

Jets and fragmentation at the EIC

Felix Ringer

UC Berkeley/LBL

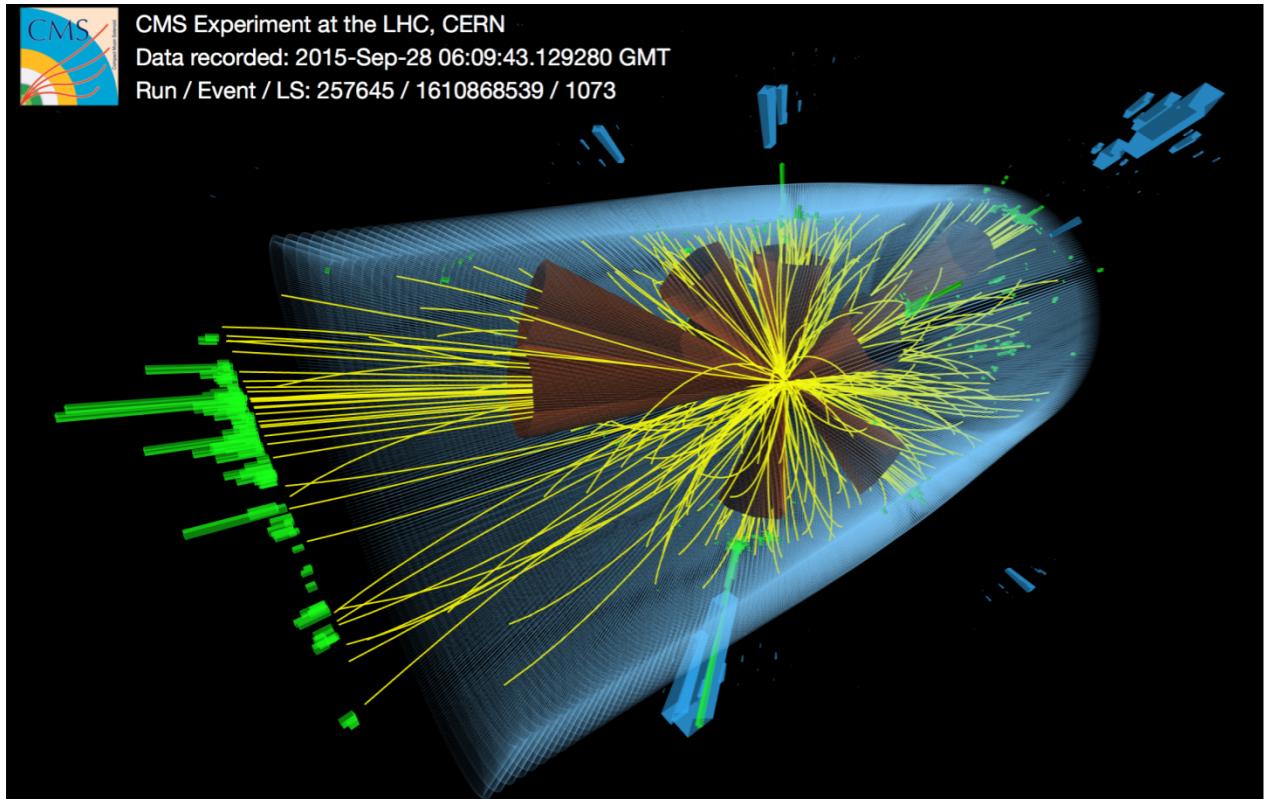
In collaboration with: Miguel Arratia, Elke Aschenauer, Barbara Jacak, Kyle Lee, Xiaohui Liu, Brian Page, Youqi Song, Werner Vogelsang, Feng Yuan



Berkeley
UNIVERSITY OF CALIFORNIA

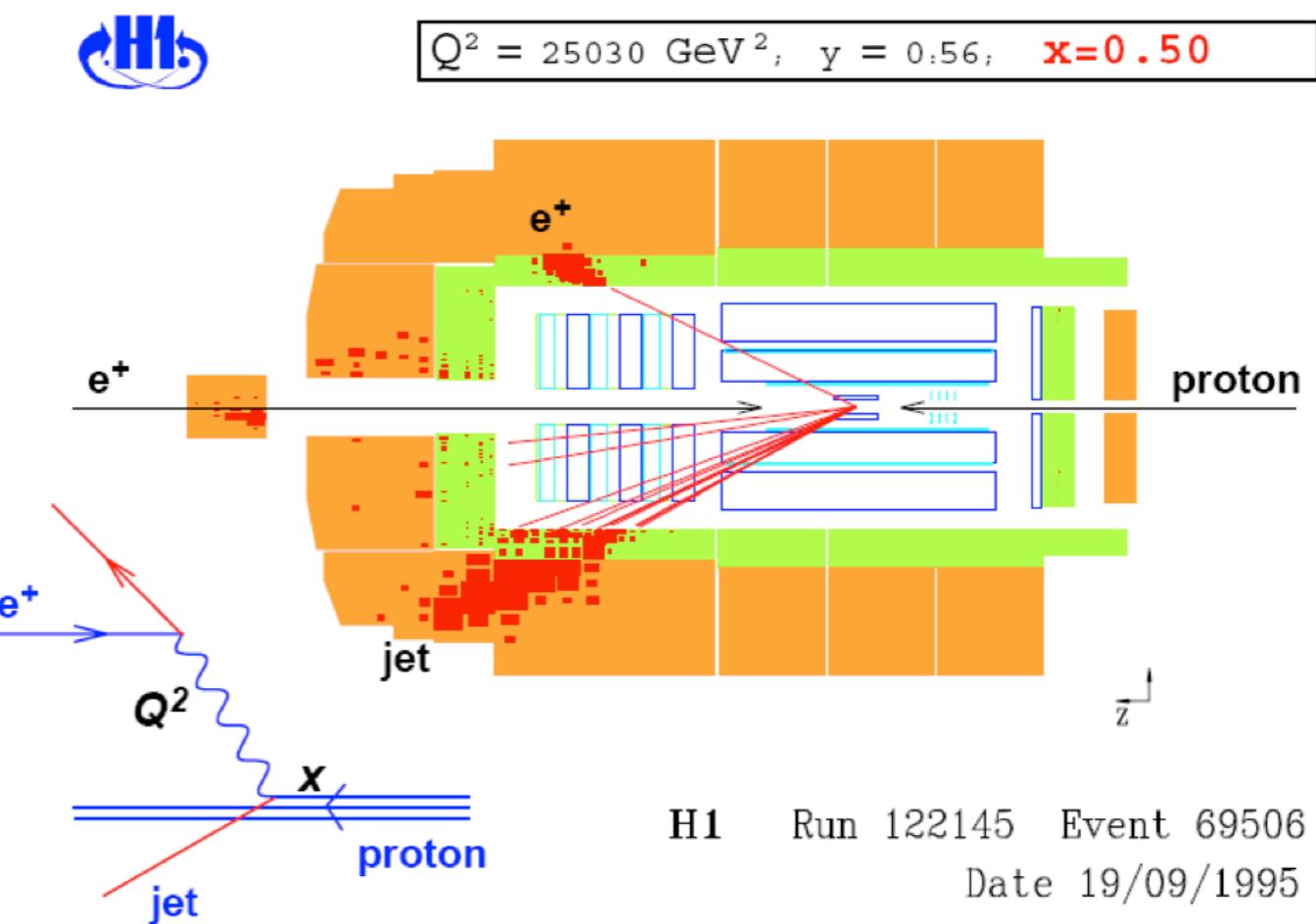
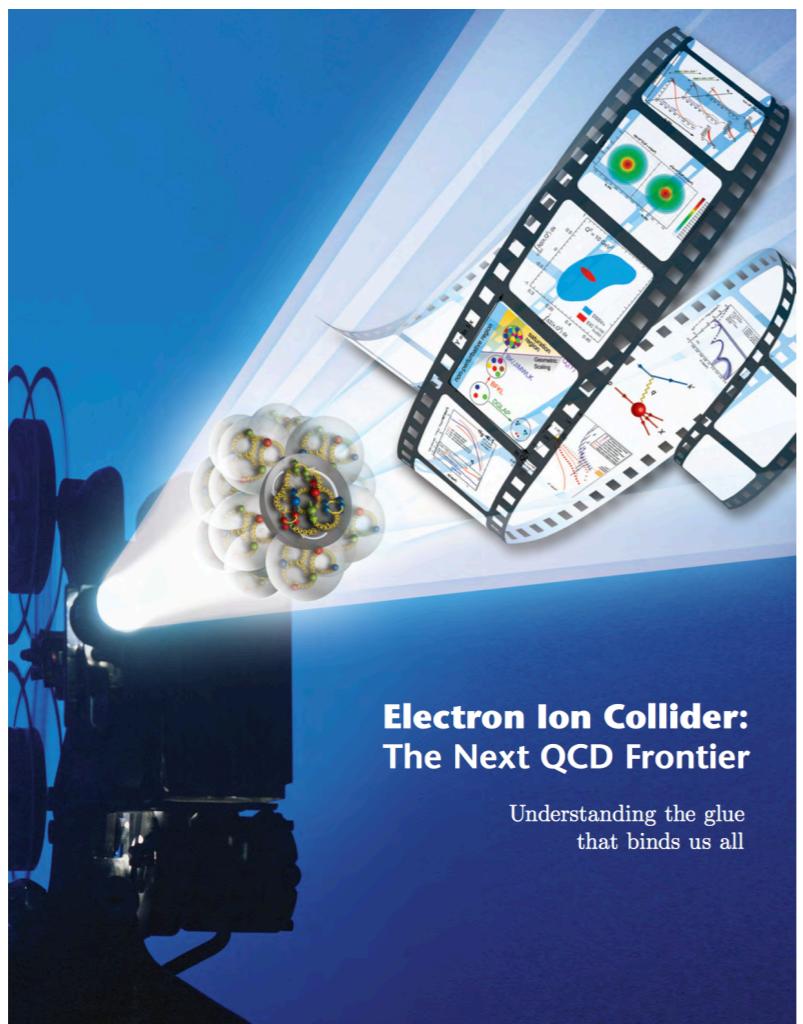
Mumbai, 06/01/20





Jets and jet substructure at

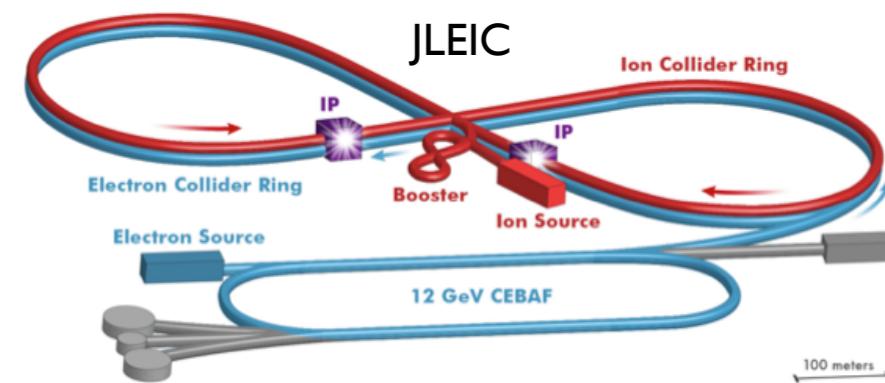
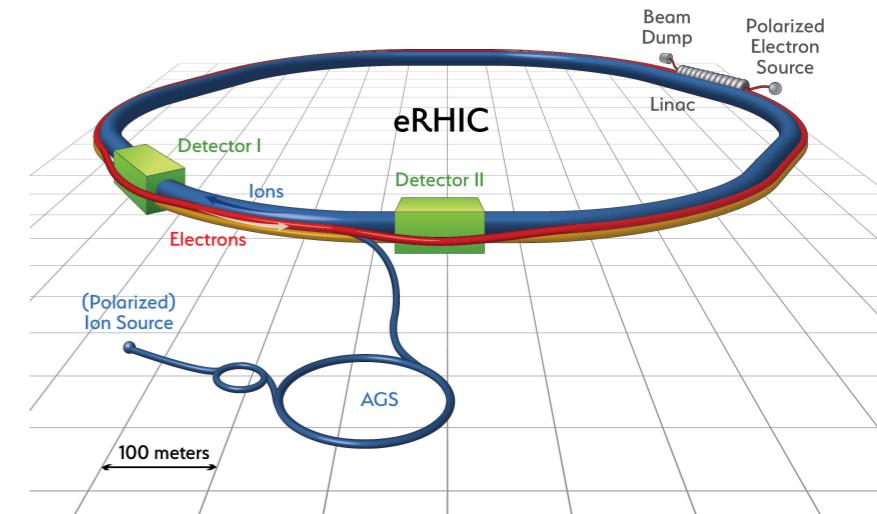
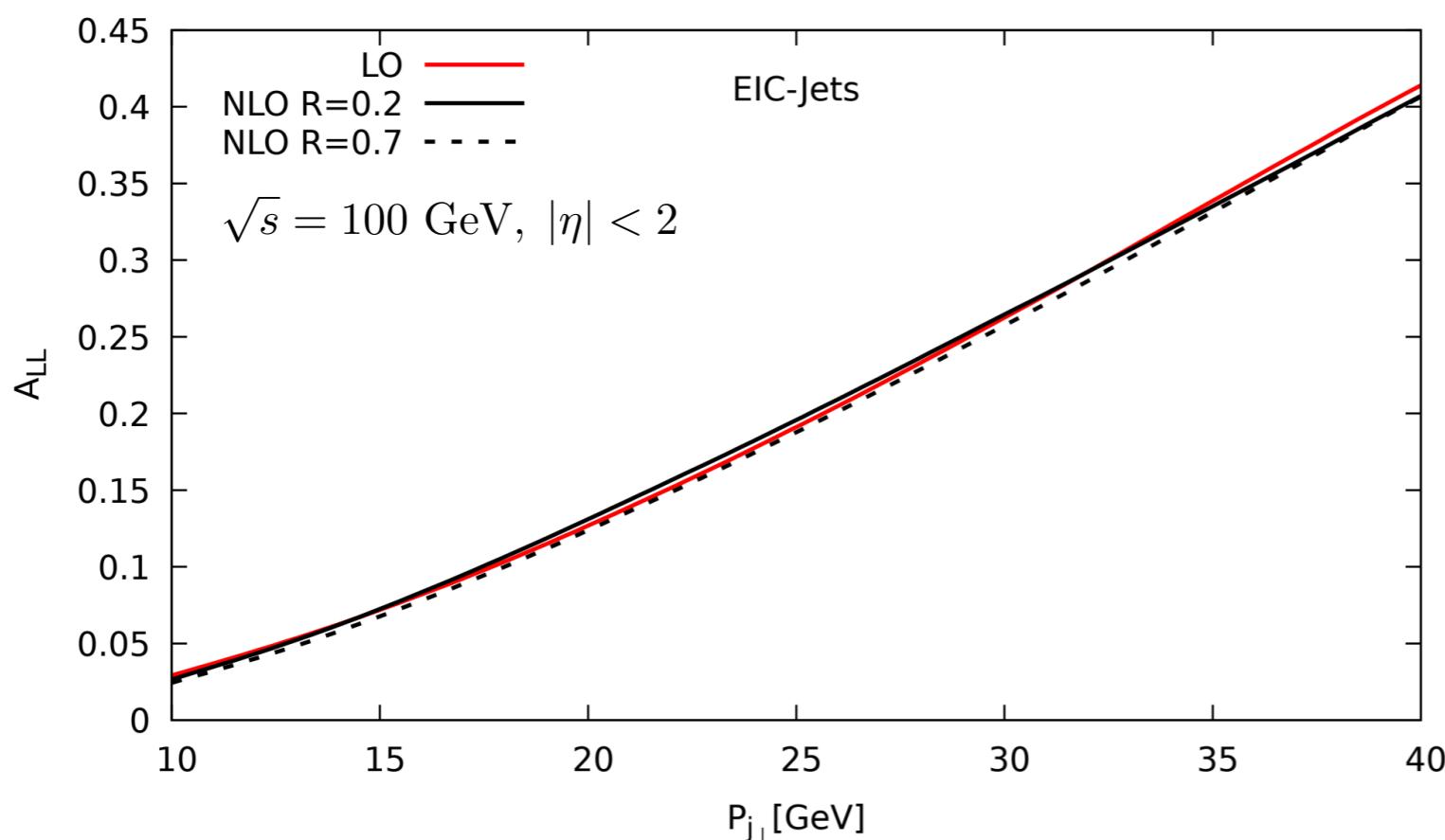
- LEP, HERA
- LHC, RHIC, Tevatron
- EIC



Jets at the EIC

- Constrain non-perturbative quantities
Collinear and TMD (un)polarized PDFs

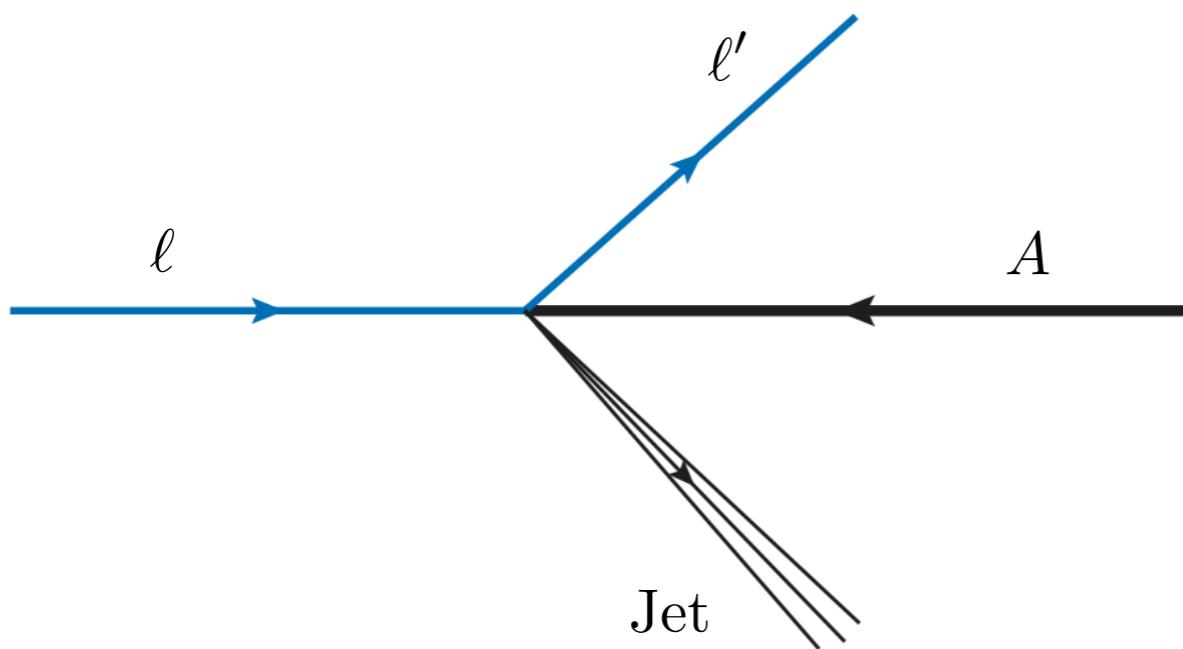
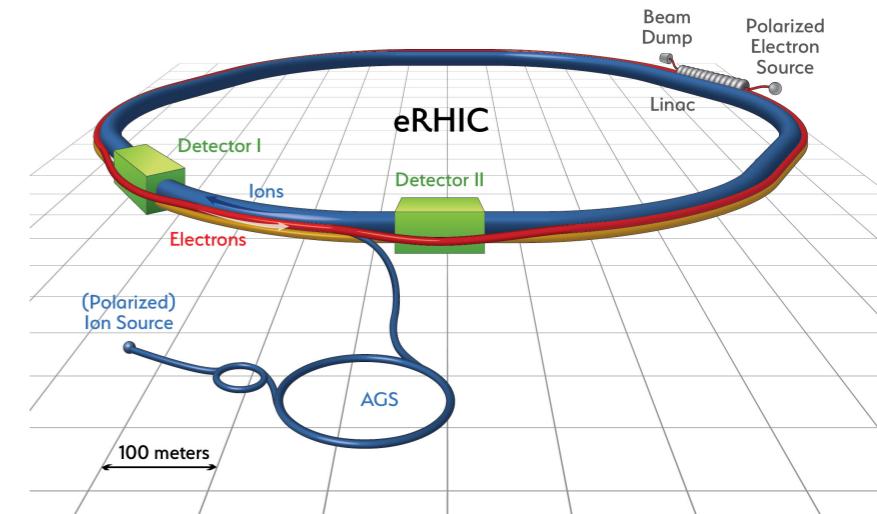
Double spin asymmetries in $ep \rightarrow \text{jet} + X$



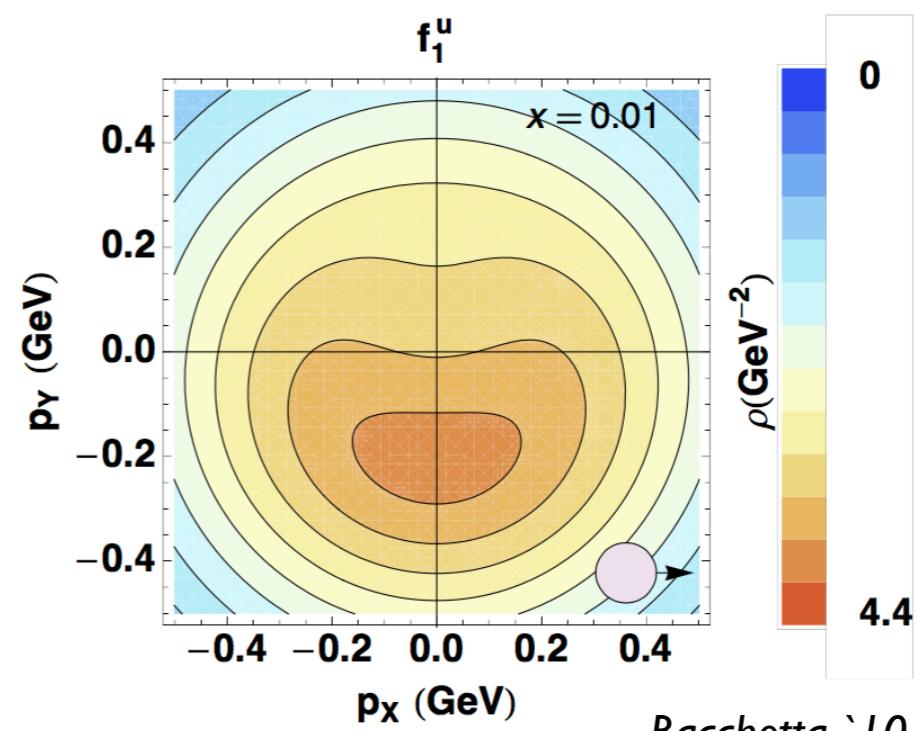
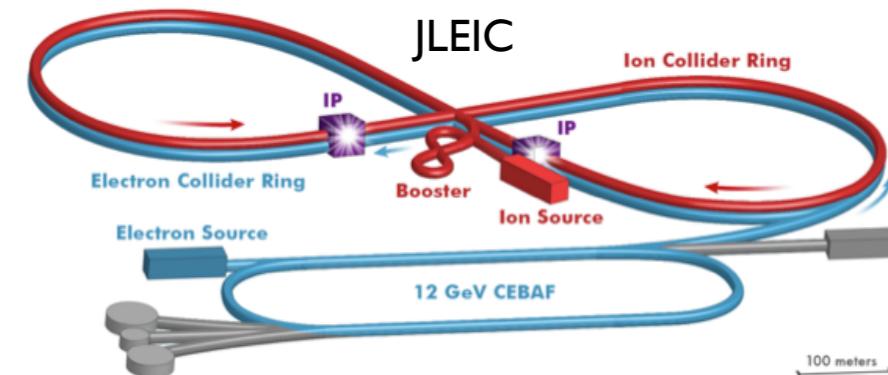
- Potentially enhance gluon contribution by tagging the final state jet

