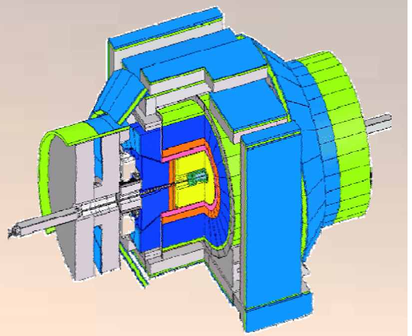
Jets in CDF



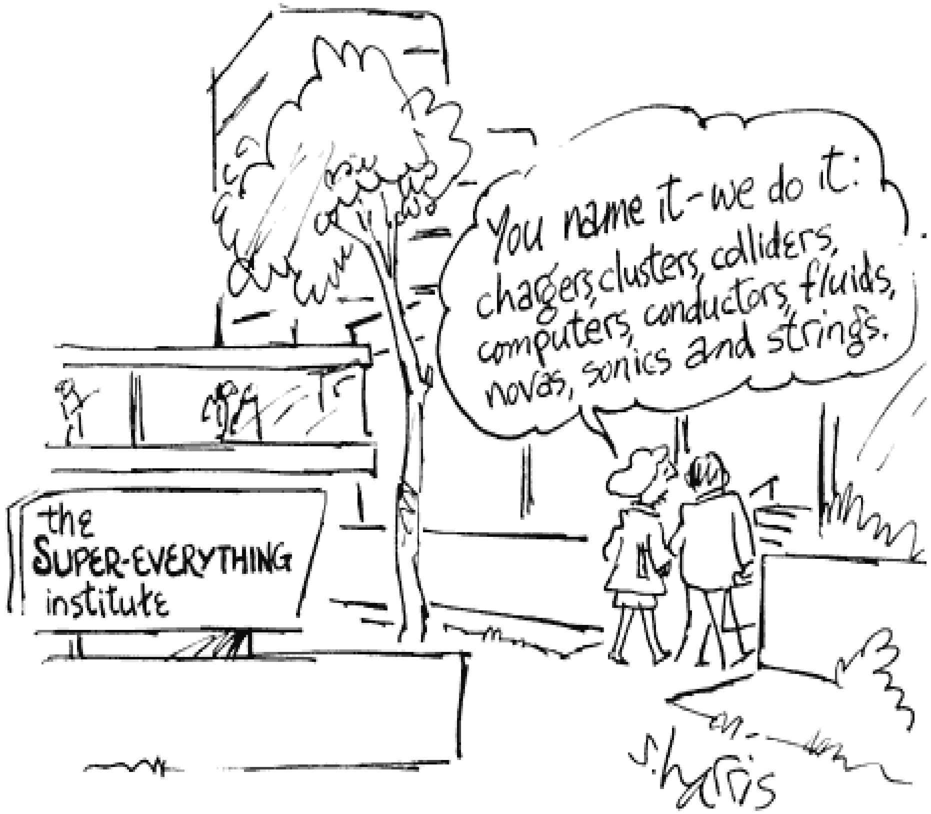
M. Martínez-Pérez

ICREA/IFAE-Barcelona

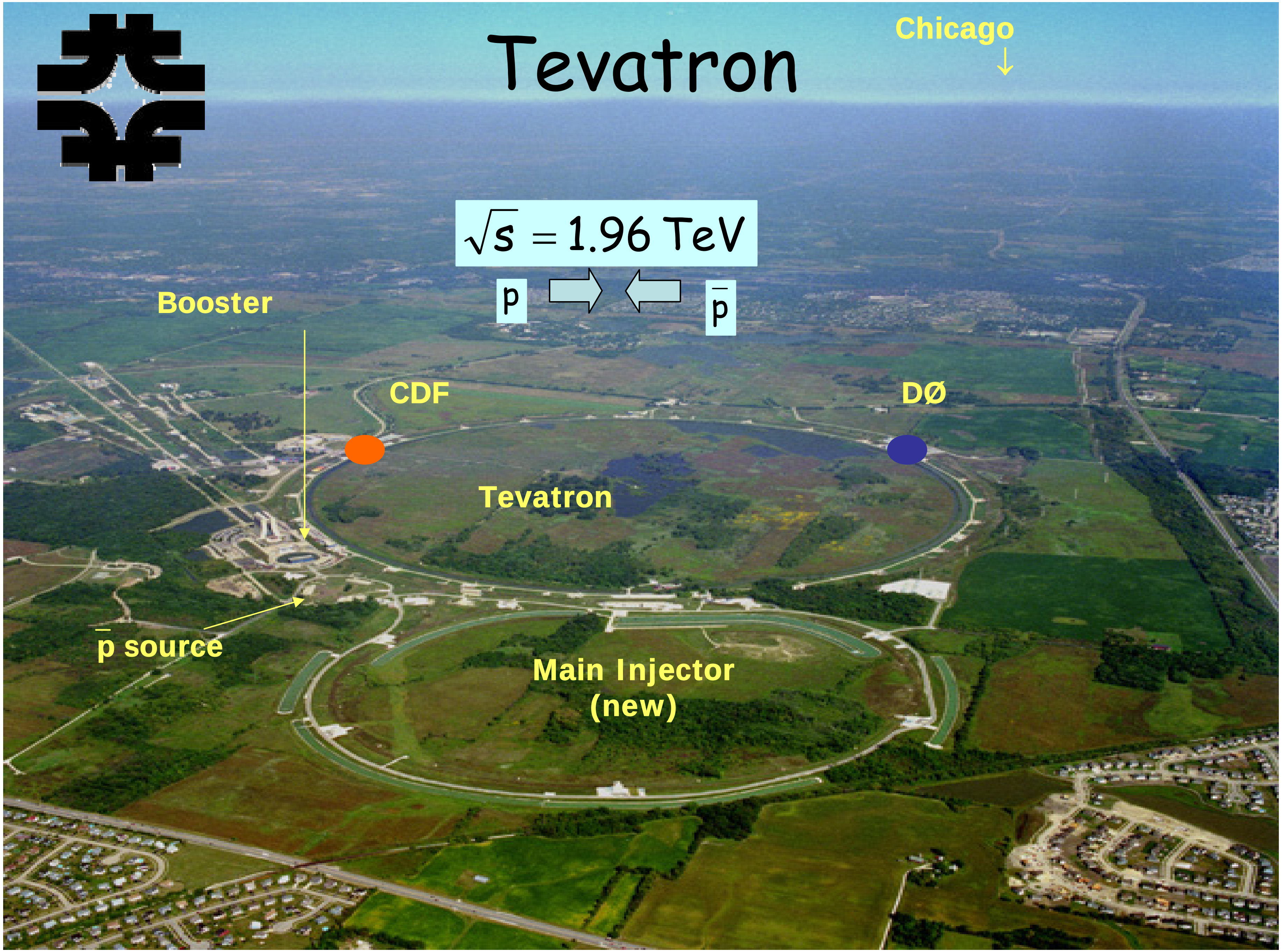
Journée Jets, LPNHE Paris, June 20th 2008

Outline

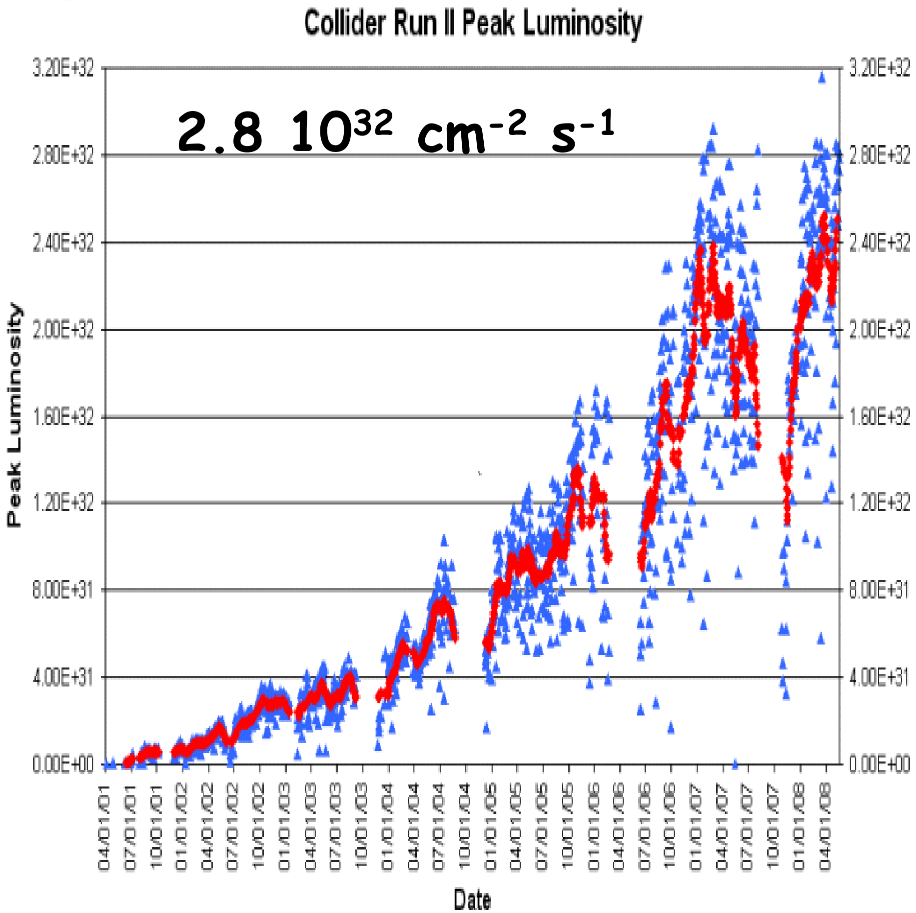
- Tevatron, CDF
- Jet Reconstruction in Run I/RunII
- Jet Energy Calibration Procedure
  - Calorimeter in situ calibration
  - Tuning of Monte Carlo simulation
  - Recipe for cone-based algorithms
  - Modifications for K_T
- QCD at large P_T
  - Inclusive Jet Production
  - Dijet Production
  - B-jet Production
- Underlying Event Studies
  - Energy Flows
  - Jet Shapes
- Z+jets Production
- Final Remarks

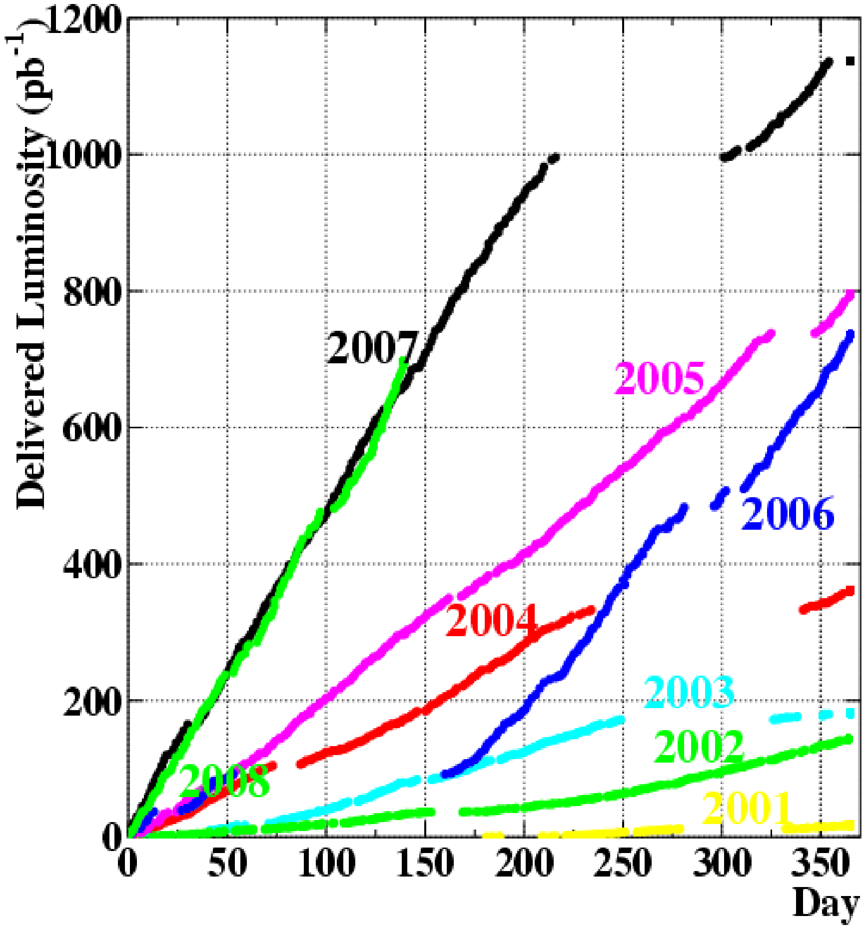


Top-specific jet corrections not covered in this talk..


Tevatron
Chicago
$\sqrt{s} = 1.96$ TeV
p
$\bar{p}$
Booster
CDF
DØ
Tevatron
$\bar{p}$ source
Main Injector
(new)

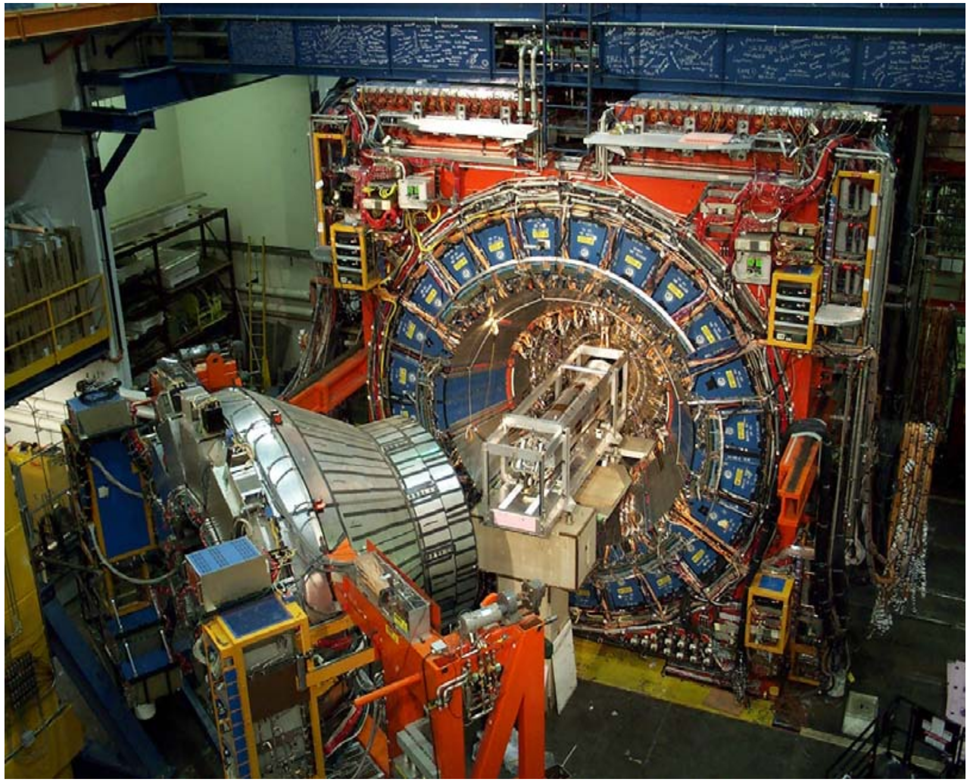
Tevatron Performance

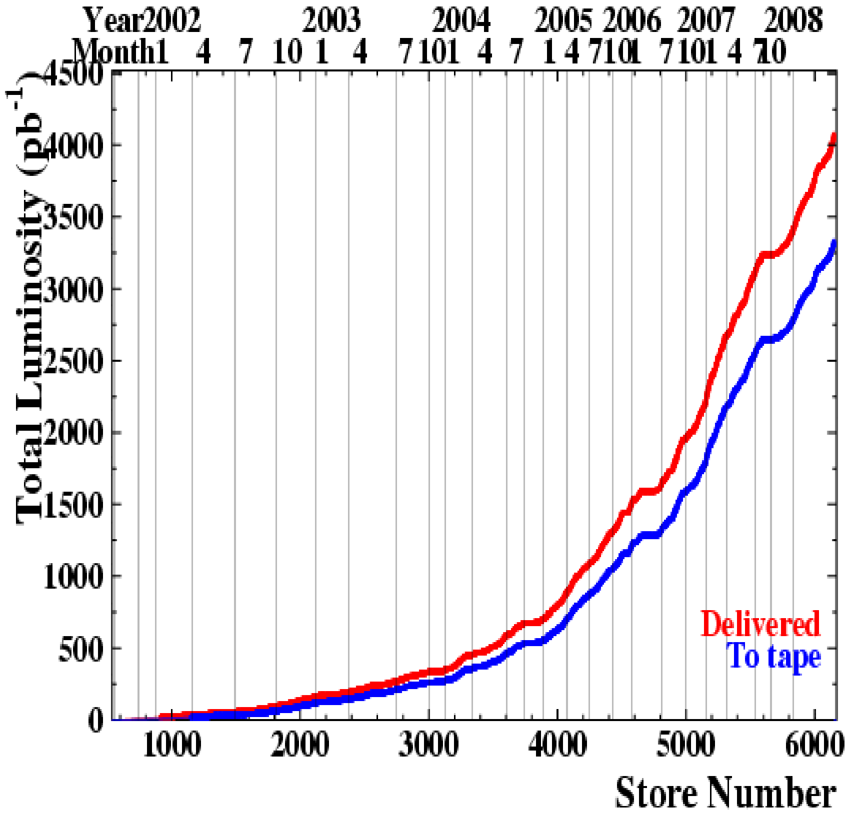




Tevatron delivered > 4 fb^{-1}
(6-7 fb^{-1} expected by end FY09)

CDF Detector

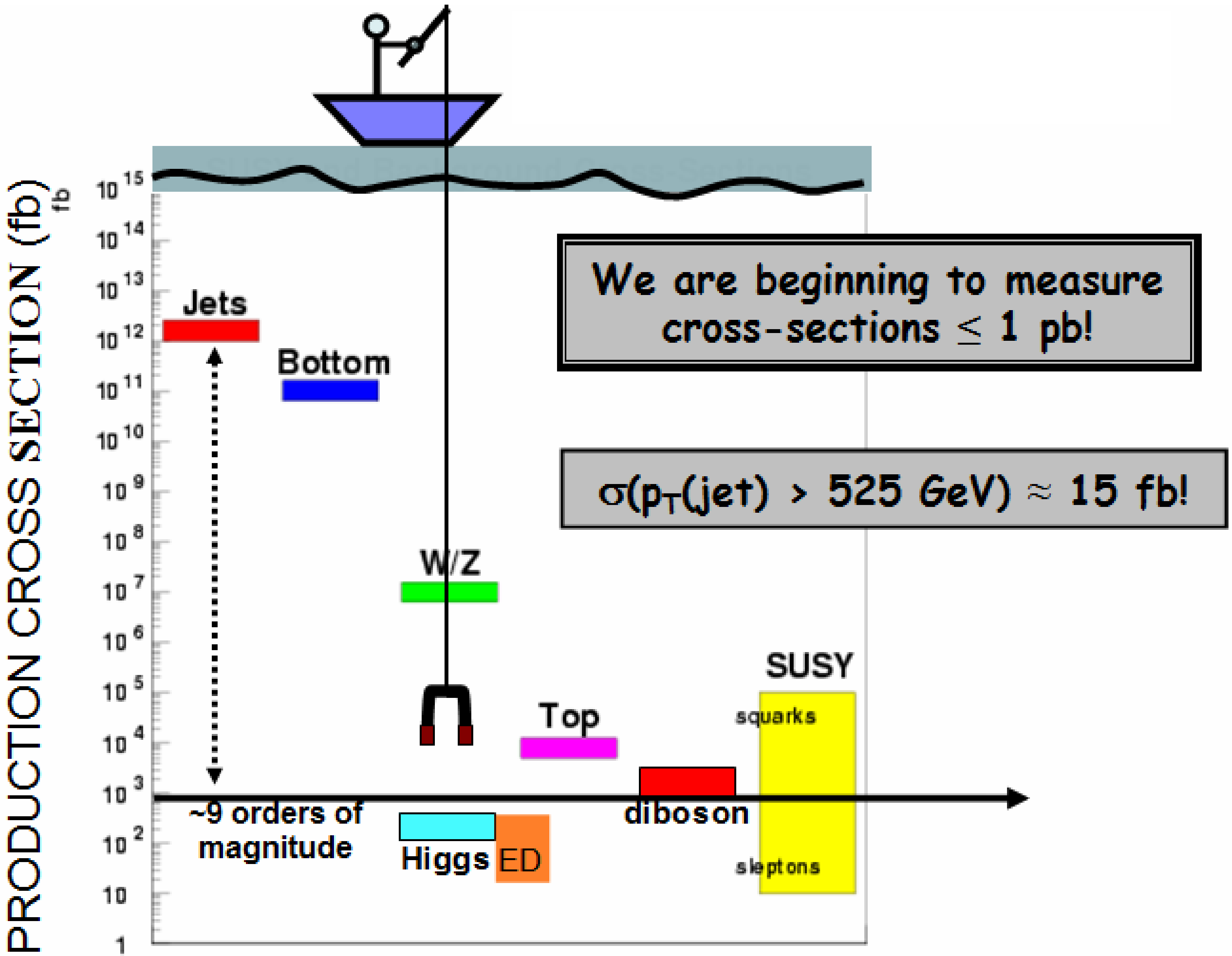




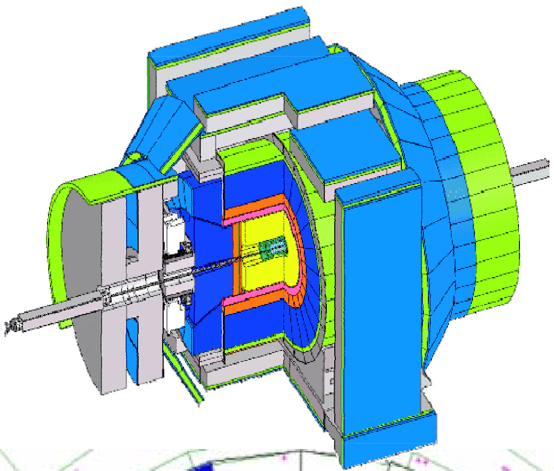
CDF operating well and recording physics quality data with very high efficiency (~85%)

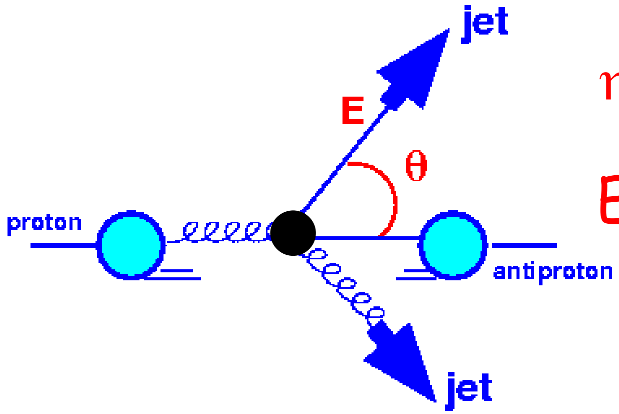
The experiment has already collected > 3.2 fb-1 on tape

