Lepton-Jet Azimuthal Asymmetry in H1 using MultiFold

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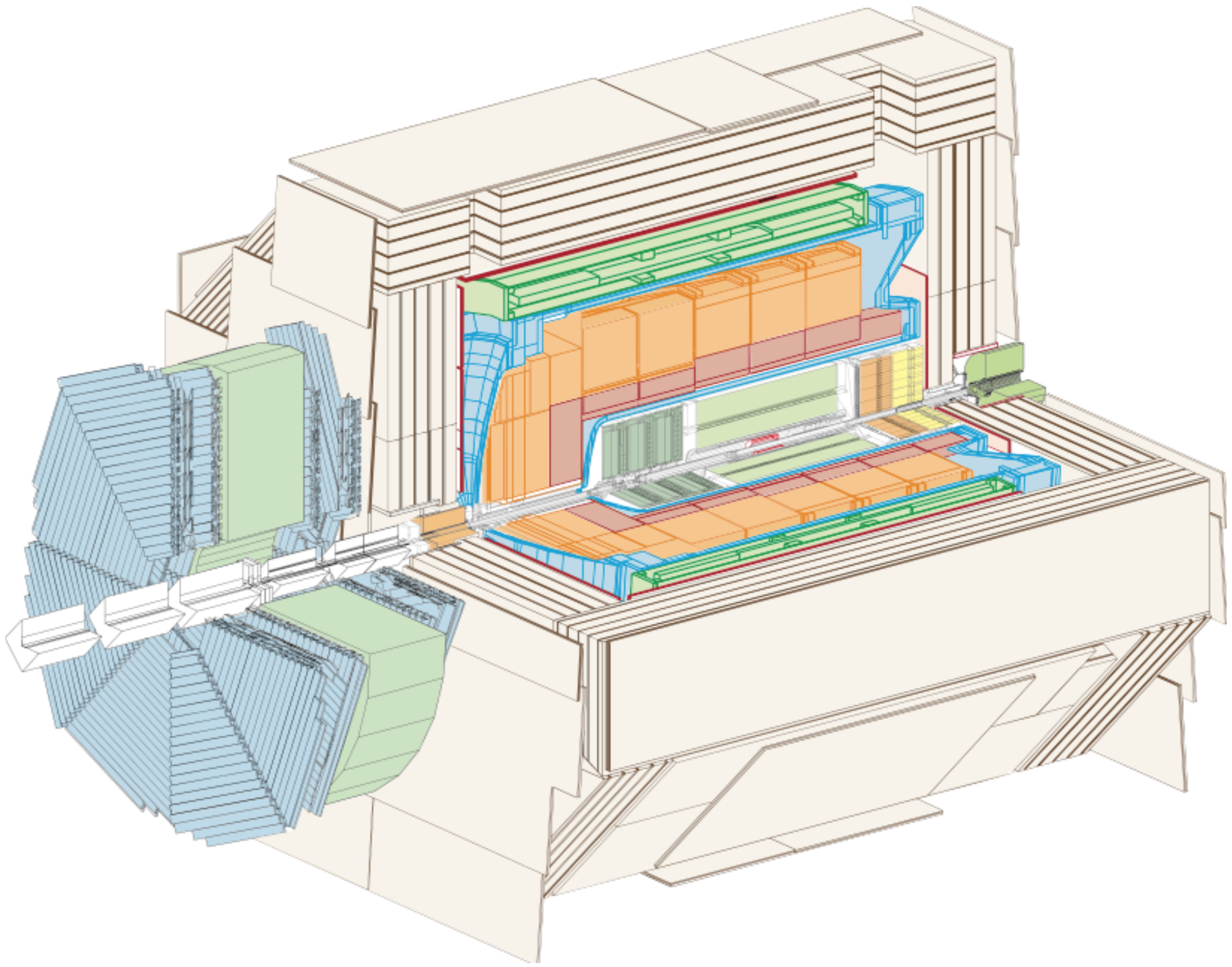
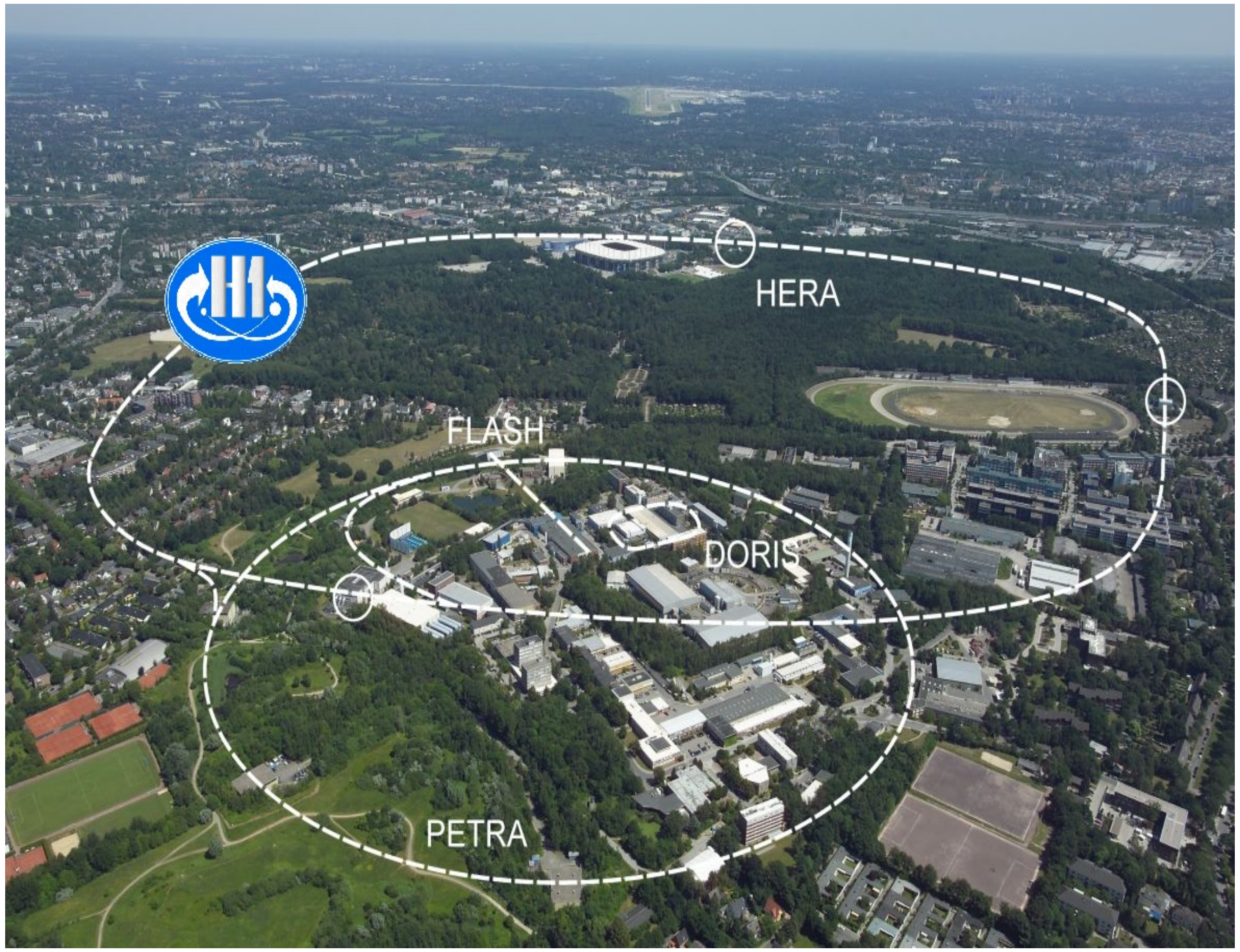
on behalf of the H1 Collaboration

H1 at HERA





- **H1 Detector at the positron-proton collider, HERA. Hosted in Hamburg Germany**
- **Major goal was to study internal structure of the proton through deep inelastic scattering**

$$e(k) + q(p_1) \to e'(k_\ell) + jet(k_J) + X$$

Lepton Jet Asymmetry

Key Ingredients:

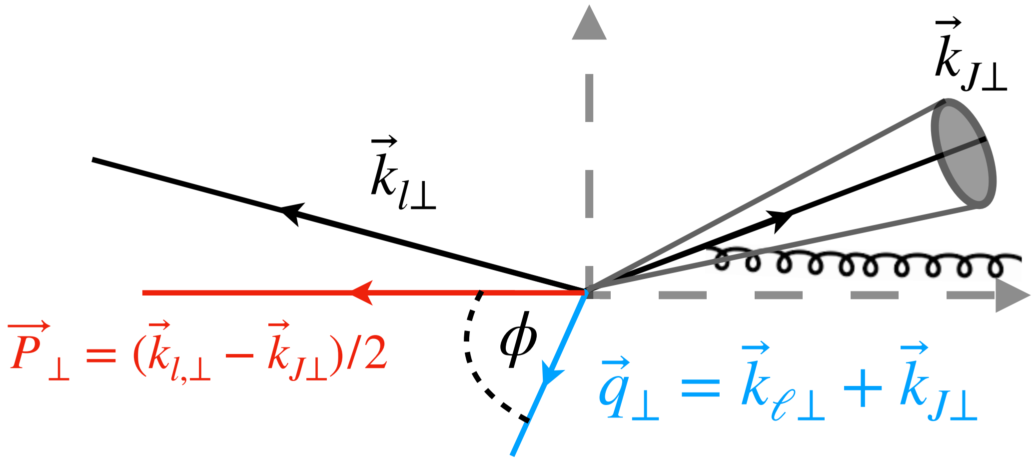
- $q_\perp$ = Total transverse momentum
- $P_\perp$ = Transverse Momentum *Difference*
- ϕ = Angle between $q_\perp$ and $P_\perp$

