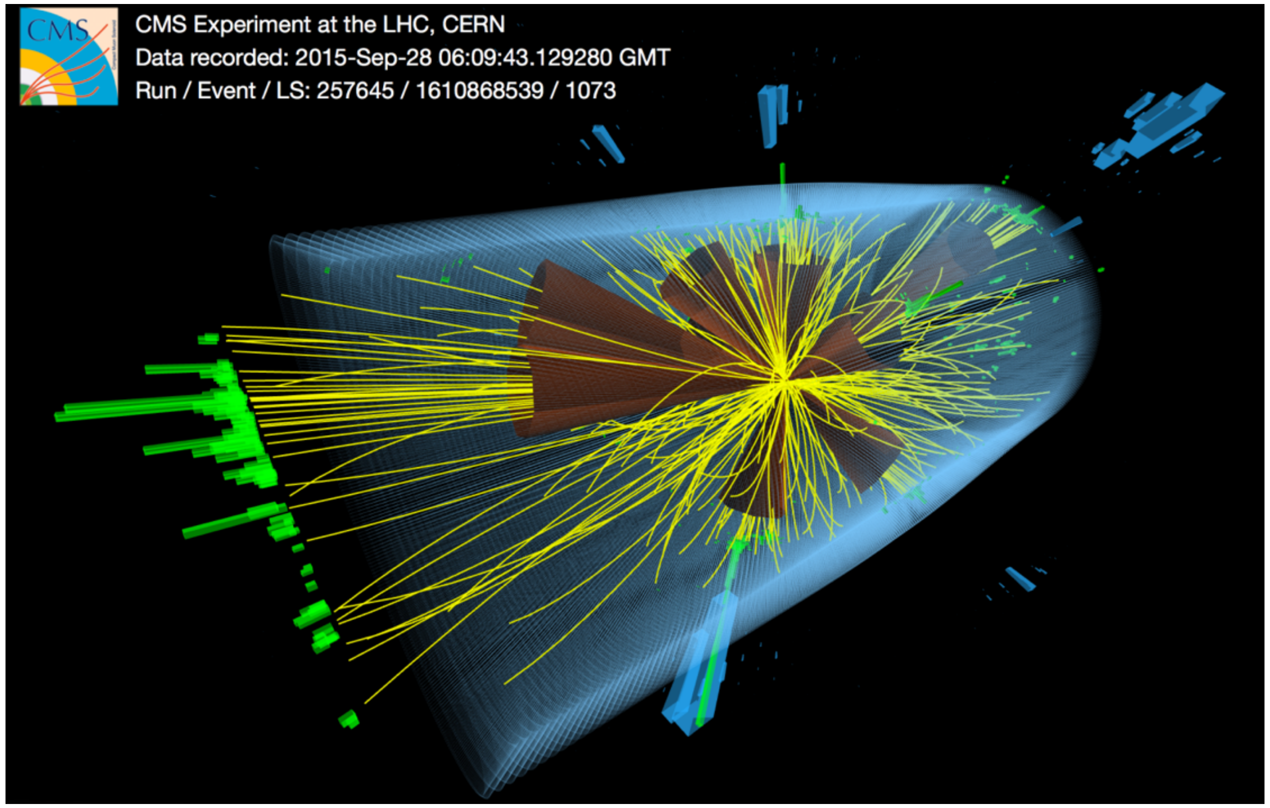
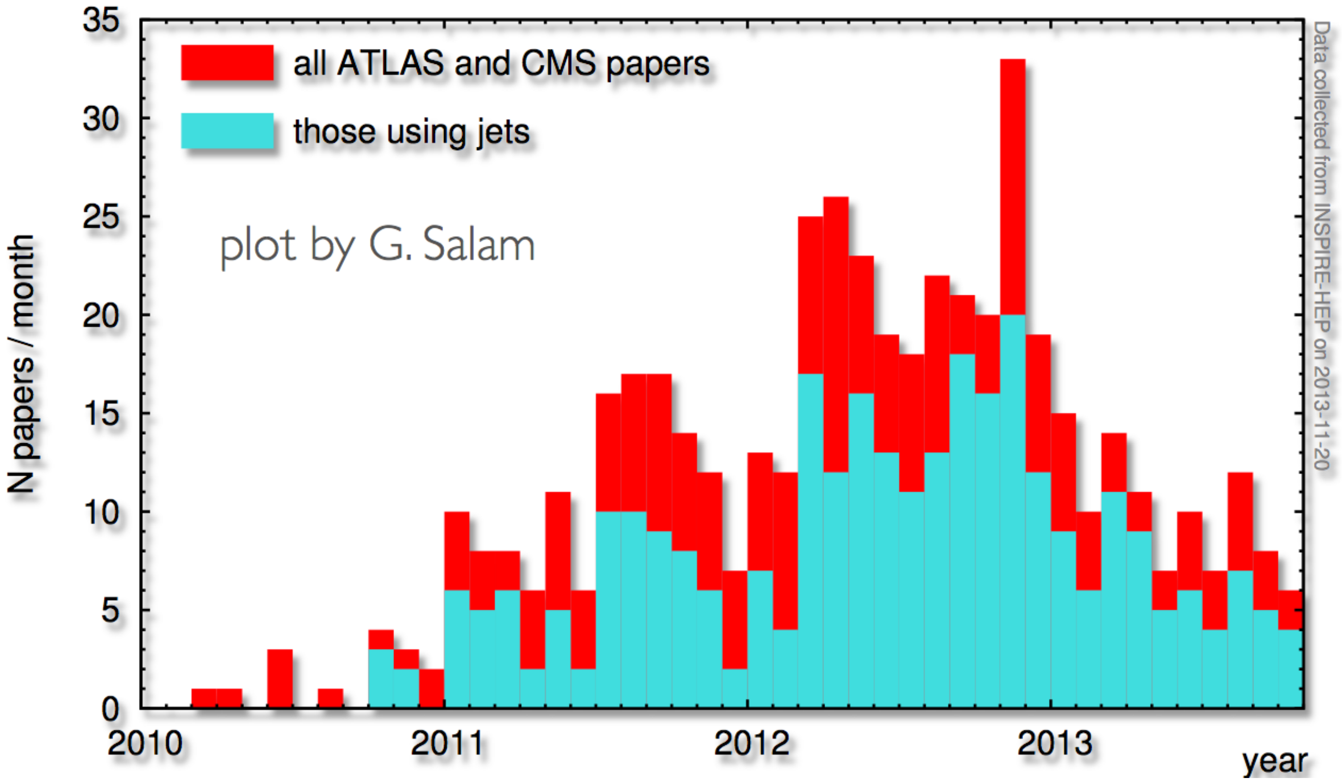
Jet substructure measurements at the LHC and EIC

Kyle Lee
Stony Brook University

QCD Evolution 2018
05/20/18 - 05/24/18

Jets at the LHC



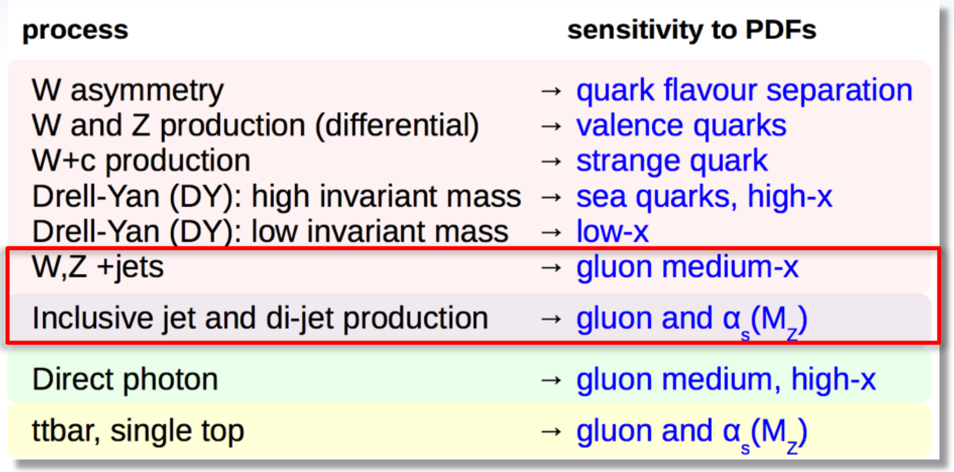


- Jets are produced copiously at the LHC

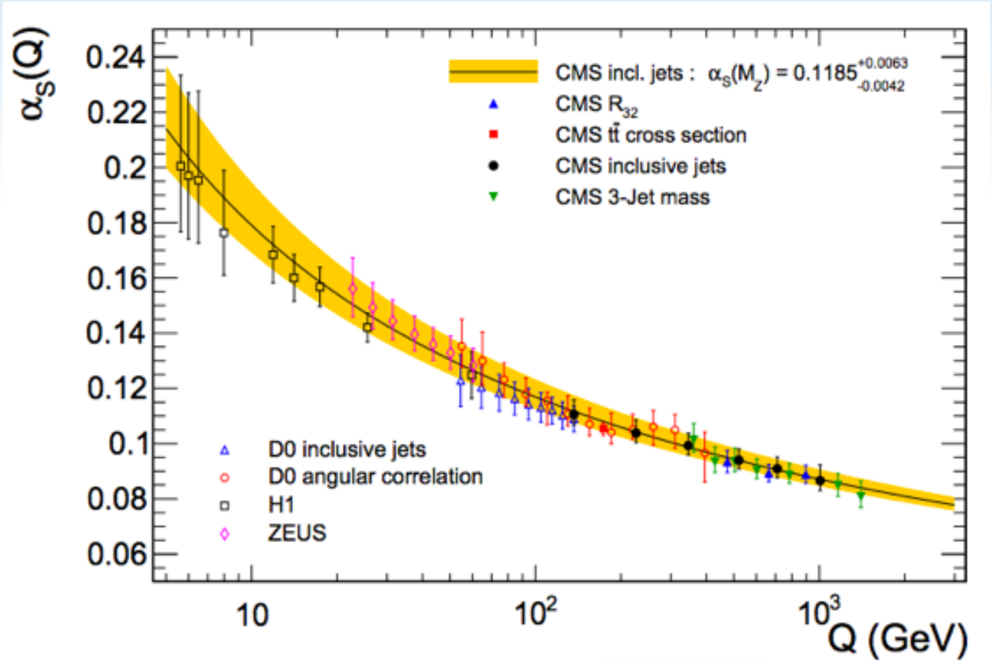
- At the LHC, 60 - 70 % of ATLAS & CMS papers use jets in their analysis!

Application of jet studies at the LHC

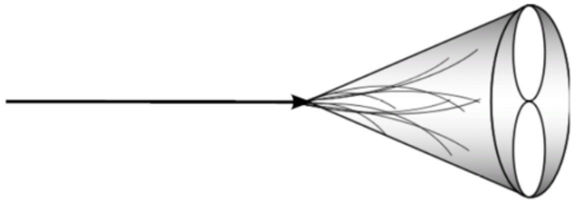
- Precision probe of QCD



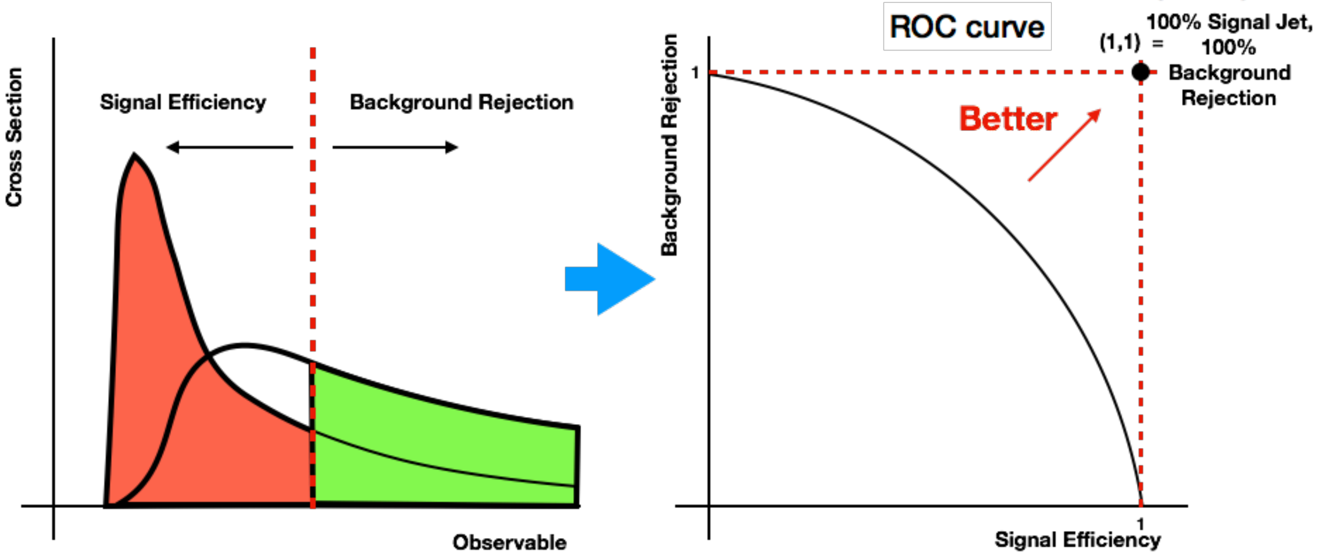
process	sensitivity to PDFs
W asymmetry	→ quark flavour separation
W and Z production (differential)	→ valence quarks
W+c production	→ strange quark
Drell-Yan (DY): high invariant mass	→ sea quarks, high-x
Drell-Yan (DY): low invariant mass	→ low-x
W,Z +jets	→ gluon medium-x
Inclusive jet and di-jet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



