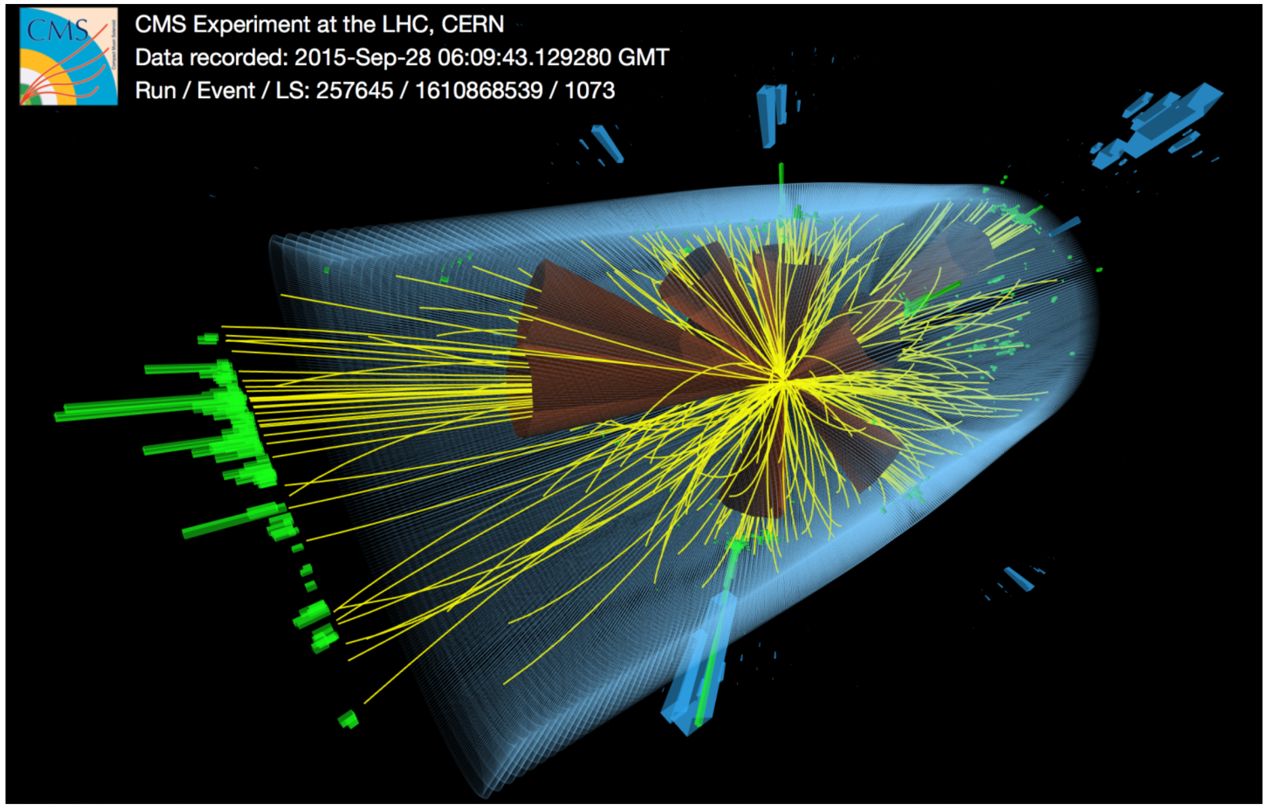
Theory review of jets at the EIC

Felix Ringer

Lawrence Berkeley National Laboratory

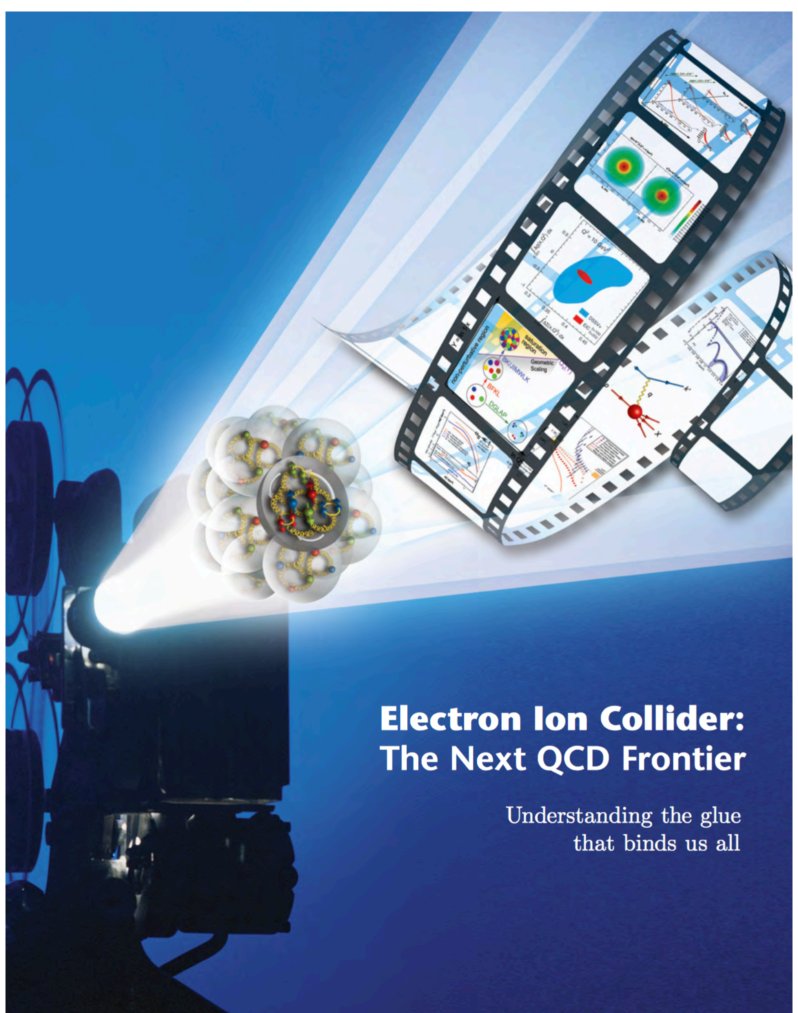
INT, Seattle, 10/17/18

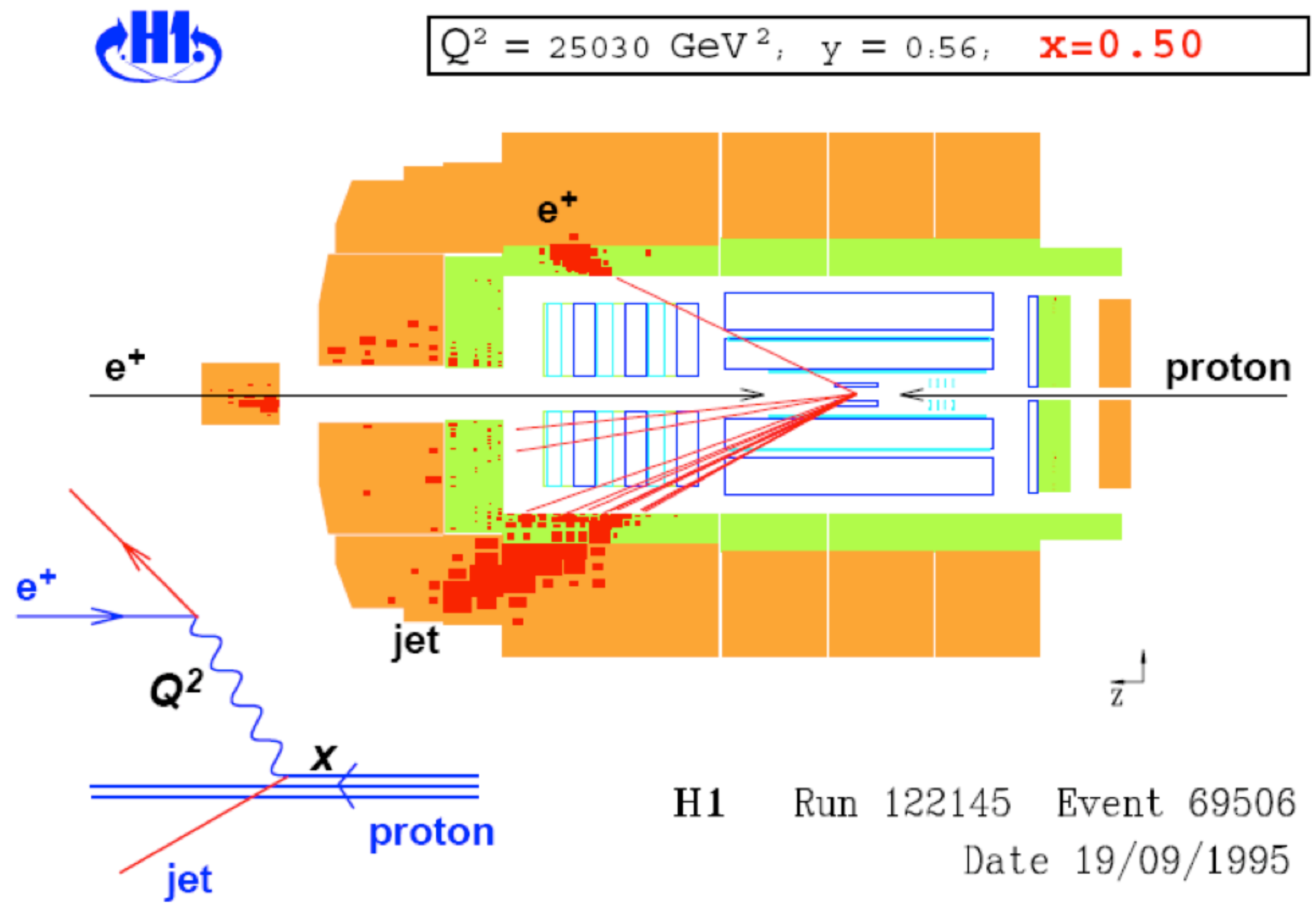
BERKELEY LAB



Jets and jet substructure at

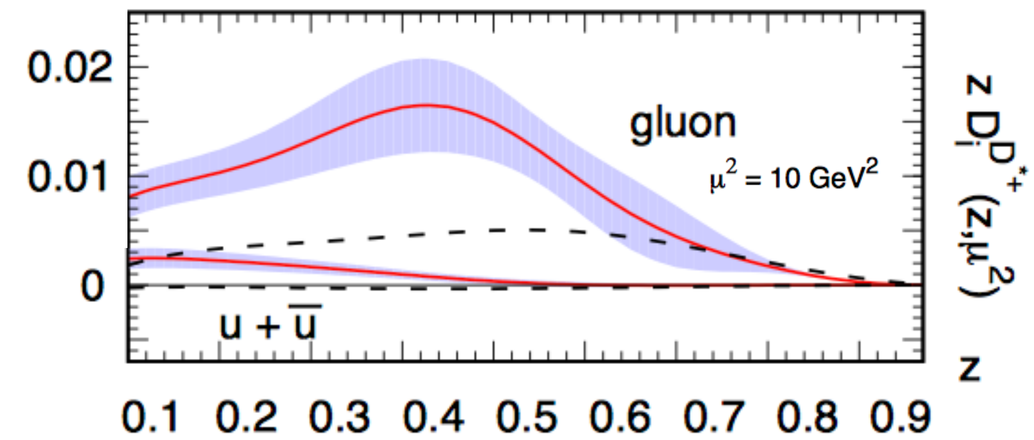
- LEP, HERA
- Tevatron, RHIC, LHC
- EIC



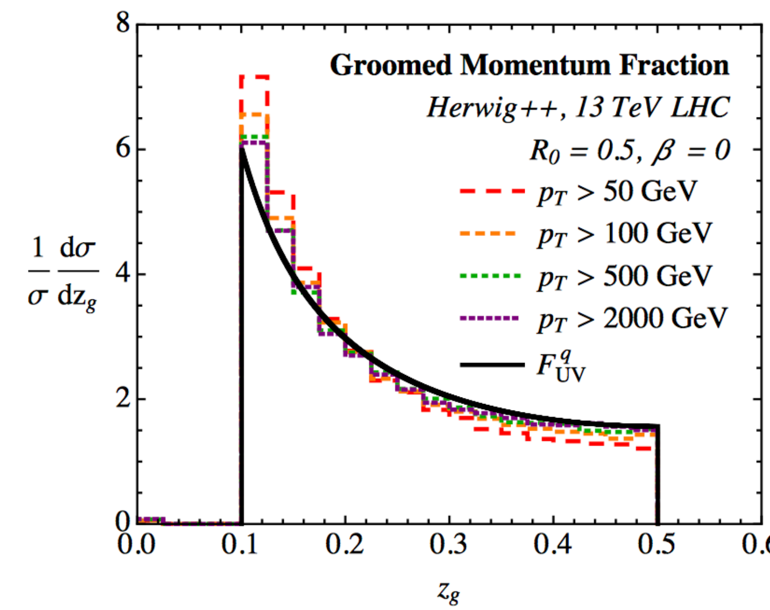


A few of recent examples:

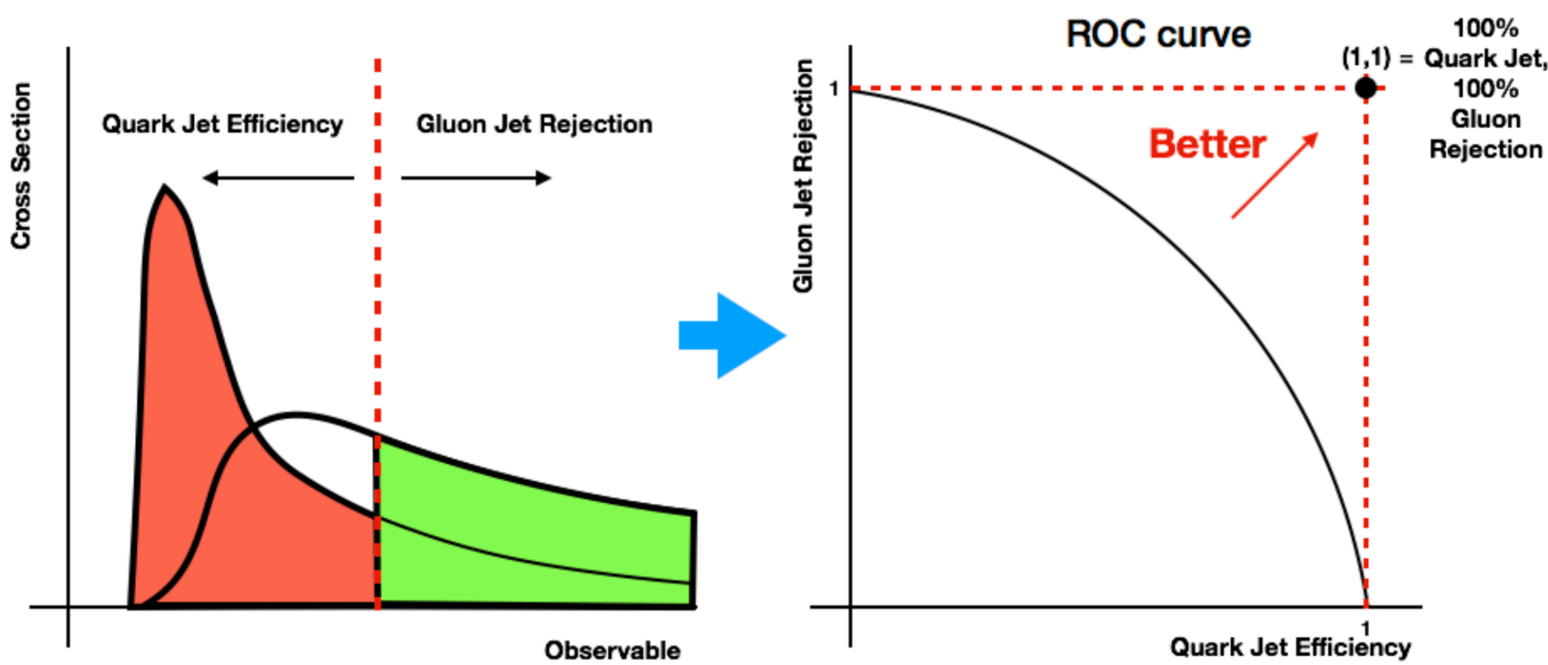
- Quark/ gluon tagging using for example jet angularities
- Jet charge
- Hadron-in-jet distributions
- Possible extraction of α_s *Les Houches `17*
- Measurement of the QCD splitting function using Soft drop or subjets



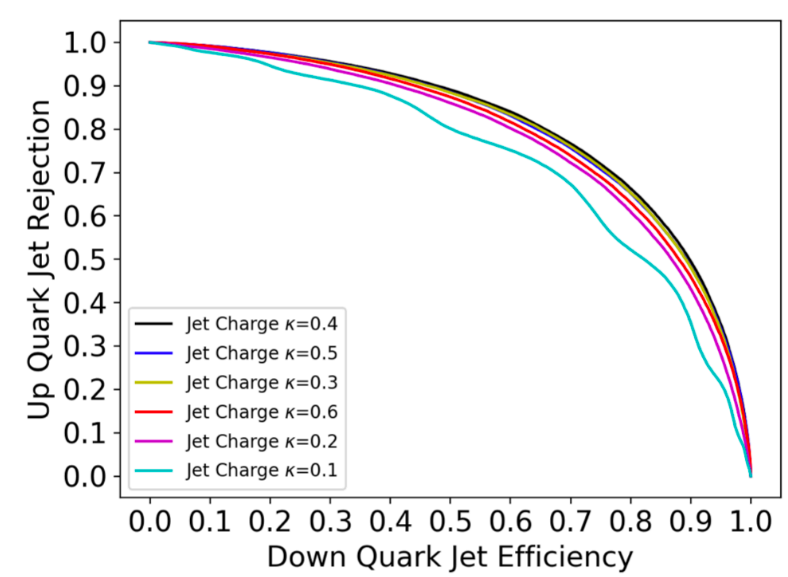
Anderle, Kaufmann, Stratmann, FR, Vitev `17



