Precision calculations for groomed event shapes at HERA

DIS 2024, 10 April 2024

[arXiv:2306.17736]

see also

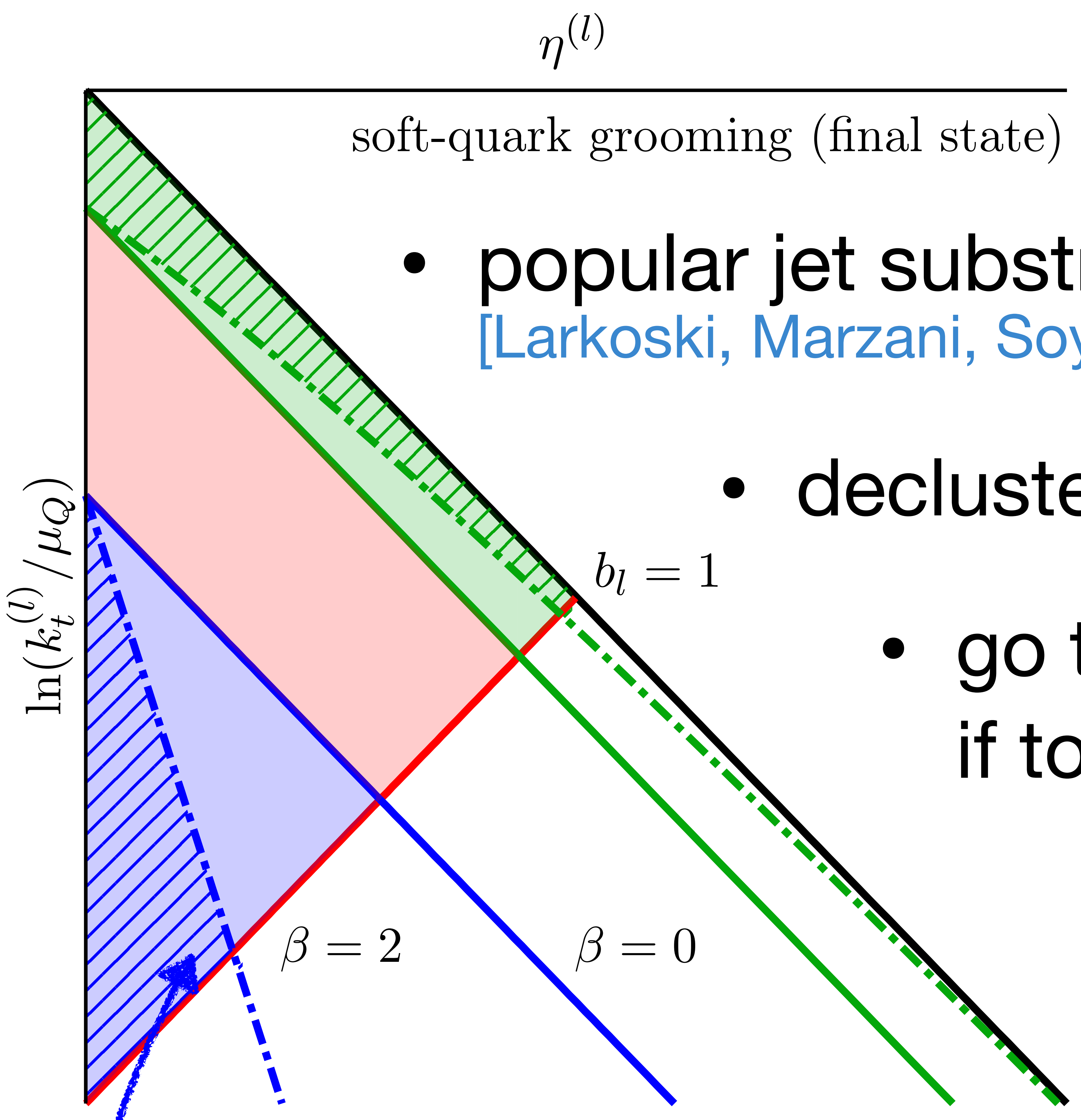
[arXiv:2403.10109] (talk by Johannes)
[arXiv:2403.10134] (talk by Henry)
[arXiv:2403.08982] (talk by Zhiqing)

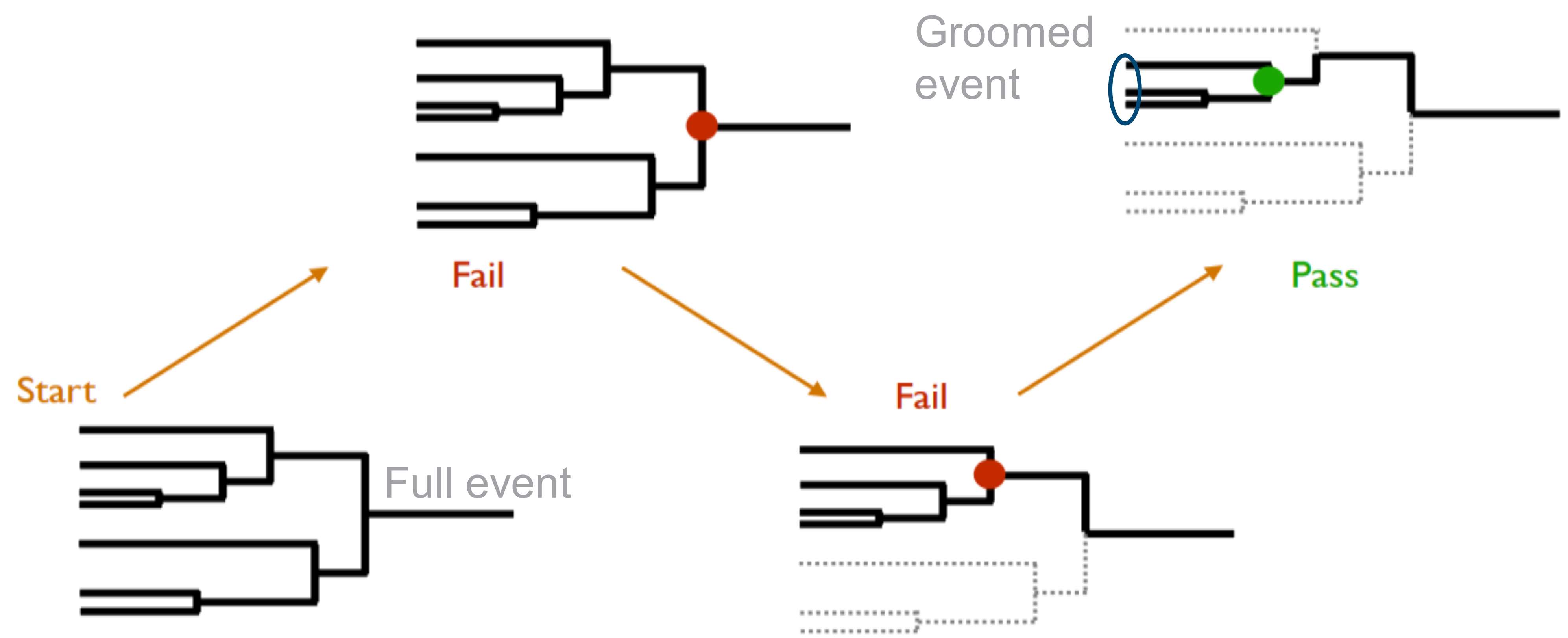
Daniel Reichelt, work with Max Knobbe, Steffen Schumann, Leon Stöcker and the H1 collaboration

Motivation

- future collider will include DIS machines like EIC, LHeC, FCC-ep ⇒ prepare general purpose event generators like Sherpa
- new measurement techniques learnt at LHC (jettiness, grooming) applied to Hera (H1) data ⇒ state of the art predictions from Sherpa
  - MC@NLO / MEPS / MEPS@NLO
  - + resummation in CAESAR formalism matched to NNLO QCD from Sherpa using technology from [Höche, Kuttimalai, Li ’18]
  - include Sherpa NP corrections via transfer matrices
- use DIS data in tuning, intermediate step with beam-fragmentation but no UE
  - uncertainties from replica tunes

Soft drop method



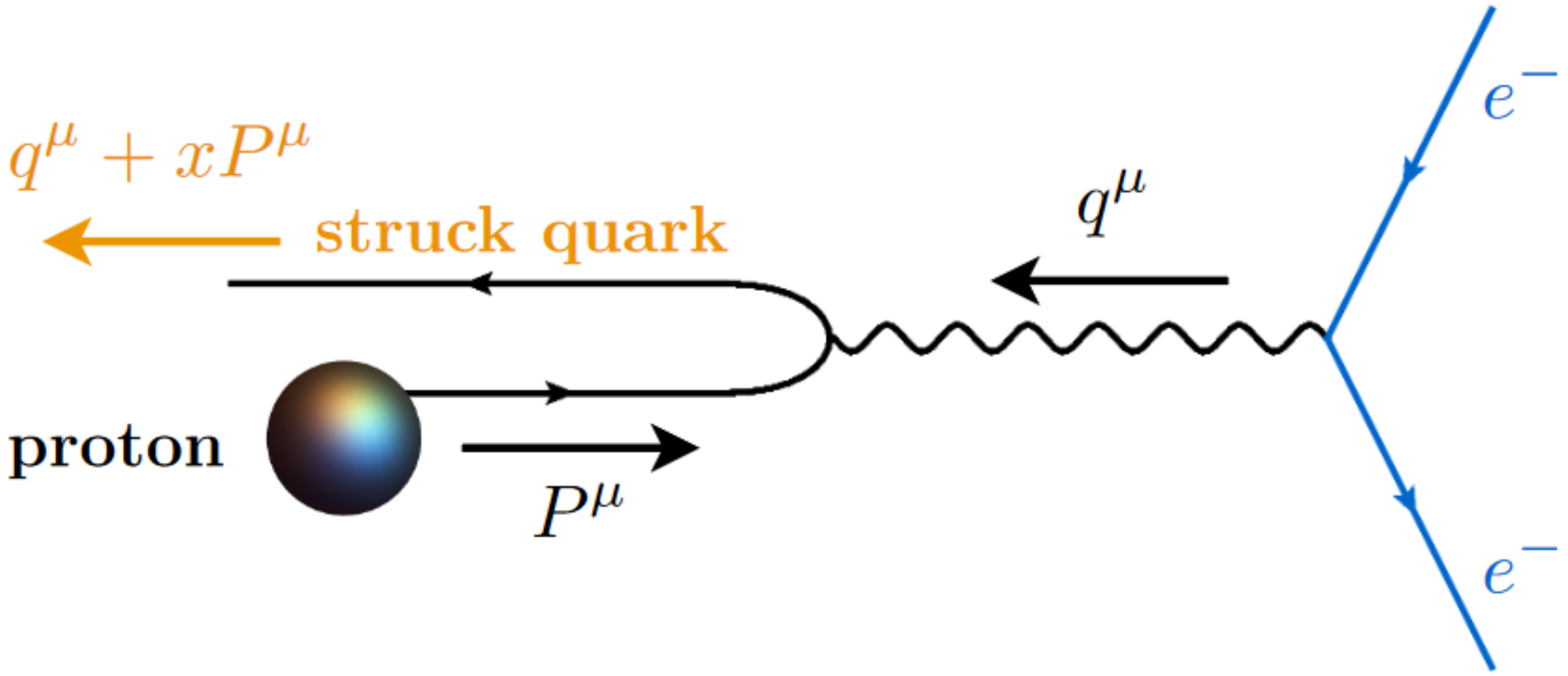


- popular jet substructure technique: [Larkoski, Marzani, Soyez, Thaler ’14]
  - decluster given jet
    - go through sequence, remove softer branch if too soft (relative to parameter z_{cut})