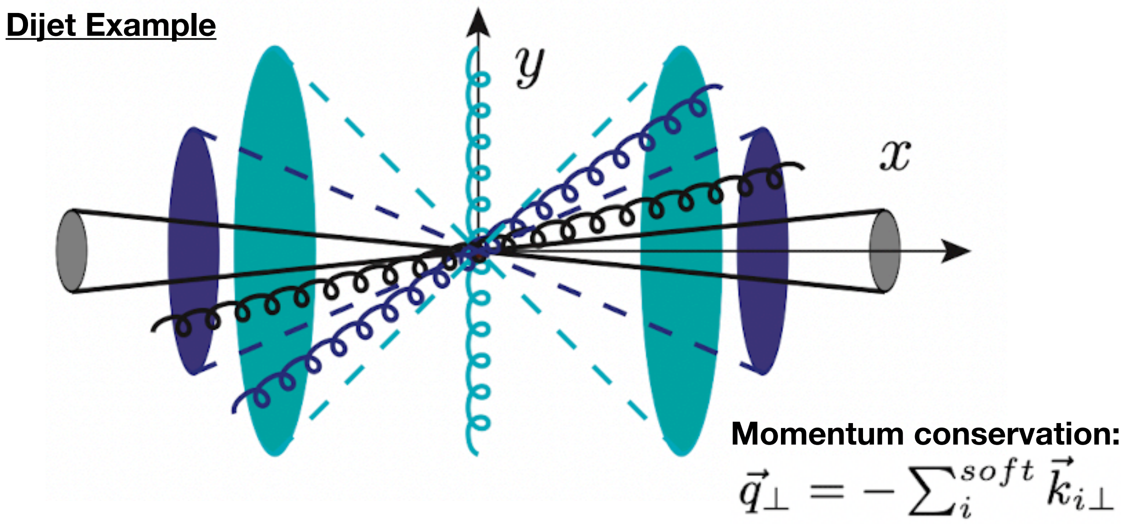
$$\vec{q}_\perp = \vec{k}_{\ell\perp} + \vec{k}_{J\perp}$$

$$\overrightarrow{P_\perp} = (\vec{k}_{\ell\perp} - \vec{k}_{J\perp})\ /\ 2$$

$$\phi = \mathrm{acos}[(\vec{q}_\perp \cdot \overrightarrow{P_\perp})\ /\ |\vec{q}_\perp||\overrightarrow{P_\perp}|]$$

$$\cos(\phi) = (\vec{q}_\perp \cdot \overrightarrow{P_\perp})\ /\ |\vec{q}_\perp||\overrightarrow{P_\perp}|$$





Momentum conservation:

$\vec{q}_\perp = -\sum_i^{soft} \vec{k}_{i\perp}$

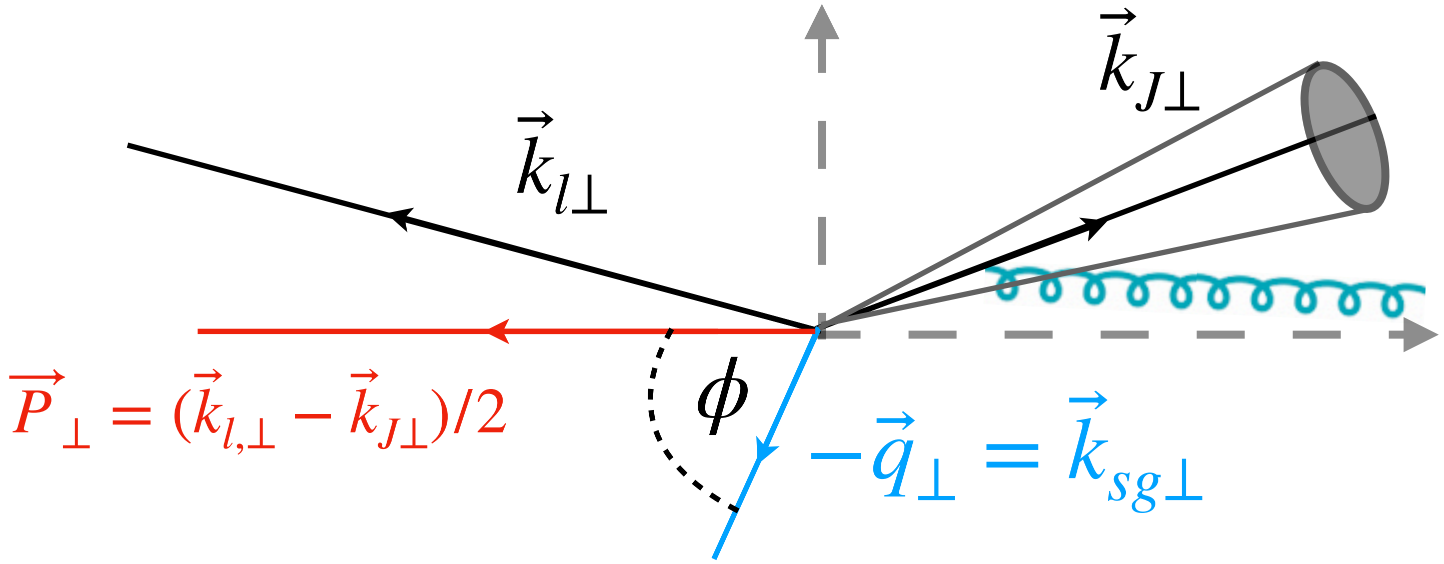
k_i, and therefore $q_\perp$ will tend to point in the direction of the jet

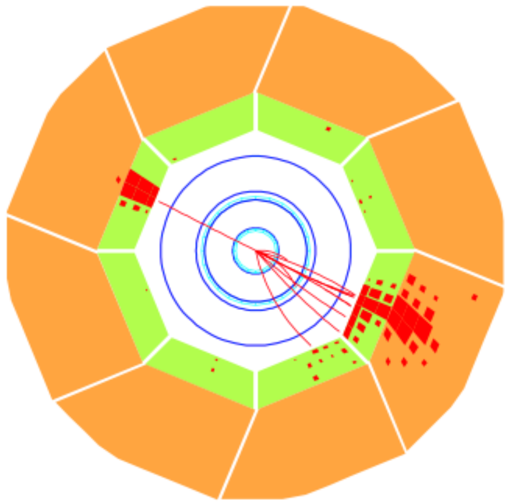
Darker colors indicate probability of gluon emission

Lepton Jet Measurement

Description

- Final state lepton and jet are mostly back-to-back
  - Significant interest in studying transverse momentum dependent (TMD) parton distributions
- Total transverse momentum of the outgoing system $\vec{q}_\perp = \vec{k}_{\ell\perp} + \vec{k}_{J\perp}$, is typically *small but nonzero*
- Imbalance can come from perturbative initial and final state radiation
  - e.g. Emission of soft gluon with momentum $k_{\perp g}$
  - unrelated to TMDs or intrinsic transverse momentum of target gluons
- Depending on kinematics, soft gluon radiation can dominate
  - $P_\perp \gg q_\perp$
  - Radiative corrections enhanced approximately as $(\alpha_s \ln^2 P_\perp^2/q_\perp^2)^n$





$e(k) + q(p_1) \to e'(k_\ell) + jet(k_J) + X$

Physics Motivation

1. Probes soft gluon radiation $S(g)$
   - Soft gluon radiation can be the primary contribution to asymmetry for certain kinematics
     - Hard gluon radiation is present, but is power suppressed

2. Asymmetry is perturbative
   - Opportunity to compare unfolded H1 data to soft gluon resumption
   - Precision measurements of QCD
     1. α_s, as well as relevance to various jet measurements

3. May represent a vital reference for other signals, in particular TMD PDF measurements
   - In TMD factorization framework, one can factorize contributions from transverse momentum dependent (TMD) PDFs and Soft gluon radiation

4. Observable is sensitive to gluon saturation phenomena, possibly measurable at the EIC

H1 Data

- Same data / selection / unfolding as arXiv:2108.12376
  - “Measurement of lepton-jet correlation in deep-inelastic scattering with the H1 detector using machine learning for unfolding”

