Jet observable at the EIC

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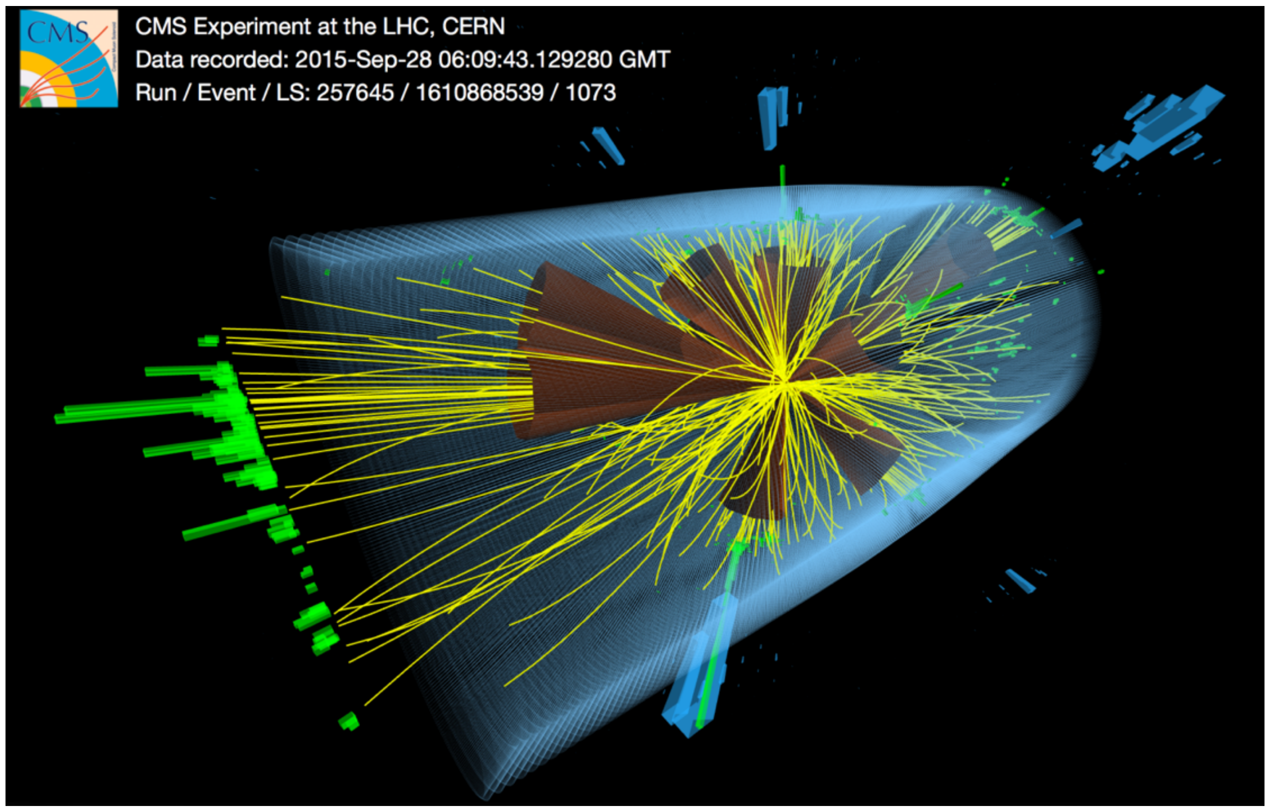
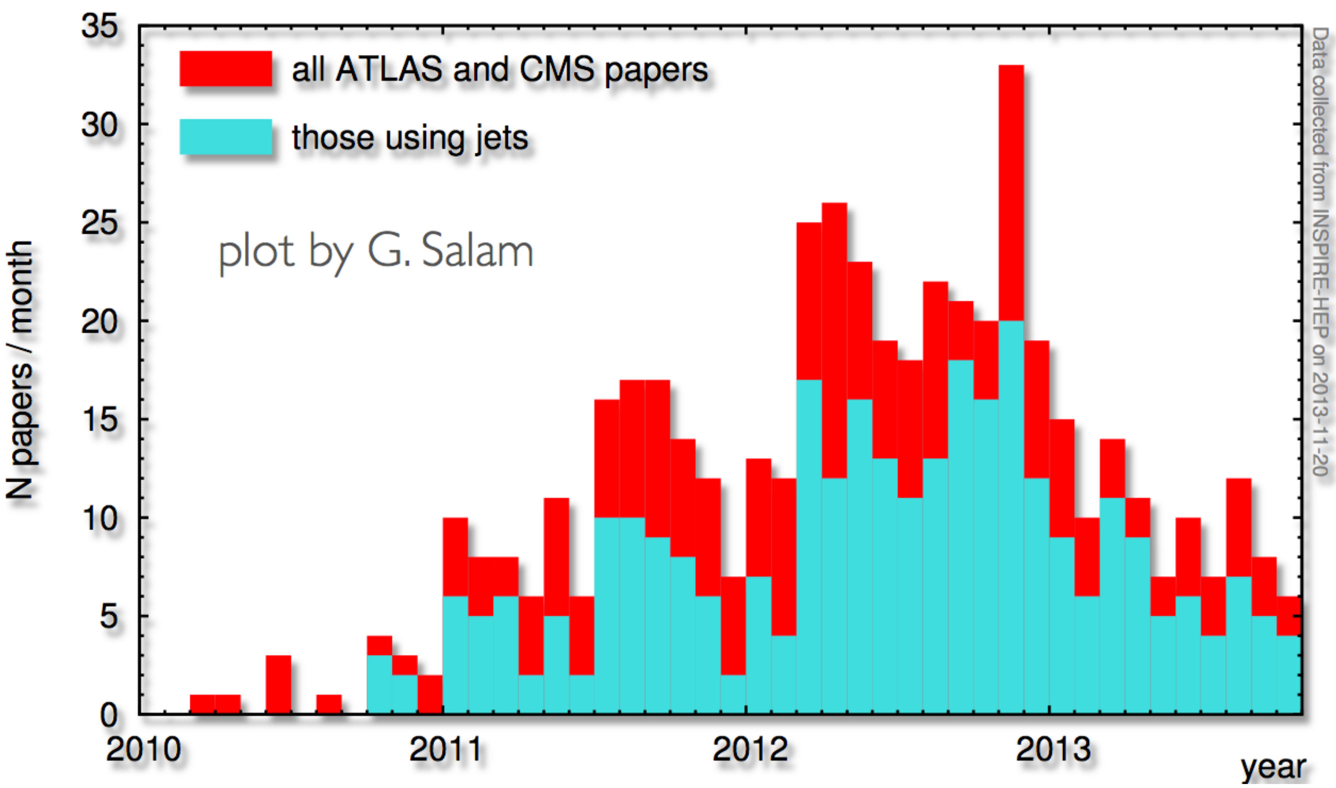
Stony Brook University

EICUGM
07/30/18 - 08/02/18

Jets at the LHC

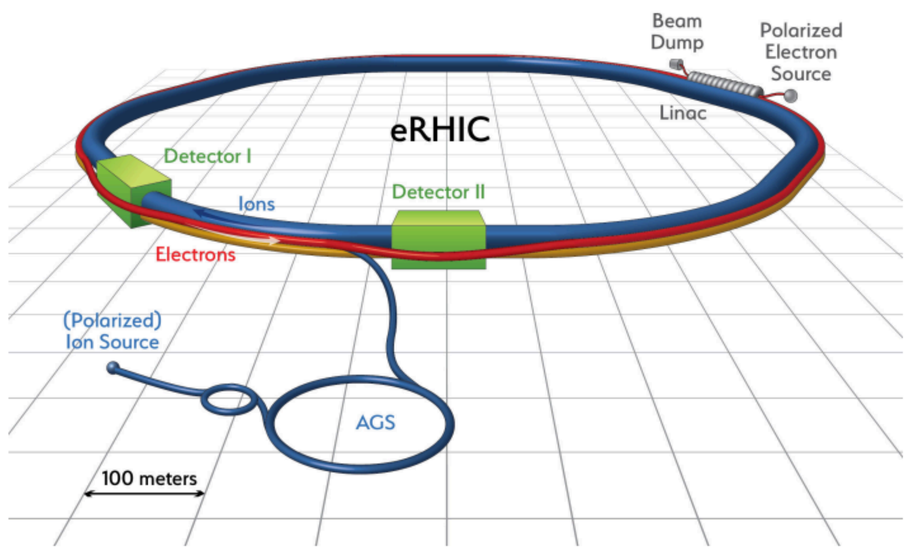


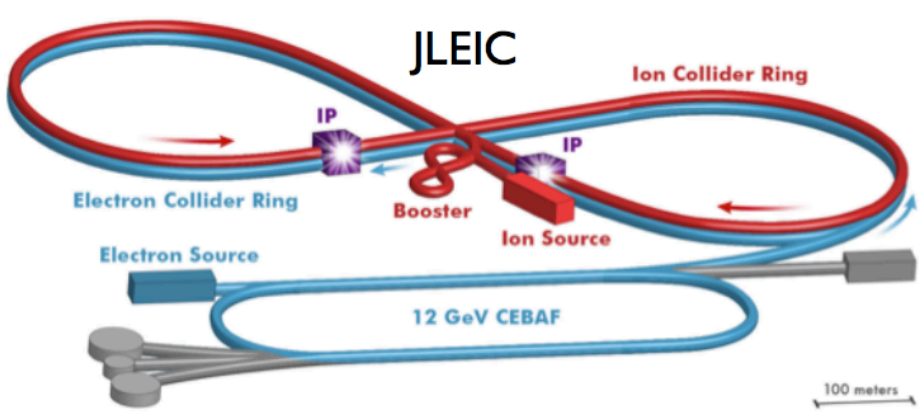


- Jets are produced copiously at the LHC

- At the LHC, 60 - 70 % of ATLAS & CMS papers use jets in their analysis!

Jets at the EIC

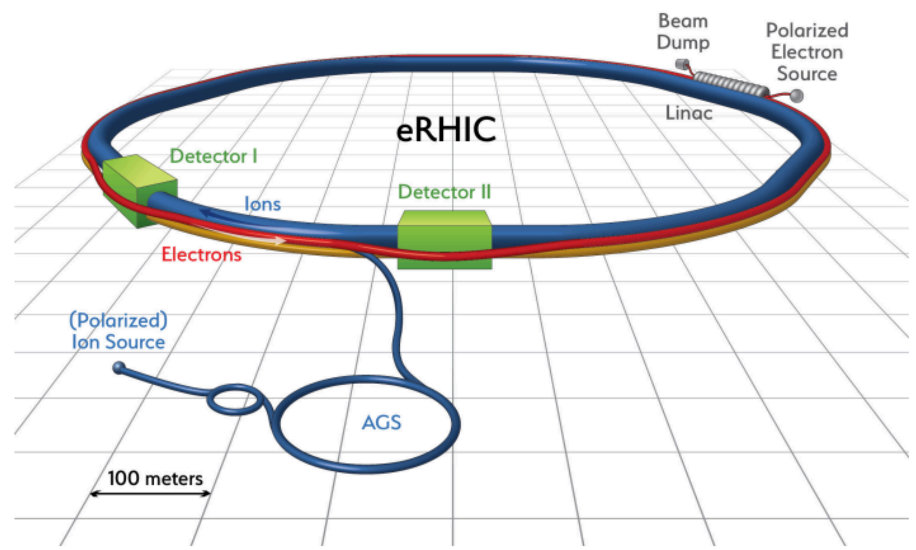


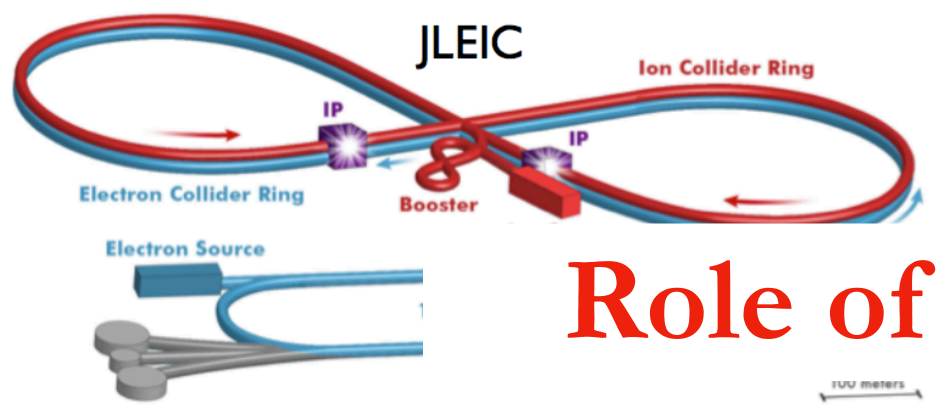


- $\sqrt{S_{\rm EIC}} \ll \sqrt{S_{\rm LHC}} \Leftrightarrow \sqrt{p_{T_J,\rm EIC}} \ll \sqrt{p_{T_J,\rm LHC}}$
  Lower $p_{T,J}$ for EIC
- $N_{J,EIC} \ll N_{J,LHC}$
  Smaller jet multiplicity for EIC
- Less contamination from underlying events and pileups

- **Different circumstances compared with the LHC and New opportunities**

Jets at the EIC





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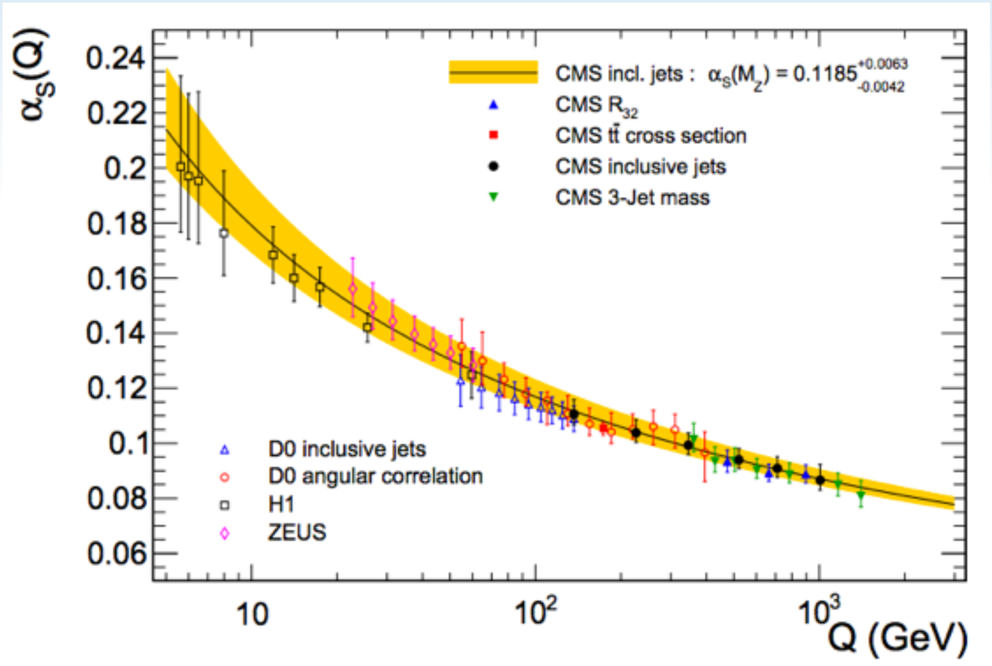
Role of higher power corrections?

- **Different circumstances compared with the LHC and New opportunities**

Application of jet studies at the LHC

- **Precision probe of QCD**

process	sensitivity to PDFs
W asymmetry	→ quark flavour separation
W and Z production (differential)	→ valence quarks
W+c production	→ strange quark
Drell-Yan (DY): high invariant mass	→ sea quarks, high-x
Drell-Yan (DY): low invariant mass	→ low-x
W,Z +jets	→ gluon medium-x
Inclusive jet and di-jet production	→ gluon and $\alpha_s(M_Z)$
Direct photon	→ gluon medium, high-x
ttbar, single top	→ gluon and $\alpha_s(M_Z)$



Inclusive jets - perturbative probe

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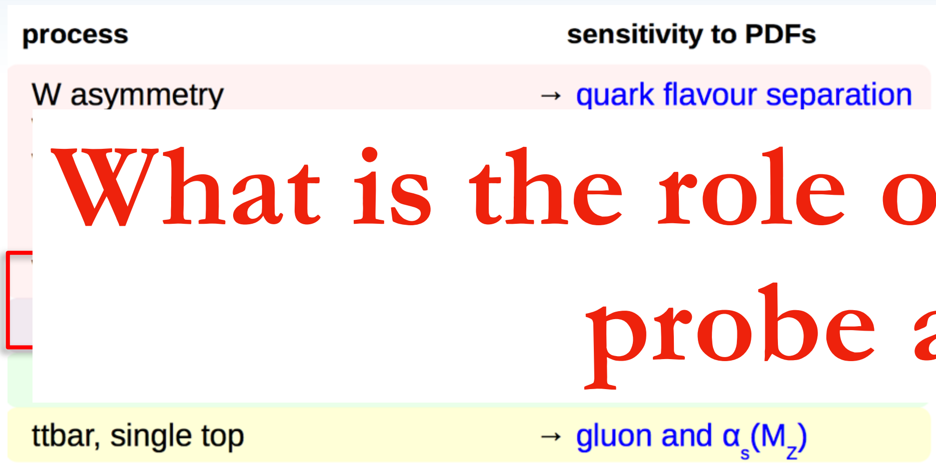

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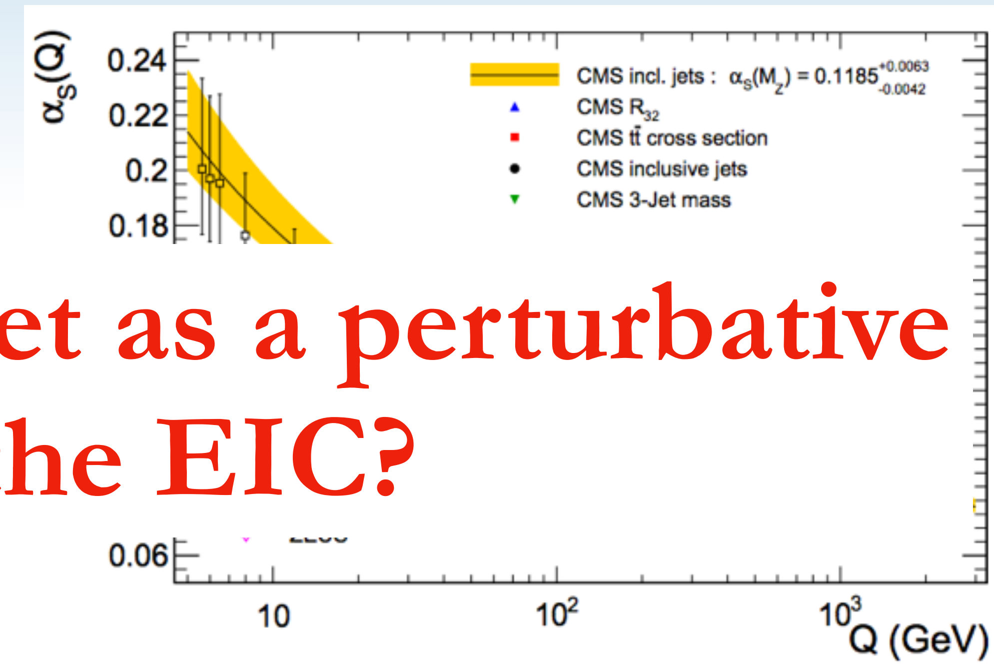

What is the role of jet as a perturbative probe at the EIC?

