Jet Substructure at the LHC

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DESY - May 19, 2014

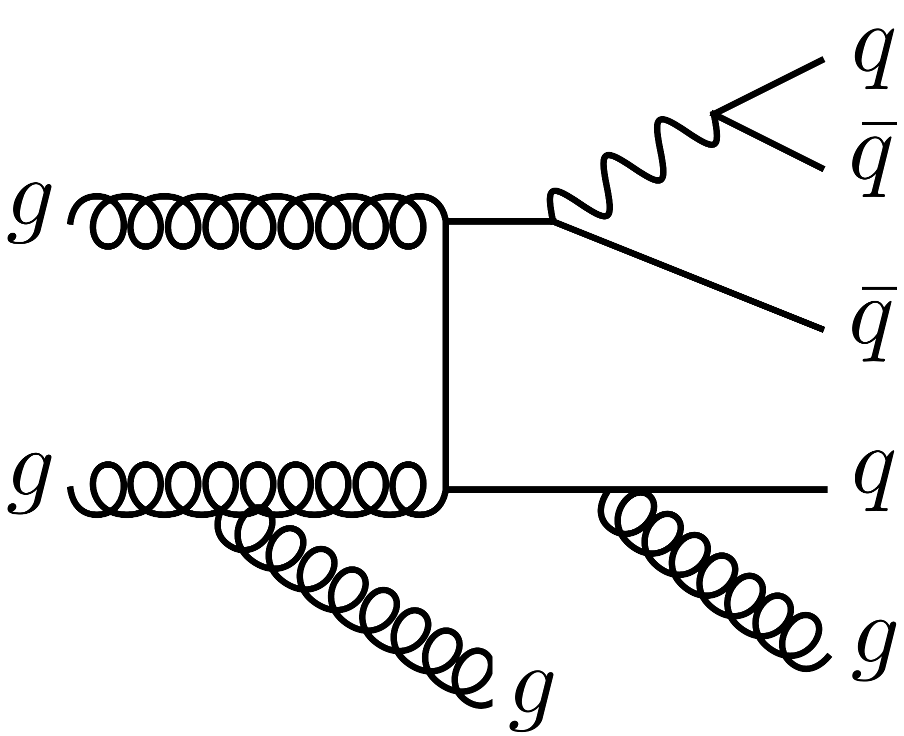
Outline

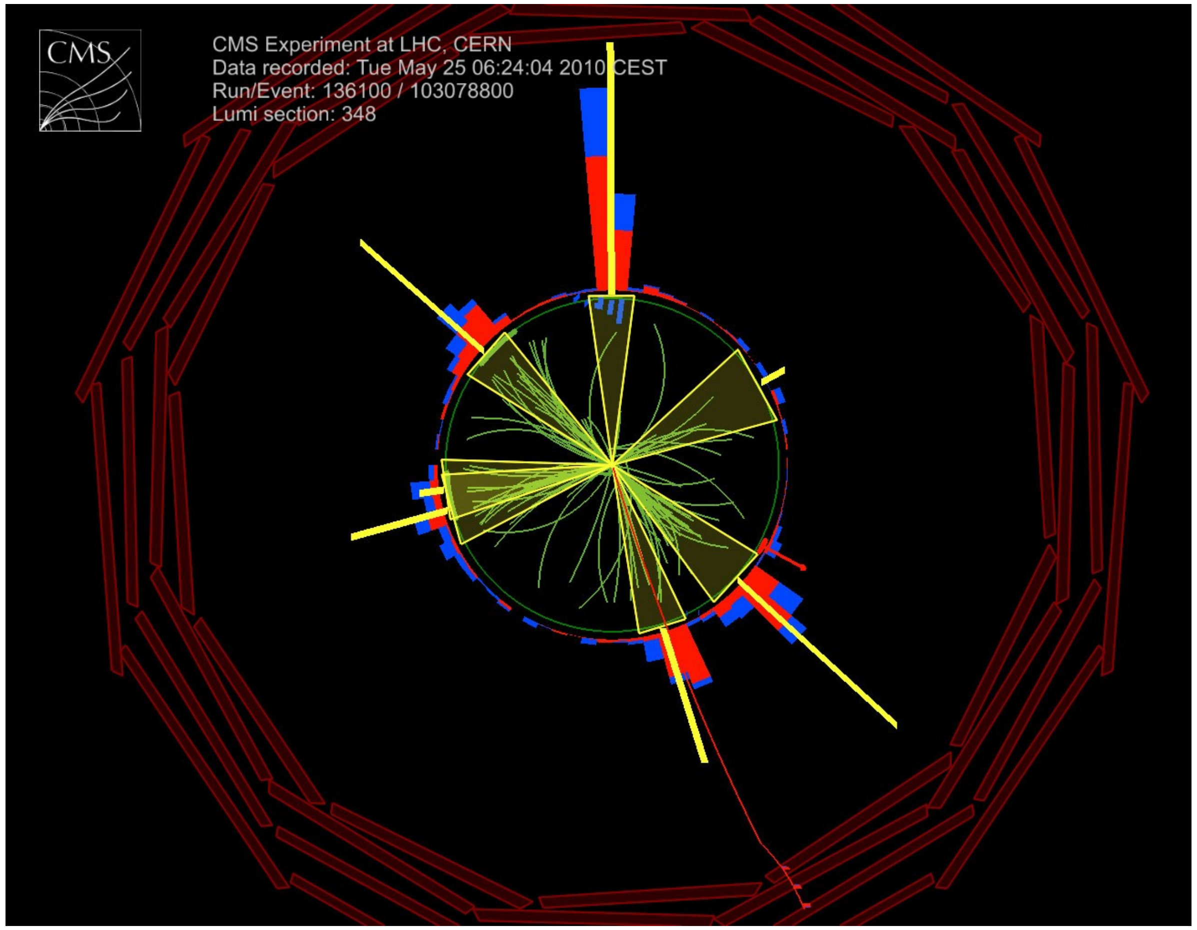
- Introduction
- Jet Charge
- Track-Based Observables
- Jet Mass
- Hadronization of Jets
- Conclusions

Introduction

What is a Jet?

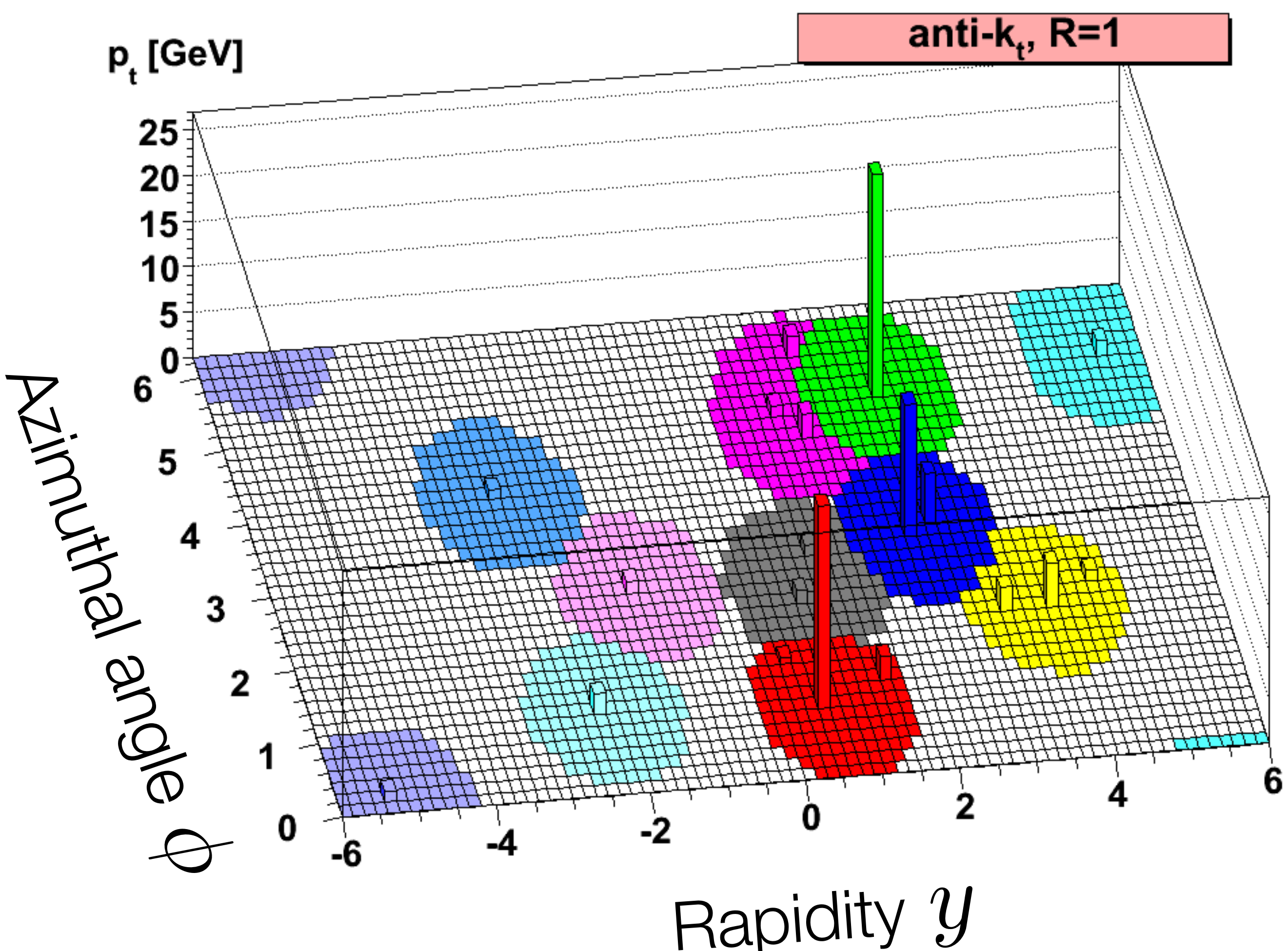
Energetic quarks and gluons radiate and hadronize $\rightarrow$ Produce jets of hadrons





Jet Algorithms

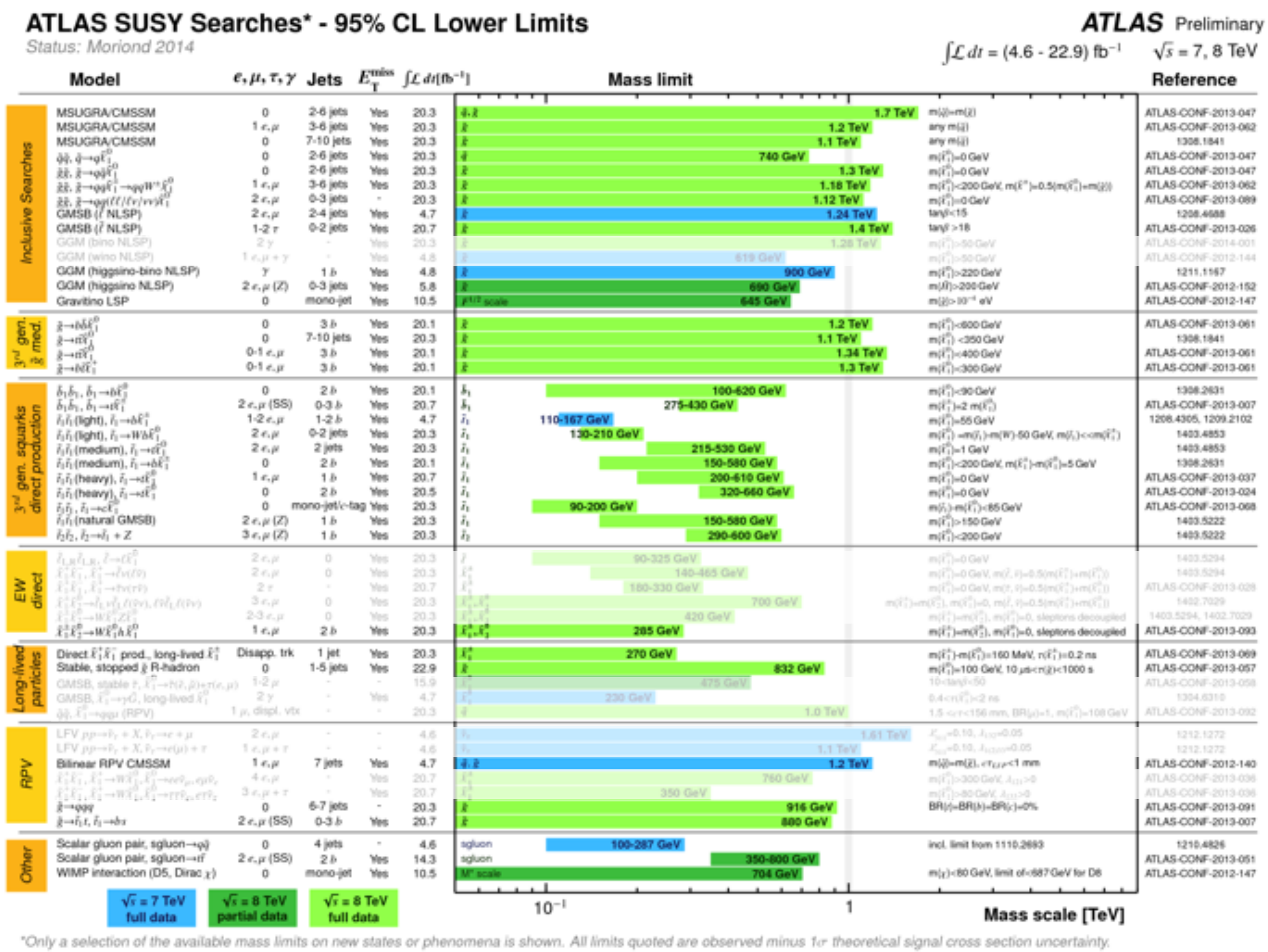
- Repeatedly cluster nearest "particles" $p_i, p_j \to p_i + p_j$
- Cut off by jet radius R
- Default at LHC: anti-k_T (Cacciari, Salam, Soyez)



(arXiv:0802.1189)

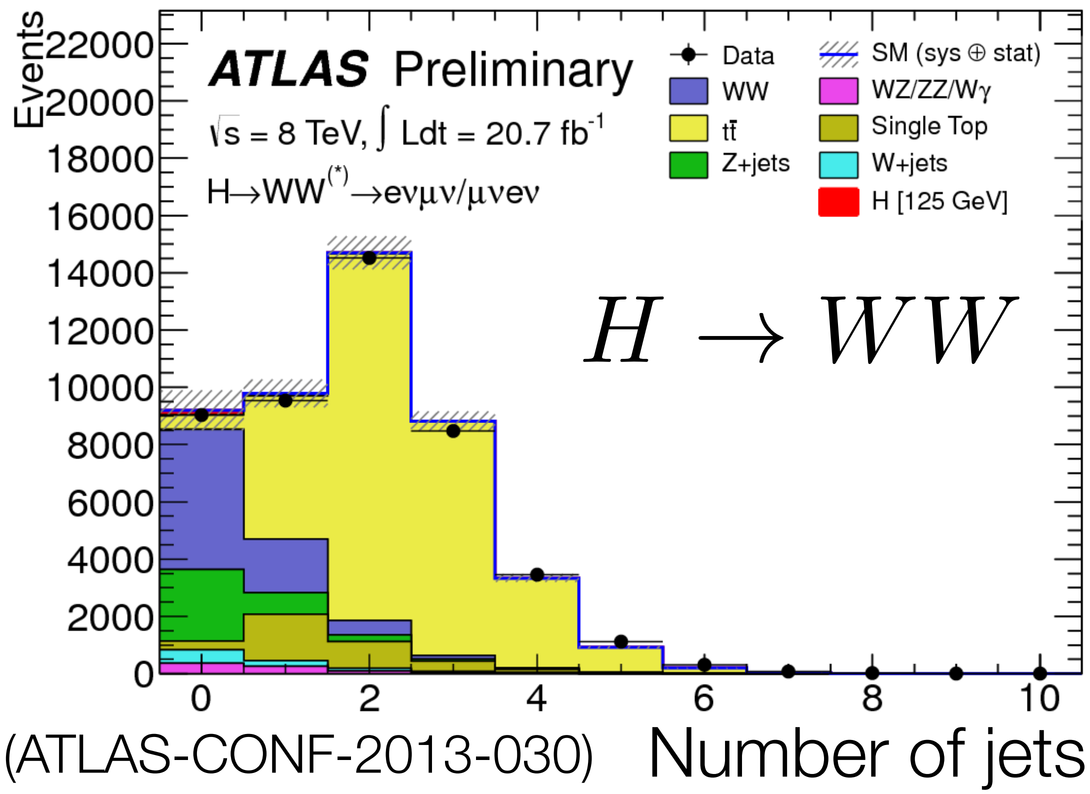
Jets at the LHC

- Most measurements involve jets as signal or background



Jet Cross Sections

- Bin by jet multiplicity to improve background rejection



(ATLAS-CONF-2013-030)

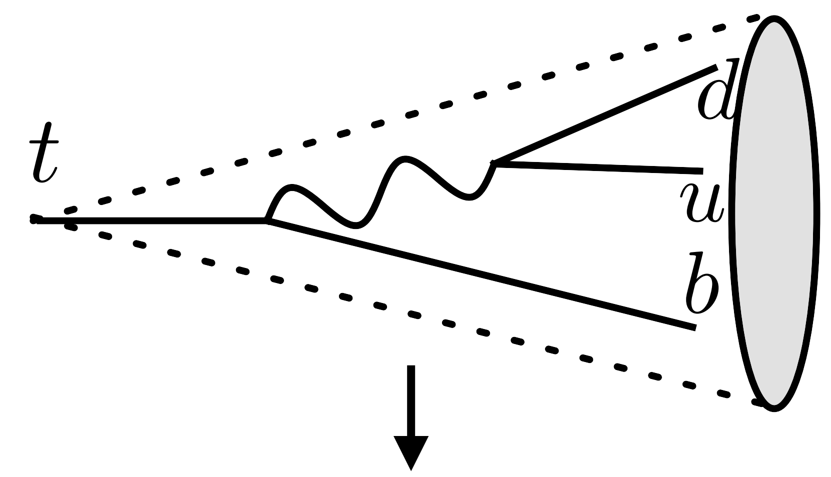
- Large logarithms lead to large theory uncertainties

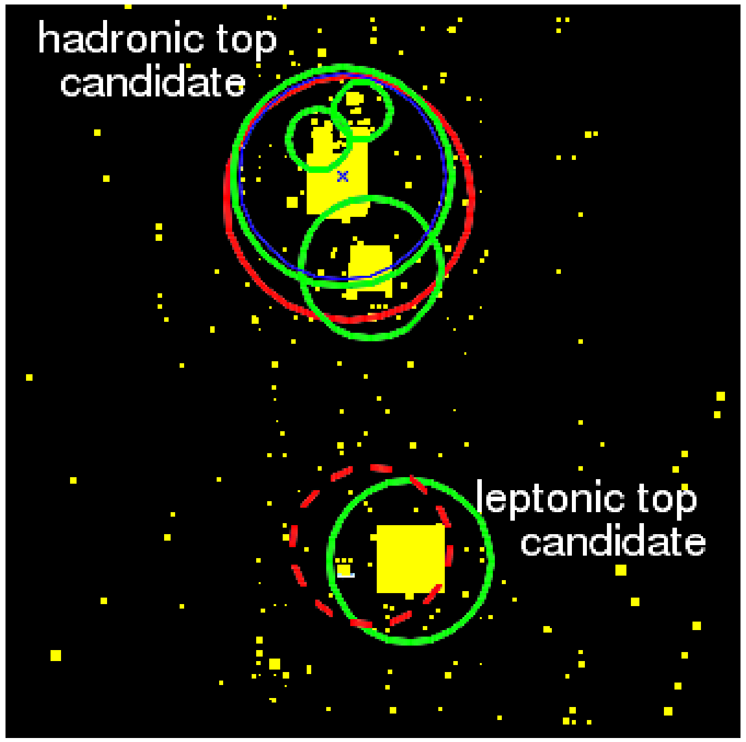
$$\sigma(H + 0\text{ jets}) \propto 1 - \frac{6\alpha_s}{\pi} \ln^2 \frac{p_T^{\text{cut}}}{m_H} + \ldots$$

(Berger, Marcantonini, Stewart, Tackmann, WW; Banfi, Monni, Salam, Zanderighi, Becher, Neubert, Rothen; Stewart, Tackmann, Walsh, Zuberi; Liu, Petriello; Boughezal, Liu, Petriello, Tackmann, Walsh; Bernlocher, Gangal, Gillberg, Tackmann, …)

Jet Substructure for Boosted Objects

- Decay products of boosted t, W, H can lie within one jet

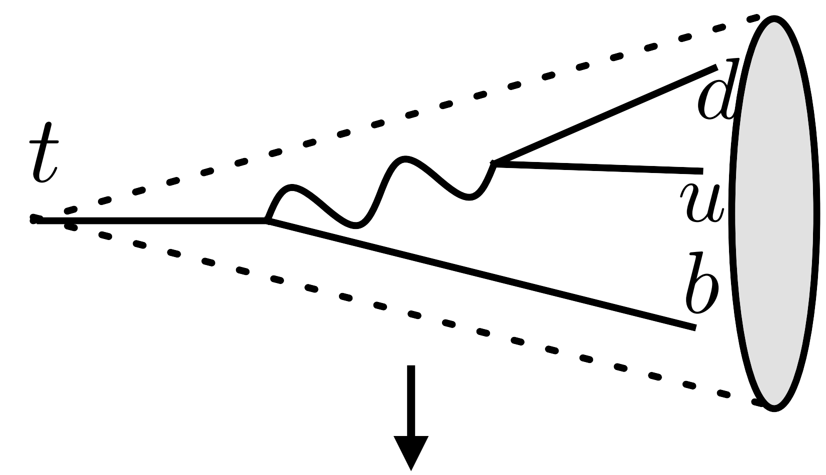


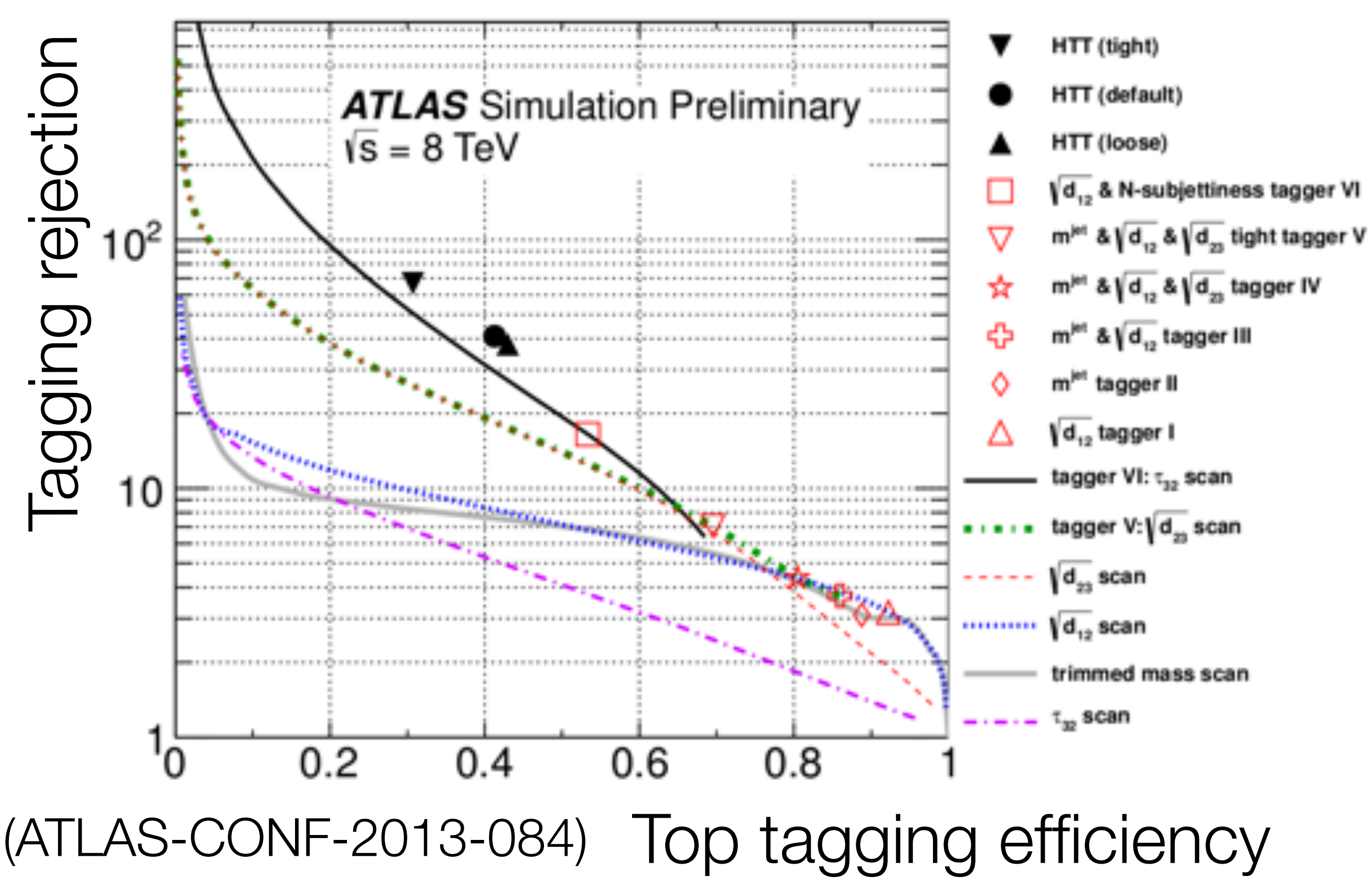


(ATLAS-CONF-2013-052)