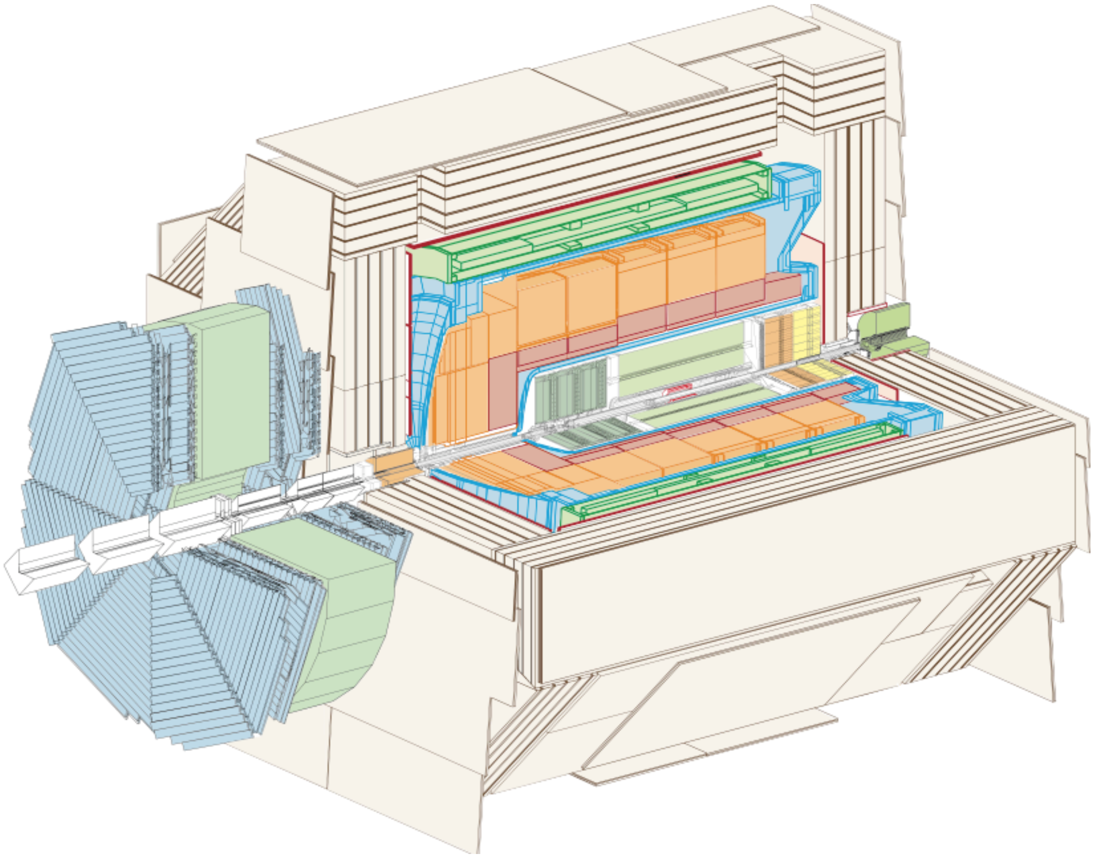
- H1 Data from 2006 and 2007 periods at 130 pb^{-1}
  - Positron-proton collisions

- Fiducial Cuts:
  - $0.2 < y < 0.7$
  - $Q^2 > 150\ \mathrm{GeV}^2$
  - $p_T^{\mathrm{jet}} > 10\ \mathrm{GeV}$
  - $-1 < \eta_{\mathrm{lab}} < 2.5$
  - $\mathrm{k_T}, R = 1.0$
  - $q_\perp/Q < 0.25$
  - $q_\perp/p_{\mathrm{T},jet} < 0.3$

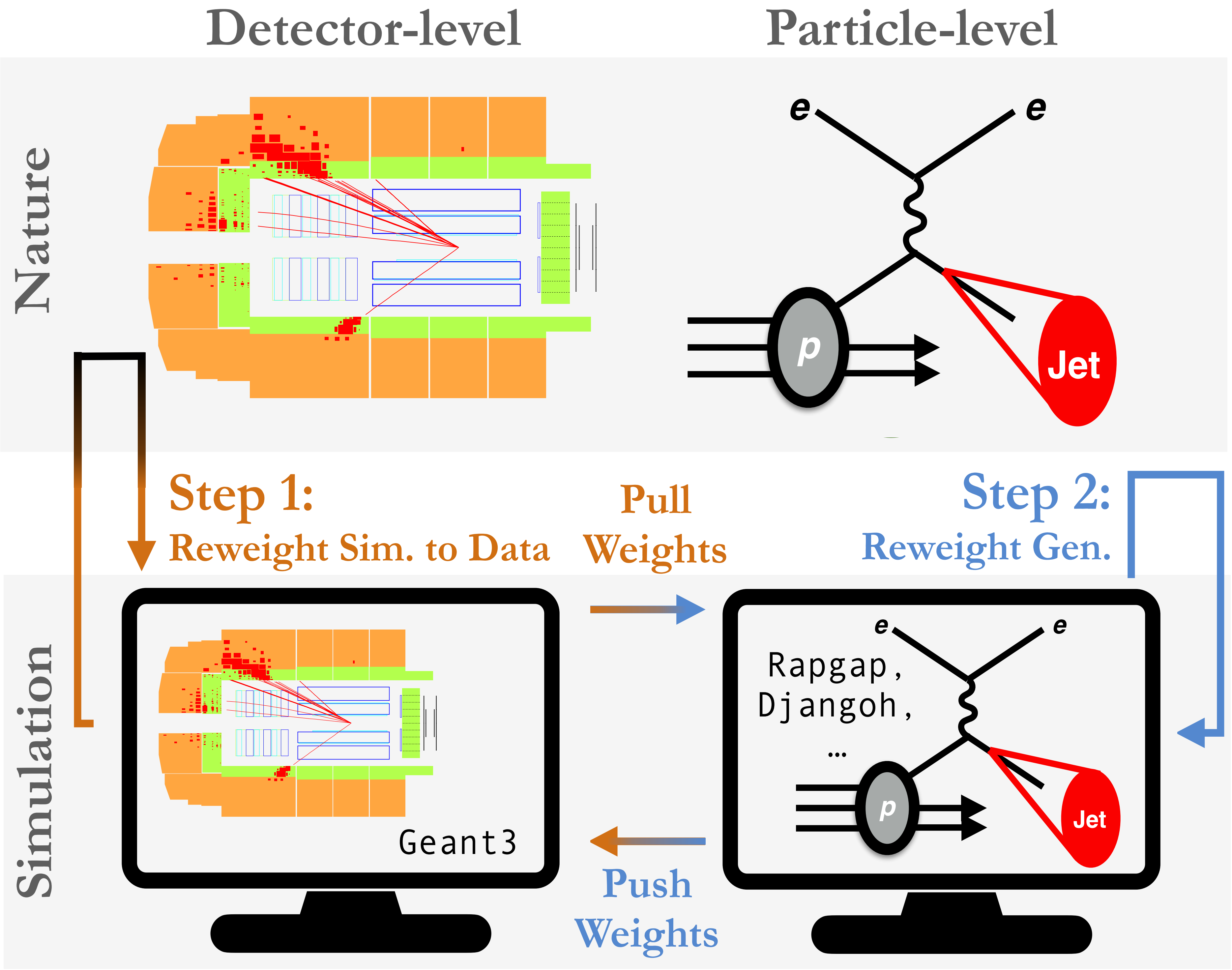
Taking the *leading jet*

Cut on $q_\perp/p_{\mathrm{T},jet}$ to satisfy $P_\perp \gg q_\perp$:

$$p_{\mathrm{T,jet}} \approx P_\perp/2$$



MultiFold



2 step iterative approach

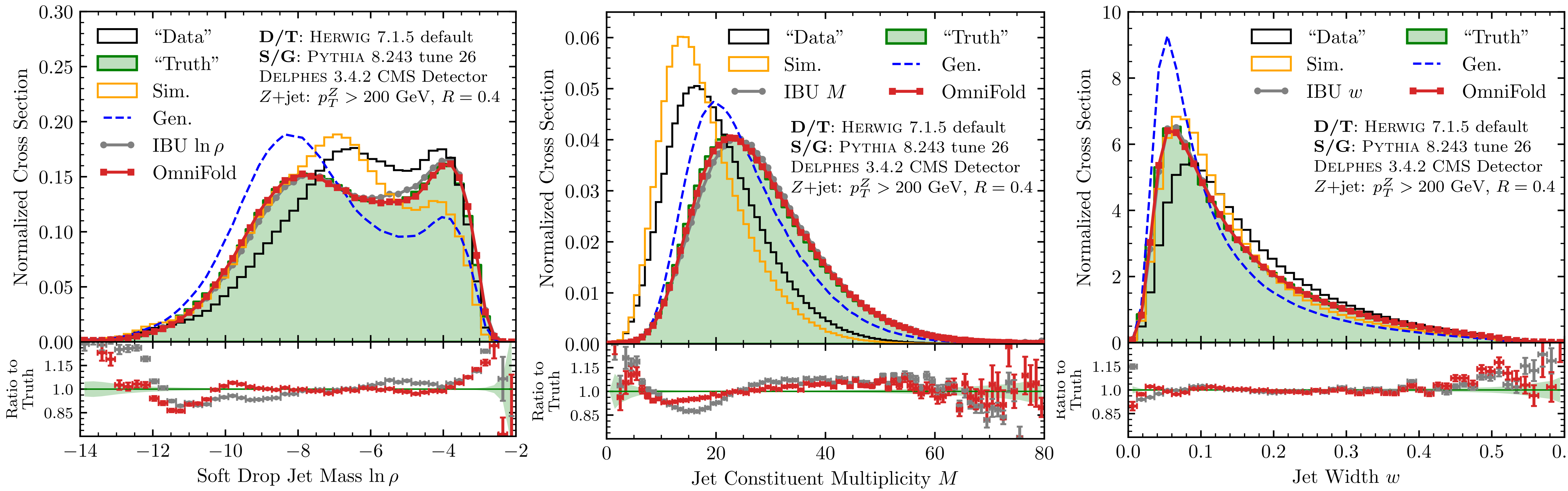
- Simulated events after detector interaction are re-weighted to match the data
- Create a "new simulation" by transforming weights to a proper function of the generated events

Machine learning is used to approximate 2 likelihood functions:

Reco MC to **Data** reweighting

Previous and **new Gen** reweighting

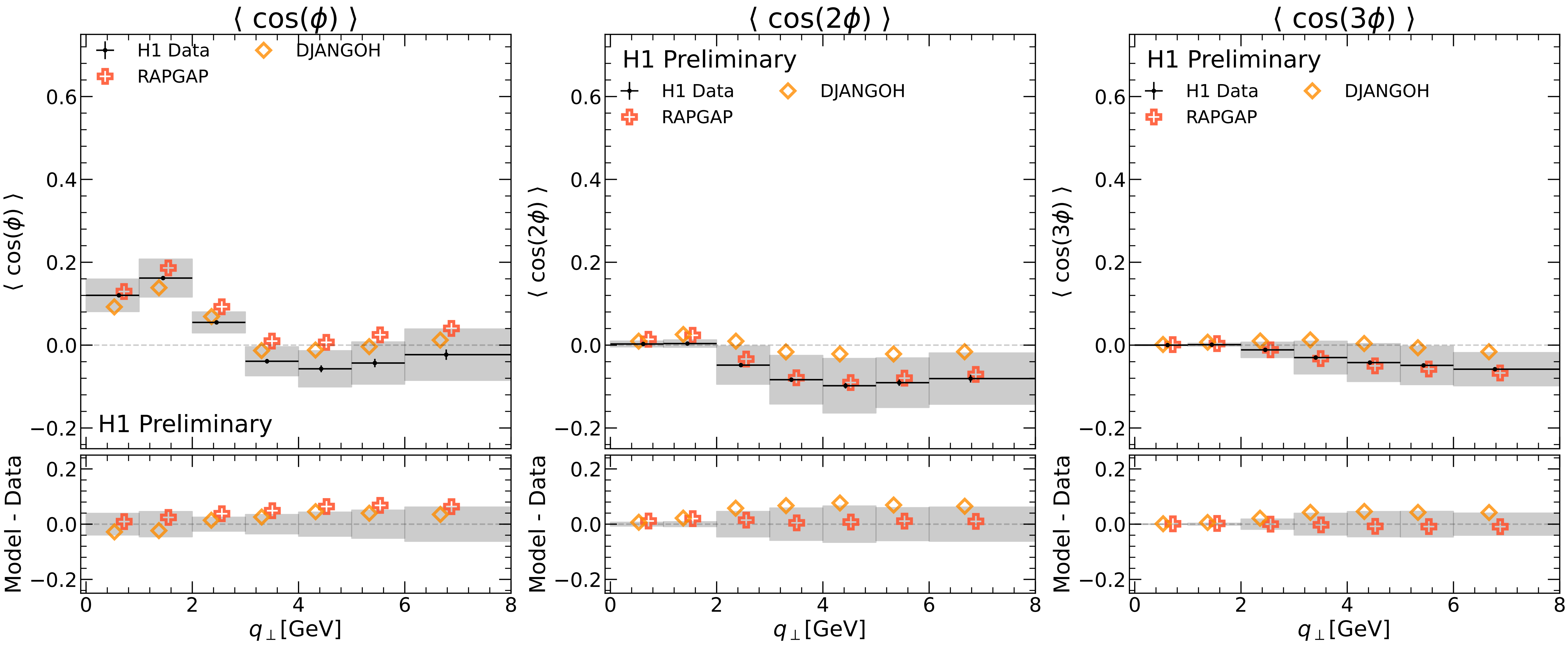
MultiFold Example



arXiv:1911.09107

Generalization the widely studied bayesian iterative unfolding approach
Does not inherently depend on the accuracy of particle-level simulation

H1 Unfolded Data



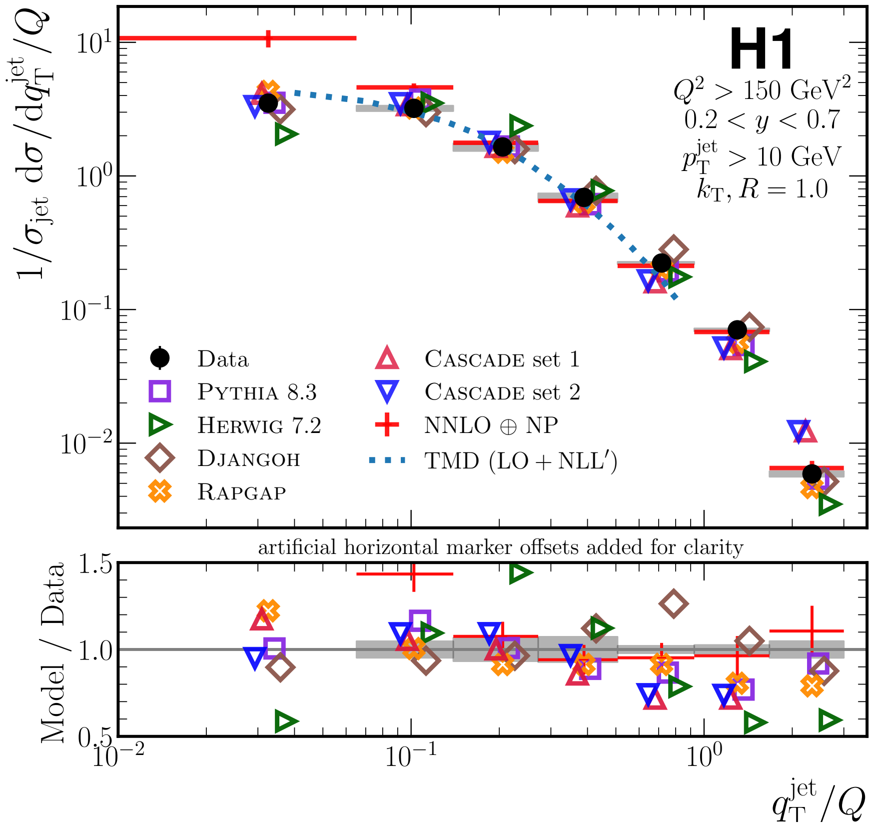
- Leading moment is $\langle \cos(\phi) \rangle$, expected in lepton-jet events
- All harmonics approach 0.0 at higher $q_\perp$, *may* compromise $P_\perp \gg q_\perp$
- Rapgap and Django, tuned to HERA II data, exhibit good agreement
- Note *small absolute* value of central values

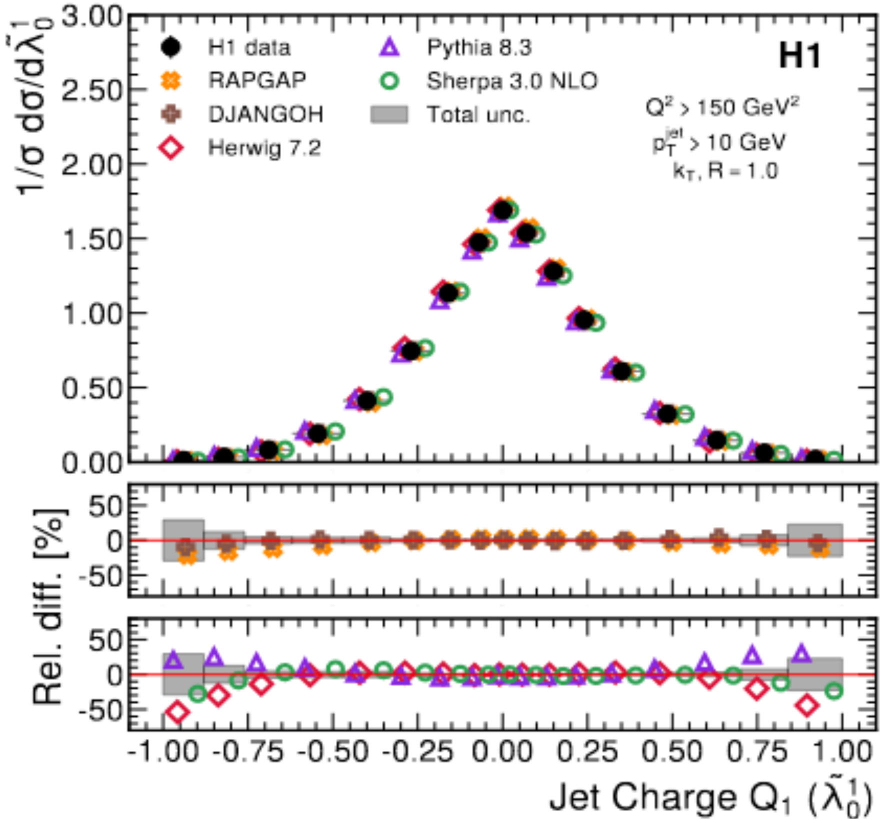
ML Unfolding Motivations

- Multi-dimensional, un-binned unfolding result
  - Lepton-Proton momentum imbalance
  - PhysRevLett.128.132002

- Jet constituent-level unfolding
  - Unbinned Deep Learning unfolding of Jet Substructure

