QCD Jets in DIS

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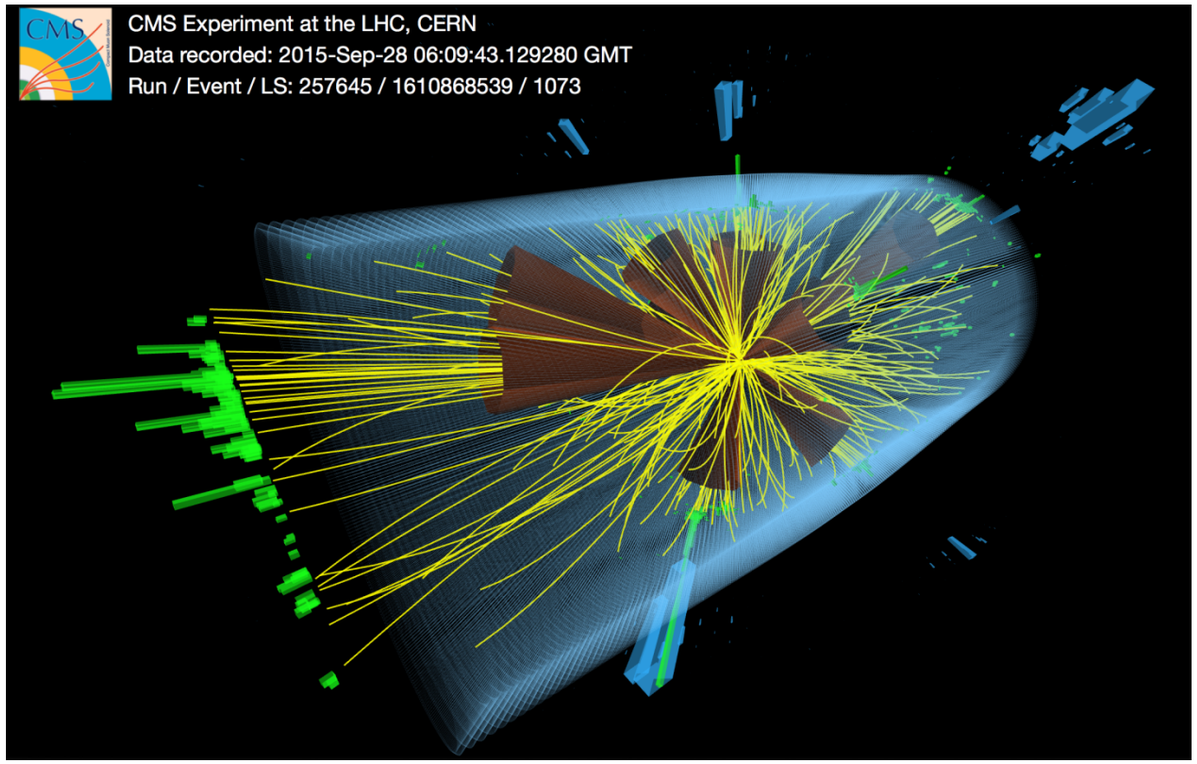
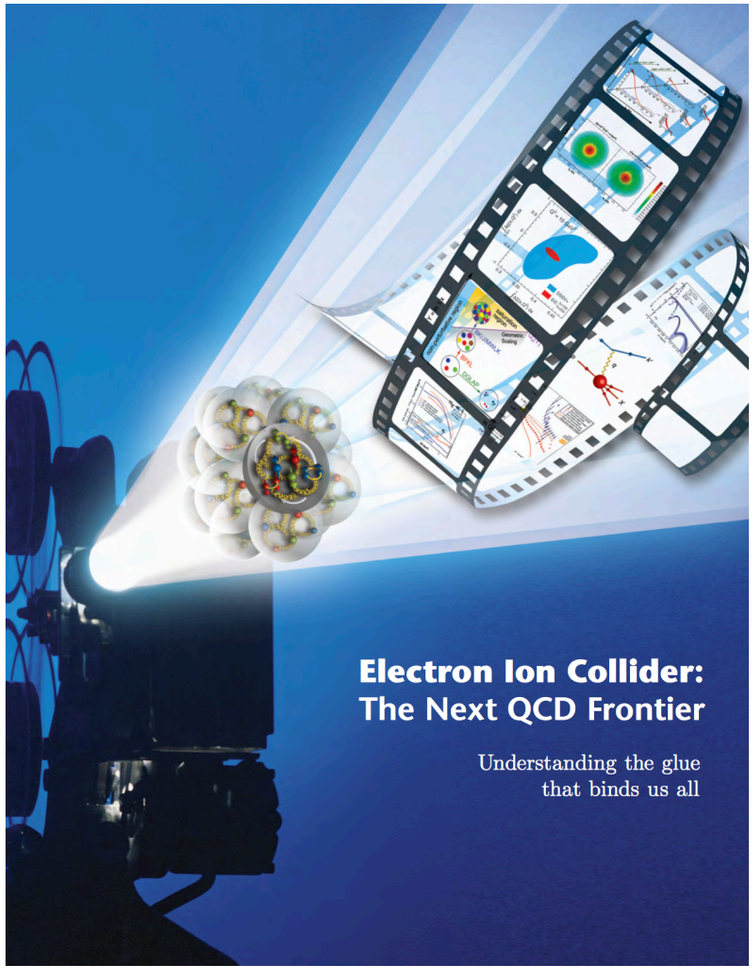
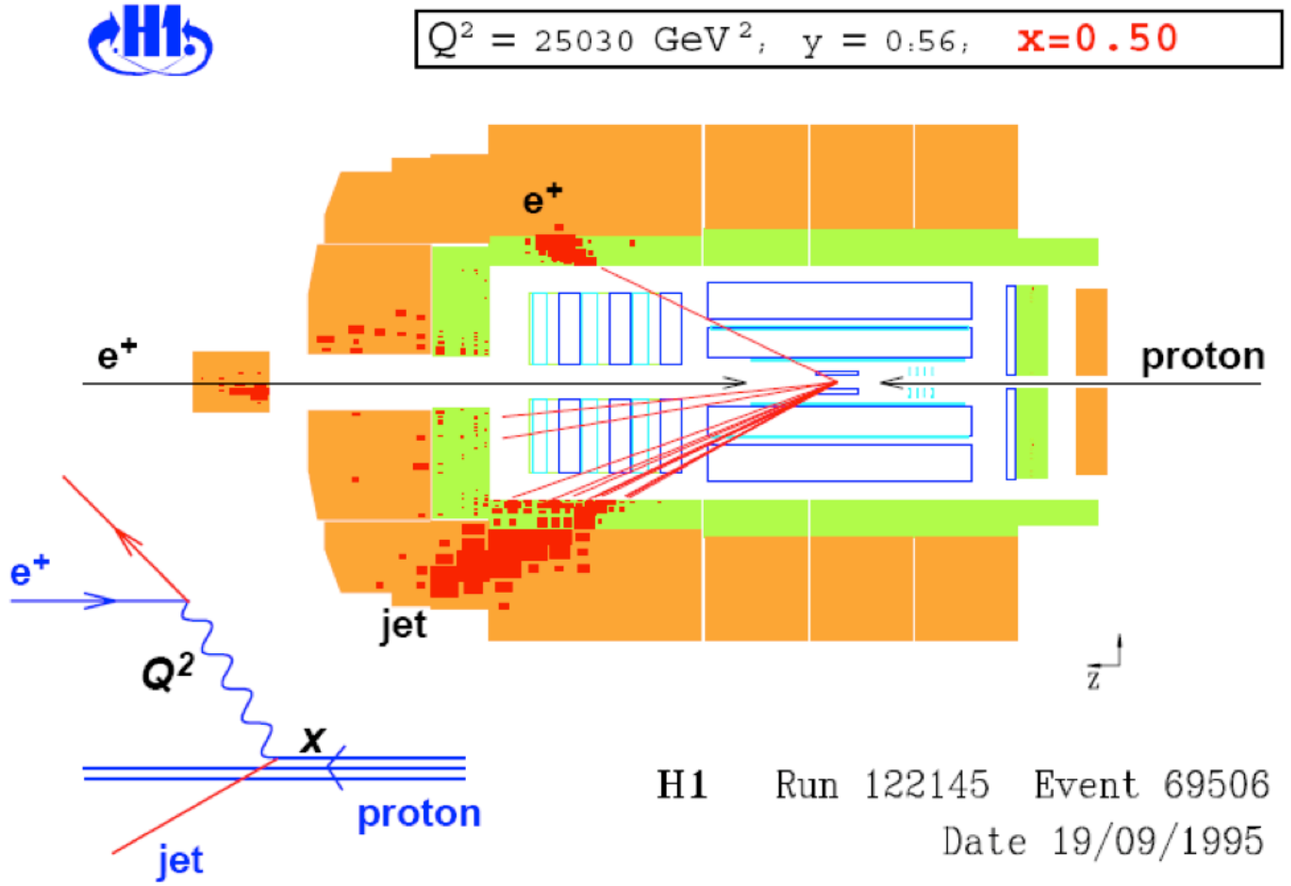
DIS 18, Kobe Japan, 04/19/18



