Semi-inclusive Jet Observables

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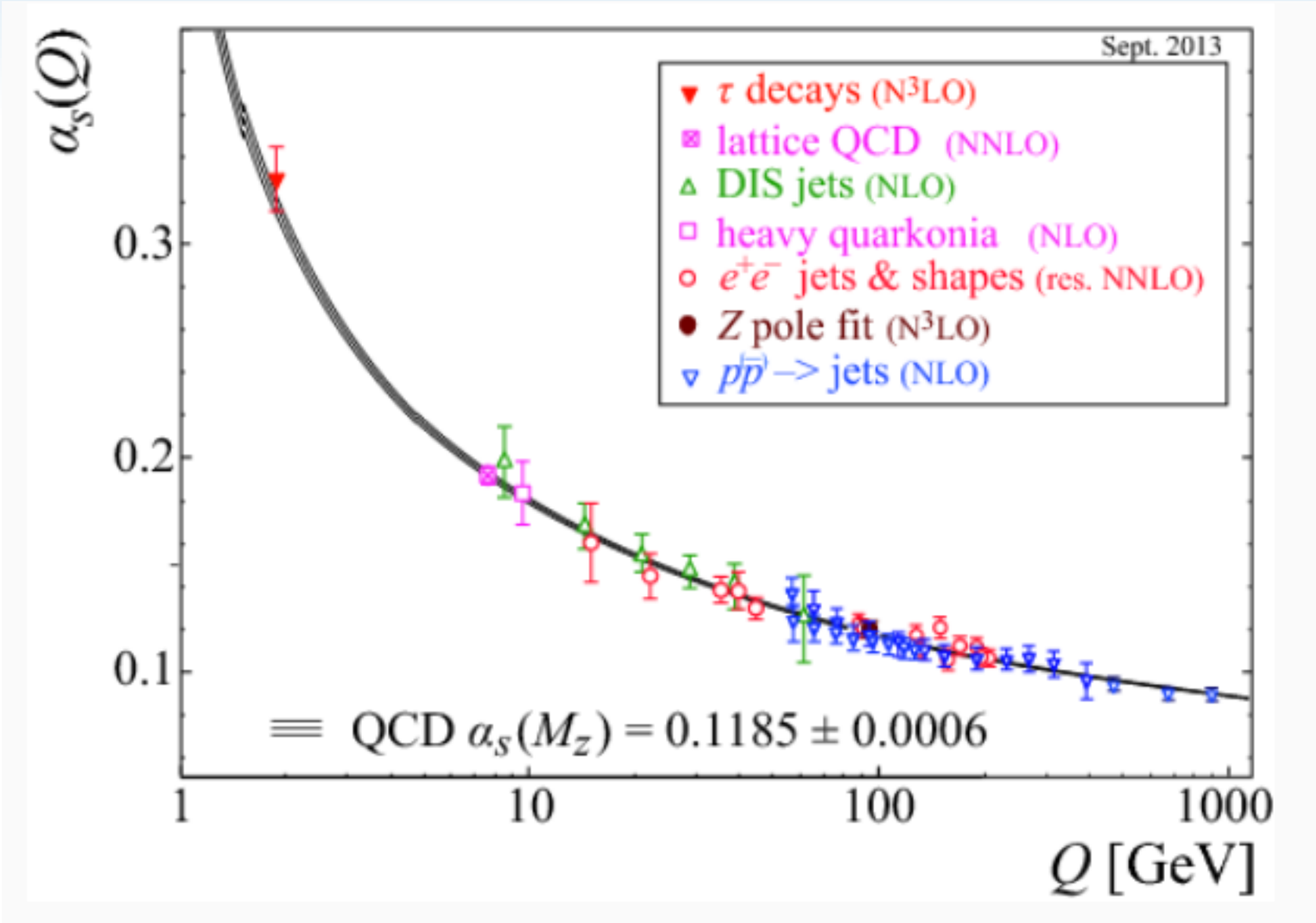
JLab,
08/27/2018

IR safety and factorization



- Asymptotic freedom "only" allows us to compute interactions of quarks and gluons at short-distance (partonic cross-sections).

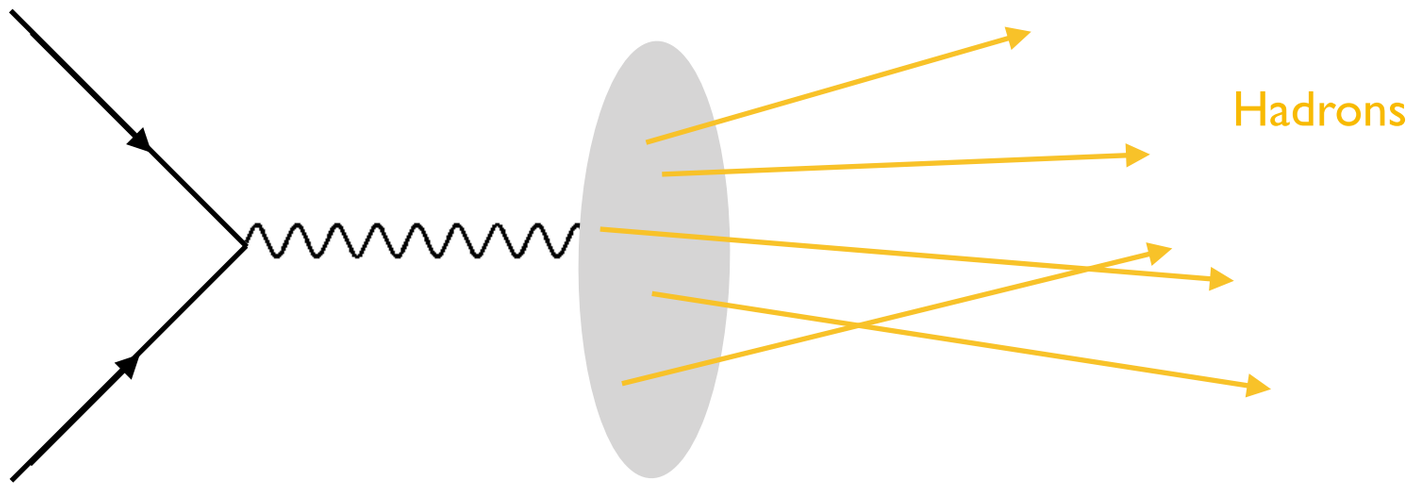
- Detectors are long-distance away. Experiments can only see hadrons and not free partons.

IR safety and factorization

IR-safe observables:

- **Observables which are independent of long-distance physics.**
  Asymptotic freedom is enough to guarantee a full theoretical (perturbative) calculation.

- **One of the simplest observable:** $e^+e^- \to \text{hadrons}$



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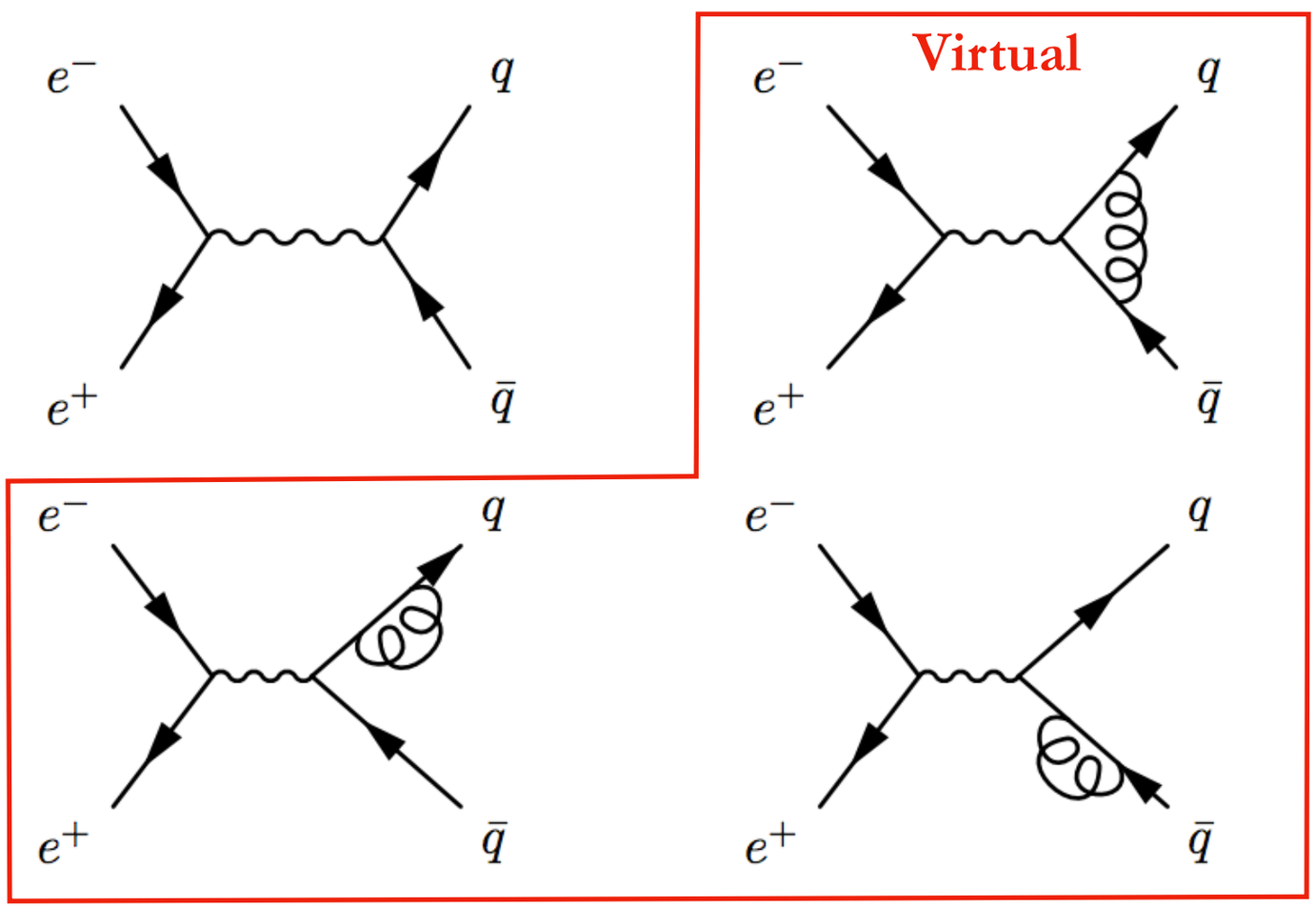
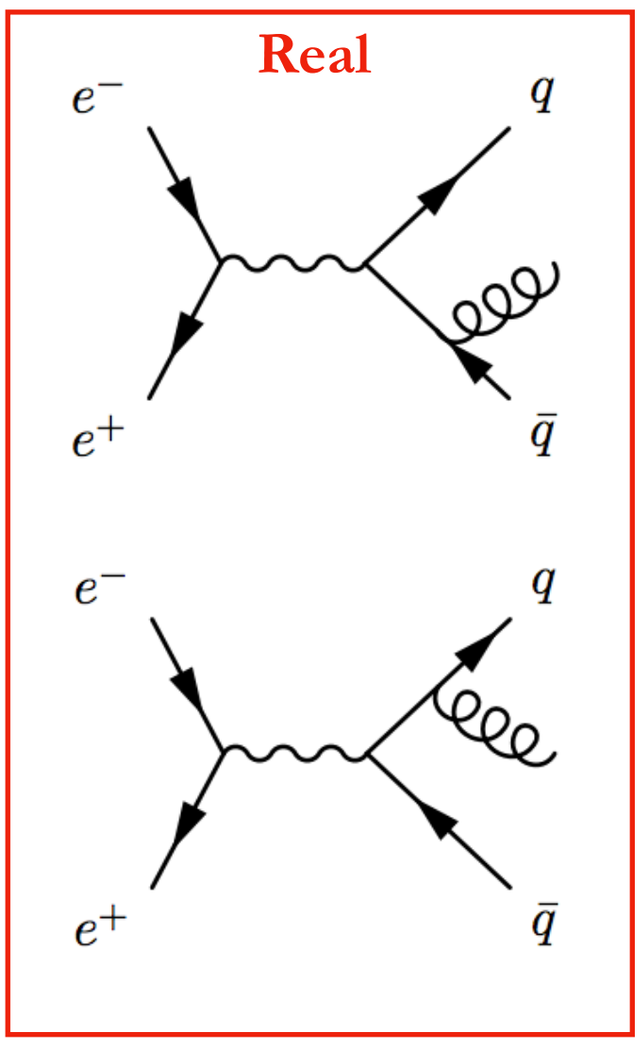
  1-loop example: individually divergent, but finite sum!

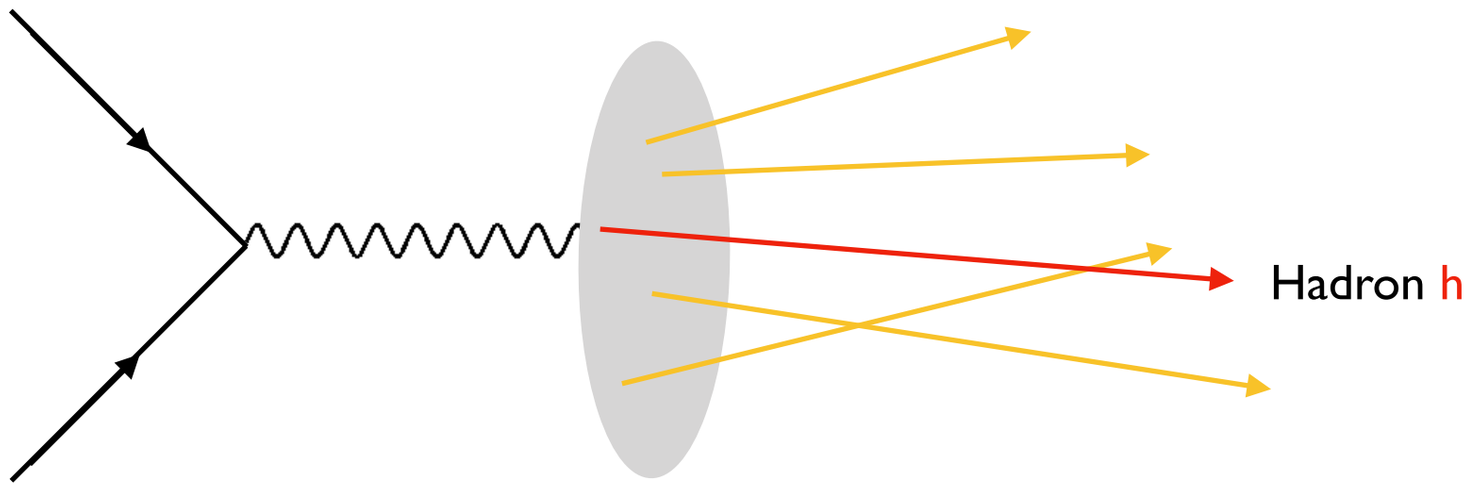




IR safety and factorization

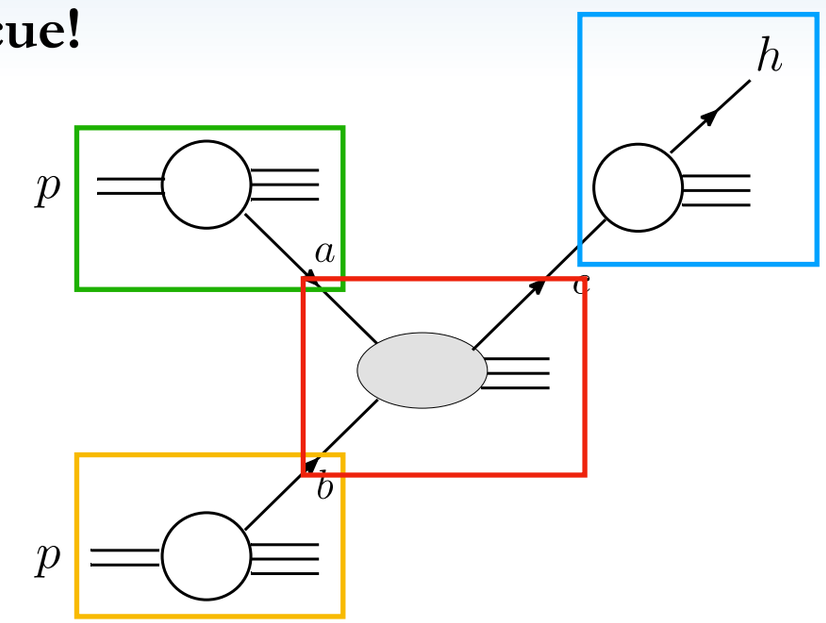
- **Asking a long-distance sensitive question will give sensitivity to non-perturbative physics!**

i.e. $e^+e^- \to h + X$



IR safety and factorization

- **Factorization to the rescue!**



$$pp \to h + X$$

Factorization

Evolution

Hadron

$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes D^h_c$$

$$\mu \frac{d}{d\mu} D^h_i = \sum_j P_{ji} \otimes D^h_j$$

Perturbatively computable

Non-perturbative but universal

Kang, Ringer, Vitev `16

IR safety and factorization

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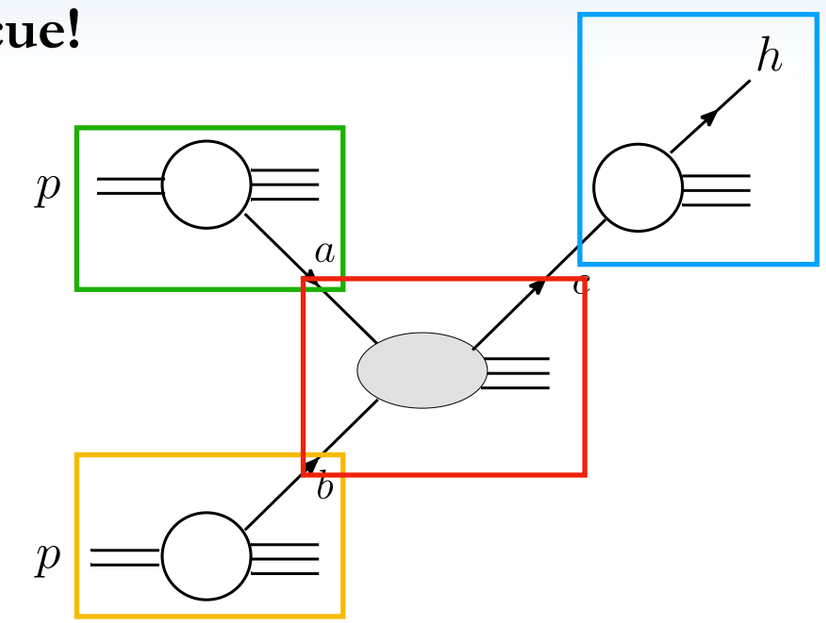

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Perturbatively computable

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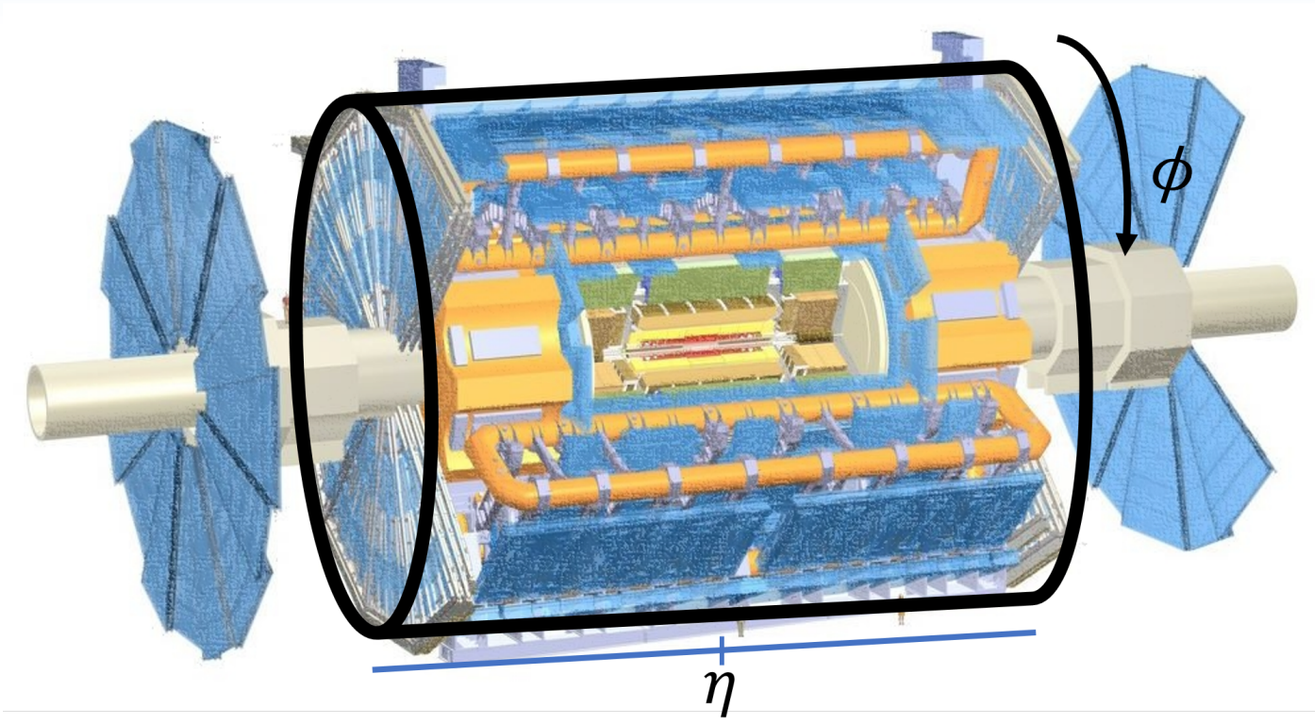
DGLAP evolution

Kang, Ringer, Vitev `16

IR-safe observables

- Jet is another IR-safe observable!

What are Jets?



- **Azimuthal angle** ϕ **and pseudorapidity** $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$

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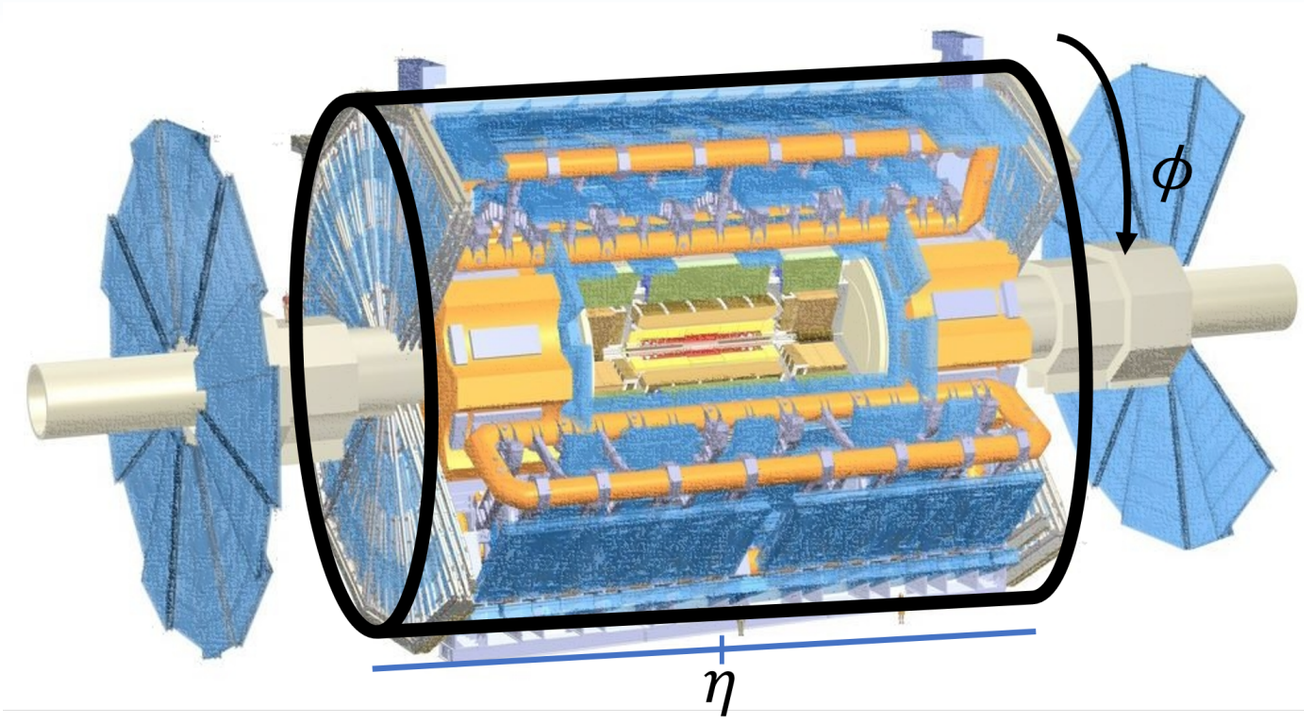

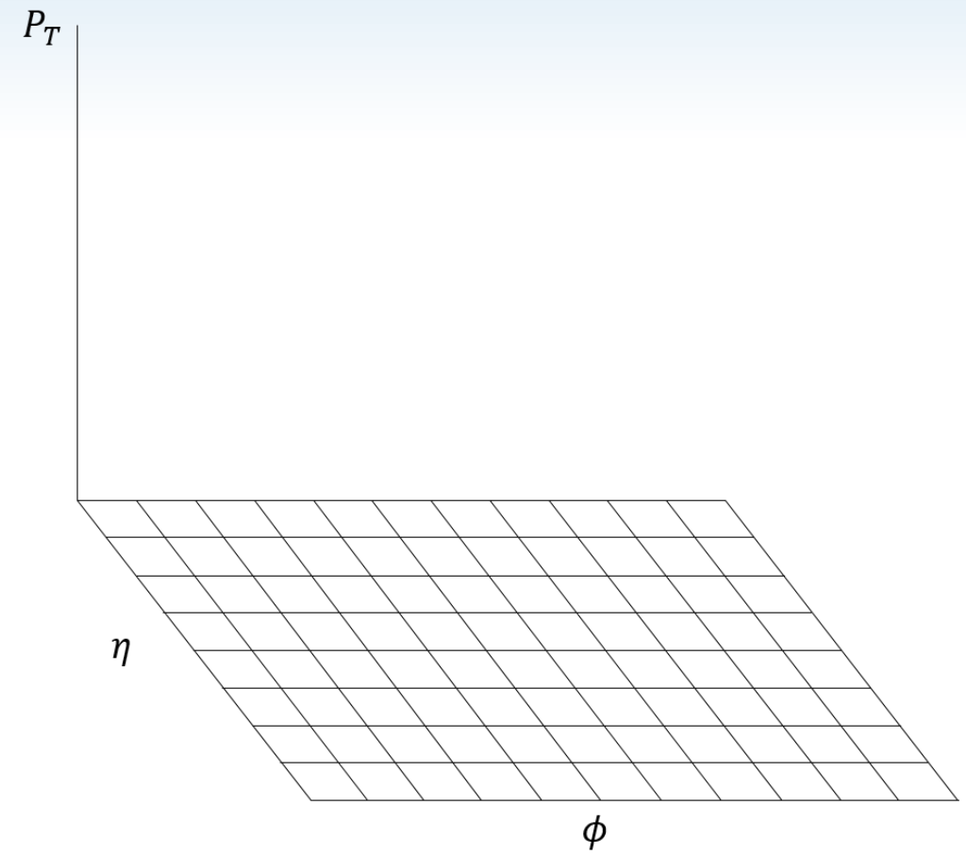

- **Azimuthal angle** ϕ **and pseudorapidity** $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$
- **We open the cylinder and plot observed particles'** P_T **and it's angular distribution.**

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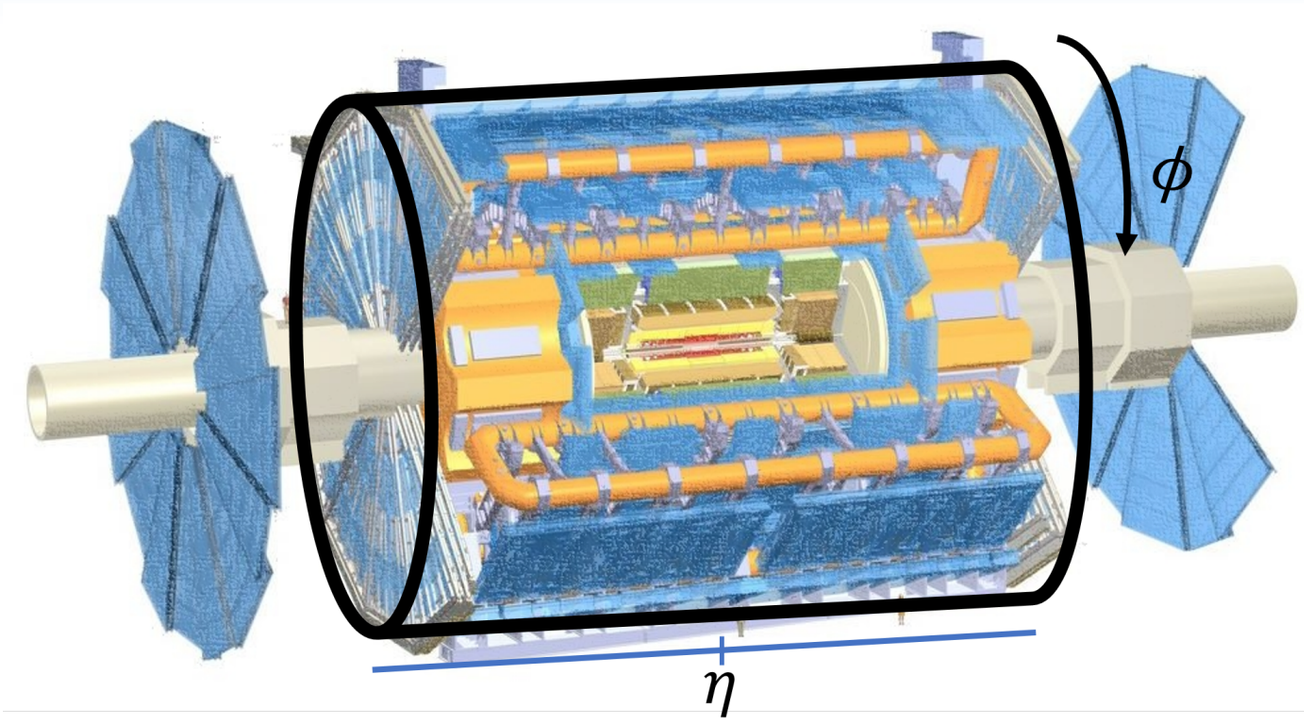
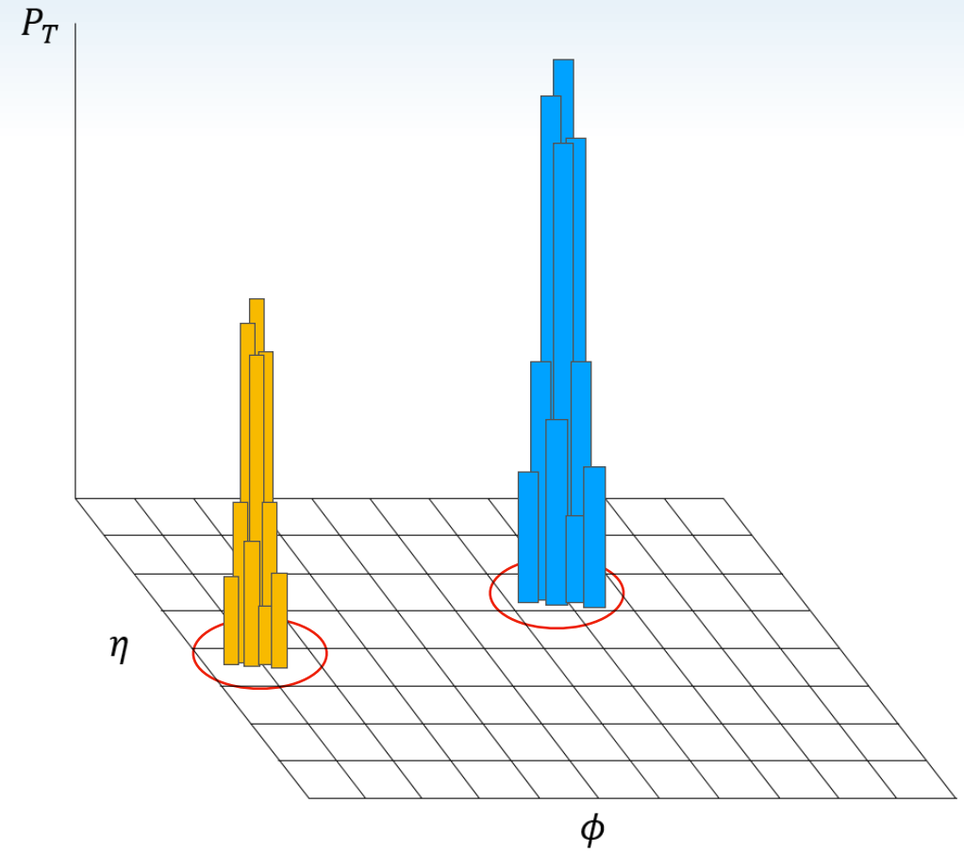
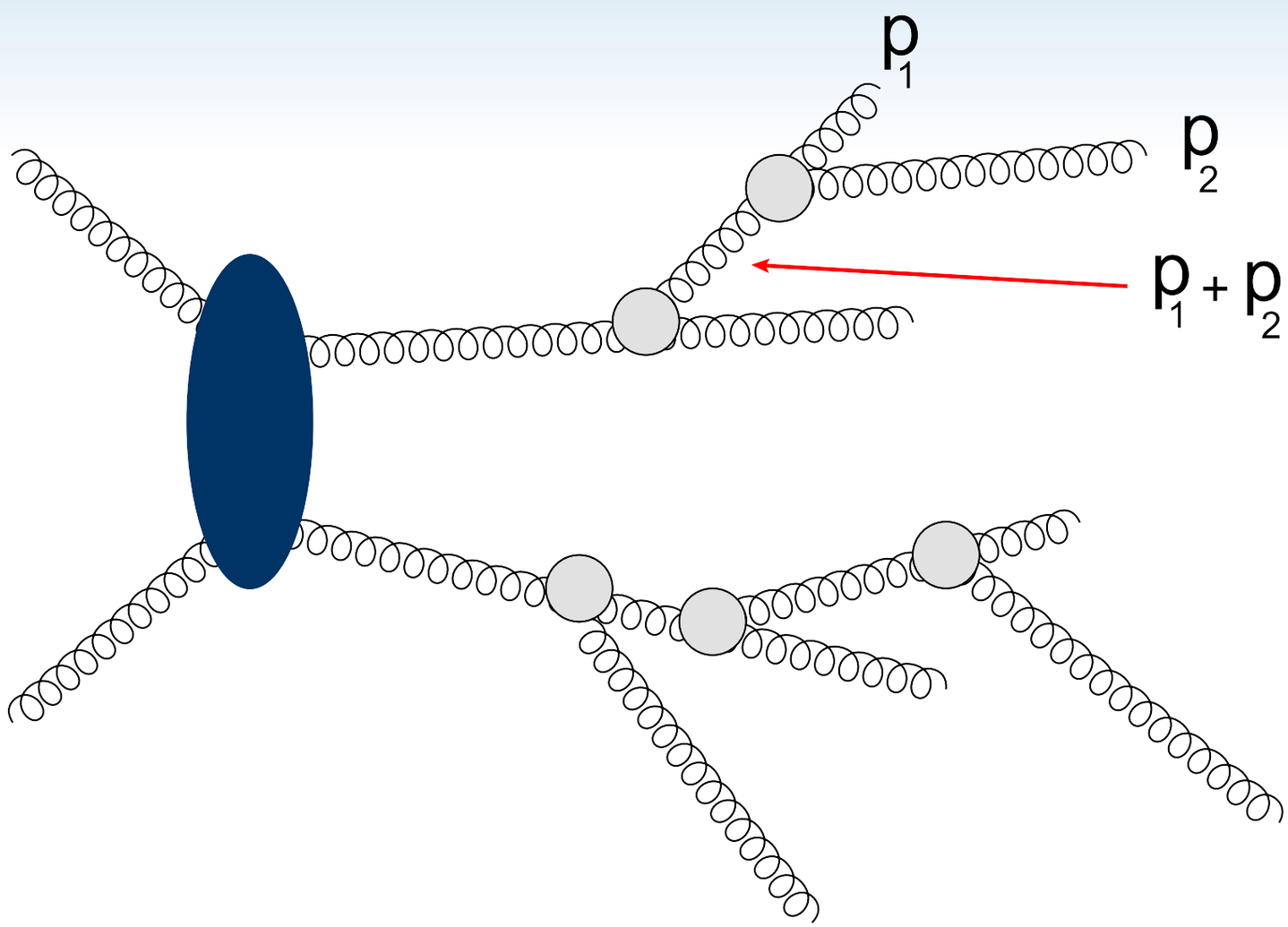


