

QCD at DØ:
A Review of Recent Results

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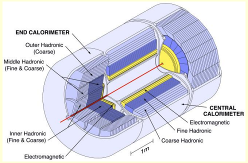
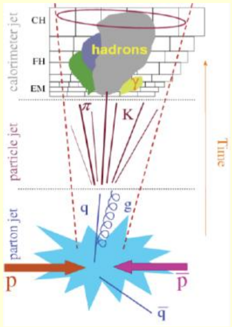
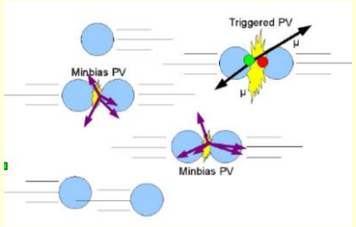
Outline

The collider and the detector

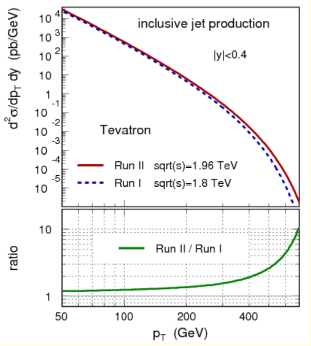


The data and the systematics



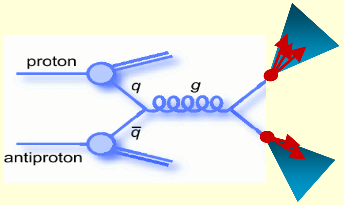


Non-perturbative Results
- Angular Correlation in Minimum Bias Events
- Double Parton Interactions

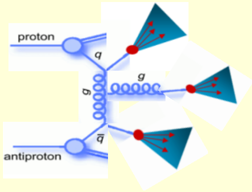


Inclusive Jet Results

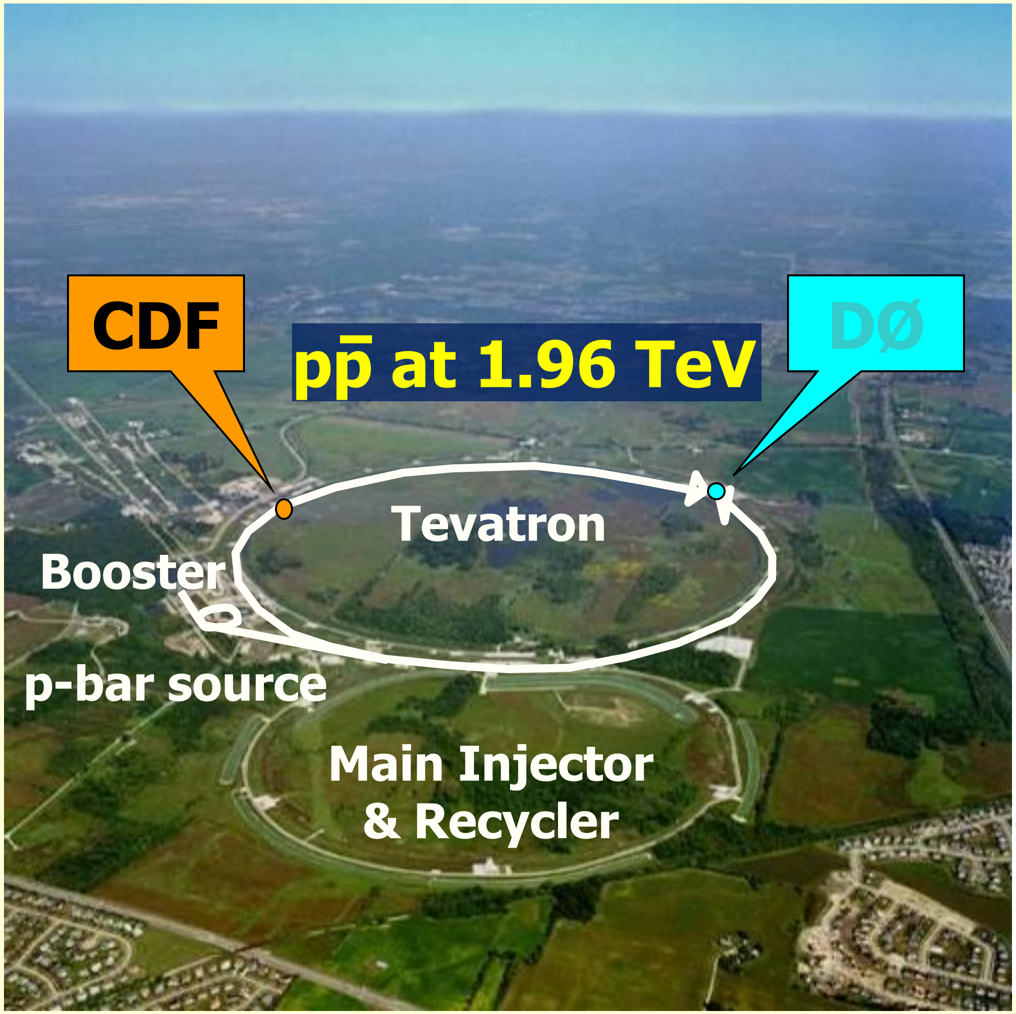
Dijet Results



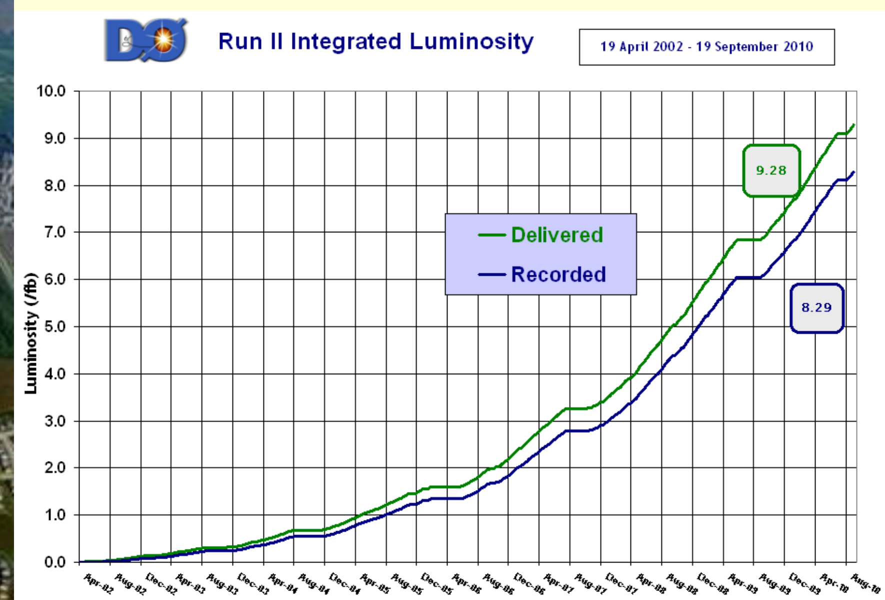
Multijet Results



Fermilab Tevatron - Run II



- 36x36 bunches
- Collision at $\sqrt{s}$ = 1.96 TeV
- bunch crossing 396 ns
- Run II started in March 2001
- Peak Luminosity:4E32 cm^{-2} sec^{-1}
- Run II delivered: ~9 fb^{-1}

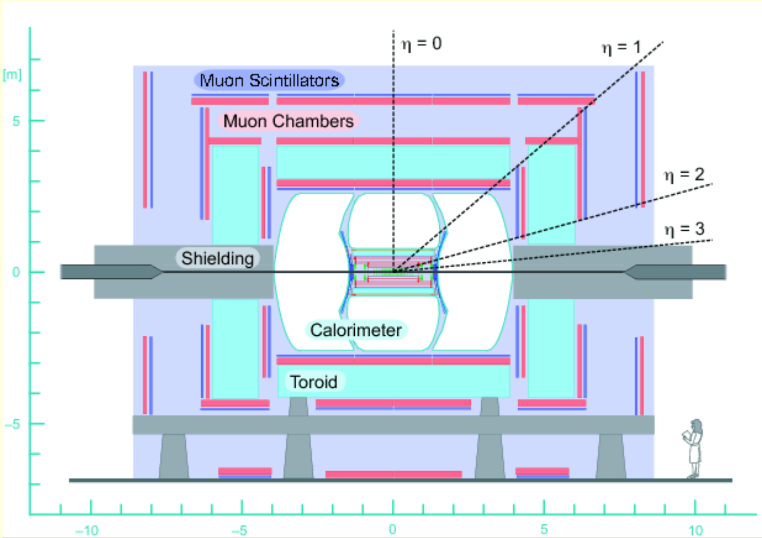


- Run II Goal: 12 fb^{-1} end of 2011

The DØ Detector

Resume:

- Good central tracking
  - Si μstrip tracker
  - Scintillating Fiber Tracker
  - 2T central solenoid
- Excellent Calorimetry
- Wide muon coverage
  - Central and forward toroids



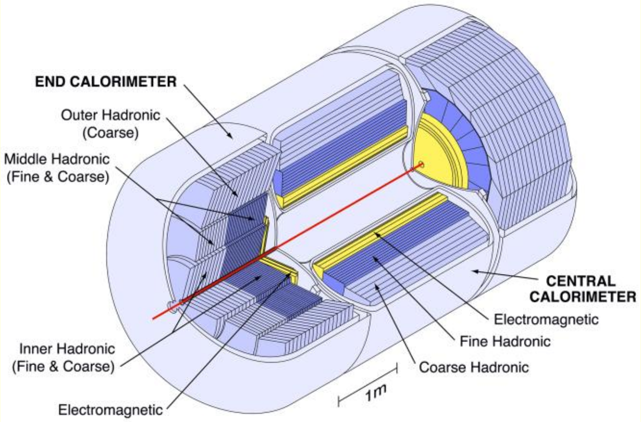
Coordinates Primer:

Unless otherwise noted –

ϕ = Azimuthal angle

η = pseudorapidity = $-\ln(\tan(\theta/2))$

y = rapidity = ½ ln [(1+βcosθ)/1-βcosθ)]



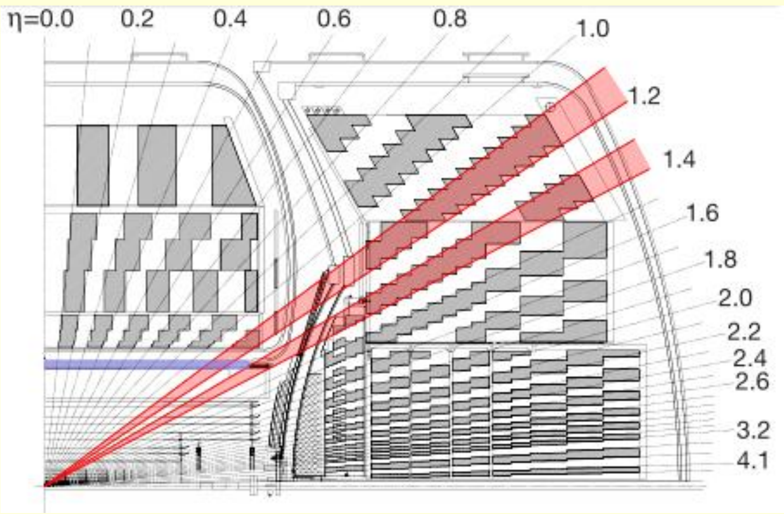
Calorimeter Details:

-lAr/U primarily

- Four EM layers (~20 X_0)

-3 to 4 Hadronic Layers (7 to 8 X_I)

- 0.1 x 0.1 segmentation in $\Delta\eta \times \Delta\phi$ (0.05 x 0.05 at EM shower max)



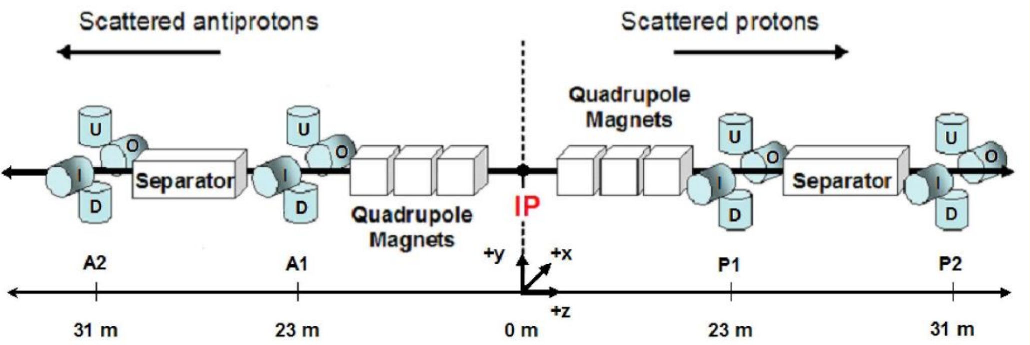
Energy Resolution:

e: $\sigma_E / E = 15\% / \sqrt{E} + 0.3\%$

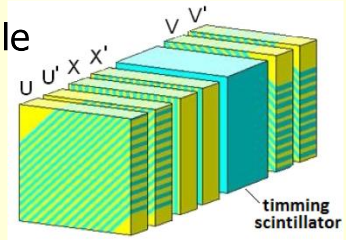
π: $\sigma_E / E = 45\% / \sqrt{E} + 4\%$

Elastic Collisions

Froward Proton Detector (FPD)



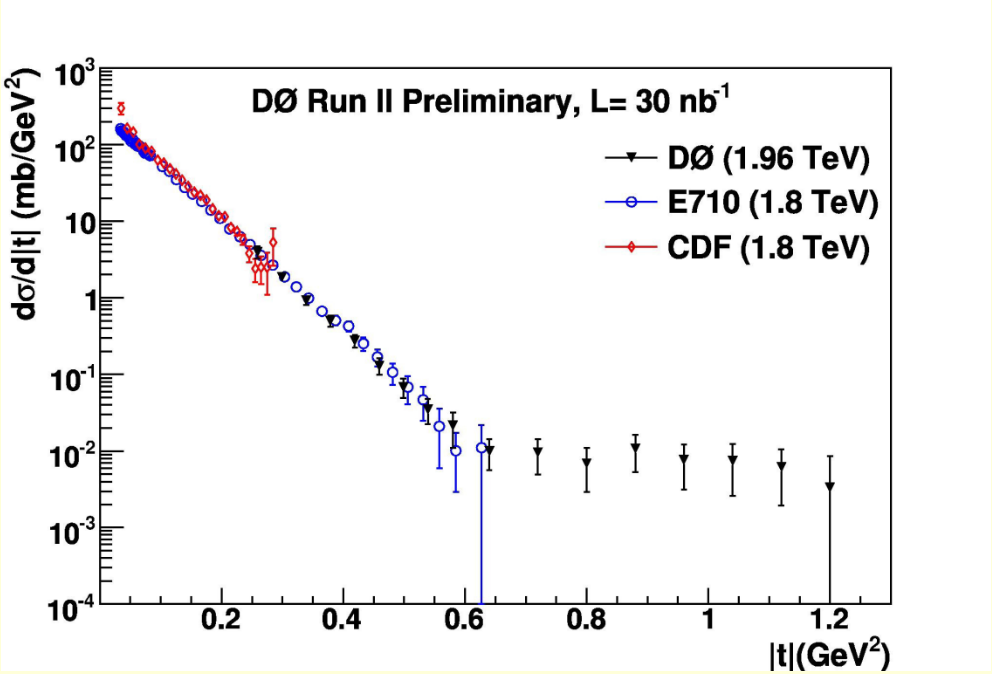
- 8 quadrupole spectrometers
- 6 layers of scintillating fibers in each
- Special Tevatron running ($L \sim 30\ nb^{-1}$, $\beta^* = 1.6m$, single bunch)



DØ Preliminary ➔ $d\sigma/d|t|$ (shown at DIS2010)

-0.25<|t|<0.6 GeV2 and
0.6 < |t| < 1.2 GeV2

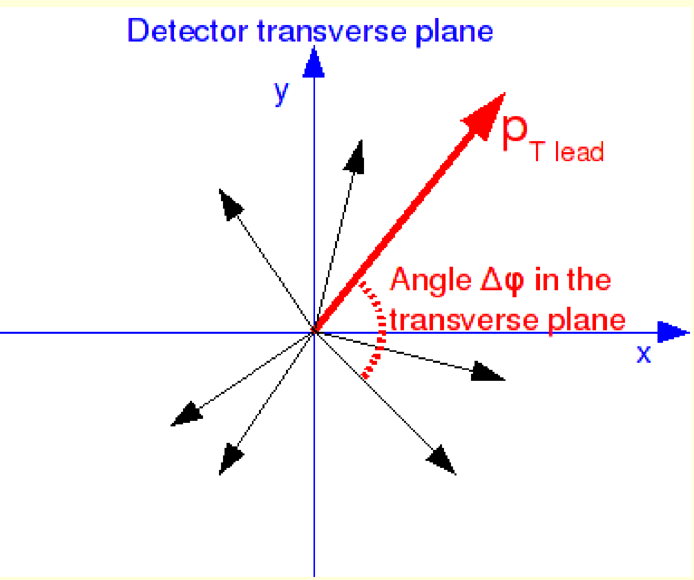
- 14.3% luminosity uncertainty not shown
- Great deal effort to commission, alignment FPD, understand efficiencies, etc.

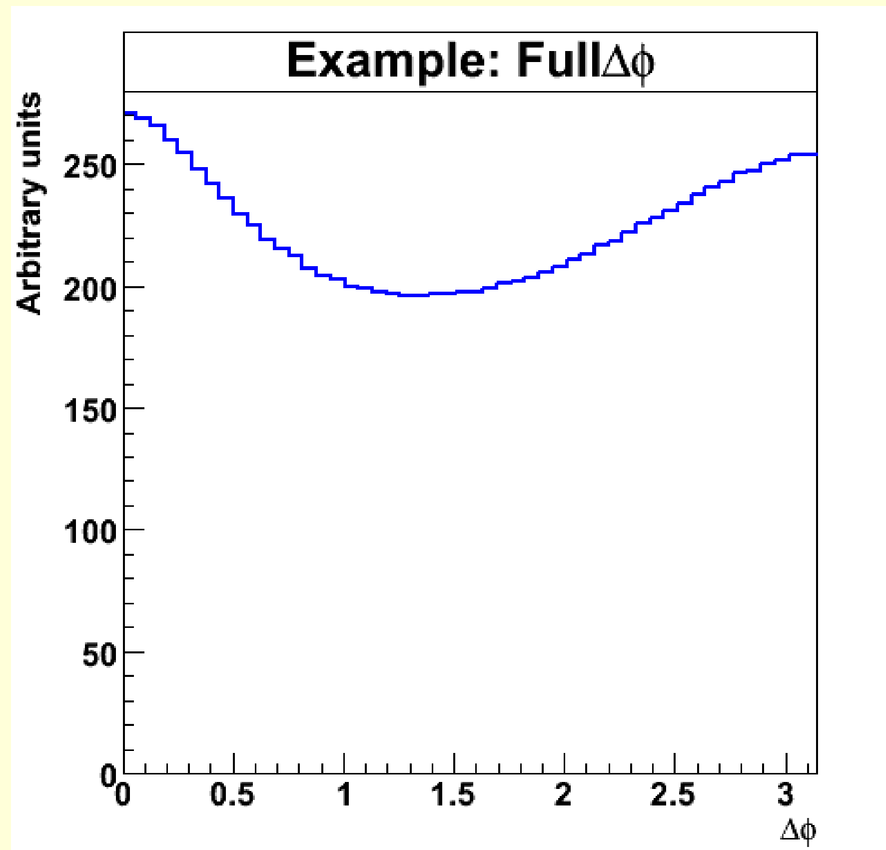


Track Correlations in Minimum Bias Events

- Use correlations in Δ φ to characterize Minimum Bias Events
- Compare data to various Monte Carlo tunes and models

From full distribution…

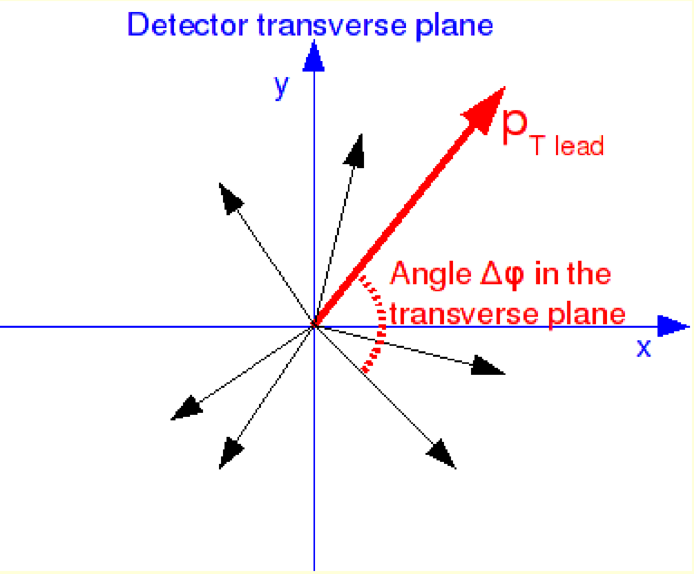


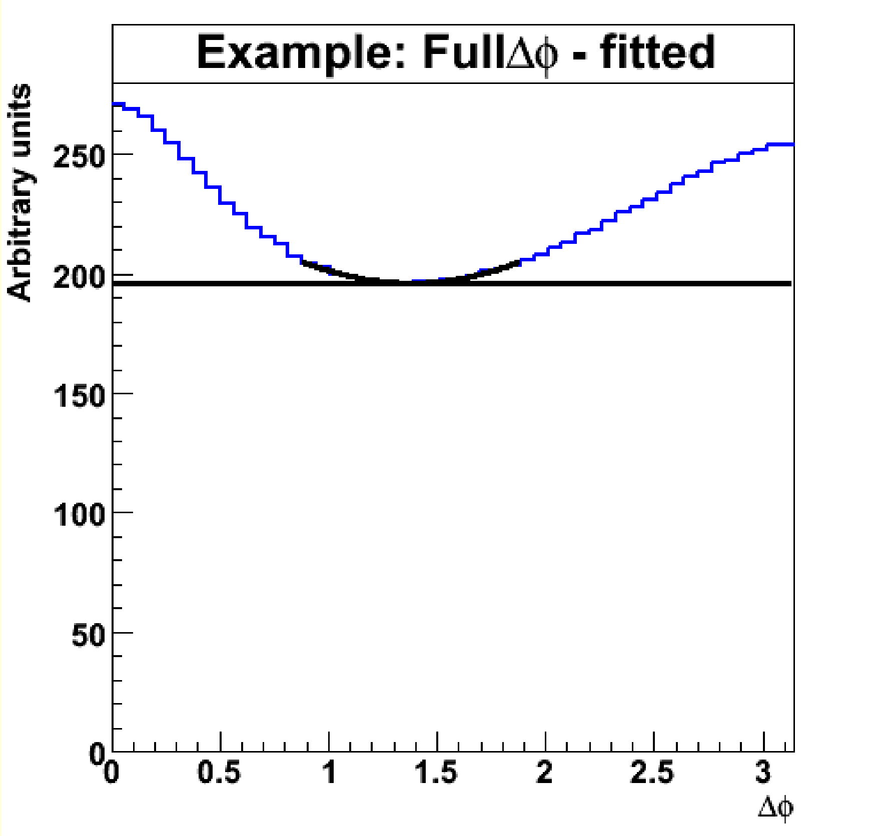


Track Correlations in Minimum Bias Events

- Use correlations in Δ φ to characterize Minimum Bias Events
- Compare data to various Monte Carlo tunes and models

