Jet Substructure at the LHC

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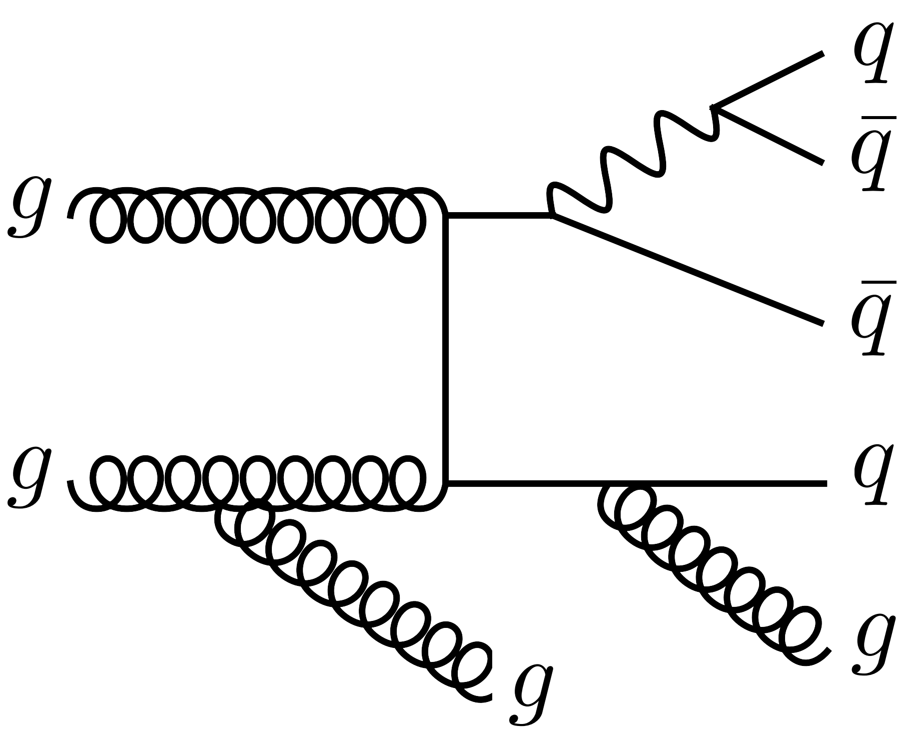
Outline

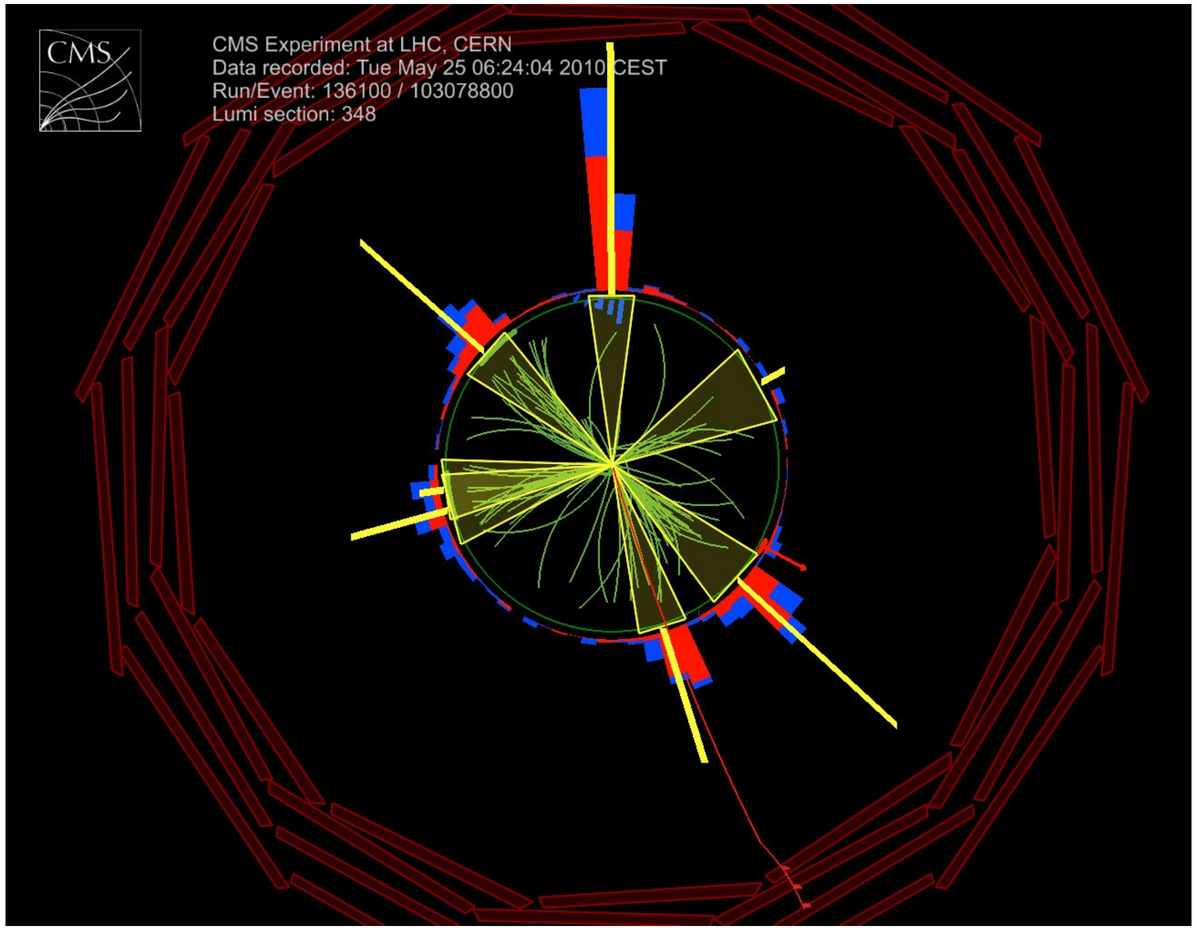
- Introduction
- Jet Charge
- Jet Mass
- Hadronization of Jets
- Quark/Gluon Discrimination
- Conclusions

Introduction

What is a Jet?

Energetic quarks and gluons radiate and hadronize → Produce jets of hadrons

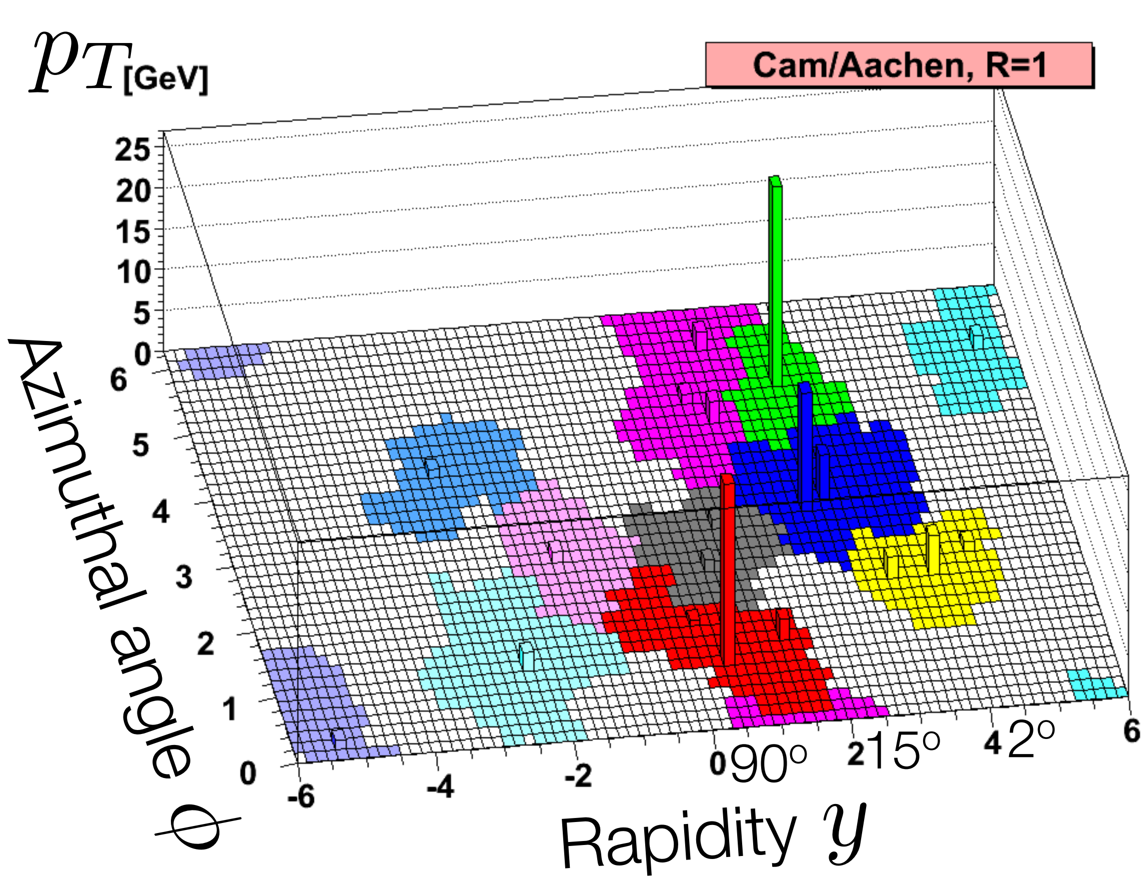




Jet Algorithms

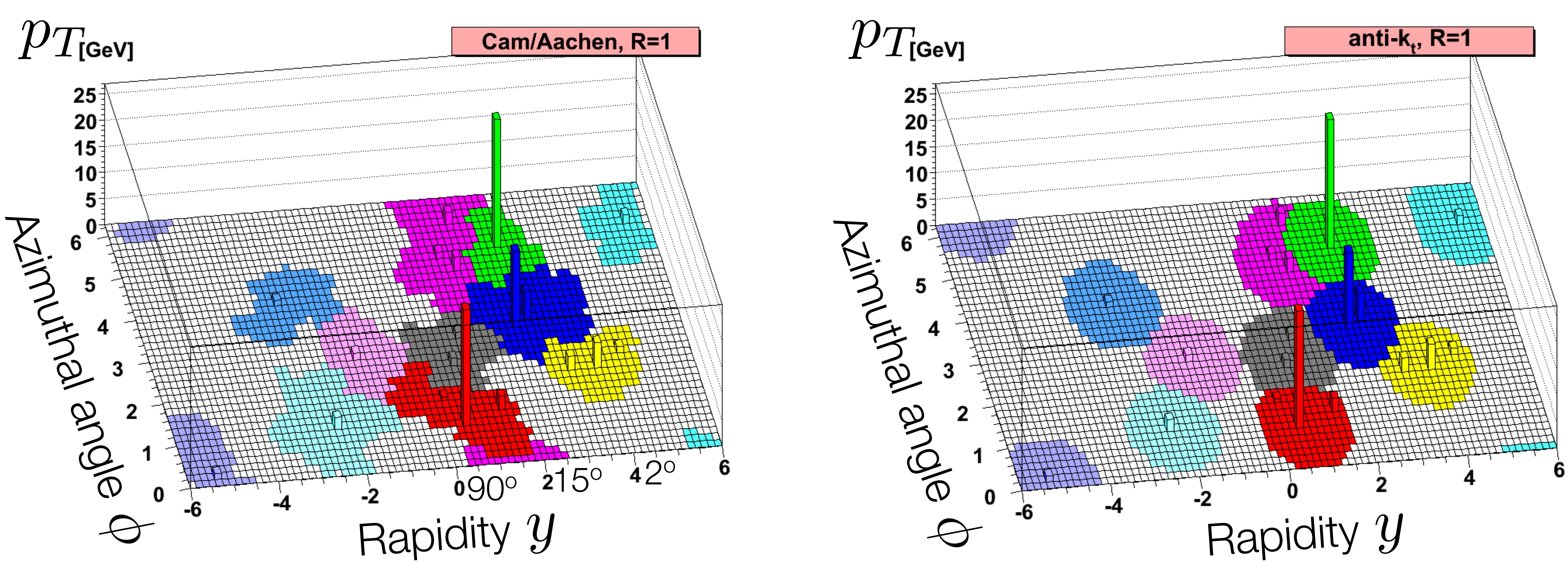
- Repeatedly cluster nearest "particles" $p_i, p_j \to p_i + p_j$
- Cut off by jet "radius" R

$$\text{distance} = (\Delta y)^2 + (\Delta \phi)^2$$



Jet Algorithms

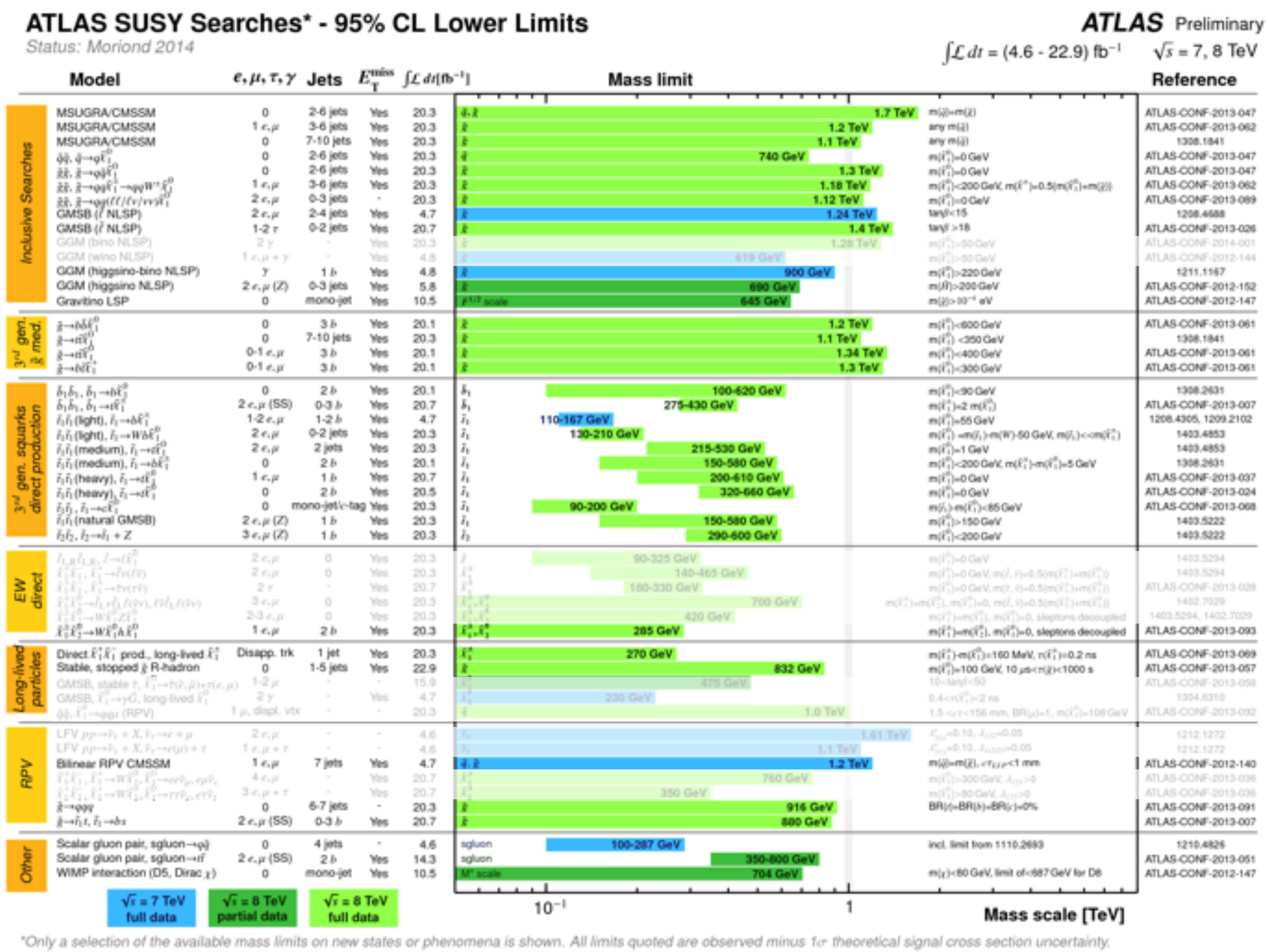
- Repeatedly cluster nearest "particles" $p_i, p_j \to p_i + p_j$
- Cut off by jet "radius" R
- Default at LHC: anti-k_T (Cacciari, Salam, Soyez)



(arXiv:0802.1189)

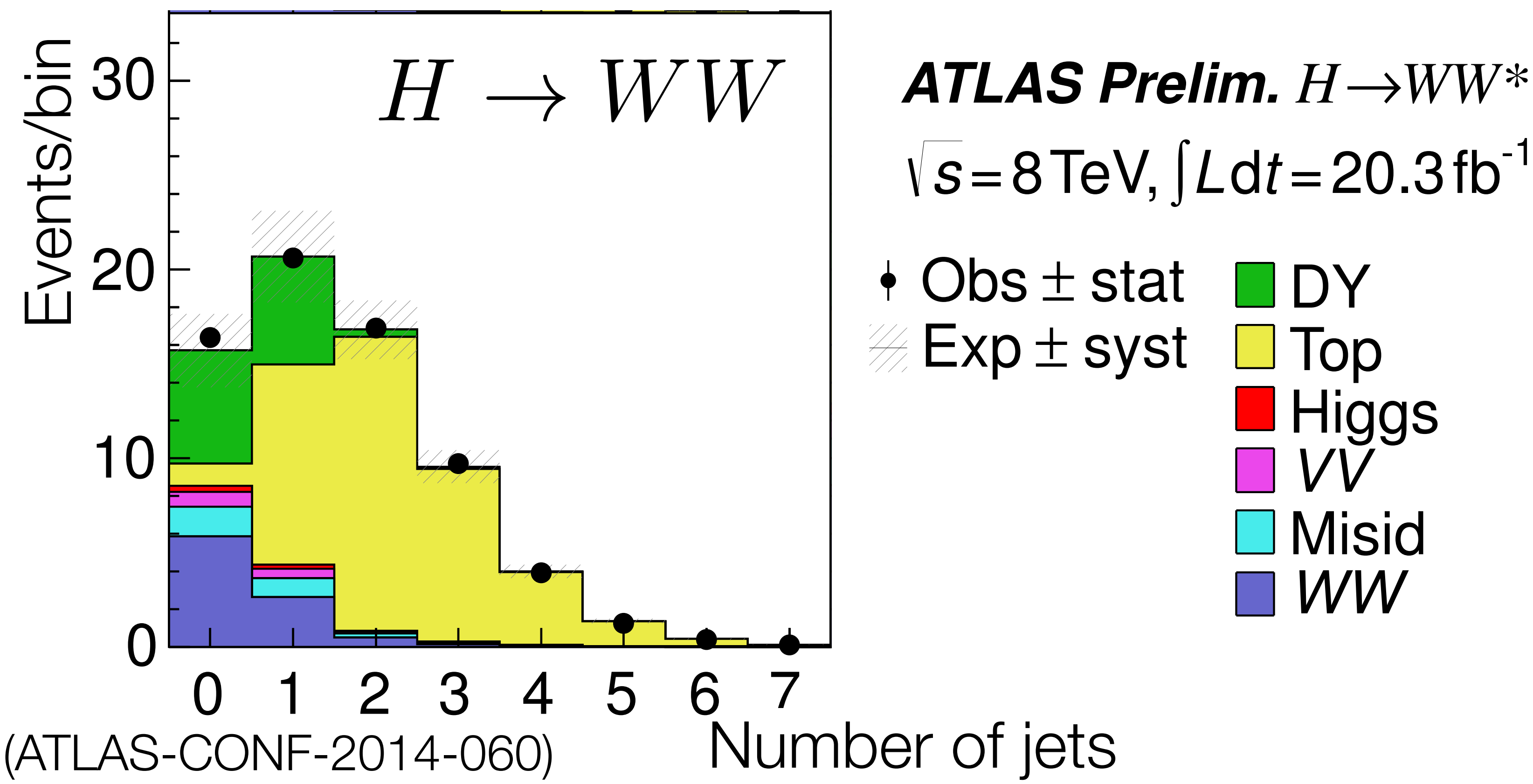
Jets at the LHC

- Most measurements involve jets as signal or background



Jet Cross Sections

- Bin by jet multiplicity to improve background rejection



(ATLAS-CONF-2014-060)

- Large logarithms lead to large theory uncertainties

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

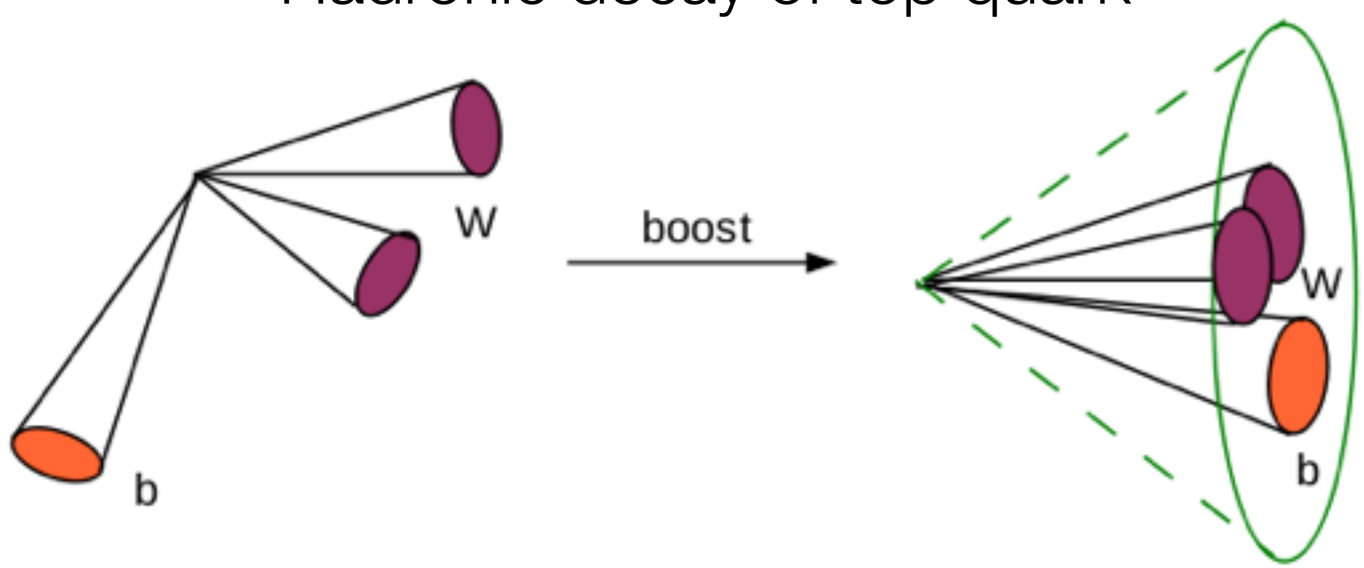
no jets above this p_T

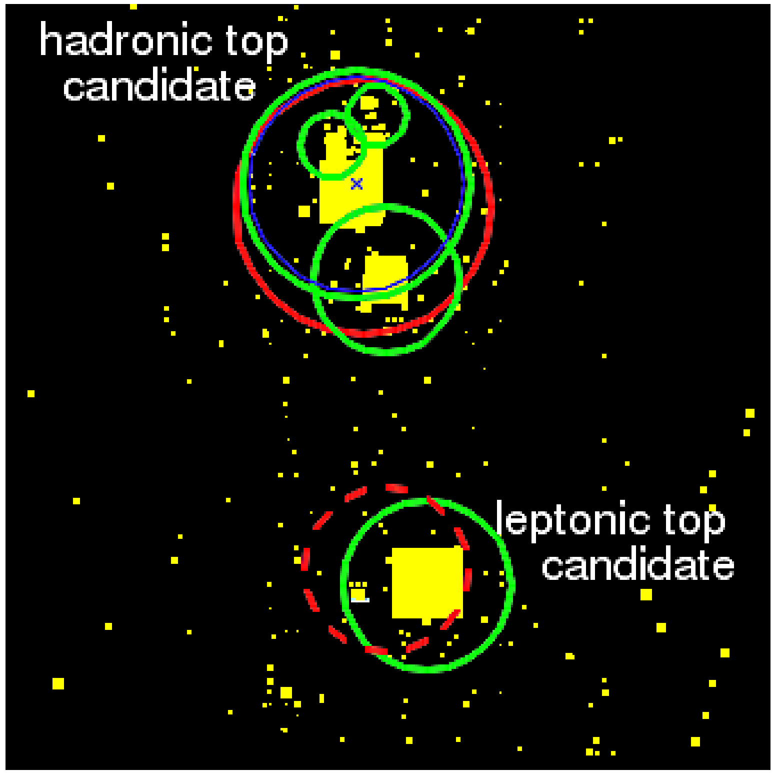
(Berger, Marcantonini, Stewart, Tackmann, WW; Banfi, Monni, Salam, Zanderighi, Becher, Neubert, Rothen; Stewart, Tackmann, Walsh, Zuberi; Liu, Petriello; Boughezal, Focke, Li, Liu; Jaiswal, Okui, …)

