Measurements of Lepton-Jet Azimuthal Decorrelations and 1-Jetttiness event shape at high Q^2 in DIS with H1 experiment at HERA

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on behalf of the H1 collaboration

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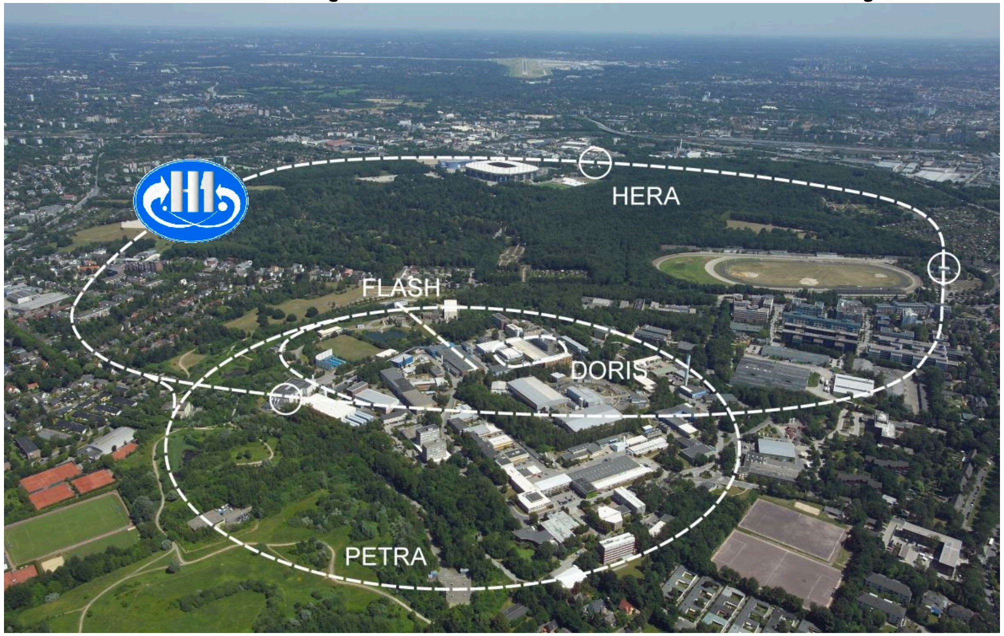
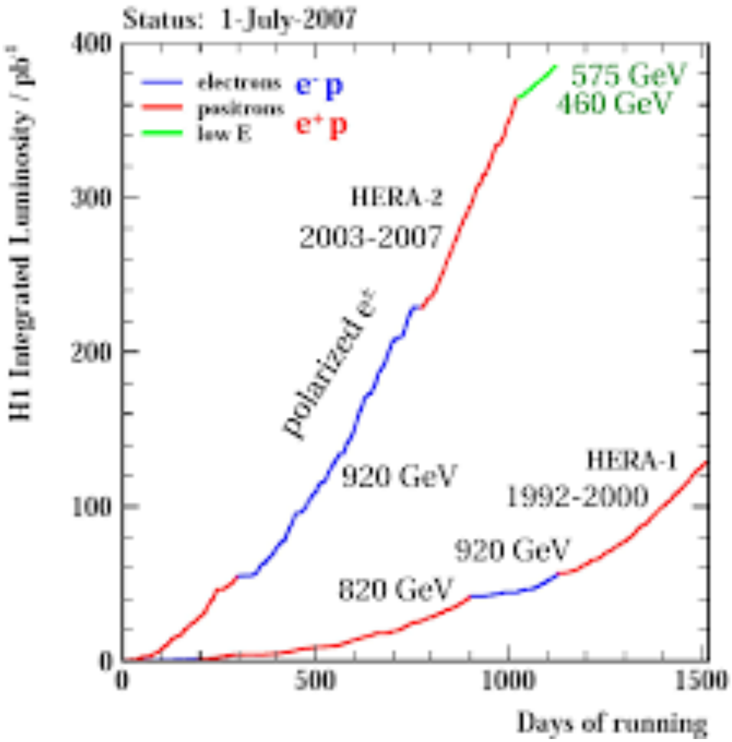
HERA (1992-2007)

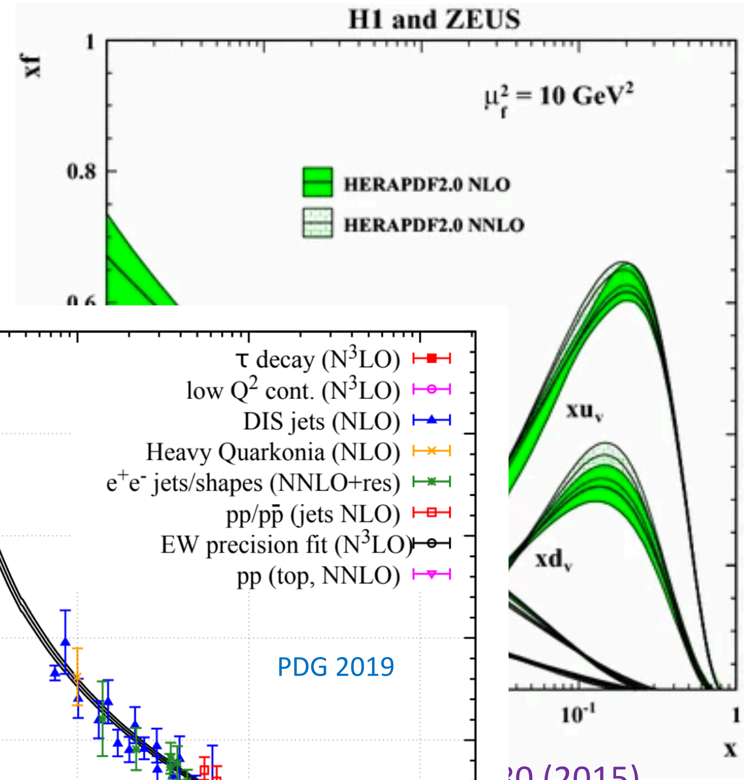


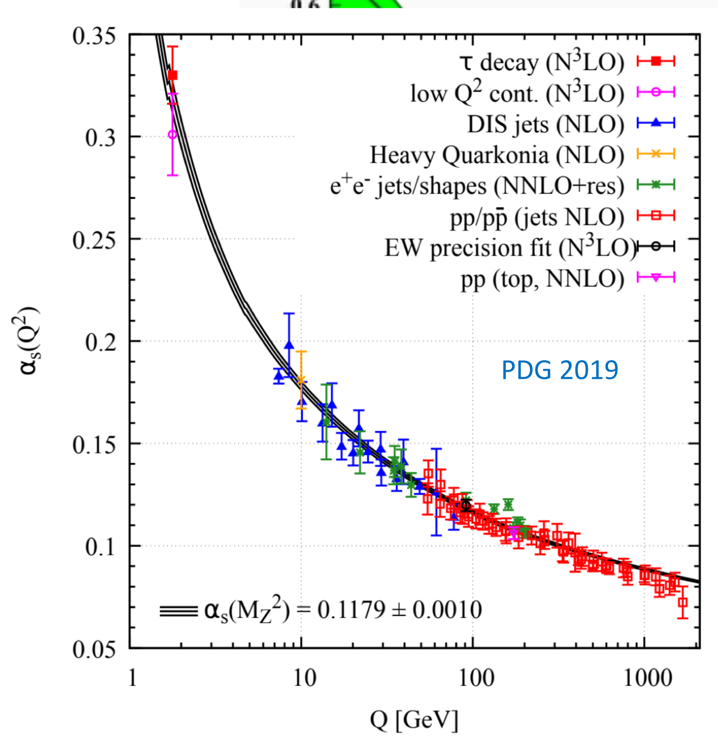


- First (and so far the only) *ep* collider
- Electron and positron as well as polarized (~40%) runs.
- E_e = 27.6 GeV, E_p = 920 GeV, $\sqrt{s}$ = 319 GeV
- Total integrated luminosity of 356.1 pb^{-1}

