Stony Brook University

Center for Frontiers
in Nuclear Science

Jet Physics from HERA to EIC

A Heavily Biased Account

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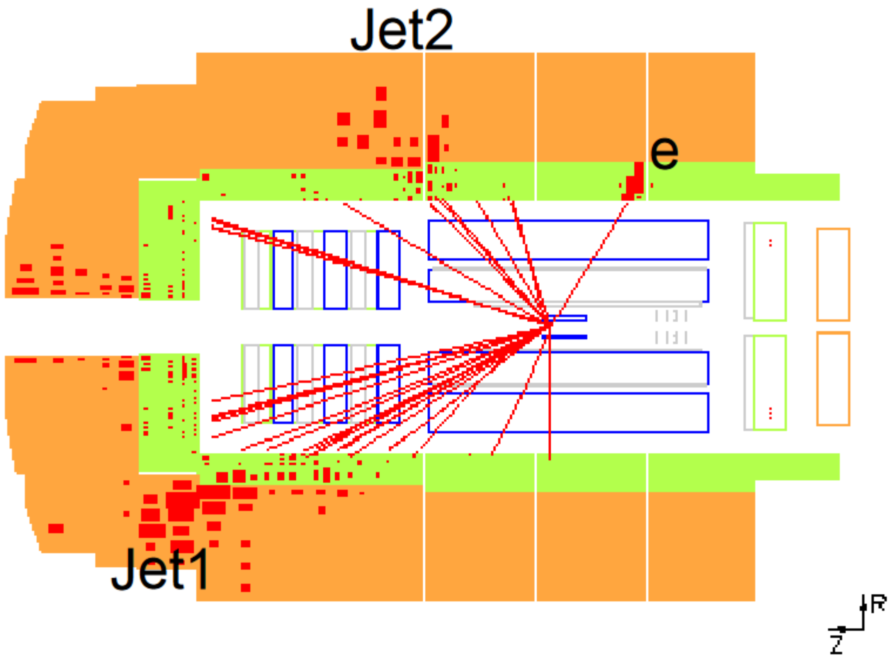
July 25, EICUG EC Workshop

FAR
BEYOND

Jet Physics

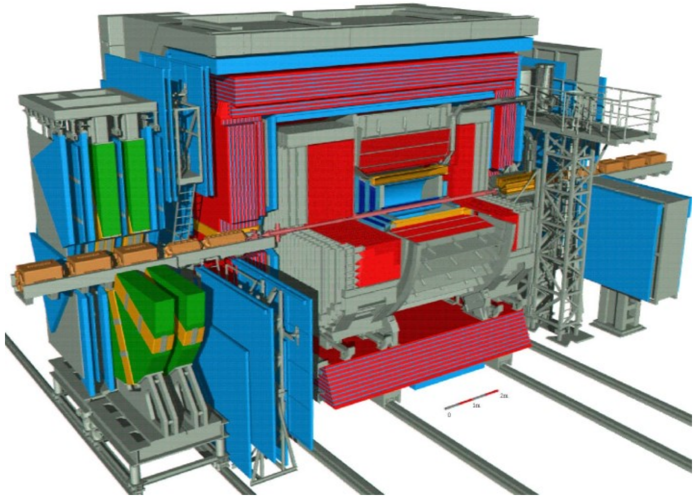
- Jet physics relies on interplay between precise theory and experiment
- Some of the thrusts of modern jet physics are:
  - Multi-jet configurations
    - Compare to fixed-order calculations, extraction of PDFs, α_s
  - Jet Substructure
    - Grooming, jet shapes, flavor discrimination
  - Monte Carlo Event Generator Tuning
    - Parton shower, hadronization model discrimination
  - Heavy ions
    - Jet quenching, parton energy loss in-medium



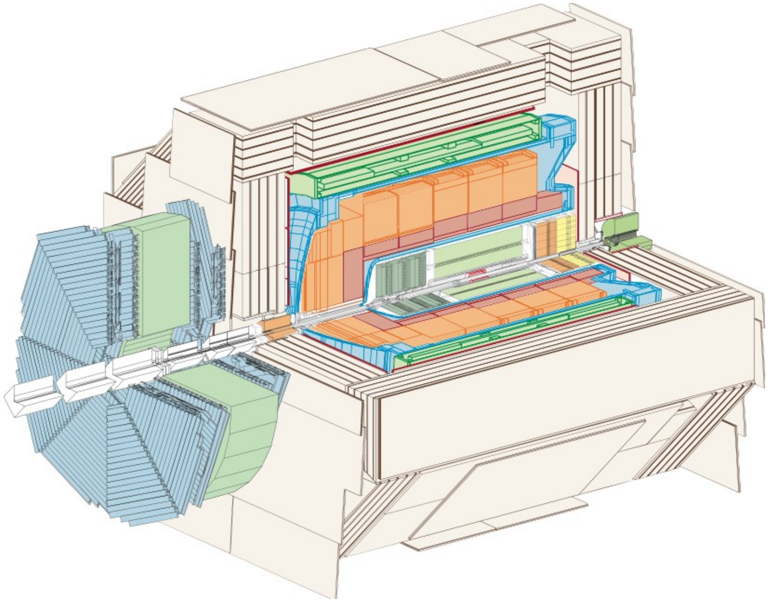
Dijet event in e+p DIS at H1

HERA

- World's first and only electron*-proton collider
  - Ran from 1992 – 2007
  - 27.5 GeV electron on 920 GeV proton - $\sqrt{s} \cong 318$ GeV
  - Delivered ~ 0.5 fb^{-1} to each of the two general purpose experiments, ZEUS and H1
- ZEUS and H1 focused on high precision calorimetry
  - Excellent for jet studies!
- Won't discuss HERMES or HERA-B in this talk



Top: ZEUS, DU Cal in Red
Bottom: H1, LAr Cal in Orange/Red



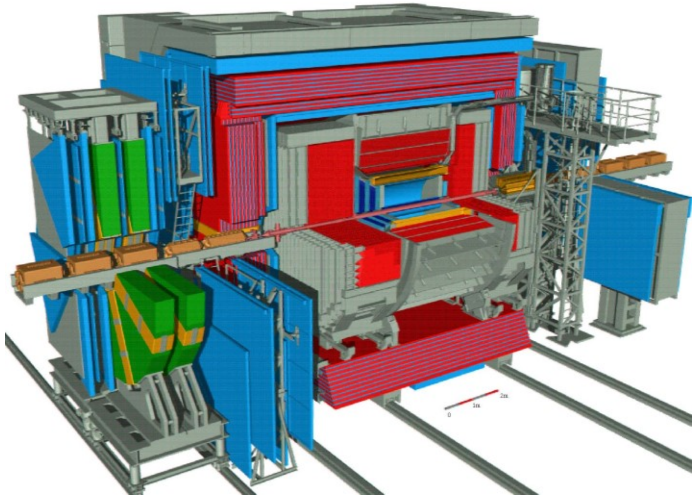
*electron and positron are used here interchangeably, roughly equal data sets gathered with e^+ and e^-

HERA vs. EIC

- HERA $\sqrt{s}$ preferable for pQCD studies
  - Larger maximum Q^2 accessible, better perturbative convergence
  - Even at HERA, high Q^2 events were rare O(1 per min)

- HERA hadronic calorimetry was excellent
  - ZEUS: $\sim \frac{35\%}{\sqrt{E}} \oplus 2\%$ - Depleted uranium
  - H1: $\sim \frac{50\%}{\sqrt{E}} \oplus 2\%$ - Liquid argon
  - Unmatched for collider experiments!

- HERA EM calorimetry worse than EIC designs
  - ZEUS: $\sim \frac{18\%}{\sqrt{E}} \oplus 1\%$ - Depleted uranium
  - H1: $\sim \frac{11\%}{\sqrt{E}} \oplus 1\%$ - Liquid argon



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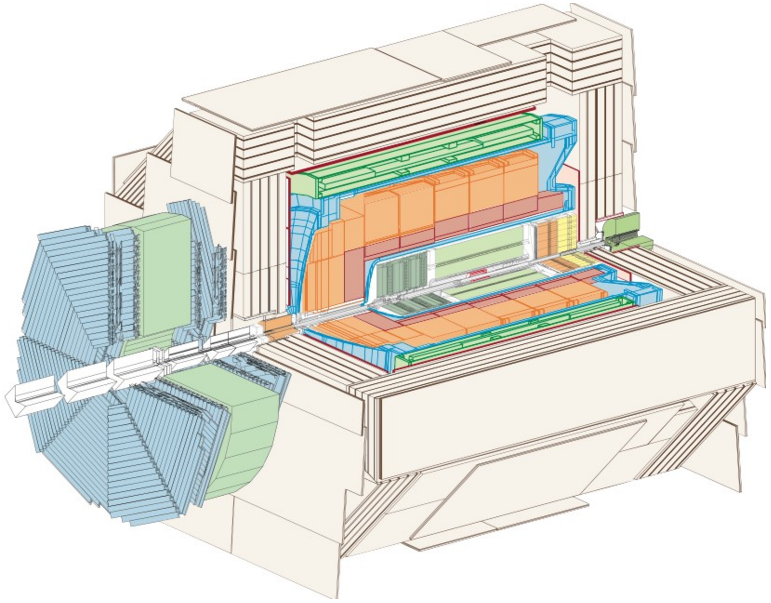
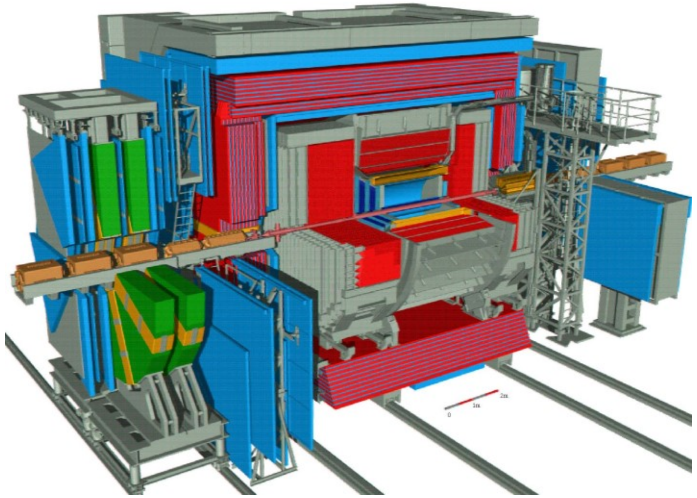


HERA vs. EIC

- EIC luminosity blows HERA away
  - **EIC will collect 10x-100x the entire 15 years of HERA integrated luminosity in one year of running**
  - Even for $Q^2 > 100\ \mathrm{GeV}^2$, EIC statistics will dominate HERA

- EIC tracking and PID will be superior
  - High momentum PID (> 1 GeV)
    - ZEUS & H1 had only dE/dx
  - Modern tracking with far less material
    - Thin silicon vs. thick wire chambers

- HERA had only lepton beam polarized
  - Lepton beam polarized via Sokolov–Ternov effect
  - Polarized hadron beam unlocks a large variety of jet measurements!



