Jet mass for the semi-inclusive jet production at the LHC

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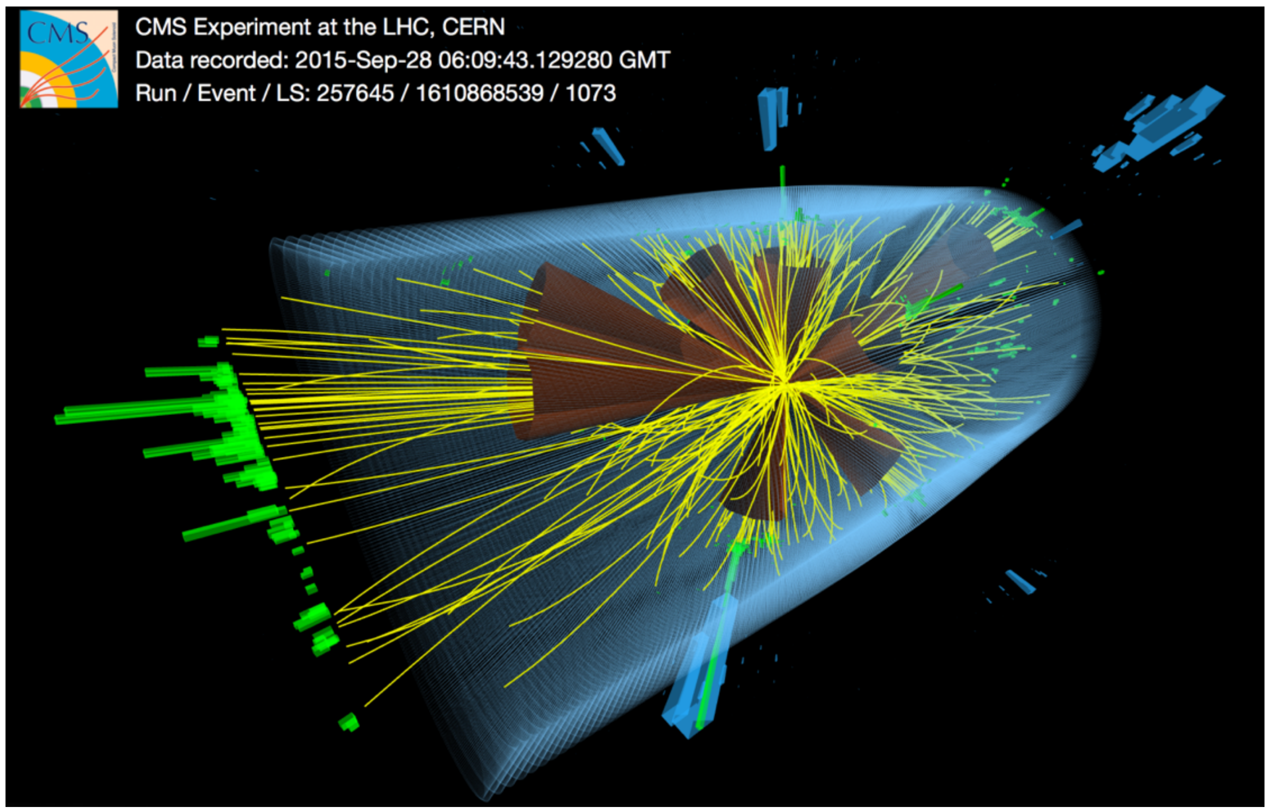
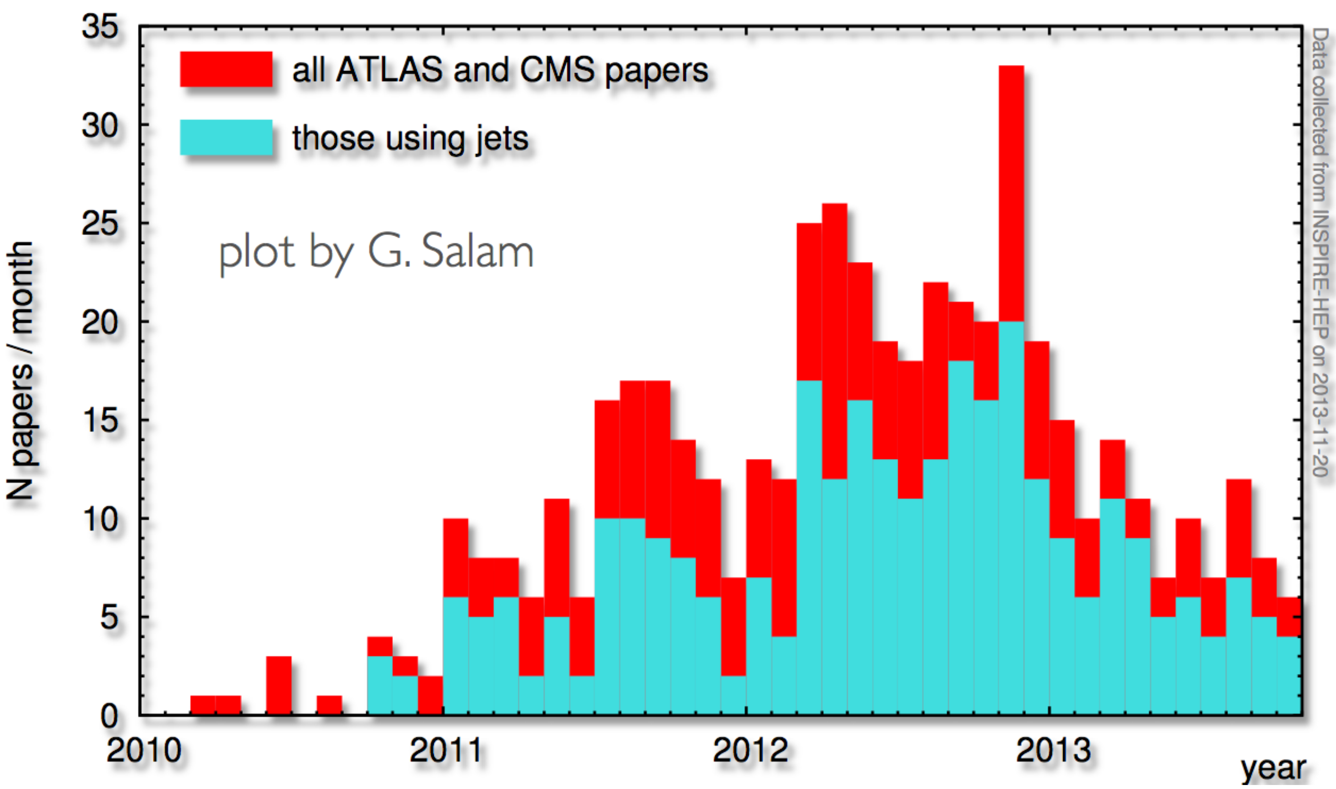
Jets at the LHC





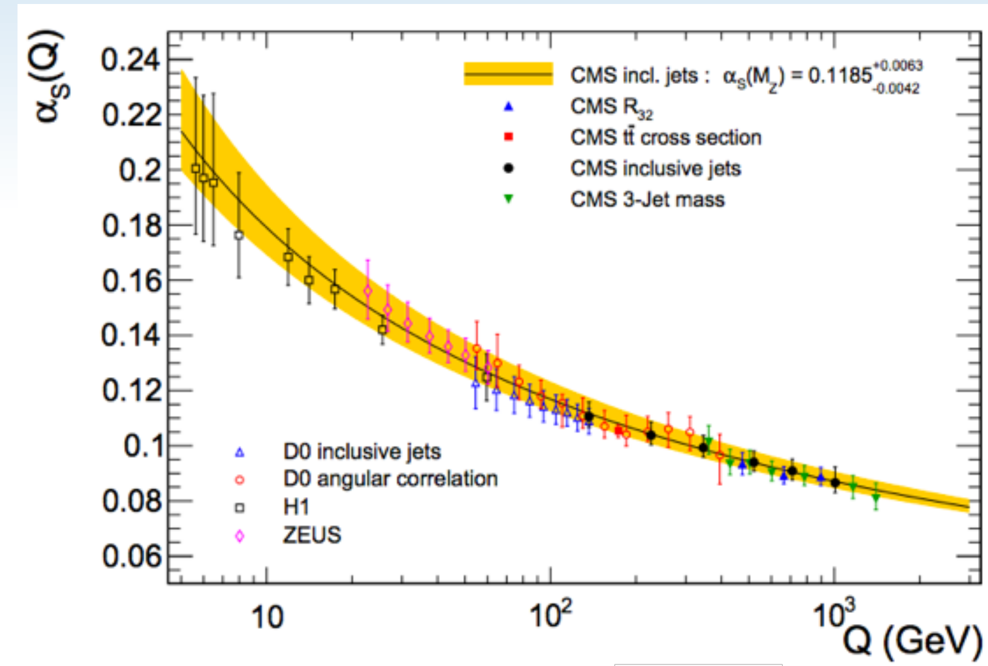
- Jets are produced copiously at the LHC

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

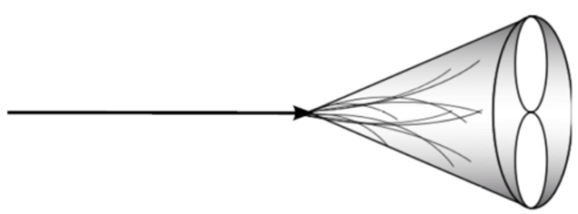
Application of jet studies at the LHC

- **Precision probe of QCD**

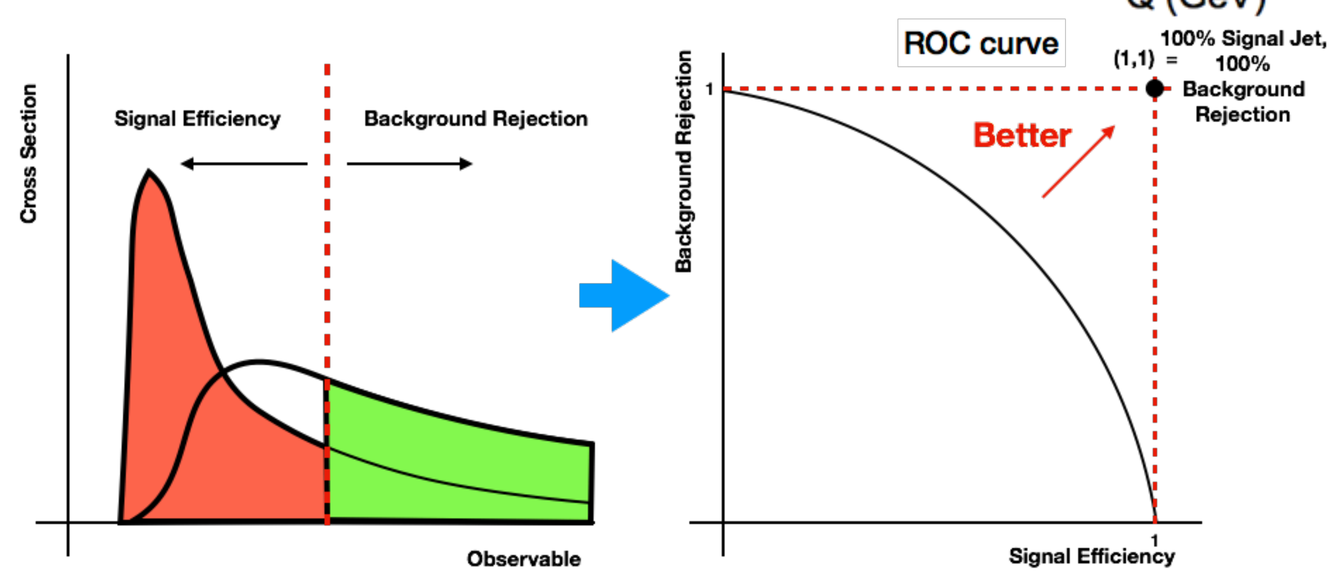
process	sensitivity to PDFs
W asymmetry	→ quark flavour separation
W and Z production (differential)	→ valence quarks
W+c production	→ strange quark
Drell-Yan (DY): high invariant mass	→ sea quarks, high-x
Drell-Yan (DY): low invariant mass	→ low-x
W,Z +jets	→ gluon medium-x
Inclusive jet and di-jet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