Deep-inelastic Scattering (DIS) at HERA

- Legacy of HERA, ep collider studying DIS
  - Proton structure and parton shower
  - Diffractive physics,
  - Electroweak interactions
  - Beyond standard model (BSM) physics
  - Determination of strong coupling constant – single inclusive jets, dijets.





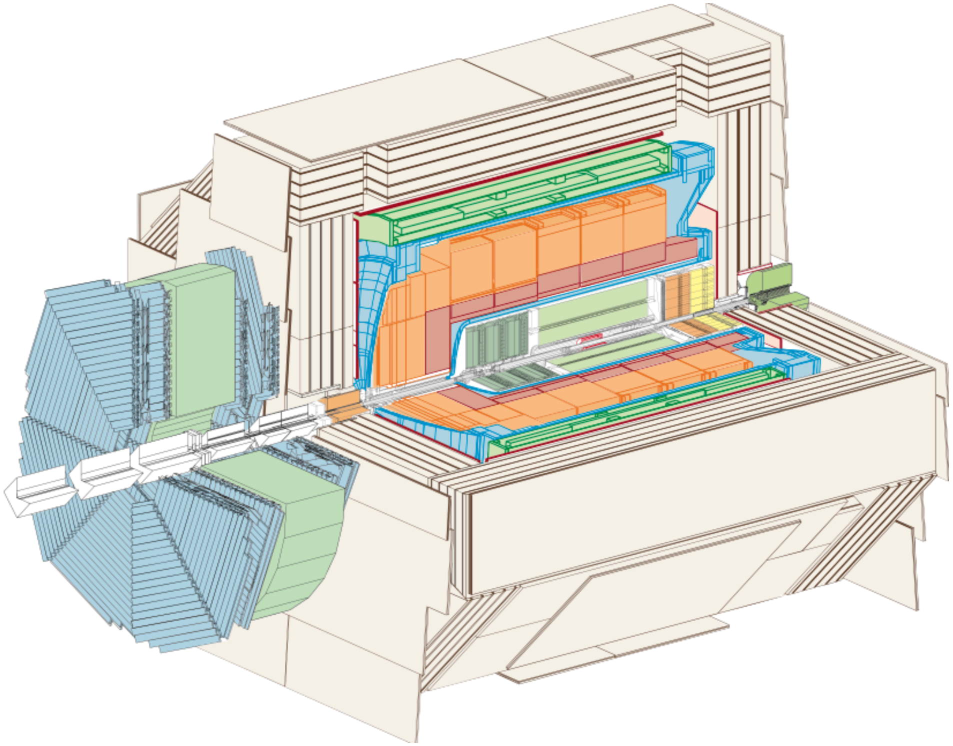
Deep-inelastic Scattering (DIS) and jet physics at EIC

arXiv:2103.05419

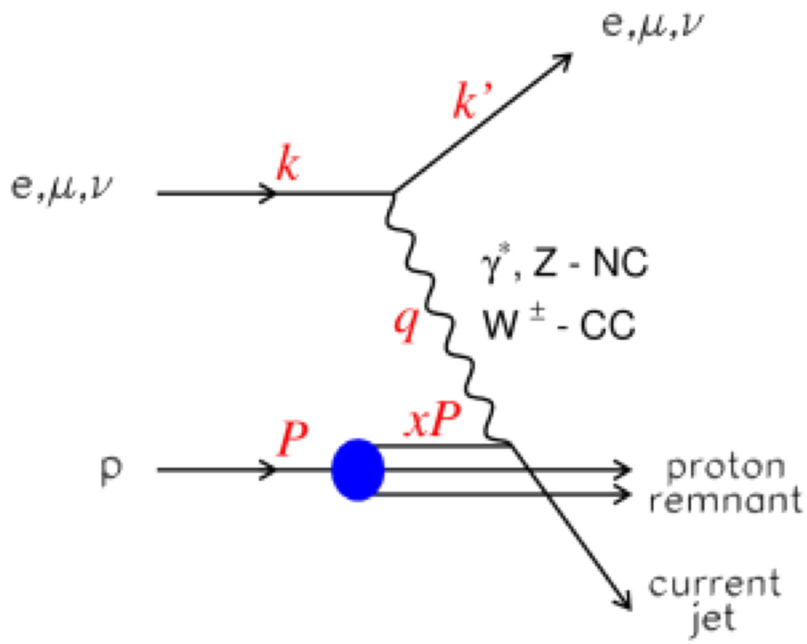
- Forthcoming EIC era
  - Proposed measurements involving jets in DIS such as jet substructure, global event shape, correlations are rich in physics such as
    - 3-dimensional description of nucleon and hadronization, flavor dependence, precision measurements for QCD and BSM.
  - Theoretical and experimental advancement
    - pQCD calculation at NNLO and beyond, pushing N3LL accuracy in ressumation.
    - Theory frameworks dealing with multiscale problems such as transverse momentum dependent (TMD) and soft-collinear effective theory (SCET).
    - Grooming technique, ML, sensor technology of a few μm, etc.
  - Motivates us to revisit HERA data!

H1 experiment at HERA

- Fully instrumented with
  - Trackers (silicon strip + drift chamber + multi-wire proportional chamber)
  - Calorimeter (Liquid-Argon + Lead- scintillating fiber, EM+ hadronic in both)
  - Solenoid, muon-chambers, etc.
- Particle flow algorithm used for charged/neutral particle reconstruction.
- Events triggered by requiring high-energetic cluster in LAr calorimeter
  - electron or hadron
  - $> 99\%$ efficient for $y < 0.7$



Neutral current DIS



- Neutral current DIS
  - e p → e’ X (e : e+ or e-)

