Confronting Jet Shape Measurements with Resummation Calculation

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LPC/CTEQ Joint Workshop: Confronting Theory with Experiment

- Challenges: to describe jet energy profile and jet mass
- Puzzles: underlying event tuning
- Opportunities: tool for new physics search

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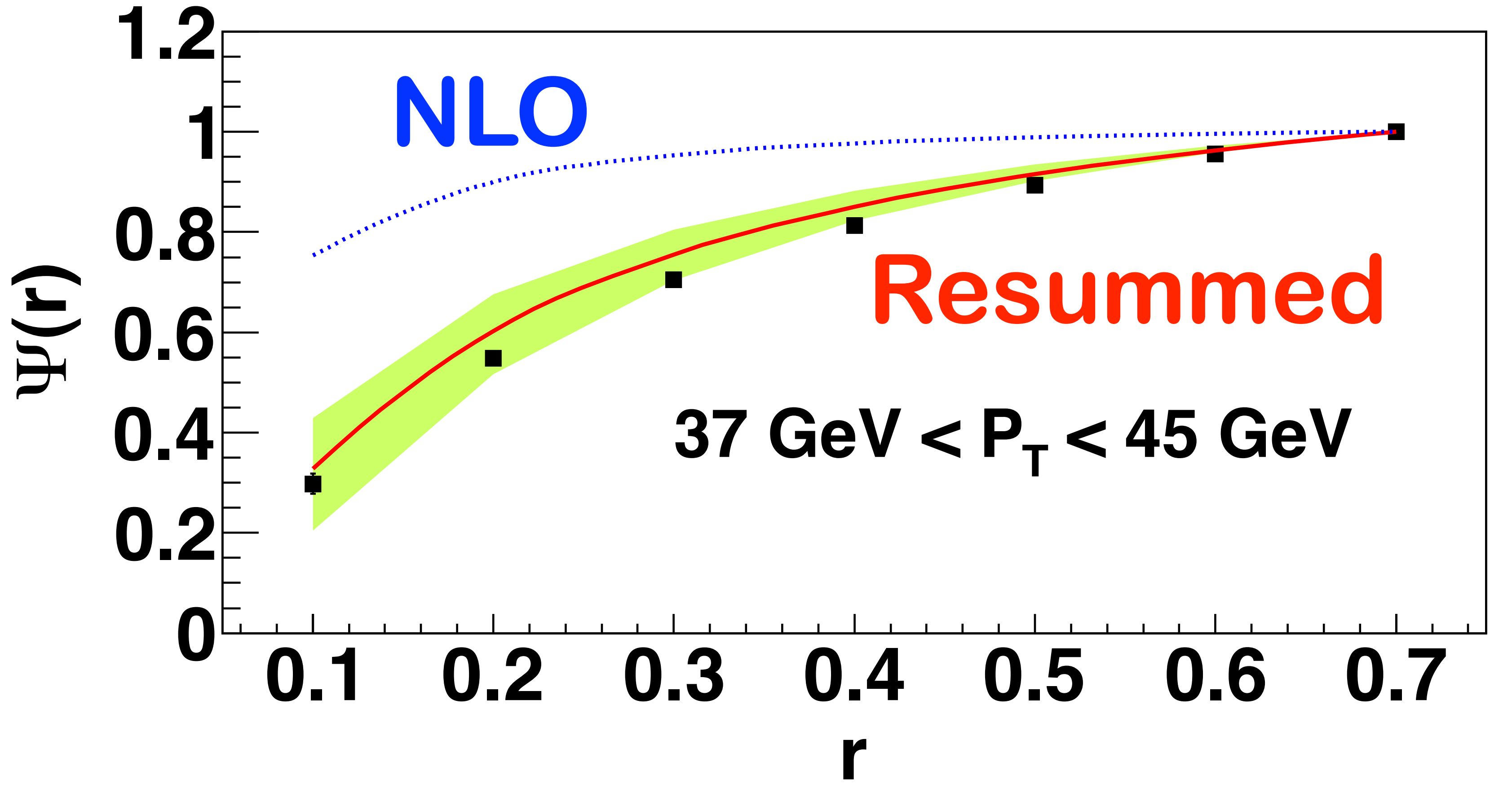
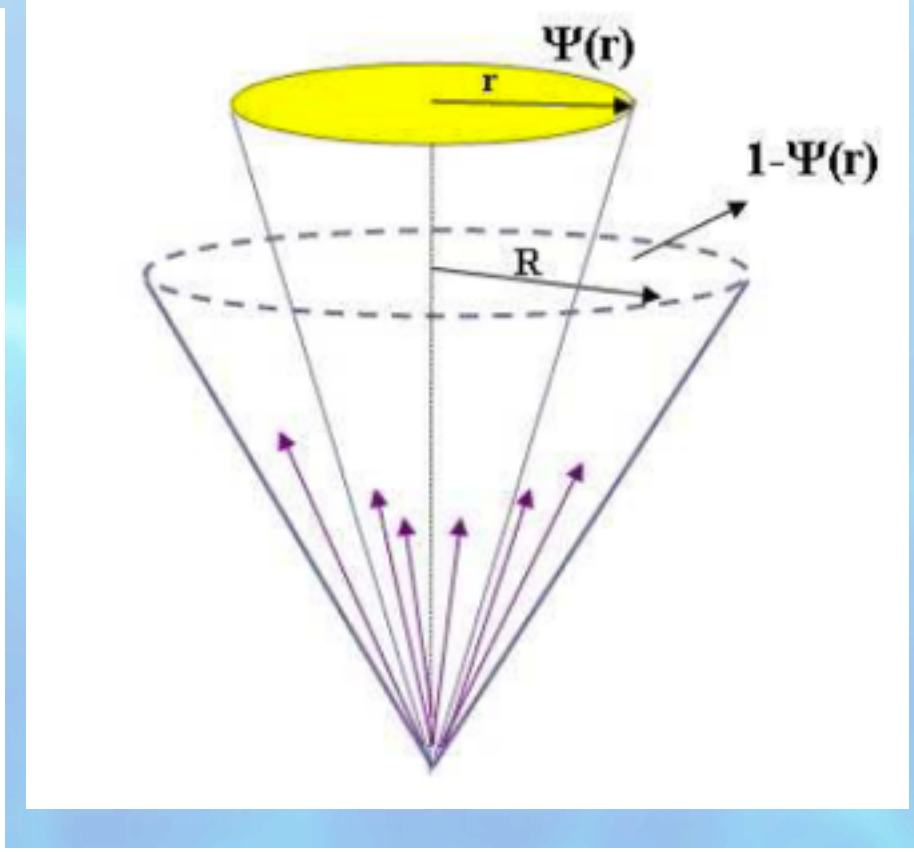
PRL 107 (2011) 152001

Challenges

Jet energy profile @ CDF



CDF data PRD71(2005)112002

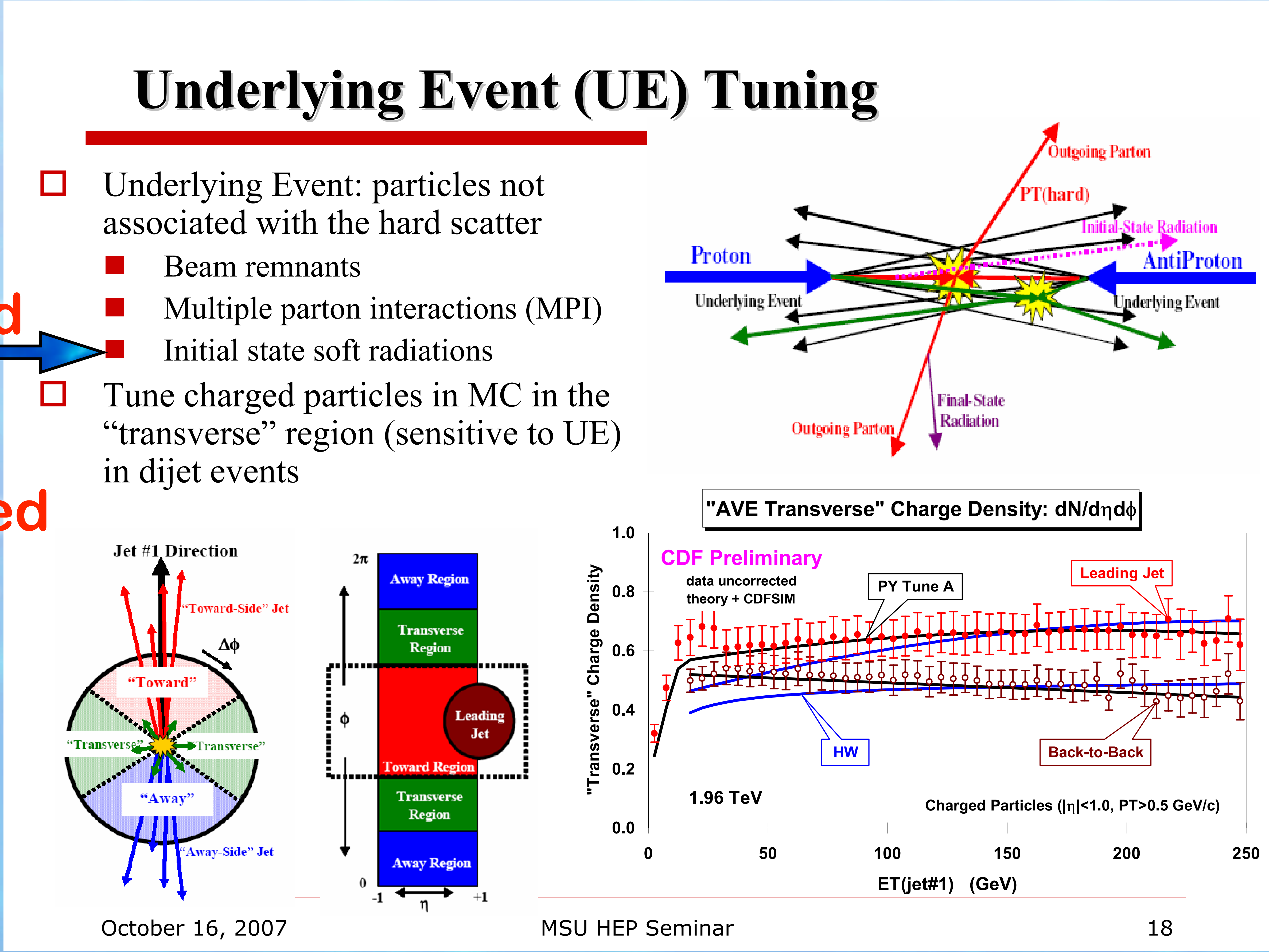


$$\Psi(r) = \frac{1}{\mathrm{N_{jet}}} \sum_{\mathrm{jets}} \frac{P_T(0,r)}{P_T(0,R)}, \qquad 0 \leq r \leq R$$

Predicted by pQCD with resummation calculation, in contrast to fitted by tuned PYTHIA, etc.

Puzzles

ISR should not be included here.