Dijet event



- **Azimuthal angle** ϕ **and pseudorapidity** $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$
- **We open the cylinder and plot observed particles'** P_T **and it's angular distribution.**
- **Jets = collimated spray of particles.**

Why do we have jets?



- **Production of jet is consistent with the partonic picture of QCD.**

- **High probability of collinear and soft splittings: with** $p_1^2 = 0,\ p_2^2 = 0$

$$\frac{1}{(p_1+p_2)^2} = \frac{1}{2E_1E_2(1-\cos\theta)} \to \infty \quad \textbf{when} \quad p_1 \to 0 \quad \textbf{or} \quad p_2 \to 0 \quad \textbf{or} \quad p_1 \sim p_2$$

(Of course, probability cannot be infinities. Should really think of it as degenerate states.)

Sterman-Weinberg Jets

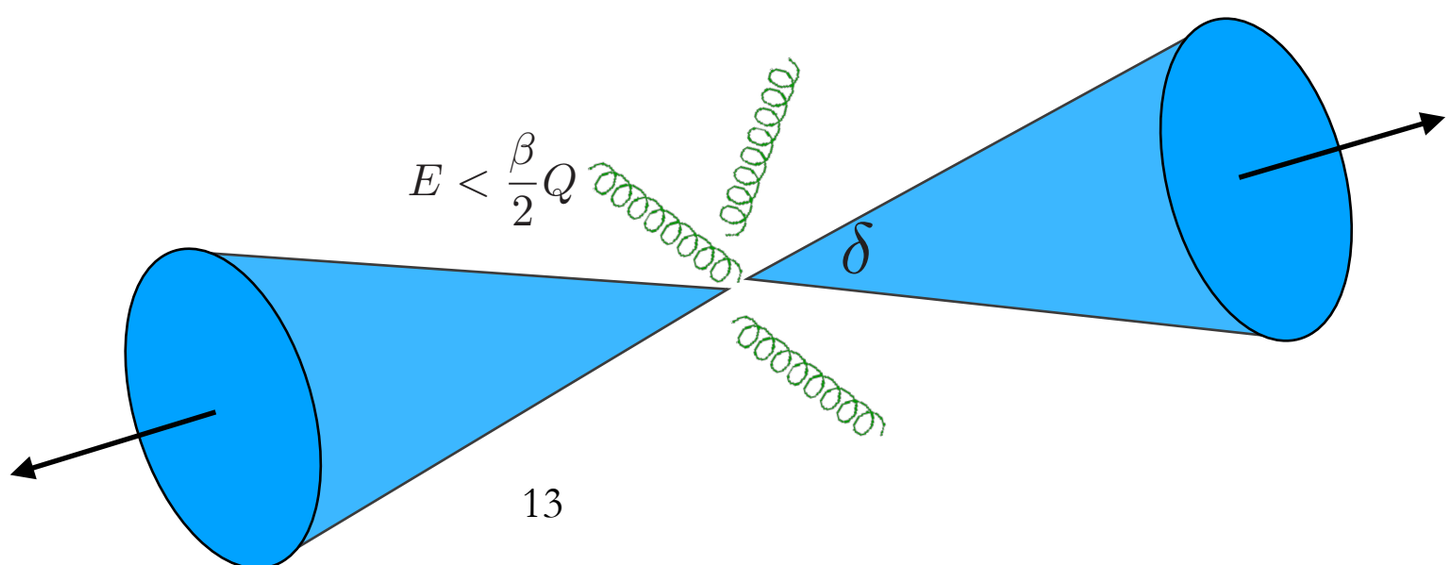
- **IR safety tells us must be sufficiently inclusive to cancel IR divergences.**

Dijet events

$$\sigma_{2\to 2} = \sigma(e^+e^- \to q\bar{q}) + \sigma(e^+e^- \to q\bar{q}g)|_{\delta,\beta}$$

$$= \sigma_0 \left(1 + \frac{\alpha_s C_F}{4\pi}(-16\ln\delta\ln\beta - 12\ln\delta + c_0)\right)$$

- **All energy must be inside narrow cones of half-angle δ except for a small fraction $\beta/2$ of the center-of-mass energy Q.**



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Some issues:

Large logs

$$\ln\delta, \quad \ln\beta$$

Scale choices

$$\mu \sim Q, \; Q\delta, \; Q\beta, \; Q\delta\beta?$$

- **Physics at multiple scale!**

Resummation

Almeida, Ellis, Lee, Sterman, Walsh, '14

$$\{\tilde{\sigma}(\nu), R(\tau)\} = 1 + \frac{\alpha_s}{4\pi}\left[b_{12}L^2 + b_{11}L + b_{10}\right] + \left(\frac{\alpha_s}{4\pi}\right)^2\left[b_{24}L^4 + b_{23}L^3 + b_{22}L^2 + b_{21}L + b_{20}\right] + \left(\frac{\alpha_s}{4\pi}\right)^3\left[b_{36}L^6 + b_{35}L^5 + b_{34}L^4 + b_{33}L^3 + b_{32}L^2 + b_{31}L + b_{30}\right] + \cdots + D(\alpha_s)\,,$$

Sudakov type logarithms.

Resummation

CTTW counting,

Almeida, Ellis, Lee, Sterman, Walsh, '14

$$R(\tau) = C(\alpha_s)\Sigma(\tau,\alpha_s) + D(\tau,\alpha_s)\,,$$

$$C(\alpha_s) = 1 + \sum_{n=1}^{\infty}\left(\frac{\alpha_s}{2\pi}\right)^n C_n\,,$$

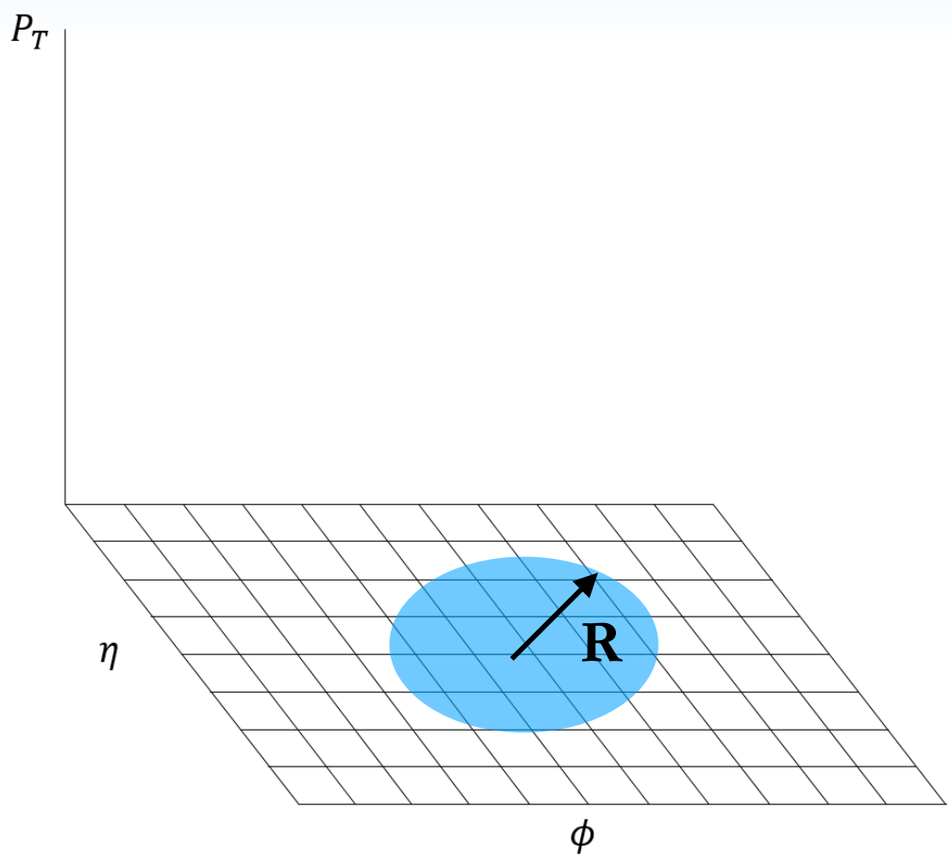
$$\begin{aligned}\ln\Sigma(\tau,\alpha_s) &= \sum_{n=1}^{\infty}\sum_{m=1}^{n+1}\left(\frac{\alpha_s}{2\pi}\right)^n G_{nm}\ln^m\frac{1}{\tau}\\ &= \boxed{\left(\frac{\alpha_s}{2\pi}\right)\left(G_{12}\ln^2\frac{1}{\tau}\right.}+\left.G_{11}\ln\frac{1}{\tau}\right)\\ &\quad+\left(\frac{\alpha_s}{2\pi}\right)^2\left(G_{23}\ln^3\frac{1}{\tau}+G_{22}\ln^2\frac{1}{\tau}+G_{21}\ln\frac{1}{\tau}\right)\\ &\quad+\left(\frac{\alpha_s}{2\pi}\right)^3\left(G_{34}\ln^4\frac{1}{\tau}+G_{33}\ln^3\frac{1}{\tau}+G_{32}\ln^2\frac{1}{\tau}+G_{31}\ln\frac{1}{\tau}\right)+\cdots\,,\end{aligned}$$

$$\begin{aligned}\mathrm{LL} &: \mathcal{O}(\alpha_s^{-1})\\ \mathrm{NLL} &: \mathcal{O}(1)\\ \mathrm{NNLL} &: \mathcal{O}(\alpha_s)\\ \mathrm{NNNLL} &: \mathcal{O}(\alpha_s^2)\end{aligned}$$

Sudakov type logarithms.

No unique way to define a jet

Cone-type algorithm



- **Particles within some radius 'R' in (η, ϕ)- plane are defined as a jet.**

Recombination-type algorithm (k_T - type)

1. **Begin with list of particles**
2. **Define metrics (a = -1, 0, 1 for k_T, Cambridge-Aachen(CA), anti-k_T)**

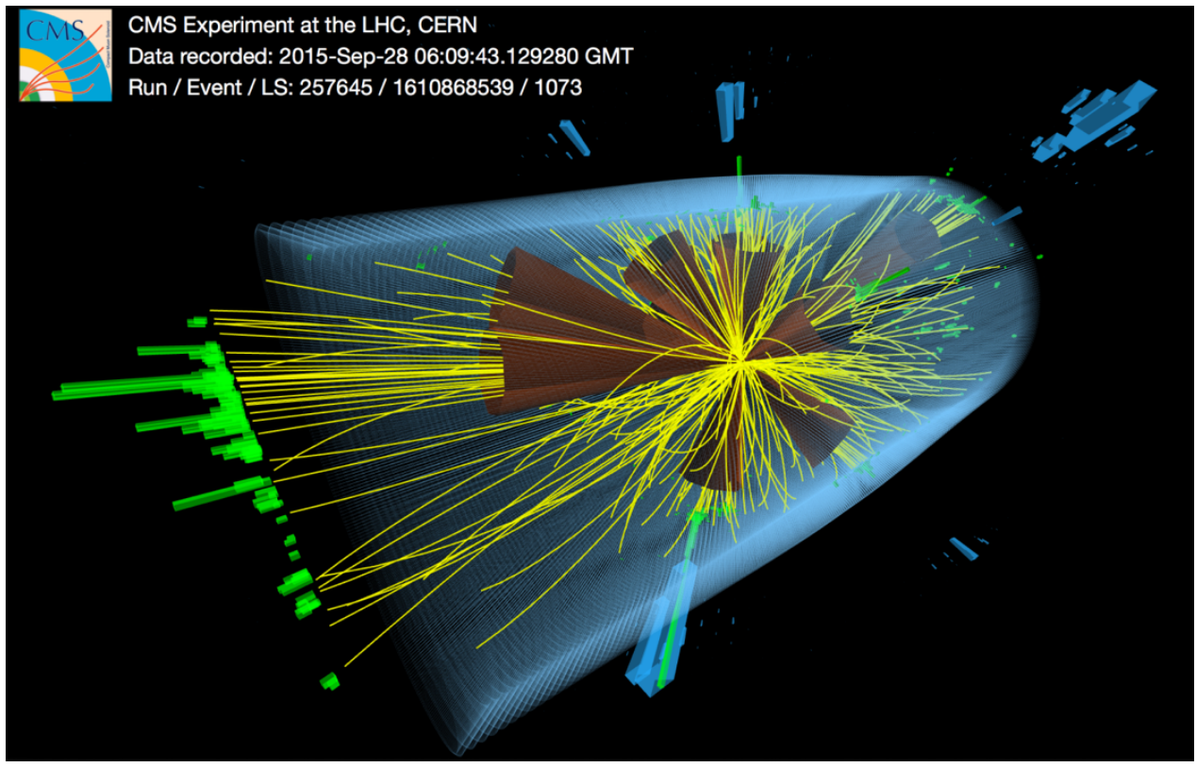
$$d_{ij} = \frac{\min\left(p_{T_i}^{2a}, p_{T_j}^{2a}\right)}{R^2}[(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2]$$

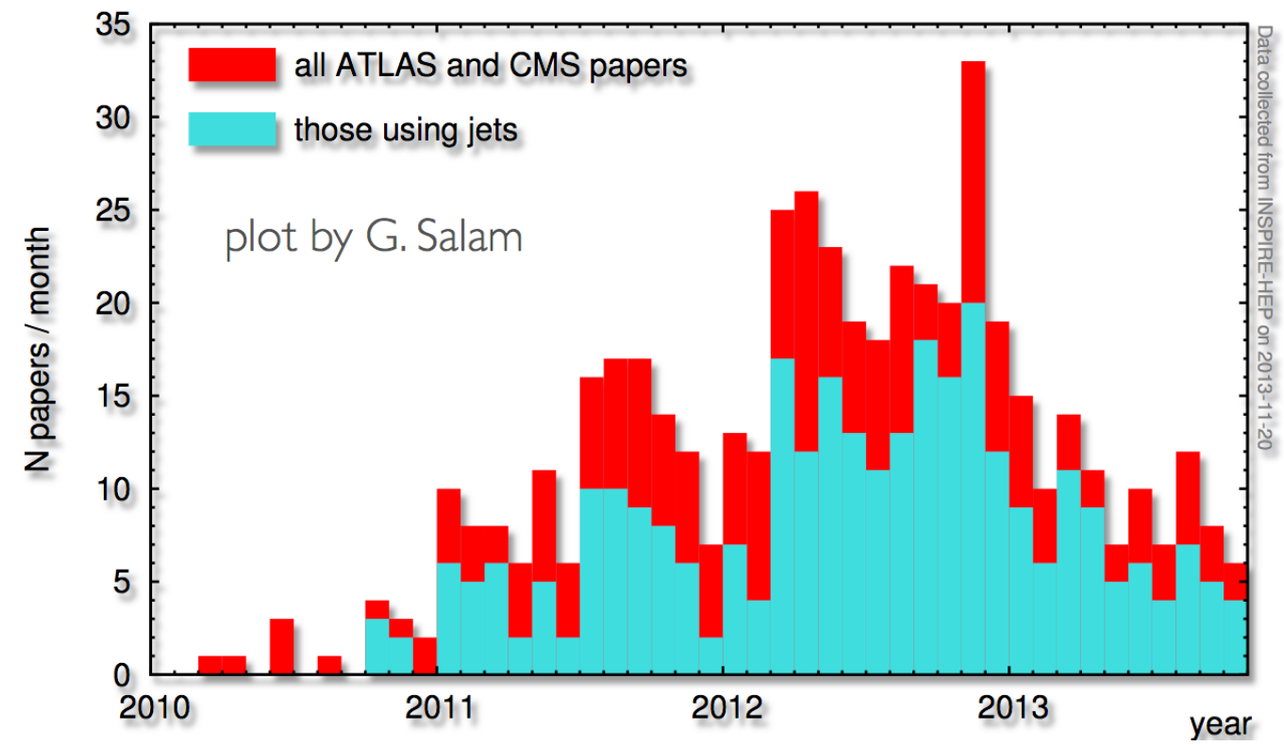
$$d_i = p_{T_i}^{2a}$$

$$d_{\min} = \min\{d_{ij}, d_i\}$$

3. **Merge particle i and j if $d_{\min} = d_{ij}$. Add i to list of jets if $d_{\min} = d_i$.**
4. **Back to 1 until only left with list of jets.**

Jets at the LHC

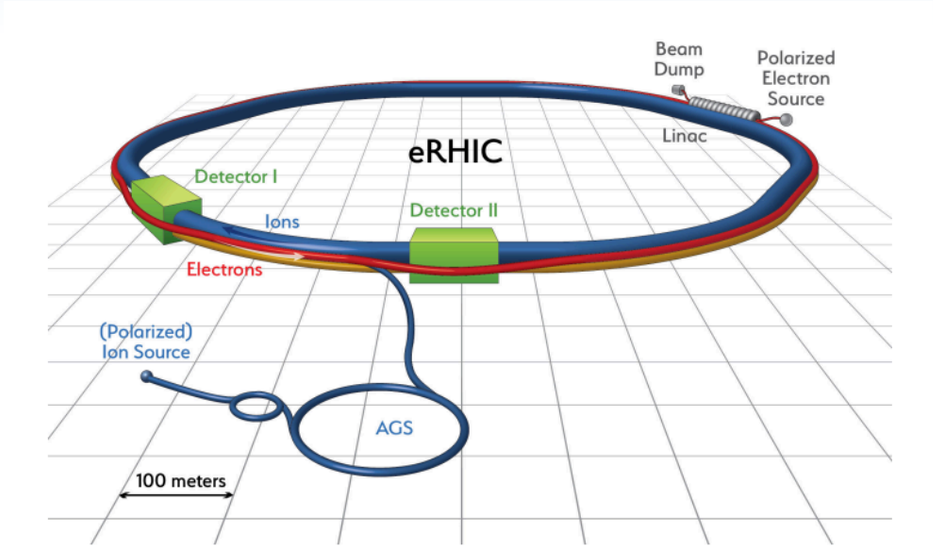


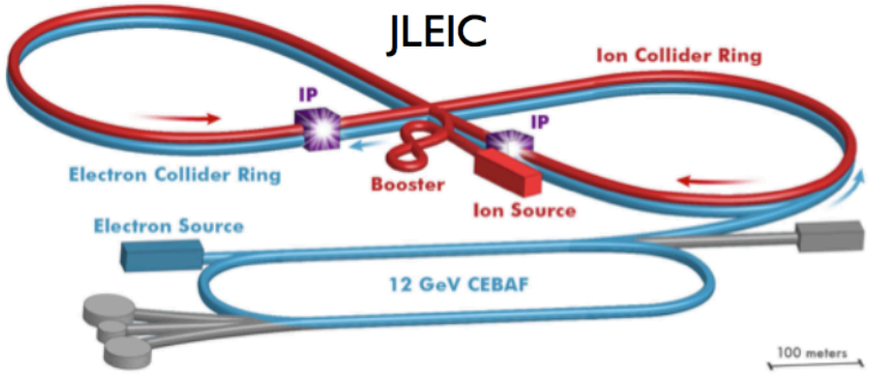


- **Jets are produced copiously at the LHC**

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

Jets at the EIC

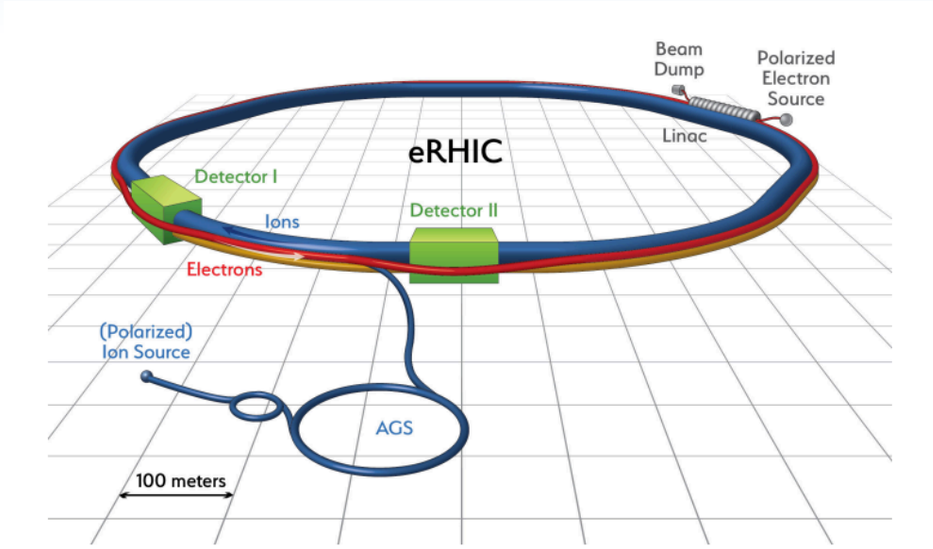




- $\sqrt{S_{\rm EIC}} \ll \sqrt{S_{\rm LHC}} \Leftrightarrow \sqrt{p_{T_J,\rm EIC}} \ll \sqrt{p_{T_J,\rm LHC}}$
  Lower $p_{T,J}$ for EIC
- $N_{J,EIC} \ll N_{J,LHC}$
  Smaller jet multiplicity for EIC
- Less contamination from underlying events and pileups

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

Jets at the EIC



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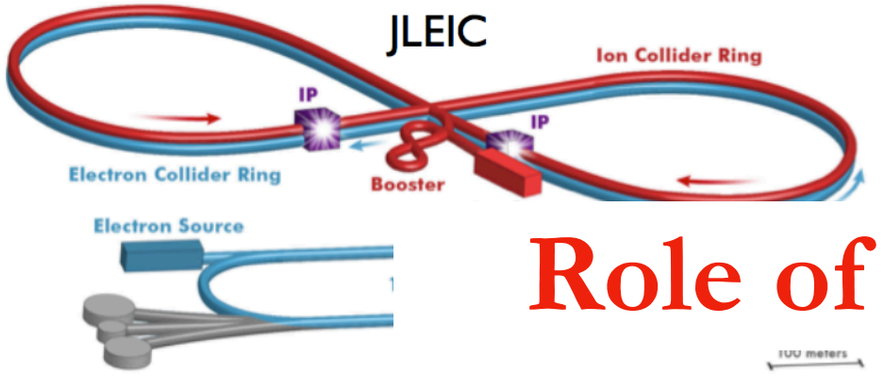


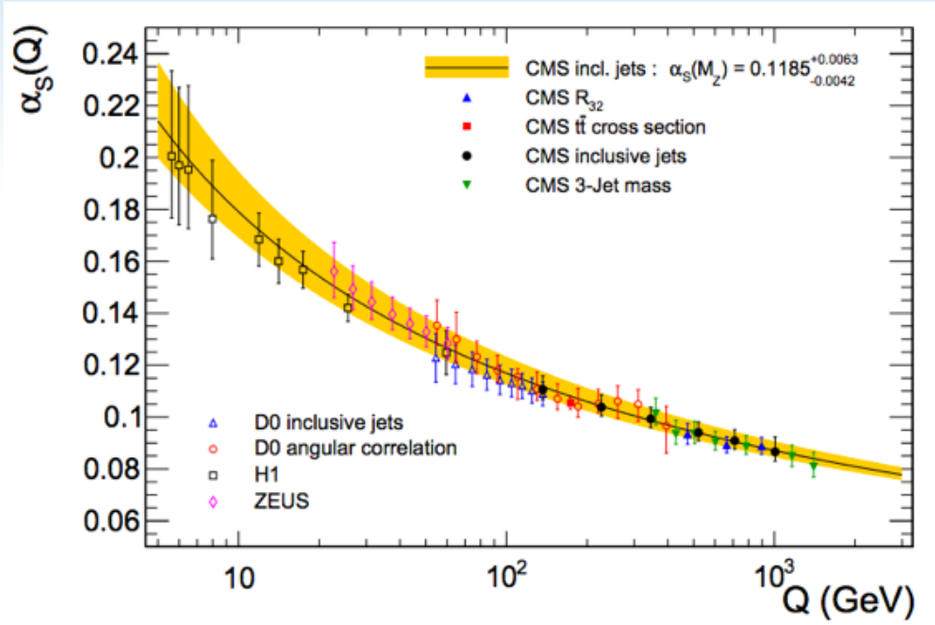
Role of higher power corrections?

- **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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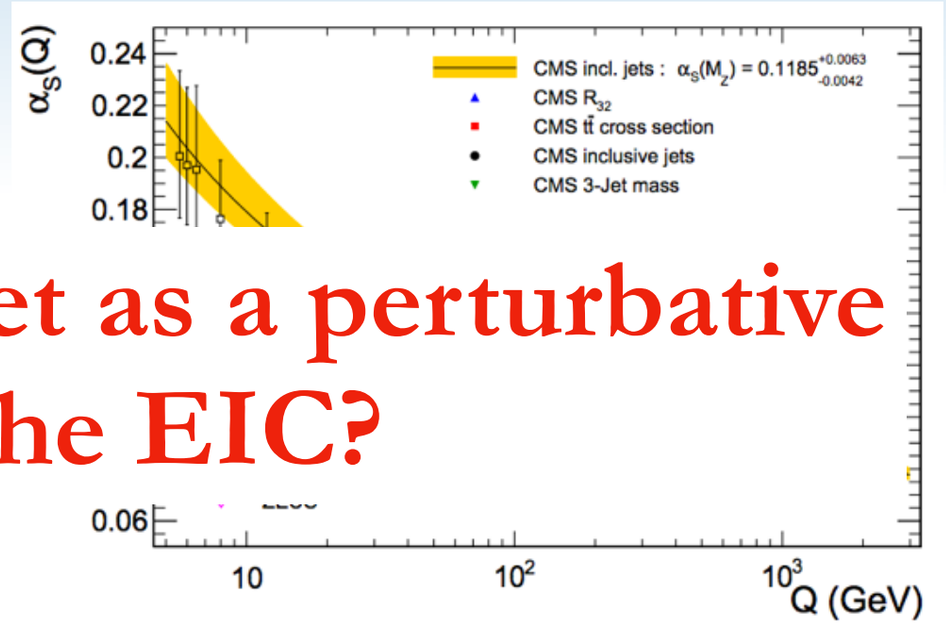

What is the role of jet as a perturbative probe at the EIC?