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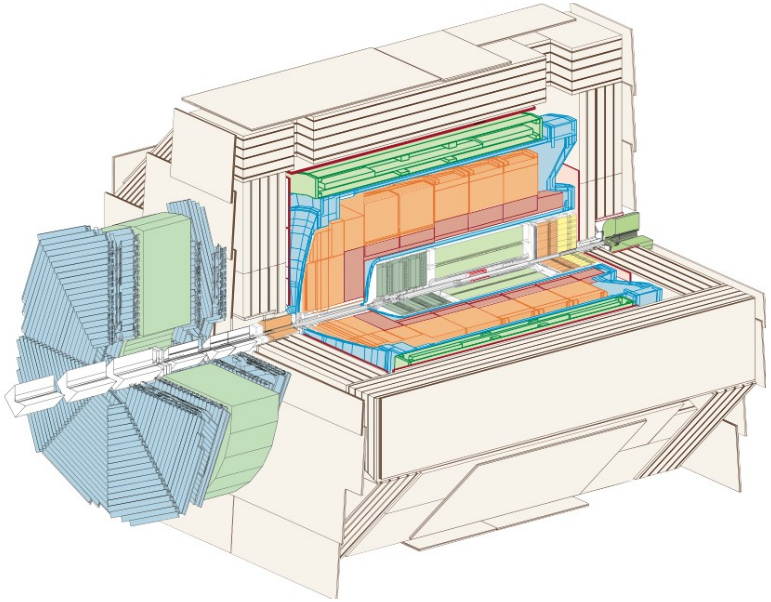
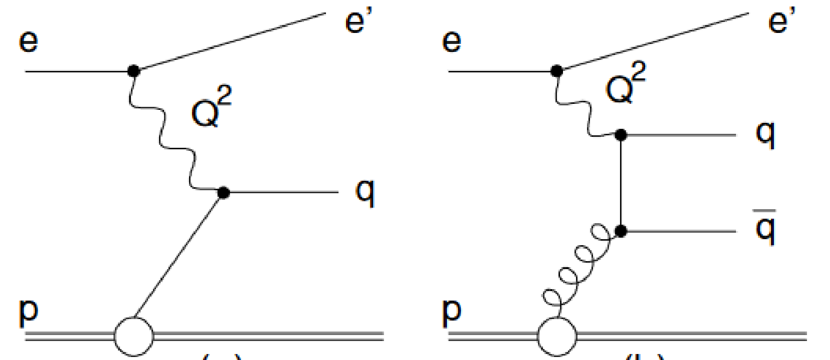


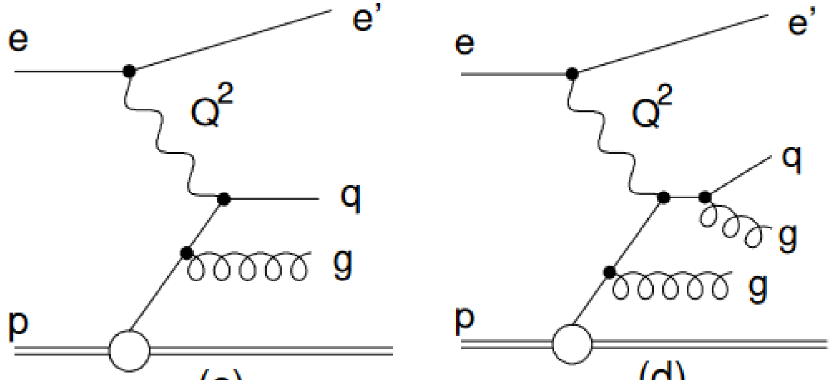
Recent HERA Jet Measurements

- Inclusive Jets in DIS & Photoproduction
  - Dijet, Trijet cross sections
  - High Q^2 (150 -> 15000 GeV^2) and low Q^2 (5.5 -> 80 GeV^2)
- Exclusive Diffractive Dijets
  - Diffractive PDFs, α_s
- Lepton-Jet Azimuthal Correlation*
  - Tested OmniFold ML-based unfolding procedure – PRL 2022
- Charge correlations in jets*
  - H1 Preliminary
- Groomed Event Shapes*
  - First application of new Centauro algorithm, first use of grooming at HERA – H1 Preliminary



(a) One Jet

(b) Two Jets



(c) Two Jets

(d) Three Jets

Figure 1: Deep-inelastic *ep* scattering at different orders in α_s: (a) Born contribution to inclusive NC DIS ($O(\alpha_{em}^2)$), (b) photon-gluon fusion ($O(\alpha_{em}^2\alpha_s)$), (c) QCD Compton scattering ($O(\alpha_{em}^2\alpha_s)$) and (d) a trijet process $O(\alpha_{em}^2\alpha_s^2)$.

* Measurements performed with EIC in mind, by EIC-involved manpower!

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"Standard" jet measurements performed many times at HERA

* Measurements performed with EIC in mind, by EIC-involved manpower!

Recent HERA Jet Measurements

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“New” jet measurements based on new experimental techniques and new theory

* Measurements performed with EIC in mind, by EIC-involved manpower!

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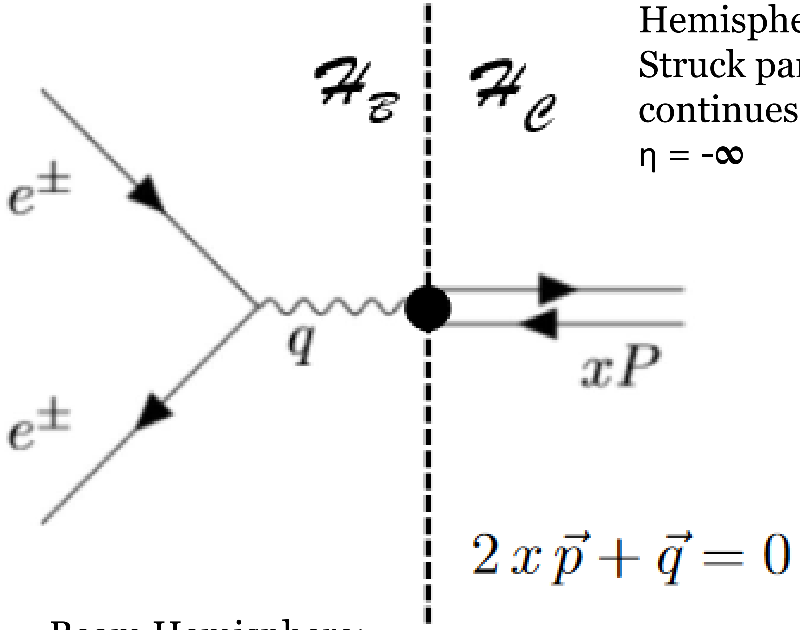
Rest of the talk will focus on this, since this is what I’ve been directly involved in

(This is an early career workshop after all!)

The Breit Frame

- Defined as the frame where $2x\vec{P} + \vec{q} = 0$
- Exchanged boson collides with struck parton and reverses the parton's momentum
- Event is cleanly divided geometrically into two hemispheres: "beam" hemisphere and "current" hemisphere



Current
Hemisphere:
Struck parton
continues at
η = -∞

Beam Hemisphere:
Proton remnant
continues at η = ∞

Incoming parton + outgoing parton + virtual photon = (0,0,0,0)

xP + xP + q = (0,0,0,0)

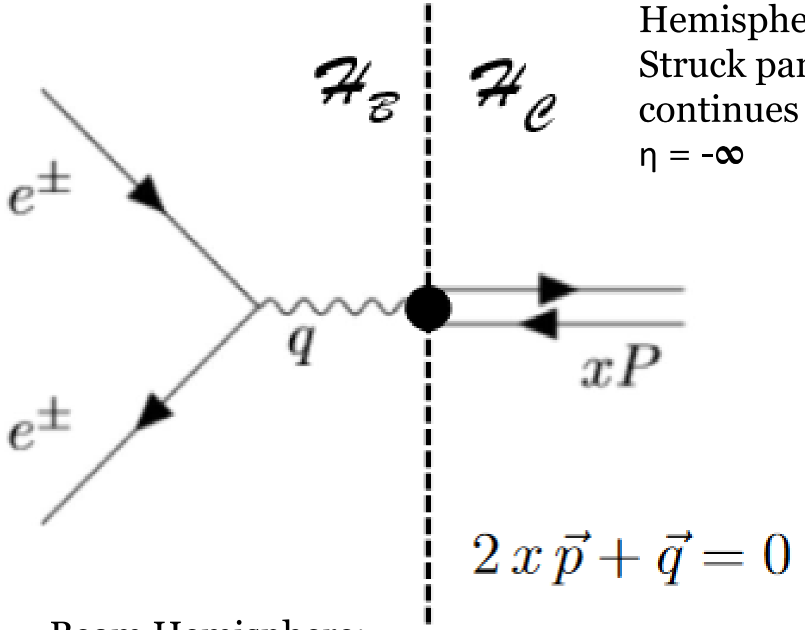
P = proton beam momentum, 920 GeV at HERA

$(2xP+E_\gamma, P_{x_\gamma}, P_{y_\gamma}, 2xP+P_{z_\gamma}) = (0,0,0,0)$

Boost away photon transverse components, balance parton and photon longitudinal components

The Breit Frame

- Natural reference frame for jet studies
  - Current hemisphere typically populated by radiation from struck parton
  - Beam hemisphere populated by QCD ISR and target fragmentation
  - Lab frame can't easily distinguish between beam and current jets, typically beam jet energies are higher



Current Hemisphere: Struck parton continues at η = -∞

Beam Hemisphere: Proton remnant continues at η = ∞

Incoming parton + outgoing parton + virtual photon = (0,0,0,0)

xP + xP + q = (0,0,0,0)

P = proton beam momentum, 920 GeV at HERA

$(2\text{xP}+E_\gamma, P_{x_\gamma}, P_{y_\gamma}, 2\text{xP}+P_{z_\gamma}) = (0,0,0,0)$

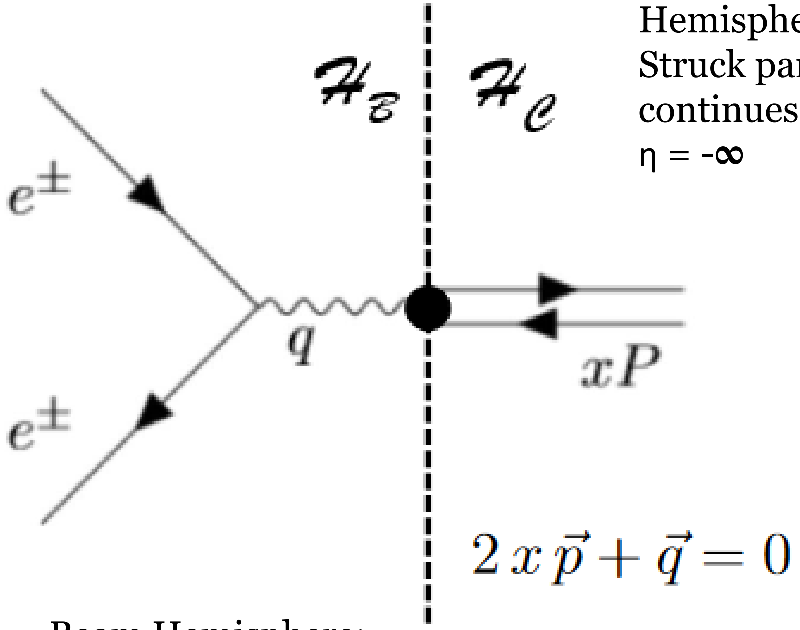
Boost away photon transverse components, balance parton and photon longitudinal components

The Breit Frame

- One major experimental drawback: kinematics must be precisely measured
  - x and q must be measured to perform the boost
  - Error on kinematics directly translates to error on measurement
  - Resolution of x typically limits Breit frame measurements to certain regions of phase space

- In some regions of (x,Q) phase space, the detector becomes significantly warped by the boost ($\gamma >> 1$)
  - Don't want entire current hemisphere to be one calorimeter cell in the lab frame!
  - Issues arise at large y, large θ_{HFS}

Current Hemisphere: Struck parton continues at $\eta = -\infty$



Beam Hemisphere: Proton remnant continues at $\eta = \infty$

Sensitive to QED ISR!