Jet Substructure for Boosted Objects

- New heavy particles could produce boosted top, W, Higgs → decay products lie within one "fat" jet
- Distinguish from QCD jets using jet substructure
- Avoids combinatorial background

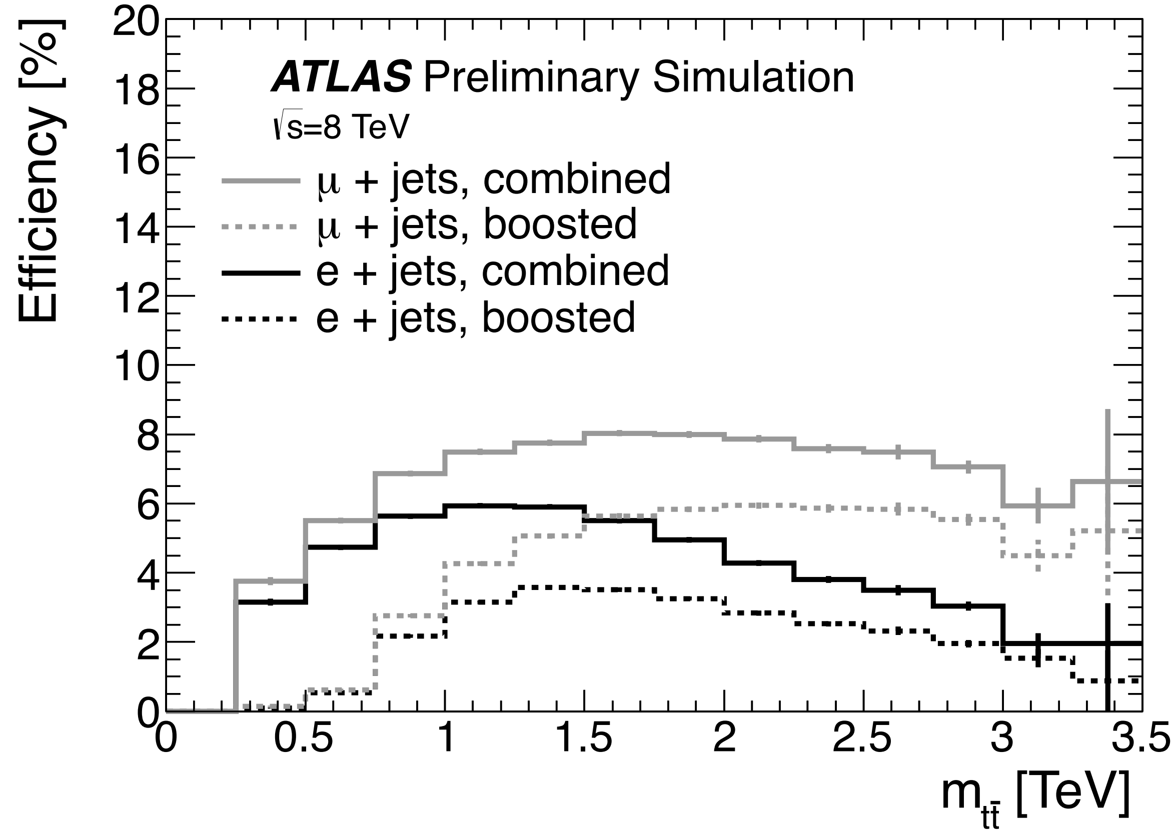
Hadronic decay of top quark

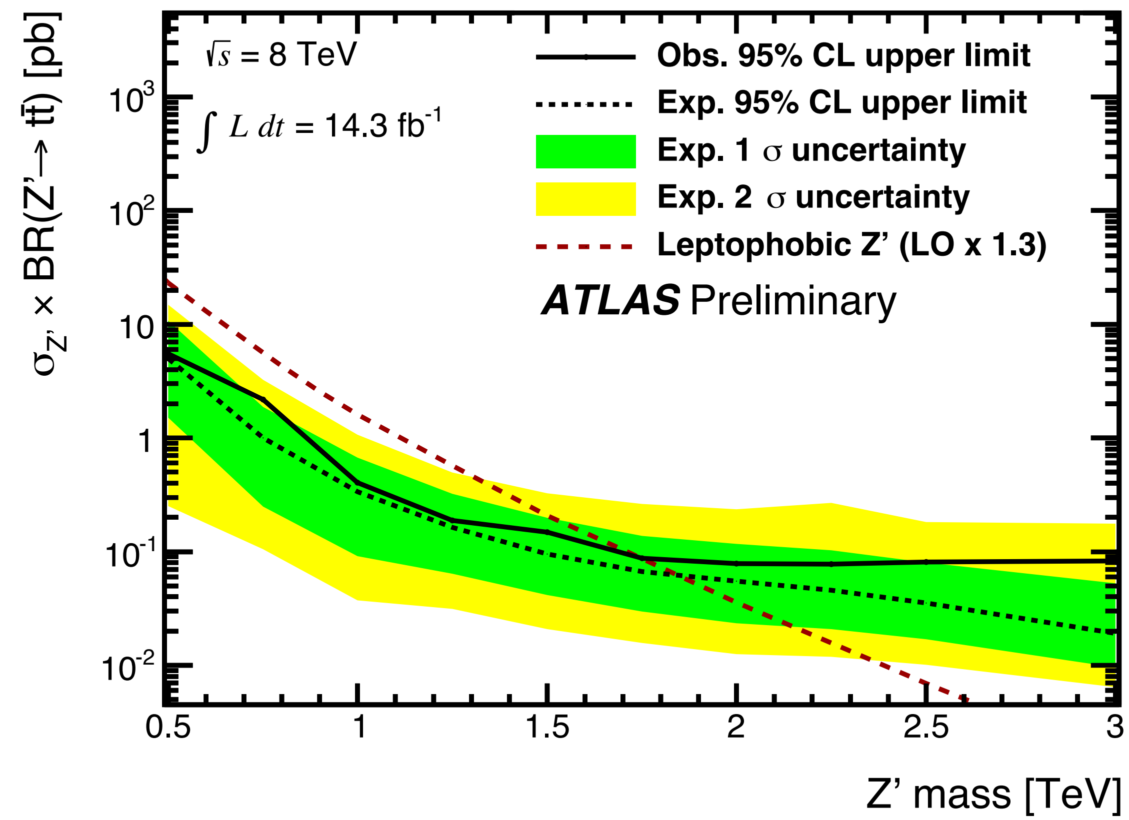




(ATLAS-CONF-2013-052)

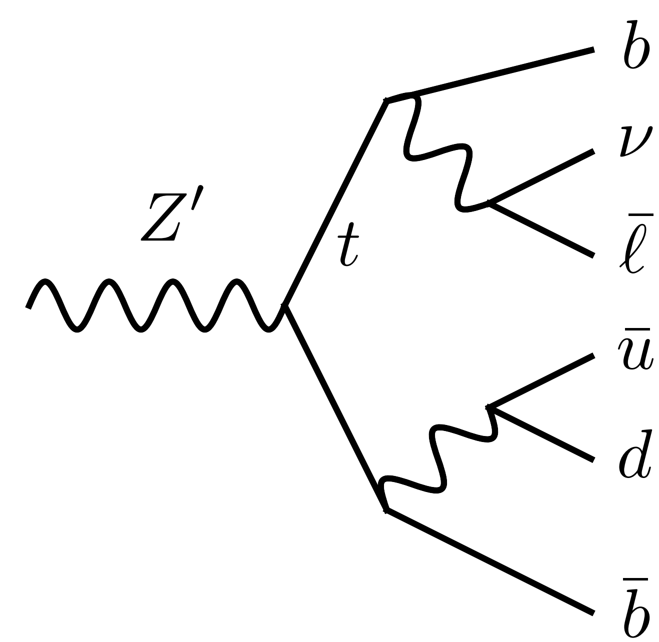
Top Tagging in $Z' \to t\bar{t}$





(ATLAS-CONF-2013-052)

- One leptonic and one hadronic top
- Boosted analysis crucial for large $m_{Z'}$

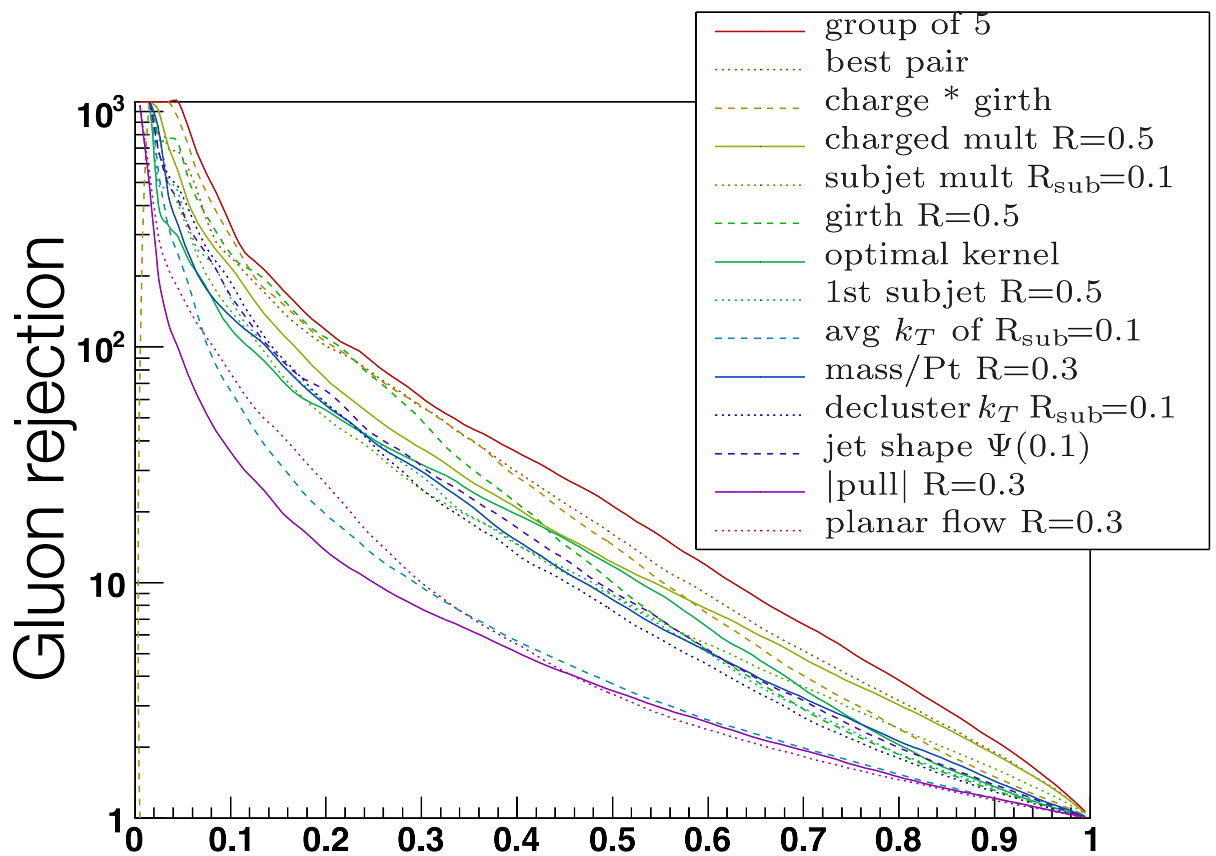


Jet Substructure for Quark/Gluon Discrimination

- New physics often more quarks than QCD backgrounds
- 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

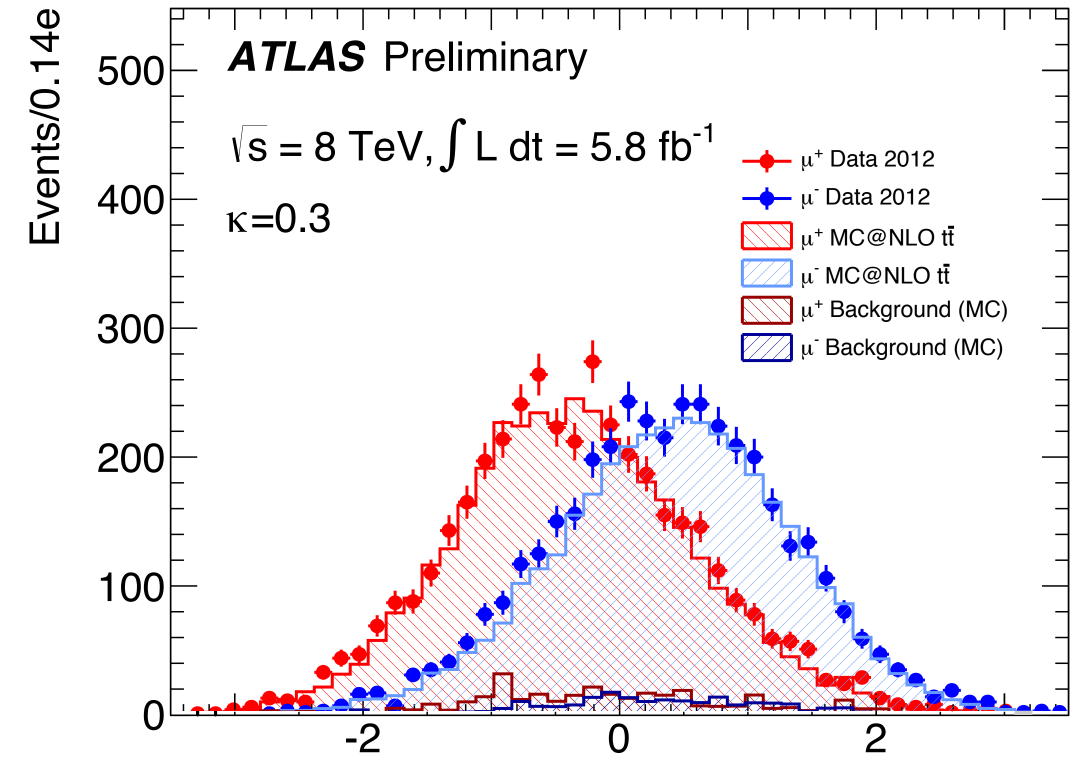


(arXiv:1106.3076)

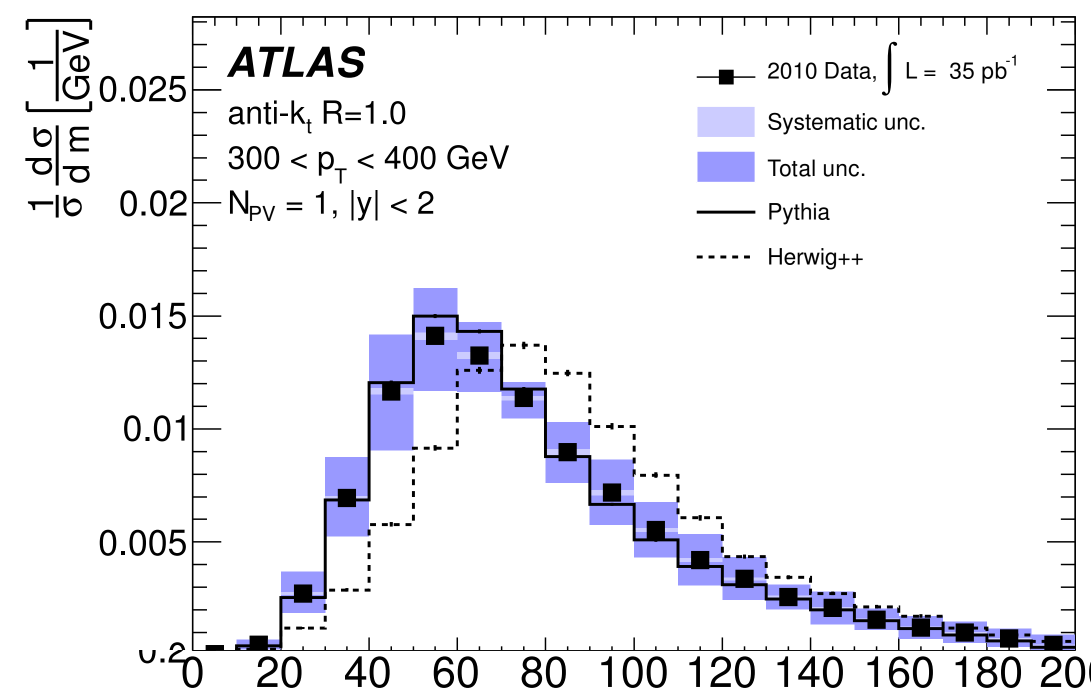
Jet Mass and Charge

Motivation:

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



(ATLAS-CONF-2013-086) Jet charge [e]



(arXiv:1203.4606) Jet mass [GeV]

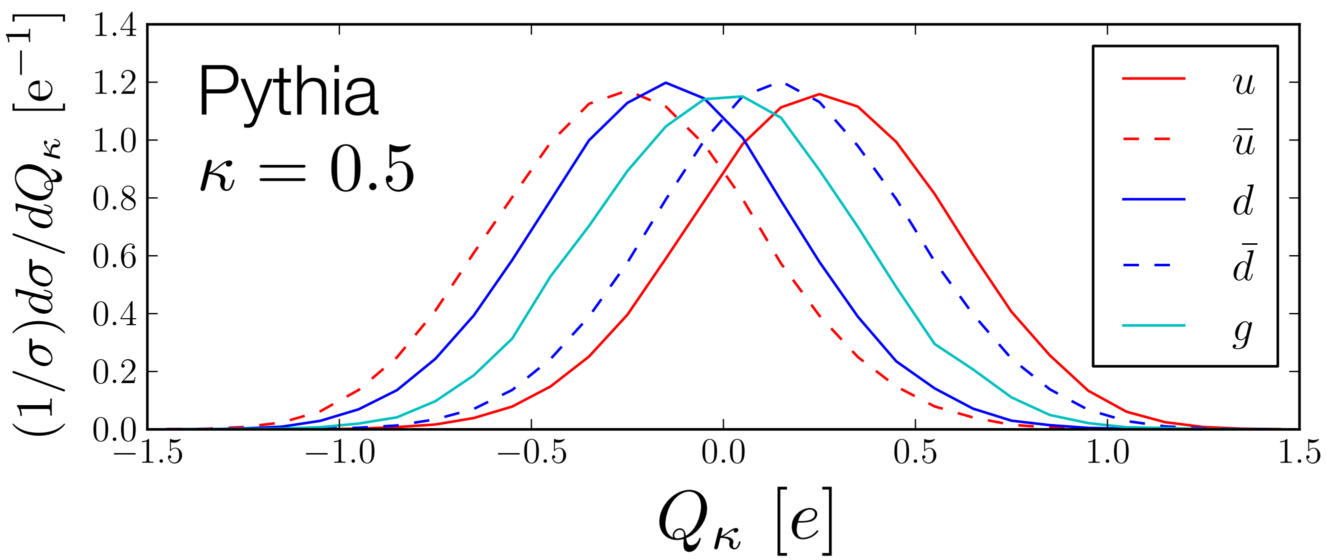
Jet Charge

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)

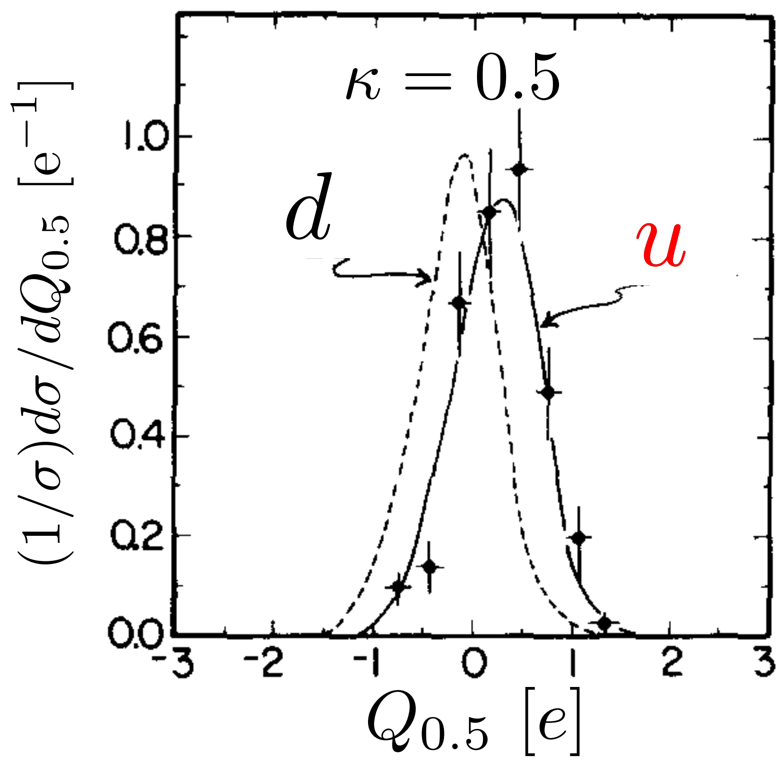


- If κ too small: sensitive to soft hadrons $\rightarrow$ contamination
- If κ too large: only sensitive to most energetic hadron
  ➞ need more statistics

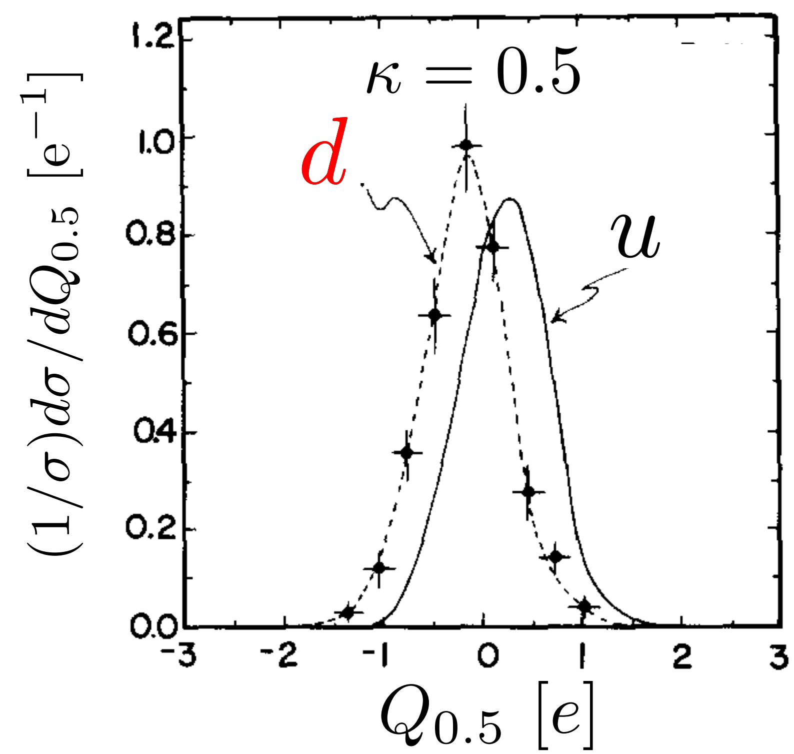
Historical Applications

- Test parton model

(Nucl. Phys. B184, 13 (1981))