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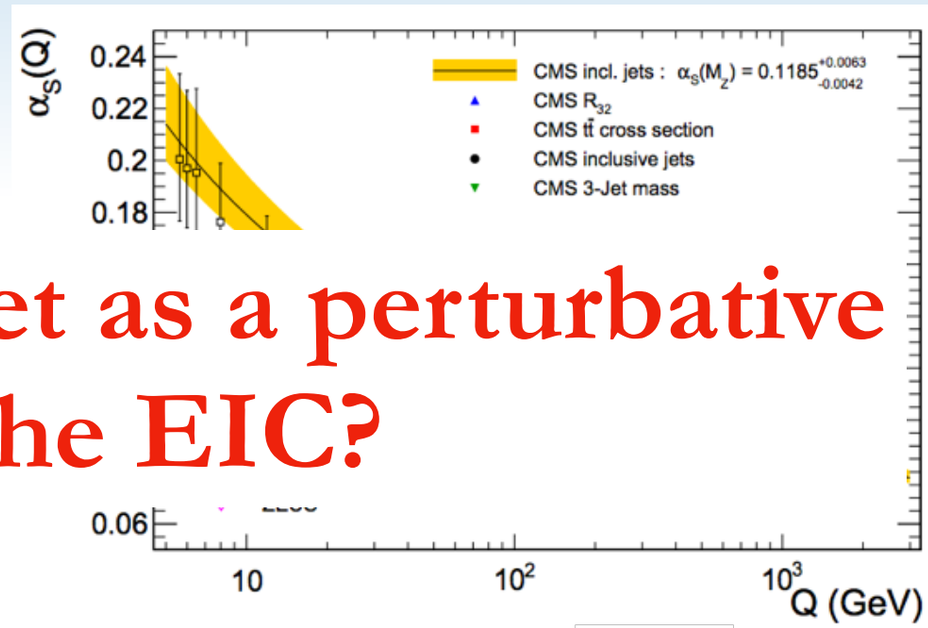
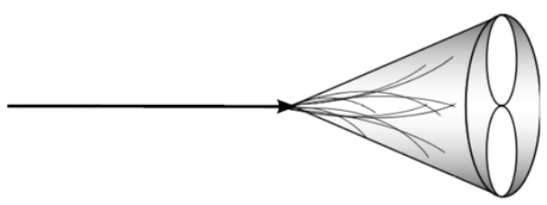
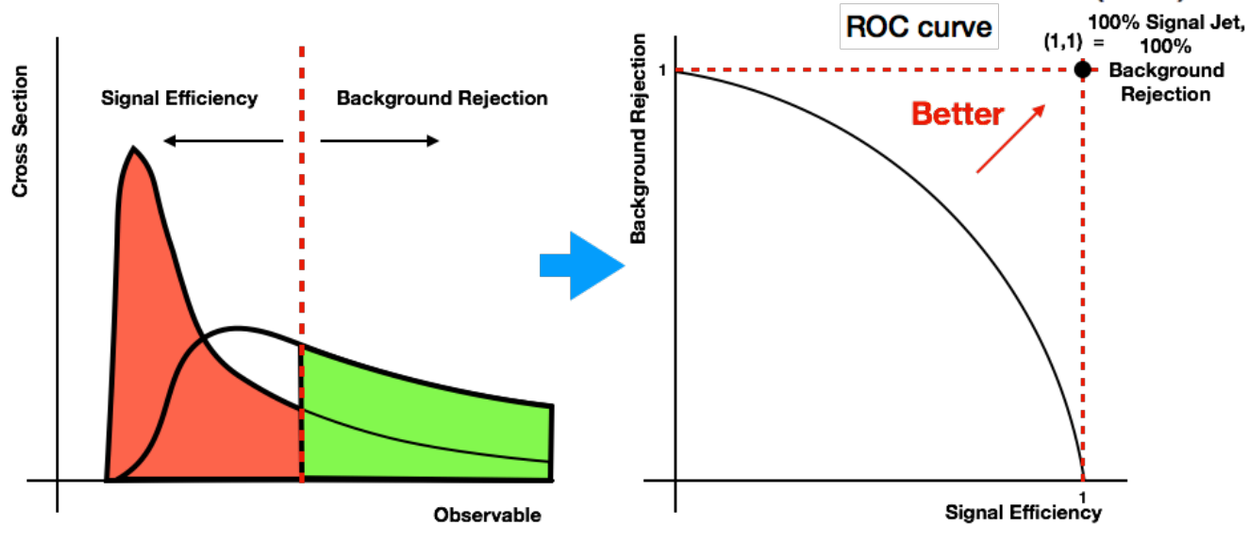


What is the role of jet as a perturbative probe at the EIC?

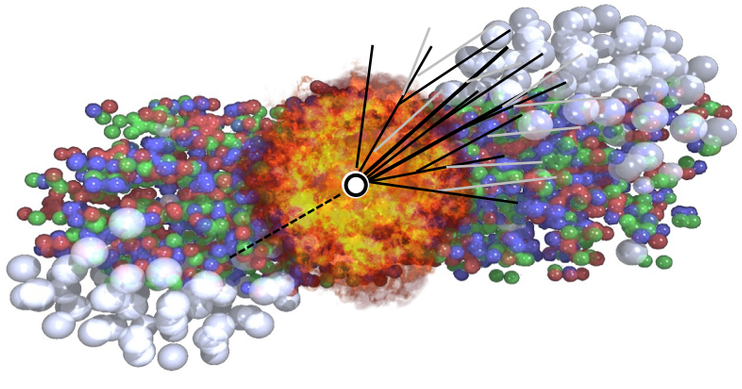
- **Constrain BSM Models**



Fat jet from BSM signal



- **Probe of quark gluon plasma**



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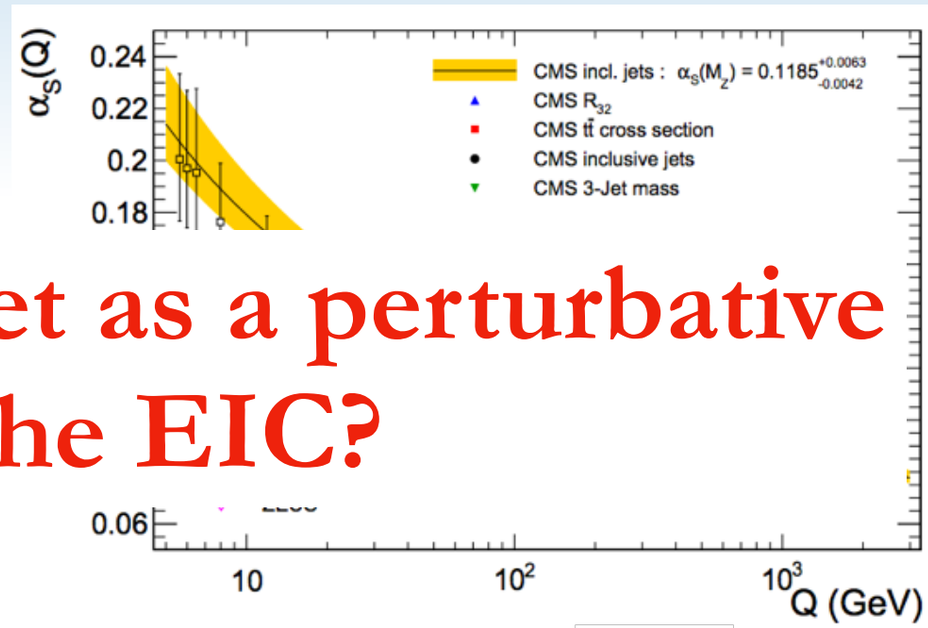

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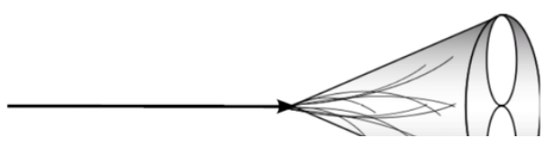
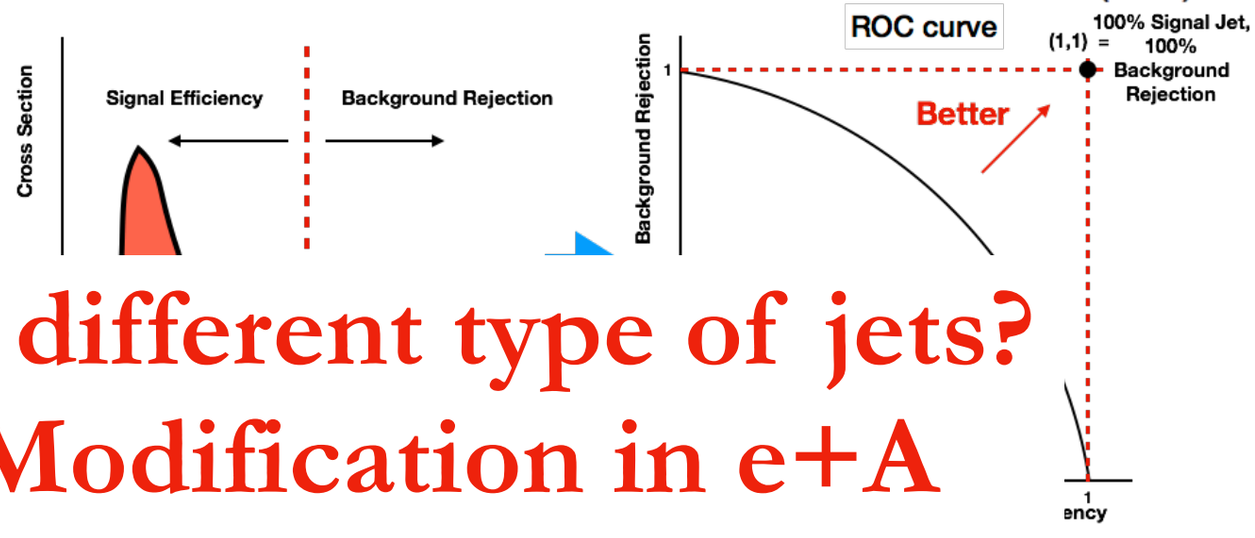
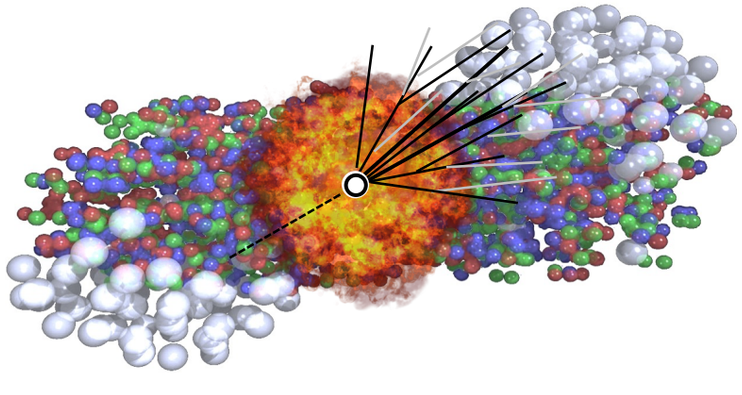


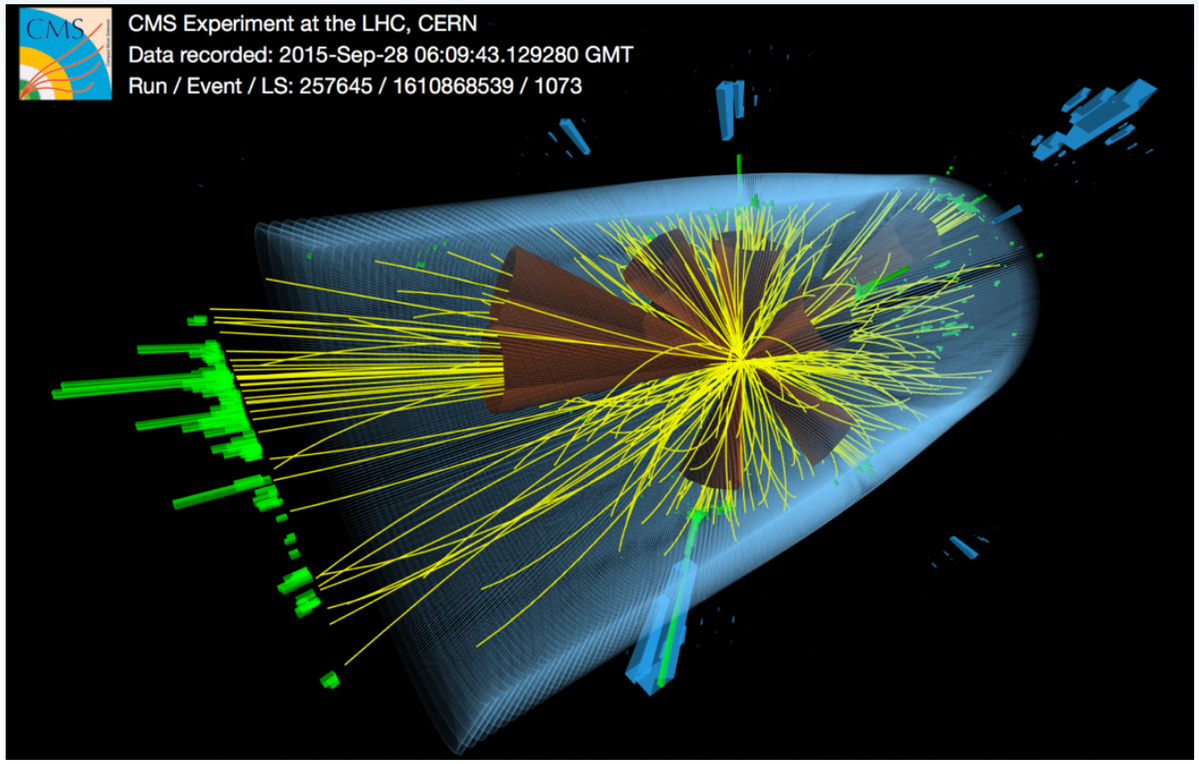


Classification of different type of jets?
Cold Nuclear Modification in e+A

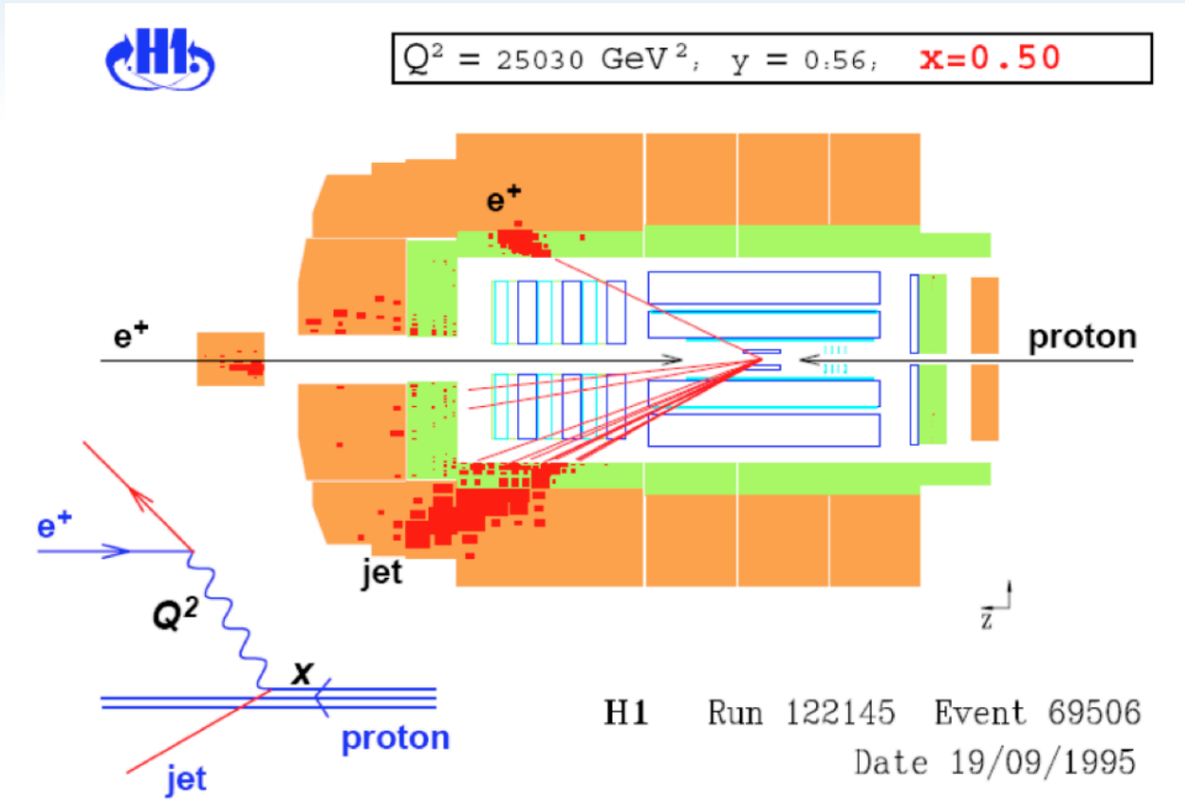
- Probe of quark gluon plasma



Application of jet studies at the LHC



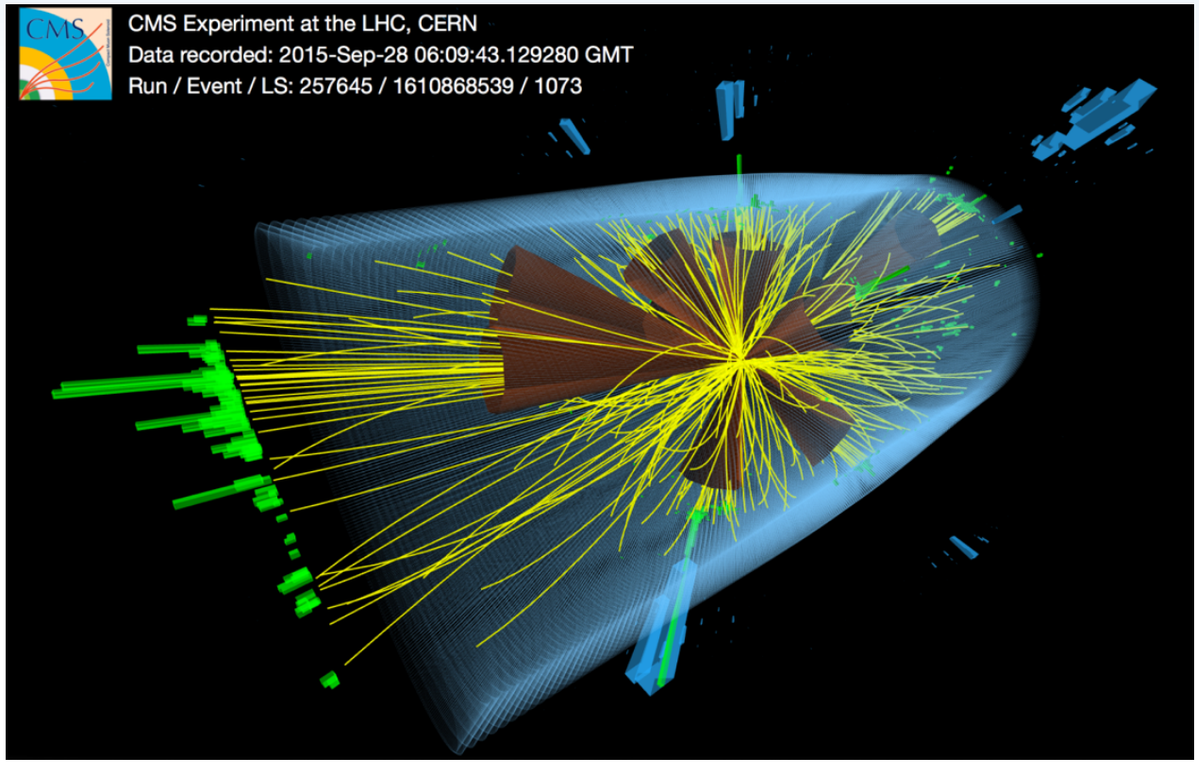
LHC



HERA

- Typical event at the LHC and HERA

Application of jet studies at the LHC



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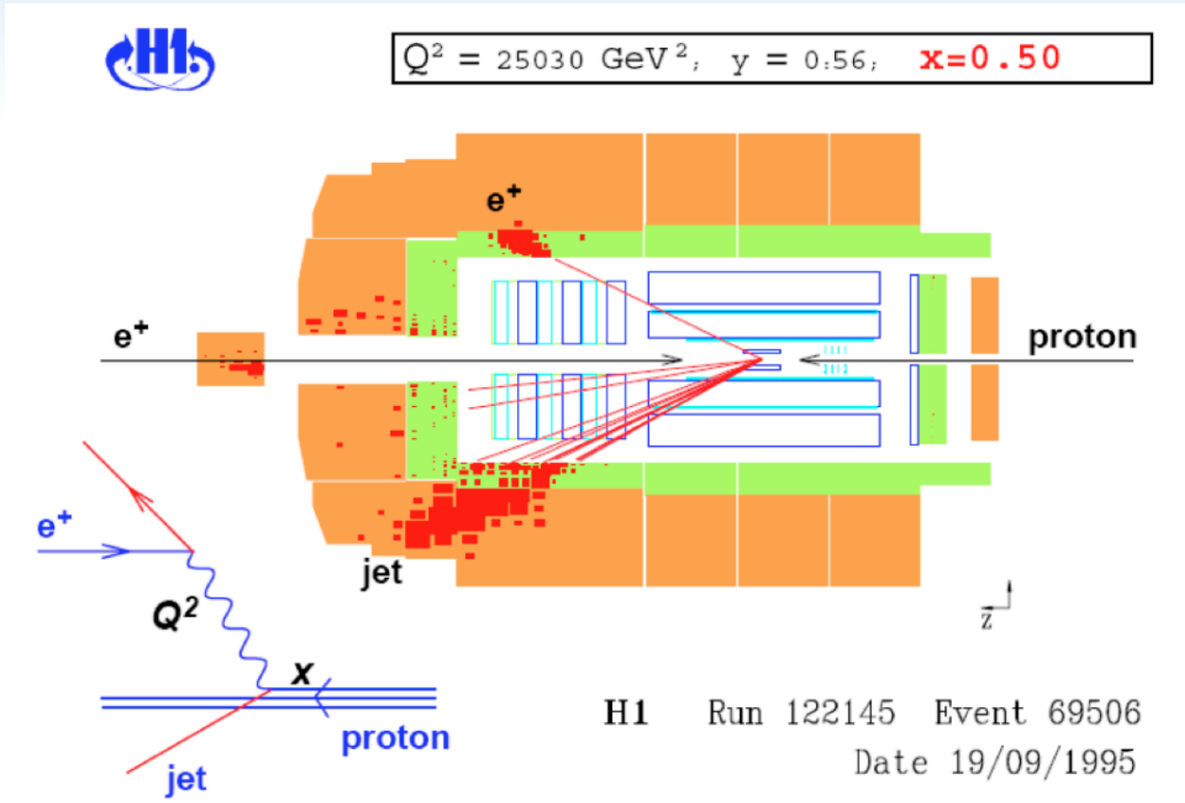

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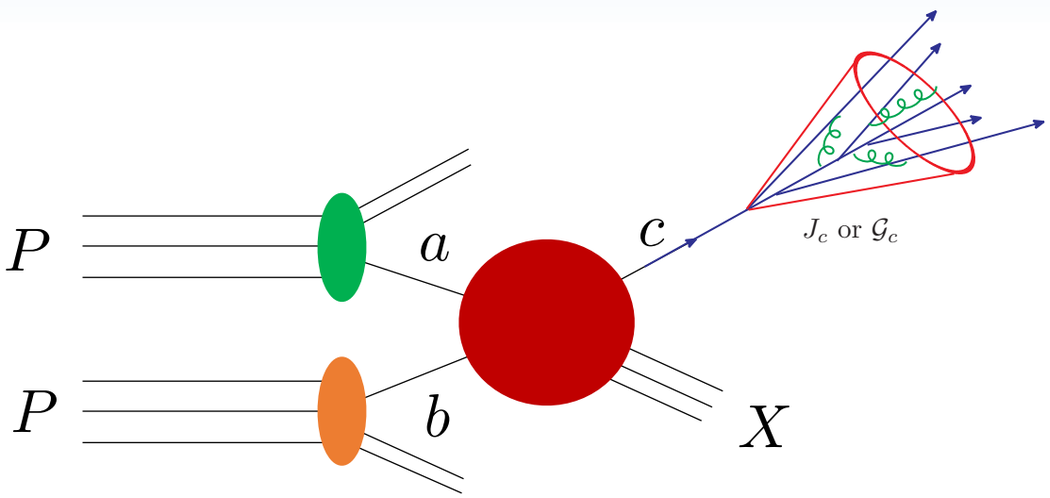
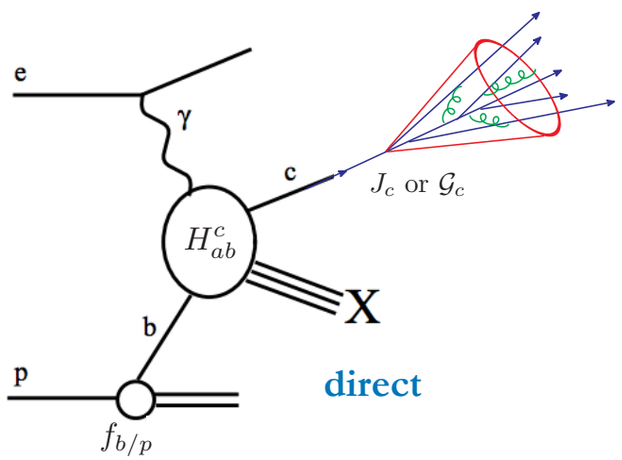
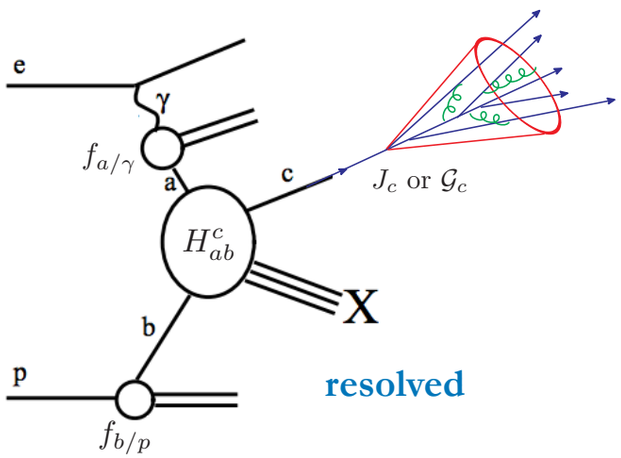
What is the role of NP physics at the EIC?

Processes of Interest







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

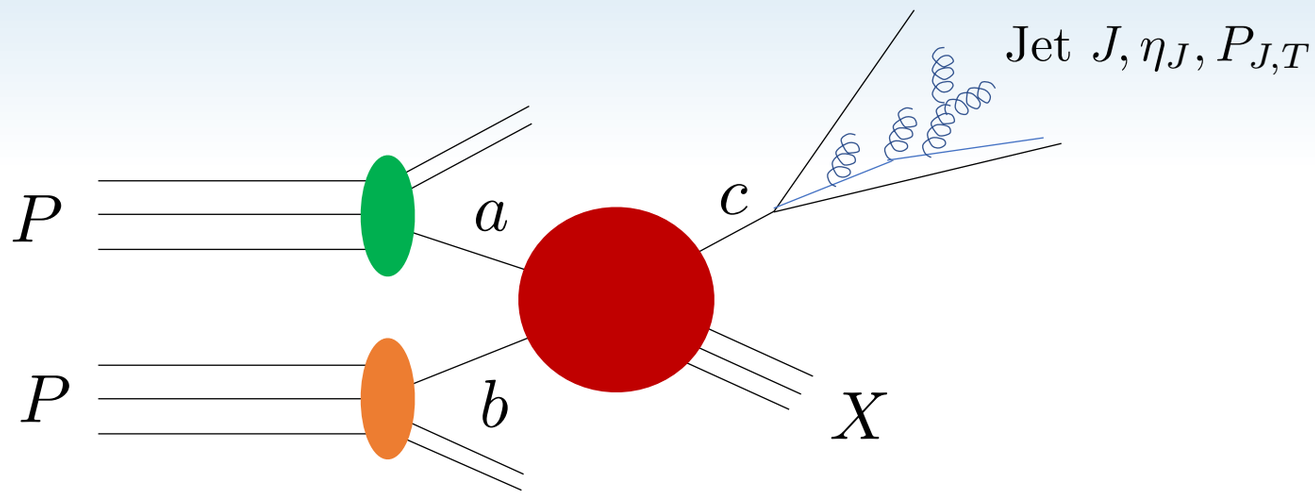
  photoproduction at the EIC
  e + p $\longrightarrow$ e + Jet((with/without) substructure) + X

- More statistics. No veto on additional jets.

Plans of this talk

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

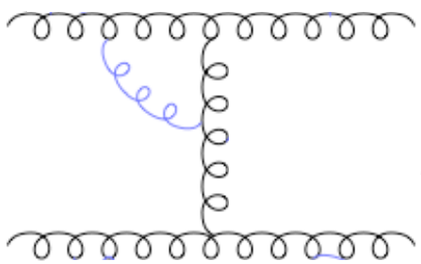
Inclusive Jet Production



- A completely perturbative process (IR safe), perturbative computation can be made.
- Fixed order calculation gives :

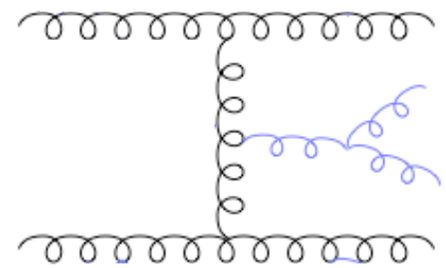
$$E\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} \propto \sum_{a,b} \int \frac{dx_a}{x_a} f_a^p(x_a) \int \frac{dx_b}{x_b} f_b^p(x_b) \boxed{H_{ab}}$$

Inclusive Jet Production



NLO 1990

Ellis, Kunszt, Soper `90



NNLO 2016

Currie, Glover, Pires `16

- A completely perturbative process (IR safe), perturbative computation can be made.
- Fixed order calculation gives :

$$E\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} \propto \sum_{a,b}\int \frac{dx_a}{x_a} f_a^p(x_a)\int \frac{dx_b}{x_b} f_b^p(x_b) H_{ab}$$

$$H_{ab} = \alpha_s^2\left(H_{ab}^{(0)} + \alpha_s H_{ab}^{(1)} + \alpha_s^2 H_{ab}^{(2)} + \ldots\right)$$

- H_{ab} has $(\alpha_s \ln R)^n$ which must be resummed. **(not Sudakov type logs)**

Inclusive Jet Production

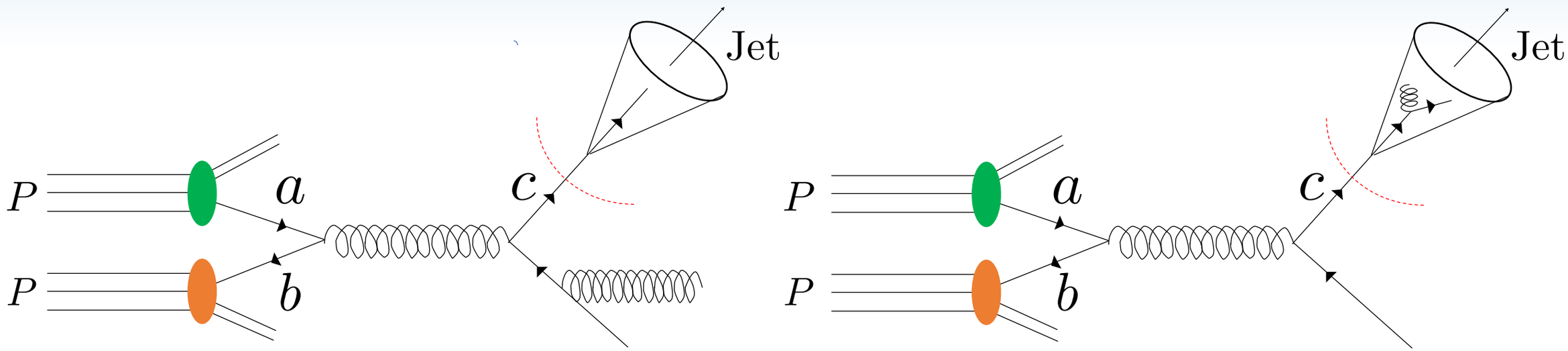
Almeida, Ellis, Lee, Sterman, Walsh, '14

$$\{\tilde{\sigma}(\nu), R(\tau)\} = 1 + \frac{\alpha_s}{4\pi}\left[b_{12}L^2 + b_{11}L + b_{10}\right] + \left(\frac{\alpha_s}{4\pi}\right)^2\left[b_{24}L^4 + b_{23}L^3 + b_{22}L^2 + b_{21}L + b_{20}\right] + \left(\frac{\alpha_s}{4\pi}\right)^3\left[b_{36}L^6 + b_{35}L^5 + b_{34}L^4 + b_{33}L^3 + b_{32}L^2 + b_{31}L + b_{30}\right] + \cdots + D(\alpha_s)\,,$$

Sudakov type logarithms.

