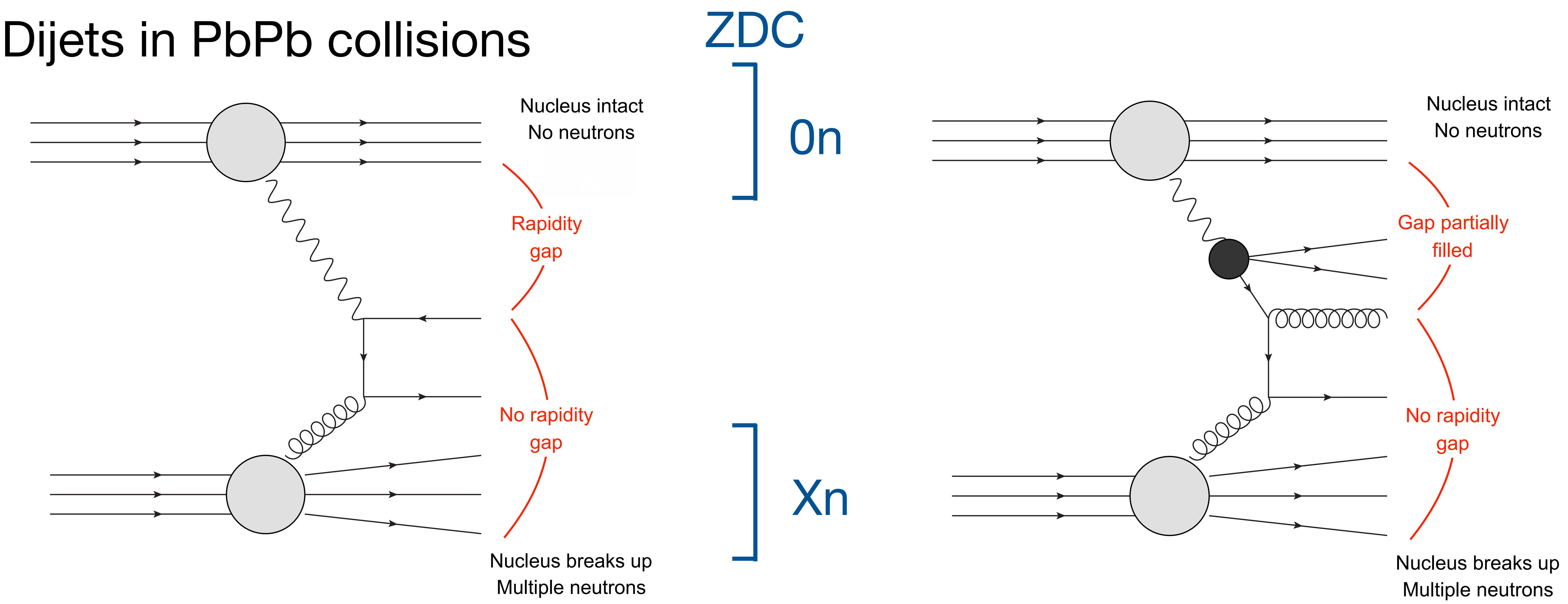


Inclusive photoproduction at the LHC

Dijets in PbPb collisions

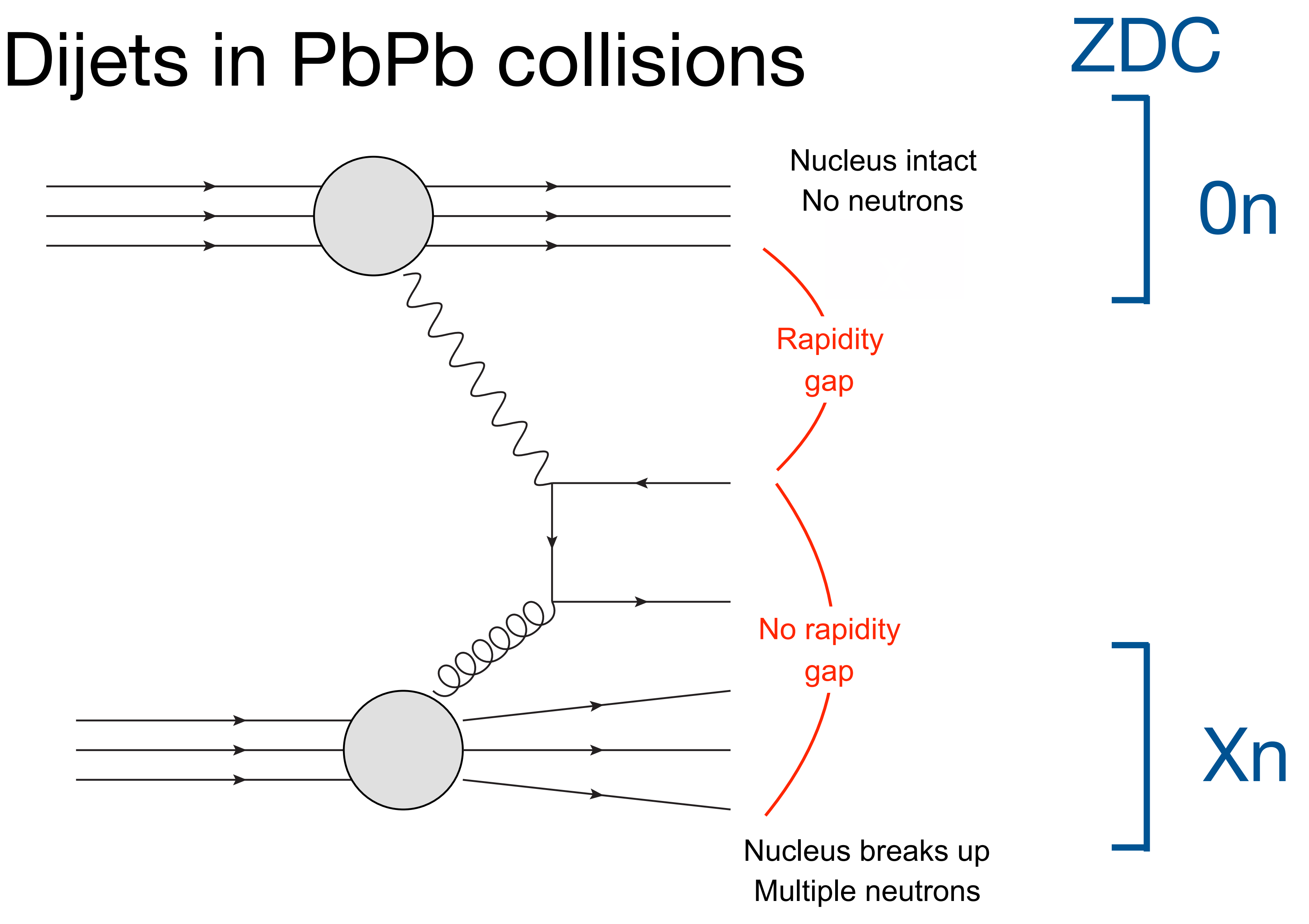


direct photon

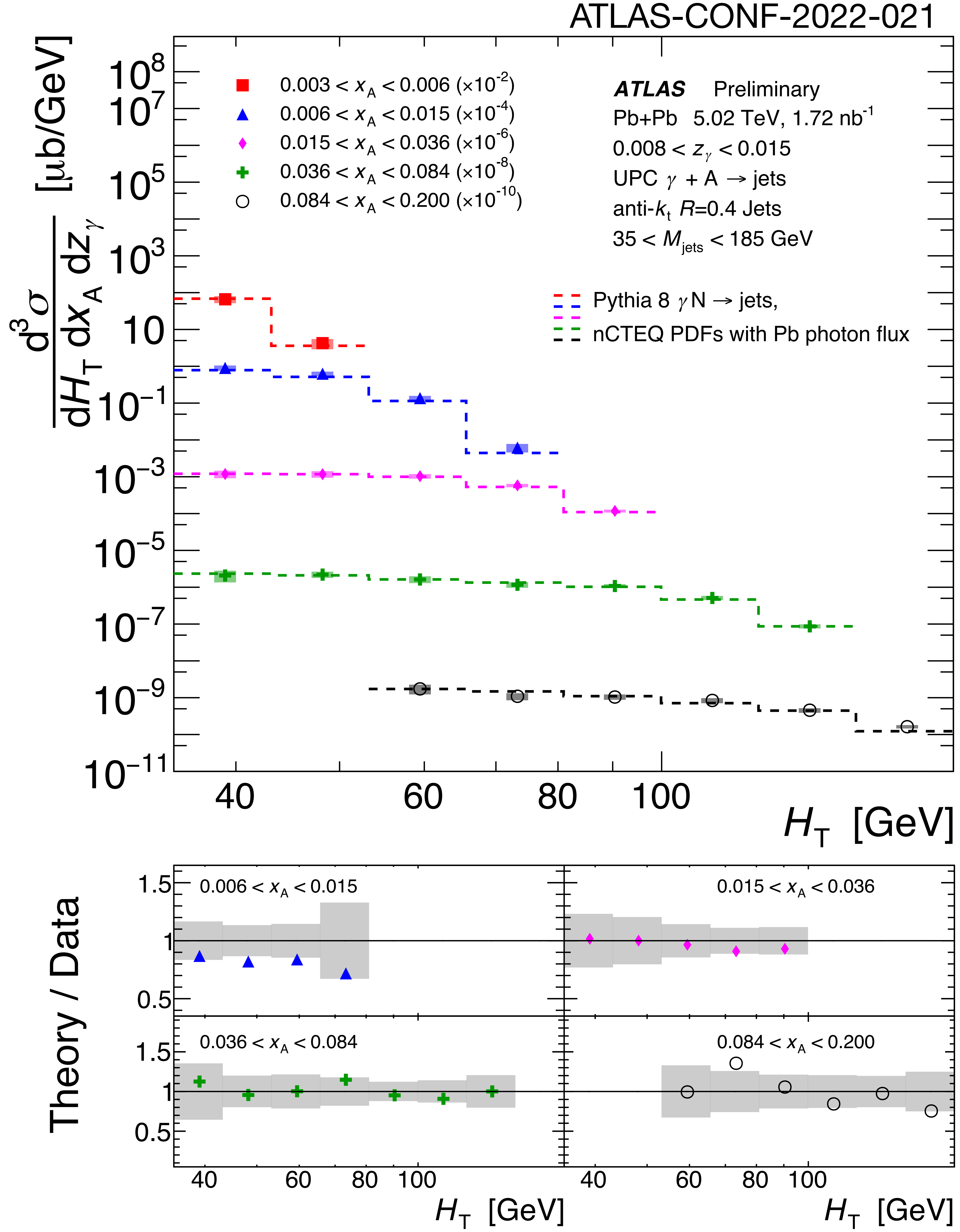
resolved photon

Inclusive photoproduction at the LHC

Dijets in PbPb collisions



direct photon



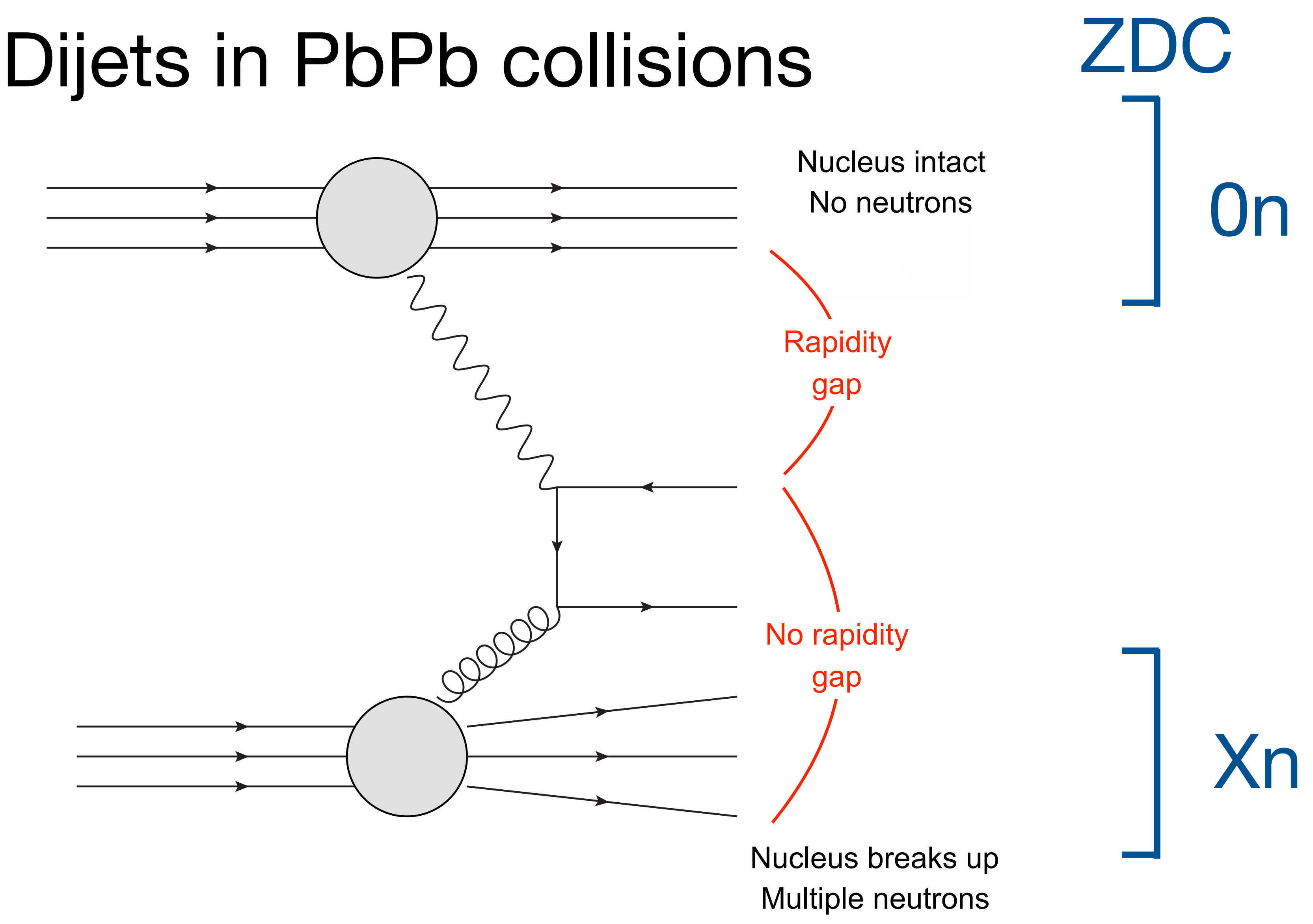
$$H_T = \sum_{\text{jet}} p_{T,\text{jet}} \xrightarrow{2\to 2} 2Q$$

$$z_\gamma = \frac{M_{\text{jets}}}{\sqrt{s_{NN}}} e^{+y_{\text{jets}}}$$

$$x_A = \frac{M_{\text{jets}}}{\sqrt{s_{NN}}} e^{-y_{\text{jets}}}$$

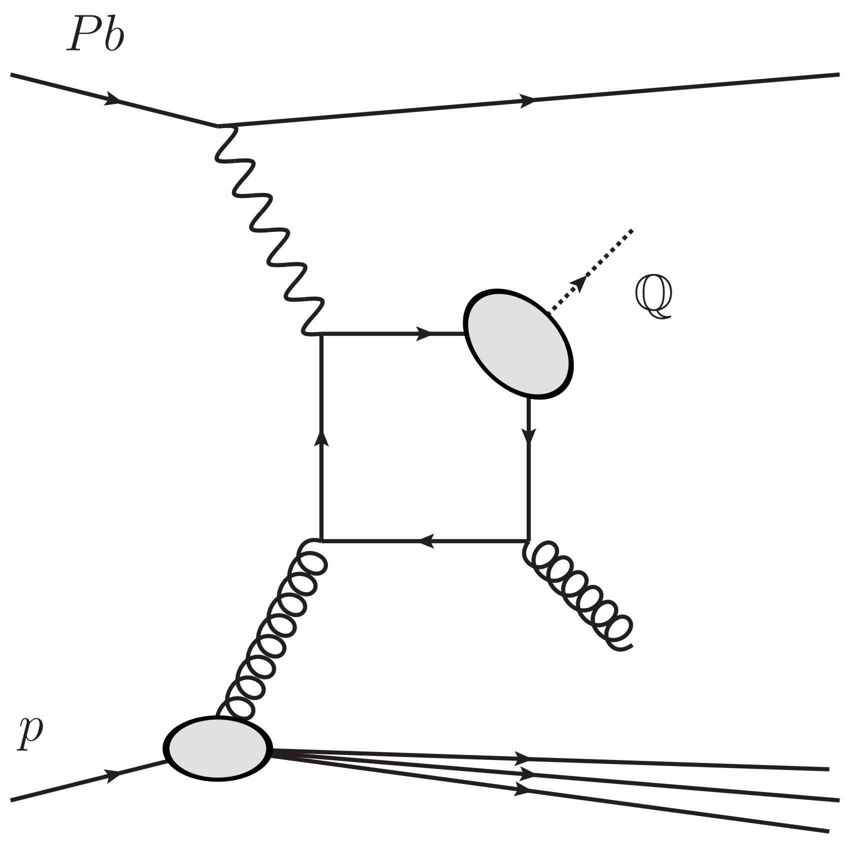
Inclusive photoproduction at the LHC

Dijets in PbPb collisions



direct photon

Quarkonia in pPb collisions



Investigation of quarkonium production mechanism, gluon distribution

cf. study by K. Lynch,
see e.g. Quarkonia as Tools 2024

TMD PDFs at the LHC and EIC

LHC

quark polarisation (columns) / nucleon polarisation (rows)