idea: avoid soft wide-angle phase space

- extended to DIS in [Makris ’21]
- based on Centauro jet measure [Arratia, Makris, Neill, Ringer, Sato ’21]
- calculation based on implementation in [Baron, DR, Schumann, Schwanemann, Theeuwes ’21]

Breit frame



[Makris '21]

- define by $q^\mu = (0,0,0,-Q)$
- reference vectors

  $n_+ = (1,0,0,1)$

  $n_- = (1,0,0,-1)$
- two hemispheres (analogous to thrust hemispheres in e^+e^-):
  - $\mathscr{H}_C$ current hemisphere

    $p_i \cdot n_+ > p_i \cdot n_-$
  - $\mathscr{H}_B$ beam hemisphere

    $p_i \cdot n_+ < p_i \cdot n_-$

- Photon virtuality $Q^2 = -q^2$
  - scale of perturbative process
- Bjorken $x_B = \dfrac{Q}{2P \cdot q}$
  - momentum fraction (infinite momentum frame) of proton
- Inelasticity $y = \dfrac{P \cdot q}{P \cdot k}$
  - energy fraction (proton rest frame) transferred from electron to parton

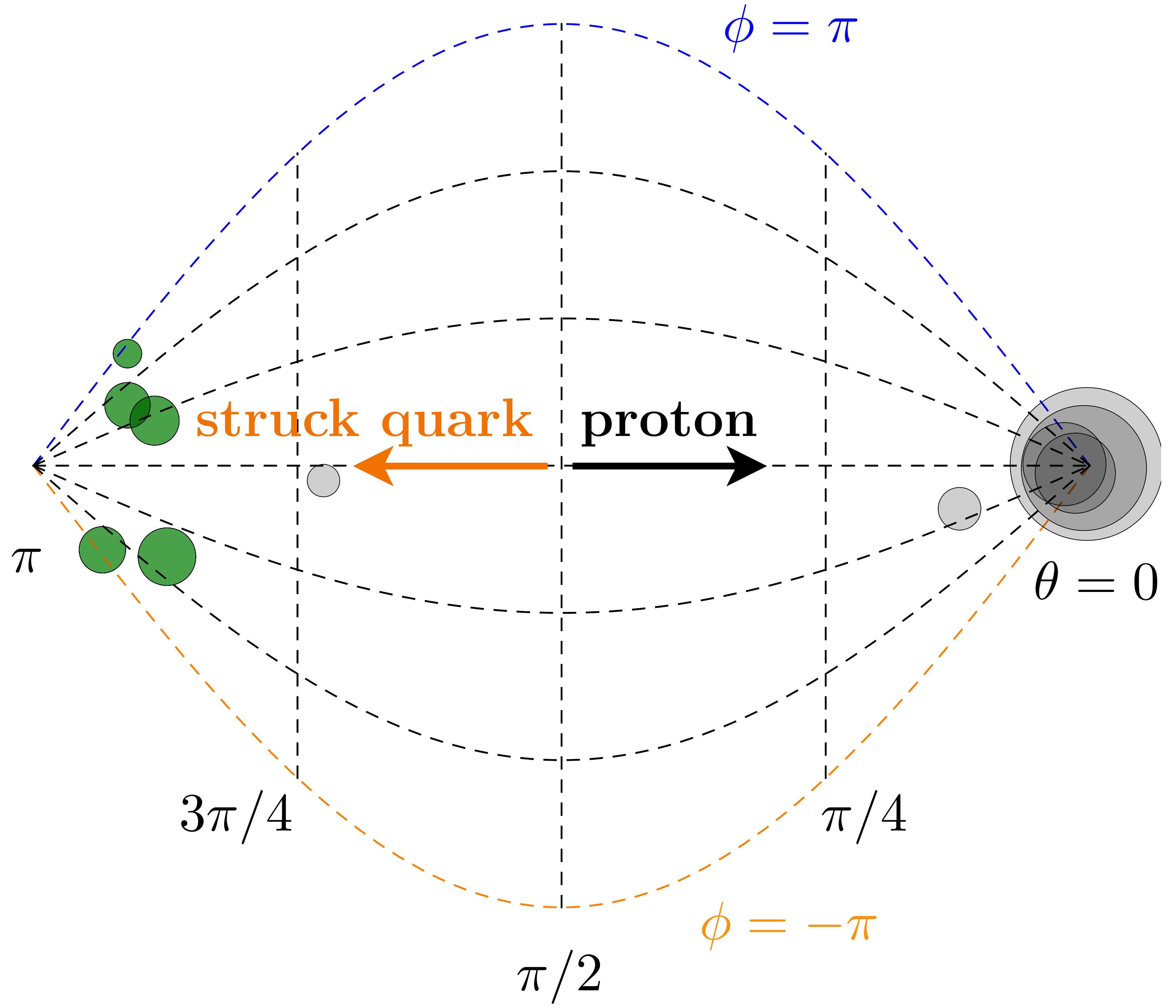
Soft Drop Mass

- grooming with Centauro [Arratia, Makris, Neill, Ringer, Sato '21] measure in Breit frame, in the soft-collinear limit:

$$d_{ij} = (\Delta\bar{z}_{ij})^2 + 2\bar{z}_i\bar{z}_j(1 - \cos\Delta\phi_{ij})\,,$$

$$\text{with} \quad \bar{z}_i = 2\sqrt{1 + \frac{q\cdot p_i}{x_B P\cdot p_i}} \quad \text{and} \quad \Delta\bar{z}_{ij} = \bar{z}_i - \bar{z}_j$$

  - all particles are clustered to the "struck quark", starting with the closest in angle
  - grooming goes through inversely start with soft partons in "beam" hemisphere, remove "forward particles"
  - leftover final state: either hard or collinear to the current hemisphere direction
    - define observable corresponding to the combined mass as $M_{\text{Gr.}}$



Calculation setup - Cliff notes

- CAESAR formalism for soft gluon resummation at NLL [Banfi, Salam, Zanderighi ’04]
- available as implementation in Sherpa [Gerwick, Höche, Marzani, Schumann ’15] [Baberuxki, Preuss, DR, Schumann ’19]
- multiplicative matching (⇒ NLL’ accurate)
- necessary extensions for jet observables… :
  - modified wide angle behaviour [Dasgupta, Khelifa-Kerfa, Marzani, Spannowski ‘12] [Caletti, Fedkevych, Marzani, DR, Schumann, Soyez, Theeuwes ’21] [DR, Caletti, Fedkevych, Marzani, Schumann, Soyez ‘22]
  - non-global logs [Dasgupta, Salam ’01]
- … and for soft drop grooming [Larkoski, Marzani, Soyez, Thaler ’14]
  - CEASAR style formulas available [Baron, DR, Schumann, Schwanemann, Theeuwes ‘20]

Calculation setup - details

- master formula for rIRC save observable: [Banfi, Salam, Zanderighi ’04]

$$\Sigma^{\delta}_{\mathrm{res}}(v) = \int d\mathcal{B}_\delta \frac{d\sigma_\delta}{d\mathcal{B}_\delta} \exp\left[-\sum_{l\in\delta} R_l^{\mathcal{B}_\delta}(L)\right] \mathcal{P}^{\mathcal{B}_\delta}(L)\mathcal{S}^{\mathcal{B}_\delta}(L)\mathcal{F}^{\mathcal{B}_\delta}(L)\mathcal{H}^{\delta}(\mathcal{B}_\delta)$$

