The Status of QCD

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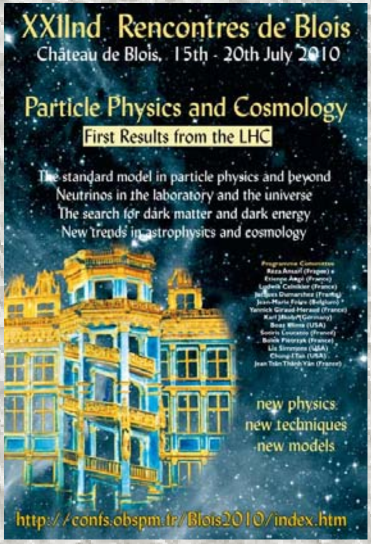
Results from
HERA/Tevatron/LHC

22nd Rencontres de Blois
Particle Physics and Cosmology
Blois
July 15-20, 2010



Outline

- The Landscape
- Parton Distribution Functions
- Jet Production
- Direct Photon Production
- W/Z + Jets
- The Underlying Event
- Charged Particle Spectra
- Final Words

More results in the Backup slides

Details in the Parallel Talks

- Sunday 14:00-16:00
  - Particle Multiplicities in Minimum Bias Event with the ATLAS Detector at 7 TeV – **R. Zaidan**
  - Single and Double Particle Studies at CMS – **K. Stenson**
- Sunday 16:30-19:30
  - Properties of the Underlying Event in Minimum Bias Collisions with the ATLAS Detector at 7 TeV – **G. Hare**
  - Jet Production with the ATLAS Detector at 7 TeV – **Z. Marshall**
  - Recent QCD Results from CMS – **G. Safronov**
  - Recent QCD Results from the Tevatron – **M. Strauss**
  - Status of PDFs from HERA – **S. Glazov**

References

https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults

https://twiki.cern.ch/twiki/bin/view/CMS/PublicPhysicsResults"

http://aliceinfo.cern.ch/Collaboration/Documents/Publications/index.html

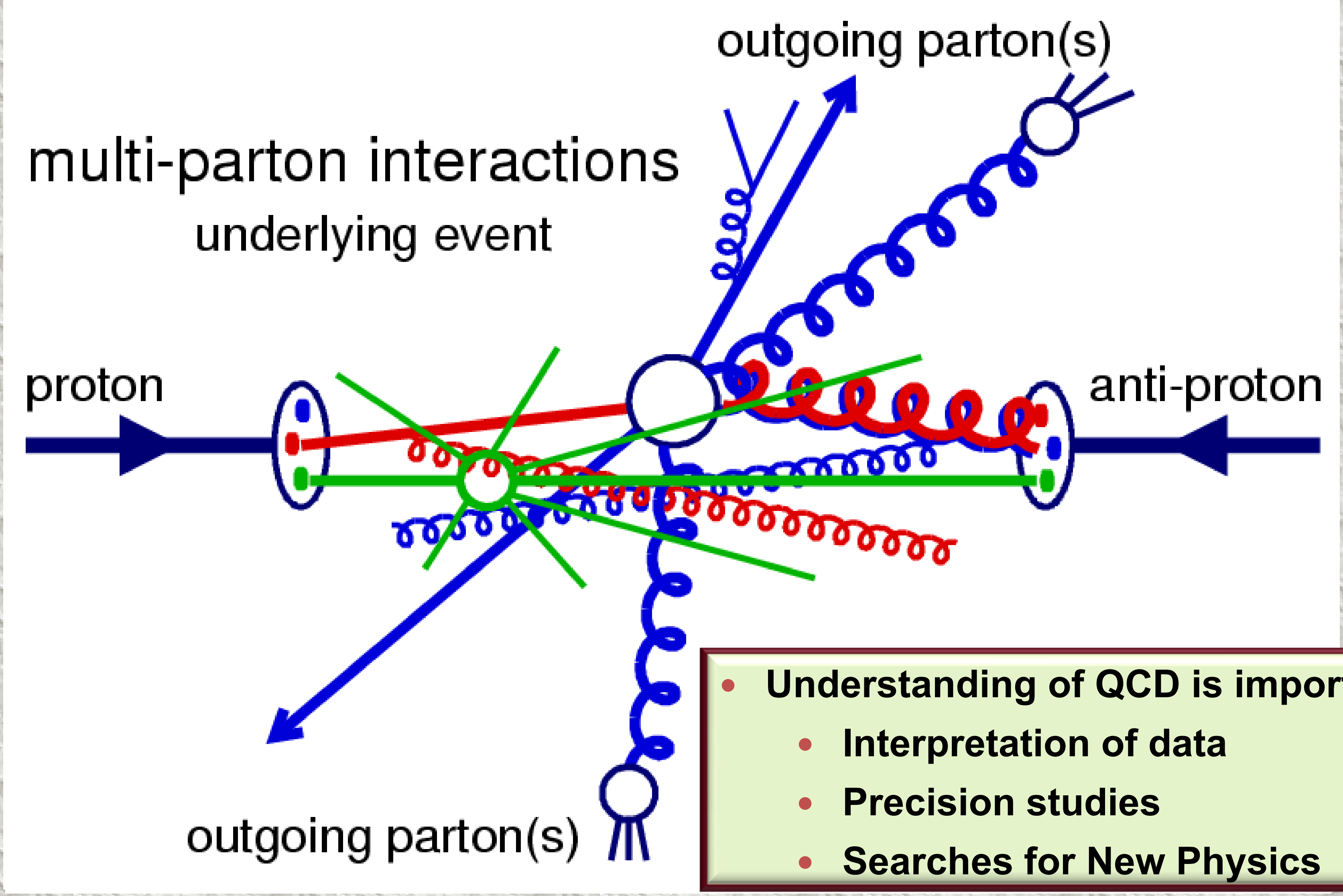
http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm

http://www-zeus.desy.de/publications.php3

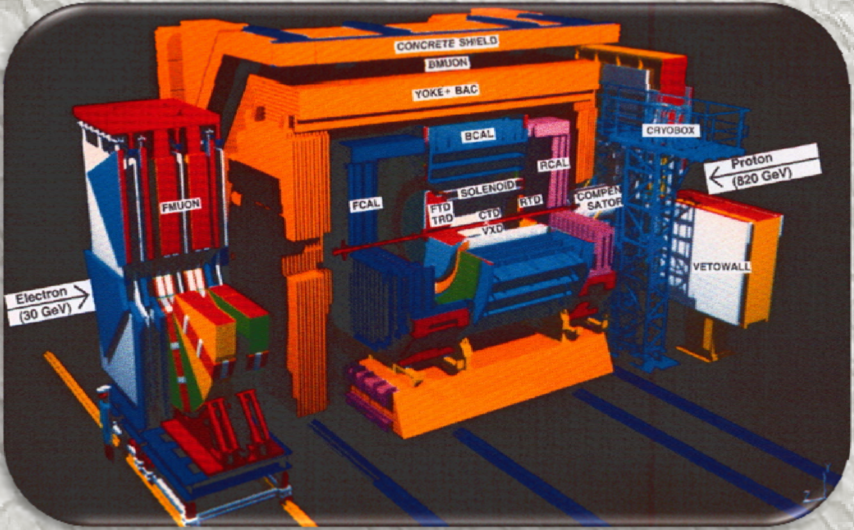
http://www-h1.desy.de/h1/www/publications/H1_sci_results.shtml

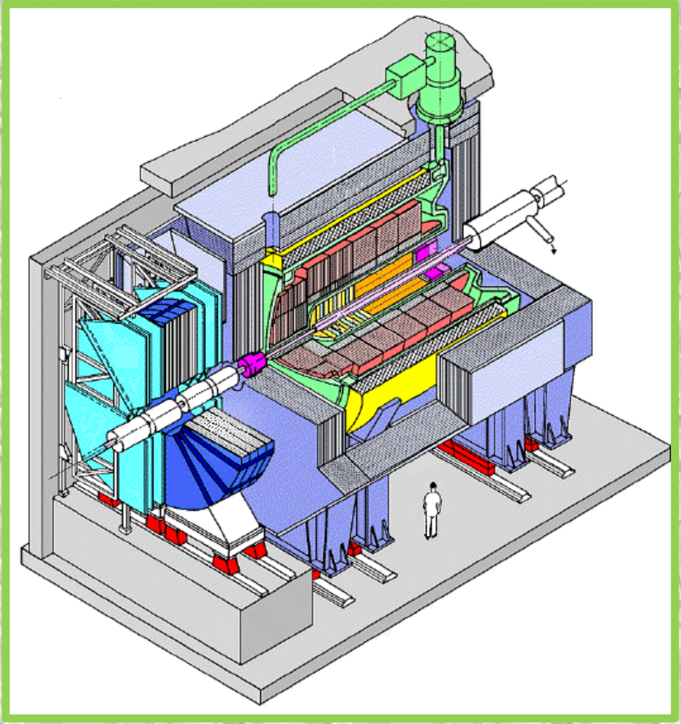
QCD at Hadron Colliders

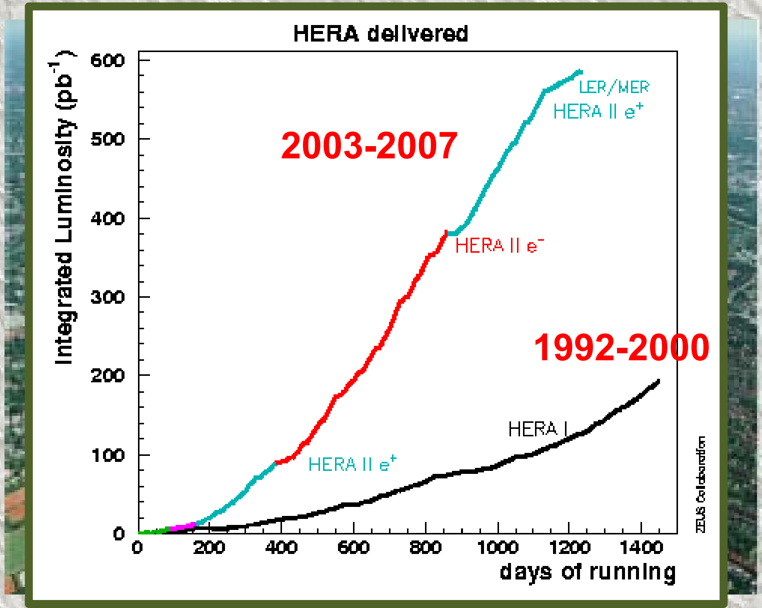


- Understanding of QCD is important for
  - Interpretation of data
  - Precision studies
  - Searches for New Physics

The HERA Experiments

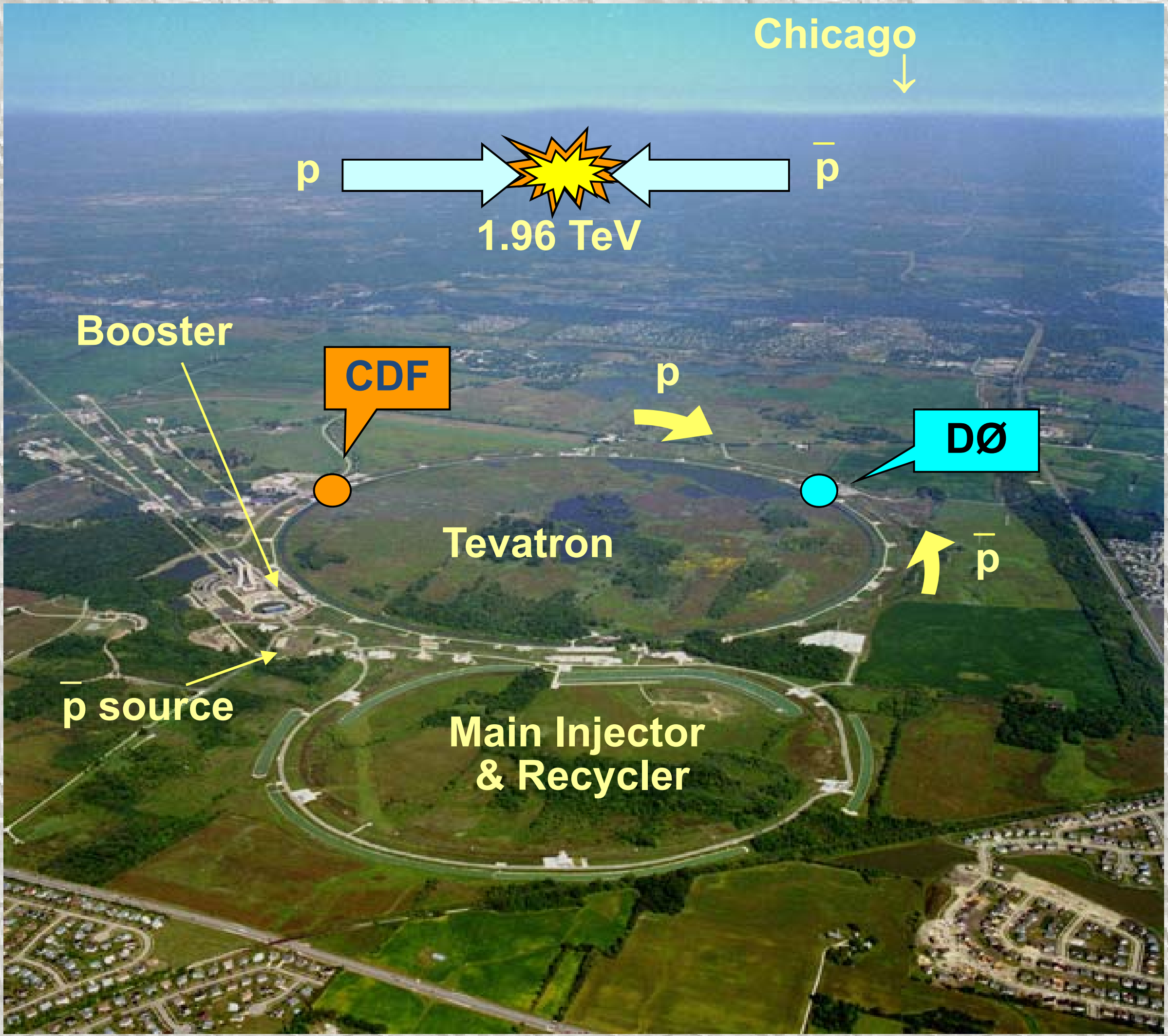






Running Period: 1992 – 2007
p 920(820) GeV
(Low Energy Runs: 575, 460 GeV)
e^+/e^- 27.5 GeV
→ $\sqrt{s}$ = 318 GeV

Tevatron Complex



Run I

1992-1996
$\sqrt{s}$ = 1.8 TeV
~120 pb^{-1}
(0.63 TeV ~600 nb^{-1})

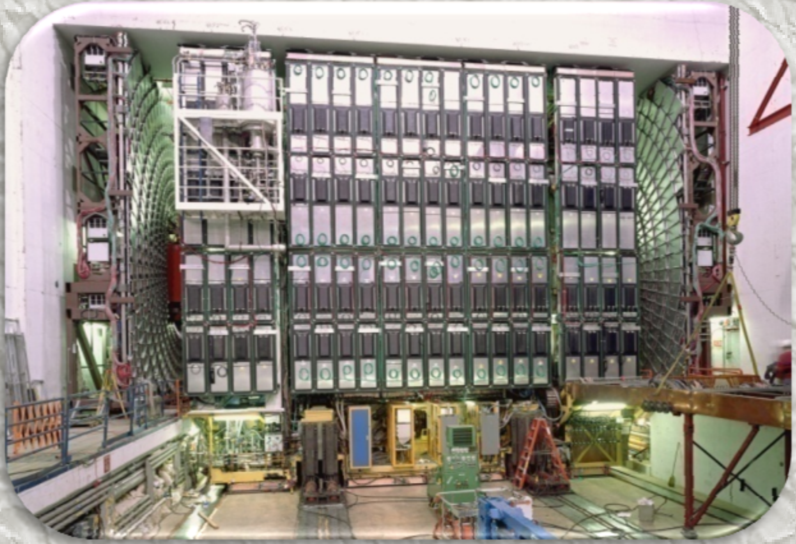
Run IIA

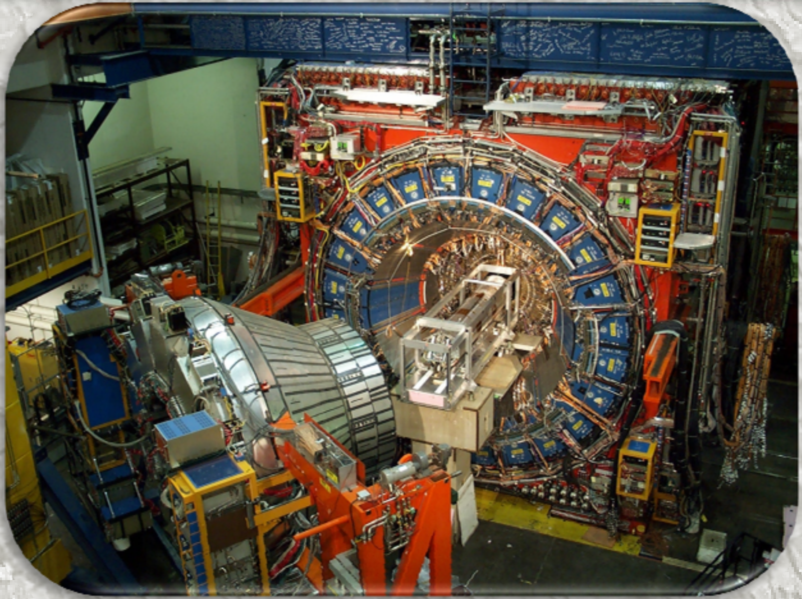
2002-2005
$\sqrt{s}$ = 1.96 TeV
~ 1.5 fb^{-1}

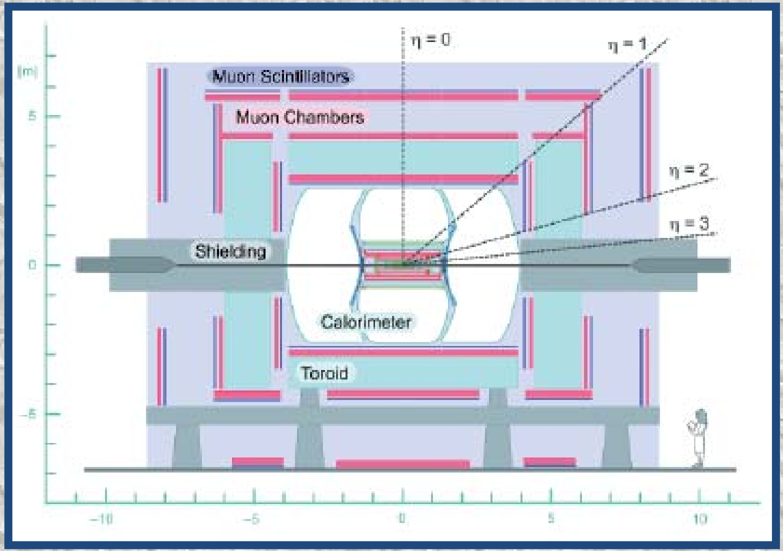
Run IIB

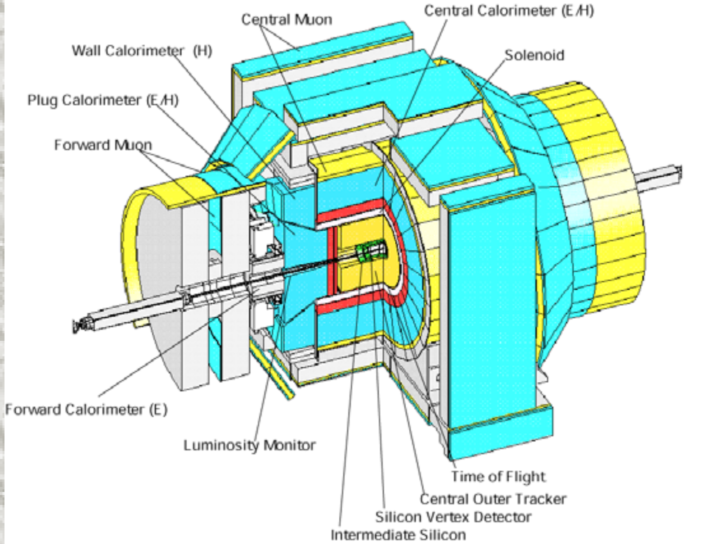
2006-
$\sqrt{s}$ = 1.96 TeV
~ 7.5 fb^{-1}

Tevatron Detectors

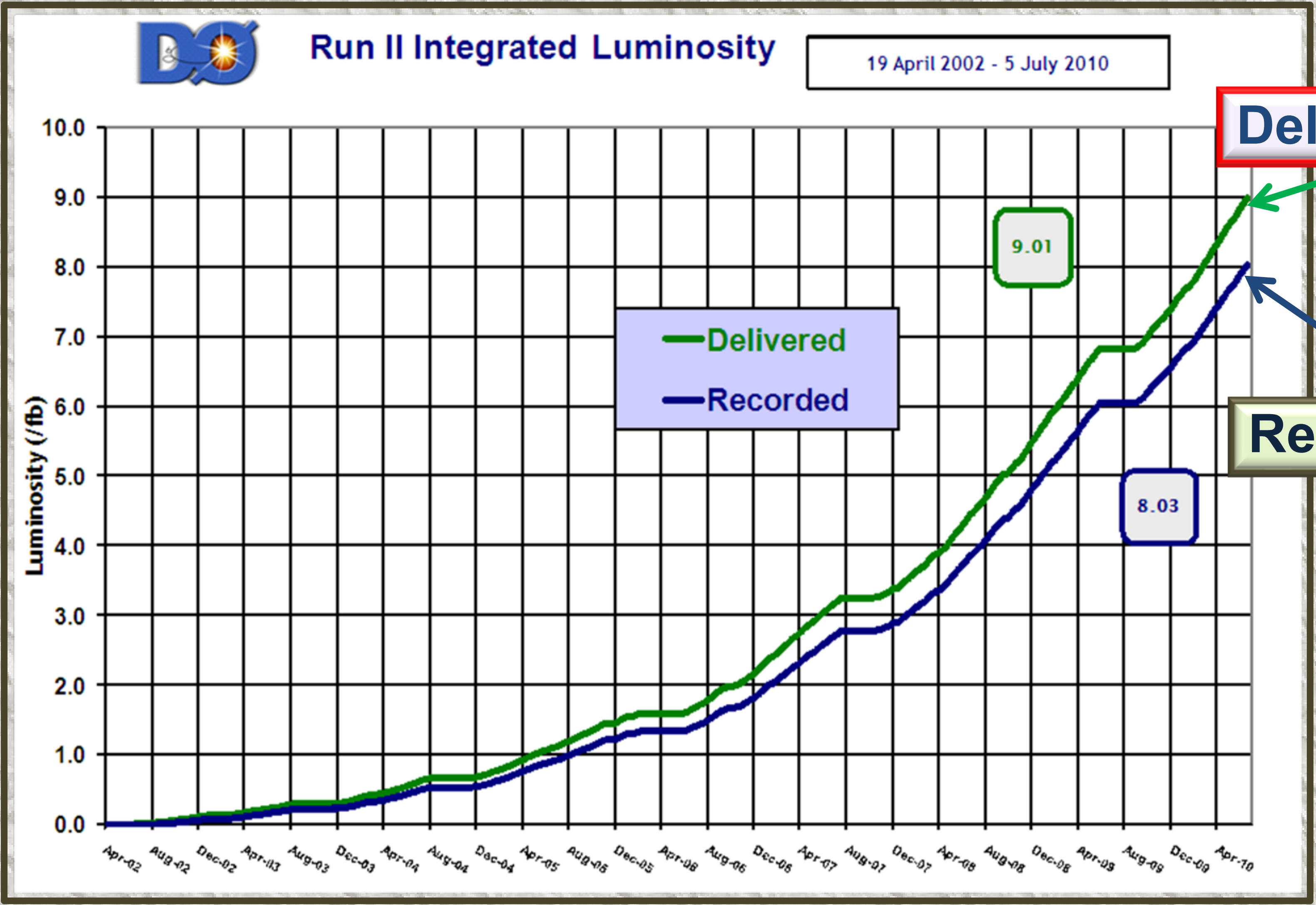








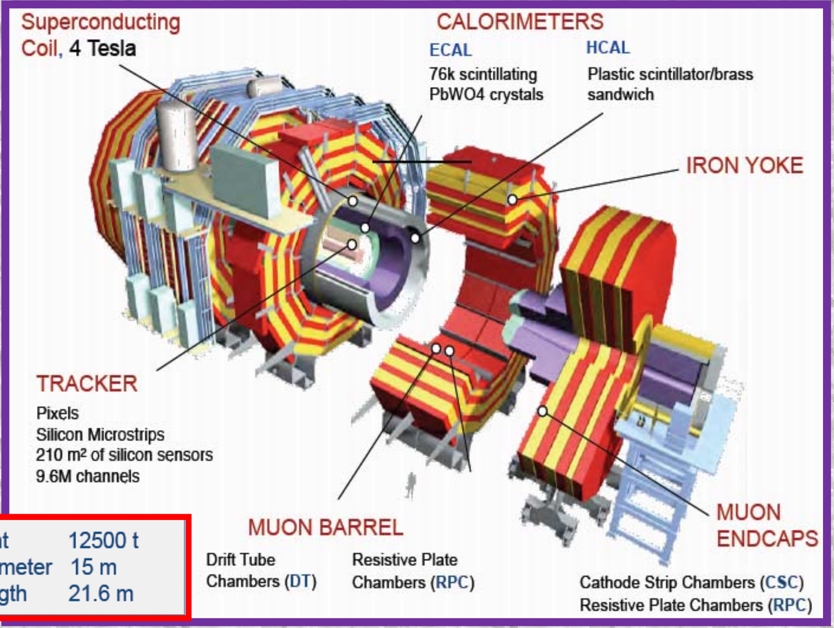
Tevatron Luminosity



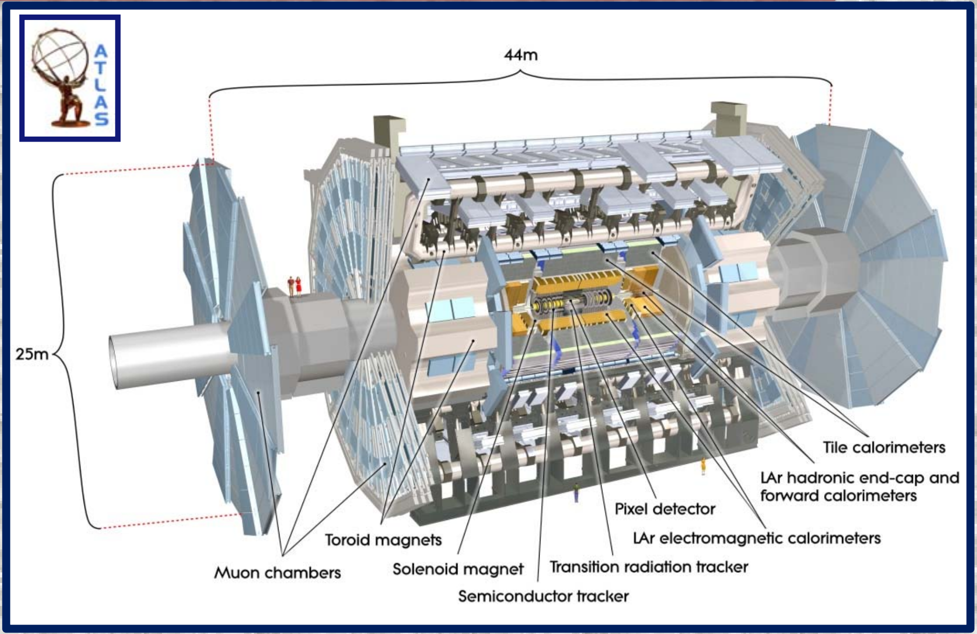
Delivered ~9 fb^{-1}

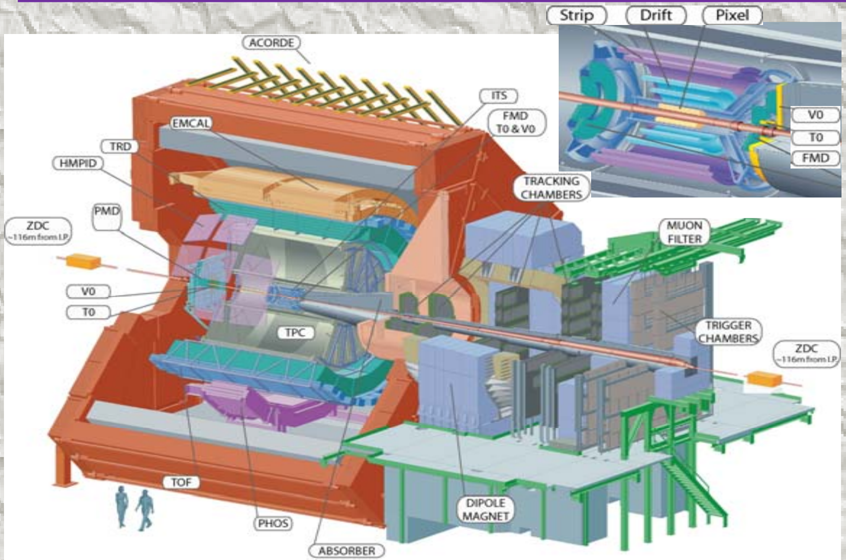
Recorded ~8 fb^{-1}

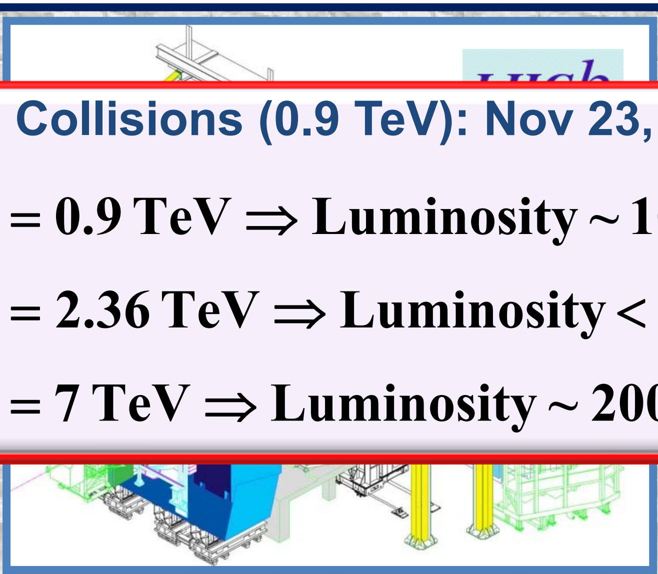
The LHC Experiments



Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m







1st pp Collisions (0.9 TeV): Nov 23, 2009

$$\sqrt{s} = 0.9\,\text{TeV} \Rightarrow \text{Luminosity} \sim 10\ \mu\text{b}^{-1}$$

$$\sqrt{s} = 2.36\,\text{TeV} \Rightarrow \text{Luminosity} < 1\ \mu\text{b}^{-1}$$

$$\sqrt{s} = 7\,\text{TeV} \Rightarrow \text{Luminosity} \sim 200\ \text{nb}^{-1}$$

PDFs

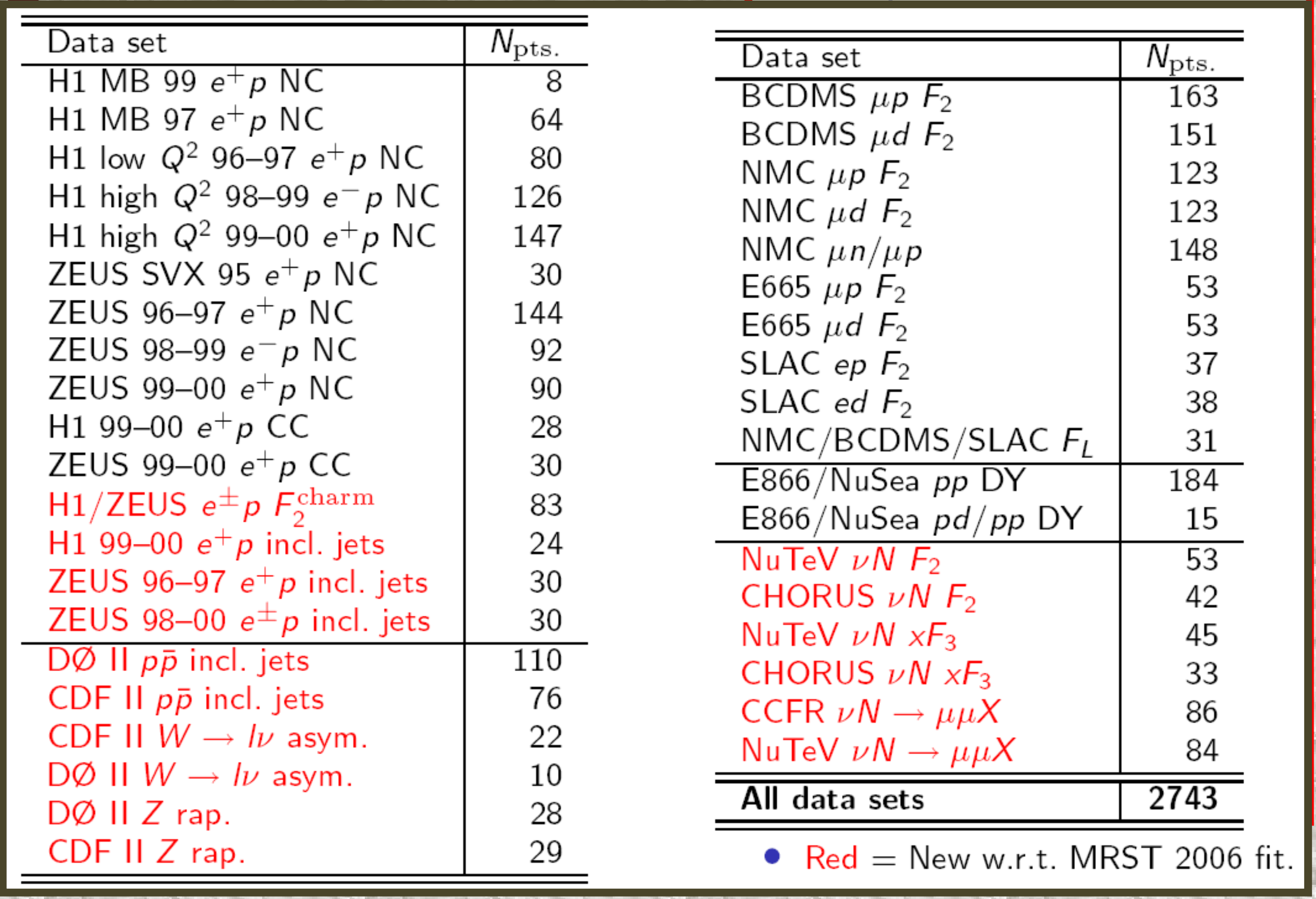
PDFs

$$d\sigma(h_1 h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1, \mu_F^2)\, f_{b/h_2}(x_2, \mu_F^2)\, d\hat{\sigma}^{(ab\to cd)}(Q^2, \mu_F^2)$$

Determine PDFs from global fits to many observables

- **DIS (HERA, fixed tar**
- **Drell-Yan (Tevatron,**
- **Vector boson produc**
- **Jet Production (Teva**
- **Heavy quark produc**

Data used in MRST 2006



Data set	$N_{\rm pts.}$
H1 MB 99 e^+p NC	8
H1 MB 97 e^+p NC	64
H1 low Q^2 96–97 e^+p NC	80
H1 high Q^2 98–99 e^-p NC	126
H1 high Q^2 99–00 e^+p NC	147
ZEUS SVX 95 e^+p NC	30
ZEUS 96–97 e^+p NC	144
ZEUS 98–99 e^-p NC	92
ZEUS 99–00 e^+p NC	90
H1 99–00 e^+p CC	28
ZEUS 99–00 e^+p CC	30
H1/ZEUS $e^\pm p$ $F_2^{\rm charm}$	83
H1 99–00 e^+p incl. jets	24
ZEUS 96–97 e^+p incl. jets	30
ZEUS 98–00 $e^\pm p$ incl. jets	30
DØ II $p\bar{p}$ incl. jets	110
CDF II $p\bar{p}$ incl. jets	76
CDF II $W \to l\nu$ asym.	22
DØ II $W \to l\nu$ asym.	10
DØ II Z rap.	28
CDF II Z rap.	29