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



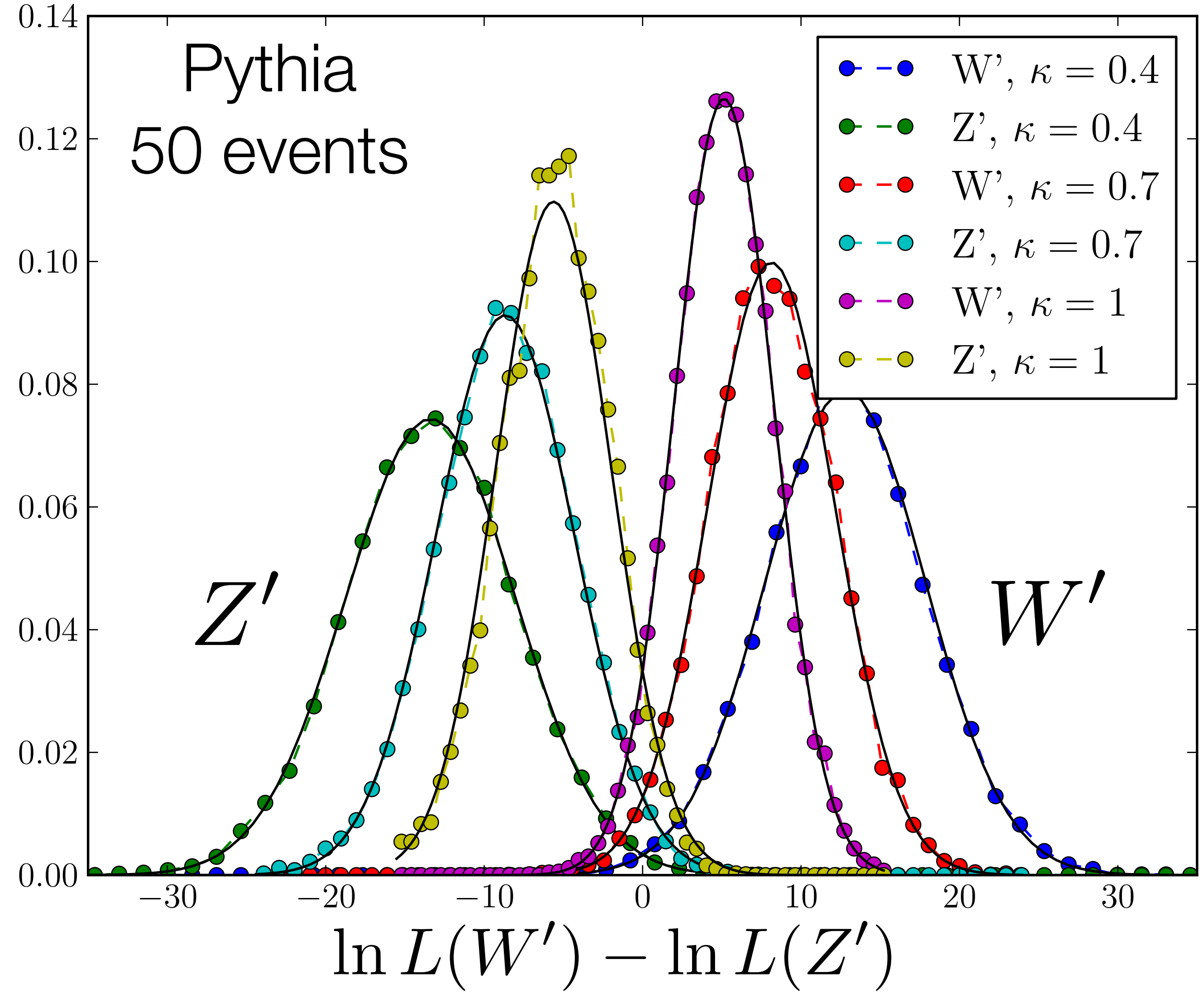
$\bar{\nu}_\mu p \to \mu^+ d X$

- 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'

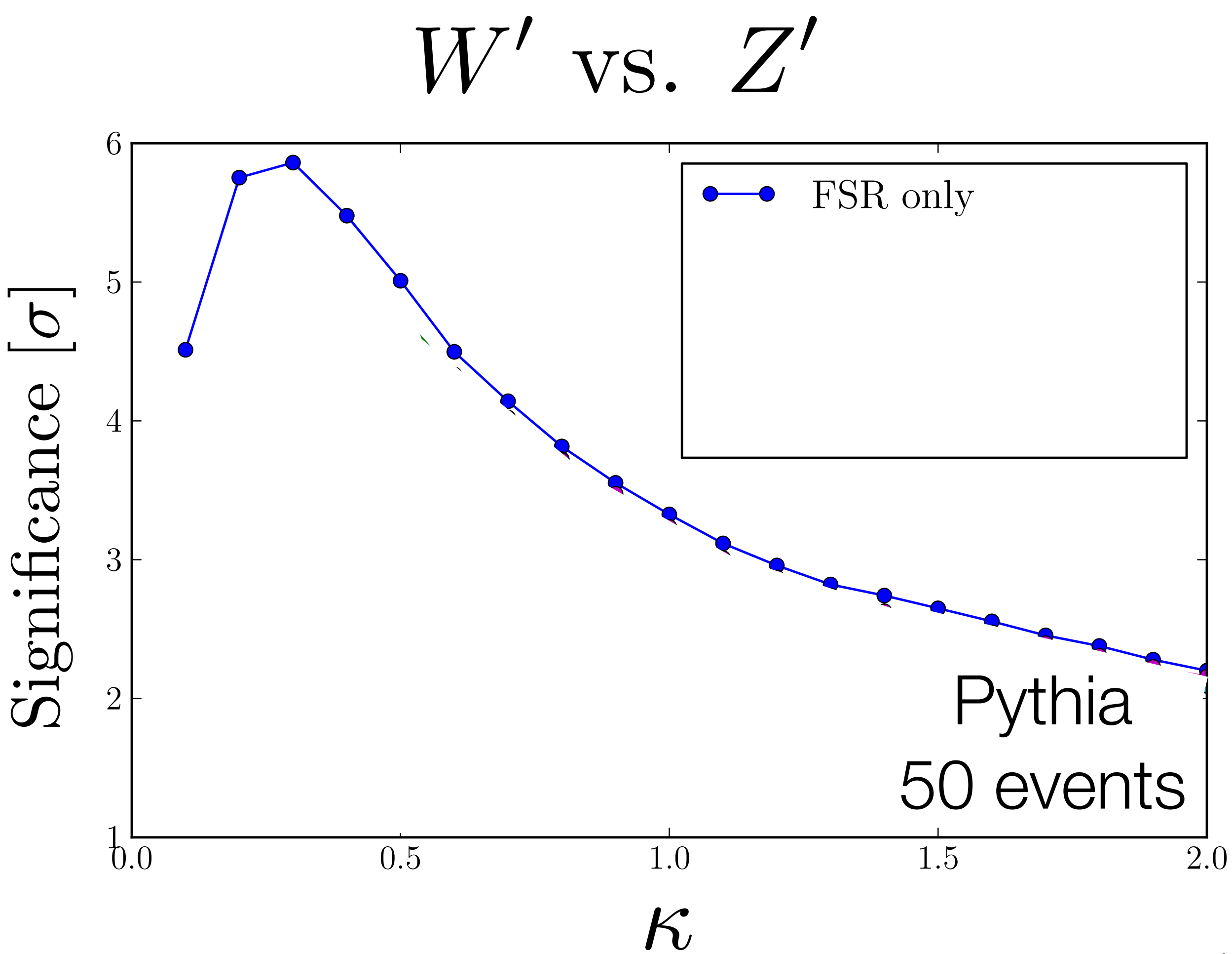
- Hadronically decaying W' or Z' with 1 TeV mass
- 2-dim. likelihood discriminant based on both jet charges

$$Z' \to u\bar{u}$$
$$Z' \to d\bar{d}$$
vs.
$$W' \to u\bar{d}$$
$$W' \to d\bar{u}$$



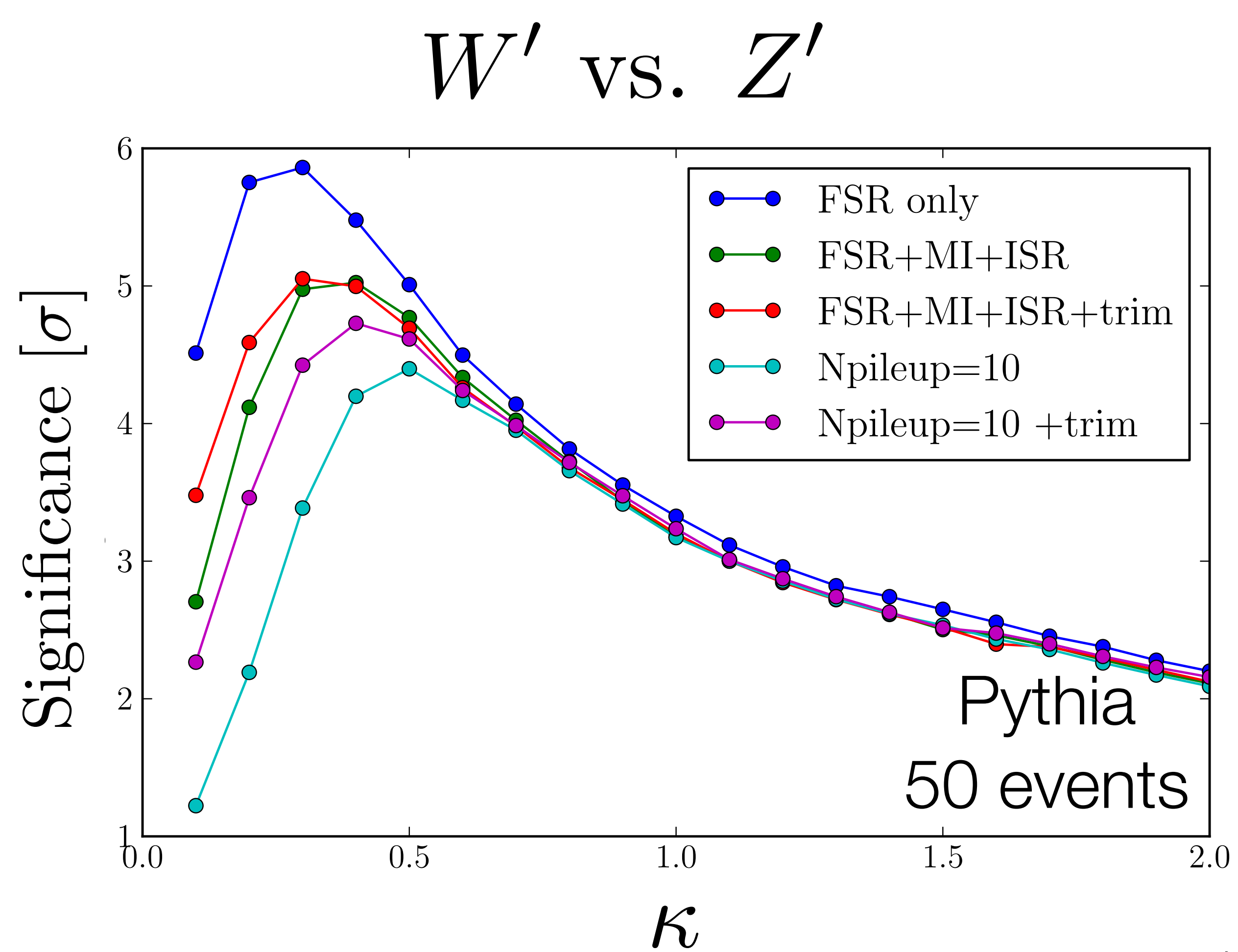
LHC Challenges

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



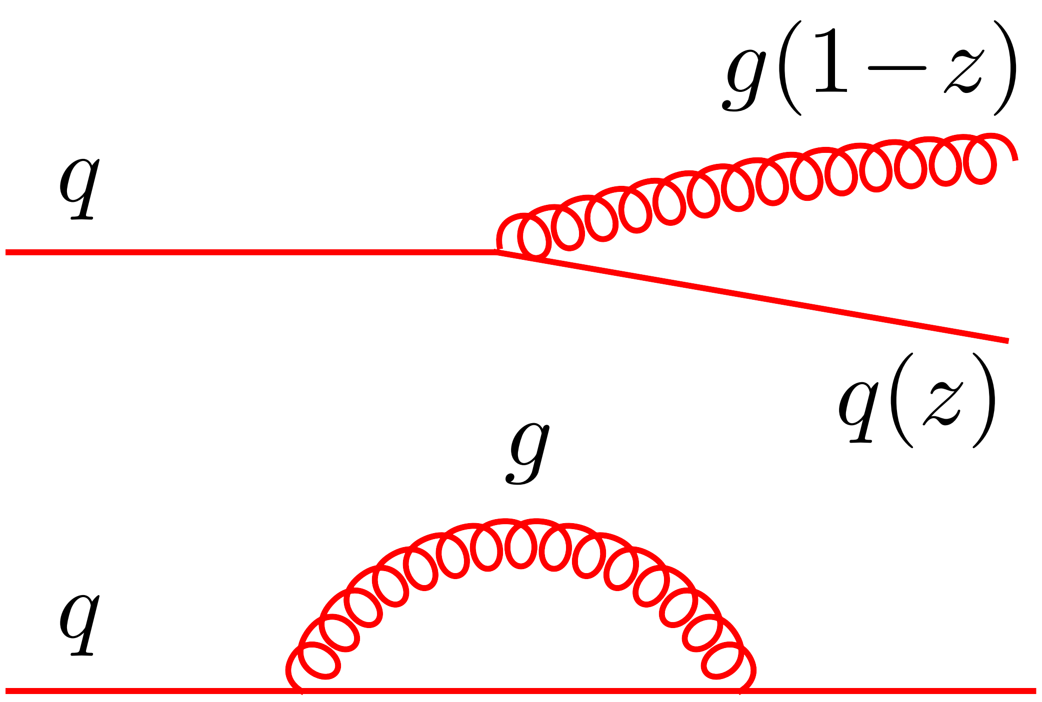
LHC Challenges

- 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 ➞ increase κ



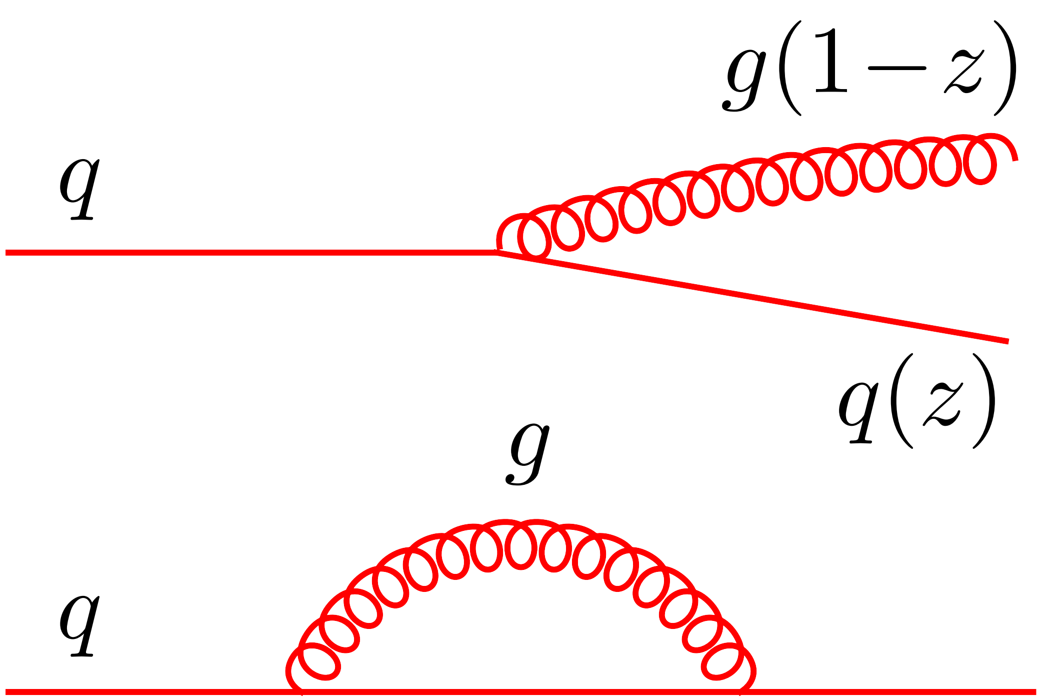
Jet Charge Not IR Safe

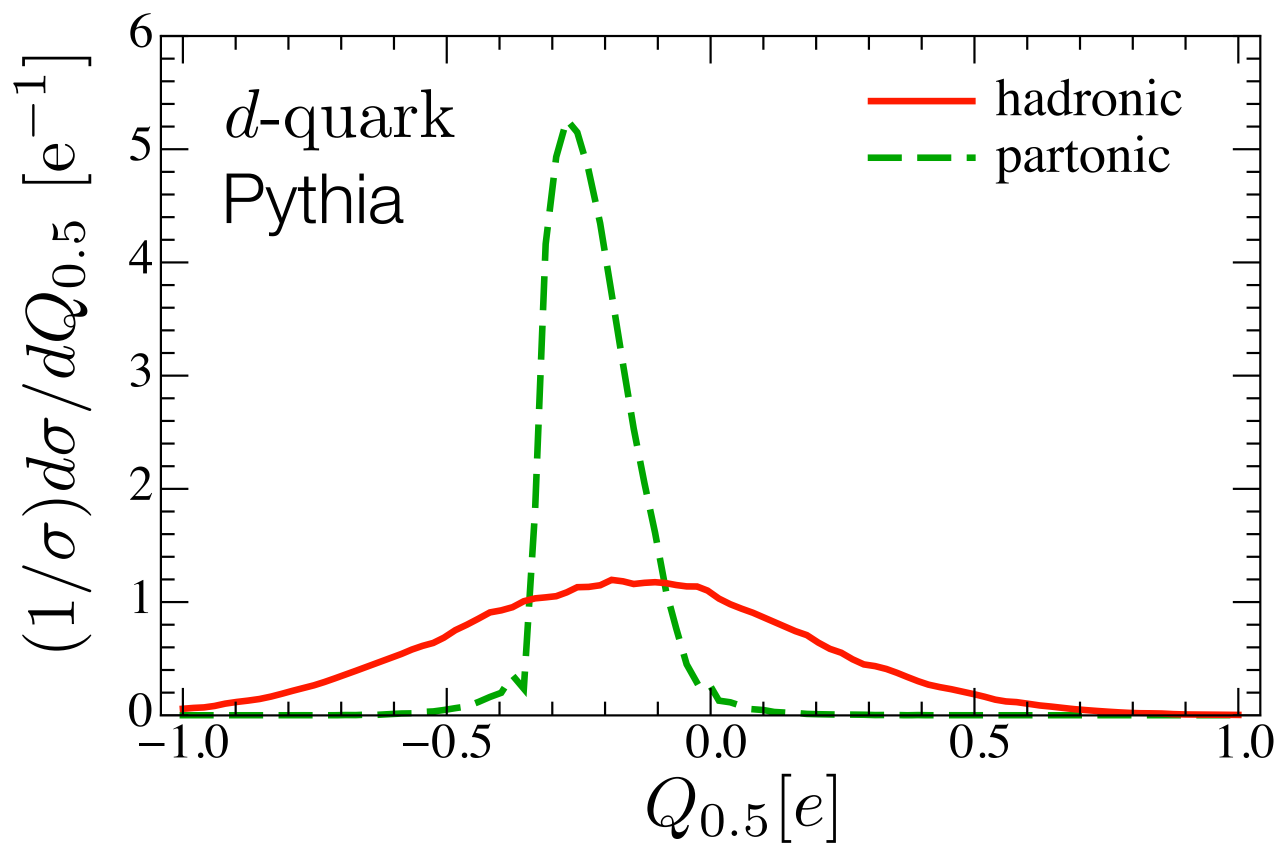
- Consider $q \to qg$ in collinear limit
- $Q_q z^\kappa \neq Q_q$ ➞ divergences don't cancel between real/virtual



Jet Charge Not IR Safe

- Consider $q \to qg$ in collinear limit
- $Q_q z^\kappa \neq Q_q$ ➞ 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

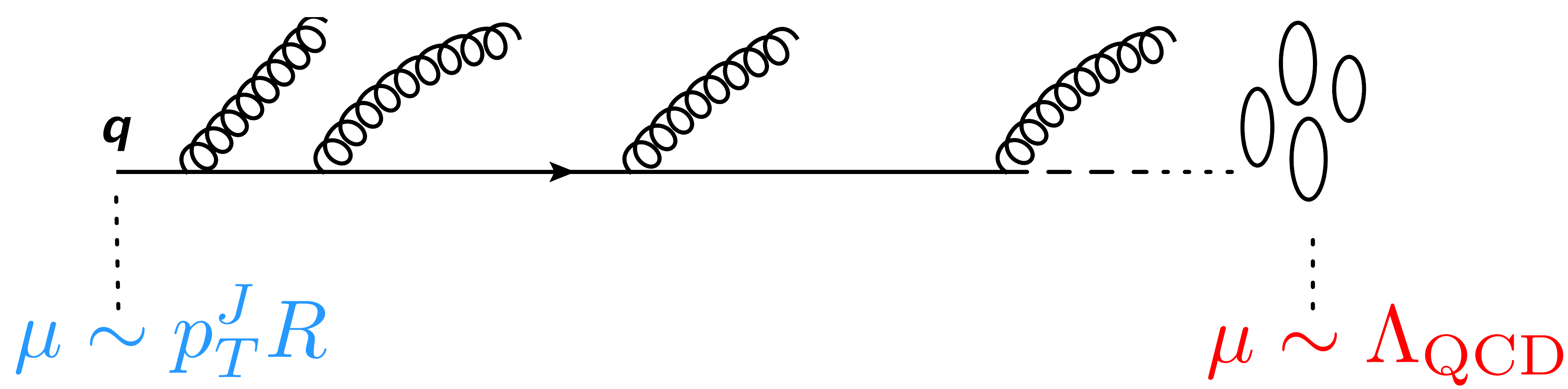
- At LO, weight = fragmentation function $D_q^h(z, \mu \sim p_T^J R)$