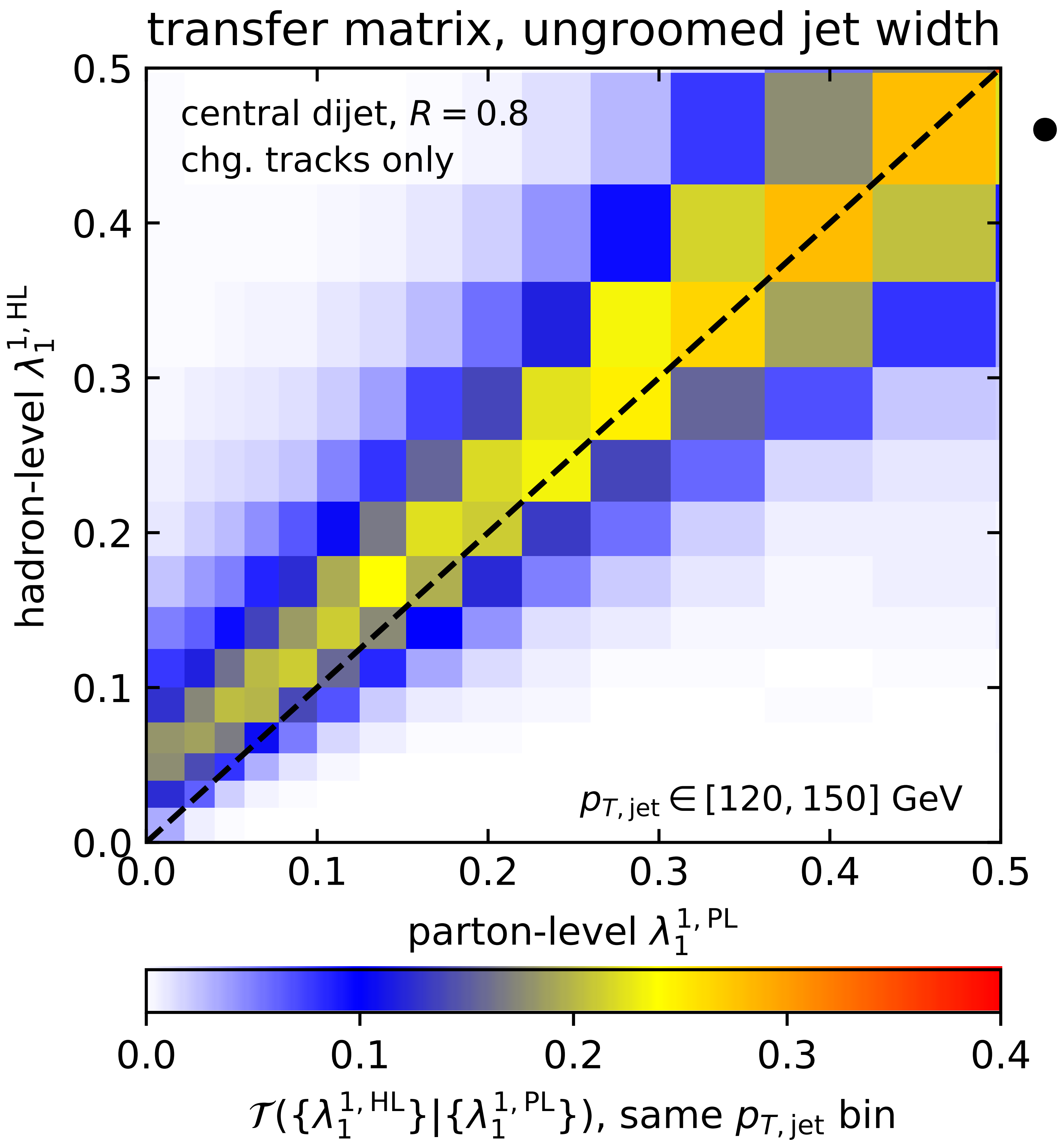
- ingredients known analytically in this case
- matching: $\Sigma_{\mathrm{matched}} = \Sigma_{\mathrm{res}} \left(1 + \frac{\Sigma^{(1)}_{\mathrm{fo}} - \Sigma^{(1)}_{\mathrm{res}}}{\sigma^{(0)}} + \frac{\Sigma^{(2)}_{\mathrm{fo}} - \Sigma^{(2)}_{\mathrm{res}}}{\sigma^{(0)}} - \frac{\Sigma^{(1)}_{\mathrm{res}}}{\sigma^{(0)}} \frac{\Sigma^{(1)}_{\mathrm{fo}} - \Sigma^{(1)}_{\mathrm{res}}}{\sigma^{(0)}}\right)$
- note $\Sigma^{(2)}_{fo}$ included → using “projection to Born” technique in Sherpa

[Höche, Kuttimalai, Li ’18]

  - cross sections / normalisation correct to NNLO, distributions at NLO

    → overall label as (N)NLO

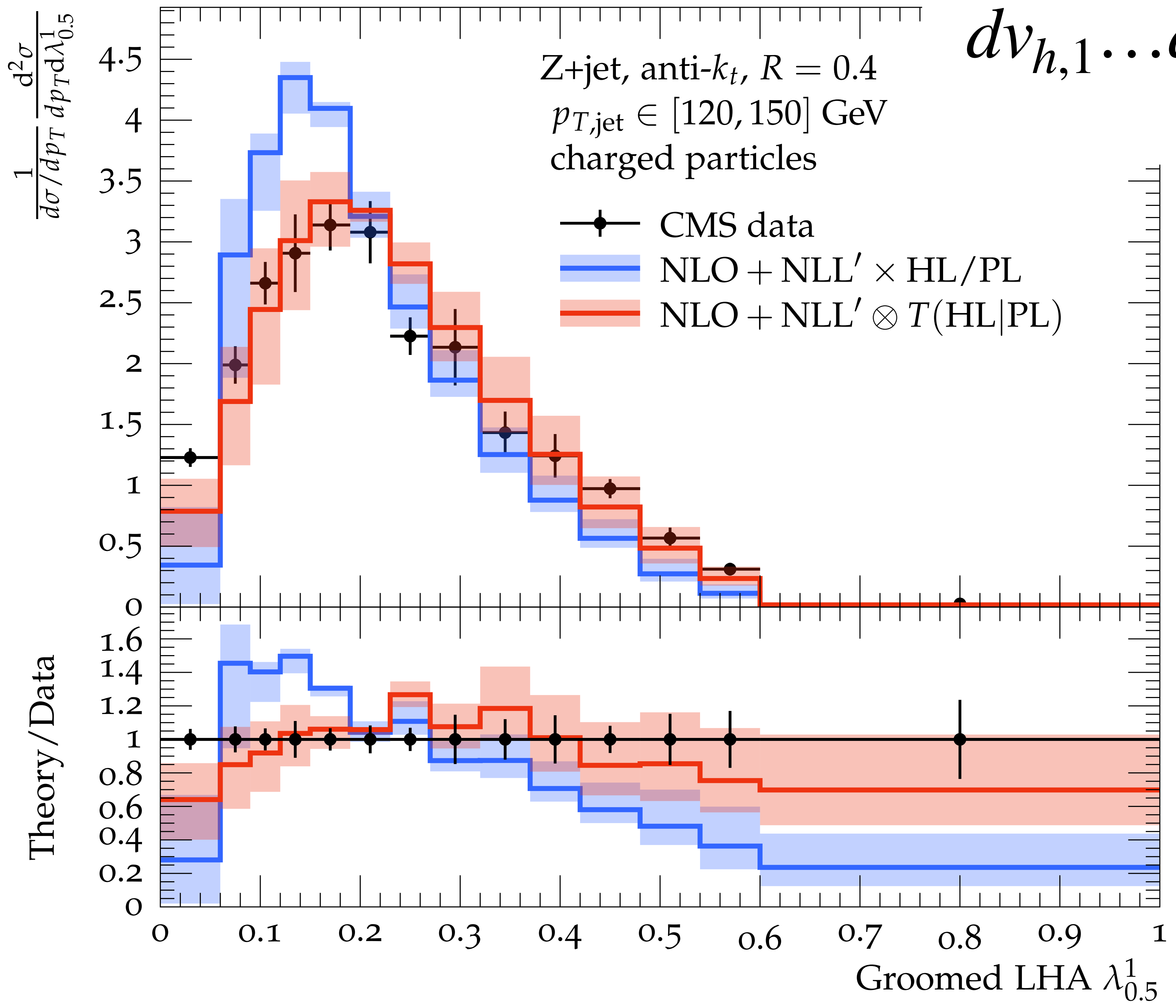
Non-perturbative corrections



examples from [DR, Caletti, Fedkevych, Marzani, Schumann, Soyez '22]

- earlier approach:

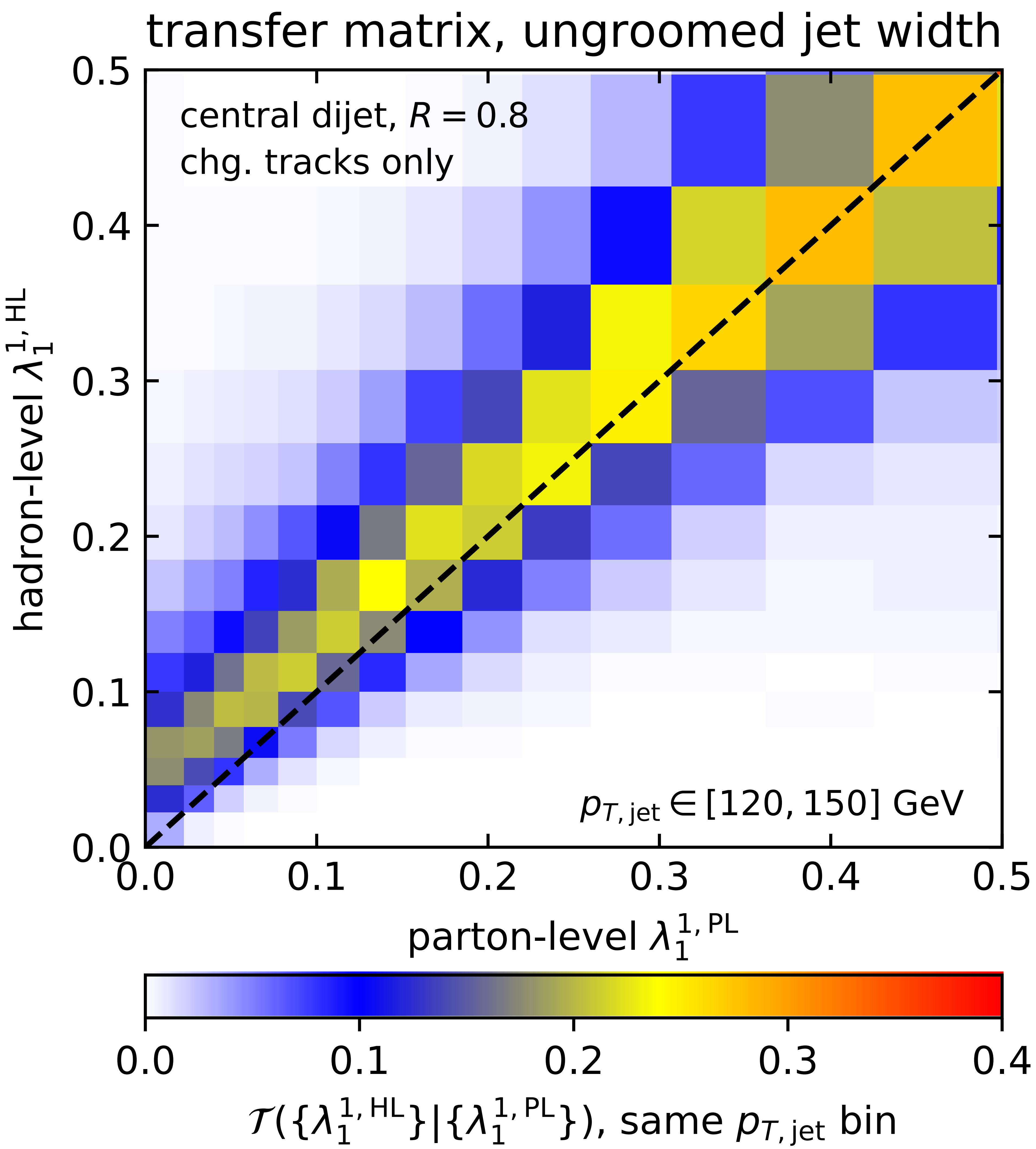
$$\frac{d\sigma^{\text{HL}}}{dv} = \frac{d\sigma^{\text{MC,HL}}/dv}{d\sigma^{\text{MC,PL}}/dv}\frac{d\sigma^{\text{PL}}}{dv}$$