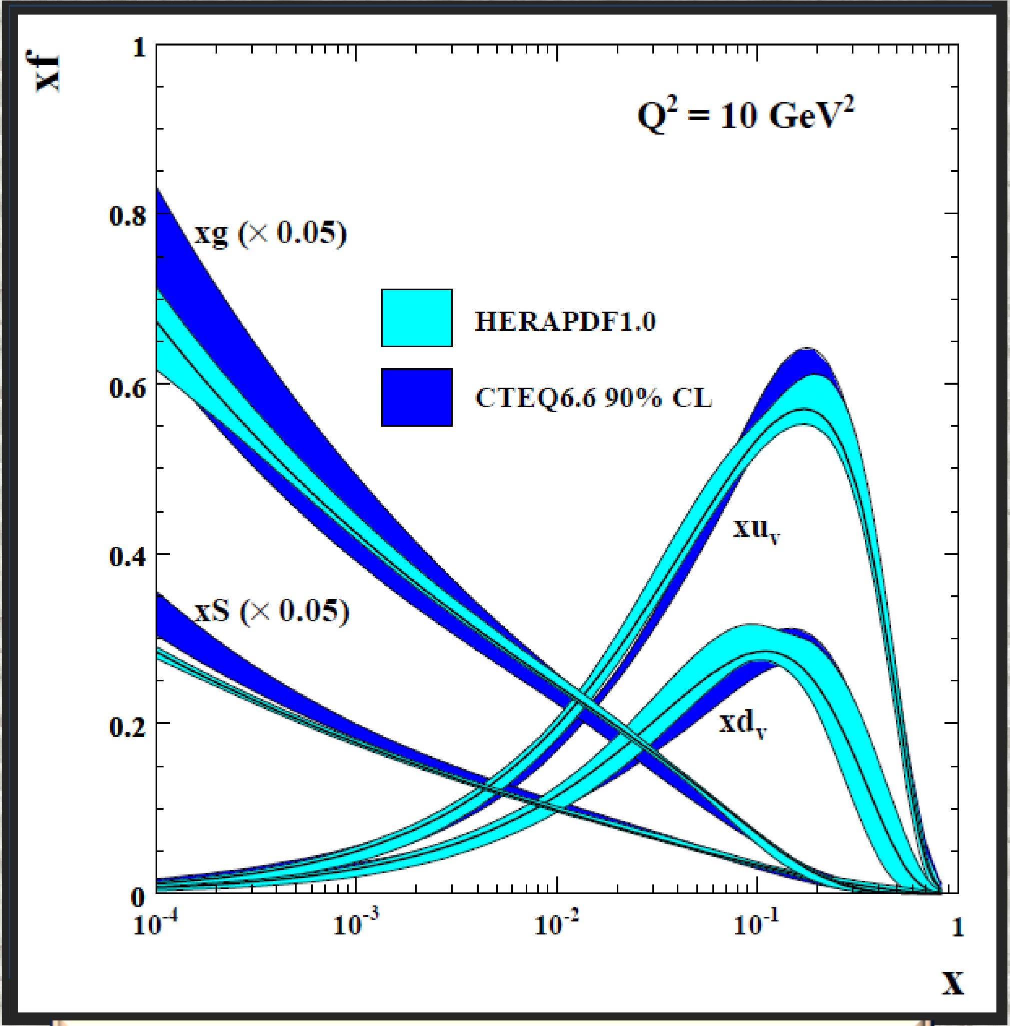
Data set	$N_{\rm pts.}$
BCDMS μp F_2	163
BCDMS μd F_2	151
NMC μp F_2	123
NMC μd F_2	123
NMC $\mu n/\mu p$	148
E665 μp F_2	53
E665 μd F_2	53
SLAC ep F_2	37
SLAC ed F_2	38
NMC/BCDMS/SLAC F_L	31
E866/NuSea pp DY	184
E866/NuSea pd/pp DY	15
NuTeV νN F_2	53
CHORUS νN F_2	42
NuTeV νN xF_3	45
CHORUS νN xF_3	33
CCFR $\nu N \to \mu\mu X$	86
NuTeV $\nu N \to \mu\mu X$	84
All data sets	**2743**

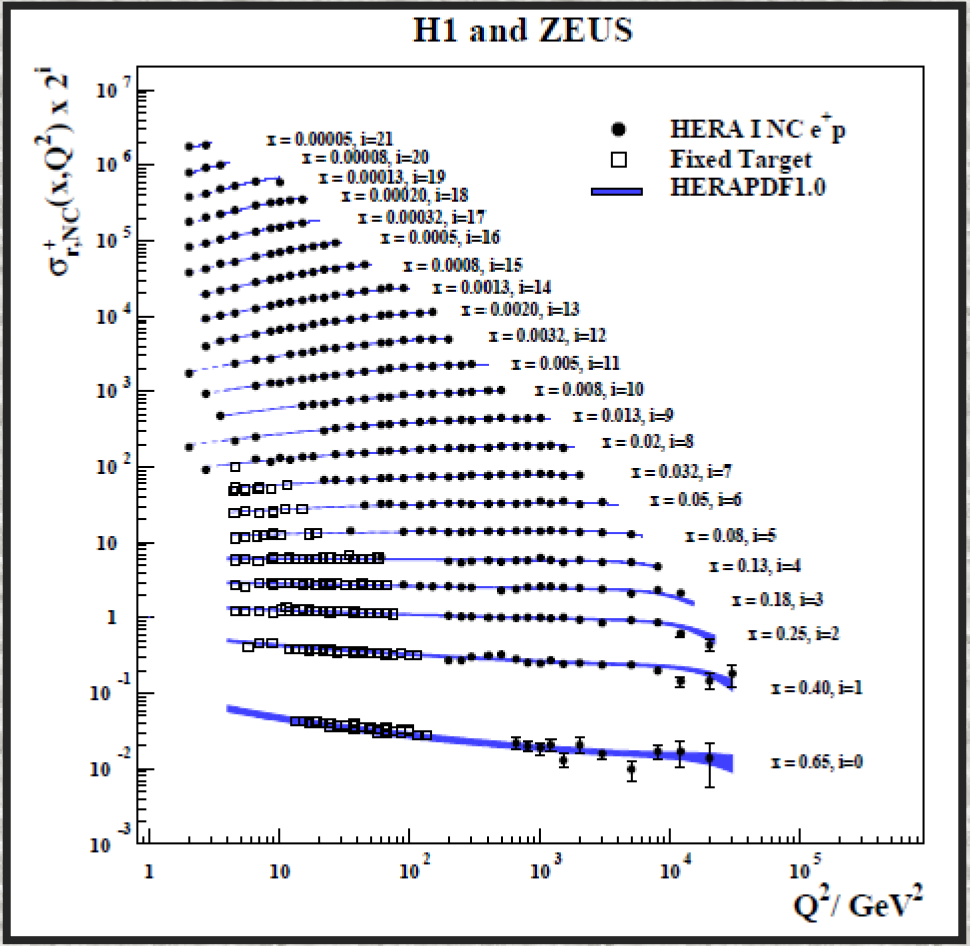
- Red = New w.r.t. MRST 2006 fit.

PDF Global Fits

- MSTW: (DIS+DY+jets, LO/NLO/NNLO) (Martin, Stirling, Thorne, Watt)
  - MRS→…→MSTW2008
  - http://projects.hepforge.org/mstwpdf/ arXiv: 0901.002
- CTEQ: (DIS+DY+jets, LO/NLO) (Pumplin, Huston, Lai, Nadolsky, Tung, Yuan)
  - CTEQ→…→CTEQ6.6→CT10 (to be released)
  - http://www.phys.psu.edu/~cteq/#PDFs arXiv: 0802.0007
- NNPDF: (DIS+DY+jets, NLO) (Ball, Del Debbio, Forte, Guffanti, Latorre, Rojo, Ubiali)
  - NNPDF1.0→…→NNPDF2.0
  - http://sophia.ecm.ub.es/nnpdf/ arXiv: 1002.4407
- JR: (DIS+DY, NLO/NNLO) (Jiminez-Delgado, Reya)
  - http://durpdg.dur.ac.uk/hepdata/grv.html arXiv: 0810.4274
- ABKM: (DIS+DY, NLO/NNLO) (Alekhin, Blümlein, Klein, Moch) arXiv:0908.2766
- HERAPDF: (DIS, NLO)
  - http://www-h1.desy.de/ arXiv: 0911.0884

ZEUS-H1 Combined Results





Combined H1-ZEUS data reduce uncertainties

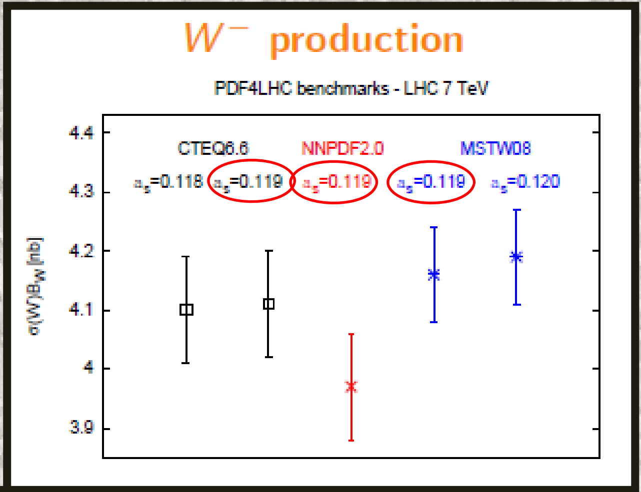
Combined H1-ZEUS inclusive data HERAPDF fits work well

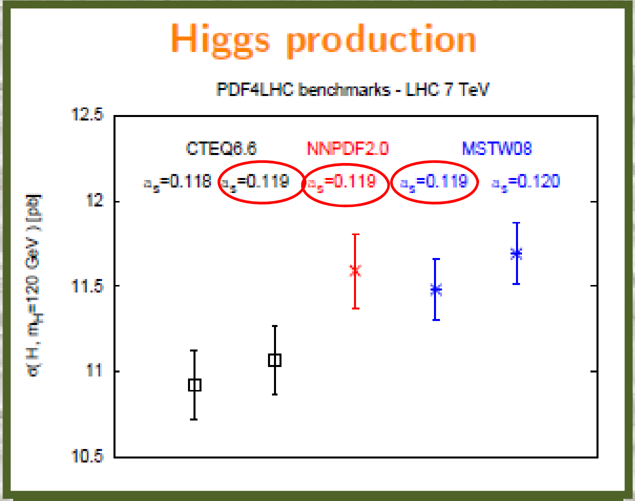
H1 & ZEUS: JHEP 1001:109 (2010)

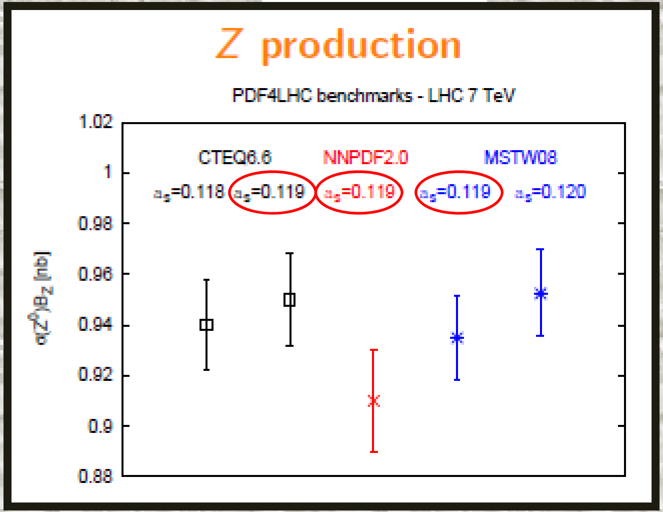
LHC Standard Candles

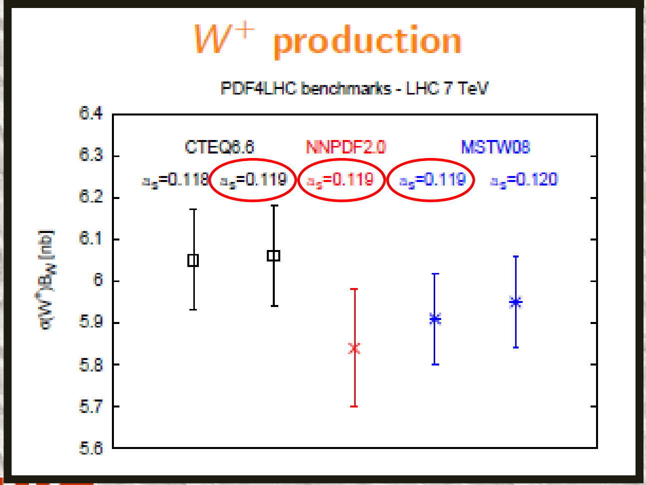
- **Different values of $\alpha_s(M_Z)$ and its uncertainties are used in PDF fits**
  - **CTEQ used 0.118 and NNPDF 0.119, where MSTW2008 uses 0.12 as determined by their best fit**
  - **PDG value: $\alpha_s(M_Z)$ = 0.1184   0.0007**
- **Evaluate LHC standard candles with same value of α_s**

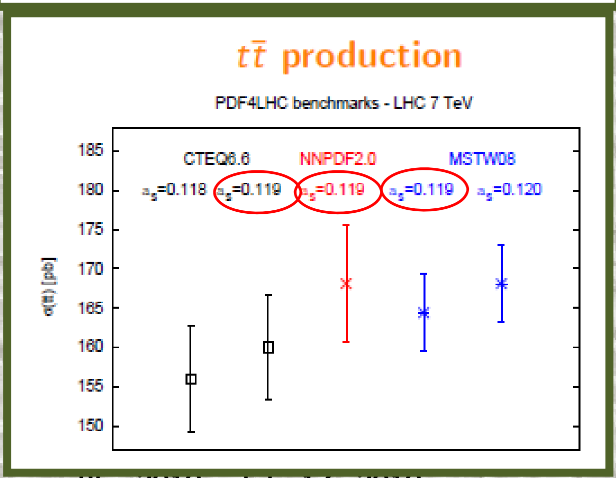
Maria Ubiali DIS 2010









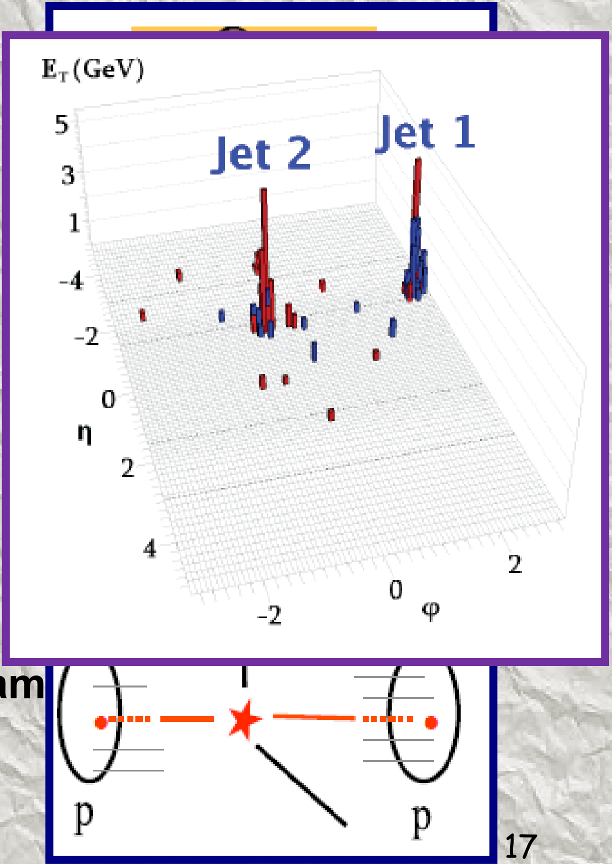


Reasonable agreement among the PDF groups

Jet Production

Jet Reconstruction

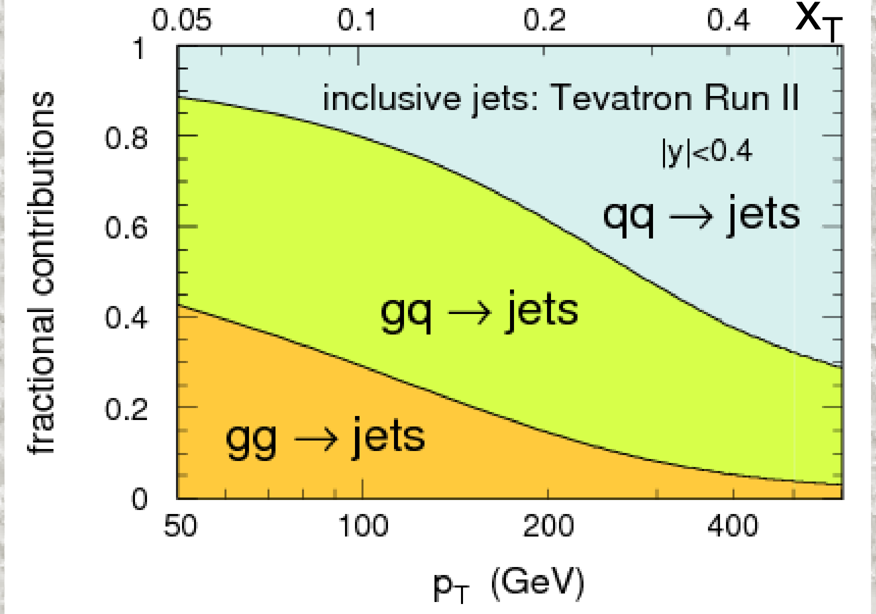
- **Inputs:**
  - Calorimeter Jets
    - Clustering of energy depositions
    - EM+HAD towers
    - Use of topological energy clusters in finely segmented calorimeter
  - Track Jets
    - Clustering of tracks
    - Sampling only charged particles
  - Particle Flow (PFlow)
    - Clustering of tracks, photons, and neutral hadrons
  - JetPlusTrack
    - Calorimeter jets with energy corrections based on tracks
- **Clustering algorithms:**
  - Cone algorithms:
    - Iterative Cone/JetClu
    - Midpoint
    - Seedless Infrared Safe Cone (SISCone)
  - Recombination algorithms: $d_{ii} = p_{T,i}^{2p}$ $d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{D^2}$
    - p=1 → k_T jet algorithm
    - p=0 → Cambridge/Aachen jet algorithm
    - p=-1 → “Anti-k_T” jet algorithm
      - Soft particles will first cluster with hard particles before am
      - Almost a cone jet near hard partons
      - No merge/split

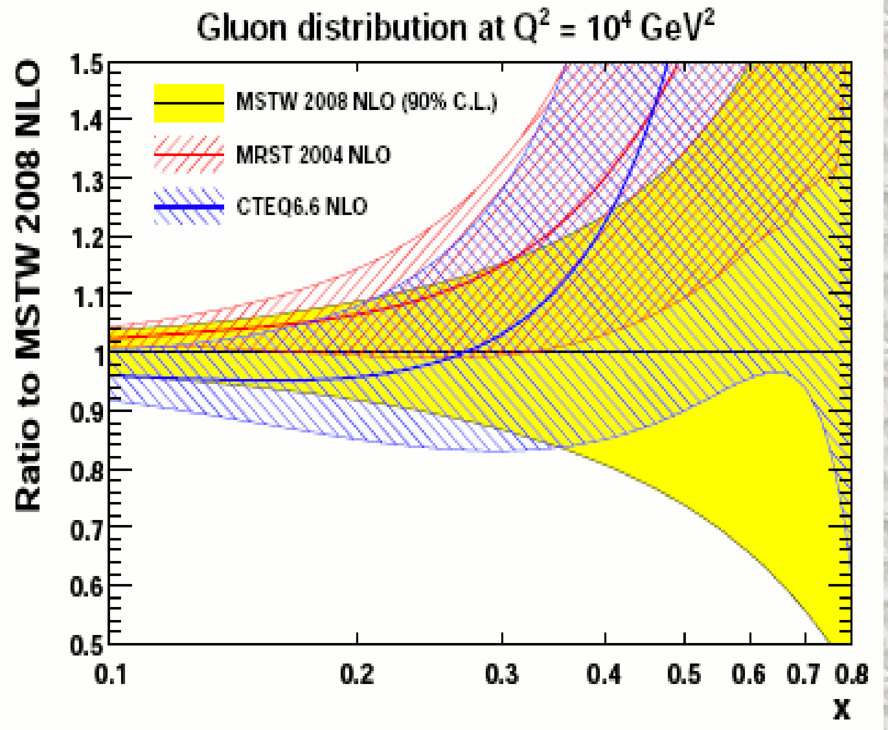


Jet Production at Tevatron

- Confront pQCD calculations
  - NLO predictions reliable @ 15% level
- Sensitive to dynamics, PDFs, α_s
  - Reach to high-x gluons

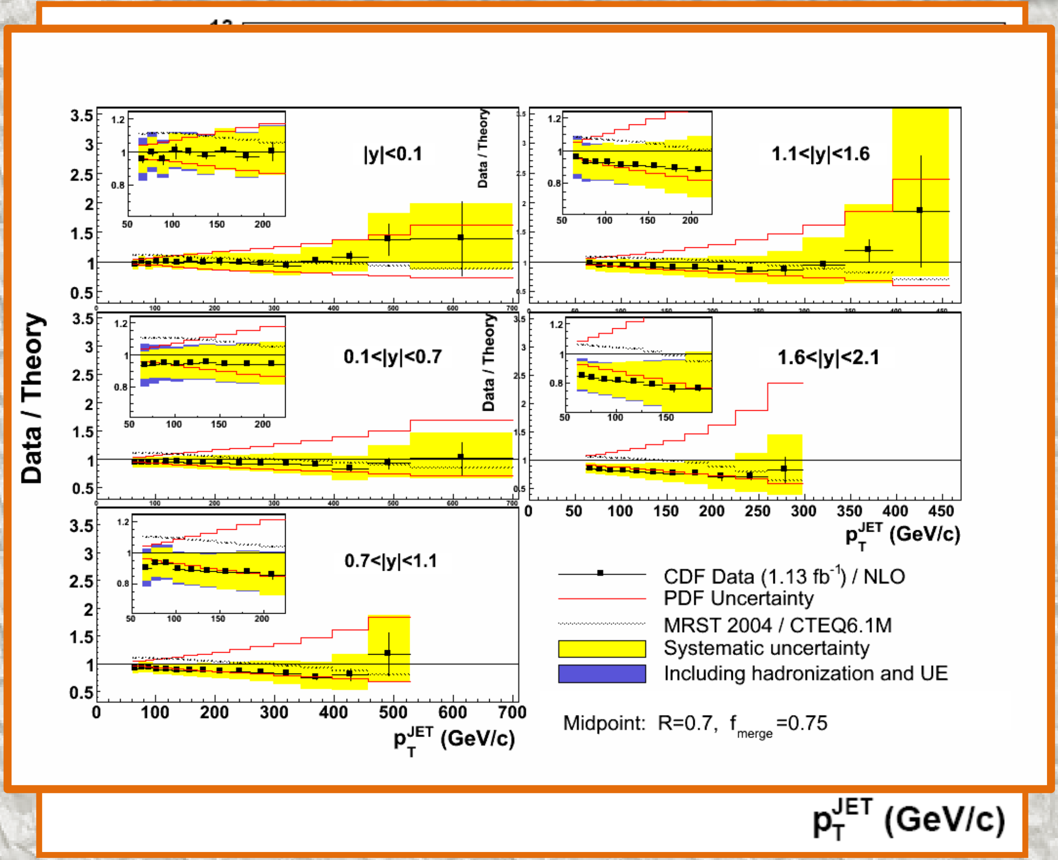
Large kinematic reach

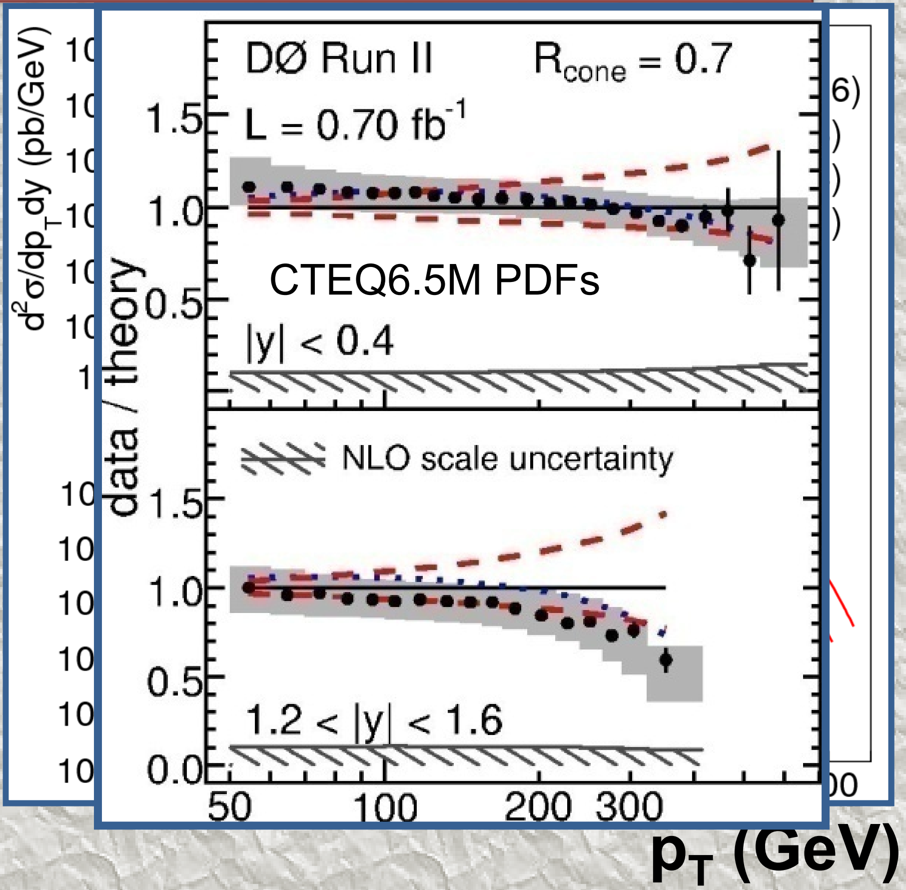




- Sensitivity to new physics (e.g., quark substructure, new particles decaying into jet final states, extra dimensions, ...)

Inclusive Jet Cross Section





steeply falling pT spectrum:

1% error in jet energy calibration

→ 5—10% (10—25%)

central (forward) x-section

Provide Input to PDF:

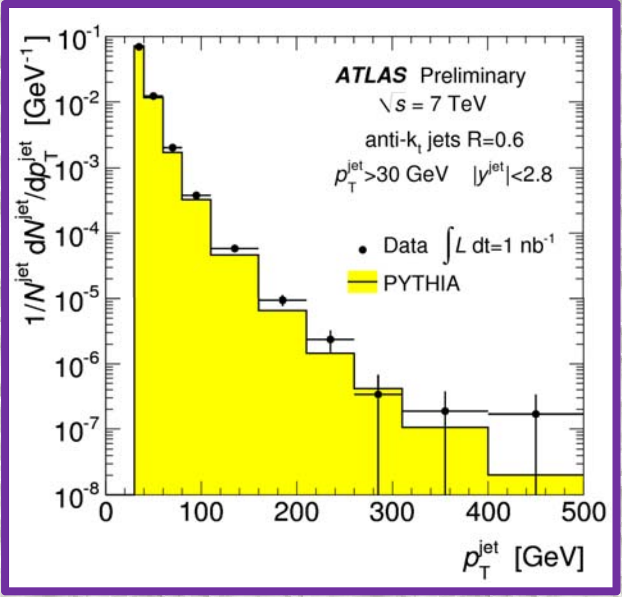
MSTW2008 uses CDF and DØ results

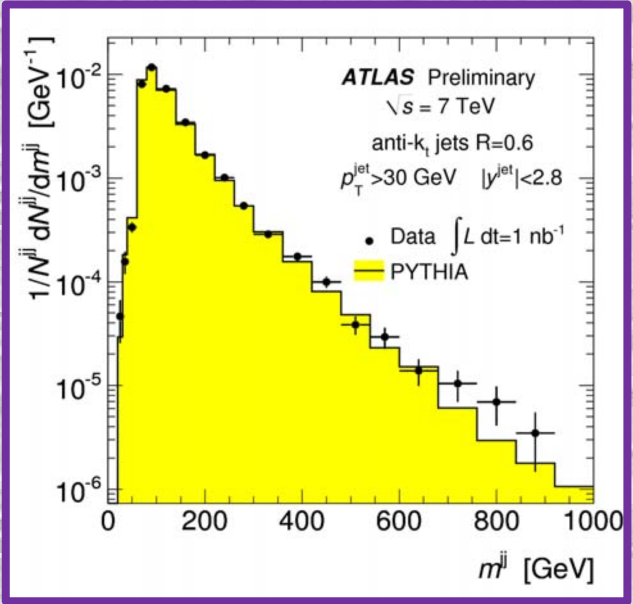
Data prefer lower gluon PDF at high-x

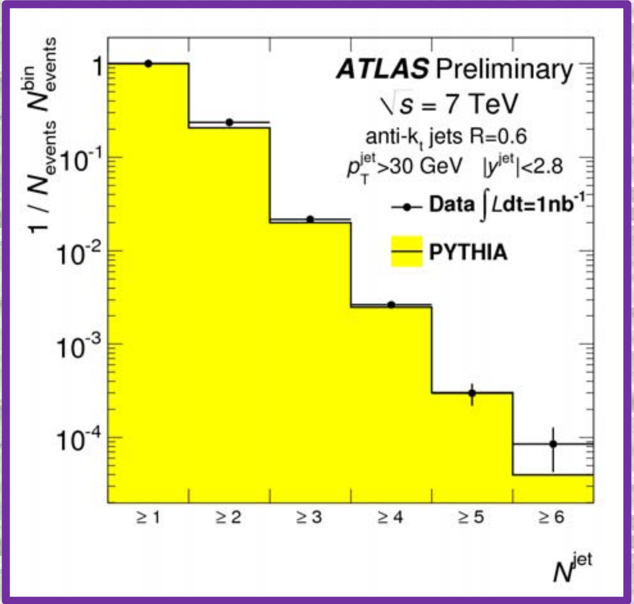
CDF: PRD 78, 052006 (2008)

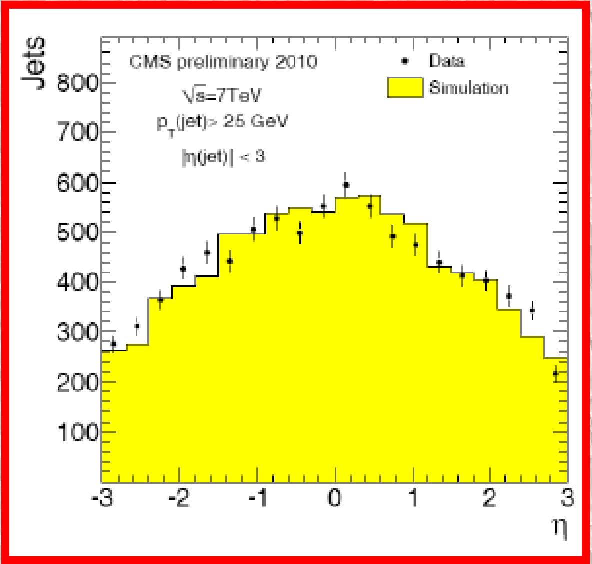
DØ: PRL 101, 062001 (2008)

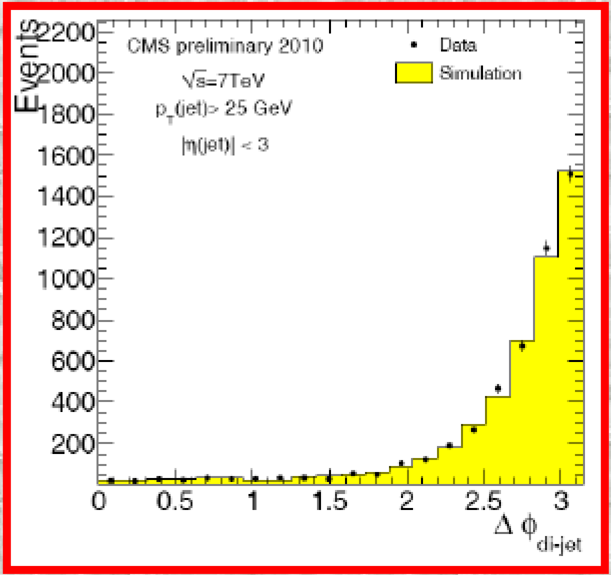
Jet Commissioning at LHC







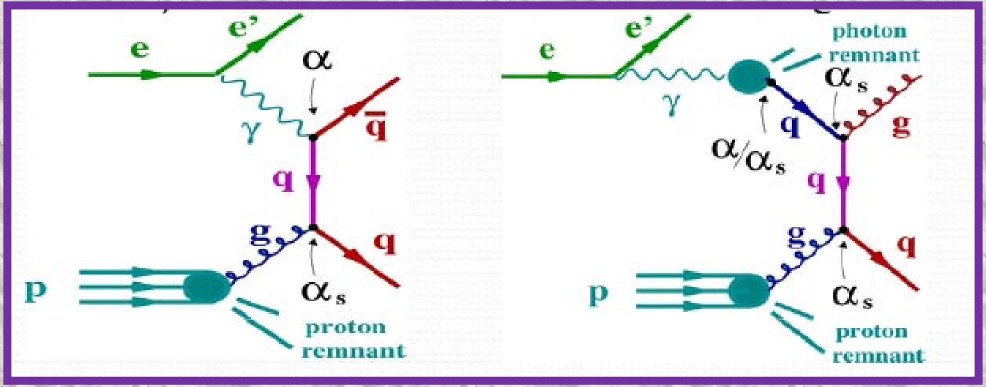




- Jets reconstructed with anti-k_T clustering algorithm
- Reach of M_{jj} ~ 0.8 TeV with 1 nb^{-1} of data

Jet Production in DIS (HERA)

- Confront pQCD
  - Extraction of $\alpha_s(M_Z)$ and test of running of α_s
  - Constraints on proton + photon PDFs
- Photoproduction of jets
  - $Q^2 < 1$ GeV^2 – photon virtuality



- Jet production in NC DIS

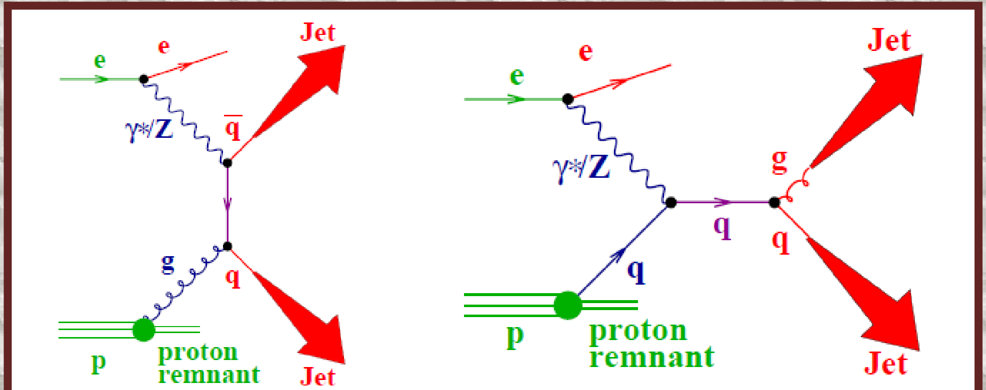
$$d\sigma_{\text{jet}} = \sum_{a=q,\bar{q},g} \int dx\, f_a(x,\mu_F)\, d\hat{\sigma}_a(x,\alpha_s(\mu_R),\mu_R,\mu_F)$$