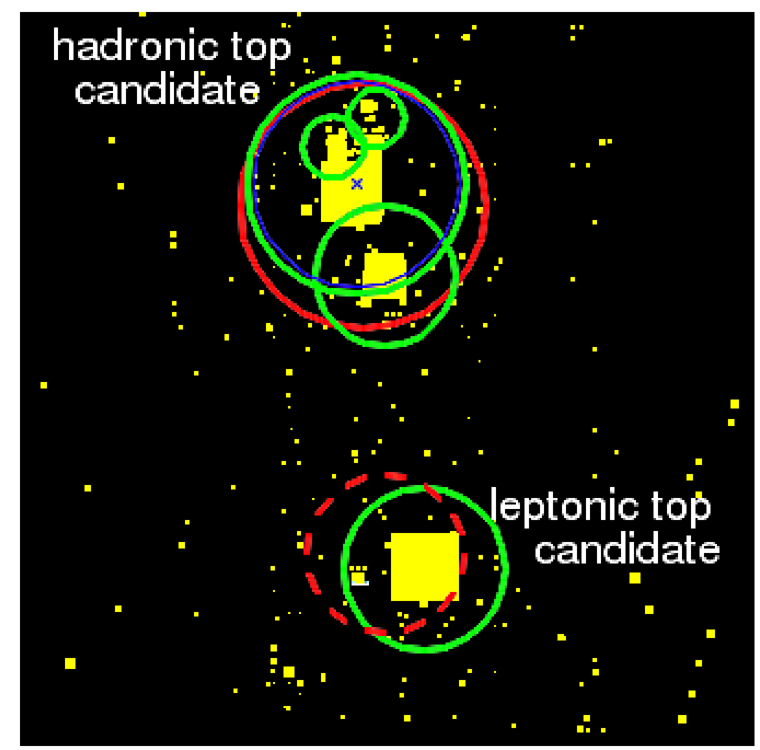
Jet Substructure for Boosted Objects

- Decay products of boosted t, W, H can lie within one jet
- It started with mass drop for $H \to b\bar{b}$
  (Butterworth, Davison, Rubin, Salam)
- Plethora of substructure techniques





(ATLAS-CONF-2013-084)



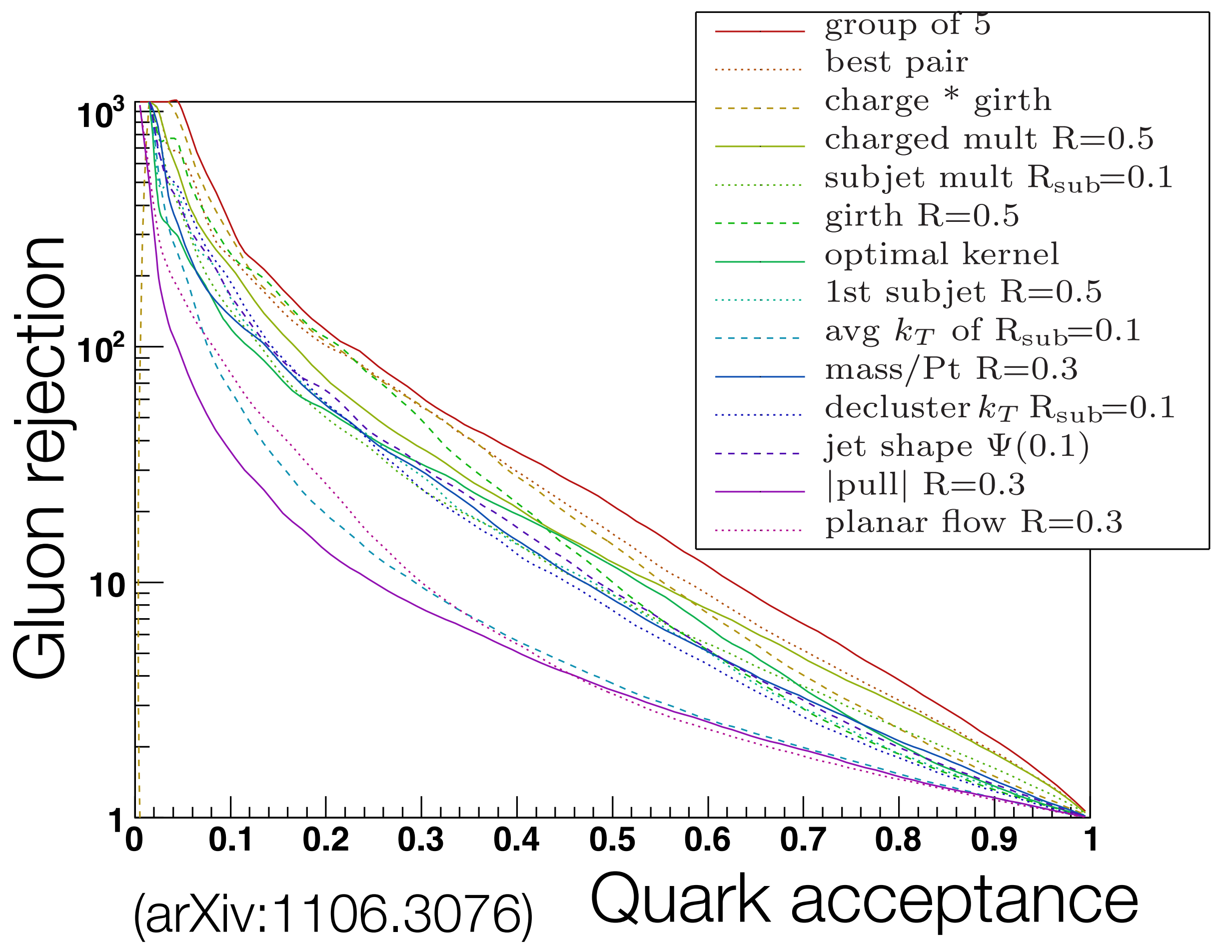
(ATLAS-CONF-2013-052)

Jet Substructure for Quark/Gluon Discrimination

- New physics often quark, QCD backgrounds often gluon
- Extensive Pythia study (Gallicchio, Schwartz)
  - Charged track multiplicity and jet "girth" are good

$$\text{girth} = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^J} \sqrt{(y_i - y_J)^2 + (\phi_i - \phi_J)^2}$$

  - More variables only give marginal improvement

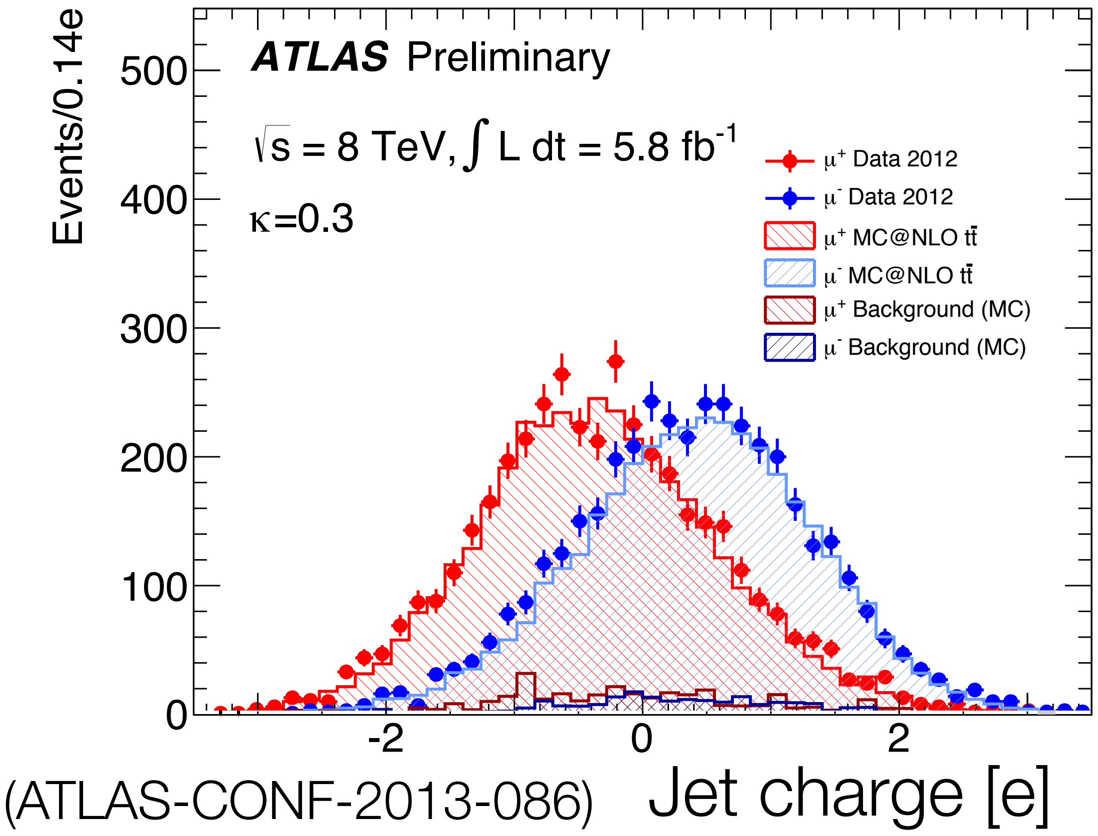


(arXiv:1106.3076)

Jet Mass and Charge

Motivation:

- Measured at the LHC
- Benchmark for our ability to calculate substructure
- Test and improve Monte Carlo: Herwig and Pythia differ



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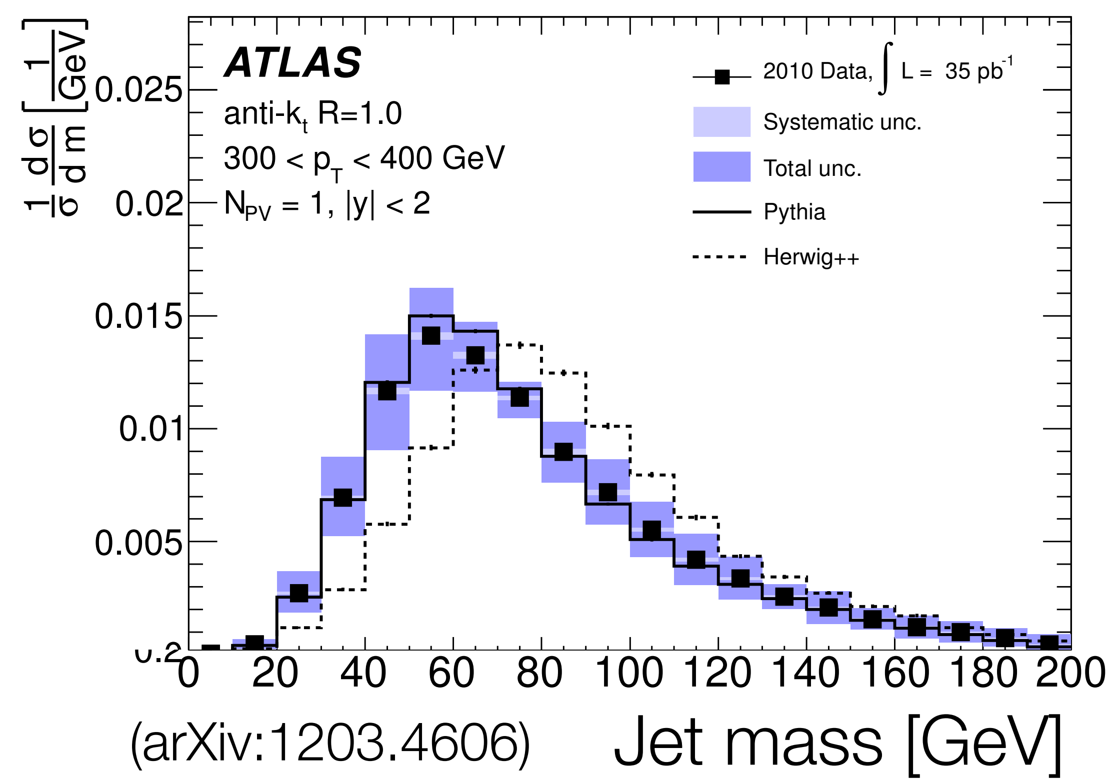


(arXiv:1203.4606)

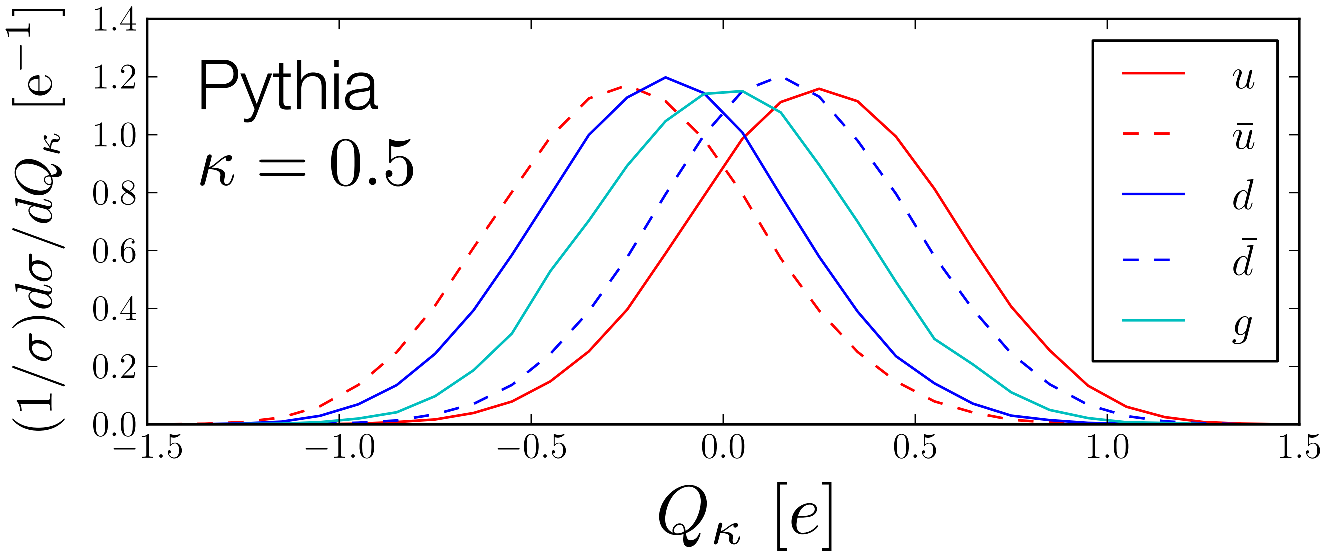
Jet Charge

Krohn, Lin, Schwartz, WW (arXiv:1209.2421)
WW (arXiv:1209.3091)

Defining Jet Charge

$$Q_\kappa = \sum_{i \in \text{jet}} Q_i \left(\frac{p_T^i}{p_T^J}\right)^\kappa$$

(Feynman, Field)



If κ too small:

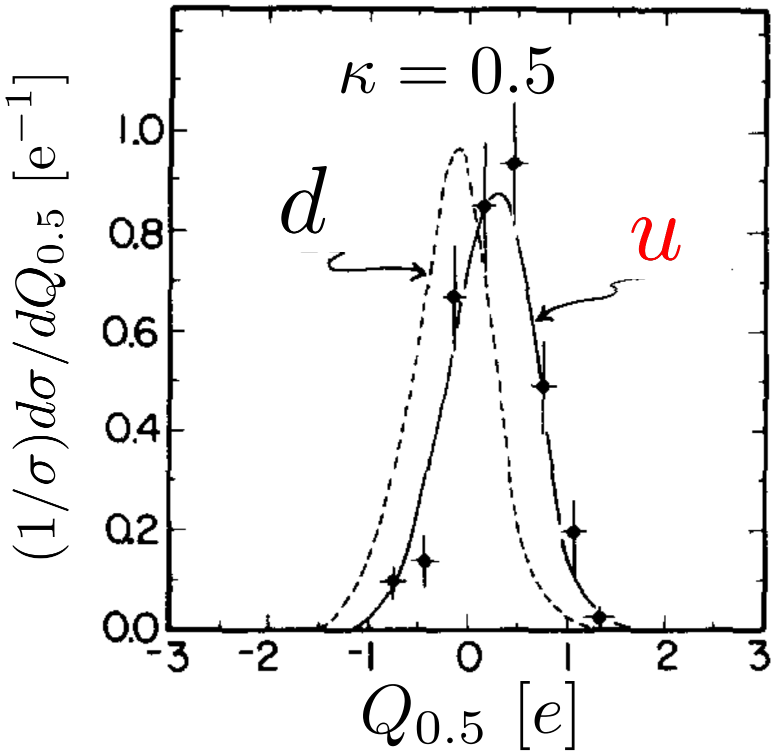
- Sensitive to soft hadrons $\rightarrow$ contamination
- $\kappa = 0$ similar to multiplicity (Recent work by Bolzoni, Kniehl, Kotikov)

If κ too large:

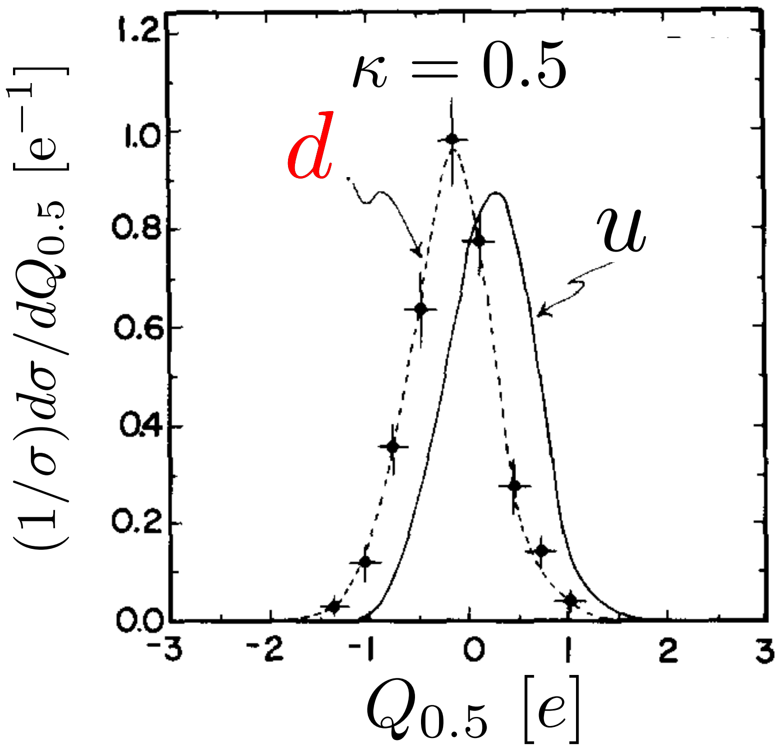
- Only sensitive to leading hadron $\rightarrow$ need more statistics

Historical Applications

- Test parton model (Fermilab (1980))



$\nu_\mu p \to \mu^- u X$



$\bar{\nu}_\mu p \to \mu^+ d X$

- Jet charge at LEP:
  - Forward-backward charge asymmetry (AMY (1990),…)
  - $B^0 \leftrightarrow \overline{B^0}$ mixing (ALEPH (1992), …)

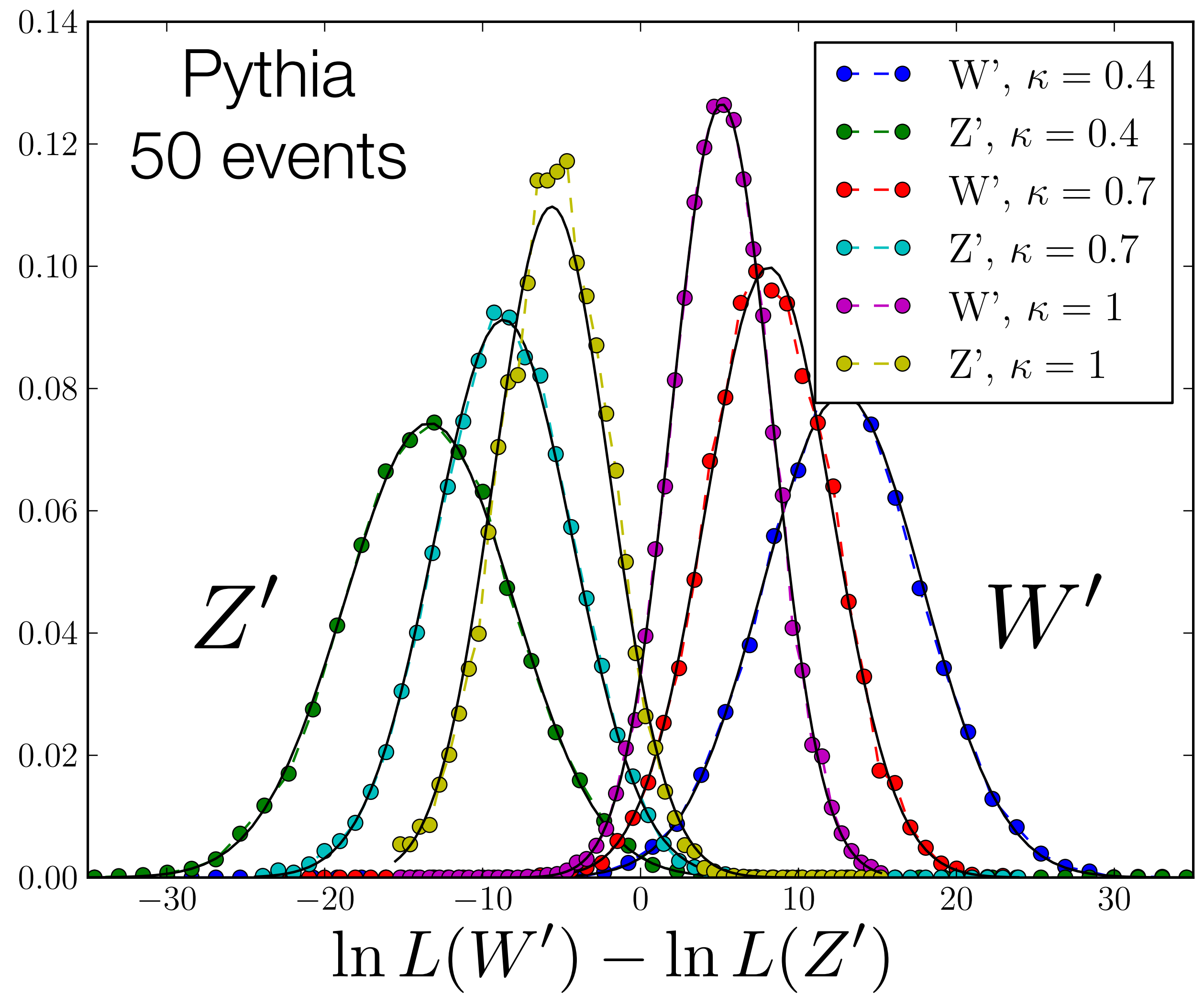
Possible LHC application: W' vs. Z'

- Hadronically decaying W' or Z' with 1 TeV mass
- 2-dim. likelihood discriminant based on both jet charges

$$Z' \to u\bar{u}$$
$$Z' \to d\bar{d}$$

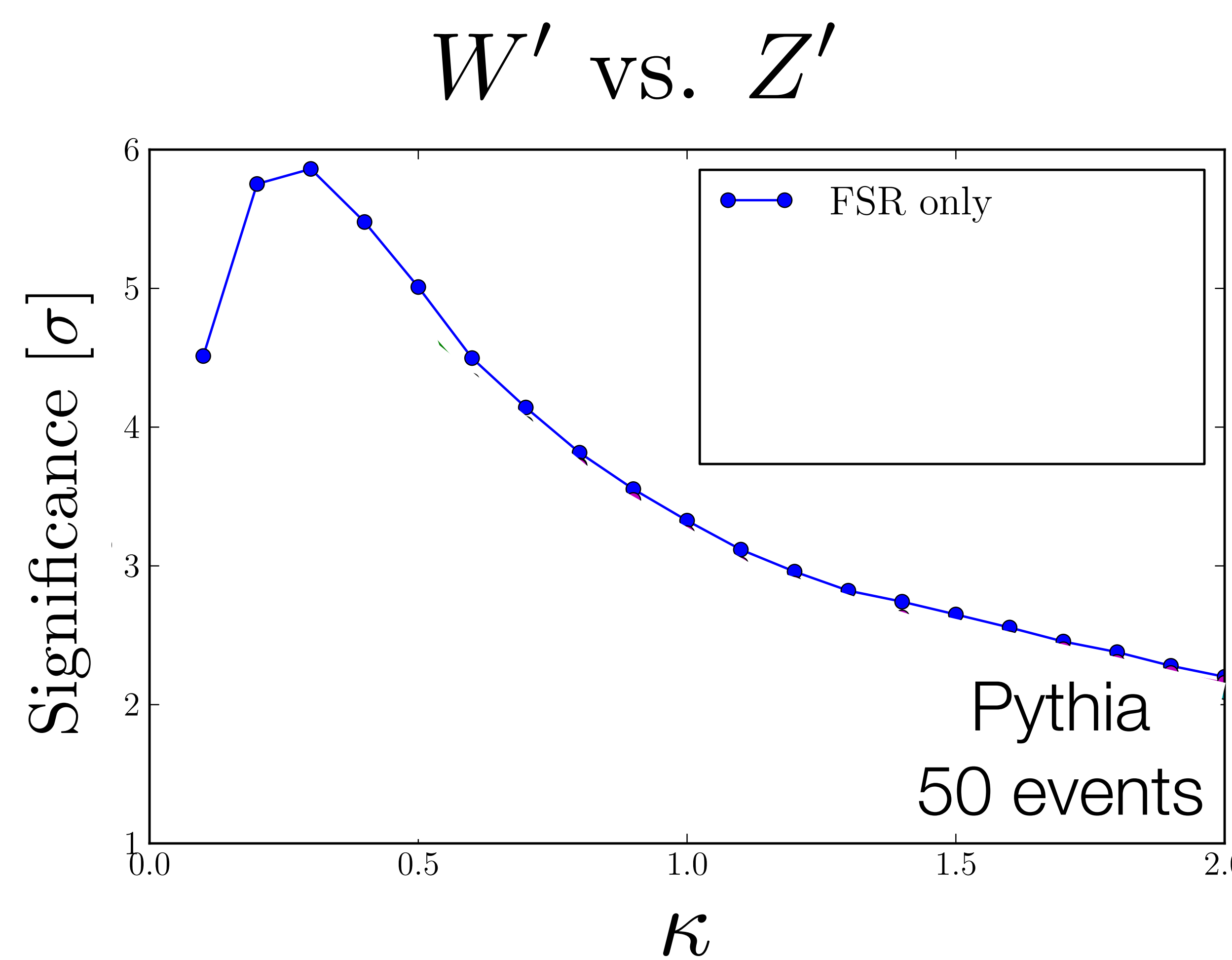
vs.