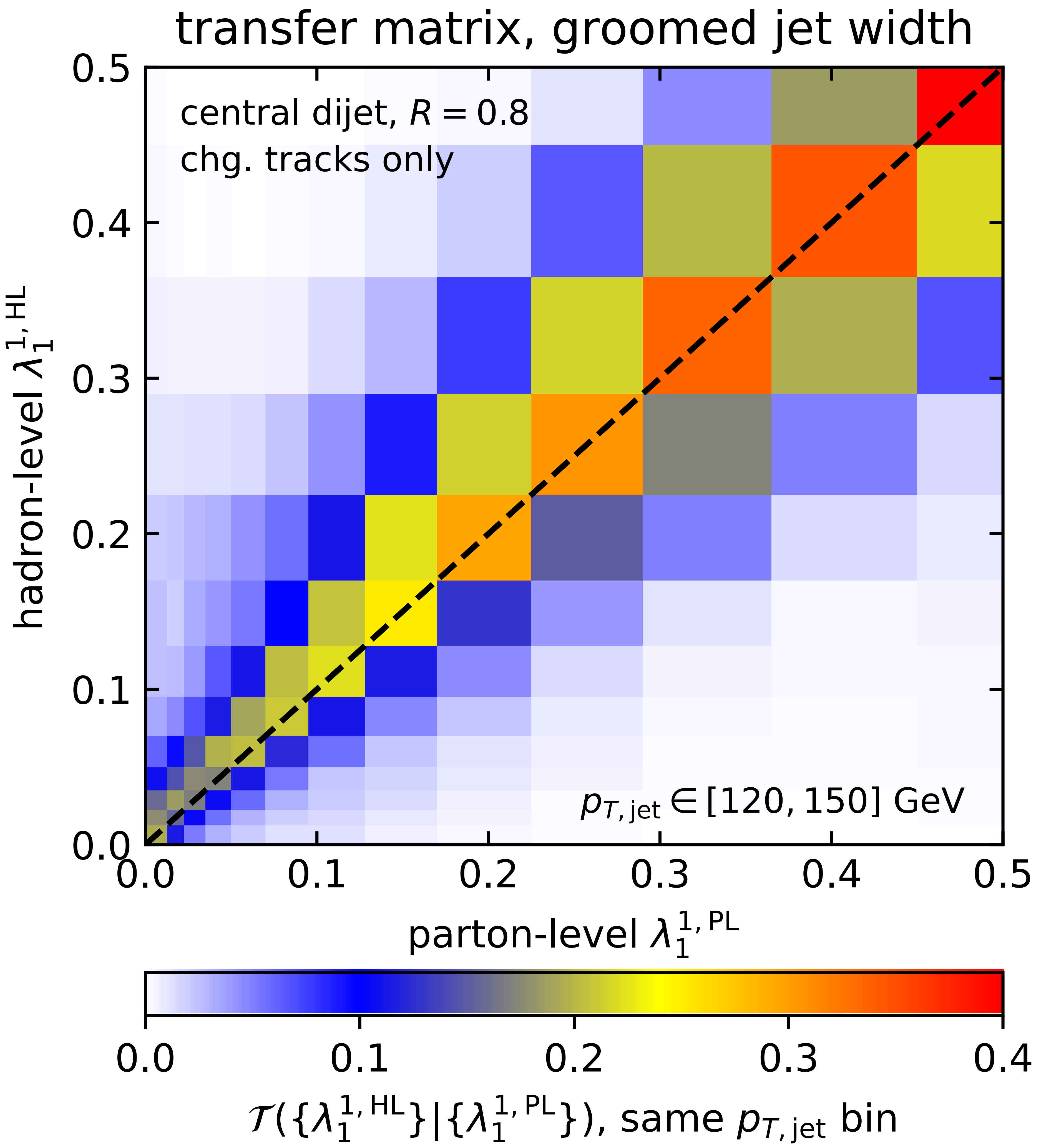


- here, extract transition matrix between parton- and hadron level bins in p_T and observable v

$$\frac{d^m\sigma^{\text{HL}}}{dv_{h,1}\ldots dv_{h,m}} = \int d^m\vec{v}_p\ \mathscr{T}(\vec{v}_h|\vec{v}_p)\frac{d^m\sigma^{\text{PL}}}{dv_{p,1}\ldots dv_{p,m}}$$

Non-perturbative corrections with SD



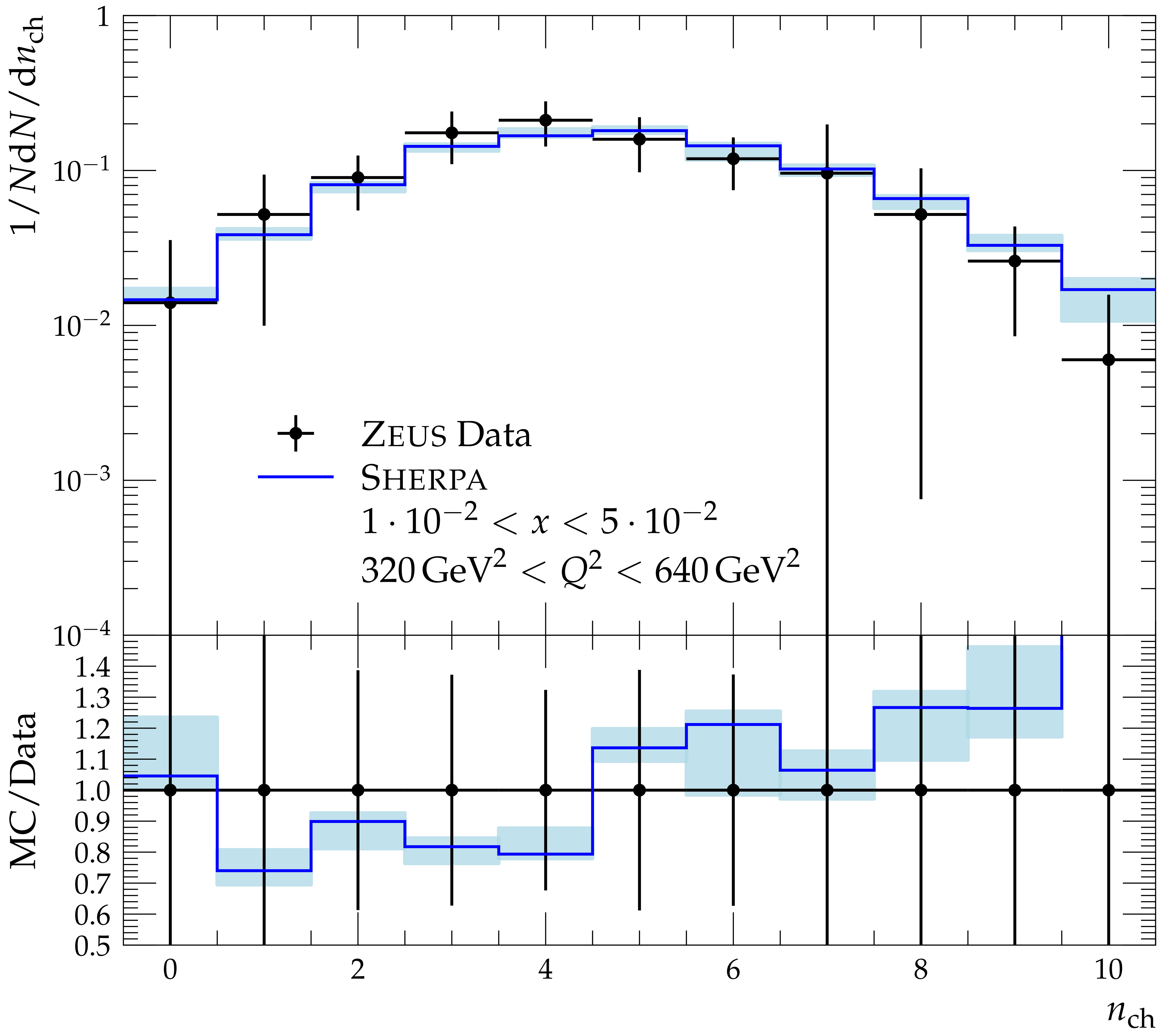


Sherpa MEPS@NLO - setup

- using Sherpa 3.0.0β
- several developments in DIS specific tools (see WG4 talks tomorrow)
- here use Sherpa, ⇒ general purpose tools including MC@NLO matching, CKKW merging to include

$$e^- p \to e^- + 1,2\,j\,@\,\mathrm{NLO} + 3,4\,j\,@\,\mathrm{LO}$$

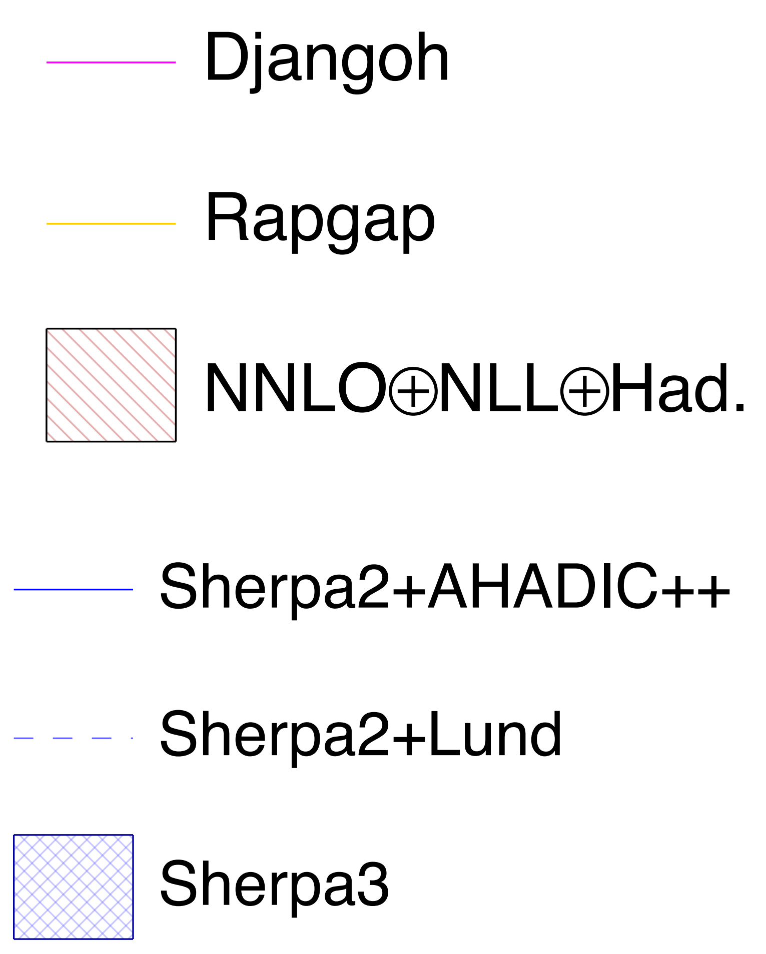
- cluster hadronisation, tuning of beam-fragmentation parameters in DIS
- replica tunes to estimate related tuning uncertainty