Tevatron Jet Physics



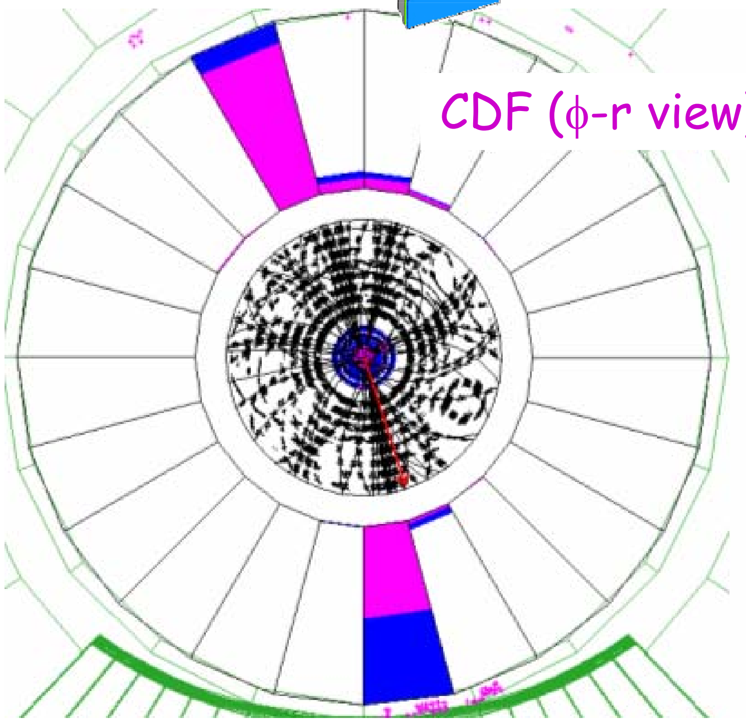
High P_T Jet Event in CDF



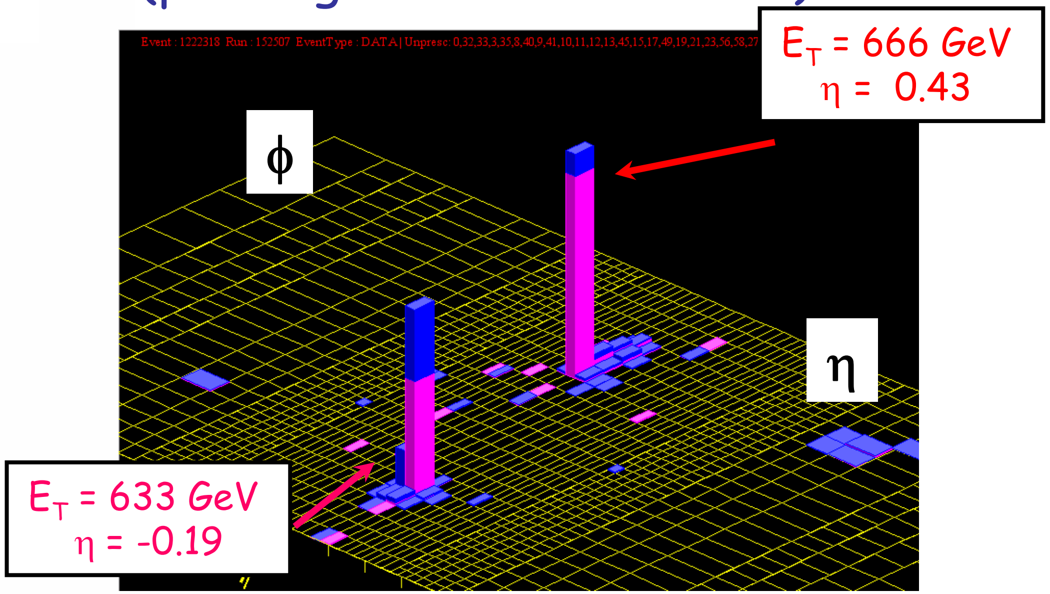


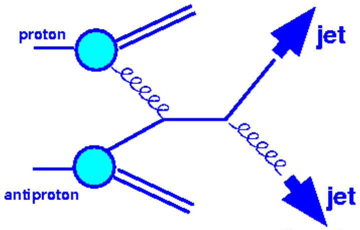
$$\eta = -\ln(\tan\frac{\theta}{2})$$

$$E_T = E\sin\theta$$

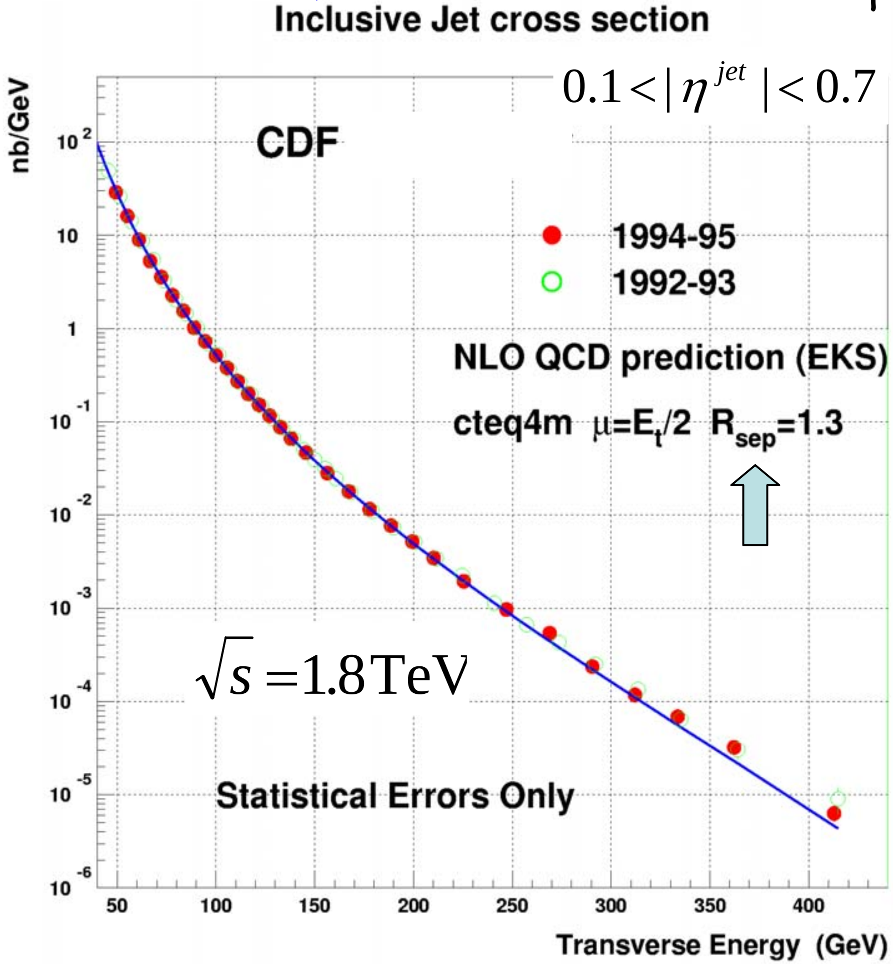


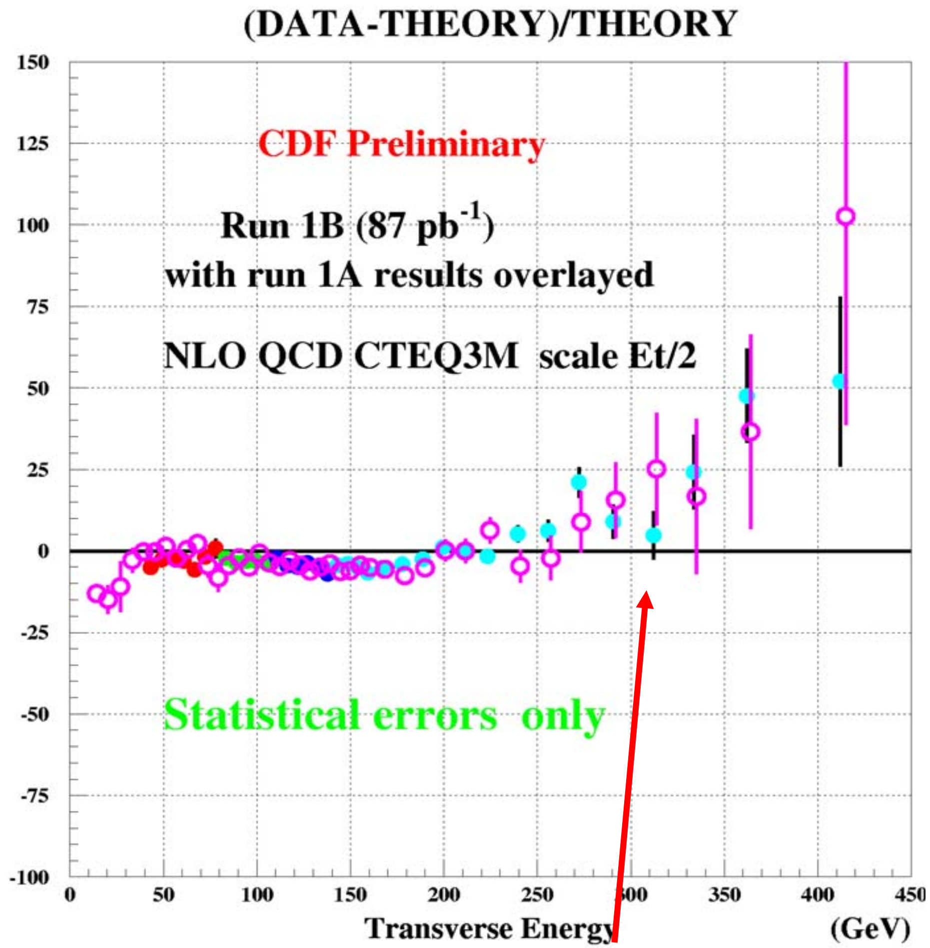
Dijet Mass = 1.36 TeV
(probing distance ~10^{-19} m)





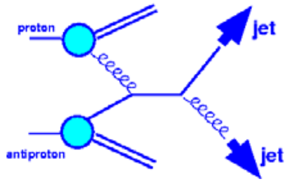
Run I $\frac{d\sigma}{dE_T^{JET}}$ Results





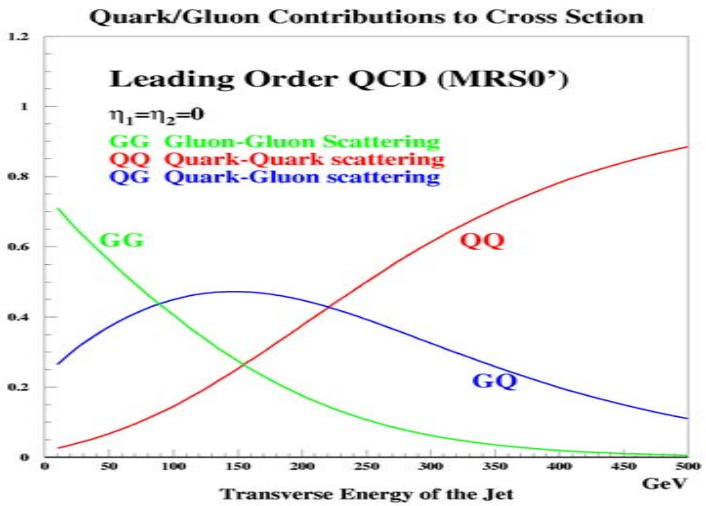
Run I data compared to pQCD NLO

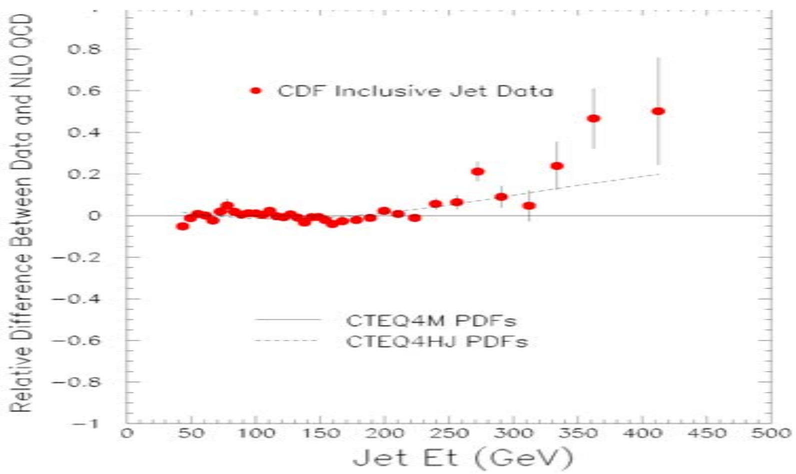
Observed deviation in tail ……..
was this a sign of new physics ?

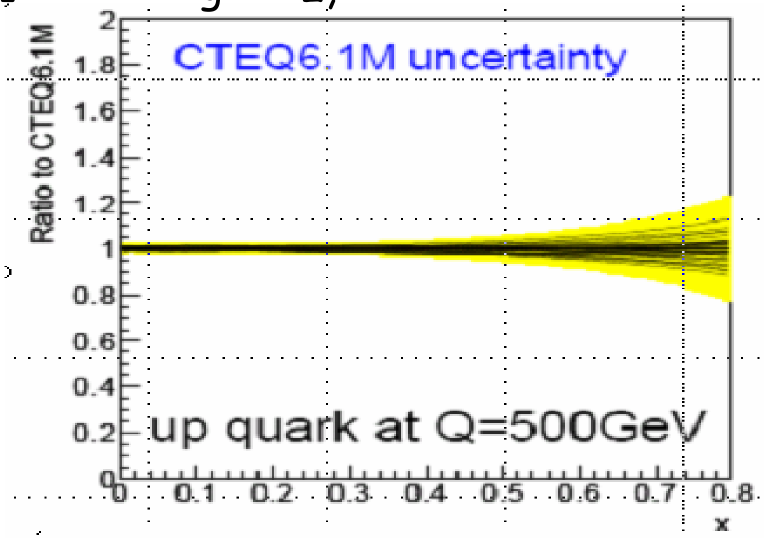


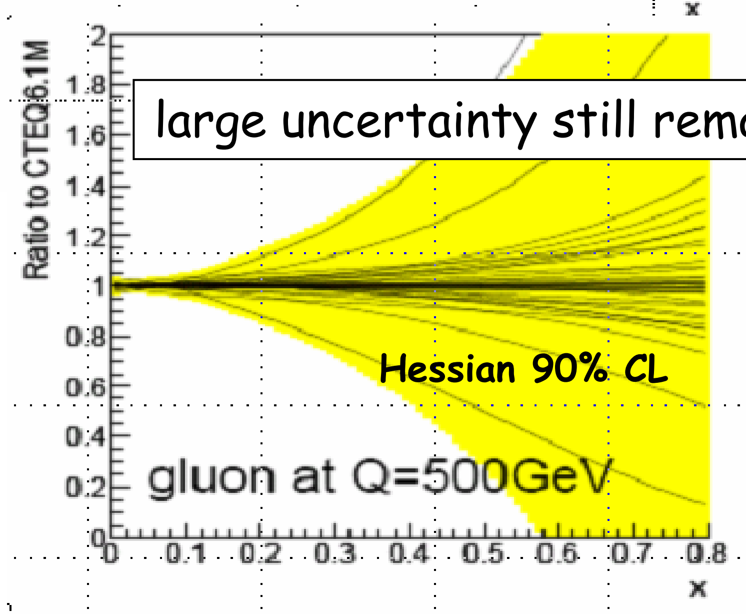
gluon PDFs at high-x

$$\sigma^{total} = \sum \int dx_1 dx_2 f_q(x_1,Q^2) f_g(x_2,Q^2)\sigma^{parton}$$









large uncertainty still remains

Important GG and GQ contrib. at high-E_T

...room for SM explanation....

Run I Cone algorithm

1. Seeds with $E_T > 1$ GeV

2. Preclustering…and ratcheting

3. Draw a cone around each seed and reconstruct the "proto-jet"

$$E_T^{jet} = \sum_k E_T^k,$$

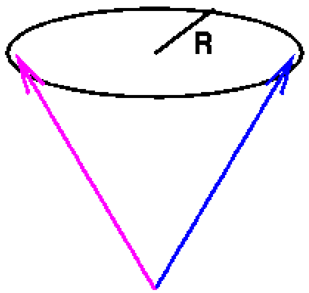
$$\eta^{jet} = \frac{\sum_k E_T^k \cdot \eta_k}{E_T^{jet}}, \quad \phi^{jet} = \frac{\sum_k E_T^k \cdot \phi_k}{E_T^{jet}}$$

4. Draw new cones around "proto-jets" and iterate until stability is achieved

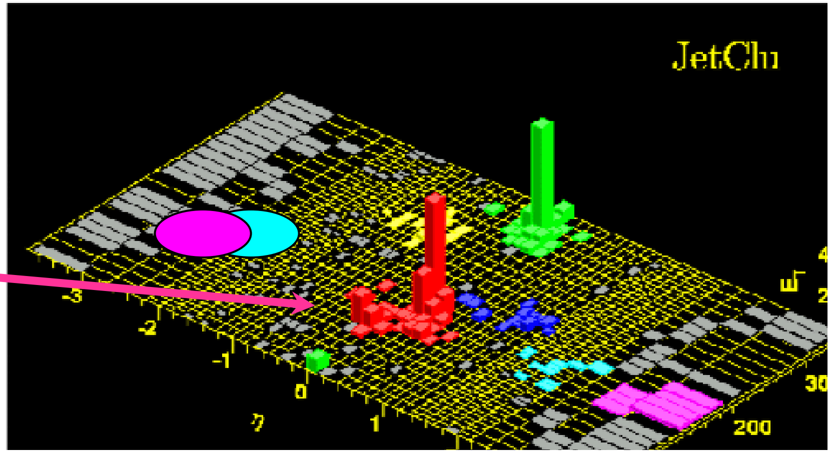
5. Look for possible overlaps

merged if common transverse energy between jets is more than 75 % of smallest jet…..

In inclusive jet production:
pQCD NLO does not have overlaps
(at most two partons in one jet)

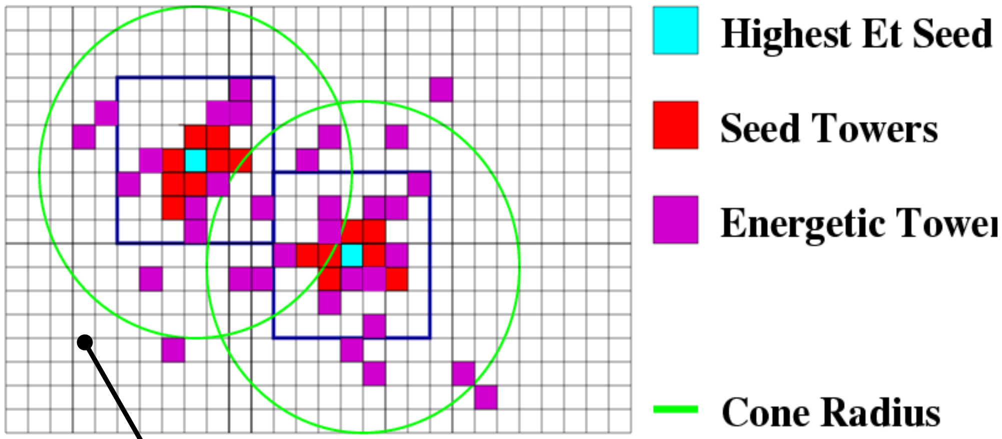


Therefore it uses larger cone
R' = Rsep x R to emulate
experimental procedure
-> arbitrary parameter



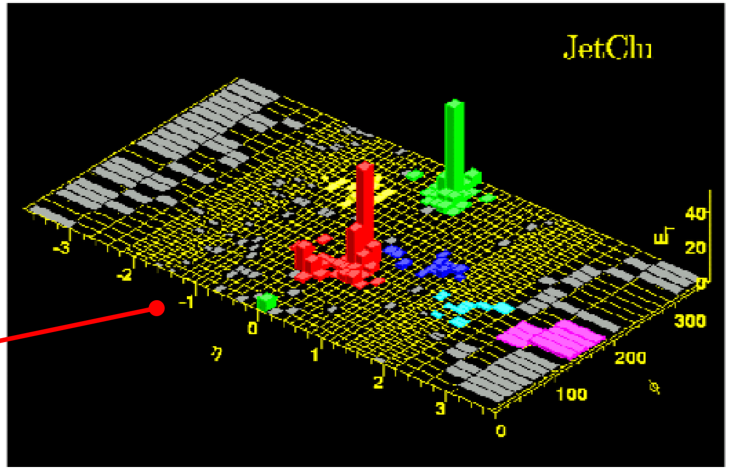
Pre-clustering and ratcheting

- Pre-clustering:
  - Adjacent seed towers are clustered before algorithm starts considering a window of 2Rx2R towers in CAL
  - Centroid is now the new seed



Significant impact on final jet algorithm

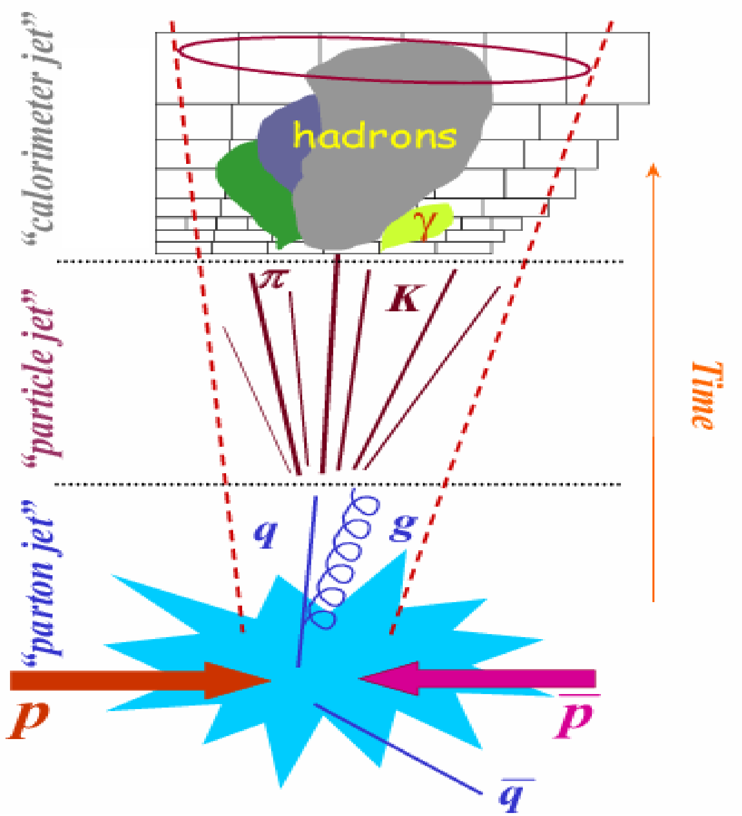
- Ratcheting:
  - During iteration, seed towers belonging to a given cluster are always included in the centroid calculation….and thus will never leave the jet…..
  - Jet is not free to explore the full ($\eta-\phi$) space and ends having "particular shapes"

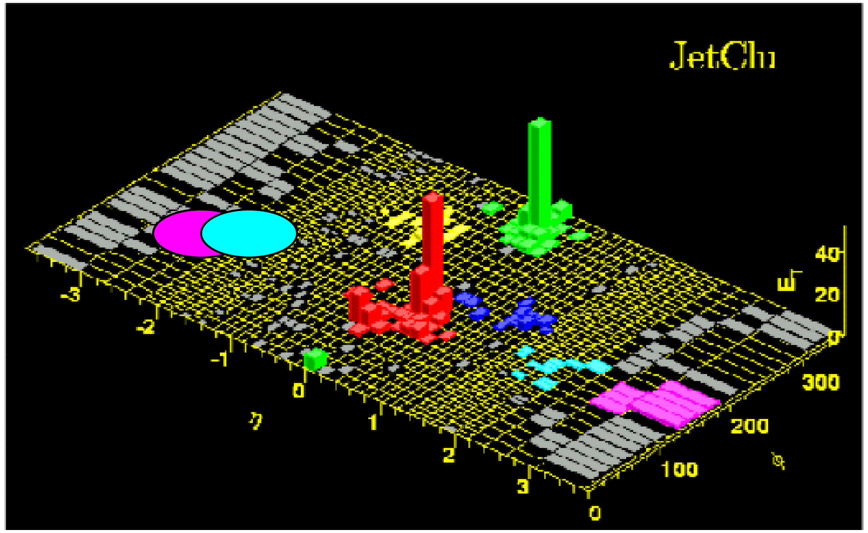


- Attached to CDF geometry and impossible to emulate at hadron level !!

Motivation for the K_T algorithm

- Run I cone-based algorithms is not infrared/collinear safe → Midpoint ☹ ?
- Cone-based jet algorithms include an "experimental" prescription to resolve situations with overlapping cones
- This is emulated in pQCD theoretical calculations by an arbitrary increase of the cone size : R → R' = R * 1.3 ☹





Nature (QCD ?) prefers to separate partons into jets according to their relative transverse momentum

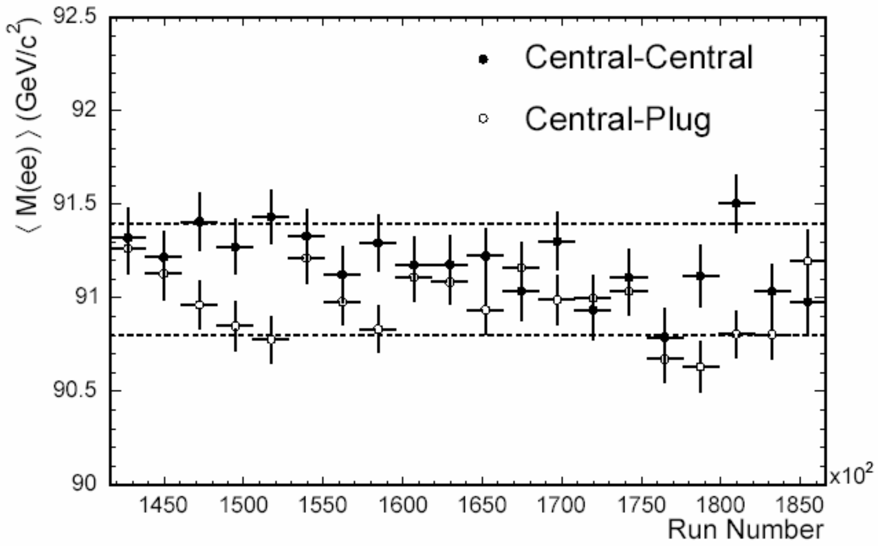
⇩

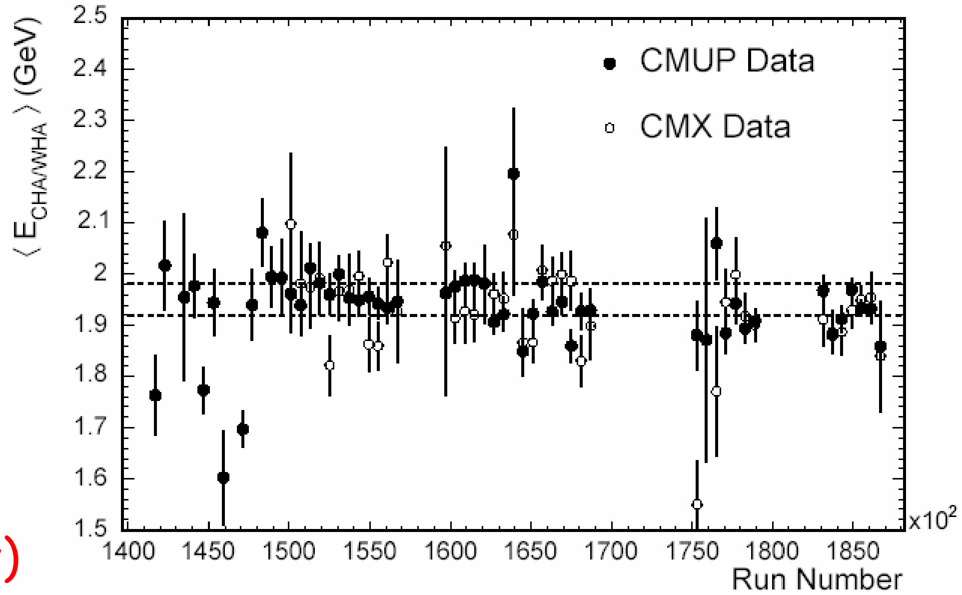
K_T algorithm preferred by theory

In situ CAL Calibration vs Time

- Electromagnetic Calorimeter
  - Tower-to-tower relative calibration carried out using e/p for electrons (cluster vs track)
  - Absolute energy scale using $Z \rightarrow e^+e^-$ samples (Z-mass peak)
- Hadronic Calorimeter:
  - Using MIPs from $W \rightarrow \mu\ \nu$ and J/Ψ to test stability vs time
- Results
  - 0.3% uncertainty in EM
  - 1.5% uncertainty in HAD

→ 0.5% uncert. on Jet Energy (assumes 70% EM and 30% HAD energy)