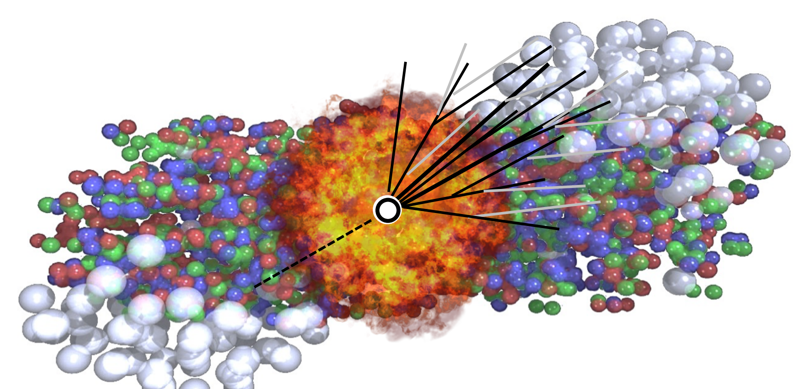
- **Constrain BSM Models**



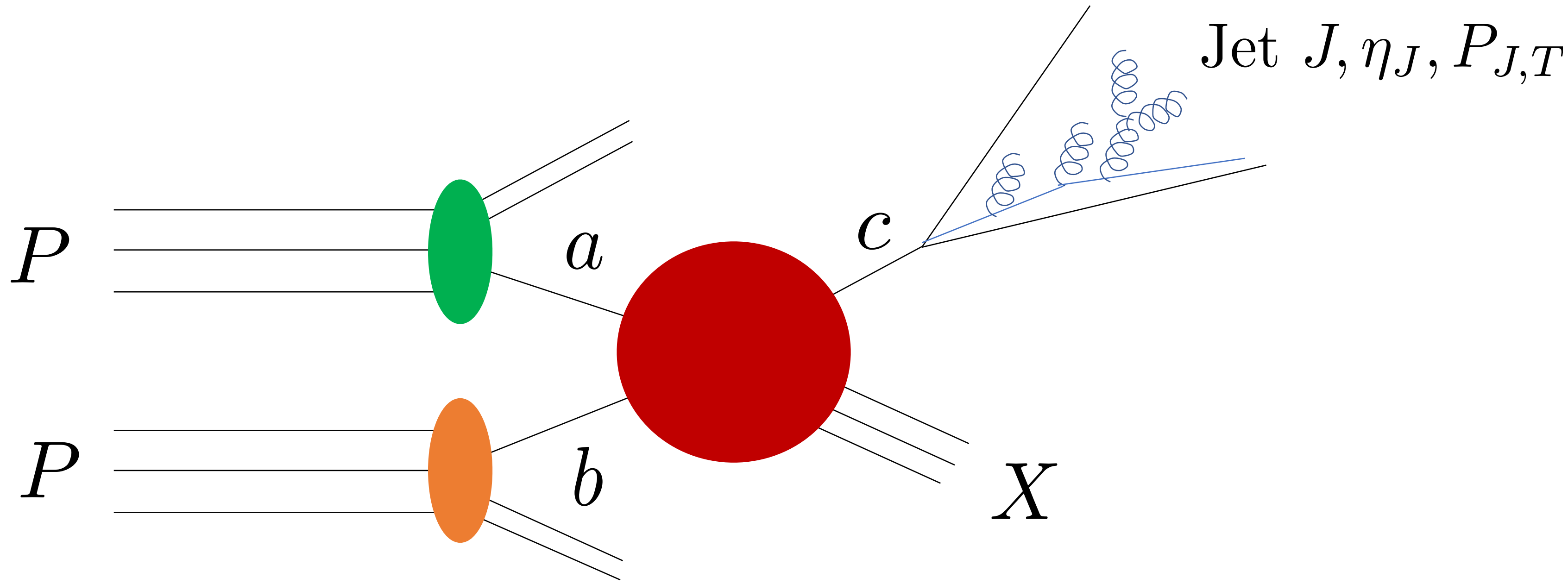
Fat jet from BSM signal



- **Probe of quark gluon plasma**



Processes of Interest

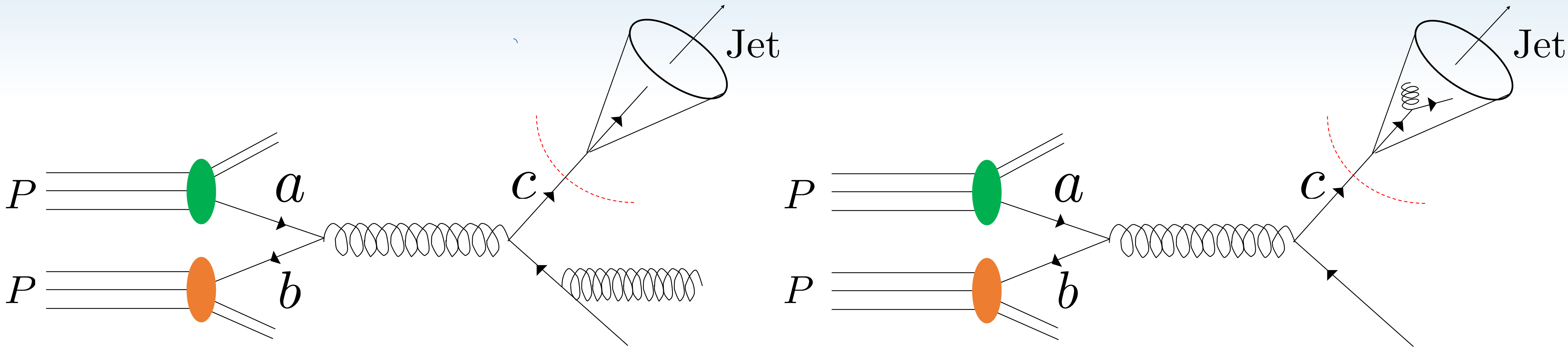


- We want to study semi-inclusive jet production event:
  p + p $\longrightarrow$ Jet((with/without) substructure) + X

Plans of this talk

- Inclusive jet production
- Formalism for jet mass measurements
- Role of non-perturbative effects
- The groomed jet mass
- Conclusions

Factorization



Example of NLO diagrams

- Relevant scales :

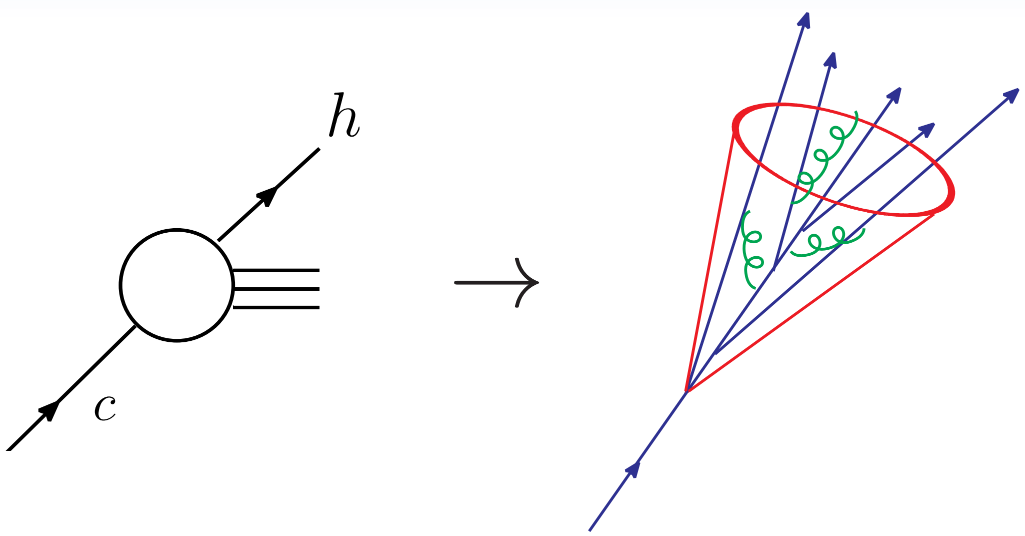
  1.Hard scale: $\mu_H \sim p_T$ 2. Jet scale: $\mu_J \sim p_T R$

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

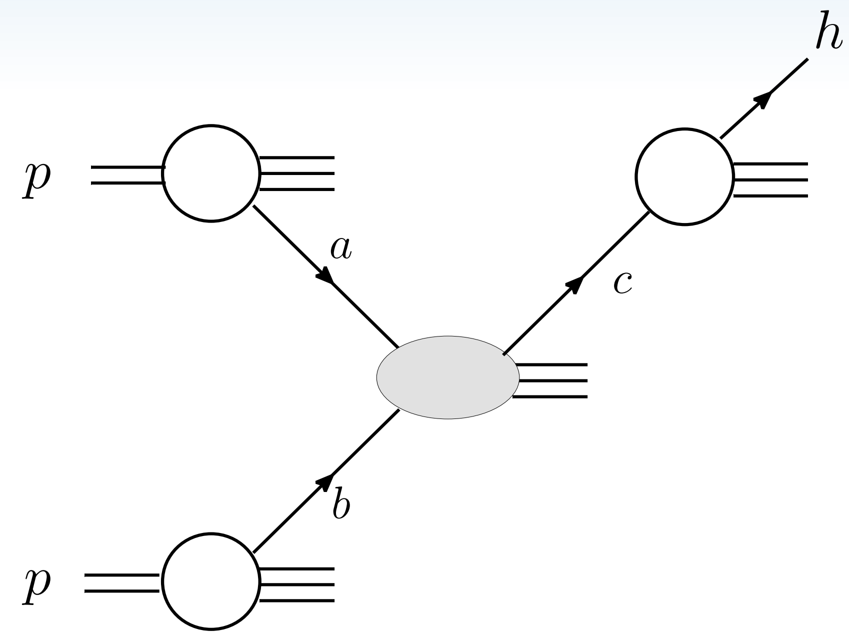
$$E\frac{d\sigma^{pp\to \text{jet}X}}{d\eta_J P_{T,J}} \propto \sum_{a,b,c} \int \frac{dx_a}{x_a} f_a^p(x_a) \int \frac{dx_b}{x_b} f_b^p(x_b) \int \frac{dz_c}{z_c^2} d\hat{\sigma}_{ab}^c J_c(z_c)$$

Kang, Ringer, Vitev `16

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.**

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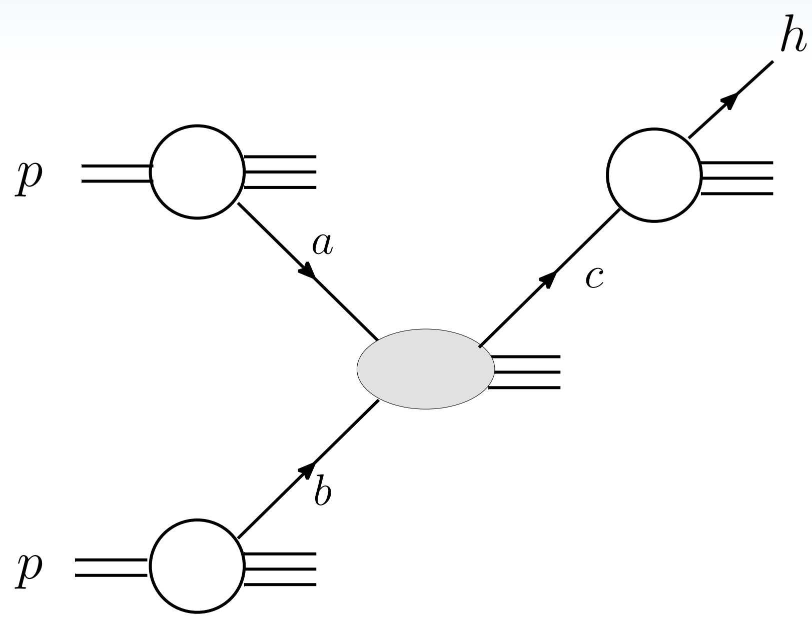
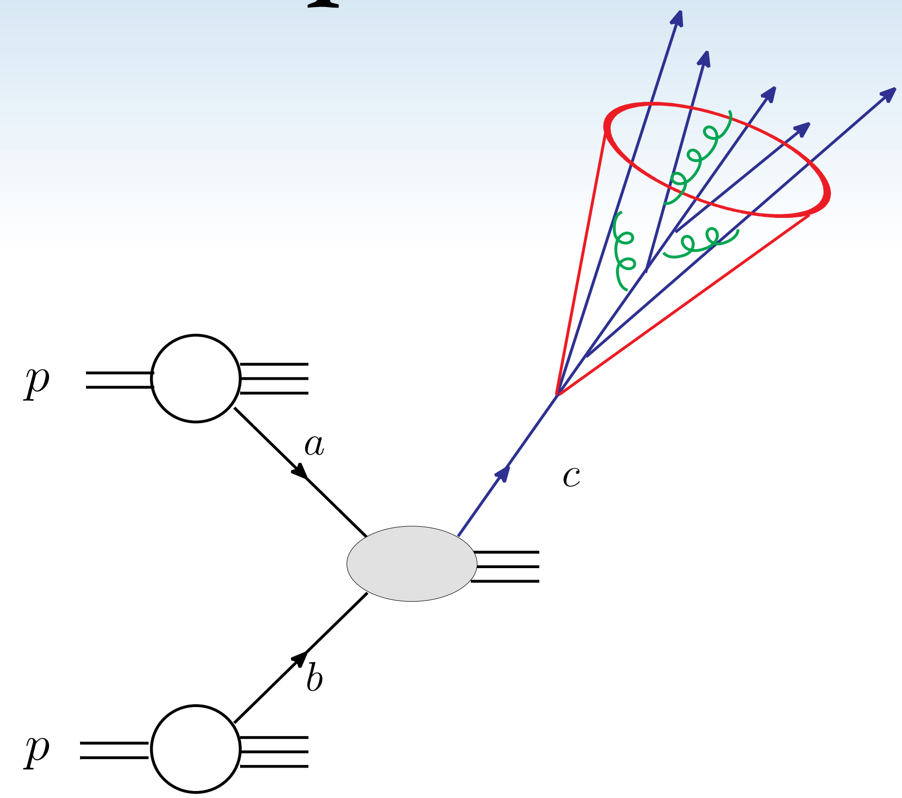
Comparison with the inclusive hadron production case