Fit minimum: subtract to remove pedestal and suppress fakes, noises, …

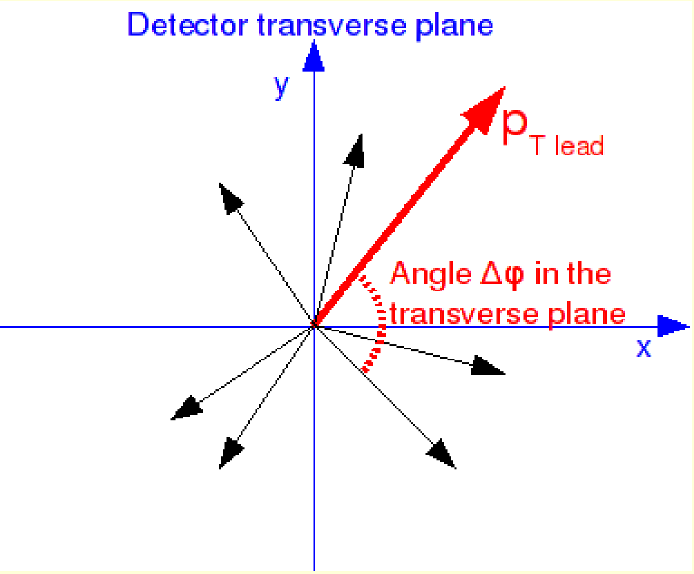


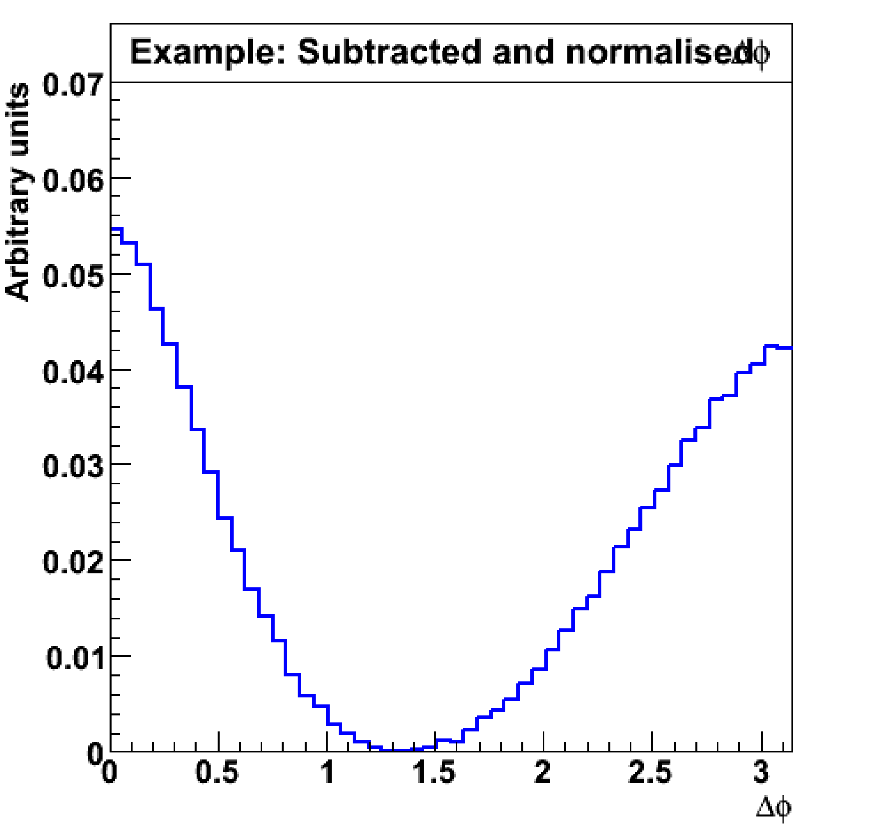


Track Correlations in Minimum Bias Events

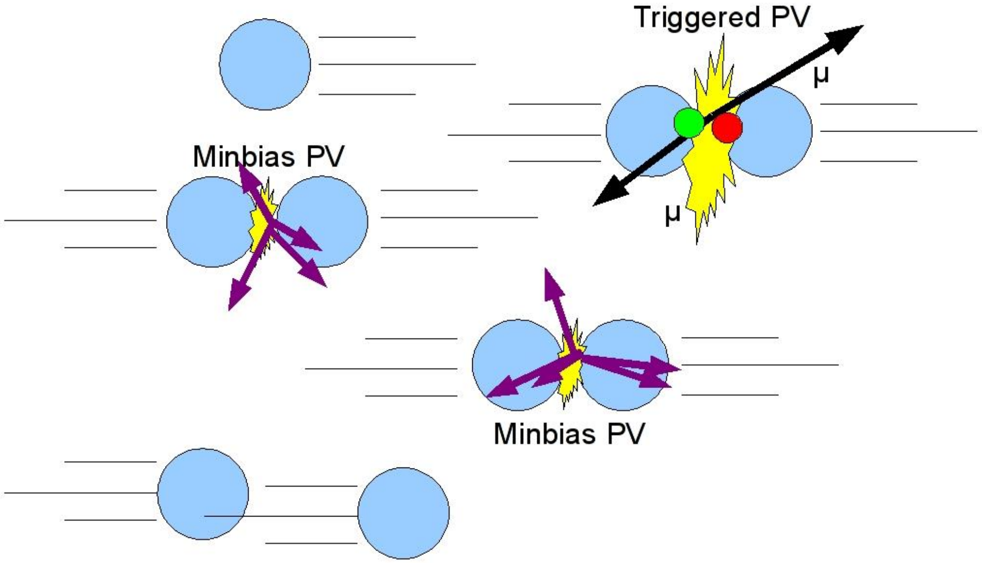
- Use correlations in $\Delta\varphi$ to characterize Minimum Bias Events
- Compare data to various Monte Carlo tunes and models

Subtract then normalize to get crest shape observable





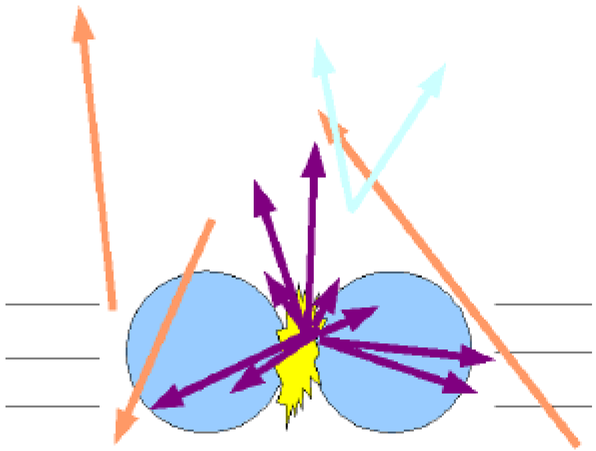
Choosing a Minimum Bias Event Sample



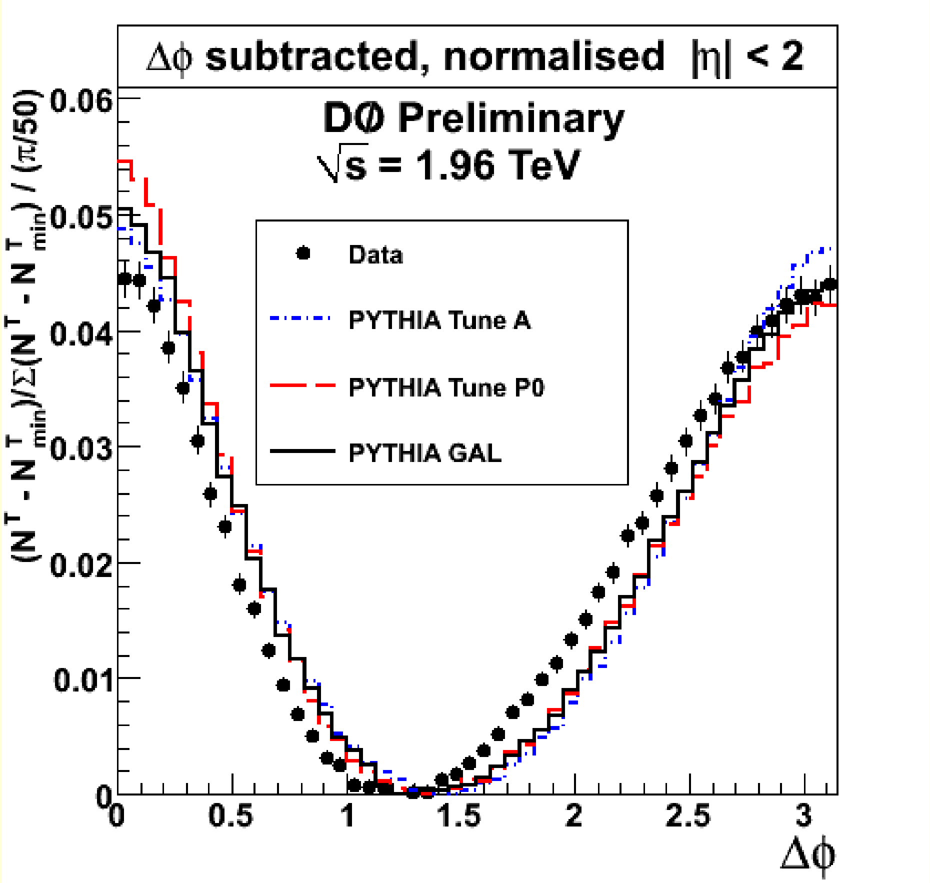
- Trigger on dimuon events
- Require exactly 2 muons w/ p_T > 2 GeV associated with the same primary vertex (PV)
- Then require one or more Minimum Bias PVs
  - At least 5 tracks
  - At least 0.5cm from triggered PV
  - Within 20cm of center of detector

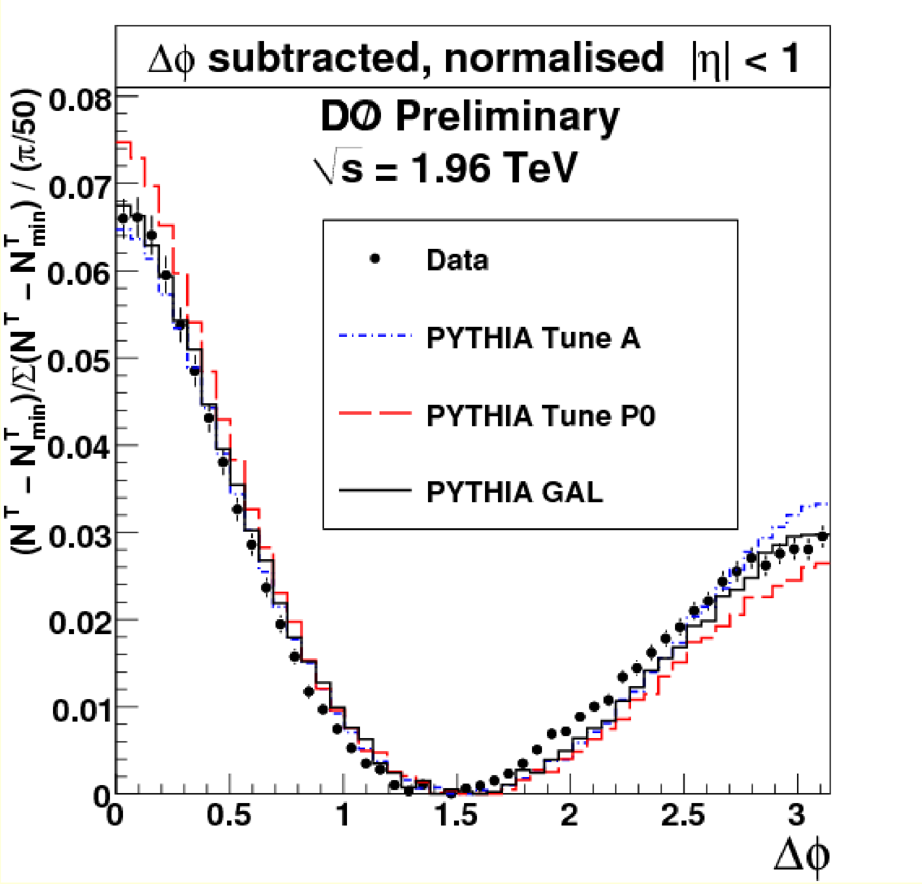
Strategy: Associate all tracks to PVs and then select good quality tracks associated to minbias PVs. Minimize fakes, cosmics, conversions, long-lived resonances, vertex mis-associations

- pT>0.5GeV
- $|\eta|<2$



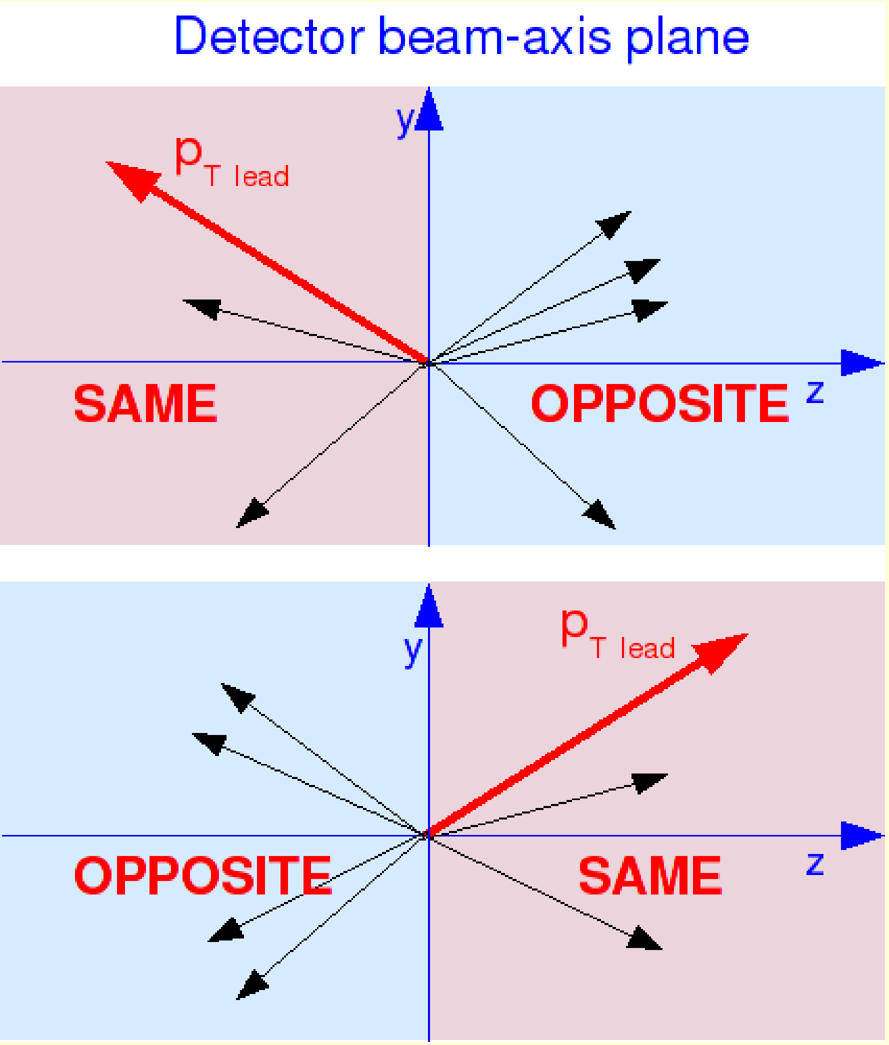
Δφ comparison to MC





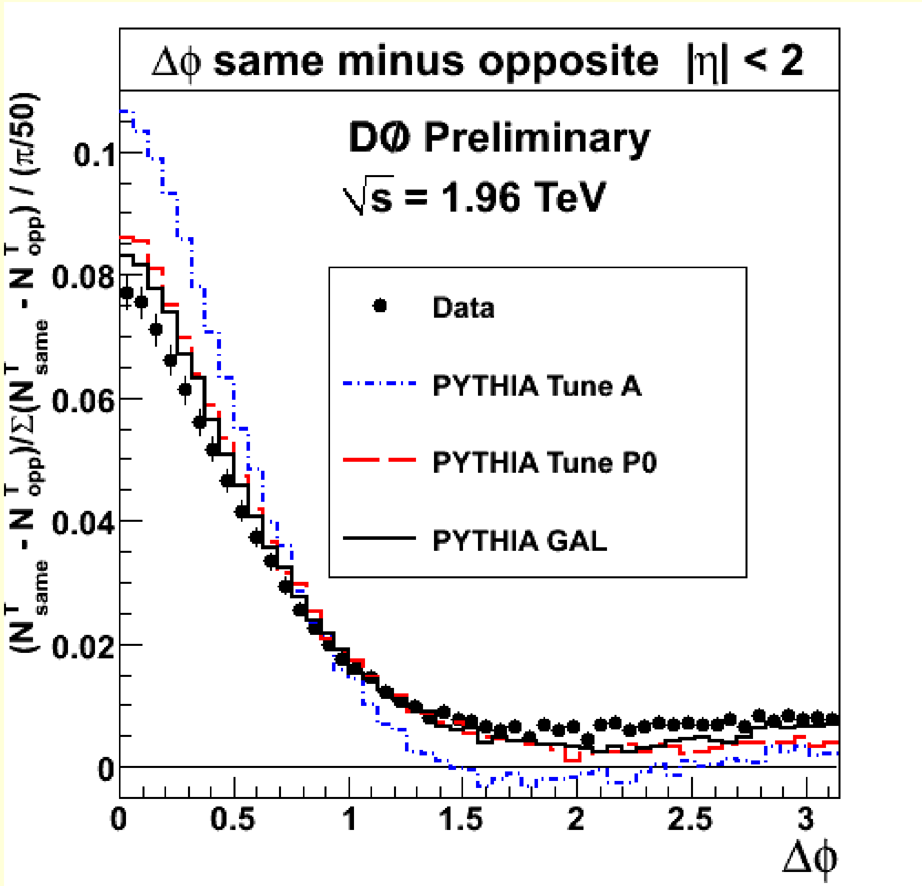
Comparisons to some broadly used tunes .
"GAL" = "General Area Law" model of color reconnections

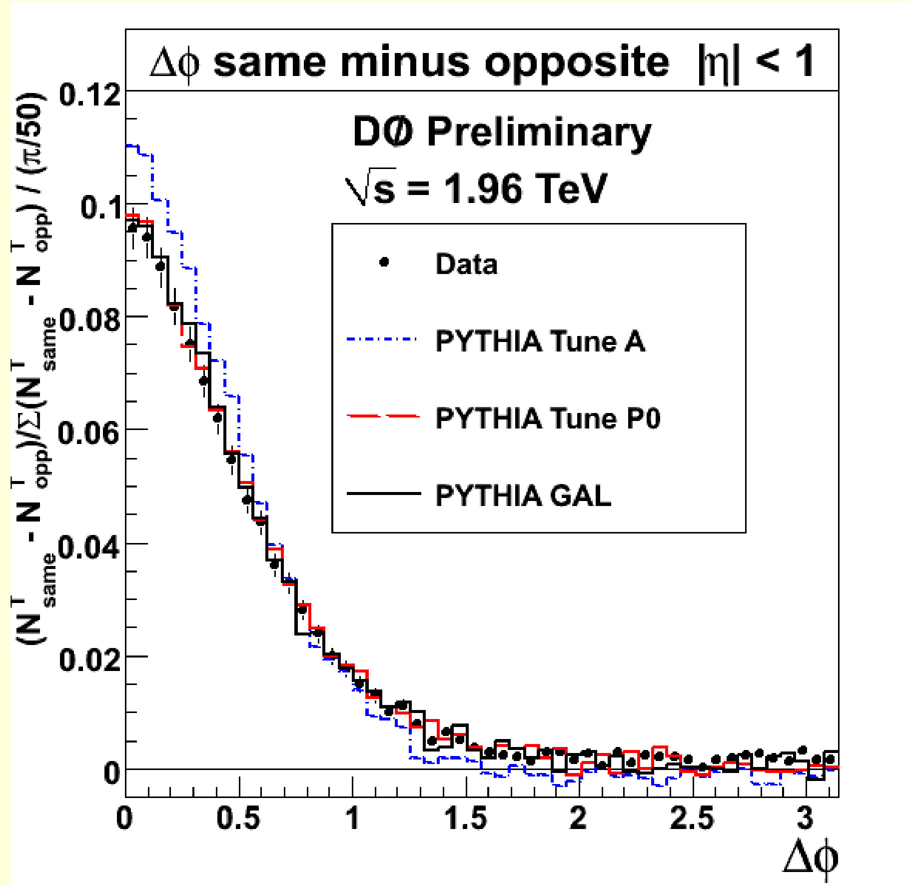
Opposite vs Same Side



- Subtract opposite side from same side distribution
- Removes unwanted effects from uncorrelated fakes and tracking efficiencies

Δφ comparison to MC

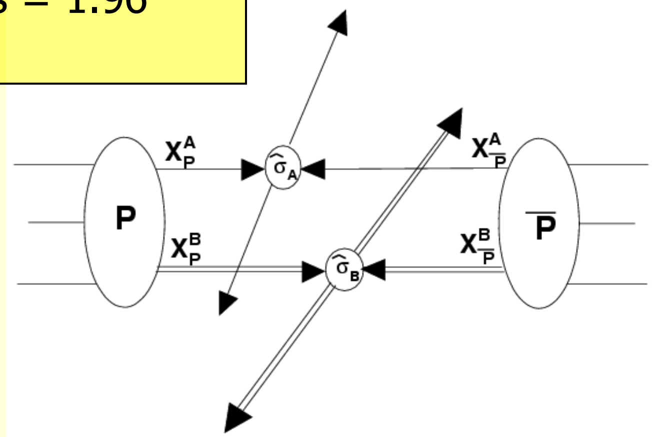




Other interesting comparisons possible focusing on aspects of minimum bias modeling
(ISR, color reconnections, PDFs, treatment of beam remnants, etc)

Double Parton Interactions

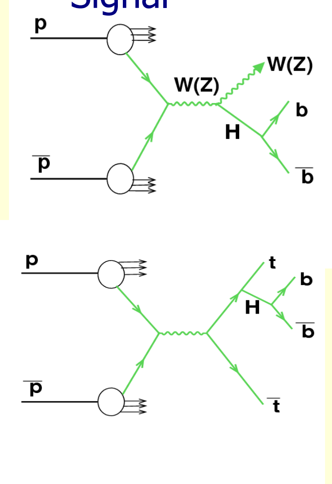
"Double parton interactions γ+3 jet events in pp collisions at $\sqrt{s}$ = 1.96 TeV", V. Abazov, et al. Phys. Rev. D **81**, 052012 (2010)



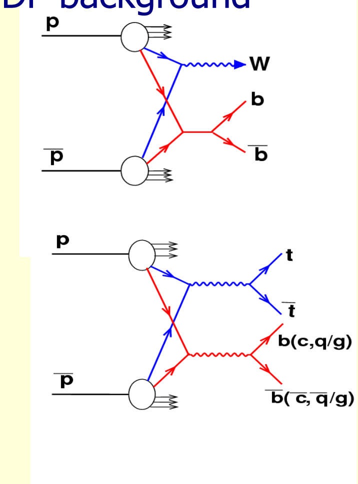
- Provides insight into parton spatial distributions
  - May impact PDFs
- Double Parton cross-section given on a scaling parameter σ_{eff}
  - Large values → Uniform spatial distribution
- Double Parton interaction can be background to several important rare channels, including Higgs searches

$$\sigma_{DP} = \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

Signal

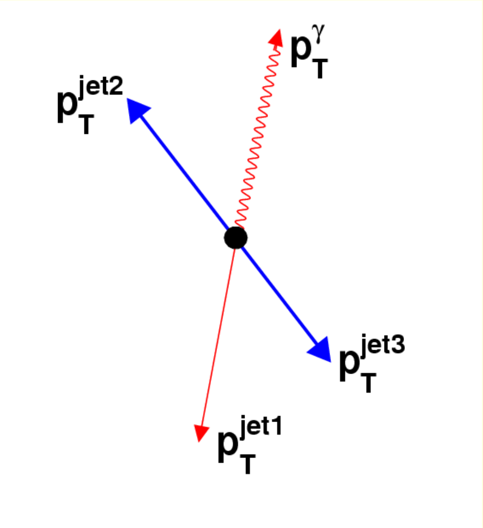


DP background

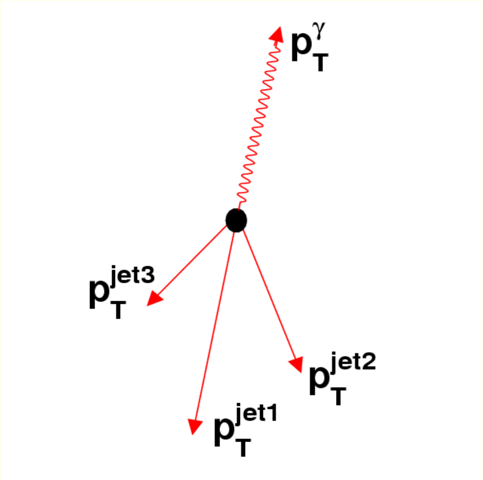


γ+3 Jets DP Topology

Double Parton



Single Parton



Signal: Double Parton (DP) production:
1st parton process produces γ-jet pair,
while 2nd process produces dijet pair.

Background: Single Parton (SP) production:
single hard γ-jet scattering with 2 radiation
jets in 1vertex events.

