Jet substructure tools

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1st COFI Workshop on Precision Electroweak
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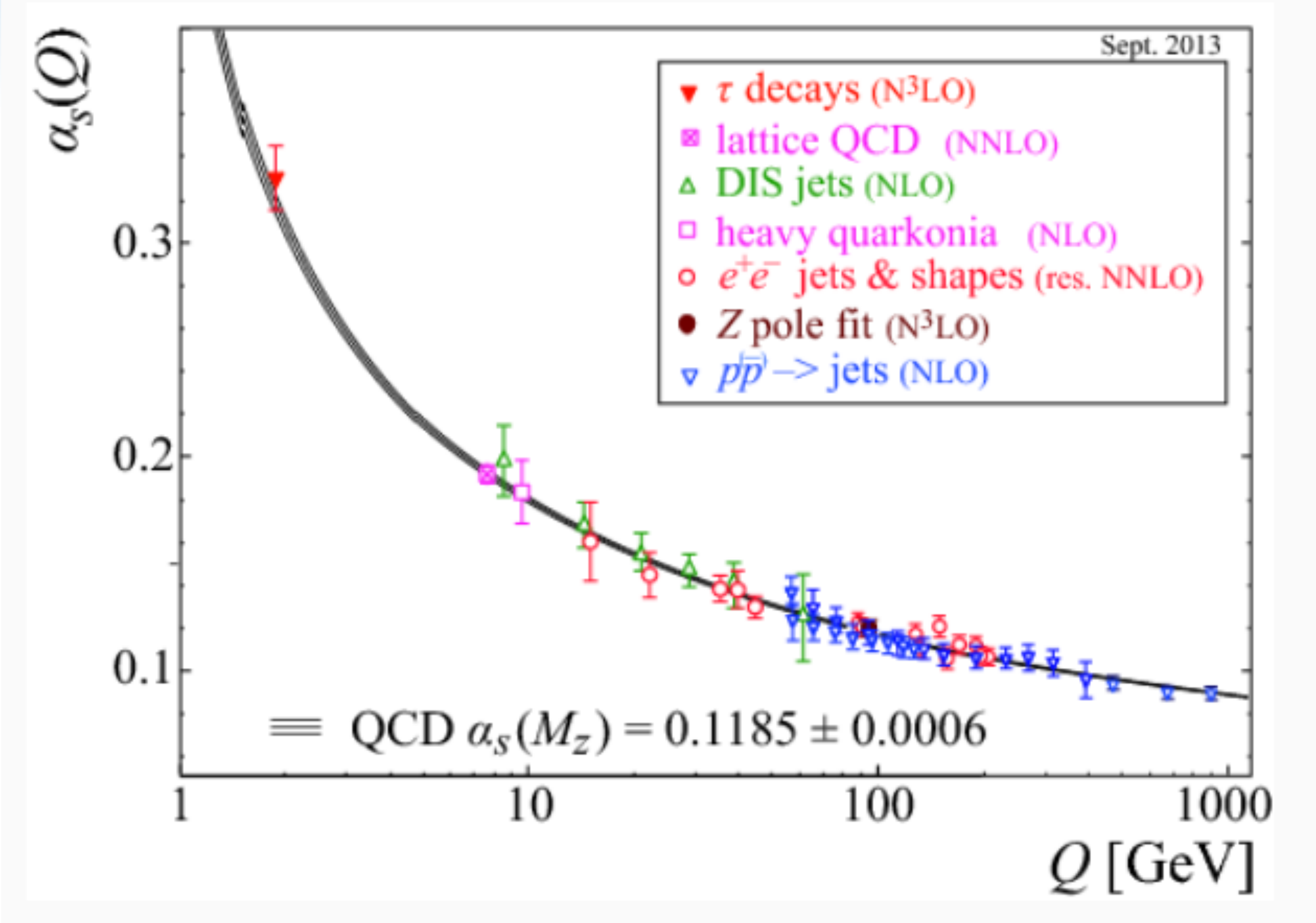
IR safety and factorization



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

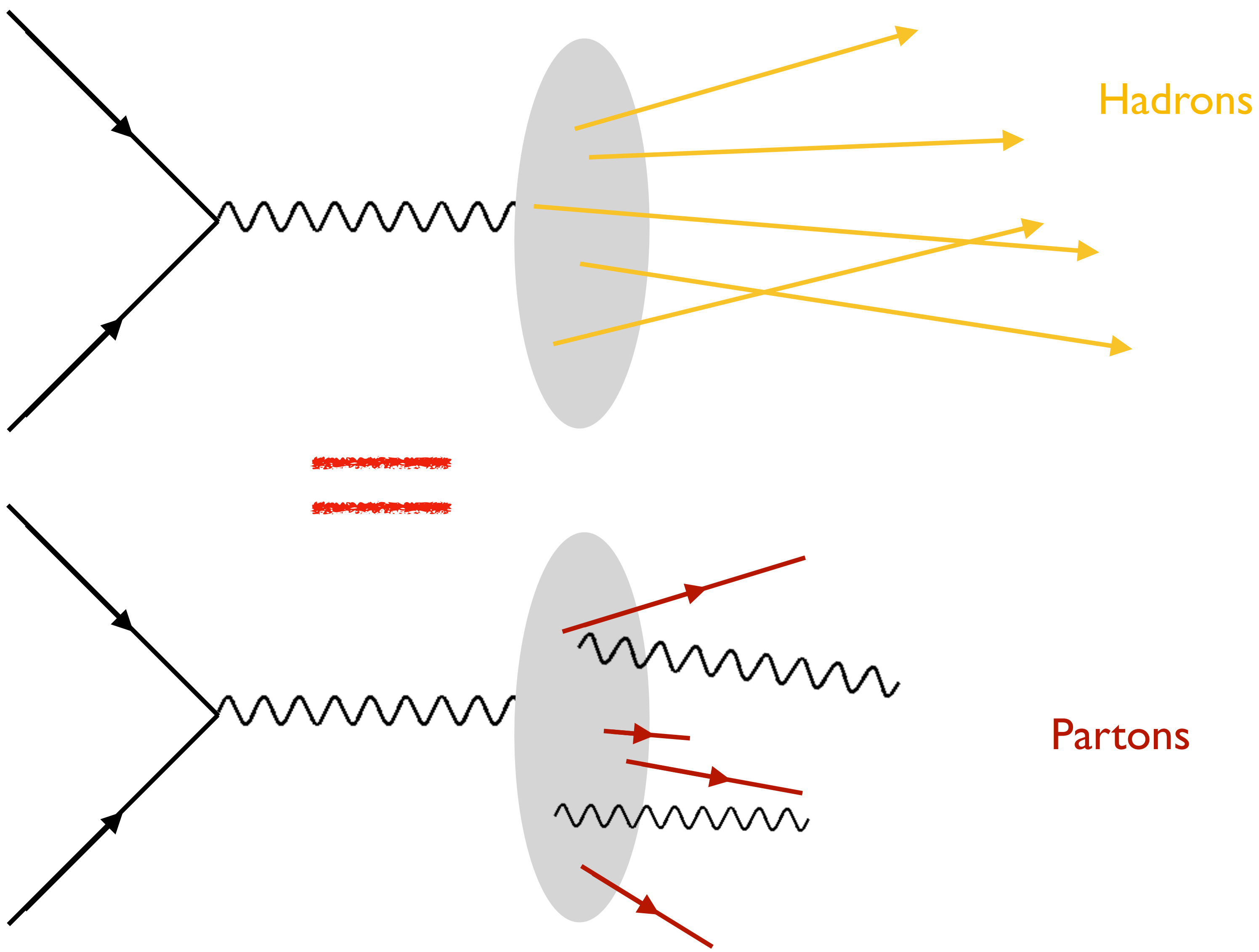
- Detectors are long-distance away. Experiments can only see hadrons and not free partons.

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: $e^+e^- \to \text{hadrons}$



IR safety and factorization

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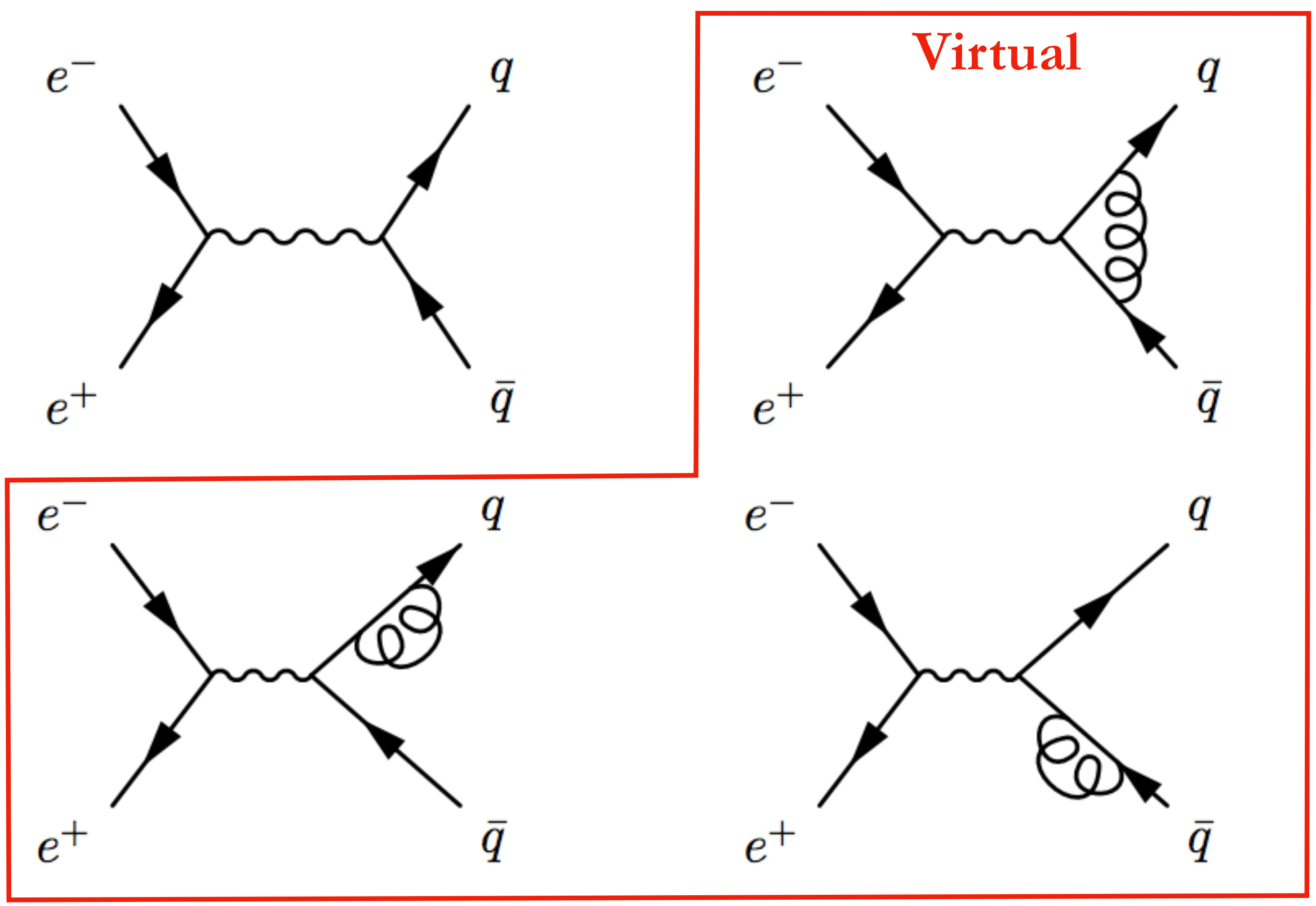
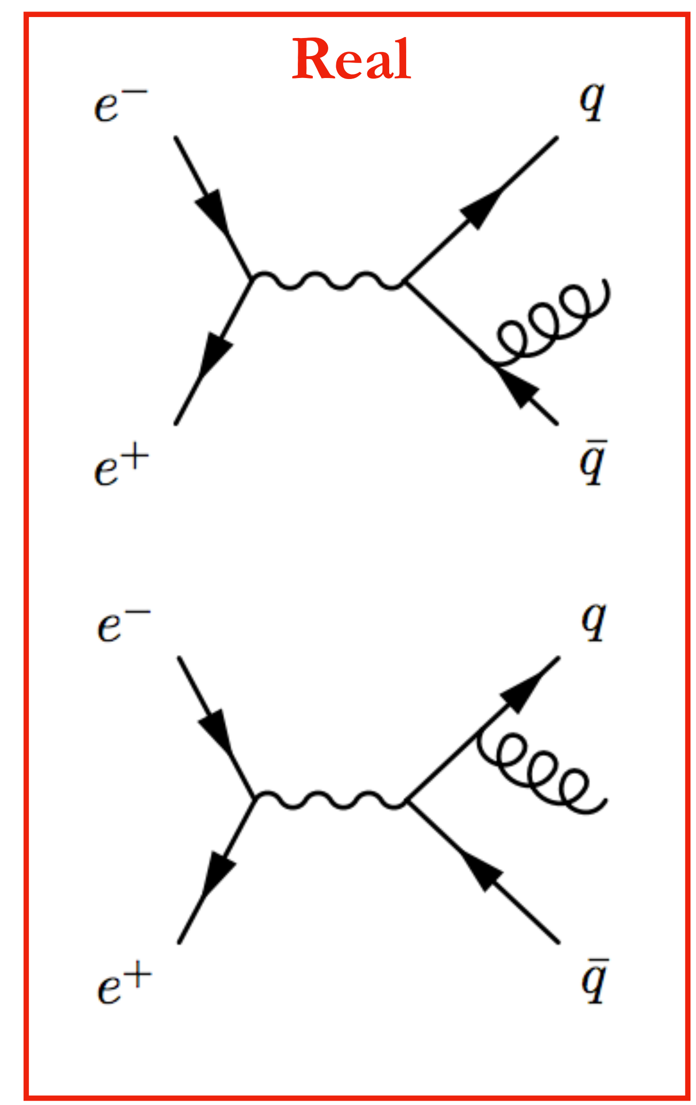
1-loop example: individually divergent, but finite sum!

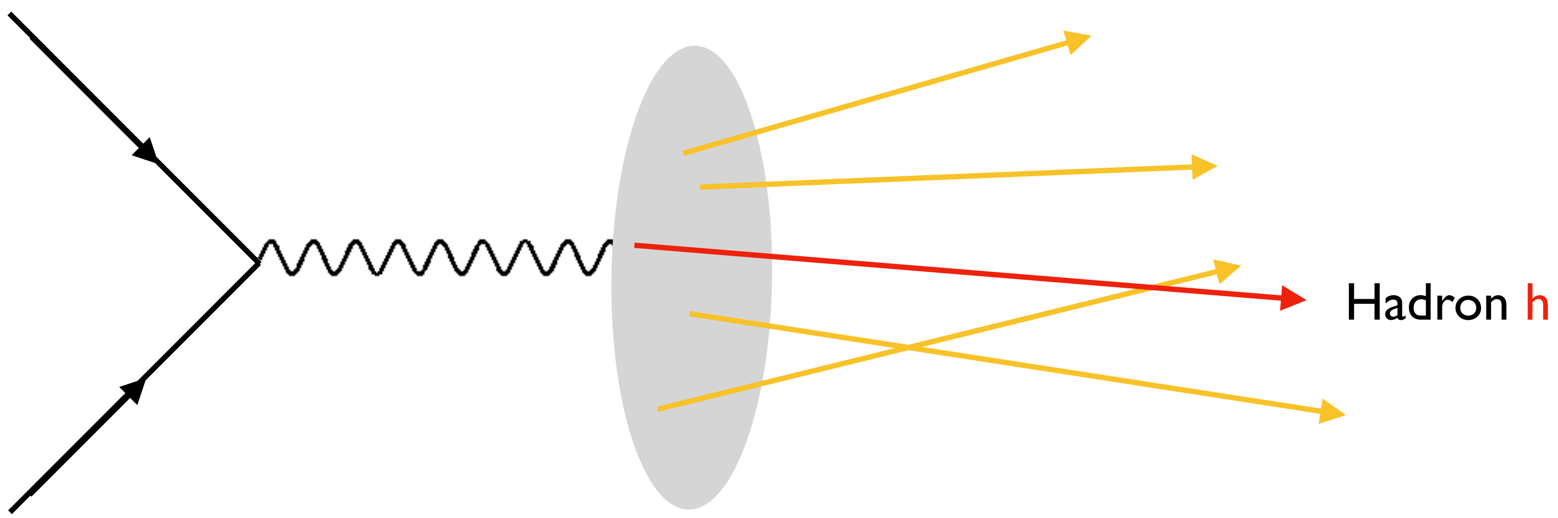




IR safety and factorization

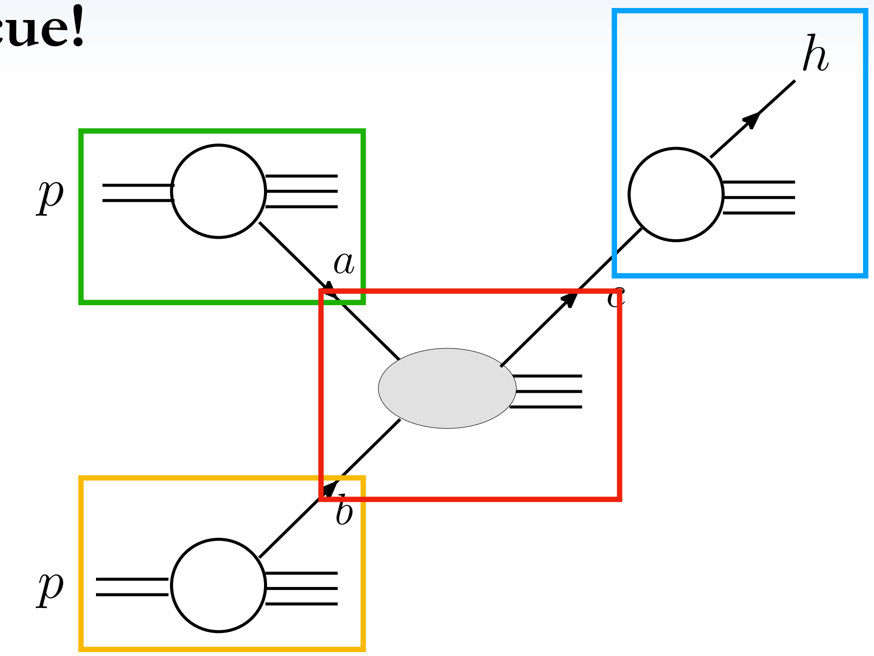
- **Asking a long-distance sensitive question will give sensitivity to non-perturbative physics!**

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



IR safety and factorization

- **Factorization to the rescue!**



$$pp \to h + X$$

Factorization

Hadron

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

Evolution

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

Perturbatively computable

Non-perturbative but universal

Separation of dynamics

DGLAP evolution

IR safety and factorization

In summary,

IR safe observables

$$\sigma_{exp} = \sigma_{pert}$$

Factorizable observables

- Allows separation of dynamics :

$$\sigma_{exp} = \sigma_{pert,1}\, \sigma_{pert,2} \cdots \sigma_{NP,1}\, \sigma_{NP,2} \cdots$$

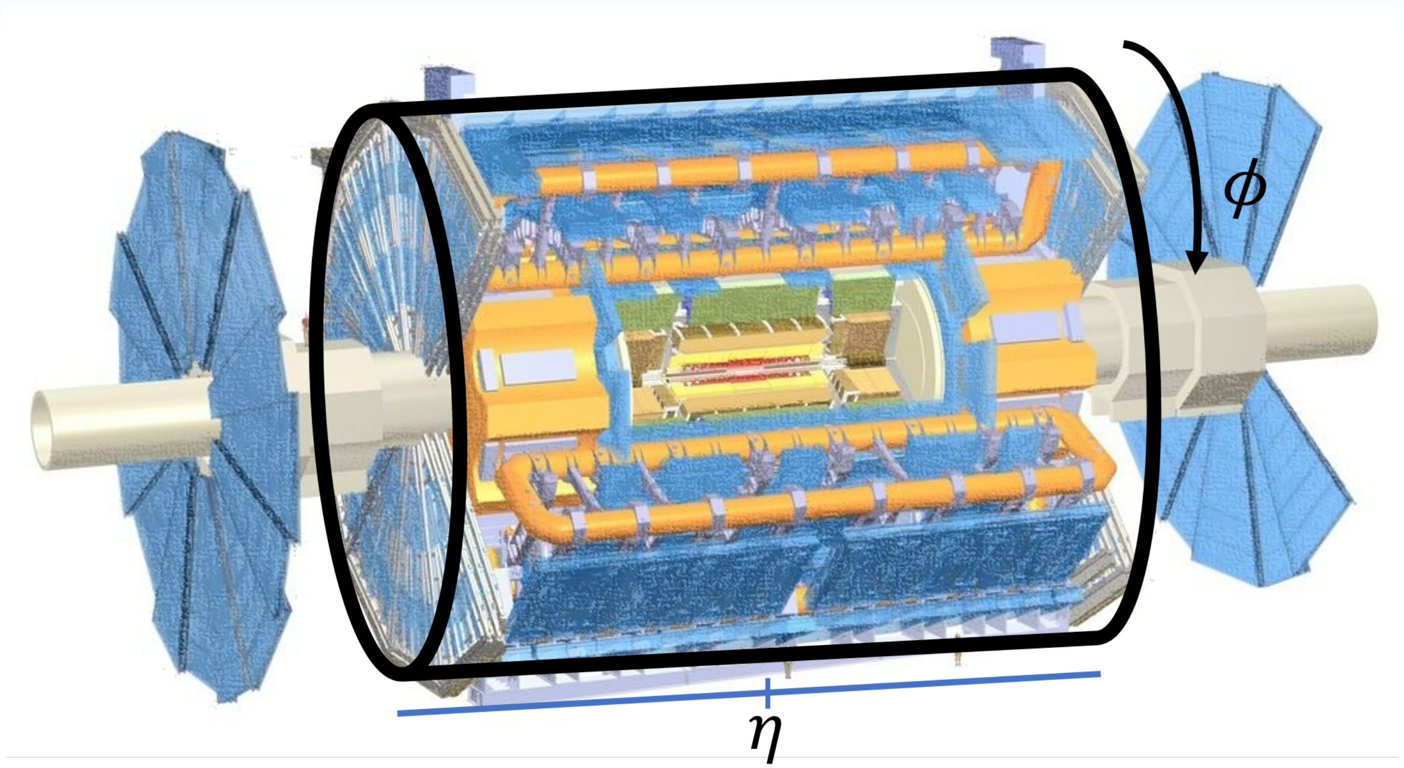
- F_{NP} is a non-perturbative, but universal function.

ex: PDFs or FFs

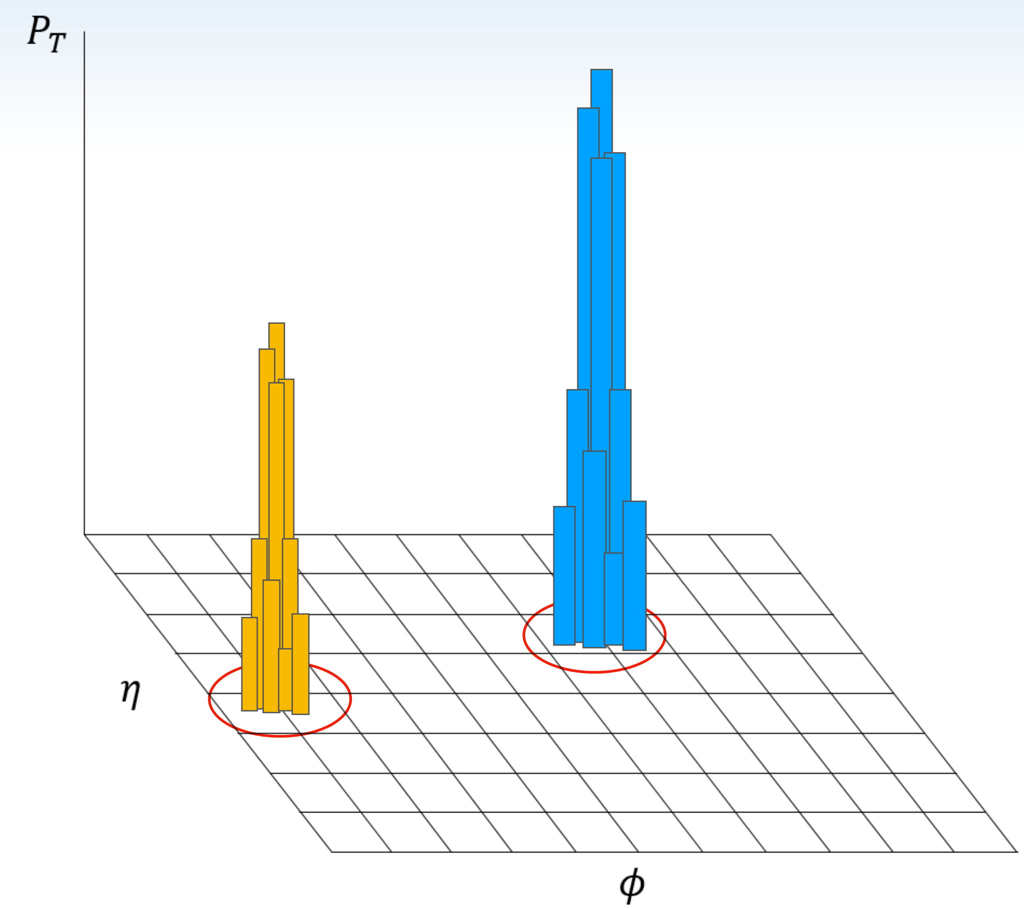
IR-safe observables

- Jet cross-section is an another IR-safe observable!

What are Jets?

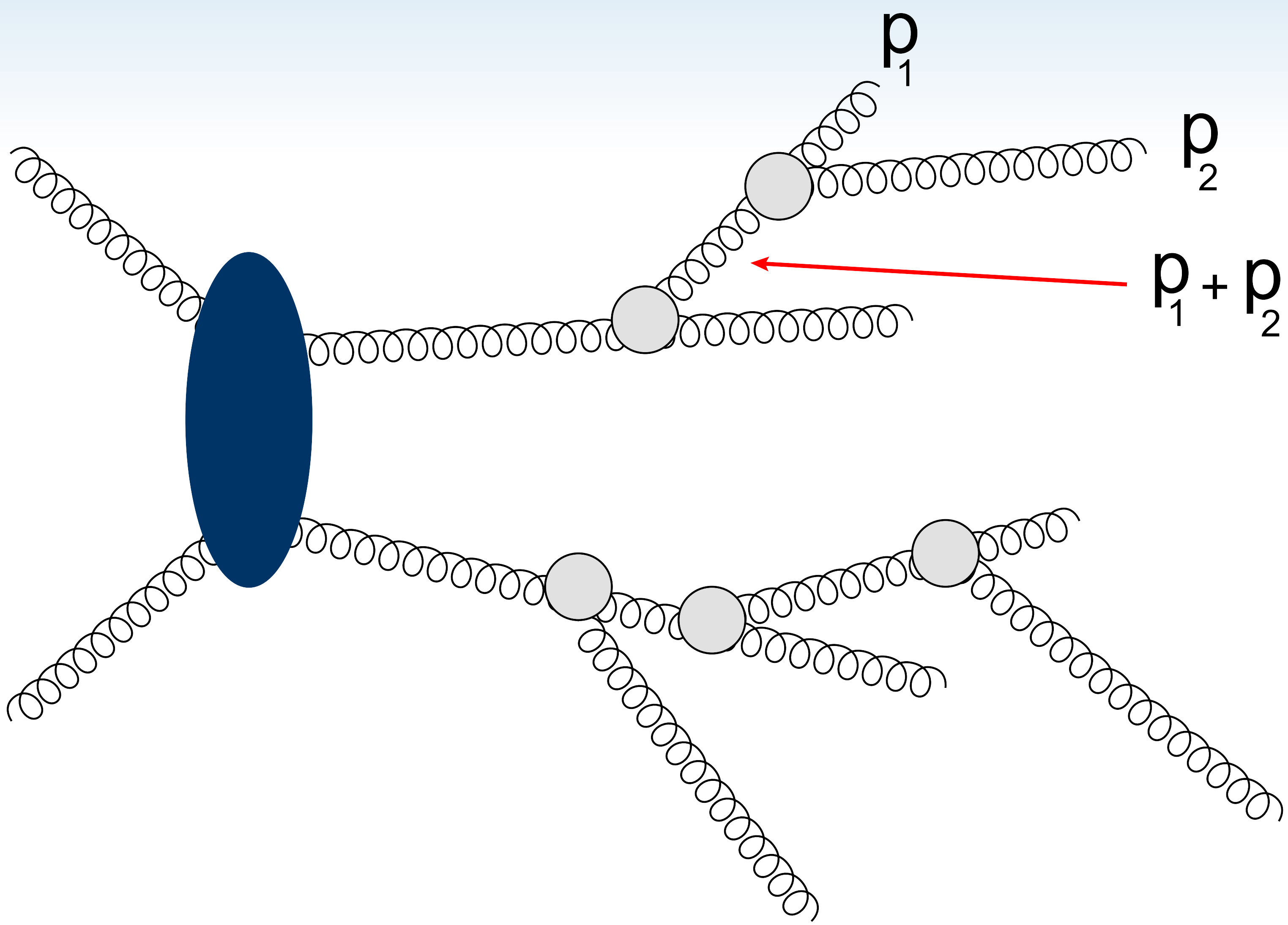


Dijet event



- **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?