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

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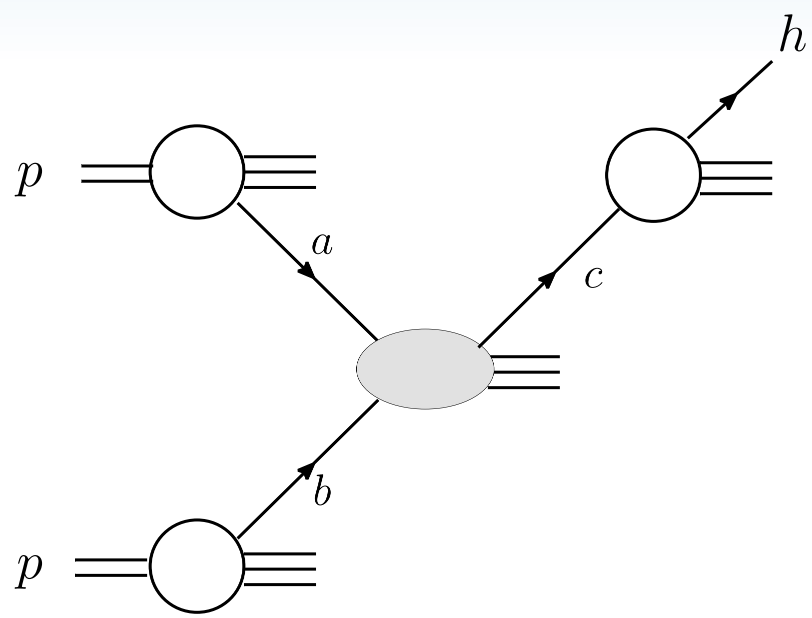
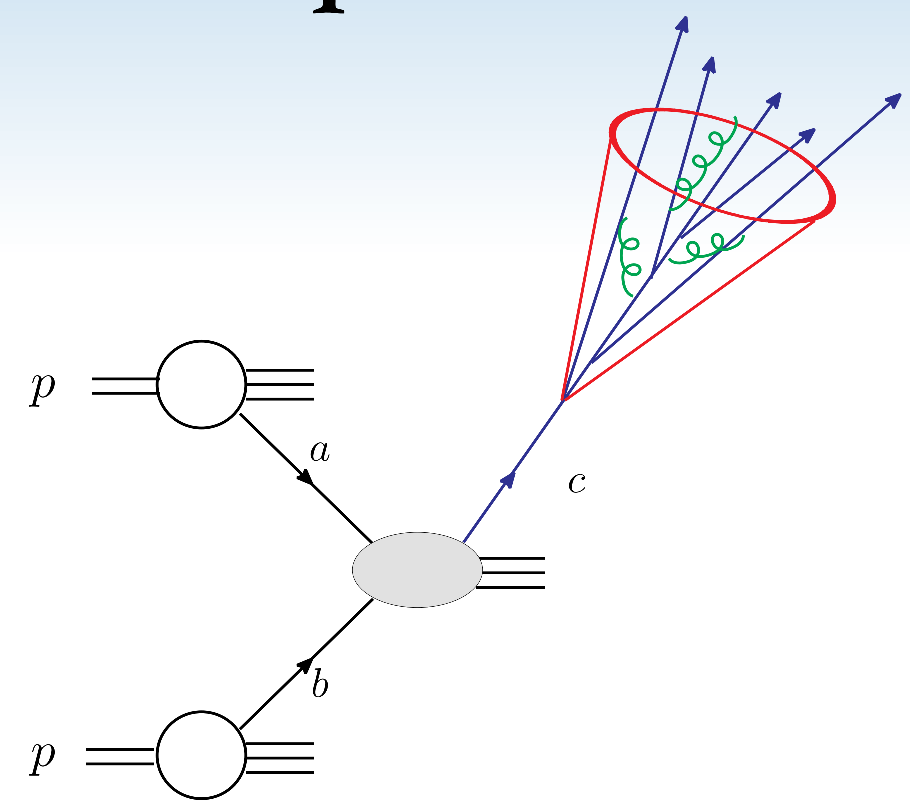
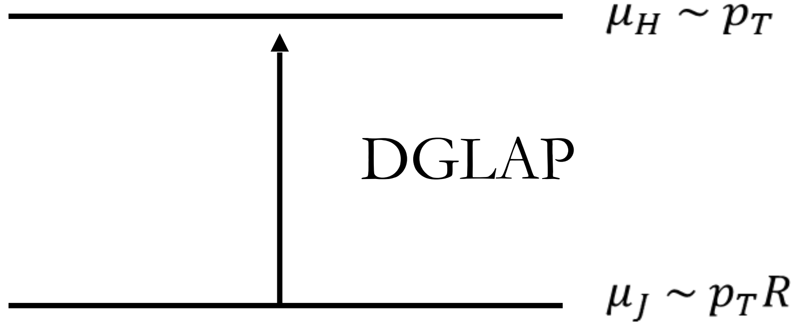






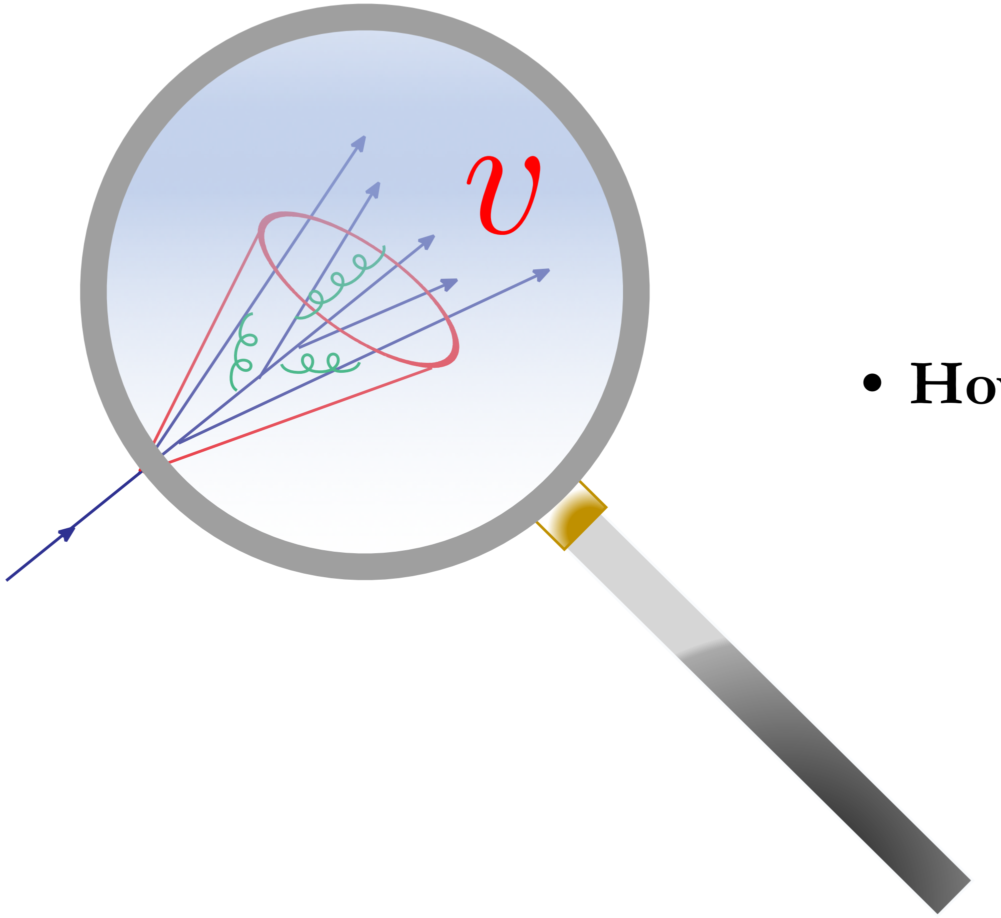
Evolution

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

$$\mu \frac{d}{d\mu} D_i^h = \sum_j P_{ji} \otimes D_j^h$$

Kang, Ringer, Vitev `16

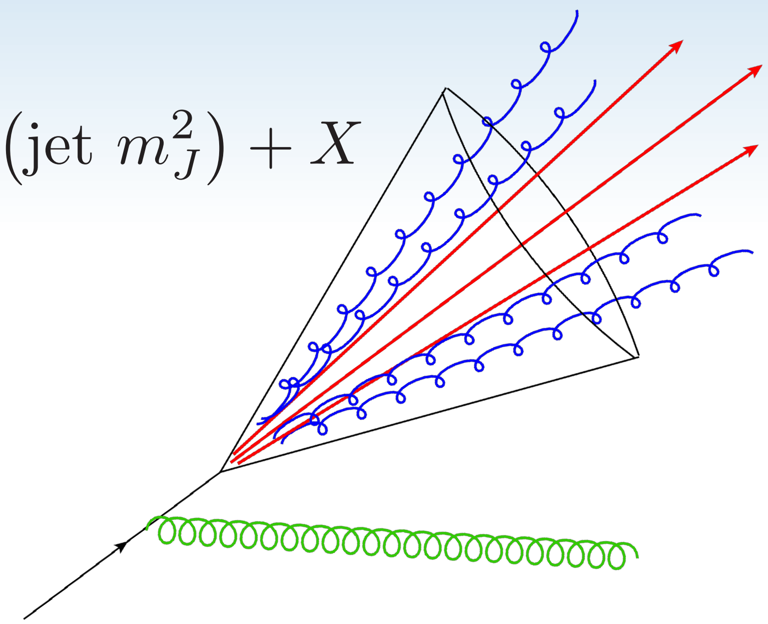
Jet Substructure Measurements



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

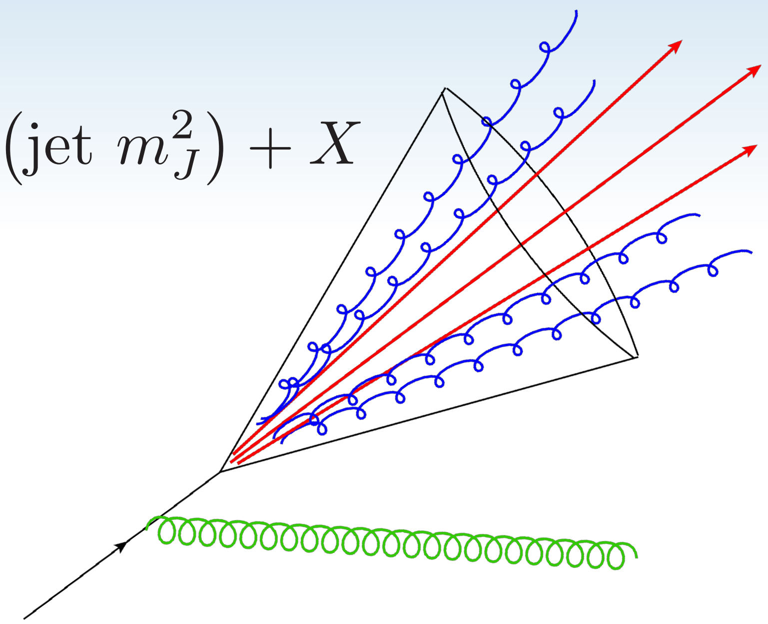
Jet mass

- Jet mass $m_J^2 = \left(\sum_{i \in J} p_i\right)^2$ for semi-inclusive jet production, $pp \to (\text{jet } m_J^2) + X$



- Useful in discriminating quark and gluon jets.
- Tagger for boosted objects.
- Related to jet angularity (a = 0)

Jet mass



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- Useful in discriminating quark and gluon jets.
- Tagger for boosted objects.
- Related to jet angularity (a = 0)

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

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

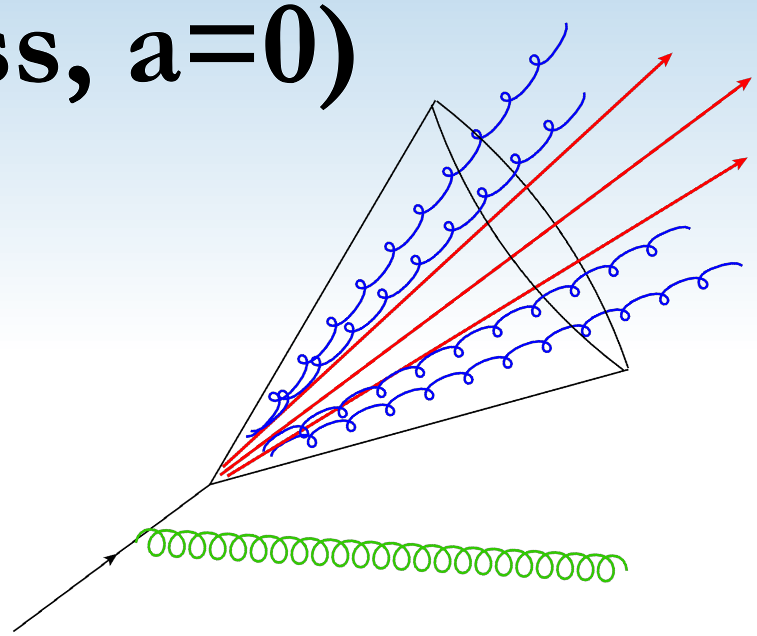
$$\tau_0^{pp} = \frac{m_J^2}{p_T^2} + \mathcal{O}\left(\left(\tau_0^{pp}\right)^2\right)$$

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

- 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 (jet mass, a=0)

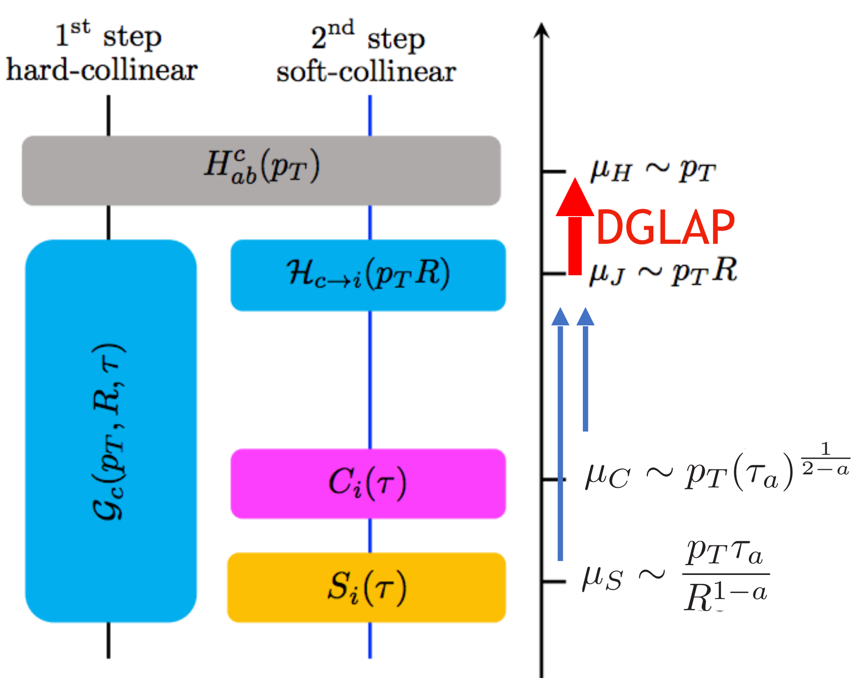


- Replace $J_c(z, p_T R, \mu) \to \mathcal{G}_c(z, p_T R, \tau_a, \mu)$
- When $\tau_a \ll R^2$, refactorize $\mathcal{G}_c$ as