- Kinematic variables

$$Q^2 = -q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$

$$s = (P + k)^2 = \frac{Q^2}{x \cdot y}$$

DIS kinematics reconstruction

- Reconstruction methods
  - Σ method

$$y_\Sigma = \frac{\Sigma_{i\in HFS}\,(E-p_z)_i}{\Sigma_{i\in HFS}\,(E-p_z)_i + E_{e'}(1-cos\theta_{e'})}$$

$$Q^2_\Sigma = \frac{E^2_{e'}\,sin\theta^2_{e'}}{1-y}$$

HFS: hadronic final state

  - IΣ method

$$y_{I\Sigma} = y_\Sigma \,, Q^2_{I\Sigma} = Q^2_\Sigma$$

$$x_{I\Sigma} = \frac{E_{e'}}{E_p}\;\frac{\cos^2(\,\theta_{e'}/2)}{y_\Sigma}$$

→ Largely insensitive to initial state QED radiative effects

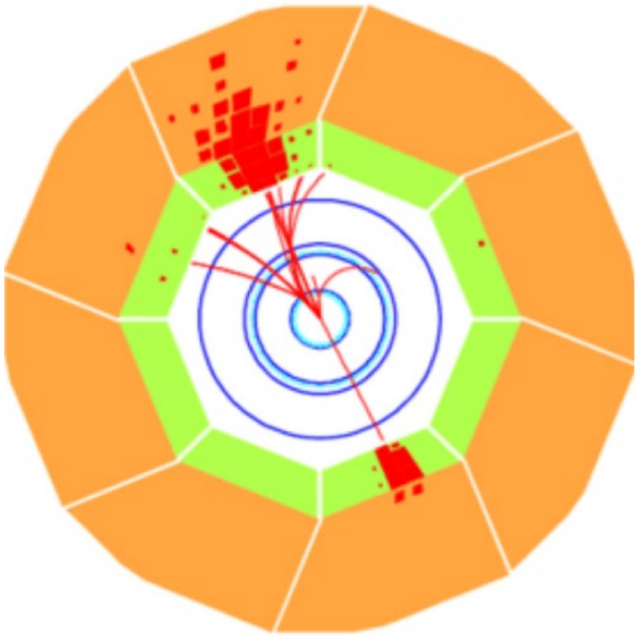
Lepton-jet decorrelation

- Novel way of probing transverse motion of quarks in proton, i.e. quark TMD PDF.
- Exploit lepton-jet p_T balance in Born kinematics

Liu et al. PRL. 122, 192003 (2019)
Gutierrez et al. PRL. 121, 162001 (2019)

Lepton-jet p_T imbalance

$$q_T = |\vec{k}_\perp^l + \vec{p}_\perp^{jet}|$$



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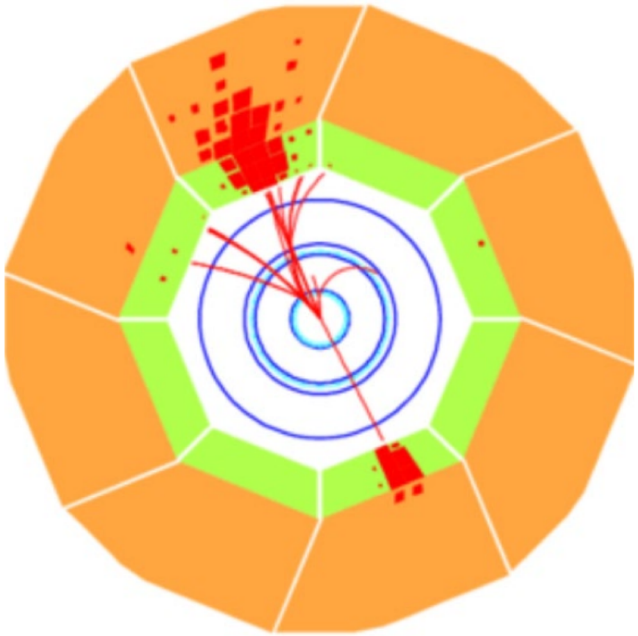
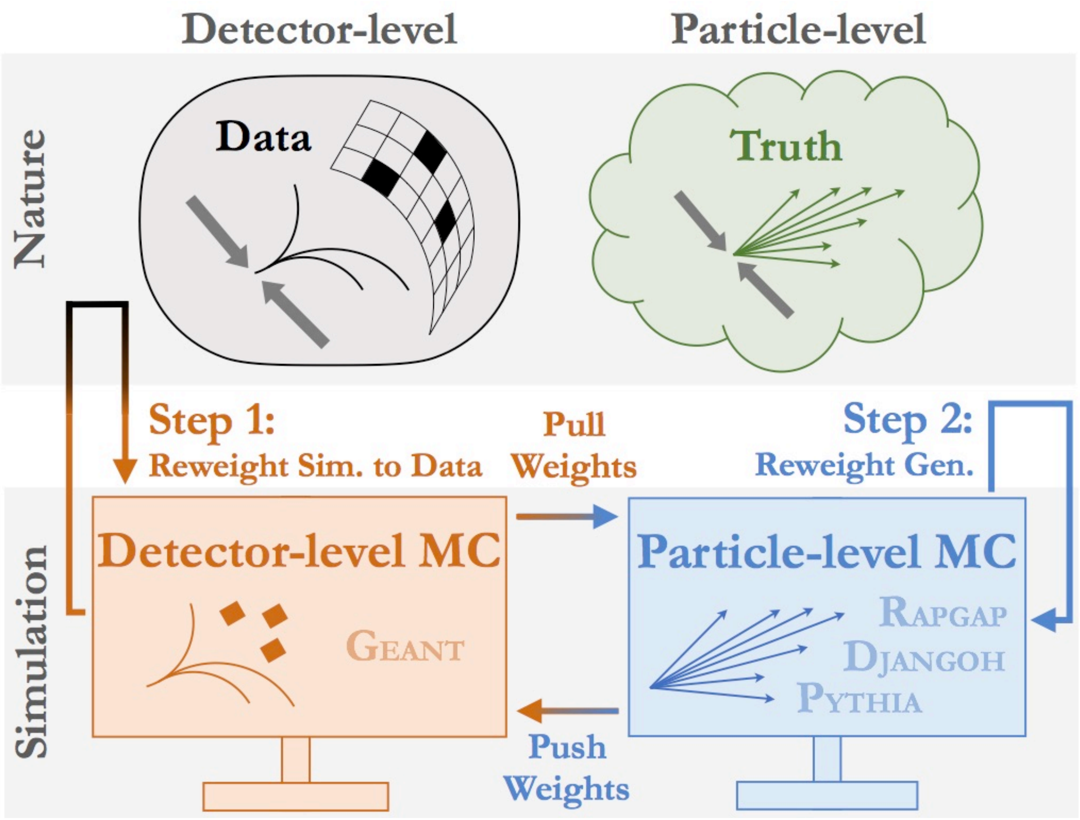
$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2 k_{\ell\perp} d^2 q_\perp} = \sigma_0 \int d^2 k_\perp d^2 \lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F) \times H_{\mathrm{TMD}}(Q, \mu_F) S_J(\lambda_\perp, \mu_F) \times \delta^{(2)}(q_\perp - k_\perp - \lambda_\perp).$$