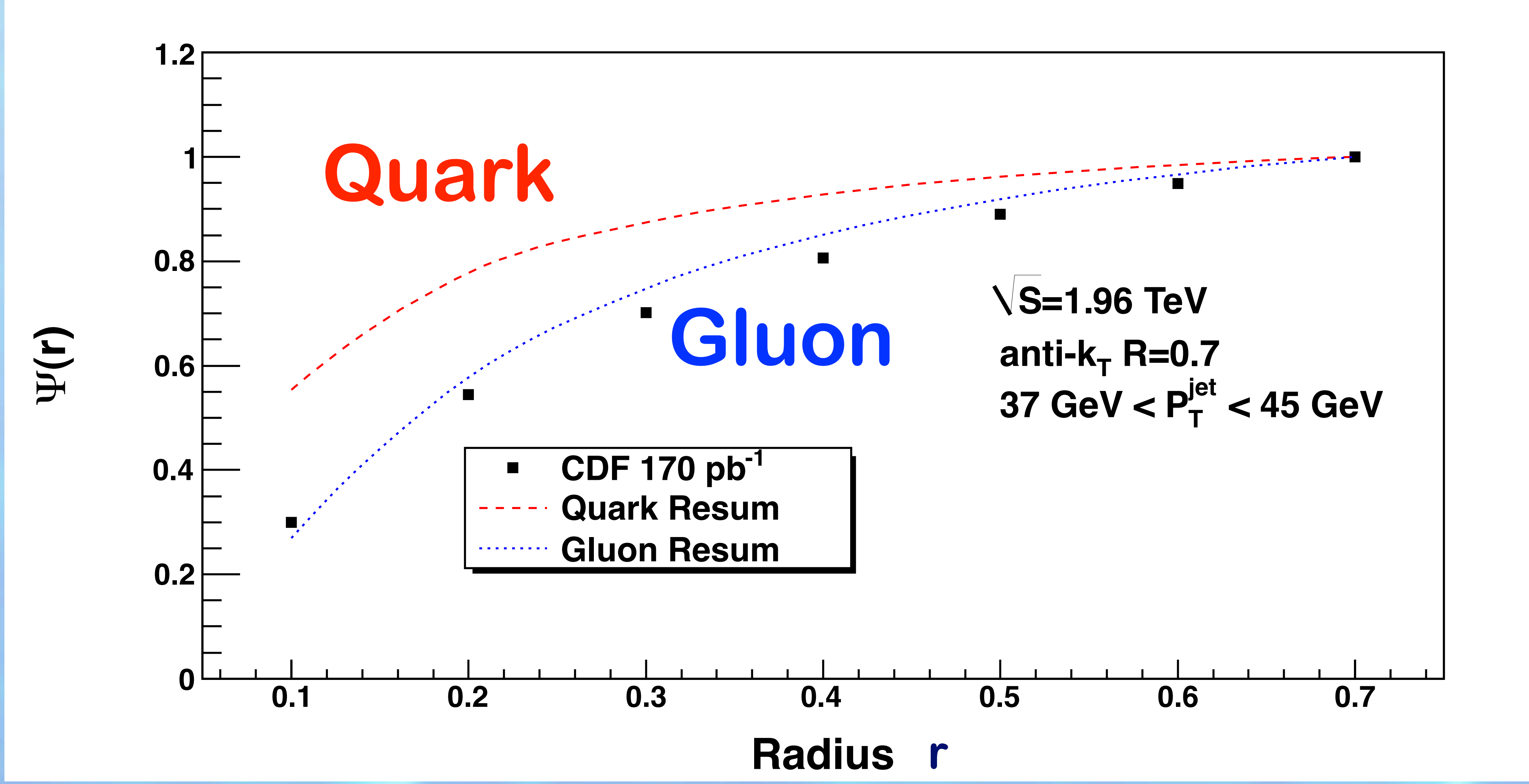


Underlying Event (UE) Tuning

- ☐ Underlying Event: particles not associated with the hard scatter
  - Beam remnants
  - Multiple parton interactions (MPI)
  - Initial state soft radiations
- ☐ Tune charged particles in MC in the "transverse" region (sensitive to UE) in dijet events

Opportunities at LHC

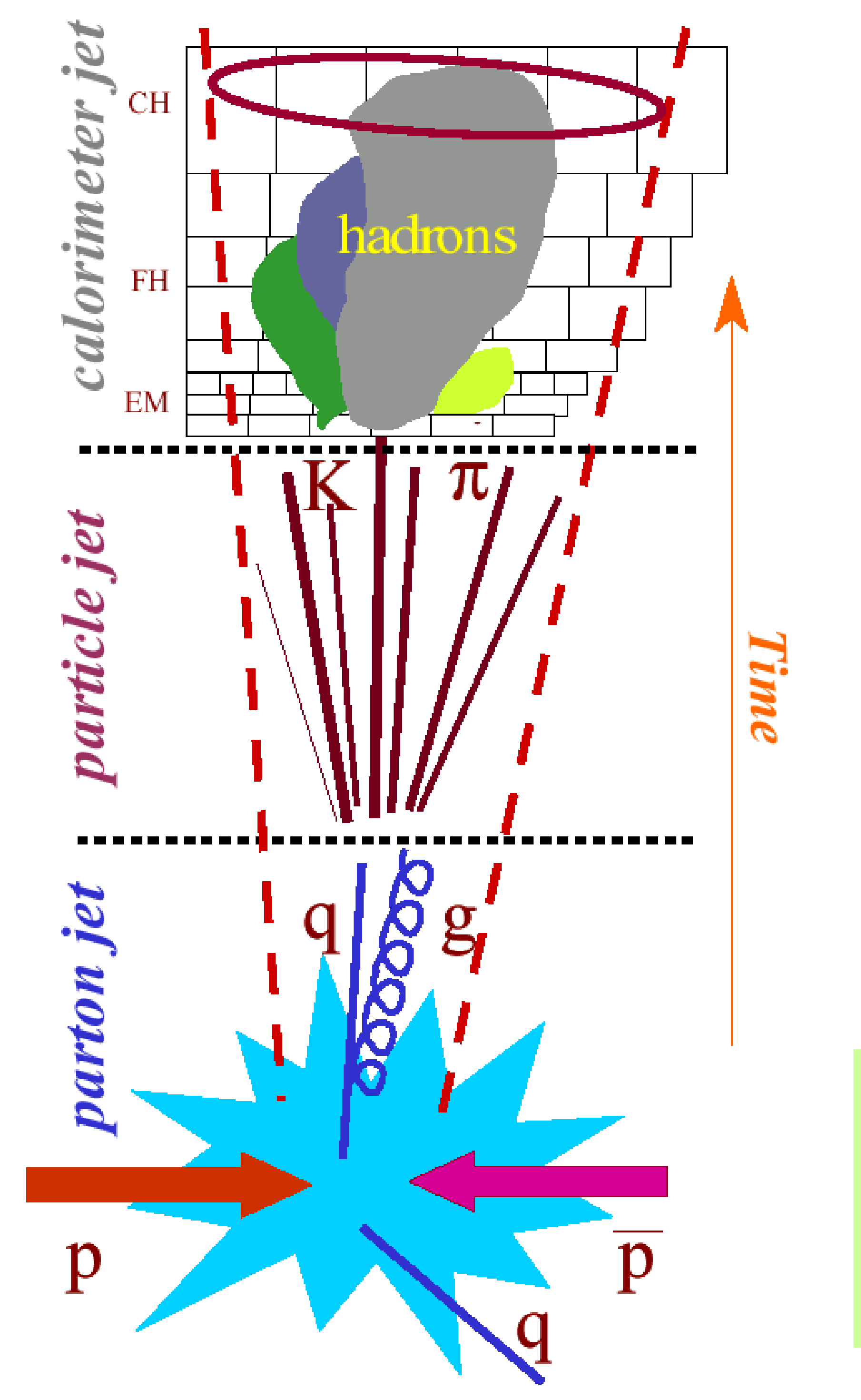
- Discriminate gluon from quark jets via energy profile



- test SM and new physics models from the composition (gluon vs quark) of observed jets. E.g., CDF "W+jj" anomaly (test side-bands of the mass bump with SM)

