Jet physics at the EIC and medium modifications

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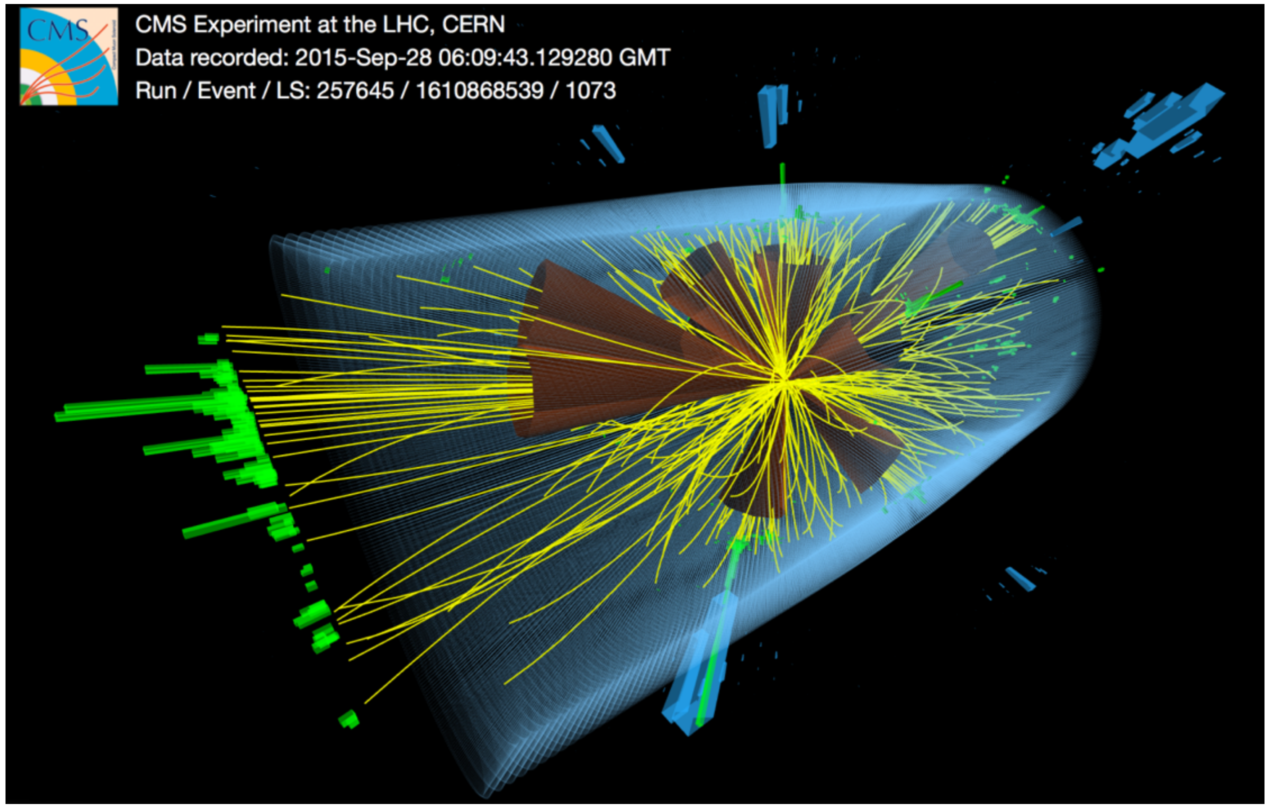
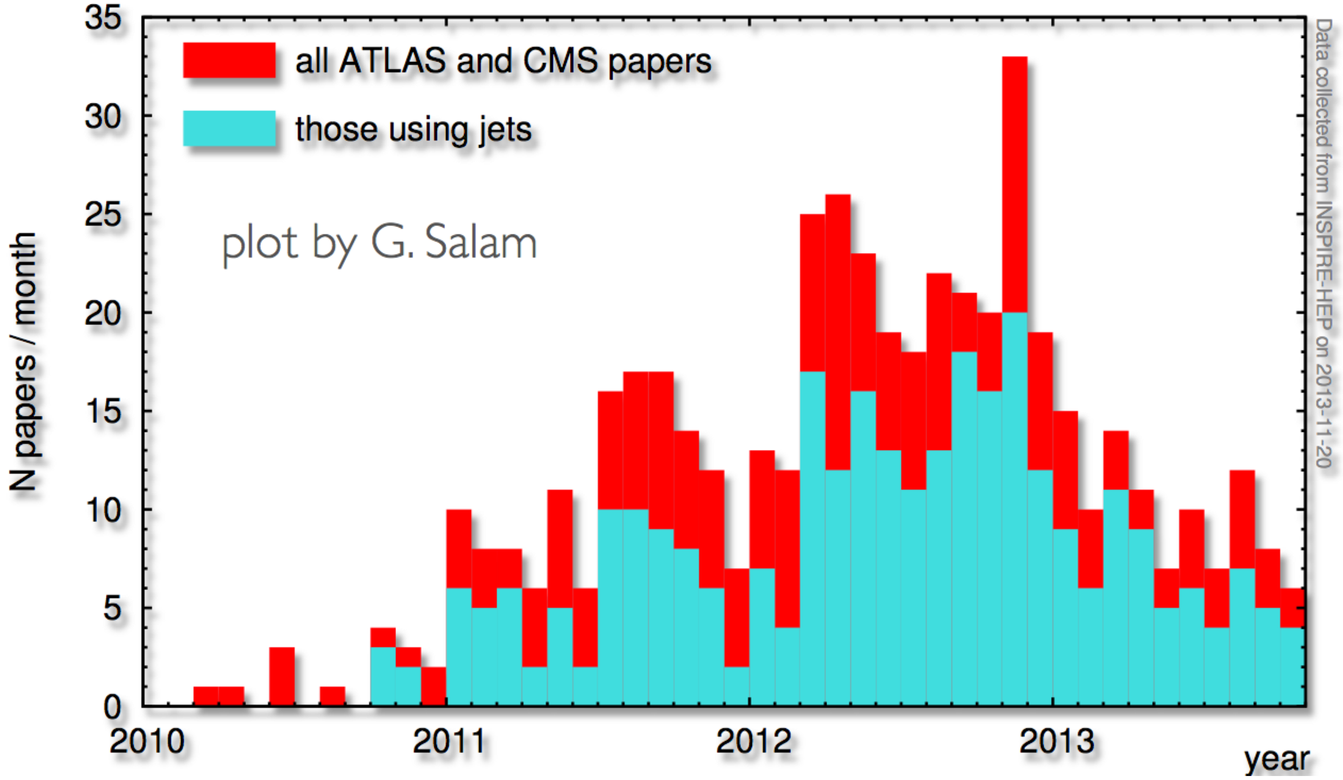
Stony Brook University

INT 2018 week 7
11/12/18 - 11/16/18

Jets at the LHC

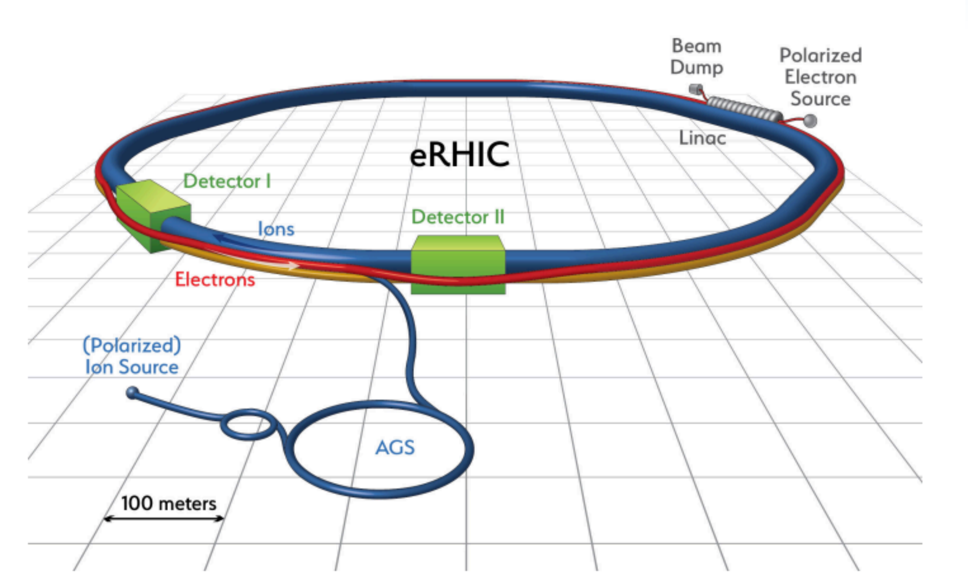


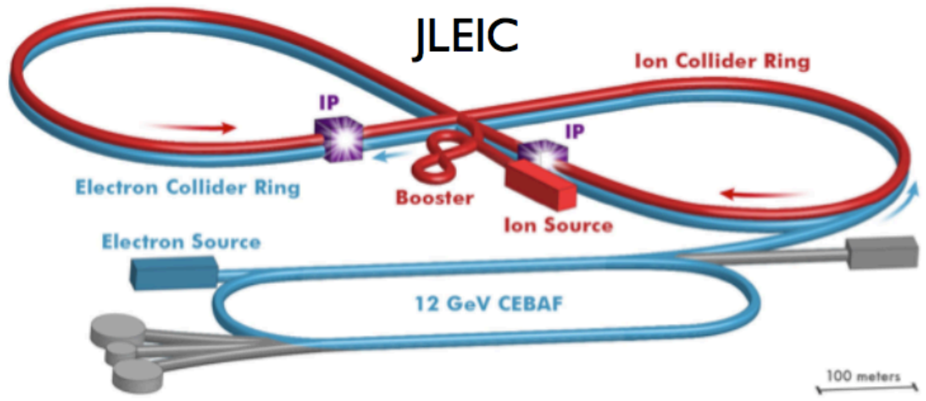


- Jets are produced copiously at the LHC

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

Jets at the EIC

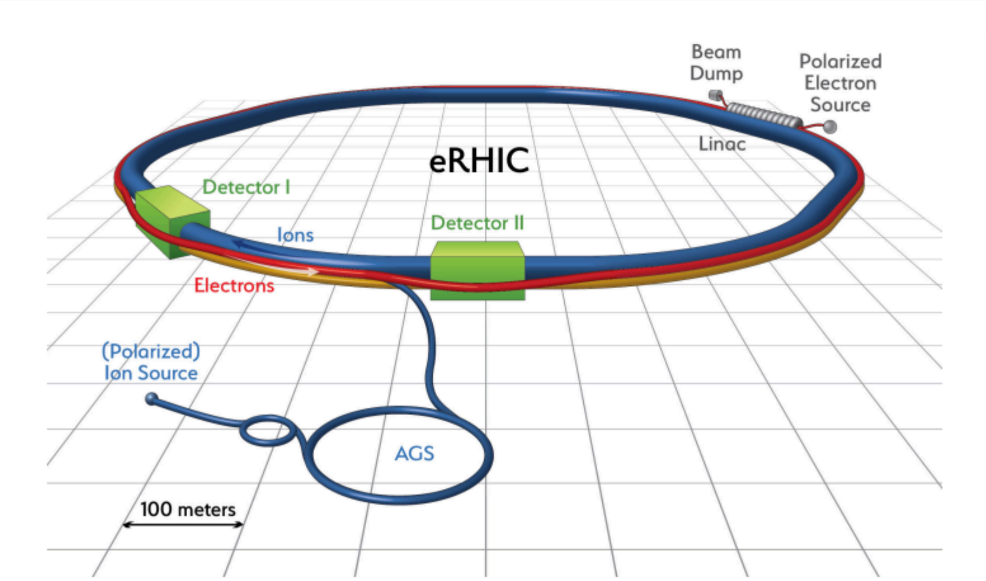


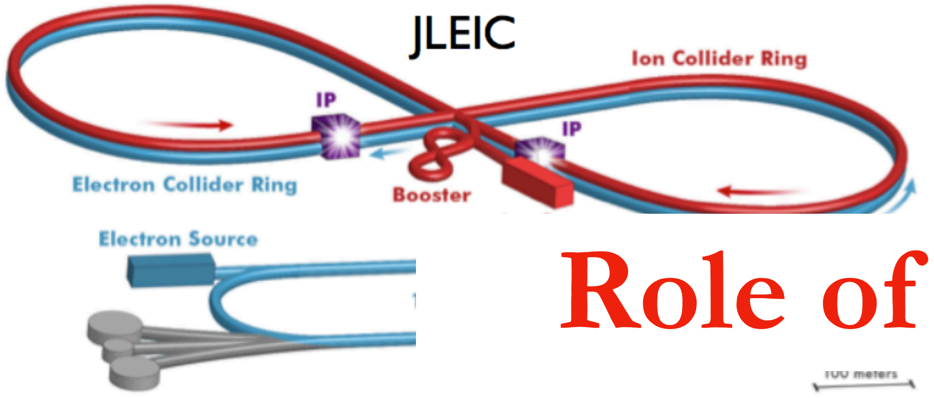


- $\sqrt{S_{\mathrm{EIC}}} \ll \sqrt{S_{\mathrm{LHC}}} \Leftrightarrow \sqrt{p_{T_J,\mathrm{EIC}}} \ll \sqrt{p_{T_J,\mathrm{LHC}}}$
  Lower $p_{T,J}$ for EIC
- $N_{J,EIC} \ll N_{J,LHC}$
  Smaller jet multiplicity for EIC
- Less contamination from underlying events and pileups

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

Jets at the EIC





- $\sqrt{S_{\rm EIC}} \ll \sqrt{S_{\rm LHC}} \Leftrightarrow \sqrt{p_{T_J,\rm EIC}} \ll \sqrt{p_{T_J,\rm LHC}}$
  Lower $p_{T,J}$ for EIC
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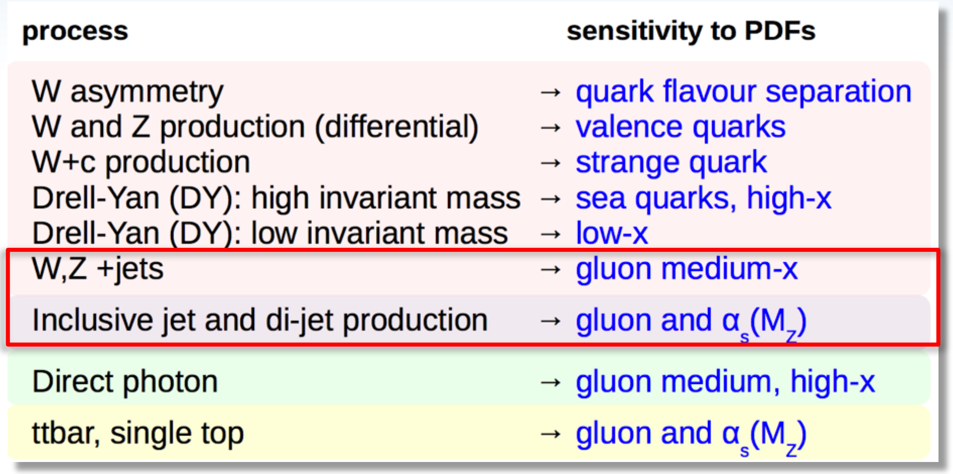
Role of higher power corrections?

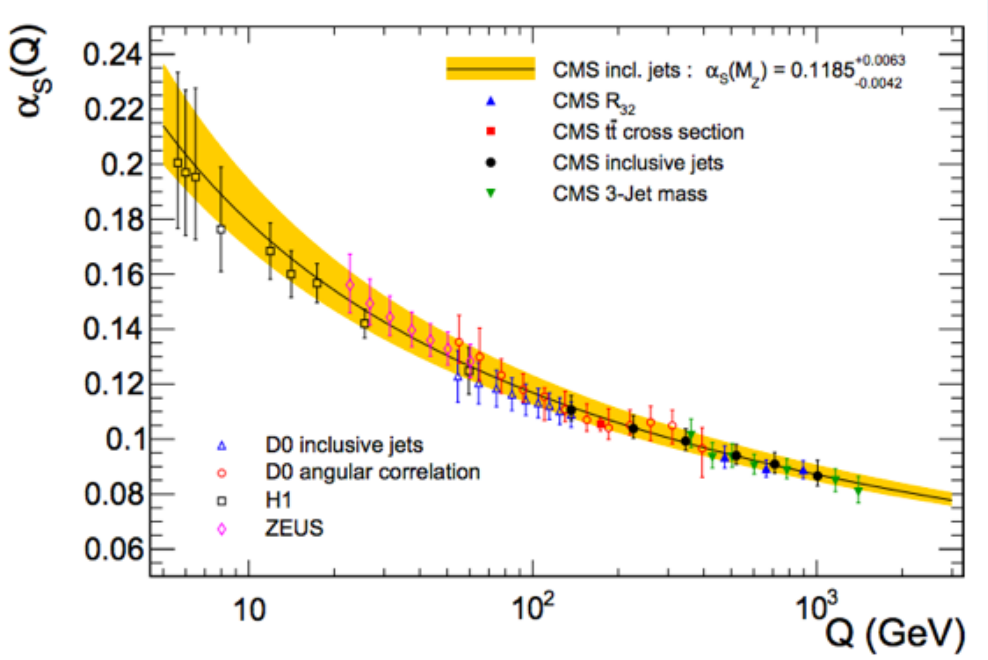
- **Different circumstances compared with the LHC and New opportunities**

Application of jet studies at the LHC

- **Precision probe of QCD**



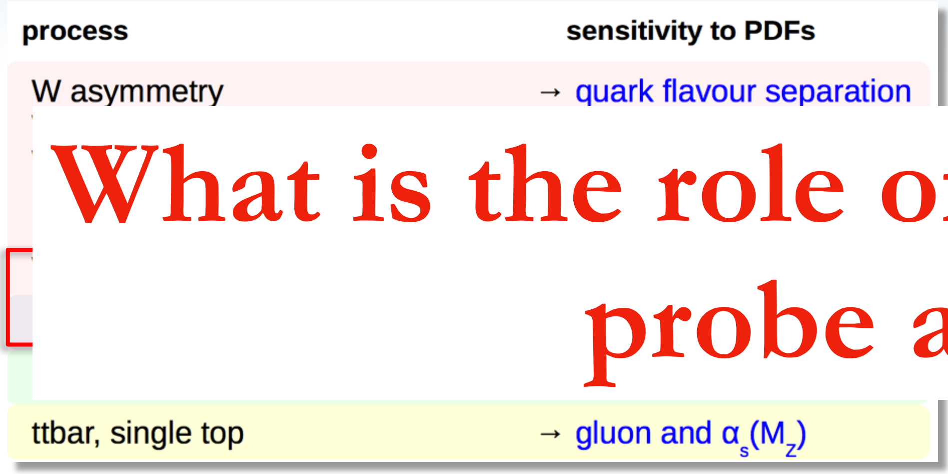
process	sensitivity to PDFs
W asymmetry	→ quark flavour separation
W and Z production (differential)	→ valence quarks
W+c production	→ strange quark
Drell-Yan (DY): high invariant mass	→ sea quarks, high-x
Drell-Yan (DY): low invariant mass	→ low-x
W,Z +jets	→ gluon medium-x
Inclusive jet and di-jet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

Application of jet studies at the LHC

- **Precision probe of QCD**



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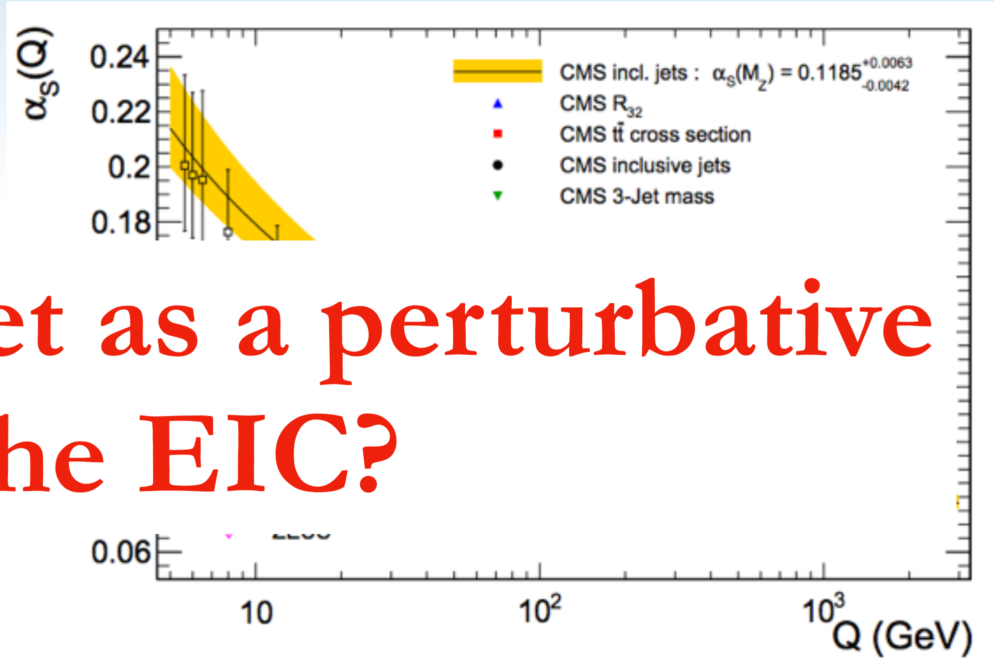
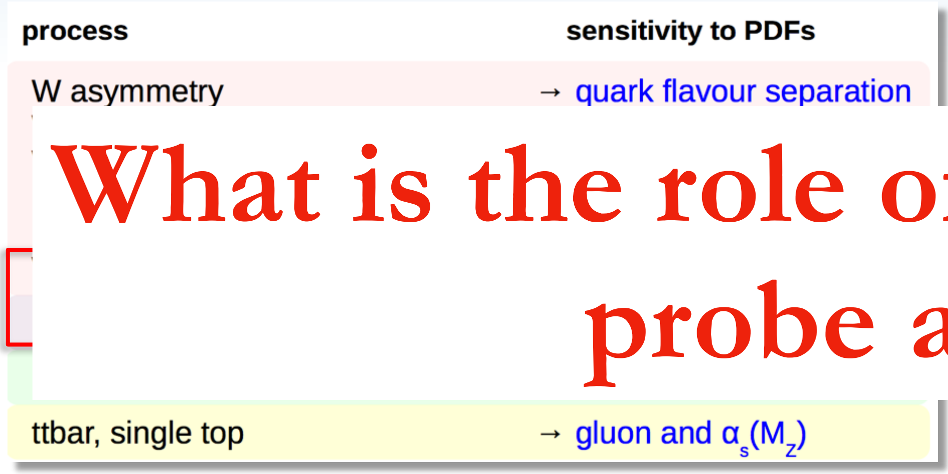


What is the role of jet as a perturbative probe at the EIC?