Lepton-jet p_T imbalance

$$q_T = |\vec{k}_\perp^{\,l} + \vec{p}_\perp^{\,jet}|$$



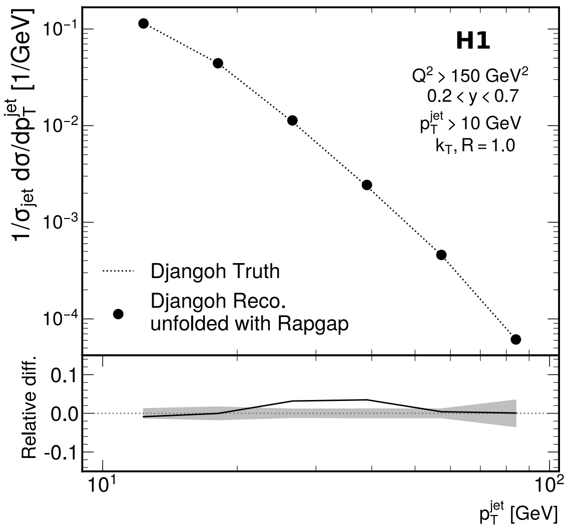
Machine-learning based unfolding

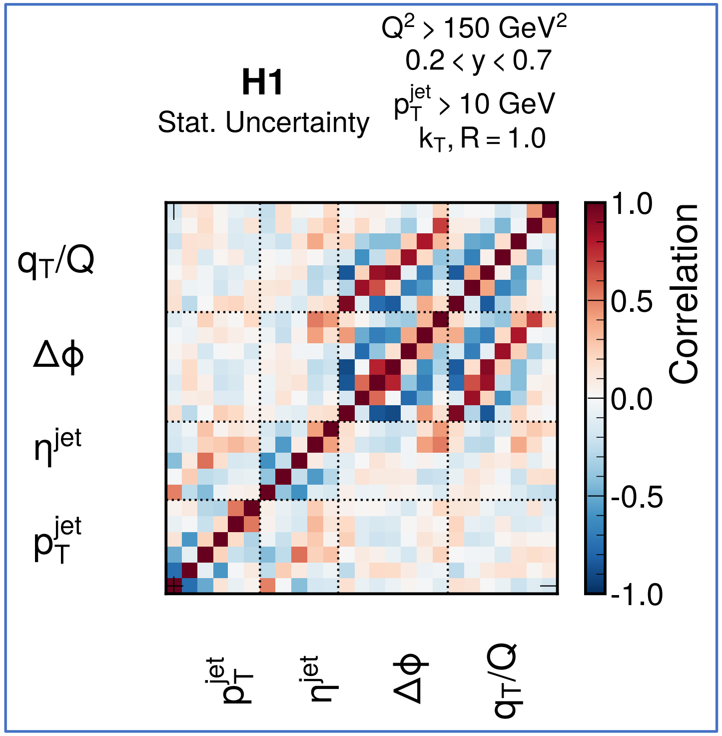


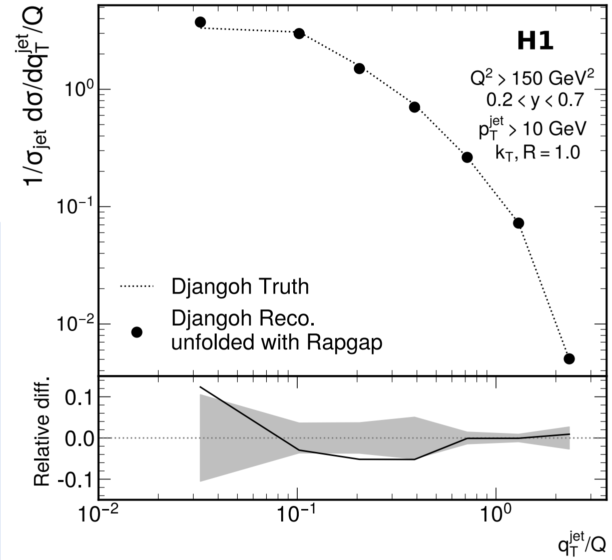
PRL 124, 182001 (2020)
Omnifold

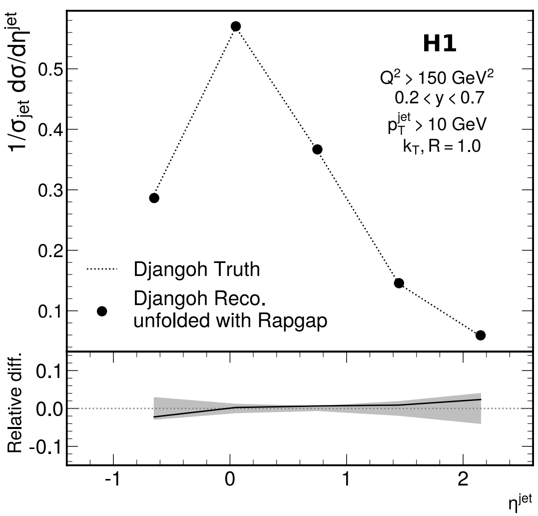
- Unbinned multi-dimensional unfolding.
- Deep neural networks trained to learn detector effects.
- Weight assigned to each event in MC.
- Unfolded distributions are obtained by binning reweighted events.

