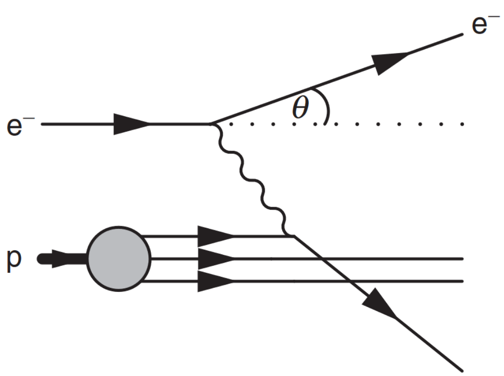
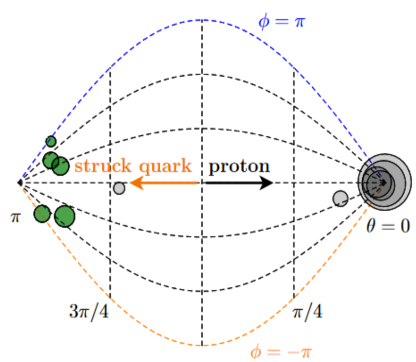
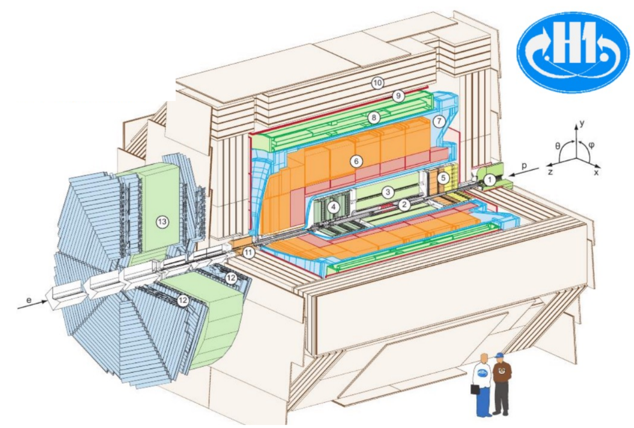
Measurement of groomed event shape observables in electron-proton collisions

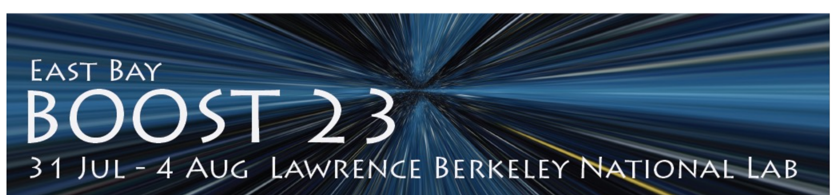
Peter Jacobs
Lawrence Berkeley National Laboratory
for the H1 Collaboration





$$\frac{\min(z_i, z_j)}{z_i + z_j} > z_{\rm cut}\,,$$



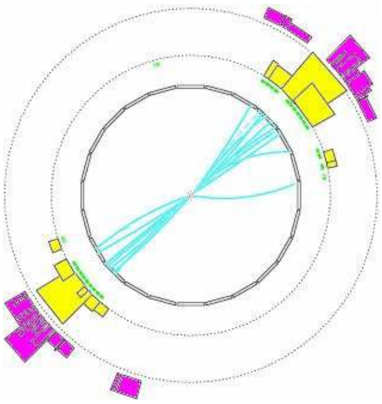


Event shapes

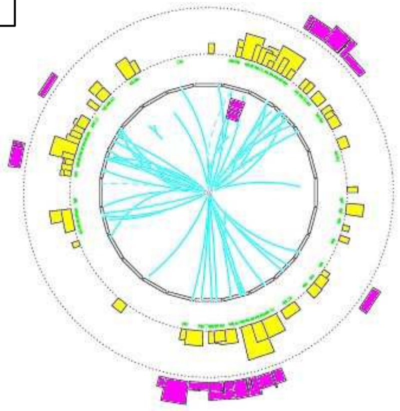
e$^+$e$^-$

Prototypical event shape: Thrust

$$T = \max_{|n|=1} \left[\frac{\Sigma_i |p_i \cdot n|}{\Sigma_i |p_i|} \right]$$



2 jets: Thrust~1



3 jets: Thrust~2/3

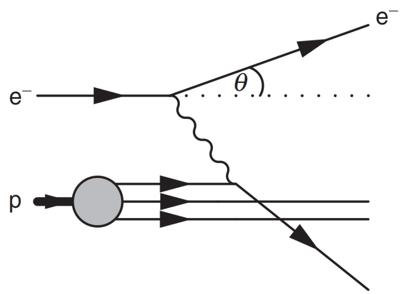
Global event observable: all particles contribute

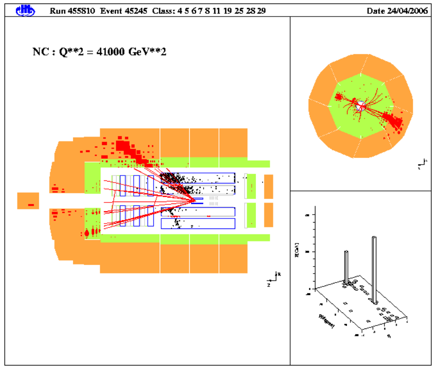
Theory: fixed-order perturbation theory, all-order resummation, MC event generators

Extensive measurements in e$^+$e$^-$, e+p DIS, hadronic collisions

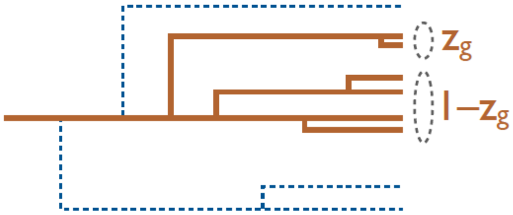
Testbed for precision QCD: α_S, color factors, analytic/modeling of hadronization, MC tuning,…

This talk:
groomed event shapes in e+p DIS collisions





+



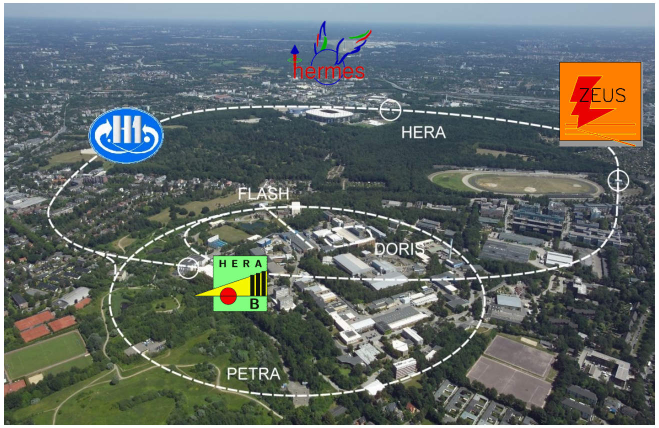
+

$$T = \max_{|n|=1}\left[\frac{\Sigma_i |p_i \cdot n|}{\Sigma_i |p_i|}\right]$$

(actually: groomed
1-jettiness and inv mass)

HERA and H1

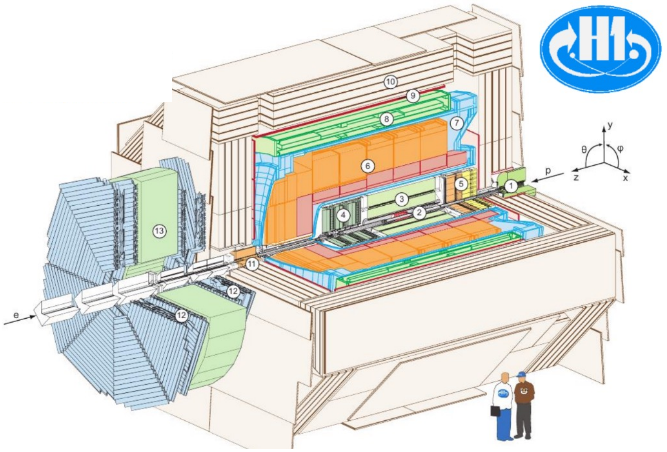
HERA: e+p collider operated 1992-2007
Electrons: 27.6 GeV, protons: 920 GeV → $\sqrt{s} = 319$ GeV



