A Field Theory Look at the Underlying Event

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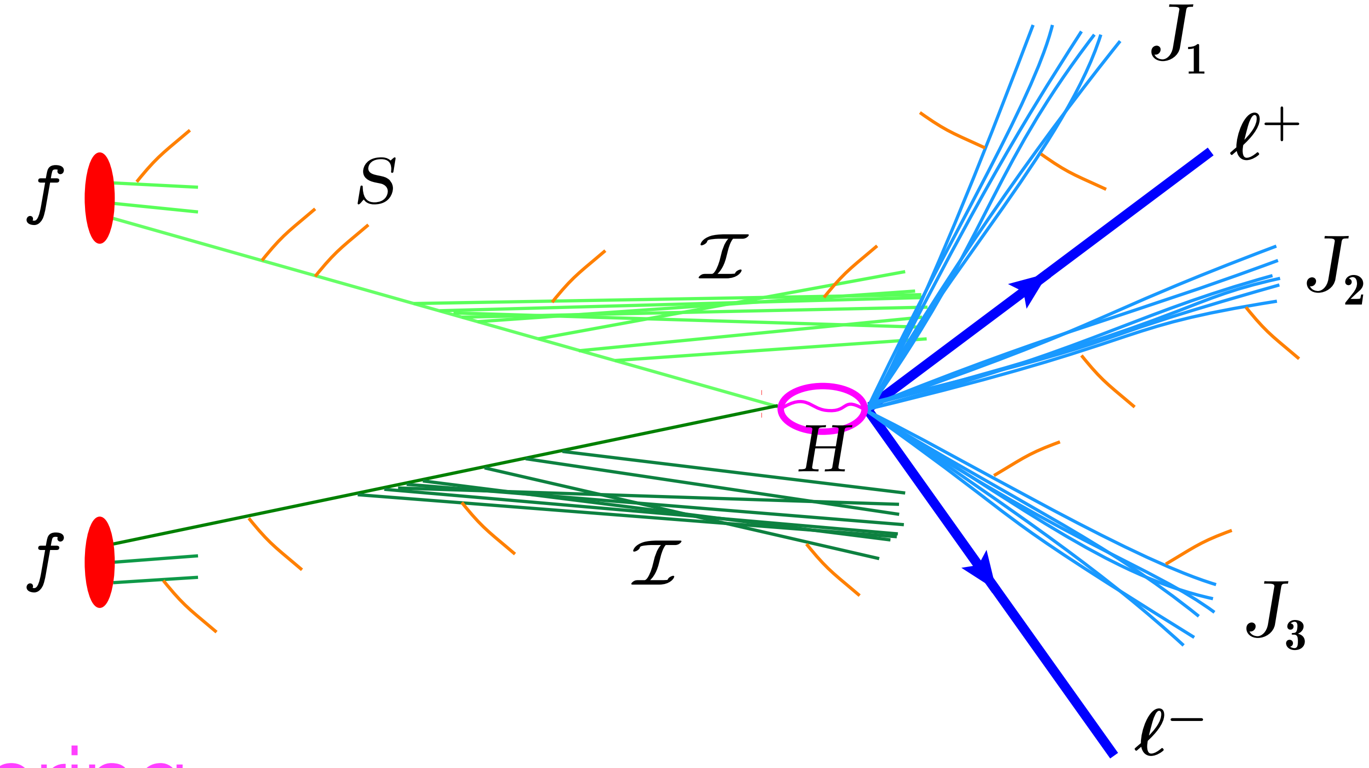
Introduction

Collisions at the LHC

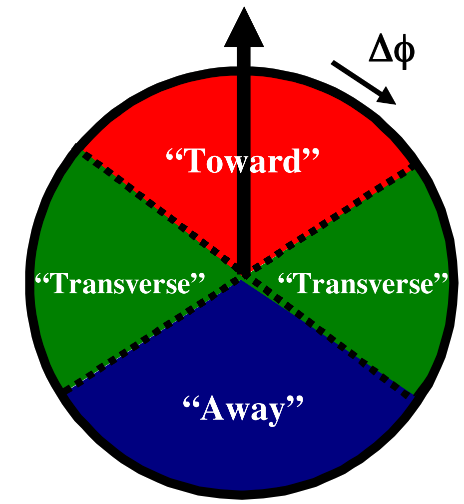


- Hard scattering
- Initial and final state radiation
- Soft radiation
- Hadronization
- Multiparton interactions
- Beam remnants

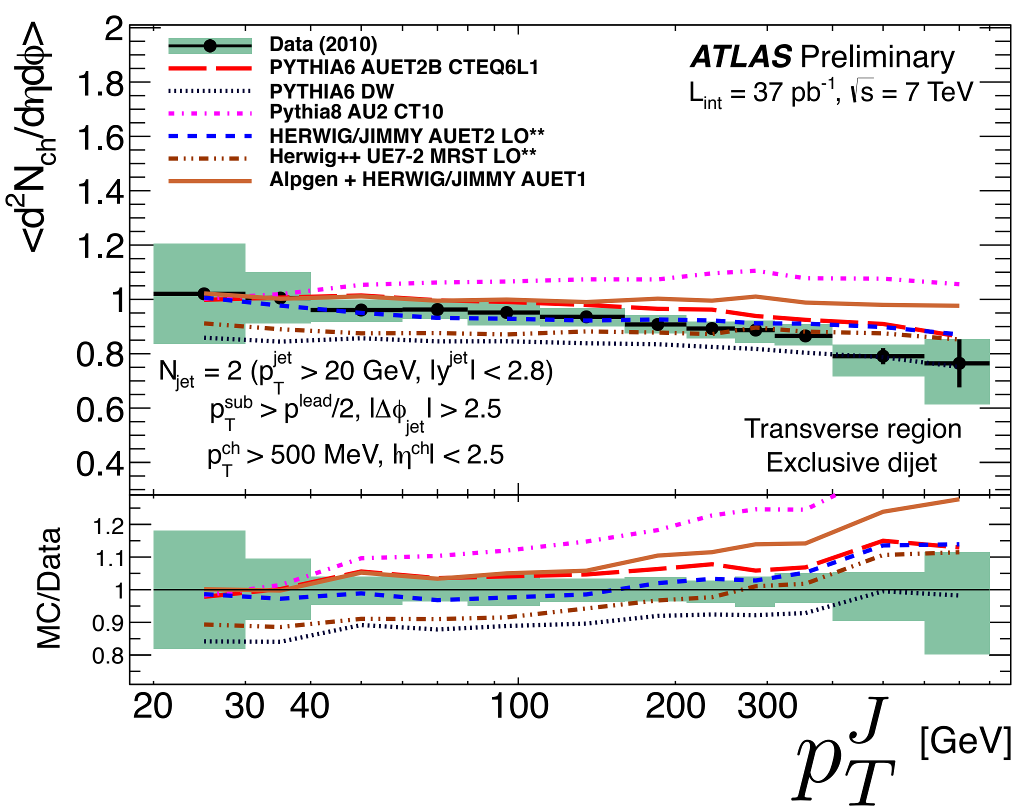
} Standard picture in factorization

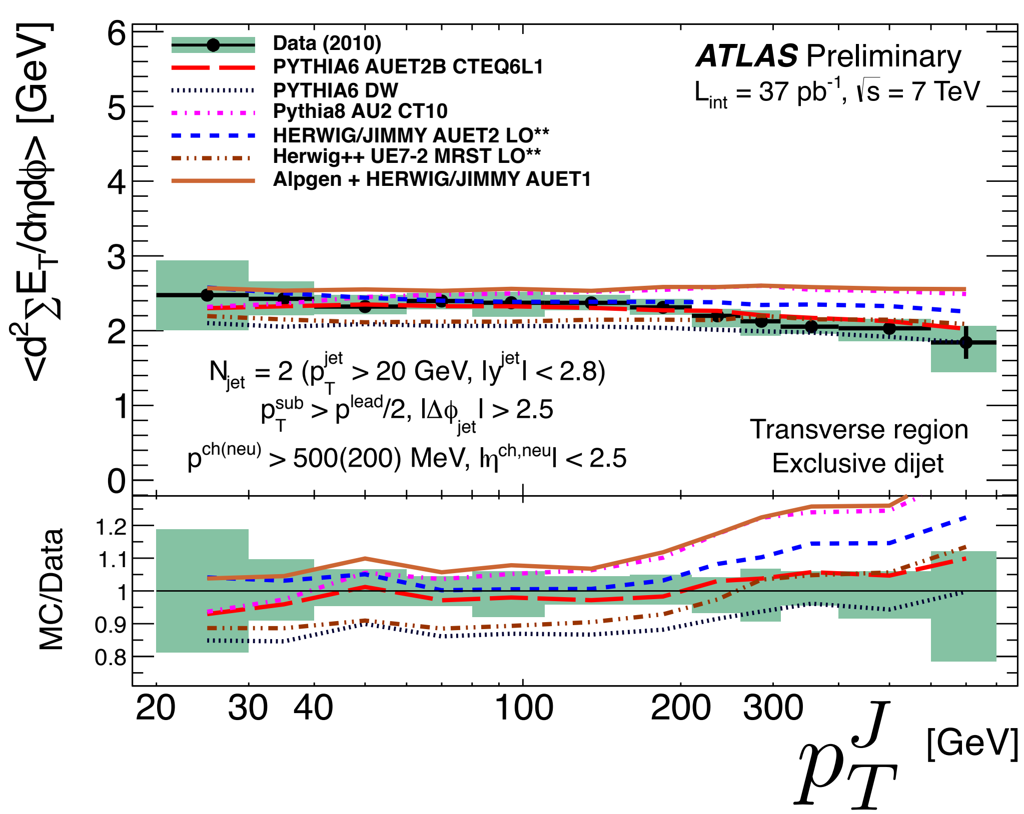
Experimental Evidence for Underlying Event

