QCD results from the Tevatron

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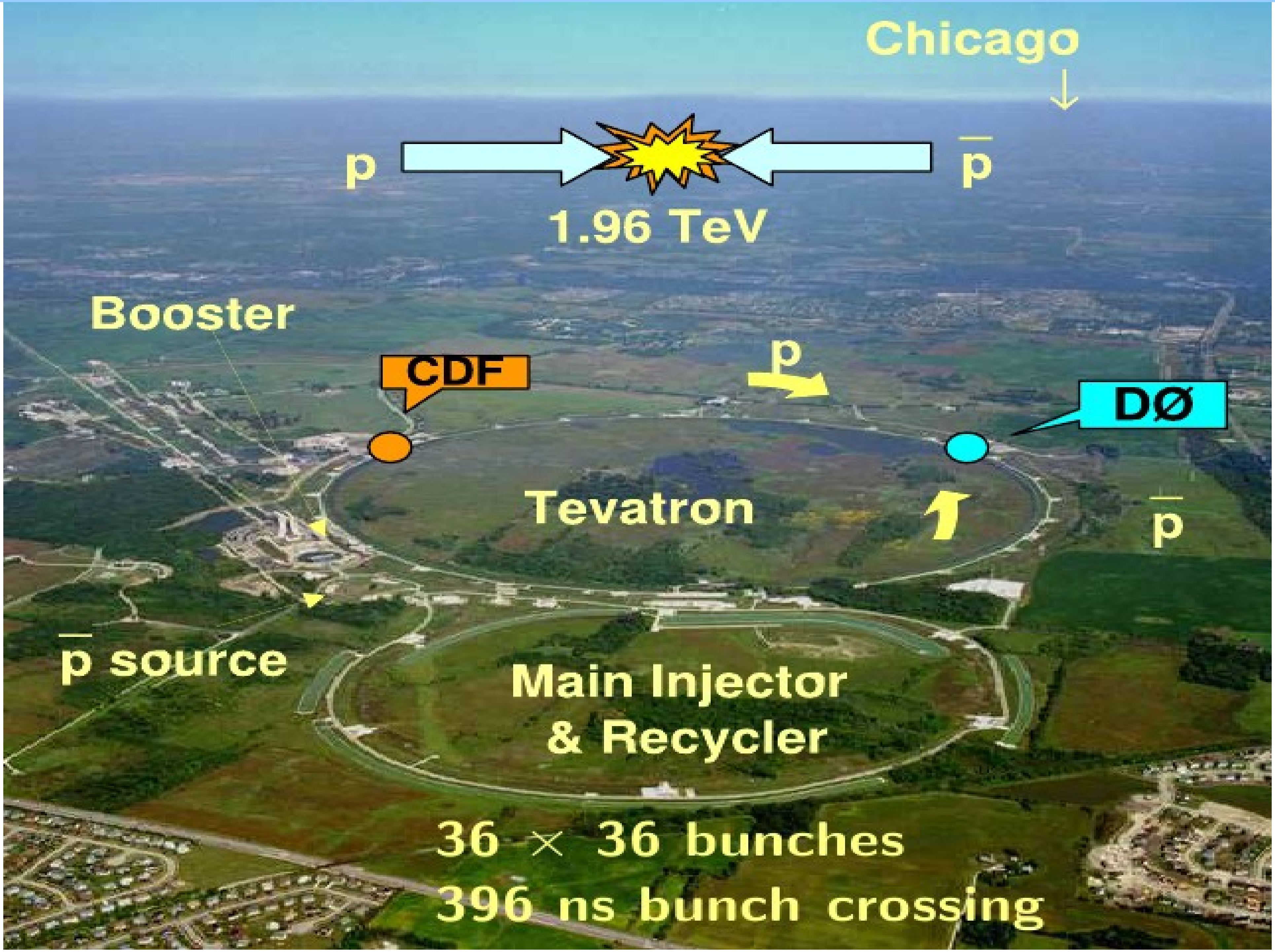
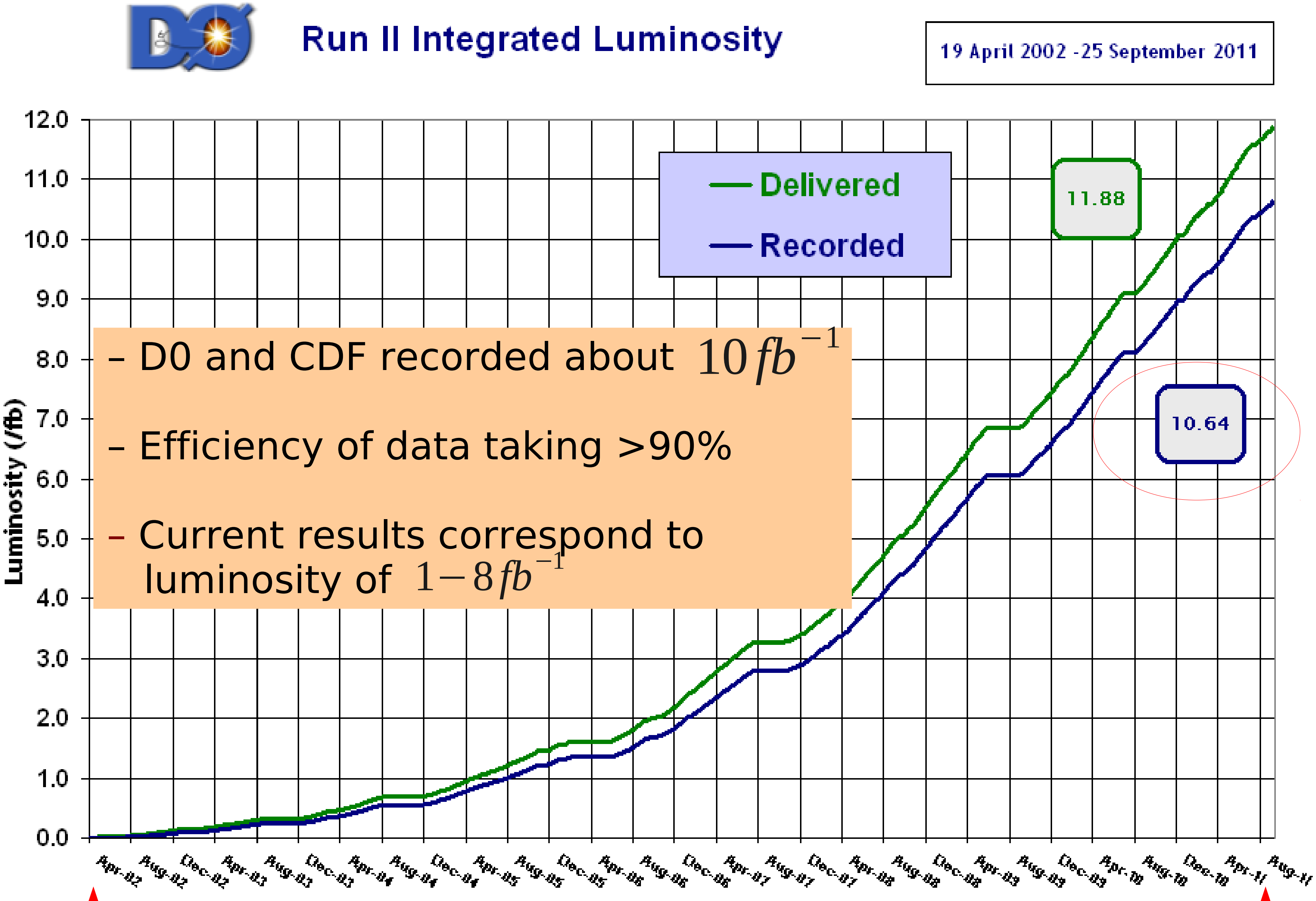
On behalf of D0 and CDF Collaborations