$$W' \to u\bar{d}$$
$$W' \to d\bar{u}$$



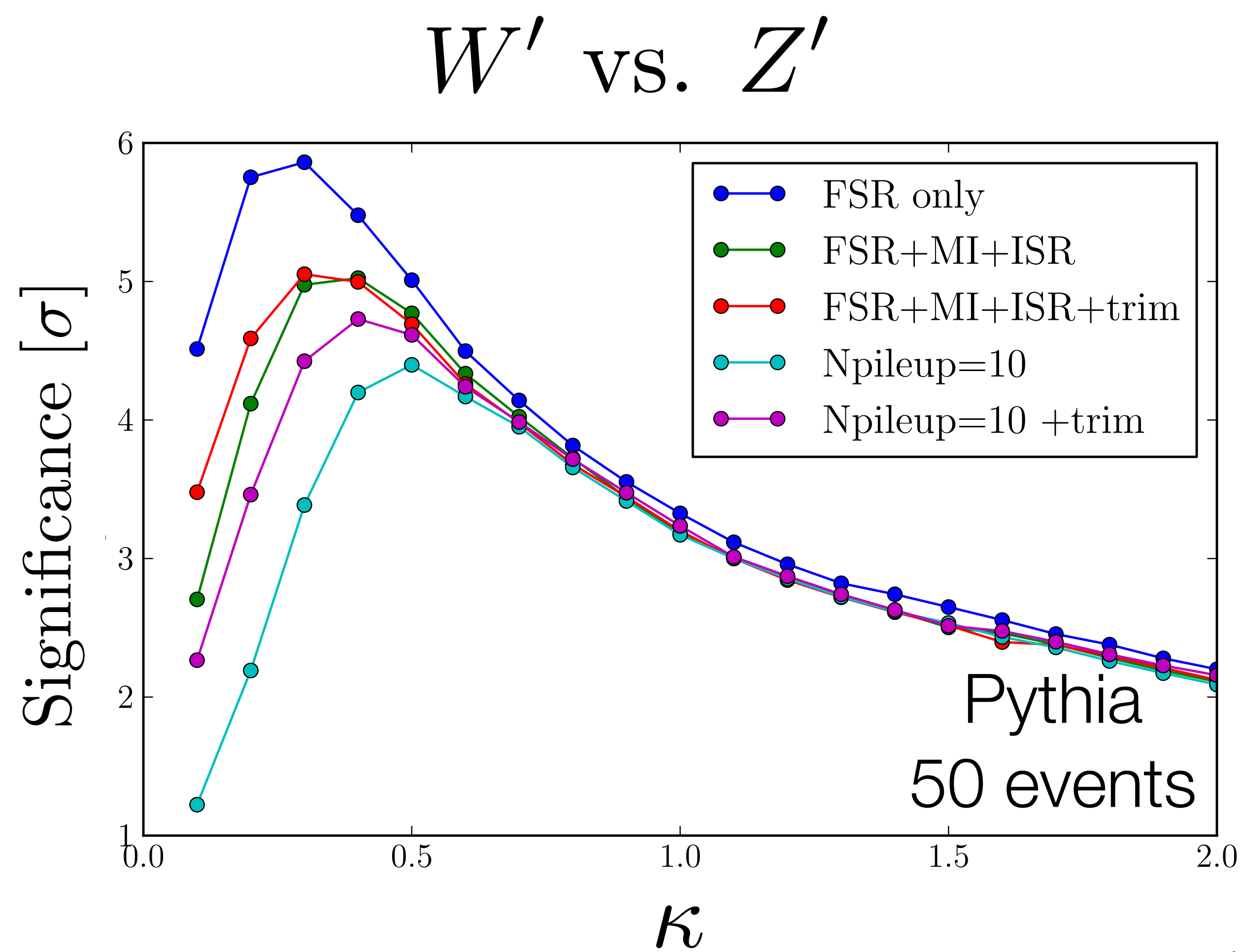
LHC Challenges

- Trade off between soft contamination and statistics
- We did not include: backgrounds, detector effects, …



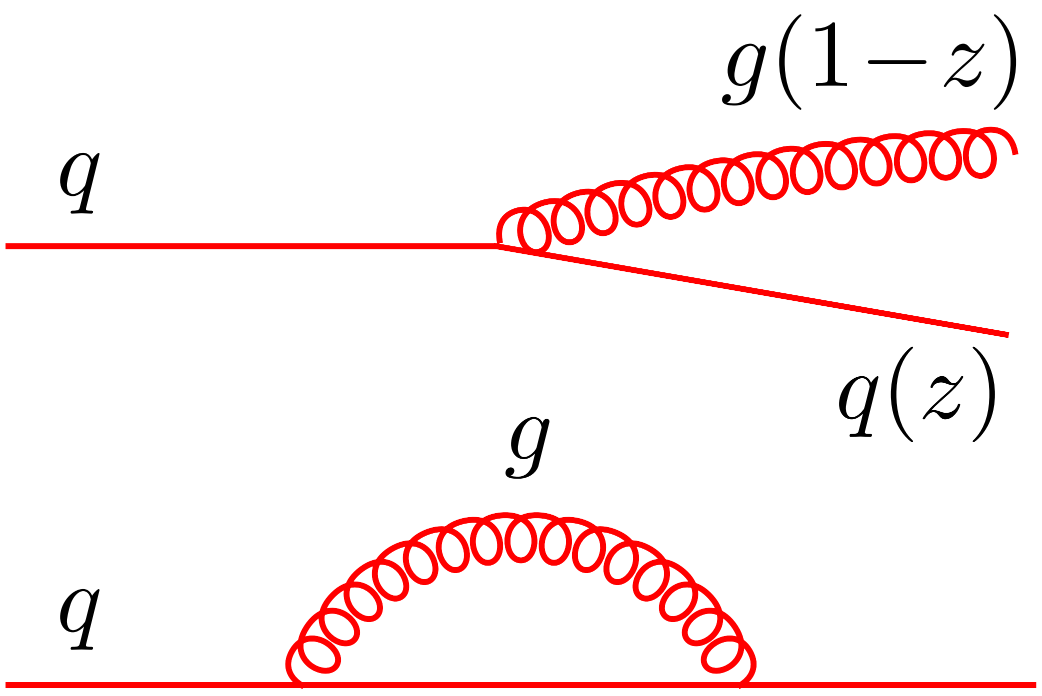
LHC Challenges

- Trade off between soft contamination and statistics
- We did not include: backgrounds, detector effects, …
- Various sources of contamination:
  - Initial State Radiation
  - Multiparton Interactions
  - Pile-up (overestimated)
- All soft $\rightarrow$ increase κ



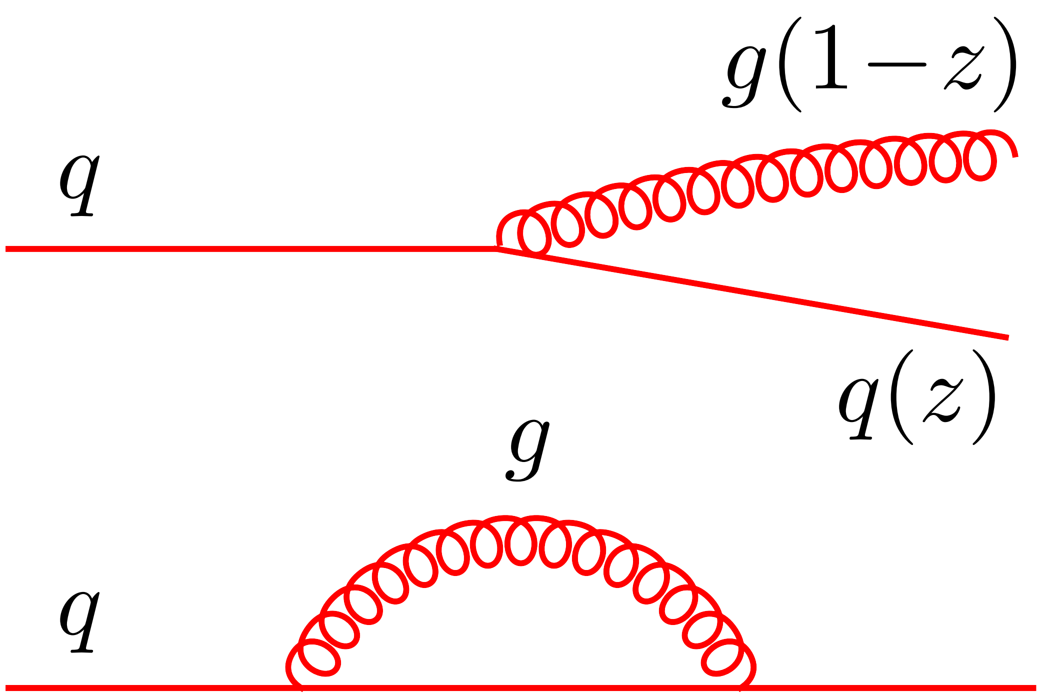
Jet Charge Not IR Safe

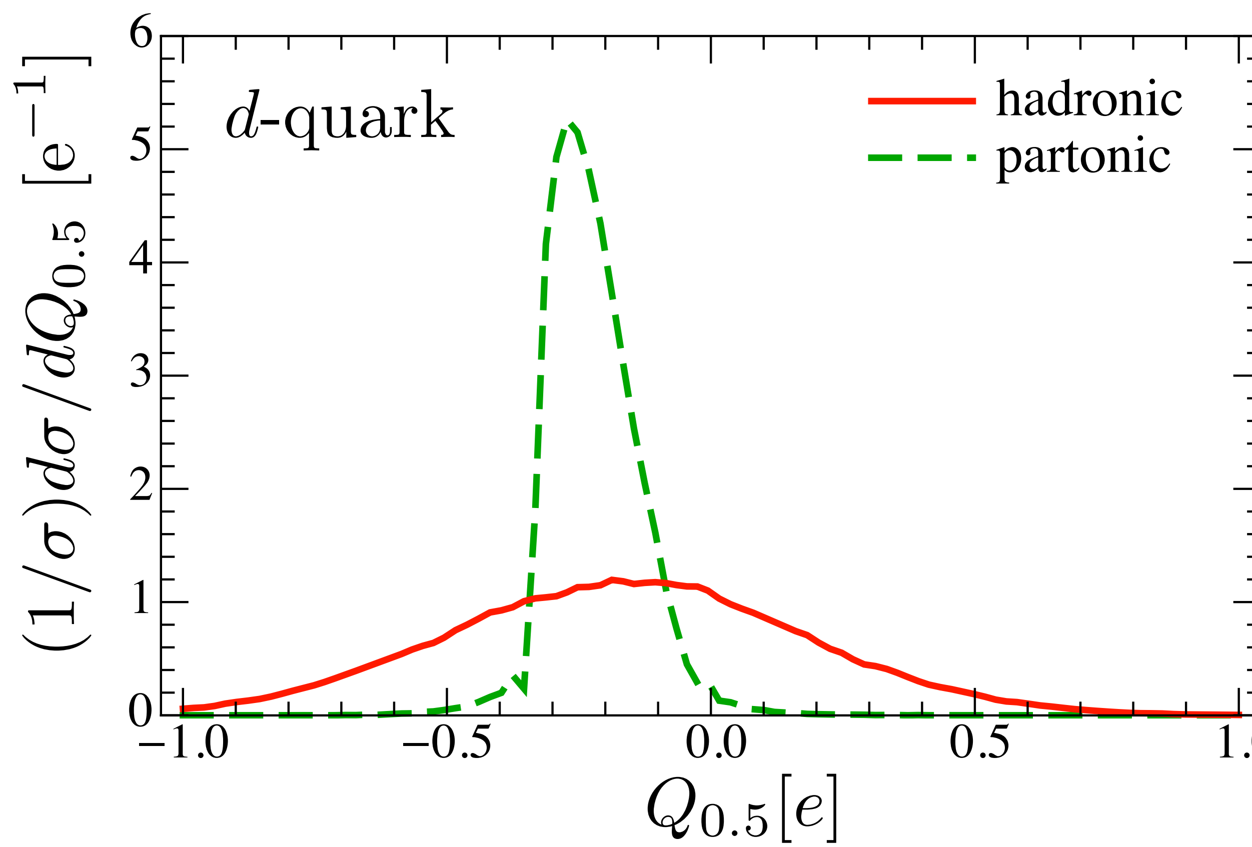
- Consider $q \to qg$ in collinear limit
- $Q_q z^\kappa \neq Q_q \to$ divergences don't cancel between real/virtual



Jet Charge Not IR Safe

- Consider $q \to qg$ in collinear limit
- $Q_q z^\kappa \neq Q_q \to$ divergences don't cancel between real/virtual
- Jet charge only defined for hadrons





Average Jet Charge Calculation

$$\langle Q_\kappa \rangle = \underbrace{\sum_h \int dz}_{\text{hadron } h} \ \underbrace{Q_h z^\kappa}_{\text{charge}} \ \underbrace{\frac{1}{\sigma_{\text{jet}}} \frac{d\sigma_{h\in \text{jet}}}{dz}}_{\text{weight}}$$

Jet scale

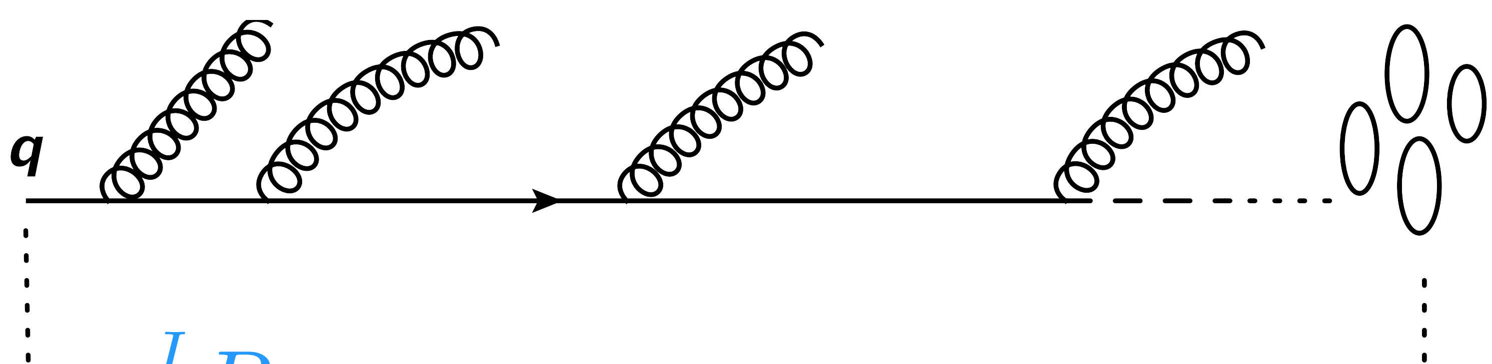
- At LO, weight = fragmentation function $D_q^h(z, \mu \sim p_T^J R)$

Average Jet Charge Calculation

$$\langle Q_\kappa \rangle = \underbrace{\sum_h \int dz}_{\text{hadron } h} \; \underbrace{Q_h z^\kappa}_{\text{charge}} \; \underbrace{\frac{1}{\sigma_{\text{jet}}} \frac{d\sigma_{h\in\text{jet}}}{dz}}_{\text{weight}}$$

Jet scale

- At LO, weight = fragmentation function $D_q^h(z, \mu \sim p_T^J R)$
- Calculate p_T^J, R dependence from evolution to $\mu \sim \Lambda_{\text{QCD}}$
- $D_q^h(z, \mu \sim \Lambda_{\text{QCD}})$ describes hadronization



$\mu \sim p_T^J R$ $\quad\quad$ $\mu \sim \Lambda_{\text{QCD}}$

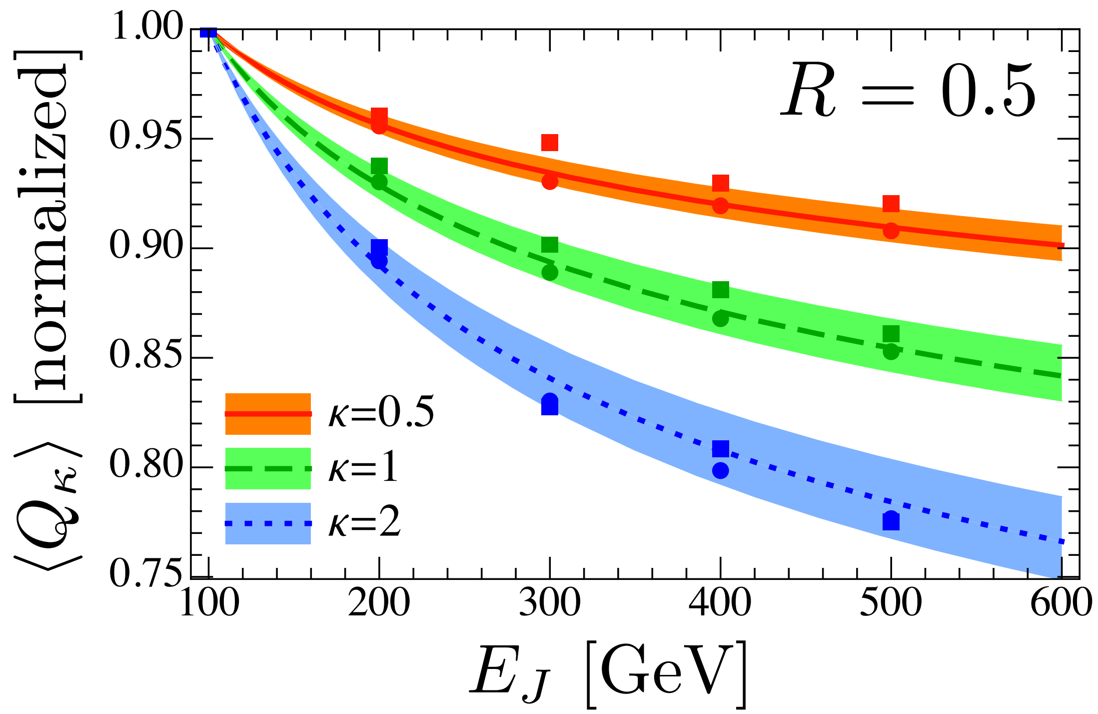
DGLAP Evolution vs. Pythia's Shower

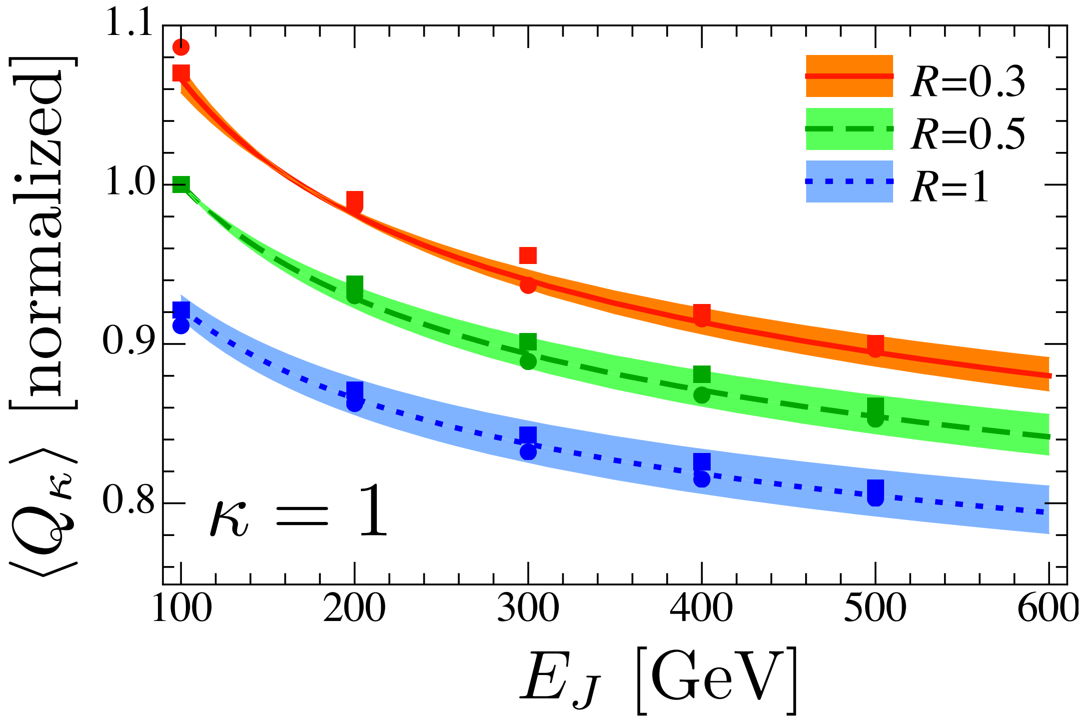
$$\langle Q_\kappa(E_J R, \text{flavor})\rangle = \underbrace{\text{perturbative}}_{}(\kappa, E_J R) \times \text{hadronization}(\kappa, \text{flavor})$$

perturbative splitting + evolution

- Normalize average jet charge: $\dfrac{\langle Q_\kappa(E_J R)\rangle}{\langle Q_\kappa(50\text{ GeV})\rangle}$

  $\rightarrow$ Hadronization (and flavor dependence) drops out





- Good agreement (including perturbative splitting)

Fragmentation Functions vs. Pythia's Hadronization

- Average jet charge at $E_J = 100\ \mathrm{GeV}, R = 0.5$

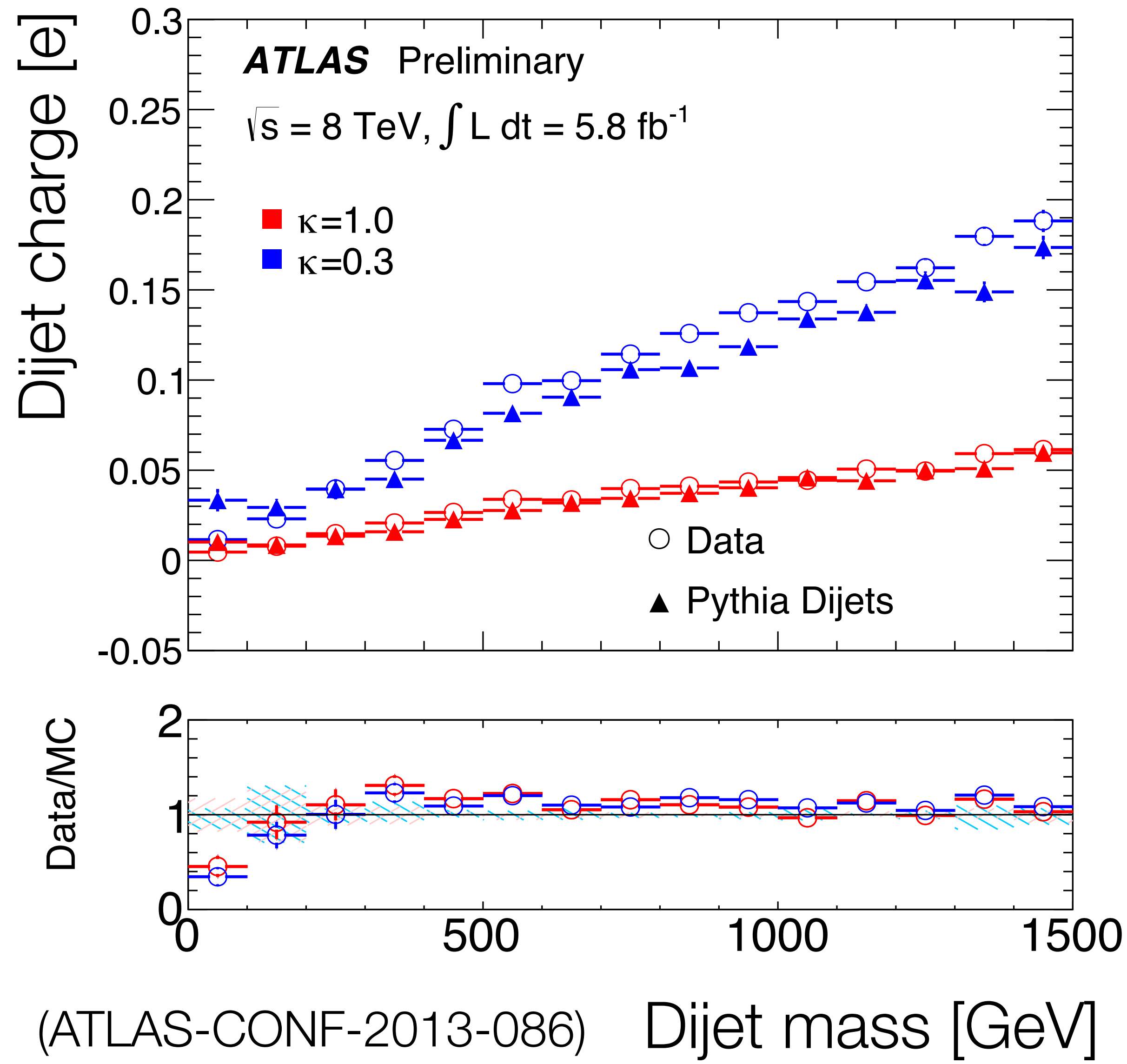
	u-quark			d-quark		
κ	PYTHIA	DSS	AKK08	PYTHIA	DSS	AKK08
0.5	0.271	0.237	0.221	-0.162	-0.184	-0.062
1	0.144	0.122	0.134	-0.078	-0.088	-0.046
2	0.055	0.046	0.064	-0.027	-0.030	-0.027

(DSS = De Florian, Sassot, Stratmann, AKK08 = Albino, Kniehl, Kramer)

- Pythia consistent with fragmentation functions
- Large uncertainties as we need $D_q^{h^+} - D_q^{h^-} = D_q^{h^+} - D_{\bar{q}}^{h^+}$
  Most fragmentation data is e^+e^- giving $D_q^{h^+} + D_{\bar{q}}^{h^+}$

Average Dijet Charge at the LHC

- Charge increases with dijet mass due to PDFs
- Pure QCD measurement of valence structure of proton!