- H_{ab} has $(\alpha_s \ln R)^n$ which must be resummed. **(not Sudakov type logs)**

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, $H_{ab} \to \sum_c \int \frac{dz_c}{z_c^2} \boxed{H_{ab}^c} \boxed{J_c(z_c)}$, giving

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

Semi-inclusive jet function $J_c(z_c, p_T R, \mu)$

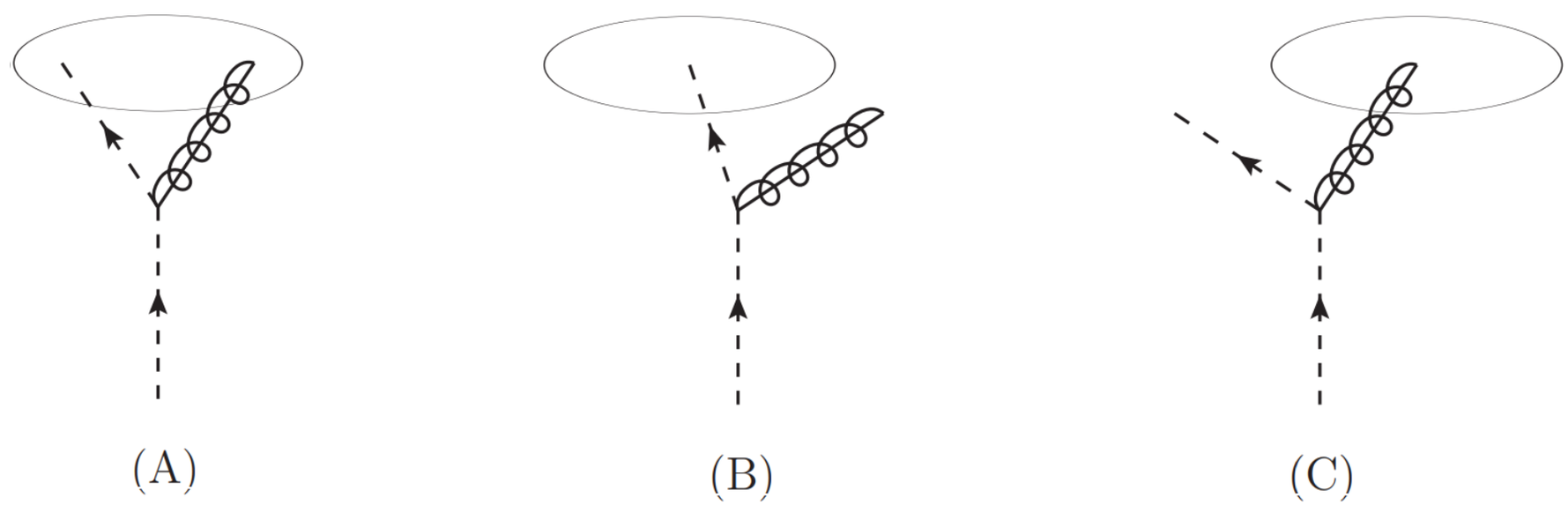
- Using Effective-field theory, we can write operator definition of J_c :

$$J_q(z, p_T R, \mu) = \frac{z}{2N_c} \mathrm{Tr}\left[\frac{\gamma \cdot \bar{n}}{2} \langle 0|\delta\left(\omega - \bar{n}\cdot\mathcal{P}\right)\chi_n(0)|JX\rangle\langle JX|\bar{\chi}_n(0)|0\rangle\right]$$

$$J_g(z, p_T R, \mu) = -\frac{z\,\omega}{2(N_c^2-1)} \langle 0|\delta\left(\omega - \bar{n}\cdot\mathcal{P}\right)\mathcal{B}_{n\perp\mu}(0)|JX\rangle\langle JX|\mathcal{B}^{\mu}_{n\perp}(0)|0\rangle,$$

Kang, Ringer, Vitev `16

- At NLO, (quark initiated) we have the following diagrams :



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Kang, Ringer, Vitev `16

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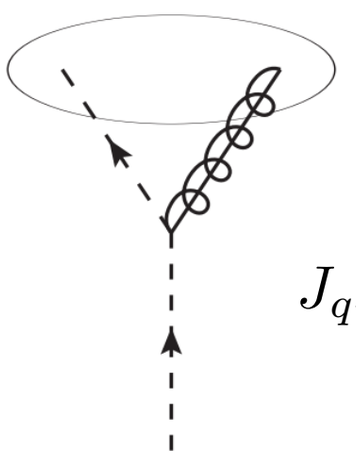

(A)

$$J_{q\to qg}(z, p_T R) = \delta(1-z)\frac{\alpha_s}{2\pi}\left[C_F\left(\boxed{\frac{1}{\epsilon^2}} + \frac{3}{2\epsilon} + \frac{1}{\epsilon}L + \boxed{\frac{1}{2}L^2} + \frac{3}{2}L\right) + d_q^{\mathrm{alg}}\right]$$

Semi-inclusive jet function $J_c(z_c, p_T R, \mu)$

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Kang, Ringer, Vitev `16

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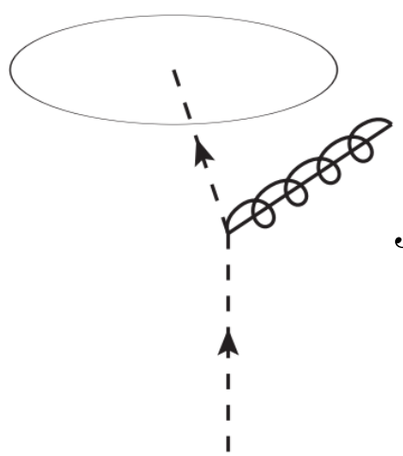

(B)

$$J_{q\to q(g)}(z, p_T R) = \frac{\alpha_s C_F}{2\pi}\Big[\delta(1-z)\Big(-\boxed{\frac{1}{\epsilon^2}} - \frac{1}{\epsilon}L - \boxed{\frac{1}{2}L^2} + \frac{\pi^2}{12}\Big)$$
$$+\Big(\frac{1}{\epsilon} + L\Big)\frac{1+z^2}{(1-z)_+} - 2(1+z^2)\Big(\frac{\ln(1-z)}{1-z}\Big)_+ - (1-z)\Big]$$

Semi-inclusive jet function $J_c(z_c, p_T R, \mu)$

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Kang, Ringer, Vitev `16

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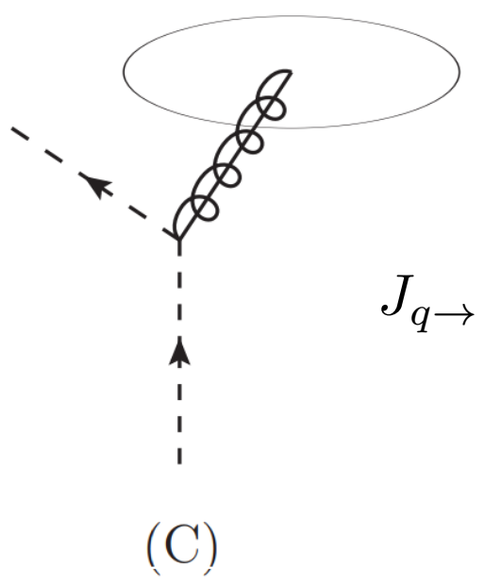


$$J_{q\to(q)g}(z, p_T R) = \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon} + L\right)P_{gq}(z) - \frac{\alpha_s}{2\pi}\left[P_{gq}(z)2\ln(1-z) + C_F z\right]$$

- Adding the contributions, we have cancellation of $\frac{1}{\epsilon^2}$ and L^2 :

$$J_q(z, p_T R) = J_{q\to qg}(z, p_T R) + J_{q\to q(g)}(z, p_T R) + J_{q\to (q)g}(z, p_T R)$$
$$\supset \frac{\alpha_s C_F}{2\pi}\frac{1}{\epsilon}(P_{qq}(z) + P_{gq}(z))$$
$$J_g(z, p_T R) \supset \frac{\alpha_s C_F}{2\pi}\frac{1}{\epsilon}(P_{gg}(z) + 2n_f P_{qg}(z))$$

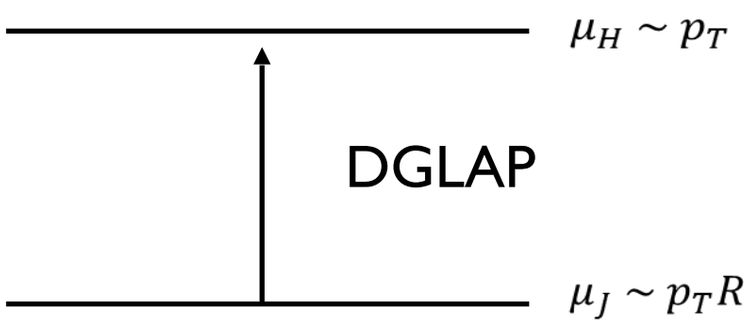
- The UV poles give DGLAP RG equation for J_c :

$$\mu\frac{d}{d\mu}J_i(z, p_T R, \mu) = \frac{\alpha_s(\mu)}{\pi}\sum_j \int_z^1 \frac{dz'}{z'} P_{ji}(\frac{z}{z'}, \mu) J_j(z', p_T R, \mu)$$

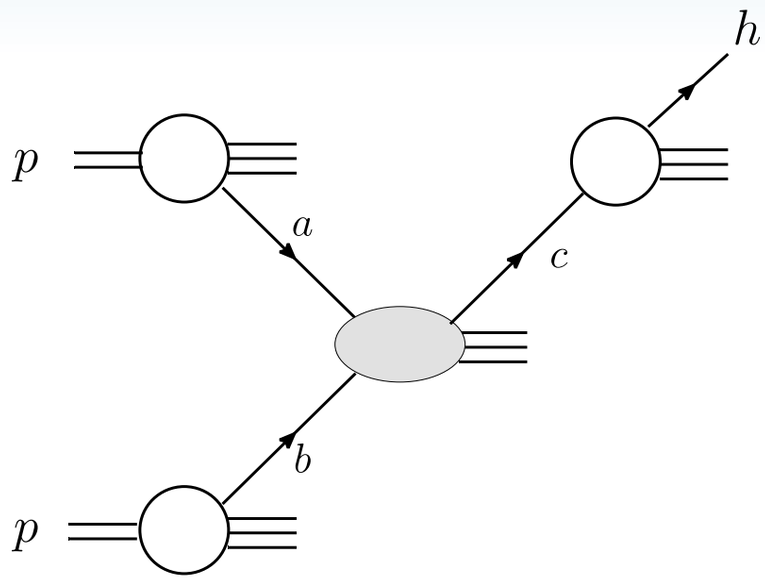
where P_{ij} are the standard splitting functions.

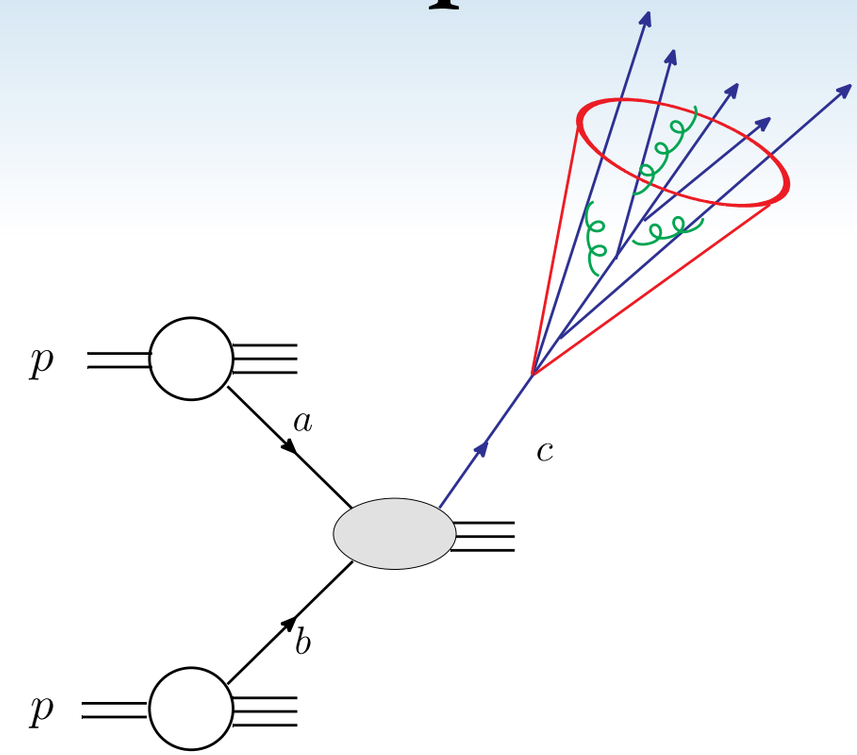
- Evolution from μ_J to μ_H gives $(\alpha_s \ln R)^n$ resummations.

- See *Liu, Moch, Ringer `18* for joint resummation of threshold log and jet radius logs, and phenomenology.



Comparison with the inclusive hadron production





More relevant for the EIC

	Factorization	Evolution
Jet	$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes J_c + \mathcal{O}(R^2) + \mathcal{O}(\frac{\Lambda_{QCD}}{p_T R})$	$\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j$
Hadron	$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes D^h_c$	$\mu \frac{d}{d\mu} D^h_i = \sum_j P_{ji} \otimes D^h_j$

Kang, Ringer, Vitev `16

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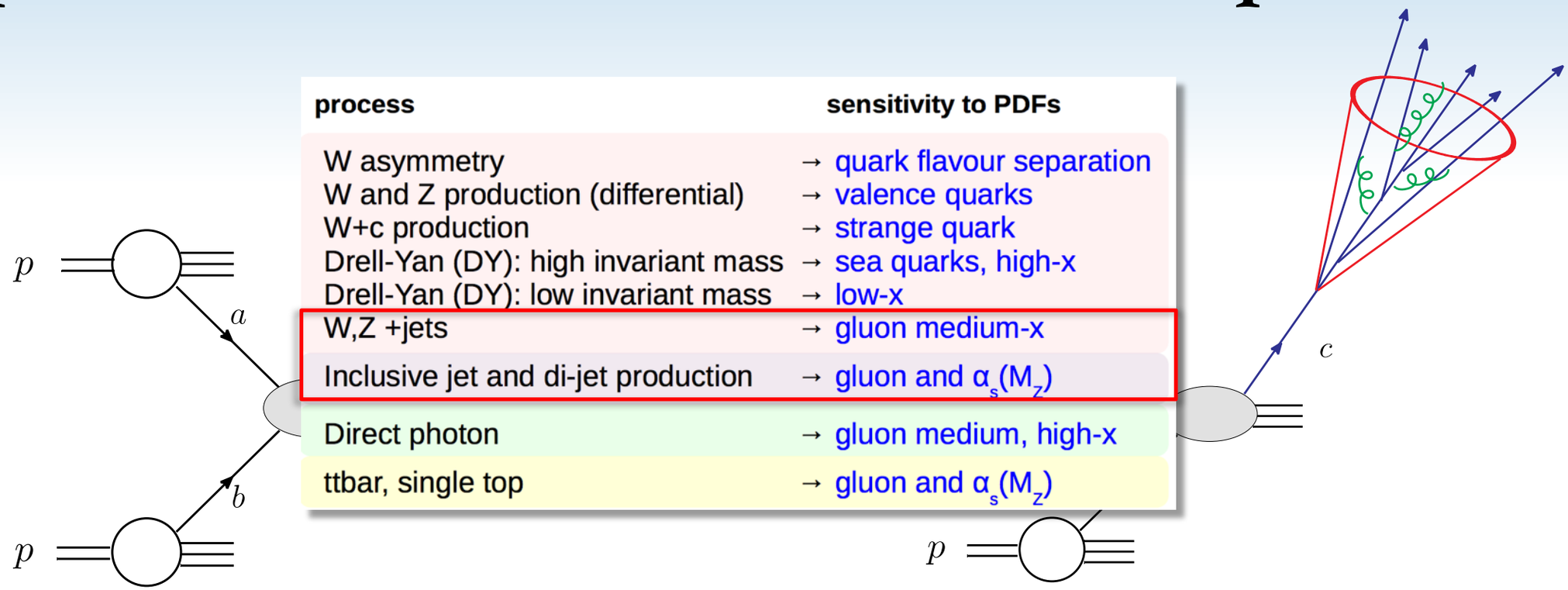

process	sensitivity to PDFs
W asymmetry	→ quark flavour separation
W and Z production (differential)	→ valence quarks
W+c production	→ strange quark
Drell-Yan (DY): high invariant mass	→ sea quarks, high-x
Drell-Yan (DY): low invariant mass	→ low-x
W,Z +jets	→ gluon medium-x
Inclusive jet and di-jet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

More relevant for the EIC

	Factorization	Evolution
Jet	$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes J_c + \mathcal{O}(R^2) + \mathcal{O}(\frac{\Lambda_{QCD}}{p_T R})$	$\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j$
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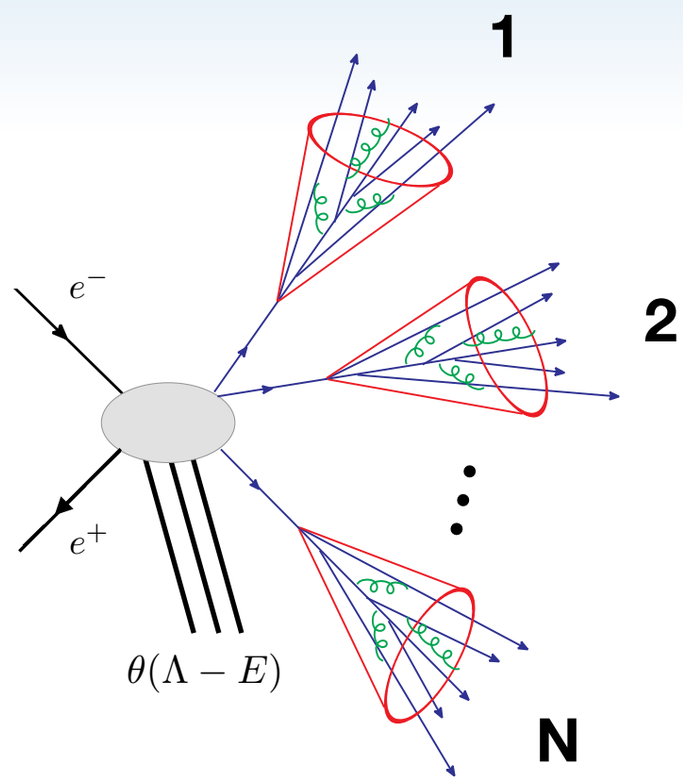
Kang, Ringer, Vitev `16

Comparison with the exclusive jet production case

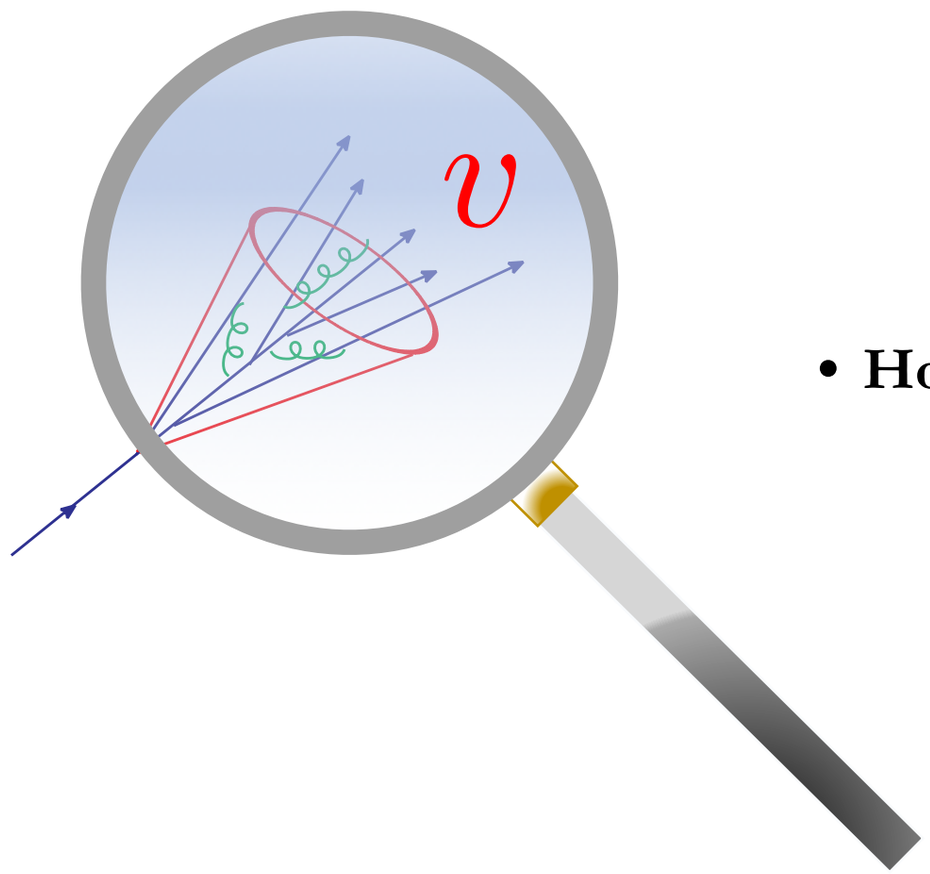


$$d\sigma^{e^+e^- \to \mathrm{jet}_1 \cdots \mathrm{jet}_N} \propto H_{1,2,\ldots,N} \otimes J_1^{excl} \cdots J_N^{excl} S$$

Ellis, Vermilion, Walsh, Hornig, Lee '10

- The operator definition of the J_c^{excl} is similar to the semi-inclusive case, except it has an additional restriction $\delta_{(N(X_n)-1)}$, which restricts amount of energy outside the jet.

Jet Substructure Measurements



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

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

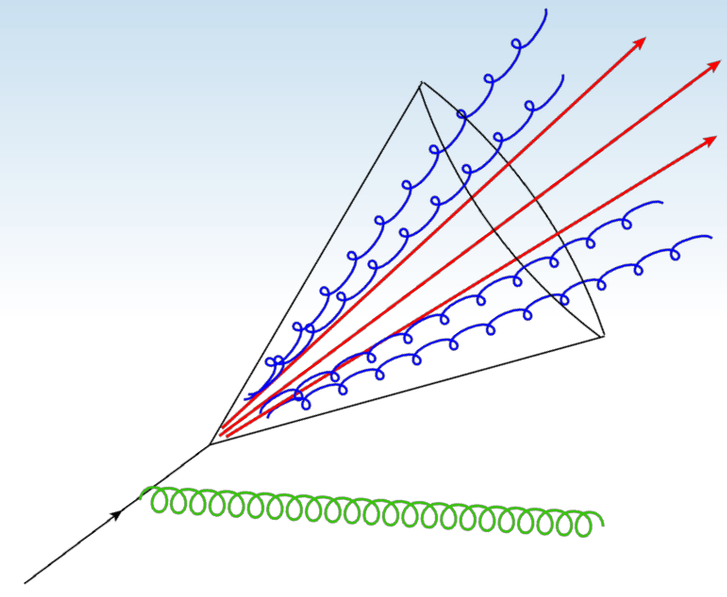
$$\tau_a^{pp} = \frac{1}{p_T}\sum_{i\in J} p_{T,i}(\Delta R_{iJ})^{2-a} = \left(\frac{2E_J}{p_T}\right)^{2-a} \tau_a^{e^+e^-} + \mathcal{O}((\tau_a^{pp})^2)$$

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

- **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

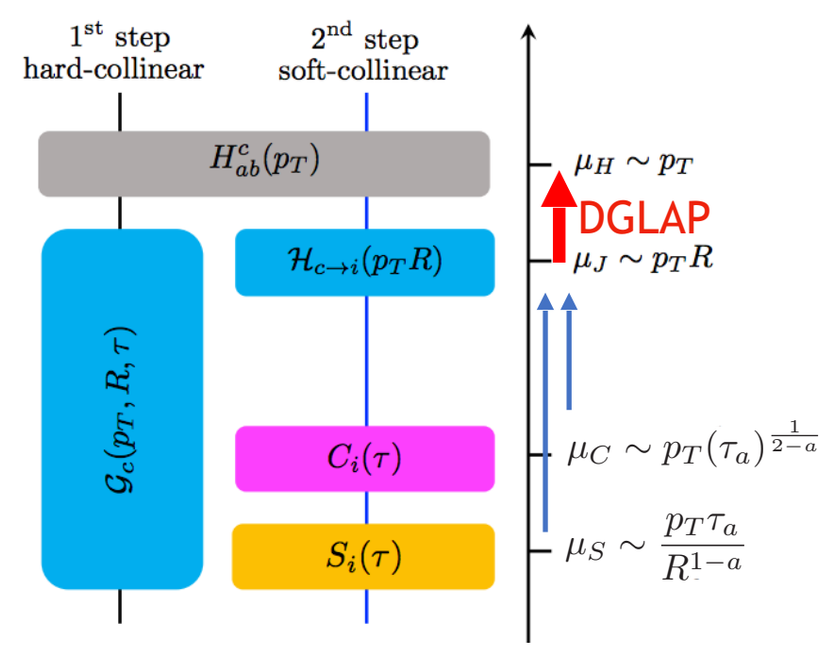
Jet angularity



- 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

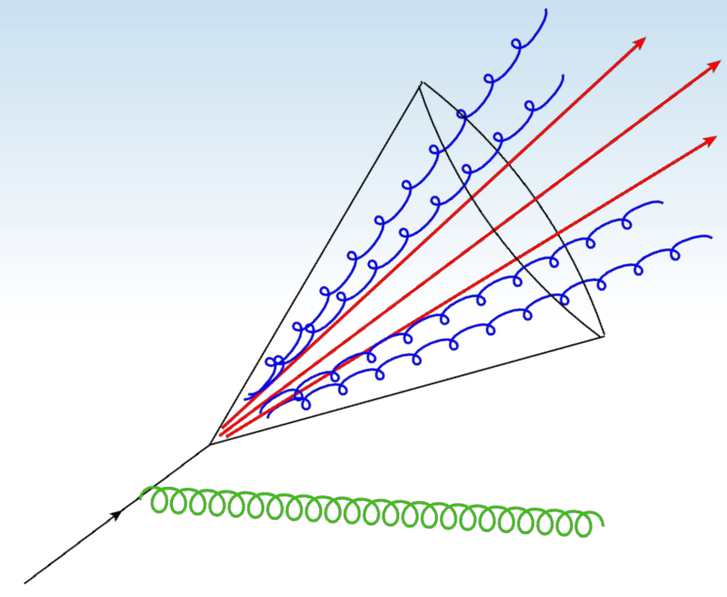
$$\mathcal{G}_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu)$$
$$\times \int d\tau_a^{C_i} d\tau_a^{S_i} \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) C_i(\tau_a^{C_i}, p_T \tau_a^{\frac{1}{2-a}}, \mu) S_i(\tau_a^{S_i}, \frac{p_T \tau_a}{R^{1-a}}, \mu) + \mathcal{O}\left(\frac{m^2}{p_T^2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

- 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

Jet angularity



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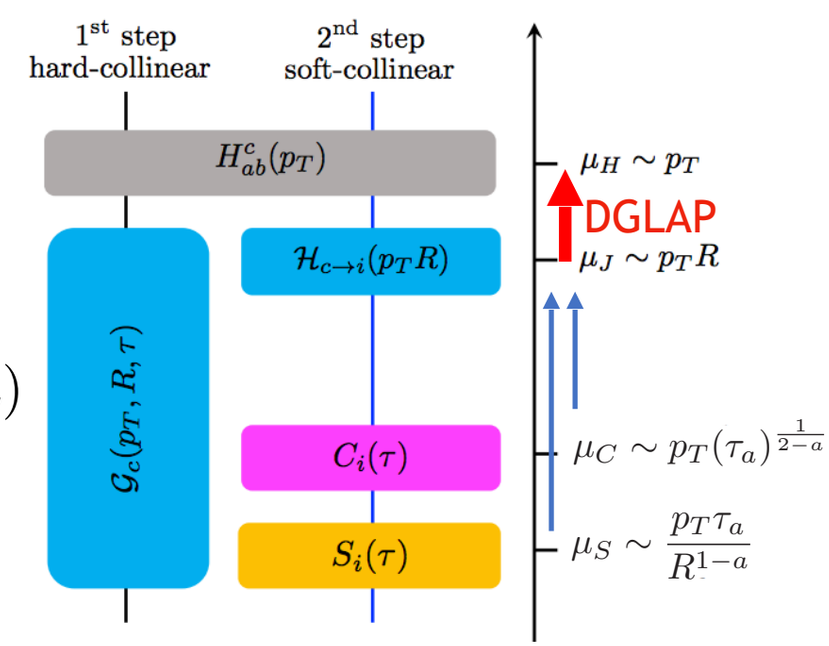
- $H_{c\to i}$, C_i and S_i have double poles, which cancel once evolved to μ_J.

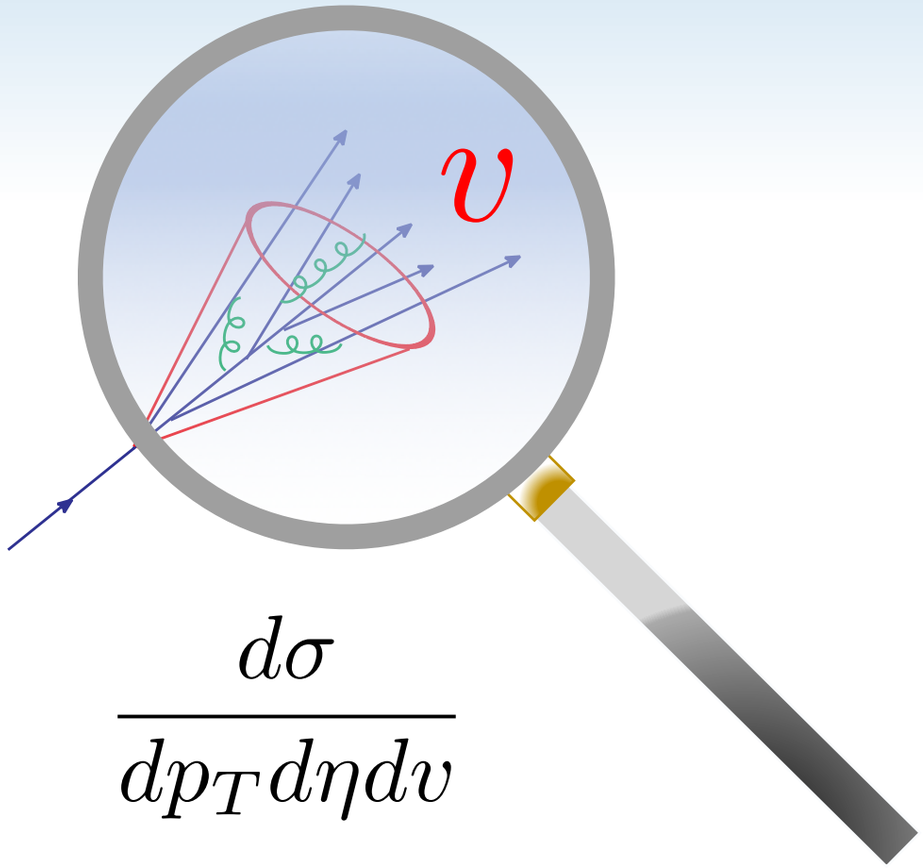
- $\mathcal{G}_c(z, p_T R, \tau_a, \mu)$ follows DGLAP from μ_J to μ_H :

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

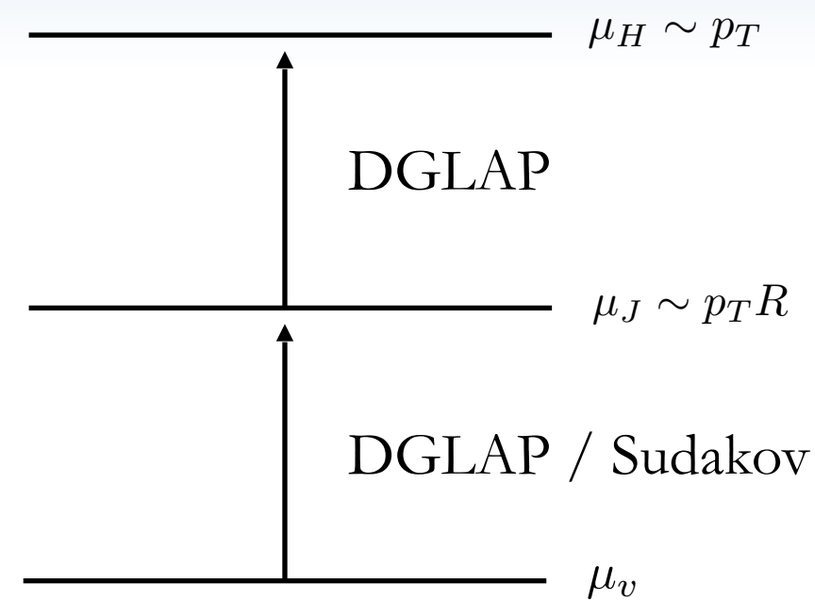


Kang, KL, Ringer `18

Patterns emerging



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



- 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.