Larkoski, Marzani, Thaler `15



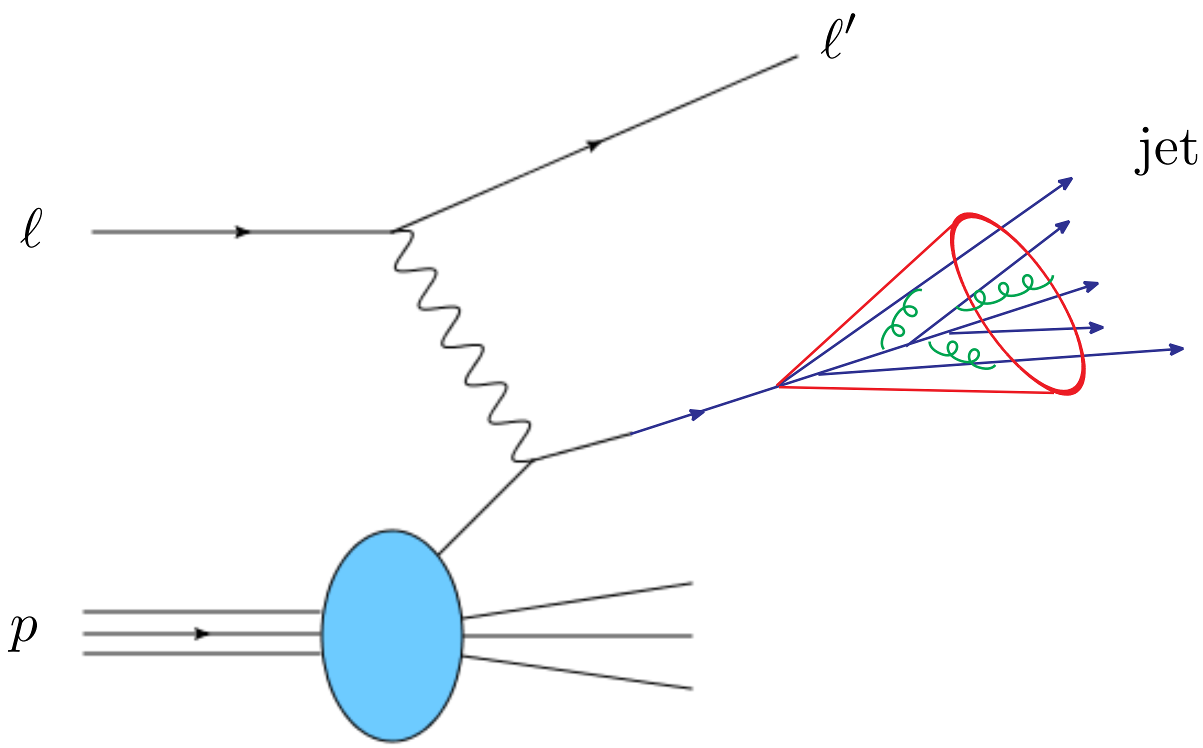
Kang, Lee, FR `18

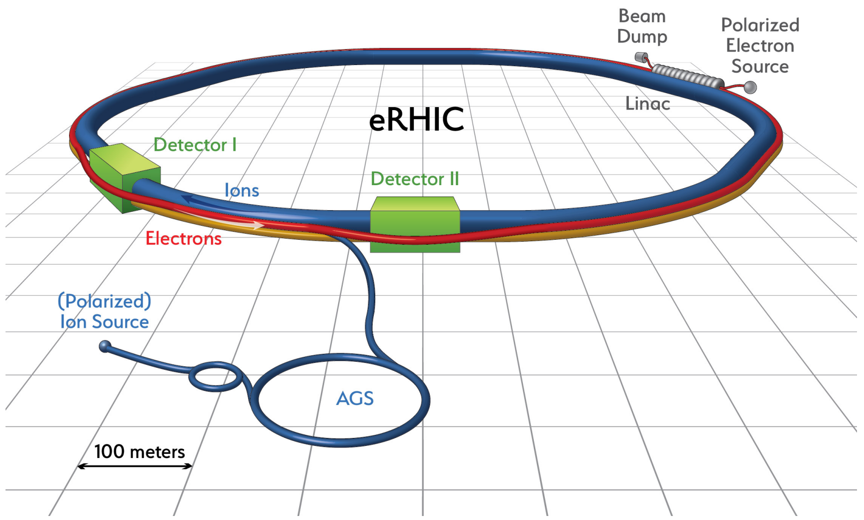


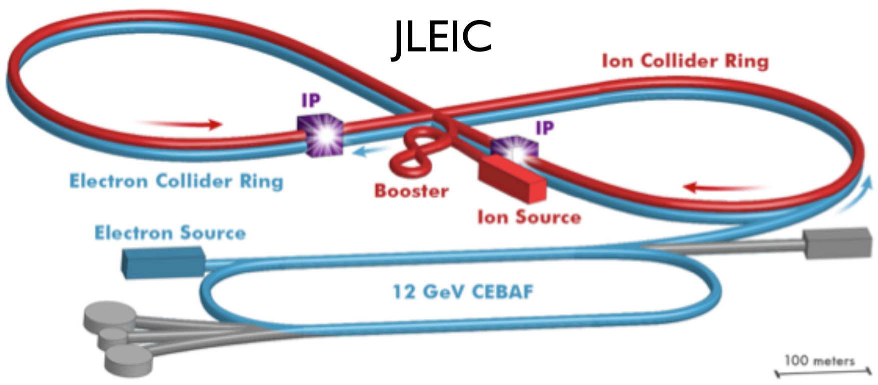
Fraser, Schwartz `18

Jets at an EIC

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



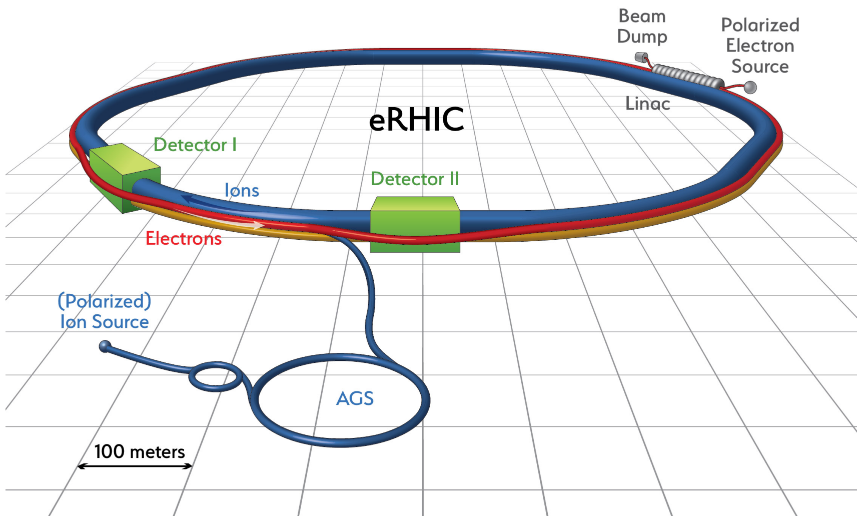


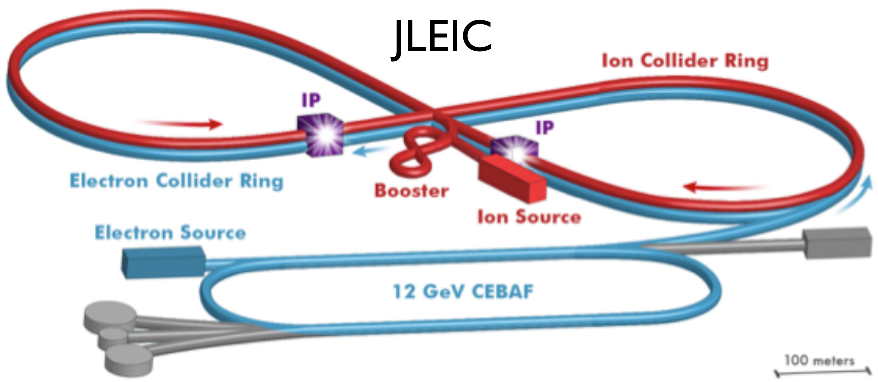


For recent work see for example: Schlegel, Hinderer, Vogelsang `15, Abelov, Boughezal, Liu, Petriello `16, Klasen, Kovarik `18, Currie, Gehrmann, Glover, Huss, Niehus, Vogt `18, Chu, Aschenauer, Lee, Zhang `17 …

Jets at an 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

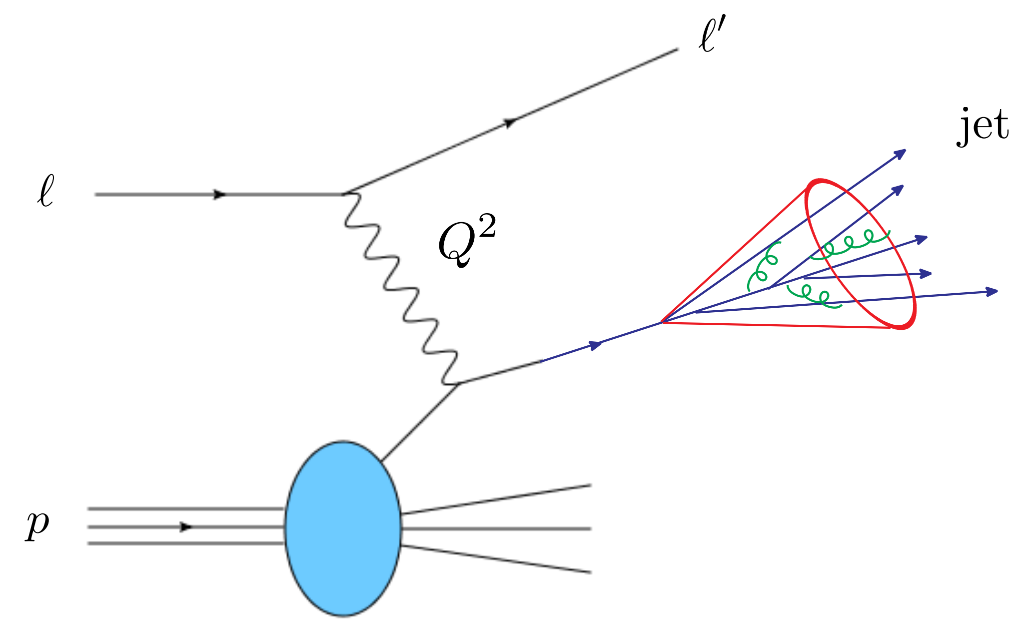
1. Validate with RHIC, HERA measurements or
2. Compare to MC simulations

Outline

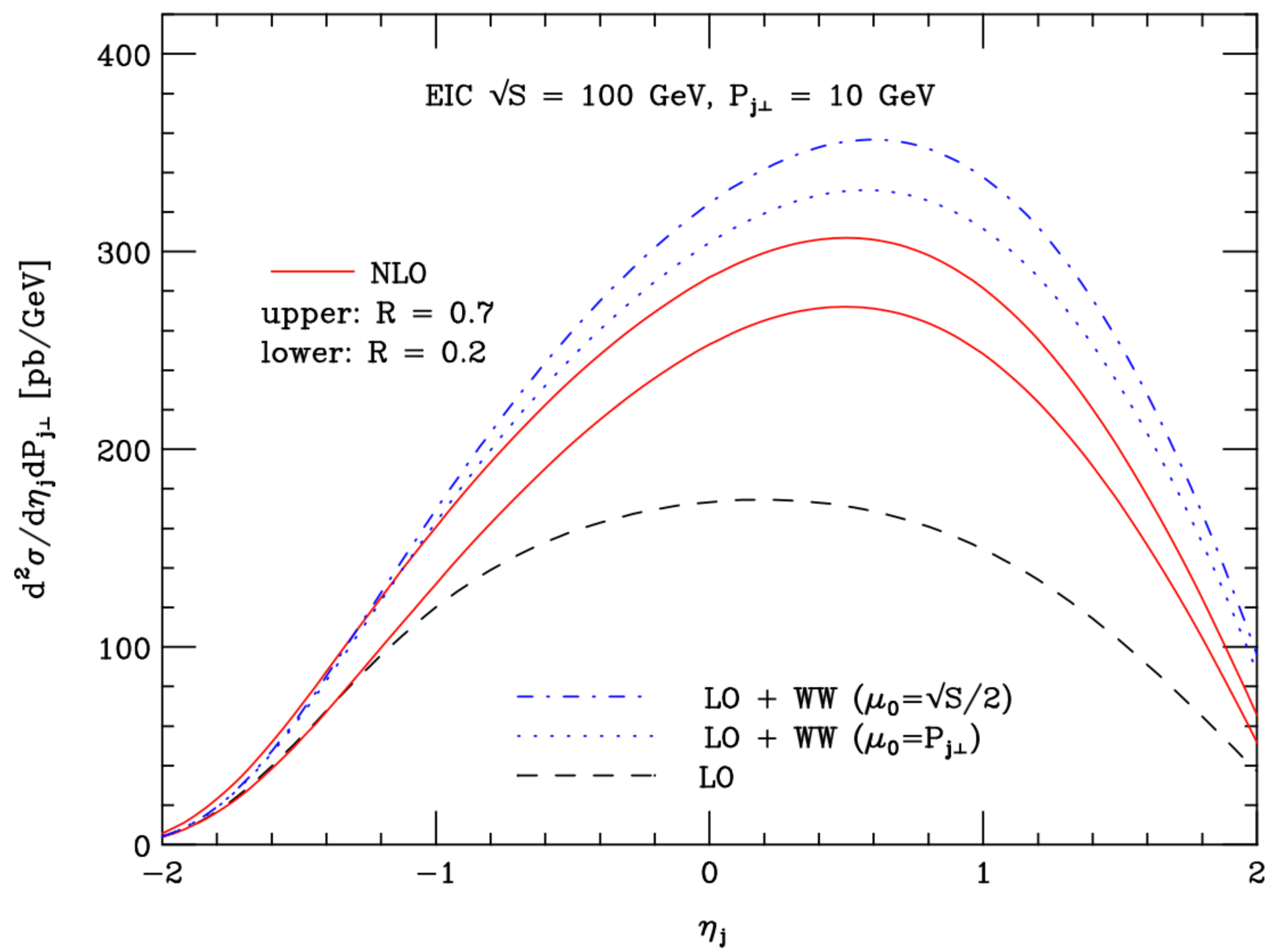
- Introduction
- Inclusive jets at the EIC
- Jet substructure
- Jet correlations
- Conclusions

Single inclusive jets at the EIC

- $pp \to \text{jet} + X$ Lepton unobserved, high p_T



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

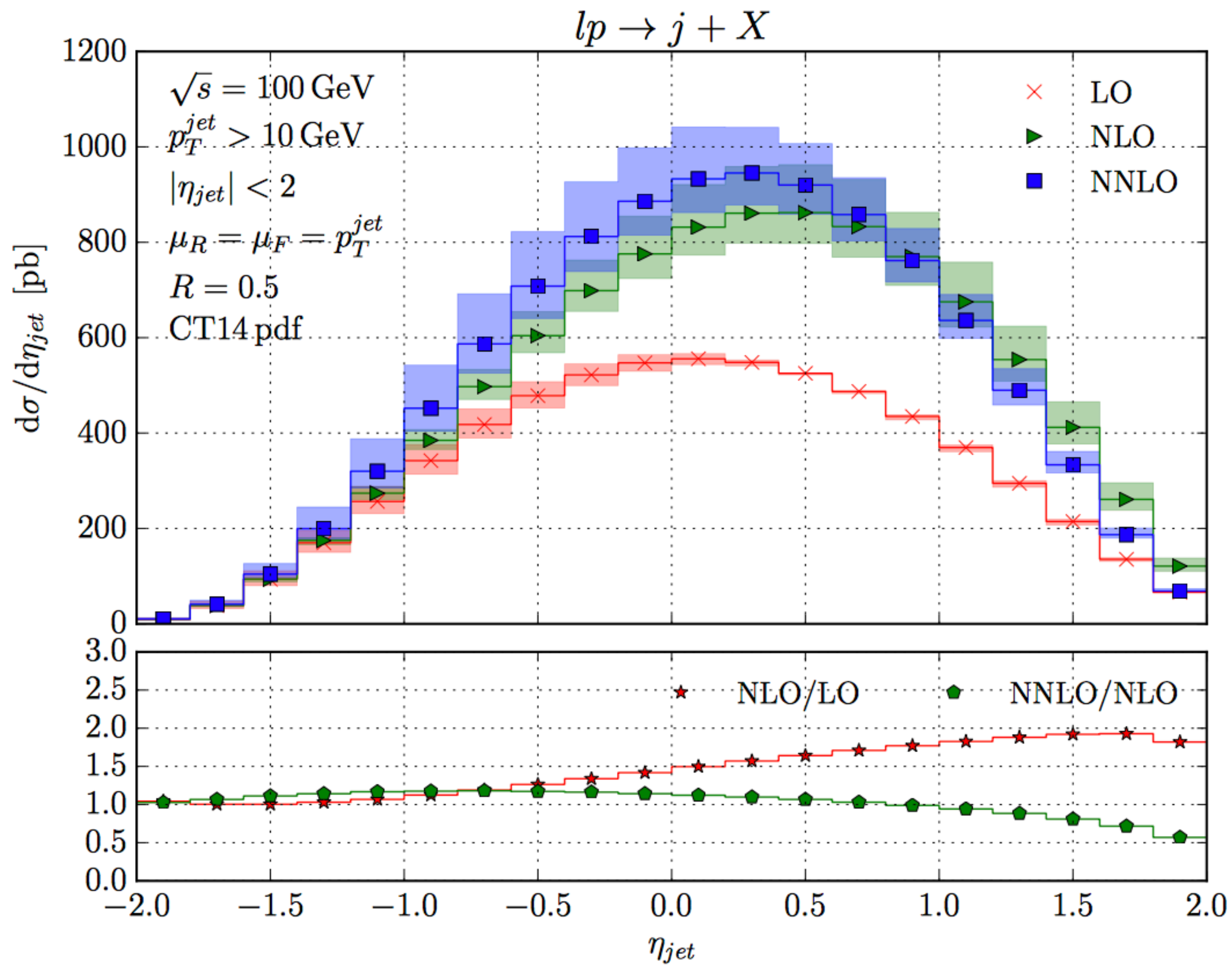


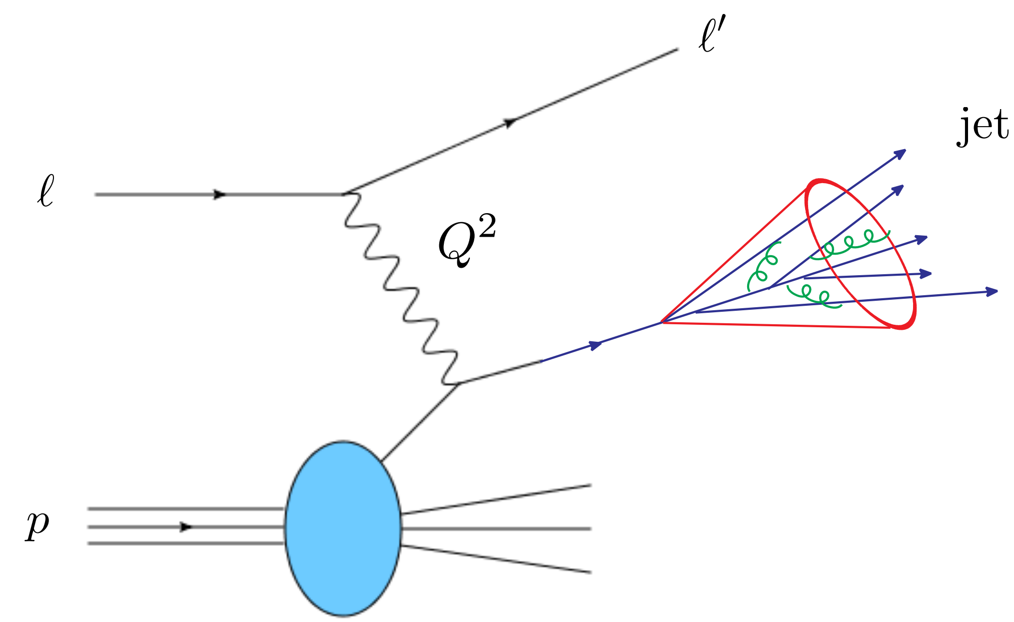
Schlegel, Hinderer, Vogelsang `15, `17,
Abelov, Boughezal, Liu, Petriello `16,
Boughezal, Petriello, Xing `18