Jets and jet substructure at

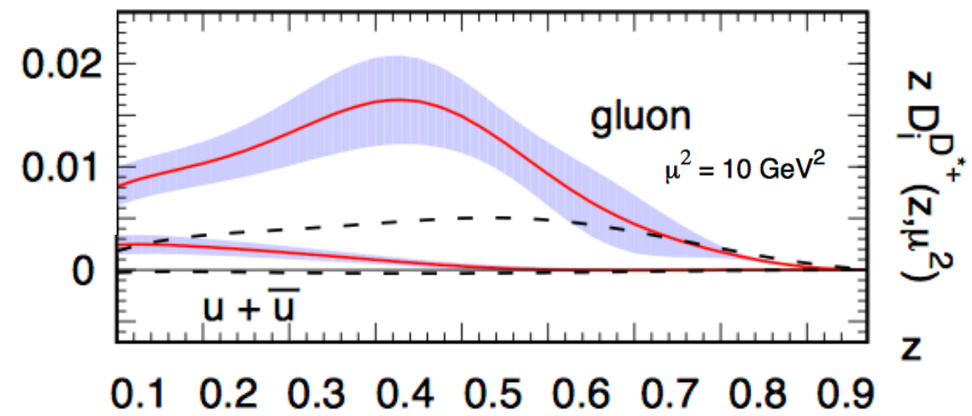
- HERA
- LHC, RHIC
- the future EIC, LHeC

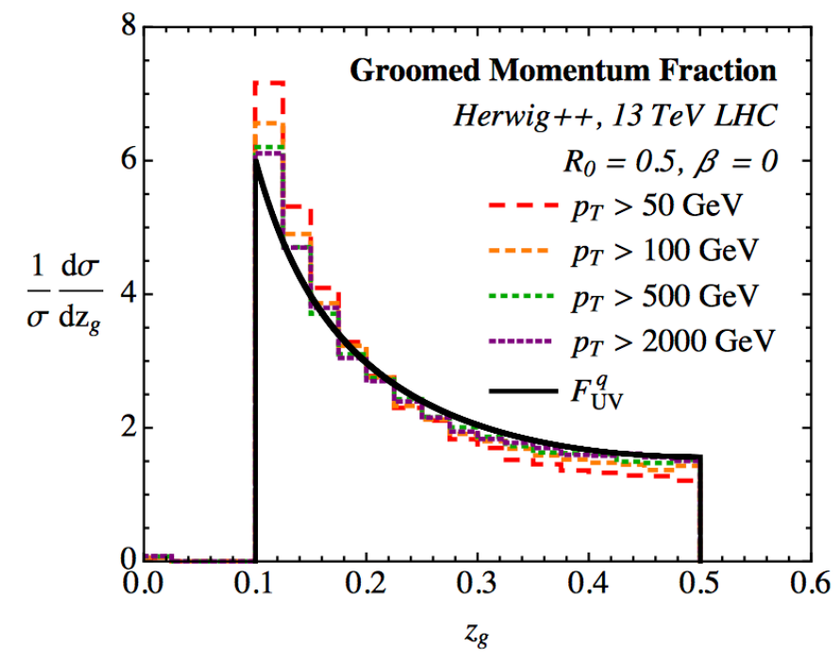


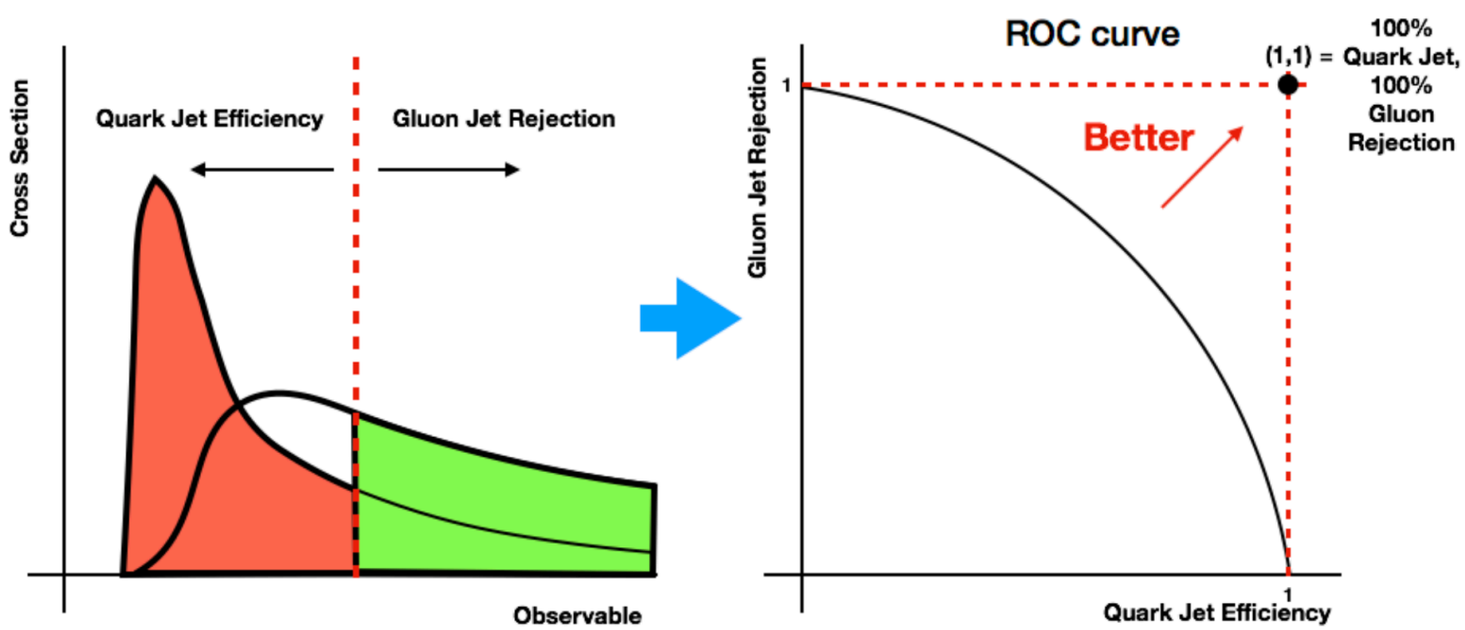


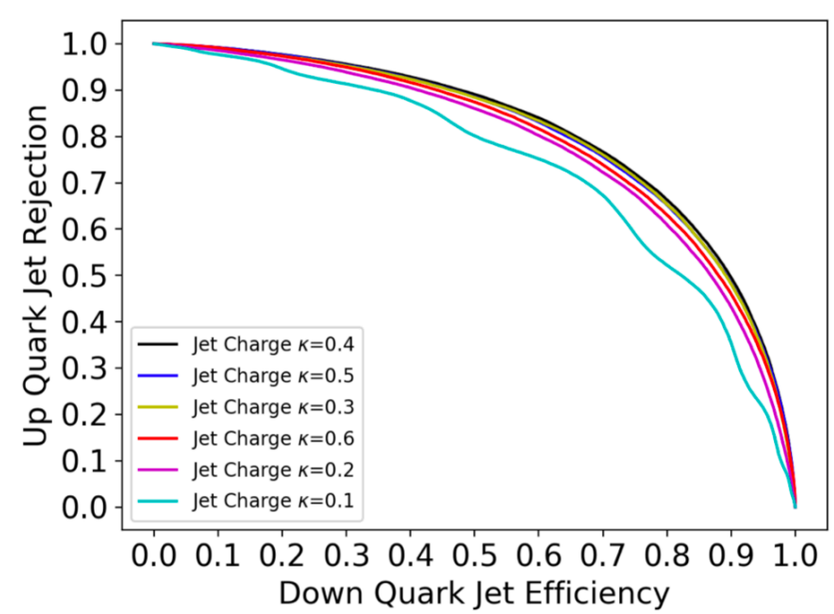
A few of recent examples:

- Hadron-in-jet distributions
  Anderle, Kaufmann, Stratmann, FR, Vitev `17
- Measurement of the QCD splitting function
  Soft drop or subjets
  Larkoski, Marzani, Thaler `15; Kang, FR, Waalewijn `18
- Quark/ gluon tagging: e.g. jet angularities
- Jet charge *Waalewijn `12, Fraser, Schwartz `18*