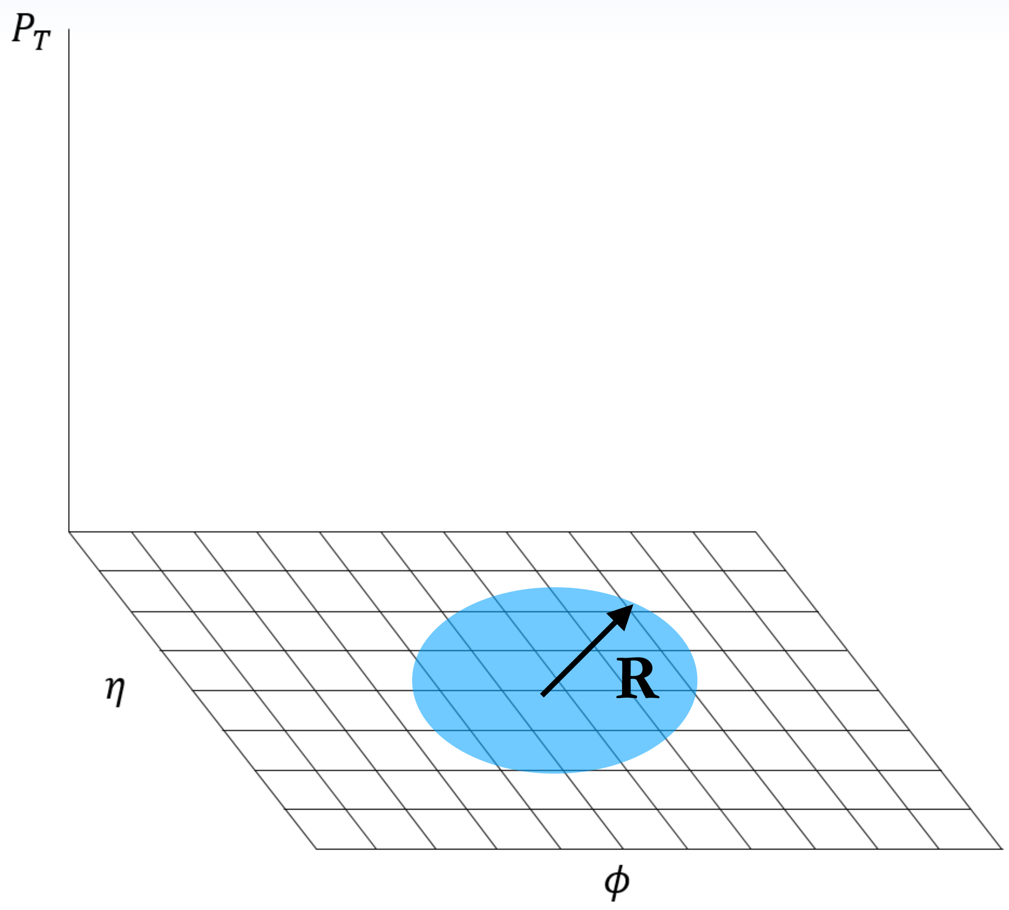
- **Production of jet is consistent with the partonic picture of QCD.**
- **High probability of collinear and soft splittings: with** $p_1^2 = 0, \; p_2^2 = 0$

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

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

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)

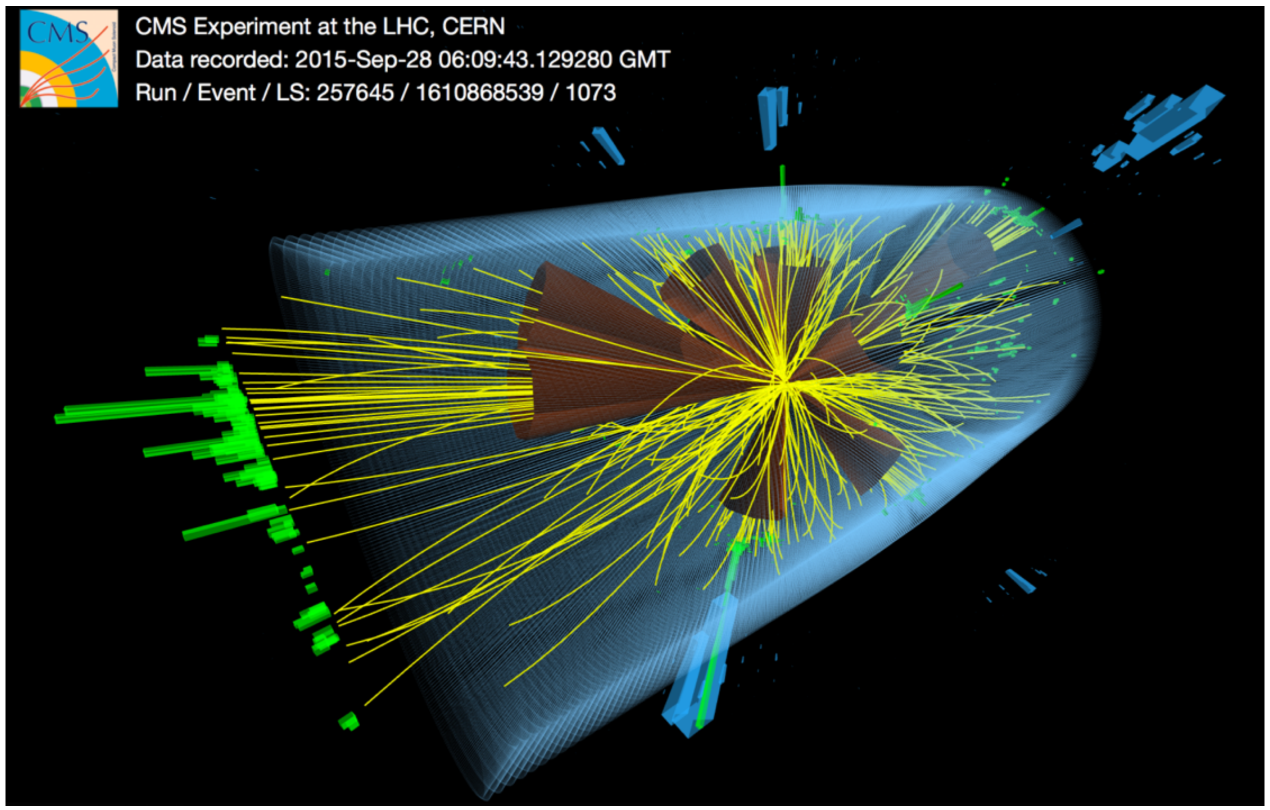
1. Begin with list of particles
2. Define metrics (a = -1, 0, 1 for k_T, Cambridge-Aachen(CA), anti-k_T)

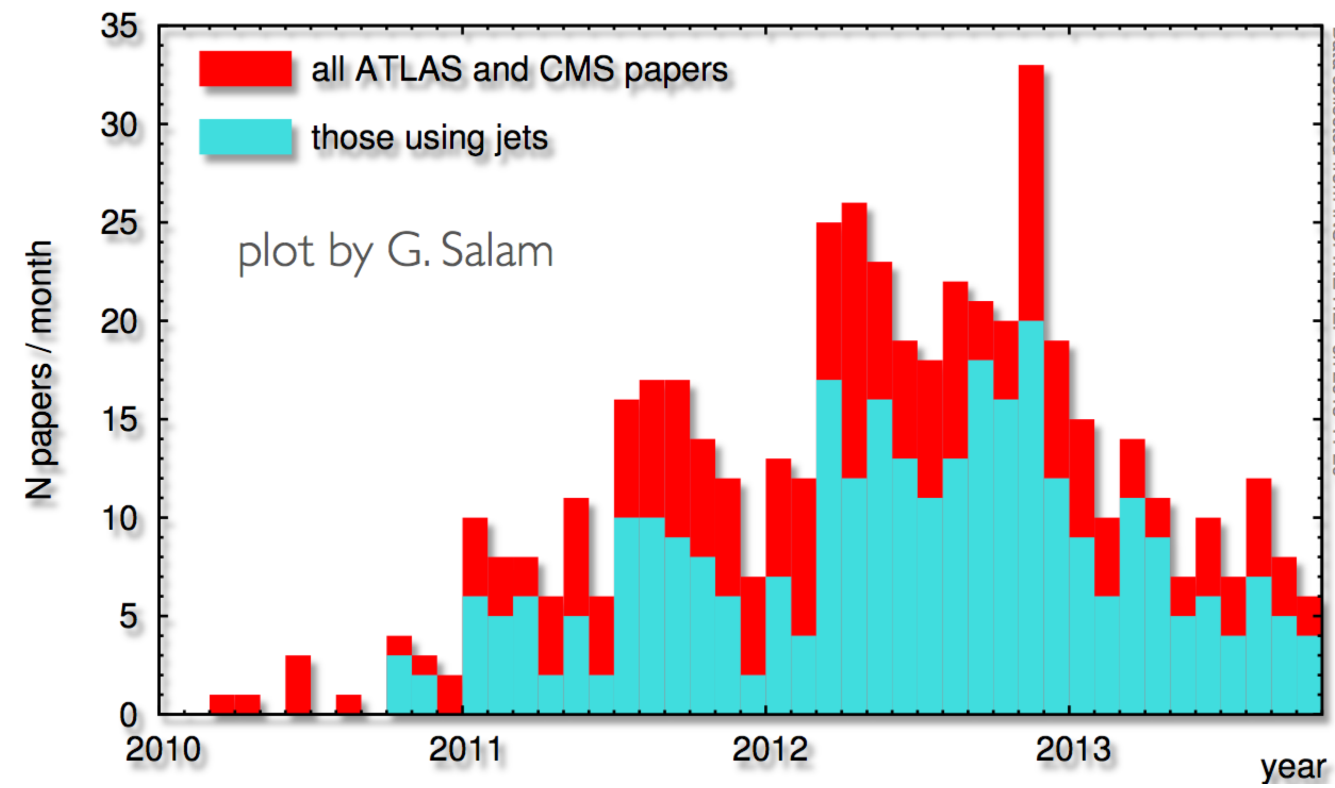
$$d_{ij} = \frac{\min\left(p_{T_i}^{2a}, p_{T_j}^{2a}\right)}{R^2}\left[(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2\right]$$
$$d_i = p_{T_i}^{2a}$$

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

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

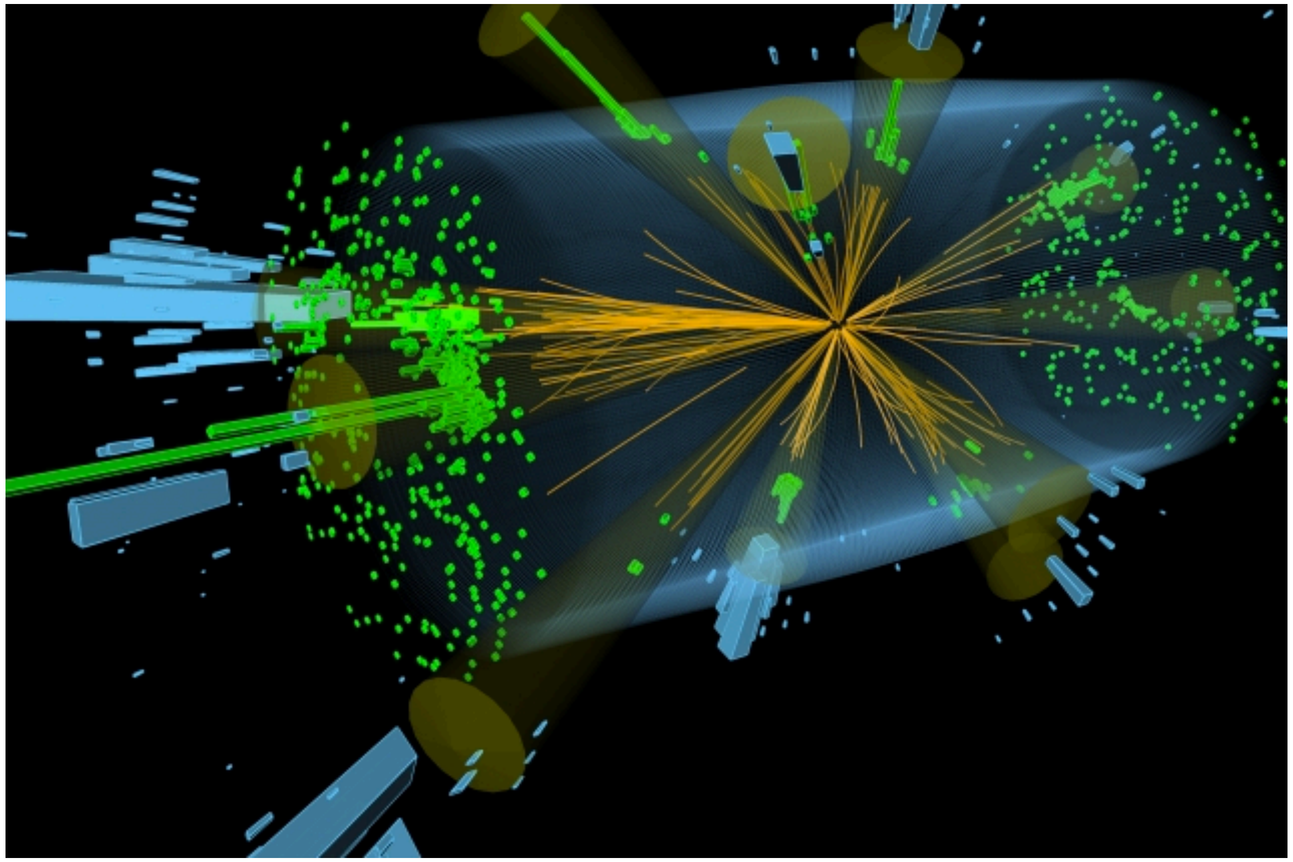


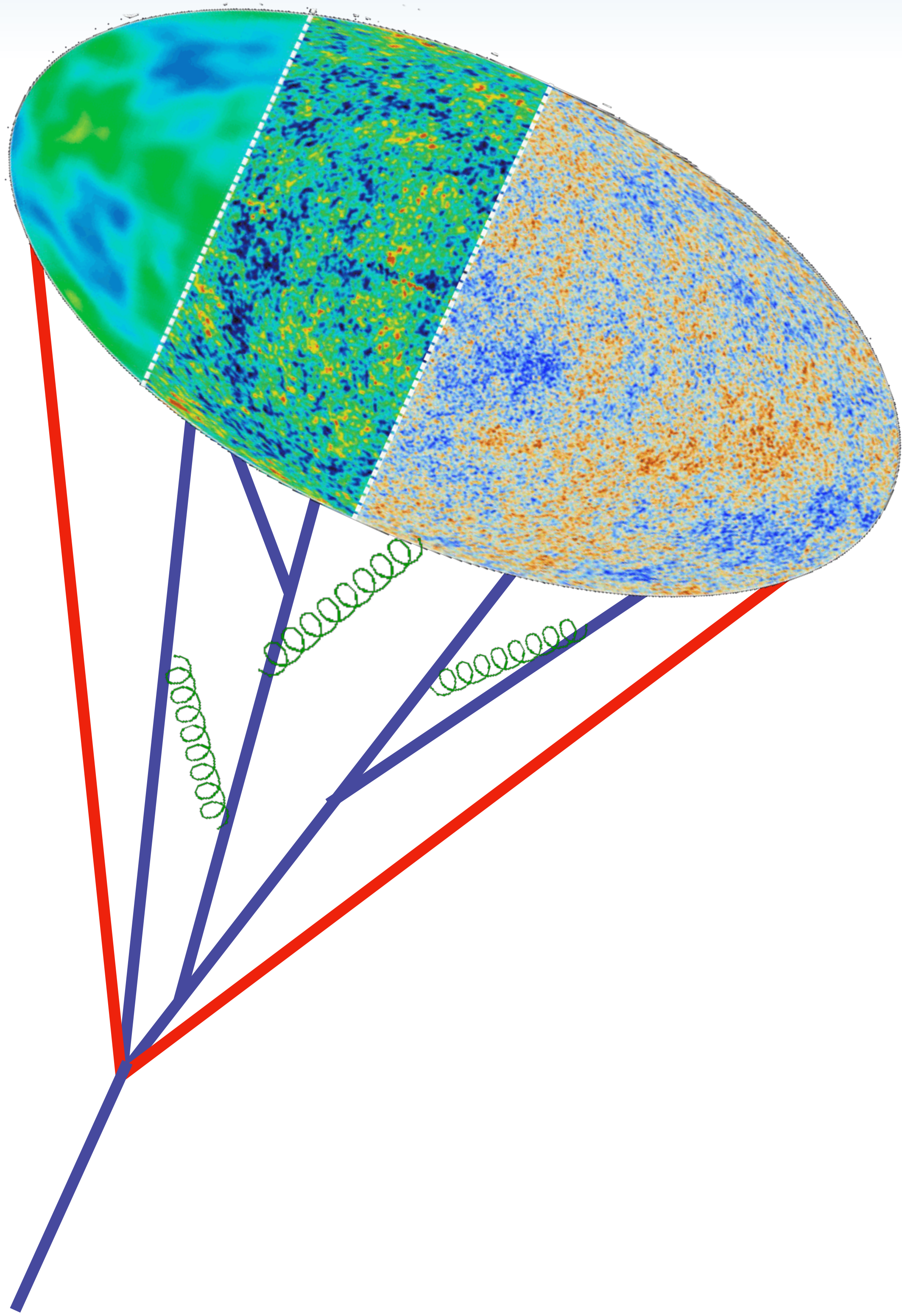


- Jets are produced copiously at the LHC

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

Internal structure of Jets





- **Precise determination of the internal structures of jets**

Jet substructures and characteristic scales

Single prong observables

- Jet angularities
- Energy-energy correlations
- Jet shape

Multi-prong observables

- N-subjettiness
- D_2

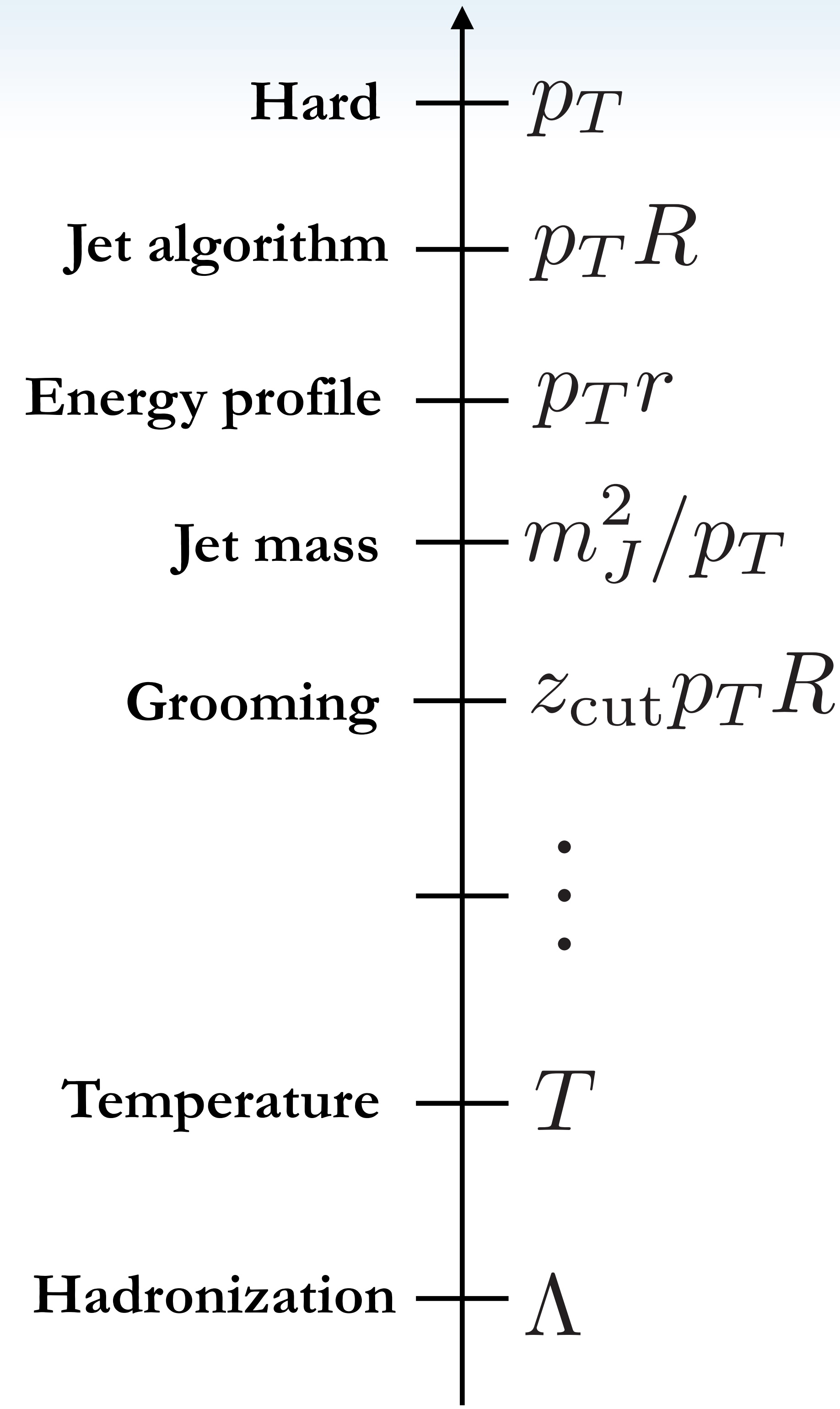
IRC unsafe observables

- Hadron in jet
- Multiplicities
- Jet charge

Groomed observables

- All of the above
- Observables characterizing grooming (SD): $z_g, \quad \theta_g = R_g/R$

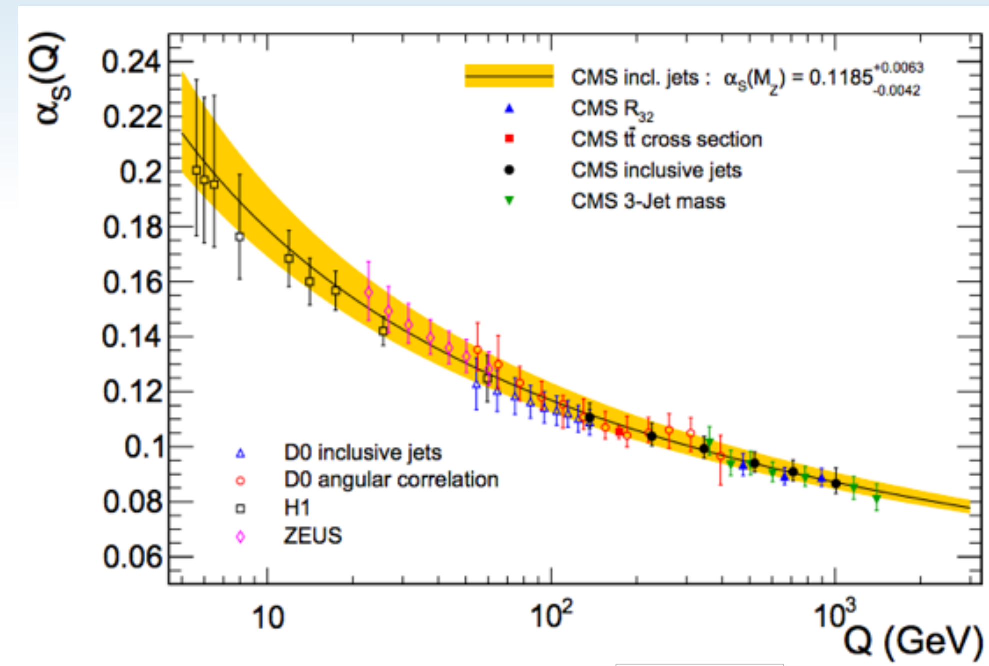
and many more



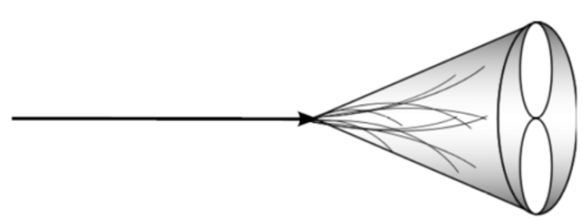
Application of jet studies at the LHC

- **Precision probe of QCD**

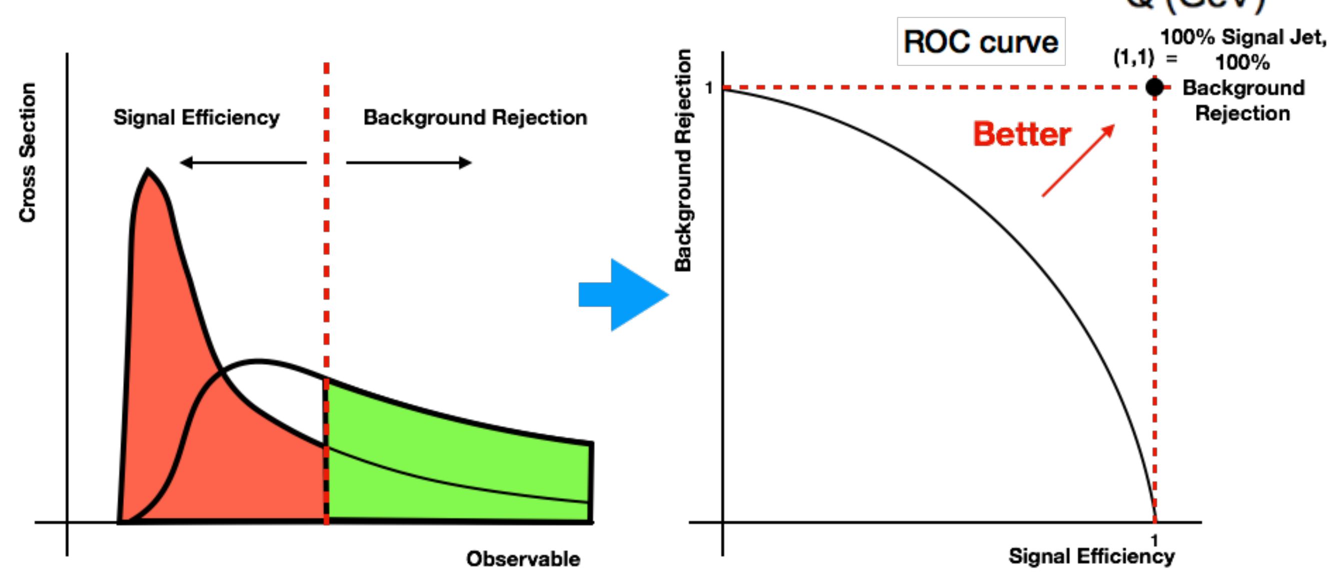
process	sensitivity to PDFs
W asymmetry	→ quark flavour separation
W and Z production (differential)	→ valence quarks
W+c production	→ strange quark
Drell-Yan (DY): high invariant mass	→ sea quarks, high-x
Drell-Yan (DY): low invariant mass	→ low-x
W,Z +jets	→ gluon medium-x
Inclusive jet and di-jet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