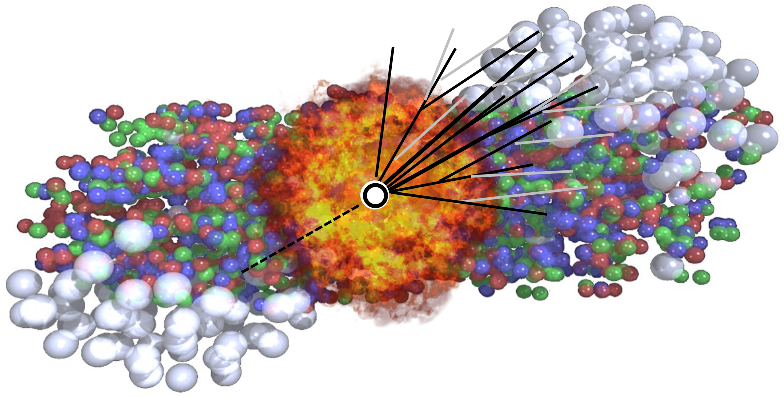
- Constrain BSM Models



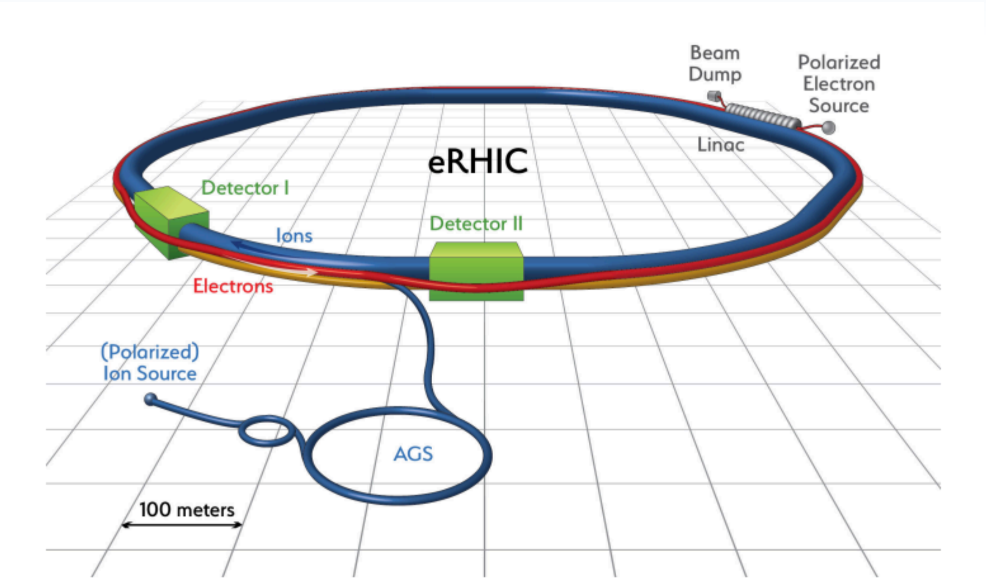
Fat jet from BSM signal

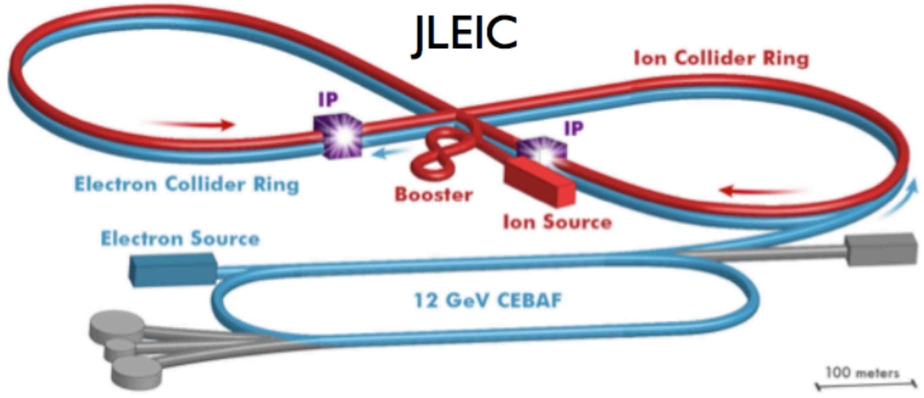


- Probe of quark gluon plasma



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

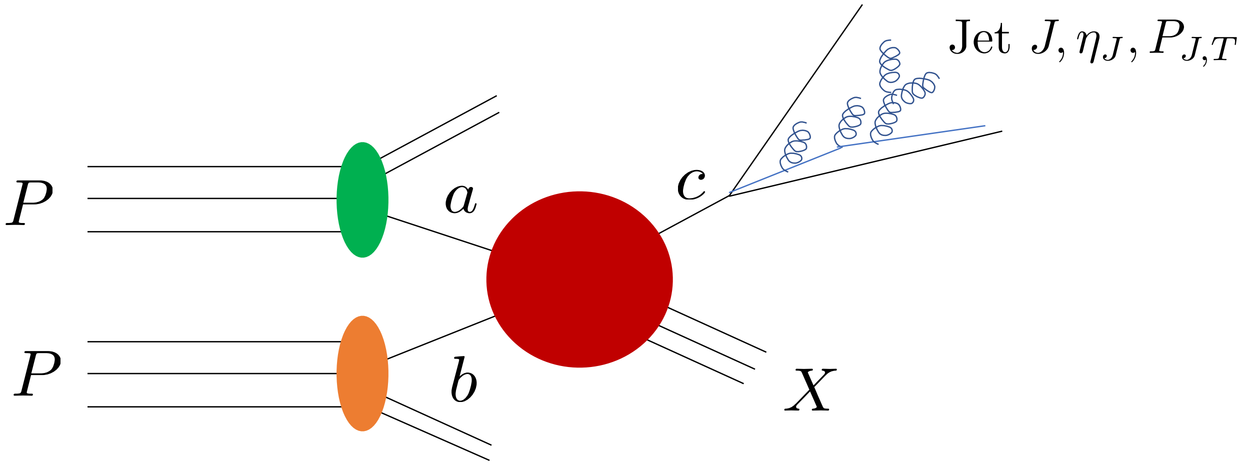
- $N_{J,EIC} \ll N_{J,LHC}$

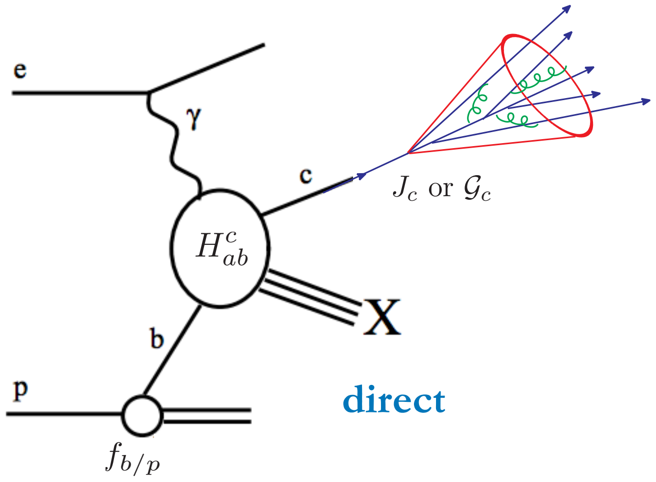
  Smaller jet multiplicity for EIC

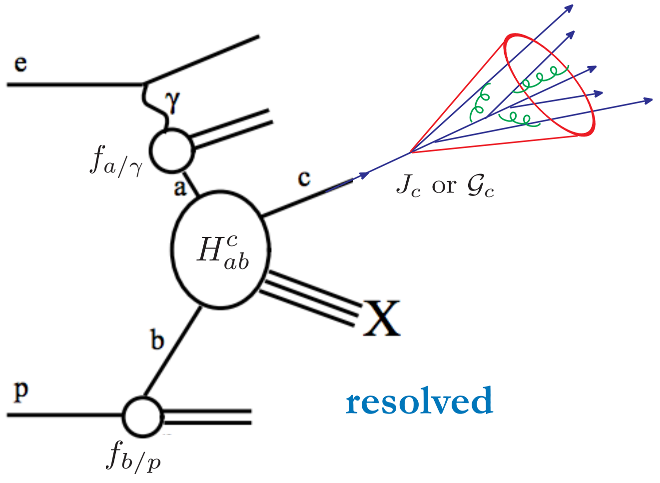
- Less contamination from underlying events and pileups

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

Processes of Interest







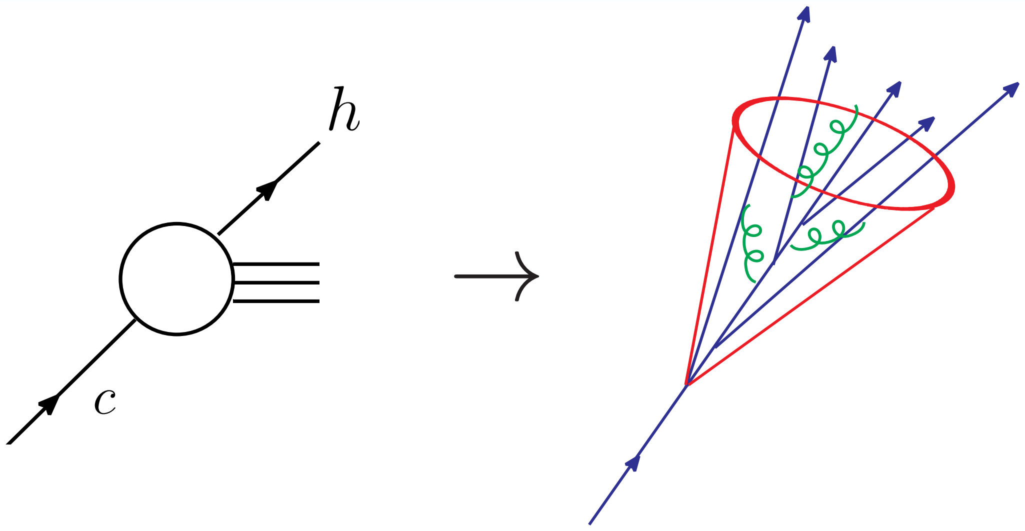
- **We want to study semi-inclusive jet production event:**
  p + p $\longrightarrow$ Jet((with/without) substructure) + X

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

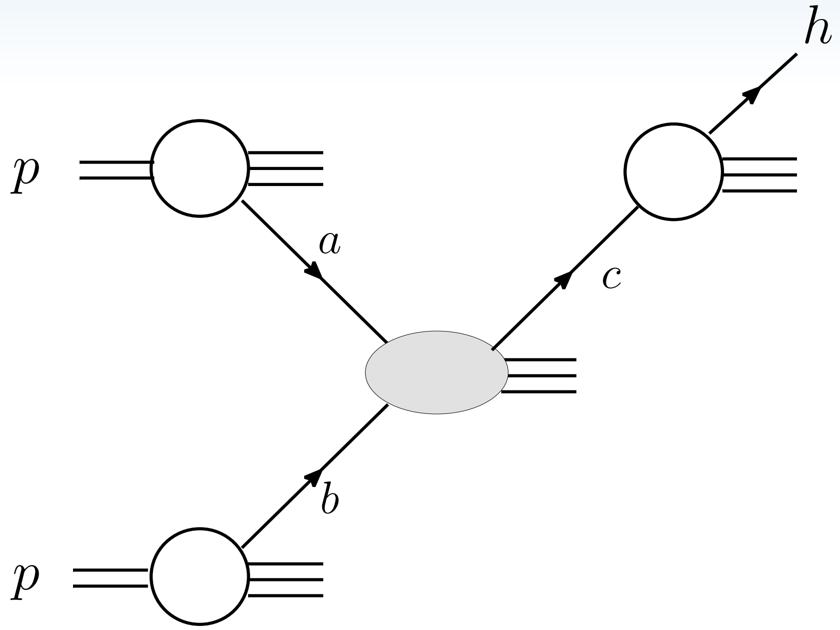
Plans of this talk

- Inclusive jet production at the LHC
- Substructure measurements at the LHC
- Role of non-perturbative effects
- Extension to the EIC case
- Conclusions

Factorization of Inclusive Jet Production



from

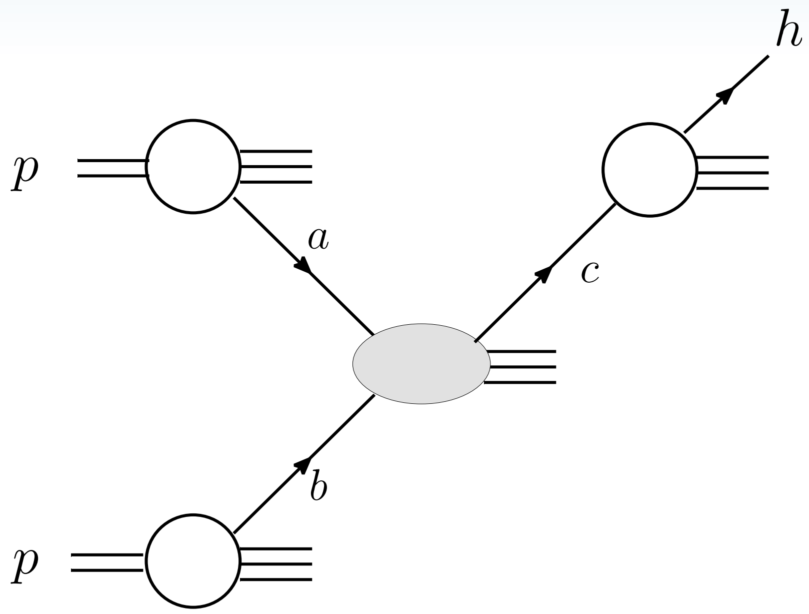


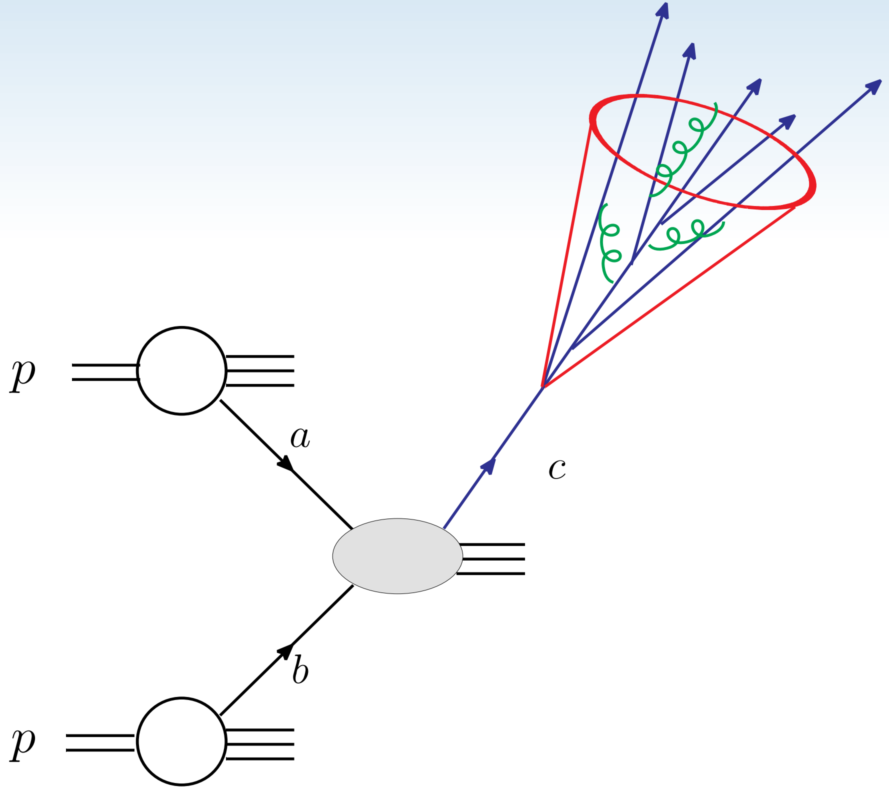
$$D_c^h \quad \rightarrow \quad J_c$$

- **Simple replacement of the fragmentation function by “semi-inclusive jet function” from semi-inclusive hadron production case.**

Kang, Ringer, Vitev `16

Comparison with the inclusive hadron production case

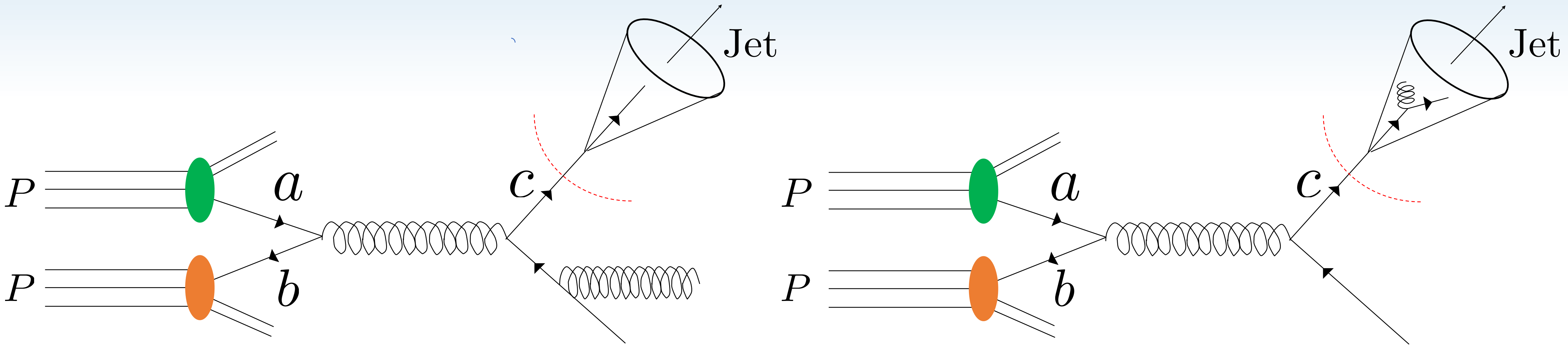




	Factorization	Evolution
Inclusive Jet	$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c + \mathcal{O}(R^2)$	$\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j$
Hadron	$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes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

Kang, Ringer, Vitev `16

Factorization



Example of NLO diagrams

- Relevant scales :

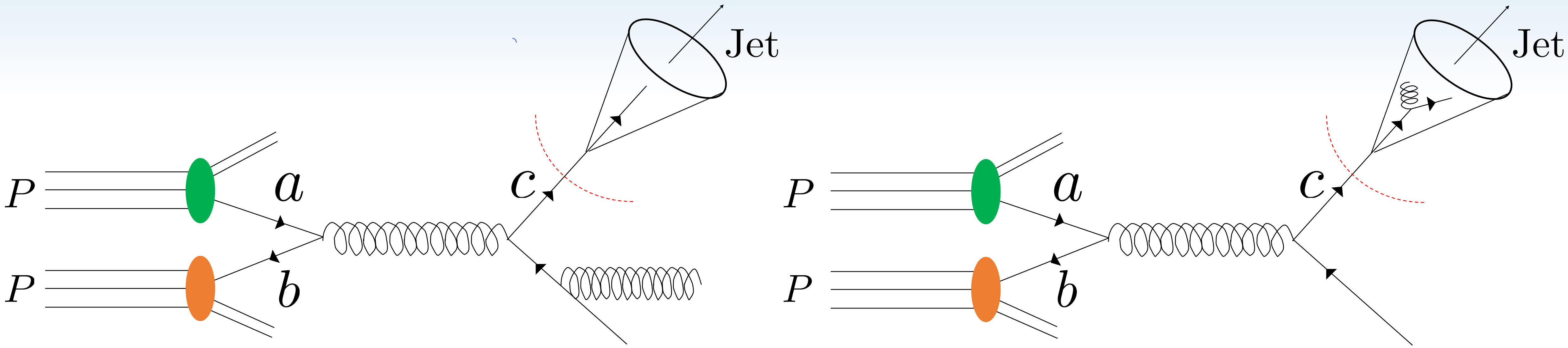
1.Hard scale: $\mu_H \sim \boxed{p_T}$ 2. Jet scale: $\mu_J \sim \boxed{p_T R}$