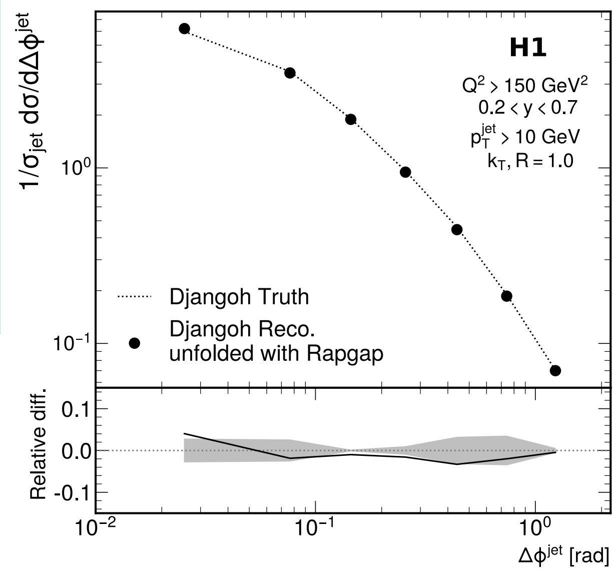
Closure tests





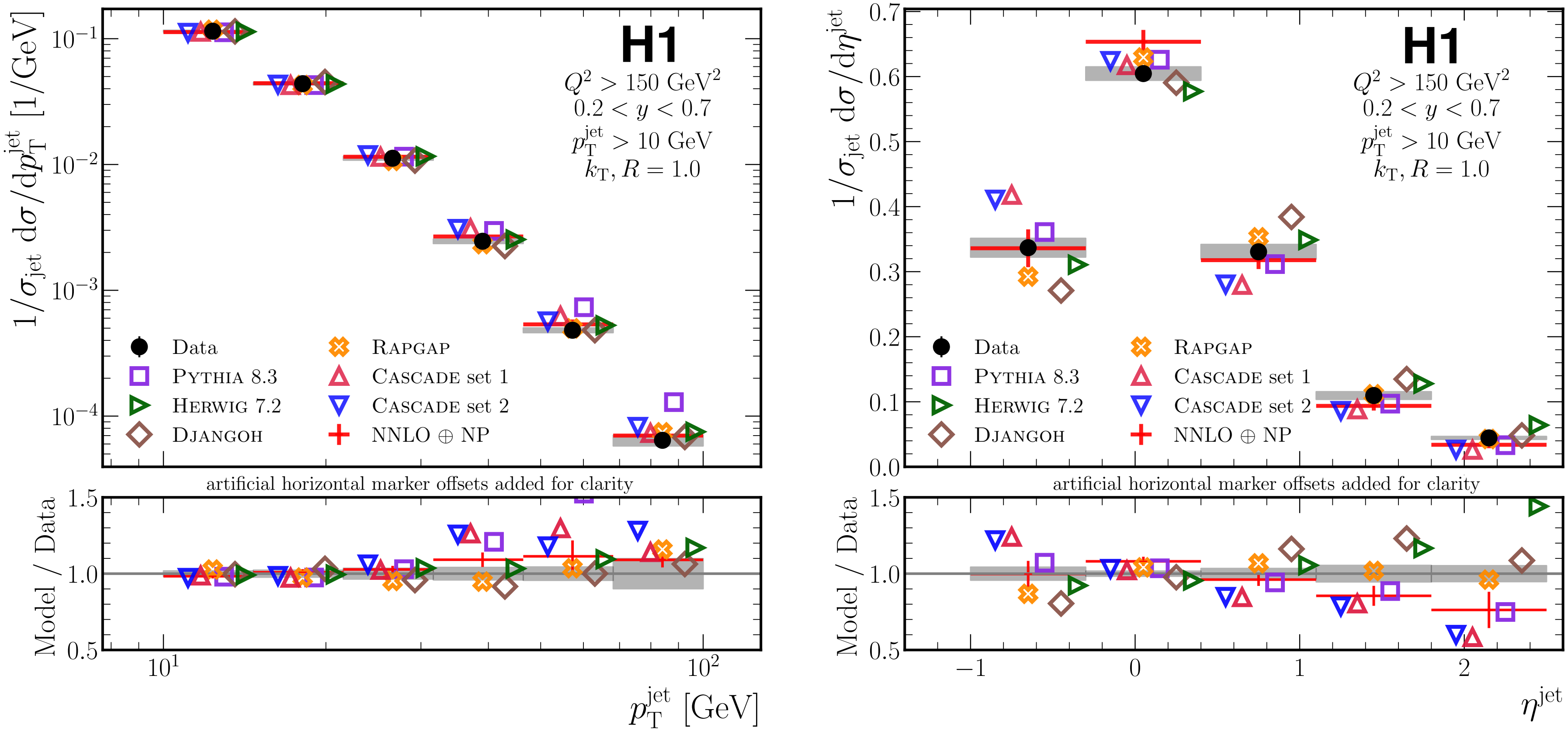






Jet transverse momentum and pseudorapidity

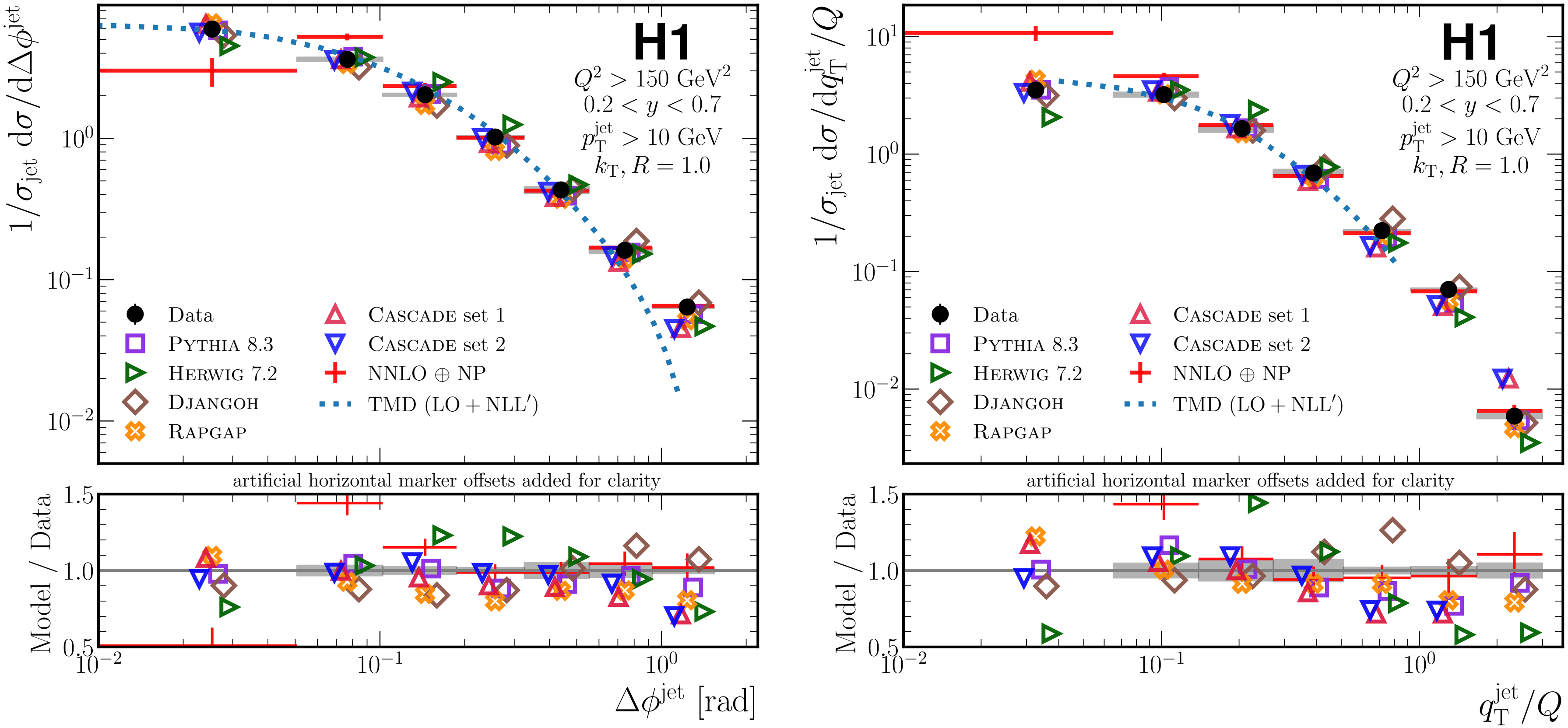
arXiv:2108.12376



- p_T and η of jets reasonably well described by NNLO + NP.
- Rapgap of all MC best describes data.
- Overall shape difference seen for Cascade (TMD based) in both variables.

Lepton-jet momentum imbalance and azimuthal angular distance

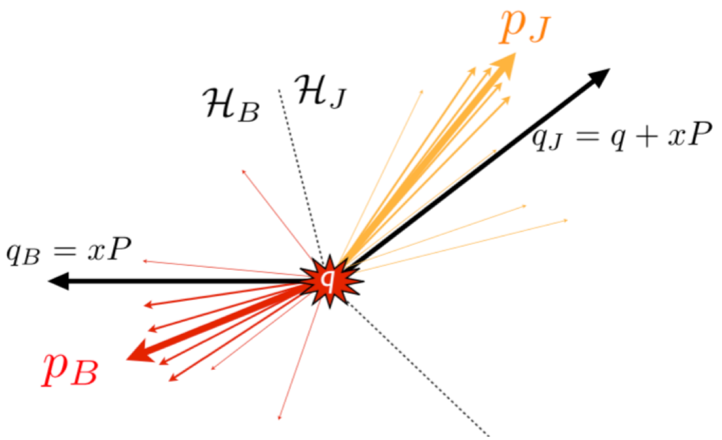
arXiv:2108.12376



- q_T reasonably well described by NNLO in higher region and by TMD at lower region, similar pattern for $\Delta\phi$.
- Large overlap covered by data will help constrain matching between TMD and collinear pQCD frameworks.