	U	L	T
U	f_1		$h_1^{\perp}$

gluon polarisation (columns) / nucleon polarisation (rows)

	U	circular	linear
U	f_1^g		$h_1^{\perp g}$

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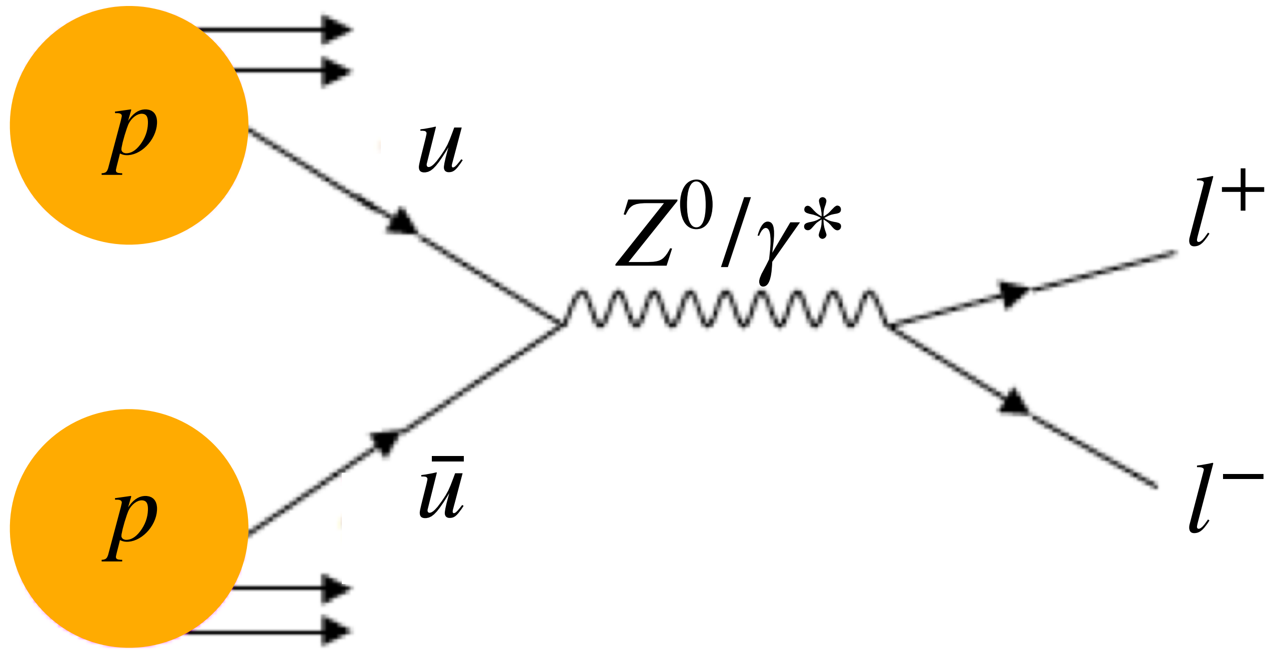
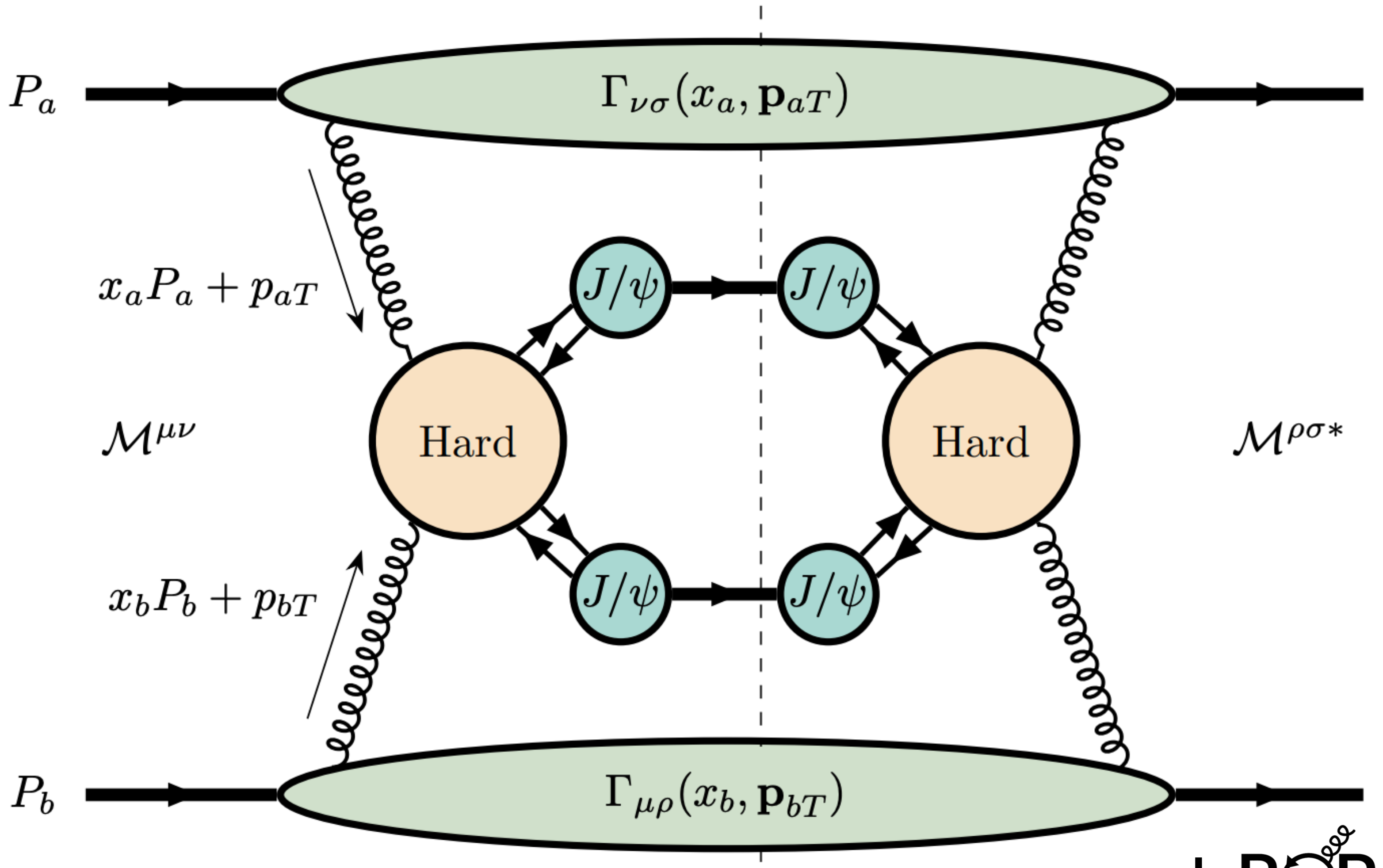




J. BOR

TMD PDFs at the LHC and EIC

quark polarisation (columns) / nucleon polarisation (rows)

	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	$h_{1T}\, h_{1T}^{\perp}$

EIC

gluon polarisation (columns) / nucleon polarisation (rows)

	U	circular	linear
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g, h_{1T}^{\perp g}$

TMD PDFs at the LHC and EIC

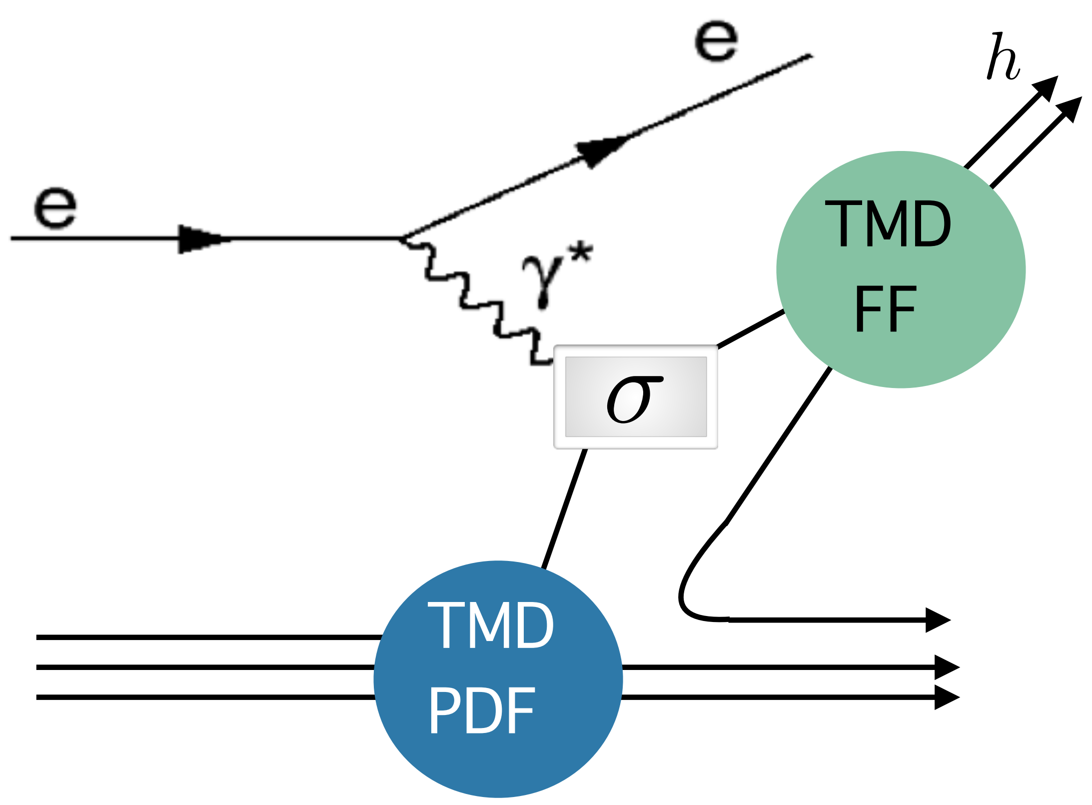
quark polarisation (columns) / **nucleon polarisation** (rows)

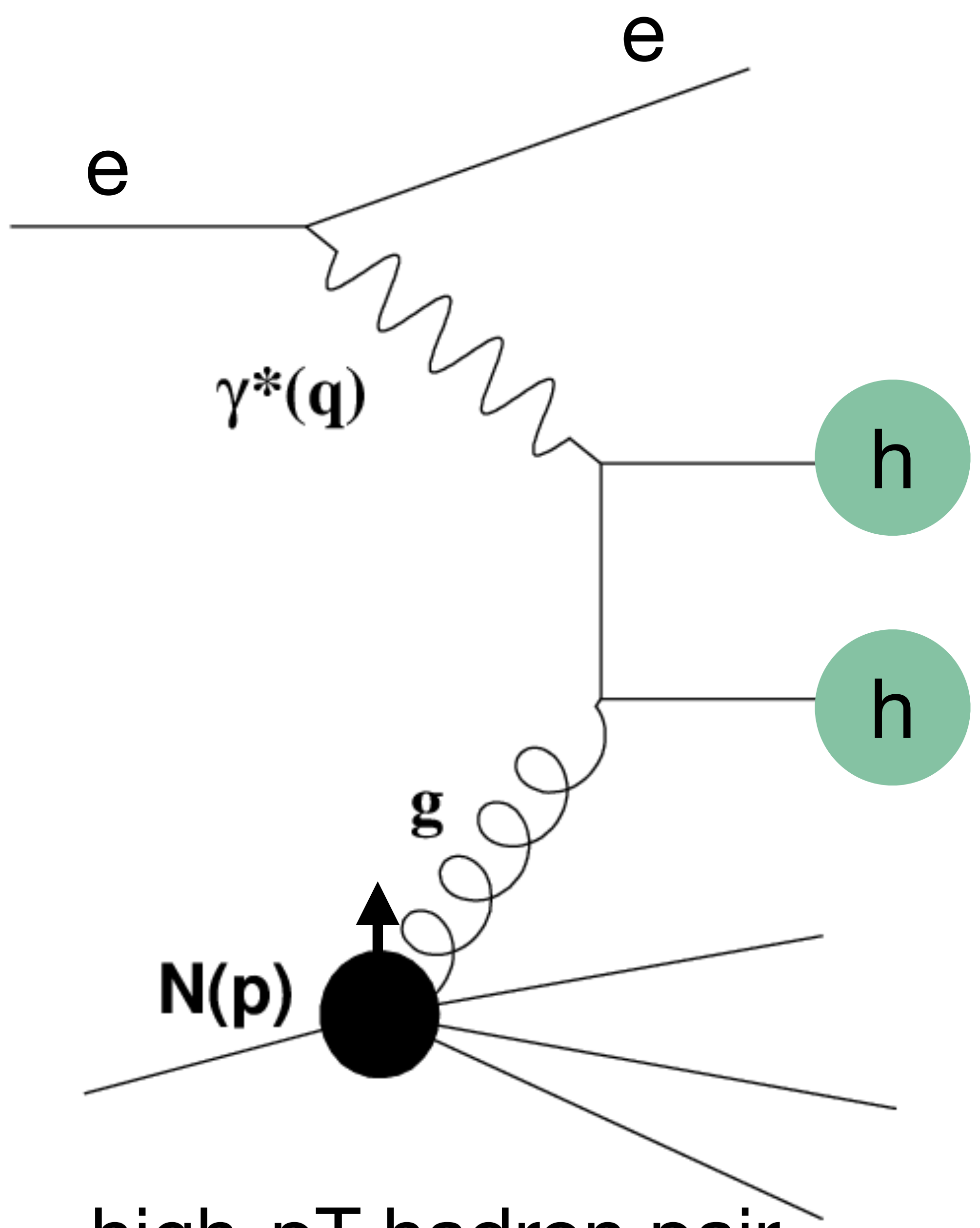
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_{1T}\, h_{1T}^\perp$

EIC

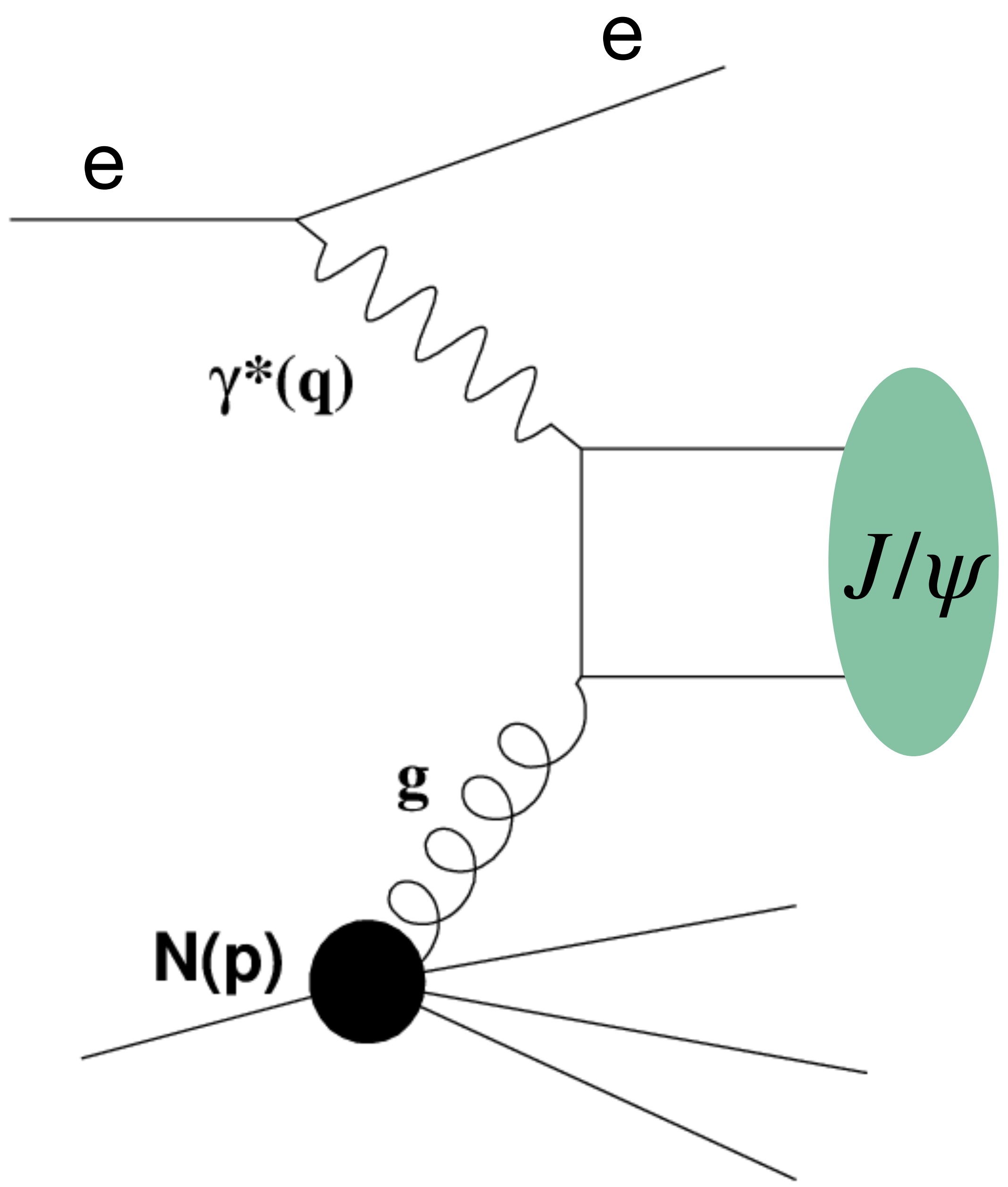
gluon polarisation (columns) / nucleon polarisation (rows)