Inclusive jets - perturbative probe

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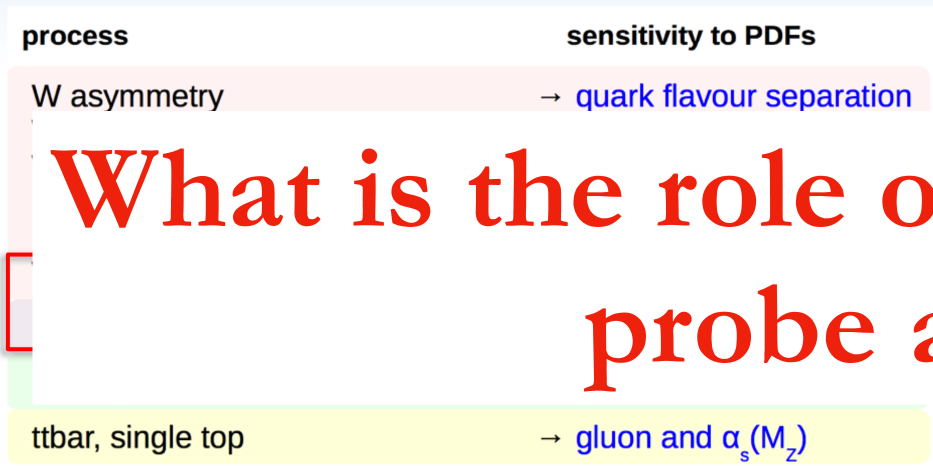
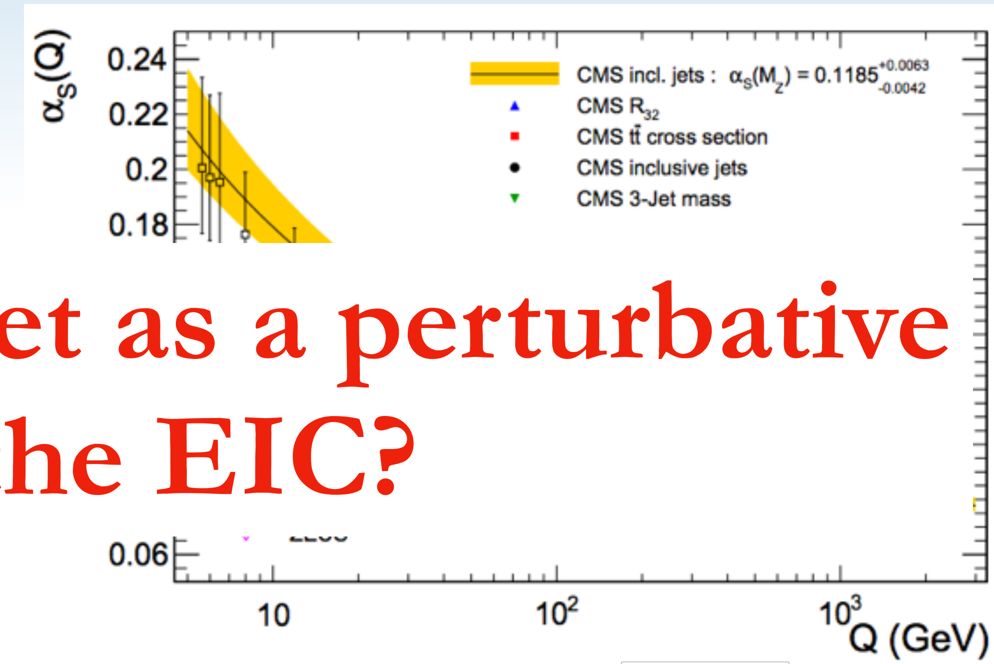
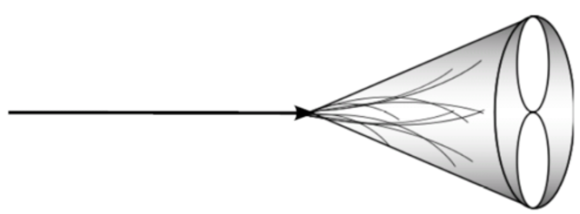


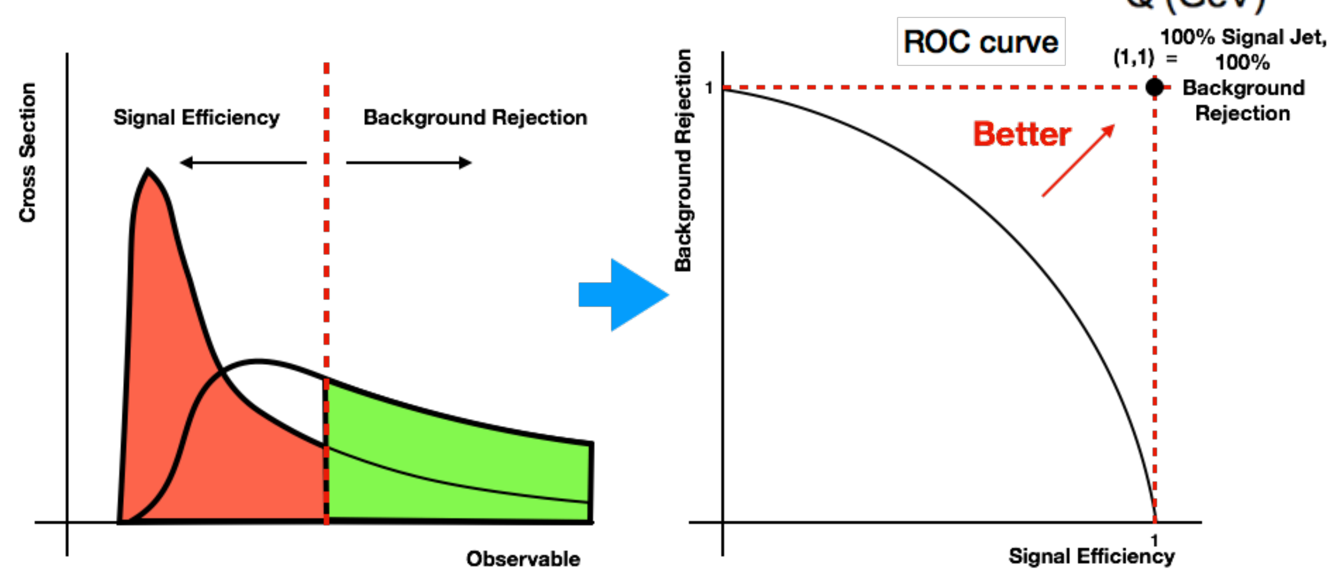


What is the role of jet as a perturbative probe at the EIC?

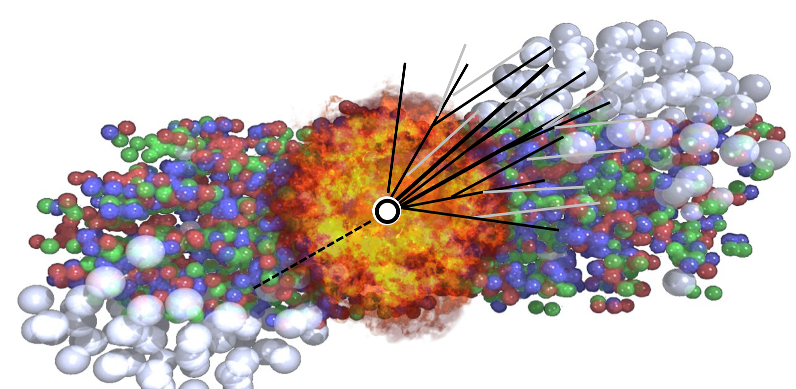
- Constrain BSM Models



Fat jet from BSM signal

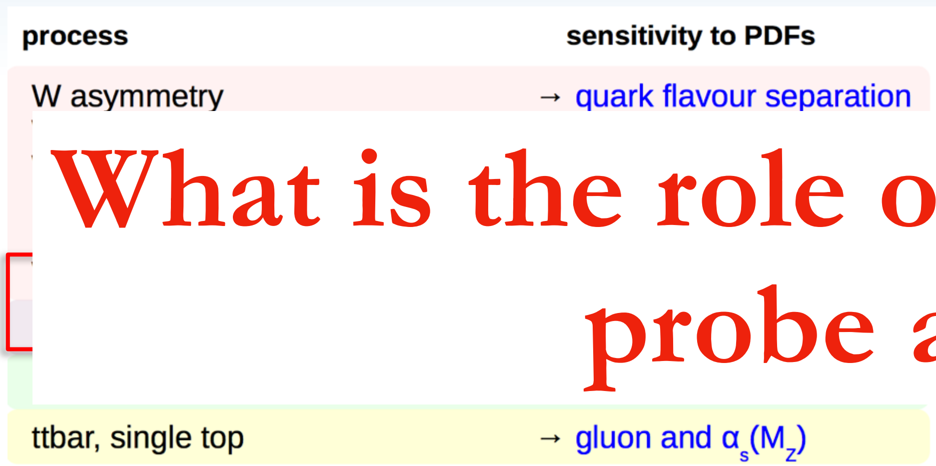


- Probe of quark gluon plasma



Application of jet studies at the LHC

- Precision probe of QCD



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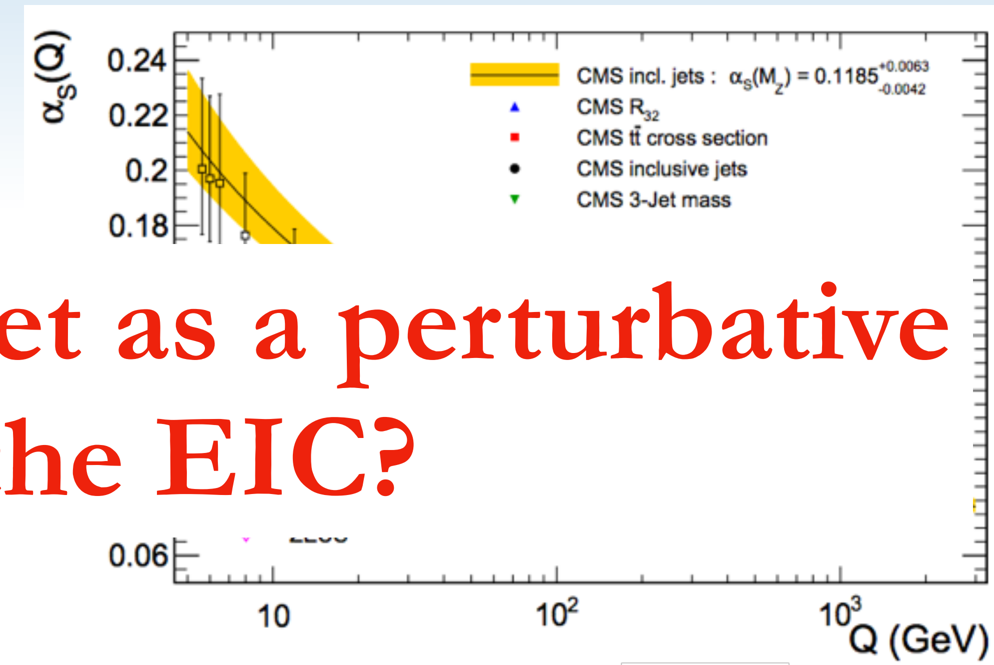

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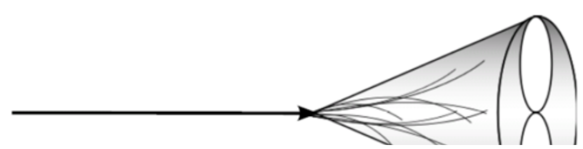
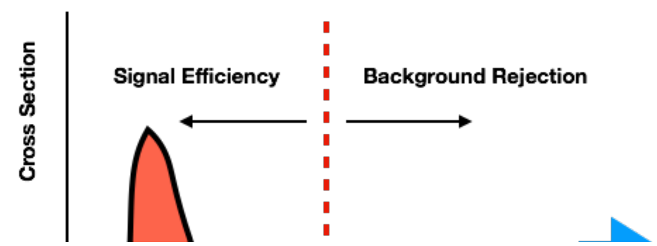
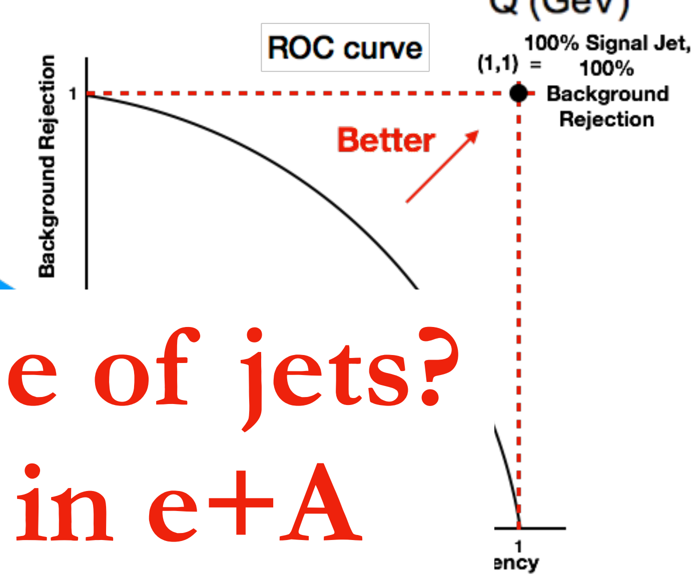


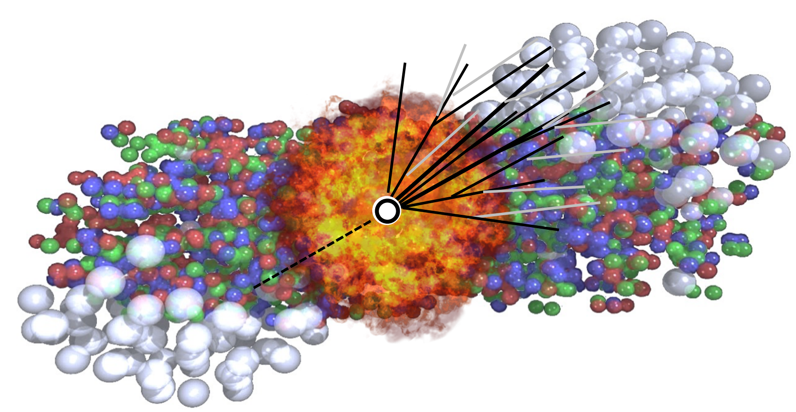




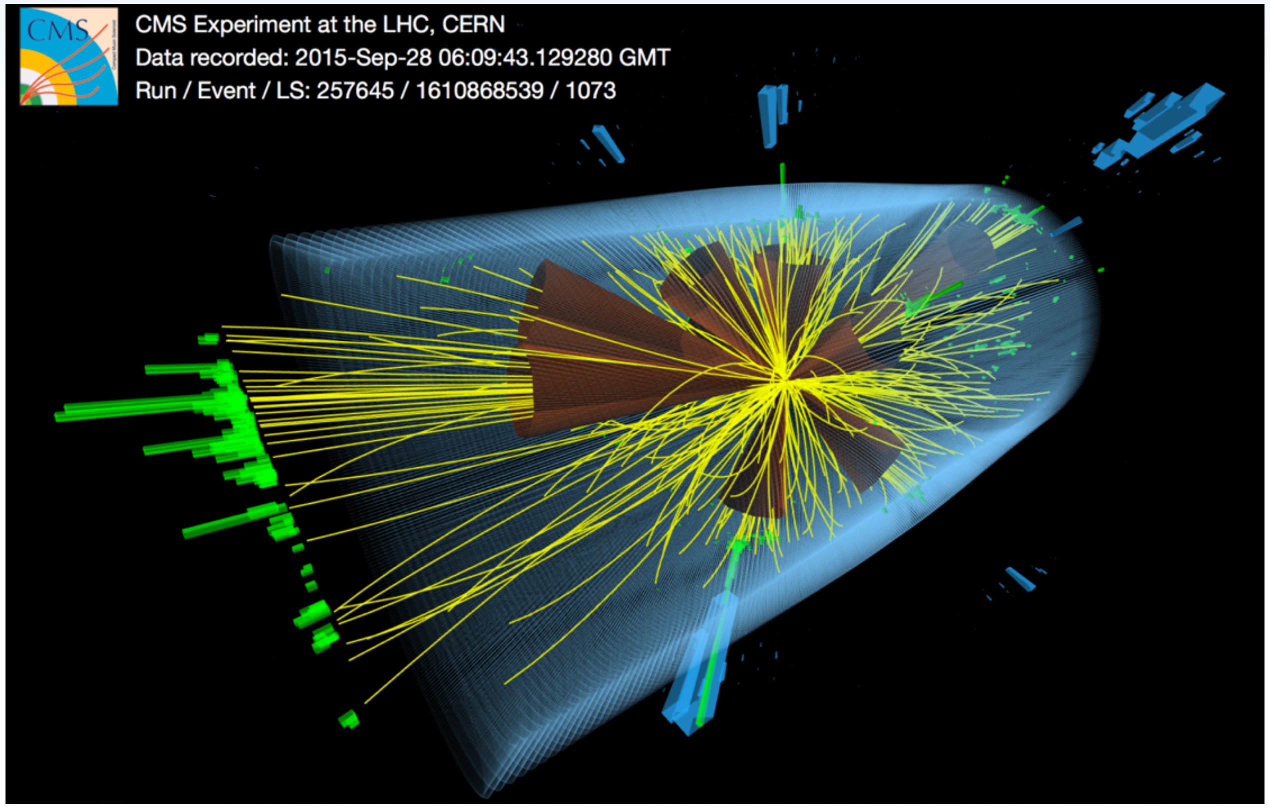
Classification of different type of jets?