- Consider transverse region in $pp \to 2\ \mathrm{jets}$
- Charged particle and energy density fairly independent of p_T^J



(Rick Field et.al. 2002)

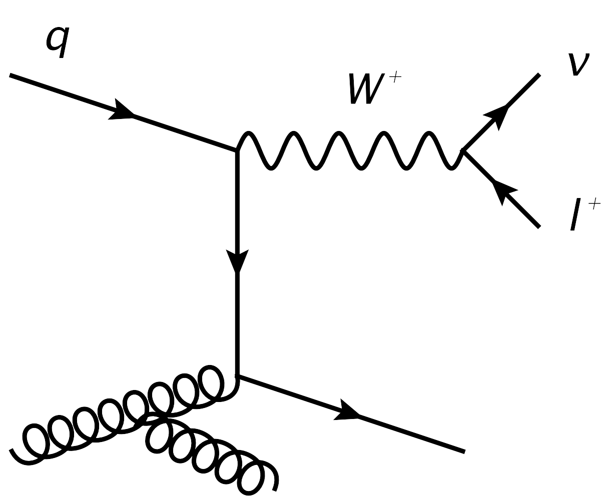




What is the proper field theory description of this effect?

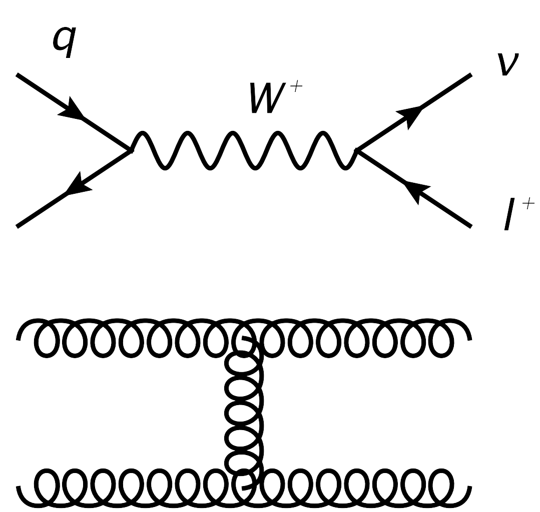
Experimental Evidence: Double Parton Scattering

$$pp \rightarrow W + 2 \text{ jets}$$

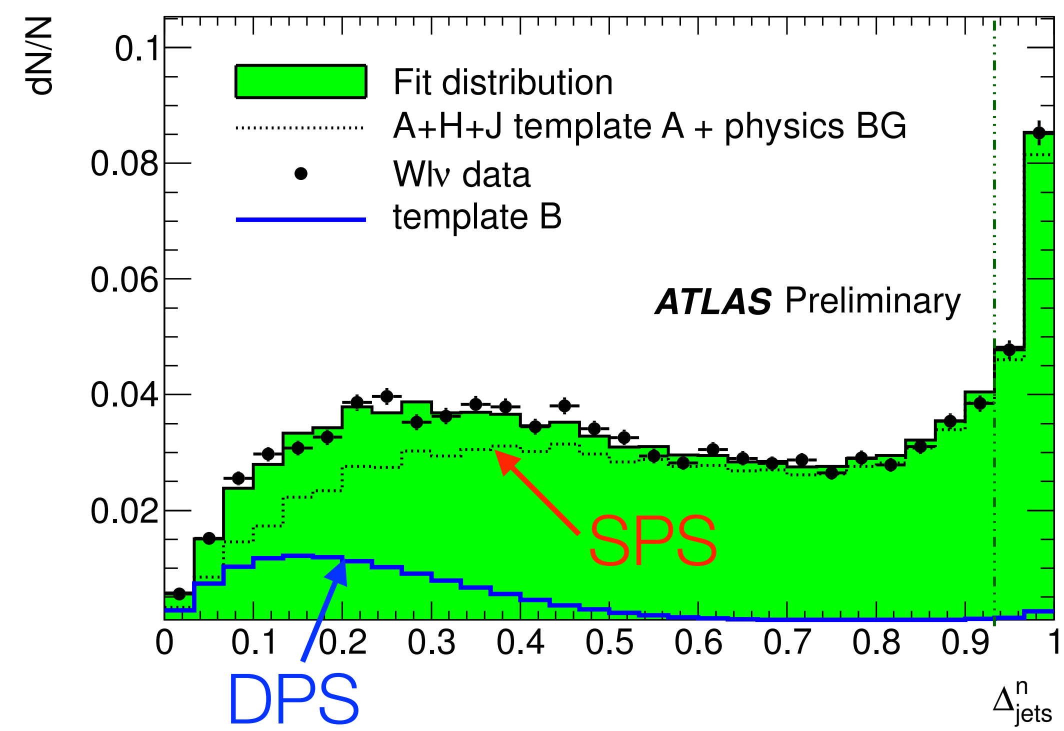


SPS

vs.



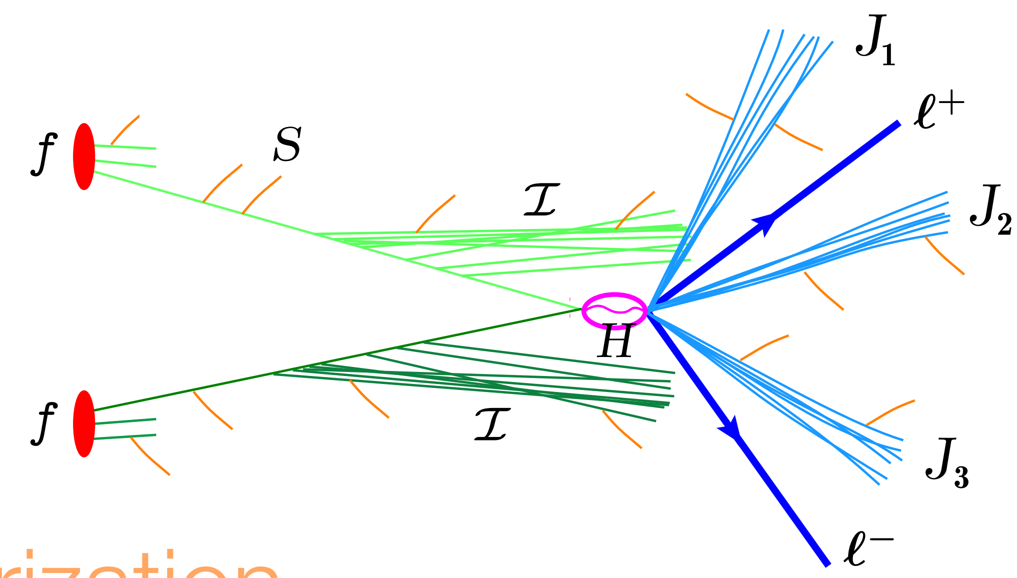
DPS



Recoil of jets

- Additional hard scatterings are suppressed by $\Lambda^2_{\text{QCD}}/Q^2$
- Except for certain phase space regions (e.g. $\Delta^{\text{n}}_{\text{jets}} \sim 0$)

What is the Underlying Event?



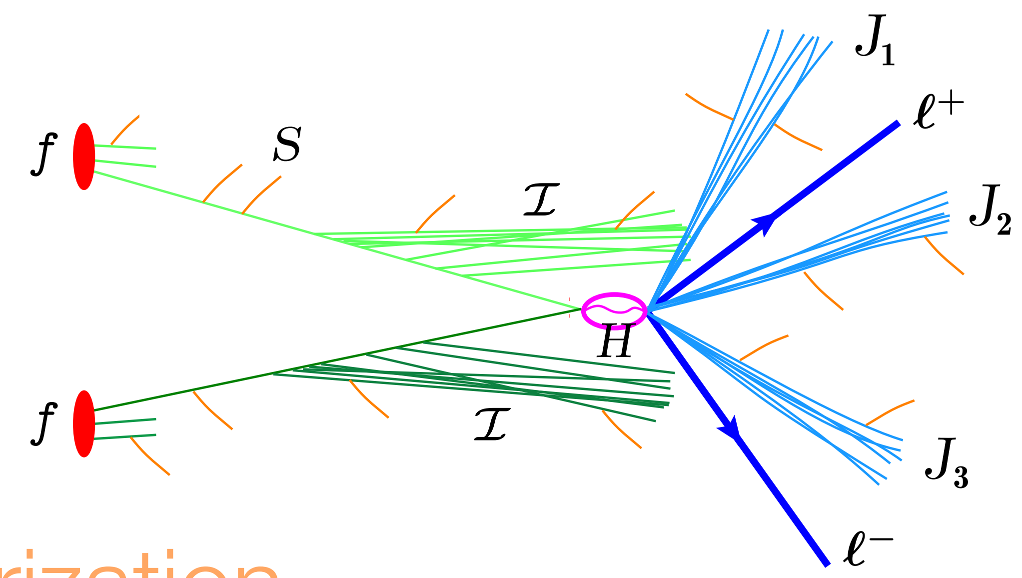
Possible contributions:

1. Primary soft radiation within factorization
2. Multiparton interactions
3. Beam remnants, factorization violation

Monte Carlo programs use 2:

- MI for small Q produce underlying event
- Tuned away from jets and extrapolated to jet regions

What is the Underlying Event?