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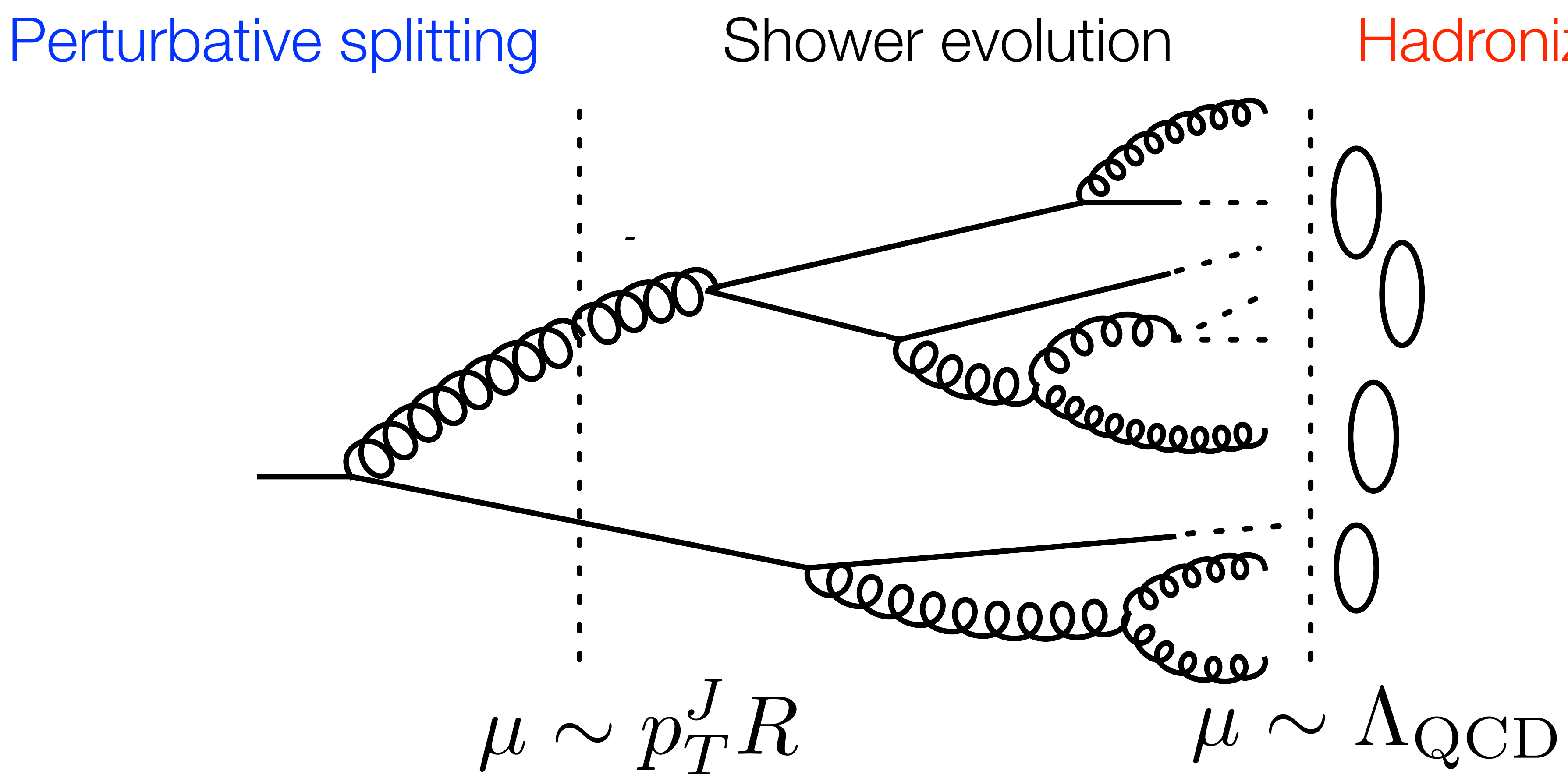
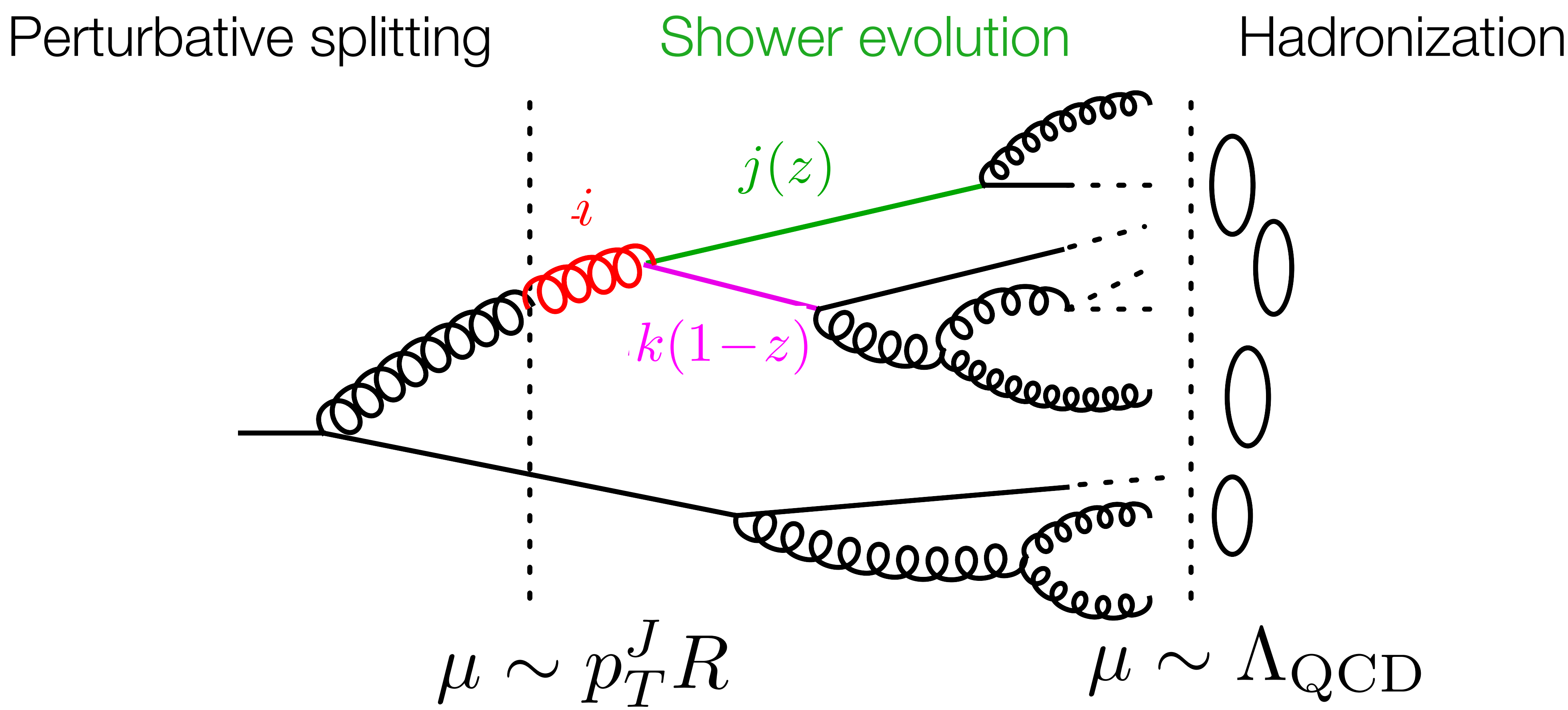
Full Jet Charge Distribution



- Perturbative splitting reduces μ-dependence (Jain, Procura, WW)
- Hadronization depends on full charge distribution $D_i(Q_\kappa, \mu)$
  - Similar to multi-hadron fragmentation function

Full Jet Charge Distribution



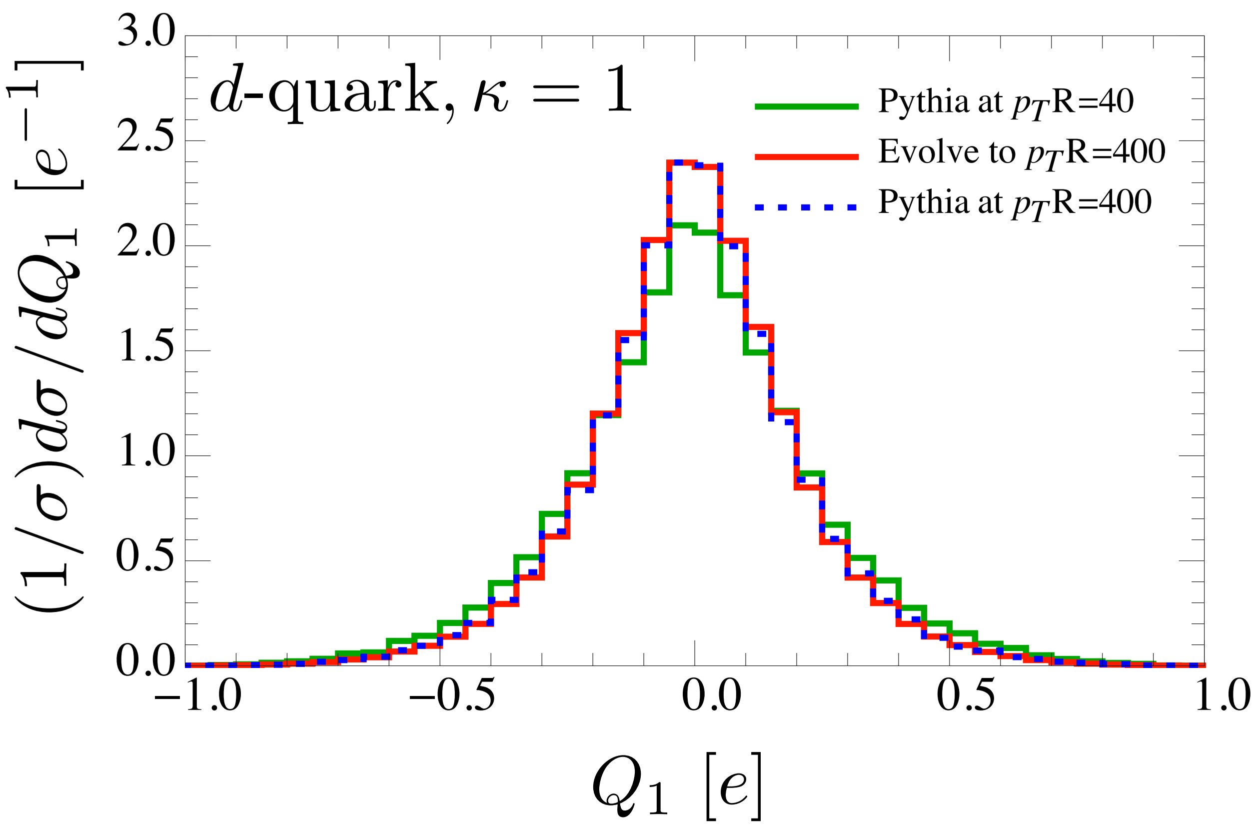
- DGLAP:

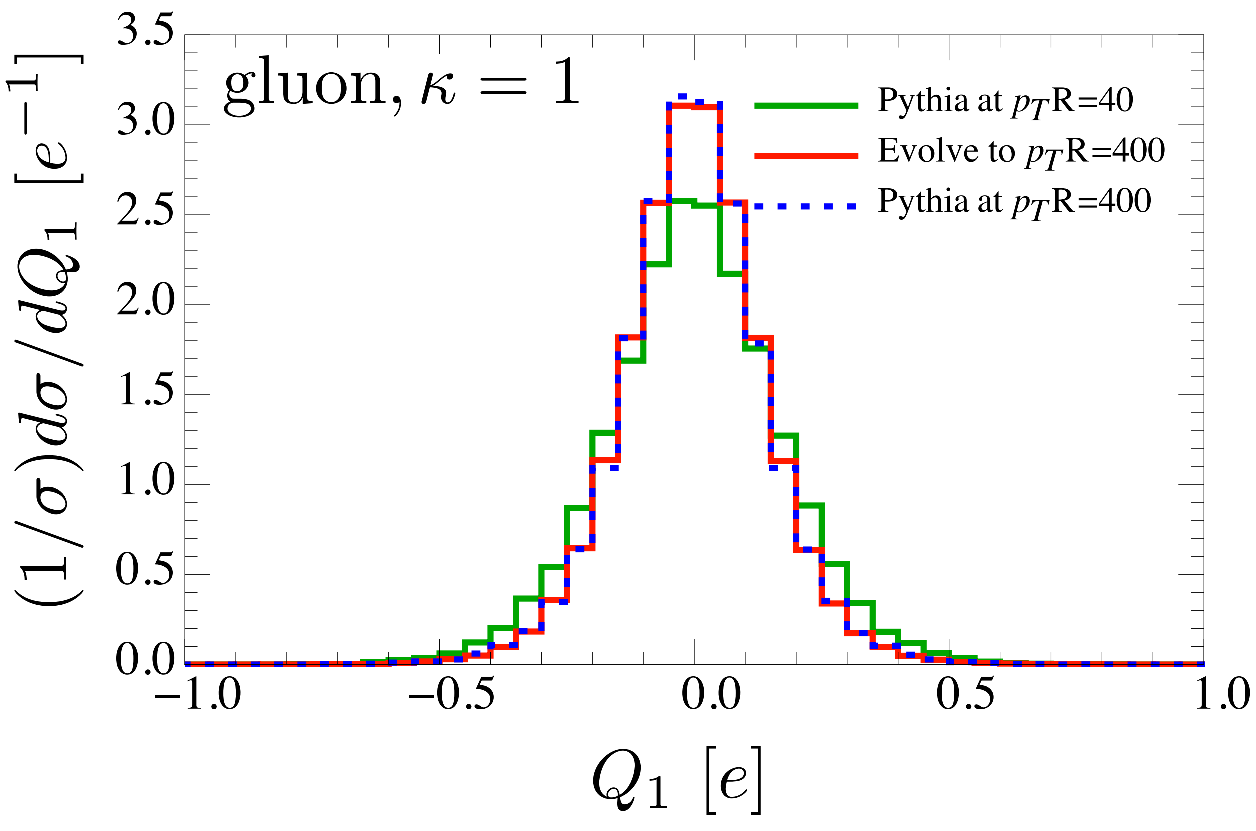
$$\mu \frac{d}{d\mu} D_i(Q_\kappa, \mu) = \overbrace{\sum_j \int dz\, \frac{\alpha_s}{2\pi} P_{ji}(z)}^{\text{Splitting probability}} \overbrace{\int dQ_\kappa^a\, D_j(Q_\kappa^a, \mu) \int dQ_\kappa^b\, D_k(Q_\kappa^b, \mu)}^{\text{Sample over distributions of branches}}$$

$$\times \underbrace{\delta[Q_\kappa - z^\kappa Q_\kappa^a - (1-z)^\kappa Q_\kappa^b]}_{\text{Charge is (weighted) sum of branches}}$$

DGLAP Evolution vs. Pythia's Shower

- Use Pythia as input and evolve, good agreement
- Distribution changes much more slowly than PDF or FF

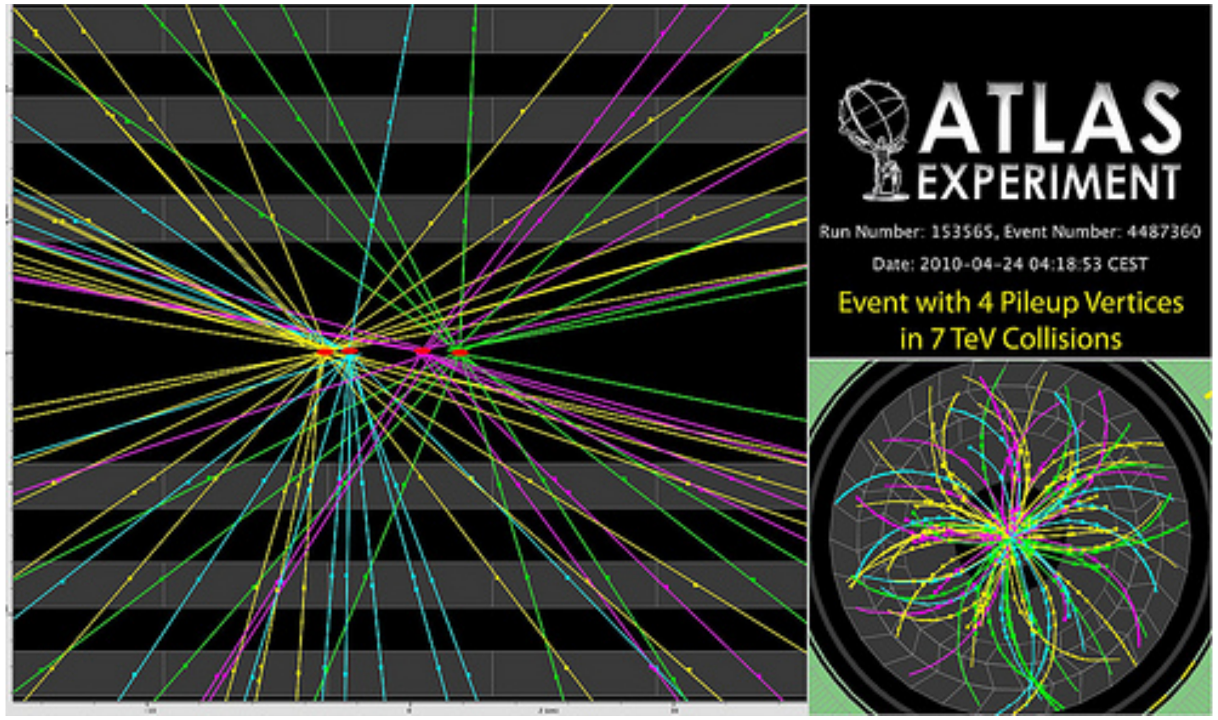




Track-Based Observables

Chang, Procura, Thaler, WW (arXiv:1303.6637, 1306.6630)

Track-Based Observables



- Advantages:
  - better angular resolution
  - less sensitive to pile-up
- Disadvantages:
  - smearing of resonance peaks
  - not collinear safe

Formalism

- Calculating an IR safe observable e:

$$\frac{d\sigma}{de} = \sum_N \int d\Pi_N \, \frac{d\sigma_N}{d\Pi_N} \, \delta[e - \hat{e}(\{p_i^\mu\})]$$

- Corresponding track-based observable $\bar{e}$:

$$\frac{d\sigma}{d\bar{e}} = \sum_N \int d\Pi_N \, \frac{d\bar{\sigma}_N}{d\Pi_N} \underbrace{\int \prod_{i=1}^{N} dx_i \, T_i(x_i)}_{\text{hadronization}} \, \delta[\bar{e} - \hat{e}(\{x_i p_i^\mu\})]$$

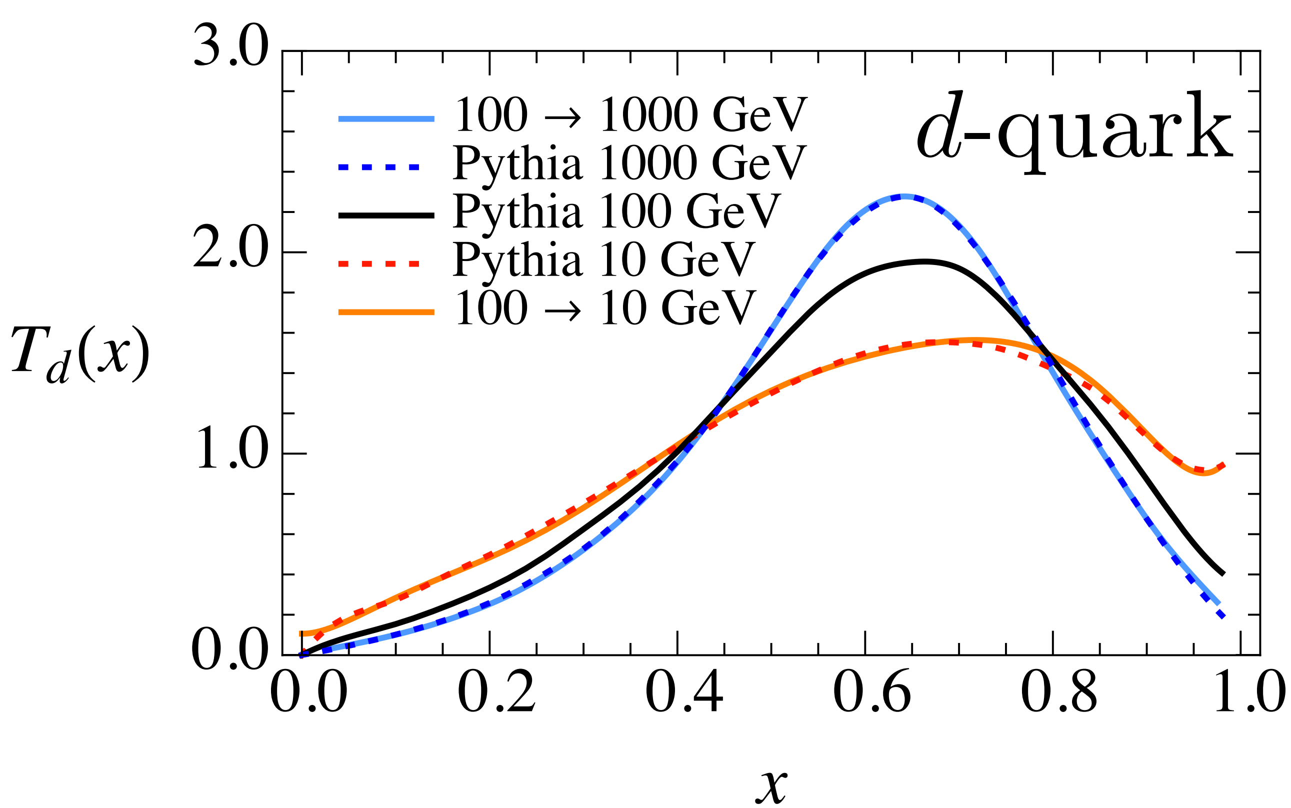
IR div. removed

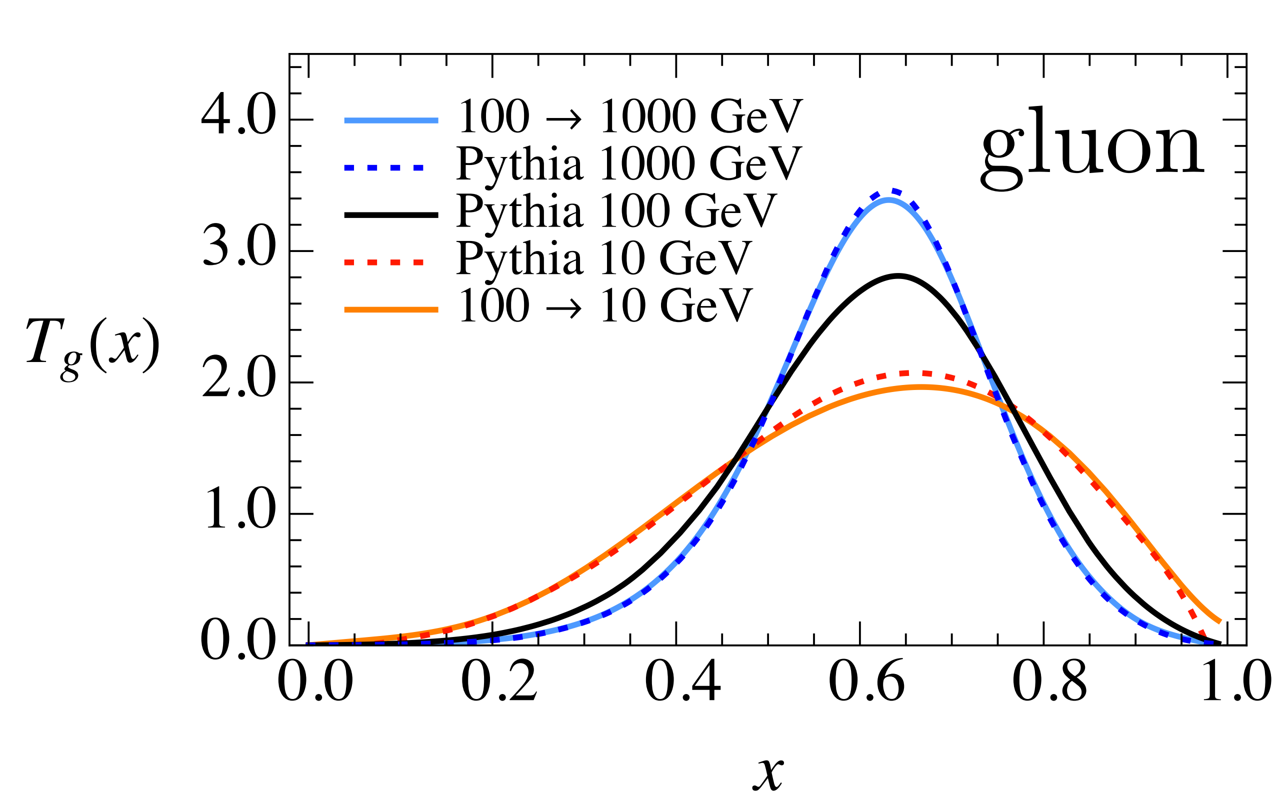
conversion to tracks: $\bar{p}_i^\mu = x_i p_i^\mu + \mathcal{O}(\Lambda_{\rm QCD})$