- Recycling of unfolded event weights

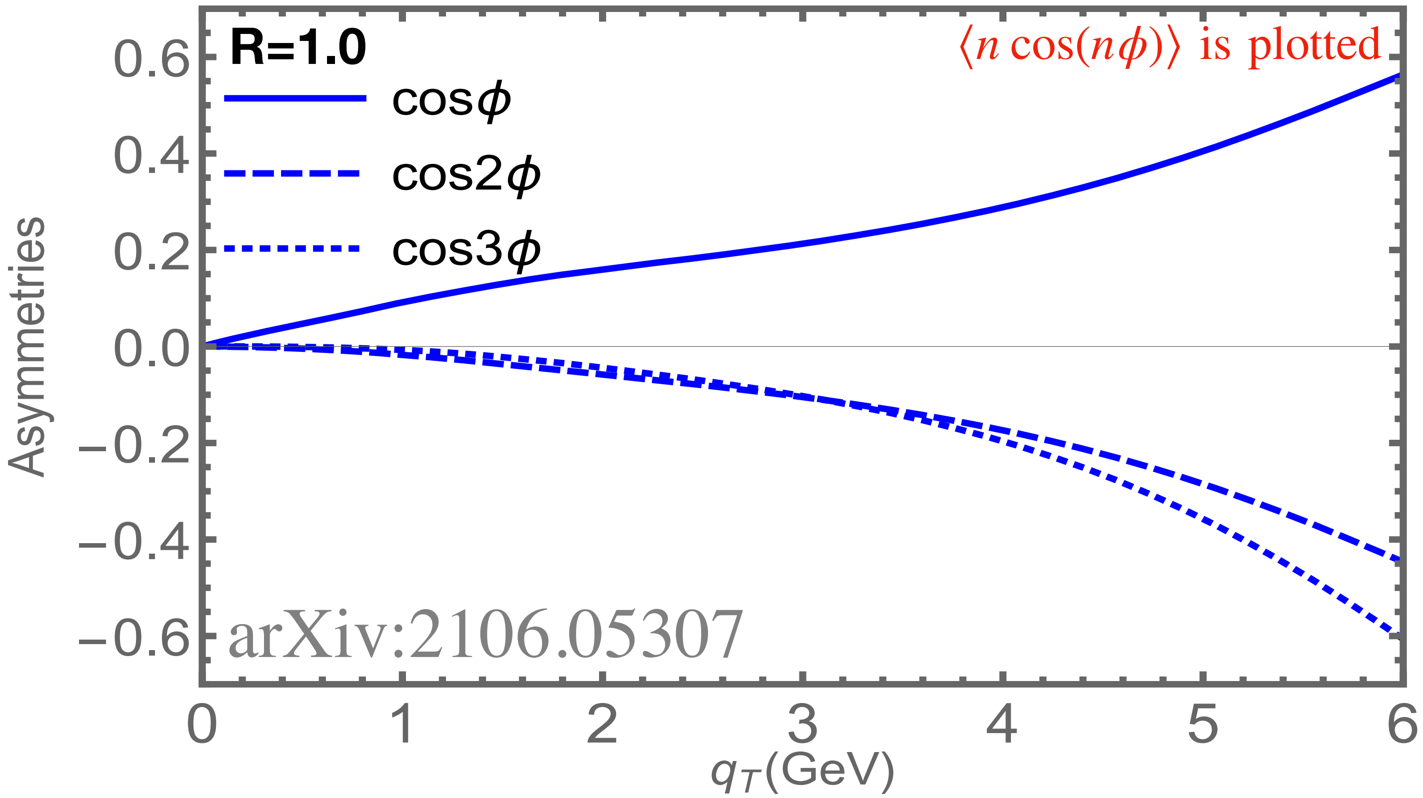




Multifold already used to unfold:

p_x^e, p_y^e, p_z^e, p_T^{jet}, η^{jet}, ϕ^{jet}, $\Delta\phi^{jet}$, q_T^{jet}/Q

Two Sets of Calculations (Compare 2nd)



arXiv:2106.05307

$$\vec{q}_\perp = \vec{k}_{\ell\perp} + \vec{k}_{J\perp}$$

$$\overrightarrow{P_\perp} = (\vec{k}_{\ell\perp} - \vec{k}_{J\perp}) / 2$$

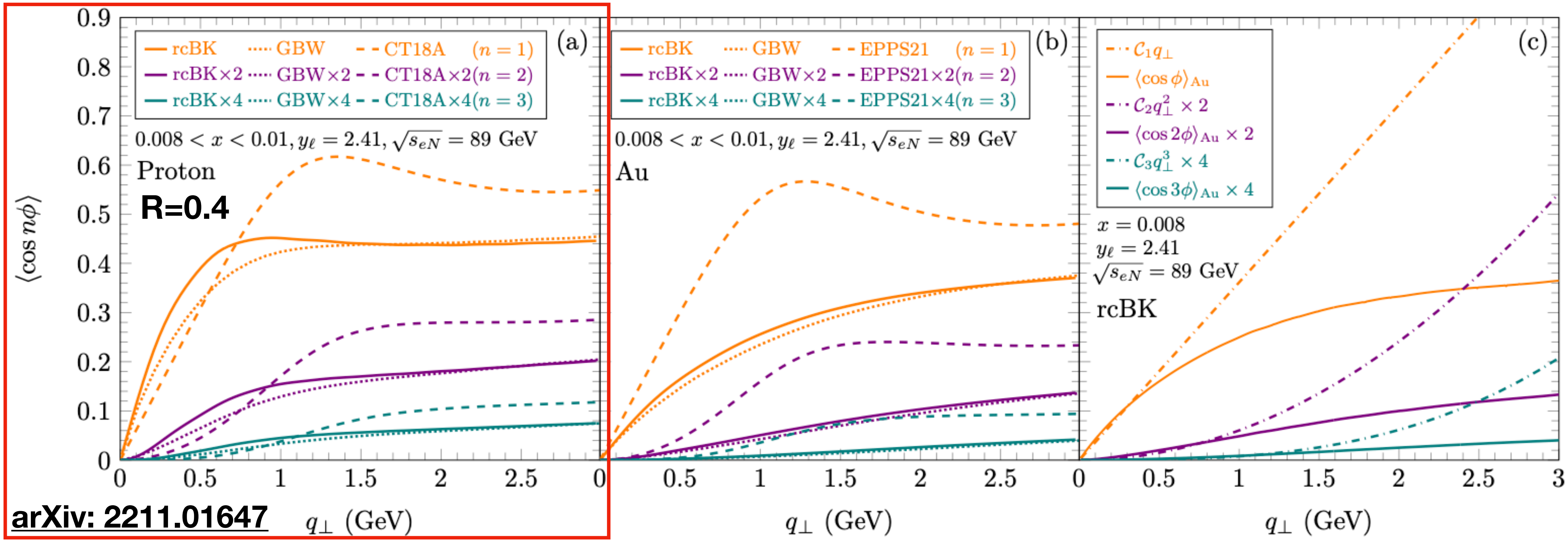
$\sqrt{s}$ =140 GeV, $P_\perp$ = 20 GeV,