So that's jet physics and the Breit frame in what was hopefully 5 minutes

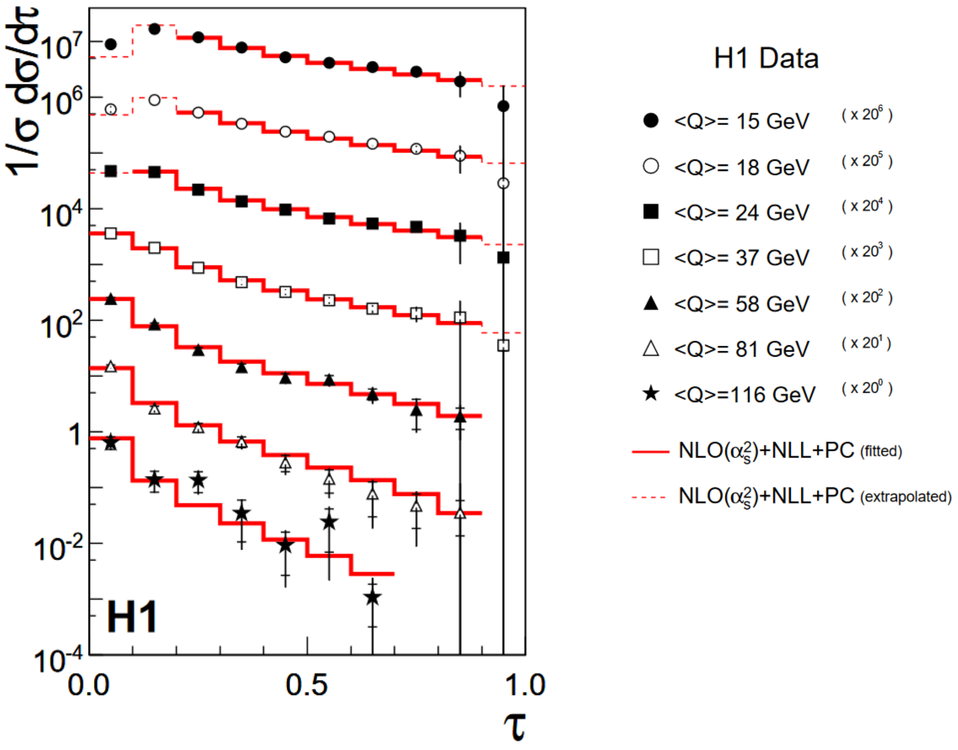
Now let's do a measurement…

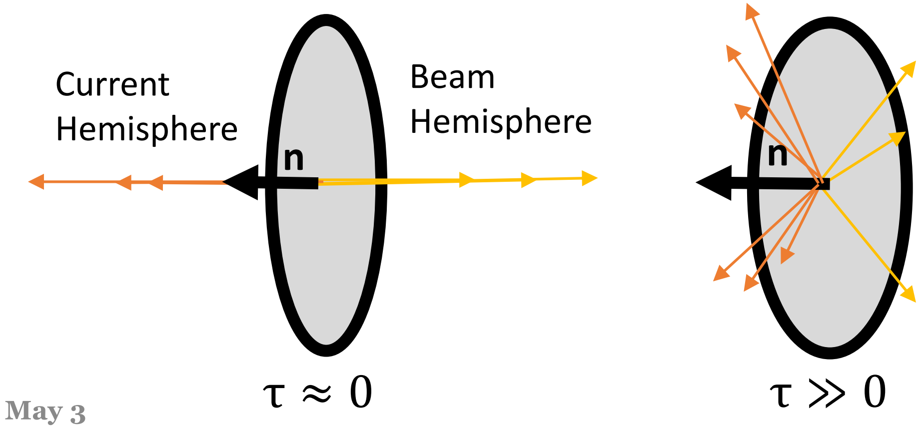
Groomed Event Shapes!

Event Shapes

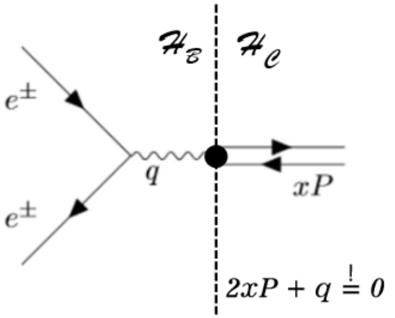
$$\tau = 1 - T \quad \text{with} \quad T = \frac{\sum_h |\vec{p}_{z,h}|}{\sum_h |\vec{p}_h|}$$

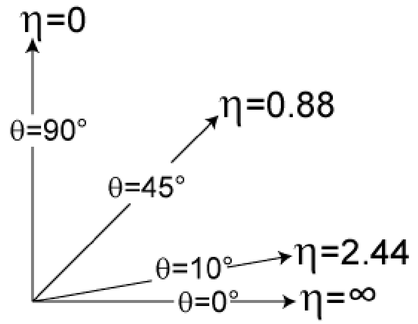
- Inclusive observables where all particles contribute
    - E.g. Thrust – measures degree of collimation along an axis
- **Sensitive to QCD across scales**
- Calculable to high precision in perturbation theory
    - Fixed-order QCD → tail of thrust distribution
    - Soft-collinear effective theory (SCET) calculations → peak of thrust distribution
- Used extensively in e^+e^- and Breit frame e+p collisions



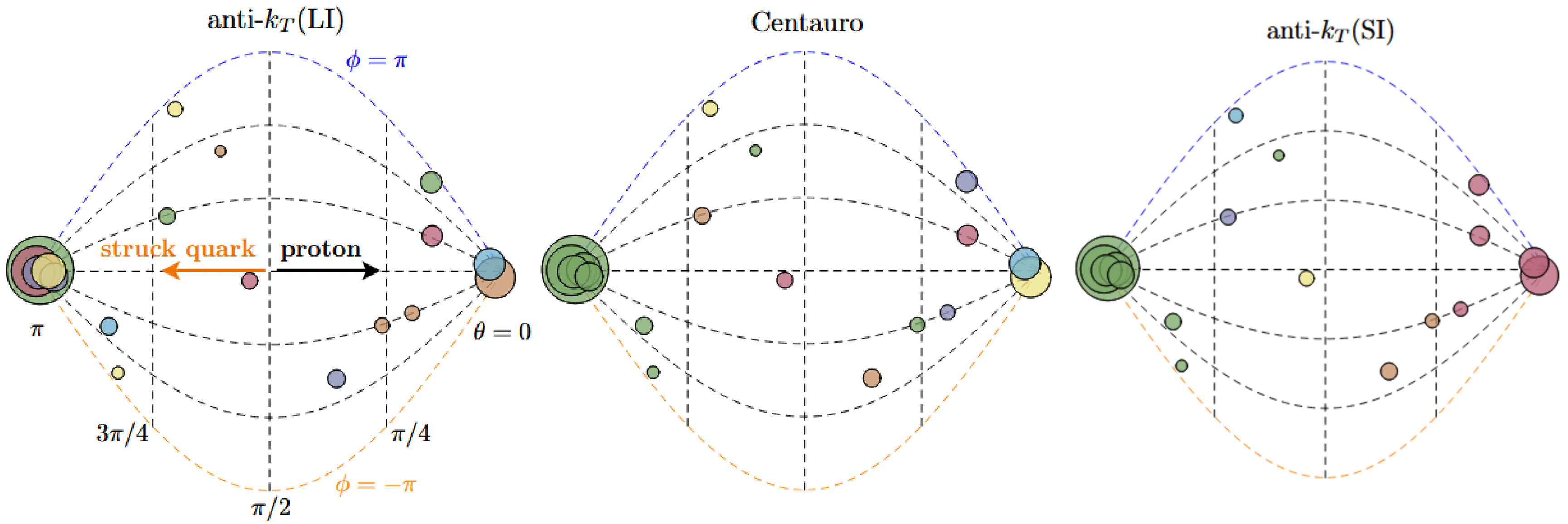


Centauro

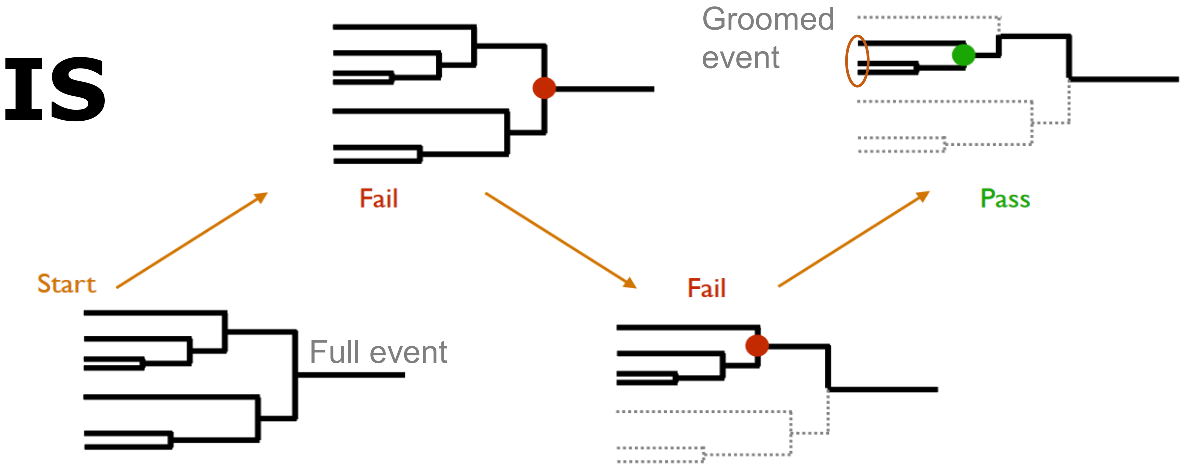




- Typical longitudinally-invariant jet algorithms cluster in (rapidity, azimuthal angle) space
  - Born-level jet is at η = −∞
  - Makes study of single-jet Born level configuration impossible!
- Use jet algorithm with asymmetric clustering measure!
  - Treat current hemisphere and beam hemisphere differently



Event Grooming in DIS

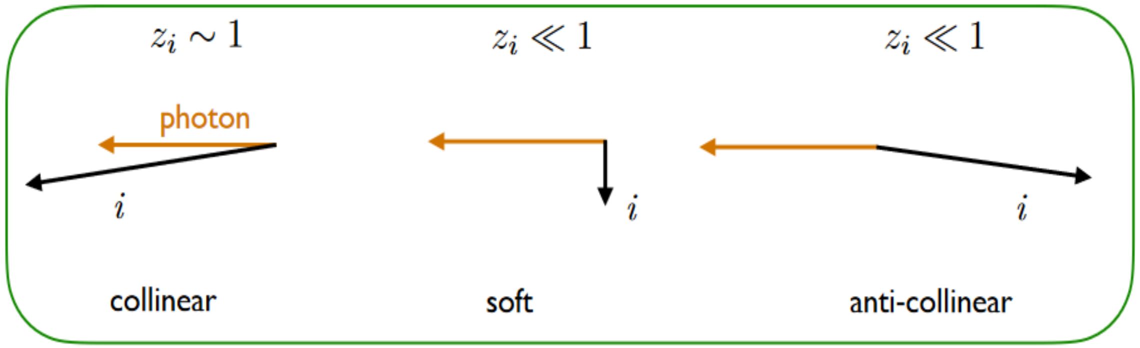


- Whole event is clustered into one “jet”