Inclusive jets - perturbative probe

Application of jet studies at the LHC

- Precision probe of QCD



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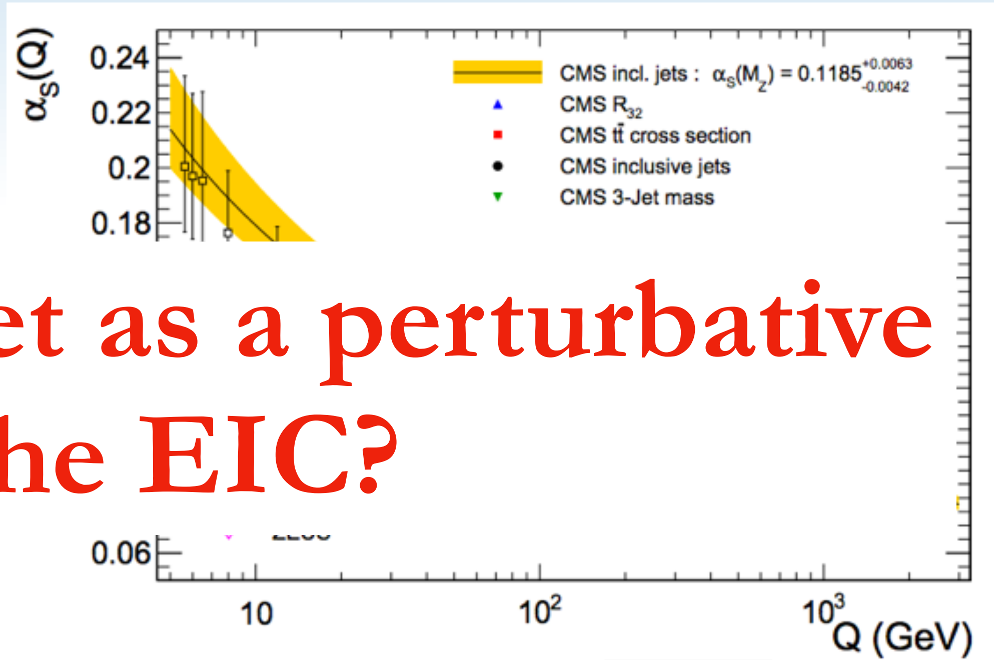
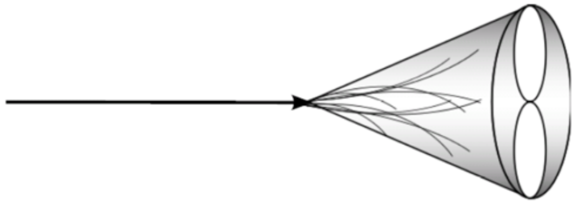
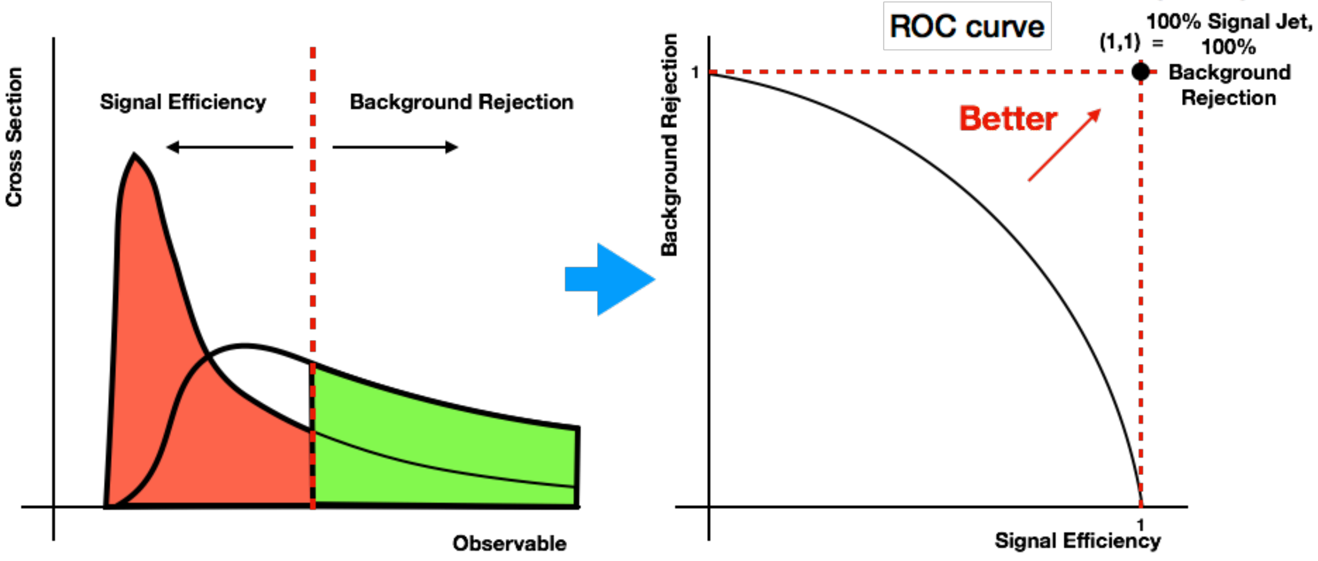


What is the role of jet as a perturbative probe at the EIC?

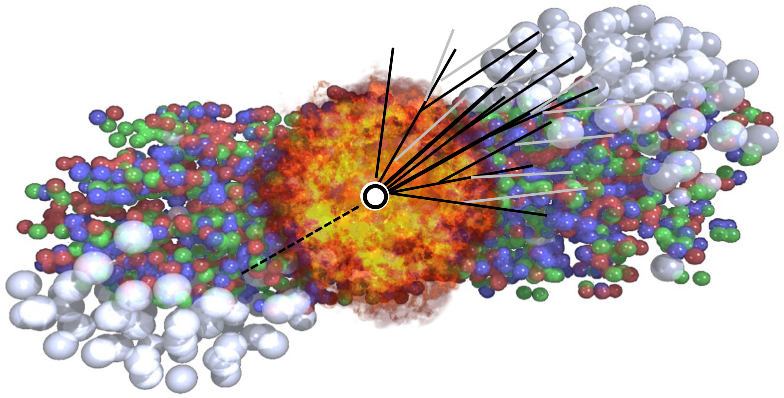
- Constrain BSM Models



Fat jet from BSM signal

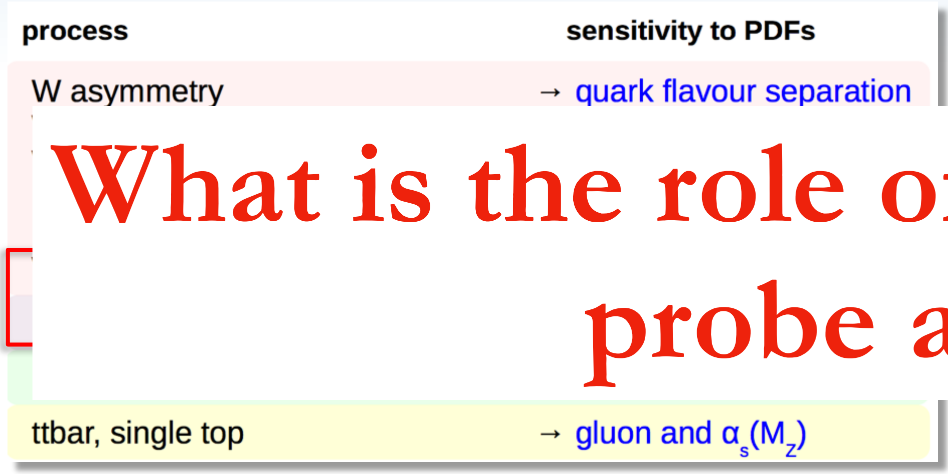


- Probe of quark gluon plasma



Application of jet studies at the LHC

- Precision probe of QCD



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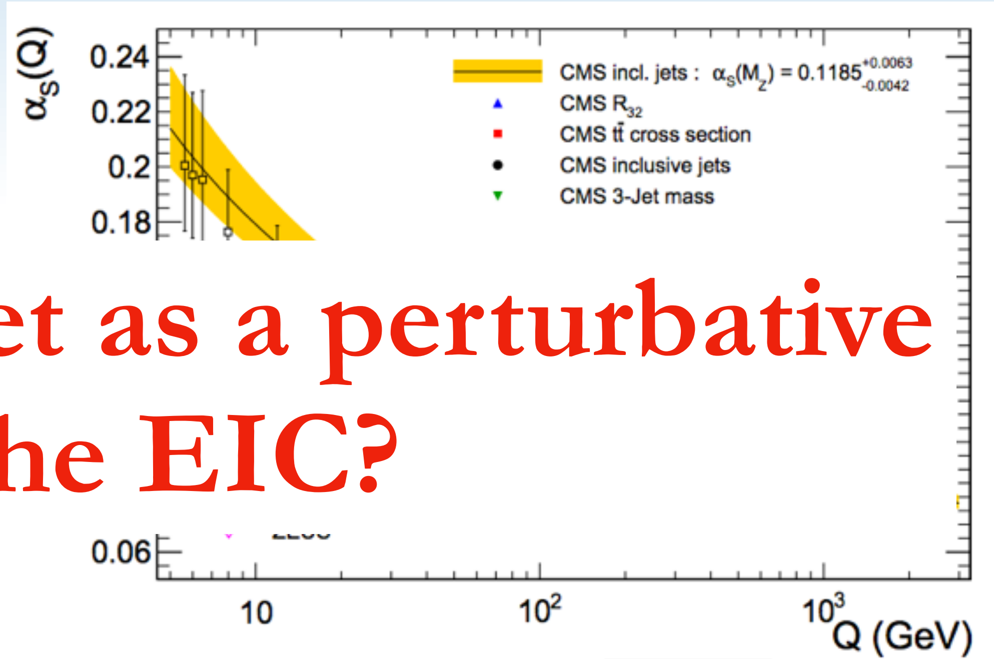

What is the role of jet as a perturbative probe at the EIC?

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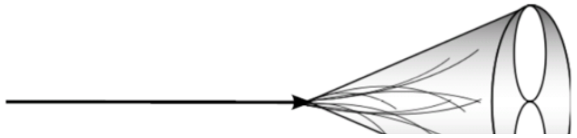
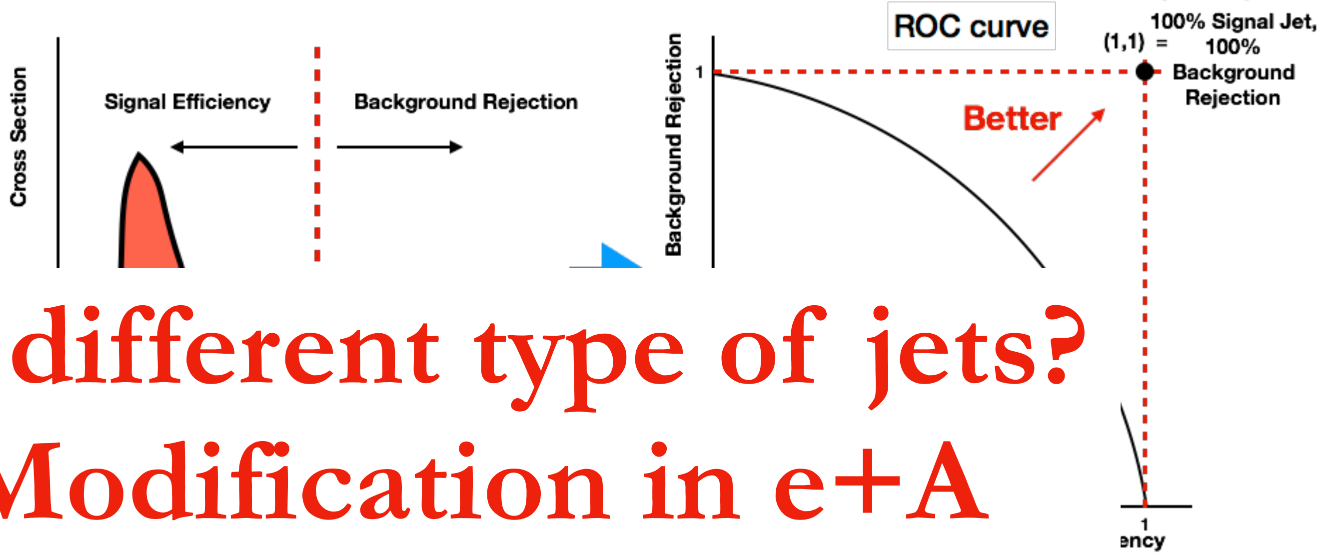
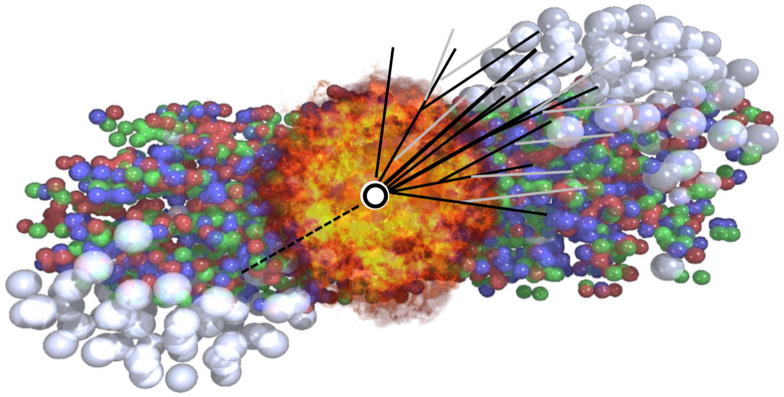




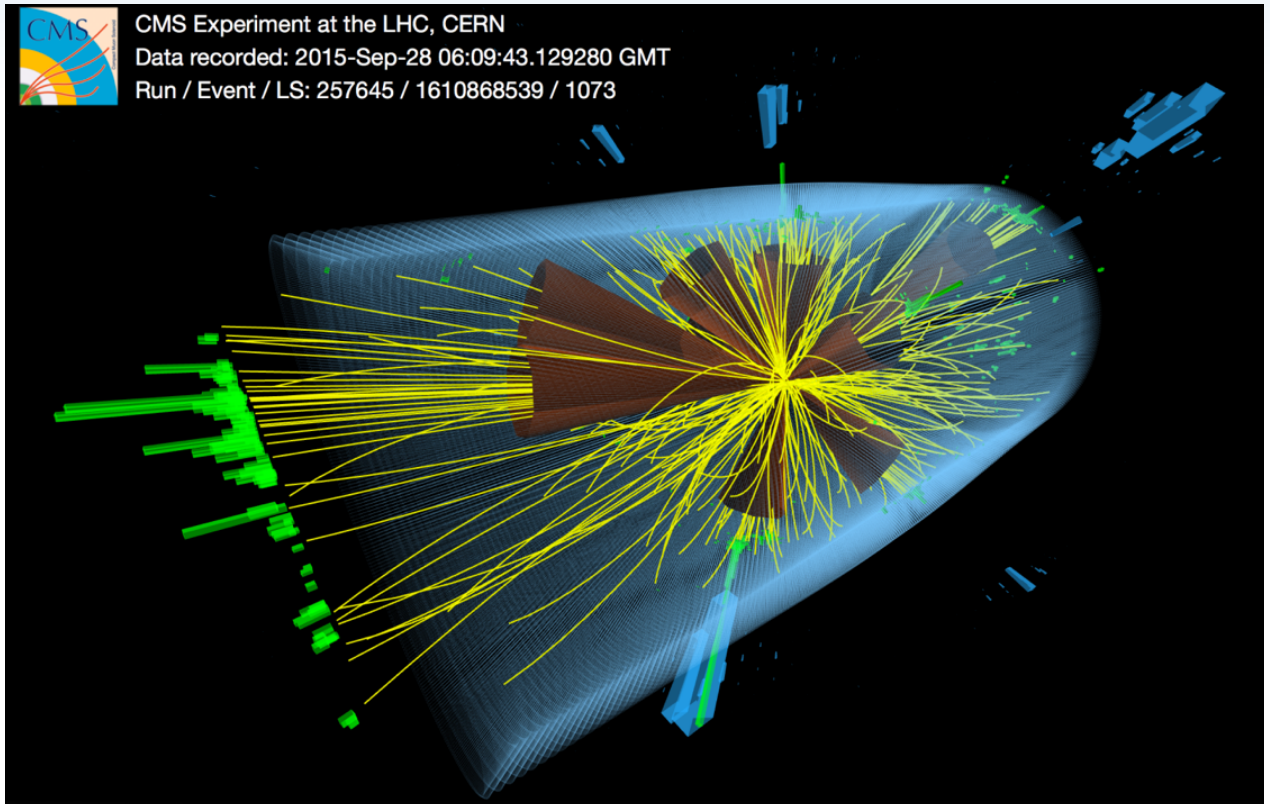
Classification of different type of jets?