Cold Nuclear Modification in e+A

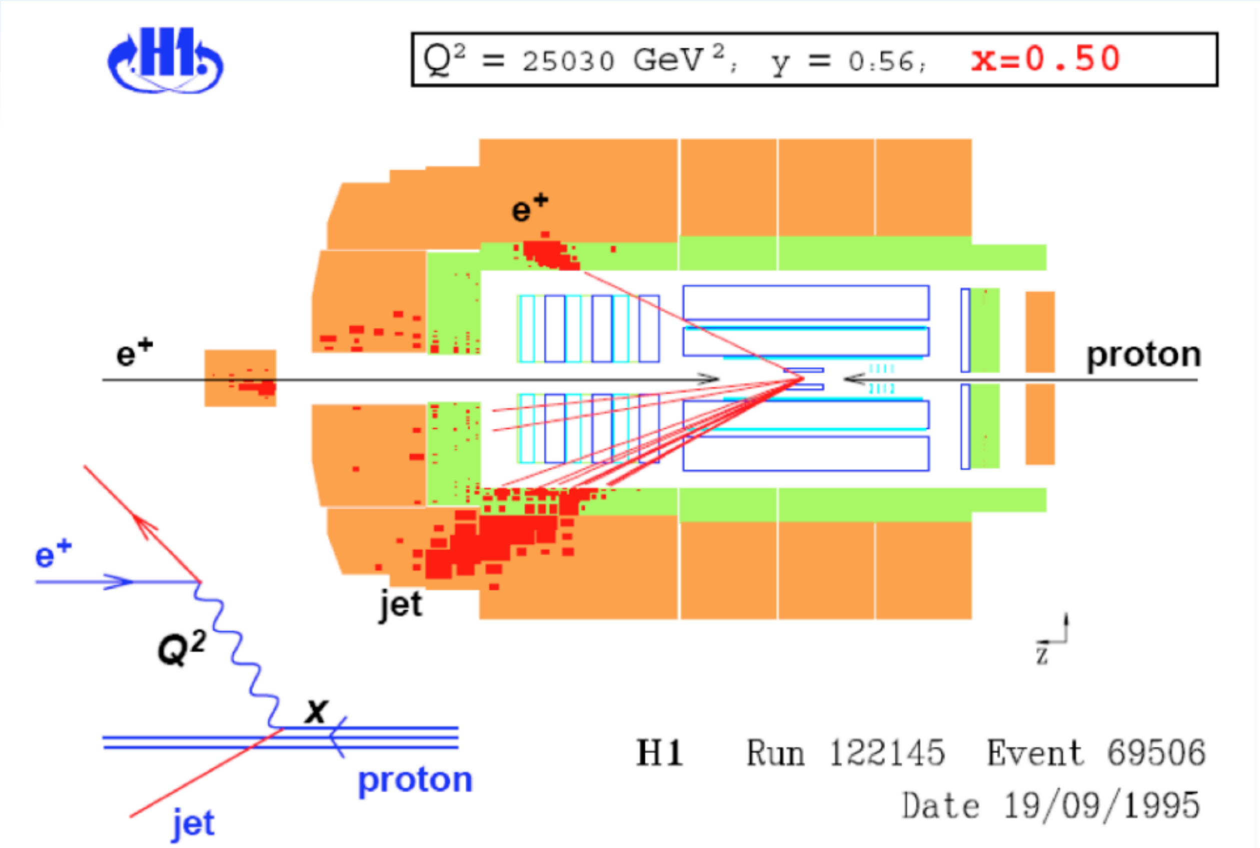
- Probe of quark gluon plasma



Application of jet studies at the LHC



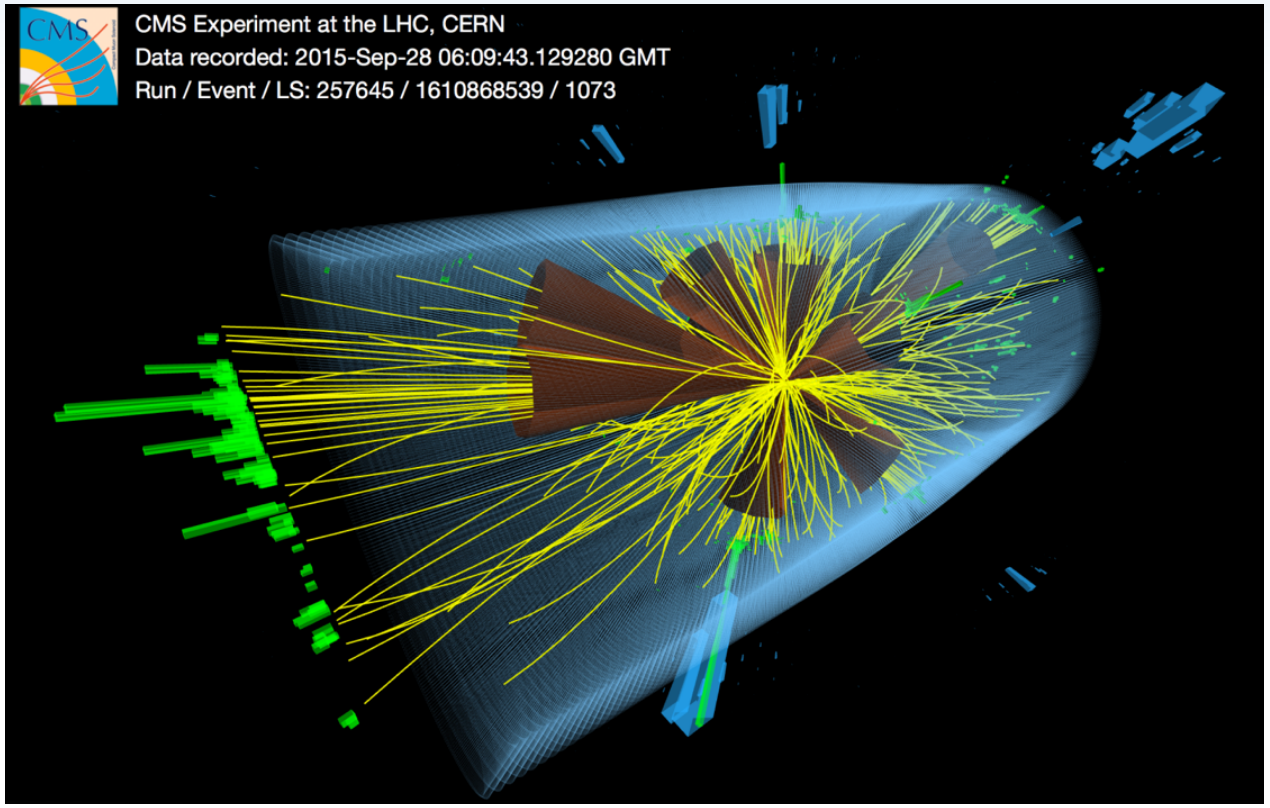
LHC



HERA

- Typical event at the LHC and HERA

Application of jet studies at the LHC



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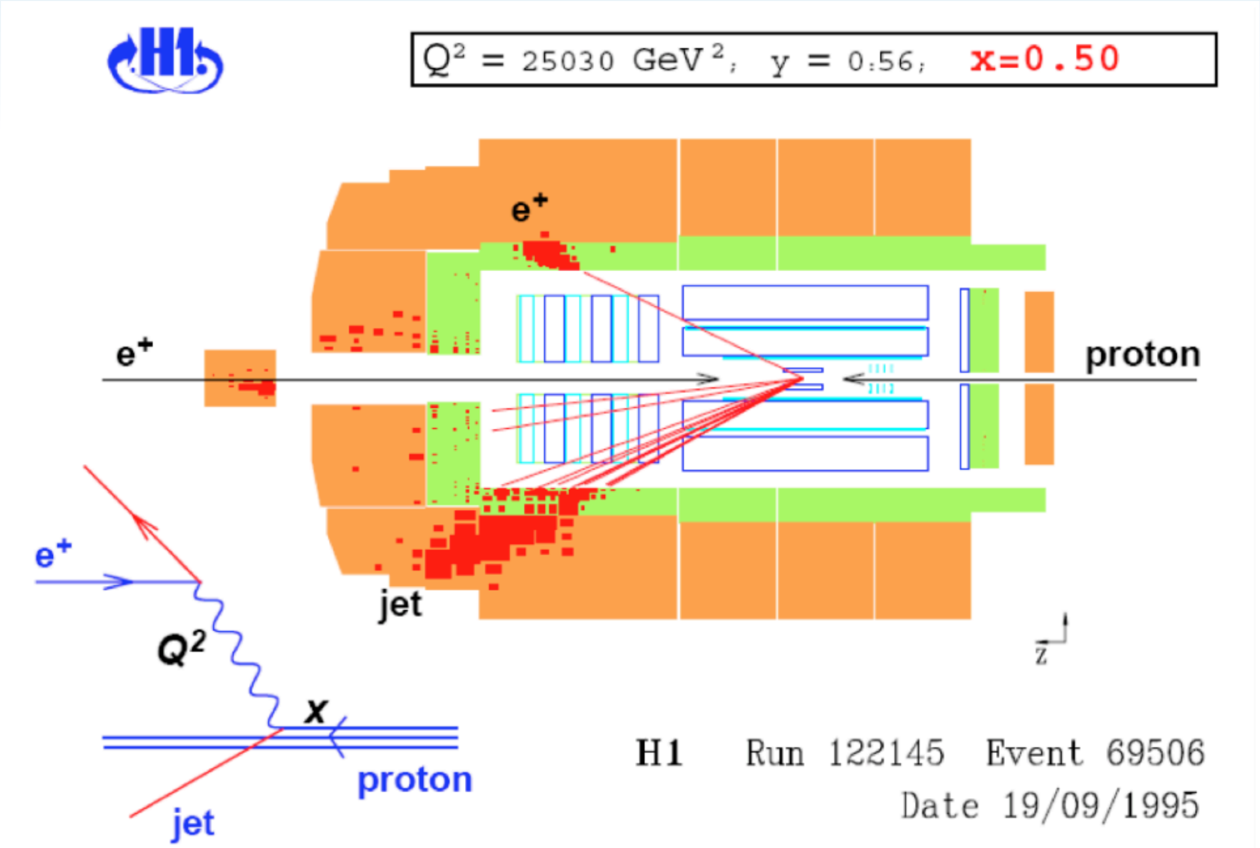
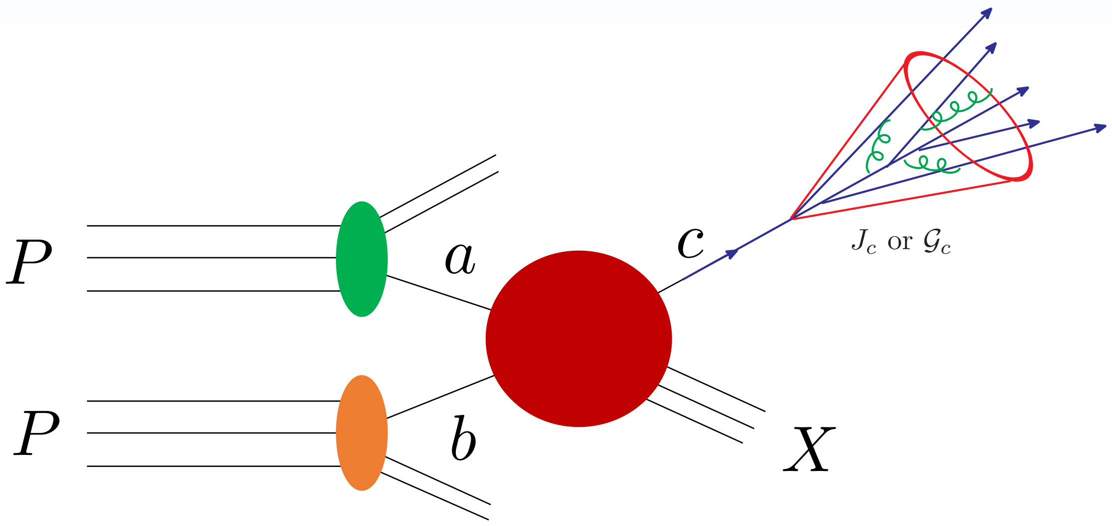


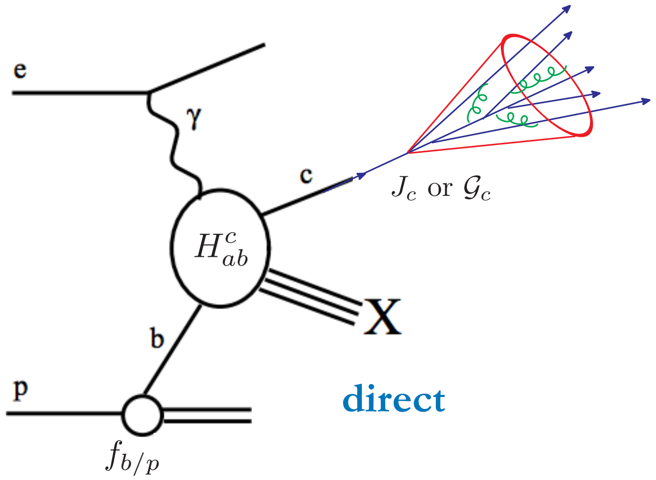
HERA

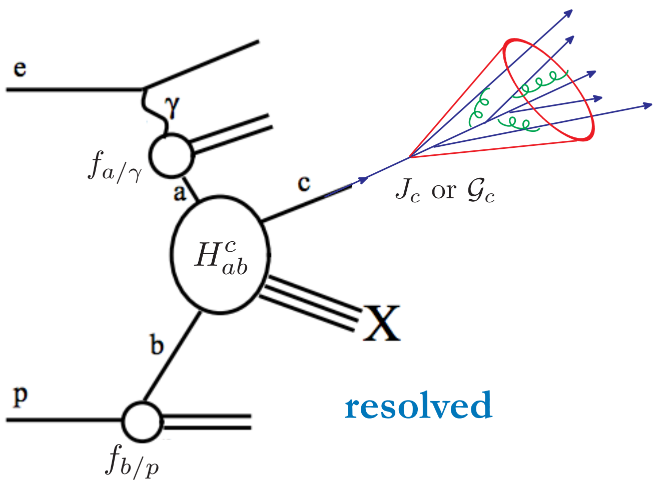
- Typical event at the LHC and HERA

What is the role of NP physics at the EIC?

Processes of Interest







- We want to study semi-inclusive jet production
  p + p $\longrightarrow$ Jet((with/without) substructure) + X

  photoproduction at the EIC
  e + p $\longrightarrow$ e + Jet((with/without) substructure) + X

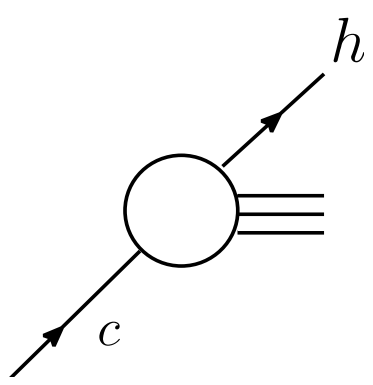
- More statistics. No veto on additional jets.

Plans of this talk

- Inclusive jet production at the LHC
- Jet substructure measurements at the LHC
- Role of non-perturbative effects
- Study of the EIC case
- Conclusions

Factorization of Inclusive Jet Production

$R \ll 1$



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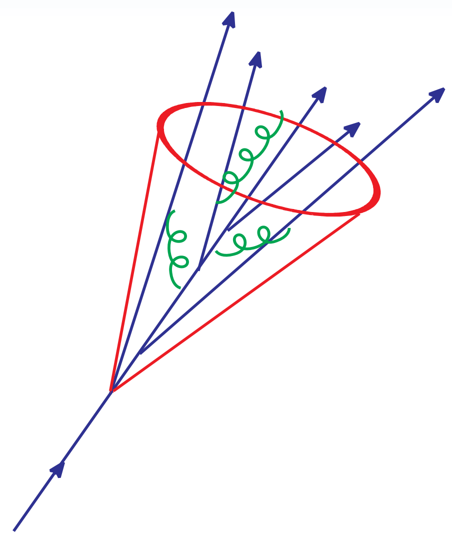

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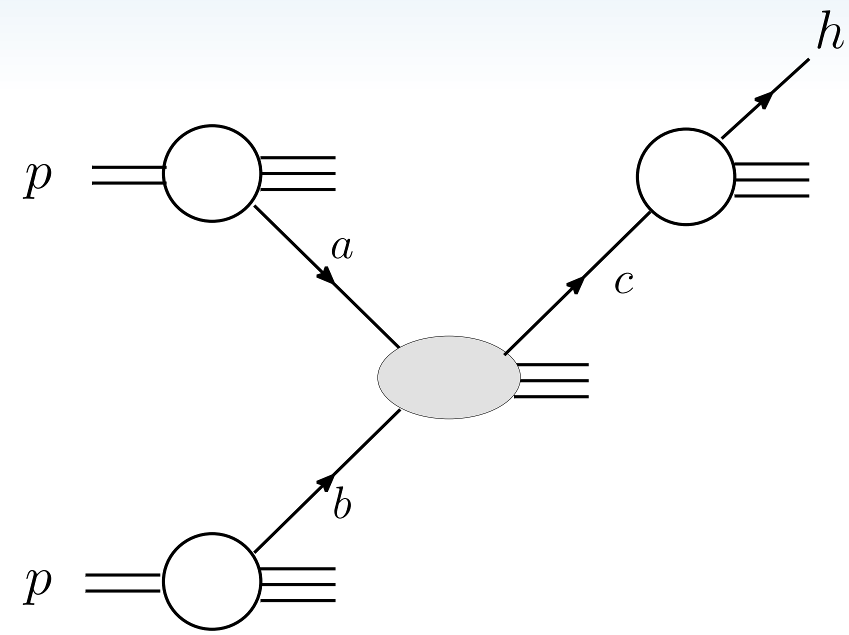


$D_c^h \quad \rightarrow \quad J_c$

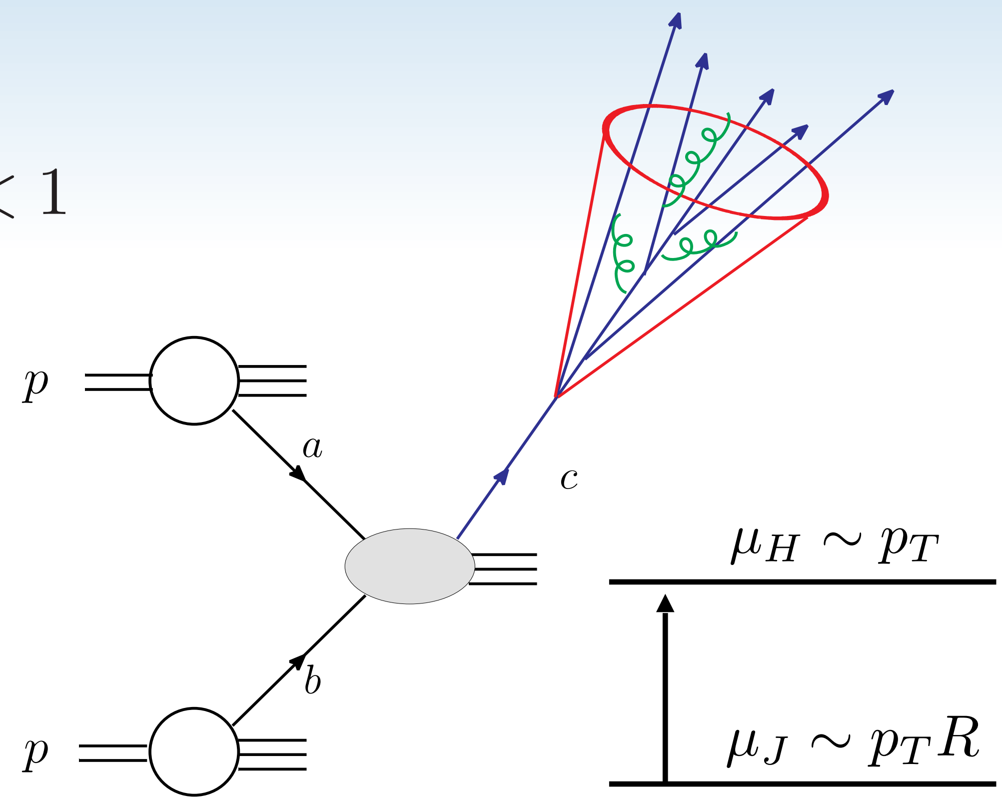
$pp \rightarrow hX$

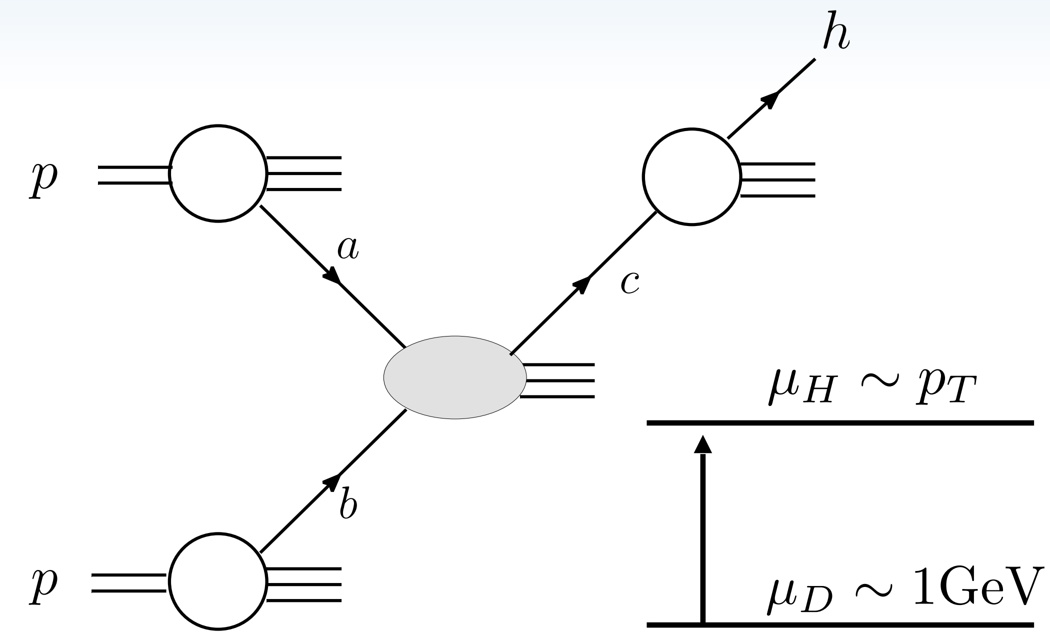
- **Simple replacement of the fragmentation function by "semi-inclusive jet function".**

Kang, Ringer, Vitev `16

Comparison with the inclusive hadron production case

$R \ll 1$





	Factorization	Evolution
Inclusive Jet	$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c + \mathcal{O}(R^2) + \mathcal{O}(\frac{\Lambda_{QCD}}{p_T R})$	$\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j$
Hadron	$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes D_c^h$	$\mu \frac{d}{d\mu} D_i^h = \sum_j P_{ji} \otimes D_j^h$

Kang, Ringer, Vitev `16

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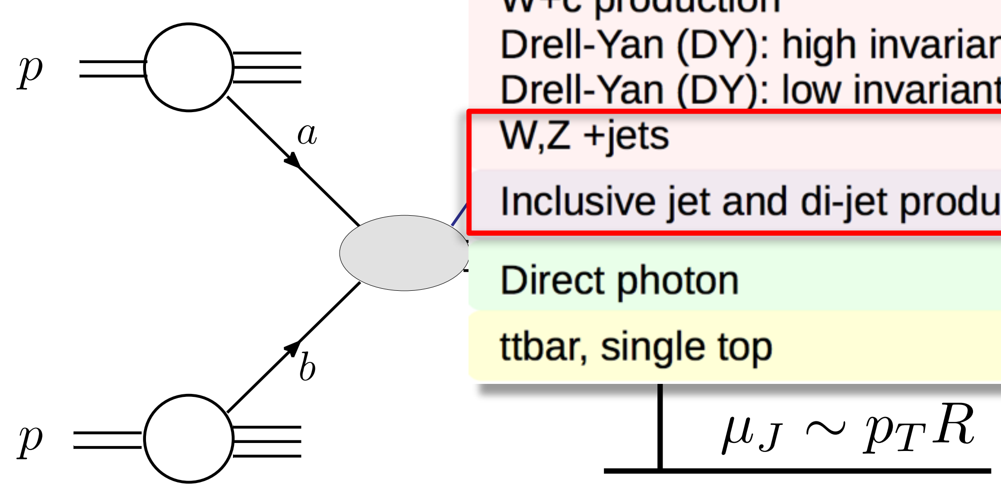

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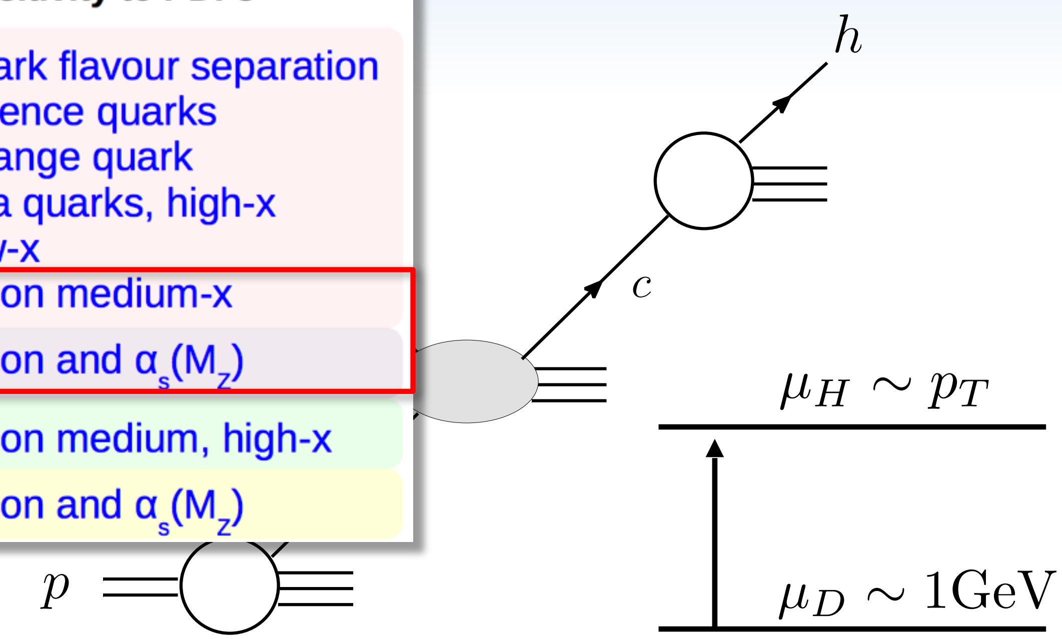

