Jet Shapes in Hadron Collisions

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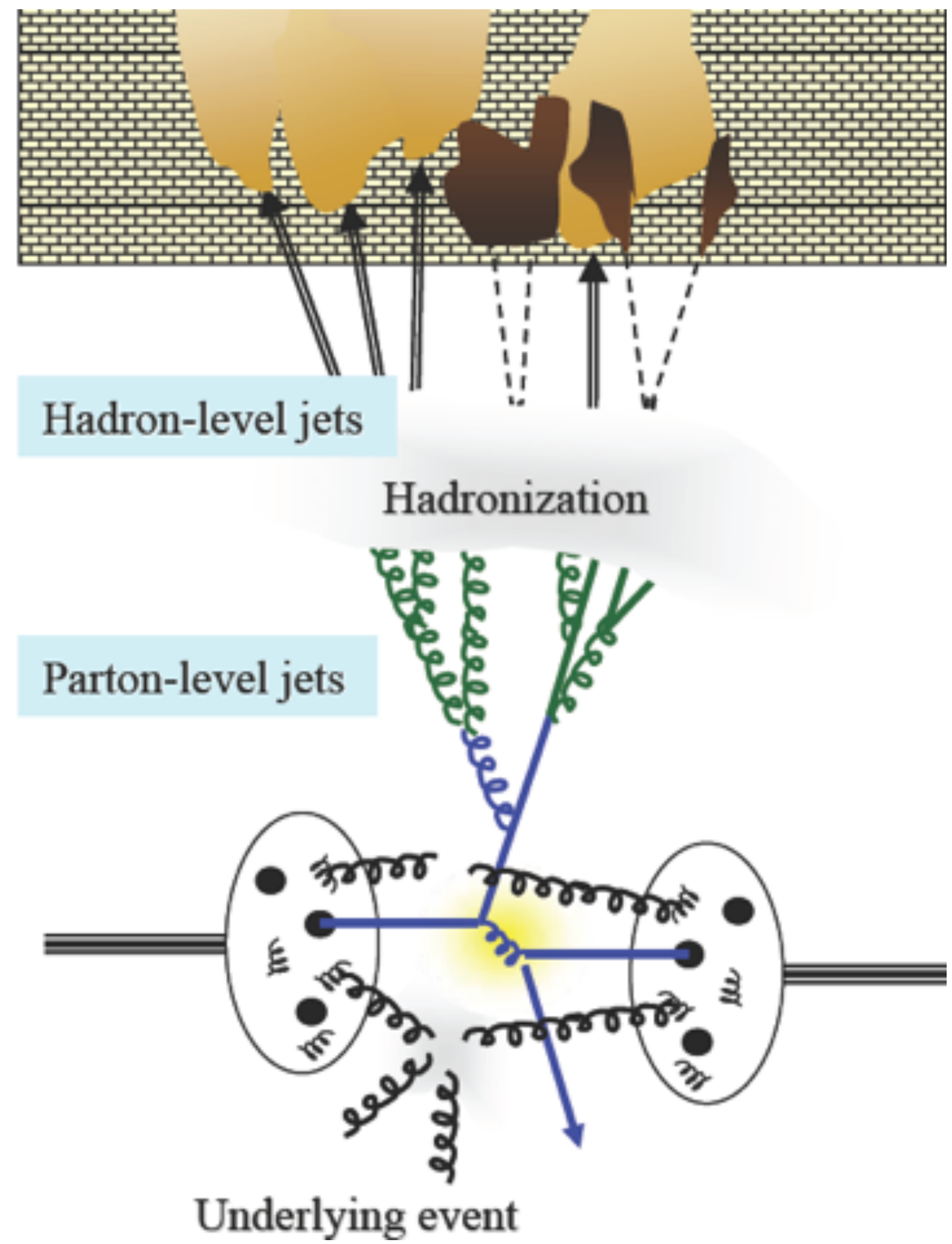
Outline

- **Motivation**
- **Jet function factorization**
- **Resummation**
- **Jet mass distribution**
- **Jet energy profile**
- **Summary**

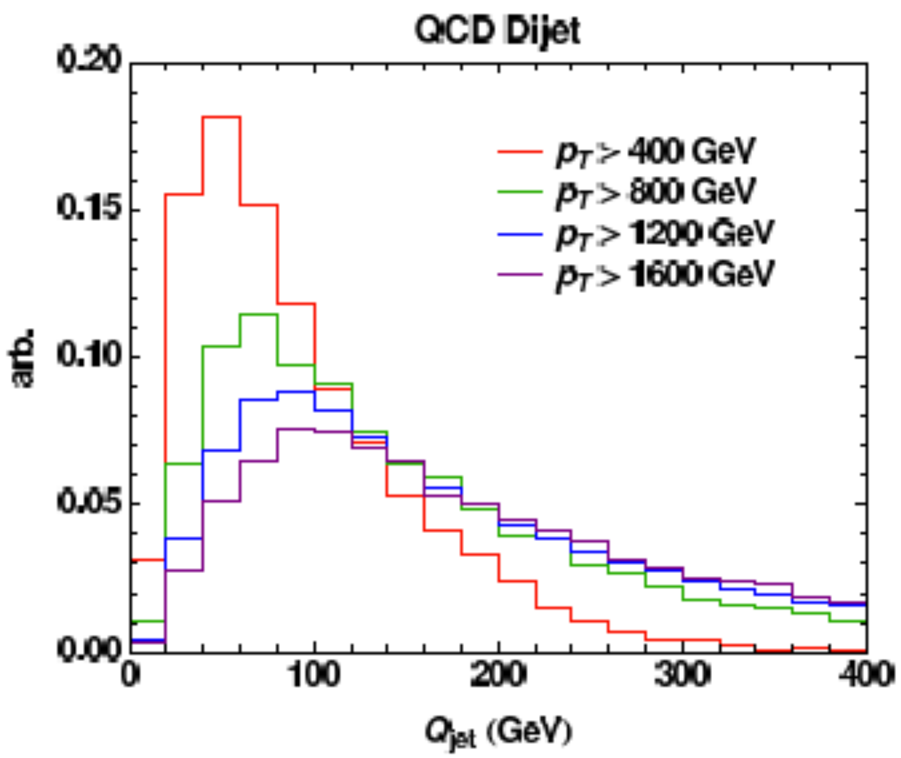
Motivation

- Copious production of jets at Hadron colliders.
- Boosted top quark (or New Physics particles) could produce single jet signal at the Large Hadron Collider (LHC).
- To discriminate QCD jets from boosted top jet (or New Physics) signal, we