y_l = 1.5, Q = 25 GeV

Radiative corrections

enhanced $\propto (\alpha_s \ln^2 P_\perp^2/q_\perp^2)^n$

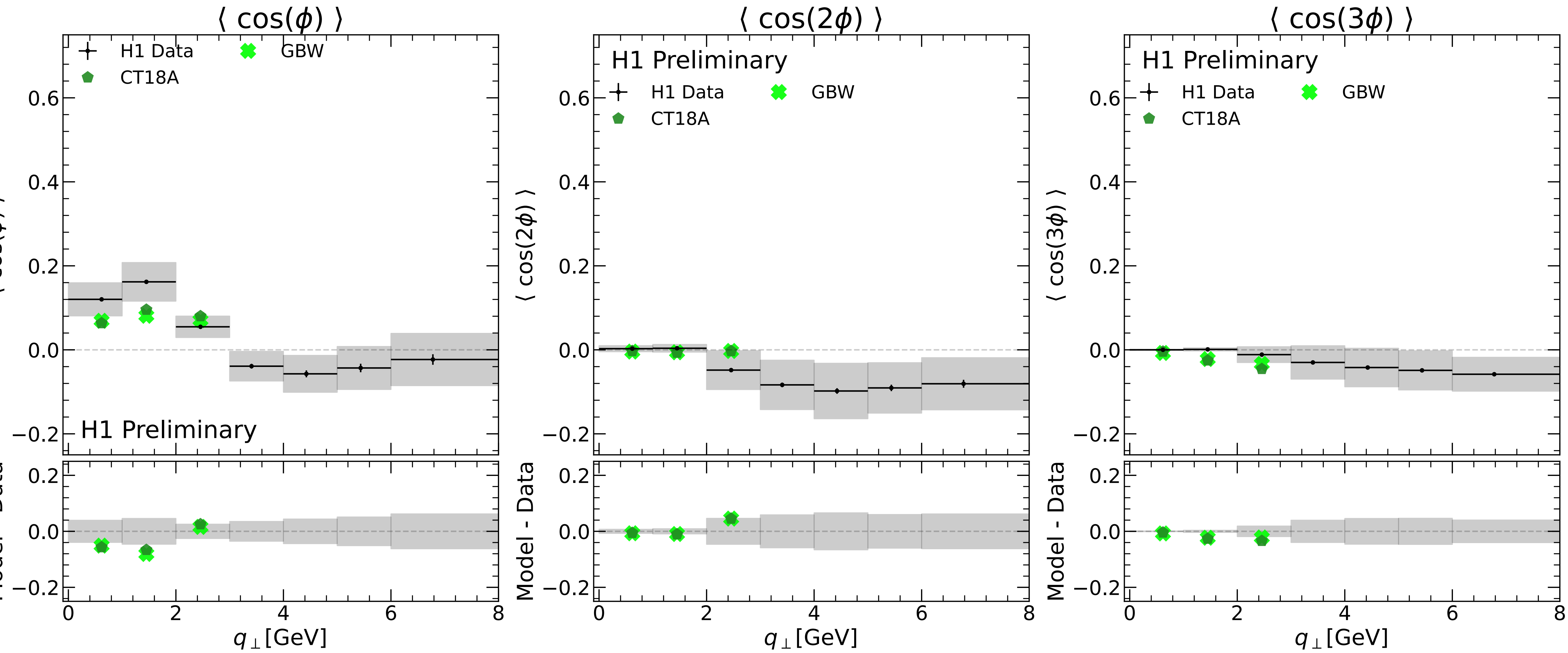
Soft Gluon Resummation



arXiv: 2211.01647

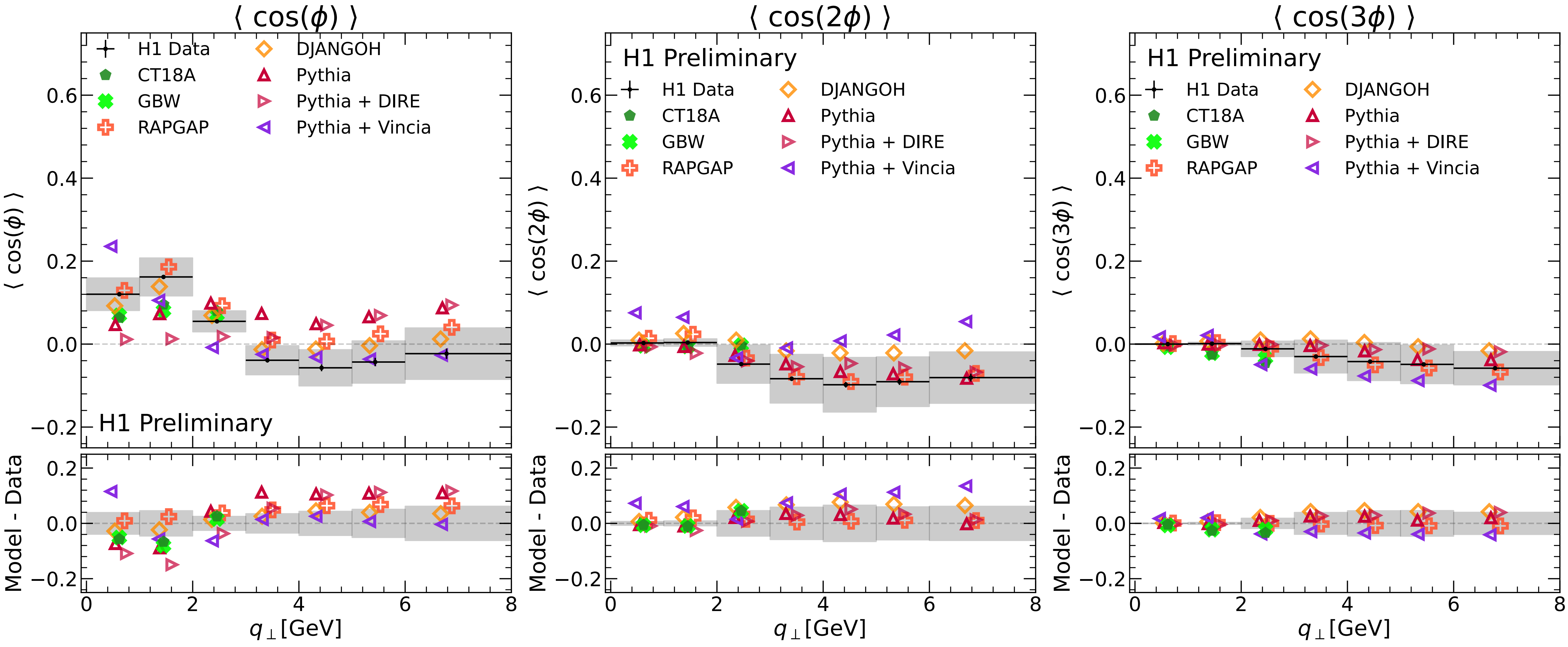
Harmonics of saturation with inputs from *GBW* model and CT18A PDF

H1 Unfolded Data



- **Note: Calculations done $q_\perp \leq 3.0$ GeV**
- **Differences could be due to sample bin average within the fiducial cuts**
- **CT18A is also a TMD calculation, disagreement could also be in kinematics constraints**

H1 Unfolded Data



- **Three harmonics of the azimuthal angular asymmetry between the lepton and leading jet as a function of $q_\perp$.**
- **Predictions from multiple simulations as well as a pQCD calculation are shown for comparison.**
- **PYTHIA, not tuned to HERA II, performs inconsistently**

Conclusions

- Promising measurement to probe soft gluon radiation
  - Important reference for lepton-jet DIS measurements!
  - Test of pQCD calculations
  - Comparison to 3 generators, agree within $q_\perp < 2.0$ GeV

- MultiFold
  - First recycling of unfolded event weights! Reusability is a key advantage of MultiFold
  - This work presents a measurement of *moments*, requiring the *unbinned unfolding!*
  - Model bias may be due regularized unfolding procedure (i.e. IBU may exhibit similar bias)

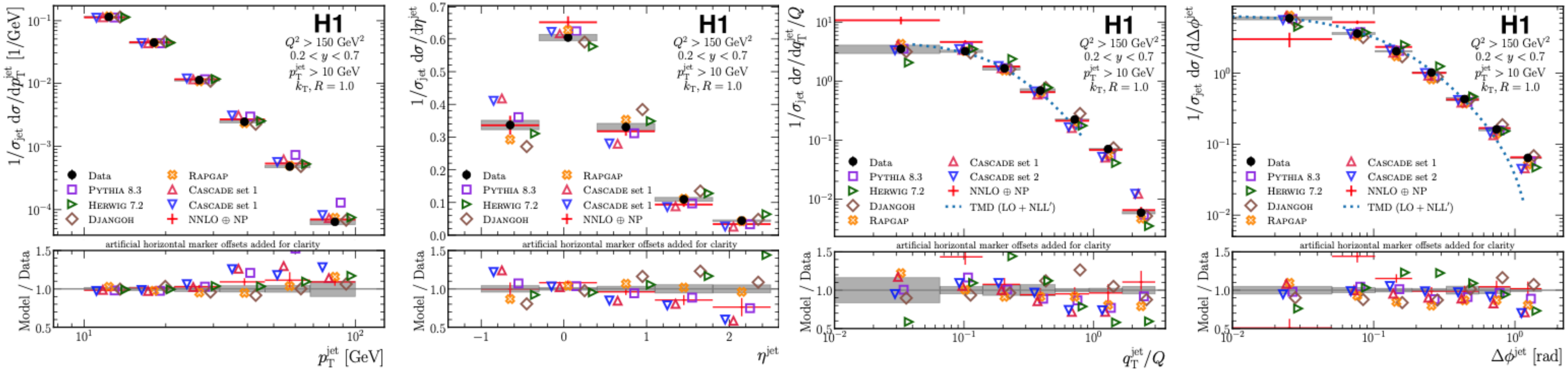
- Outlook:
  - Because of H1's fantastic data and simulation conservation, we can use recent insight and advances in methodology to analyze 15 year old data
  - Important Implications for studies at EIC, both in observable and methods

END

Backup

Backup Further Background

- Machine learning (OmniFold) is used to perform an 8-dimensional, unbinned unfolding.
- Use the 8-dimensional result to explore the Q^2 dependence and any other observables that can be computed from the electron-jet kinematics



Extracted from the same phase-space as Yao's analysis, but reporting a different observable

OmniFold

1. $$\omega_n(m) = \nu_{n-1}^{\text{push}}(m)\underline{L[(1,\text{Data}), (\nu_{n-1}^{\text{push}}, \text{Sim.})](m)}$$

$$\nu_{n-1}(t) = \nu_n^{\text{push}}(m)$$

- Detector level simulation is weighted to match the data
- $L[(1,\text{Data}), (\nu_{n-1}^{\text{push}}, \text{Sim.})](m)$ approximated by classifier trained to distinguish the *Data* and *Sim*.

2. $$\nu_n(t) = \nu_0(t)\underline{L[(\omega_n^{\text{pull}}, \text{Gen.}), (\nu_0, \text{Gen.})](t)}$$

$$\omega_n^{\text{pull}}(t) = \omega_n(m)$$

- Transform weights to a proper function of the generated events to create a new simulation
- $L[(\omega_n^{\text{pull}}, \text{Gen.}), (\nu_{n-1}, \text{Gen.})](t)$ approximated by classifier trained to distinguish Gen. with *pulled* weights from Gen. using $\text{weights}_{\text{old}}$ / $\text{weights}_{\text{new}}$