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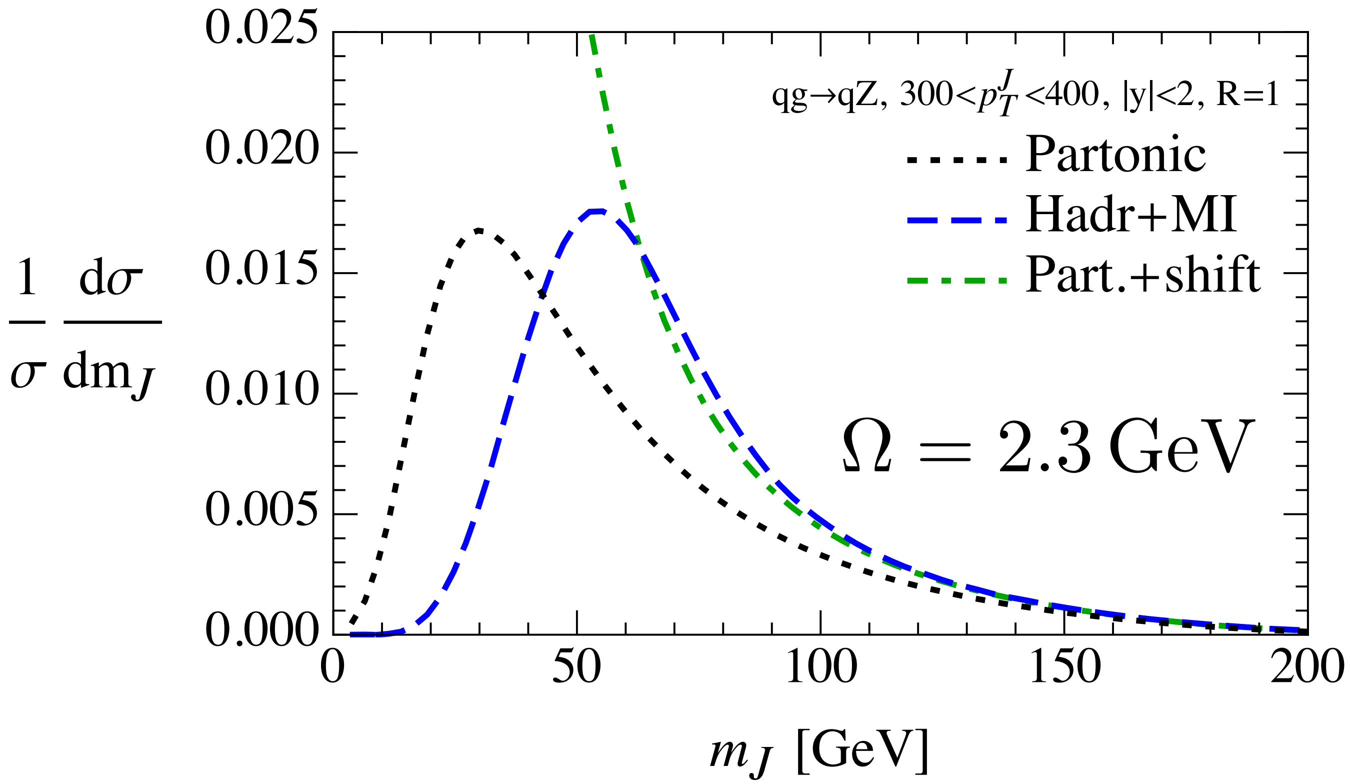
Option 1 can be studied in factorization.
We explore how well using only option 1 works for jet mass.

Underlying Event in Factorization

Hadronization and MI in Pythia describes UE data reasonably well

We will compare the features of the UE in Pythia
with our predictions from factorization

Jet Mass in Pythia vs. Factorization

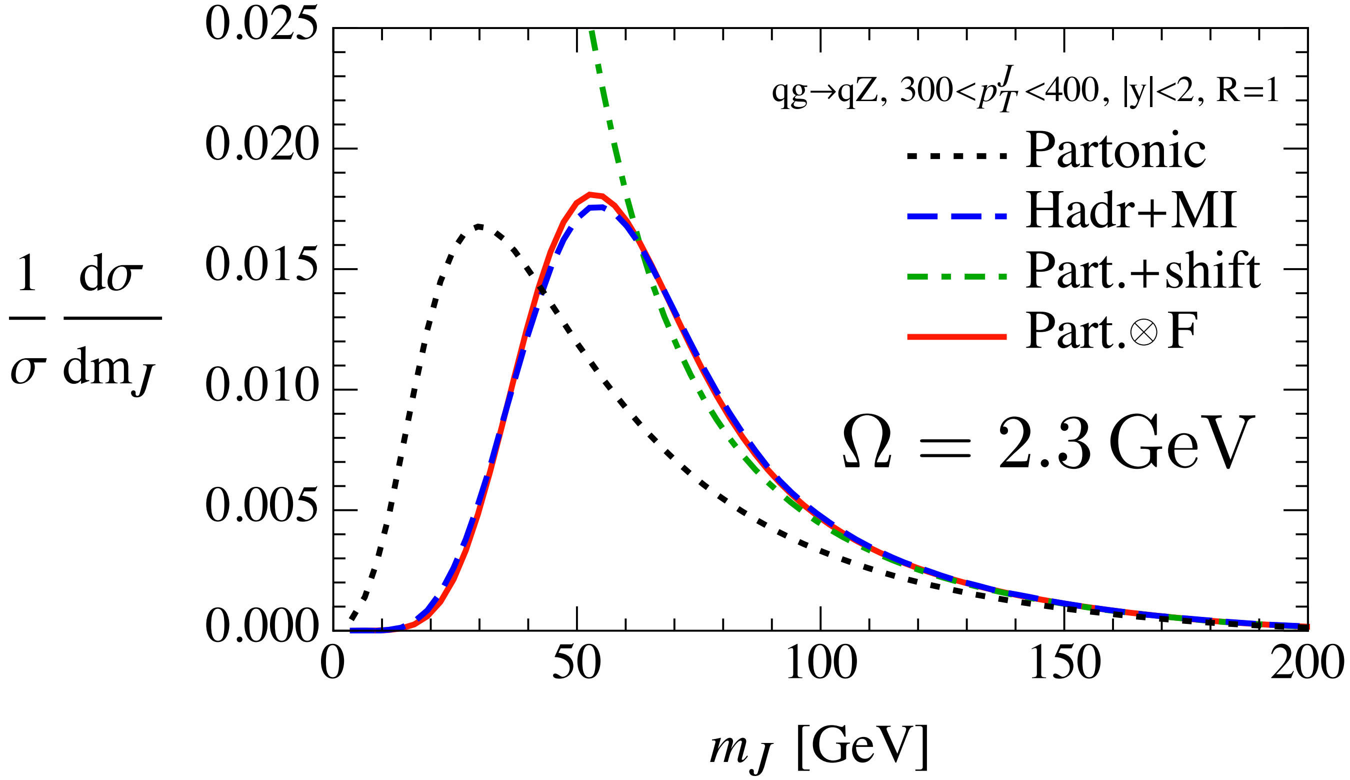


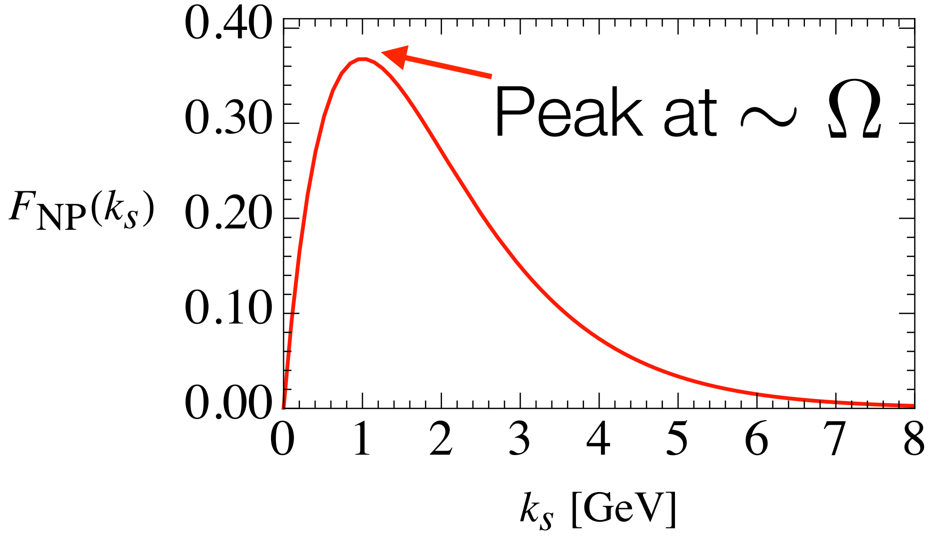
(Always anti-k_T jets)