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

- Iteratively de-cluster until grooming condition is passed
  - Analogous to Soft Drop in p+p

Limits (geometric interpretation in the Breit frame)



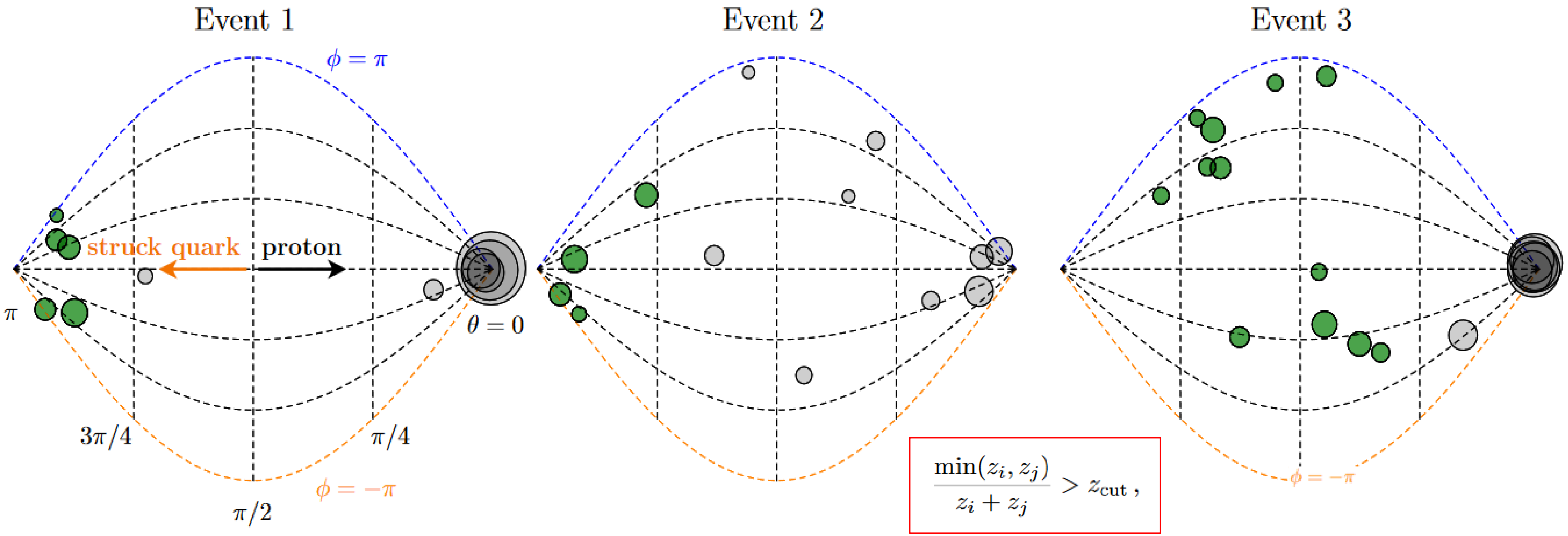
- Groomed events are similar to groomed jets!

$$\frac{\min(p_{t1},p_{t2})}{p_{t1}+p_{t2}} > z_{\text{cut}} \longrightarrow \frac{\min(z_i,z_j)}{z_i+z_j} > z_{\text{cut}}$$

p+p Soft Drop condition

DIS grooming condition

Breit Frame Event Displays

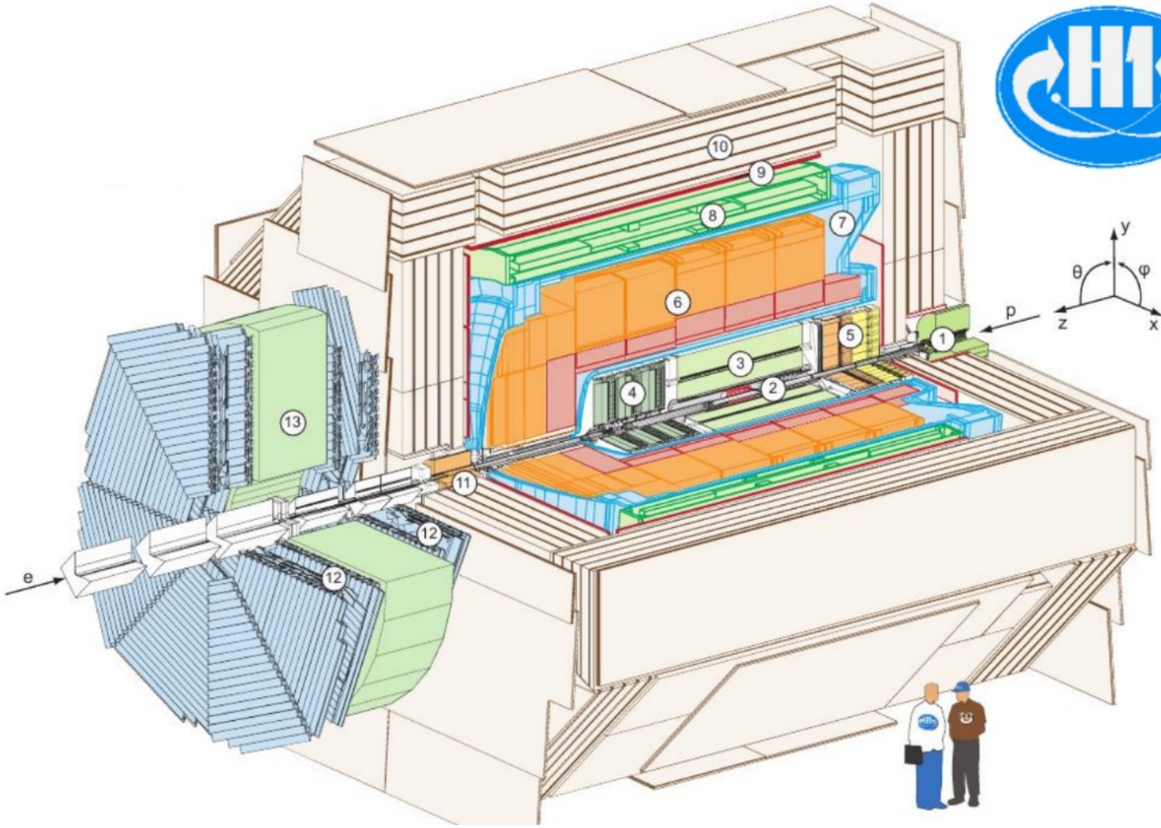


$$\frac{\min(z_i, z_j)}{z_i + z_j} > z_{\rm cut}\,,$$

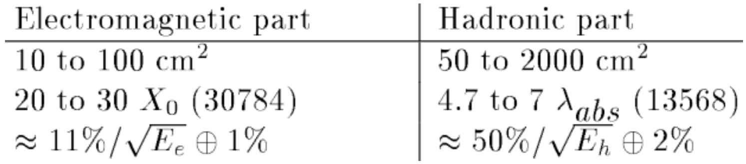
Figure 2. Visualization of three PYTHIA 8 events at $\sqrt{s} = 63$ GeV and $Q \sim 10$ GeV before and after grooming. The particles in this events are represented by disks on the unfolded sphere. Green disks represent particles that pass grooming where grayed-out particles are removed from the event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

H1 Detector

- Hermetic detector with asymmetric design
  - More instrumentation in forward (proton-going) direction
  - Drift chamber + silicon tracking
  - High-resolution LAr calorimeter
- Trigger on high-energy hadronic or EM LAr cluster
  - > 99% efficient for $y < 0.7$



H1 LAr Calorimeter Specifications



Electromagnetic part	Hadronic part
10 to 100 cm^2	50 to 2000 cm^2
20 to 30 X_0 (30784)	4.7 to 7 λ_{abs} (13568)
$\approx 11\%/\sqrt{E_e} \oplus 1\%$	$\approx 50\%/\sqrt{E_h} \oplus 2\%$

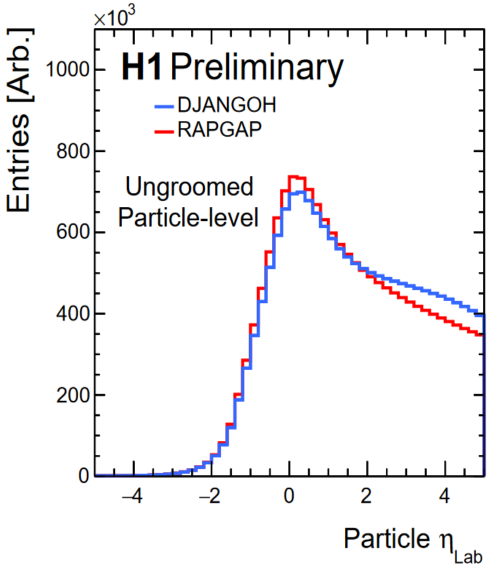
This analysis uses the 352 pb^{-1} collected in HERA-II run period from 2003-2007

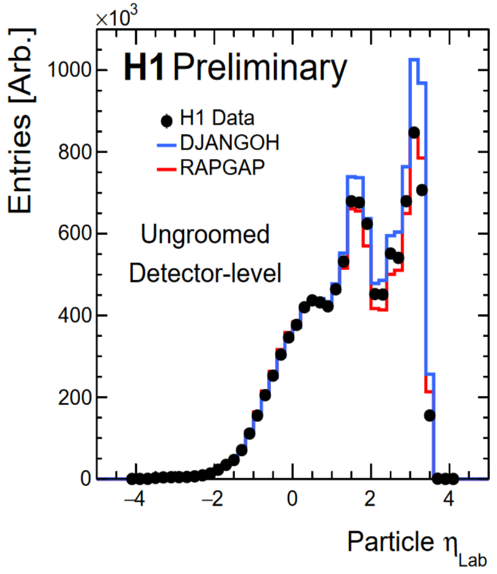
Grooming Benefits

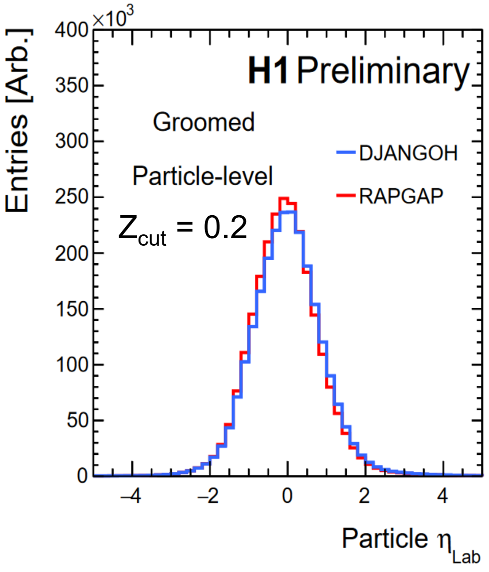
- No underlying event, why groom?
    - Less affected by lab-frame detector acceptance
    - Mitigate QCD remnant, ISR
    - More theory-friendly

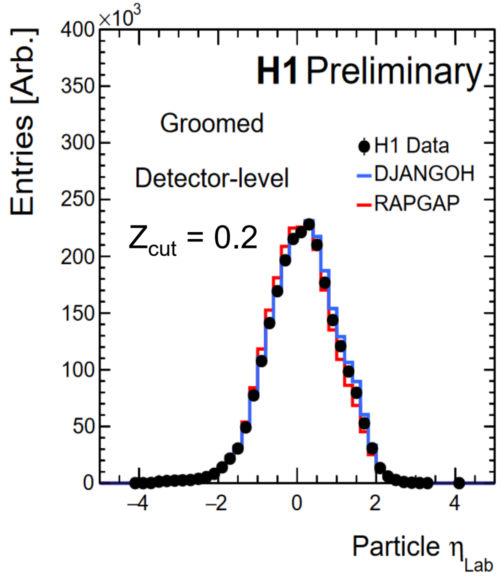
- Ungroomed detector-level shows significant difference from particle-level
    - Detector acceptance, efficiencies

- Grooming events brings particle-level and detector-level distributions into much better agreement!