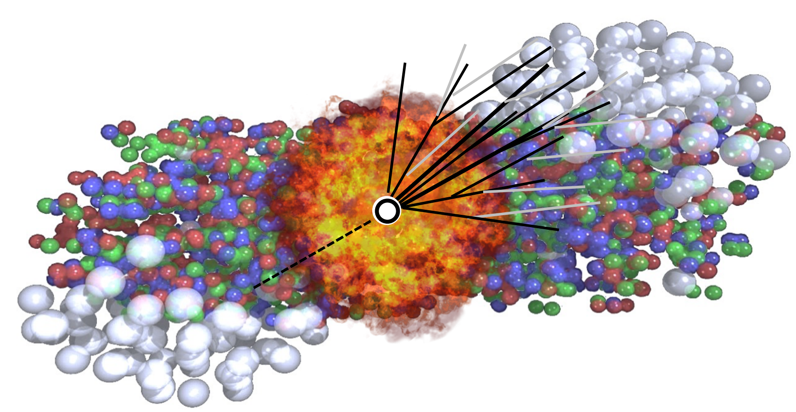
- **Constrain BSM Models**



Fat jet from BSM signal



- **Probe of quark gluon plasma**

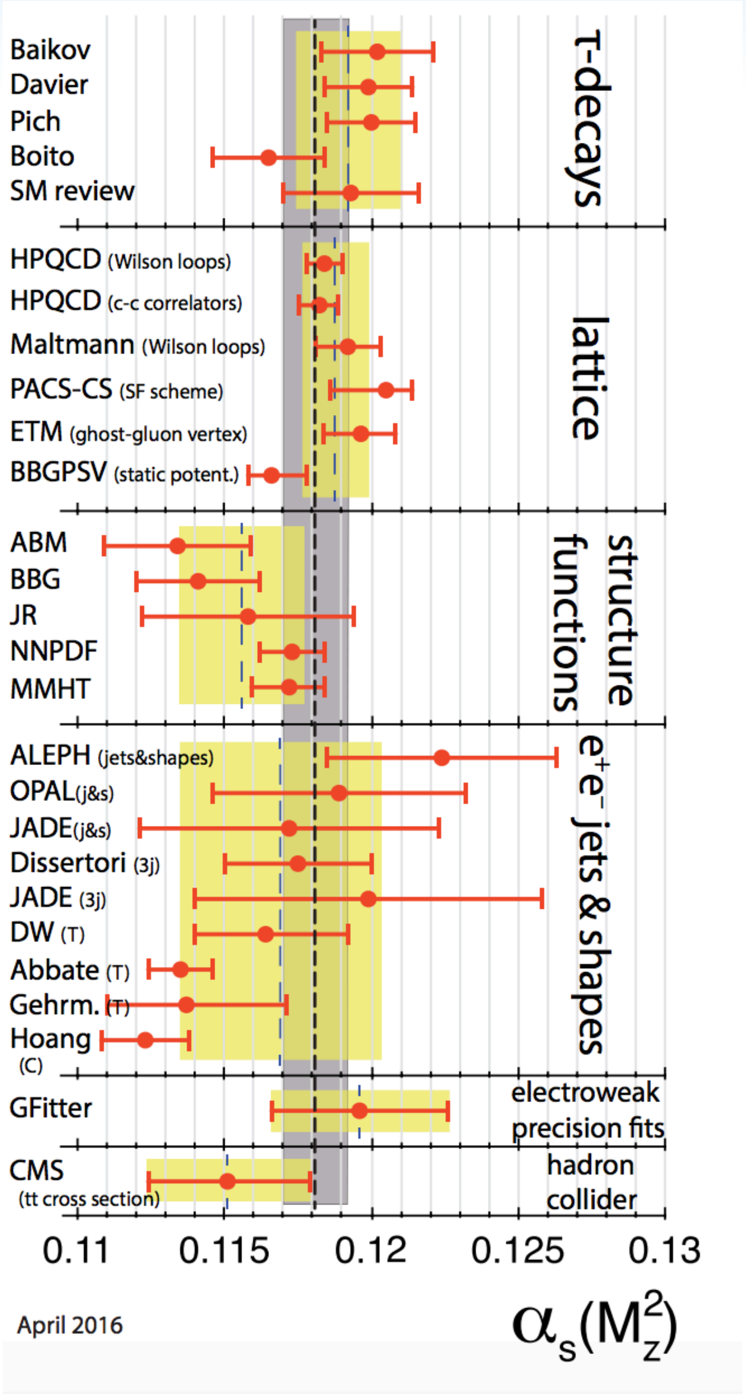


and many more

Jet substructure tools

Some applications more relevant to this workshop :

- Determination of PDFs — Inclusive Jets
- α_s extraction — Jet angularity
- Boosted boson discrimination / low-mass resonance searches — $D_2,\ \tau_{21}$
- Top quark mass determination — Heavy quark jet mass



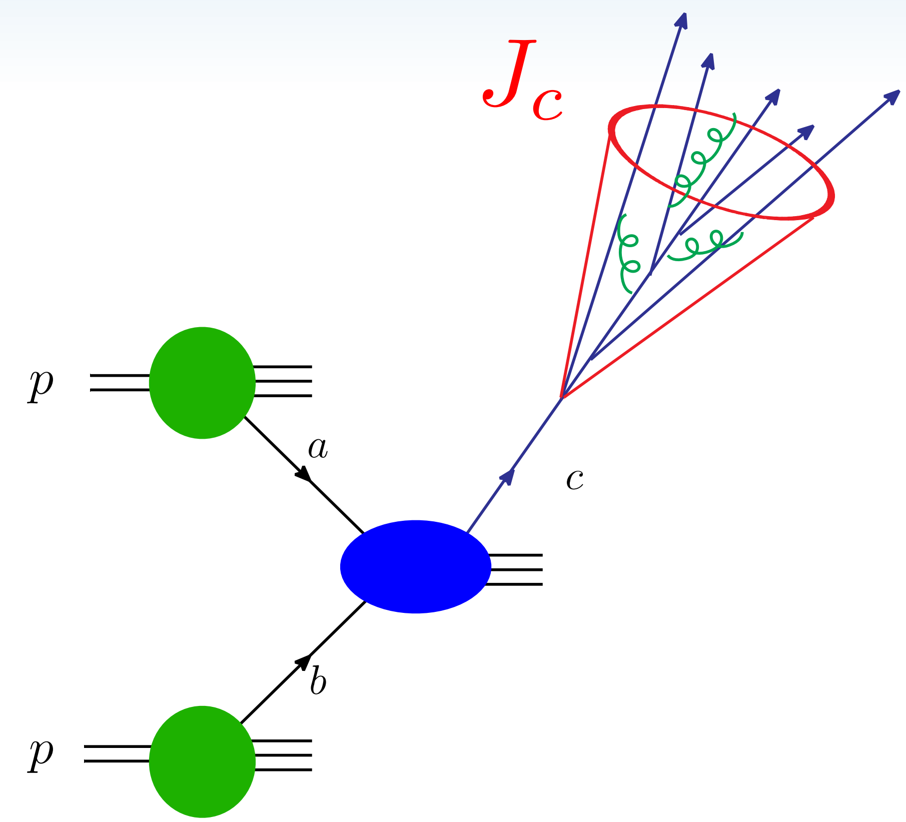
QCD factorization

Inclusive jet production $pp \to \text{jet} + X$

$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \boxed{J_c}$$

Λ_{QCD} $\quad p_T \quad p_T R$

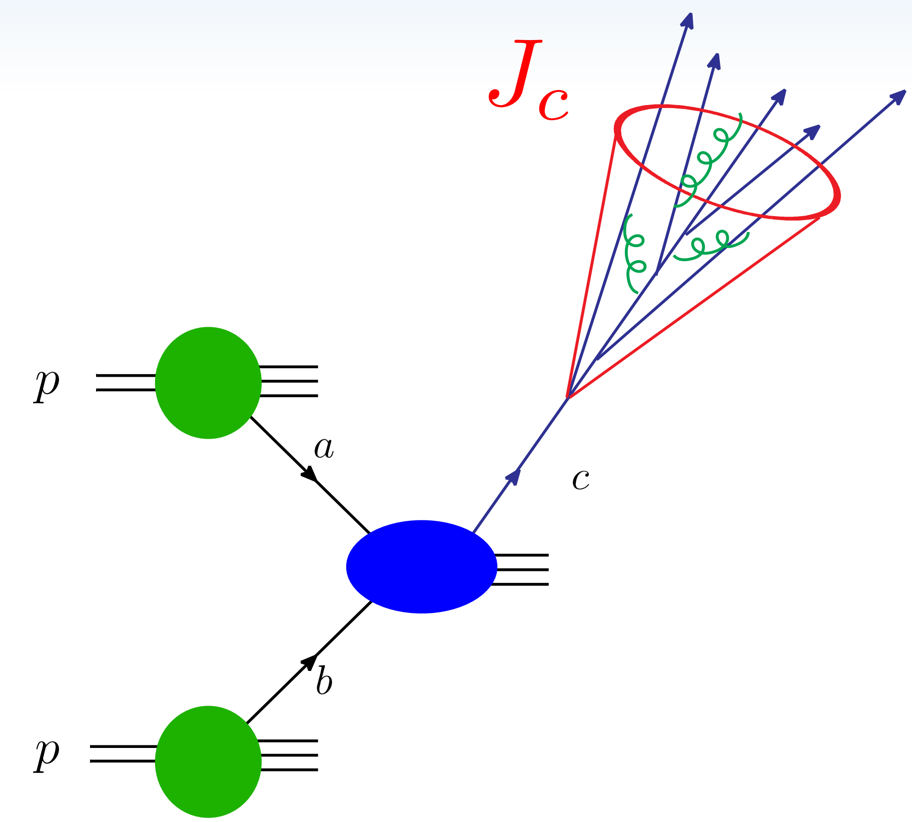
$$\boxed{\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \boxed{D_c^h}}$$



Also exclusive processes and $pp \to Z/\gamma + \text{jet} + X$

Dasgupta, Dreyer, Salam, Soyez `15
Kaufmann, Mukherjee, Vogelsang `15
Kang, Ringer, Vitev `16
Dai, Kim, Leibovich `16

QCD factorization



Inclusive jet production $pp \to \text{jet} + X$

$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

Λ_{QCD} $\quad p_T \quad p_T R$

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

Also exclusive processes and $pp \to Z/\gamma + \text{jet} + X$

$\mu_H \sim p_T$

$\mu_J \sim p_T R$

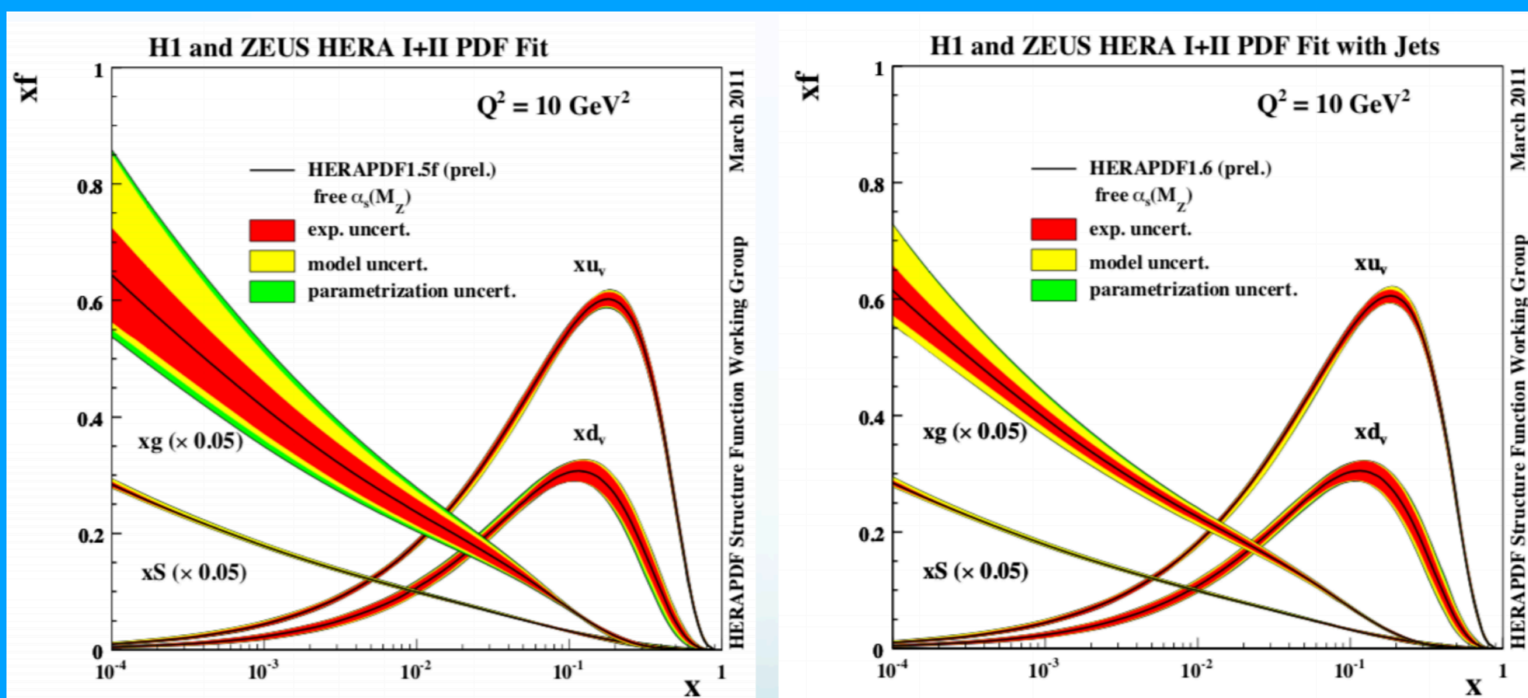
$$\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j$$

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

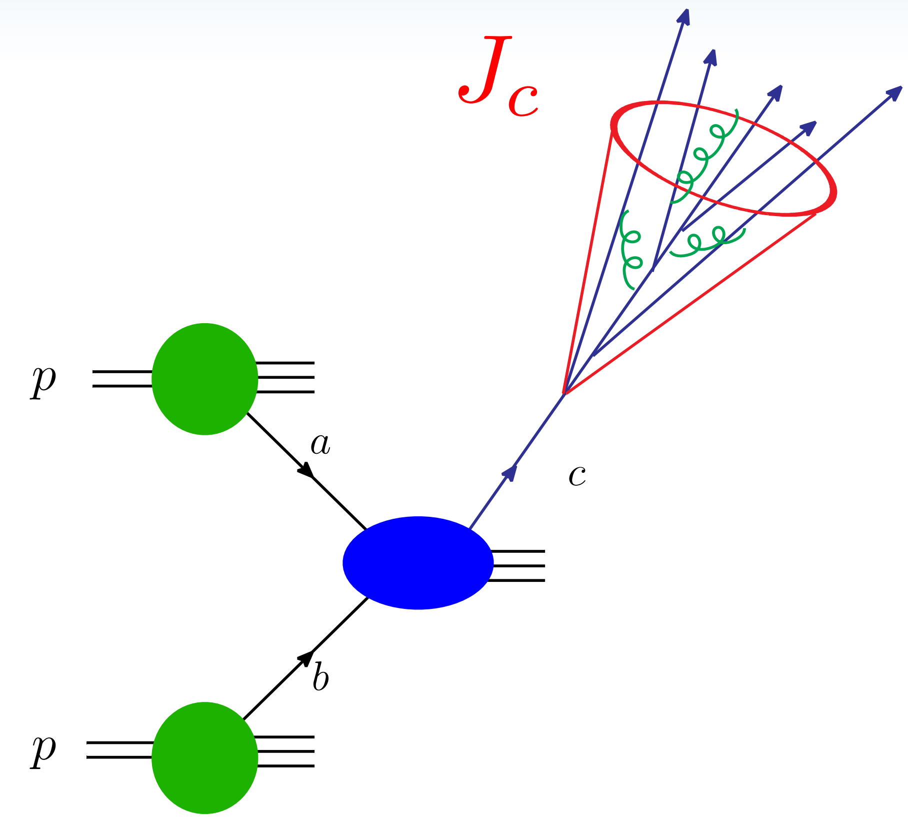
$\alpha_s^n \ln^n R$ **resummation**

Dasgupta, Dreyer, Salam, Soyez `15
Kaufmann, Mukherjee, Vogelsang `15
Kang, Ringer, Vitev `16
Dai, Kim, Leibovich `16

Determination of PDFs

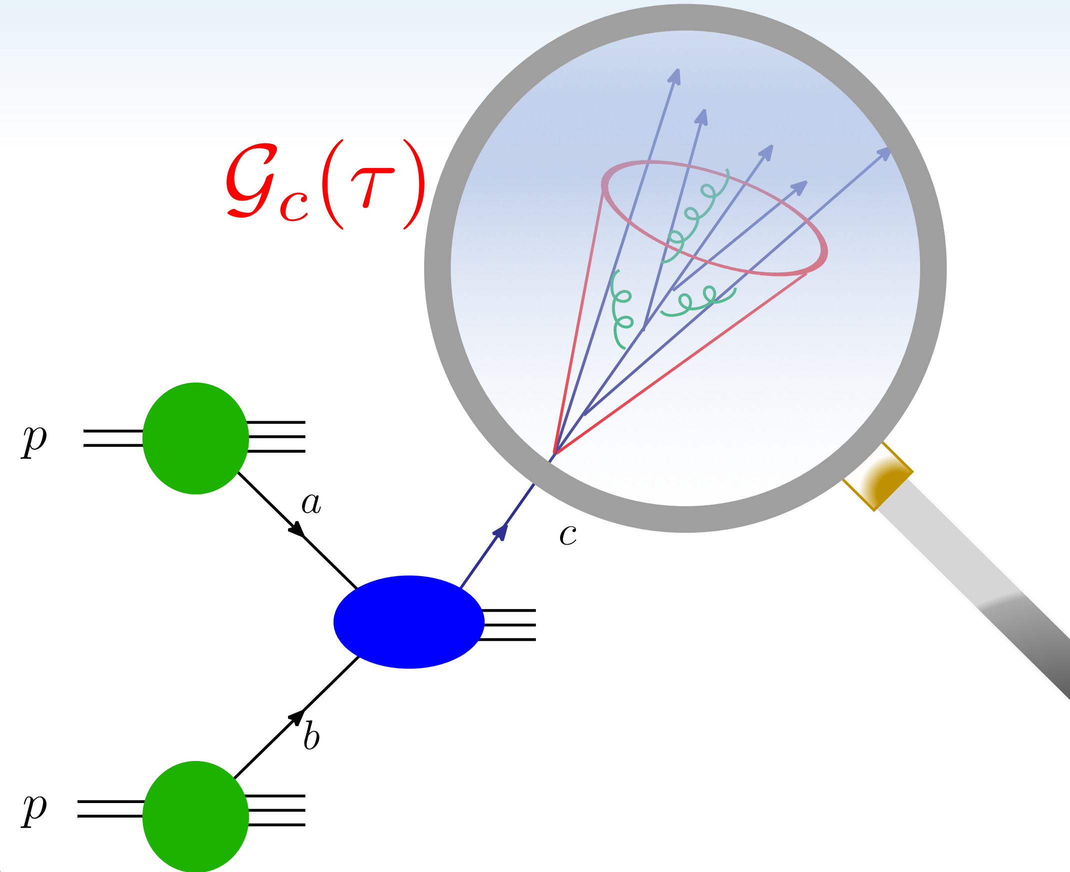


(HERA, but similar conclusion for the pp)



- Sensitivity to gluon pdfs.
- One less NP function to fit compared to inclusive hadron

QCD factorization



Inclusive jet production $pp \to \mathrm{jet} + X$

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} \underset{\Lambda_{\mathrm{QCD}}}{f_a \otimes f_b} \otimes \underset{p_T}{H_{ab}^c} \otimes \underset{p_T R}{\boxed{J_c}}$$

Jet substructure τ

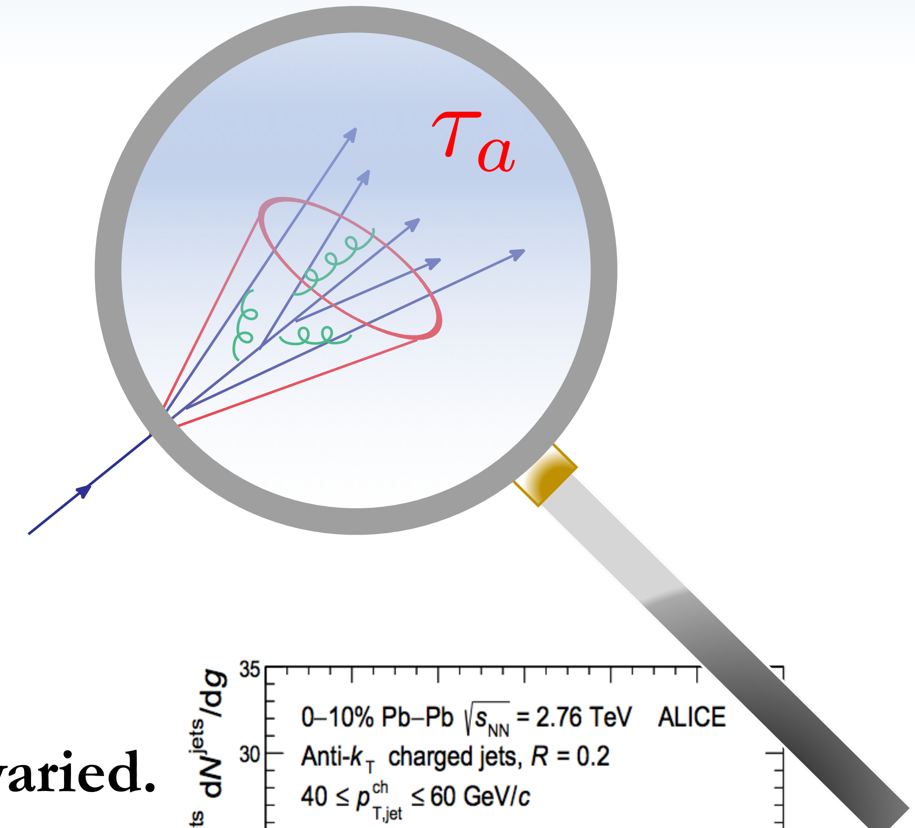
$$\frac{d\sigma^{pp\to \mathrm{jet}(\tau)X}}{dp_T d\eta d\tau} = \sum_{a,b,c} \underset{\Lambda_{\mathrm{QCD}}}{f_a \otimes f_b} \otimes \underset{p_T}{H_{ab}^c} \otimes \underset{p_T R}{\boxed{\mathcal{G}_c(\tau)}}$$

and other scale(s) depending on τ

Jet angularity

- A generalized class of IR safe observables ($-\infty < a < 2$), angularity (applied to jet):

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

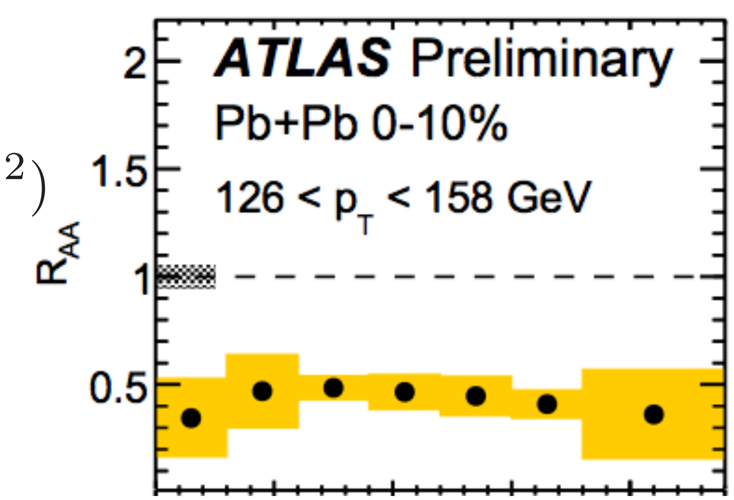


Sterman et al. `03, `08,
Hornig, C. Lee, Ovanesyan `09, Ellis, Vermilion, Walsh, Hornig, C.Lee `10,
Chien, Hornig, C. Lee `15, Hornig, Makris, Mehen `16, Kang, KL, Ringer `18

- **Varying sensitivity to collinear radiations as the parameter is varied.**

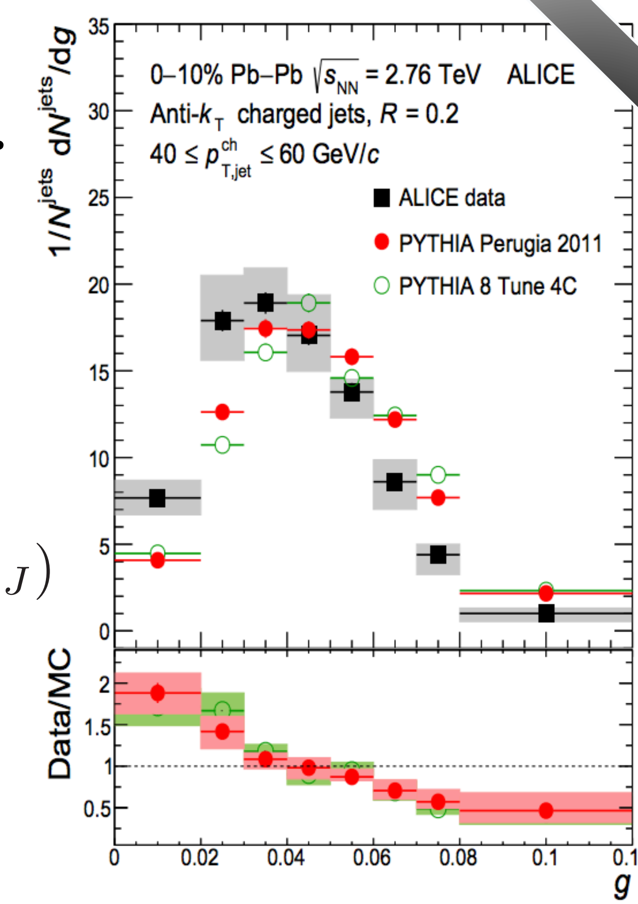
$a = 0$

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

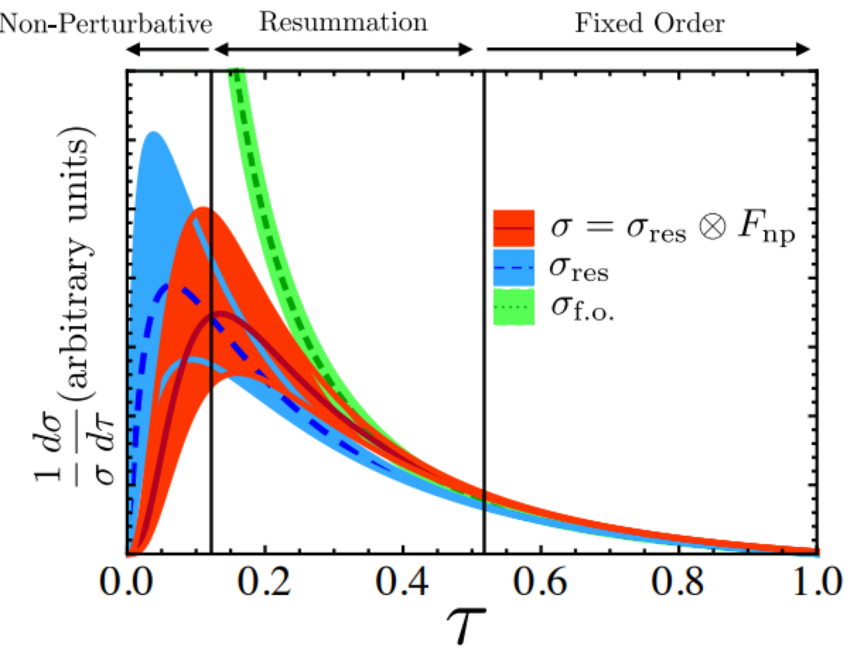


$a = 1$

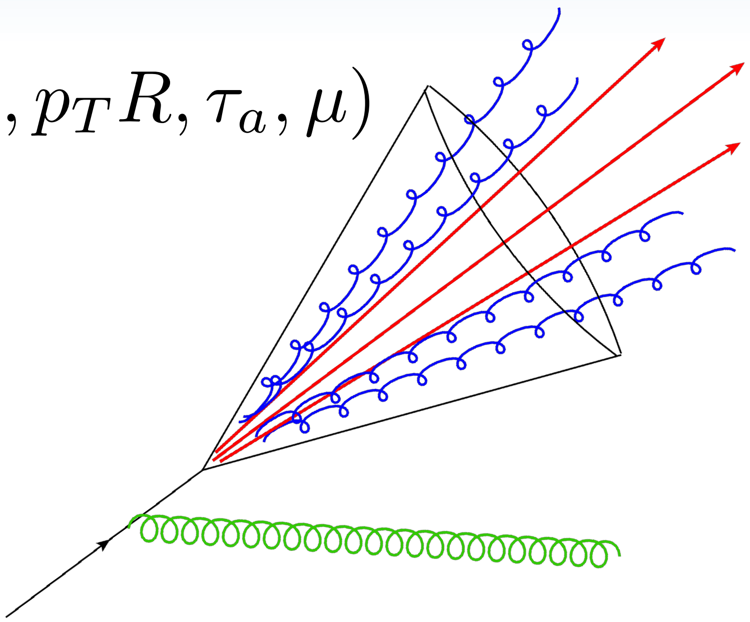
$$g(\text{girth}) = \frac{1}{p_T} \sum_{i \in J} p_{T,i} \, (\Delta R_{iJ})$$



Factorization for the jet angularity



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



Relevant modes for $\tau_a \ll R^{2-a}$

$\tau_a \sim z\,\theta^{2-a}$

Collinear

$z_c \sim 1$ $\quad \theta_c \sim \tau_a^{\frac{1}{2-a}}$ $\quad \mu_C \sim p_T \tau_a^{\frac{1}{2-a}}$