Factorization expectations:

- In the tail factorization predicts $m_J^2 \to m_J^2 + 2p_T^J\Omega$ which agrees with Hadr.+MI

Factorization reproduces Pythia's Underlying Event





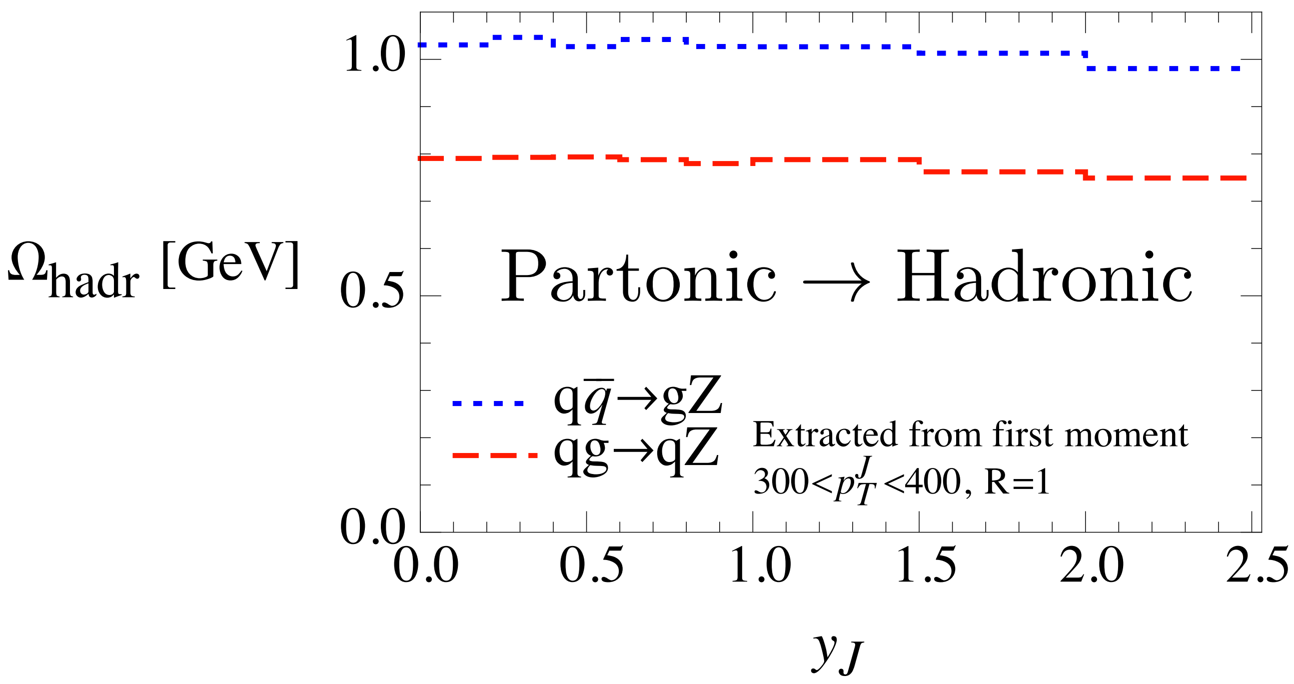
$$\int dk_s\, k_s\, F_{\rm NP}(k_s) = \Omega$$

Factorization expectations:

- In the tail factorization predicts $m_J^2 \to m_J^2 + 2p_T^J\Omega$ which agrees with Hadr.+MI
- More general: $\frac{d\sigma}{dm_J^2} \to \int_0^\infty dk_s\, \frac{d\sigma}{dm_J^2}(m_J^2 - 2p_T^J k_s)\, F_{\rm NP}(k_s)$

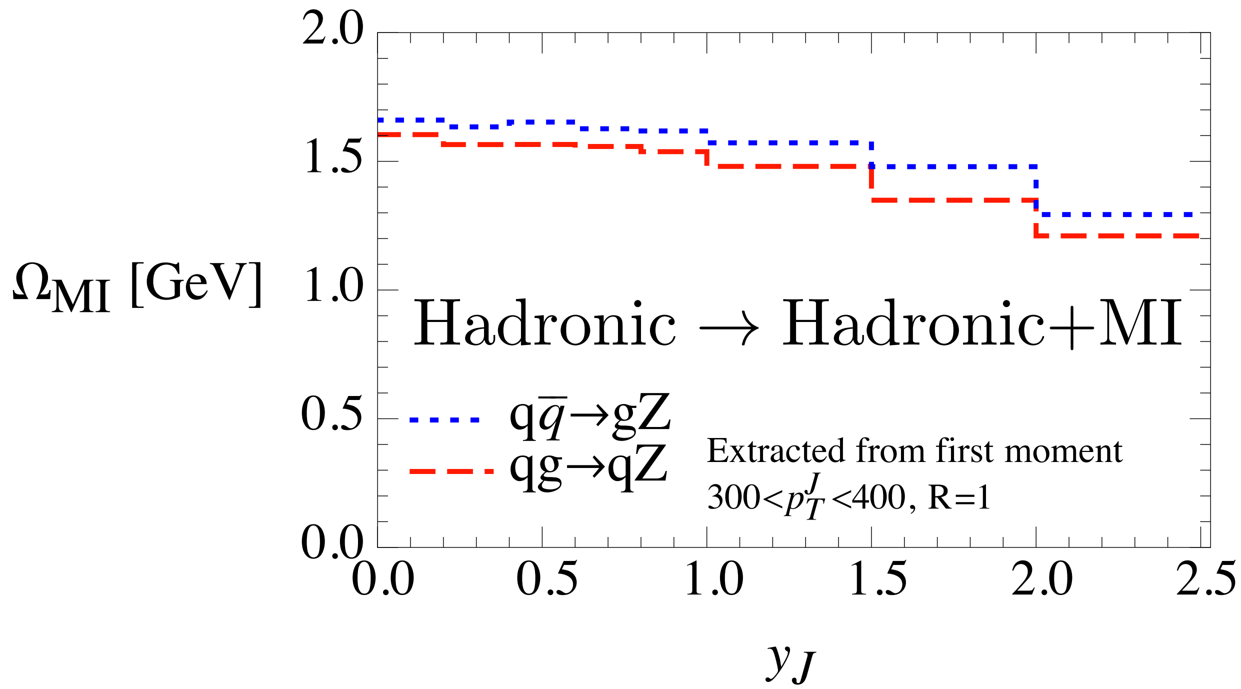
Properties of Ω in Pythia

- Hadr. and MI described by
  $m_J^2 \to m_J^2 + 2p_T^J\Omega$



We find:

- Ω independent of p_T^J
- $\Omega_{\rm hadr}$ independent of y_J, depends on part. channel
- $\Omega_{\rm MI}$ depends on y_J, independent of channel