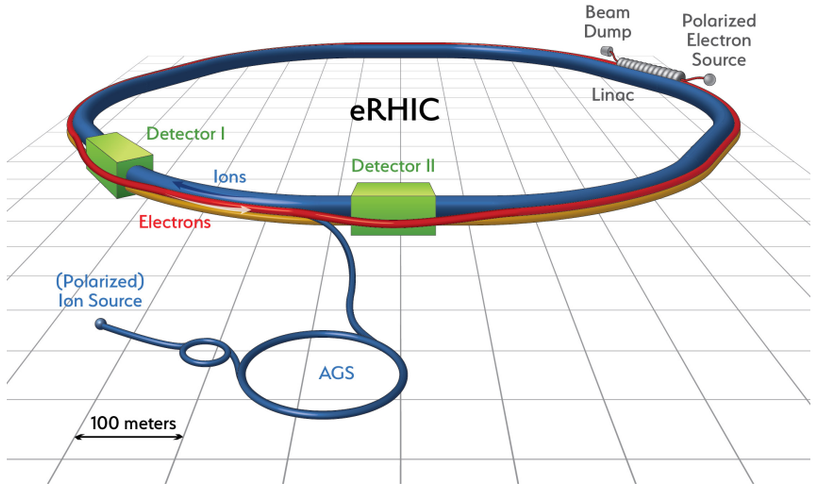


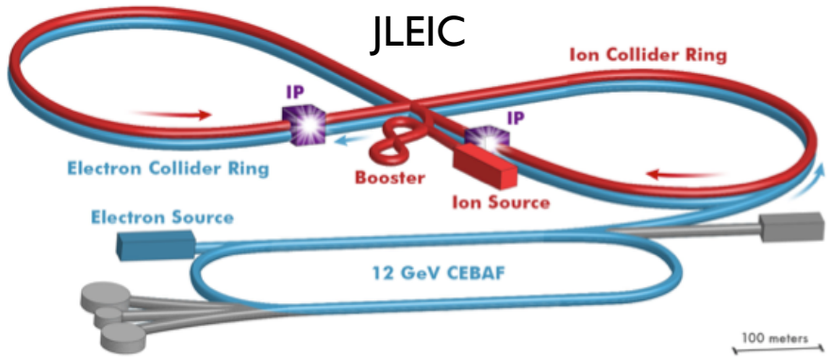




Jets at the EIC

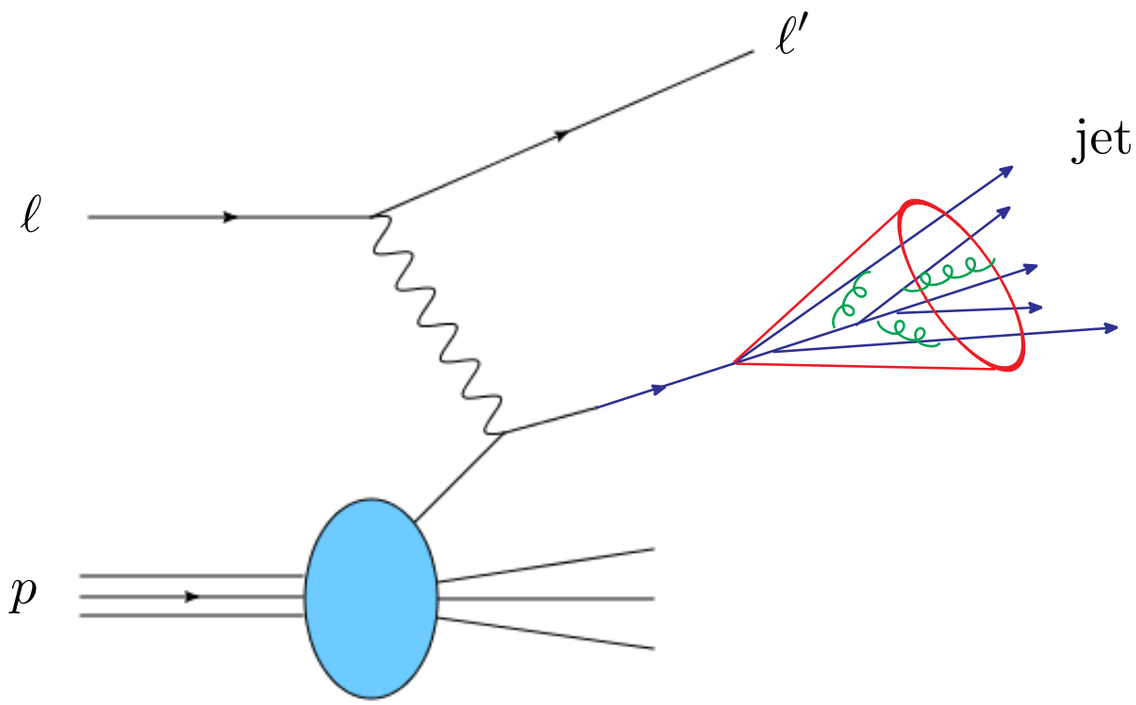
- Jets are inherently interesting

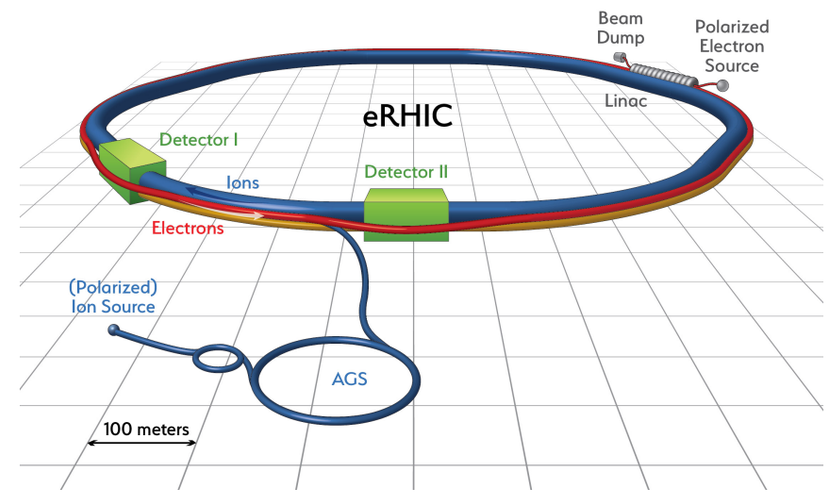


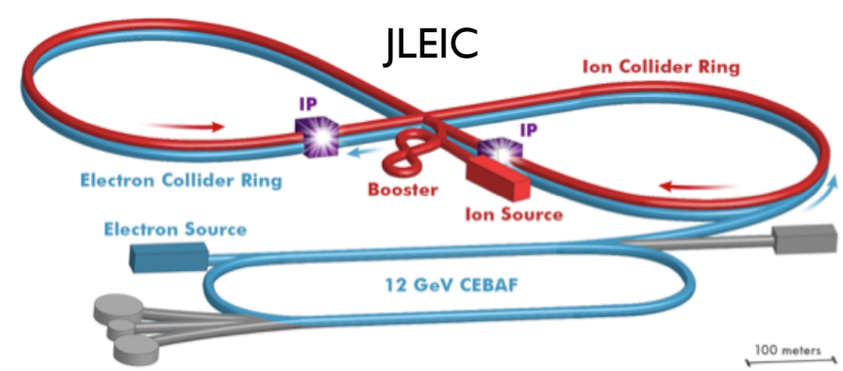


Jets at the EIC

- Jets are inherently interesting
- Constrain non-perturbative quantities
  e.g. collinear and TMD (un)polarized PDFs



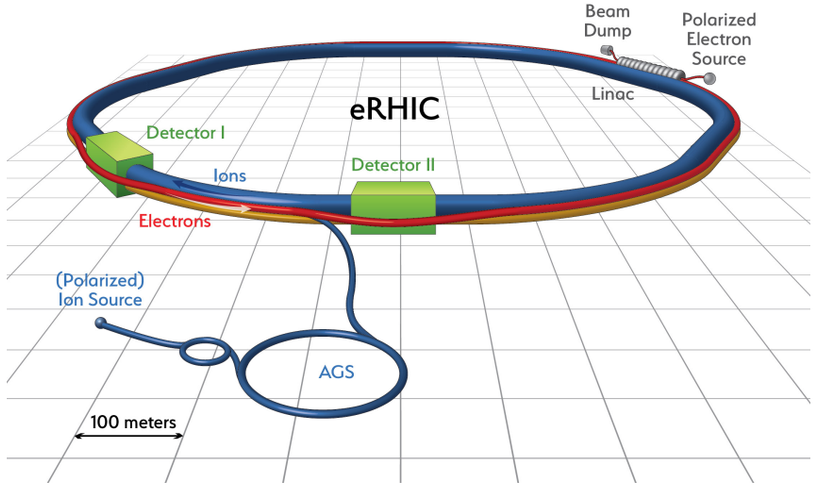


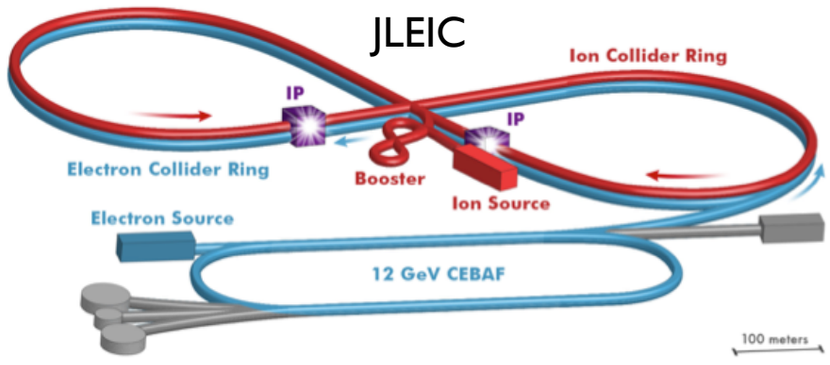


For recent work see for example: Schlegel, Hinderer, Vogelsang `15, Abelov, Boughezal, Liu, Petriello `16, Klasen, Kovarik `18, Currie, Gehrmann, Glover, Huss, Niehus, Vogt `18, Chu, Aschenauer, Lee, Zhang `17 …

