QCD resummation for jet substructures

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Outlines

- Motivation
- Jet factorization
- Resummation
- Jet energy profiles
- Heavy-quark jet
- Summary

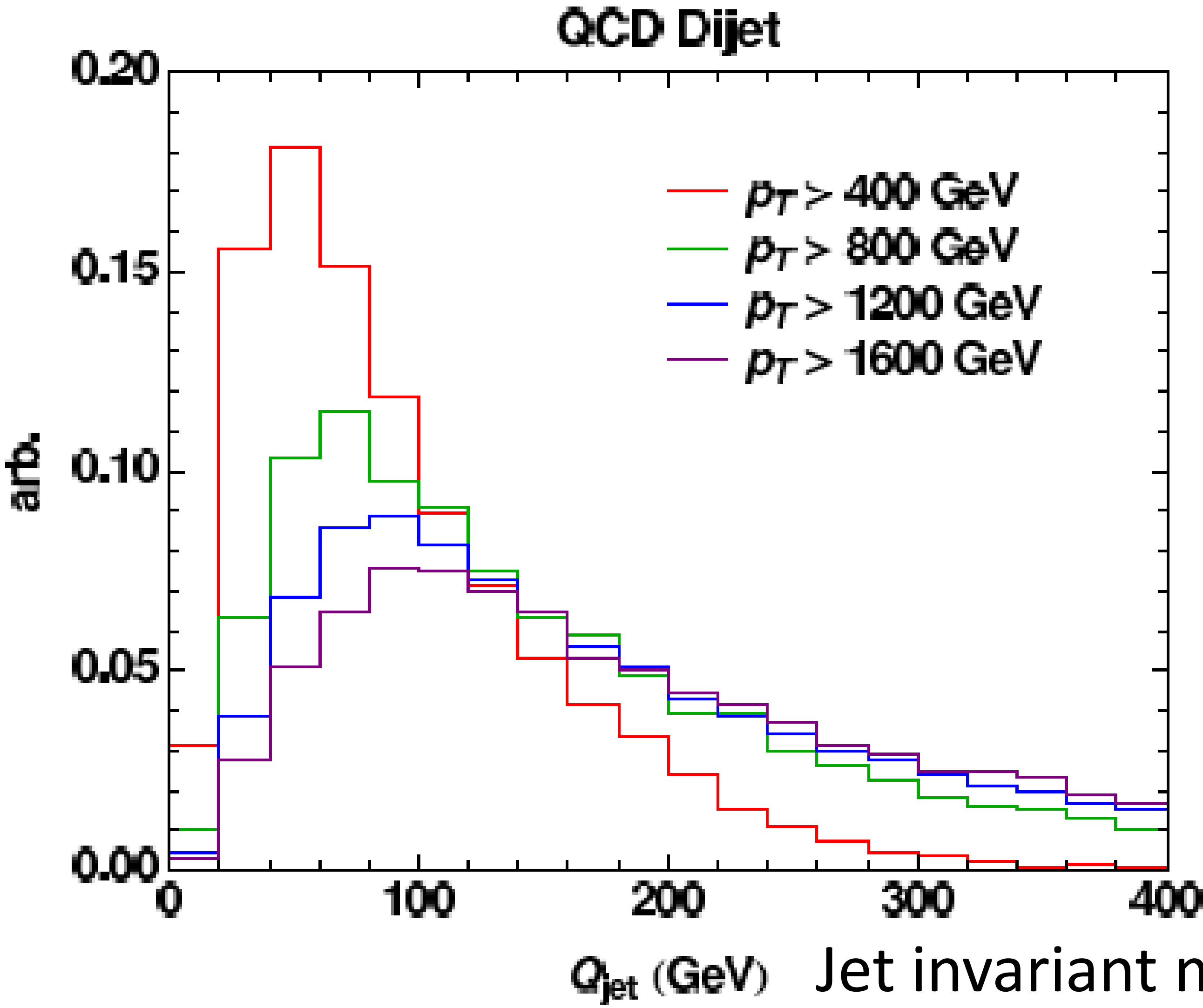
Motivation

To propose a theoretical framework for study of jet physics based on perturbative QCD

Boosted heavy particles

- Large Hadron Collider (LHC) provide a chance to search new physics
- New physics involve heavy particles decaying possibly through cascade to SM light particles
- New particles, if not too heavy, may be produced with sufficient boost -> a single jet
- How to differentiate heavy-particle jets from ordinary QCD jets?
- Similar challenge of identifying energetic top quark at LHC