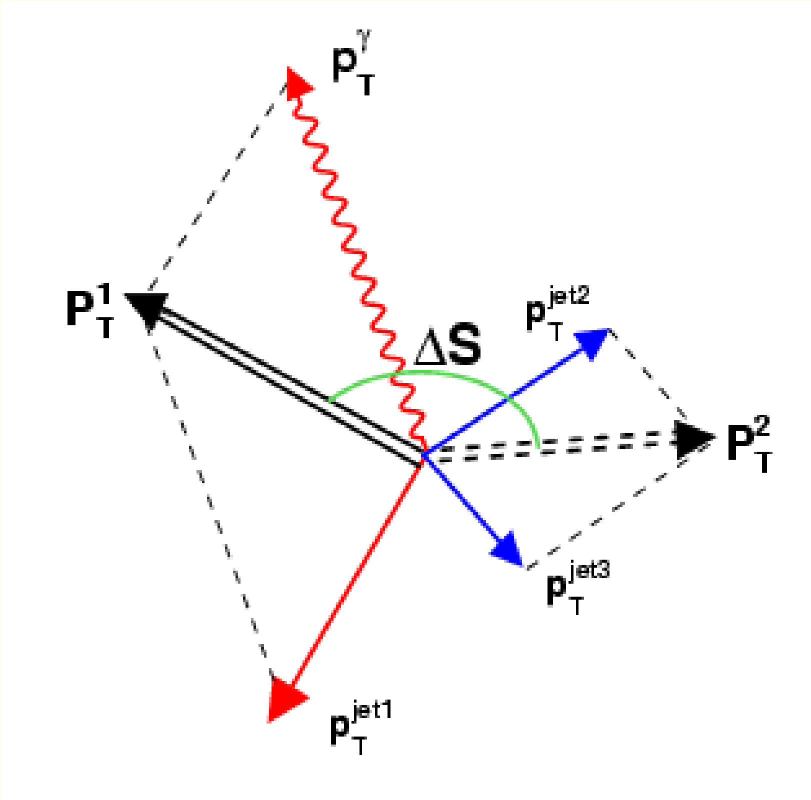
Discriminating Variables

$$\Delta S = \Delta\phi(p_T^{\gamma,\,\mathrm{jet}}, p_T^{\mathrm{jet}_i,\,\mathrm{jet}_k})$$

- $\Delta\phi$ angle between two best pT-balancing pairs
- The pairs should correspond to a minimum ΔS value:

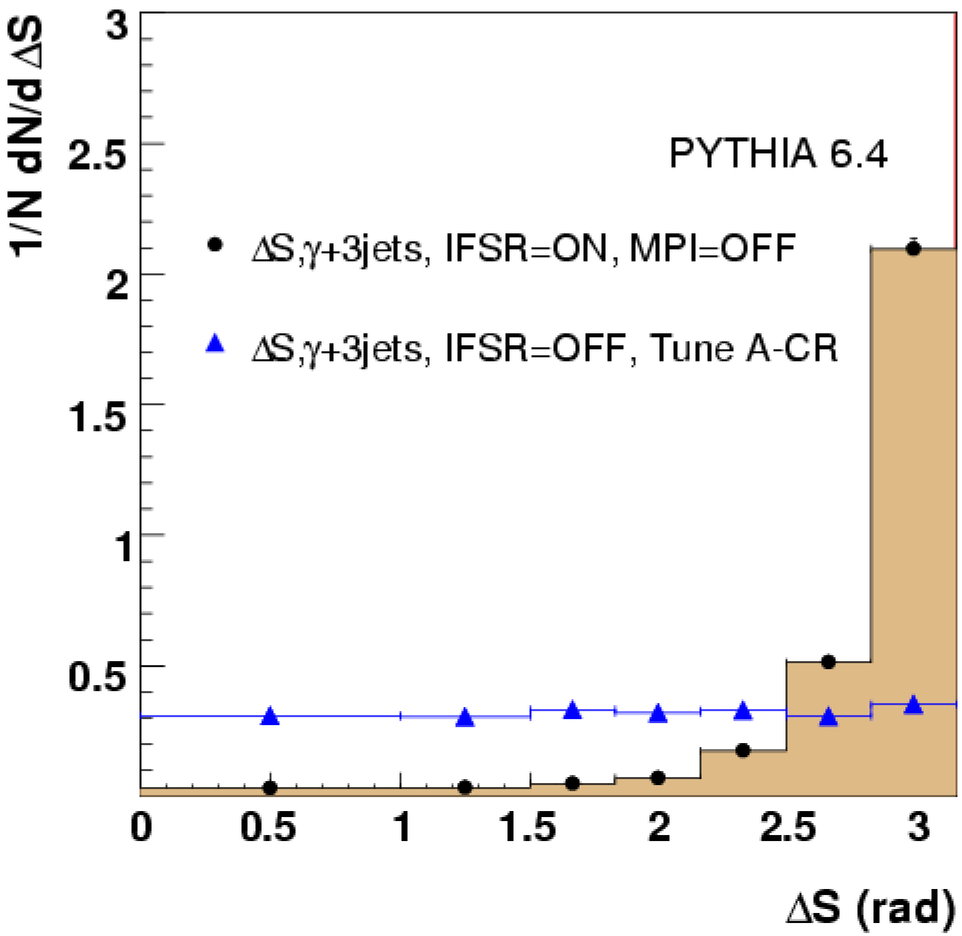
$$S_\phi = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{\Delta\phi(\gamma,i)}{\delta\phi(\gamma,i)}\right)^2 + \left(\frac{\Delta\phi(j,k)}{\delta\phi(j,k)}\right)^2}$$

$$S_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|\vec{P_T}(\gamma,i)|}{\delta P_T(\gamma,i)}\right)^2 + \left(\frac{|\vec{P_T}(j,k)|}{\delta P_T(j,k)}\right)^2}$$



In the signal sample most likely (>94%) S-variables are minimized by pairing photon with the leading jet.

Single Parton ΔS: γ+3-Jets

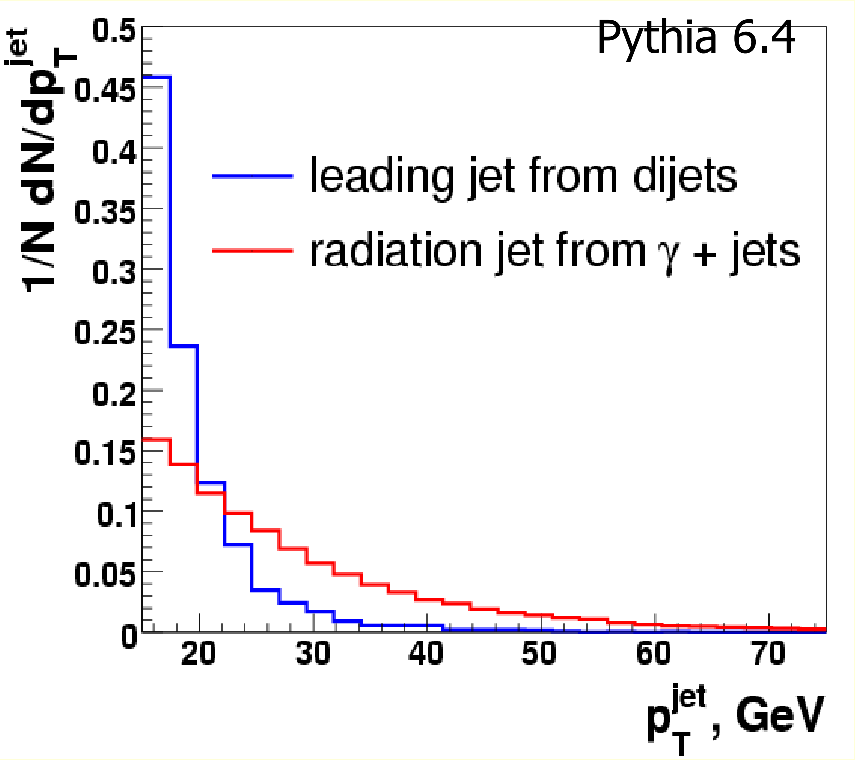


➔ For "γ+3jets" events from Single Parton scattering we expect ΔS to peak at π,

Should be flat for "ideal" DP interaction
(2nd and 3rd jets are from dijet production).

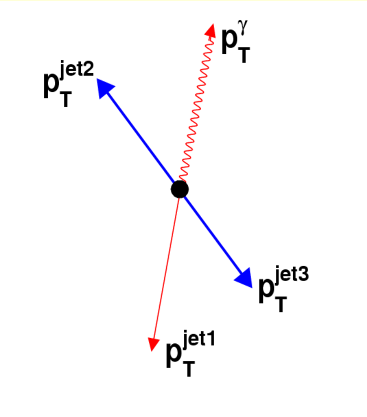
P_T Binning: Motivation

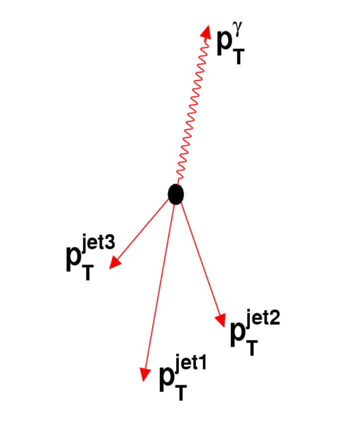
Jet P_T: jet from dijets vs. radiation jet from γ+jet events



$\sim 1/p_T^4$

$\sim 1/p_T^2$



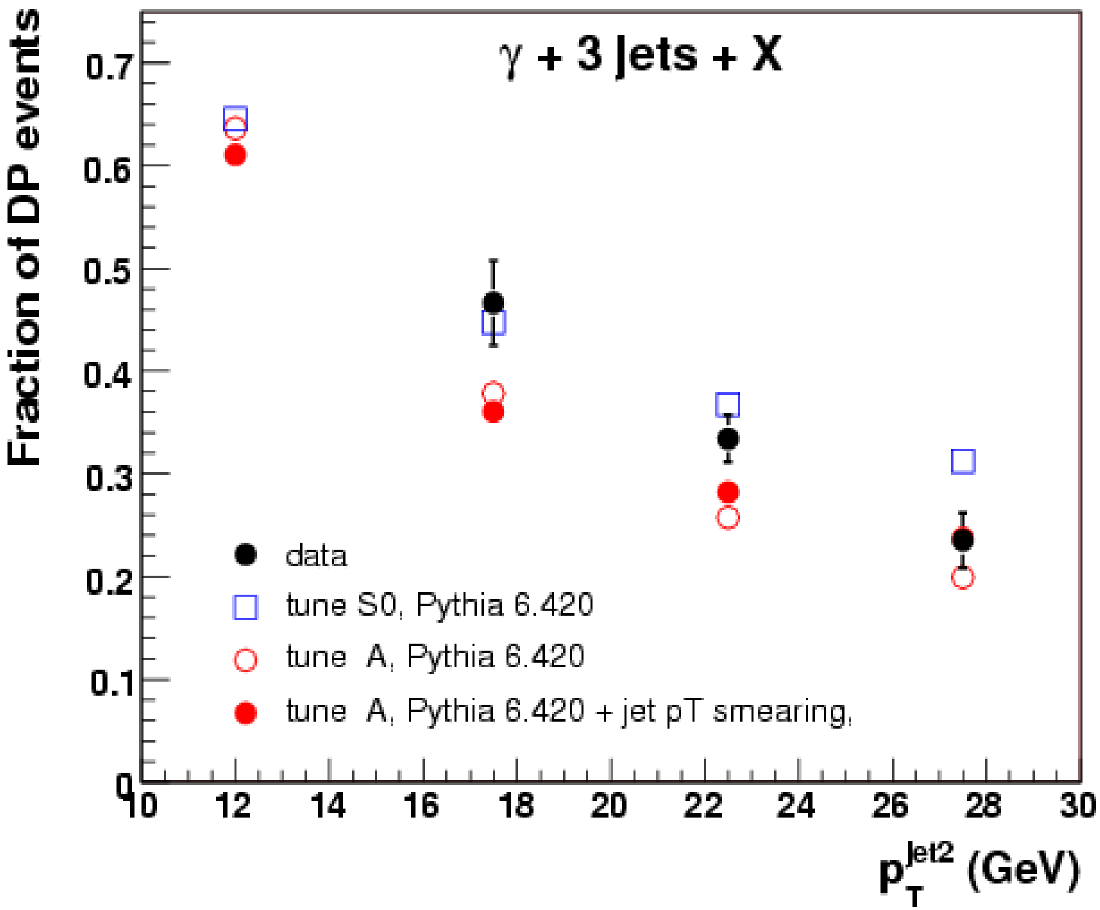


- Jet p_T from dijets falls much faster than that for radiation jets, i.e.

➔ Fraction of dijet (Double Parton) events should drop with increasing jet p_T

➔ Measurement is done in the three bins of 2nd jet p_T: 15-20, 20-25, 25-30 GeV

Fraction of DP Events



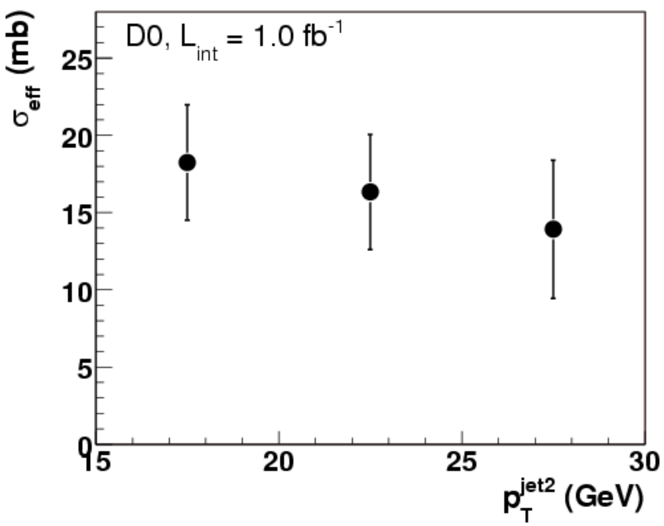
Pythia MPI tunes A and S0 are considered.

Data are in between the model predictions.

Data are not yet corrected to the particle level.

Will be done later to find the best MPI Tune

Calculation of σ_{eff}



σ_{eff} values in different jet p_T bins agree with each other within their uncertainties. (a slight fall can be also suggestive)

Uncertainties have very small correlations between jet2 p_T bins.

One can calculate the averaged (weighted by uncertainties) values over jet2 p_T bins:

$$\sigma_{eff}^{ave} = 16.4 \pm 0.3(stat) \pm 2.3(syst)\, mb$$

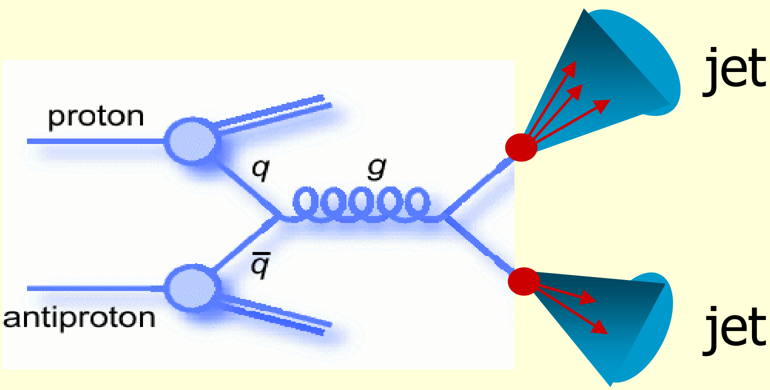
Main systematic and statistical uncertainties (in %) for σ_{eff}:

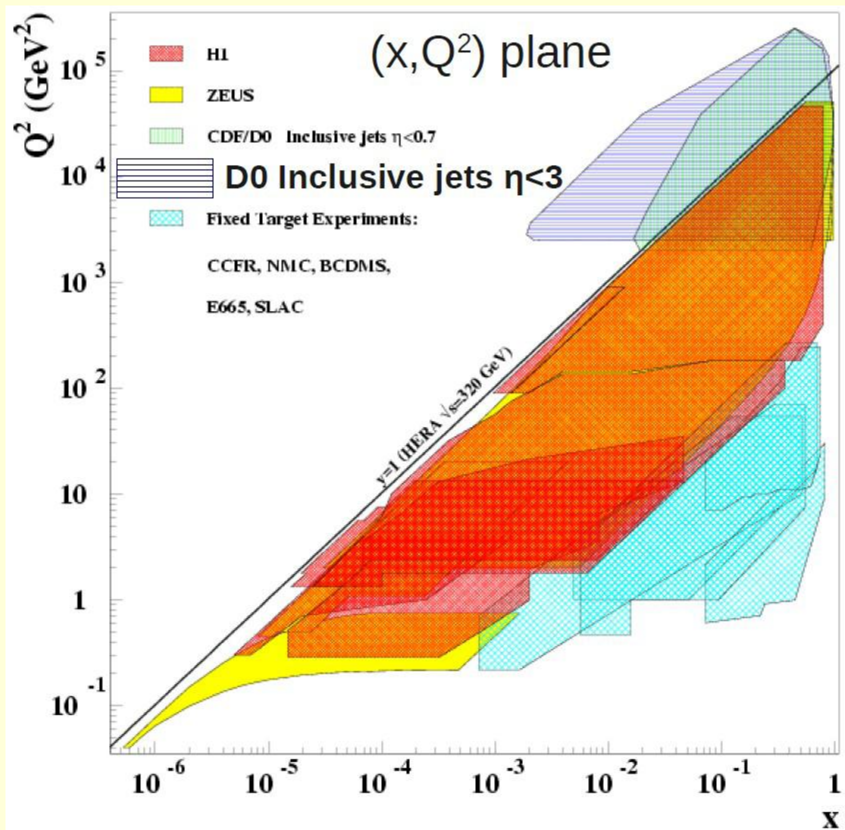
p_T^{jet2} (GeV)	Systematic uncertainty sources f_{DP}	f_{DI}	$\varepsilon_{DP}/\varepsilon_{DI}$	JES	$R_c\sigma_{hard}$	δ_{syst} (%)	δ_{stat} (%)	δ_{total} (%)
15 – 20	7.9	17.1	5.6	5.5	2.0	20.5	3.1	20.7
20 – 25	6.0	20.9	6.2	2.0	2.0	22.8	2.5	22.9
25 – 30	10.9	29.4	6.5	3.0	2.0	32.2	2.7	32.3

Jet Production

largest high pT cross section at a hadron collider
→ **highest energy reach**

Unique sensitivity to **new physics**:
- new particles decaying to jets,
- quark compositeness,
- extra dimensions,
- …(?)…



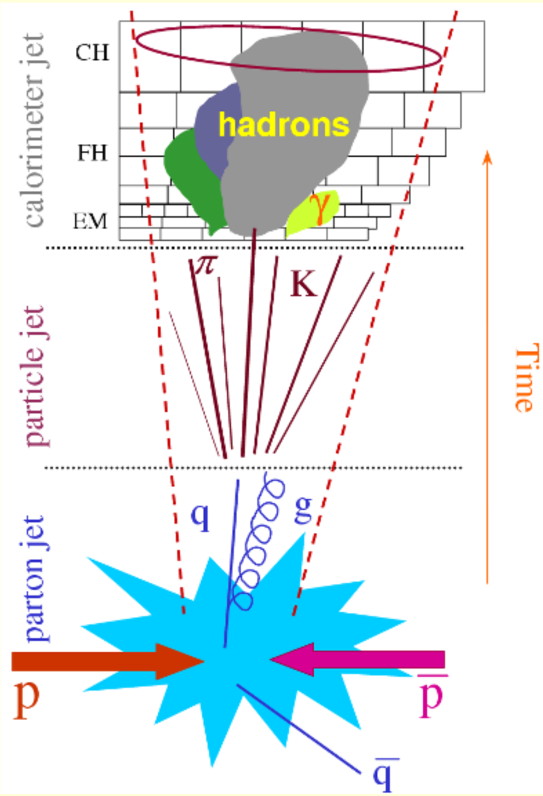


In the absence of new physics:

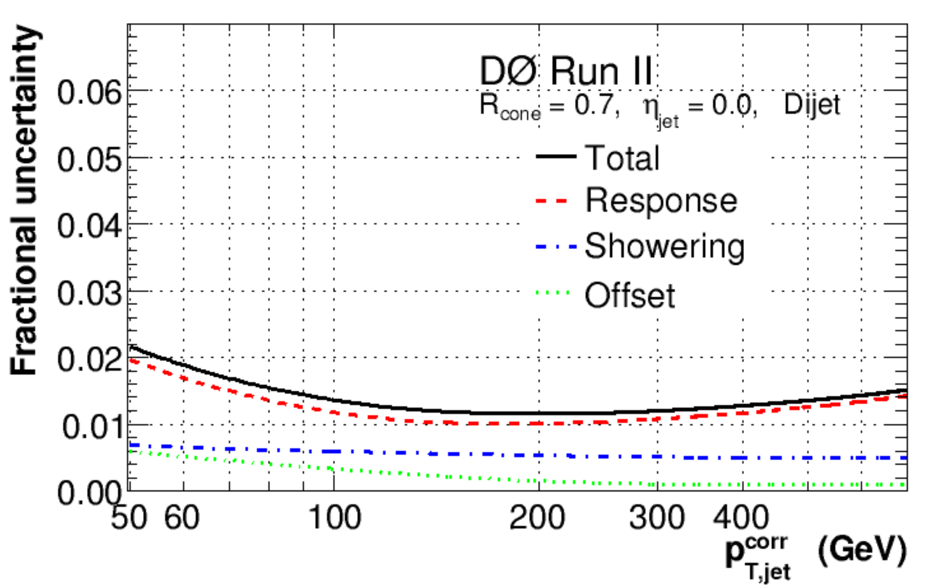
Theory @NLO is reliable (±10%)

→ **Precision phenomenology**
- broad kinematic reach ➔
- sensitivity to PDFs → high-x gluon
- sensitive to α_s

Comparing Data to Predictions



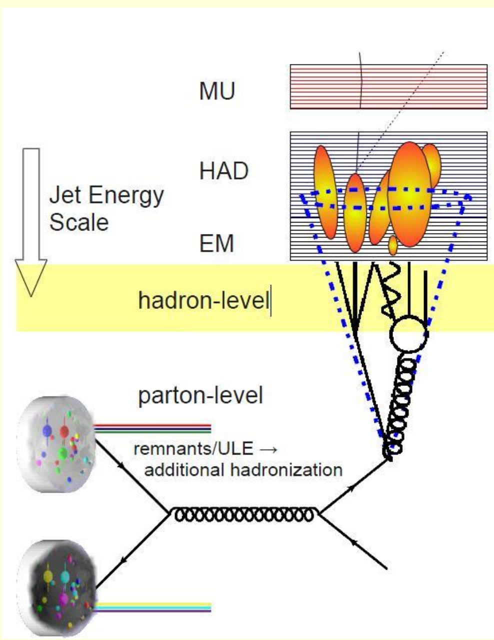
- Use Jet Definition to relate Observables defined on Partons, Particles, Detector
- Measure cross section for pp-bar → jets on "particle-level"
  - Correct for experimental effects (efficiencies, resolution, …) calculated using a fast detector parametrization
  - Include uncertainties and correlations from jet energy scale, non-pertubative effects & UE, id efficiencies, correction for muons & ν's, etc
  - Apply correction to the pQCD calculation
- Comparison to NLO pQCD implemented using NLOjet++, FastNLO program
  - Interpolation techniques for PDFs(x,μ), $\alpha_s(\mu)$



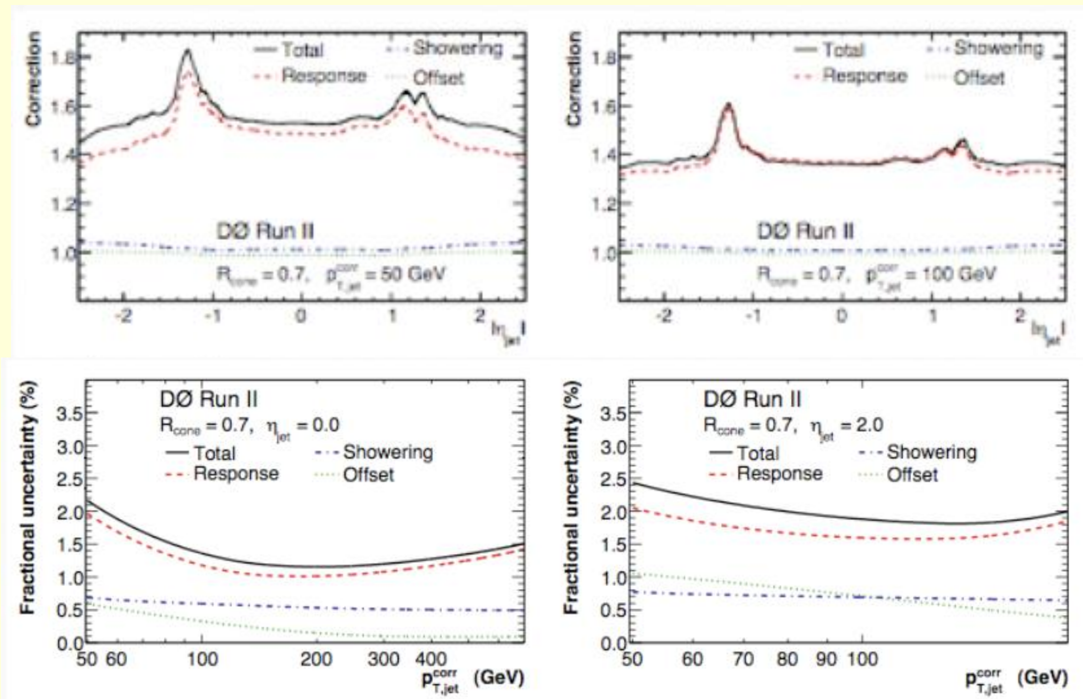
Energy scale uncertainty: 1-2% !