Kinematics:

- momentum transfer:

  $Q^2 = -q^2 = -(k-k')^2$
- Bjorken x: $x = \frac{Q^2}{2P\cdot q}$
- inelasticity:

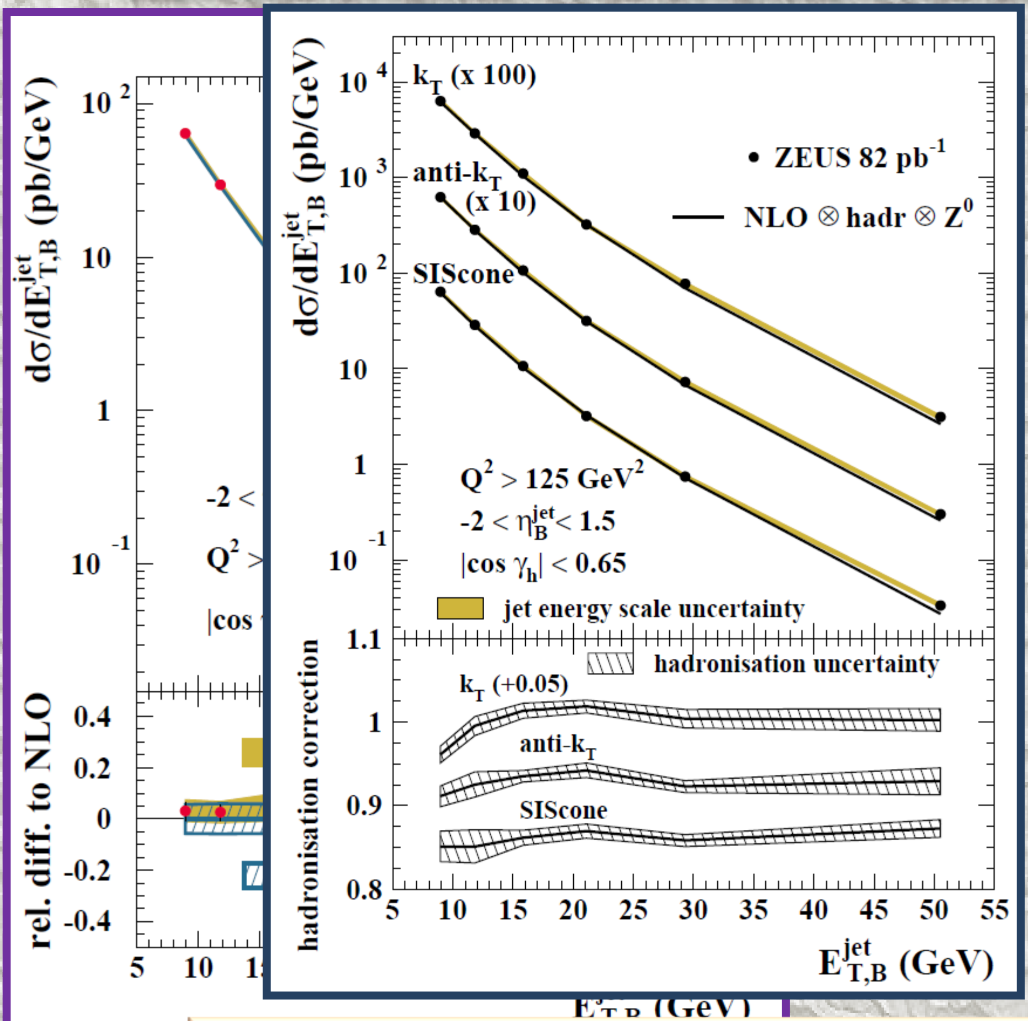
  $y = \frac{P\cdot q}{P\cdot k} = 1 - \frac{E'_e(1-\cos\theta_e)}{2E_e}$

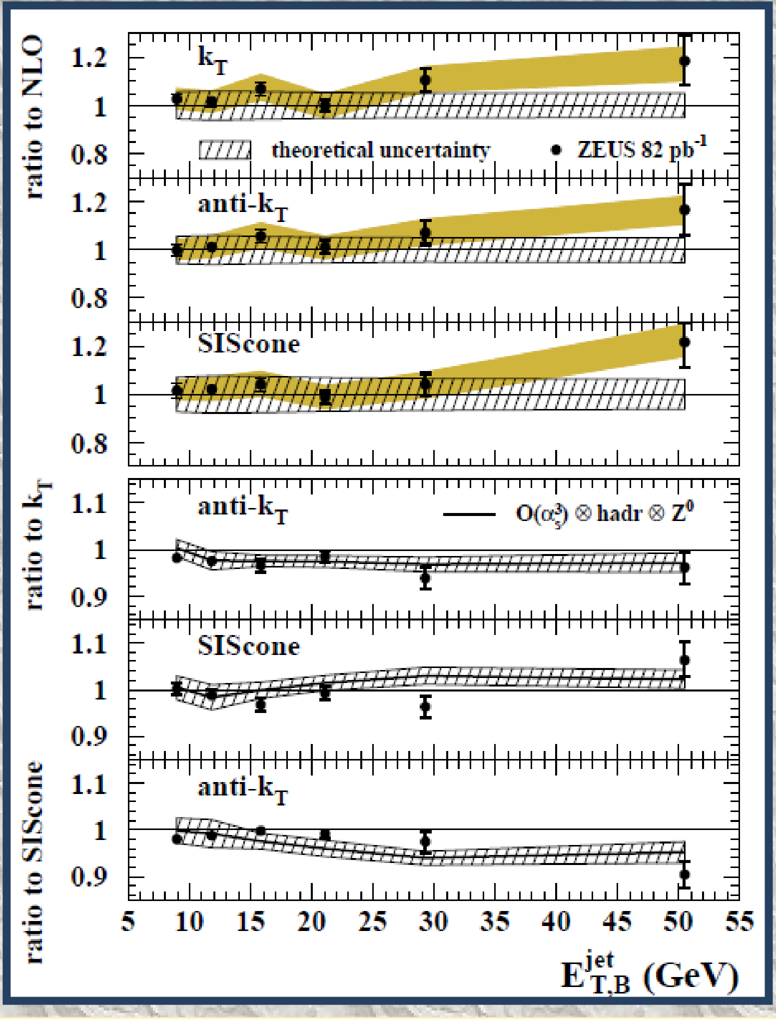


Boson-gluon fusion

QCD Compton

Jet Cross Sections in NC DIS





Good ag

Larger hadronization corrections for SISCone than anti-k$_T$ (similar to k$_T$)
Similar shape and normalization between data and theory for the 3 algos

ZEUS: DESY-10-034

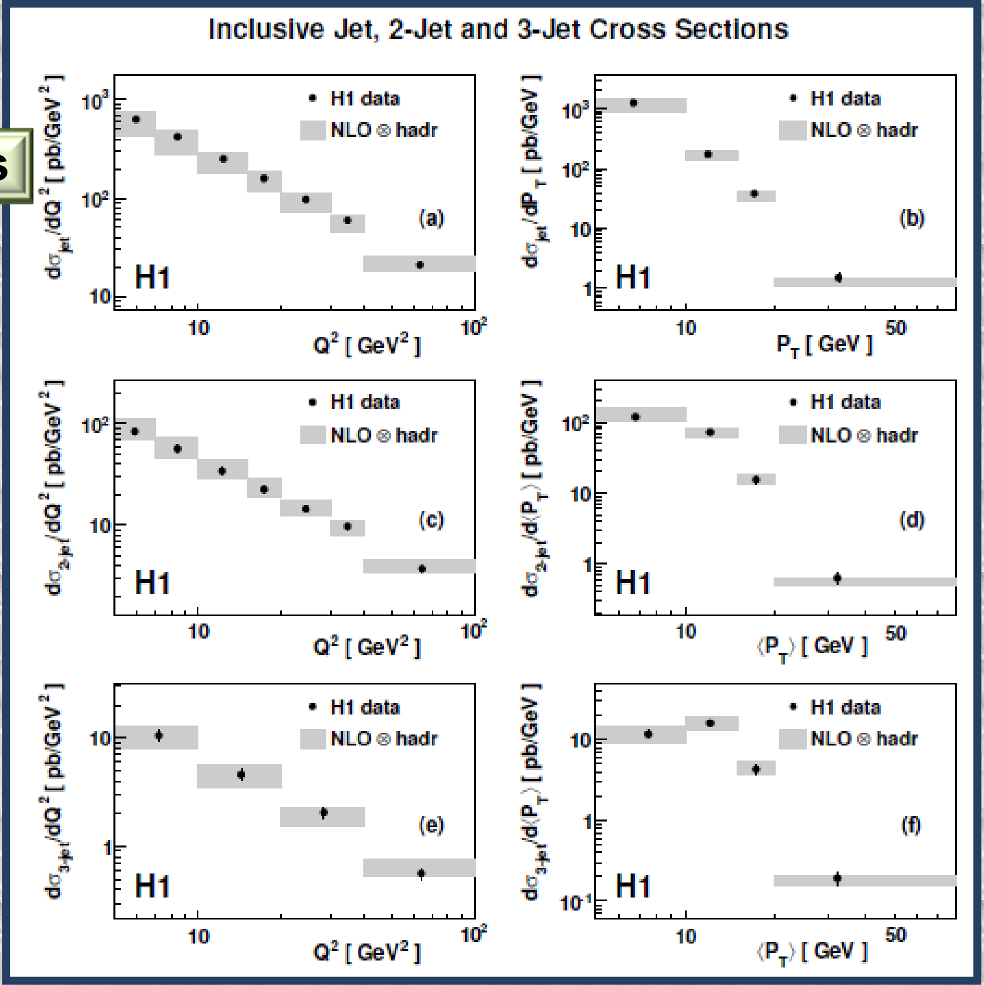
The Strong Coupling Constant

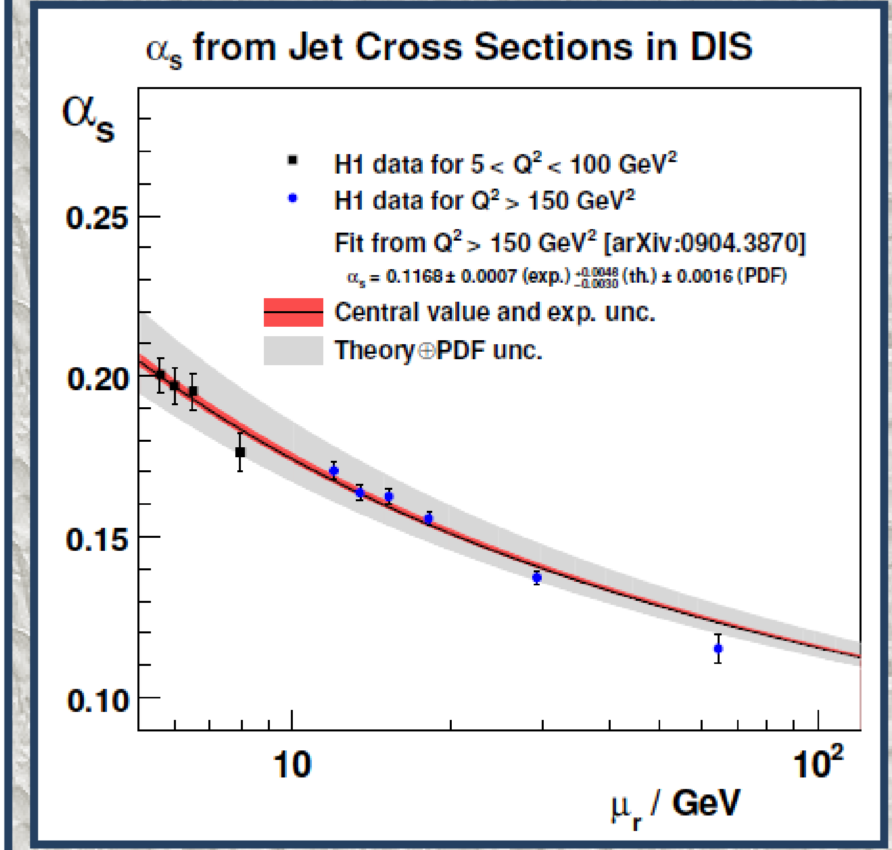
- **Inclusive jet, 2- and 3-jet cross sections are used to derive α_s**
  - **Use of $5 < Q^2 < 100$ GeV^2 and $Q^2 > 150$ GeV^2**

Incl. jets

2 jets

3 jets



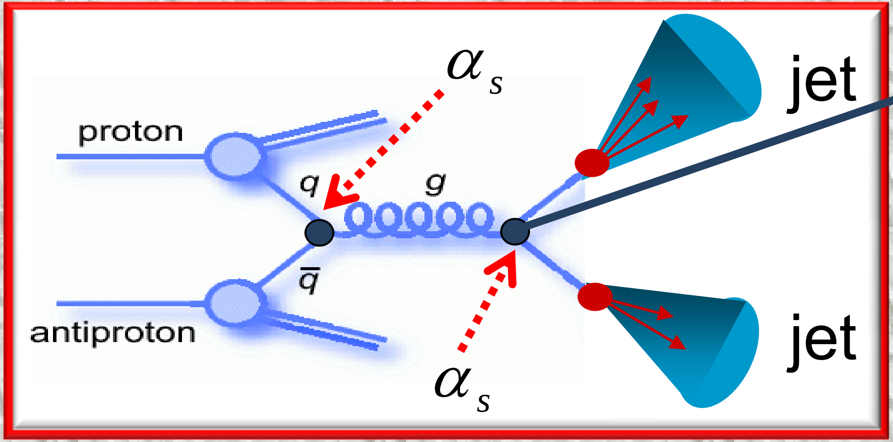


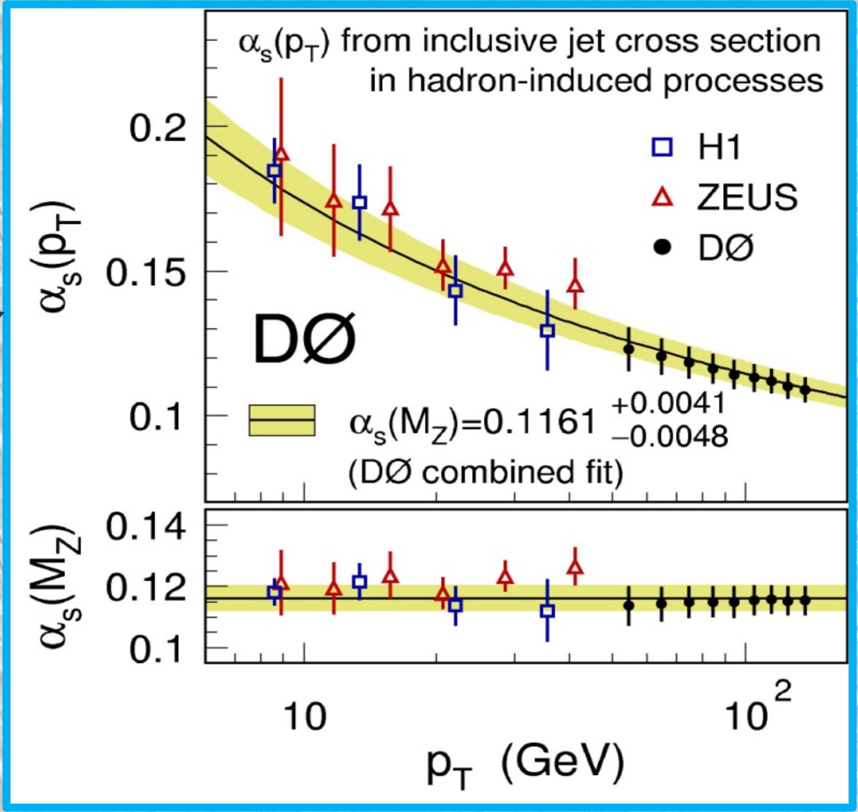
EPJ C67, 1 (2010)
EPJ C65, 363 (2010)

α_s Determination at Tevatron

- **Inclusive jet cross section is sensitive to α_s**
  - α_s is determined from 22 inclusive cross section data points at the range $50<p_T<145$ GeV
  - MSTW2008NNLO PDFs
- **Most precise determination of α_s from a hadron collider**

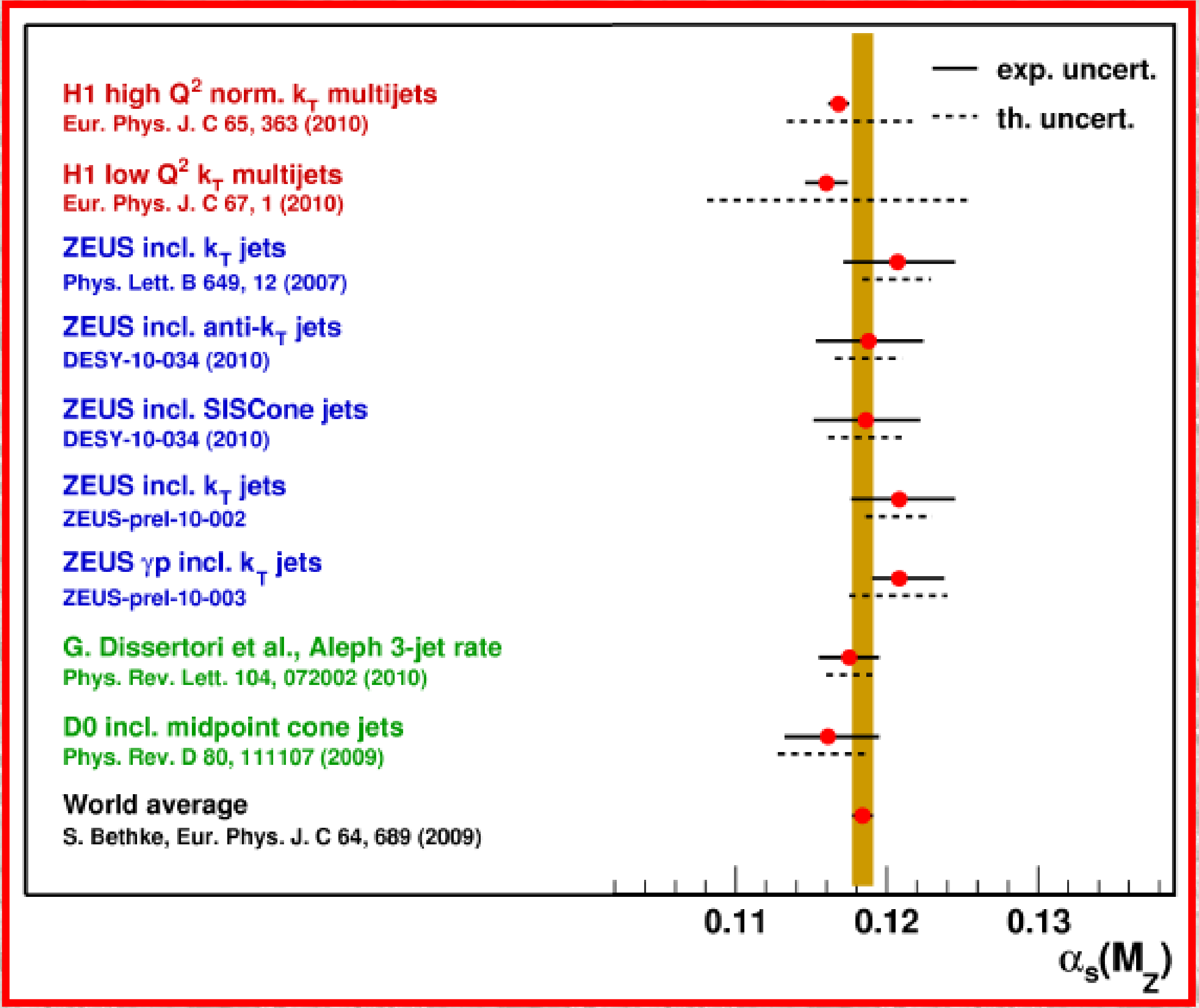
$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$





PRL 101, 062001 (2008)

α_s Summary

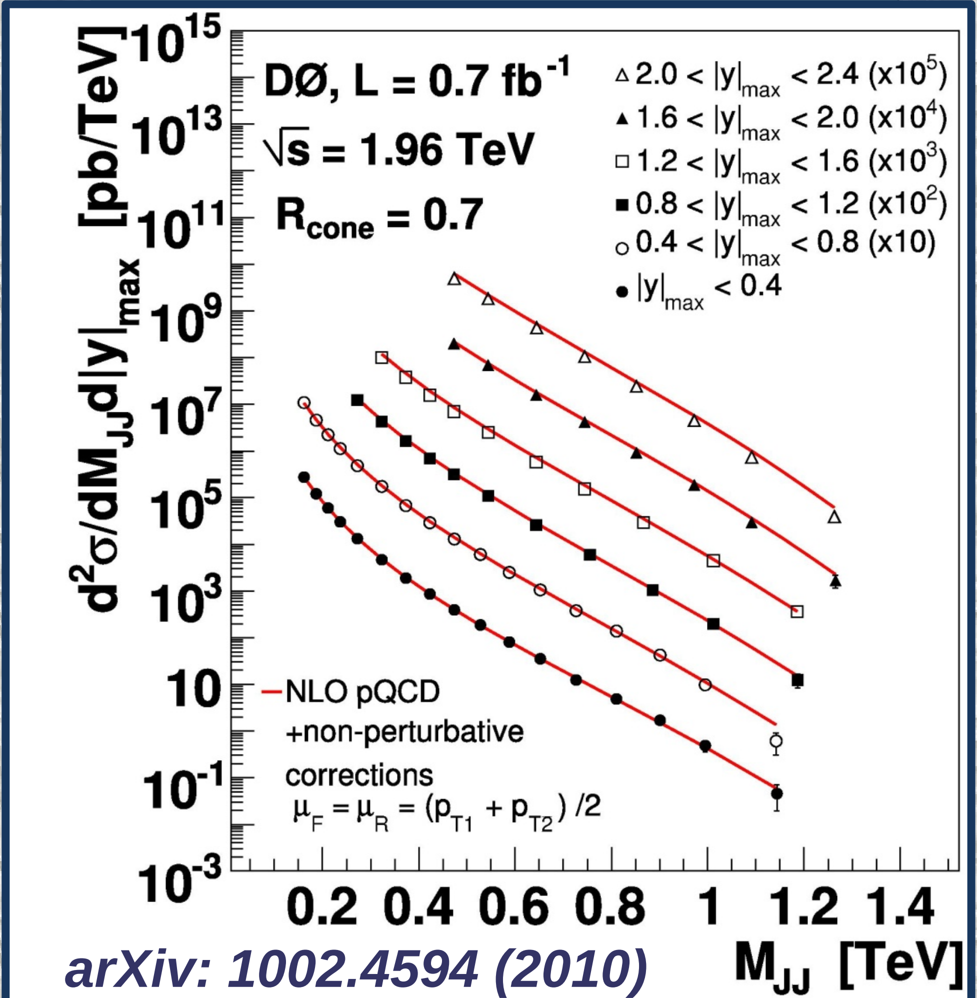


Consistent results from many processes

Katharina Müller, QCD2010

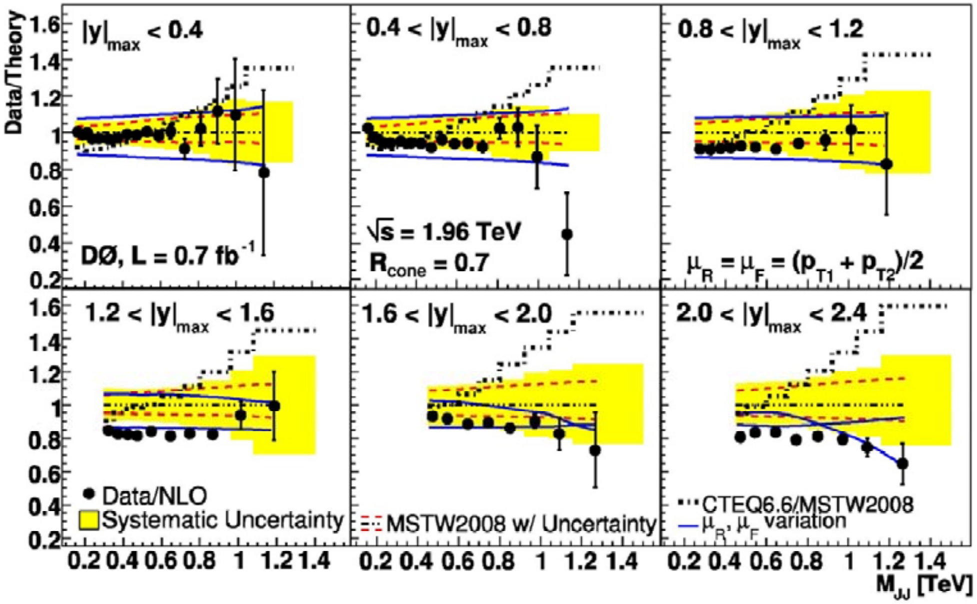
Dijet Mass Cross Sections

Unfolded Cross Sections

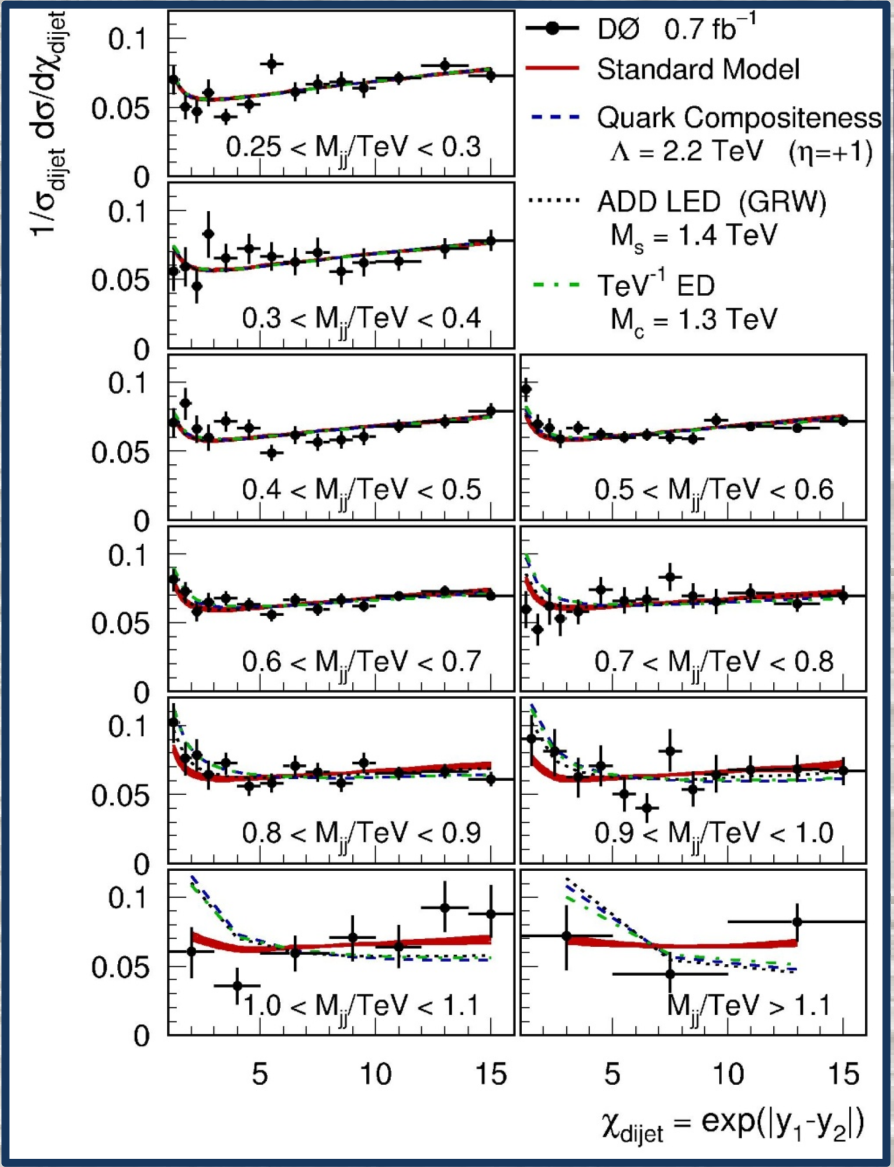


arXiv: 1002.4594 (2010)
Submitted to Phys. Lett. B

- Measurement in six $|y|_{max}$ regions
- Jet Energy Scale is the leading source of data systematic uncertainty
- NLO+MSTW2008 consistent w/ data
  - 5-15% uncertainty
  - 10-15% $\mu_{R,F}$ variation

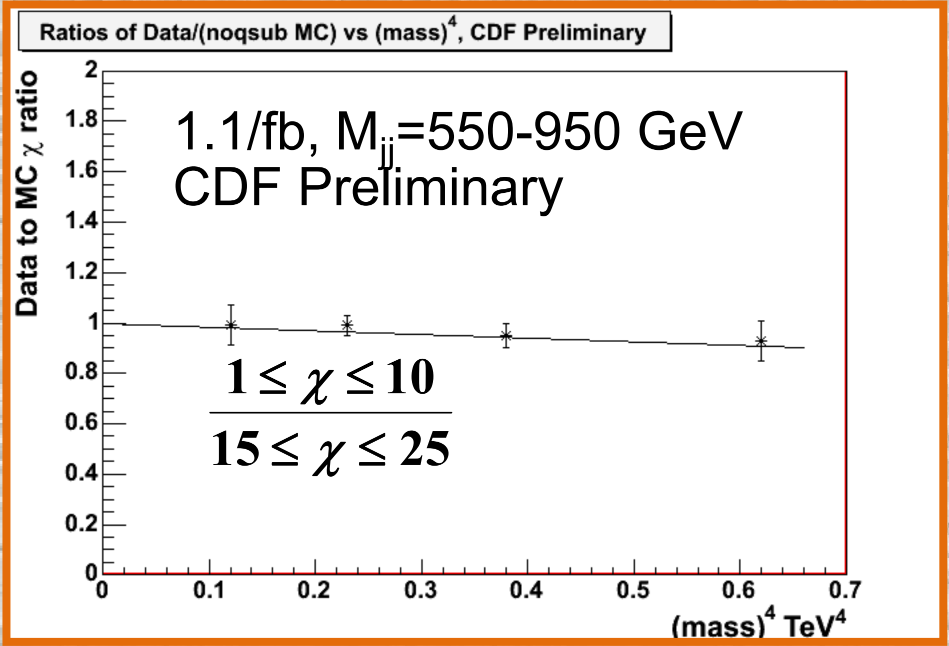


Dijet Angular: Results



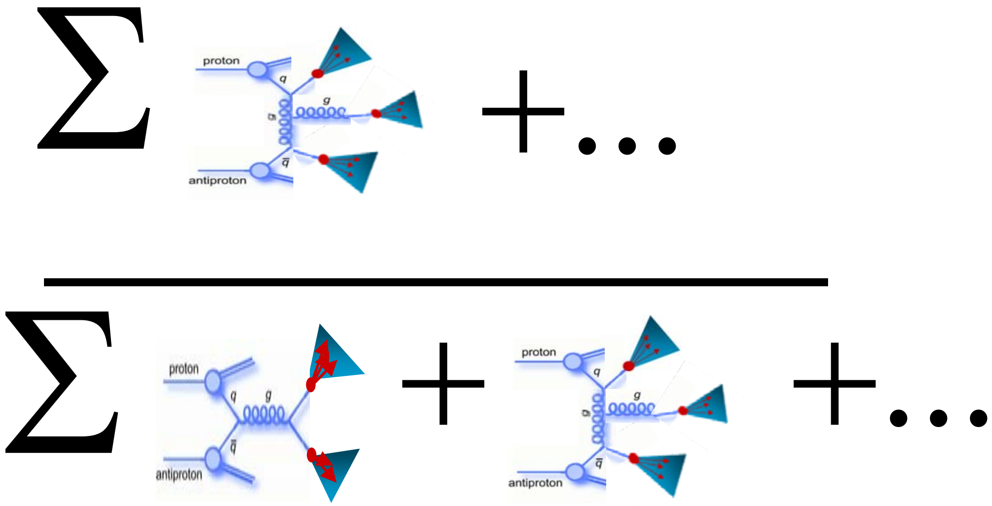
DØ: PRL 103, 191803 (2009)

- Compositeness (Λ): ~2.8 – 3 TeV
- ADD LED (GRW, M_s): ~1.6 – 1.7 TeV
- TeV^{-1} Extra Dim (M_C): ~1.6 – 1.7 TeV



CDF: Λ > 2.4 TeV for λ = -1

$R_{3/2}$: 3-Jet/2-Jet Cross Section Ratio

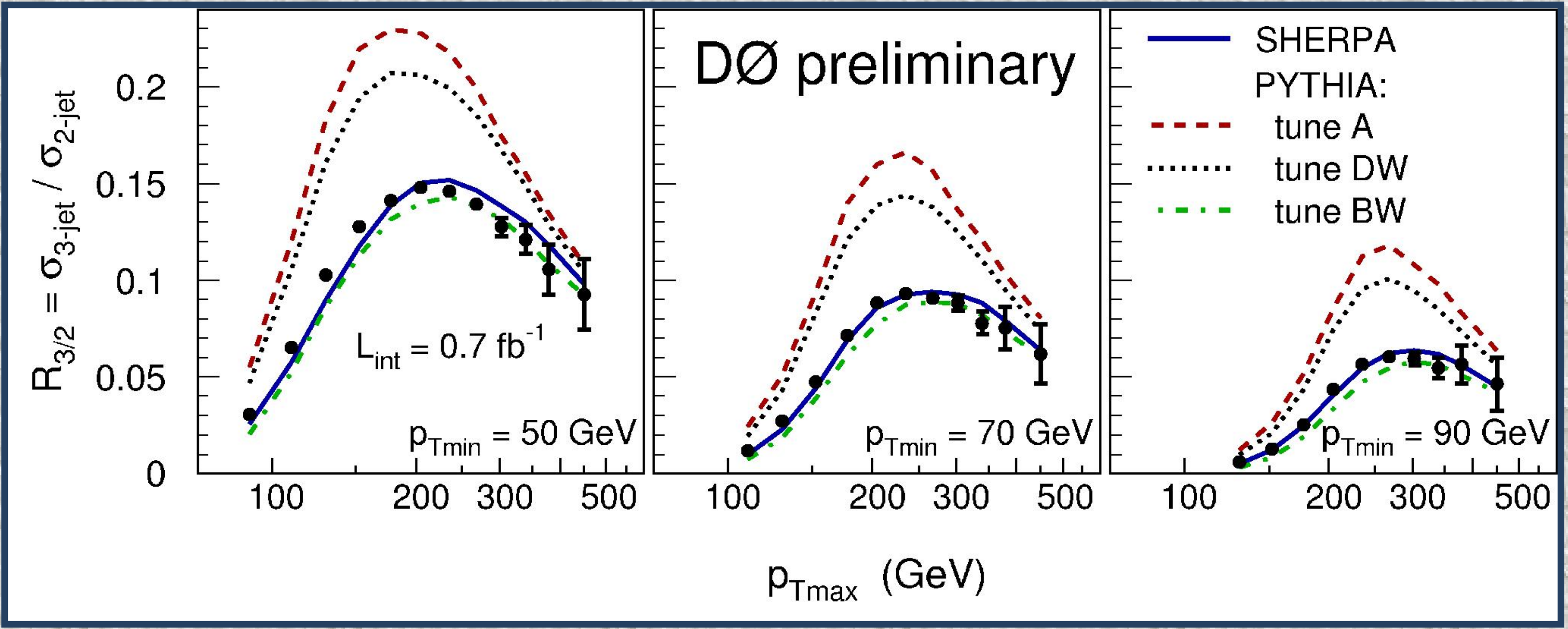


$$R_{3/2} = \sigma_{3\text{-jet}} / \sigma_{2\text{-jet}} = \frac{\sum \; + \ldots}{\sum \; + \; + \ldots}$$

