# QCD Results from the Tevatron at $\sqrt{s} = 1.96\,\text{TeV}$

From Colliders to Cosmic Rays

September 7-13, 2005, Prague


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on behalf of the CDF and DØ collaborations

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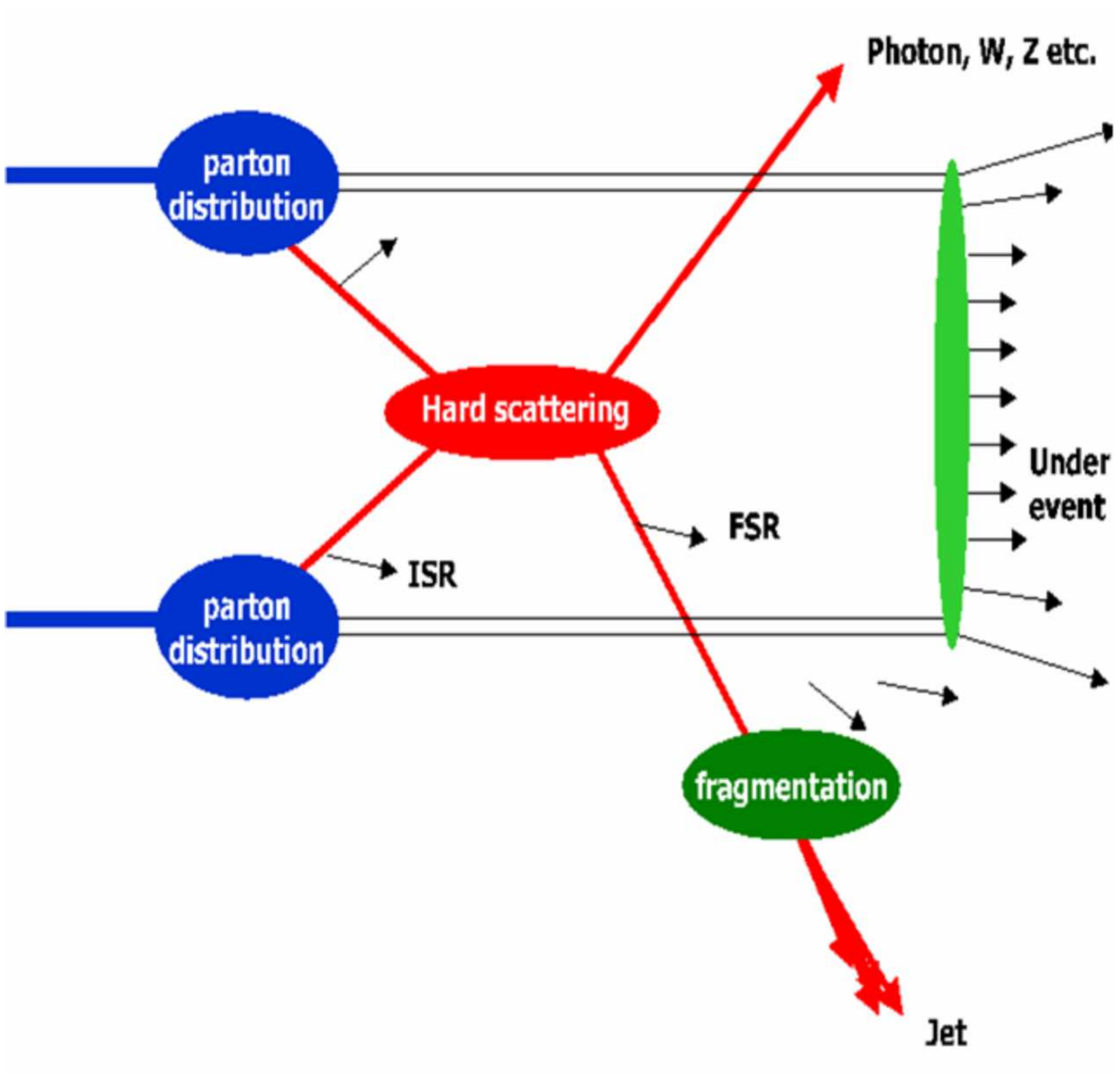
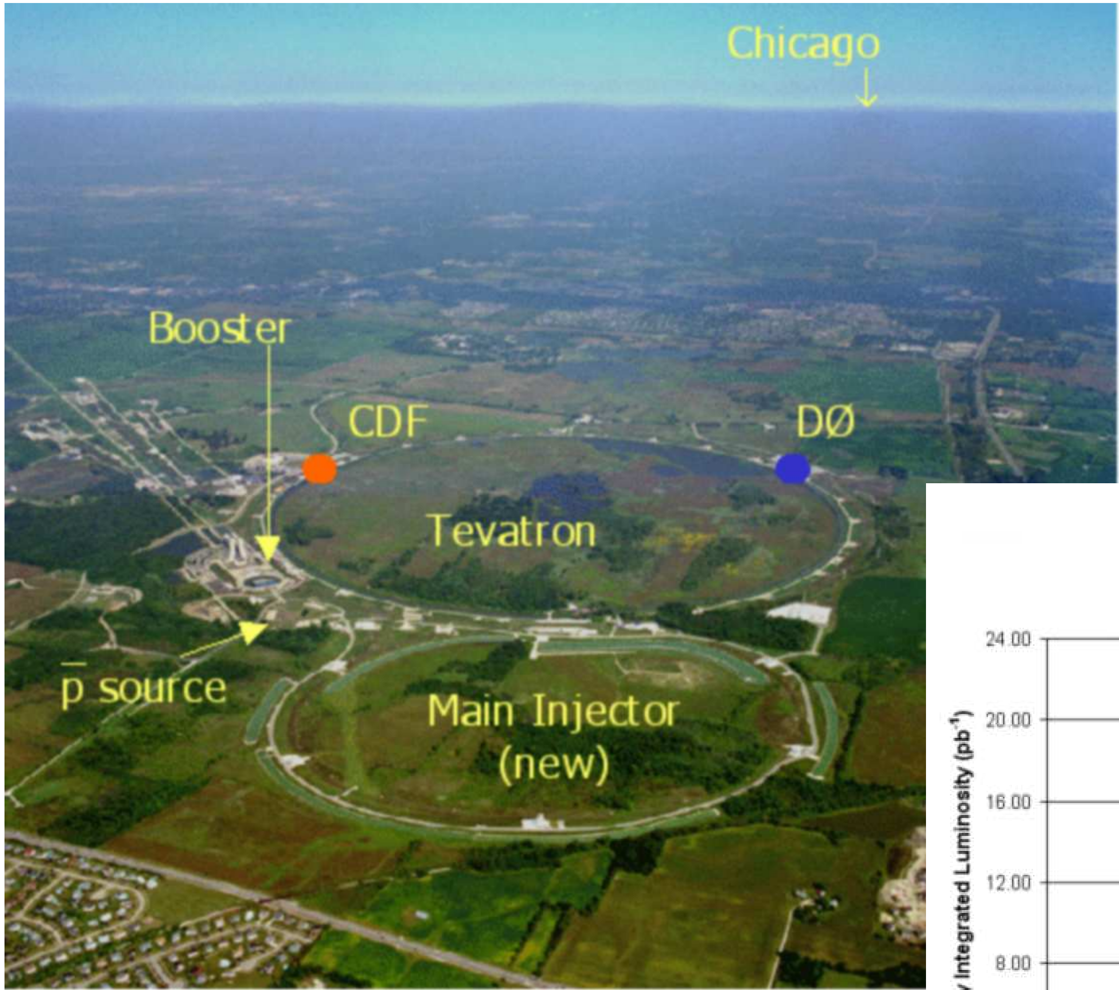
# QCD at hadron-hadron colliders



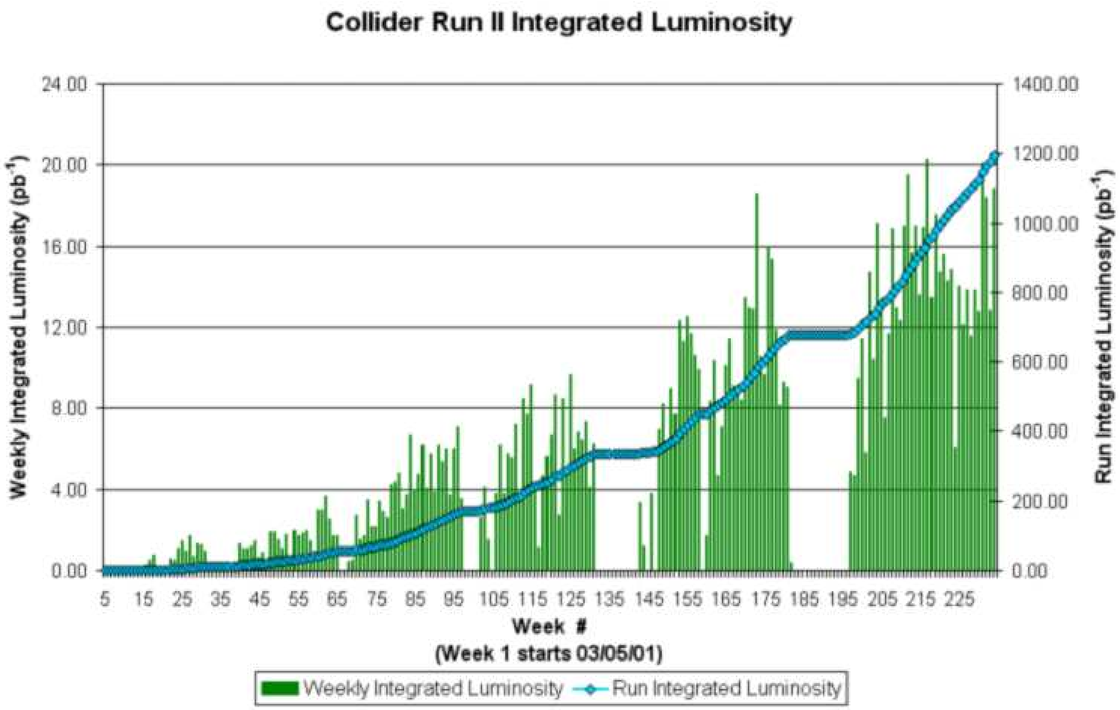

- high $p_T$ physics
  - central inclusive jet production
- multi-parton radiation
  - dijet azimuthal decorrelations
  - jet shapes
- soft physics
  - studies of soft underlying event

# Tevatron



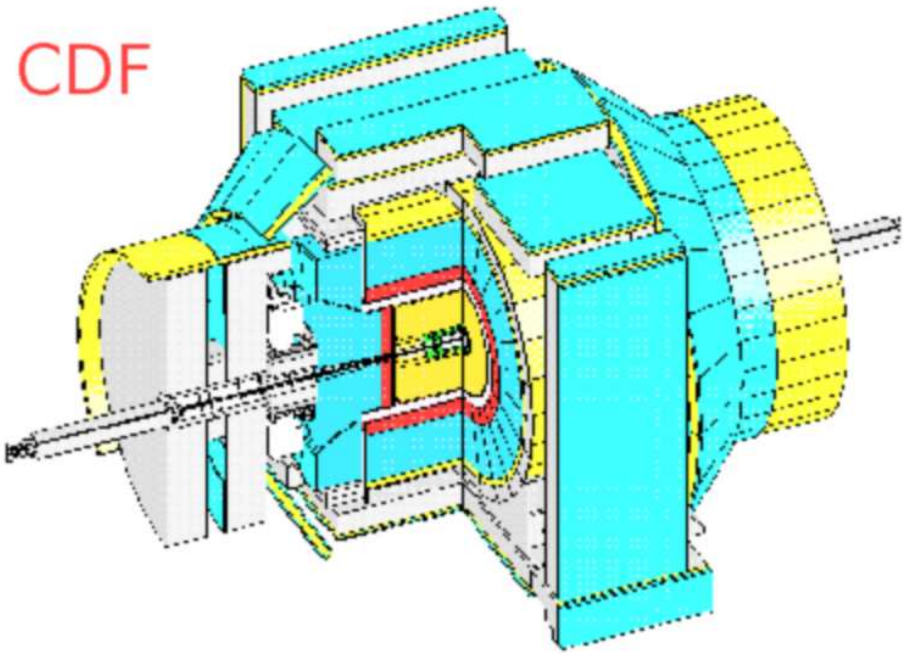

- Run I → Run II
  - $1.8\,$TeV → $1.96\,$TeV
  - luminosity upgrade
- Tevatron operates now at