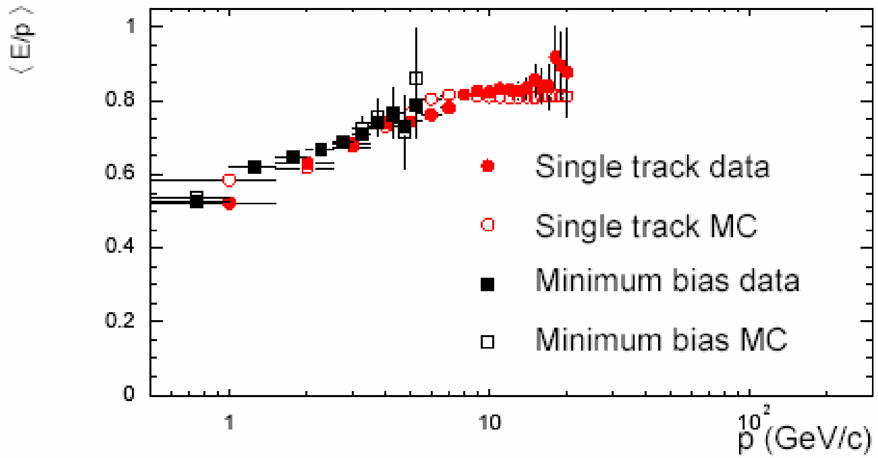


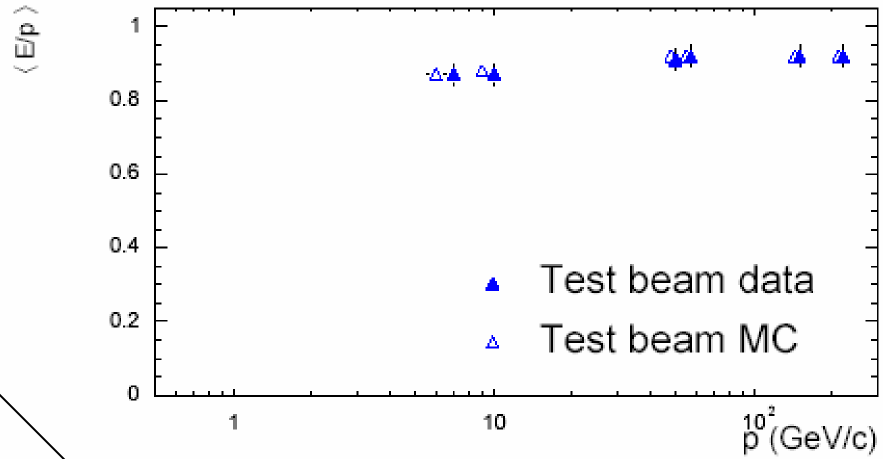


Note on Monte Carlo Tuning

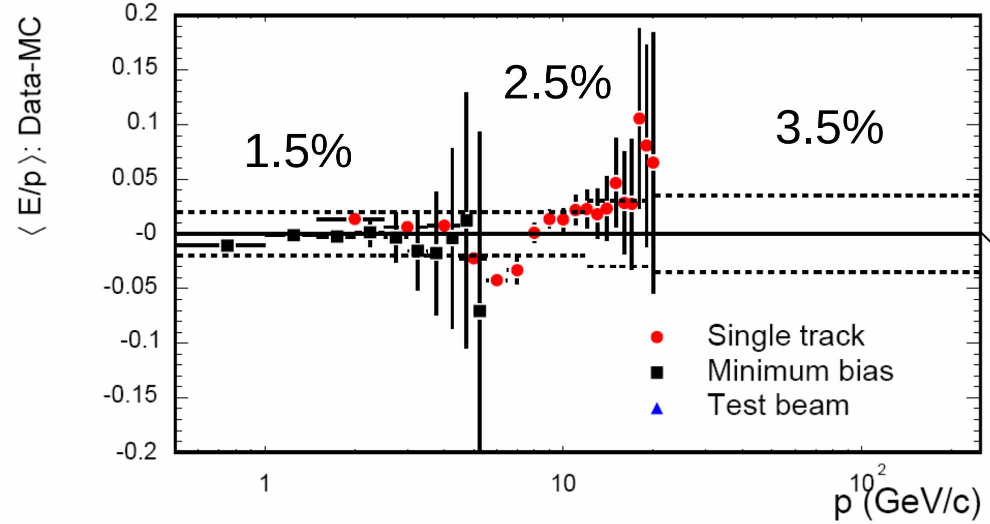
- Lots of work invested to tune the simulation of the calorimeter response to single particles
- Combination of test beam data and data samples of isolated tracks (uses E/p)
- Also a lot of work to tune the shower profiles and parameters in GFLASH

For the central calorimeter





uncertainties



plus 1.9% (1.6%) uncertainty at the boundary between towers for HAD (EM)

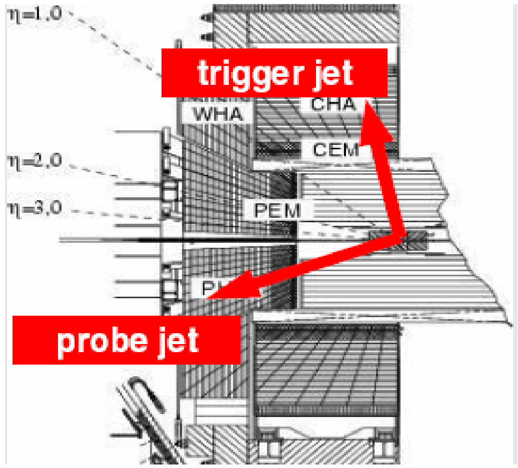
Jet Energy Corrections
(for a cone-based jet algorithm)

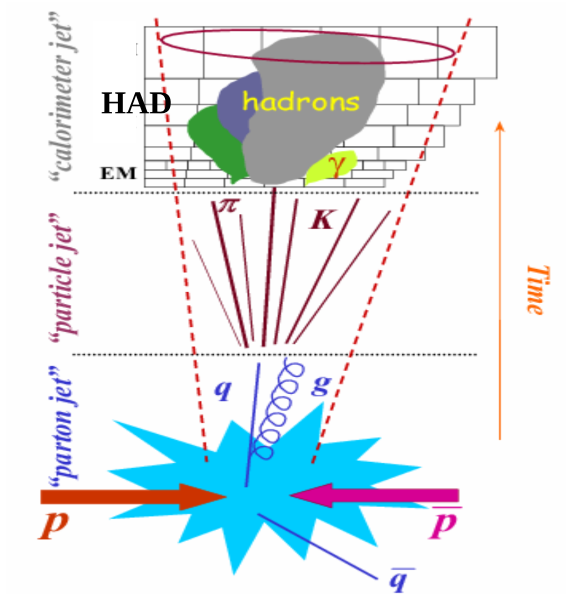
1. Relative Corrections
   - Jet response referred to central region
   - Imposing dijet balance in dijet events
   - Bias on dijet definition (veto on third jets)

2. Pileup
   - Due to multiple pp collisions at high Inst. Lumi
   - Remove a given amount of transverse energy for each additional primary vertex
   - Obtained using MB and random cones in $\eta-\phi$

3. Average correction to hadron level
   - Bring the jet energy back to the hadron level (correct for calorimeter response)
   - Extracted using Monte Carlo samples

4. Corrections “back to the parton level” 😐☹
   - Not-well defined and model dependent
   - Taken from Monte Carlo samples
   - Used in top mass measurements



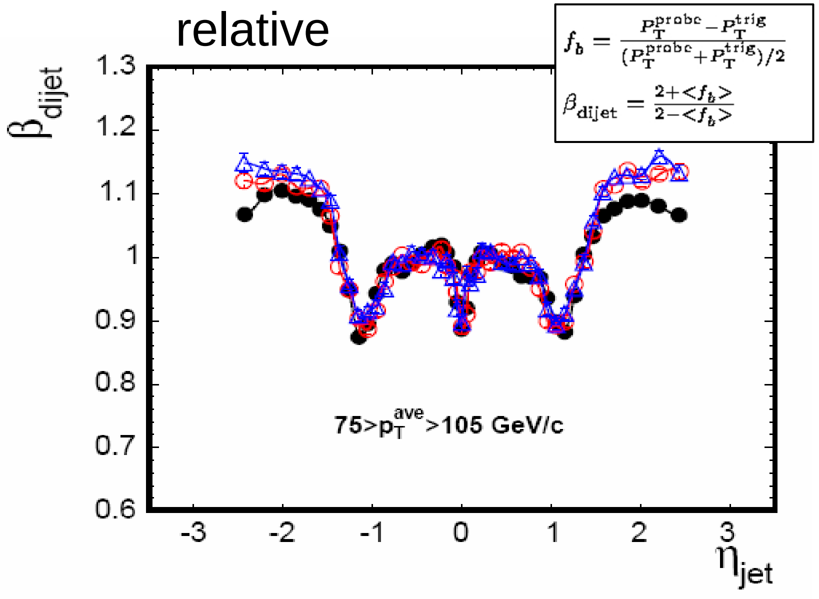


$$P_{T\,jet}(R) = [\, P_{T\,jet}^{raw}(R) \times f_{rel}(R) - MPI(R)] \times f_{abs}(R) - UE(R) + OC(R)$$

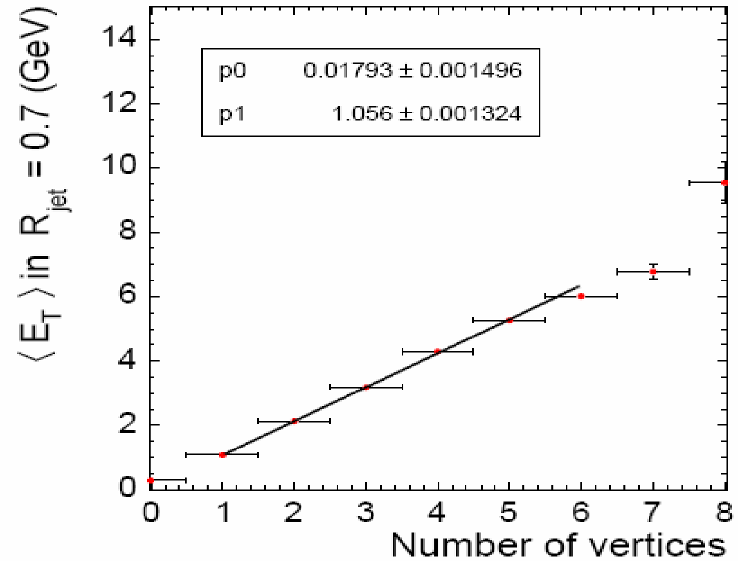
Jet Energy Corrections (cont.)

(for a cone-based jet algorithm)

relative

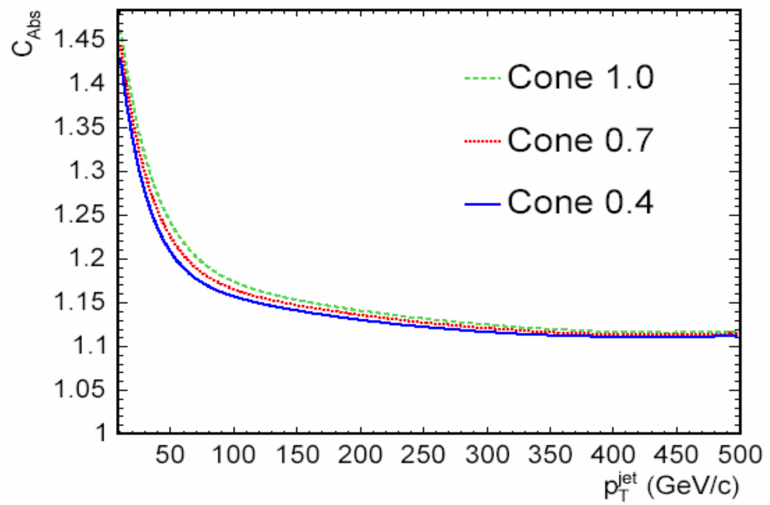


pileup

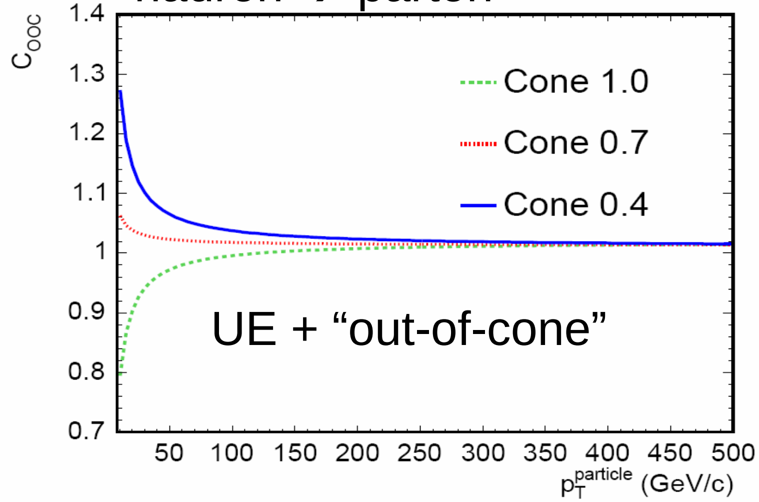


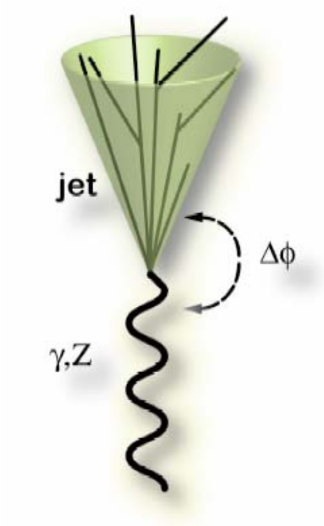
As they appear in CDF NIM publication (2005)

detector → hadron



hadron → parton

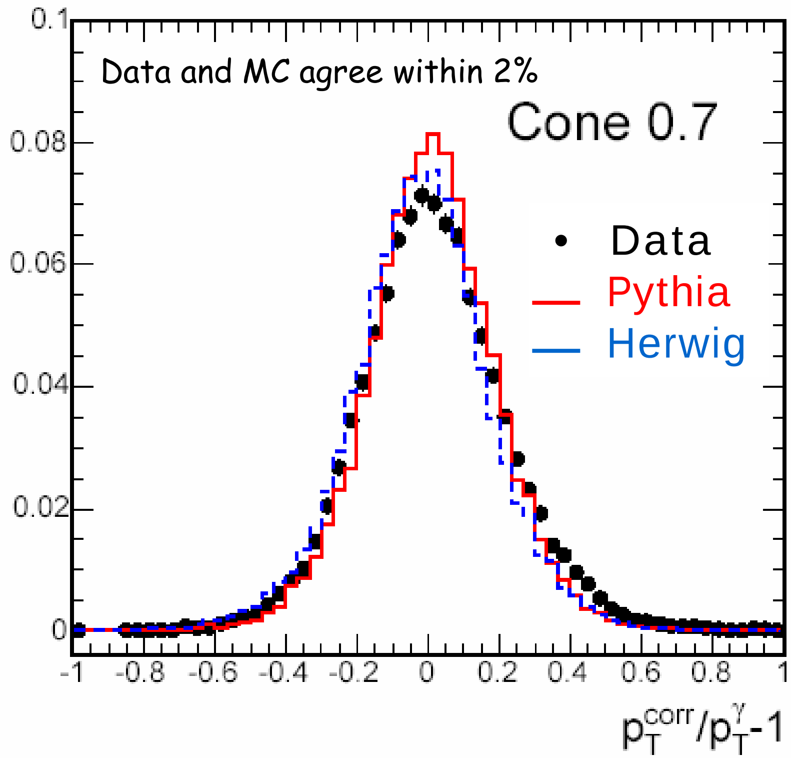




Tests with γ/Z+jet

$$p_T\text{Balance} = \frac{p_T^{jet}}{p_T^{\gamma}} - 1$$

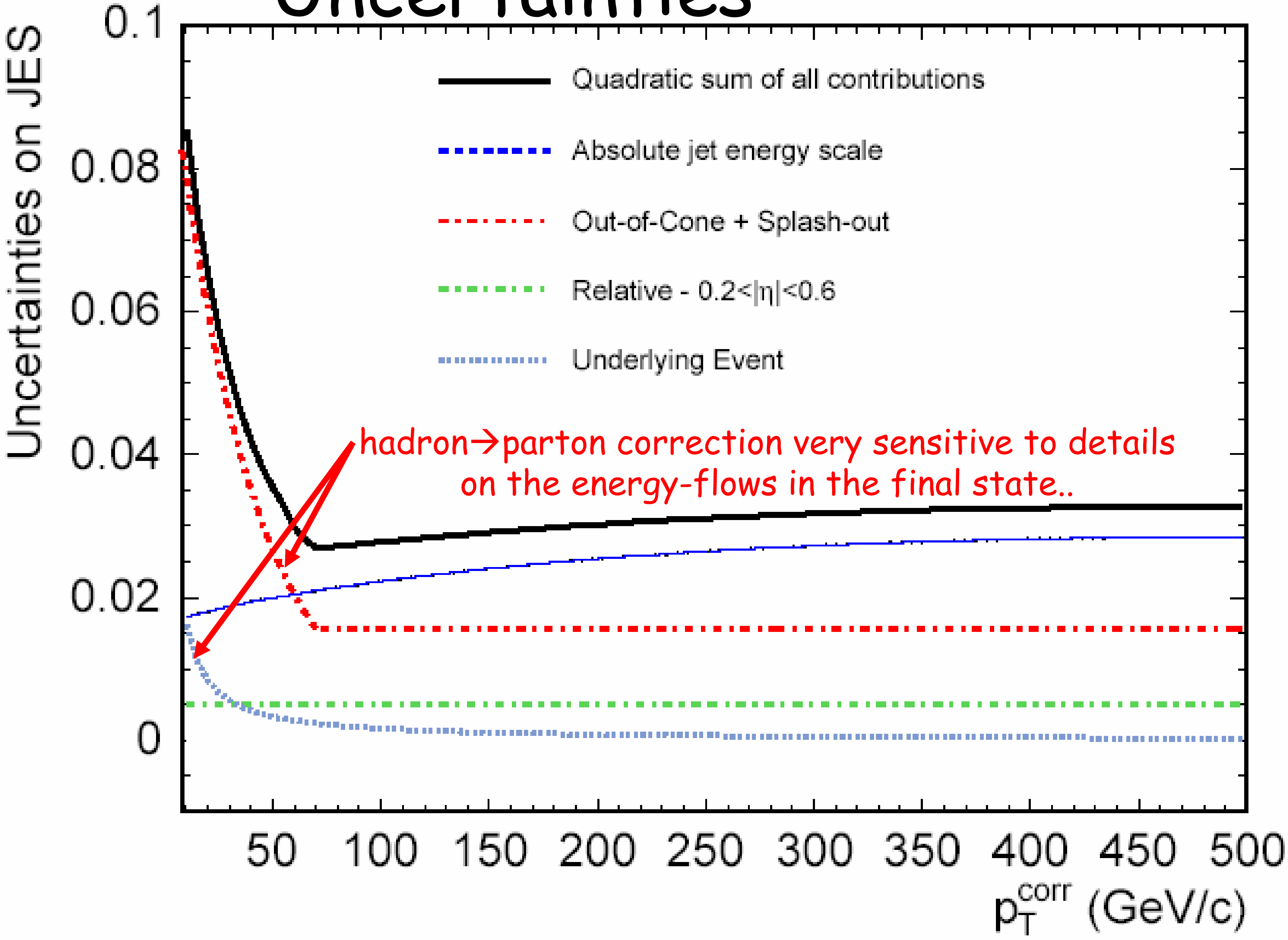
- E_T leading jet > 25 GeV
- E_T (second jet) < 3 GeV
- $\Delta\phi$ (Jet-γ) > 3



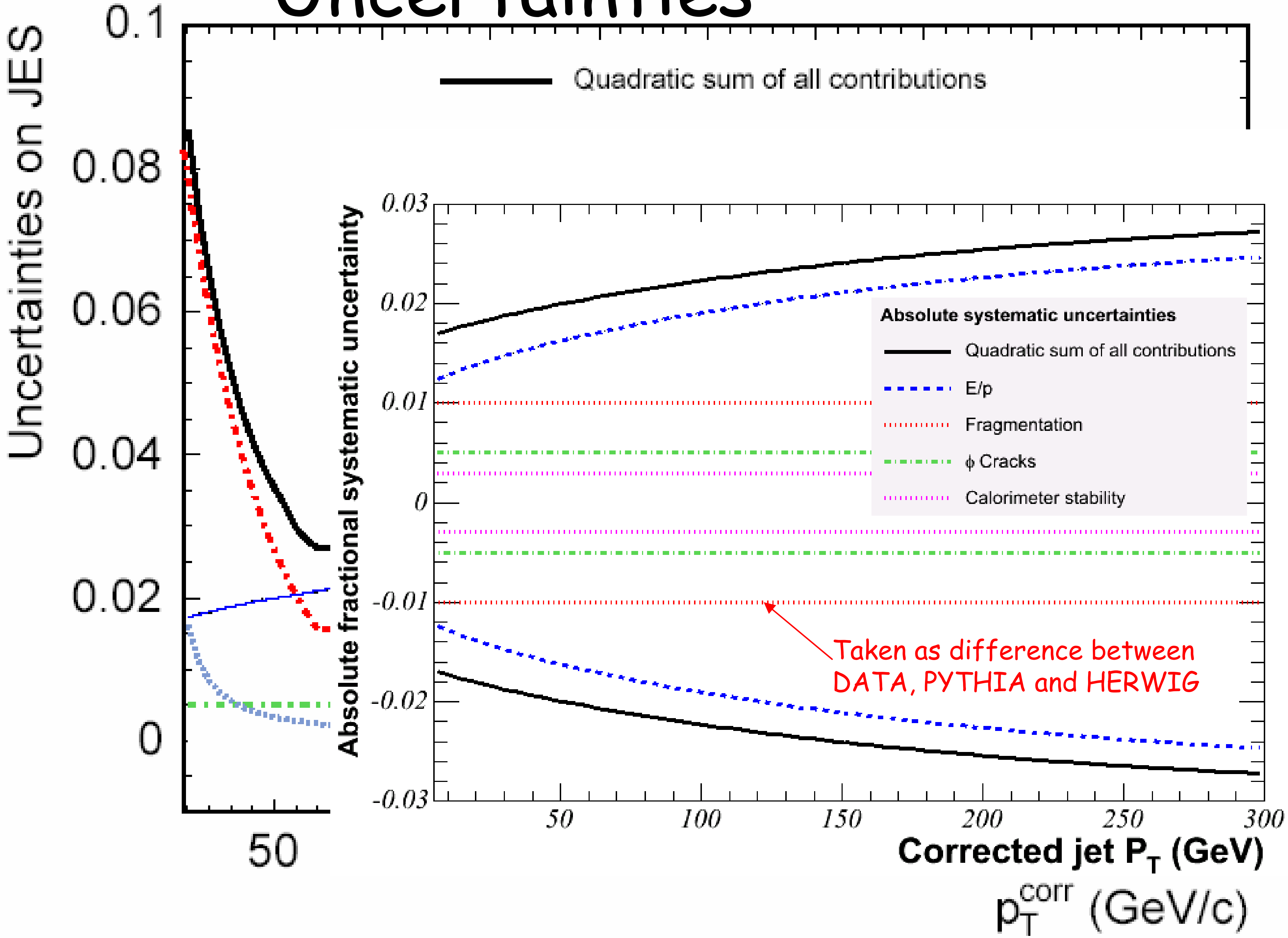
- CDF does not use γ/Z+jets data to calibrate the calorimeter (it is used just only as a check sample)
- It is used also to determine uncertainties on out-of-cone hadron → parton correction
- Defined as the difference between data and MCs PYTHIA and HERWIG in the energy observed at 1.0 < R < 1.3

In MC …very sensitive to details of the hadronic final state (2nd jets veto, UE…)

Uncertainties

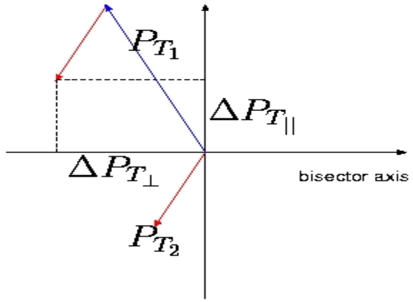


Uncertainties



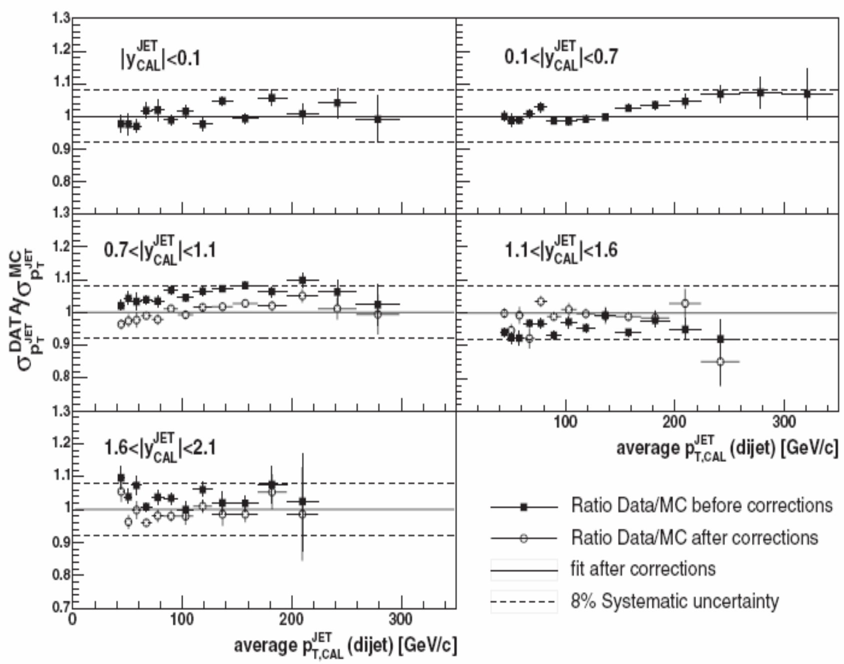
$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}$$

Notes on Jet Correction for K_T

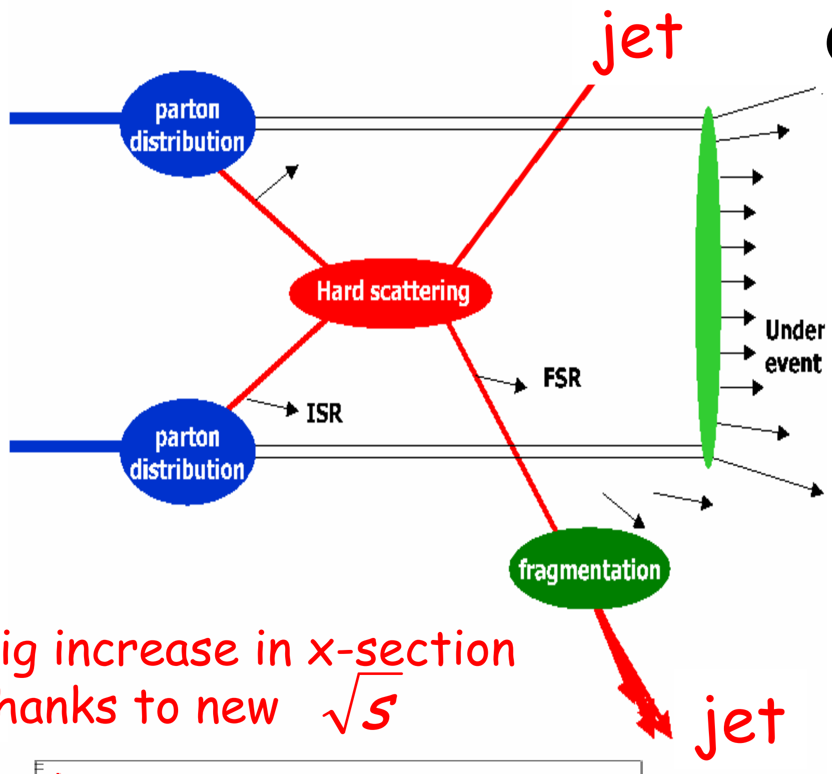


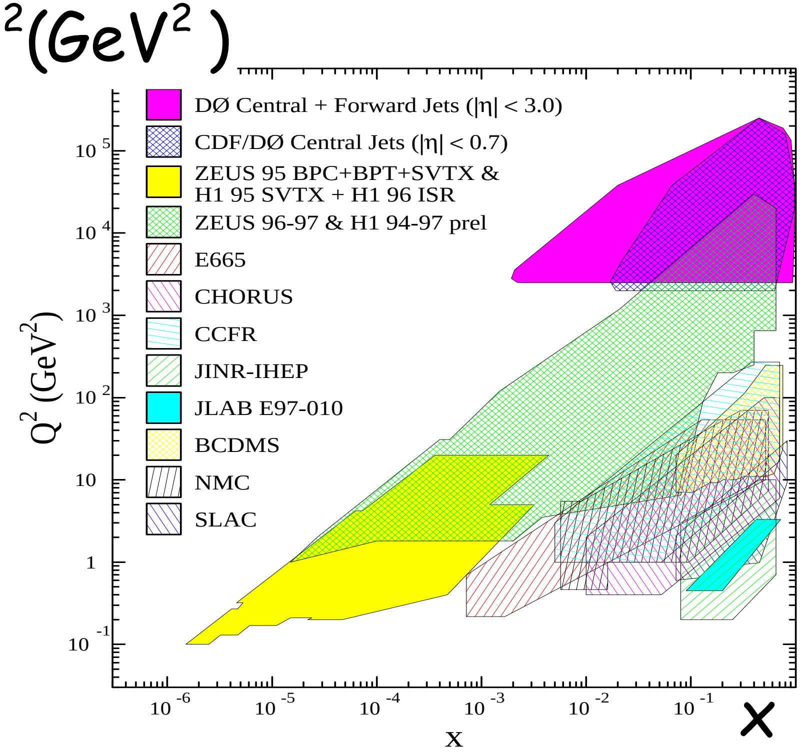
- $\sigma_{||}$ = RMS of the $\Delta p_T^{||}$
- σ_{PERP} = RMS of the Δp_T^{PERP}
- $\sigma_D = \sqrt{\sigma_{||}^2 - \sigma_{PERP}^2}$