Fat QCD jet fakes top jet at high pT

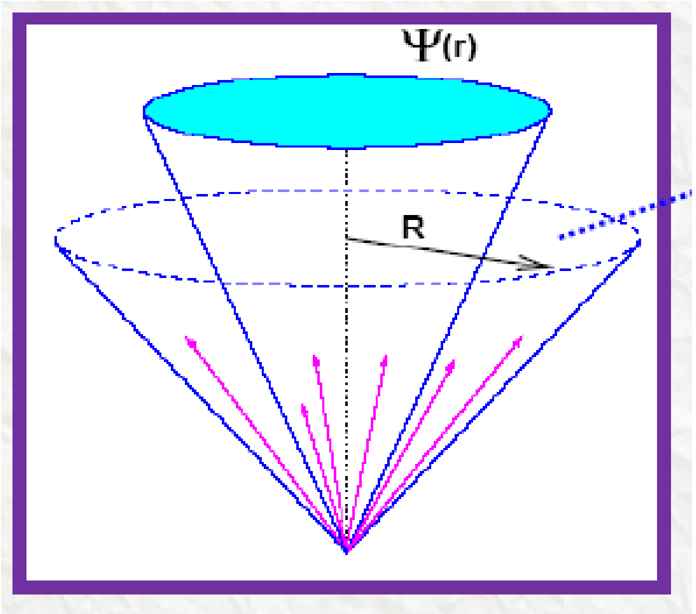


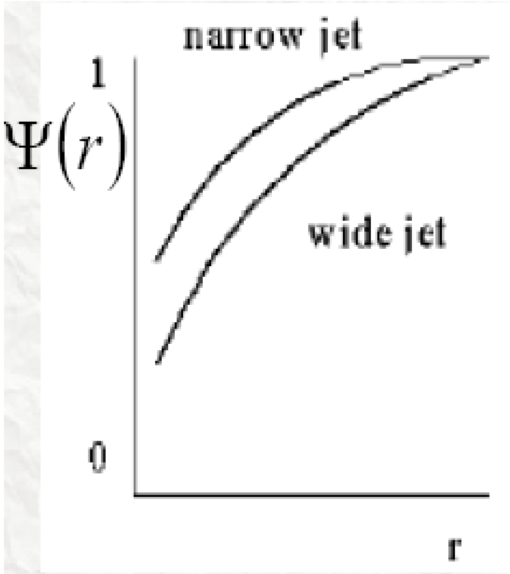
Jet invariant mass

Thaler & Wang 0806.0023 Pythia 8.108

Jet substructure

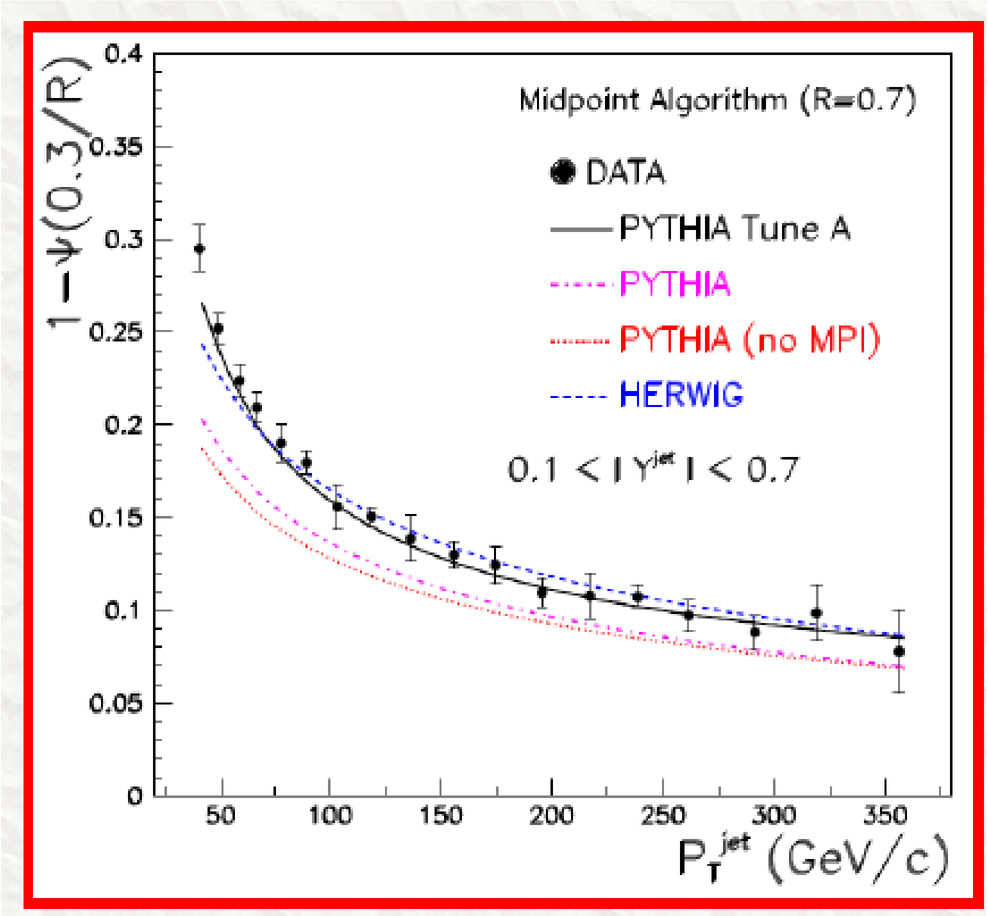
- Make use of jet internal structure in addition to standard event selection criteria
- Energy fraction in cone size of r, $\Psi(r), \Psi(R)=1$
- Quark jet is narrower than gluon jet
- Heavy quark jet energy profile should be different





Why resummation?

- Monte Carlo may have ambiguities from tuning scales for coupling constant
- NLO is not reliable at small jet mass
- Predictions from QCD resummation are necessary



Tevatron data vs MC predictions

N. Varelas 2009

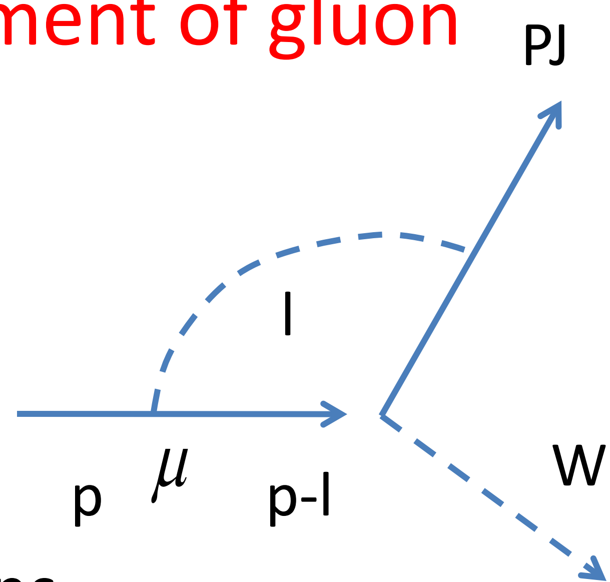
Jet factorization

Achieved by eikonalization and Ward identity

Eikonalization

- Jet is dominated by collinear dynamics from loop momentum l to parallel jet momentum P_J^+
- For attachment of collinear gluon, eikonalization holds -> detachment of gluon
- For $l^- << l^+$

$$\frac{(p-l)_\alpha \gamma^\alpha + m_t}{(p-l)^2 - m_t^2}\gamma^\mu \approx \frac{\xi^\mu}{-\xi\cdot l}$$



eikonal vertex, eikonal propagator

-> Wilson line, collect collinear gluons

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

Jet definitions

Almeida et al. 08

- Eikonalization leads to factorization
- Quark

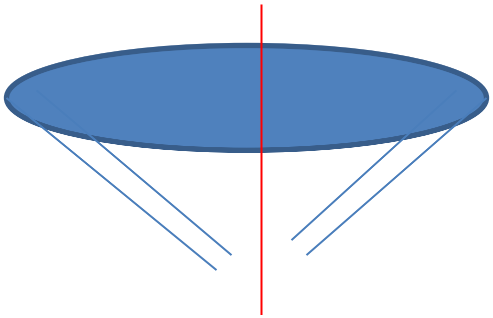
$$J_i^q(m_J^2, p_{0,J_i}, R) = \frac{(2\pi)^3}{2\sqrt{2}(p_{0,J_i})^2}\frac{\xi_\mu}{N_c}\sum_{N_{J_i}} Tr\left\{\gamma^\mu \langle 0|q(0)\Phi_\xi^{(\bar{q})\dagger}(\infty,0)|N_{J_i}\rangle\right.$$
$$\left.\times\langle N_{J_i}|\Phi_\xi^{(\bar{q})}(\infty,0)\bar{q}(0)|0\rangle\right\}\delta(m_J^2 -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