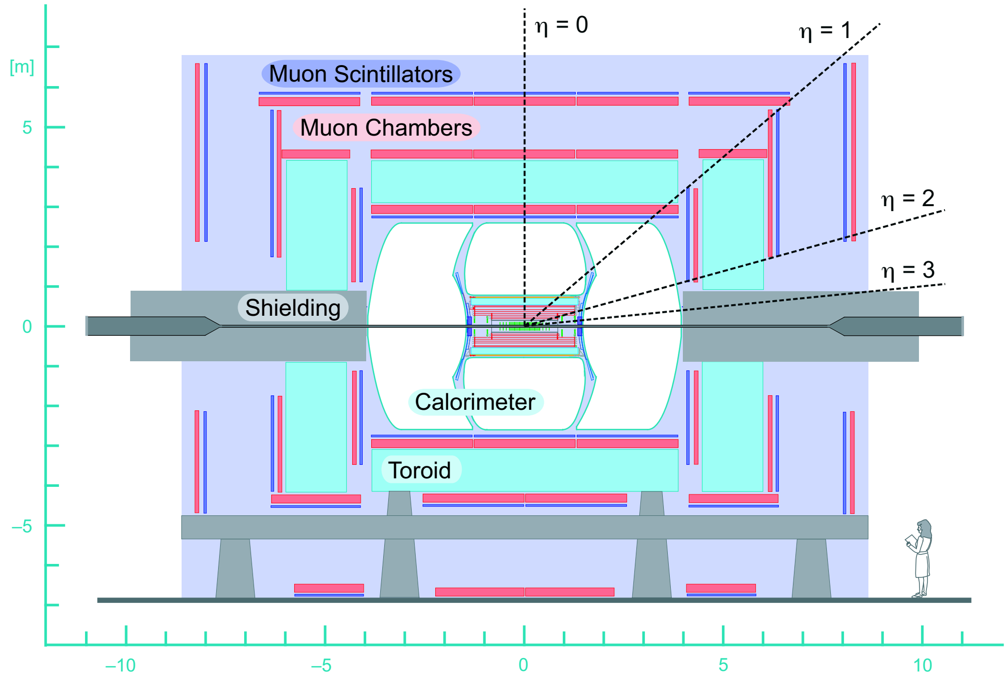
$$\mathcal{L} \sim 1.2 \times 10^{32}\,\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$$




- Long Term Luminosity Plans (2009)
  - base goal: $4.4\,\mathrm{fb}^{-1}$, design: $8.5\,\mathrm{fb}^{-1}$

# CDF and DØ detectors

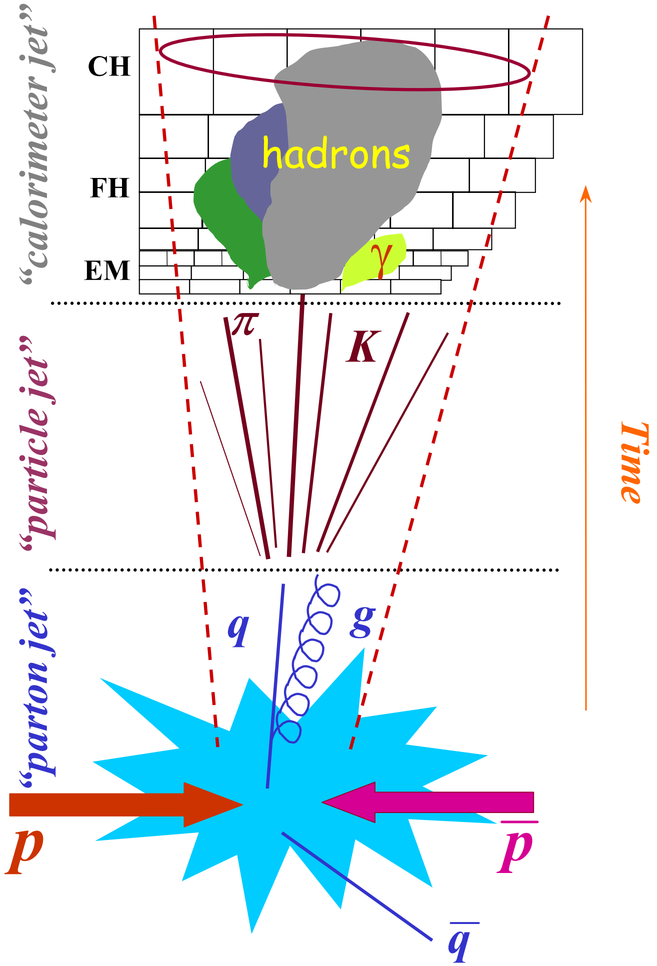



- lead/iron + scinitillator/gas chamber calorimeter
- uranium + liquid argon calorimeter

- the same calorimeters as in RunI - faster readout and trigger electronics
  - $396$ ns between $p\bar{p}$ bunches in RunII; $2.4\,\mu$s in RunI
- completely new tracking detectors (in case of DØ added also magnet)

# Jets




▷ calorimeter jet

- jet is a collection of calorimeter towers
- correct for detector effects (calibration, resolution, . . .)

▷ particle jet

- no theory from the first principles of QCD
- predictions are model dependent

▷ parton jet

- hard parton jets (fixed order calculations) or after development of parton showers (resummation)

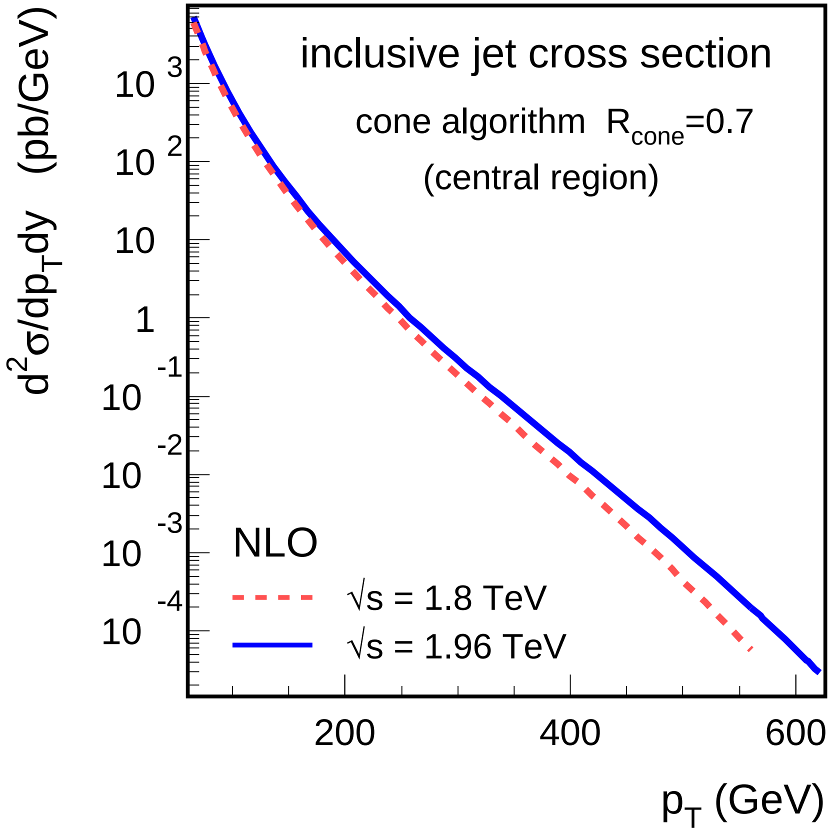
▷ Jet algorithm

- geometrical definition (cone algorithms): midpoint algorithm in Run II
- pQCD motivated algorithms ($k_T$-algorithms)

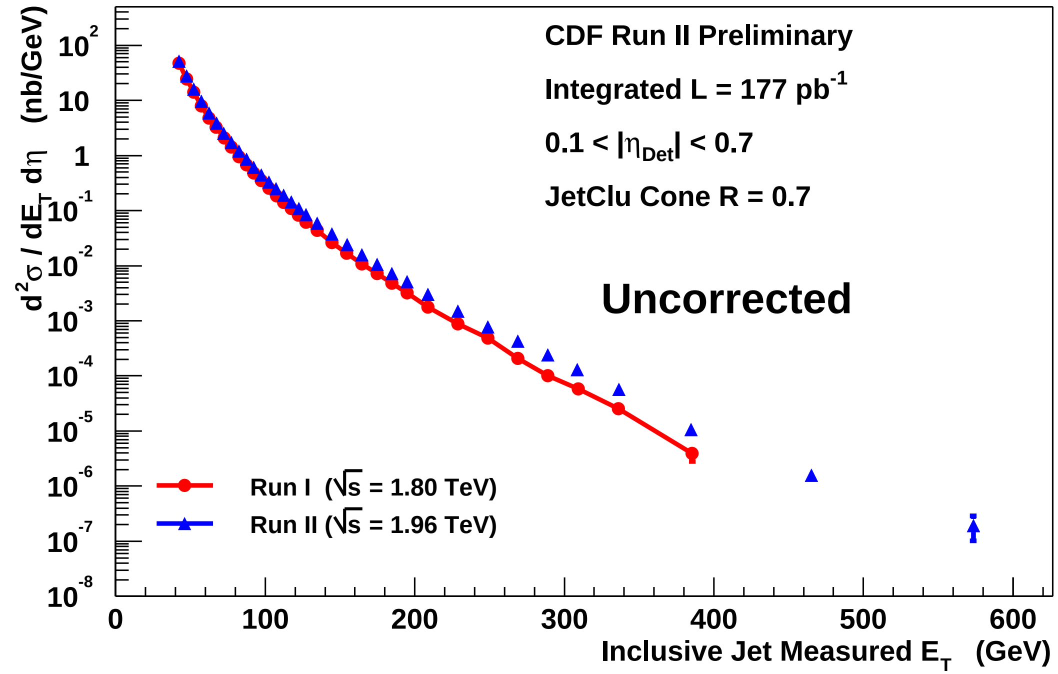
# High $p_T$ jets in RunII

- higher $\sqrt{s}$ $(1.8 \rightarrow 1.96$ TeV)