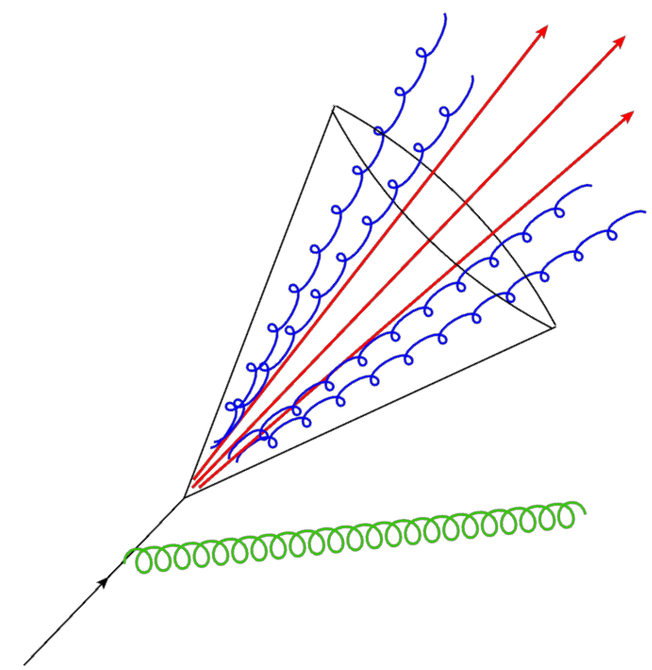
Relation to inclusive jet function

$$\int \frac{d\sigma}{dp_T d\eta d\tau_a} d\tau_a = \frac{d\sigma}{dp_T d\eta} \Leftrightarrow \int_0^\infty d\tau_a \mathcal{G}_i(z, p_T, R, \tau_a, \mu) = J_i(z, p_T, R, \mu)$$

See also Chien, Hornig, C. Lee `15

- Correct integration over substructure should give inclusive case.

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



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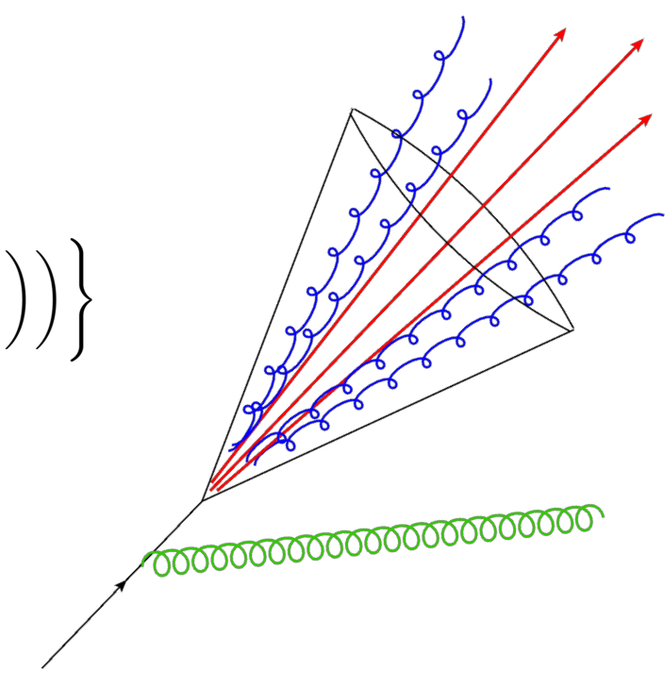
$$\begin{aligned}
\mathcal{H}_{q\to q}(z, p_T R, \mu) =& \delta(1-z) - \frac{\alpha_s C_F}{2\pi} \Bigg\{ \delta(1-z) \Bigg[\boxed{\frac{1}{\epsilon^2}} + \boxed{\frac{3}{2}\frac{1}{\epsilon}} + \boxed{\frac{\ln\left(\frac{\mu^2}{p_T^2 R^2}\right)}{\epsilon}} \\
&+ \frac{1}{2}\ln^2\left(\frac{\mu^2}{p_T^2 R^2}\right) + \frac{3}{2}\ln\left(\frac{\mu^2}{p_T^2 R^2}\right) - \frac{\pi^2}{12} \Bigg] \\
&+ 2\left((1+z^2)\frac{\ln(1-z)}{1-z}\right)_+ + (1-z) - P_{qq}(z)\left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{p_T^2 R^2}\right)\right) \Bigg\} \\
\mathcal{H}_{g\to q}(z, p_T R, \mu) =& \frac{\alpha_s}{2\pi} P_{gq}(z)\left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{p_T^2 R^2}\right) - \ln(1-z)^2\right) - \frac{\alpha_s C_F}{2\pi} z \\
C_q(\tau_0, p_T, R, \mu) =& C_q^{\text{l.p.}}(\tau_0, p_T, \mu) + \Delta C_q^{\text{alg}}(\tau_0, R)
\end{aligned}$$

$$\begin{aligned}
\int_0^{\tau_0^{\max}} d\tau_0\, C_q^{\text{l.p.}}(\tau_0, p_T, \mu) =& 1 + \frac{\alpha_s C_F}{2\pi} \Bigg\{ \boxed{\frac{2}{\epsilon^2}} + \boxed{\frac{3}{2\epsilon}} - \boxed{\frac{2}{\epsilon}\ln\left(\frac{\tau_0^{\max} p_T^2}{\mu^2}\right)} + \ln^2\left(\frac{\tau_0^{\max} p_T^2}{\mu^2}\right) \\
&- \frac{3}{2}\ln\left(\frac{\tau_0^{\max} p_T^2}{\mu^2}\right) + \frac{7}{2} - \frac{\pi^2}{2} \Bigg\}
\end{aligned}$$

$$\int_0^{\tau_0^{\max}} d\tau_0\, \Delta C_q^{k_T}(\tau_0, R) = \frac{\alpha_s C_F}{2\pi}\left(3 - \frac{\pi^2}{3} - 3\ln 2 + 4\ln^2 2\right)$$

$$\int_0^{\tau_0^{\max}} d\tau_0\, S_q(\tau_0, p_T, R, \mu) = 1 + \frac{\alpha_s C_F}{2\pi}\left\{ -\boxed{\frac{1}{\epsilon^2}} + \boxed{\frac{2}{\epsilon}\ln\left(\frac{\tau_0^{\max} p_T}{\mu R}\right)} + \frac{\pi^2}{12} - 2\ln^2\left(\frac{\tau_0^{\max} p_T}{\mu R}\right) \right\}$$



Relation to inclusive jet function

$$\int \frac{d\sigma}{dp_T d\eta d\tau_a} d\tau_a = \frac{d\sigma}{dp_T d\eta} \Leftrightarrow \int_0^\infty d\tau_a \mathcal{G}_i(z, p_T, R, \tau_a, \mu) = J_i(z, p_T, R, \mu)$$

See also Chien, Hornig, C. Lee `15

- Correct integration over substructure should give inclusive case.

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

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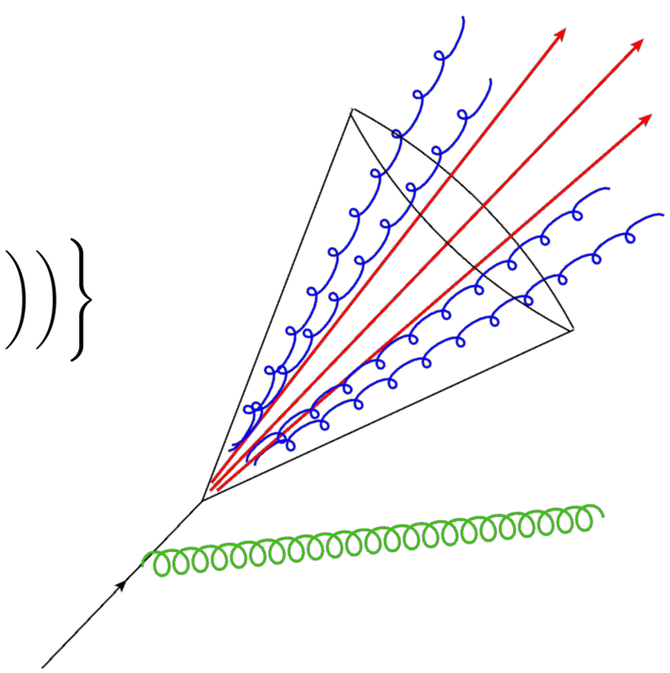
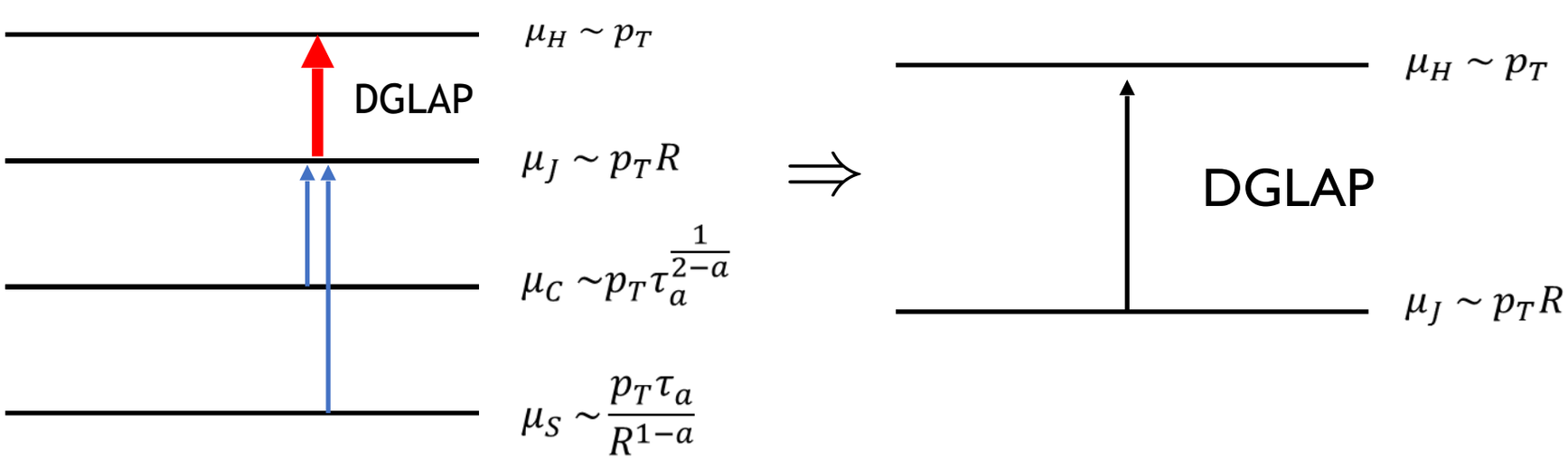
$$\int_0^{\tau_0^{\max}} d\tau_0\, \Delta C_q^{k_T}(\tau_0, R) = \frac{\alpha_s C_F}{2\pi}\left(3 - \frac{\pi^2}{3} - \boxed{3\ln 2} + \boxed{4\ln^2 2}\right)$$

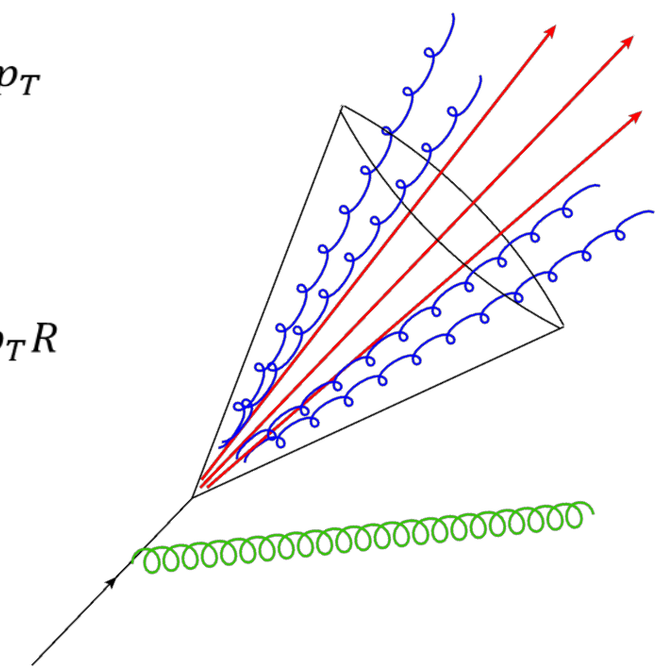
$$\int_0^{\tau_0^{\max}} d\tau_0\, S_q(\tau_0, p_T, R, \mu) = 1 + \frac{\alpha_s C_F}{2\pi}\left\{ -\boxed{\frac{1}{\epsilon^2}} + \boxed{\frac{2}{\epsilon}\ln\left(\frac{\tau_0^{\max} p_T}{\mu R}\right)} + \frac{\pi^2}{12} - \boxed{2\ln^2\left(\frac{\tau_0^{\max} p_T}{\mu R}\right)} \right\}$$



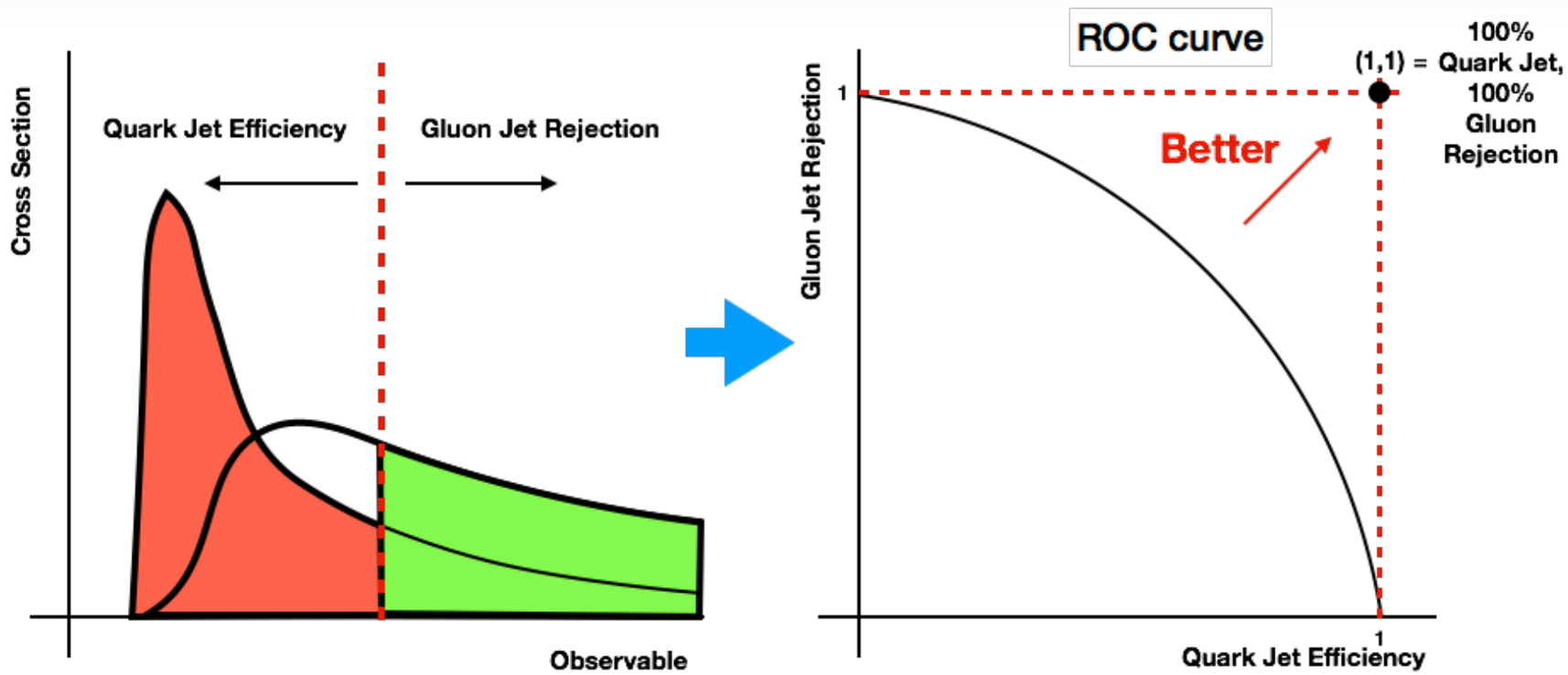
Relation to inclusive jet function

- poles except ones associated with DGLAP cancel.
- logs except ones associated with the jet scale cancel.
- Inclusive jet reproduced. Hard-collinear-soft structure collapse to Hard-collinear factorization.



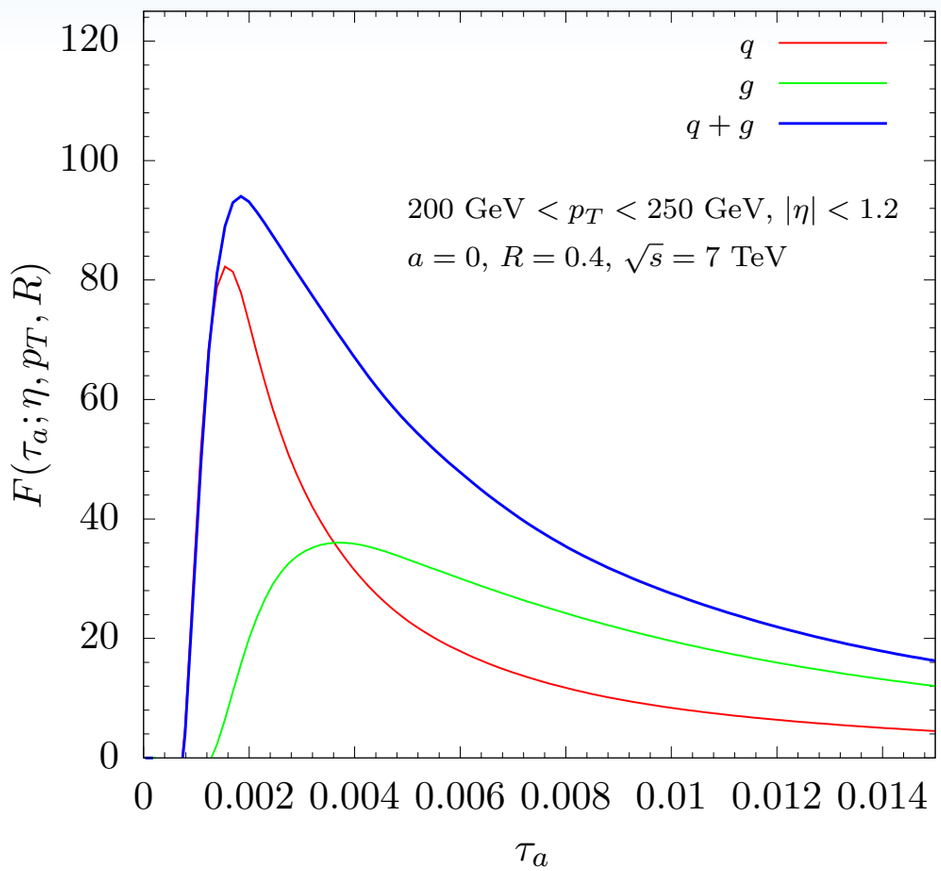


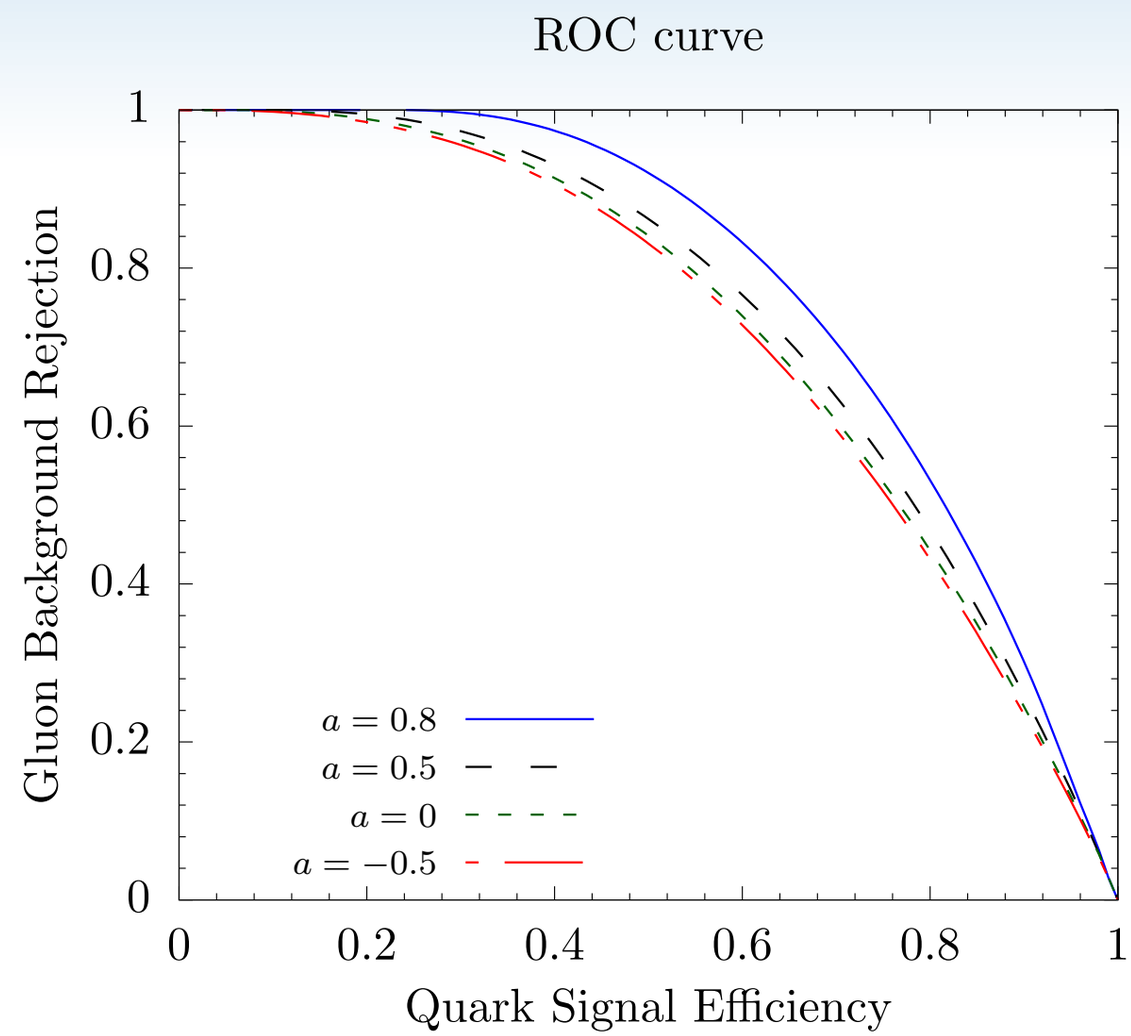
Quark and gluon discrimination



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

Quark and gluon discrimination

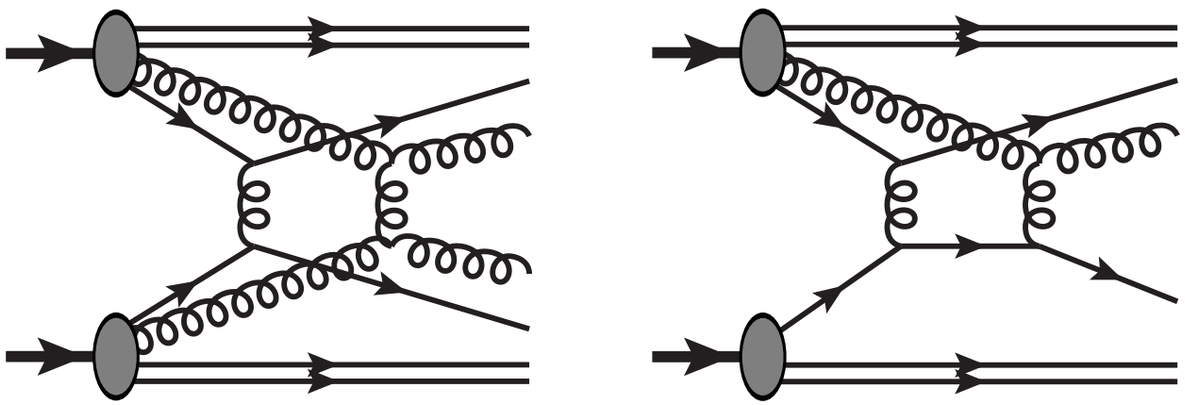




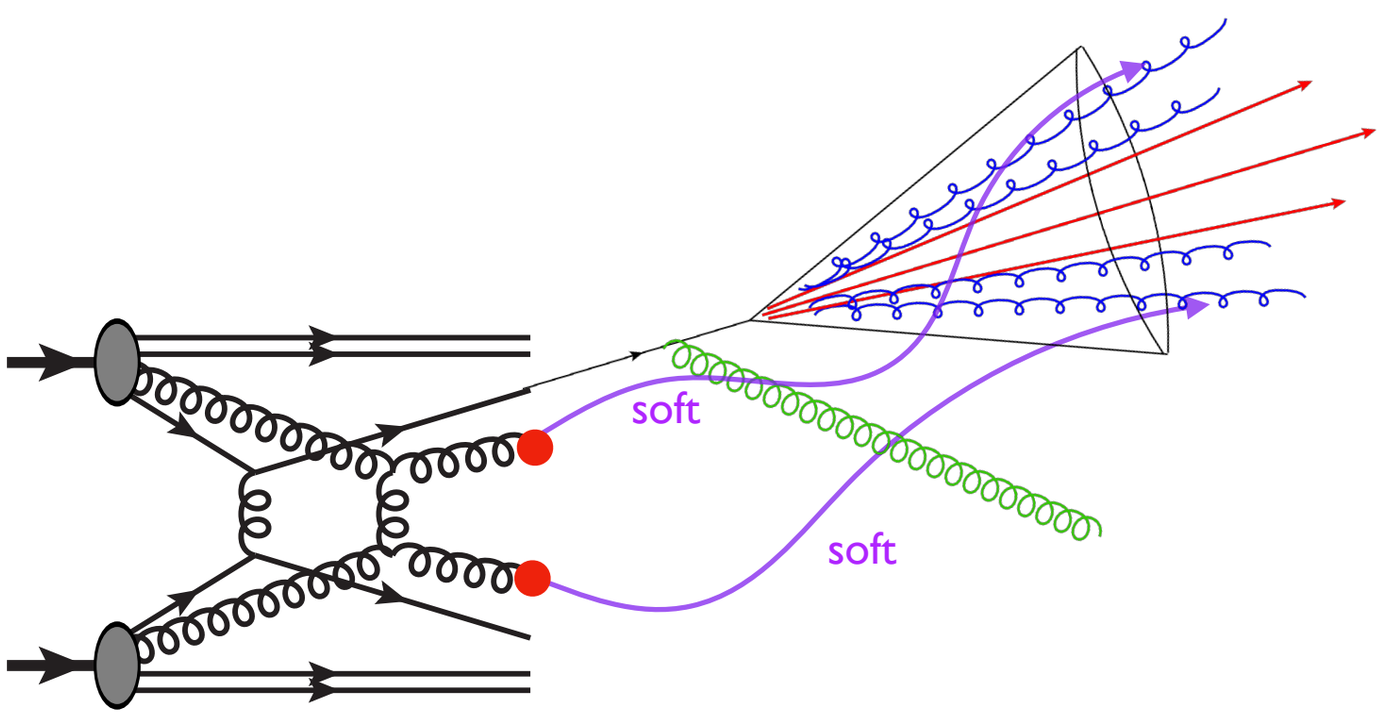
- We can study how well angularity discriminates between quark and gluon jet as a continuous function of 'a'.
- As 'a' increases, better discrimination but more sensitive to non-perturbative effects.