- For small-R jet, we have hierarchy between the two different scales and jet cross-section is factorized, $d\hat{\sigma}_{ab}^{jet} \to \sum_c \int \frac{dz_c}{z_c^2} \boxed{d\hat{\sigma}_{ab}^c} \boxed{J_c(z_c)}$, giving

$$E\frac{d\sigma^{pp\to \text{jet}X}}{d\eta_J P_{T,J}} \propto \sum_{a,b,c} \int \frac{dx_a}{x_a} f_a^p(x_a) \int \frac{dx_b}{x_b} f_b^p(x_b) \int \frac{dz_c}{z_c^2} \boxed{d\hat{\sigma}_{ab}^c} \boxed{J_c(z_c)}$$

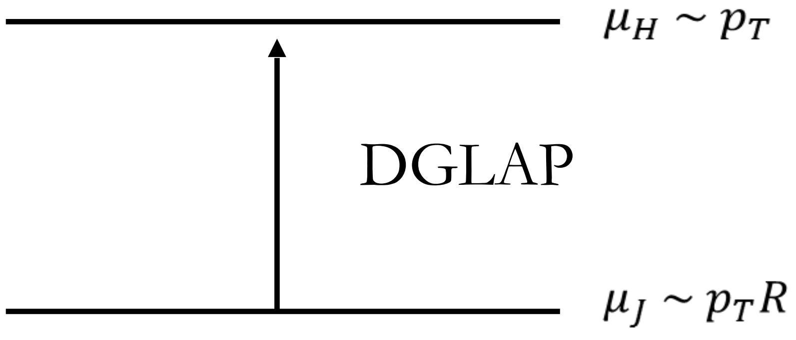
Kang, Ringer, Vitev `16

Factorization



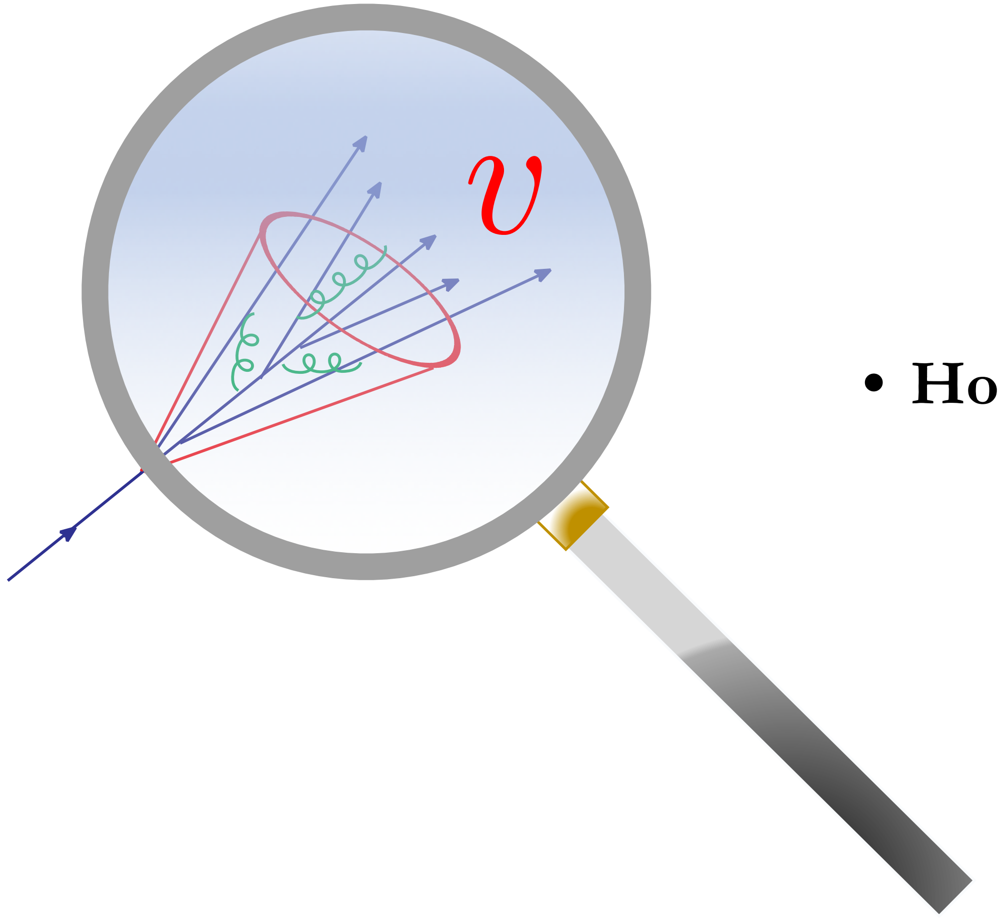
Example of NLO diagrams

- Evolution from μ_J to μ_H gives $(\alpha_s \ln R)^n$ resummations.
- See *Liu, Moch, Ringer `18* for joint resummation of threshold log and jet radius and phenomenology.



- Inclusive jet measurements are only sensitive to hard and collinear radiations!

Jet Substructure Measurements



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

Jet angularity

- Thrust was defined as an event shape parameter to understand radiation pattern

$$T = \frac{1}{Q}\max_{\mathbf{t}} \sum_{i \in X} |\mathbf{t}\cdot\mathbf{p}_i| = 1 - \tau_0$$

- $\tau_0 \to 0$ is equivalent to dijet limit

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

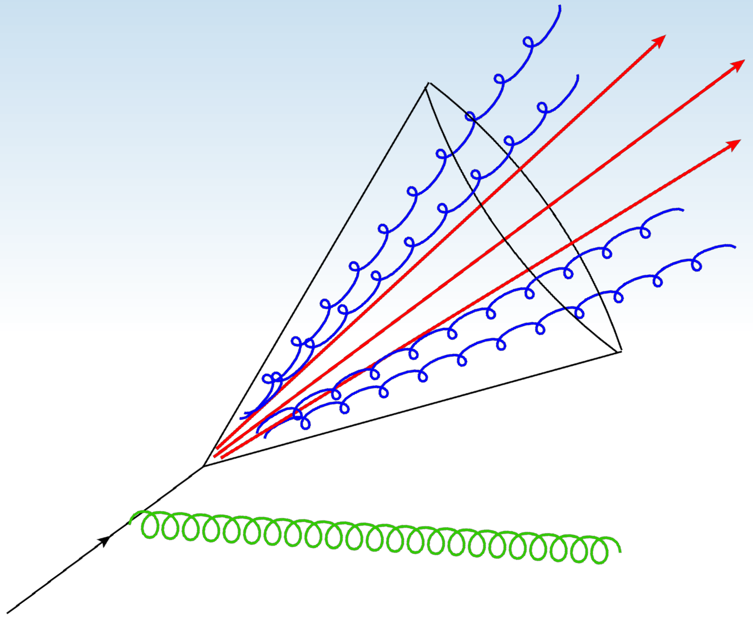
$$\tau_a^{e^+e^-} = \frac{1}{E_J}\sum_{i\in J} E_i \theta_{iJ}^{2-a}$$

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

- 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

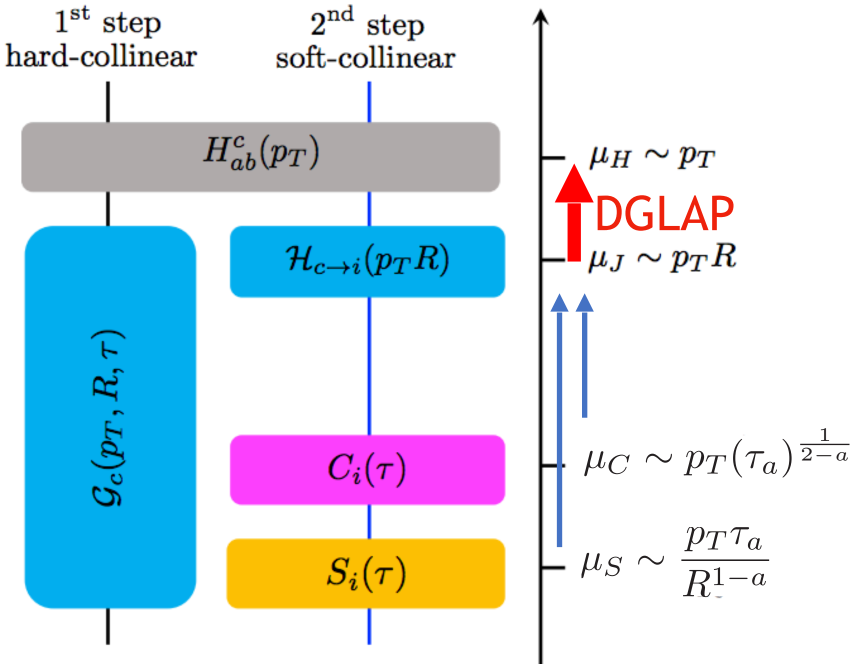
Jet angularity



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

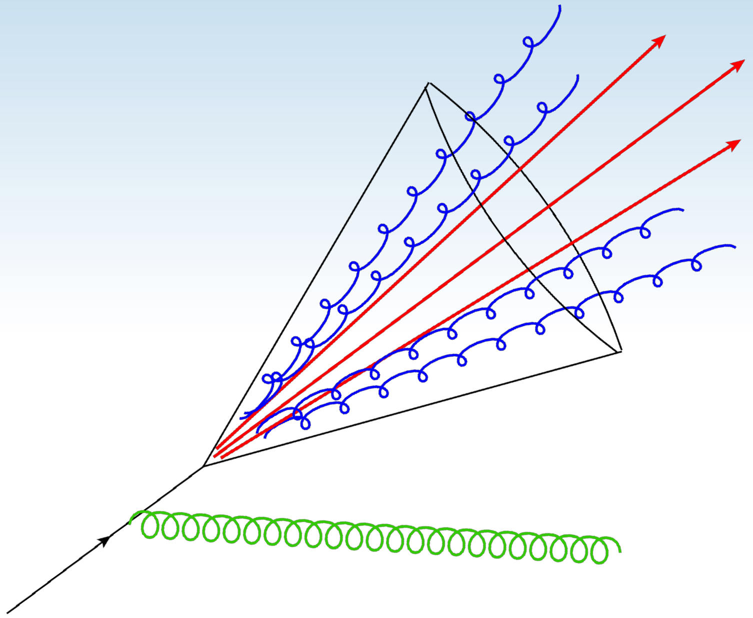
$$\mathcal{G}_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu) \times \int d\tau_a^{C_i} d\tau_a^{S_i} \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) C_i(\tau_a^{C_i}, p_T \tau_a^{\frac{1}{2-a}}, \mu) S_i(\tau_a^{S_i}, \frac{p_T \tau_a}{R^{1-a}}, \mu)$$

- 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

Jet angularity



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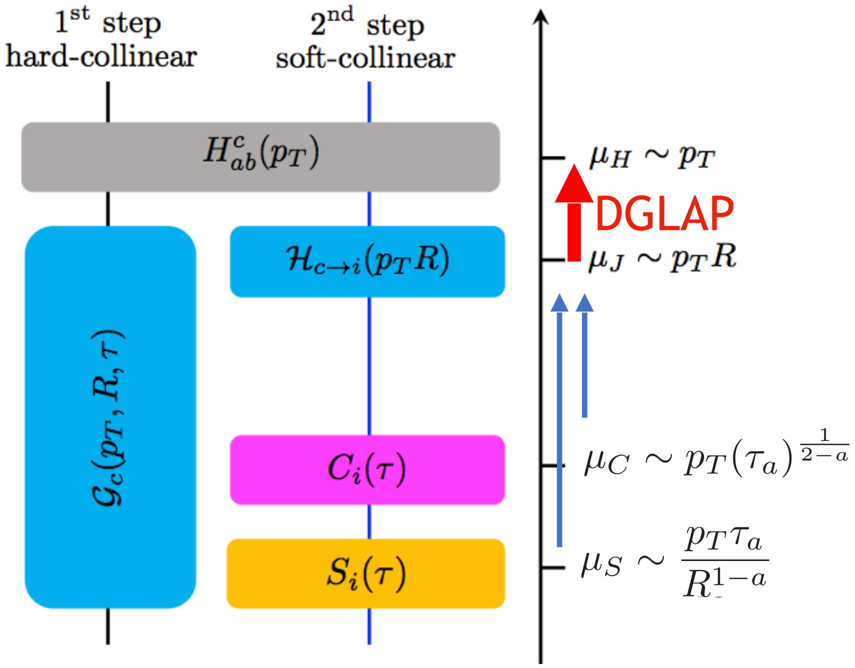
- $H_{c\to i}$, C_i and S_i have double poles, which cancel once evolved to μ_J.

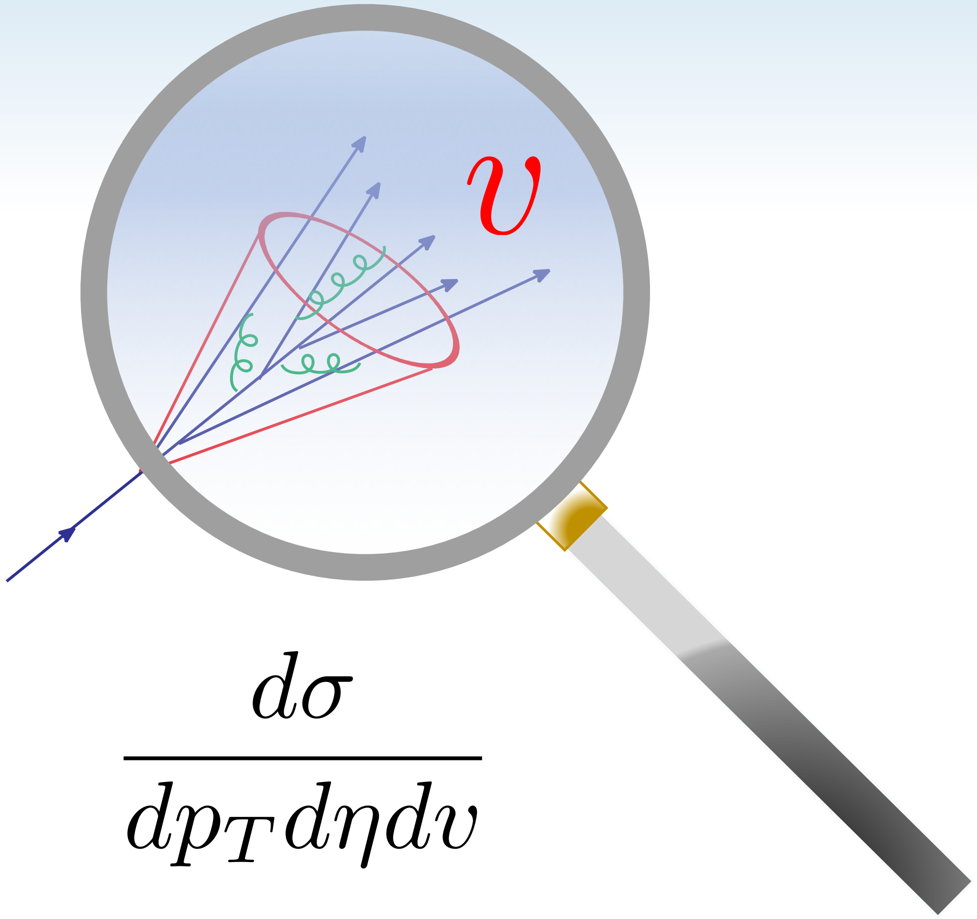
- $\mathcal{G}_c(z, p_T R, \tau_a, \mu)$ follows DGLAP from μ_J to μ_H :

$$\mu\frac{d}{d\mu}\mathcal{G}_i(z, p_T R, \tau_a, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji}(\frac{z}{z'}, \mu) \mathcal{G}_j(z', p_T R, \tau_a, \mu)$$