  need to study jet substructure

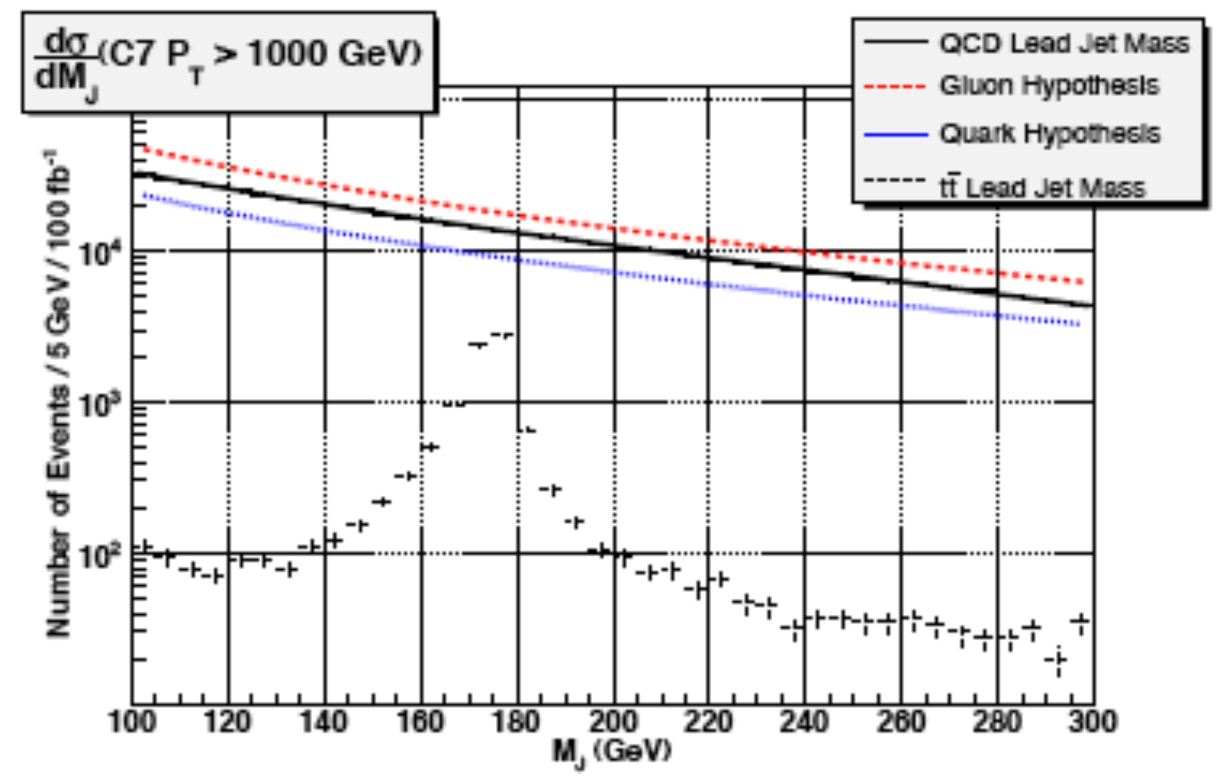


Jet substructure observables

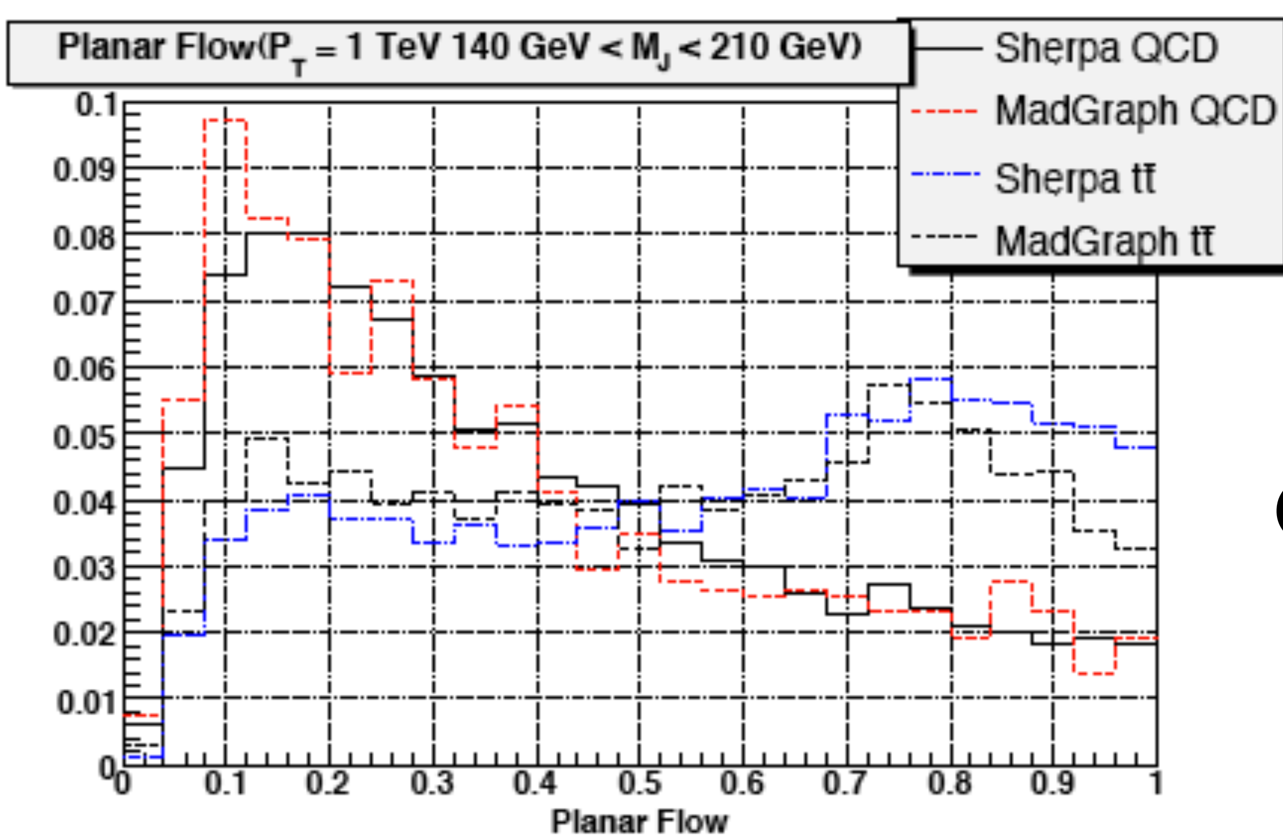


jet mass

Thaler & Wang, arxiv:0806.0023



Almeida, arxiv:0810.0934



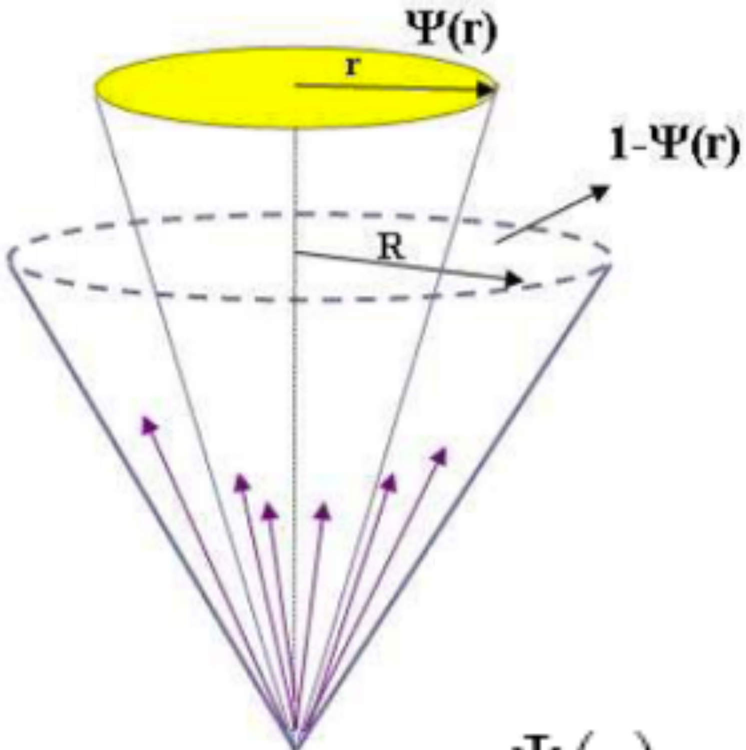
energy flow

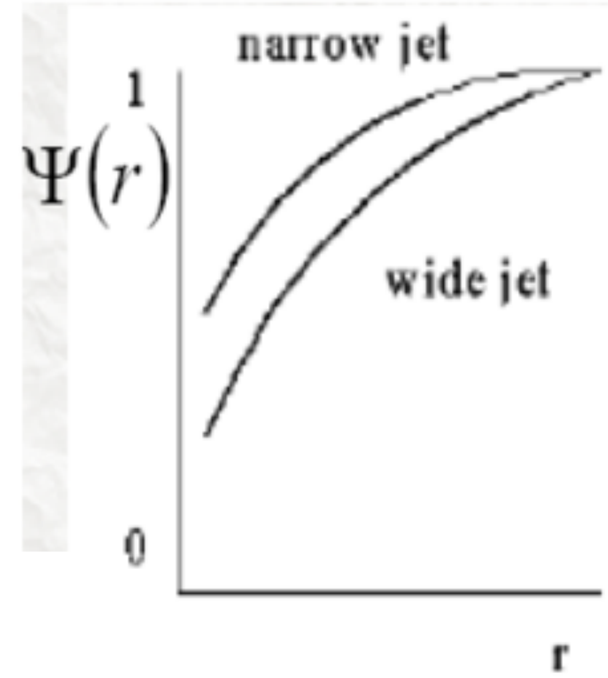
QCD: 1 to 2; linear energy flow

Top jets: 1 to 3; planar flow

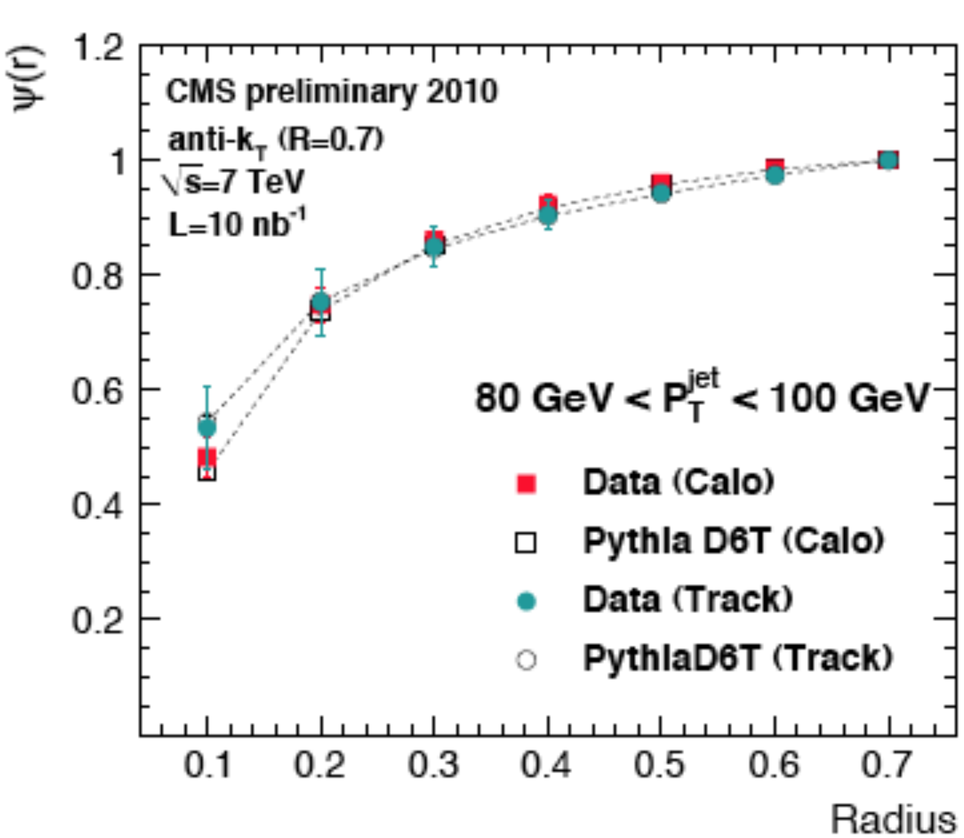
Almeida, arxiv:0807.0234

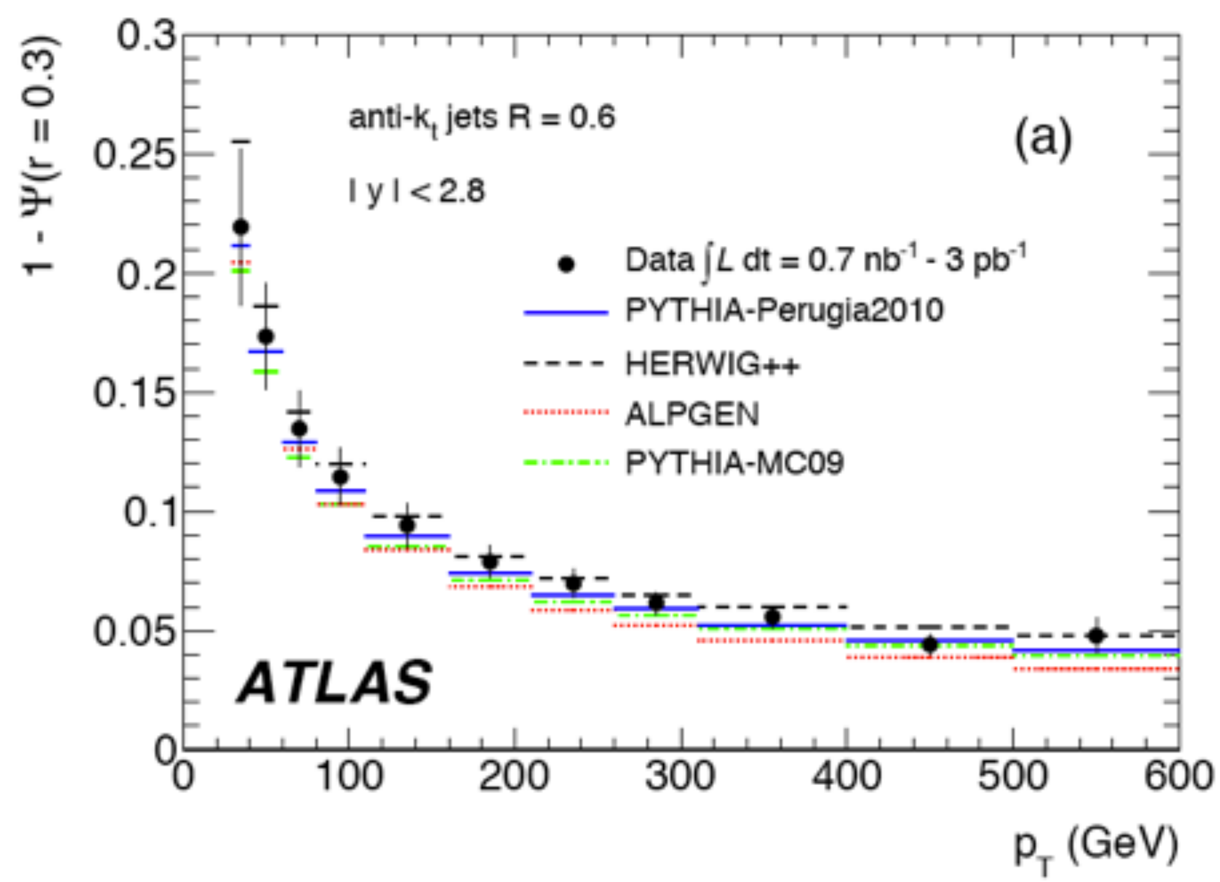
Jet Energy Profile





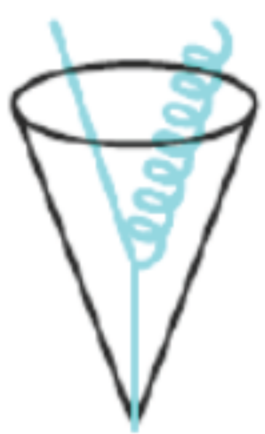
$$\Psi(r) = \frac{1}{\mathrm{N_{jet}}} \sum_{\mathrm{jets}} \frac{P_T(0,r)}{P_T(0,R)}, \qquad 0 \le r \le R$$





Various Theoretical Predictions

- **Event Generators**: leading log radiations, hadronization, underlying events, etc.
- **Fixed order QCD calculation**: finite number of soft/collinear radiations
- **Resummation**: all order soft/collinear radiations