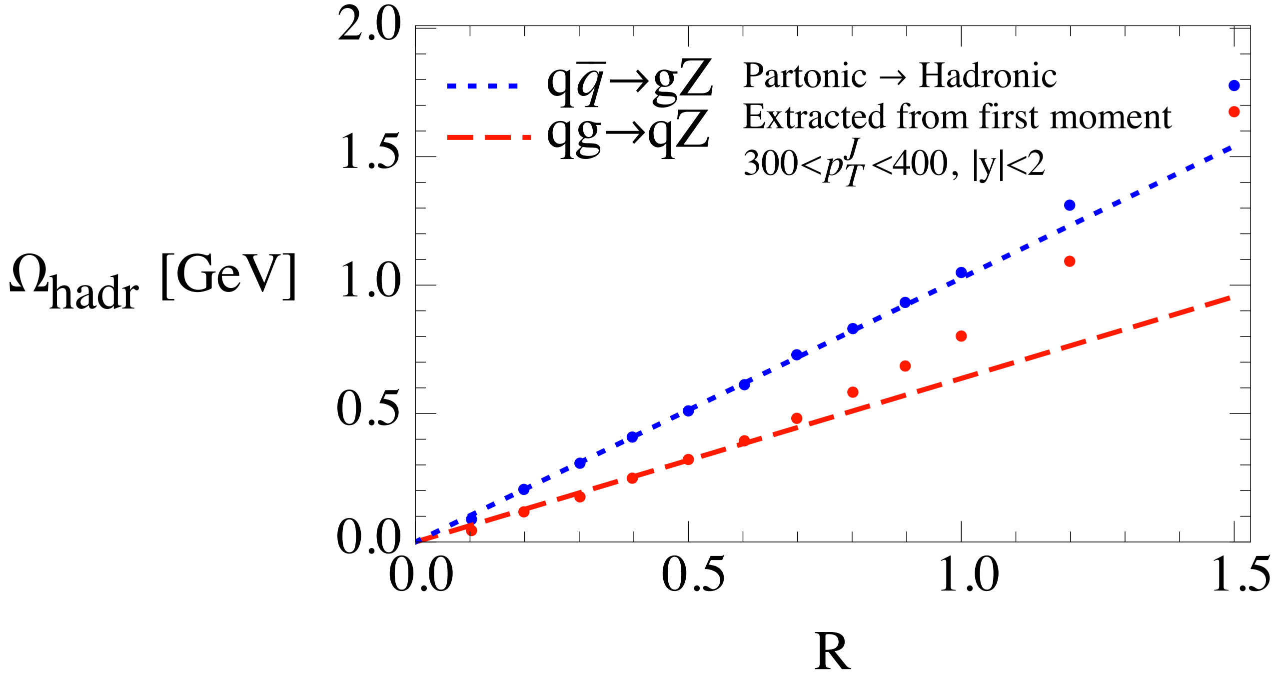


$$\Omega = \Omega_{\rm hadr} + \Omega_{\rm MI}$$

Properties of Ω in Pythia

- Hadr. and MI described by

$$m_J^2 \to m_J^2 + 2p_T^J\Omega$$

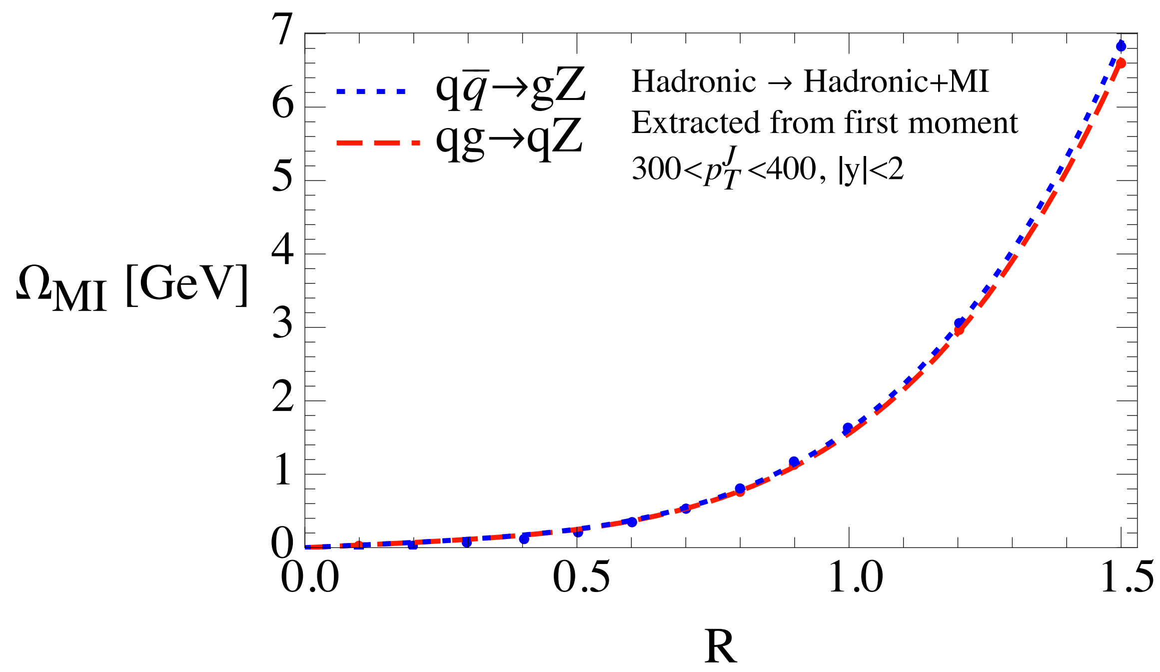


We also find:

- $\Omega_{\rm hadr} \sim R$ for $R \ll 1$
- $\Omega_{\rm MI} \sim R^4 + (\text{smaller }\#)R$

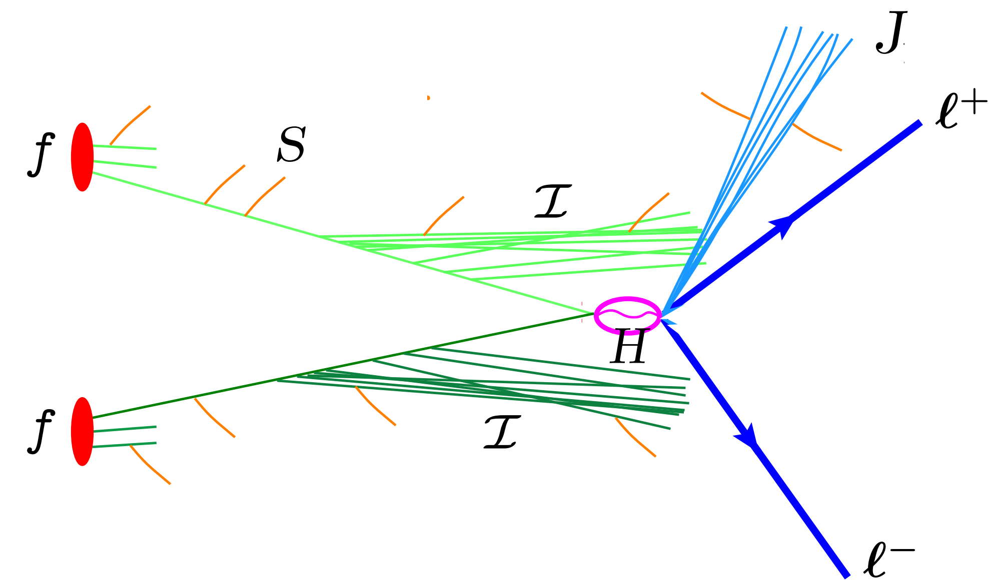
(Agrees with Dasgupta et.al. 0712.3014)

additional hadronization



Which properties (dis)agree if primary soft radiation accounts for UE?

Factorization for Jet Mass



$$\frac{d\sigma}{dm_J^2} = f\, f\, \mathcal{I}\, \mathcal{I}\, H \int dk_s\, J(m_J^2 - 2p_T^J k_s)\, S(k_s)$$

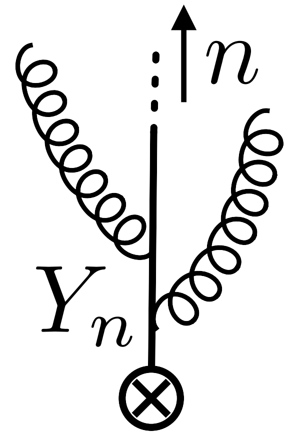
Jet function Soft function

- Soft function describes primary soft radiation:

$$S(k_s) = \langle 0 | Y_J^\dagger(y_J) Y_{\bar{n}}^\dagger Y_n^\dagger\, \delta(k_s - \cosh y_J\, n_J \cdot \hat{p}_J)\, Y_n Y_{\bar{n}} Y_J(y_J) | 0 \rangle$$

Measurement

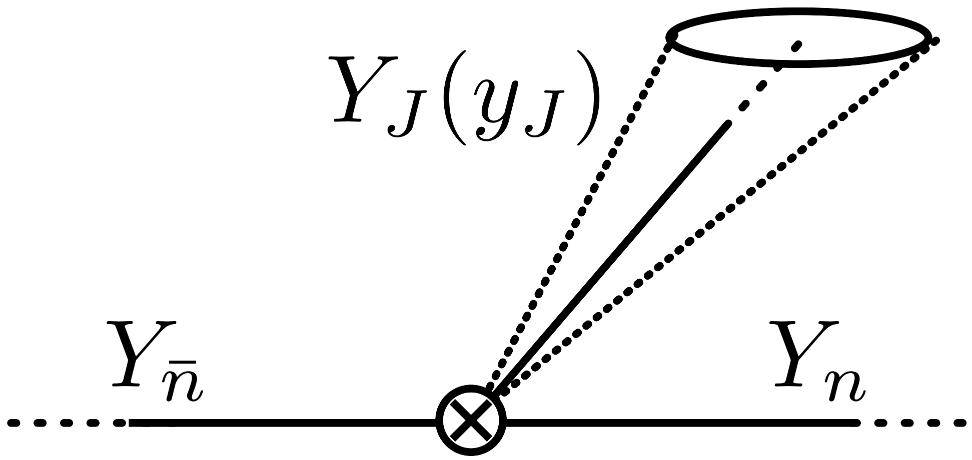
- Color indices are not written out
- Factorization implies that Ω is independent of p_T^J



Factorization for Jet Mass

$$\Omega = \langle 0 | Y_J^\dagger(y_J) Y_{\bar{n}}^\dagger Y_n^\dagger \; \cosh y_J \, n_J \cdot \hat{p}_J \, Y_n Y_{\bar{n}} Y_J(y_J) | 0 \rangle$$

Momentum in jet

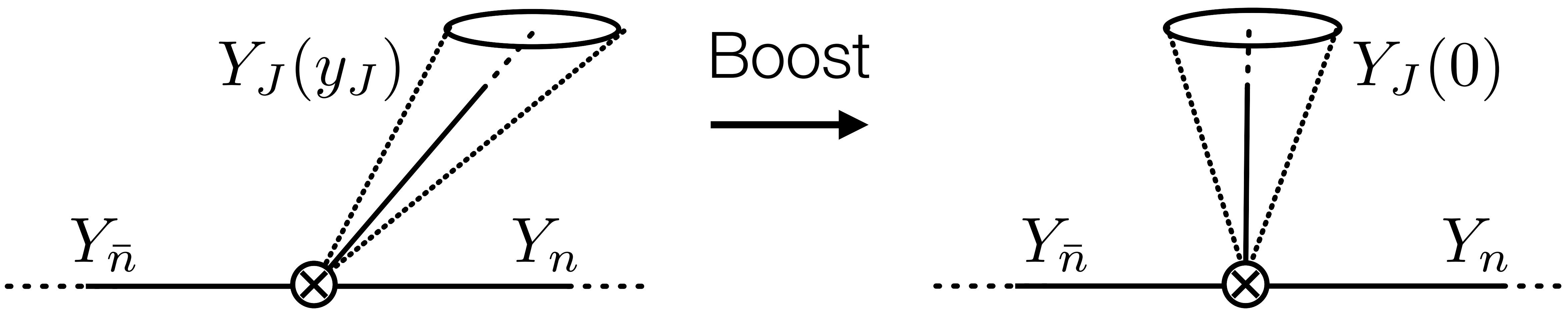


- Y's and thus Ω depend on quark vs. gluon (color config.)