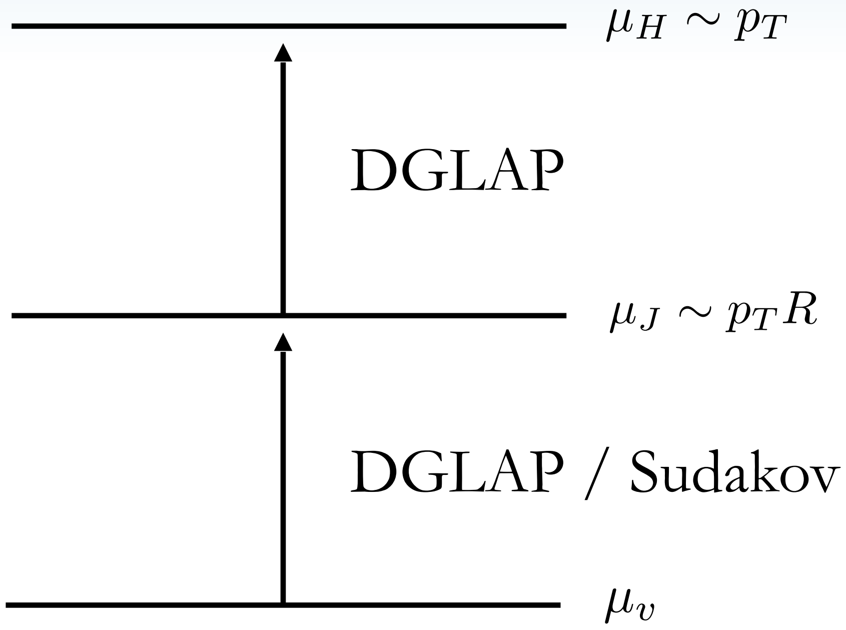


Kang, KL, Ringer `18

Patterns emerging



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



$\mu_H \sim p_T$

DGLAP

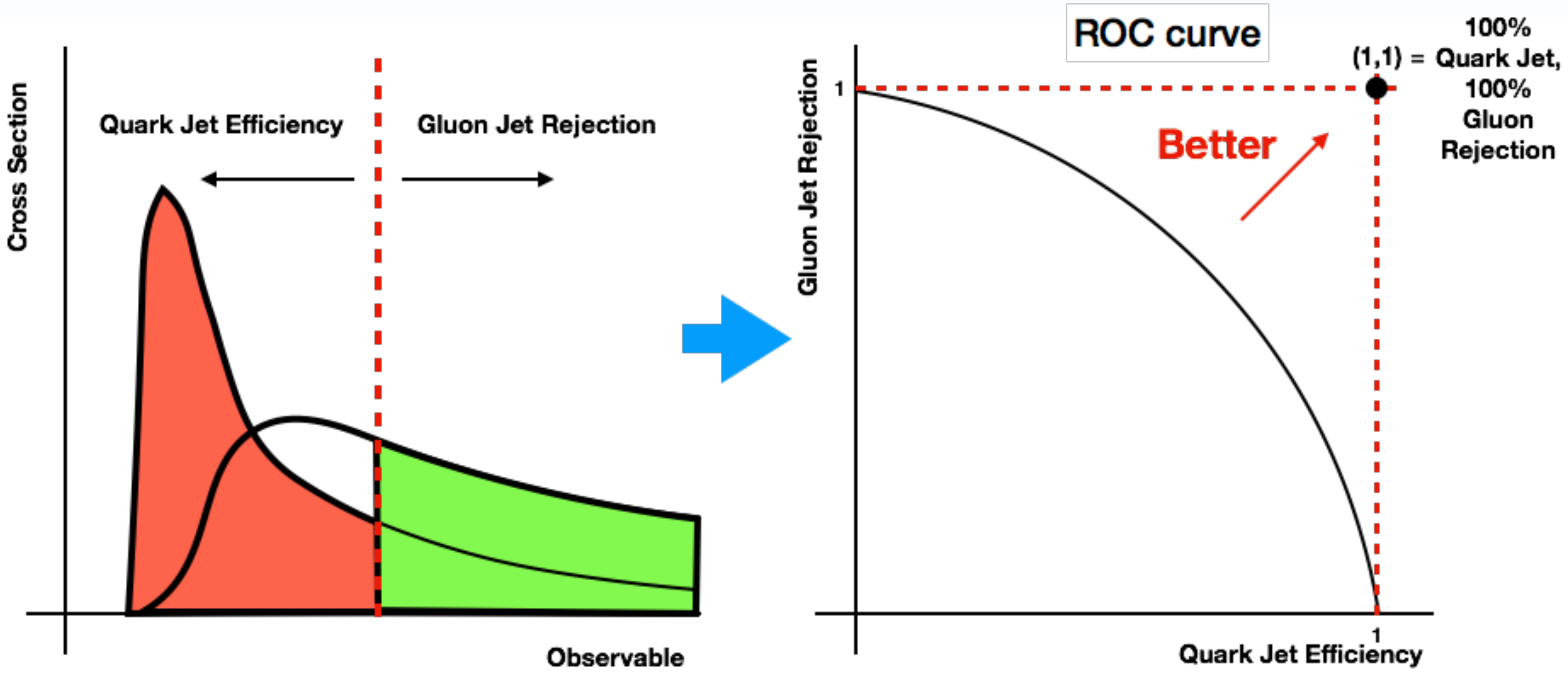
$\mu_J \sim p_T R$

DGLAP / Sudakov

μ_v

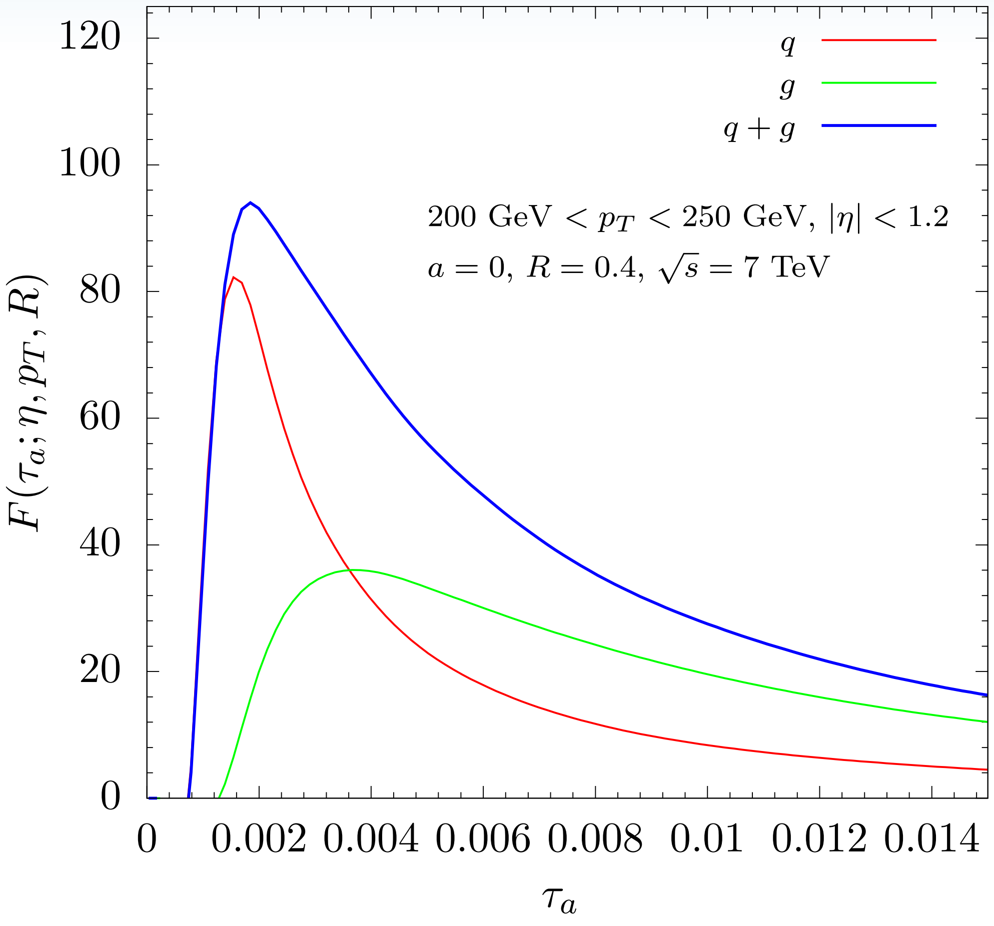
- When we measure substructure v from the jet, once we evolve to μ_J the remaining evolution to μ_H is given by DGLAP evolution!
- Two step factorization:
  a) production of a jet
  b) probing the internal structure of the jet produced.

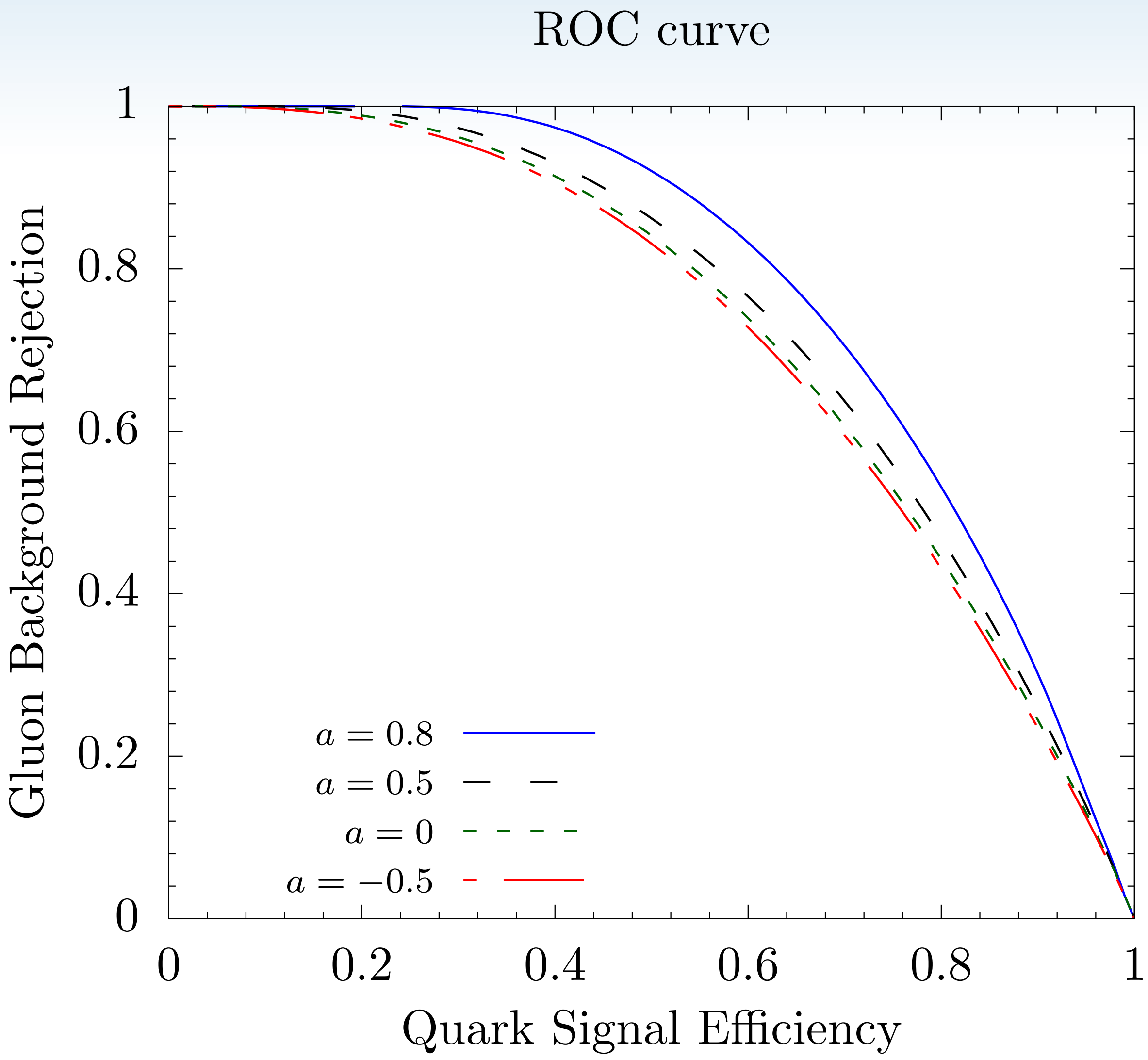
Quark and gluon discrimination



- We can study how well angularity discriminates between quark and gluon jet as a continuous function of ‘a’.

Quark and gluon discrimination

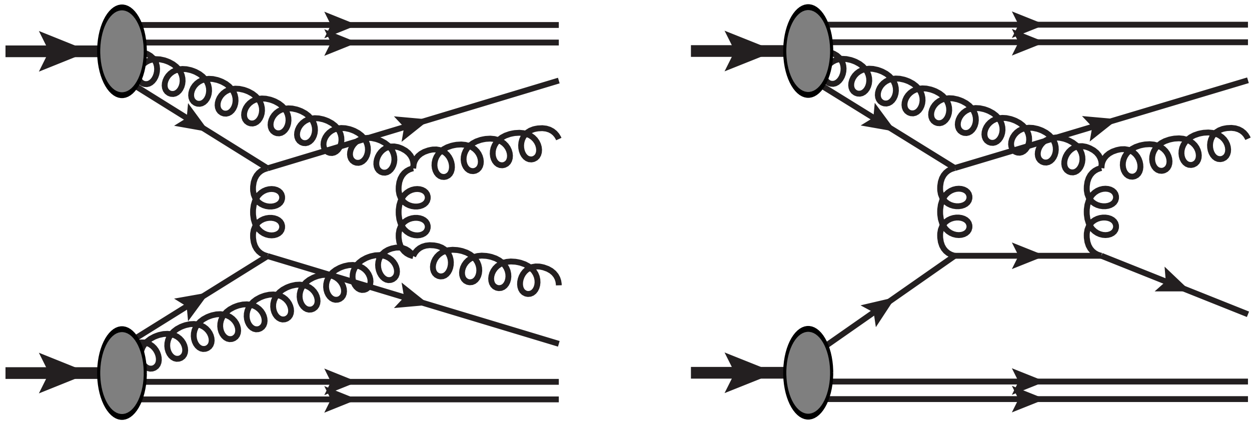




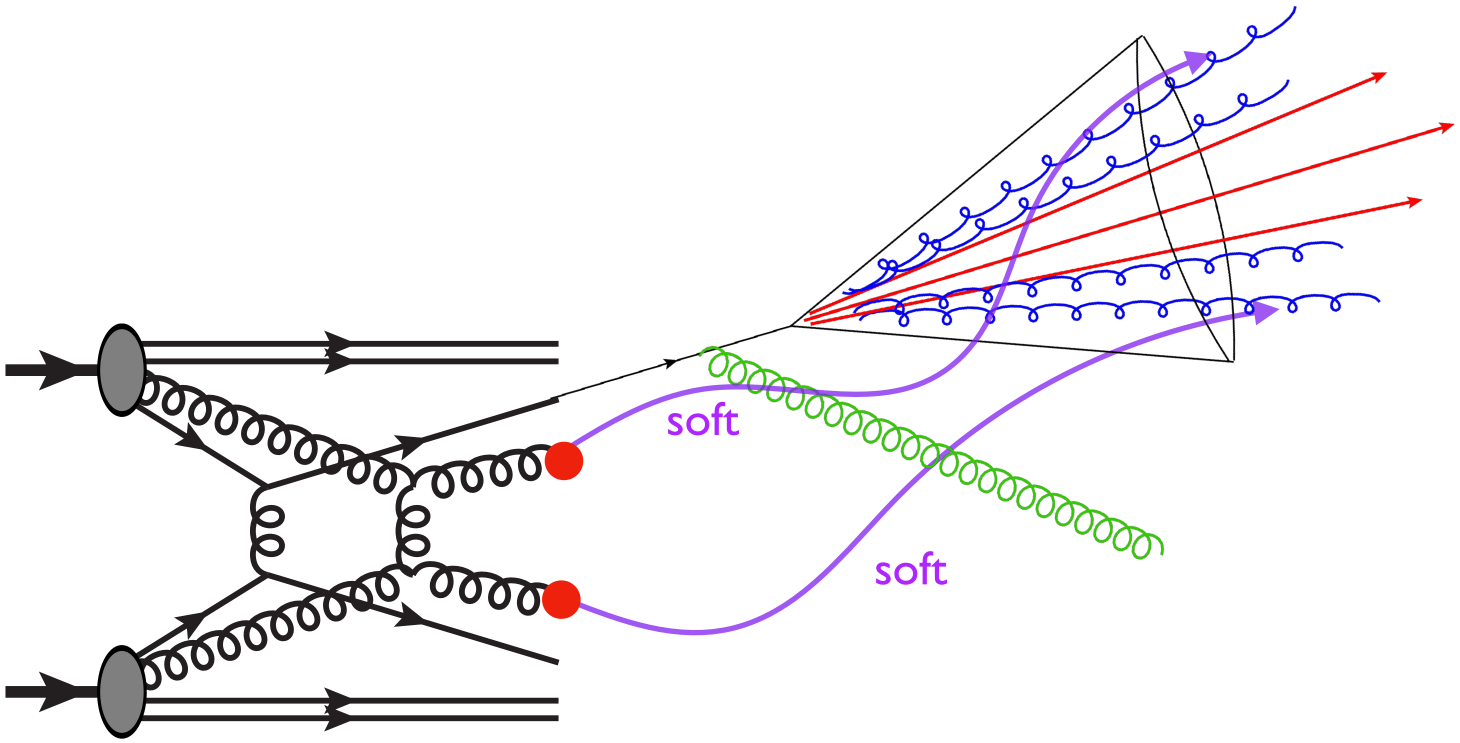
- We can study how well angularity discriminates between quark and gluon jet as a continuous function of ‘a’.
- As 'a’ increases, better discrimination but more sensitive to non-perturbative effects.