$\rightarrow$ higher cross section at high $p_T$

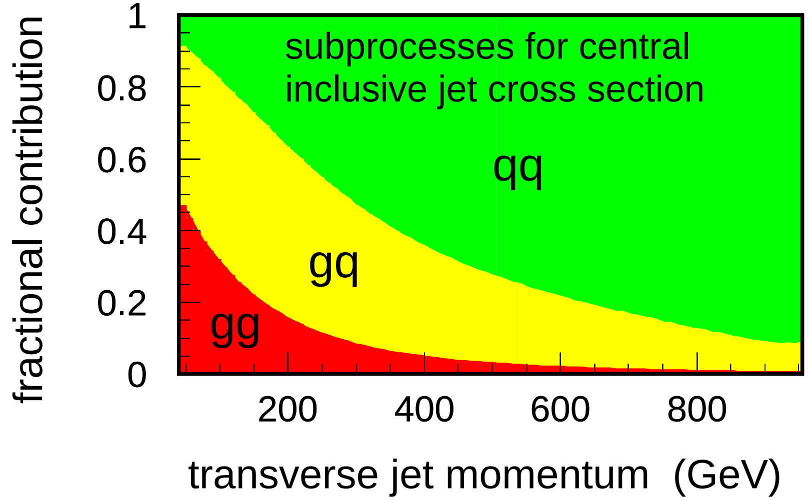



+ more luminosity

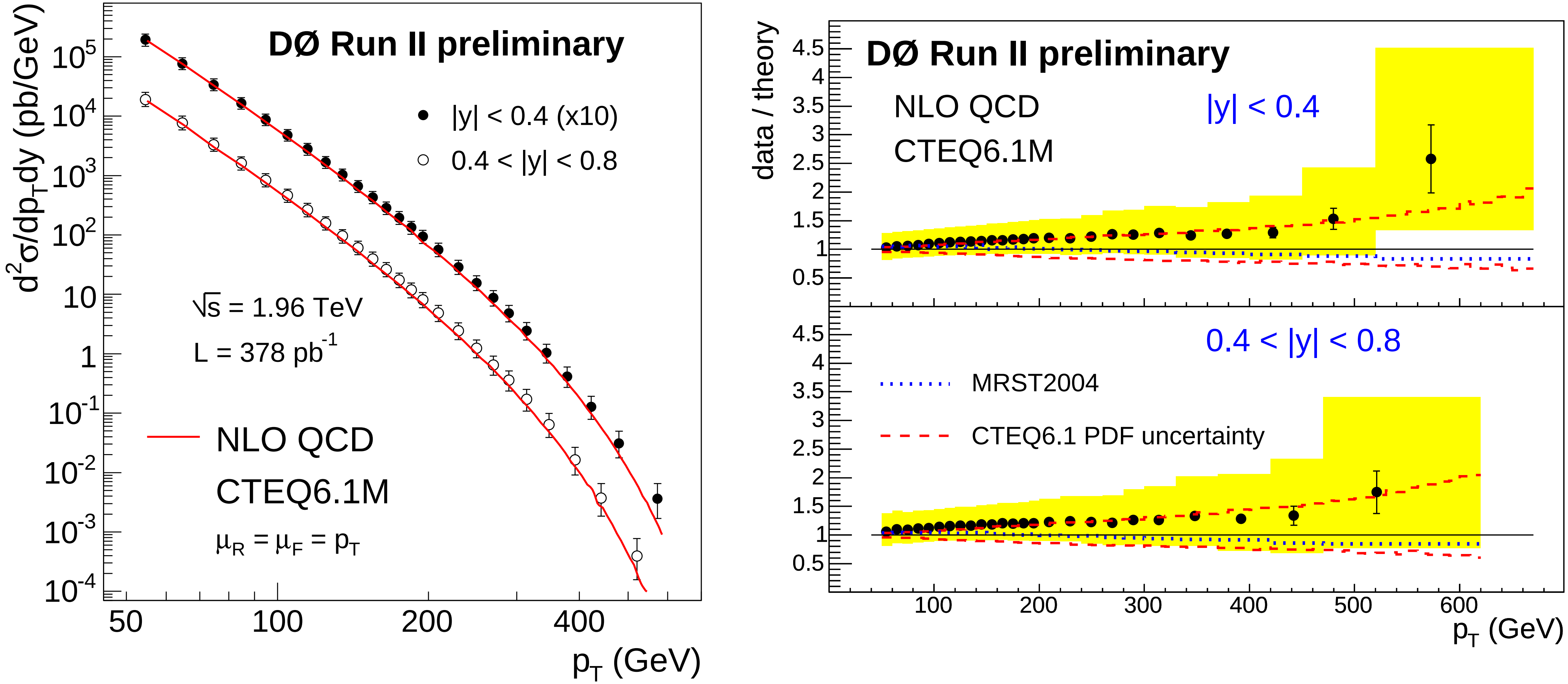



$\Rightarrow$ reach in jet $p_T$ significantly increased

- sensitivity to gluon PDF at high $x$

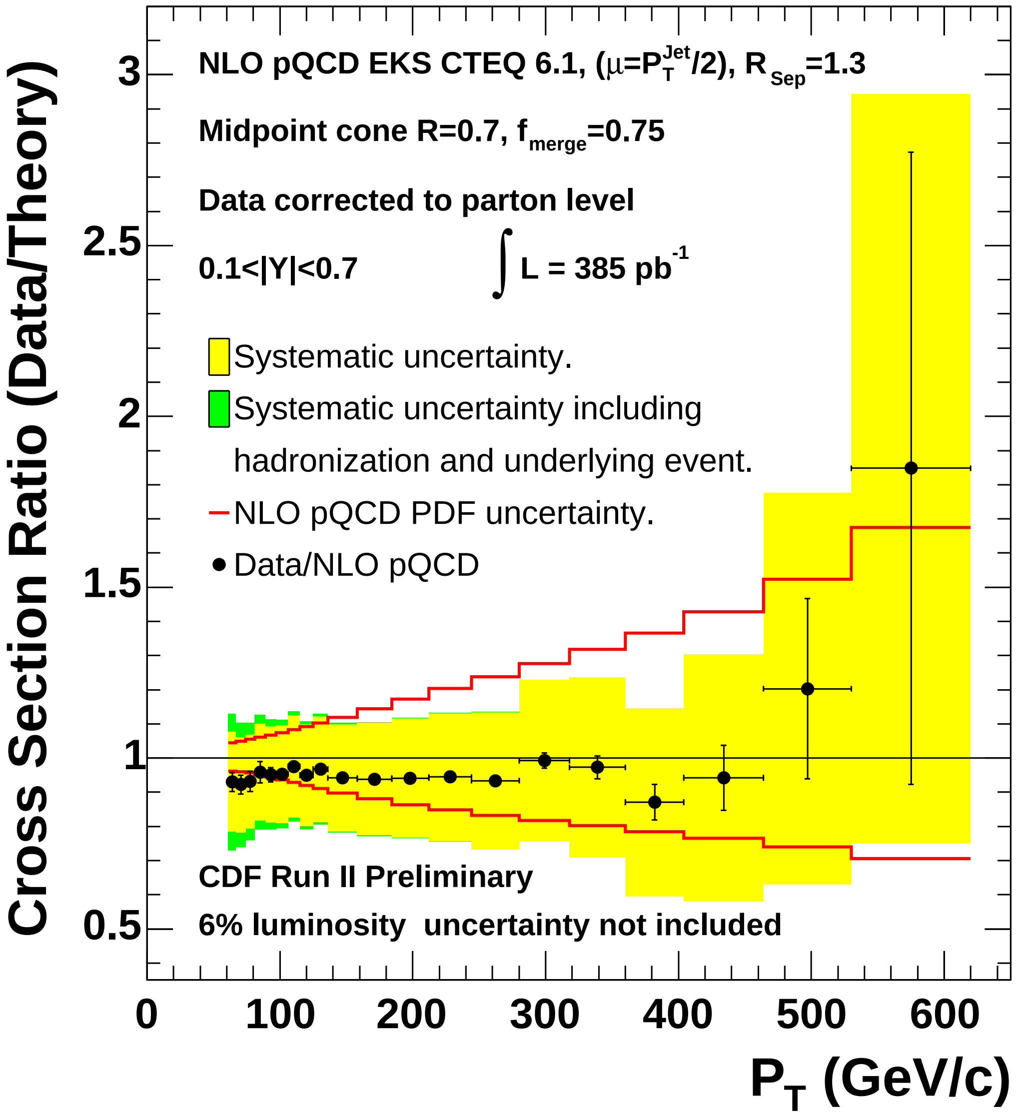


# Central jet inclusive cross sections (DØ)

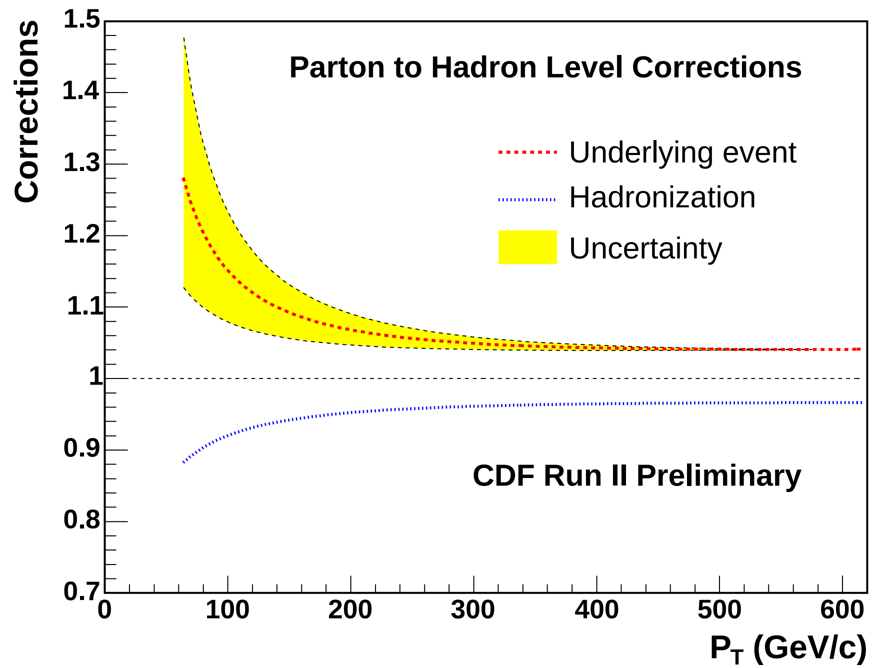



- dominant experimental uncertainty - jet energy calibration
- good agreement with NLO QCD over 8 orders of magnitude
- theory uncertainty at high $p_T$ is dominated by uncertainty on gluon density at large $x$

# Central jet inclusive cross sections (CDF)



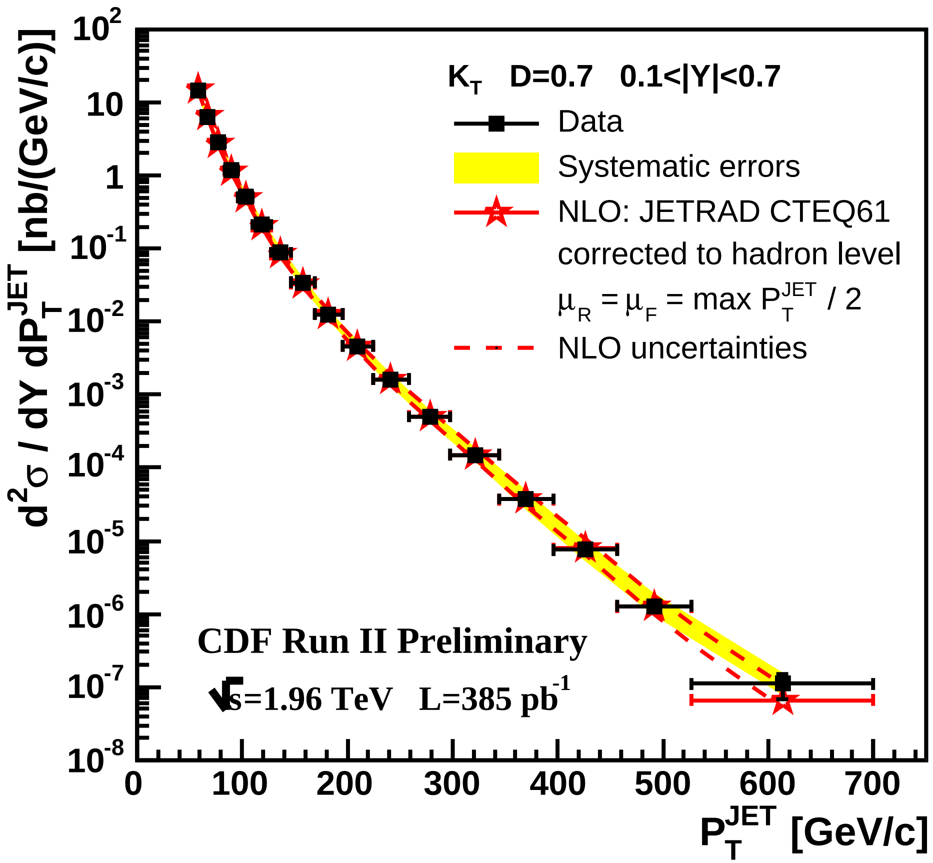

- data corrected to the parton level

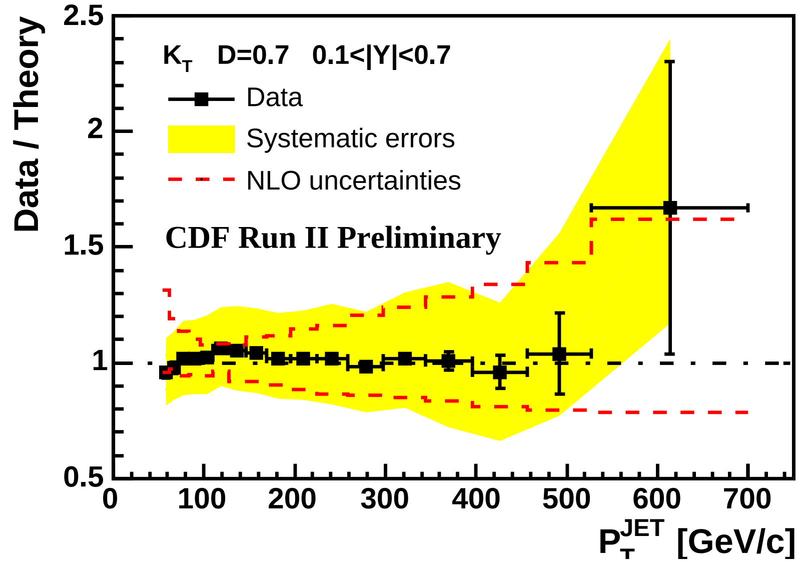


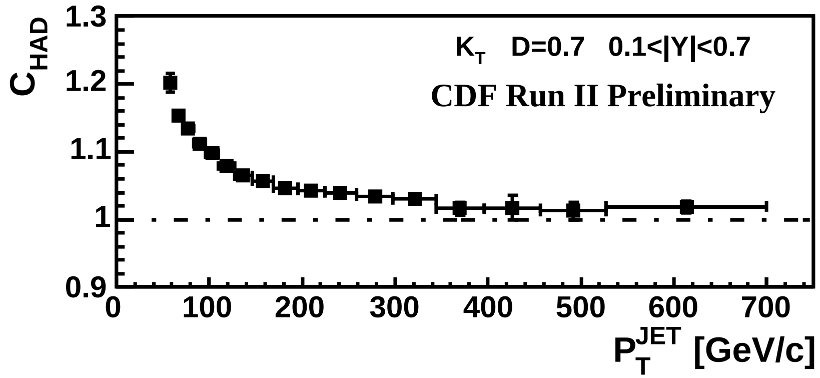

- in Run I, possible excess observed at high $p_T$
- Run II data consistent with CTEQ6.1M PDF