A Few Jet Details

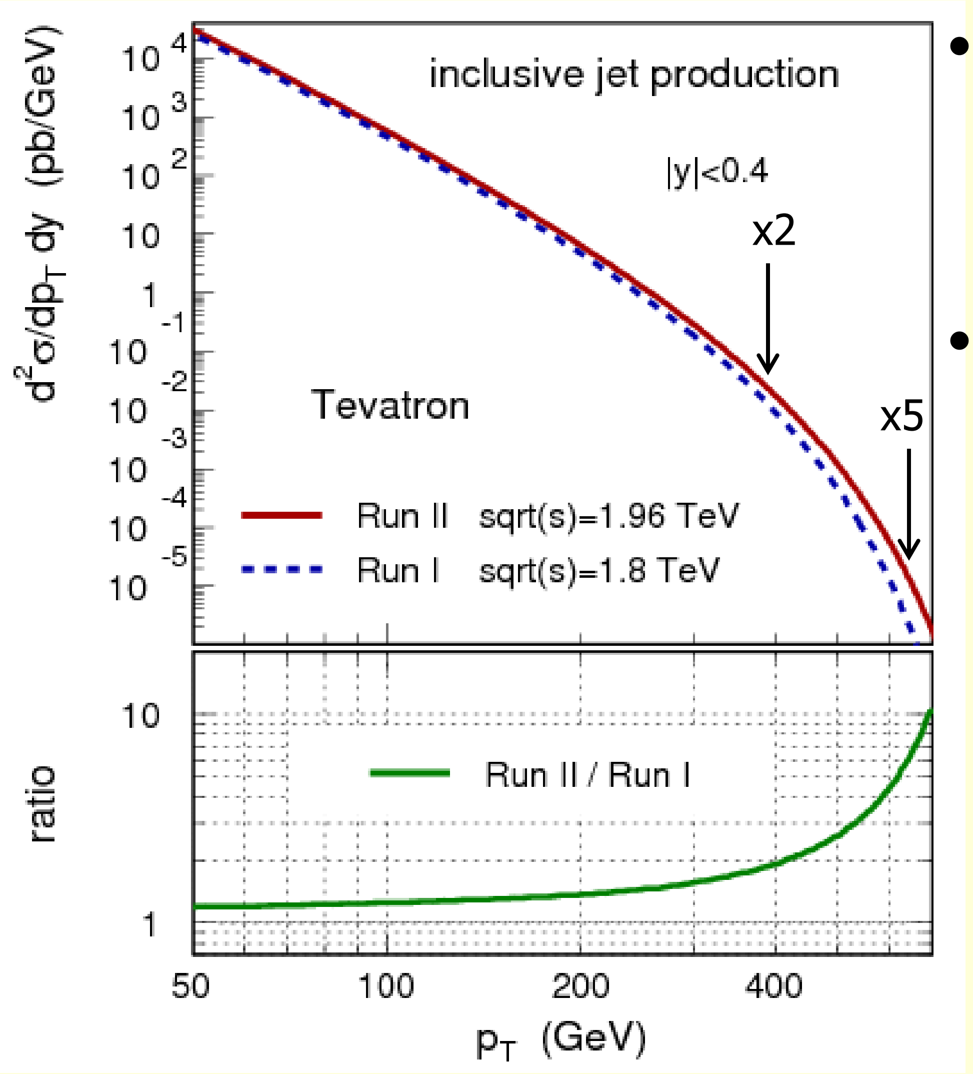
- Jet Finding
  - DØ Run II Midpoint Algorithm
    - Can run on calorimeter towers/MC particles/pQCD partons
    - Fixed cone: R_{cone} = 0.5 or 0.7 (most jet studies)
    - pTmin = 8 GeV
  - Use all particles + midpoints btwn jets as seeds.
  - Merge jets if overlap in p_T by more than f = 50%.



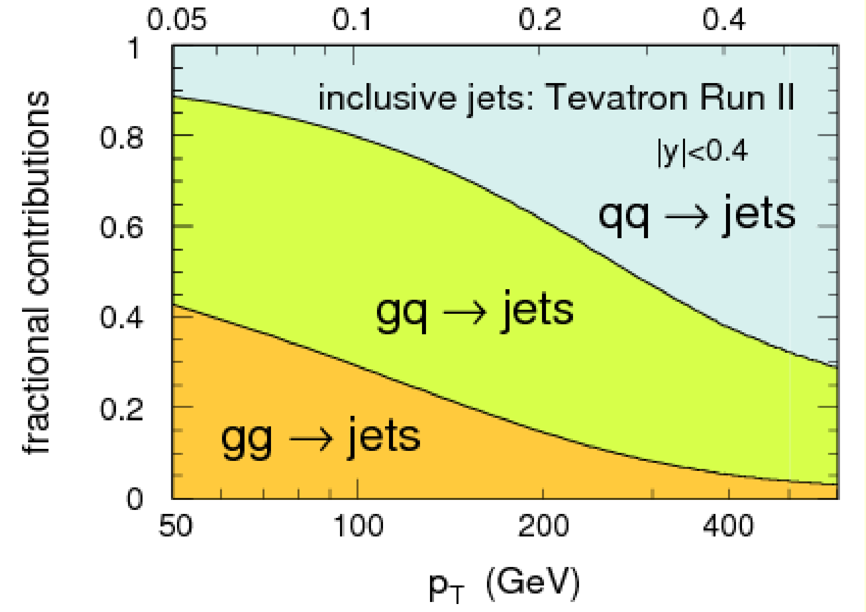
- Jet Energy Scale (JES)
  - $E_{particle} = E_{cal} – O / (R·S)$
    - E_{cal} = Calorimeter energy
    - O = Offset Energy
      - Electronics noise, U noise, pileup,…
    - S = Showering Correction
  - Response measured in γ + jet
    - EM scale set by Z mass fit.
    - Checked with dijet balance



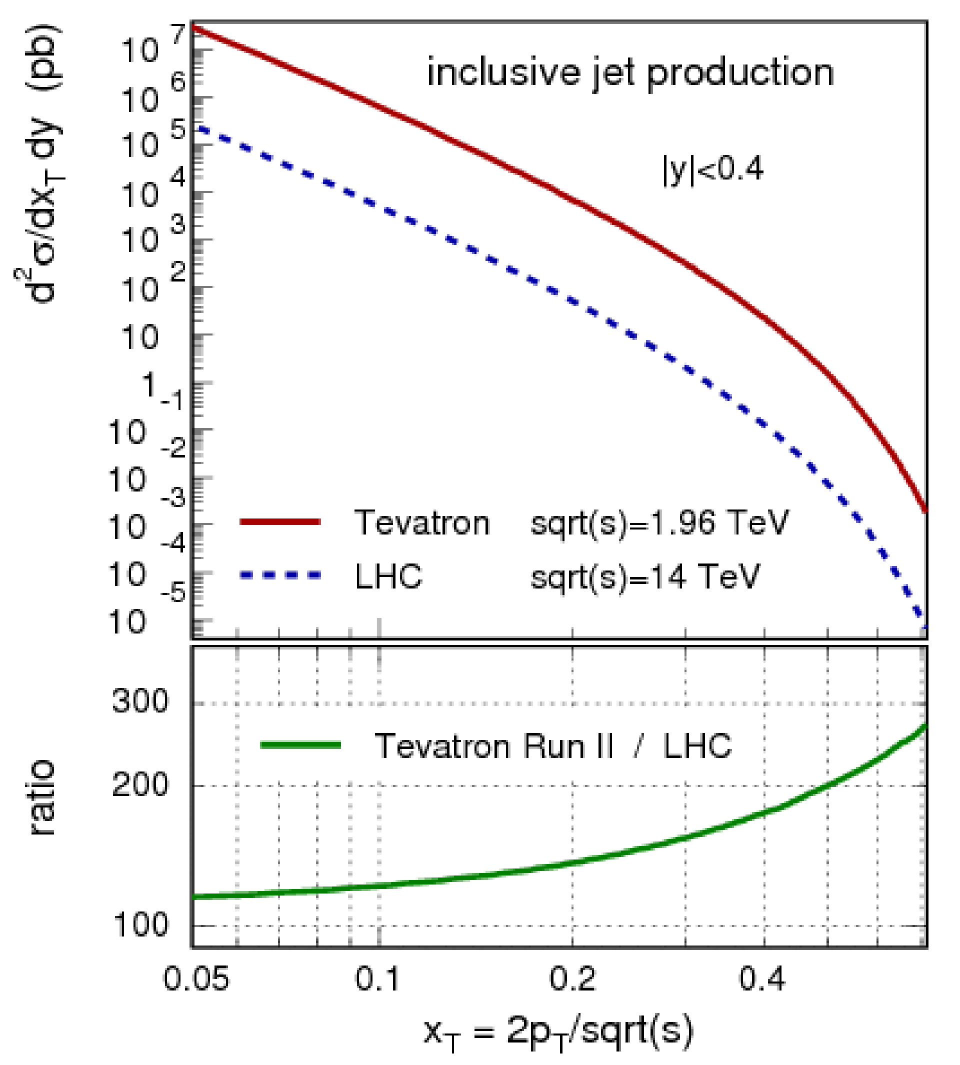
Inclusive Jet Production



- Run II: Increased x5 at pT=600GeV
  → sensitive to "New Physics":
  Quark Compositeness,
  Extra Dimensions, …(?)…
- Theory @NLO is reliable (±10%)
  → sensitivity to PDFs
  → unique: high-x gluon



Inclusive Jets: Tevatron vs. LHC



PDF sensitivity:

→ compare jet cross section at fixed

$x_T = 2\ p_T\ /\ sqrt(s)$

Tevatron (ppbar)

>100x higher cross section @ all x_T

>200x higher cross section @ x_T >0.5

LHC (pp)

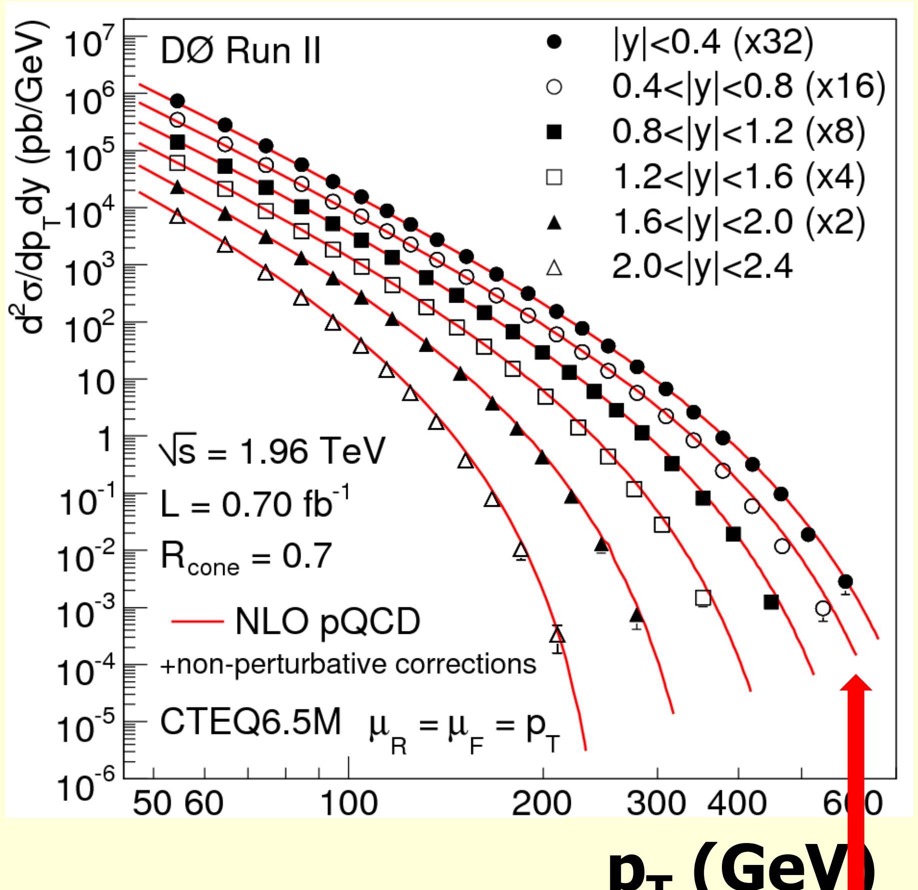
- need more than 2400 fb^{-1} luminosity to improve Tevatron@12 fb^{-1}
- more high-x gluon contributions
- but more steeply falling cross sect. at highest p_T (=larger uncertainties)

Inclusive Jets

The inclusive jet cross section – doubly differential vs. (p_T,y)

Phys. Rev Lett. 101, 062001 (2008)
Detailed Phys Rev. D in preparation

Analysis details:
- Use L = 0.7 fb-1 with well-measured JES
- Single jet trigger
- Require at least 1 jet with p_T > 50 GeV



Benefits from:
- high luminosity in Run II
- increased Run II cm energy → high p_T
- hard work on jet energy calibration

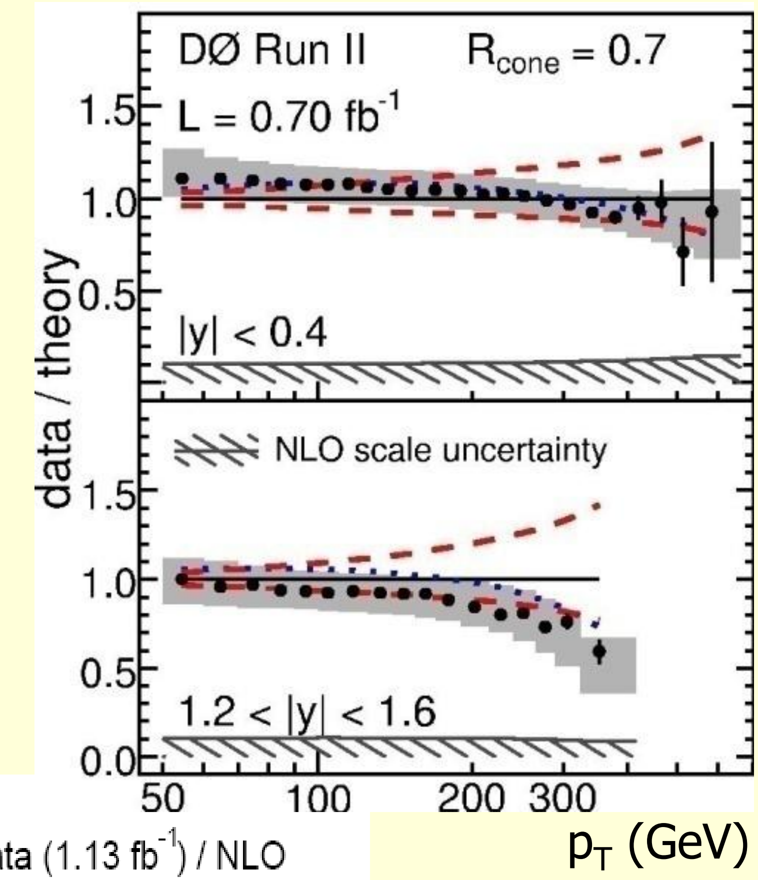
steeply falling p_T spectrum:
1% error in jet energy calibration
→ 5—10% (10—25%)
central (forward) x-section

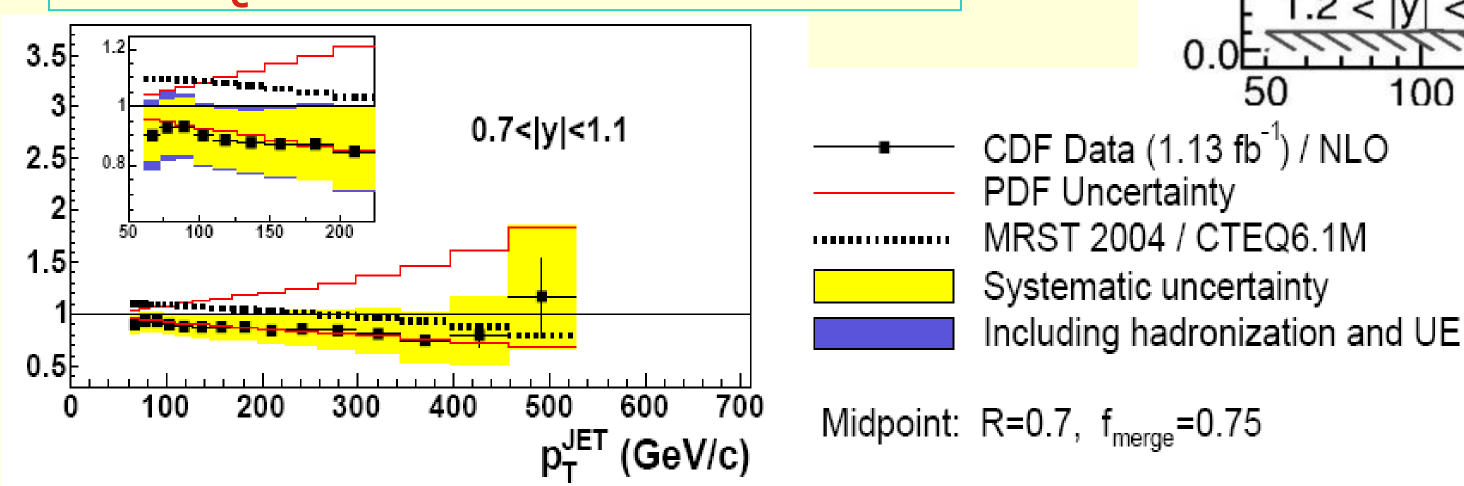
Inclusive Jets

- high precision results
- consistency between CDF/D0
- well-described by NLO pQCD
- experimental uncertainties:
  smaller than PDF uncertainties!!

→ sensitive to distinguish between PDFs

Data are used in PDF fits
→included in MSTW2008 PDFs
& CTEQ CT10 PDFs





Strong Coupling Constant

Phys. Rev. D 80, 111107 (2009)

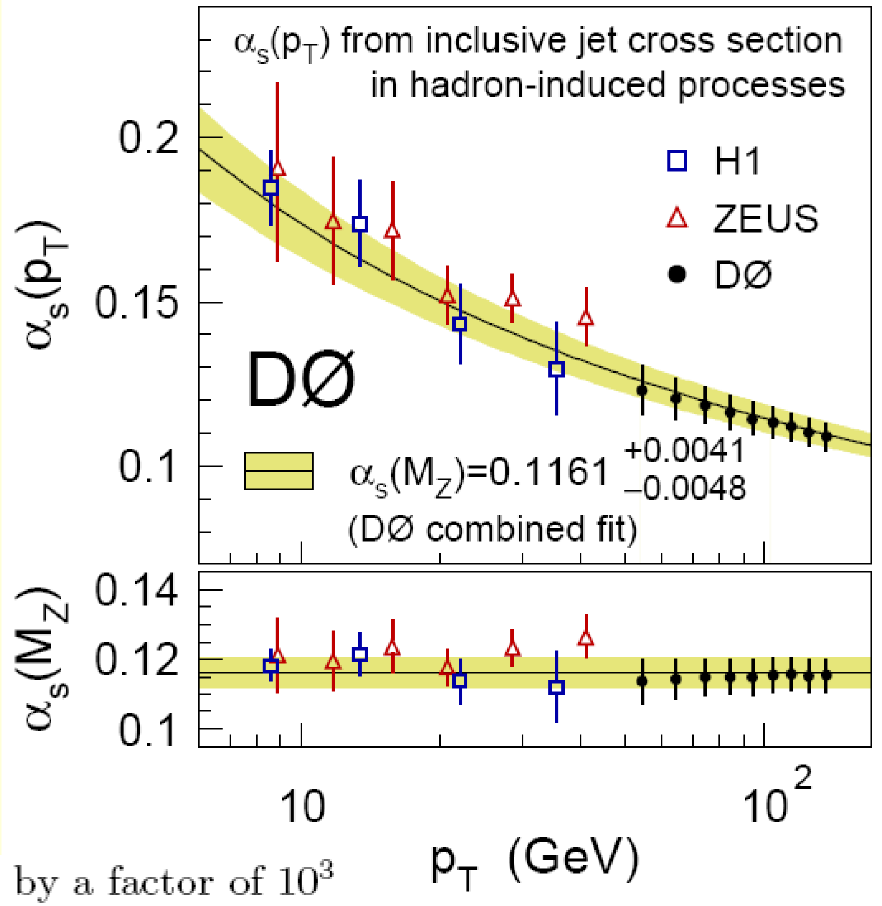
Use MSTW2008NNLO PDFs as input

→ Cannot test RGE at p_T >200 GeV (RGE already assumed in PDFs)

→ Exclude data points with $x_{max} \gtrsim 0.25$ (unknown correlation with PDF uncert.)

→ 22 (out of 110) inclusive jet cross section data points at $50<p_T<145$ GeV

→ NLO + 2-loop threshold corrections

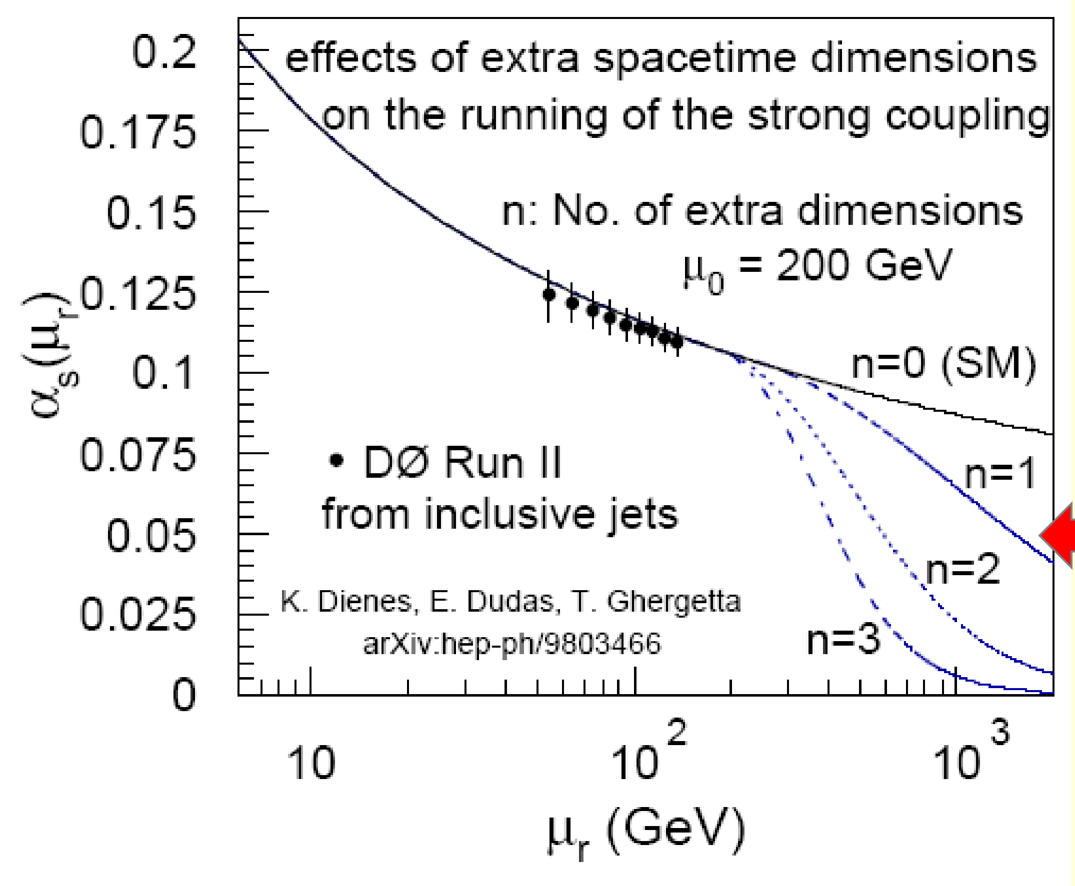


$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$

All uncertainties are multiplied by a factor of 10^3

	Total uncertainty	Experimental uncorrelated	Experimental correlated	Nonperturb. correction	PDF uncertainty	$\mu_{r,f}$ variation
0.1161	$^{+4.1}_{-4.8}$	± 0.1	$^{+3.4}_{-3.3}$	$^{+1.0}_{-1.6}$	$^{+1.1}_{-1.2}$	$^{+2.5}_{-2.9}$

Running of alpha-s (?)