Hera-II 2003-2007: 352 pb^{-1}

H1 Experiment

- Hermetic detector with asymmetric design
- Drift chamber + silicon tracking
- High-resolution LAr calorimeter
- Trigger: energetic hadronic or EM LAr cluster
  - 99% efficient for inelasticity y < 0.7



H1+Zeus: extensive data preservation effort

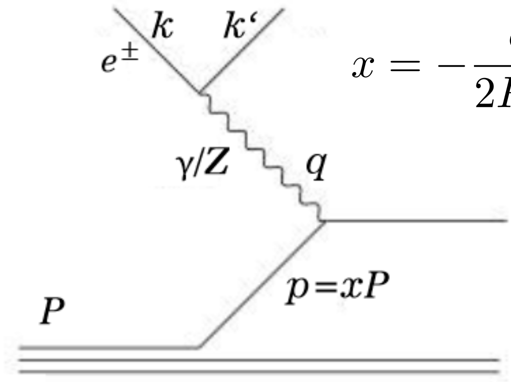
- collaborations still very active
- modern software for MC and analysis

Unique opportunity to explore QCD with new tools and concepts that were developed after HERA turned off

Breit Frame in DIS

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

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



Center-of-momentum frame of virtual photon and struck quark:

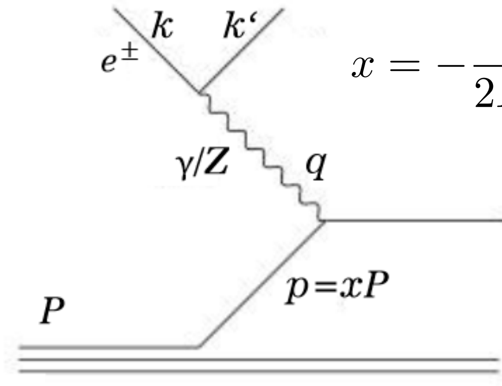
$$2x_{\mathrm{Bj}}\cdot P + q = 0$$

Measure x, q → boost to Breit frame

Breit Frame in DIS

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

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



Center-of-momentum frame of virtual photon and struck quark:

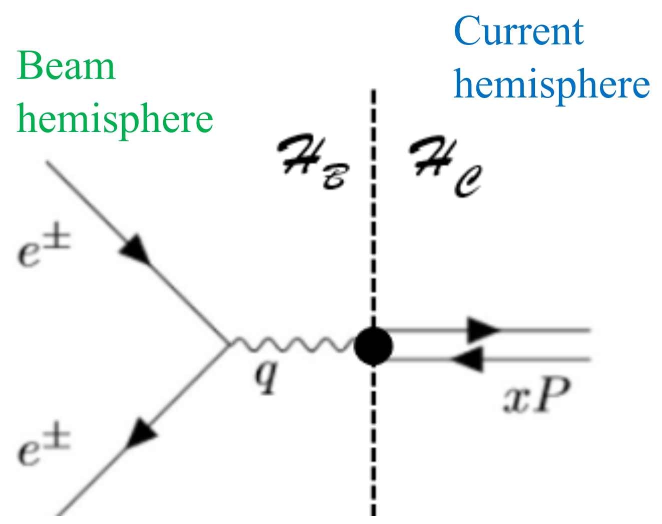
$$2x_{\mathrm{Bj}} \cdot P + q = 0$$

Measure *x*, *q* → boost to Breit frame

Divides event into two hemispheres:

Current (p_z<0): contains mainly radiation associated with struck parton

Beam (p_z>0): contains mainly radiation associated with proton remnant



Breit Frame in DIS

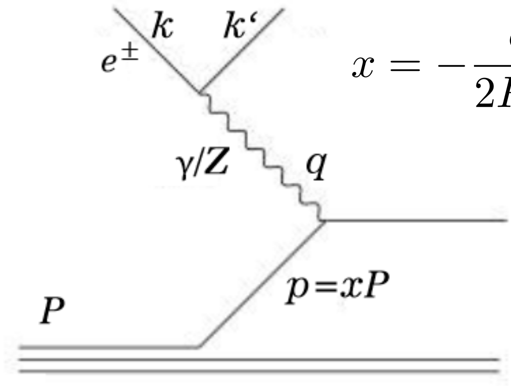
$$Q^2 = -q^2 = -(k-k')^2$$

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

Center-of-momentum frame of virtual photon and struck quark:

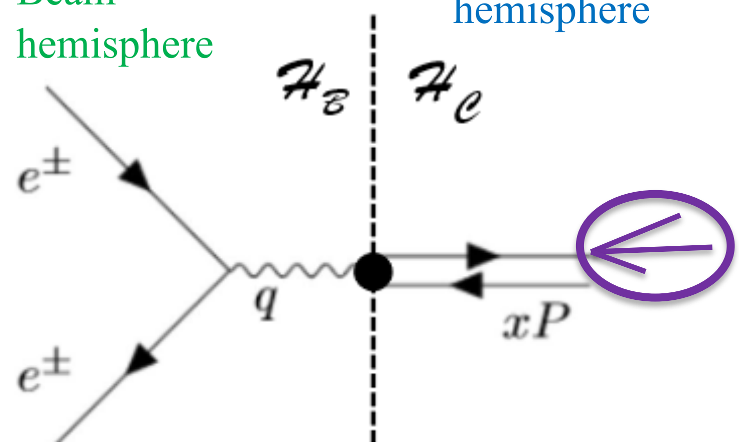
$$2x_{\mathrm{Bj}} \cdot P + q = 0$$

Measure x, q → boost to Breit frame



Divides event into two hemispheres:

Current (p_z<0): contains mainly radiation associated with struck parton
Beam (p_z>0): contains mainly radiation associated with proton remnant



Struck parton fragmentation: Lorentz Inv. momentum fraction

$$z_i = \frac{P\cdot p_i}{P\cdot q} \xrightarrow[\text{frame}]{\text{Breit}} z_i = \frac{n\cdot p_i}{Q} = \frac{p_i^+}{Q}; \quad \sum_i z_i = 1$$

High z: fragments aligned with virtual photon

Why groom DIS events?

UE is negligible; background suppression not needed…?

Revisiting the role of grooming in DIS

Y. Makris[1,*]

[1] *INFN Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy*

(Dated: February 16, 2021)

Phys.Rev.D 103 (2021), 054005
arXiv:2101.02708

- Construct observables that are free from non-global logarithms
- Suppress soft radiation
- Suppress beam remnants and initial state radiation (significant uncertainty source)
- Mitigate hadronization corrections; vary NP contributions in a controllable way

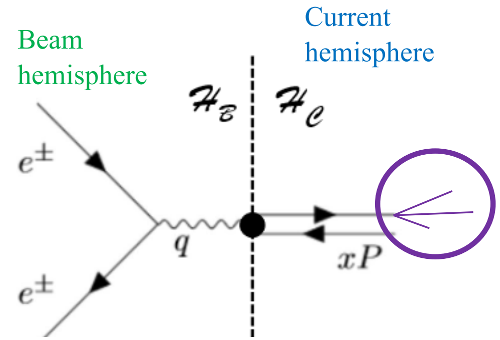
Jet clustering in DIS: Centauro algorithm

Asymmetric jet clustering in deep-inelastic scattering

M. Arratia,[1,2,*] Y. Makris,[3,†] D. Neill,[4,‡] F. Ringer,[5,6,§] and N. Sato[7,¶]

Phys.Rev.D 104 (2021), 034005
arXiv:2006.10751

e+p DIS closely resembles single-jet production

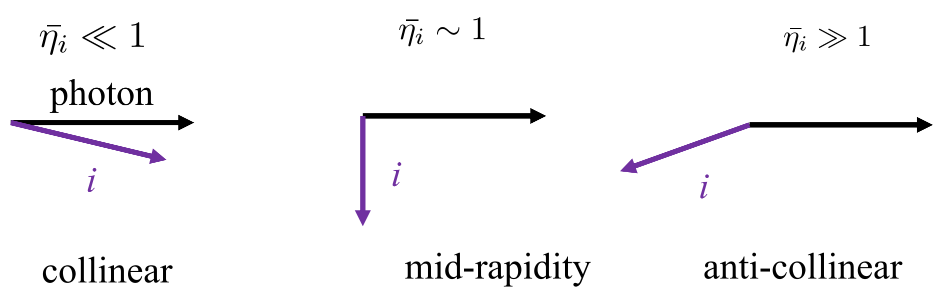


Highly asymmetric: needs asymmetric clustering algorithm that is longitudinally invar. in the Breit frame and that captures the struck-quark jet → Centauro