# Inclusive cross section with $k_T$ jets

- $d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\Delta R_{ij}^2/D^2$
- $d_i = p_{Ti}^2$
- recombine closest pair
- infrared/collinear safe
- no split/merge procedure

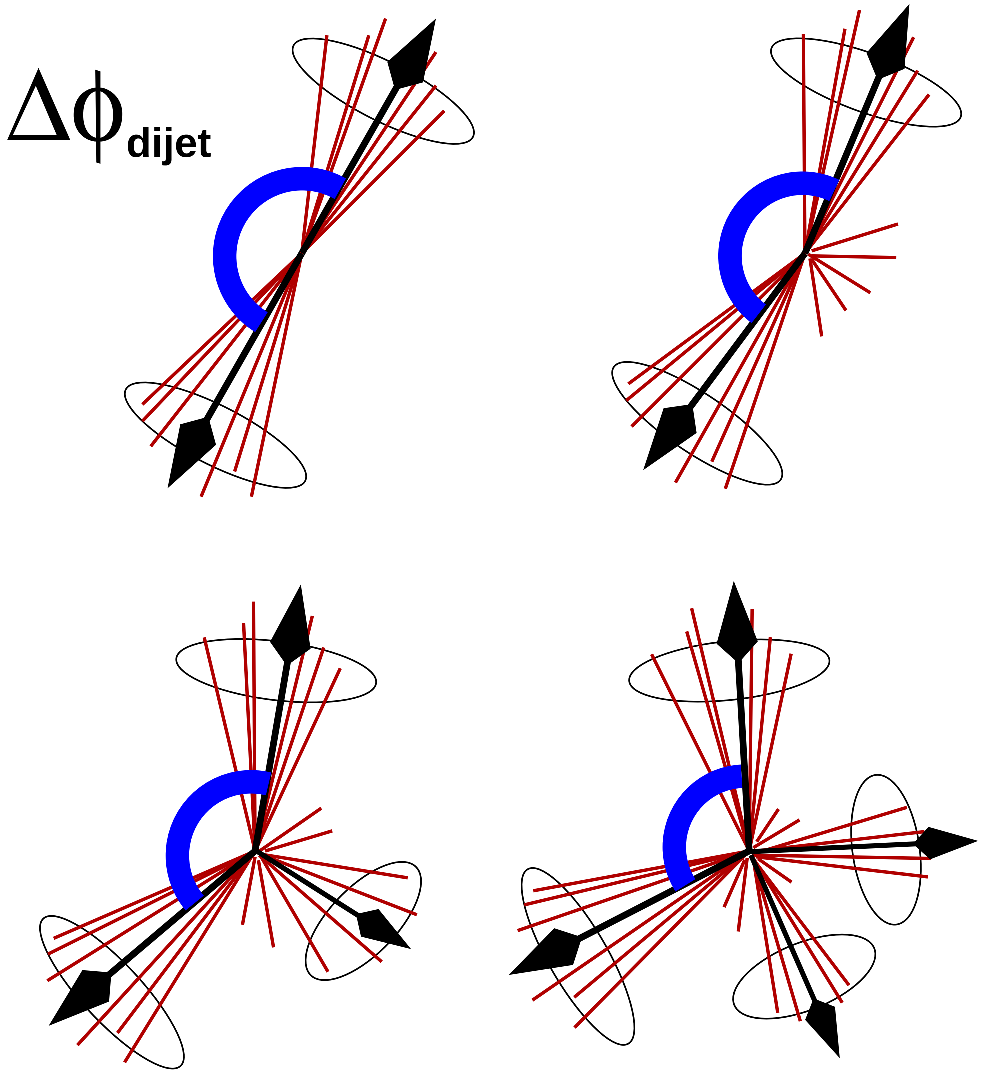


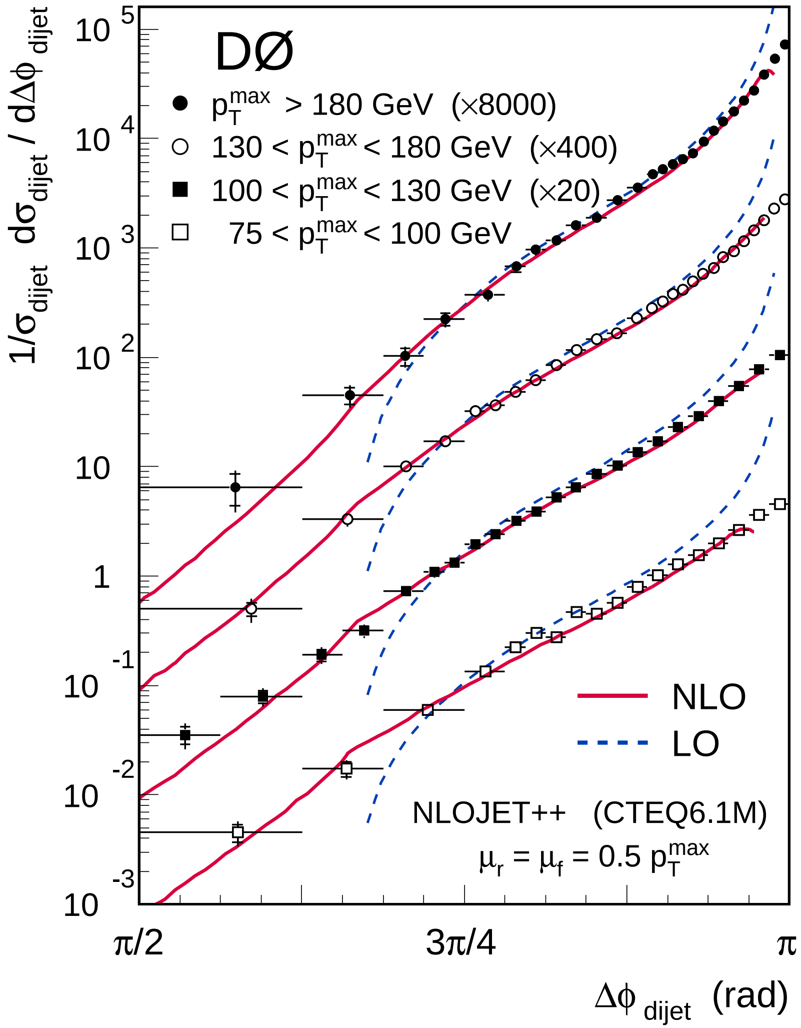

- measured for $D = 0.5,\ 0.7,\ 1.0$
- good agreement with NLO QCD

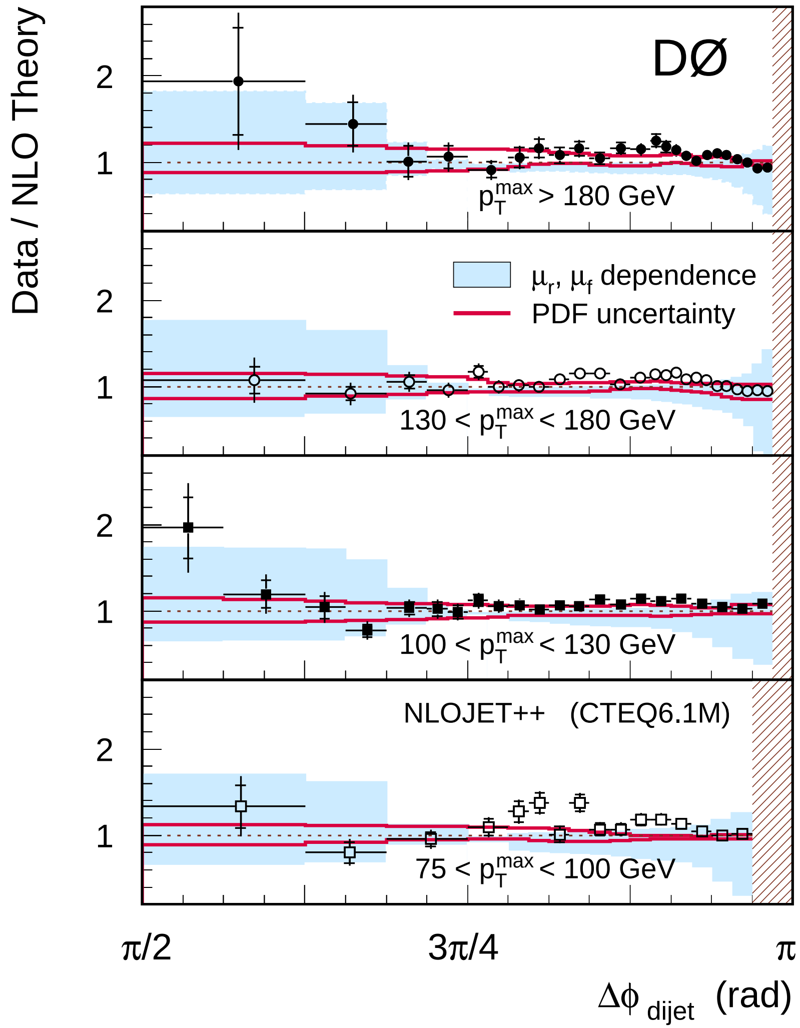
# Dijet azimuthal decorrelations




- different regions of $\Delta\phi_{dijet}$ are sensitive to different aspects of multiparton emissions
- a clean and simple way to study QCD radiative processes
  - reduced sensitivity to jet energy calibration
- Phys.Rev.Lett.94:221801,2005

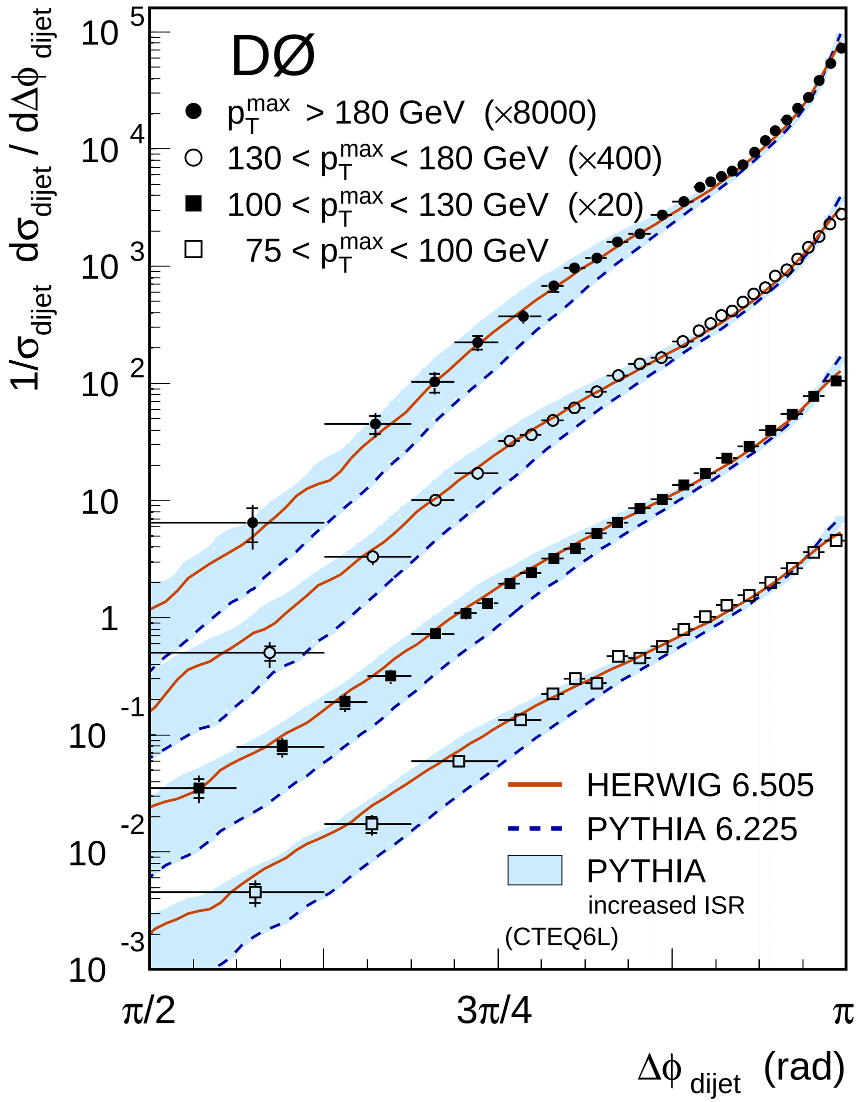
# $\Delta\phi$ - comparison with pQCD




- comparison with $2 \to 3$ NLO calculations (these were not available in Run I)
- agreement with NLO QCD except $\Delta\phi \to \pi$ where resummation is needed