- $R_{3/2}$: probability to find a third jet in an inclusive dijet event
- Sensitive to high order radiation and α_s
- Almost independent of PDFs

- Use inclusive *n-jet* (*n*=2,3) sample with *n* (or more) jets above p_{Tmin}
- $|y_{jet}| < 2.4$, $\Delta R_{jet\text{-}jet} > 1.4$
- Measurement of $R_{3/2}(p_{Tmax}, p_{Tmin})$ vs. p_{Tmax} (i.e. leading jet p_T)

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

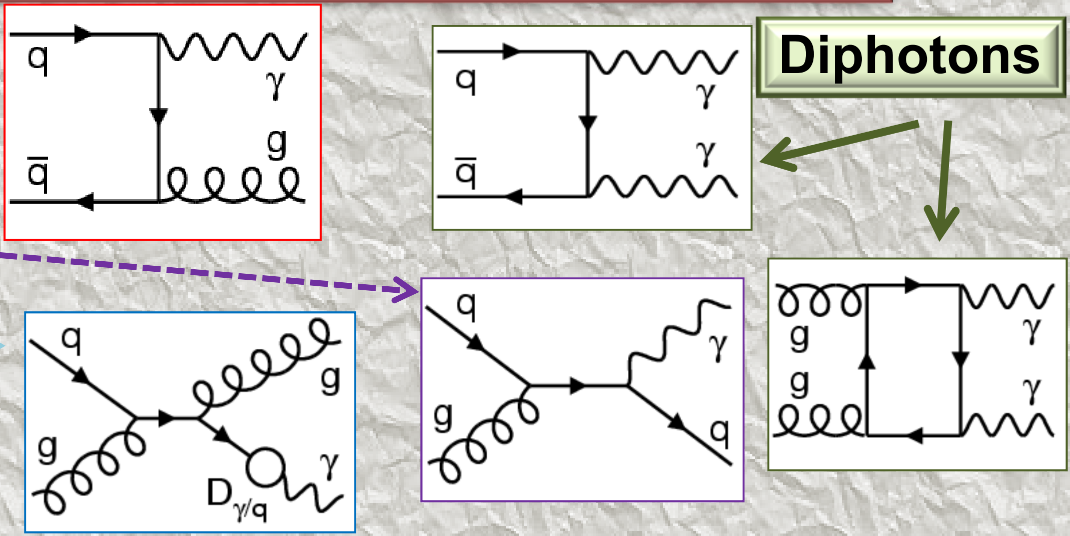


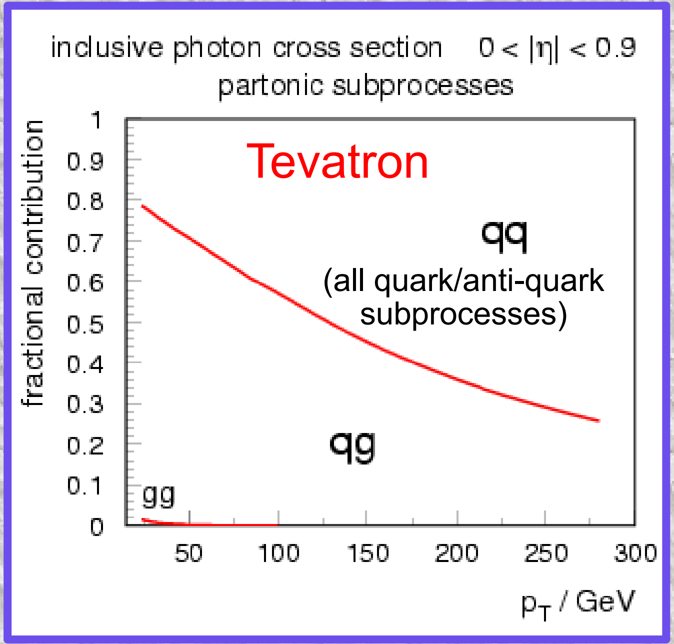
- Data can discriminate against PYTHIA tunes
  - Reasonable agreement with tune BW
  - Disagreement with tunes A & DW
- SHERPA describes the data well

Direct Photons

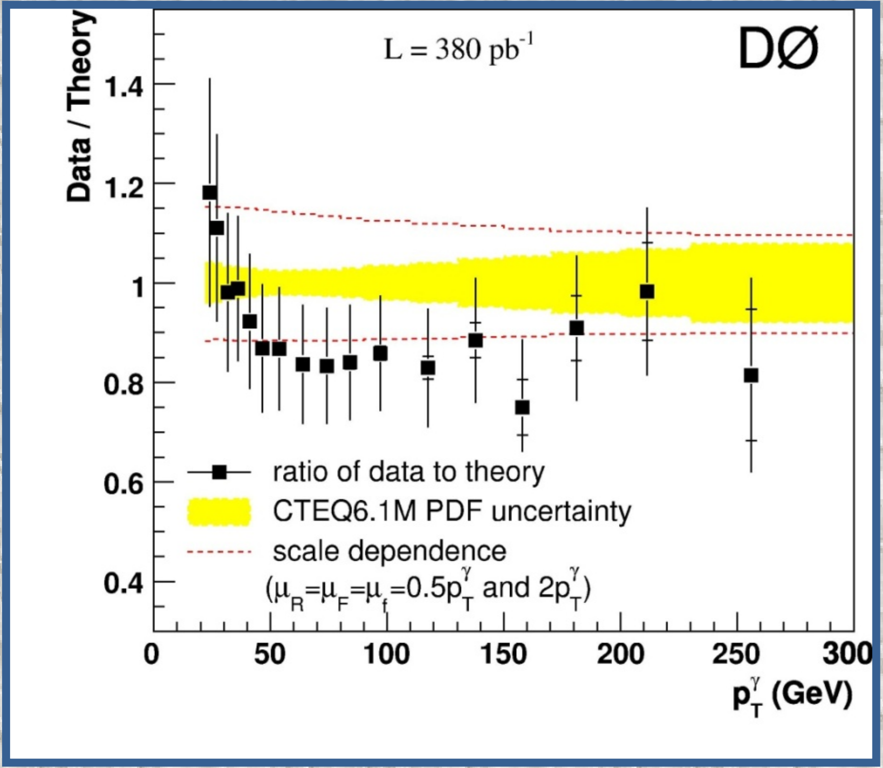
Direct Photon Production

- **Photon processes:**
  - **Annihilation**
  - **Compton**
- **Also fragmentation contributes**
  - **But suppressed with isolation**
- **Directly sensitive to hard scatter**
- **Important for QCD studies, detector calibration, gluon PDFs, background to new physics**
- **Challenging measurement**
- **Large QCD jet background**
  - **Observable: isolated photons**

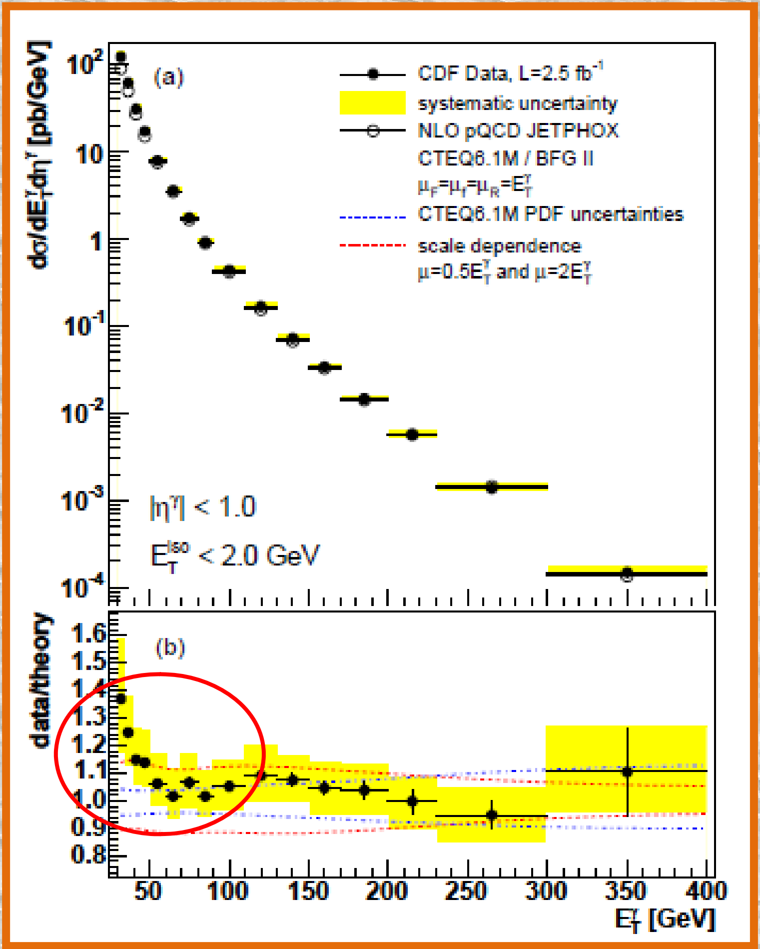

Diphotons



Inclusive Photon Cross Section



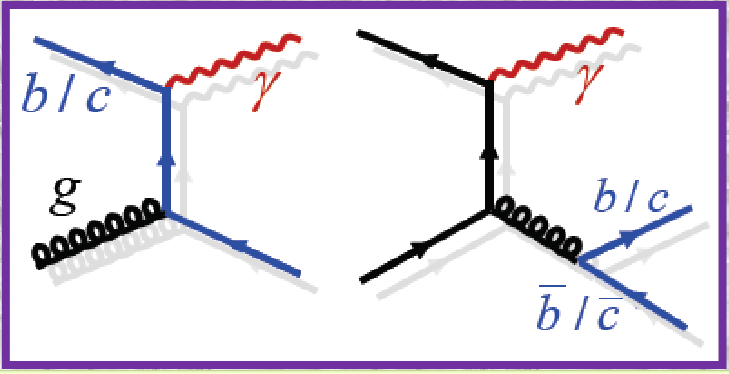
Similar effect observed: PLB 639, 151 (2006)



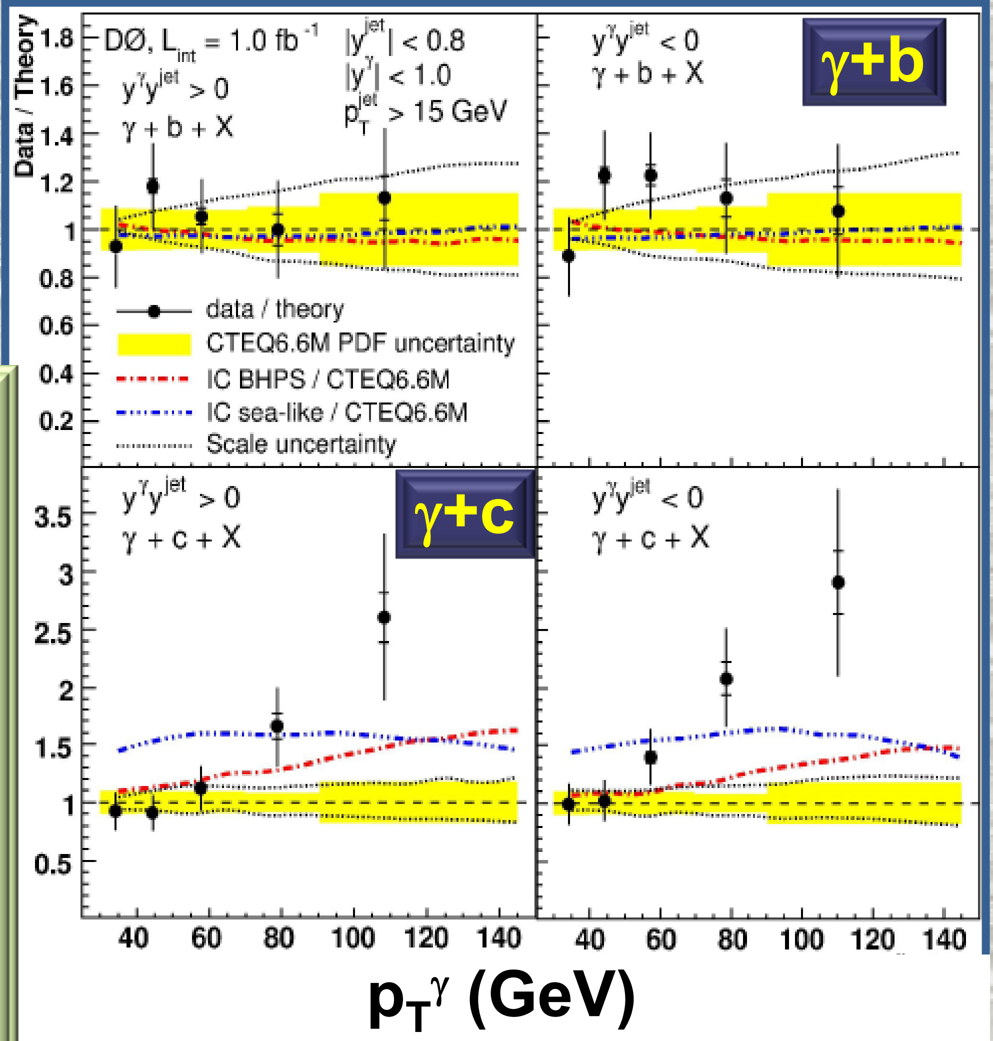
PRD 80, 11106 (2009)

- **Data/theory: shape discrepancies at low-p_T**
- **Experimental and theory uncertainties ~ PDF uncertainty → No PDF sensitivity yet**

Photon + HF Jet Production



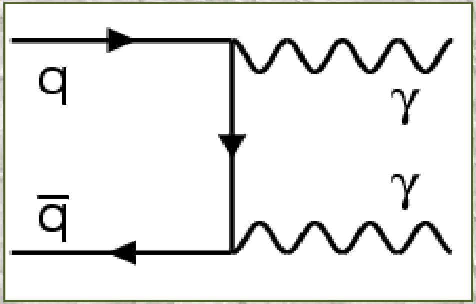
- Sensitive to HF-content of photon
- Photon p_T : 30 – 150 GeV
- Rapidities: $|y^{\gamma}|<1.0$, $|y^{jet}|<0.8$
- Probe PDFs in $0.01<x<0.3$ range
- Photon+b:
  - Agreement over full p_T range
- Photon+c:
  - Agree only at $p_T<50$ GeV
  - Using PDF w/ intrinsic charm (IC) improves the theory behavior vs p_T

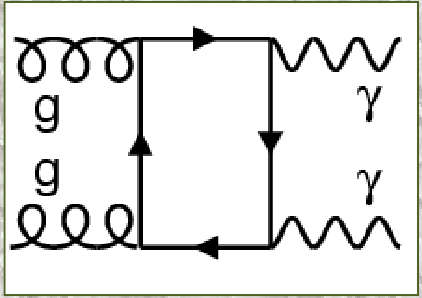


DØ: PRL 102, 192002 (2009)

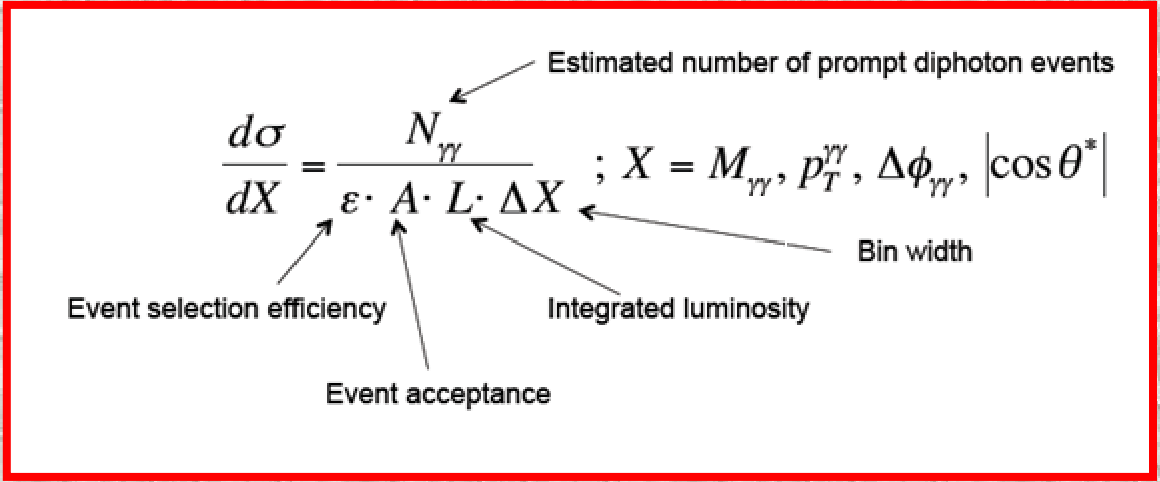
CDF: PRD 81, 052006 (2010)

Di-Photon Production





- 2 photons with p_T > 21(20) GeV
- $|y^\gamma|<0.9$, $\Delta R(\gamma,\gamma)>0.4$, $p_T(\gamma\gamma)<M(\gamma\gamma)$
- Data are compared to RESBOS, DIPHOX, PYTHIA



Estimated number of prompt diphoton events

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

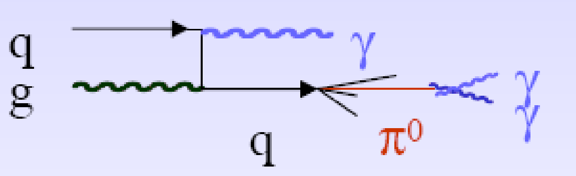
Bin width

Event selection efficiency

Integrated luminosity

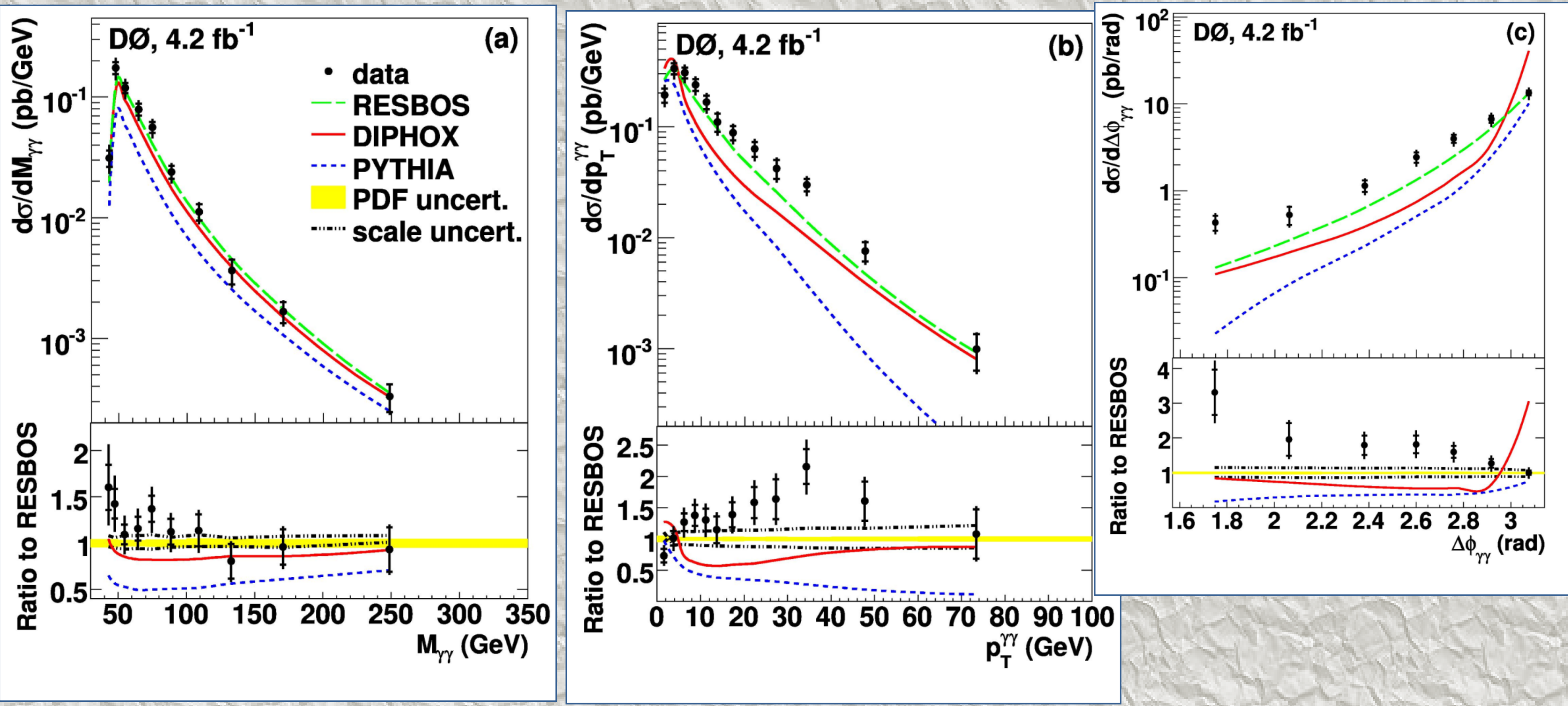
Event acceptance

Accepted by PLB
arXiv:1002.4917 (2010)



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

Di-Photon Results

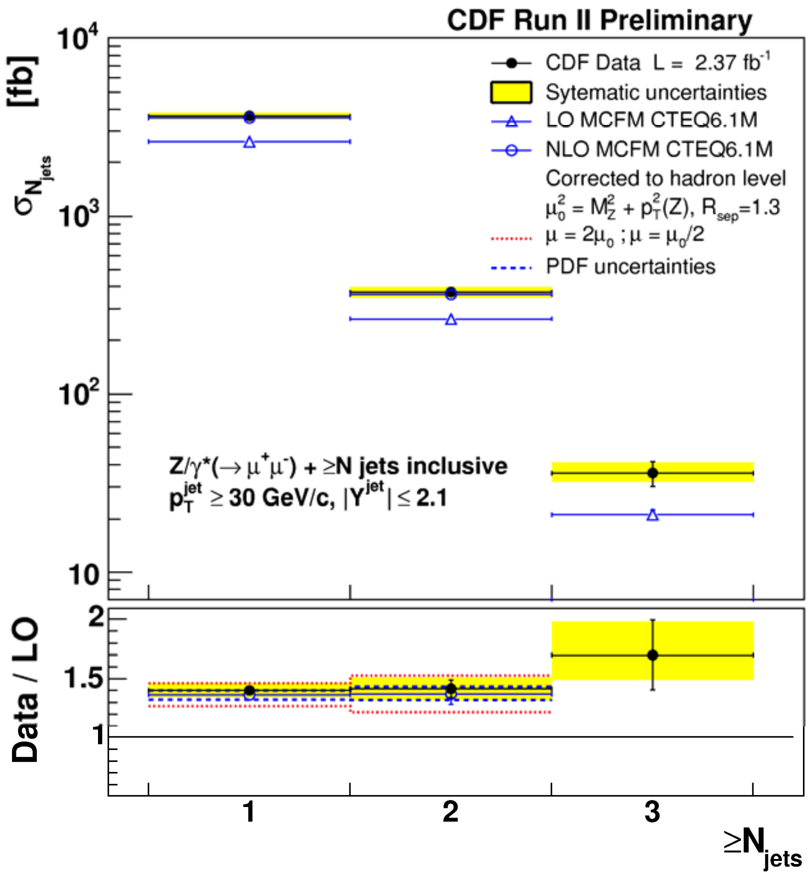


Discrepancies between data and theoretical predictions

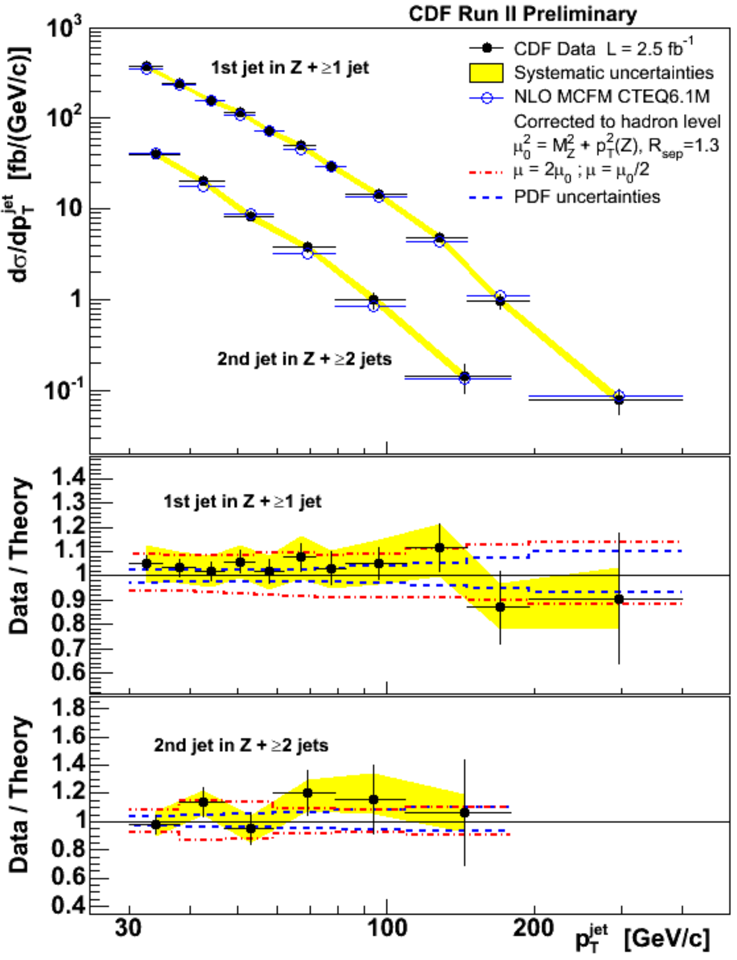
Z(W)+Jets

Z + Jets

Jet multiplicity



1st and 2nd leading jet p_T



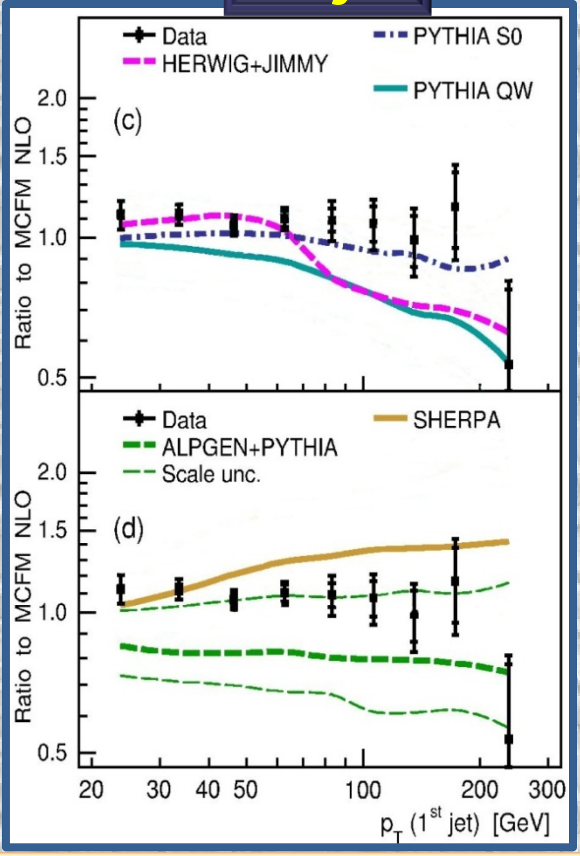
Good agreement with NLO MCFM

PRL 100, 102001 & update

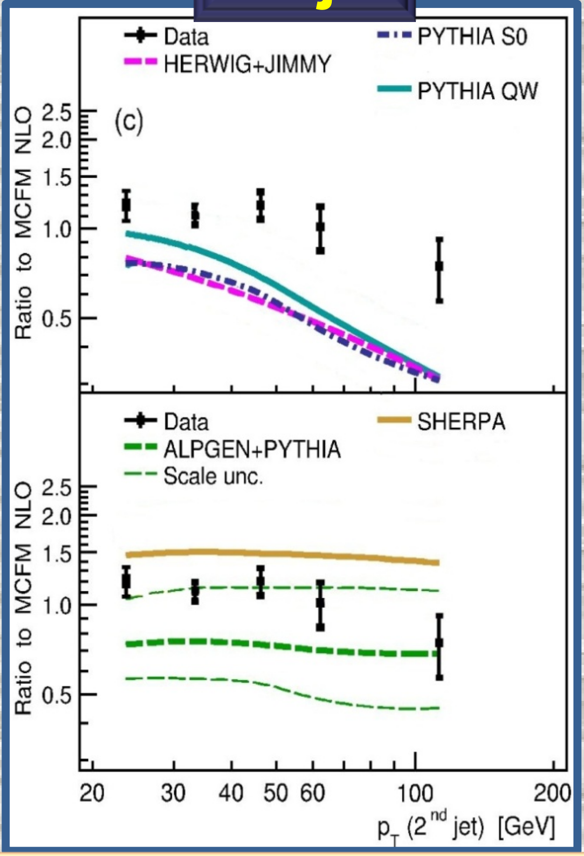
Z(ee) + (1, 2, 3) Jets: p_T Spectra

Normalize to inclusive Z production → compare to MC Event Generators

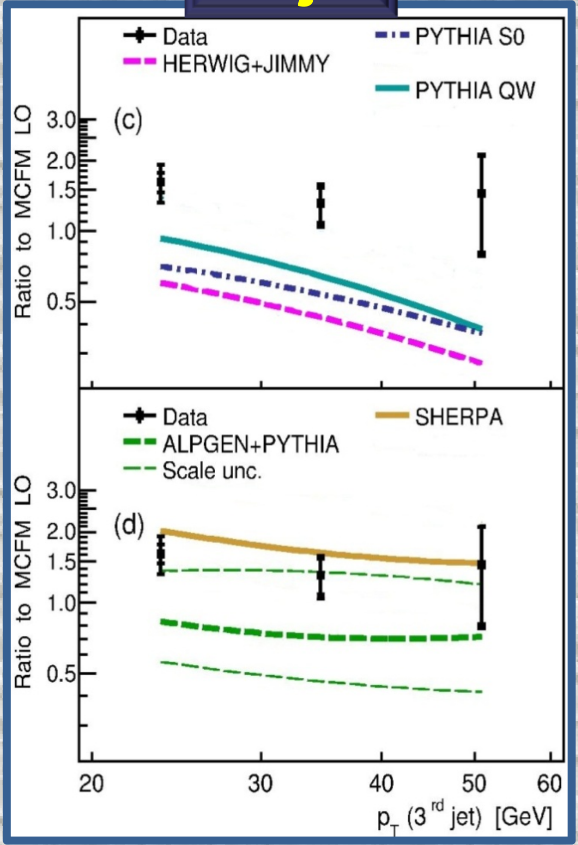
1st jet



2nd jet



3rd jet



Parton-shower MCs disagree in shape & normalization

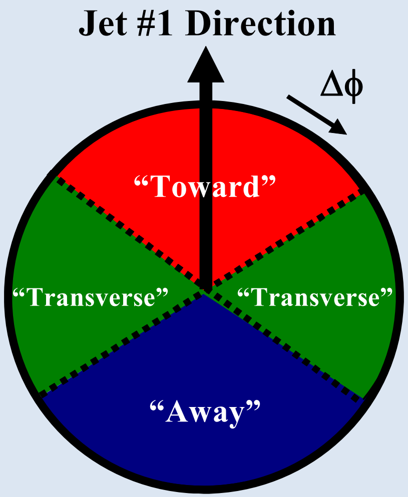
ME + Parton-shower generators describe shape better

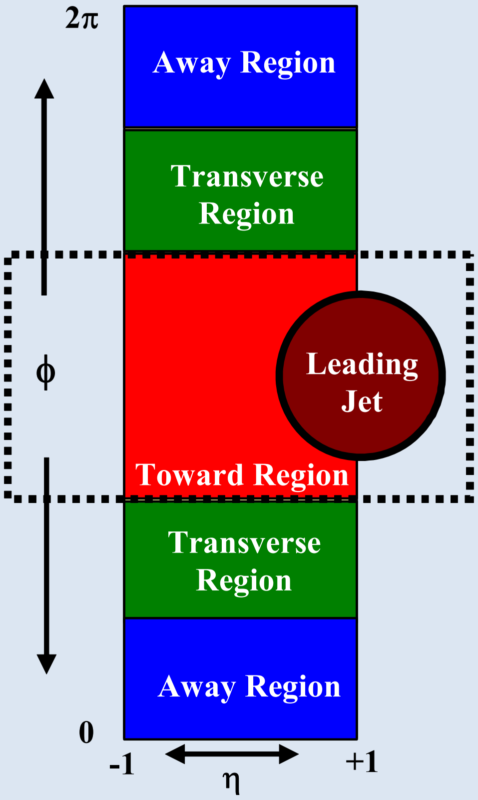
PLB 669, 278 (2008)
PLB 678, 45 (2009)

Soft QCD

The Underlying Event

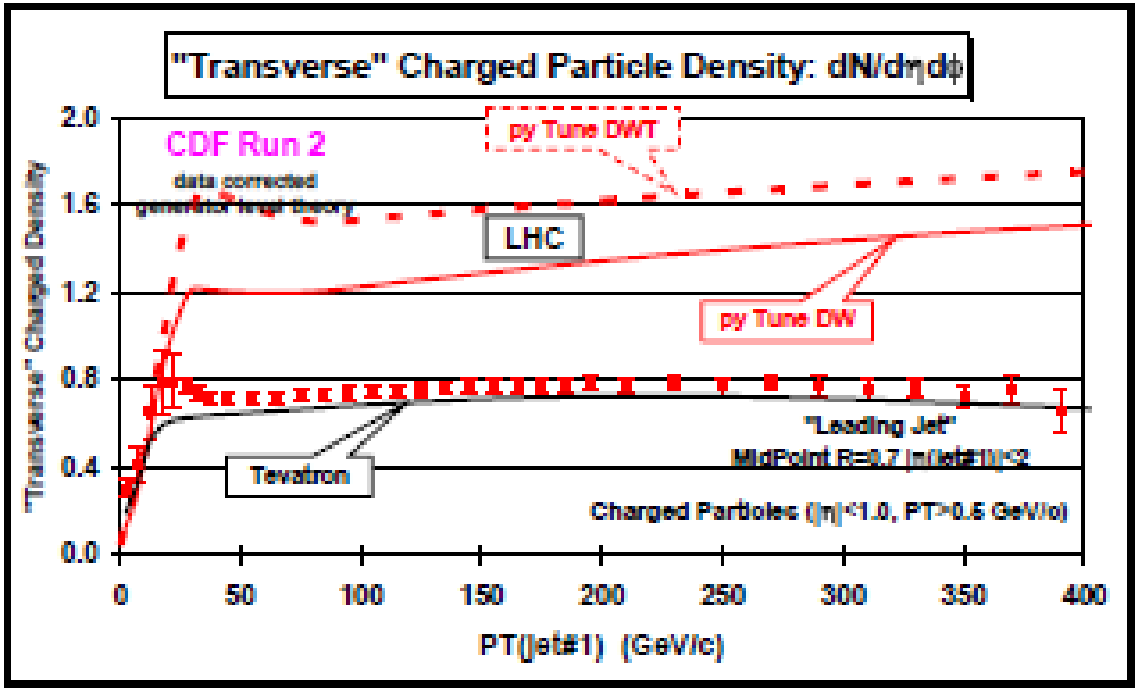
- Define three regions:
  - “toward”
  - “away”
  - “transverse”
    - Sensitive to UE
- Study
  - charged particle multiplicity
  - p_T and E_T sum density
  - Average charge particle p_T
- Tevatron measurements are used to tune MC event generators