	U	circular	linear
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\, h_{1T}^{\perp g}$

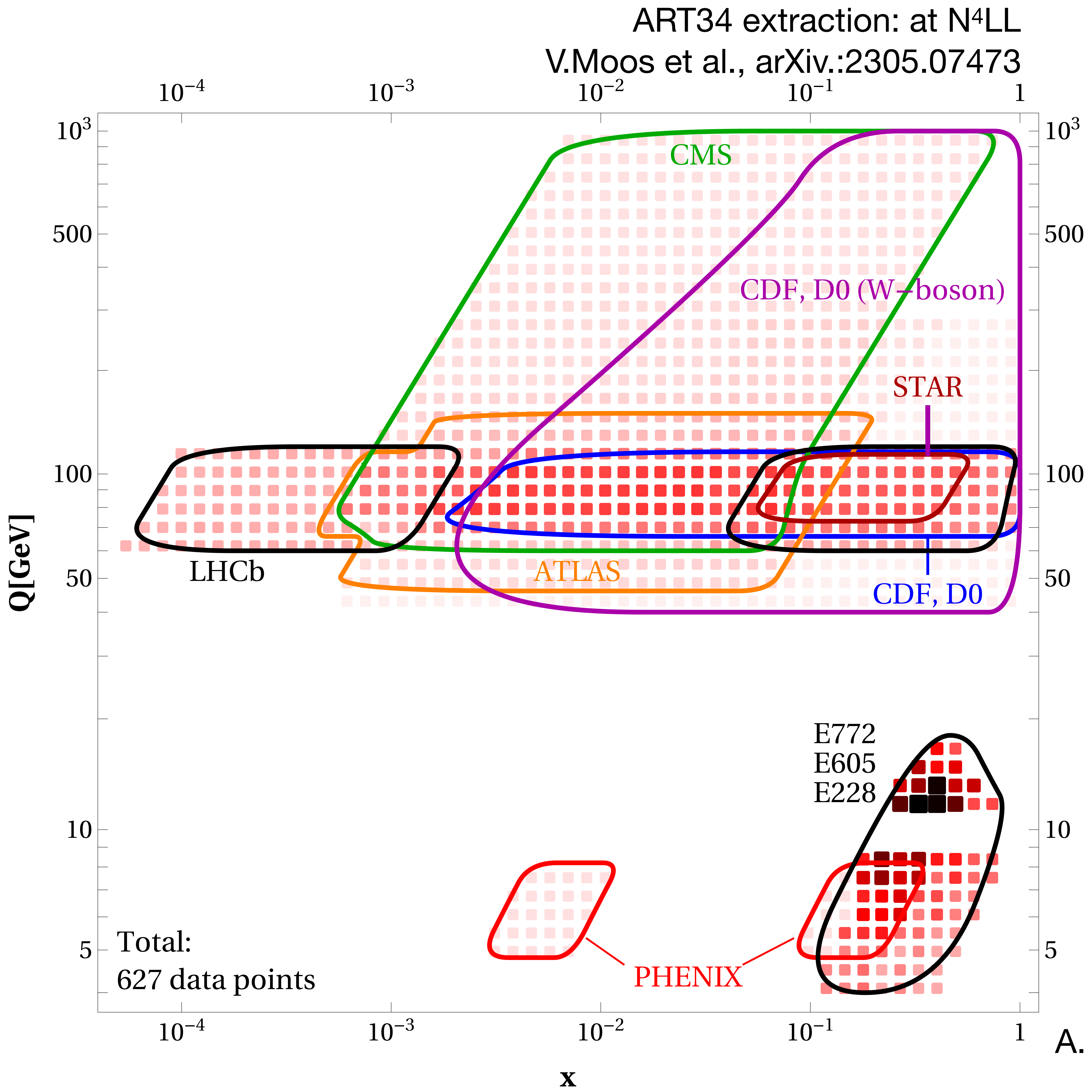




high-pT hadron pair



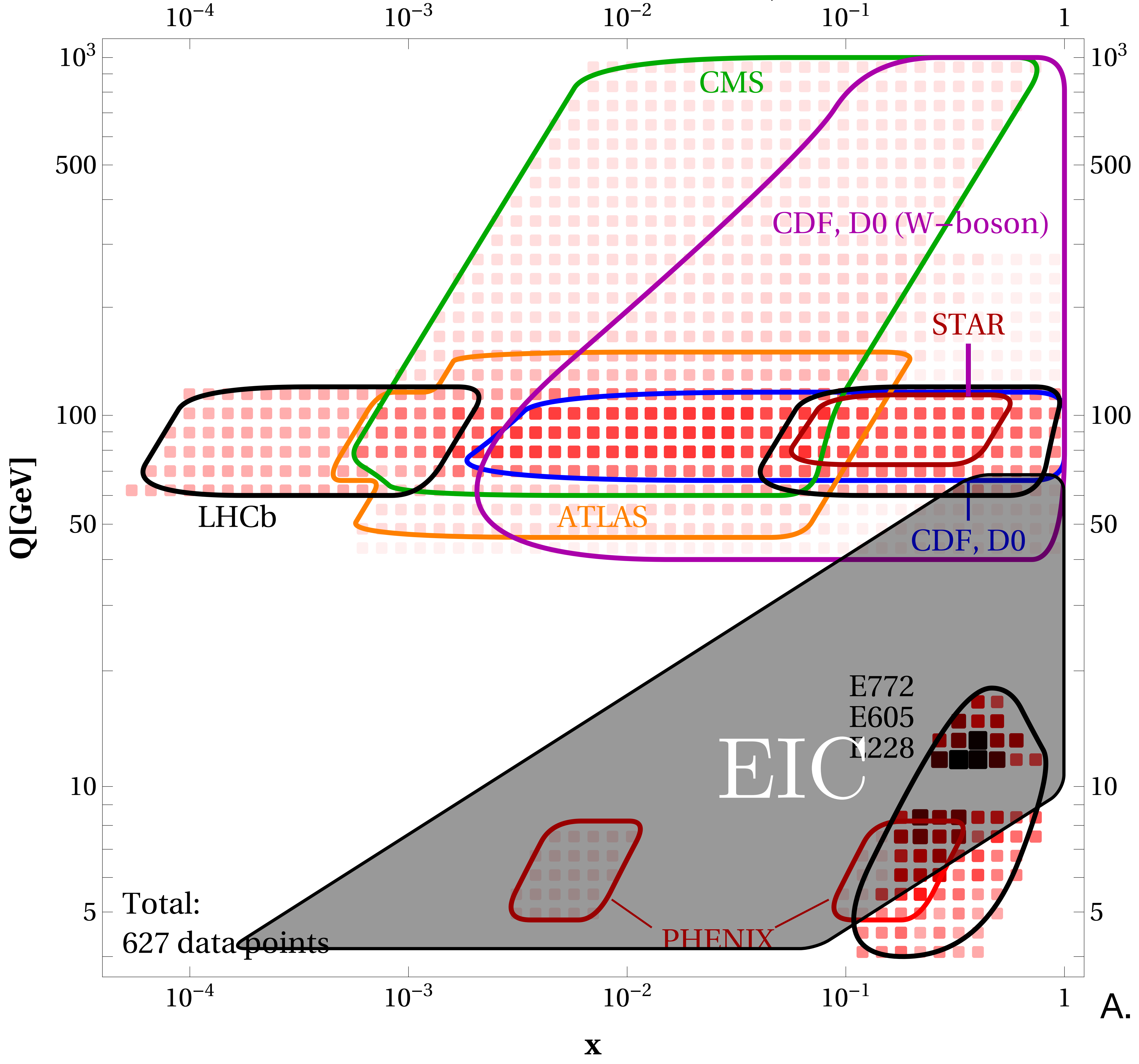
Spin-independent quark TMD PDFs at the LHC and EIC



A. Vladimirov

Spin-independent quark TMD PDFs at the LHC and EIC

ART34 extraction: at N⁴LL
V.Moos et al., arXiv.:2305.07473



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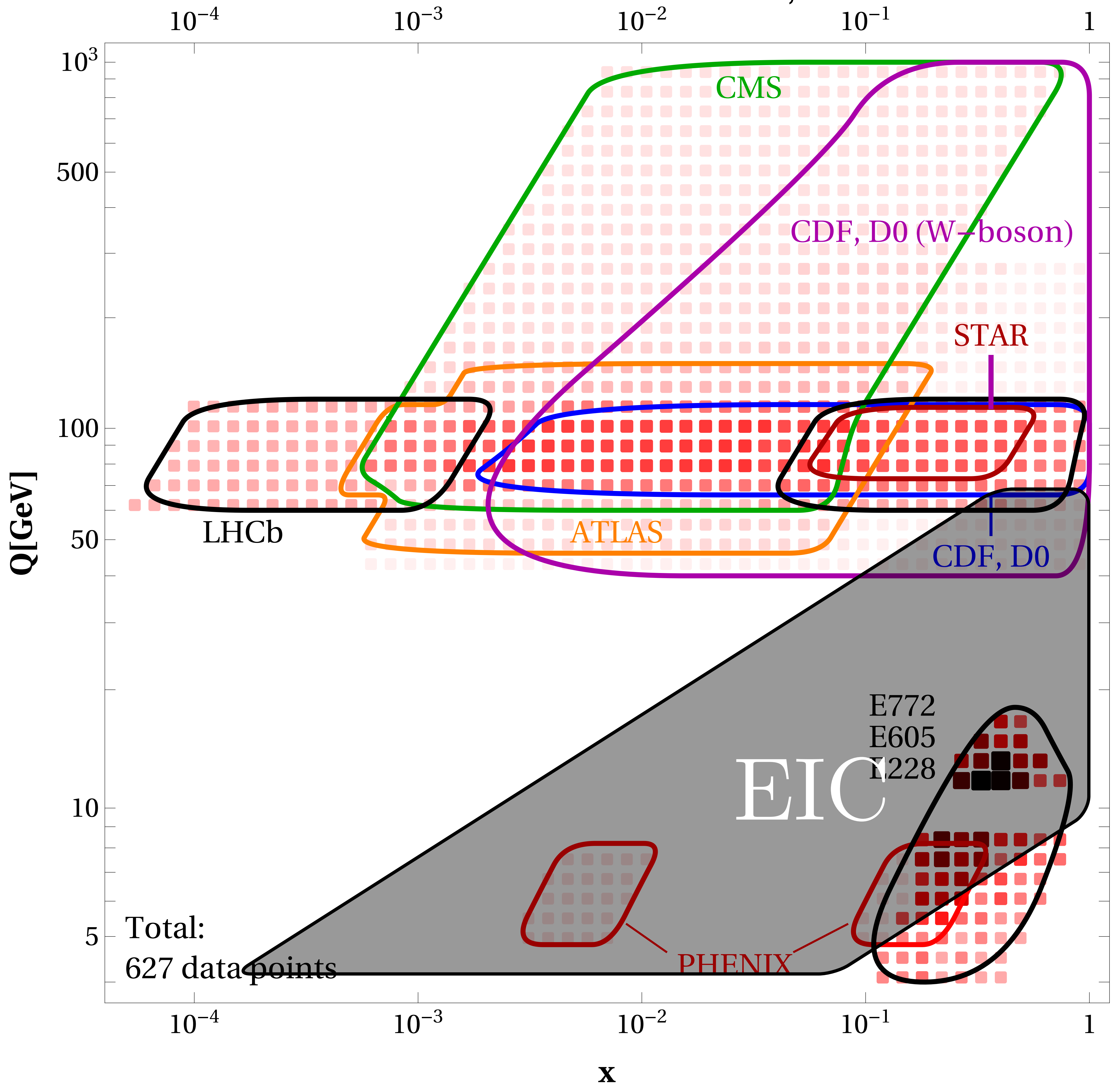
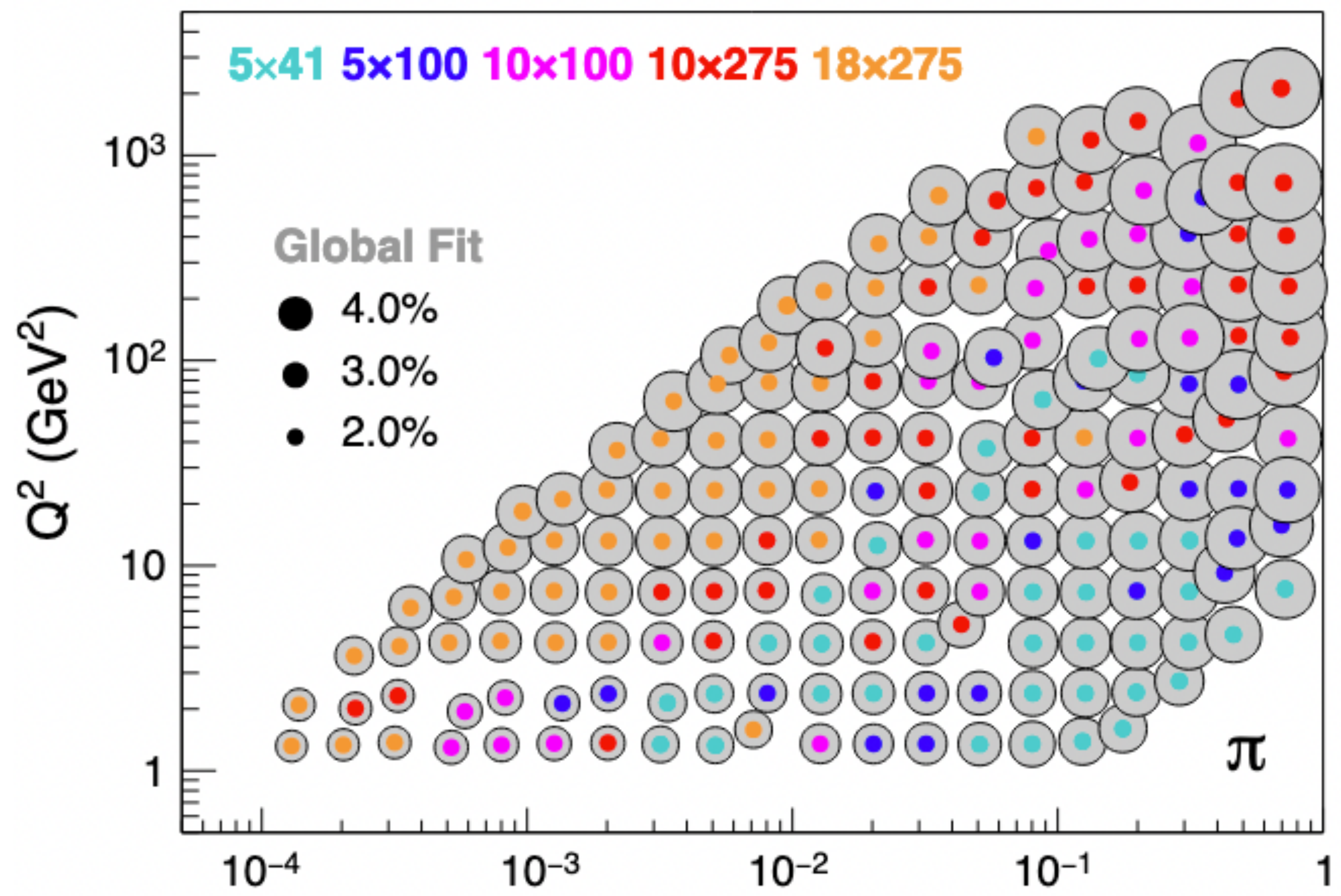


A. Vladimirov

EIC ATHENA



EIC uncertainties dominated
by assumed
3% point-to-point uncorrelated uncertainty
3% scale uncertainty

Theory uncertainties dominated by
TMD evolution.