Single inclusive jets at the EIC

- $pp \to \text{jet} + X$ Lepton unobserved, high p_T

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

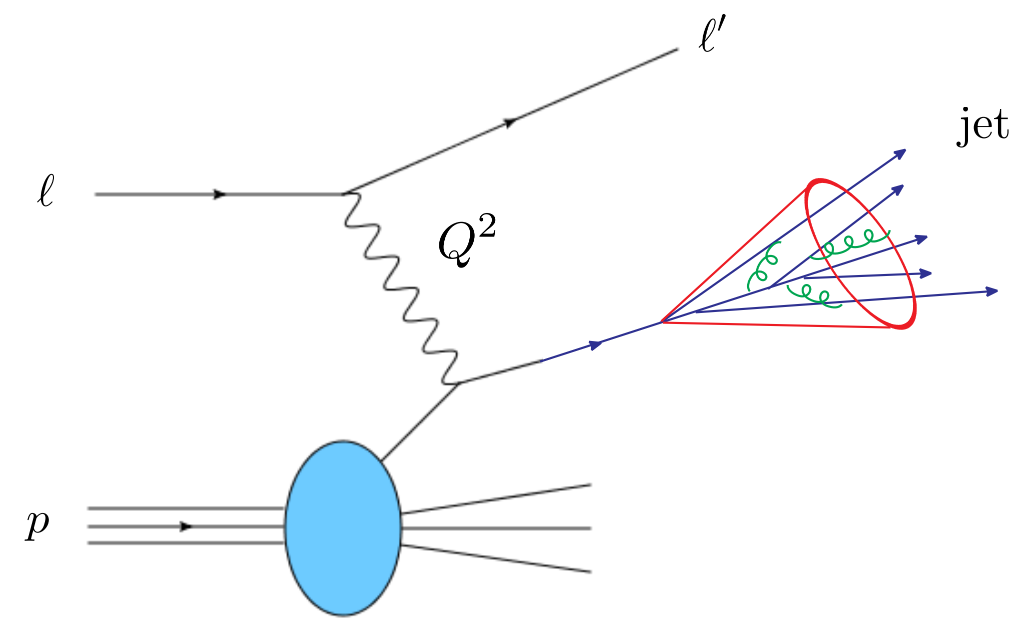




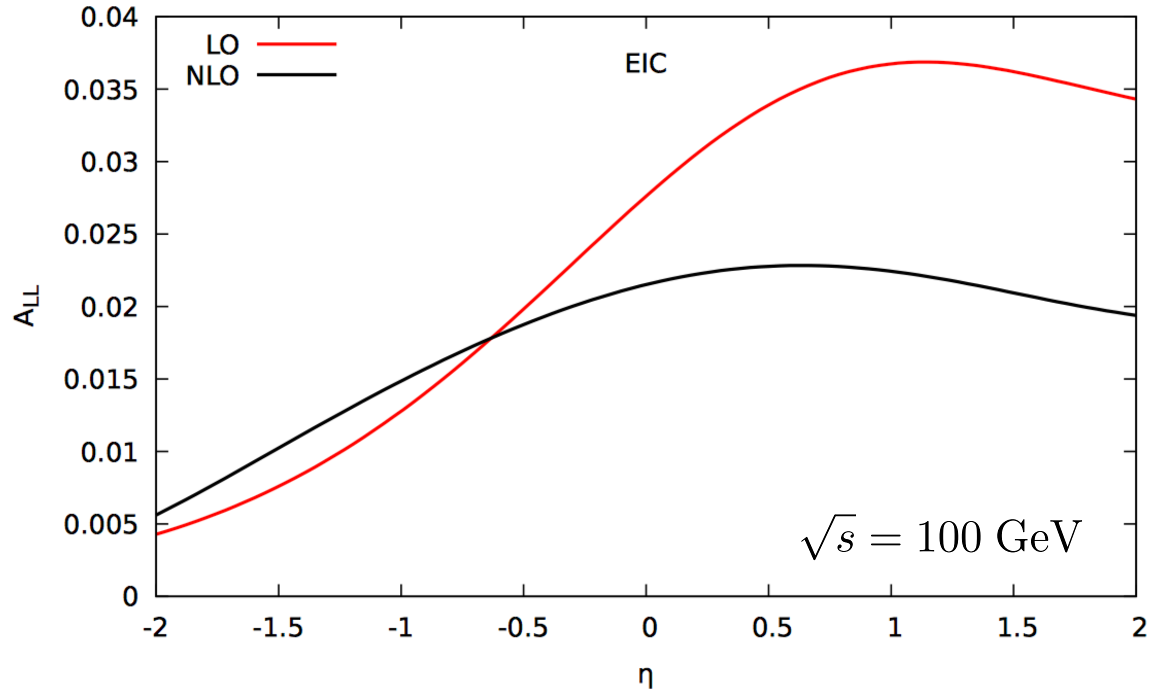
Schlegel, Hinderer, Vogelsang `15, `17,
Abelov, Boughezal, Liu, Petriello `16,
Boughezal, Petriello, Xing `18

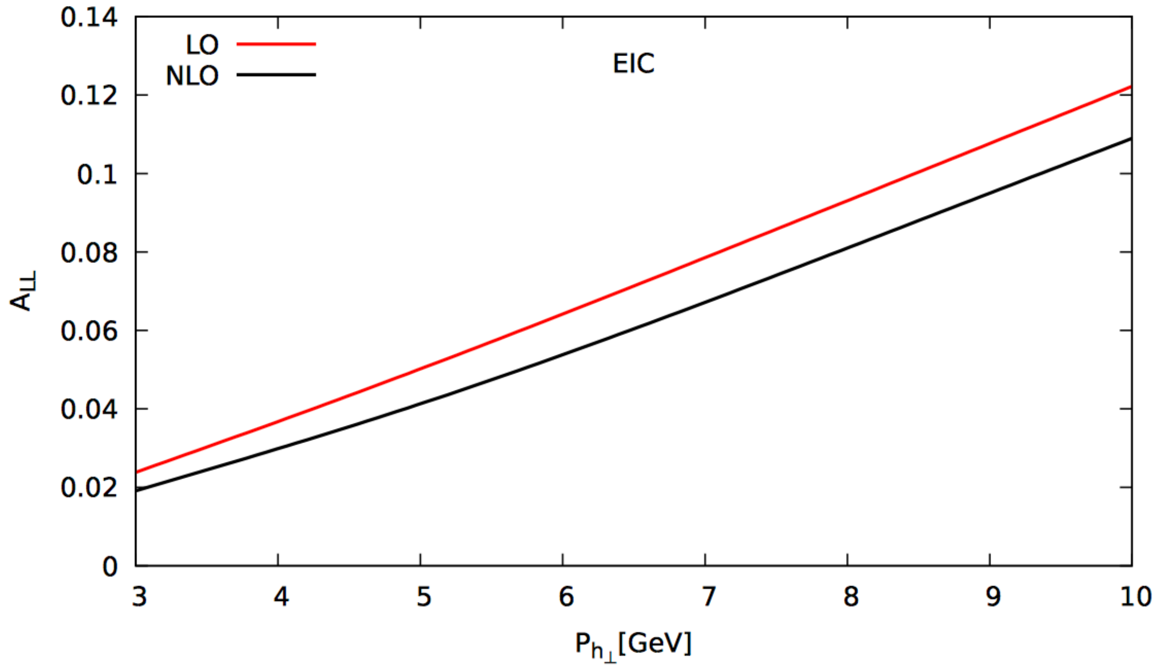
Single inclusive jets at the EIC

- $pp \to \text{jet} + X$ Lepton unobserved, high p_T



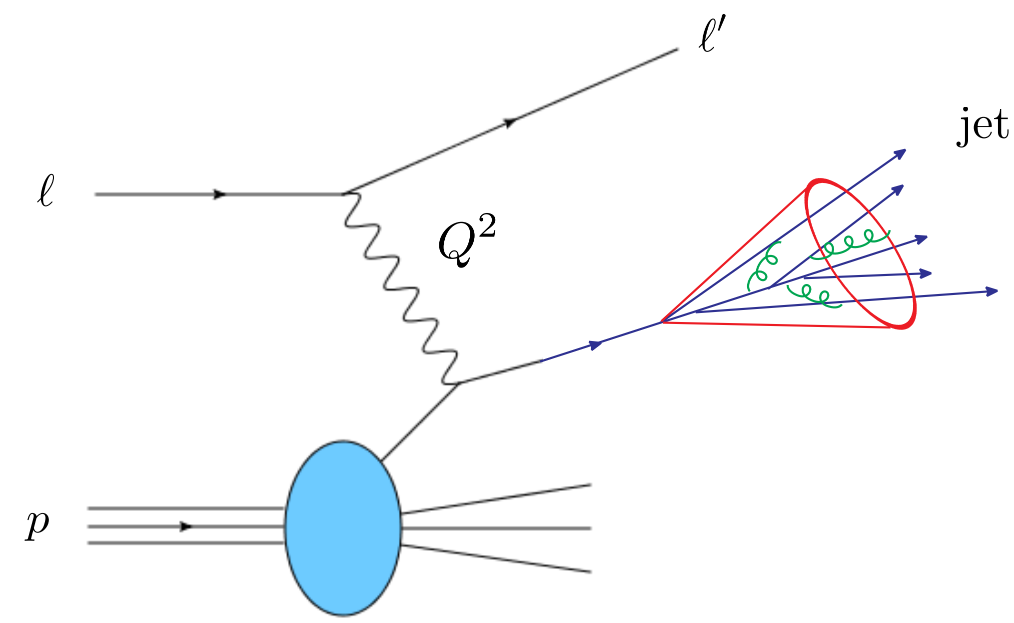
$$\frac{d\sigma}{dp_T d\eta}$$





Schlegel, Hinderer, Vogelsang `15, `17,
Abelov, Boughezal, Liu, Petriello `16,
Boughezal, Petriello, Xing `18

Single inclusive jets at the EIC



- $pp \to \text{jet} + X$ Lepton unobserved, high p_T

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

- $pp \to \ell + \text{jet} + X$ DIS, high p_T, Q^2

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

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

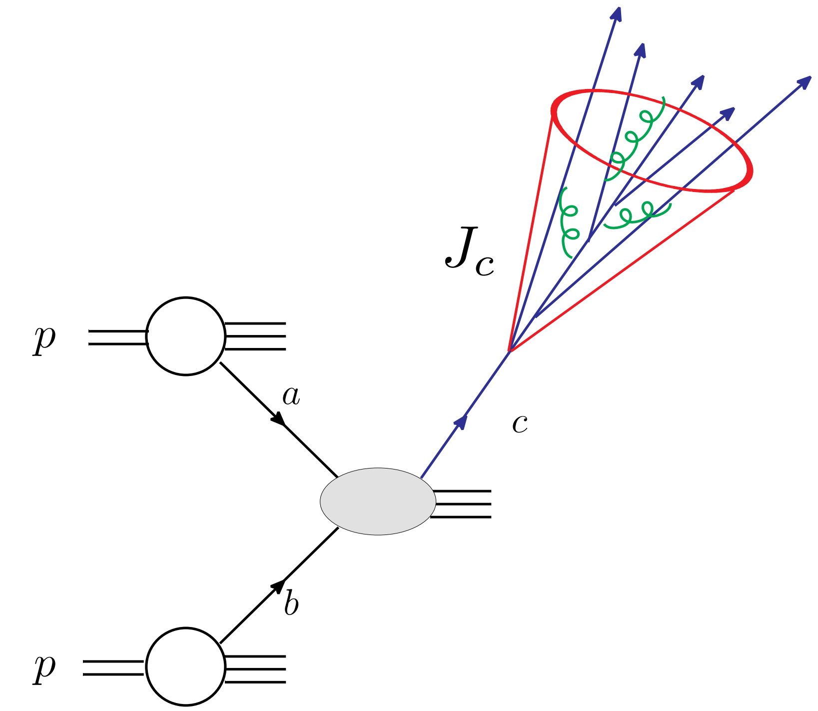
$$\frac{d\sigma}{dp_T d\eta dQ^2}$$

QCD factorization

- Inclusive jet production $pp \to \mathrm{jet} + X$

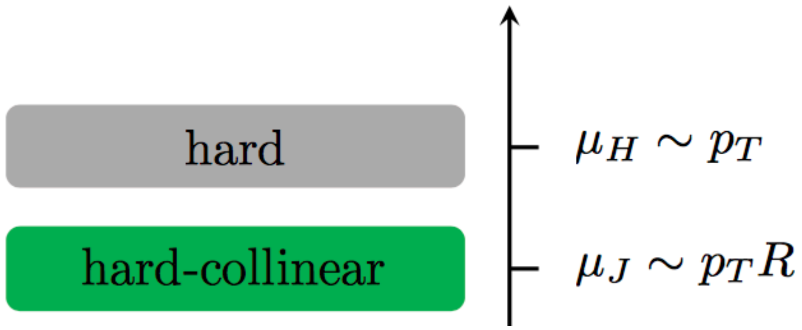
$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c \quad + \mathcal{O}(R^2)$$

perturbatively calculable



RG evolution of jet functions

$$\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j$$



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

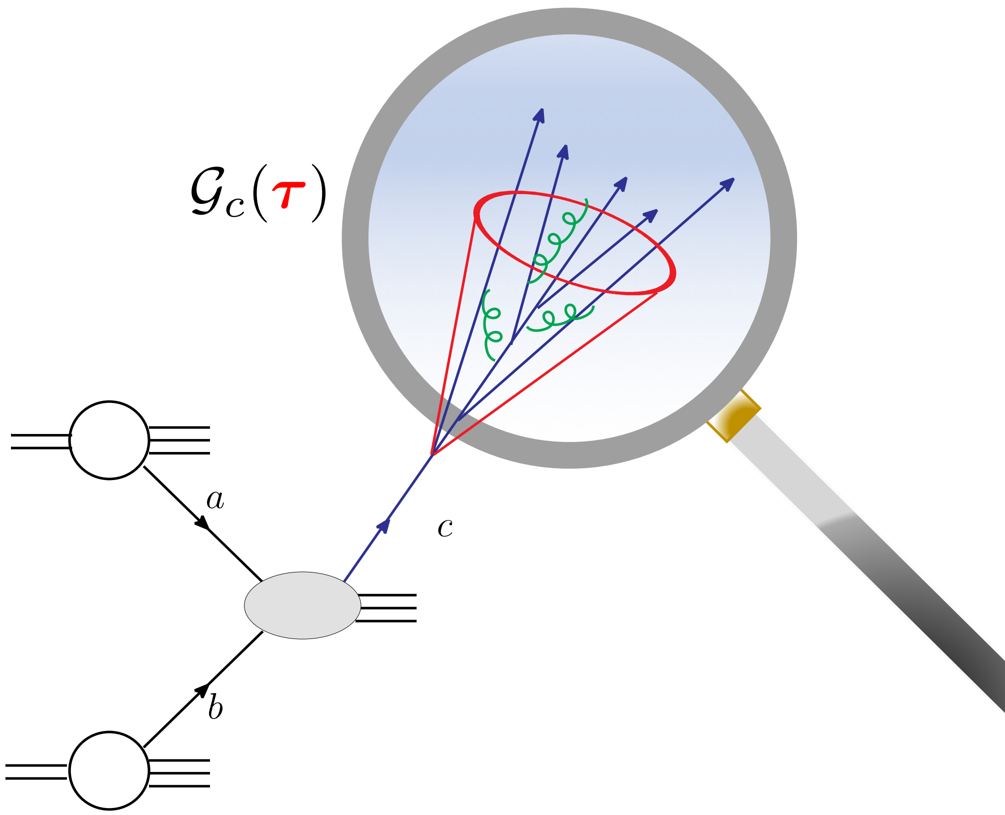
QCD factorization

- Inclusive jet production $pp \to \mathrm{jet} + X$

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \boxed{J_c} + \mathcal{O}(R^2)$$

- Jet substructure τ

$$\frac{d\sigma^{pp\to (\mathrm{jet}\,\tau)X}}{dp_T d\eta d\tau} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \boxed{\mathcal{G}_c(\tau)} + \mathcal{O}(R^2)$$

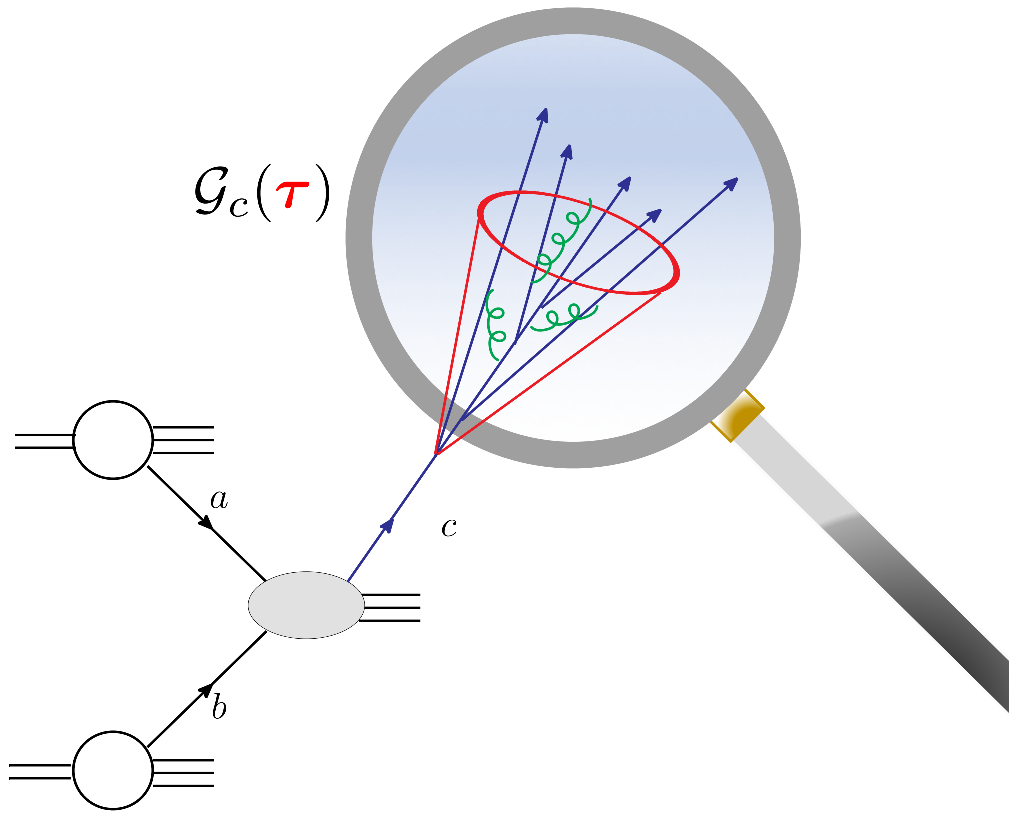


Dasgupta, Dreyer, Salam, Soyez `15
Kaufmann, Mukherjee, Vogelsang `15
Kang, FR, Vitev `16
Dai, Kim, Leibovich `16

QCD factorization

- Inclusive jet production $pp \to \text{jet} + X$

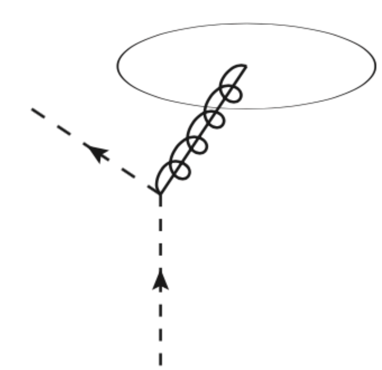
$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \boxed{J_c} + \mathcal{O}(R^2)$$



- Jet substructure τ

$$\frac{d\sigma^{pp\to(\text{jet}\,\tau)X}}{dp_T d\eta d\tau} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \boxed{\mathcal{G}_c(\tau)} + \mathcal{O}(R^2)$$

- Hard functions for lepton-proton scattering, e.g. $\dfrac{d\sigma^{\ell p\to \ell' \,\text{jet}+X}}{dp_T d\eta dQ^2 d\tau}$



  - Photoproduction

    Jäger, Stratmann, Vogelsang `03

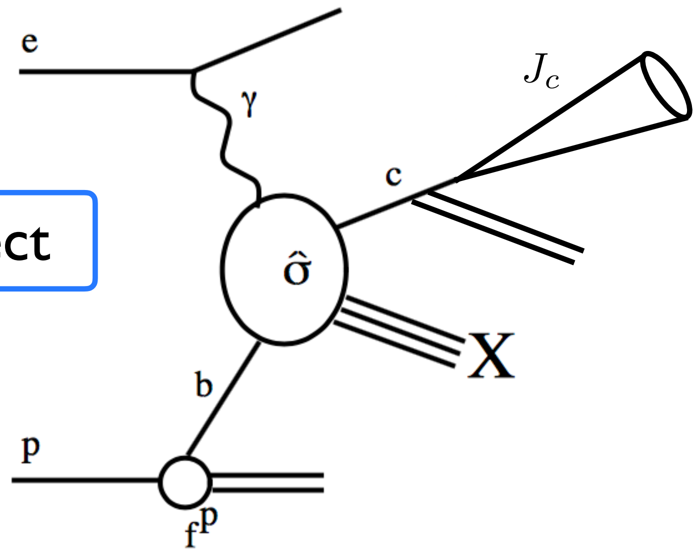
    (unpolarized and polarized)

  - DIS

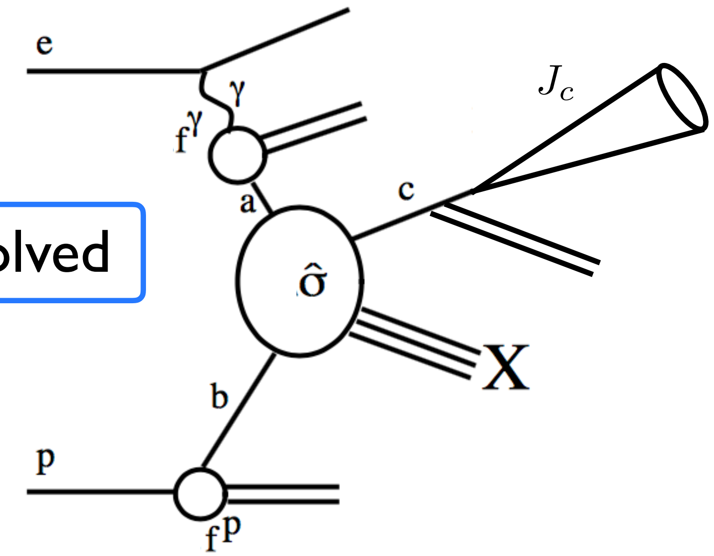
    Daleo, de Florian, Sassot `04,
    Gonzalez-Hernandez, Rogers, Sato, Wang `18