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

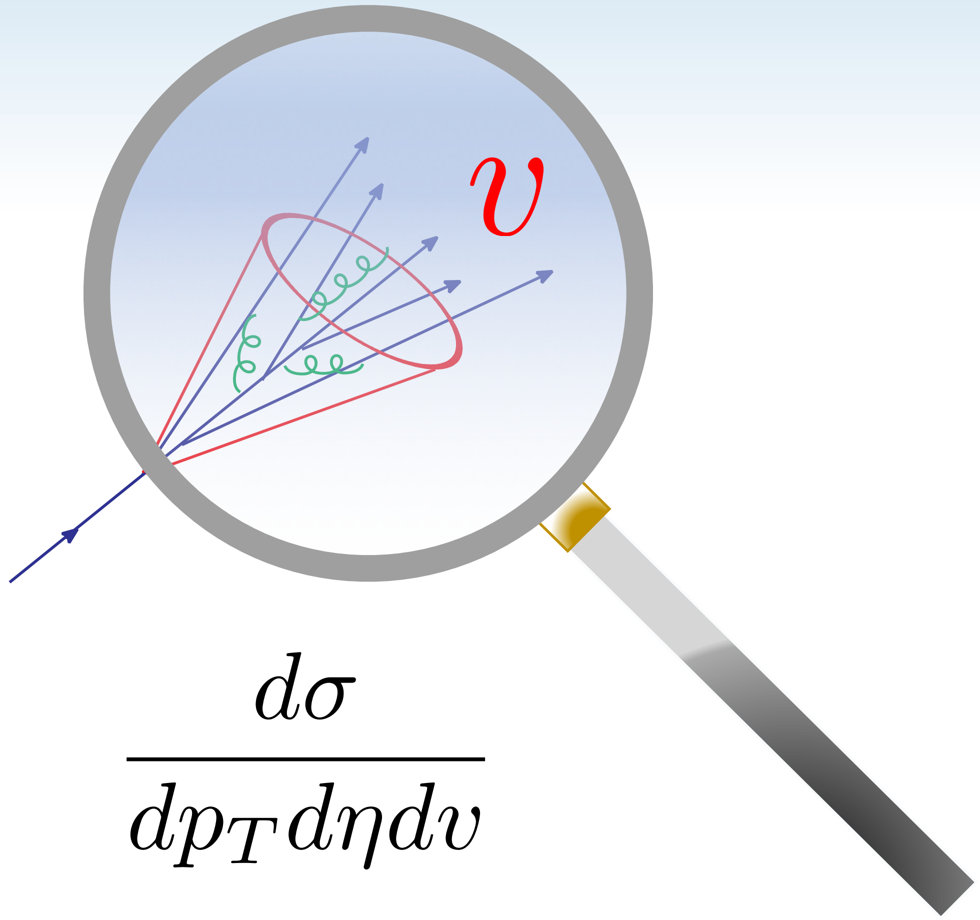
- Each pieces describe physics at different scales.
- $\mu_J \to \mu_H$ evolution follows DGLAP evolution equation again
- Resums $(\alpha_s \ln R)^n$ and $(\alpha_s \ln^2 \frac{R}{\tau_a^{1/(2-a)}})^n$
- $\int \frac{d\sigma}{dp_T d\eta d\tau_a} d\tau_a = \frac{d\sigma}{dp_T d\eta} \Leftrightarrow \int_0^\infty d\tau_a \mathcal{G}_i(z, p_T, R, \tau_a, \mu) = J_i(z, p_T, R, \mu)$

See also Chien, Hornig, C. Lee `15

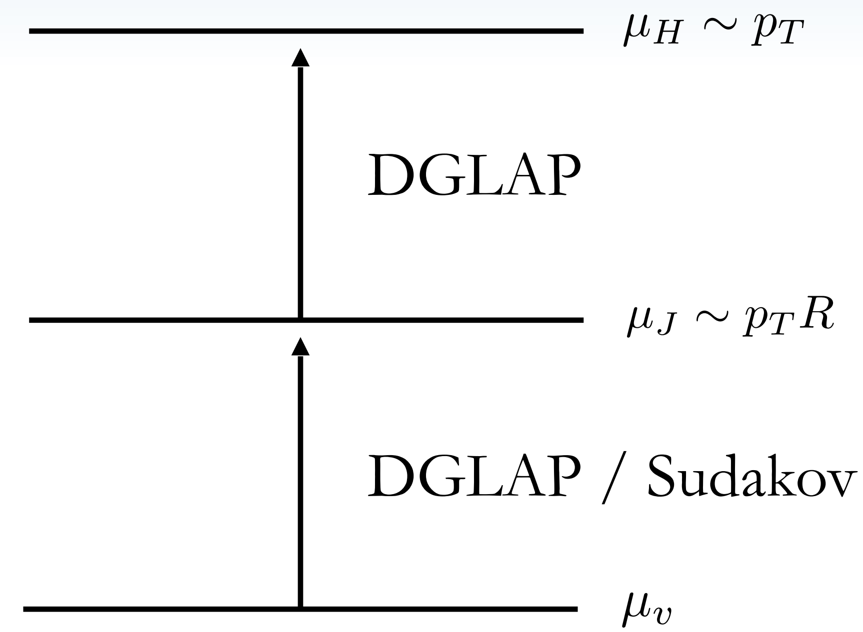


Kang, KL, Ringer `18

Patterns emerging

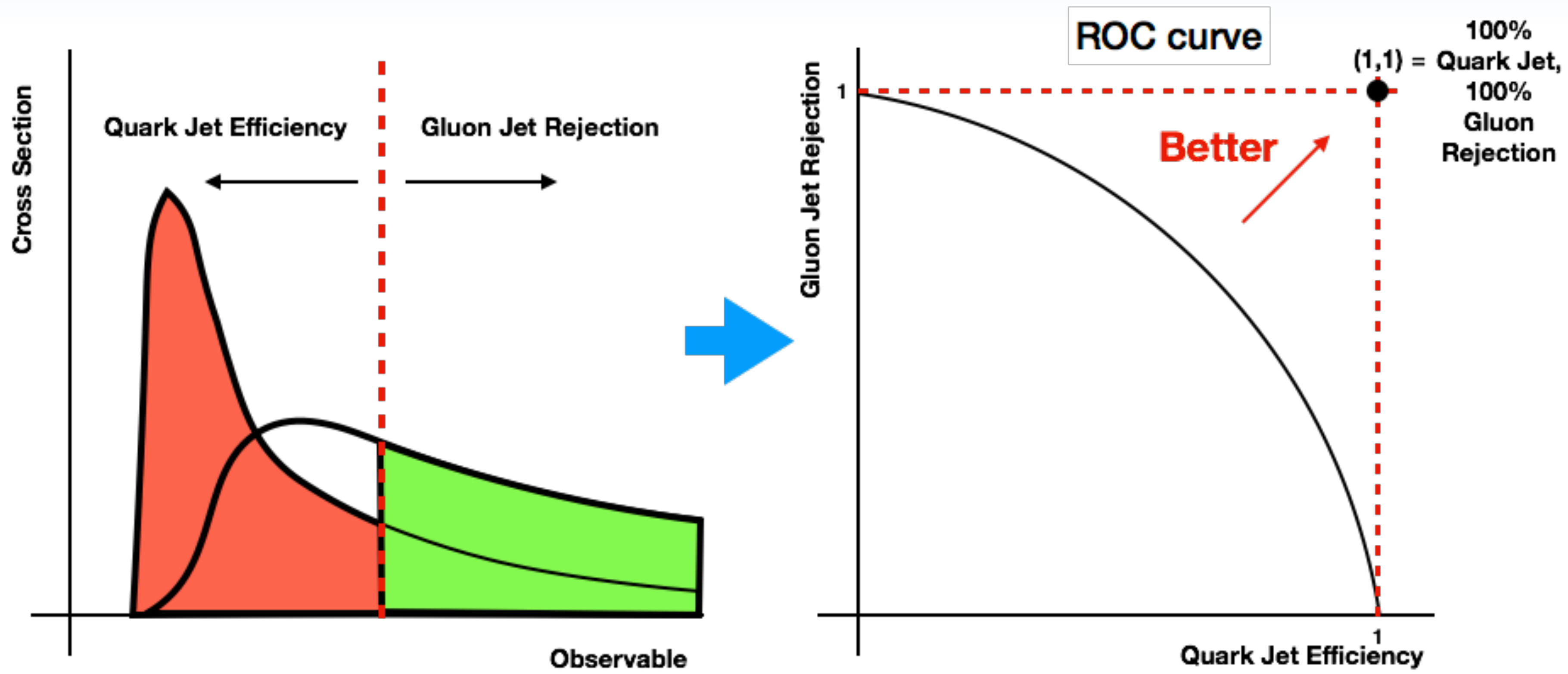


$$\frac{d\sigma}{dp_T d\eta dv}$$



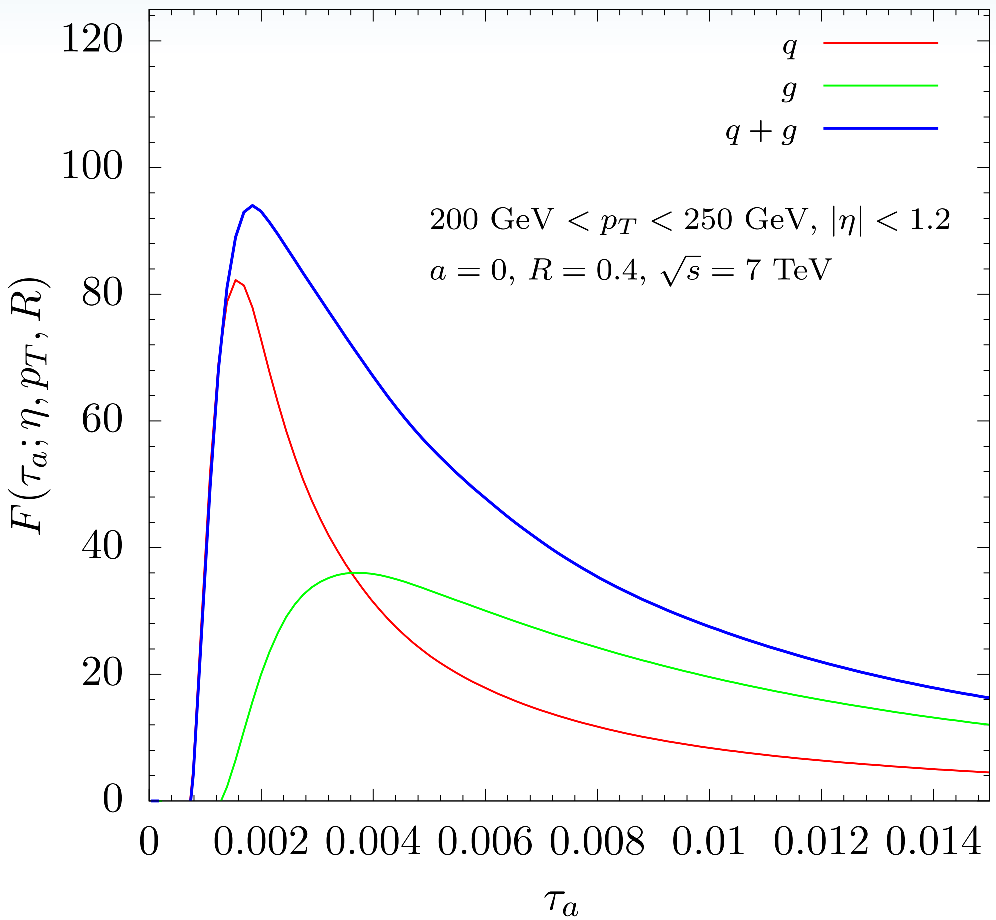
- When we measure substructure v from the jet, once we evolve to μ_J the remaining evolution to μ_H is given by DGLAP evolution!
- Two step factorization:
  a) production of a jet
  b) probing the internal structure of the jet produced.