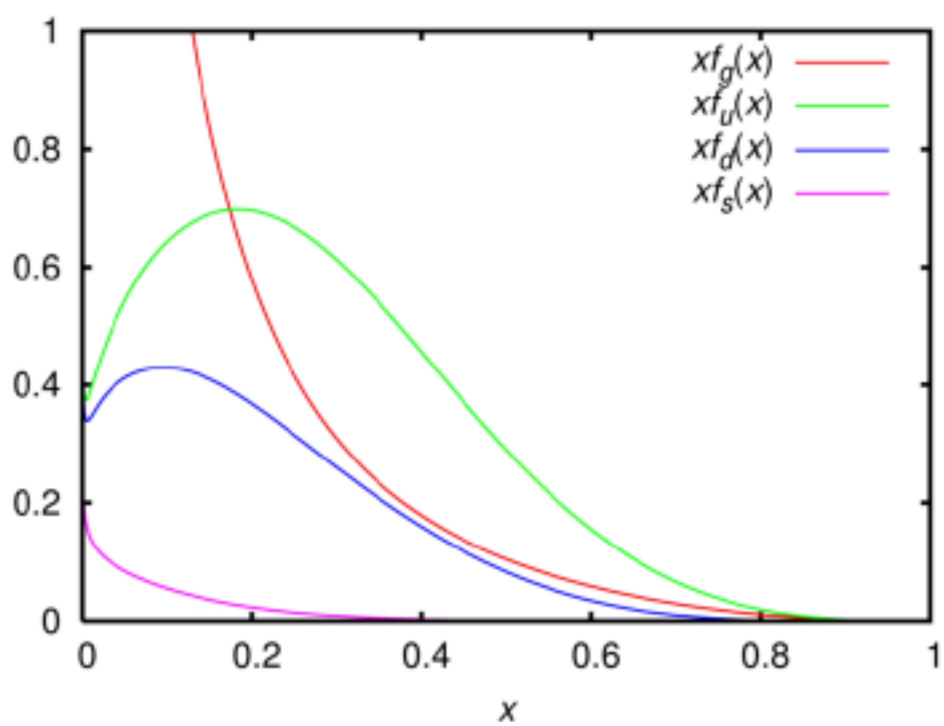
Factorization Theorem

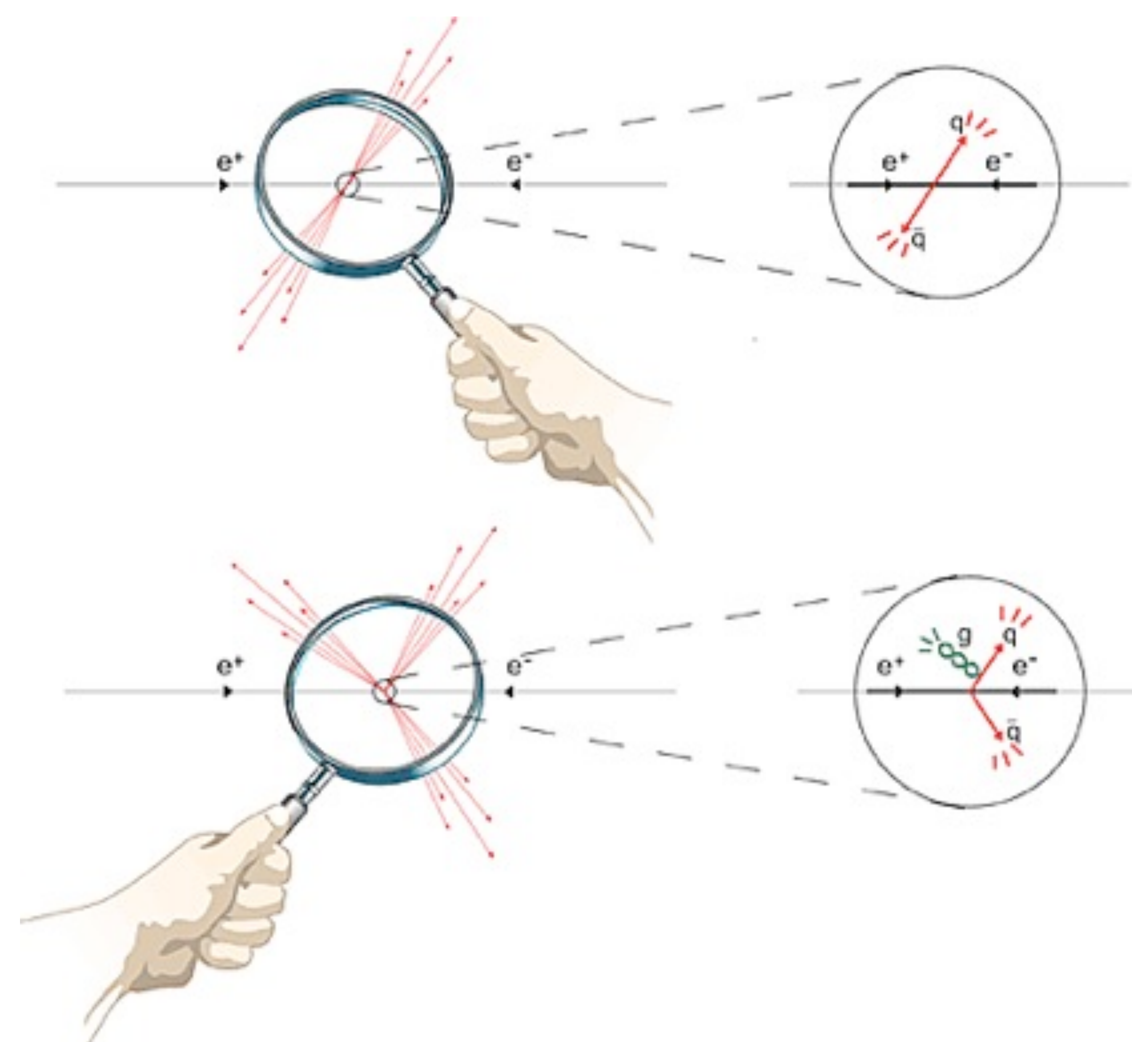
$$\sigma_{hh'} = \sum_{i,j} \int_0^1 dx_1 dx_2\, \phi_{i/h}(x, Q^2)\, H_{ij}\left(\frac{Q^2}{x_1 x_2 S}\right) \phi_{j/h'}(x_2, Q^2)$$

Nonperturbative, but universal, hence measurable

Infrared safe (IRS), calculable in pQCD

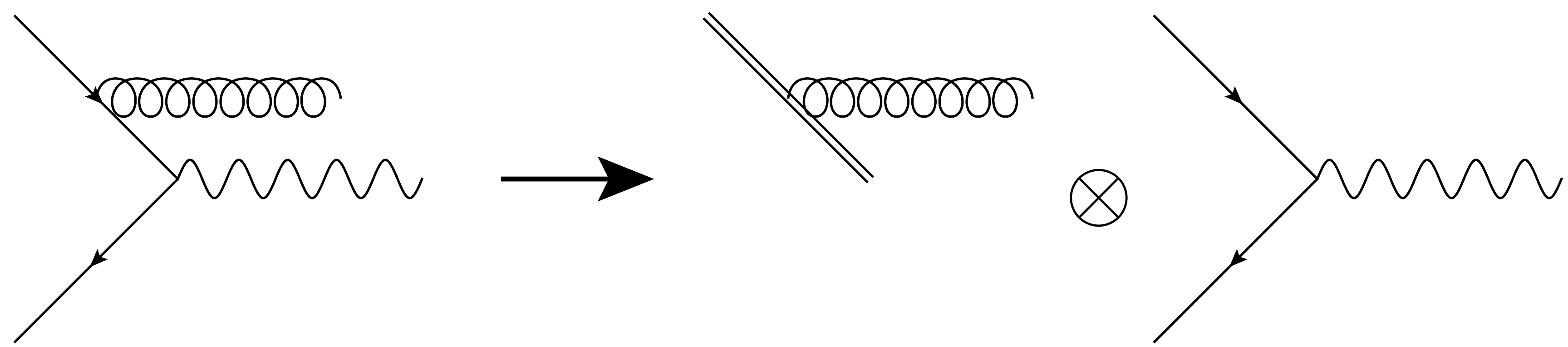
CTEQ
MSTW
NNPDF





Eikonalization

Soft/collinear radiations can be detached by eikonalization



Eikonal vertices and eikonal propagators of soft/collinear radiations can be factorized and combined into Wilson line

$$\Phi_{\xi}^{(f)}(\infty, 0; 0) = \mathcal{P}\left\{ e^{-ig\int_0^\infty d\eta\, \xi\cdot A^{(f)}(\eta\,\xi^\mu)} \right\},$$

Jet Function

LO Jet: $J_i^{(0)}(m_{J_i}^2, p_{0,J_i}, R) = \delta(m_{J_i}^2).$

Quark Jet:

$$J_i^q(m_J^2, p_{0,J_i}, R) = \frac{(2\pi)^3}{2\sqrt{2}\,(p_{0,J_i})^2}\frac{\xi_\mu}{N_c}\sum_{N_{J_i}} \mathrm{Tr}\left\{\gamma^\mu \langle 0|q(0)\Phi_\xi^{(\bar{q})\dagger}(\infty,0)|N_{J_i}\rangle\langle N_{J_i}|\Phi_\xi^{(\bar{q})}(\infty,0)\bar{q}(0)|0\rangle\right\}$$
$$\times\delta\left(m_J^2 - \tilde{m}_J^2(N_{J_i},R)\right)\delta^{(2)}(\hat{n}-\tilde{n}(N_{J_i}))\delta(p_{0,J_i}-\omega(N_{J_c})), \qquad \text{(A.3)}$$

Gluon Jet:

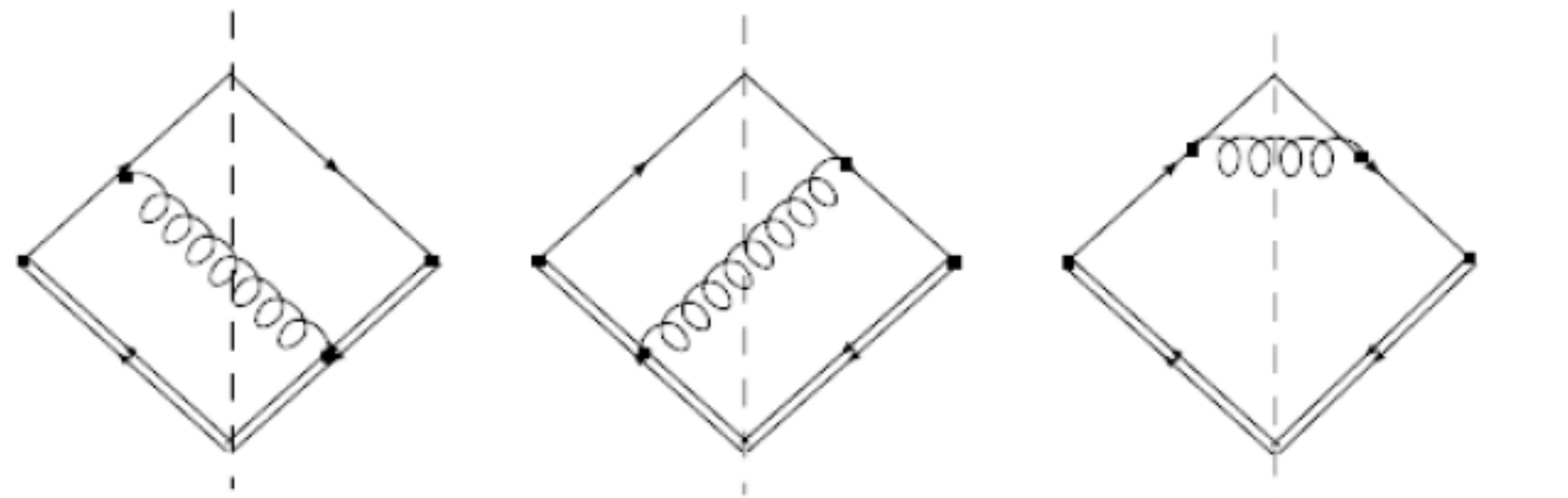
$$J_i^g(m_J^2, p_{0,J_i}, R) = \frac{(2\pi)^3}{2(p_{0,J_i})^3}\sum_{N_{J_i}}\langle 0|\xi_\sigma F^{\sigma\nu}(0)\Phi_\xi^{(g)\dagger}(0,\infty)|N_{J_i}\rangle\langle N_{J_i}|\Phi_\xi^{(g)}(0,\infty)F_\nu{}^\rho(0)\xi_\rho|0\rangle$$
$$\times\delta\left(m_J^2 - \tilde{m}_J^2(N_{J_i},R)\right)\delta^{(2)}(\hat{n}-\tilde{n}(N_{J_i}))\delta(p_{0,J_i}-\omega(N_{J_c})). \qquad \text{(A.4)}$$

$$\frac{d\sigma(R)}{dp_T dm_J} = \sum_c J^c(m_J, p_T, R)\,\frac{d\hat{\sigma}^c(R)}{dp_T},$$