Observables

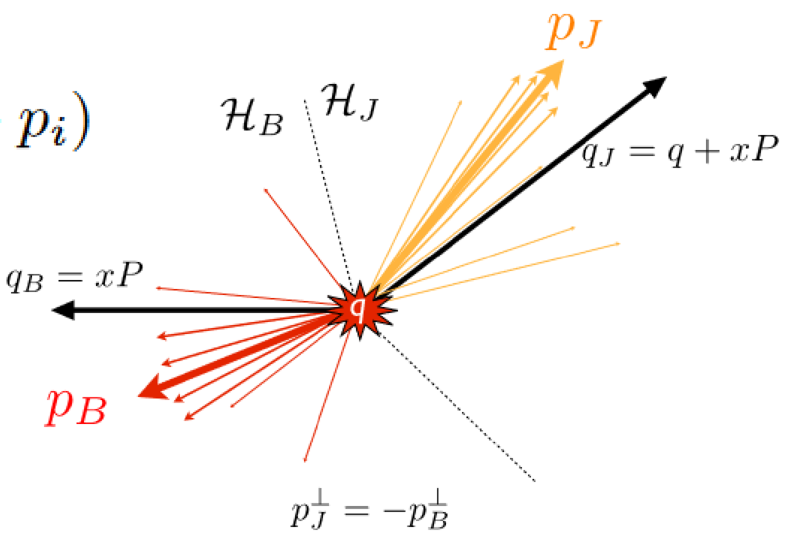
- After grooming procedure, a subset of particles survives
  - Event shape is calculated with these particles
  - Two event shapes studied here

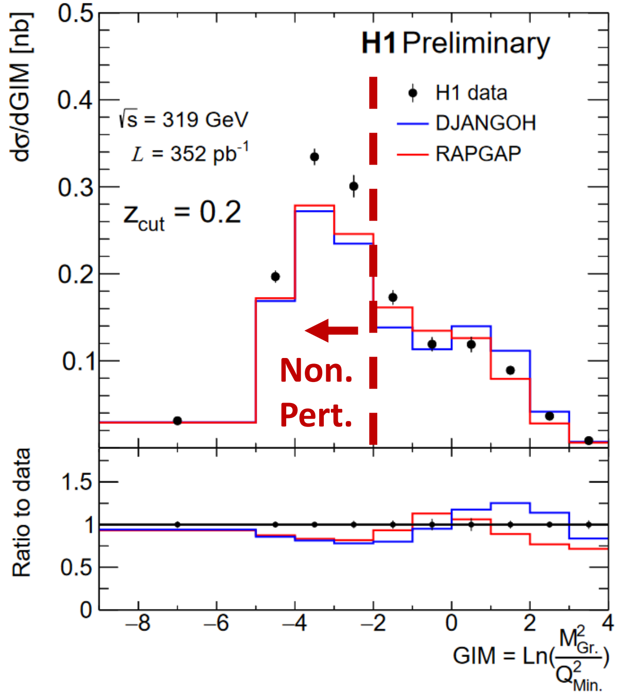
- Groomed Invariant Mass (GIM) $M^2_{Gr.} = (\sum_i p_i^\mu)^2$

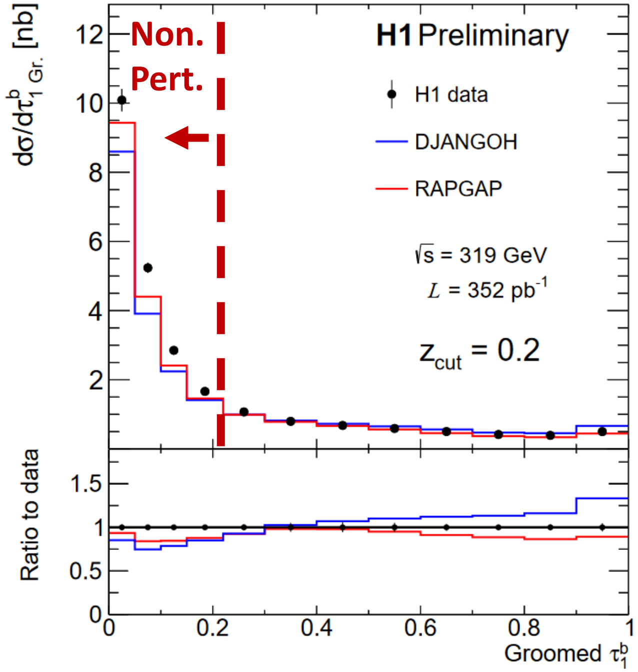
- Groomed 1-Jettiness τ_1^b (analogous to thrust)

$$\tau_1 = \frac{2}{Q^2} \sum_{i\in \text{gr. ent.}} \min(q_B\cdot p_i,\, q_J\cdot p_i)$$

$$\tau_1^b \rightarrow \quad q_J = q + xP, \quad q_B = xP$$

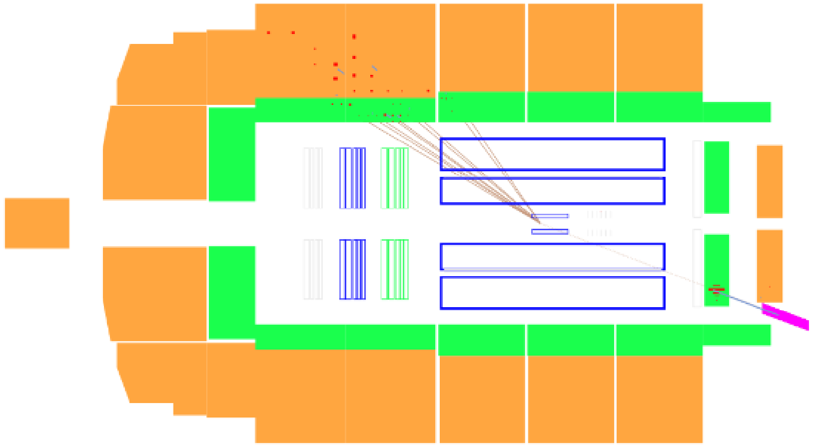


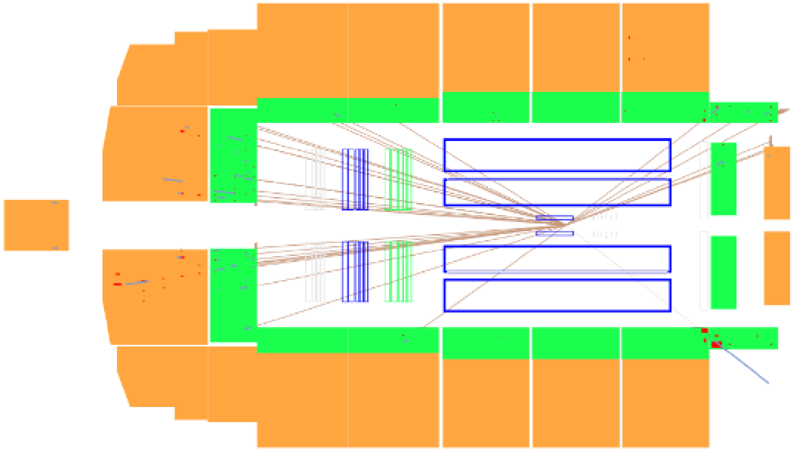




Observables

H1 Event Displays



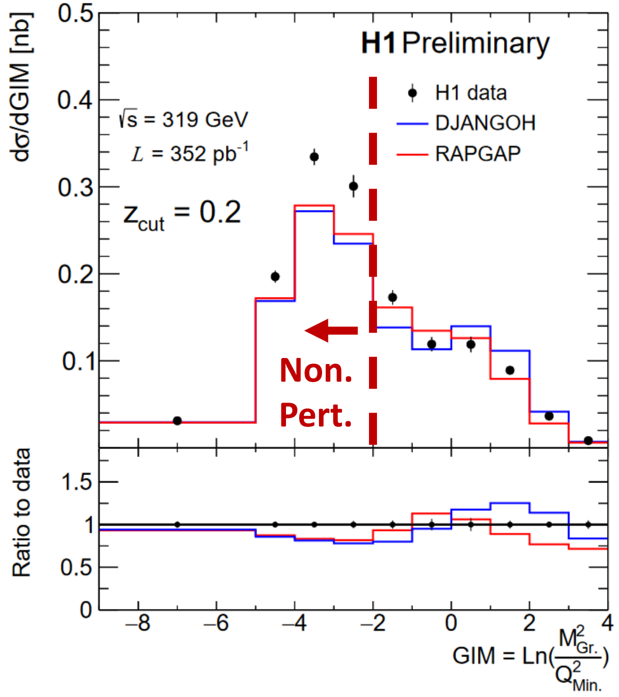


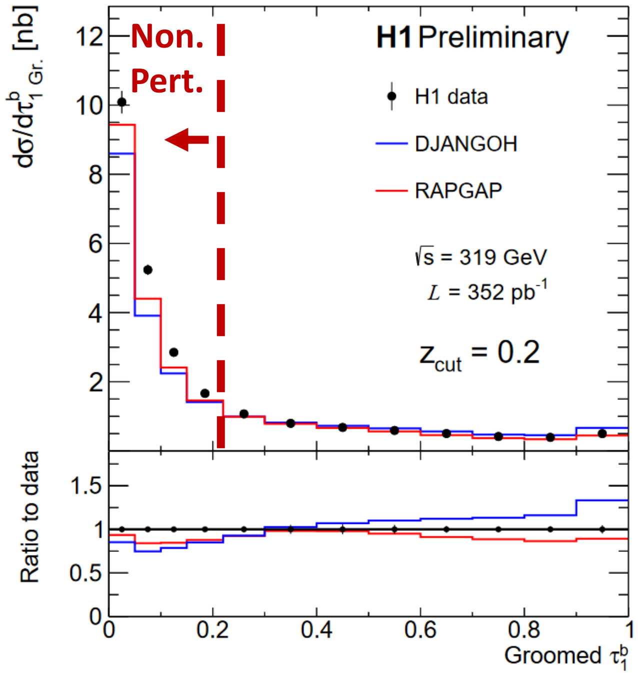
- DIS 1-jet configuration
- Most HFS particles collinear to scattered parton
  → Small τ_1^b
  → Small $M^2_{Gr.}$