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

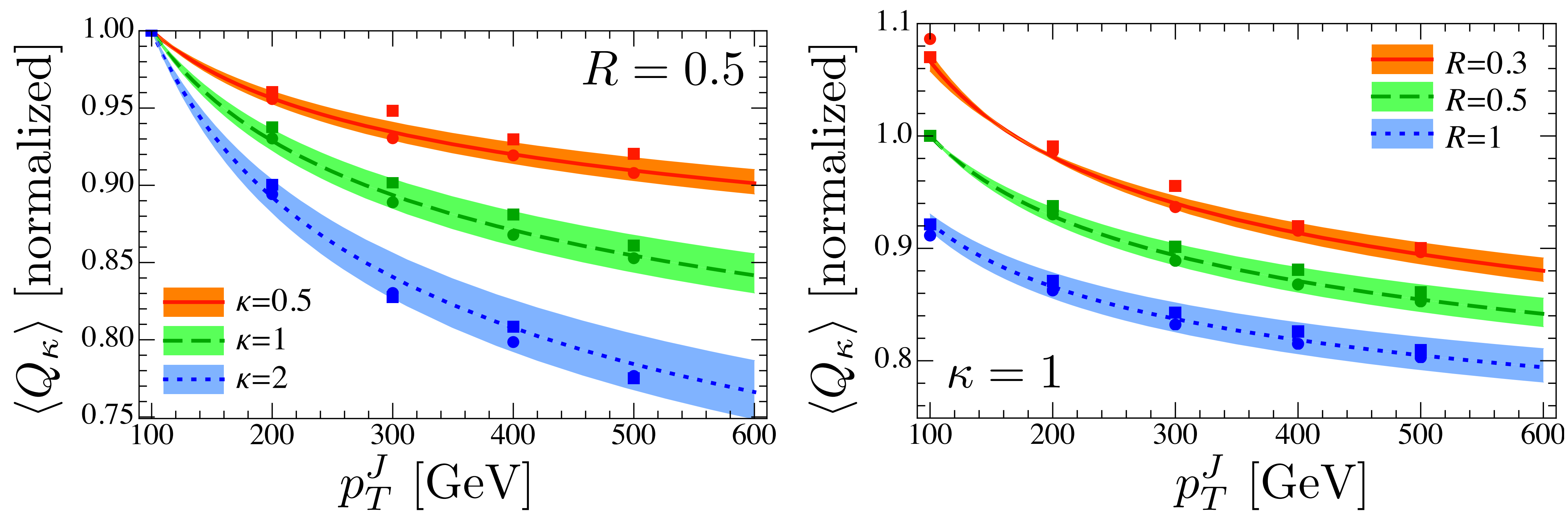


RG Evolution vs. Pythia's Parton Shower

$$\langle Q_\kappa(p_T^J R, \text{flavor})\rangle = \underbrace{\text{perturbative}}_{\text{perturbative splitting + evolution}}(\kappa, p_T^J R) \times \text{hadronization}(\kappa, \text{flavor})$$

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

→ Hadronization (and flavor dependence) drops out



✓ Good agreement

Fragmentation Functions vs. Pythia's Hadronization

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

κ	u-quark			d-quark		
	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)

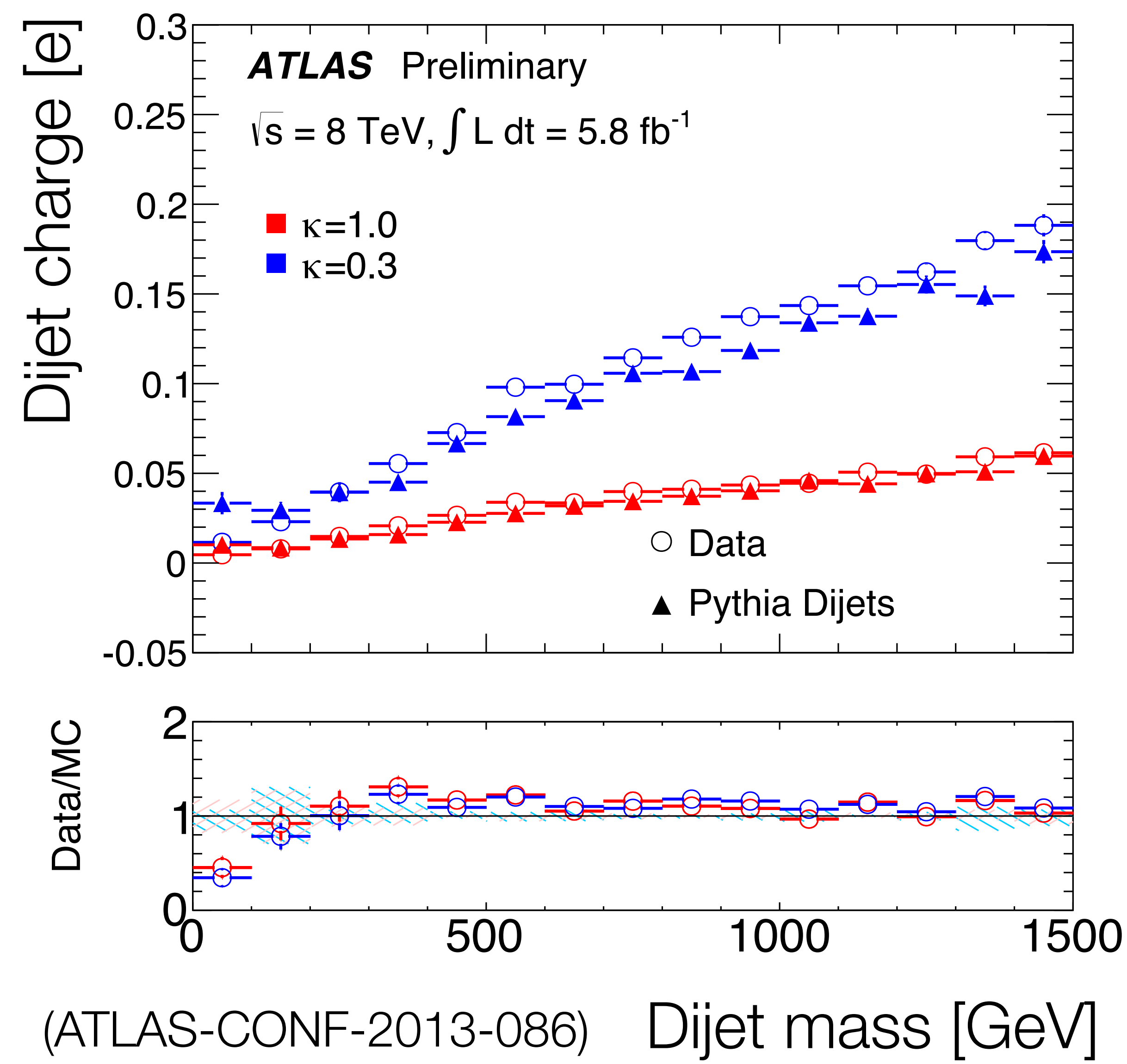
✓ Pythia consistent with fragmentation functions

- 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 $D_q^{h^+} + D_{\bar{q}}^{h^+}$

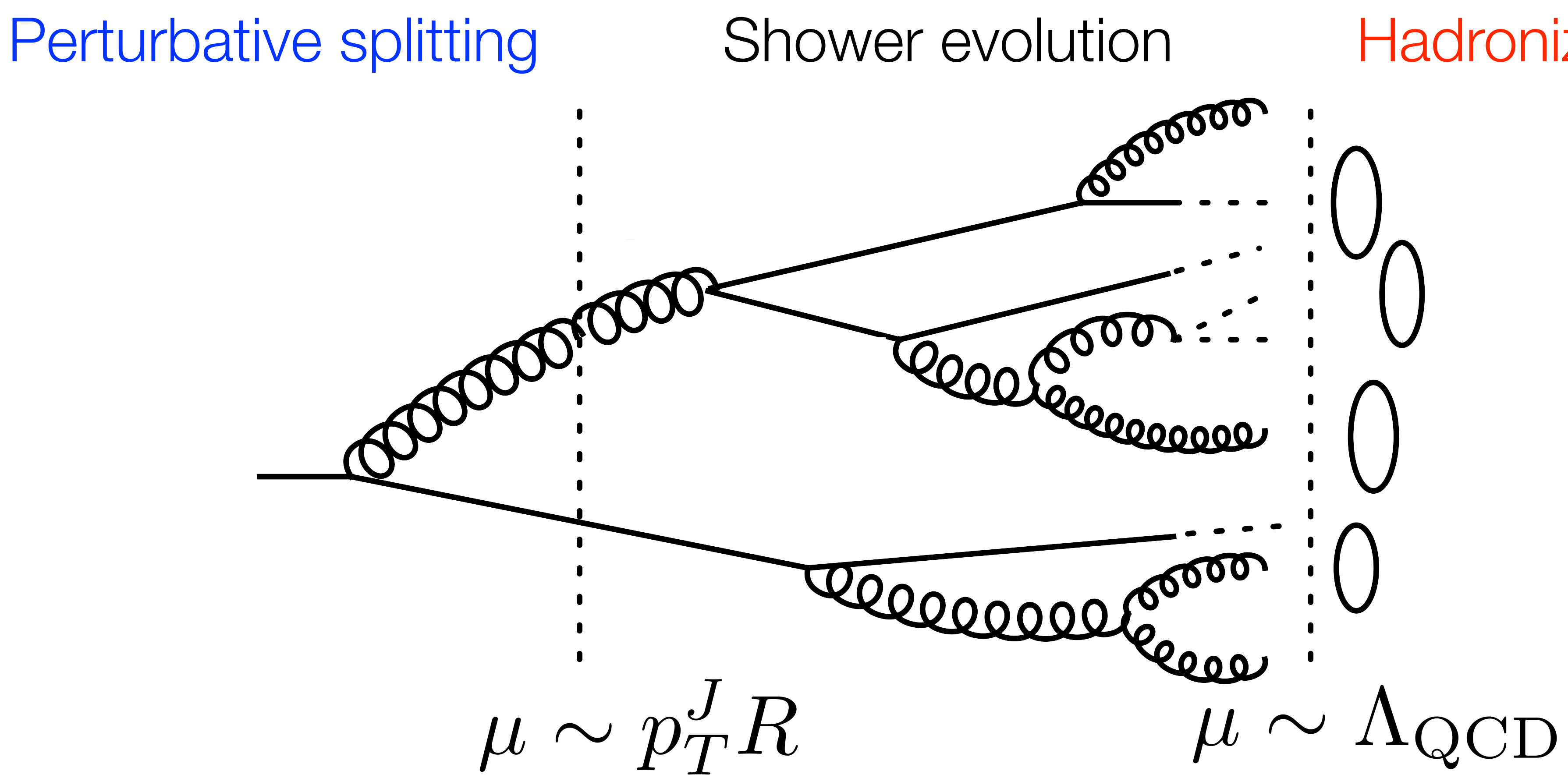
Average Dijet Charge at the LHC

- Depends on proton structure and scattering process
- Pure QCD measurement of valence structure of proton!
- Study of scale violation effect is ongoing



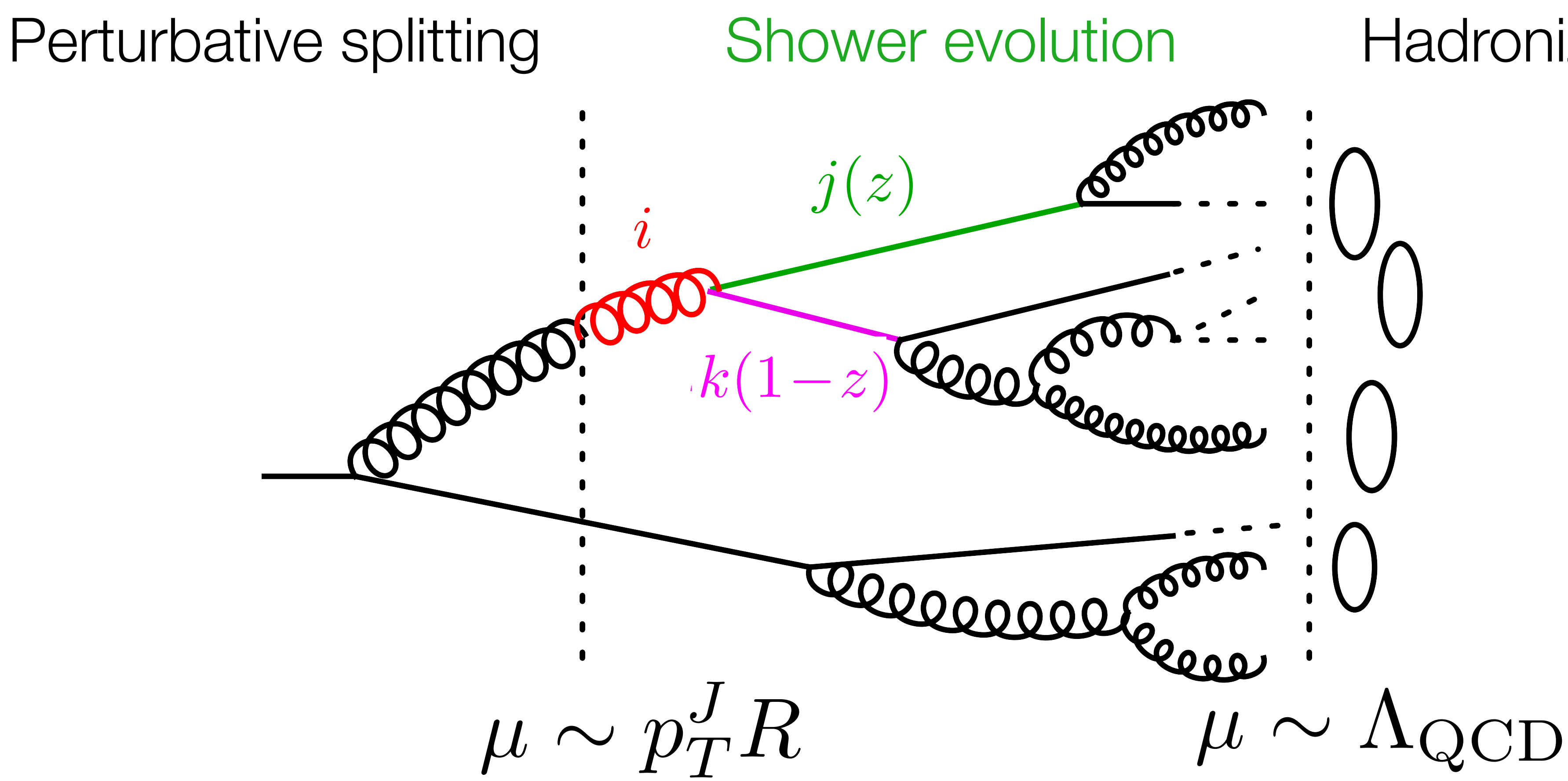
(ATLAS-CONF-2013-086)

Full Jet Charge Distribution



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

Full Jet Charge Distribution



- RGE:

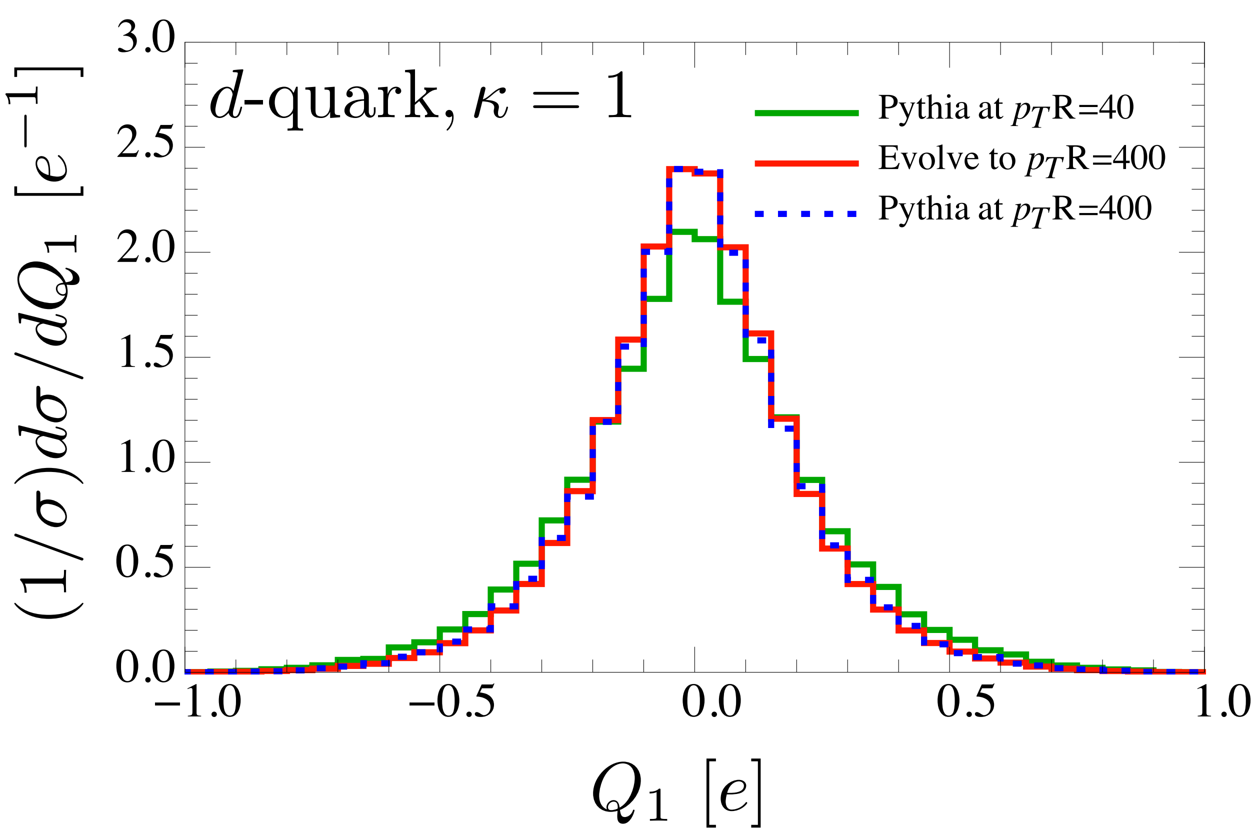
$$\mu \frac{d}{d\mu} D_i(Q_\kappa, \mu) = \overbrace{\sum_j \int dz \, \frac{\alpha_s}{2\pi} P_{ji}(z)}^{\text{Splitting probability}} \overbrace{\int dQ_\kappa^a \, D_j(Q_\kappa^a, \mu) \int dQ_\kappa^b \, D_k(Q_\kappa^b, \mu)}^{\text{Sample over distributions of branches}}$$

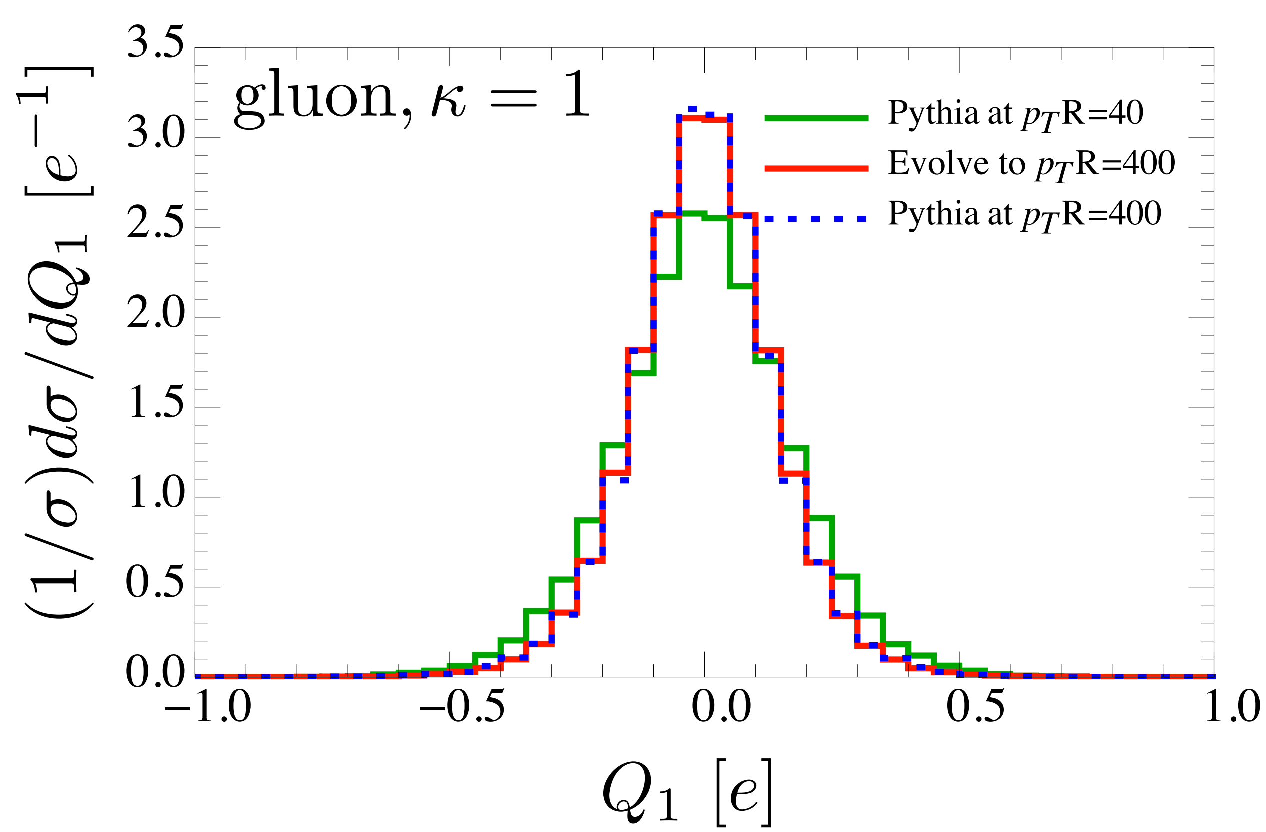
$$\times \underbrace{\delta[Q_\kappa - z^\kappa Q_\kappa^a - (1-z)^\kappa Q_\kappa^b]}_{\text{Charge is (weighted) sum of branches}}$$

RG Evolution vs. Pythia's Parton Shower

✓ Use Pythia as input and evolve → good agreement

- Distribution changes more slowly than single hadron distributions (e.g. fragmentation functions)





Jet Mass

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

Jet Mass Resummation

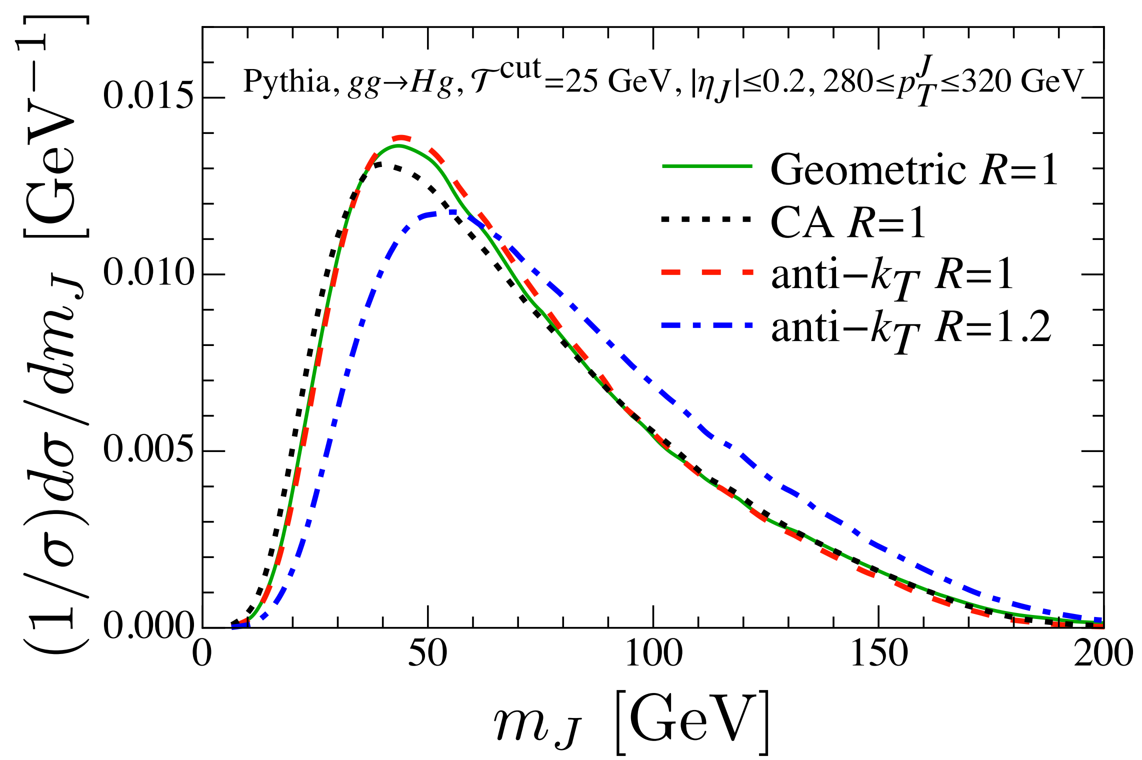
- Jet mass is defined as $m_J^2 = \Big(\sum_{i\in \text{jet}} p_i^\mu\Big)^2$
- Cross section contains logarithms of $L = \ln(m_J^{\text{cut}}/p_T^J)$