Non-perturbative Model

- Non-perturbative effects:



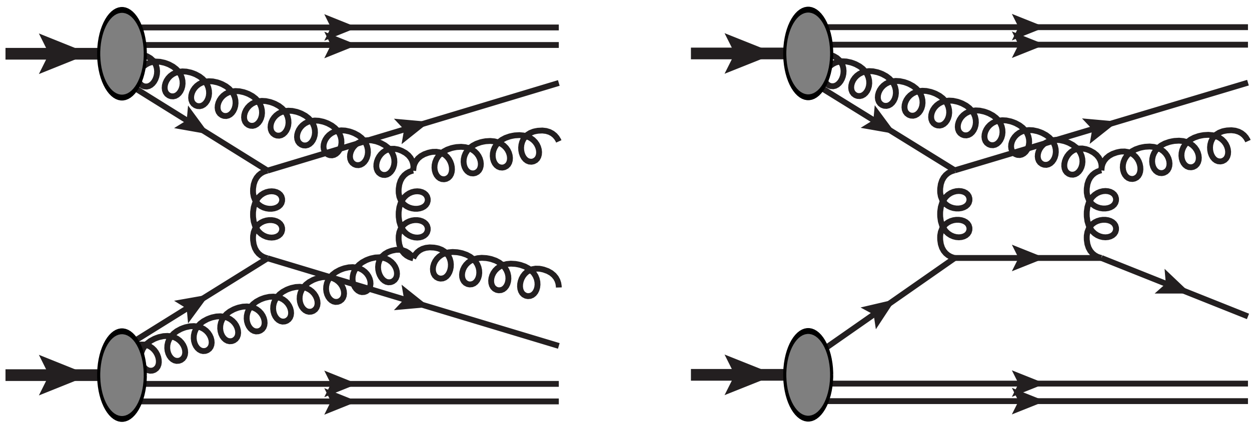
Figs from P. Bartalini et al. `11



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

Non-perturbative Model

- **Non-perturbative effects:**



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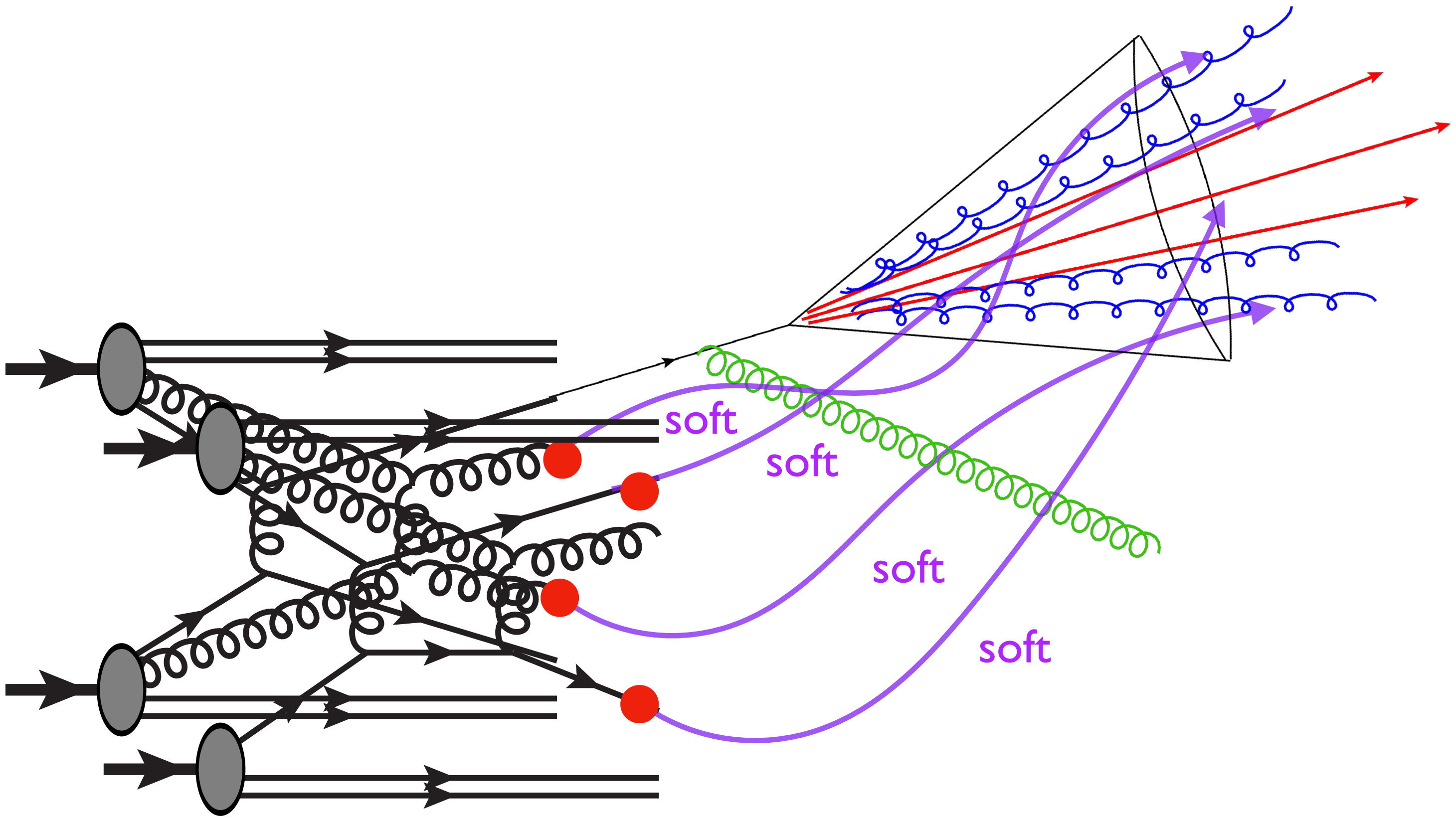
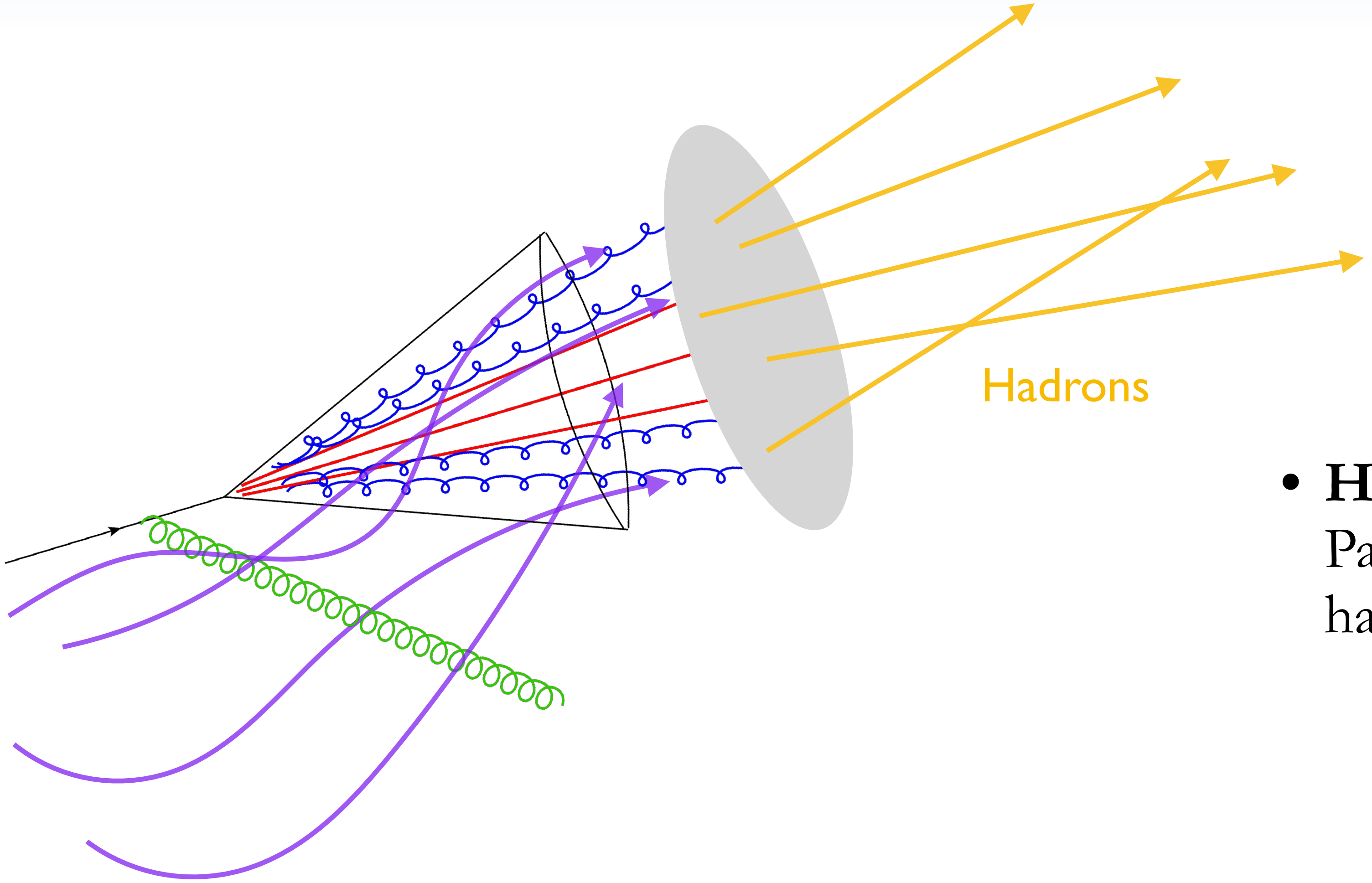


- **Multi-Parton Interactions (MPI) (Underlying Events (UE))** Multiple secondary scatterings of partons within the protons may enter and contaminate jet.
- **Pileups** Secondary proton collisions in a bunch may enter and contaminate jet.

Non-perturbative Model

- **Non-perturbative effects:**



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

Non-perturbative Model

- As τ_a gets smaller, $\mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$ (smallest scale) can approach a non-perturbative scale.

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

$$\frac{d\sigma}{d\eta dp_T d\tau_a} = \int dk F(k) \frac{d\sigma^{\text{pert}}}{d\eta dp_T d\tau_a}\left(\tau_a - \frac{R^{1-a}}{p_T} k\right)$$

- Single parameter NP soft function :

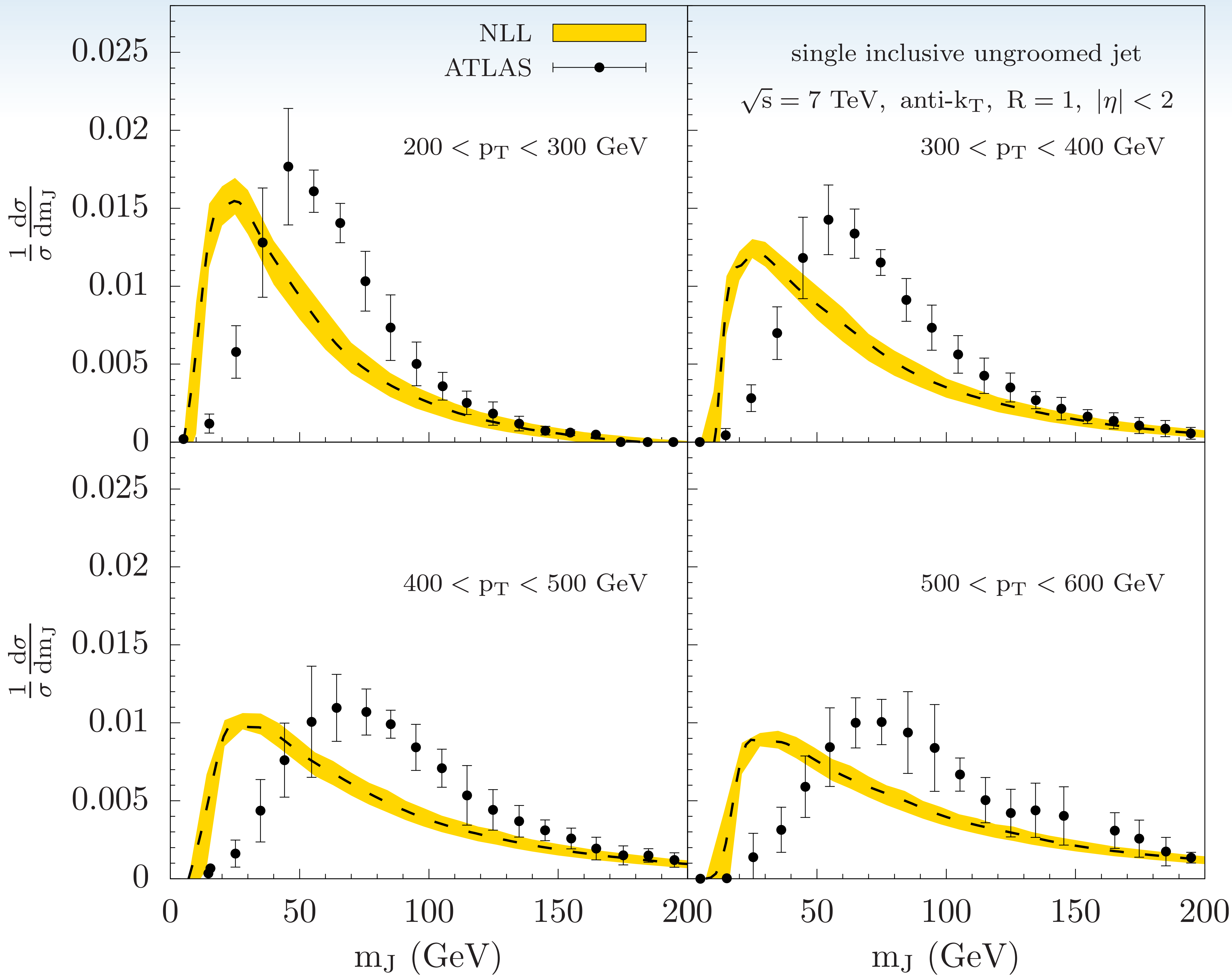
$$F_\kappa(k) = \left(\frac{4k}{\Omega_\kappa^2}\right) \exp\left(-\frac{2k}{\Omega_\kappa}\right)$$

Stewart, Tackmann, Waalewijn `15

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

- $\int dk\ k\ F_\kappa(k) = \Omega_\kappa(R)$, represents the non-perturbative parameter and $\sim 1\ \text{GeV} \sim \Lambda_{\text{hadrons}}$ corresponds to non-perturbative effects coming primarily from the hadronization alone.

Phenomenology (a=0, jet mass)