→ so far tested
up to μ_r = 200 GeV

Could be modified
for scales $\mu_r > \mu_0$
e.g. by extra dimensions

here: μ_0 = 200 GeV
and n=1,2,3 extra dim.
(n=0 → Standard Model)

α_s extraction from inclusive jets uses PDFs which were derived assuming the RGE

→ We cannot use the inclusive jets to test the RGE in yet untested region

Lessons from incl. jets

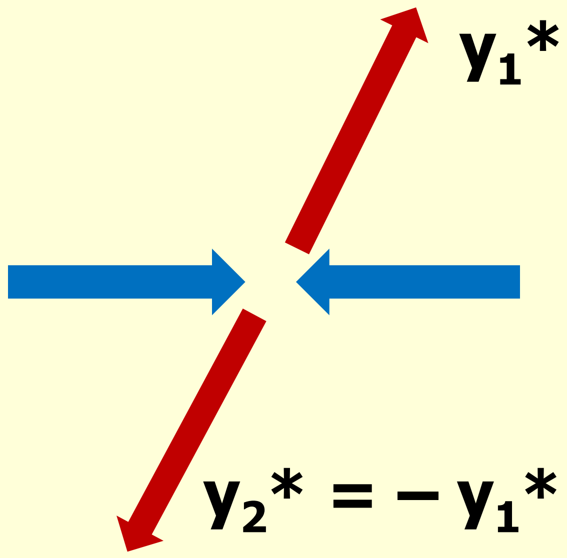
The inclusive jet cross section – double differentially vs. (p_T ,y)

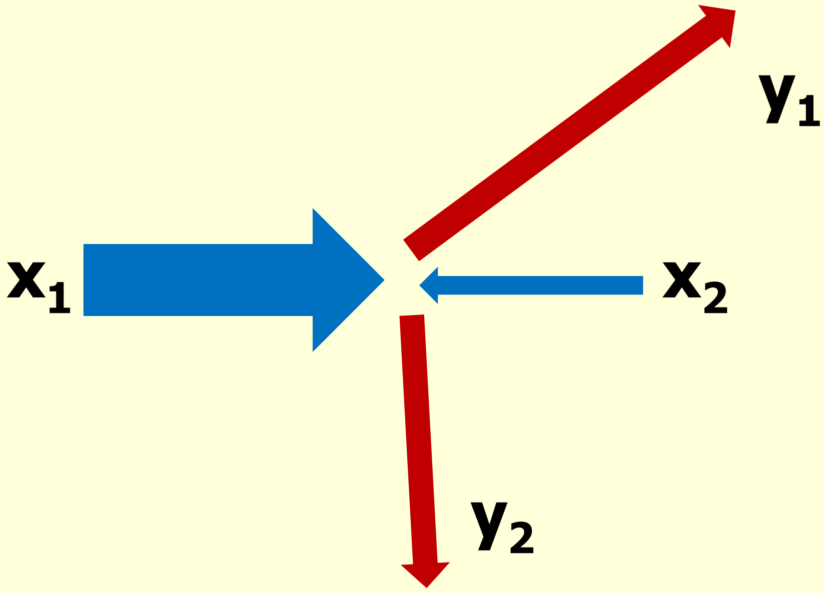
- Consistency between CDF and D0 (and between cone/k_T)
- Traditionally THE measurement to constrain PDFs
  → although triple dijet cross section (p_T,y*,yboost) is more sensitive
- More useful if measured with IR safe jet algorithms
  → if possible successive recombination: k_T, CA, anti-k_T
- this measurement requires
  - best possible energy calibration
    → Calibrate jets / or detector objects?
  - Knowledge of correlations of uncertainties (calibration, resolution) over p_T and rapidity: D0 uses 48 separate sources

Dijets in CM frame and detector

The physics:
in the dijet CM frame (*)

The observation:
in the lab / detector frame





$$y^* = \tfrac{1}{2}\,|y_1 - y_2| = \tfrac{1}{2}\,|y_1^* - y_2^*| = |y_1^*| = |y_2^*|$$

$$y_{boost} = \tfrac{1}{2}\,(y_1 + y_2) = \tfrac{1}{2}\log(x_1/x_2)$$

Dijet Production

Described by eight variables – for example:

1. Dijet Mass Mjj
2. $y^* = \frac{|y_1 - y_2|}{2}$ or: $\chi_{\text{dijet}} \equiv \exp(2y^*)$
3. $y^{\text{boost}} = \frac{y_1 + y_2}{2}$
4. $\Delta\phi = |\phi_1 - \phi_2|$
5. p_{T2}/p_{T1}
6. M/E (jet1)
7. M/E (jet2)
8. Overall rotation in azimuthal angle

features of 2→2 process (→ 1, 2)

PDFs (→ 3)

"hard" higher-order effects (→ 4, 5)

"soft" higher-order effects (→ 6, 7)

irrelevant in unpolarized pp-bar (no reference axis) (→ 8)

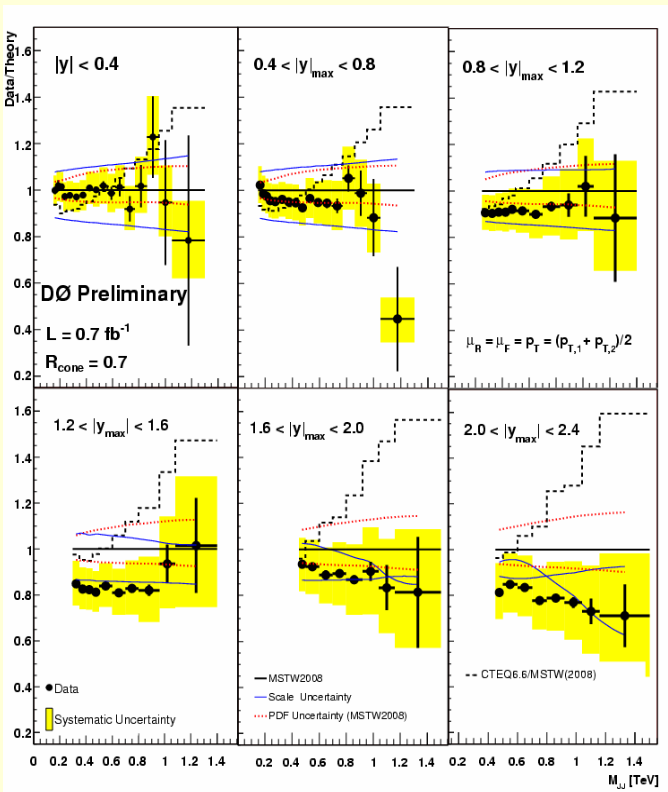
Dijet Mass Spectrum

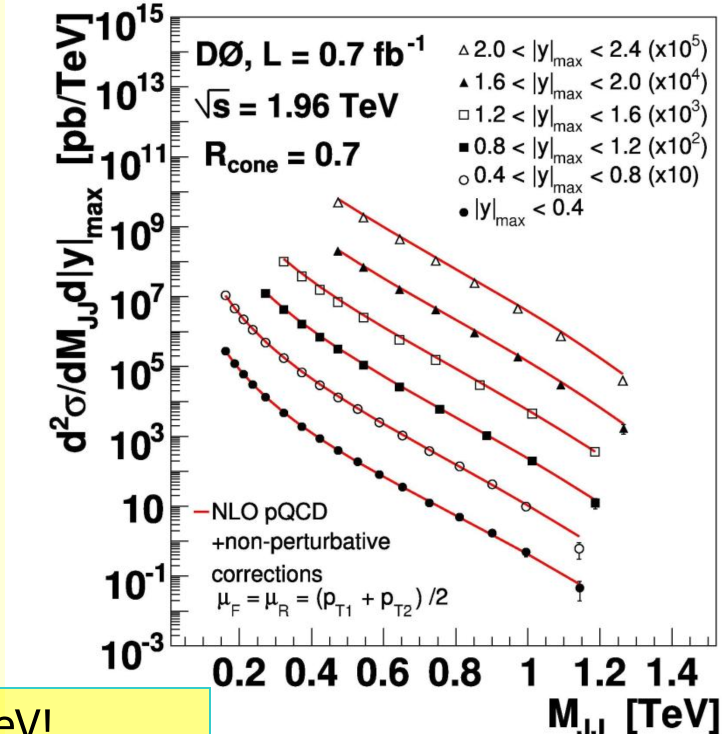
Phys. Lett. B 693, pp. 209-214 (2010)
(last week!)

Measure in six $|y|_{max}$ regions

$0<|y|_{max}<2.4$

Extend QCD tests to forward region

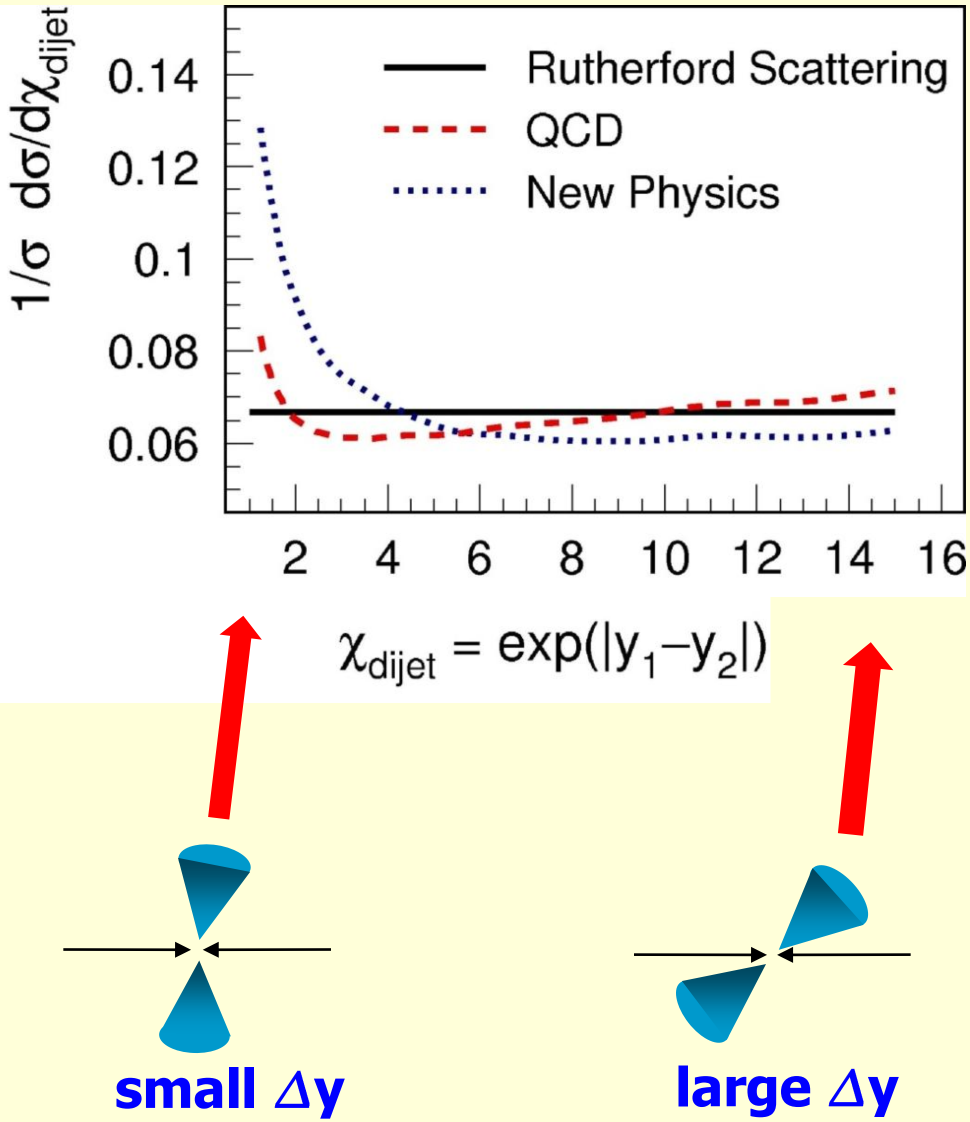




→ data with Mjj > 1.2 TeV!
→ described by NLO pQCD
- no indications for resonances

→ PDF sensitivity at large |y|-max
- CTEQ6.6 prediction too high
- MSTW2008 consistent w/ data (but correlation of experimental and PDF uncertainties!)

Dijet Angular Distribution



variable:

$$\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$$

at LO, related to CM scattering angle

$$\chi_{\text{dijet}} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

- flat for Rutherford scattering
- slightly shaped in QCD
- new physics, like
  - quark compositeness
  - extra spatial dimensions

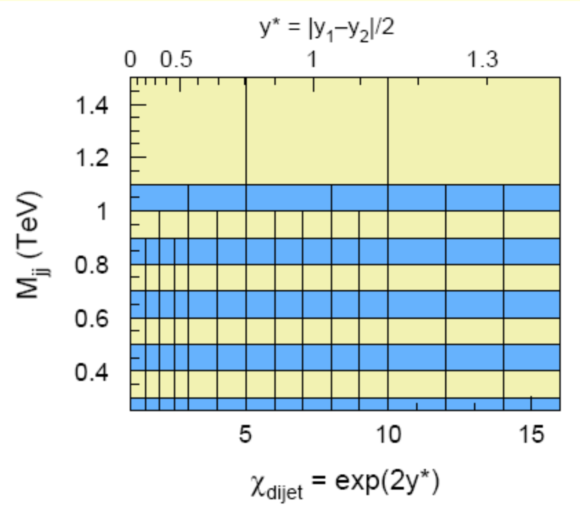
→ enhancements at low χ_{dijet}

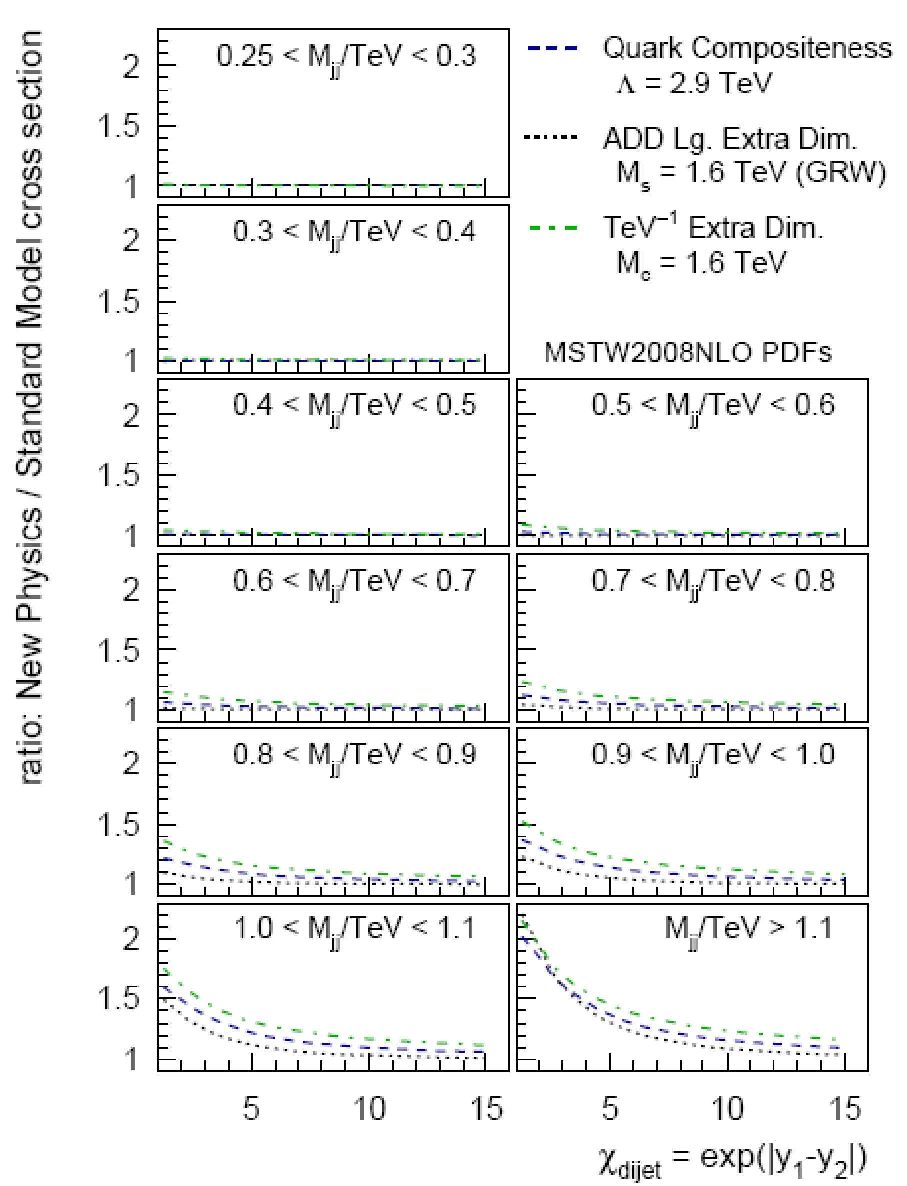
Sensitivity to New Physics

Ratio of NP/SM in different dijet mass regions
→ Highest sensitivity to New Physics at high dijet masses

Strategy:

- Measure $\chi_{dijet} = \exp(2y^*)$ (higher sensitivity in CM frame)
- Go to **highest masses** (even if statistics per bin is small)
- Analyze **whole shape** of distribution





Dijet Angular Distribution

Phys. Rev. Lett. 103, 191803 (2009)

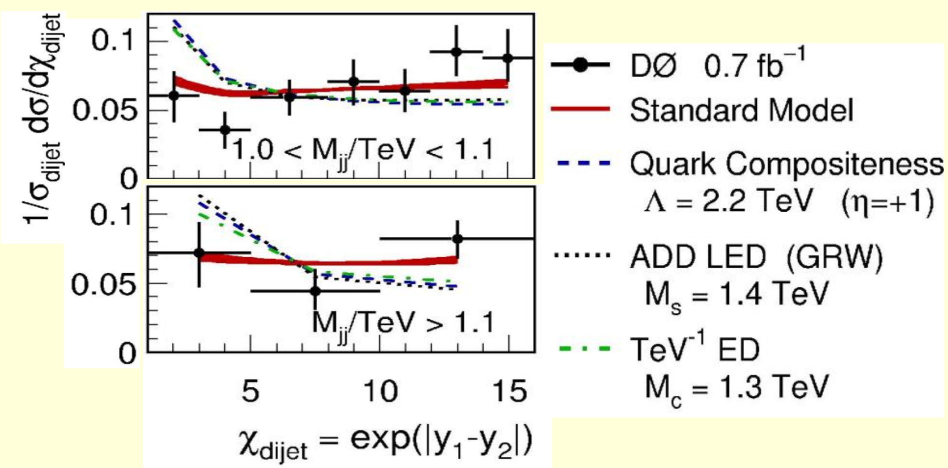
→ normalized distribution $\frac{1}{\sigma}\frac{d\sigma}{d\chi_{\mathrm{dijet}}}$

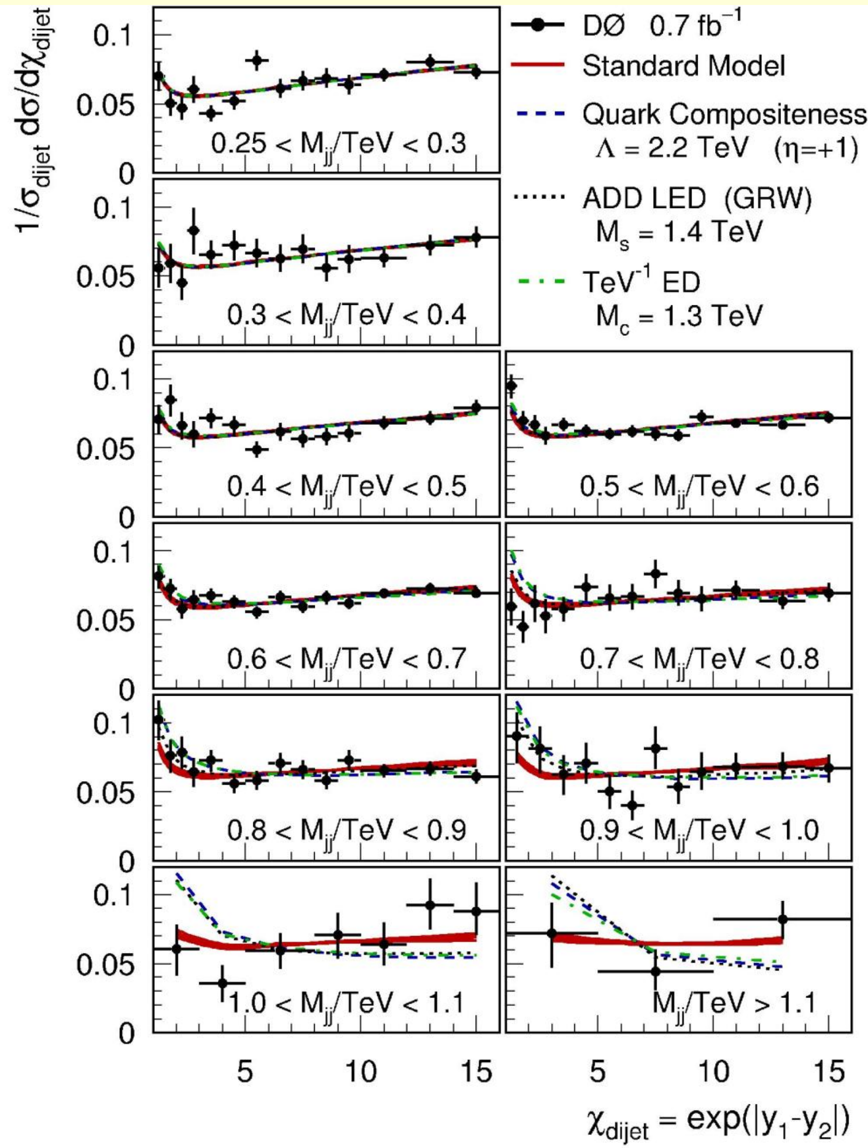
→ reduced experimental and theoretical uncertainties

→ Measurement for dijet masses from 0.25 TeV to >1.1 TeV

First time:

Rutherford experiment above 1TeV

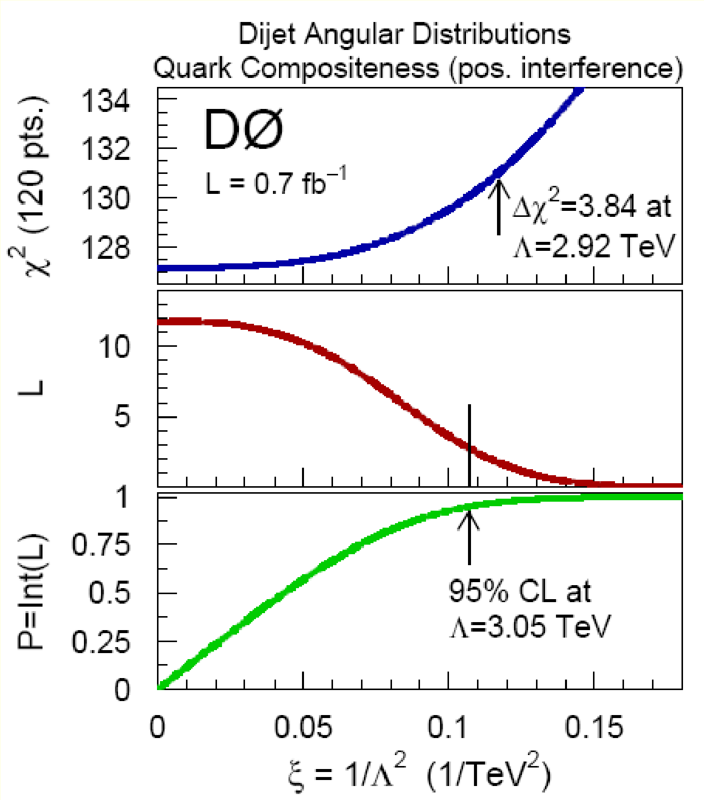




Dijet Angular Distribution: New Physics Limits

Test multiple models at highest possible energies:

- Probing quark substructure
- Sensitive to extra spatial dimensions
  - virtual exchange of KK excitation of graviton (ADD LED)
  - virtual KK excitation of gluon (TeV-1 ED)



Use full χ_{dijet} shape of corrected data

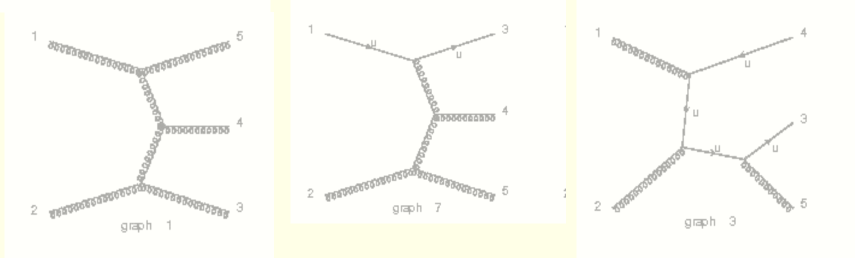
Bayesian and $\Delta\chi^2$ methods @95%CL

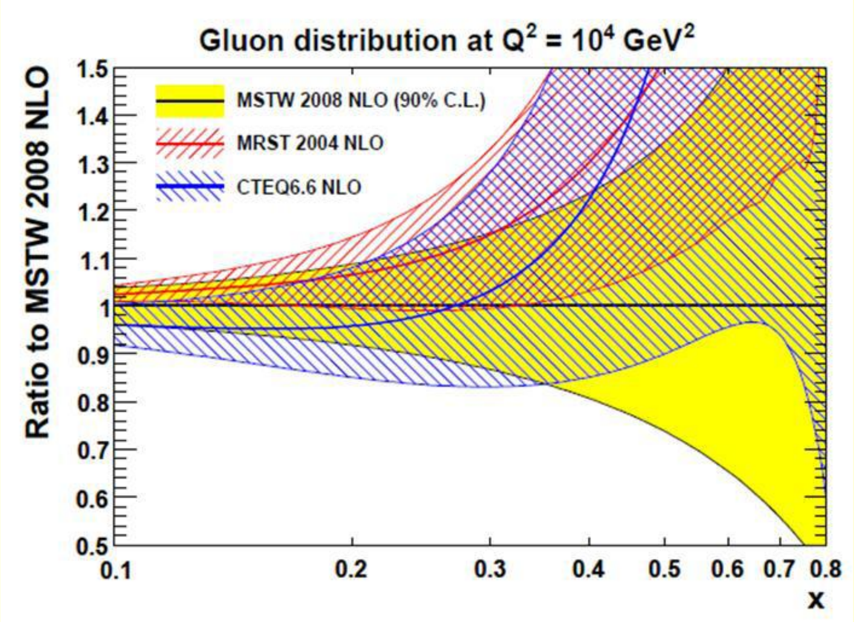
- Quark Compositeness Λ > 2.9TeV
- ADD LED (GRW) Ms > 1.6 TeV
- TeV-1 ED Mc > 1.6 TeV

all: most stringent limits!