Jets at the EIC

- Constrain non-perturbative quantities
Collinear and TMD (un)polarized PDFs

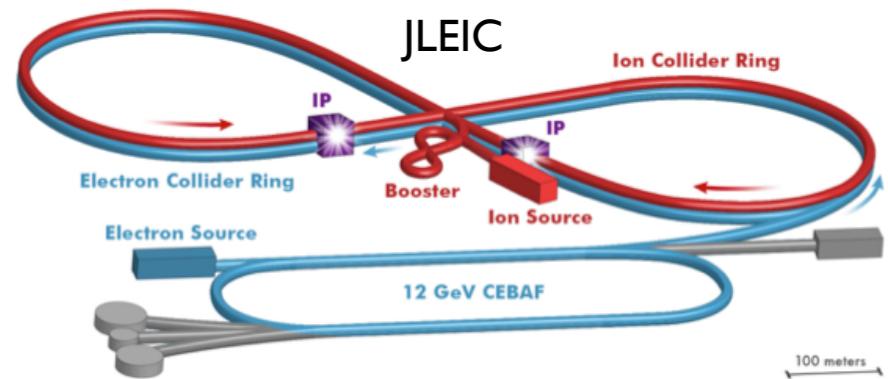
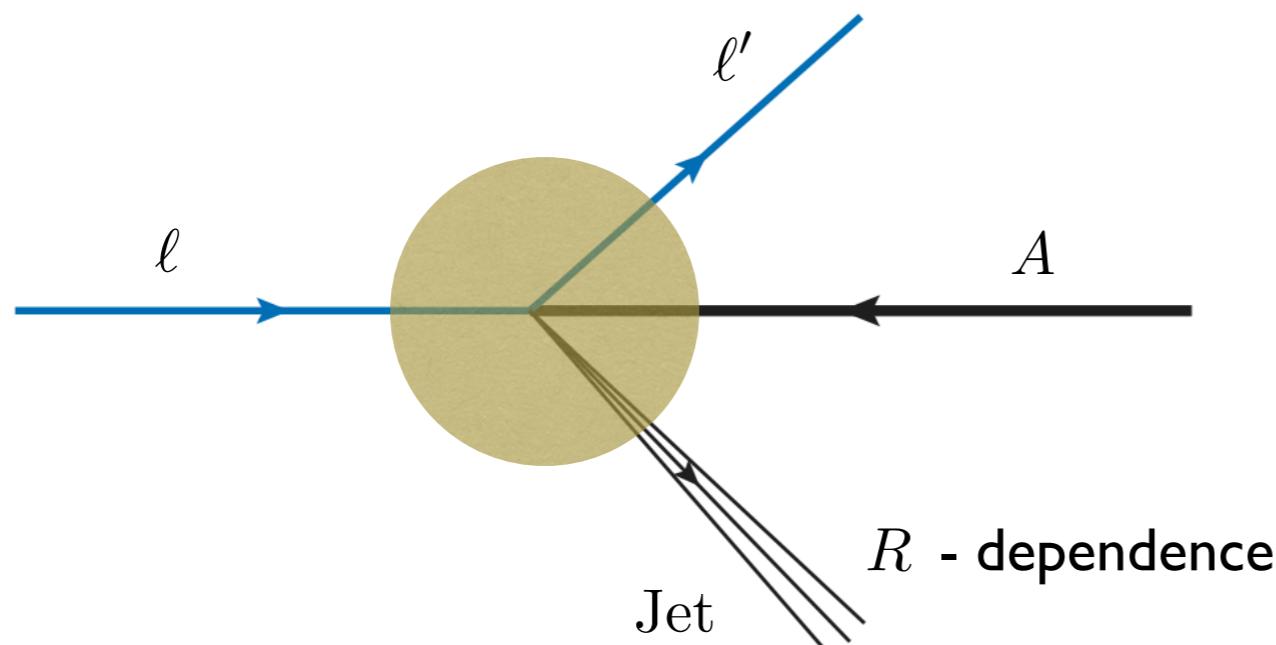
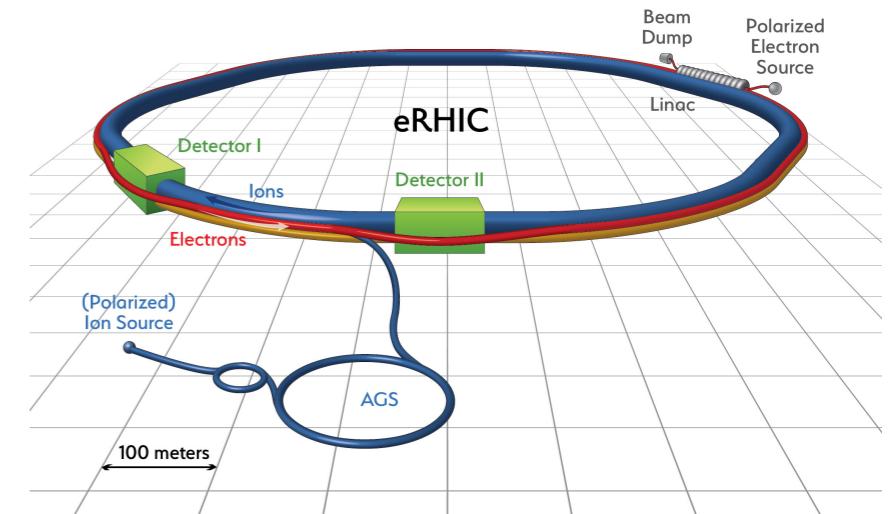


Liu, FR, Vogelsang, Yuan '18



Jets at the EIC

- Constrain non-perturbative quantities
Collinear and TMD (un)polarized PDFs
- Probe of nuclear matter effects in eA
Parton energy loss in cold nuclear matter



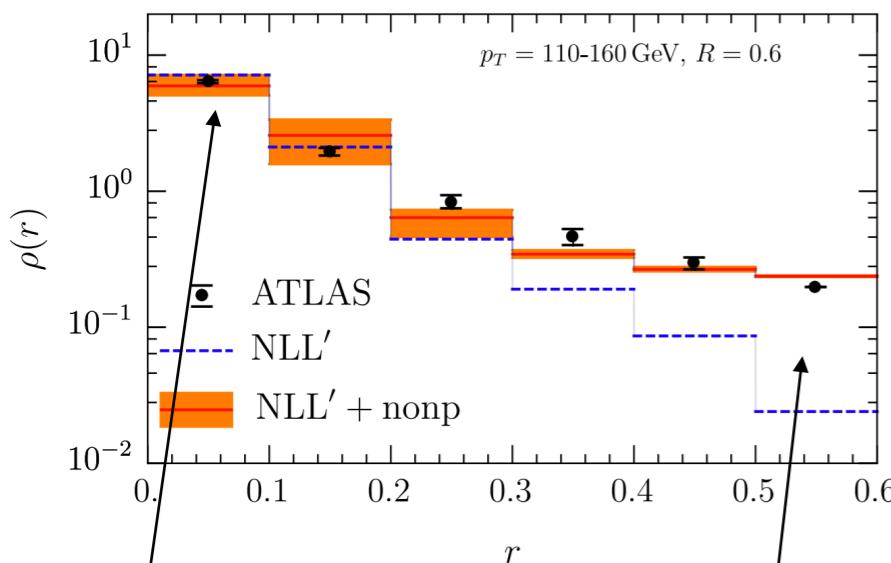
Determine \hat{q} for example

Liu, FR, Vogelsang, Yuan '18

Jets at the EIC

- Constrain non-perturbative quantities
Collinear and TMD (un)polarized PDFs
- Probe of nuclear matter effects in eA
- Tune parton showers, tag quark/gluon jets + quark flavor
The jet shape

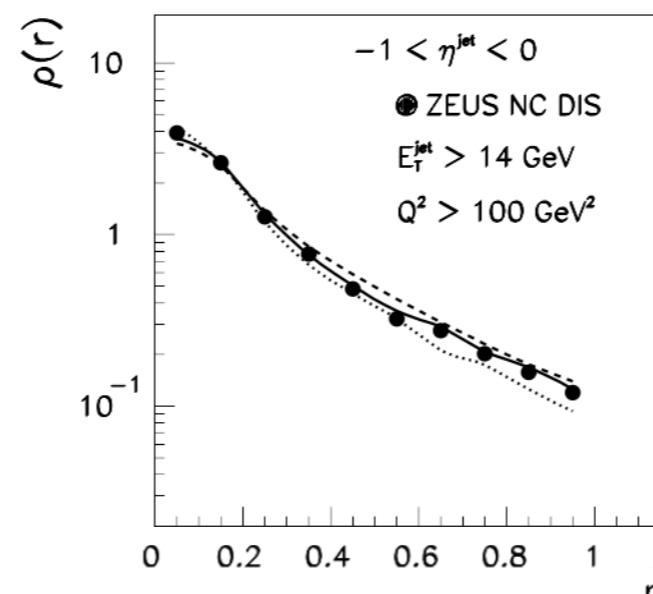
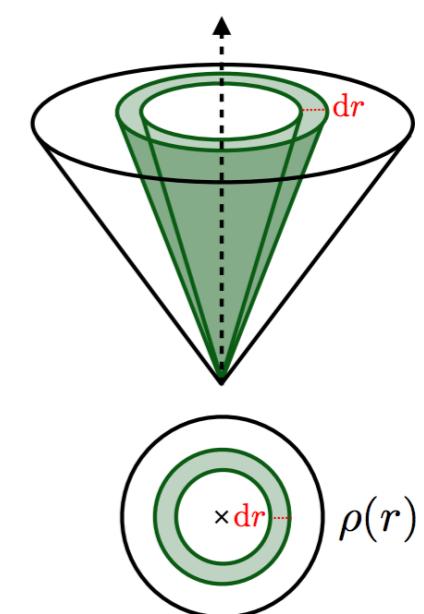
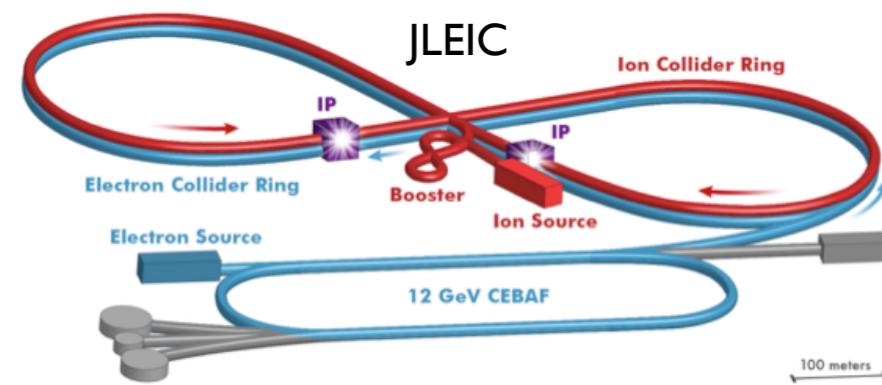
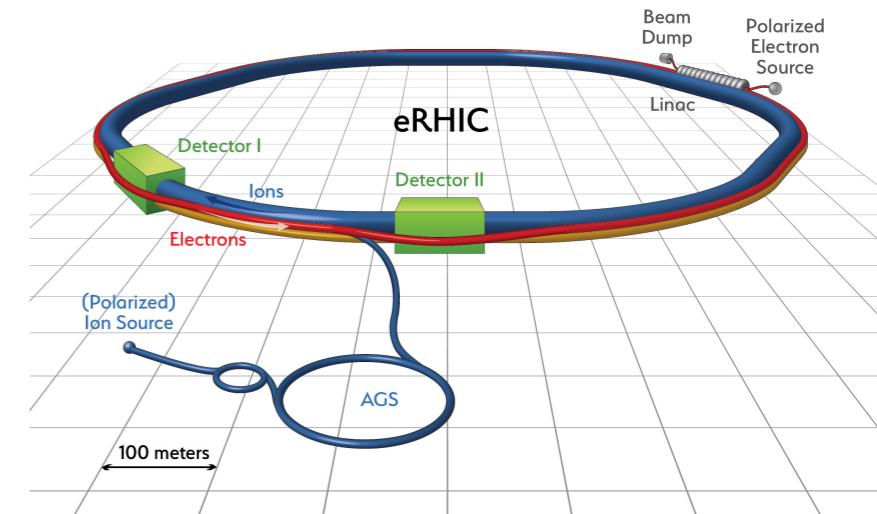
see *Christine Aidala's talk*



Perturbative

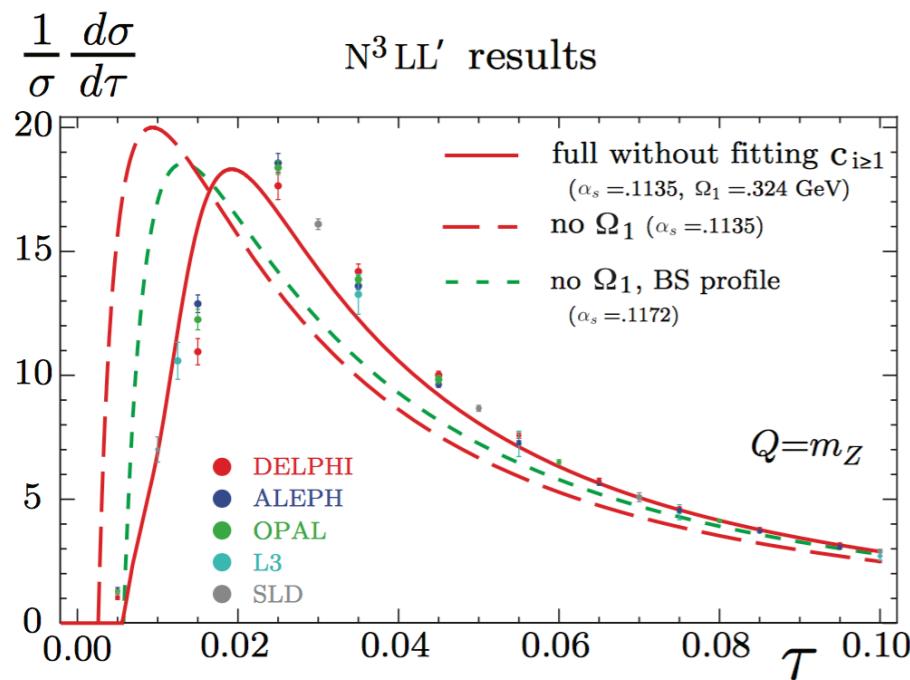
Hadronization
MPI, ISR

New NLL' → parton shower



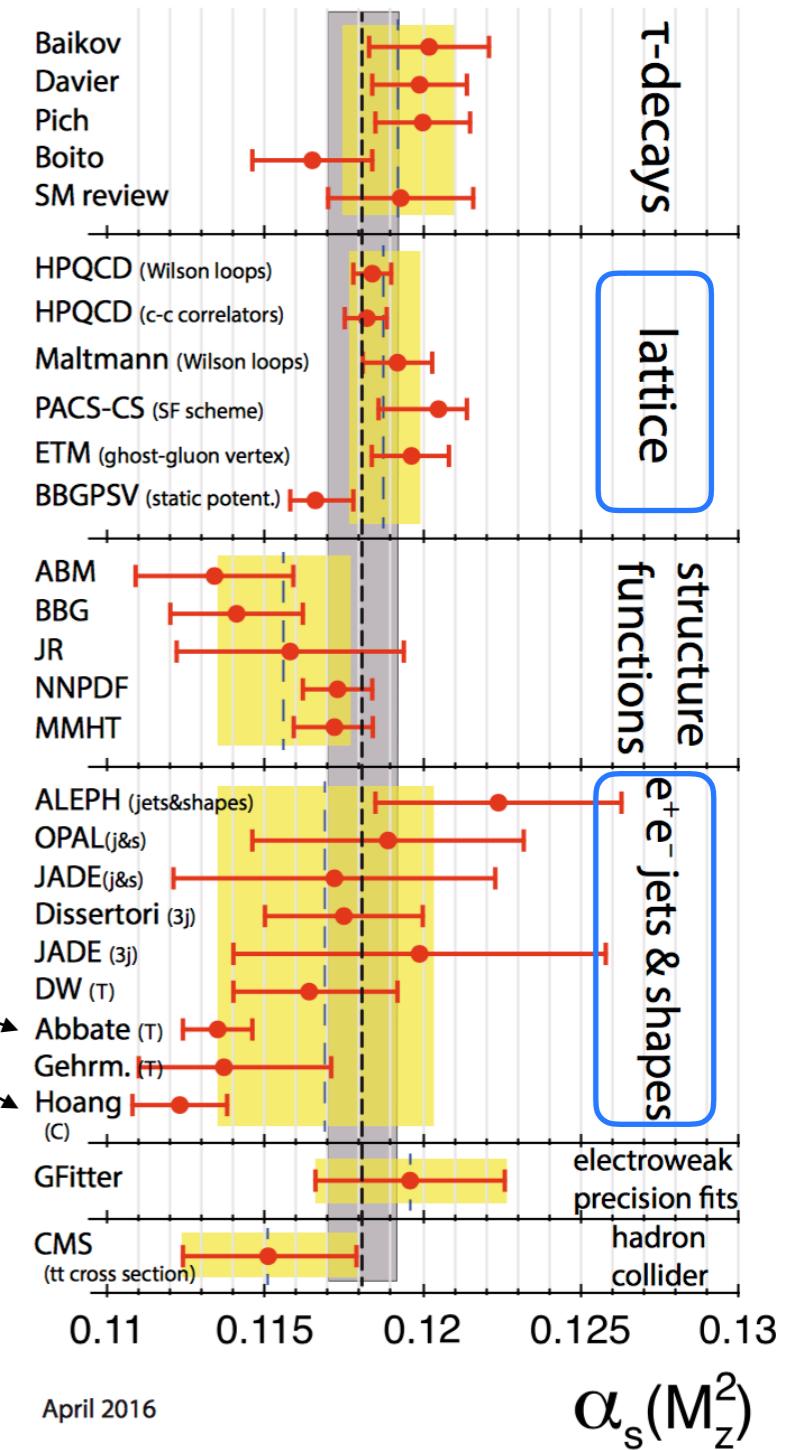
Jets at the EIC

- Constrain non-perturbative quantities
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- Tune parton showers, tag quark/gluon jets
The jet shape
- Determine the strong coupling constant α_s
High luminosity



Most precise results from
 e^+e^- event shapes

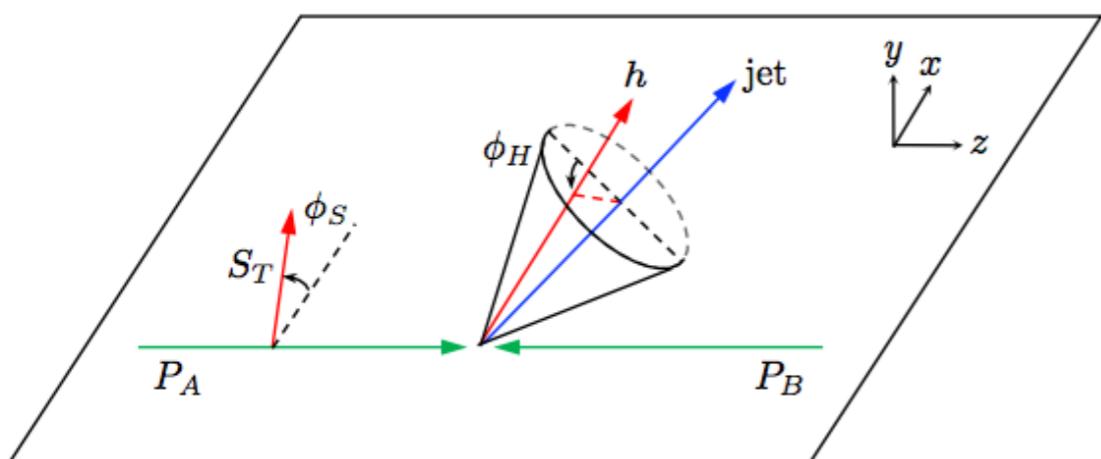
Thrust



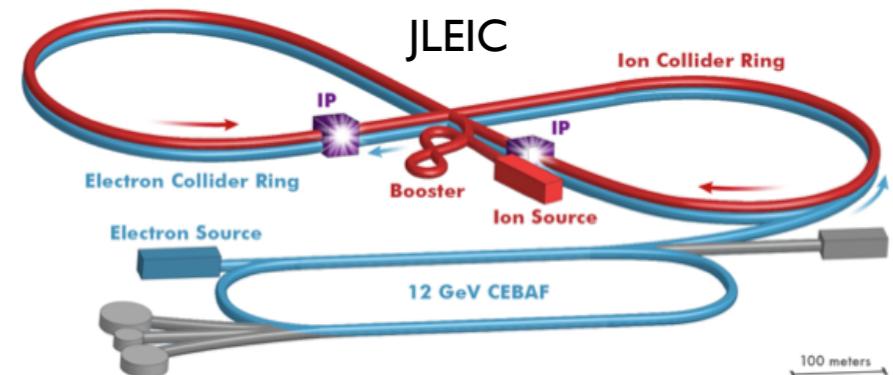
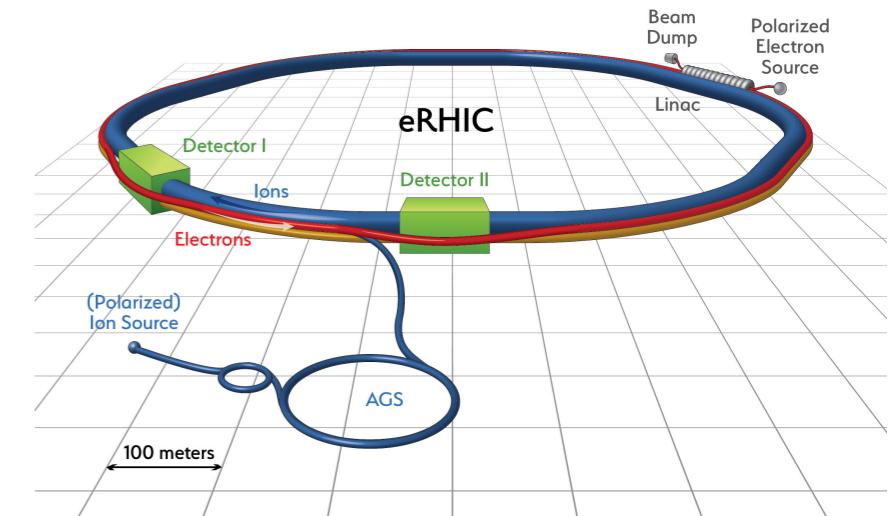
$$\alpha_s(M_Z) = 0.1181 \pm 0.0011$$

Jets at the EIC

- Constrain non-perturbative quantities
Collinear and TMD (un)polarized PDFs
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- Tune parton showers, tag quark/gluon jets
The jet shape
- Determine the strong coupling constant α_s
Jet mass of narrow jets or DIS event shapes like thrust
- Jet fragmentation functions and hadronization

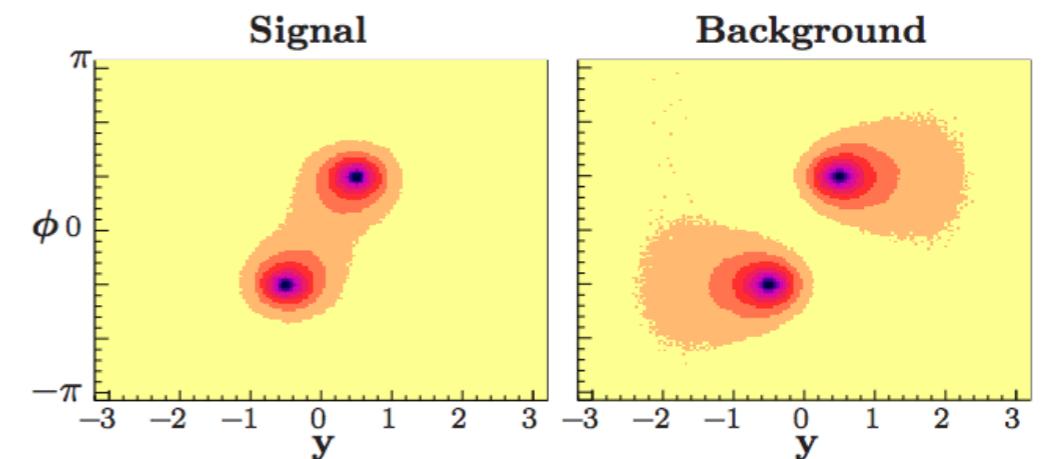


Probe universality



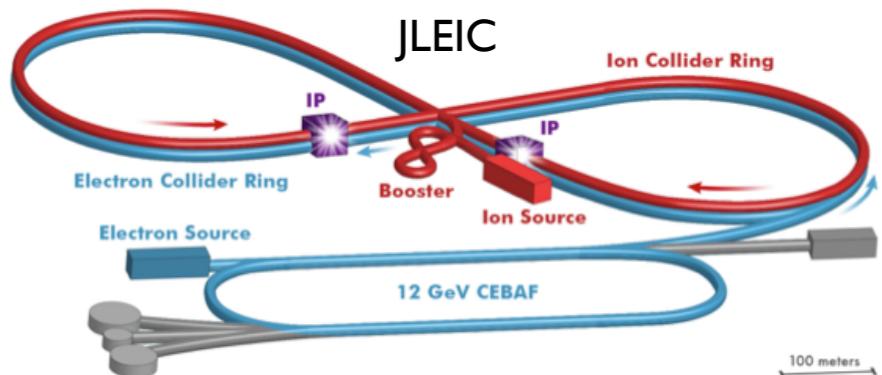
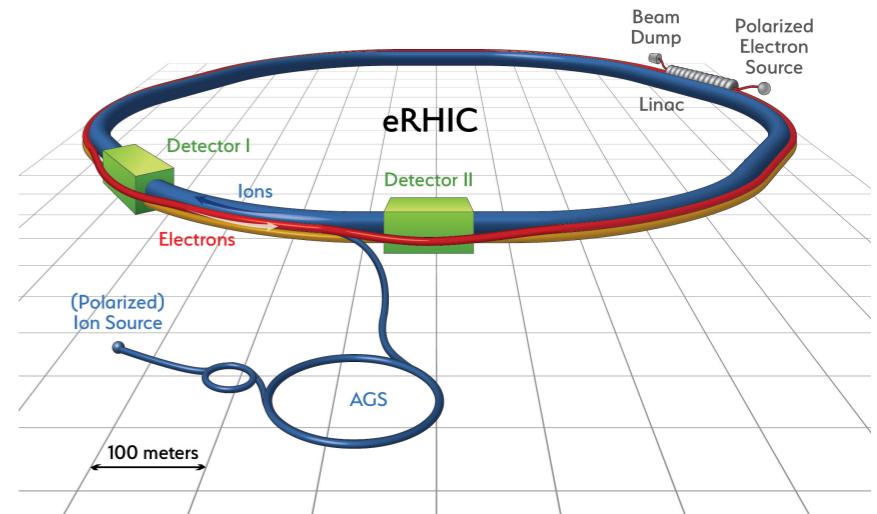
Gallicchio, Schwartz '10