Jet
in experimental data

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 (UE) Tuning

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  - Beam remnants
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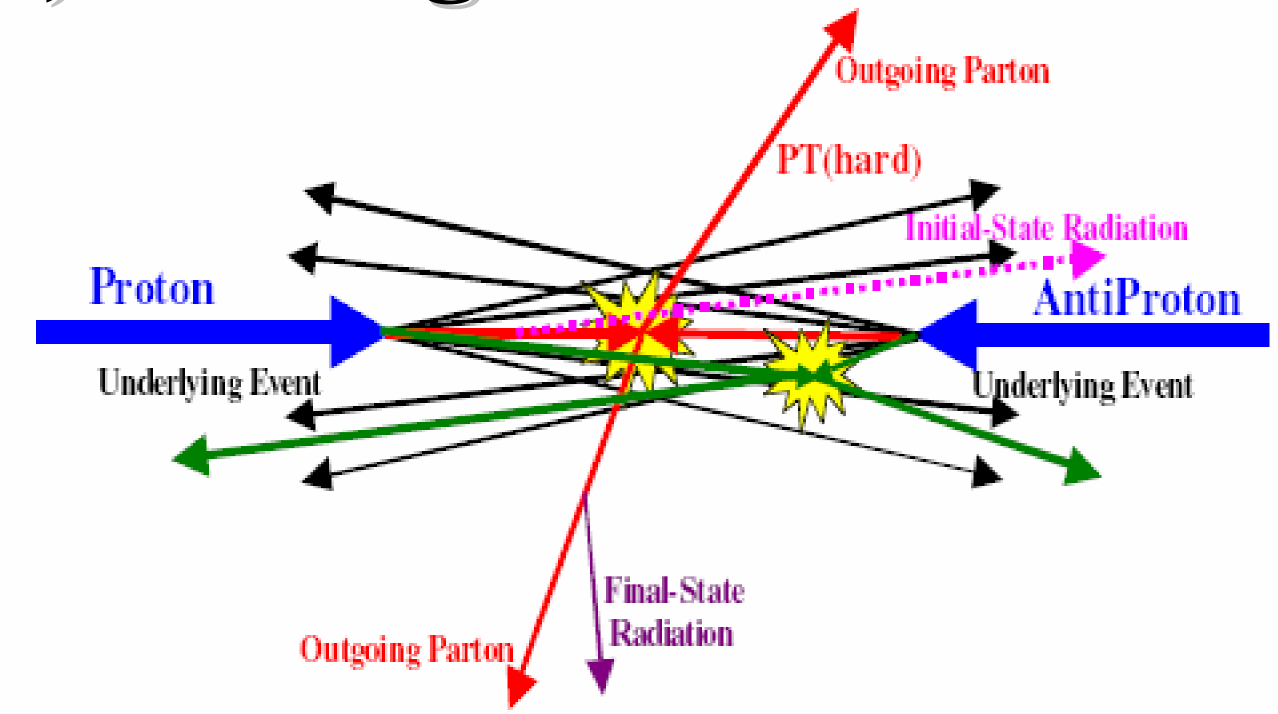
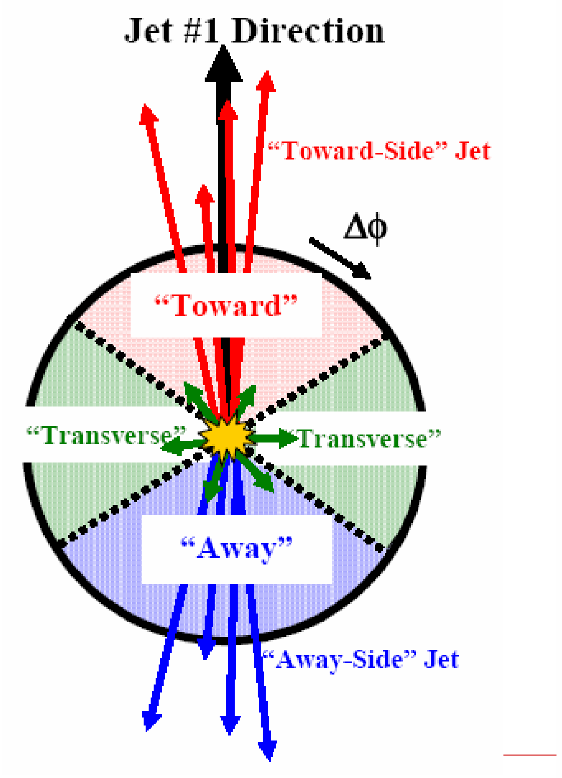
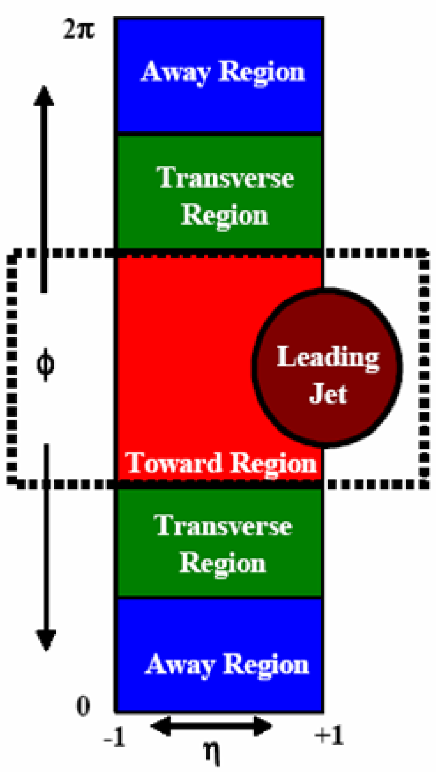
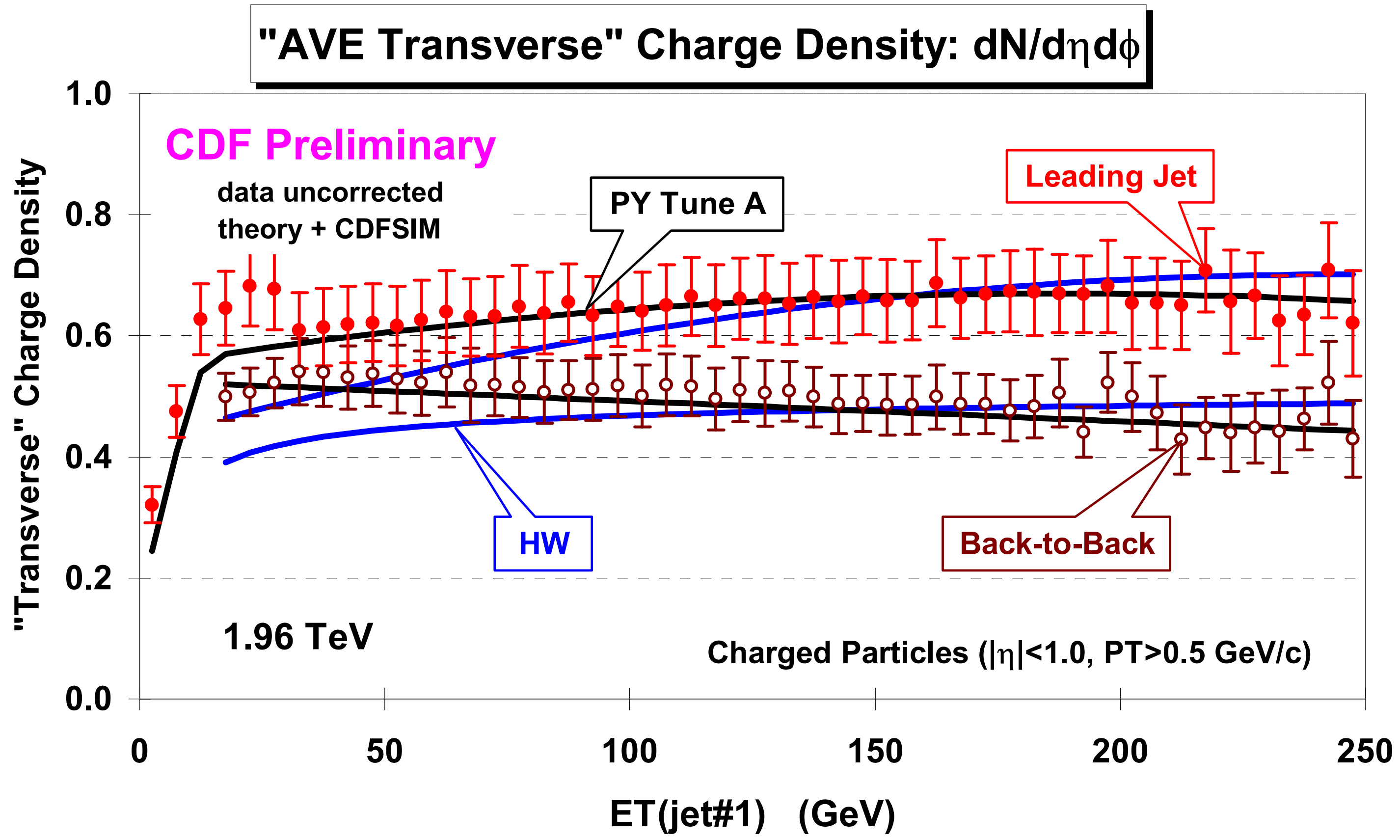
- Tune charged particles in MC in the “transverse” region (sensitive to UE) in dijet events