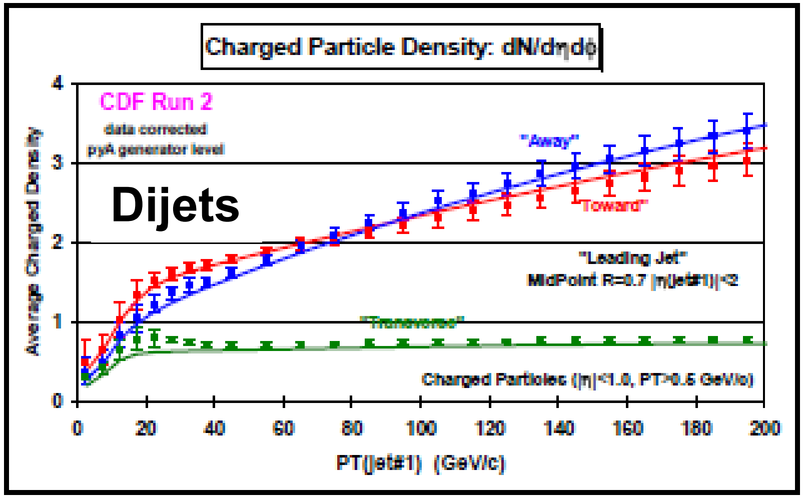


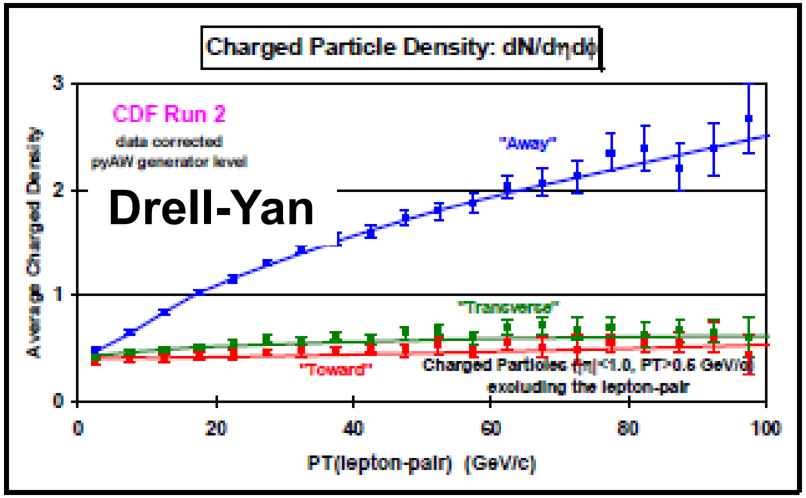


UE in Drell-Yan and Jet Production

- Use the direction of the lepton pair per event to define the three regions
- Correct observables to particle level
- Comparison of distributions between jets and DY



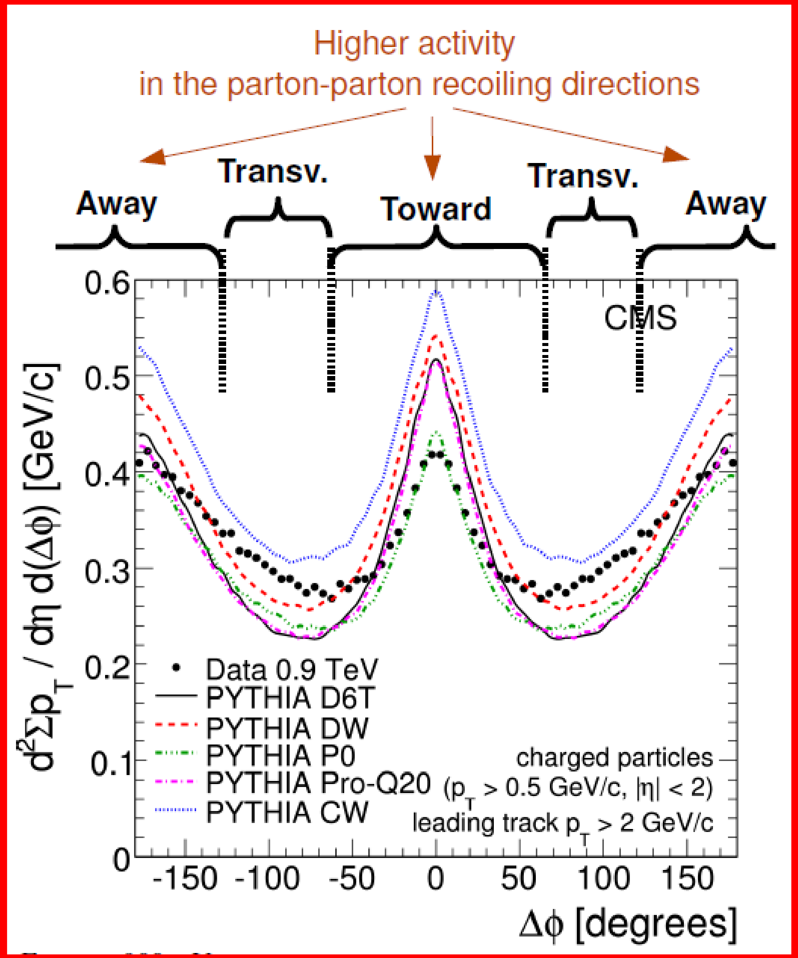


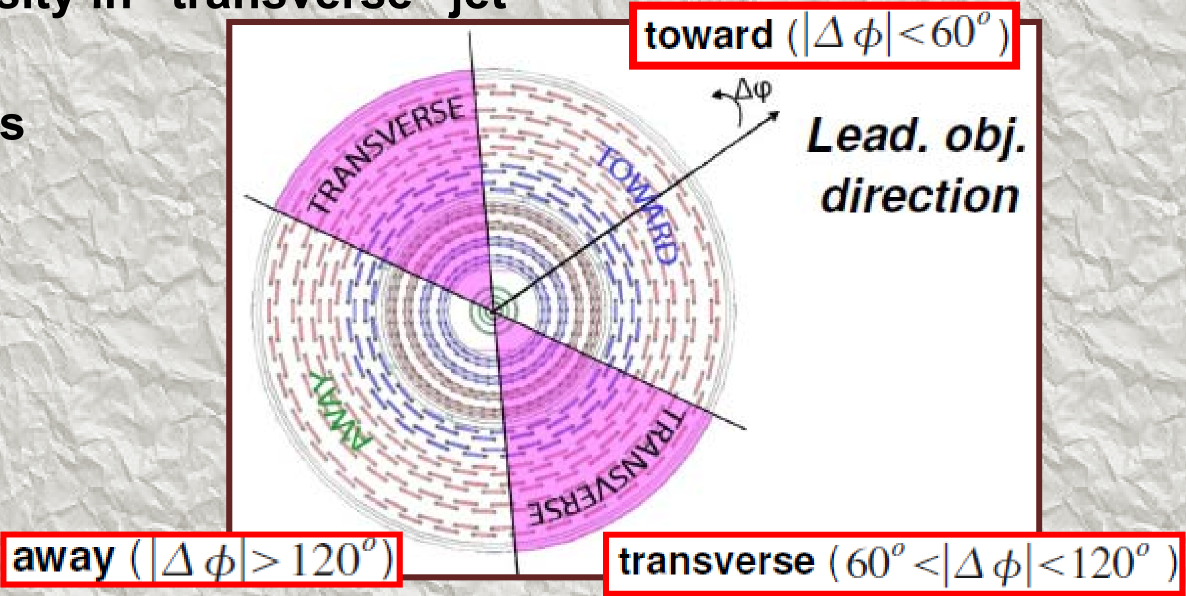


CDF: Submitted to PRD
arXiv: 1002.3146

Underlying Event at LHC (0.9 TeV)

- Study track multiplicity and p_T density in "transverse" jet region - CDF approach
- Data are compared to PYTHIA tunes





→ **Toward**:
all PYTHIA tune (except **P0**) predictions are significantly above the data, poor description by tune **Pro-Q20** compared to that of **P0** (both LEP fragmentation, but only **P0** has new MPI and pT-ordered showering)

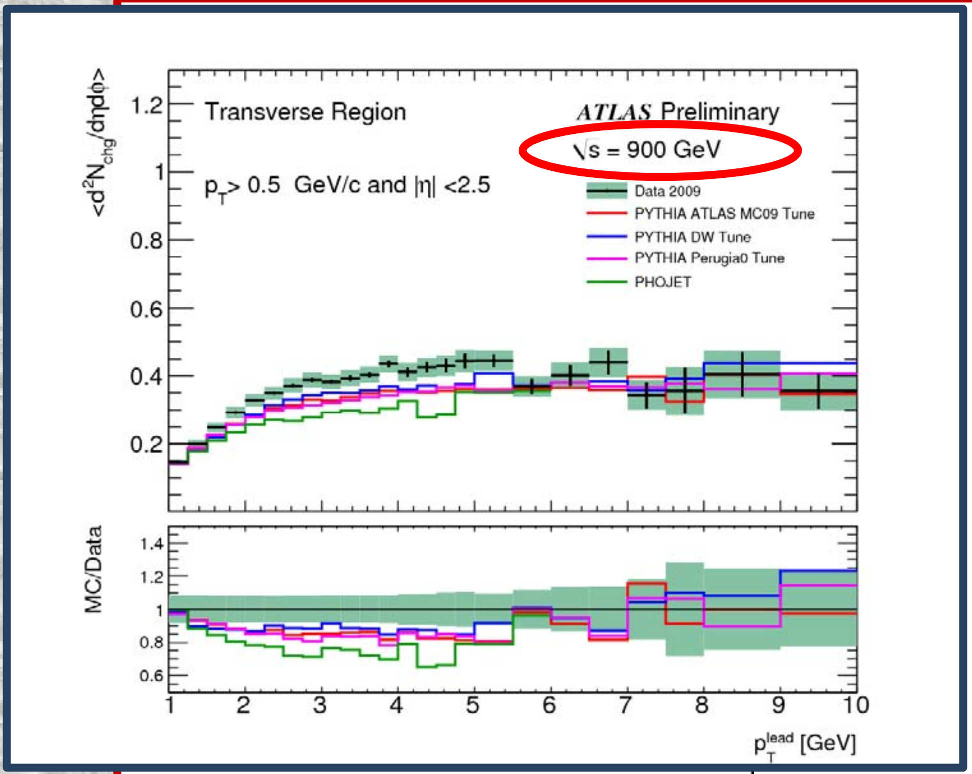
→ **Away**:
better description (except **DW** and **CW**)

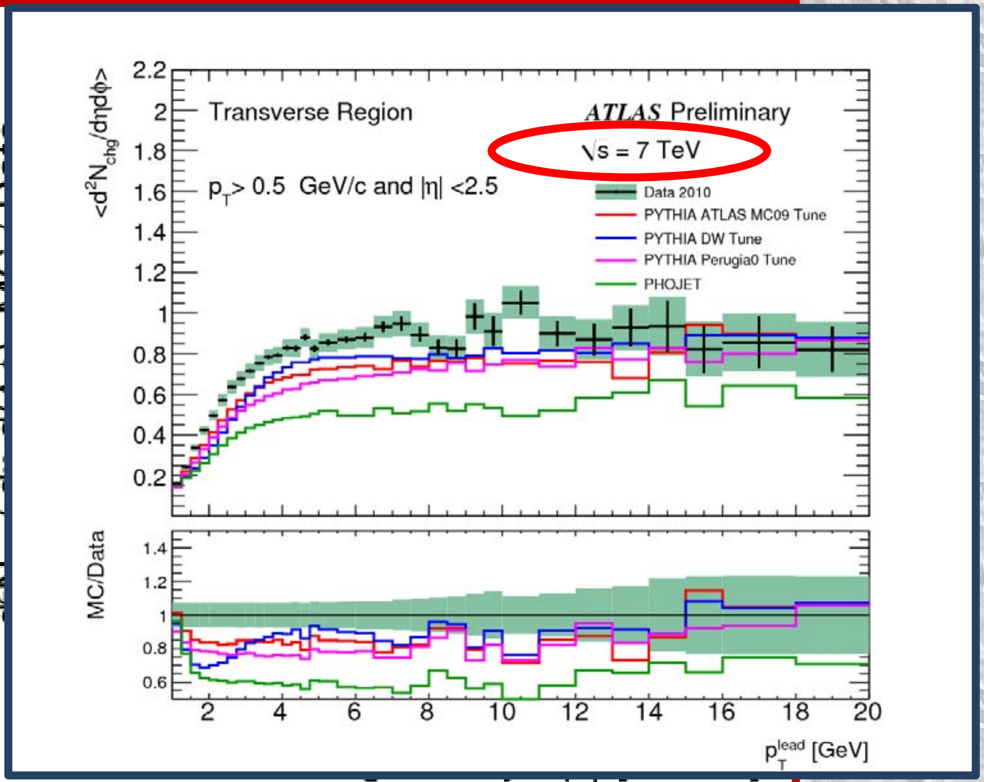
→ **Transverse**:
best described by **DW** and **CW**

CMS: Submitted to EPJ
arXiv: 1006.2083

UE @ 0.9 TeV: Particle & Energy Densities

- **Charged particle multiplicity and scalar Σp_T as a function of leading track-jet p_T**
- **Study performed in the transverse region**





CW and DW PYTHIA tunes bracket the data over most of the p_T range
Discrepancies between the various tunes and data of order ~25%

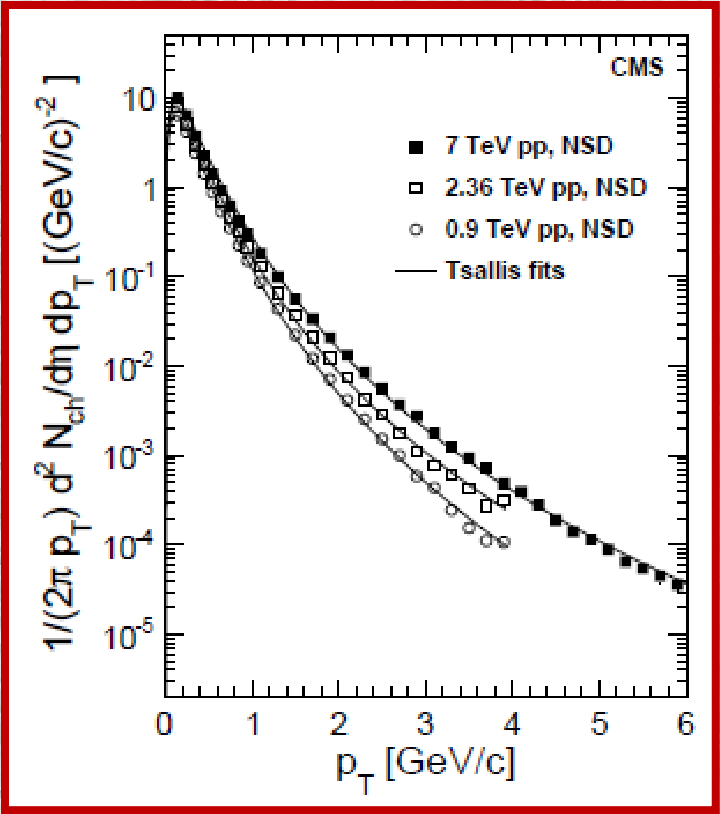
CMS: Submitted to EPJ
arXiv: 1006.2083

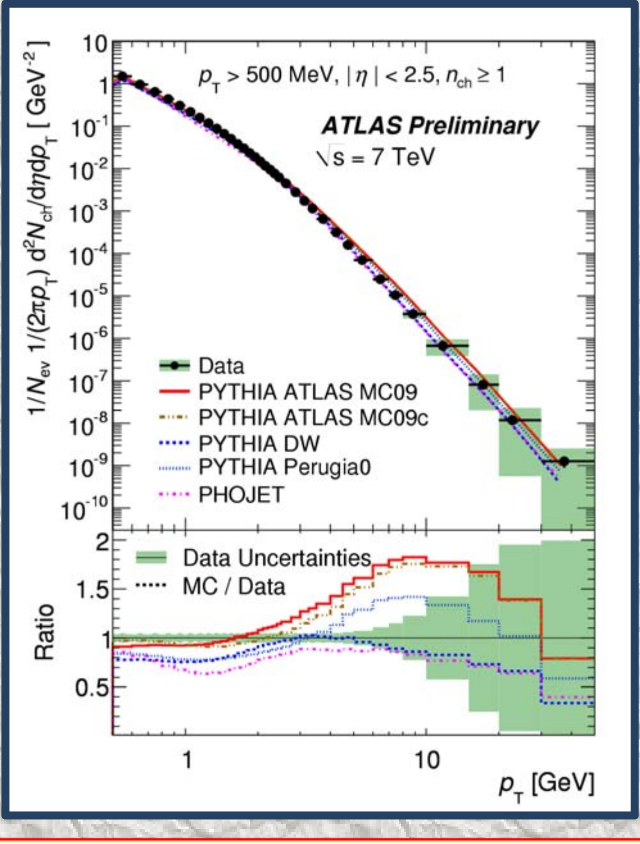
Charged Particle Spectra

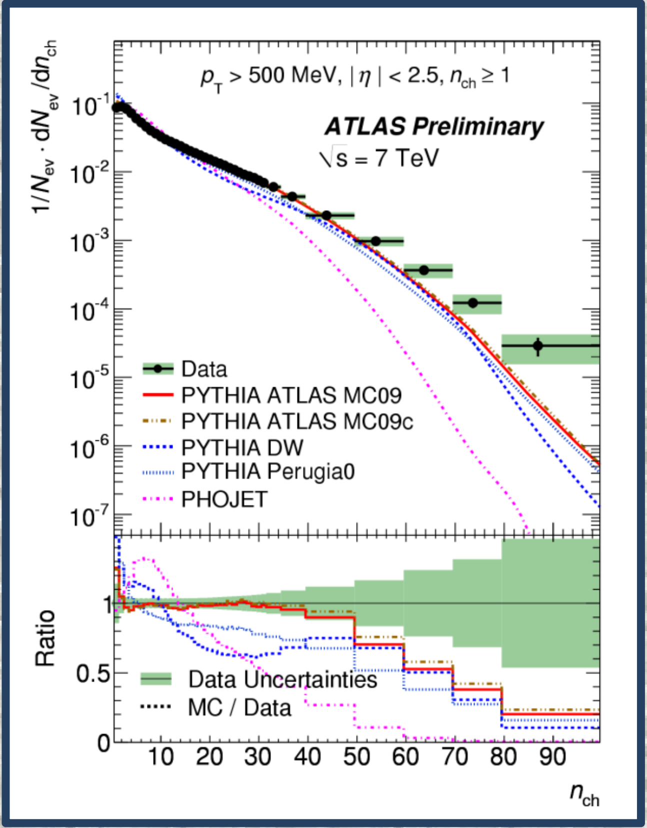
CMS: PRL 105, 022002 (2010)
JHEP 02, 041 (2010)

p_T Spectra

Multiplicity Spectra



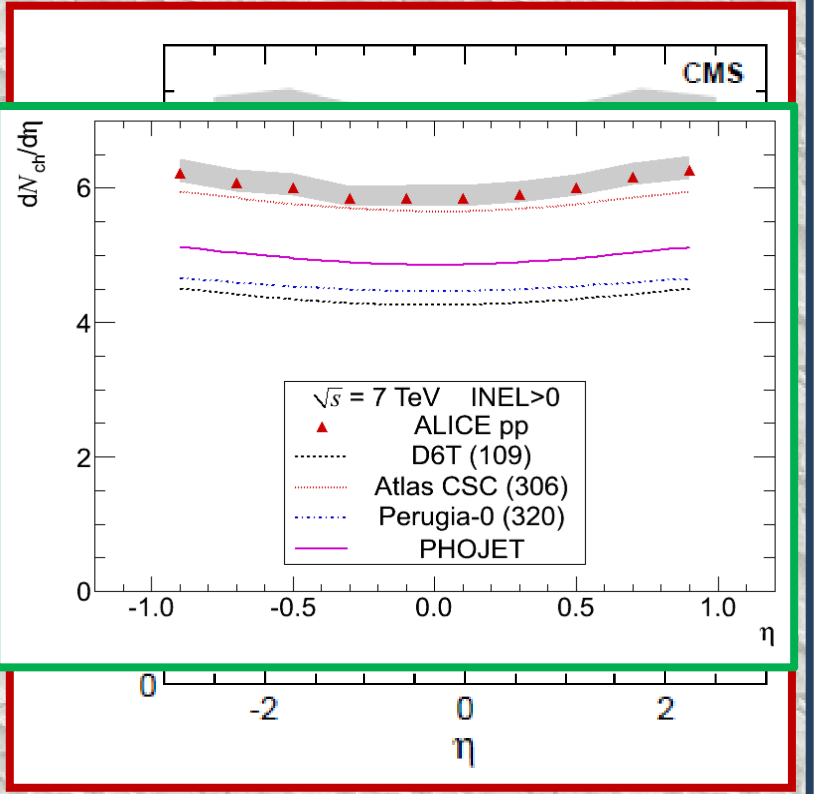


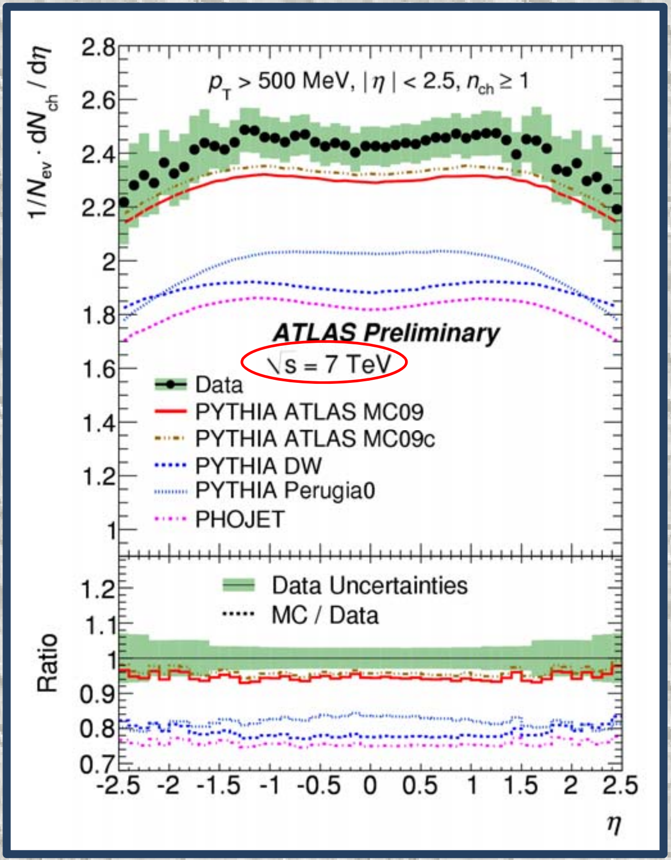


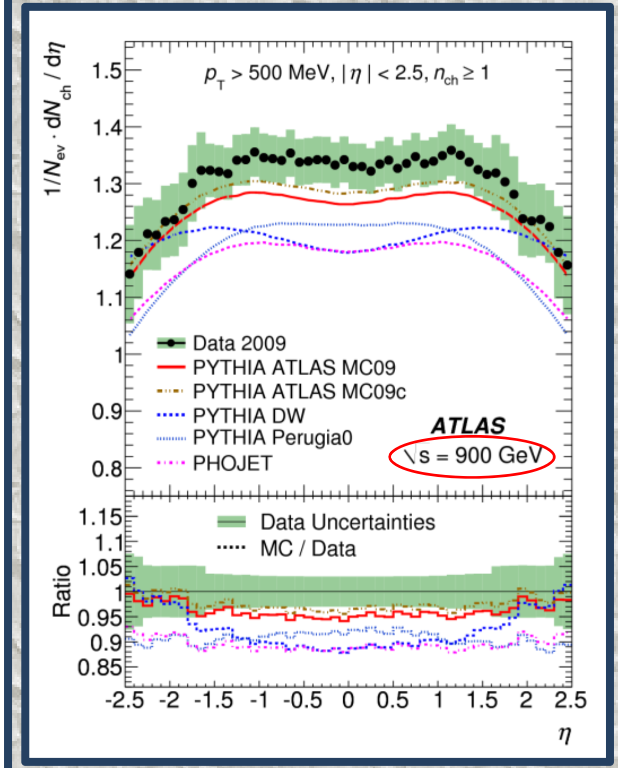
Discrepancies with MC tunes on the particle p_T and multiplicity distributions

Charged Particle Multiplicity

CMS: PRL 105, 022002 (2010)
JHEP 02, 041 (2010)





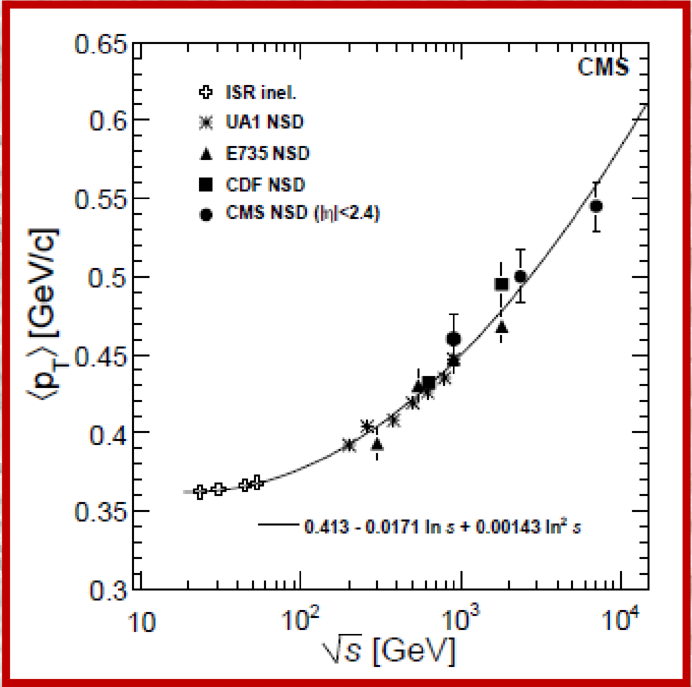


Agreement with ALICE and UA5 $dN_{ch}/d\eta$ distributions

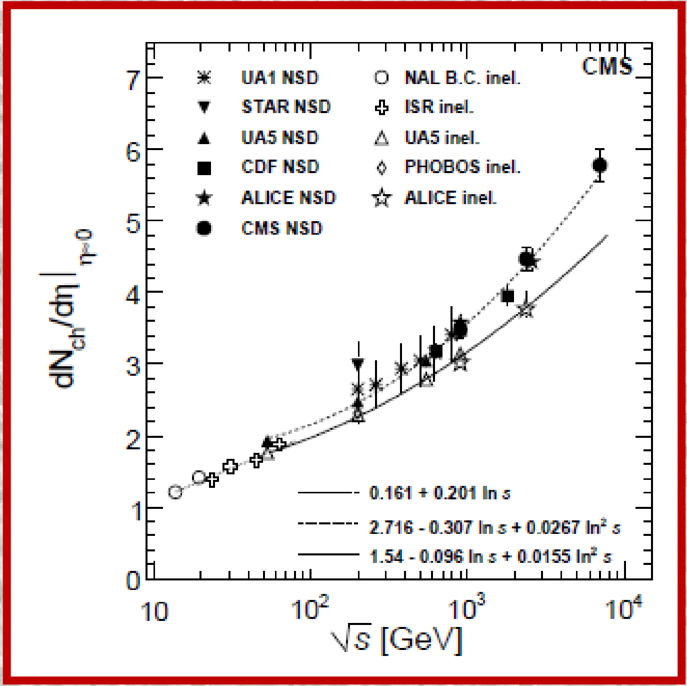
All MC tunes underestimate the particle multiplicity distributions

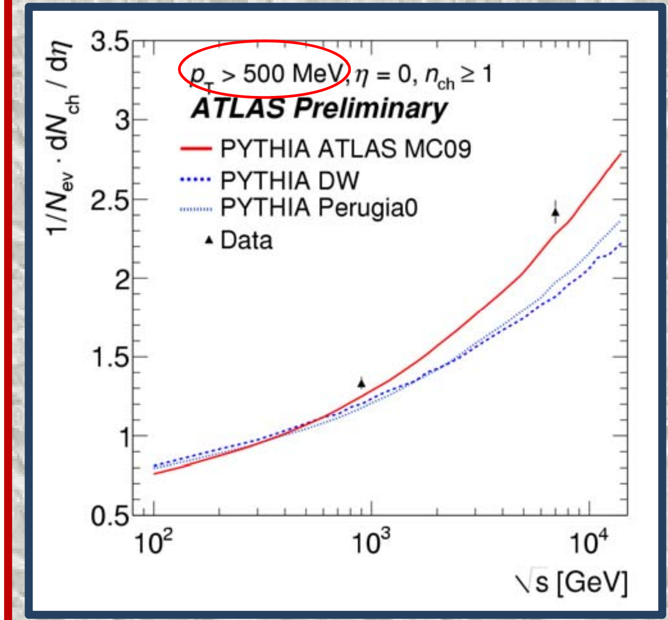
Particle Spectra: √s Dependence

<p_T> vs √s



N(η=0) multiplicity vs √s





<p_T> and $dN_{ch}/d\eta$ distributions increase with the C.M. energy

Power law dependence fits the data well

Consistent results with previous measurements at same √s

Final Words

- Recent combined cross section results from HERA will help to increase the precision of PDFs
- Measurements at HERA and Tevatron have reached higher precision than theoretical predictions
- LHC experiments have started producing first rate physics results
- QCD is important at LHC for understanding signals and backgrounds
    - Precision phenomenology at LHC requires an accurate knowledge of PDFs
- The golden time of QCD at LHC has started

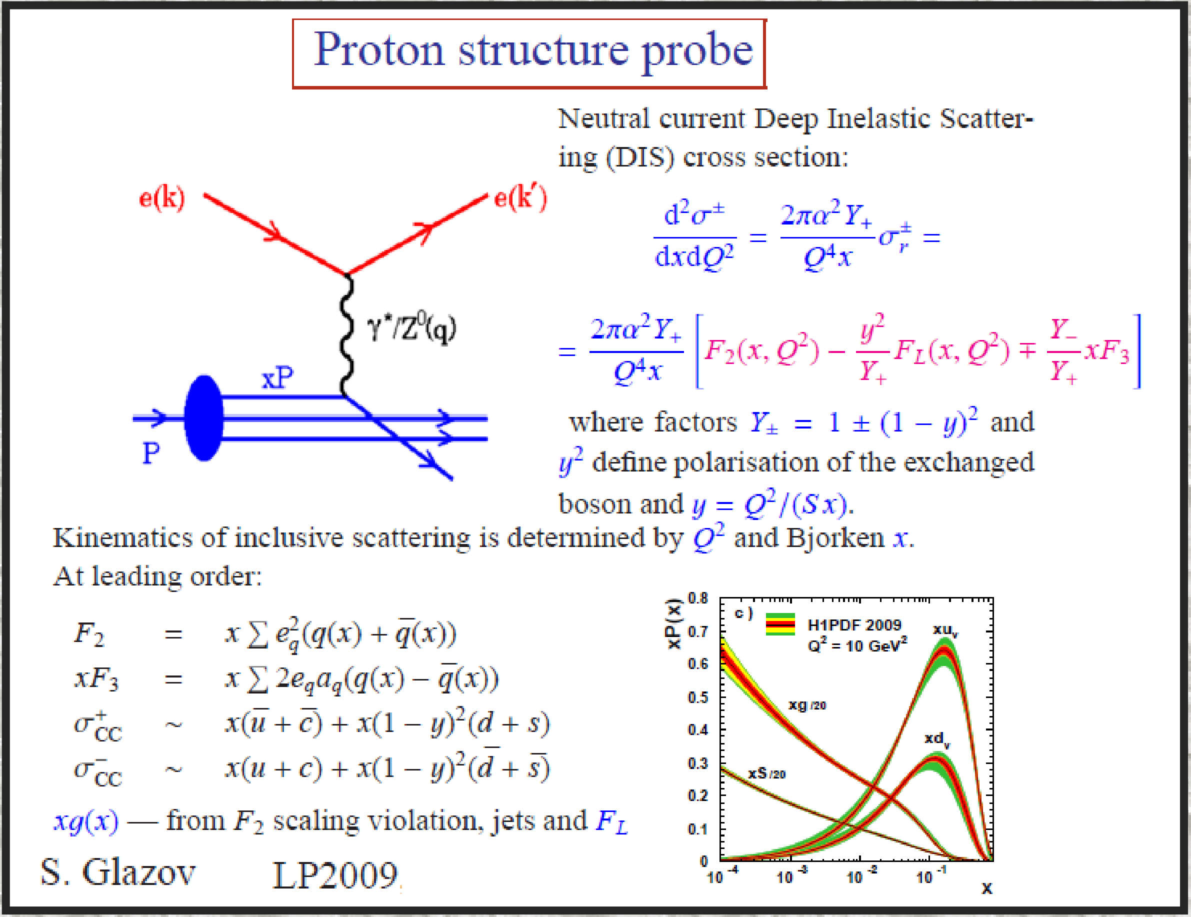
Let's enjoy it!

The Stairway to Heaven

Backup Slides

PDFs

PDFs @ HERA



Proton structure probe

Neutral current Deep Inelastic Scattering (DIS) cross section:

$$\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x}\sigma_r^\pm =$$

$$= \frac{2\pi\alpha^2 Y_+}{Q^4 x}\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3\right]$$

where factors $Y_\pm = 1 \pm (1-y)^2$ and y^2 define polarisation of the exchanged boson and $y = Q^2/(Sx)$.

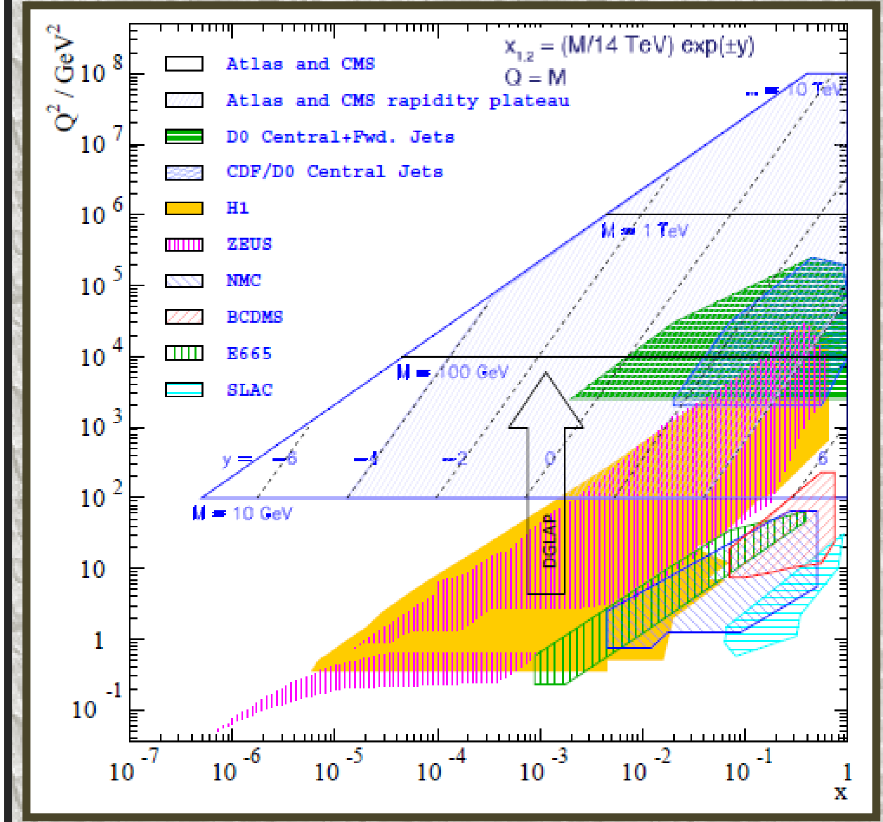
Kinematics of inclusive scattering is determined by Q^2 and Bjorken x.