Breit frame rapidity

$$\bar{\eta}_i = 2\sqrt{1+\frac{q\cdot p_i}{x_B P\cdot p_i}} \xrightarrow[\text{frame}]{\text{Breit}} \frac{2p_i^\perp}{p_i^+}$$

Limits



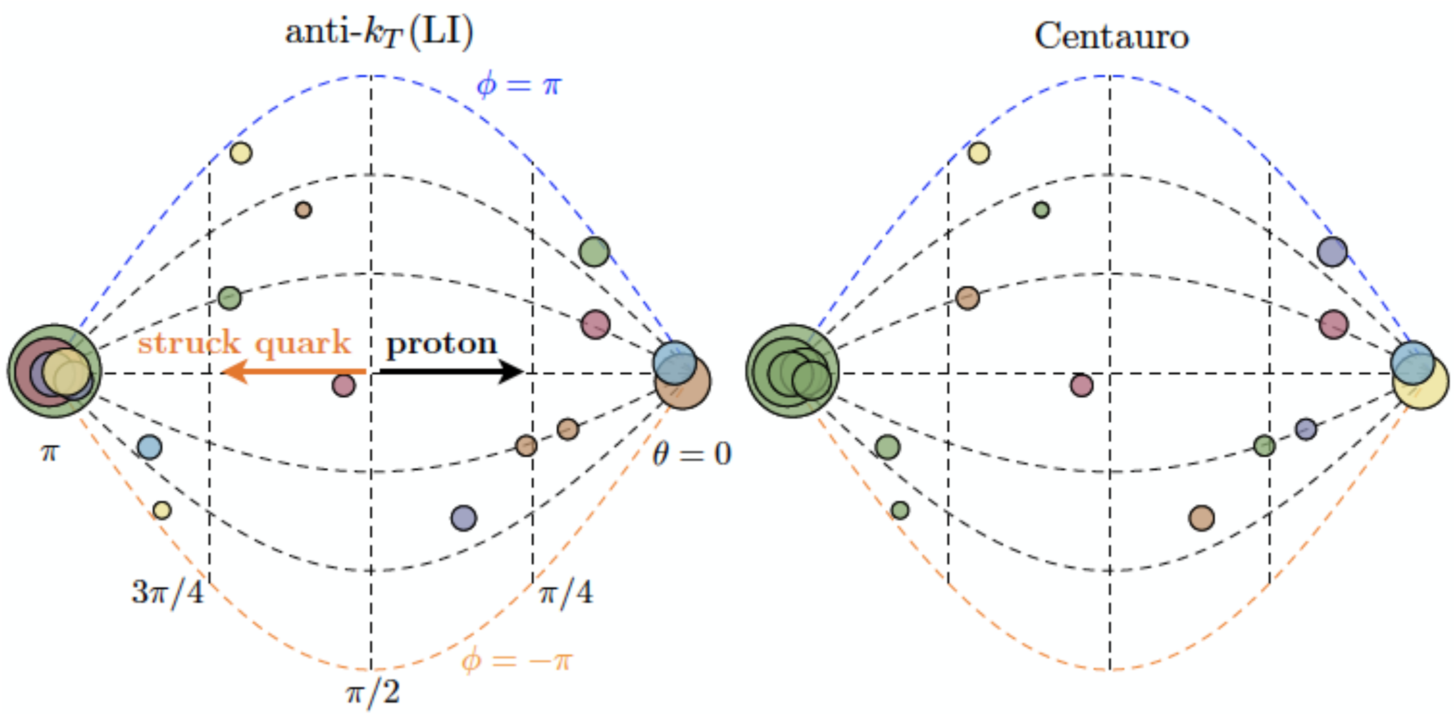
Distance metric for clustering

$$d_{ij} = (\bar{\eta}_i - \bar{\eta}_j)^2 + 2\bar{\eta}_i\bar{\eta}_j\left(1-\cos\left(\phi_i-\phi_j\right)\right)$$

$$d_{i,Beam} = 1$$

Clustering of an e+p DIS event

Longitudinally invariant anti-k_T vs. Centauro



Each color tags a different reconstructed jet

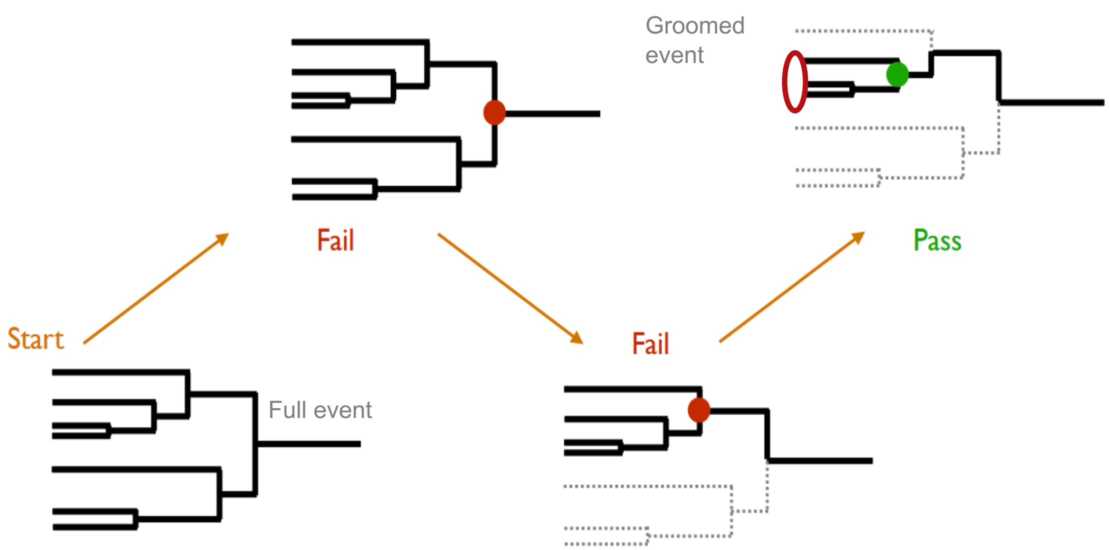
DIS event grooming using Centauro

Y. Makris, *Phys.Rev.D* 103 (2021), 054005
arXiv:2101.02708

Analogous to SoftDrop: iteratively decluster until grooming condition is passed

$$z_i = \frac{P \cdot p_i}{P \cdot q} \xrightarrow[\text{frame}]{\text{Breit}} z_i = \frac{n \cdot p_i}{Q} = \frac{p_i^+}{Q}$$