- Gluon

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

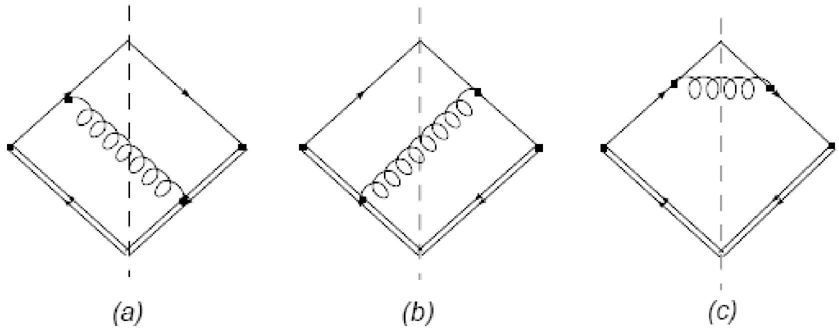
- LO jet

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

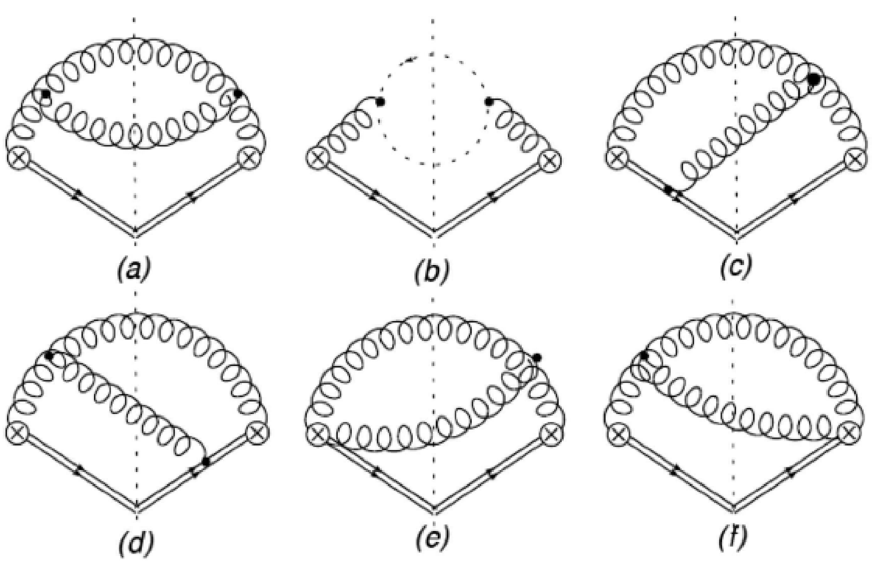


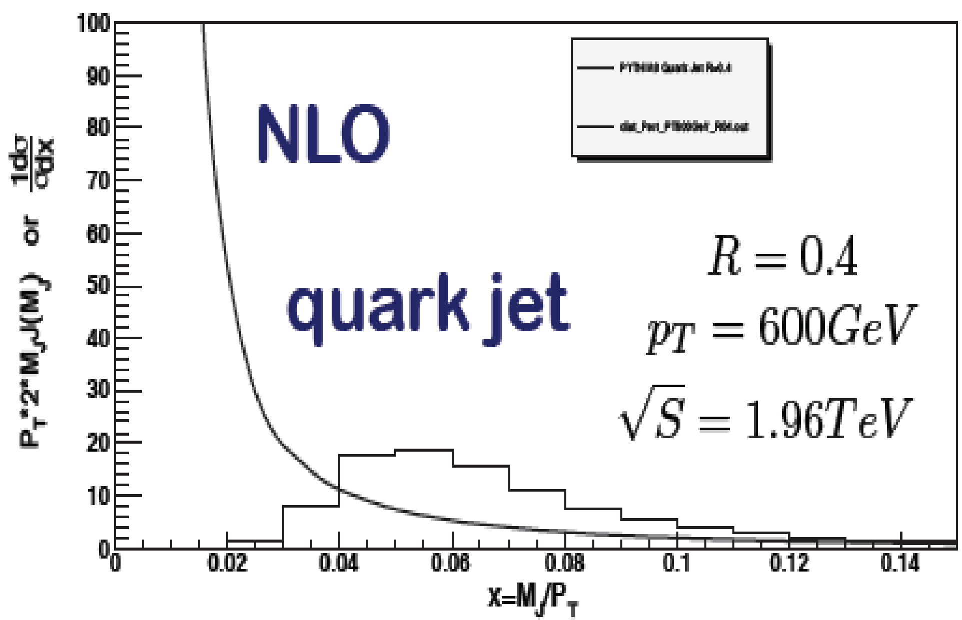
NLO diagrams

- quark jet



- gluon jet





Resummation

Technical part, ideas only

See alternative approach based on SCET, Ellis et al. 2010

Key idea

- Vary Wilson line to arbitrary vector n
- Collinear dynamics is independent of n
- Variation effect does not contain collinear dynamics, and can be factorized from jet
- Study derivative $-\frac{n^2}{P_J\cdot n}P_{J\alpha}\frac{d}{dn_\alpha}J$
- Differentiation applies only to Wilson line

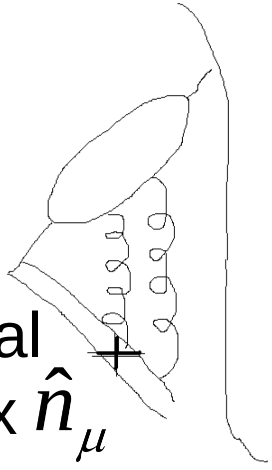
special vertex ↓

$$-\frac{n^2}{P_J\cdot n}P_{J\alpha}\frac{d}{dn_\alpha}\frac{n_\mu}{n\cdot l}=\frac{n^2}{P_J\cdot n}\left(\frac{P_J\cdot l}{n\cdot l}n_\mu-P_{J\mu}\right)\frac{1}{n\cdot l}=\frac{\hat{n}_\mu}{n\cdot l}$$

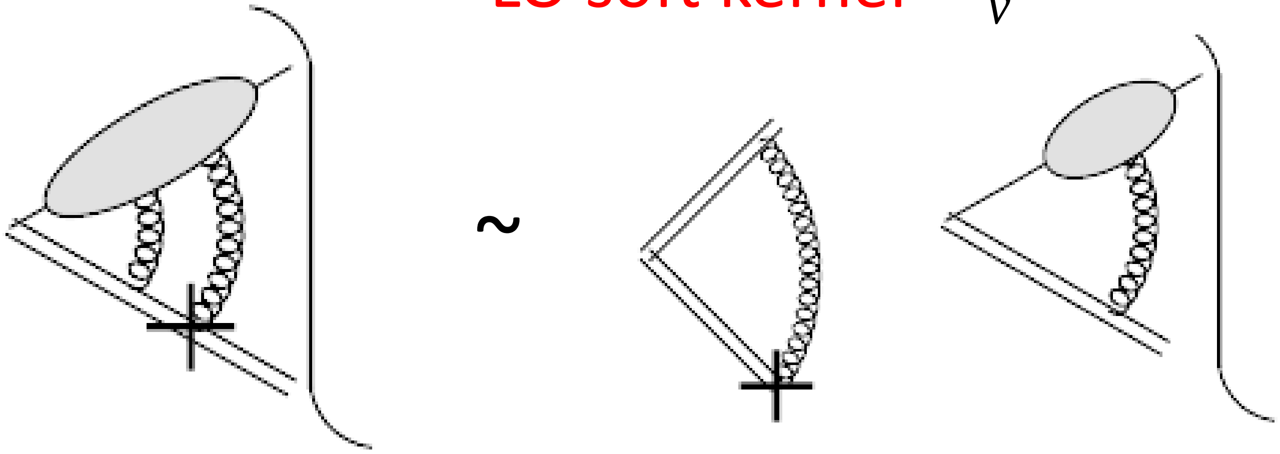
- Differentiated gluon gives hard or soft contribution

Soft factorization (virtual)

- If differentiated gluon is soft, special vertex locates at outer end of Wilson line
- If it locates inside (see figure), both gluons are soft
  -> NLO soft kernel



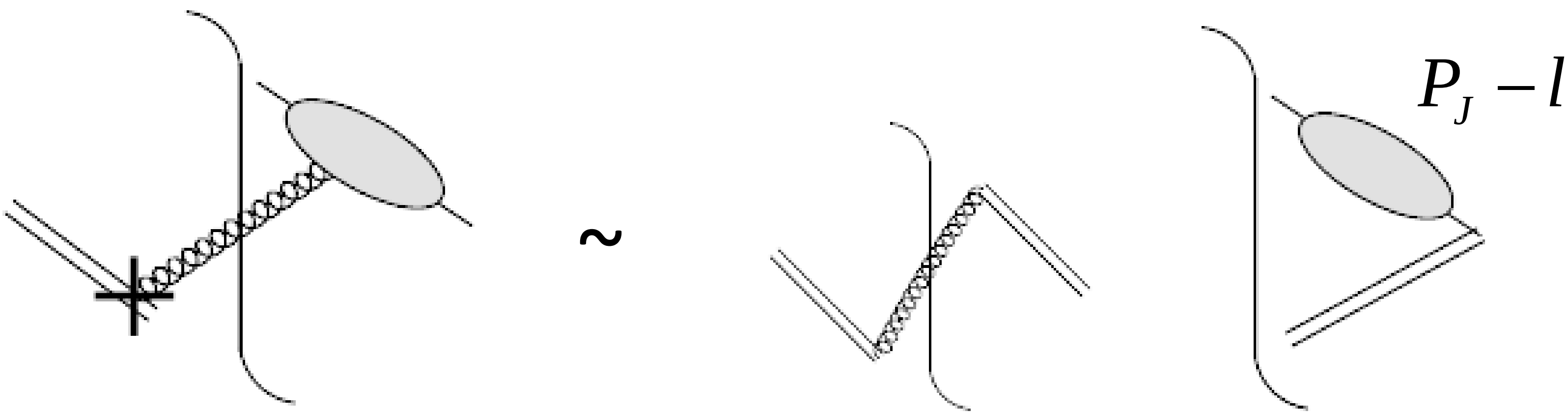
LO soft kernel $K_v^{(1)}$



Soft factorization (real)

- Similar argument applies to factorization of differentiated soft real gluon

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

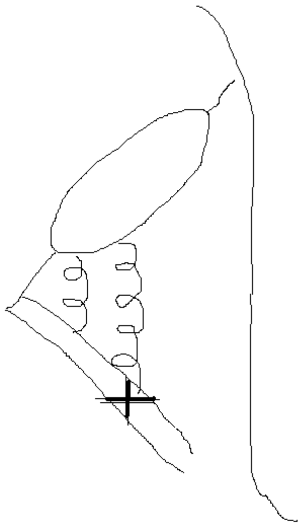


$$g^2 C_F \int \frac{d^4 l}{(2\pi)^4} \frac{\hat{n}\cdot P_J}{(n\cdot l + i\epsilon)(P_J\cdot l - i\epsilon)} 2\pi\delta(l^2 - a^2) J(m_J^2 - 2P_J\cdot l, P_J\cdot n, n^2, R)$$