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

LL NLL NNLL

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

Jet Mass and Jet Definition



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

$\mathcal{N}$-Jettiness Event Shape (Stewart, Tackmann, WW)

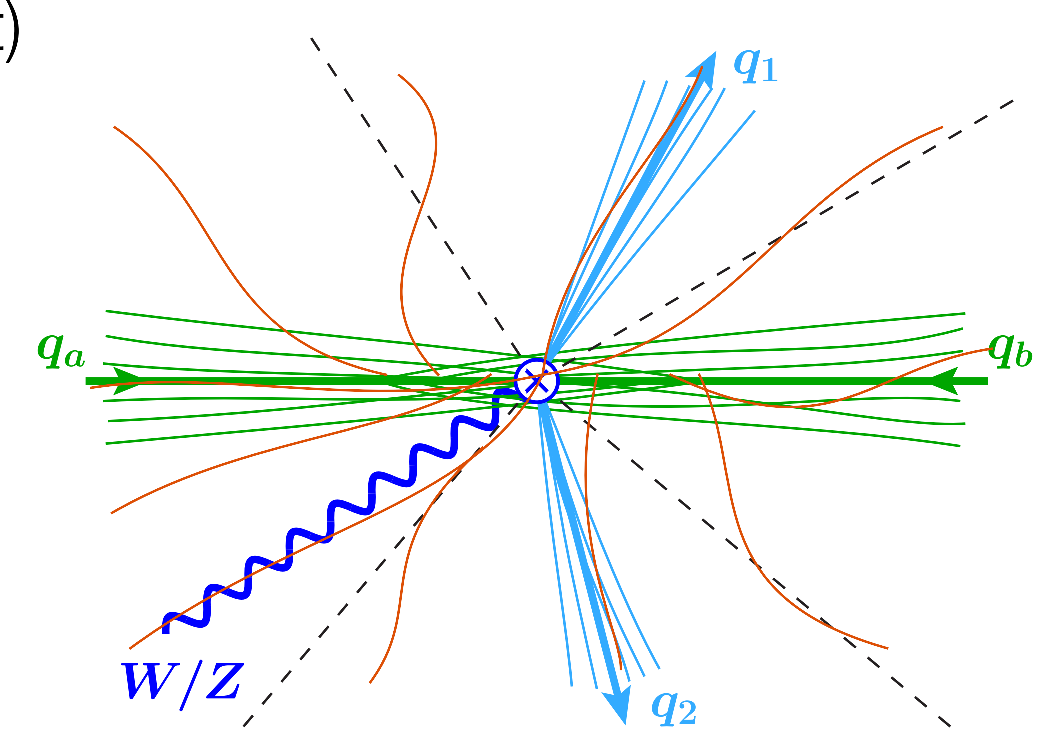
$$\mathcal{T}_N = \sum_i \min\{\hat{q}_a \cdot p_i, \hat{q}_b \cdot p_i, \hat{q}_1 \cdot p_i, \ldots\}$$

beams jets

jet axis

jet size parameter

- 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 N narrow jets, $\mathcal{T}_N$ large for $> N$ jets
- Used as substructure (Thaler, van Tilburg), 1-jettiness in DIS (Kang, Liu, Mantry, Qiu; Kang, Lee, Stewart)



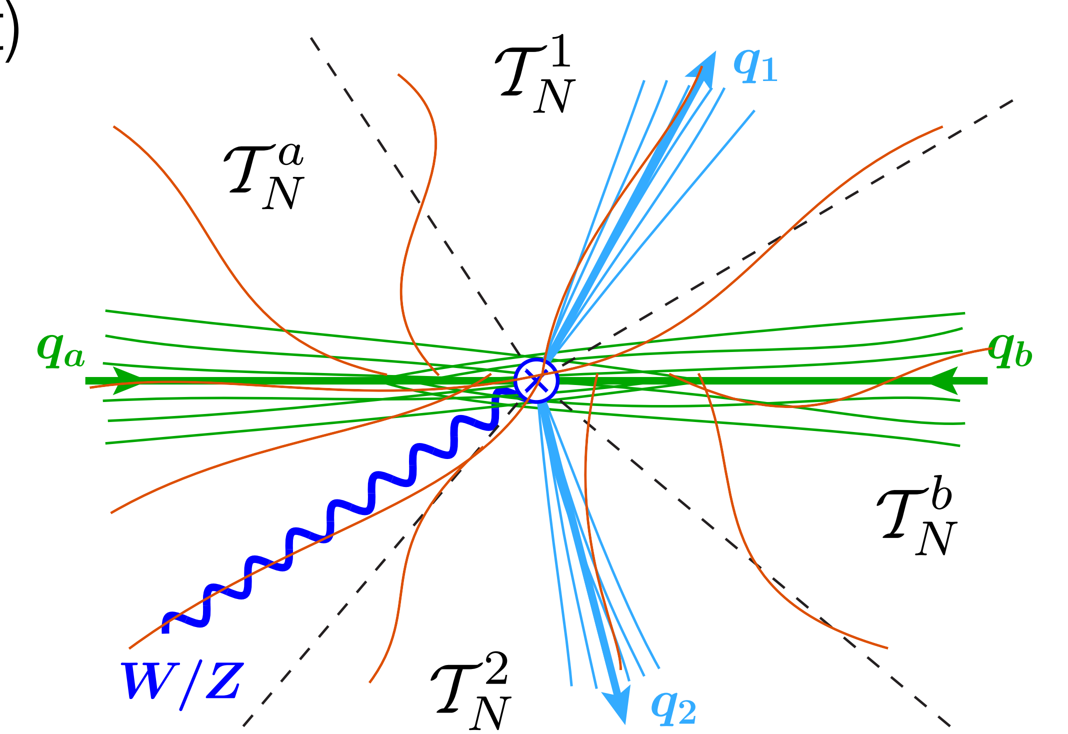
N-Jettiness Event Shape (Stewart, Tackmann, WW)

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

beams jets

- Reference vectors: $\hat{q}_{a,b} = (1, 0, 0, \pm 1)$, $\hat{q}_J = (1, \hat{n}_J)/\rho_J$
- $\mathcal{T}_N \to 0$ for N narrow jets, $\mathcal{T}_N$ large for $> N$ jets
- Used as substructure (Thaler, van Tilburg), 1-jettiness in DIS (Kang, Liu, Mantry, Qiu; Kang, Lee, Stewart)
- $\mathcal{T}_N$ splits into contributions from each beam/jet region
- Related to jet mass:

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

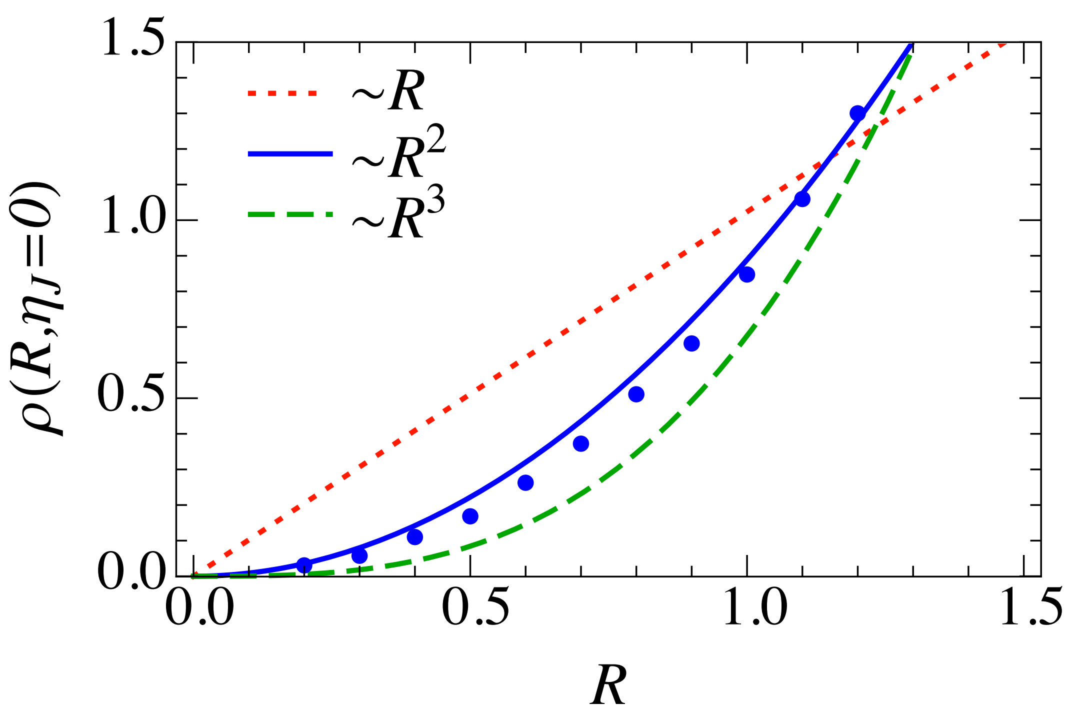


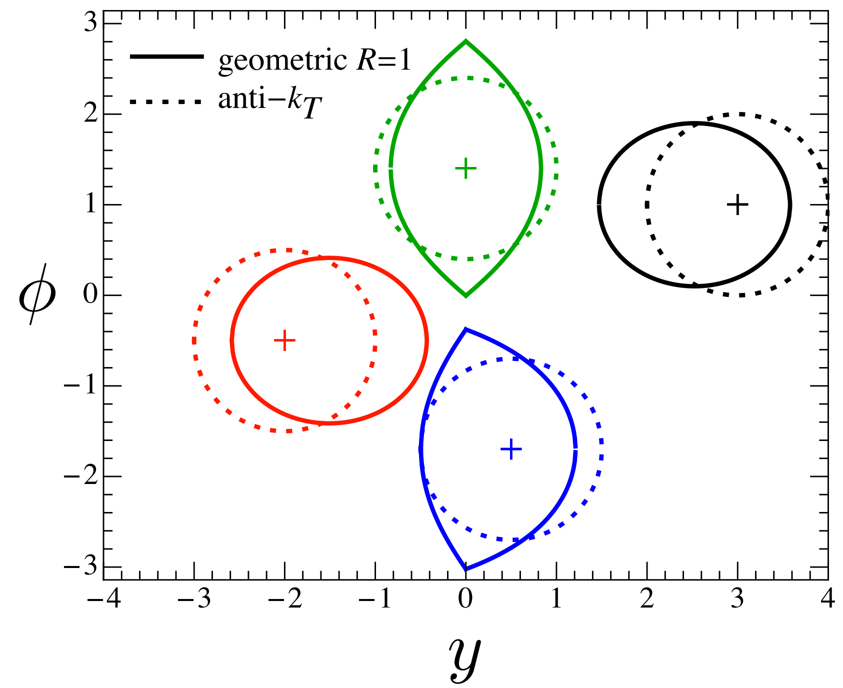
N-Jettiness Parameters

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

beams jets

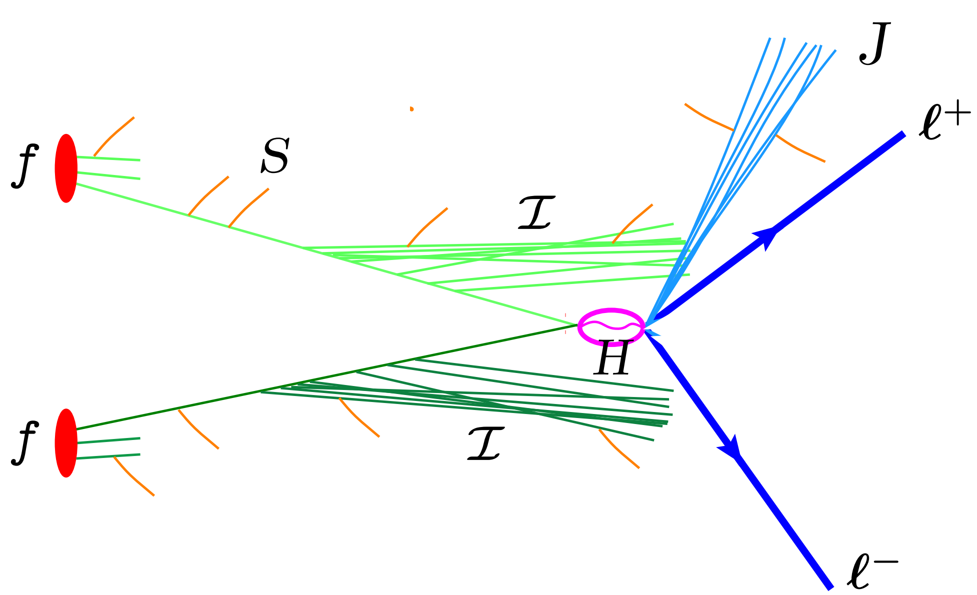
- Reference vectors: $\hat{q}_{a,b} = (1,0,0,\pm 1)$, $\hat{q}_J = (1, \hat{n}_J)/\rho_J$
- $\hat{n}_J$ by minimizing $\mathcal{T}_N$ or from jet alg. (same for $\mathcal{T}_N \to 0$)
- Choose $\rho_J = \rho(R, \eta_J)$ to match jet area of anti-k_T





N-Jettiness Factorization

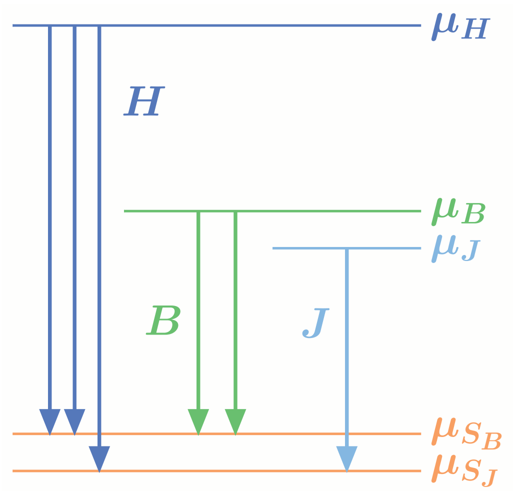
$$\frac{d\sigma(N\ \text{jets})}{d\mathcal{T}_N^a\, d\mathcal{T}_N^b \cdots d\mathcal{T}_N^N} = \int dx_a\, dx_b\, d(\text{phase space}) \sum_\kappa \int dt_a\, B_{\kappa_a}(t_a, x_a, \mu)$$
$$\times \int dt_b\, B_{\kappa_b}(t_b, x_b, \mu) \prod_{J=1}^{N} \int ds_J\, J_{\kappa_J}(s_J, \mu)\ \text{tr}\Big[H_N^\kappa(\{q_i^\mu\}, \mu)$$
$$\times\, S_N^\kappa\Big(\mathcal{T}_N^a - \frac{t_a}{Q_a}, \mathcal{T}_N^b - \frac{t_b}{Q_b}, \ldots, \mathcal{T}_N^N - \frac{s_N}{Q_N}, \{\hat{q}_i\}, \mu\Big)\Big]$$



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

N-Jettiness Factorization

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



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

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

- 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.

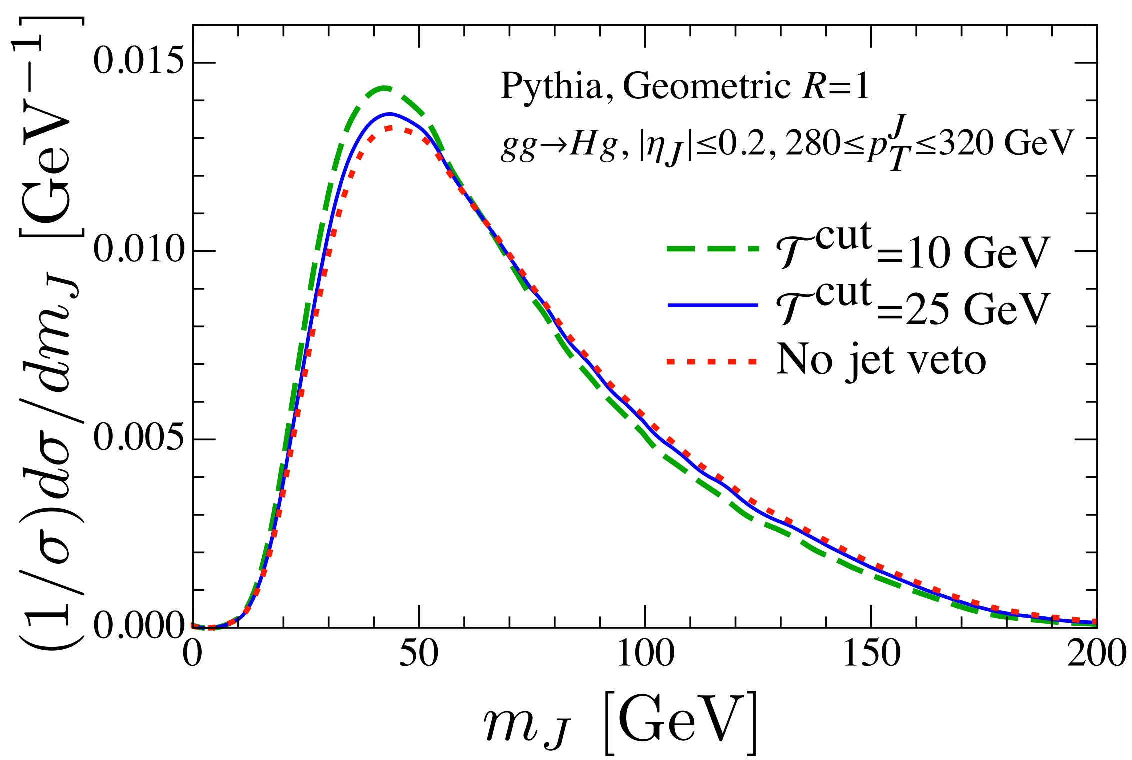
Three-loop cusp: Korchemsky, Radyushkin; Moch, Vermaseren, Vogt, Two-loop non-cusp known from: Kramer, Lampe; Harlander; Aybat, Dixon, Sterman; Becher, Neubert; Becher, Schwartz; Stewart, Tackmann, WW

Normalization

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

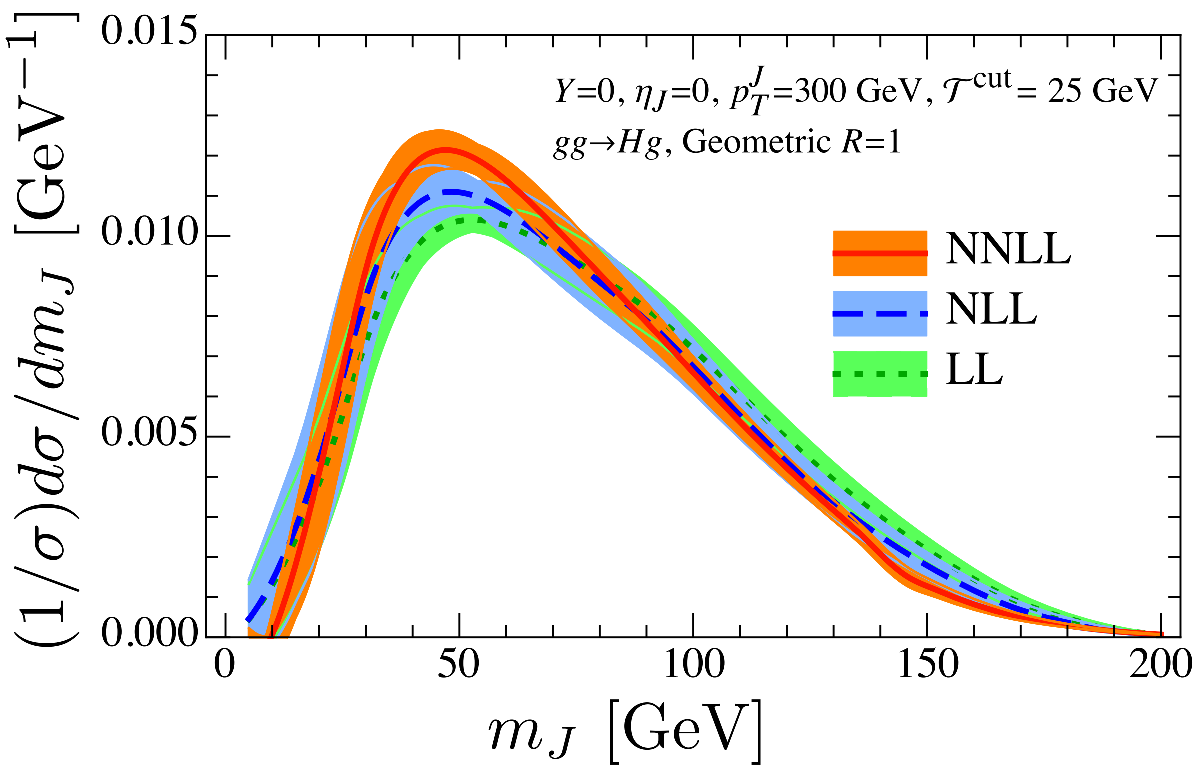
$$\frac{\sigma(\mathcal{T}_1^a, \mathcal{T}_1^b \leq \mathcal{T}^{\mathrm{cut}}, m_J, p_T^J, y^J, Y)}{\int dm_J\, \sigma(\mathcal{T}_1^a, \mathcal{T}_1^b \leq \mathcal{T}^{\mathrm{cut}}, m_J, p_T^J, y^J, Y)}$$