Grooming condition: $$\frac{\min(z_i, z_j)}{z_i + z_j} > z_{\text{cut}}$$



DIS event grooming using Centauro

Y. Makris, *Phys.Rev.D* 103 (2021), 054005
arXiv:2101.02708

z_{cut}=0.1

green=pass
grey = fail

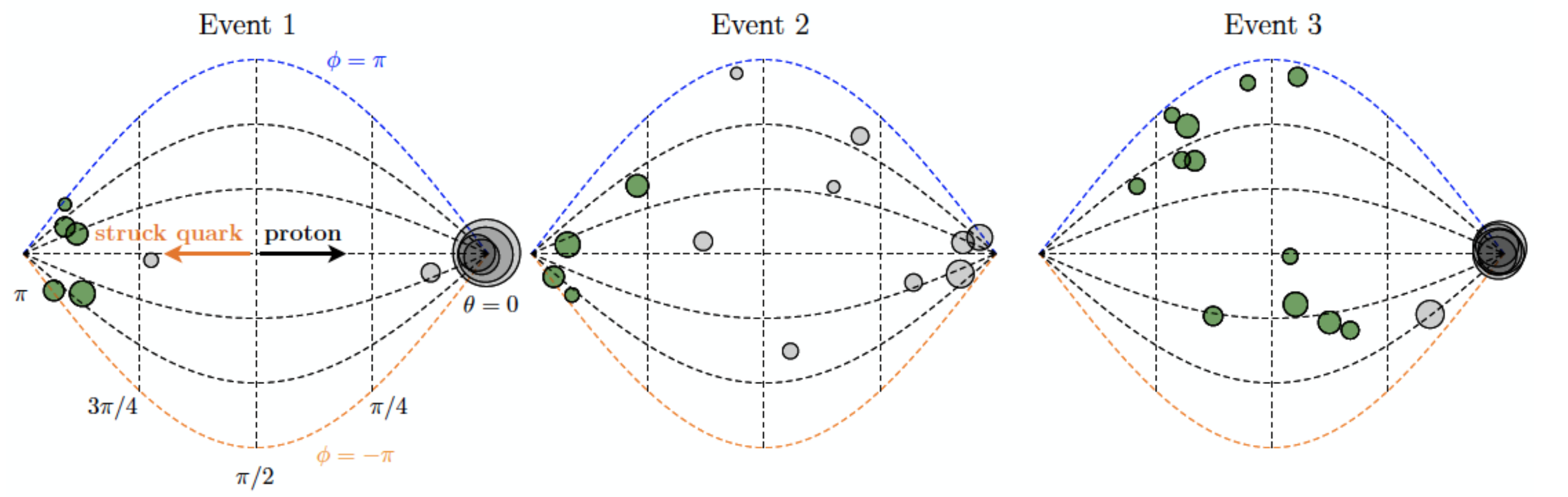


Figure 2. Visualization of three PYTHIA 8 events at $\sqrt{s} = 63$ GeV and $Q \sim 10$ GeV before and after grooming. The particles in this events are represented by disks on the unfolded sphere. Green disks represent particles that pass grooming where grayed-out particles are removed from the event by the grooming procedure. For the grooming parameter we use here $z_{\rm cut} = 0.1$

Application of grooming to H1 archived data

Analysis Note: H1prelim-22-033
https://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-22-033.long.html

Henry Klest (Stony Brook→ Argonne), Ph.D Thesis

H1 paper in preparation

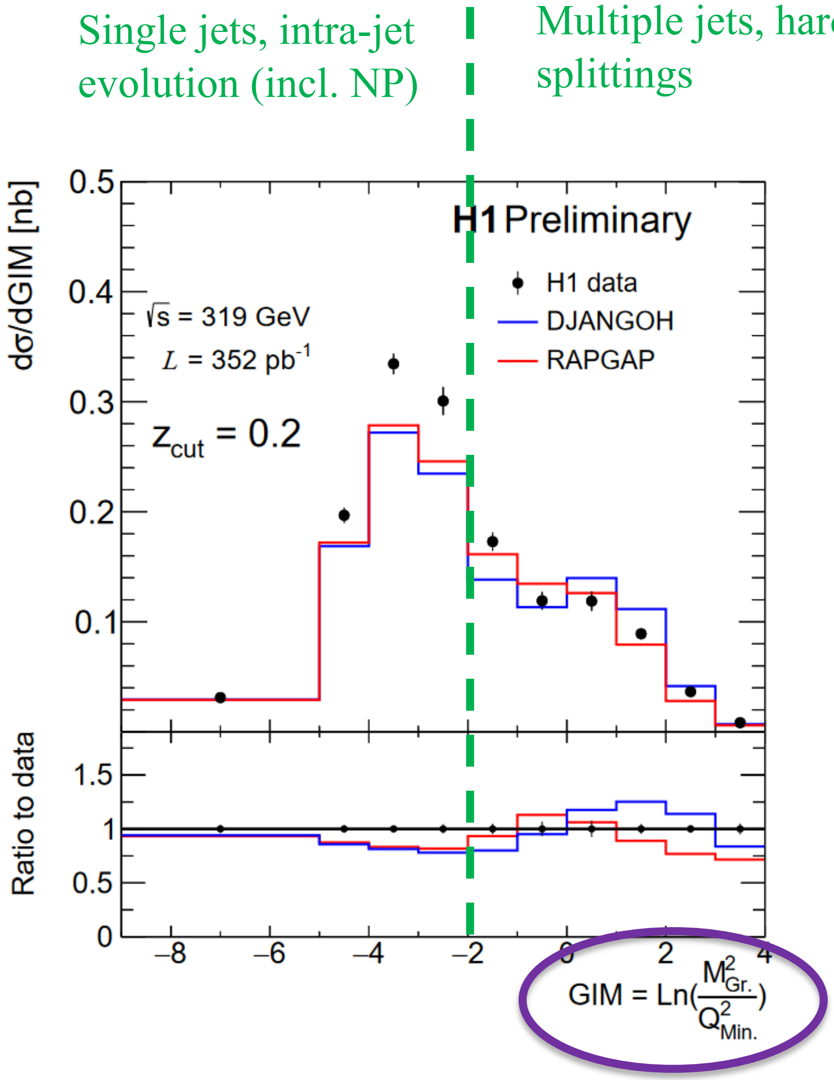
Measure global event shape observables using all particles that survive grooming:

- Groomed Invariant Mass (GIM)
- 1-jettiness (τ_1^b)

Observable I: Groomed Invariant Mass

Single jets, intra-jet evolution (incl. NP)

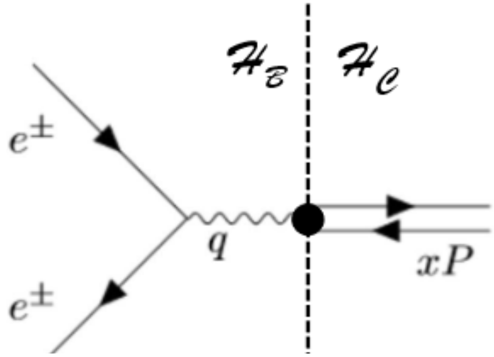
Multiple jets, hard splittings

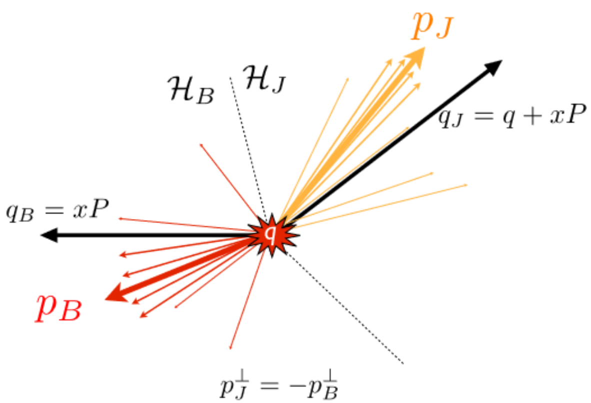


$$M_{Gr}^2 = \left(\sum_{i \in \text{groomed}} p_i^\mu \right)^2$$

Q^2_{Min}=minimum Q^2 in analysis

Observable II: 1-jettiness





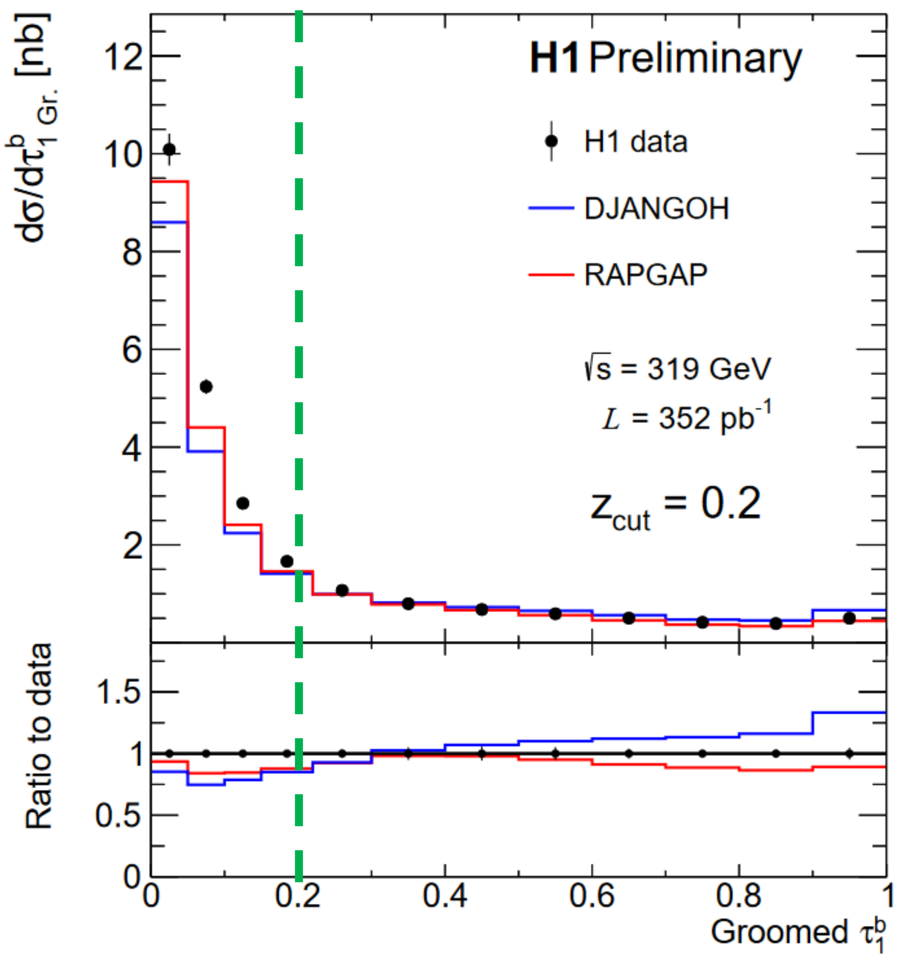
$$\tau_1^b = \frac{2}{Q^2} \sum_{i \in \text{groomed}} \min\left(q_B \cdot p_i, q_J \cdot p_i\right)$$