Non-perturbative Effects

- **Non-perturbative effects:**



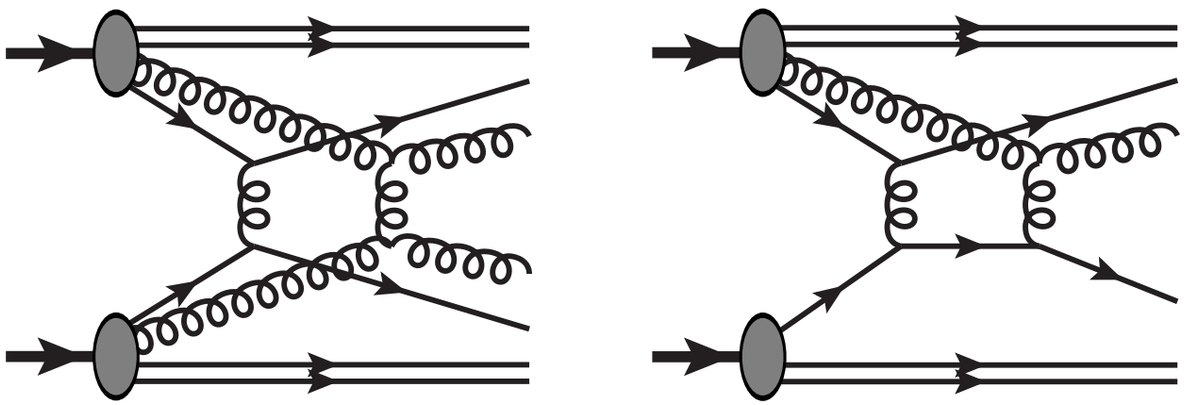
Figs from P. Bartalini et al. `11



- **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:**



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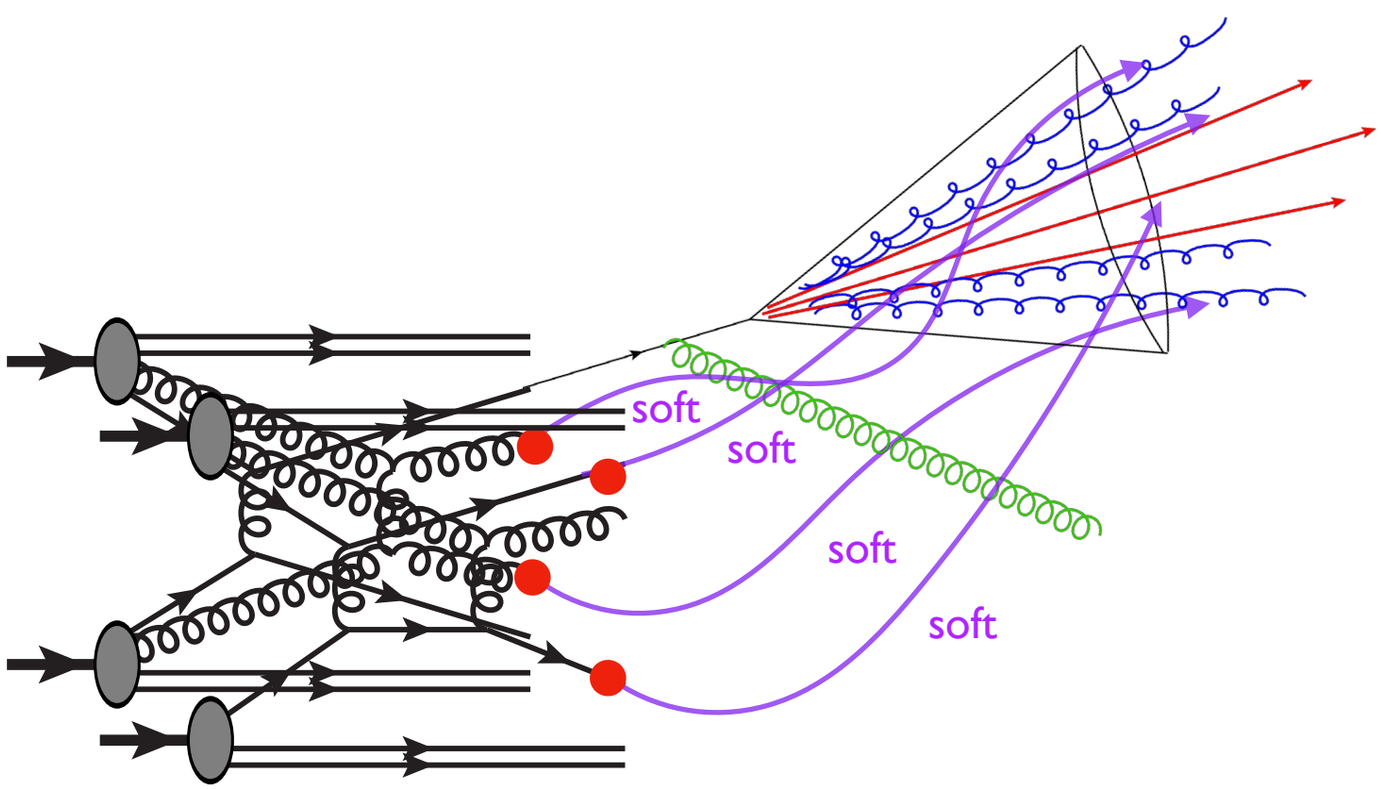
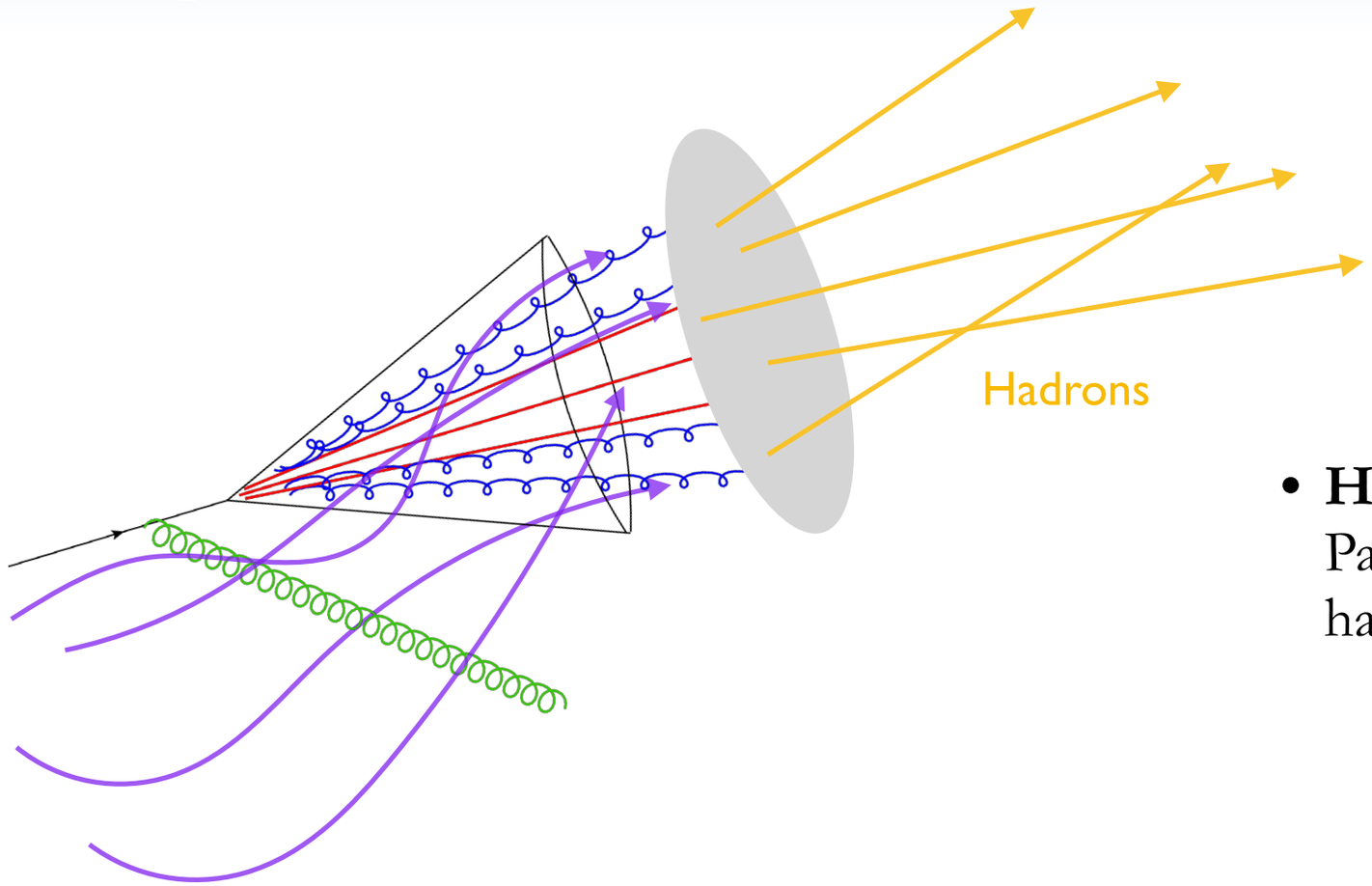


- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.
- **Pileups**
  Secondary proton collisions in a bunch may enter and contaminate jet.

Non-perturbative Effects

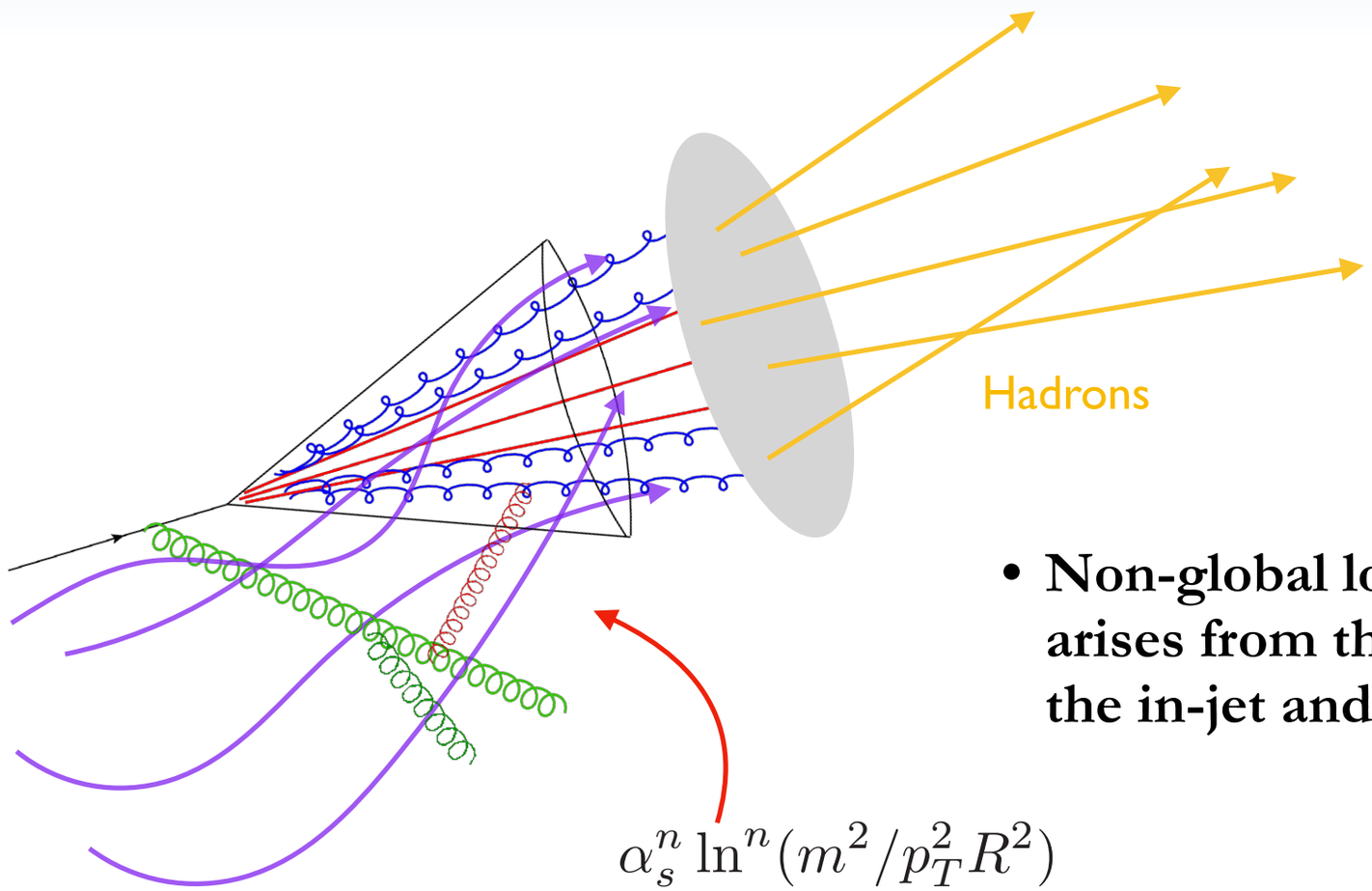
- **Non-perturbative effects:**



- **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.**

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

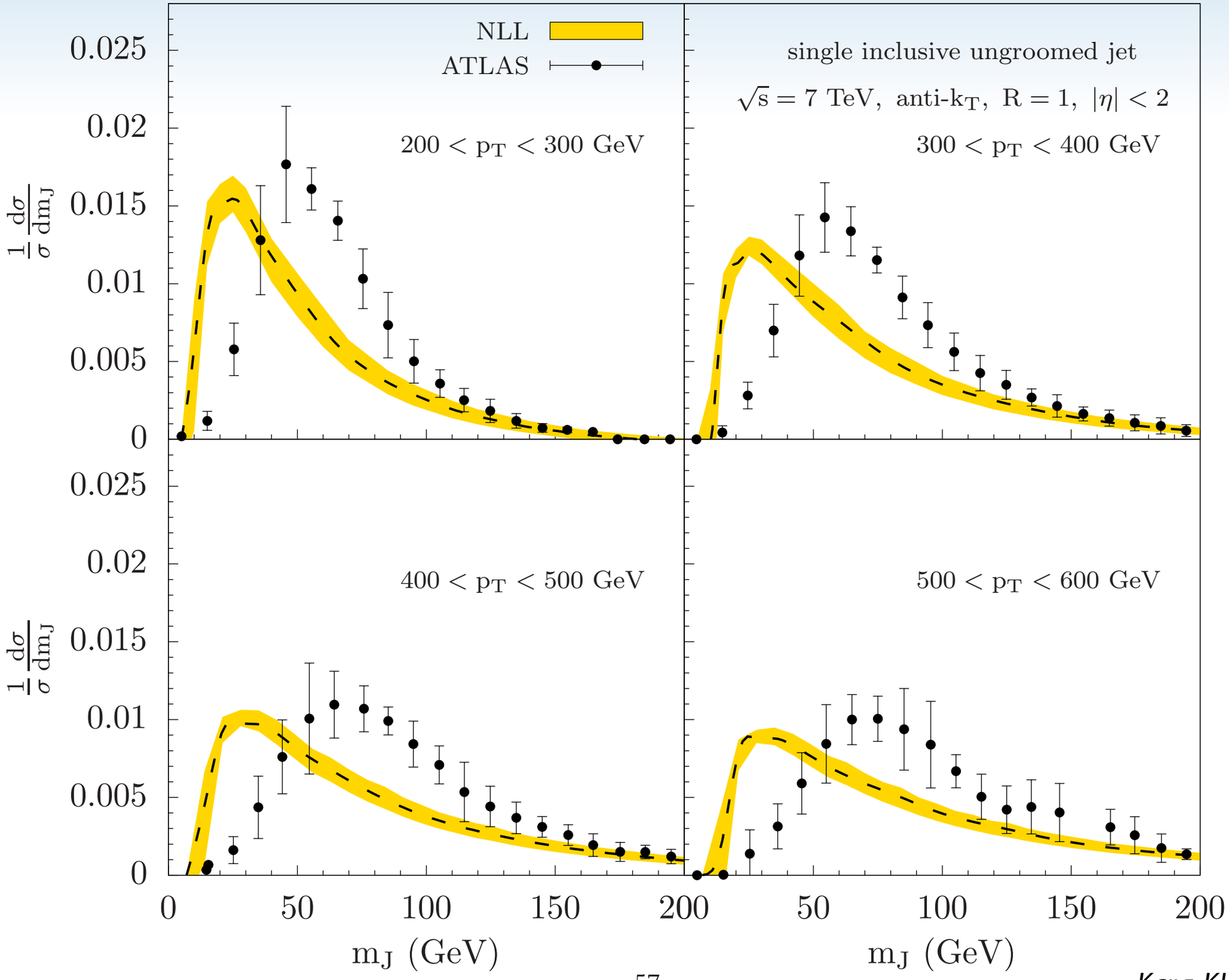
- Both hadronization and MPI effects in jet mass is well-represented by just shifting first-moments.

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

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

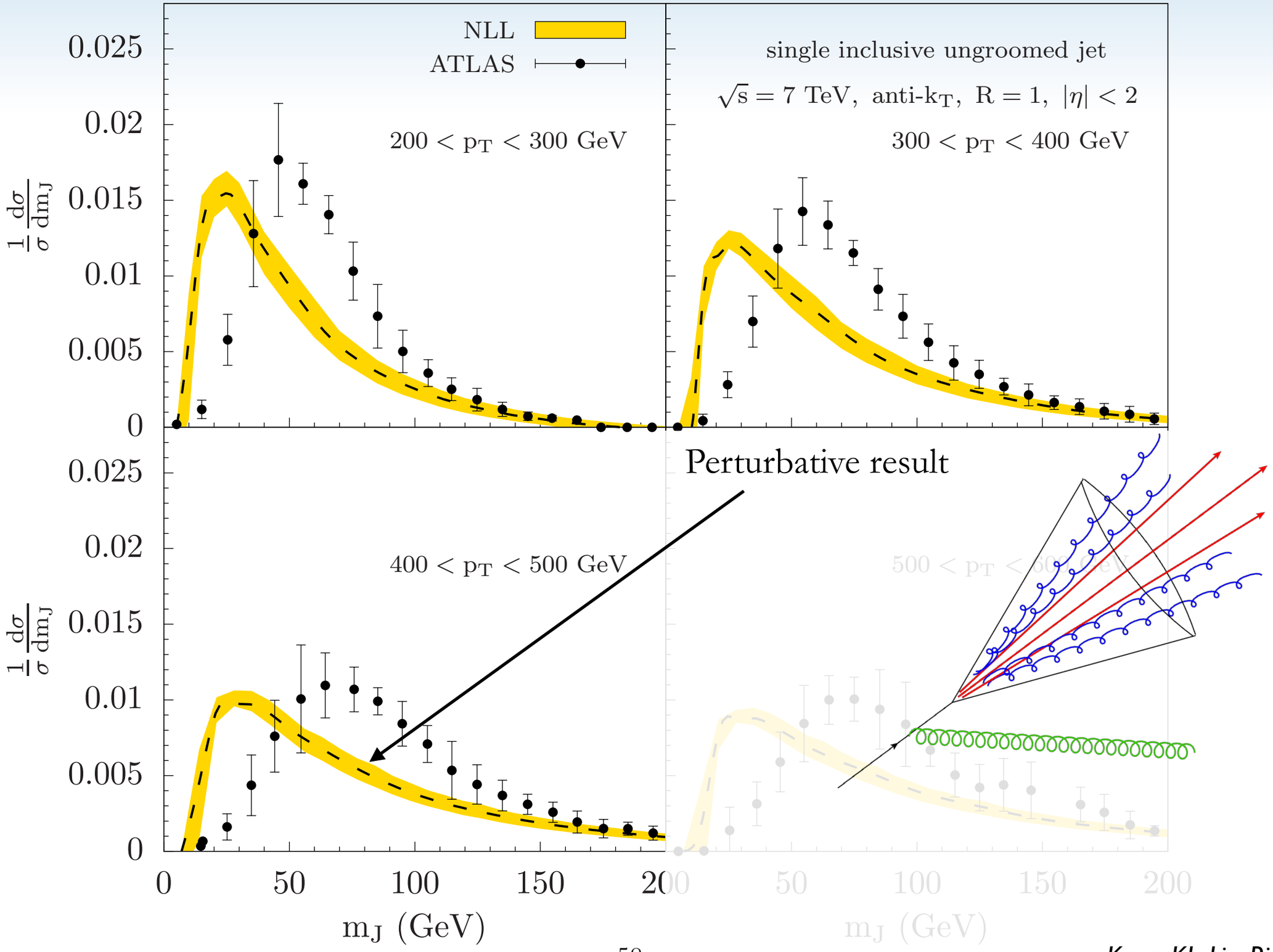
$\Omega_\kappa \sim \Lambda_{had} \sim 1\,\text{GeV}$ corresponds to non-perturbative effects coming primarily from the hadronization alone.

Phenomenology



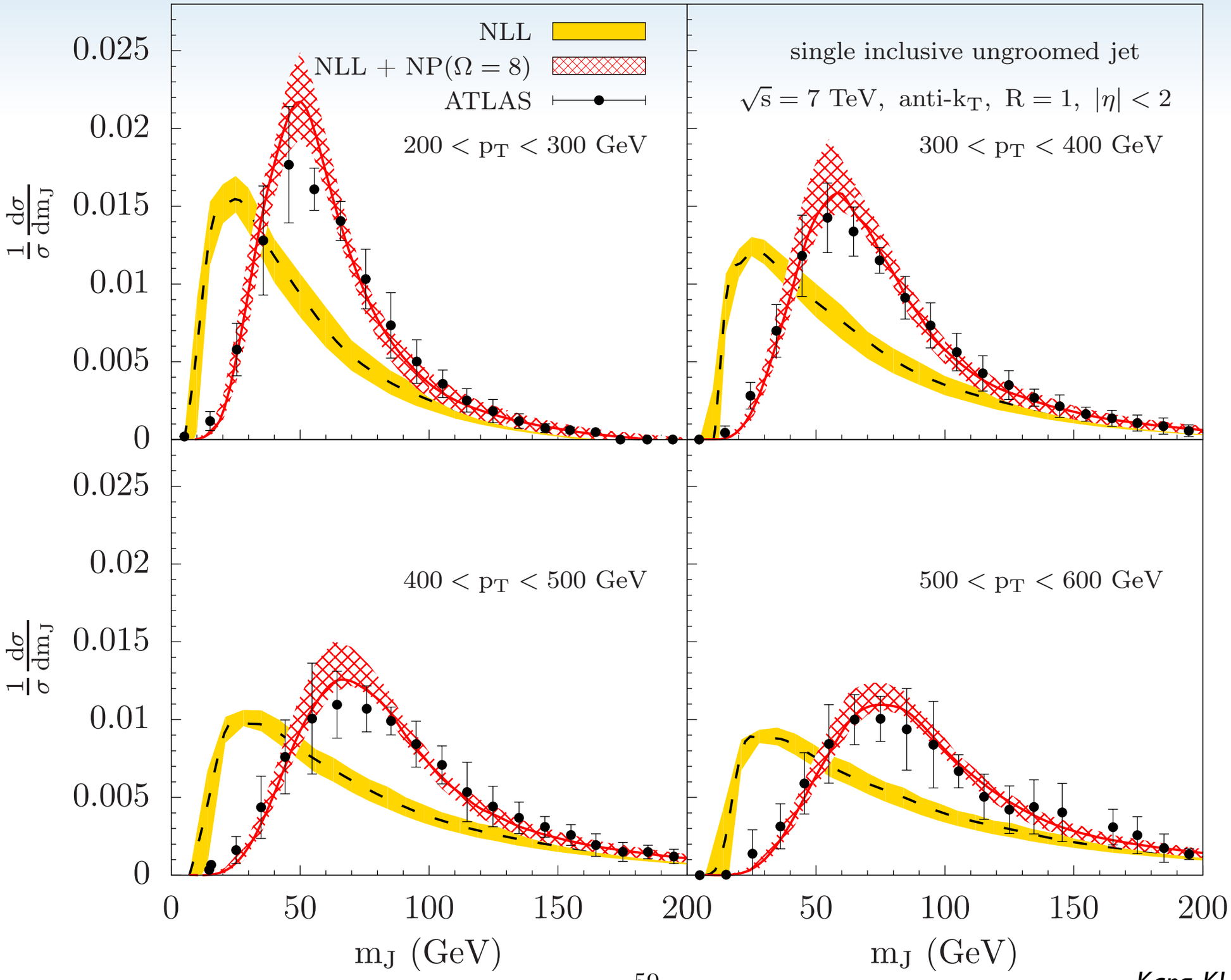
Kang, KL, Liu, Ringer `18

Phenomenology



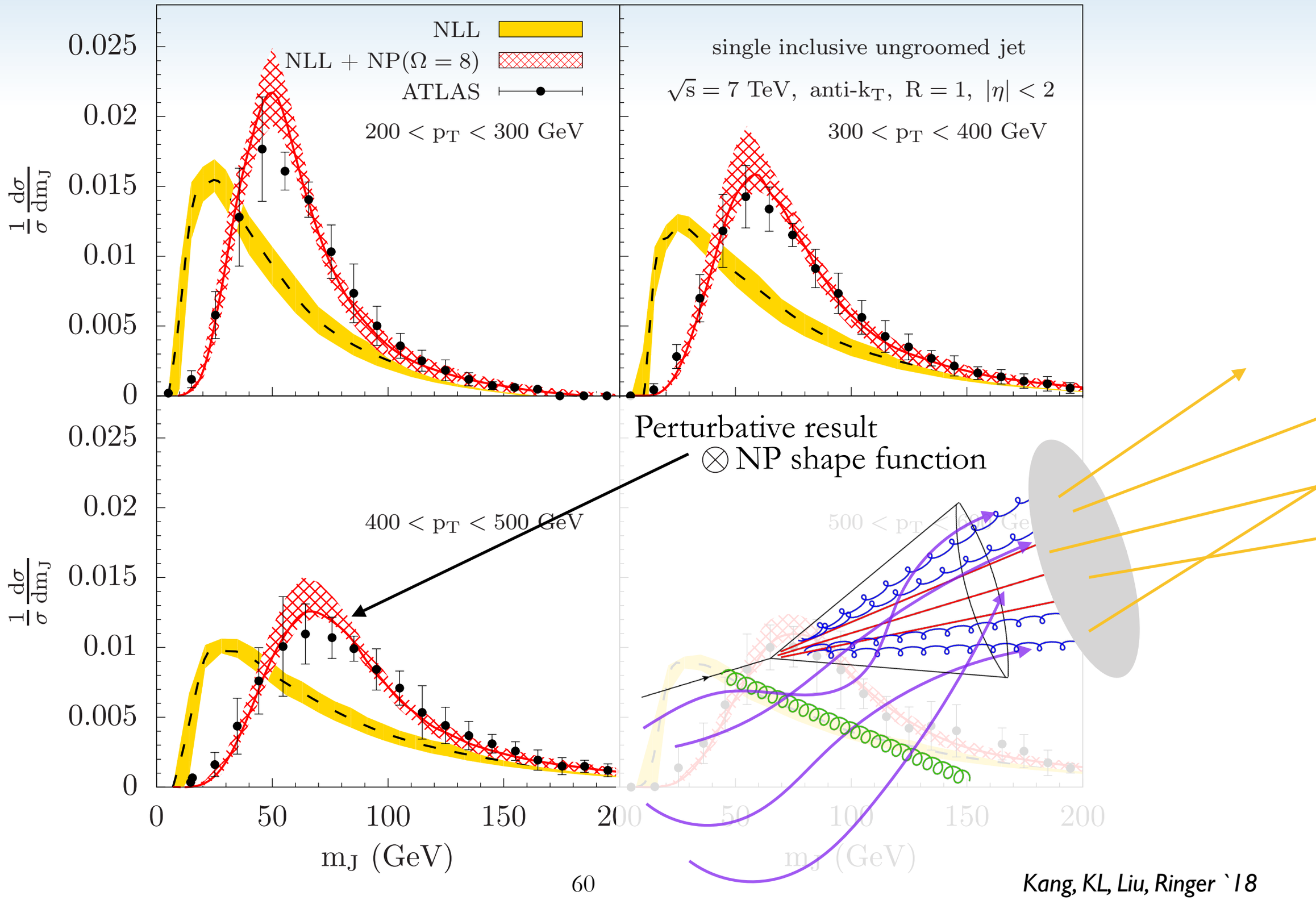
Kang, KL, Liu, Ringer `18

Phenomenology



Kang, KL, Liu, Ringer `18

Phenomenology



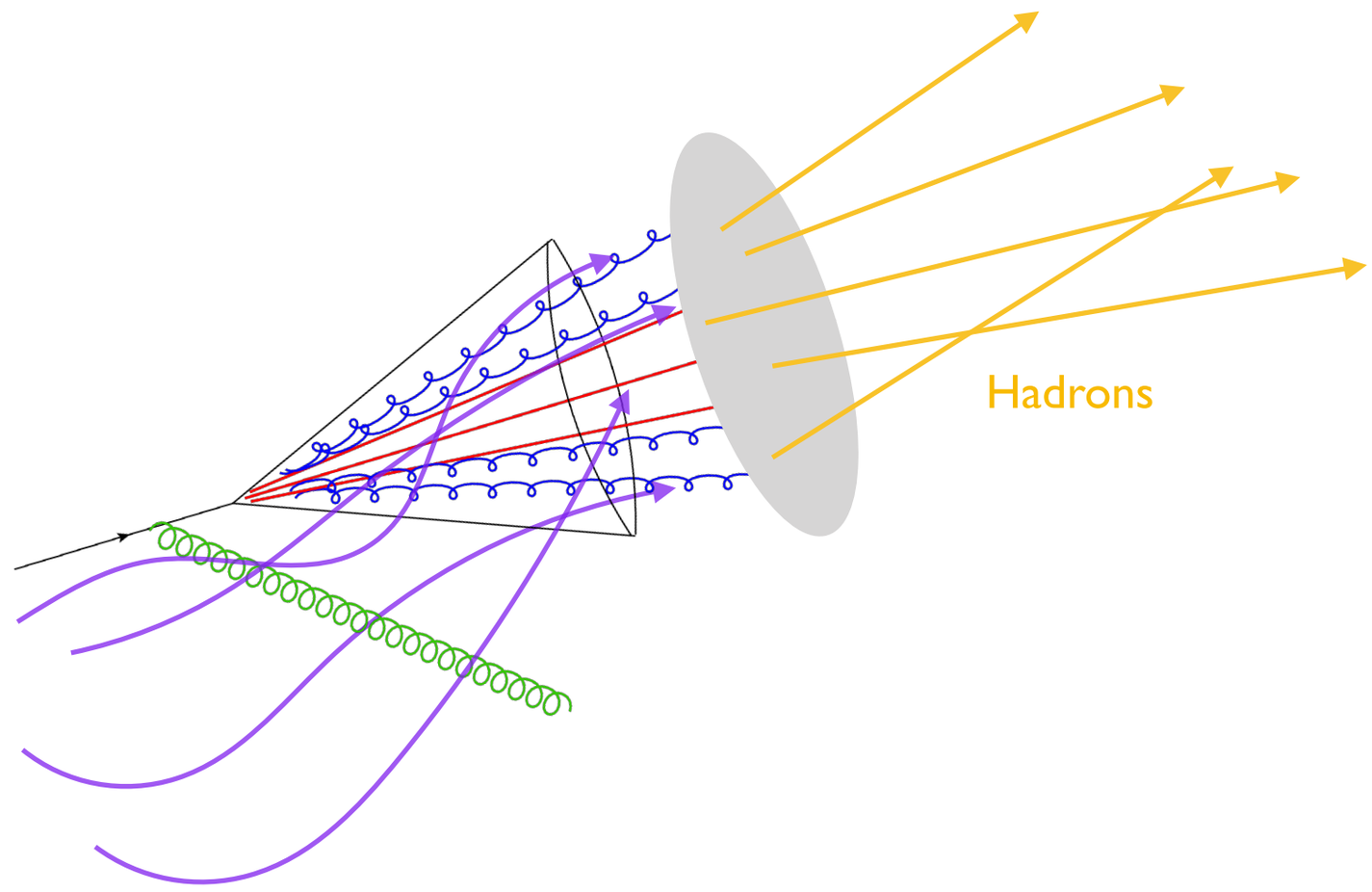
Kang, KL, Liu, Ringer `18

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.



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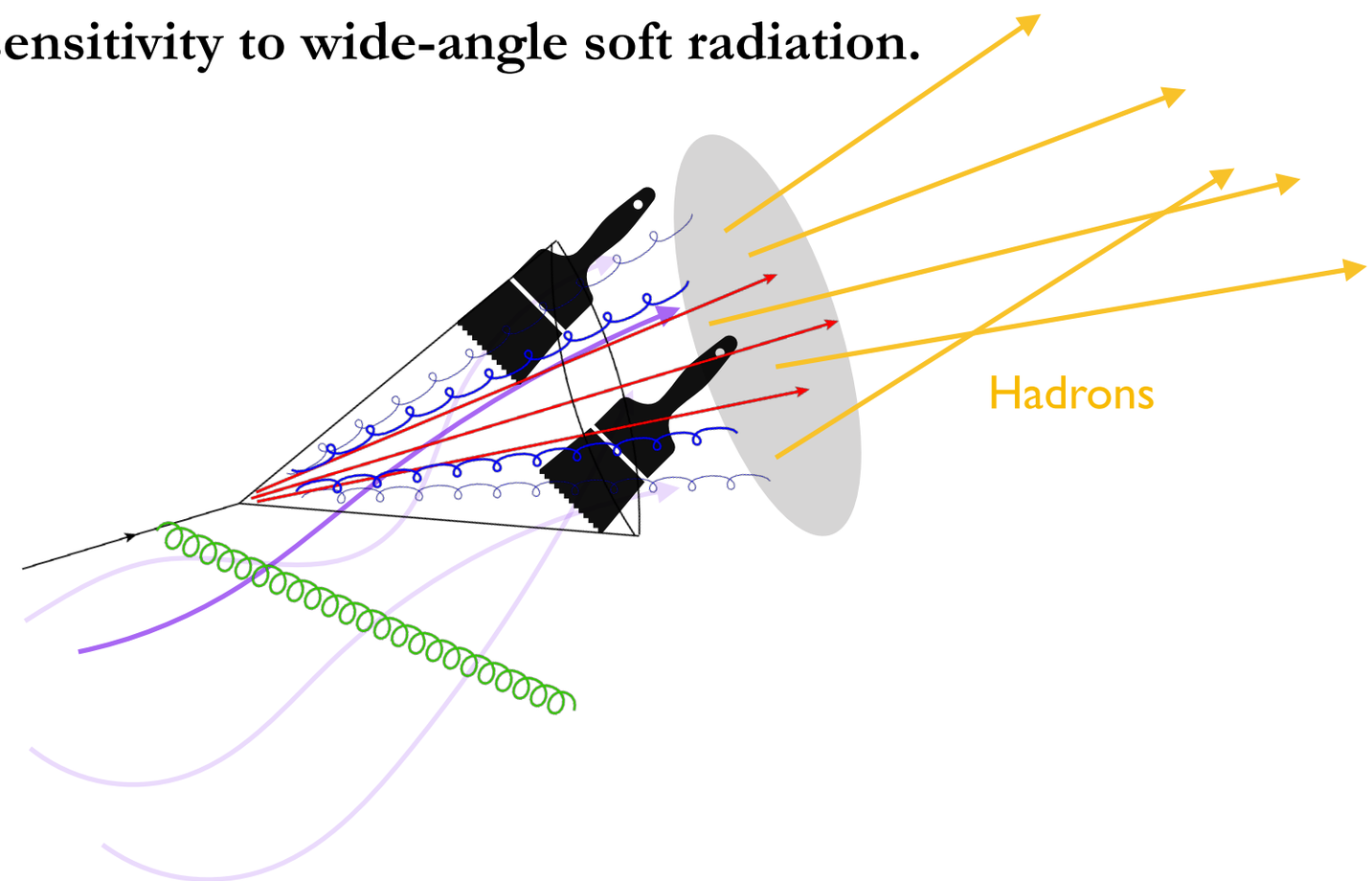
  Groom jets to reduce sensitivity to wide-angle soft radiation.



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.