At leading order:

$$\begin{aligned} F_2 &= x\sum e_q^2(q(x)+\bar{q}(x)) \\ xF_3 &= x\sum 2e_q a_q(q(x)-\bar{q}(x)) \\ \sigma_{CC}^+ &\sim x(\bar{u}+\bar{c}) + x(1-y)^2(d+s) \\ \sigma_{CC}^- &\sim x(u+c) + x(1-y)^2(\bar{d}+\bar{s}) \end{aligned}$$

$xg(x)$ — from F_2 scaling violation, jets and F_L

S. Glazov LP2009



From scaling violations:
$F_L \sim \alpha_s xg(x,Q^2)$

At LHC we will access PDFs down to x~10^{-6} and Q^2 up to 100 TeV^2

PDFs Then and Now

PDFs in 1984

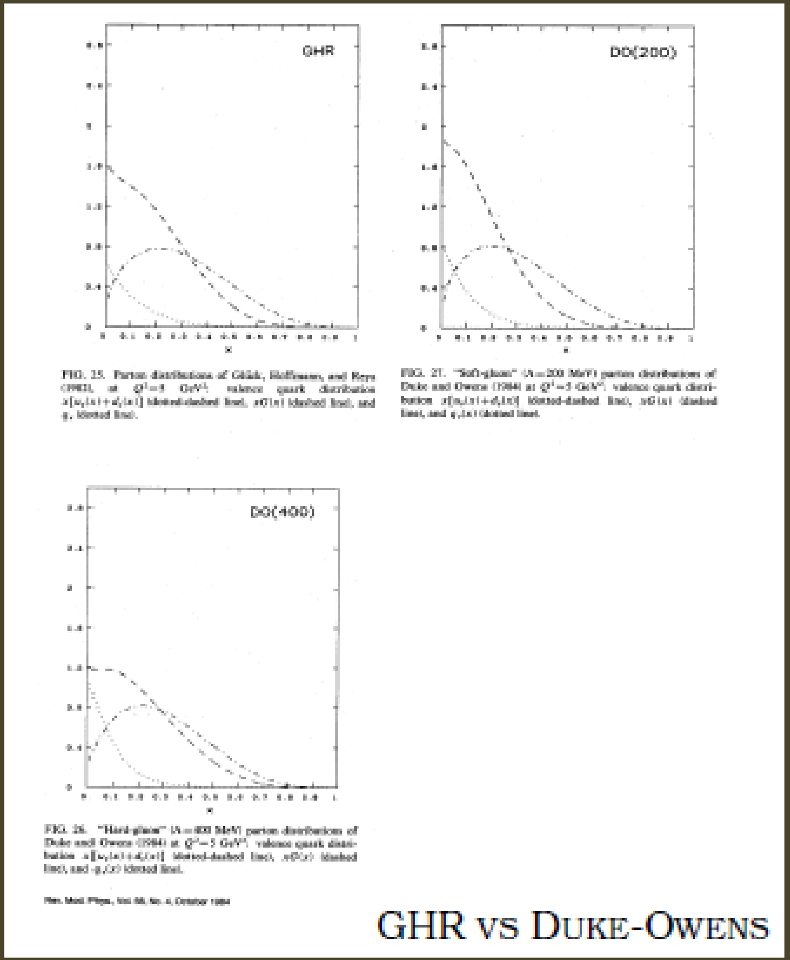


FIG. 25. Parton distributions of Glück, Hoffmann, and Reya (1982), at $Q^2=5$ GeV²: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and q_s (dotted line).

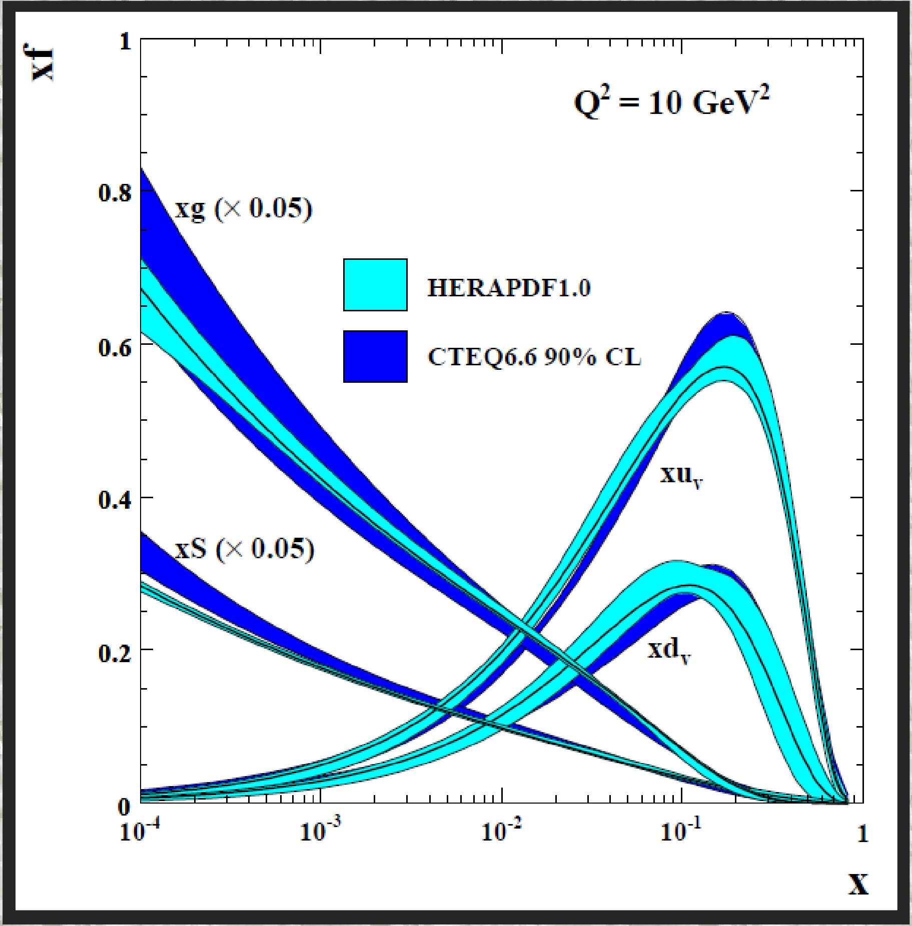
FIG. 27. "Soft-gluon" ($\Lambda=200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2=5$ GeV²: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_s(x)$ (dotted line).

FIG. 26. "Hard-gluon" ($\Lambda=400$ MeV) parton distributions of Duke and Owens (1984) at $Q^2=5$ GeV²: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_s(x)$ (dotted line).

Rev. Mod. Phys., Vol. 56, No. 4, October 1984

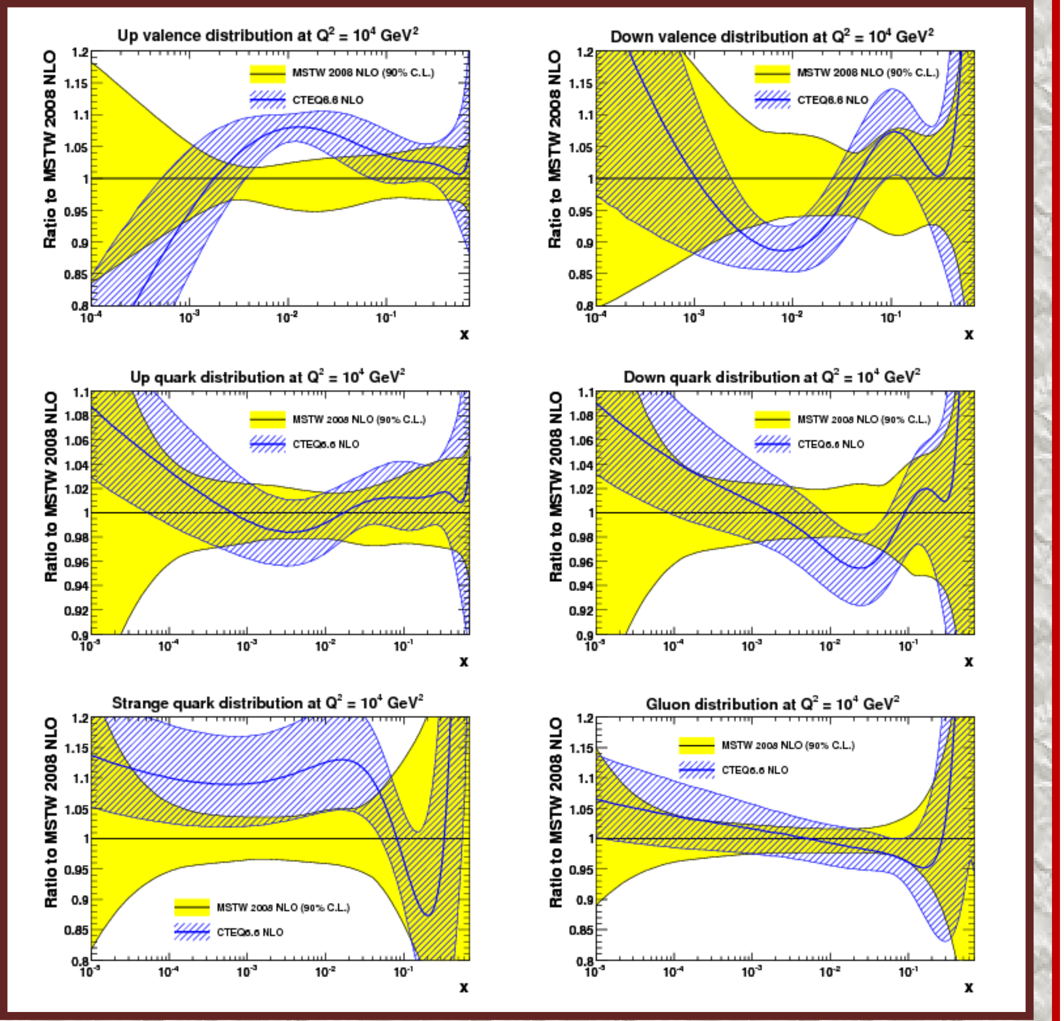
GHR vs Duke-Owens

PDFs 25 years later

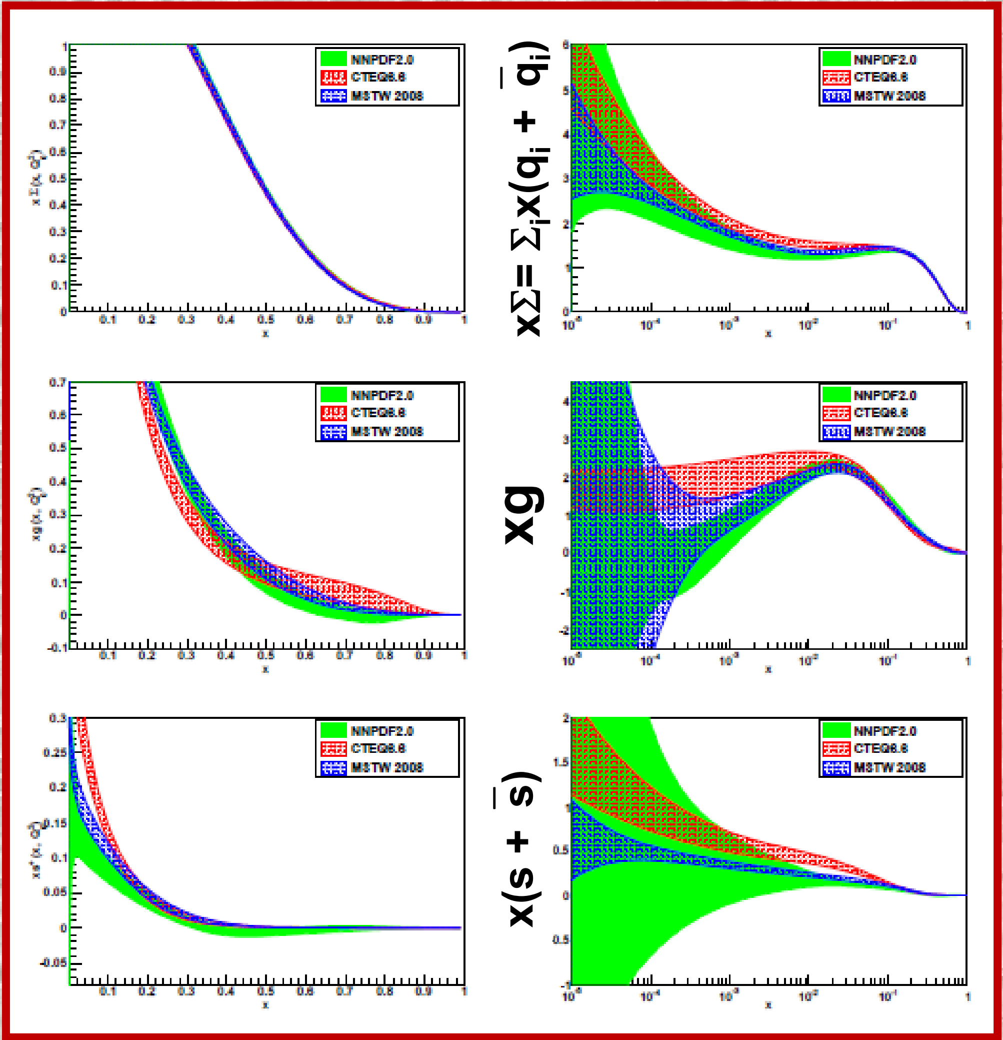


Comparison of PDFs: Do they agree?

MSTW2008 vs CTEQ6.6

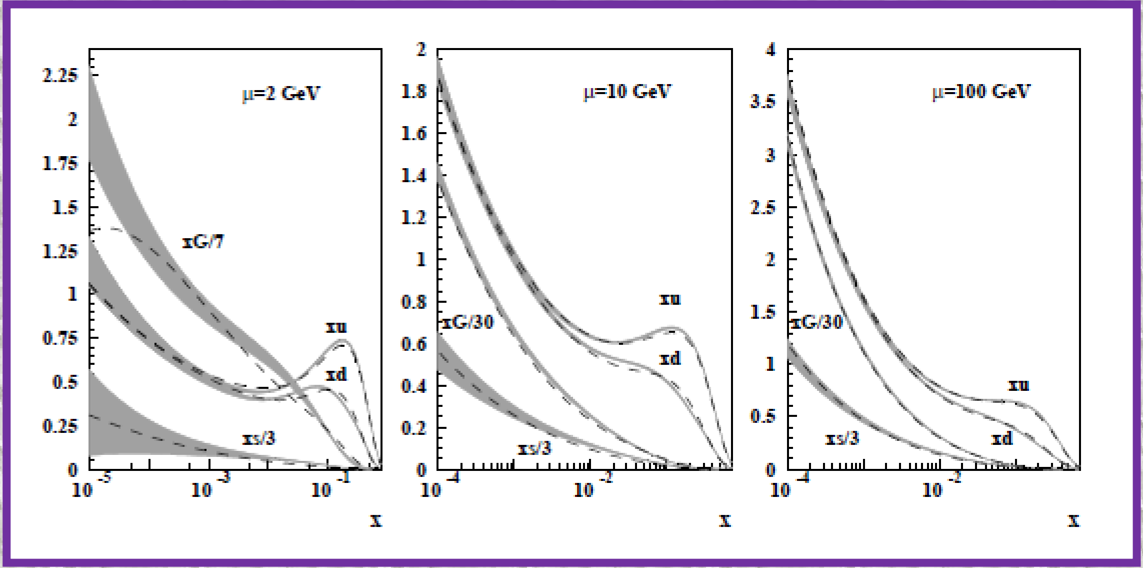


NNPDF2.0 vs MSTW2008 vs CTEQ6.6

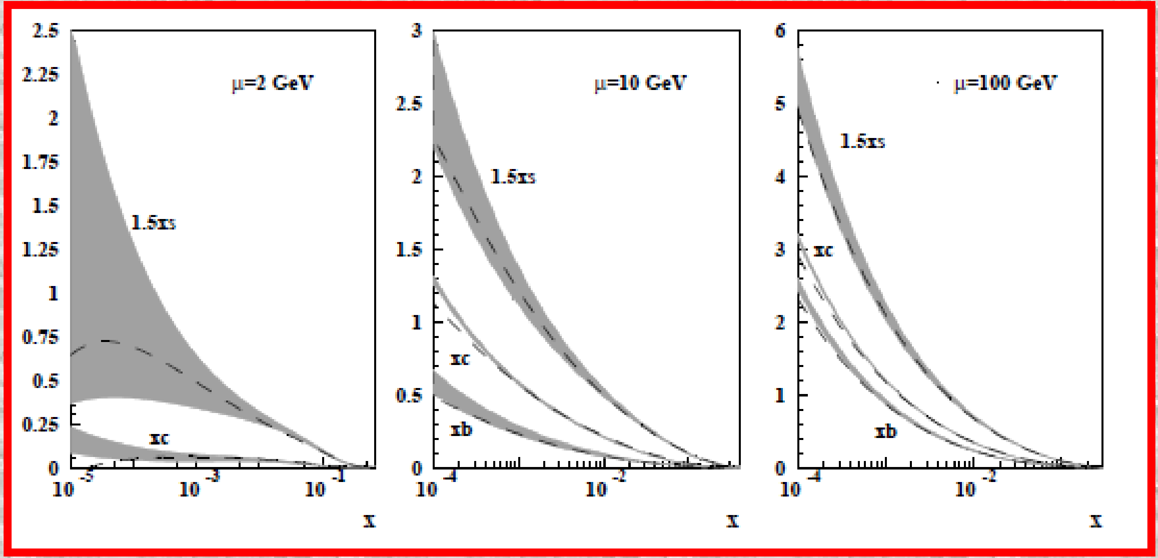


Reasonable agreement within uncertainties

Comparisons of PDFs (2)



ABKM (band) **vs JR** (dashed)



MS d)

ABKM (s, c, b)

vs

MSTW2008

arXiv: 0908.2766

Jet Production

Inclusive Jets – The Old Days

$$\frac{1}{\Delta E_T \Delta\eta}\iint d\eta\, dE_T \frac{d^2\sigma}{dE_T d\eta} \longleftrightarrow \frac{N_{jet}}{\Delta E_T \Delta\eta\, \varepsilon \int L dt} \text{ vs. } E_T$$

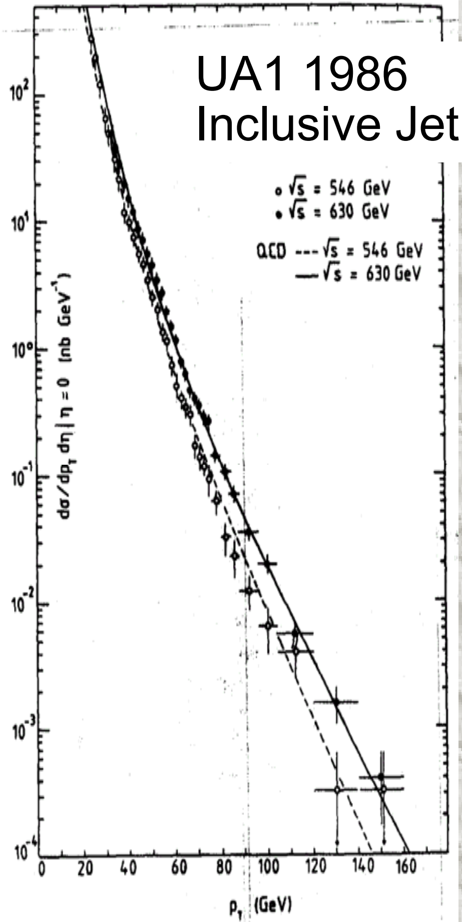
$\Delta E_T \rightarrow E_T$ bin size

$\varepsilon \rightarrow$ selection efficiency

$\Delta\eta \rightarrow \eta$ bin size

$L \rightarrow$ inst. Luminosity

$N_{jet} \rightarrow$ # of jets in the bin


UA1 1986
Inclusive Jet CS

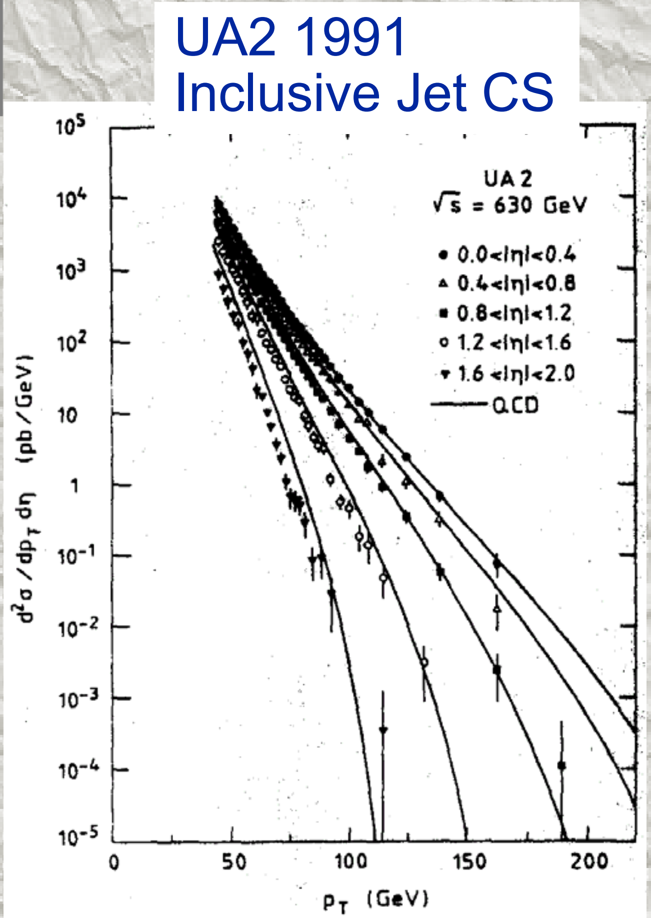
Uncertainties ~ 70% on CS:
±50% accept./jet corr (smearing)
±40% calib ±10% aging ±15% Lum
Λ_C > 400 GeV *"Exp and theo. Uncerts. taken in to account"*

- **√s = 0.5 – 0.6 TeV**
- **Cone jet clustering**
- **P_T range: 20 – 200 GeV**
- **Comparison to LO QCD**
- **Compositeness Λ_C > 0.8 TeV**

$$\frac{d\sigma}{dP_T} \approx \sum_{a,b} \int dx_a f_{a/A}(x_a,\mu) \int dx_b f_{b/B}(x_b,\mu) \frac{d\hat\sigma}{dP_T}$$

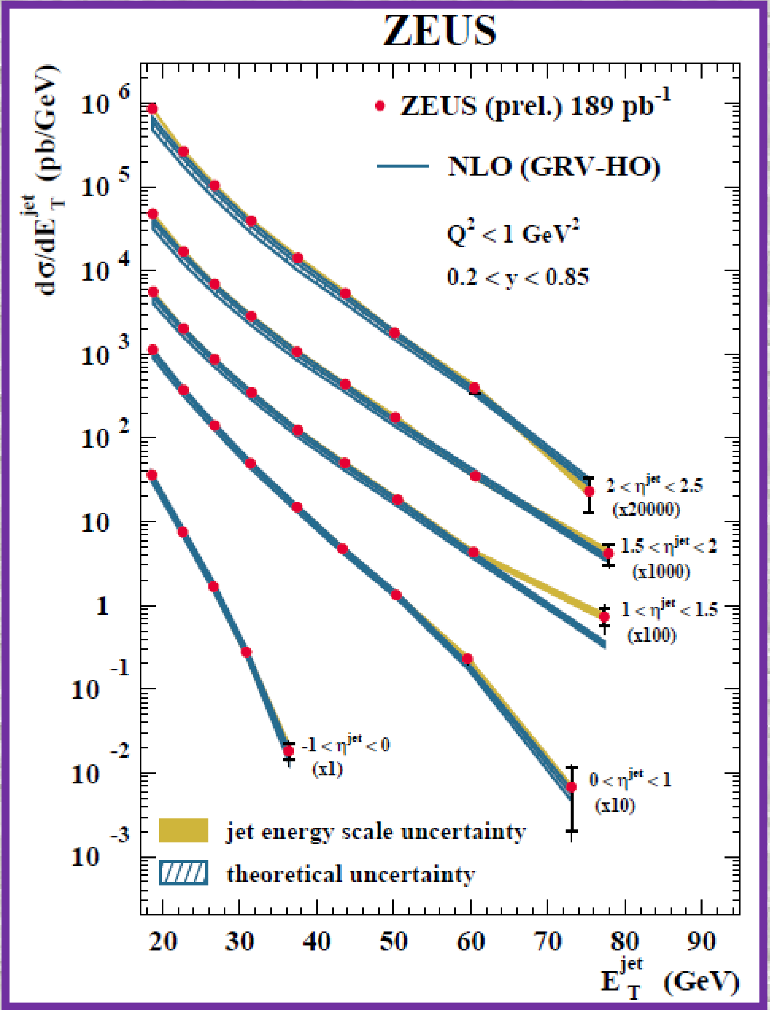
$$\frac{d\hat\sigma}{dP_T}(ab \rightarrow cd) \approx \sum_N \left(\frac{\alpha_s(\mu^2)}{\pi}\right)^N M_N$$

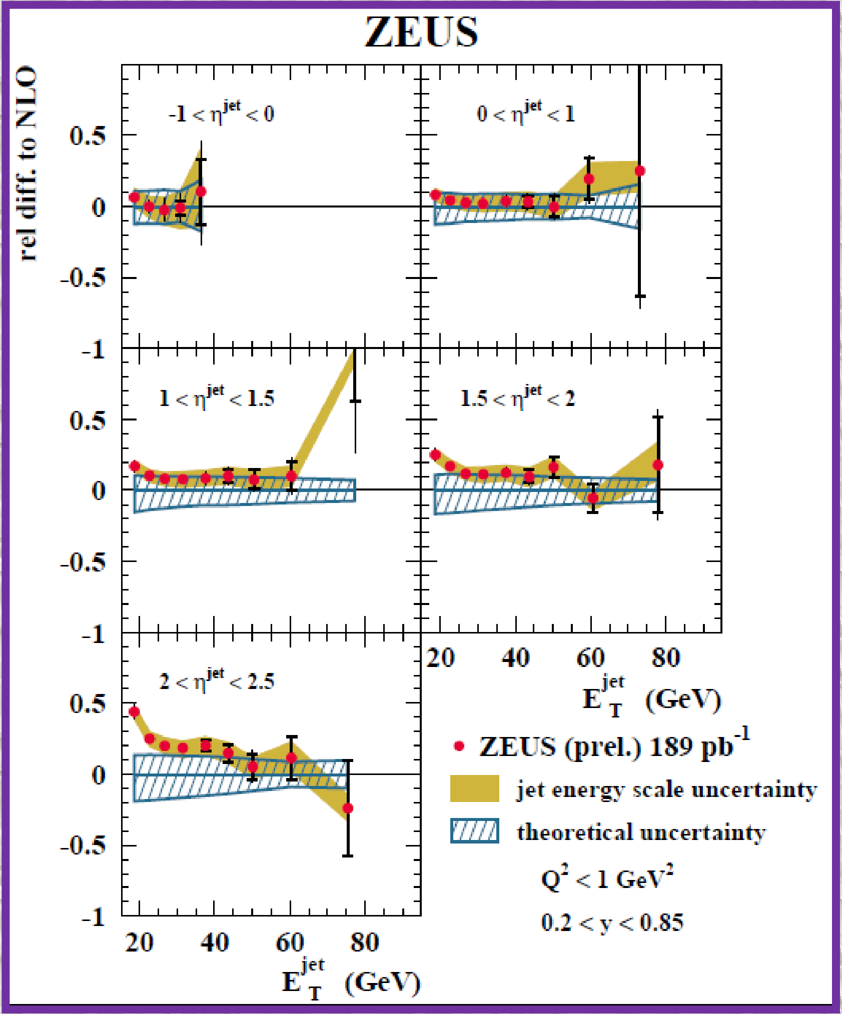
State of art: 3-jet production @ NLO
(Next-to-Leading Order ~$O(\alpha_s^4)$)


UA2 1991
Inclusive Jet CS

Uncertainties ~ 32% on CS:
±25% model dep. (fragmentation)
±15% jet alg/analysis params
±11% calib ±5% Lum
Λ_C > 825 GeV *"...include sys. effects which could distort the CS shape"*

Photoproduction of Jets

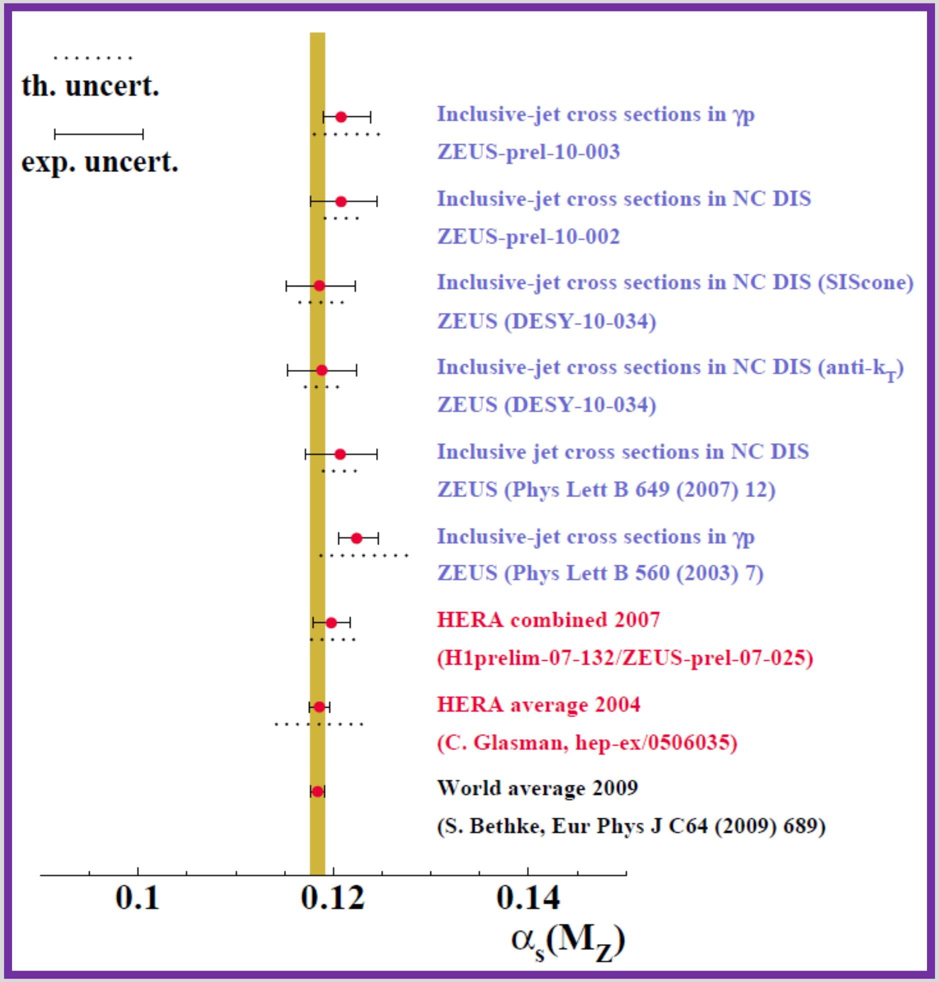


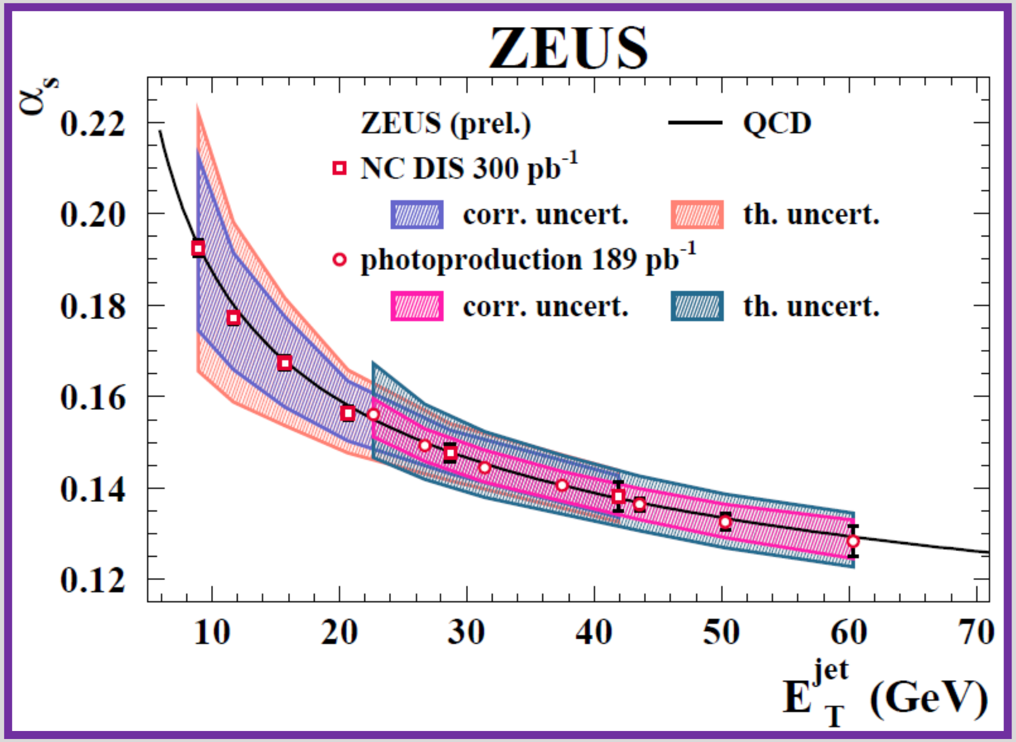


Discrepancies between data and NLO QCD at low E$_T^{jet}$ and high η^{jet}

ZEUS_prel_10_003

The Strong Coupling Constant





Consistent measurements of $\alpha_s(M_Z)$ with world average and of the running of $\alpha_s(Q^2)$ over a wide range of E_T^{jet} → Great Success of QCD!