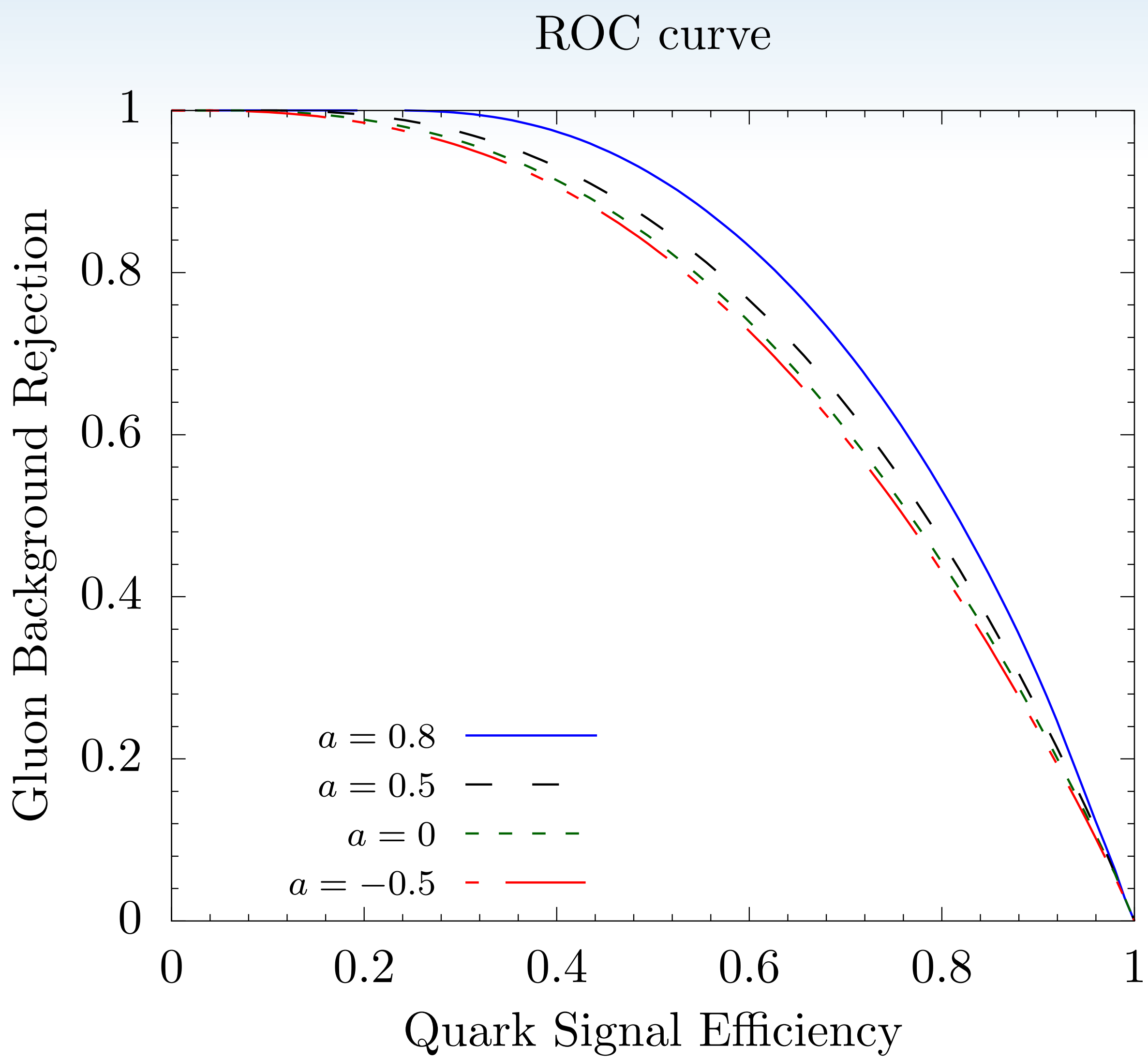
Quark and gluon discrimination



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

Quark and gluon discrimination

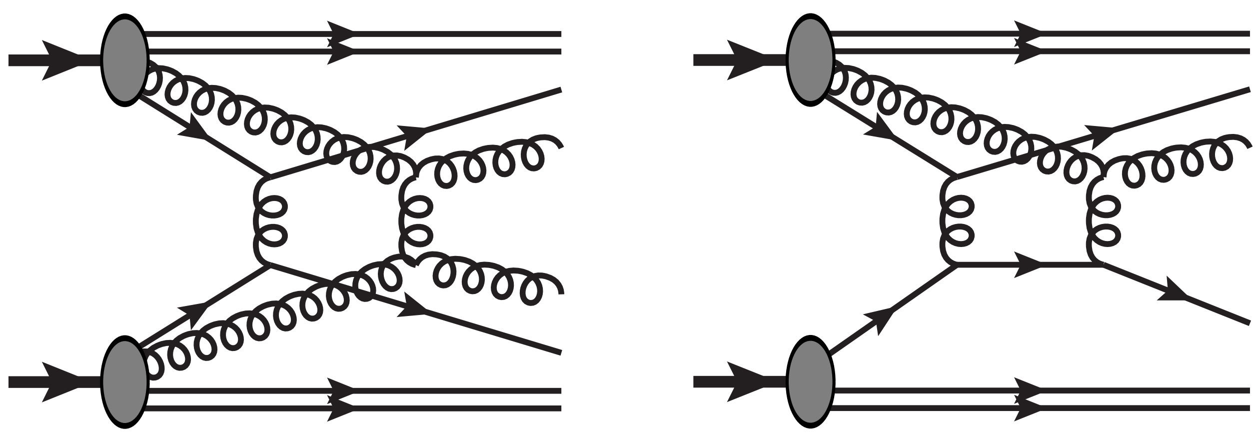




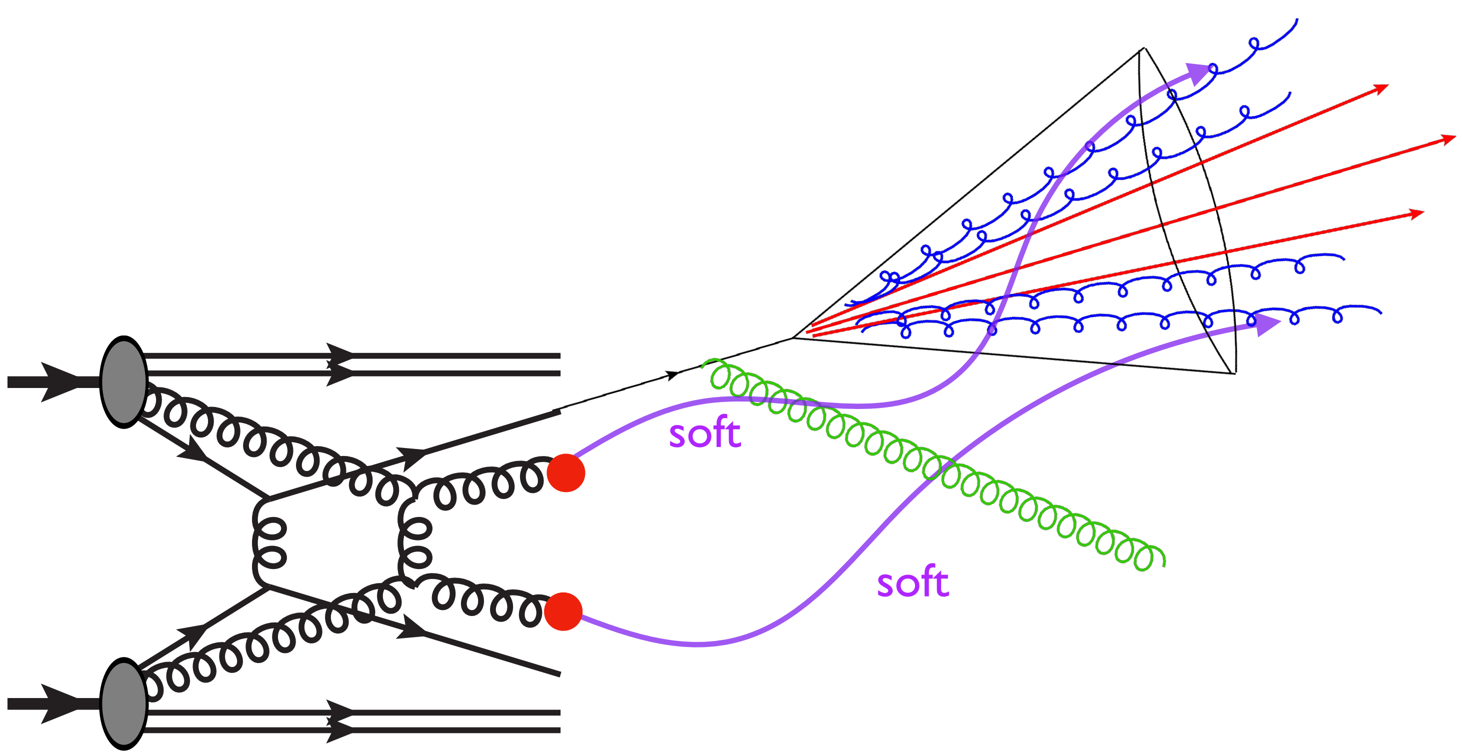
- We can study how well angularity discriminates between quark and gluon jet as a continuous function of 'a'.
- As 'a' increases, better discrimination but more sensitive to non-perturbative effects.

Non-perturbative Model

- **Non-perturbative effects:**



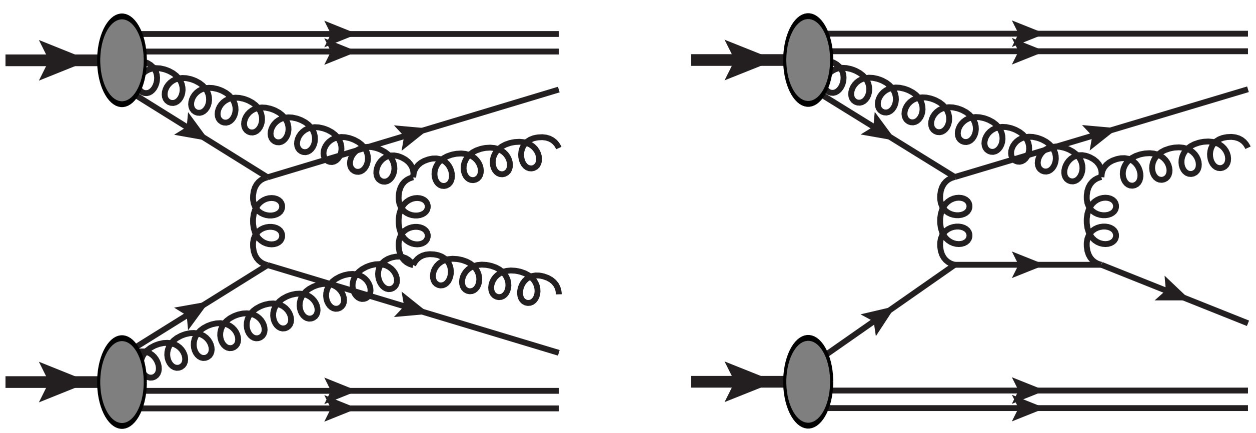
Figs from P. Bartalini et al. `11



- **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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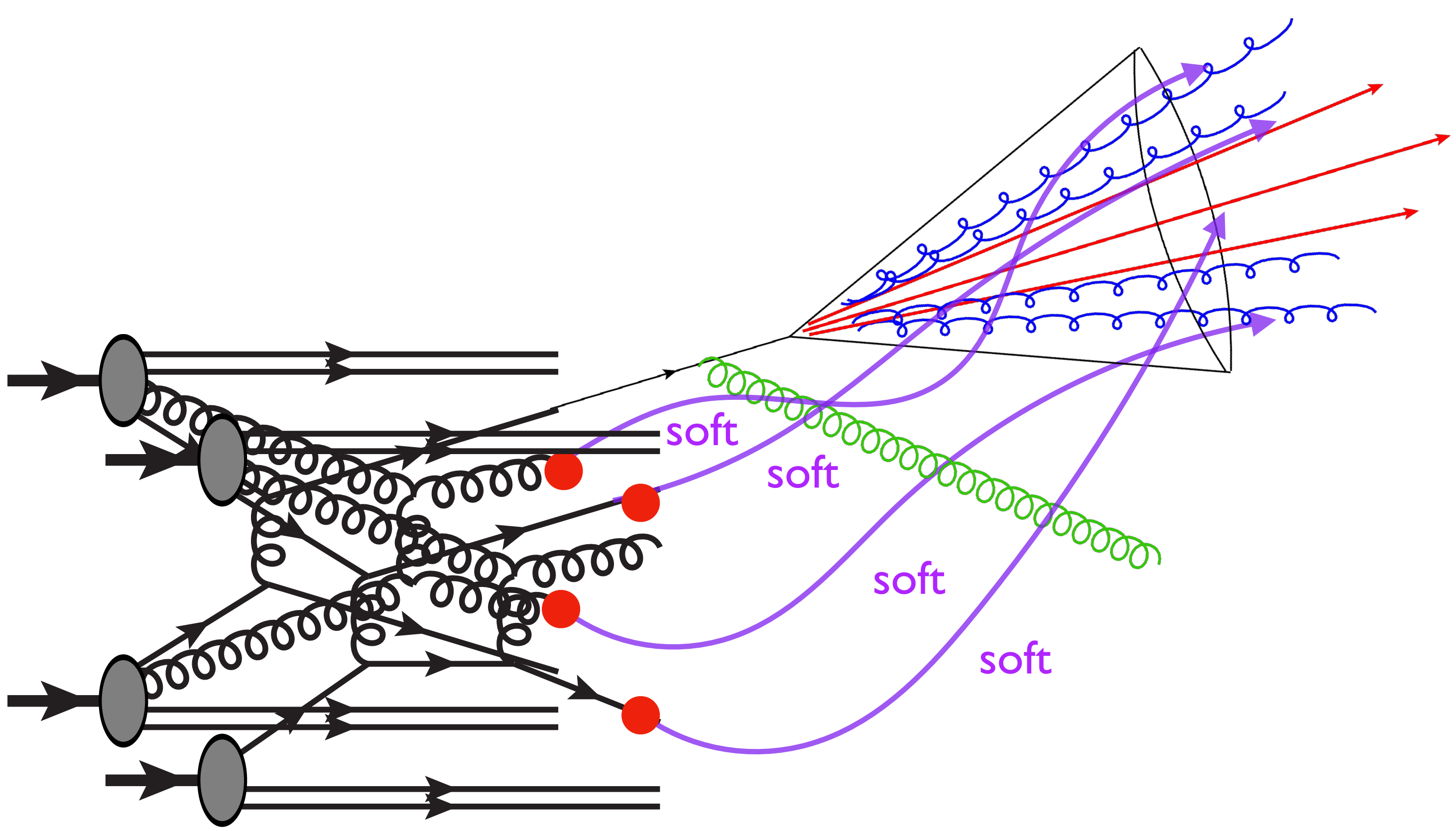
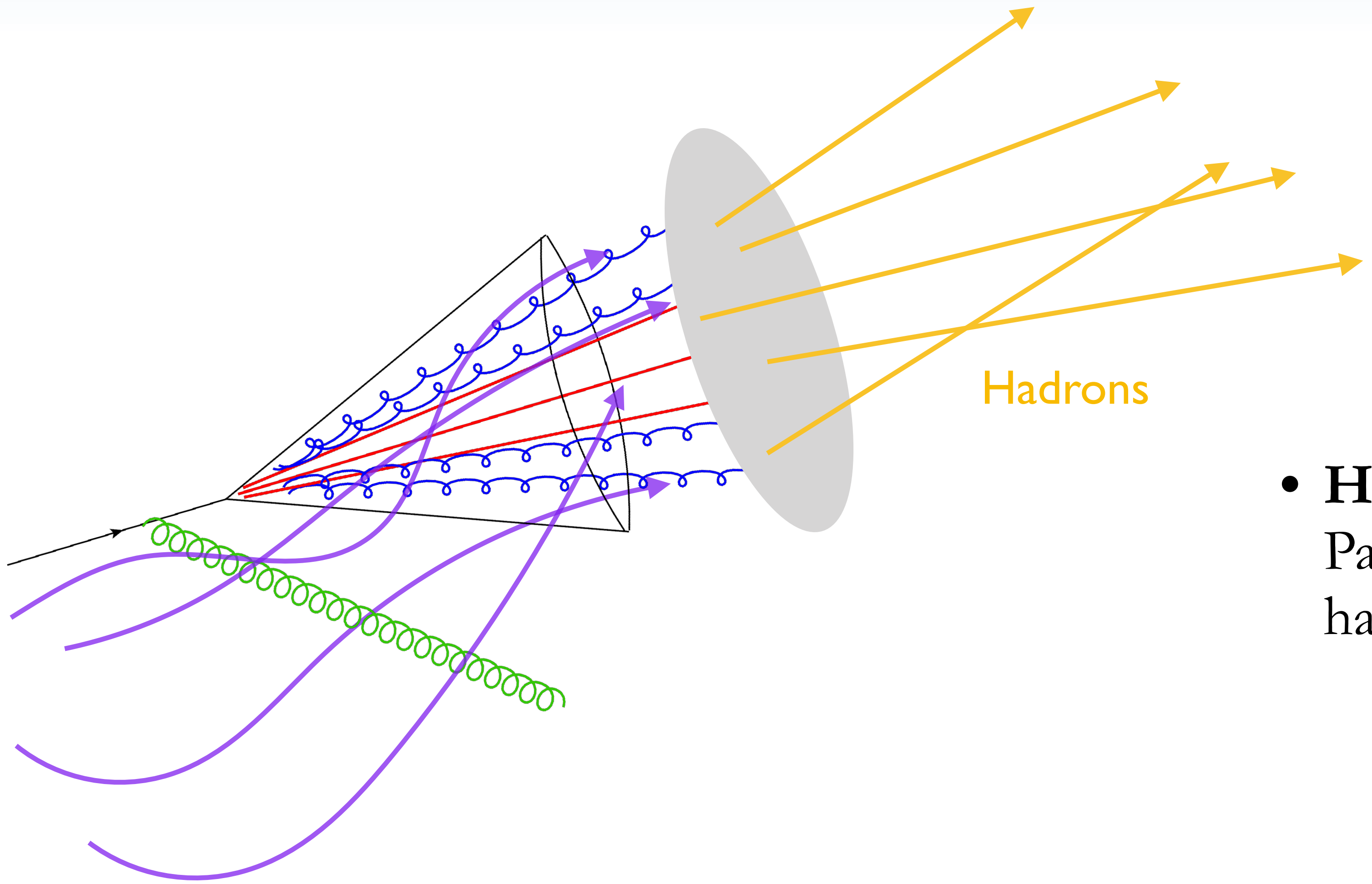


- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.
- **Pileups**
  Secondary proton collisions in a bunch may enter and contaminate jet.