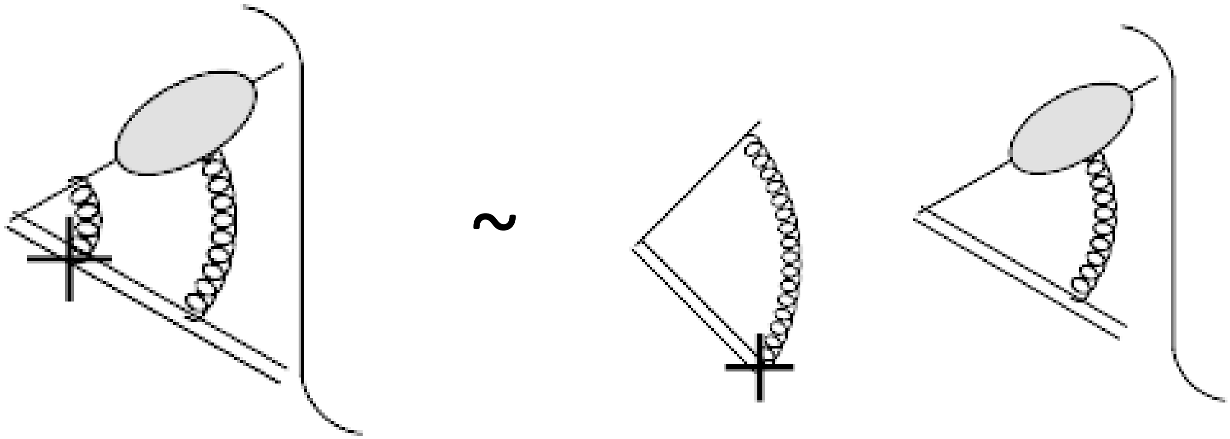
Jet invariant mass excluding soft momentum l, $(P_J - l)^2$

Hard factorization

- If differentiated gluon is hard, special vertex locates at inner end of Wilson line
- If it locates at outside, both gluons are hard -> NLO hard kerr



LO hard kernel $G^{(1)}$



Resummation equation

- Up to leading logs, resummation equation

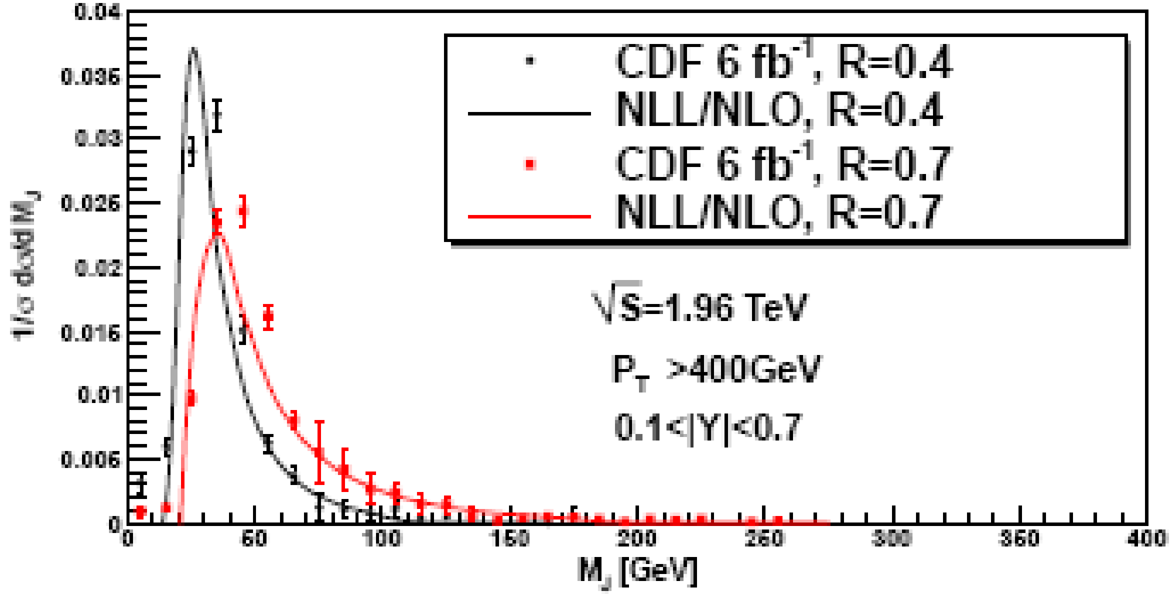
$$-\frac{n^2}{P_J \cdot n} P_J^\alpha \frac{d}{dn^\alpha} J = [G^{(1)} + K_v^{(1)} + K_r^{(1)}] \otimes J$$

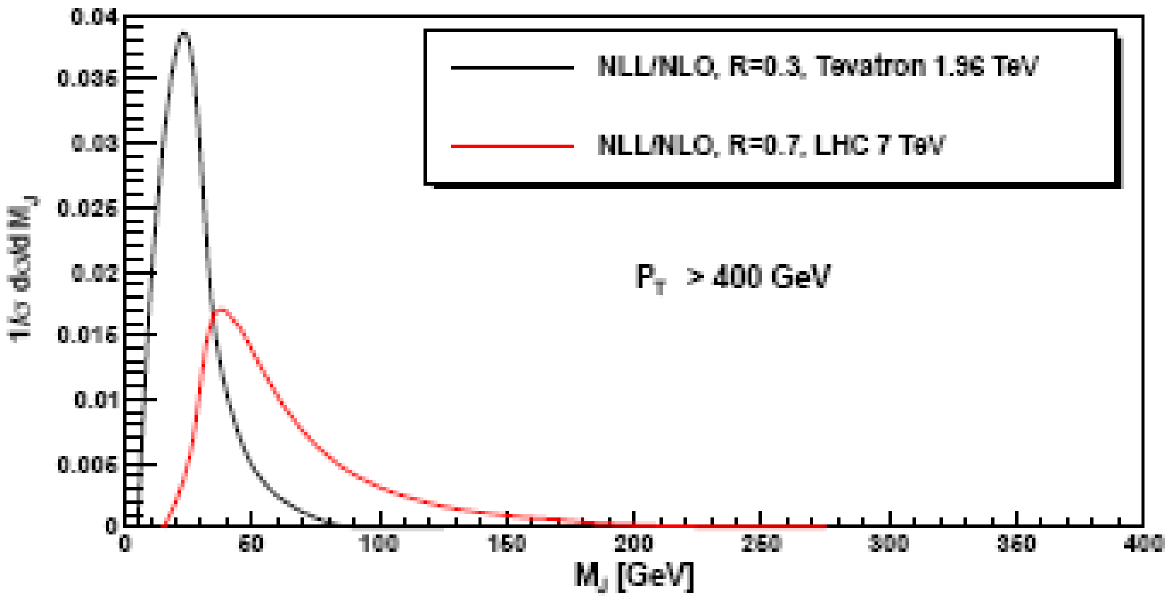
- For next-to-leading-logarithm accuracy, G and K are evaluated to two loops
- Solve the equation in Mellin N space

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

$$x \equiv m_J^2/(RP_T)^2 \quad \nu^2 \equiv 4(v \cdot n)^2/|n^2| \quad v = \bar{P_J}/P_J^0$$

Predictions for jet mass distribution





NLL in resummation

NLO in initial condition

CTEQ6L PDFs

Jet energy profiles

Jet energy function

- Define jet energy function $J^E(r)$ by associating $k_i^0\Theta(r-\theta_i)$ with each final-state particle i within jet cone r, r<R
- Still vary Wilson direction n.
- Separation $\sum_i k_i^0\Theta(r-\theta_i) = \sum_i' k_i^0\Theta(r-\theta_i) + l^0\Theta(r-\theta)$