- No relative correction applied
- Dijet Balance and Bisector Method employed to test MC simulation (average response and resolution)
  - Some weighting of MC needed
- Pileup correction applied differently
  - still using the number of primary vertices but correction factor per vertex is obtained by requiring the measurement to be independent on Inst. Lumi.
  - For D=0.7 → 1.9 GeV/c per vertex
- Detector → hadron level correction taken from Monte Carlo
  - Same uncertainties applied as in the cone

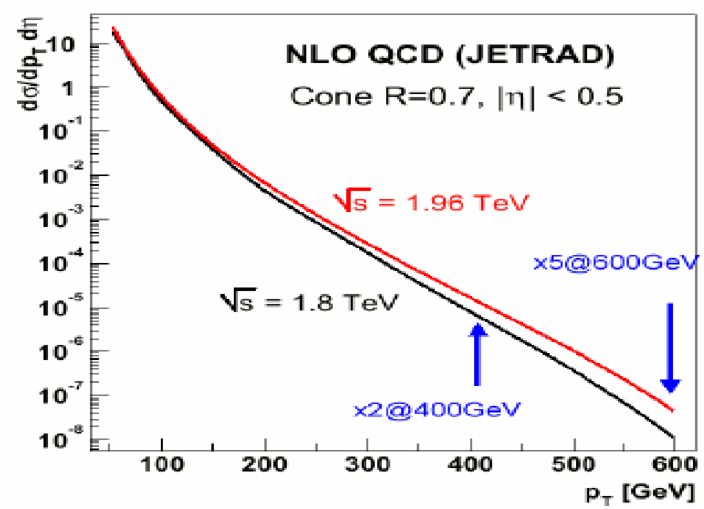


High Pt Jet Physics at 2 TeV





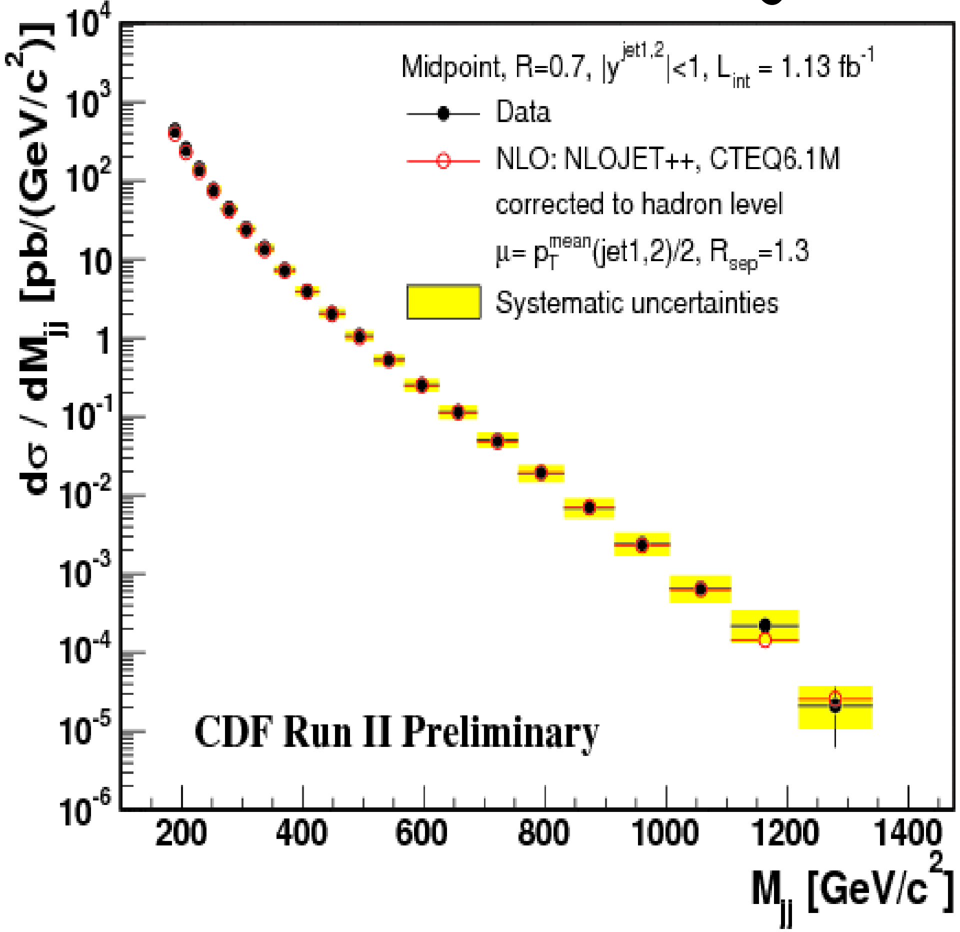
Big increase in x-section thanks to new $\sqrt{s}$

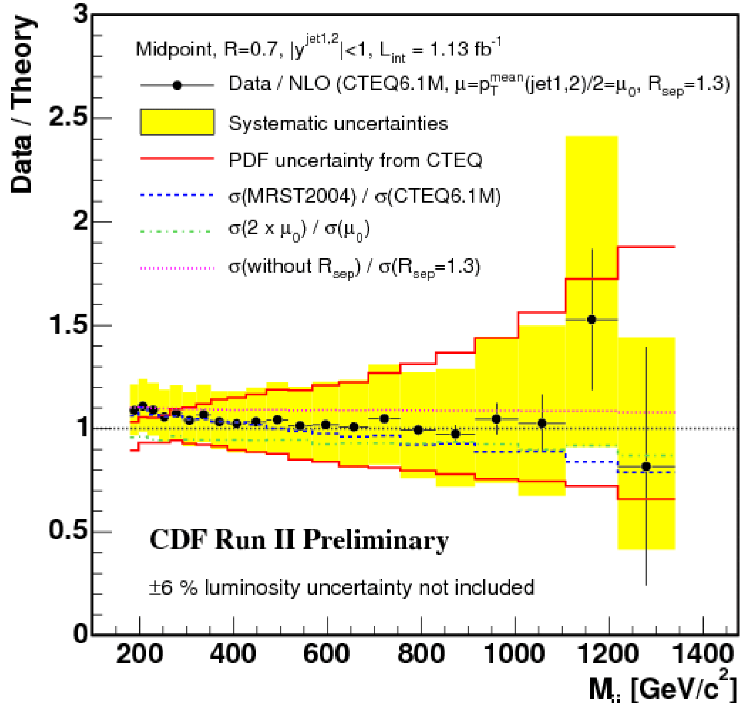


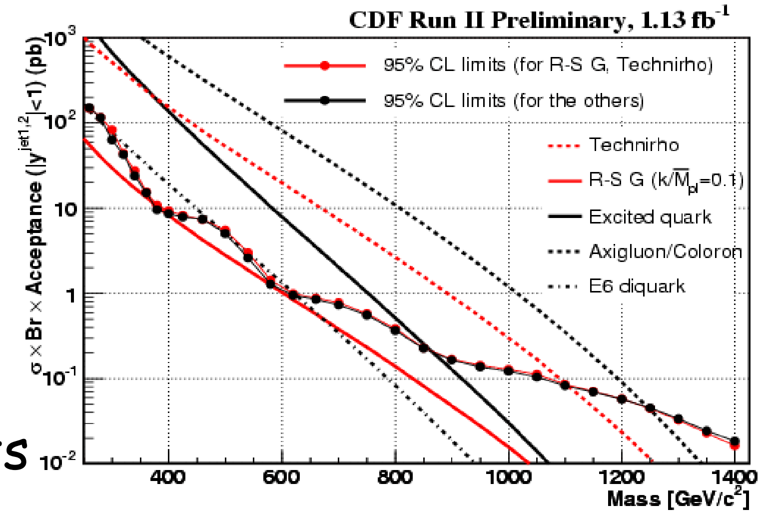
Huge step forward in Run II

- Pt range increased by 150 GeV/c
- Measurements in wide rapidity region
- Use of K_T and cone jet algorithms
- Inclusion of non-pQCD contributions

Dijet Mass







Dijet Mass distribution in good agreement with NLO pQCD predictions

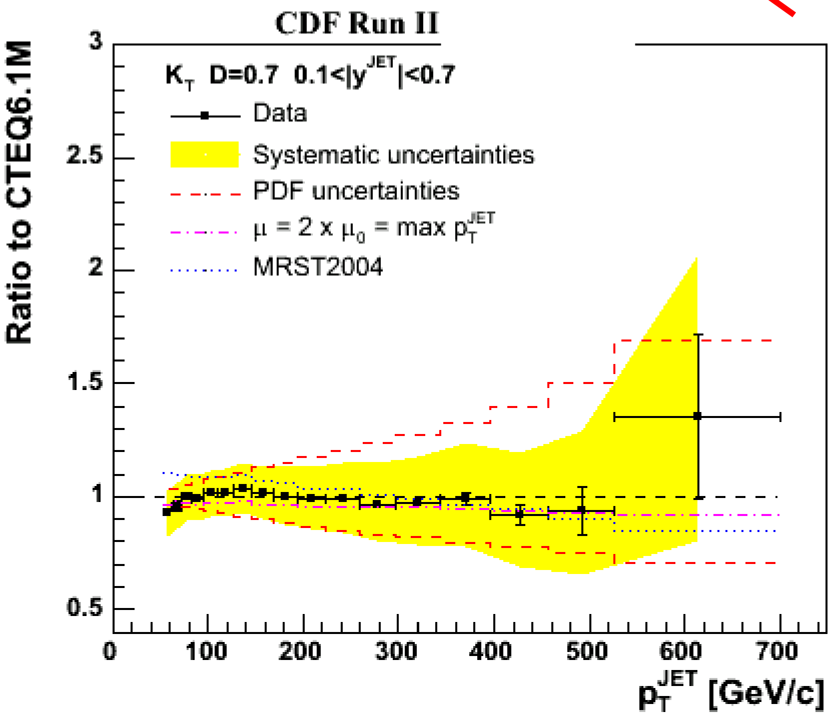
→ Limits on new particles decaying into jets

Inclusive Jet Production

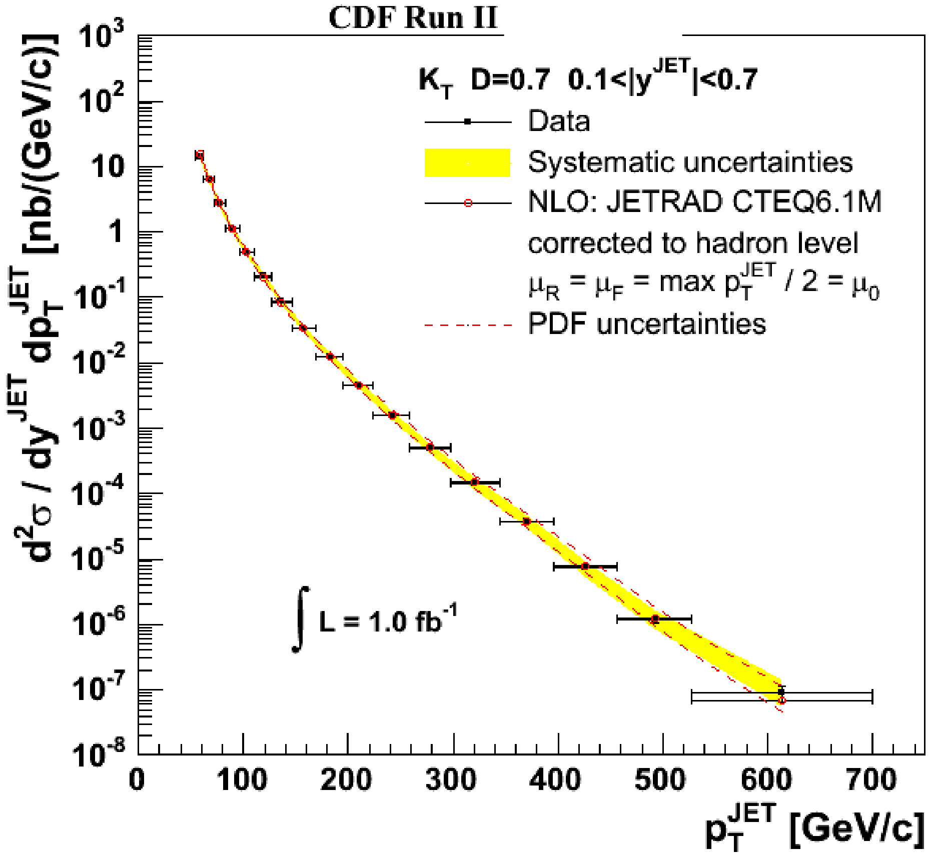
- Inclusive K_T algorithm

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}$$

$$d_i = (P_{T,i})^2$$



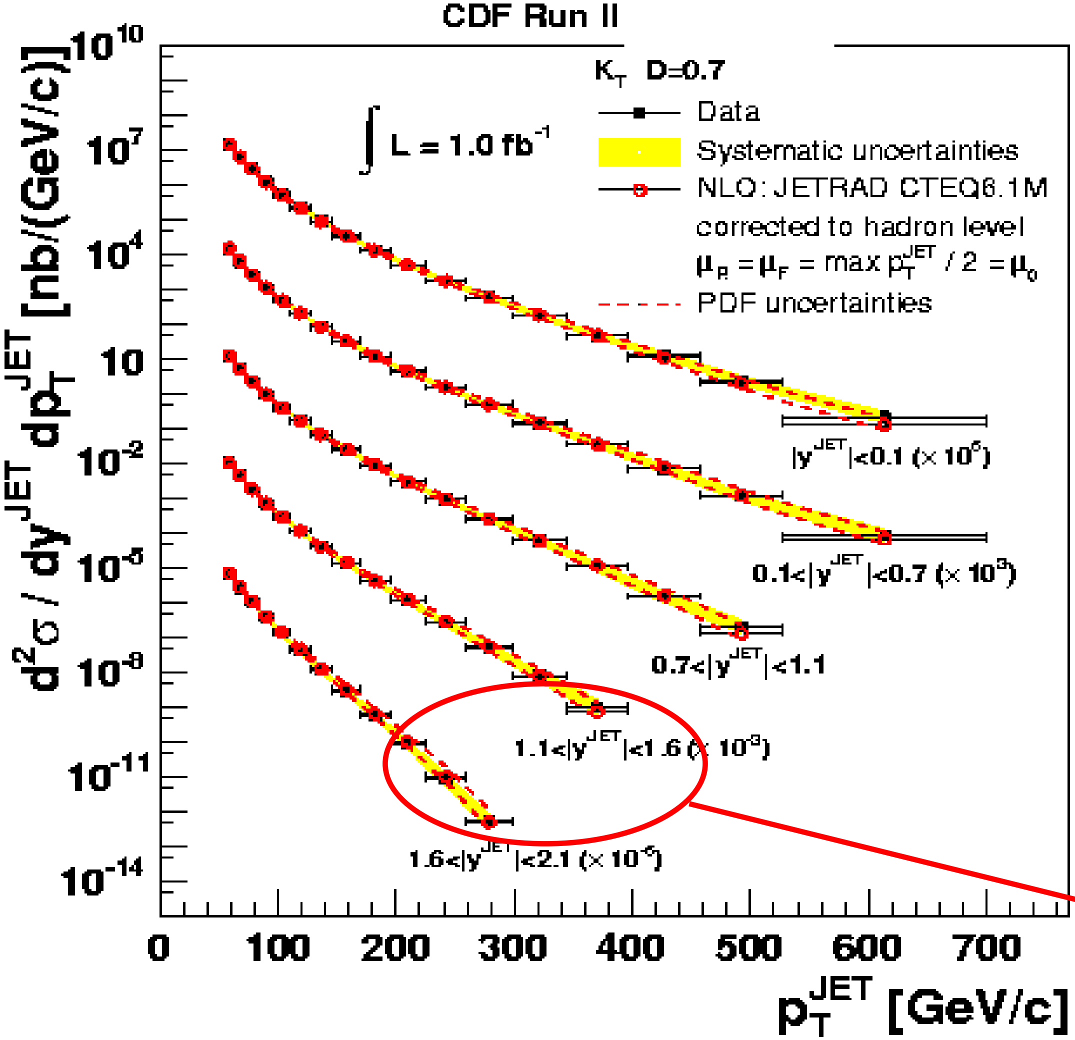
NLO pQCD is corrected for Hadronization & Underlying Event (this is important at low Pt)

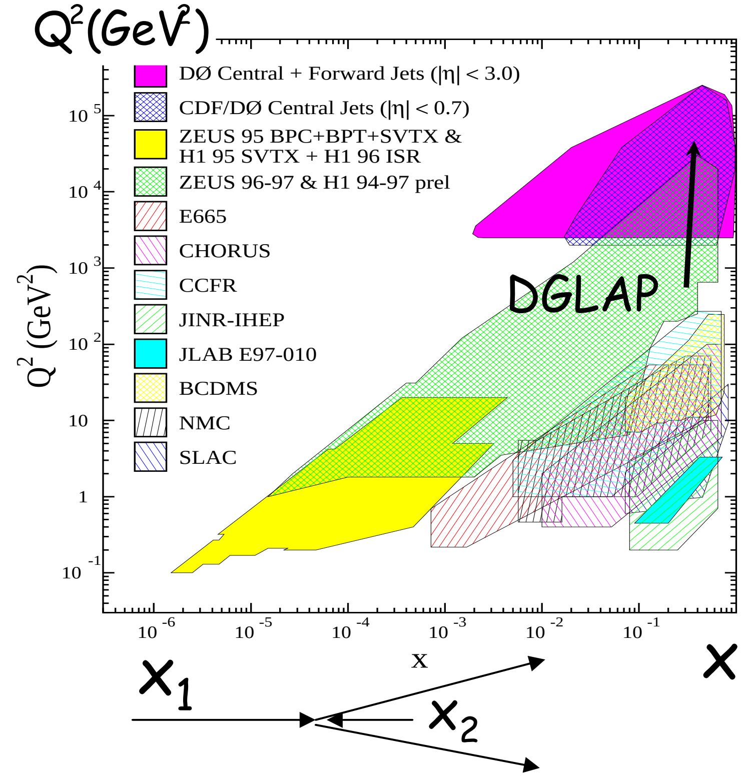


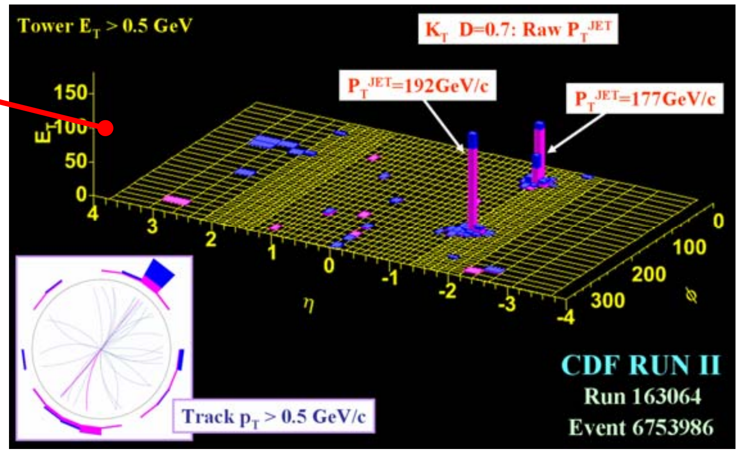
- Good agreement Data vs Theory
  - Data uncertainty -> 2-2.7% e-scale
  - pQCD uncertainty -> PDFs
- K_T robust in hadron collisions

  → relevant for LHC strategies

Measurement in five |y^{jet}| ranges

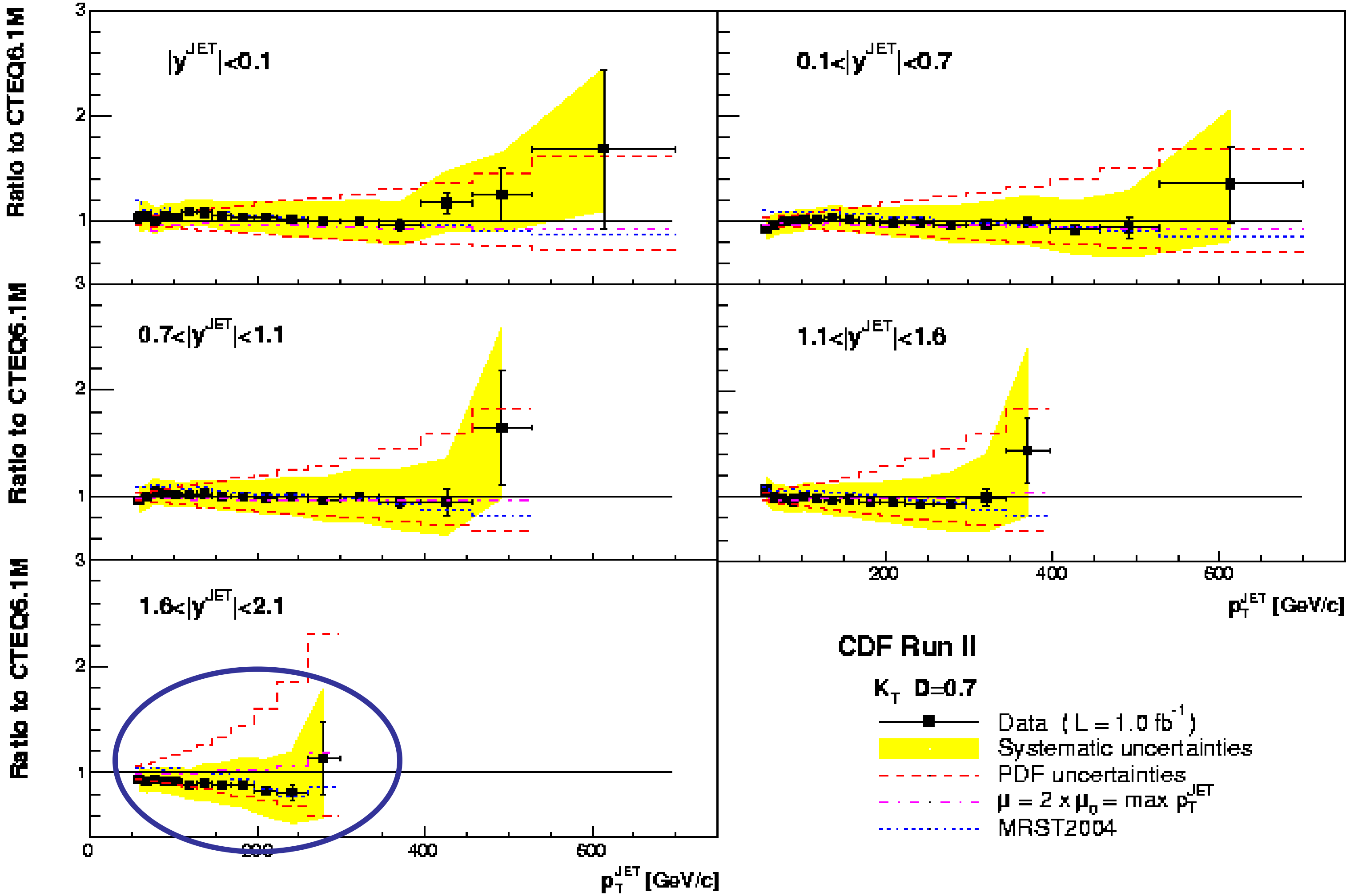






Forward jet measurements further constrain the gluon PDF in a region in P_T where no new physics is expected

Ratio Data/pQCD NLO

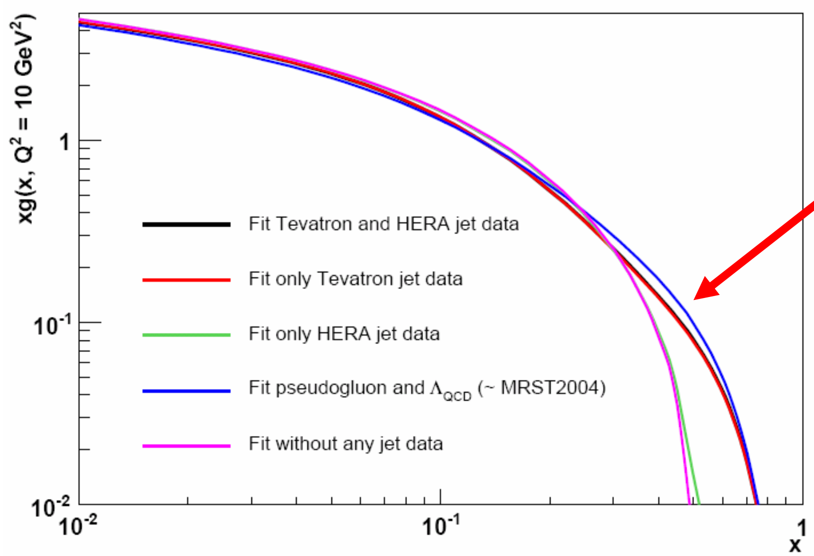


Data uncertainty smaller than that on pQCD NLO

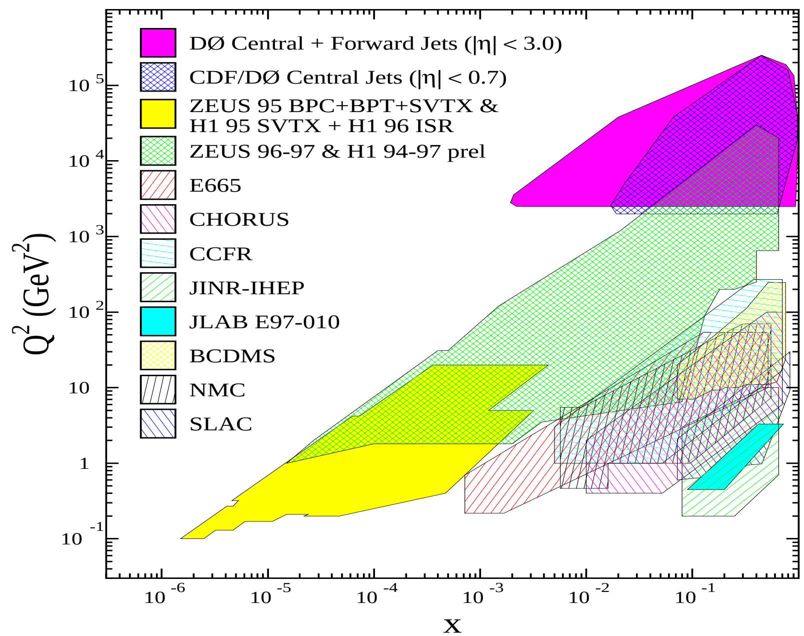
CDF contribution to a better knowledge of gluon PDF