Cold Nuclear Modification in e+A

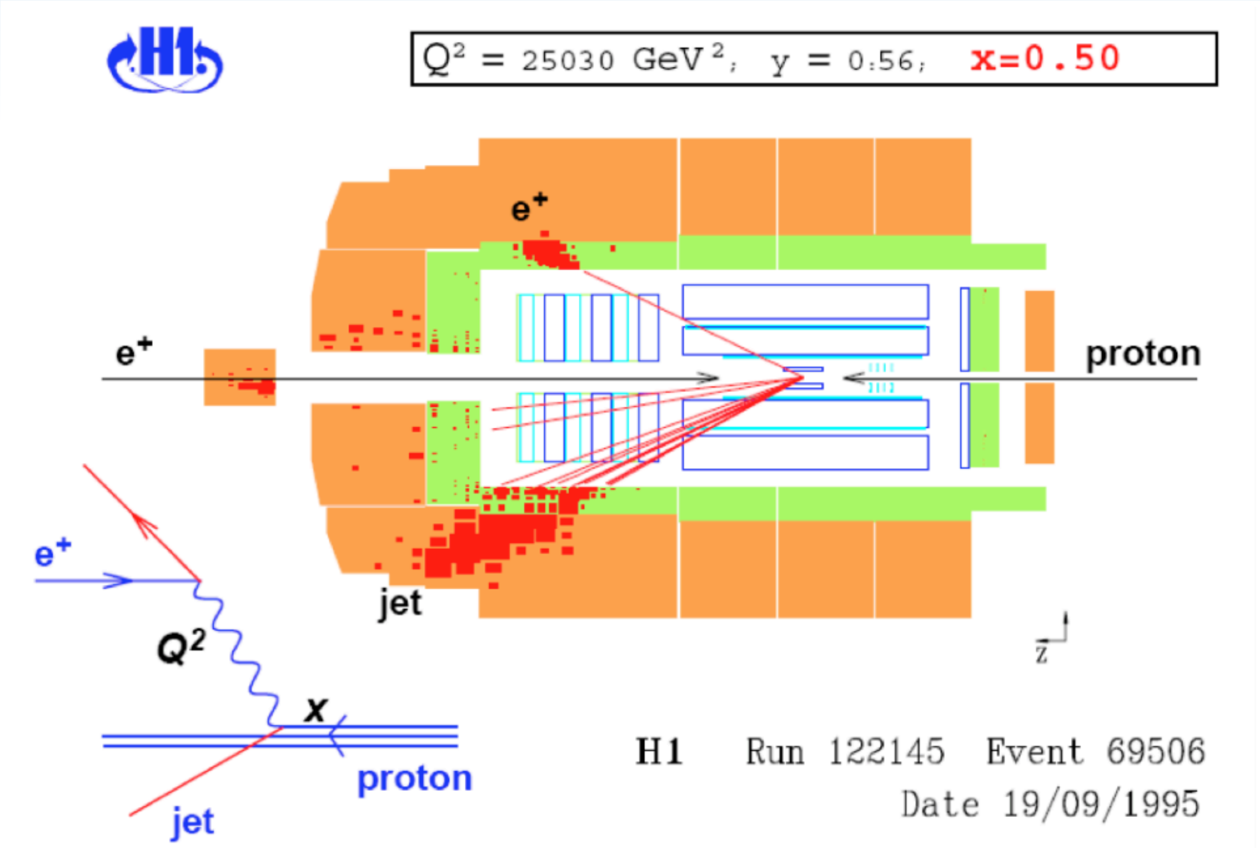
- Probe of quark gluon plasma



Application of jet studies at the LHC



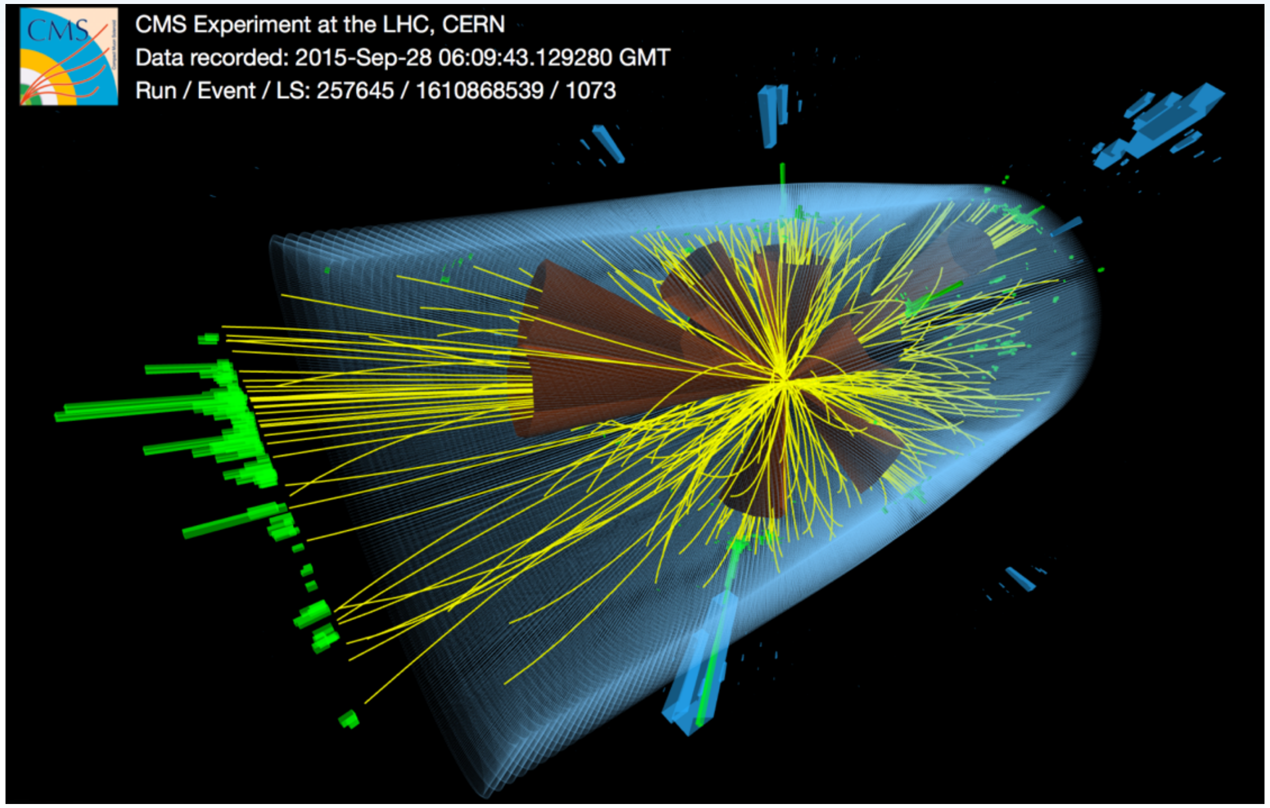
LHC



HERA

- Typical event at the LHC and HERA

Application of jet studies at the LHC



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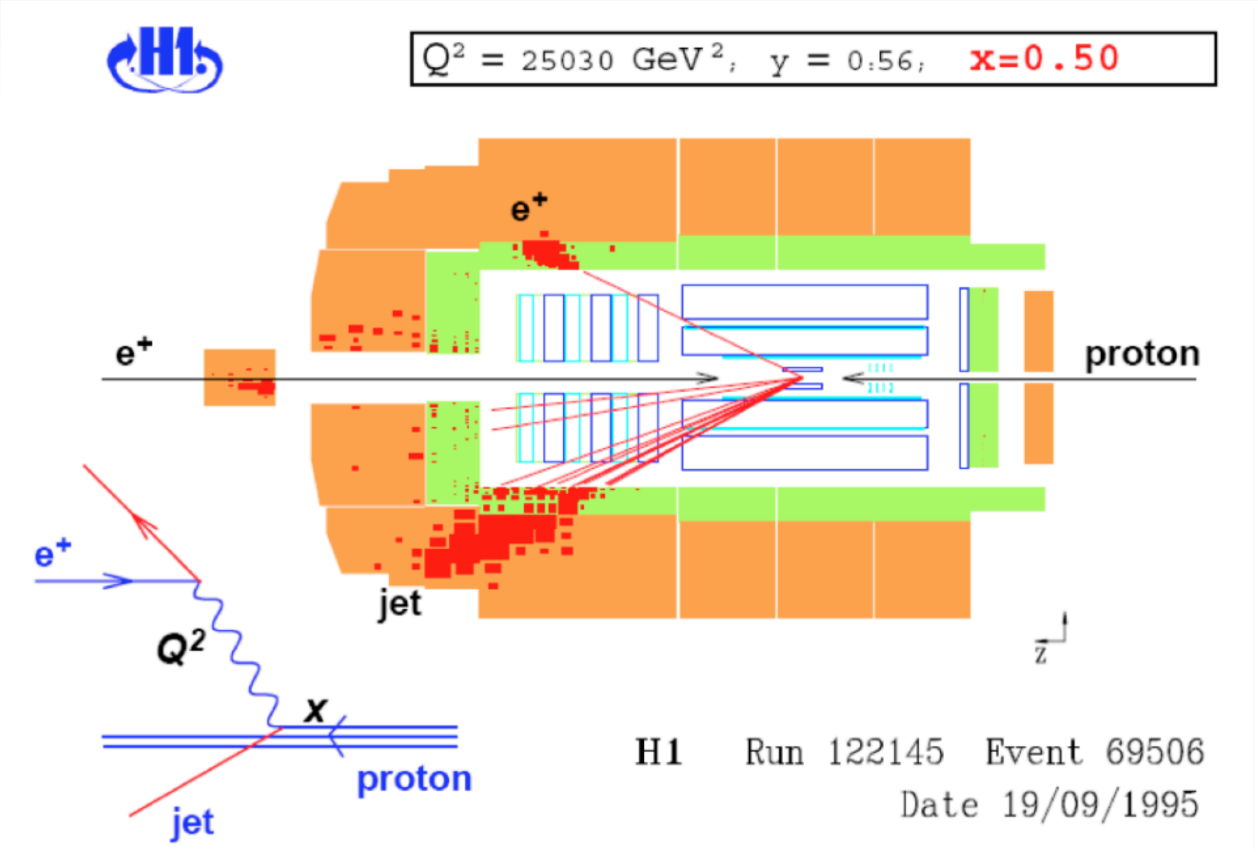


HERA

- Typical event at the LHC and HERA

What is the role of NP physics at the EIC?

Plans of this talk

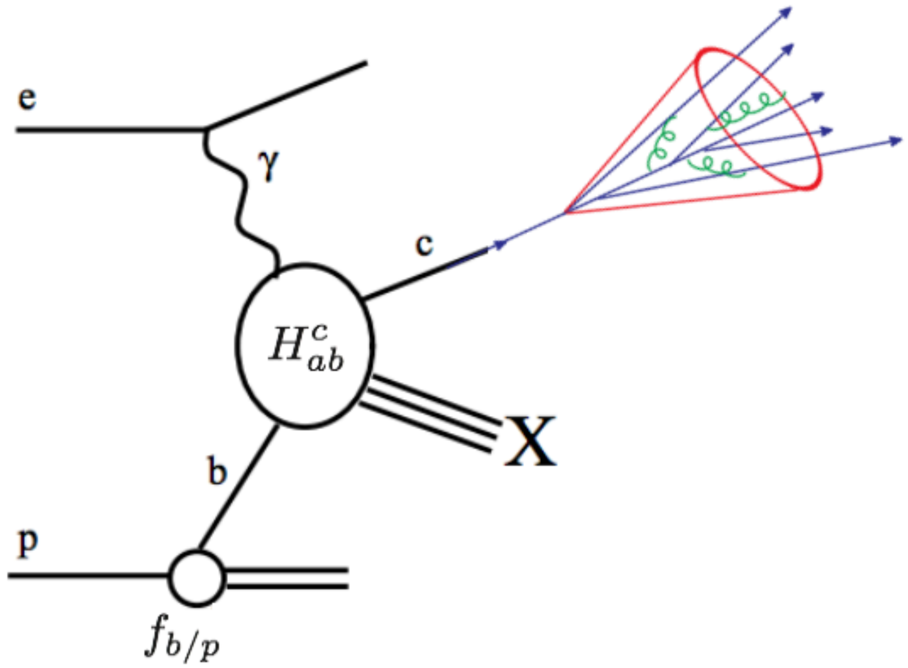
- **Inclusive jets**
- **Jet substructure measurements at the LHC**
- **Subtracted moments**
- **Conclusions**

Inclusive Jets

- $ep \to \text{jet} + X,$ **final lepton unobserved, high p_T**

  Boughezal, Petriello, Xing `18,
  Hinderer, Schlegel, Vogelsang `18,
  Uebler, Schfer, Vogelsang `17,
  Abelof, Boughezal, Liu, Petriello, `16

- $ep \to e + \text{jet} + X,$ **DIS, high p_T and Q^2**



- $ep \to e + \text{jet} + X,$ **photoproduction, high p_T and $Q^2 < 1\ \text{GeV}^2$**

Inclusive Jets

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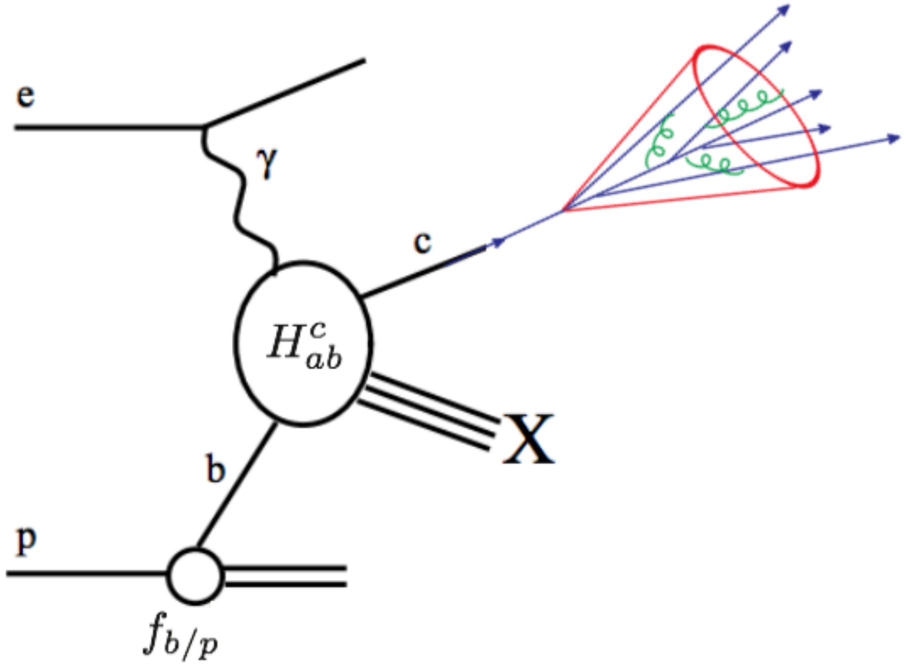
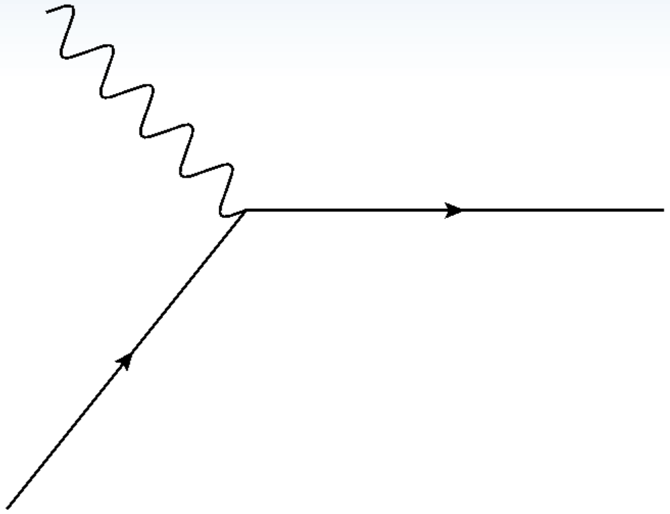


- $ep \to e + \text{jet} + X,$ **photoproduction, high p_T and $Q^2 < 1\ \text{GeV}^2$**

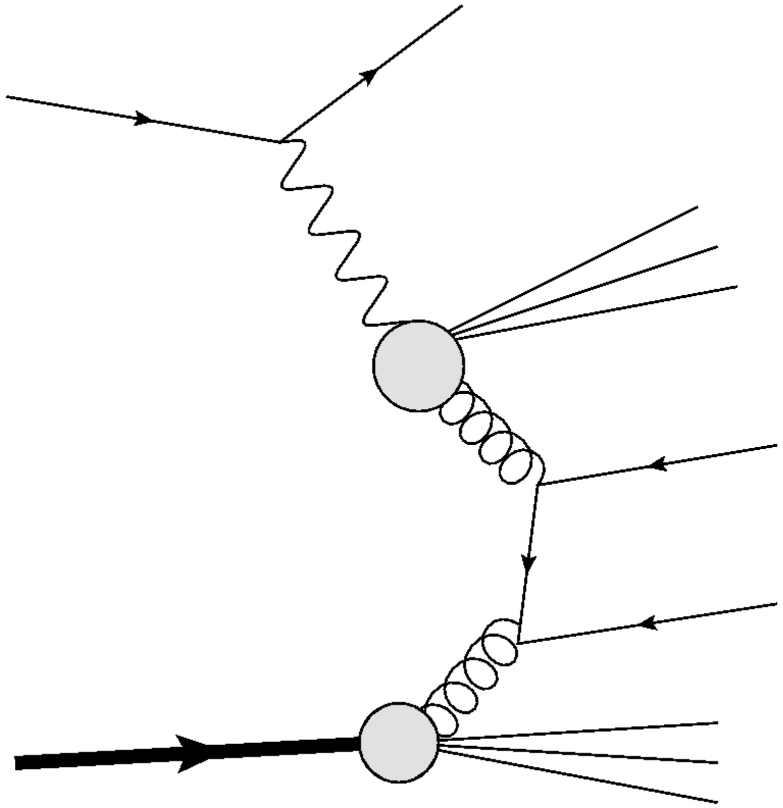
We focus on the photoproduction

Relevant Subprocesses

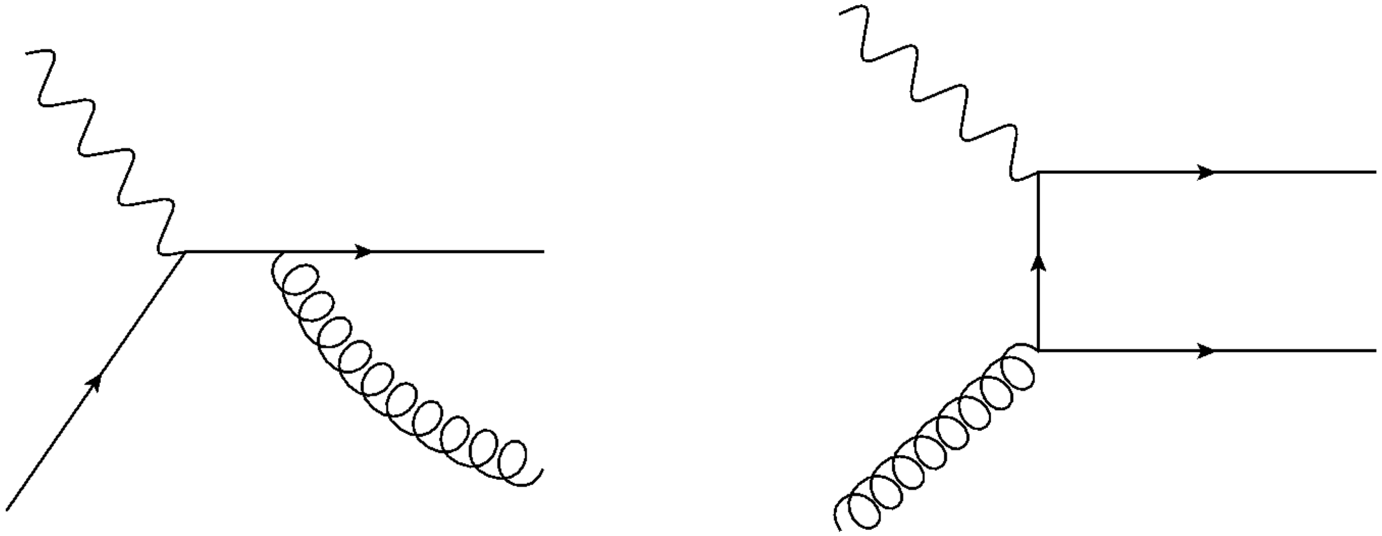
LO DIS



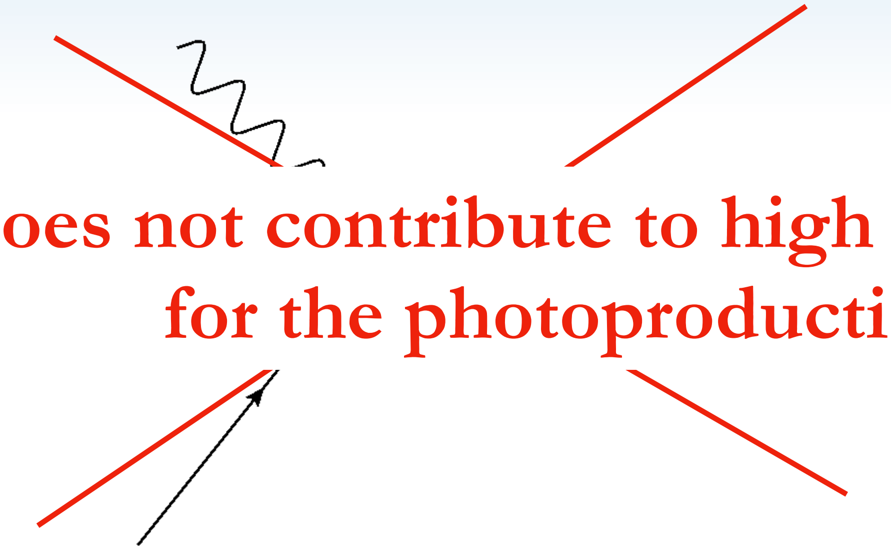
Resolved



Direct

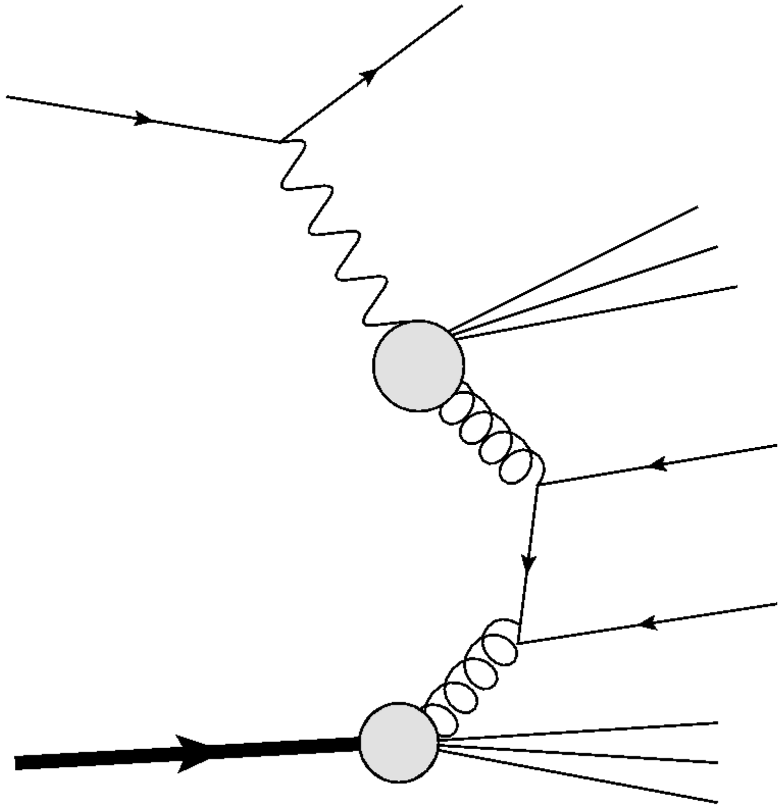


Relevant Subprocesses



LO DIS does not contribute to high pT jet production for the photoproduction.