Dijet Mass Distribution

- Select jets with |y|<1.0
- Sensitive to new particles decaying to dijets

Data described by NLO pQCD

No indications for resonances

Exclusions mass ranges:

excited quarks

260 - 870 GeV

Axigluon, flavor-universal coloron

260 - 1250 GeV

E_6 Diquark

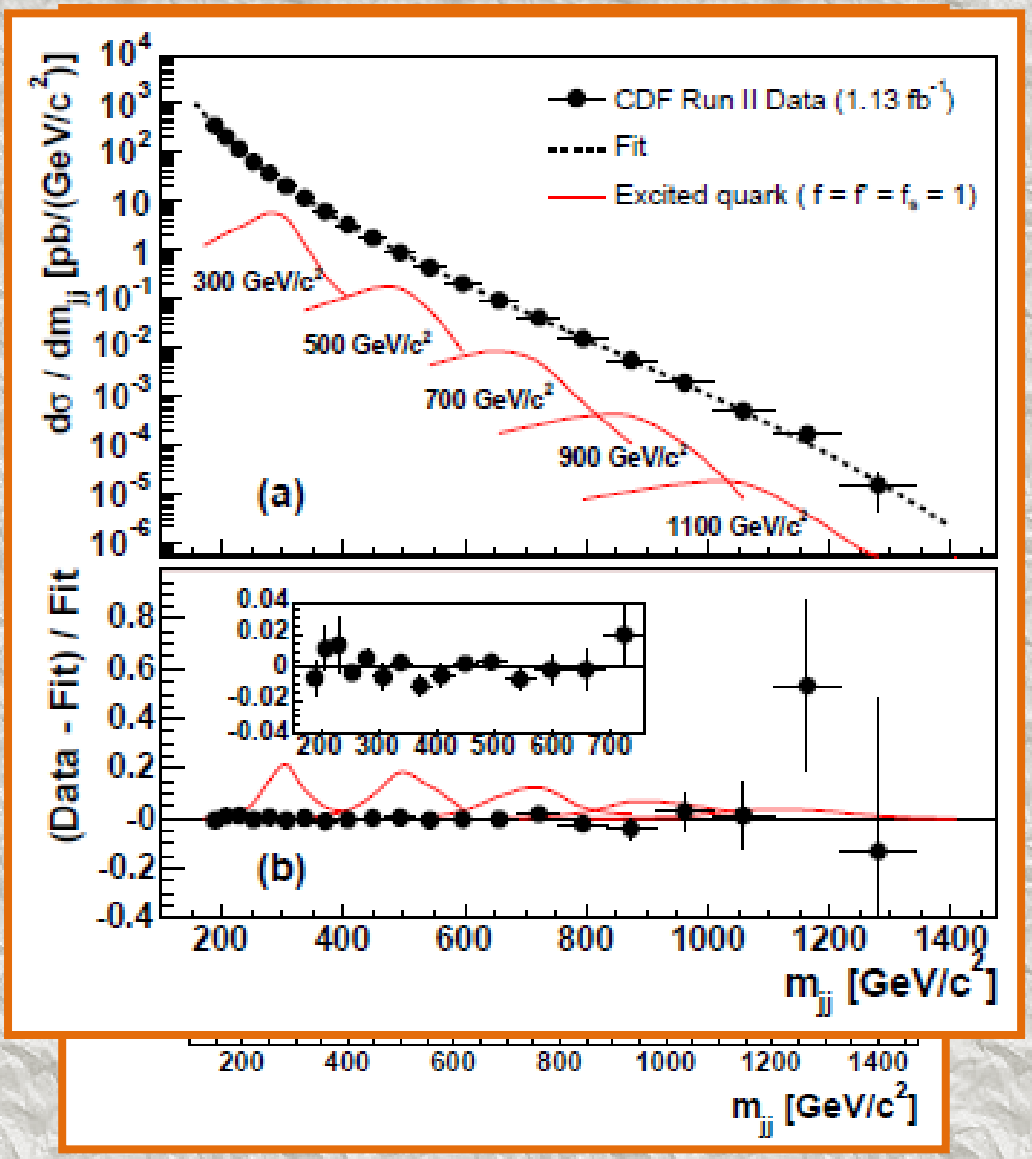
290 - 630 GeV

Color-octet techni-ρ

260 - 1100 GeV

W' : 280 - 840 GeV

Z' : 320 - 740 GeV

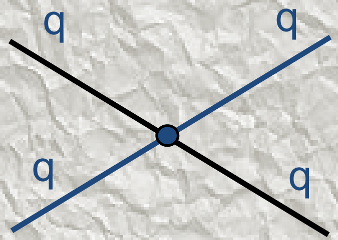


Dijet Angular Distributions

$d\sigma \sim$ [QCD + Interference + Compositeness]

$$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$$

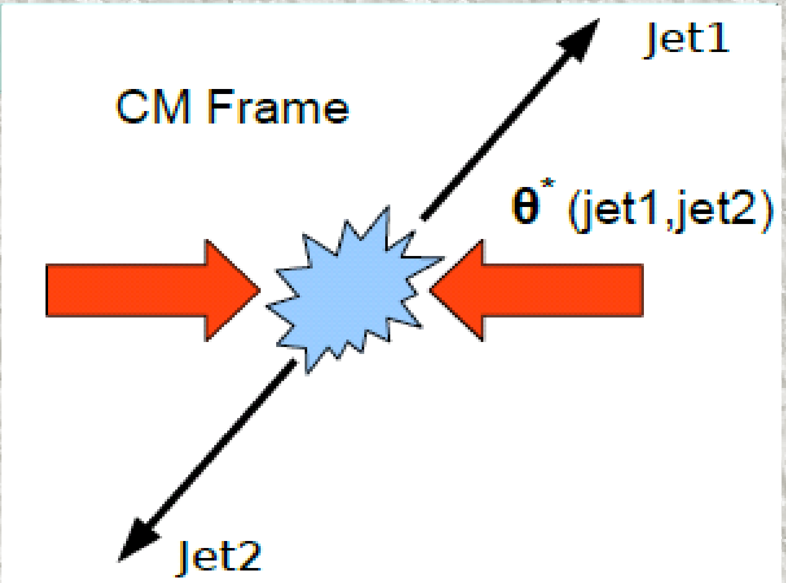
$$\alpha_s^2(\mu^2)\frac{1}{\hat{t}^2} \qquad \alpha_s(\mu^2)\frac{1}{\hat{t}}\cdot\frac{\hat{u}^2}{\Lambda^2} \qquad \left(\frac{\hat{u}}{\Lambda^2}\right)^2$$

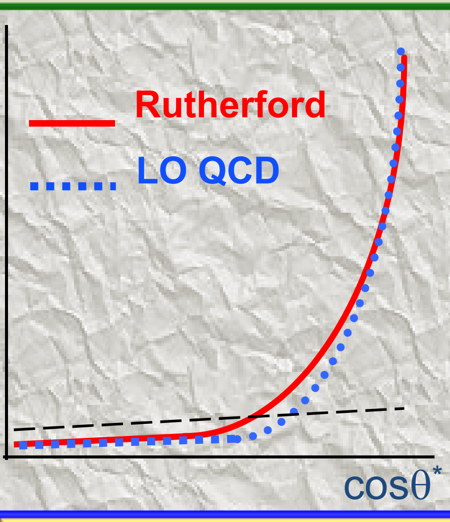


$\sqrt{\hat{s}} << \Lambda$

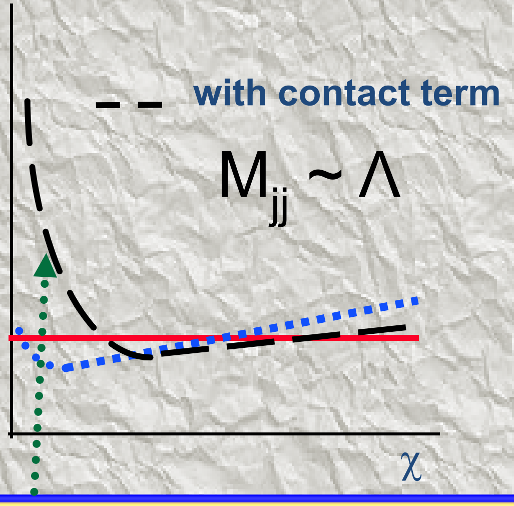
$d\sigma \sim 1/(1-\cos\theta^*)^2$ angular distribution

$d\sigma \sim (1+\cos\theta^*)^2$ angular distribution





$\Rightarrow$

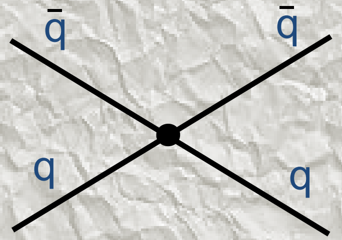


dN/dχ sensitive to contact interactions

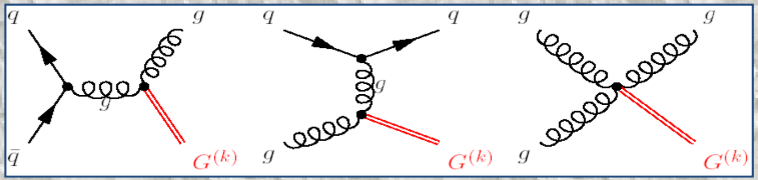
Compositeness and Large Extra Dim.

- **Quark Compositeness:**
  - For $\sqrt{\hat{s}} << \Lambda$ the composite interactions can be represented by contact terms:

$$L_{qq} = \pm \frac{g^2}{2\Lambda^2} \bar{q}_L \gamma^\mu q_L \bar{q}_L \gamma_\mu q_L$$



    - Eichten, Lane, Peskin, PRL 50, 811 (1983)
    - $\Lambda=\infty$ → point-like quarks
    - Λ=finite → substructure of mass scale Λ



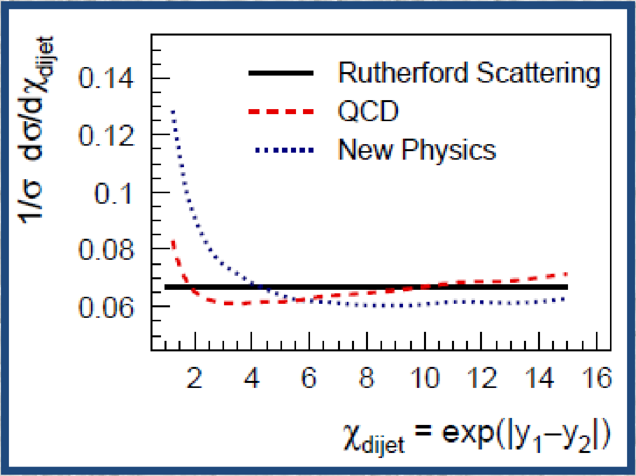
- **Large Extra Dimensions (LED)**
  - In the ADD Model:
    - N.Arkani-Hamed, S.Dimopoulos, G.R.Dvali, PLB 429, 263 (1998), *et al.*
    - 3+n spacelike dimensions
    - n dimensions compactified to a n-torus with radius R
      - R~1 mm for n=2, R~3 nm for n=3, …
    - All SM fields are confined to a 3-dim membrane (*brane)*
    - Only gravity propagates in all dimensions *(bulk)*
  - Mass hierarchy problem is solved
  - The unification scale can be lowered to M_s~TeV

TeV^{-1} Extra Dimensions

- **In the TeV^{-1} Extra Dimension Model**
    - **K.Dienes, E.Dudas, T.Gherghetta, Nucl. Phys. B 537, 47 (1999)**
    - **A.Pomarol, M.Quirós, PLB 438, 255 (1998)**
    - **I.Antoniadis, K.Benakli, M.Quirós, PLB 460, 176 (1999), *et al.***
- **Matter resides on a *p*-brane (spacelike dim *p*>3):**
- **Fermions are confined to 3-dim world**
- **SM gauge bosons can also propagate in the extra (*p*-3) dimensions**
    - **SM cross sections are modified due to the exchange of virtual Kaluza-Klein excitations ($M_n = \sqrt{M_{SM}^2 + n^2 / R^2}$, *n*=1,2,…) of the SM gauge bosons (e.g., gluons) through the ED**
    - **Compact dimension R=1/M_C (M_C is the compactification scale)**
        - **the 95% CL limit: M_C=6.6 TeV from combined LEP data**

Search for BSM Signatures

- BSM signatures will populate the low-χ region at high M_{jj}:
  - Compositeness (scale Λ)
  - Virtual exchange of KK excitations of graviton (ADD LED scale M_s)
  - Virtual KK excitation of gluon (TeV^{-1} ED scale M_C)
- Theory implementation:



$$\sigma_{NP}^{NLO} = \sigma_{QCD}^{NLO} \cdot \frac{\sigma_{NP}^{LO}}{\sigma_{QCD}^{LO}} = \sigma_{NP}^{LO} \cdot \frac{\sigma_{QCD}^{NLO}}{\sigma_{QCD}^{LO}}$$

$$\sigma_{NP} = ME_{SM} + \xi \cdot ME_{\mathrm{int}} + \xi^2 \cdot ME_{NP}$$

$$\xi = \lambda / \Lambda^2 \ (\mathrm{QC})$$

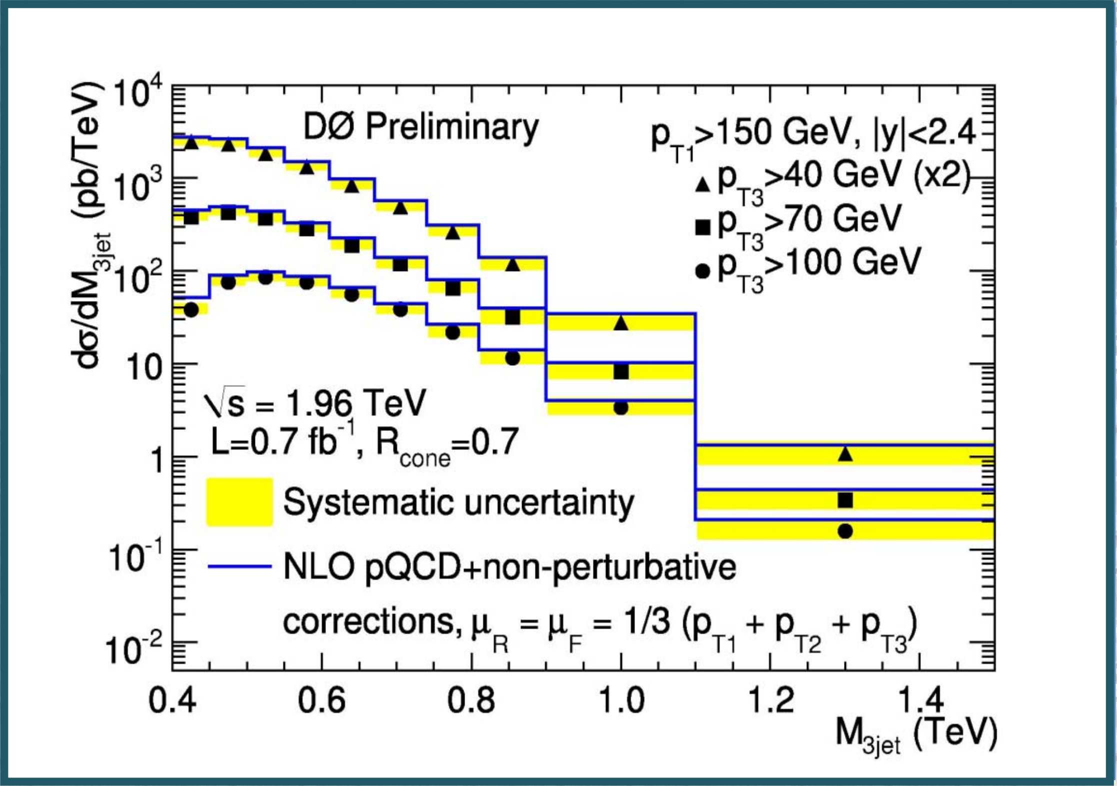
$$\xi = 1/M_s^4 \ (\mathrm{ADD\ LED})$$

$$\xi = 1/M_C^2 \ (\mathrm{TeV^{-1}\ ED})$$

3-Jet Mass Cross Section

- First measurement of 3-jet cross section at Tevatron
- Require at least 3 jets in the event
  - Jet1 $p_T > 150$ GeV
  - Jet 2,3 $p_T > 40$ GeV
  - Jets separated by $\Delta R > 1.4 = 2{*}R_{cone}$
- Measurement performed in:
  - rapidity intervals $|y| < 0.8, 1.6, 2.4$
  - p_T ranges of the 3rd jet: $p_T^{Jet3} > 40, 70, 100$ GeV
- Compared data to NLO pQCD

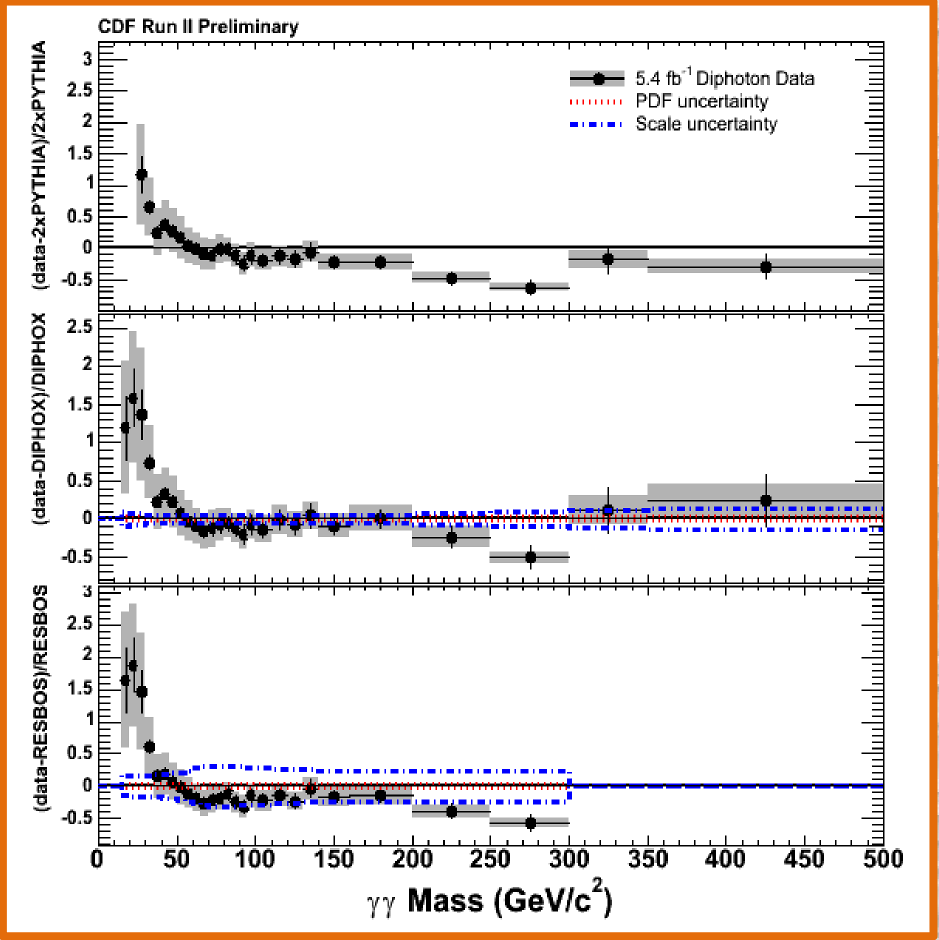
p_T^{Jet3} Dependence

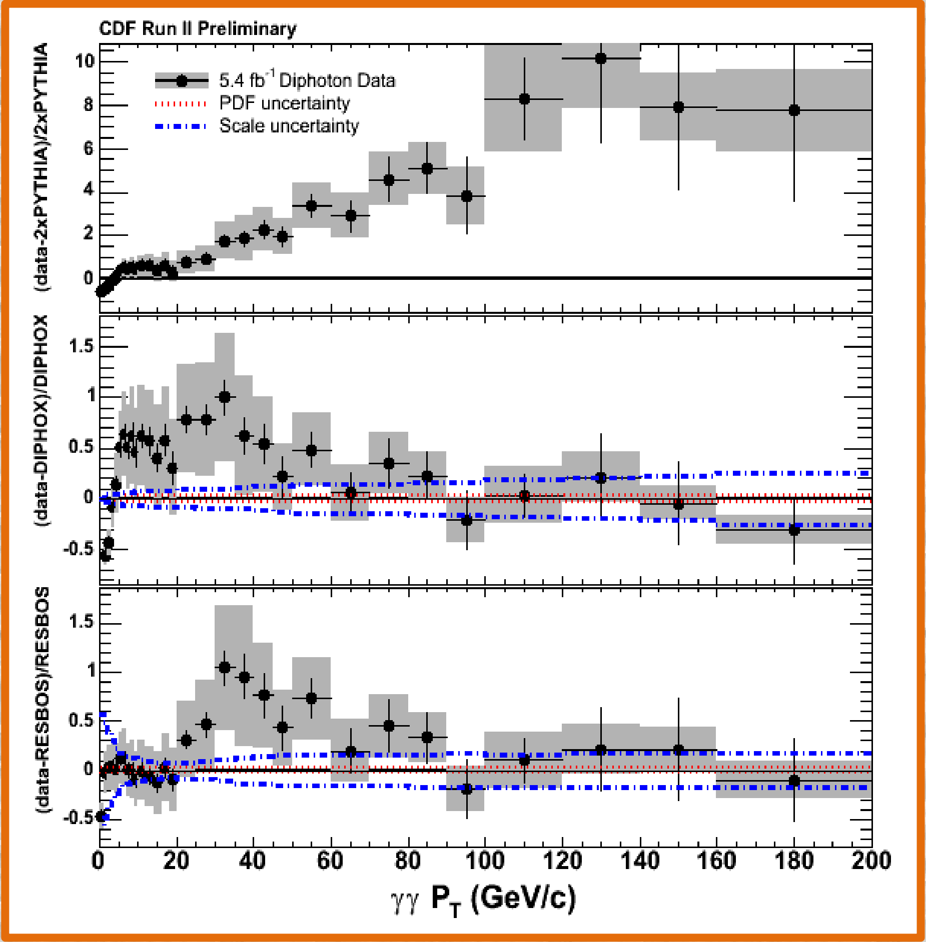


$$\frac{d\sigma}{dM_{3\mathrm{jet}}} = \frac{1}{L \cdot \Delta M_{3\mathrm{jet}}} \cdot \left(\sum_{i=1}^{N_{\mathrm{evt}}} \frac{1}{\epsilon_{\mathrm{V}}^{i}} \right) \cdot C_{\mathrm{unsmear}}$$

Direct Photons

Di-Photon Results

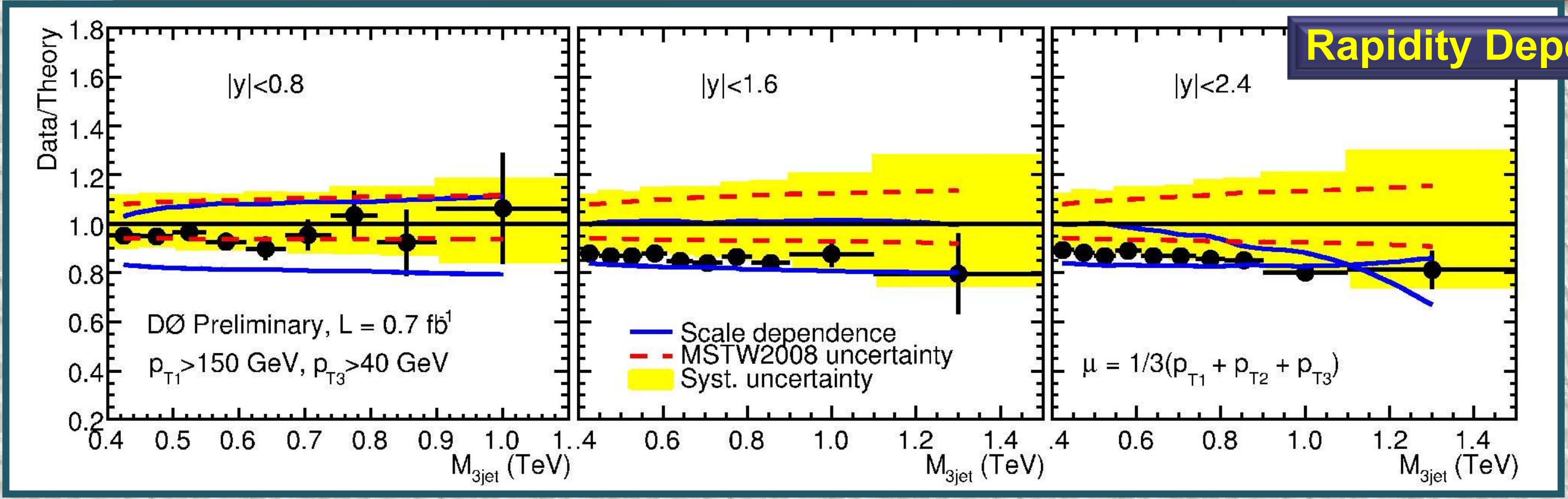




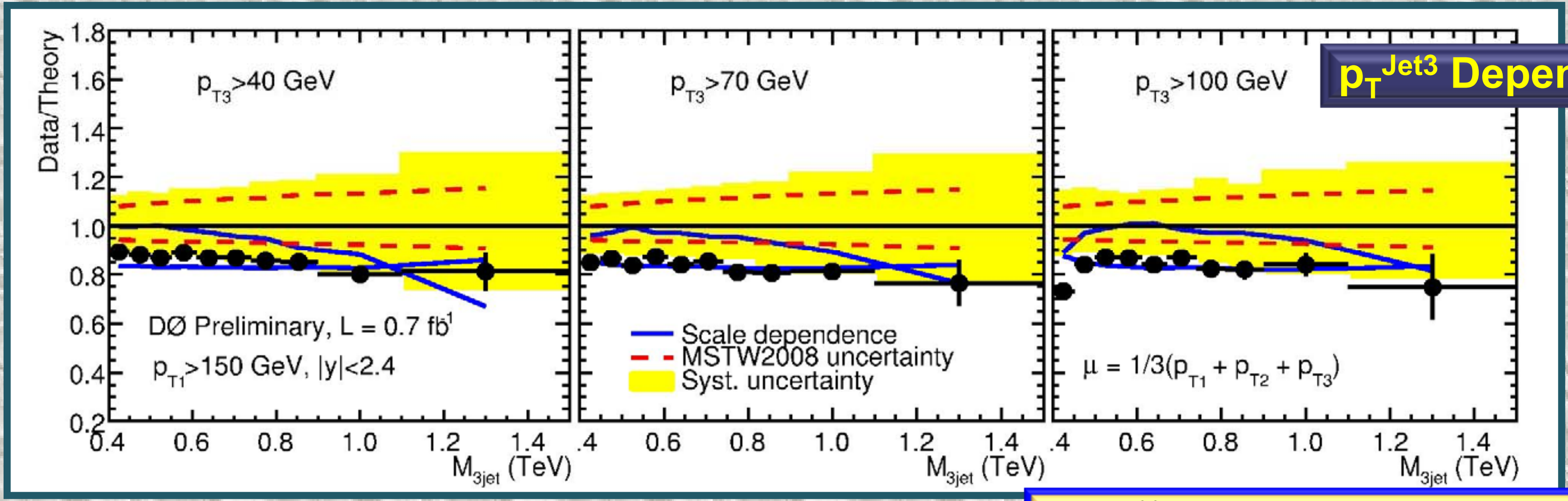
Diphoton results w/ 5.4 fb^{-1} → show discrepancies with predictions

W/Z+Jets

3-Jet Mass: Data vs pQCD



Rapidity Dependence



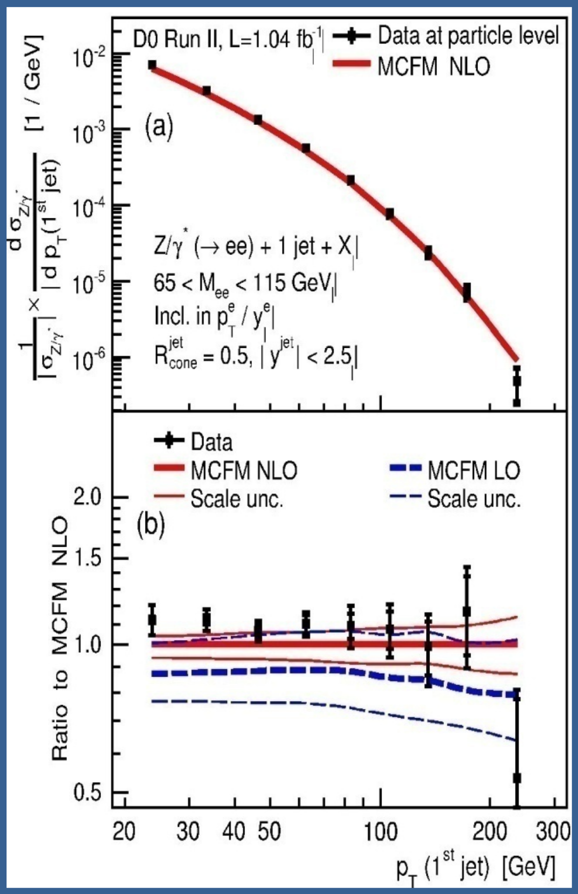
p_T^{Jet3} Dependence

Well described by NLO pQCD

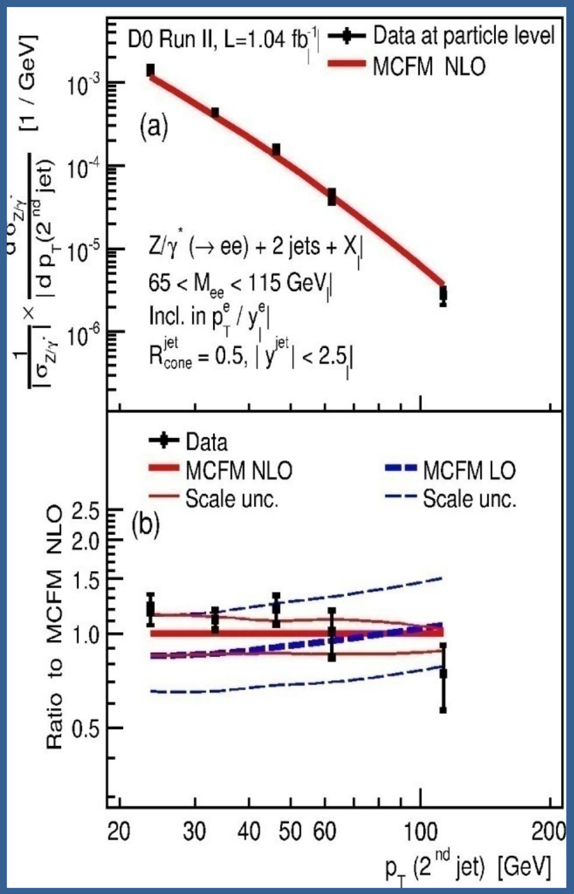
Z(ee) + (1, 2, 3) Jets: p_T Spectra

Normalize to inclusive Z production → compare to pQCD @ LO / NLO

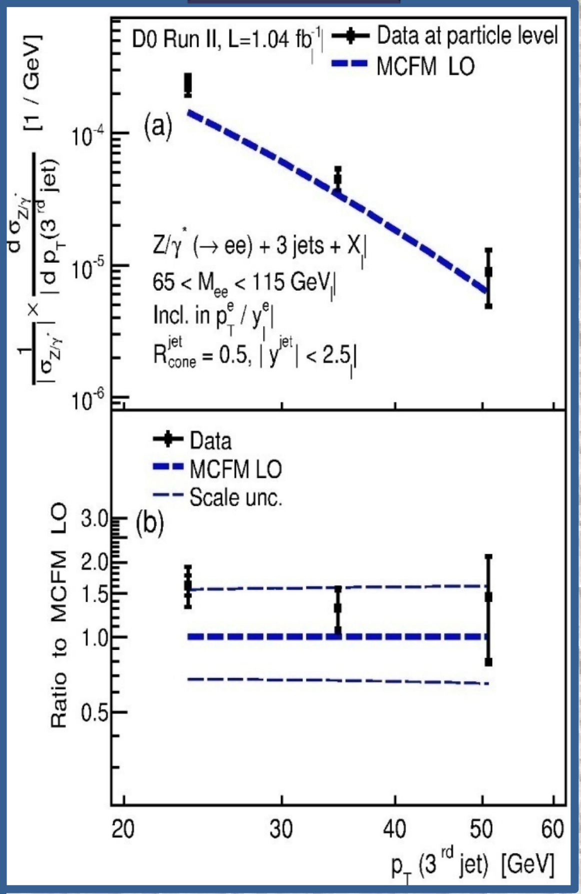
1st jet



2nd jet



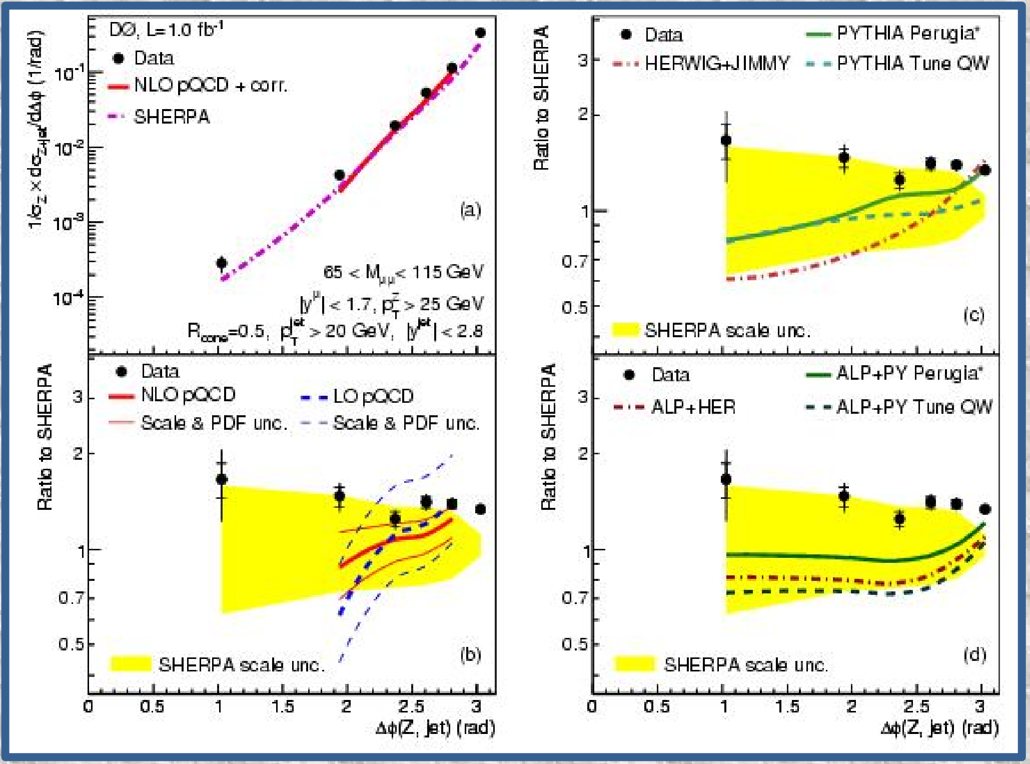
3rd jet



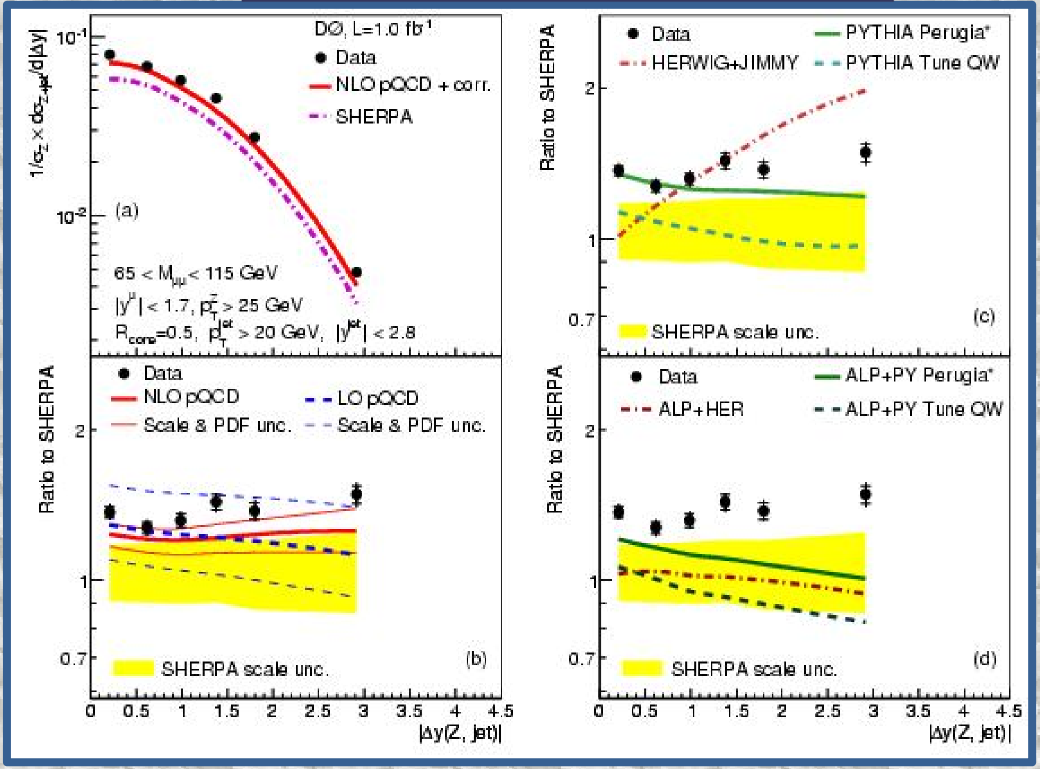
PLB 669, 278 (2008) & PLB 678, 45 (2009)

Z(μμ) + Jets: Rapidity, Azimuth

σ(Z+jet) vs. Δφ(Z,jet)