- Similar to matching PDFs but now one track function for each parton

Track Functions $T_i(x, \mu)$

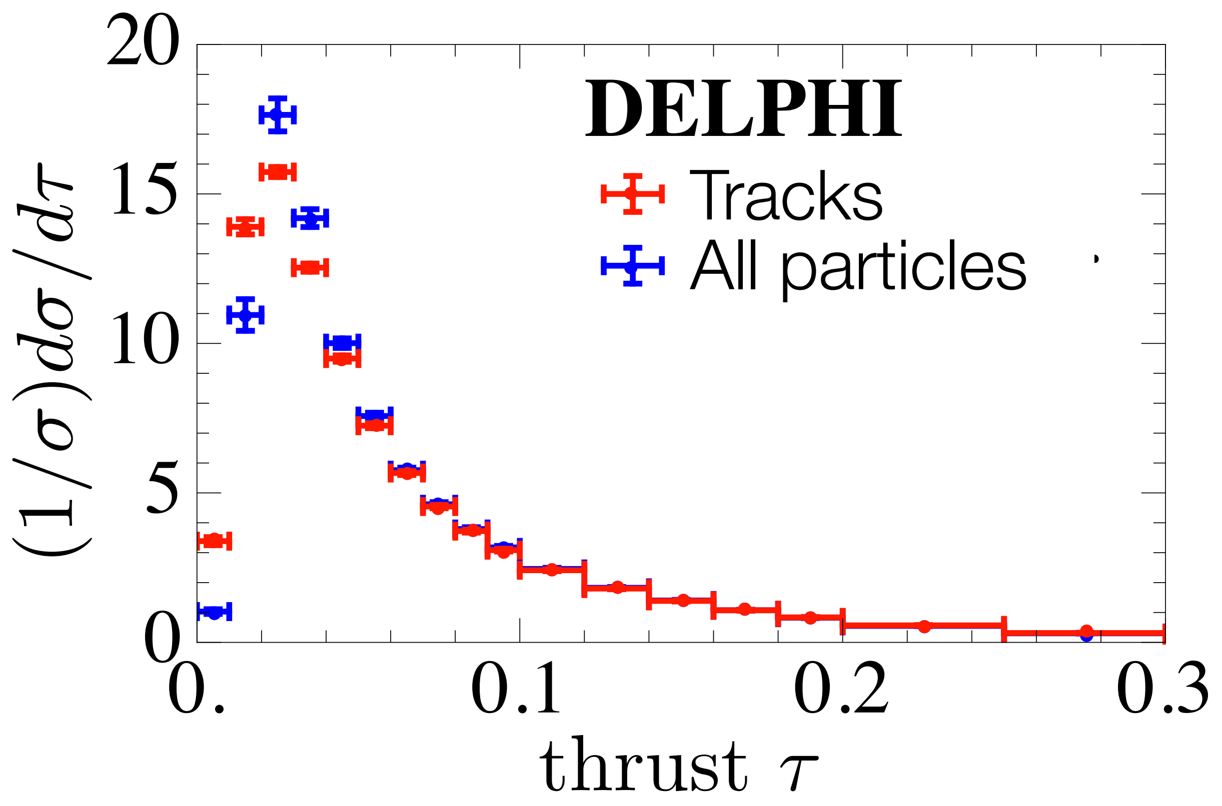
- Describes average energy fraction x converted to tracks
- Large width from hadronization fluctuations (smearing)
- Similar μ-evolution as jet charge, agrees with Pythia





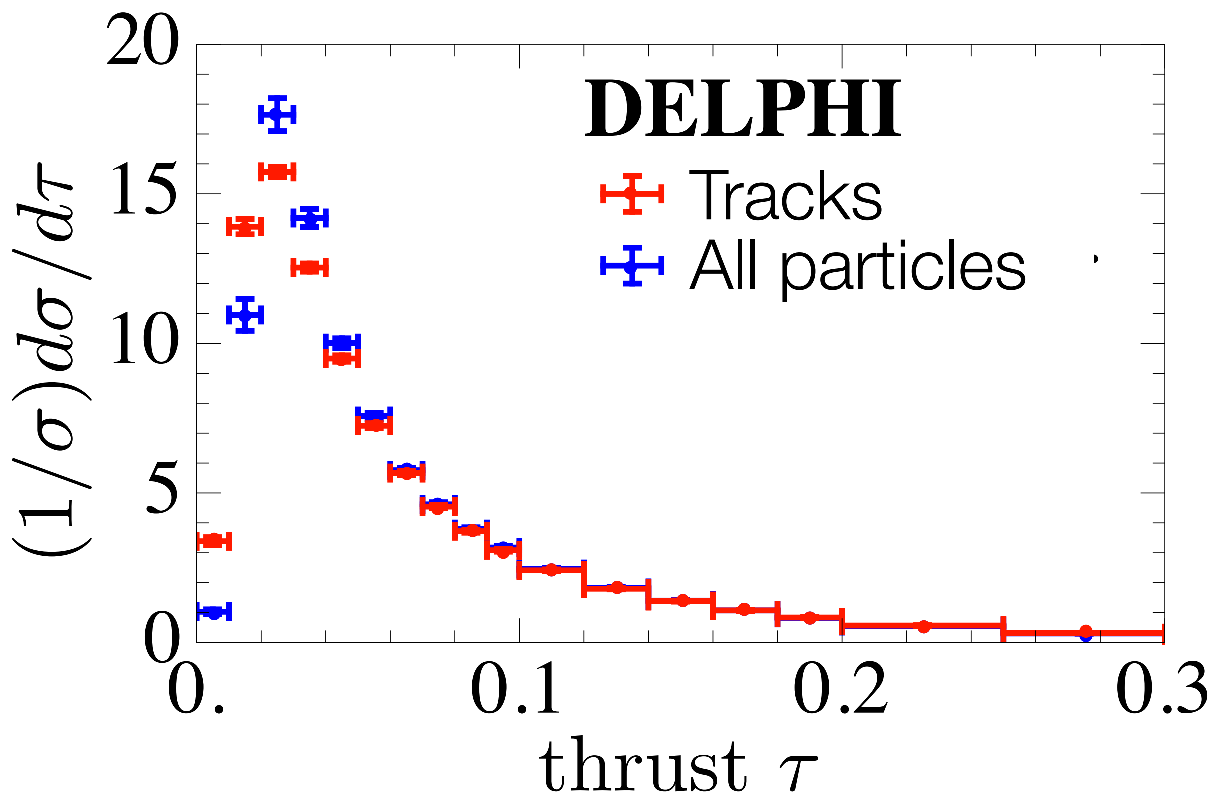
Track-based thrust

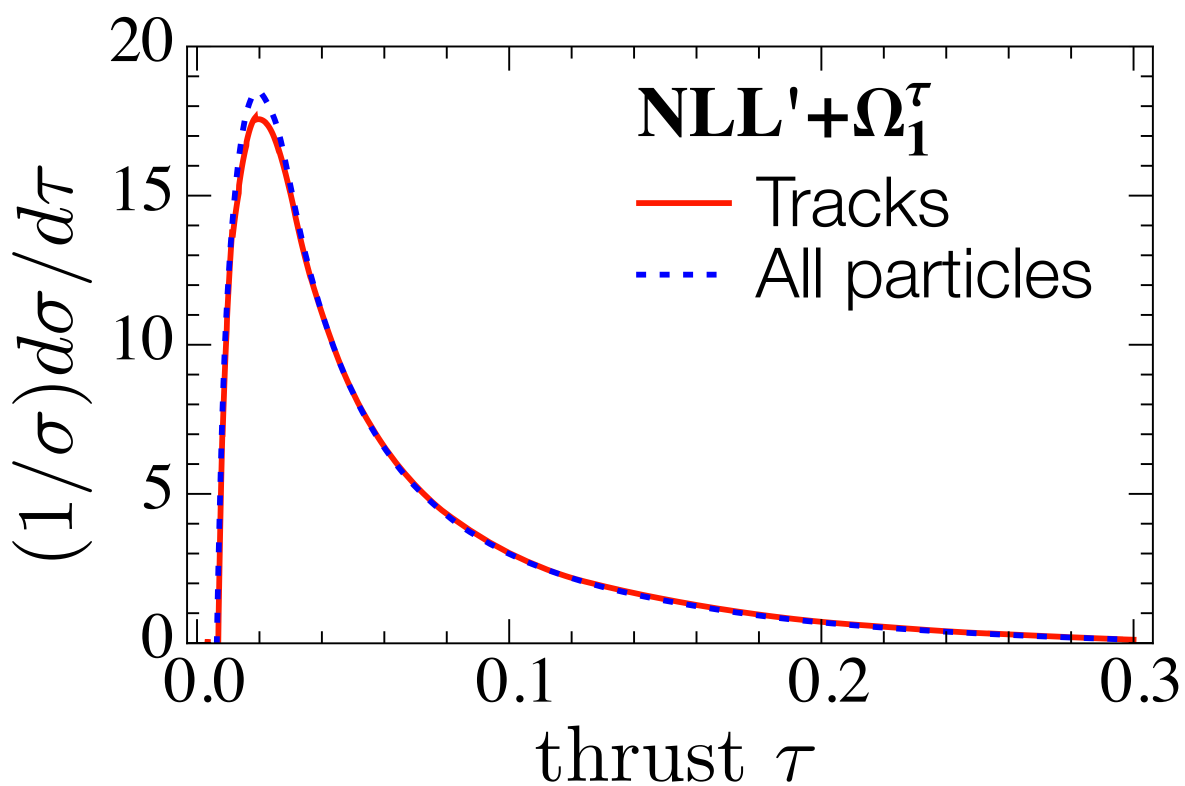
- Measured at LEP using charged and all particles



Track-based thrust

- Measured at LEP using charged and all particles
- We find same except in non-perturbative peak
- Smearing of peak is small for dimensionless ratios





Jet Mass

Jouttenus, Tackmann, Stewart, WW (arXiv:1302.0846)
Tackmann, Stewart, WW (to appear)

Jet Mass Resummation

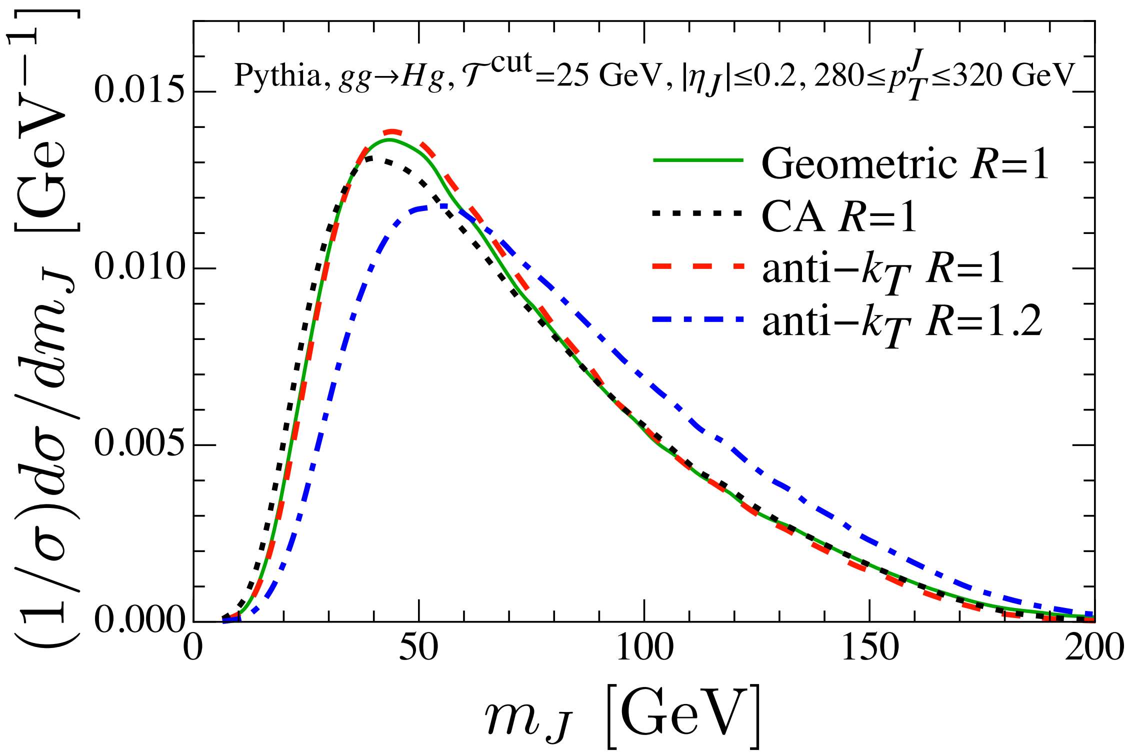
- Jet mass is defined as $m_J^2 = \left(\sum_{i \in \mathrm{jet}} p_i^\mu \right)^2$
- Cross section contains logarithms of $L = \ln(m_J^{\mathrm{cut}}/p_T^J)$

$$\int_0^{m_J^{\mathrm{cut}}} dm_J \, \frac{d\sigma}{dm_J} = \sigma_0 \{ 1 + \alpha_s [c_{12} L^2 + c_{11} L + c_{10} + n_1(m_J^{\mathrm{cut}})]$$
$$+ \alpha_s^2 [c_{24} L^4 + c_{23} L^3 + c_{22} L^2 + c_{21} L + c_{20} + n_2(m_J^{\mathrm{cut}})]$$
$$+ \alpha_s^3 [c_{36} L^6 + c_{35} L^5 + c_{34} L^4 + c_{33} L^3 + c_{32} L^2 + \dots]$$
$$+ \quad \vdots \quad + \quad \vdots \quad + \quad \vdots \quad + \quad \vdots \quad + \quad \ddots \}$$

LL NLL NNLL

- Need to resum dominant higher-order effects for $m_J \ll p_T^J$
- Nonsingular n_i is suppressed by $(m_J^{\mathrm{cut}}/p_T^J)^2$

Jet Mass and Jet Definition



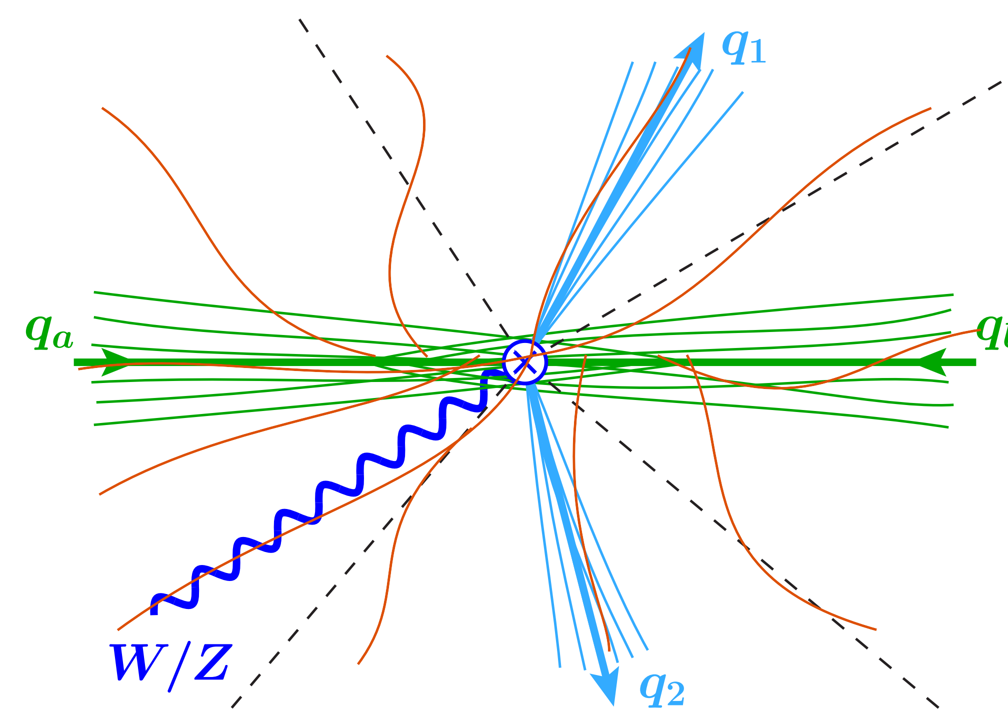
- Clustering algorithms theoretically complicated
- Jet mass spectrum is fairly independent of jet definition $\rightarrow$ use N-jettiness (with correct R)

N-Jettiness Event Shape (Stewart, Tackmann, WW)

$$\mathcal{T}_N = \sum_i \min\{\hat{q}_a \cdot p_i, \hat{q}_b \cdot p_i, \hat{q}_1 \cdot p_i, \ldots\}$$

beams jets

- Reference vectors: $\hat{q}_{a,b} = (1,0,0,\pm 1)$, $\hat{q}_J = (1, \hat{n}_J)/\rho_J$ (jet axis: $\hat{n}_J$; jet size parameter: ρ_J)
- $\mathcal{T}_N \to 0$ for exactly N jets, $\mathcal{T}_N$ large for $> N$ jets
- Very successfully used as substructure: N-Subjettiness (Thaler, van Tilburg)



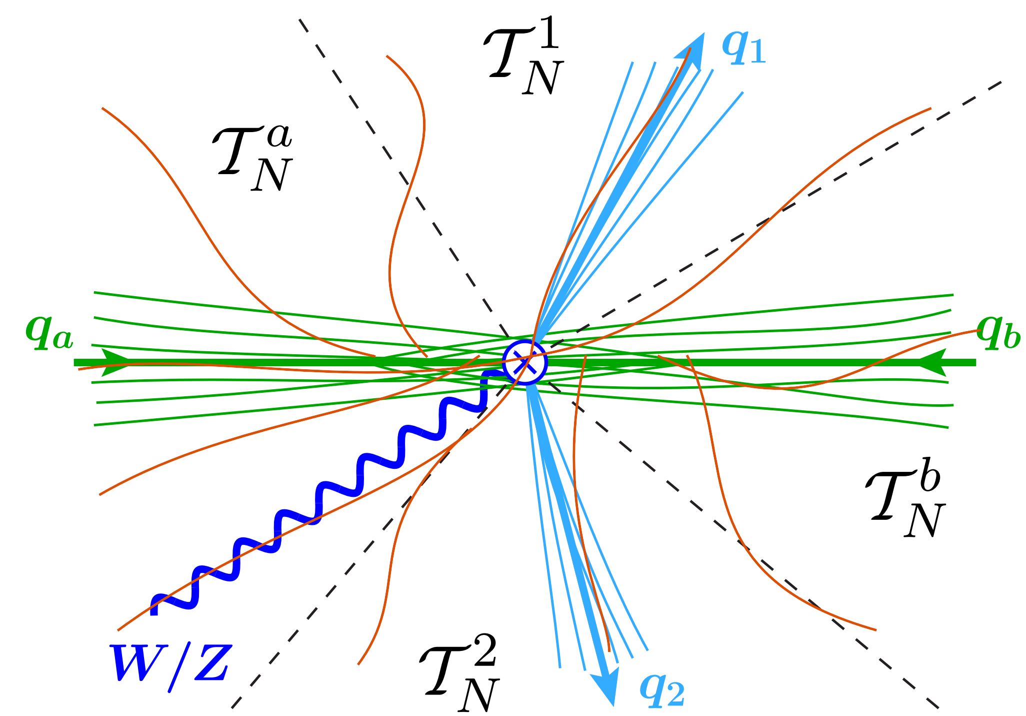
N-Jettiness Event Shape (Stewart, Tackmann, WW)

$$\mathcal{T}_N = \sum_i \min\{\hat{q}_a \cdot p_i, \hat{q}_b \cdot p_i, \hat{q}_1 \cdot p_i, \dots\} = \mathcal{T}_N^a + \mathcal{T}_N^b + \mathcal{T}_N^1 + \dots$$

beams jets

- Reference vectors: $\hat{q}_{a,b} = (1,0,0,\pm 1)$, $\hat{q}_J = (1, \hat{n}_J)/\rho_J$
- $\mathcal{T}_N \to 0$ for exactly N jets, $\mathcal{T}_N$ large for $> N$ jets
- Very successful substructure technique: N-Subjettiness (Thaler, van Tilburg)
- $\mathcal{T}_N$ splits into contributions from each beam/jet region
- Related to jet mass:

$$m_J^2 = 2\rho_J E_J \mathcal{T}_N^J$$

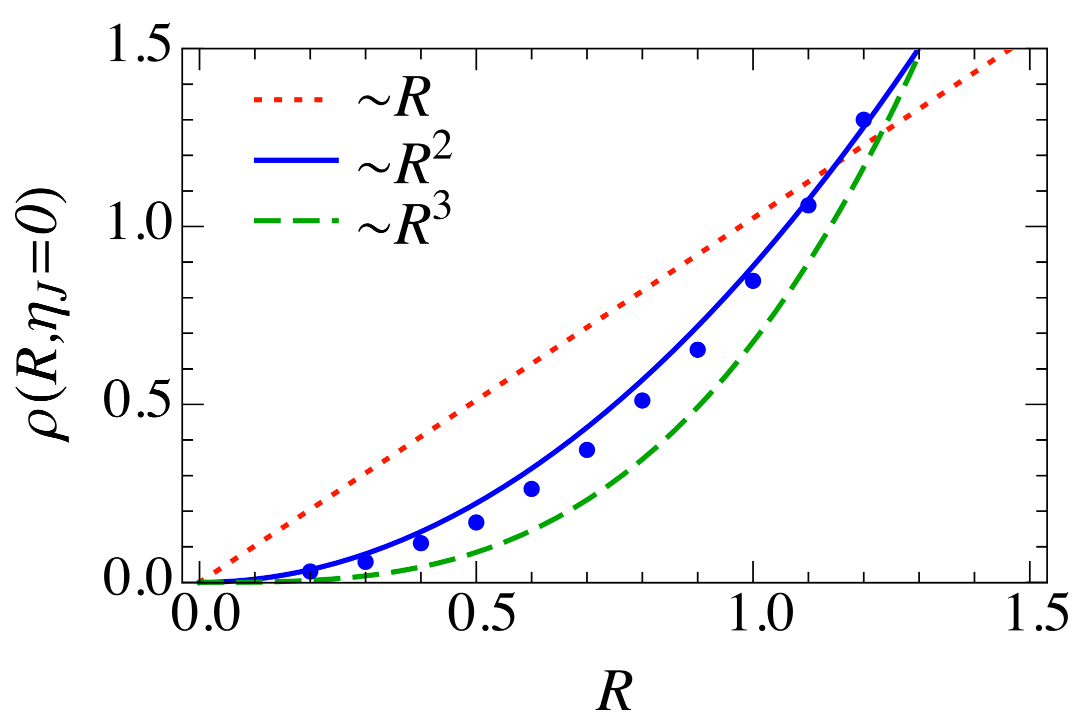


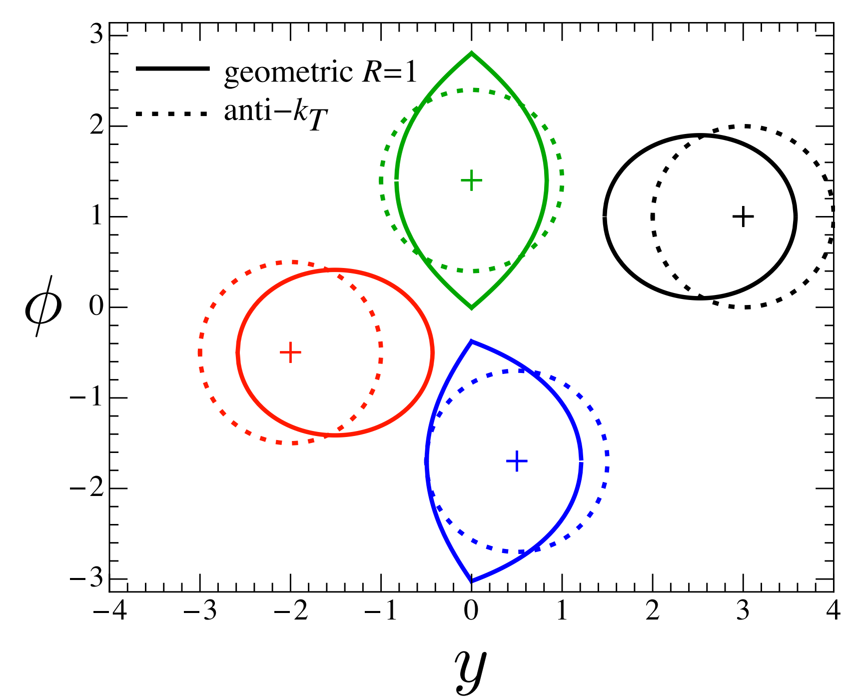
N-Jettiness Parameters

$$\mathcal{T}_N = \sum_i \min\{\hat{q}_a \cdot p_i, \hat{q}_b \cdot p_i, \hat{q}_1 \cdot p_i, \ldots\} = \mathcal{T}_N^a + \mathcal{T}_N^b + \mathcal{T}_N^1 + \ldots$$

beams jets

- Reference vectors: $\hat{q}_{a,b} = (1, 0, 0, \pm 1)$, $\hat{q}_J = (1, \hat{n}_J)/\rho_J$
- $\hat{n}_J$ by minimizing $\mathcal{T}_N$ or from jet alg. (same for $\mathcal{T}_N \to 0$)
- Choose $\rho_J = \rho(R, \eta_J)$ to match jet area of anti-k_T