1-jettiness global event shape

- 1-jettiness
  - $\tau_1^b = \frac{2}{Q^2} \Sigma_{i \in X} \min\{q_J \cdot p_i, q_B \cdot p_i\}$,
    where $q_J = xP + q, q_B = xP$
  - Global, Lorentz invariant and infrared-safe observable
  - Sensitive to strong coupling constant α_s and PDFs

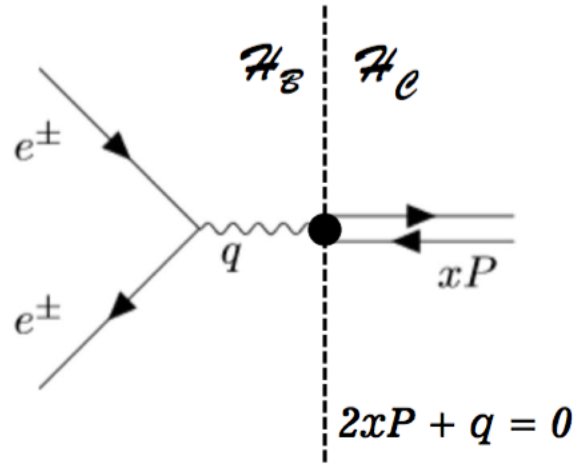


Kang, Lee, Stewart, PRD 88 (2013) 054004

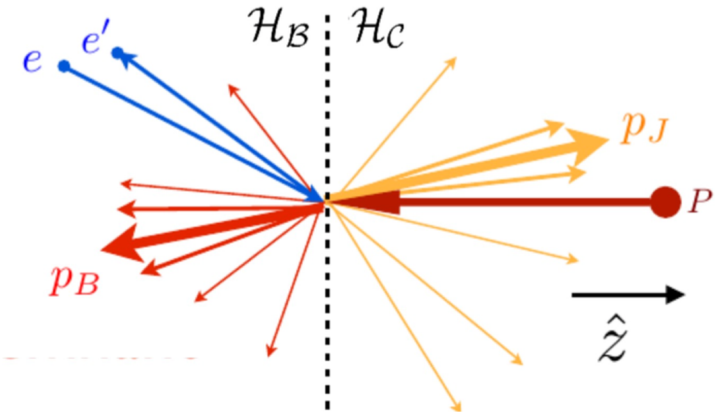
N2LL published, N3LL WIP

In Breit Frame

- Breit frame
  - Only spatial component in exchanged boson momentum.
  - Direction of momentum reversed after boson-parton head-on collision, i.e. brick-wall frame.

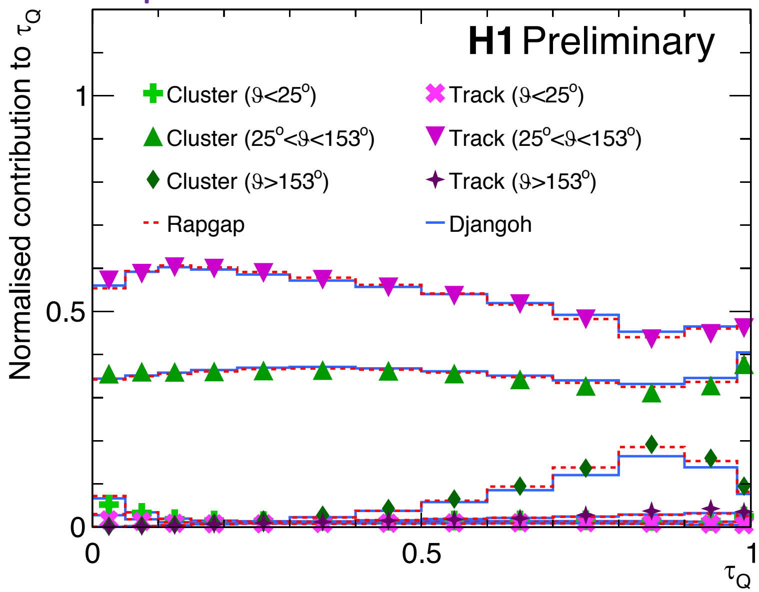


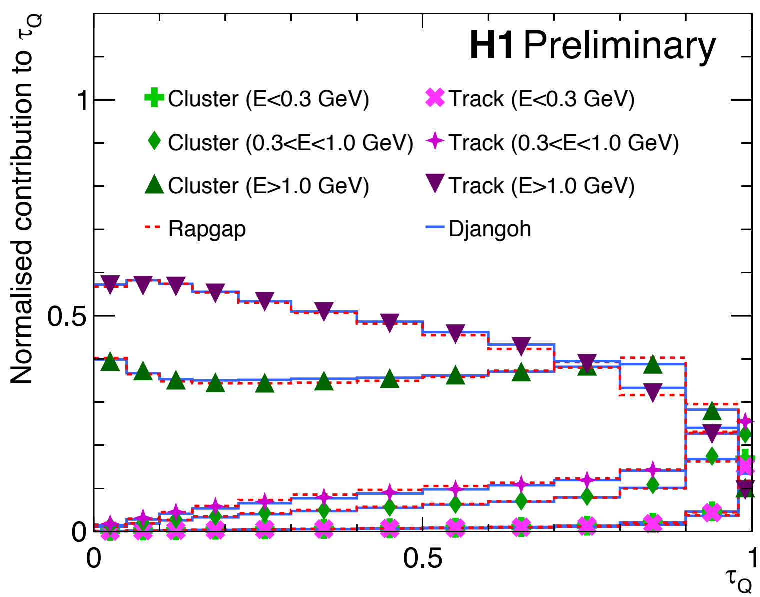
- $\tau_Q \stackrel{\text{def}}{=} 1 - \frac{2}{Q} \sum_{i \in \mathcal{H}_C} p_{z,i}^{Breit}$