differentiated soft real gluon

negligible in soft region

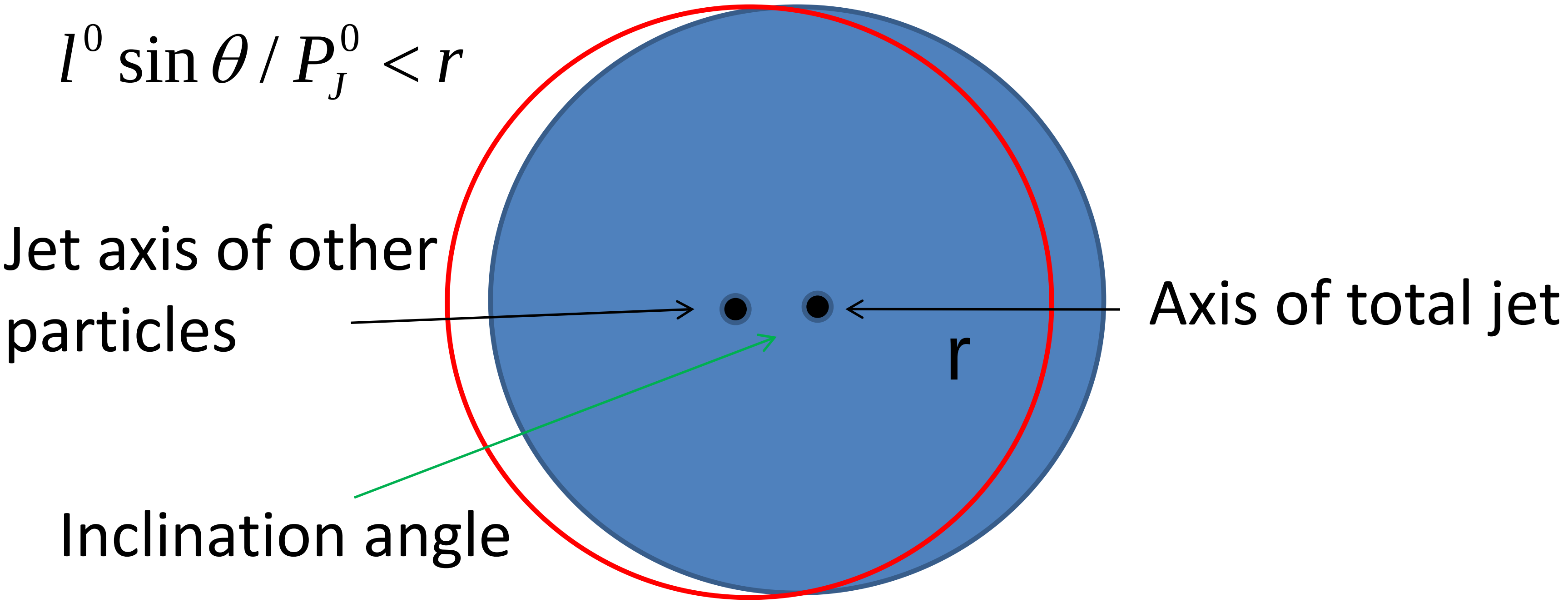
- First term gives

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

Soft gluon effect

- Differentiated soft real gluon renders jet axis of other particles inclined by small ar $l^0 \sin\theta / P_J^0$
- This jet axis can not go outside of the subcone

$$l^0 \sin\theta / P_J^0 < r$$



Resummation equation

- Resummation equation for jet profile

$$\bar{K}_r^{(1)}(1) = g^2 C_F \int \frac{d^4 l}{(2\pi)^3} \frac{n^2}{(n \cdot l + i\epsilon)^2} \delta(l^2 - a^2) \Theta\left(r - \frac{|\mathbf{l}| \sin\theta}{P_J^0}\right)$$

$$- \frac{n^2}{v \cdot n} v_\alpha \frac{d}{dn_\alpha} \bar{J}_q^E(1, P_T, \nu^2, R, r)$$

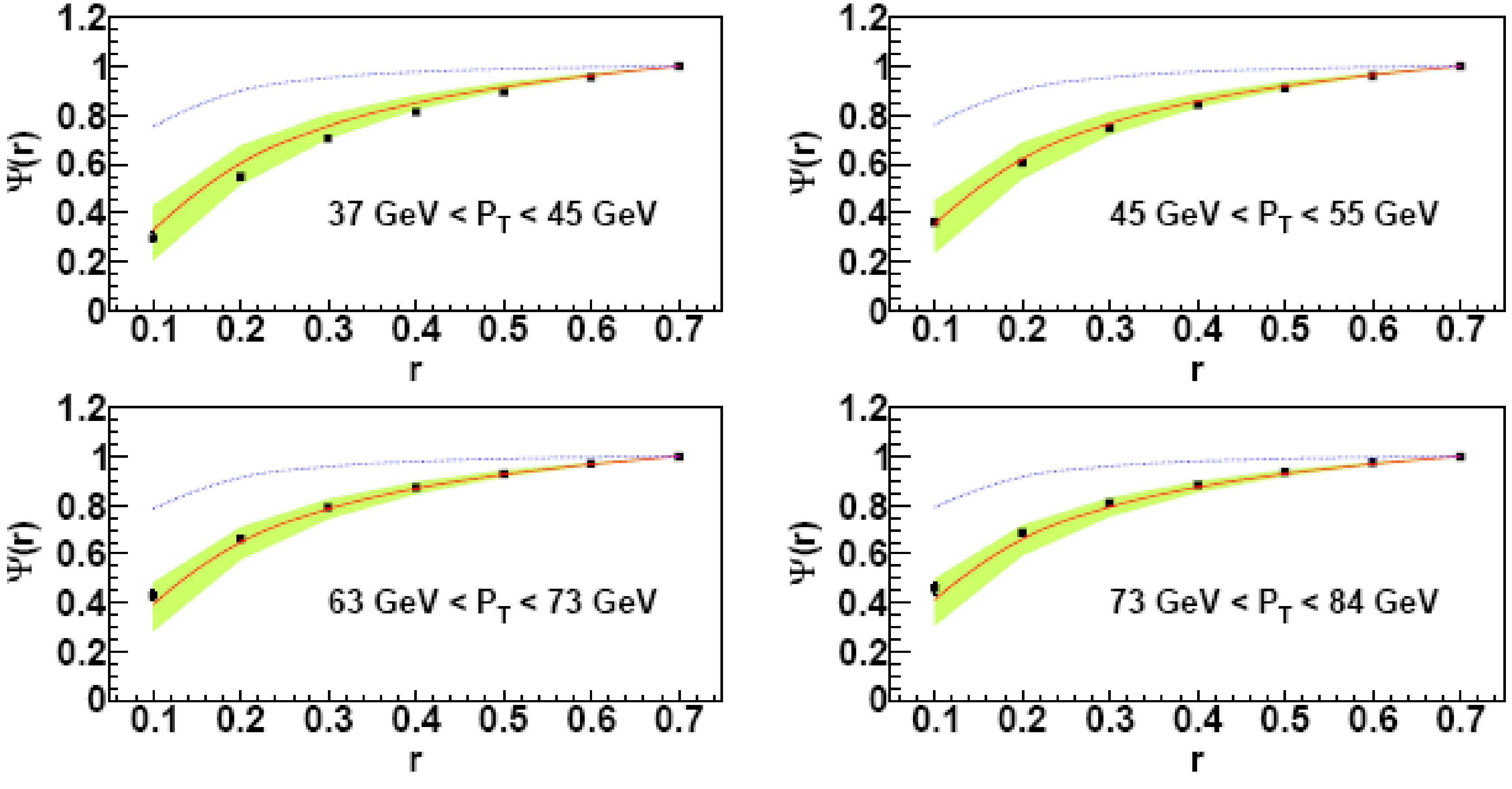
$$= 2[G^{(1)} + K^{(1)}(1)] \bar{J}_q^E(1, P_T, \nu^2, R, r)$$