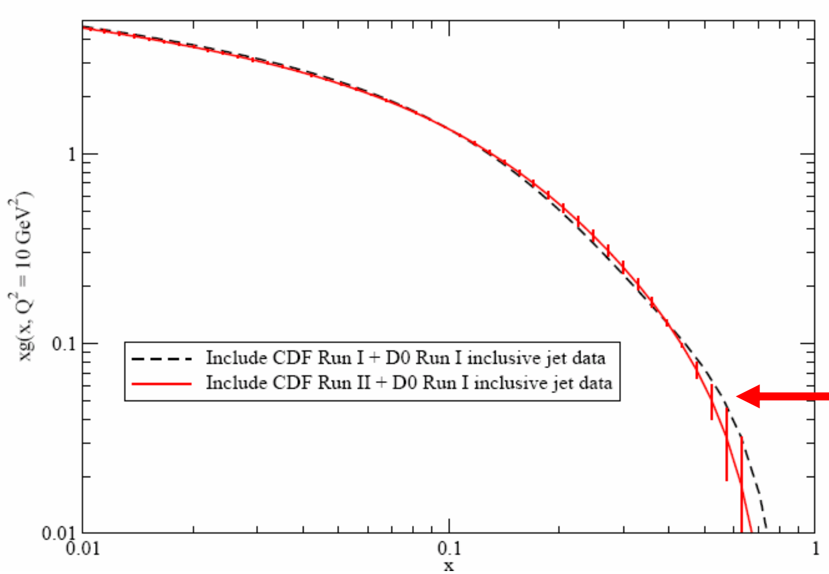
(March 2007)

New Gluon (MRST/MSTW)



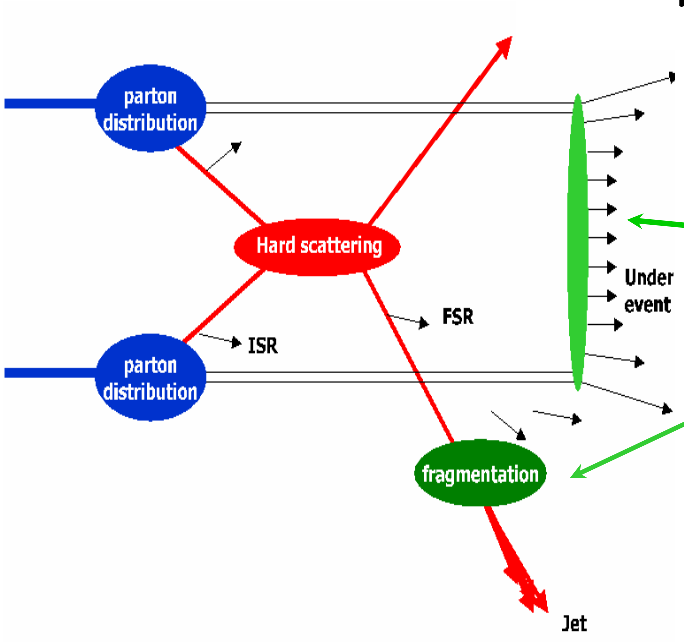
Tevatron data is the only constrain for gluon PDF for x>0.3





New data prefer less gluons at high-x (significant change)

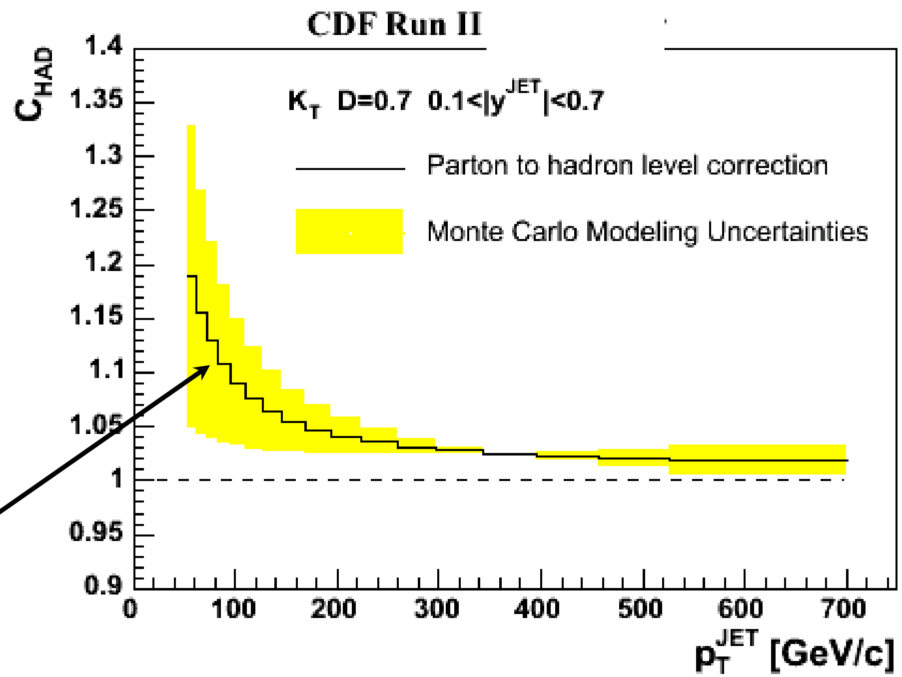
Non-pQCD Contributions



- Non-pQCD contributions
- Underlying Event (remnant-remnant interactions)
- Fragmentation into hadrons

Underlying Event and Fragmentation contributions must be considered before comparing to NLO QCD predictions (only way to perform a fair comparison)

Precise measurements at low Pt require good modeling of the non-pQCD terms

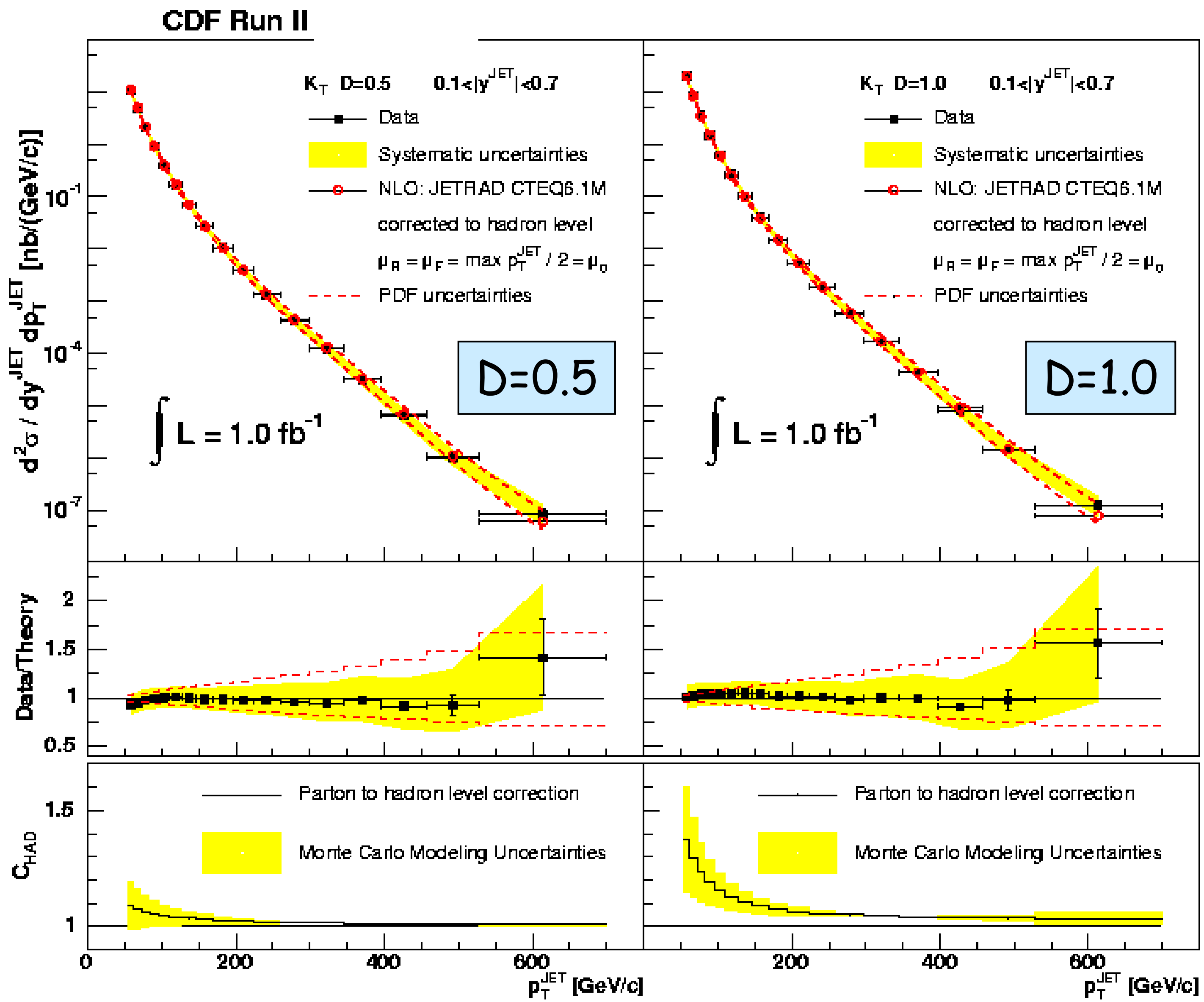


Dedicated measurements are needed to validate the Monte Carlo modeling

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j})\frac{\Delta R^2}{D^2}$$

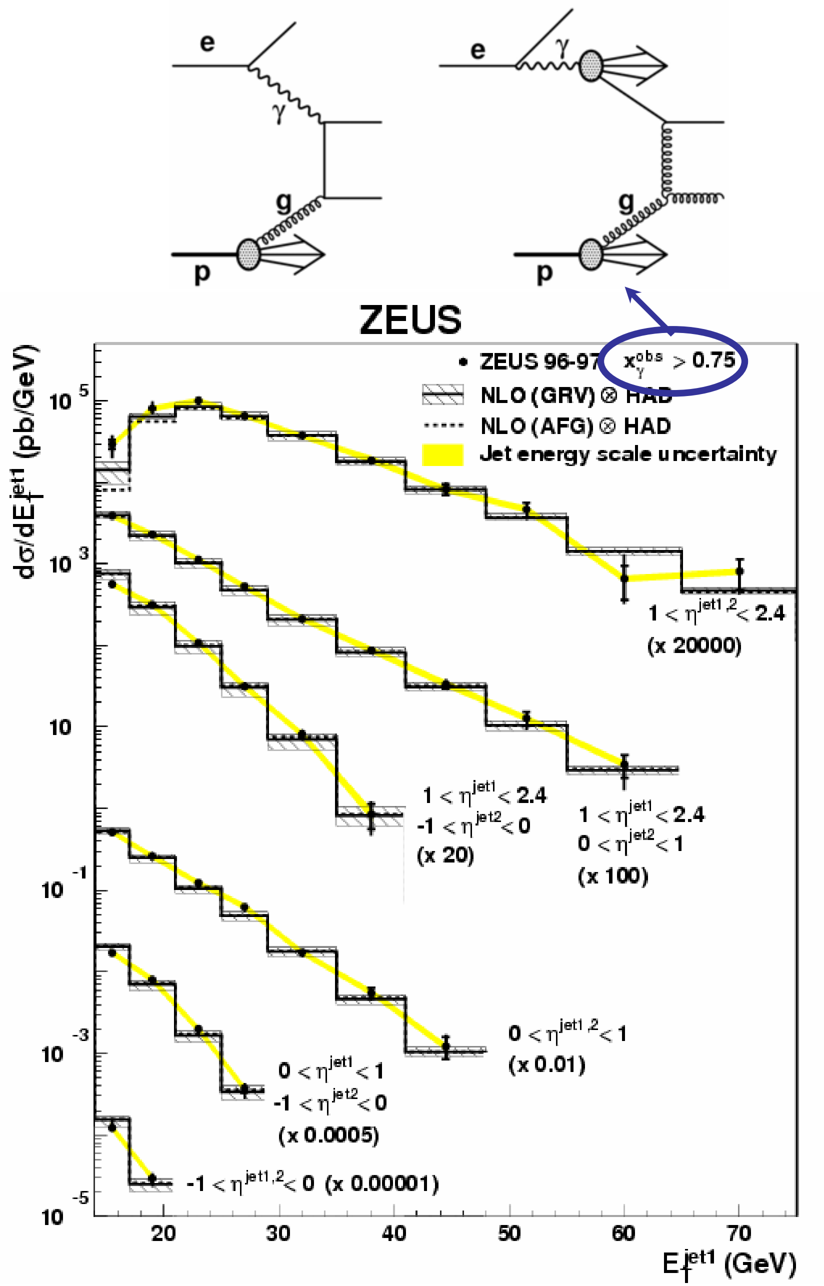
K_T Jets vs D

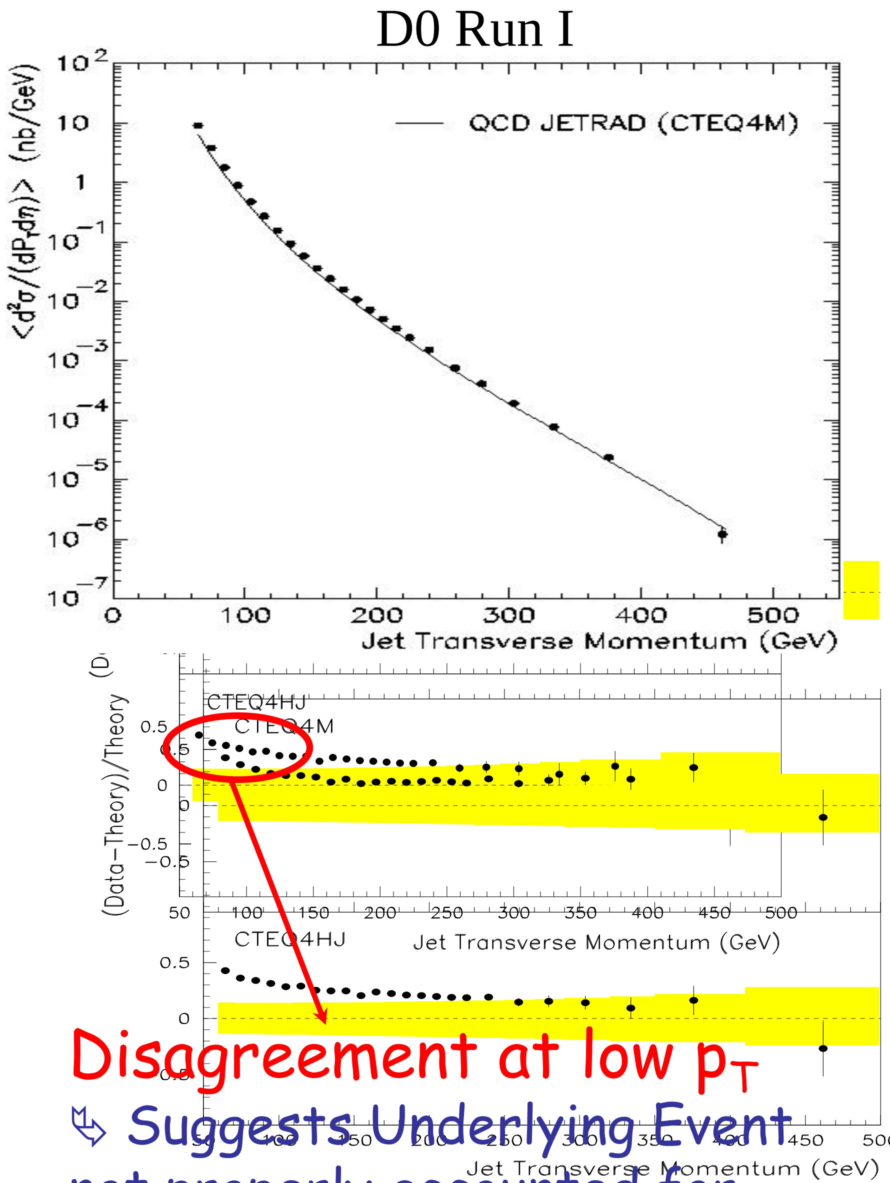
1 fb^{-1}



As D increases the required non-perturbative corrections increase at low P_T

Results from ZEUS / D0 Run I

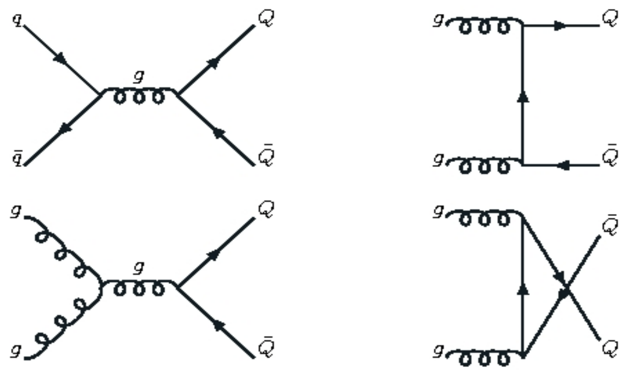


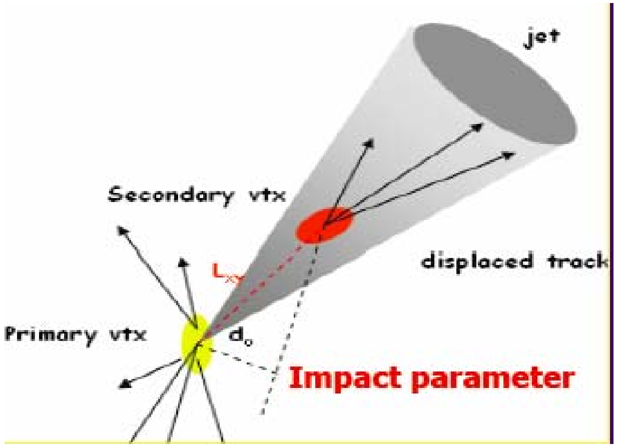


Disagreement at low p_T

↳ Suggests Underlying Event not properly accounted for

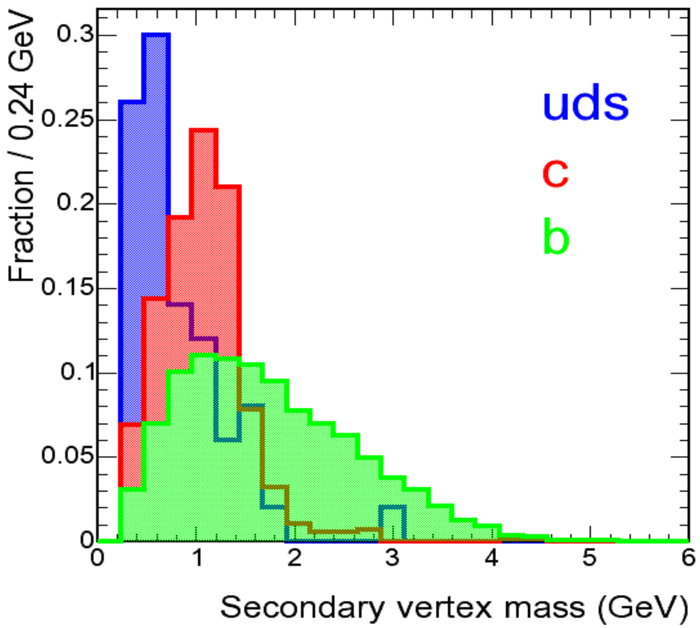
Dijet Production ($b\bar{b}$)

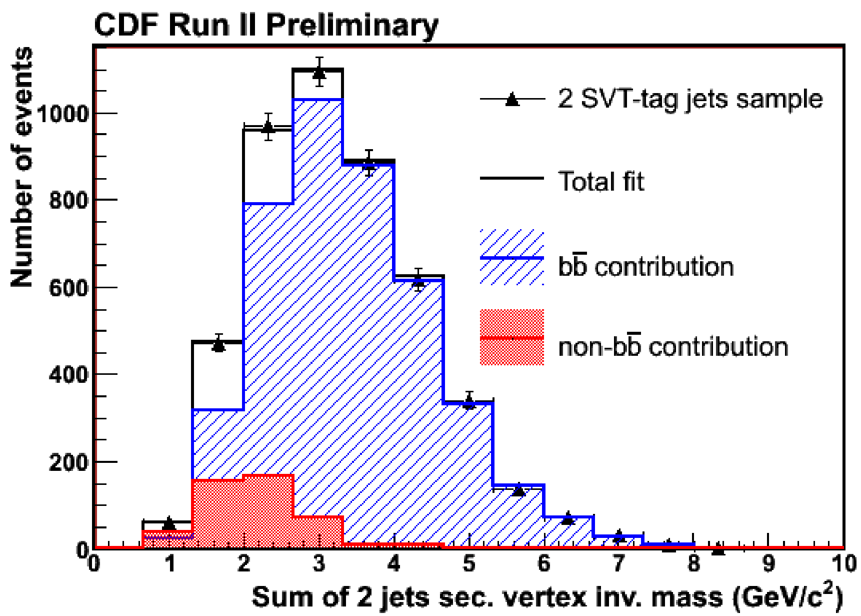




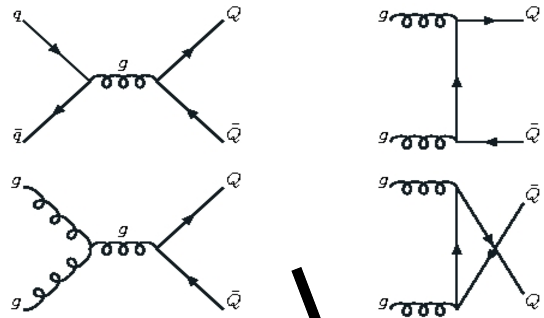
2 jets with $E_T >$ 35 (32) GeV and $|\eta| < 1.2$
Identified secondary decay vertex (b-tagged)

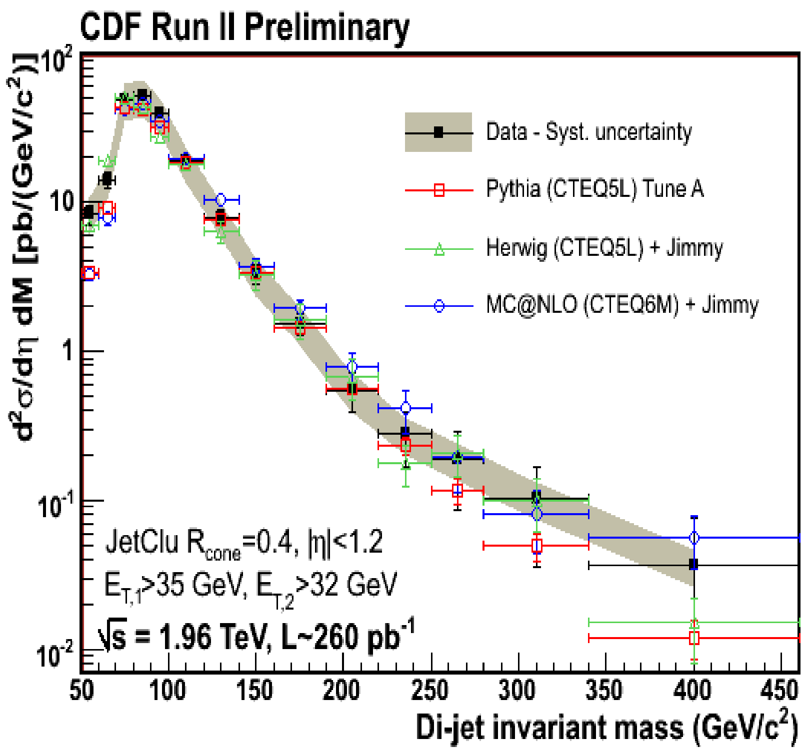
Secondary vertex mass used to separate bottom from (uds + c) contributions

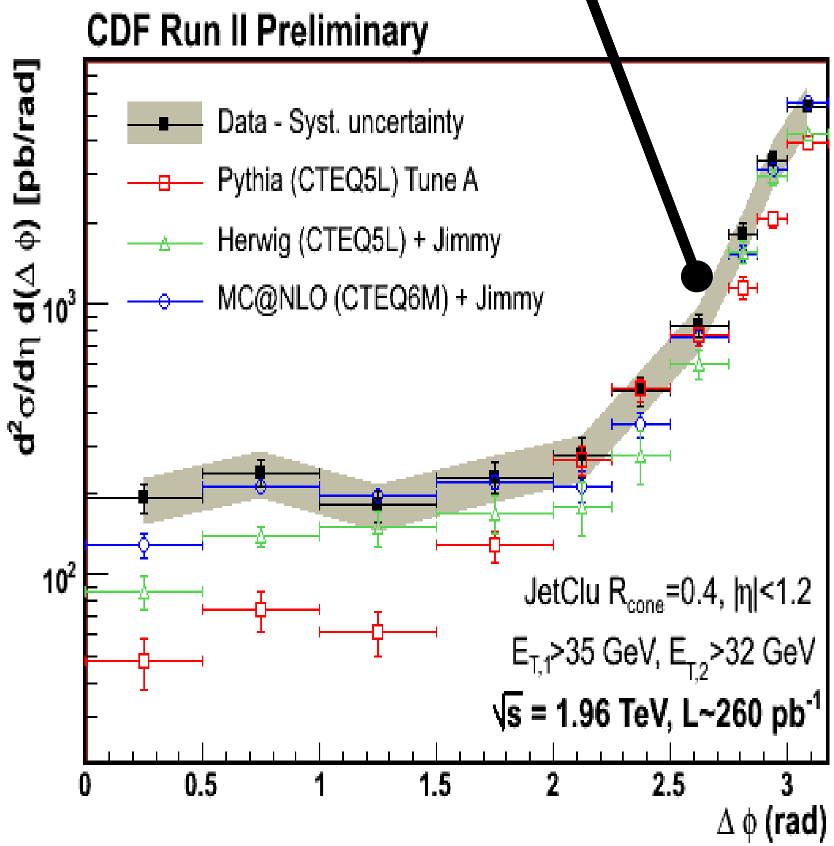


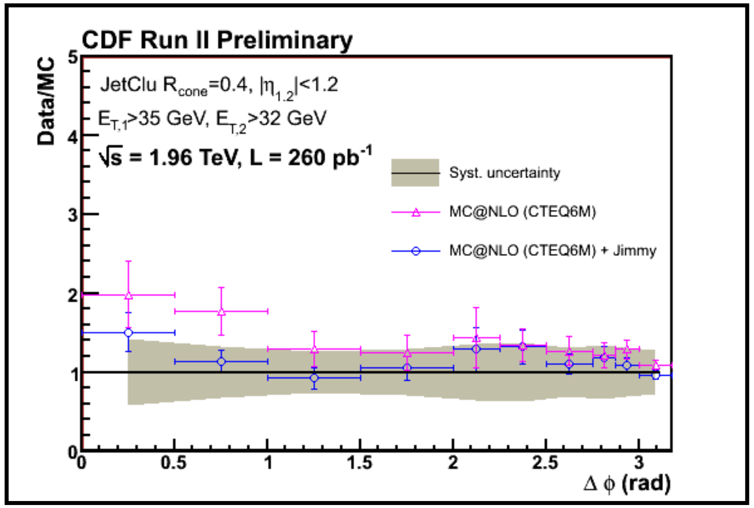


Dijet Production (bb)