Jet pull to probe the color flow in the event
Sudakov safety



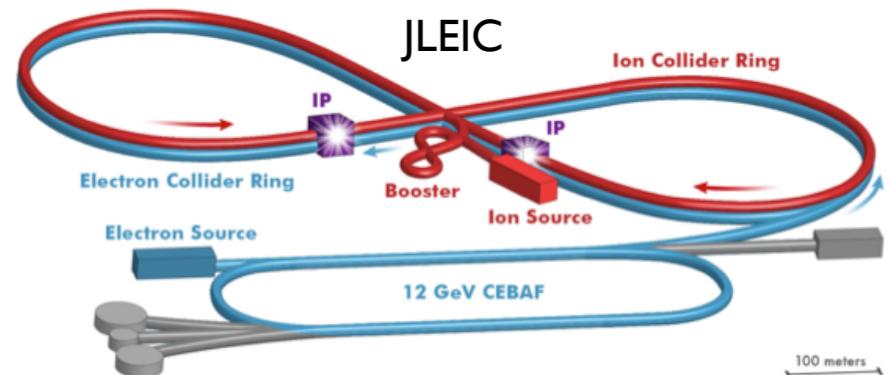
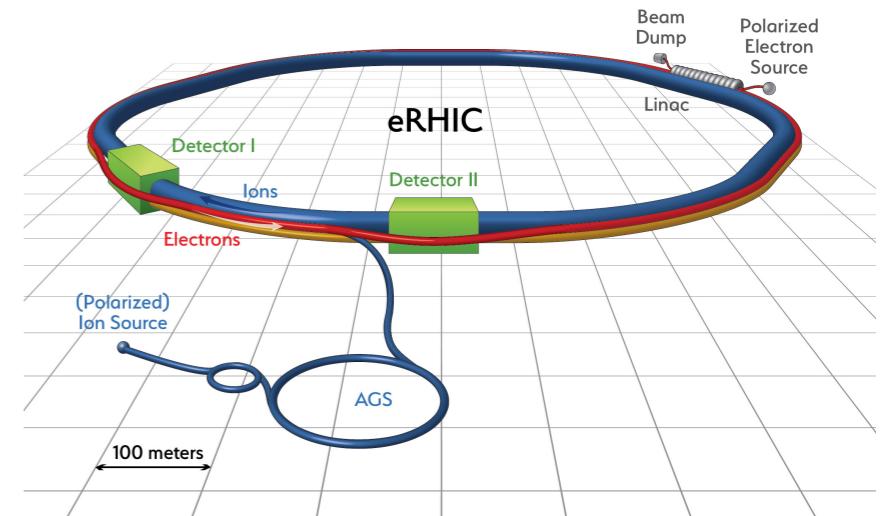
Jets at the EIC

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- Need to understand non-perturbative aspects and power corrections at low particle multiplicities and low jet p_T



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Jet mass of narrow jets or DIS event shapes like thrust
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- Need to understand non-perturbative aspects and power corrections at low particle multiplicities and low jet p_T
- Validate with low p_T jet data from HERA, RHIC
- Compare to MC simulations and pQCD results

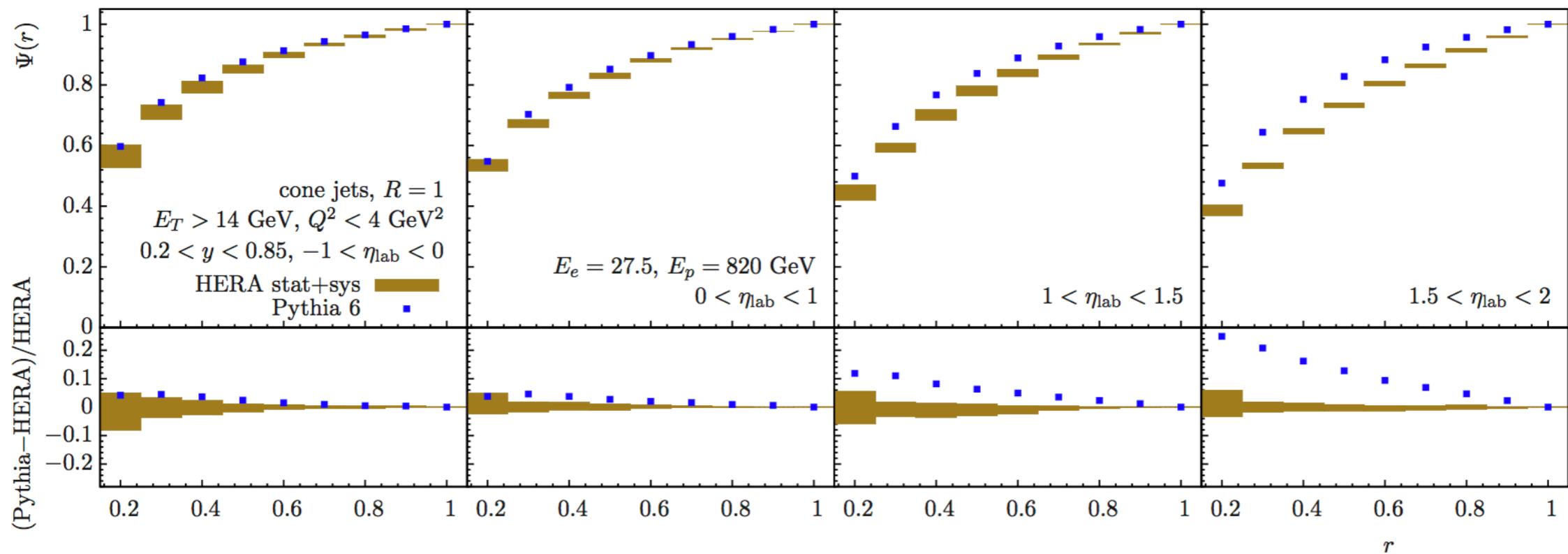
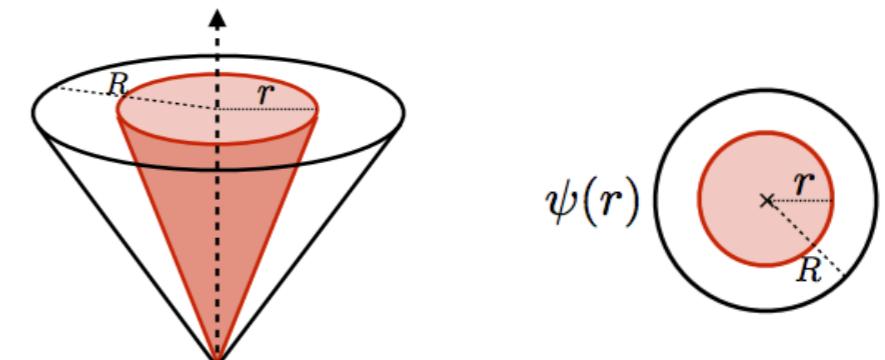


Outline

- Introduction
- Jet production at the EIC
- Jet substructure
- Lepton-jet correlations
- Conclusions

Monte Carlo simulations

- Pythia6 based eRHIC tune
 - Comparison to HERA jet shape data
 - SAS ID-LO photon PDF *Schuler, Sjoestrond '95*
 - Hadronization, ISR, no MPI



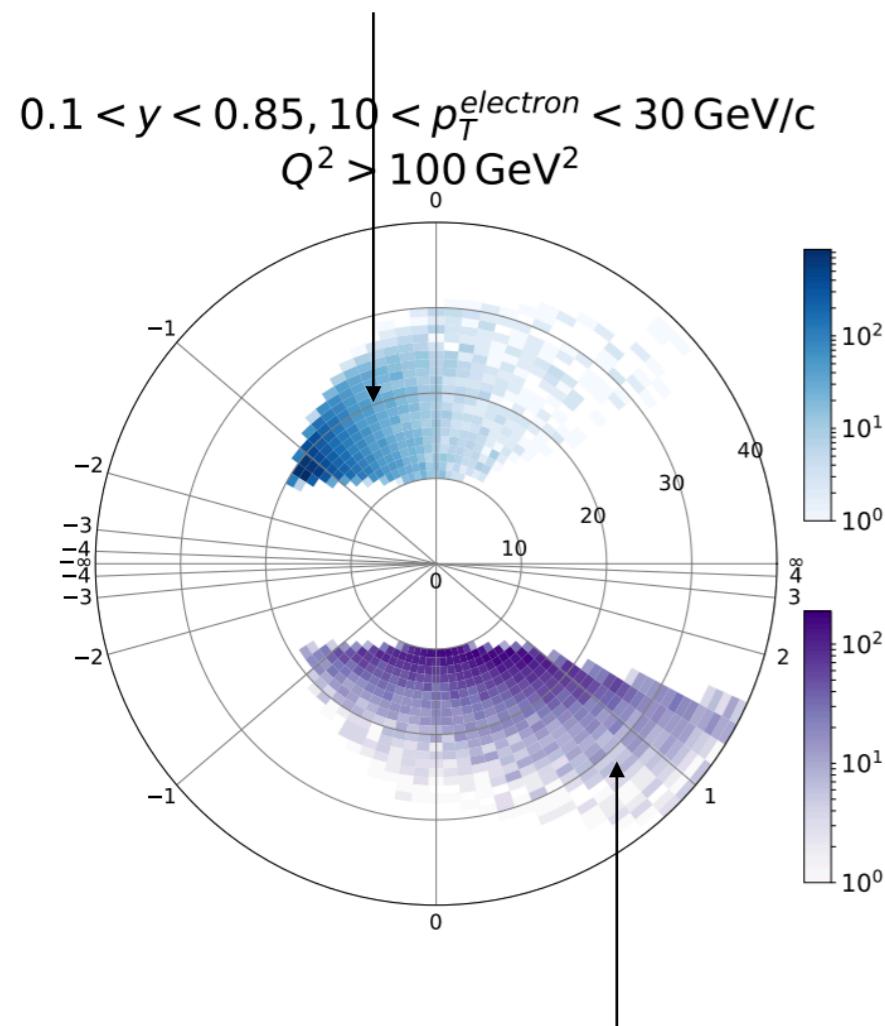
ZEUS, Eur. Phys. J C2 (1998) 61

- Pythia8 with the DIRE dipole shower *Höche, Prestel '15*

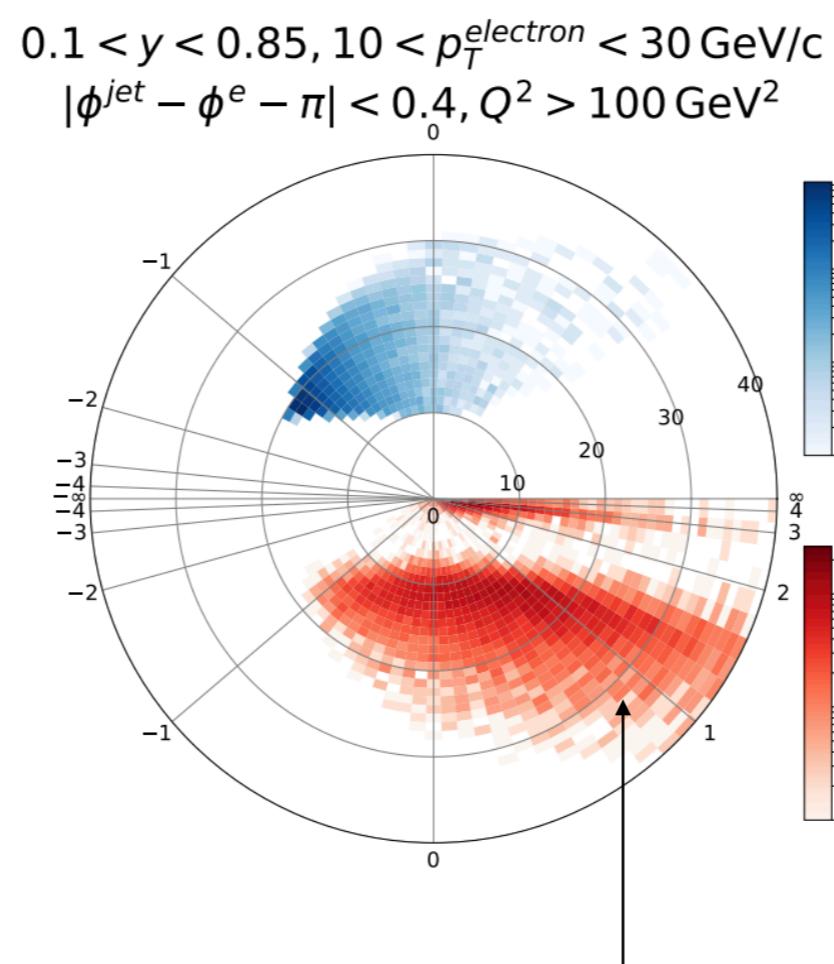
Jets at the EIC

Scattered lepton

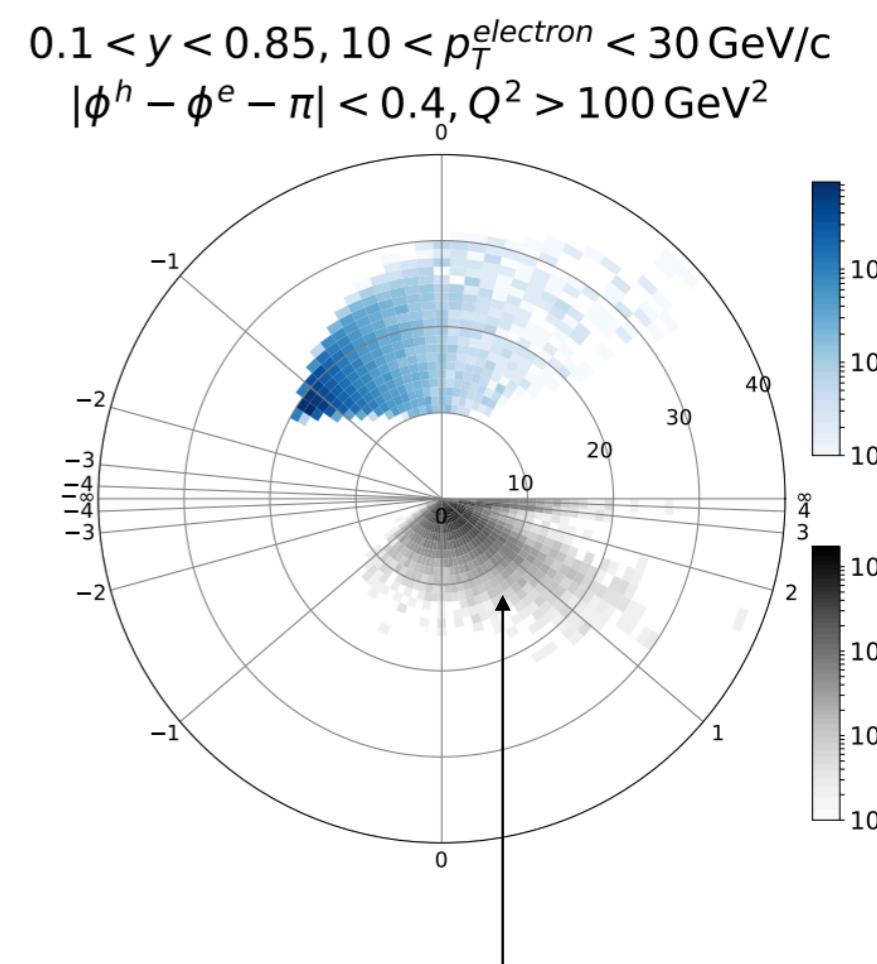
$\sqrt{s} = 89 \text{ GeV}$



Struck quark



Jets

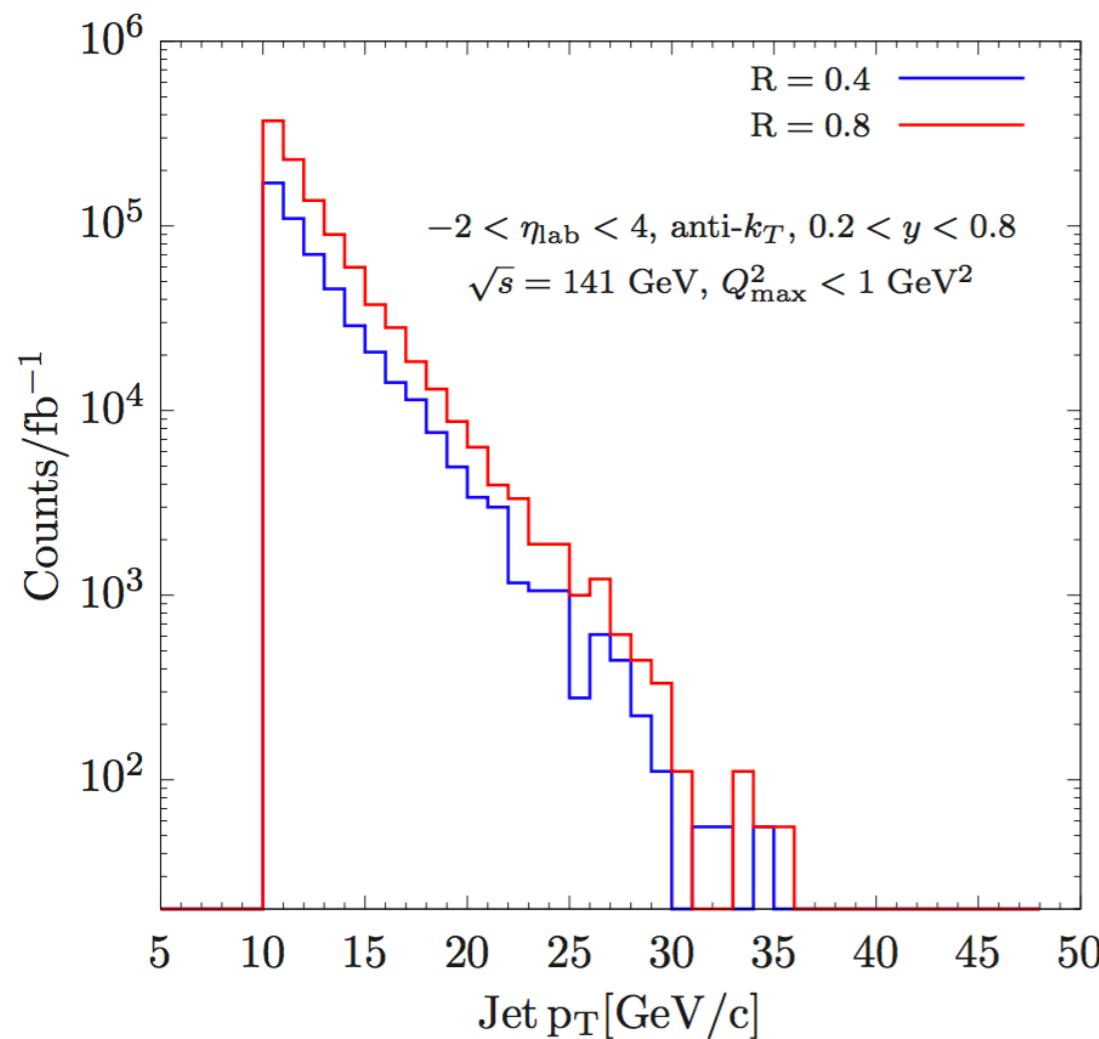


Hadrons

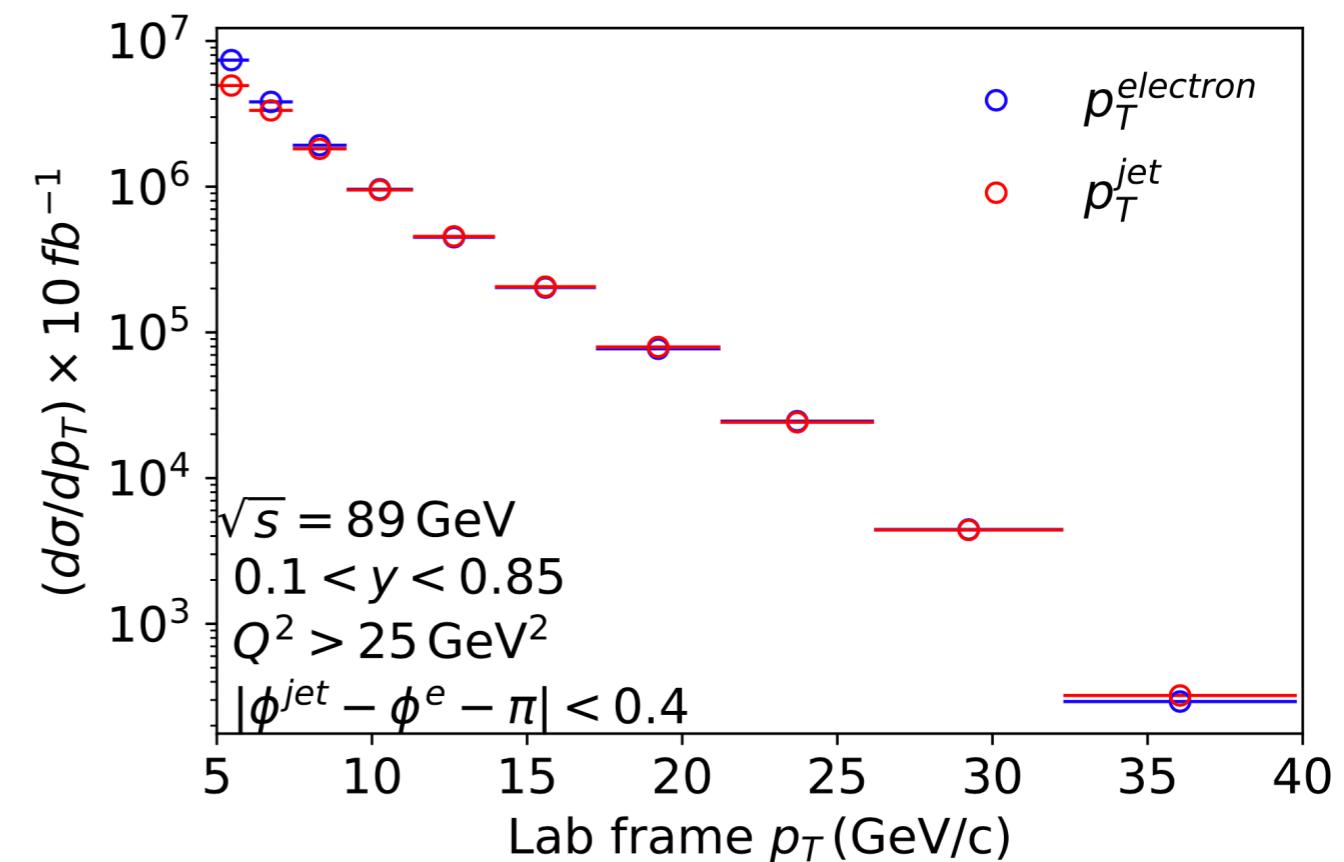
Rapidity and momentum

Jet transverse momentum spectra

Photoproduction



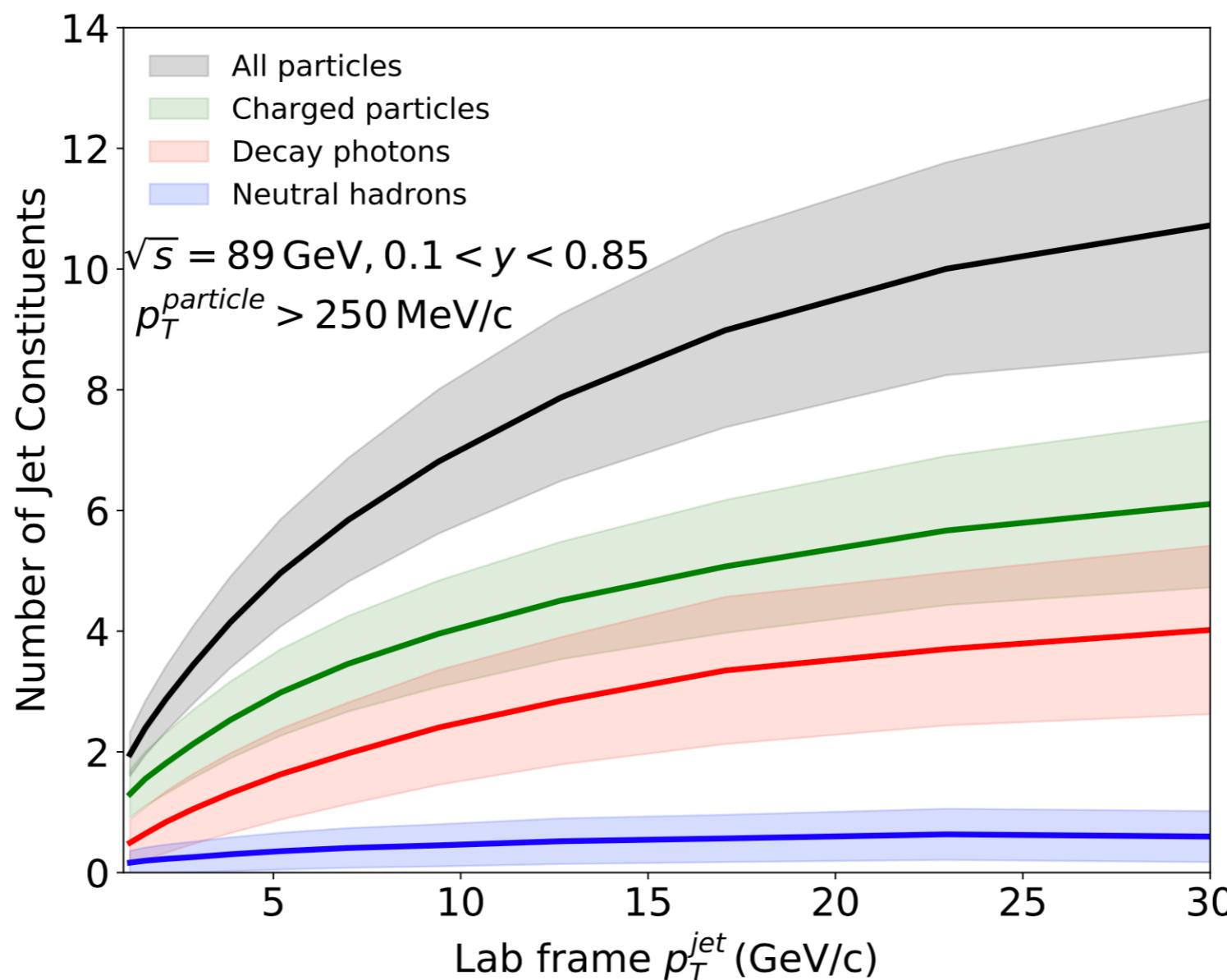
Deep Inelastic Scattering



Number of particles inside jets

Arratia, Jacak, FR, Song '19

Deep Inelastic Scattering



Jet production at the EIC

- $\ell p \rightarrow \text{jet} + X$ Lepton unobserved, high p_T

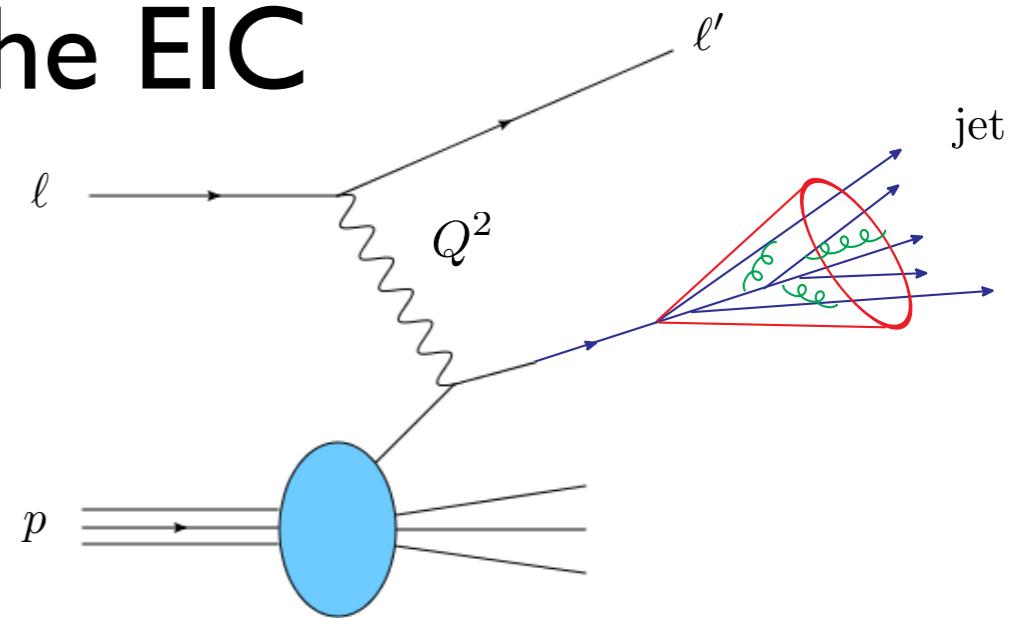
$$\frac{d\sigma}{dp_T d\eta}$$

- $\ell p \rightarrow \ell' + \text{jet} + X$ DIS, high p_T, Q^2

$$\frac{d\sigma}{dp_T d\eta dQ^2}$$

- $\ell p \rightarrow \ell' + \text{jet} + X$ Photoproduction, high $p_T, Q^2 < 0.1 \text{ GeV}^2$