$\tau_1^b \to 0:$ single collimated jet

$\tau_1^b \to 1:$ spherical event

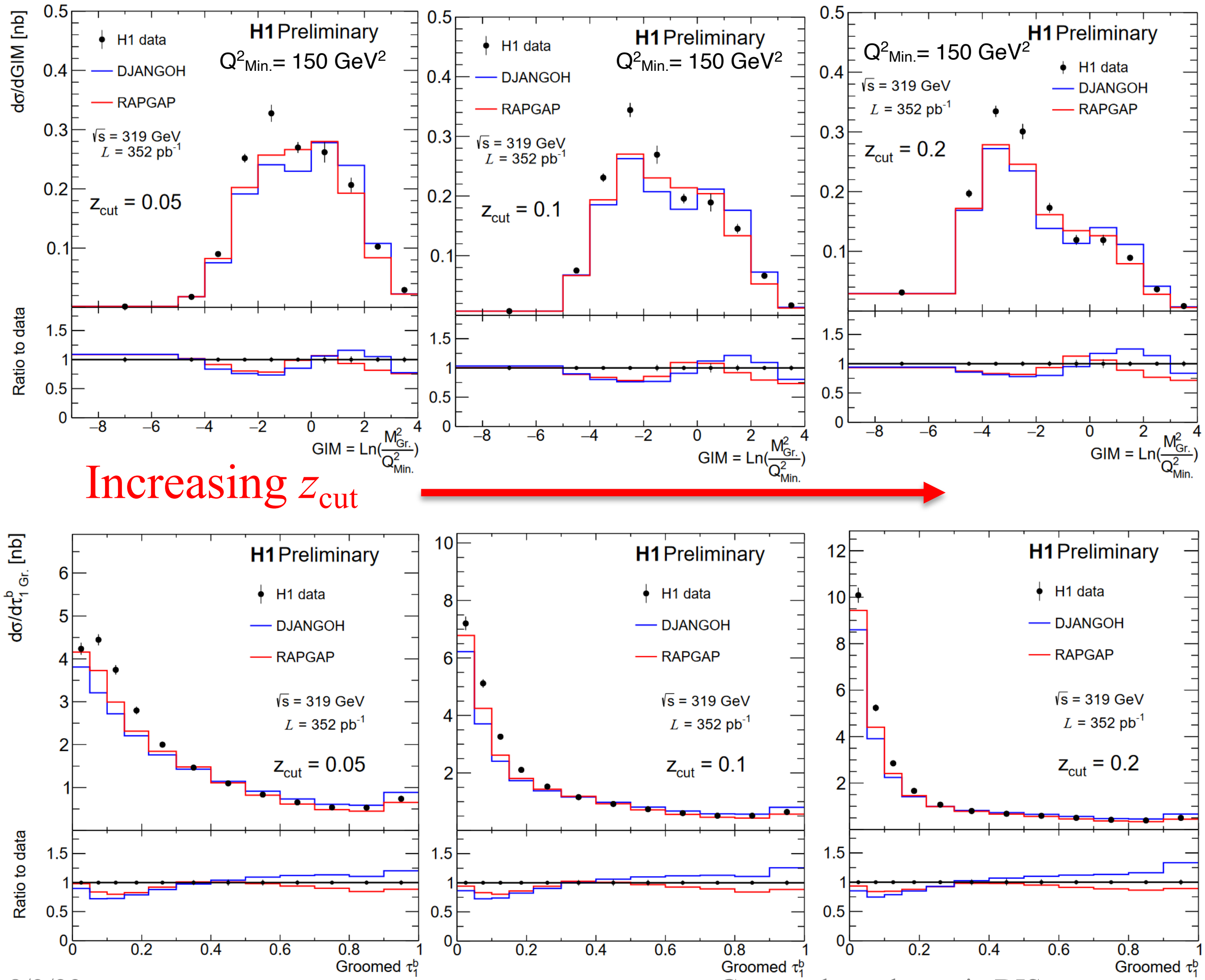
Single jets, intra-jet evolution (incl. NP)

Multiple jets, hard splittings



Corrected data

Preliminary: bin-wise correction
Corrected for real QED ISR and FSR



Uncertainty:
- statistical + systematic
- dominated by model uncertainty

Final data will be corrected by unfolding
- projected uncertainty <10%

Grooming: theoretical effects

(N)NLO + NLL′ accurate predictions for plain and groomed 1-jettiness in neutral current DIS

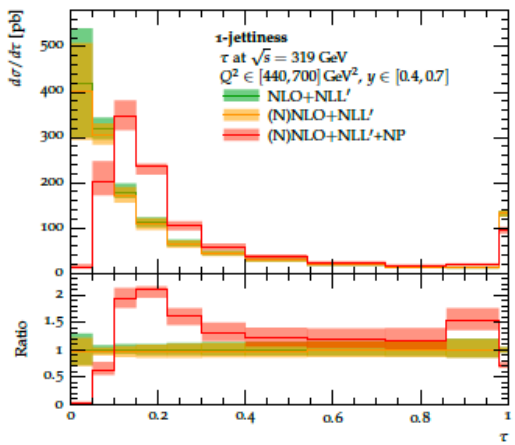
Max Knobbe*[1], Daniel Reichelt†[2], and Steffen Schumann¶[1]