Resolved



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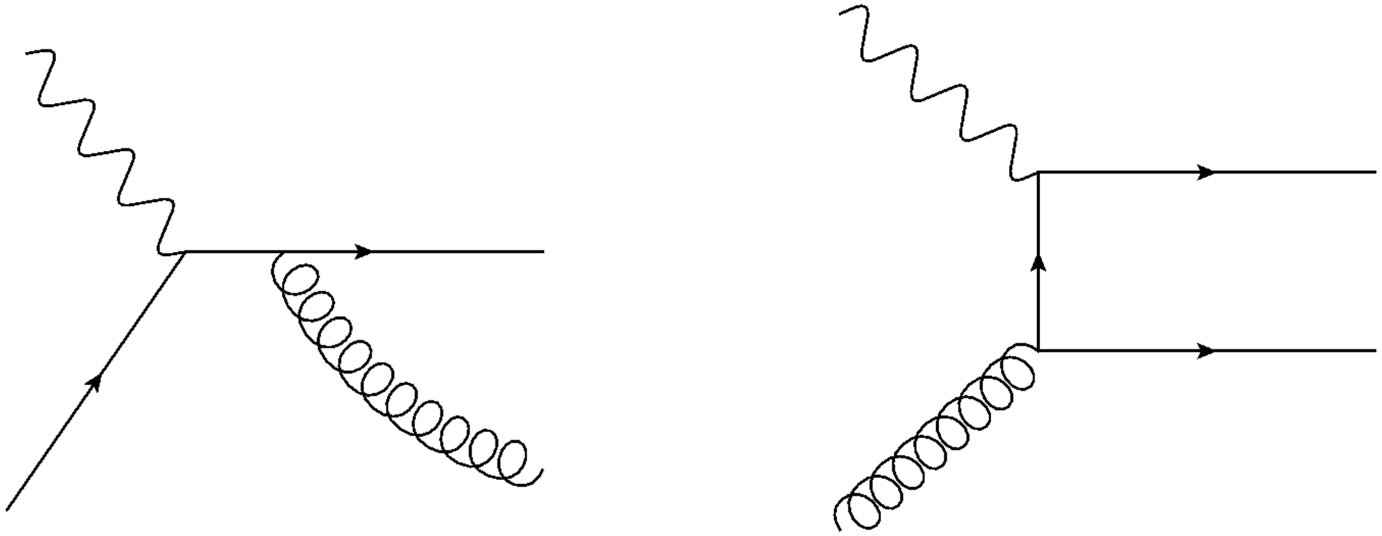
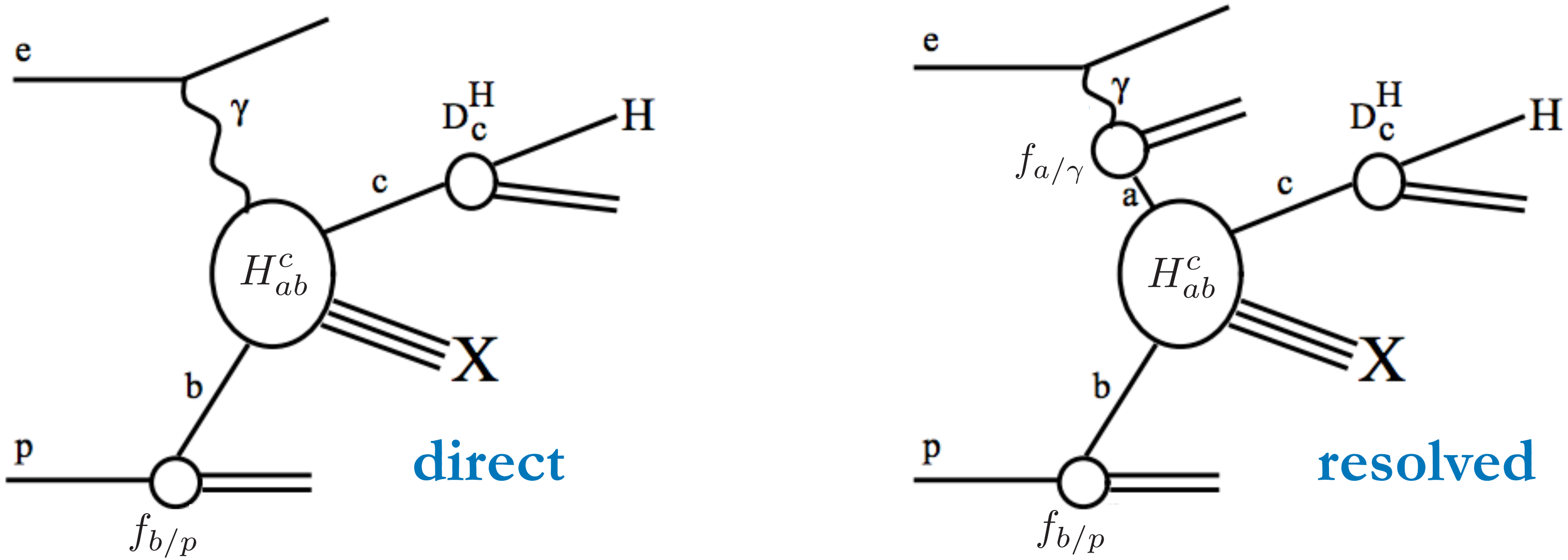


Photoproduction at the EIC



For polarized case,

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

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

Weizsäcker-Williams spectrum

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

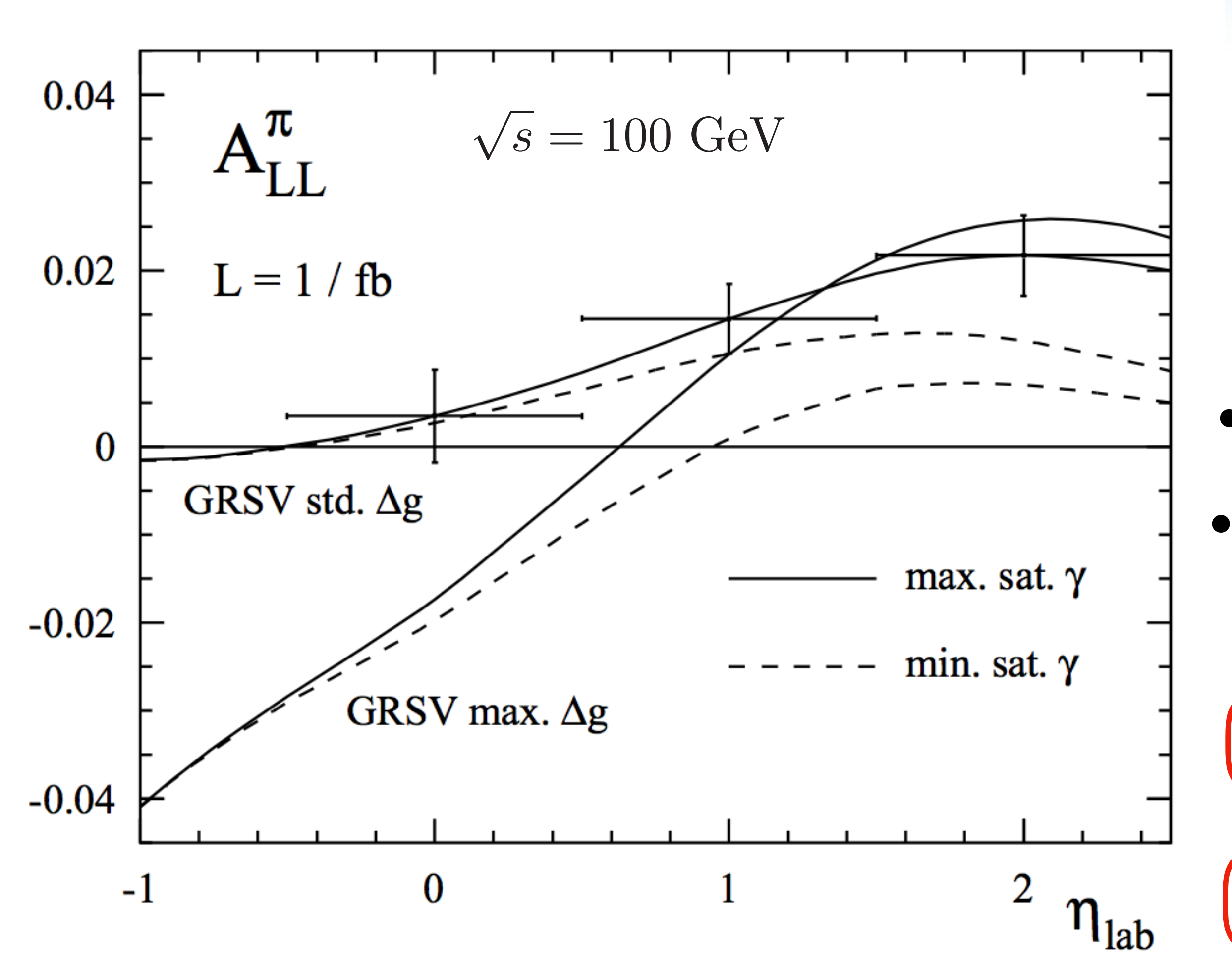
- For the direct process, $f_{a/\gamma} = \delta(1 - x_\gamma)$.
- Observe outgoing lepton to tag Q^2
- Require high p_T and $Q^2 < 1\ \text{GeV}^2$ (near on-shell photon)

See Jäger, Stratmann, Vogelsang `03

Polarized Gluon and Photon PDF

Study in 2003,

Jäger, Stratmann, Vogelsang `03



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

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

- 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.

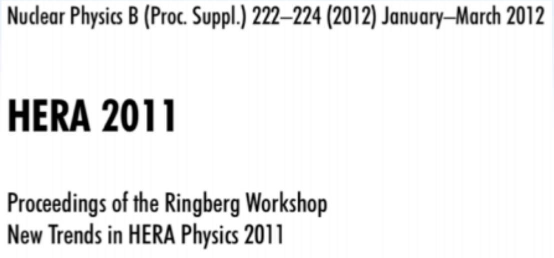
Use inclusive jets as a perturbative probe!

- 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

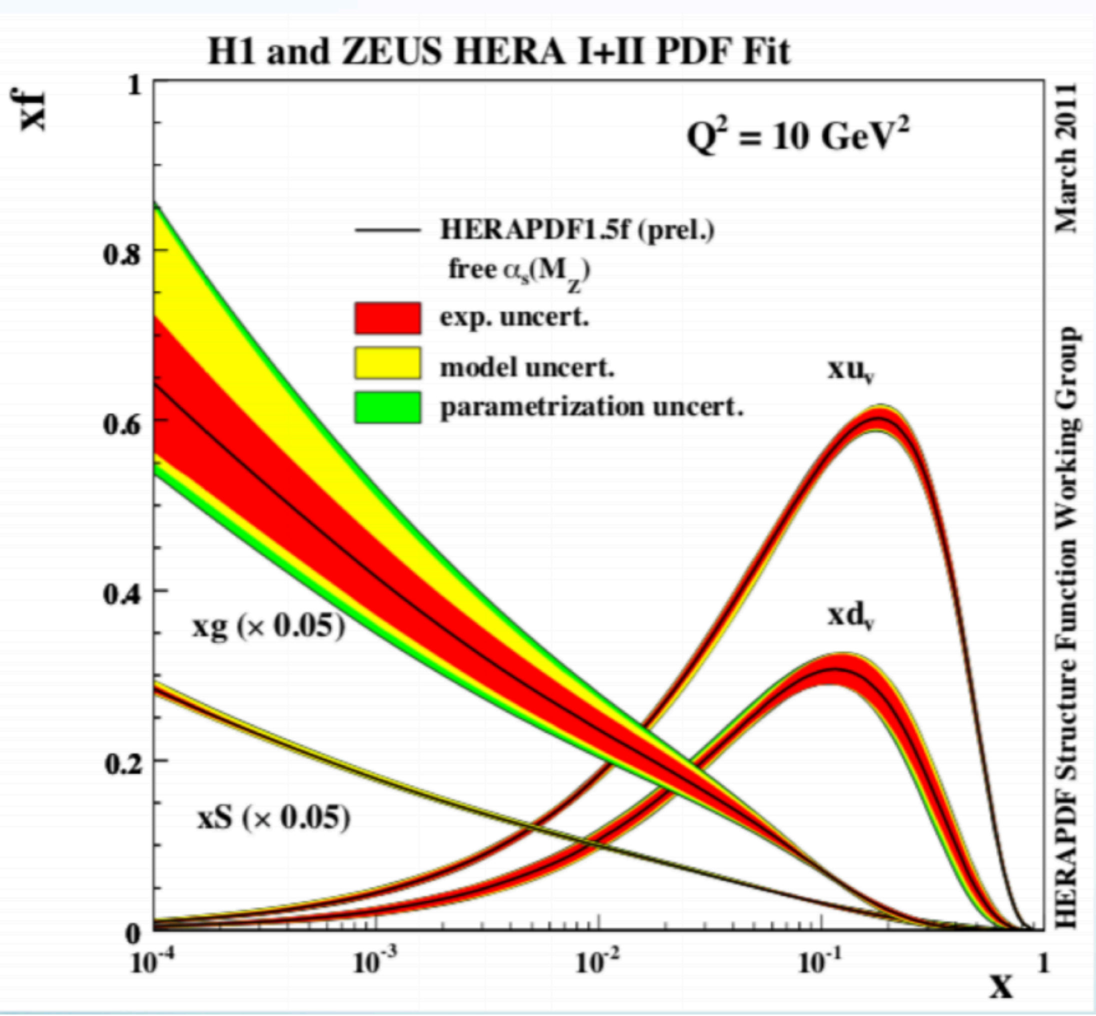
- Important for constraining gluon PDF



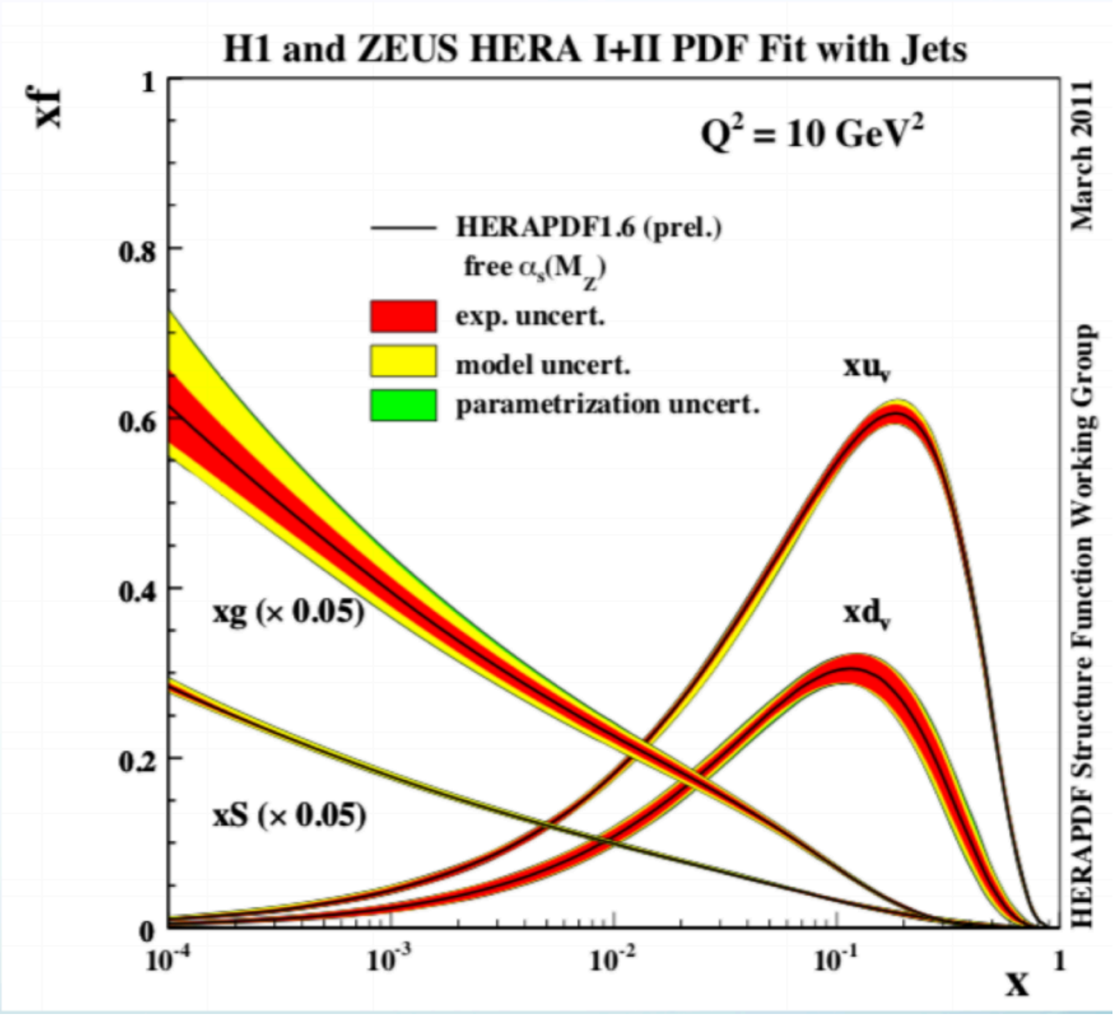
Nuclear Physics B (Proc. Suppl.) 222–224 (2012) January–March 2012

HERA 2011

Proceedings of the Ringberg Workshop
New Trends in HERA Physics 2011



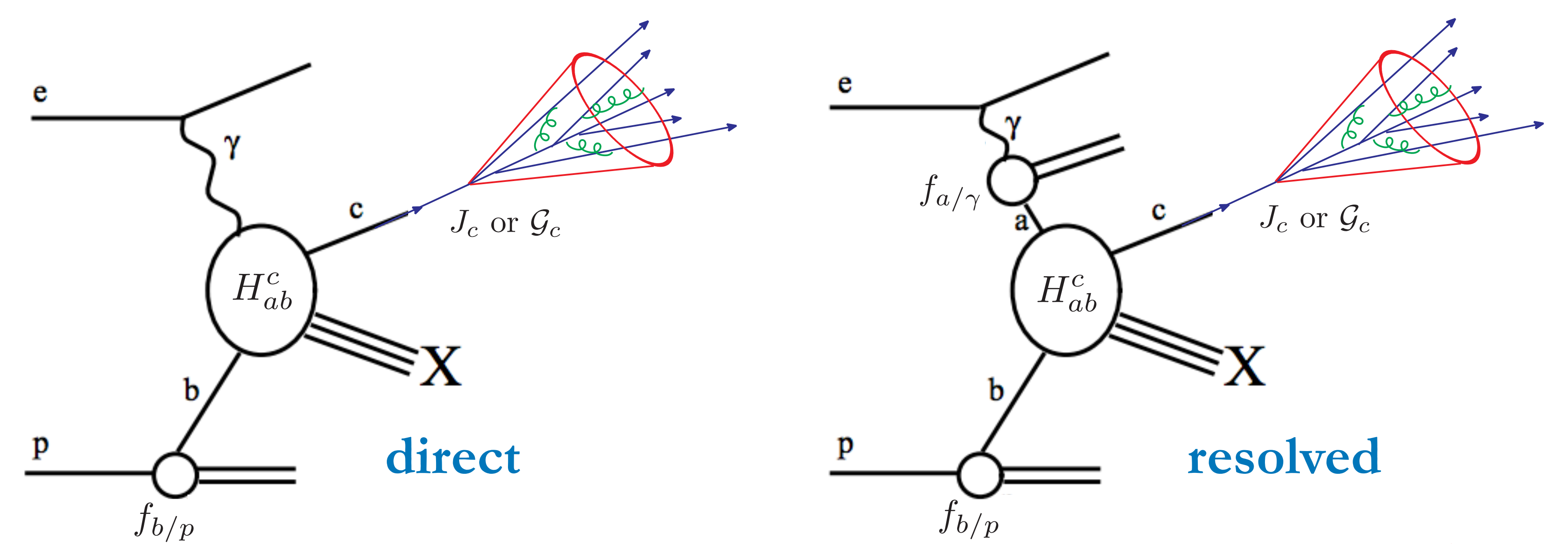
Without jets



With jets

Role as a perturbative probe

Photoproduction at the EIC



For polarized case,

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

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Inclusive Jet $$\frac{d\sigma^{ep\to ejetX}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes J_c + \mathcal{O}(R^2) + \boxed{\mathcal{O}\left(\frac{\Lambda_{QCD}}{p_T R}\right)}$$