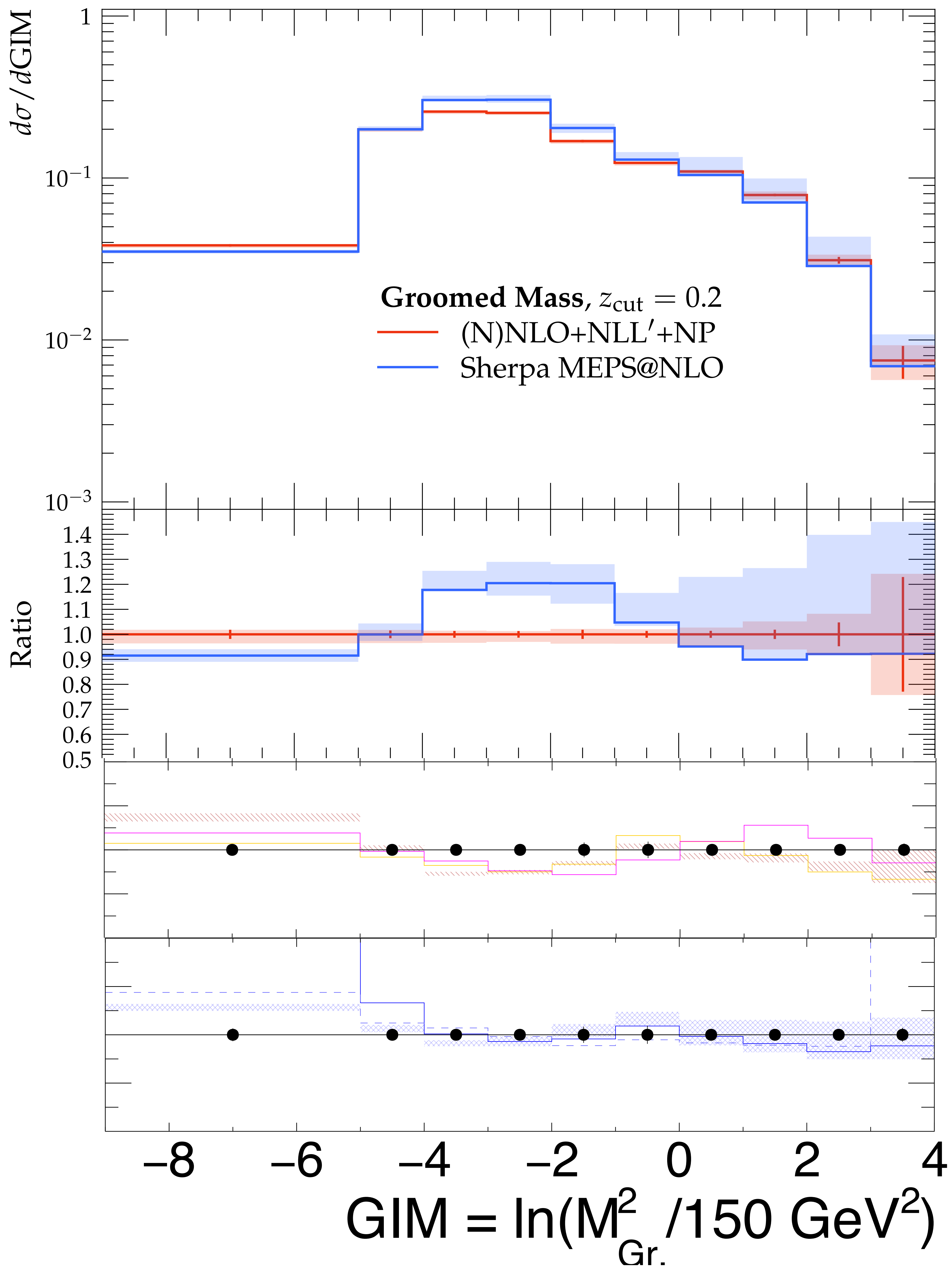


Soft Drop Mass at H1

- electron proton collisions from HERA at $\sqrt{s} = 319$ GeV

  $E_e = 27.6$ GeV, $\quad E_p = 920$ GeV
- data shown here recorded in 2003-2007, corresponding to $\mathscr{L} = 351.6\ \mathrm{pb}^{-1}$
- focus on higher $Q^2 > 150\ \mathrm{GeV}^2$ range
- ratio to H1 data see next talk by Henry for full details

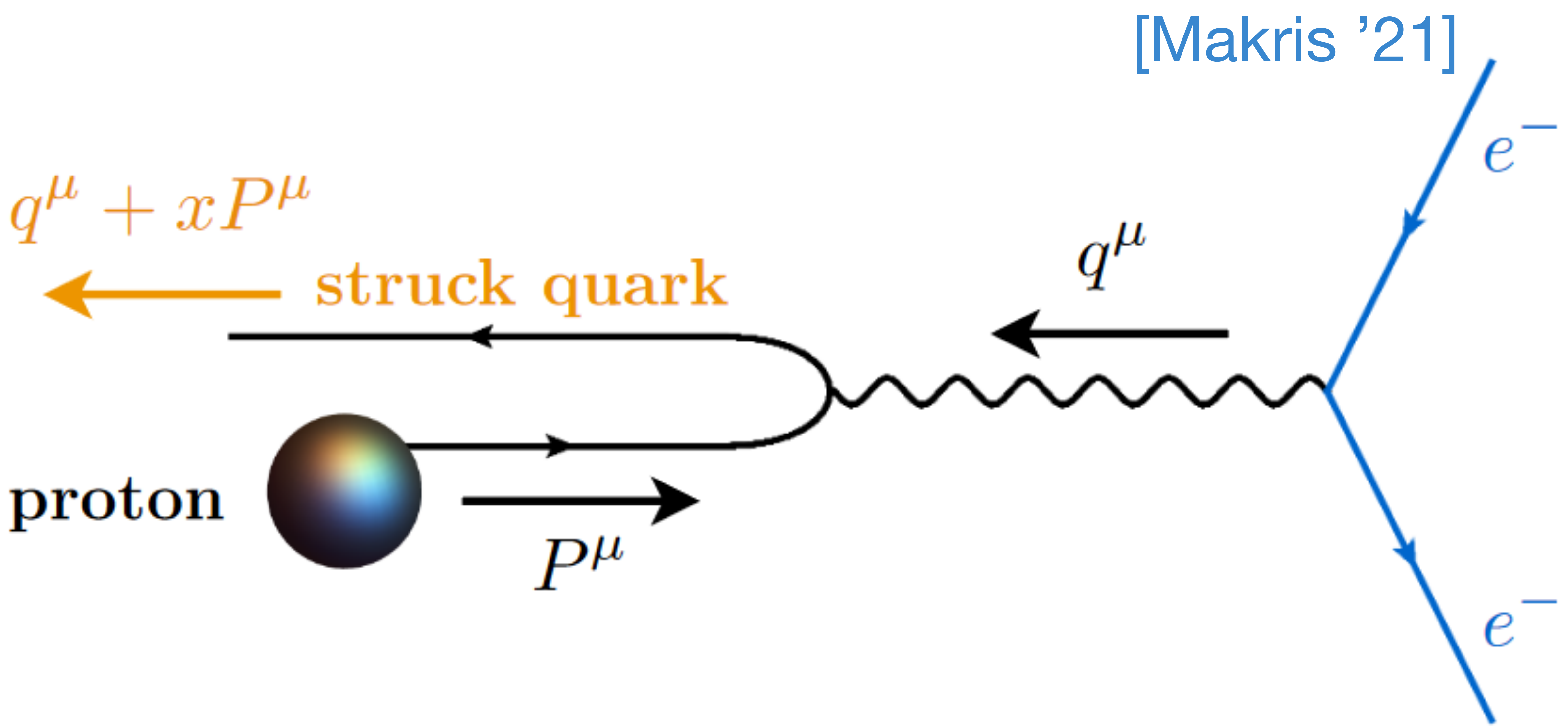




1-jettiness

- $\tau^1 = \frac{1}{Q} \sum \min(p_i \cdot n_+, p_i \cdot n_-)$

  see also [Stewart, Tackmann, Waalewijn '10]
  [Kang, Mantry, Qiu '12]
  [Kang, Liu, Mantry '13]