- Dijet event
- More and larger contributions to the sum over the HFS
  → Large τ_1^b
  → Large $M^2_{Gr.}$

$$\tau_1 = \frac{2}{Q^2} \sum_{i\in\text{gr. ent.}} \min(q_B \cdot p_i,\, q_J \cdot p_i)$$

$$M^2_{Gr.} = \Big(\sum_i p_i^\mu\Big)^2$$





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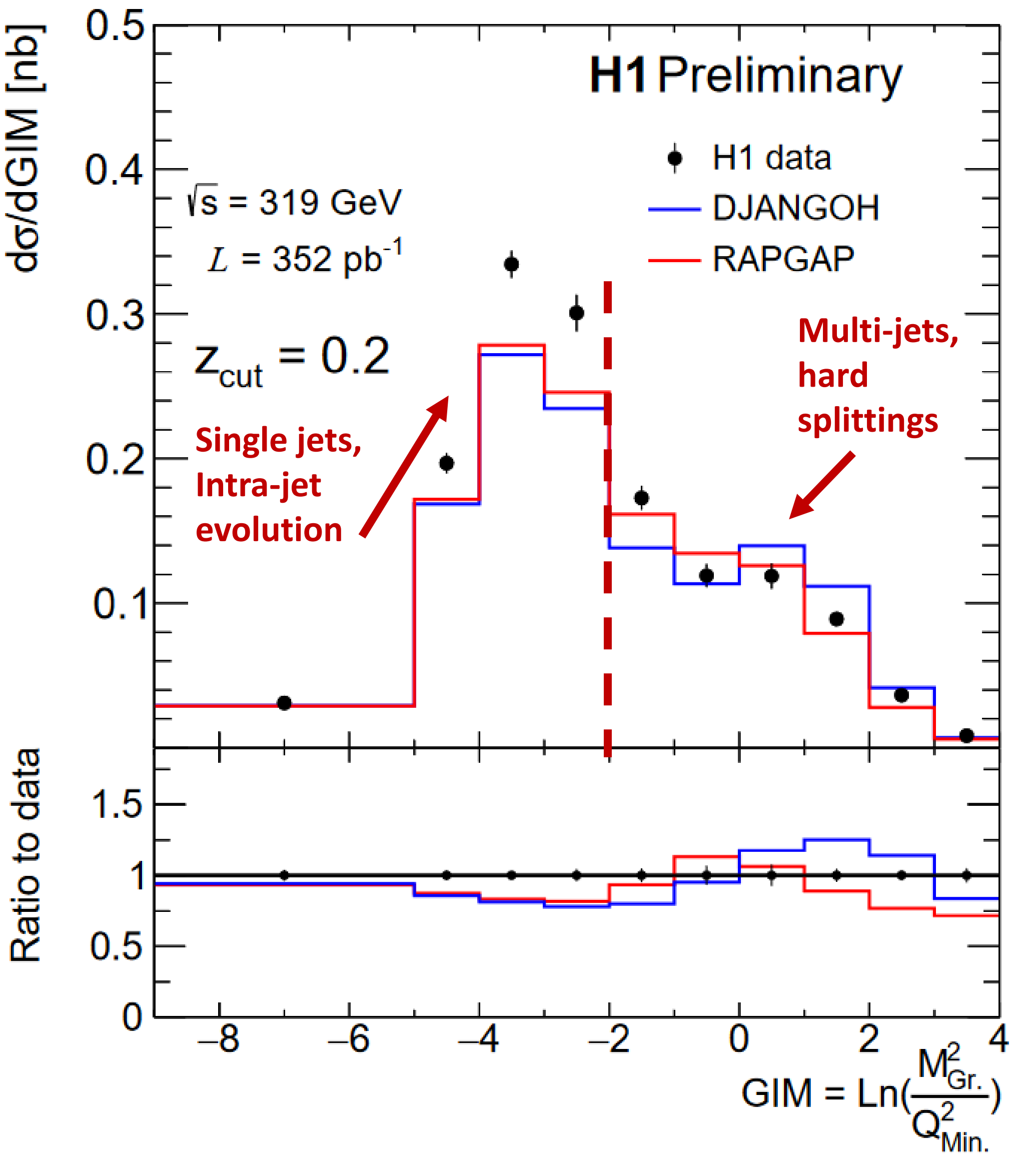
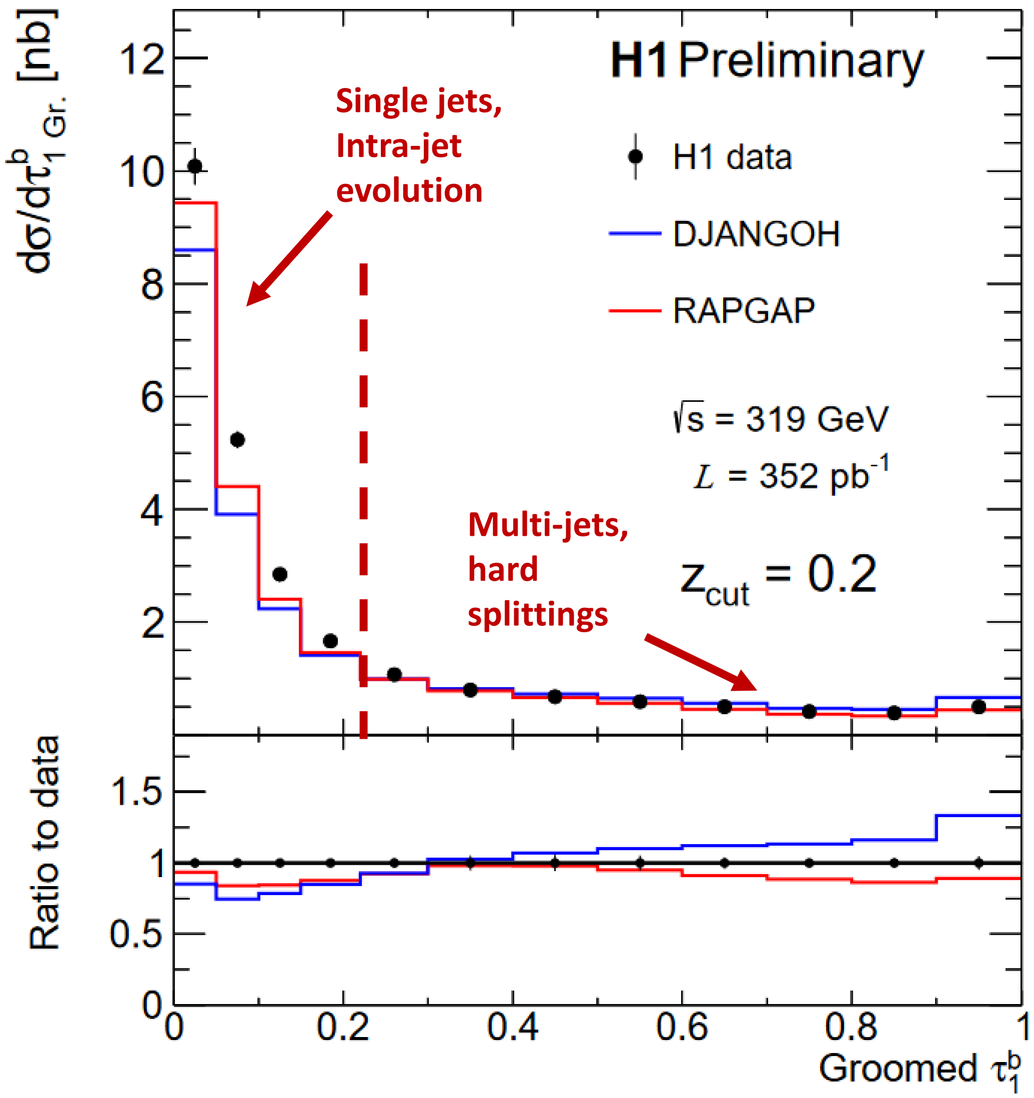