More relevant for the EIC

Factorization

Evolution

Inclusive Jet

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

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

Hadron

$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes D_c^h$$

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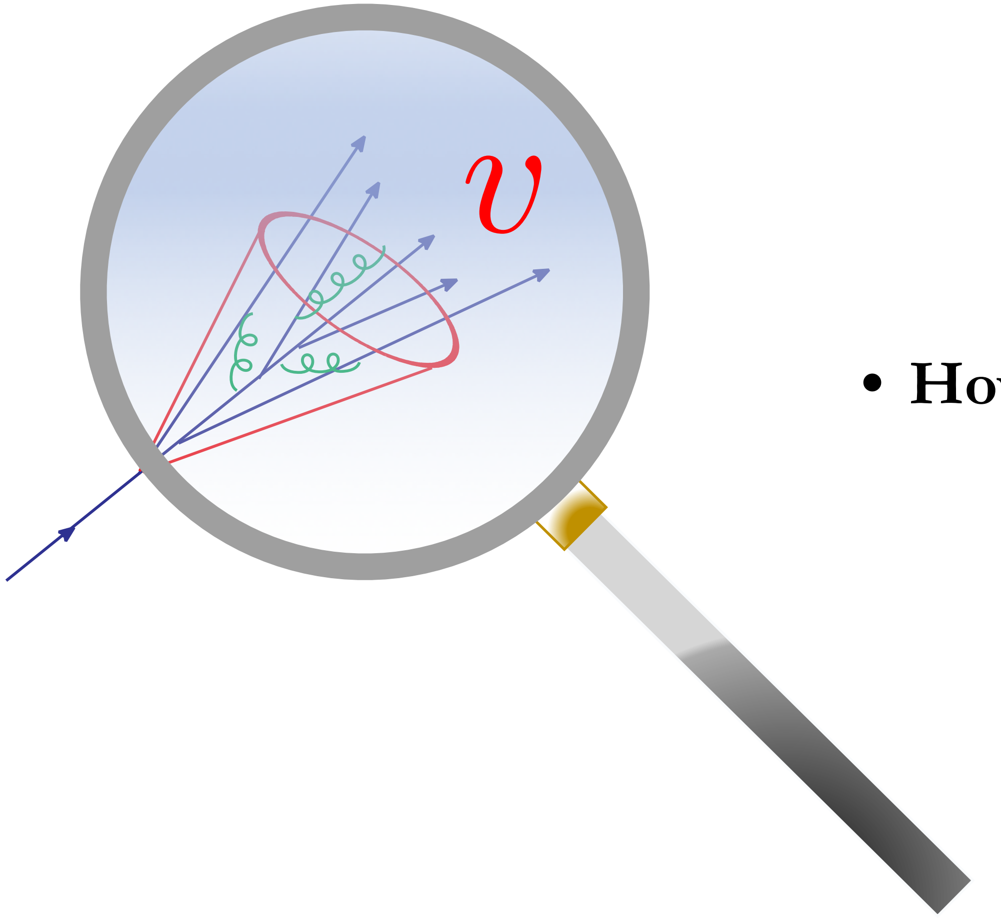
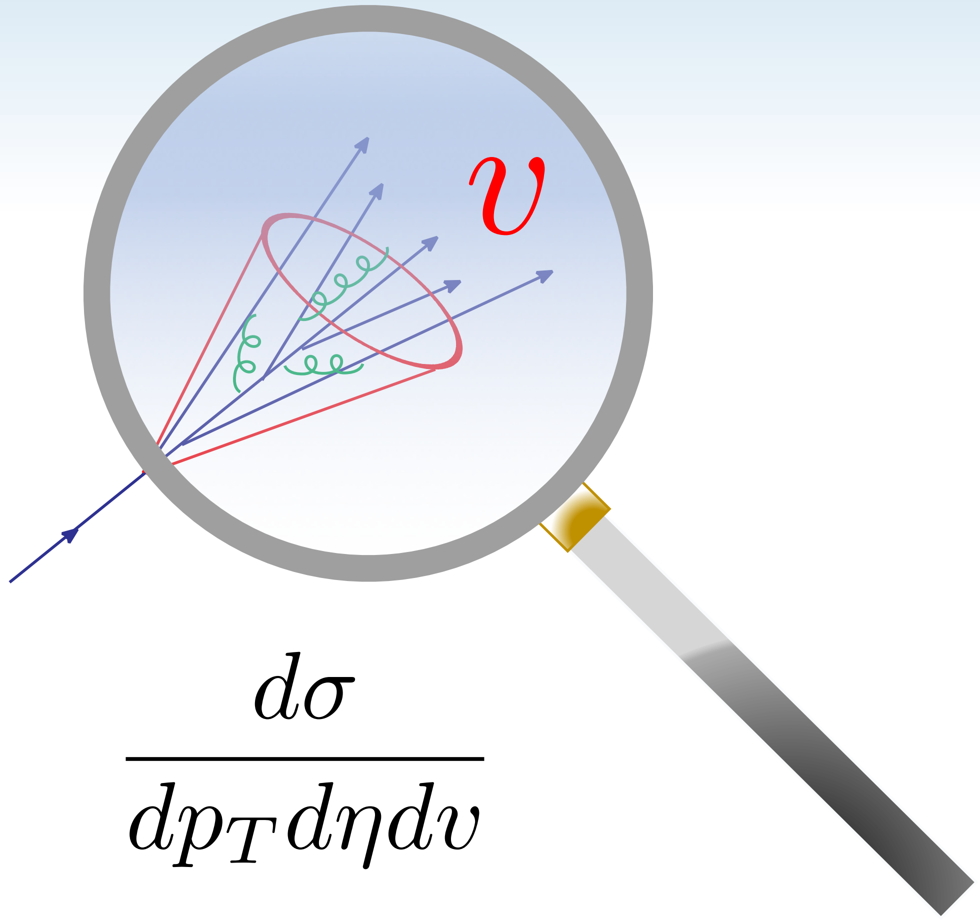
Kang, Ringer, Vitev `16

Jet Substructure Measurements

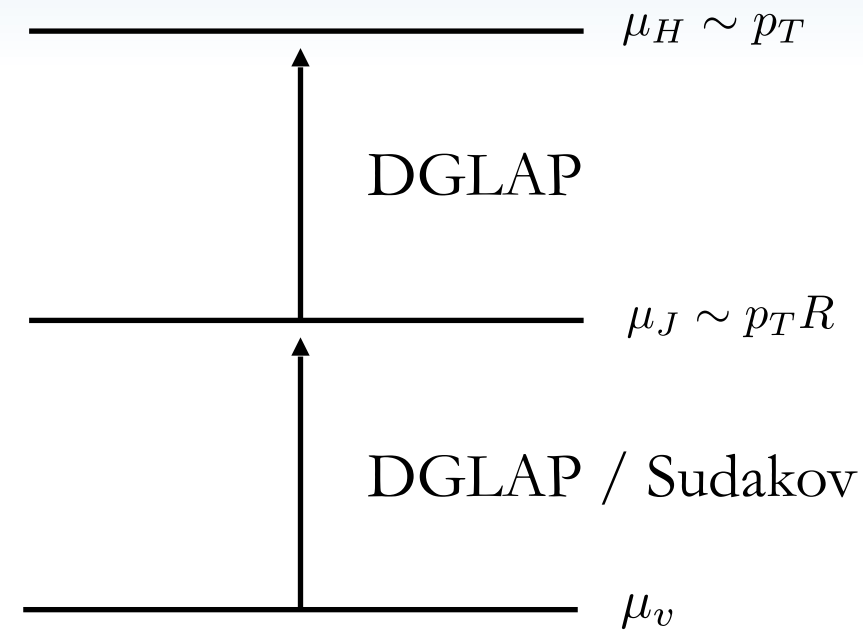


- **How do we measure a substructure v inside the jet?**

Jet Substructure Measurements



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



- When we measure a substructure v from the jet, once we evolve to μ_J the remaining evolution to μ_H is given by DGLAP evolution!
- Two step factorization:
  a) production of a jet
  b) probing the internal structure of the jet produced.

Jet angularity

- A generalized class of IR safe observables, angularity (applied to jet):

$$\tau_a^{e^+e^-} = \frac{1}{E_J}\sum_{i\in J} E_i \theta_{iJ}^{2-a}$$

More relevant for the EIC

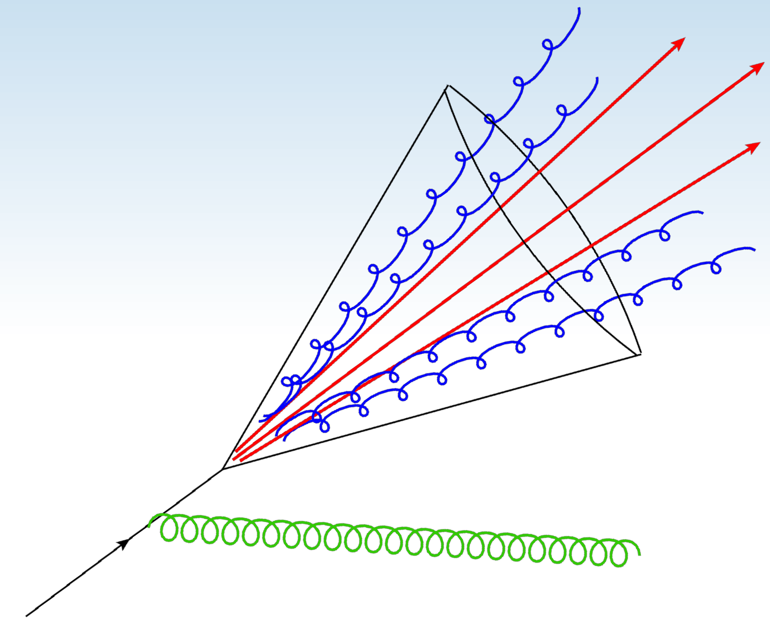
$$\tau_a^{pp} = \frac{1}{p_T}\sum_{i\in J} p_{T,i}(\Delta R_{iJ})^{2-a} = \left(\frac{2E_J}{p_T}\right)^{2-a} \tau_a^{e^+e^-} + \mathcal{O}((\tau_a^{pp})^2)$$

$$\tau_0^{pp} = \frac{m_J^2}{p_T^2} + \mathcal{O}((\tau_0^{pp})^2)$$

- More sensitive to collinear radiation as ‘a’ gets larger. (factorization breaks at a=2).
- a=0 related to thrust (jet mass)
- a=1 related to jet broadening (sensitive to rapidity divergence)
- Many studies done for exclusive case :

Sterman et al. \`03, \`08,
Hornig, C. Lee, Ovanesyan \`09, Ellis, Vermilion, Walsh, Hornig, C.Lee \`10,
Chien, Hornig, C. Lee \`15, Hornig, Makris, Mehen \`16

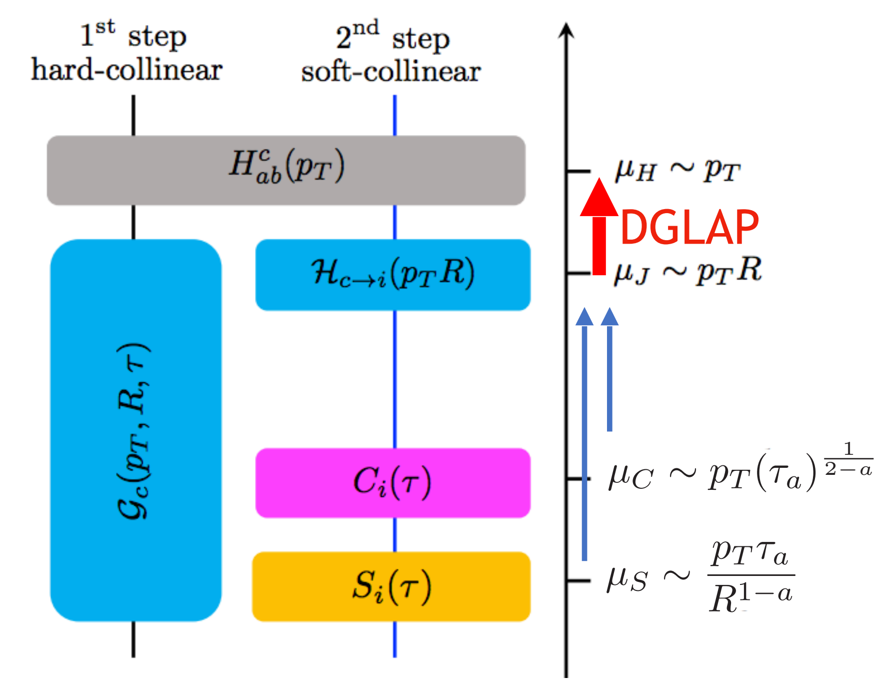
Jet angularity



- Replace $J_c(z, p_T R, \mu) \to \mathcal{G}_c(z, p_T R, \tau_a, \mu)$
- When $\tau_a \ll R^2$, Refactorize $\mathcal{G}_c$ as

$$\mathcal{G}_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu)$$
$$\times \int d\tau_a^{C_i} d\tau_a^{S_i} \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) C_i(\tau_a^{C_i}, p_T \tau_a^{\frac{1}{2-a}}, \mu) S_i(\tau_a^{S_i}, \frac{p_T \tau_a}{R^{1-a}}, \mu) + \mathcal{O}\left(\frac{m^2}{p_T^2 R^2}\right)$$

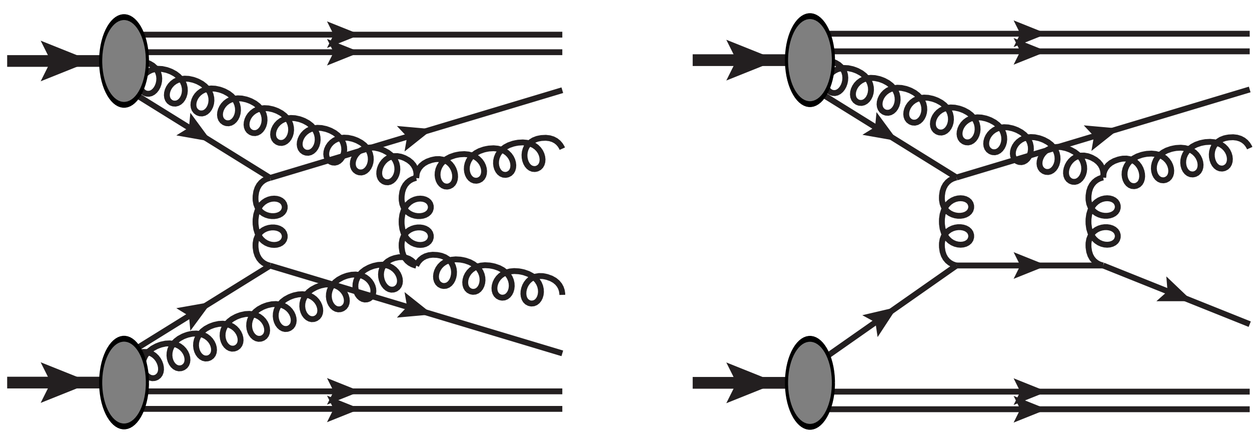
- Each pieces describe physics at different scales.
- $\mu_J \to \mu_H$ evolution follows DGLAP evolution equation again
- Resums $(\alpha_s \ln R)^n$ and $(\alpha_s \ln^2 \frac{R}{\tau_a^{1/(2-a)}})^n$



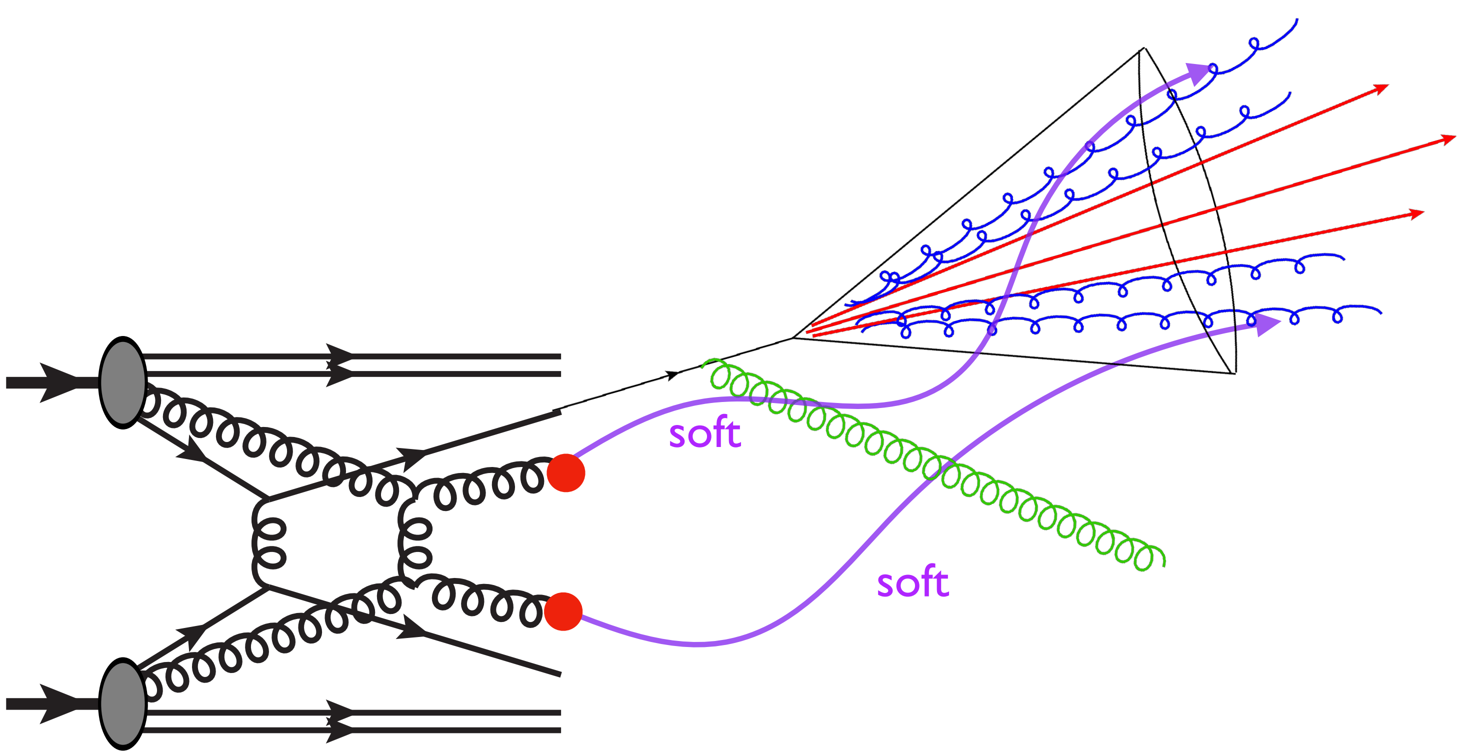
Kang, KL, Ringer `18

Non-perturbative Effects

- **Non-perturbative effects:**



Figs from P. Bartalini et al. `11



- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.

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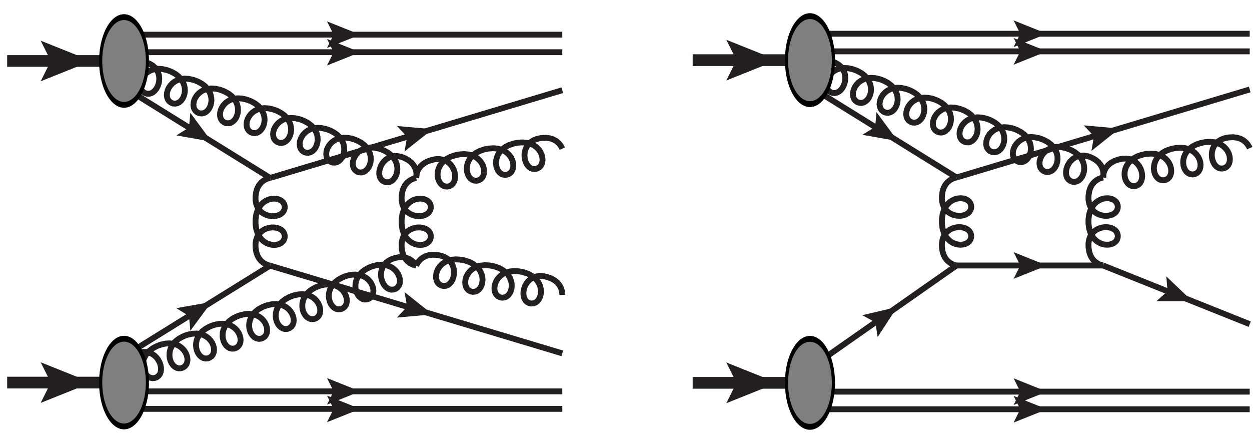