- equivalently $\tau^1 = 1 - \frac{2}{Q} \sum_{i \in \mathscr{H}_C} p_{z,i}$

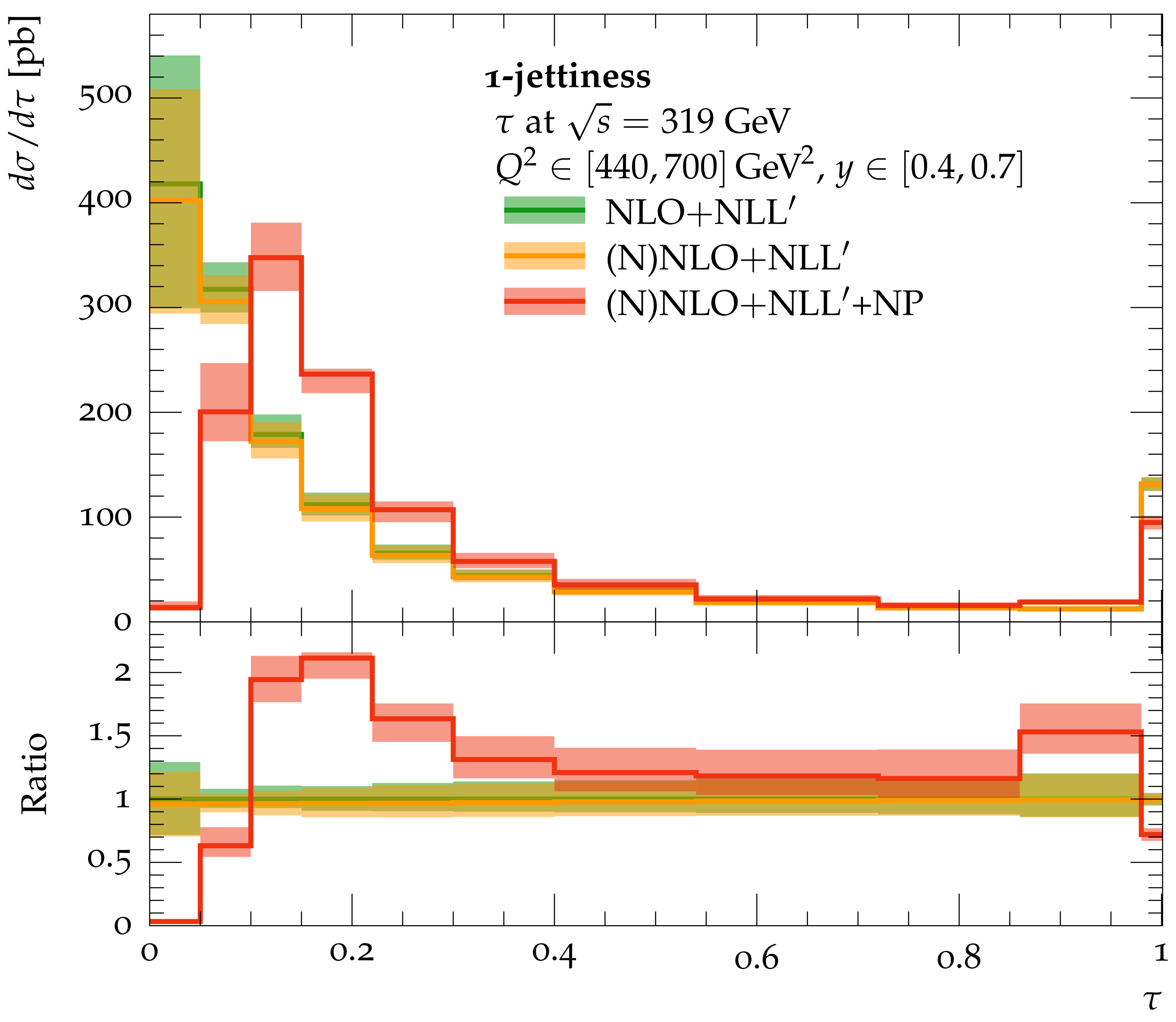
  (in Breit frame) → thrust in DIS

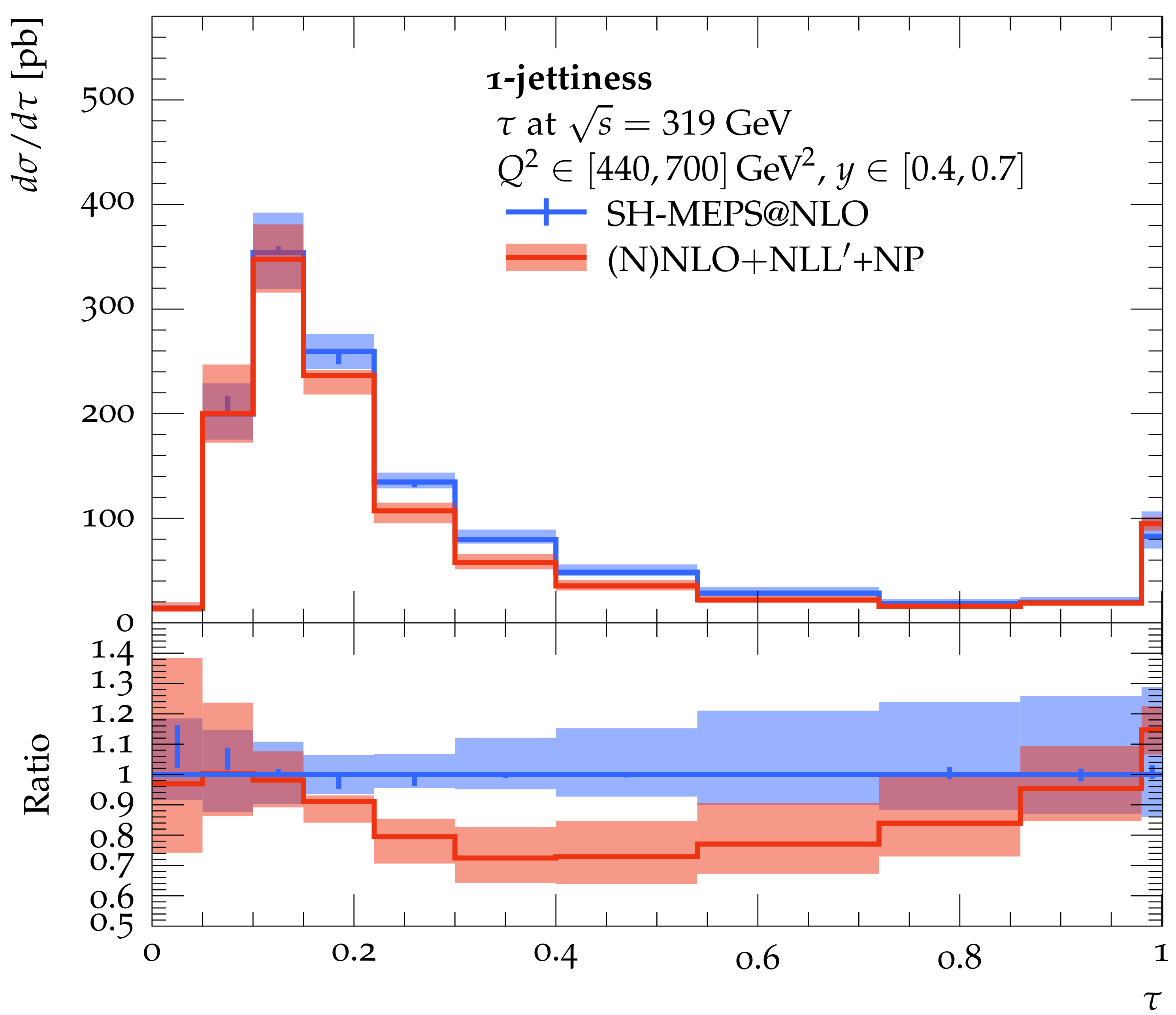
  see also [Antonelli, Dasgupta, Salam '00],
  [Dasgupta Salam '02]

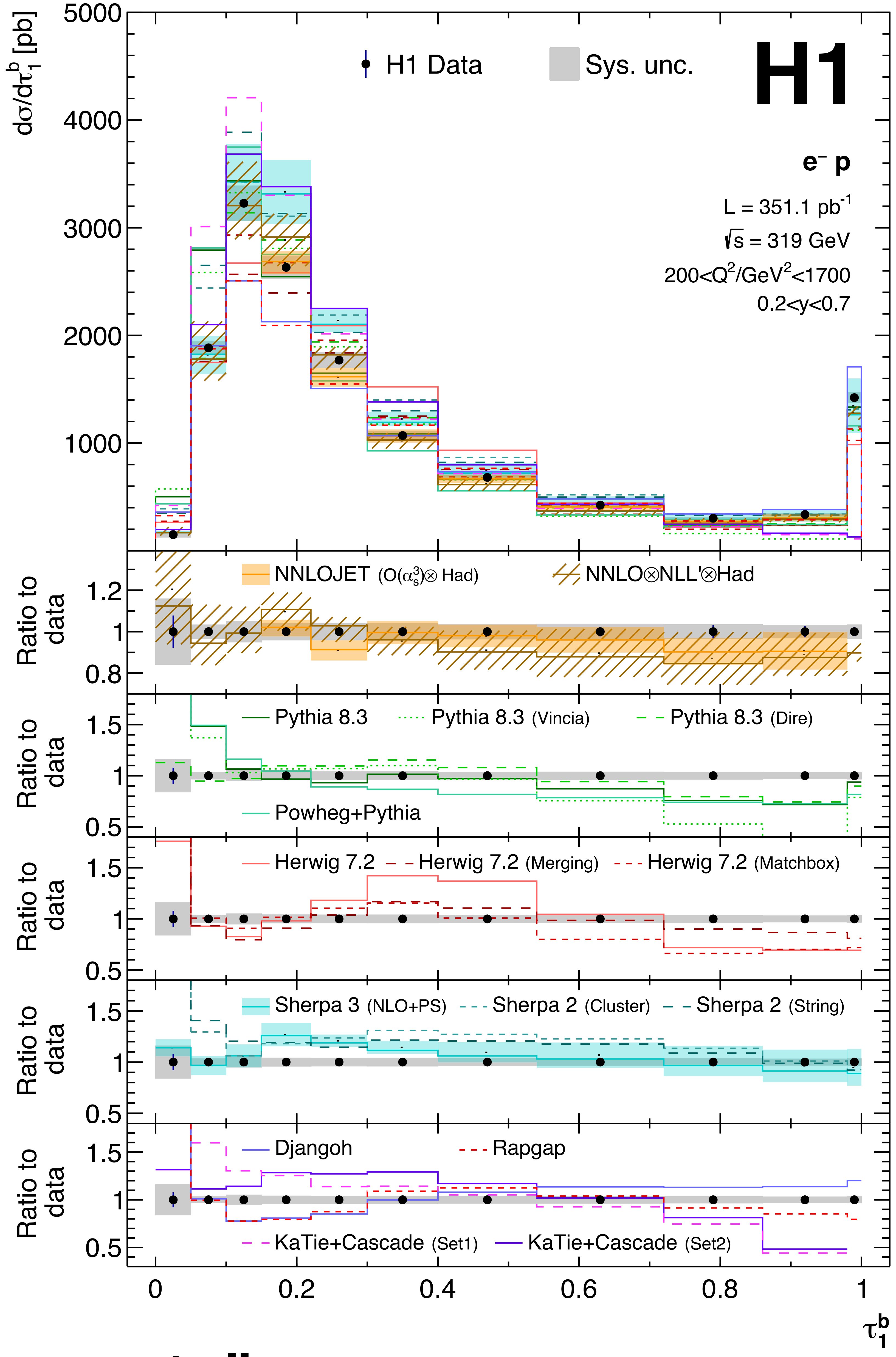
- manifestly global (sensitive to radiation everywhere in phase space)

- see talk by Johannes yesterday!