- Experimental results are also normalized

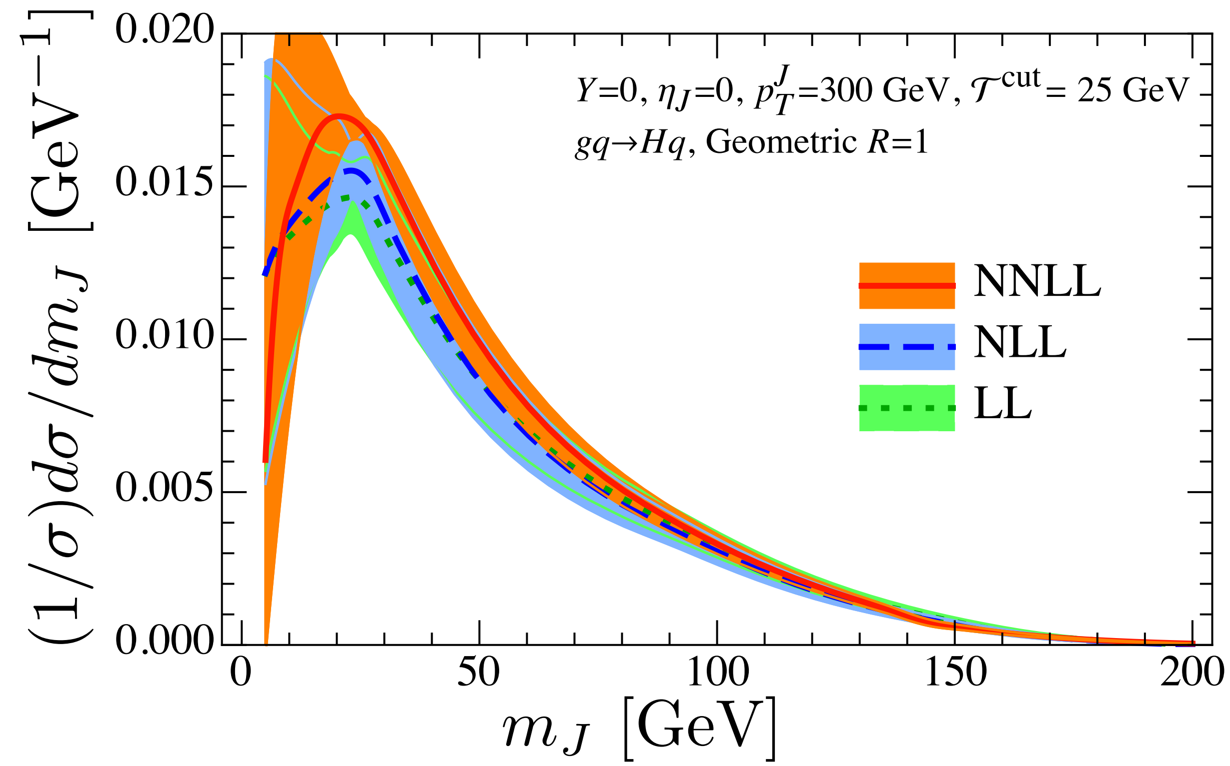


Perturbative Convergence

Gluon



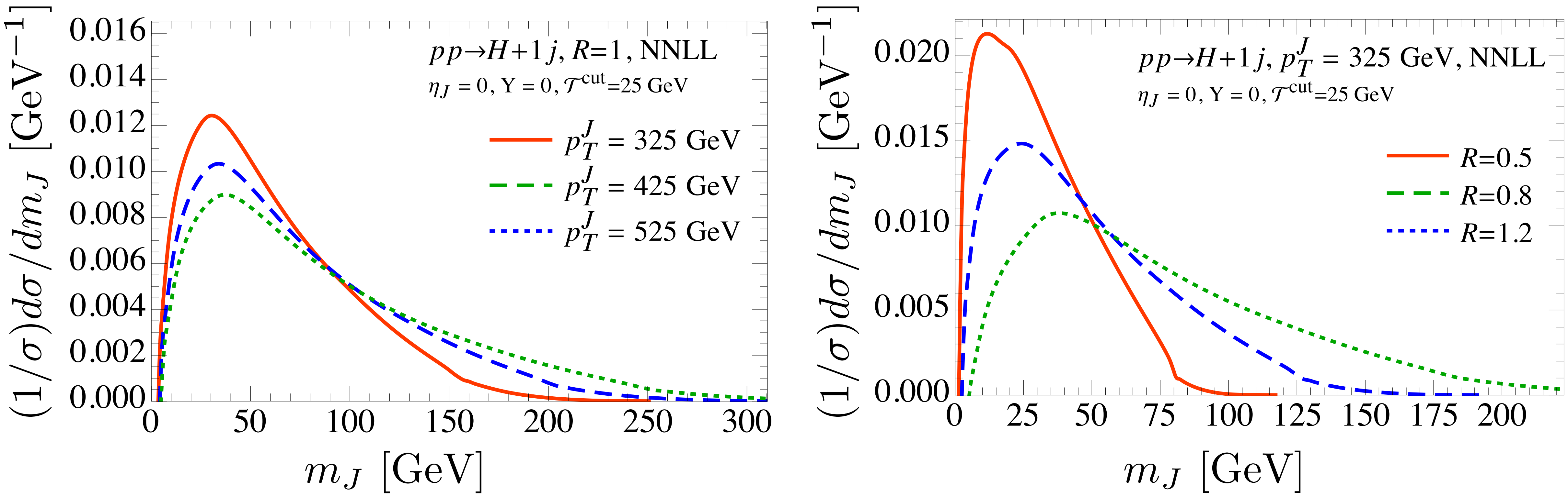
Quark



- We consider $gg \to Hg$ and $gq \to Hq$ (proxies for gluon and quark jets)

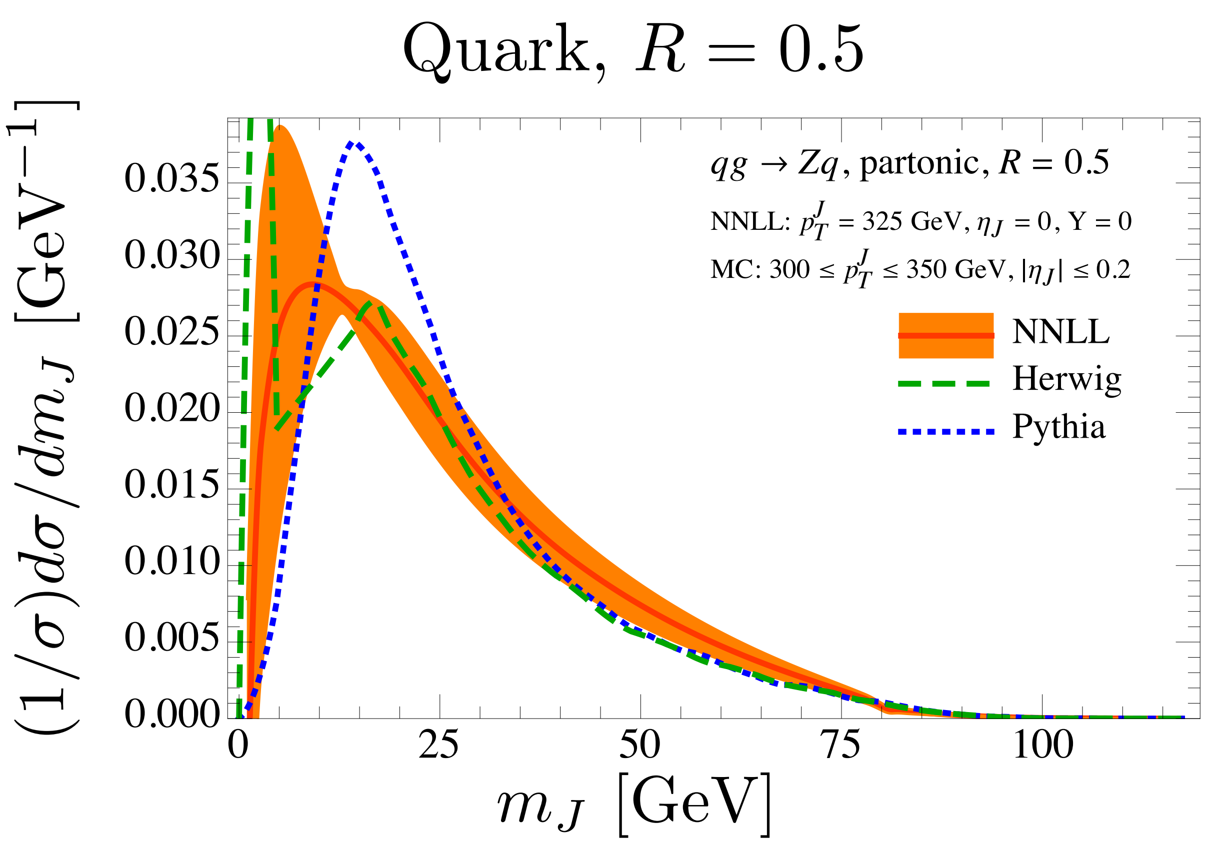
✓ Good agreement between LL, NLL, NNLL

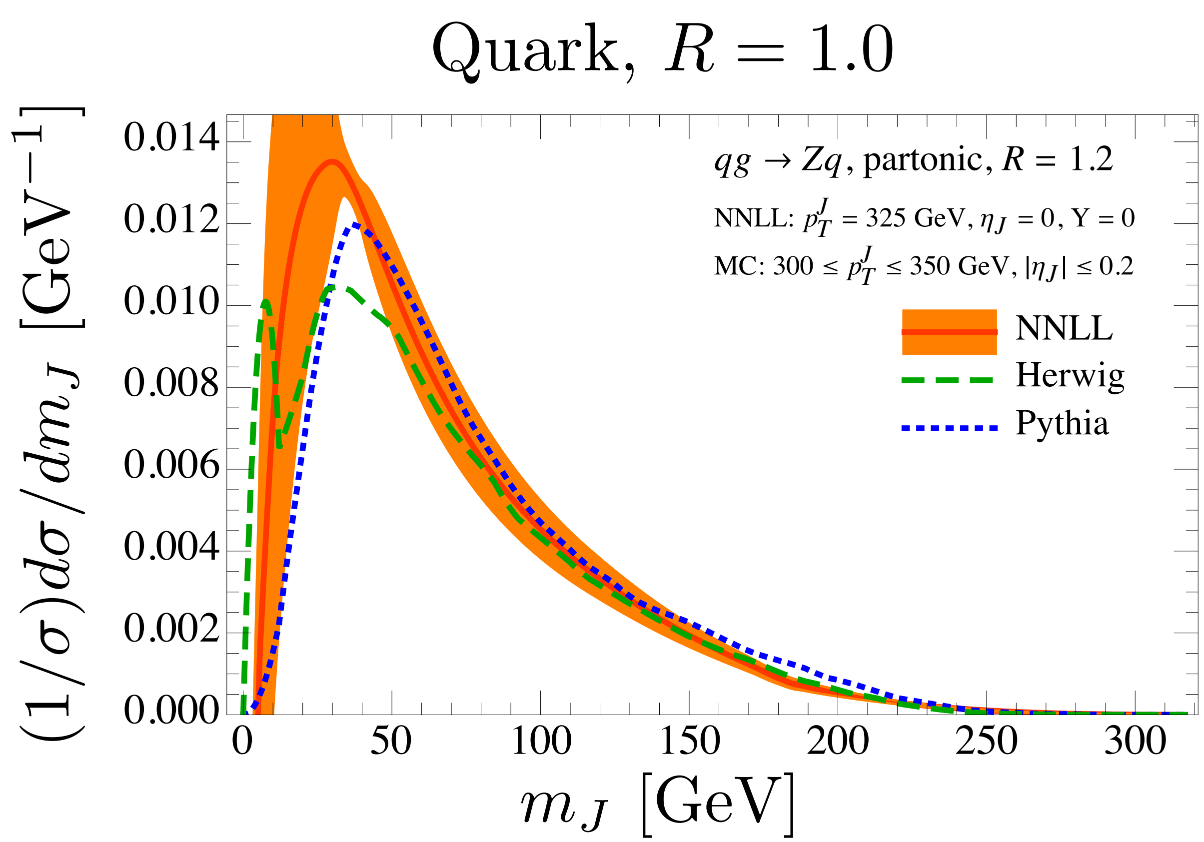
Dependence on Kinematics and Jet Radius



- 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

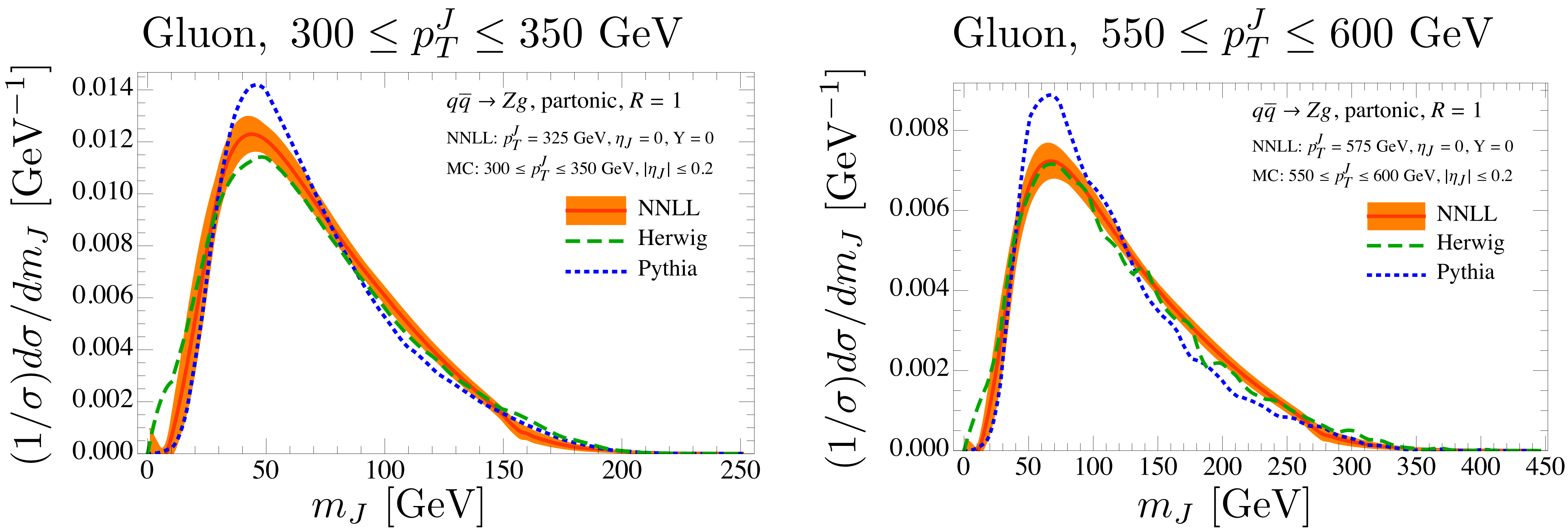




✓ Reasonable agreement over a range of kinematics and R

- 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
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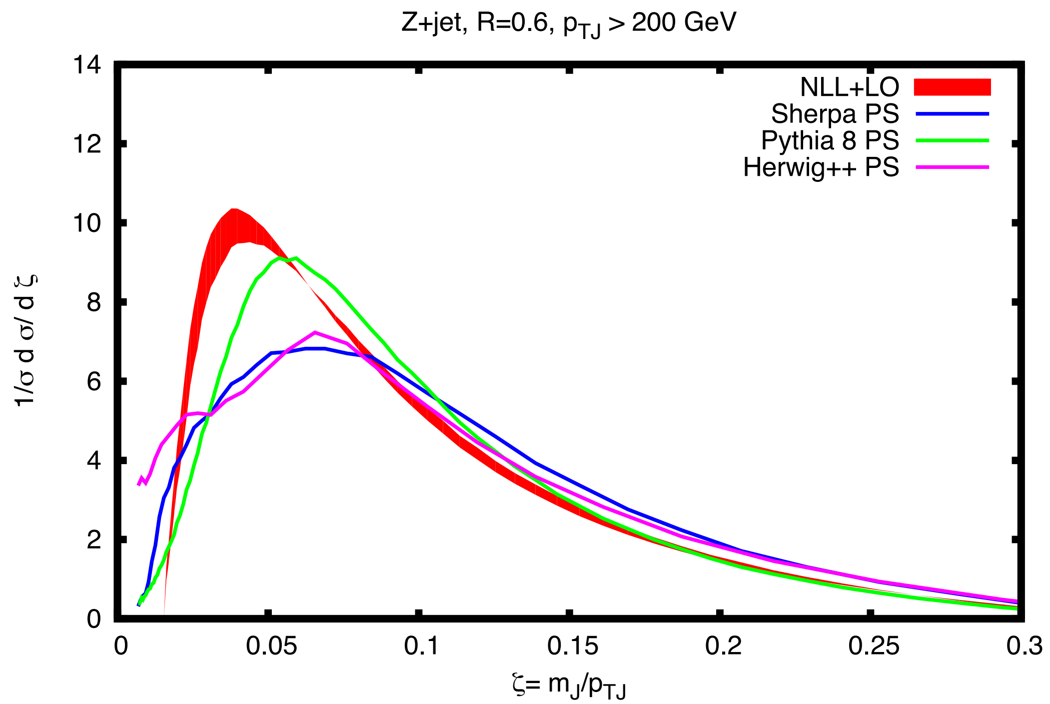
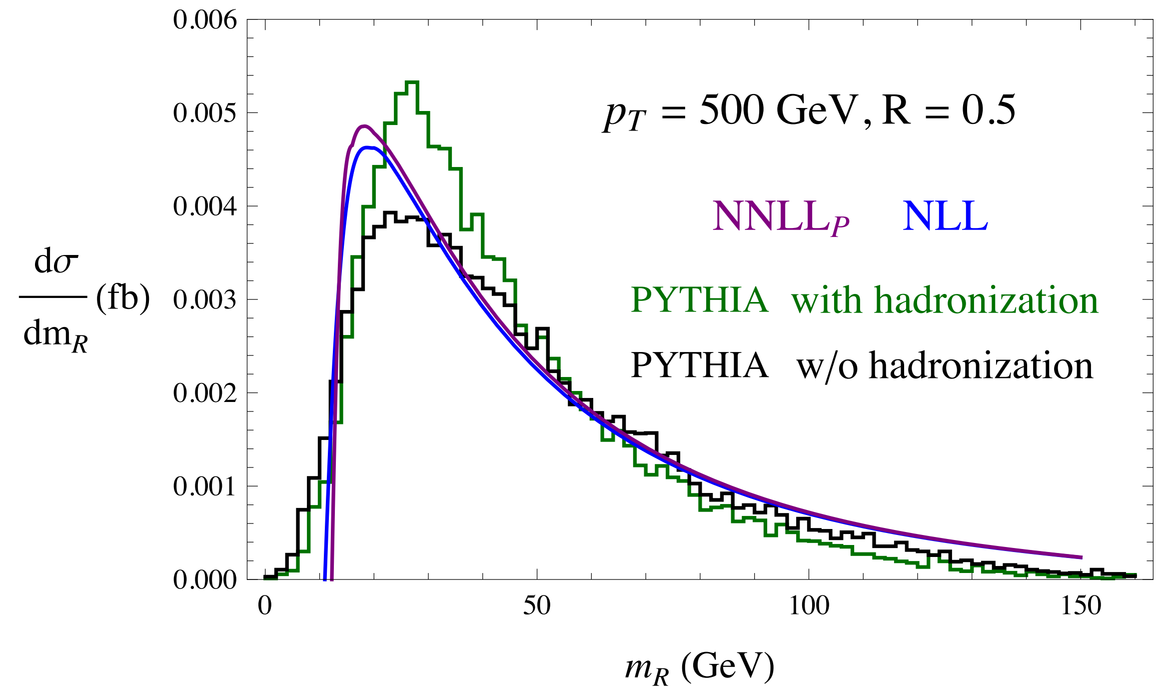
Other Jet Mass Calculations





Dasgupta et al. (arXiv:1207.1640)

- Z+jet and dijets
- NLL+NLO

Chien et al. (arXiv:1208.0010)

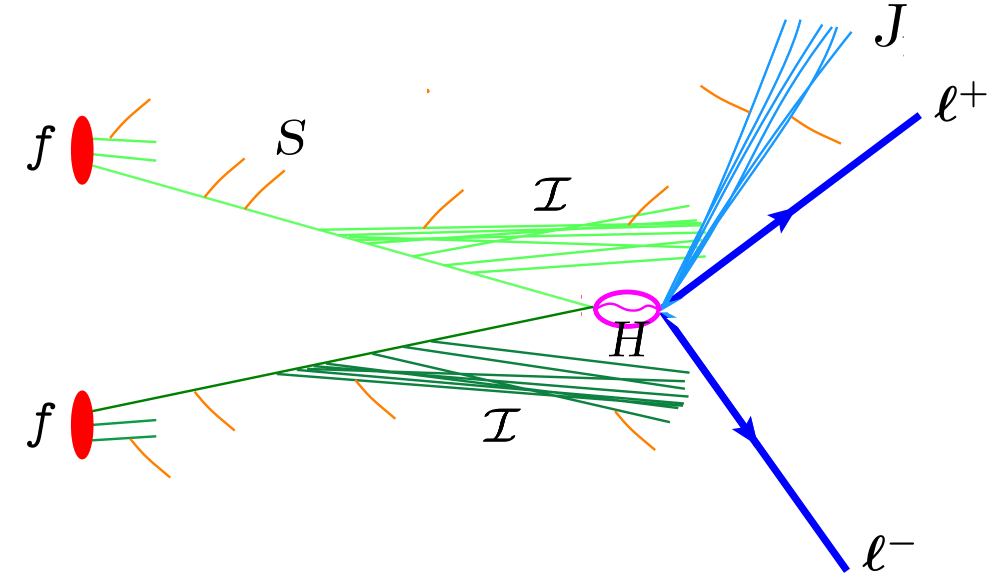
- γ+jet
- NNLL threshold resum.

Key differences:
- jet algorithm
- no jet veto → large nonglobal logarithms

Hadronization of Jets

Tackmann, Stewart, WW (arXiv:1405.6722)

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 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   eikonal Wilson lines

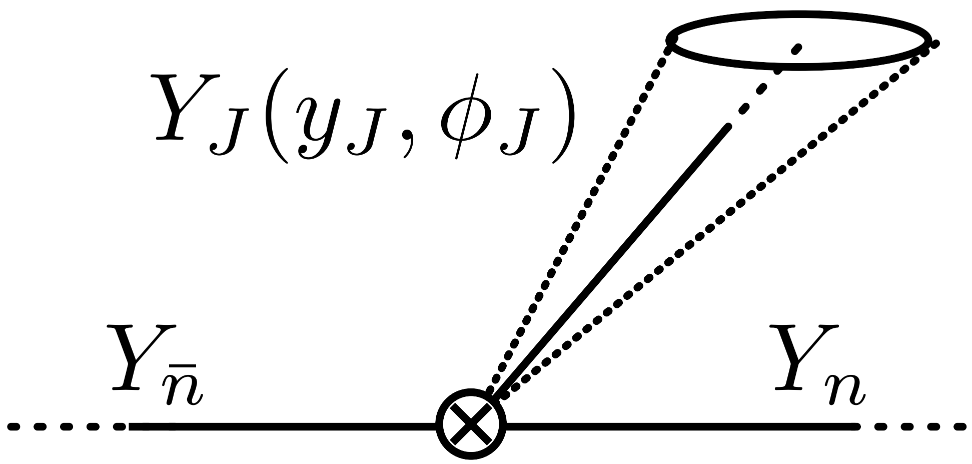
- Color indices on Wilson lines are not written out

- Perturbative and nonperturbative contribution:

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

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

Leading Nonperturbative Effect Ω



- Expanding $F_{\rm NP}(k_s) = \delta(k_s) - \Omega\, \delta'(k_s) + \ldots$

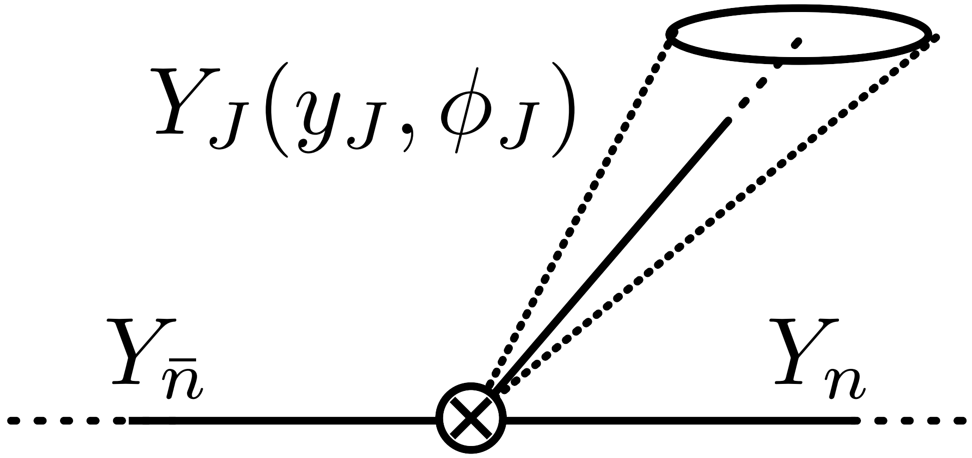
  $$\Omega = \langle 0 | Y_J^\dagger(y_J, \phi_J) Y_{\bar{n}}^\dagger Y_n^\dagger \cosh y_J\, n_J \cdot \hat{p}_J\, Y_n Y_{\bar{n}} Y_J(y_J, \phi_J) | 0 \rangle$$

- Shifts jet mass spectrum $m_J^2 \to m_J^2 + 2 p_T^J \Omega$
  (valid in tail of distribution)

- Ω is universal for e^+e^- event shapes.
  (Dokshitzer, Webber; Akhoury, Zakharov; Lee, Sterman; Mateu, Stewart, Thaler)

  How is this affected by jets?