Almeida, arxiv:0810.0934

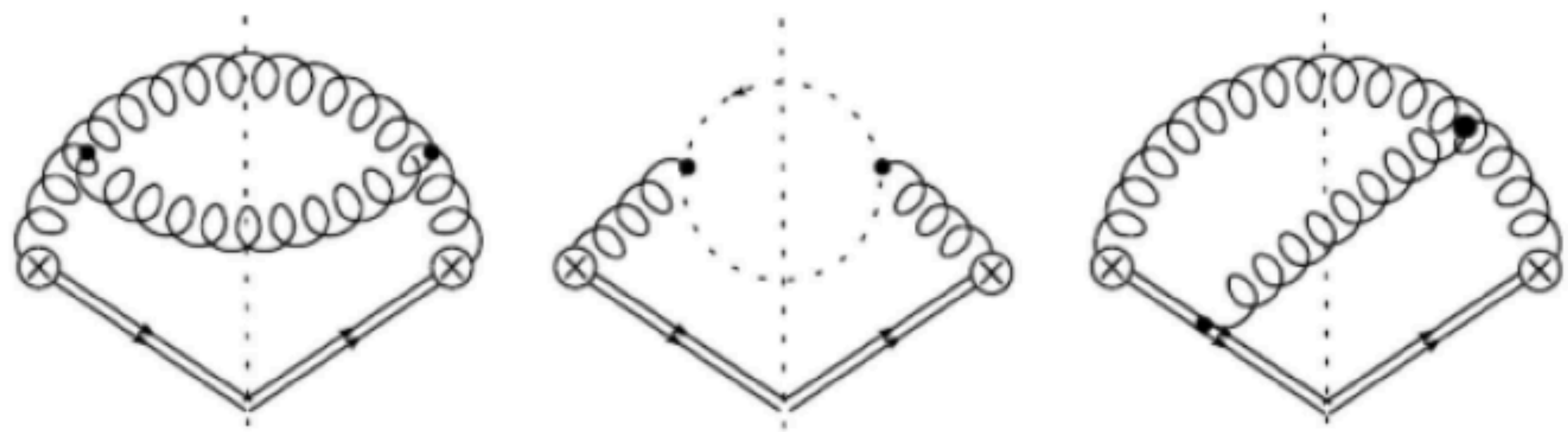
Diagrams for NLO calculations

NLO Quark:

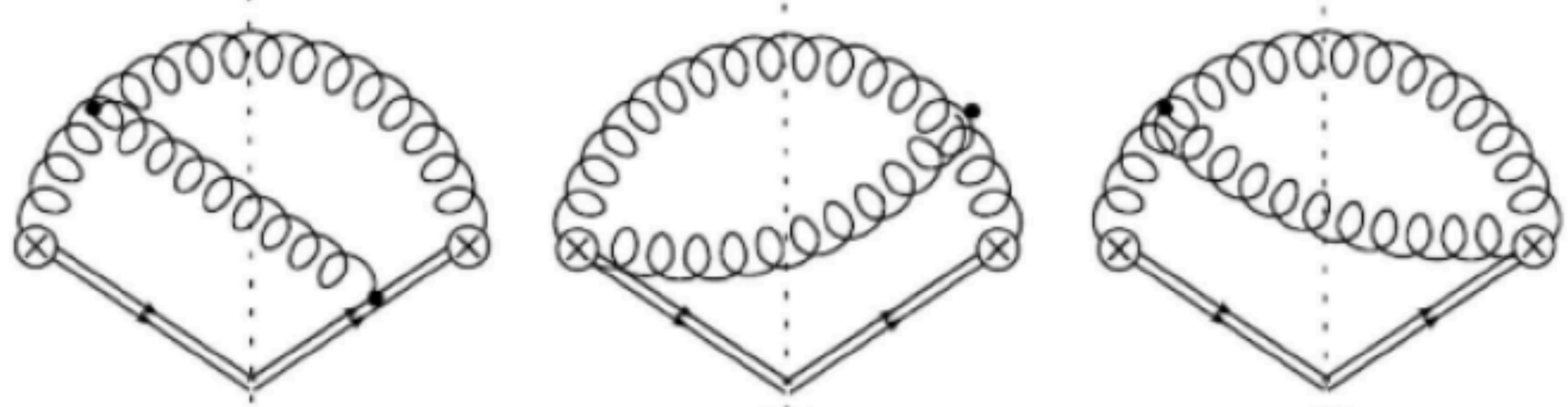


(a) (b) (c)

NLO Gluon:



(a) (b) (c)



(d) (e) (f)

Resummation for Jet function (jet mass distribution)

In fixed order calculations, there are large logarithmic terms of the ratio of jet energy to jet mass,

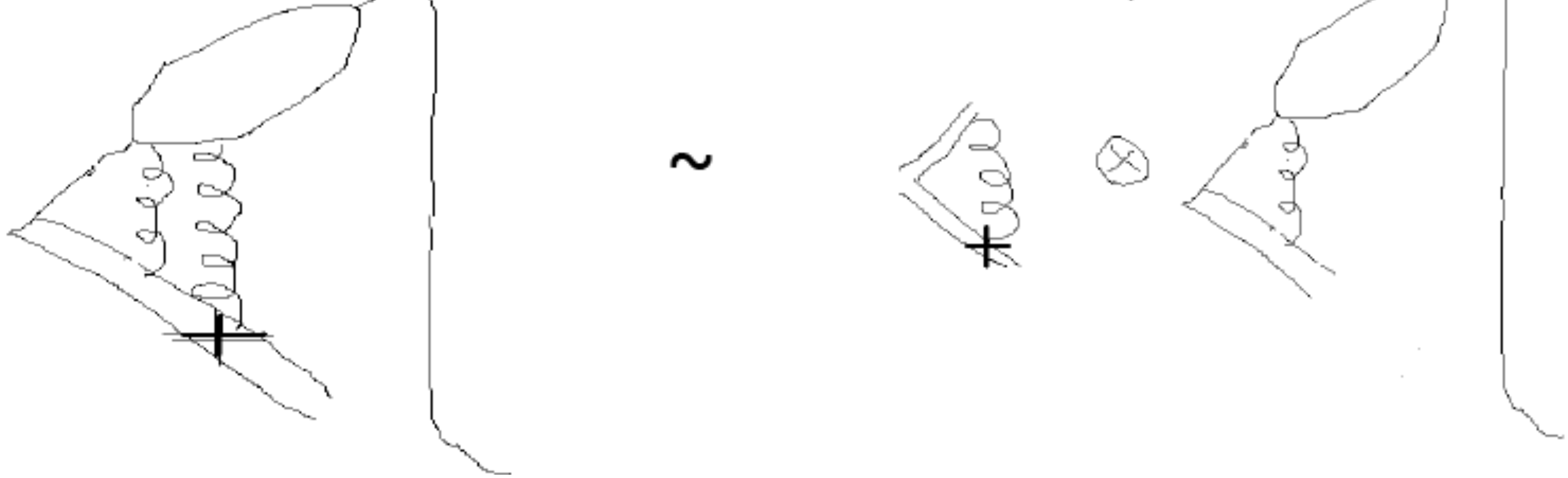
$$\ln(P_J^0/m_J)$$

which can be resummed by applying renormalization group (RG) technique.

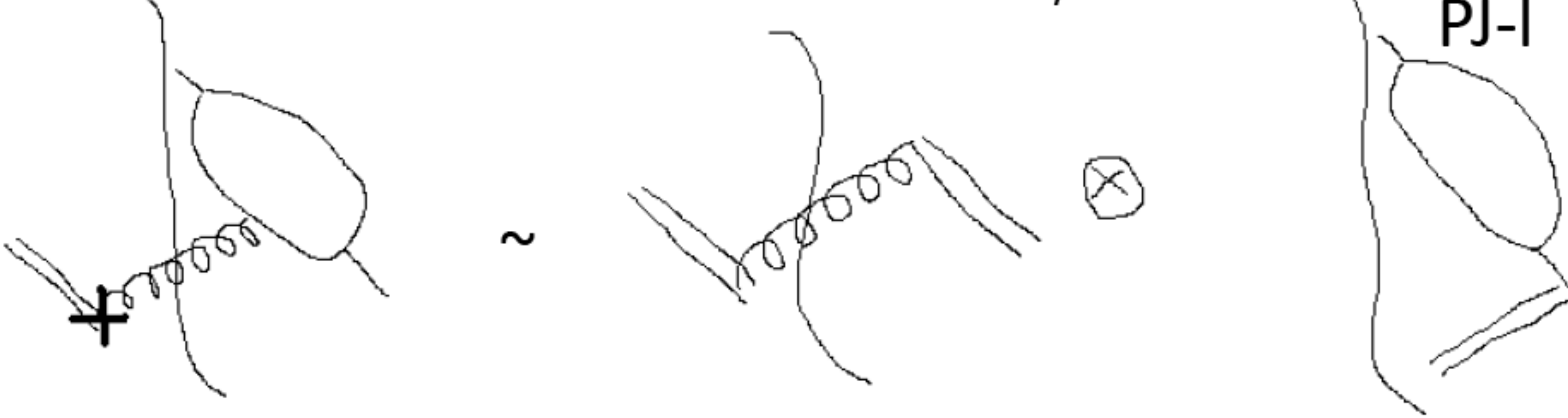
The key idea of resummation technique is to vary Wilson line direction to arbitrary gauge vector n, since collinear dynamics is independent of n.

Soft Gluon Factorization

LO soft kernel $K_v^{(1)}$



LO soft kernel $K_r^{(1)}$



RG Equation for Jet function

Up to leading logarithms, RG equation is

$$-\frac{n^2}{P_J \cdot n} P_J^\alpha \frac{d}{dn^\alpha} J = [G^{(1)} + K_v^{(1)} + K_r^{(1)}] \otimes J$$

To include next-to-leading-log contribution, G and K are evaluated to two loops.