Each iteration of step 2 learns the correction from the original ν_0 weights

Advantage: Easier implementation, no need to store previous ν_n model

Disadvantage: Learning correction from ν_0 is more computationally expensive

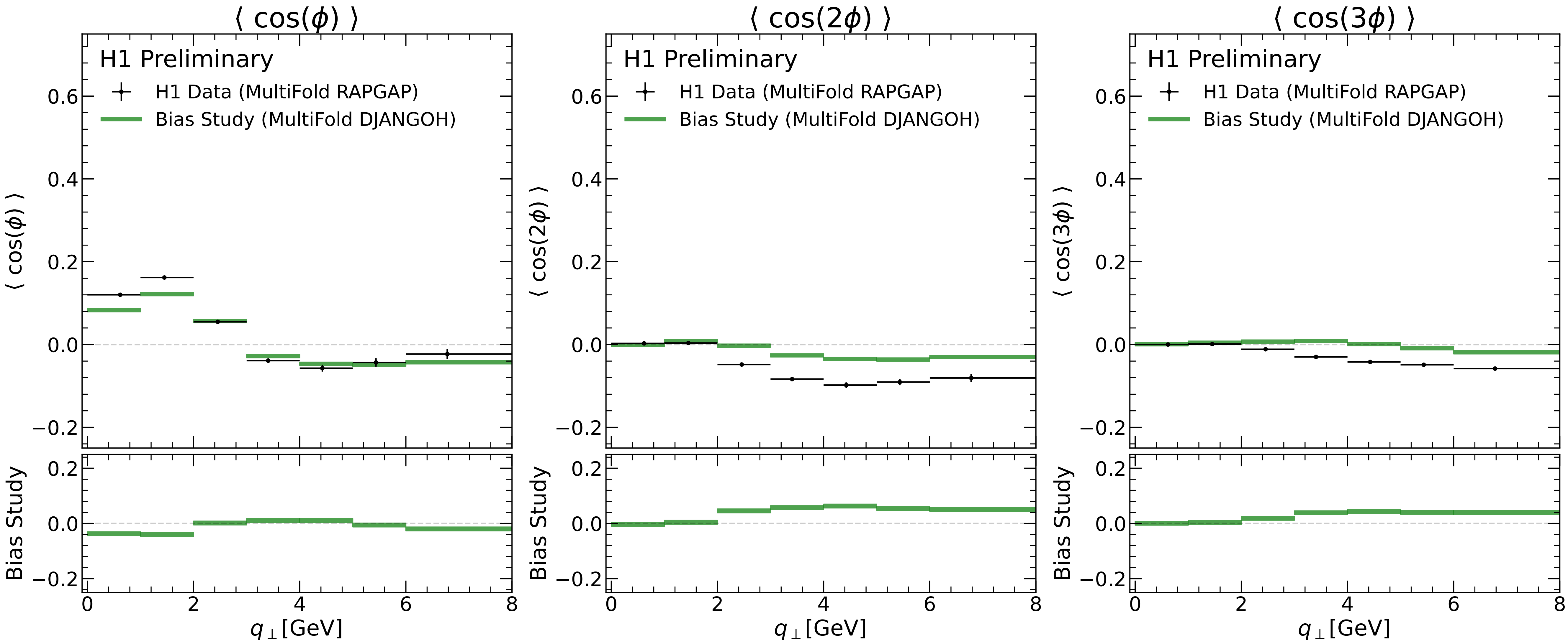
Systematic Uncertainties

- Model Dependance:
  - The bias of the unfolding procedure is determined by taking the difference in the result when unfolding using RAPGAP and DJANGO
  - The two generators have different underlying physics, thus providing a realistic evaluation of the procedure bias

- QED Radiation Corrections
  - Difference of correction between RAPGAP and DJANGO
  - Take RAPGAP with and without QED corrections
  - Take DJANGO with and without QED corrections

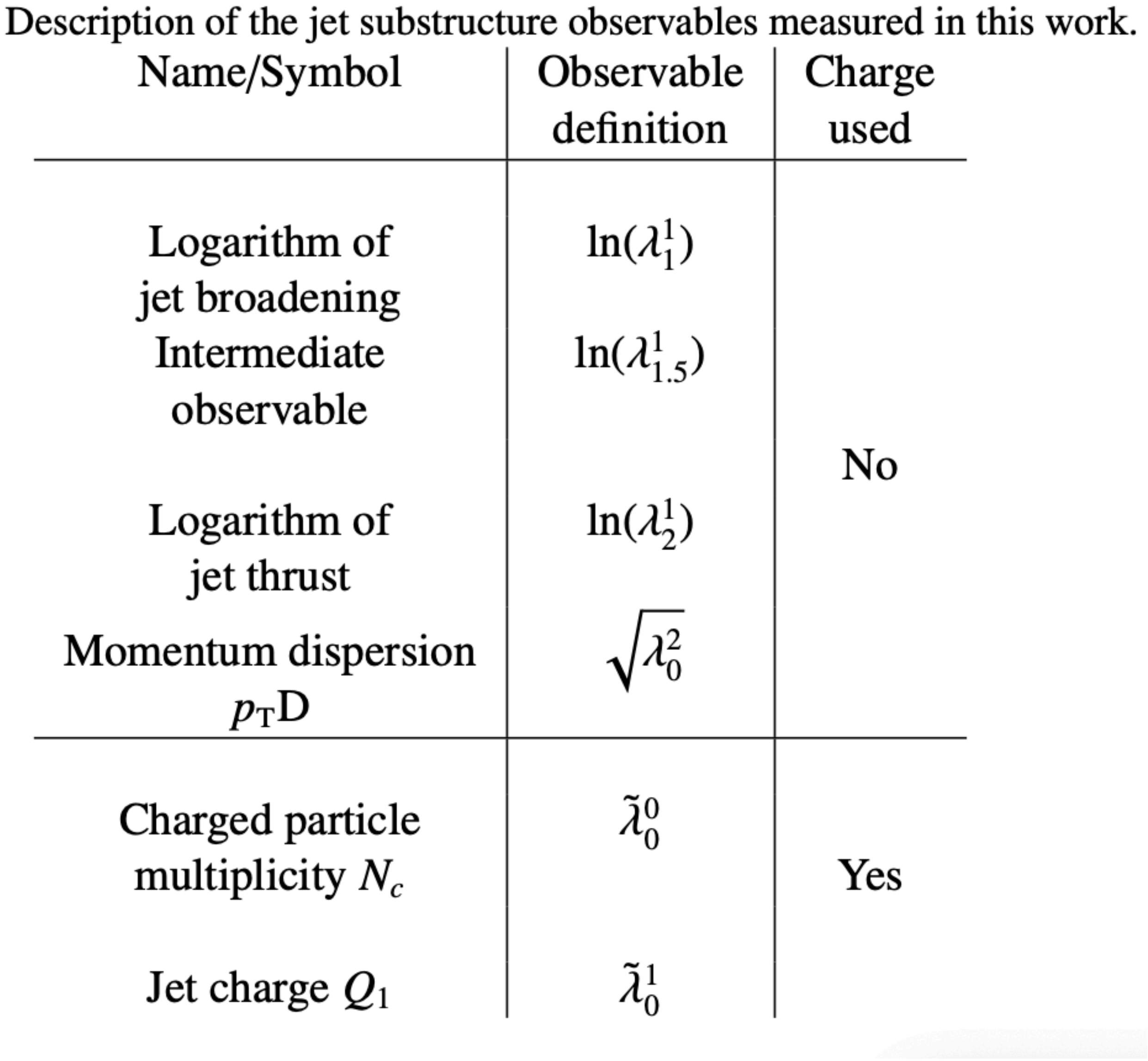
- Systematic uncertainties are determined by varying an aspect of the simulation and repeating the unfolding
  - These values detail the magnitude of variation:
  - HFS-object energy scale: $\pm 1\,\%$
  - HFS-object azimuthal angle: ± 20 mrad
  - Scattered lepton azimuthal: ± 1 mrad
  - Scattered lepton energy: $\pm 0.5 - 1.0\,\%$

Investigation of Model Bias vs. $q_\perp$ [GeV]



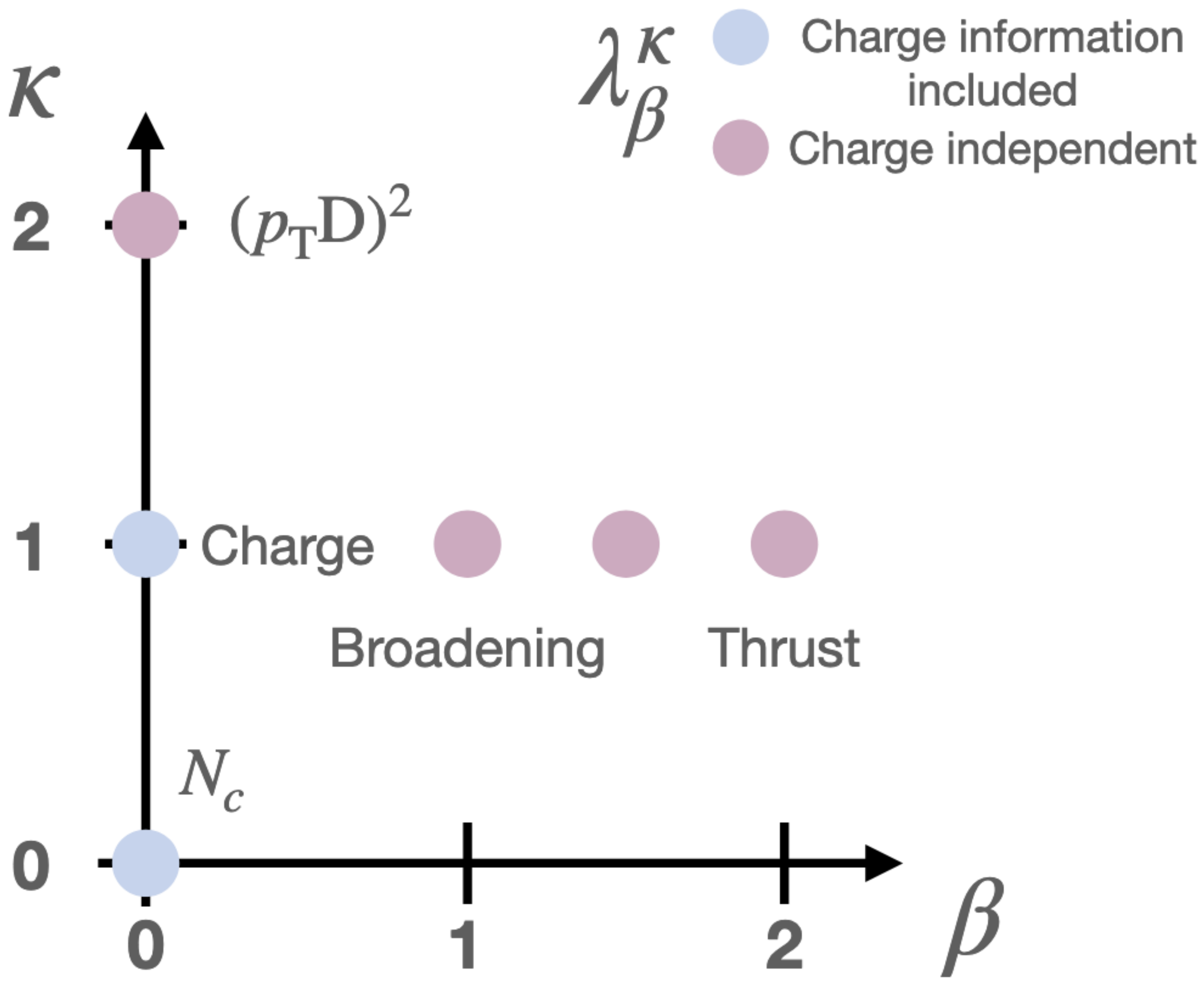
- Leading uncertainty is model bias in the unfolding for $\cos(2\phi)$ and $\cos(3\phi)$
- Difference in the result when unfolding using RAPGAP and DJANGO
- Reporting Abs. Errors; central values are very close to 0.0
- The Total Uncertainty is quite stable between harmonics

Jet Substructure Observables



Description of the jet substructure observables measured in this work.