(Collinear-)soft

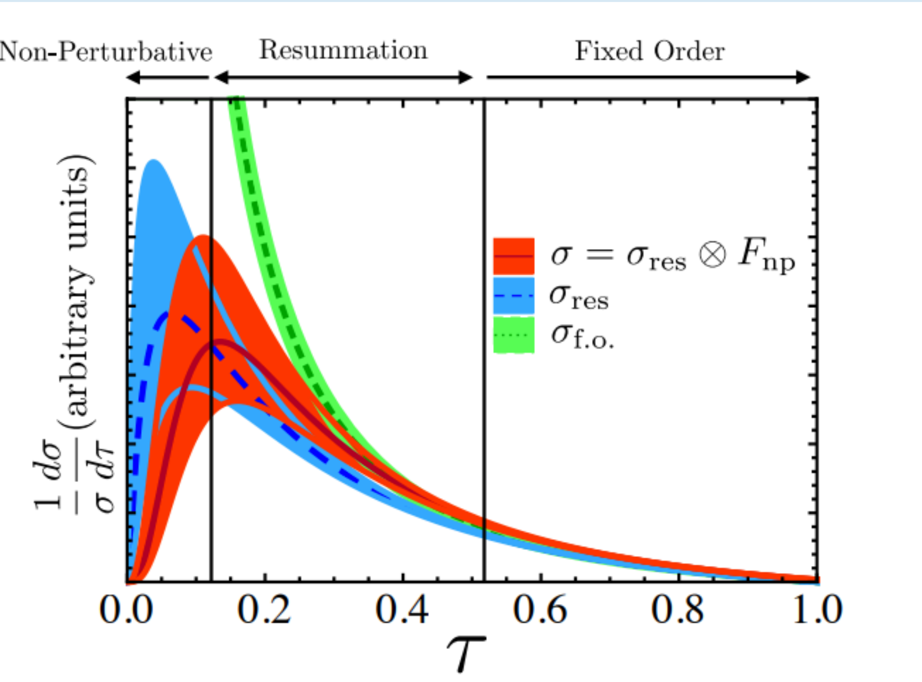
$\theta_s \sim R$ $\quad z_{cs} \sim \frac{\tau_a}{R^{2-a}}$ $\quad \mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$

Hard-collinear

$\theta_{\mathcal{H}} \sim R$ $\quad z_{\mathcal{H}} \sim 1$ $\quad \mu_{\mathcal{H}} \sim p_T R$

Kang, KL, Ringer, arXiv:1801.00790

Factorization for the jet angularity



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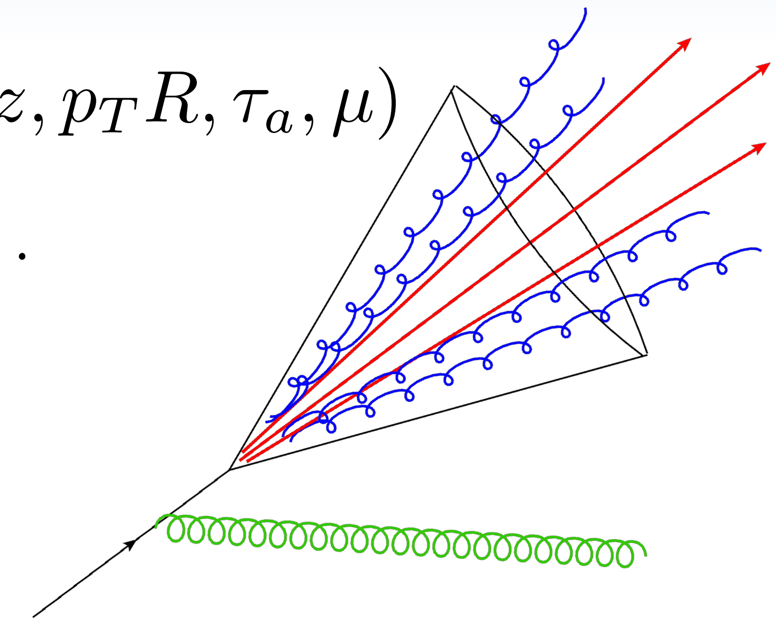
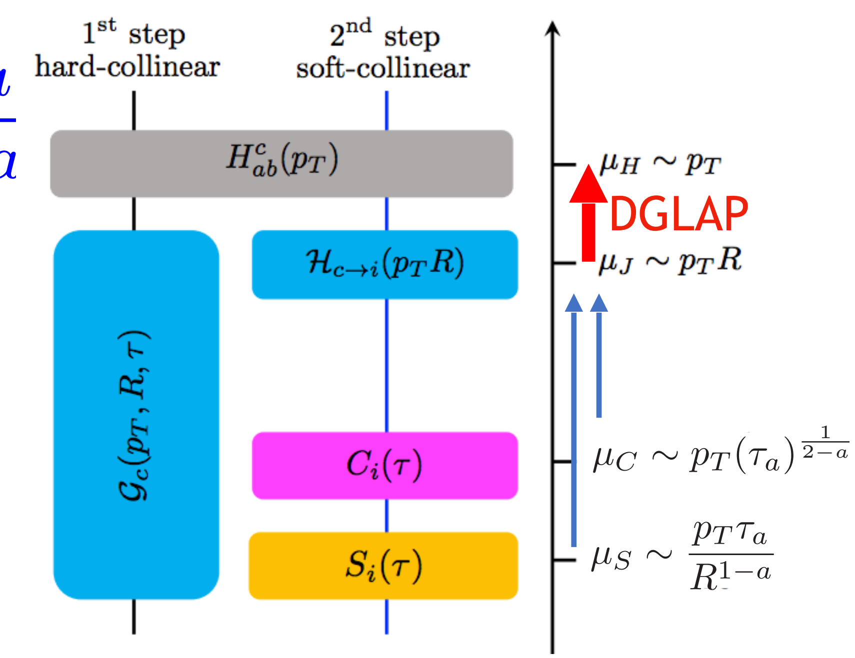


- **The ungroomed case ($\tau_a \ll R^{2-a}$)**

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

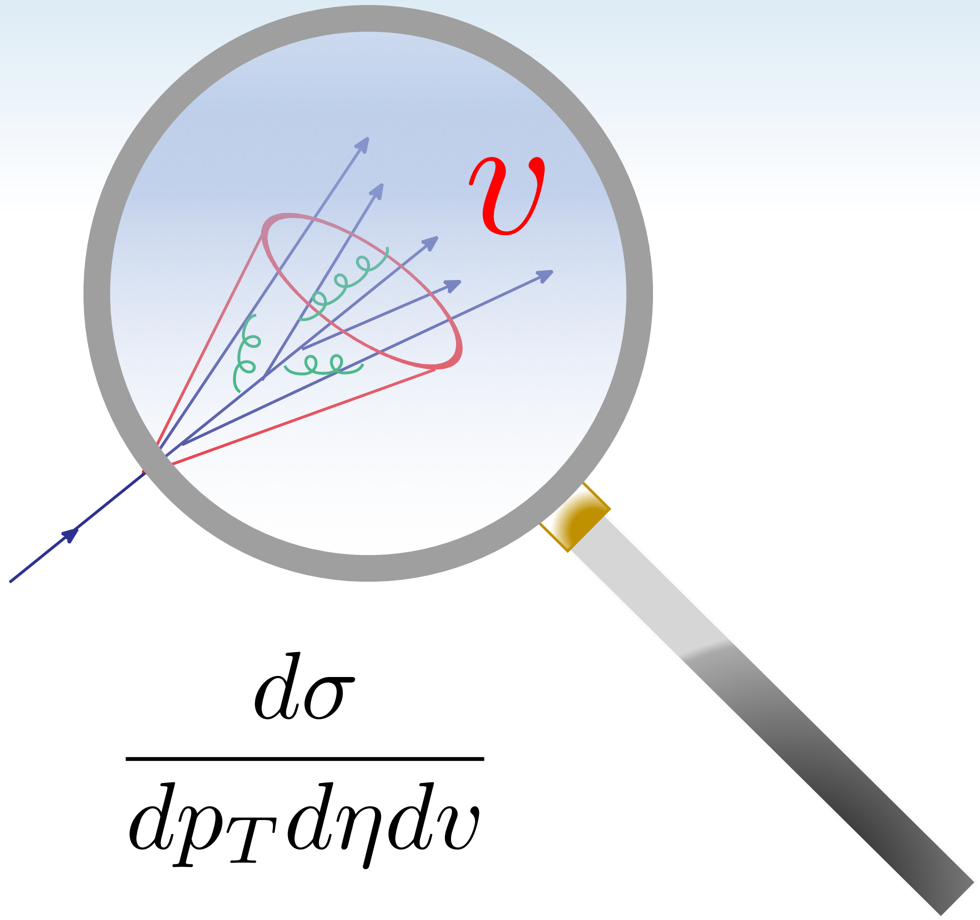
$$p_T R \qquad p_T \tau_a^{\frac{1}{2-a}} \qquad \frac{p_T \tau_a}{R^{1-a}}$$



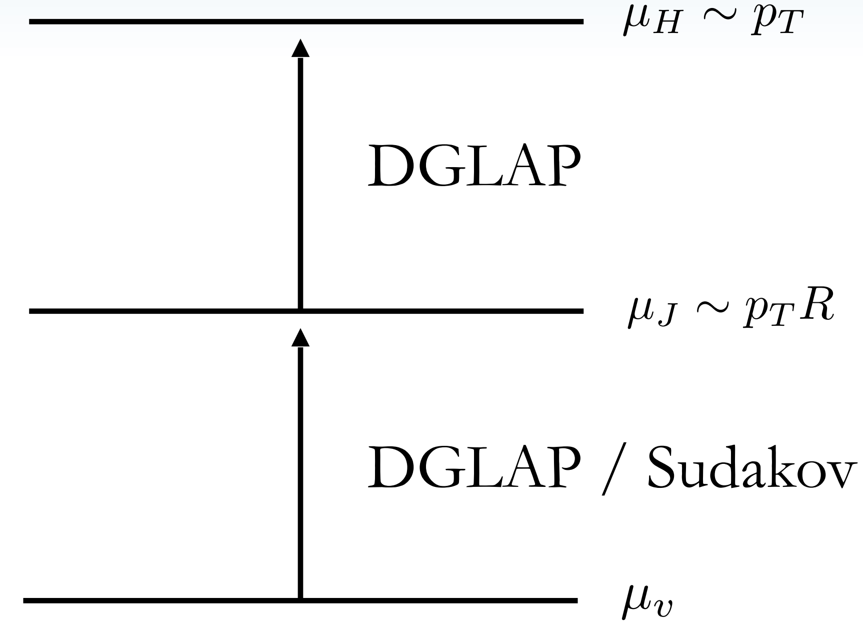
- **Jointly resums large logs** $\alpha_s^n \ln^n R$ **and** $\alpha_s^n \ln^{2n} \tau_a^{\frac{1}{2-a}}/R$

Kang, KL, Ringer, arXiv:1801.00790

Patterns emerging



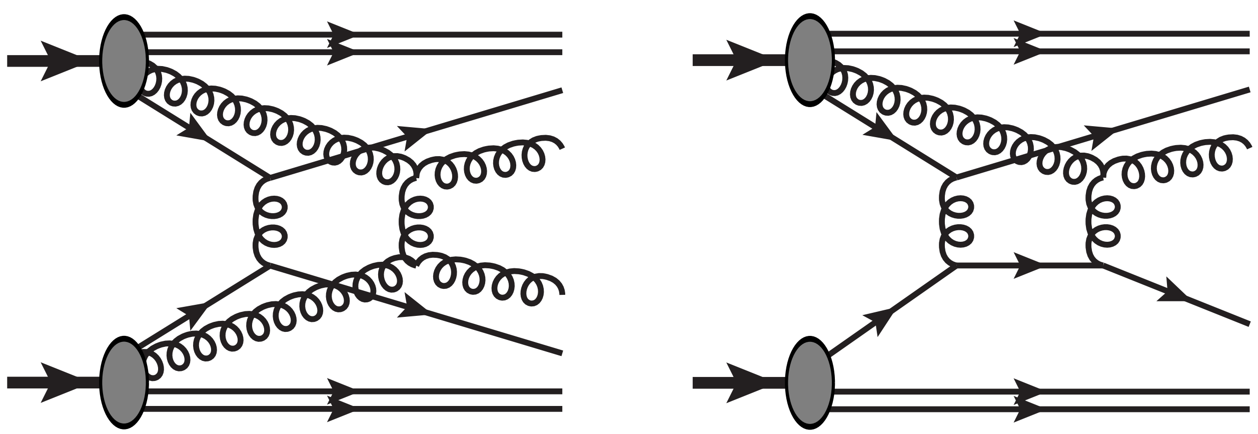
$$\frac{d\sigma}{dp_T\, d\eta\, dv}$$



- 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.

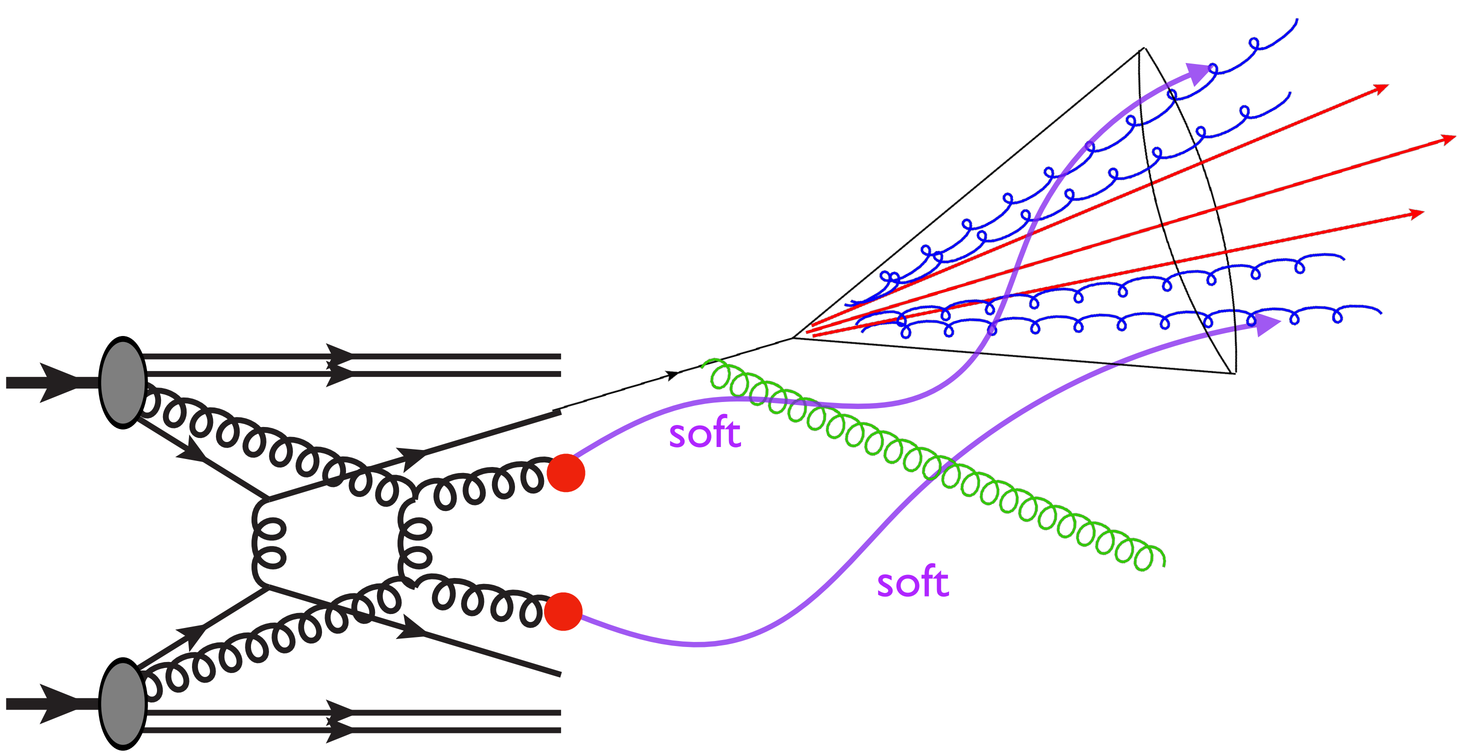
Non-perturbative Effects

- **Non-perturbative effects:**



Figs from P. Bartalini et al. `11

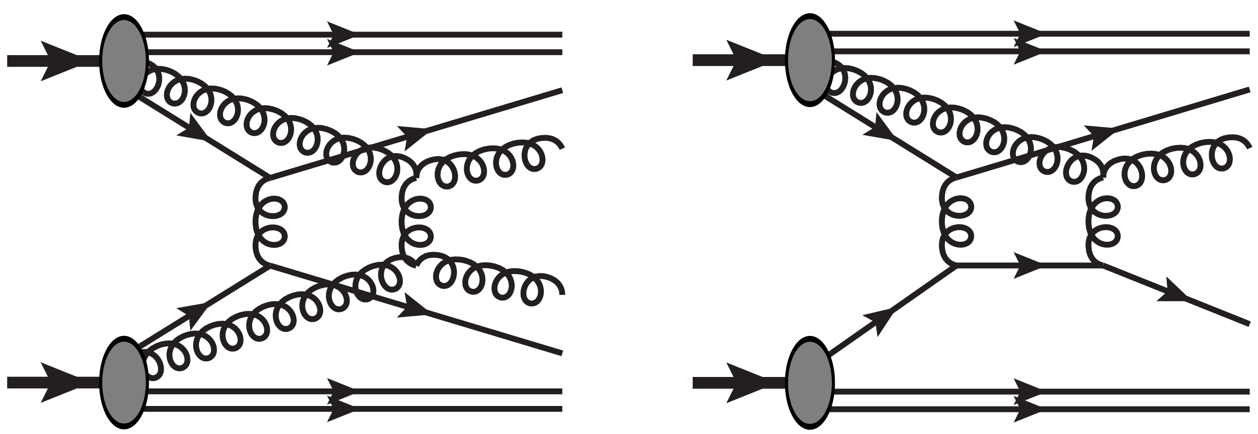
$$\mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$$



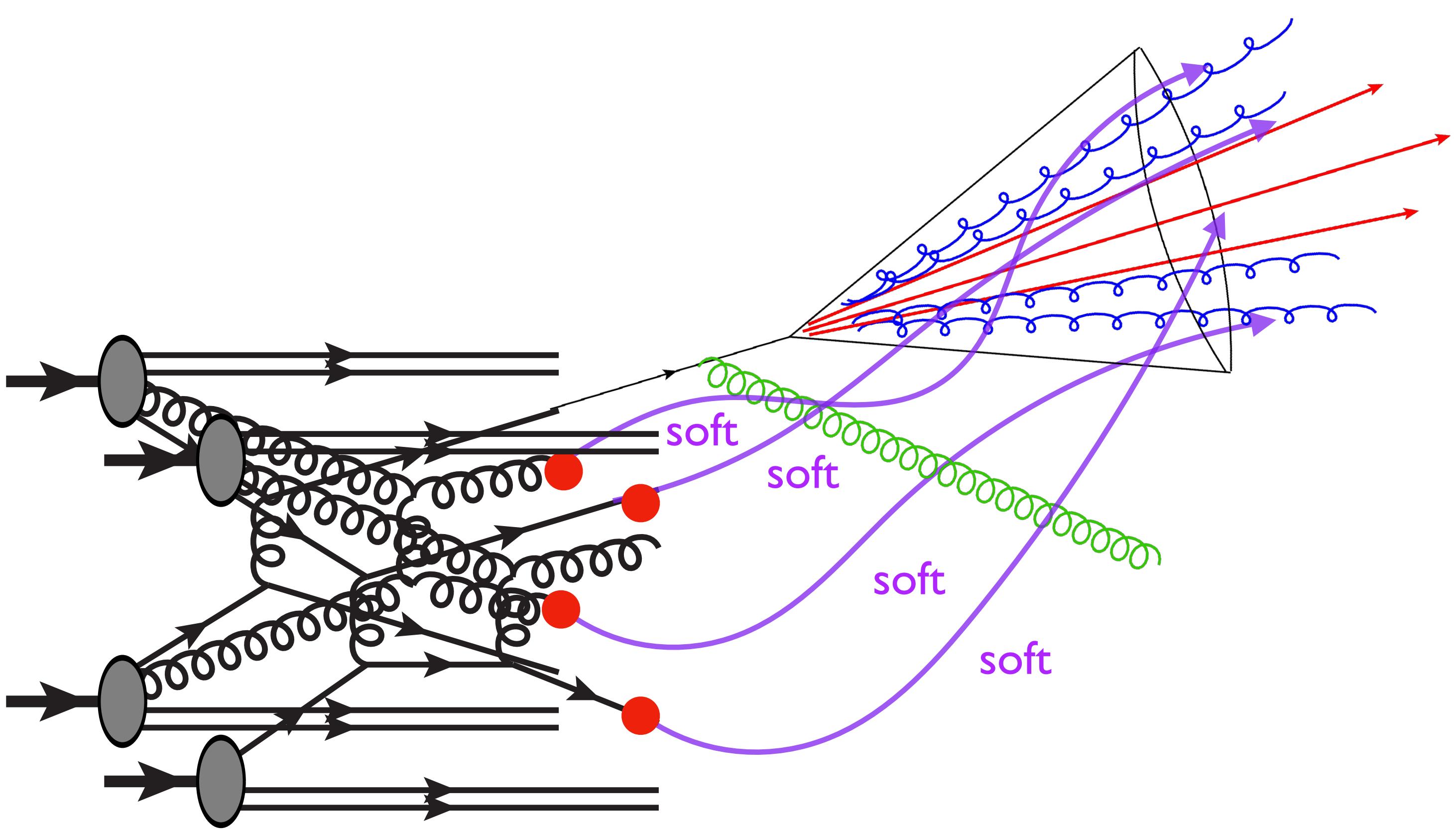
- **Multi-Parton Interactions (MPI) (Underlying Events (UE))**
  Multiple secondary scatterings of partons within the protons may enter and contaminate jet.

Non-perturbative Effects

- Non-perturbative effects:



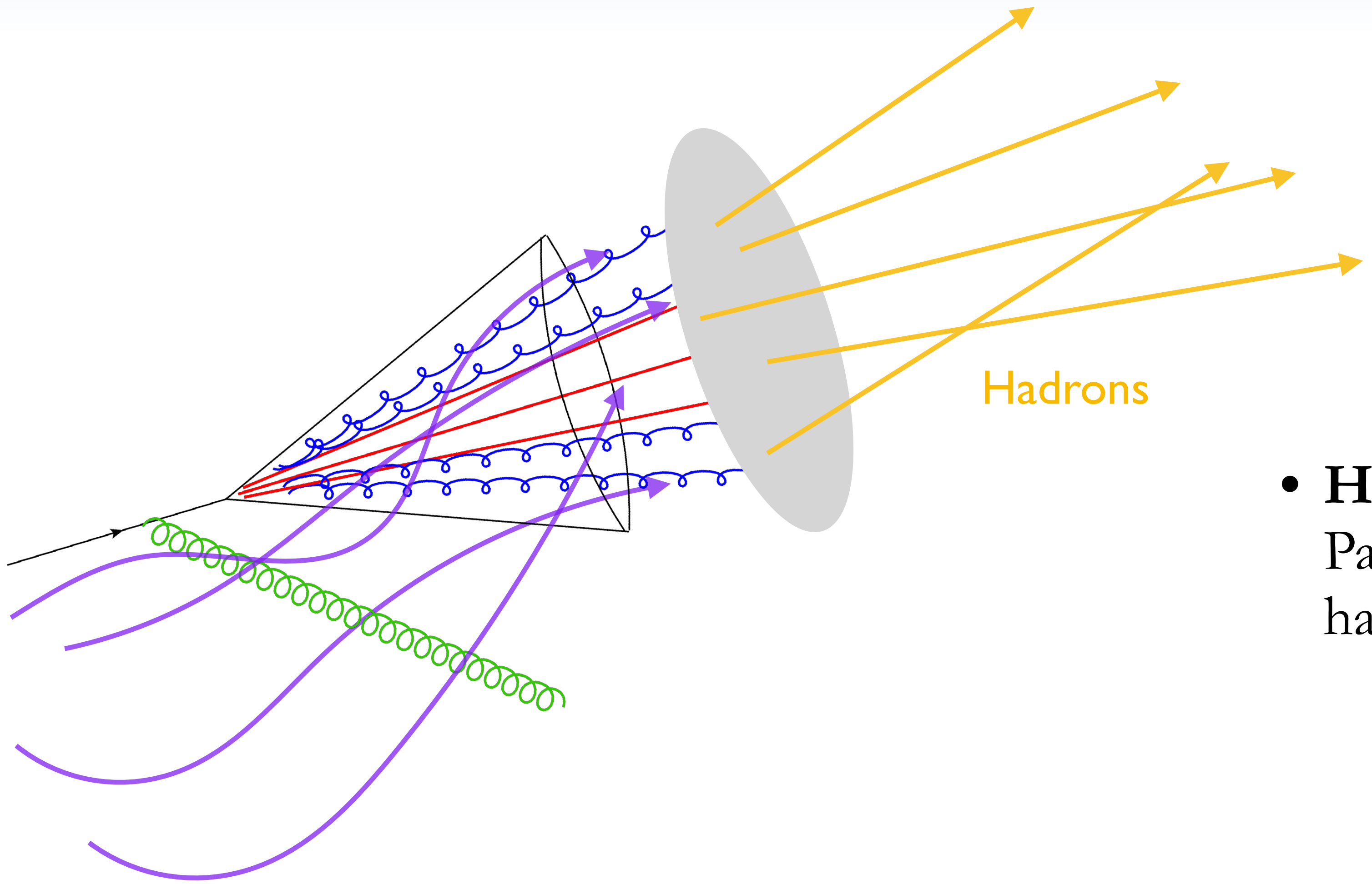
Figs from P. Bartalini et al. `11



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

Non-perturbative Effects

- **Non-perturbative effects:**



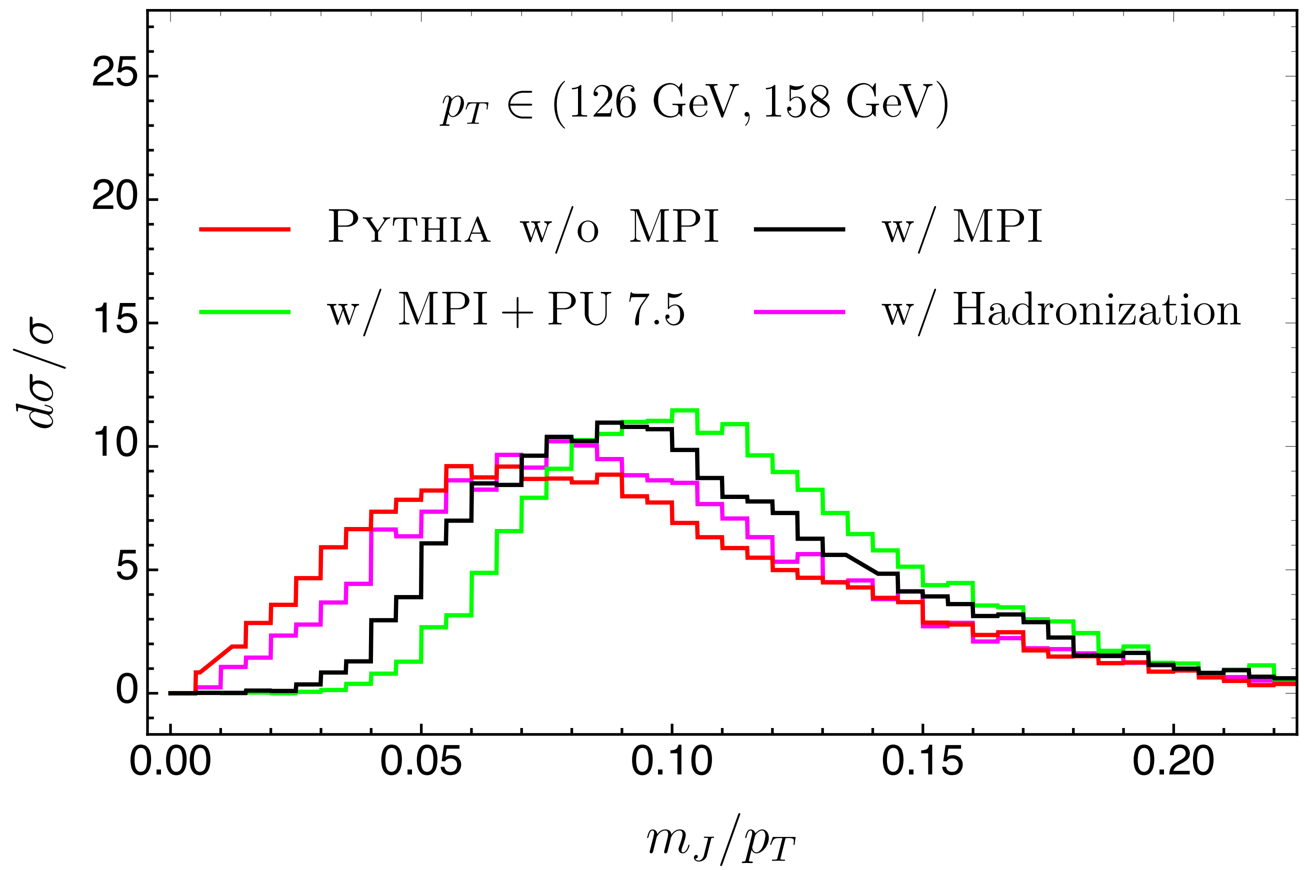
- **Hadronization**
  Partons forming the jet eventually hadronizes.