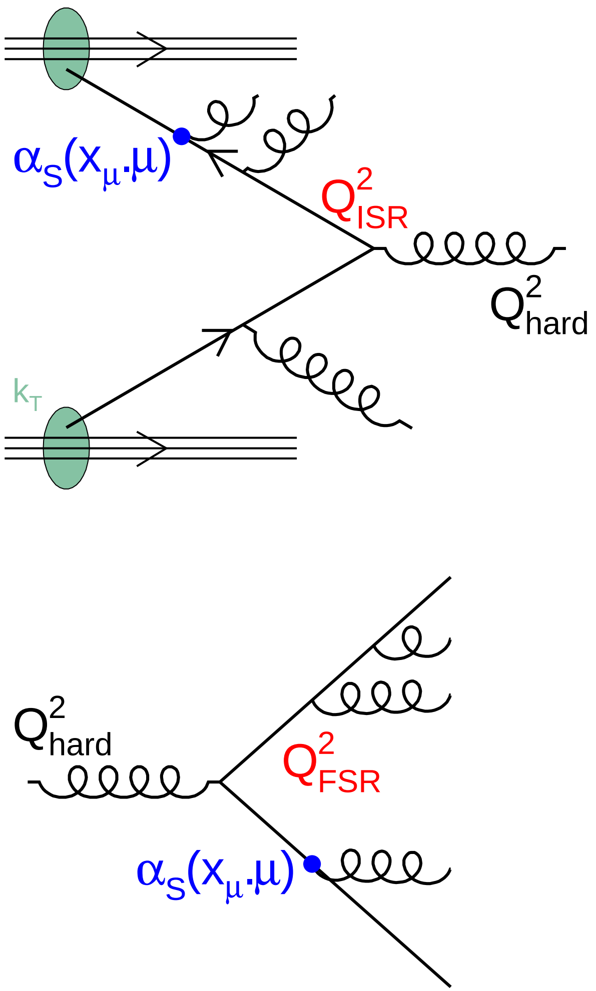
# $\Delta\phi$ - comparison with MC

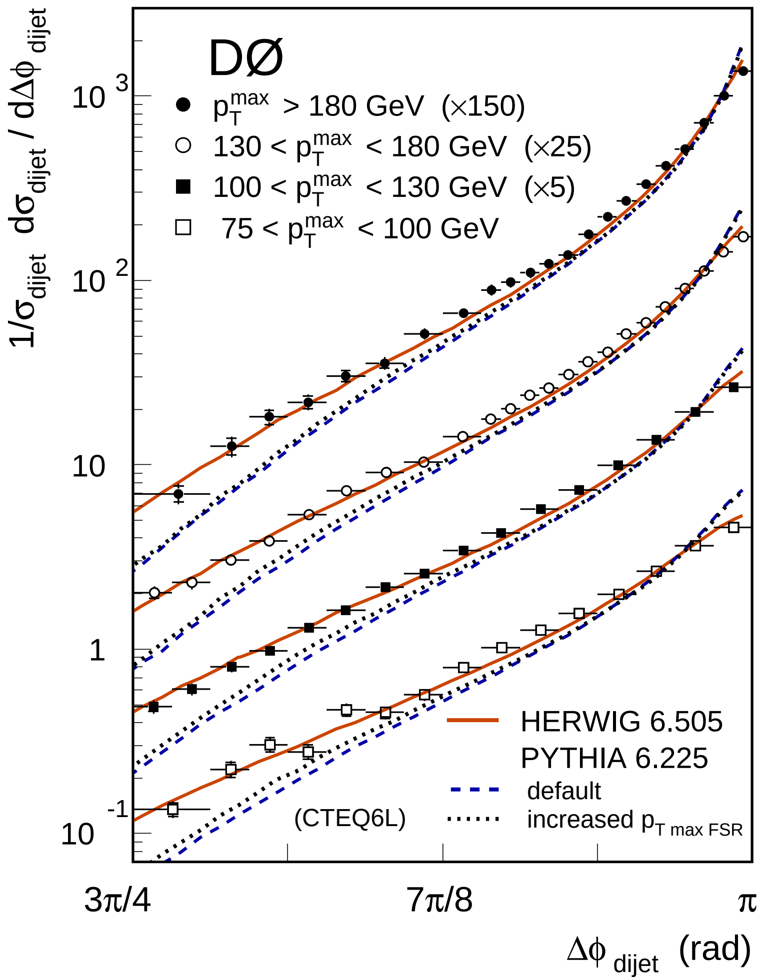


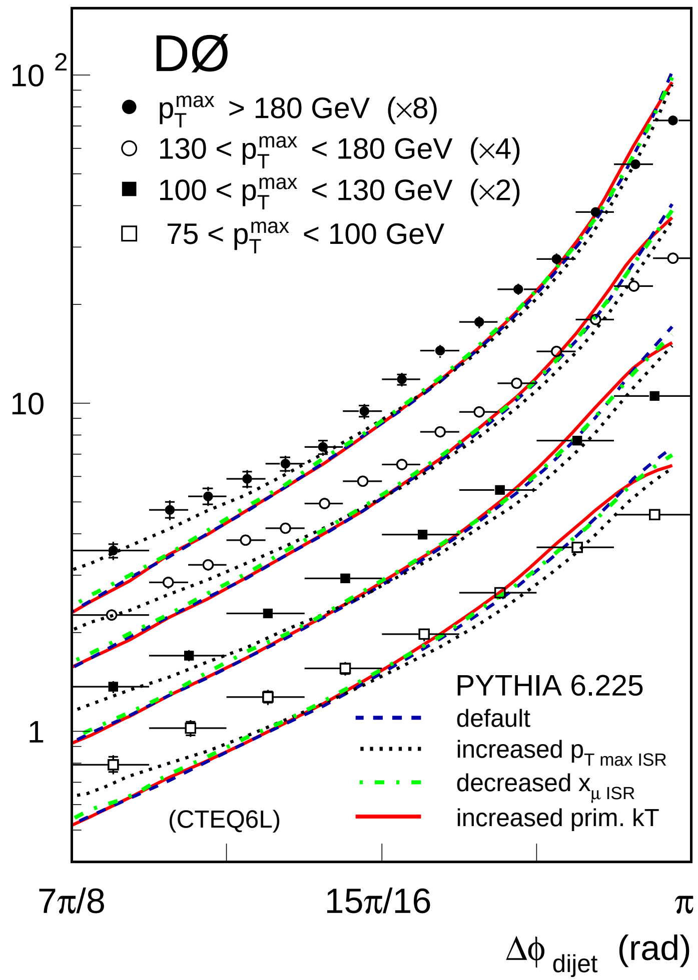

- HERWIG shows a good agreement with the data
- not true for default setting of PYTHIA
  - the distribution is sensitive to `PARP(67)` which controls the maximal allowed virtuality in the initial state parton shower
  - PARP(67)=2.5 fits the data well

The plot demonstrates the impact on tuning the MC generators

# $\Delta\phi$ - and partonic shower in Pythia




Sensitivity only to the maximal allowed virtuality in ISR

# Jet shapes

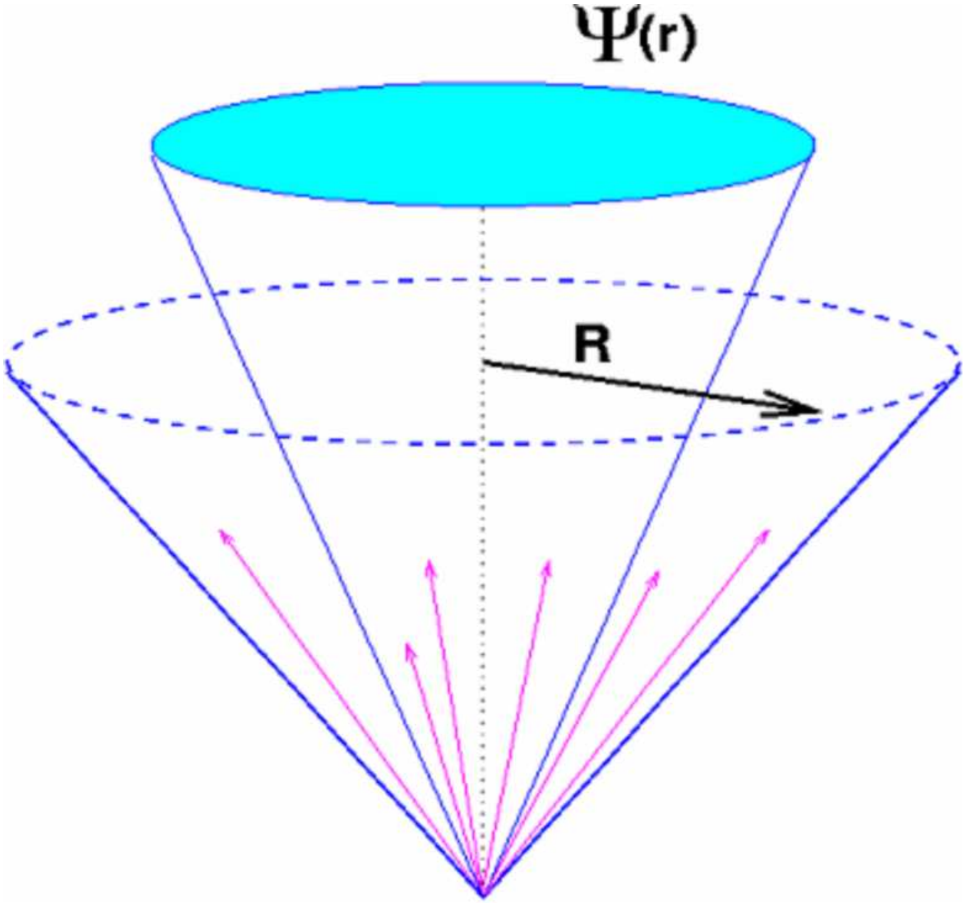
- sensitive to multi-parton radiation from primary hard parton

$\Rightarrow$ test of parton shower models

- sensitive to $\alpha_S$ and its running
- different for quark/gluon induced jets
- for low $p_T$ jets - sensitive to the soft underlying physics

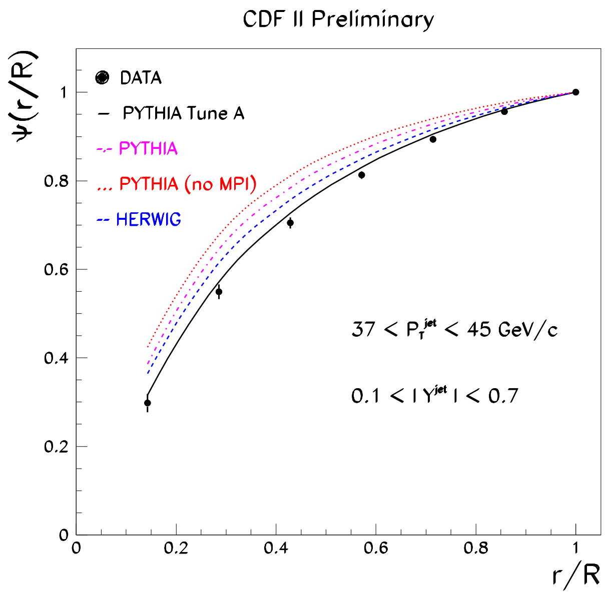
- measured with midpoint algorithm

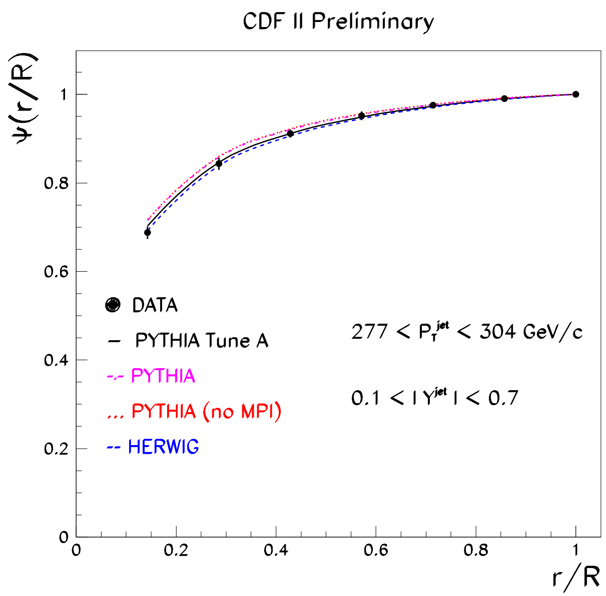
- Phys. Rev. D71, 112002 (2005)