Name/Symbol	Observable definition	Charge used
Logarithm of jet broadening	$\ln(\lambda_1^1)$	No
Intermediate observable	$\ln(\lambda_{1.5}^1)$	
Logarithm of jet thrust	$\ln(\lambda_2^1)$	
Momentum dispersion $p_{\mathrm{T}}\mathrm{D}$	$\sqrt{\lambda_0^2}$	
Charged particle multiplicity N_c	$\tilde{\lambda}_0^0$	Yes
Jet charge Q_1	$\tilde{\lambda}_0^1$	



IBU Generalization

IBU

$$t_j^{(n)} = \sum_i \mathrm{Pr}_{n-1}(\text{truth is } j | \text{measure } i)\,\mathrm{Pr}(\text{measure } i)$$

$$= \sum_i \frac{R_{ij} t_j^{(n-1)}}{\sum_k R_{ik} t_k^{(n-1)}} \times m_i$$

Continuous Generalization

$$\nu_1(t)\,p_{\mathrm{Gen}}(t) = \int dm'\, p_{\mathrm{Gen}|\mathrm{Sim}}(t|m')\,p_{\mathrm{Data}}(m')$$

Using Classifiers that approximate the Likelihood ratio

$$L[(w, X), (w', X')](x) = \frac{p_{(w,X)}(x)}{p_{(w',X')}(x)}$$

Both converge to maximum likelihood estimate of particle-level distribution

Cross Section & ϕ

$$\frac{d^5\sigma^{ep\to e'qX}}{dy_\ell d^2P_\perp d^2q_\perp} = \sigma_0^{eq} x f_q(x)\delta^{(2)}(q_\perp)$$

Gluon Matrix Element

$$\mathcal{M}^{\mu\nu}(x,k_\perp) = \int \frac{d\xi^- d^2\xi_\perp}{P^+(2\pi)^3} e^{-ixP^+\xi^- + i\vec{k}_\perp\cdot\vec{\xi}_\perp} \qquad (\\ \times\langle P|F_a^{+\mu}(\xi^-,\xi_\perp)\mathcal{L}^\dagger_{vab}(\xi^-,\xi_\perp)\mathcal{L}_{vbc}(0,0_\perp)F_c^{\nu+}(0)|P\rangle$$

Integration over emitted gluon phase space

$$g^2\int\frac{d^3k_g}{(2\pi)^3 2E_{k_g}}\delta^{(2)}(q_\perp + k_{g\perp})C_F S_g(k_J,p_1) \\ = \frac{\alpha_s C_F}{2\pi^2 q_\perp^2}\left[\ln\frac{Q^2}{q_\perp^2} + \ln\frac{Q^2}{k_{\ell\perp}^2} + c_0 + 2c_1\cos(\phi) + 2c_2\cos(2\phi) + \cdots\right],$$

$$c_n = \ln\frac{1}{R^2} + f(n) + g(nR)\,,$$

Fourier Coefficient (Introduces ϕ dependance)

$$f(n) = \frac{2}{\pi}\int_0^\pi d\phi(\pi-\phi)\frac{\cos\phi}{\sin\phi}(\cos n\phi - 1)\,,$$

$$g(nR) = \frac{4}{\pi}\int_0^1 \frac{d\phi}{\phi}\tan^{-1}\frac{\sqrt{1-\phi^2}}{\phi}\left[1-\cos(nR\phi)\right] \\ = \frac{n^2R^2}{4}\,{}_2F_3\left(1,1;2,2,2;-\frac{n^2R^2}{4}\right).$$

Differential Cross Section

- Back-to-back electron-jet production from *ep* collision,

$$e(l) + p(P) \to e(l') + J_q(p_J) + X$$

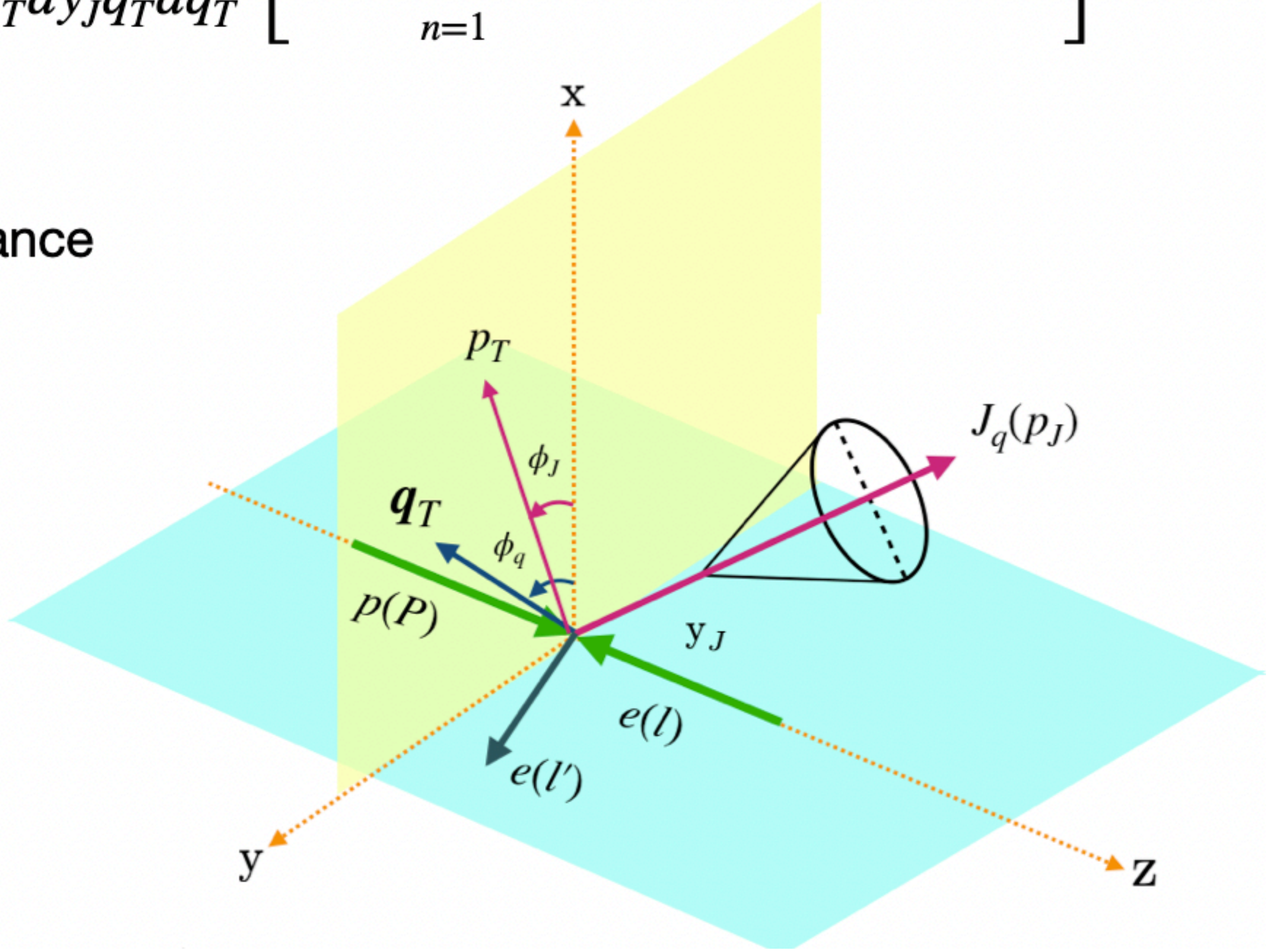
$$\frac{d\sigma}{d^2\boldsymbol{p}_T dy_J d\phi_J d^2\boldsymbol{q}_T} = \frac{d\sigma}{2\pi d^2\boldsymbol{p}_T dy_J q_T dq_T}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T, y_T)\cos(n(\phi_q - \phi_J))\right]$$

q_T : transverse momentum imbalance

$$\boldsymbol{q}_T = \boldsymbol{l}'_T + \boldsymbol{p}_{JT}$$

p_T : jet transverse momentum

y_J : jet rapidity



Note: slightly different angle definition, but background still applies]

Credit: Fanyi Zhao