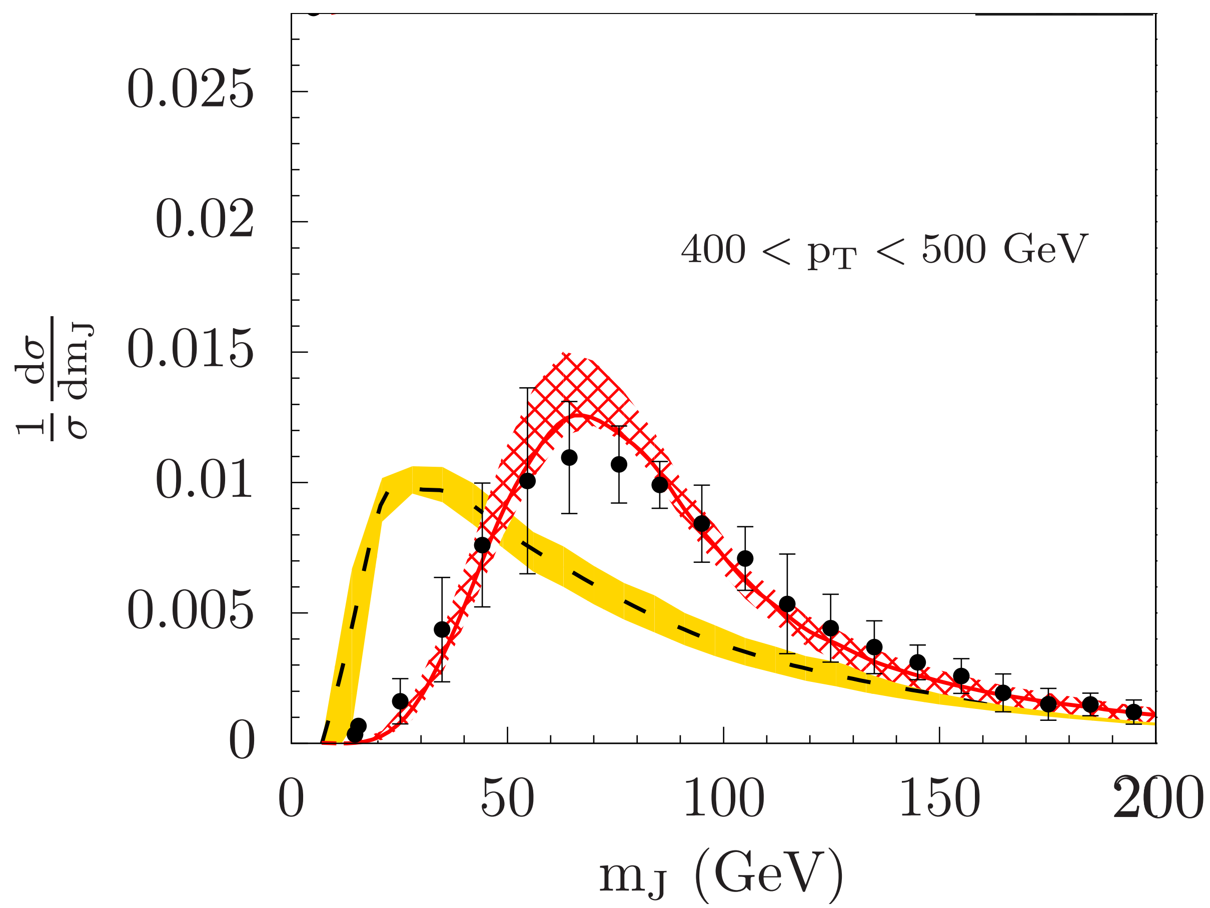
Non-perturbative Effects

$$\frac{d\sigma}{dp_T d\eta d\tau_a} = \frac{d\sigma^{\text{pert}}}{dp_T d\eta d\tau_a} \otimes F_{\text{NP}}$$

$$\mu_S \sim \frac{p_T \tau_a}{R^{1-a}}$$

Large non-perturbative effects:





Non-perturbative Model

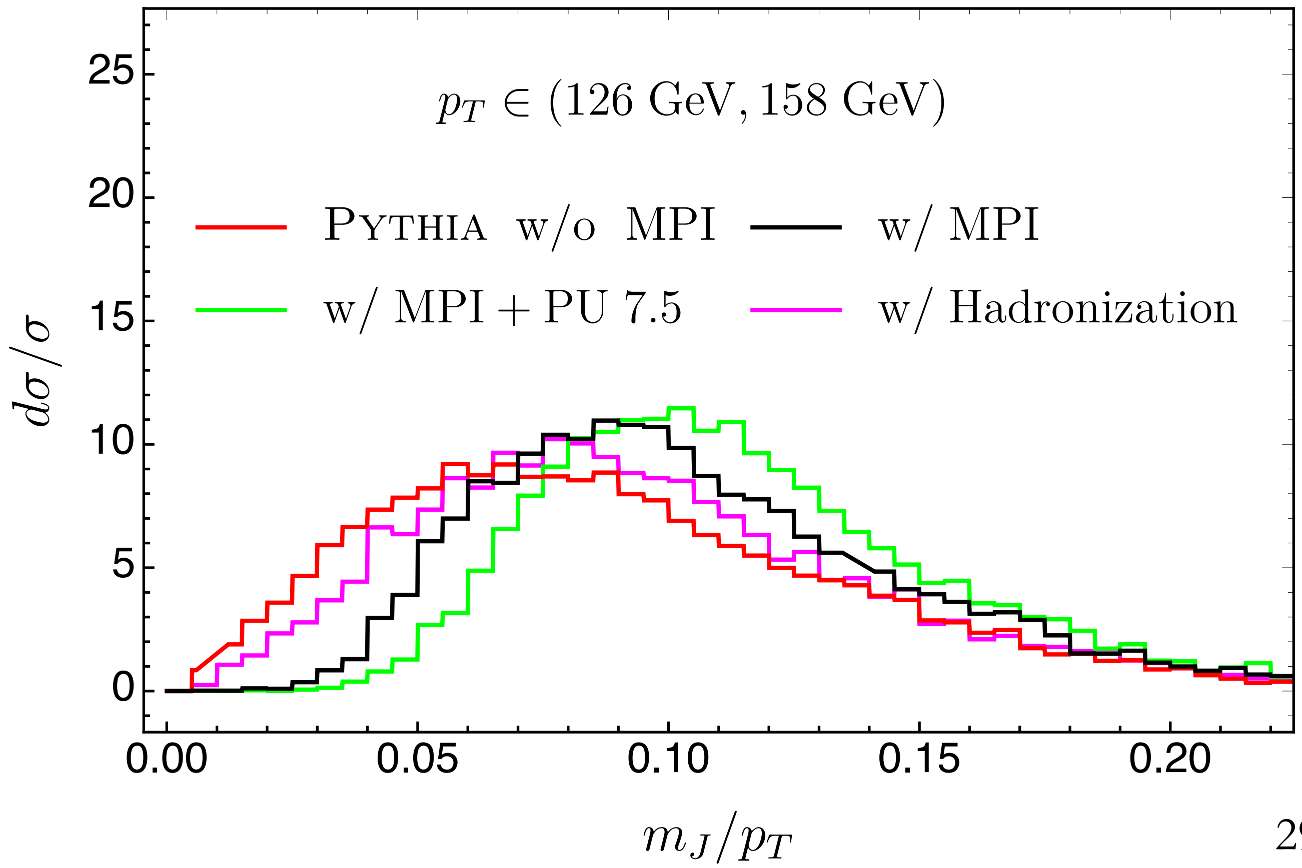
$$\frac{d\sigma}{d\eta dp_T d\tau} = \int dk F_\kappa(k) \frac{d\sigma^{\text{pert}}}{d\eta dp_T d\tau}\left(\tau - \frac{R}{p_T}k\right)$$

- **Single parameter NP shape function :**

Stewart, Tackmann, Waalewijn `15

$$F_\kappa(k) = \left(\frac{4k}{\Omega_\kappa^2}\right)\exp\left(-\frac{2k}{\Omega_\kappa}\right) \qquad \Omega_\kappa = \int dk\, k\, F(k)$$

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

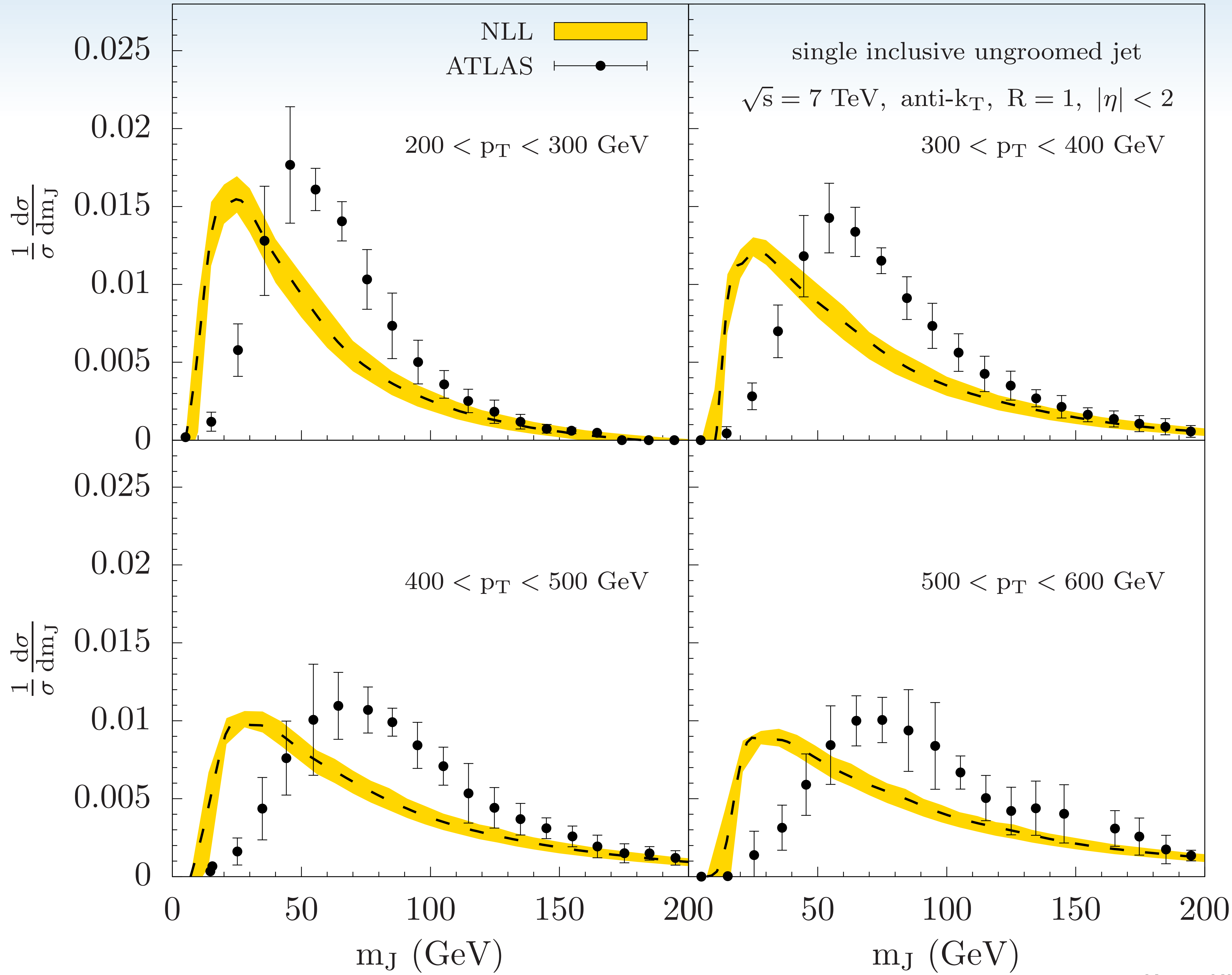


$$\Omega_\kappa = \Omega_\kappa^{\text{had}} + \Omega_\kappa^{\text{MPI}}$$

$\Omega_\kappa^{\text{had}} = \langle 0|\mathcal{O}|0\rangle \sim 1\text{ GeV}$ **is universal.**

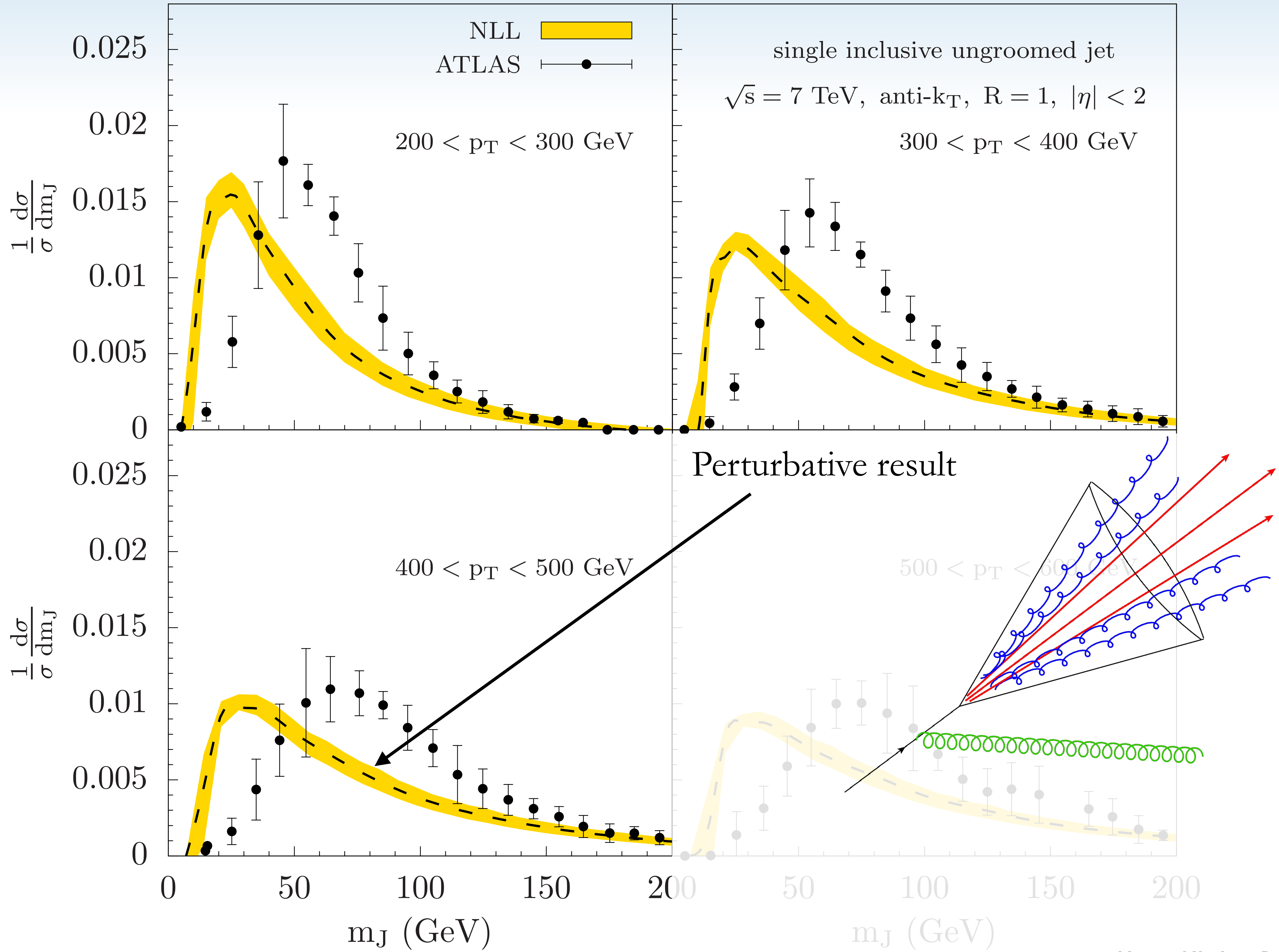
Lee, Sterman `07

Phenomenology



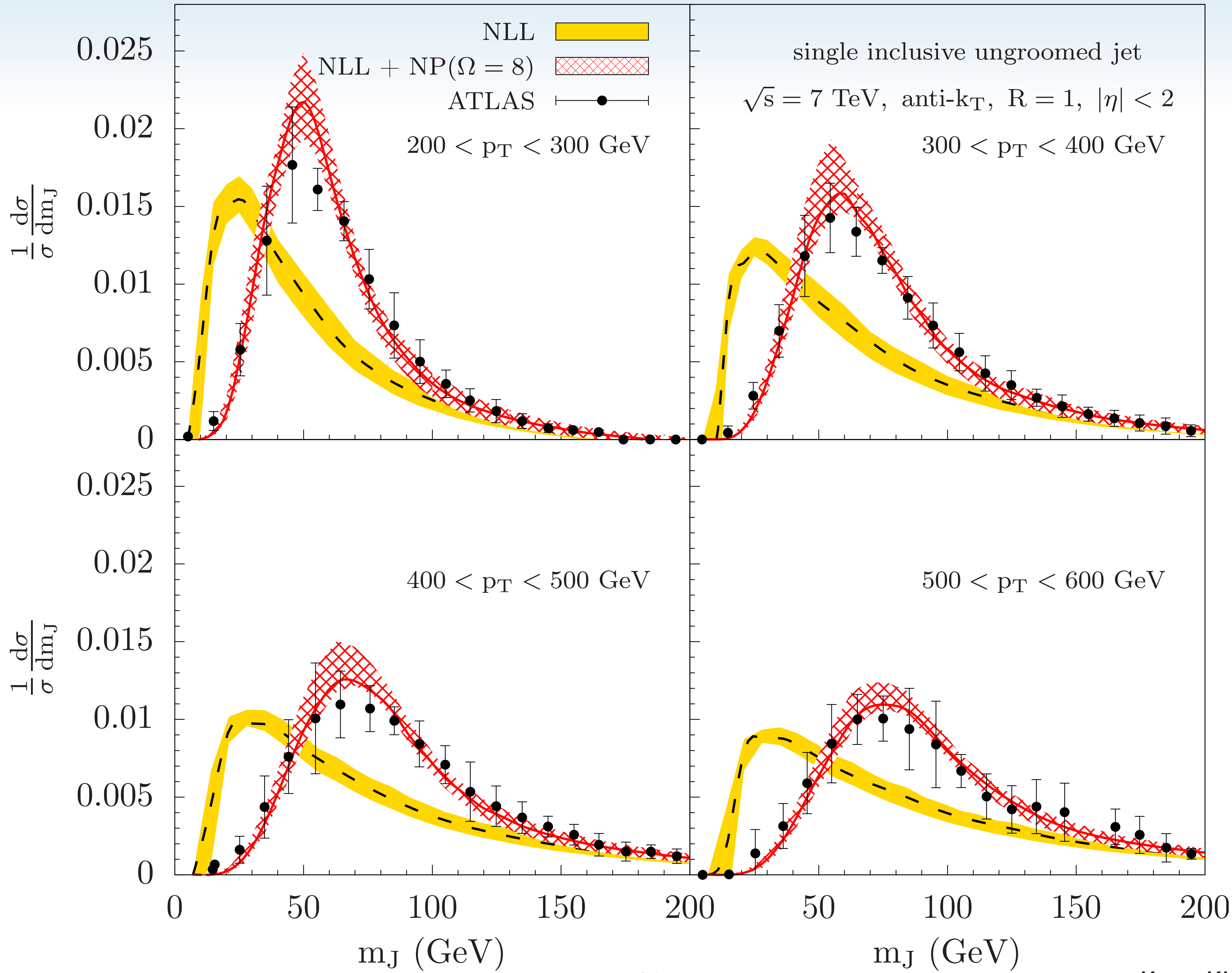
Kang, KL, Liu, Ringer `18

Phenomenology



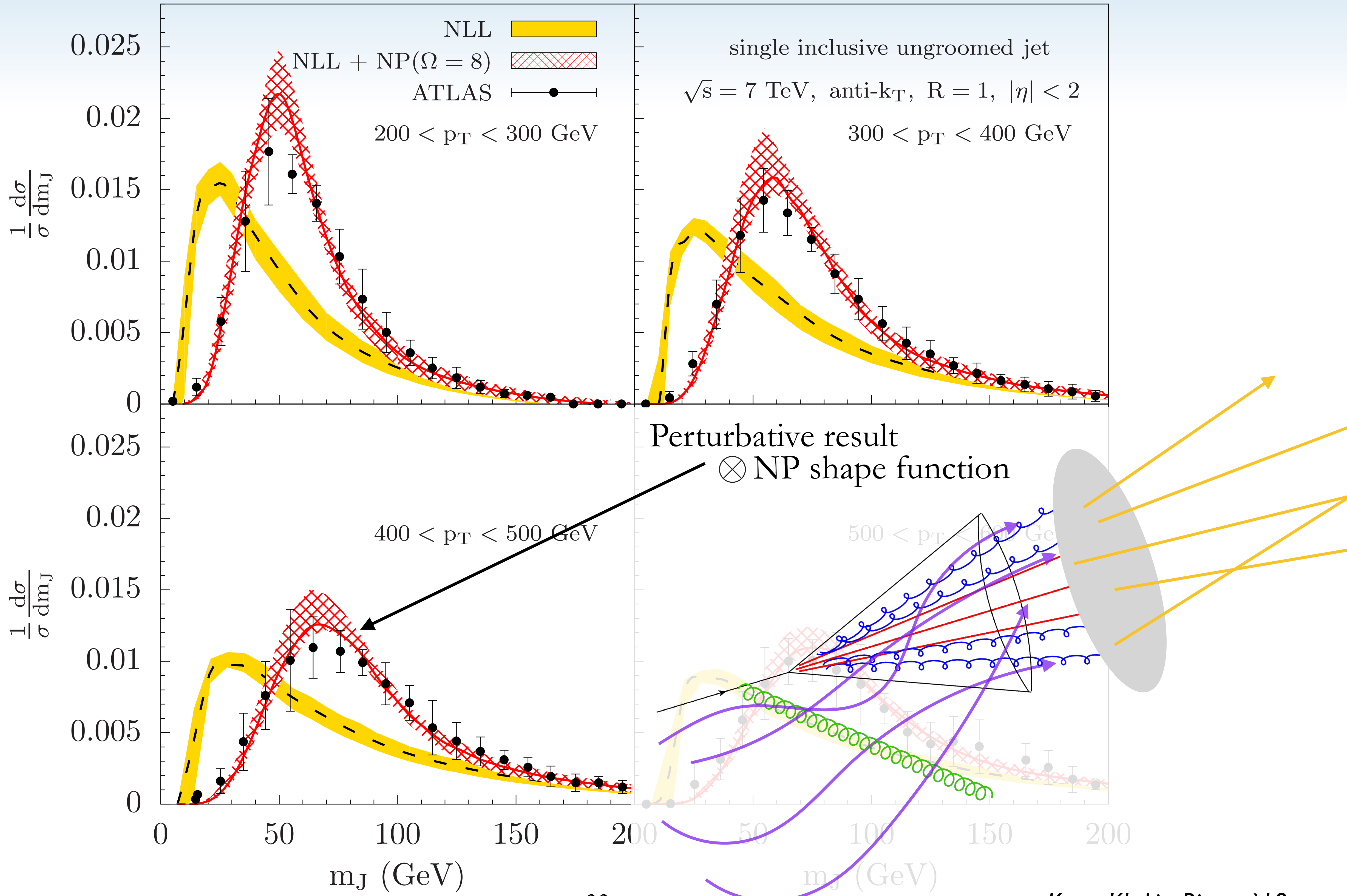
Kang, KL, Liu, Ringer `18

Phenomenology



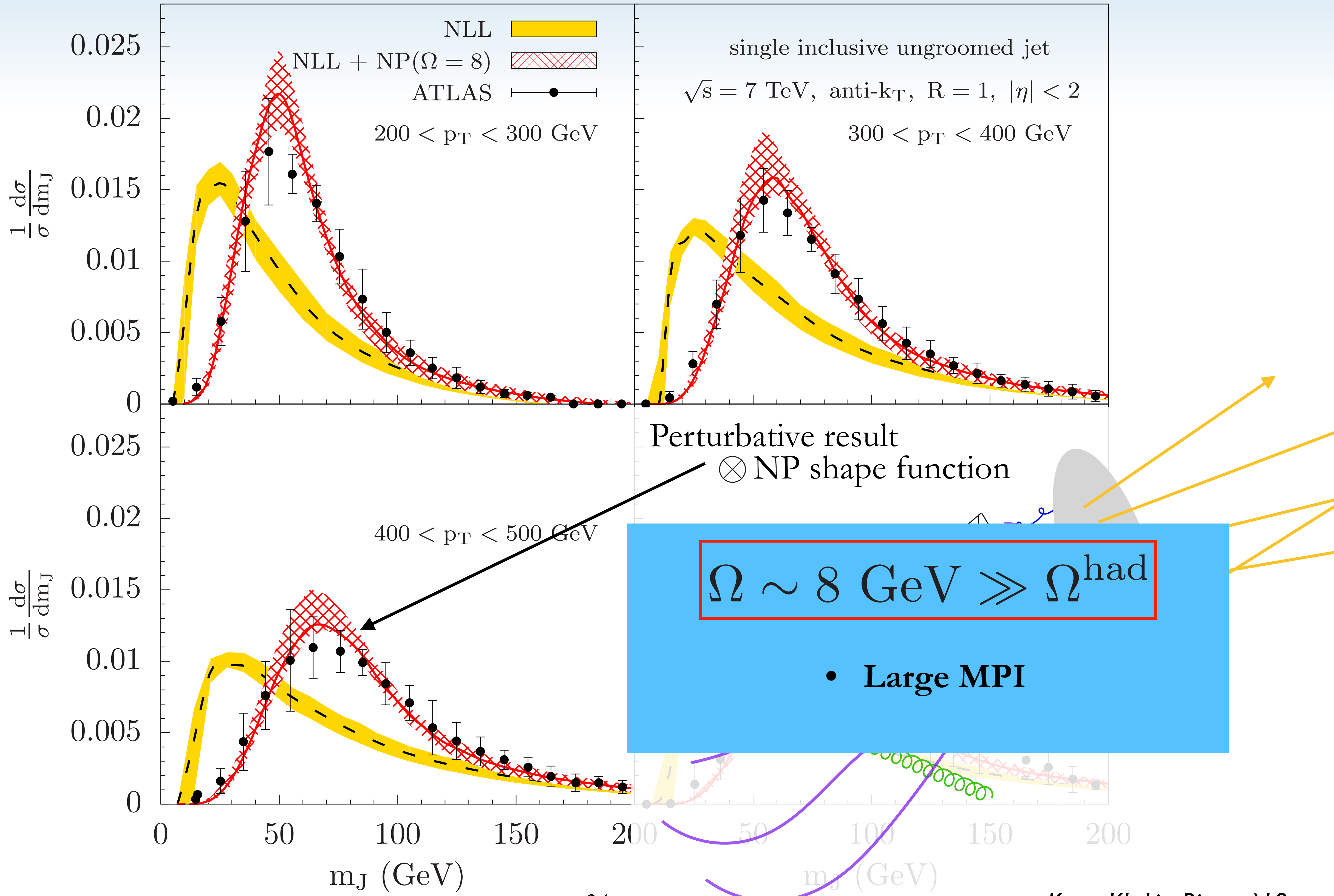
Kang, KL, Liu, Ringer `18

Phenomenology



Kang, KL, Liu, Ringer `18

Phenomenology



Perturbative result
⊗ NP shape function

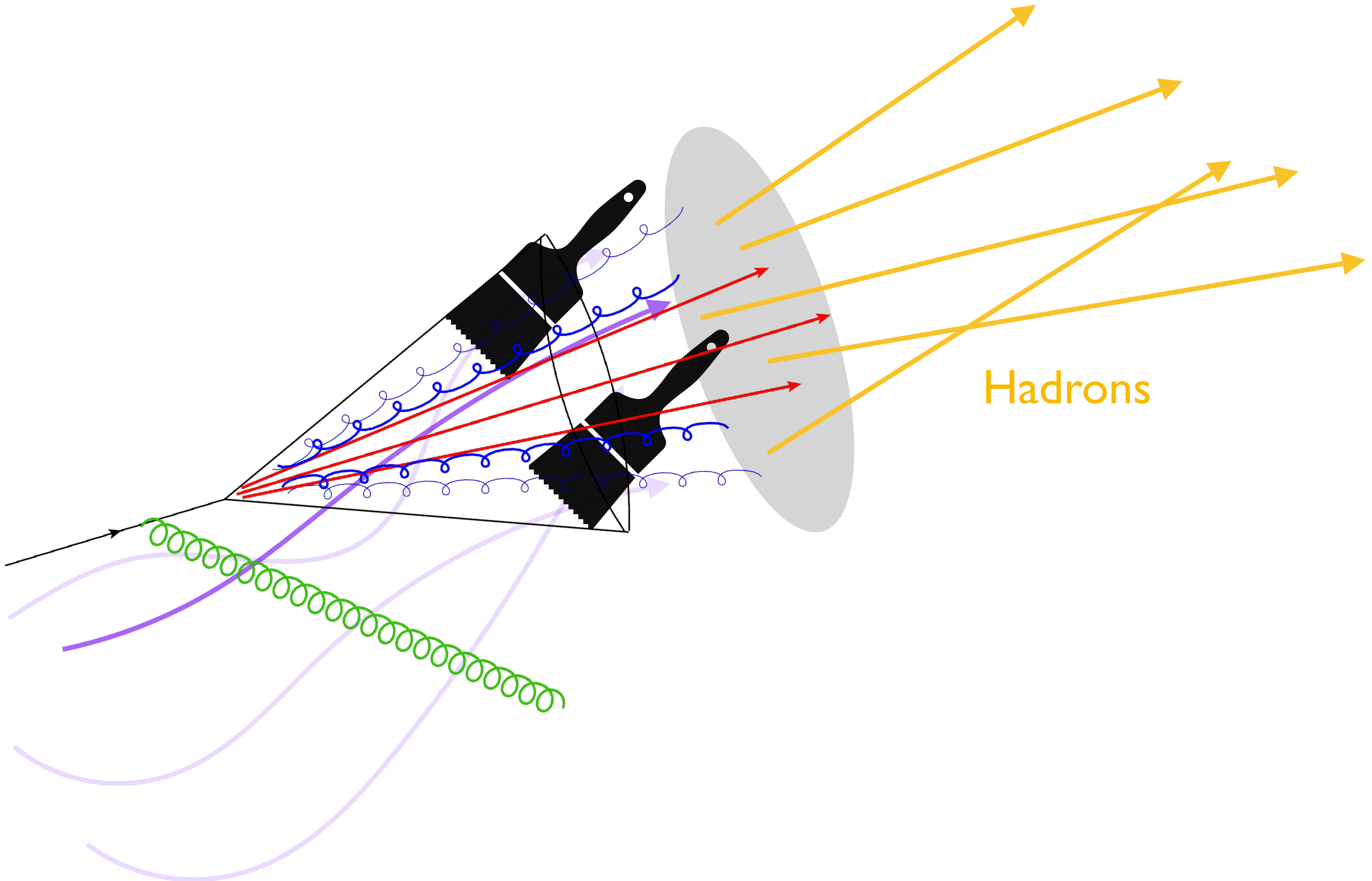
$\Omega \sim 8$ GeV $\gg \Omega^{\text{had}}$

- **Large MPI**

Kang, KL, Liu, Ringer `18

Soft Drop Grooming

- Taming wide angle soft radiations, giving sensitivity to MPI, PU, and NGLs directly changing distribution.