Mellin transform converts convolution to multiplication

$$\bar{J}(N, P_J, \nu^2, R, \mu) \equiv \int_0^1 dx (1-x)^{N-1} J(x, P_J, \nu^2, R, \mu),$$

$$x \equiv m_J^2/(P_J^0)^2$$

$$-\frac{n^2}{v \cdot n} v_\alpha \frac{d}{dn_\alpha} \bar{J}(N, P_J^0, \nu^2, R, \mu) = 2\nu^2 \frac{d}{d\nu^2} \bar{J}(N, P_J^0, \nu^2, R, \mu)$$

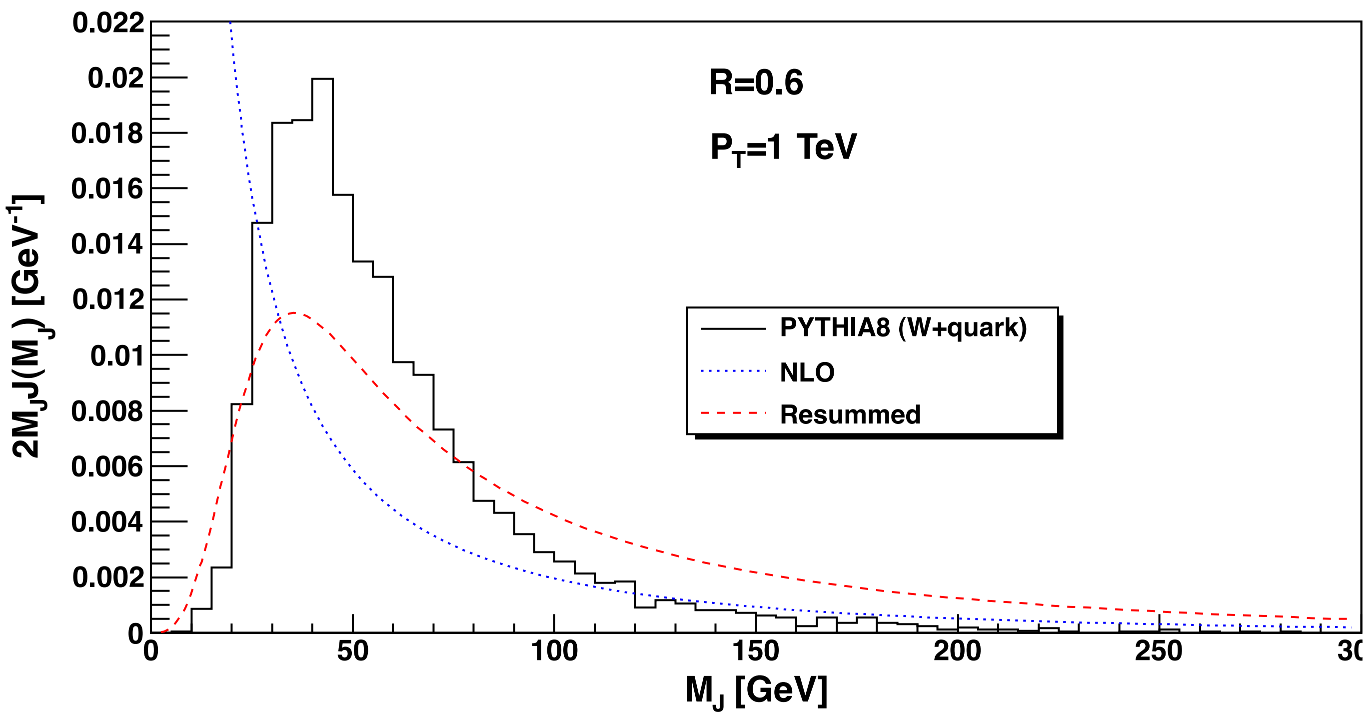
$$= -\left[2 \int_{1/\bar{N}}^{\nu^2} \frac{dz}{z} \lambda_K(\alpha_s(zP_J^0)) - \frac{\alpha_s\left(\nu^2 P_J^0\right)}{\pi} C_F \right] \bar{J}(N, P_J^0, \nu^2, R, \mu).$$

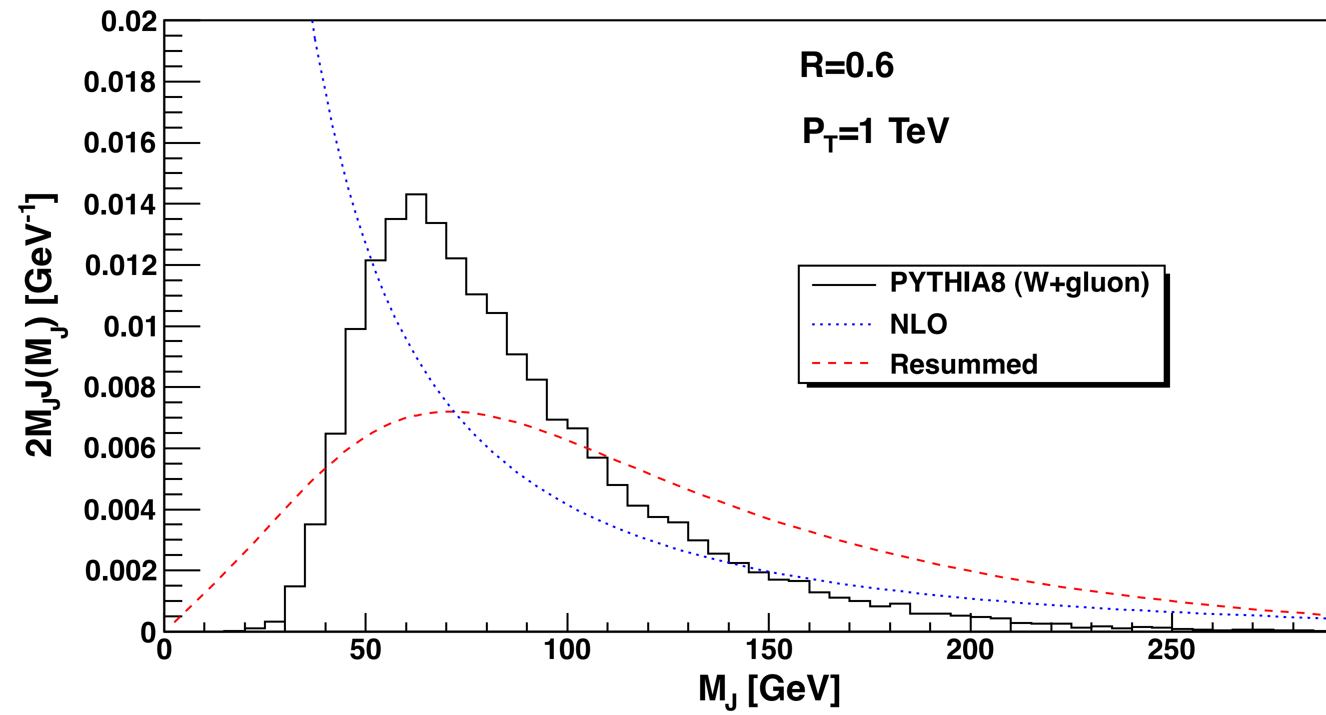
Jet function (in Mellin space), including resummation effect:

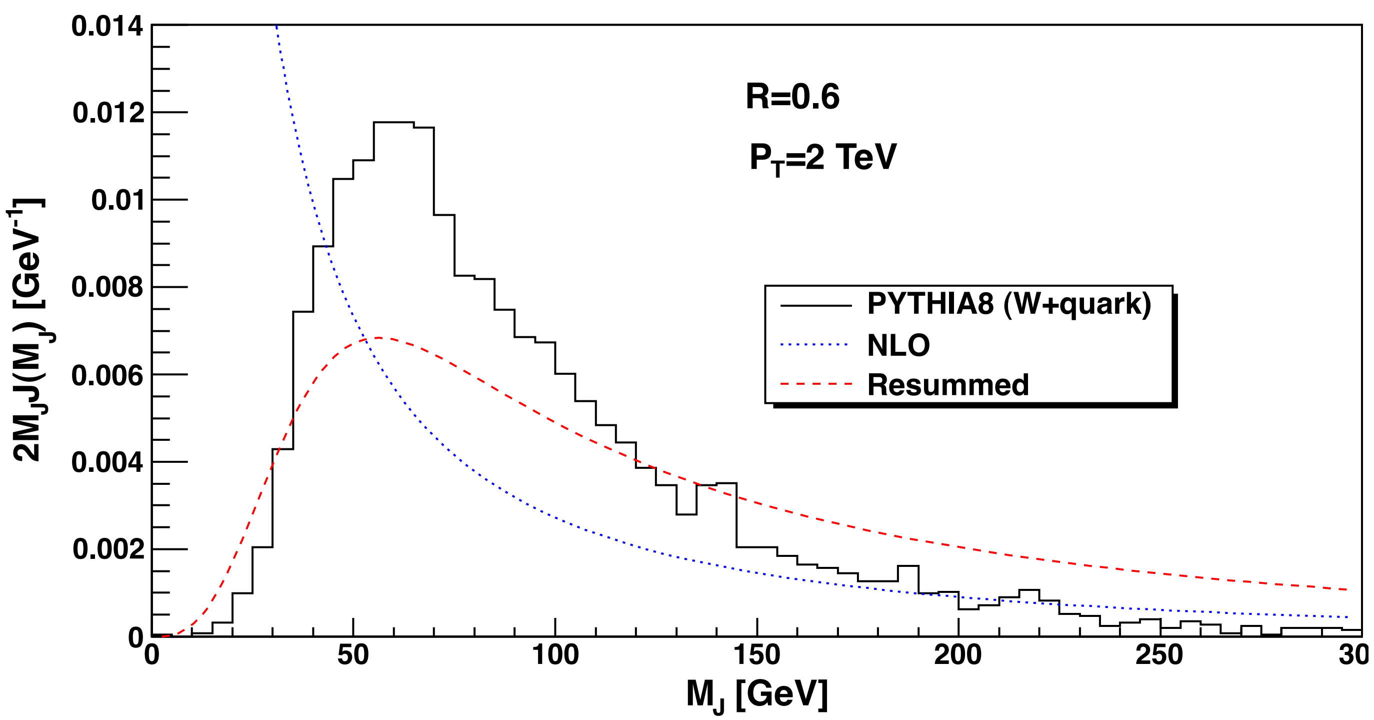
$$\bar{J}(N, P_J^0, \nu_{\rm fi}^2, R, \mu) = \bar{J}(N, P_J^0, \nu_{\rm in}^2, R, \mu) \times \exp\left\{ -\int_{1/\bar{N}}^{C} \frac{dy}{y} \left[\int_{1/\bar{N}}^{y} \frac{dz}{z} \lambda_K(\alpha_s(zP_J^0)) - \frac{\alpha_s\left(yP_J^0\right)}{2\pi} C_F \right] \right\},$$

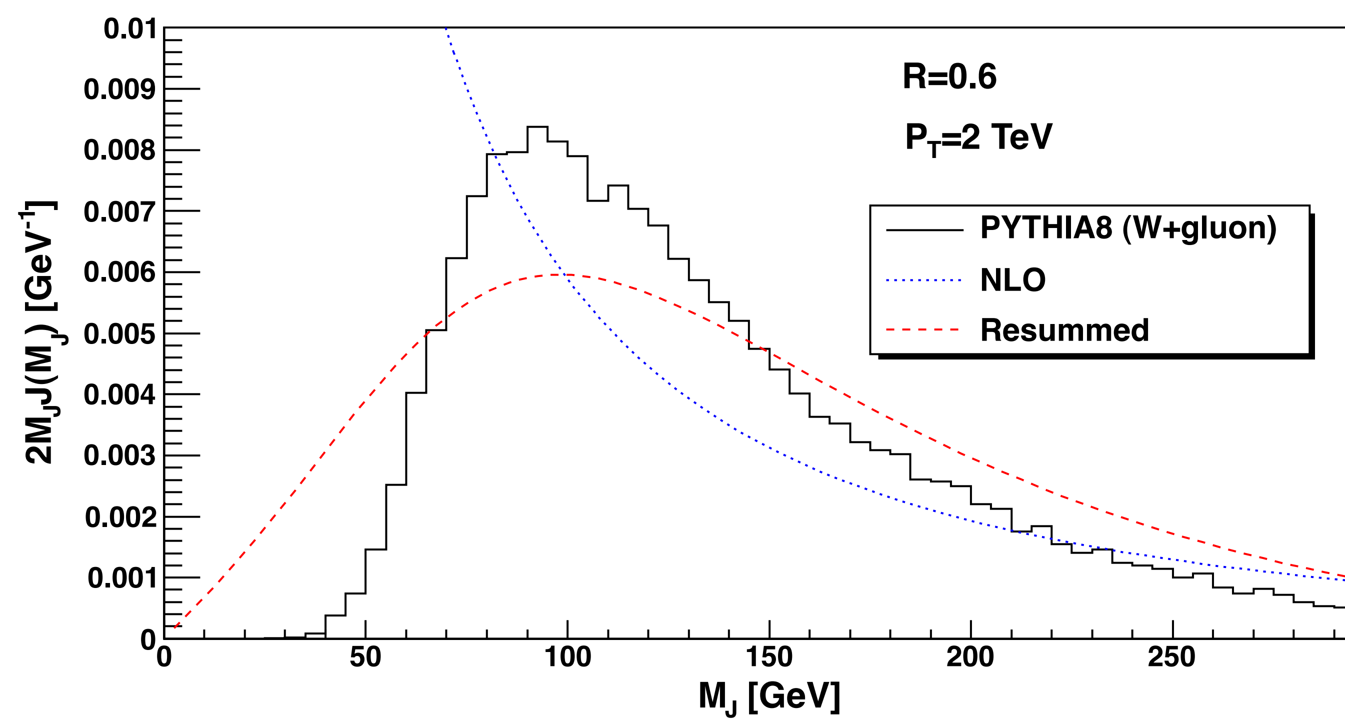
Initial condition, without large log, is evaluated up to NLO.