Jets at the EIC

- Jets are inherently interesting
- Constrain non-perturbative quantities
  e.g. collinear and TMD (un)polarized PDFs
- No fragmentation functions required
- Complimentary to observables with identified hadrons
- Probe of nuclear matter effects in eA
- Can make use of new methods developed for the LHC and RHIC like jet substructure and tagging





Challenge: We have to understand the NP physics of jets

1. Validate with RHIC, HERA measurements or
2. Compare to MC simulations

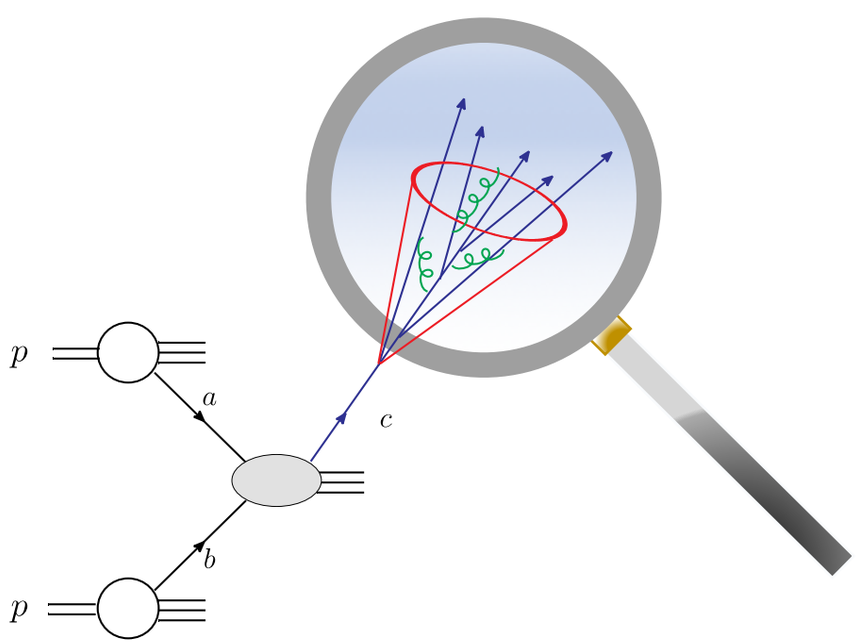
Outline

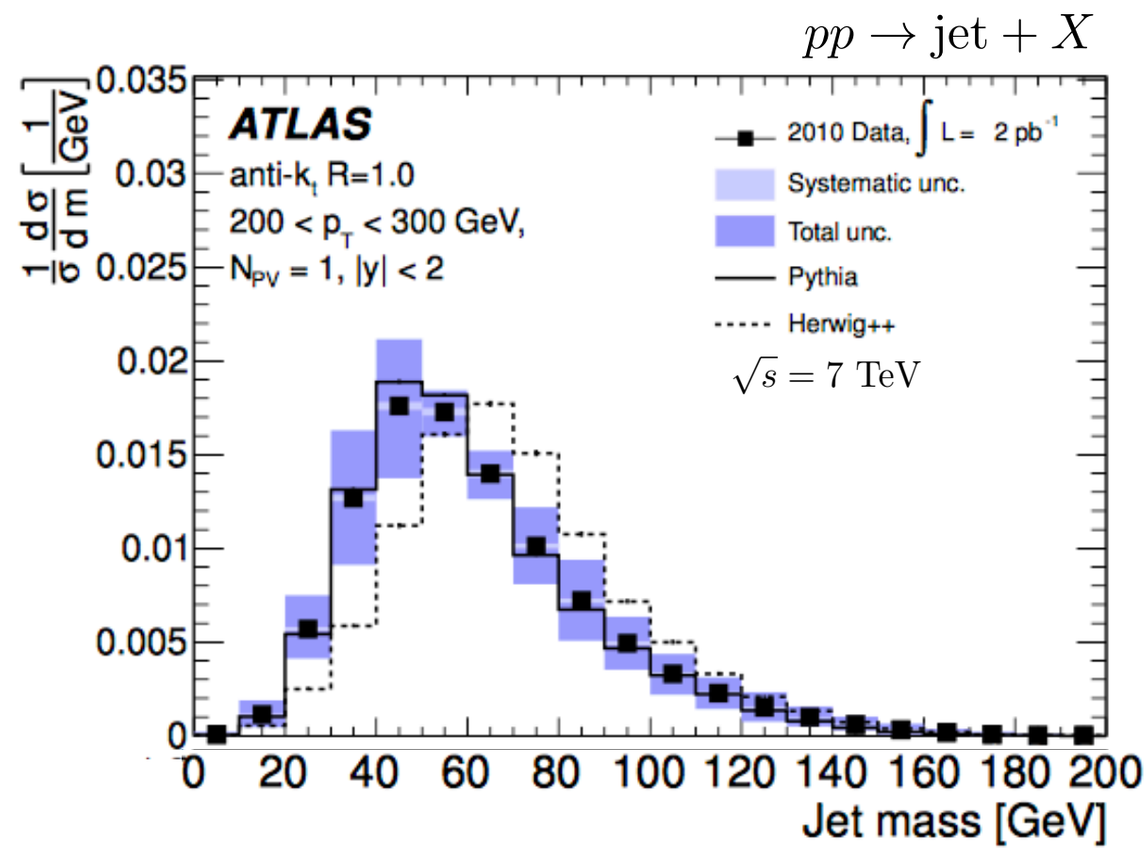
- Introduction
- Semi-inclusive jet observables
- Lepton-jet correlations
- Conclusions

The jet mass at the LHC

Kang, Lee, FR `18,
Kang, Lee, Liu, FR `18

- Jet mass $m_J^2 = \left(\sum_{i\in J} p_i\right)^2$ for inclusive jet production $pp \to (\text{jet}\, m_J^2)X$
- Quark-gluon discrimination
- NP contribution:
  - Multi parton interactions (MPI)
  - Hadronization
  - Pileup





ATLAS, JHEP 1205 (2012) 128

see also: Li, Li, Yuan `11,
Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky `12, …

Factorization

Kang, Lee, FR `18,
Kang, Lee, Liu, FR `18

- Hard-collinear factorization $R \ll 1$

$$\frac{d\sigma}{d\eta dp_T d\tau} = \sum_{abc} f_a(x_a,\mu) \otimes f_b(x_b,\mu) \otimes H^c_{ab}(x_a,x_b,\eta,p_T/z,\mu) \otimes \mathcal{G}_c(z,p_T,R,\tau,\mu)$$

$$\tau = \frac{m_J^2}{p_T^2}$$

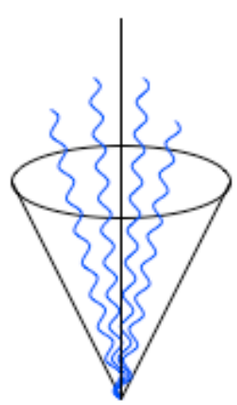
$$pp \to (\text{jet}\, m_J^2)X$$

- Hard-collinear-soft factorization $\tau \ll R^2$

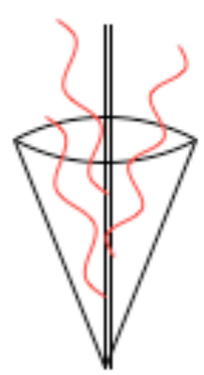
$$\mathcal{G}_c(z,p_T,R,\tau,\mu) = \sum_i \mathcal{H}_{c\to i}(z,p_T R,\mu)\, C_i(\tau,p_T,\mu) \otimes S_i(\tau,p_T,R,\mu)$$