Soft Drop Grooming

- **Taming wide angle soft radiations, giving sensitivity to UE, PU, and NGLs directly changing distribution.**

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

- **Soft drop grooming algorithms:**

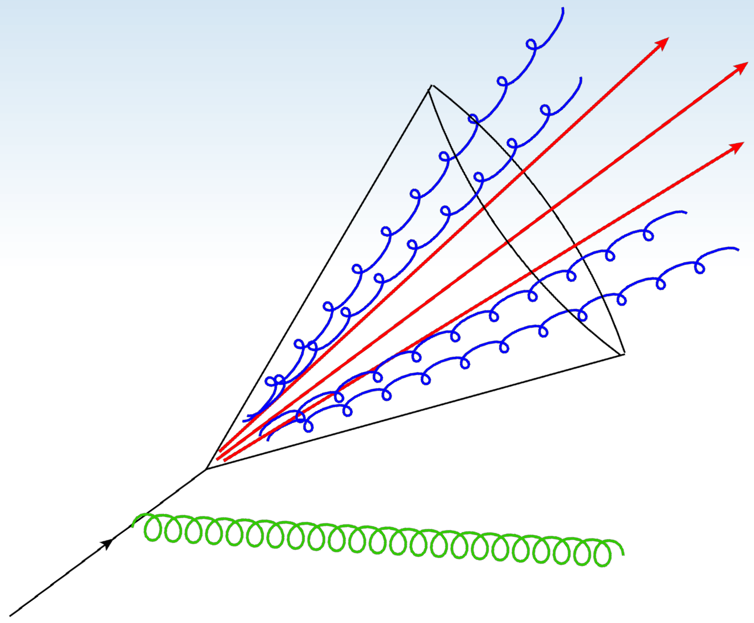
1. Reorder emissions in the identified jet according to their relative angle using C/A jet algorithm.

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

$$\frac{\min[p_{T,1}, p_{T,2}]}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

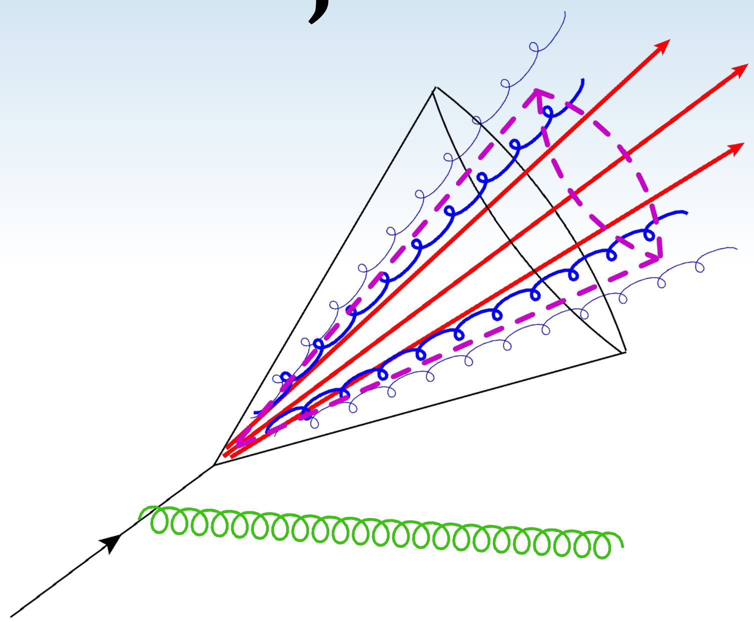
Larkoski, Marzani, Soyez, Thaler `14
Frye, Larkoski, Schwartz, Yan `16

Relevant modes in the groomed jet



$$\tau_a \sim z\,\theta^{2-a}$$

$$z > z_{\rm cut}(\theta/R)^\beta$$



- The ungroomed case ($\tau_a \ll R^{2-a}$)

Hard-collinear

$\theta_{\mathcal{H}} \sim R \qquad z_{\mathcal{H}} \sim 1$

Collinear

$z_c \sim 1 \qquad \theta_c \sim \tau_a^{\frac{1}{2-a}}$

(Collinear-)soft

$\theta_s \sim R \qquad z_{cs} \sim \dfrac{\tau_a}{R^{2-a}}$

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

Hard-collinear

$\theta_{\mathcal{H}} \sim R \qquad z_{\mathcal{H}} \sim 1$

Collinear

$z_c \sim 1 \qquad \theta_c \sim \tau_a^{\frac{1}{2-a}}$

$\notin$ *gr* soft

$\theta_{\notin \rm gr} \sim R \qquad z_{\notin \rm gr} \sim z_{\rm cut}\left(\dfrac{\theta}{R}\right)^\beta = z_{\rm cut}$

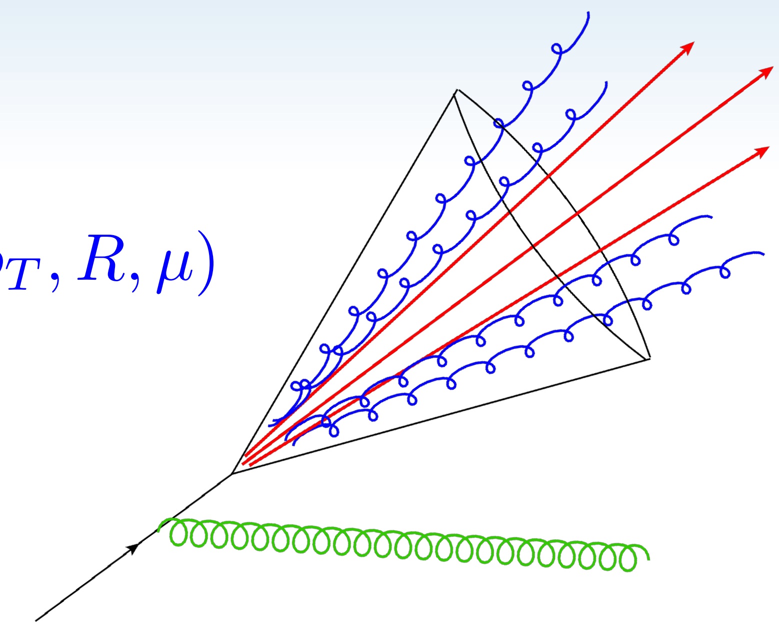
$\in$ *gr* soft (collinear-soft)

$z_{\in \rm gr} \sim z_{\rm cut}\left(\dfrac{\theta}{R}\right)^\beta = z_{\rm cut}^{\frac{2-a}{2-a+\beta}}\left(\dfrac{\tau_a}{R^{2-a}}\right)^{\frac{\beta}{2-a+\beta}} \qquad \theta_{\in \rm gr} \sim \left(\dfrac{\tau_a R^\beta}{z_{\rm cut}}\right)^{\frac{1}{2-a+\beta}}$

Factorization for the groomed jet angularity

$J_c \to \mathcal{G}_c$

- **The ungroomed case (** $\tau_a \ll R^{2-a}$ **)**



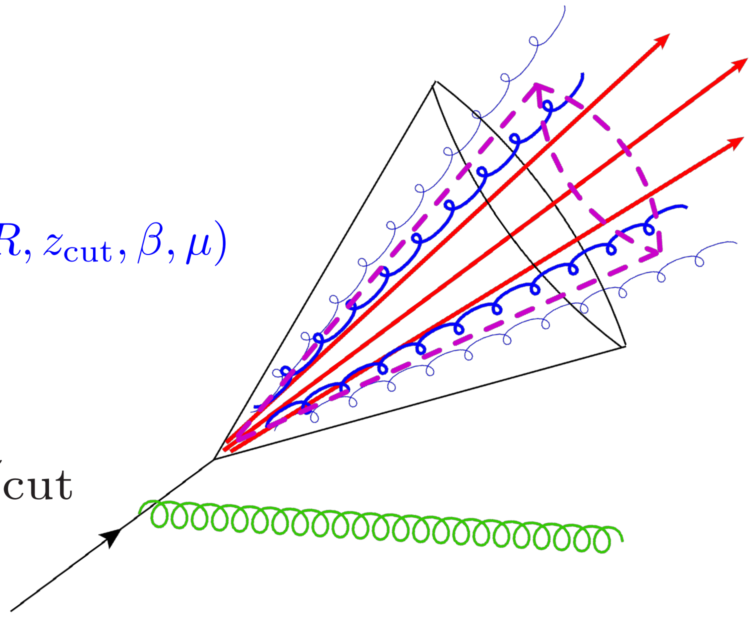
$$\mathcal{G}_i(z, p_T R, \tau_a, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) C_j(\tau_a, p_T, \mu) \otimes S_j(\tau_a, p_T, R, \mu)$$

- **Jointly resums large logs** $\alpha_s^n \ln^n R$ **and** $\alpha_s^n \ln^{2n} \tau_a^{\frac{1}{2-a}}/R$

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

$\theta_{\mathcal{H}} \sim R$

$\theta_{\notin \rm gr} \sim R$

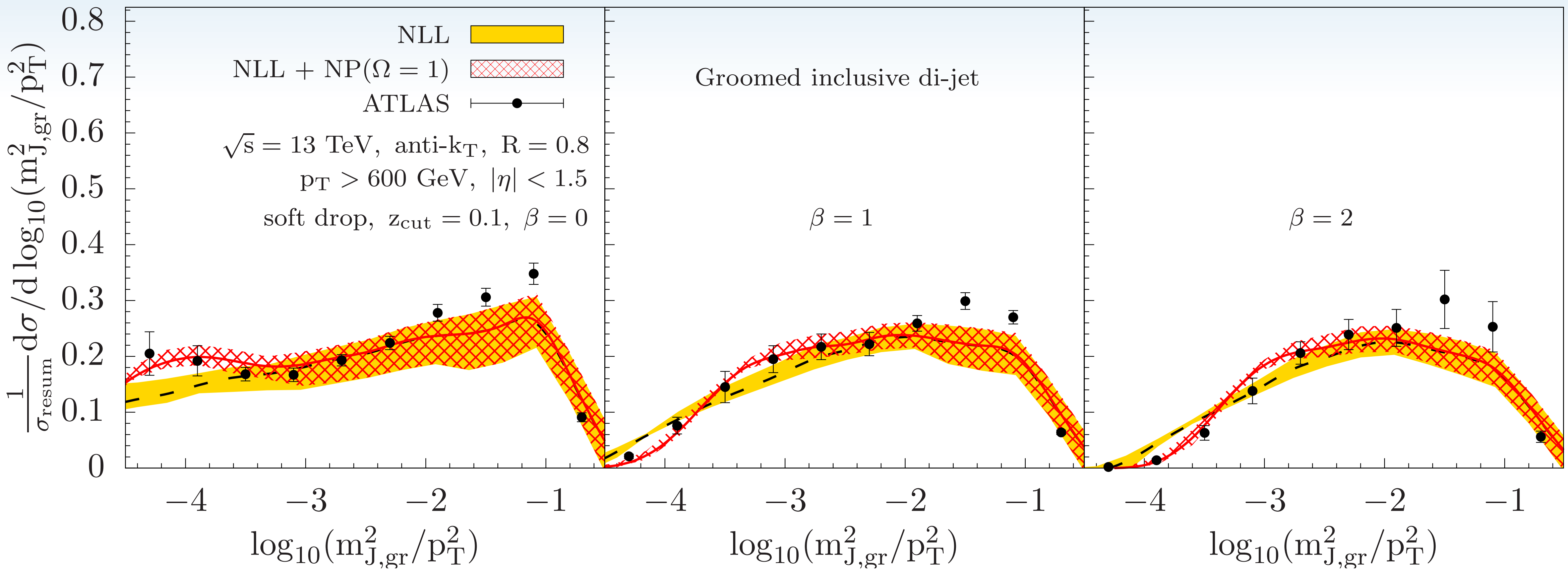


$$\mathcal{G}_i(z, p_T R, \tau_a, z_{\rm cut}, \beta, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu) S_j^{\notin \rm gr}(p_T, R, z_{\rm cut}, \beta, \mu) C_j(\tau_a, p_T, \mu) \otimes S_j^{\in \rm gr}(\tau_a, p_T, R, z_{\rm cut}, \beta, \mu)$$

- **Jointly resums large logs** $\alpha_s^n \ln^n R$, $\alpha_s^n \ln^{2n} \tau_a^{\frac{1}{2-a}}/R$, **and** $\alpha_s^n \ln^{2n} z_{\rm cut}$

Kang, KL, Liu, Ringer `18

Phenomenology (groomed jet mass)

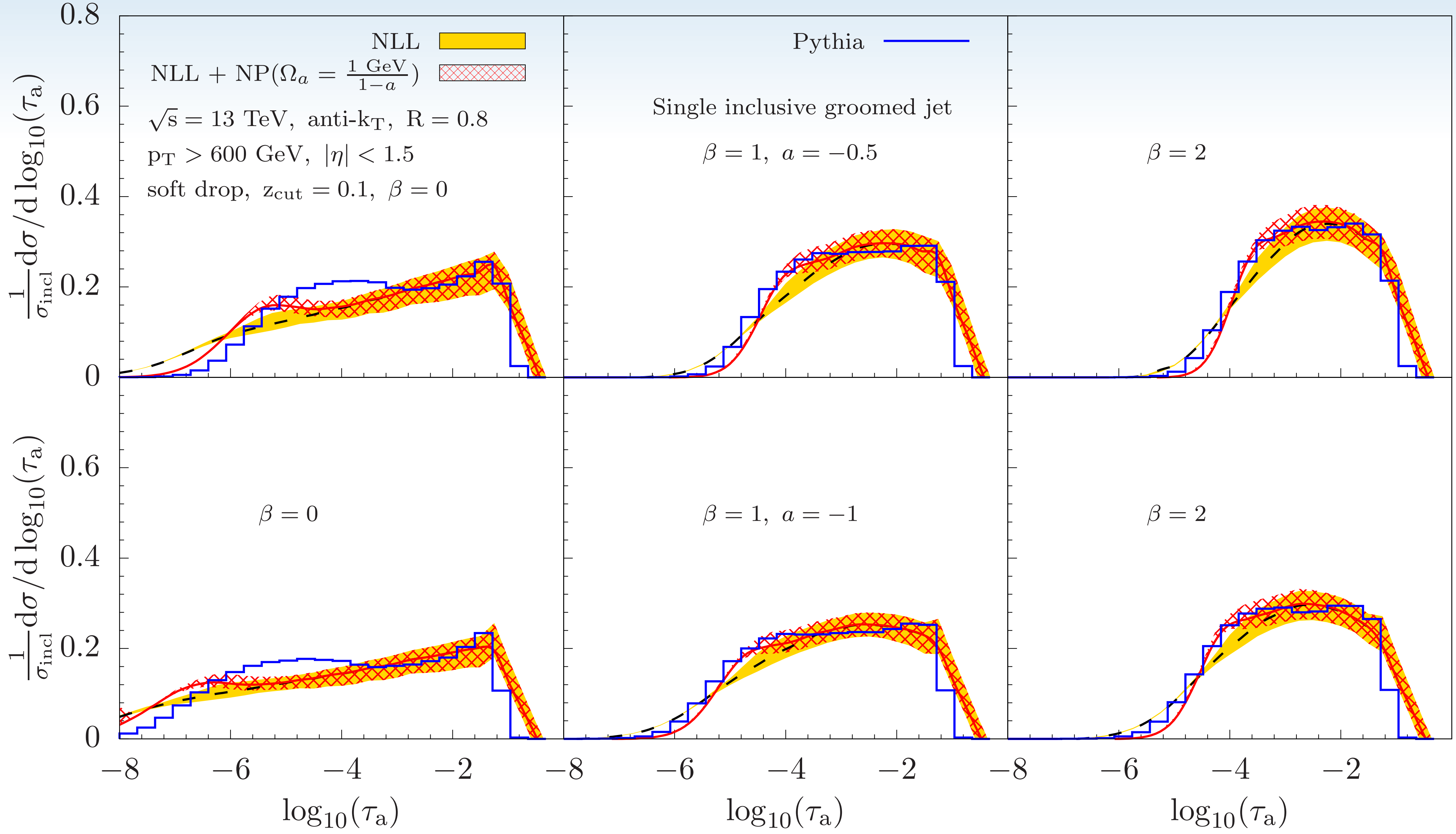


- Developed the formalism for single inclusive groomed jet mass cross-section.
- Shows very good agreement with the data.
- $\Omega_k = 1$ GeV $\Longrightarrow$ Reduced contamination as expected. NP effects mostly from hadronization.

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

Kang, KL, Liu, Ringer `18

Phenomenology



- General angularities show good agreement with Pythia with reduced contamination from MPI/PU.

Kang, KL, Liu, Ringer `18

α_s extraction

- World Average with 0.9% total uncertainty

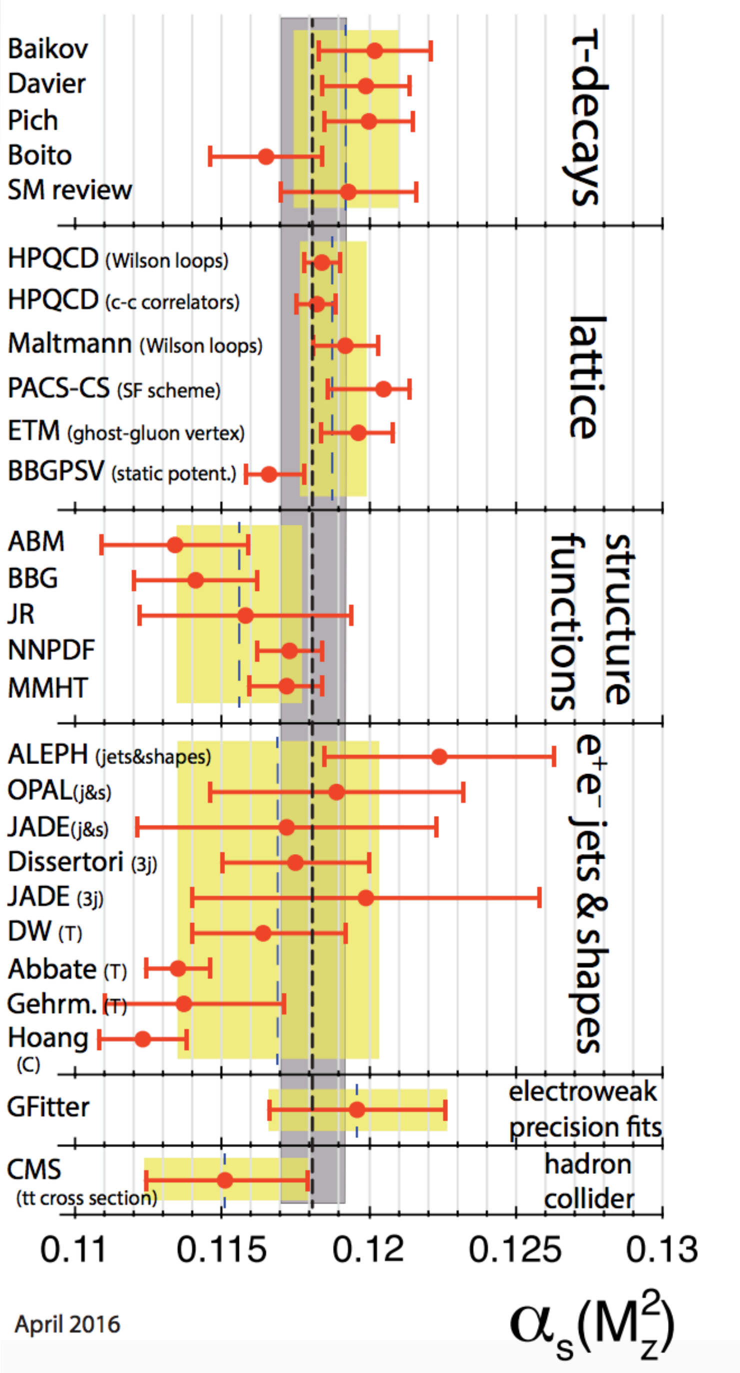
$$\alpha_s(m_Z) = 0.1181 \pm 0.0011$$

- Most precise input: lattice determination
- Most numerous input: e^+e^- event shape determination: thrust and C-parameter.
  - $3-4\sigma$ tension with lattice.

Using pp-extractions:

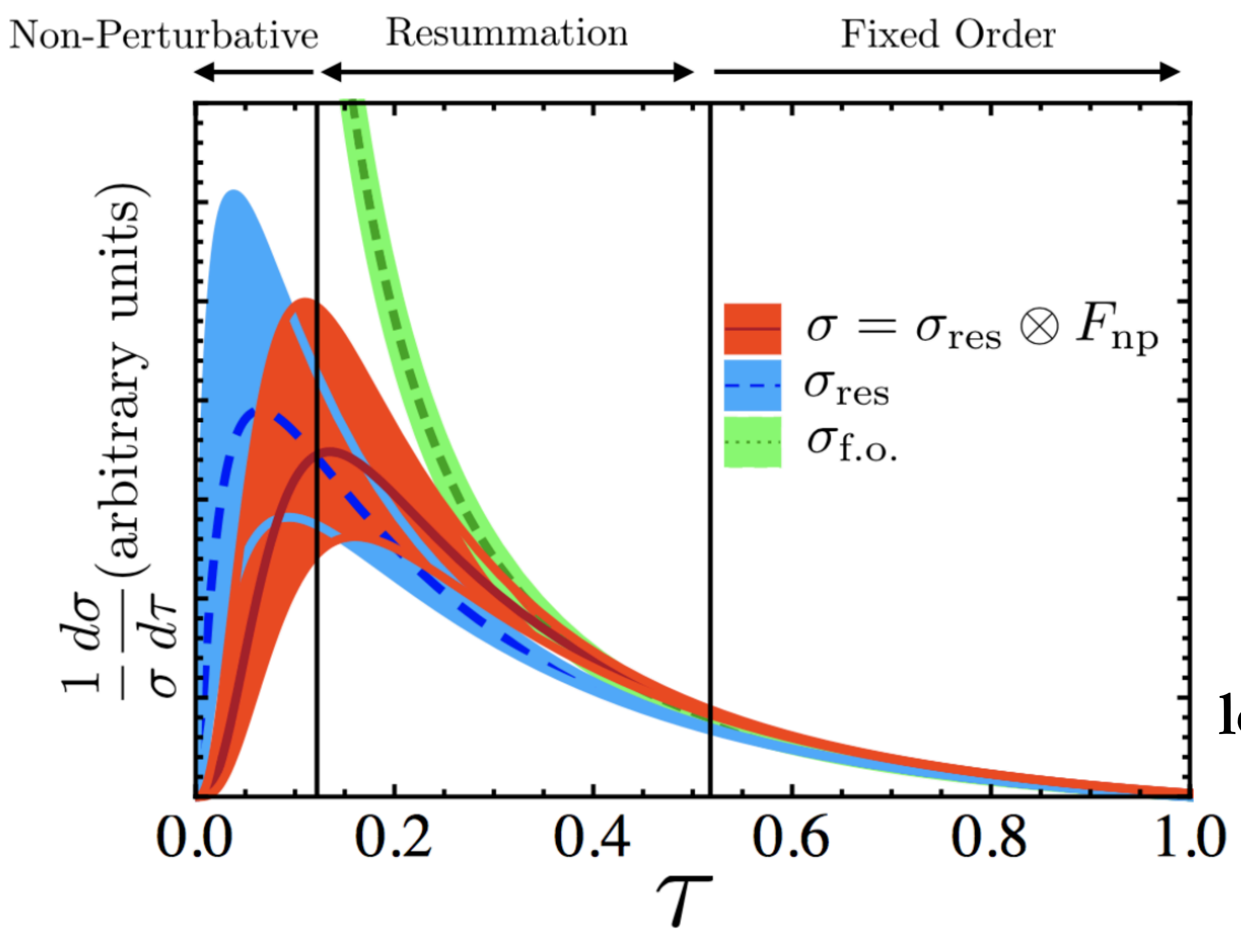
- High-quality of data pouring out of the LHC.
- Complimentary study to e^+e^- extractions.
- Currently feasible to determine with 10% uncertainty.