$$\frac{d\sigma}{dp_T d\eta dQ^2}$$



Can change from lab to Breit frame

Analytical control for these processes

Other observables are possible and will “only” need to adjust q/g fractions

Hinderer, Schlegel, Vogelsang ‘17
Boughezal, Petriello, Xing ‘18

Daleo, de Florian, Sassot ‘04,
Gonzalez-Hernandez, Rogers,
Sato, Wang ‘18

Jäger, Stratmann, Vogelsang ‘03

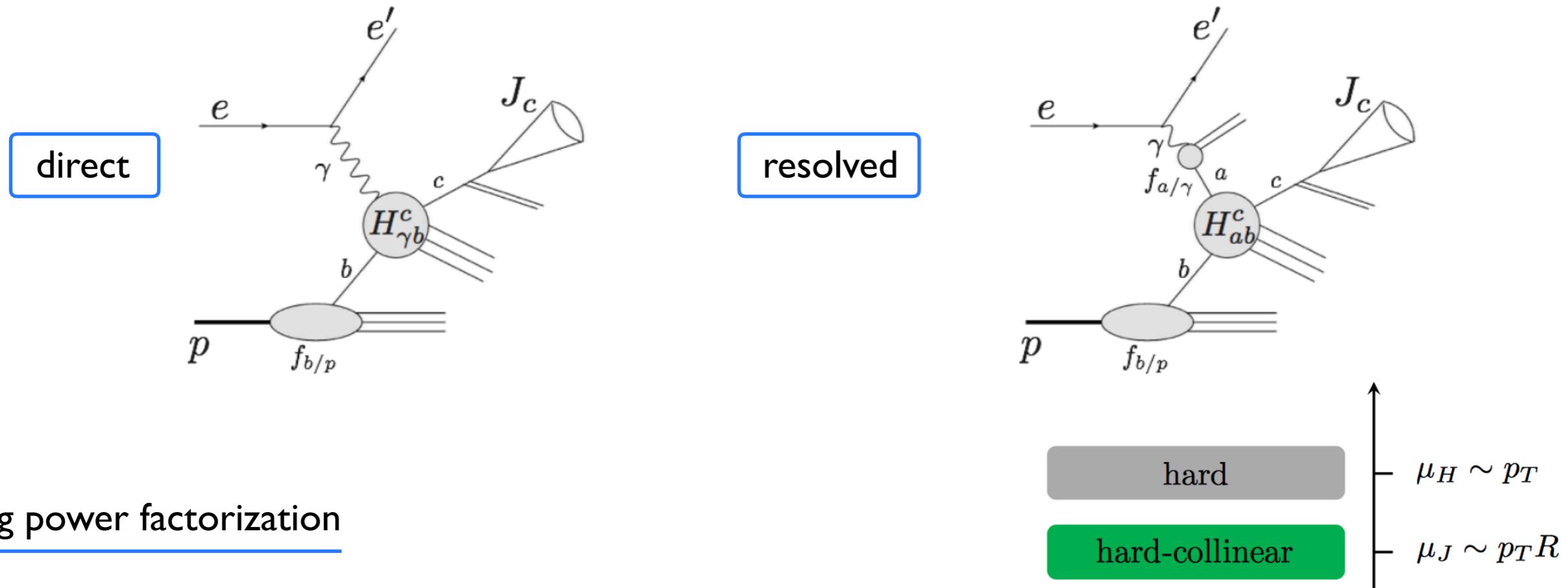
Photoproduction at the EIC



- Require high p_T and $Q^2 < 0.1 \text{ GeV}^2$
- Access the parton content of (polarized) photons

Jäger, Stratmann, Vogelsang '03
de Florian, Pfeuffer, Schäfer, Vogelsang '13
Chu, Aschenauer, Lee, Zhang '17

Photoproduction at the EIC



Leading power factorization

- Inclusive jets

$$\frac{d\sigma}{dp_T d\eta dQ^2} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes J_c$$

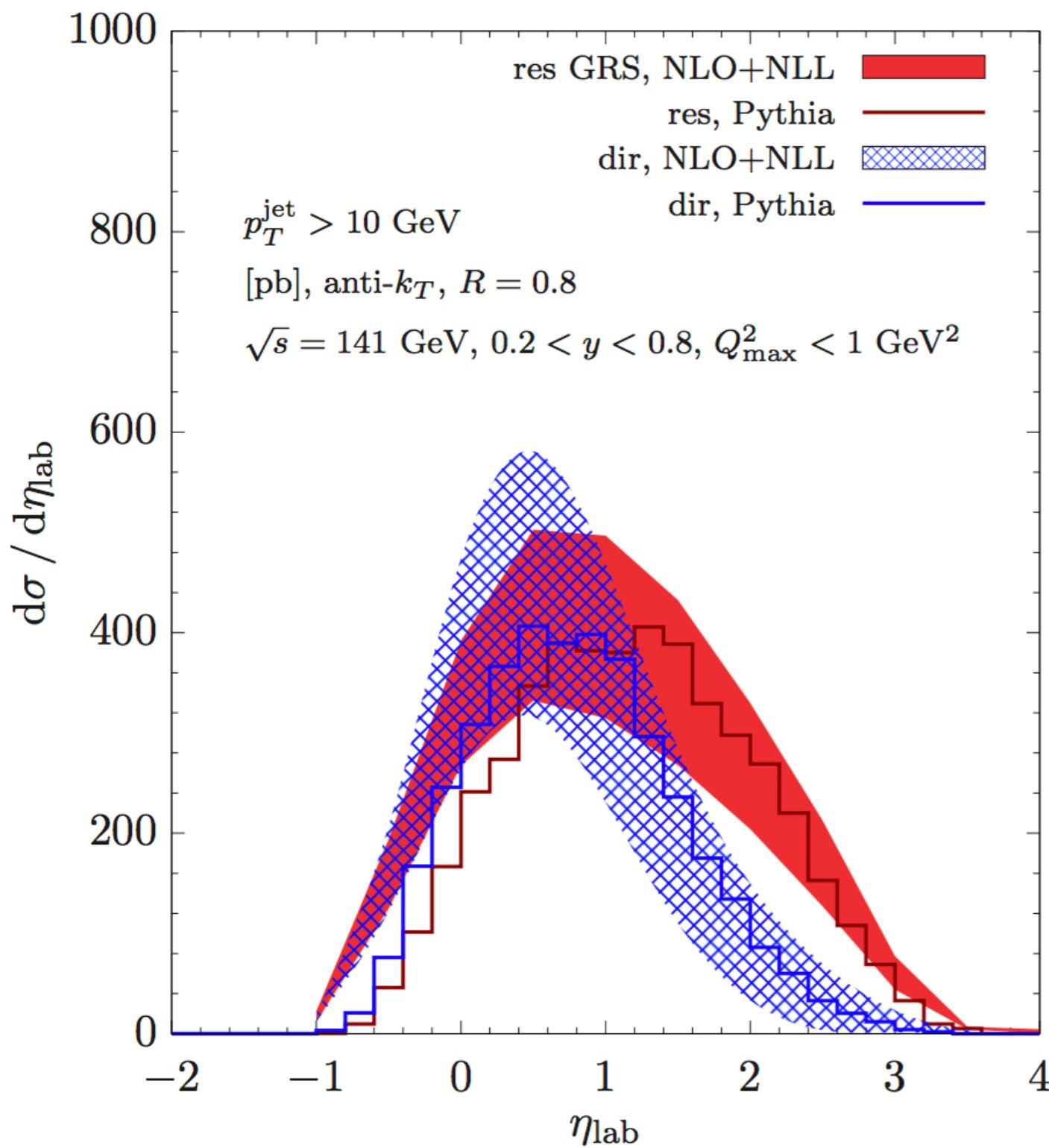
Weizsäcker-Williams spectrum
resolved: $\otimes f_{a/\gamma}$

- Jet mass

$$\frac{d\sigma}{dp_T d\eta dQ^2 dm_J} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes \mathcal{G}_c(m_J)$$

Dasgupta, Dreyer, Salam, Soyez '15
Kaufmann, Mukherjee, Vogelsang '15
Kang, FR, Vitev '16
Dai, Kim, Leibovich '16

Photoproduction of jets at the EIC



$$\ell p \rightarrow \ell' + \text{jet} + X$$

$$\eta_{\text{lab}} = \eta + \frac{1}{2} \ln \frac{E_p}{E_e}$$

$$E_e = 20 \text{ GeV}$$

$$E_p = 250 \text{ GeV}$$

- Theory uncertainties need to be studied more carefully

Outline

- Introduction
- Jet production at the EIC
- Jet substructure
- Lepton-jet correlations
- Conclusions

Jet substructure at the EIC

- Which observables are useful?
 - Sensitivity to soft physics and scales
 - Control of nonperturbative physics

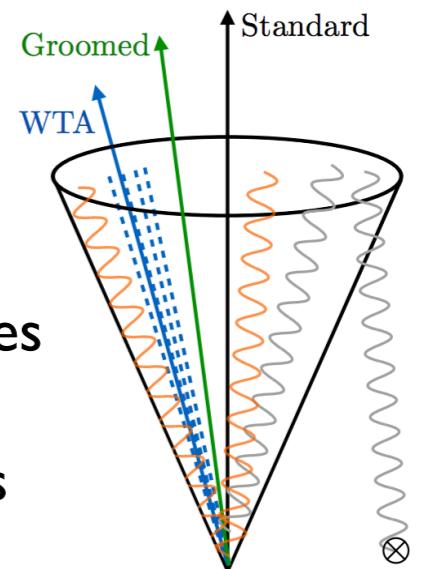
Angles between jet axes

IRC safe + control of hadronization corrections

$$\exp(-g_K \ln(\mu/\mu_0))$$

see Alessandro's talk

- Study hadronization
- Spin dependence
- Modification in eA

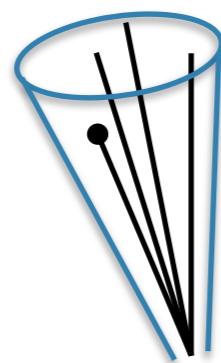


Cal, Neill, FR, Waalewijn '19

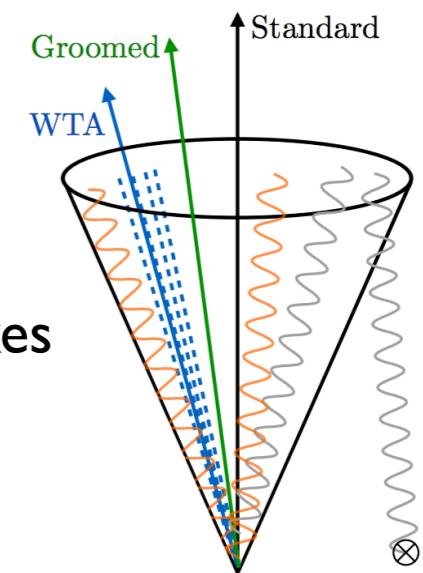
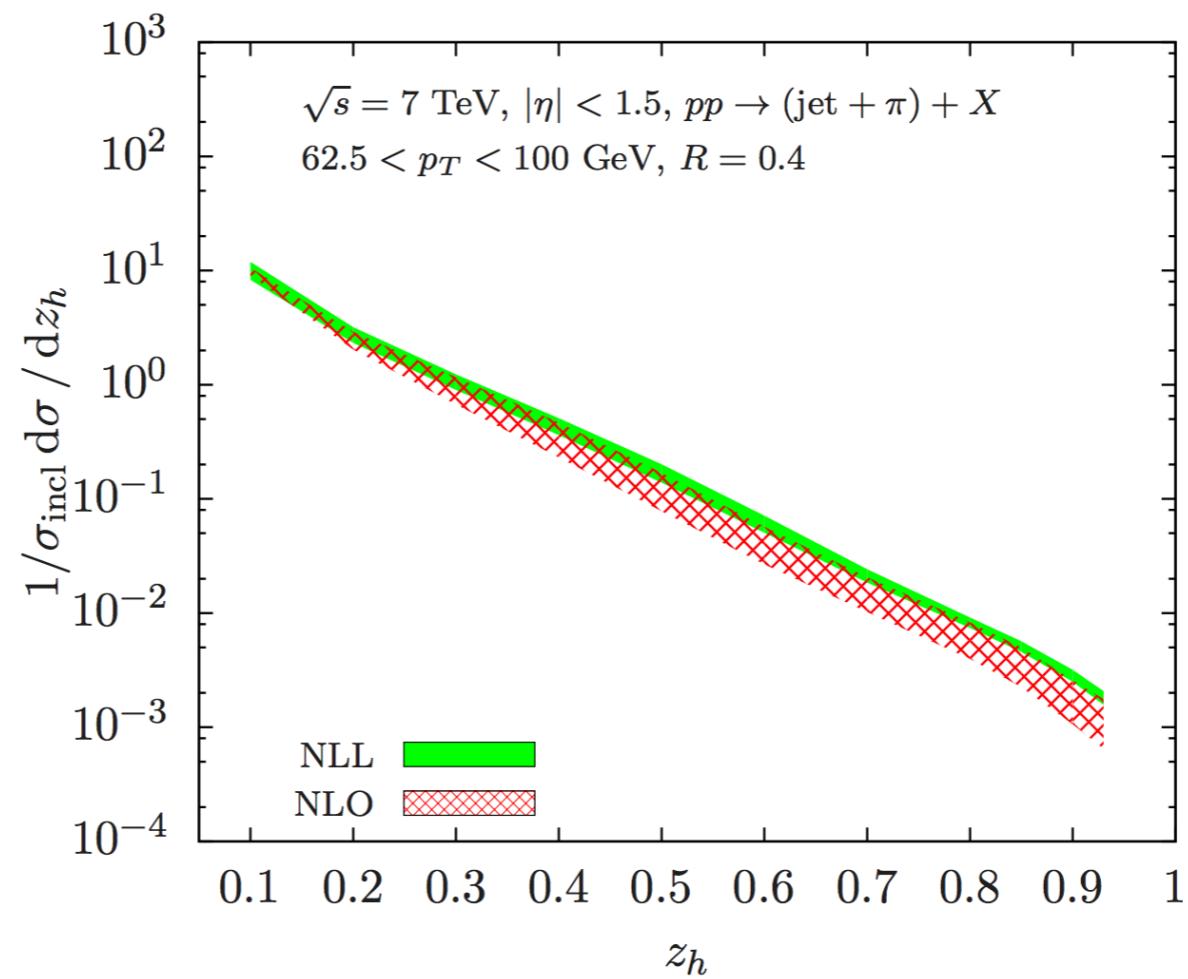
Jet substructure at the EIC

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Hadrons inside jets



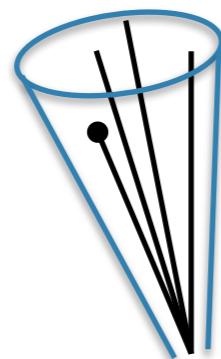
- Study collinear and TMD fragmentation functions



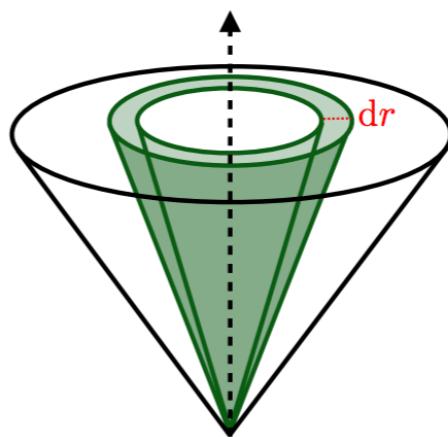
Jet substructure at the EIC

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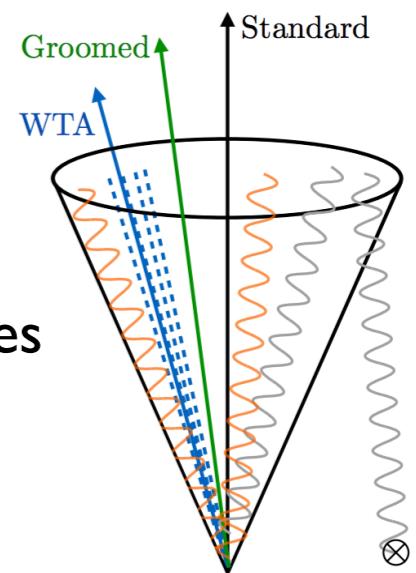
Hadrons inside jets



Jet shapes



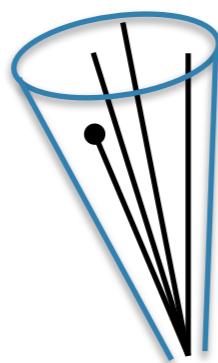
Angles between jet axes



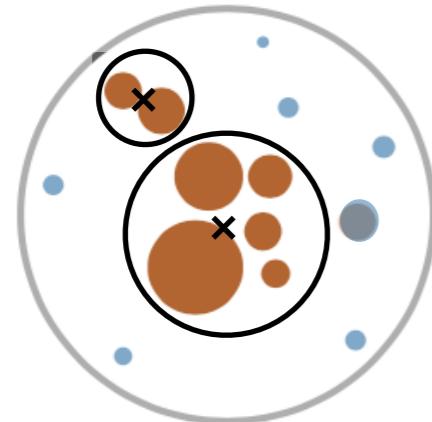
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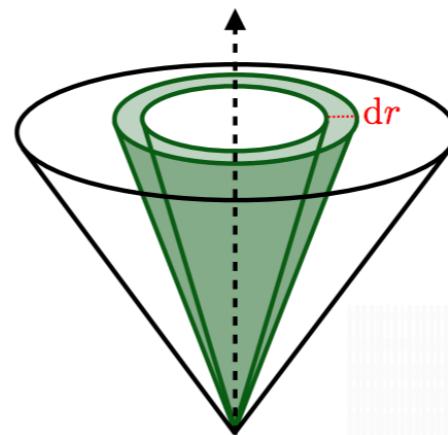
Hadrons inside jets



Soft drop grooming z_g, R_g



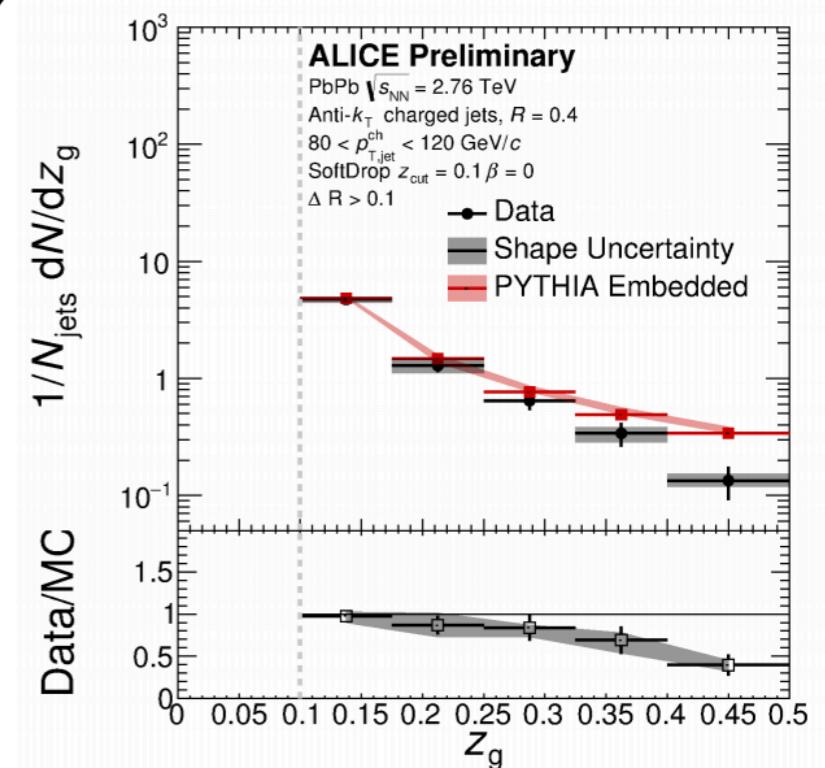
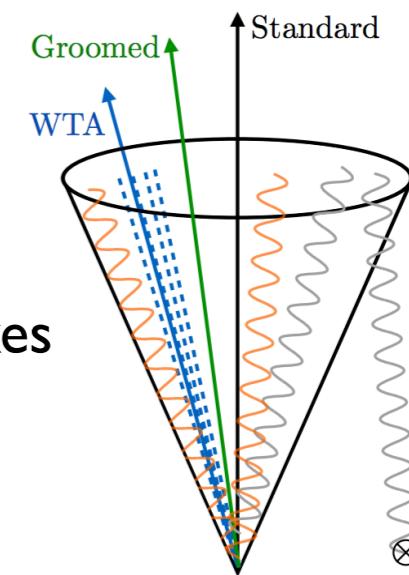
Jet shapes



ALICE 1905.02512
CMS PRL 120 (2018) 142302

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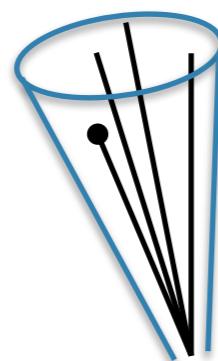
Angles between jet axes



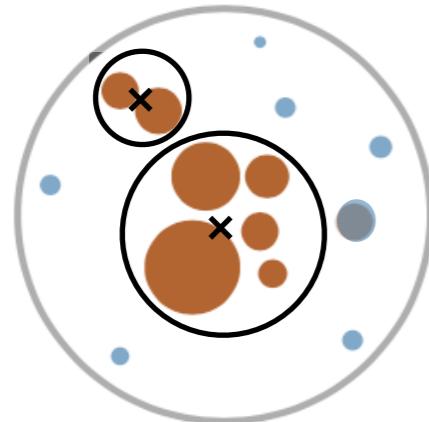
Jet substructure at the EIC

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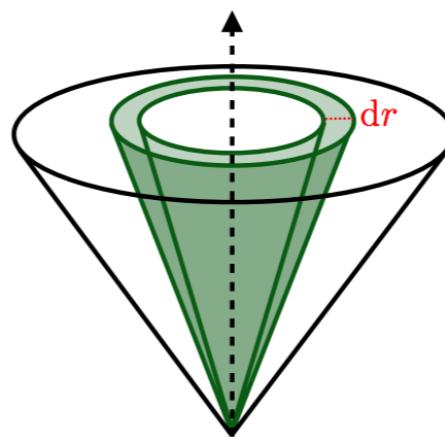
Hadrons inside jets