- By momentum conservation
  - $\tau_Q = \tau_1^b$

H1prelim-21-032





MC simulations

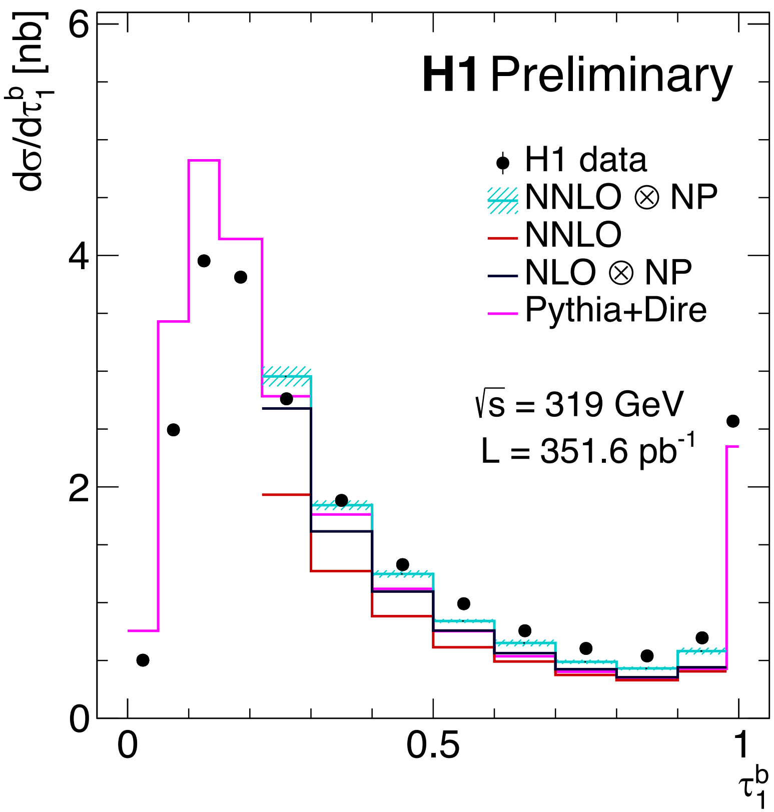
- Contributions of different particles to τ_1^b
  - Major contribution from tracks in central region and particles with E > 1GeV.
  - Dominated by well measured particles.

- Kinematic phase space:
  - 150 < Q^2< 20,000 GeV2
  - 0.2 < y < 0.7

Single differential cross section

- Limits of τ_1^b
  - $\tau_1^b \to 0$: two pencil-like jets
  - $\tau_1^b \gg 0$: multi-jets
  - $\tau_1^b = 1$: empty current hemisphere
- NNLO (α_s^2) prediction from NNLOJET + NP corrections
  - Description of far-tail region sensitive to fixed-order (FO) improved by higher order NNLO.
  - Near peak region, improvement by NP corrections (Pythia 8.3).

H1prelim-21-032

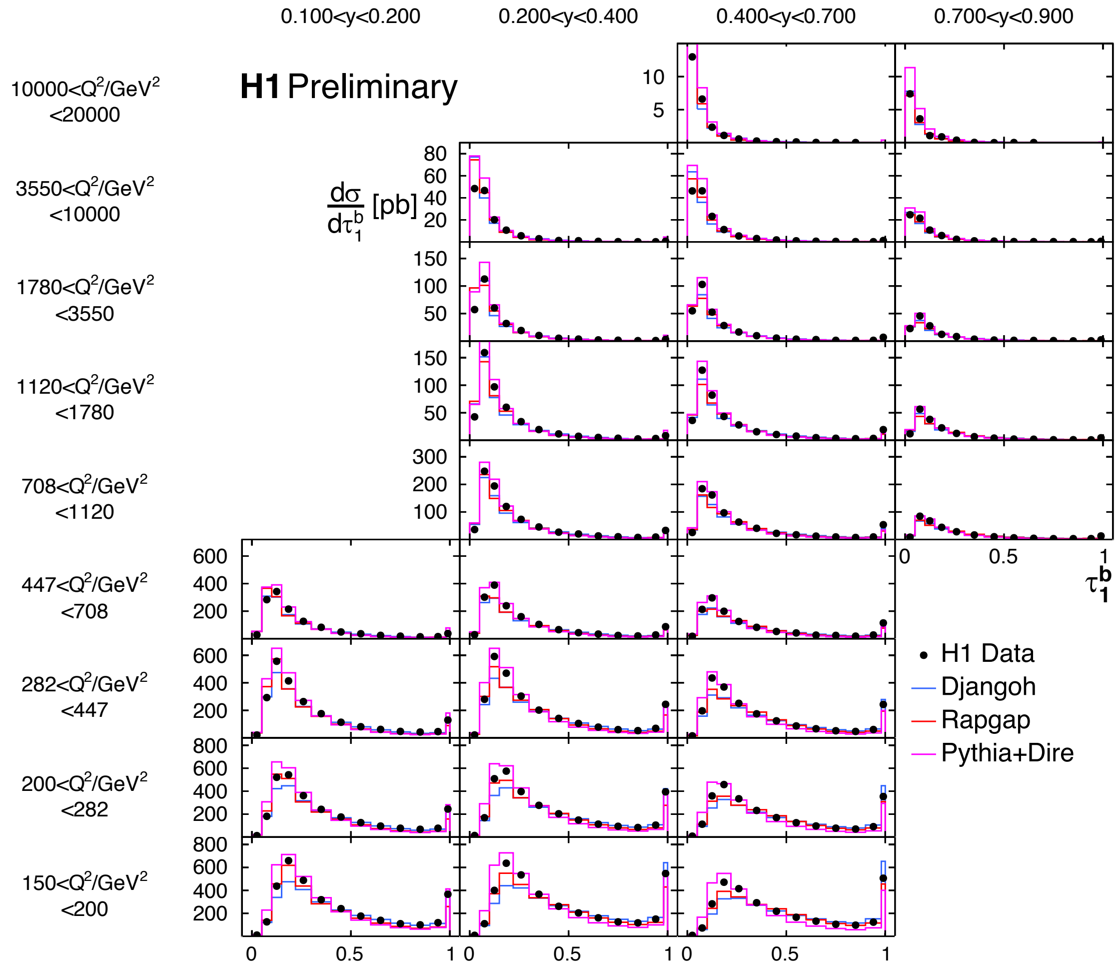


- Unfolded by bin-by-bin correction.
- QED radiative effects corrected.