1-jettiness results

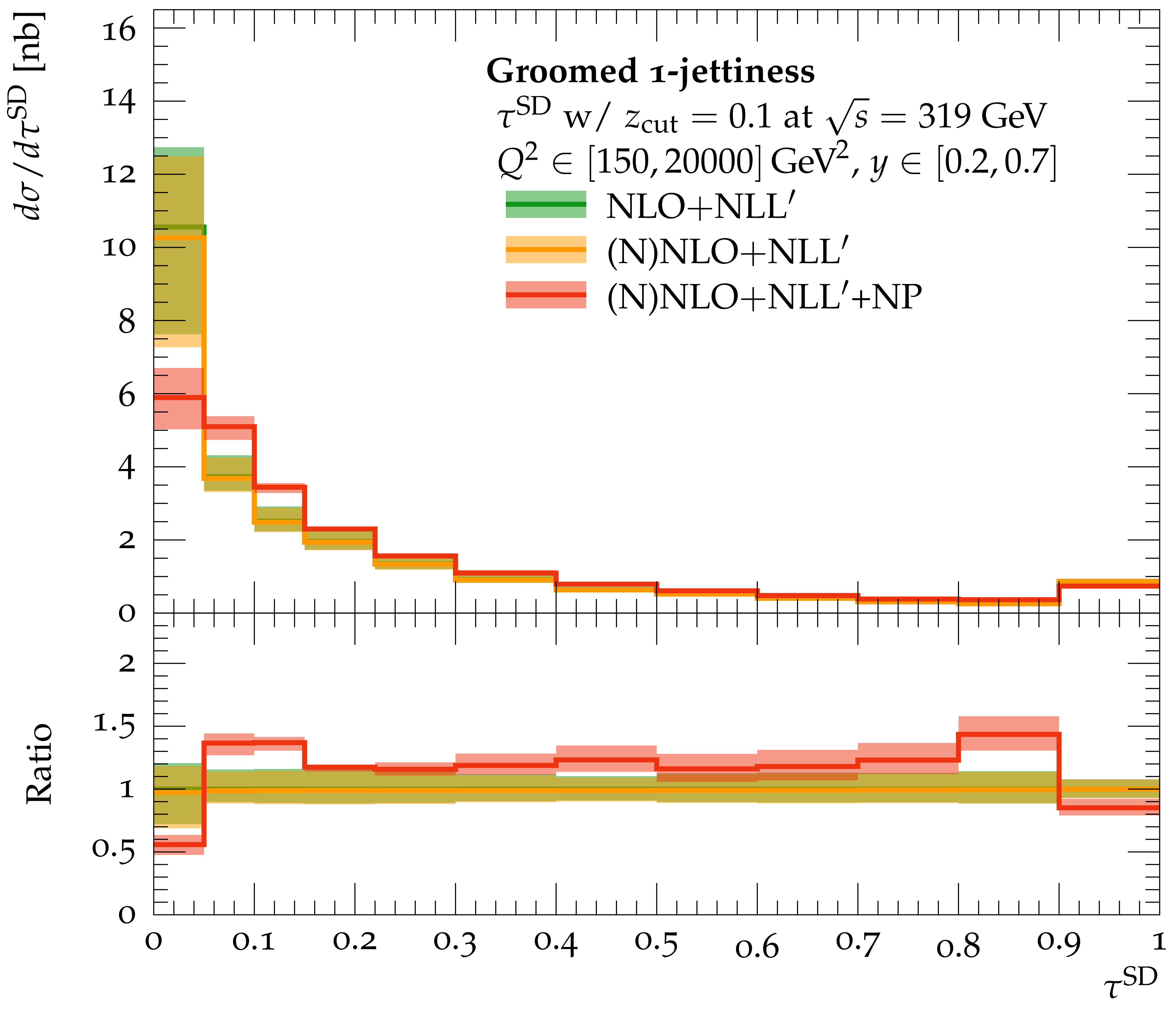




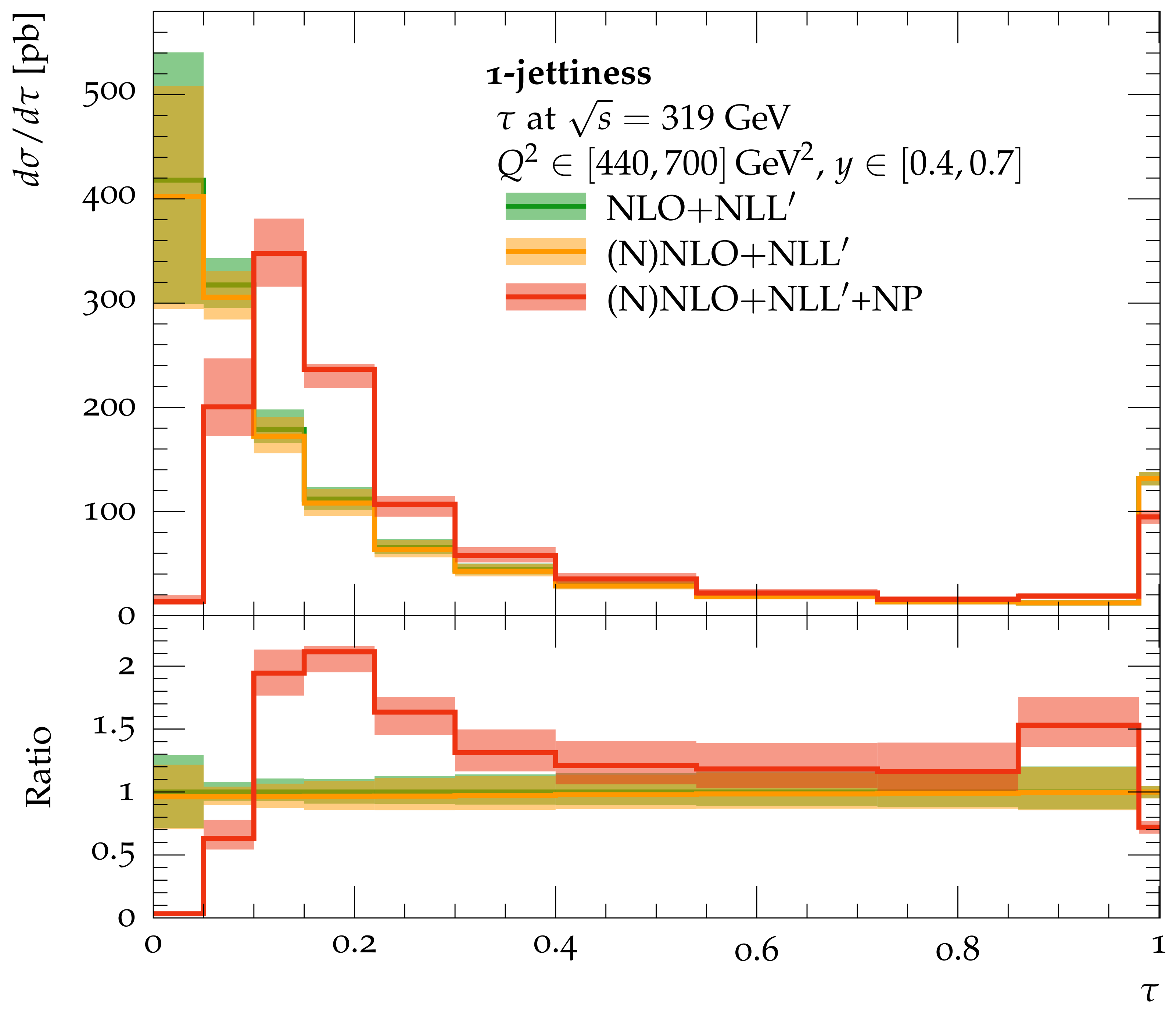


- 1-jettiness with $0.4 < y < 0.7$ at mid Q^2
- small corrections from NNLO normalisation
- relatively large non-perturbative corrections!
- excess at $\tau \to 1$ driven by "empty hemisphere events", see talk by Zhiqing