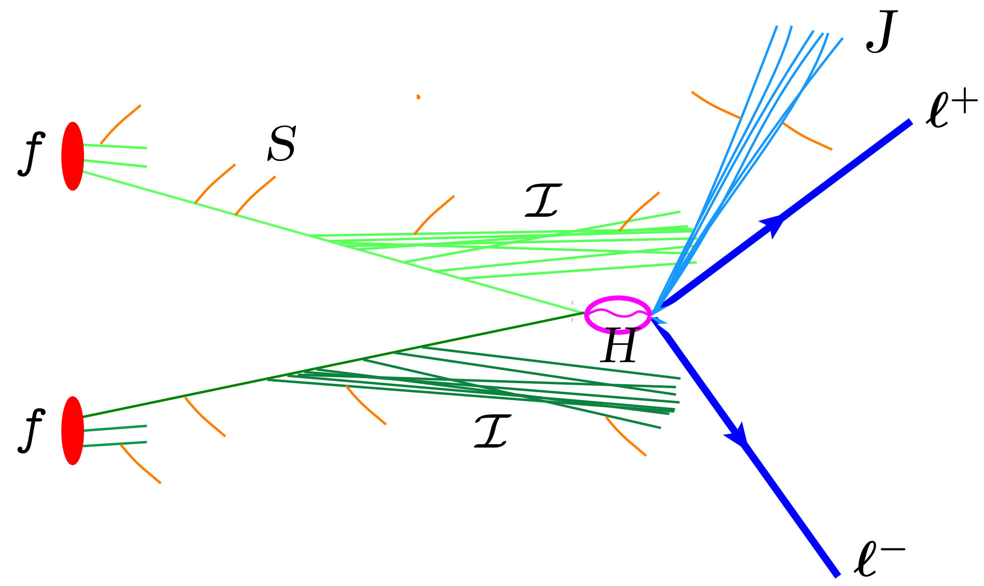


N-Jettiness Factorization

$$\frac{d\sigma(N \text{ jets})}{d\mathcal{T}_N^a \, d\mathcal{T}_N^b \cdots d\mathcal{T}_N^N} = \int dx_a \, dx_b \, d(\text{phase space}) \sum_{\kappa} \int dt_a \, B_{\kappa_a}(t_a, x_a, \mu)$$

$$\times \int dt_b \, B_{\kappa_b}(t_b, x_b, \mu) \prod_{J=1}^{N} \int ds_J \, J_{\kappa_J}(s_J, \mu) \, \mathrm{tr}\Big[H_N^{\kappa}(\{q_i^{\mu}\}, \mu)$$

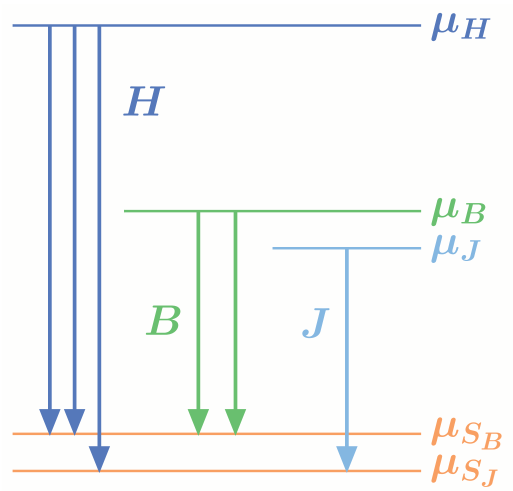
$$\times S_N^{\kappa}\Big(\mathcal{T}_N^a - \frac{t_a}{Q_a}, \mathcal{T}_N^b - \frac{t_b}{Q_b}, \ldots, \mathcal{T}_N^N - \frac{s_N}{Q_N}, \{\hat{q}_i\}, \mu\Big)\Big]$$



- Hard scattering
- Initial state radiation (+PDFs)
- Final state radiation
- Soft radiation

N-Jettiness Factorization

$$\frac{d\sigma(N\ \text{jets})}{d\mathcal{T}_N^a\, d\mathcal{T}_N^b \cdots d\mathcal{T}_N^N} = \int dx_a\, dx_b\, d(\text{phase space}) \sum_\kappa \int dt_a\, B_{\kappa_a}(t_a, x_a, \mu)$$



$$\times \int dt_b\, B_{\kappa_b}(t_b, x_b, \mu) \prod_{J=1}^{N} \int ds_J\, J_{\kappa_J}(s_J, \mu)\ \text{tr}\Big[H_N^\kappa(\{q_i^\mu\}, \mu)$$

$$\times S_N^\kappa\Big(\mathcal{T}_N^a - \frac{t_a}{Q_a}, \mathcal{T}_N^b - \frac{t_b}{Q_b}, \ldots, \mathcal{T}_N^N - \frac{s_N}{Q_N}, \{\hat{q}_i\}, \mu\Big)\Big]$$

- Separating physics at different scales enables resummation
- At NNLL order need one-loop B, J, H, S

B: Stewart, Tackmann, WW; Mantry, Petriello, J: Bauer, Manohar; Fleming, Leibovich, Mehen; Becher, Schwartz
One-loop H for H+1-jet: Schmidt, One-loop S for N-jettiness: Jouttenus, Stewart, Tackmann, WW

- Three-loop cusp and two-loop non-cusp anomalous dim.

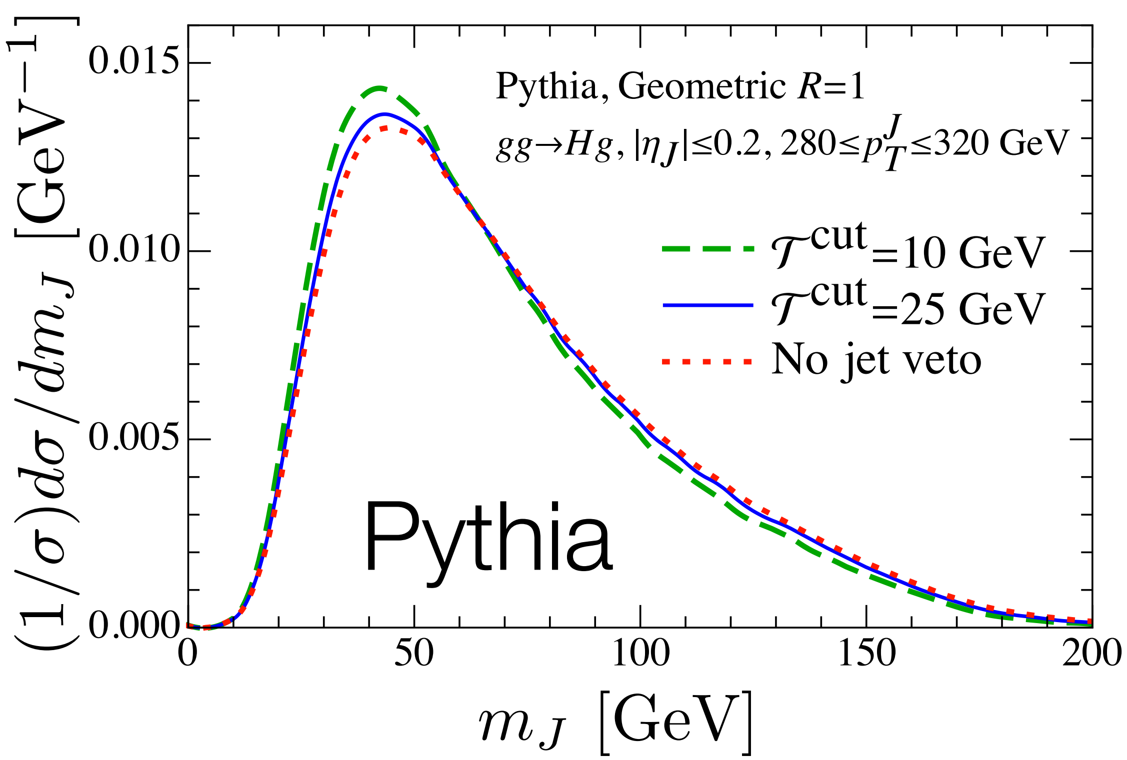
Three-loop cusp: Korchemsky, Radyushkin; Moch, Vermaseren, Vogt, Two-loop non-cusp known from: Kramer, Lampe; Harlander; Aybat, Dixon, Sterman; Becher, Neubert; Becher, Schwartz; Stewart, Tackmann, WW

Normalization

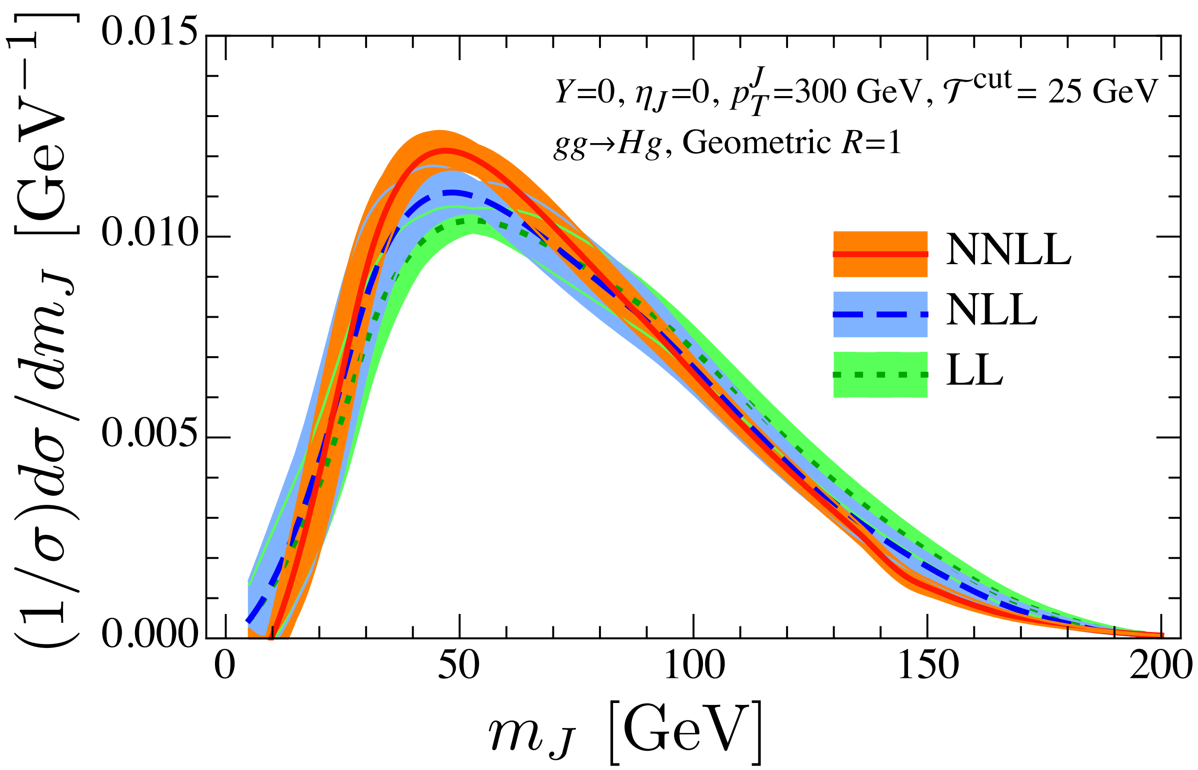
- We are required to veto additional jets through $\mathcal{T}_1^a, \mathcal{T}_1^b$
- Normalizing the spectrum removes this dependence:

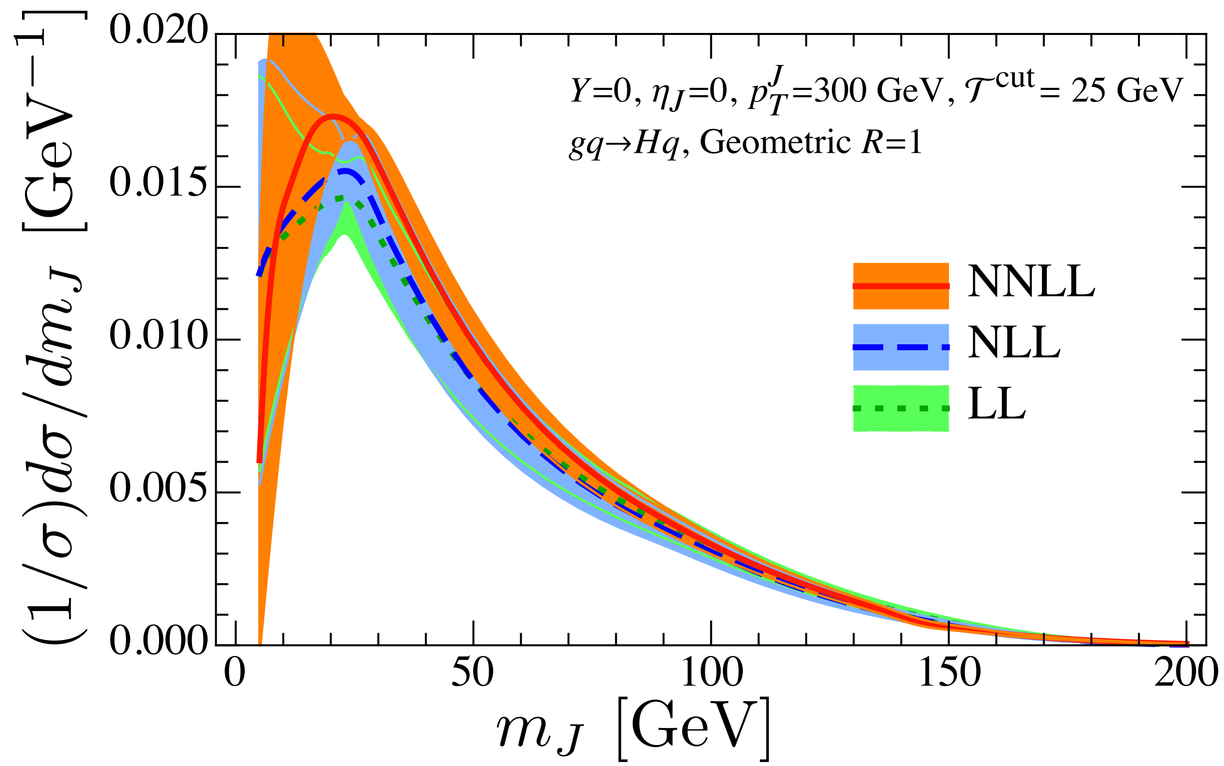
$$\frac{\sigma(\mathcal{T}_1^a, \mathcal{T}_1^b \leq \mathcal{T}^{\rm cut}, m_J, p_T^J, y^J, Y)}{\int dm_J\, \sigma(\mathcal{T}_1^a, \mathcal{T}_1^b \leq \mathcal{T}^{\rm cut}, m_J, p_T^J, y^J, Y)}$$

- Experimental results are also normalized



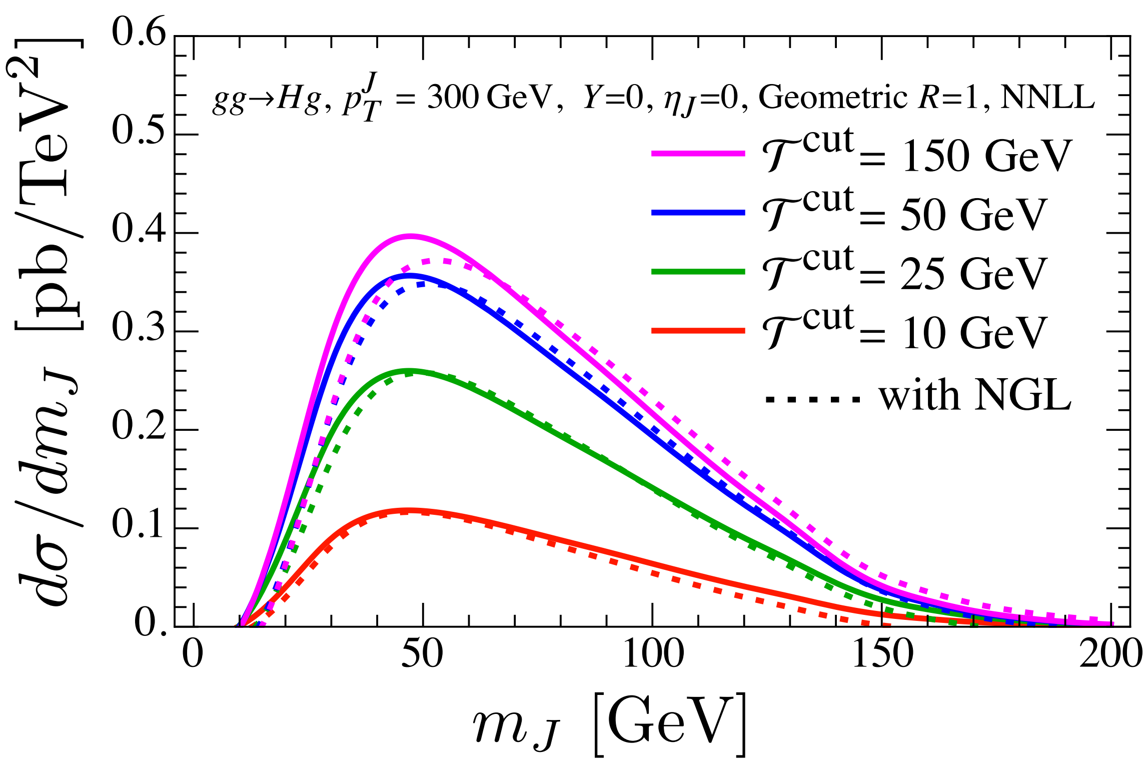
Perturbative Convergence

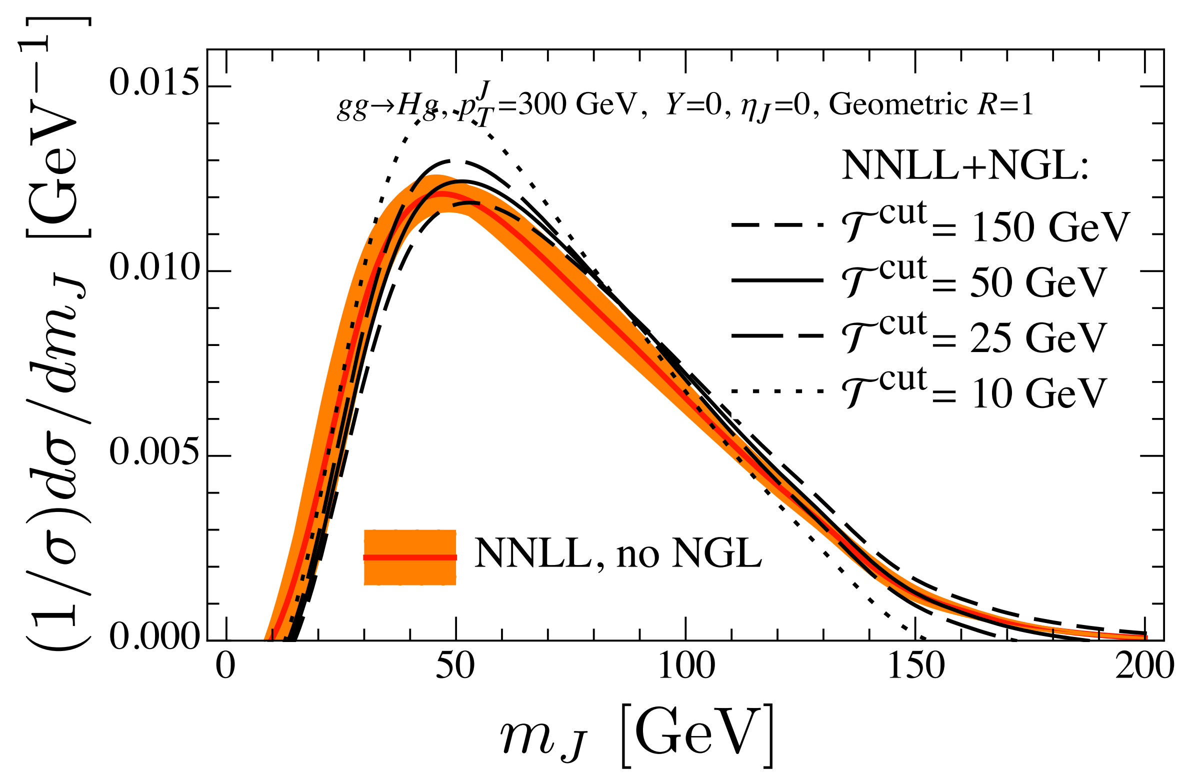




- We consider $gg \to Hg$ and $gq \to Hq$ (proxies for gluon and quark jets)
- Good agreement between LL, NLL, NNLL

Non-Global Logarithms





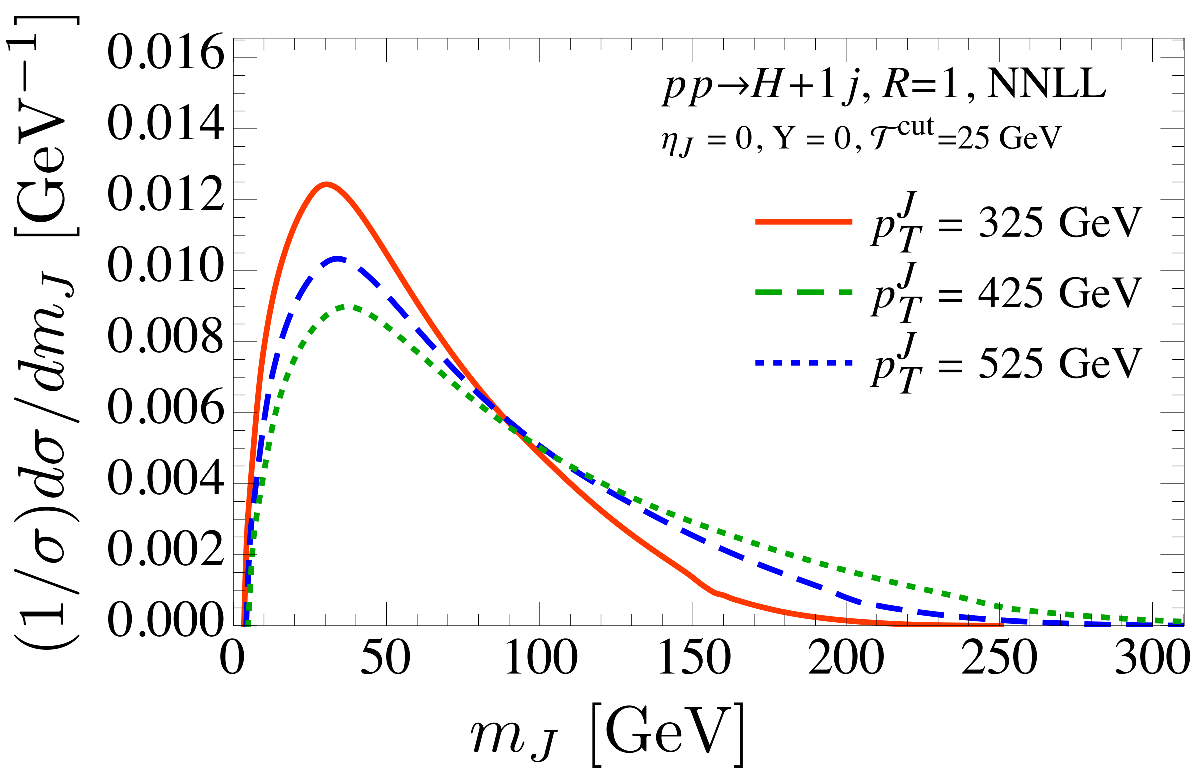
- NGLs arise when soft probes multiple scales, $\mathcal{T}_N^i \ll \mathcal{T}_N^j$
- We find their effect to be small by testing with