Multi-Jet Production

- ***Inclusive jet production and dijets sensitive to PDFs and α_s^2***
- ***Three-jet production***
  - ***same PDF sensitivity***
  - ***But sensitive to α_s^3***
  - ***Sensitivity to contribution from higher order diagrams.***
- ***Testing higher-order processes provides direct insight into strong dynamics***

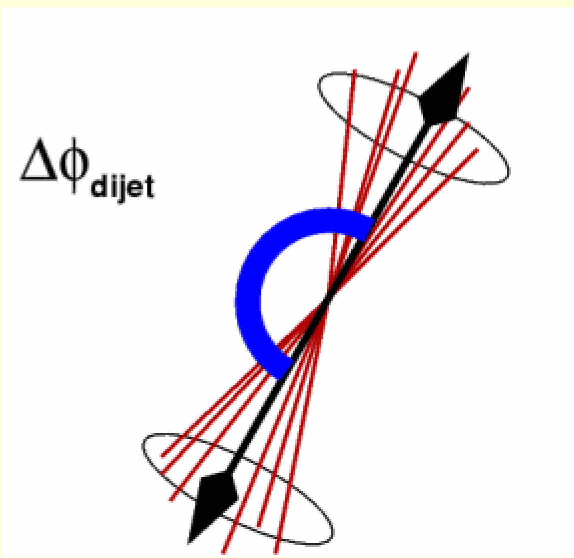




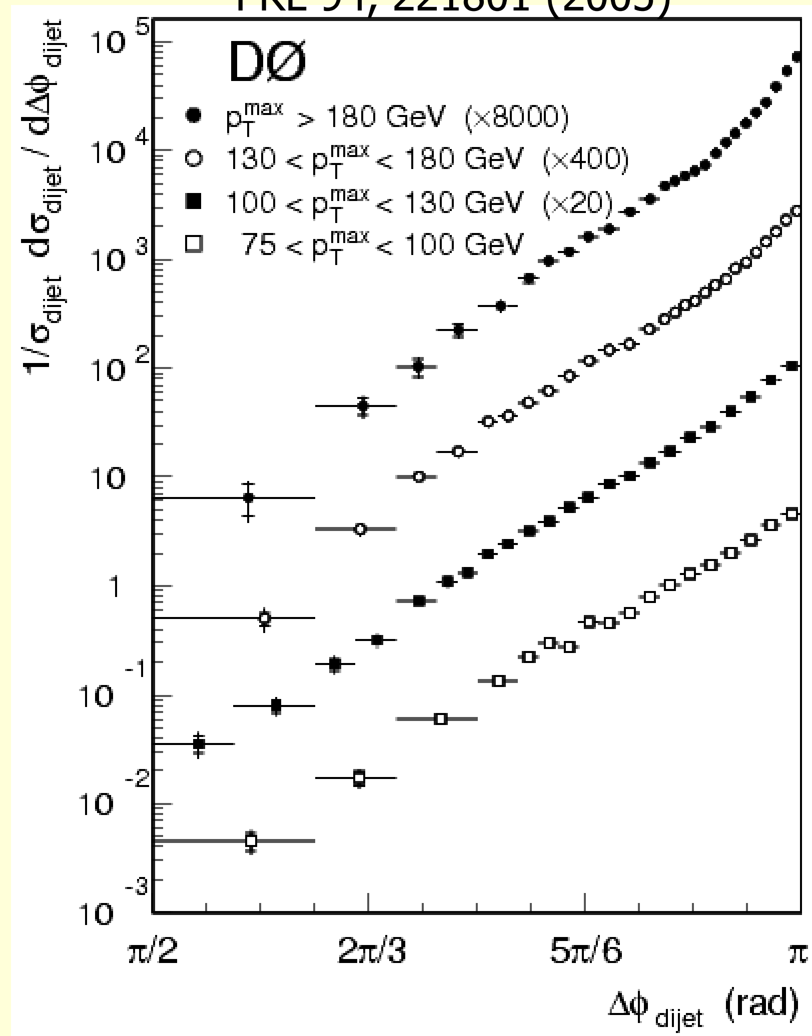
Dijet Azimuthal Decorrelation

Idea: Dijet Azimuthal Angle is Sensitive to Soft & Hard Emissions:

- Test Parton-Shower
- Test 3-Jet NLO



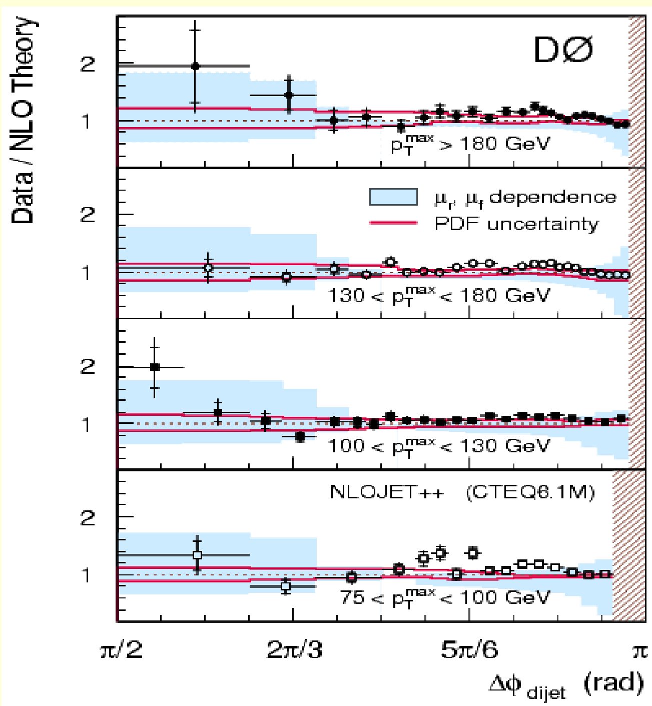
PRL 94, 221801 (2005)



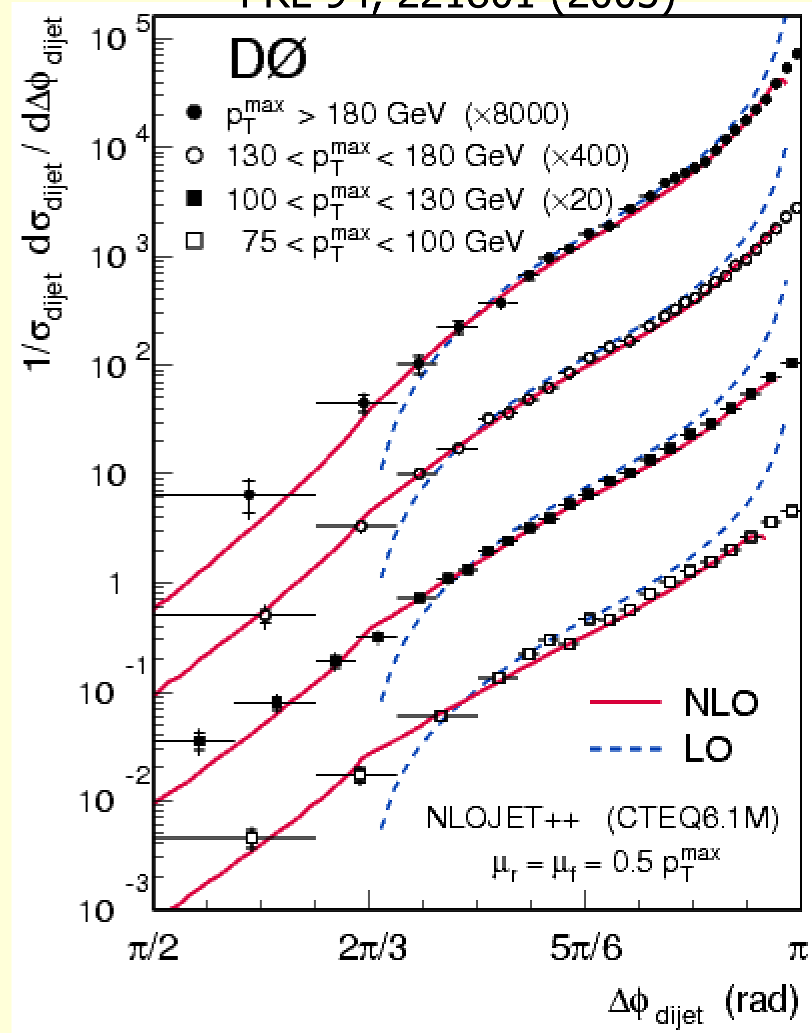
Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation >2pi/3
  & Divergence towards pi
- NLO is very good – down to pi/2
  & better towards pi
  … still: resummation needed



PRL 94, 221801 (2005)

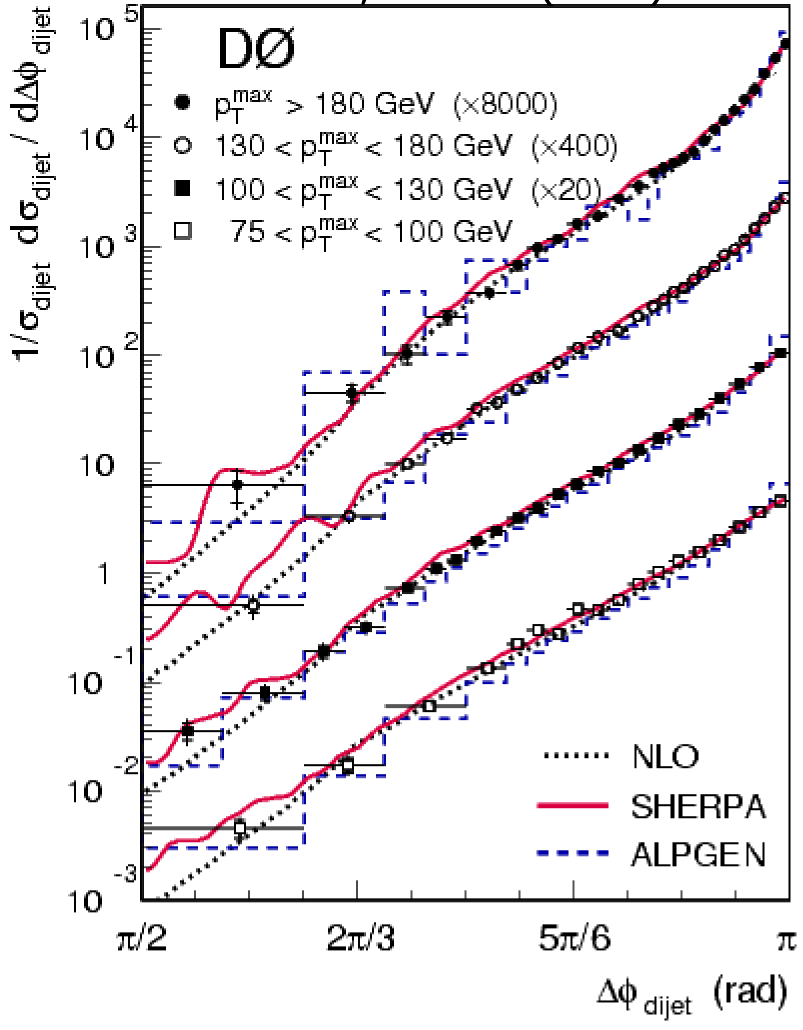


Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation >2pi/3
  & Divergence towards pi
- NLO is very good – down to pi/2
  & better towards pi
  … still: resummation needed
- HERWIG is perfect “out-the-box”
- PYTHIA is too low in tail …
  … but it can be tuned (tune DW)
  (“tune A” is too high!)
- SHERPA is great
- ALPGEN looks good – but low efficiency → large stat. fluctuations

PRL 94, 221801 (2005)



Three-jet Mass

First Measurement of three-jet cross section at the Tevatron
→ First corrected 3-jet mass distribution
→ First comparison to NLO pQCD calculations for 3-jet cross sections

Strategy:

Measure cross sect. vs. invariant three-jet mass

- in different rapidity intervals $|y| < 0.8, 1.6, 2.4$

For the largest rapidity interval

- for different p_T requirements of the 3rd jet $p_T^{Jet3} > 40, 70, 100$ GeV

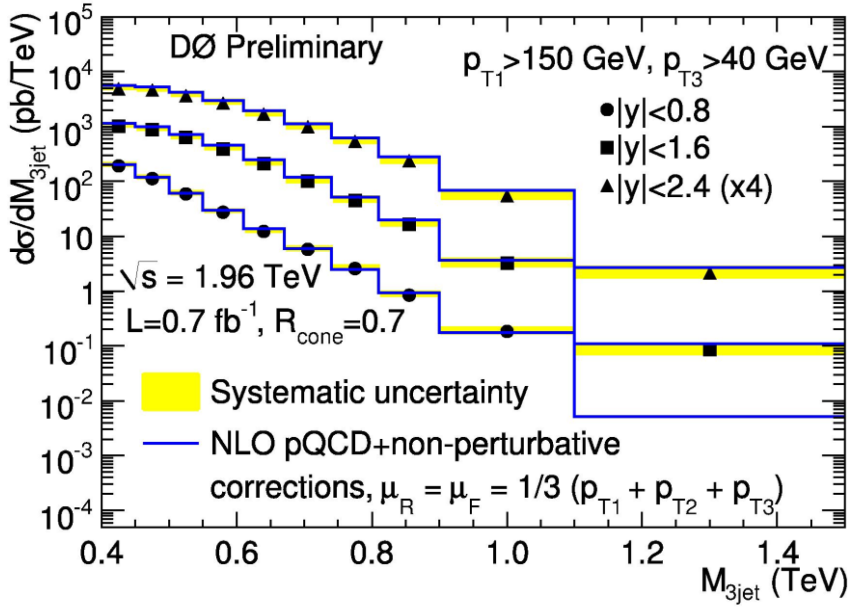
Data Set:

- 0.7 fb-1 inclusive jet triggers
- Require at least 3 reconstructed jets passing data quality and jet id criteria
  - Jet 1 $p_T > 150$ GeV
  - Jet 2, 3 $p_T > 40$ GeV
  - All jets separated by $\Delta R > 1.4 = 2*R_{cone}$

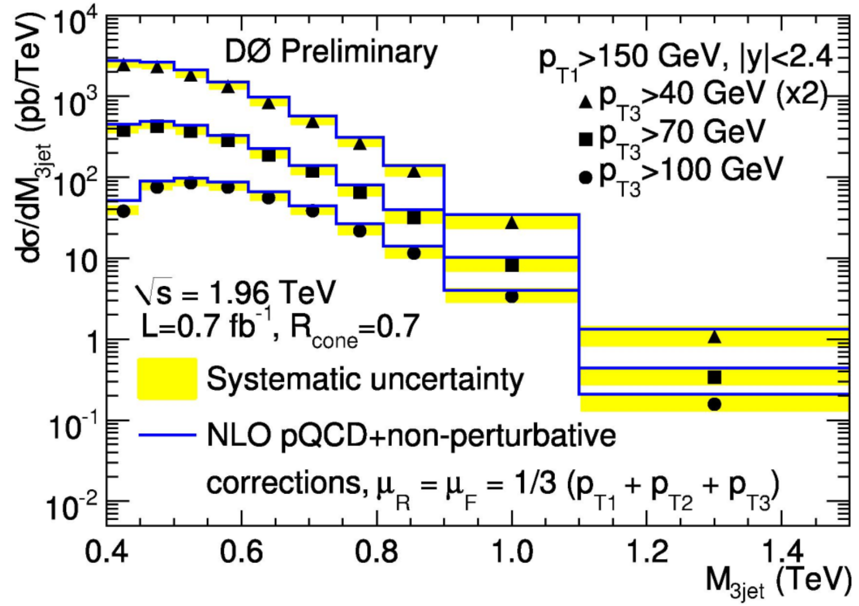
Three-jet Mass

$$\frac{d\sigma}{dM_{3jet}} = \frac{1}{L \cdot \Delta M_{3jet}} \cdot \left(\sum_{i=1}^{N_{evt}} \frac{1}{\epsilon_v^i} \right) \cdot C_{unsmear}$$

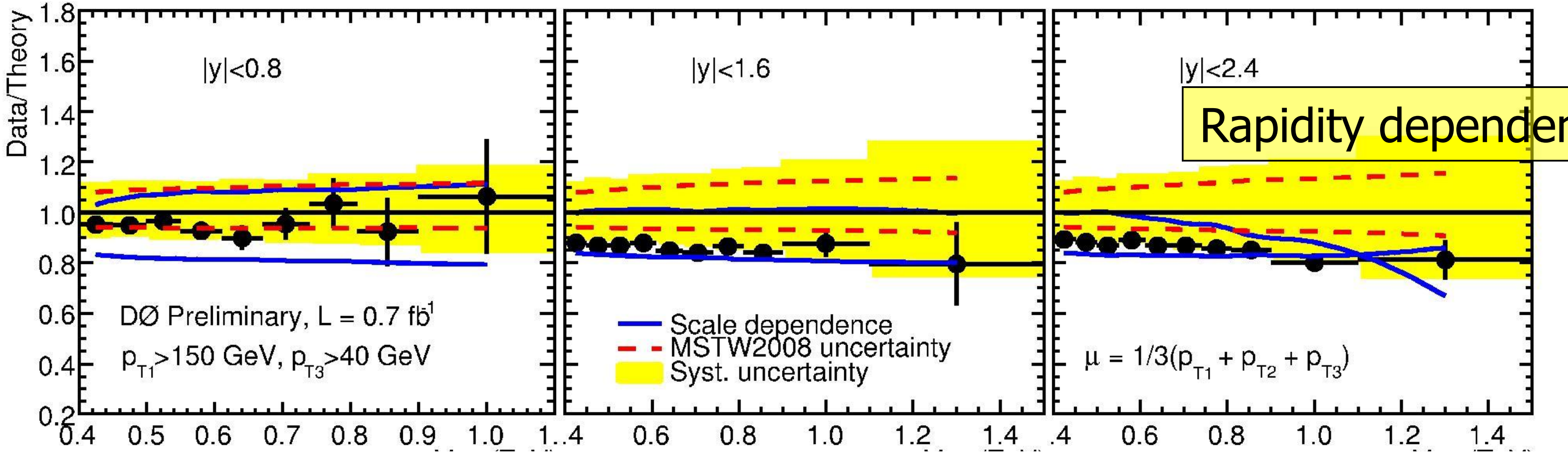
Rapidity dependence



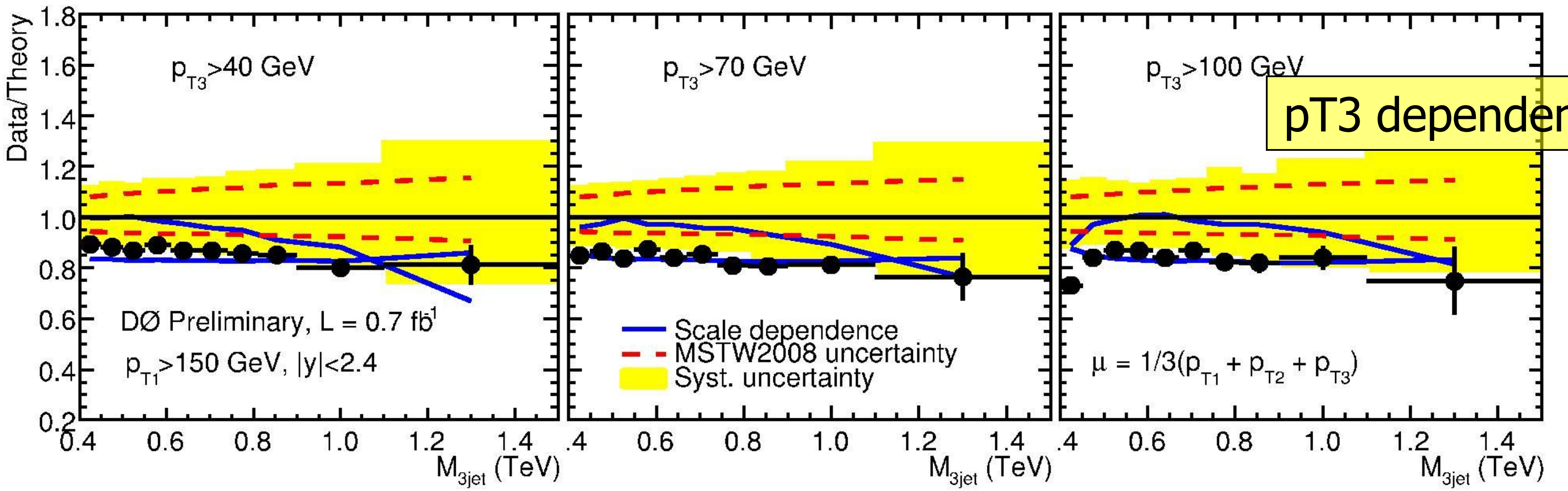
p_T^{Jet3} dependence



Three-jet mass distrib.



Rapidity dependence



pT3 dependence

Well described by pQCD: 1st test 3-jet NLO cross section!