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:

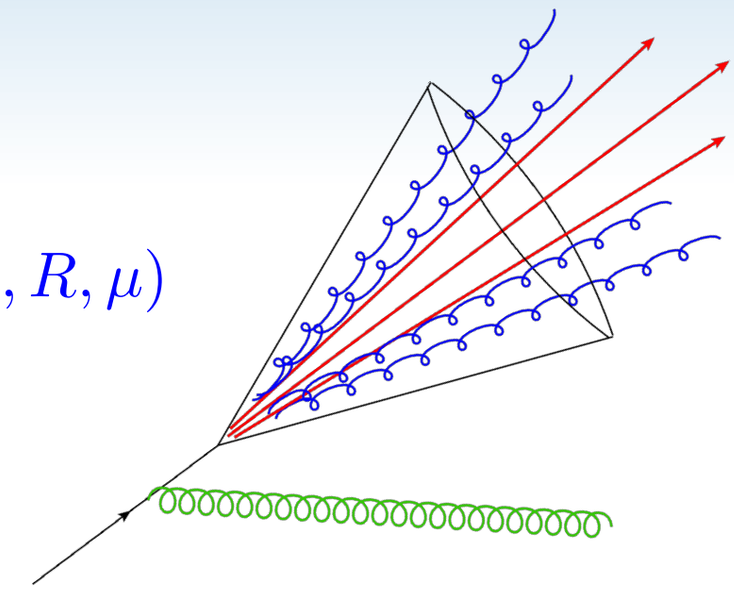
$$\frac{\min[p_{T,i}, p_{T,j}]}{p_{T,i} + p_{T,j}} > z_{\rm cut} \left(\frac{R_{ij}}{R}\right)^{\beta}$$

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

Groomed jet mass factorization

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

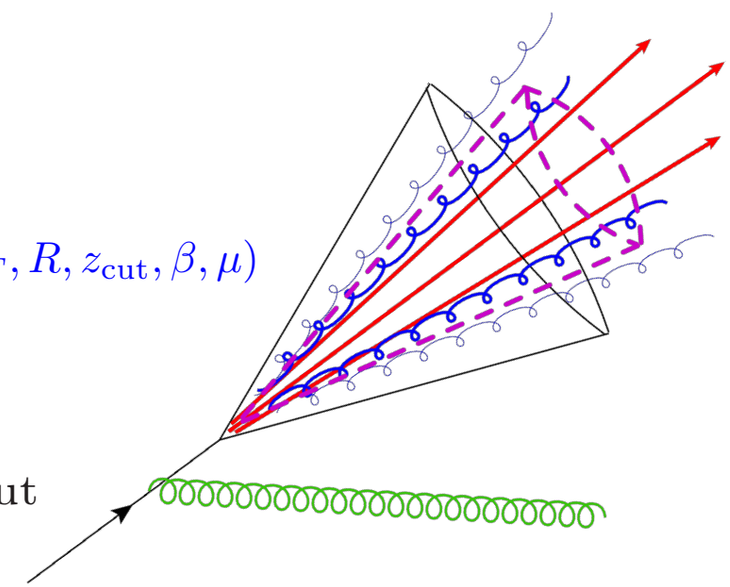
$$\mathcal{G}_i(z, p_T R, \tau, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) C_j(\tau, p_T, \mu) \otimes S_j(\tau, p_T, R, \mu)$$



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

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

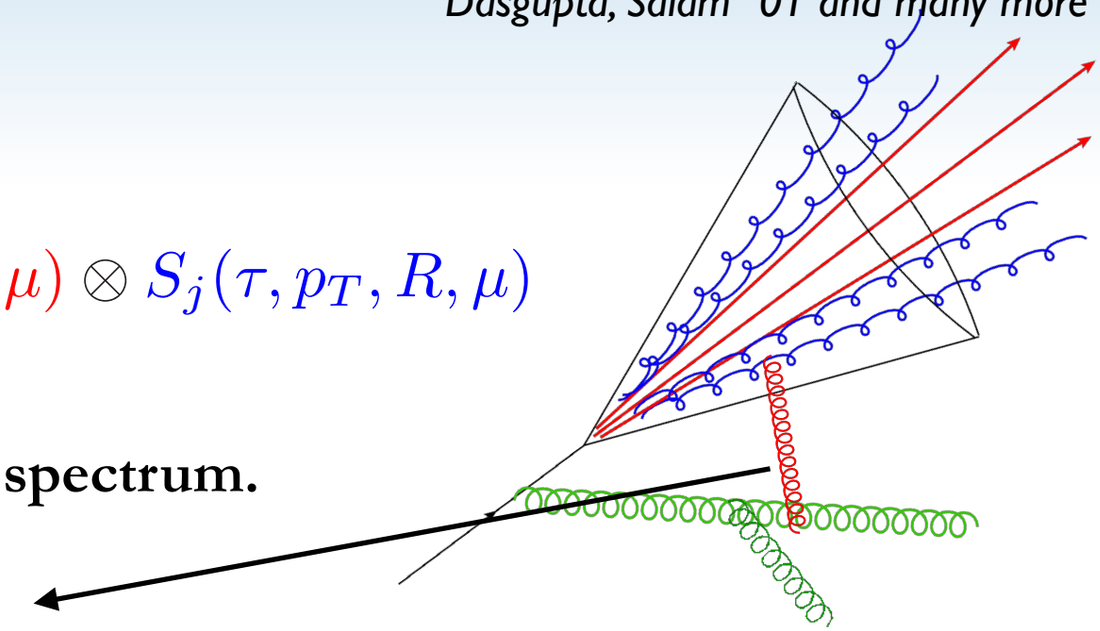
$$\mathcal{G}_i(z, p_T R, \tau_{\rm gr}, z_{\rm cut}, \beta, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) S_j^{\notin {\rm gr}}(p_T, R, z_{\rm cut}, \beta, \mu) C_j(\tau, p_T, \mu) \otimes S_j^{\in {\rm gr}}(\tau, p_T, R, z_{\rm cut}, \beta, \mu)$$



- **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

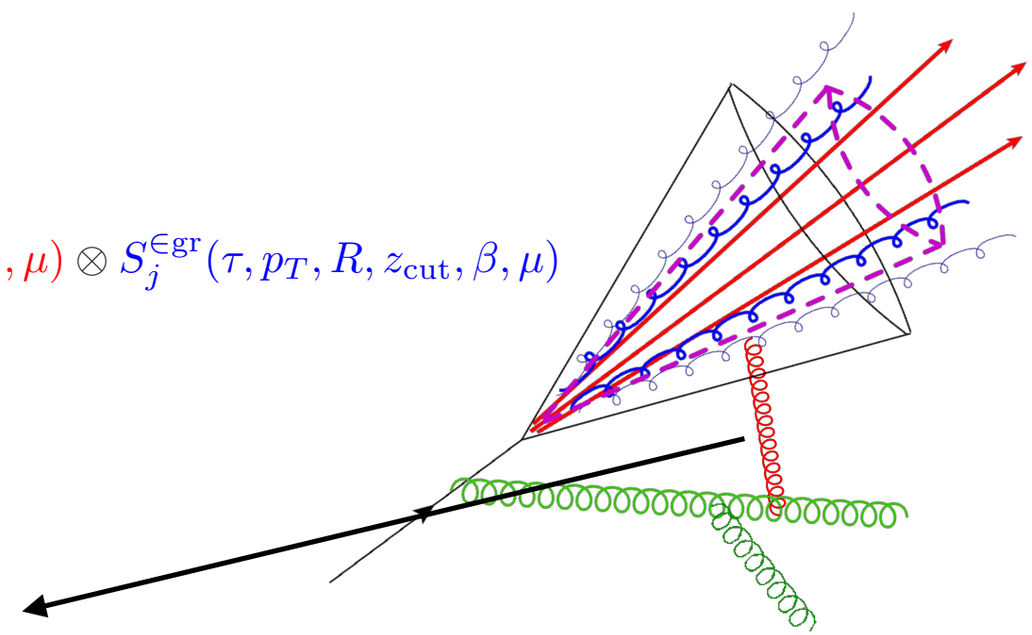


- **The ungroomed case ($\tau \ll R^2$)**

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

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

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



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

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

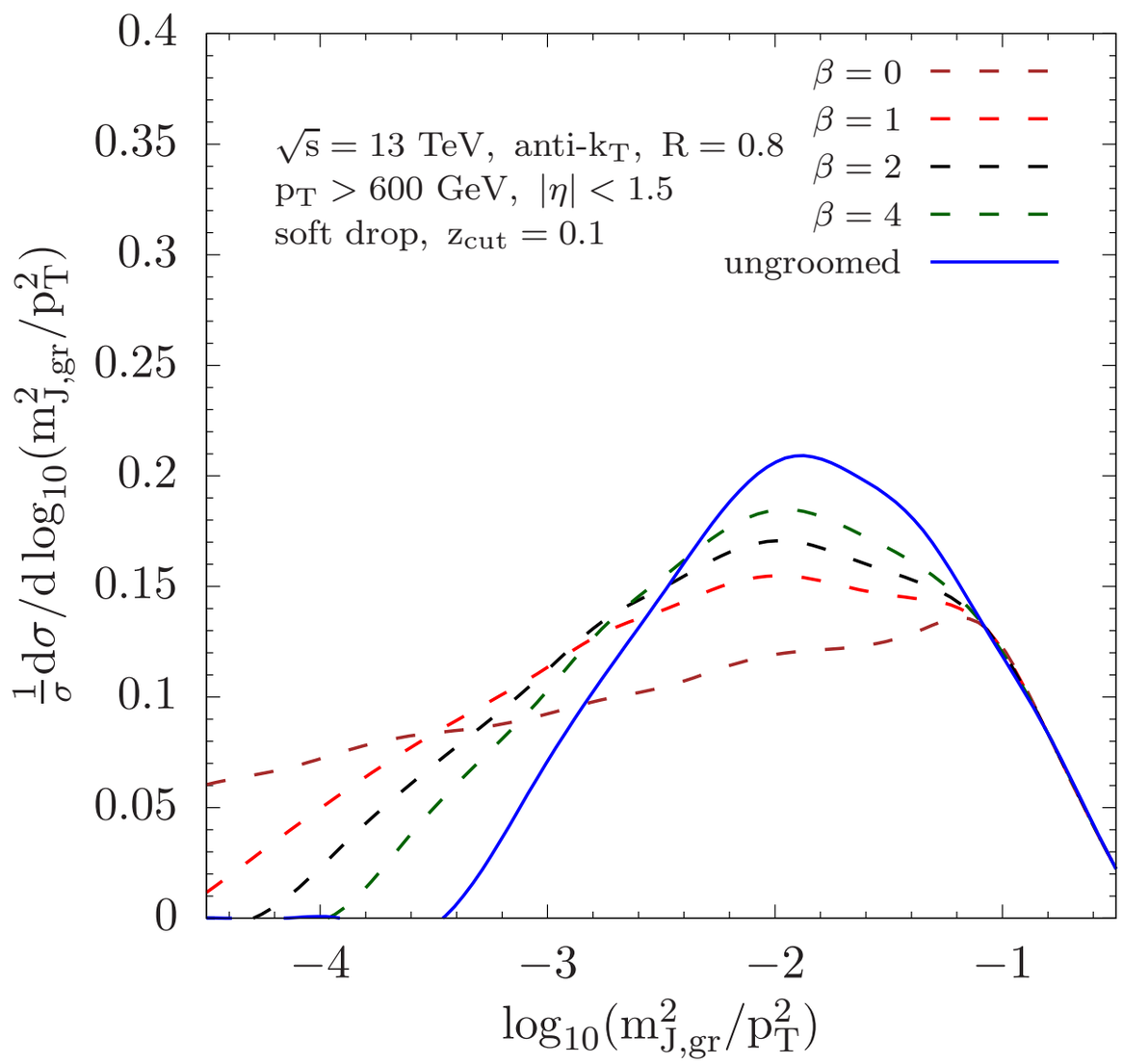
- **Non-global logs only indirectly affects the jet mass spectrum through normalization.**

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

Limit to the ungroomed case

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

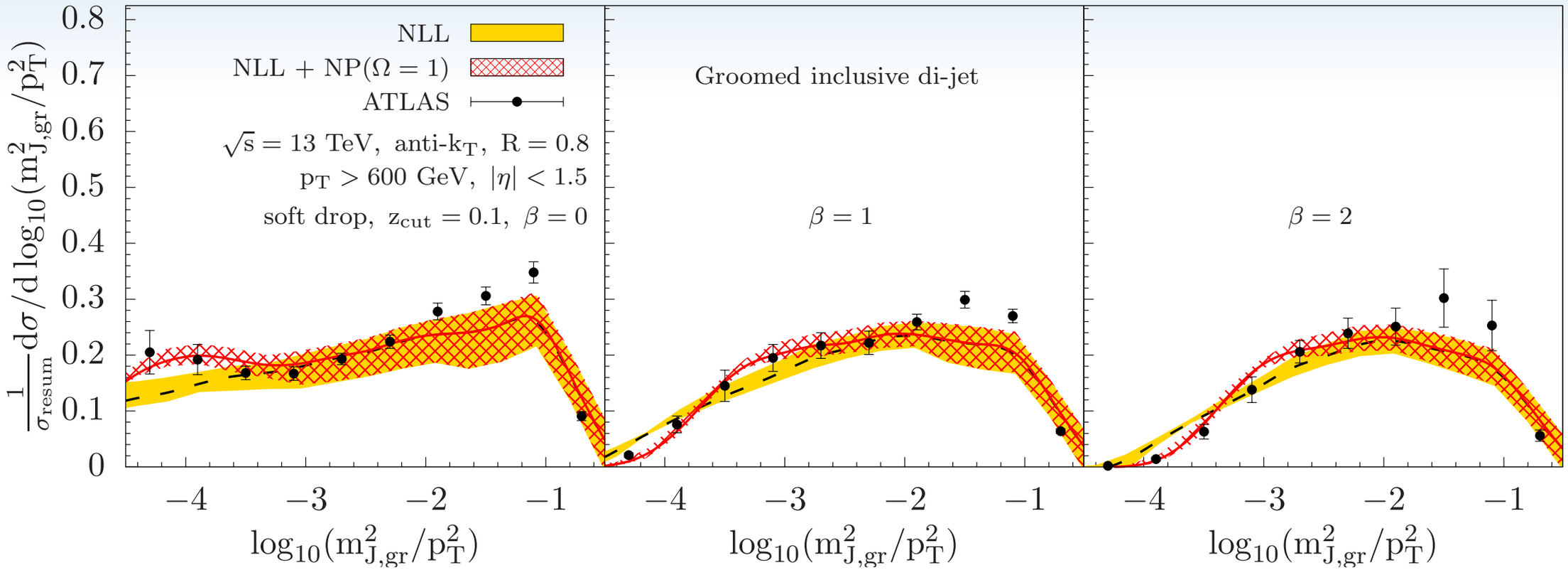
$$\frac{\min[p_{T,i}, p_{T,j}]}{p_{T,i} + p_{T,j}} > z_{\rm cut} \left(\frac{R_{ij}}{R}\right)^{\beta} \to 0 \quad \textbf{when} \quad \beta \to \infty$$



Checked both numerically and analytically.

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

Phenomenology (groomed jet mass)

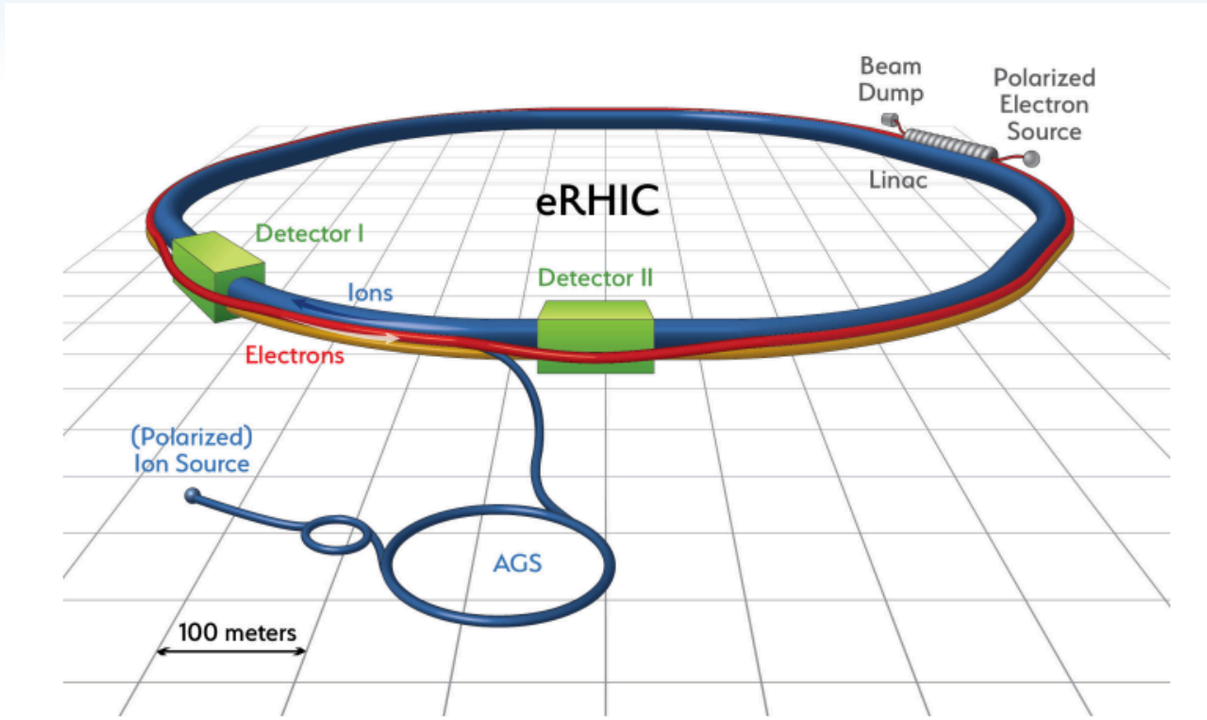


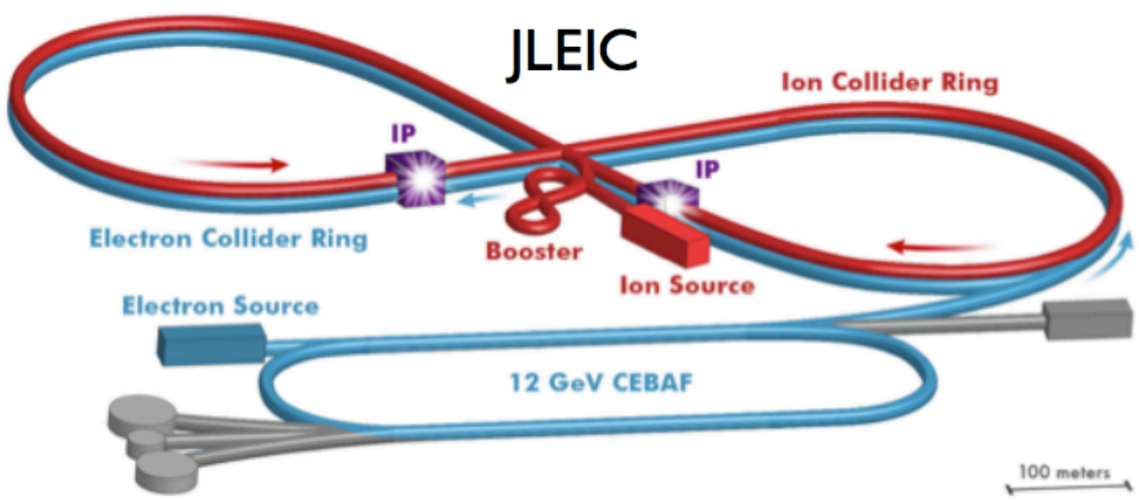
- Developed the formalism for single inclusive groomed jet mass cross-section.
- Shows very good agreement with the data.
- $\Omega_k = 1$ GeV $\Longrightarrow$ Reduced contamination as expected. NP effects mostly from hadronization.

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

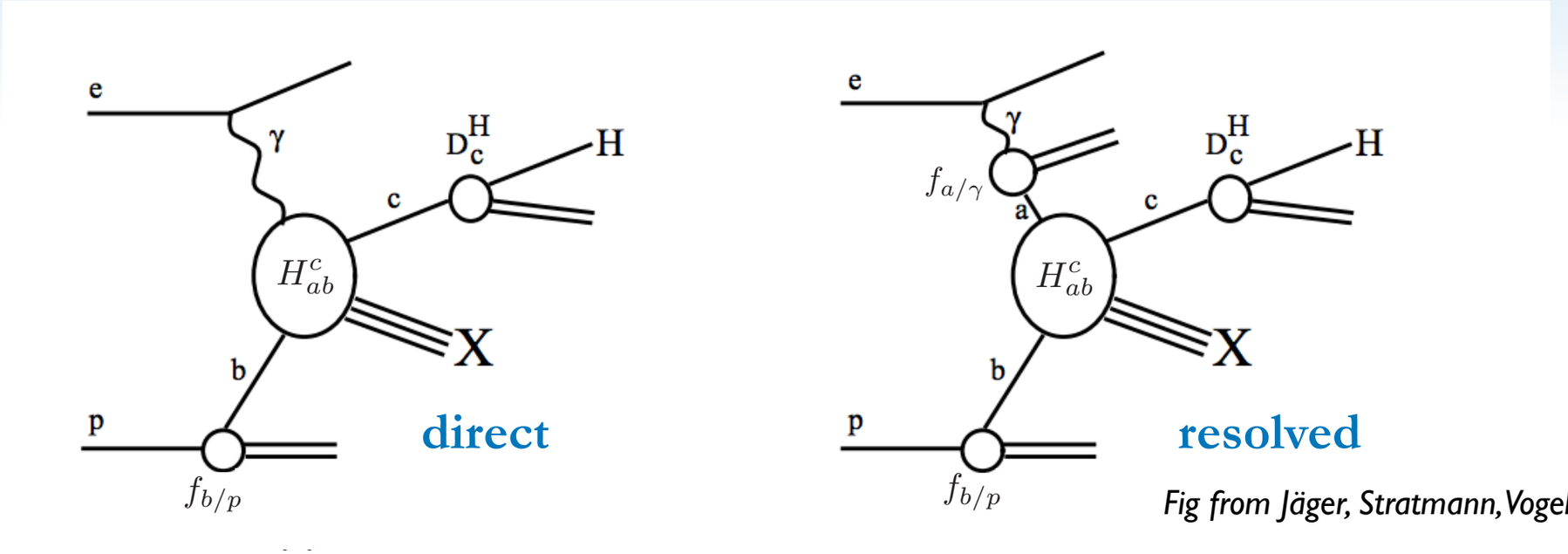


Fig from Jäger, Stratmann, Vogelsang `03

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

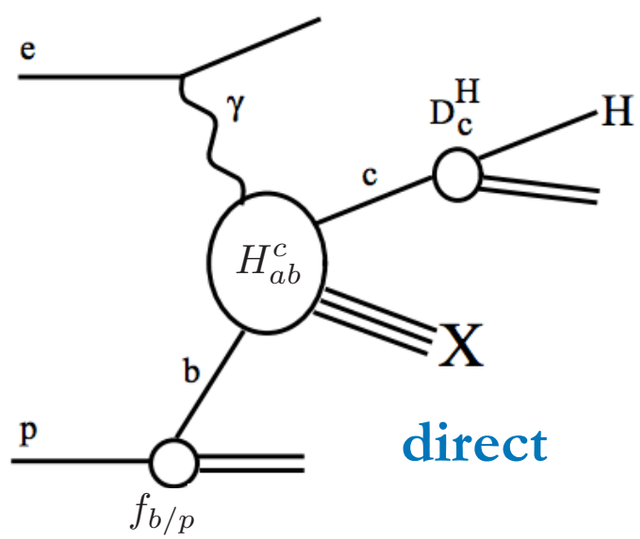
Weizsäcker-Williams spectrum

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

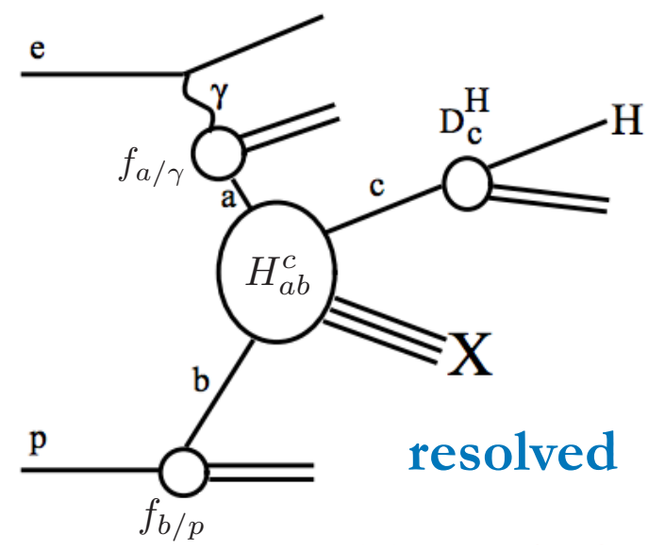
- For the direct process, $f_{a/\gamma} = \delta(1 - x_\gamma)$.
- Observe outgoing lepton to tag Q^2
- Require high p_T and $Q^2 < 0.1\ \mathrm{GeV}^2$ (near on-shell photon)

See Jäger, Stratmann, Vogelsang `03

Photoproduction at the EIC



direct



resolved

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 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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- Observe outgoing lepton to tag Q^2
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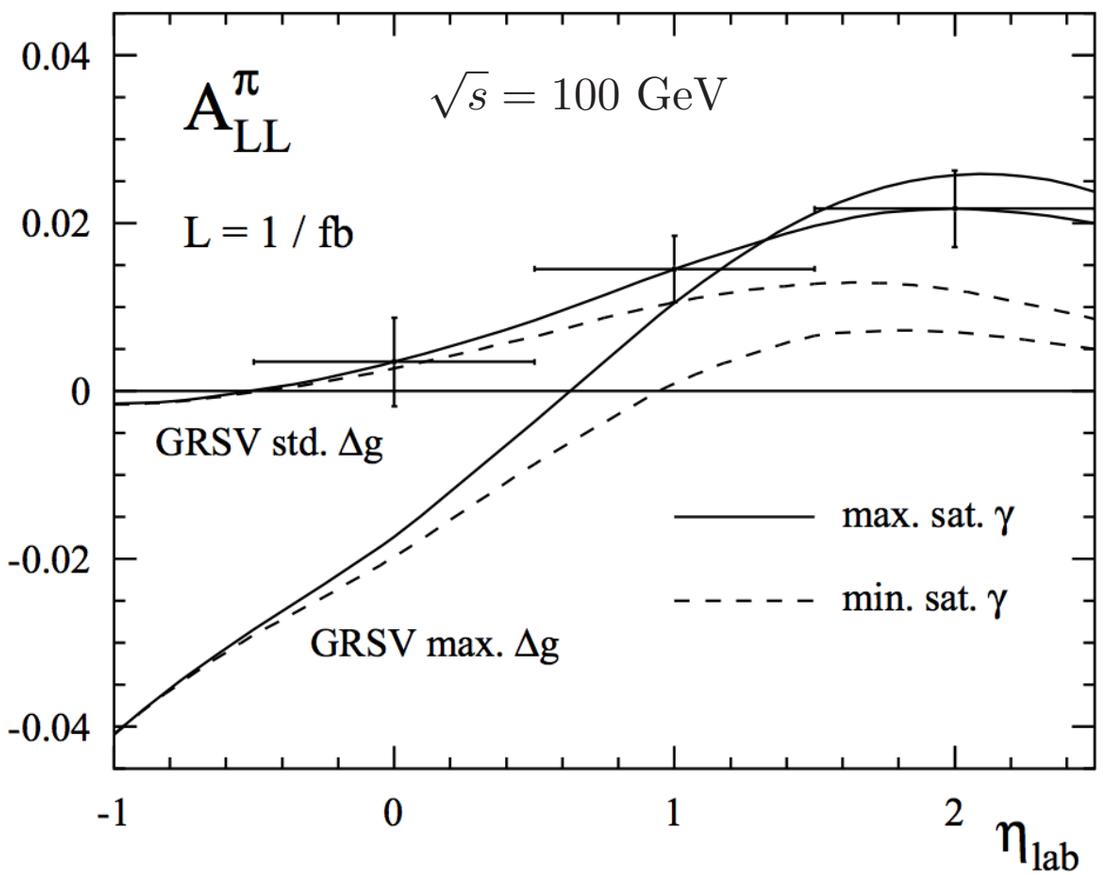
See Jäger, Stratmann, Vogelsang `03

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!