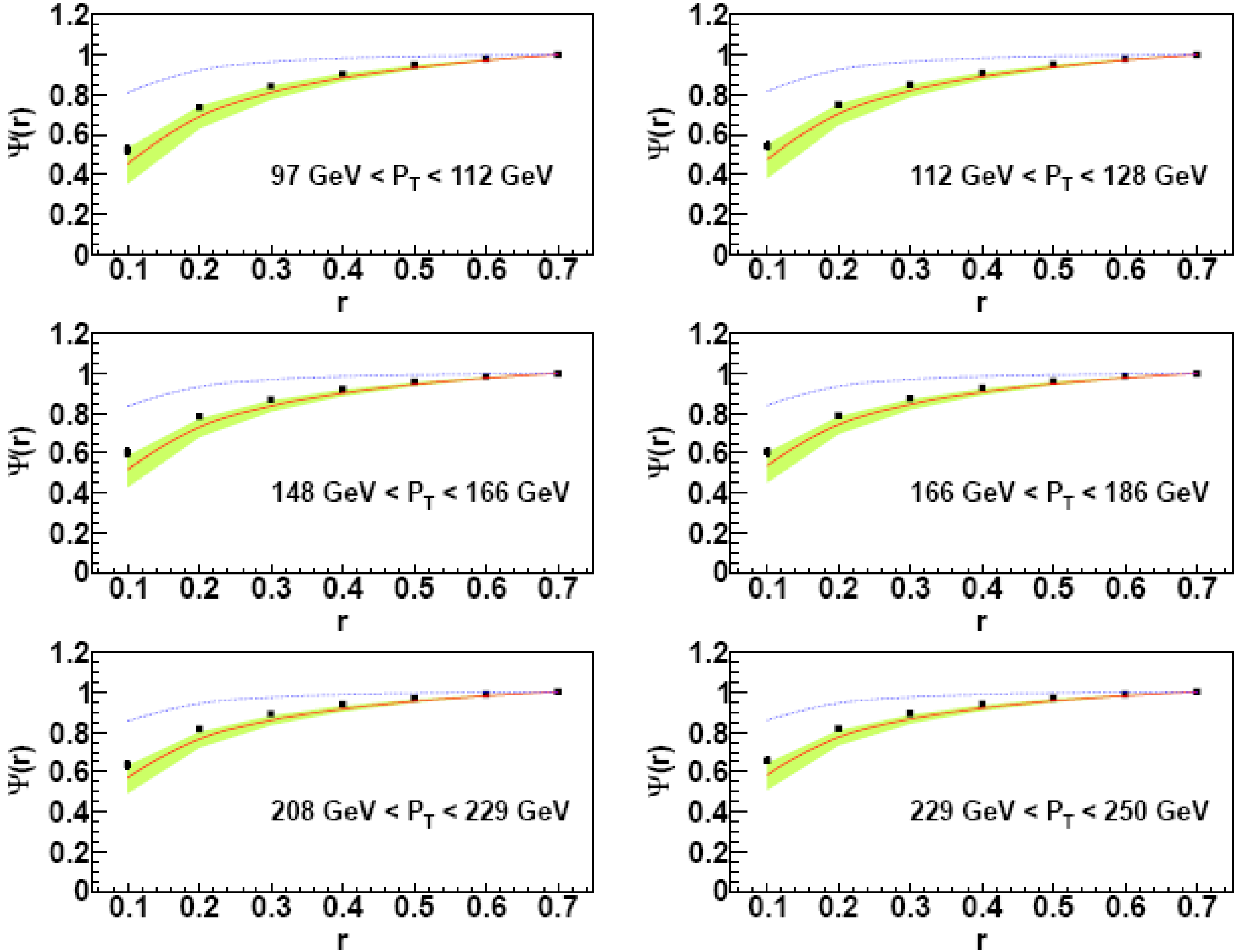
- Have considered N=1 here, corresponding to integration over jet mass (insensitive to nonperturbative physics)
- Resum $\alpha_s \ln^2 r, \alpha_s \ln r$ from phase space constraint for real gluons

Comparison with CDF data

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

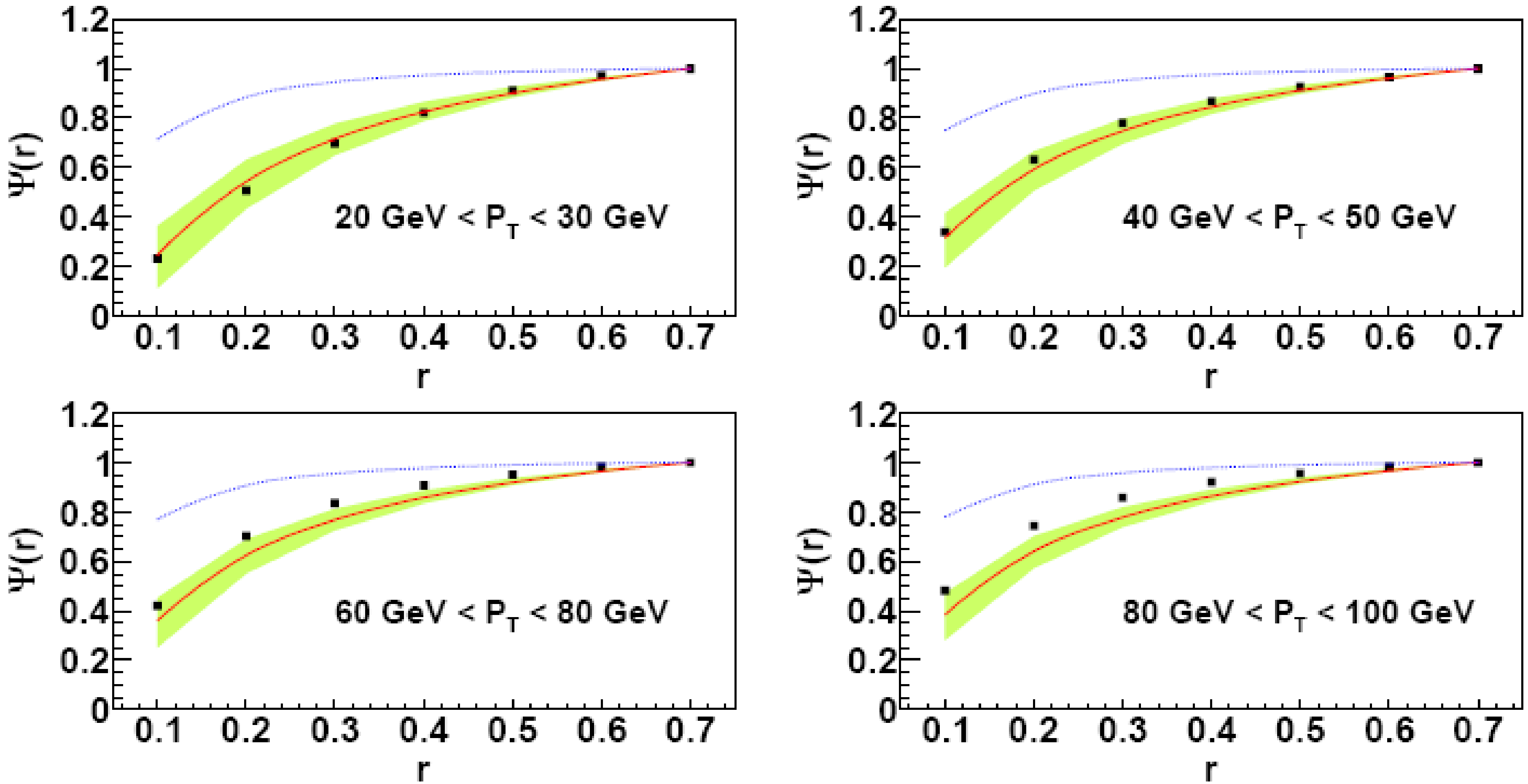
quark, gluon jets, convoluted with LO hard scattering, PDFs





97 GeV < P_T < 112 GeV
112 GeV < P_T < 128 GeV
148 GeV < P_T < 166 GeV
166 GeV < P_T < 186 GeV
208 GeV < P_T < 229 GeV
229 GeV < P_T < 250 GeV
Ψ(r)
r