Photoproduction at the EIC

direct



resolved

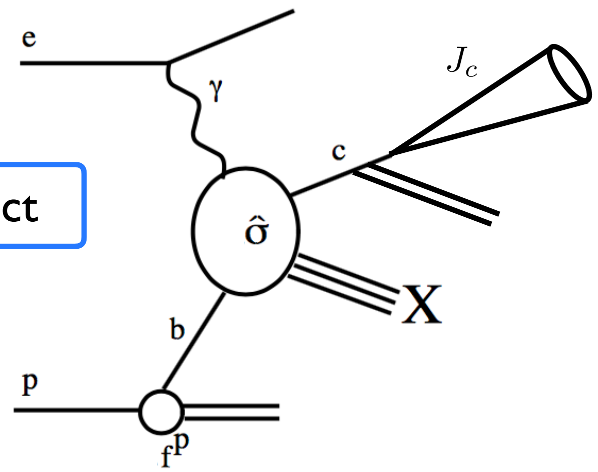


- Require high p_T and $Q^2 < 0.1 \text{ GeV}^2$
- Access the parton content of (polarized) photons

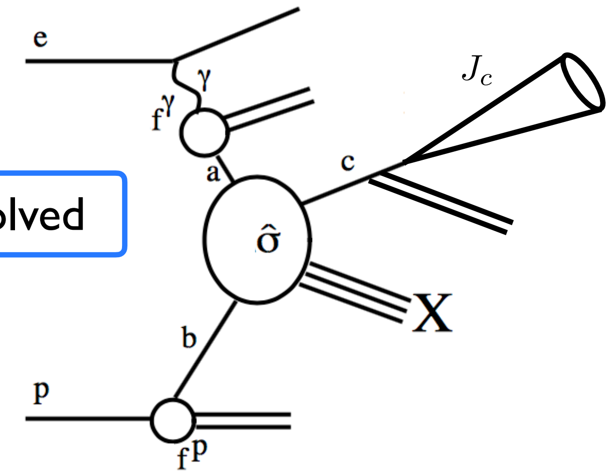
Jäger, Stratmann, Vogelsang `03
de Florian, Pfeuffer, Schäfer, Vogelsang `13
Chu, Aschenauer, Lee, Zhang `17

Photoproduction at the EIC

direct



resolved



- Inclusive jets

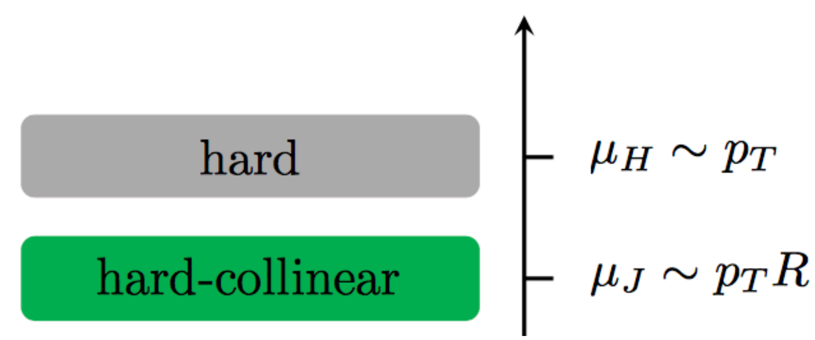
$$\frac{d\sigma}{dp_T d\eta dQ^2} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes J_c$$

Weizsäcker-Williams spectrum

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

- Jet mass

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



Jäger, Stratmann, Vogelsang `03

Chu, Aschenauer, Lee, Zhang `17

Phenomenology

$\sqrt{s} = 141$ GeV

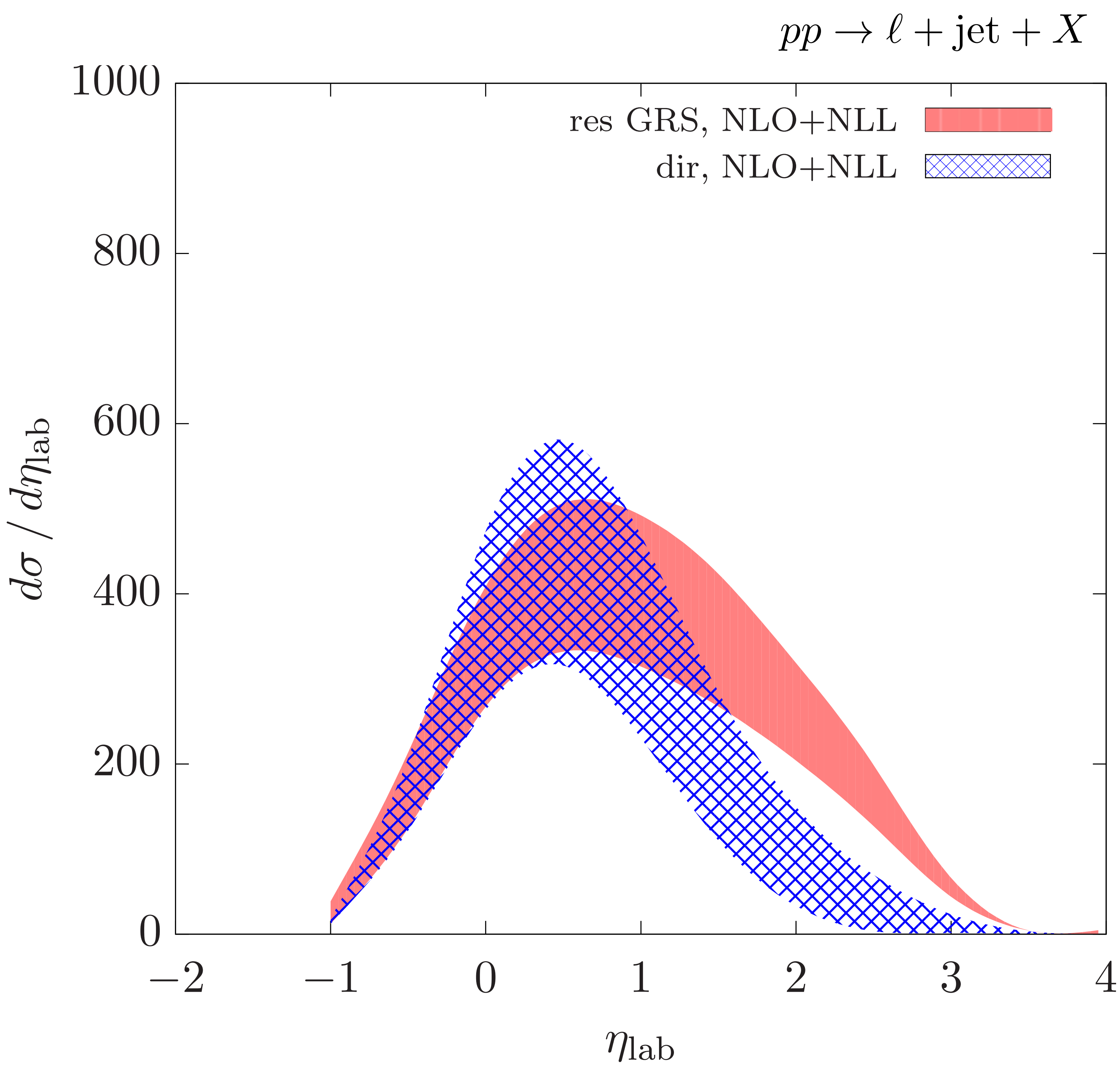
$R = 0.8$

$p_T > 10$ GeV

$Q^2 < 0.1$ GeV^2

$E_e = 20$ GeV

$E_p = 250$ GeV



in collaboration with Aschenauer, Page

Phenomenology

$\sqrt{s} = 141$ GeV

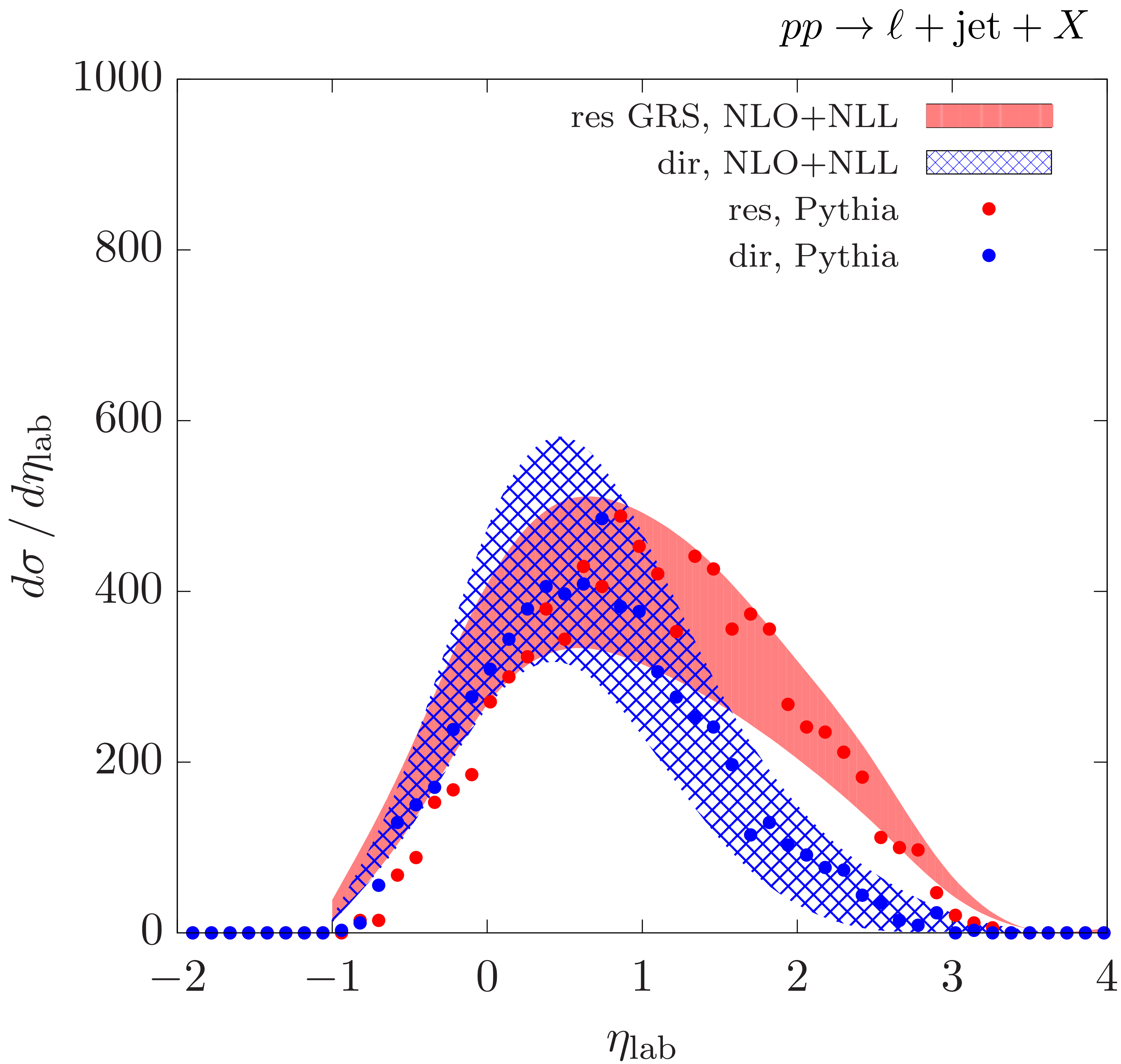
$R = 0.8$

$p_T > 10$ GeV

$Q^2 < 0.1$ GeV^2

$E_e = 20$ GeV

$E_p = 250$ GeV



in collaboration with Aschenauer, Page

Cold nuclear matter effects in eA

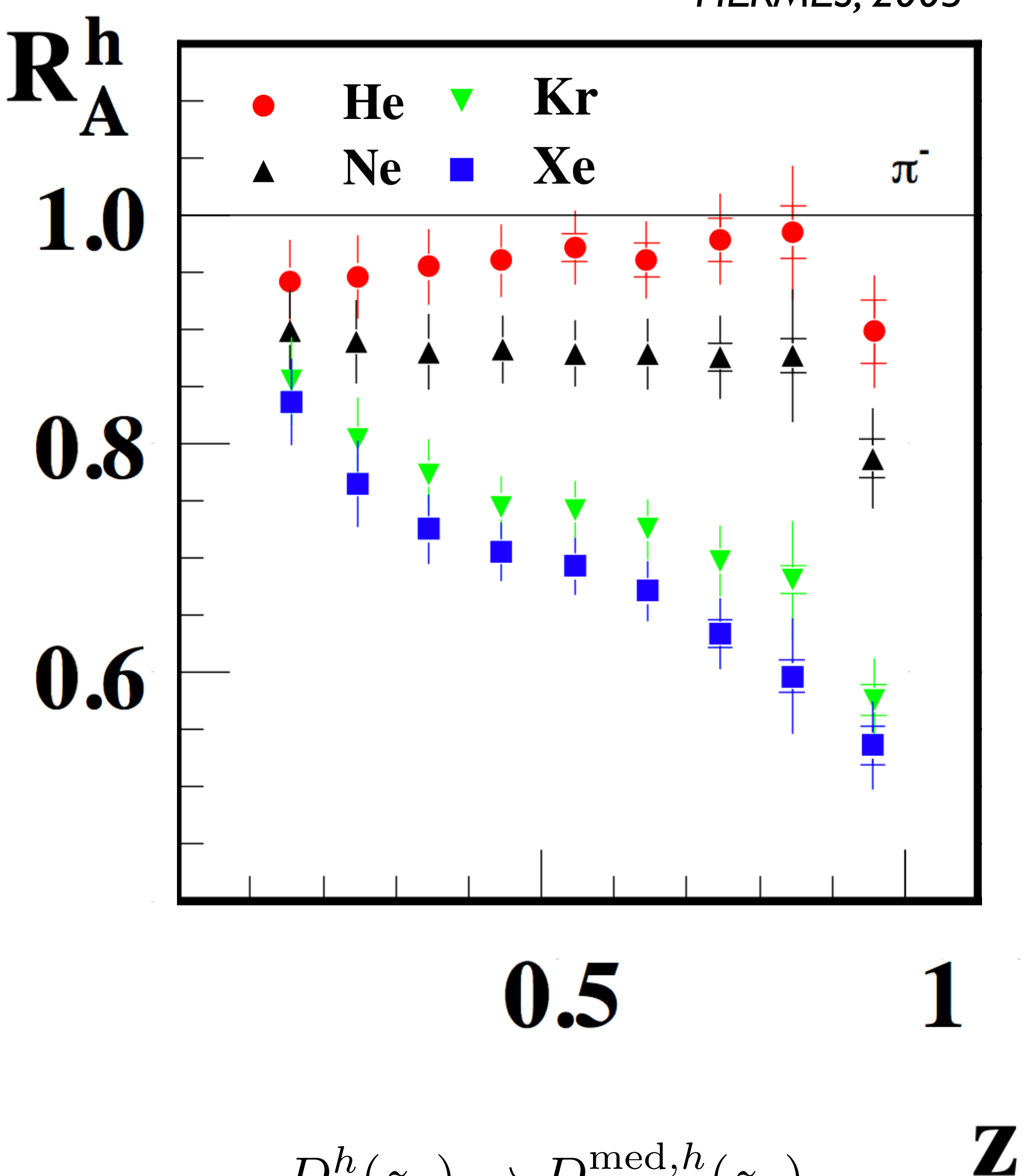
FR, Sato, Vitev - in preparation

- Hadron multiplicity ratios $d\sigma/dz_h$
- SIDIS

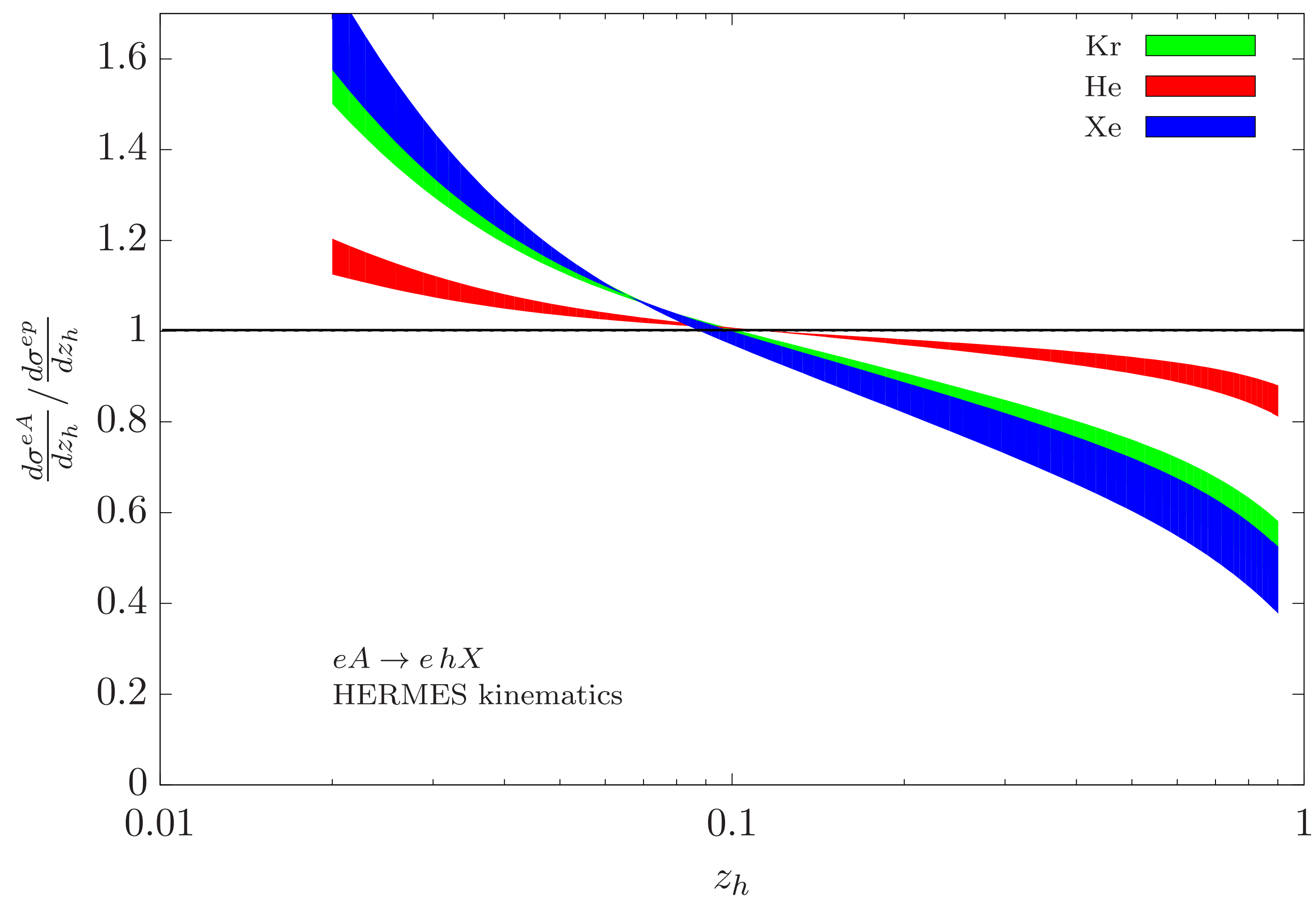
$Q^2 > 1\ \mathrm{GeV}^2 \qquad \nu < 23\ \mathrm{GeV}$