1-jettiness results with grooming

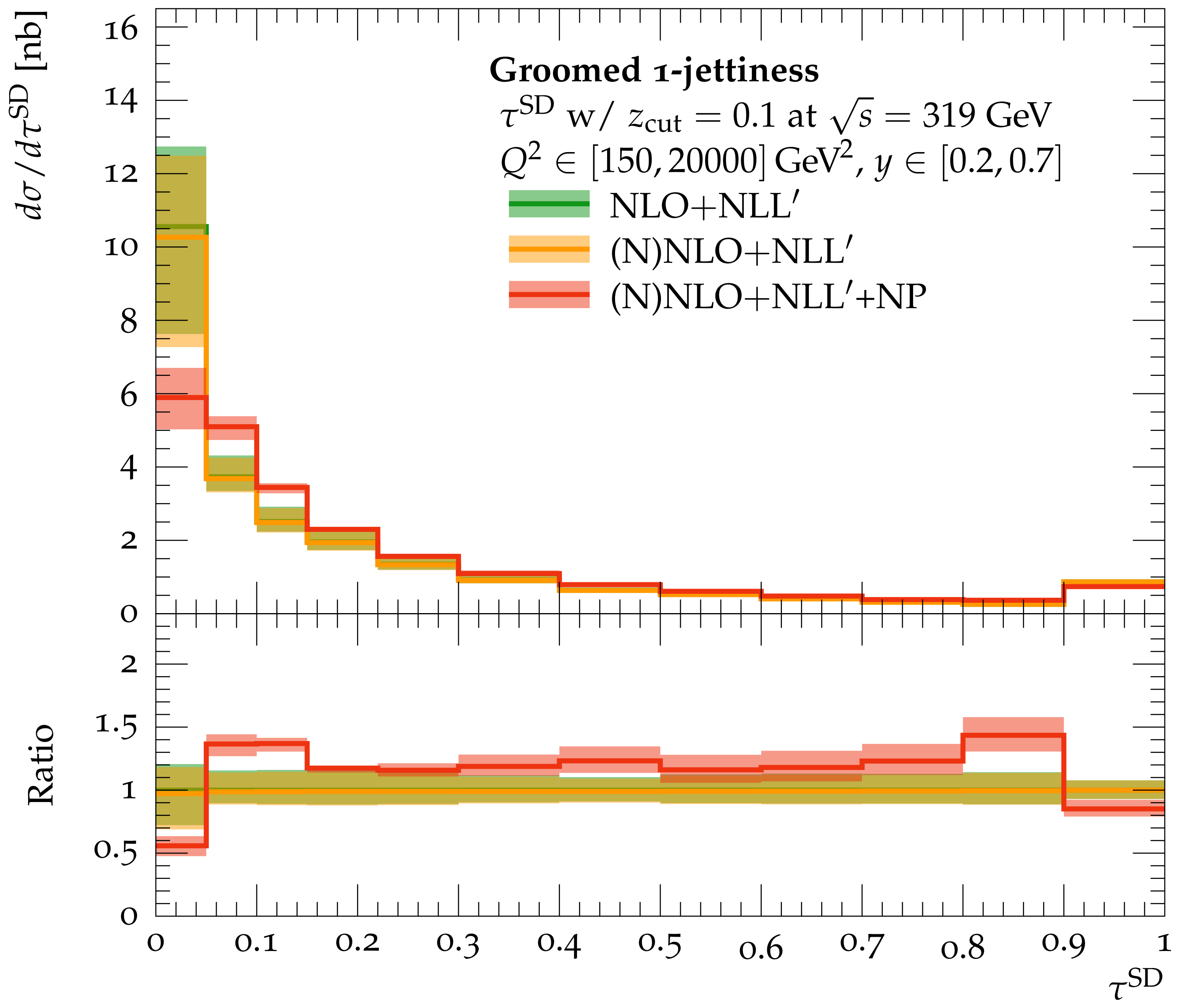


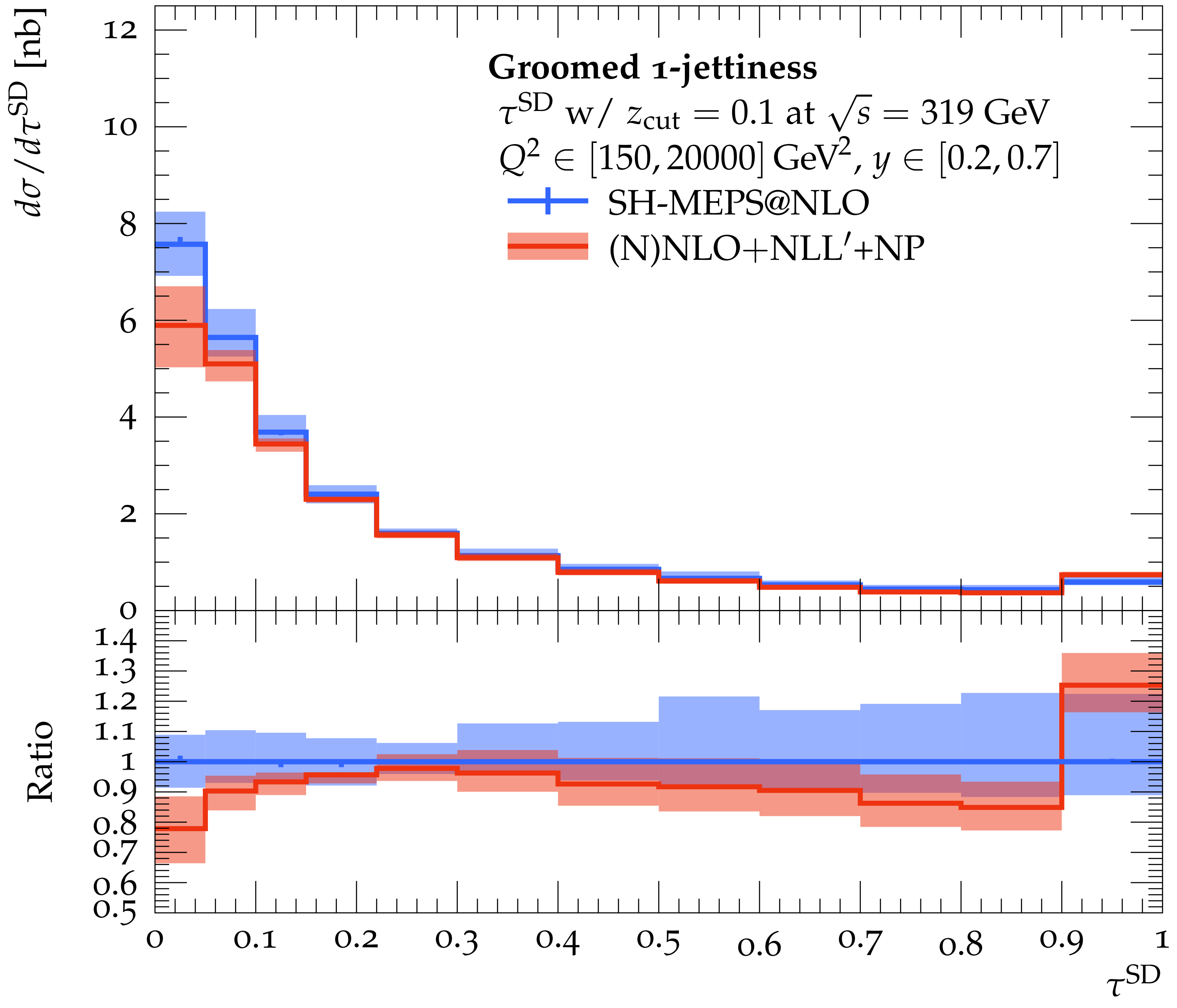
Reminder: without grooming

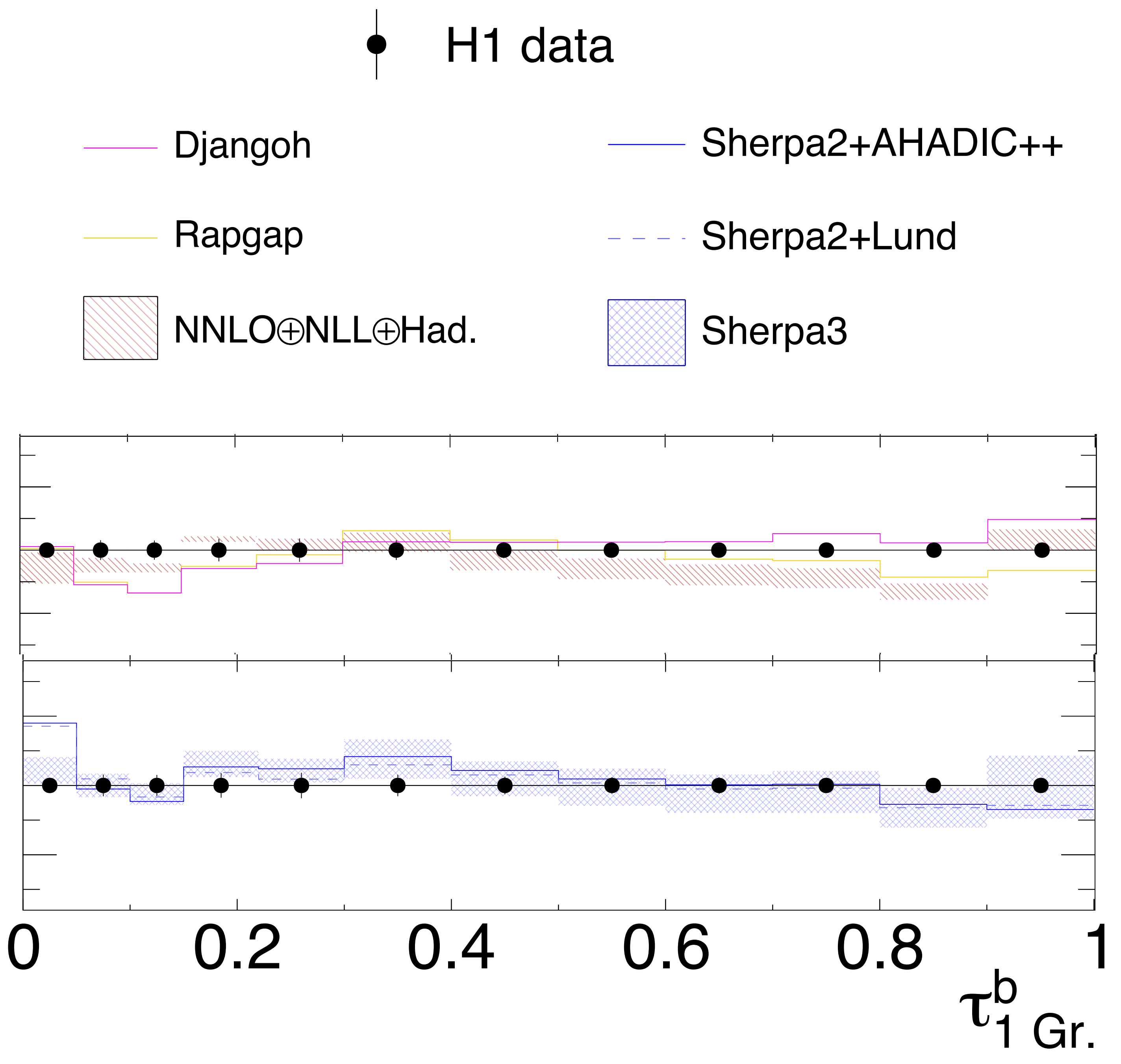


Grooming achieves significant reduction of non-perturbative corrections!

Sherpa MEPS@NLO results with SD







- differences significantly reduced compared to ungroomed case → agreement within uncertainties for most τ values
- some discrepancies appearing around transition point for larger z_{cut}

Summary

- Predictions for measurements of groomed mass and 1-jettiness/groomed 1-jettiness with the H1 detector at $\sqrt{s} = 319\ \mathrm{GeV}$

- New calculations
  - state-of-the art Monte Carlo predictions with Sherpa at MEPS@NLO accuracy: $e^- p \rightarrow e^- + 1, 2\, j\, @\, \mathrm{NLO} + 3, 4\, j\, @\, \mathrm{LO}$
  - (N)NLO+NLL'+HAD predictions from Sherpa+CAESAR