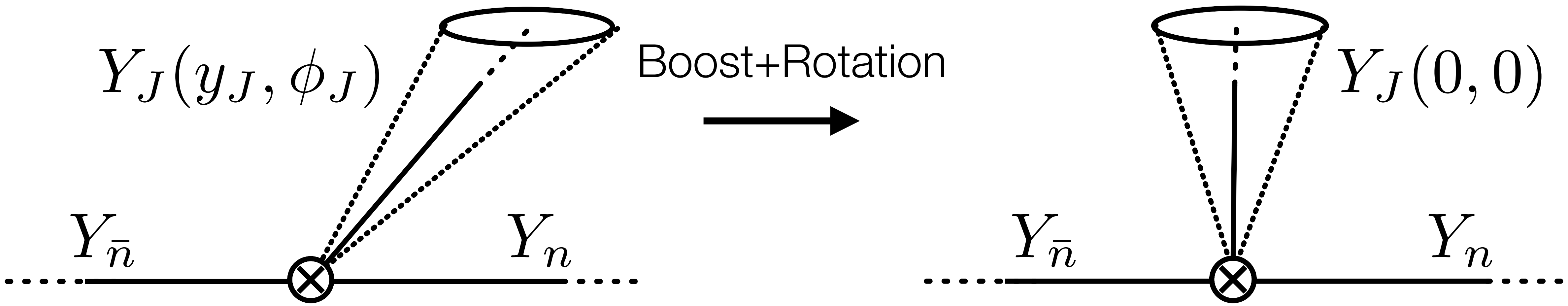
Properties of Ω



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

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

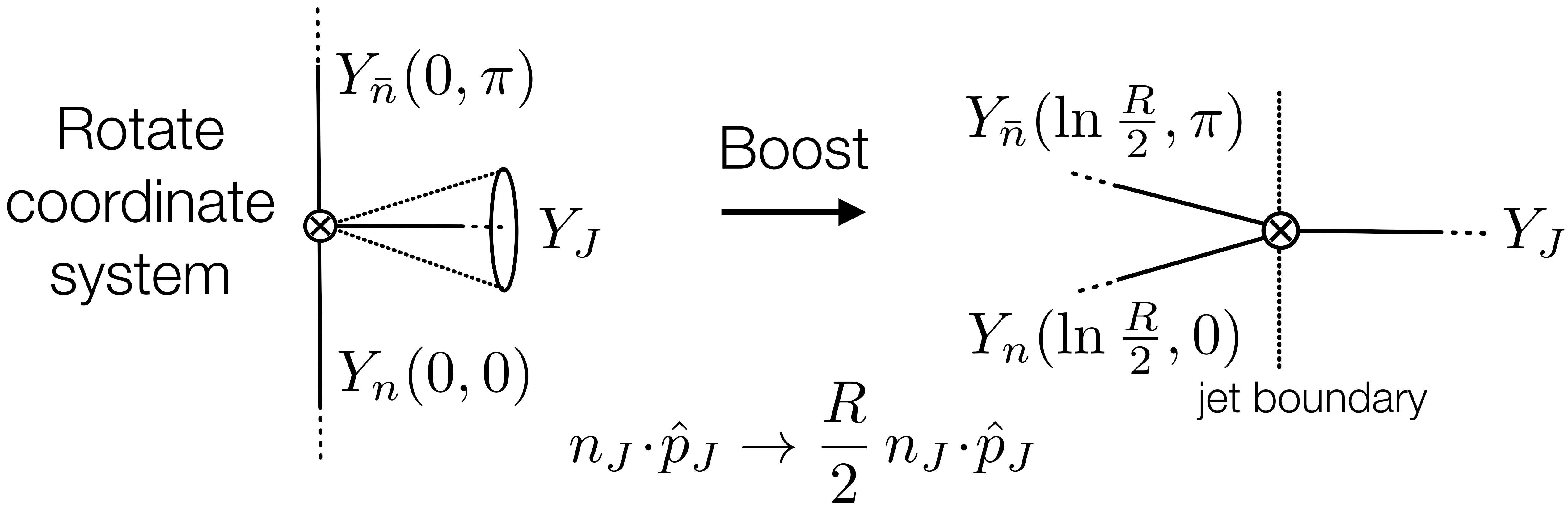
Properties of Ω



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

- 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

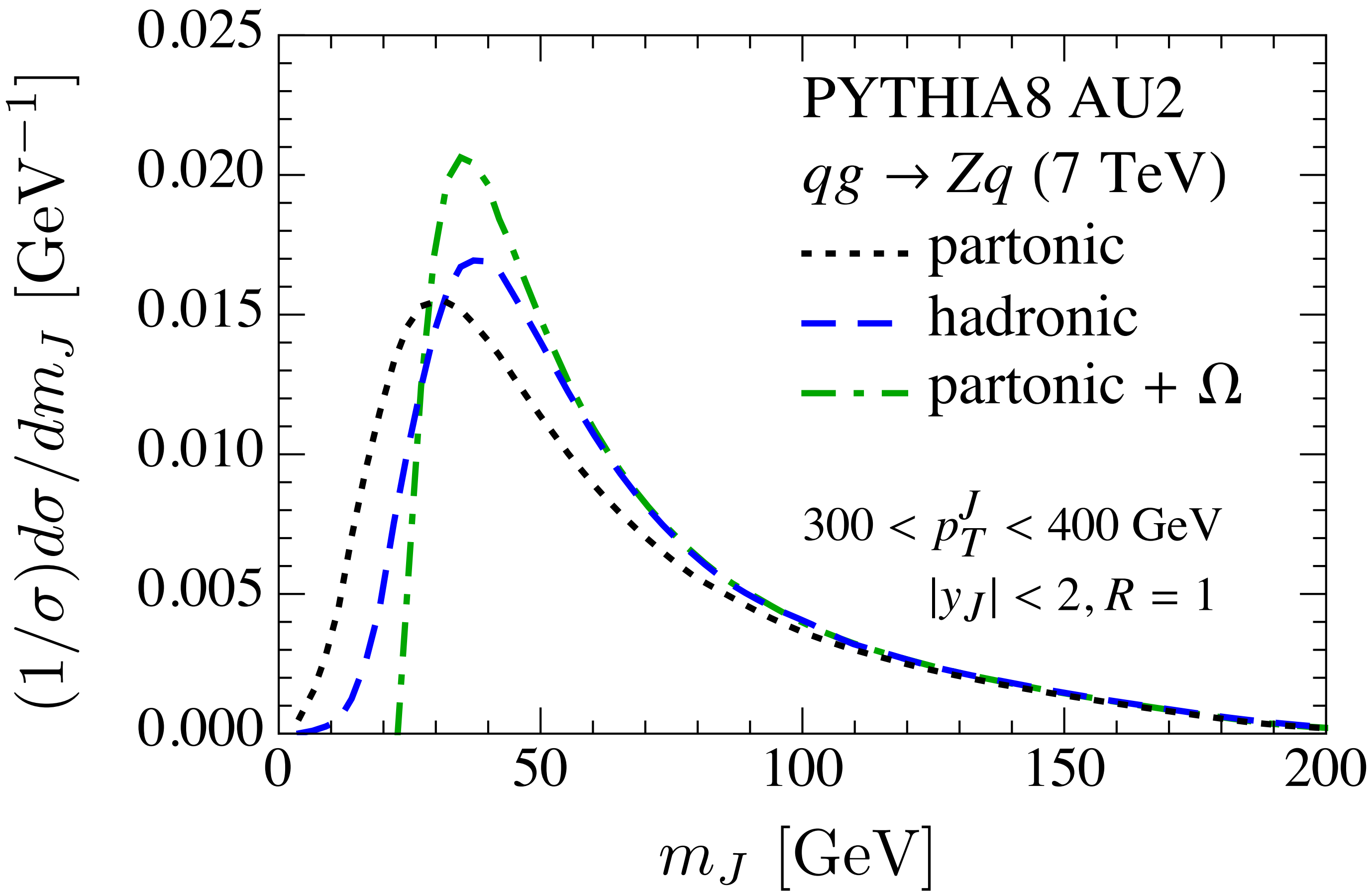
Dependence of Ω on Jet Radius R



- For $R \ll 1$, the beam Wilson lines fuse and $\Omega = \frac{R}{2}\,\Omega_0 + \ldots$
- Ω_0 only depends on quark vs. gluon, equal to Ω_{DIS} (for q)

  (Ω_{DIS}: Dasgupta, Salam; Kang, Liu, Mantry, Qiu; Kang, Lee, Stewart)
- Only odd powers of R arise

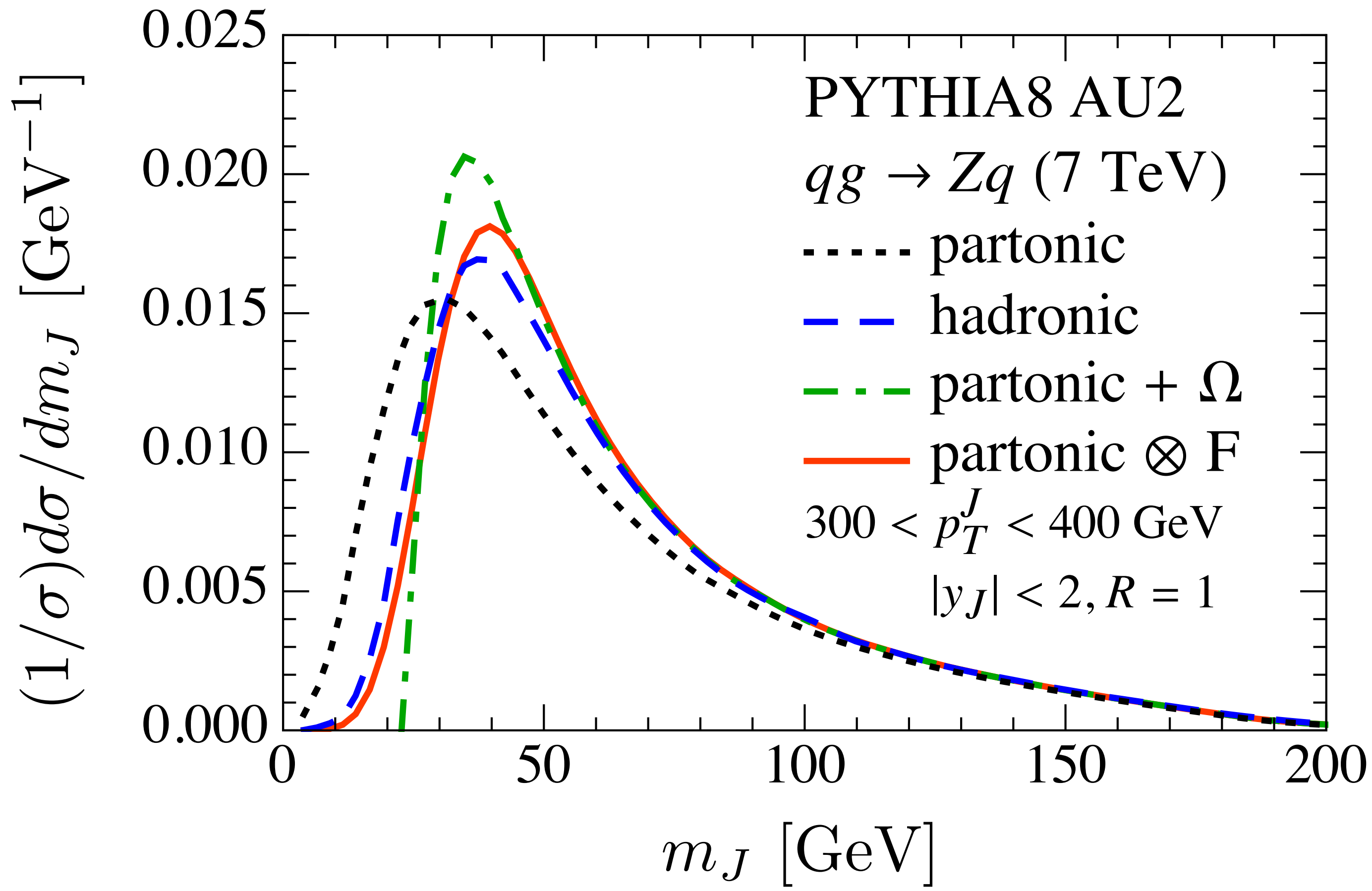
Hadronization captured by Ω

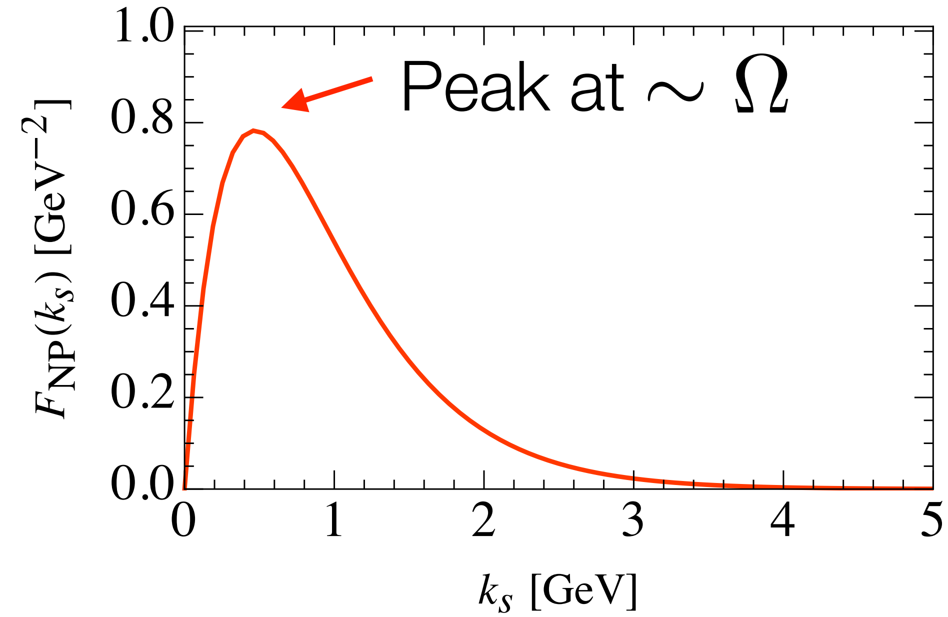


Agrees with factorization predictions:

✓ Hadronization in the tail satisfies $m_J^2 \to m_J^2 + 2p_T^J\Omega$

Hadronization captured by Ω





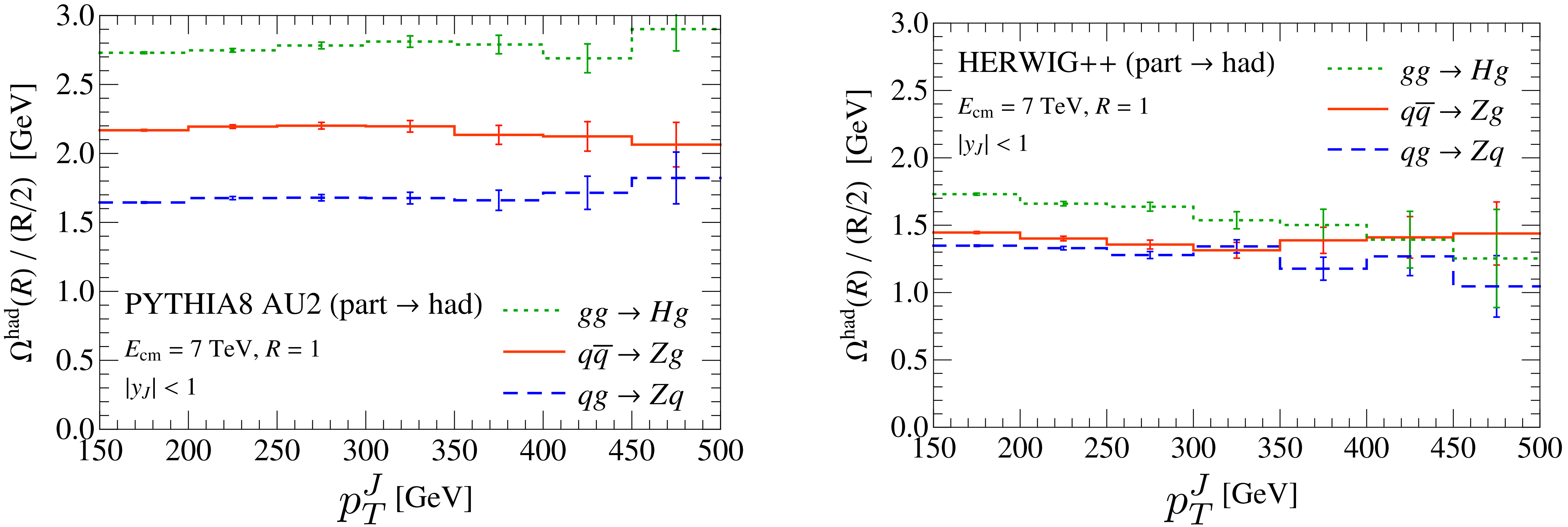
$$\Omega = \int dk_s\, k_s\, F_{\rm NP}(k_s)$$

Agrees with factorization predictions:

✓ Hadronization in the tail satisfies $m_J^2 \to m_J^2 + 2p_T^J\Omega$

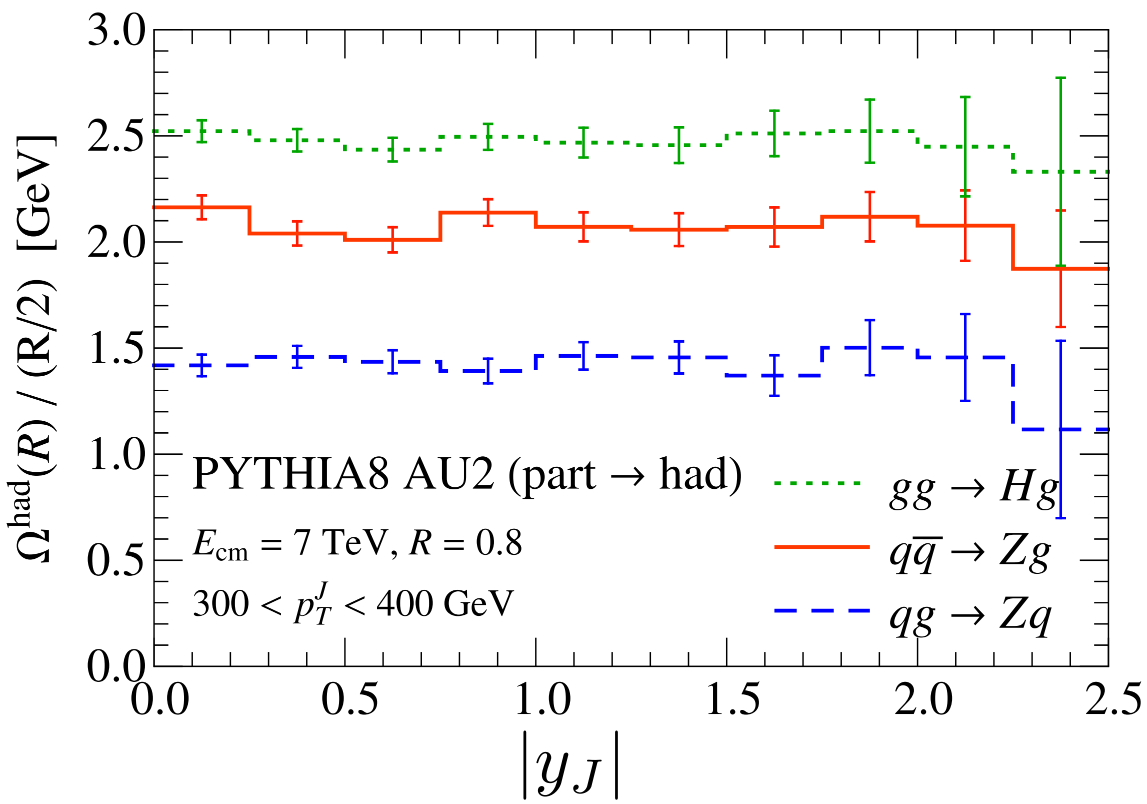
✓ More general: $\dfrac{d\sigma}{dm_J^2} \to \displaystyle\int_0^\infty dk_s\, \frac{d\sigma}{dm_J^2}(m_J^2 - 2p_T^J k_s)\, F_{\rm NP}(k_s)$