Factorization for Jet Mass

$$\Omega = \langle 0 | Y_J^\dagger(y_J) Y_{\bar{n}}^\dagger Y_n^\dagger \, \cosh y_J \, n_J \cdot \hat{p}_J \, Y_n Y_{\bar{n}} Y_J(y_J) | 0 \rangle$$

Momentum in jet

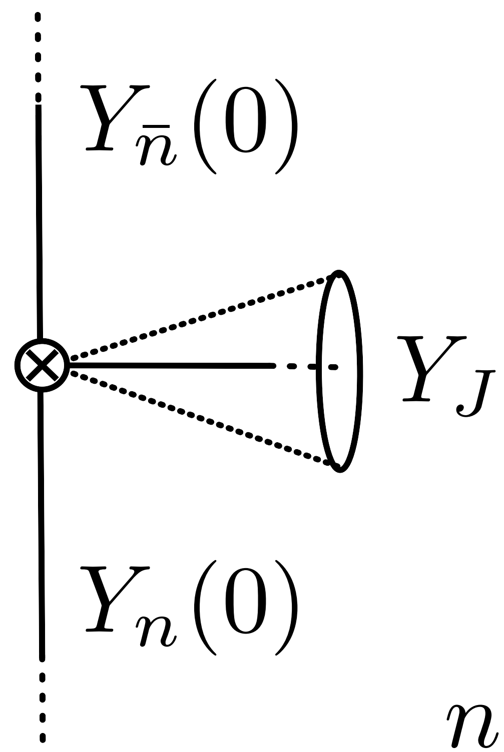


- Y's and thus Ω depend on quark vs. gluon (color config.)
- Boosting shows that Ω is independent of y_J

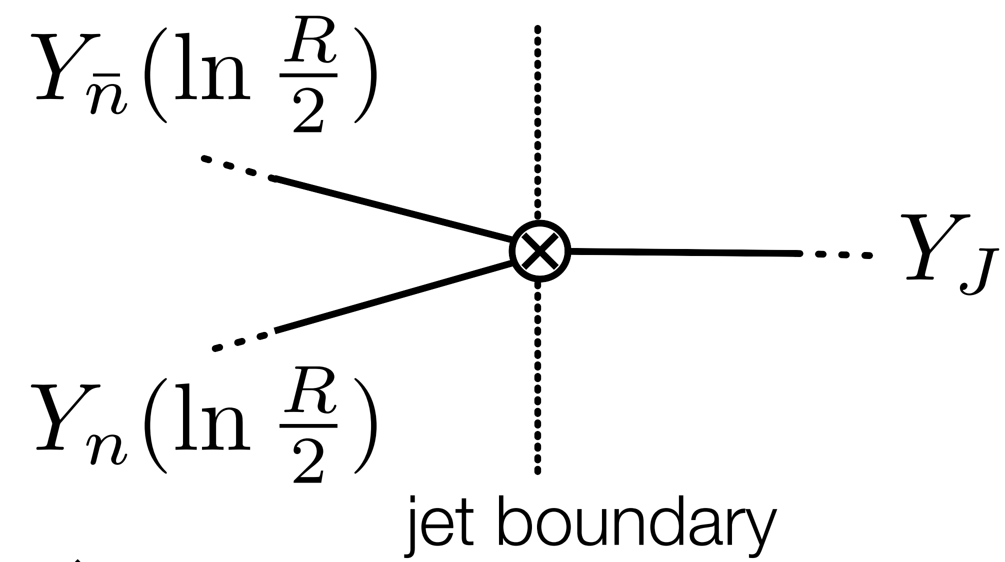
But unlike e^+e^- the rapidity dependence of the observable matters

Dependence on Jet Radius R

Rotate coordinate system



Boost →

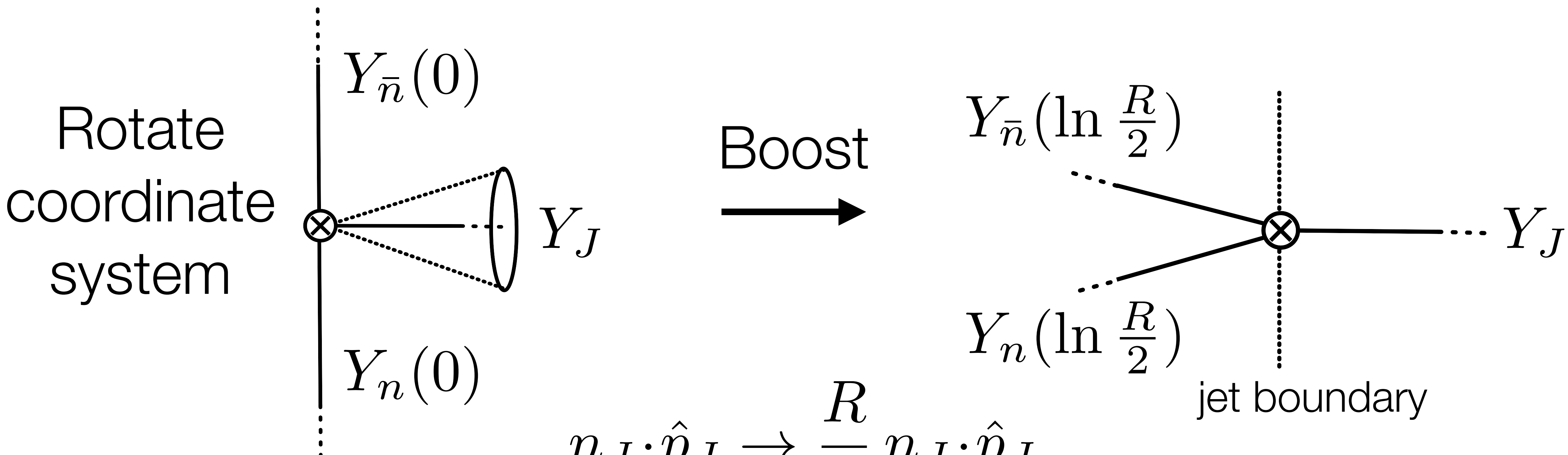


$$n_J \cdot \hat{p}_J \to \frac{R}{2}\, n_J \cdot \hat{p}_J$$

$$\Omega = \frac{R}{2}\int_0^\infty dy\, e^{-y} \langle 0| Y_J^\dagger Y_{\bar{n}}^\dagger(\ln \tfrac{R}{2}, \pi) Y_n^\dagger(\ln \tfrac{R}{2}, 0) \hat{\mathcal{E}}_\perp(r, y, \phi)(...)|0\rangle$$

Energy flow

Jet Radius Dependence



$$n_J \cdot \hat{p}_J \to \frac{R}{2}\, n_J \cdot \hat{p}_J$$

$$\Omega = \frac{R}{2} \int_0^\infty dy\, e^{-y} \langle 0 | Y_J^\dagger Y_{\bar{n}}^\dagger (\ln \tfrac{R}{2}, \pi) Y_n^\dagger (\ln \tfrac{R}{2}, 0) \underbrace{\hat{\mathcal{E}}_\perp (r, y, \phi)}_{\text{Energy flow}} (...) | 0 \rangle$$

- For $R \ll 1$, the beam Wilson lines fuse and $\boxed{\Omega = \frac{R}{2}\, \Omega_0 + \ldots}$
- The universal Ω_0 can be extracted from DIS event shapes

(DIS Ω_0: Dasgupta, Salam; Kang, Liu, Mantry, Qiu; Kang, Lee, Stewart)

"Underlying Event" Contribution

- No formal separation between hadronization and UE, but there are higher order in R contributions
- Decompose the measurement using energy flow $\mathcal{E}_T$

$$\Omega = \int_0^1 dr \int_{-\infty}^{\infty} dy \int_0^{2\pi} d\phi \, f(r, y, \phi, R) \langle 0 | Y_J^\dagger(0) Y_{\bar{n}}^\dagger Y_n^\dagger \, \hat{\mathcal{E}}_T(r, y, \phi) \, Y_n Y_{\bar{n}} Y_J(0) | 0 \rangle$$

$$f_E(r, y, \phi, R) = \theta(y^2 + \phi^2 < R^2) \left[(1 - r) + \frac{1}{2} y^2 + \frac{r}{2} \phi^2 + \dots \right]$$