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 :

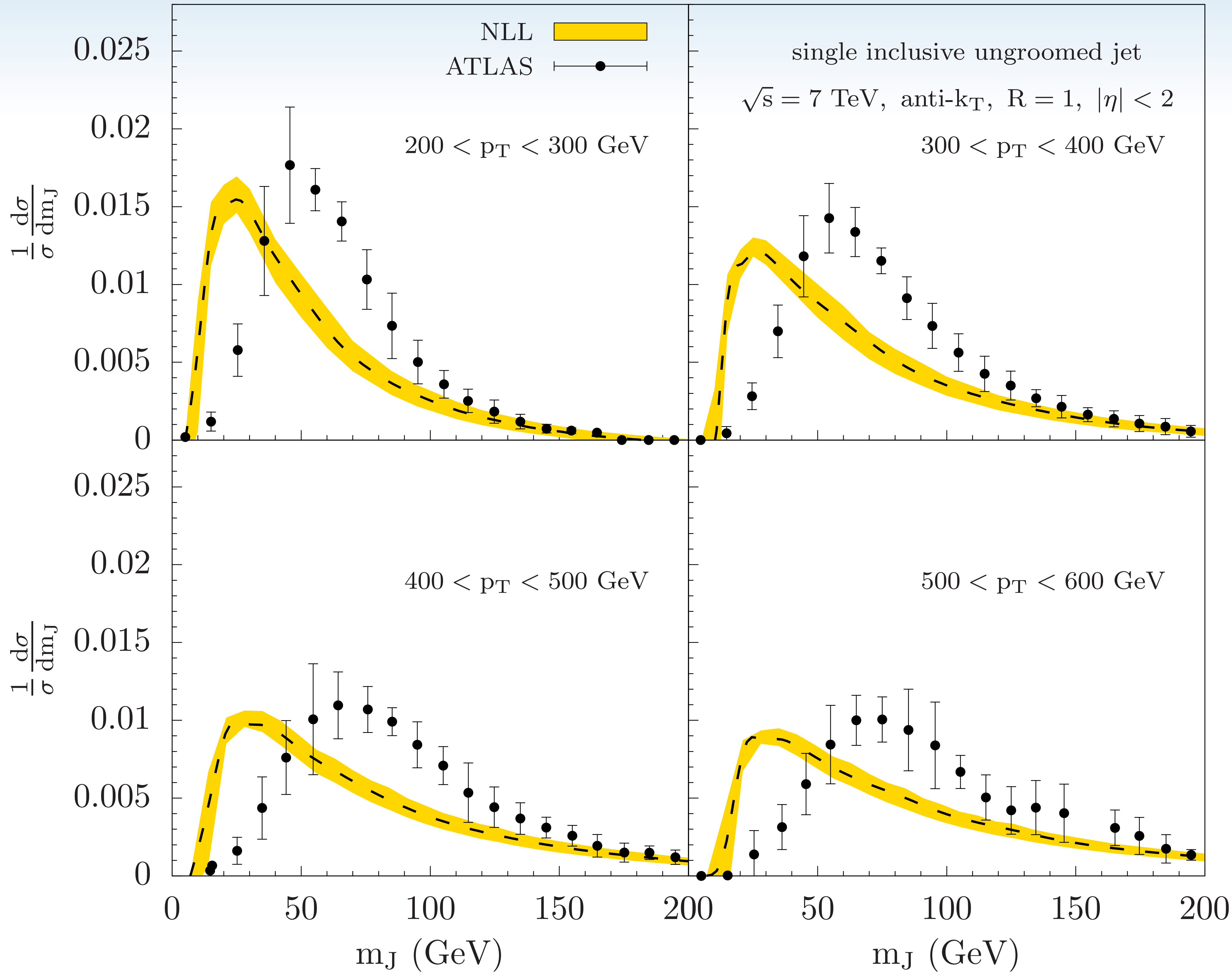
$$F_\kappa(k) = \left(\frac{4k}{\Omega_\kappa^2}\right)\exp\left(-\frac{2k}{\Omega_\kappa}\right)$$

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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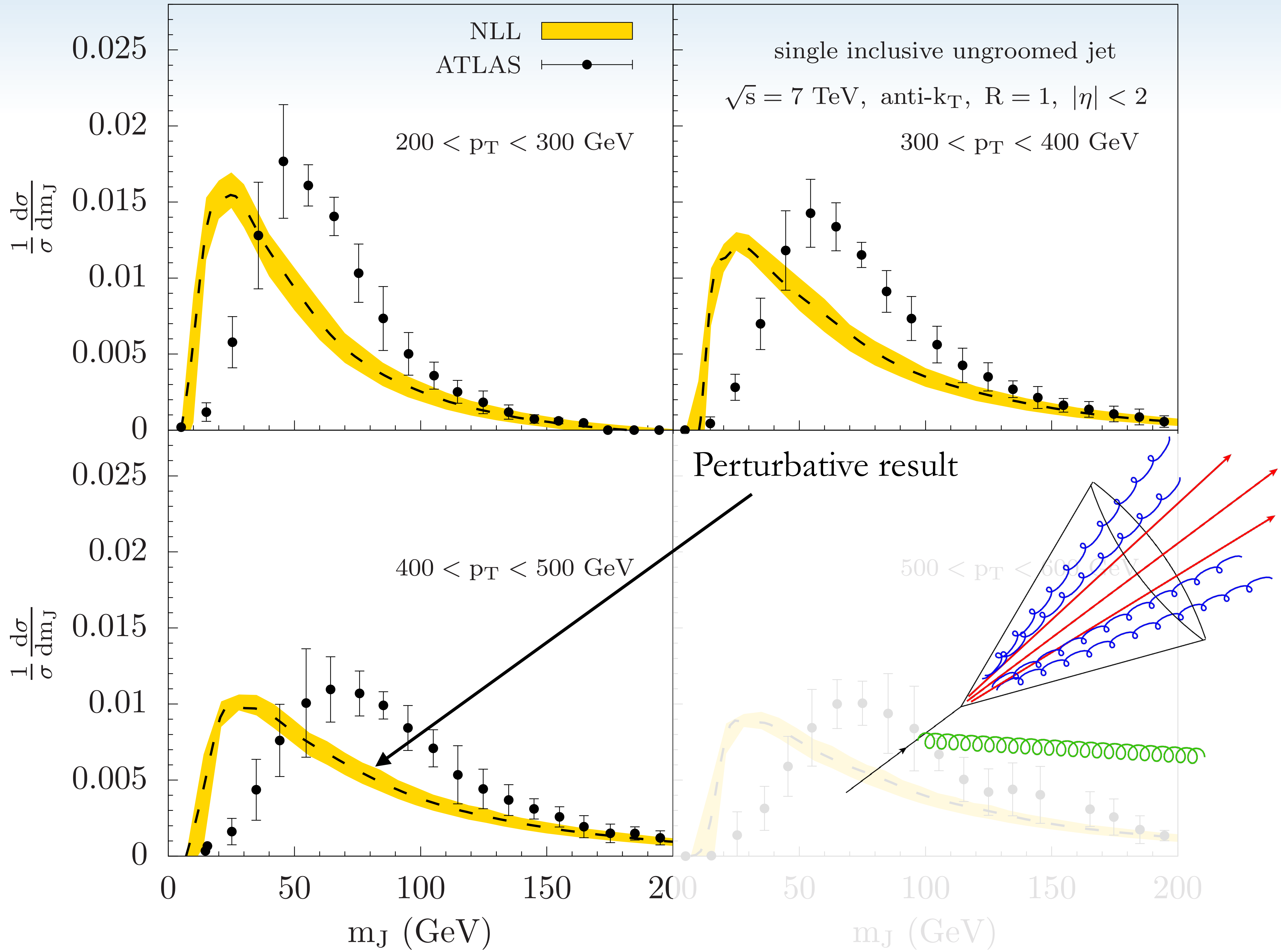

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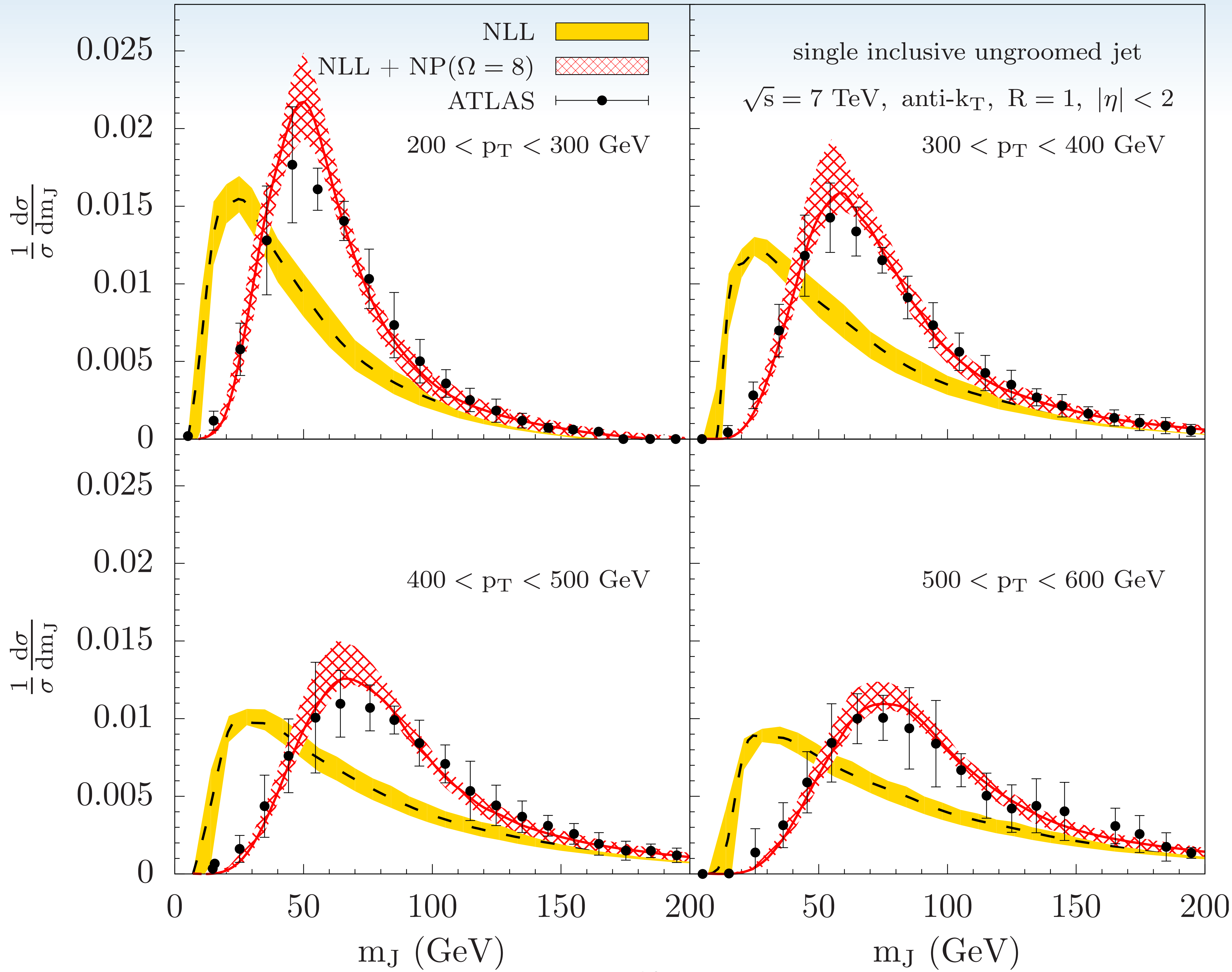