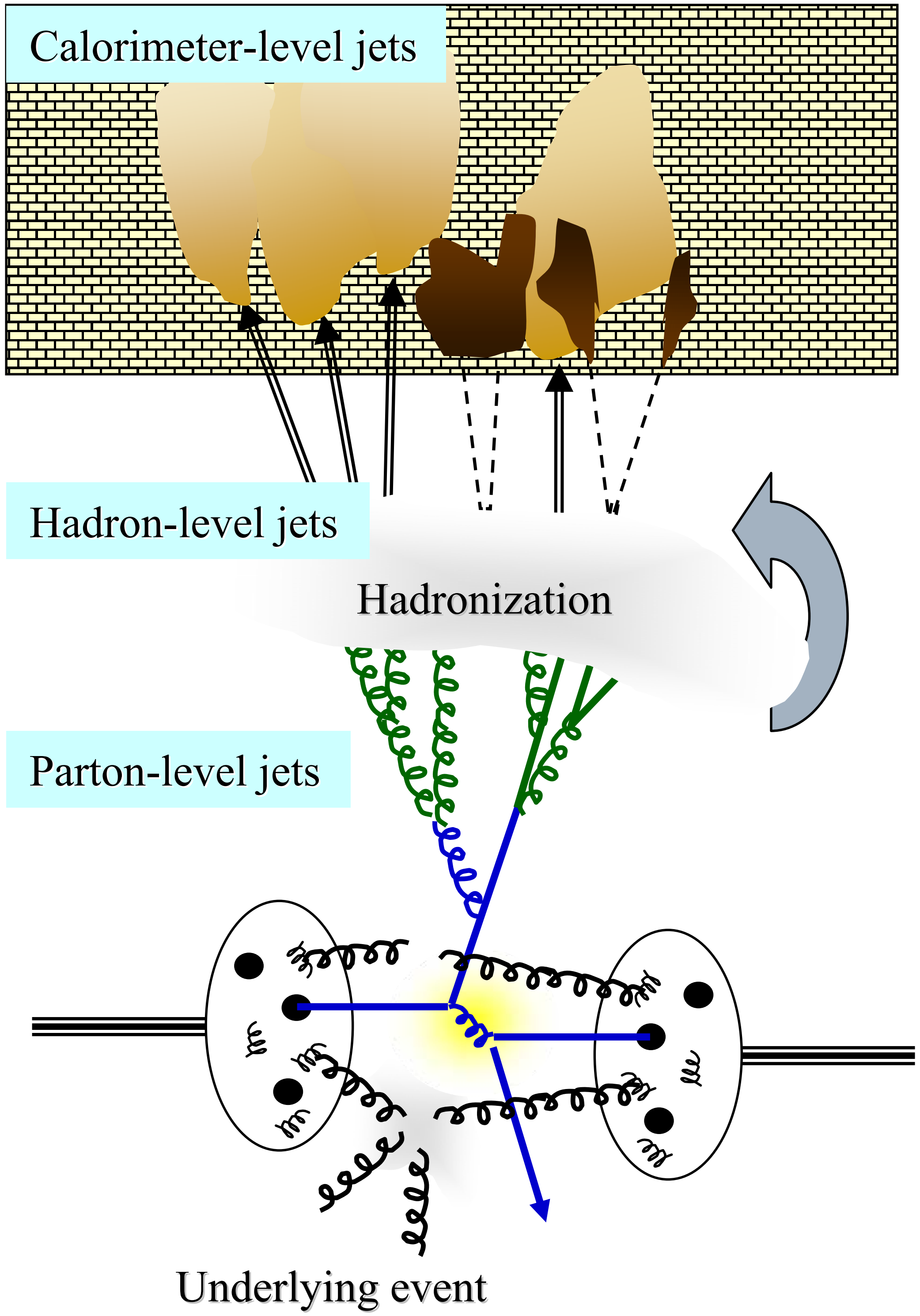




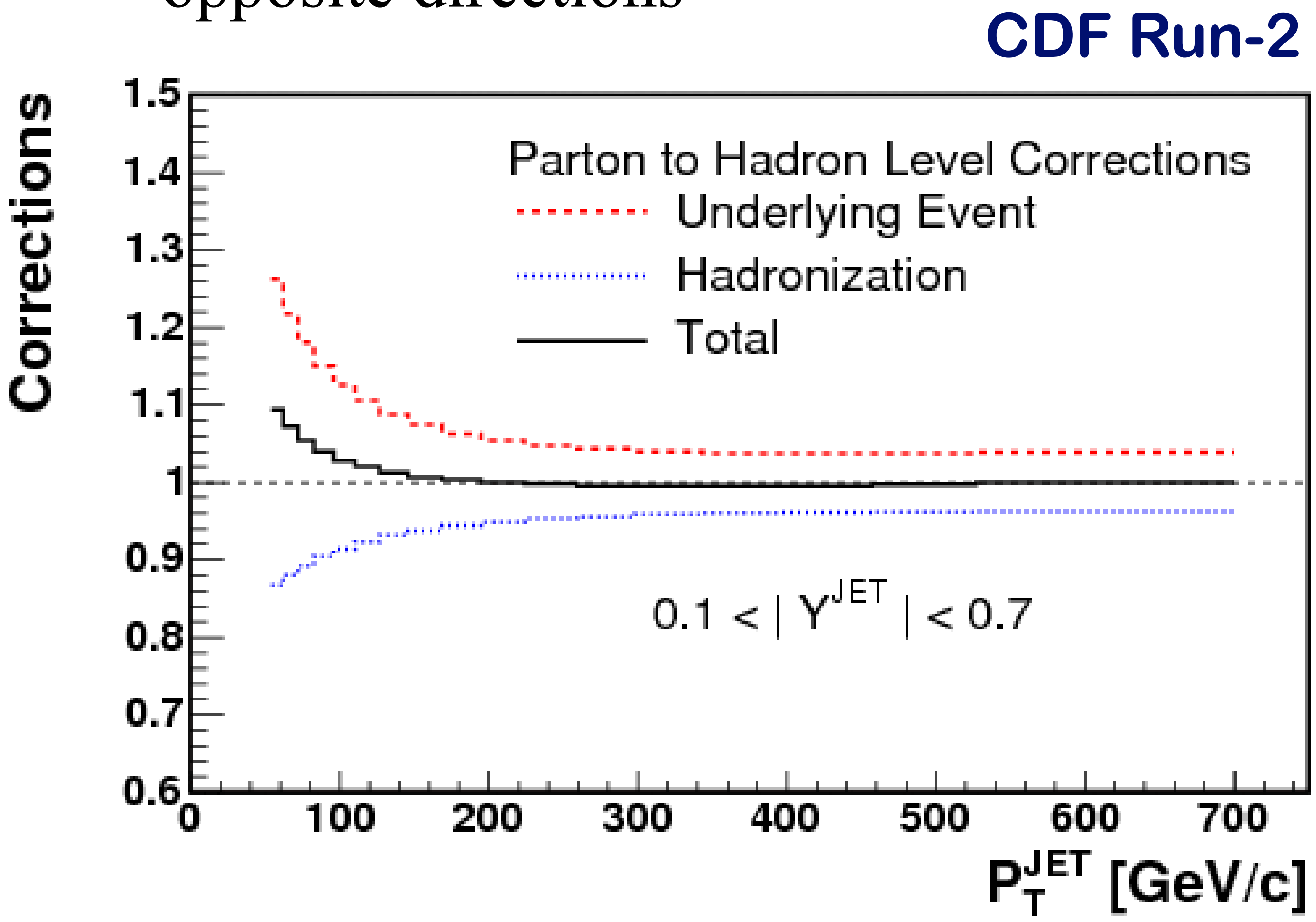




Underlying Event & Hadronization Correction



- 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

Problem in Data Analysis

- Effect from initial state radiation should not be subtracted.
- It is needed to construct an infrared-safe observable: Energy Profile of a jet.
- This effect is more important for low pT jets.

Various Theoretical Predictions

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

NLO

Our resummation results

- At first time, **pQCD resummation approach** is established to investigate jets.

- Jet **energy profile** and **mass distribution** improve NLO prediction and can describe CDF and CMS data.

Jet Function

LO Jet:

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

Quark Jet:

$$J_i^q(m_J^2, p_{0,J_i}, R) = \frac{(2\pi)^3}{2\sqrt{2}(p_{0,J_i})^2}\frac{\xi_\mu}{N_c}\sum_{N_{J_i}} Tr\left\{\gamma^\mu \langle 0|q(0)\Phi_\xi^{(\bar{q})\dagger}(\infty,0)|N_{J_i}\rangle\right.$$

$$\left.\times\langle N_{J_i}|\Phi_\xi^{(\bar{q})}(\infty,0)\bar{q}(0)|0\rangle\right\}\delta(m_J^2 - \tilde{m}_J^2(N_{J_i},R))$$

$$\times\delta^{(2)}(\hat{n} - \tilde{n}(N_{J_i}))\delta(p_{0,J_i} - \omega(N_{J_c}))$$

Gluon Jet:

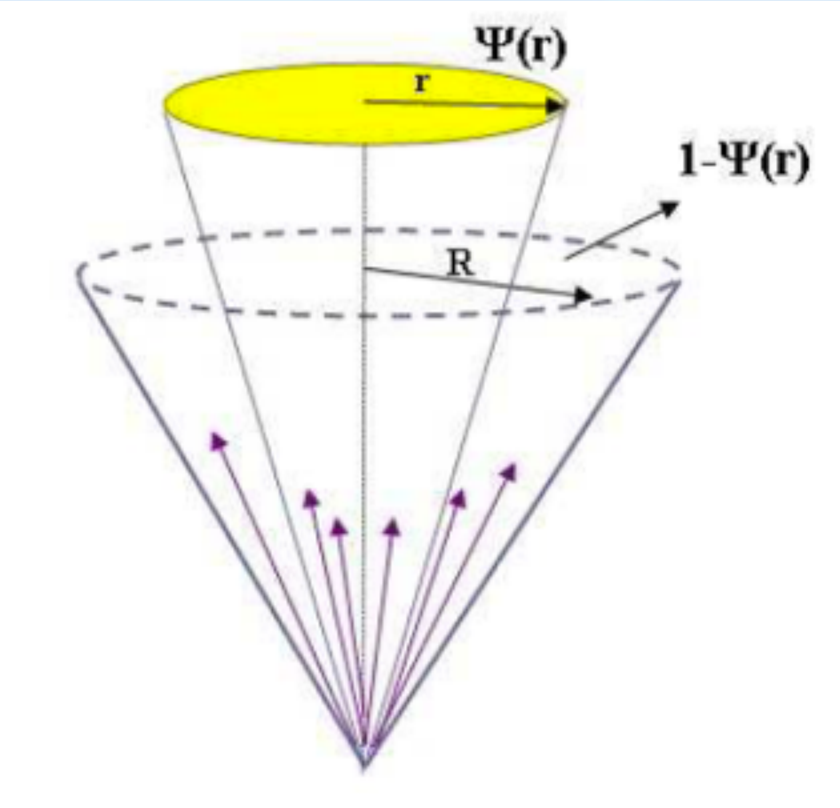
$$J_i^g(m_J^2, p_{0,J_i}, R) = \frac{(2\pi)^3}{2(p_{0,J_i})^3}\sum_{N_{J_i}}\langle 0|\xi_\sigma F^{\sigma\nu}(0)\Phi_\xi^{(g)\dagger}(0,\infty)|N_{J_i}\rangle$$

$$\times\langle N_{J_i}|\Phi_\xi^{(g)}(0,\infty)F_\nu^\rho(0)\xi_\rho|0\rangle\delta(m_J^2 - \tilde{m}_J^2(N_{J_i},R))$$

$$\times\delta^{(2)}(\hat{n} - \tilde{n}(N_{J_i}))\delta(p_{0,J_i} - \omega(N_{J_c}))$$

Almeida, et. al. PRD79 (2009) 074012

Jet energy profile



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

$$\begin{aligned}
\Psi(r, P_T) &= \frac{\sum_c \int dM_J^2 \sum_{r_i<r, i\in J} P_{Ti} d\sigma_c/(dP_T dM_J^2)}{\sum_c \int dM_J^2 \sum_{r_i<R, i\in J} P_{Ti} d\sigma_c/(dP_T dM_J^2)} \\
&= \frac{\sum_c \int dM_J^2 \sum_{r_i<r, i\in J} P_{Ti} (d\sigma_c/dP_T) J_c(M_J^2, P_T, R)}{\sum_c \int dM_J^2 \sum_{r_i<R, i\in J} P_{Ti} (d\sigma_c/dP_T) J_c(M_J^2, P_T, R)}
\end{aligned}$$

$$= \frac{\sum_c \int dM_J^2 (d\sigma_c/dP_T) J_c^E(M_J^2, P_T, R, r)}{\sum_c \int dM_J^2 (d\sigma_c/dP_T) J_c^E(M_J^2, P_T, R, R)}$$

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

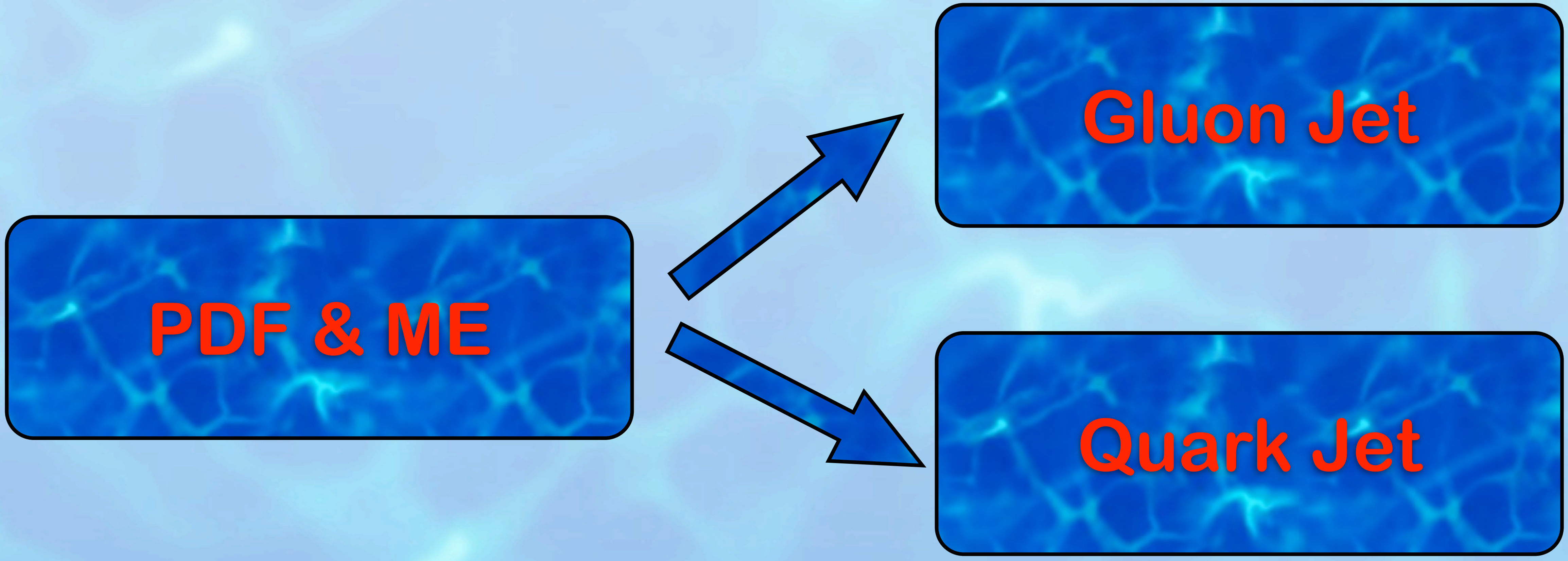
$$
\begin{aligned}
&J_q^{E(1)}(m_J^2, P_T, \nu^2, R, \mu^2) \;=\\
&\frac{(2\pi)^3}{2\sqrt{2}(P_J^0)^2 N_c}\sum_{\sigma,\lambda}\int \frac{d^3p}{(2\pi)^3 2\omega_p}\frac{d^3k}{(2\pi)^3 2\omega_k}\left[p^0\Theta(R-\theta_p)+k^0\Theta(R-\theta_k)\right]\\
&\times \mathrm{Tr}\left\{\not{\xi}\langle 0|q(0)W_\xi^{(\bar{q})\dagger}(\infty,0)|p,\sigma;k,\lambda\rangle\langle k,\lambda;p,\sigma|W_\xi^{(\bar{q})}(\infty,0)\bar{q}(0)|0\rangle\right\}\\
&\times\delta(m_J^2-(p+k)^2)\delta(\hat{n}-\hat{n}_{\vec{p}+\vec{k}})\delta(P_J^0-p^0-k^0),
\end{aligned}
$$

At NLO,

$$
\boxed{\bar{J}_E^q \approx \frac{\alpha_s C_F}{P_J^0 \pi}\left[-\frac{1}{4}\ln^2\frac{R^2}{r^2}-\frac{3}{4}\ln\frac{R^2}{r^2}\right].}
$$

which is an integrable singularity.