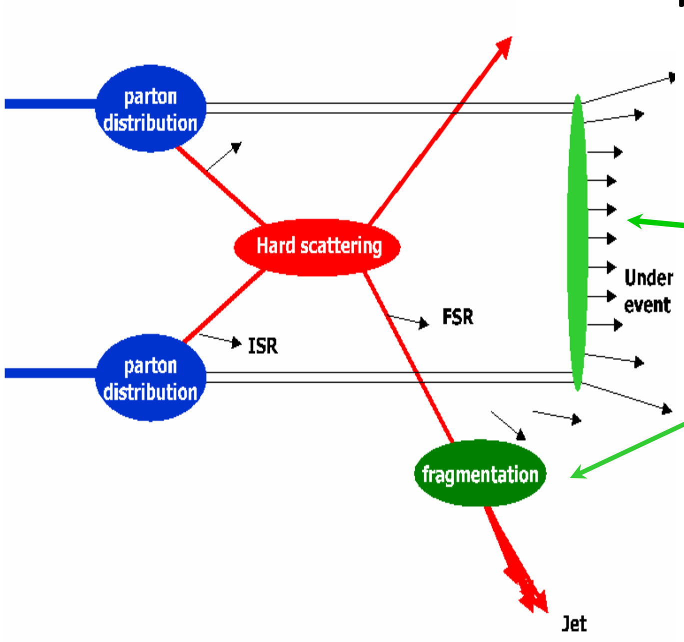






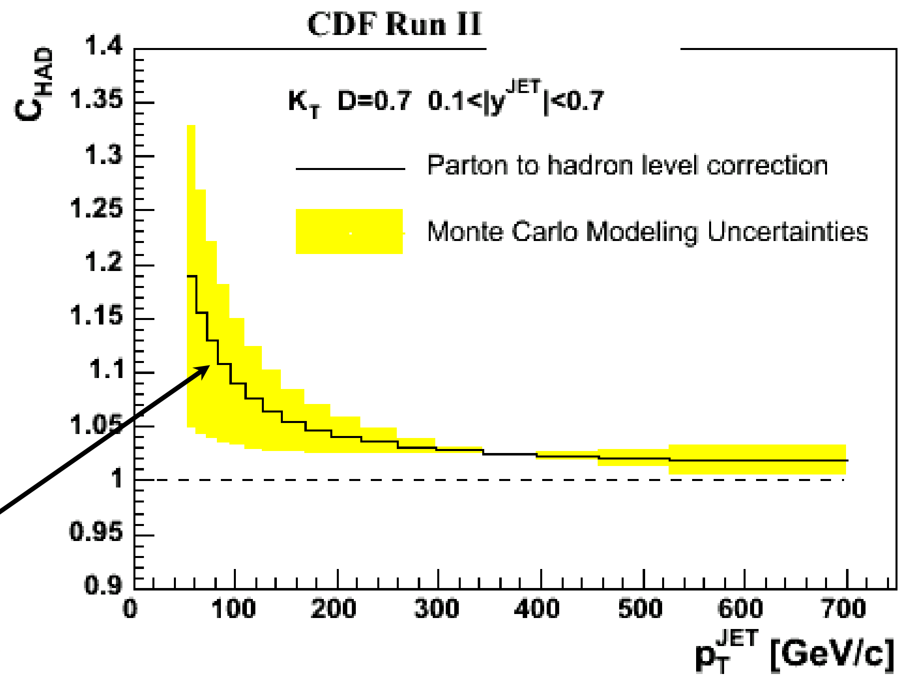
NLO prediction closest to the data
(once again one needs UE contribution to
bring NLO predictions to the data)

Non-pQCD Contributions



- Non-pQCD contributions
- Underlying Event
(remnant-remnant interactions)
- Fragmentation into hadrons

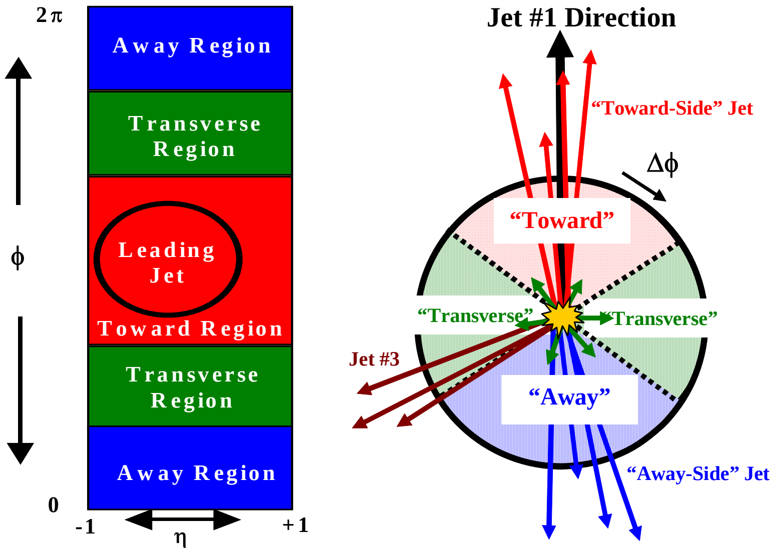
Underlying Event and Fragmentation contributions must be considered before comparing to NLO QCD predictions
(only way to perform a fair comparison)

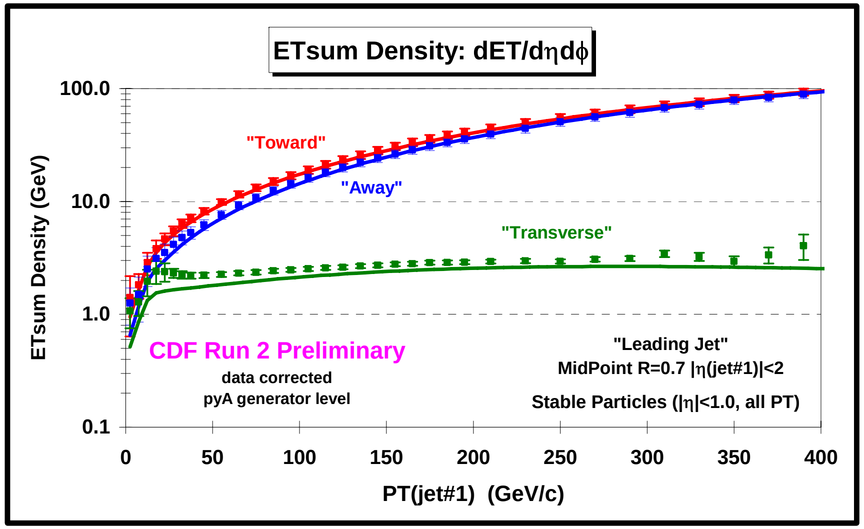


Precise measurements at low Pt require good modeling of the non-pQCD terms

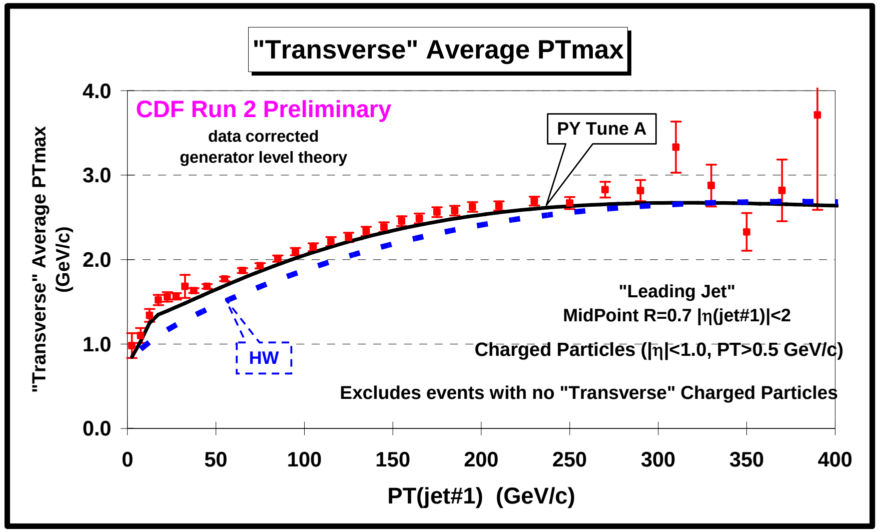
Dedicated measurements are needed to validate the Monte Carlo modeling

Underlying Event Studies





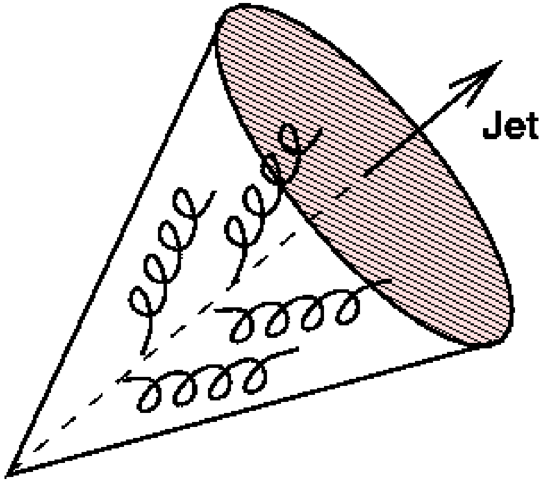
$p_T^{track} > 0.5\ \mathrm{GeV}, \quad |\eta^{track}| < 1$

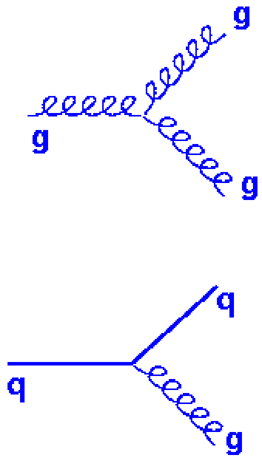


transverse region sensitive to soft underlying event activity

Good description of the underlying event by PYTHIA after tuning the amount of initial state radiation, MPI and selecting CTEQ5L PDFs (known as PYTHIA Tune A)

Jet Shapes



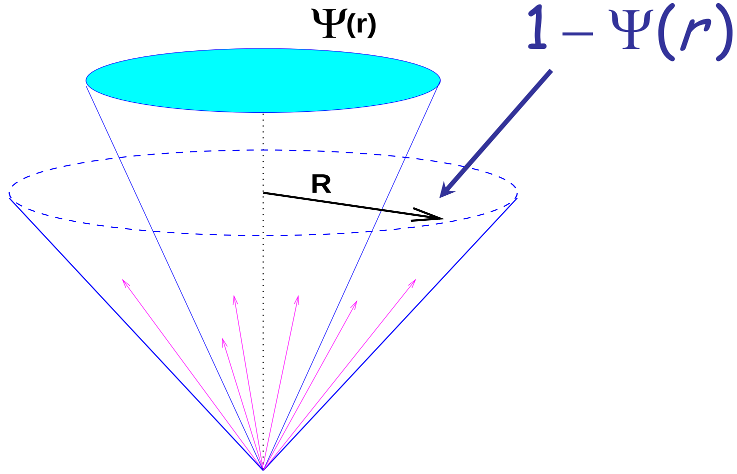


Gluons radiate more than quarks (QCD color charges)

↓

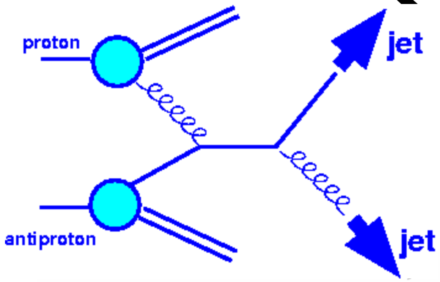
Gluon jets Broader

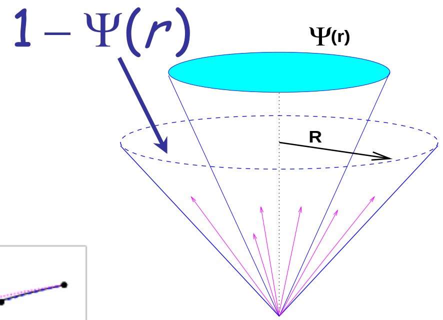
- Jet shape dictated by multi-gluon emission form primary parton
- Test of parton shower models and their implementations
- Sensitive to quark/gluon final state mixture and run of strong coupling
- Sensitive to underlying event structure in the final state



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

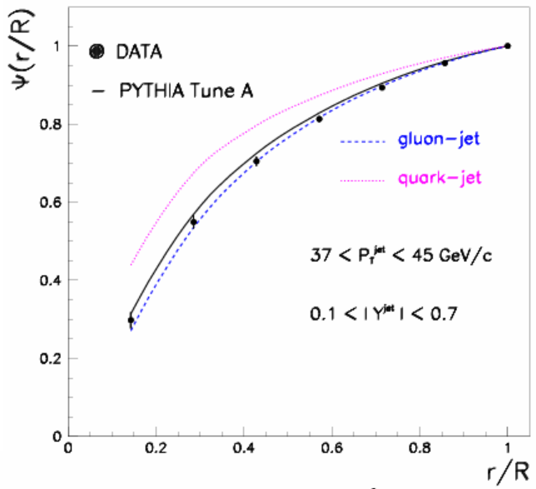
Quark and Gluon Jets

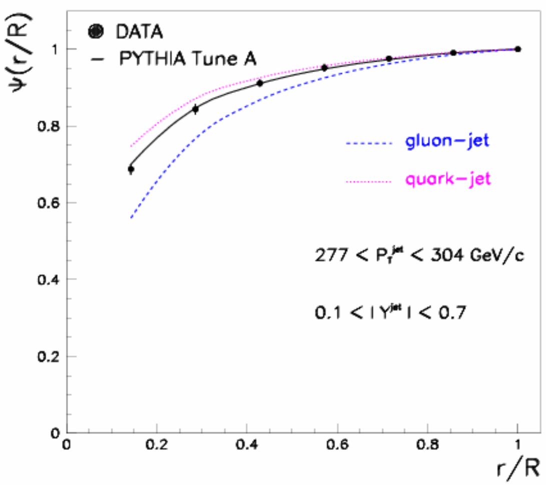


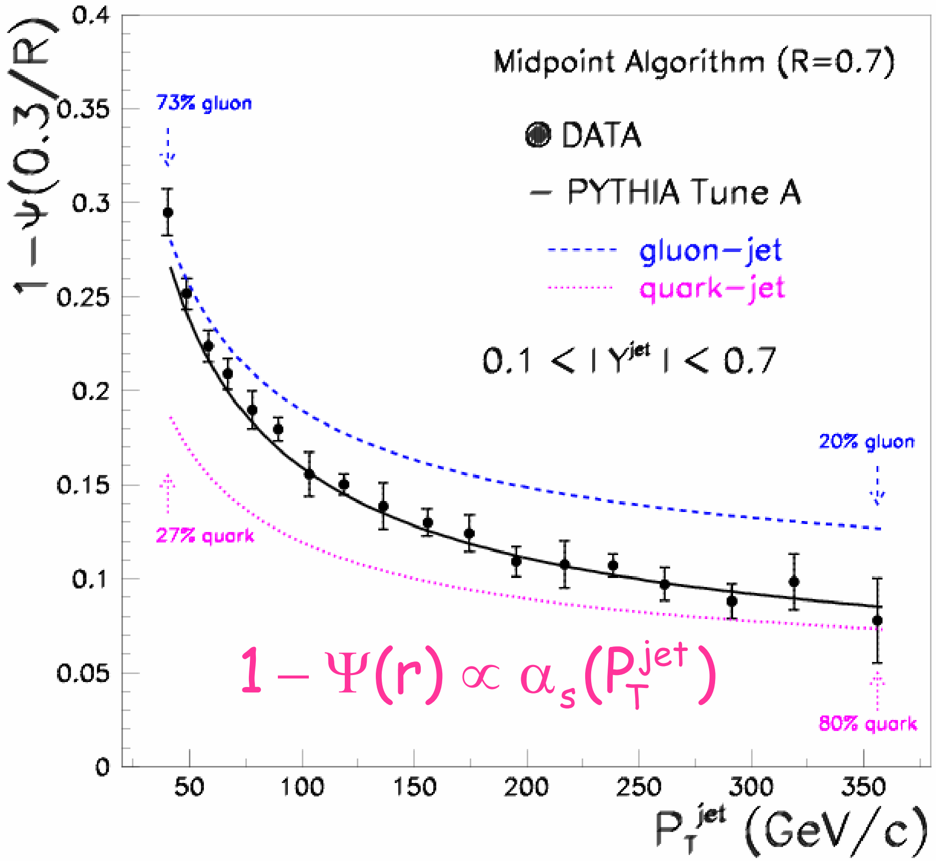


Jet narrows as Pt increases

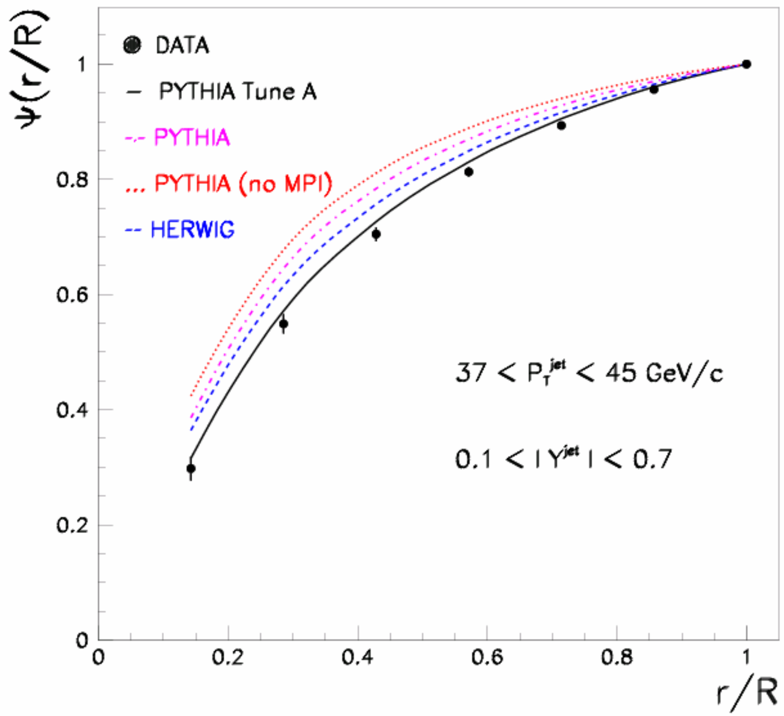
- gluon/quark mixture
- running coupling

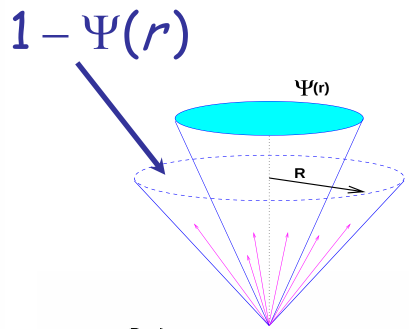


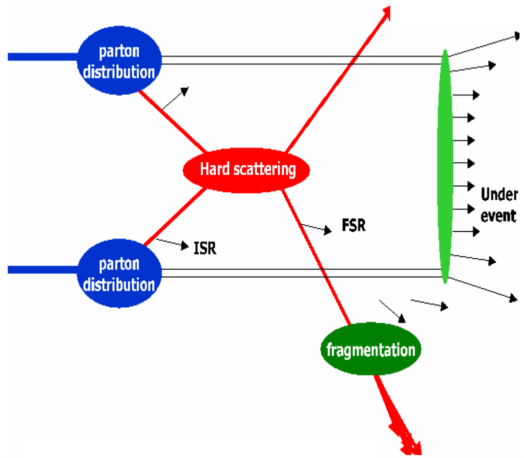


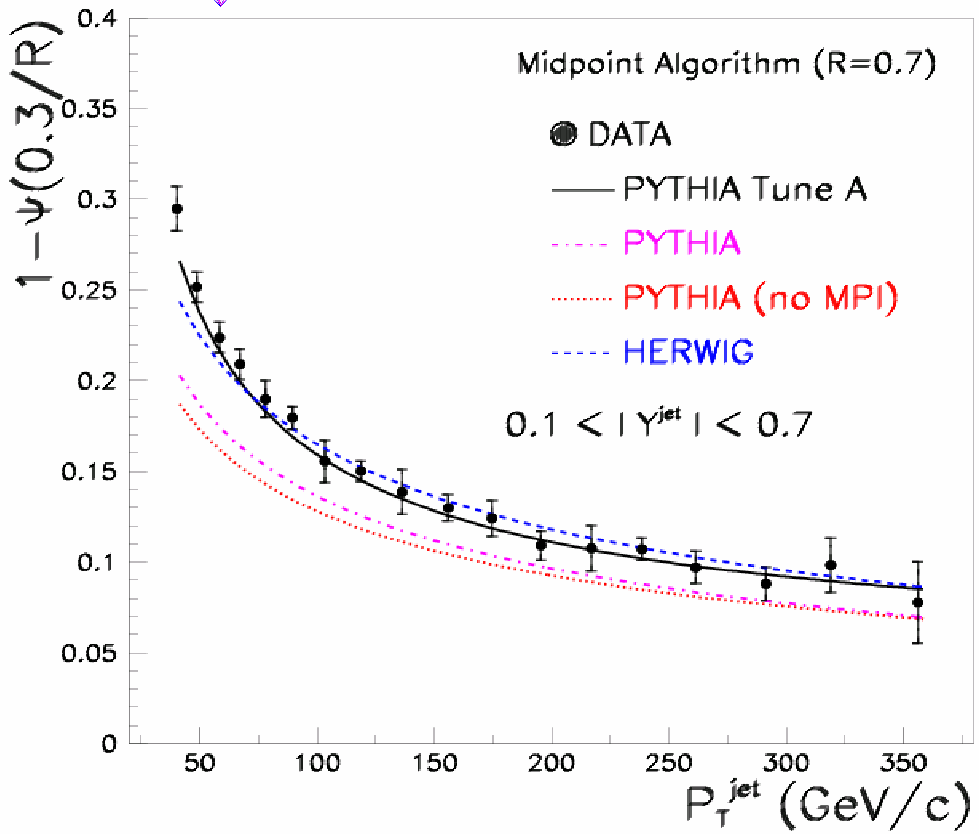


Jet shapes





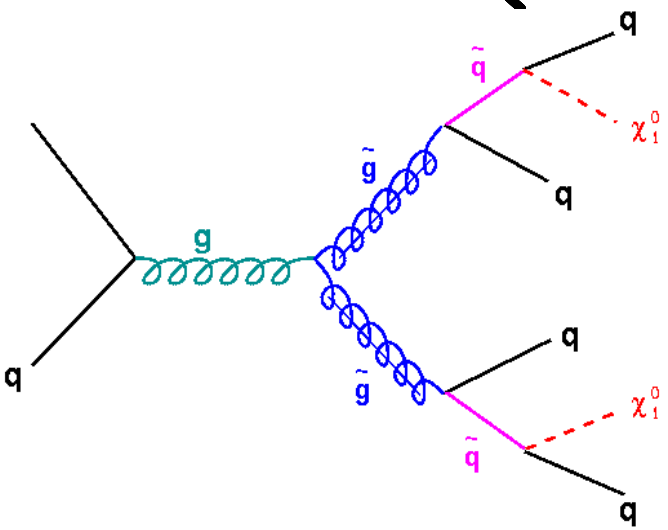


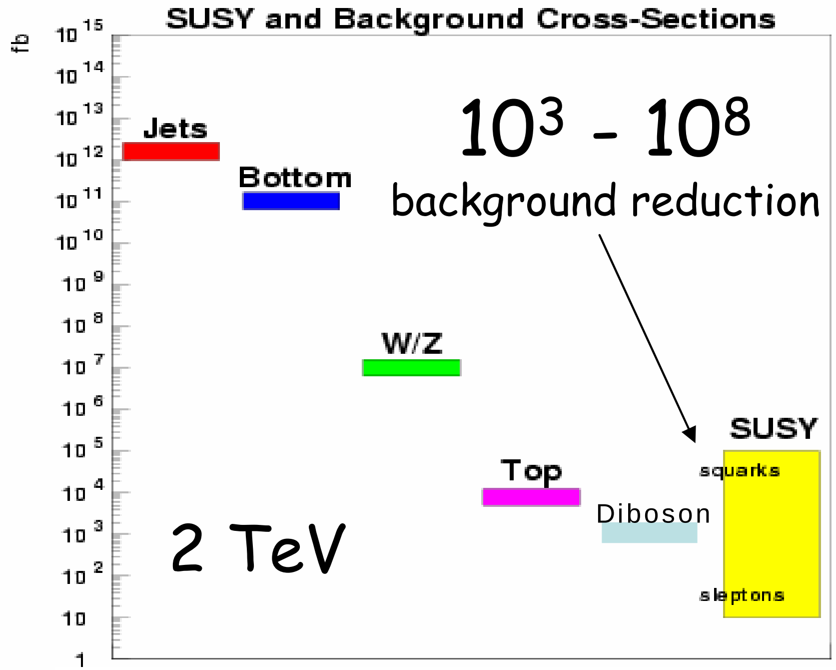


- PYTHIA Tune A describes the data (enhanced ISR + MPI tuning)
- PYTHIA default too narrow
- MPI are important at low Pt
- HERWIG too narrow at low Pt

We know how to model the UE at 2 TeV for QCD jet processes

QCD & New Physics

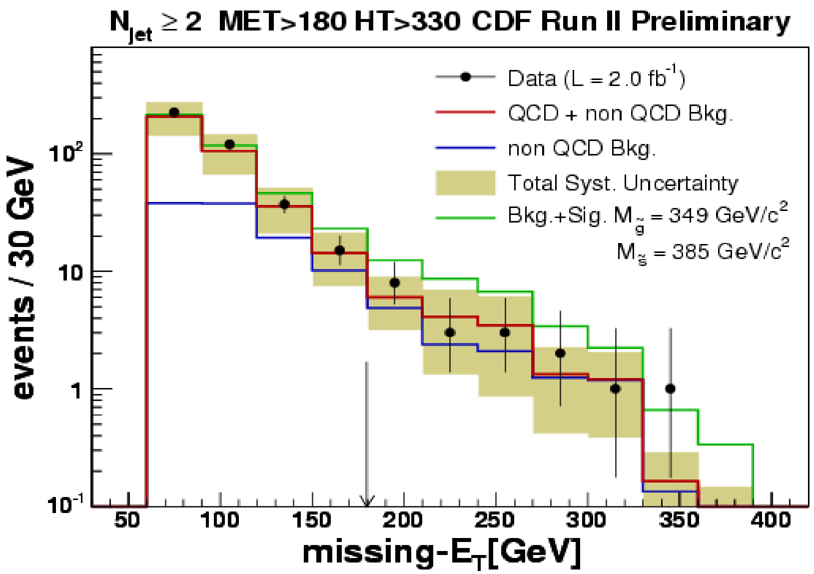




channel with the best sensitivity
to mSUGRA at the energy frontier

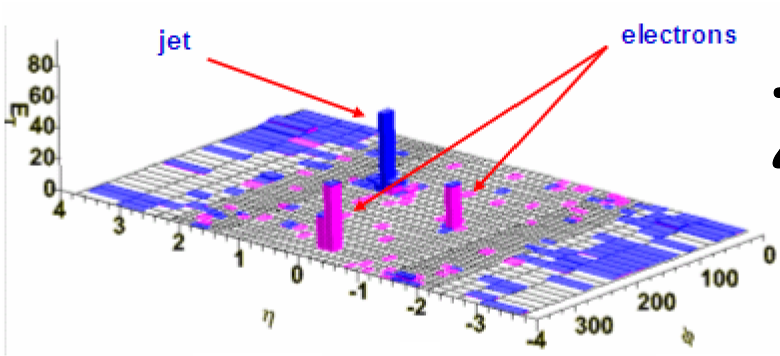
Backgrounds

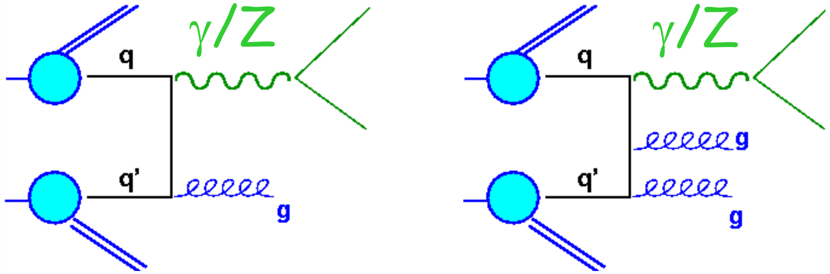
- QCD
- $Z \rightarrow \nu\nu$ + jets
- $W \rightarrow e\,\nu$ + jets
- $W \rightarrow \tau\,\nu$ + jets
- Top
- WW....