Jet mass distribution





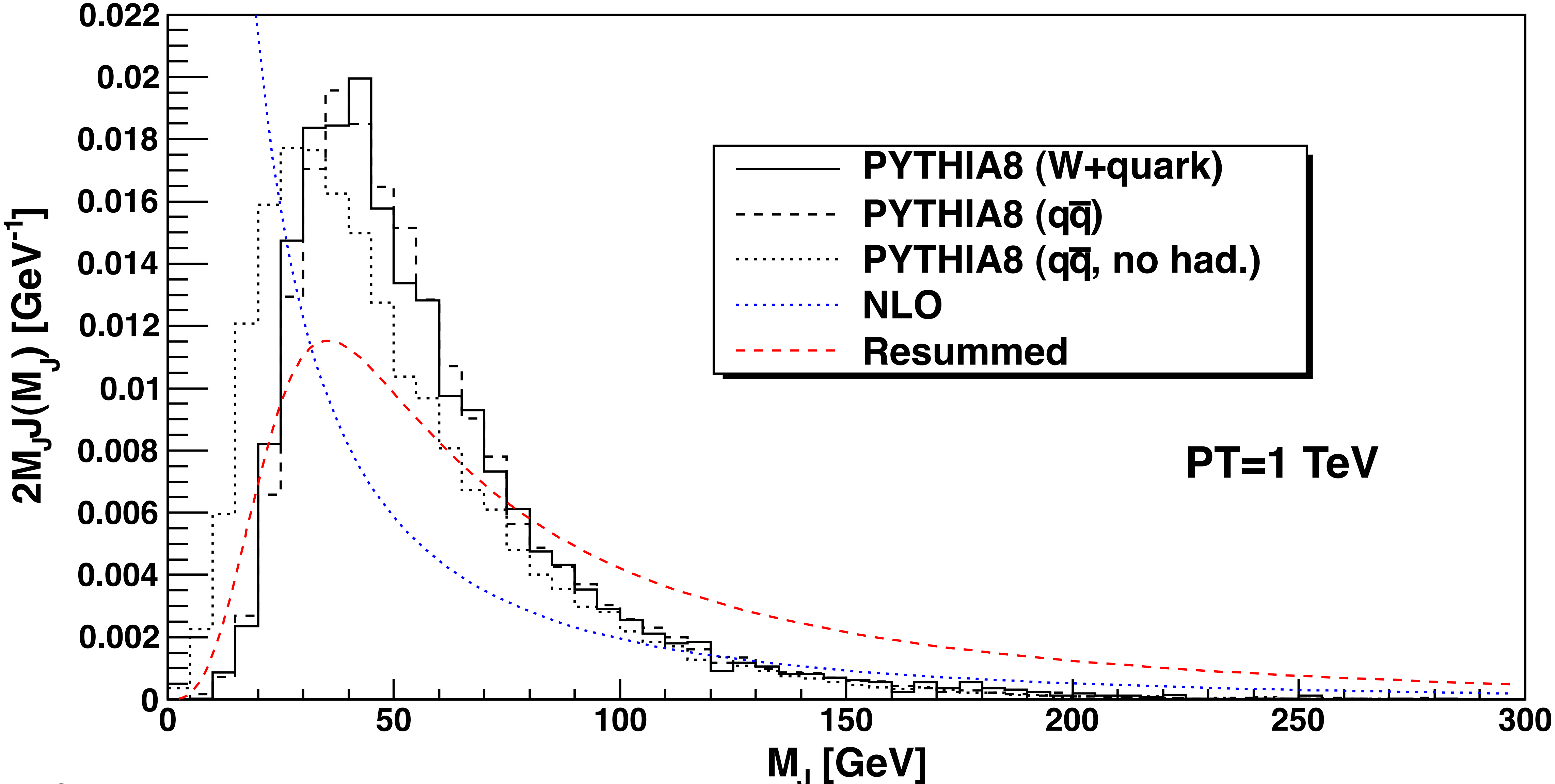




Comparisons in Jet Mass distributions

- Resummation has great improvement in small jet mass region, as compared to NLO prediction.
- Resummed jet function has similar peak position, but generally different shape, as compared to full event generator PYTHIA8.
- Gluon jet has broader jet mass distribution, as compared to quark jet.
- More radiation is needed in PYTHIA to agree with resummation prediction in jet mass distribution. PYTHIA undershoots resummation prediction around top quark mass region for a TeV jet.

More comparisons in jet mass distribution



- Jet function J(M) is process independent, similar in W+jet and di-jet events.
- Resummation calculation contains non-perturbative contribution to better describe the small jet mass region.

Jet energy profile

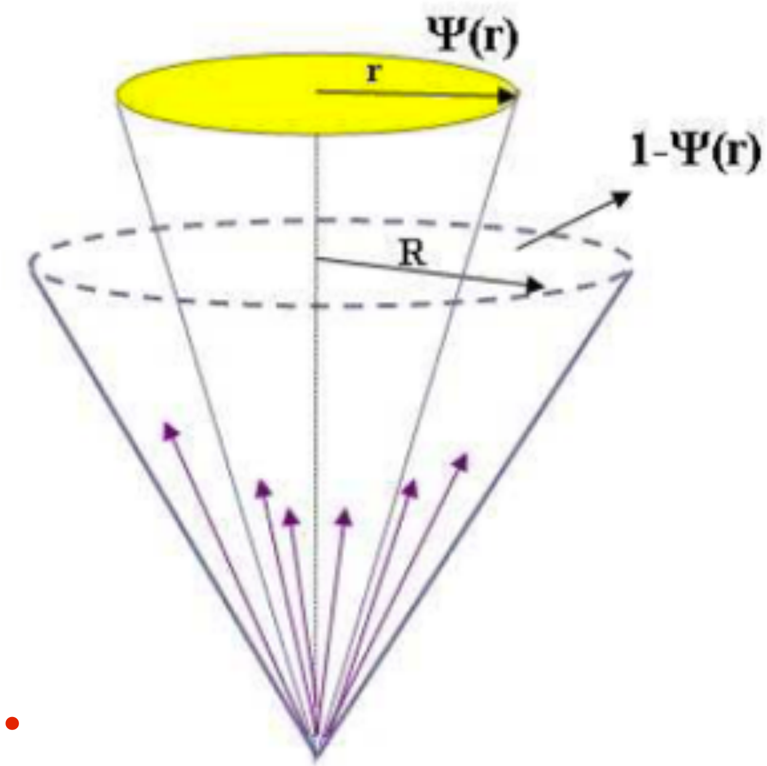
$$\Psi(r) = \frac{1}{\mathrm{N_{jet}}} \sum_{\mathrm{jets}} \frac{P_T(0,r)}{P_T(0,R)}, \qquad 0 \le r \le R$$

Jet energy profile J^E can be obtained by inserting the following step function in the jet function:

$$\sum_i k_i^0 \Theta(r-\theta_i) = \sum_i{}' k_i^0 \Theta(r-\theta_i) + l^0 \Theta(r-\theta).$$

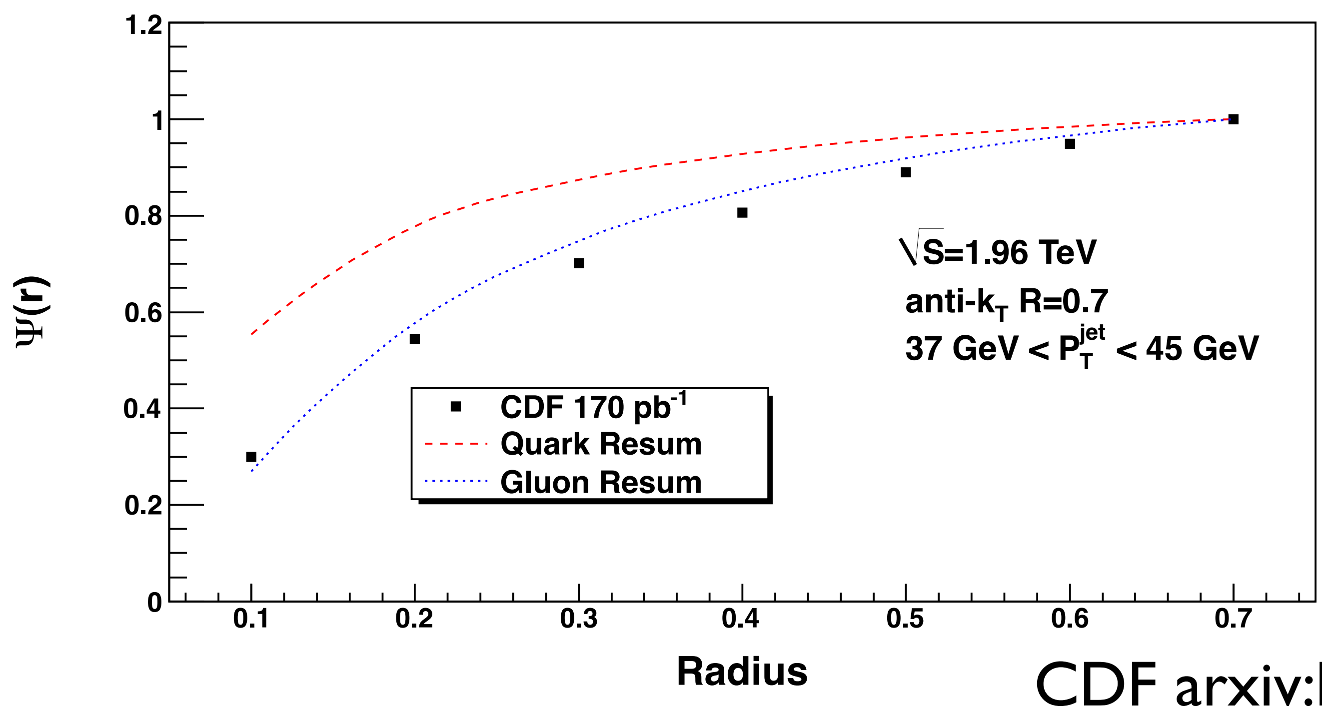
The first term modifies the R.H.S. of RG equation for jet energy distribution