Les Houches 2017 I. Moult, B. Nachman, G. Soyez, J. Thaler (section coordinators)



α_s extraction

- **Key challenges in α_s extraction is the degeneracy with non-perturbative effects.**



$$\frac{d\sigma}{d\tau_a}(\tau_a) \xrightarrow[\rm NP]{} \frac{d\sigma}{d\tau_a}(\tau_a - c_{\tau_a}\frac{\mathcal{A}}{Q})$$

$$c_{\tau_a} = \frac{2}{1-a} \qquad \mathcal{A} = \frac{1}{N_C}\,\mathrm{Tr}\,\langle 0|\,\overline{Y}_{\bar{n}}^{\dagger} Y_n^{\dagger} \mathcal{E}_T(0) Y_n \overline{Y}_{\bar{n}}\,|0\rangle$$

leading shift of the first moment shown to be universal

α_s extraction

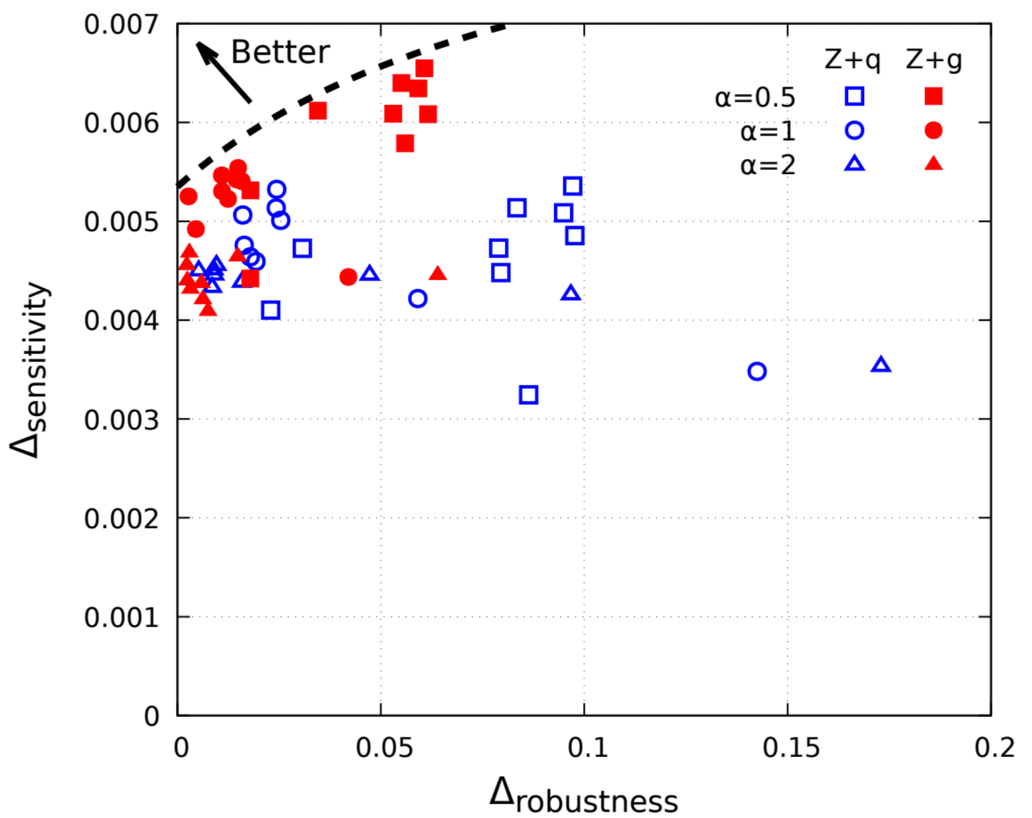
Ungroomed: $$\mu_S \sim \frac{p_T \tau}{R}$$

SD Groomed: $$\mu_S \sim \frac{p_T \tau}{R} \left(\frac{z_{\text{cut}} R^2}{\tau^2} \right)^{\frac{1}{2+\beta}}$$

with $\mu_S = \Lambda_{\text{QCD}} \sim 1 \text{ GeV}$**,**

Onset of NP physics

$$\tau_{\text{gr}} = \tau_{\text{ungr}} \left(\frac{\Lambda_{QCD}}{p_T R z_{\text{cut}}} \right)^{\frac{1}{1+\beta}}$$

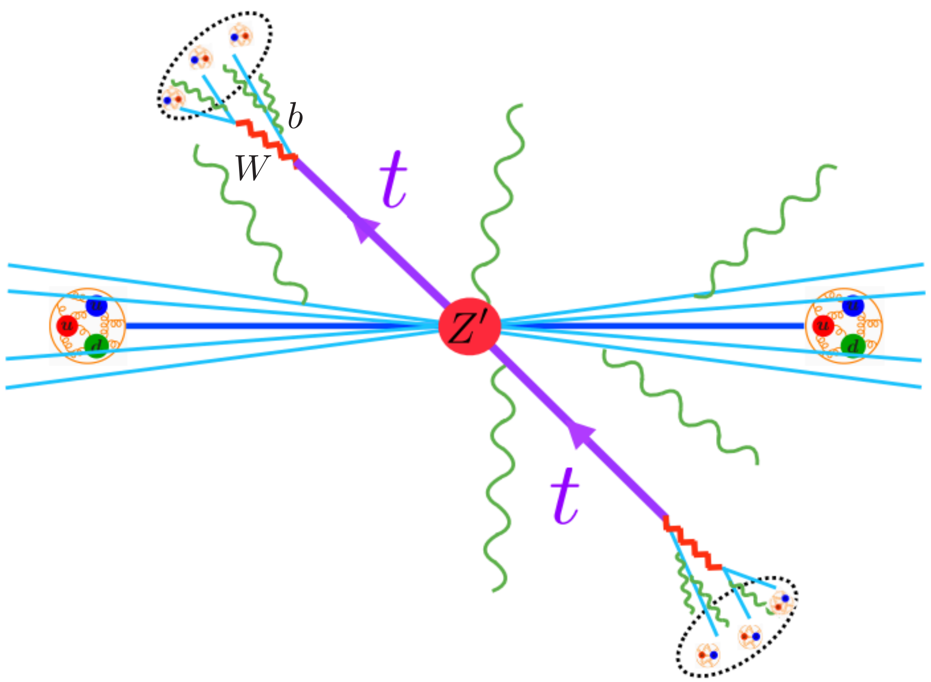


- **Extend range of validity by two orders for 1 TeV jet.**
- **Reduced robustness to NP effects and increased sensitivity to** α_s
- **Groomed angularities or energy-energy correlations provide additional independent handles with \`a'.**
- **Currently feasible to determine with 10% uncertainty.**

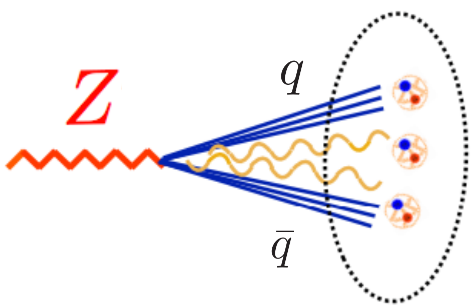
Les Houches 2017 I. Moult, B. Nachman, G. Soyez, J. Thaler (section coordinators)

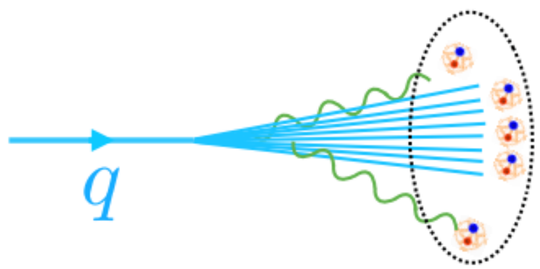
Electroweak scale objects as jets

- Hadronically decayed electroweak scale objects can have sufficiently high p_T to appear as multi-prong jets.



Boosted top





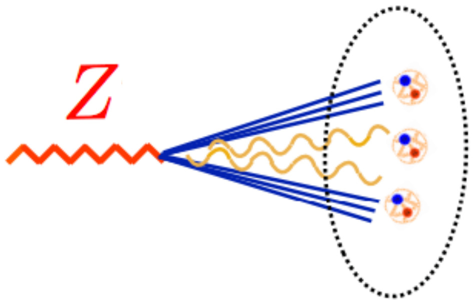
- Measuring jet substructures can help us distinguish the origin of the jets observed.

Multi-prong jet substructures

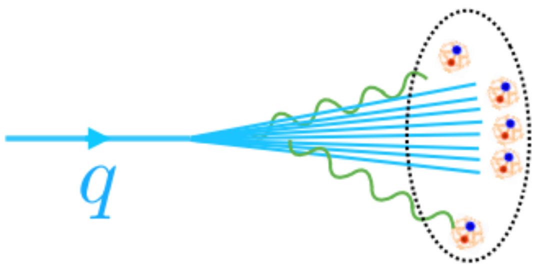
- Construct an observable using a set of IRC safe observables to discriminate different configurations.
  - N-Jettiness as a basis :

$$\tau_N^{(\alpha)} = \frac{1}{p_T} \sum_{i \in J} p_{T,i} \min\{\Delta R_{i,1}^{\alpha}, \Delta R_{i,2}^{\alpha}, \cdots, \Delta R_{i,N}^{\alpha}\}$$

Note that $\tau_a = \tau_1^{(2-a)}$

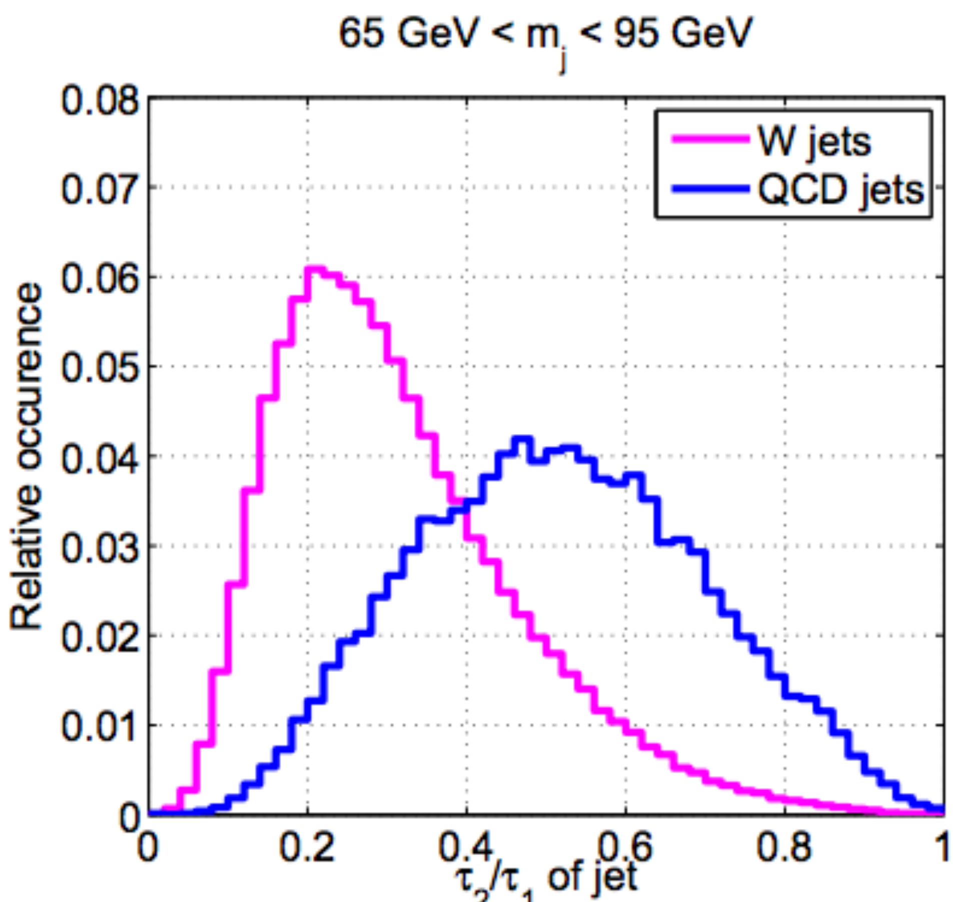


$\tau_1^{\alpha} \gg \tau_2^{\alpha}$



$\tau_1^{\alpha} \sim \tau_2^{\alpha}$

$$\tau_{21}^{\alpha} \equiv \frac{\tau_2^{\alpha}}{\tau_1^{\alpha}}$$



Thaler, Van Tilburg `10
Dasgupta, Schunk, Soyez `16
Larkoski, Moult `16

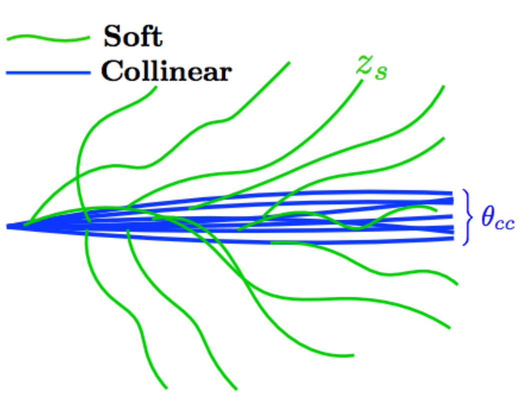
Multi-prong jet substructures

- **N-point energy (p_T) correlations as a basis :**

$$e_2^\alpha = \frac{1}{p_T^2} \sum_{i<j\in J} p_{T,i}\, p_{T,j}\, \Delta R_{ij}^\alpha$$

$$e_3^\alpha = \frac{1}{p_T^3} \sum_{i<j<k\in J} p_{T,i}\, p_{T,j}\, p_{T,k}\, \Delta R_{ij}^\alpha\, \Delta R_{jk}^\alpha\, \Delta R_{ik}^\alpha$$

Soft Haze

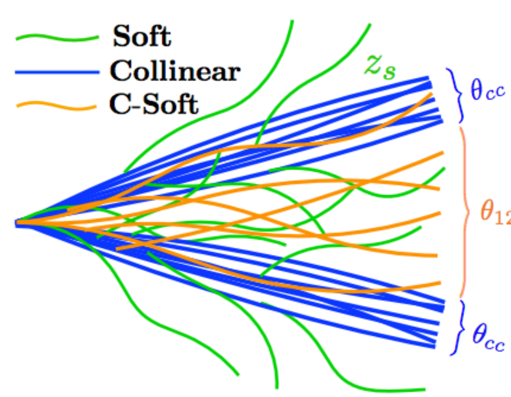


$$e_2^\alpha \sim z_s + \theta_c^\alpha$$
$$e_3^\alpha \sim \theta_{cc}^{3\alpha} + z_s^2 + \theta_{cc}^\alpha z_s$$

↓

$$(e_2^\alpha)^3 < e_3^\alpha < (e_2^\alpha)^2$$

Collinear Subjets



$$e_2^\alpha \sim \theta_{12}^\alpha$$
$$e_3^\alpha \sim \theta_{cc}^\alpha \theta_{12}^{2\alpha} + \theta_{12}^\alpha z_s + \theta_{12}^{3\alpha} z_{cs} + z_s^2$$

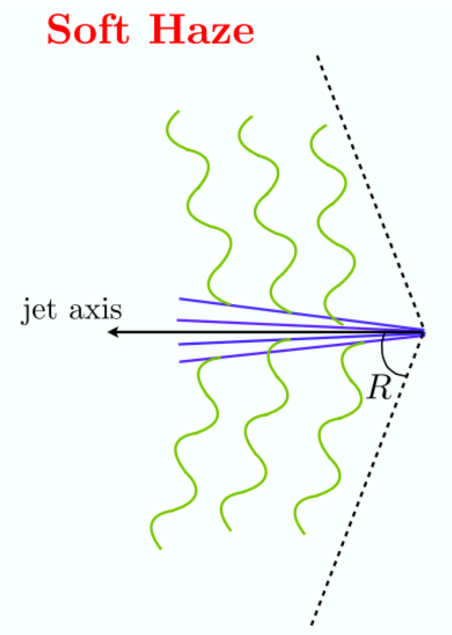
↓

$$e_3^\alpha < (e_2^\alpha)^3$$

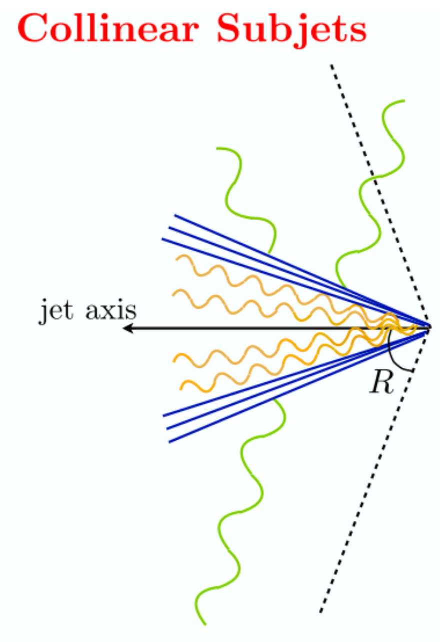
Larkoski, Moult, Neill `16-17

Multi-prong jet substructures

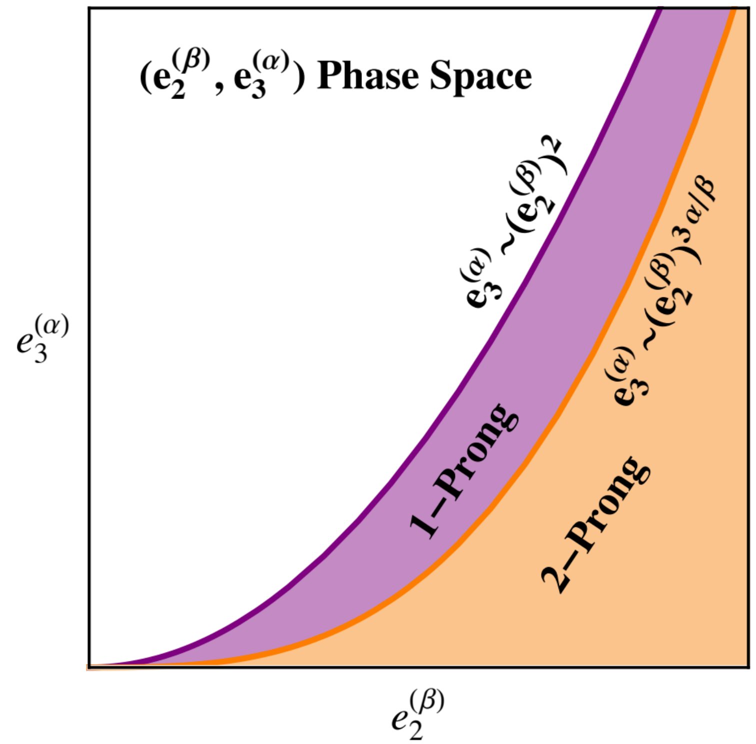
- **N-point energy (p_T) correlations as a basis :**

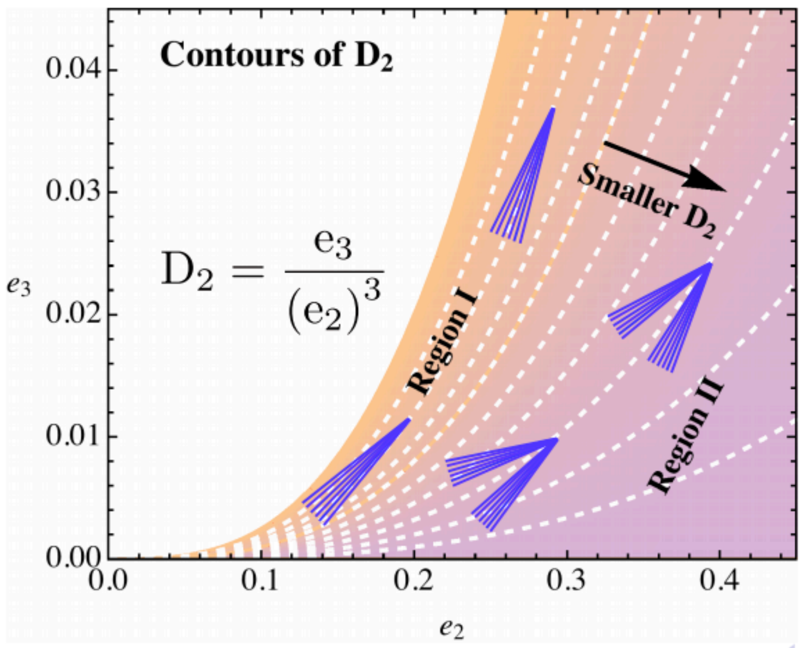


$(e_2^{(\beta)})^3 < e_3^{(\beta)} < (e_2^{(\beta)})^2$



$e_3^{(\beta)} < (e_2^{(\beta)})^3$



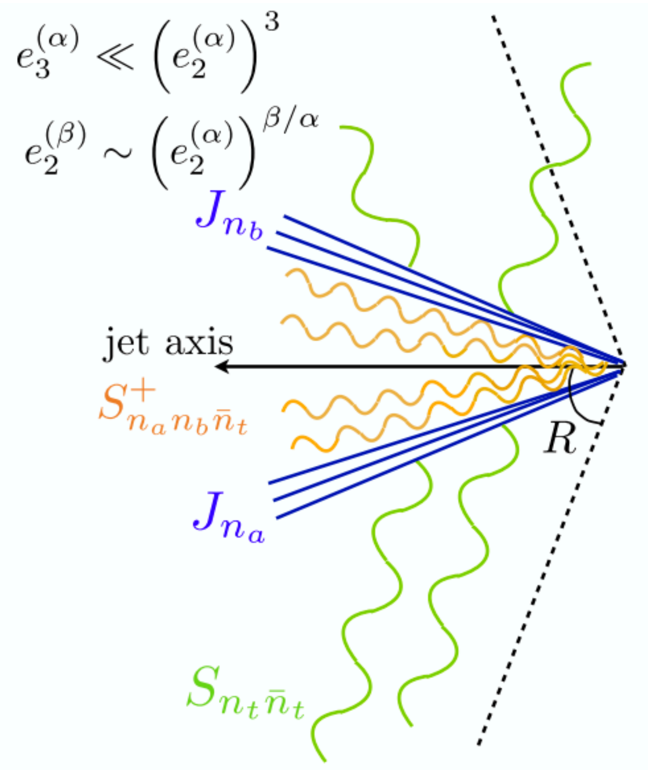


- **Define** $D_2 = \dfrac{e_3}{(e_2)^3}$ **to discriminate the two configurations**

- **Each regions require respective factorization for analytical computation**

Larkoski, Moult, Neill `16-17

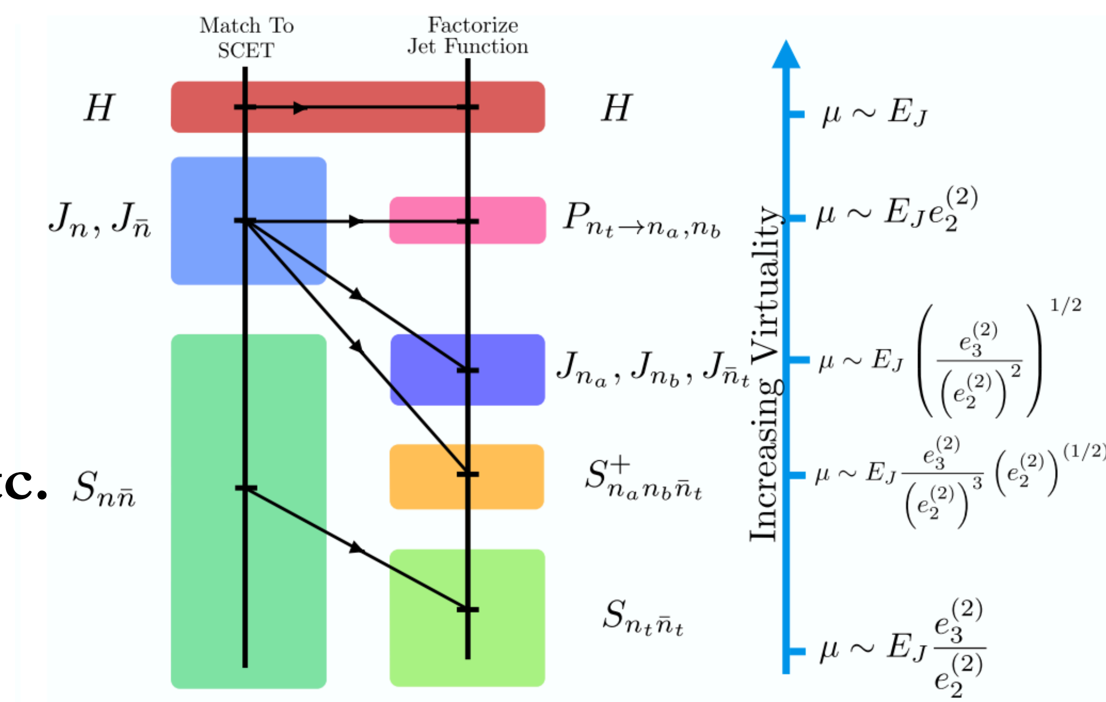
Factorization of different regions



Collinear Subjets

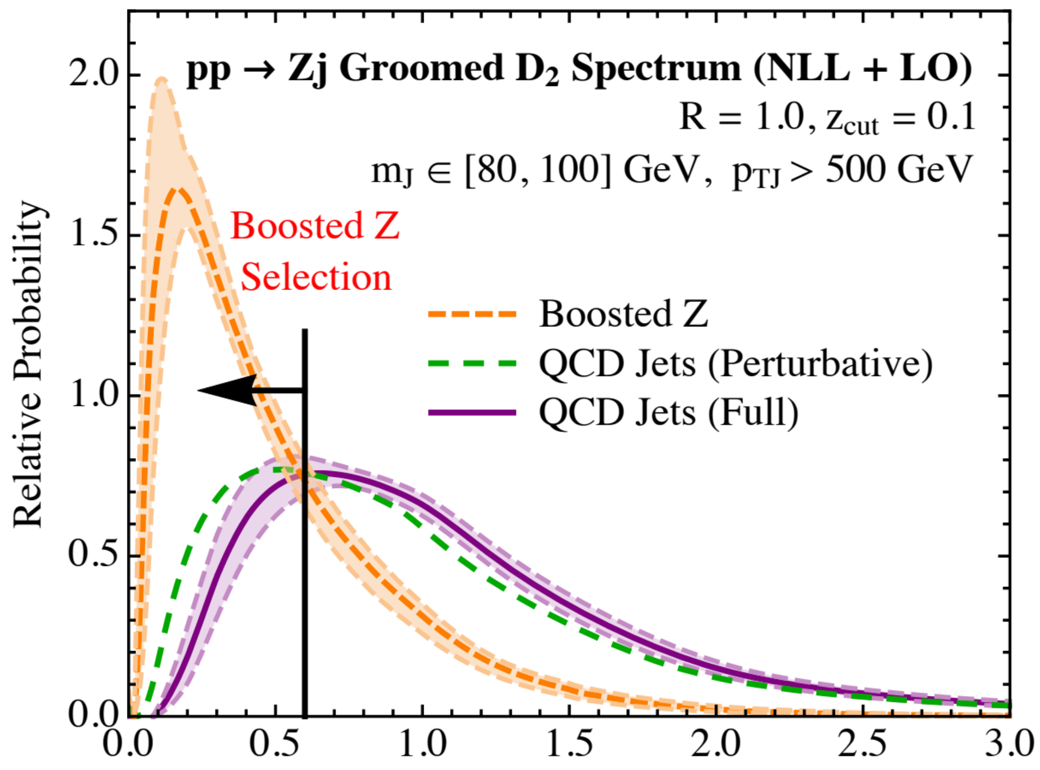
$$\frac{d\sigma}{dZ\, de_2^{(\alpha)} de_3^{(\alpha)}} = \sum_{f,f_a,f_b} H^f_{n_t \bar{n}_t} J_{\bar{n}_t} P^{f\to f_a f_b}_{n_t \to n_a, n_b}\left(Z; e_2^{(\alpha)}\right) \int de_3^c\, de_3^{\bar{c}}\, de_3^s\, de_3^{cs}$$
$$\delta\left(e_3^{(\alpha)} - e_3^c - e_3^{\bar{c}} - e_3^s - e_3^{cs}\right) J^{f_a}_{n_a}\left(Z; e_3^c\right) J^{f_b}_{n_b}\left(1 - Z; e_3^{\bar{c}}\right) S_{n_t \bar{n}_t}(e_3^s) S^+_{n_a n_b \bar{n}_t}\left(e_3^{cs}\right)$$

- **Gives resummation of large logarithms**
- **And likewise factorize 1-prong configuration, etc.**



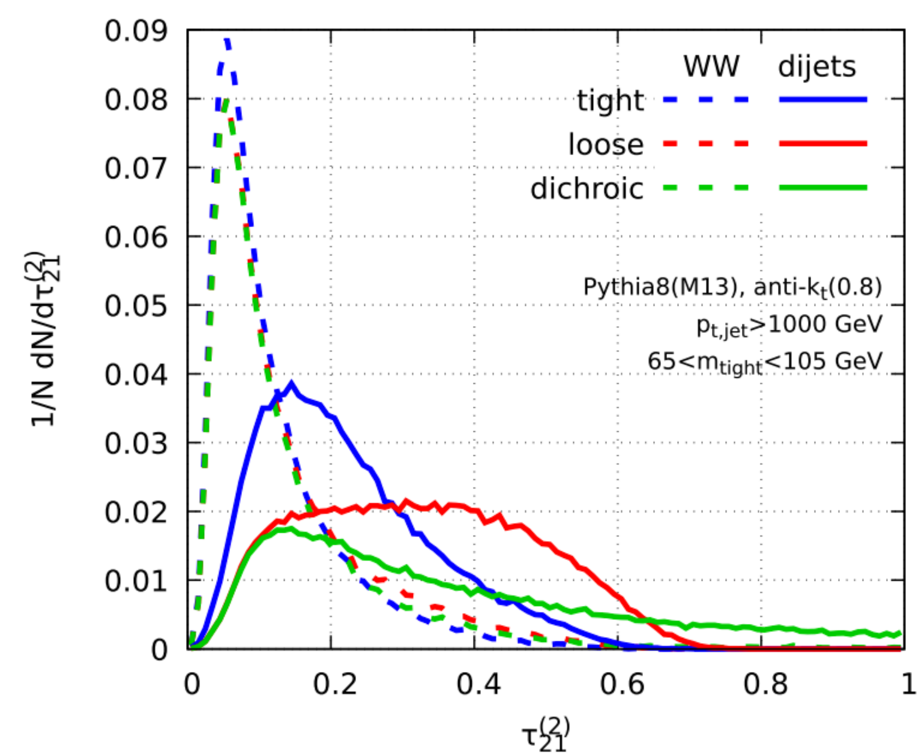
Larkoski, Moult, Neill `16-17

Discrimination



Larkoski, Moult, Neill `16-17

- Systematically improvable analytic calculations of next-generation jet substructures.
- Gives separation of non-perturbative and perturbative effects.
- Subject to extraneous effects of hadron colliders; groomed, dichroic $D_2, \tau_{21}, \cdots$



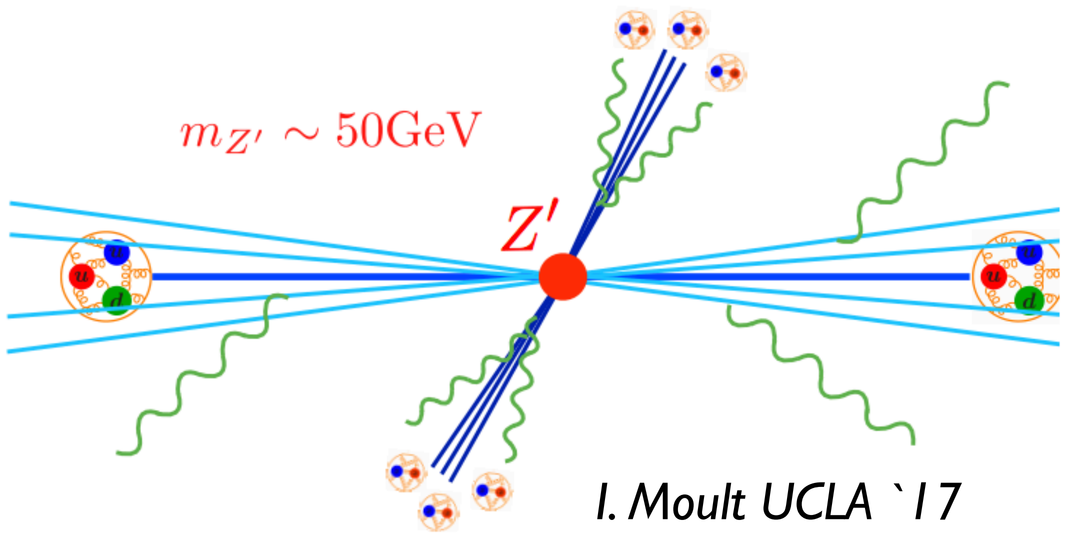
- Study of performance and robustness of various jet substructure observables as two-prong taggers.