Transverse velocity   Jet region   Momentum projection

- Ignoring the jet Wilson line, $\hat{\mathcal{E}}_T(r, y, \phi)$ is approx. constant

$$\Omega_{\rm UE} = \int_0^1 dr \left[(1 - r) \pi R^2 + \frac{1}{8} (1 + r) \pi R^4 \right] \hat{\mathcal{E}}_T(r)$$

- In the massless case ($r = 1$), we find $\Omega_{\rm UE} \sim R^4$

Perturbative Radiation

- There are perturbative and nonperturbative soft effects

$$S_{\rm pert} \to S_{\rm pert} \otimes F_{\rm NP}$$

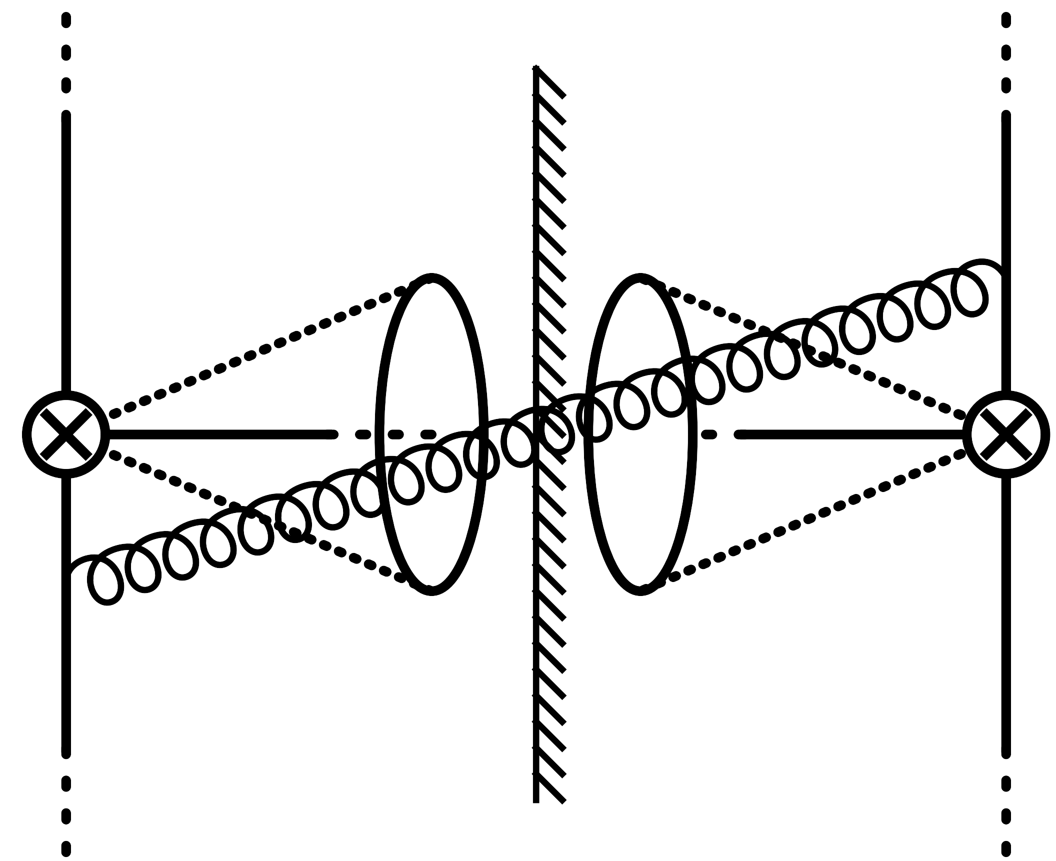
(discussed before)

- Perturbative "UE" contribution

$$S_{\rm pert} = \underbrace{I_0}_{=R^2} \underbrace{\frac{\alpha_s C}{\pi} \frac{1}{\mu} \frac{-1}{(k_s^+/\mu)}_+}_{\sim R^2 \text{ with Sudakov}} + \dots$$

(Jouttenus et.al.)

- Parton channels have different color factor C and Sudakov



Conclusions

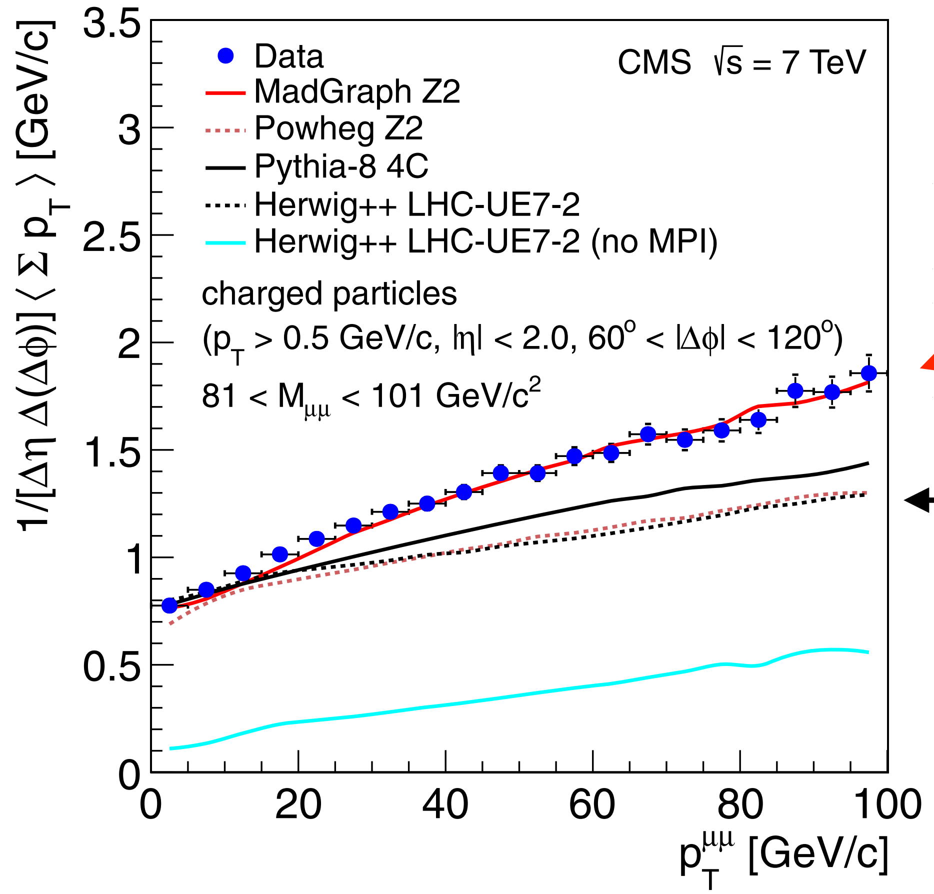
- The underlying event for jet mass is described by a single parameter and is consistent with multiple interactions (Pythia) but also with primary soft radiation in factorization

Ω's dependence	Pythia (hadr, MI)	Factorization
Partonic channel	Yes, No	Yes
p_T^J	No, No	No
y_J	No, Yes	No
R	$R + \dots, R^4 + \dots$	$R, R^2, R^4, \dots$

- Factorization relates the coefficient of leading R term to hadronization effects in DIS event shapes