$W^2 > 10\ \mathrm{GeV}^2$

HERMES, 2003



$D_i^h(z_h) \to D_i^{\mathrm{med},h}(z_h)$



Constrain medium input and extrapolate to jets at the EIC

Outline

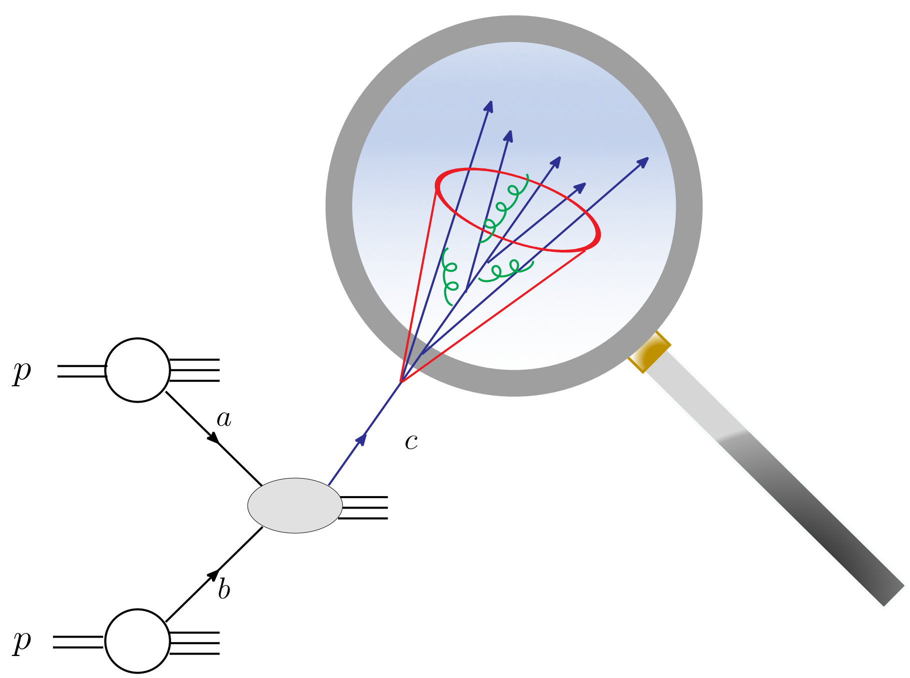
- Introduction
- Inclusive jets at the EIC
- Jet substructure
- Jet correlations
- Conclusions

The jet mass at the LHC

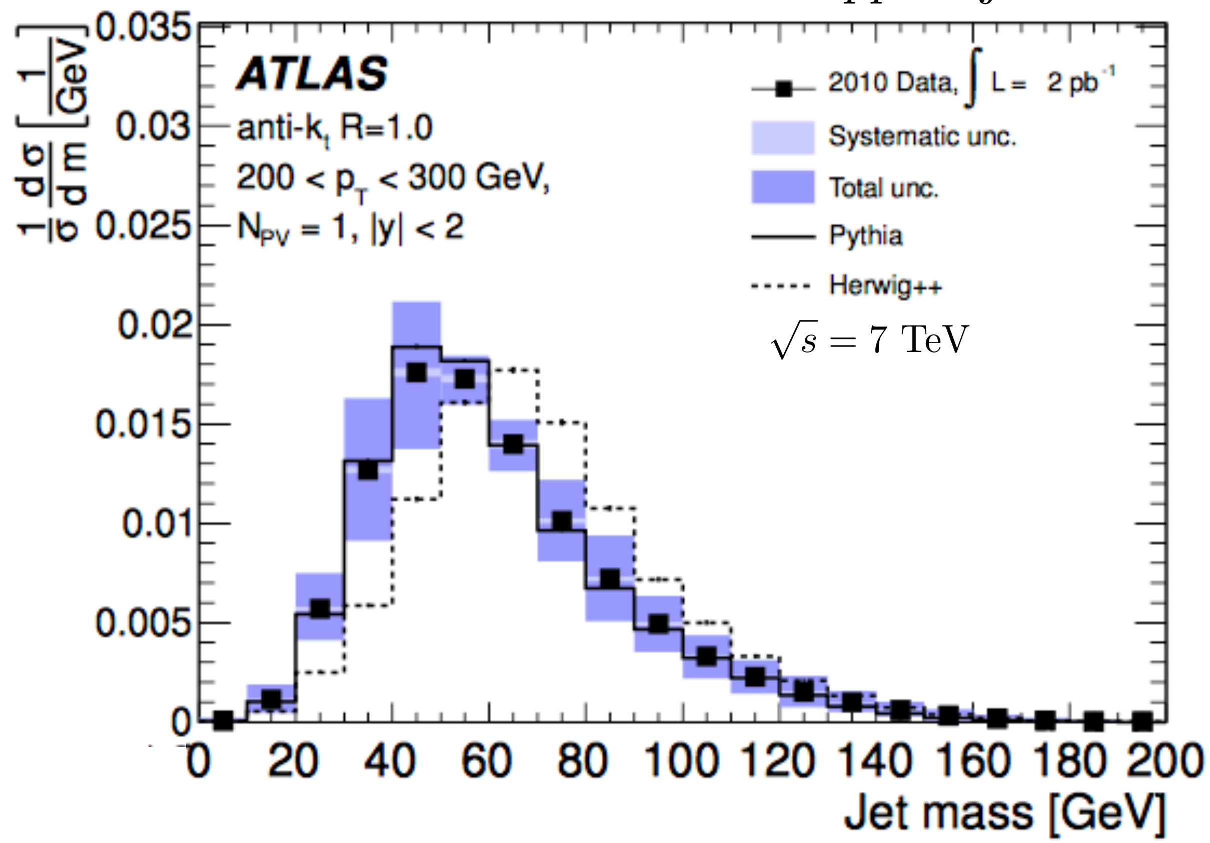
Kang, Lee, FR `18,
Kang, Lee, Liu, FR `18

- 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
- Including soft drop: α_s extraction possible

Les Houches `17



$pp \to \text{jet} + X$



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 $R \ll 1$

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

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

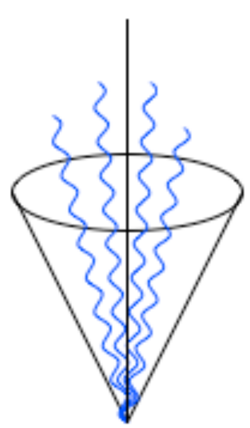
$$pp \to (\mathrm{jet}\, m_J^2)X$$

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

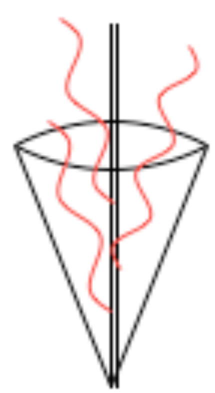
$$\mathcal{G}_c(z,p_T,R,\tau,\mu) = \sum_i \mathcal{H}_{c\to i}(z,p_T R,\mu)\, {\color{blue}C_i(\tau,p_T,\mu)} \otimes {\color{red}S_i(\tau,p_T,R,\mu)}$$

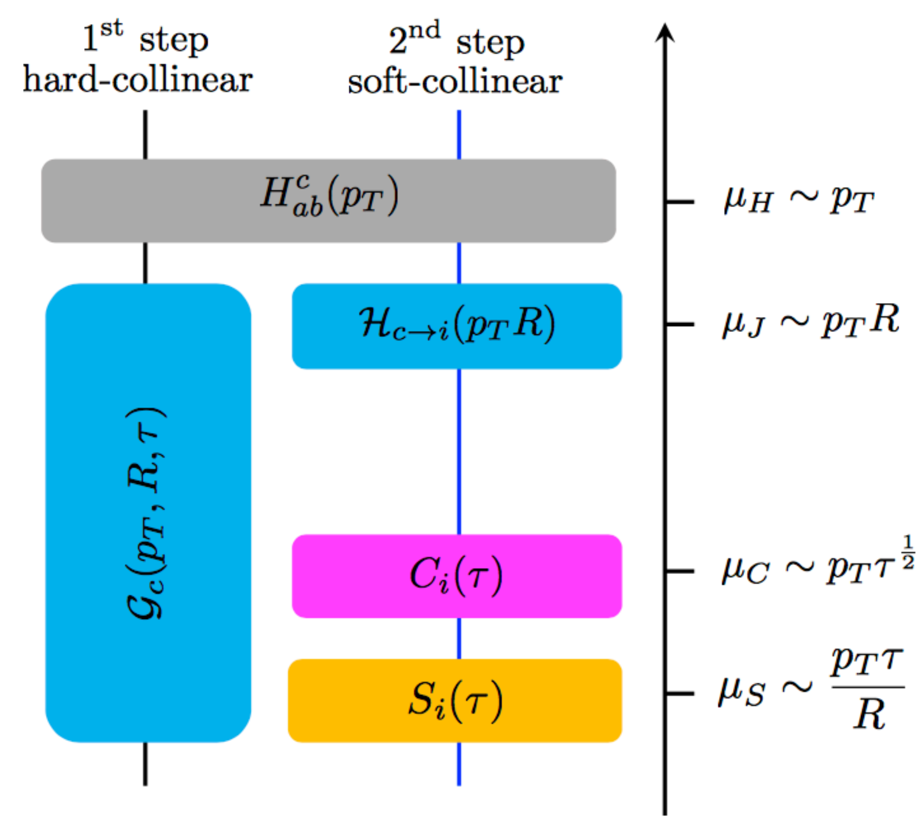
hard-matching

collinear



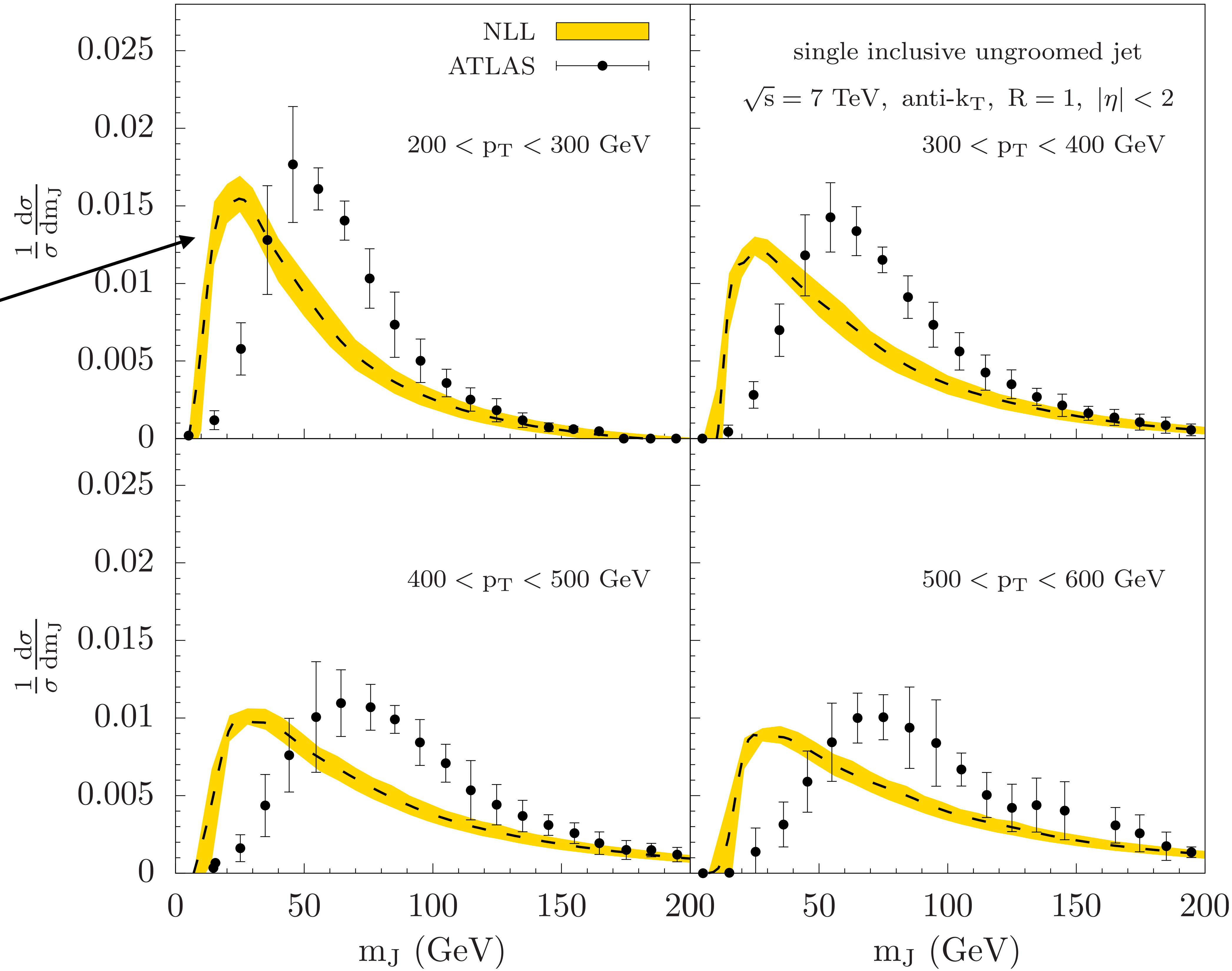
soft





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

Perturbative result



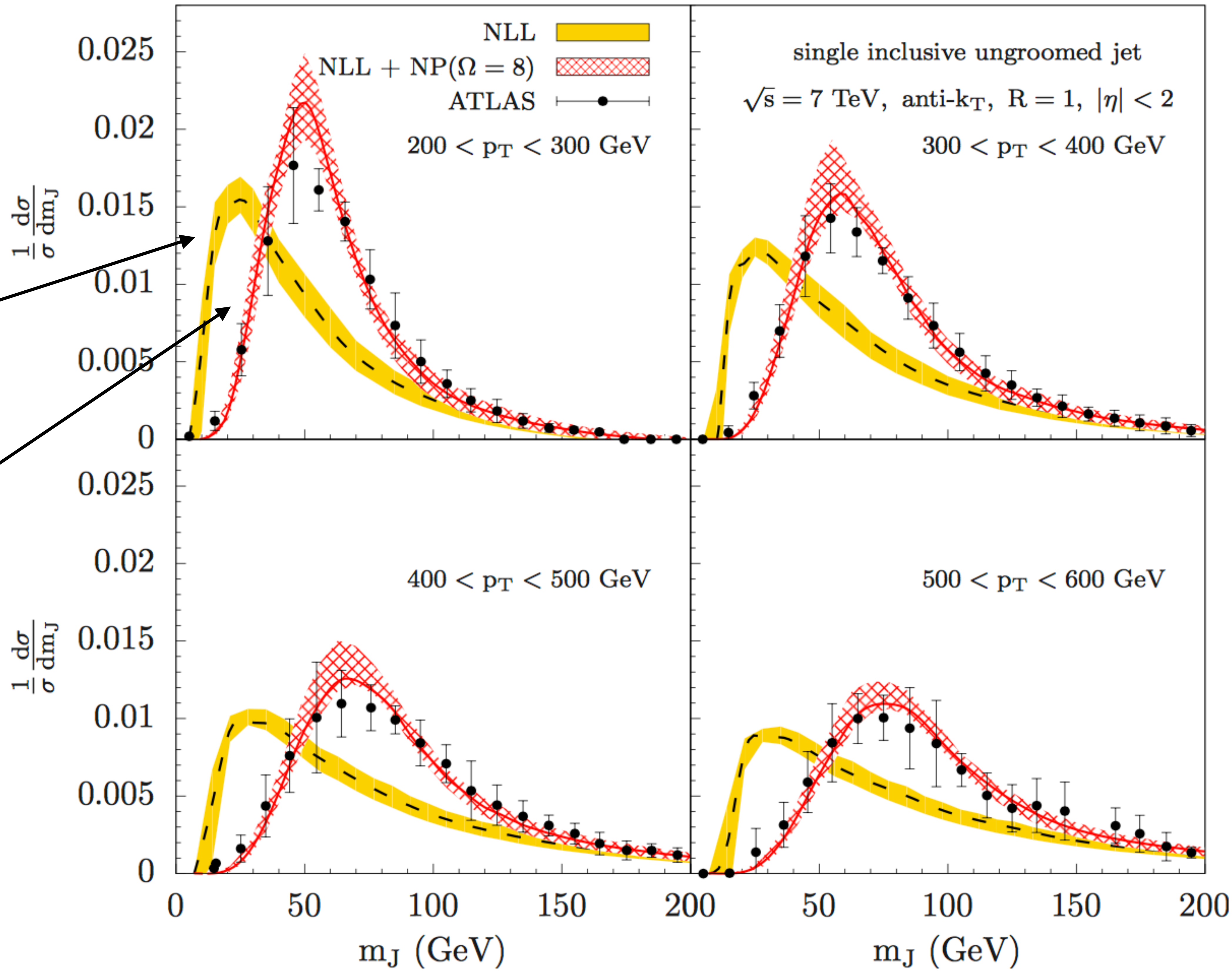
ATLAS, JHEP 05 (2012) 128

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

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

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

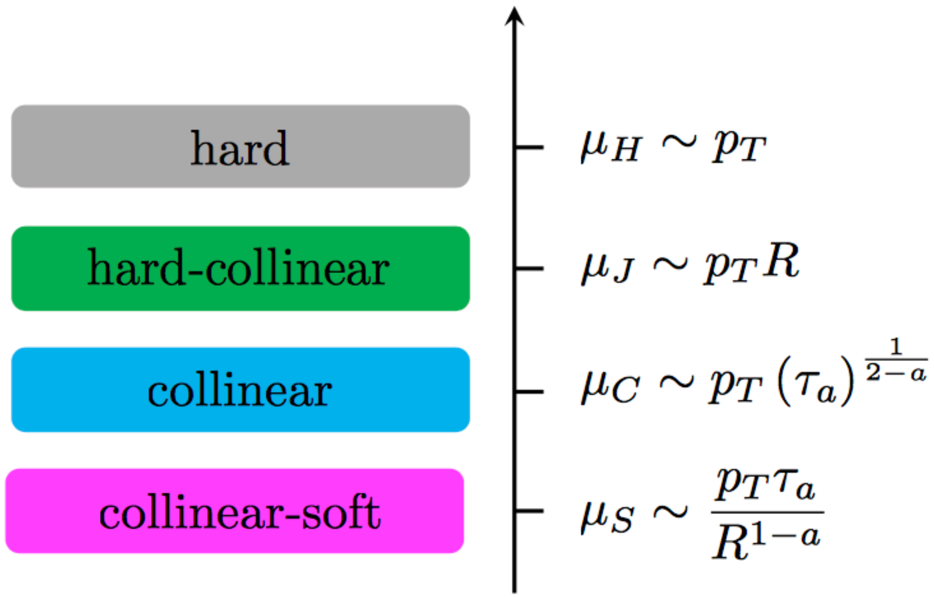
Kang, Lee, FR `18,
Kang, Lee, Liu, FR `18

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 ($a = 1$)
- Dependence on jet axis: standard, recoil free
- Event shape type of observables