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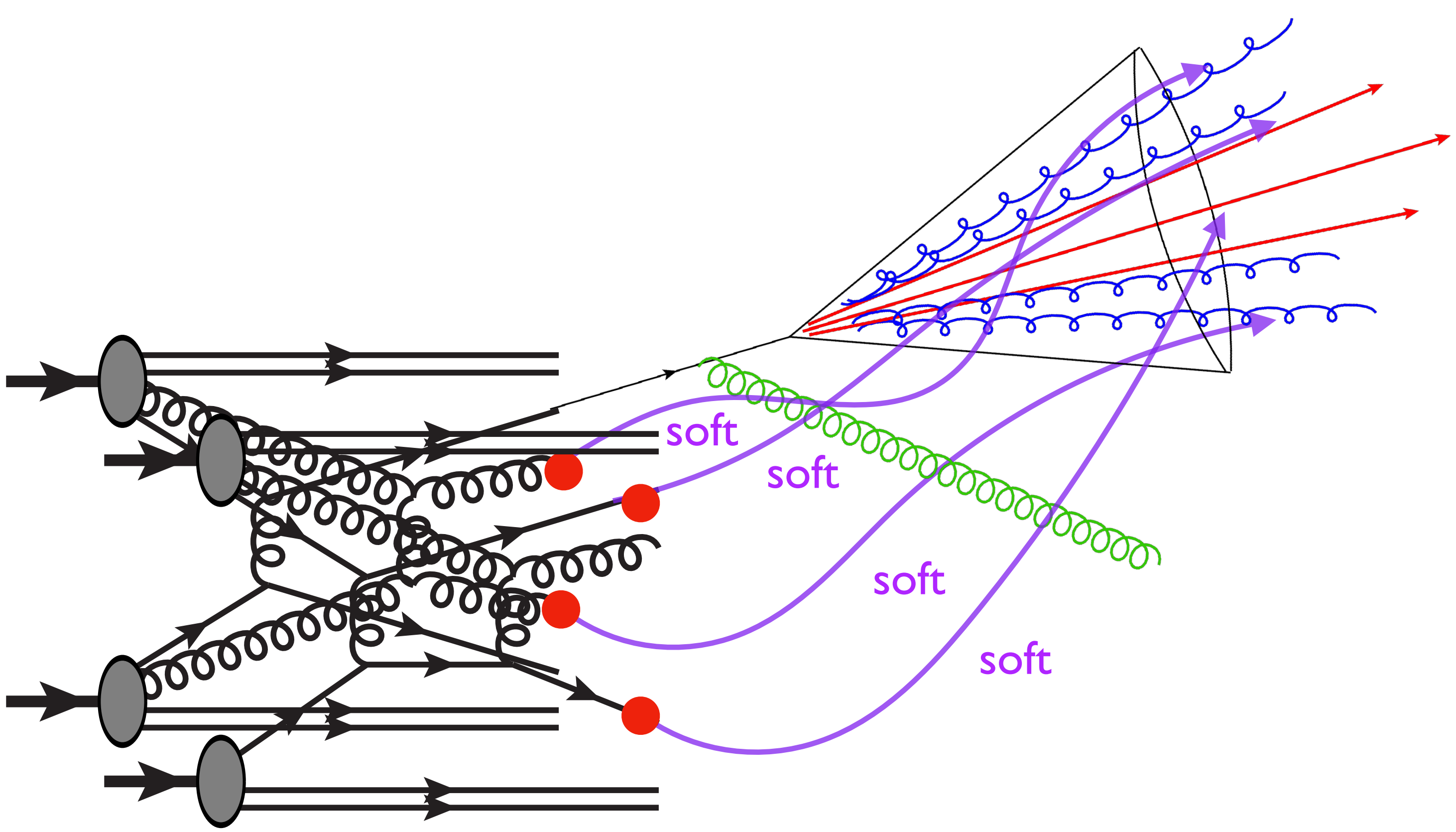
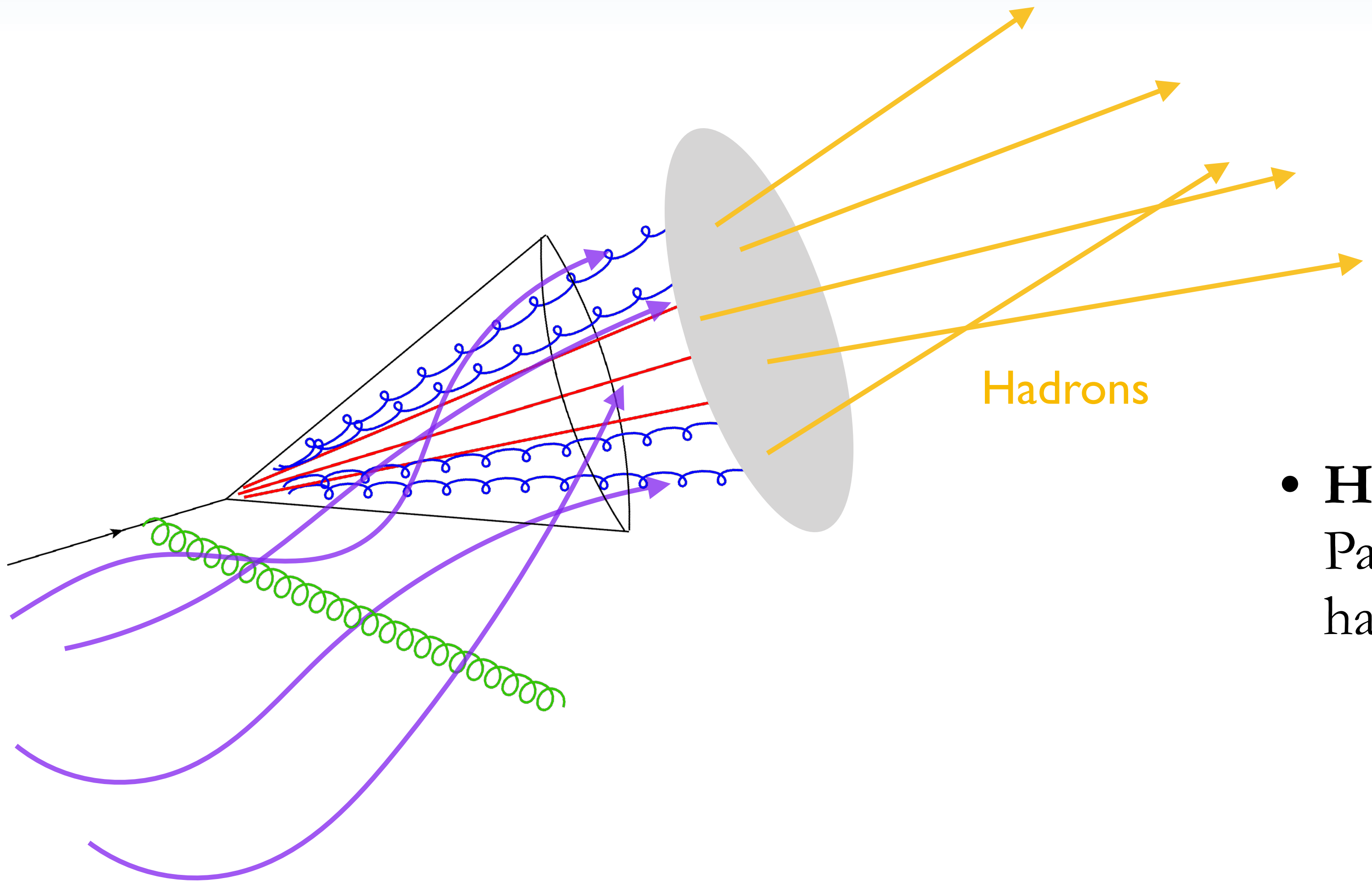


- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.
- **Pileups**
  Secondary proton collisions in a bunch may enter and contaminate jet.

Non-perturbative Effects

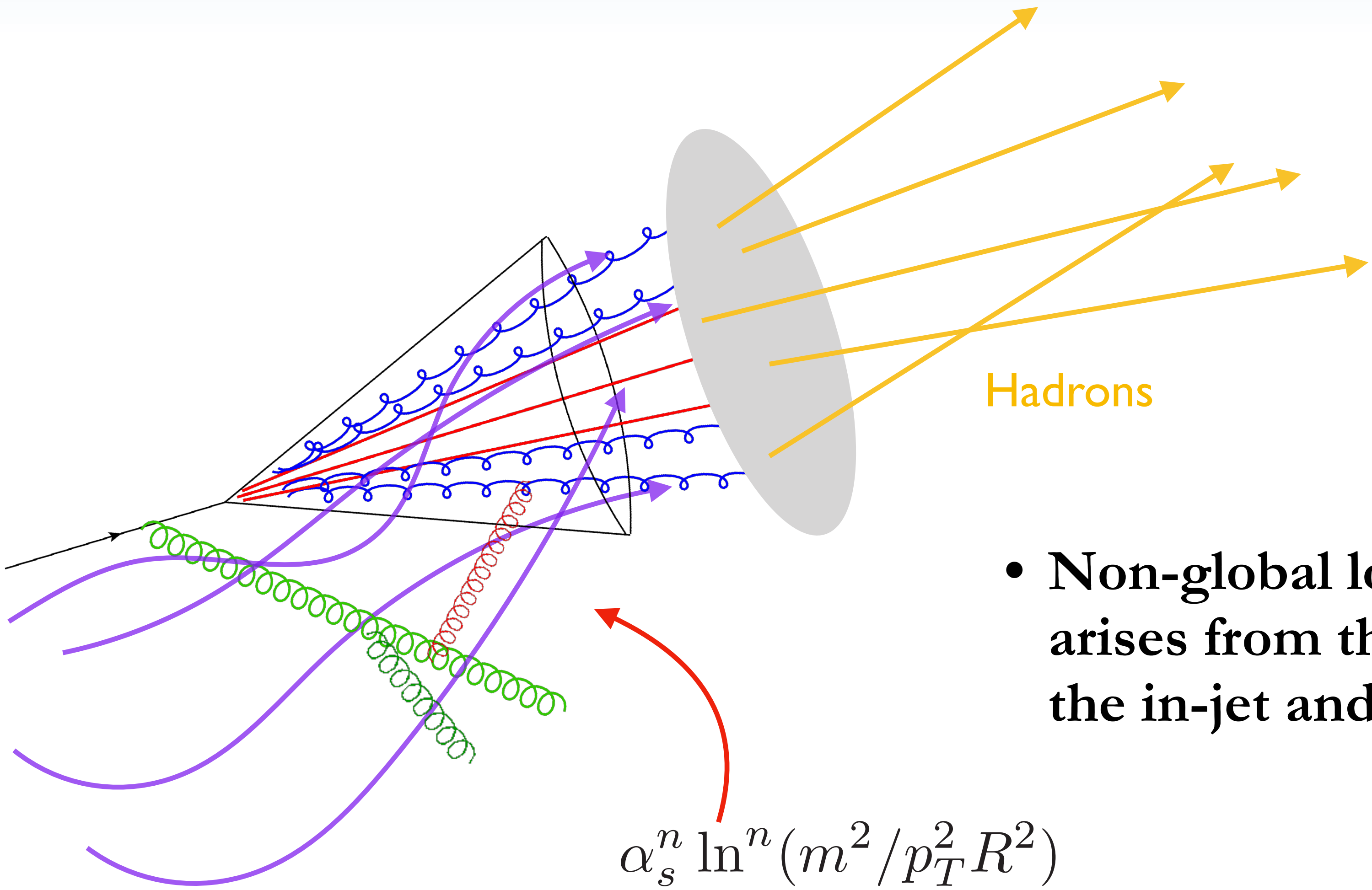
- **Non-perturbative effects:**



- **Hadronization**
  Partons forming the jet eventually hadronizes.

Non-global logarithms

Dasgupta, Salam `01
Banfi, Marchesini, Smye `02
Larkoski, Moult, Neill `15
Becher, Rahn, Shao `17 …



- **Non-global logarithms (NGLs): arises from the correlation between the in-jet and out-of-jet radiation.**

$\alpha_s^n \ln^n(m^2/p_T^2 R^2)$

rather small effect for jet mass

can be larger for the EIC

Non-perturbative Model

- As τ gets smaller, $\mu_S \sim \frac{p_T \tau}{R}$ (smallest scale) can approach a non-perturbative scale.

  We shift our perturbative results by convolving with non-perturbative shape function to smear

$$\frac{d\sigma}{d\eta dp_T d\tau} = \int dk F_\kappa(k) \frac{d\sigma^{\text{pert}}}{d\eta dp_T d\tau}\left(\tau - \frac{R}{p_T}k\right)$$

- Single parameter NP soft function :

$$F_\kappa(k) = \left(\frac{4k}{\Omega_\kappa^2}\right) \exp\left(-\frac{2k}{\Omega_\kappa}\right)$$

Stewart, Tackmann, Waalewijn `15

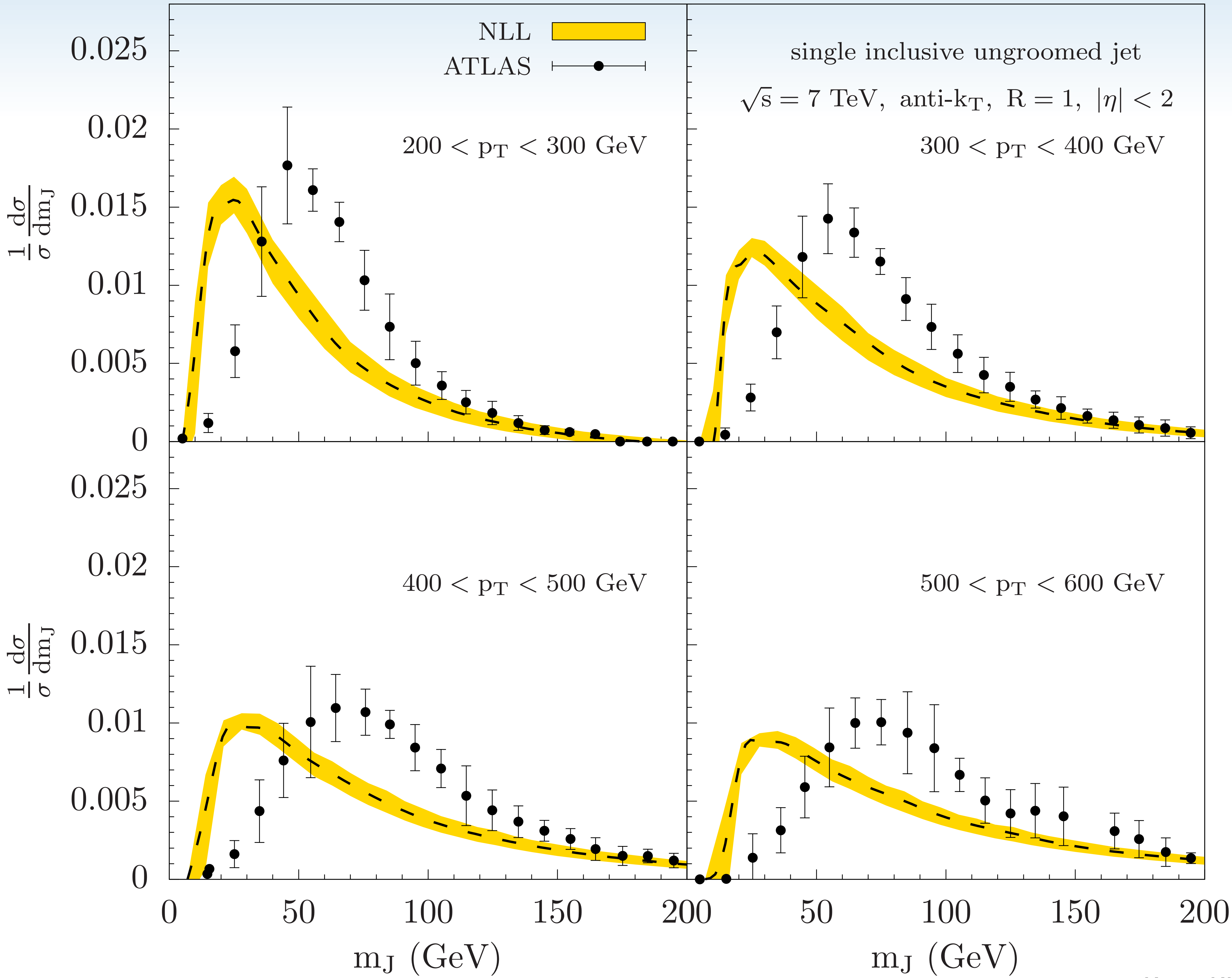
- Both hadronization and MPI effects in jet mass is well-represented by just shifting first-moments.

- The parameter Ω_κ is related to shift in the distribution:

$$\tau = \tau_{\text{pert}} + \tau_{\text{NP}} = \tau_{\text{pert}} + \frac{R\Omega_\kappa}{p_T} = \tau_{\text{pert}} + \frac{R\left(\Lambda_{\text{hadro.}} + \Lambda_{\text{MPI}}\right)}{p_T}$$

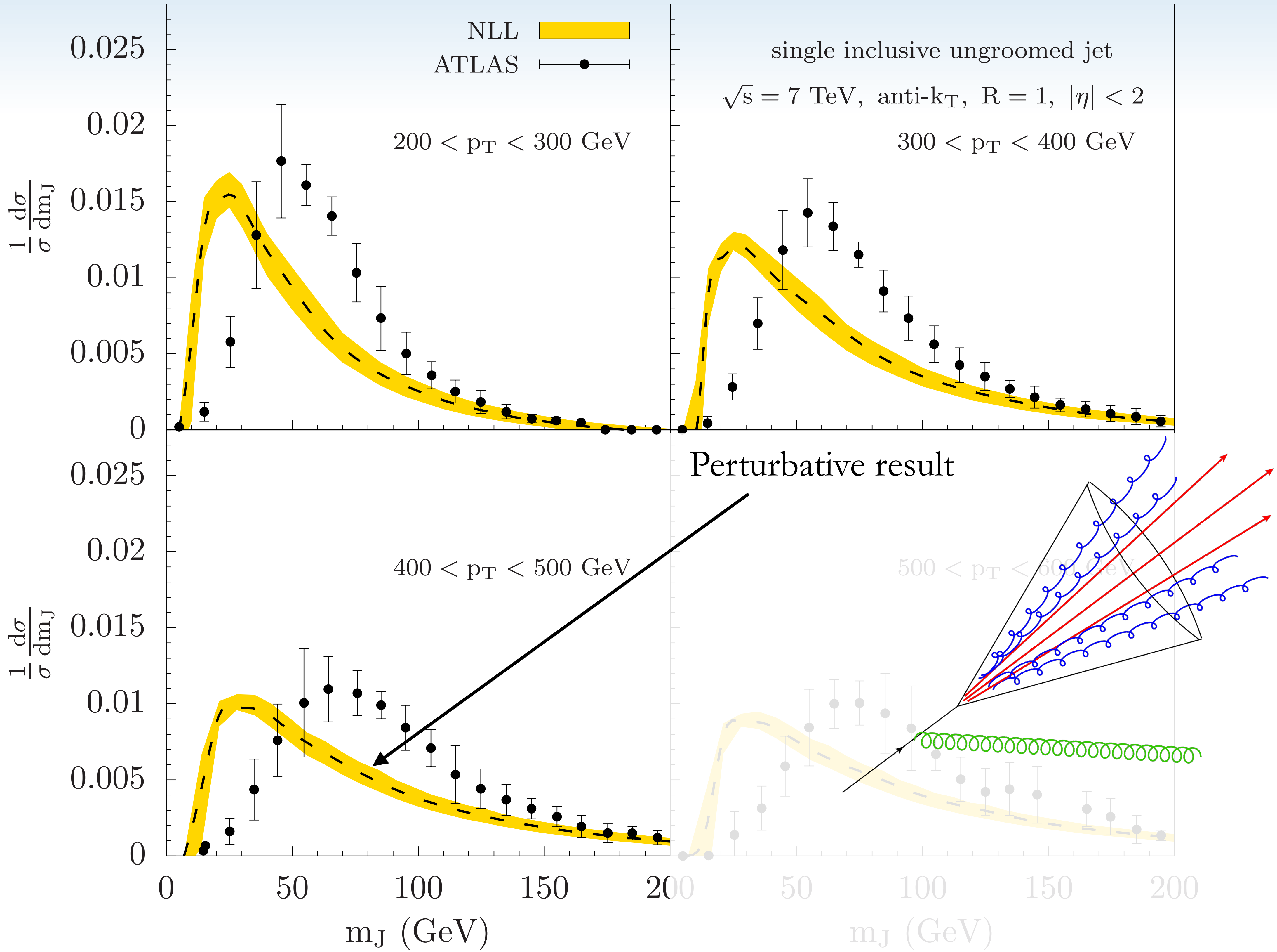
$\Omega_\kappa \sim \Lambda_{had} \sim 1\,\text{GeV}$ corresponds to non-perturbative effects coming primarily from the hadronization alone.