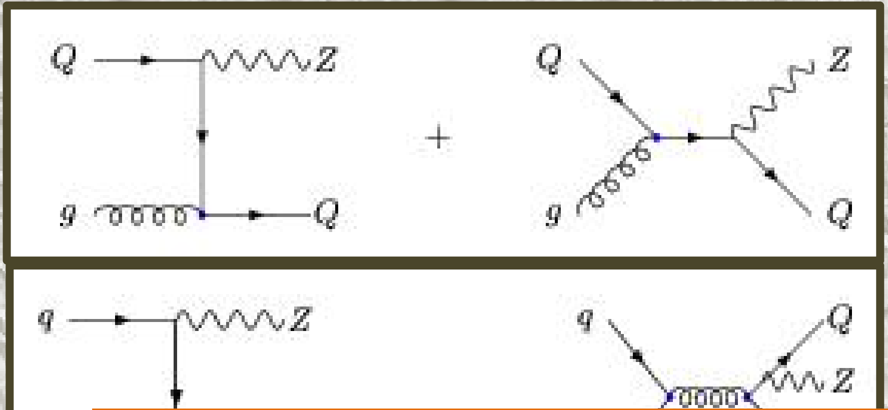
σ(Z+jet) vs. Δy(Z,jet)



PLB 682, 370 (2010)

Z + b jet

- Z+b probes the b-quark PDF and provides an important test of pQCD
- Background for many channels: ZH, top, SUSY, …



- Analysis combines Z→ee and μμ channels
- At least one jet with p_T>20 GeV, |η|<1
- 2 electrons (muons)
    - p_T>15 GeV (10 GeV), |η|<2.5 (2.0)

Measurement:

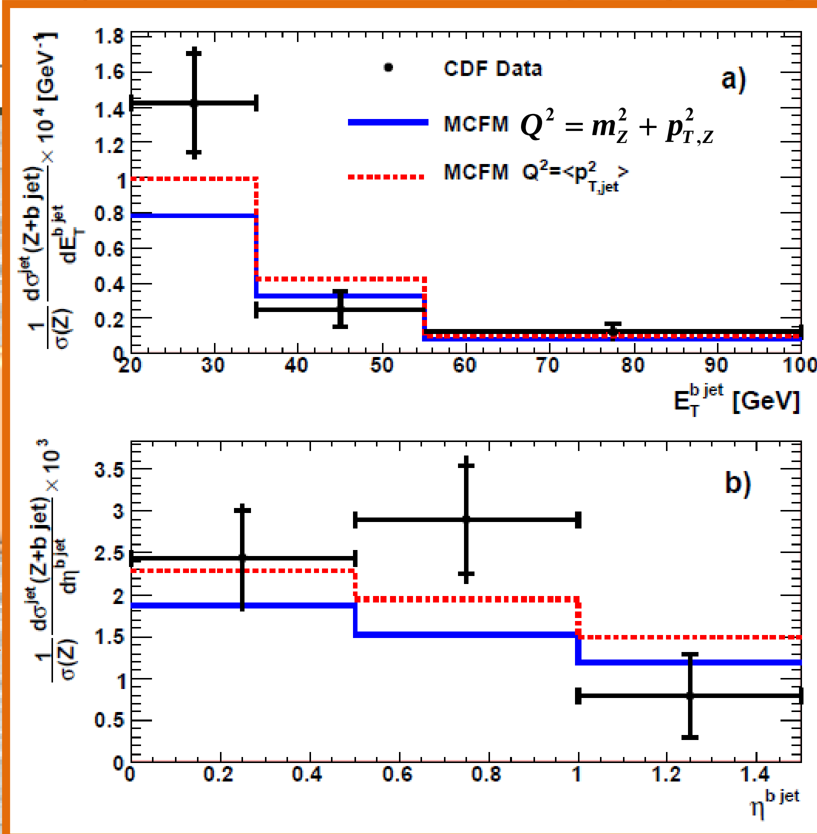
σ(Z+b)/σ(Z+j) = 0.0176±0.0024(stat)±0.0023(sys)

Good agreement with NLO QCD: 0.018±0.004

Previous measurements:

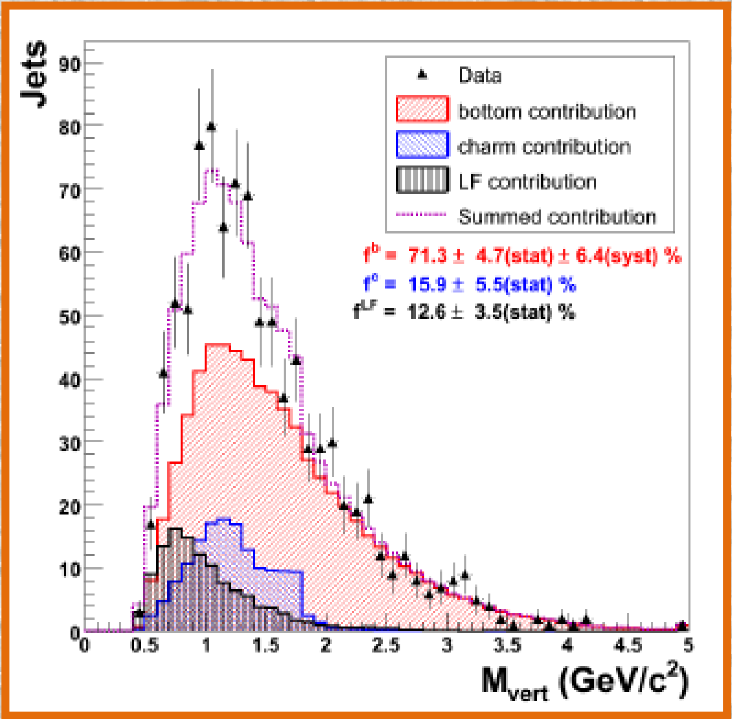
DØ: PRL 94, 161810 (2005)

CDF: PRD 79, 052008 (2009)



W + b jet

- **Important process from many searches at Tevatron and LHC**
- **Invariant mass of charged particles associated with the secondary vertex is used to discriminate between the possible jet flavors to yield the b-jet fraction**



$p_T^{e,\mu} > 20$ GeV/c, $|\eta^{e\mu}| < 1.1$, $p_T^{\nu} > 25$ GeV/c
$p_T^{bjet} > 20$ GeV, $|\eta^{bjet}| < 2.0$

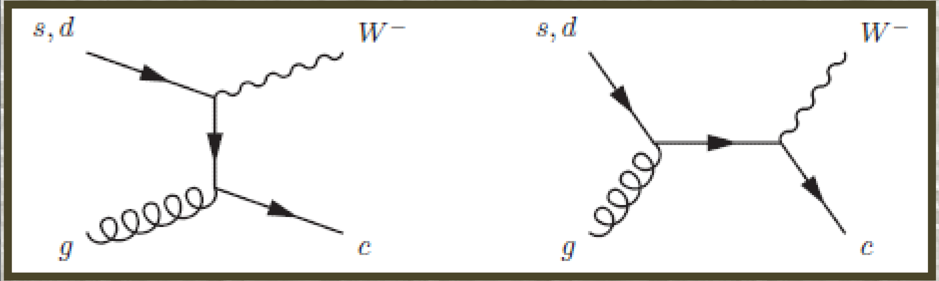
σ b-jets (W+b-jets) · BR(W → l ν) = 2.74 ± 0.27 (stat) ± 0.42(syst) pb

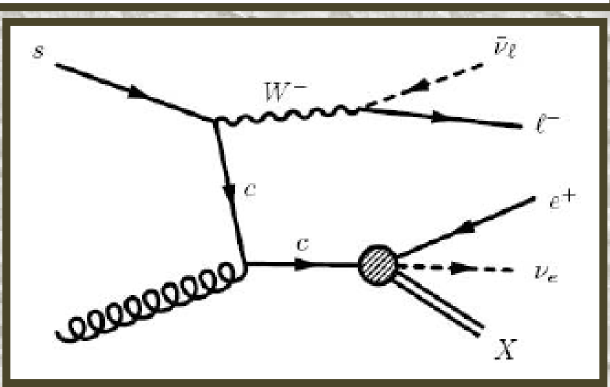
All predictions are lower than the measurement:
Pythia: 1.10 pb, ALPGEN: 0.78 pb, NLO: 1.22±0.14 pb

CDF: PRL 104, 131801 (2010)

W + Charm

- Probes s-content on proton
  - *g+s ~ 90%, g+d ~ 10%*
- At Tevatron W+c is ~5% of the inclusive W+1 jet cross section with $p_T^{jet}>10$ GeV
- Charge correlation of leptons used in event selection
- Use soft lepton tagger +NN for c-jet





Preliminary Measurement (4.3 fb^{-1})

$\sigma(W_c)\bullet BR(W \rightarrow l\nu) = 33.7 \pm 11.4\ (stat) \pm 7.3\ (syst)$ pb

Theory prediction @NLO (MCFM): 16.5 ± 4.7 pb

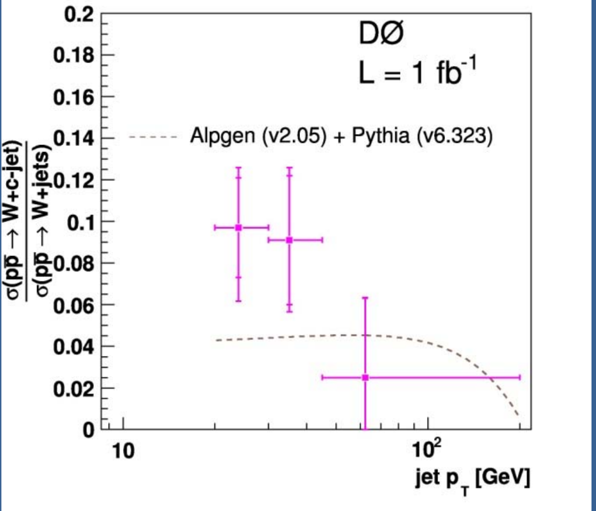
Previous CDF: PRL 100, 091803 (2008)

- **Measure of the ratio of σ(W+c jet)/σ(W+jets) cancels many systematic uncertainties**
- **$p_T^{jet}>20$ GeV, $|\eta^{jet}|<2.5$**

$$\frac{\sigma[W+c\text{-jet}]}{\sigma[W+\text{jets}]} = 0.074 \pm 0.019^{+0.012}_{-0.014}$$

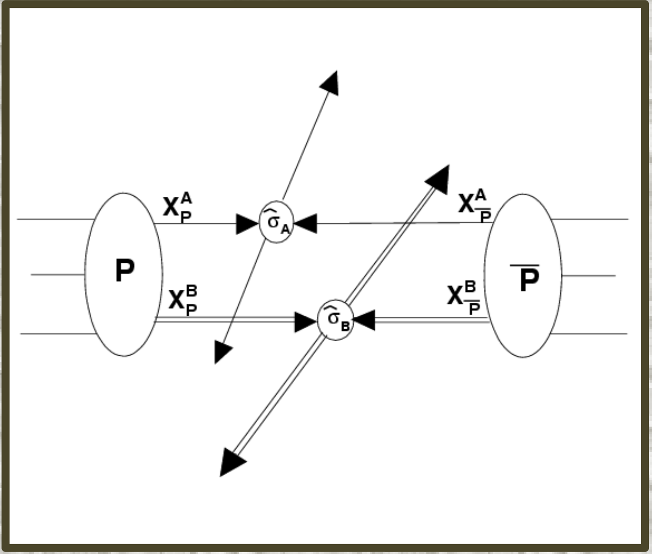
Theory: 0.044±0.003
Alpgen+Pythia

DØ: PLB 666, 23 (2008)

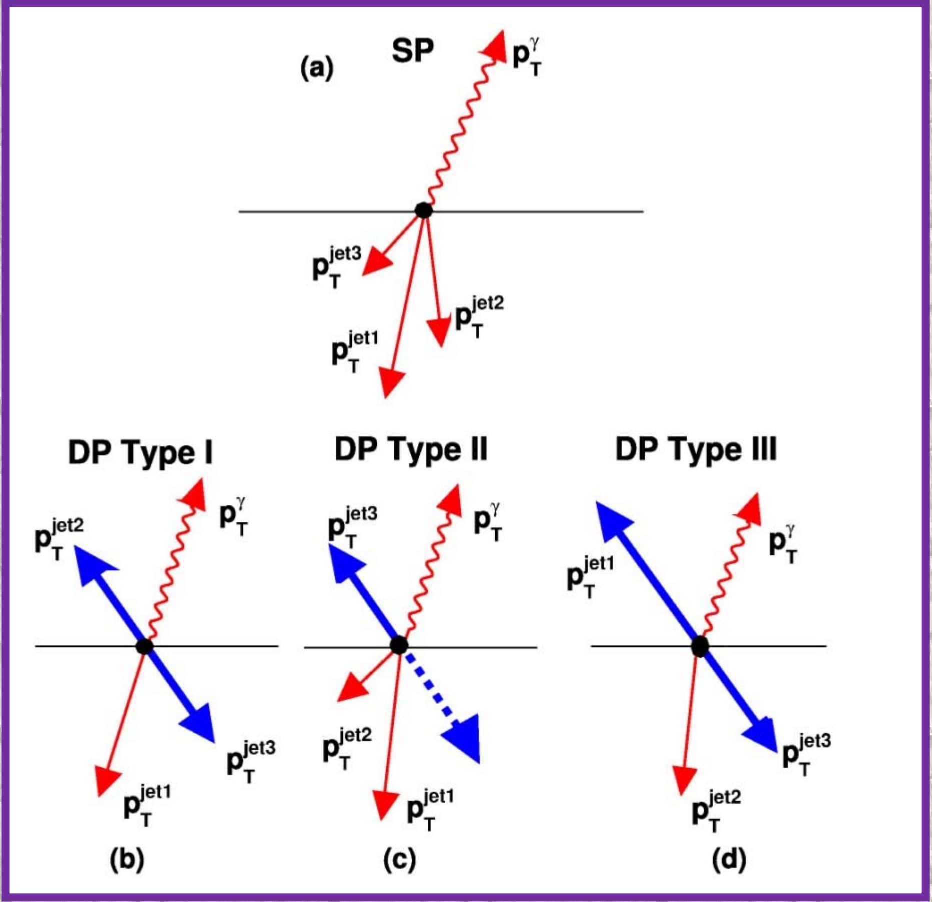


Soft QCD

Double Parton in γ + 3 Jets

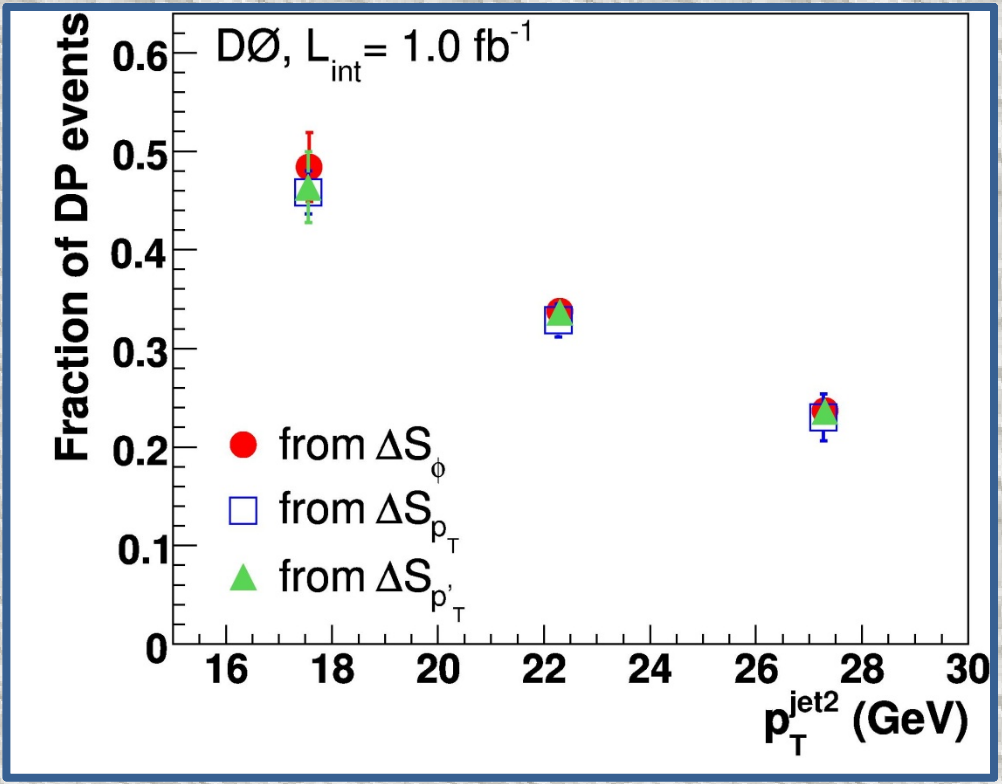


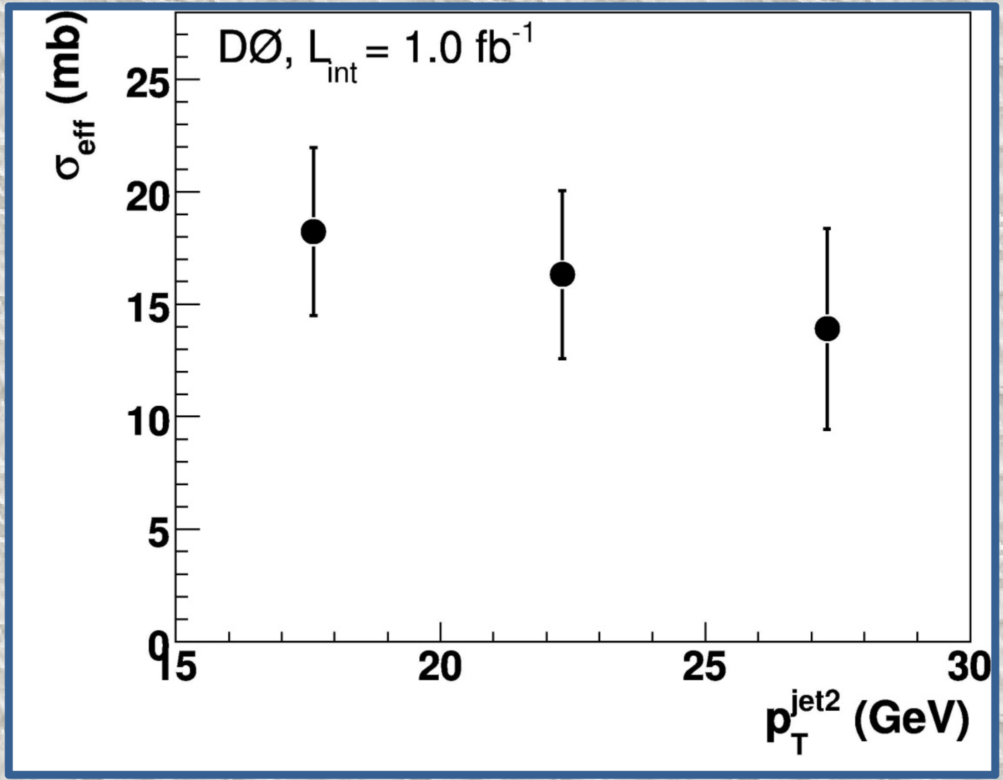
$$\sigma_{DP} = \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$



- Scattering of two parton pairs in a collision
- σ_{eff}: a measure of effective size of interaction region
  - Contains information on the spatial distribution of partons
  - Uniform → Large σ_{eff} → small σ_{DP}
  - Clumpy → Small σ_{eff} → large σ_{DP}
- Double parton scattering can be background to many rare processes

Double Parton: Results





DØ: PRD 81, 052012 (2010)

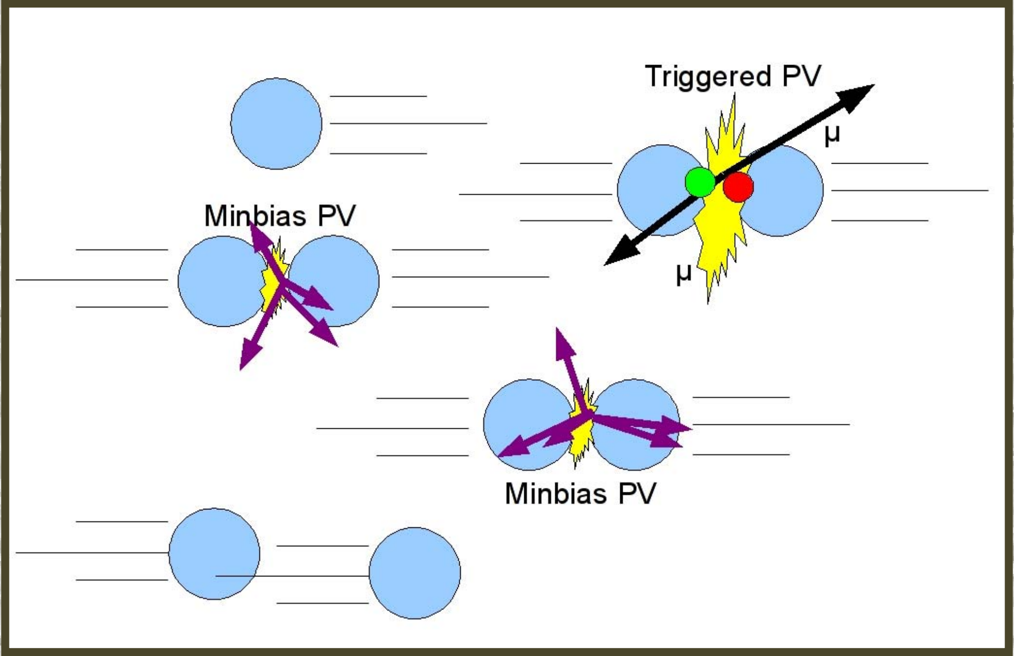
Average σ_{eff} = 16.4 ± 0.3(stat) ± 2.3 (syst) mb

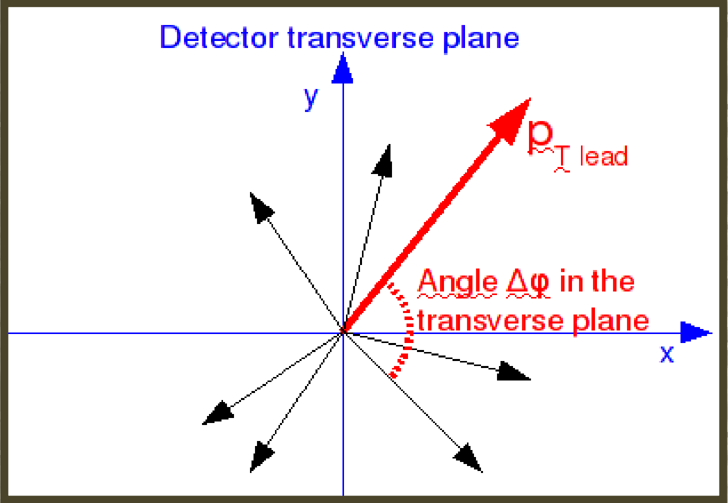
In agreement with previous CDF measurements:

PRD 47, 4857 (1993); PRL 79, 584 (1997)

Charged Particle Correlations in MB Events

- **Selection of MB Sample:**
  - Trigger on dimuon events
  - Then require one or more Minimum Bias primary vertex
    - At least 0.5 cm away from triggered PV
    - Within 20 cm from z=0
    - With at least 5 tracks



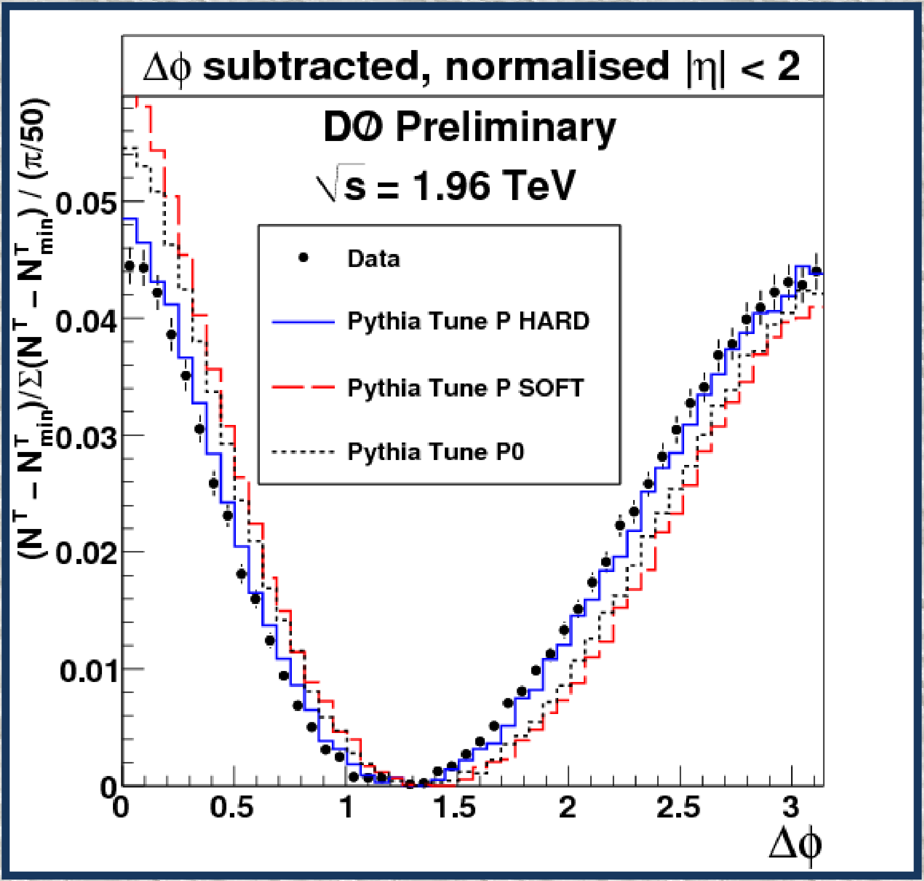


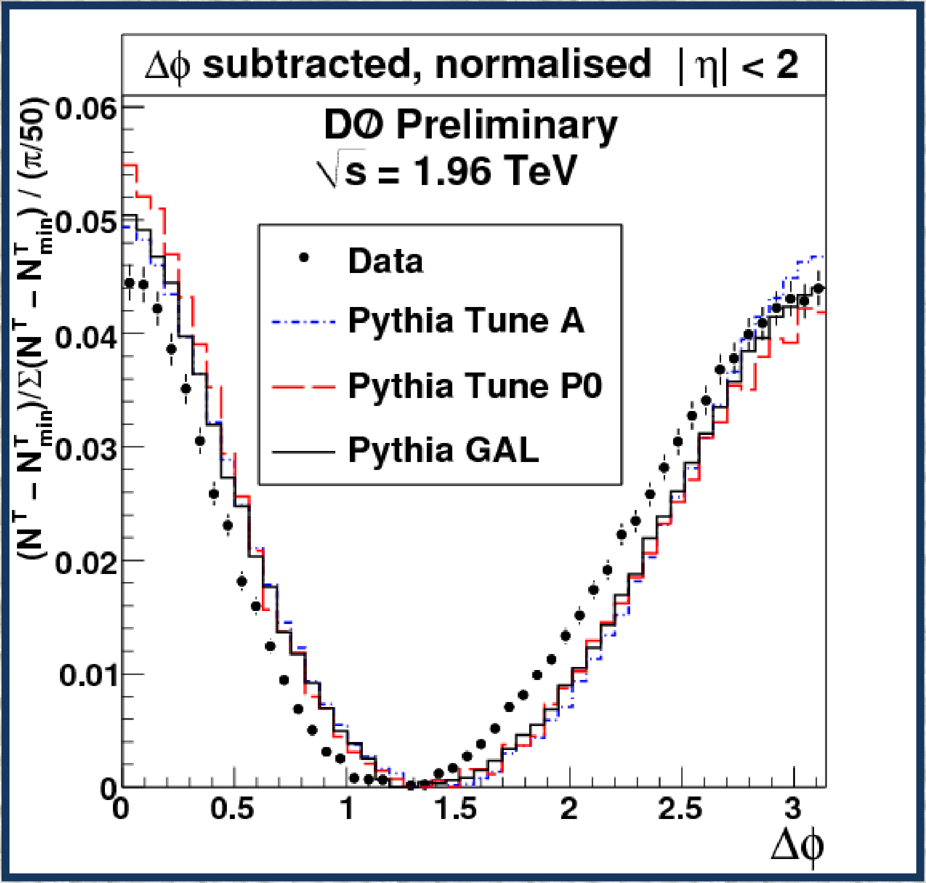
Observable:
(background subtracted, normalized) $\Delta\phi$ distribution of tracks from leading p_T track

Regions: $|\eta| < 1$, $|\eta| < 2$, same/opposite sides

Compare data to Pythia predictions

Charged Particle Correlations: Results

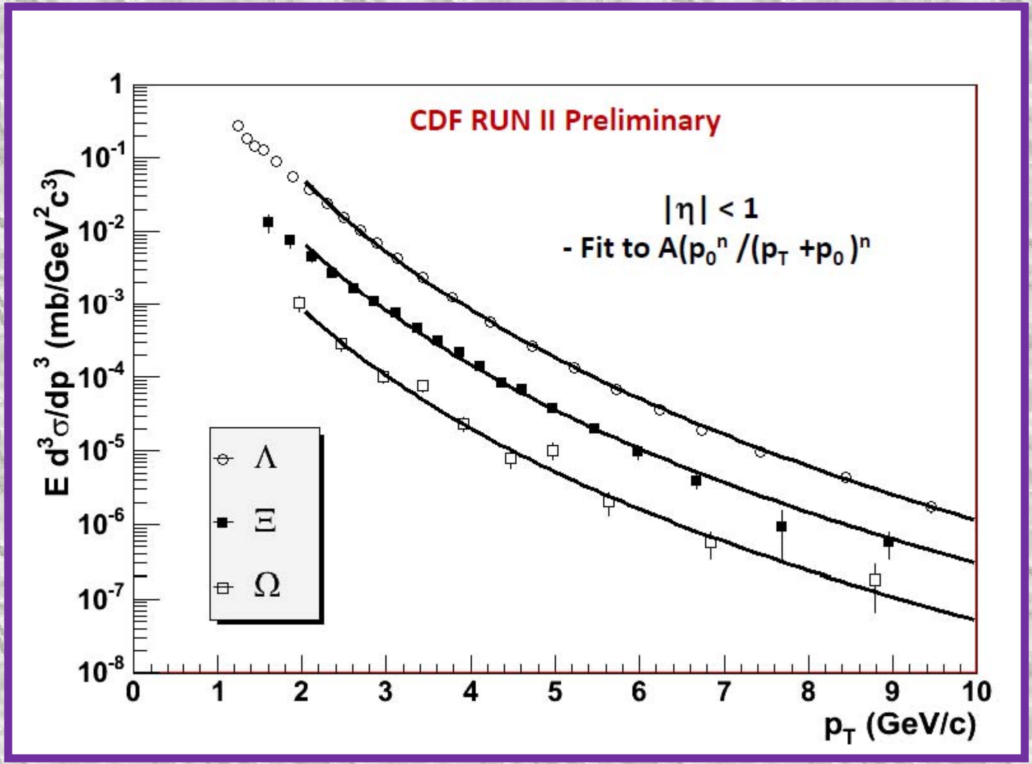


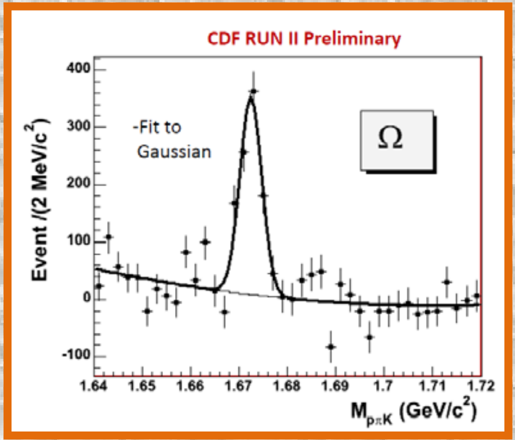


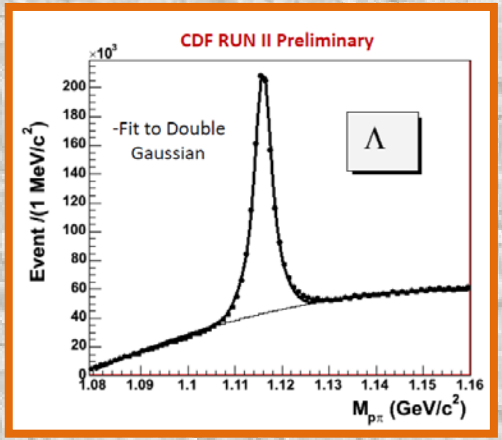
Sensitivity to Pythia tunes → Further studies are under way

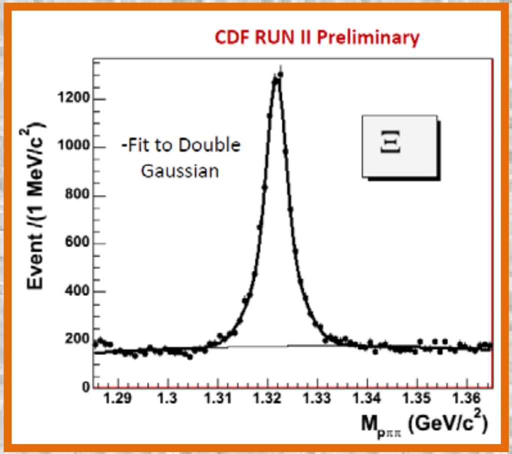
Hyperon Production in Min. Bias

- p_T differential cross section of hyperons with $|\eta|<1$
  - $\Lambda^0 \rightarrow p\pi$, $\Xi \rightarrow \Lambda^0\pi$, $\Omega \rightarrow \Lambda^0 K$
- Use Minimum Bias sample









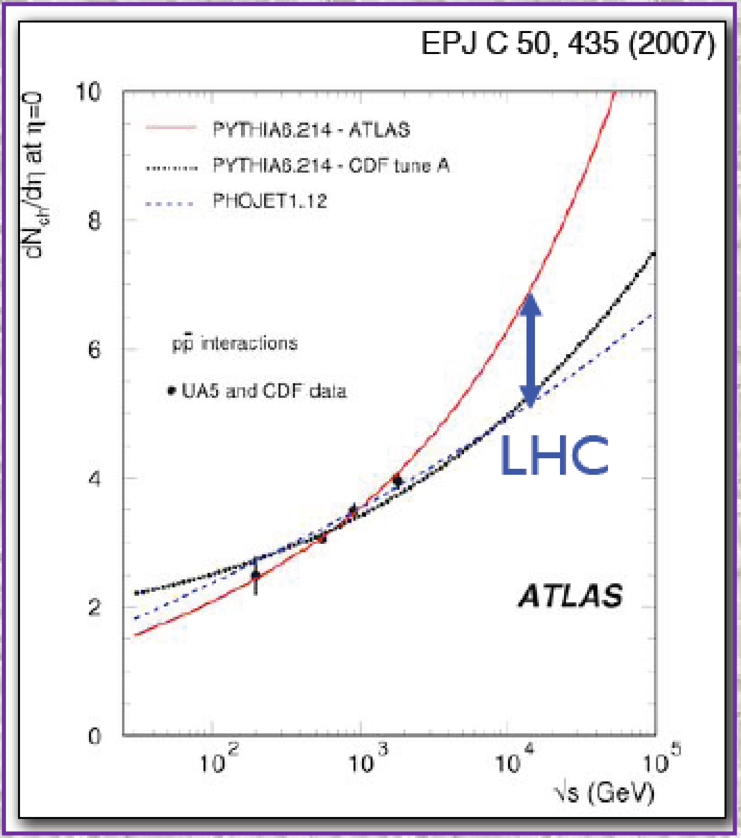
Cross section drops by 7 for each s quark

Minimum Bias Studies at LHC

- **Traditionally defined as Non-Single Diffractive events:**

$$\sigma_{tot} = \sigma_{elas} + \sigma_{sd} + \underbrace{\boxed{\sigma_{dd} + \sigma_{nd}}}_{\text{NSD}}$$

- **Large model dependence on LHC expectations/predictions based on lower energy data**
  - **Need to understand the properties of inelastic events as they will be background due to pile-up at high luminosities**



EPJ C 50, 435 (2007)