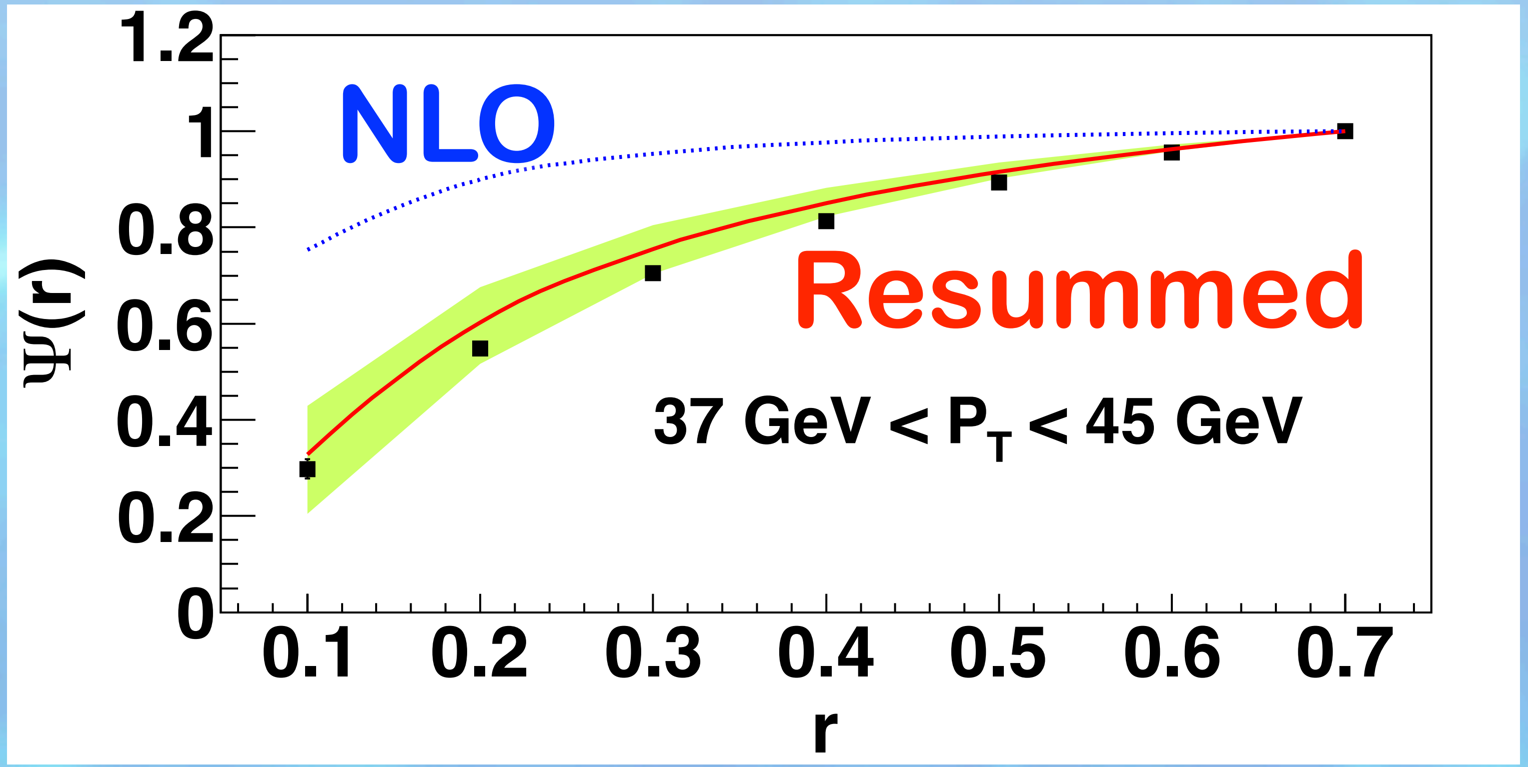
Convolute with di-jet hard scattering (integrate out jet mass)