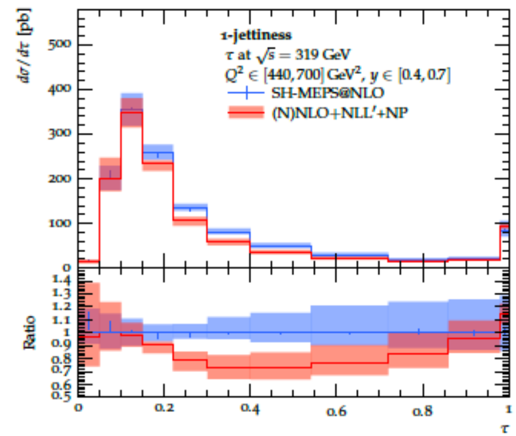
arXiv:2306.17736

w/wo NP

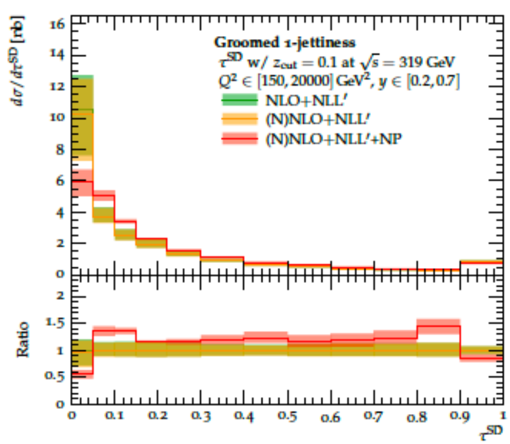
SHERPA vs analytic

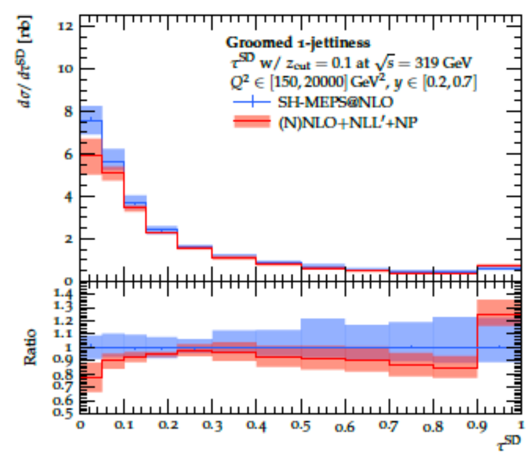
Ungroomed
$440<Q^2<700$ GeV^2





Groomed, $z_{cut}=0.1$
$150<Q^2<20K$ GeV^2

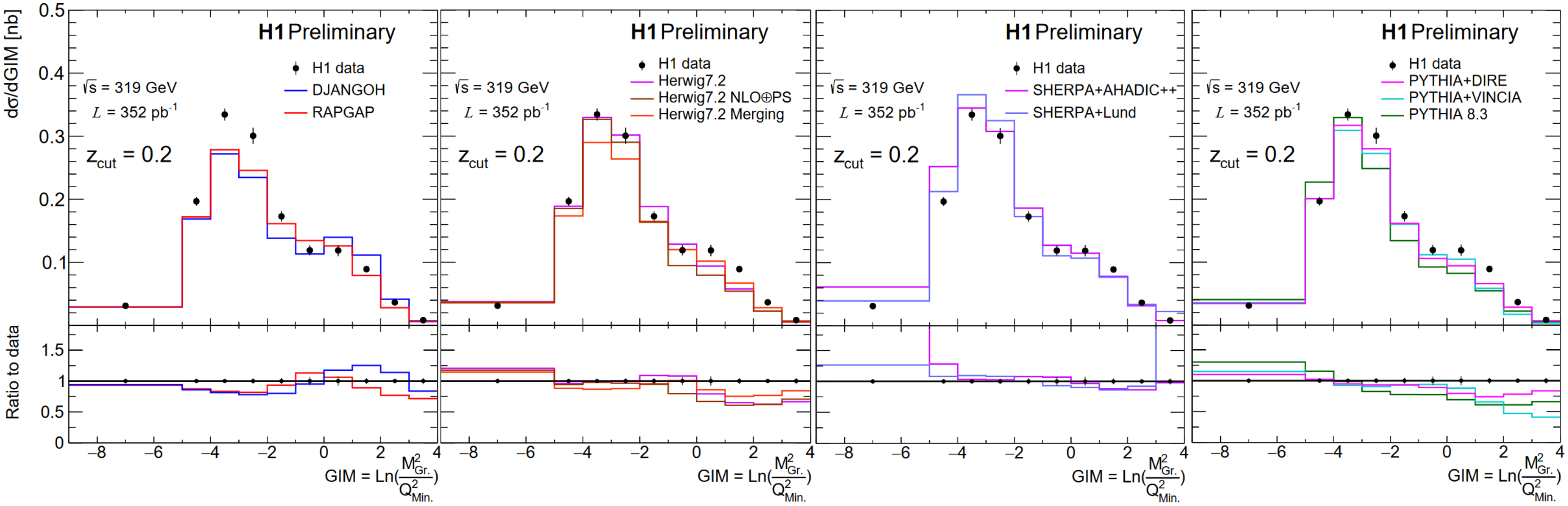




Reduced sensitivity to NP effects

Better agreement MC/analytic

Theory comparisons: GIM



- PYTHIA – Version 8.3
  - VINCIA – Antenna Shower
  - DIRE - Dipole shower + multijet merging
- Herwig – Version 7.2 (Angular-ordered)
  - NLO ⊕PS – AO Shower, subtractive matching
  - Merging - Dipole shower + multijet merging
- SHERPA – Version 2.2.12 (MEPS@NLO)
  - AHADIC++ - Cluster Fragmentation
  - Lund – String Fragmentation

$Q^2_{Min.}$ = 150 GeV^2

Best high mass region from SHERPA

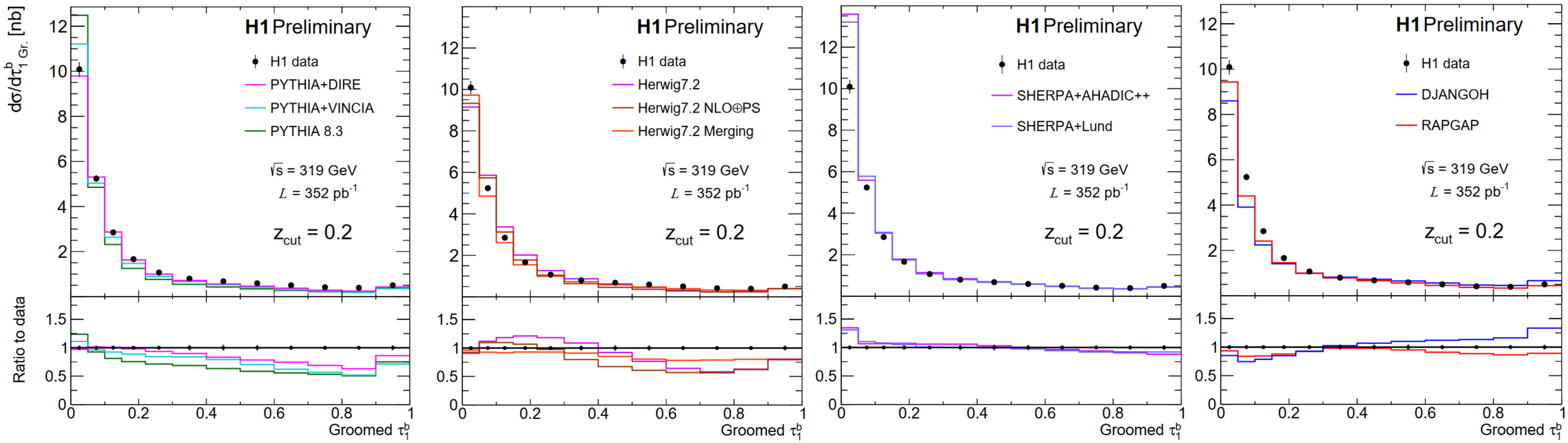
Fixed-order, multijets, hard splittings

Best low mass region from Herwig, DIRE

Resummation, parton shower, hadronization

Take-home message: rich dataset for precision MC tuning → impact on LHC and EIC

Theory comparisons: 1-jettiness



- PYTHIA – Version 8.3
  - VINCIA – Antenna Shower
  - DIRE - Dipole shower + multijet merging
- Herwig – Version 7.2 (Angular-ordered)
  - NLO ⊕PS – AO Shower, subtractive matching
  - Merging - Dipole shower + multijet merging
- SHERPA – Version 2.2.12 (MEPS@NLO)
  - AHADIC++ - Cluster Fragmentation
  - Lund – String Fragmentation

- Best tail region from SHERPA, RAPGAP
  - Fixed-order, multijets, hard splittings
- Best peak region from DIRE, Herwig Merging
  - Resummation, parton shower, hadronization