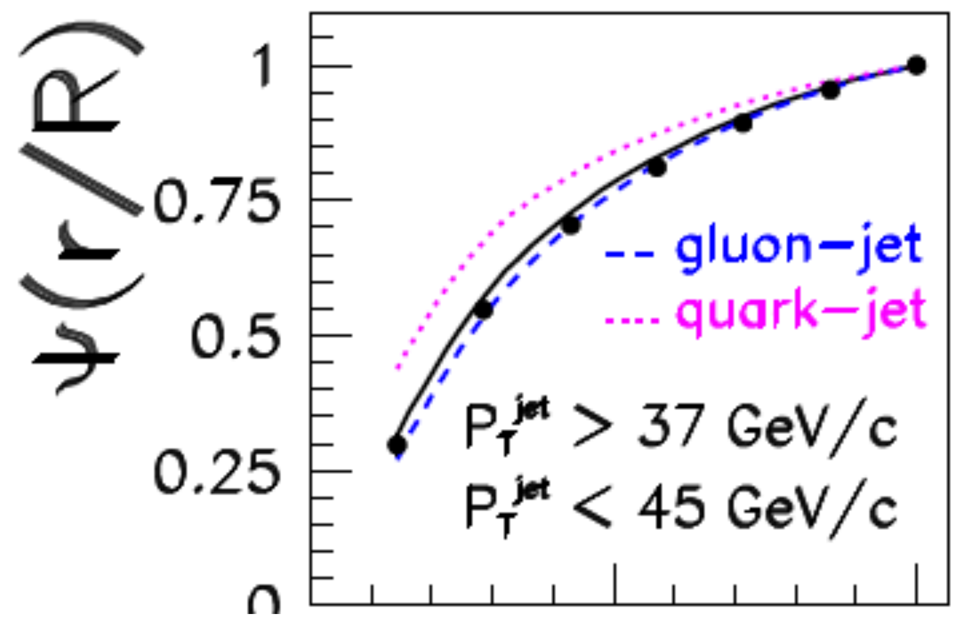
$$[G^{(1)} + K_v^{(1)} + K_r^{(1)}] \otimes J_E$$



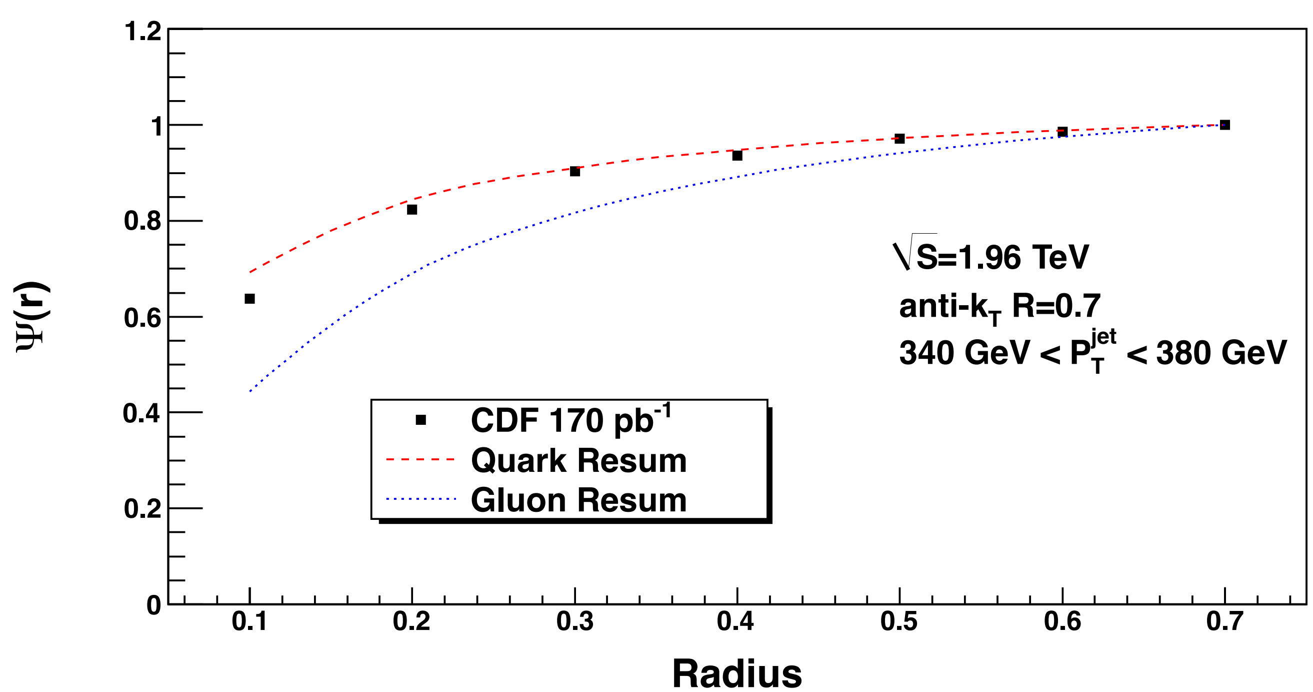
Large logs, ln(r), in J^E are resummed.