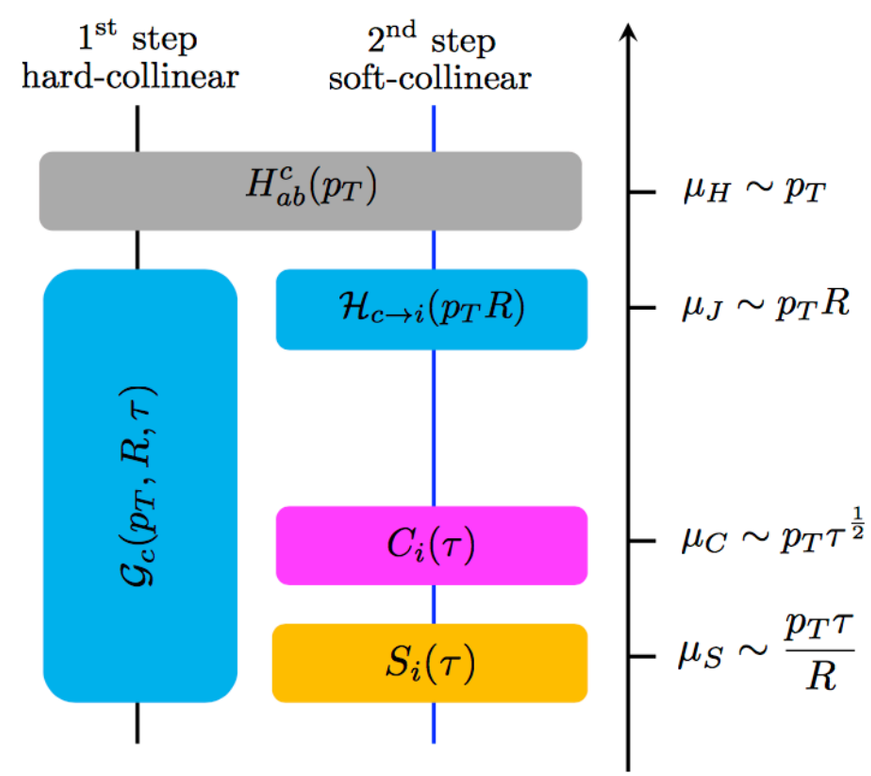
hard-matching

collinear



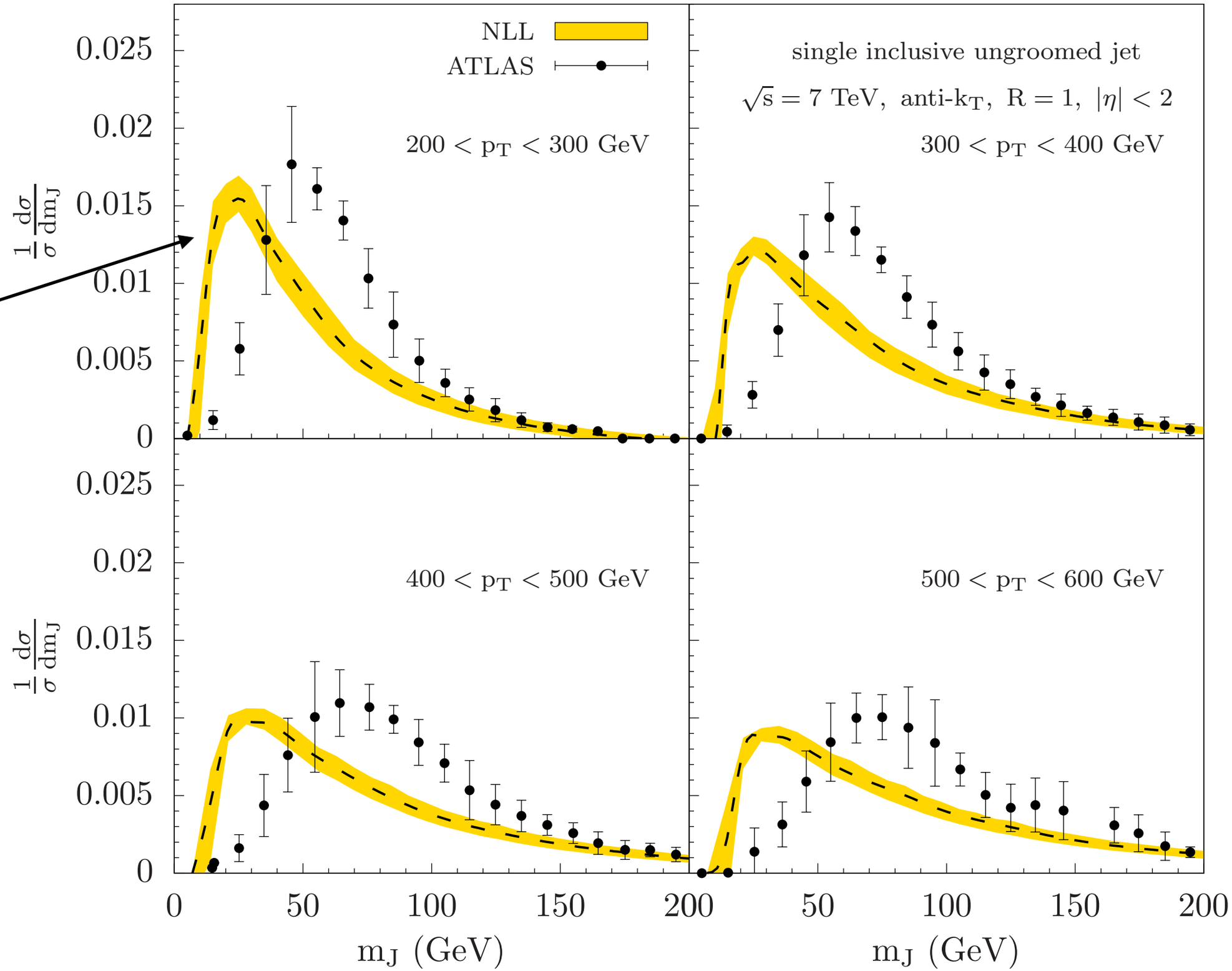
soft





$pp \to (\text{jet}\, m_J^2) X$

Perturbative result



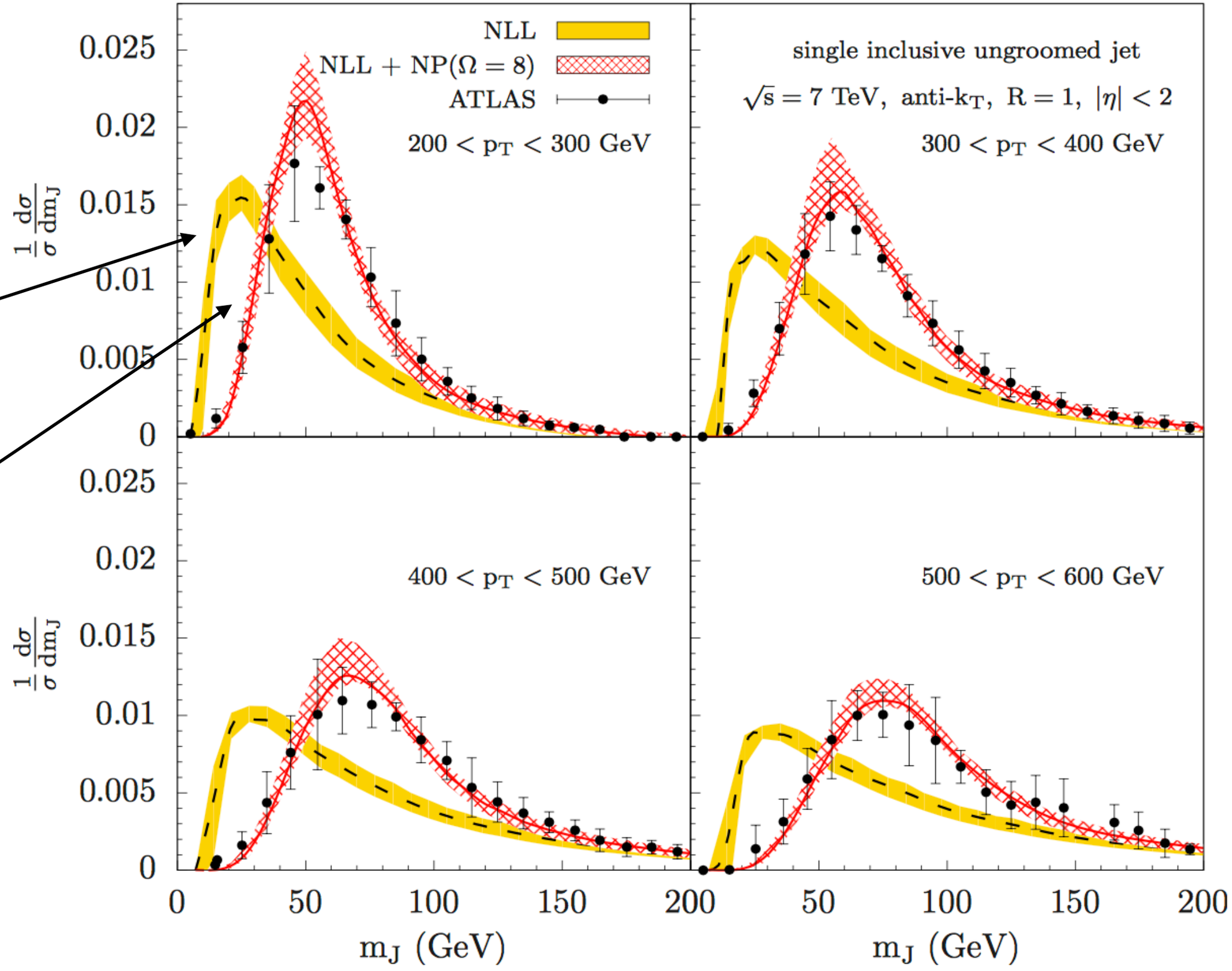
Kang, Lee, FR `18,
Kang, Lee, Liu, FR `18