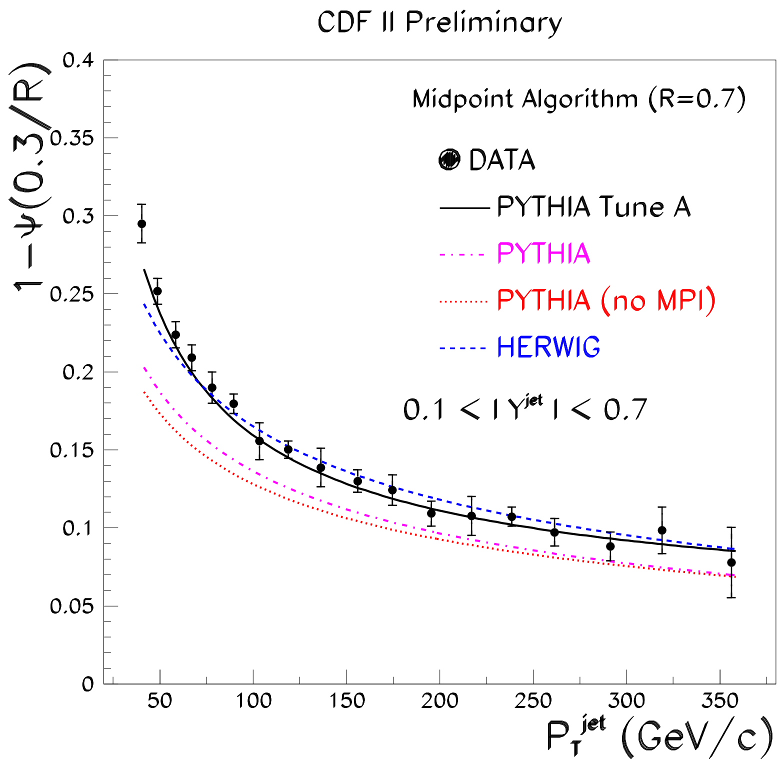



$$\Psi(r) = \frac{1}{N_{jet}} \sum_{jets} \frac{p_T(0,r)}{p_T(0,R)}$$

# Jet shapes measurement

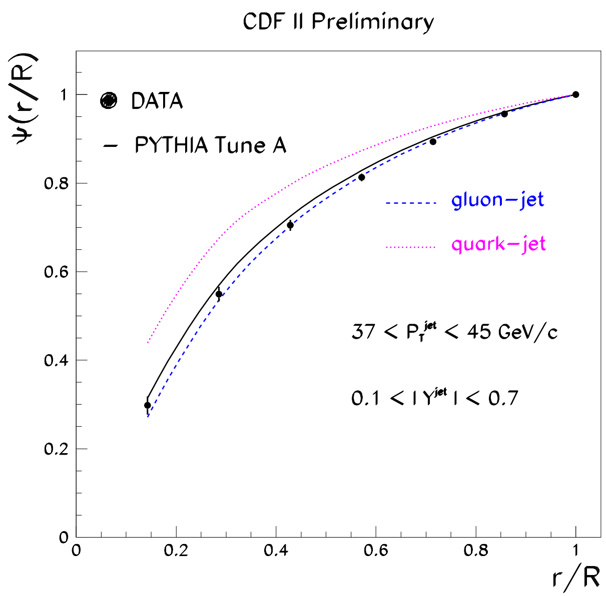


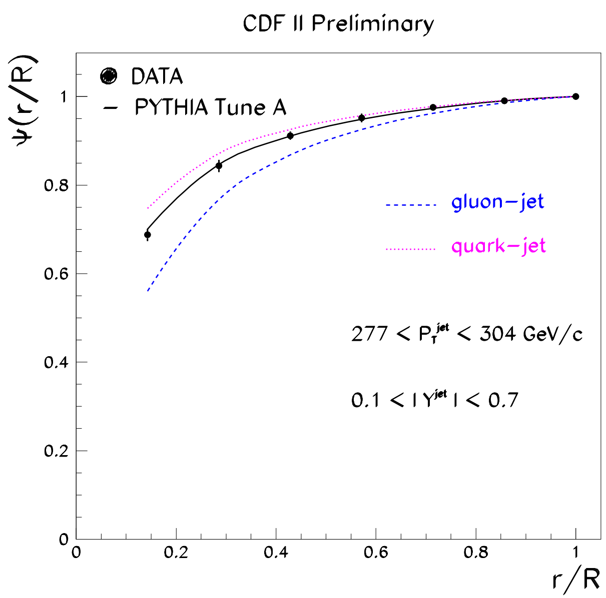



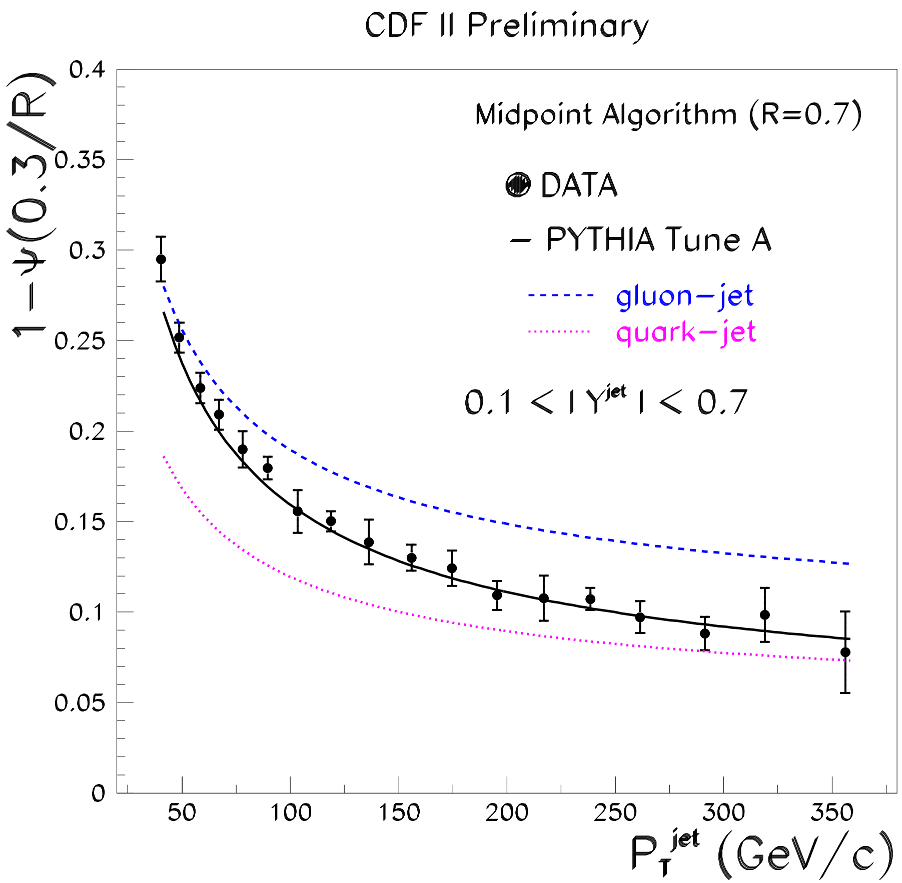




- central jets; measurement available for whole range of jet $p_T$
- default PYTHIA (w/wo MPI) too narrow
- PYTHIA Tune A (based on CDF Run I data on soft underlying event) - good description
- Herwig - too narrow jets at low $p_T$

# Quark/Gluon Jet Shapes



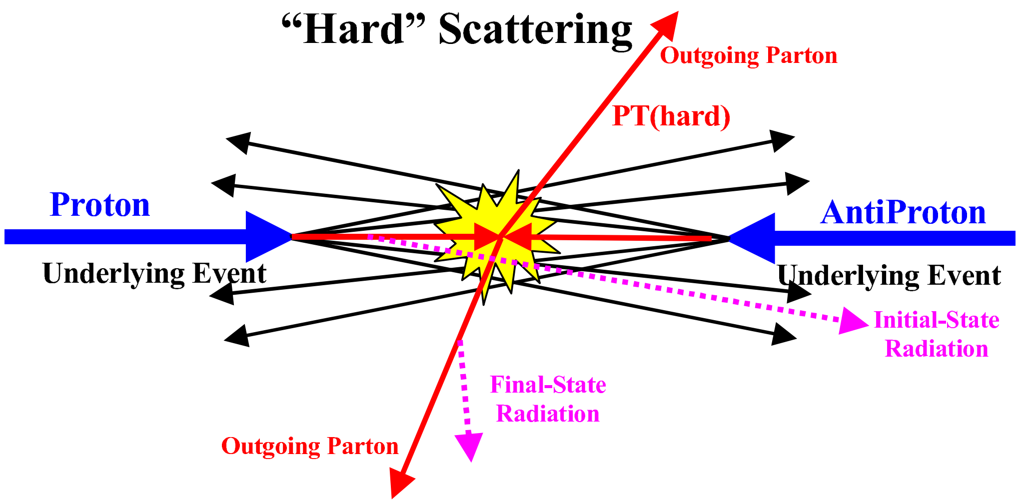




- sensitivity to running of $\alpha_S$ running

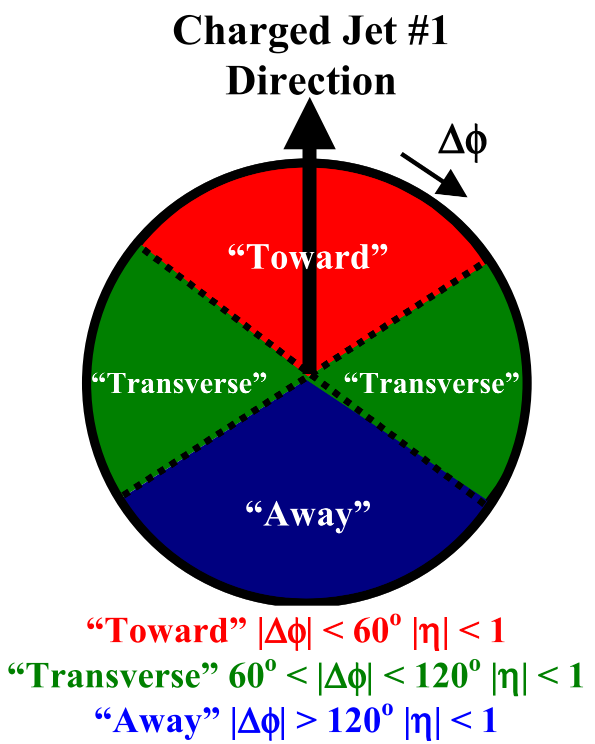
$$1 - \Psi(r_0) \propto \alpha_S(p_{T\,jet})$$

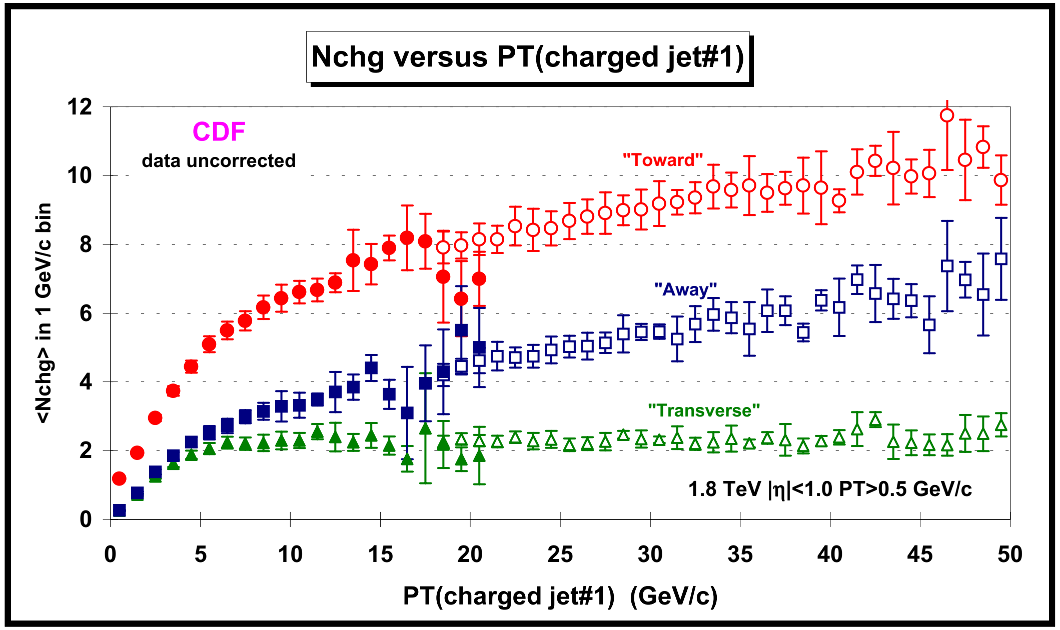
- quark jets more narrow than gluon jets