Compasion with CMS data

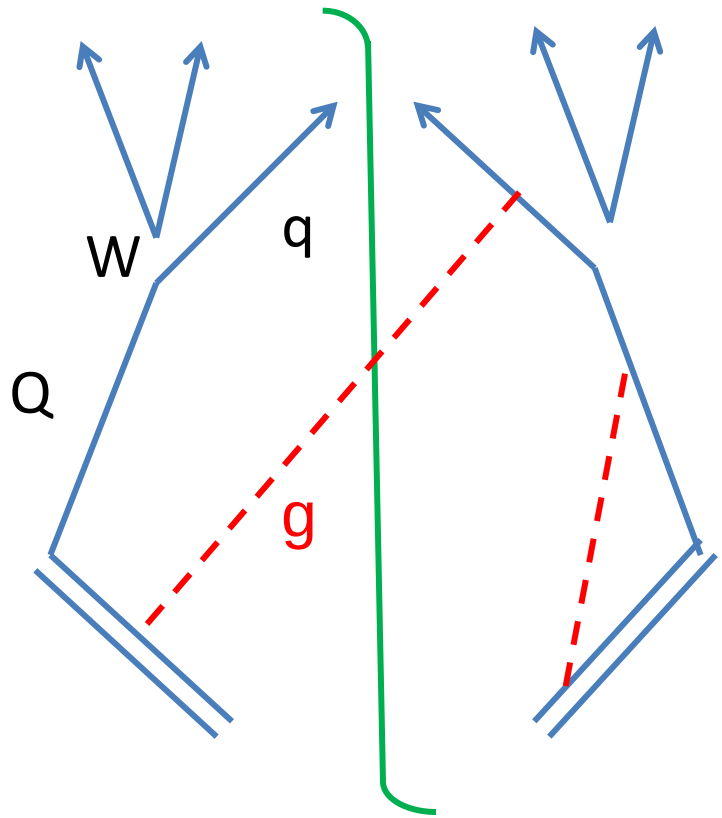


Heavy-quark jet

Work in progress

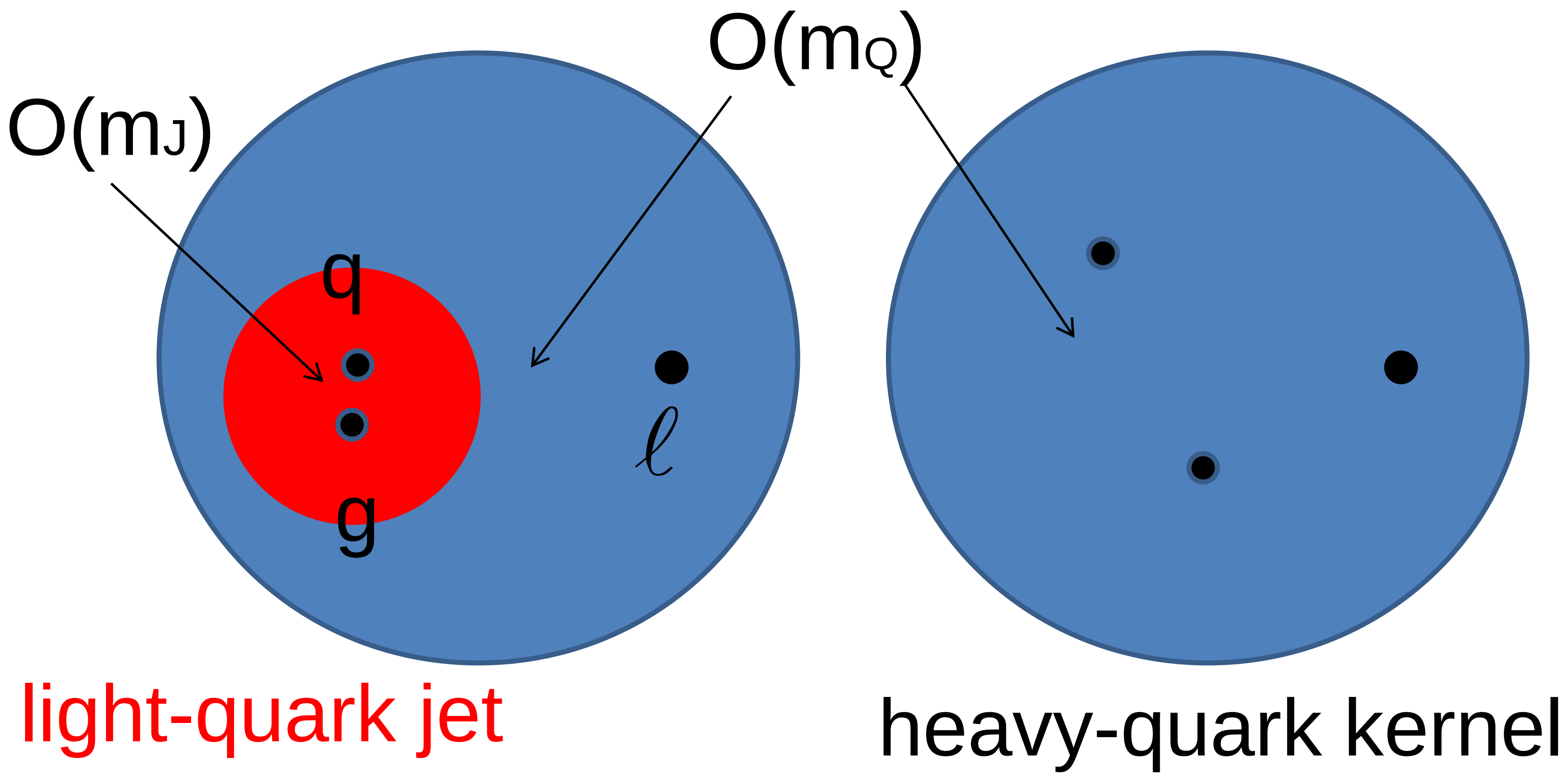
Factorization (semileptonic)

- Factorize heavy quark-quark jet first at jet energy scale E_Q, which contains weak decay



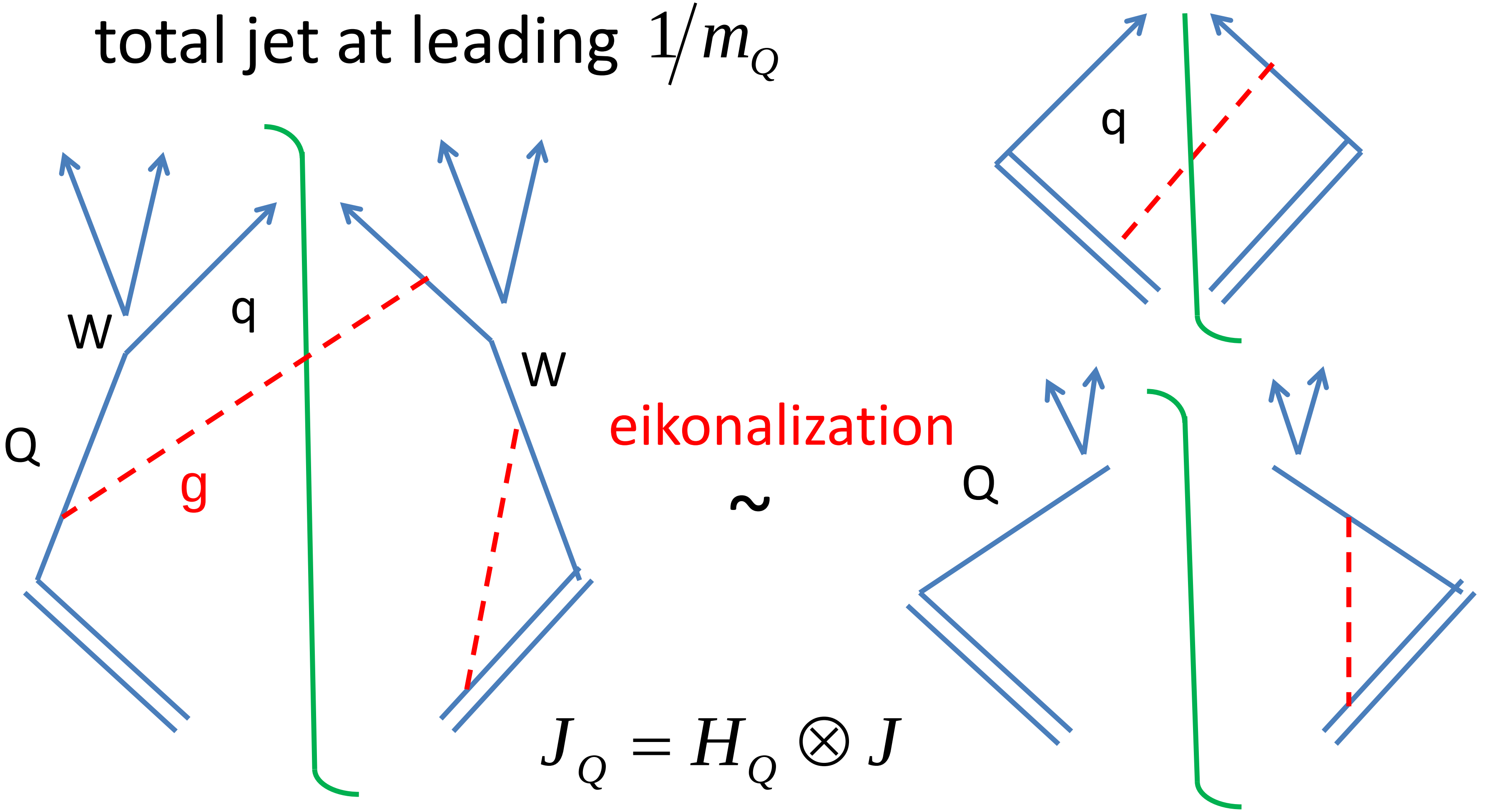
Scale hierarchy $E_Q >> m_Q >> m_J$

- The two lower scales m_Q and m_J characterize different dynamics, which can be factorized



Further factorization (HQET)