Take-home message: rich dataset for precision MC tuning
→ impact on LHC and EIC

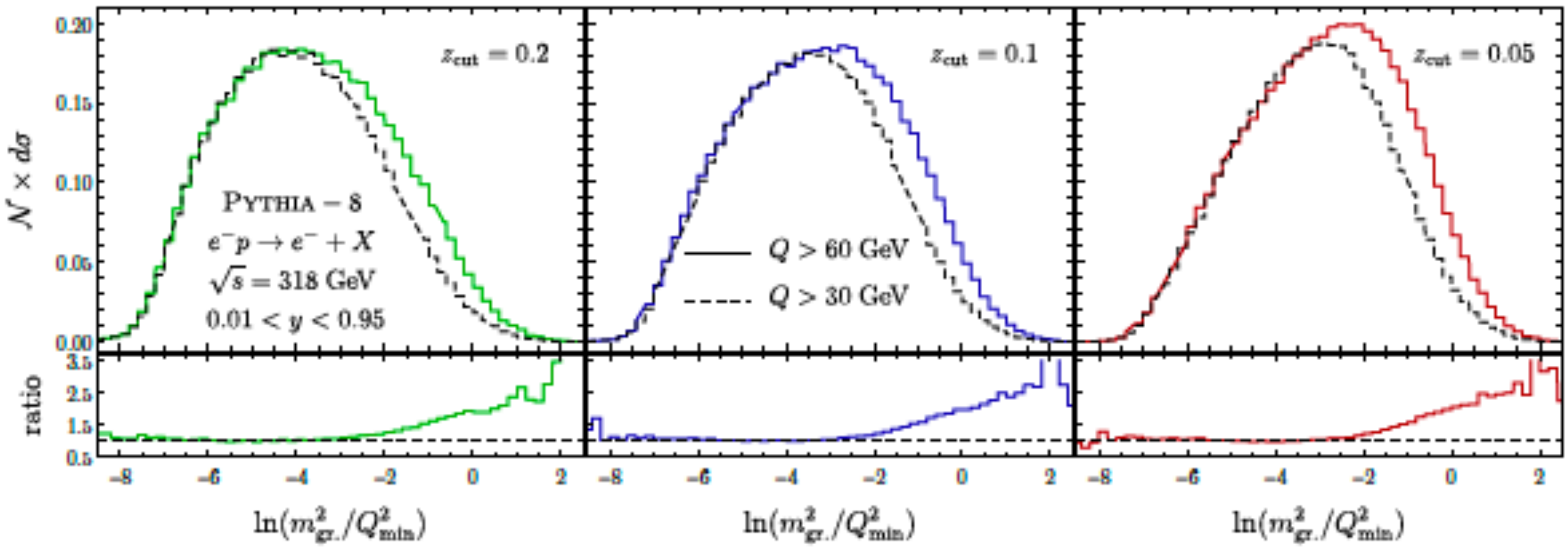
Theory comparison: SCET

Y. Makris, *Phys.Rev.D* 103 (2021), 054005
arXiv:2101.02708

SCET calculation: shape of Groomed Invariant Mass distribution at small GIM is determined by jet and soft-collinear functions, which do not depend on x and Q^2

Prediction: low-GIM distribution is independent of Q^2

PYTHIA8 test



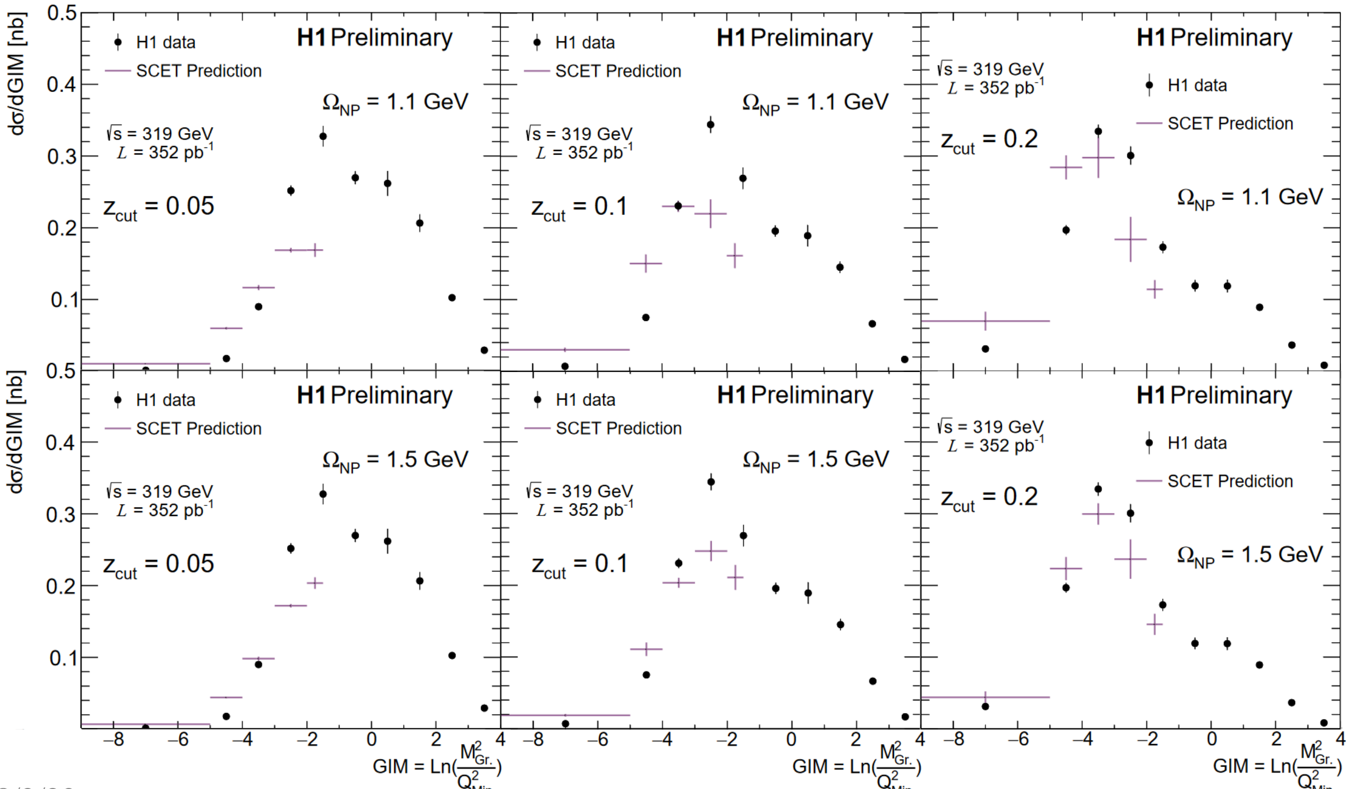
GIM: SCET vs data

NP factor Ω_{NP}:

$$\frac{d\sigma_{\text{had.}}}{dxdQ^2dm^2_{\text{gr.}}} = \int d\epsilon \frac{d\sigma}{dxdQ^2dm^2_{\text{gr.}}}\left(m^2_{\text{gr.}} - \frac{\epsilon^2}{z_{\text{cut}}}\right) f_{\text{mod.}}(\epsilon) \,,$$

$$f_{\text{mod.}}(\epsilon) = N_{\text{mod.}}\frac{4\epsilon}{\Omega^2}\exp\left(\frac{2\epsilon}{\Omega}\right)$$

Evaluated at two values of Ω_{NP}



Calculation normalized to data at low GIM

- only compare shapes

Better agreement for increasing z_{cut}, Ω_{NP}

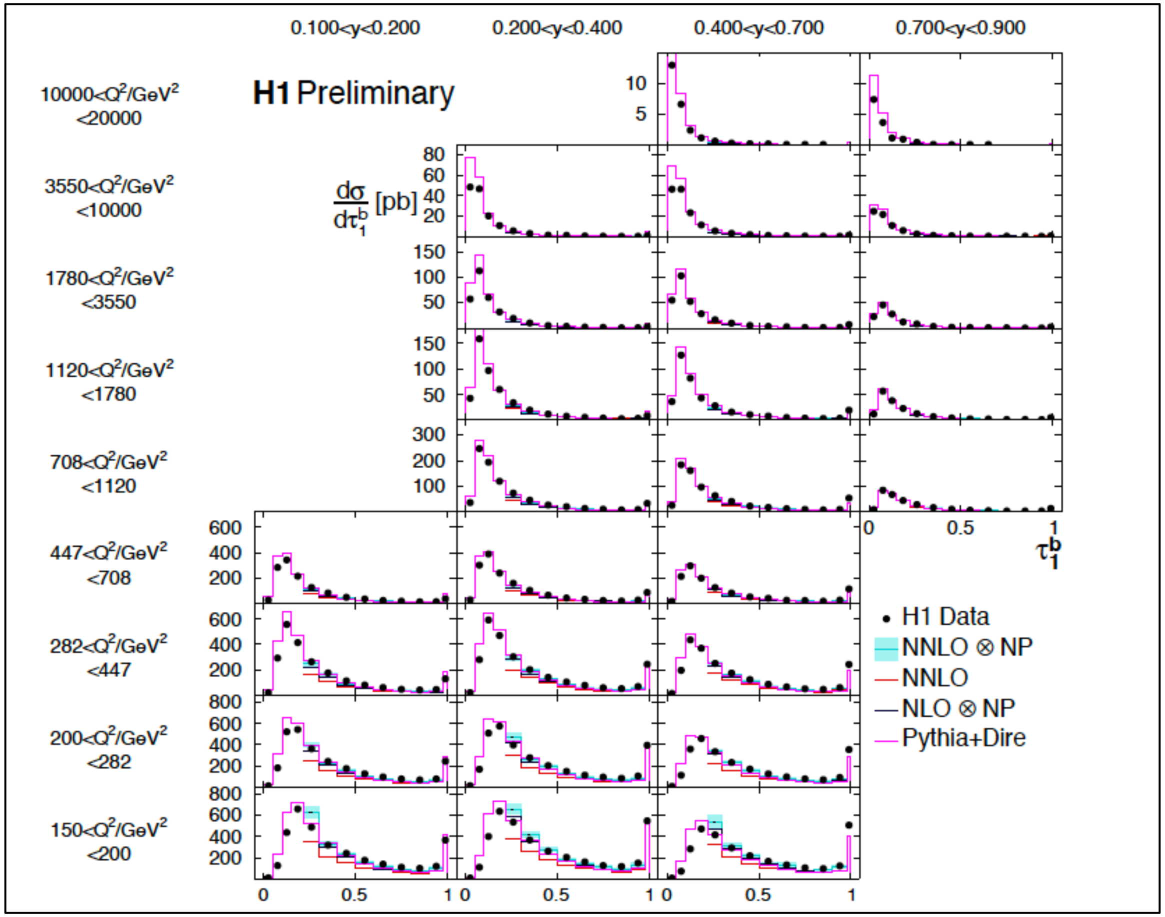
- Non-perturbative effects are significant