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

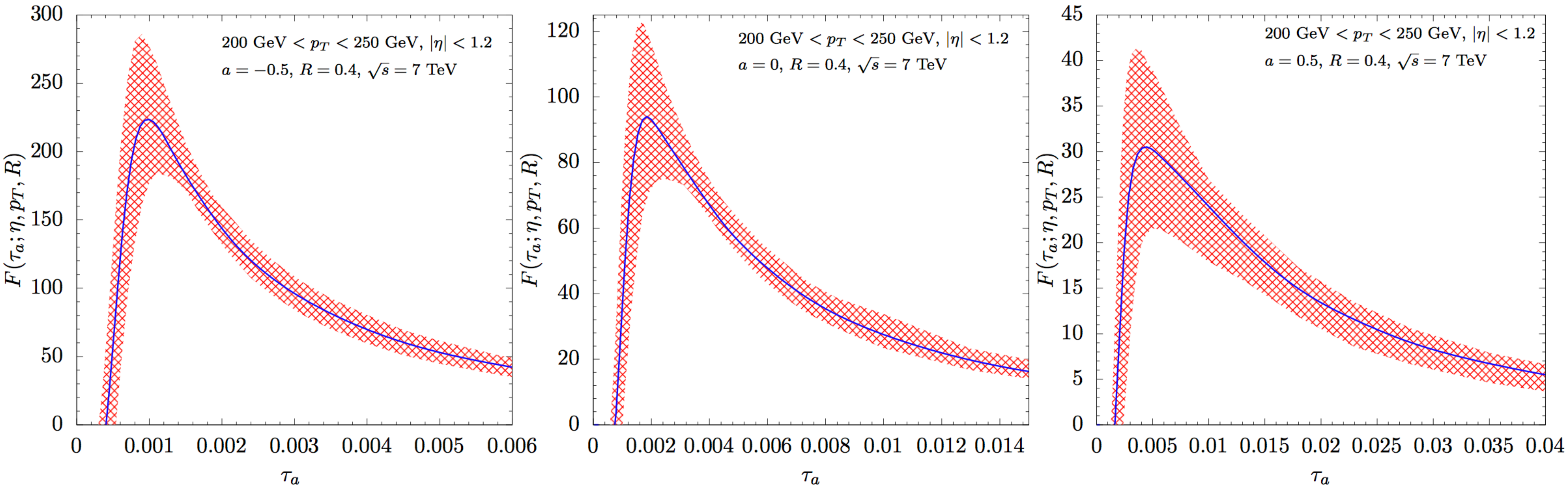


- Factorization $\tau_a^{1/(2-a)} \ll R$

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

Jet angularities

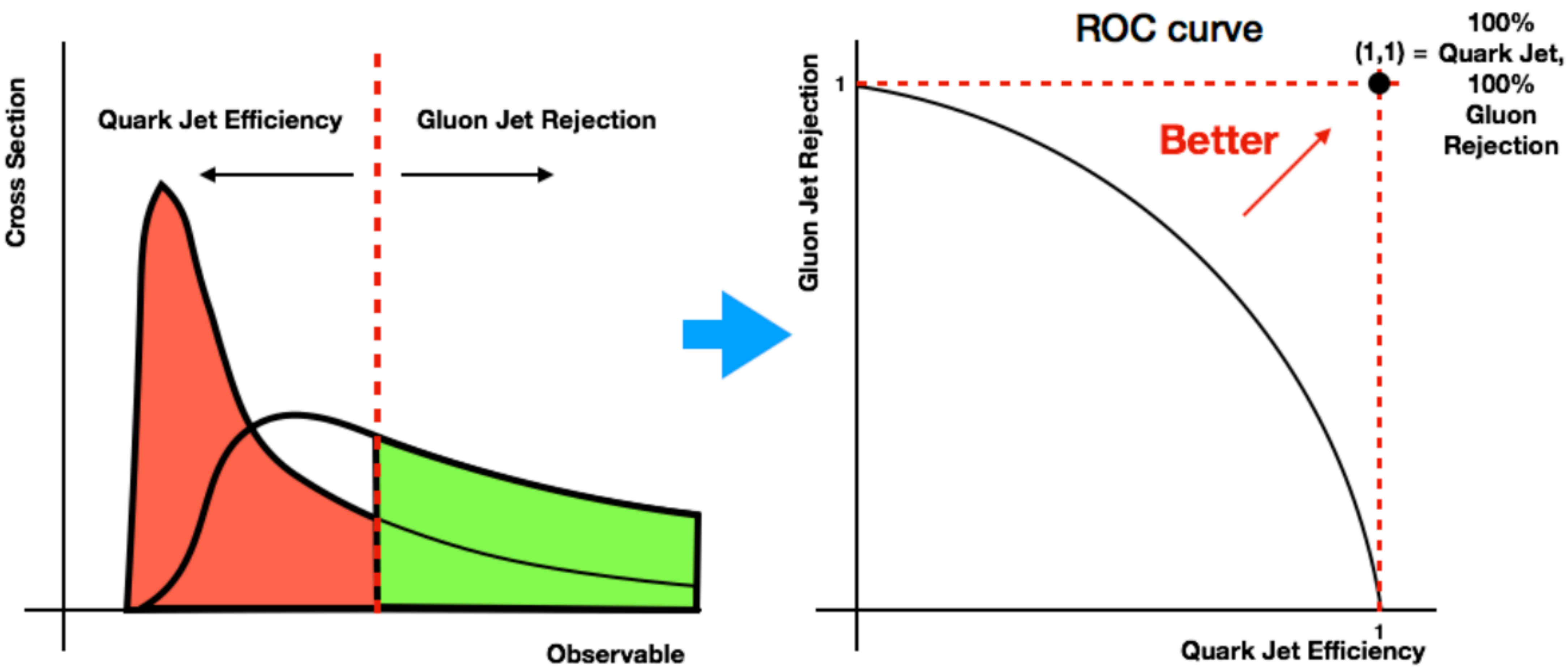
Kang, Lee, FR `18



$$F(\tau_a;\eta,p_T,R) = \frac{d\sigma^{pp\to(\text{jet}\,\tau_a)X}}{d\eta dp_T d\tau_a} \Big/ \frac{d\sigma^{pp\to\text{jet}X}}{d\eta dp_T}$$