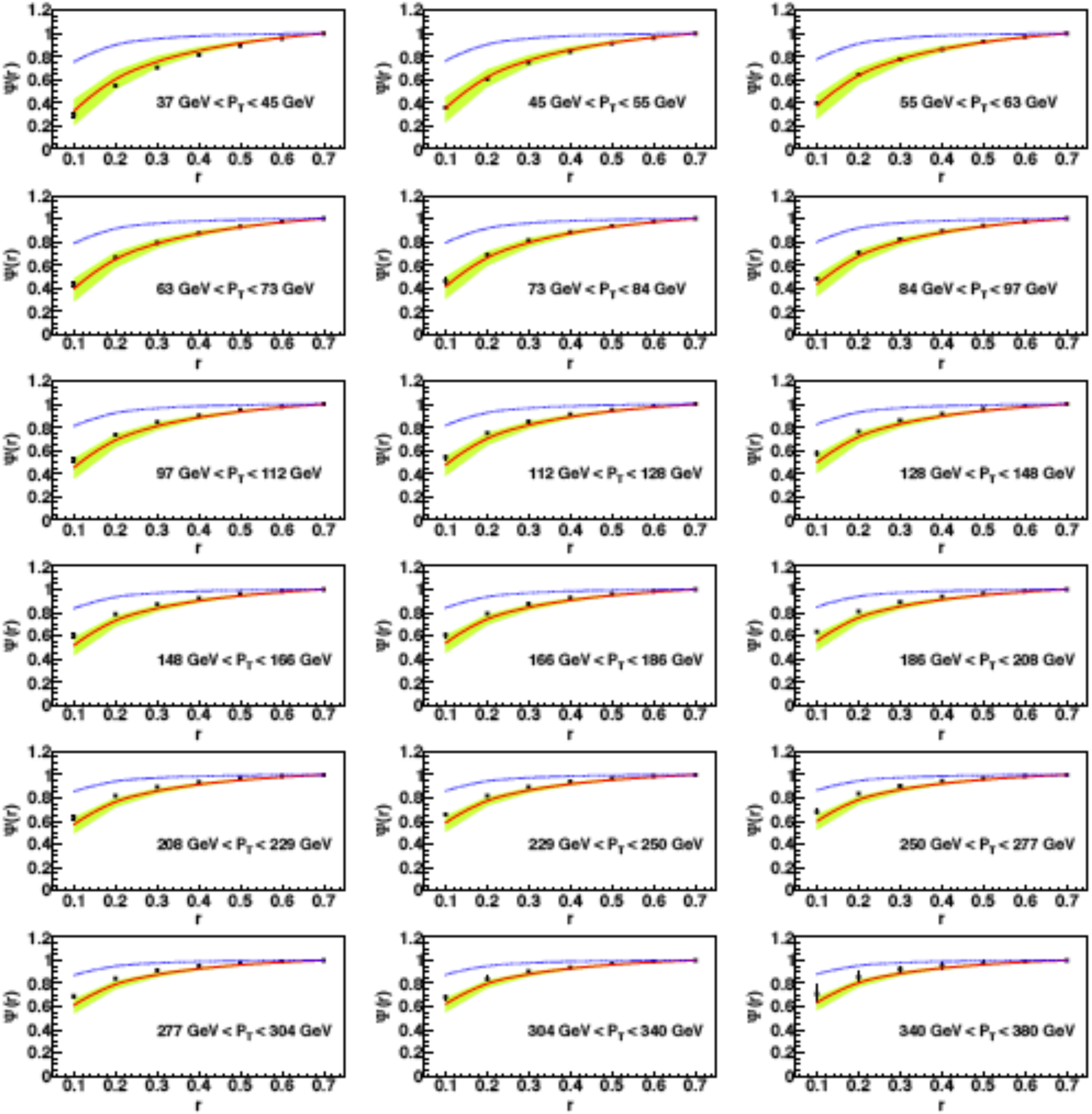
PDF & ME

Gluon Jet

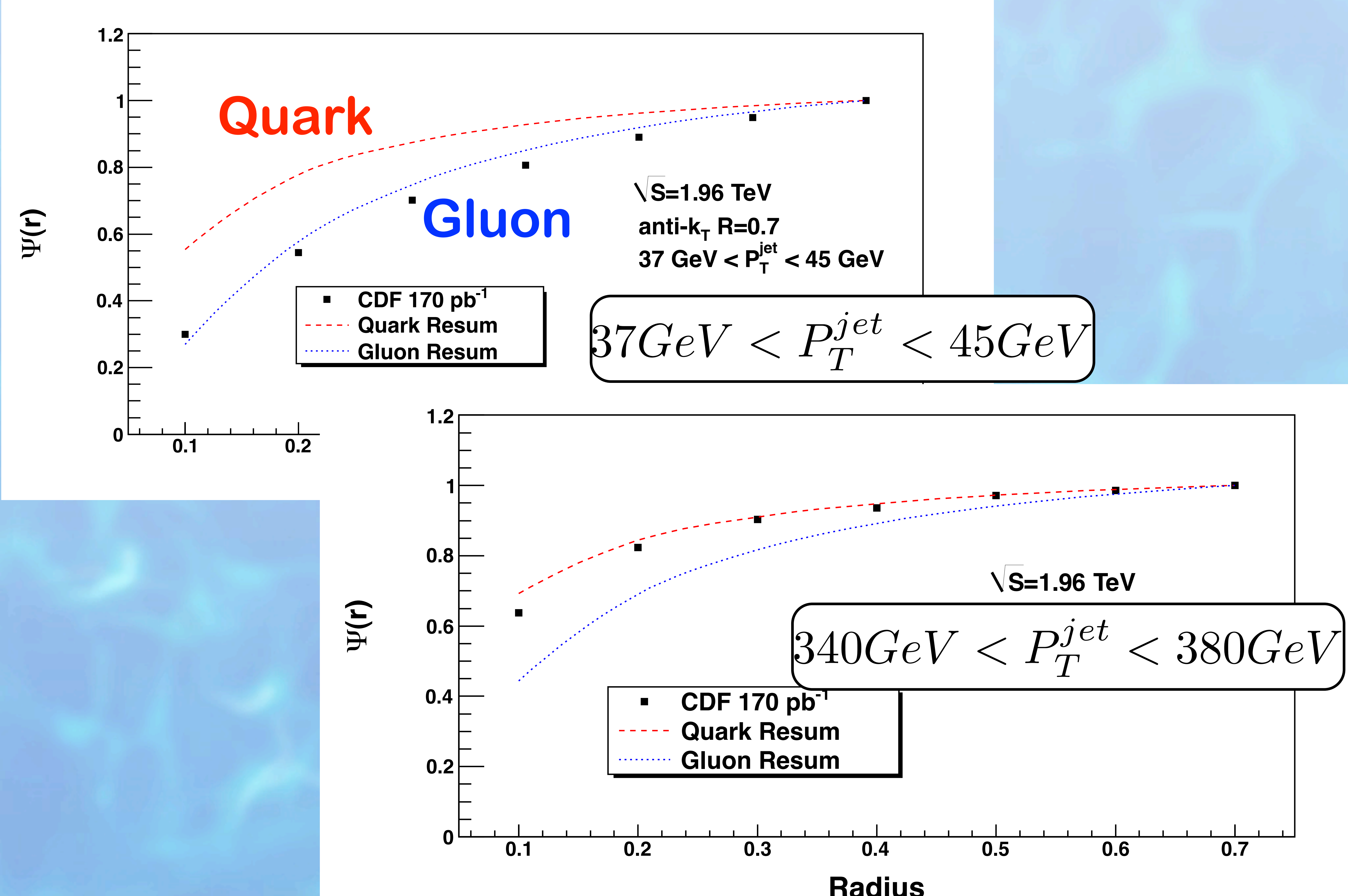
Quark Jet



CDF data PRD71(2005)112002


Ψ(r)
r
37 GeV < P_T < 45 GeV
45 GeV < P_T < 55 GeV
55 GeV < P_T < 63 GeV
63 GeV < P_T < 73 GeV
73 GeV < P_T < 84 GeV
84 GeV < P_T < 97 GeV
97 GeV < P_T < 112 GeV
112 GeV < P_T < 128 GeV
128 GeV < P_T < 148 GeV
148 GeV < P_T < 166 GeV
166 GeV < P_T < 186 GeV
186 GeV < P_T < 208 GeV
208 GeV < P_T < 229 GeV
229 GeV < P_T < 250 GeV
250 GeV < P_T < 277 GeV
277 GeV < P_T < 304 GeV
304 GeV < P_T < 340 GeV
340 GeV < P_T < 380 GeV
0
0.2
0.4
0.6
0.8
1
1.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7