- Then factorize the light-quark jet from the total jet at leading $1/m_Q$



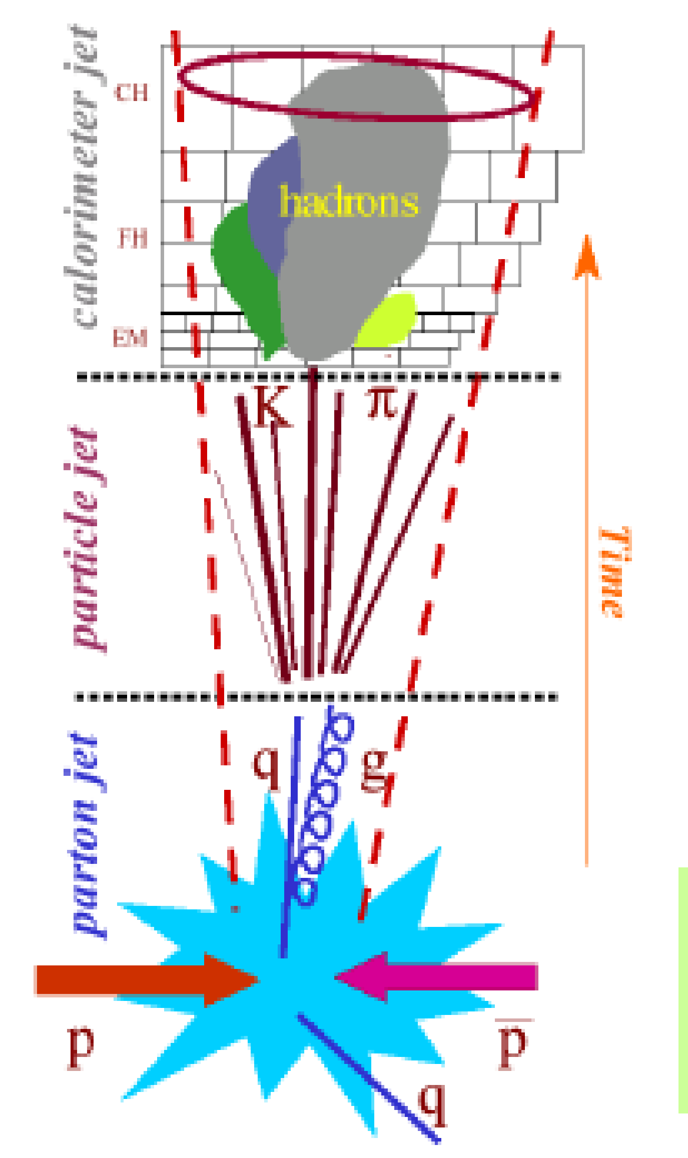
$$J_Q = H_Q \otimes J$$

Summary

- Jet substructure improves jet identification
- Perturbative calculation is not reliable in extreme kinematic region (e.g. small mJ)
- Event generators may have ambiguities (from tuning scales for coupling constant)
- QCD resummation provides reliable prediction, independent check, and alternative approach
- Analyzed jet function and profile for light particles. Results consistent with current data
- Numerical work on heavy-quark jet in progress

Back-up slides

Jet Finding



- **Calorimeter jet (cone)**
  - jet is a collection of energy deposits with a given cone *R*: $R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$
  - cone direction maximizes the total E_T of the jet
  - various clustering algorithms

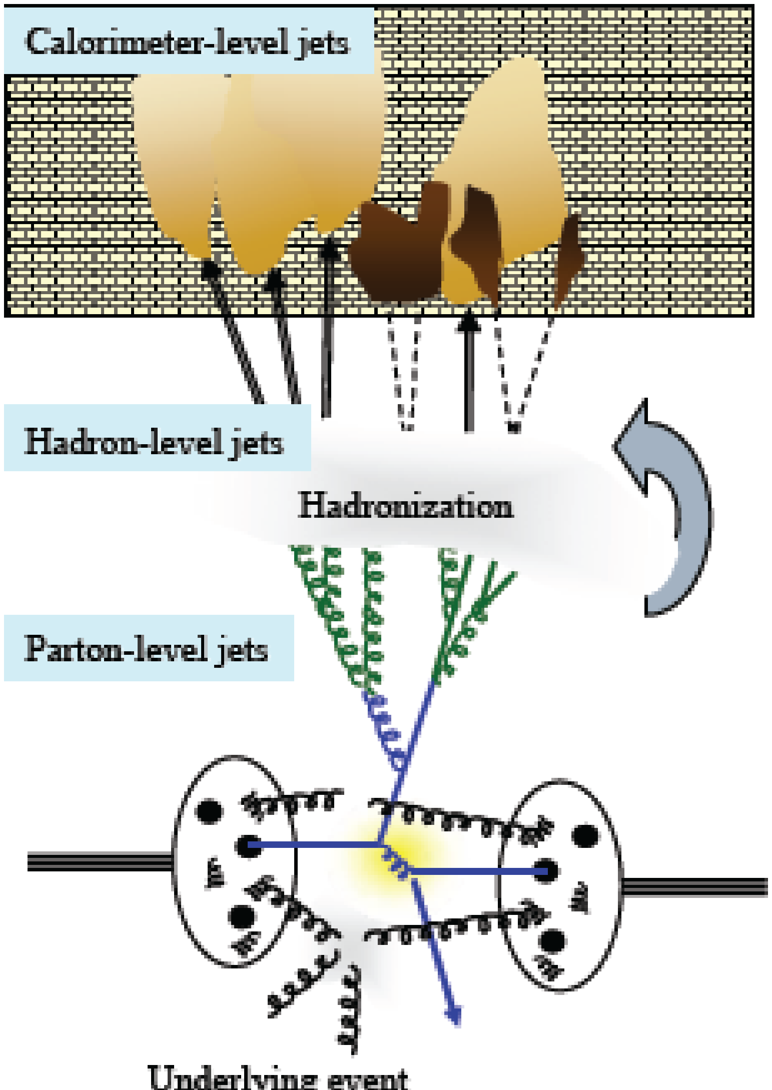
→ correct for finite energy resolution

→ subtract underlying event

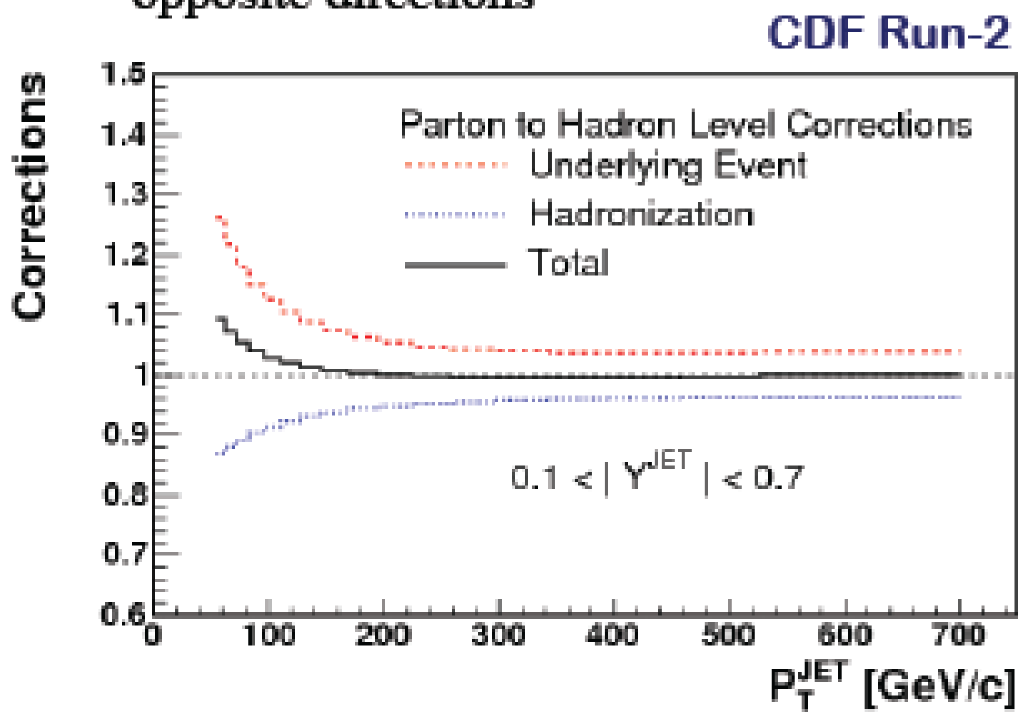
→ add out of cone energy

- **Particle jet**
  - a spread of particles running roughly in the same direction as the parton after hadronization

Underlying Event & Hadronization Correction



- UE and hadronization effects are in the opposite directions



- With R=0.7, the UE effect is larger than the hadronzation effects.
  - ~10% in cross section at low jet Pt