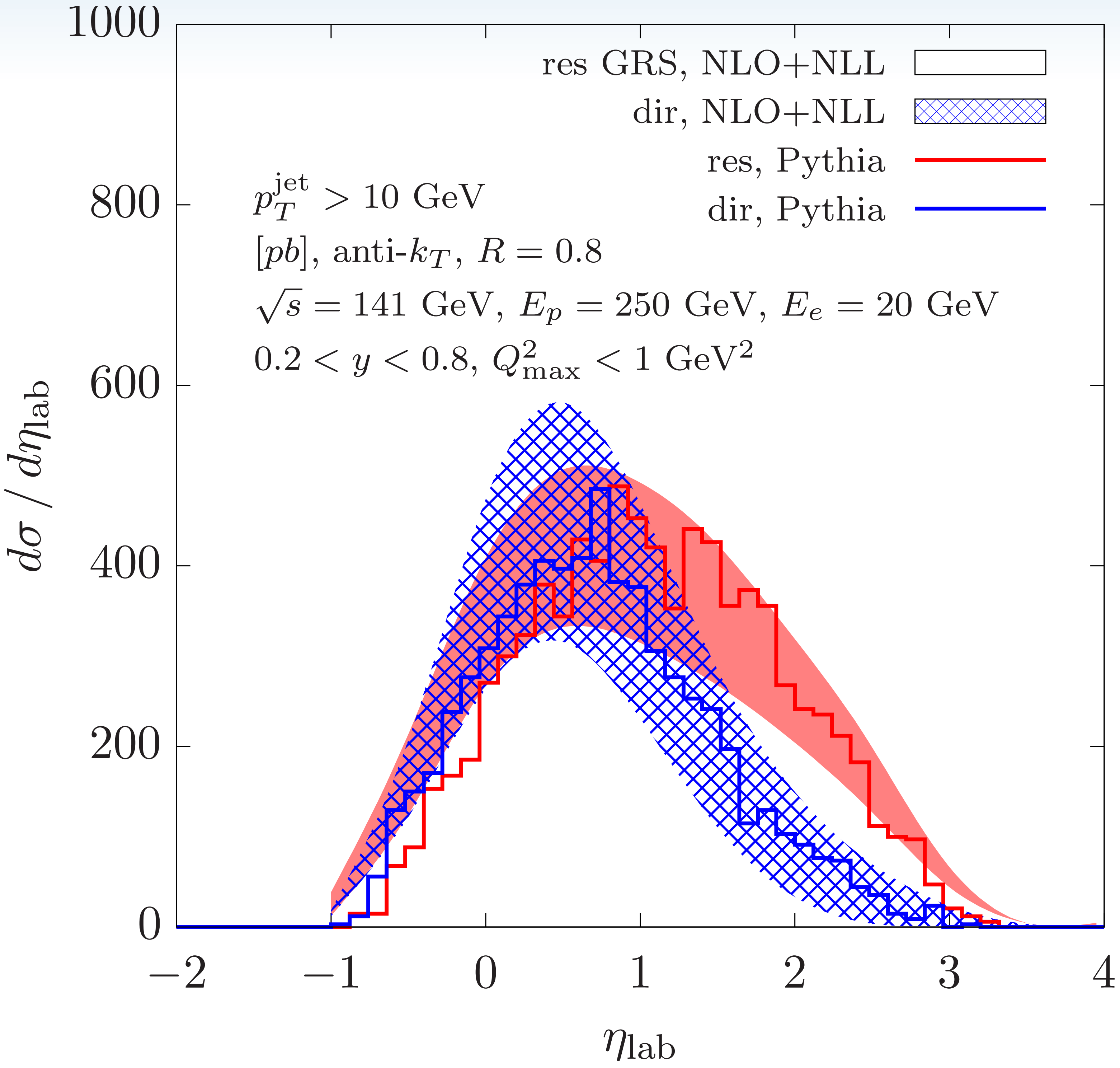
Power corrections relevant for EIC

- Replacement of the fragmentation function with the perturbative jet function.
- Sensitivity to the photon pdfs. Can be done for polarized and unpolarized case.
- Role of power corrections?

Role as a perturbative probe

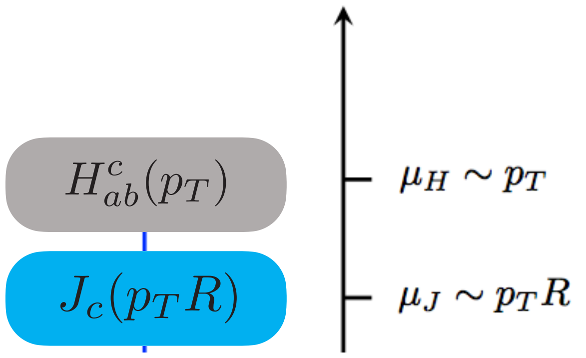
Jäger, Stratmann, Vogelsang `03
Chu, Aschenauer, Lee, Zheng `17
In collaboration with Elke Aschenauer and Brian Page

Unpolarized inclusive jets for photoproduction



- **At $p_T > 10$ GeV, we see a good agreement.**
- $\mathcal{O}(\frac{\Lambda_{QCD}}{p_T R})$ **power corrections must be studied.**

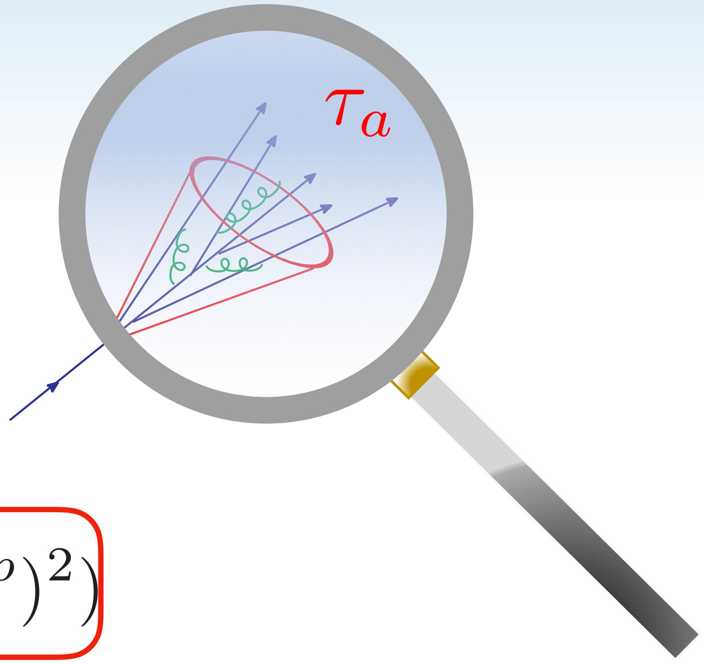
Power corrections



In collaboration with Elke Aschenauer and Brian Page

Jet angularity

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



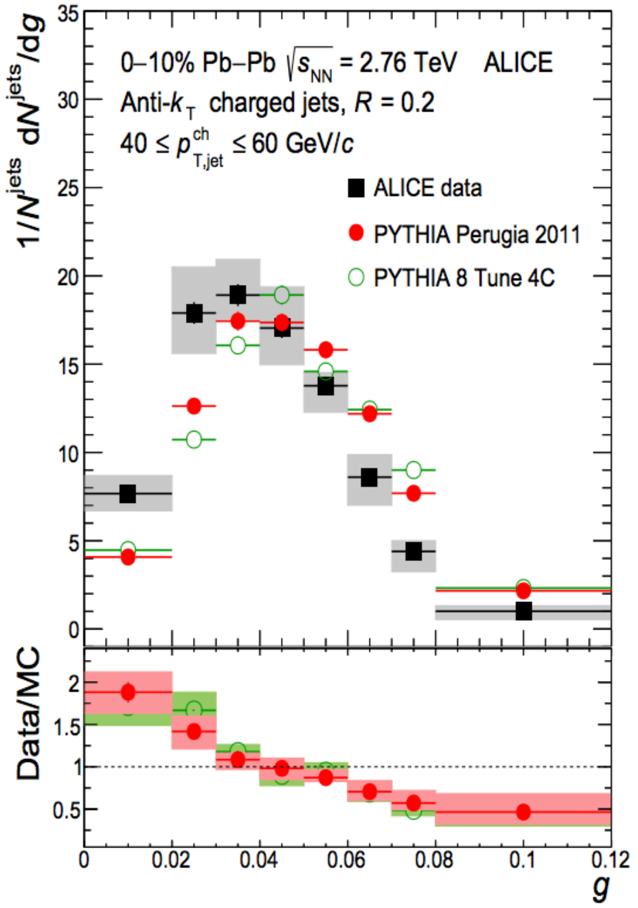
$$\tau_a^{e^+e^-} = \frac{1}{E_J}\sum_{i\in J} E_i\,\theta_{iJ}^{2-a}$$

More relevant for the EIC

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

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

Power corrections

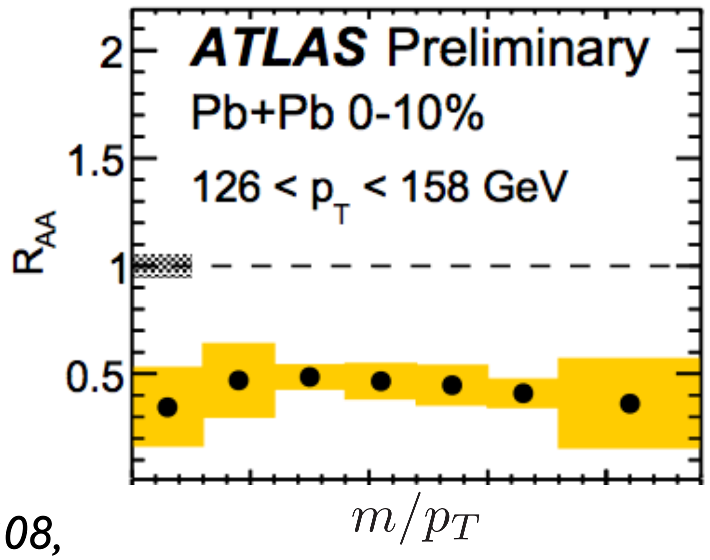


Medium modifications

$a = 1$

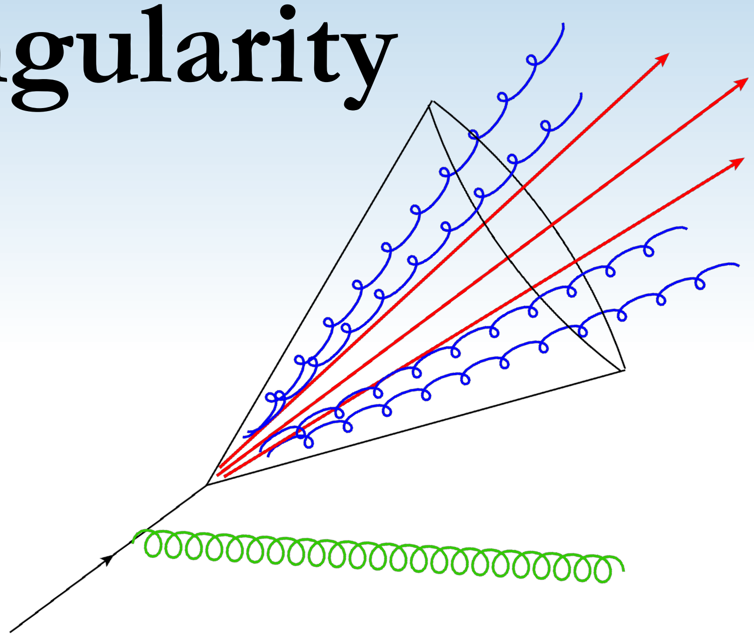
$$g(\text{girth}) = \frac{1}{p_T}\sum_{i\in J} p_{T,i}\,(\Delta R_{iJ})$$

$a = 0$



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, Kang, KL, Ringer `18

Factorization for jet angularity



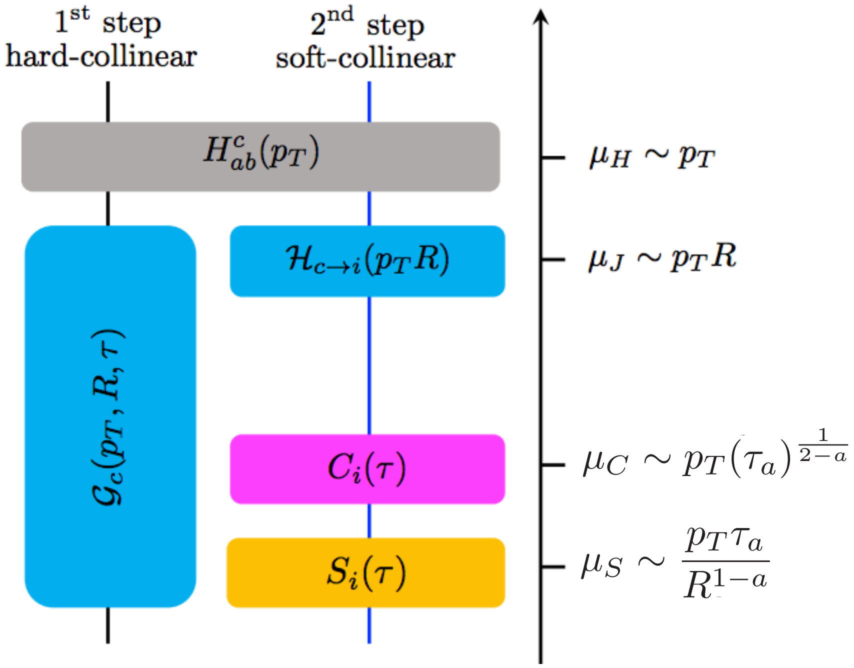
- Replace $J_c(z, p_T R, \mu) \to \mathcal{G}_c(z, p_T R, \tau_a, \mu)$
- When $\tau_a \ll R^2$, Refactorize $\mathcal{G}_c$ as

Power corrections

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

$$\times \int d\tau_a^{C_i} d\tau_a^{S_i} \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) C_i(\tau_a^{C_i}, p_T \tau_a^{\frac{1}{2-a}}, \mu) S_i\left(\tau_a^{S_i}, \frac{p_T \tau_a}{R^{1-a}}, \mu\right) \boxed{+\mathcal{O}\left(\frac{m^2}{p_T^2 R^2}\right)}$$

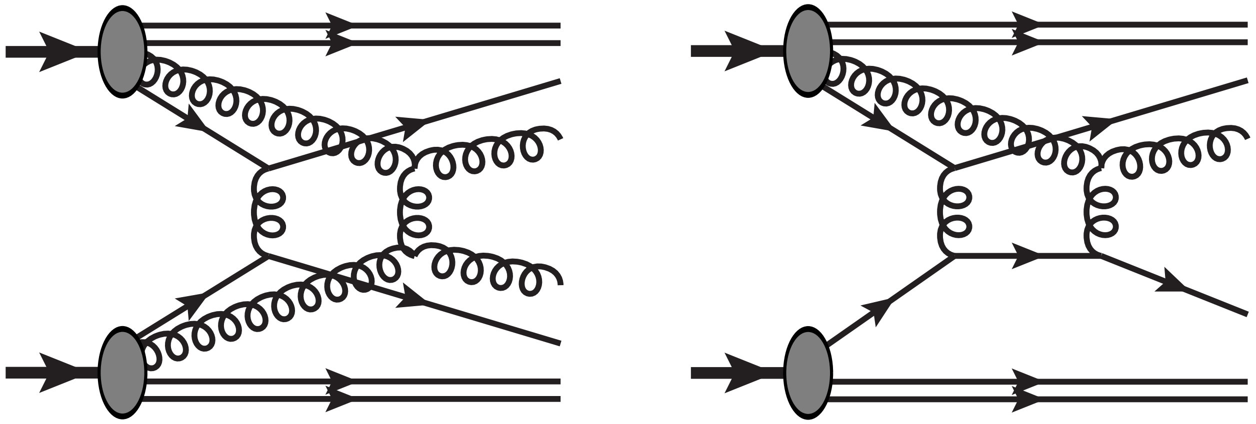
- Each pieces describe physics at different scales.
- Resums $(\alpha_s \ln R)^n$ and $(\alpha_s \ln^2 \frac{R}{\tau_a^{1/(2-a)}})^n$



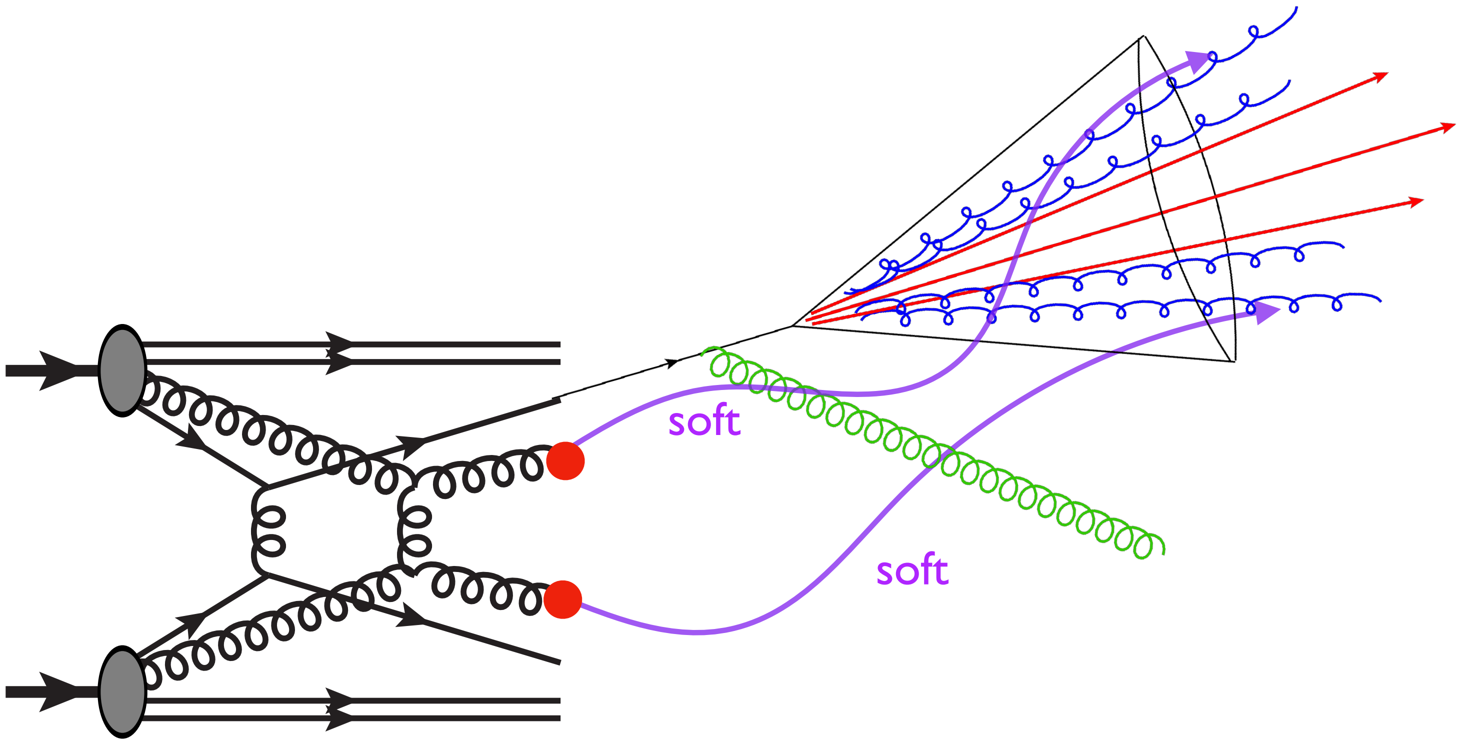
Kang, KL, Ringer `18

Non-perturbative Effects

- Non-perturbative effects:



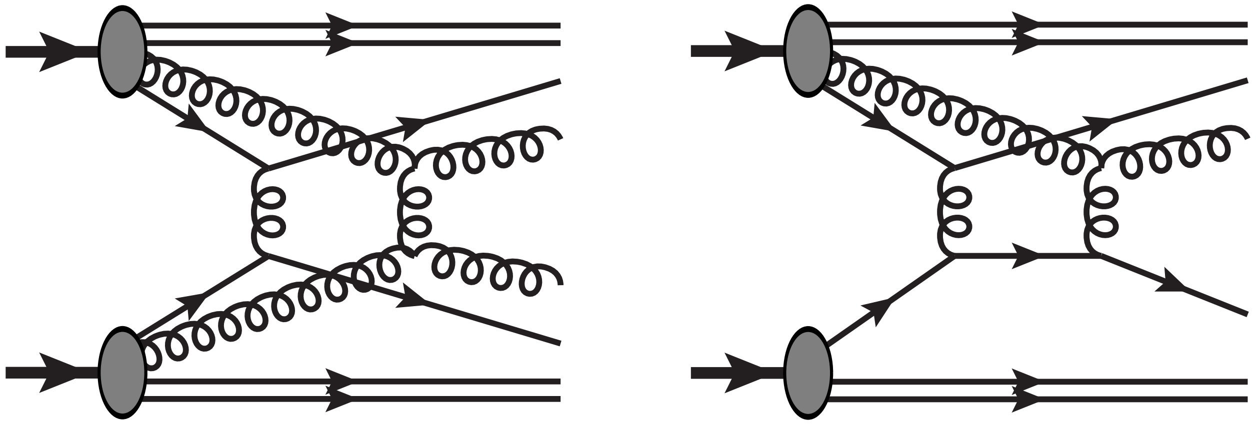
Figs from P. Bartalini et al. `11



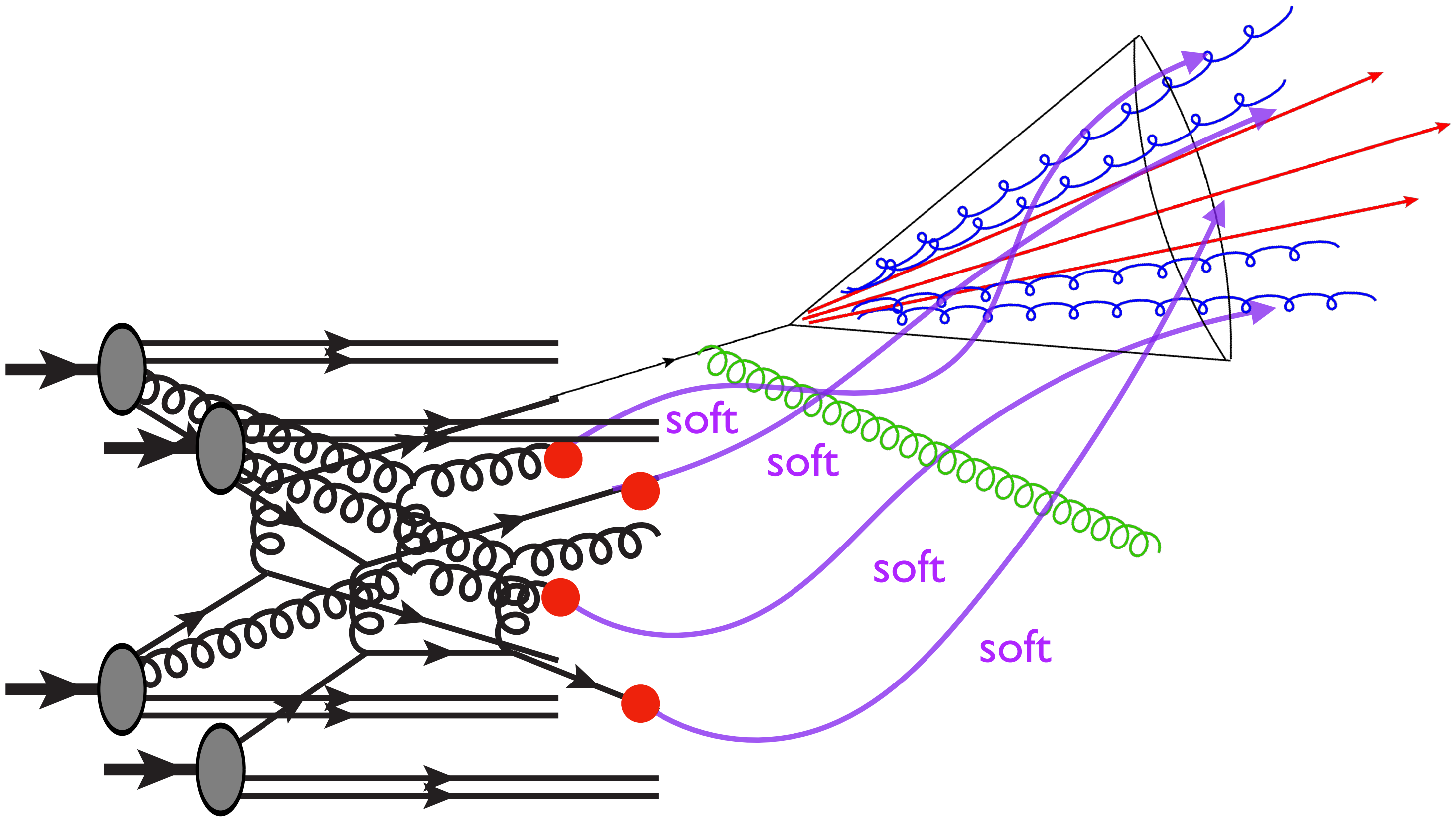
- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.

Non-perturbative Effects

- **Non-perturbative effects:**



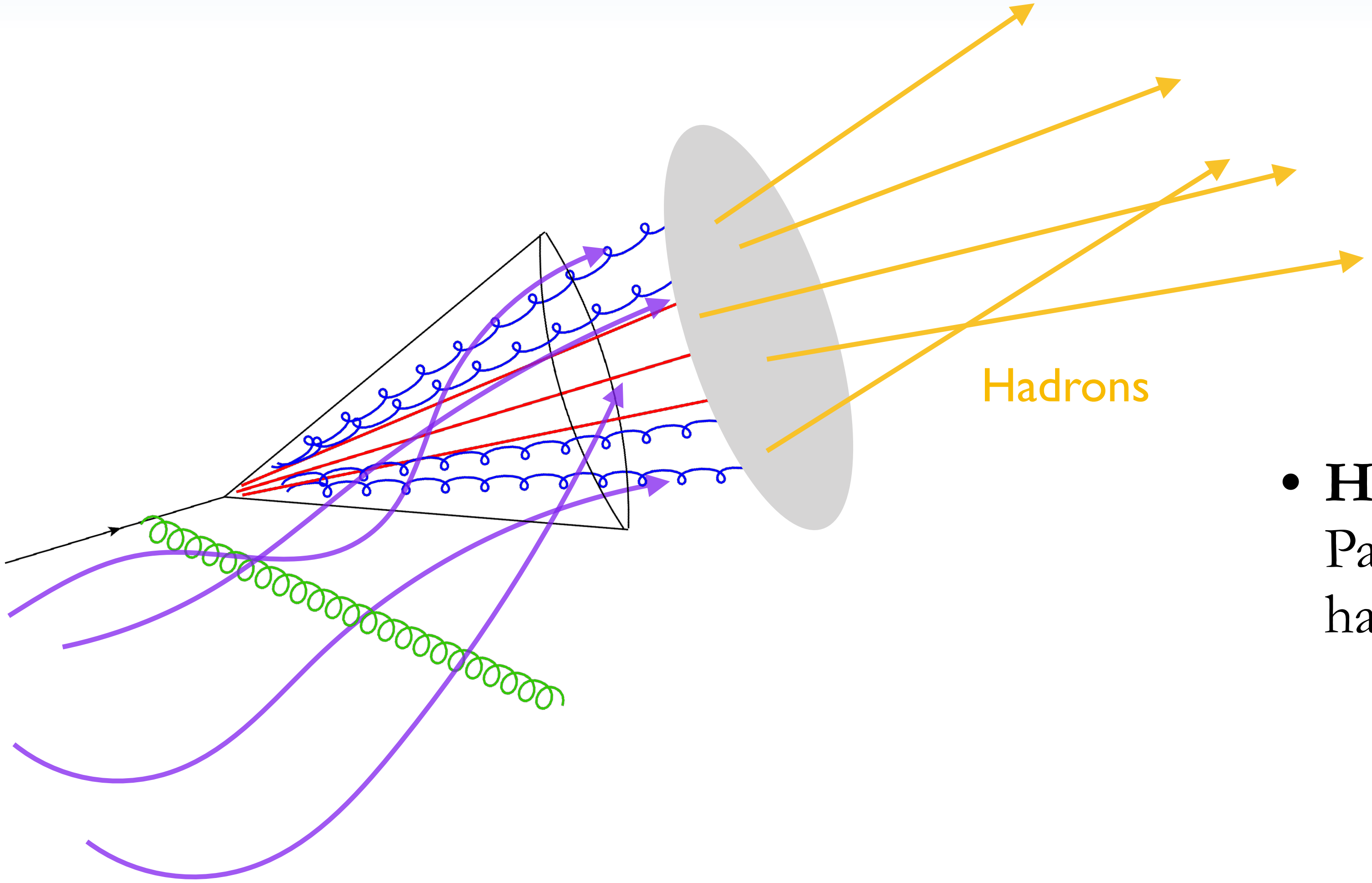
Figs from P. Bartalini et al. `11



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

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

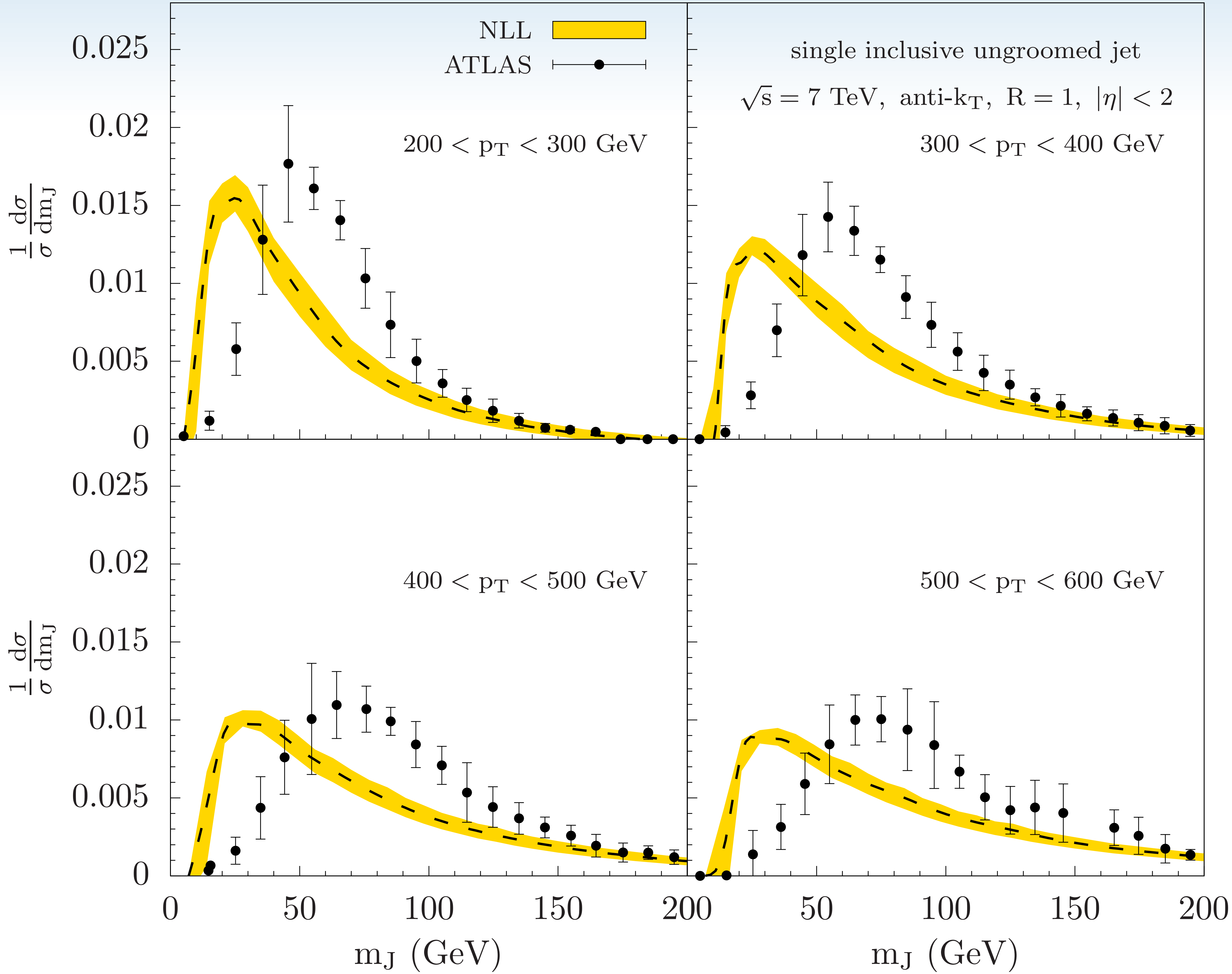
Stewart, Tackmann, Waalewijn `15

- 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:

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

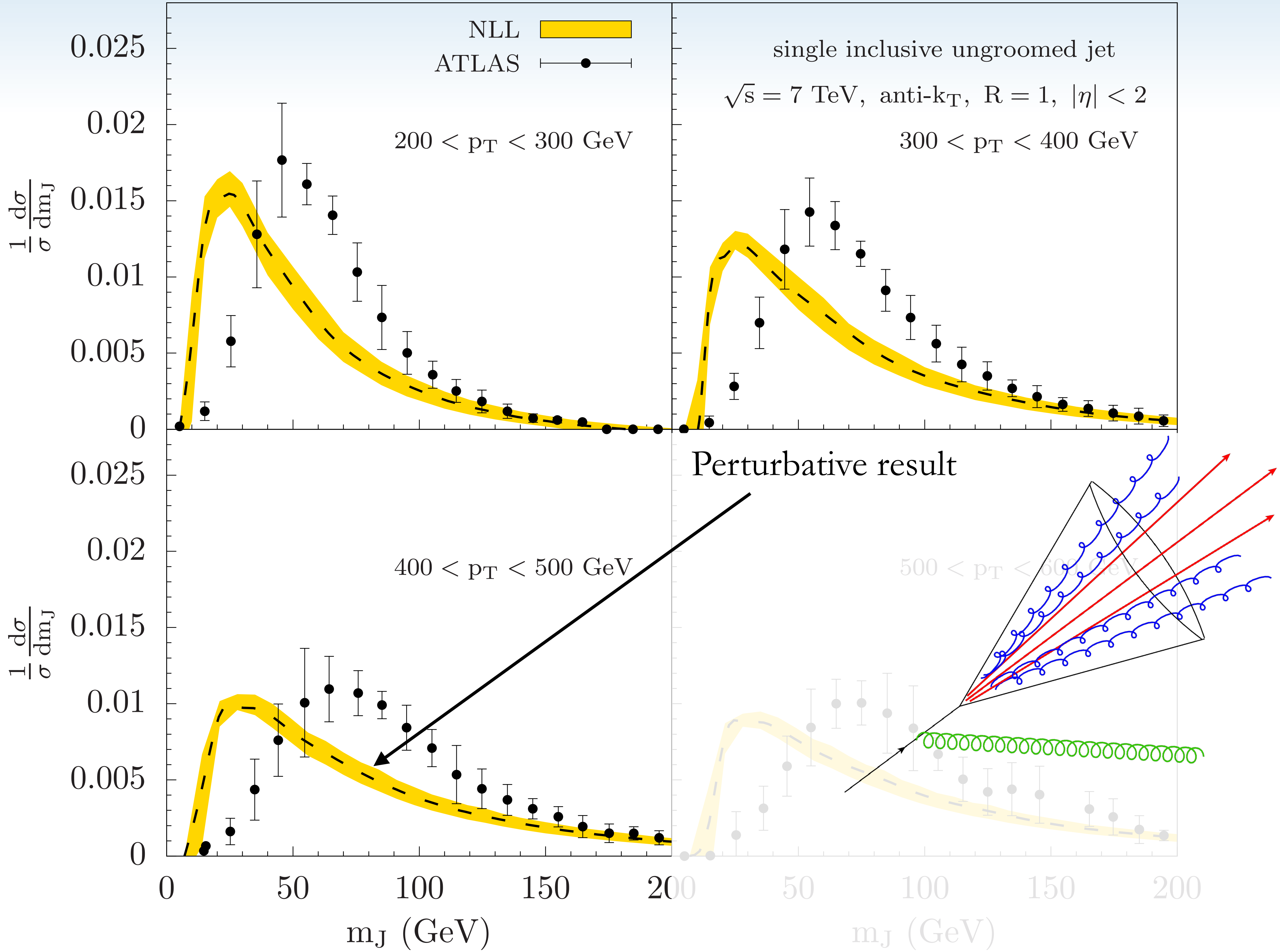
$\Omega_\kappa \sim \Lambda_{had} \sim 1\,\text{GeV}$ corresponds to non-perturbative effects coming primarily from the hadronization alone.

Phenomenology



Kang, KL, Liu, Ringer `18

Phenomenology



Perturbative result

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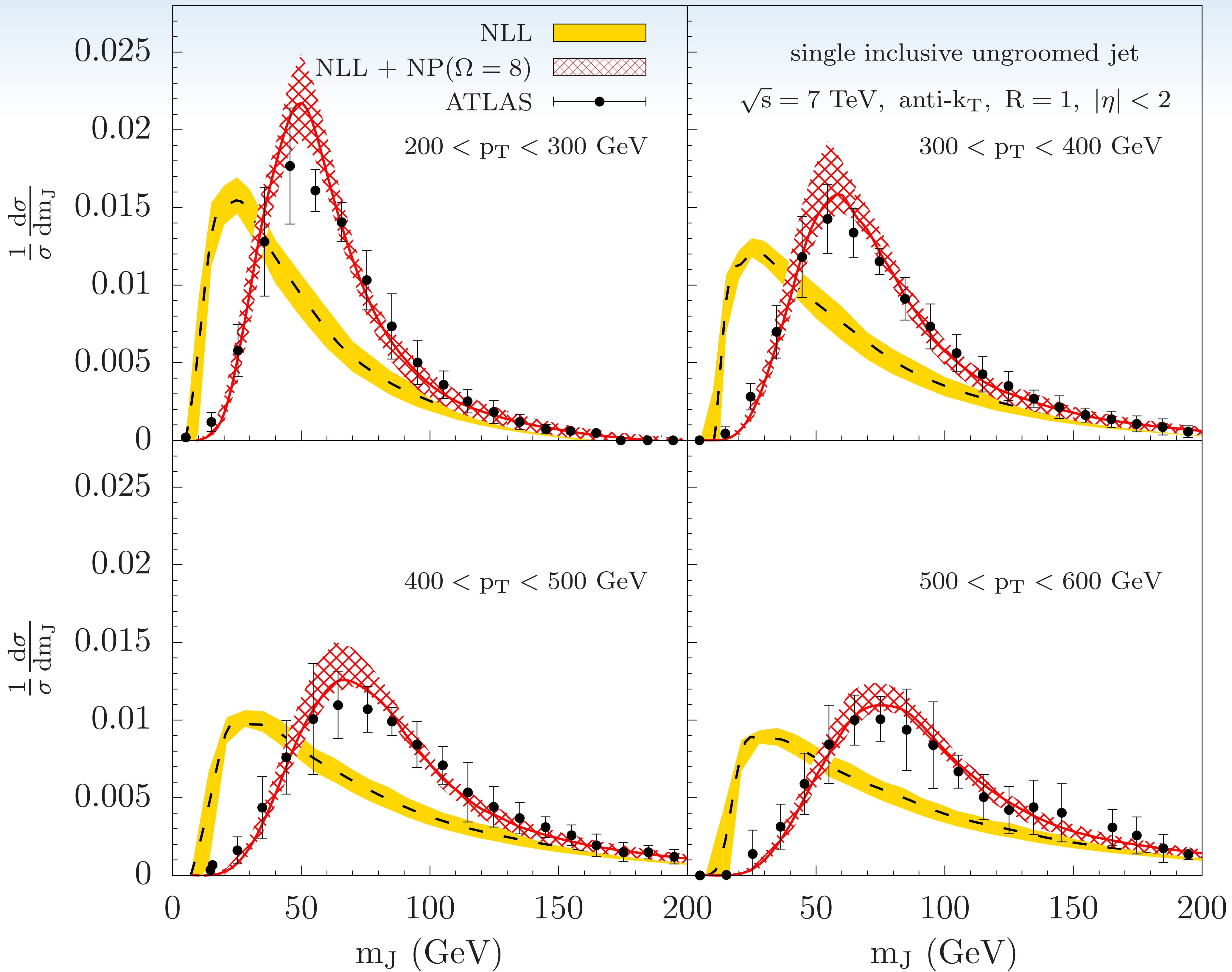
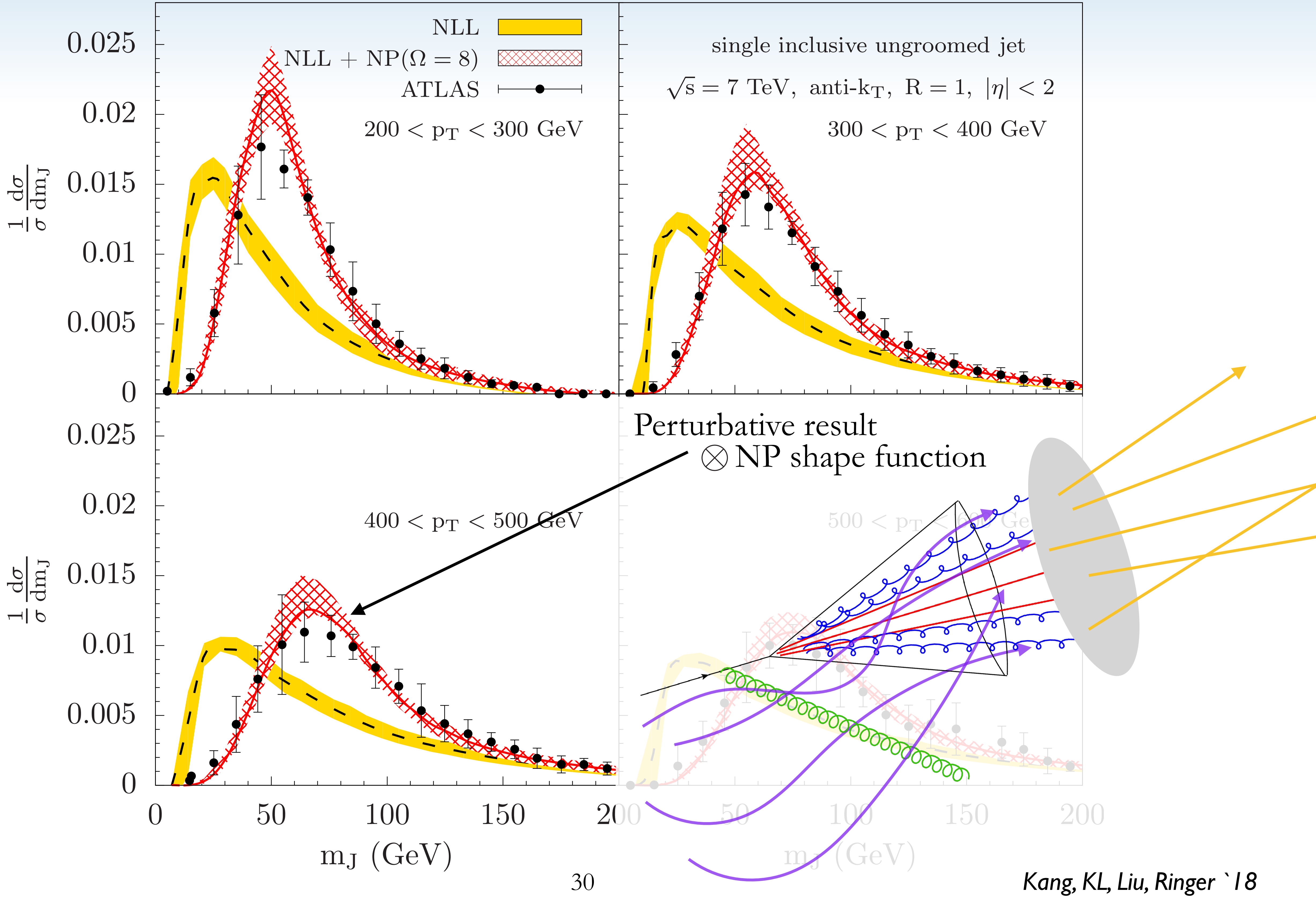
Phenomenology