# Run I underlying event studies by CDF




- "underlying event":
  parton showers, beam remnants,
  other soft part of underlying event
- Phys.Rev.D65:092002,2002
  study of charged particle flow
  in various kinematic domains



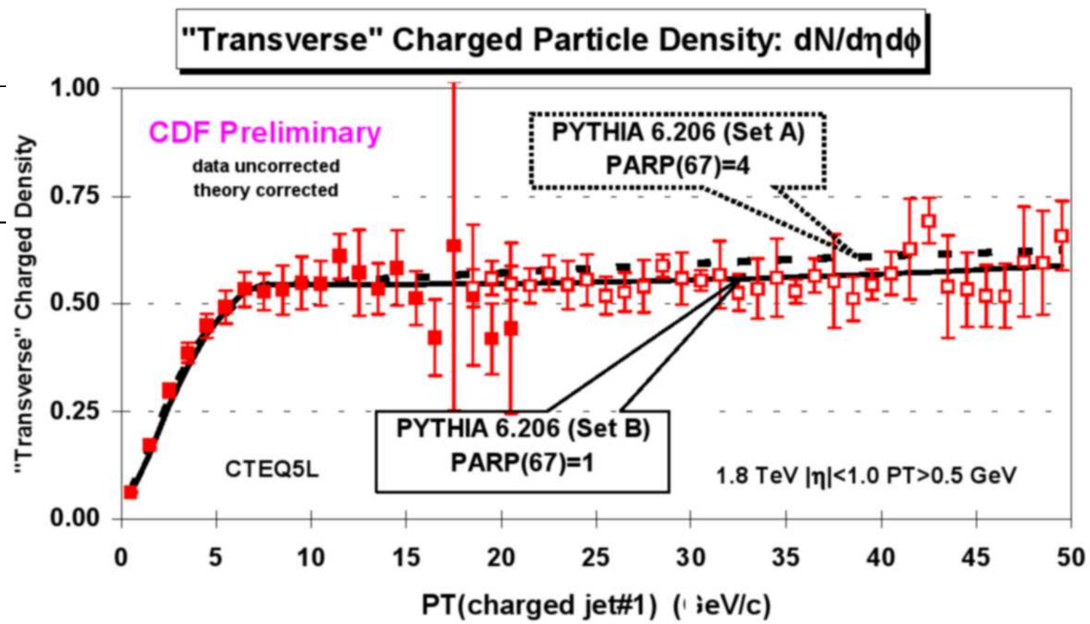



# Tune of Pythia model of soft physics

| Parameter | TuneA | TuneB | |
|---|---|---|---|
| MSTP(81) | 1 | 1 | multiple scattering (on/off) |
| MSTP(82) | 4 | 4 | model of mult. scatt. |
| PARP(82) | 2.0 GeV | 1.9 GeV | regularization of $\sigma_{2\to 2}$: $p_T^2 \to (p_T^2 + p_{T0}^2)$ |
| PARP(83) | 0.5 | 0.5 | controls matter distribution |
| PARP(84) | 0.4 | 0.4 | in proton in transverse plane |
| PARP(85) | 0.9 | 1.0 | controls fraction of scat. gluons |
| PARP(86) | 0.95 | 1.0 | and quarks and color flow |
| PARP(89) | 1.8 TeV | 1.8 TeV | controls running |
| PARP(90) | 0.25 | 0.25 | of $p_{T0}$ with $\sqrt{s}$ |
| PARP(67) | 4 old def. | 1 new def. | controls ISR |

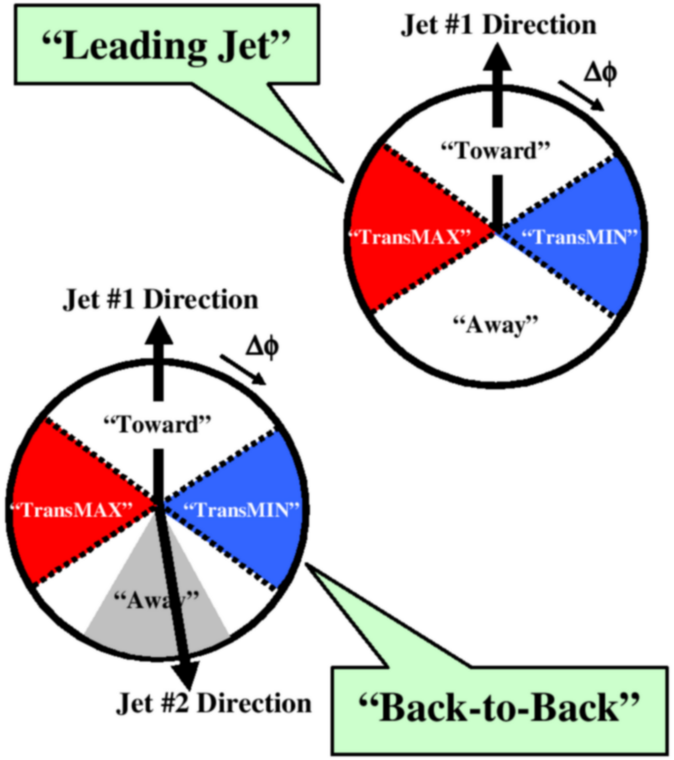
- same model as for minimum bias events
- smooth transition between soft and hard region

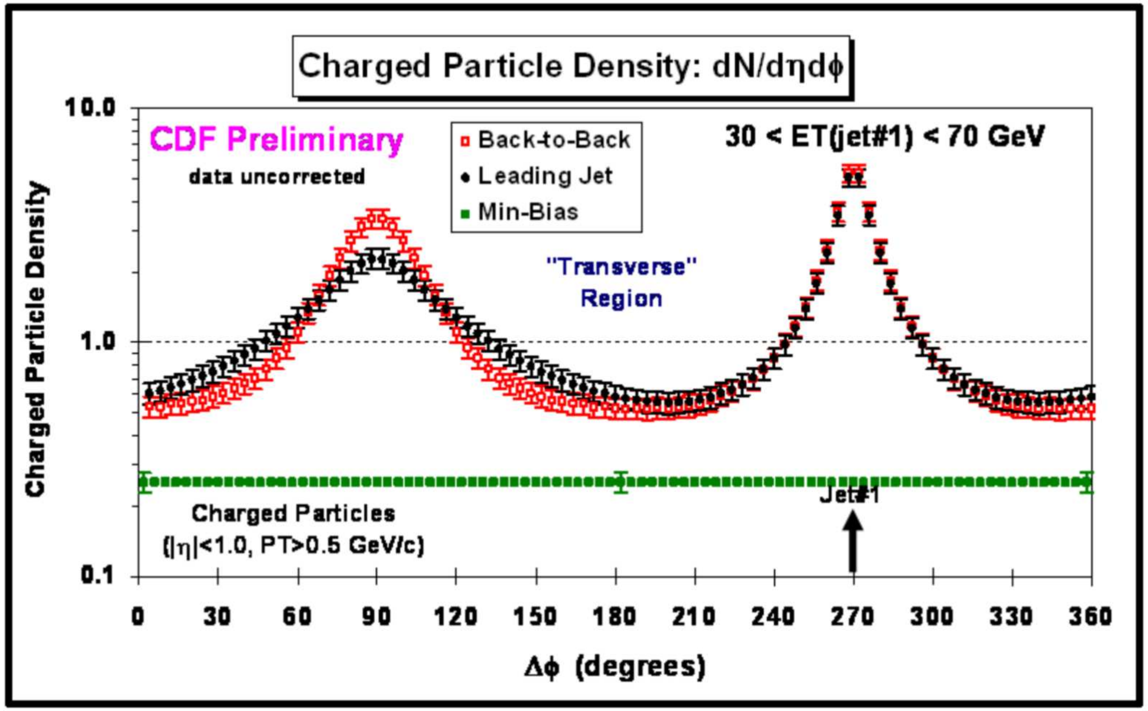
- tune related with PDF (CTEQ5L)
- TuneA is used by CDF and DØ
- JIMMY: MPI for Herwig



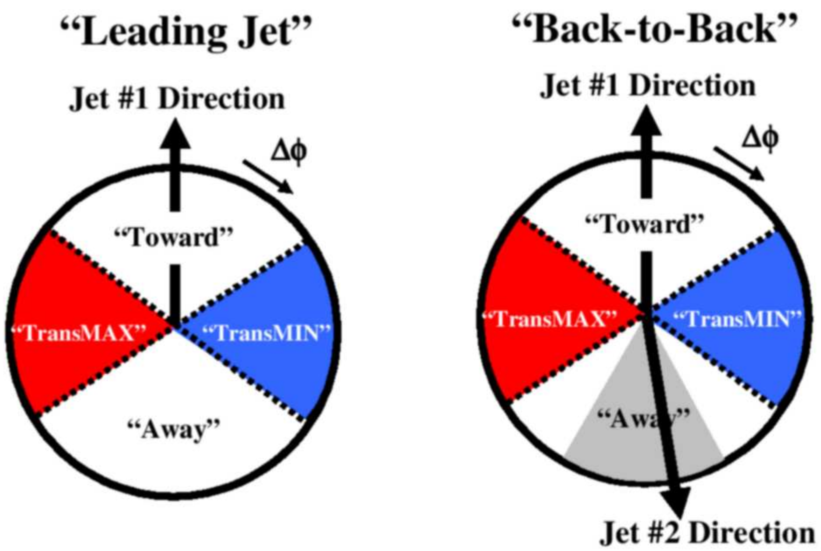
# New Run II CDF results

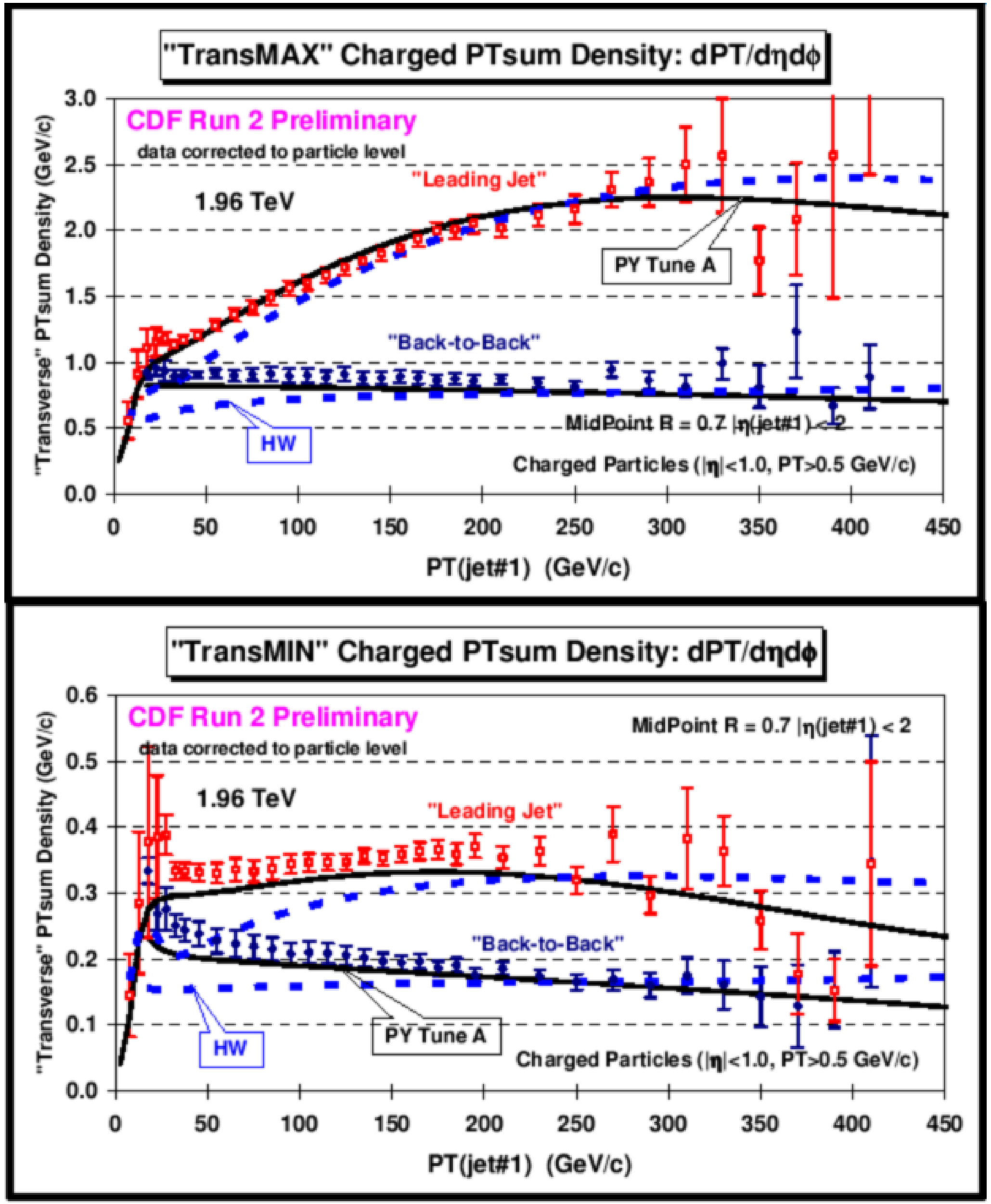
- more luminosity: $\mathcal{L} = 385\,\text{pb}^{-1}$
- new topology: leading jet, back-to-back jets
- data corrected to particle level
- added calorimeter information: study of $E_T$ density