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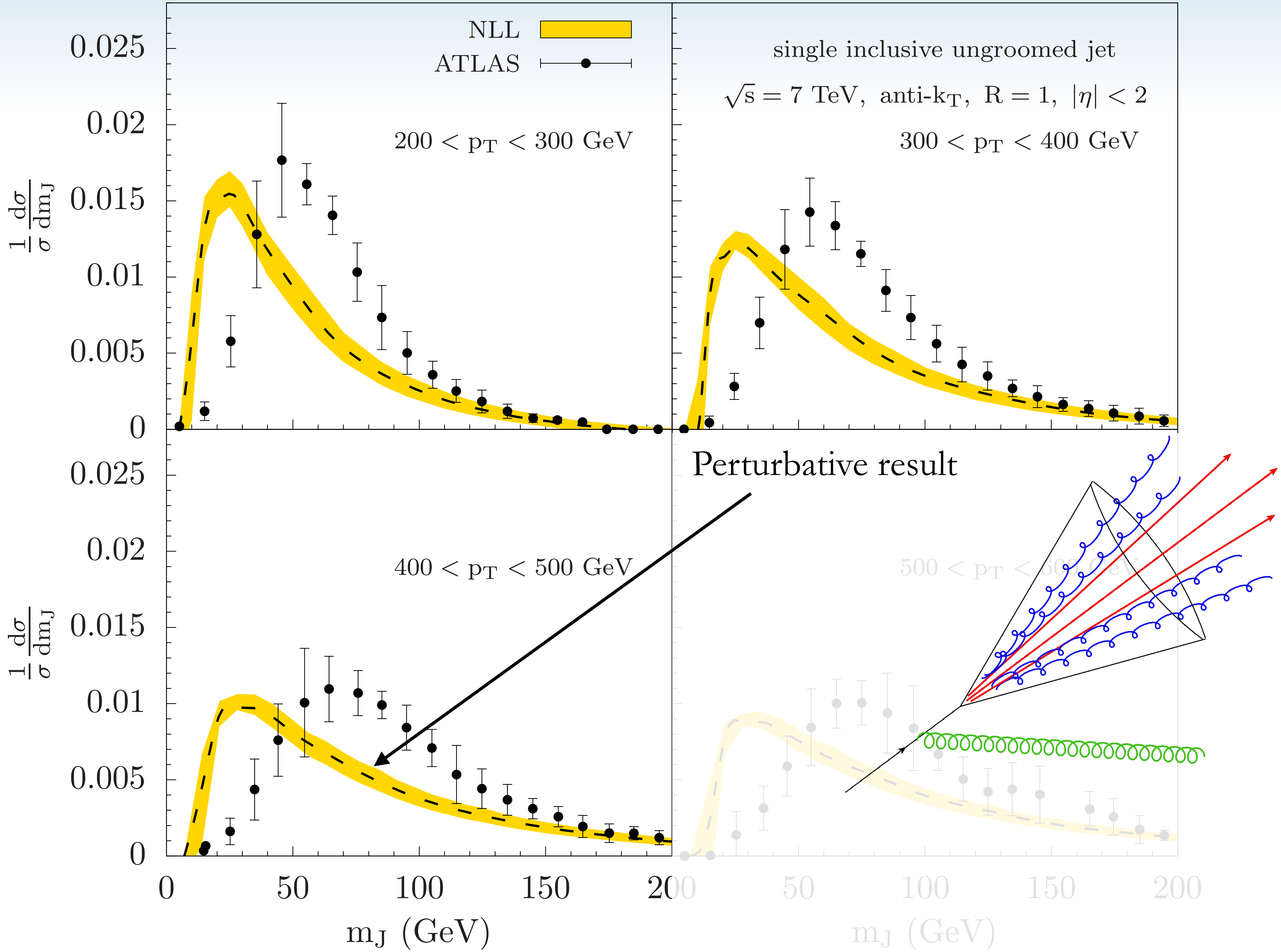
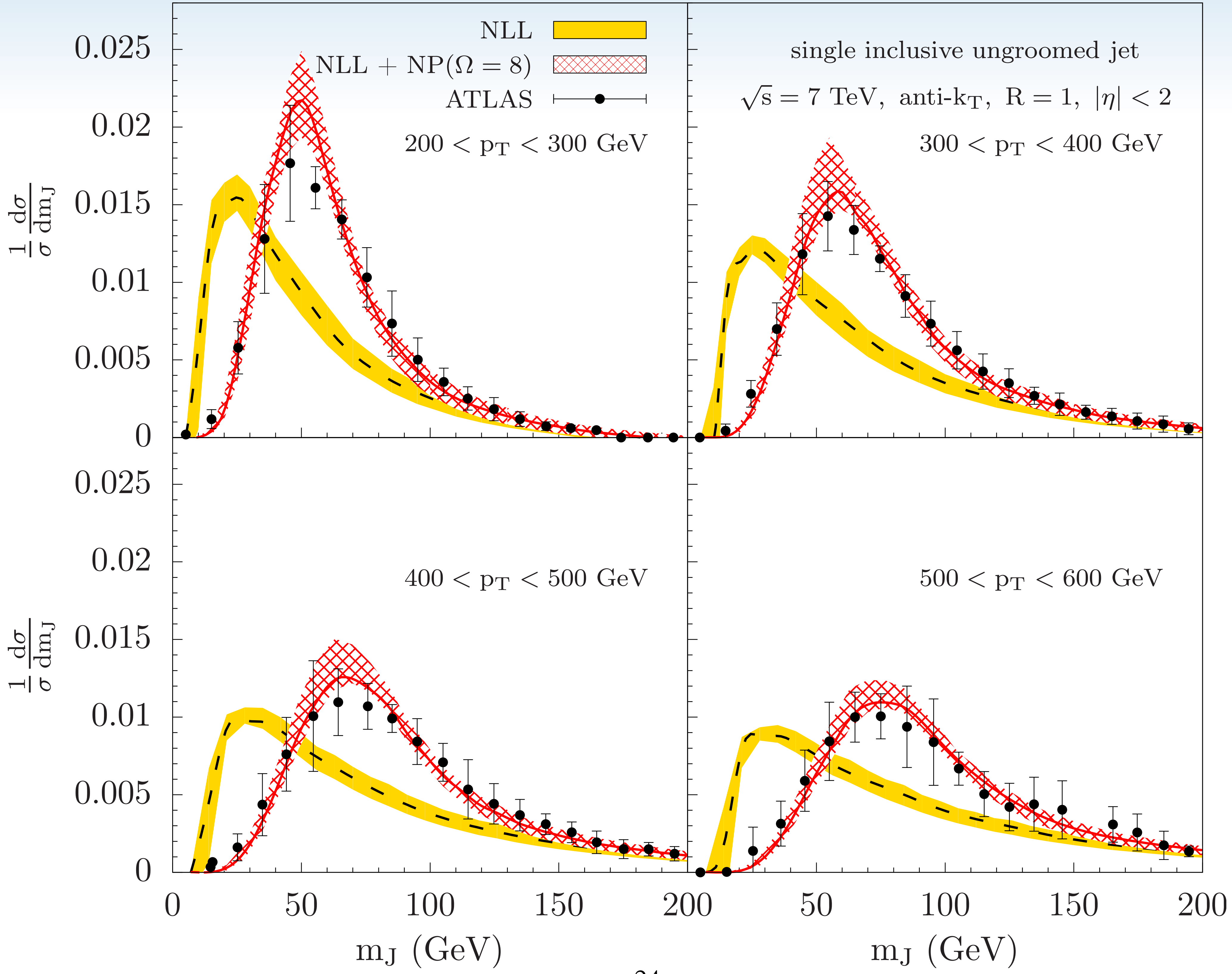


Perturbative result

Phenomenology (a=0, jet mass)



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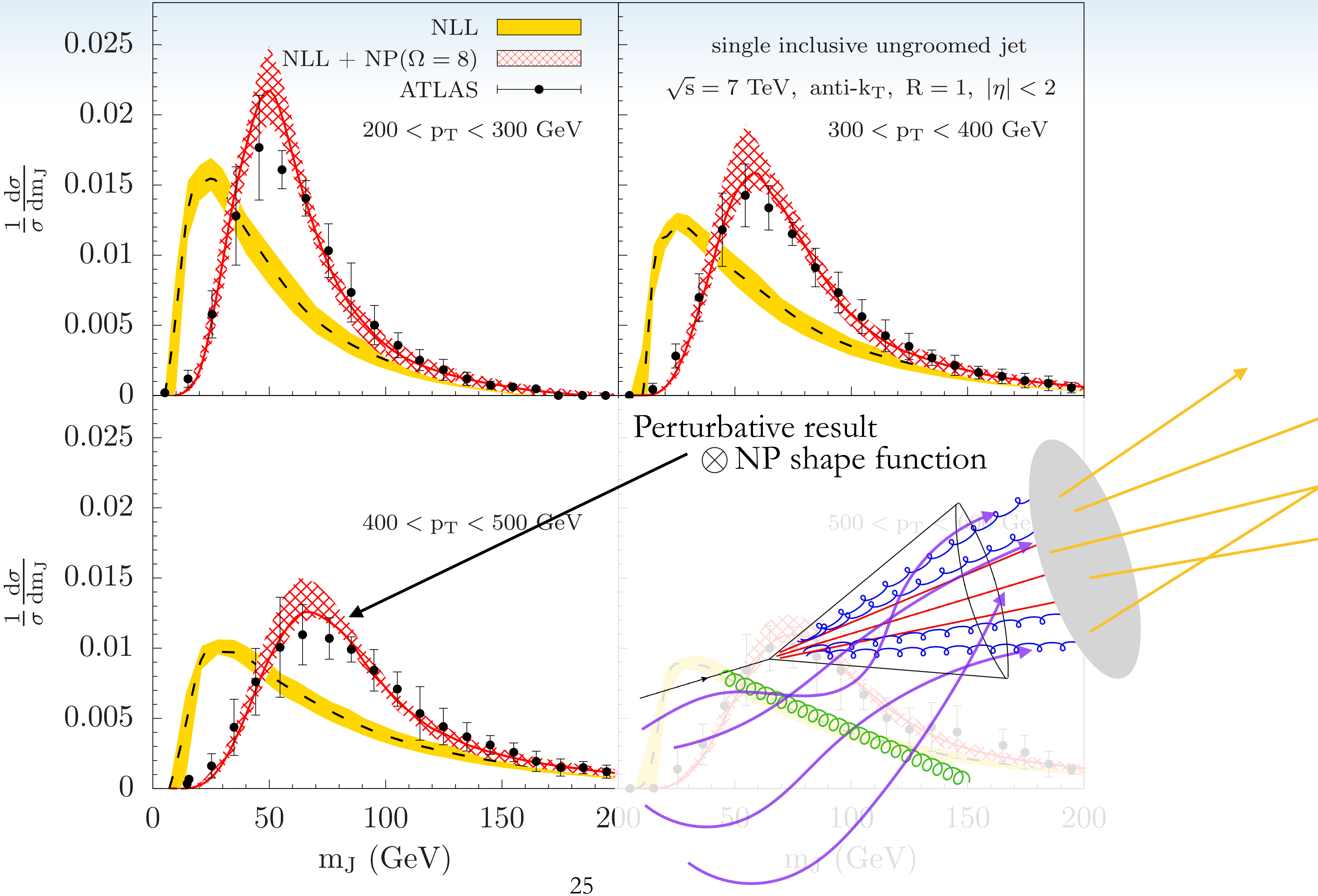


Perturbative result

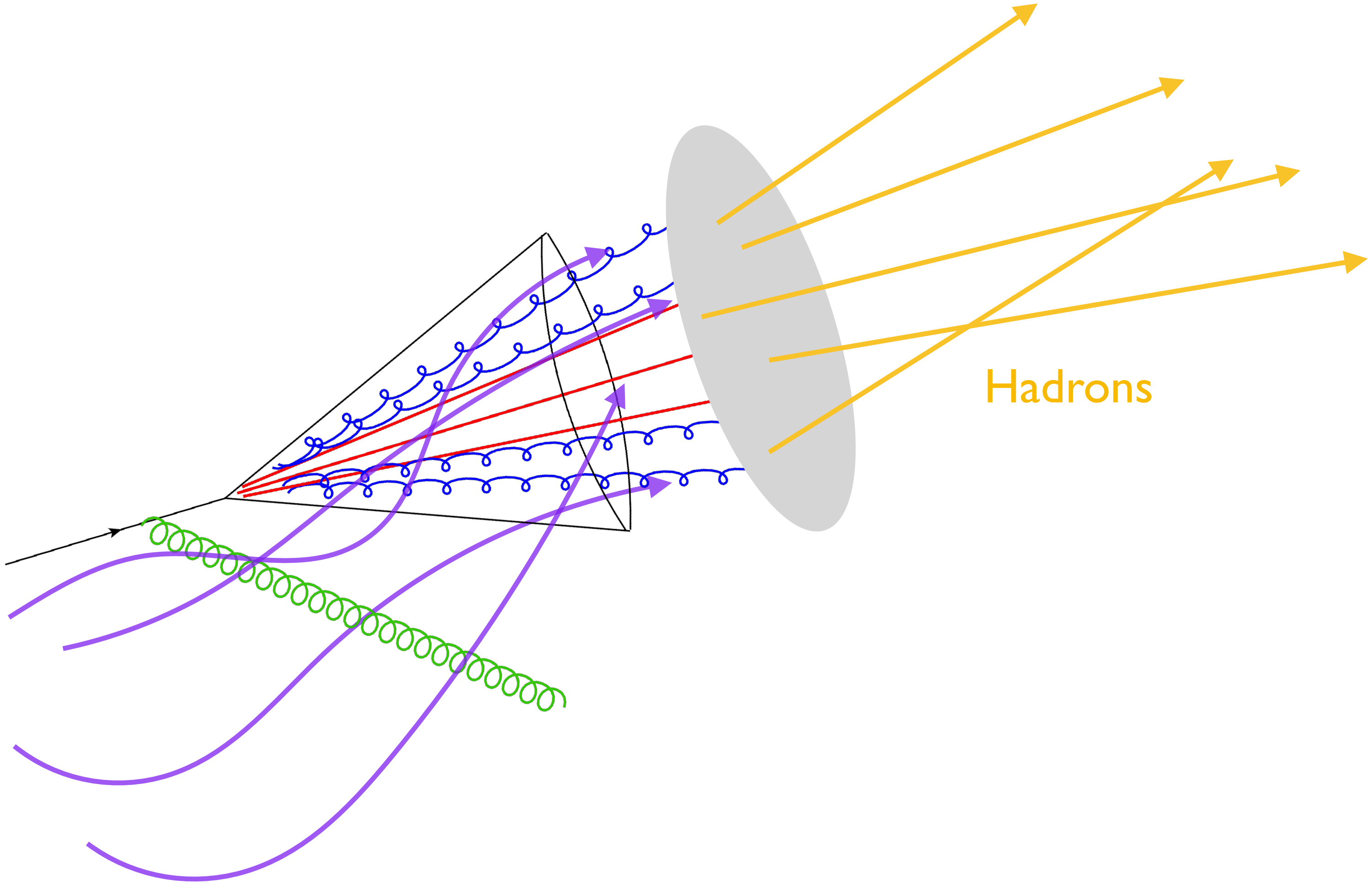
⊗ NP shape function

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.**



Soft Drop Grooming

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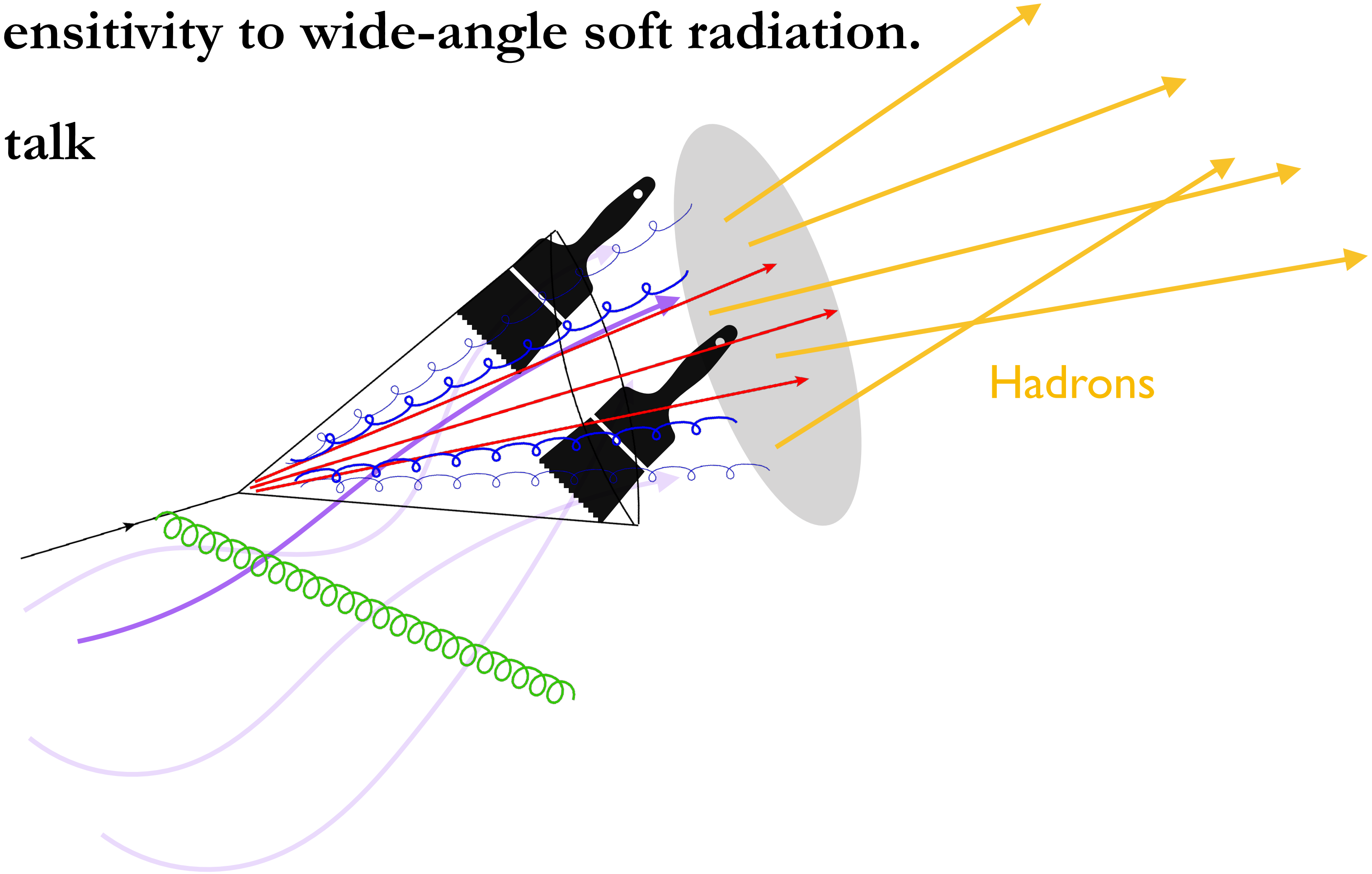
  Groom jets to reduce sensitivity to wide-angle soft radiation.