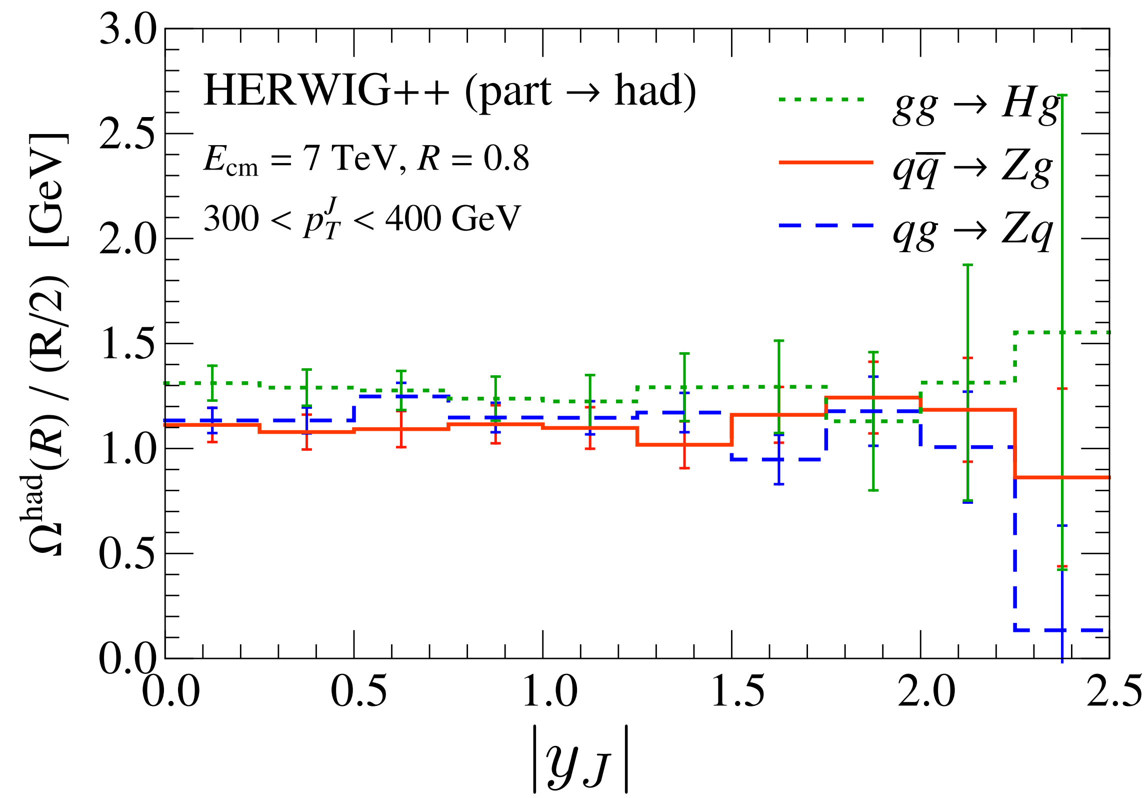
Hadronization dependence on p_T^J



✓ Agrees with factorization predictions

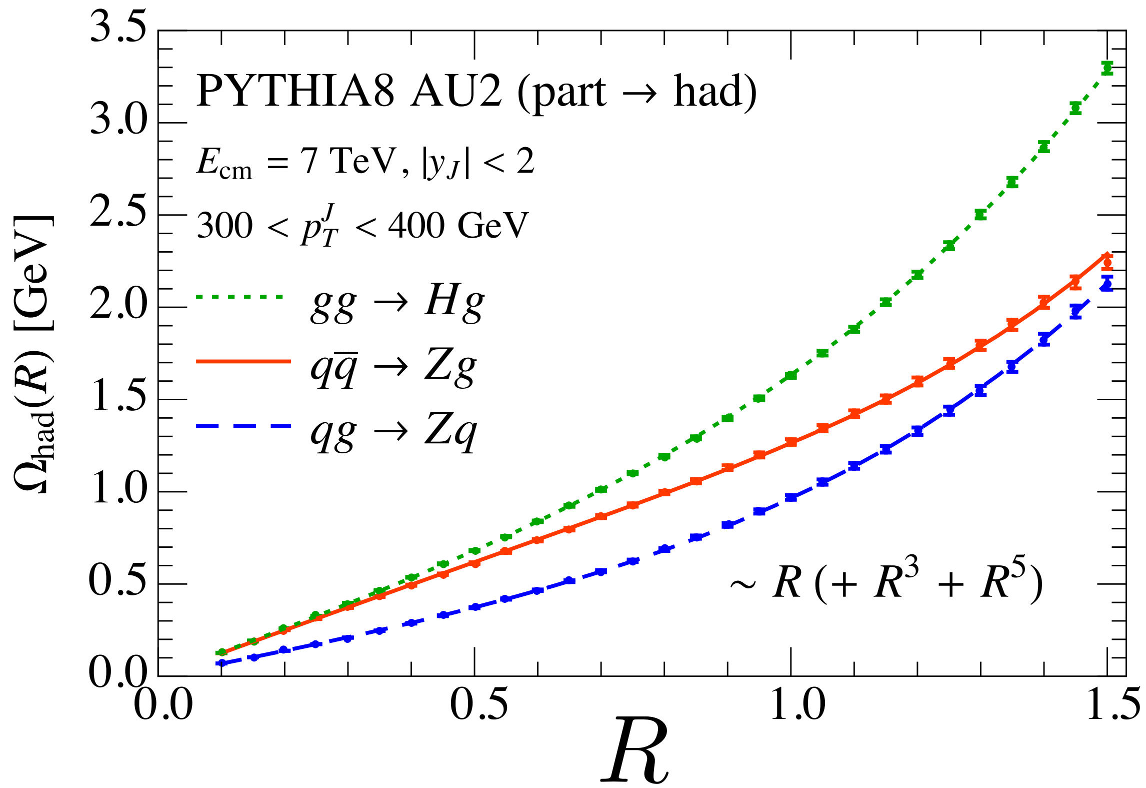
Hadronization dependence on y_J

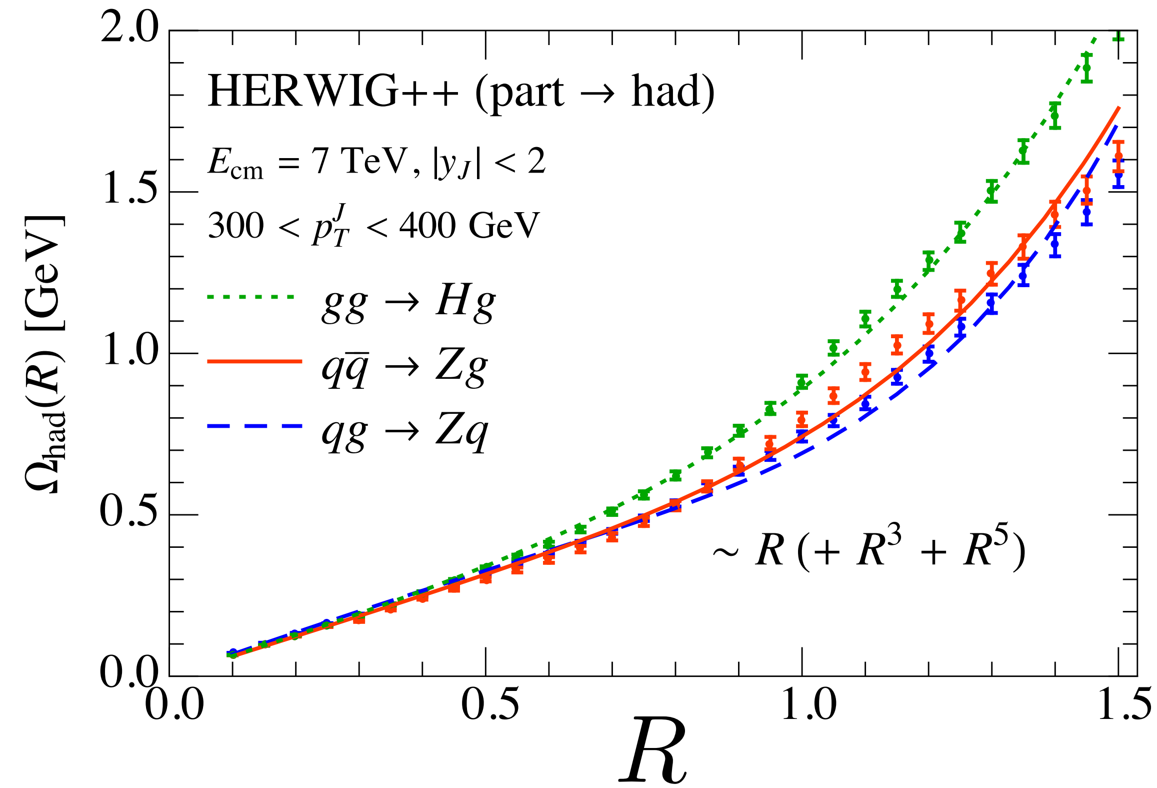




✓ Agrees with factorization predictions

Hadronization dependence on R





✓ Linear R coefficient Ω_0 only depends on quark vs. gluon

? Quark and gluon jets much more similar in Herwig

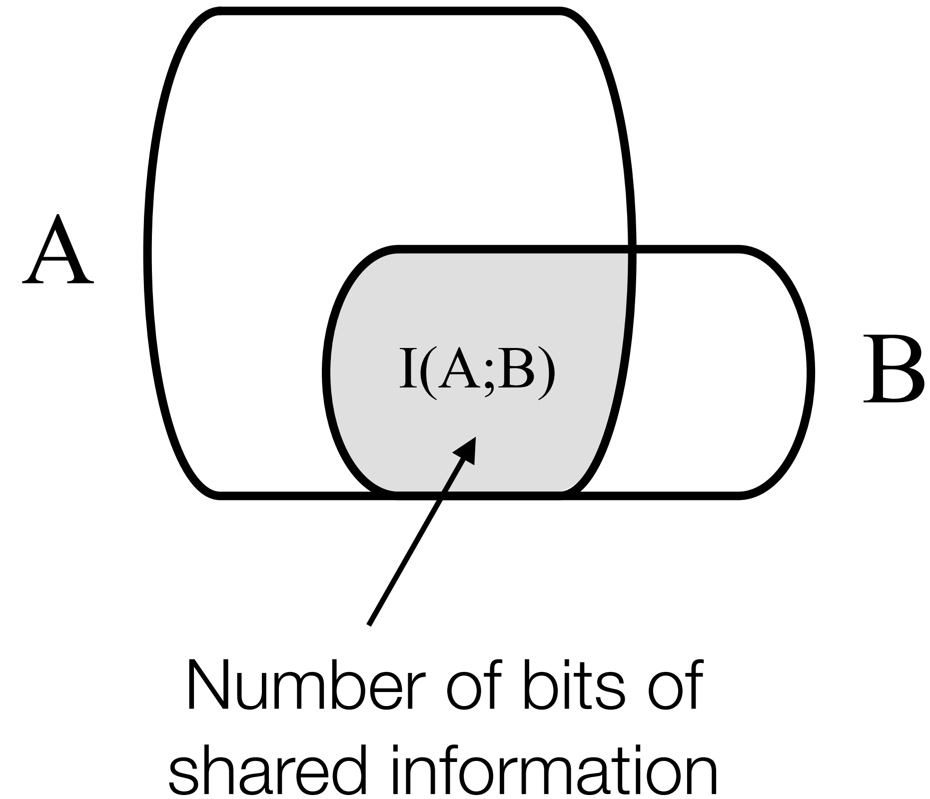
- Better fit to odd powers of R in Pythia

Quark/Gluon Discrimination

Larkoski, Thaler, WW (arXiv:1408.3122)

Mutual Information

$$I(A;B) = \int da\, db\, p(a,b) \log_2 \frac{p(a,b)}{p(a)p(b)}$$



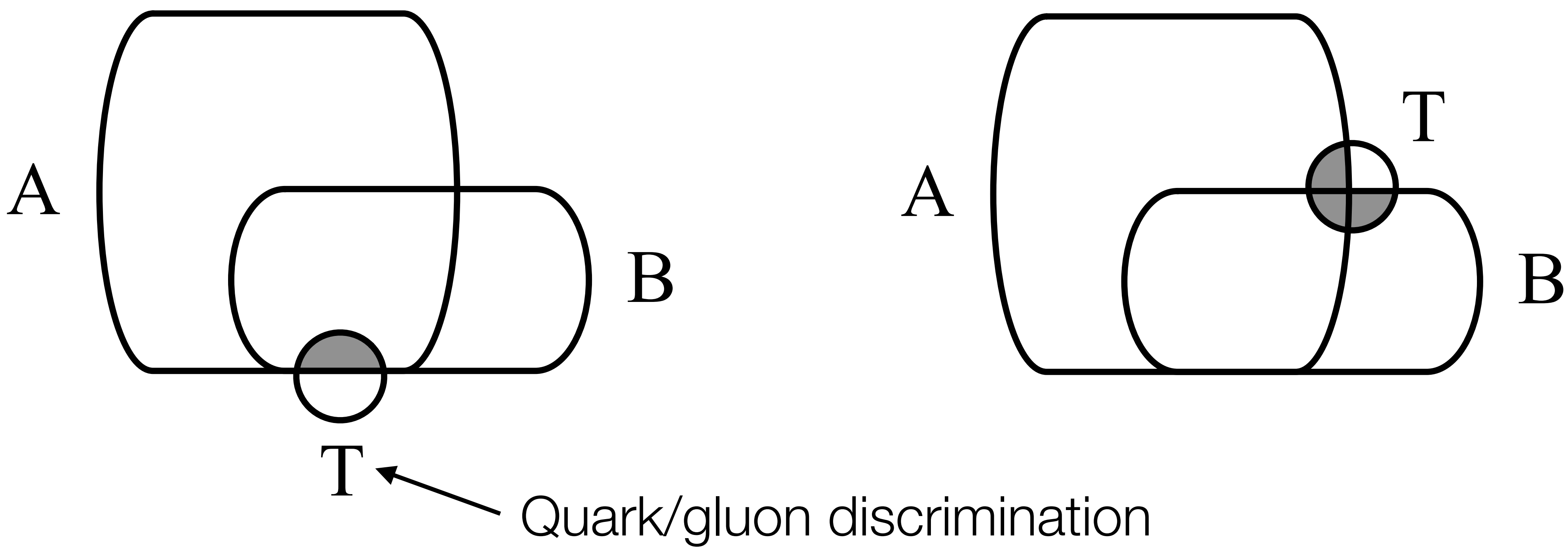
- Can directly be calculated from double diff. cross section

$$p(a,b) = \frac{1}{\sigma} \frac{d^2\sigma}{da\, db}$$

- Quark/gluon discrimination is one bit of information

Discrimination Power

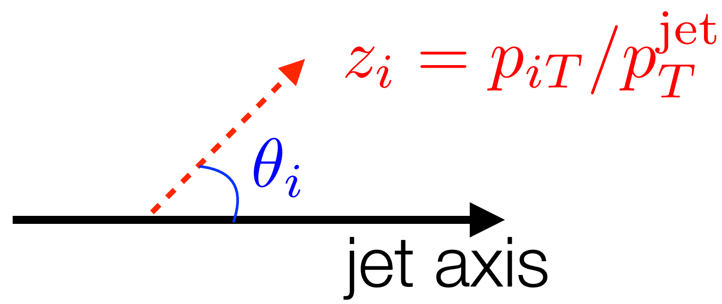
Redundant variables: Complementary variables:

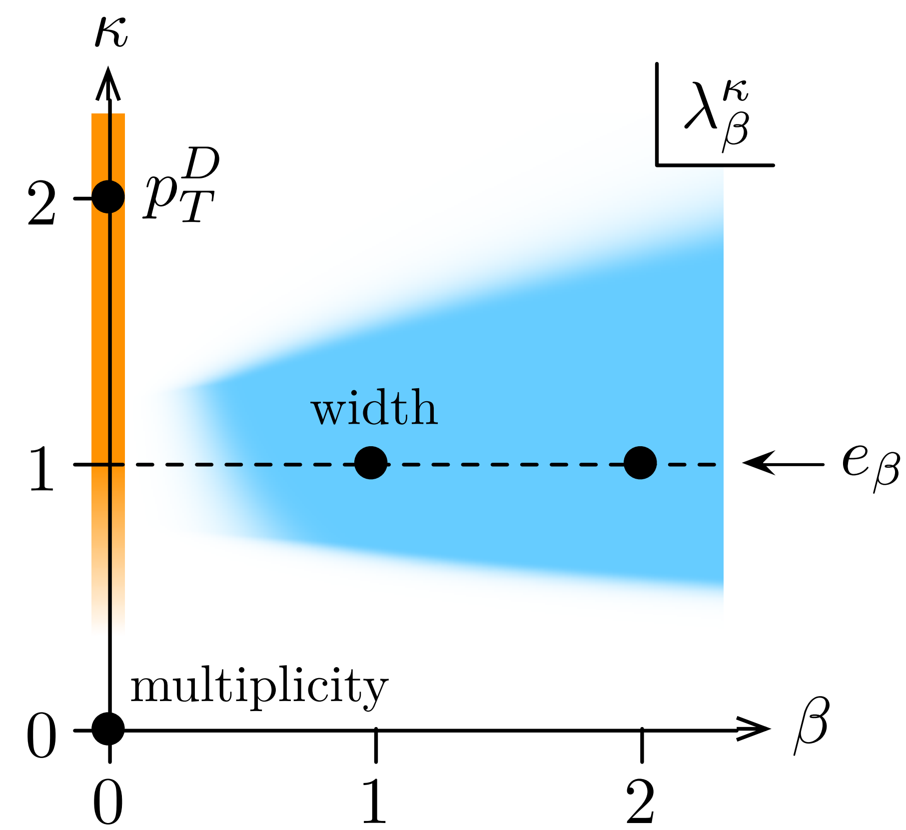


- $I(A;B)$: same correlations
- $I(T;A)$ and $I(T;B)$: same individual discrimination power
- $I(T;A,B)$: different joint discrimination power

Generalized Angularities

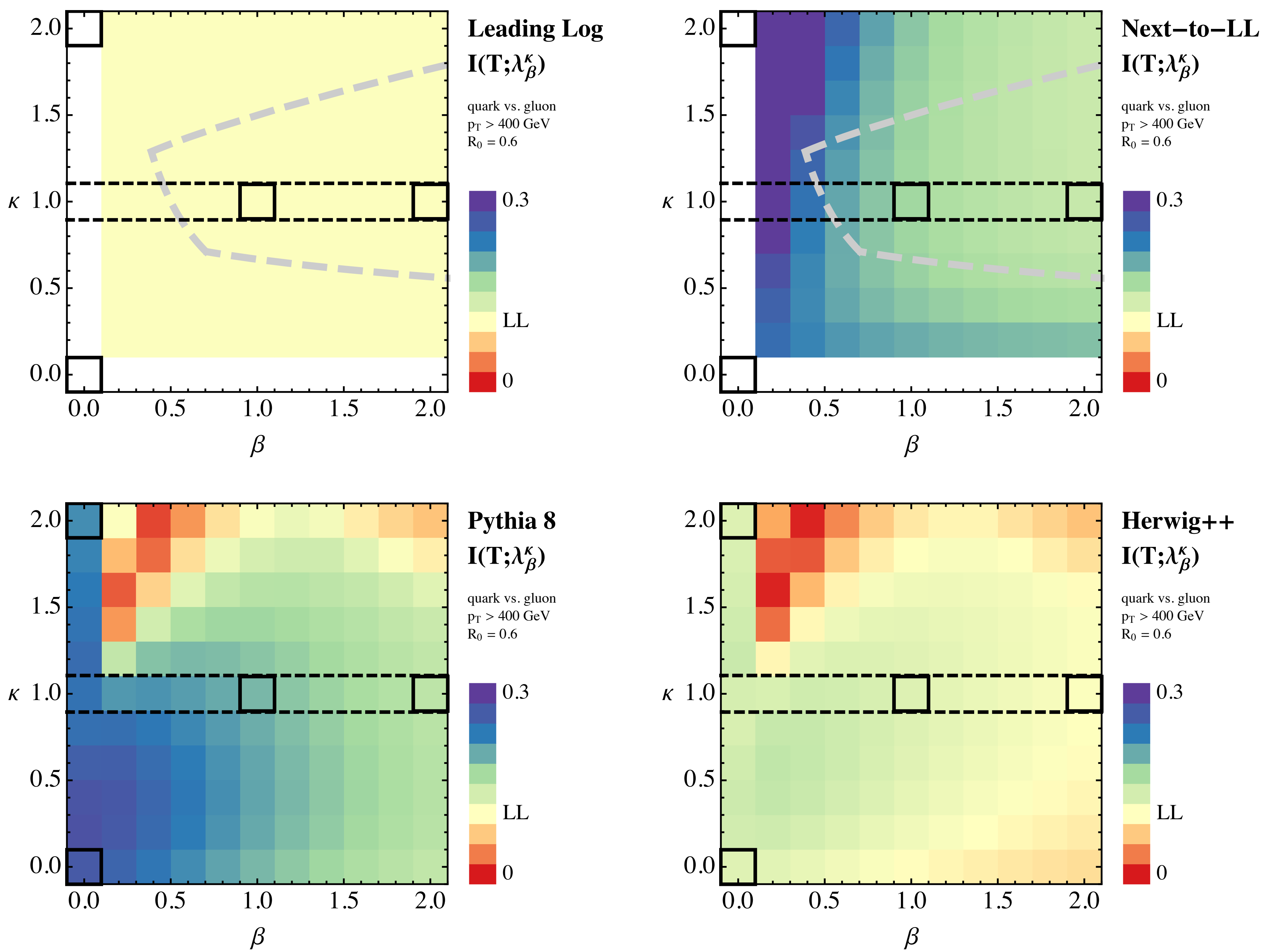
$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\theta_i}{R} \right)^\beta$$





- $\kappa = 1$: IR safe, angularities (Berger, Kucs, Sterman)
- $\beta = 0$: very IR unsafe, similar to jet charge
- blue: a bit IR unsafe, one nonpert. parameter at NLL

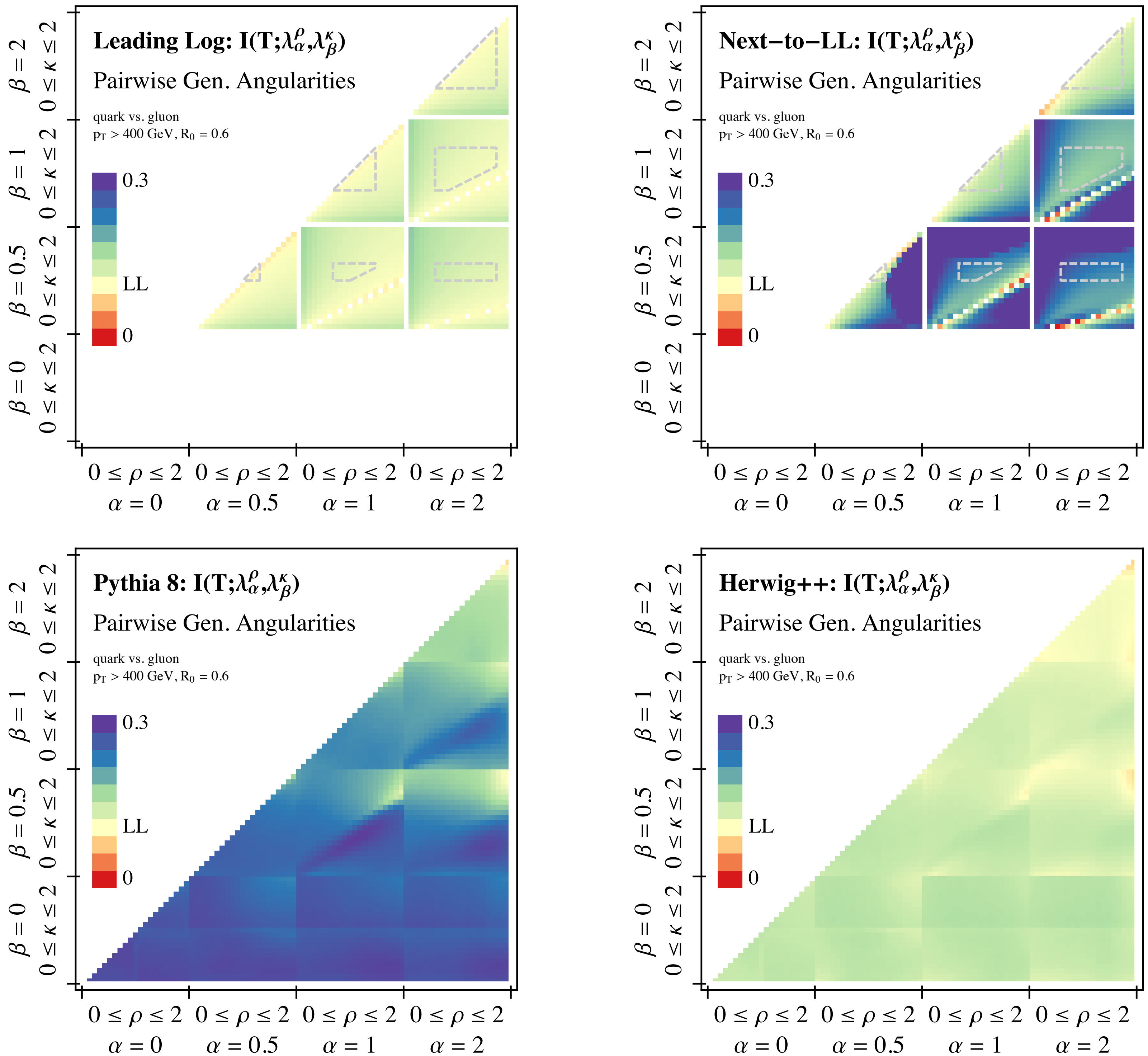
Quark/Gluon Discrimination with λ_β^κ



- (N)LL valid in grey bounds
- LL is constant
- Significant differences

Calculation uses arXiv:1306.6630 (Chang, Procura, Thaler, WW)

Quark/Gluon Discrimination with $\lambda_\alpha^\rho, \lambda_\beta^\kappa$



- (N)LL valid in grey bounds
- LL not const.
- Significant differences

Calculation uses arXiv:1401.4458 (Larkoski, Moult, Neill)

Conclusions

- Many LHC searches involves jets as signal or background
- Jet substructure provides a new set of tools for e.g.:
  - Boosted objects
  - Quark vs. gluon
- Much theoretical work remains to be done
  - Gain insight
  - Improve predictions/Monte Carlo
- Factorization is key: separating physics at different scales

→ Calculate jet mass and charge

→ Universality of hadronization for jets with $R \ll 1$

thank you!