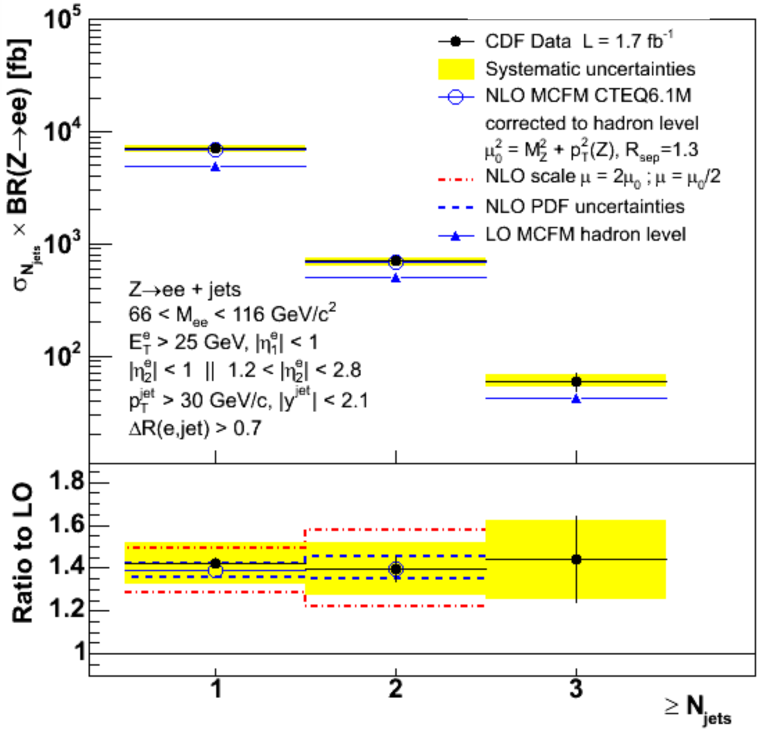


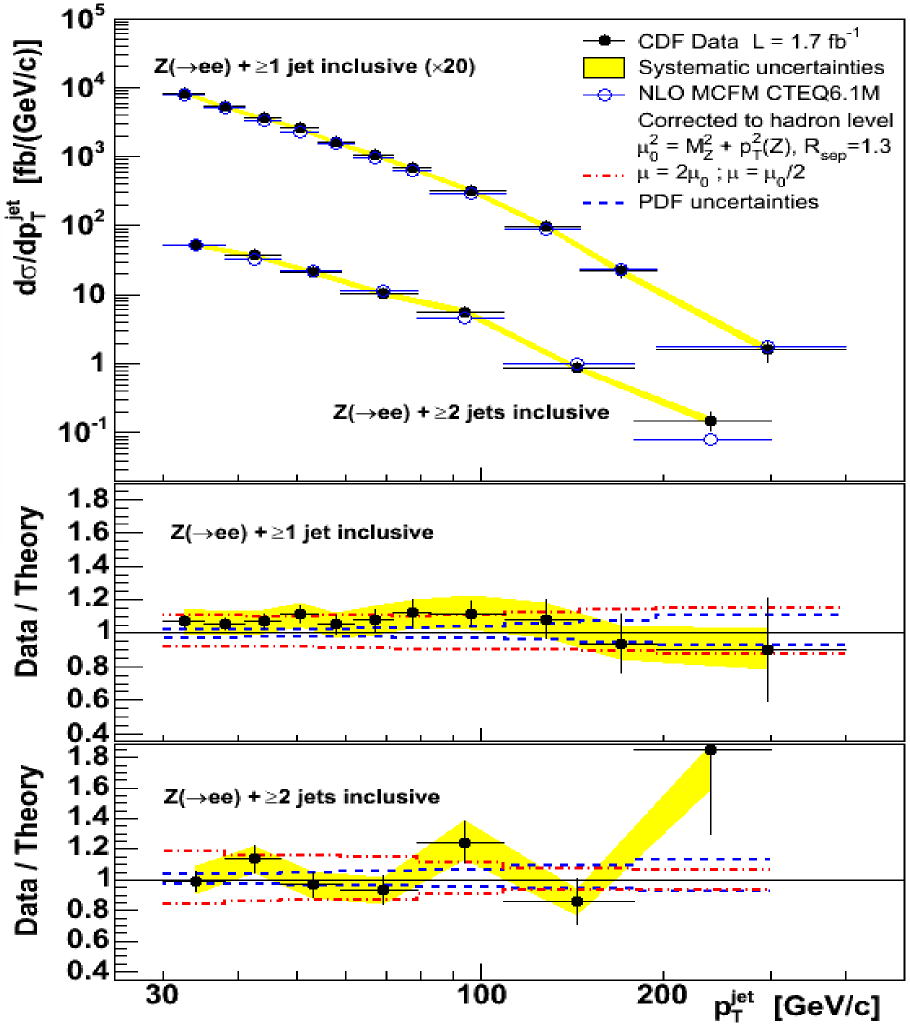
Good knowledge of Boson+jet(s) needed

Z/γ*+jet(s) Production



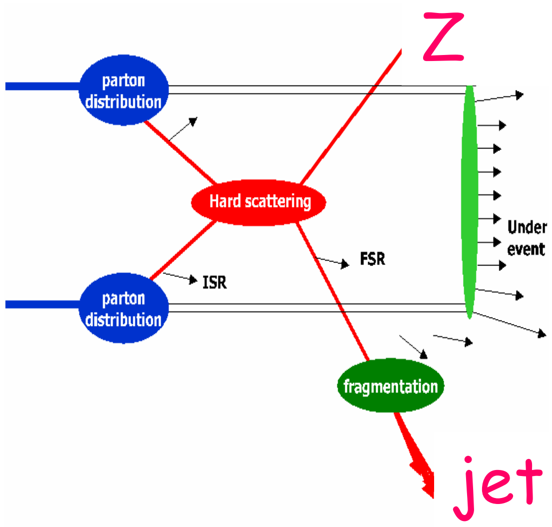


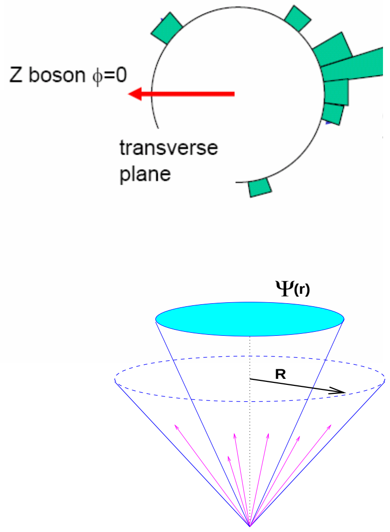


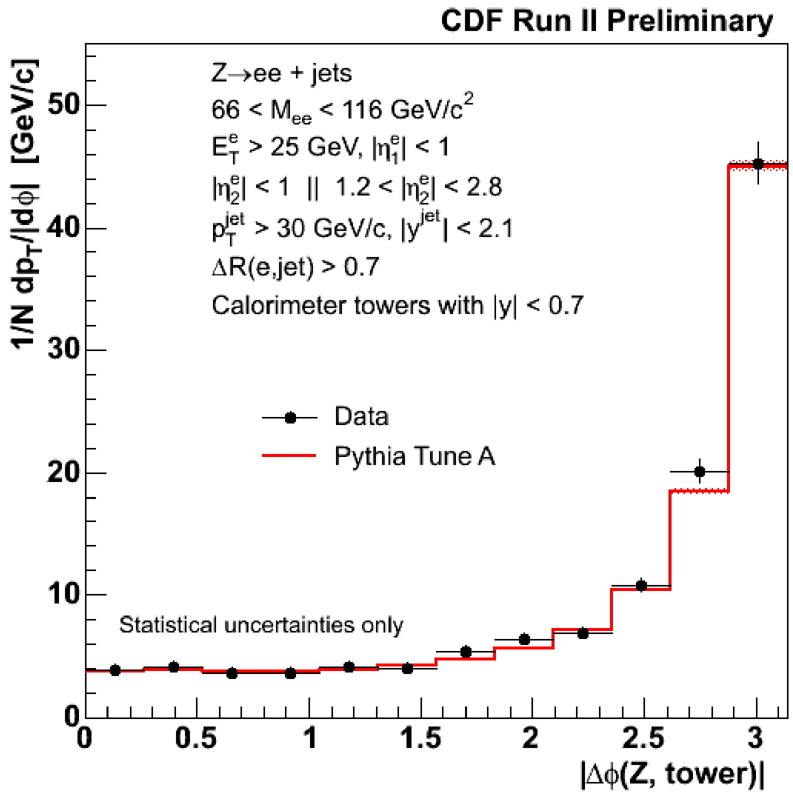


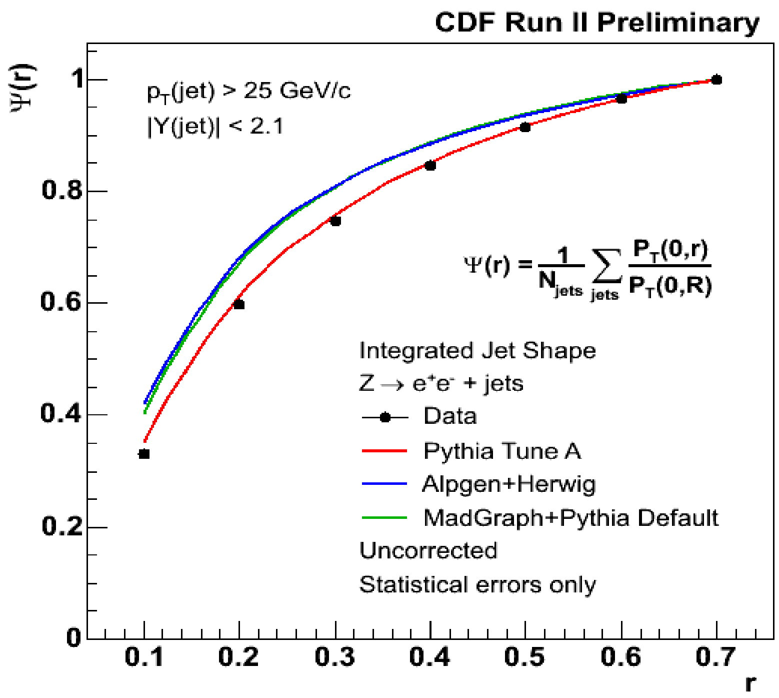
Good agreement with NLO pQCD predictions

Soft radiation in Z+jet(s)





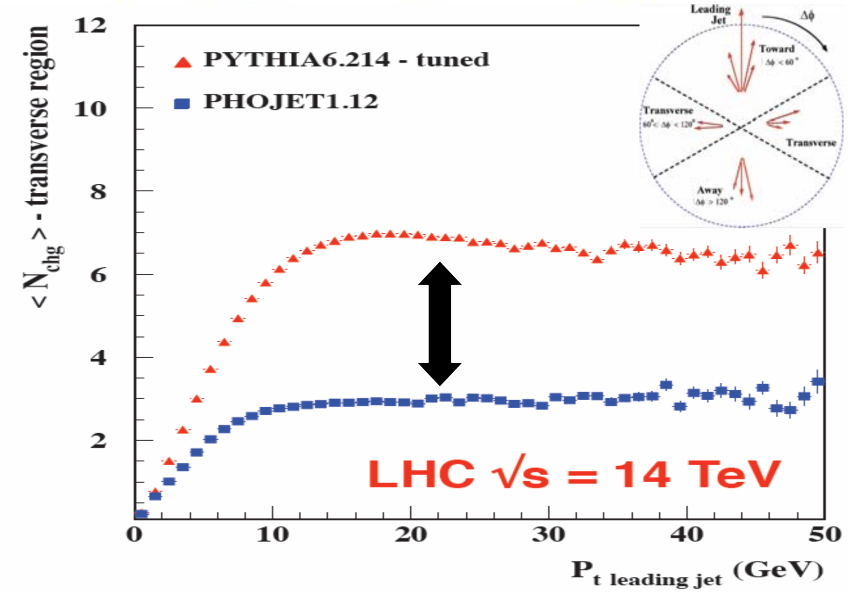


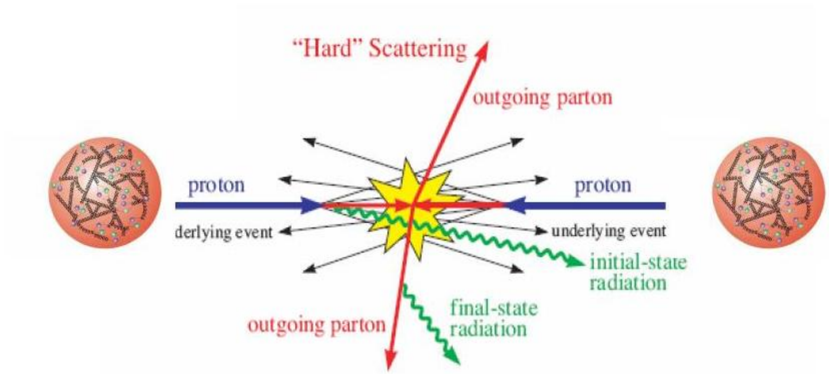


Implementation of proper modeling of UE still needed in new W/Z+Jet(s) Monte Carlos....very important

LHC will use "extra jets" veto in Higgs analyses to reduce QCD bckg.

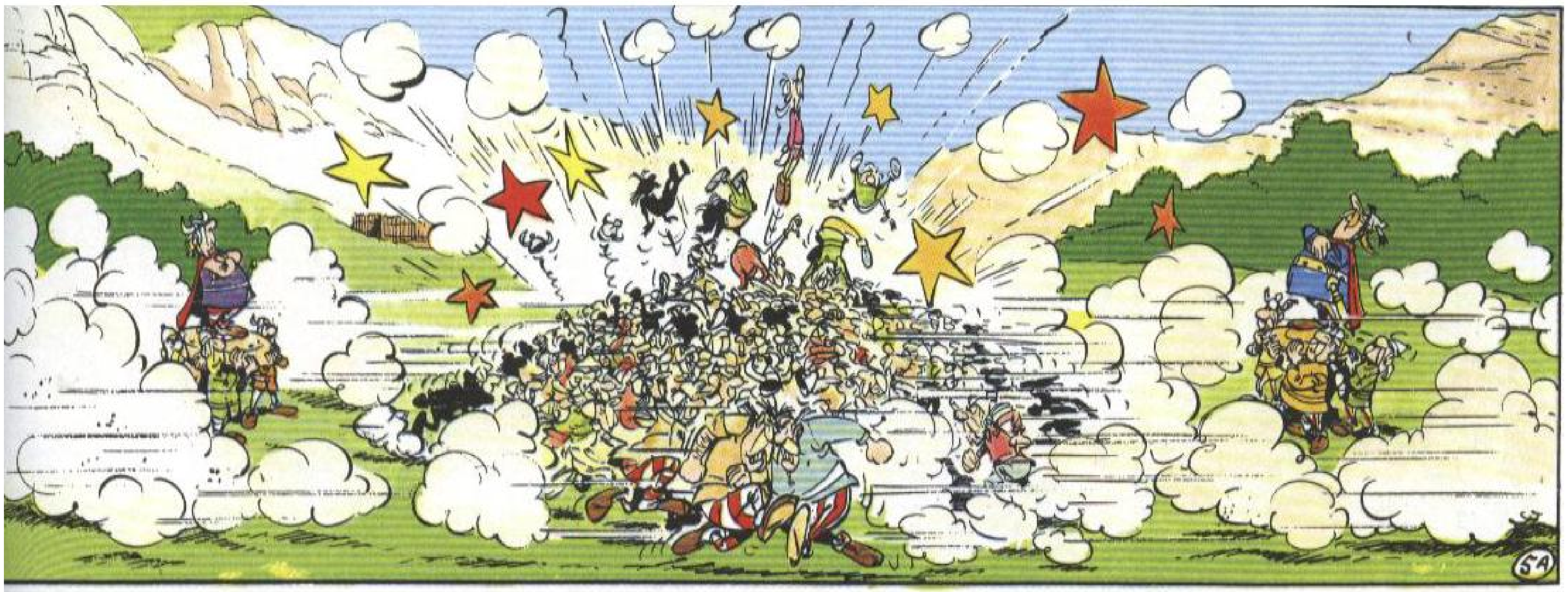
Notes on Underlying Event at LHC





This is a clear unknown at LHC energies

- Dependence with physics process
- How "hard" will be ?



Final Notes

- We reviewed the CDF standard procedures to define corrected jet energies and uncertainties

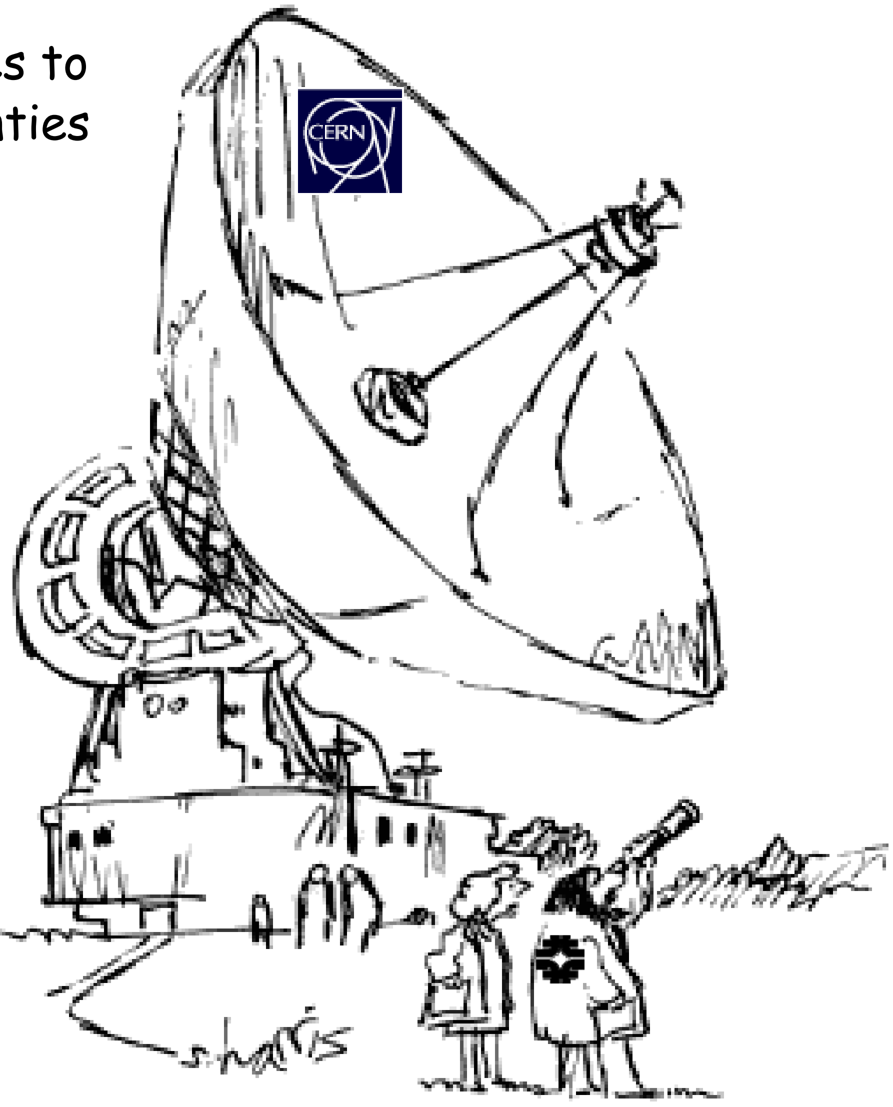
- Inclusive Jet measurements in Run II carried out over a wide rapidity range using different jet algorithms

- Contribution to a better understanding of gluon PDF thanks to forward jet results

- Proper Modeling of the Underlying Event

- Boson+jet(s) results validate background estimations in searches for new physics

- *TeV→LHC activities important to transfer the experience from Fermilab to CERN*

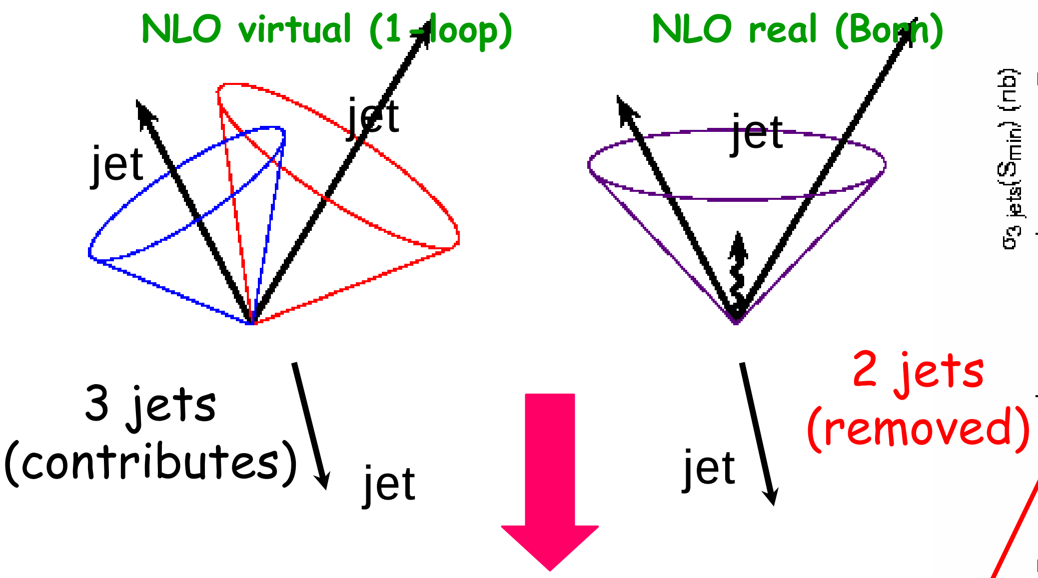


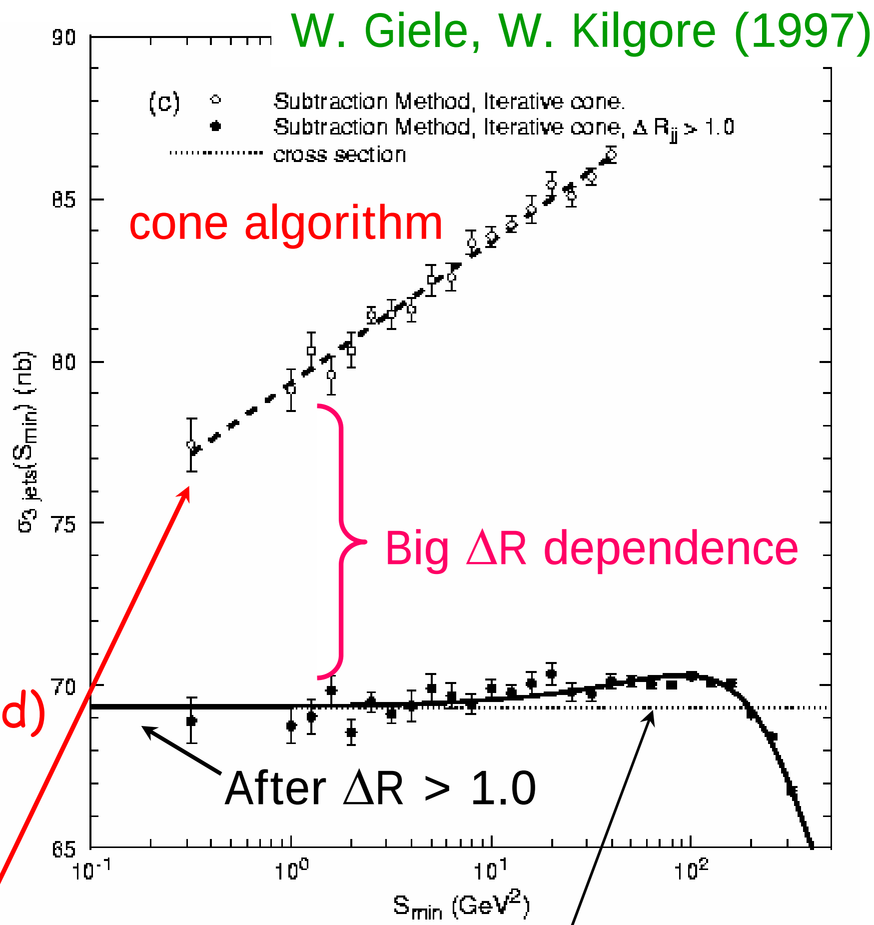
"Just checking."