ATLAS, JHEP 05 (2012) 128

$pp \to (\text{jet}\, m_J^2) X$

Perturbative result

Including $d\sigma^{\text{pert}} \otimes F$
NP shape function



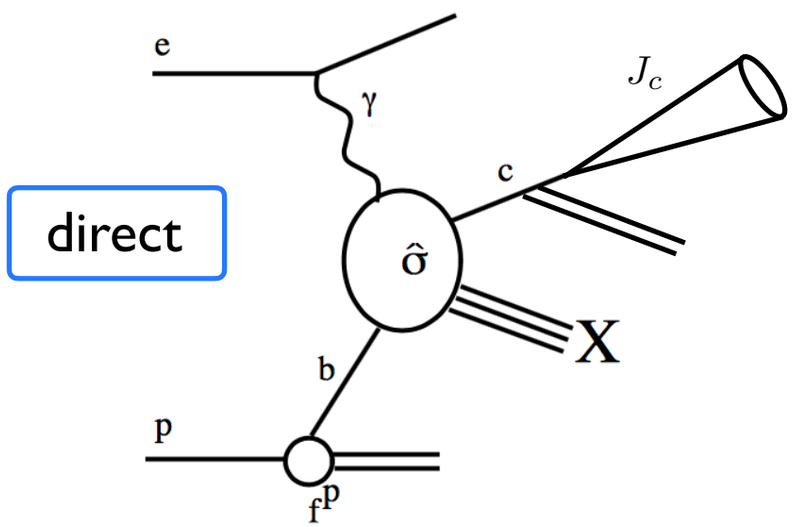
$$F_i(k) = \frac{4k}{\Omega^2} \exp(-2k/\Omega)$$

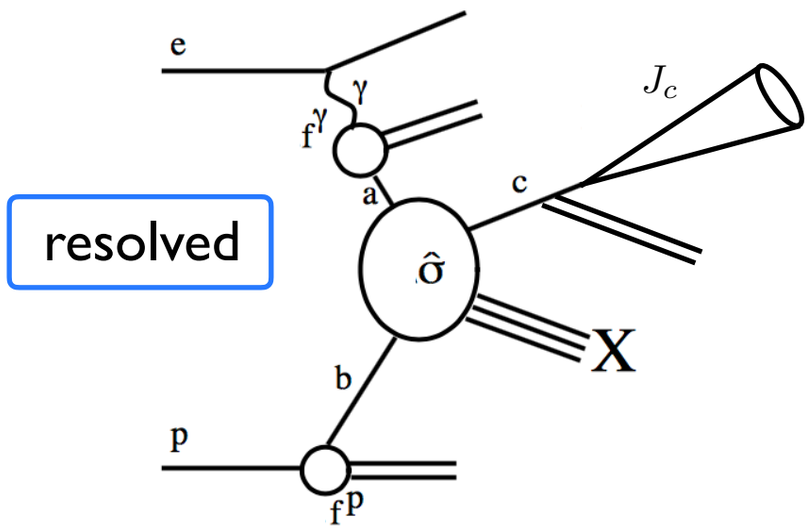
Stewart, Tackmann, Waalewijn `15

ATLAS, JHEP 05 (2012) 128

Kang, Lee, FR `18,
Kang, Lee, Liu, FR `18

For example: Photoproduction at the EIC





- Require high p_T and $Q^2 < 0.1\ \mathrm{GeV}^2$
- Access the parton content of (polarized) photons
- Measure final state jets instead of hadrons
- Jet mass allows for tagging quark/ gluon jets

Jäger, Stratmann, Vogelsang `03
de Florian, Pfeuffer, Schäfer, Vogelsang`13

- How large are NP corrections associated with the jets?
- Can we disentangle the different NP contributions?

Stewart, Tackmann, Waalewijn `15

see also Xiaoxuan Chu's talk

Chu, Aschenauer, Lee, Zhang `17
Aschenauer, Kang, Lee, Page, FR, Vogelsang, Yuan

Photoproduction at the EIC

- Inclusive jets $$\frac{d\sigma}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes J_c$$

Weizsäcker-Williams spectrum

resolved: $\otimes f_{a/\gamma}$

- Jet mass $$\frac{d\sigma}{dp_T d\eta dm_J} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes \mathcal{G}_c(m_J)$$

Universality of the semi-inclusive jet functions

Kang, FR, Vitev `16

Jäger, Stratmann, Vogelsang `03

Chu, Aschenauer, Lee, Zhang `17

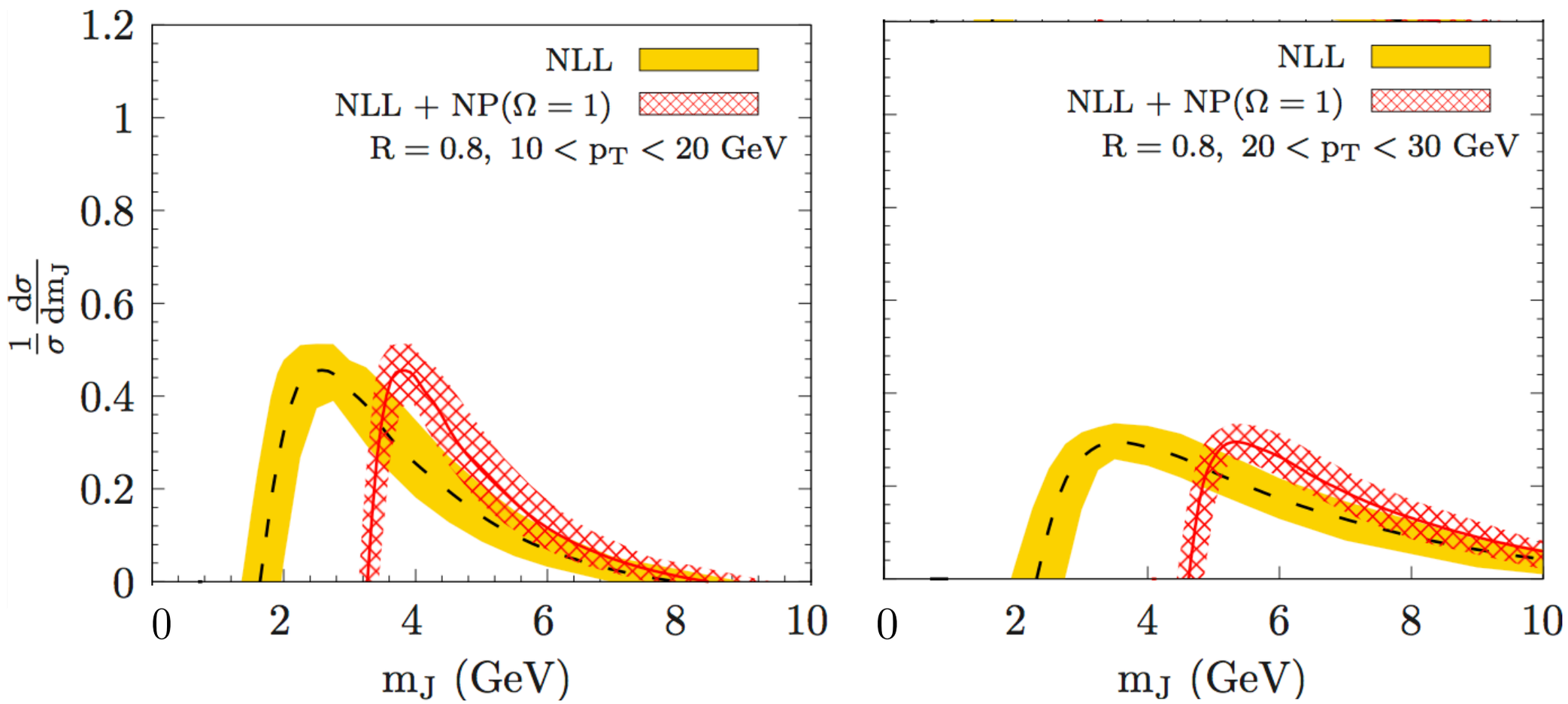
Aschenauer, Kang, Lee, Page, FR, Vogelsang, Yuan