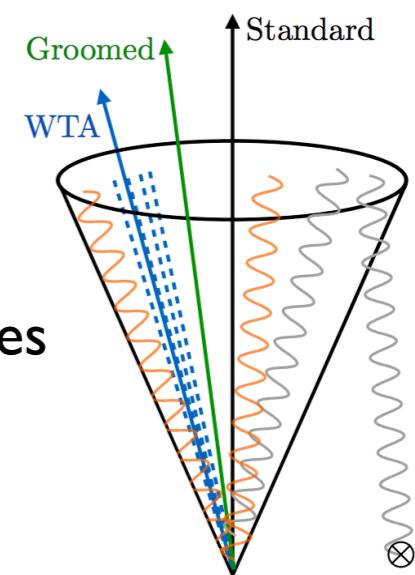
Soft drop grooming z_g, R_g



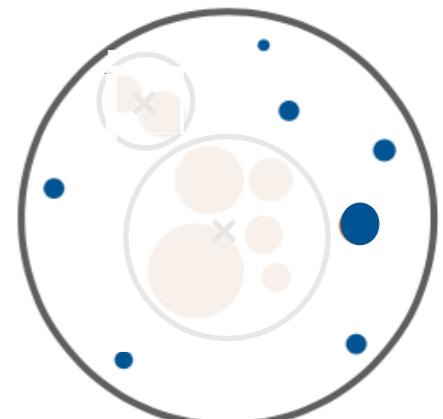
Jet shapes



Angles between jet axes



Very soft sensitive e.g. Δ_E

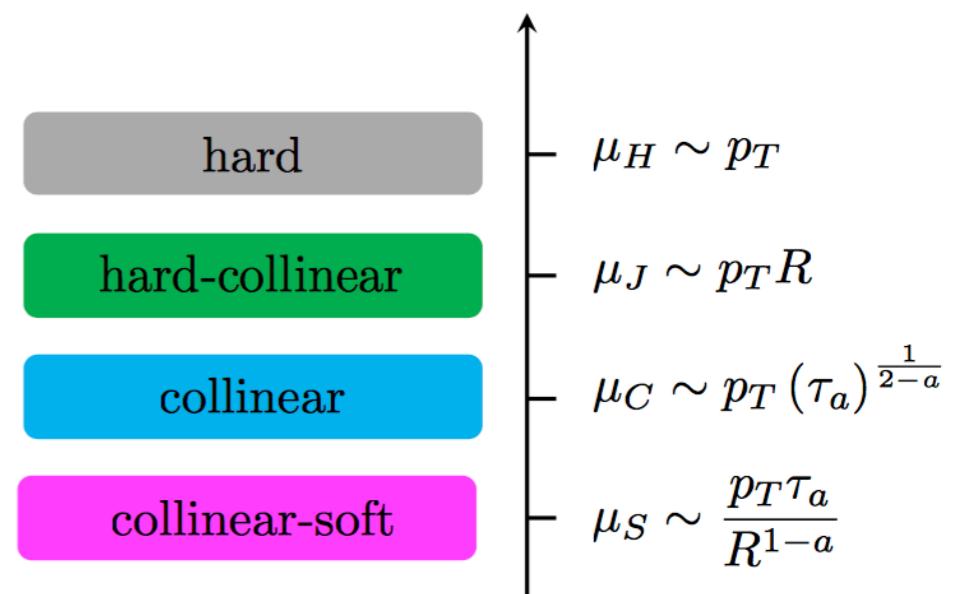


Jet angularities

Berger, Kucs, Sterman '03,
 Ellis, Vermilion, Walsh, Hornig, Lee '10,
 Hornig, Makris, Mehen '16,
 Kang, Lee, FR '18

- Family of observables with a continuous parameter a
- Jet mass ($a = 0$), jet broadening ($a = 1$)
- Event shape type of observables

$$\tau_a = \frac{1}{p_T} \sum_{i \in J} p_{Ti} \Delta R_{iJ}^{2-a}$$



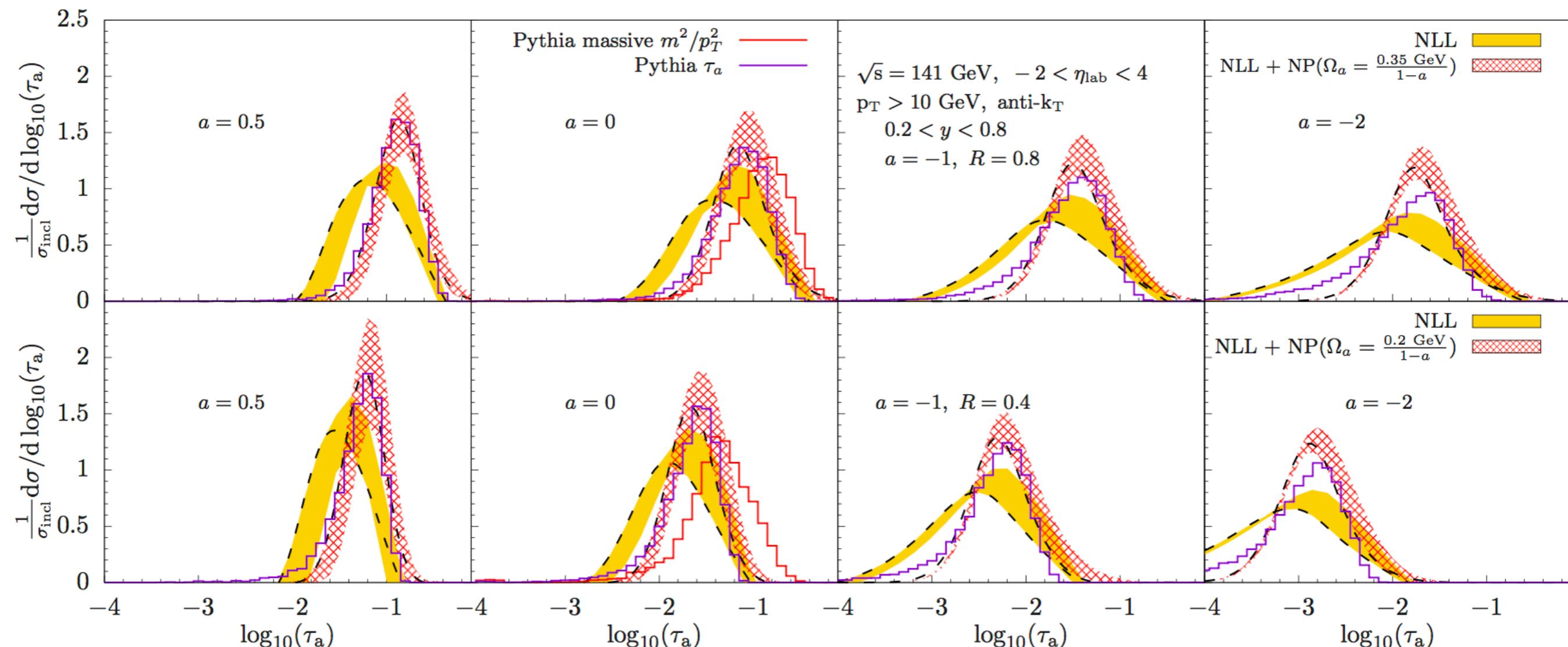
- Factorization $\tau_a^{1/(2-a)} \ll R$

$$\mathcal{G}_c(z, p_T, R, \tau, \mu) = \sum_i \mathcal{H}_{c \rightarrow i}(z, p_T R, \mu) \textcolor{blue}{C}_i(\tau, p_T, \mu) \otimes \textcolor{red}{S}_i(\tau, p_T, R, \mu)$$

- Each function has its own evolution equation e.g. $\mu \frac{d}{d\mu} C_i(\tau_a, p_T, \mu) = \int d\tau'_a \gamma_{C_i}(\tau_a - \tau'_a, p_T, \mu) C_i(\tau'_a, p_T, \mu)$

Jet angularities at the EIC

Aschenauer, Lee, Page, FR '19



CT14, GRS 99 PDFs

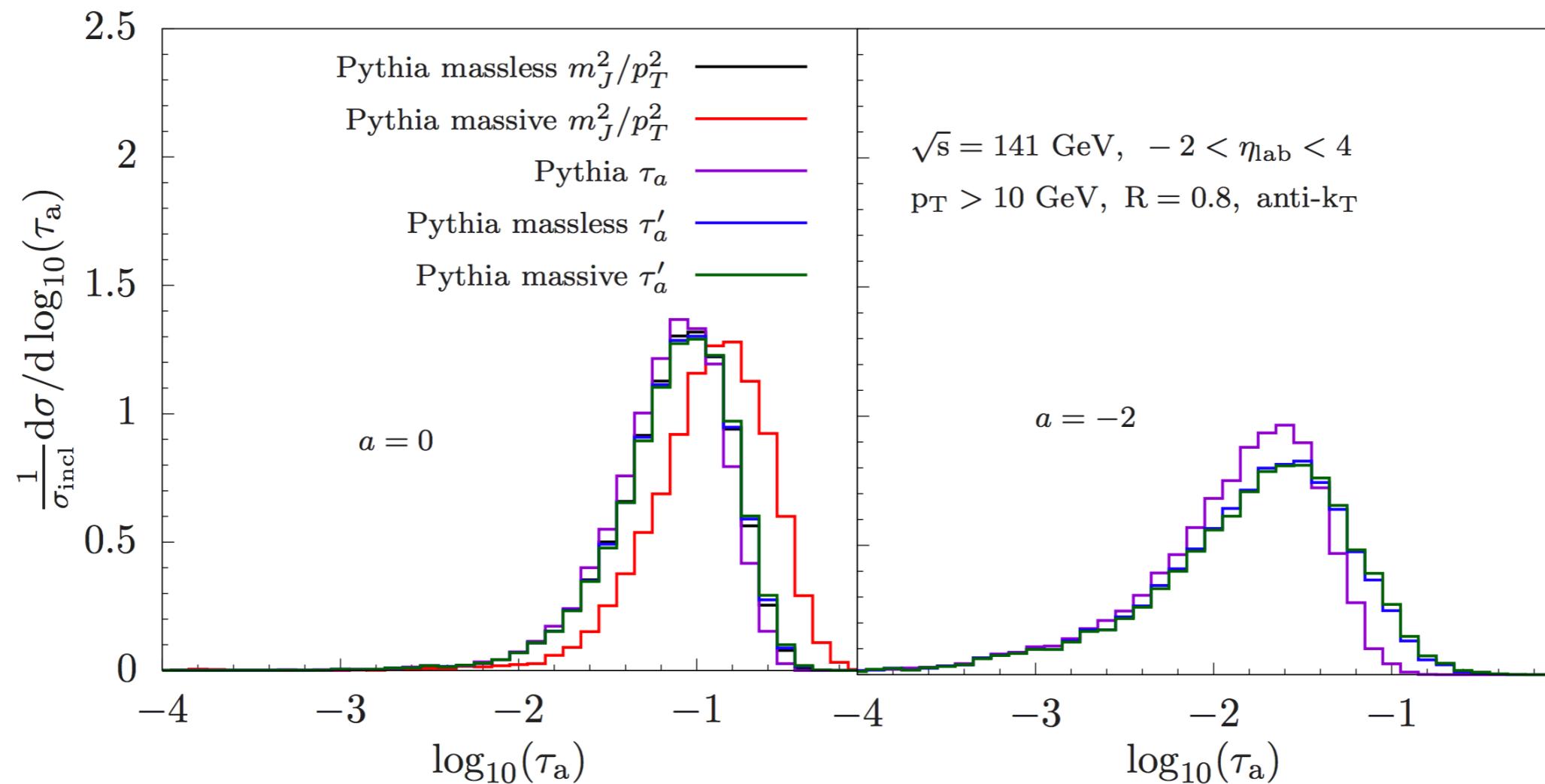
Nonperturbative shape function $F(k) = \frac{4k}{\Omega_a^2} \exp(-2k/\Omega_a)$

Jet angularities at the EIC

Aschenauer, Lee, Page, FR '19

- Power corrections

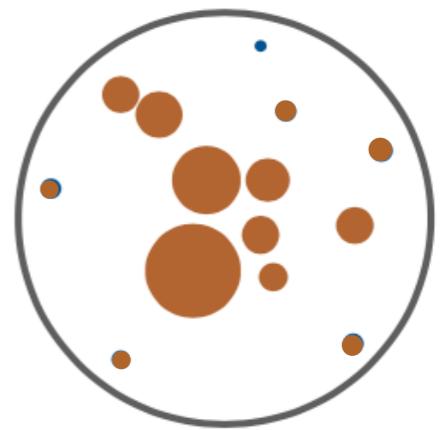
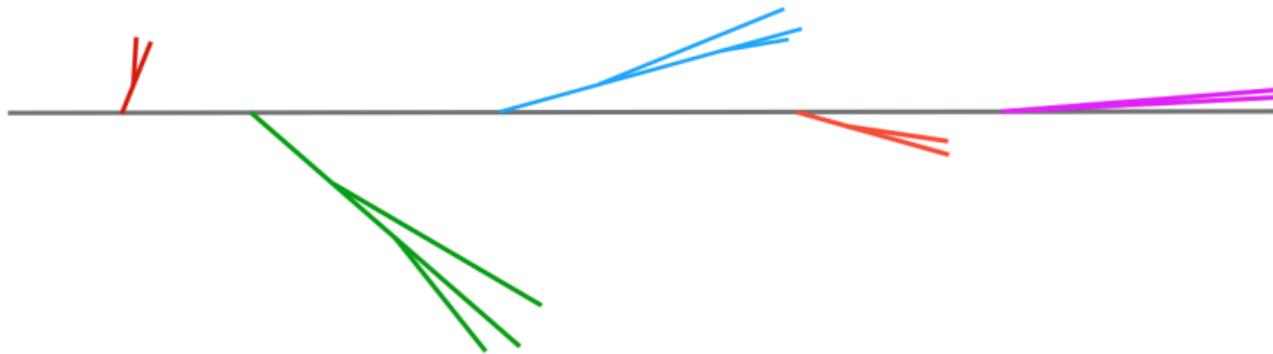
- e.g. $m_J^2 = \left(\sum_{i \in J} p_i \right)^2$ vs. $\tau_0 = \frac{1}{p_T} \sum_{i \in J} p_{Ti} \Delta R_{iJ}^2$ vs. $\tau'_a = \frac{1}{2E_J} \sum_{i \in J} |\vec{p}_T^{iJ}| \exp(-|\eta_{iJ}|(1-a))$



Soft drop grooming

*Dasgupta, Fregoso, Marzani, Salam '13
Larkoski, Marzani, Soyez, Thaler '14*

- Systematically remove soft wide-angle radiation in the jet
- Recluster jet with the C/A algorithm $d_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$

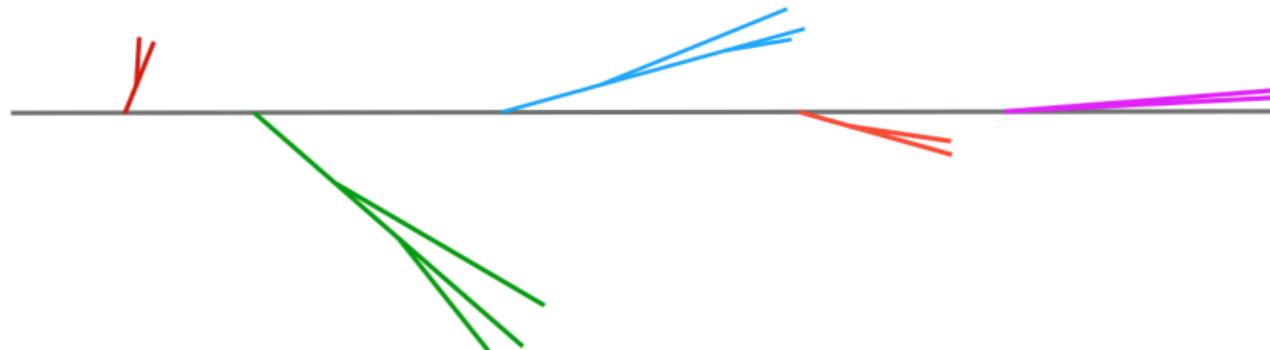


Angular ordered clustering tree

Soft drop grooming

*Dasgupta, Fregoso, Marzani, Salam '13
Larkoski, Marzani, Soyez, Thaler '14*

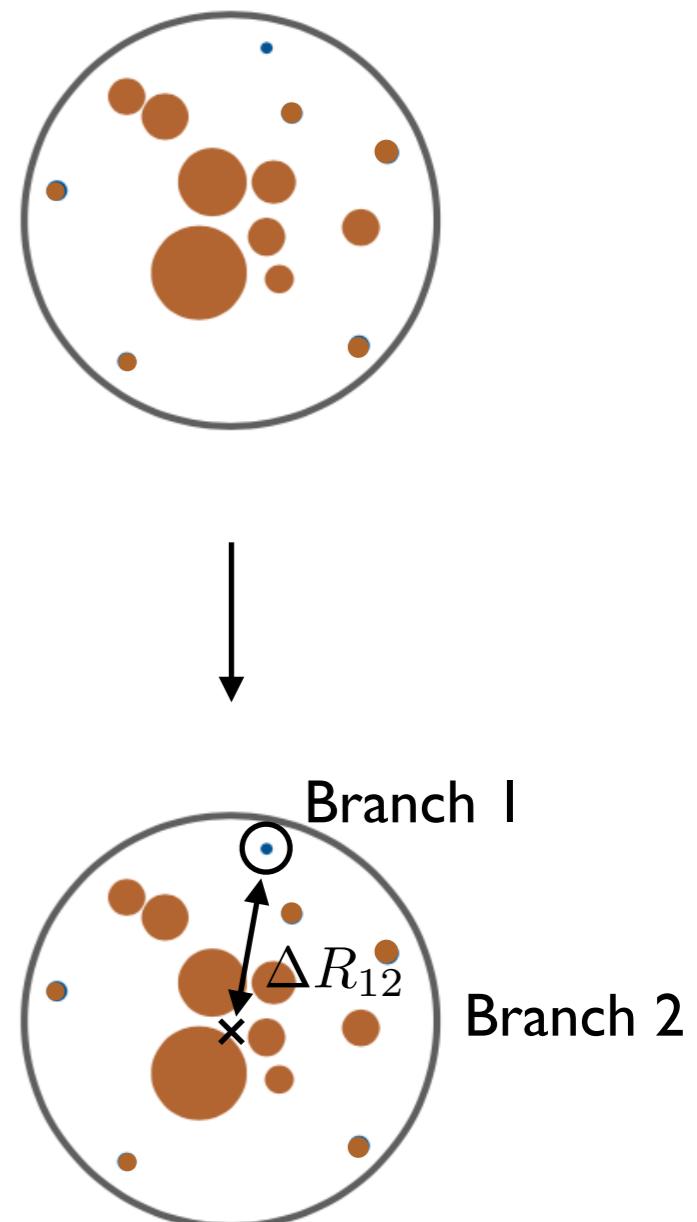
- Systematically remove soft wide-angle radiation in the jet
- Recluster jet with the C/A algorithm $d_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$



- Recursively decluster jet and check the criterion

$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R} \right)^\beta$$

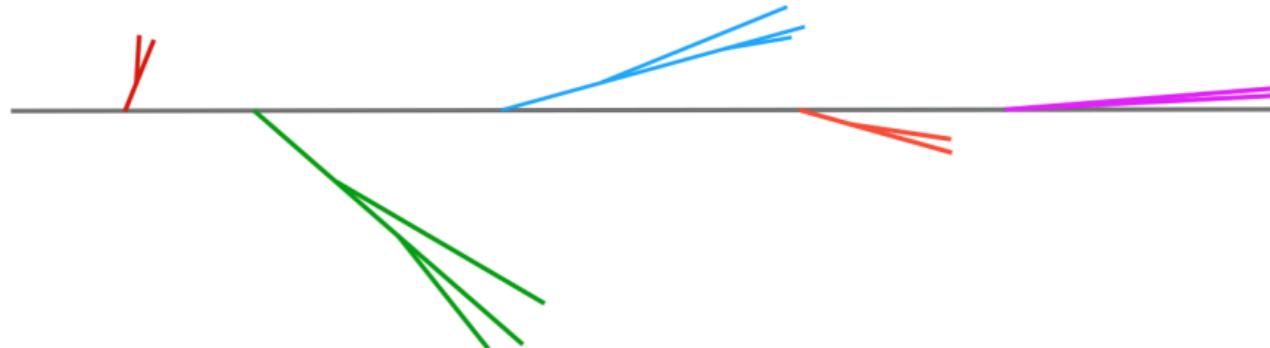
$$\Delta R_{12}^2 = \Delta\eta^2 + \Delta\phi^2$$



Soft drop grooming

Dasgupta, Fregoso, Marzani, Salam '13
Larkoski, Marzani, Soyez, Thaler '14

- Systematically remove soft wide-angle radiation in the jet
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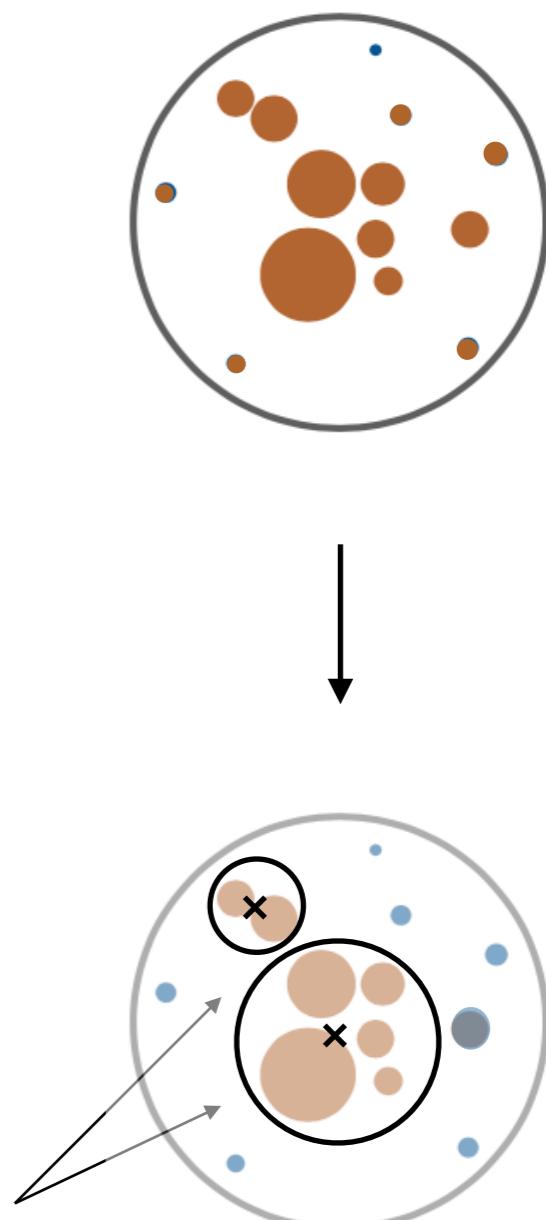


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$$\Delta R_{12}^2 = \Delta\eta^2 + \Delta\phi^2$$

Particles in the
groomed jet



Groomed jet substructure at the EIC?

- Groomed jet mass: Sensitivity to NP physics

Ungroomed: $\mu_S \sim \frac{p_T \tau}{R}$

SD groomed: $\mu_S \sim \frac{p_T \tau}{R} \left(\frac{z_{\text{cut}} R^2}{\tau^2} \right)^{\frac{1}{2+\beta}}$

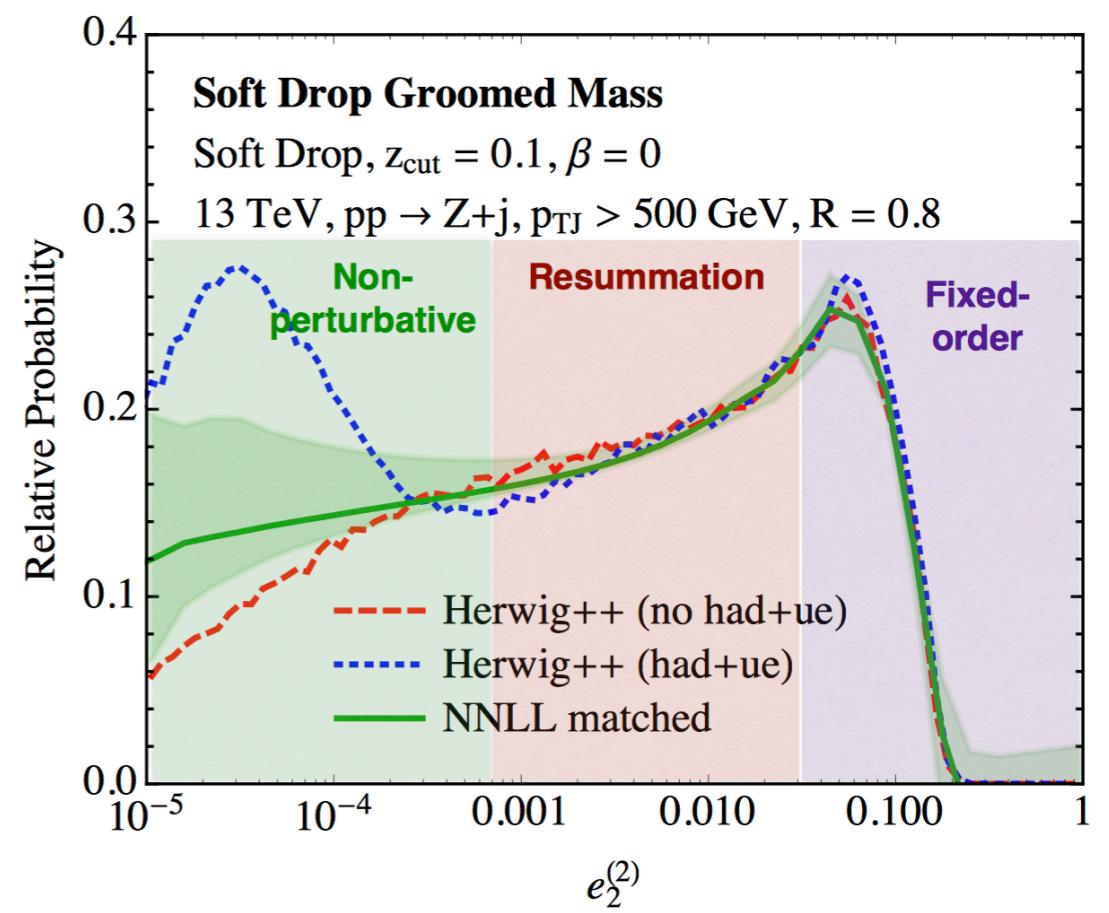
with $\mu_S = \Lambda_{\text{QCD}} \sim 1 \text{ GeV}$

→ Onset of NP physics

$$\tau_{\text{gr}} = \tau_{\text{ungr}} \left(\frac{\Lambda_{\text{QCD}}}{p_T R z_{\text{cut}}} \right)^{\frac{1}{1+\beta}}$$

Potentially 2 orders of magnitude difference for a 1 TeV jet and $z_{\text{cut}}=0.1$! *Les Houches '17*

Frye, Larkoski, Schwartz, Yan '16



$$\tau = m^2/p_T^2$$

Groomed jet substructure at the EIC?