Spin-independent quark TMD PDFs at the LHC and EIC

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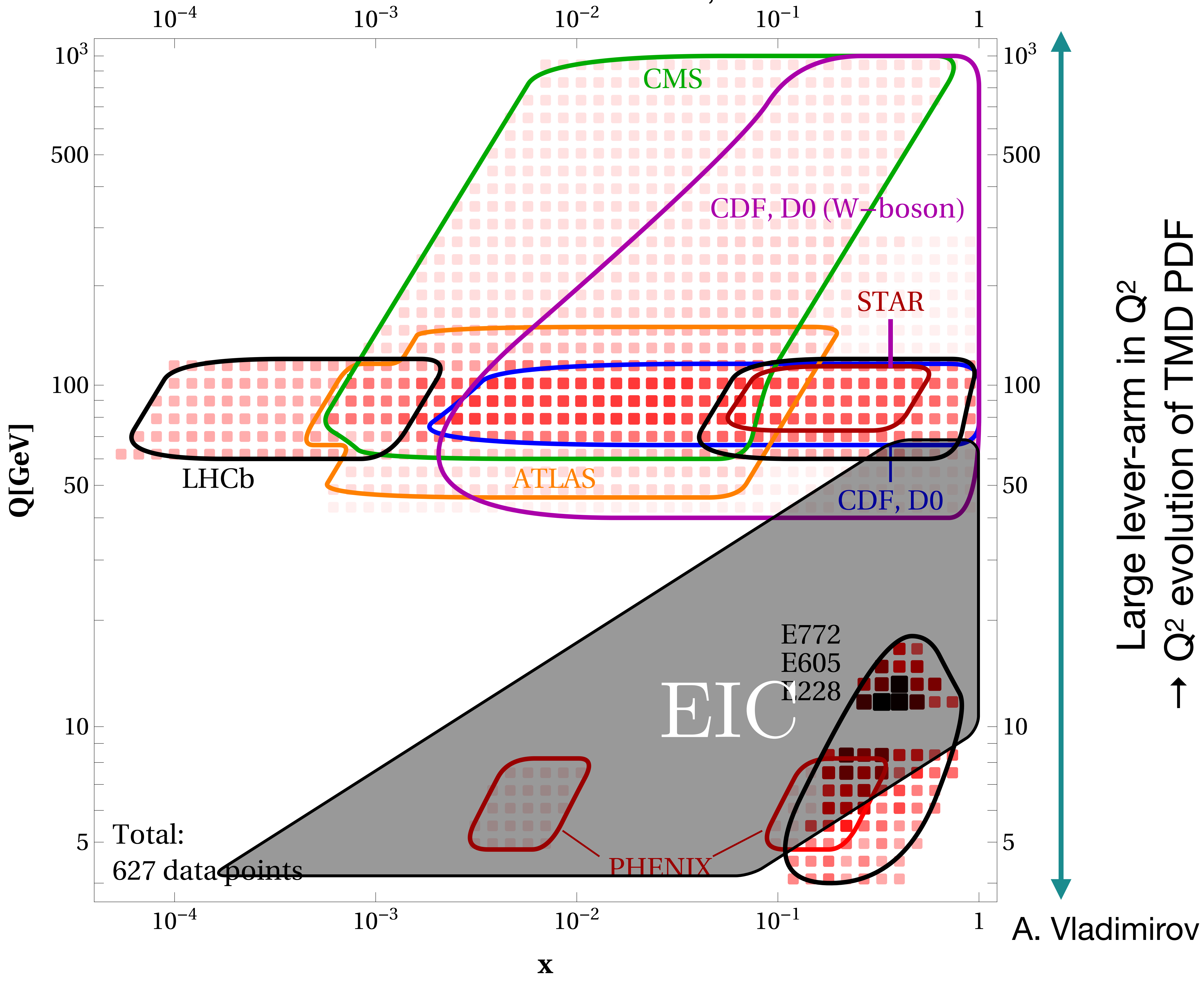
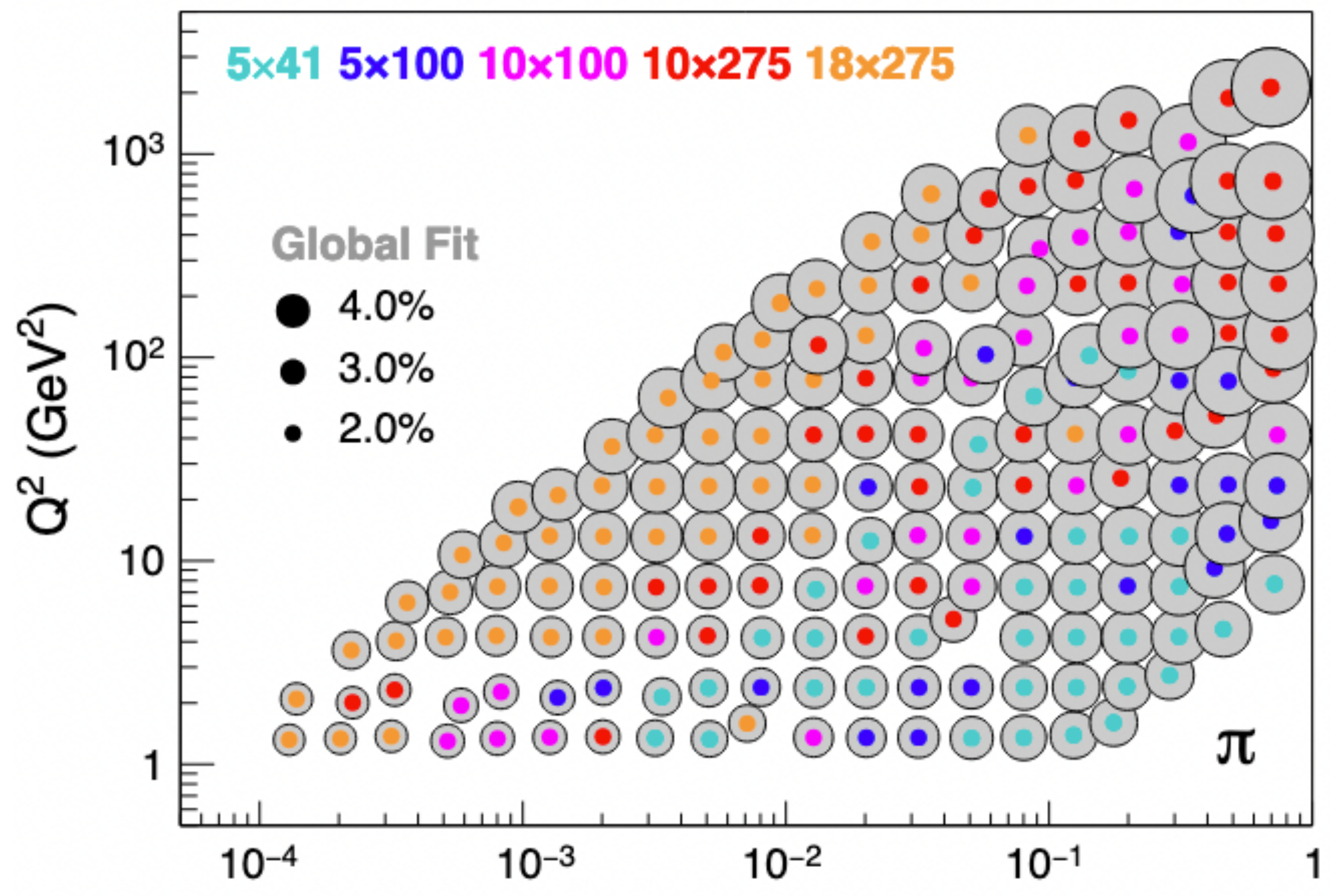


A. Vladimirov

EIC ATHENA



EIC uncertainties dominated by assumed
3% point-to-point uncorrelated uncertainty
3% scale uncertainty

Theory uncertainties dominated by TMD evolution.

Power corrections at the LHC and EIC

A. Vladimirov, arXiv 2307.13054

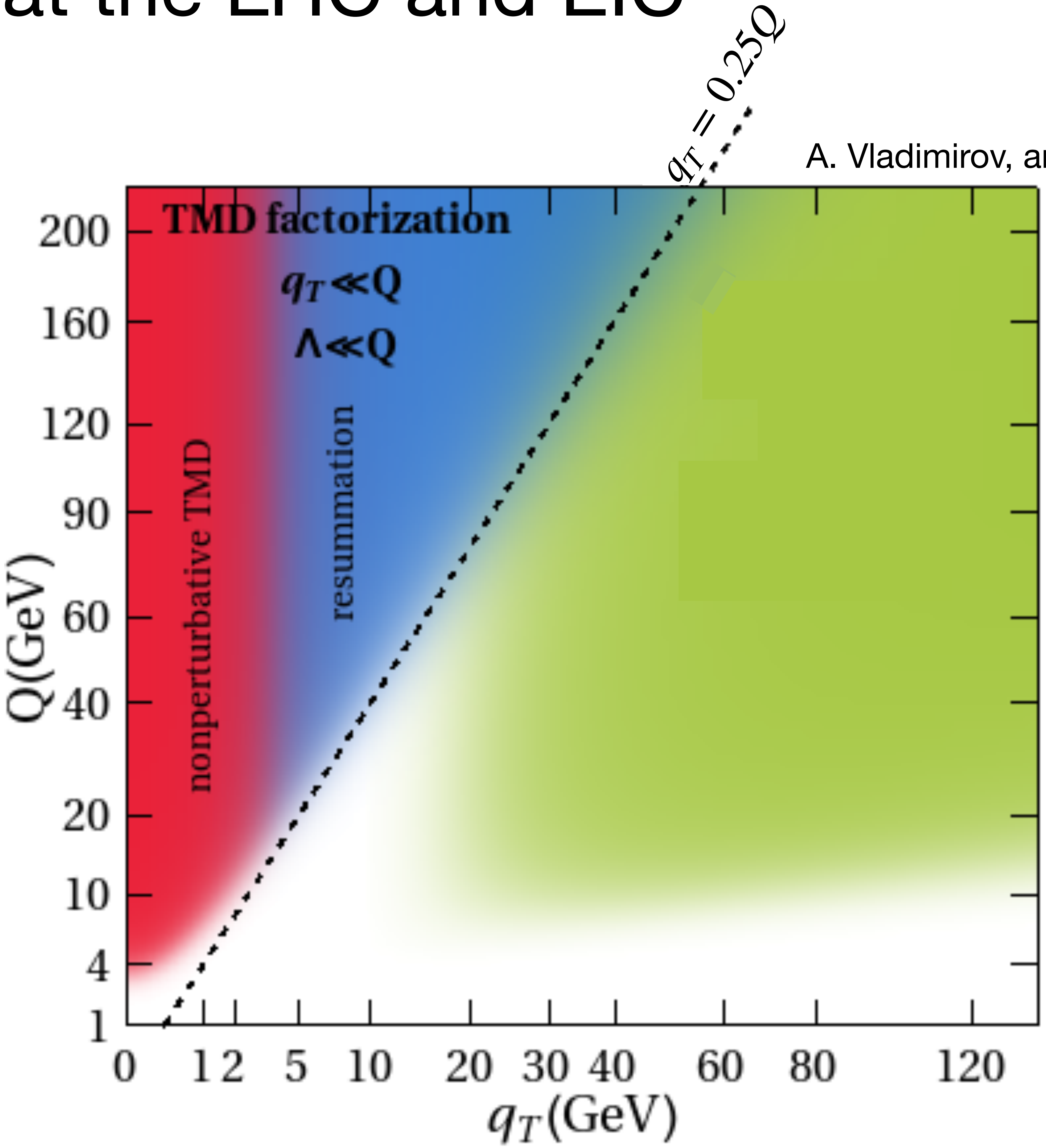
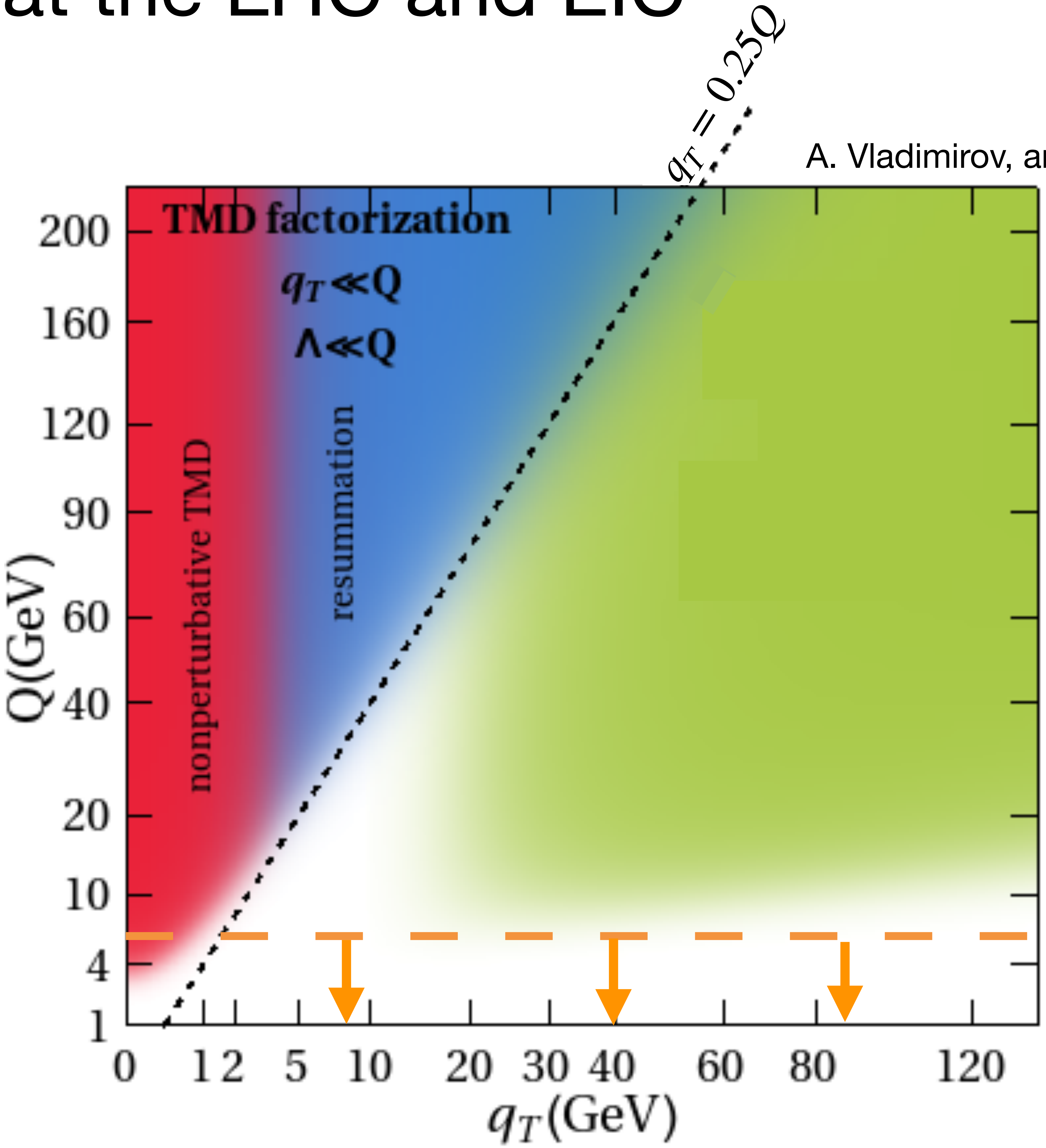