Backup

Underlying Event from Higher Order Corrections



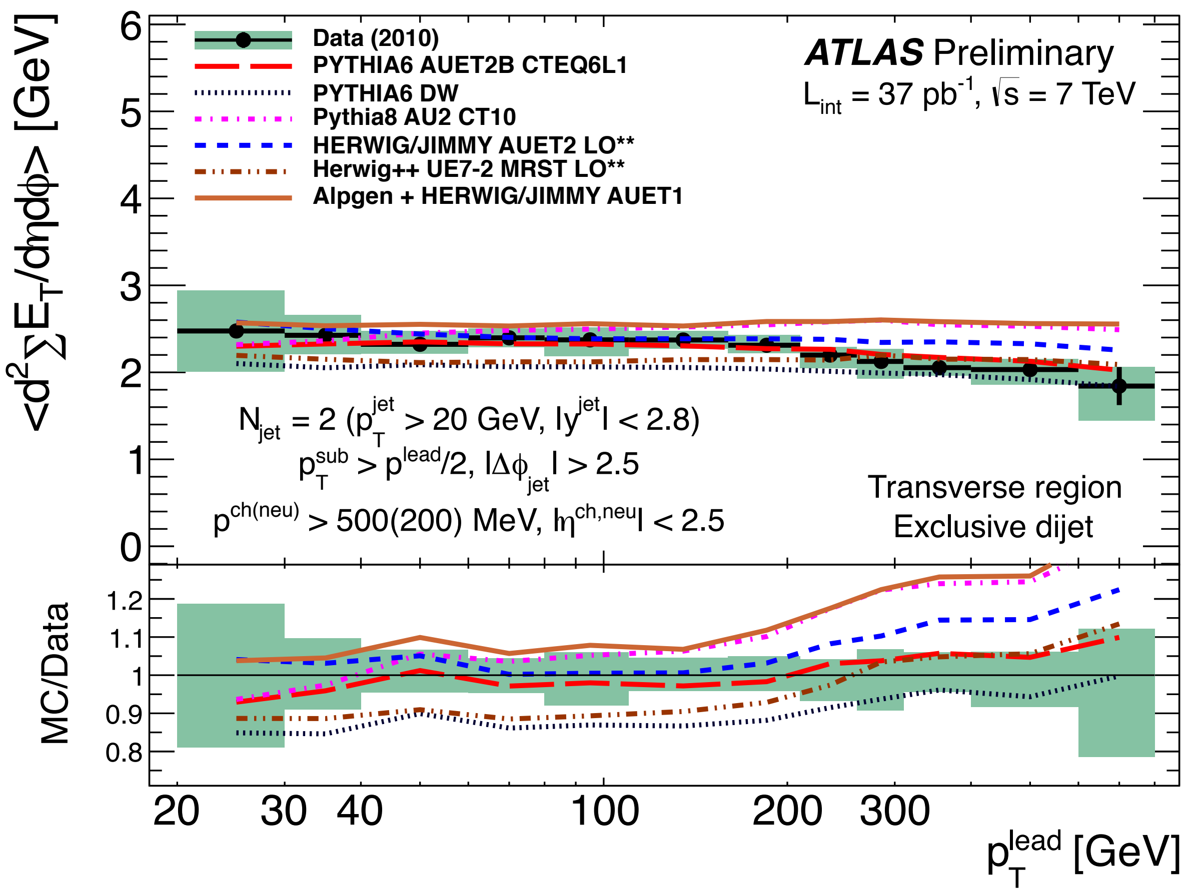
Including LO matrix elements with more final state partons

Standard Pythia/Herwig

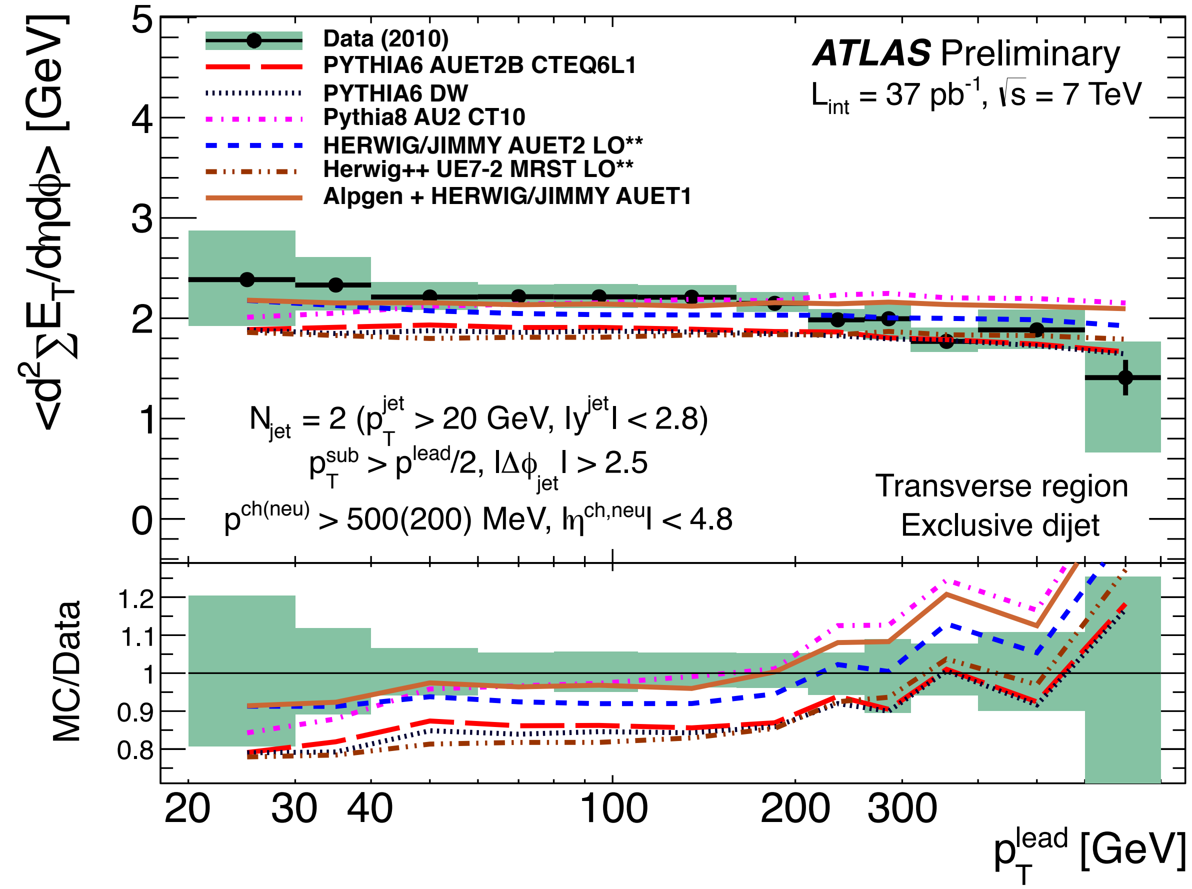
- Higher order effects significantly improve description of data
- Part of “UE” can be from perturbative primary partons

Rapidity Dependence in LHC Data

Central rapidity



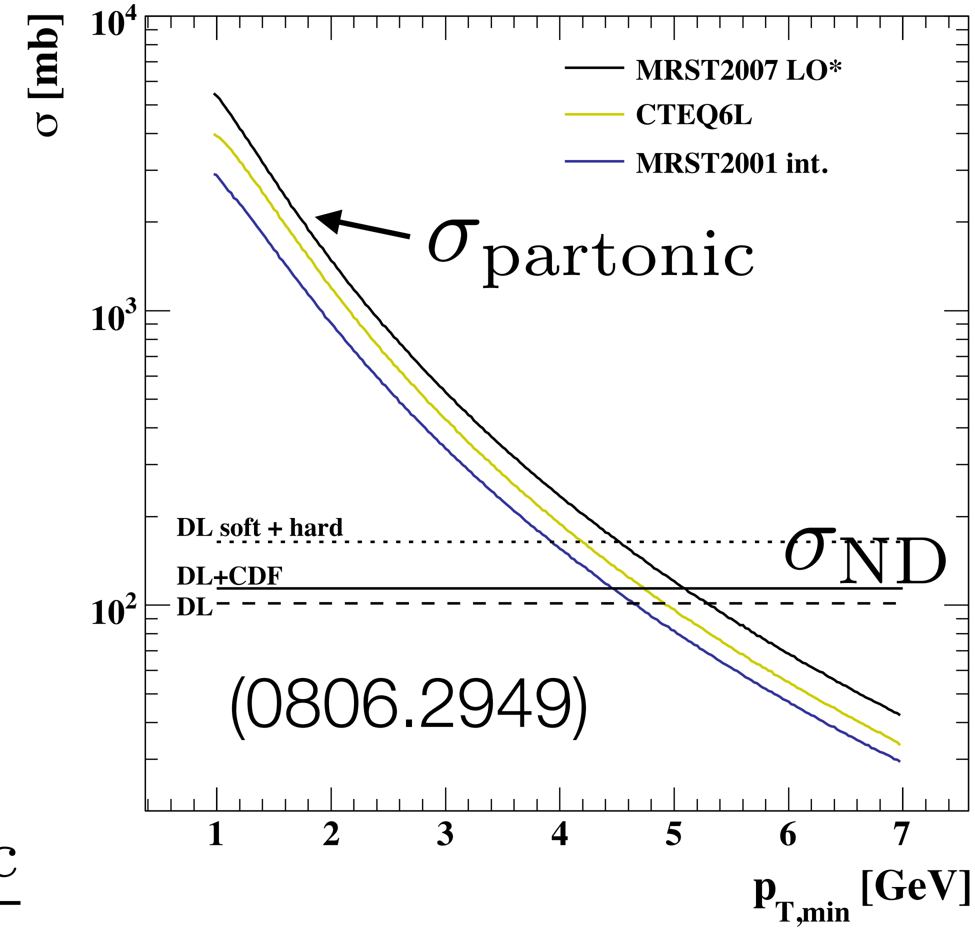
Full rapidity



Energy density going from central to full rapidity range:

- Almost no change in data (agrees with factorization)
- But reduced in multiple interaction models

Multiparton Interactions in Pythia



- t-channel singularity of partonic cross section implies MI:

$$\text{average \# of interactions} = \frac{\sigma_{\mathrm{partonic}}}{\sigma_{\mathrm{ND}}}$$

Non-Diffractive

- Relationship with Double Parton Scattering:

$$\sigma_{\mathrm{DPS}} = \frac{1}{2}\left(\frac{\sigma_{\mathrm{SPS}}}{\sigma_{\mathrm{ND}}}\right)^2 \sigma_{\mathrm{ND}} \times \frac{\sigma_{\mathrm{ND}}}{\sigma_{\mathrm{eff}}} = \frac{\sigma_{\mathrm{SPS}}^2}{2\sigma_{\mathrm{eff}}}$$

Poisson distribution   Correction