Phenomenology



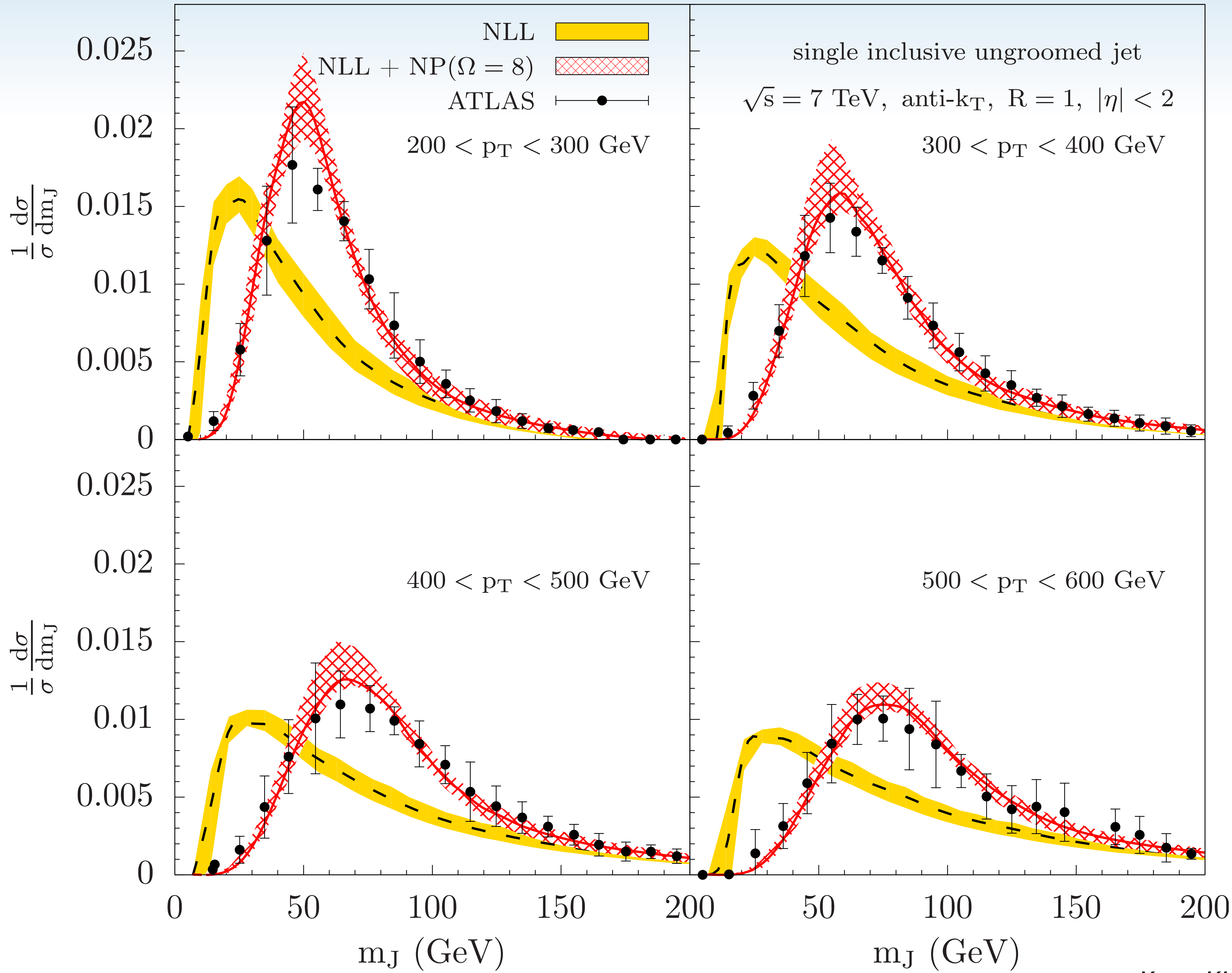
Kang, KL, Liu, Ringer `18

Phenomenology



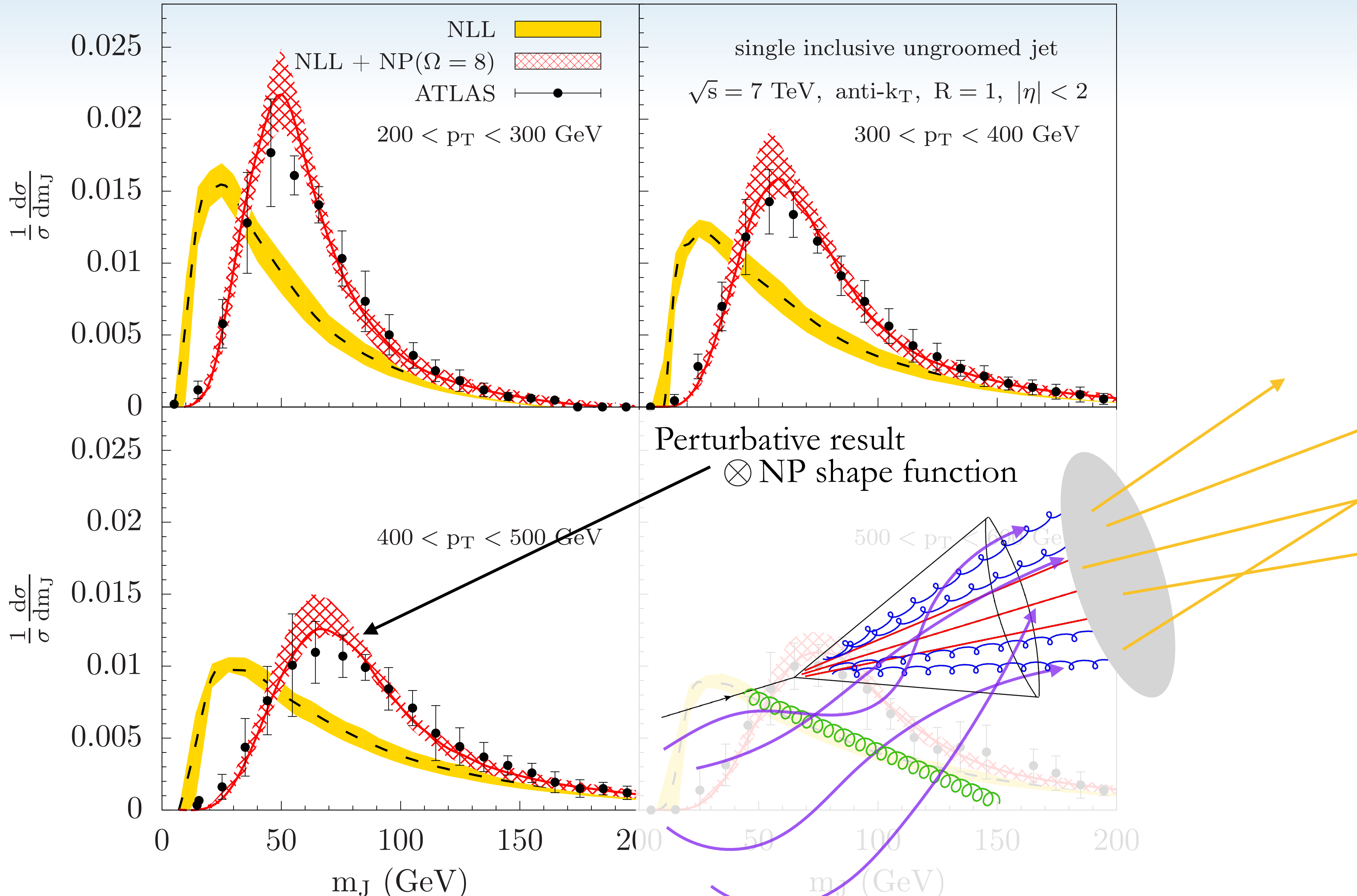
Kang, KL, Liu, Ringer `18

Phenomenology



Kang, KL, Liu, Ringer `18

Phenomenology



Kang, KL, Liu, Ringer `18

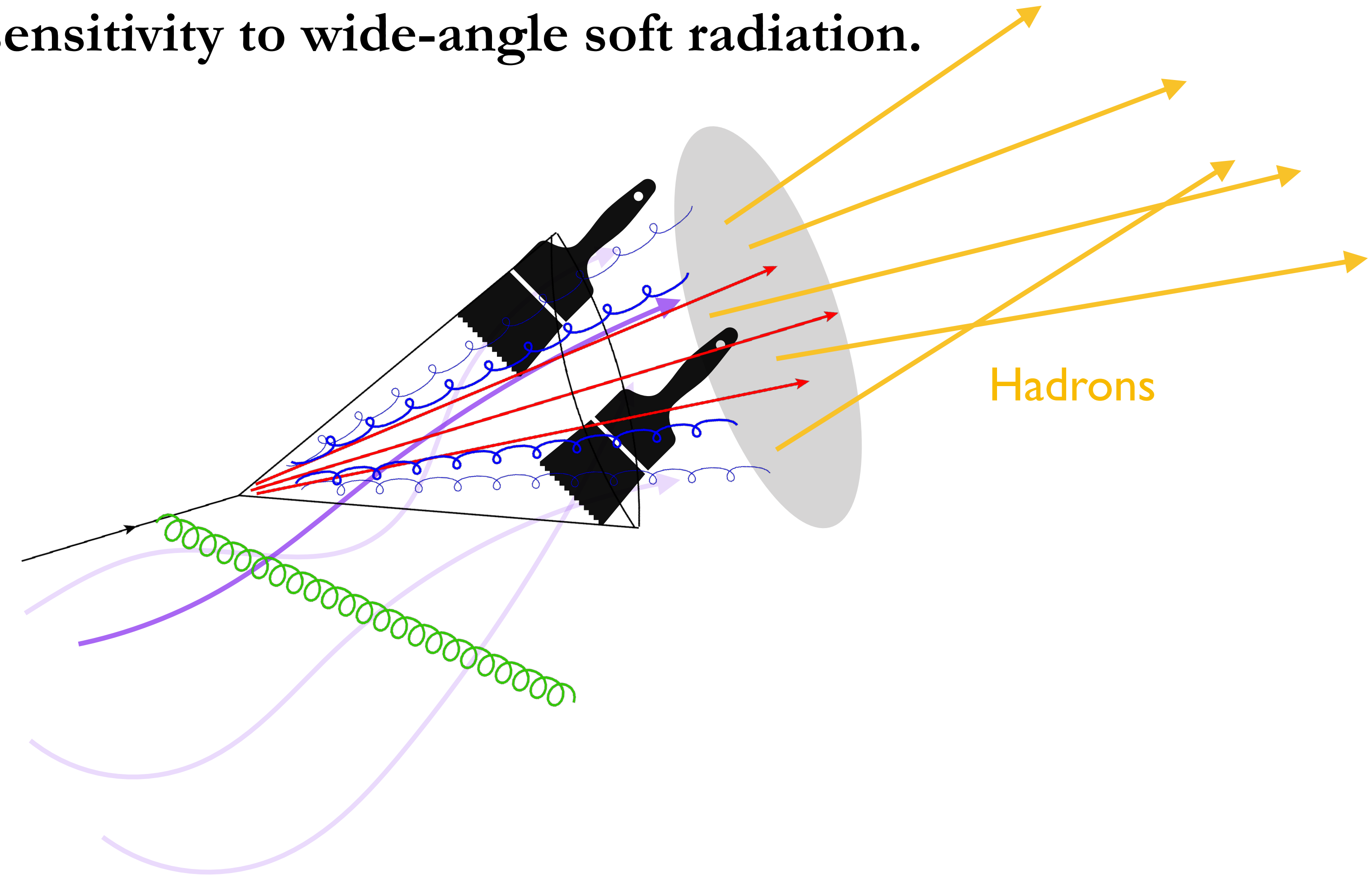
Soft Drop Grooming

- Underlying Events (UE) are difficult to understand.

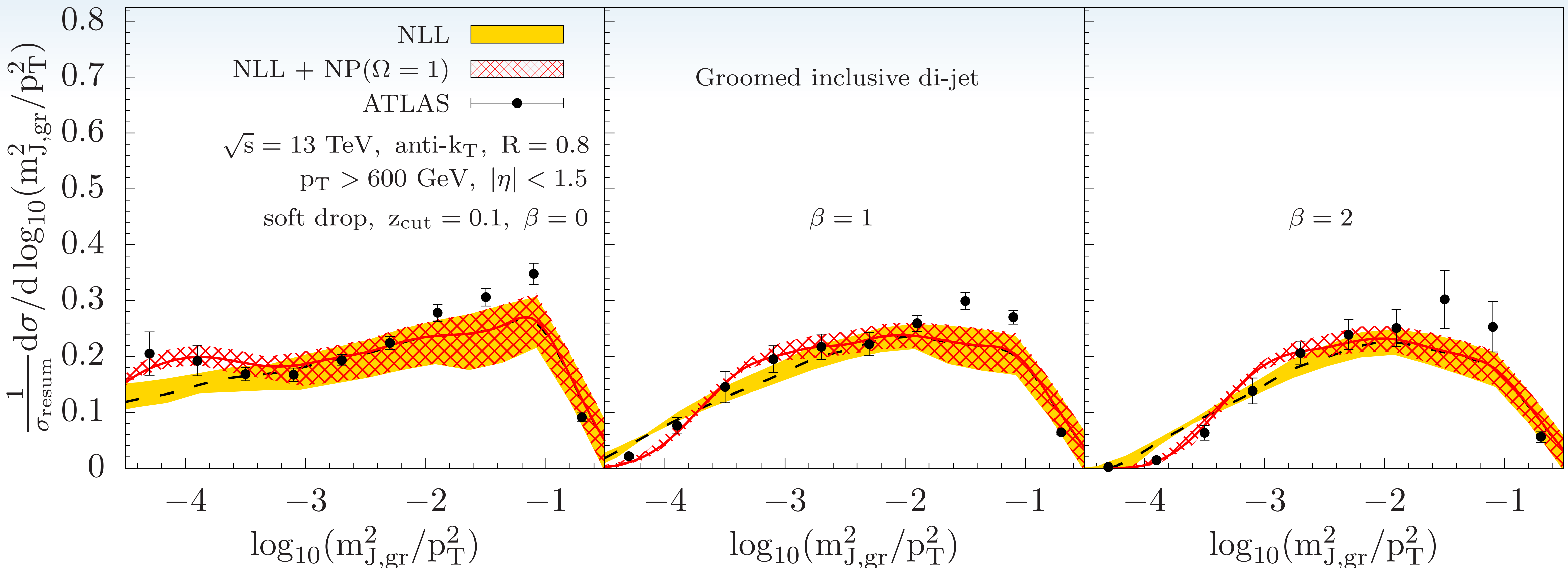
  How do we get a better hold of these contaminations in the jet?

- Hint : contamination generally from soft radiations.

  Groom jets to reduce sensitivity to wide-angle soft radiation.



Phenomenology (groomed jet mass)

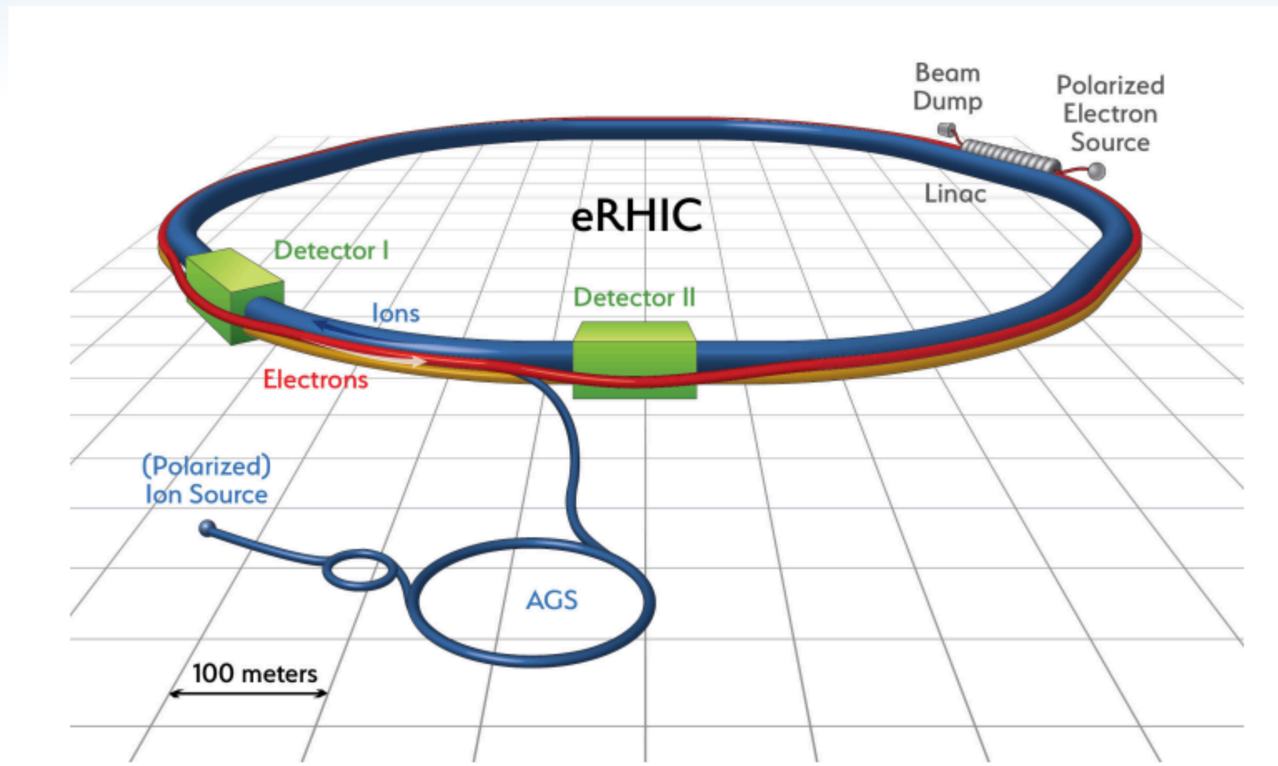


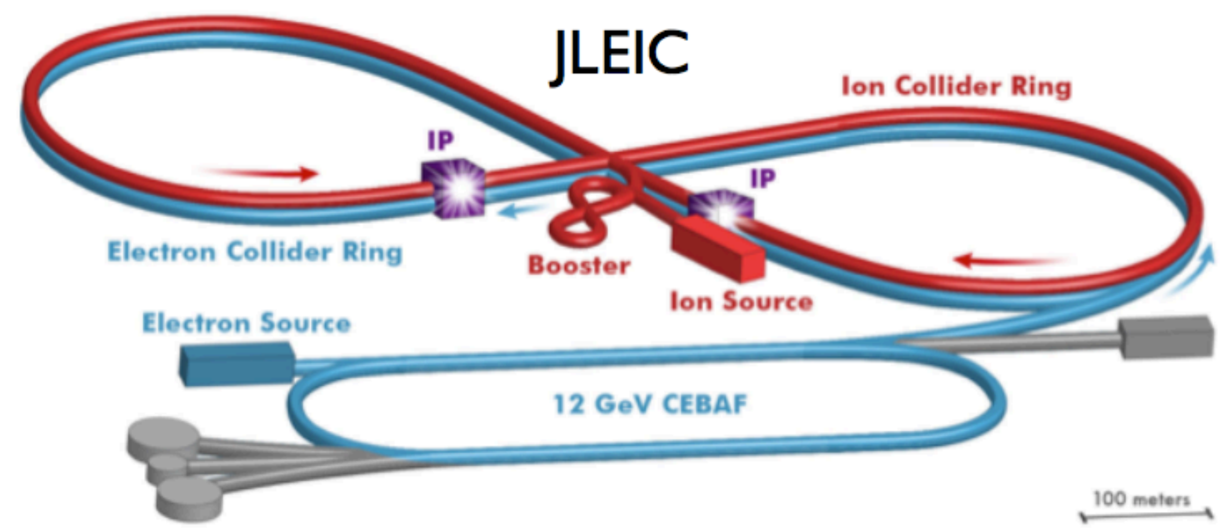
- Developed the formalism for single inclusive groomed jet mass cross-section.
- Shows very good agreement with the data.
- $\Omega_k = 1$ GeV $\Longrightarrow$ Reduced contamination as expected. NP effects mostly from hadronization.

See also
ATLAS, arXiv:1711.08341
Larkoski, Marzani, Soyez, Thaler `14
Frye, Larkoski, Schwartz, Yan `16

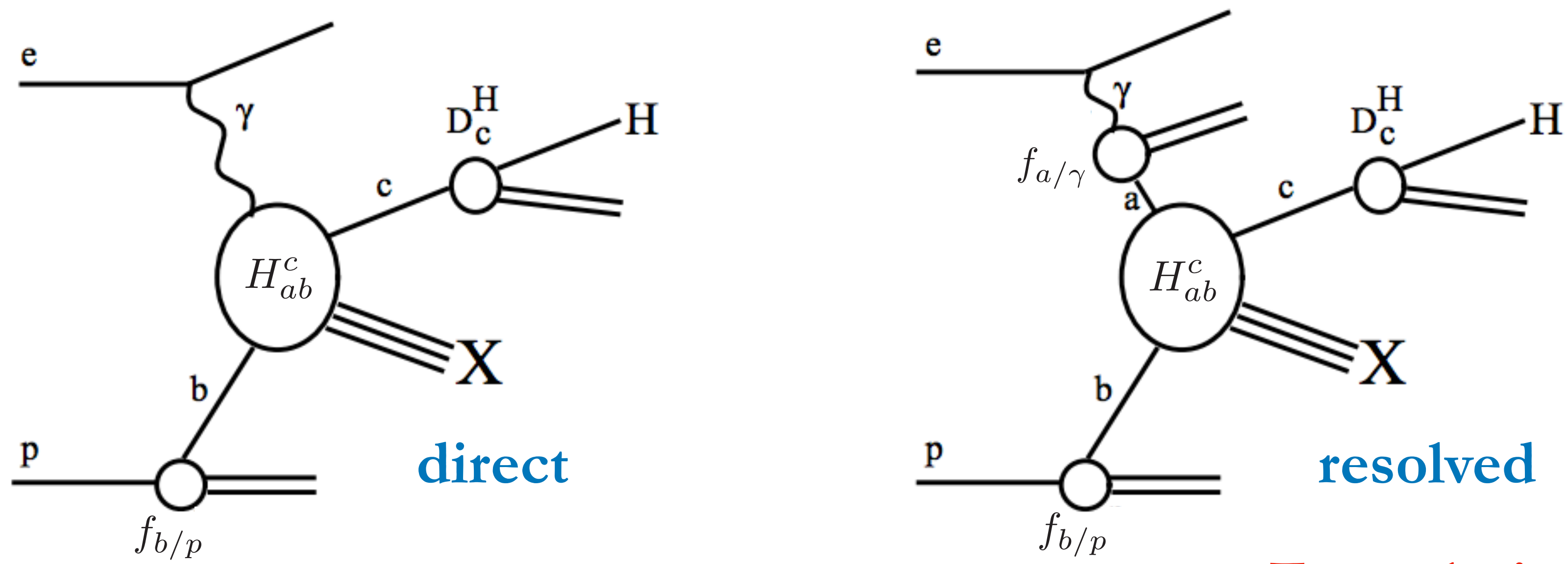
Kang, KL, Liu, Ringer `18

Jets at the EIC





Photoproduction at the EIC



For polarized case,

hadron $$\frac{d\sigma^{ep\to ehX}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes D_c^h$$

$$\frac{d\Delta\sigma^{ep\to ehX}}{dp_T d\eta} = \sum_{a,b,c} \Delta f_{a/l} \otimes \Delta f_{b/p} \otimes \Delta H_{ab}^c \otimes D_c^h$$

Weizsäcker-Williams spectrum

$$f_{a/l} = P_{\gamma l} \otimes f_{a/\gamma}$$

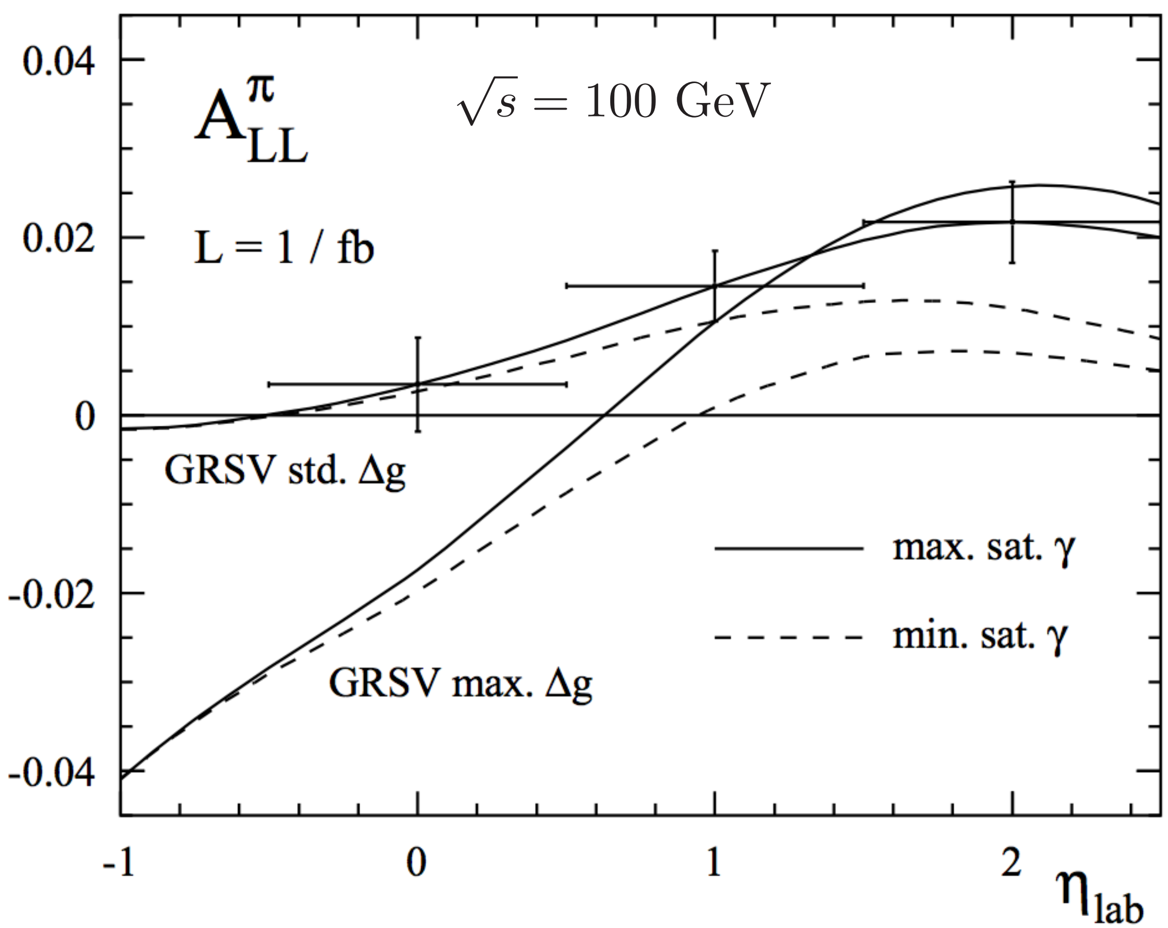
- For the direct process, $f_{a/\gamma} = \delta(1 - x_\gamma)$.
- Observe outgoing lepton to tag Q^2
- Require high p_T and $Q^2 < 0.1 \text{ GeV}^2$ (near on-shell photon)

See Jäger, Stratmann, Vogelsang `03

Polarized Gluon and Photon PDF

Study in 2003,

Jäger, Stratmann, Vogelsang `03



$$A_{LL} = \frac{d\Delta\sigma}{d\sigma} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$

$$\Delta f_{\max} = f \qquad \Delta f_{\min} = 0$$

- Sensitivity to polarized gluon pdf at low $\eta_{\rm lab}$
- Sensitivity to polarized photon pdf at high $\eta_{\rm lab}$

Assumptions: $D_c^{\pi^0}$ has been well-determined.