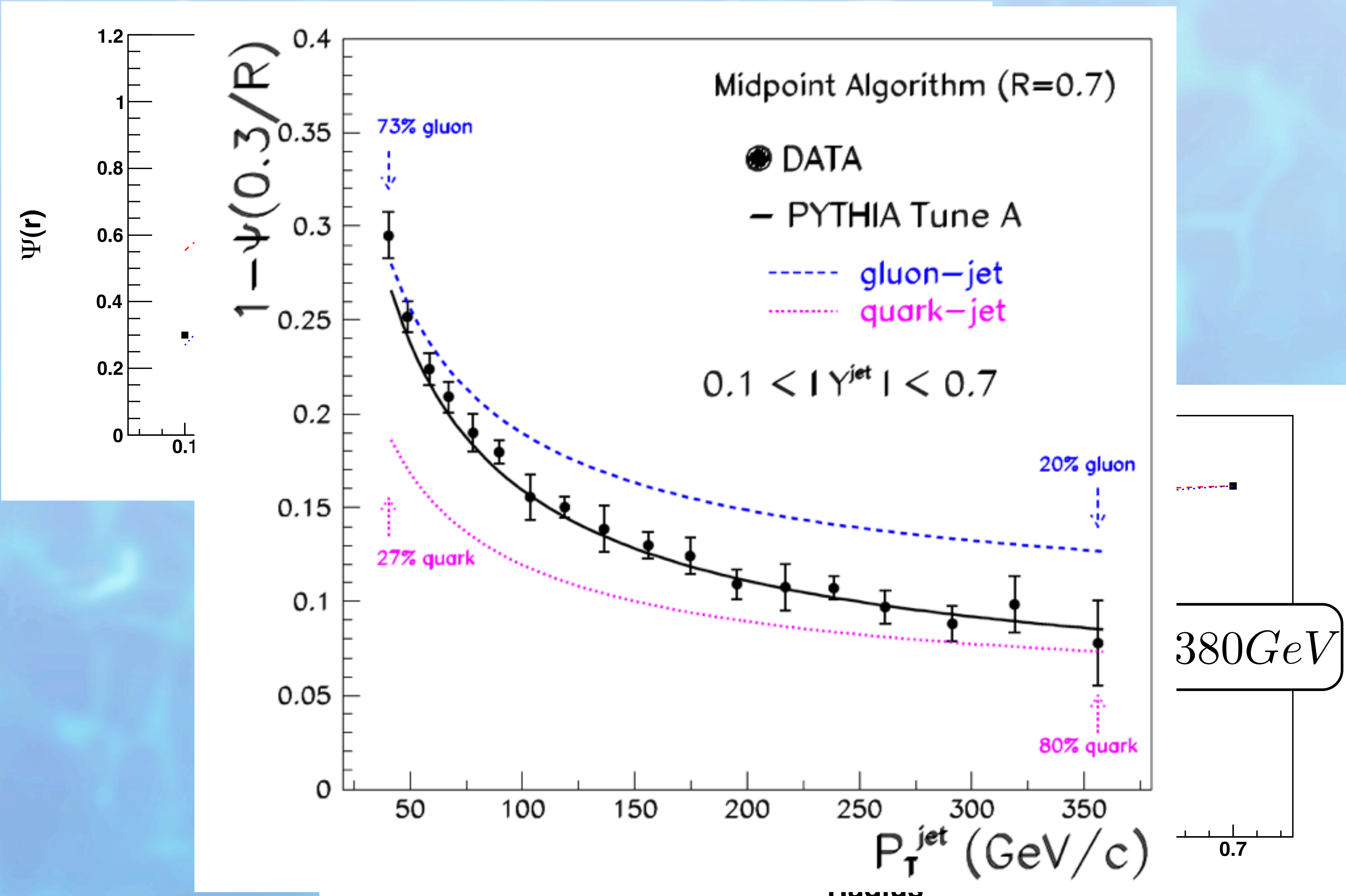
Dependence on pT@ Tevatron



$$37GeV < P_T^{jet} < 45GeV$$

$$340GeV < P_T^{jet} < 380GeV$$

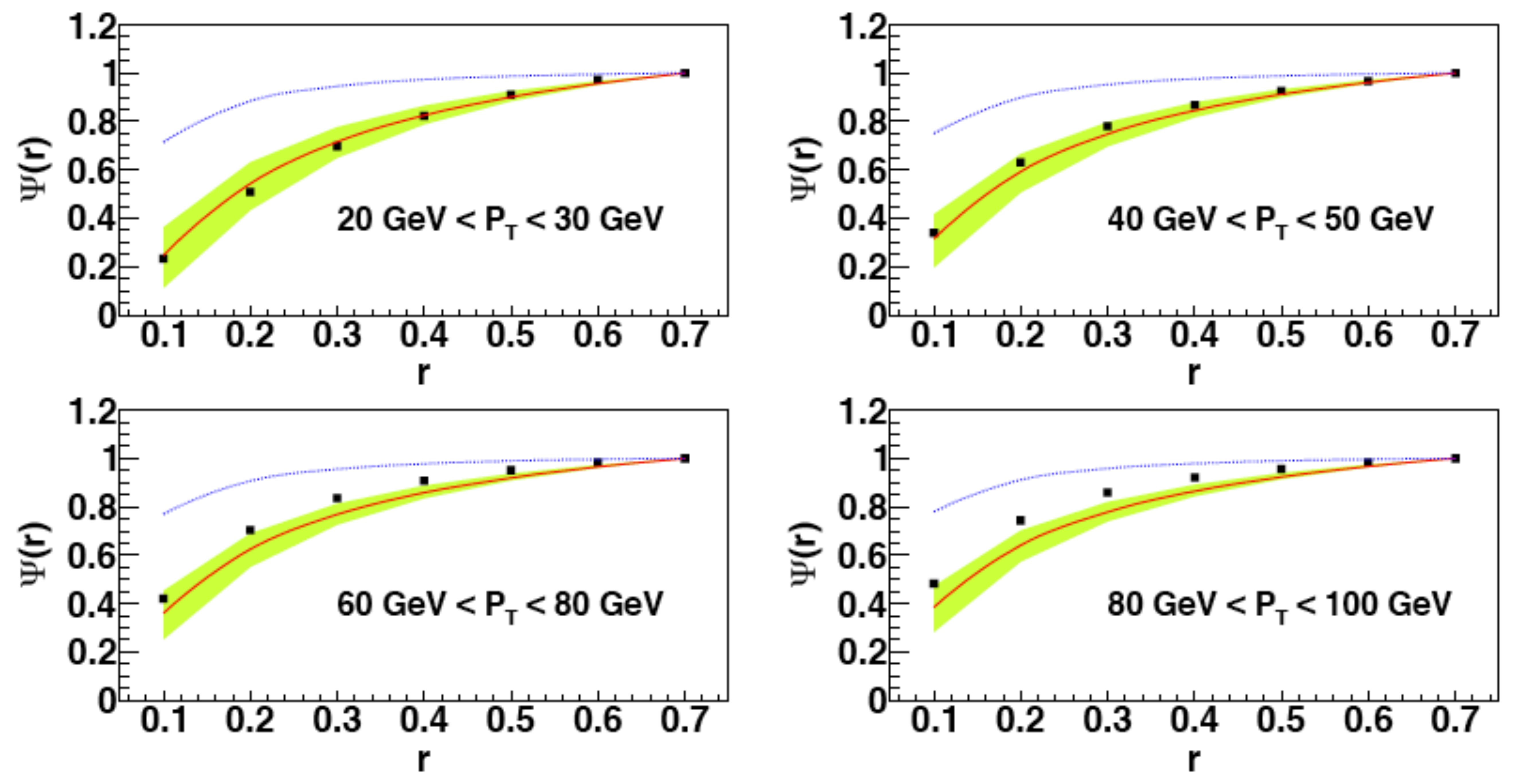
Dependence on pT@ Tevatron



Opportunities with this new pQCD calculations

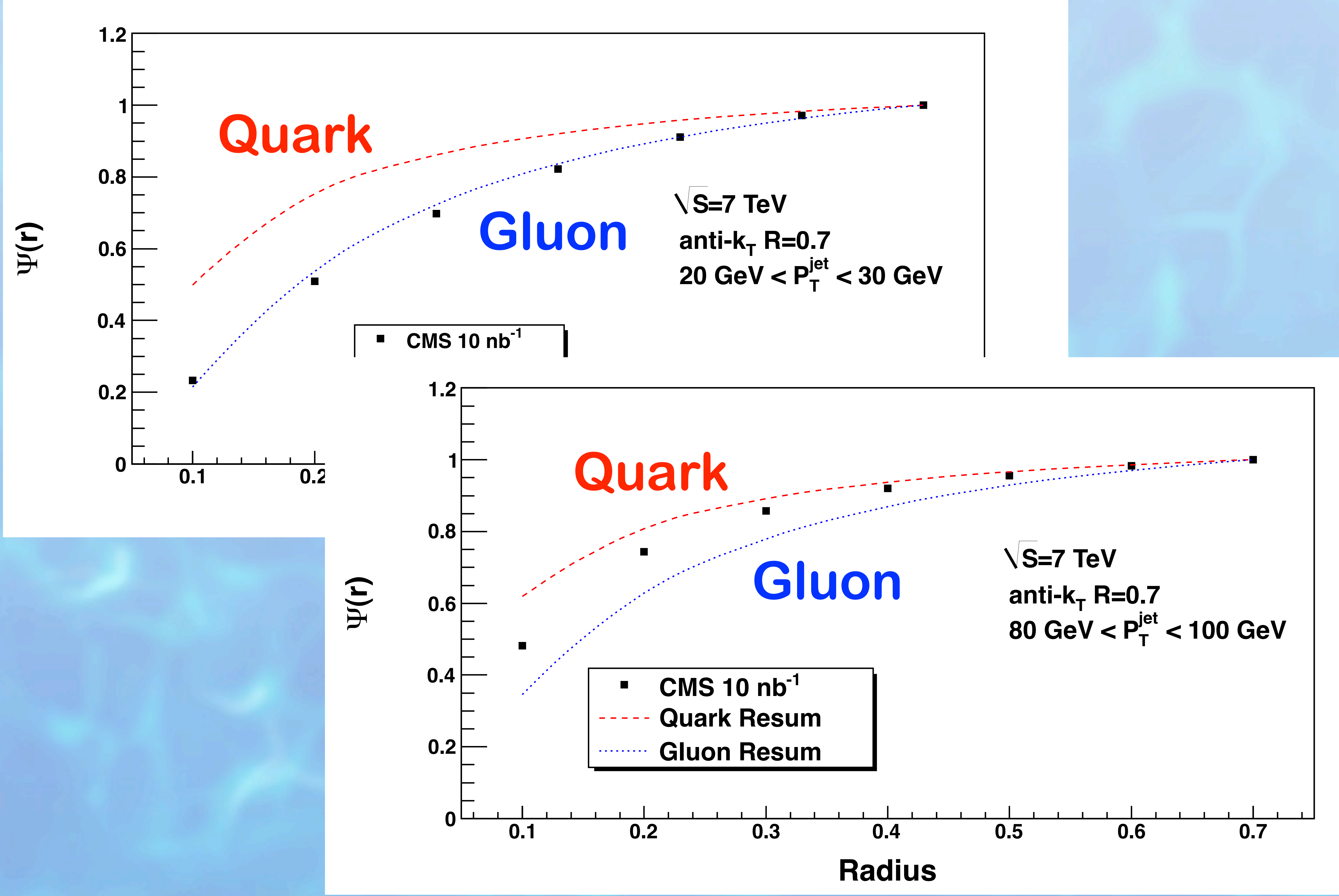
- Can discriminate gluon from quark jets using energy profile, as a function of jet pT (either at Tevatron or LHC).
- Can test SM and new physics models (for producing certain composition of extra quark and gluon jets) from the composition (gluon vs quark) of the observed jets.
- Can further analyze CDF “W+jj” anomaly events by testing the composition of jets in side-bands of the mass bump with SM predictions.

Jet energy profile @ CMS



Predicted by perturbative resummation calculation
(No non-perturbative contribution is needed.)

Dependence on pT@ LHC

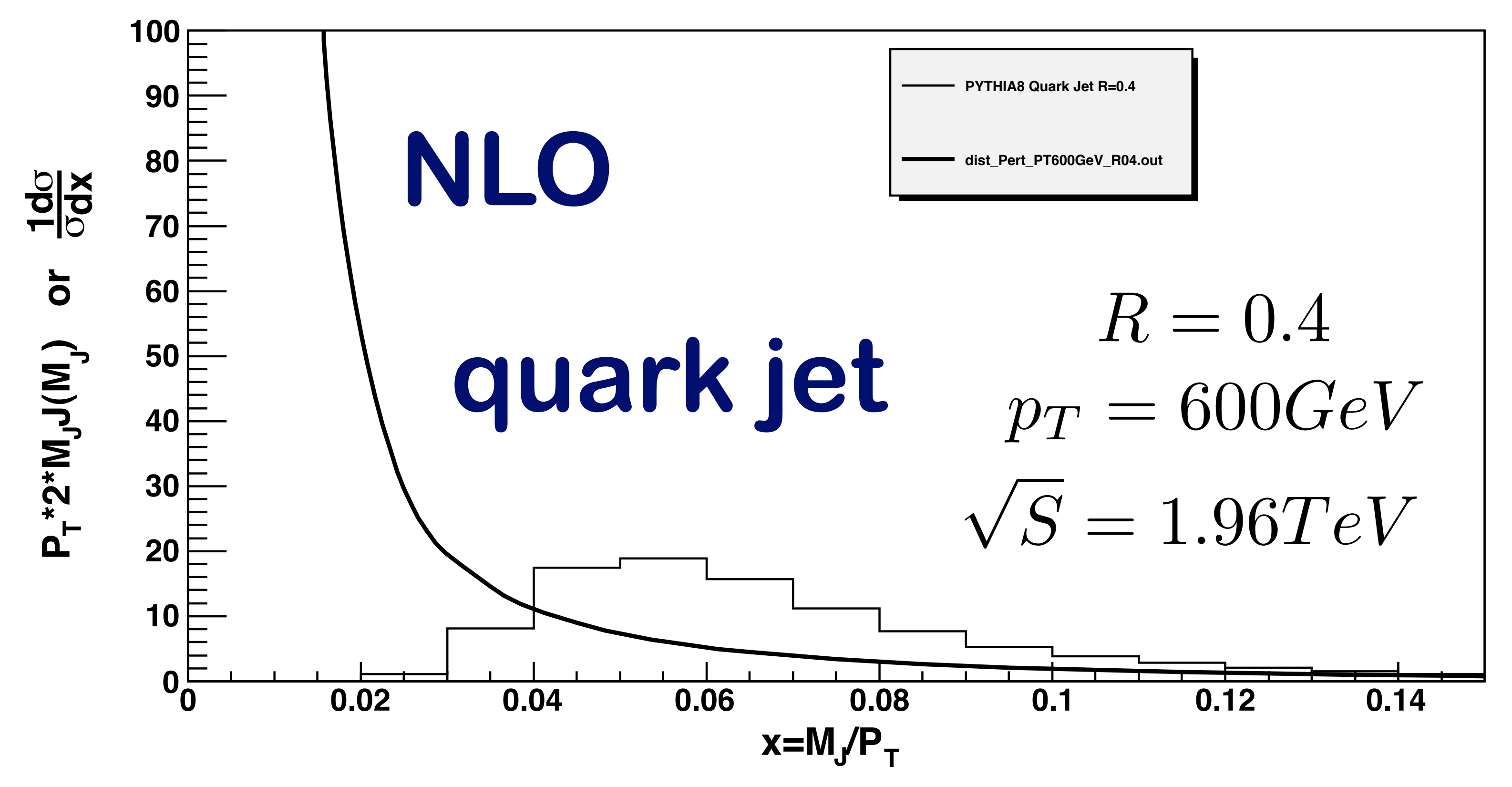


Summary & Prospect

- Studying jet substructure is useful for testing Standard Model and identifying New Physics.
- Fixed-order calculations in jet mass distribution and jet energy profile contain large logs, making predictions unreliable in small jet mass or small r region.
- QCD resummation provides reliable prediction and making independent check to full event generators.
- Resummation predictions for jet energy profile agree with CDF and CMS data.
- Resummed jet mass distribution including non-perturbative contribution agrees with PYTHIA8 for different jet pT and R, and Tevatron CDF data.
- Our formalism can be extended for heavy quark jet, e.g., a boosted top quark jet. (in progress)
- Same formalism can be used in jet study at HERA and RHIC.