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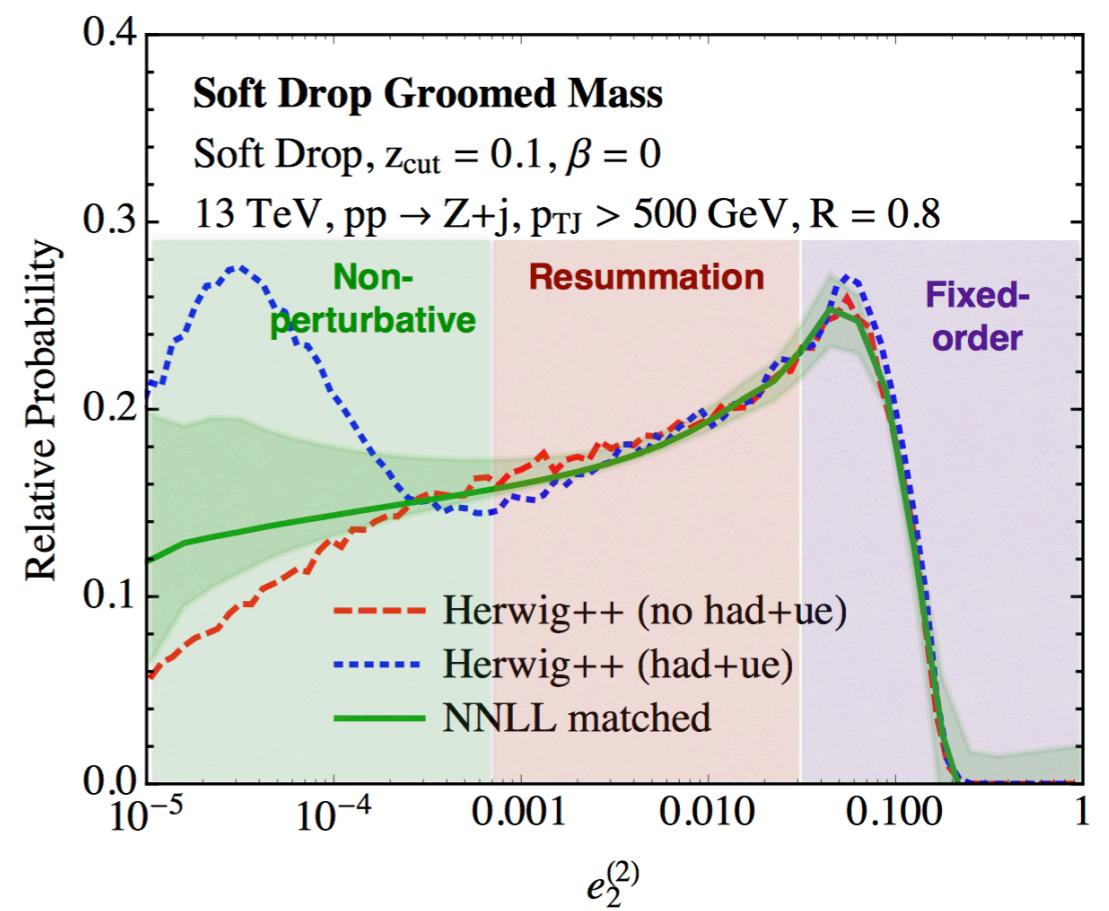
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Potentially 2 orders of magnitude difference for a 1 TeV jet and $z_{\text{cut}}=0.1!$ *Les Houches '17*

- EIC this factor is $\mathcal{O}(1)$...

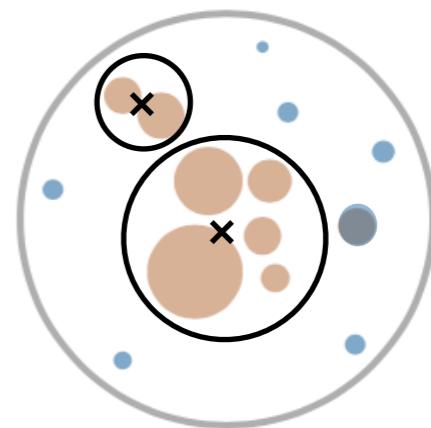
$$\tau = m^2/p_T^2$$

Frye, Larkoski, Schwartz, Yan '16



Jet substructure observables with soft drop

- Can ask different questions about the groomed jet such as
 - Groomed radius $R_g = \Delta R_{12} = \theta_g R$
 - Momentum sharing fraction $z_g = \frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}}$
 - Displacement of the jet axis $\theta_{\text{st,gr}}$
 - The jet energy drop due to grooming Δ_E
 - Soft drop jet mass
 - Angularities or energy-energy correlation functions
- These observables have interesting properties and turn out to be calculable in pQCD

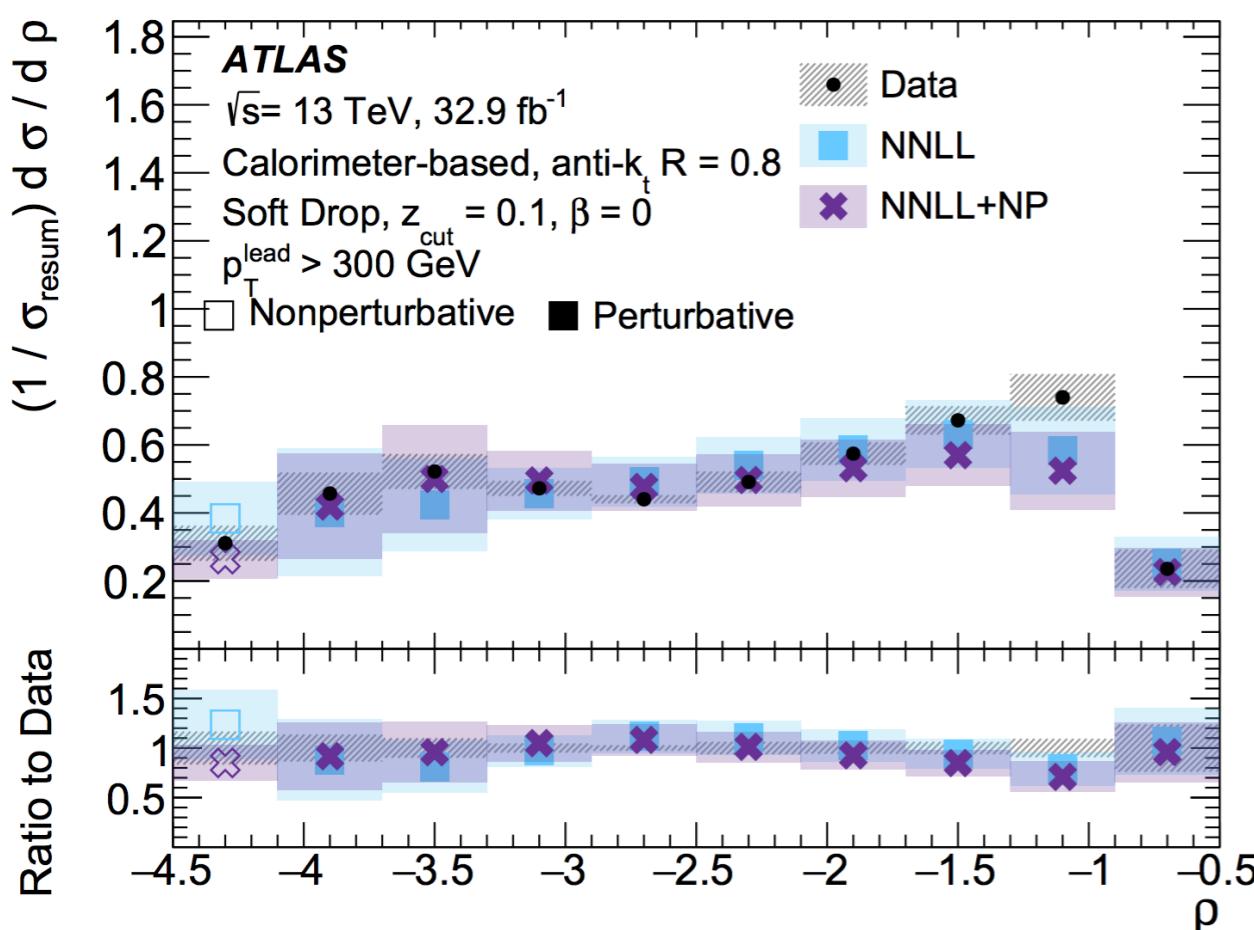


Recent results from ATLAS

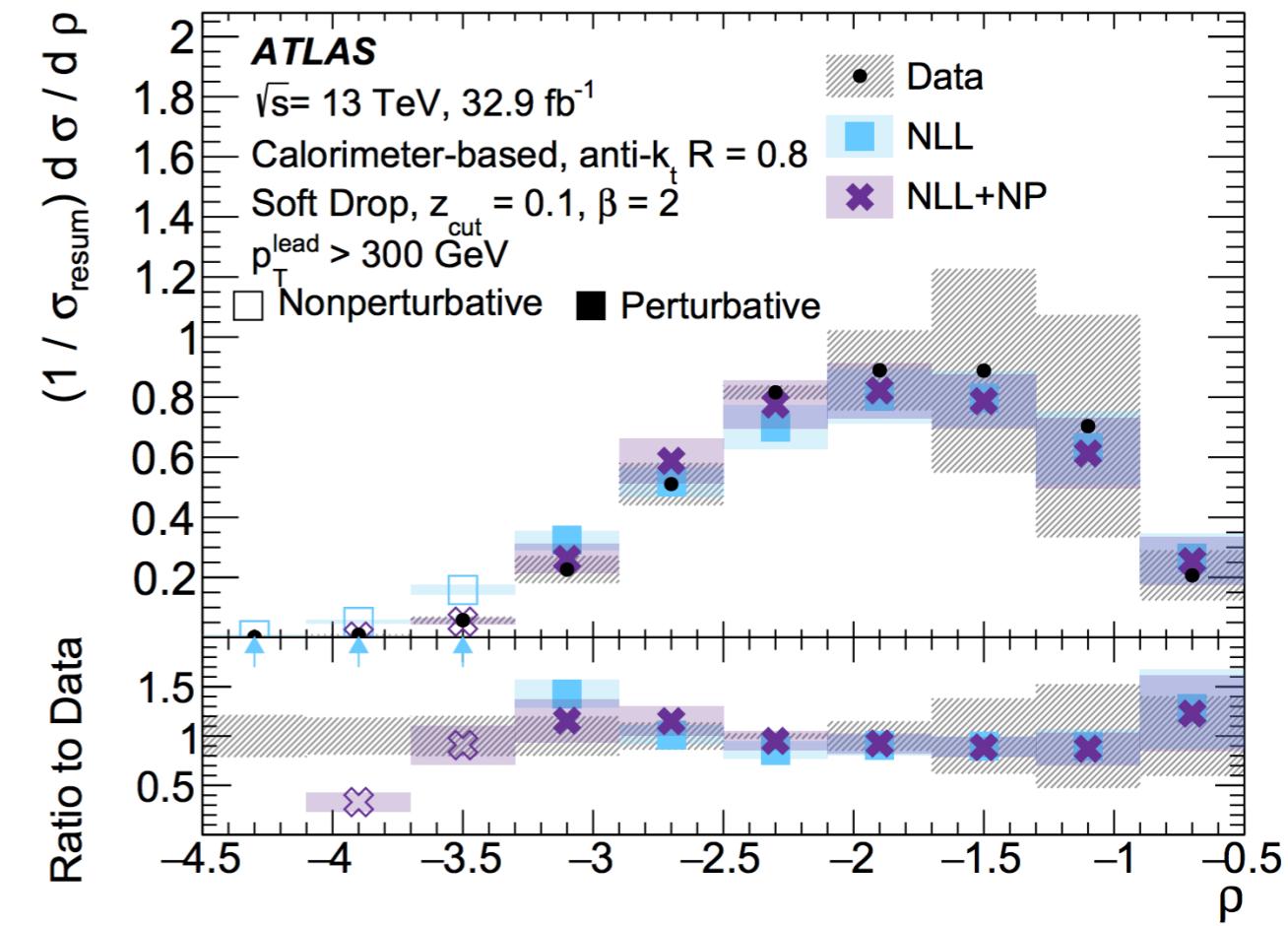
1912.09837

- The groomed jet mass

$$\beta = 0$$



$$\beta = 2$$



Kang, Lee, Liu, FR '18

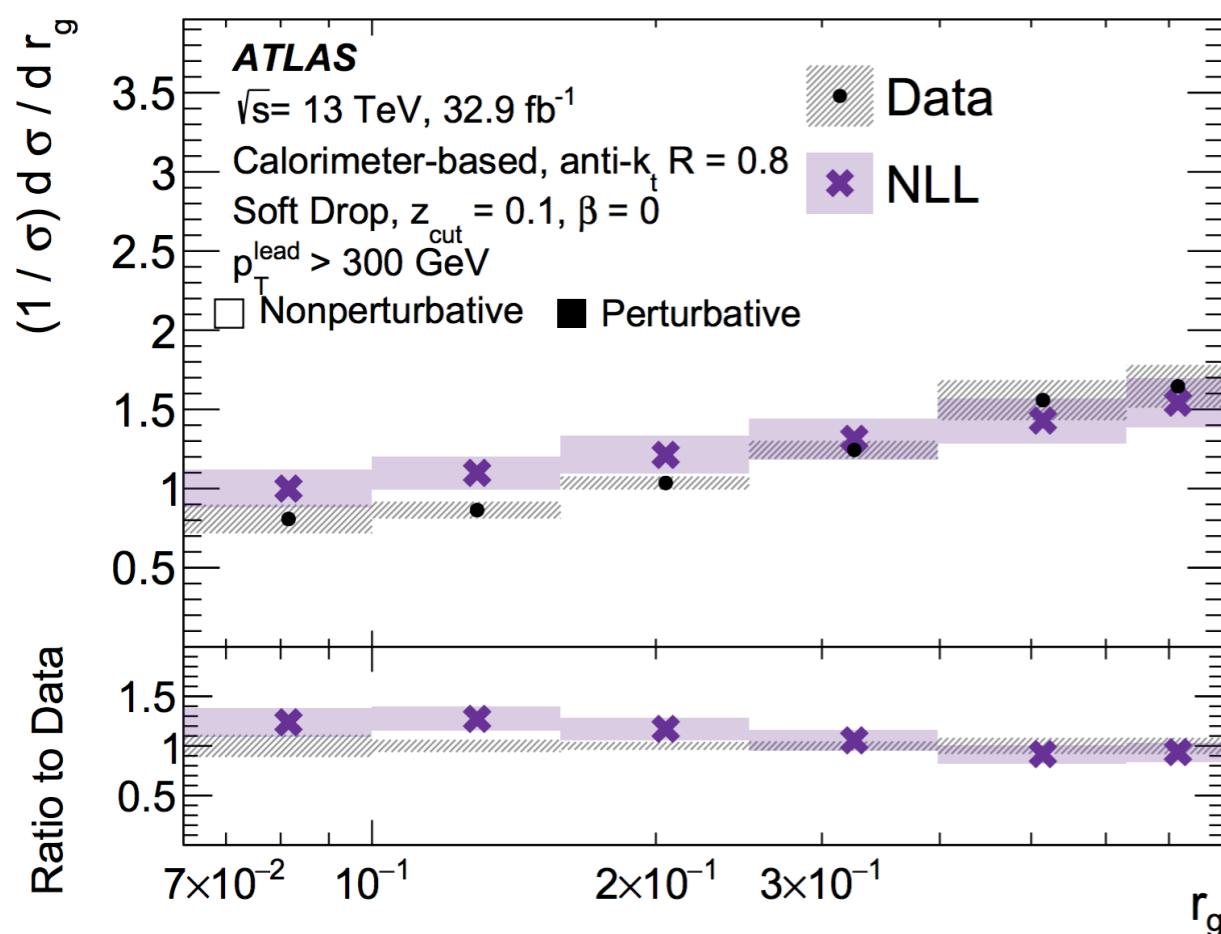
$$\rho = m^2 / p_T^2$$

Recent results from ATLAS

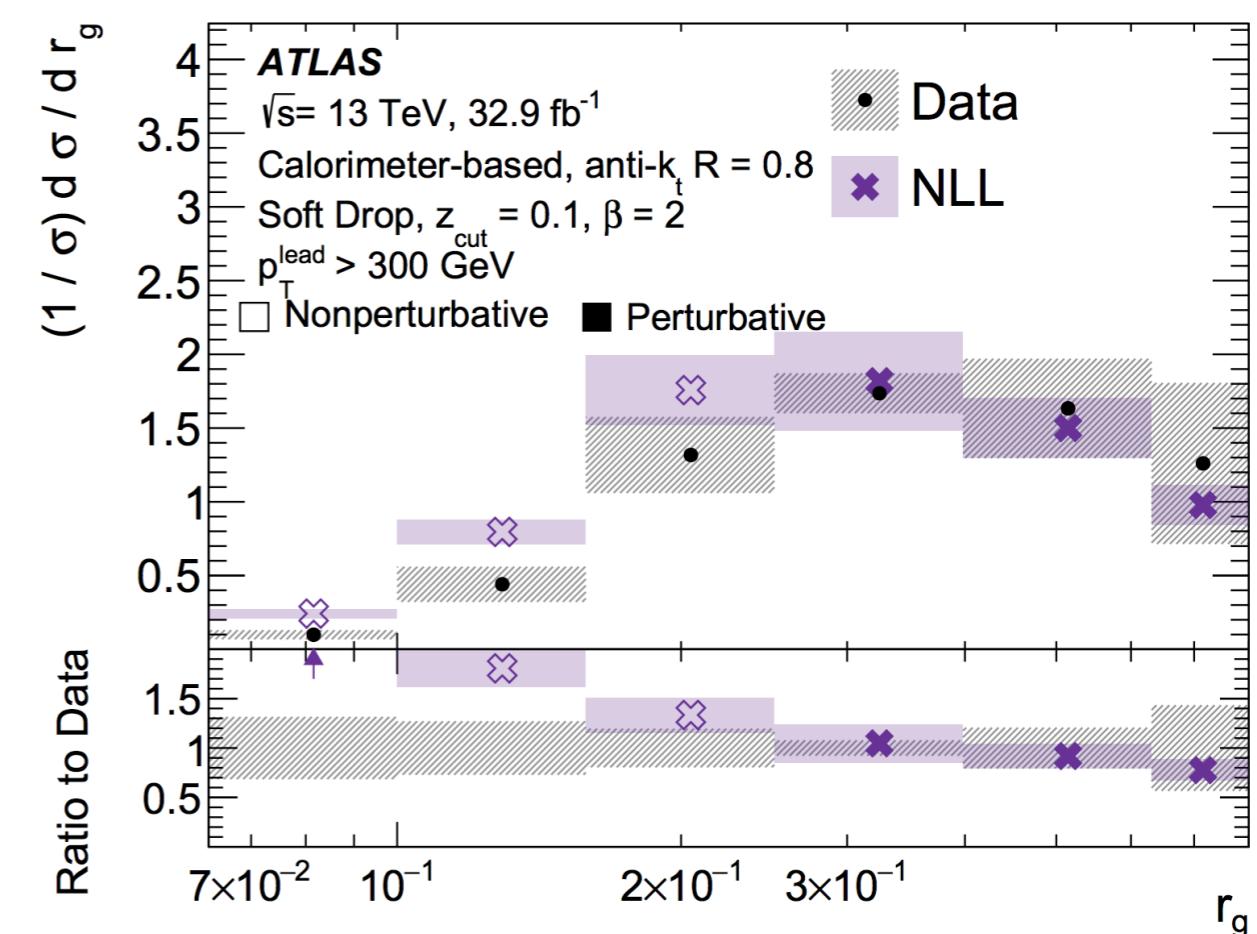
1912.09837

- The groomed jet radius R_g

$$\beta = 0$$



$$\beta = 2$$



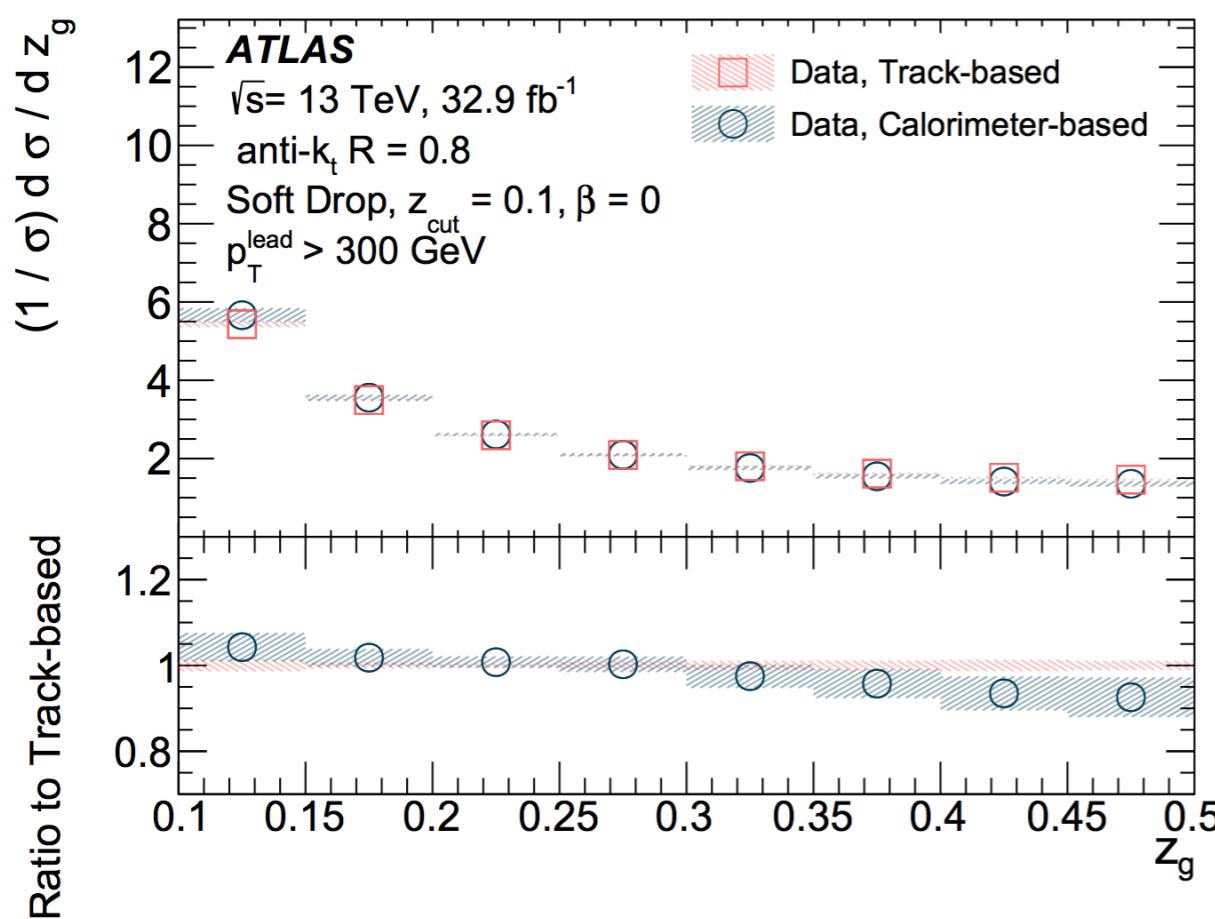
X Kang, Lee, Liu, Neill, FR '19

Recent results from ATLAS

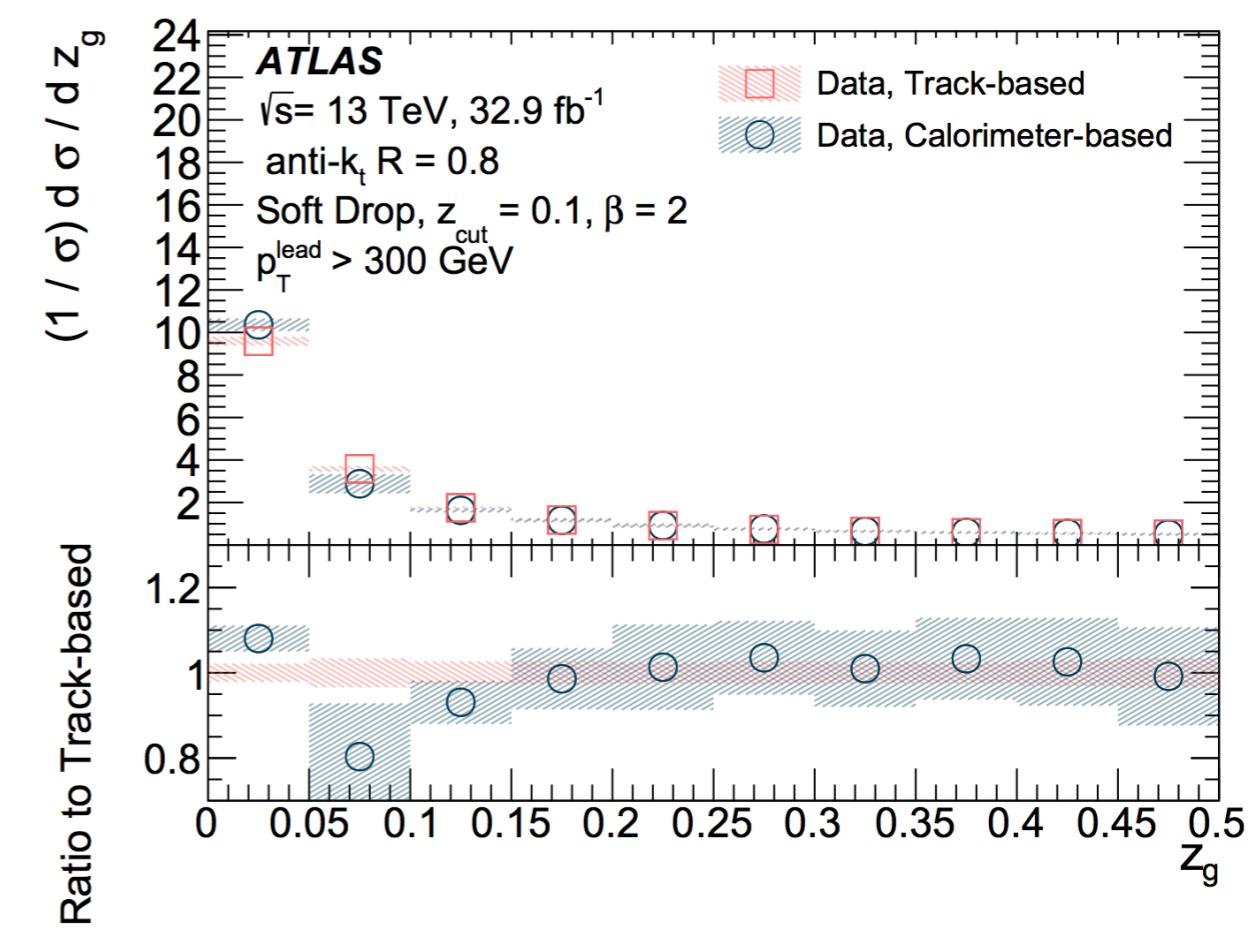
1912.09837

- The groomed momentum sharing fraction z_g

$$\beta = 0$$



$$\beta = 2$$



$$p(z_g) = \frac{1}{\sigma} \frac{d\sigma}{dz_g} = \int d\theta_g p(\theta_g) p(z_g|\theta_g)$$