Kang, KL, Liu, Ringer `18

Phenomenology



Perturbative result
⊗ NP shape function

Kang, KL, Liu, Ringer `18

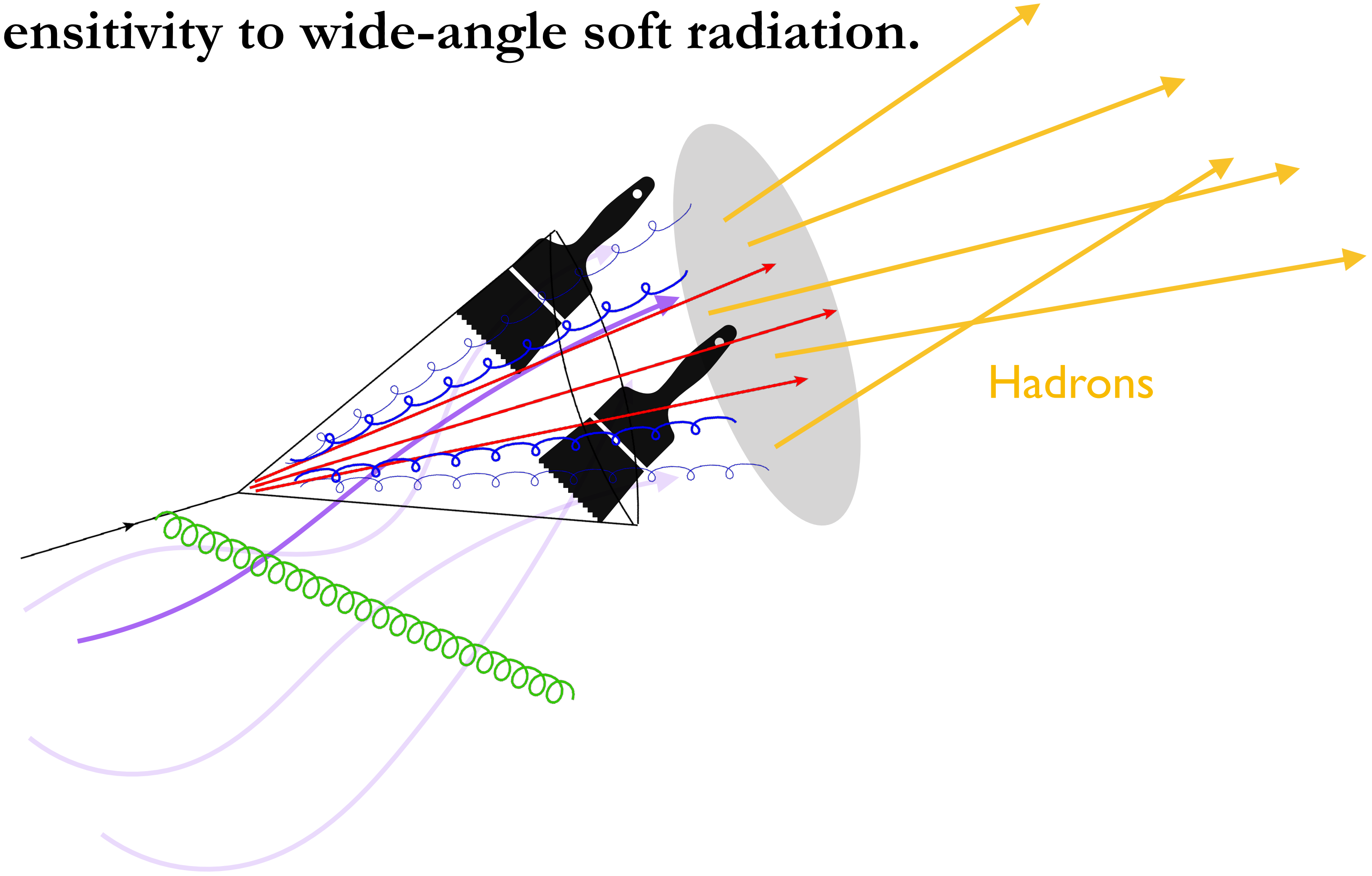
Soft Drop Grooming

- Underlying Events (UE) are difficult to understand.

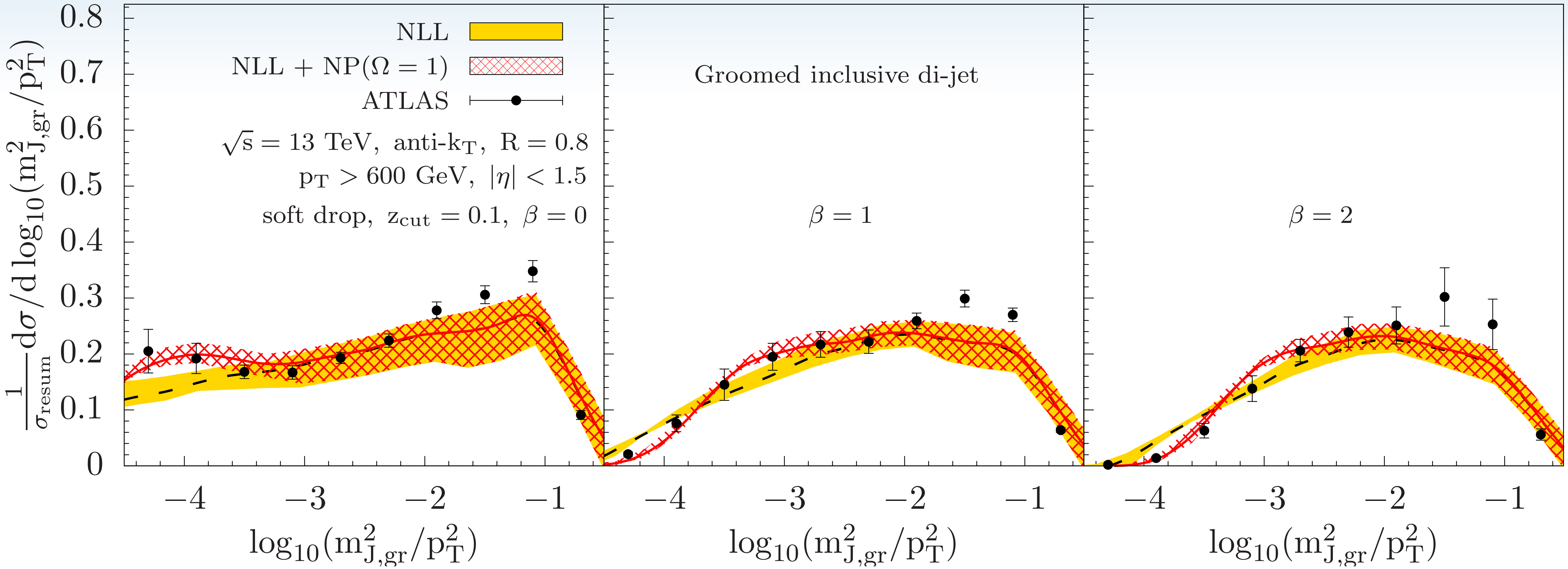
  How do we get a better hold of these soft uncorrelated contaminations (SUEs) in the jet?

- Hint : contamination generally from soft radiations.

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



Phenomenology (groomed jet mass)

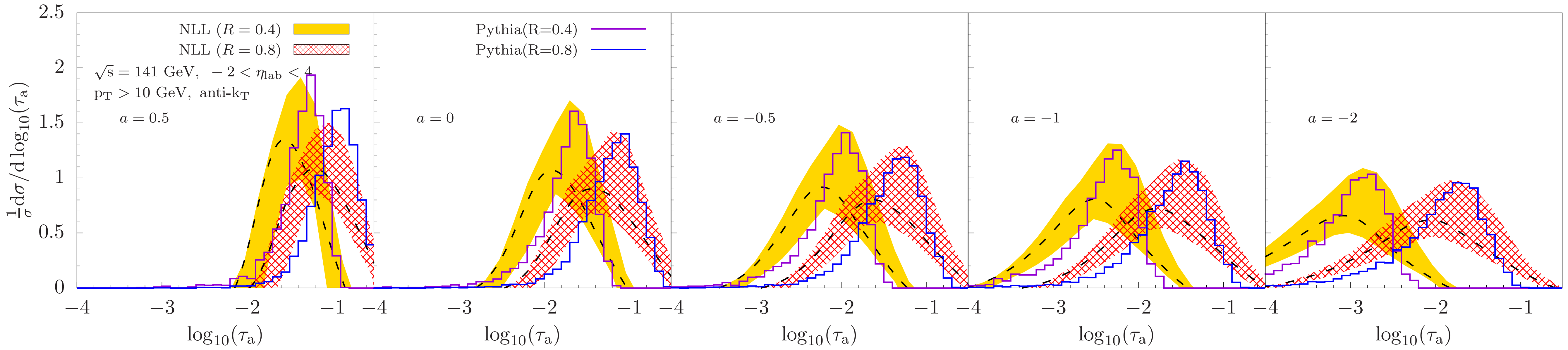


- Developed the formalism for single inclusive groomed jet mass cross-section.
- Shows very good agreement with the data.
- $\boxed{\Omega_k = 1 \text{ GeV}} \Longrightarrow$ Reduced contamination as expected.
  NP effects mostly from hadronization.

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

Kang, KL, Liu, Ringer `18

EIC results

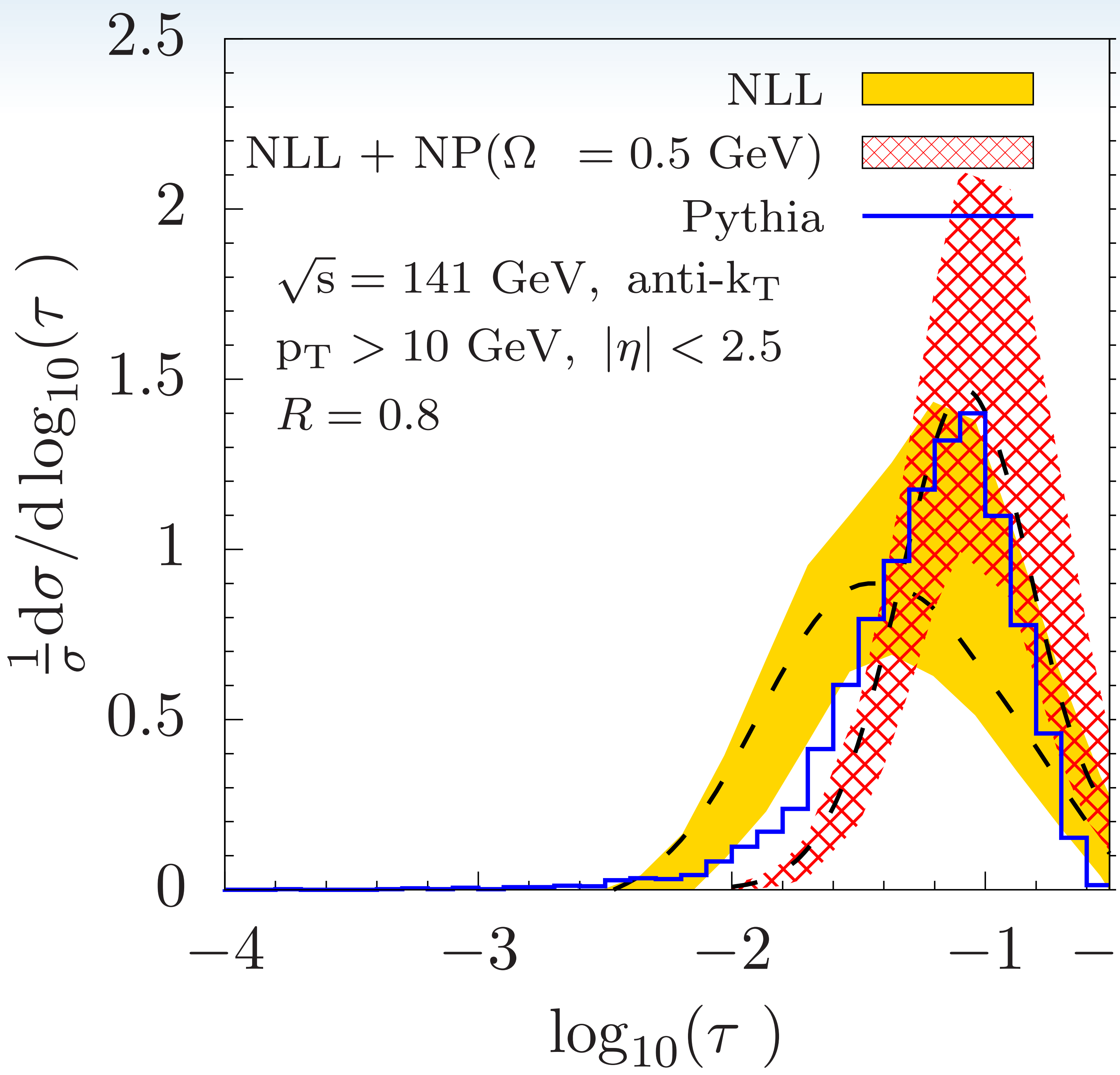


- Perturbative results show good agreement without a need for a large shift. Small contamination from UE compared to the LHC.

Non-perturbative effects

In collaboration with Elke Aschenauer and Brian Page

Shift from hadronization effects

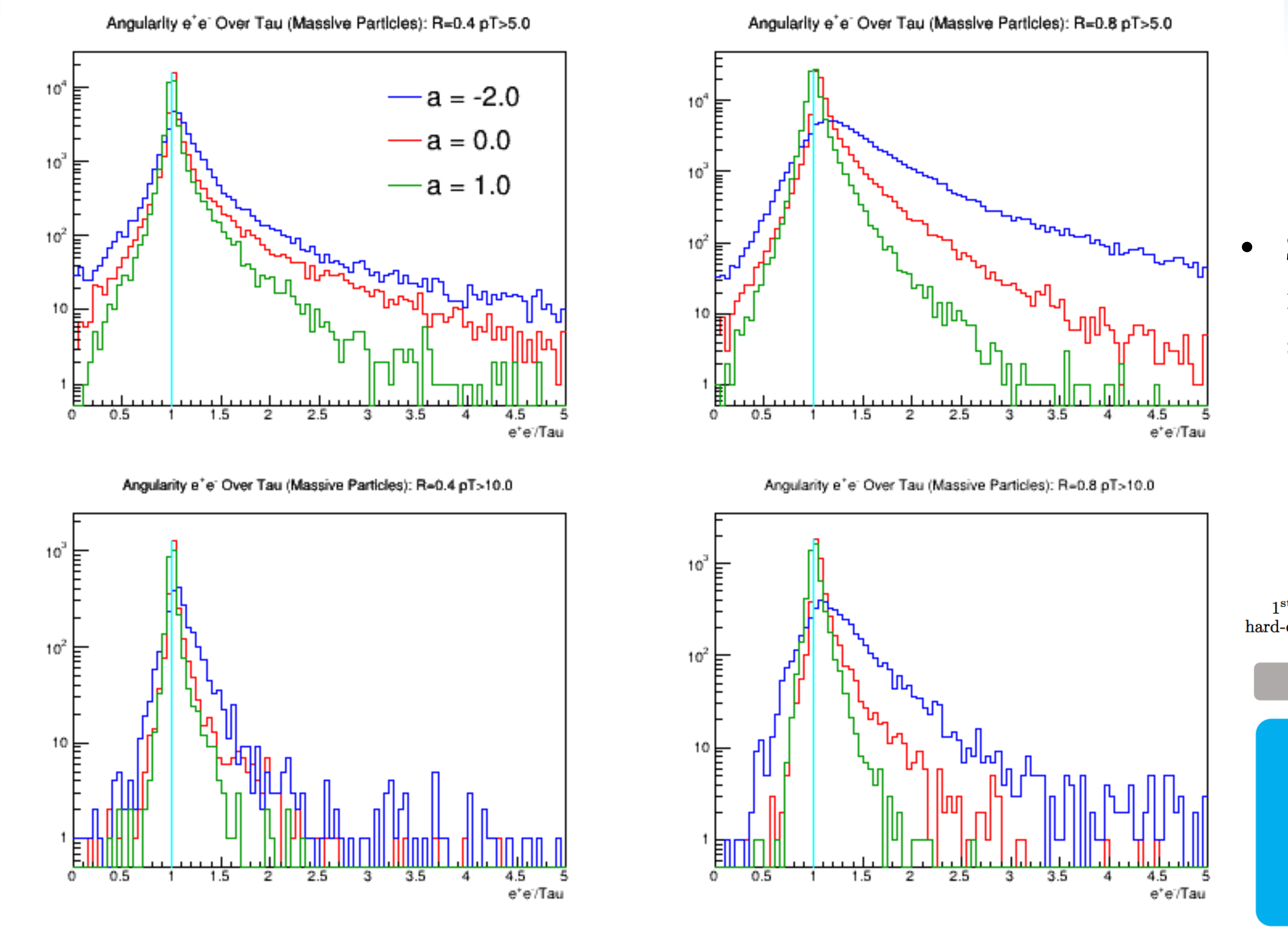


- Even without grooming, EIC results only require a small shift to agree with the Pythia result. ($\Omega \approx \Lambda_{QCD}$)
- NP effects mostly from hadronization.