Backup slides

Jet mass distribution

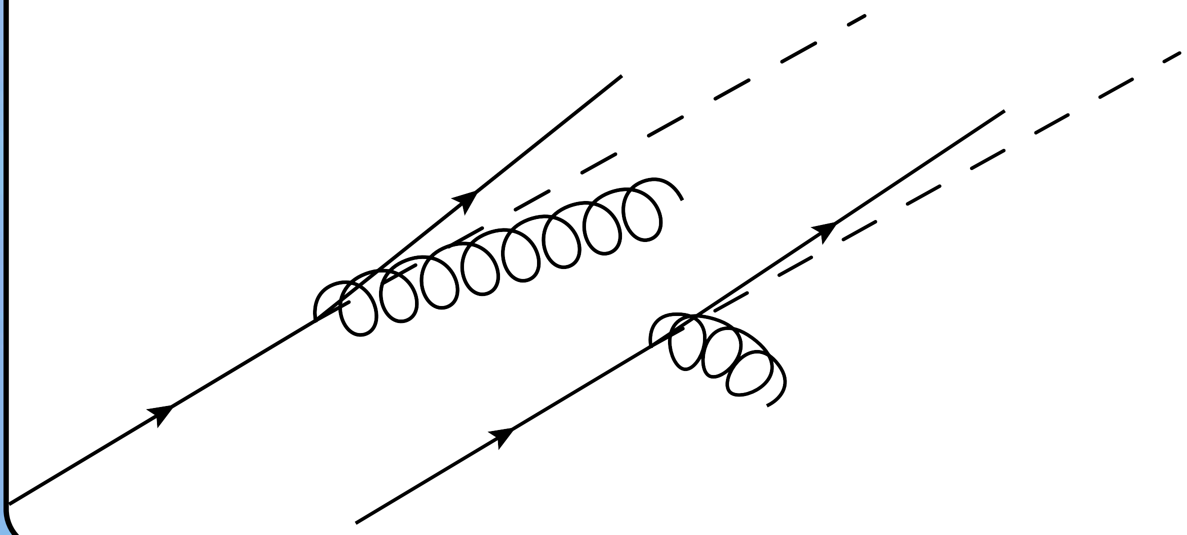


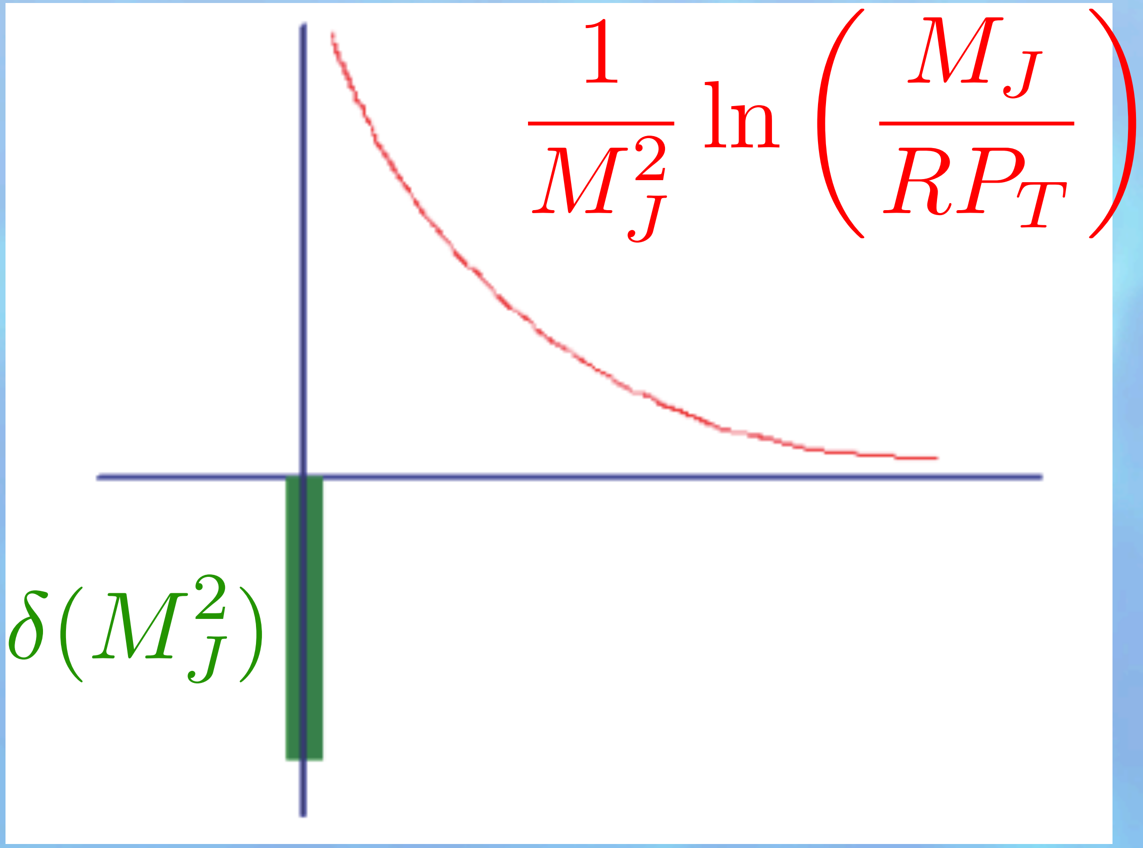
NLO

quark jet

$R = 0.4$
$p_T = 600 GeV$
$\sqrt{S} = 1.96 TeV$

$$\frac{d\sigma}{dP_T dM_J} = \sum_c 2M_J J^c(M_J, P_T, R)\frac{d\sigma^c}{dP_T}$$





Resummation for Jet Mass distribution

In fixed order calculations, there are large logarithmic terms of the ratio of pT to mass (MJ) of the jet (with radius R),

$$\boxed{\ln\left(\frac{M_J}{RP_T}\right)}$$

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

Mellin Transform

$$M_J \Longleftrightarrow N$$

RG evolution resum large log $\ln(N)$

The pQCD resummation formalism does not include all the non-perturbative effects originated from underlying event and haronization.

Hence, non-perturbative contribution needs to be introduced

$$S^{NP}(N) = \frac{N^2 Q_0^2}{R^2 P_T^2}(C_c \alpha_0 \ln N + \alpha_1) + C_c \alpha_2 \frac{N Q_0}{R P_T}$$

Non-perturbative parameters are universal, and get estimated for pT=600GeV with R=0.7.

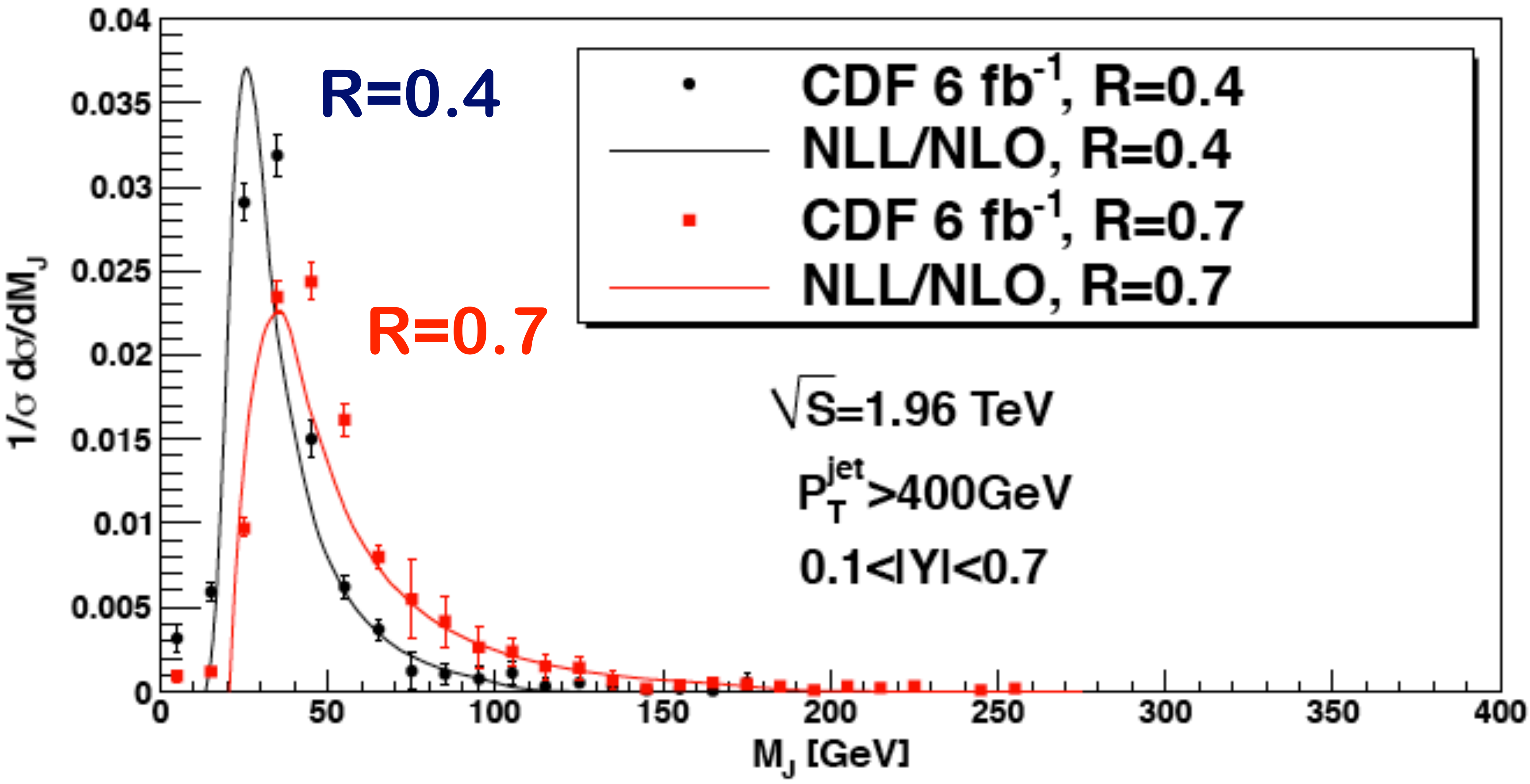
Predicting jet mass distribution at Tevatron adn LHC

- Determine universal NP parameters for jet with pT=600GeV and R=0.7, produced at Tevatron.

- Using the same parameters to predict jet mass distribution for any value of pT, R, and collider energy, e.g., to compare with CDF data for pT>400GeV with R=0.4 & 0.7,
  or to compare with LHC jet data.

Compare with CDF data

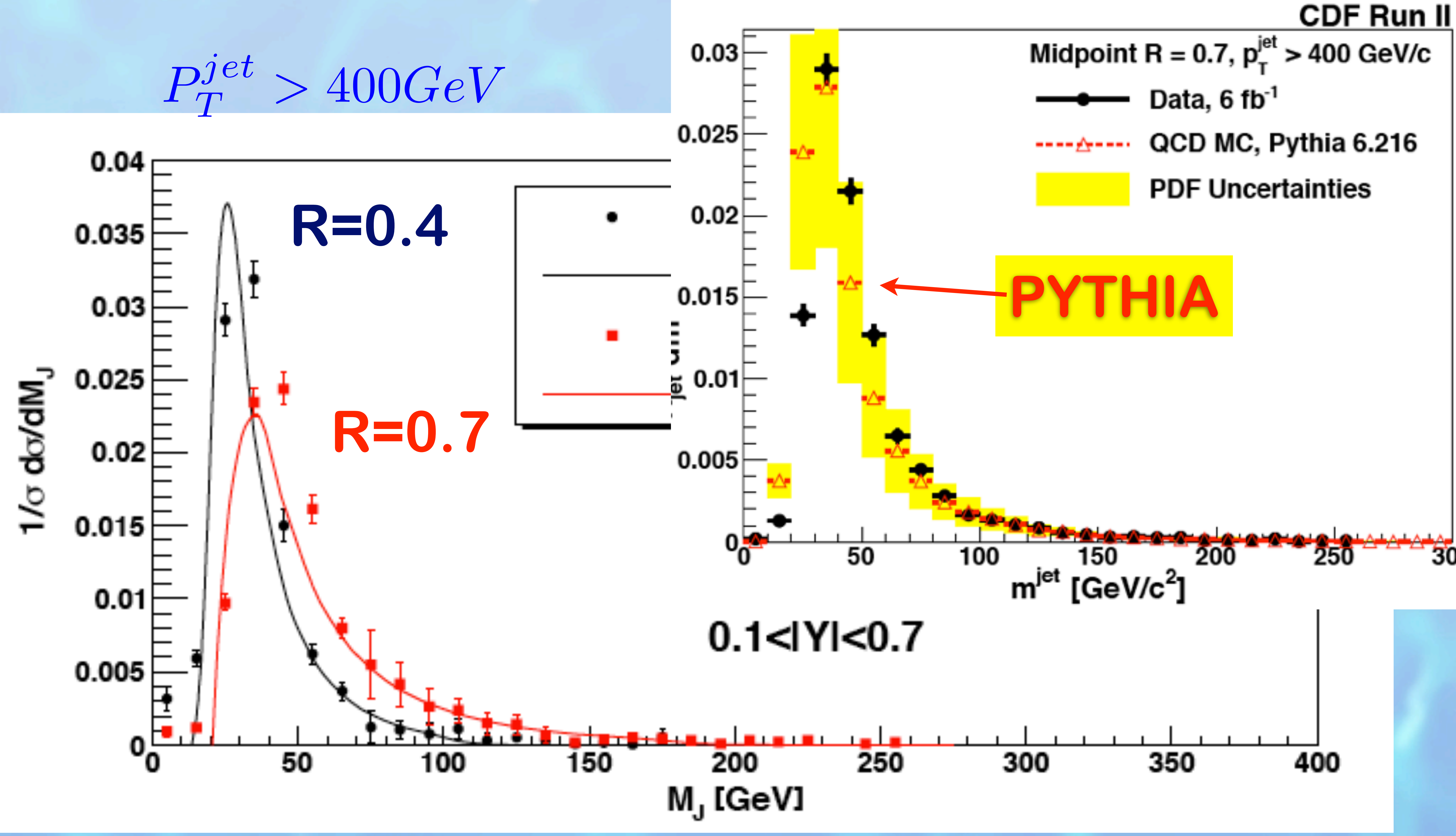
$P_T^{jet} > 400GeV$



Resummation dramatically improve prediction in small to medium jet mass range, compared to NLO.

Compare with CDF data

$P_T^{jet} > 400GeV$



Resummation dramatically improve prediction in small to medium jet mass range, compared to NLO.