$R_{3/2}$: Introduction

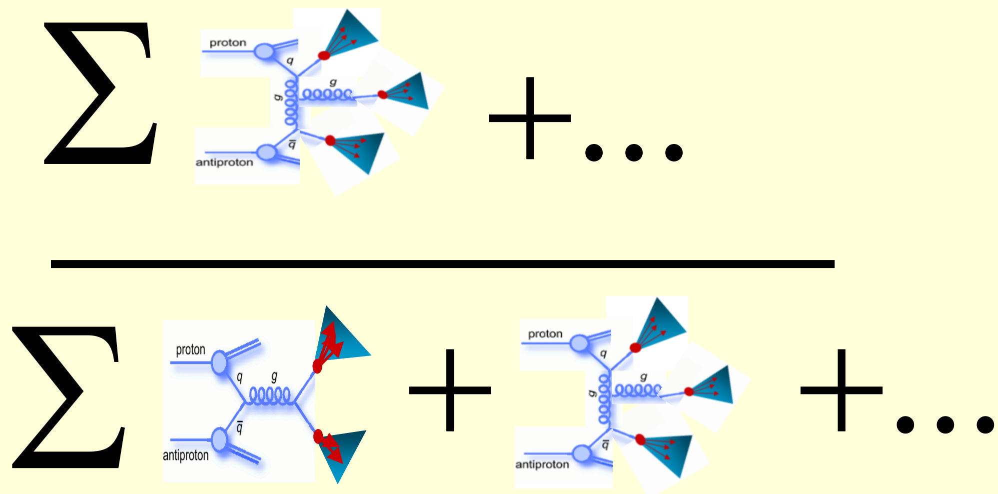
Goal: test pQCD (and α_s) independent of PDFs

Conditional probability:

$R_{3/2}$

$= P(3^{rd}\text{ jet} \mid 2\text{ jets})$

$= \sigma_{3\text{-}jet} / \sigma_{2\text{-}jet}$



- Probability to find a third jet in an inclusive dijet event
- Sensitive to α_s (3-jets: α_s^3 / 2-jets: α_s^2)
- (almost) independent of PDFs

$R_{3/2} = \sigma_{3\text{-}jet} / \sigma_{2\text{-}jet}$

Measure as function of two momentum scales:

- p_{Tmax} : common scale for both $\sigma_{2\text{-}jet}$ and $\sigma_{3\text{-}jet}$
- p_{Tmin} : scale at which 3rd jet is resolved ($\sigma_{3\text{-}jet}$ only)

Sensitive to α_s at the scale p_{Tmax}

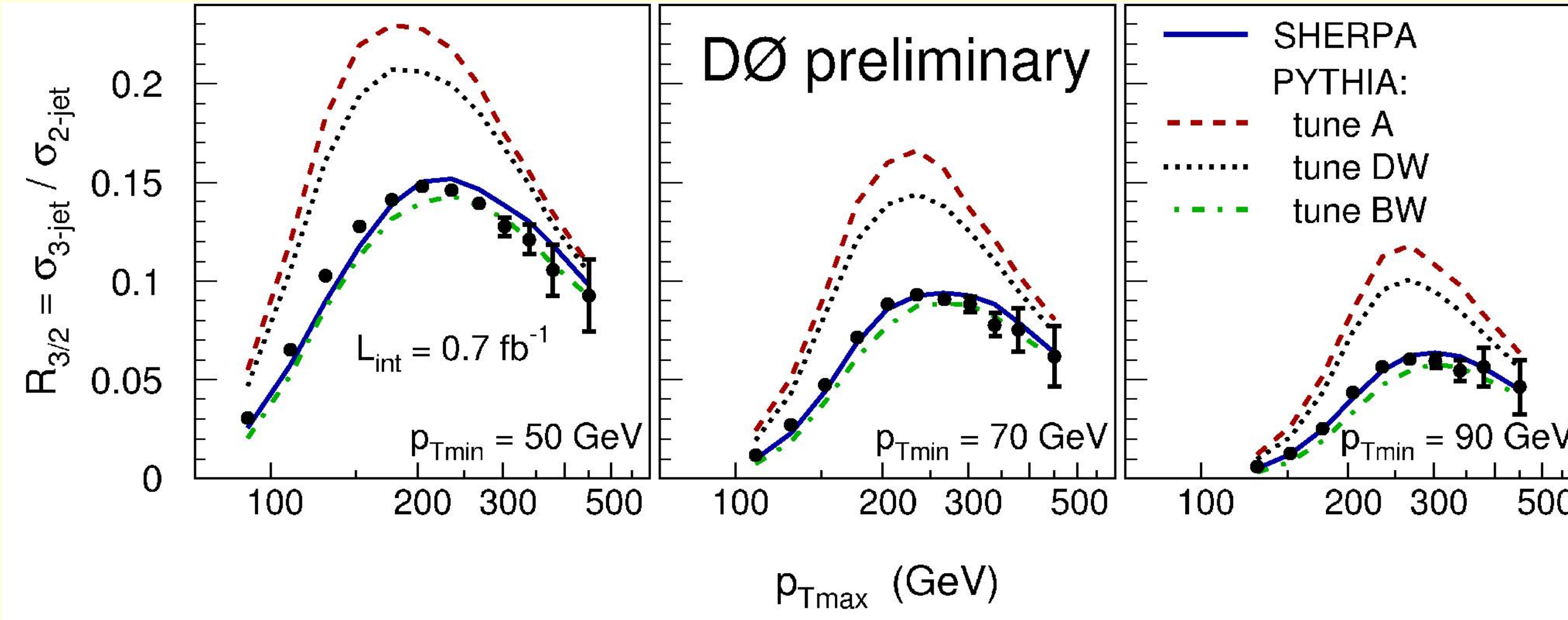
→ probe running of α_s in Tevatron energy regime → up to 500 GeV

Details:

- inclusive *n*-jet samples (*n*=3,2) with *n* (or more) jets above p_{Tmin}
- $|y|<2.4$ for all *n* leading p_T jets
- $\Delta R_{jet,jet} > 1.4$ (insensitive to overlapping jet cones)
- study p_{Tmax} dependence for different p_{Tmin} of 50, 70, 90 GeV

→ Measurement of $R_{3/2}(p_{Tmax}\,;\,p_{Tmin})$

$R_{3/2} = \sigma_{3\text{-jet}} / \sigma_{2\text{-jet}}$



SHERPA: good description (default version w/ MSTW2008LO PDFs)

PYTHIA: huge dependence on tune

- Reasonable description by tune BW
- Popular tunes A, DW → totally off

Maybe: extract strong coupling → up to p_T>400 GeV (yet untested)

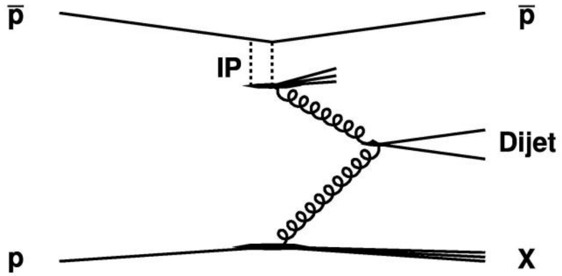
Conclusions

- DØ continues to produce a wide-range of important QCD results, ranging from low p_T scattering, through an assortment of single and double differential jet measurements
  - Not even mentioned: exclusive jet production, single and double direct photon results, W and Z + jets, W/Z + heavy flavor jets, …
  - With data currently under analysis, expect more precision QCD measurements
    - Inclusive jets at high p_T
    - Triple differential jet cross sections
    - High precision central and forward direct photon measurements
- Tevatron will continue though 2011
  - Will we run through 2014?
  - Are there additional measurements that can be made with 12 fb^{-1}?

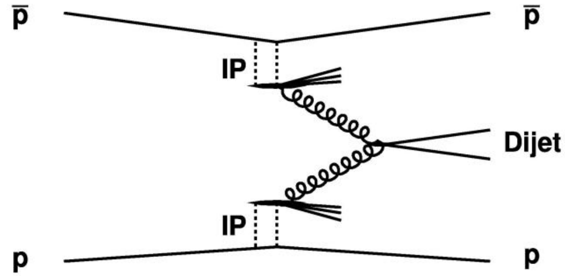
For the latest public DØ QCD results, see
http://www-d0.fnal.gov/Run2Physics/qcd/

Backup

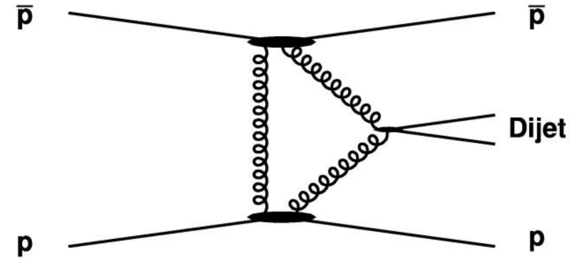
Exclusive Dijets



Single Diffraction (SD)



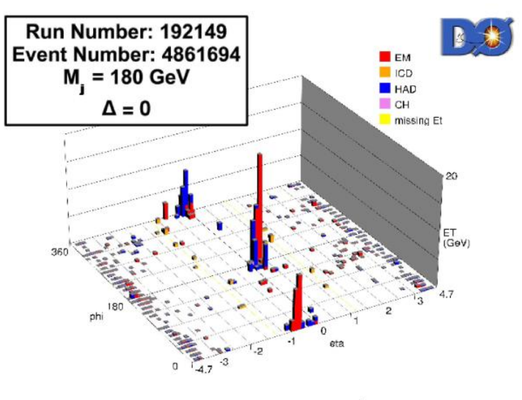
Inclusive Double Pomeron (IDP)

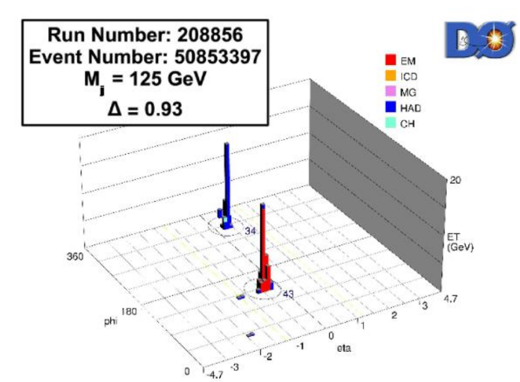


Exclusive Diffraction (EDP)

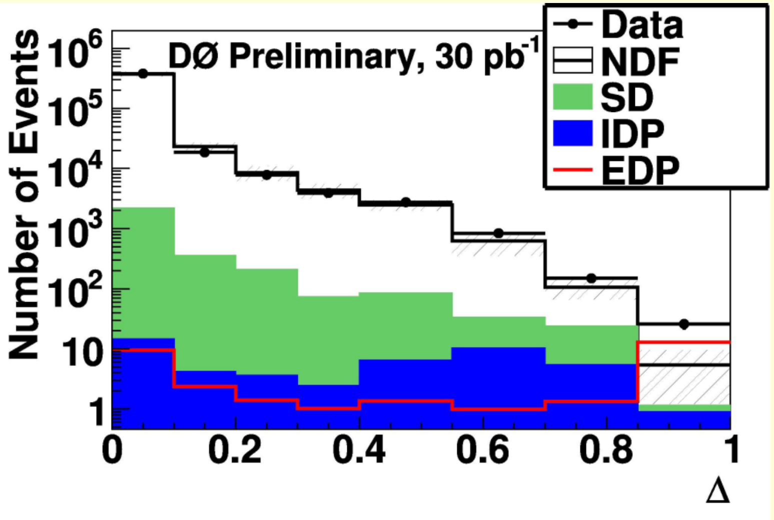
Events identified by gap devoid of activity in forward region
– Exchange of colorless object (Pomeron)
Require 2 backtoback central jets ($|y|<0.8$ and $\Delta\varphi > 3.1$rad)
– pT1>60GeV and pT2>40 GeV, Dijet invariant mass >100 GeV
- Low instantaneous luminosity: avoid multiple interactions

$$\Delta = \frac{1}{2}\exp\Big(-\sum_{2.0<|\eta|\leq 3.0} E_T/\mathrm{GeV}\Big) + \frac{1}{2}\exp\Big(-\sum_{3.0<|\eta|<4.2} E_T/\mathrm{GeV}\Big)$$

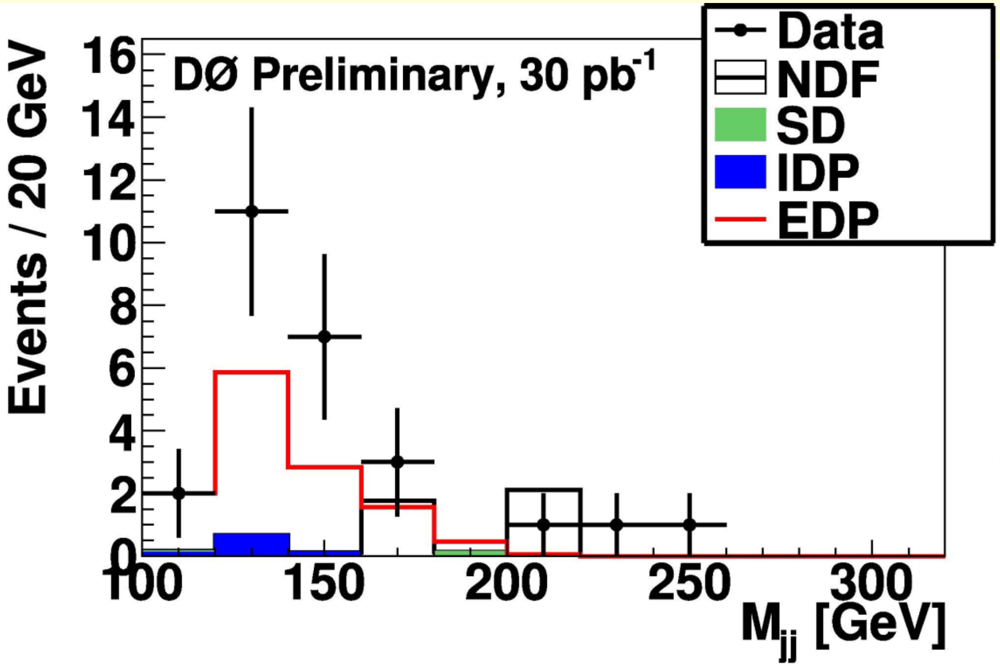


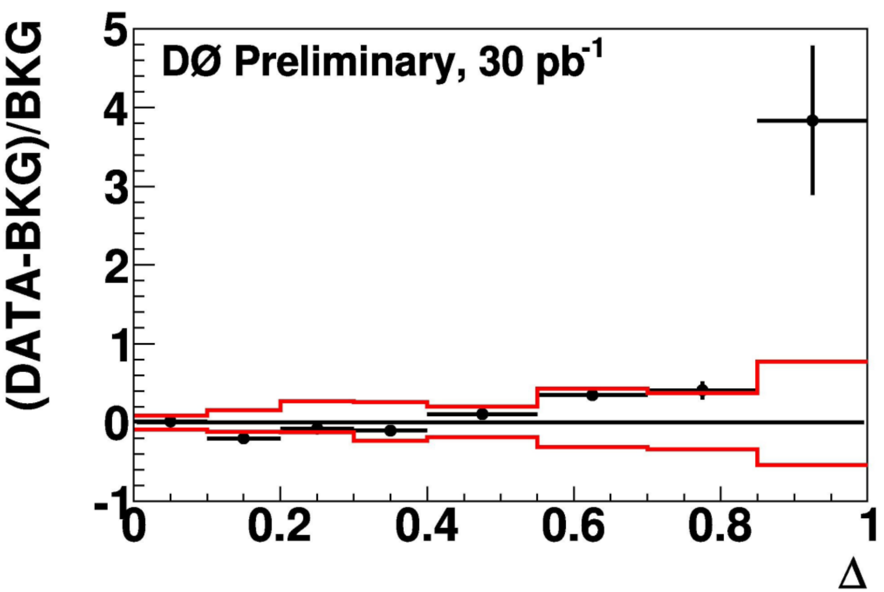


Exclusive Dijets

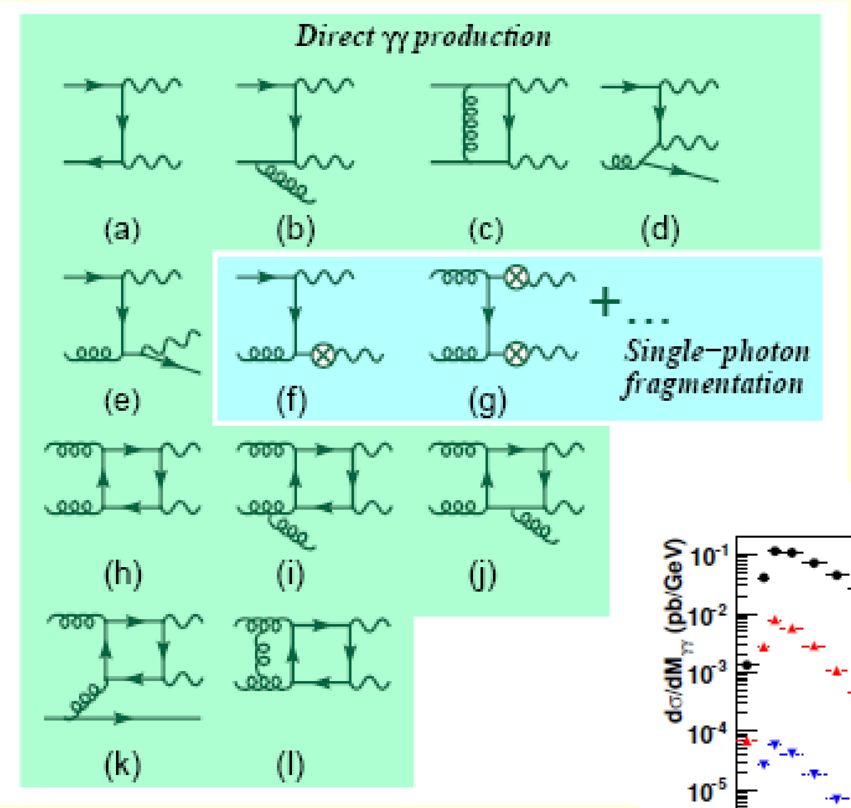


Good discrimination between signal and background
- 26 candidate events, to bkg prediction of $5.4^{+4.2}_{-2.9}$ in excess bin Δ>0.85
- Excess significance: 4.1σ

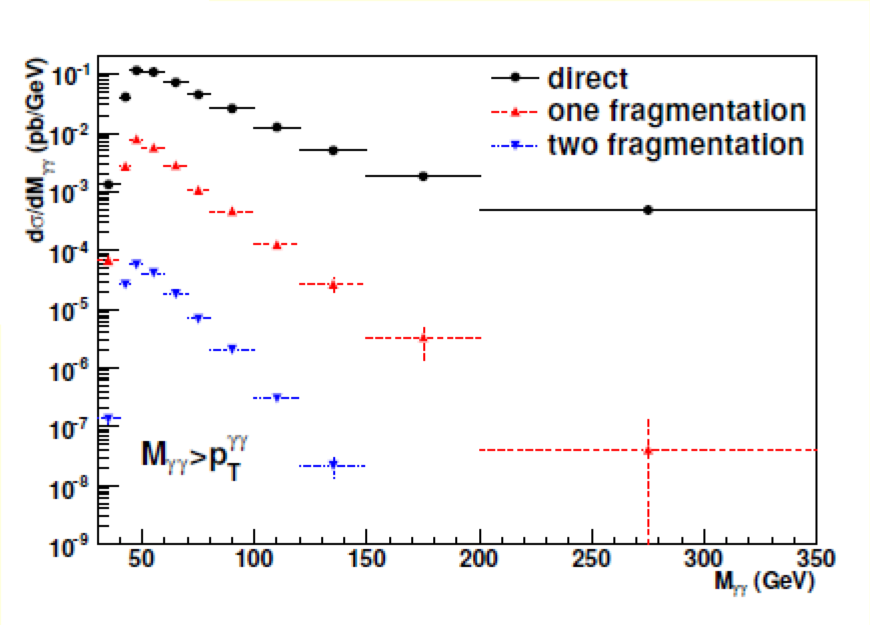




Shedding Light on QCD



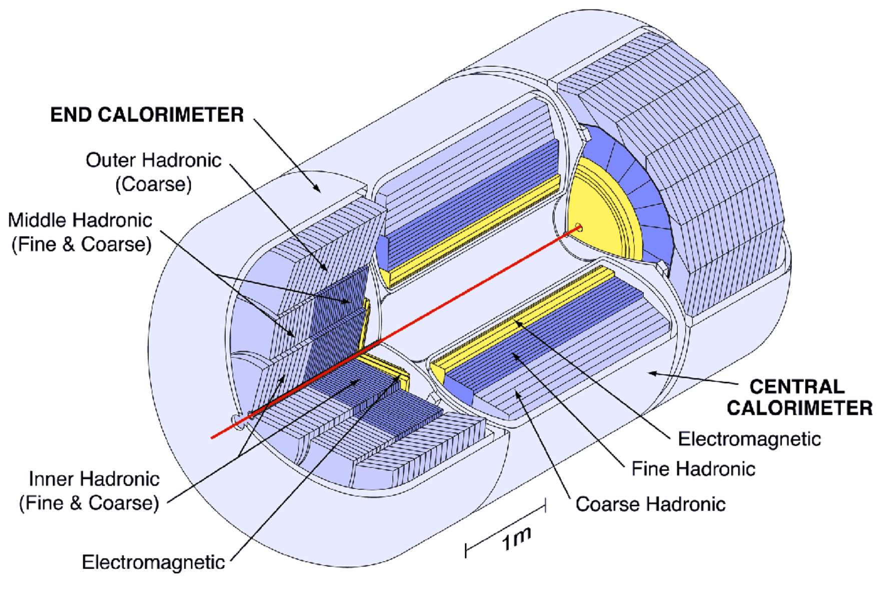
- Important test of pQCD
  - Soft gluon resummation
- Major background to H→$\gamma\gamma$
- Classes of Production
  - Direct *(a-e & h-i)*
    - "Born & Box" diagrams
  - Single Fragmentation *(f)*
  - Double Fragmentation *(g)*

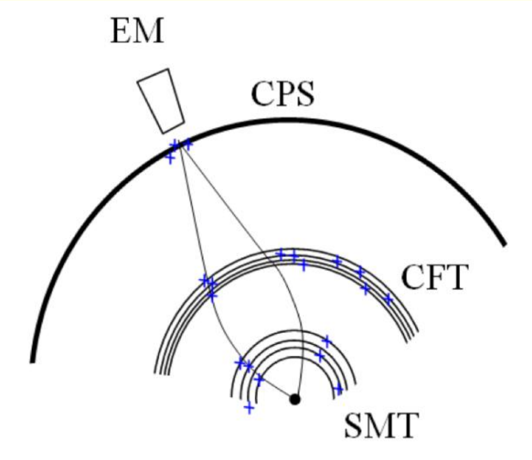


Graphs from PRD 76 013009 (2007)
Plots from DIPHOX

Finding a Photon

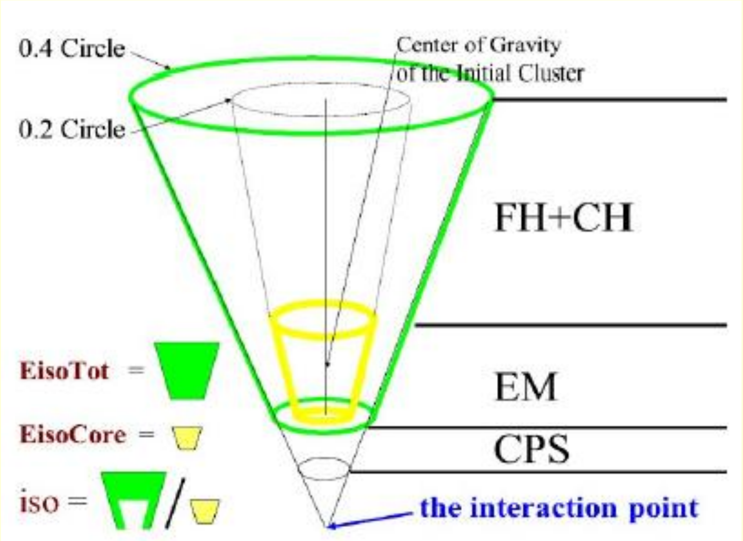
- D0 Electromagnetic Calorimeter
  - Approx 20 radiation lengths thick
  - Coverage $|\eta| < 1.1$ & $1.5<|\eta|<3.2$
  - $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (0.05x0.05 at shower max)
- High precision tracking
  - Silicon microstrip tracker
  - Central fiber tracker
  - Central & forward preshower detectors

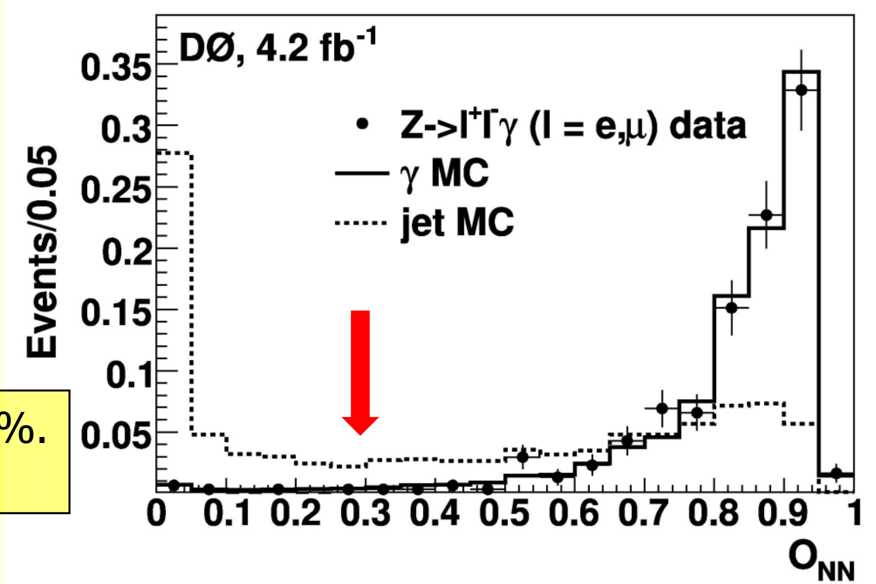




Finding a Photon

- Central photons are selected from EM clusters reconstructed within a cone with radius R=0.2 requiring:
  - High EM fraction: >97%
  - Isolated in the calorimeter
  - Isolated in the tracker
  - Shower width in 3rd EM layer consistent with an EM object.
- Photon purity is further improved by using an Artificial Neural Net (ANN) for identification
- Inputs:
  - Tracker isolation
  - Number of EM1 cells within R<0.2
  - Number of EM1 cells within 0.2<R<0.4
  - Number CPS clusters within R<0.1
  - Squared-energy-weighted width of energy deposition in the CPS





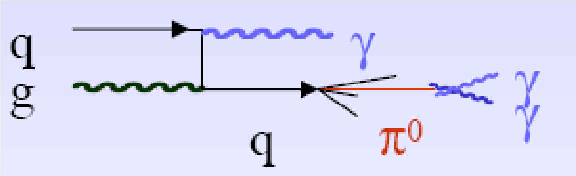
Photon efficiency: 98%. Systematic uncertainty 1.5%. Rejects ~40% of misidentified jets.