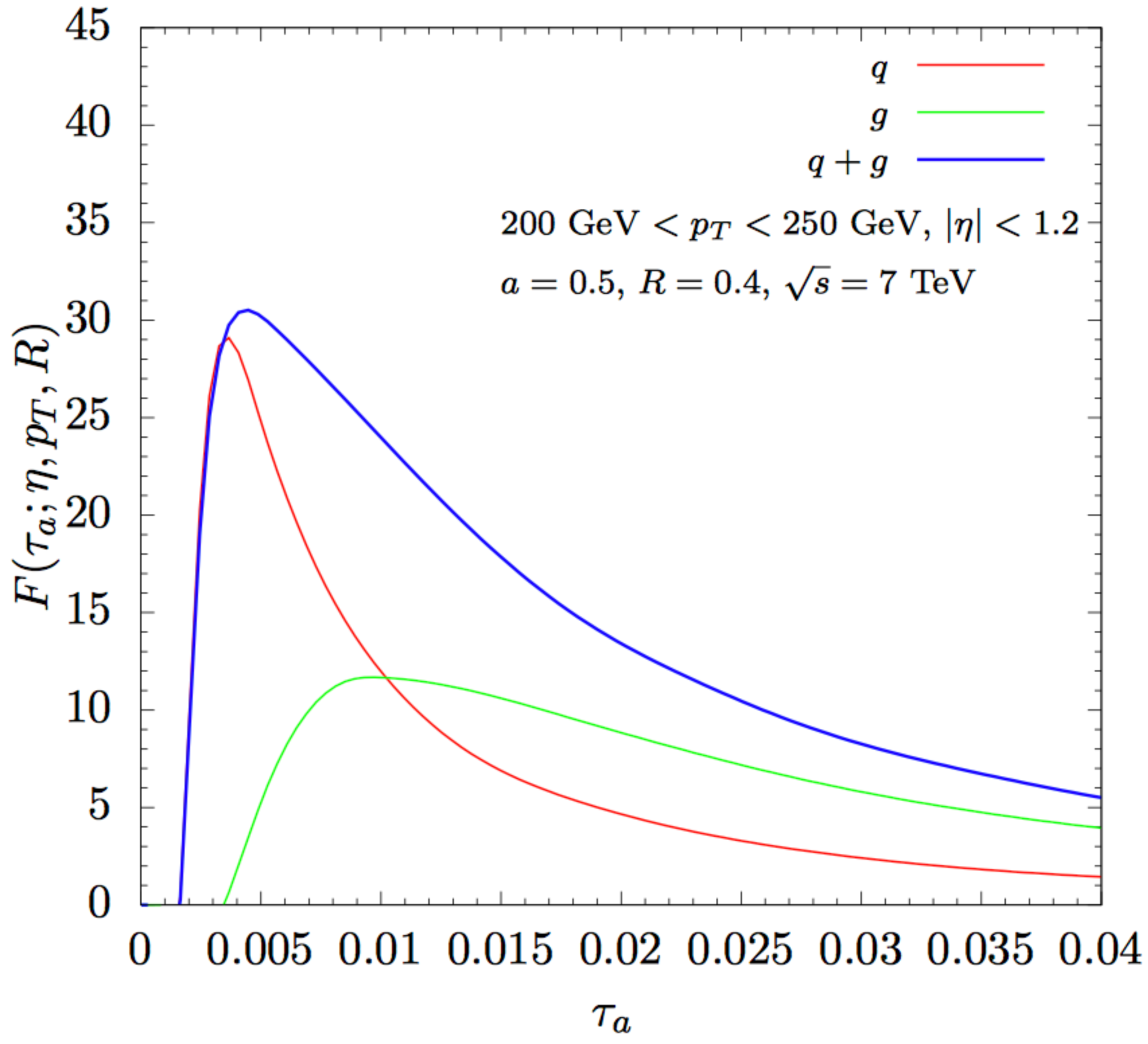
Quark-gluon discrimination

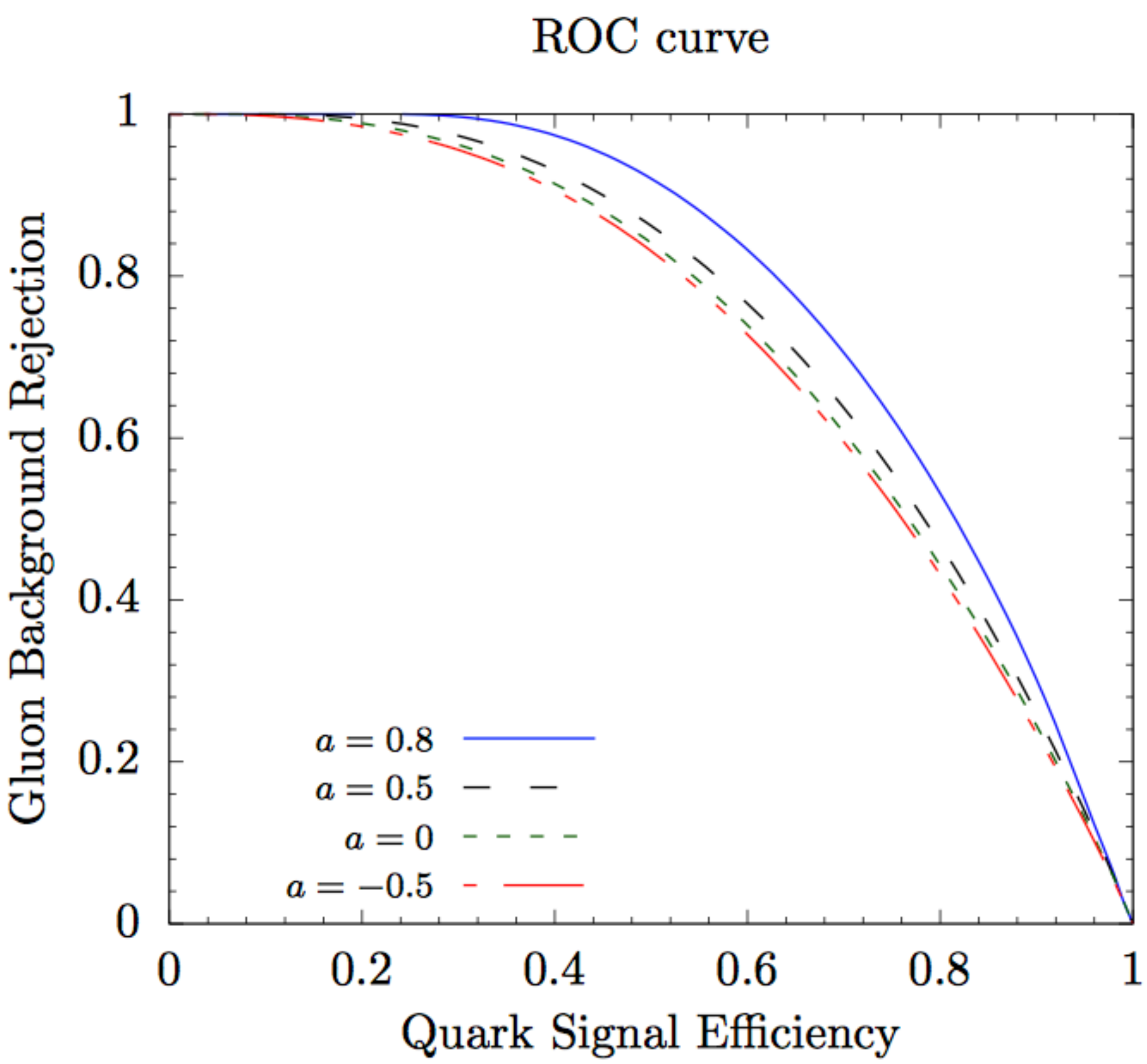
Kang, Lee, FR `18



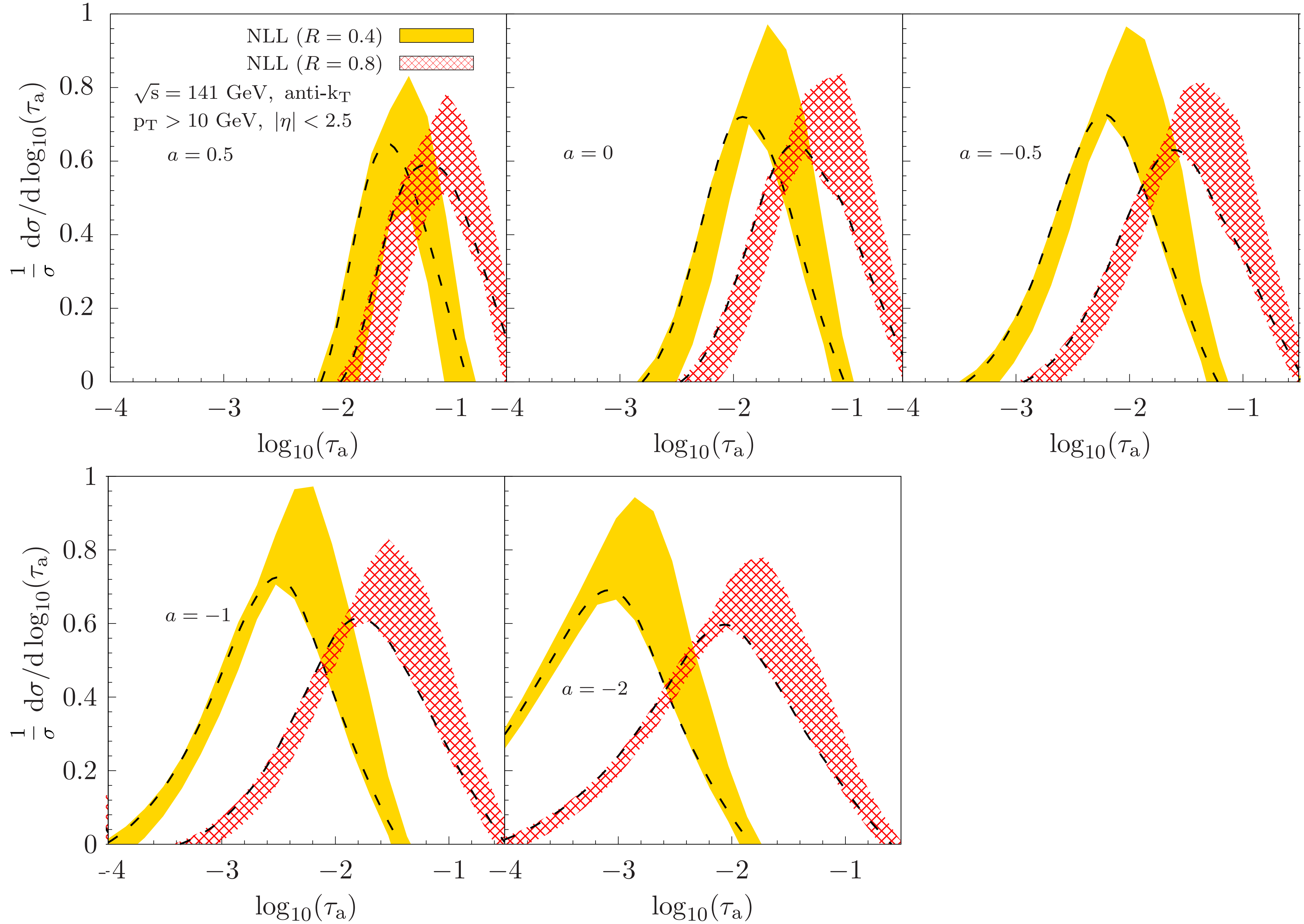
Quark-gluon discrimination

Kang, Lee, FR `18





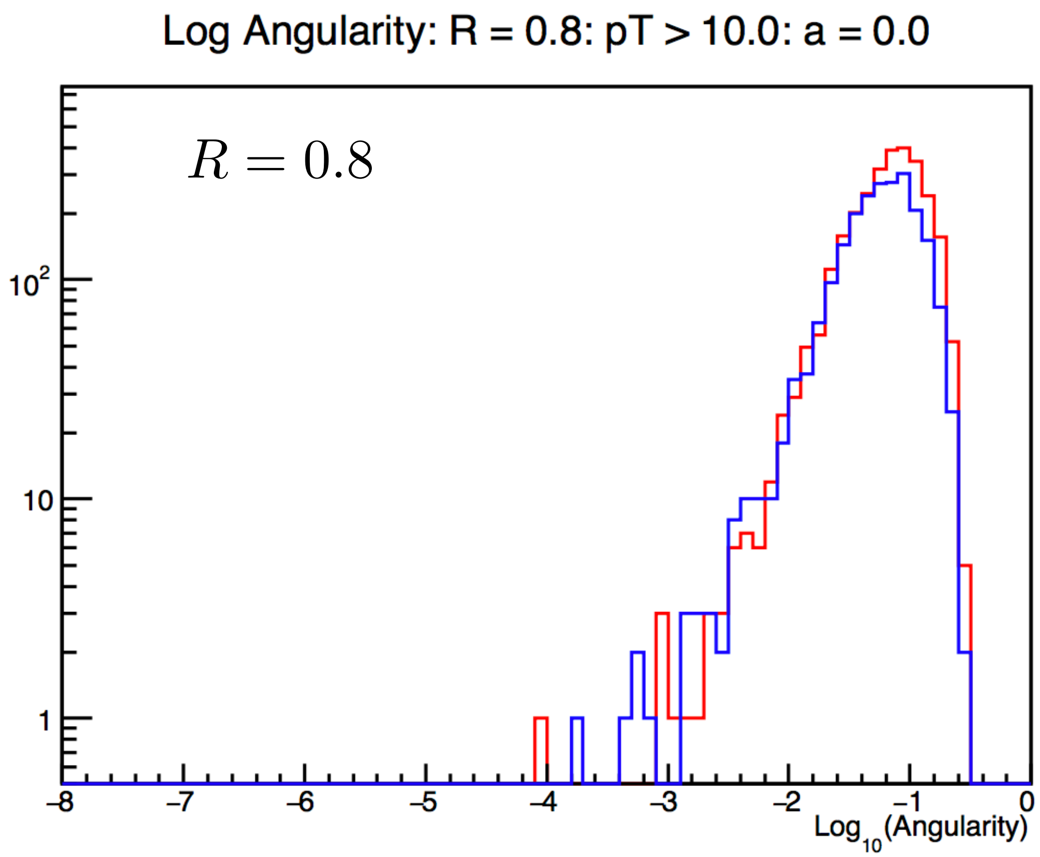
Photoproduction at the EIC

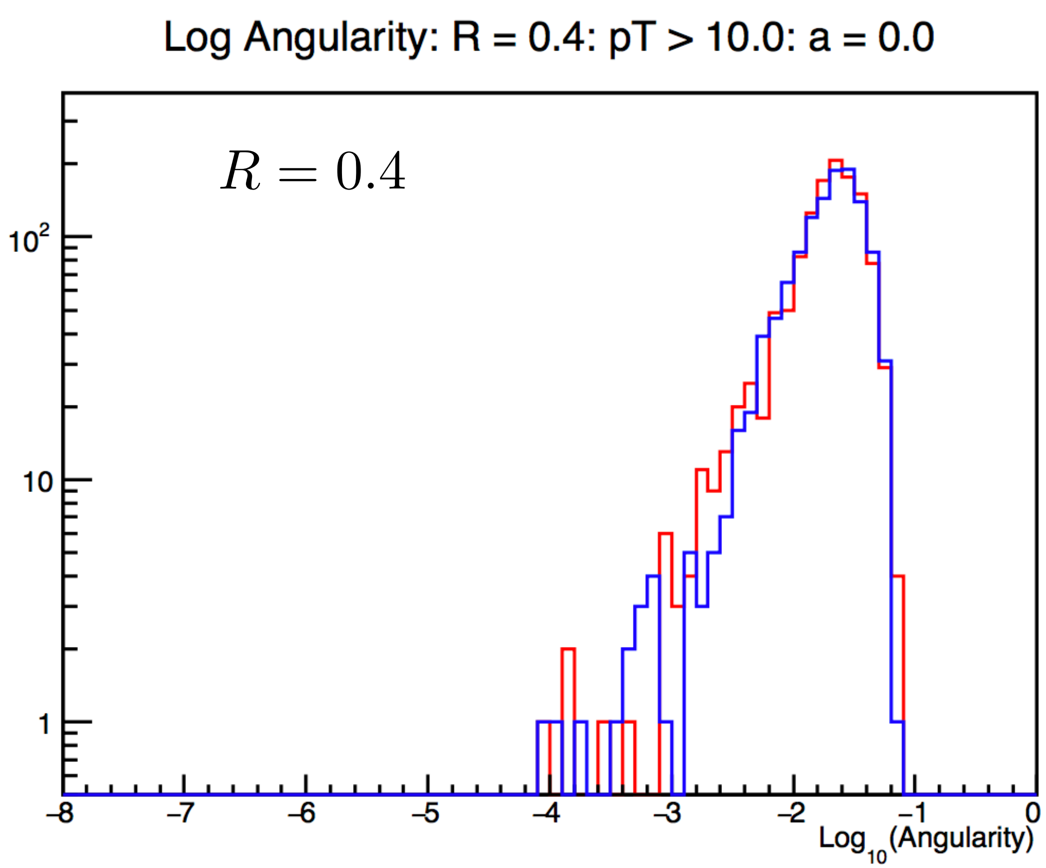


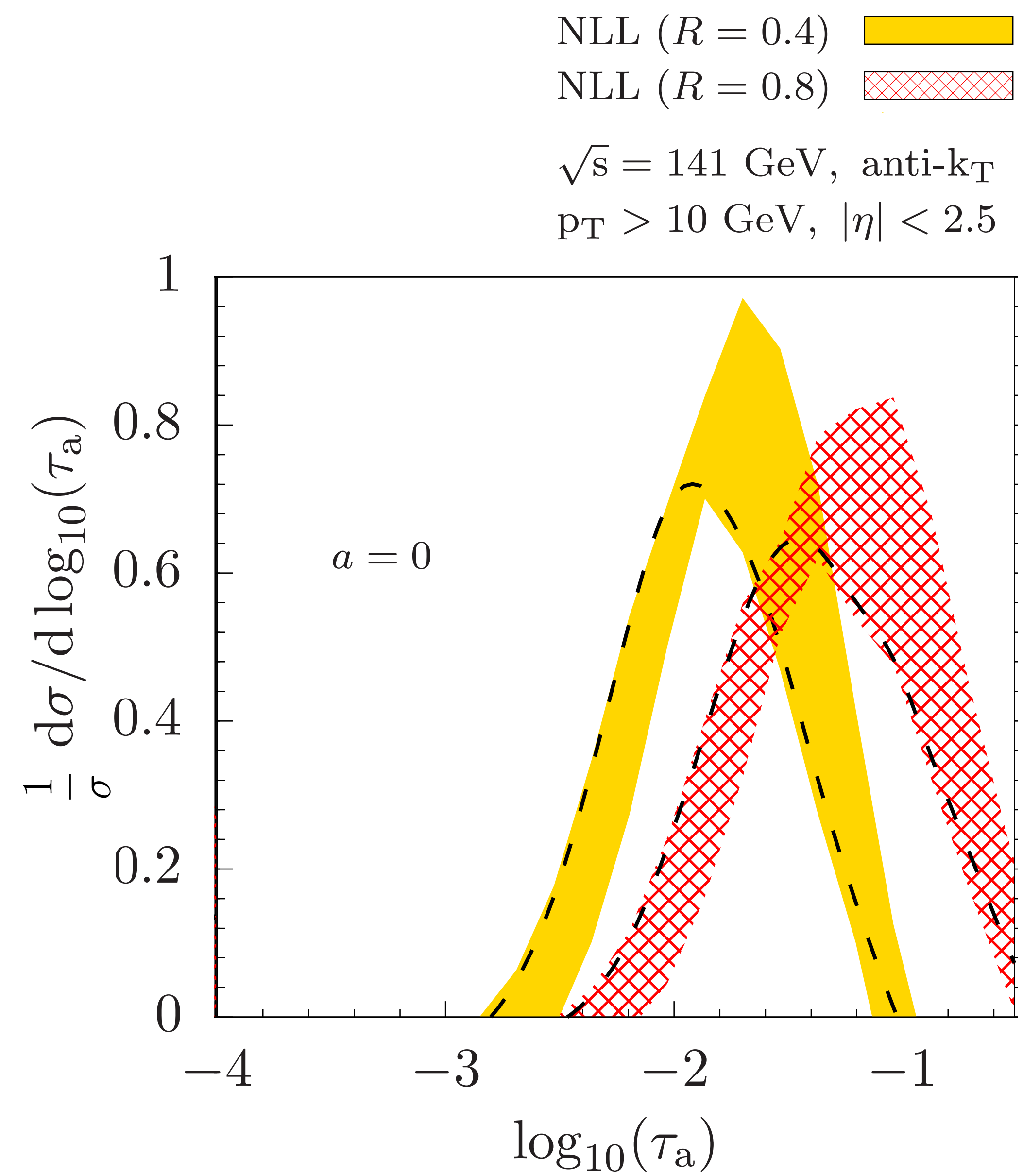
CT14, GRS 99 PDFs

in collaboration with Aschenauer, Page

Photoproduction at the EIC



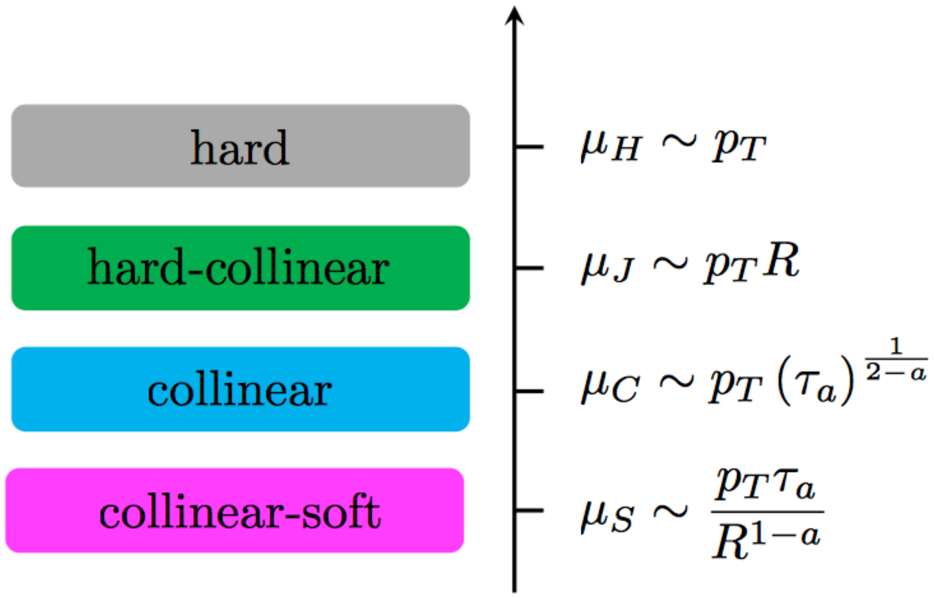


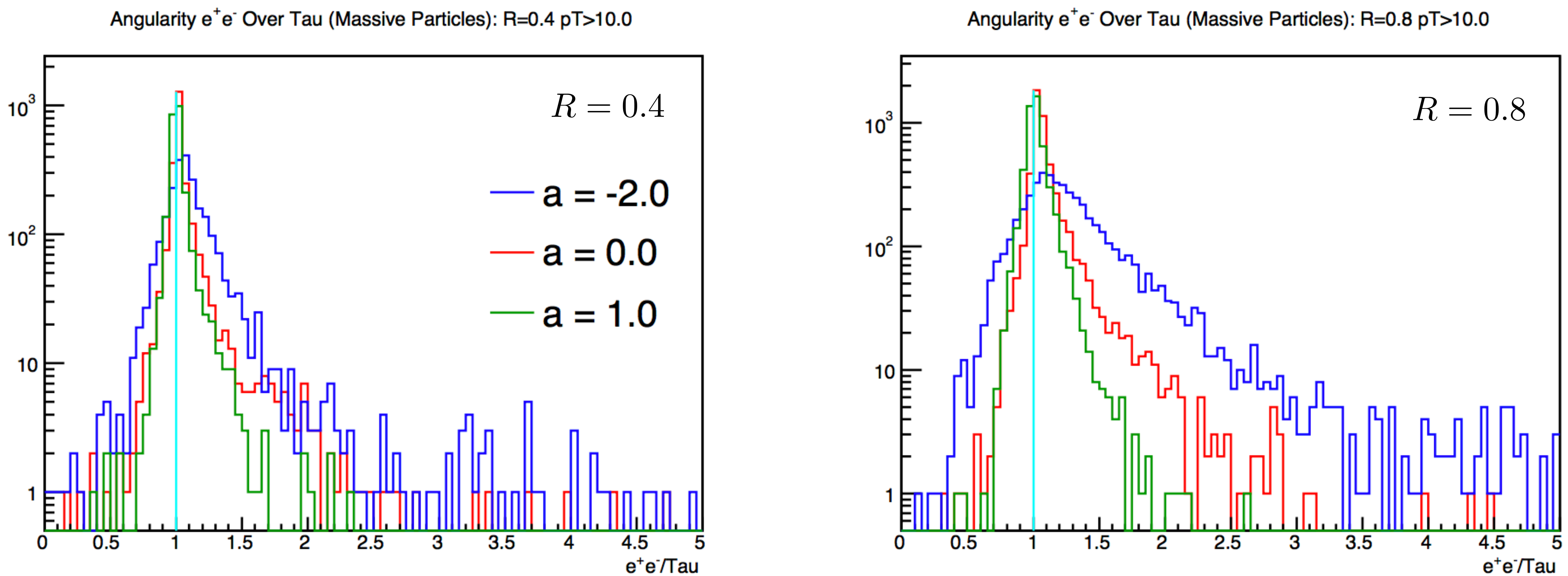


in collaboration with Aschenauer, Page

Power corrections

- e.g. $m_J^2 = \left(\sum_{i\in J} p_i\right)^2$ vs. $\tau_0 = \frac{1}{p_T}\sum_{i\in J} p_{Ti}\Delta R_{iJ}^2$

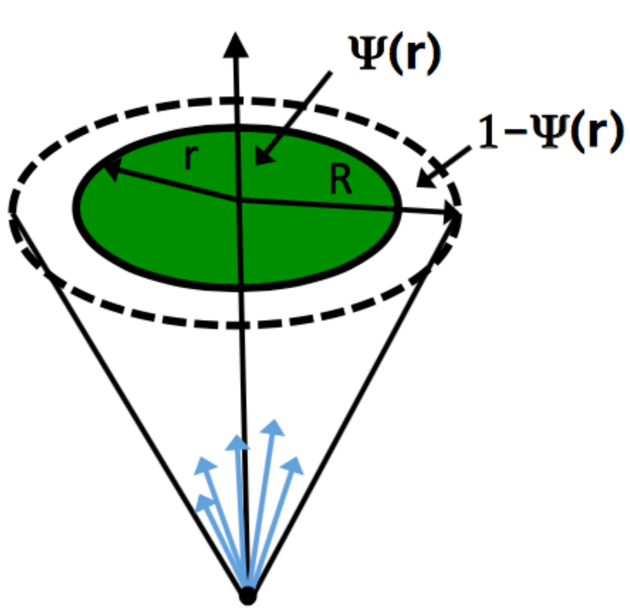




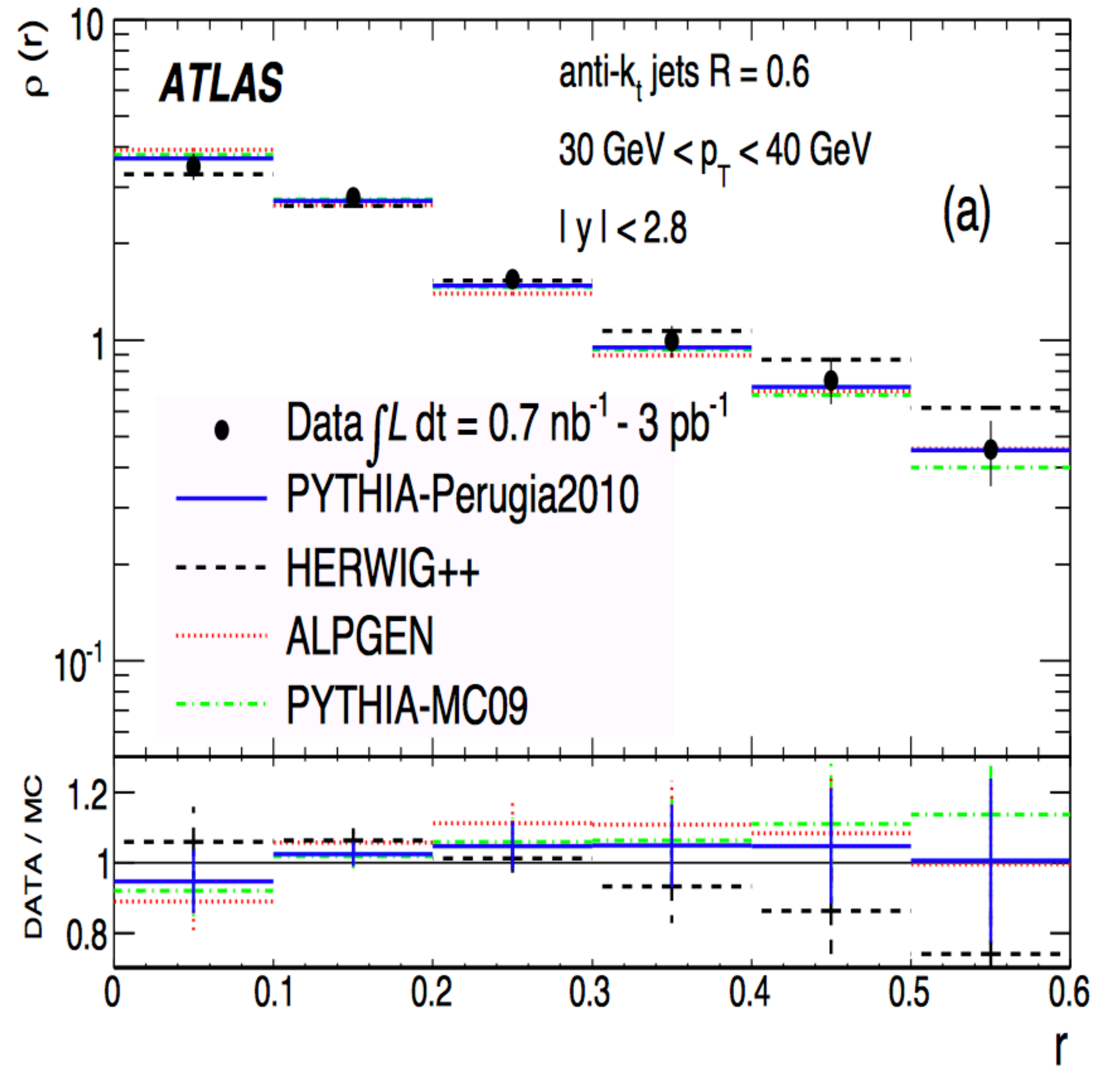
in collaboration with Aschenauer, Page

The jet energy profile

$$\psi(r) = \frac{\sum_{\Delta R_{iJ}<r} p_{Ti}}{\sum_{\Delta R_{iJ}<R} p_{Ti}} \qquad \rho(r) = \frac{\mathrm{d}\psi(r)}{\mathrm{d}r}$$



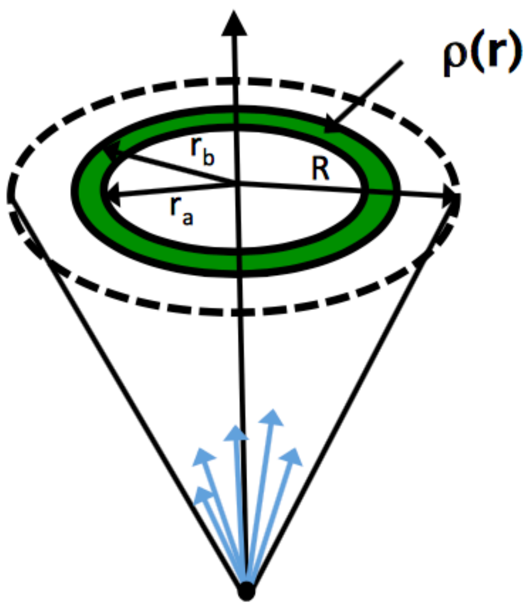
CMS, PLB 730 (2014) 243

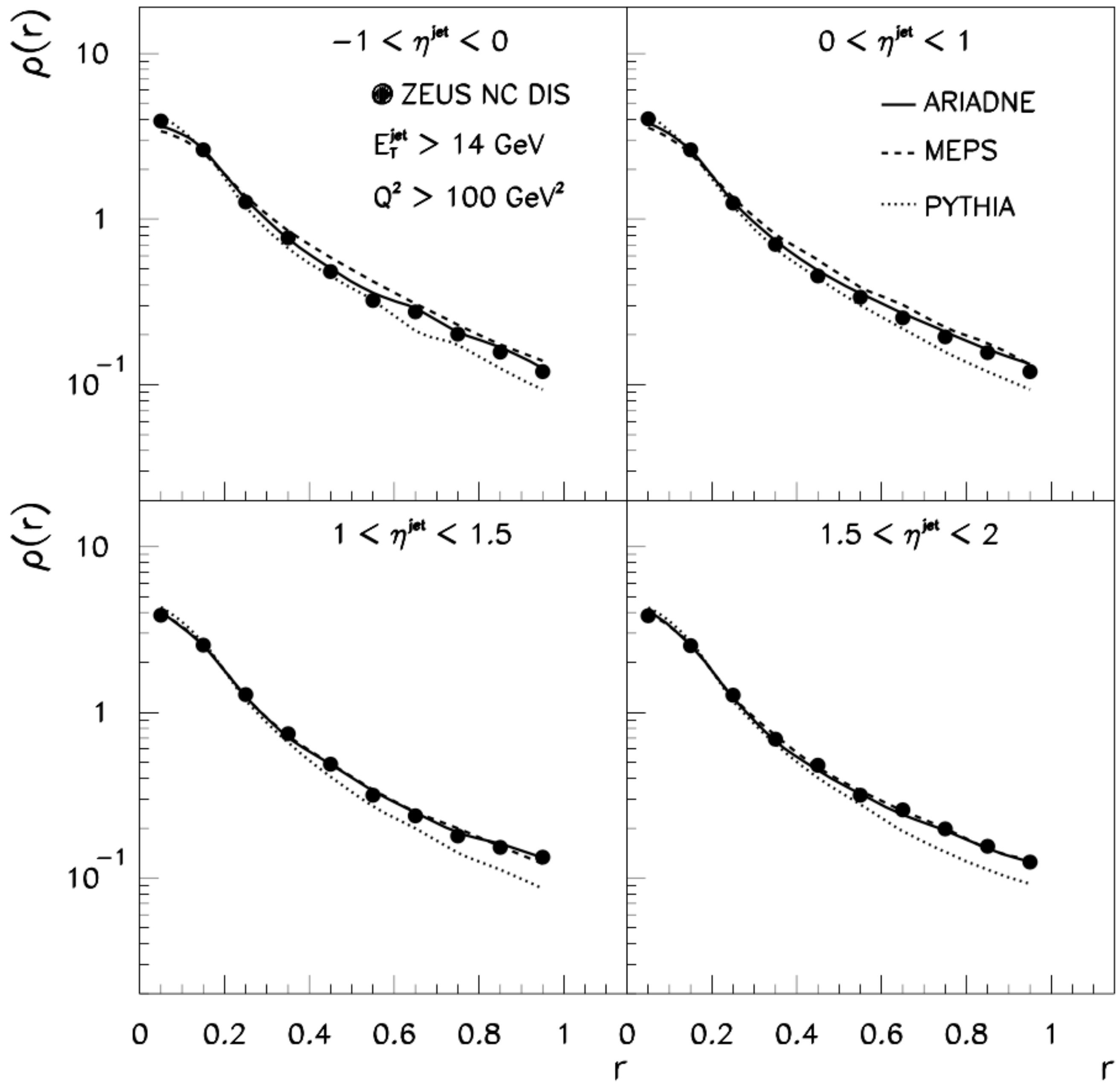


ATLAS, PRD 83 (2011) 052003

- Most frequently studied jet substructure observable
- LEP, HERA, Tevatron, LHC, …
- Inclusive jets, Z+jet, Higgs+jet, …