Fig. adapted from A. Vladimirov

Power corrections at the LHC and EIC



A. Vladimirov, arXiv 2307.13054

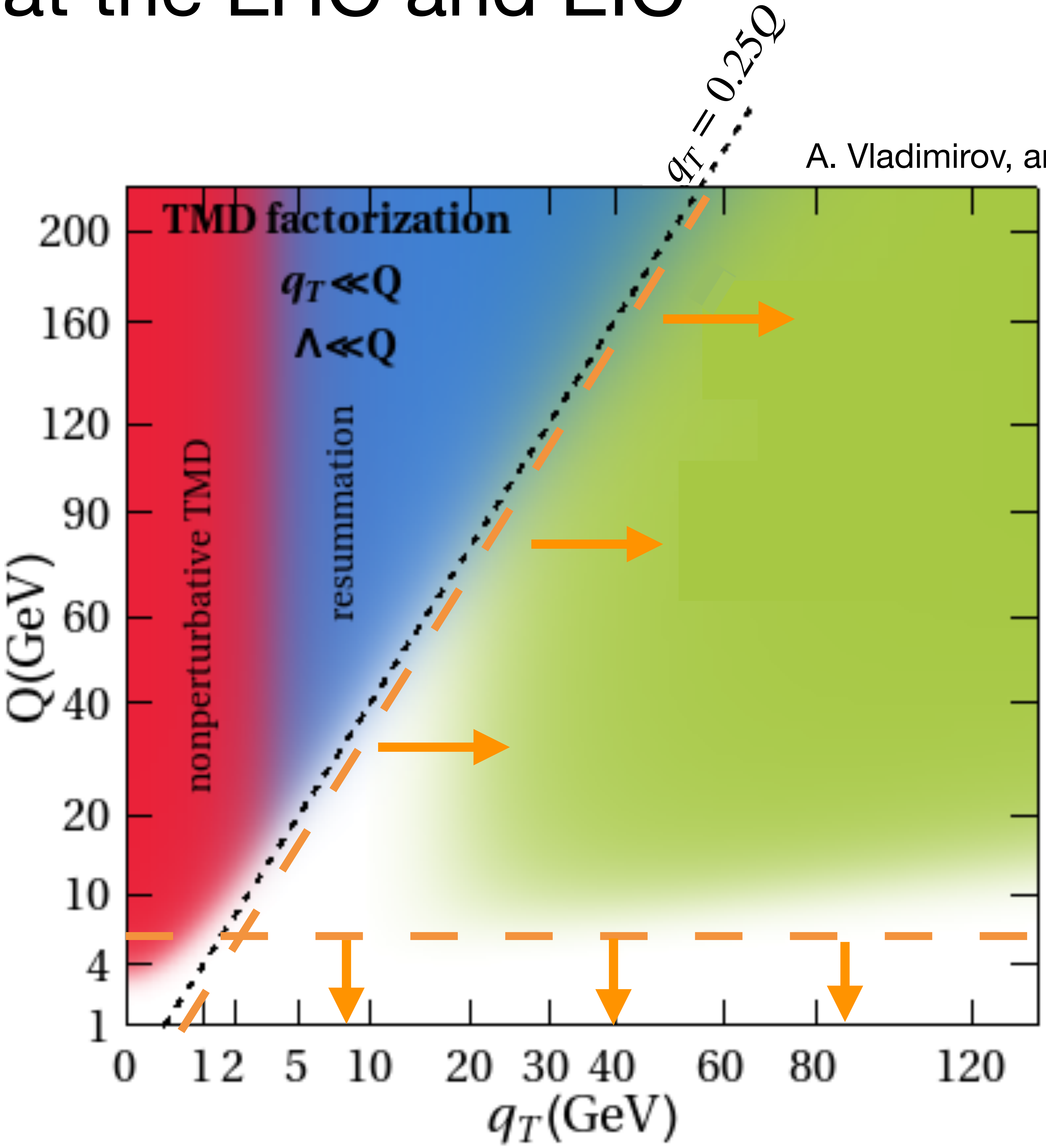
Fig. adapted from A. Vladimirov

Various power corrections:

- higher-twist (Λ/Q) corrections
- target-mass corrections

Power corrections at the LHC and EIC

A. Vladimirov, arXiv 2307.13054



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Power corrections at the LHC and EIC

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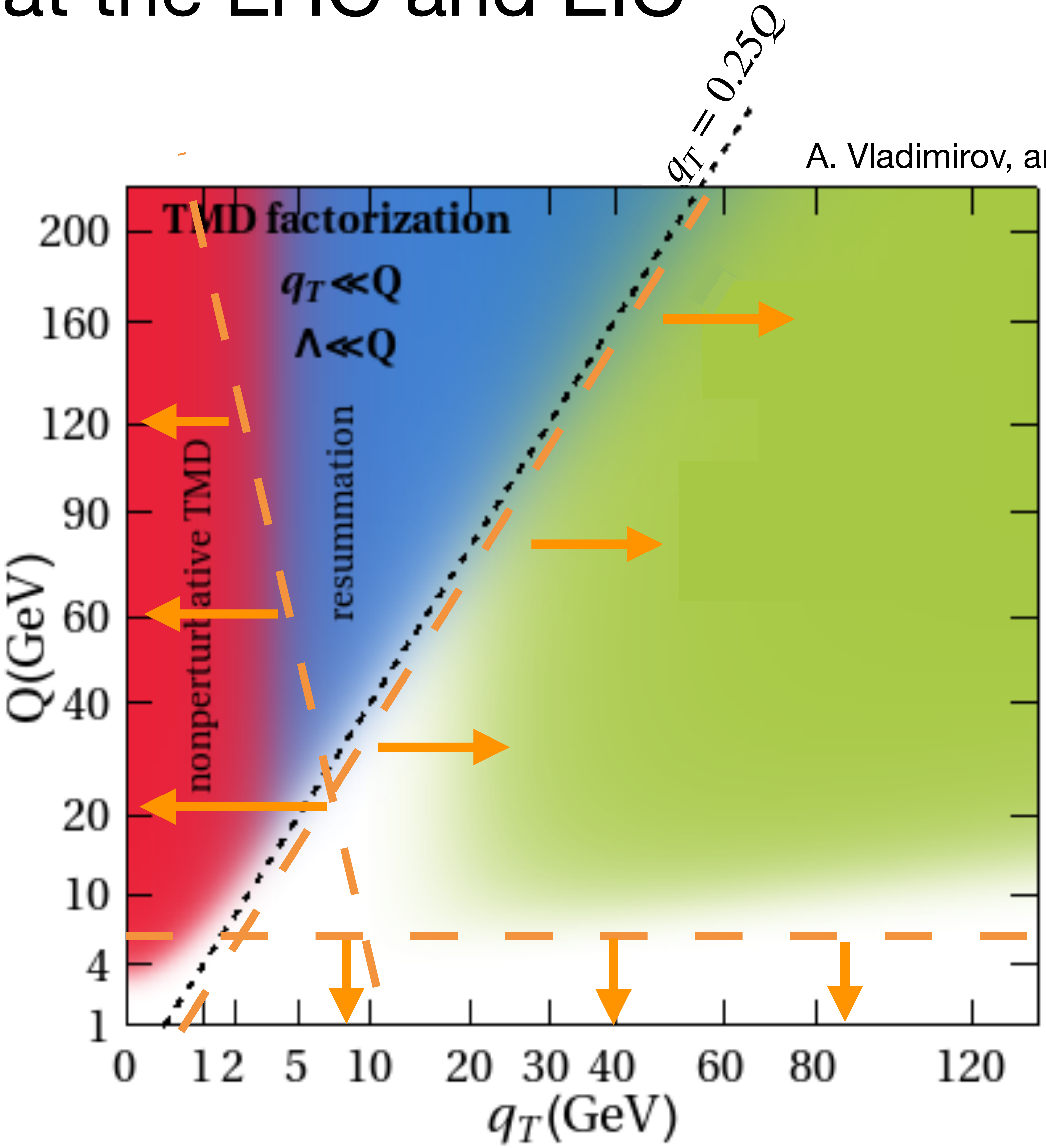

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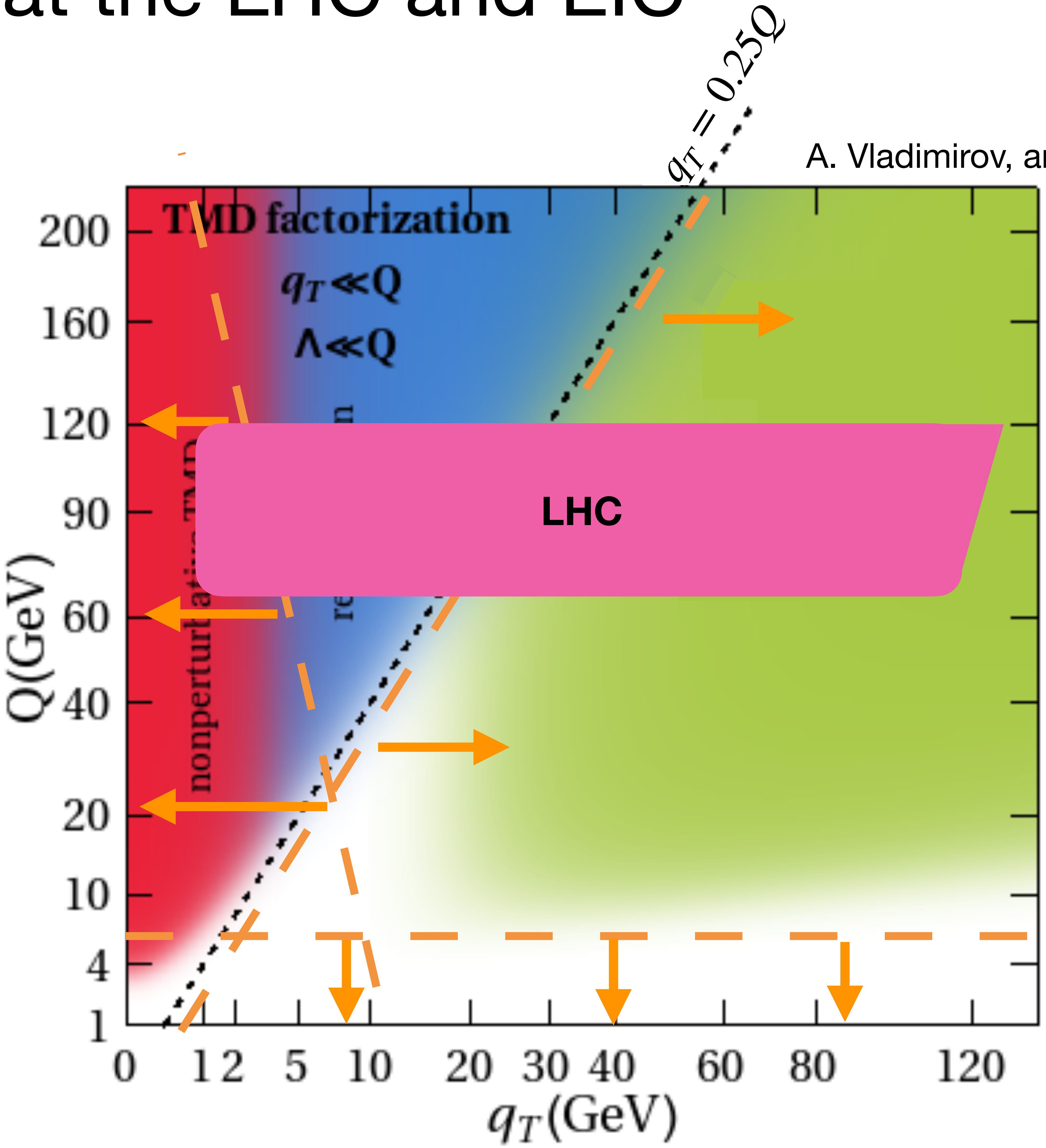

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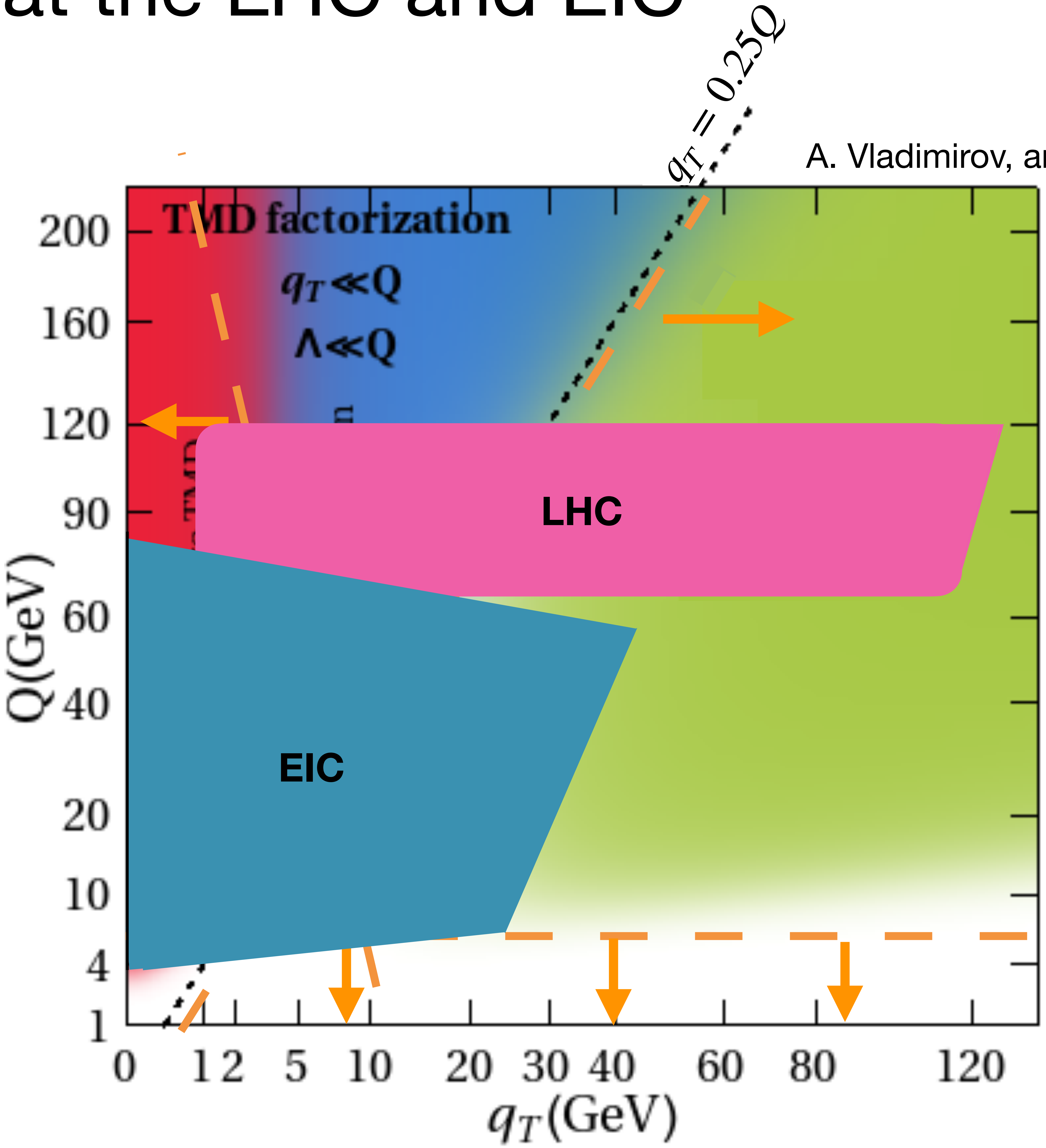


A. Vladimirov, arXiv 2307.13054

Fig. adapted from A. Vladimirov

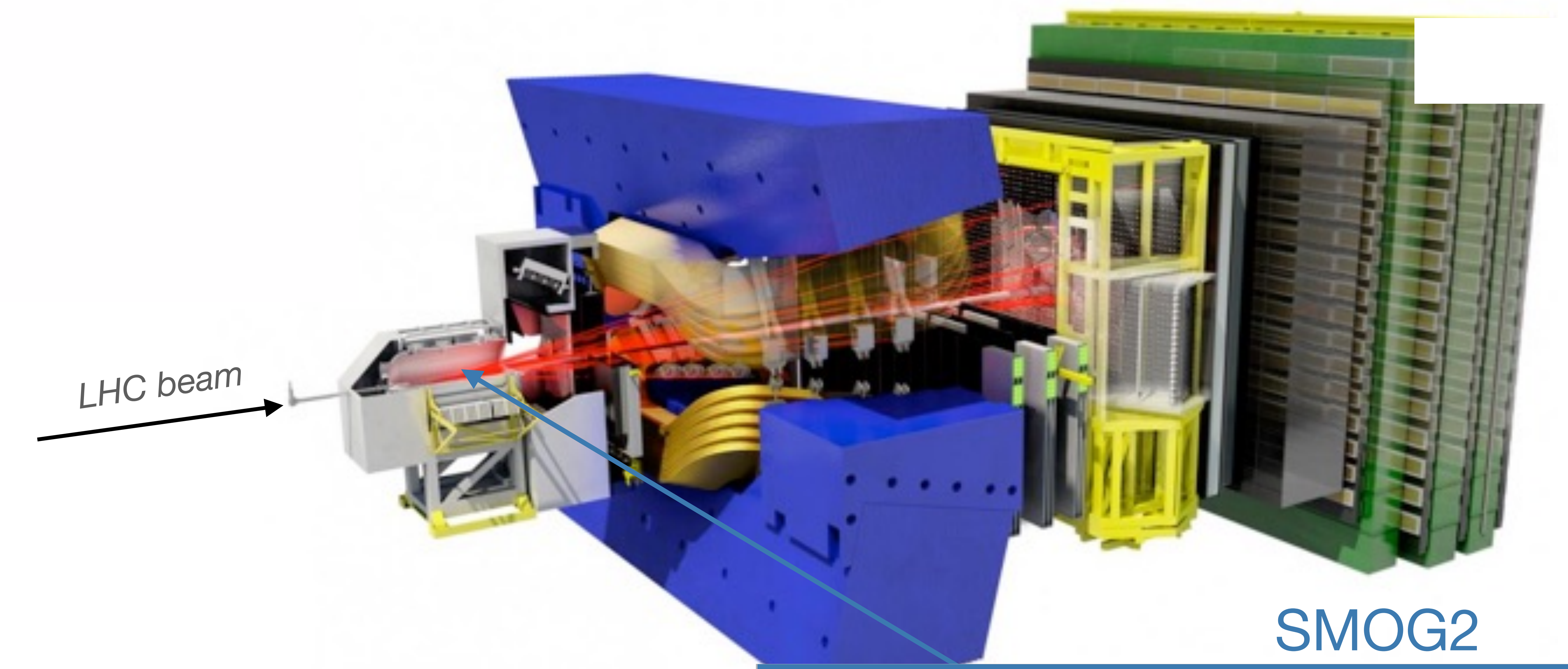
Various power corrections:

- higher-twist (Λ/Q) corrections
- target-mass corrections
- q_T/Q corrections
- k_T/Q corrections

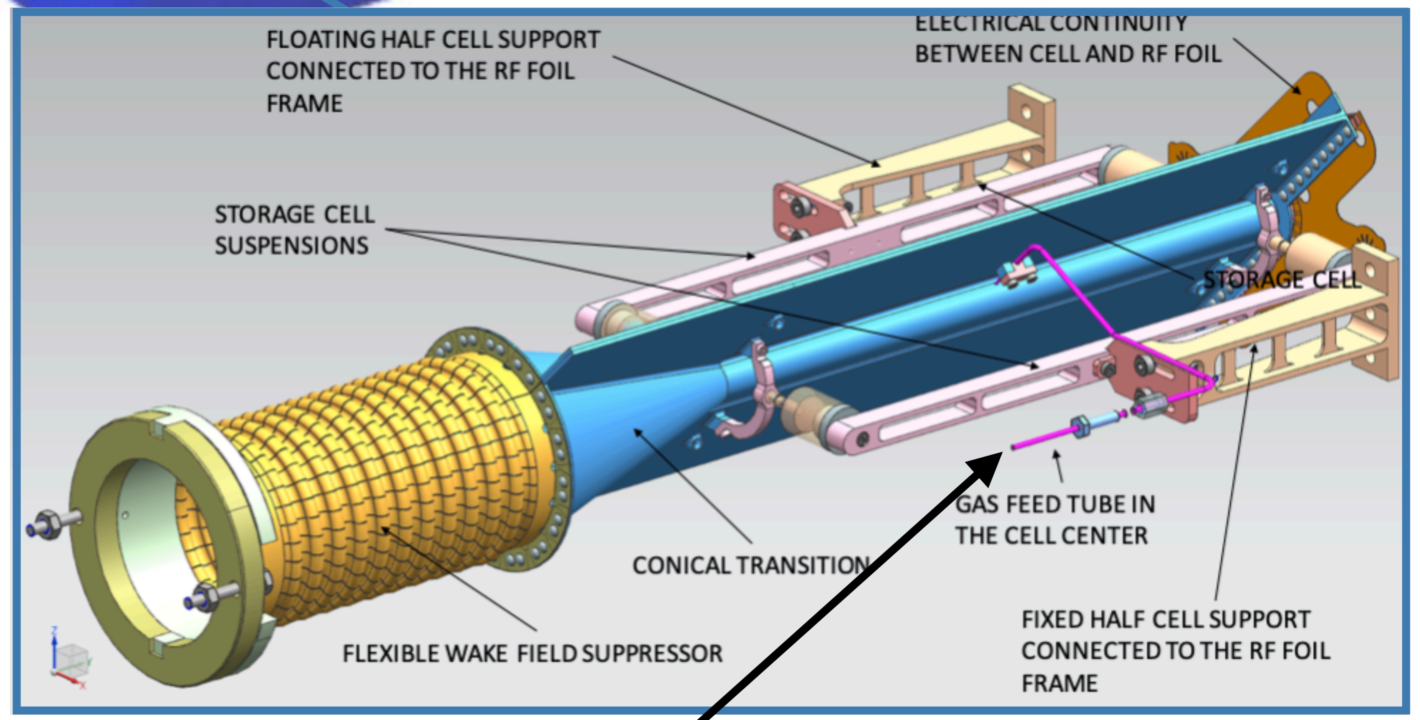
Fixed target at LHCb

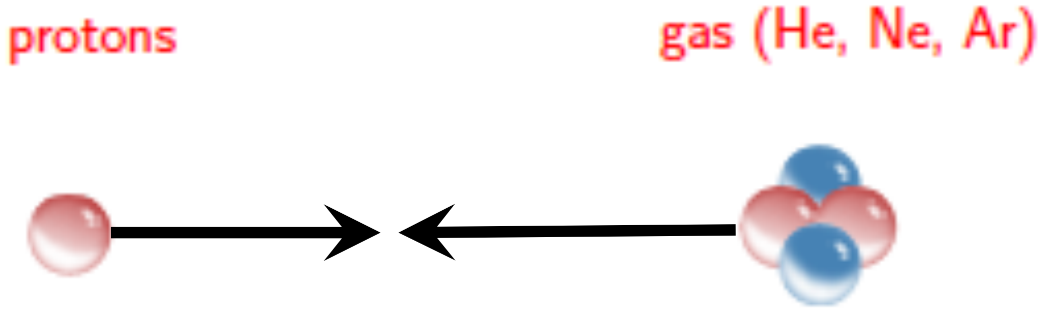
RUN3

JINST 3 (2008) S
IJMPA 30 (2015)



SMOG2





$\sqrt{s_{NN}} = 115$ GeV

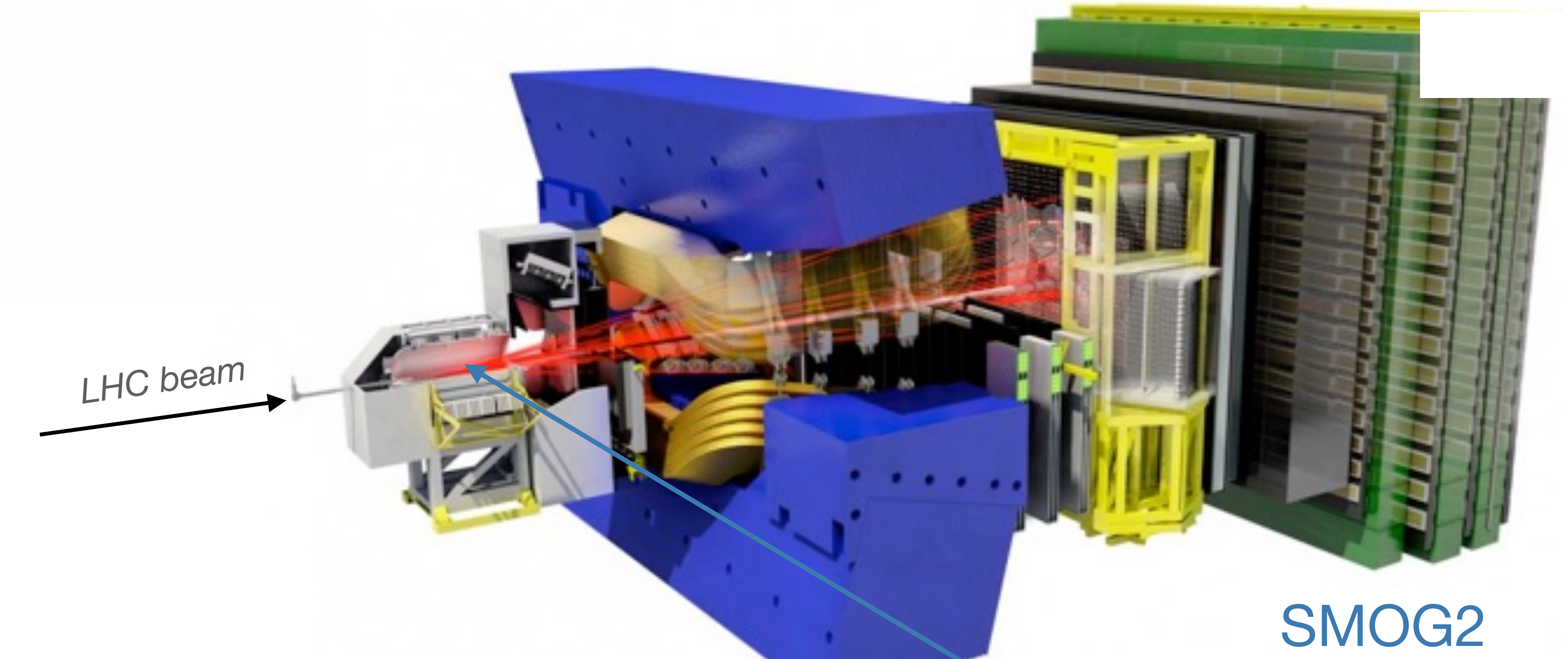
$-2.78 < y_{CM} < 0.2$

inject gas: He, Ne, Ar, and H_2, D_2

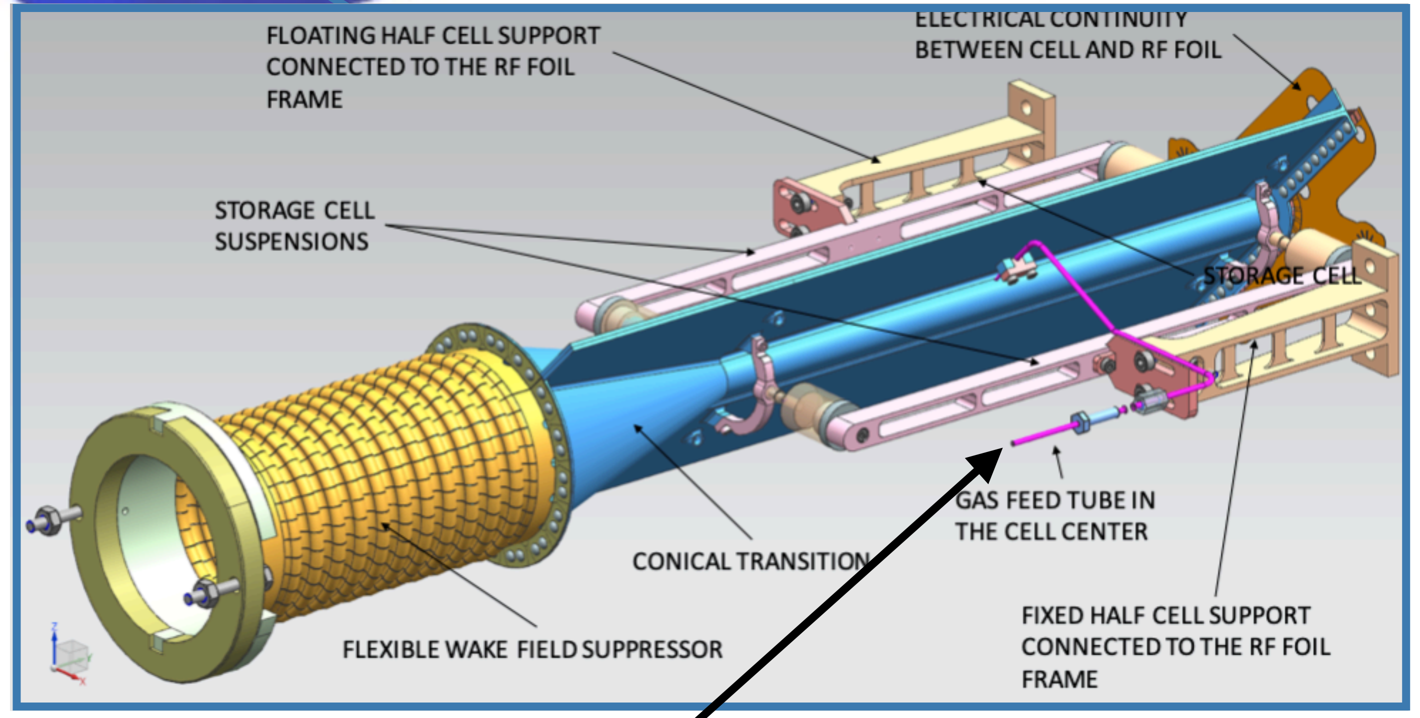
Fixed target at LHCb

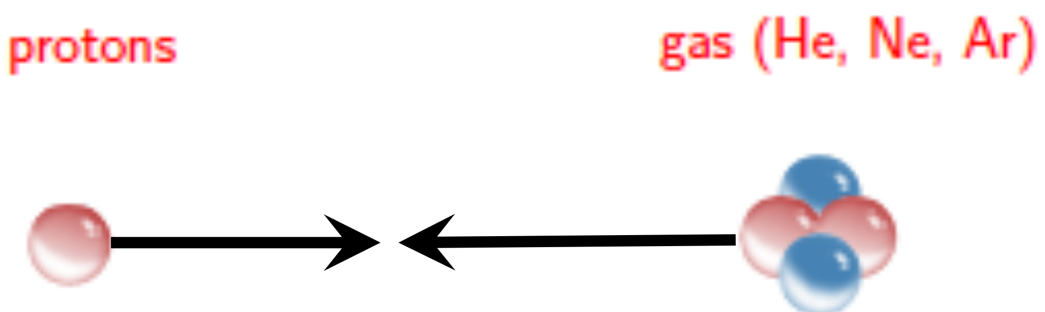
JINST 3 (2008) S
IJMPA 30 (2015)