Q^2 and y dependent cross sections

H1prelim-21-032

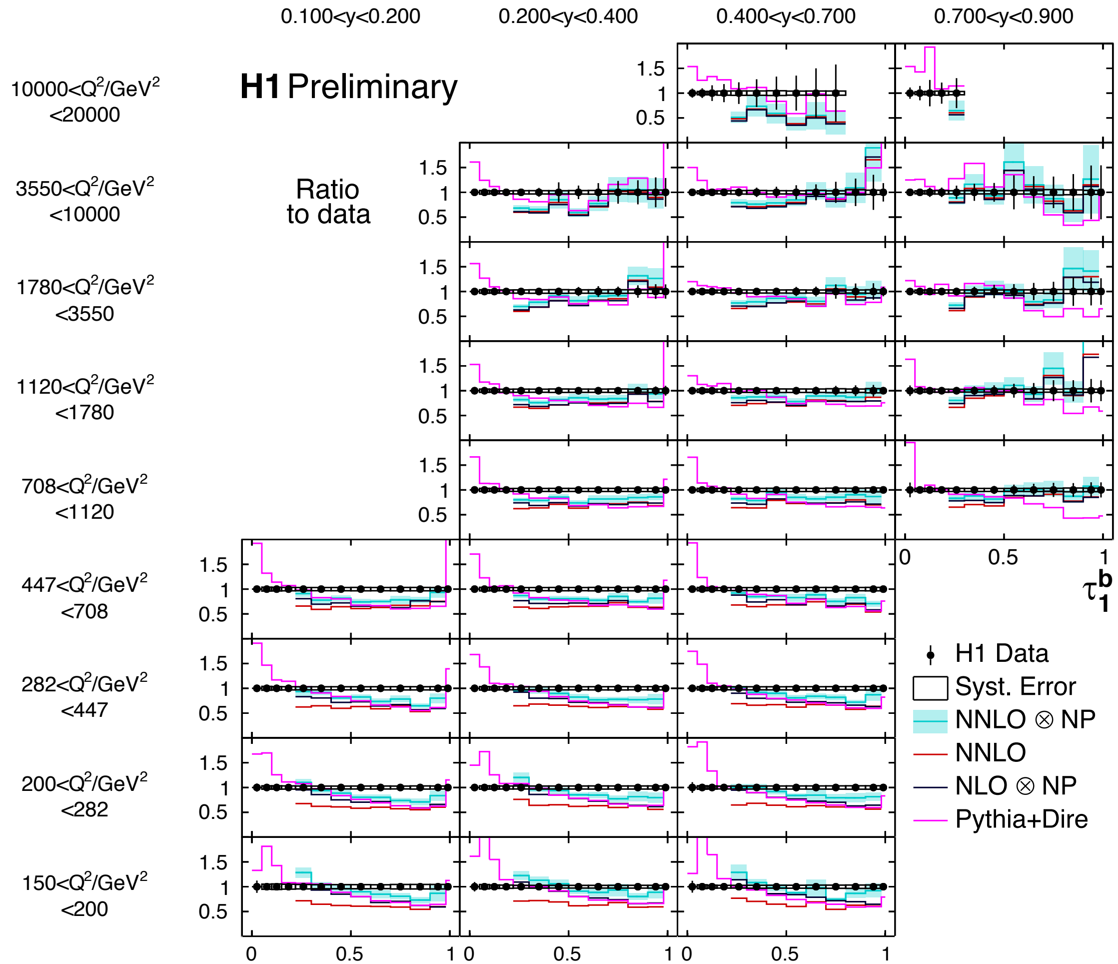
- τ_1^b-differential cross section in $y - Q^2$ space.
- Jets increasingly collimated with Q^2.
- NP effects (shift of peak position) more prominent in low Q^2.
- As y increases $\tau_1^b = 1$ peak enhanced.



Q^2 and y dependent cross sections

H1prelim-21-032

- NNLO pQCD predictions
  - High y - high Q^2 regions well described by NNLO.
  - NP corrections sizable at low Q^2.
  - Small scale uncertainty.
- Predictions with N3LL accuracy in SCET framework available soon.
  - Extended range in τ_1^b, e.g. peak to far region with a few percent level theory uncertainty (a percent level constraining power on α_s) expected in high Q - high y region.

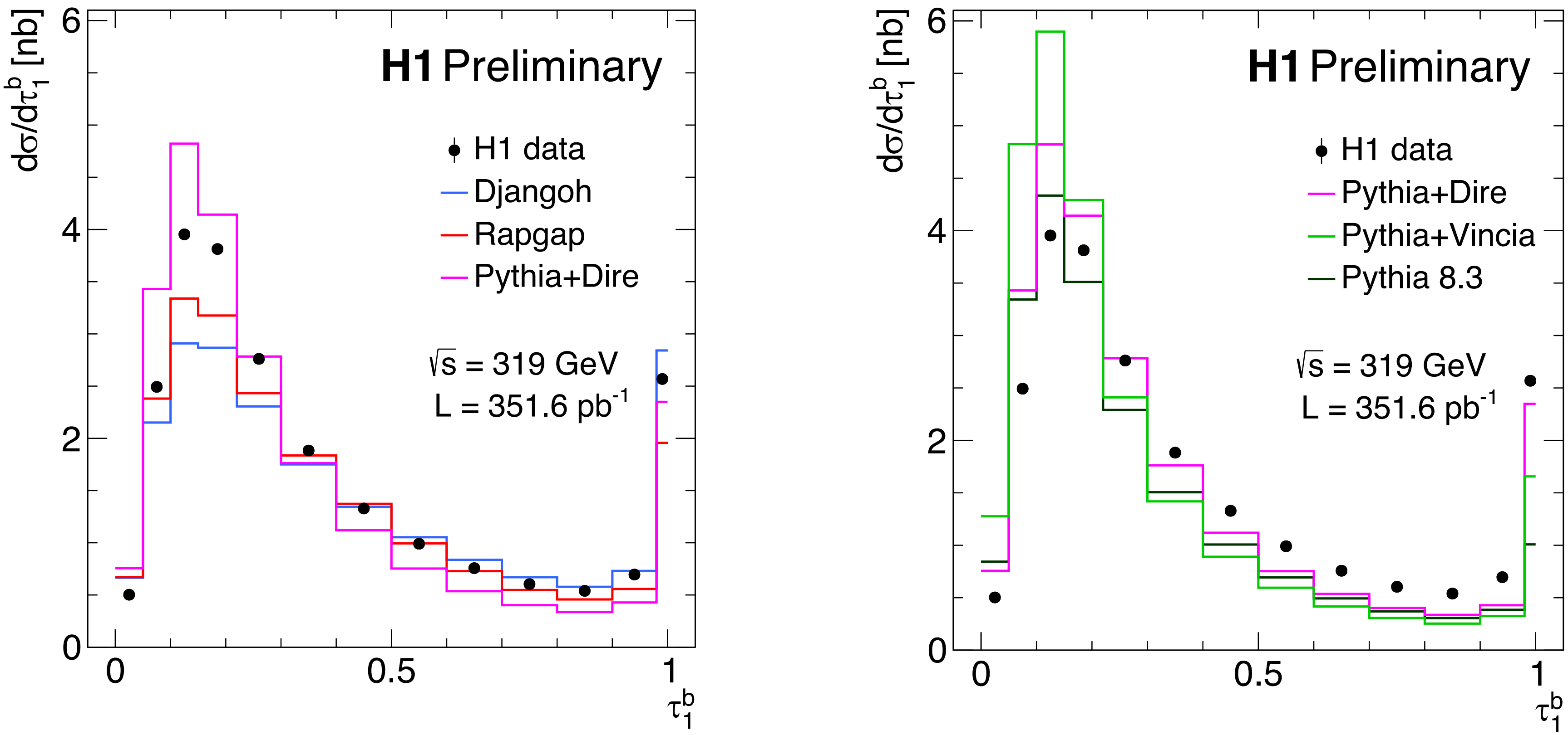


Summary and Outlook

- First measurements of **lepton jet momentum imbalance and azimuthal decorrelation** in NC DIS presented as a new way to constrain TMD PDFs and their evolution.
- TMD calculation describes low q_T region of measured data well and pQCD collinear prediction does large q_T region. Large overlap region covered by data can constrain matching between TMD and collinear frameworks.
- First measurement of **1-jettiness event shape observable** in NC DIS was presented as a new way to greatly improve precision of PDF and α_s determination.
- NNLO (α_s^2) fixed order predictions provide good description in the region of validity, but hadronization corrections are sizable.
- N3LL and NNLO+PS predictions will be compared with data.
- Sensitivity to α_s and PDFs needs to be explored.
- Data will become useful for improving description of less inclusive DIS MC generators.

backup

Single differential cross section



- Djangoh 1.4 : color-dipole model
- Rapgap 3.1 : ME + parton shower
- Dire: Dipole-like shower + inclusive NLO DGLAP corrections.

Q2 and x dependent cross sections

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Q2 and x dependent cross sections

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