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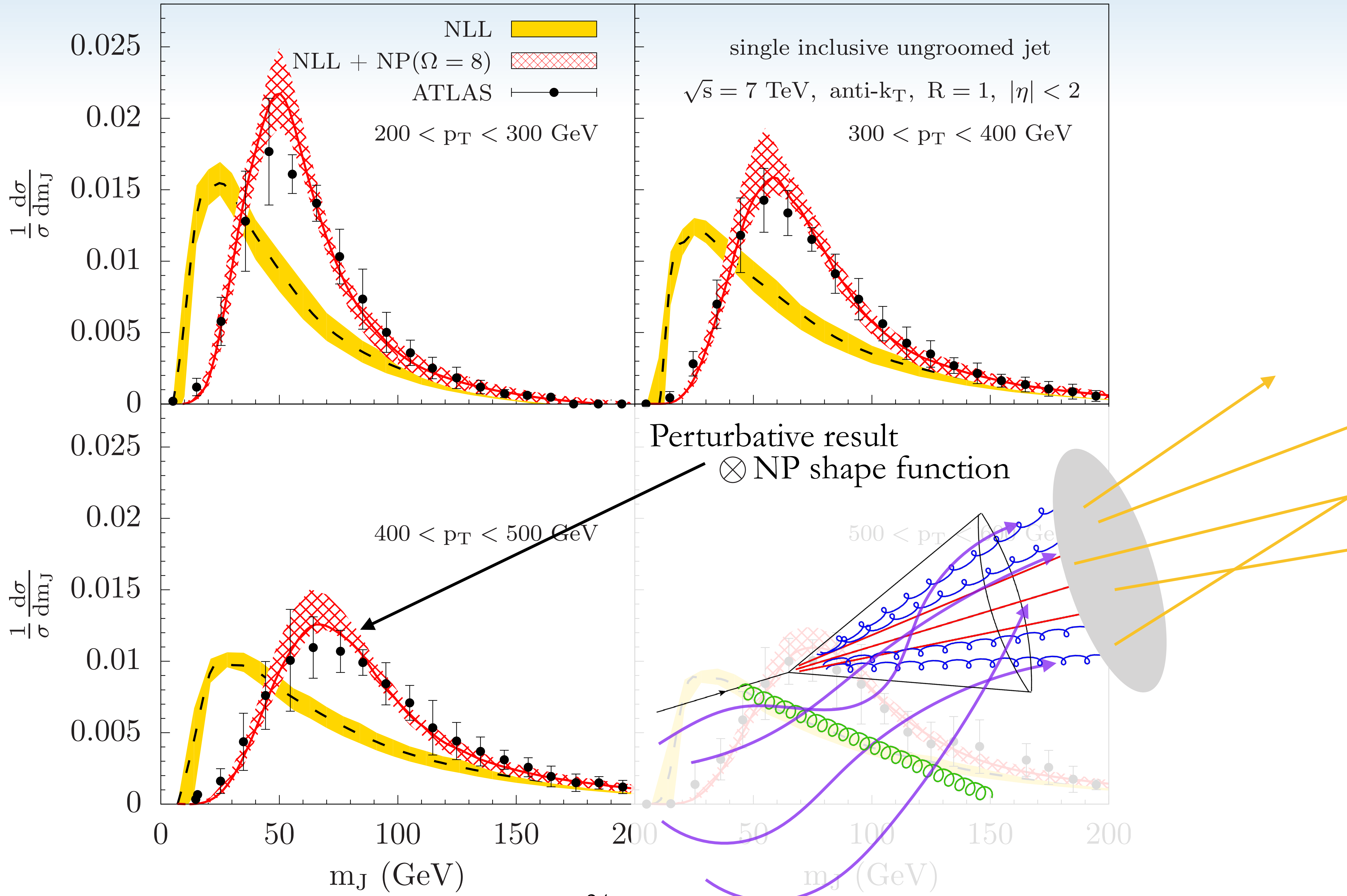
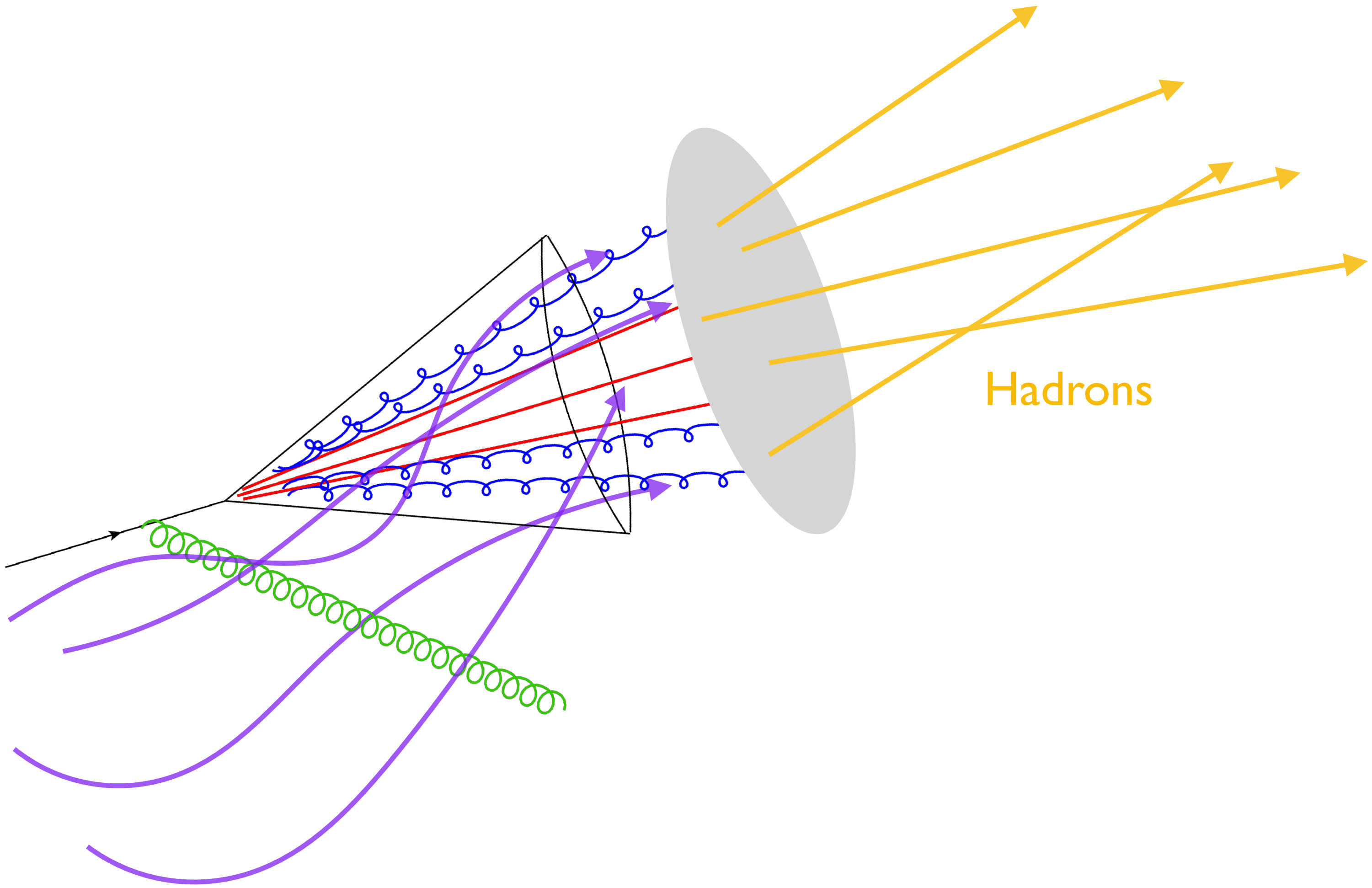


Soft Drop Grooming

- **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.**



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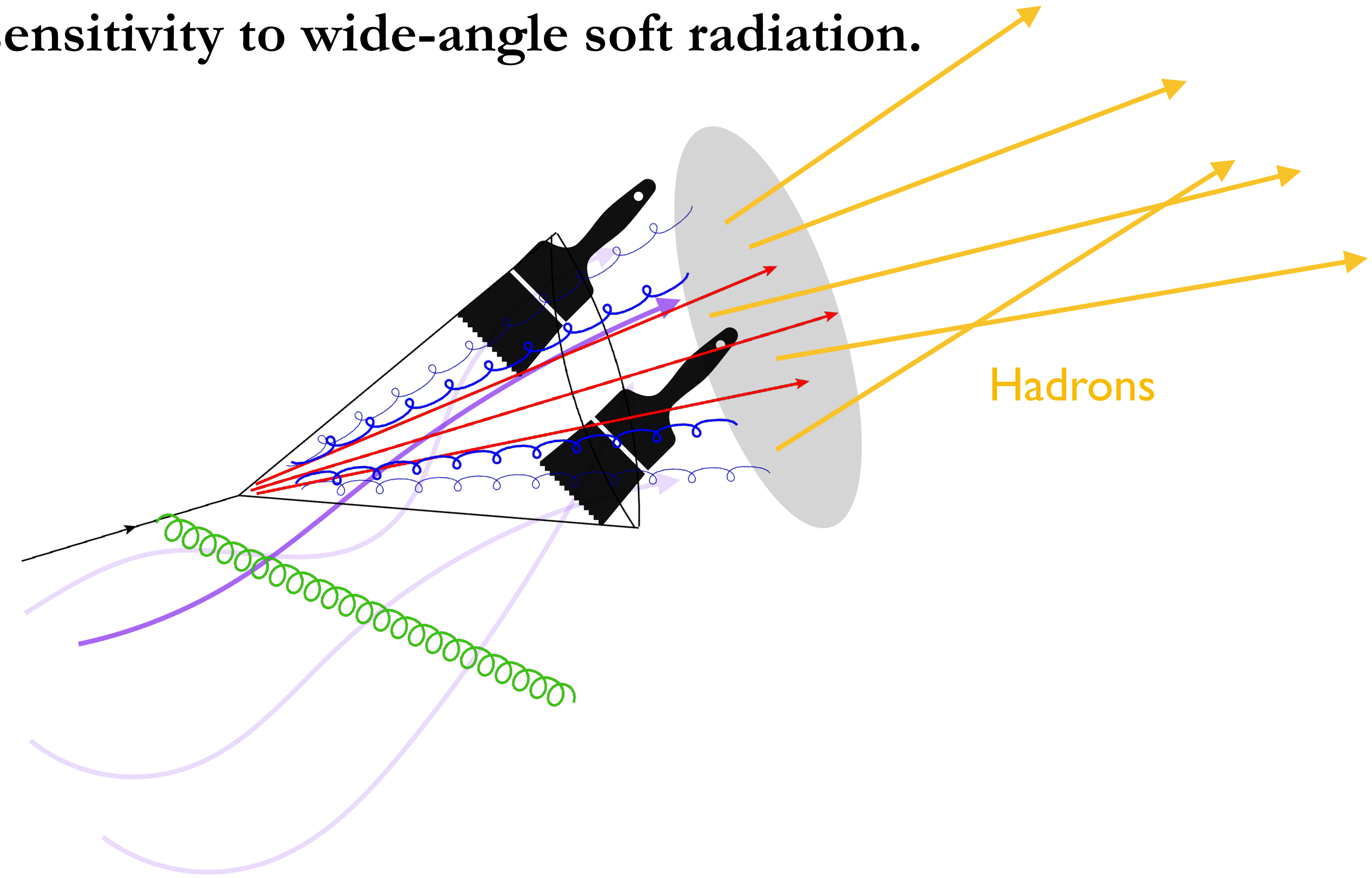
  Groom jets to reduce sensitivity to wide-angle soft radiation.



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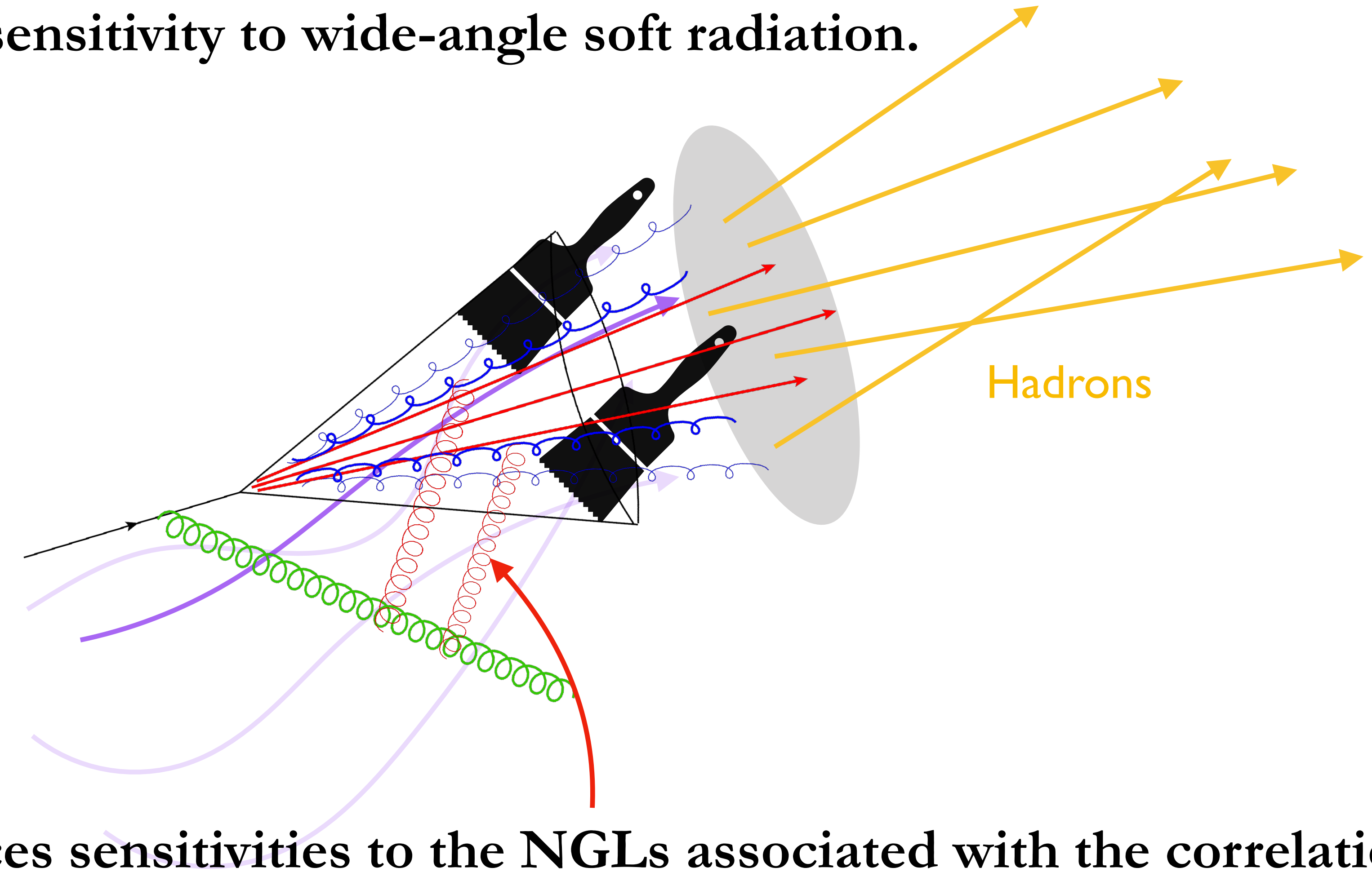

- **Also reduces sensitivities to the NGLs associated with the correlation between in-jet and out-of-jet radiation.**

Soft Drop Grooming

- **Underlying Events (UE) are difficult to understand.**

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- **Hint : contamination generally from soft radiations.**

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

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:

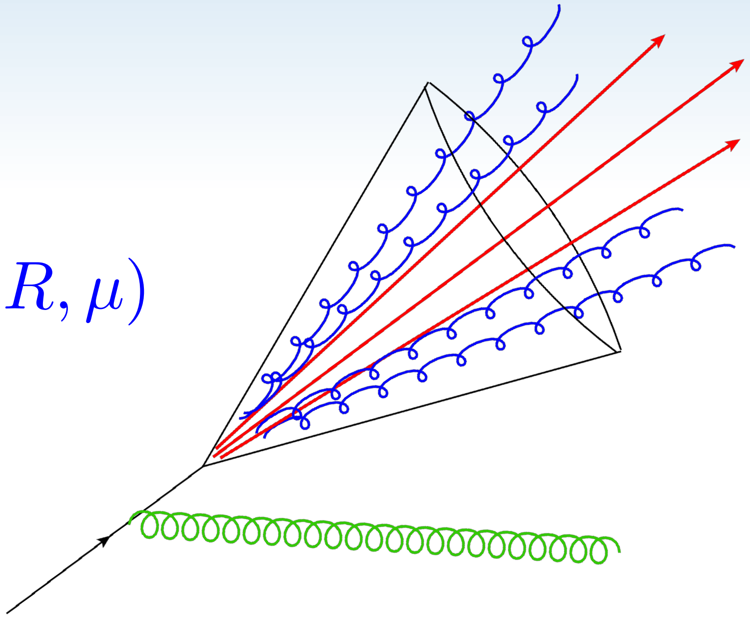
$$\frac{\min[p_{T,i}, p_{T,j}]}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left(\frac{R_{ij}}{R}\right)^{\beta}$$