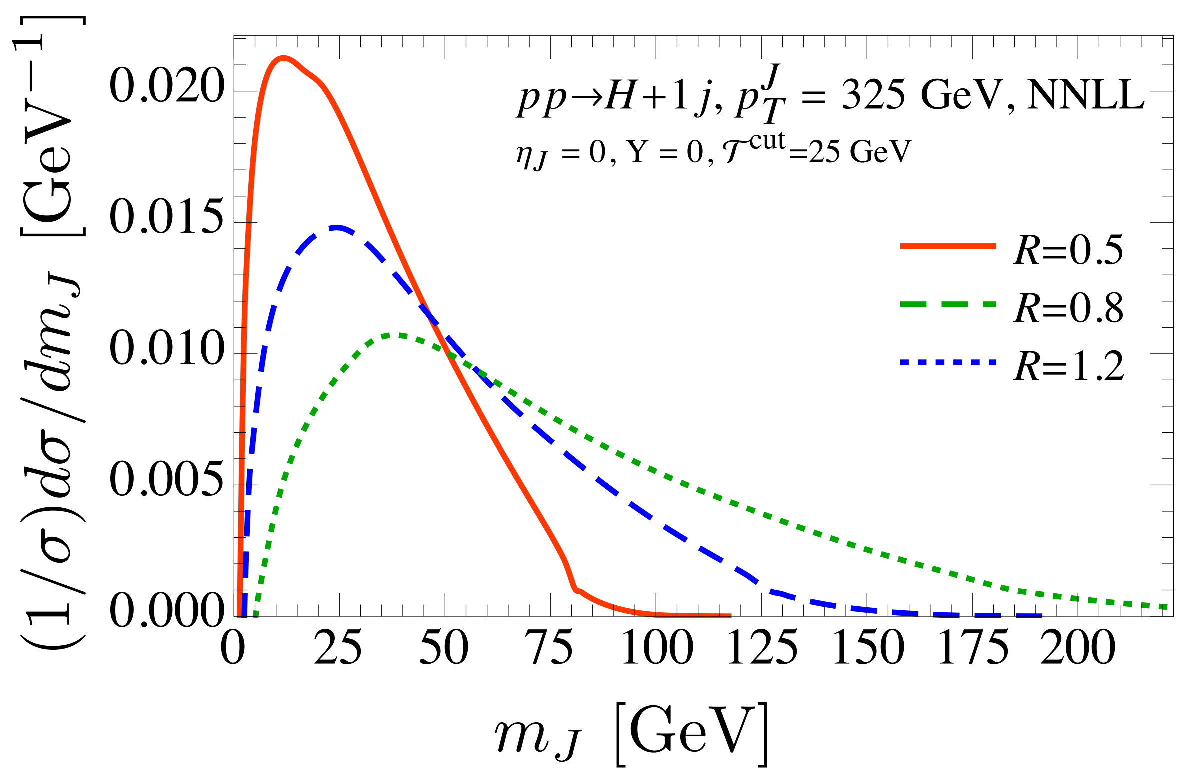
geometrical factor

$$S_{\rm NGL}(\{k_i^c\},\mu_S) = \prod_i \left(\int_0^{k_i^c} dk_i\right) S_{\rm NGL}(\{k_i\},\mu_S) = -\frac{\alpha_s^2(\mu_S)C^2}{(2\pi)^2}\sum_{i<j} G_{ij}\ln^2\left(\frac{k_i^c}{k_j^c}\right)$$

color factor

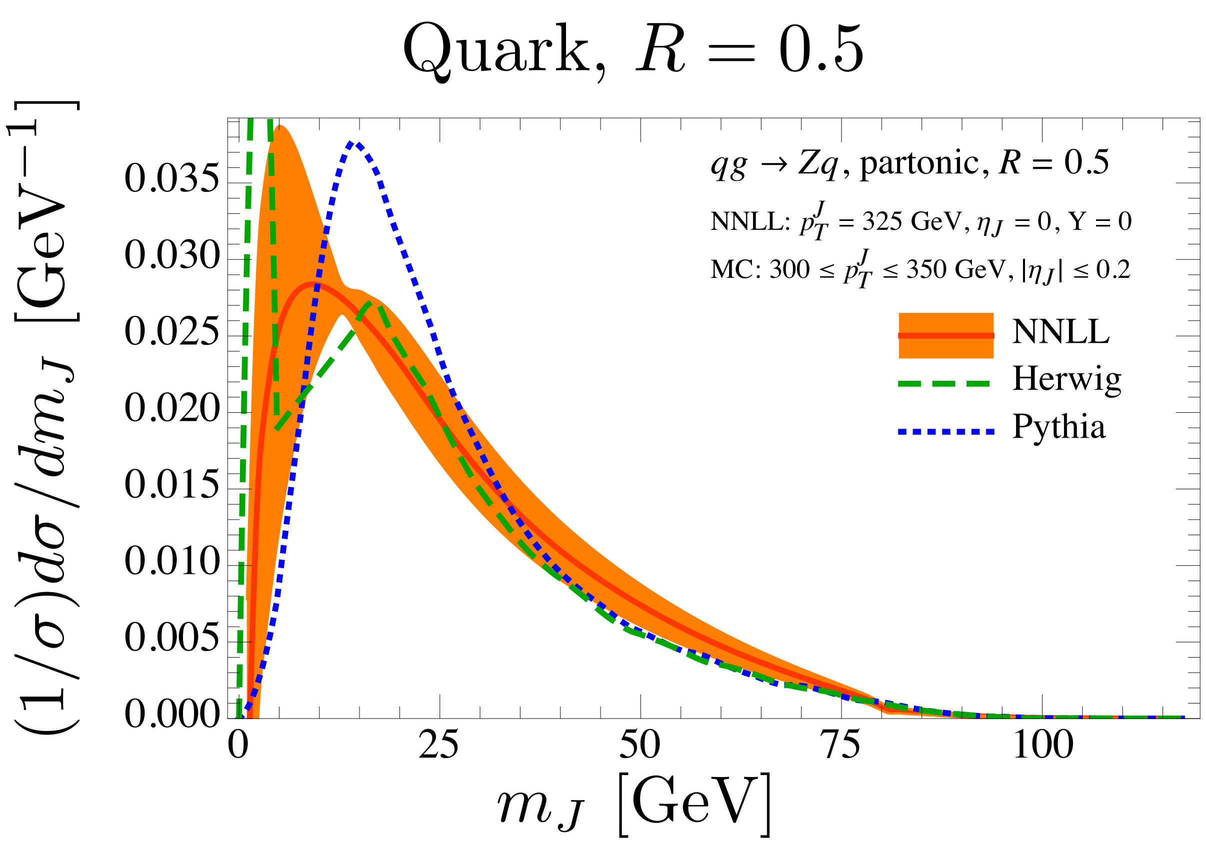
Dependence on Kinematics and Jet Radius

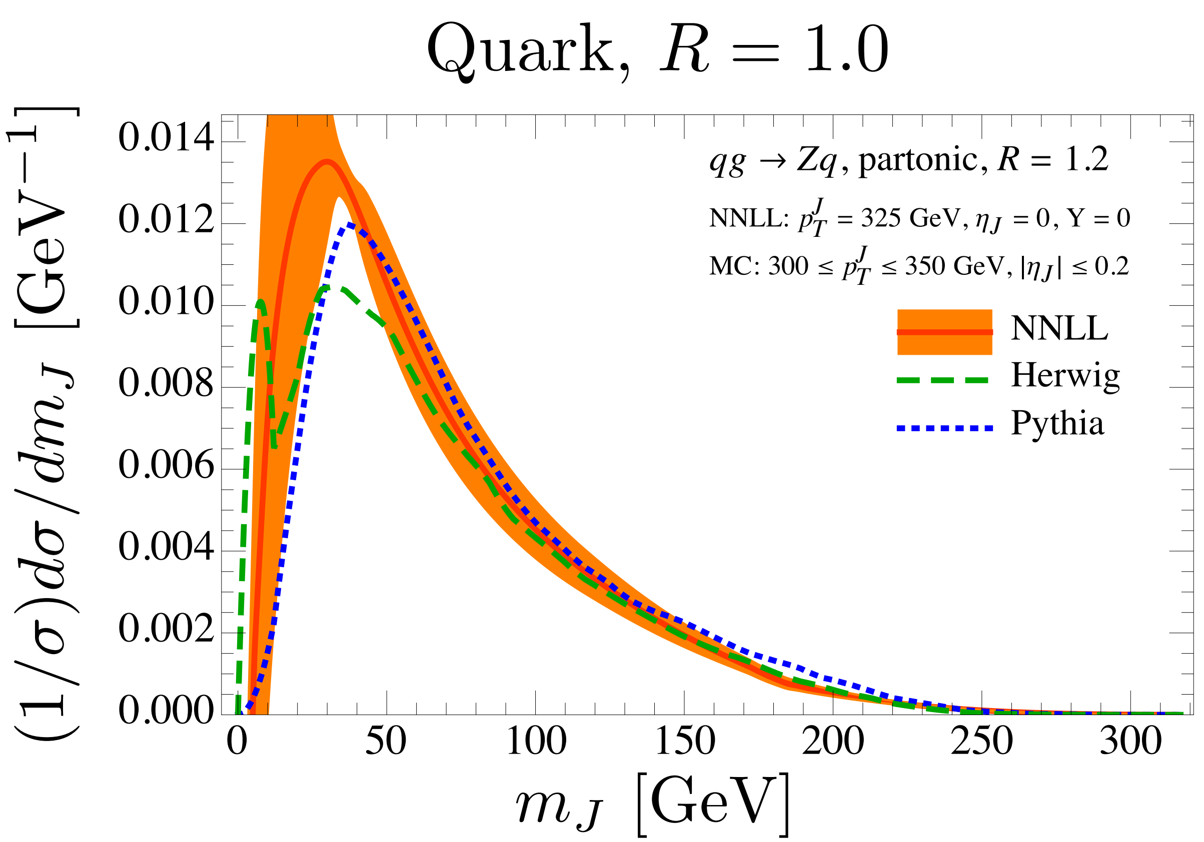




- Calculable dependence on kinematics p_T^J, y_J, Y
- Strong dependence on jet radius since $m_J \lesssim p_T^J R/\sqrt{2}$ (Nonsingular important!)

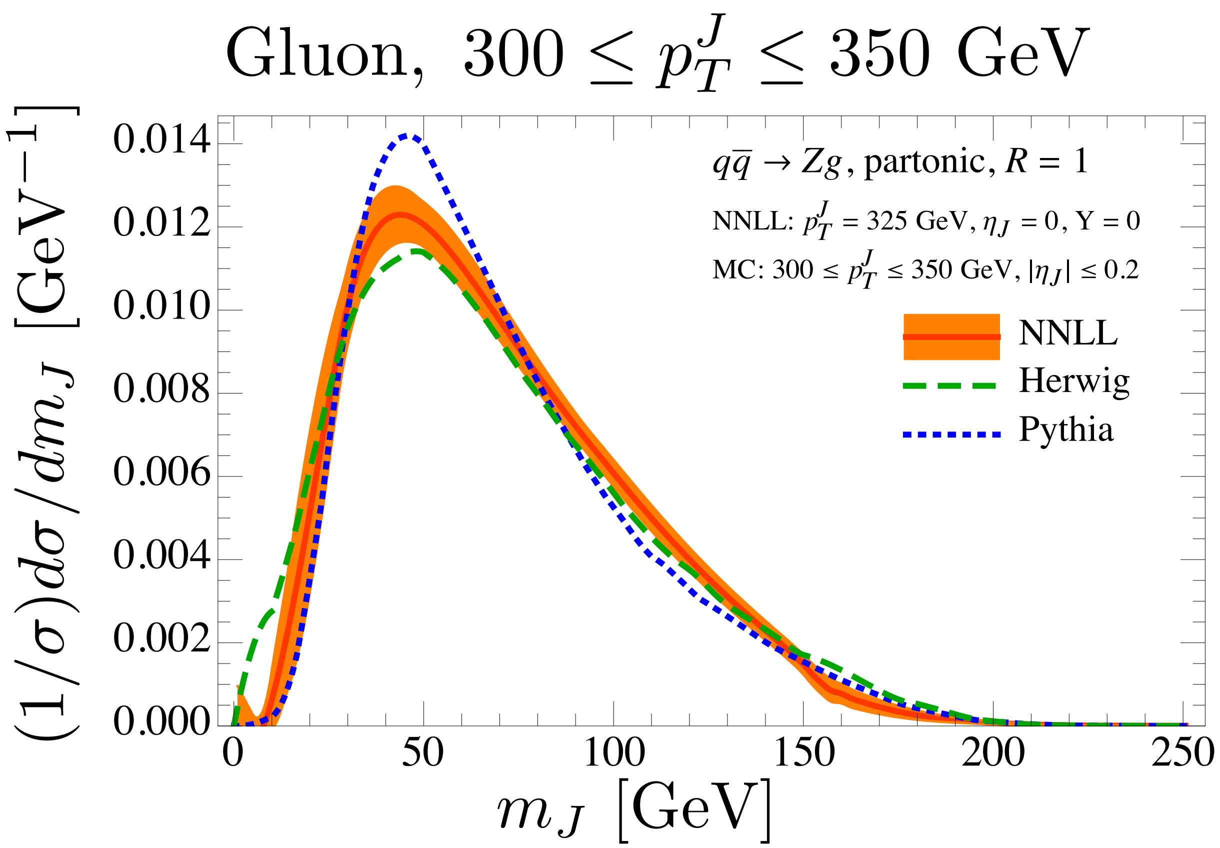
Comparison to Pythia and Herwig

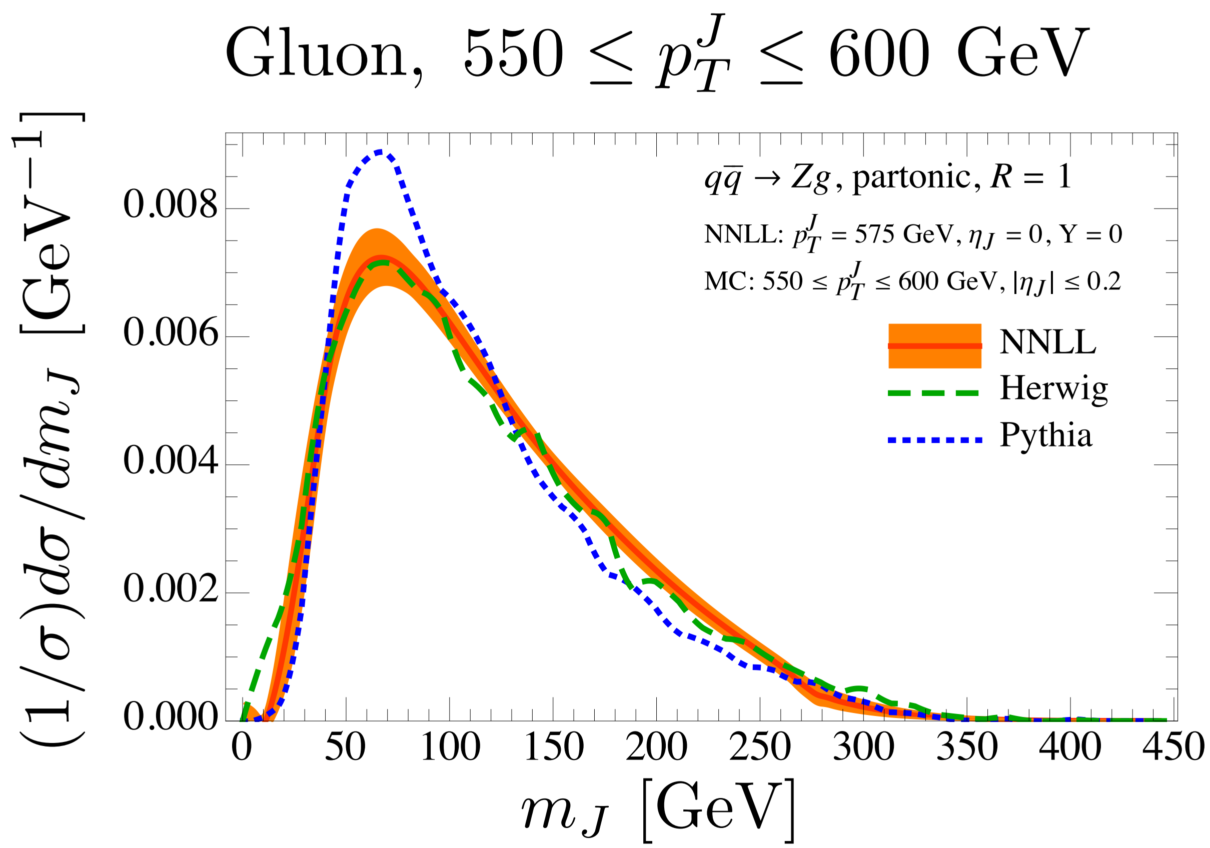




- Reasonable agreement over a range of kinematics and R
- No clear favorite between Pythia or Herwig
- Big differences for $R < 0.5$

Comparison to Pythia and Herwig



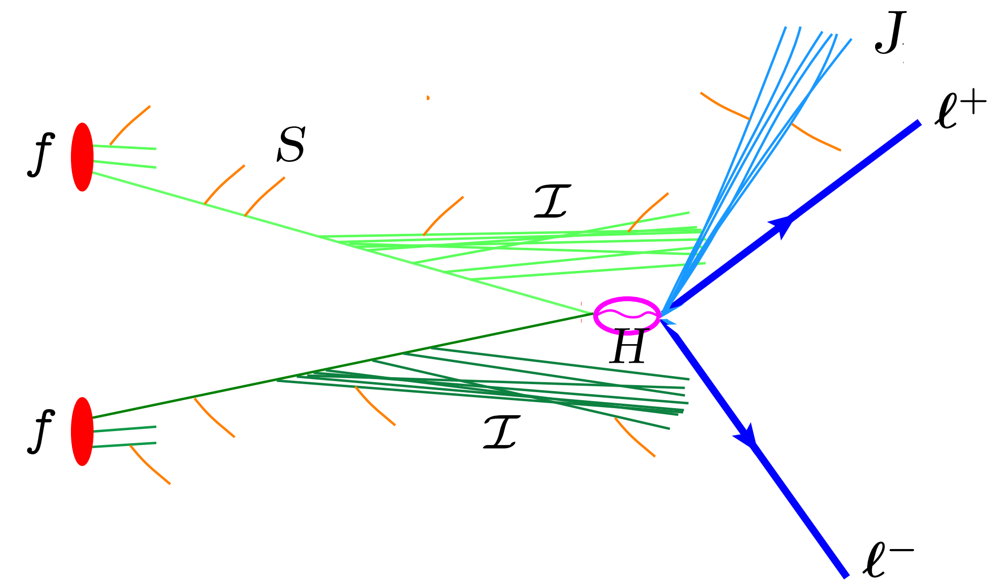


- Reasonable agreement over a range of kinematics and R
- No clear favorite between Pythia or Herwig
- Big differences for $R < 0.5$

Hadronization of Jets

Tackmann, Stewart, WW (to appear)

Nonperturbative Effects



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

Jet function   Soft function

- Soft function describes primary soft radiation:

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

- Perturbative and nonperturbative soft contribution:

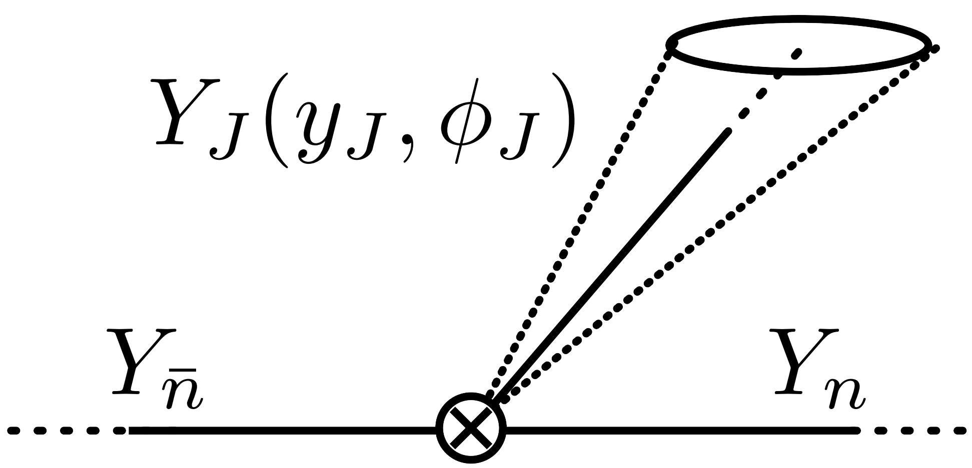
$$S(k_s) = \int dk_s'\, S_{\rm pert}(k_s - k_s') F_{\rm NP}(k_s')$$

(Korchemsky, Sterman; Hoang, Stewart; Ligeti, Stewart, Tackmann)

- Leading NP effect: $m_J^2 \to m_J^2 + 2p_T^J \Omega, \quad \Omega = \int dk_s\, k_s\, F_{\rm NP}(k_s)$

Leading Nonperturbative Effect

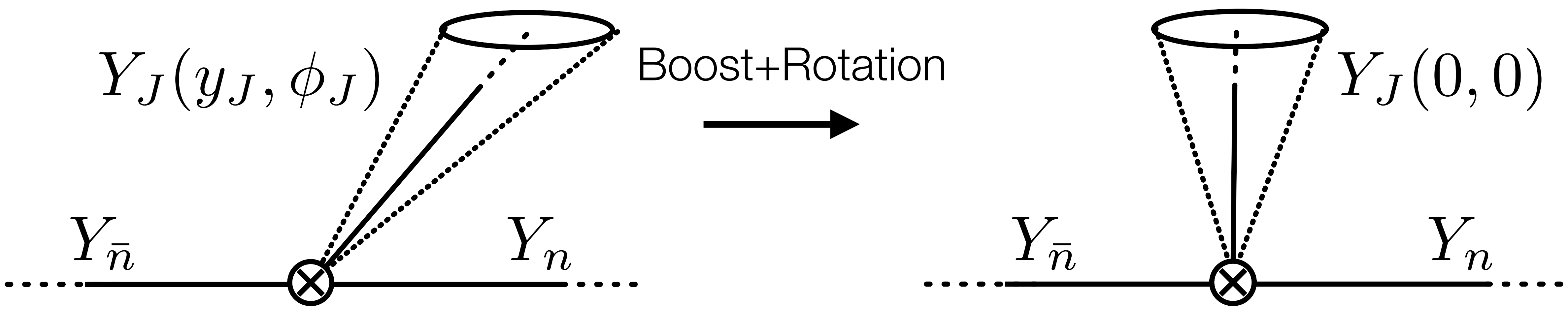
$$\Omega = \langle 0 | Y_J^\dagger(y_J,\phi_J) Y_{\bar n}^\dagger Y_n^\dagger \, \cosh y_J \, n_J \cdot \hat p_J \, Y_n Y_{\bar n} Y_J(y_J,\phi_J) | 0 \rangle$$



- Ω is independent of p_T^J by definition
- Y's and thus Ω depend on color configuration

Leading Nonperturbative Effect

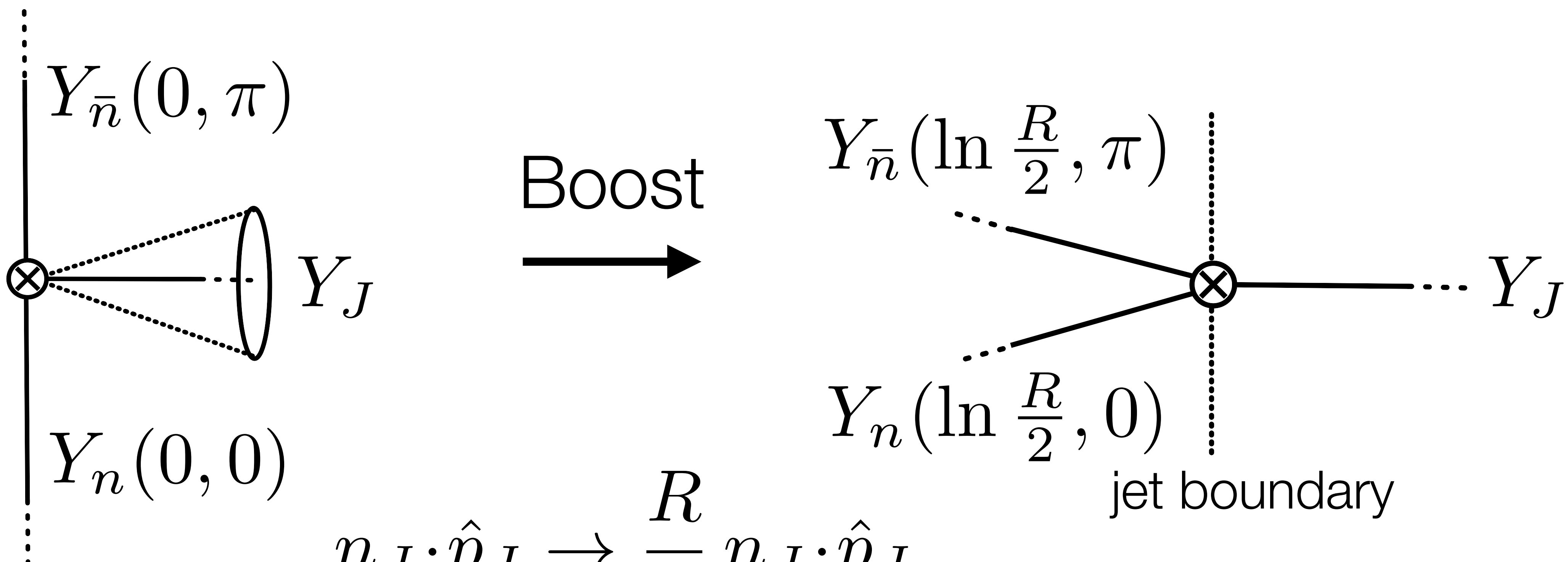
$$\Omega = \langle 0 | Y_J^\dagger(y_J, \phi_J) Y_{\bar{n}}^\dagger Y_n^\dagger \, \cosh y_J \, n_J \cdot \hat{p}_J \, Y_n Y_{\bar{n}} Y_J(y_J, \phi_J) | 0 \rangle$$



- Ω is independent of p_T^J by definition
- Y's and thus Ω depend on color configuration
- Rotating + boosting shows that Ω is independent of y_J, ϕ_J

Dependence on Jet Radius R

Rotate coordinate system



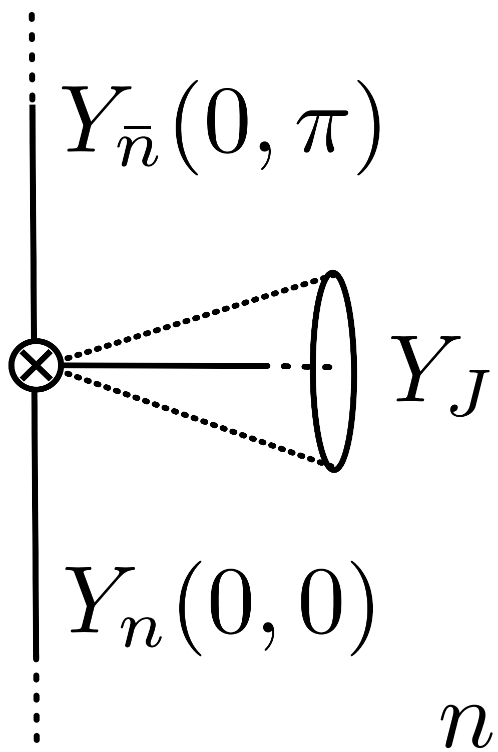
$$n_J\cdot\hat{p}_J \to \frac{R}{2}\,n_J\cdot\hat{p}_J$$