Use inclusive jets as a perturbative probe!

For using dijet process, see Xiaoxuan's talk

- Study of polarized pdfs

$$\frac{d\Delta\sigma^{ep\to e\pi^0 X}}{dp_T d\eta} = \sum_{a,b,c} \Delta f_{a/l} \otimes \Delta f_{b/p} \otimes \Delta H_{ab}^c \otimes D_c^{\pi^0}$$

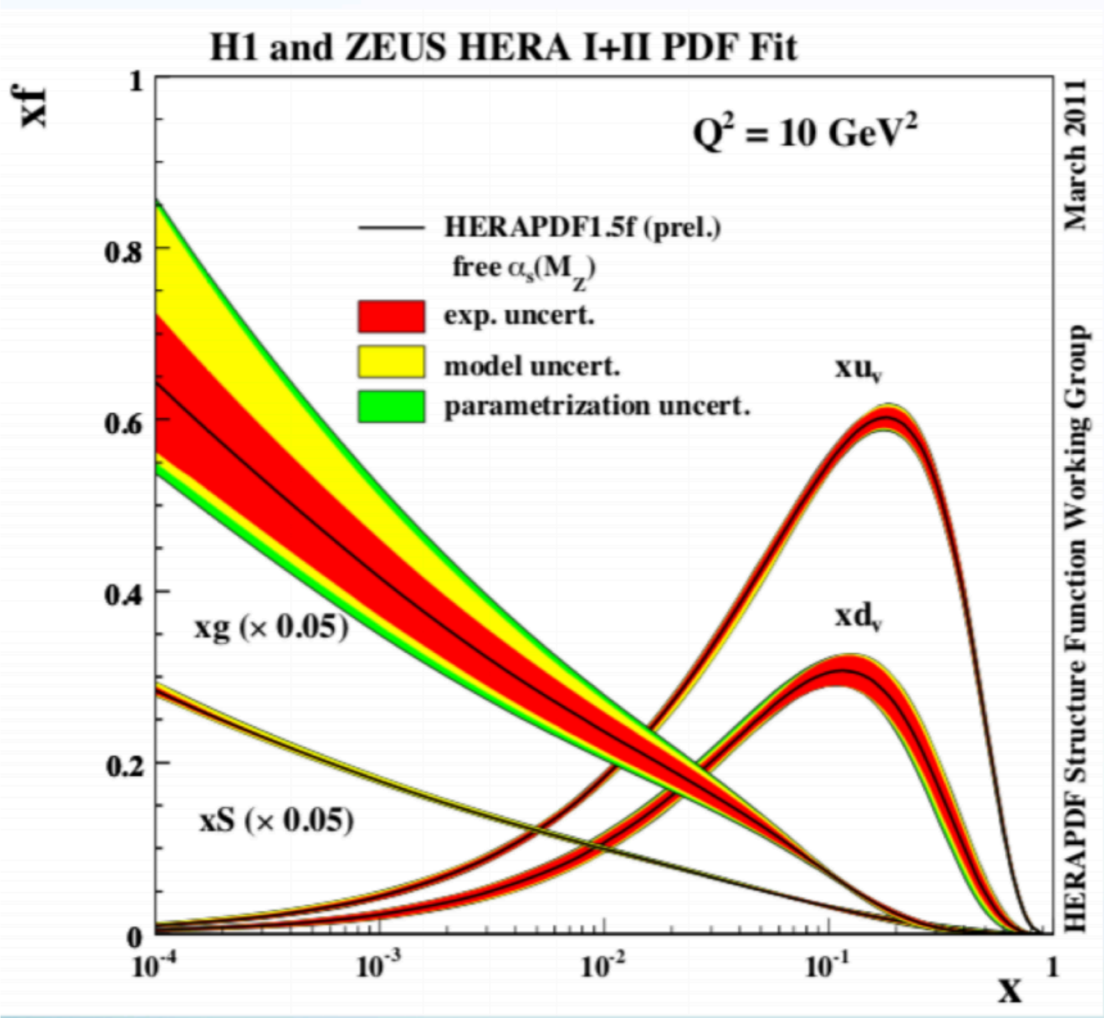
HERA PDF fit with and without jets

- Important for constraining gluon PDF

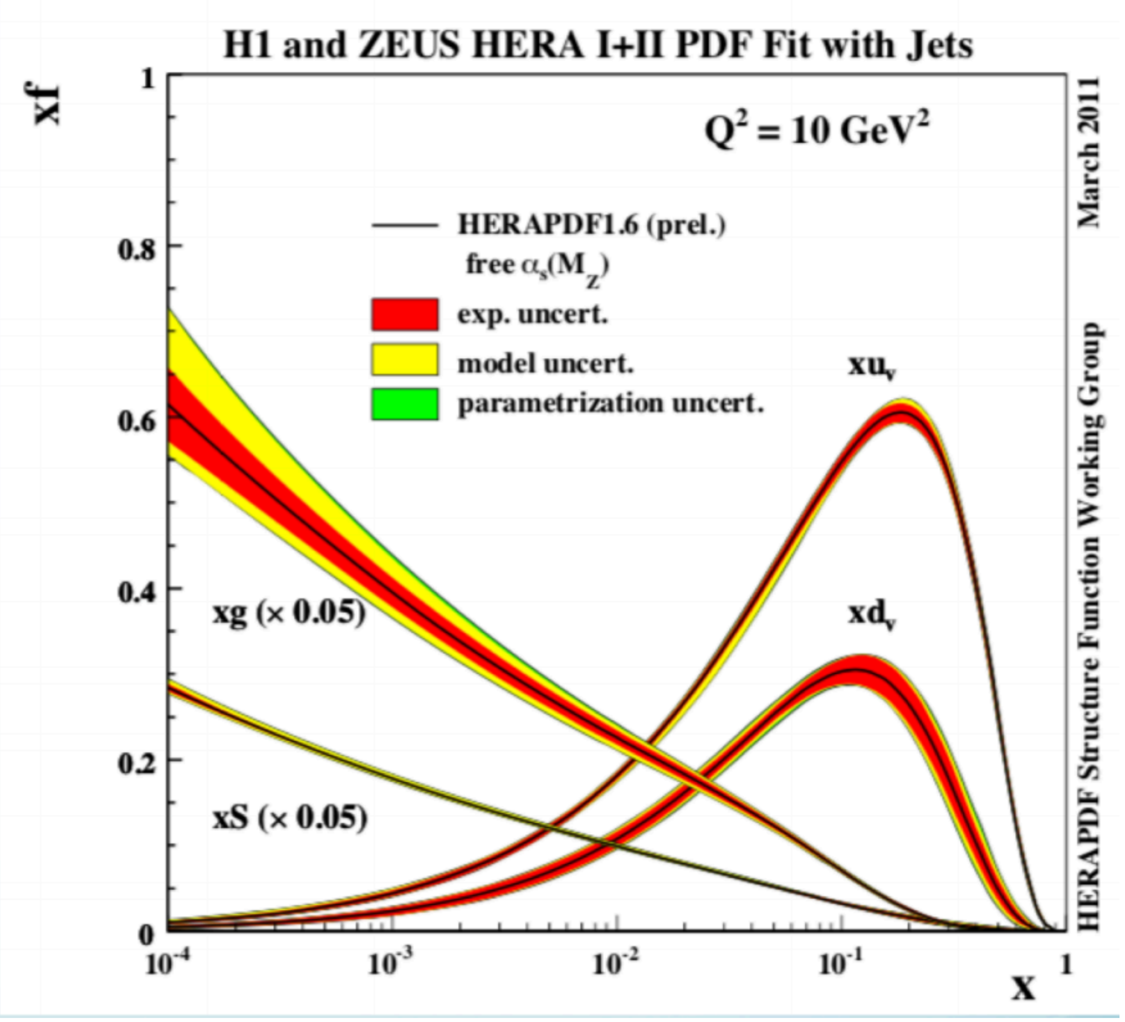
Nuclear Physics B (Proc. Suppl.) 222–224 (2012) January–March 2012

HERA 2011

Proceedings of the Ringberg Workshop
New Trends in HERA Physics 2011

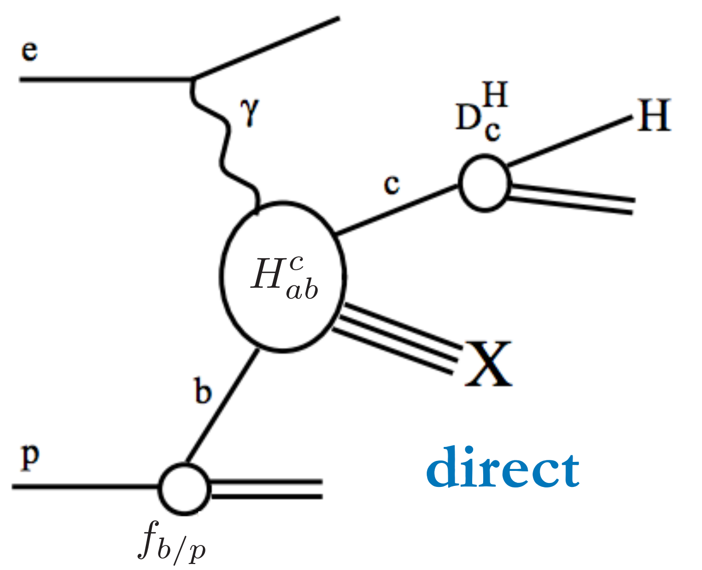


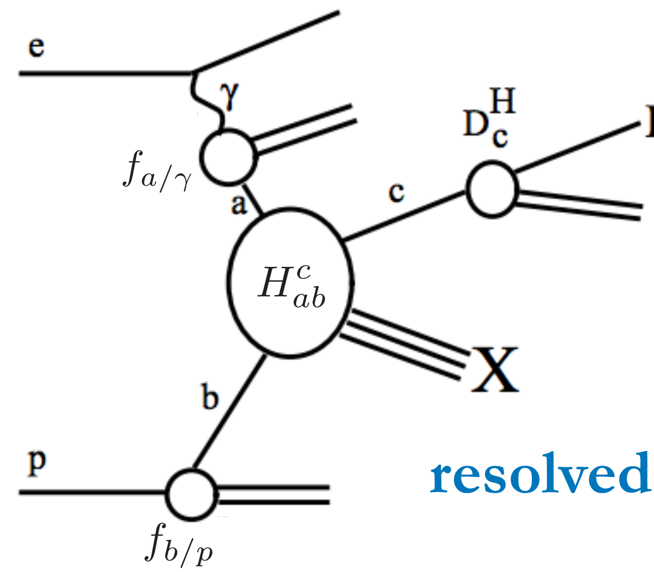
Without jets



With jets

Photoproduction at the EIC





hadron $$\frac{d\sigma^{ep\to ehX}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H_{ab}^c \otimes D_c^h$$

For polarized case,

$$\frac{d\Delta\sigma^{ep\to ehX}}{dp_T d\eta} = \sum_{a,b,c} \Delta f_{a/l} \otimes \Delta f_{b/p} \otimes \Delta H_{ab}^c \otimes D_c^h$$

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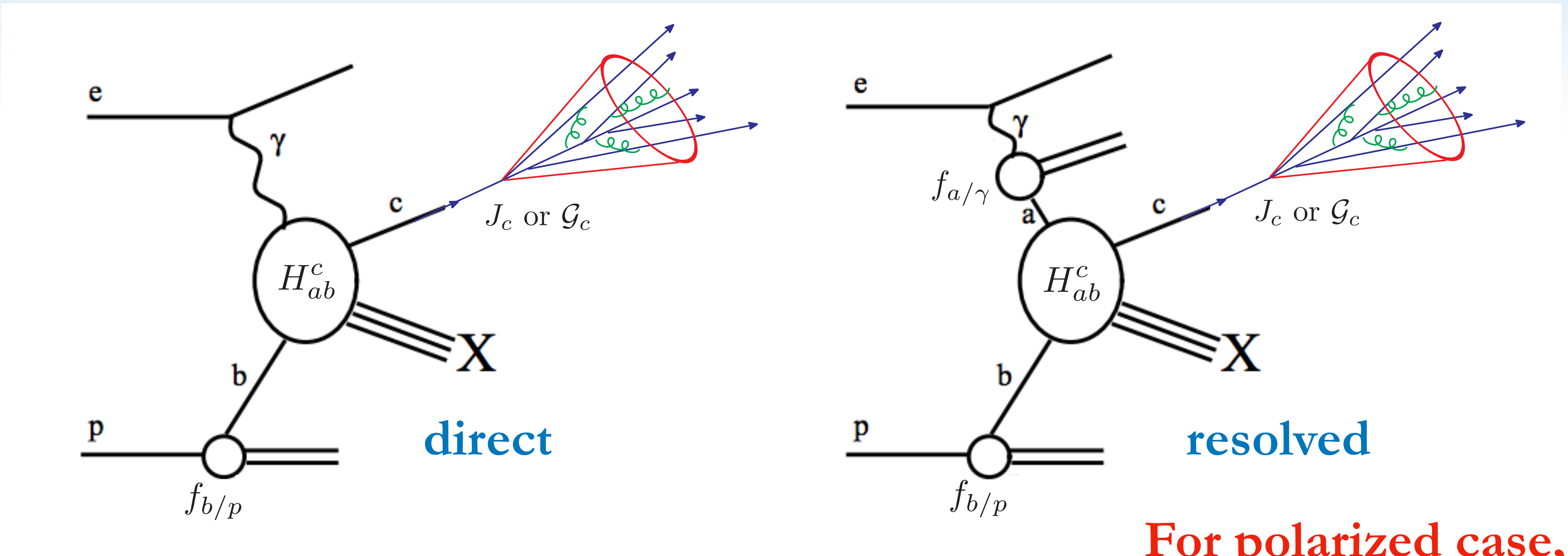
See Jäger, Stratmann, Vogelsang `03

Photoproduction at the EIC



For polarized case,

$$\frac{d\Delta\sigma^{ep\to ehX}}{dp_T d\eta} = \sum_{a,b,c} \Delta f_{a/l} \otimes \Delta f_{b/p} \otimes \Delta H^c_{ab} \otimes D^h_c$$

hadron $$\frac{d\sigma^{ep\to ehX}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes D^h_c$$

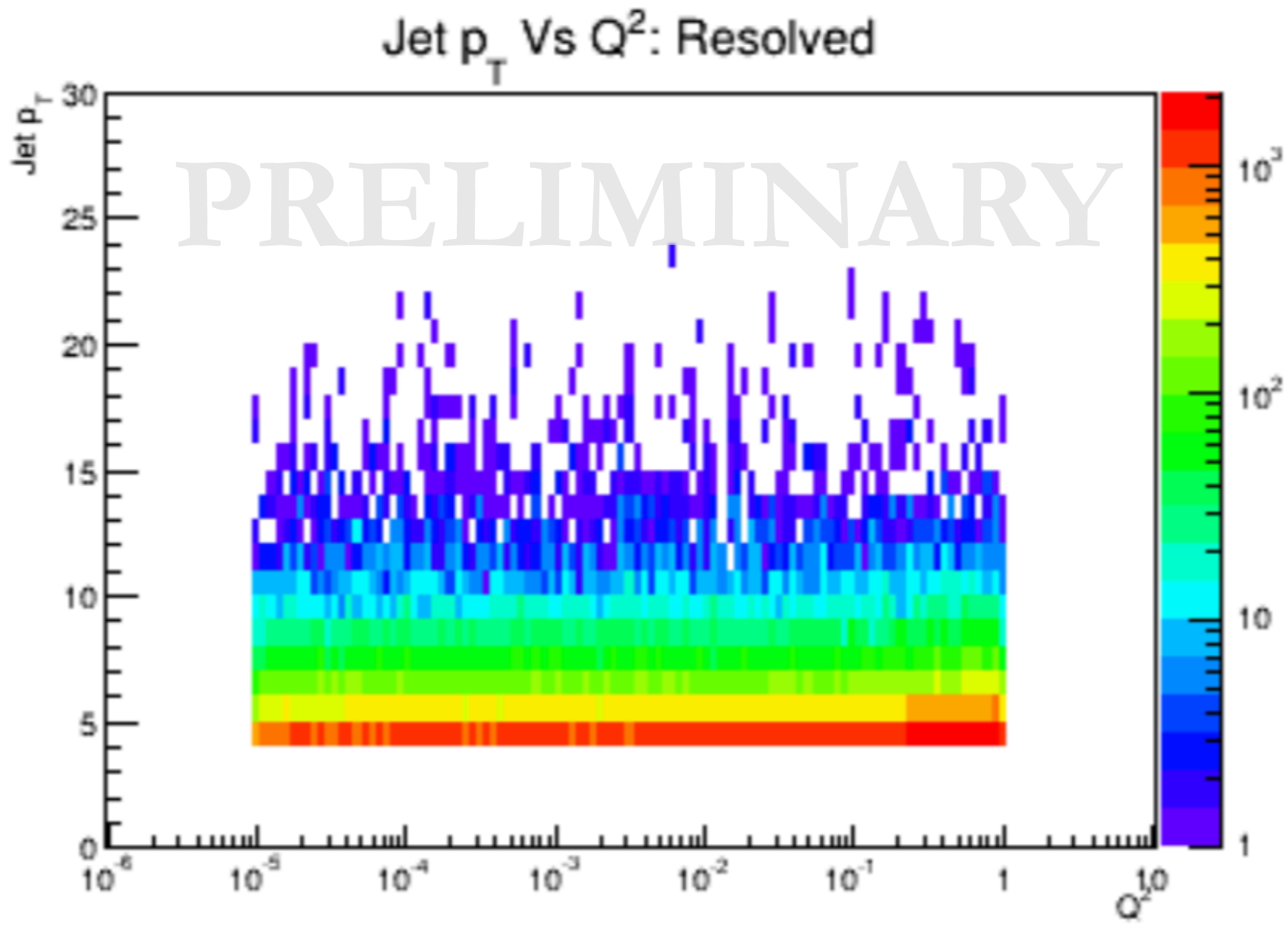
Inclusive Jet $$\frac{d\sigma^{ep\to e\mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes J_c + \mathcal{O}(R^2)$$

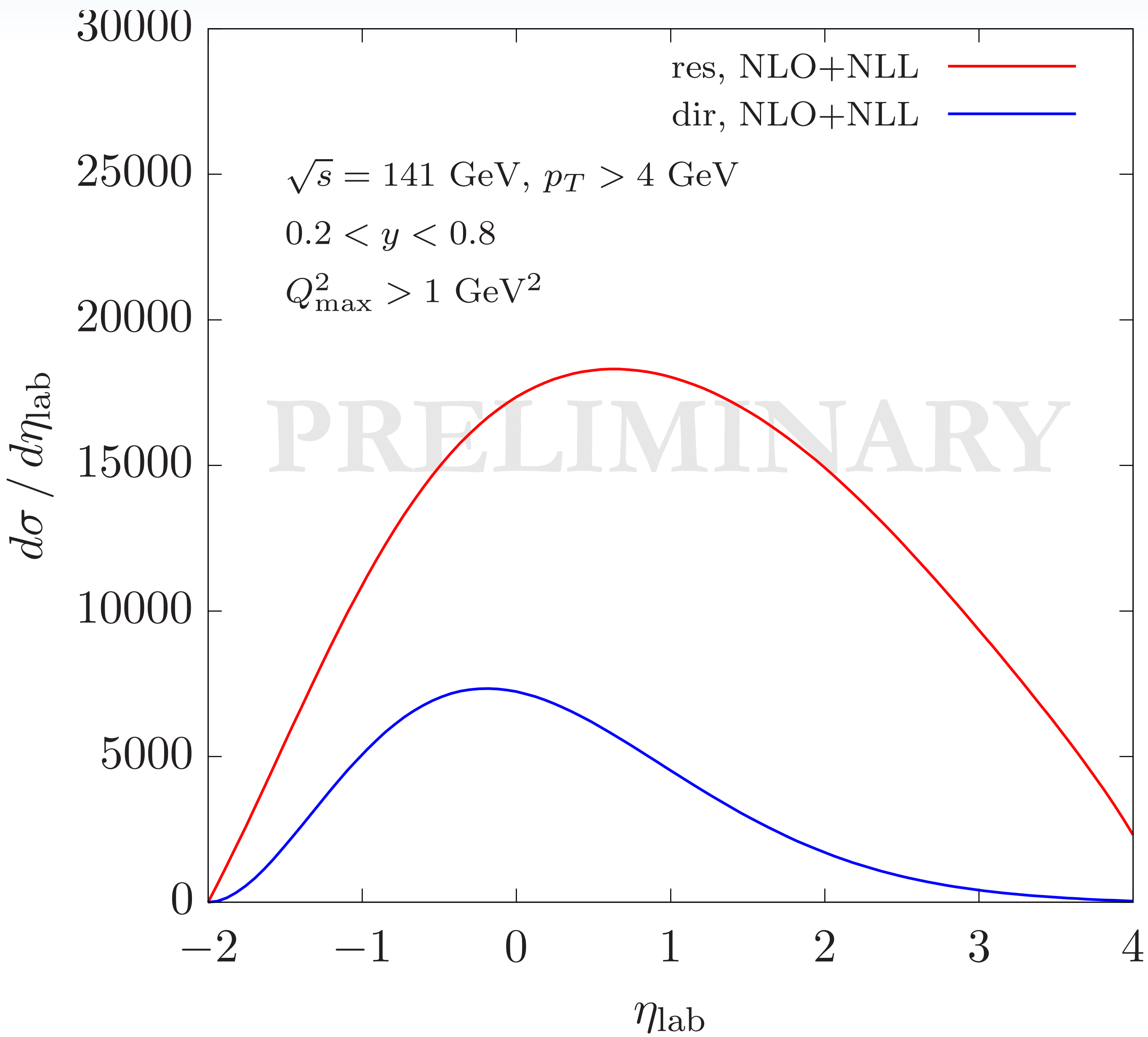
Jet mass $$\frac{d\sigma^{ep\to e\mathrm{jet}(m_J)X}}{dp_T d\eta dm_J} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes \mathcal{G}_c(m_J) + \mathcal{O}(R^2)$$

- Sensitivity to the photon pdfs. Can be done for polarized and unpolarized case.
- Quark and gluon discrimination with jet mass observed.
- Role of NP physics?