Backup Sides

Three-jet Production at NLO

Fixed-order pQCD NLO calculations rely on exact cancellations of collinear and soft singularities between diagrams





Infrared/collinear unsafe clustering leads to partial cancellations and introduces logarithmic dependence on soft emission

Slicing method parameter S_{min} = min(Mij)
(flat for well defined NLO calculation)

3-jet production vs NLO pQCD

Run I cone (R=0.7)

$E_T^{jet} > 20\,GeV,\ |\eta| < 2.0$

$\sum_{3\ jets} E_T^{jet} > 320\ \ GeV$

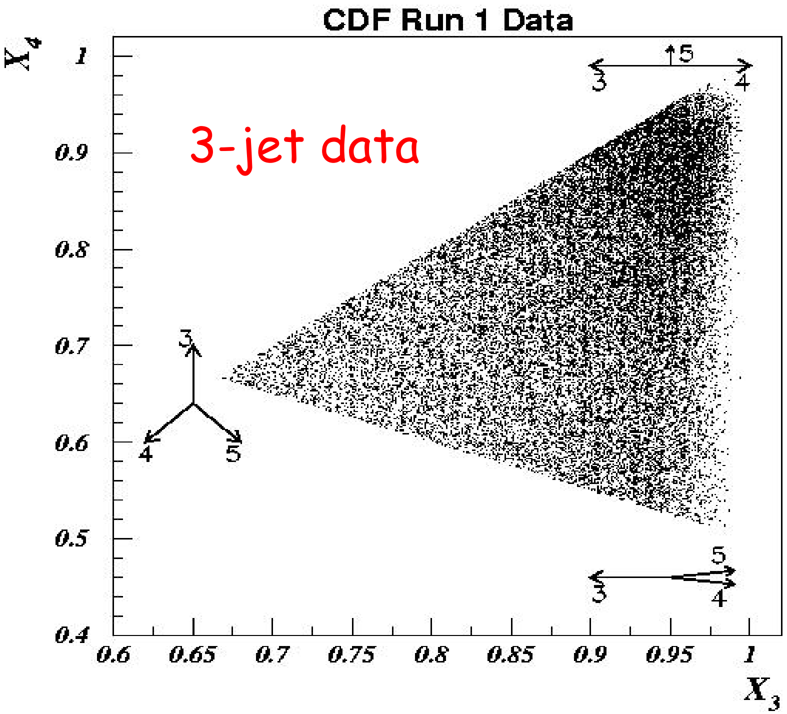
Jet separation $\Delta R > 1.0$

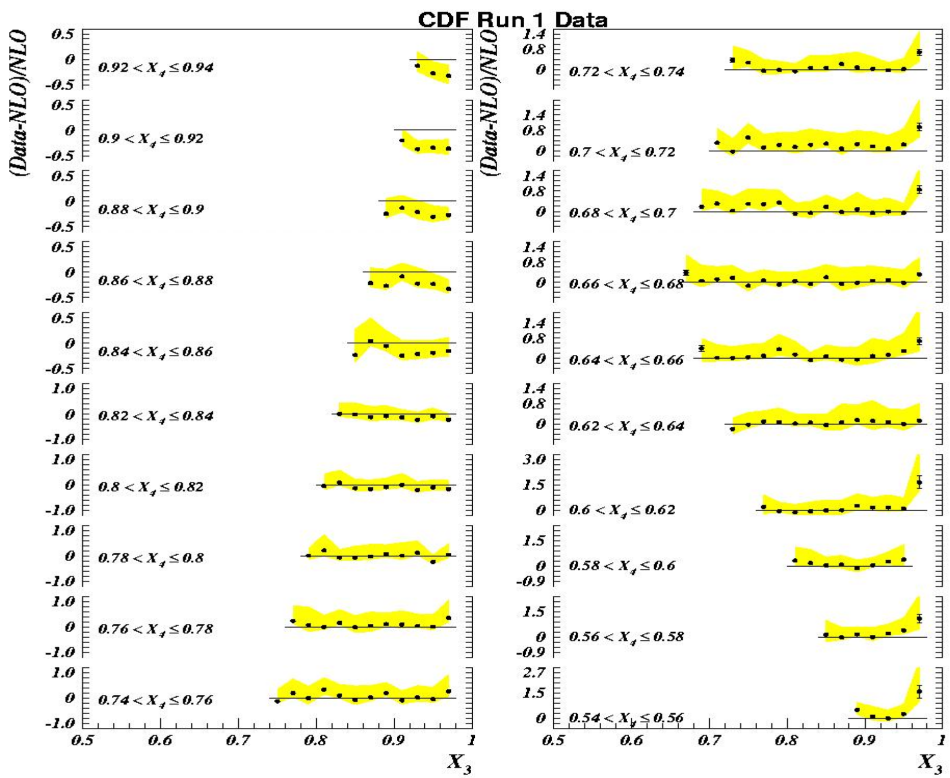
$1 + 2 \rightarrow 3 + 4 + 5$

Dalitz variables in c.m.s of 3-jets

$$X_i = \frac{2 * E_i^{jet}}{M_{3\,jets}}, \quad i = 3,4,5$$

$$X_3 > X_4 > X_5;\ X_3 + X_4 + X_5 \equiv 2$$



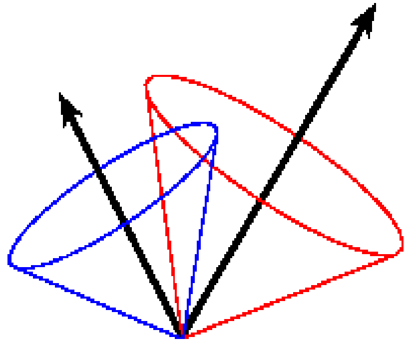


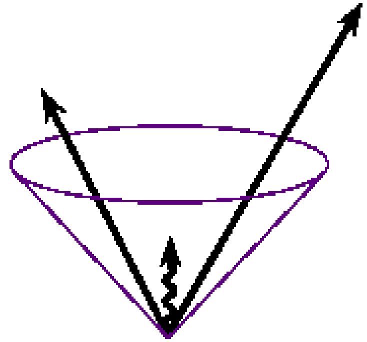
Notes on Run I Jet algorithm

$$d\hat{\sigma}_{JET} = d\Phi\,|M|^2\,F_{JET}$$

Cone algorithm not infrared safe:

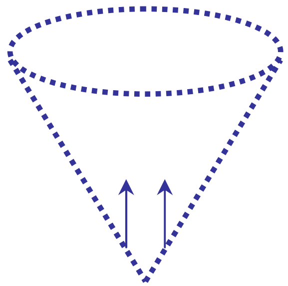
The jet multiplicity changed after emission of a soft parton



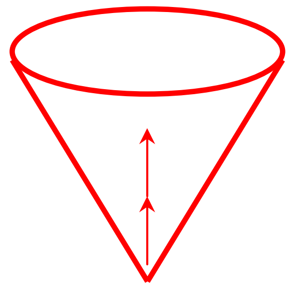


Cone algorithm not collinear safe:

Replacing a massless parton by the sum of two collinear particles the jet multiplicity changes



below threshold
(no jets)



above threshold
(1 jet)

Fixed-order pQCD calculations will contain not fully cancelled infrared divergences:

-> Inclusive jet cross section at NNLO
-> Three jet production at NLO
-> Jet Shapes at NLO

three partons inside a cone

Run II -> MidPoint algorithm

1. Define a list of seeds using CAL towers with $E_T > 1$ GeV

2. Draw a cone of radius R around each seed and form "proto-jet"

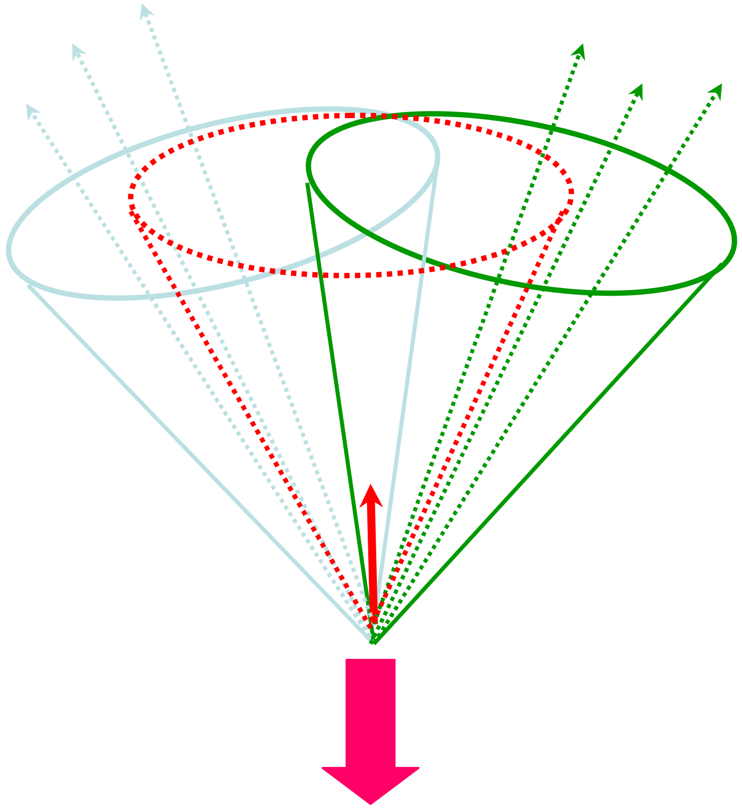
$$E^{jet} = \sum_k E^K, \quad P_i^{jet} = \sum_k P_i^K$$

(massive jets : P_T^{jet}, y^{jet})

3. Draw new cones around "proto-jets" and iterate until stable cones

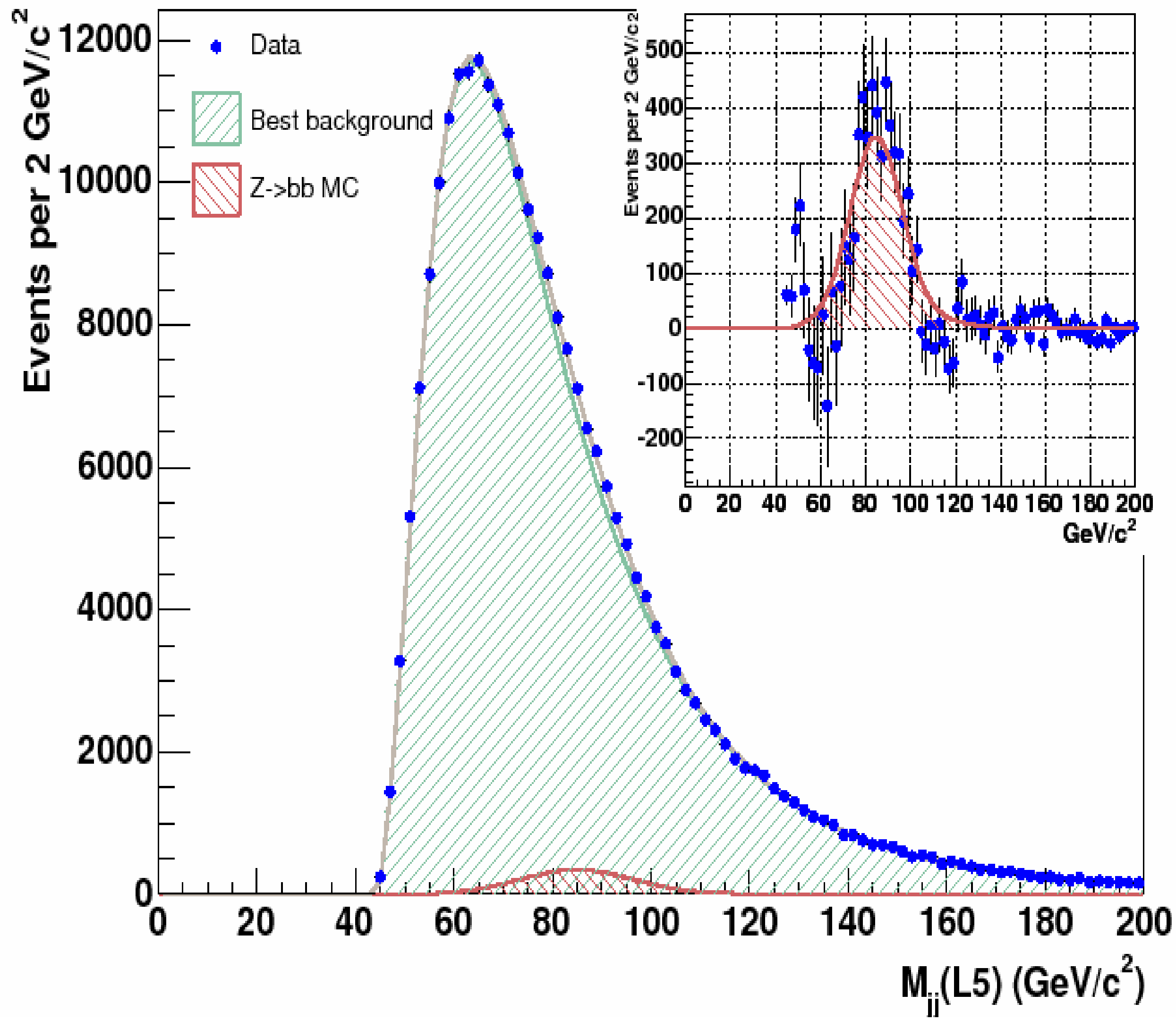
4. Put seed in Midpoint ($\eta-\phi$) for each pair of proto-jets **separated by less than 2R** and iterate for stable jets

5. Merging/Splitting (75%)



Cross section calculable in pQCD

Z→ bb



Data
Best background
Z->bb MC
Events per 2 GeV/c²
12000
10000
8000
6000
4000
2000
0
0 20 40 60 80 100 120 140 160 180 200
M_jj(L5) (GeV/c²)
Events per 2 GeV/c2
500
400
300
200
100
0
-100
-200
0 20 40 60 80 100 120 140 160 180 200
GeV/c²

Inclusive K_T Algorithm

1. Compute for each pair (i,j) and for each particle (i) the quantities:

$$d_{ij} = \min(P^2_{T,i}, P^2_{T,j}) \frac{\Delta R^2}{D^2}$$

$$d_i = (P_{T,i})^2$$

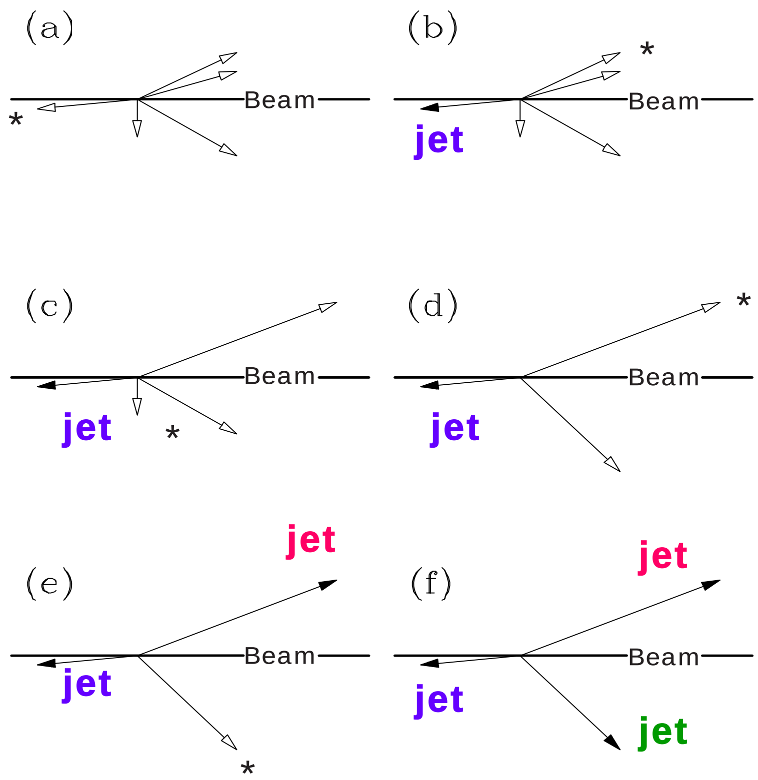
2. Starting from smallest {d_ij ,d_i}:

3. If it is a d_i then it is called a jet and is removed from the list

4. If it is a d_ij the particles are combined in "proto-jets" (E scheme)

5. Iterate until all particles are in jets

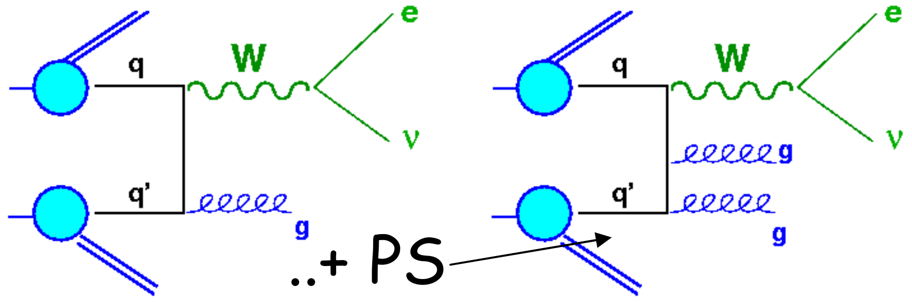
Separation in transverse momentum…
Inspired by pQCD gluon emissions.



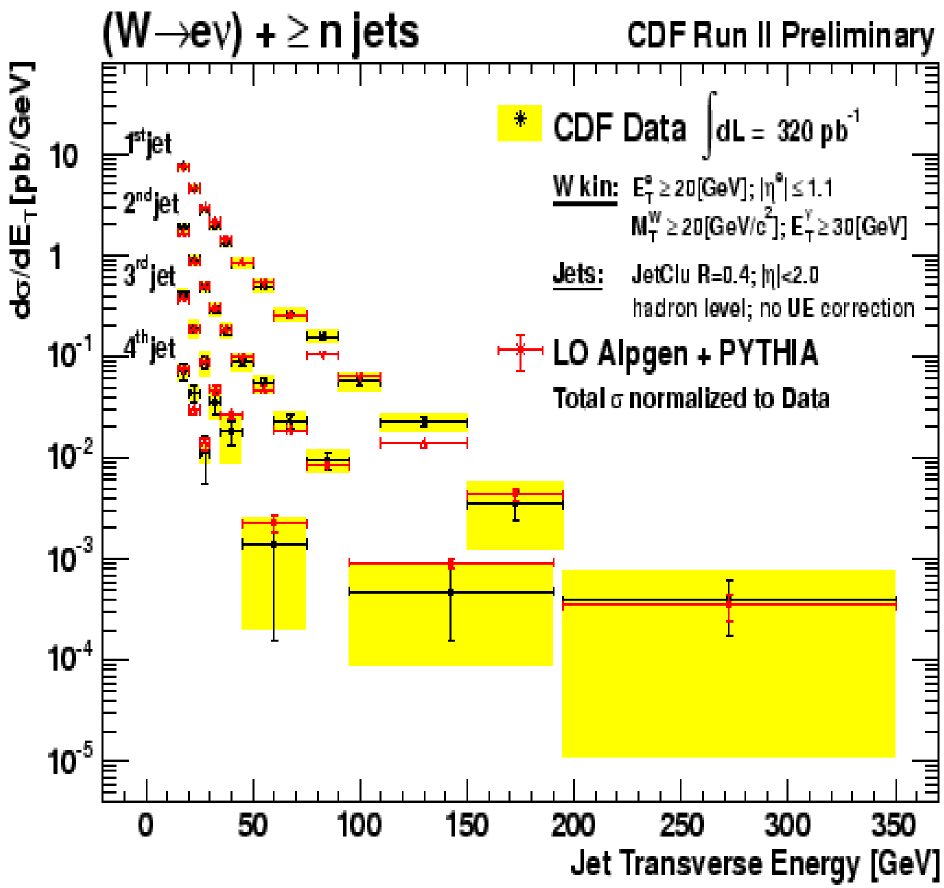
☺ No merging/splitting needed!

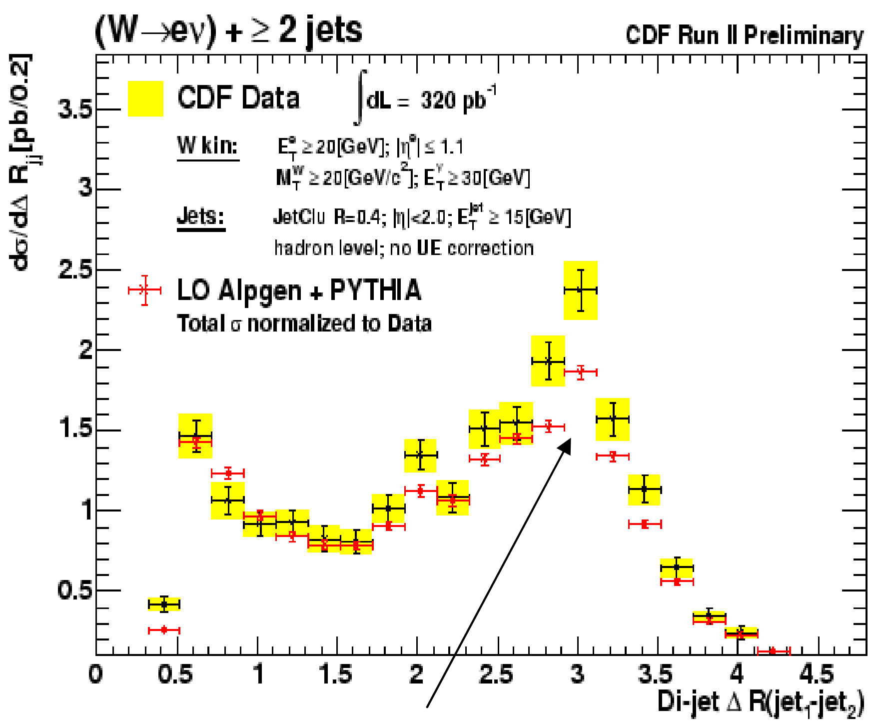
Infrared and Collinear safe to all orders in pQCD

W+jet(s) Production



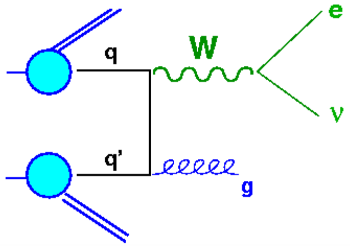
- Background top, Higgs, SUSY…
- Stringent test of pQCD predictions
- Test Ground for ME+PS techniques
  (Special matching → MLM, CKKW to avoid double counting on ME+PS interface)

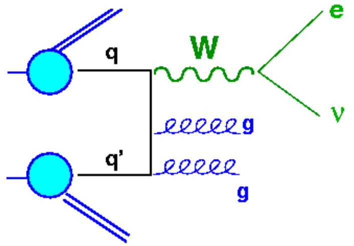


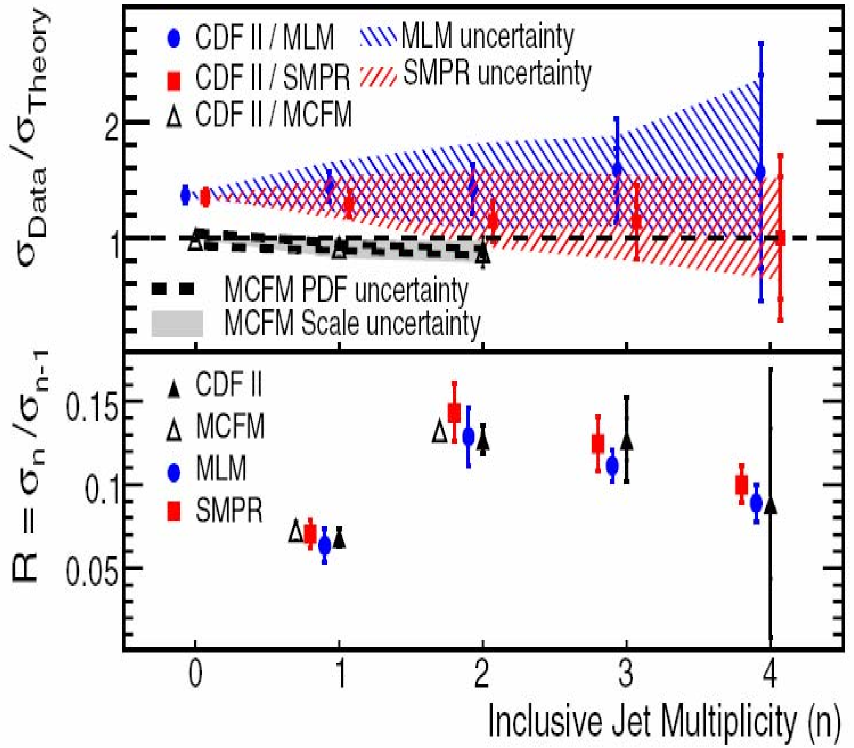


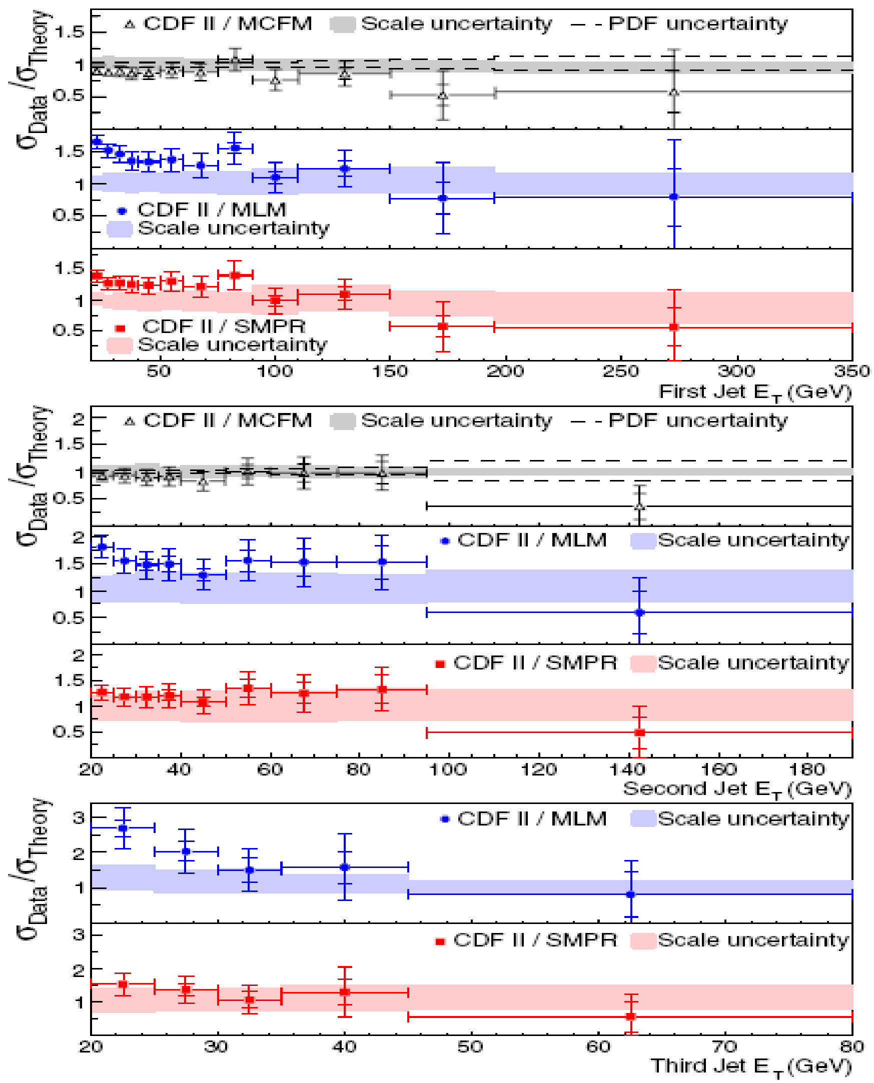
Affected by cutoff and soft radiation

W+jet(s) Production









Good agreement with pQCD NLO calculation (includes non-pQCD effects)
At low P_T Monte Carlo needs a better modeling of UE (ALPGEN+PYTHIA)