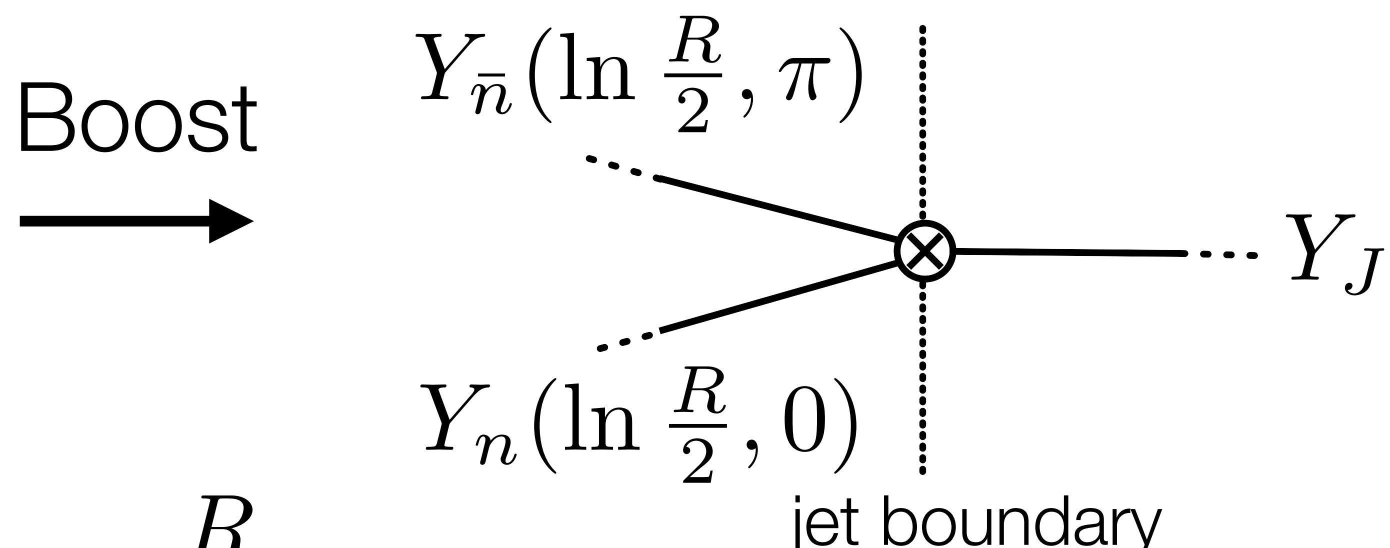
$$\Omega = \frac{R}{2}\int_0^\infty dy\, e^{-y}\langle 0|Y_J^\dagger Y_{\bar{n}}^\dagger(\ln\tfrac{R}{2},\pi)Y_n^\dagger(\ln\tfrac{R}{2},0)\hat{\mathcal{E}}_\perp(r,y,\phi)(\ldots)|0\rangle$$

energy flow operator

Dependence on Jet Radius R

Rotate coordinate system





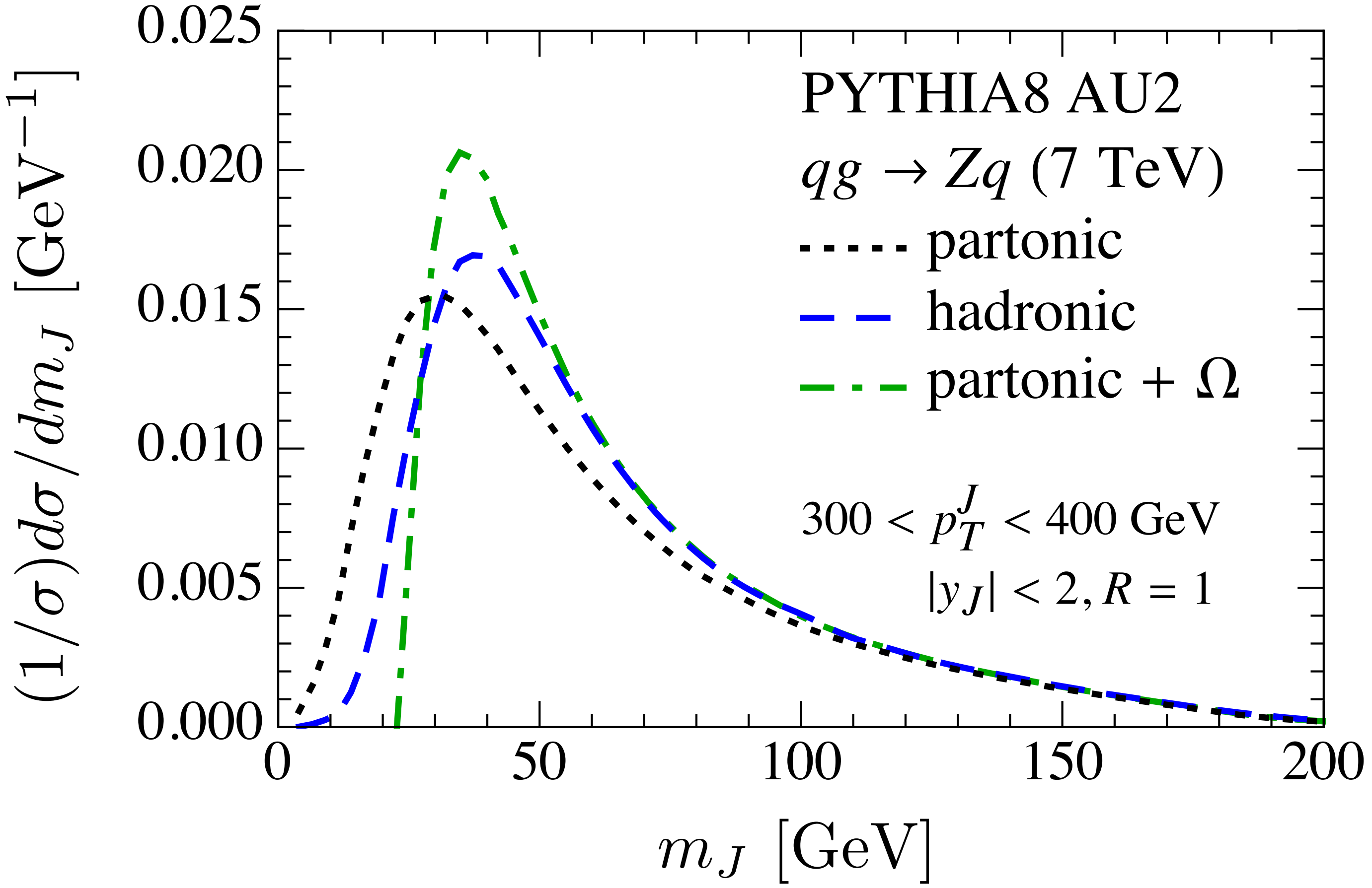
$$n_J\cdot\hat{p}_J \to \frac{R}{2}\, n_J\cdot\hat{p}_J$$

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

energy flow operator

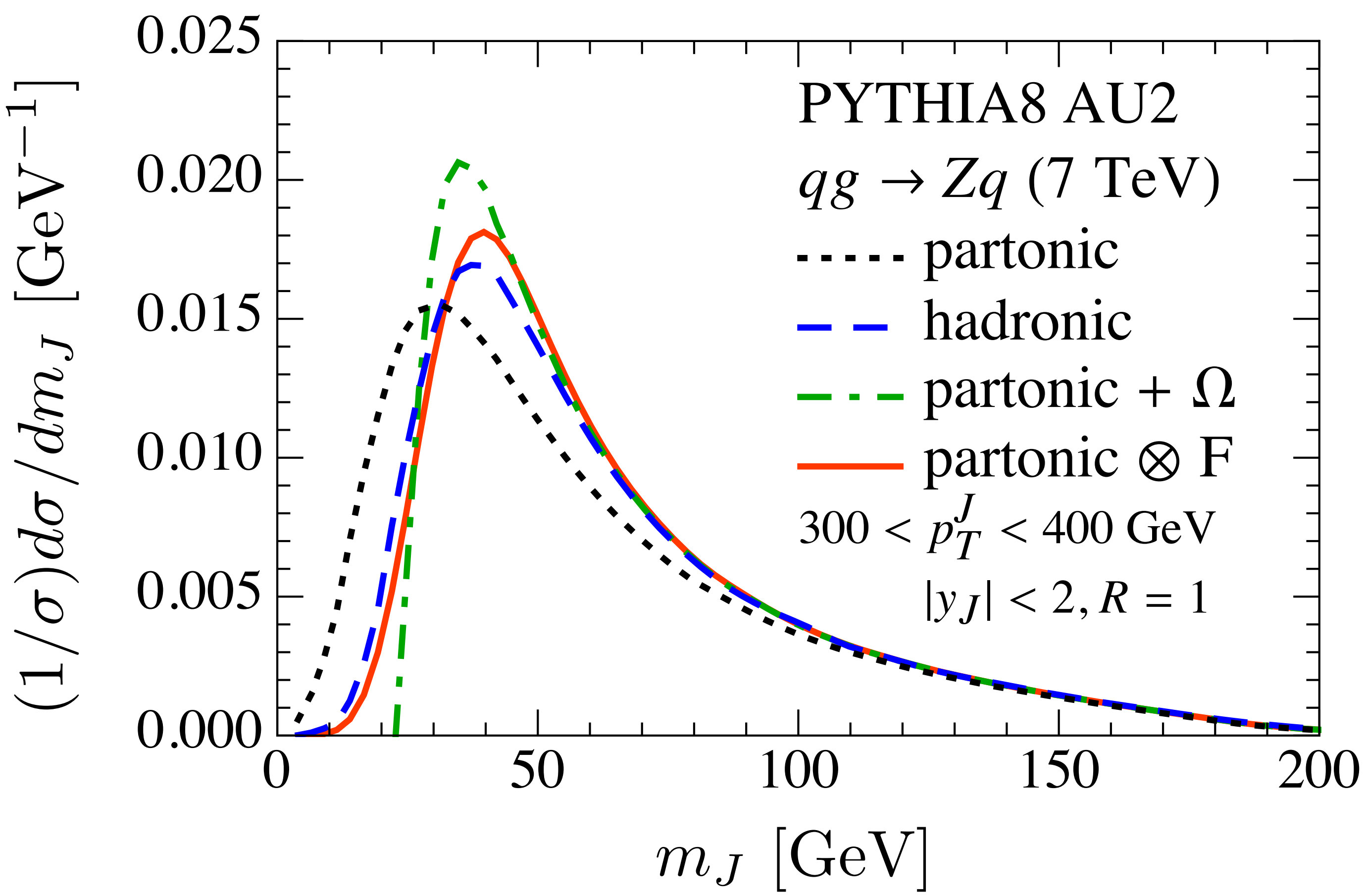
- For $R \ll 1$, the beam Wilson lines fuse and $\Omega = \Omega_0\, R/2 + \ldots$
- Only odd powers of R arise

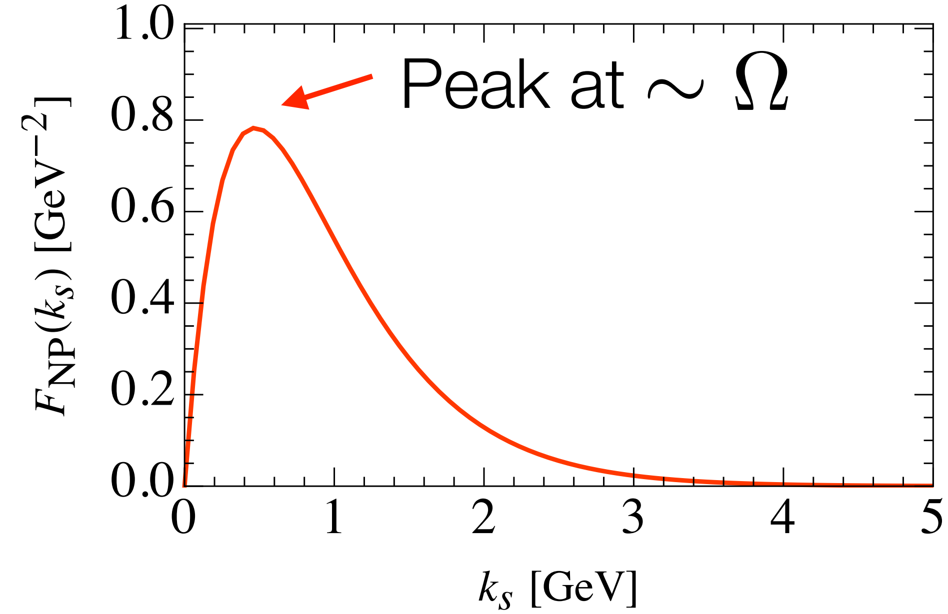
Hadronization in MC



- Hadronization in the tail described by $m_J^2 \to m_J^2 + 2p_T^J\Omega$

Hadronization in MC



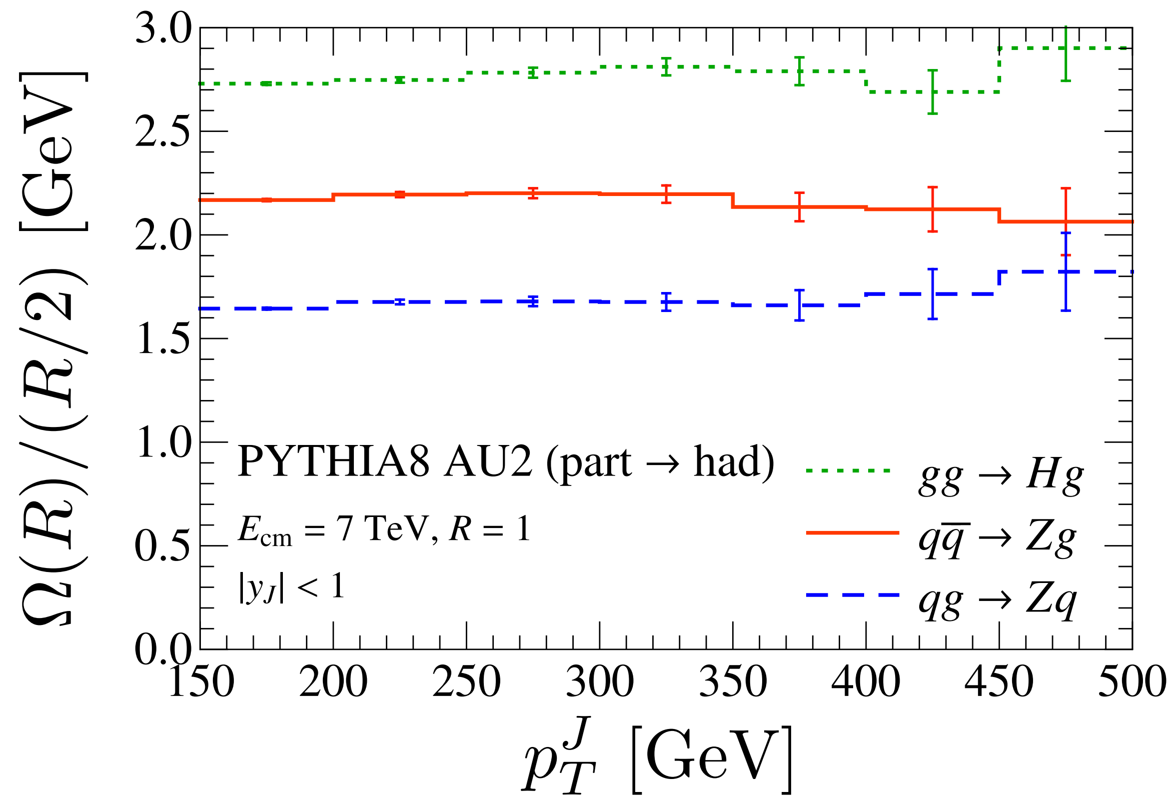


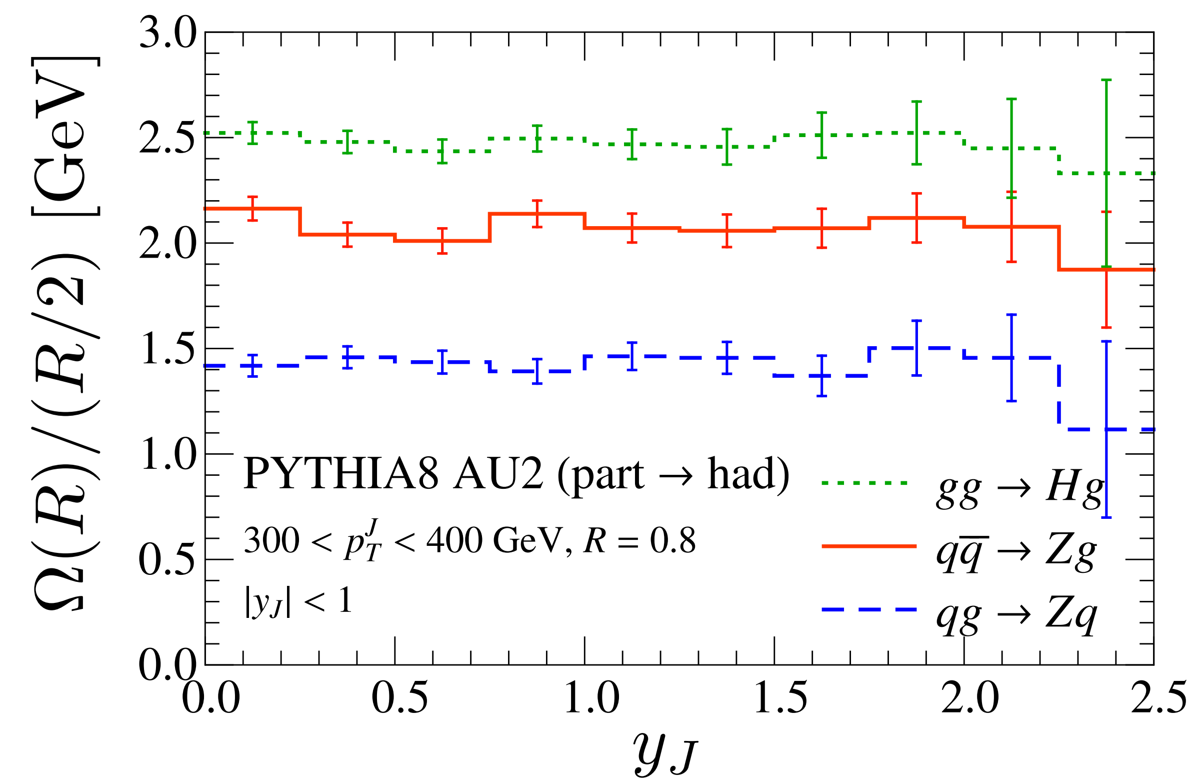
$$\Omega = \int dk_s\, k_s\, F_{\rm NP}(k_s)$$

- Hadronization in the tail described by $m_J^2 \to m_J^2 + 2p_T^J\Omega$
- $$\frac{d\sigma}{dm_J^2} \to \int_0^\infty dk_s\, \frac{d\sigma}{dm_J^2}(m_J^2 - 2p_T^J k_s)\, F_{\rm NP}(k_s)$$

  works fairly well for generic $F_{\rm NP}$ with correct Ω

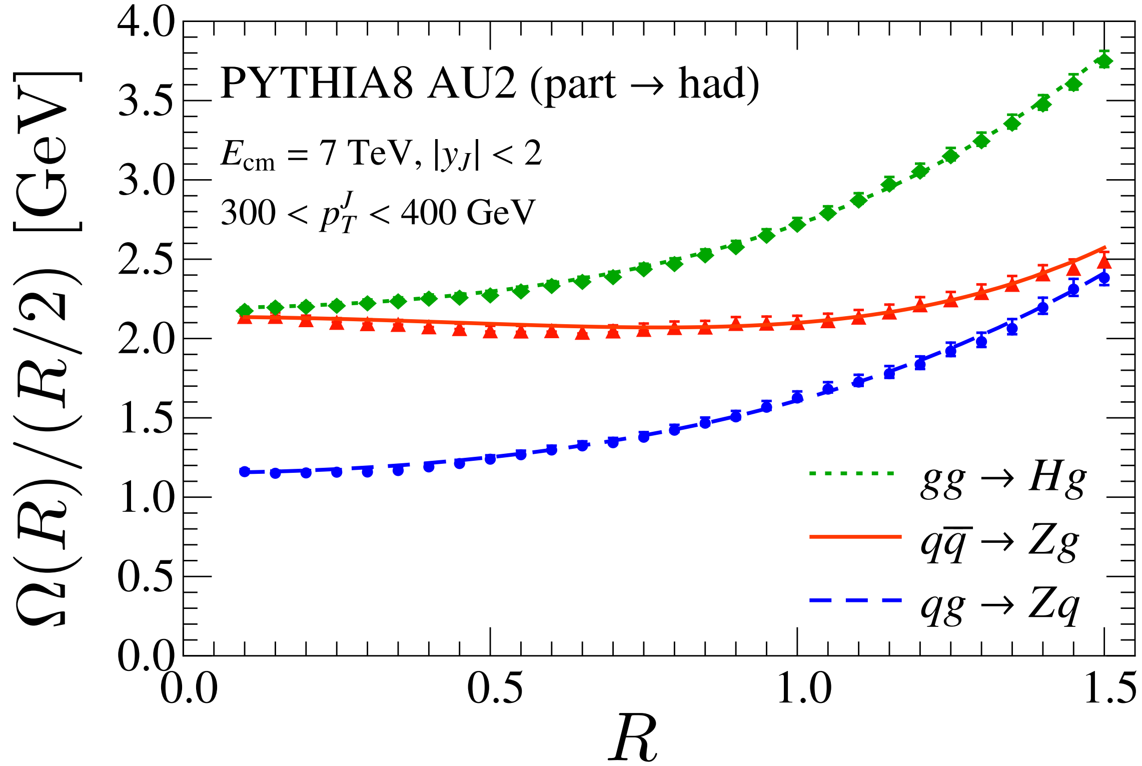
Hadronization is Nonperturbative Soft Effect

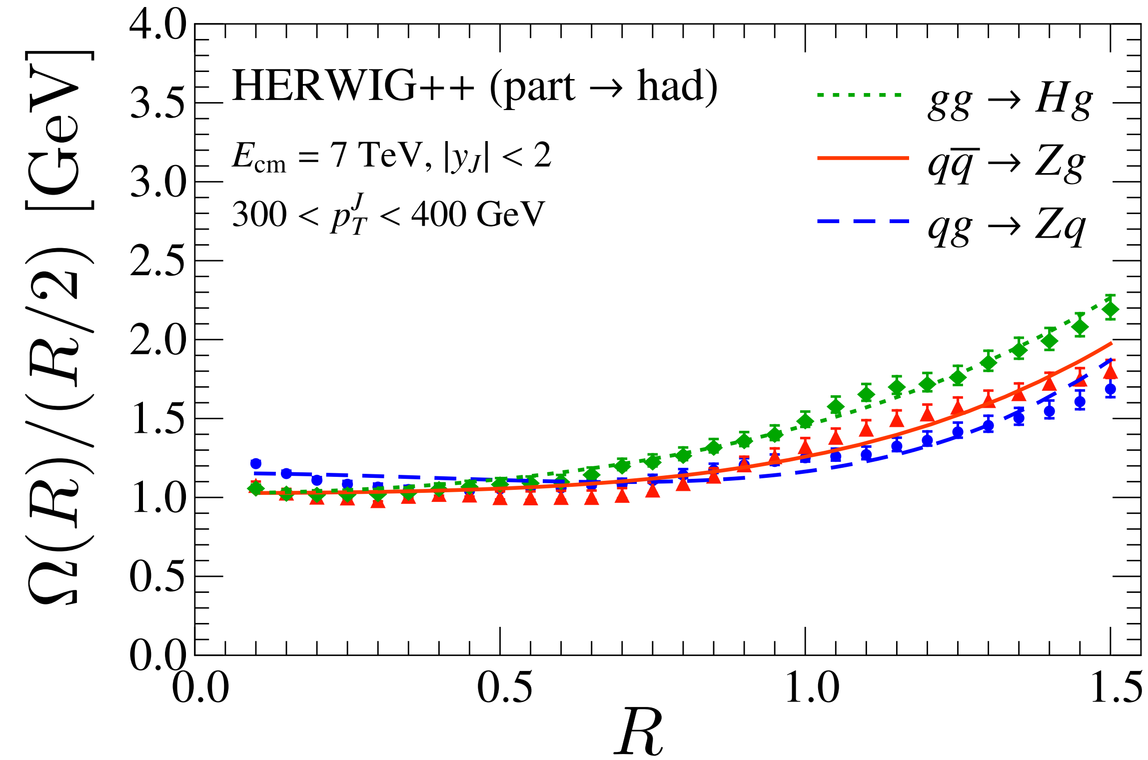




- Hadronization in MC is independent of p_T^J, y_J

Hadronization is Nonperturbative Soft Effect





- Hadronization in MC is independent of p_T^J, y_J
- $\Omega = \Omega_0 \, R/2 + \ldots$ for $R \ll 1$
- Ω_0 only depends on quark vs. gluon jet (same in Herwig?)
- The universal Ω_0^q can be extracted from DIS event shapes

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

Conclusions

- Many LHC searches involves jets as signal or background
- Jet substructure provides a new set of tools
  - Boosted objects
  - Quark vs. gluon
- Much theoretical work remains to be done
  - Improve Monte Carlo
  - Gain insight
- Factorization is key: separating physics at different scales
  - Calculate jet mass and charge
  - Nonperturbative effects for track-based observables
  - Universality of hadronization for jets with $R \ll 1$