Jäger, Stratmann, Vogelsang `03
Chu, Aschenauer, Lee, Zheng `17
In collaboration with Elke Aschenauer and Brian Page

p_T distribution for the jets in the EIC





$E_e = 20$ GeV
$E_p = 250$ GeV

$\mathcal{O}\left(\frac{\Lambda_{QCD}}{p_T R}\right)$

- 4 GeV $< p_T <$ 15 GeV for $Q^2 < 1$ GeV, contribution mostly from resolved.

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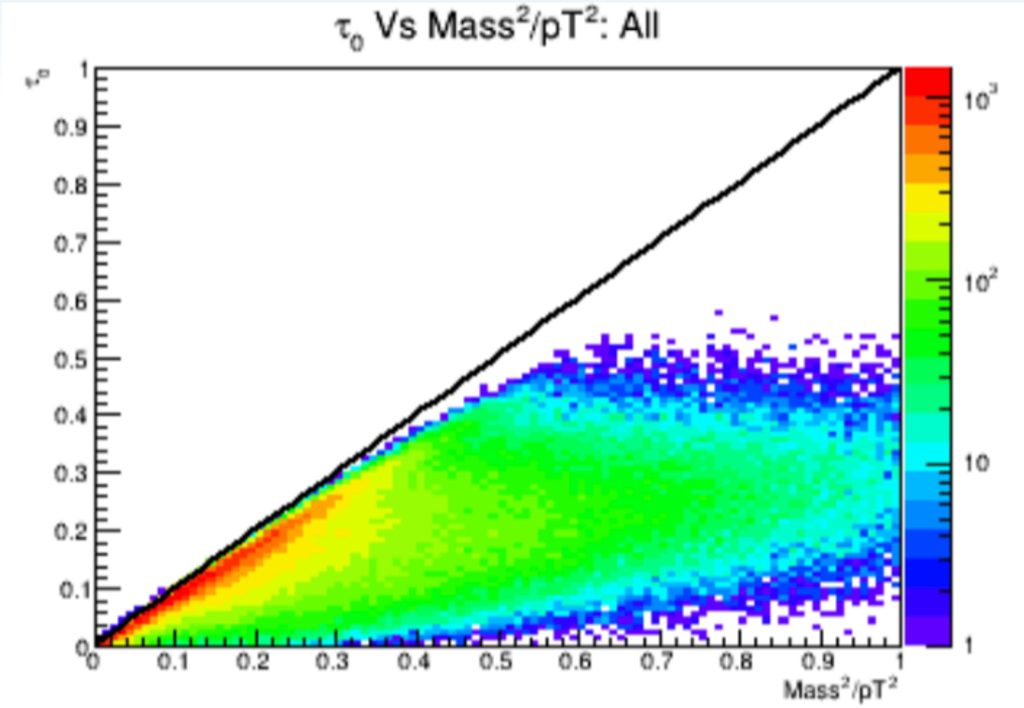
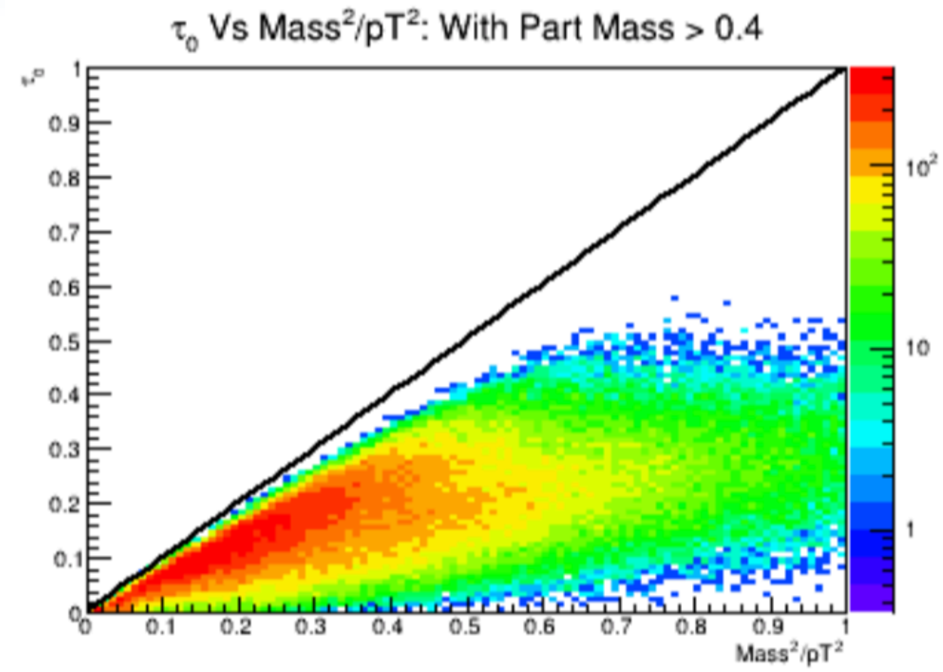
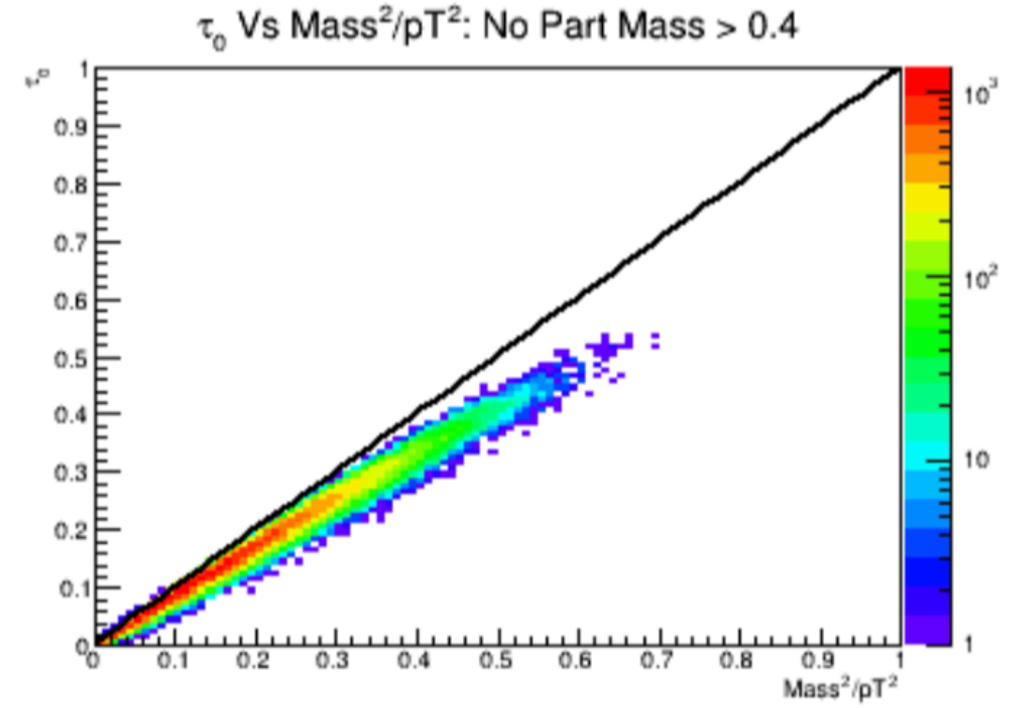
Power corrections





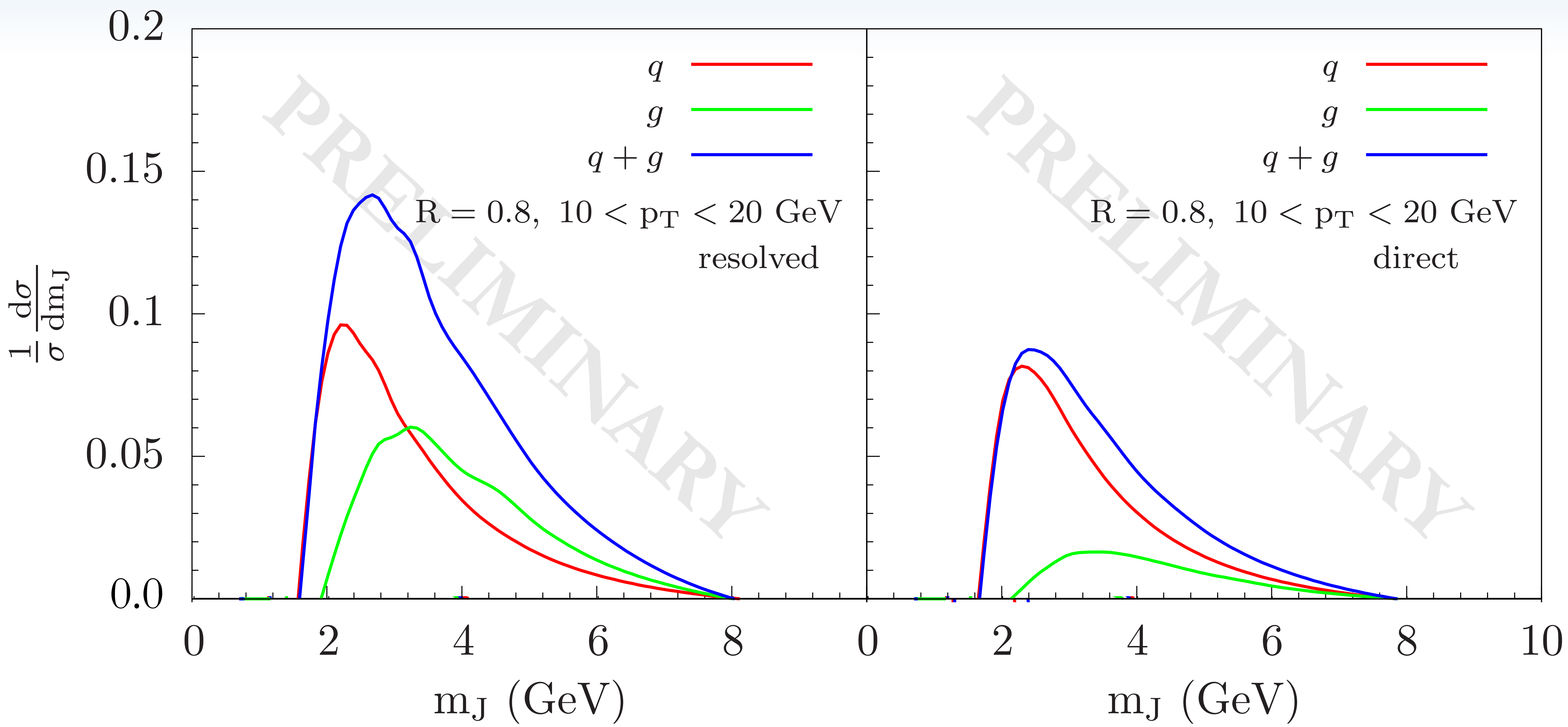


$$\tau_0^{pp} = \frac{m_J^2}{p_T^2} + \mathcal{O}((\tau_0^{pp})^2)$$

- **Mass effects: important challenge and opportunity**

In collaboration with Elke Aschenauer and Brian Page

Preliminary Plots



- **Fraction of gluon contribution is reduced for the direct process relative to the resolved process.**

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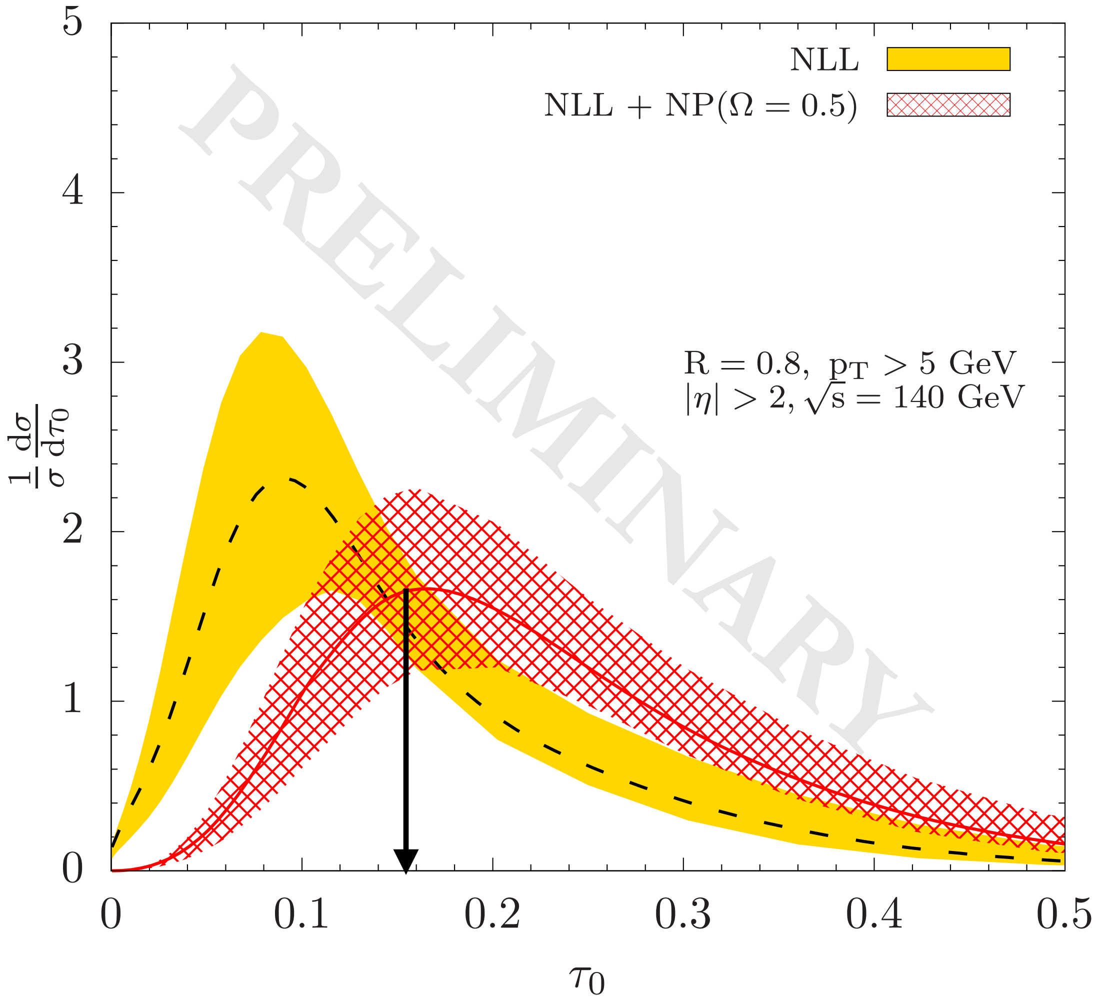
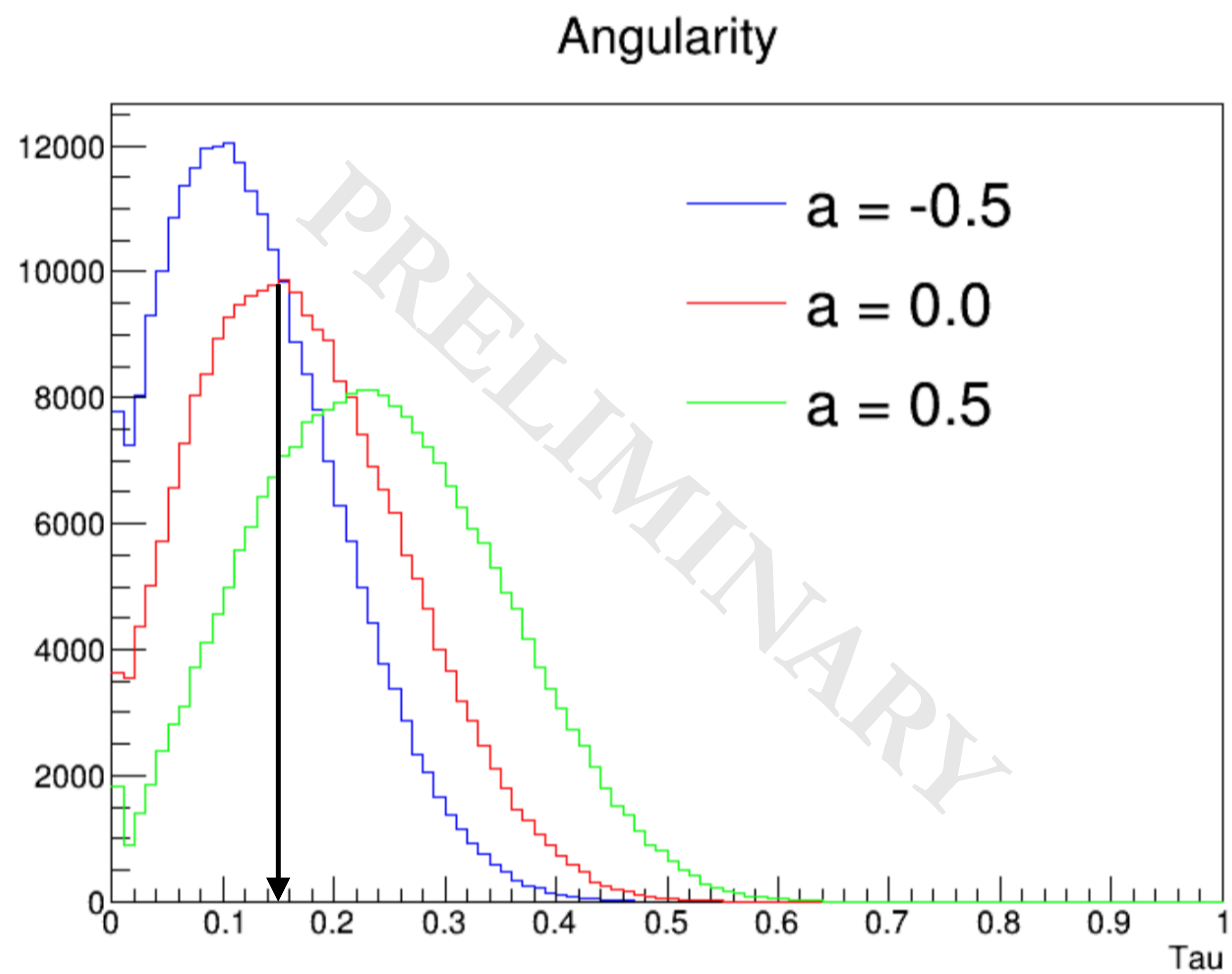
Preliminary Plots





- **Monte Carlo**

- $\Omega_\kappa = 0.5$ GeV**, assumption that NP effects only come from the hadronization gives the right peak value** $\Longrightarrow$ **less contamination from UE than LHC**

In collaboration with Elke Aschenauer and Brian Page

Conclusions

- Formalisms for studying semi-inclusive jet production with and without a substructure measurement were introduced.

- Discussed phenomenology of jet mass in the LHC.

- Discussed various non-perturbative effects.

- Jets have tremendous success at the LHC, interesting opportunities and new challenges at the EIC:

  power corrections, reduced contaminations, constraining unpolarized and polarized pdfs.