Photoproduction at the EIC

$\sqrt{s} = 140$ GeV

$R = 0.8$, anti-k_T

preliminary



→ Comparison to MC is work in progress

Here: Shift of the peak instead of convolution with shape function

CT14, GRS 99 PDFs

Aschenauer, Kang, Lee, Page, FR, Vogelsang, Yuan

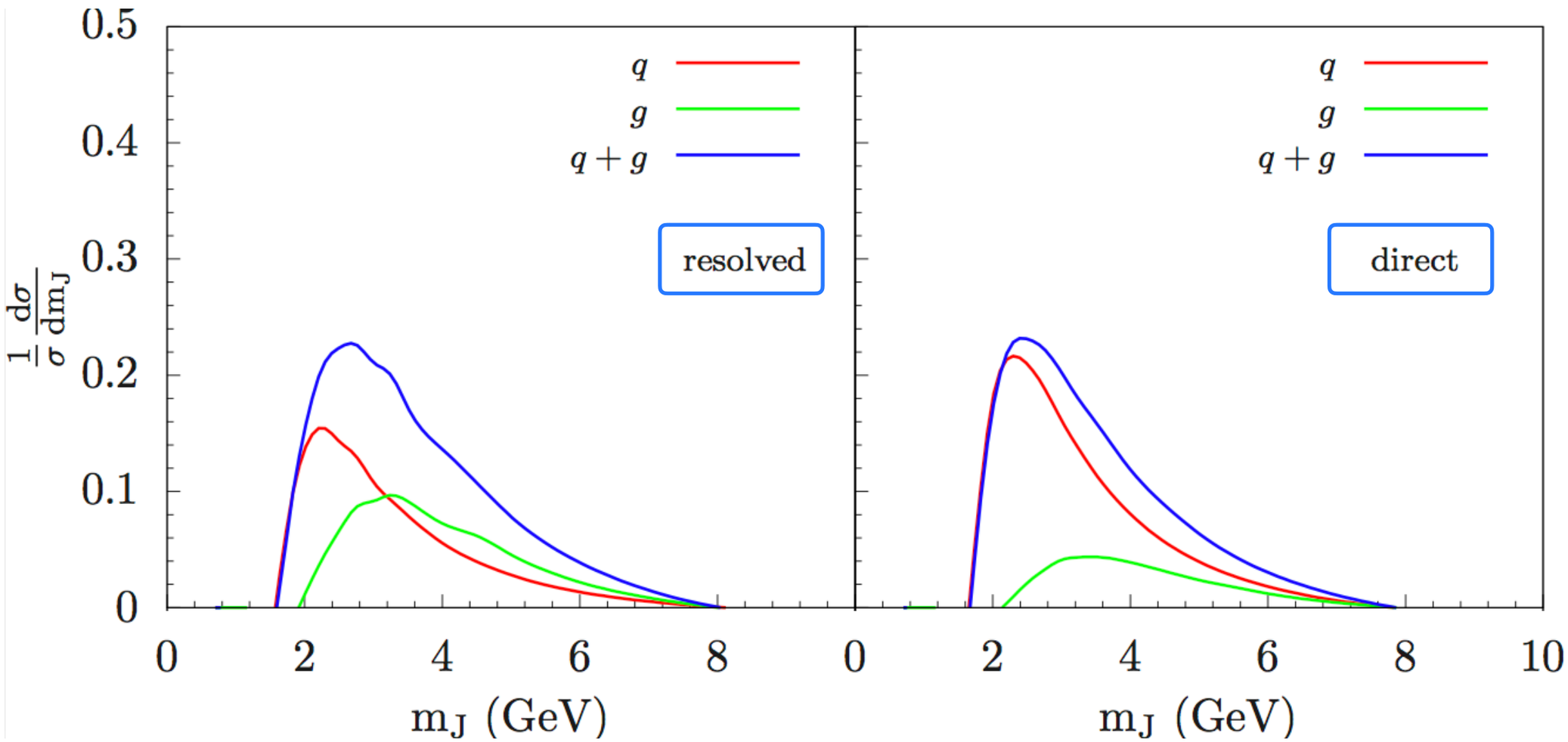
Photoproduction at the EIC

$\sqrt{s} = 140$ GeV

$R = 0.8$, anti-k_T

$10 < p_T < 20$ GeV

preliminary



CT14, GRS 99 PDFs

Aschenauer, Kang, Lee, Page, FR, Vogelsang, Yuan

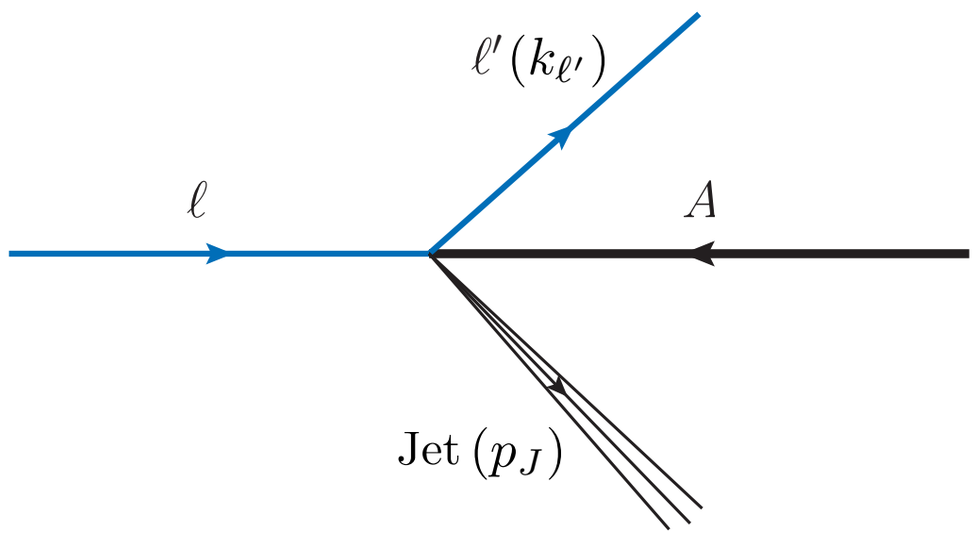
Outline

- Introduction
- Semi-inclusive jet observables
- Lepton-jet correlations
- Conclusions

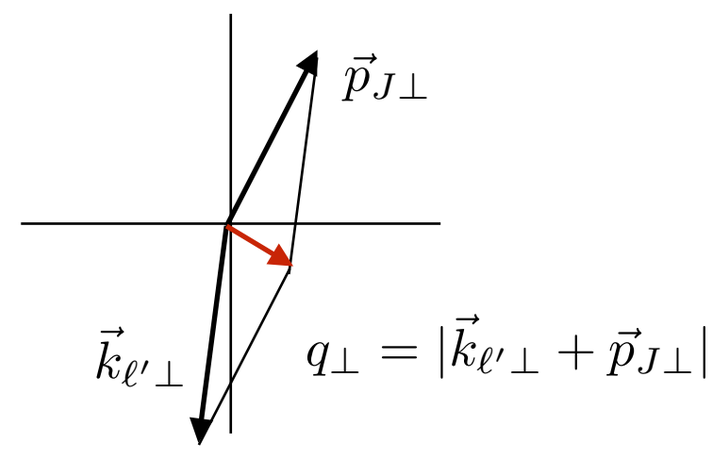
Lepton-jet correlations

Liu, FR, Yuan - in preparation

- Measure imbalance between lepton and jet
- Spin asymmetries and eA collisions
- Analogous to e.g. $pp \to \text{di-jets} + X$ *Sun, Yuan, Yuan `15*
- cms or laboratory frame; close analogy to pp collisions



Transverse plane



- Consider $\dfrac{d\sigma}{dy_{\ell'} d^2k_{\perp\ell'} d^2q_\perp}$

Requires TMD resummation for $q_\perp \ll k_{\ell'\perp}$ for the back-to-back configuration, and jet radius resummation for $R \ll 1$

Factorization

- Joint $q_\perp$ and jet radius resummation

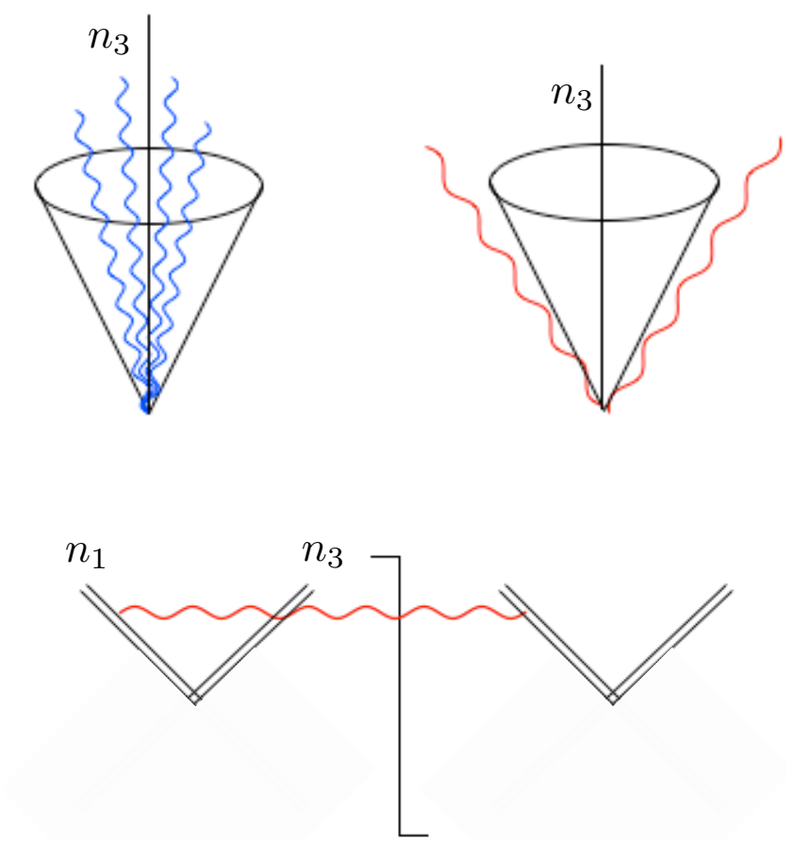
Liu, FR, Yuan - in preparation

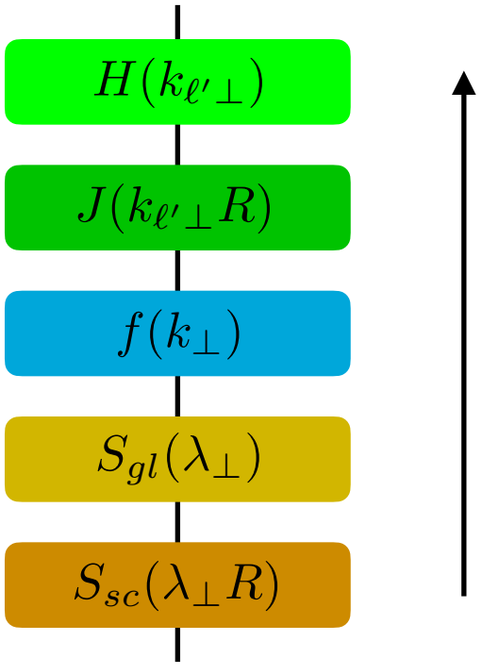
Hard (virtual) Jet function

$$\frac{d\sigma}{dy_{\ell'} d^2k_{\perp\ell'} d^2q_\perp} = H_q(k_{\ell'\perp}, \mu)\, J_q(k_{\ell'\perp} R, \mu)$$

$$\int d^2k_\perp d^2\lambda_{1\perp} d^2\lambda_{2\perp}\, x f_q(x, k_\perp, \mu, \nu)\, S_{gl}(\lambda_{1\perp}, \mu, \nu)\, S_{sc}(\lambda_{2\perp} R, \mu)\, \delta^{(2)}(q_\perp - k_\perp - \lambda_{1\perp} - \lambda_{2\perp})$$