Validity of factorization improves at higher z_{cut}

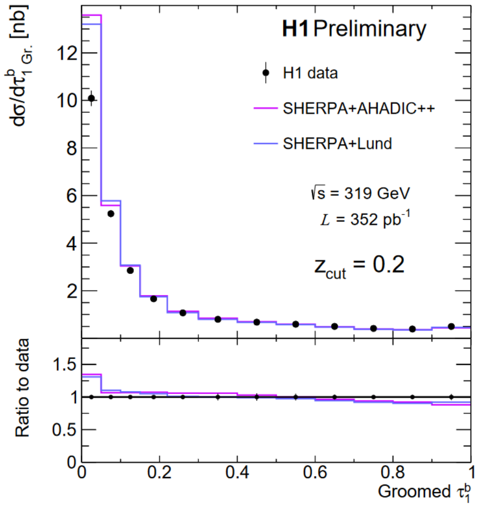
Ungroomed 1-jettiness

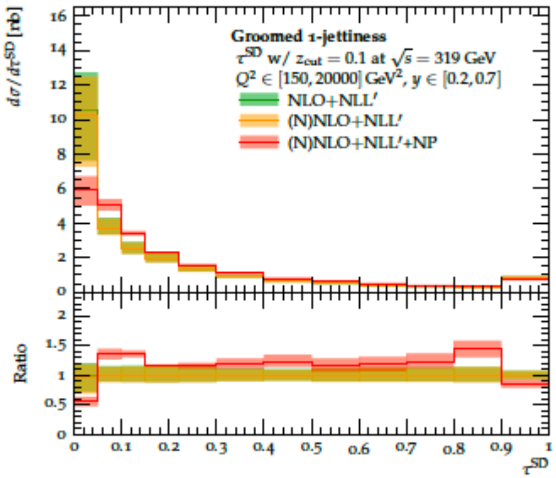
Also in preparation: measurement of triple differential cross section of τ_1^b

Analysis note: H1prelim-21-032
https://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-21-032.long.html



Summary





New analysis of groomed event shapes in e+p DIS collisions using archived H1 data

- grooming → improved experimental and theoretical precision
- triggered new theory efforts for high-order and resummed calculations

Precise data for MC tuning → impact on LHC and EIC

H1 data are immensely rich: many novel QCD analyses possible
New ideas are welcome!

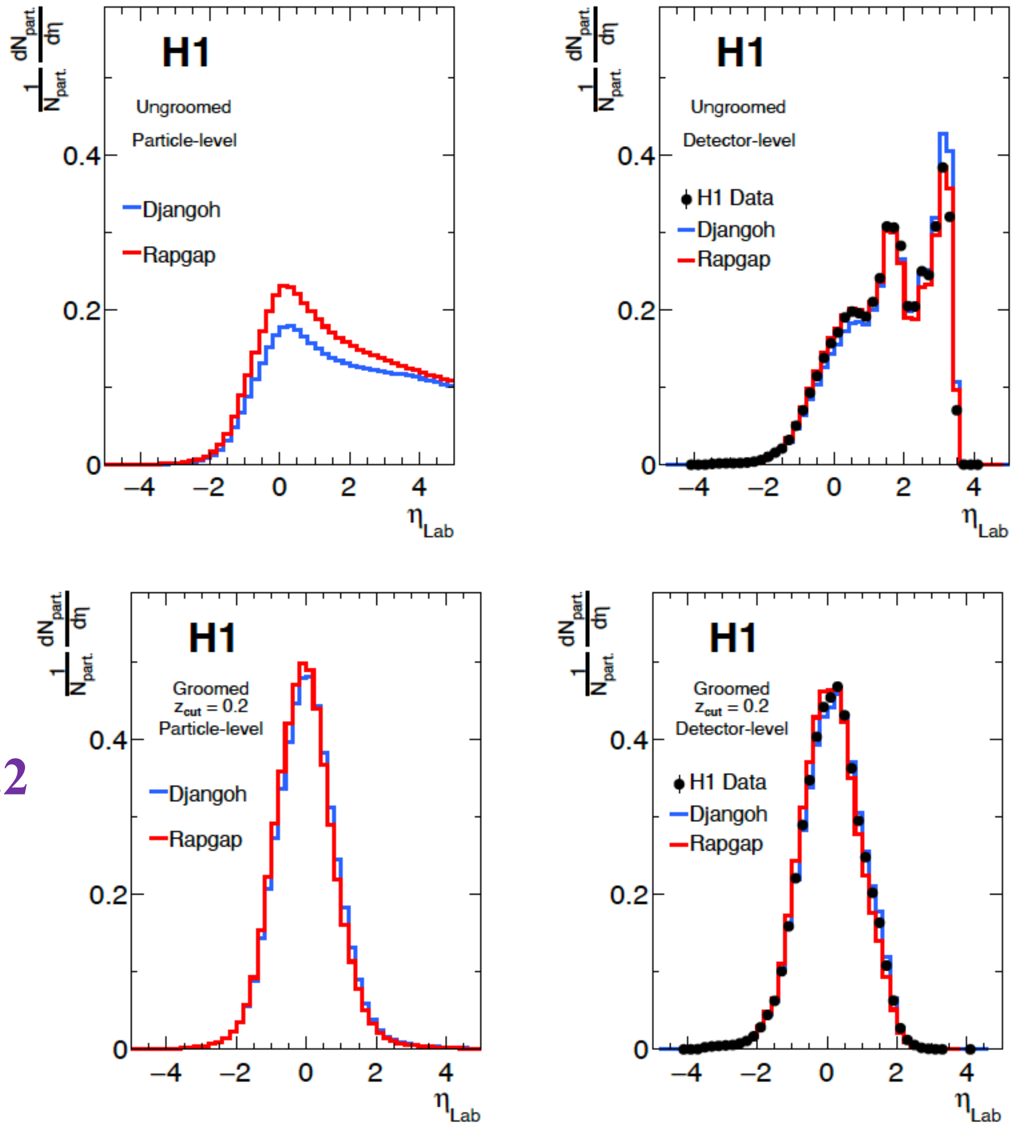
Backup

Grooming: experimental effects

particle-level detector-level

z_{cut}=0

z_{cut}=0.2



RAPGAP and DJANGOH
- Standard H1 MCs
- matrix elements $O(\alpha_S)$ from LEPTO

DJANGOH:
- Color dipole model PS + string fragmentation

RAPGAP:
- DGLAP PS + string fragmentation

Ungroomed: large differences between part and det-level

Groomed: part and det-level similar

- Soft NP radiation outside acceptance would be groomed away
- Small corrections→ high precision measurement