- **Study of polarized pdfs**

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

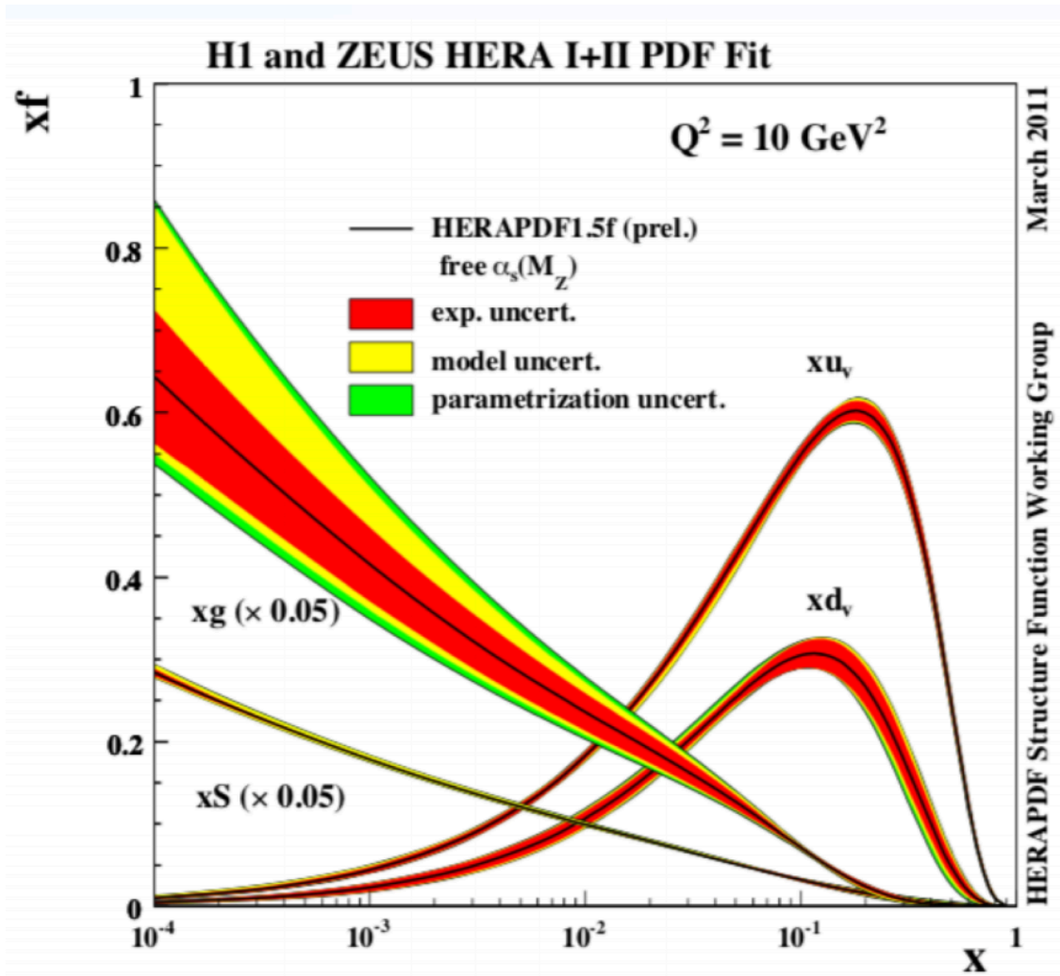
HERA PDF fit with and without jets

- Important for constraining gluon PDF

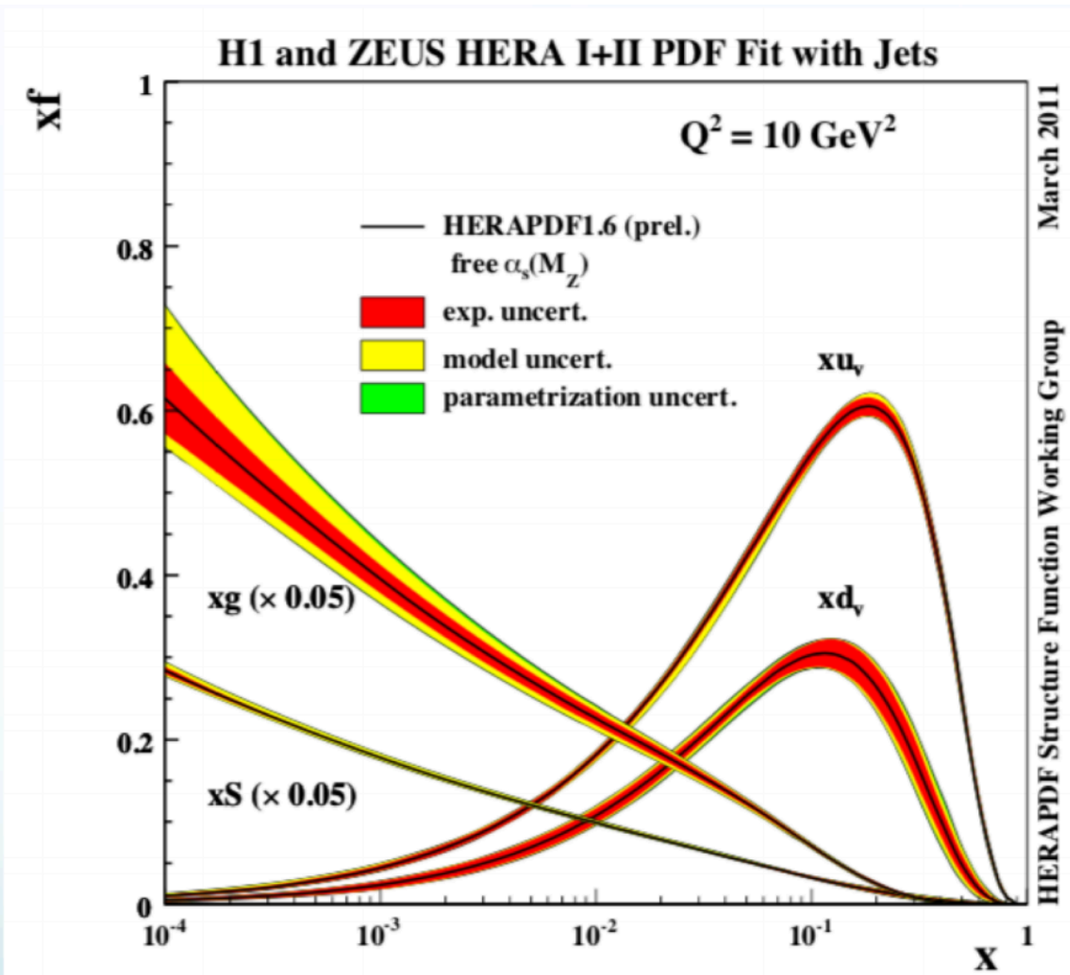
Nuclear Physics B (Proc. Suppl.) 222–224 (2012) January–March 2012

HERA 2011

Proceedings of the Ringberg Workshop
New Trends in HERA Physics 2011

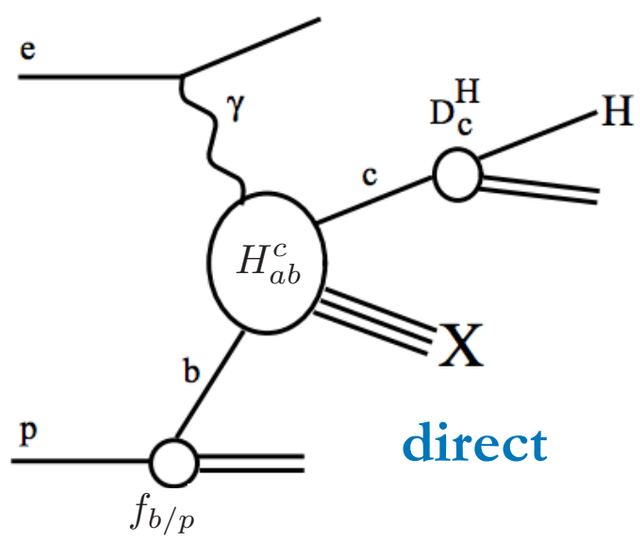


Without jets

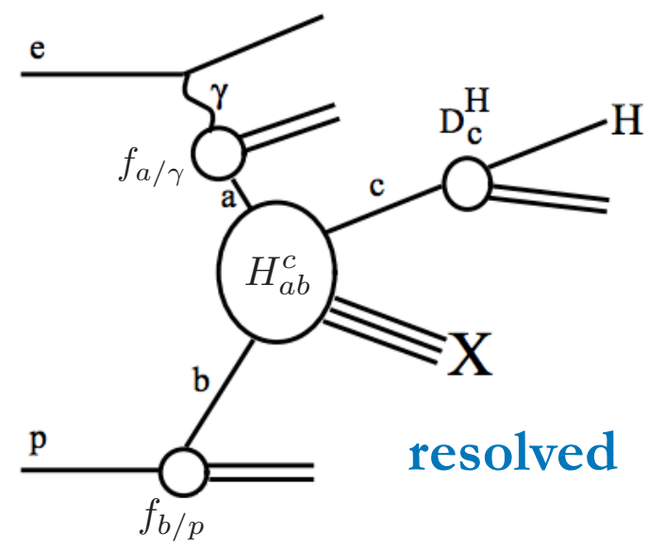


With jets

Photoproduction at the EIC



direct



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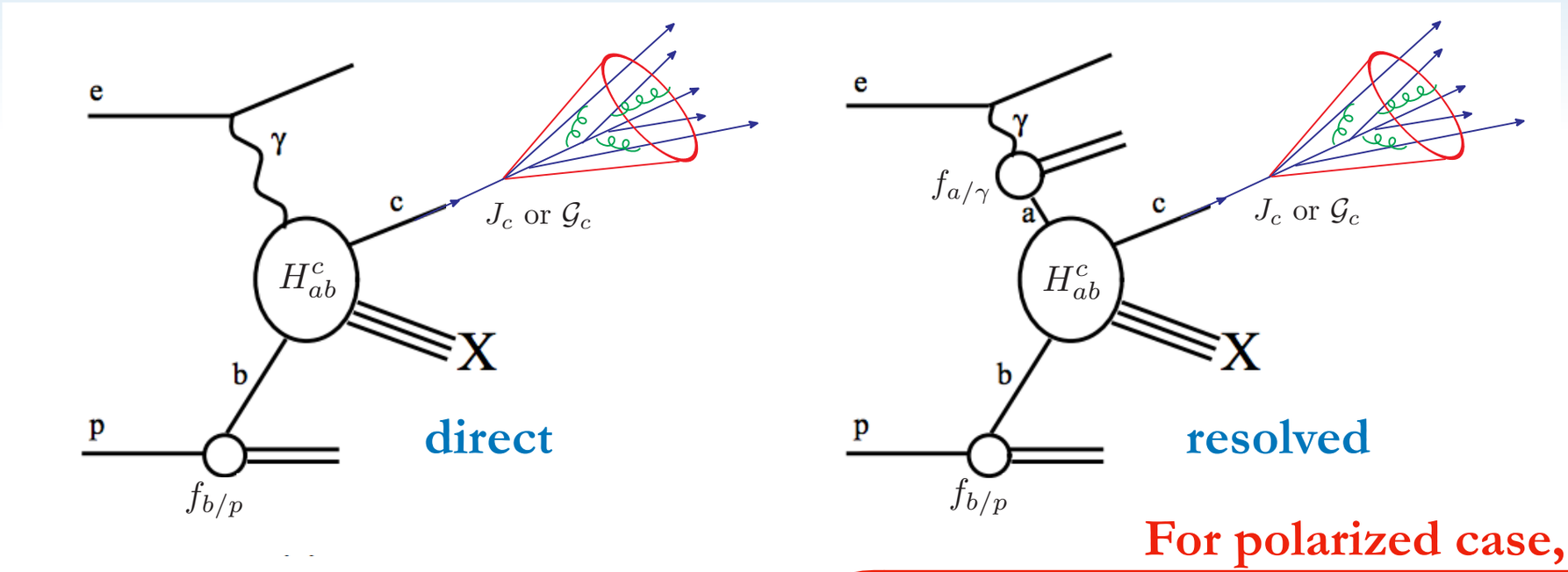
See Jäger, Stratmann, Vogelsang `03

Photoproduction at the EIC



For polarized case,

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

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

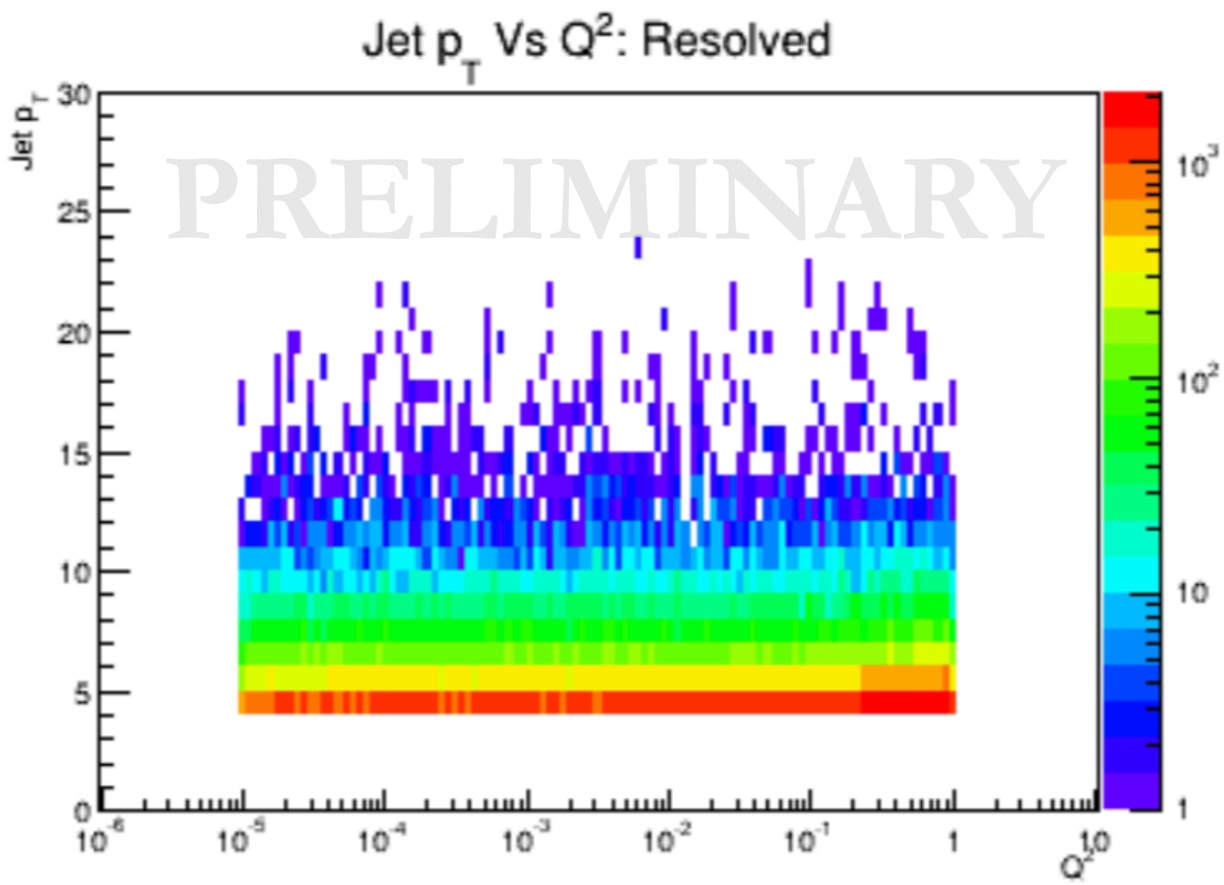
Inclusive Jet $$\frac{d\sigma^{ep\to \mathrm{ejet}X}}{dp_T d\eta} = \sum_{a,b,c} f_{a/l} \otimes f_{b/p} \otimes H^c_{ab} \otimes J_c + \mathcal{O}(R^2)$$

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

- 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

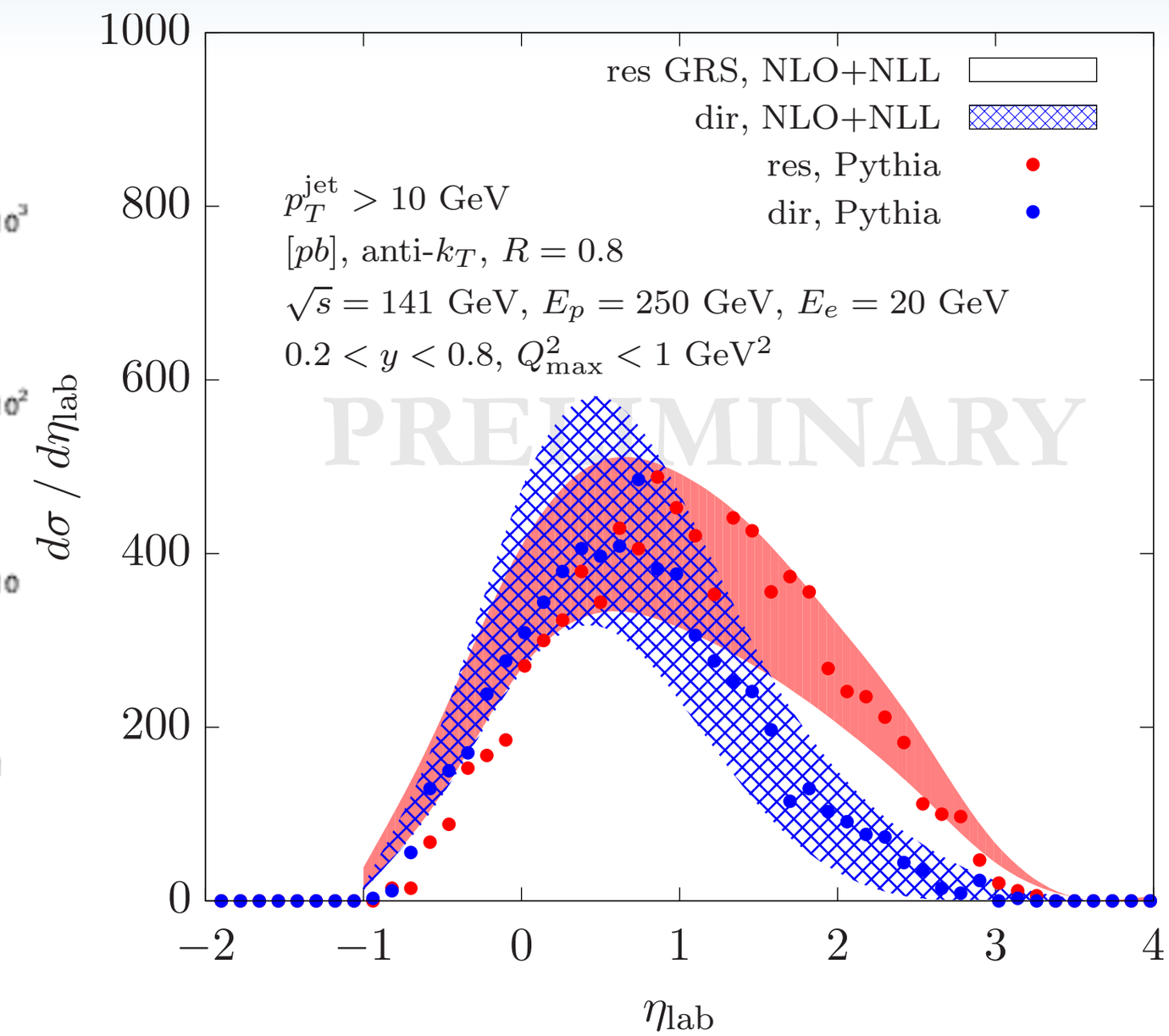
p_T distribution for the jets in the EIC



$E_e = 20$ GeV

$E_p = 250$ GeV

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



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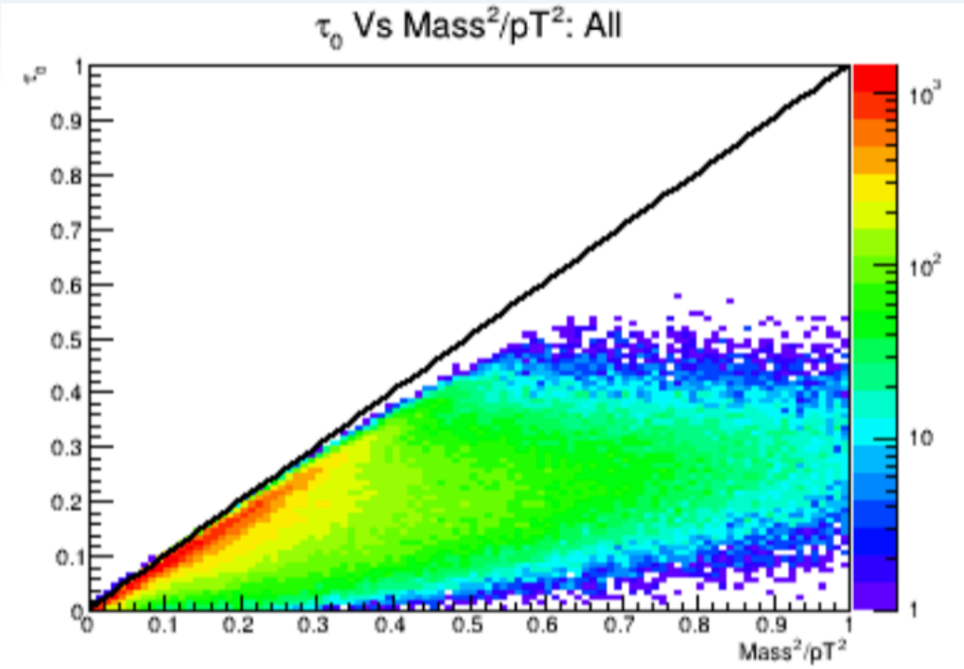
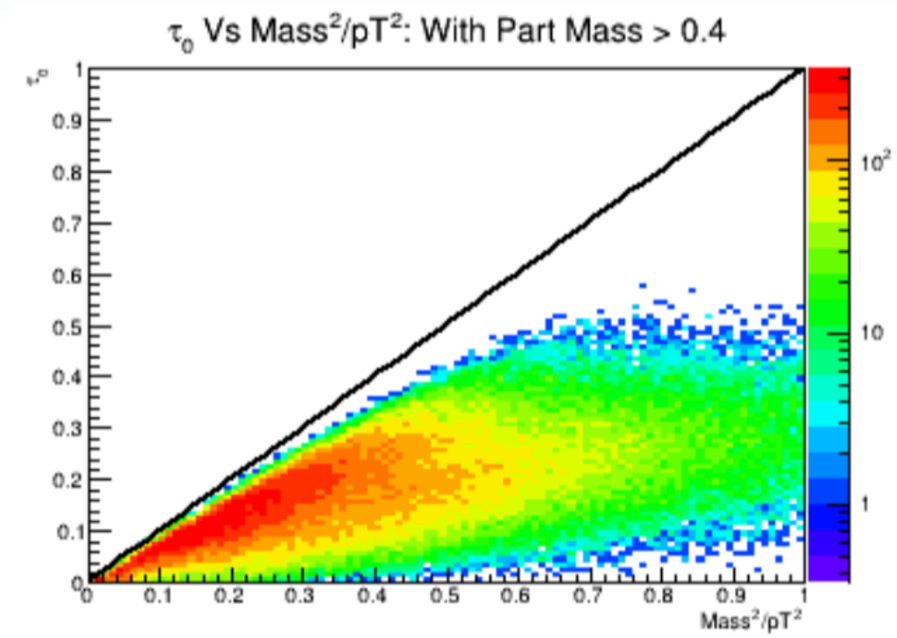
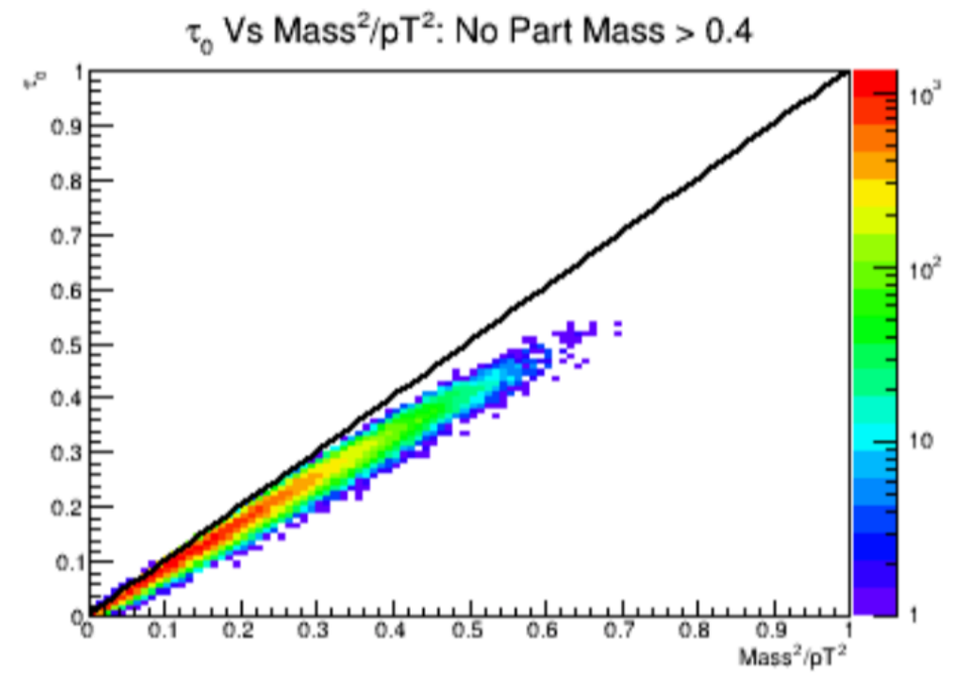
Power corrections







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

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

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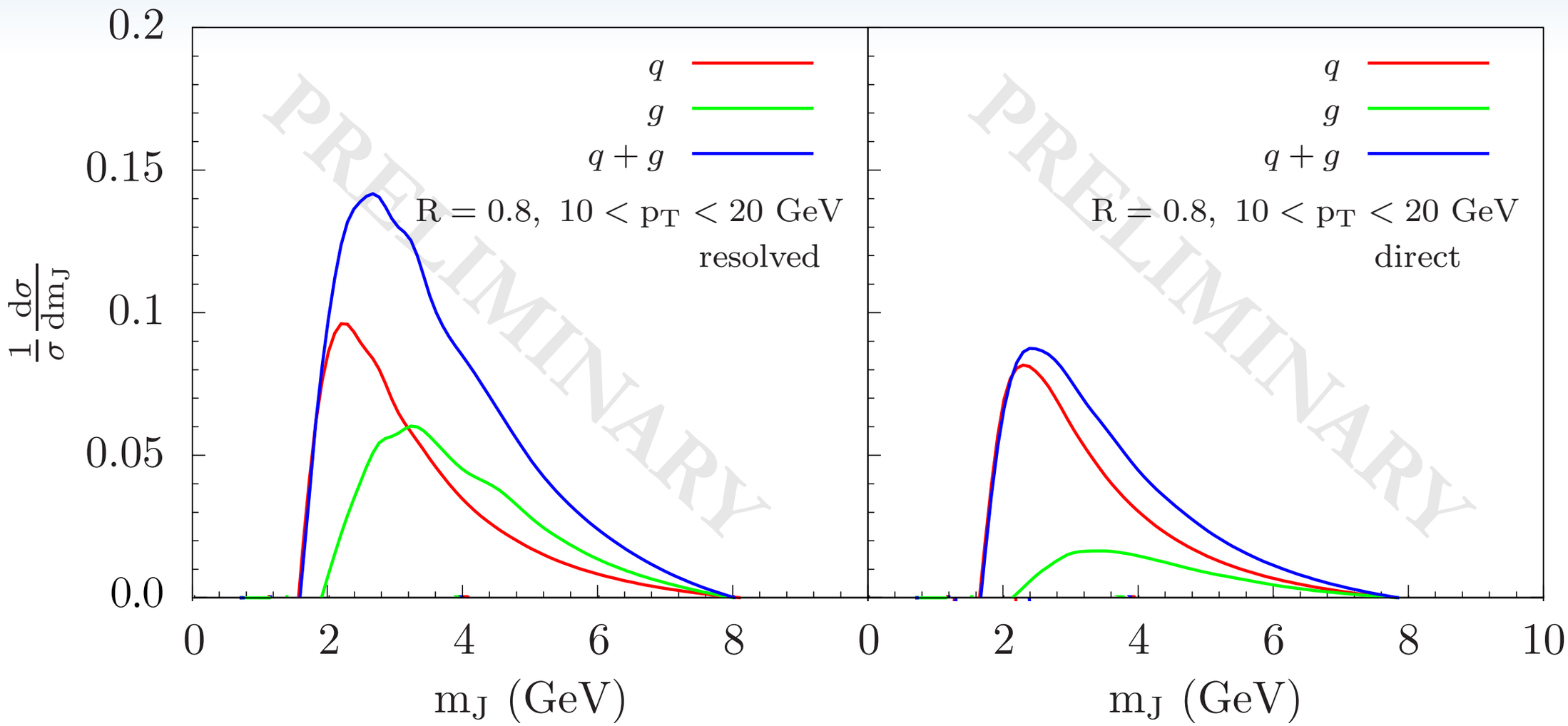
Preliminary Plots



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

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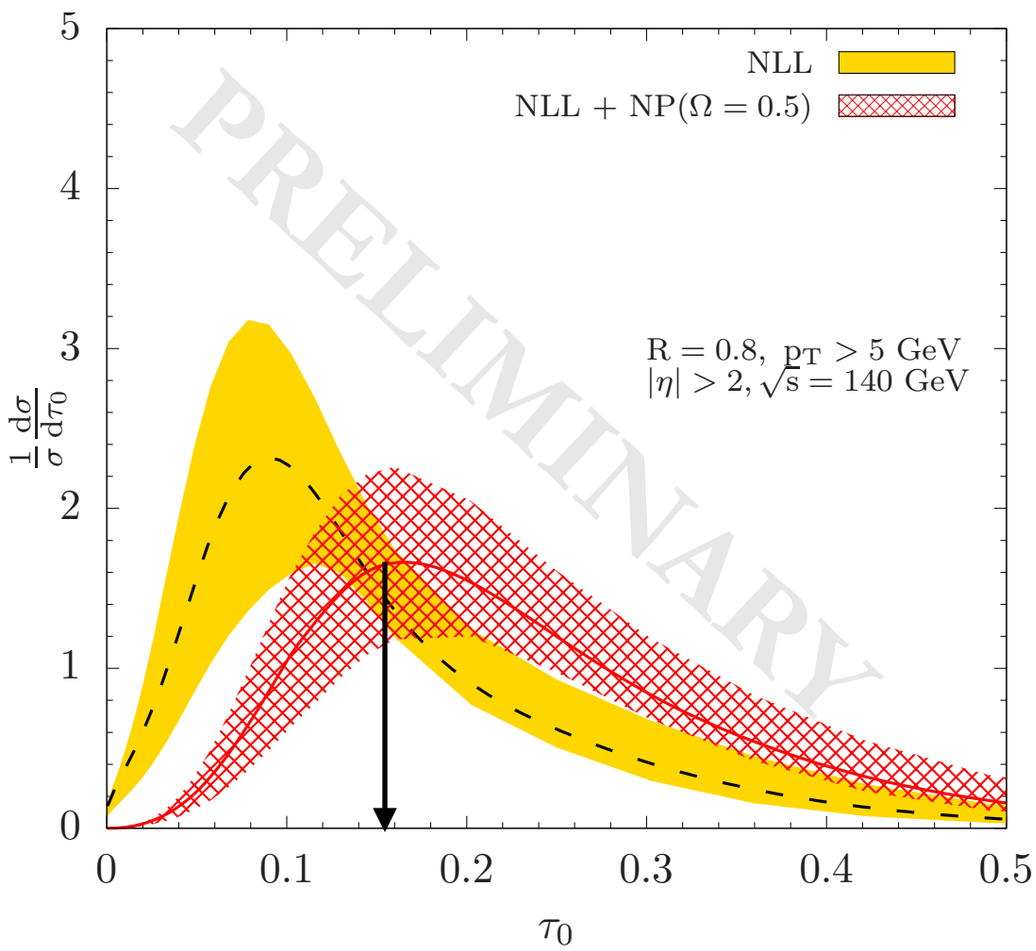
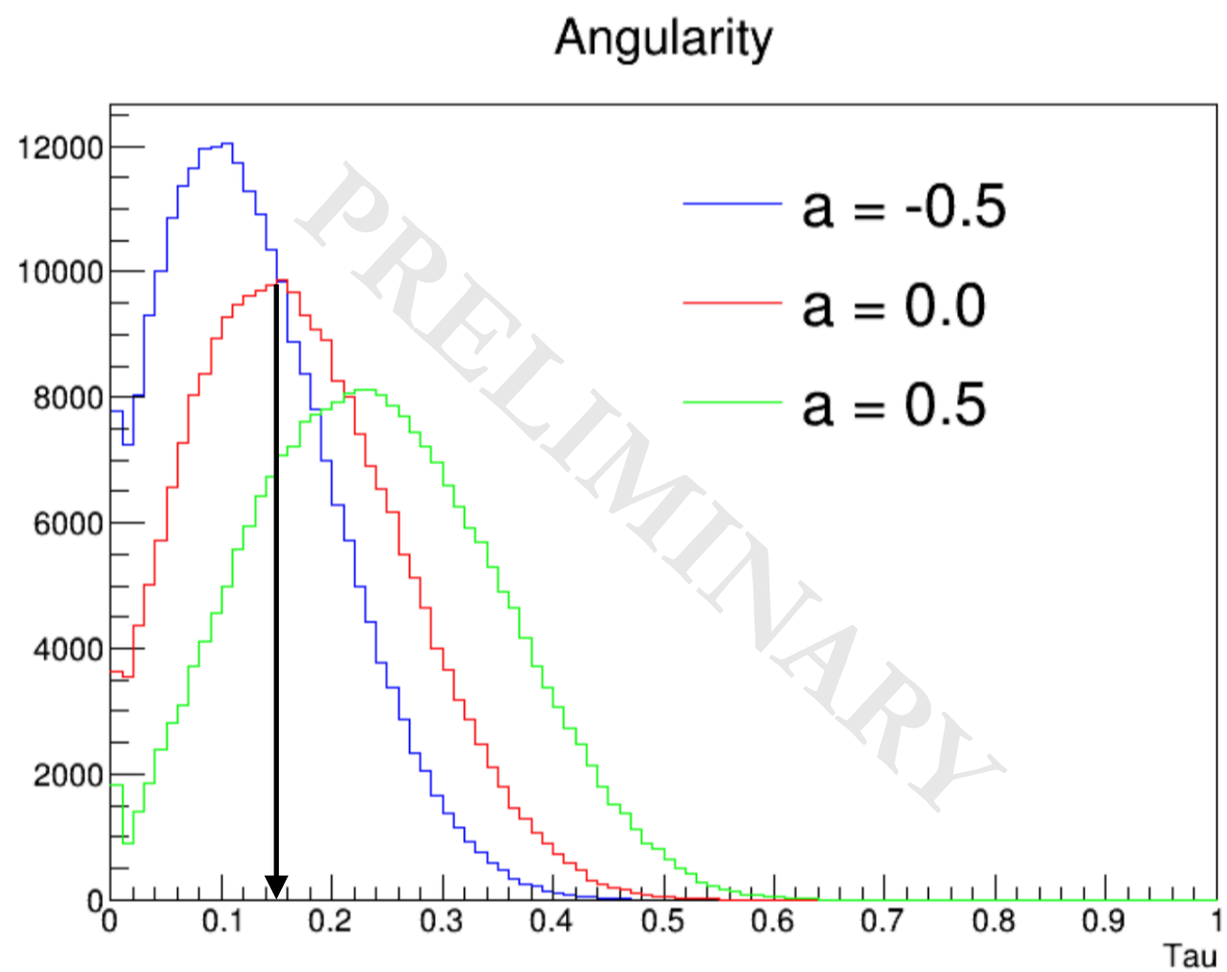
Preliminary Plots





- **Monte Carlo**

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

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Conclusions

- Formalisms for studying semi-inclusive jet production with and without a substructure measurement were introduced.
- Discussed phenomenology of ungroomed jet mass in the LHC.
- Discussed various non-perturbative effects.
- Discussed grooming which reduce contaminations from the uncorrelated radiations.
- Discussed phenomenology of groomed jet mass.
- Formalisms were extended to the photoproduction case at the EIC and was shown that EIC has a cleaner environment than the LHC.

Thank you!