  Also see Varun's talk



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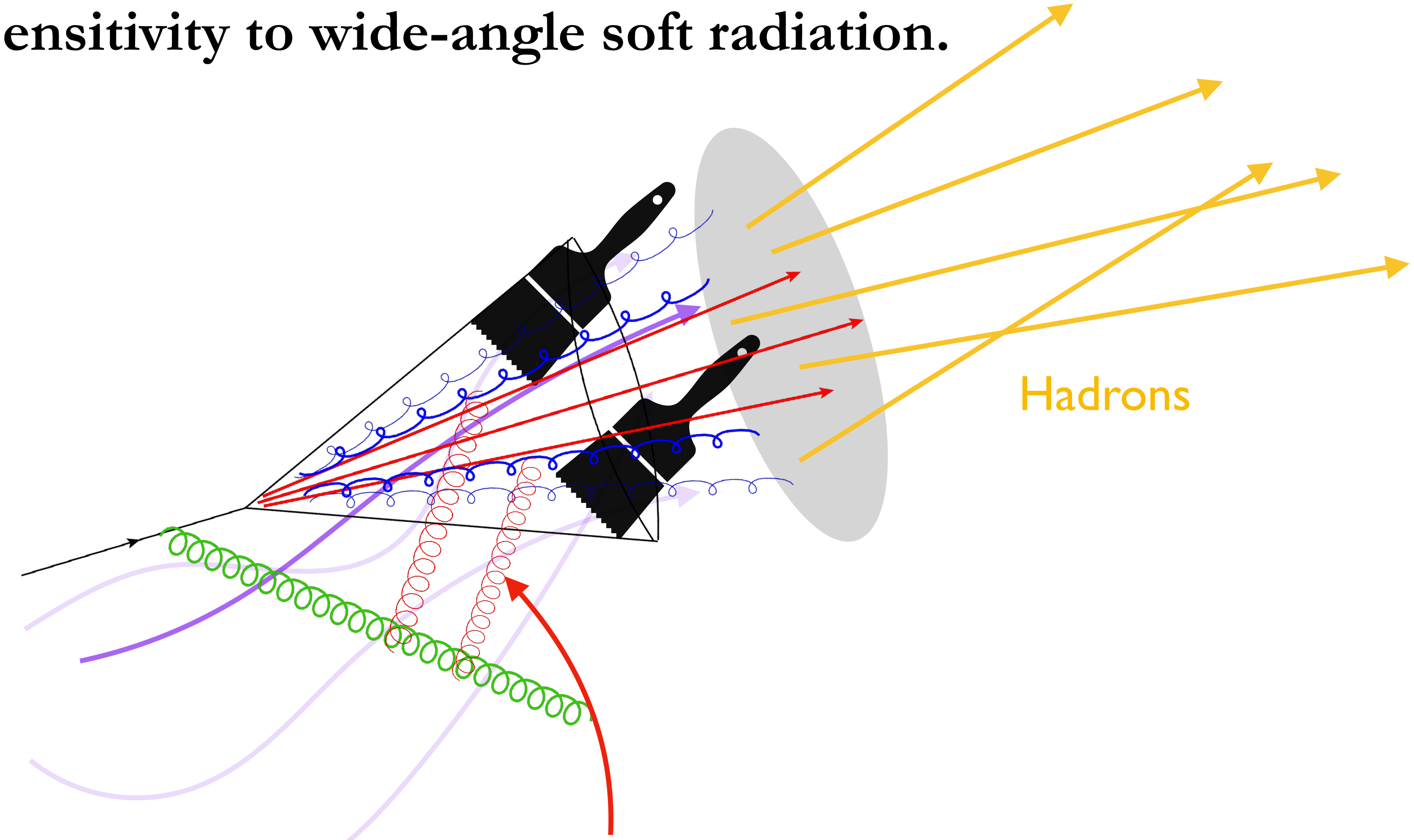

- Also reduces sensitivities to the NGLs associated with the correlation between in-jet and out-of-jet radiation. See Felix's talk.

Soft Drop Grooming

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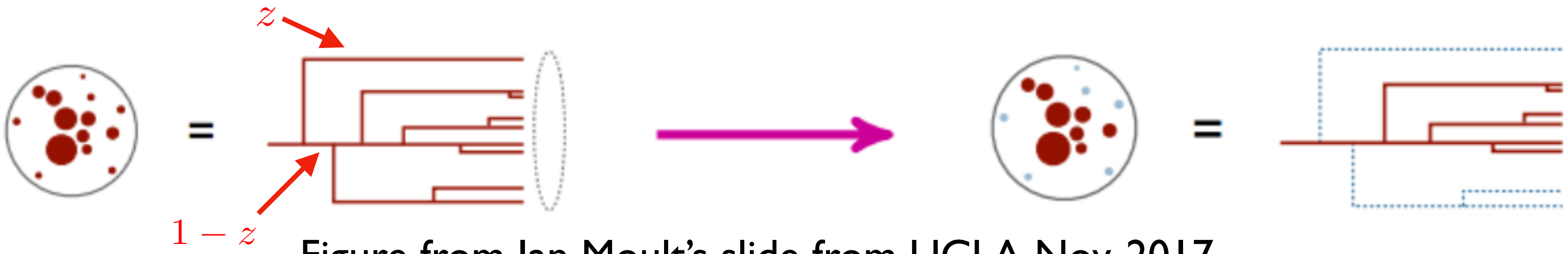


Figure from Ian Moult's slide from UCLA Nov, 2017

- **Soft drop grooming algorithms:**

1. Reorder emissions in the identified jet according to their relative angle using C/A jet algorithm.

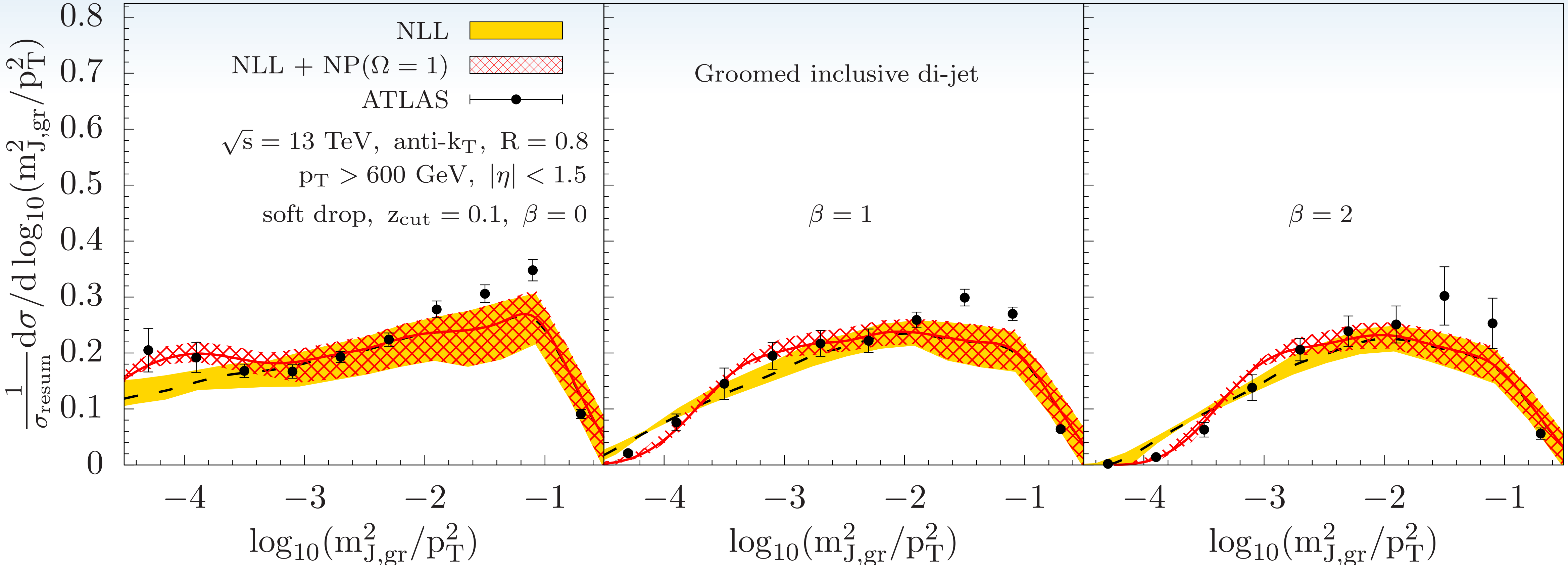
2. Recursively remove soft branches until soft drop condition is met:

$$\frac{\min[p_{T,i}, p_{T,j}]}{p_{T,i}+p_{T,j}} > z_{\mathrm{cut}} \left(\frac{R_{ij}}{R}\right)^{\beta}$$

Larkoski, Marzani, Soyez, Thaler `14
Frye, Larkoski, Schwartz, Yan `16

Phenomenology (groomed jet mass)

Kang, KL, Liu, Ringer `18



- 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

Photoproduction at the EIC

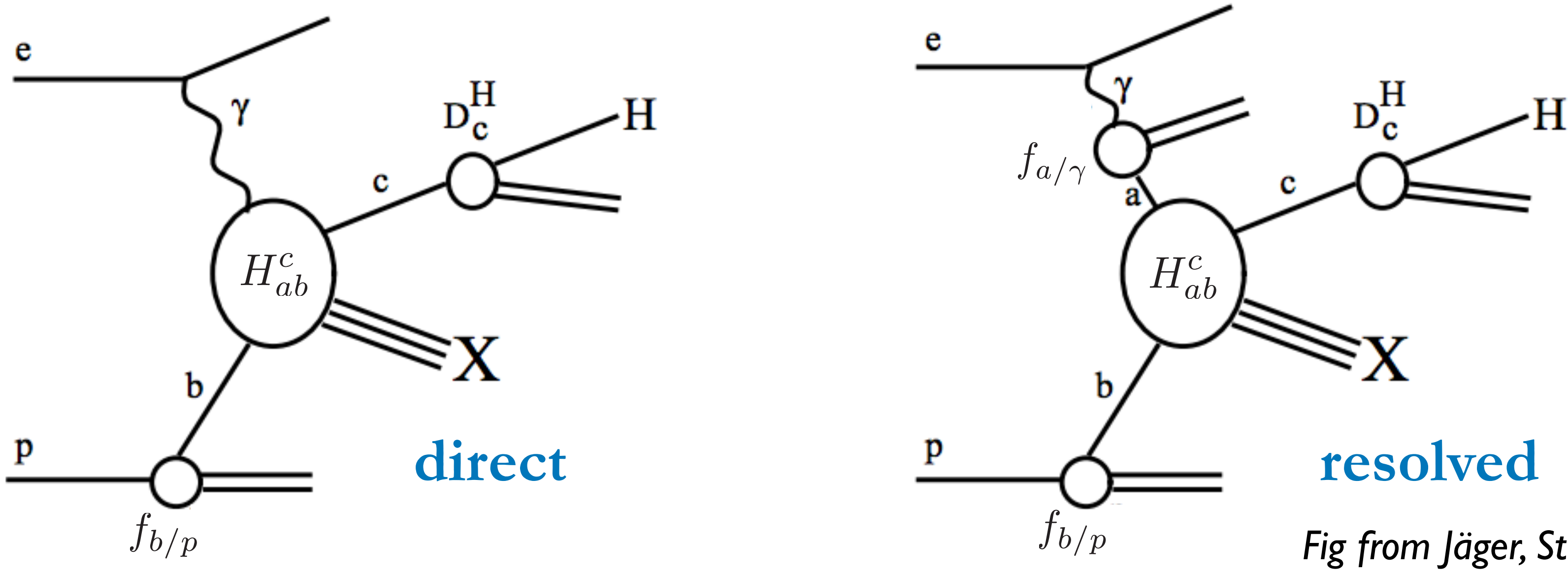


Fig from Jäger, Stratmann, Vogelsang `03

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

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 $Q^2 < 0.1\ \mathrm{GeV}^2$ (near on-shell photon)

See Jäger, Stratmann, Vogelsang `03

Photoproduction at the EIC

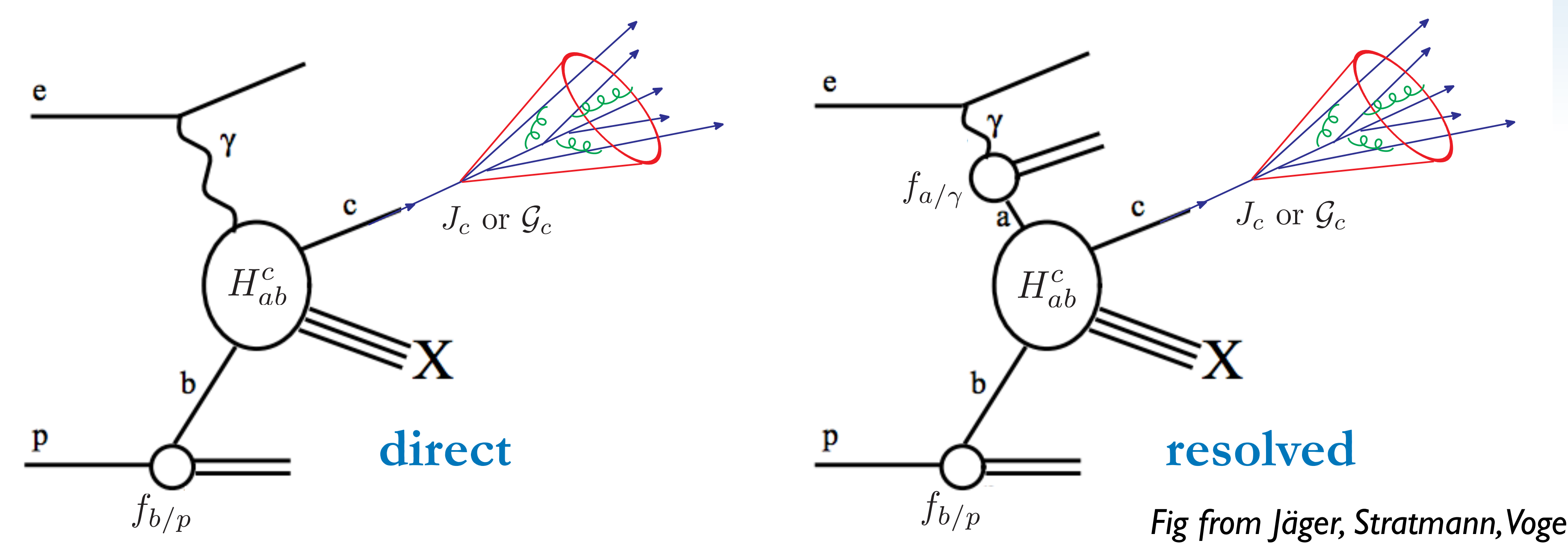


Fig from Jäger, Stratmann, Vogelsang `03

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

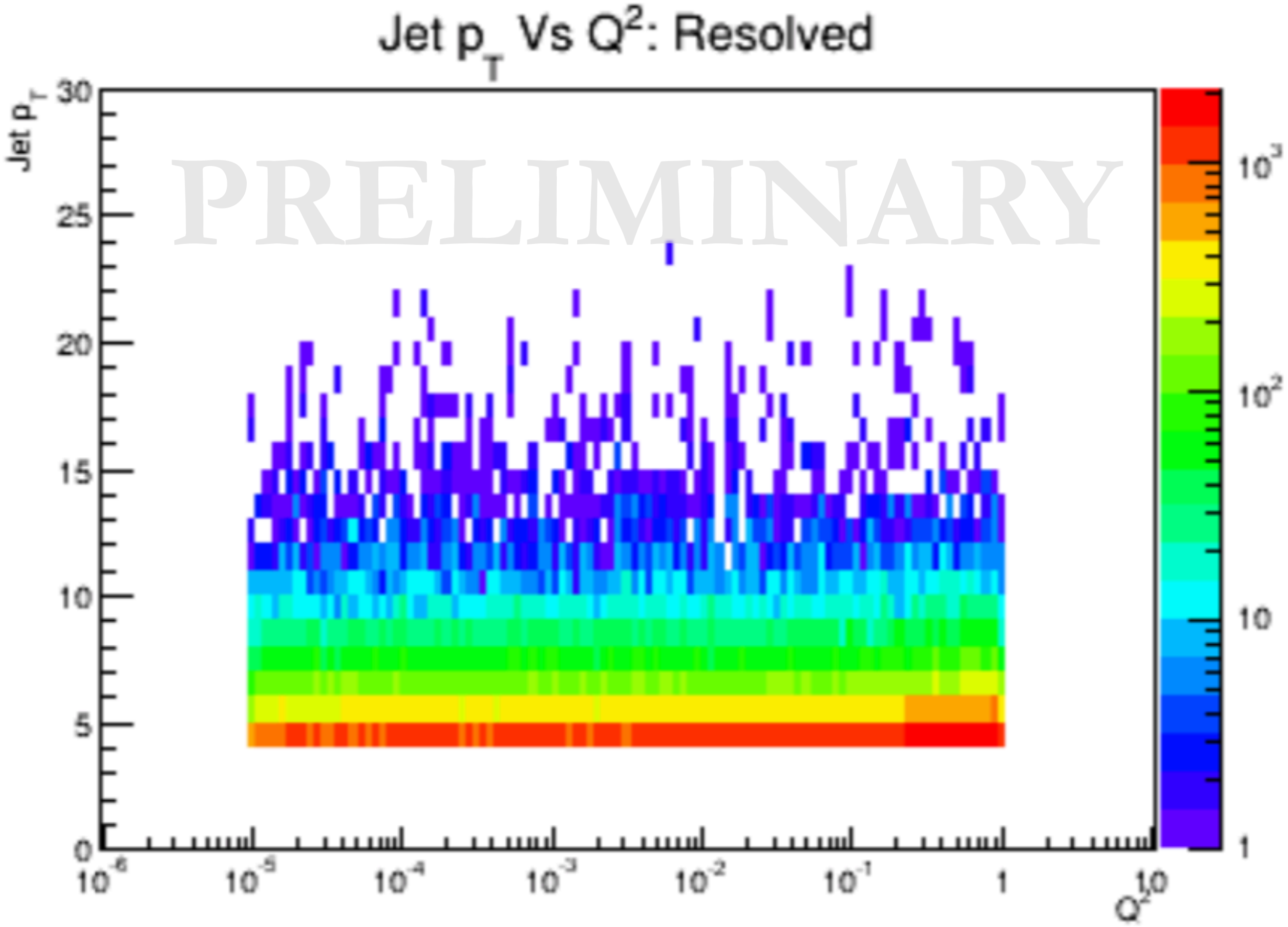
Inclusive Jet $$\frac{d\sigma^{ep\to e\mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes J_c + \mathcal{O}(R^2)$$