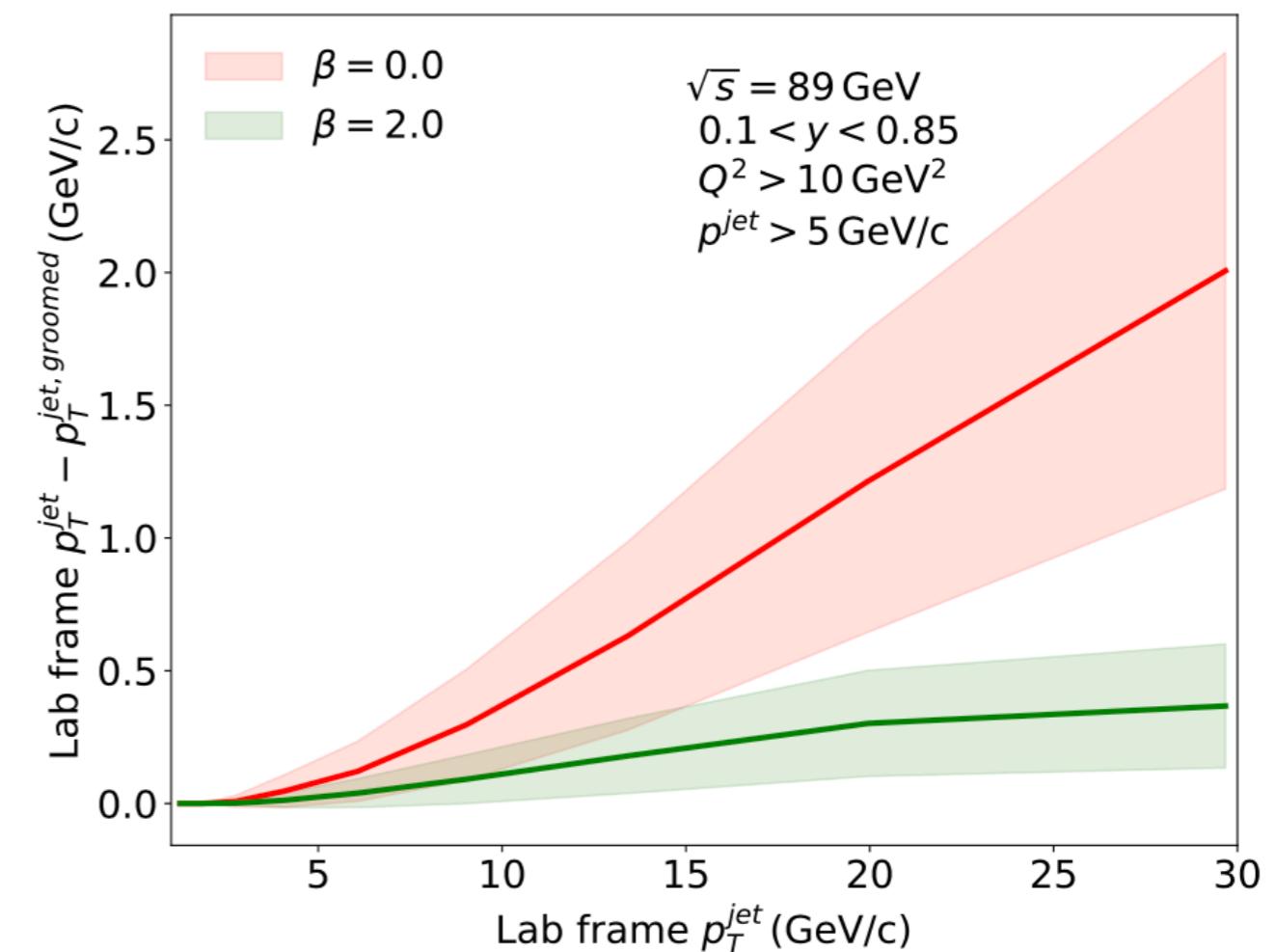
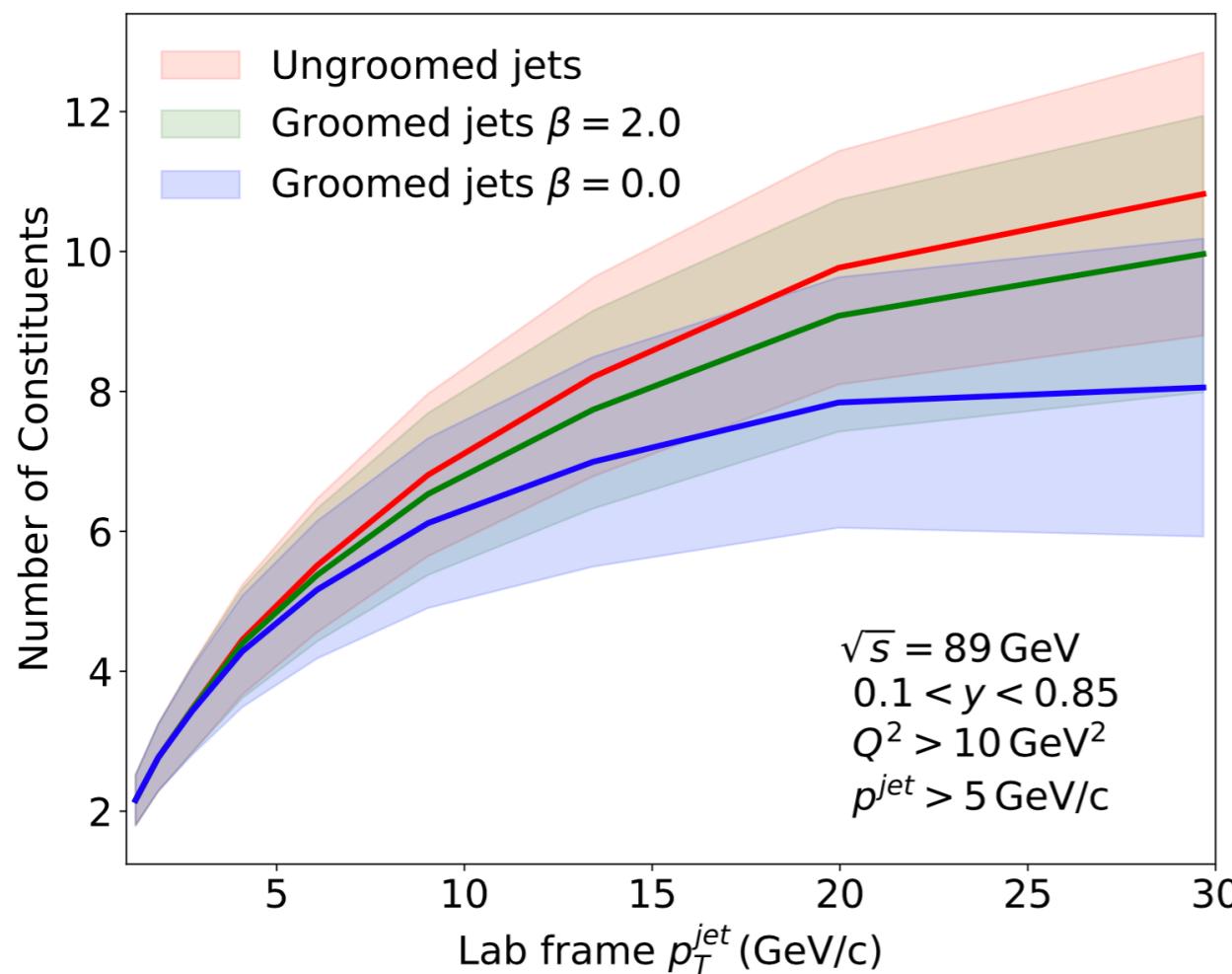
$$p(z_g|\theta_g) = \frac{\alpha_s(z_g \theta_g p_T R) \bar{P}_i(z_g)}{\int_{z_{\text{cut}}}^{1/2} dz \alpha_s(z \theta_g p_T R) \bar{P}_i(z)} \Theta(z_g - z_{\text{cut}})$$

Track functions Krohn, Schwartz, Lin, Waalewijn '12

Larkoski, Marzani, Thaler '15

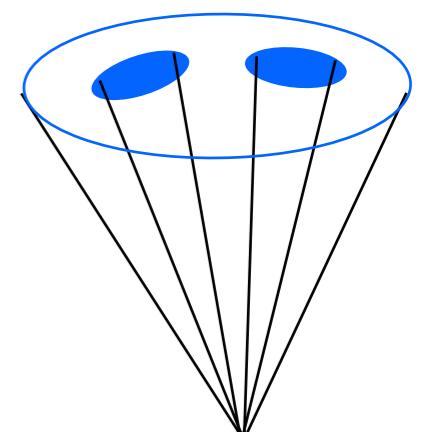
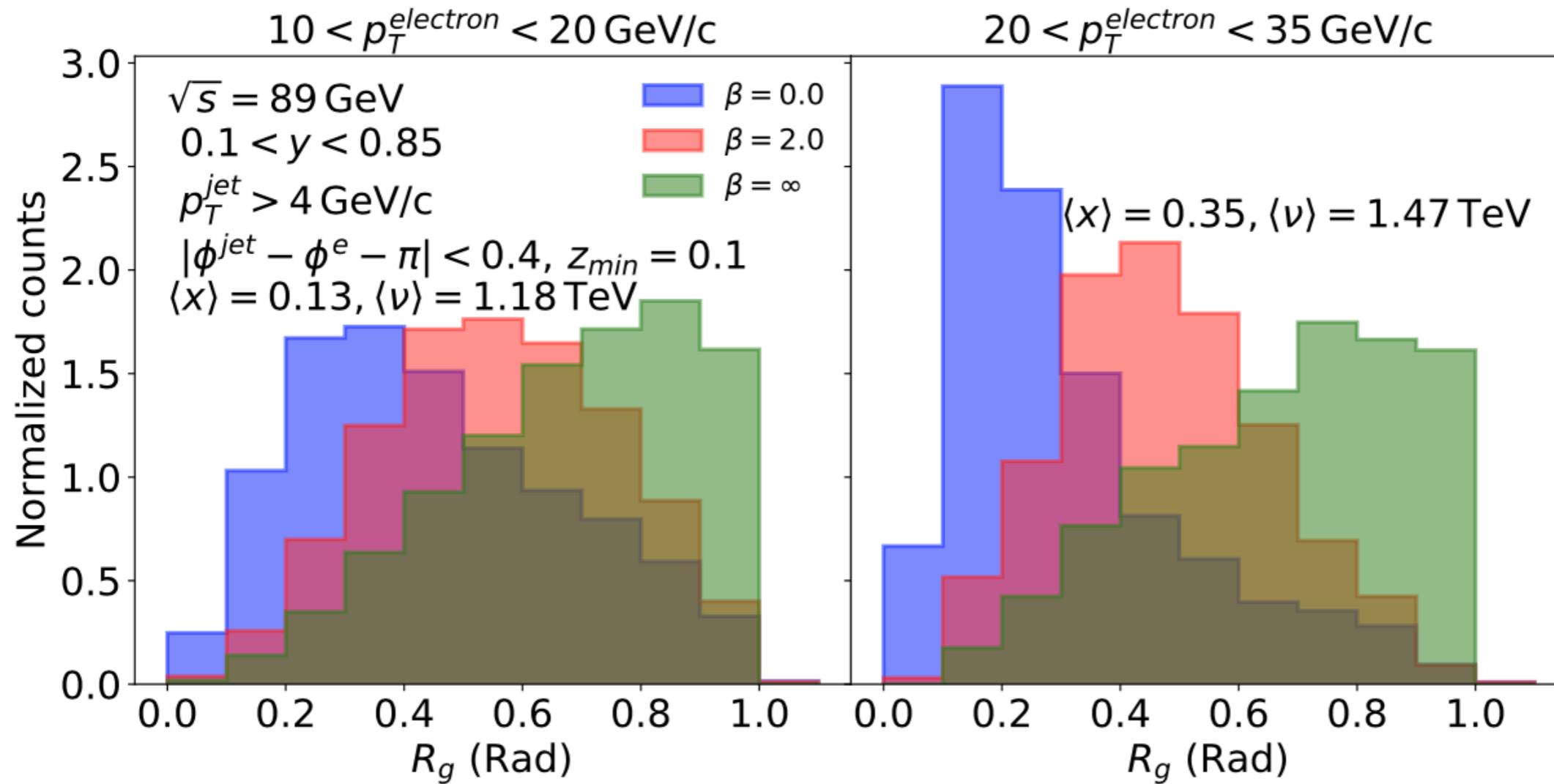
Groomed jet substructure at the EIC

Arratia, Jacak, FR, Song '19



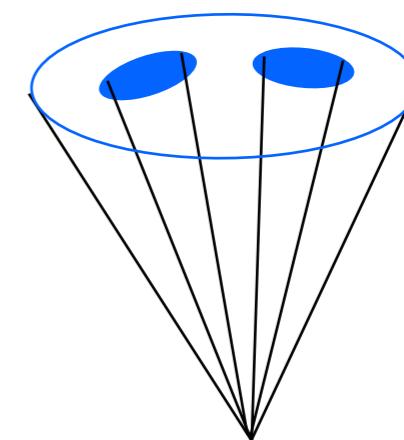
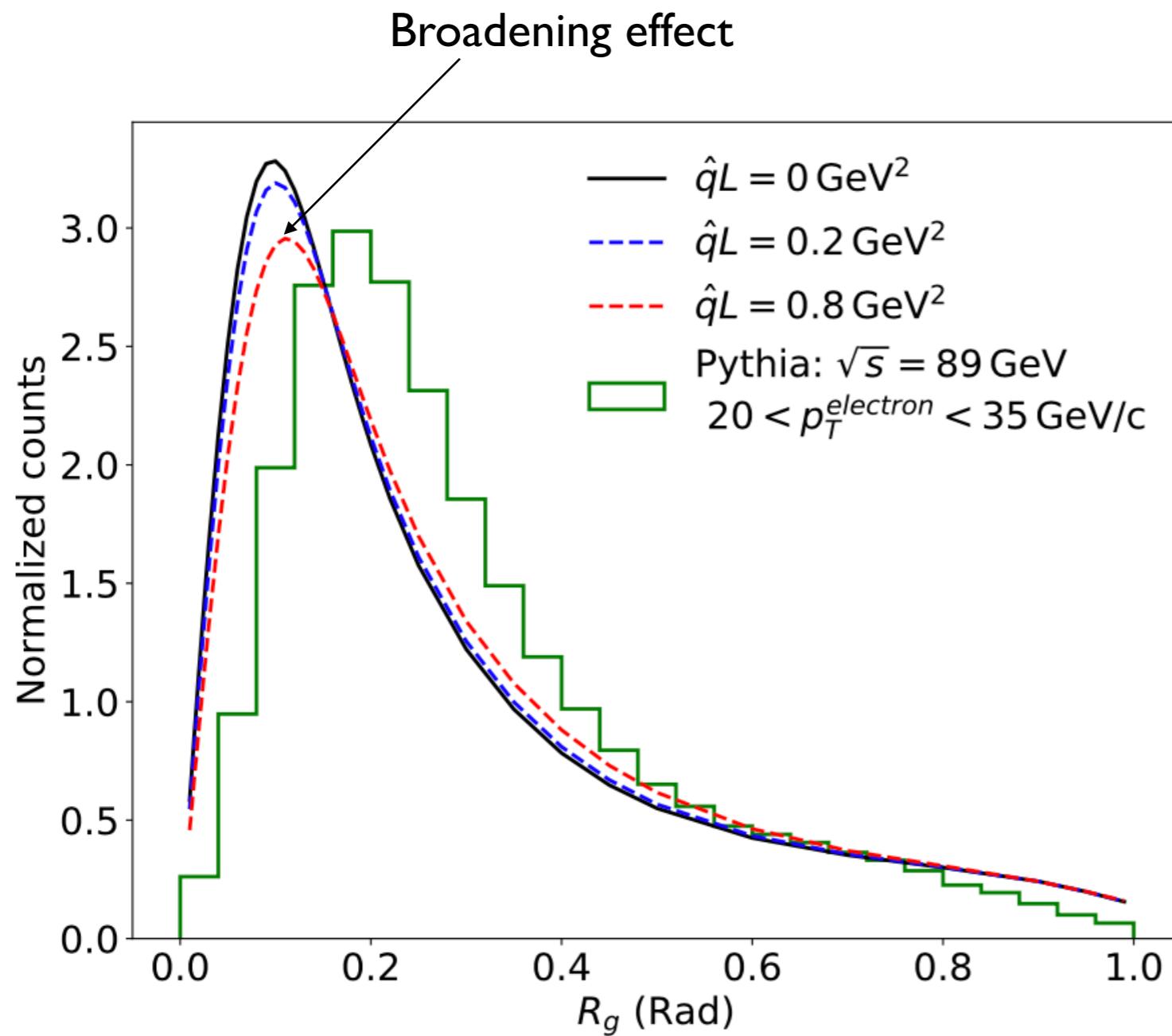
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Groomed jet substructure at the EIC

Arratia, Jacak, FR, Song '19
FR, Xiao, Yuan '19

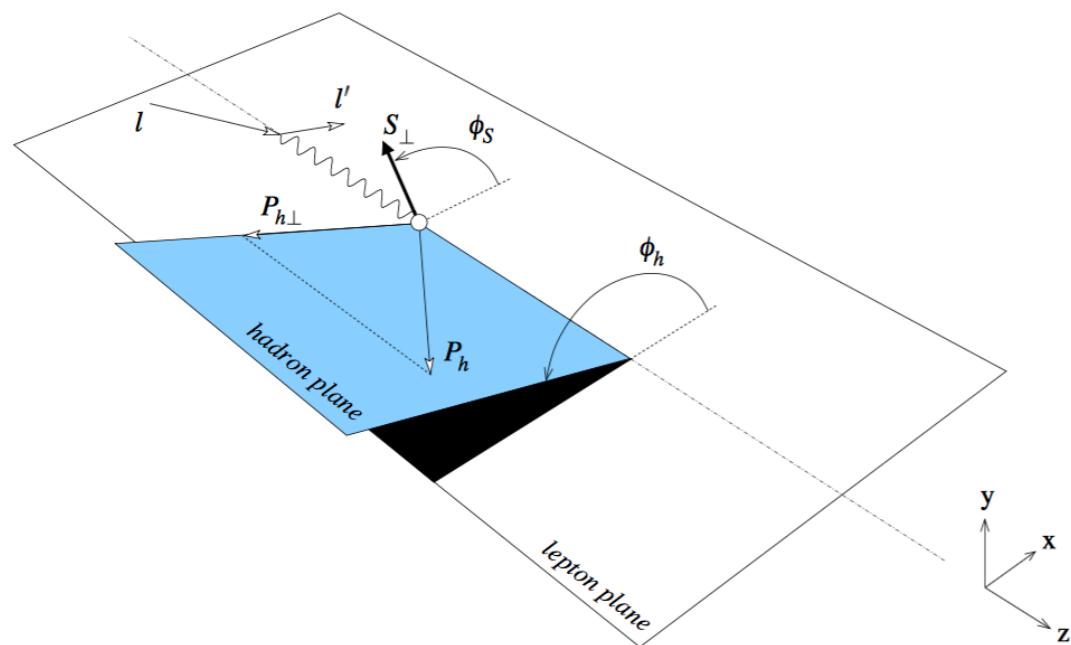


Outline

- Introduction
- Jet production at the EIC
- Jet substructure
- Lepton-jet correlations
- Conclusions

Measurement of TMD PDFs at the EIC

- Semi-Inclusive Deep-Inelastic Scattering (SIDIS)
- Measure hadrons with low transverse momentum



$$\frac{d\sigma}{dx dy d\psi dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xy Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} \right. \\ \left. + \dots \right.$$

See Alessandro Bacchetta
and Marco Radici's talks

→ Sensitivity to (polarized) TMD PDFs

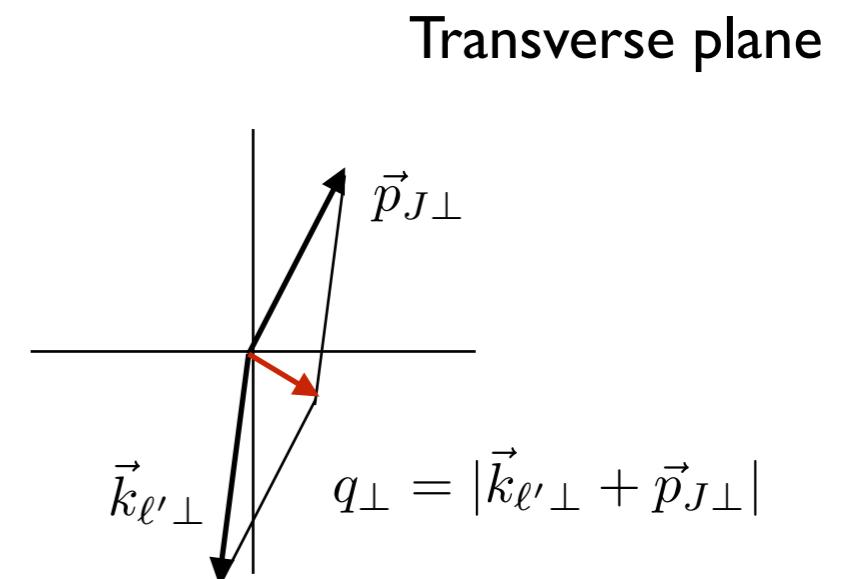
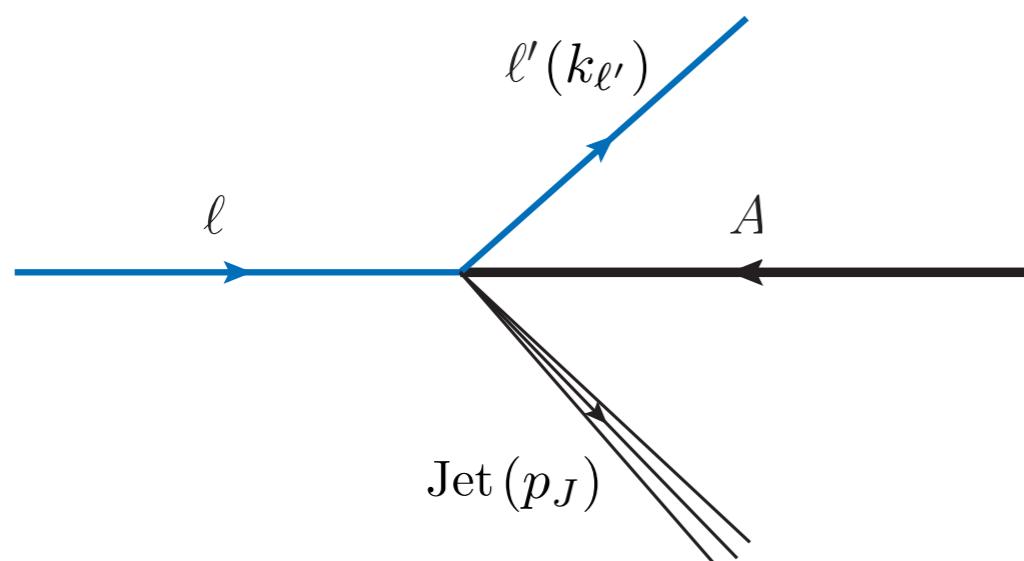
- Complementary process using jets? Universality?