Single jets, Intra-jet evolution

Multi-jets, hard splittings

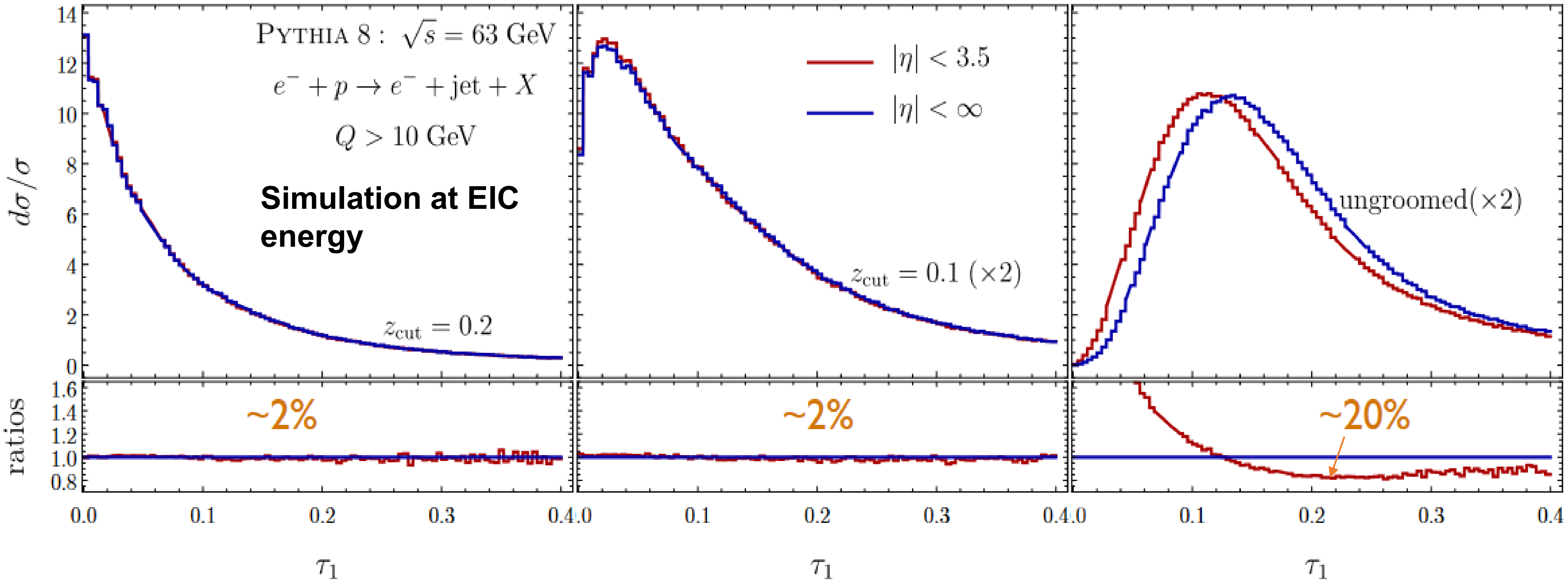


Single jets, Intra-jet evolution

Multi-jets, hard splittings

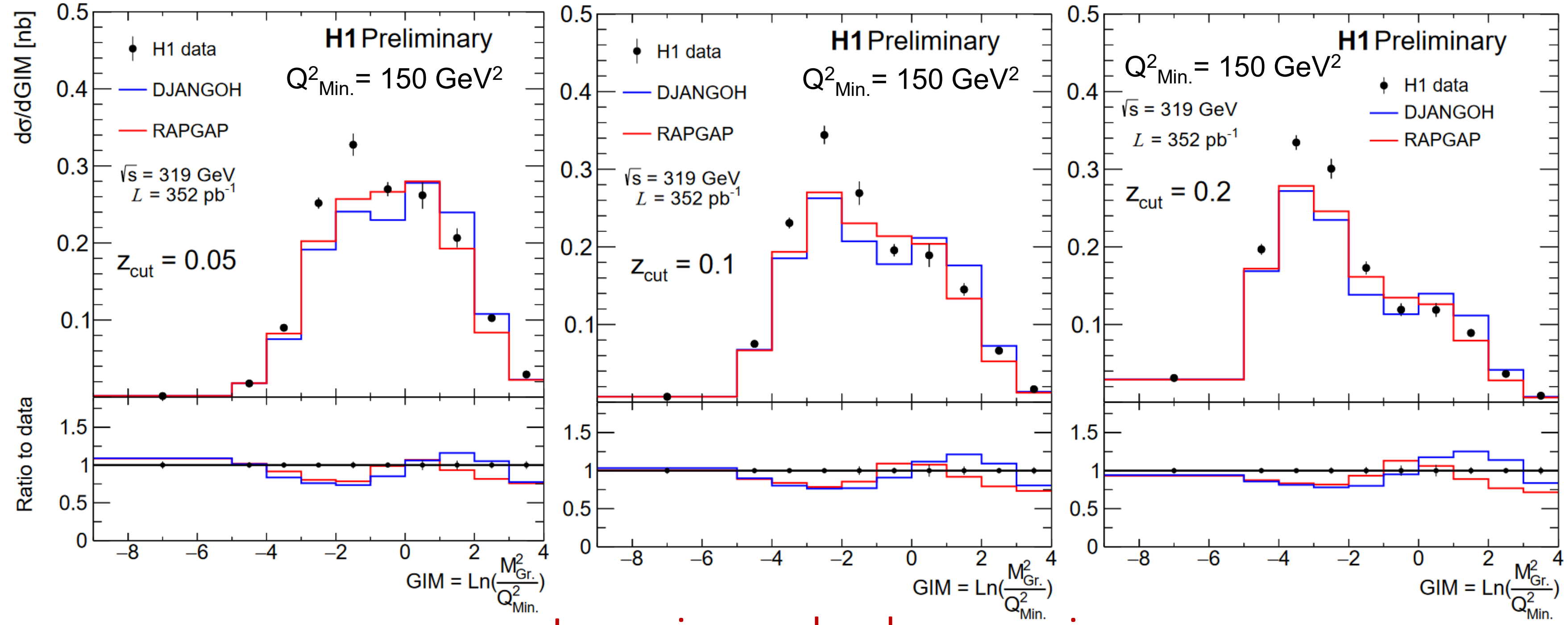
Groomed vs. Ungroomed 1-jettiness

Figure courtesy of Y. Makris

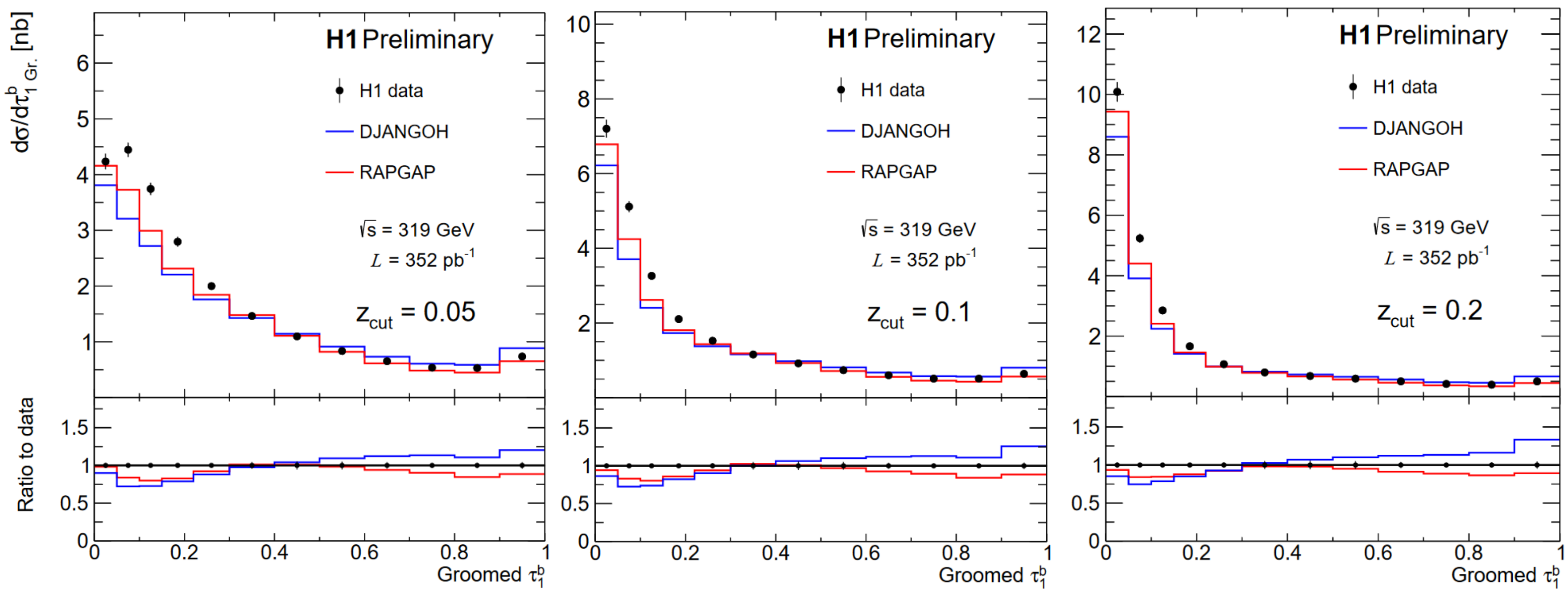


Grooming enables unbiased, precision measurement!

Results



Increasing z_{cut}, harsher grooming



- Data is corrected for real QED ISR and FSR
- Uncertainty on data is statistical ⊕ systematic
  - Dominated by model uncertainty from bin-by-bin correction
- RAPGAP and DJANGOH
  - Standard H1 MCs
  - Both use LEPTO for matrix elements $O(\alpha_S)$
- DJANGOH:
  - Color dipole model PS + string fragmentation
- RAPGAP:
  - DGLAP PS + string fragmentation

Results – Groomed 1 Jettiness

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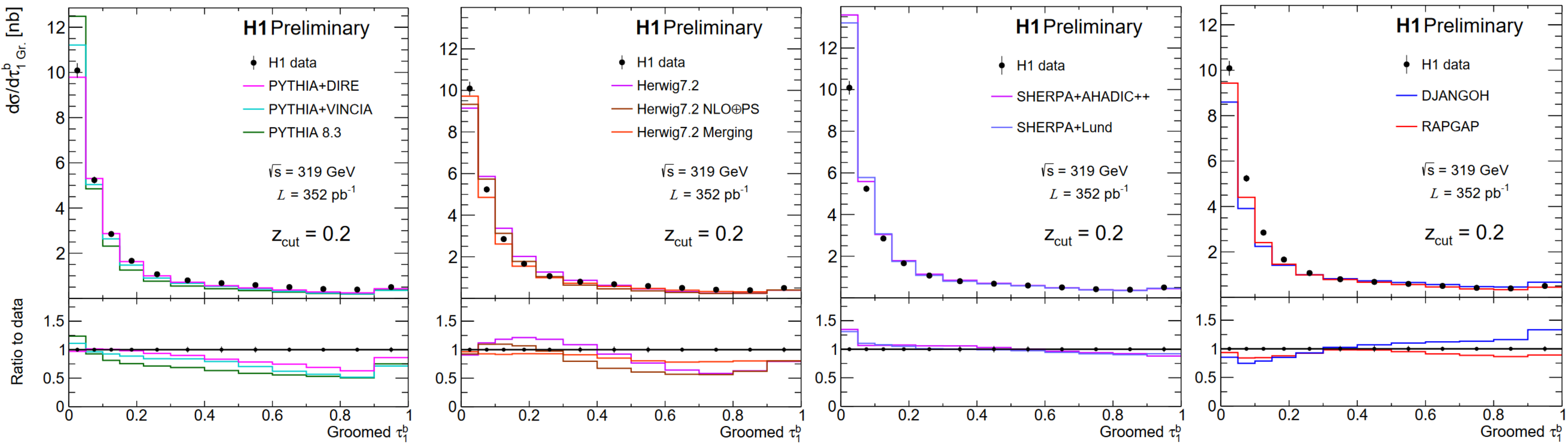
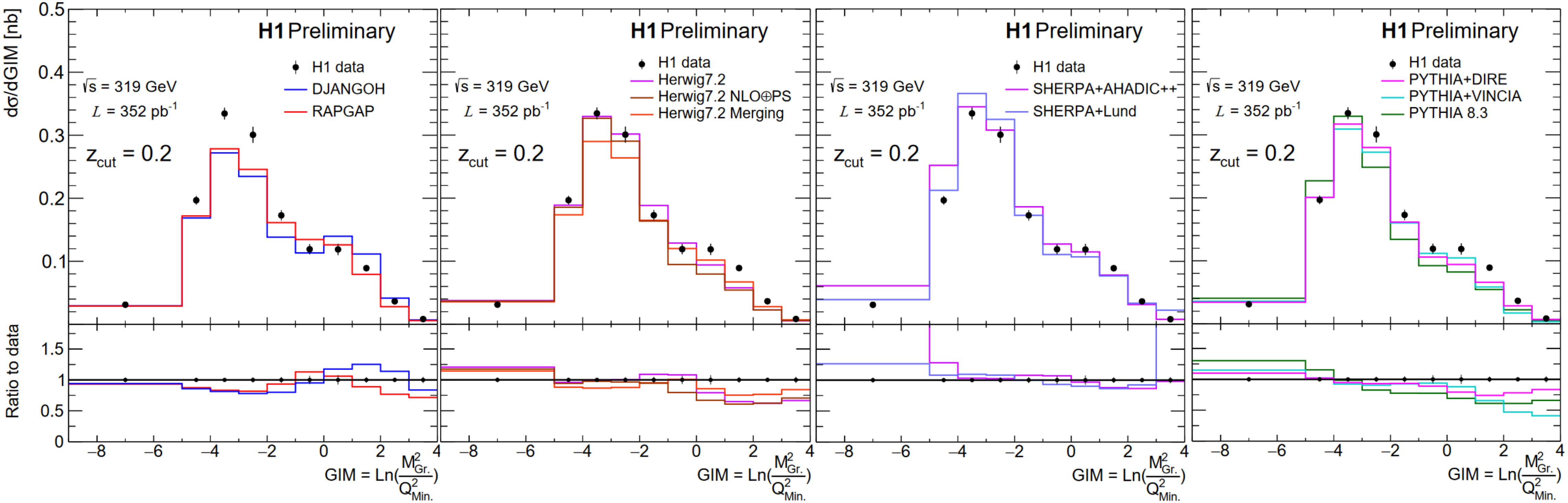


- PYTHIA – Version 8.3
  - VINCIA – Antenna Shower
  - DIRE - Dipole shower + multijet merging
- Herwig – Version 7.2 (Angular-ordered)
  - NLO ⊕PS – AO Shower, subtractive matching
  - Merging - Dipole shower + multijet merging
- SHERPA – Version 2.2.12 (MEPS@NLO)
  - AHADIC++ - Cluster Fragmentation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