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

Groomed jet mass factorization

- **The ungroomed case (** $\tau \ll R^2$ **)**

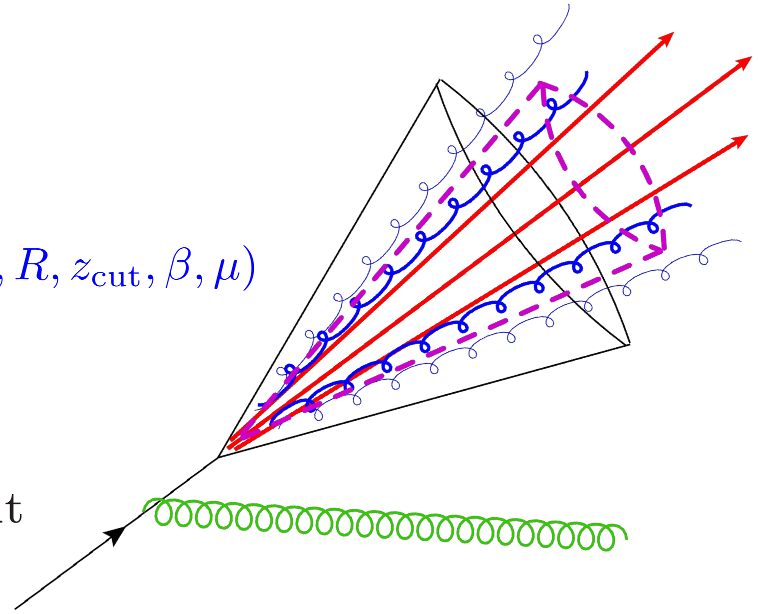
$$\mathcal{G}_i(z, p_T R, \tau, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) C_j(\tau, p_T, \mu) \otimes S_j(\tau, p_T, R, \mu)$$



- **Resums global logs** $\alpha_s^n \ln^n R$ **and** $\alpha_s^n \ln^{2n} \tau/R^2$

- **The groomed case (** $\tau_{\rm gr}/R^2 \ll z_{\rm cut} \ll 1$ **)**

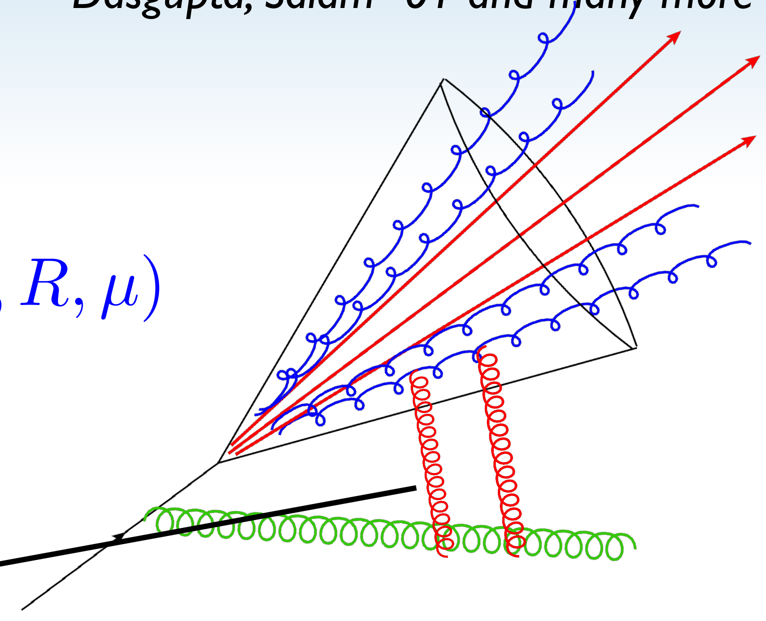
$$\mathcal{G}_i(z, p_T R, \tau_{\rm gr}, z_{\rm cut}, \beta, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) S_j^{\notin \rm gr}(p_T, R, z_{\rm cut}, \beta, \mu) C_j(\tau, p_T, \mu) \otimes S_j^{\in \rm gr}(\tau, p_T, R, z_{\rm cut}, \beta, \mu)$$



- **Resums global logs** $\alpha_s^n \ln^n R$**,** $\alpha_s^n \ln^{2n} \tau/R^2$**, and** $\alpha_s^n \ln^{2n} z_{\rm cut}$

Non-global Logarithms

Dasgupta, Salam `01 and many more



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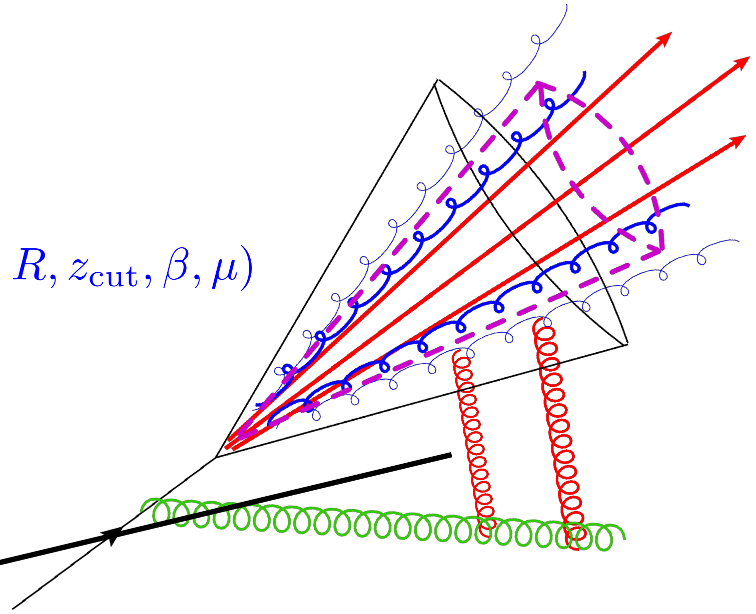
- **Non-global logs directly affect the jet mass spectrum.**

$$\alpha_s^n \ln^n(\tau/R^2) \qquad n \geq 2$$



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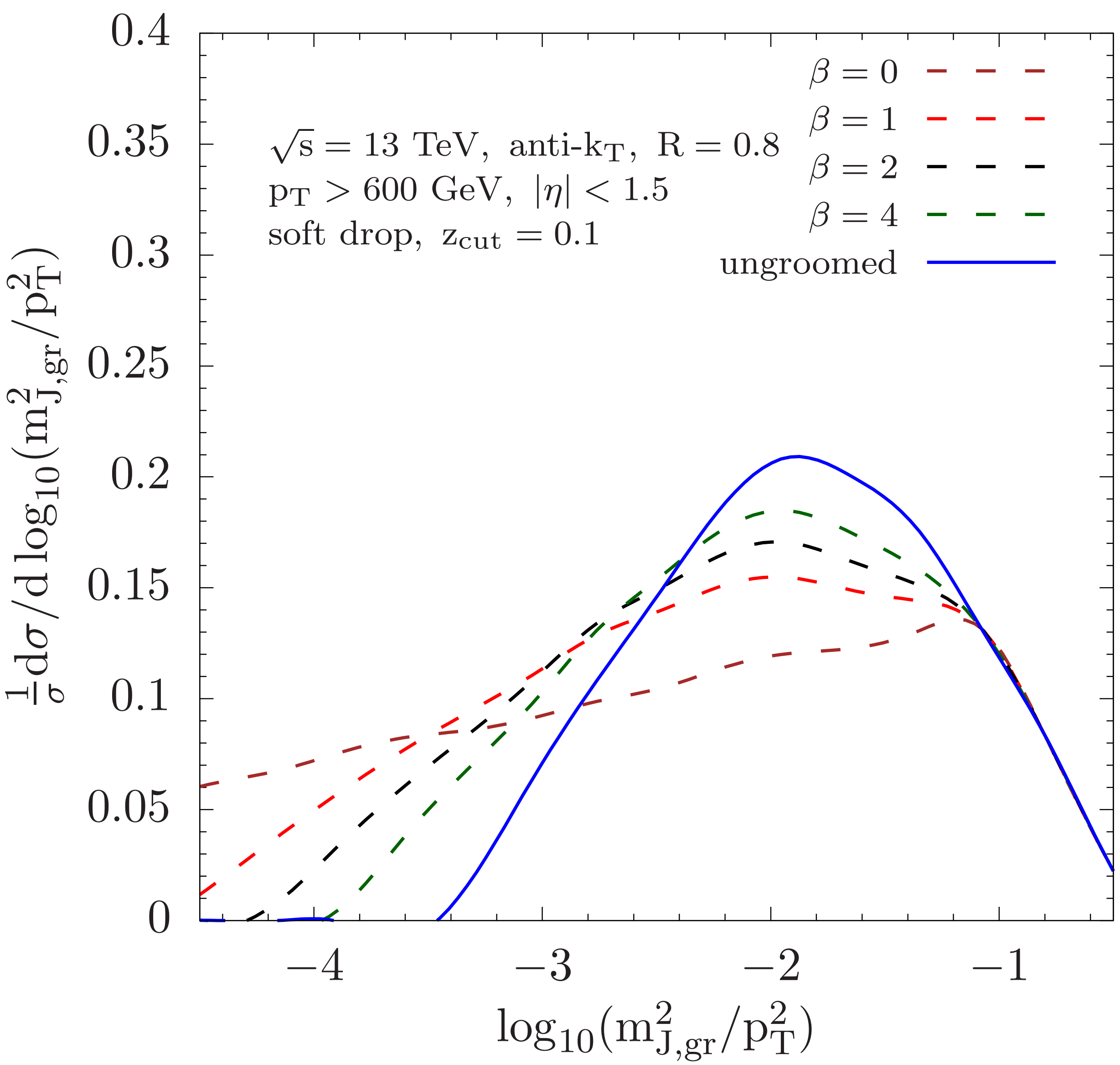
- **Non-global logs affects only indirectly affects the jet mass spectrum through normalization.**

$$\alpha_s^n \ln^n(z_{\rm cut}) \qquad n \geq 2$$

Limit to the ungroomed case

- Soft drop condition is passed trivially when $\beta \to \infty \Leftrightarrow$ returns ungroomed case.

$$\frac{\min[p_{T,i}, p_{T,j}]}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left(\frac{R_{ij}}{R}\right)^{\beta} \to 0 \quad \text{when} \quad \beta \to \infty$$

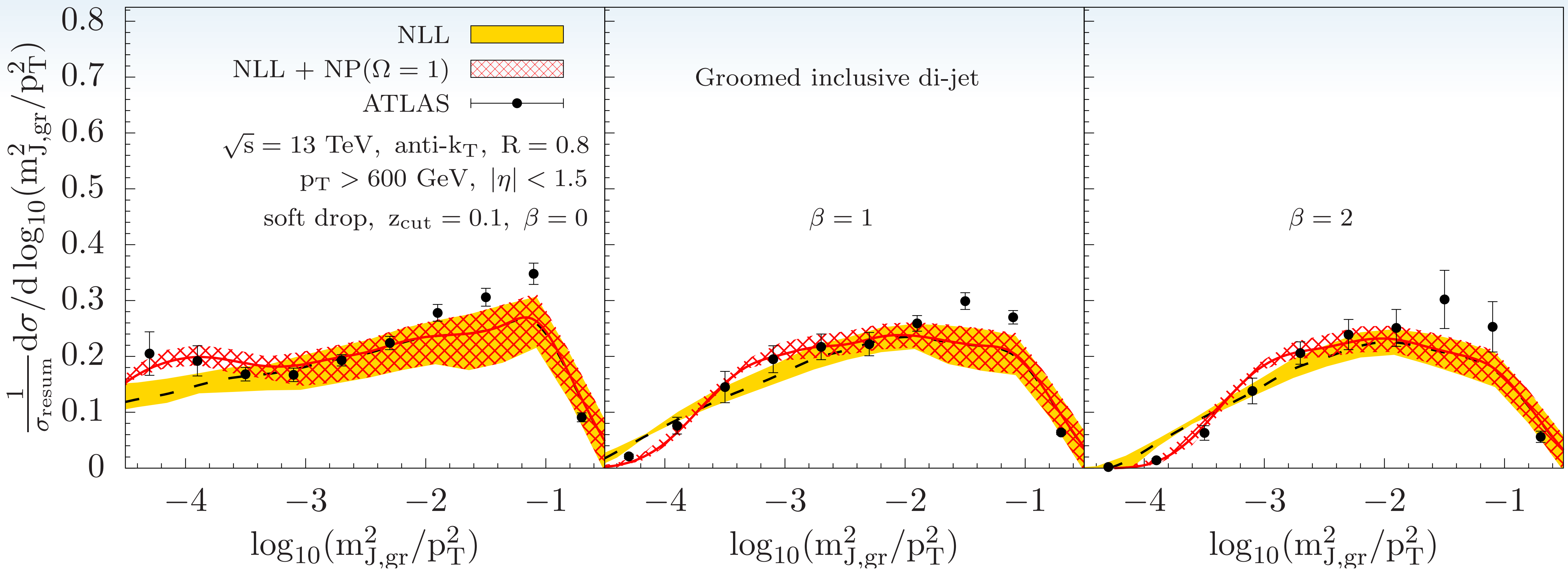


Checked both numerically and analytically.

- At $\tau_{gr} = z_{cut} R^2$, the groomed result transitions to the ungroomed case.

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
CMS PAS HIN-16-024
Larkoski, Marzani, Soyez, Thaler `14
Frye, Larkoski, Schwartz, Yan `16

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.
- Resummation of $R, \ \tau, \ z_{\rm cut}$.
- Continuous parameter dependence on quark and gluon discrimination power was considered.
- We now have a consistent baseline calculation for jet mass in pp.
  Extend to jet mass in heavy ion collisions!