Lepton-Jet Correlations

Liu, FR, Vogelsang, Yuan '18

- Require high p_T jet
- Measure imbalance q_\perp between lepton and jet in the lab frame

$$\frac{d\sigma}{dy_{\ell'} d^2 k_{\perp \ell'} d^2 q_\perp}$$



- Spin asymmetries and eA collisions
- Analogous to e.g. $pp \rightarrow$ di-jets + X
- CM or laboratory frame; close analogy to pp collisions at RHIC & the LHC

Boer, Vogelsang '04
Vogelsang, Yuan '07
Sun, Yuan, Yuan '15

Lepton-Jet Correlations

Liu, FR, Vogelsang, Yuan '18

- TMD factorization for small q_\perp

$$\ell(k) + A(P) \rightarrow \ell'(k_\ell) + \text{Jet}(P_J) + X$$

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

Hard

Quark TMD

Soft

- Small q_\perp resummation achieved in b-space

$$\frac{d^5\sigma(\ell p \rightarrow \ell' J)}{dy_\ell d^2 k_{\ell\perp} d^2 q_\perp} = H(Q, R, \mu_F) \int \frac{d^2 b_\perp}{(2\pi)^2} e^{ik_\perp \cdot b_\perp} e^{-S_{\text{pert}}^q(b_\star) - S_{\text{NP}}^q(b_\perp) + \Gamma_s(b_\perp)} \sum_i C_{q/i}(x, \mu_b/\mu) \otimes f_i(x, \mu_b)$$

with Sudakov exponent $S_{\text{pert}}^q(b_\perp) = \frac{1}{2} \int_{\mu_b^2}^{k_{\ell\perp}^2} \frac{d\mu^2}{\mu^2} \left[A_q(\alpha_s(\mu)) \ln \frac{\hat{s}}{\mu^2} + B_q(\alpha_s(\mu)) \right]$

+ non-global logarithms

see also: Gutierrez-Reyes, Makris, Vaidya, Scimemi, Zoppi '19

Azimuthal lepton-jet correlation

Liu, FR, Vogelsang, Yuan '18

- Use azimuthal angle ϕ instead of q_\perp

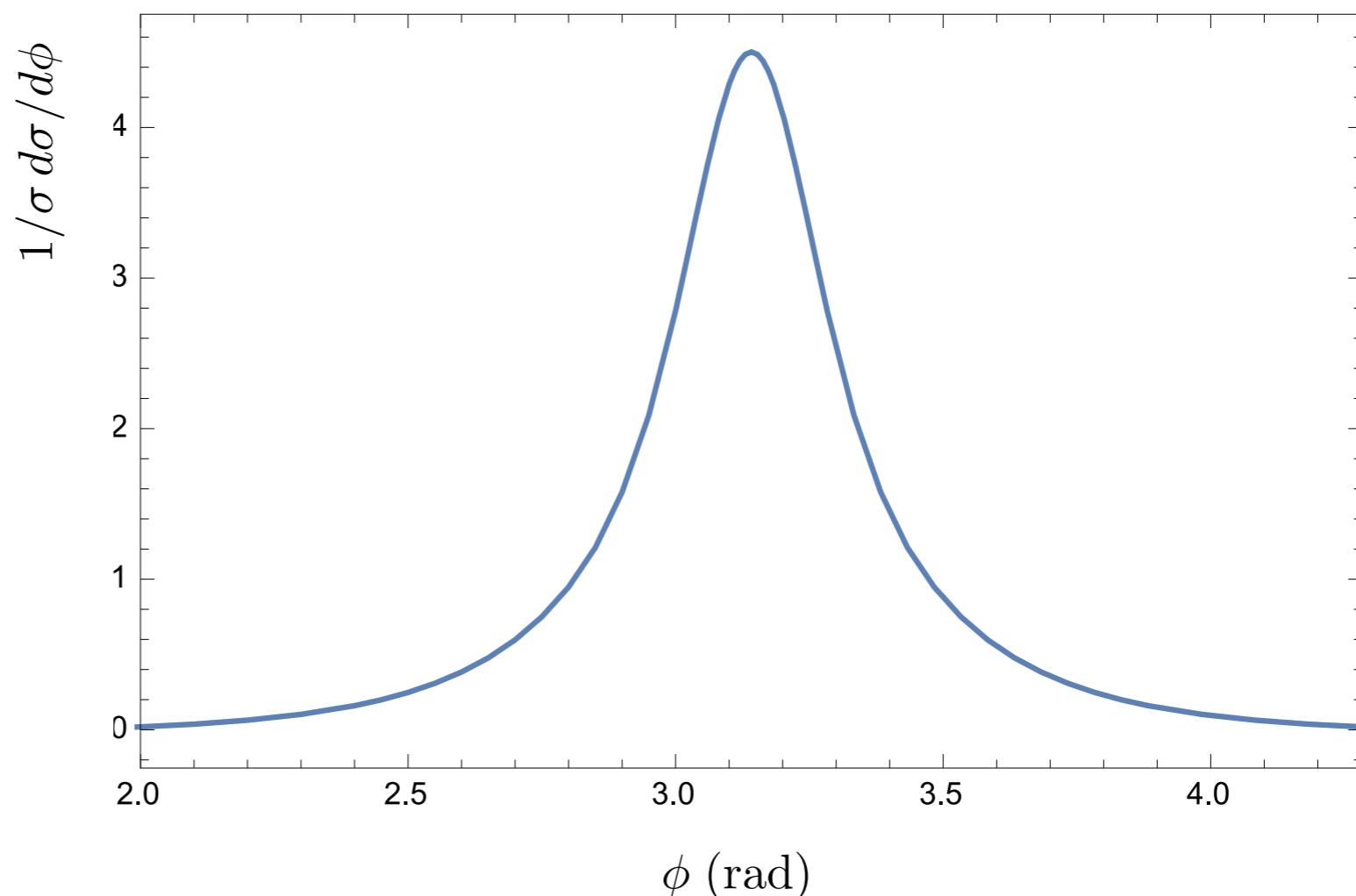
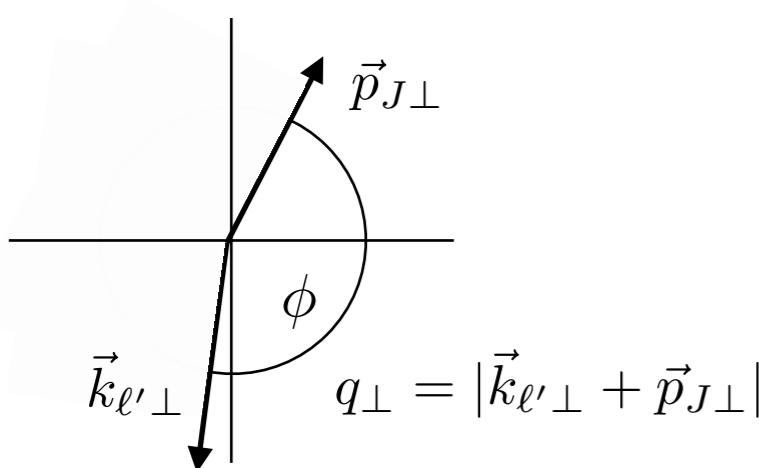
$$\ell(k) + A(P) \rightarrow \ell'(k_\ell) + \text{Jet}(P_J) + X$$

- Sample EIC kinematics

$$\sqrt{s} = 80 \text{ GeV}$$

$$k_{\ell' \perp} = 5 \text{ GeV}$$

$$5 < p_\perp < 10 \text{ GeV}$$

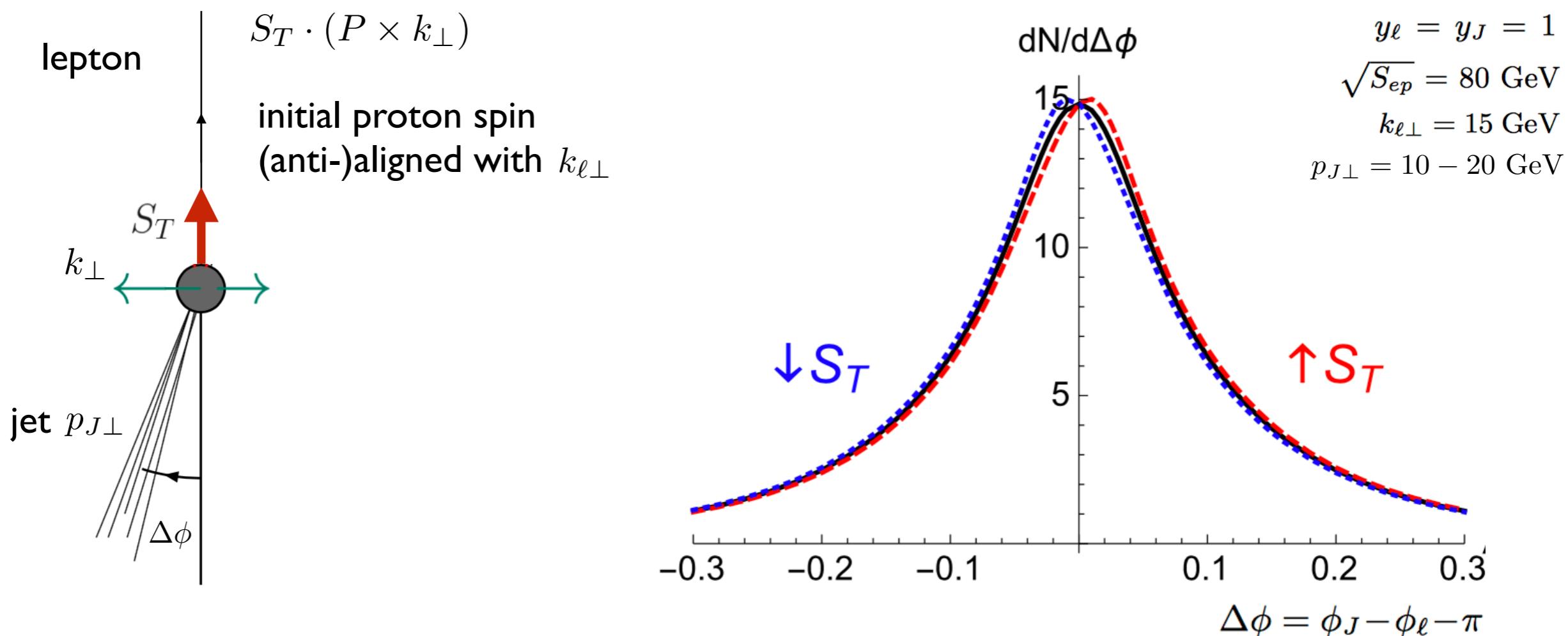


Transverse spin dependent case

Liu, FR, Vogelsang, Yuan '18

- TMD factorization for small q_\perp

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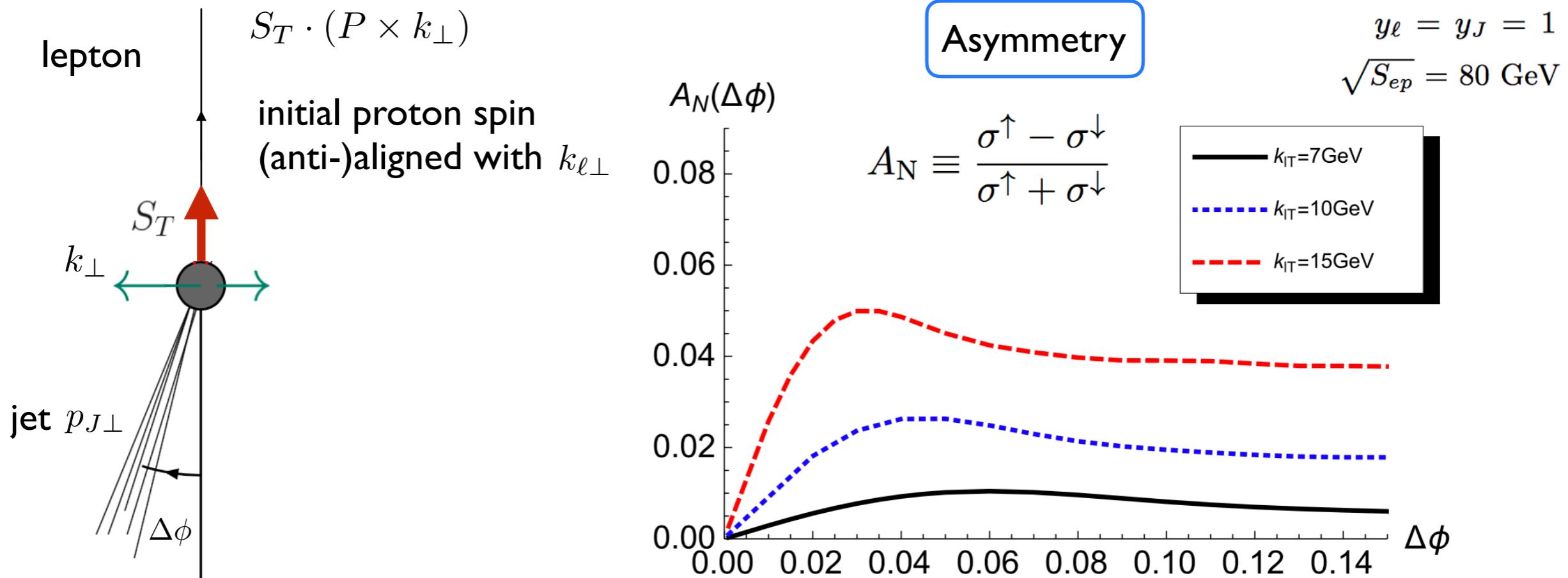
- Sensitivity to Sivers TMD PDF Sun, Yuan '13
- Test of universality and factorization breaking effects, see RHIC measurements STAR, PRL 99 (2007) 142003

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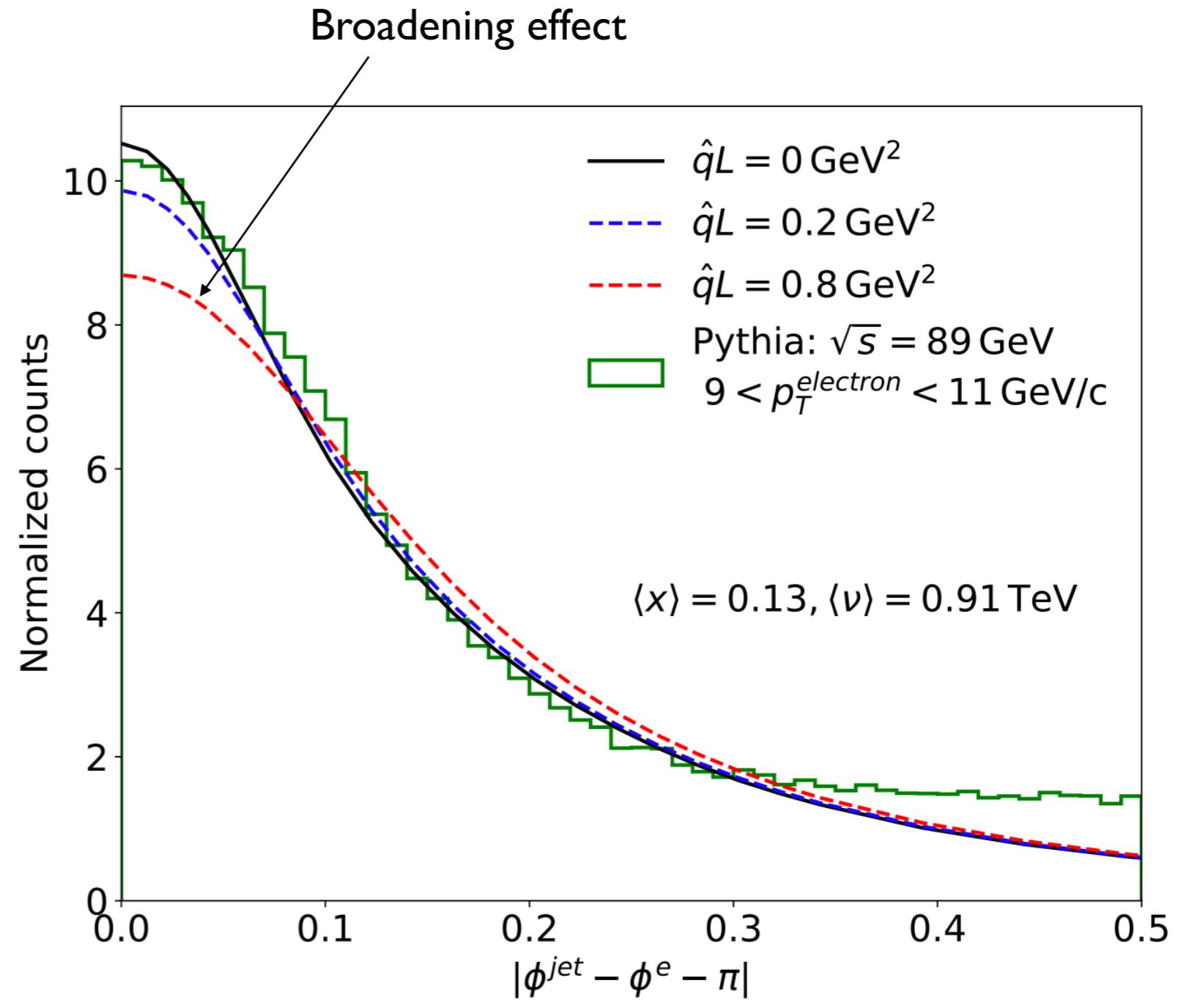
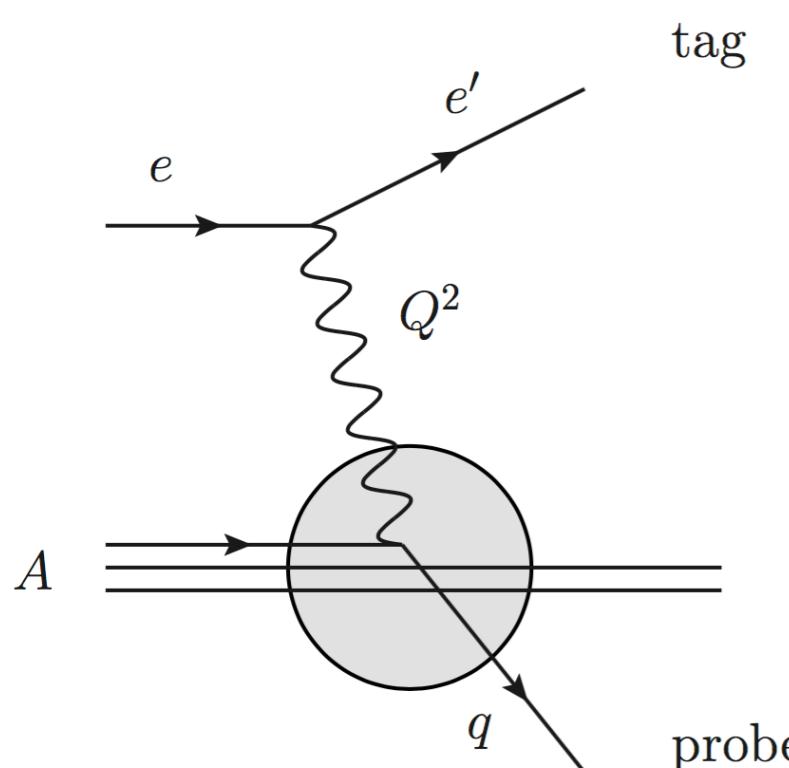
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Transverse momentum broadening in eA collisions

Liu, FR, Vogelsang, Yuan '18
Arratia, Jacak, FR, Song '19

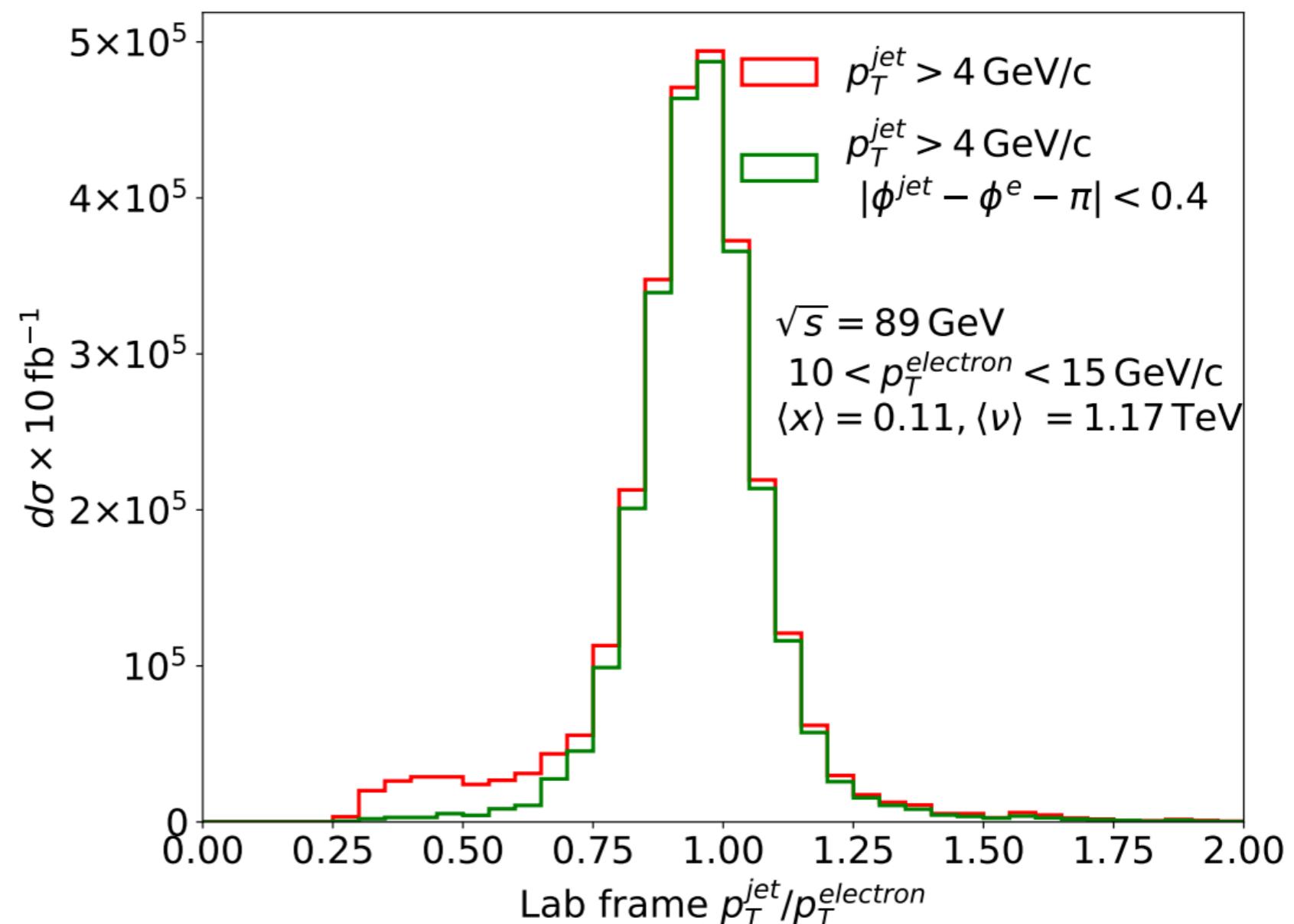
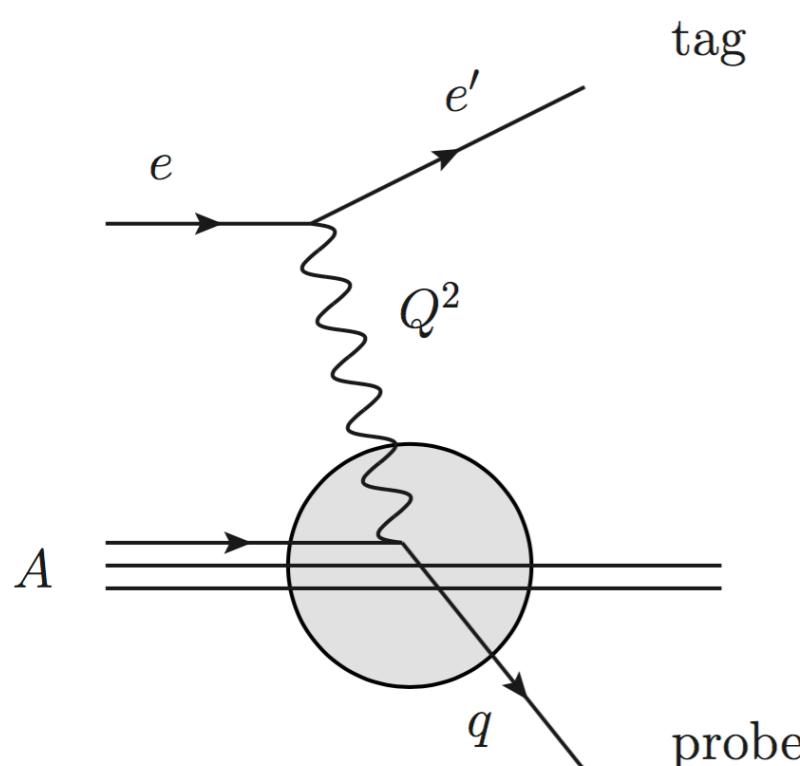
- Comparison to Pythia8
- p_T broadening due to multiple scatterings $\hat{q}L$

Mueller, Wu, Xiao, Yuan '16



Transverse momentum balance

Arratia, Jacak, FR, Song '19



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Conclusions

- Jets are unique tools at the future EIC
- Extract collinear and TMD PDFs
- Jet substructure and jet correlations
- Tune parton showers
- Probe of cold nuclear matter in eA
- Precision studies and NP effects
- Studies of fragmentation and hadronization
- Detector requirements
- Further studies needed