Results – Groomed Invariant Mass

$$M^2_{Gr.} = (\sum_i p_i^\mu)^2$$

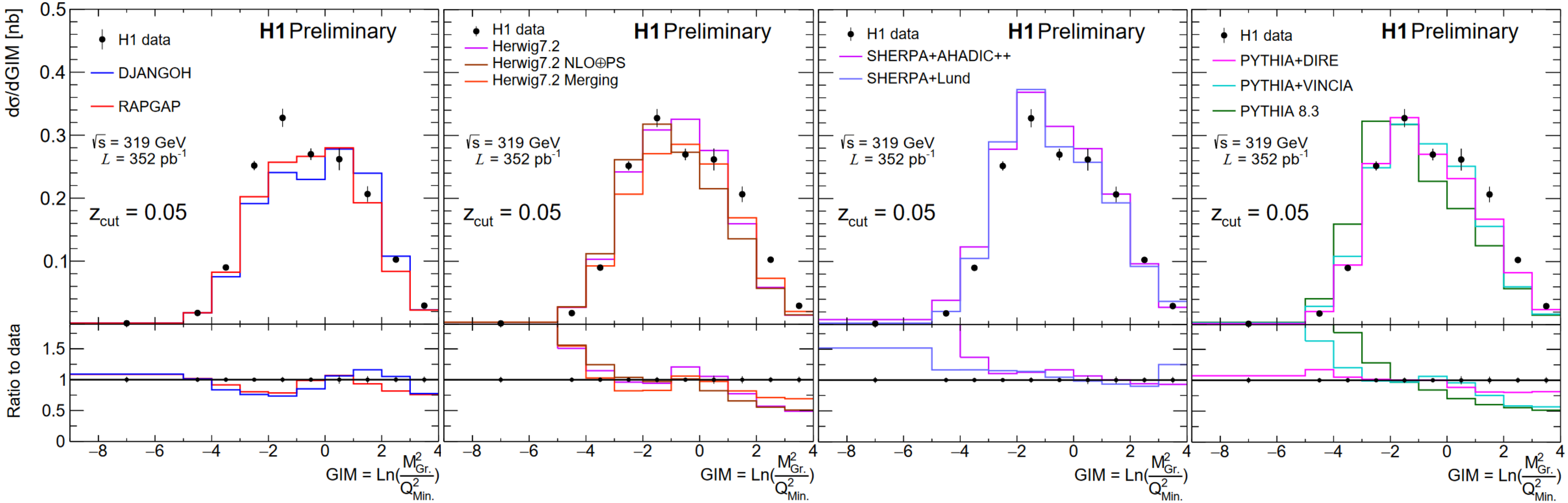


- PYTHIA – Version 8.3
  - VINCIA – Antenna Shower
  - DIRE - Dipole shower + multijet merging
- Herwig – Version 7.2 (Angular-ordered)
  - NLO ⊕PS – AO Shower, subtractive matching
  - Merging - Dipole shower + multijet merging
- SHERPA – Version 2.2.12 (MEPS@NLO)
  - AHADIC++ - Cluster Fragmentation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

- $Q^2_{Min.}$ = 150 GeV²
- Best high mass region from SHERPA
  - Fixed-order, multijets, hard splittings
- Best low mass region from Herwig, DIRE
  - Resummation, parton shower, hadronization

Results – Groomed Invariant Mass

$$M^2_{Gr.} = (\sum_i p_i^\mu)^2$$



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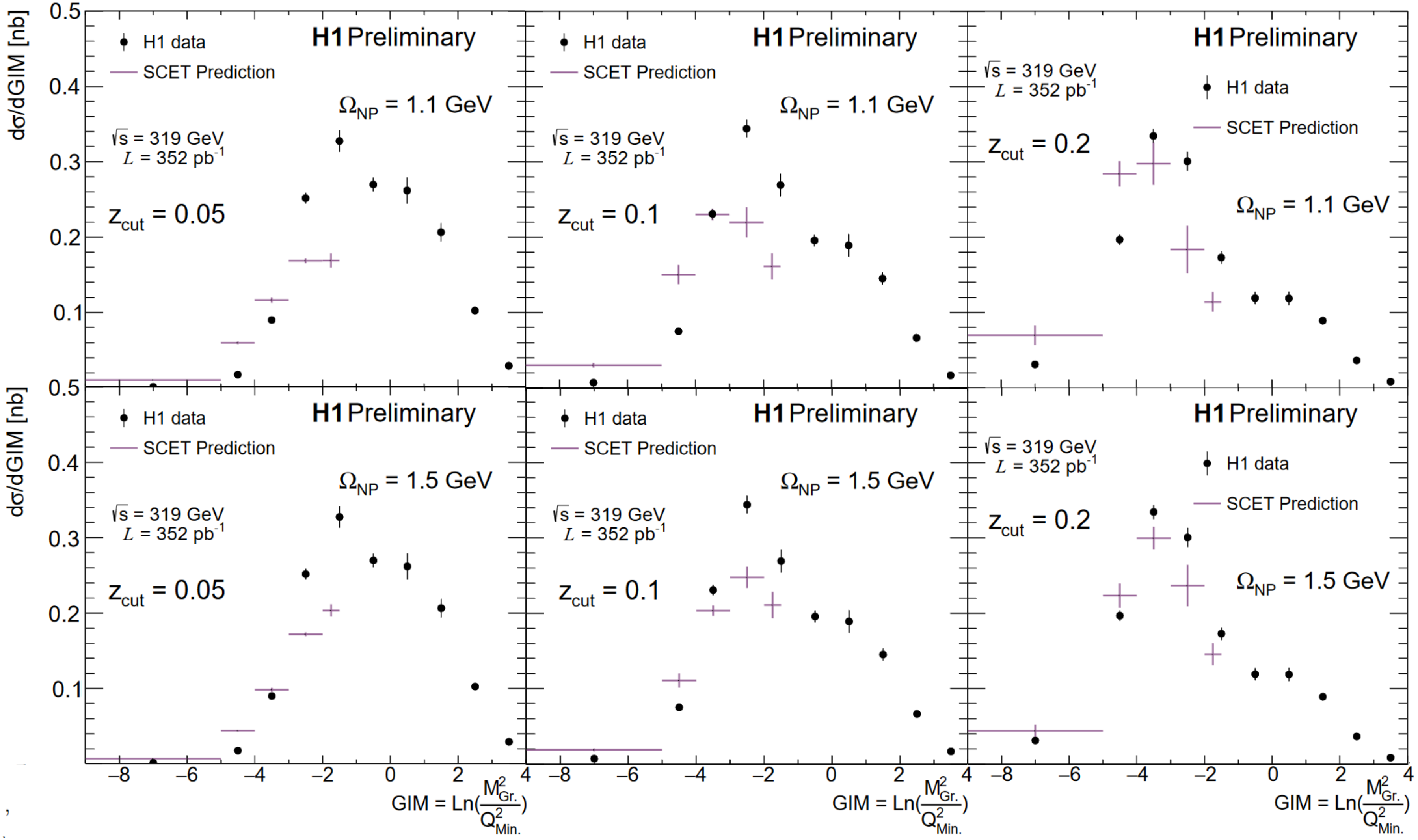
- Generally, predictions become less accurate at lower z_{cut}
  - Less grooming → Less removal of remnant hemisphere radiation
  - Remnant hemisphere is typically less well described by MC models

Results

- Analytic - SCET
  - From Y. Makris [1]
  - Evaluated at two values of Ω_{NP}
    - Shape function mean
  - No fixed-order calculation yet incorporated
- Agreement improves with increasing z_{cut}, Ω_{NP}
  - Non-perturbative effects are significant!
  - Factorization validity improves to higher z_{cut}

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

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

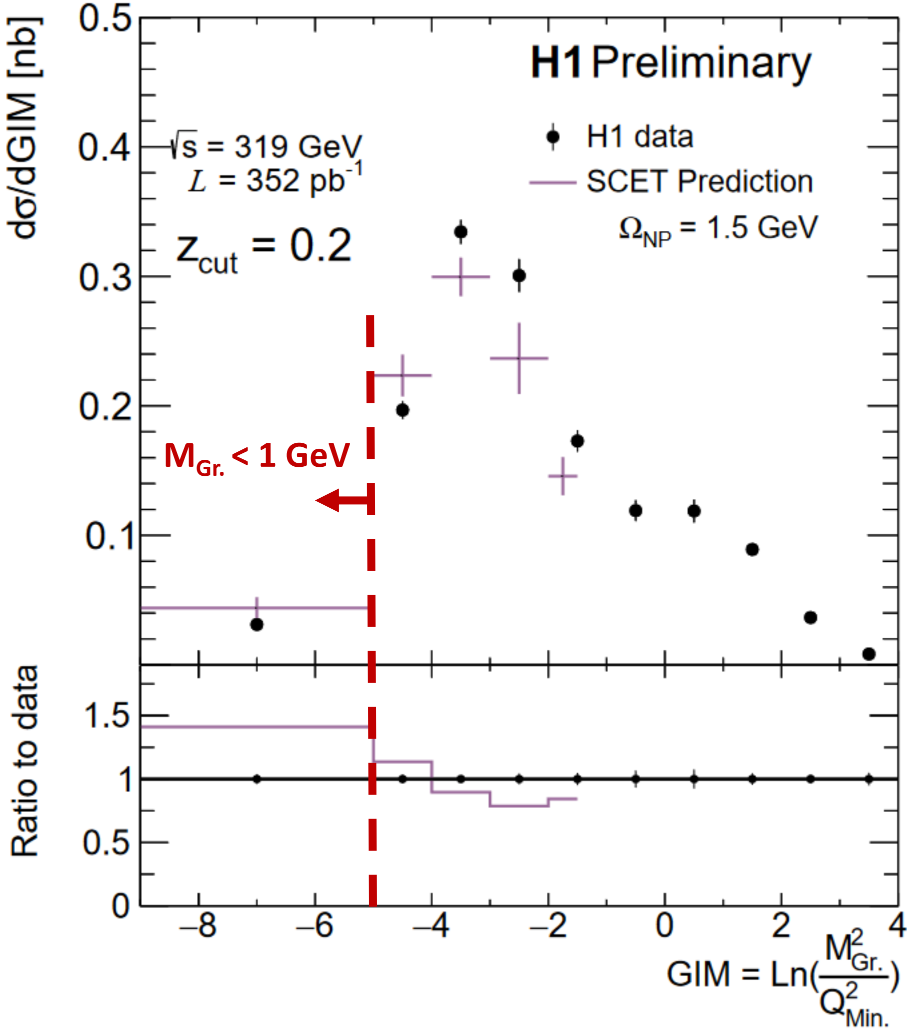


Groomed Invariant Mass - EIC

- At small invariant masses, individual hadron masses play a large role
- Analytic predictions most accurate at small masses, in the region defined by:

$$1 \gg z_{\mathrm{cut}} \gg m^2_{\mathrm{gr.}}/Q^2$$

- EIC will have significant advantages in this region
    - Hadron ID, high statistics
  - More differential measurement possible
  - New theory tools+data for high-precision studies of NP sector



Conclusion

I'm probably out of time so I'll skip the conclusion ☺

Any questions?

Postscript – TMD Breit Frame (WIP)

- The Breit frame is a purely collinear, quark-parton model construct
- In principle, one could improve it by including partonic k_T
  - Remove also parton's intrinsic transverse momentum

- Using this modified Breit frame would break the degeneracy between final-state jet evolution and initial-state effects

- Depends on event-by-event measurement of k_T via lepton-HFS imbalance → very challenging, impossible?