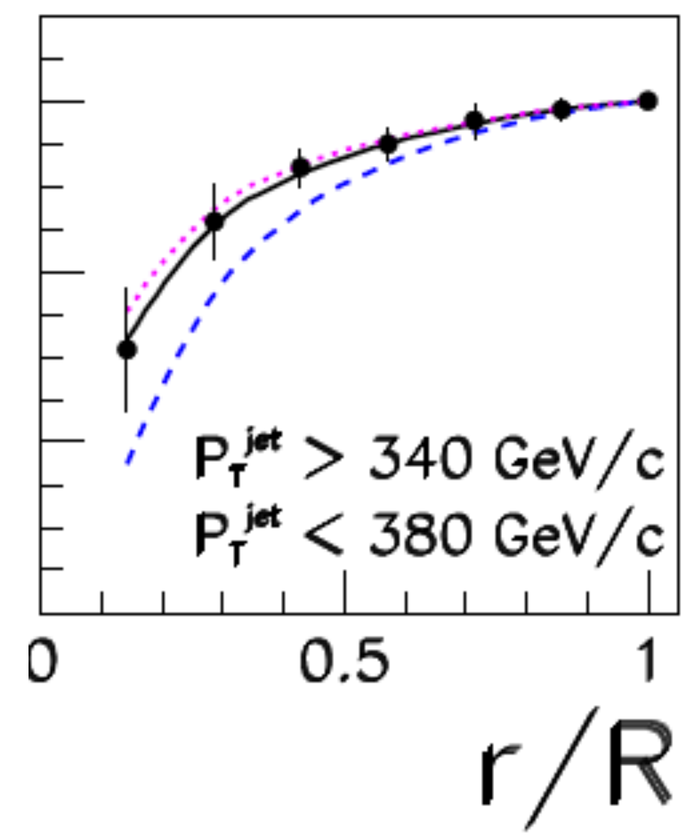
Jet energy profile @ CDF





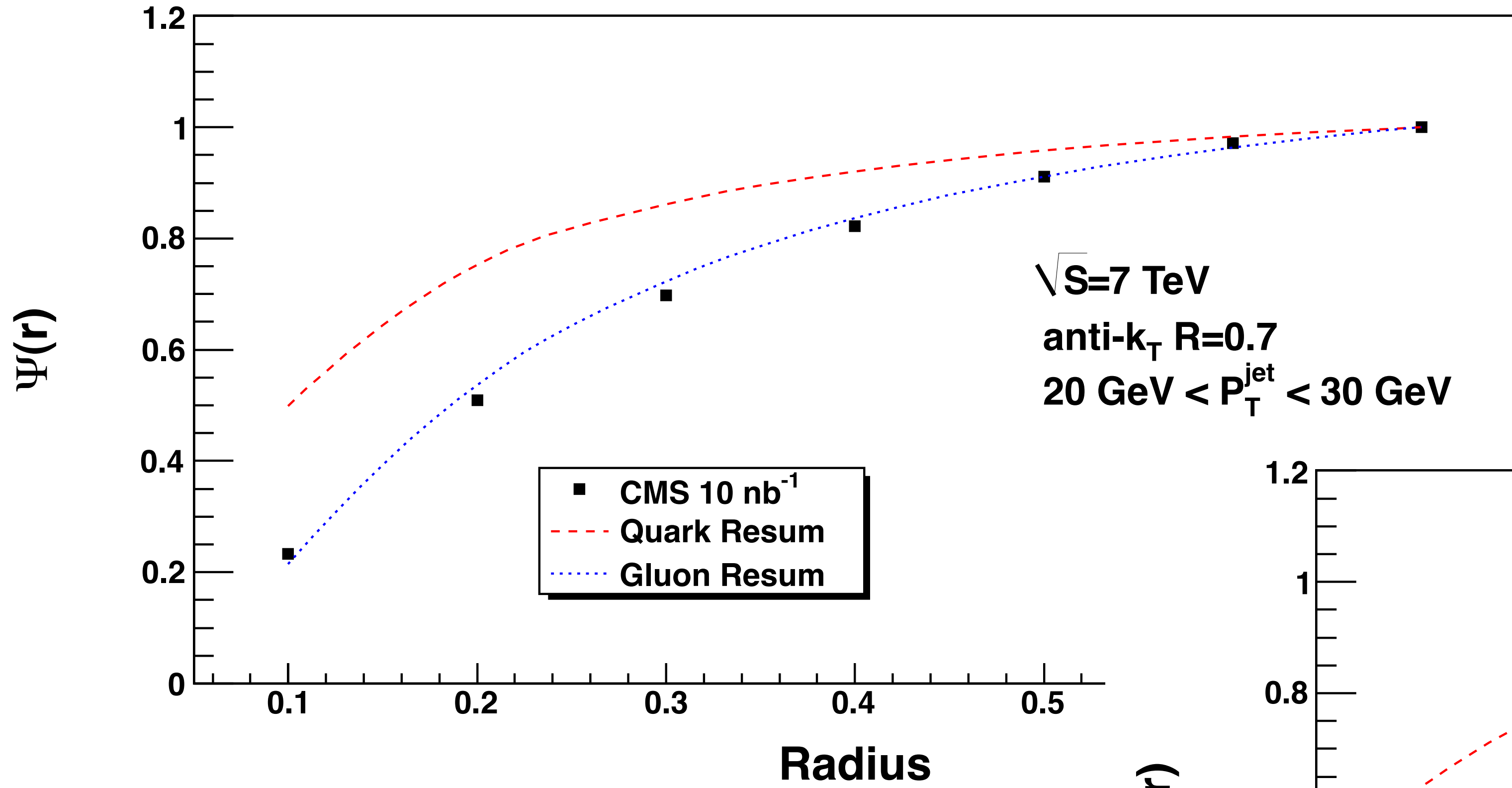
CDF arxiv:hep-ex/0505013



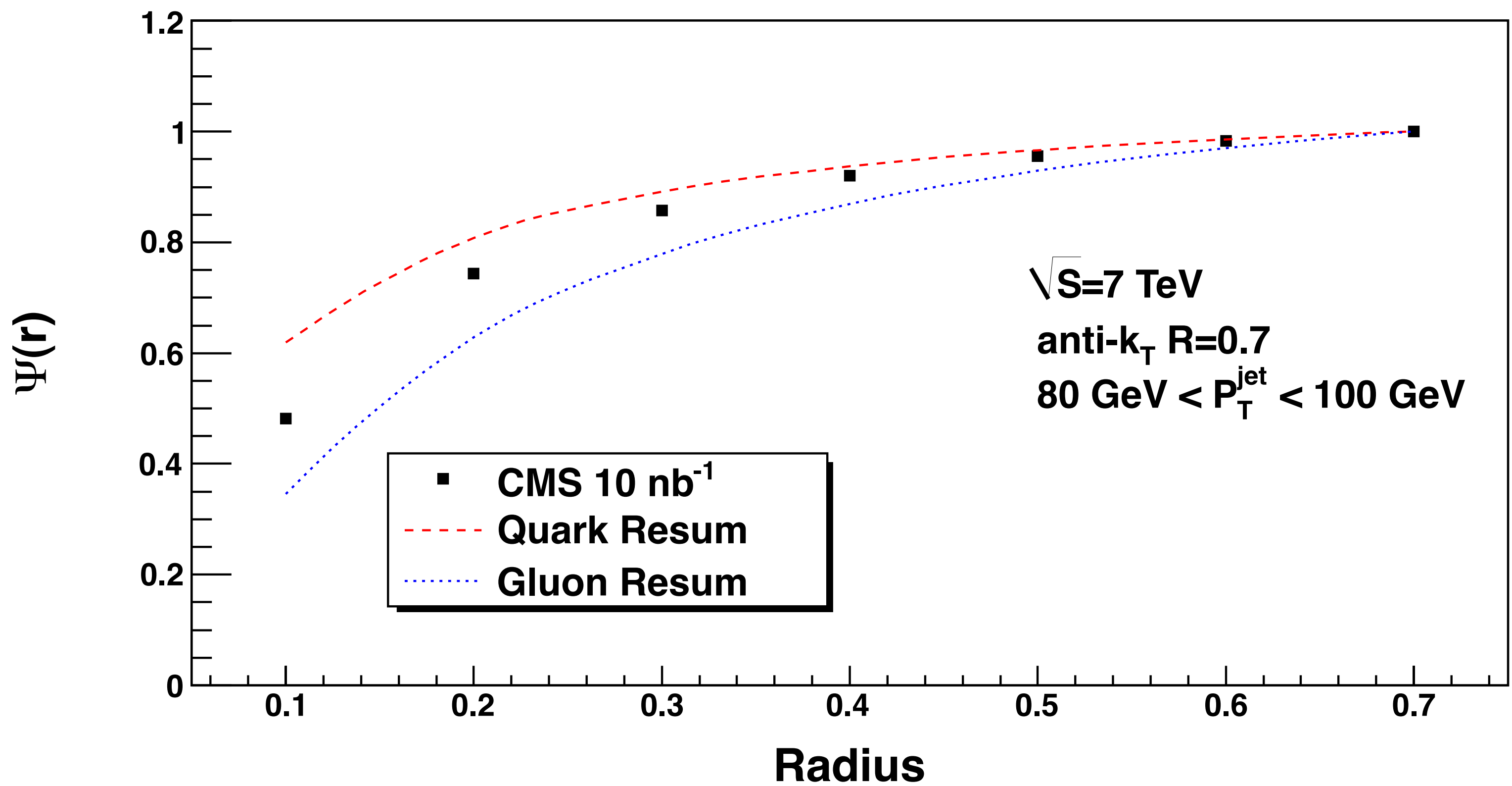


Gluon jet and quark jet dominates in low and high pT region, respectively.

Jet energy profile @ CMS



agree well with Resummation calculation



Need to convolute quark and gluon jet energy function with hard scattering amplitudes in order to compared to data directly. This calculation is in progress.

Summary

- Studying jet substructure is useful for testing Standard Model and identifying New Physics.
- Fixed-order calculations in jet function contain large logs, making predictions unreliable.
- QCD resummation provides reliable prediction and making independent check to full event generators.
- PYTHIA8 and resummation predictions do not agree on jet mass distribution. PYTHIA8 undershoots resummation prediction around the top quark mass region for a TeV jet.
- PYTHIA8 and resummation predictions agree on jet energy profile. The direct comparison to data is in progress.
- Our formalism can be extended for heavy quark jet, e.g., a boosted top quark jet. (in progress)

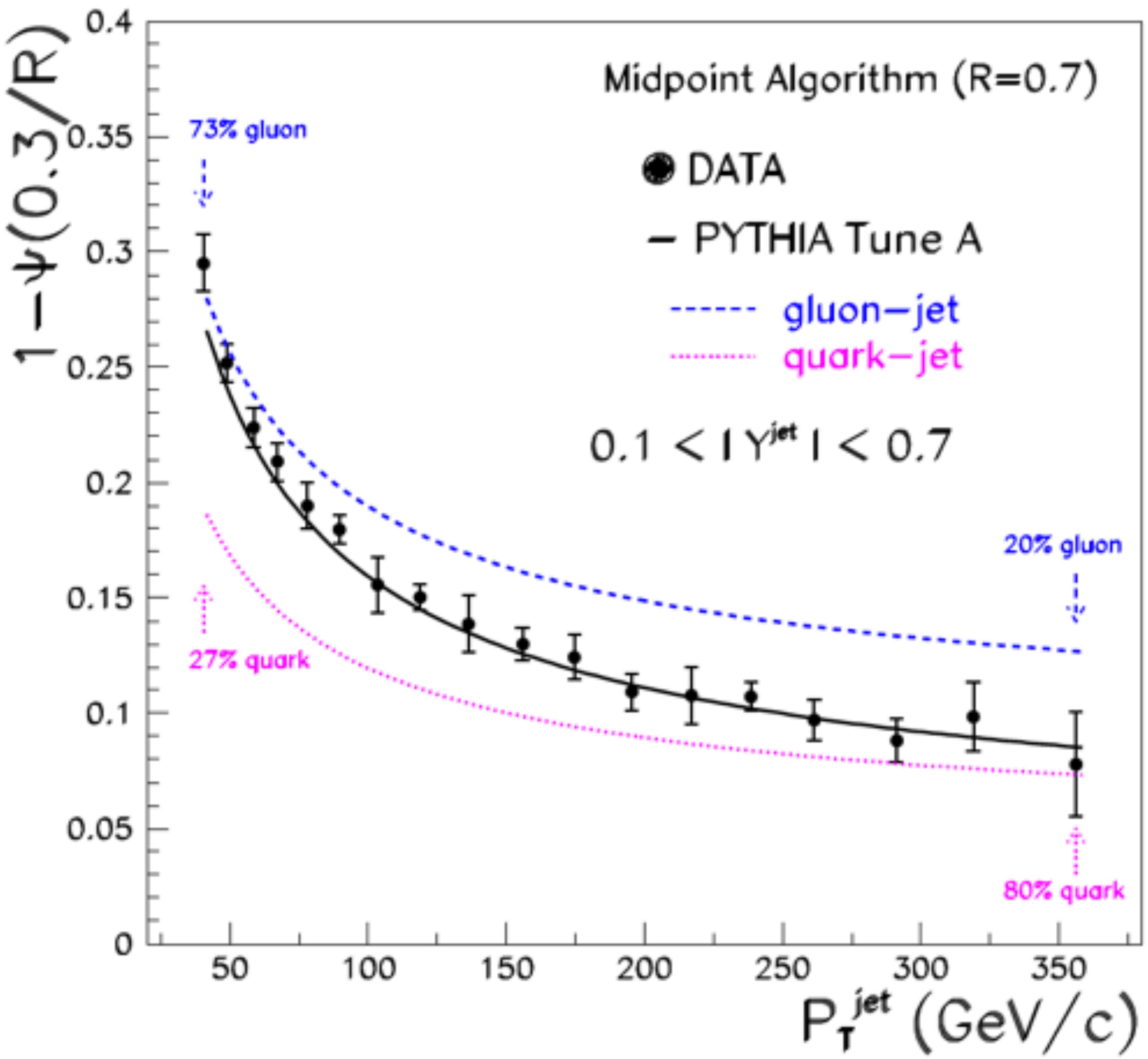
Backup slides

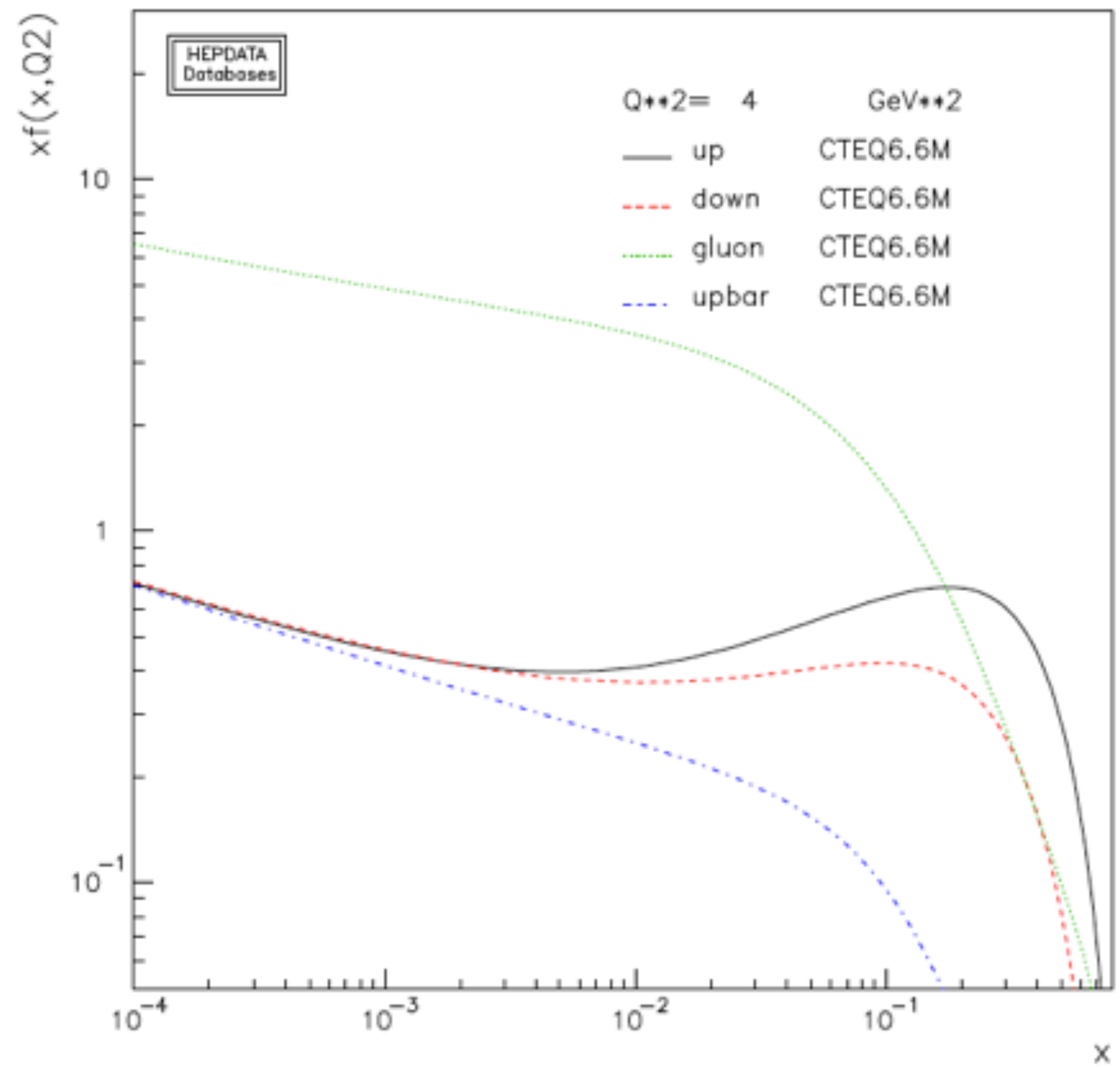
Non-perturbative term

$$S^{NP}(N) = \frac{N^2 Q_0^2}{(P_J^0)^2} \left(a_1 \ln(N) + a_2 \ln \frac{P_J^0}{Q_0} + a_3 \right),$$

Non-perturbative terms are included to improve the behavior in small jet mass region. By fitting three jet energies (200 GeV, 1 TeV and 2 TeV). The values of non-perturbative parameters can be obtained.

Dependence on pT@ CDF





Durham PDF plotter, http://durpdg.dur.ac.uk/hepdata/pdf3.html

Gluon jet and quark jet dominates in low and high pT region, respectively, mainly caused by parton density (PDFs).