Les Houches 2017

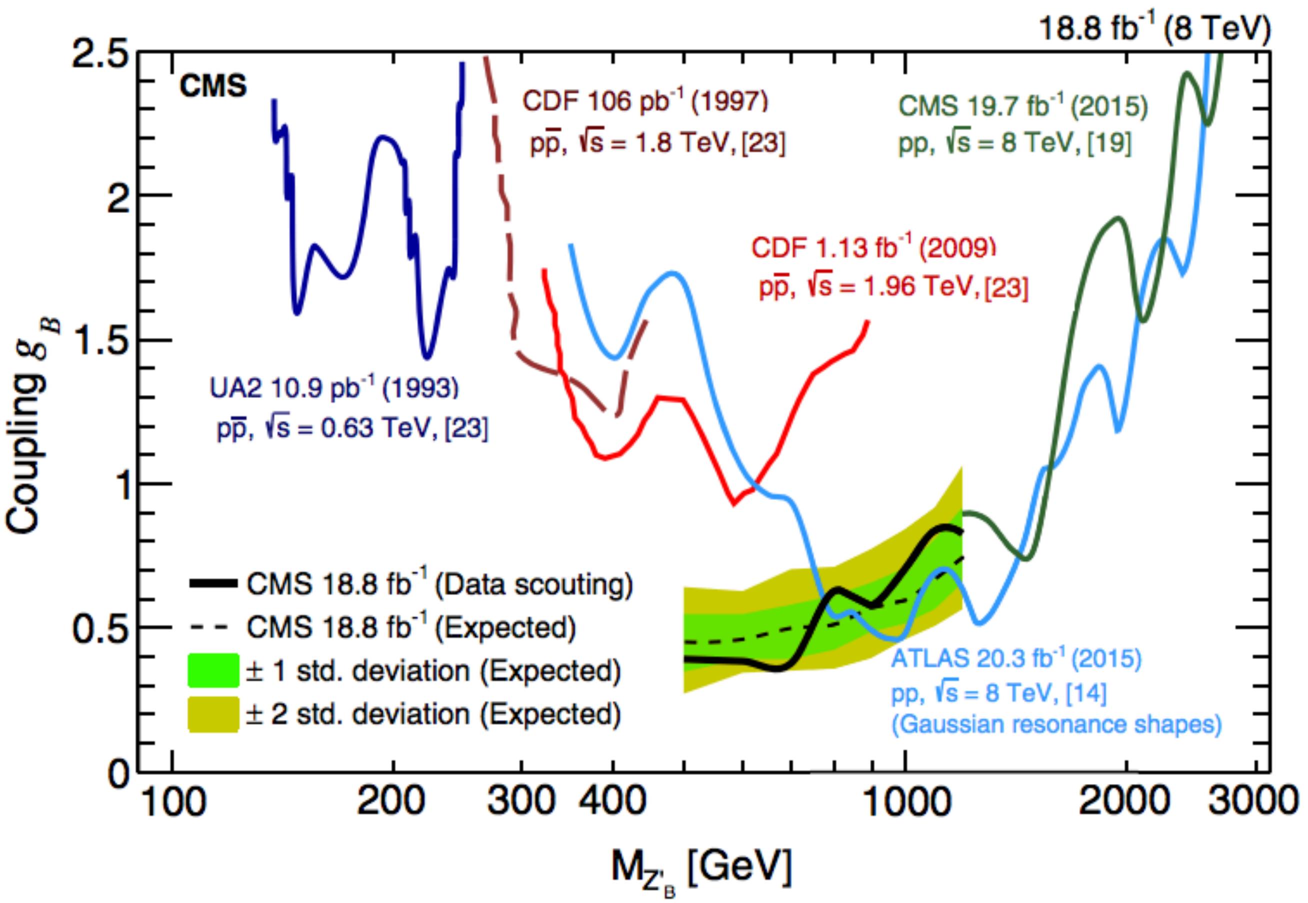
Low-mass resonance searches

$$\mathcal{L} \supset g_q Z'_{B,\mu} \bar{q} \gamma^\mu q$$

- Low masses are hard to probe at LHC due to backgrounds



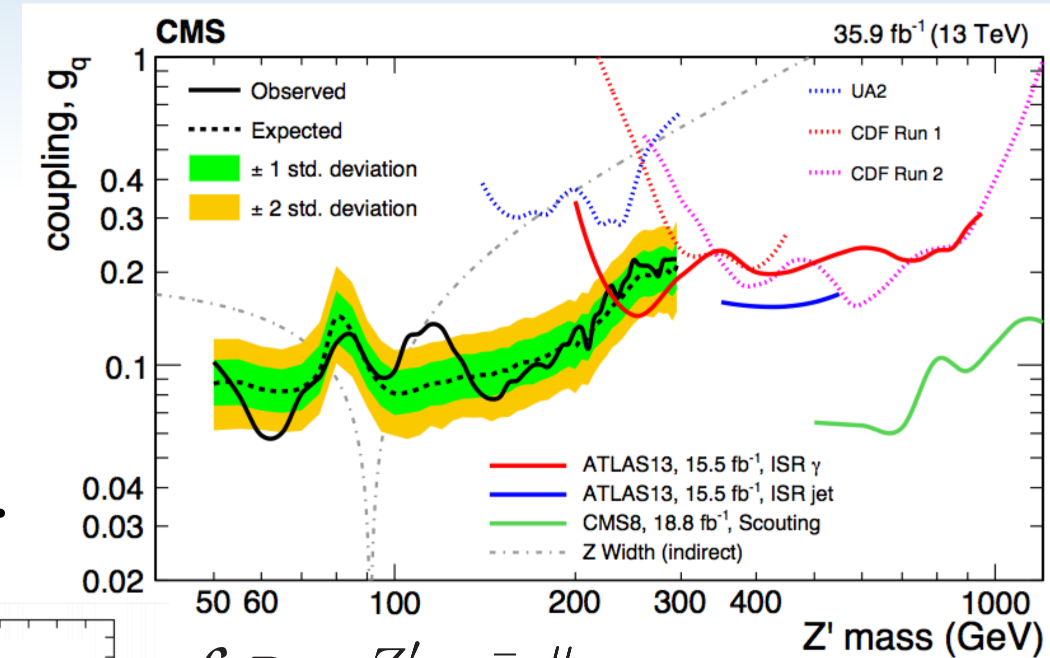
I. Moult UCLA `17



CMS Collaboration `16

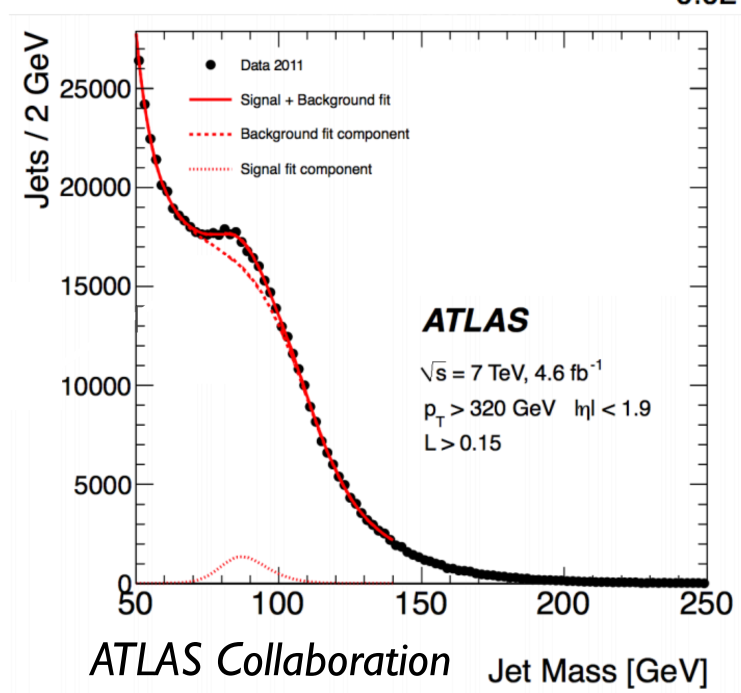
Low-mass resonance searches

- Use jet substructure to probe small scales within a high p_T jet.
- Tagger : yes/no $D_2,\ \tau_{21},\cdots$
- Look at mass distributions measured on a tagged jet.

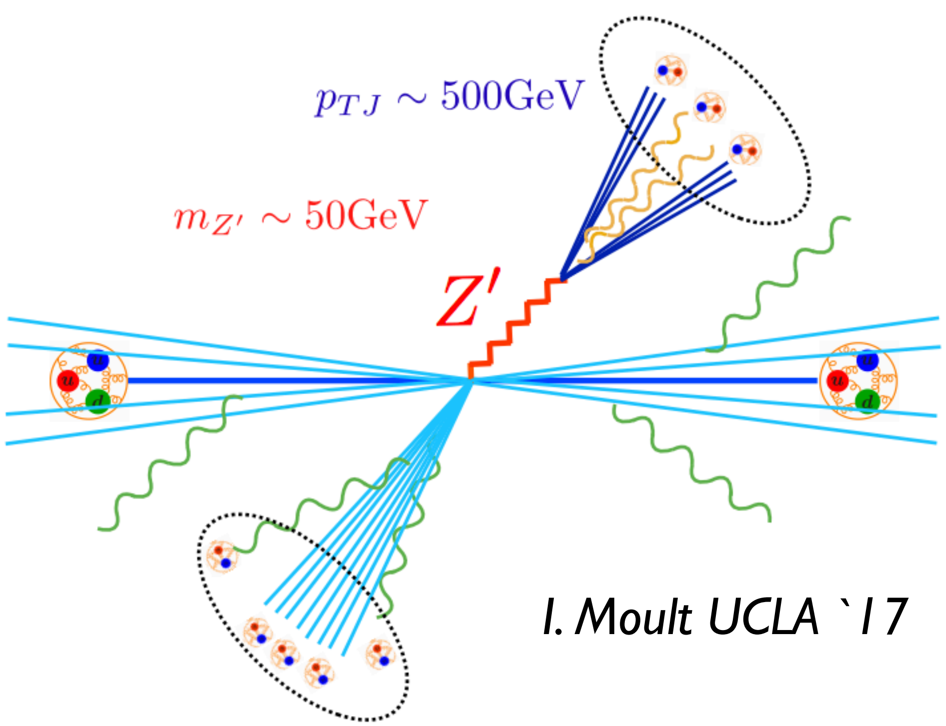


$$\mathcal{L} \supset g_q Z'_{B,\mu}\bar{q}\gamma^{\mu}q$$

CMS Collaboration `17



ATLAS Collaboration



I. Moult UCLA `17

High p_T ISR + Z'

- Nontrivial correlation between tagger and jet mass
- Extended limits to 50-300 GeV low-mass resonances.

Top quark mass determination

- **Most precise determination with help of MC:**

$$\textbf{Tevatron}: \; m_t^{\mathrm{MC}} = 174.34 \pm 0.64 \;\mathrm{GeV}$$

$$\textbf{CMS}: \; m_t^{\mathrm{MC}} = 172.44 \pm 0.49 \;\mathrm{GeV}$$

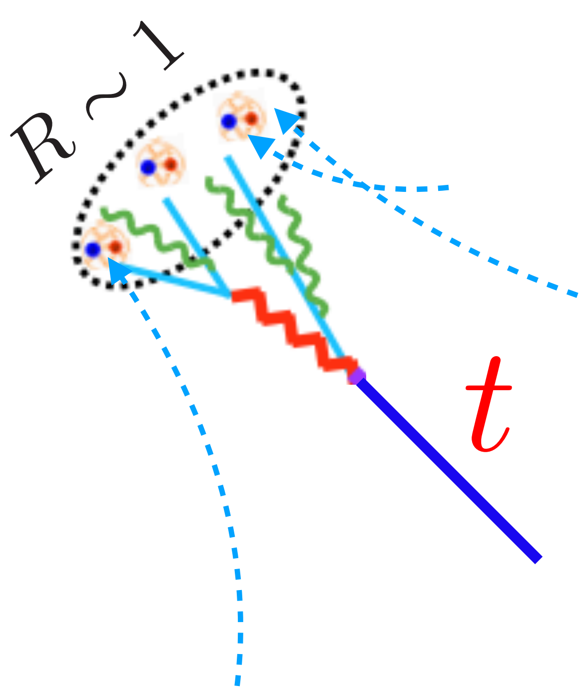
$$\textbf{ATLAS}: \; m_t^{\mathrm{MC}} = 172.84 \pm 0.70 \;\mathrm{GeV}$$

- **Unclear which renormalization scheme definition m_t^{MC} relates to.**

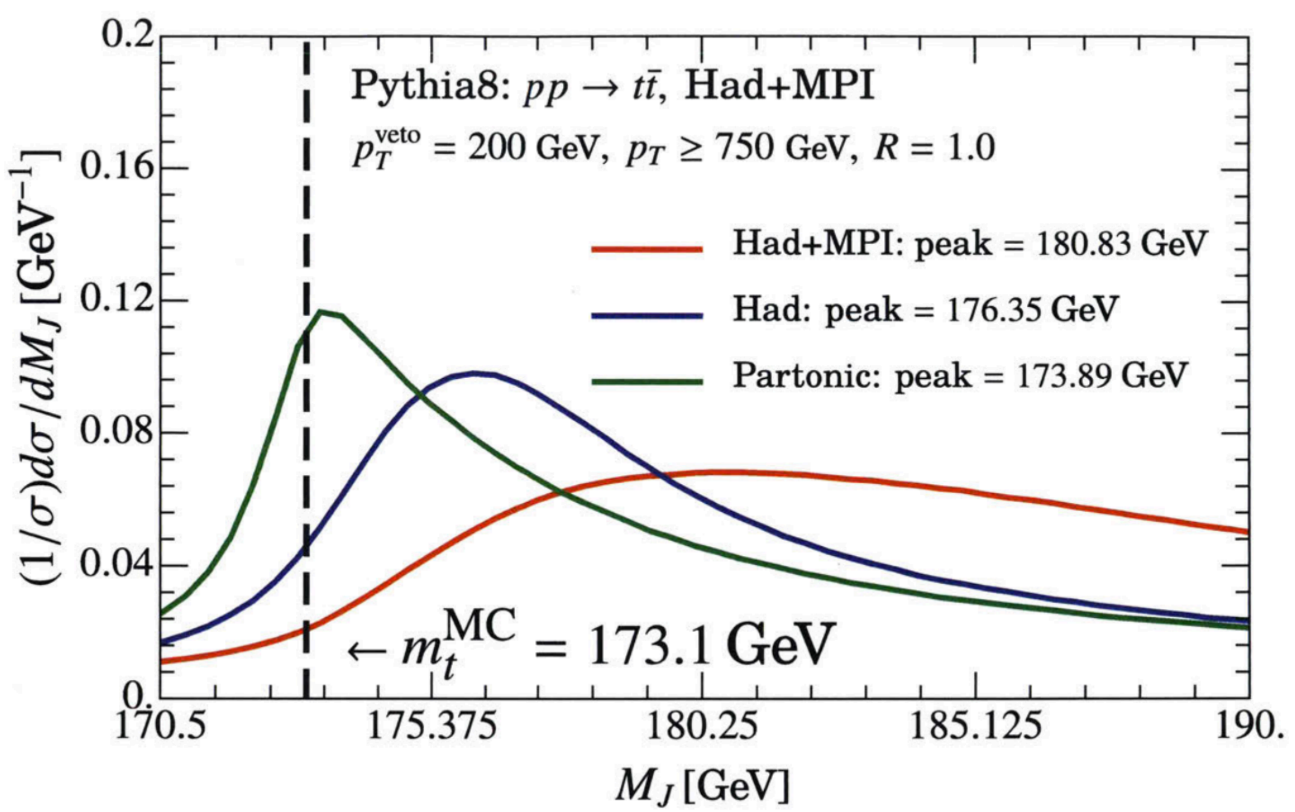
  (Sensitive to the details of MC generator)

- **Need an observable which has a systematically improvable theoretical description and a clear connection to the field theoretic definition of top quark mass.**

Measuring top mass with jet



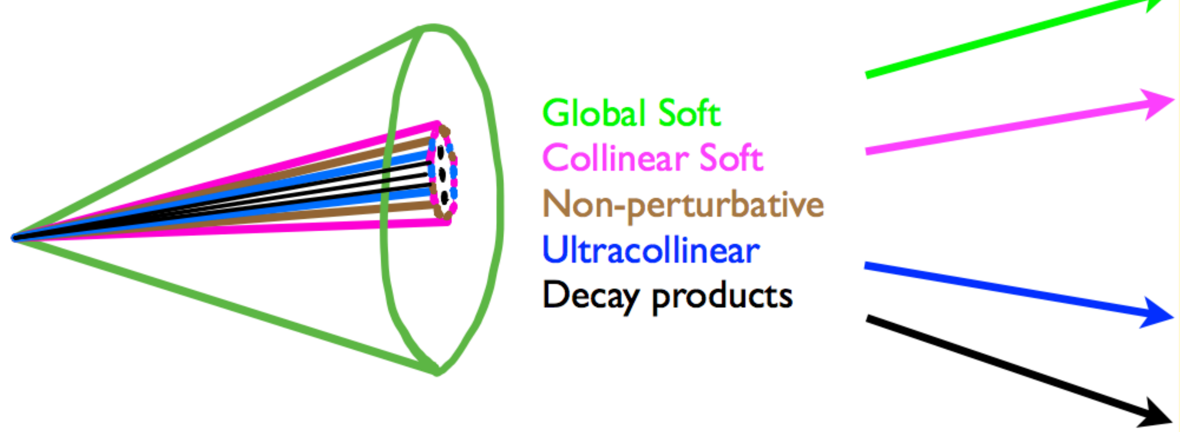
- Construct jet sufficiently large enough to capture all the decay products.
- Dependence on jet properties must be understood or eliminated.
- Multi-scale problems (gives large logs) : m_t, Γ_t, m_J, p_T
- Effects in a hadron collider : ISR, UE, PU, hadronization, …



Hoang, Mantry, Pathak, Stewart `17

Groomed top jet

- Groom away to remove soft contaminations



S. Mantry SCET `19

$$p_{S_G} \sim \frac{z_{\rm cut} Q}{2}(1,\,1,\,1)$$

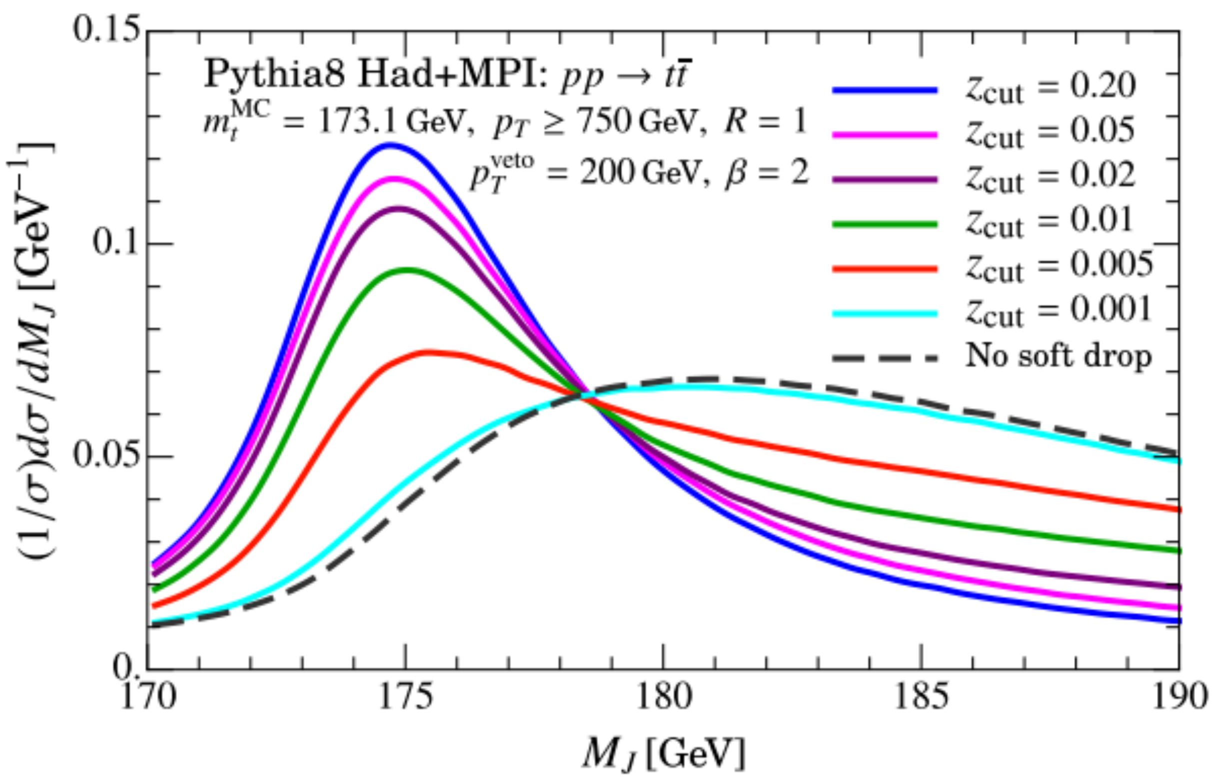
$$p^\mu_{\rm cs} \sim \Gamma_t\,\frac{Q}{m}(\lambda^2,\,\eta^2,\,\lambda\,\eta)$$

$$p^\mu_{\rm uc} \sim \Gamma_t\,\frac{Q}{m}(\lambda^2,1,\,\lambda)$$

$$p^\mu_d \sim m(\frac{hm}{Q},\frac{Q}{hm},1)$$

$$\eta \equiv \left[\left(\frac{2m}{Q}\right)^\beta z_{\rm cut}\frac{m}{\Gamma_t}\right]^{\frac{1}{\beta+2}}$$

$$\lambda \equiv \frac{m}{Q}$$



- Light grooming removes most contamination.
- Stable under further grooming (decay products not groomed away)

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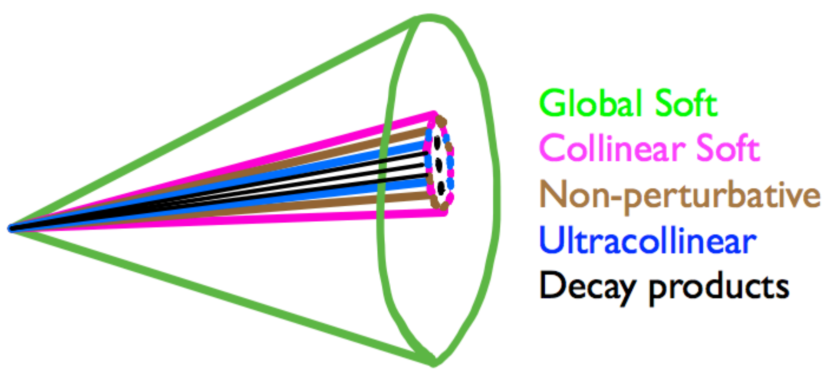
Groomed top jet

- Groom away to remove soft contaminations



S. Mantry SCET `19

$$p_{S_G} \sim \frac{z_{\rm cut} Q}{2}(1,\,1,\,1)$$

$$p^\mu_{\rm cs} \sim \Gamma_t\,\frac{Q}{m}(\lambda^2,\,\eta^2,\,\lambda\,\eta)$$

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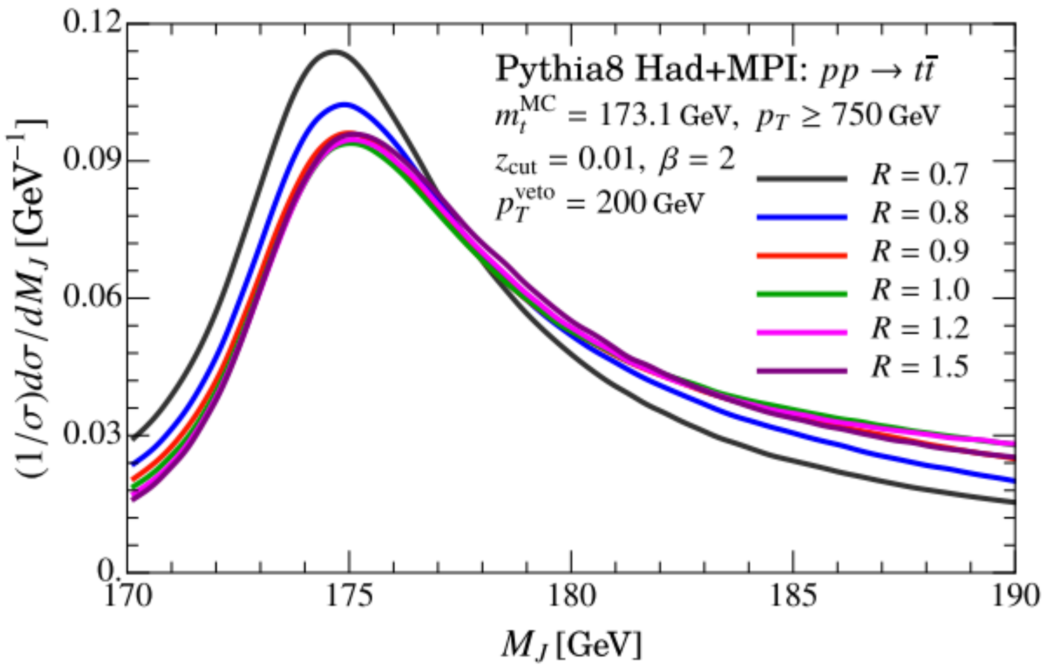
$$p^\mu_d \sim m(\frac{hm}{Q},\frac{Q}{hm},1)$$

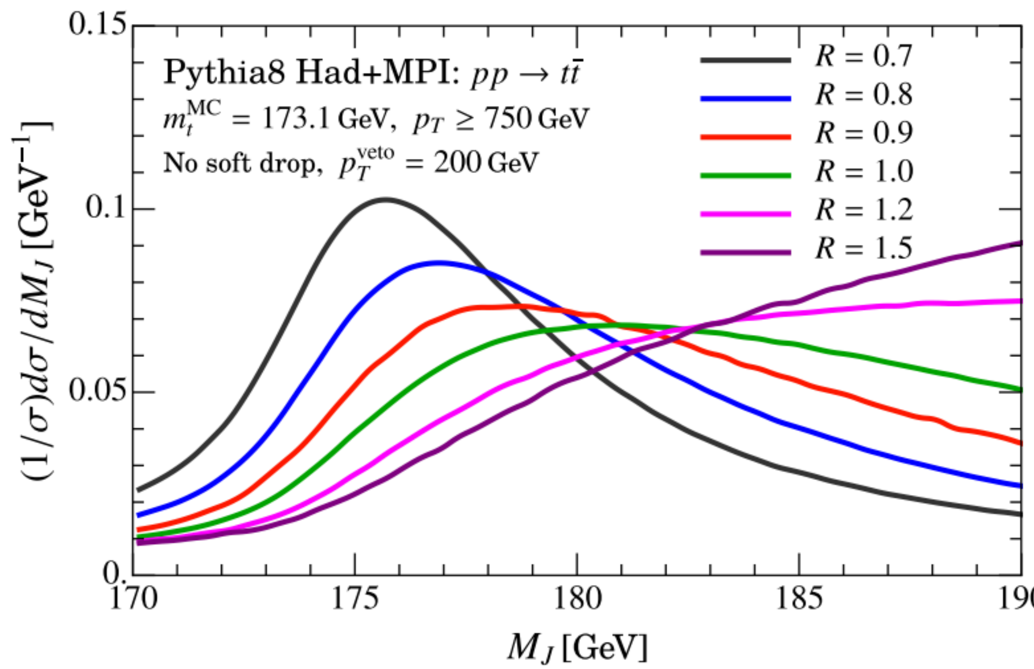
$$\eta \equiv \left[\left(\frac{2m}{Q}\right)^\beta z_{\rm cut}\,\frac{m}{\Gamma_t}\right]^{\frac{1}{\beta+2}}$$

$$\lambda \equiv \frac{m}{Q}$$

- Radius dependence



- With grooming



- Without grooming

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Conclusions

- Factorization formalism for studying jet substructures was presented
- Discussed soft drop grooming and demonstrated its reduced sensitivity to NP wide angle contaminations.
- Groomed jet angularity and its application to α_s extraction was discussed.
- Multi-prong observables and their' application as taggers were discussed.
- Discussed low-mass resonance searches and top quark mass determination using jet substructures.

Thank you!