Direct Diphotons

"Measurement of direct photon pair production cross sections in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV", V. Abazov, et al. (Submitted to Phys. Lett. B, arXiv.org:1002.4917)

- In 4.2 fb-1 of data collected with a variety of di-EM triggers
  - Trigger efficiency after offline selection is ~100%
- Require
  - 2 photons with p_T>21(20) GeV, $|\eta|$<0.9, E_T^{iso}<2.5 GeV
  - $\Delta R(\gamma,\gamma)>0.4$
  - $p_T(\gamma\gamma)<M(\gamma\gamma)$
- Primary vertex with highest number of tracks required to have $|z_{PV}|$<60 cm.
  - Photon kinematics computed with respect to this vertex.
- Results compared to RESBOS, DIPHOX, PYTHIA
  - See talk by Steffen Schumann at the MC4LHC Workshop for comparisons to SHERPA

$$E_T^{iso} = \sum_{\substack{\text{partons or hadrons} \\ \text{within } \Delta R<0.4}} p_{T,i} - p_{T\gamma}$$

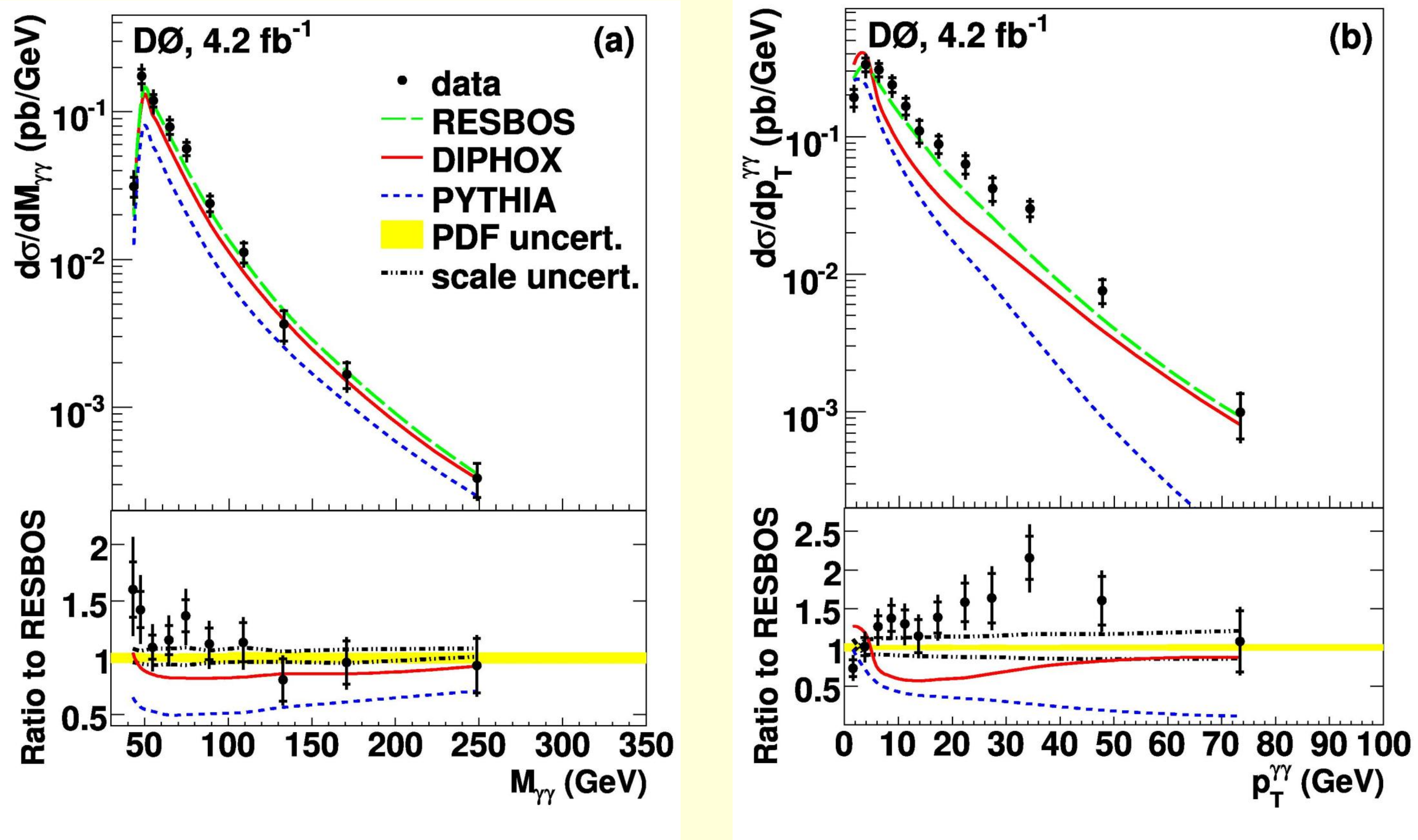


$$\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}}{\varepsilon \cdot A \cdot L \cdot \Delta X} \; ; X = M_{\gamma\gamma},\, p_T^{\gamma\gamma},\, \Delta\phi_{\gamma\gamma},\, |\cos\theta^*|$$

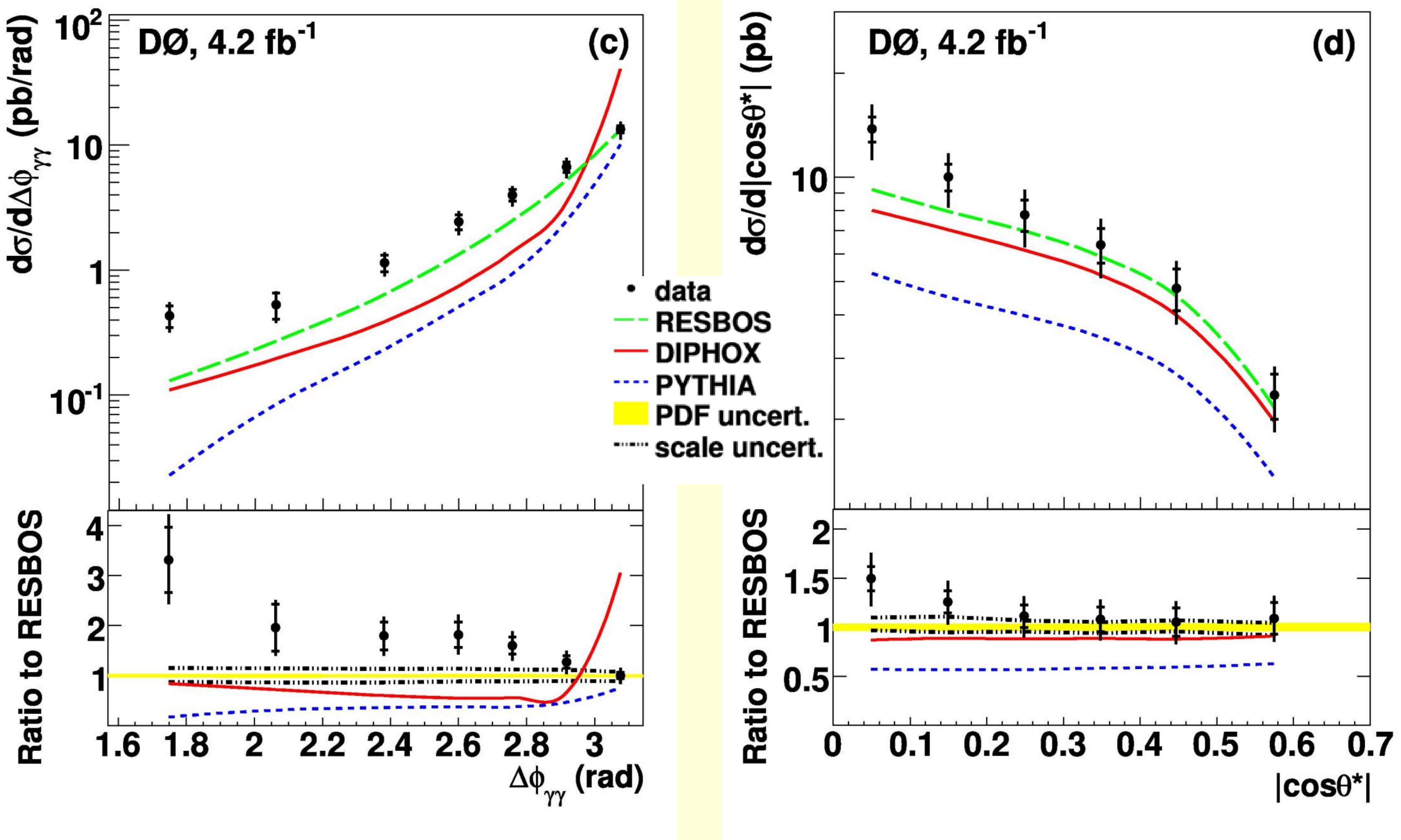
Estimated number of prompt diphoton events ($N_{\gamma\gamma}$)
Event selection efficiency (ε)
Event acceptance (A)
Integrated luminosity (L)
Bin width (ΔX)

DATA	10938
$\gamma\gamma$	7307 +/- 312
γ+jet	1791+/- 411
Dijet	1679+/- 281
Z/γ^* ->ee	161+/- 10

Single Differential Cross-Sections

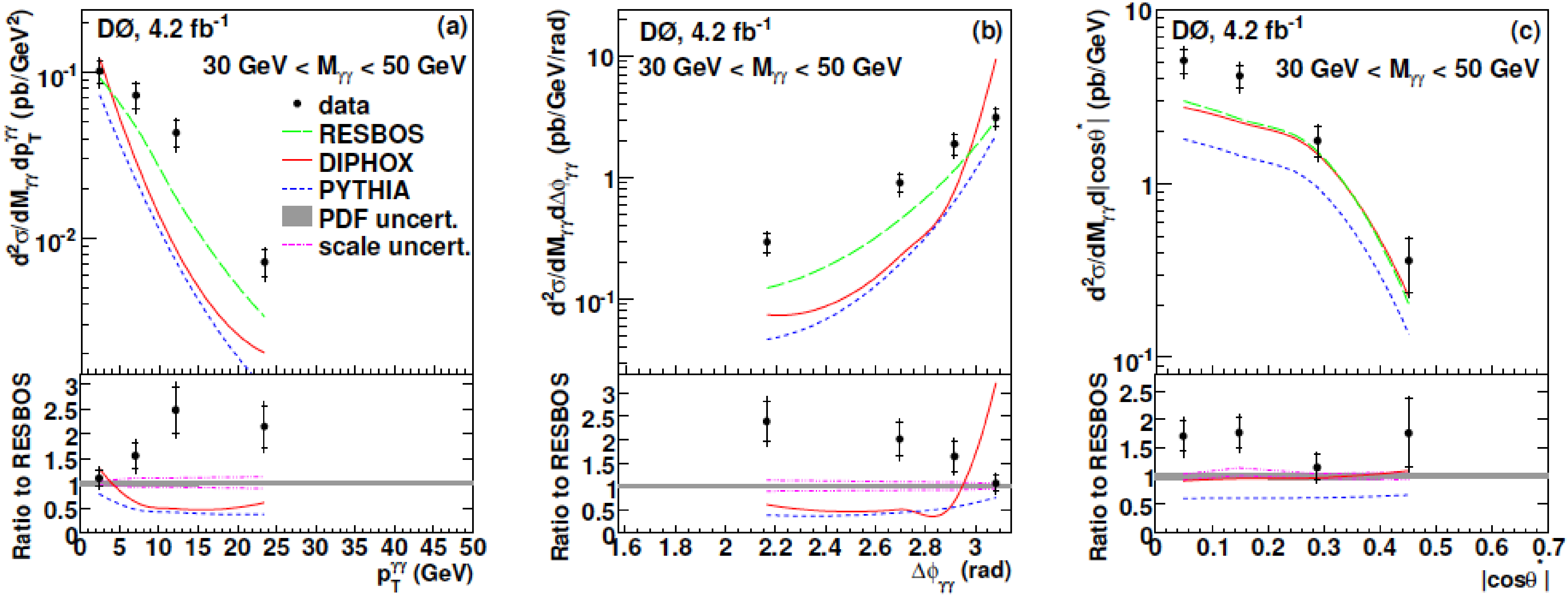


Single Differential Cross-Sections



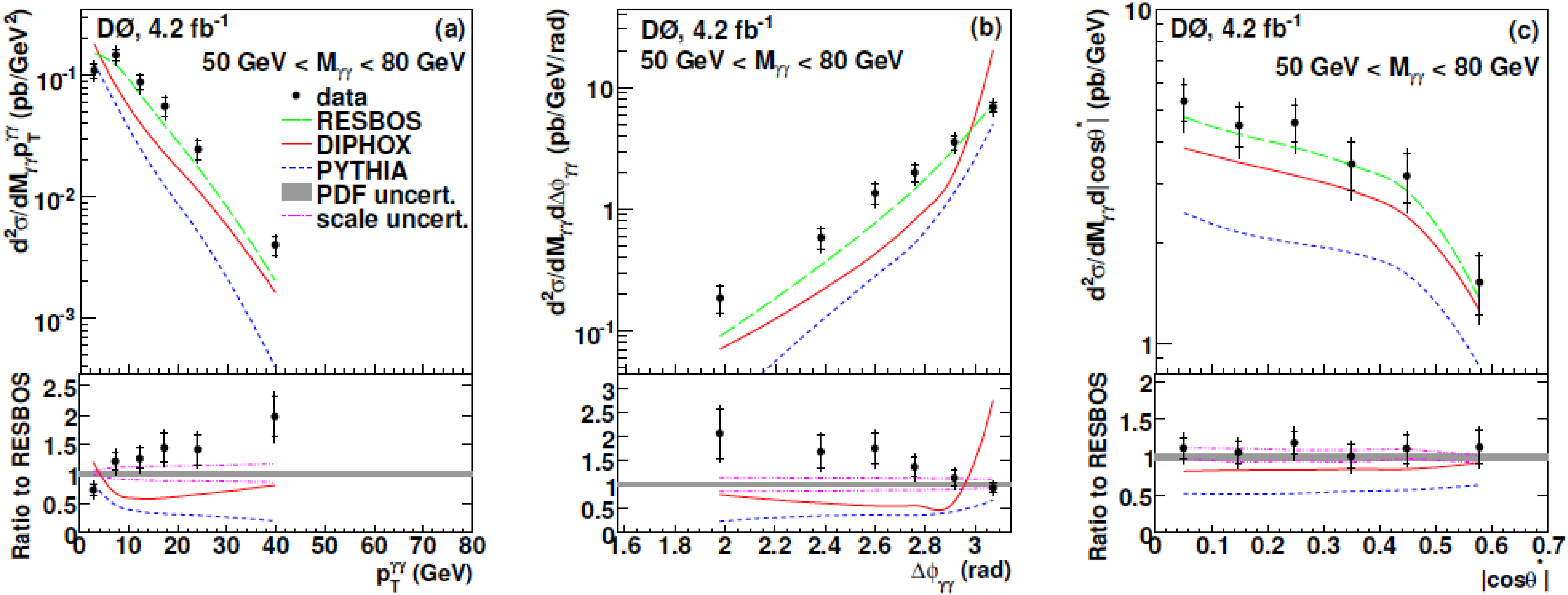
Double Differential Cross-Sections

30 < Mγγ < 50 GeV



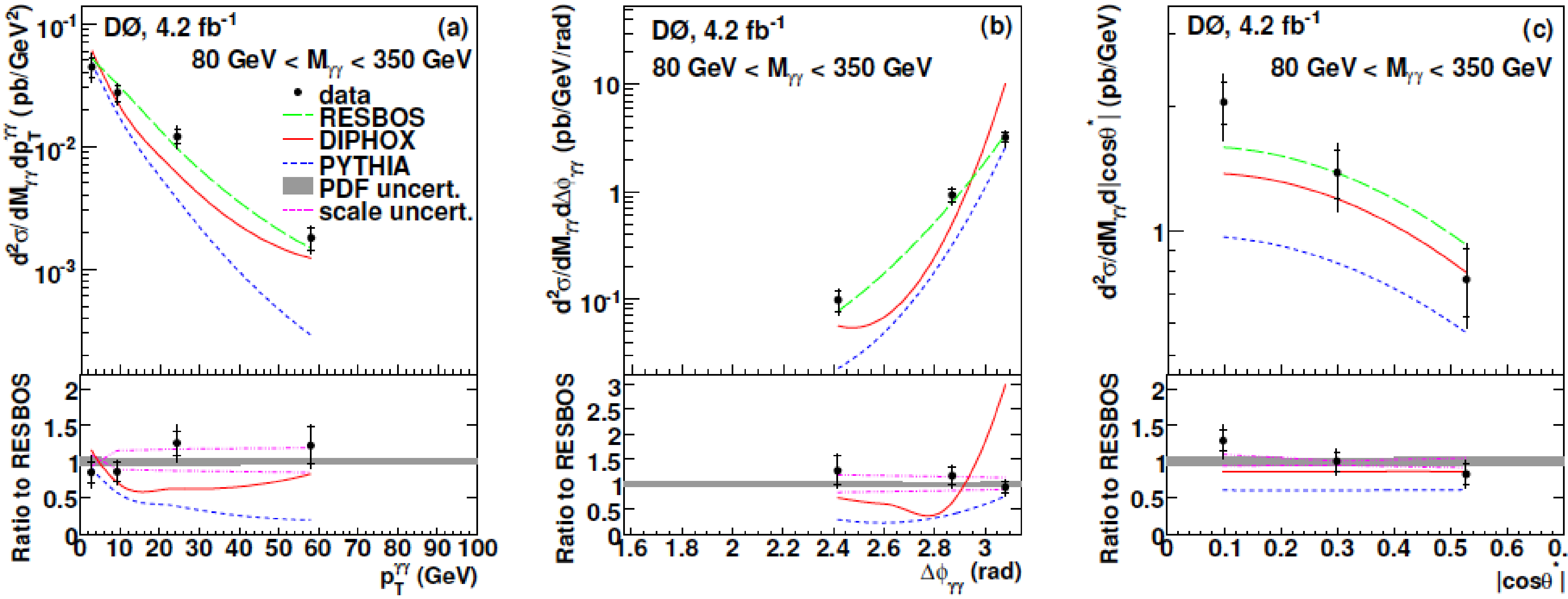
Double Differential Cross-Sections

50 < Mγγ < 80 GeV



Double Differential Cross-Sections

80 < Mγγ < 350 GeV



Direct Photon Predictions

➢RESBOS, *Phys. Rev. D 76, 013009 (2007)* :

+ Quark Scattering qqbar→$\gamma\gamma$ and Gluon Fusion gg→$\gamma\gamma$ up to ***NLO***

+ Fragmentation at LO, with additional NLO approximation

+ Resummation of soft/collinear terms of initial gluons up to all orders, cancelling divergence at NLO as $p_T(\gamma\gamma)$→0

➢DIPHOX, *Eur. Phys. J. C 16, 311 (2000)* :

+ qqbar→$\gamma\gamma$ up to **NLO** + gg→$\gamma\gamma$ at LO

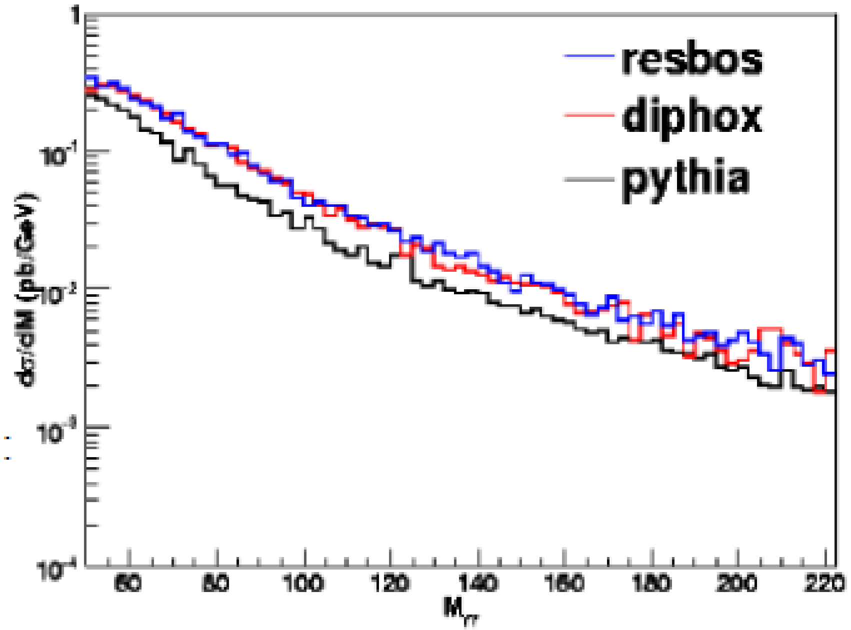
+ Fragmentation up to ***NLO***

+ asymmetry di-photon $p_T(\gamma 1) > p_T(\gamma 2)$

➢PYTHIA, *Comp. Phys. Comm. 135, 238(2001)* :

+ qqbar→$\gamma\gamma$ and gg→$\gamma\gamma$ at LO

+ Resummation via parton shower



Generators and Tunes

- PYTHIA, *Comp. Phys. Comm. 135, 238 (2001)* :
  - LO 2-jet Maxtrix Elements plus Parton Showers
  - Tunes:
    Field's (see arXiv:hep-ph/0610012 for details)
    - Tune A – Q^2-ordered showers, large starting scale for ISR. Fit using CDF underlying data
    - Tune DW - Q^2-ordered showers, tuned to match Z p_T-distribution, D0 dijet $\Delta\phi$ results.
    - Tune BW - Q^2-ordered showers, softer ISR than DW

    Sandhoff-Skands, et al.
    (see arXiv:hep-ph/0905.3418, and *Eur. Phys. J. C 39 (2005)* for details)
    - Tune S0 – p_T-order showers, annealing color reconnection.
      - "Professor pT0"
      - Perugia Series of Tunes – Refinements on Tune s0
    - General Area Law (GAL) – S0 tune with GAL color reconnections
- SHERPA, *JHEP 0902, 007 (2009)* :
  - Matched tree-level 2-,3-, and 4-jet Matrix Elements plus Parton Showers