Non-perturbative effects

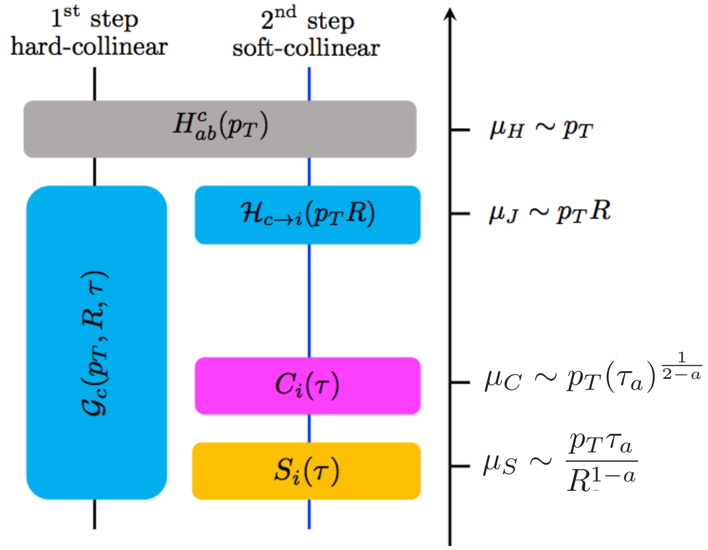
In collaboration with Elke Aschenauer and Brian Page

Power corrections



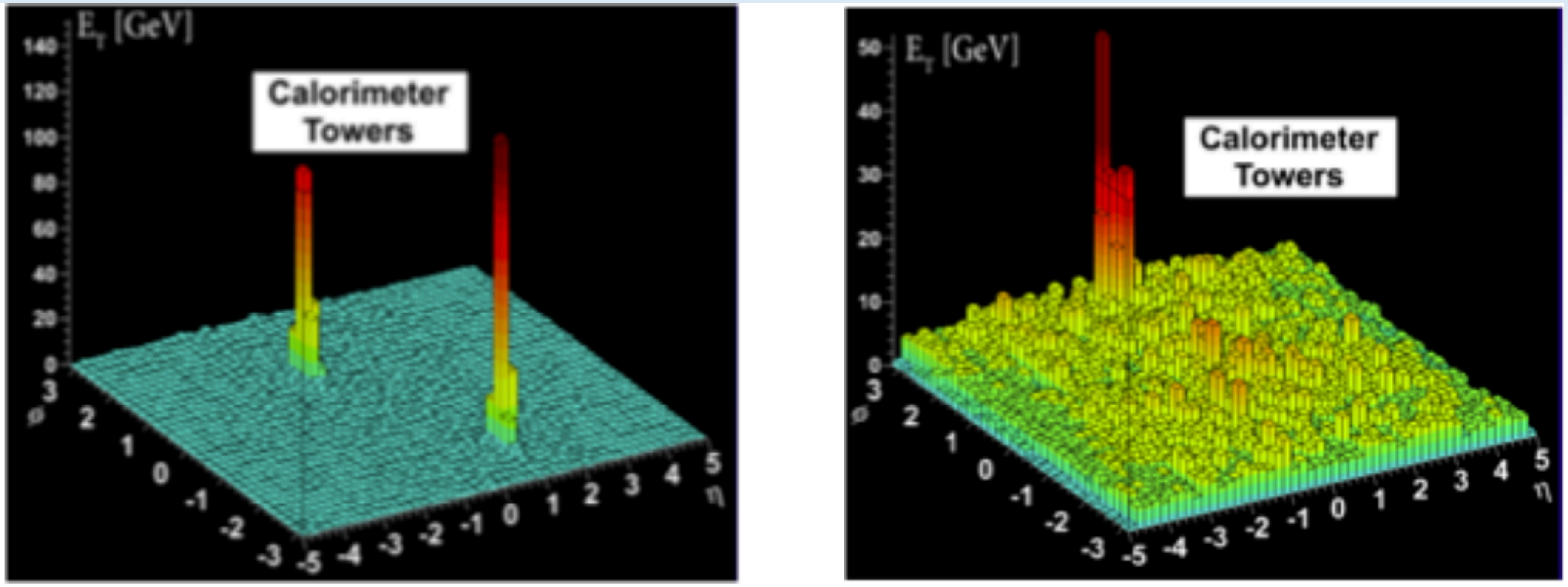
- Smaller power corrections for smaller R due to soft scales.

Power corrections



In collaboration with Elke Aschenauer and Brian Page

Subtracted moments



- **Heavy ion collisions produce large number of uncorrelated soft particles in the background contaminating the jet.**

1. **Develop a background subtraction techniques to identify true compositions of the jets.**

or

2. **Define an observable insensitive to the uncorrelated background.**
    a. Grooming (recursive algorithm)
    b. Subtracted moments

Kang, Makris, Mehen `17
Chien, Kang, KL, Makris, In Preparation

Subtracted moments

- **An observable that studies the correlation between p_T and a linearly additive substructure v.**
- **Linear additivity :**

Soft Uncorrelated Emissions (SUEs)

$$v = \sum_{i\in\text{signal}} v^i_{\text{signal}} + \sum_{j\in\text{SUEs}} v^j_{\text{SUEs}}$$

i.e. jet mass ($\sim \tau_0$) $p^-_{J,\text{signal}} + p^-_{J,\text{SUEs}} \approx p^-_{J,\text{signal}} \approx p^-_J = 2p_T$ (only signal is correlated with the p_T of the jet)

$$\tau_0 = \frac{m_J^2}{p_T^2} = \frac{p_J^- p_J^+}{p_T^2} = 2\frac{1}{p_T}(p^+_{J,\text{signal}} + p^+_{J,\text{SUEs}}) = \frac{m^2_{J,\text{signal}}}{p_T^2} + \frac{2}{p_T}p^+_{J,\text{SUEs}}$$

such separation gives the form of

$$\frac{d\sigma}{dp_T\,d\tau_0} = \int dp^+_{J,\text{SUEs}} f(p^+_{J,\text{SUEs}}) \frac{d\sigma^{\text{signal}}}{dp_T\,d\tau_0}\left(\tau_0 - \frac{2}{p_T}p^+_{J,\text{SUEs}}\right)$$

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Subtracted moments

$$\frac{d\sigma}{dp_T d\tau_0} = \int dp^+_{J,\mathrm{SUEs}} f(p^+_{J,\mathrm{SUEs}}) \frac{d\sigma^{\mathrm{signal}}}{dp_T d\tau_0}(\tau_0 - \frac{2}{p_T} p^+_{J,\mathrm{SUEs}})$$

Moments of the distribution can be separated into contribution from signal and background:

$$\langle \tau_0 \rangle = \frac{1}{\sigma} \int d\tau_0 \, \tau_0 \, \frac{d\sigma}{d\tau dp_T} = \langle \tau_{0,\mathrm{signal}} \rangle + \frac{2}{p_T} \Omega_f$$

$$\Omega_f = \int dk \, k \, f(k)$$

- Experiments often done with several bins of p_T range.
- The binned version would give:

$$\langle \tau_0 \rangle^{[n]} = \langle \tau_{0,\mathrm{signal}} \rangle^{[n]} + 2\Omega_f \langle p_T^{-1} \rangle^{[n]}$$

Subtracted moments (independent of contribution from SUEs) :

$$\Delta^{jk}_{\tau_0} = \langle \tau_0 \rangle^{[j]} - \langle \tau_0 \rangle^{[k]} \frac{\langle p_T^{-1} \rangle^{[j]}}{\langle p_T^{-1} \rangle^{[k]}} = \langle \tau_{0,\mathrm{signal}} \rangle^{[j]} - \langle \tau_{0,\mathrm{signal}} \rangle^{[k]} \frac{\langle p_T^{-1} \rangle^{[j]}}{\langle p_T^{-1} \rangle^{[k]}}$$

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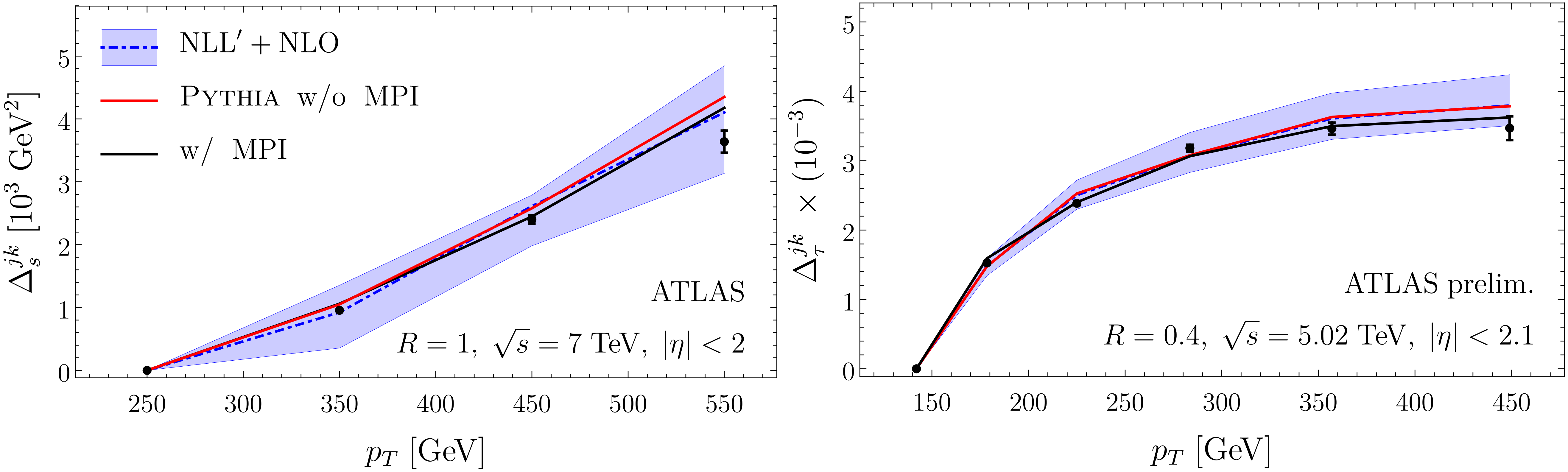
Subtracted jet mass moments



- **Independent of model, i.e. shape function.**
- **Useful to test modifications by medium with reduced sensitivity to uncorrelated radiations.**

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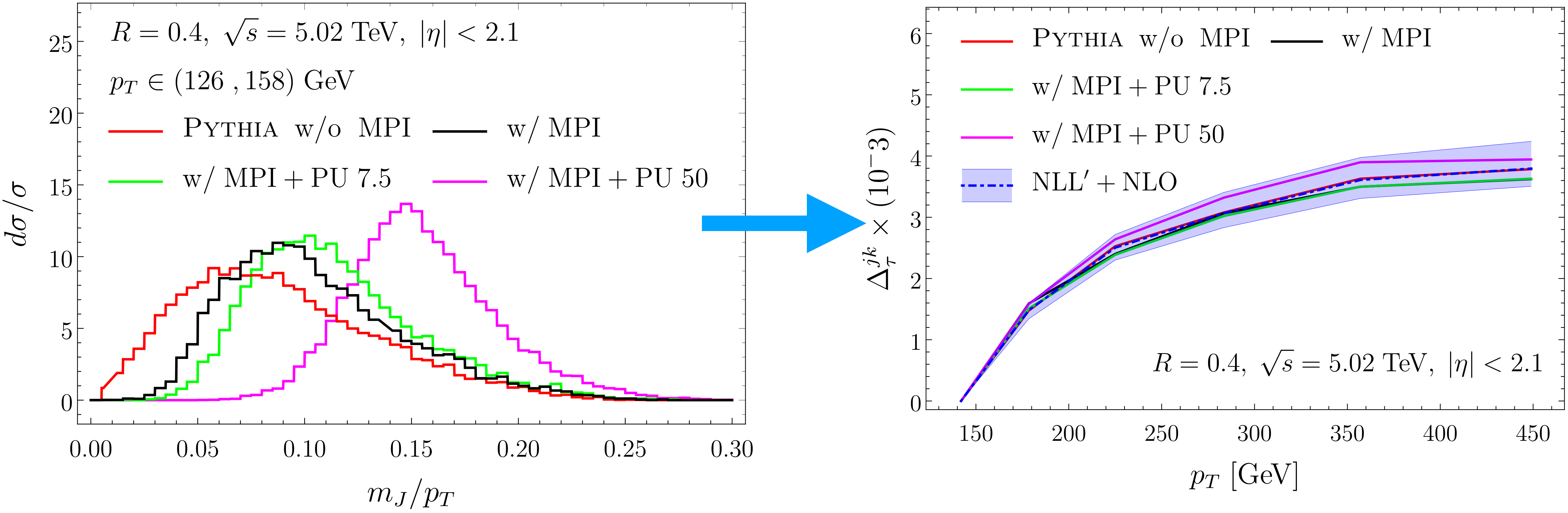
Testing limit of SUE independence



- **Even at 50 pile ups, the subtracted moments of τ_0 gives same subtracted moments!**

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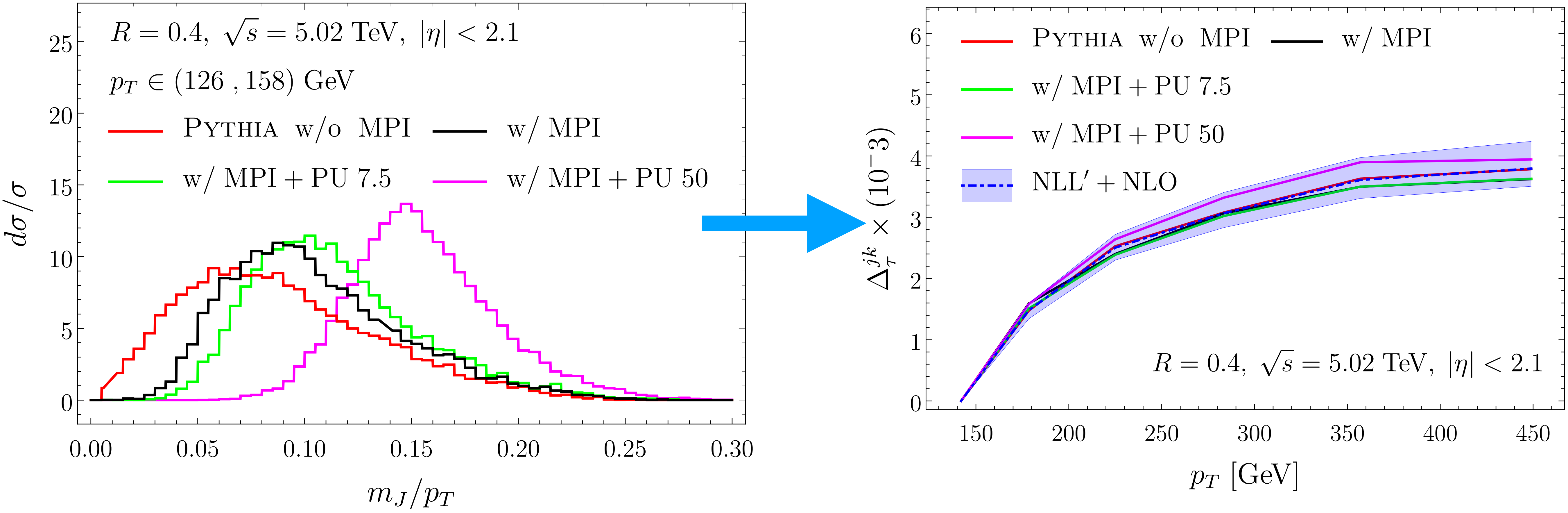
Testing limit of SUE independence



$p_{J,\text{signal}}^{-} + p_{J,\text{SUEs}}^{-} \approx p_{J,\text{signal}}^{-} \approx p_J^{-} = 2p_T$

- At higher PU events, additivity starts failing since change in p_T due to SUEs starts to become signficant.

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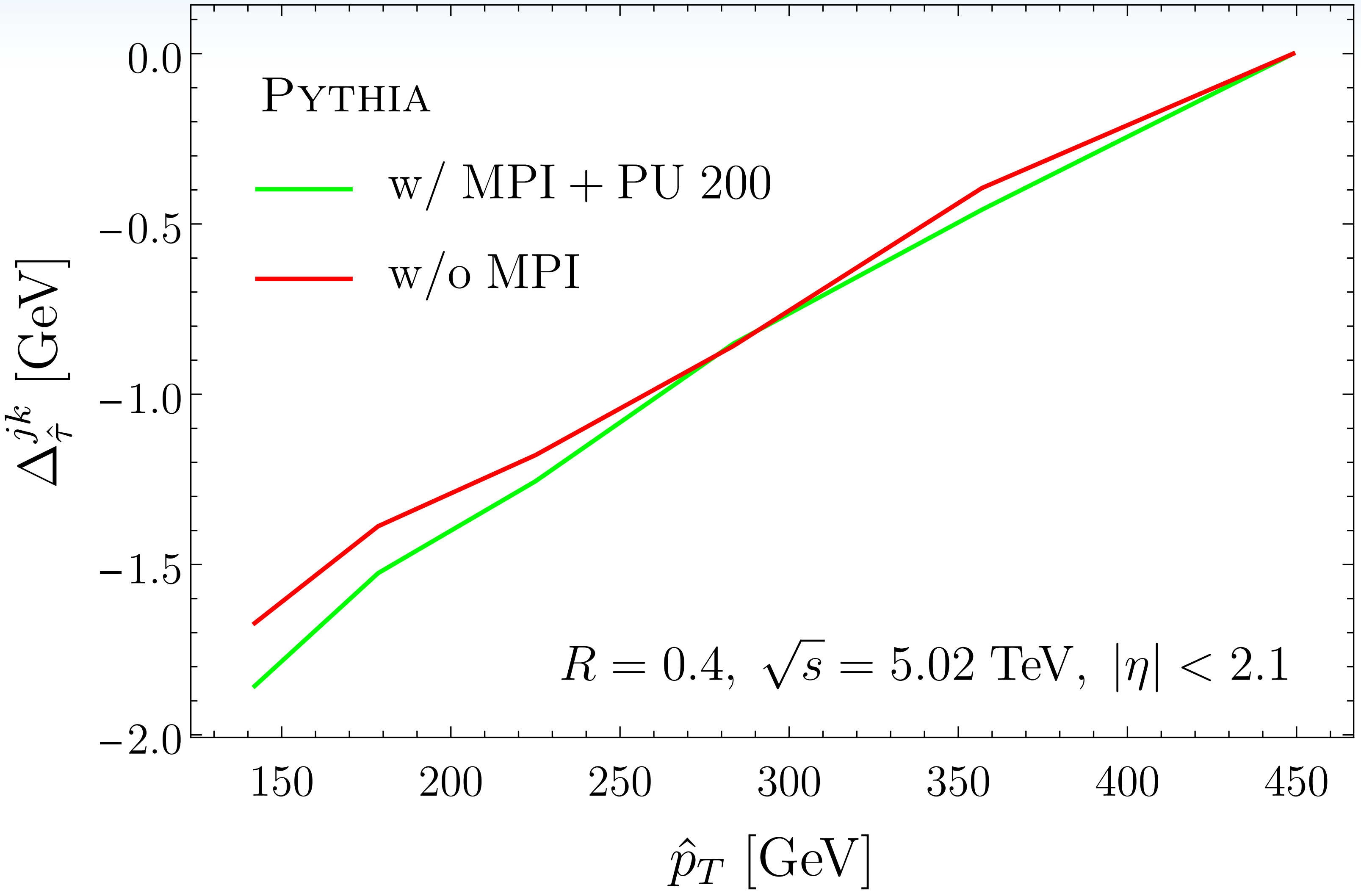
200 PU events



- Subtracted moments of $\hat\tau$ is insensitive to 200 PU events.
- Useful for studying jets in high-luminosity LHC (HL-LHC) and in the heavy ion collisions!

$$\hat\tau = \frac{m_J^2}{p_T} = \frac{p_J^- p_J^+}{p_T} = 2(p^+_{J,\text{signal}} + p^+_{J,\text{SUEs}})$$

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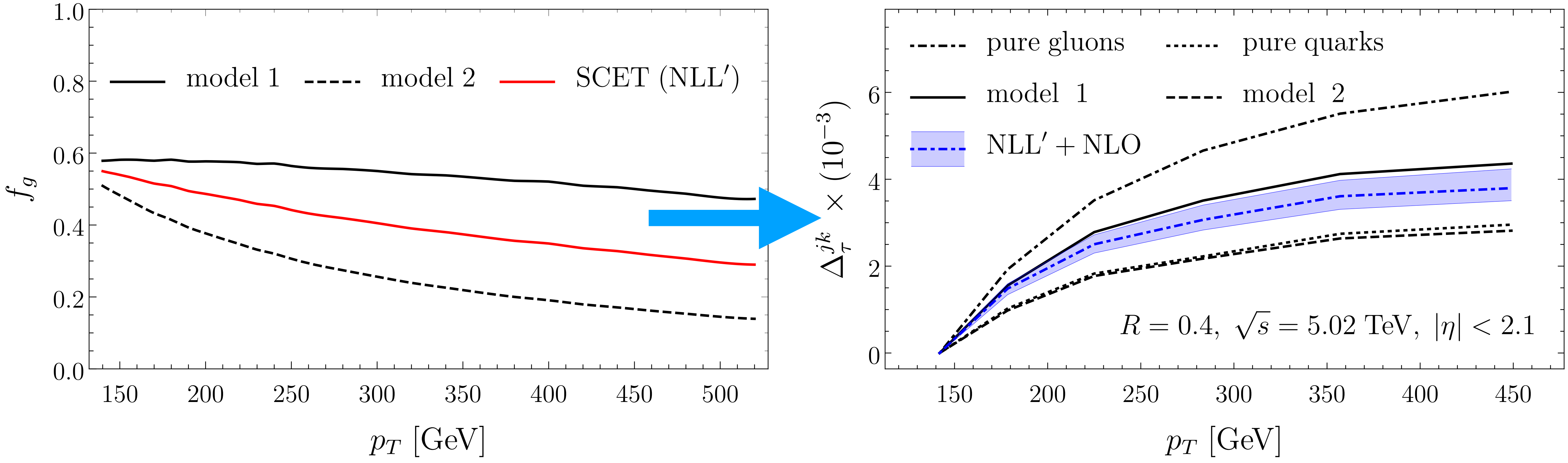
Quark and gluon fraction changes



$$\langle\tau\rangle^{[n]} = f_g^{[n]}\langle\tau\rangle_g^{[n]} + (1 - f_g^{[n]})\langle\tau\rangle_q^{[n]}$$

Medium modifications

- Subtracted moments have discriminating power on models that predict changes in quark and gluon jet fractions due to the interaction with the medium.

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Conclusions

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

- Discussed phenomenology of angularities, which are useful substructure observables to test medium modifications.

- Going from pp to ep, contamination from non-perturbative soft radiations was shown to be reduced. (can expect similar reduction from pA to eA?)

- Going from pp to ep, size of power corrections for inclusive and substructure observables for the EIC were discussed.
  (can expect similar effects from pA to eA?)

- Subtracted moments are shown to be independent of soft uncorrelated emissions and can be useful to study jets in HL-LHC and heavy ion collisions.