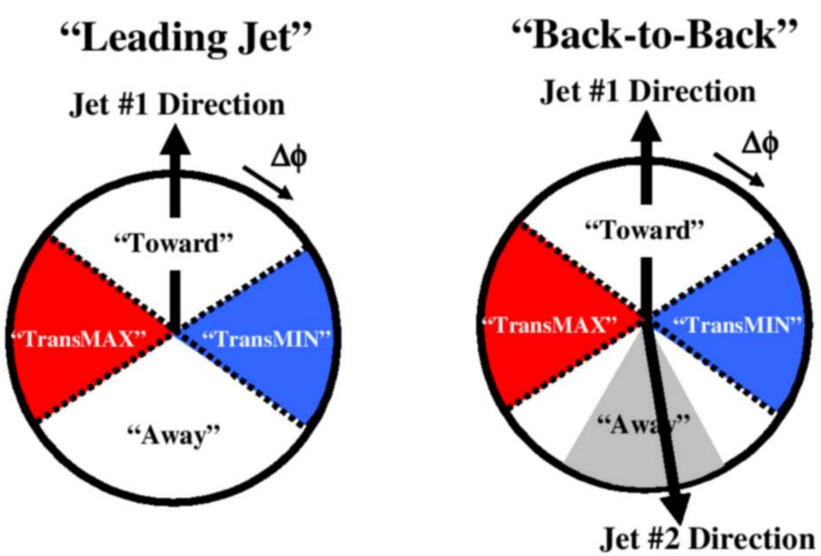
# $p_T$ sum in MIN and MAX regions



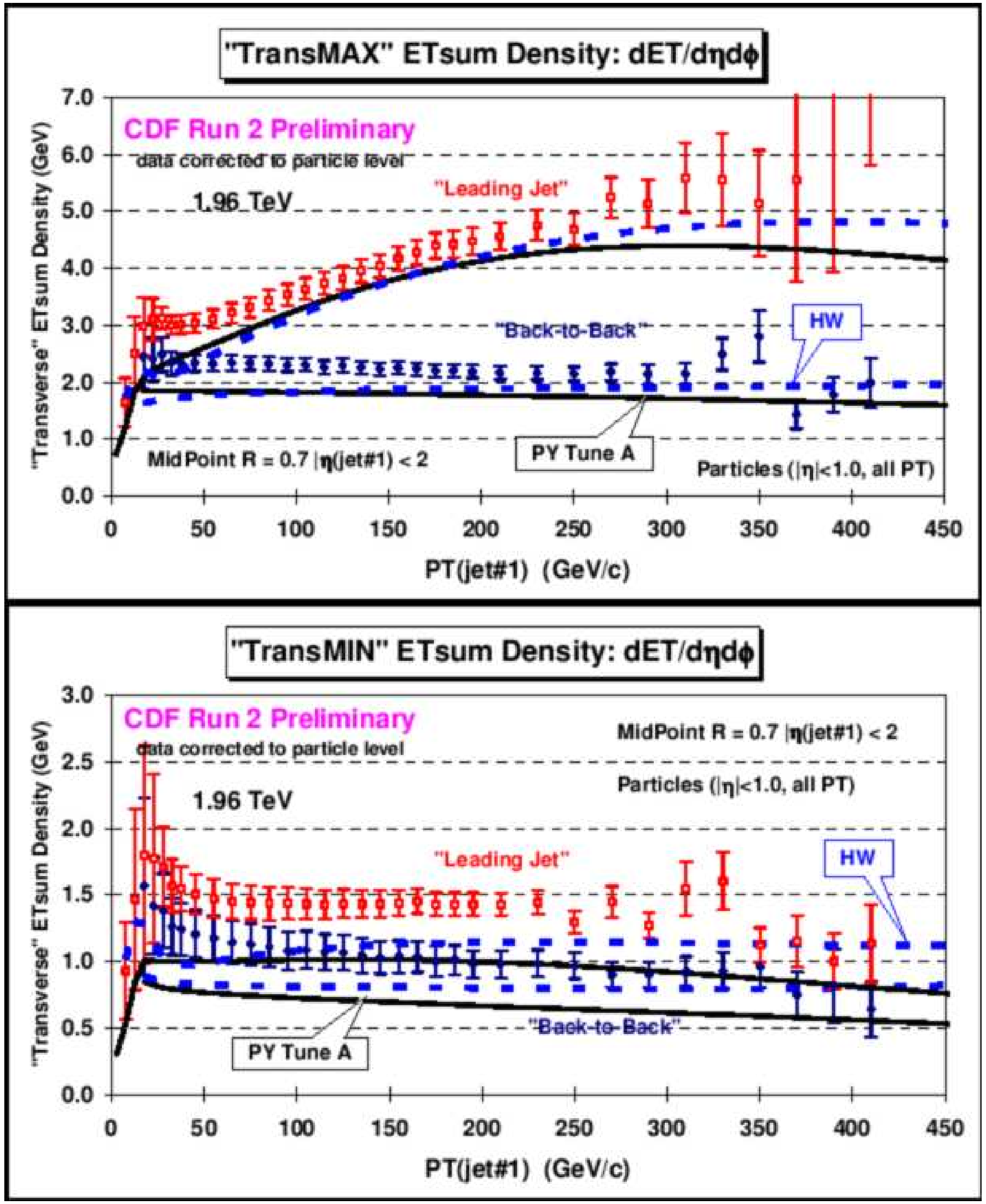




- TransMIN and TransMAX
  - defined event-by-event
  - transverse region with the smallest (largest) charged $p_T$ sum density
- TransMAX: mixture of hard and soft physics
- TransMIN: more sensitive to soft physics

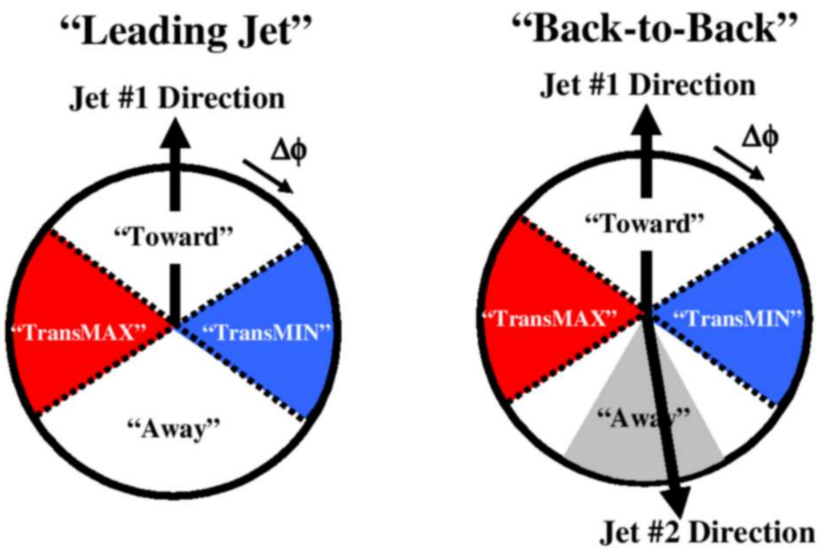
# $E_T$ sum in MIN and MAX regions



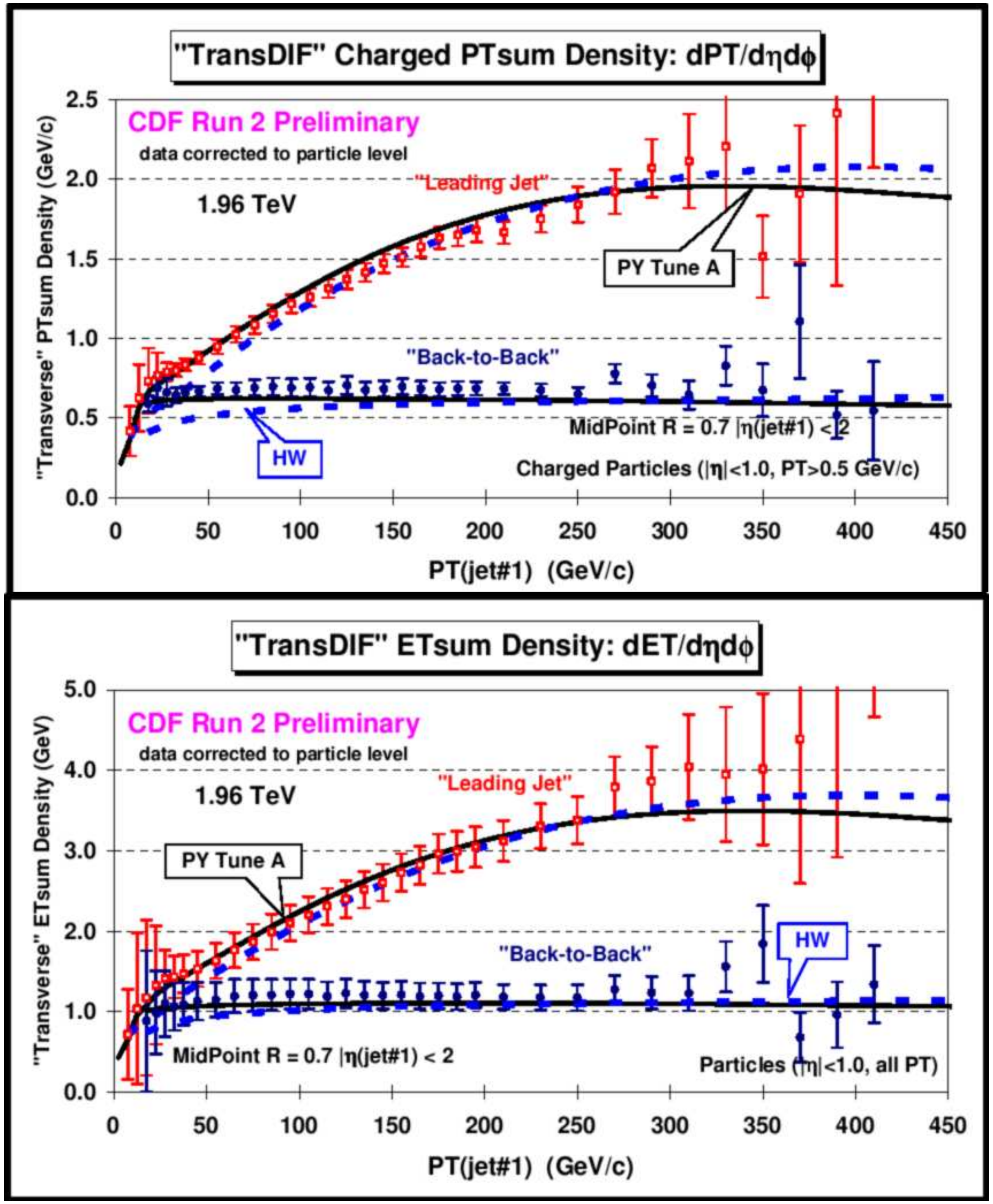

- for the 1st time, information about $E_T$ density from calorimeter is available
- TransMIN: large discrepancy between the data and models
- Underestimated production of very soft particles ($p_T < 0.5$ GeV)? Could it be tuned?



# TransDIF region




- TransDIF
  - defined event-by-event
  - DIF=MAX-MIN
  - sensitive to hard component of underlying event



# Summary

- With respect to RunI, the reach in jet $p_T$ was significantly extended for jet inclusive $p_T$ cross sections
  - testing pQCD at distances not explored before
  - cross section consistent with QCD over 8 orders of magnitude
  - new jet algorithms with better theoretical behavior (cone midpoint, $k_T$-algorithms) are being used
  - reducing experimental errors will lead to better understanding of gluon content of proton at high $x$
- Rich program of studying various aspects of pQCD multi-parton radiation and soft physics
- Good progress in understanding and modeling the underlying event has been made. However, we have not a perfect fit yet that would describe all observed features. Work on new improved Run II tunes is going on.