The jet energy profile

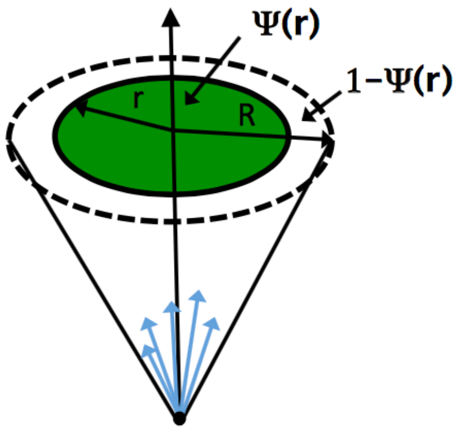




ZEUS, Eur. Phys. J C8 (1999) 367

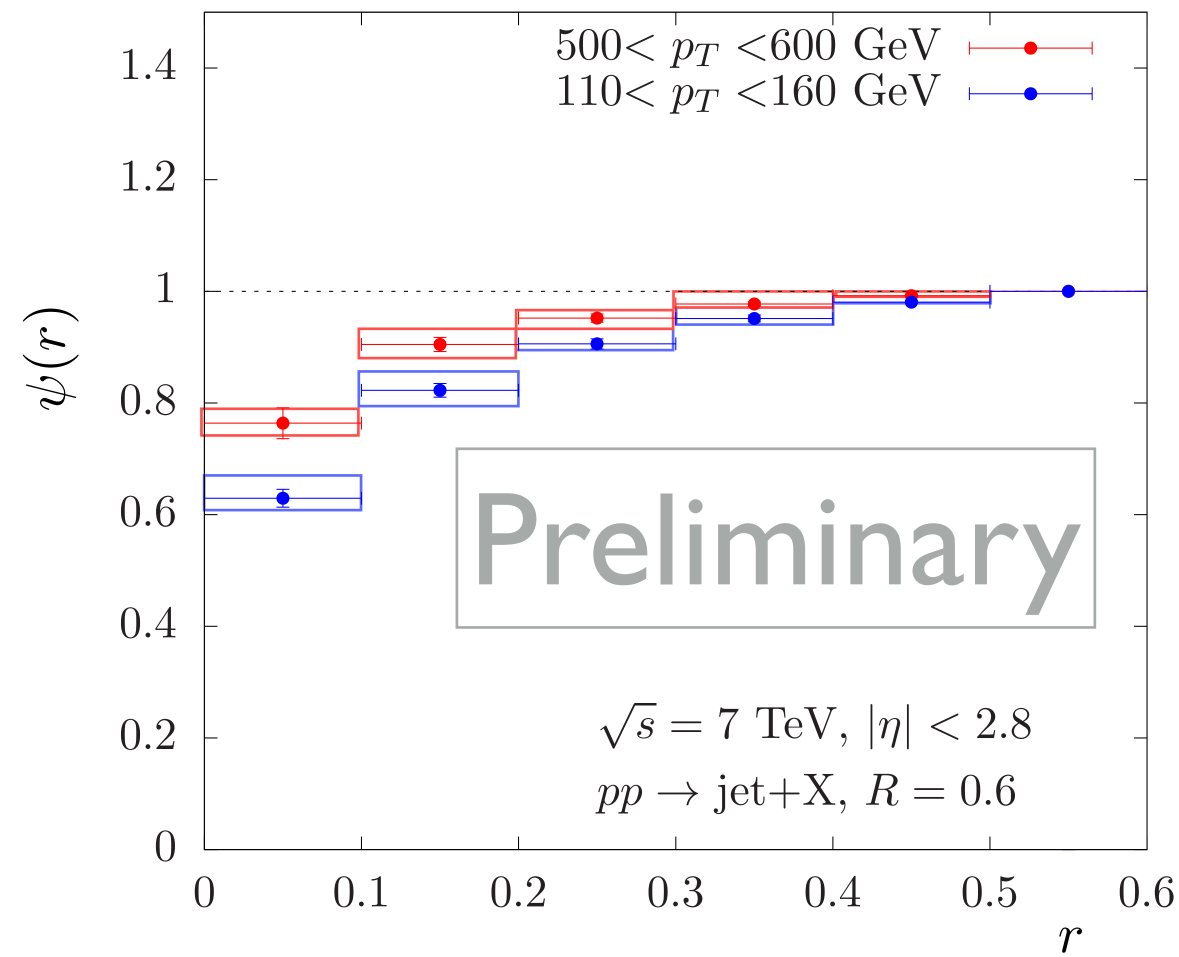
The jet energy profile

Kang, FR, Waalewijn `16
Cal, FR, Waalewijn - in preparation



$$\psi(r) = \frac{\sum_{\Delta R_{iJ}<r} p_{Ti}}{\sum_{\Delta R_{iJ}<R} p_{Ti}} \qquad \rho(r) = \frac{\mathrm{d}\psi(r)}{\mathrm{d}r}$$

ATLAS, PRD 83 (2011) 052003



- Factorization beyond leading-log

$$\mathcal{G}_i(z, p_T R, r/R, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu)$$
$$\times \int d^2k_\perp \, C_j(p_T r, k_\perp, \mu, \nu) \, S_j^{\rm G}(k_\perp, \mu, \nu R) \, S_j^{\rm NG}(r/R)$$

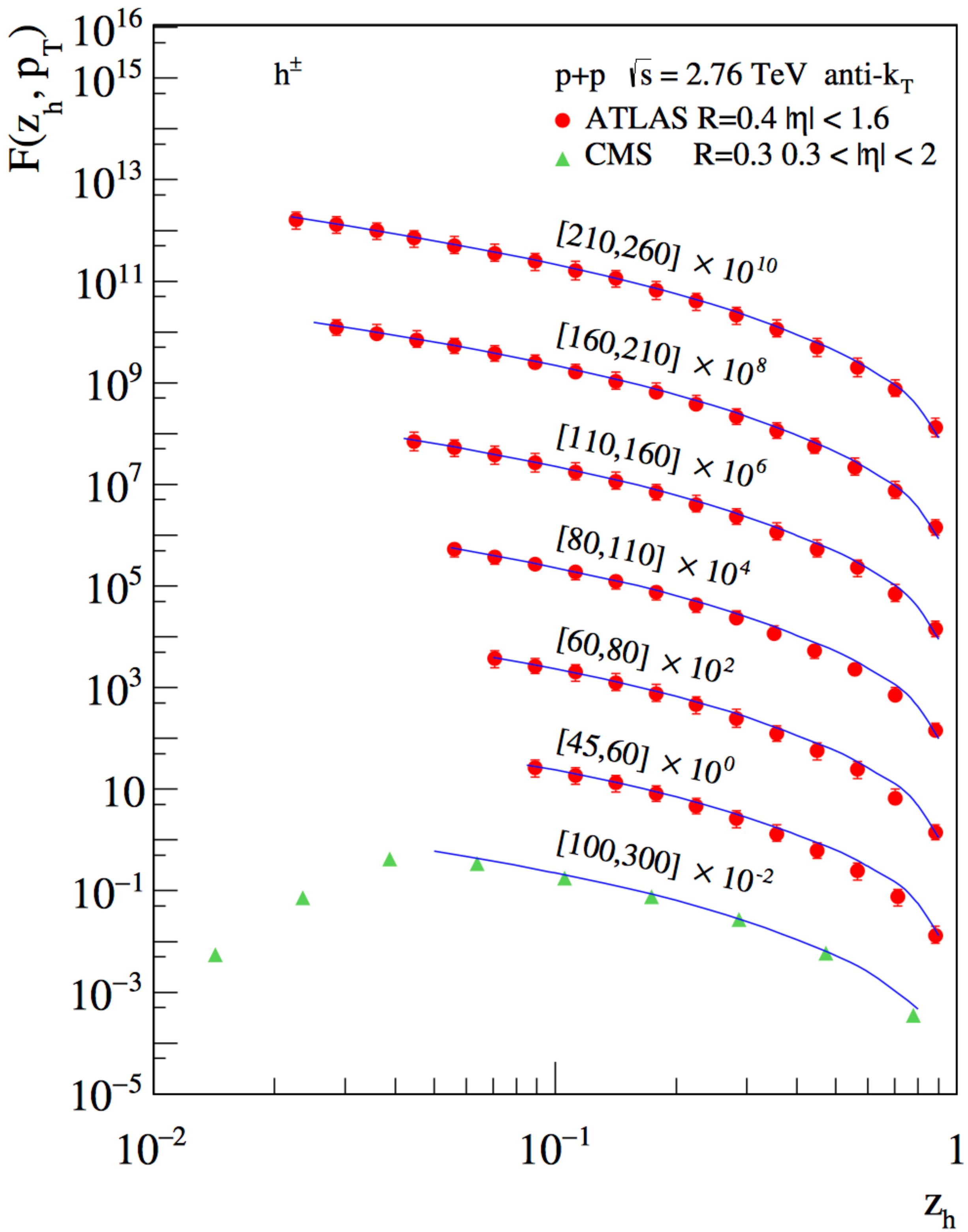
- NLL' resummation of $\ln(r/R)$
- Rapidity RG evolution, $\mathrm{SCET_{II}}$
- Soft recoil
- Non-global logarithms

Earlier work see: Ellis, Kunszt, Soper `92
Seymour `98
Li, Li, Yuan `11
Chien, Vitev `14

Identified hadrons inside jets

- Constrain fragmentation functions
- Tagging

$$\frac{d\sigma^{pp\to(\text{jet }h)X}}{dp_T d\eta dz_h} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c(z_h)$$



Arleo, Fontannaz, Guillet, Nguyen `14
Kaufmann, Mukherjee, Vogelsang `15
Kang, FR, Vitev `16

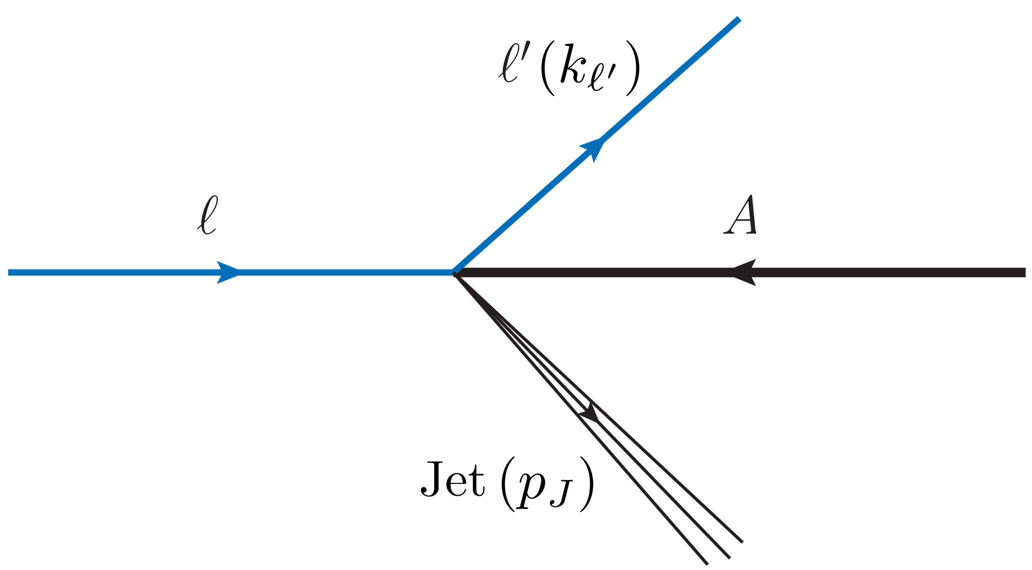
Outline

- Introduction
- Inclusive jets at the EIC
- Jet substructure
- Jet correlations
- Conclusions

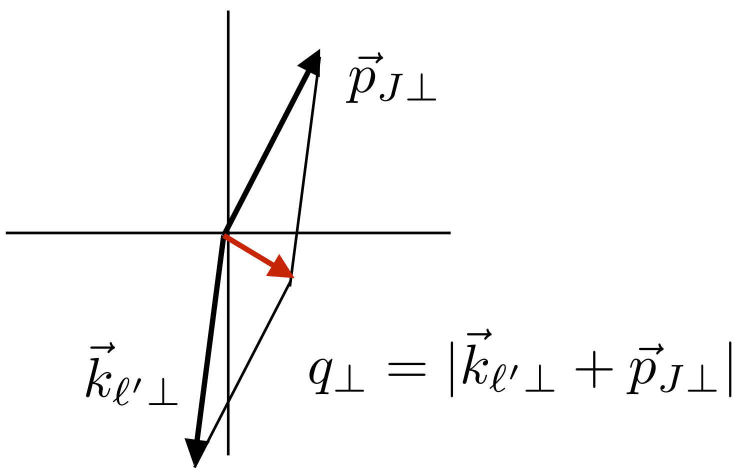
Lepton-jet correlations

Liu, FR, Vogelsang, 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

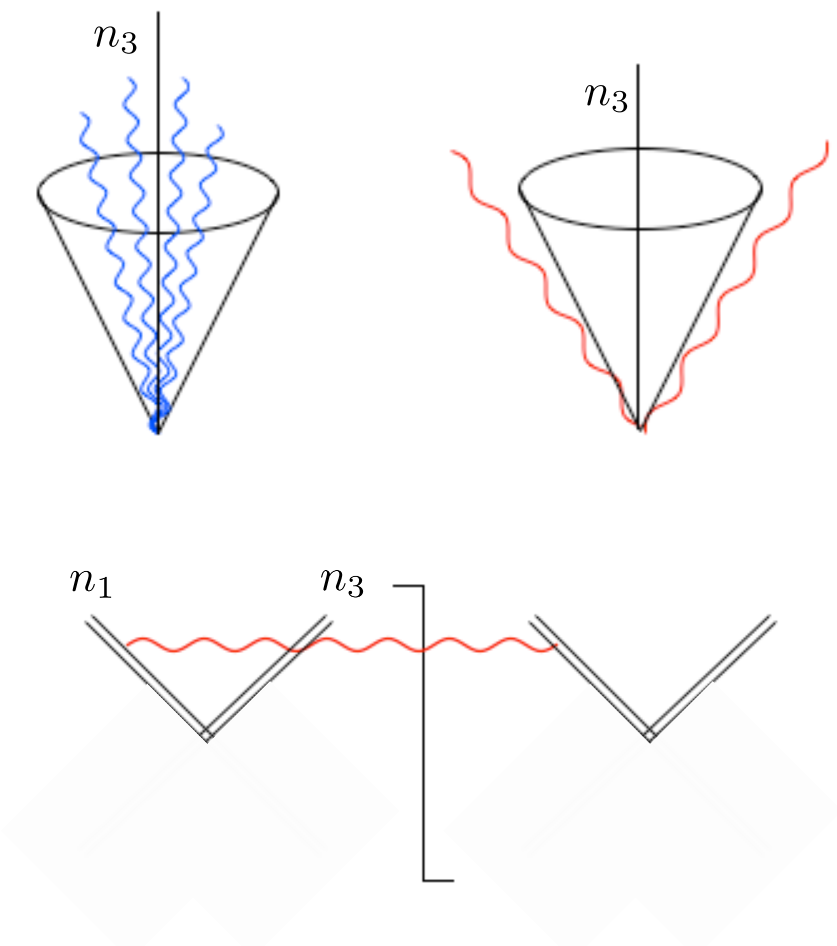
Liu, FR, Vogelsang, Yuan - in preparation

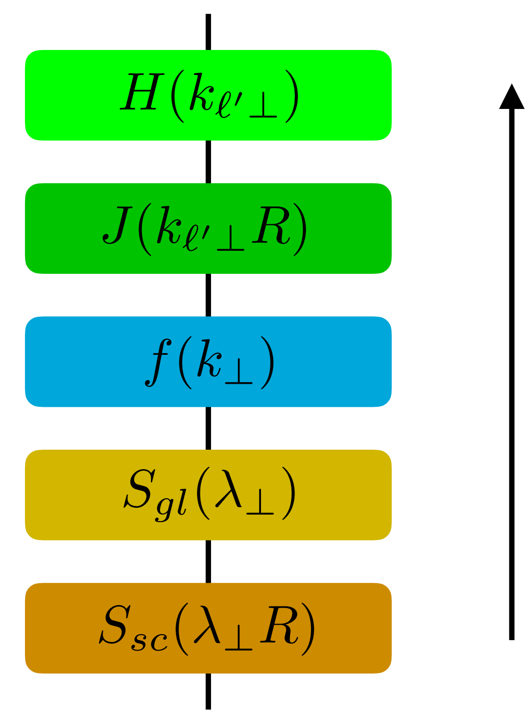
Hard (virtual) Jet function

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

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

Global soft Soft-collinear (in the jet direction)





Azimuthal lepton-jet correlation

Liu, FR, Vogelsang, Yuan - in preparation

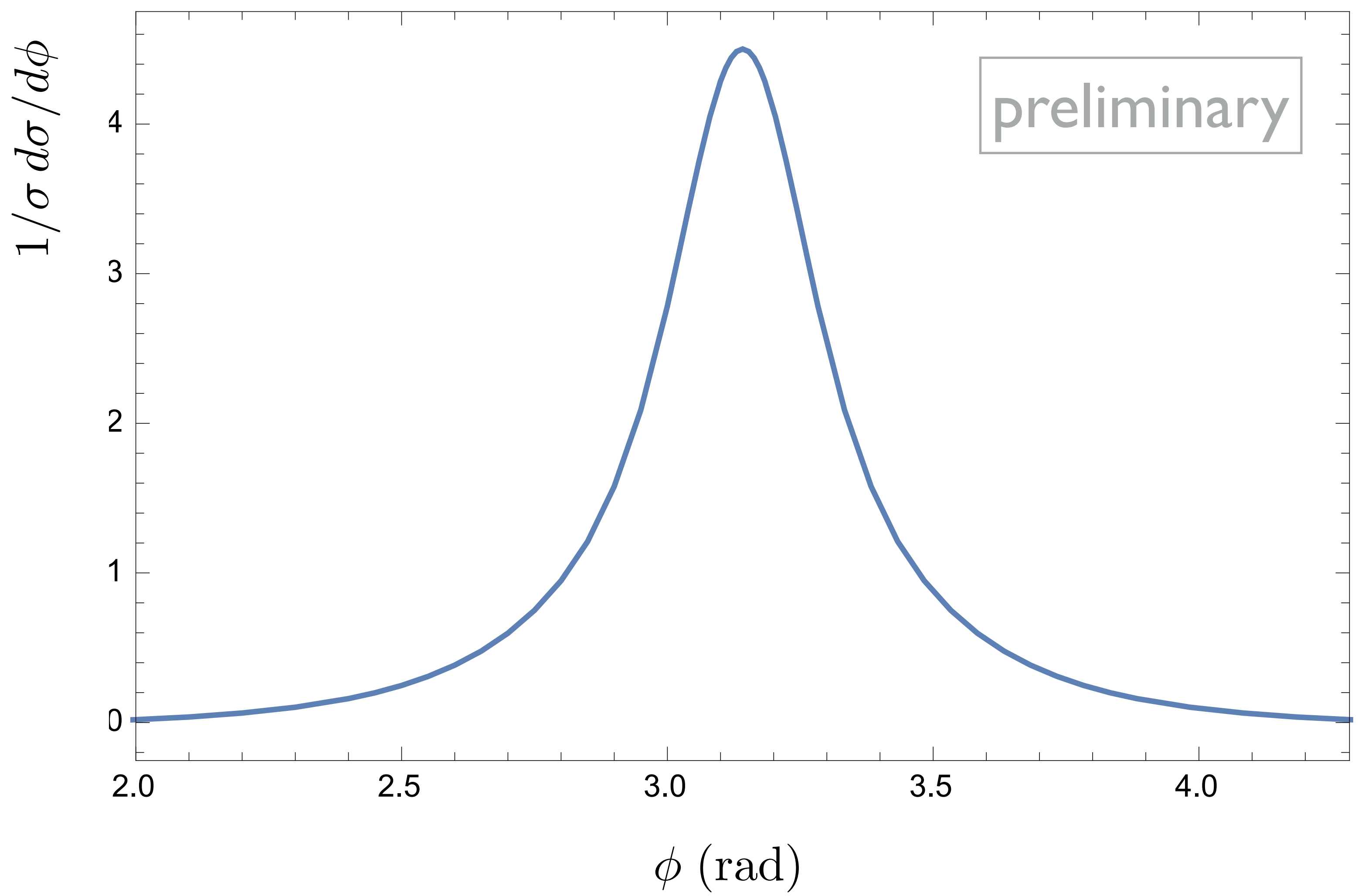
- Sample EIC kinematics

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

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

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

- currently $\ln R$ not yet resummed



Outline

- Introduction
- Inclusive jets at the EIC
- Jet substructure
- Jet correlations
- Conclusions

Conclusions

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