RUN3



SMOG2

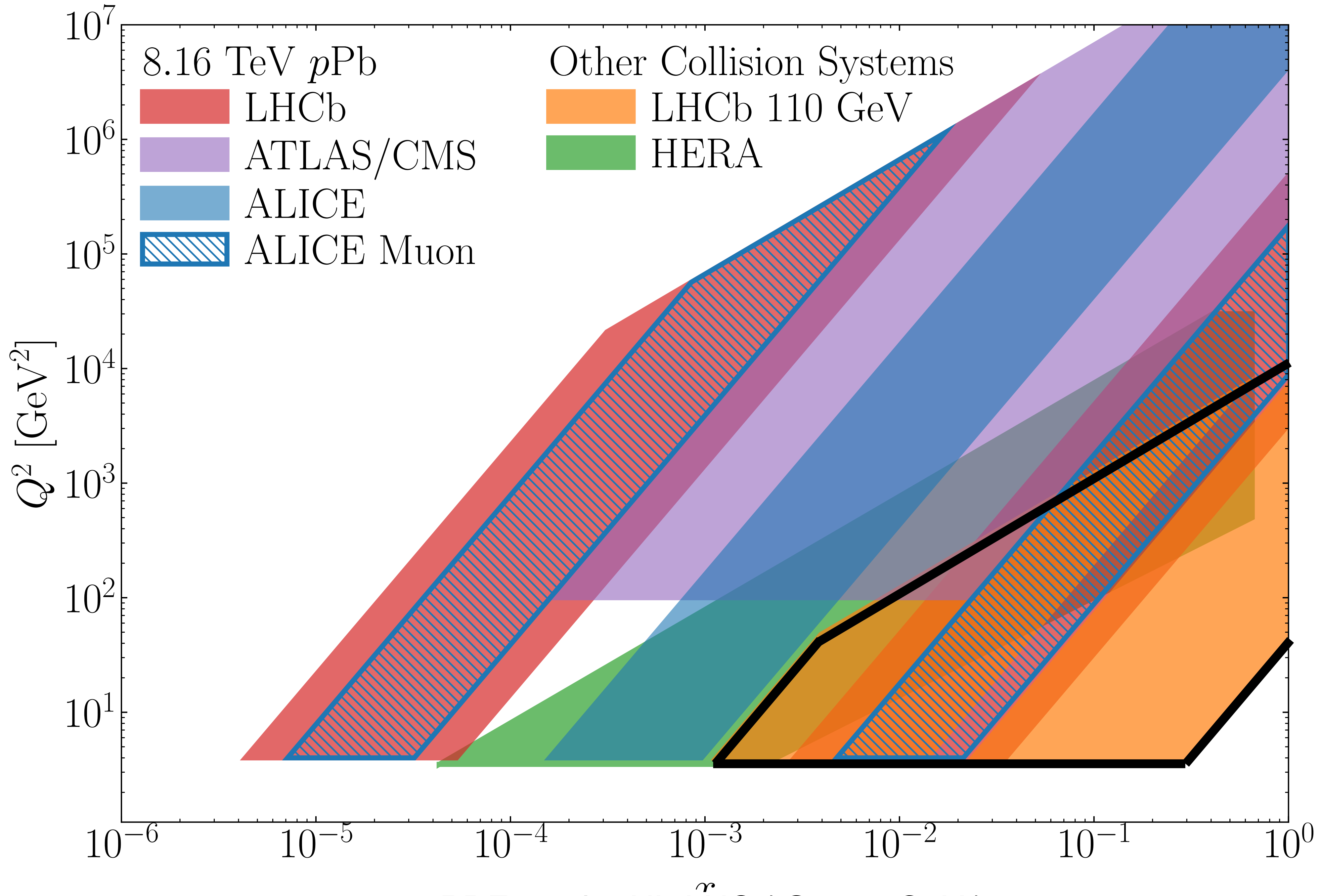




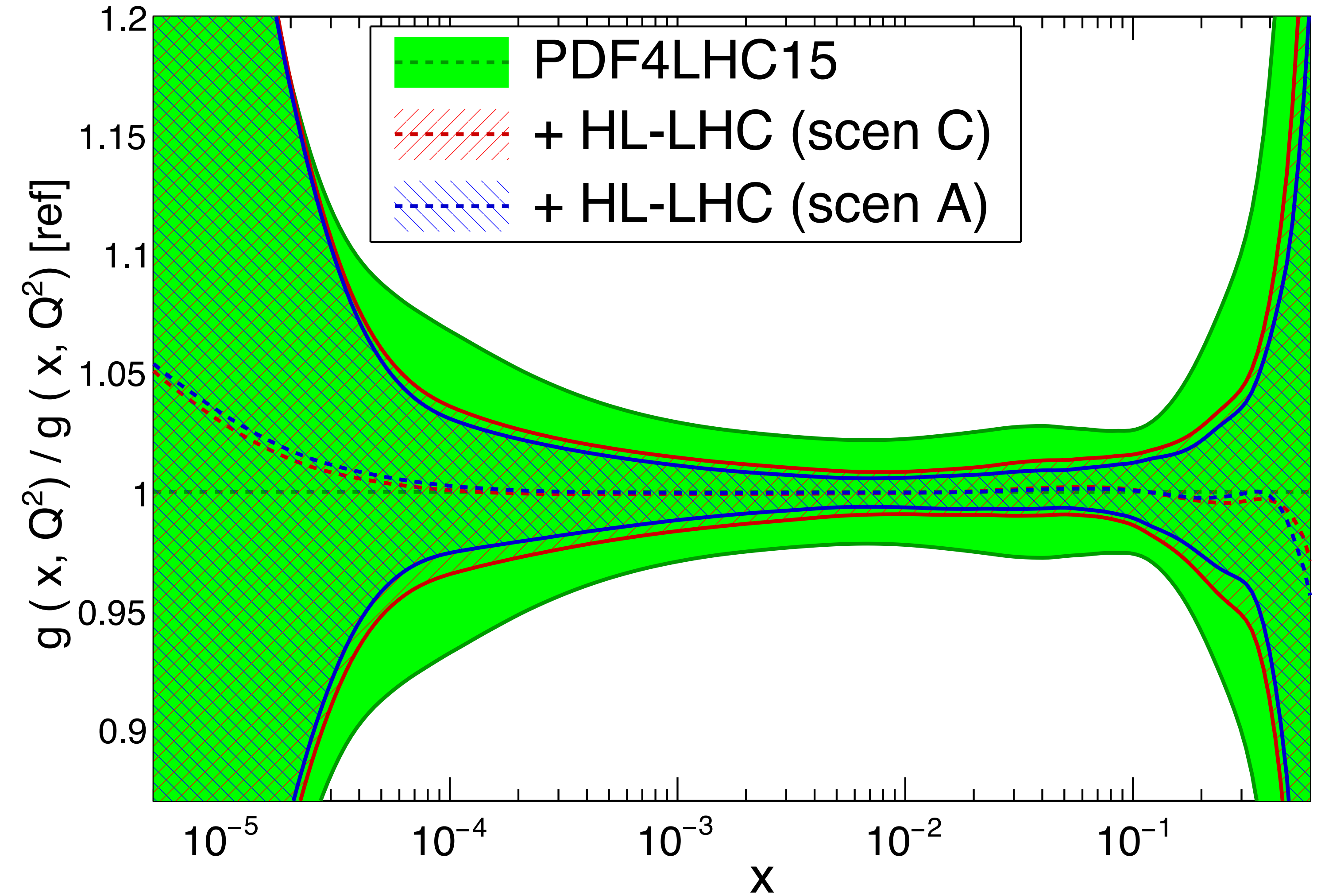
$\sqrt{s_{NN}} = 115$ GeV

$-2.78 < y_{CM} < 0.2$

inject gas: He, Ne, Ar, and H_2, D_2



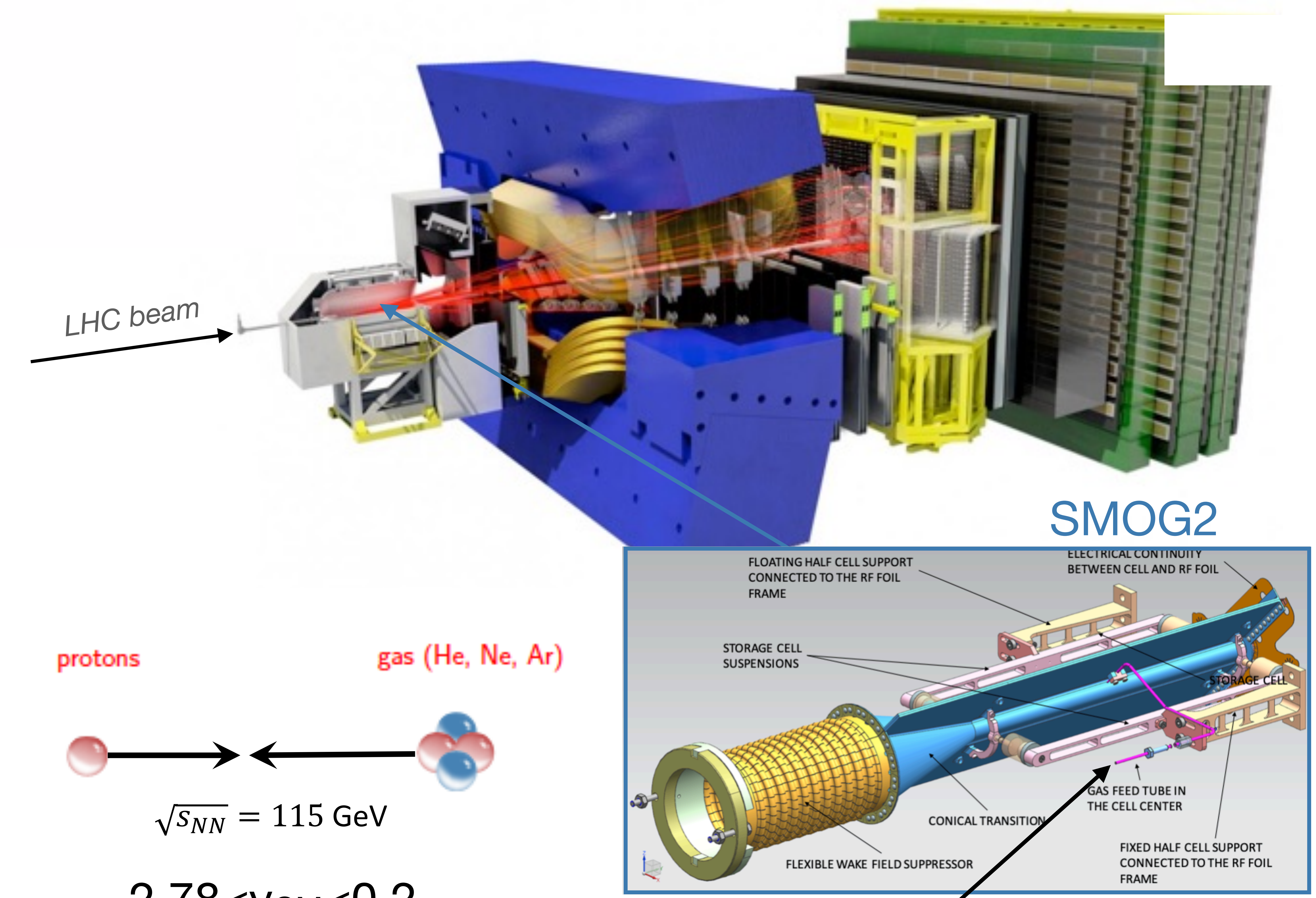
PDFs at the HL-LHC (Q = 10 GeV)



Fixed target at LHCb

RUN3

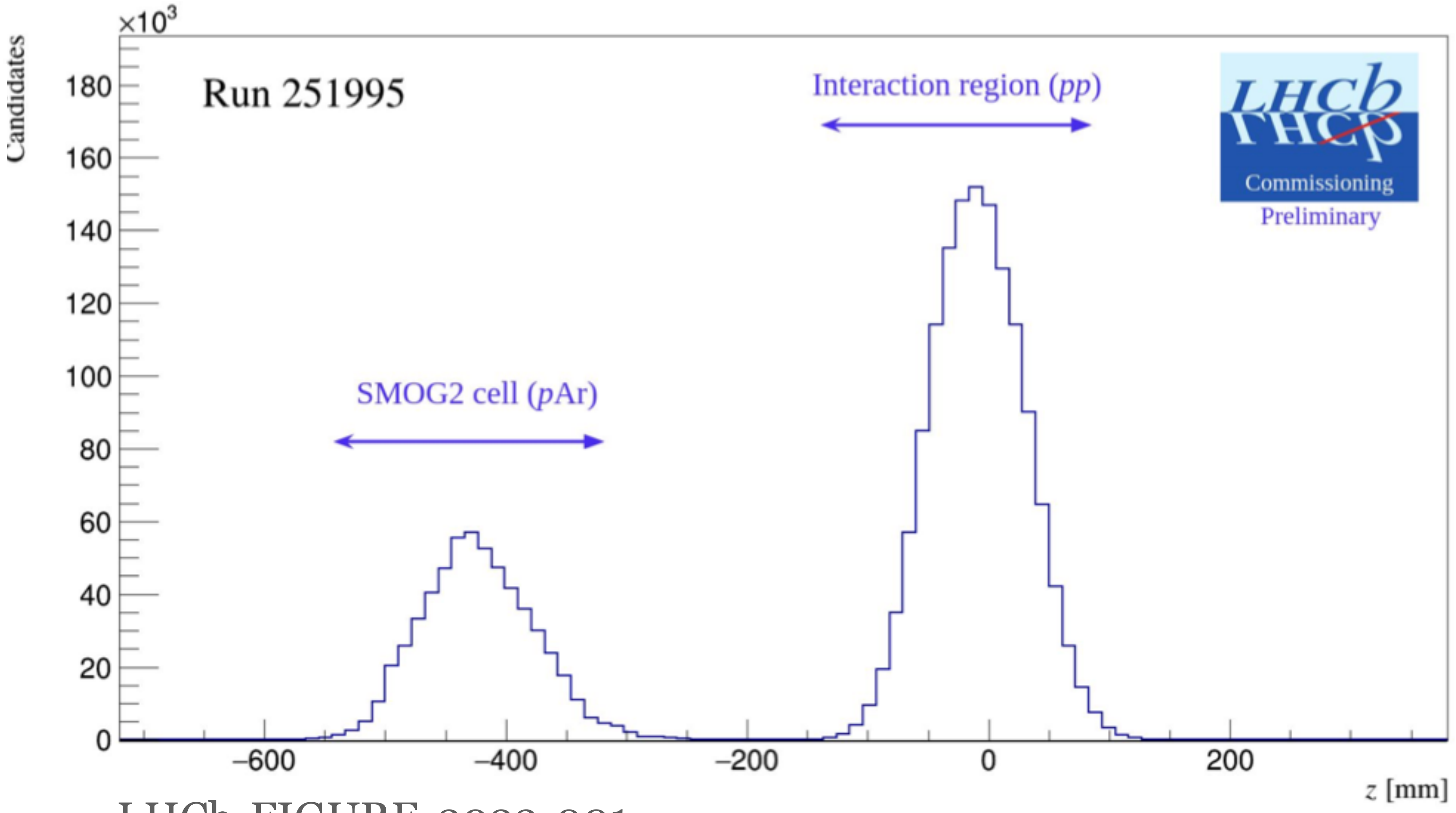
JINST 3 (2008) S
IJMPA 30 (2015)



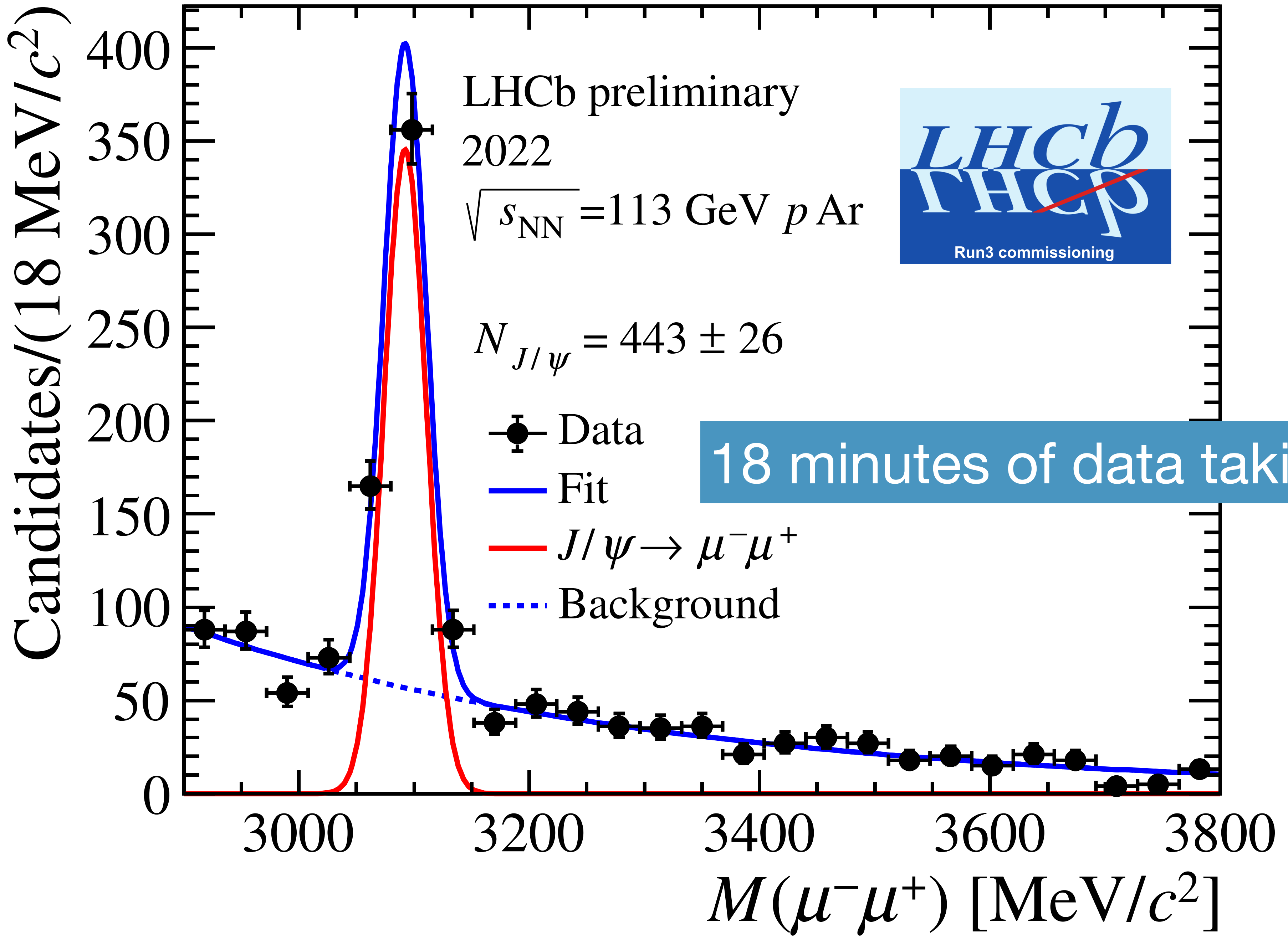
$\sqrt{s_{NN}}$ = 115 GeV

-2.78<y_{CM}<0.2

inject gas: He, Ne, Ar, and H_2, D_2



LHCb-FIGURE-2023-001

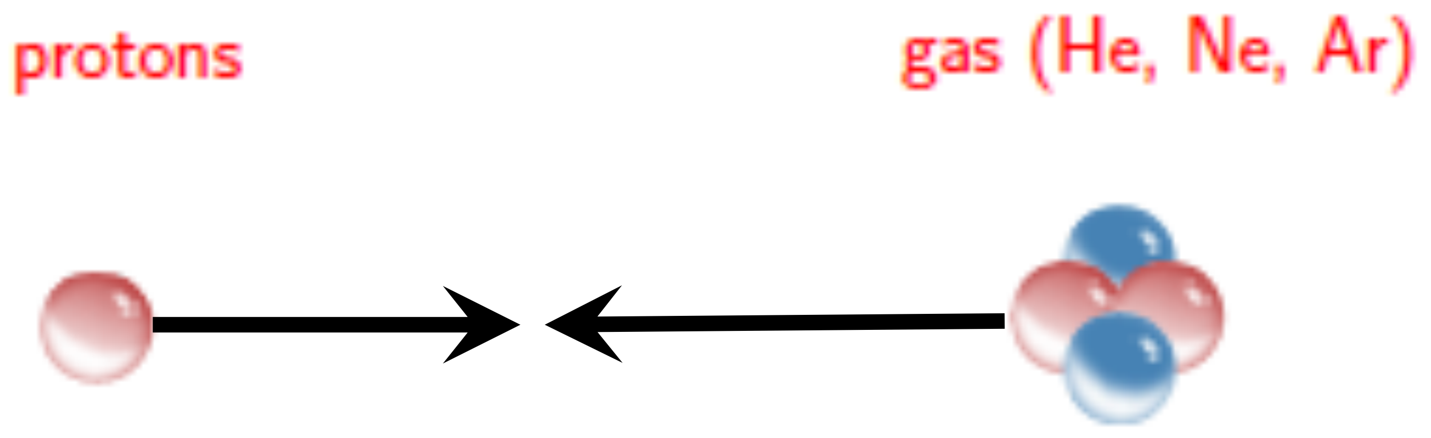


18 minutes of data taking

Fixed target at LHCb

Proposal for Run 5:

SMOG2

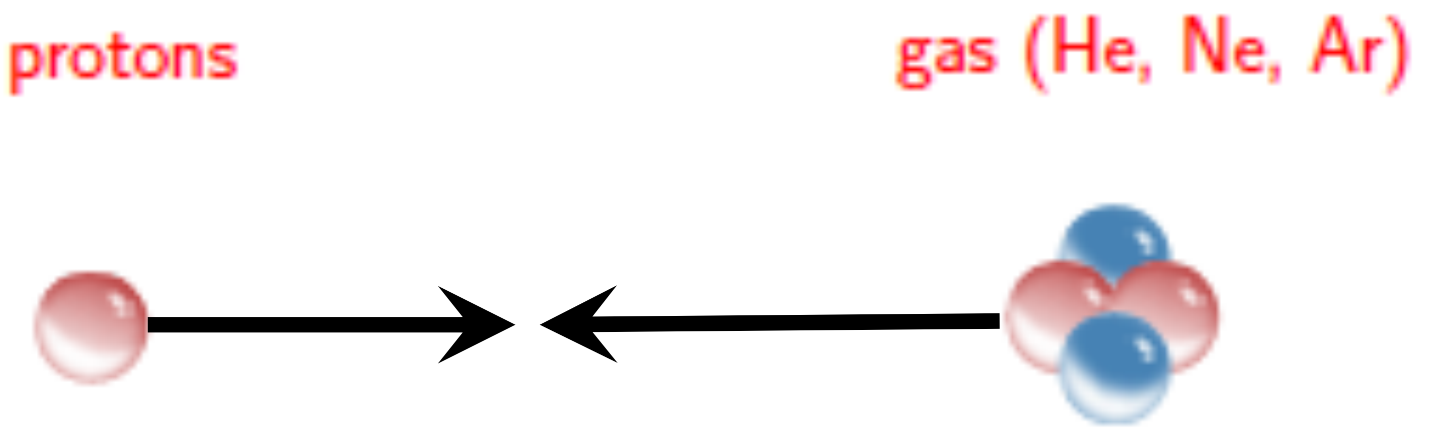


$\sqrt{s_{NN}} = 115$ GeV

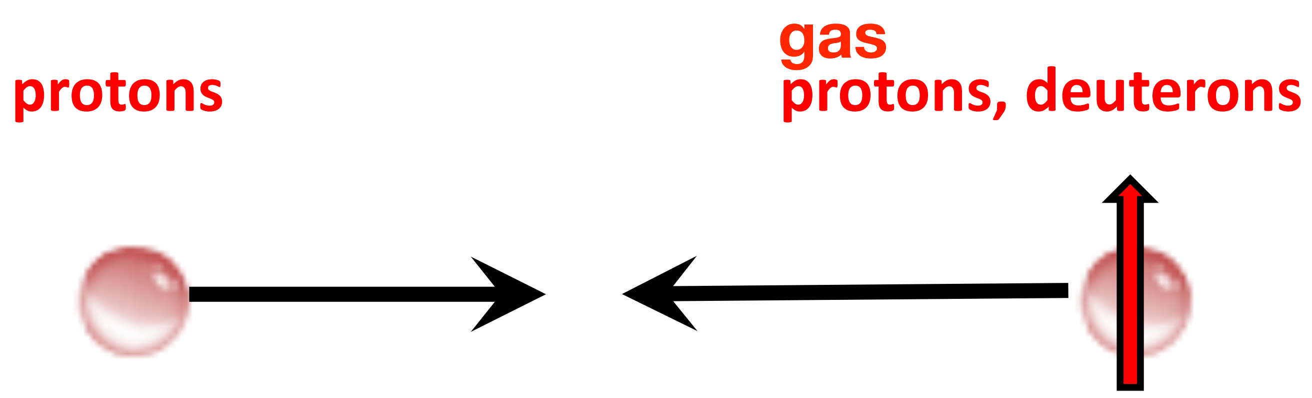
Fixed target at LHCb

Proposal for Run 5:

SMOG2 → LHCSPIN: transversely polarised gas target



$\sqrt{s_{NN}} = 115$ GeV



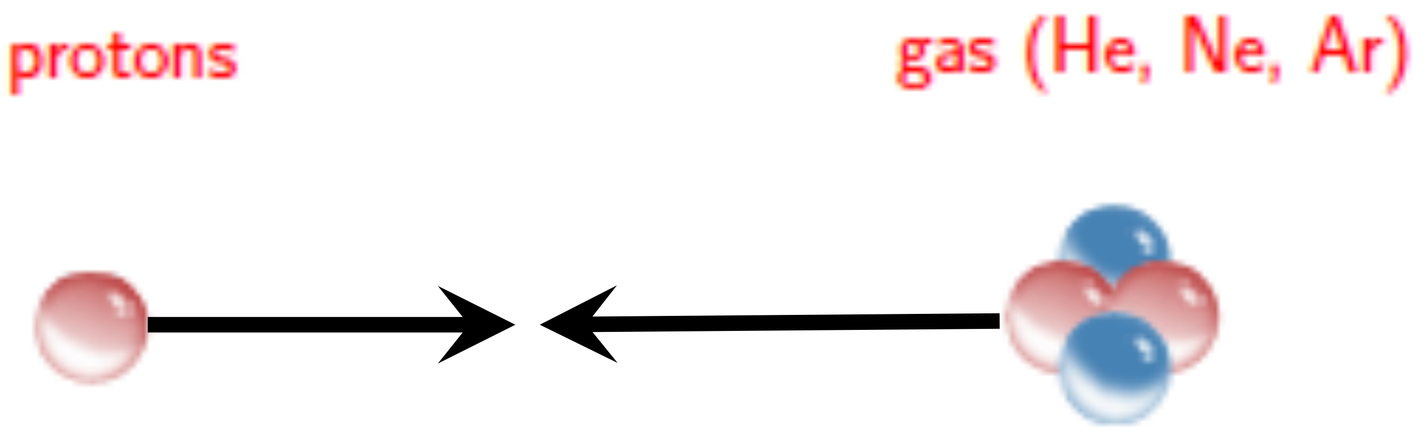
$\sqrt{s_{NN}} = 115$ GeV

$\longrightarrow$ access to spin-dependent PDFs, TMD PDFs and GPDs at the LHC

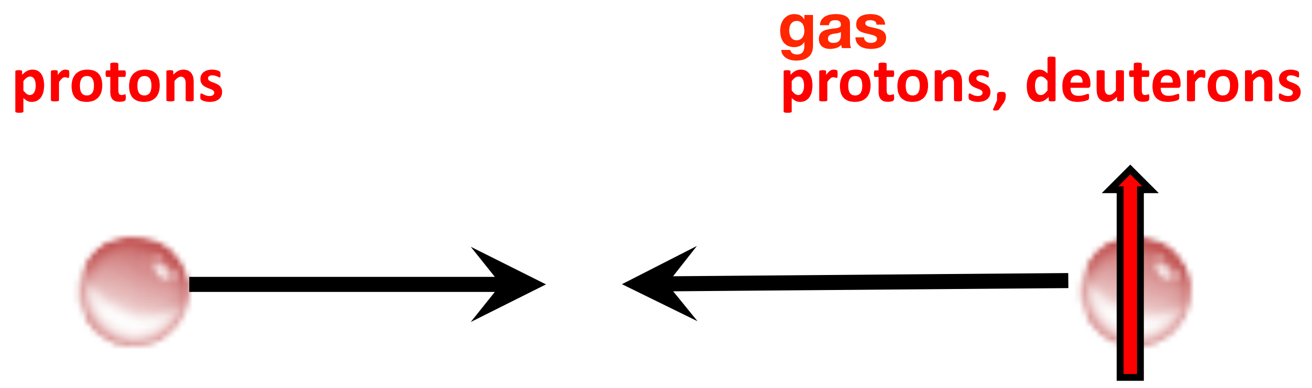
Fixed target at LHCb

Proposal for Run 5:

SMOG2 → LHCSPIN: transversely polarised gas target



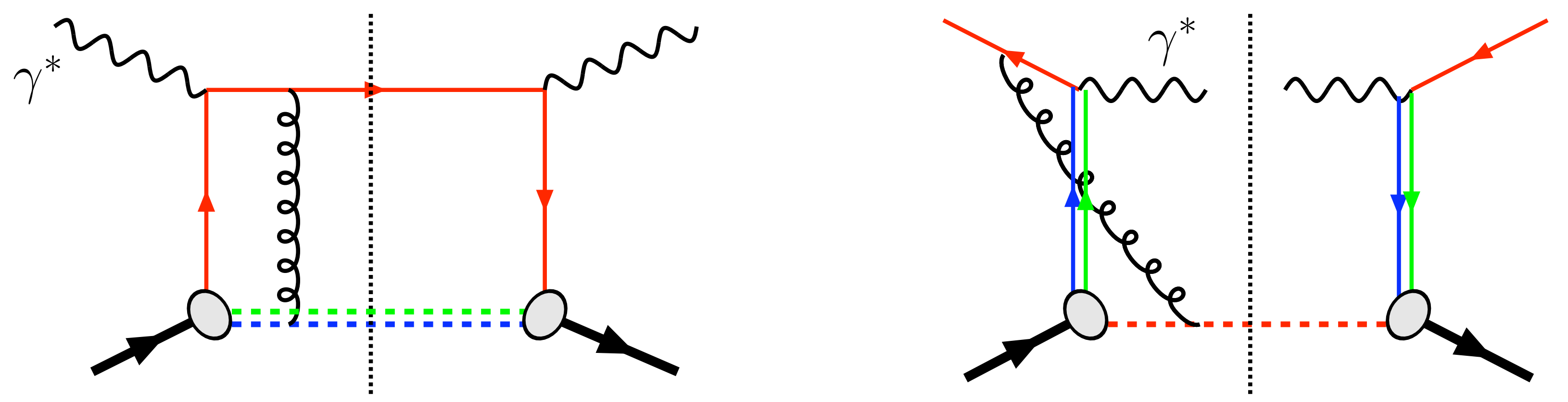
$\sqrt{s_{NN}} = 115$ GeV



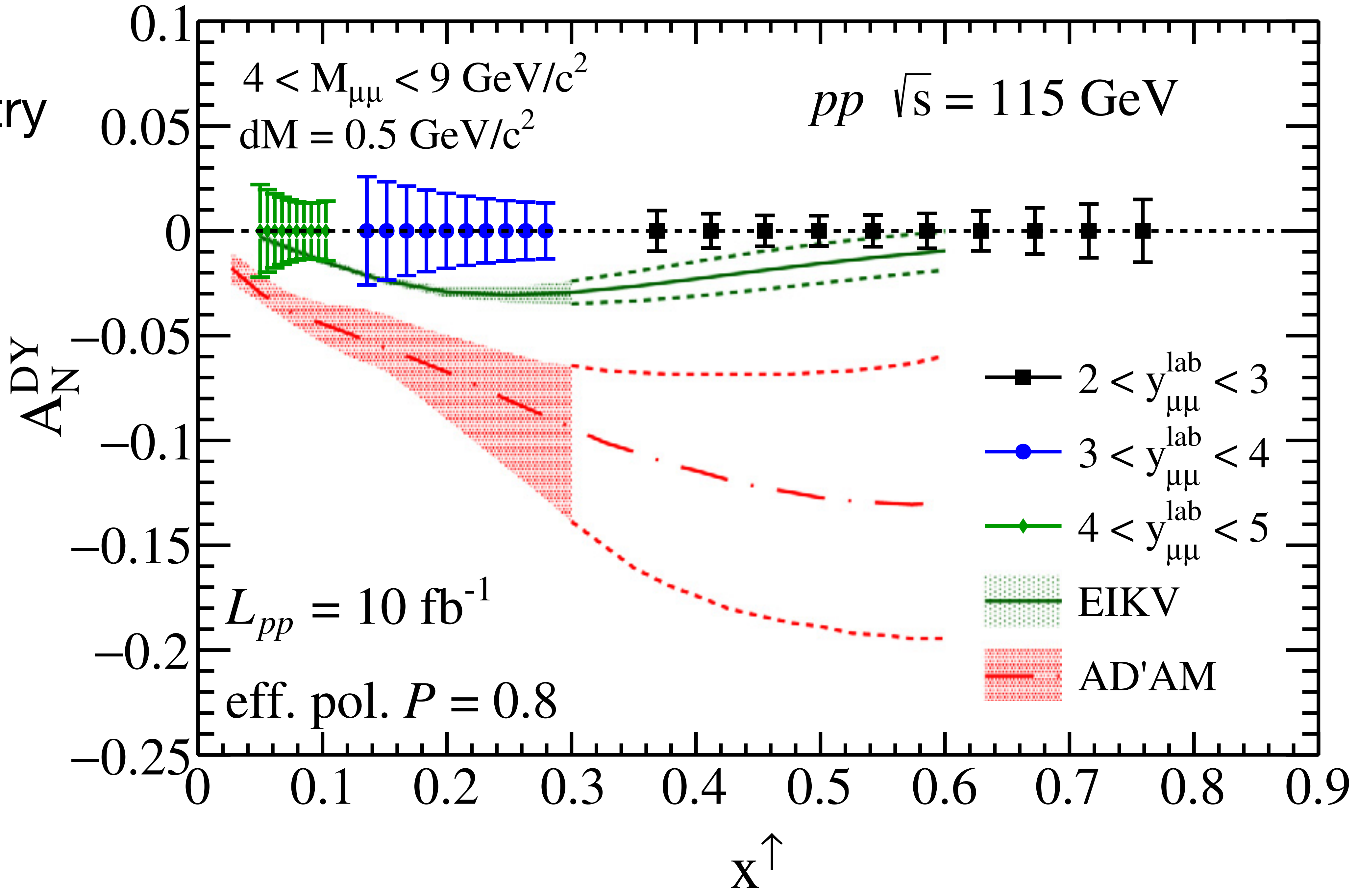
$\sqrt{s_{NN}} = 115$ GeV

⟶ access to spin-dependent PDFs, TMD PDFs and GPDs at the LHC

Sivers TMD PDF
via Drell-Yan asymmetry



$$f_{1T}^{\perp}\Big|_{SIDIS} = -f_{1T}^{\perp}\Big|_{DY}$$



Summary

- Vast complementarity between (HL-)LHC and EIC
- Study of the multi-dimensional hadron-structure:
  - EIC provides high precision and polarisation
  - LHC covers otherwise unaccessible low-x_B regions
- Nuclear matter
  - EIC covers large variety of nuclei

    —> valuable input for cold nuclear matter determination and for QGP studies

    —> precise study of hadronisation, can help to understand LHC baryon data and QGP studies
- Study of saturation effects

  Not an easy task: combined LHC and EIC data highly valuable!
- Originally not planned, but highly welcomed fixed target at the LHC
  - covers, as does the EIC, the large-x_B region
  - improved determination of PDFs in large-x_B region —> improved SM constraints and BSM searches
  - transversely polarised would allow to extend the complementarity with EIC and among others, test sign change of T-odd TMD PDFs, such as Sivers TMD PDF.