Global soft Soft-collinear (in the jet direction)





Factorization

- Joint $q_\perp$ and jet radius resummation *Liu, FR, Yuan - in preparation*

Hard (virtual) Jet function

$$\frac{d\sigma}{dy_{\ell'} d^2k_{\perp\ell'} d^2q_\perp} = H_q(k_{\ell'\perp}, \mu)\, J_q(k_{\ell'\perp} R, \mu)$$

$$\int d^2k_\perp d^2\lambda_{1\perp} d^2\lambda_{2\perp}\, x f_q(x, k_\perp, \mu, \nu)\, S_{gl}(\lambda_{1\perp}, \mu, \nu)\, S_{sc}(\lambda_{2\perp} R, \mu)\, \delta^{(2)}(q_\perp - k_\perp - \lambda_{1\perp} - \lambda_{2\perp})$$

Global soft Soft-collinear (in the jet direction)

- Identified modes similar to the joint threshold and jet radius resummation *Moch, Liu, FR `17*
- Relation to lepton-hadron correlations
- Similar analogy: Fragmentation function $\longleftrightarrow$ semi-inclusive jet functions *Kang, FR, Vitev `17*
  for inclusive hadron/ jet production

$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes D^h_c \quad \longleftrightarrow \quad \frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes J_c$$

Azimuthal lepton-jet correlation

Liu, FR, Yuan - in preparation

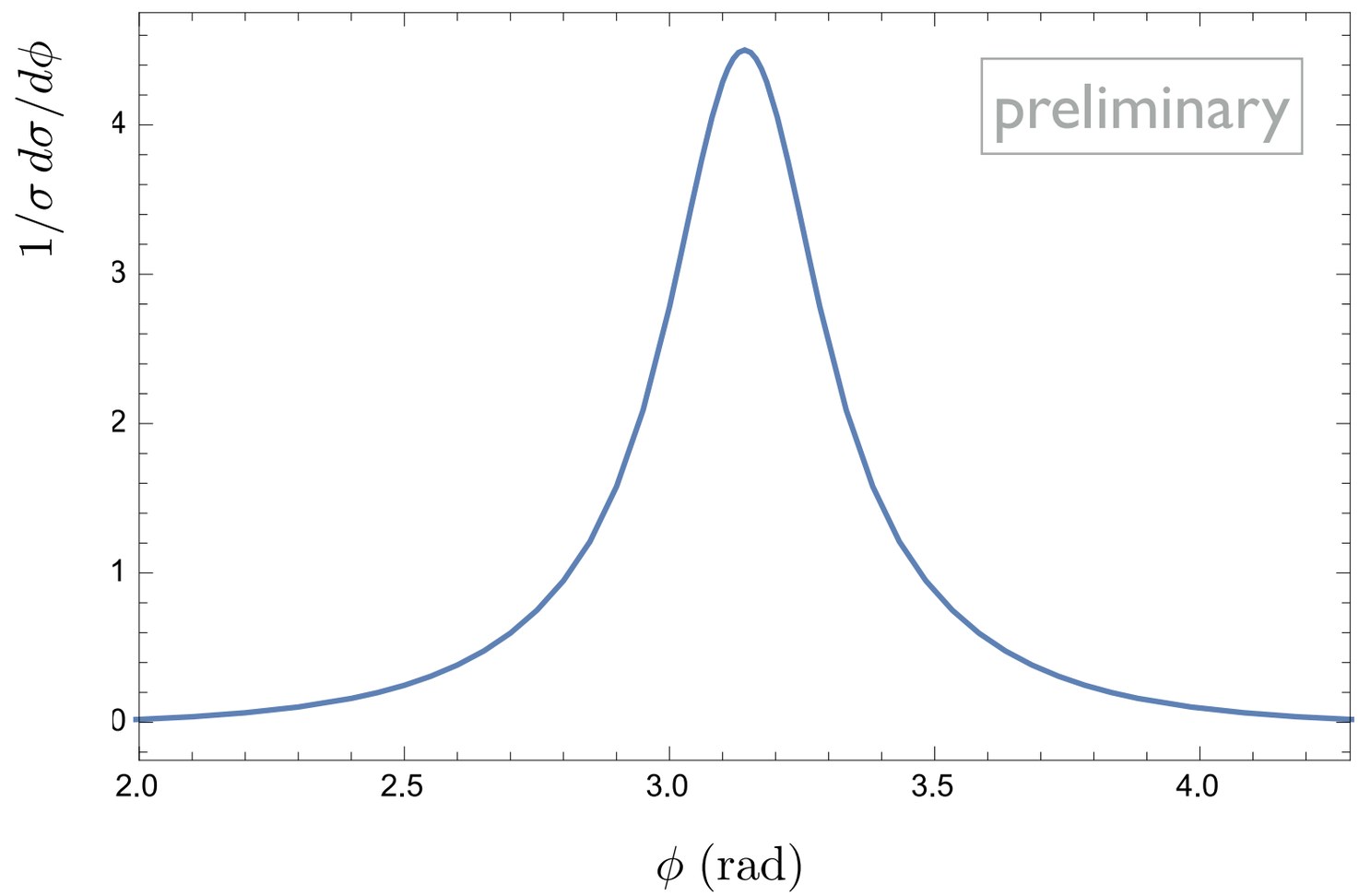
- Sample EIC kinematics

  $\sqrt{s} = 80\,\mathrm{GeV}$

  $k_{\ell'\perp} = 5\,\mathrm{GeV}$

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

- currently $\ln R$ not yet resummed

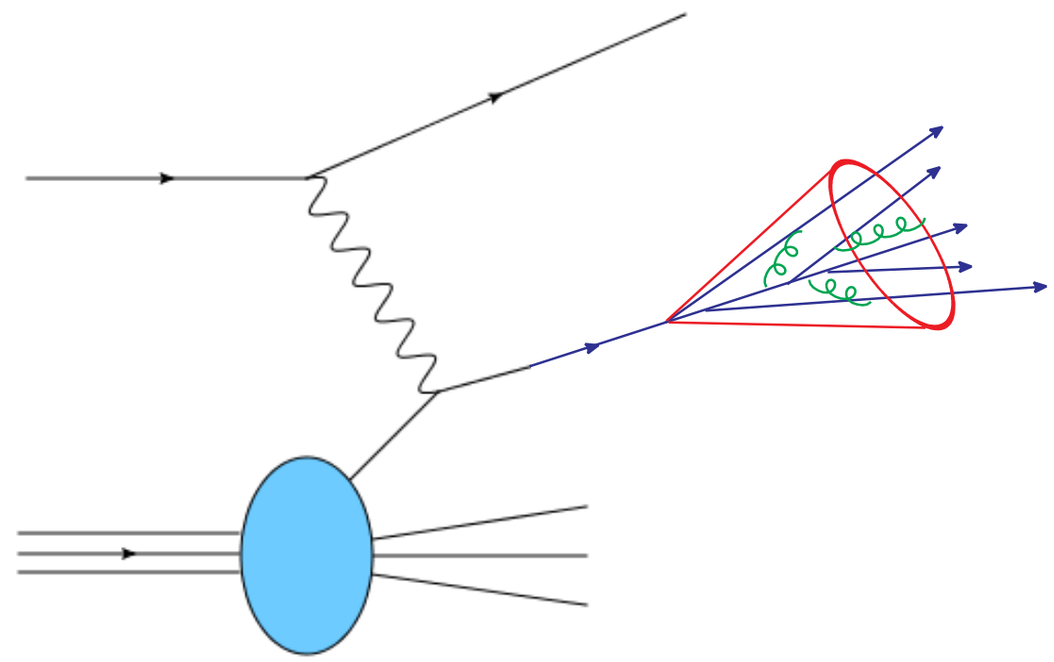


Outline

- Introduction
- Semi-inclusive jet observables
- Lepton-jet correlations
- Conclusions

Conclusions

- Jets can be a unique tool at the future EIC
- Extract collinear and TMD PDFs
- Jet substructure
- NP effects important
- Probe of nuclear matter
- LHeC



Dedicated workshop: "Probing quark-gluon matter with jets"

July 23-25, BNL