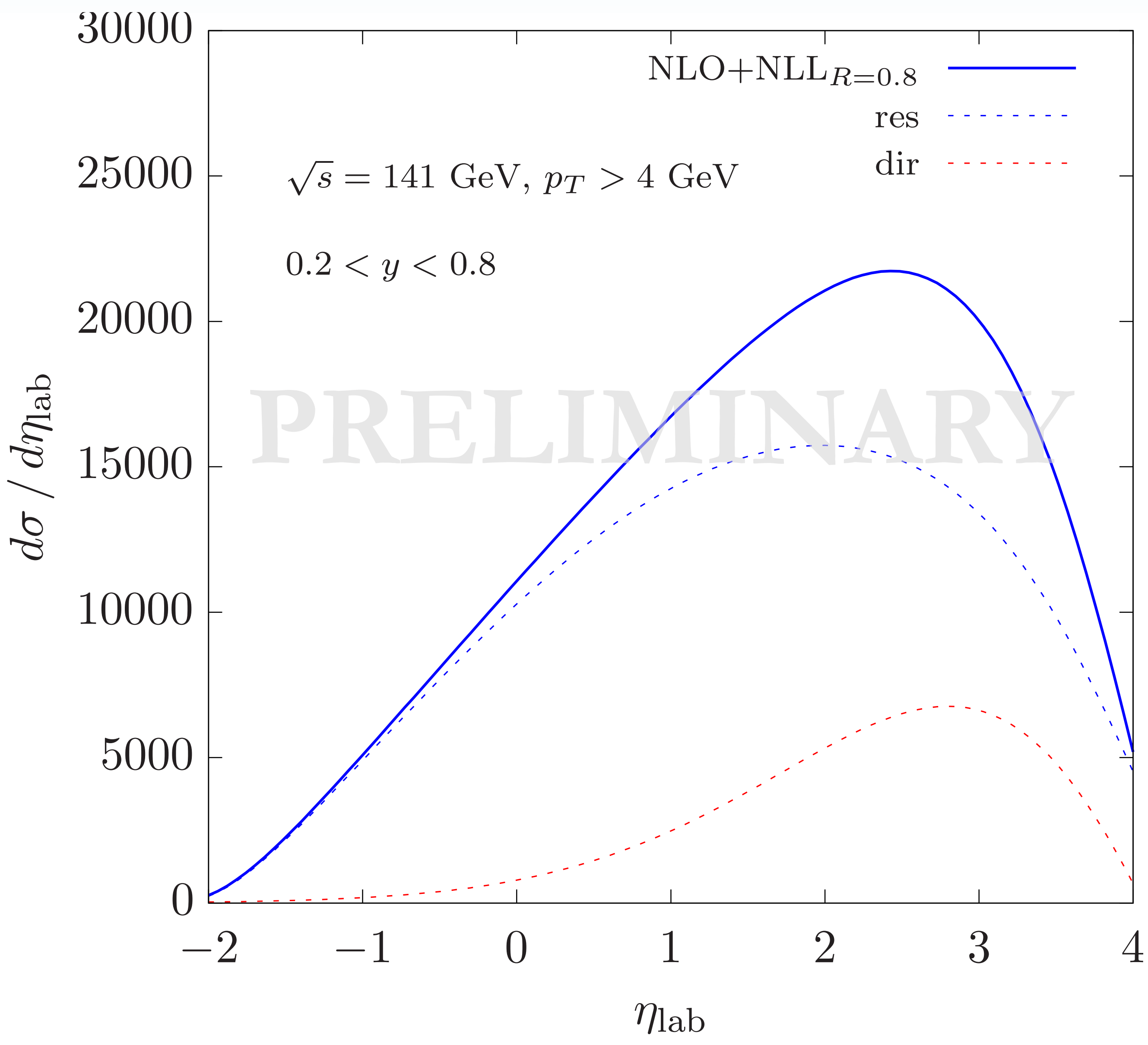
Jet mass $$\frac{d\sigma^{ep\to e\mathrm{jet}(m_J)X}}{dp_T d\eta dm_J} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes \mathcal{G}_c(m_J) + \mathcal{O}(R^2)$$

- 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

- $5\text{ GeV} < p_T < 15\text{ GeV}$ for $Q^2 < 1$ GeV, contribution mostly from resolved.

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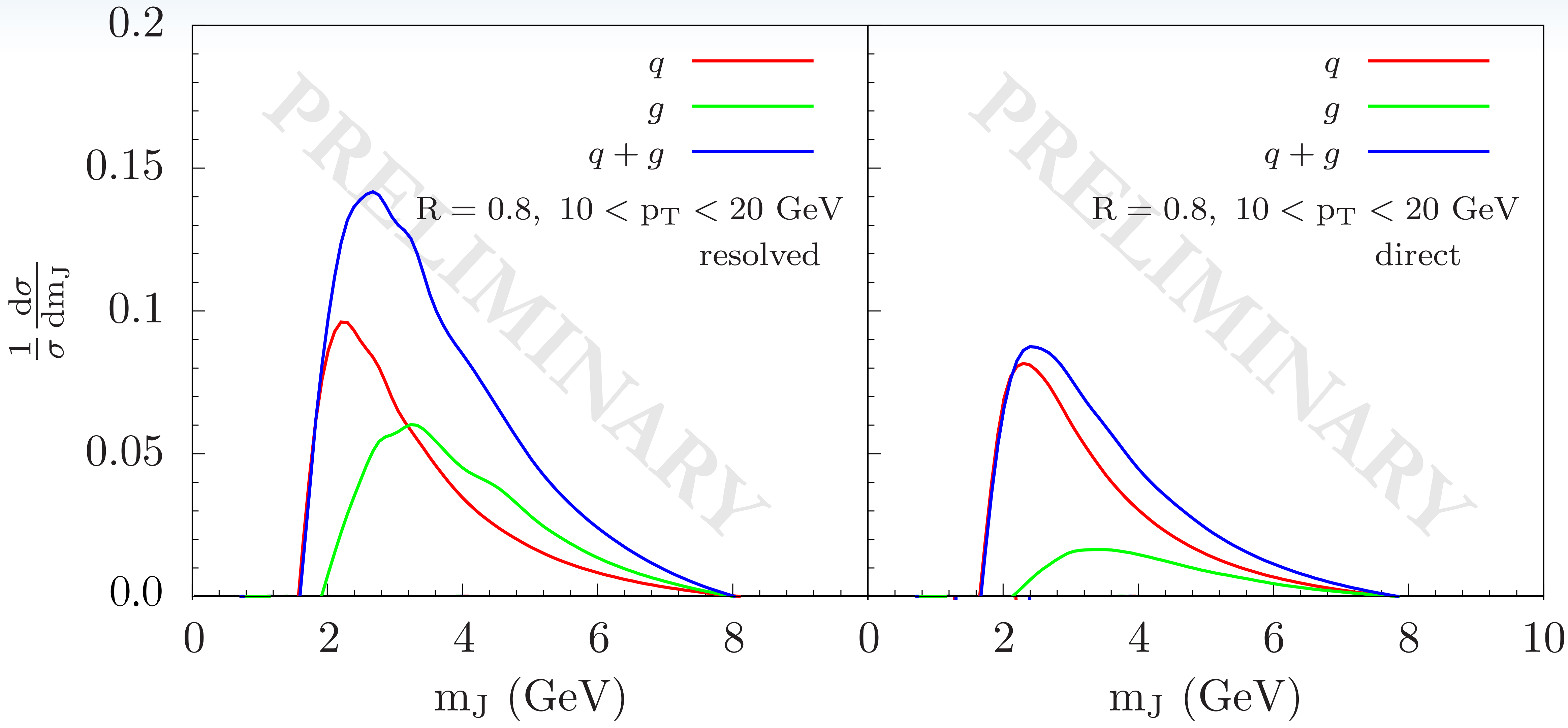
Preliminary Plots



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

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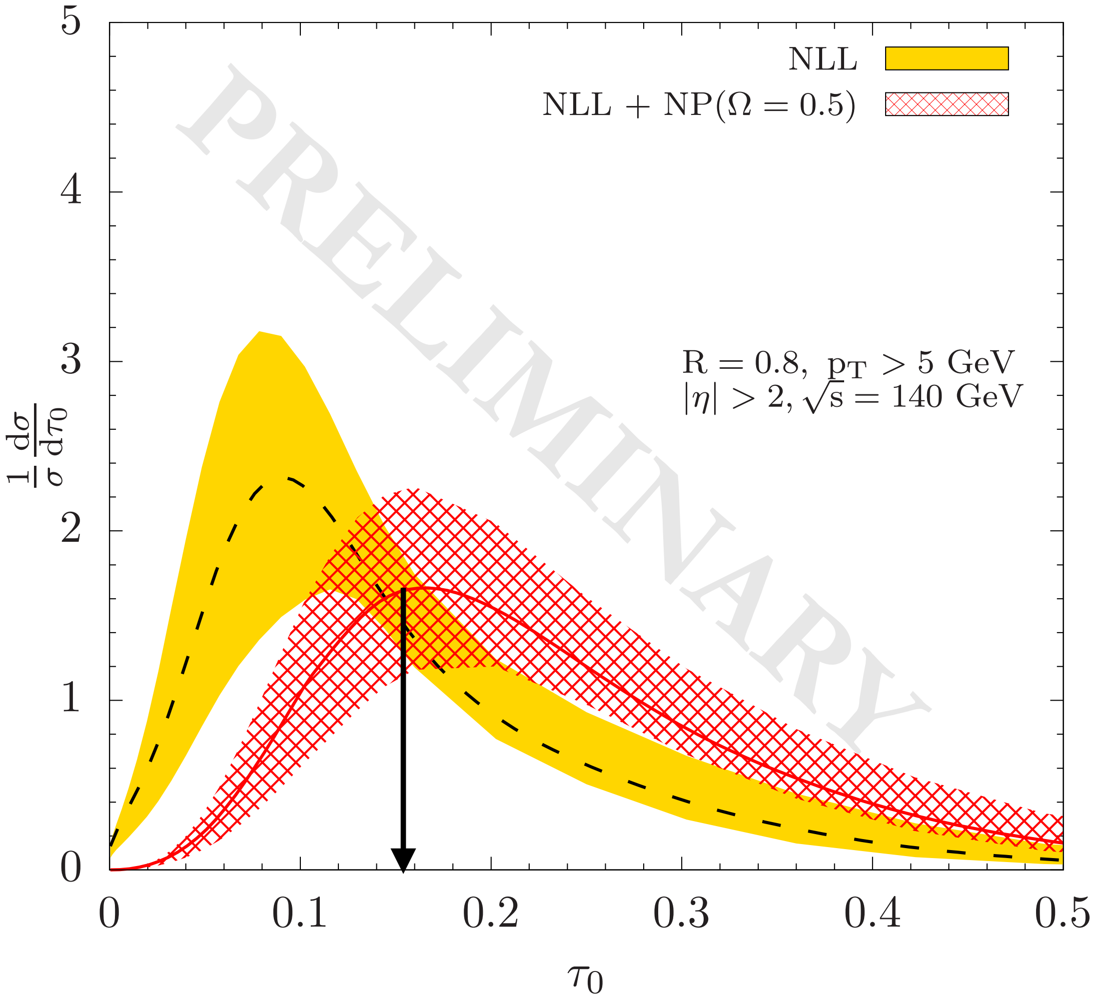
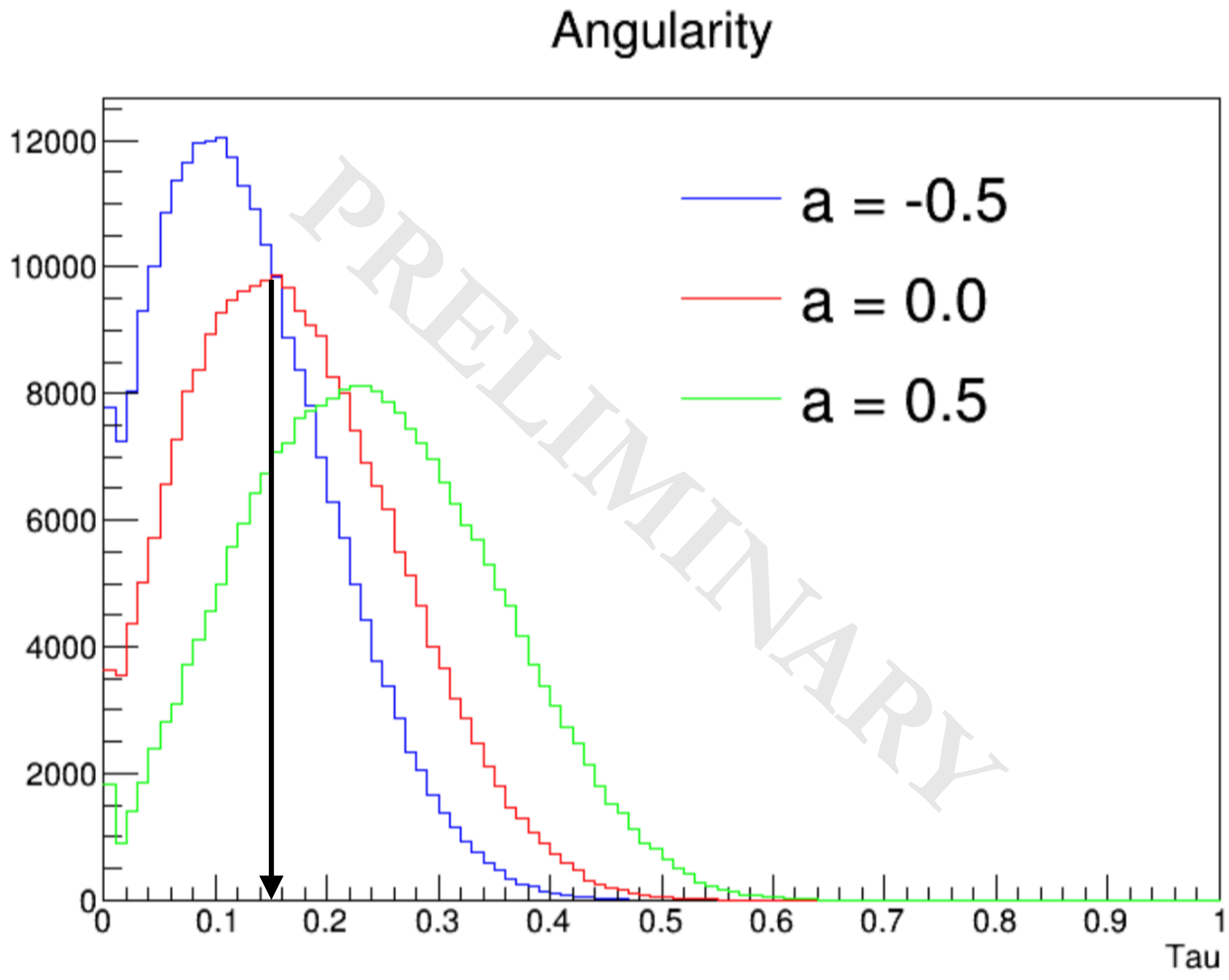
Preliminary Plots





- **Monte Carlo**

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

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Conclusions

- Formalism for studying semi-inclusive jet production with or without substructure measurements were introduced.

- From μ_J to μ_H , the semi-inclusive jet production follows DGLAP evolution.

- Discussed various non-perturbative effects and grooming which reduces contamination from the Underlying Events and Pileups.

- Formalism was extended to the photoproduction case in the EIC and showed that EIC has cleaner environments than the LHC.