International Workshop on Future Linear Colliders
September 28, Granada, Spain

Tevatron collider



Tevatron collider luminosity



- D0 and CDF recorded about $10\,fb^{-1}$
- Efficiency of data taking >90%
- Current results correspond to luminosity of $1-8\,fb^{-1}$

Apr, 2002

Sep, 2011

Sep 30 is the last day of data taking

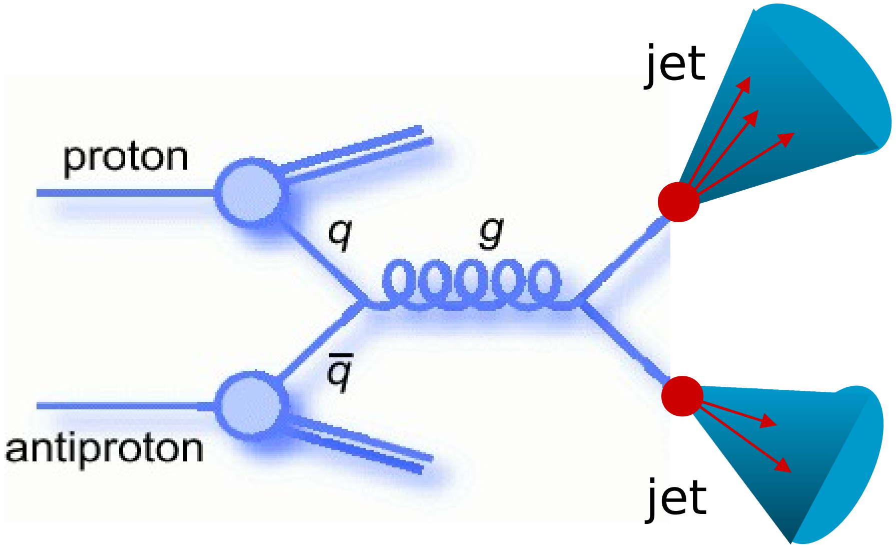
Outline

- Jet production:
  - Inclusive jets
  - Dijets
  - 3-jets

- V(=W,Z) + jets production
  - V + inclusive jets
  - V + heavy flavor jets

- Inclusive photon and di-photon production

- Underlying events and Double parton interactions



Jet Results

PDF, αs

Searches for New Physics

Motivations for the jet measurements

- Parton cross sections are well-understood by NLO pQCD
  => PDF constrain

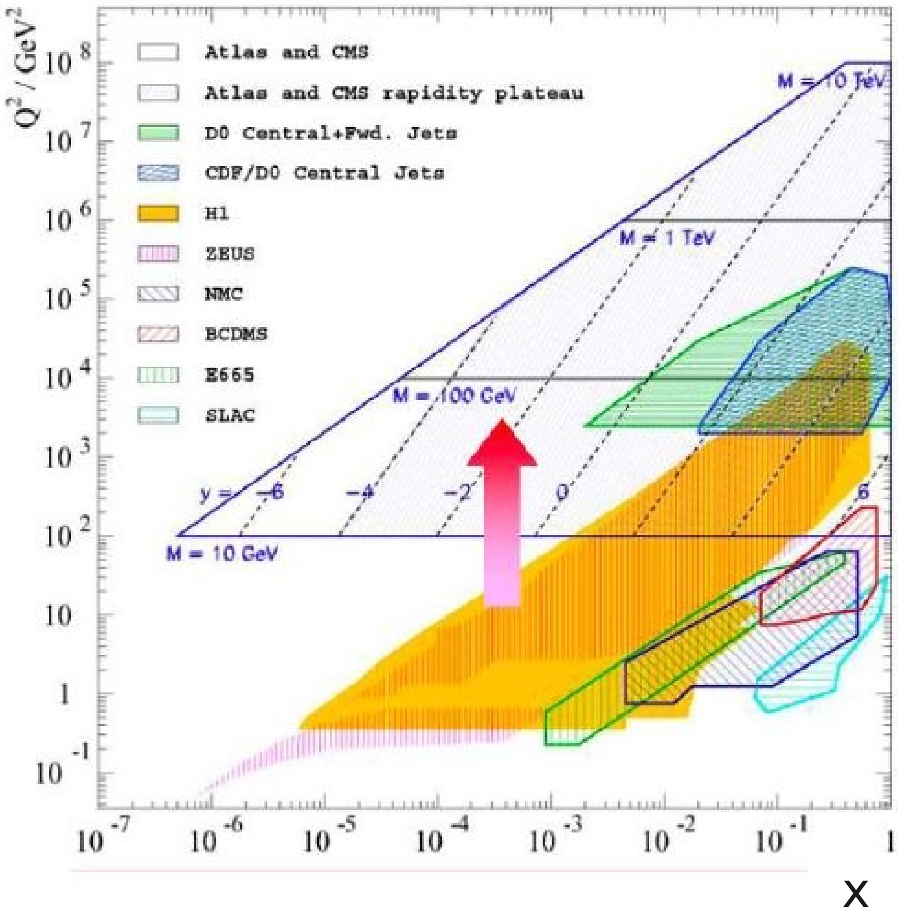
– x-Q^2 regions accessible at fixed target, DIS, Tevatron and LHC are complementary to each other

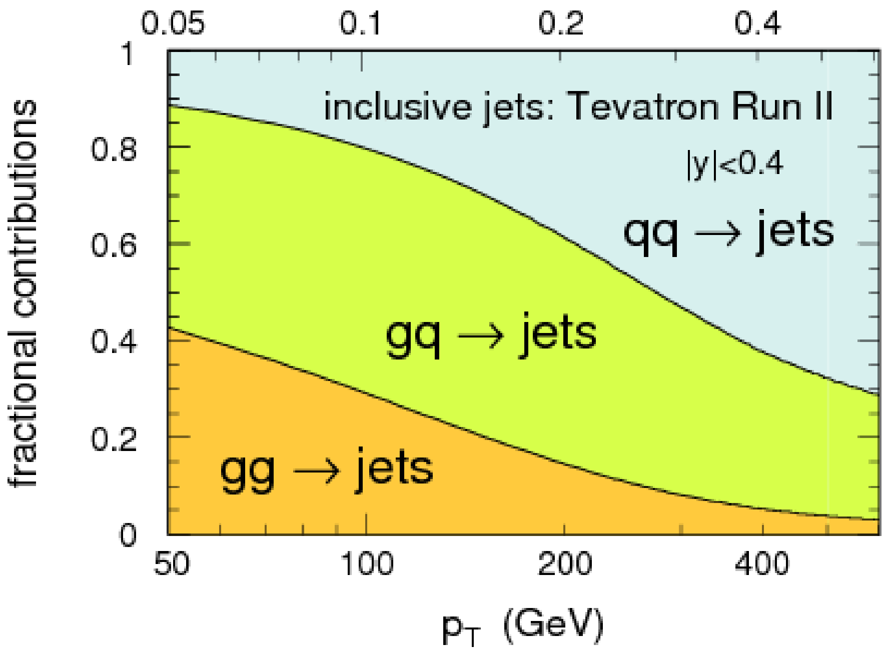
– only Tevatron incl. jet data provide significant constraint on gluon PDF at high x and high Q^2

- New Phenomena searches:

– particles decaying to jets, ED, quark compositeness, etc

– searches for new phenomena are limited without proper understanding QCD background



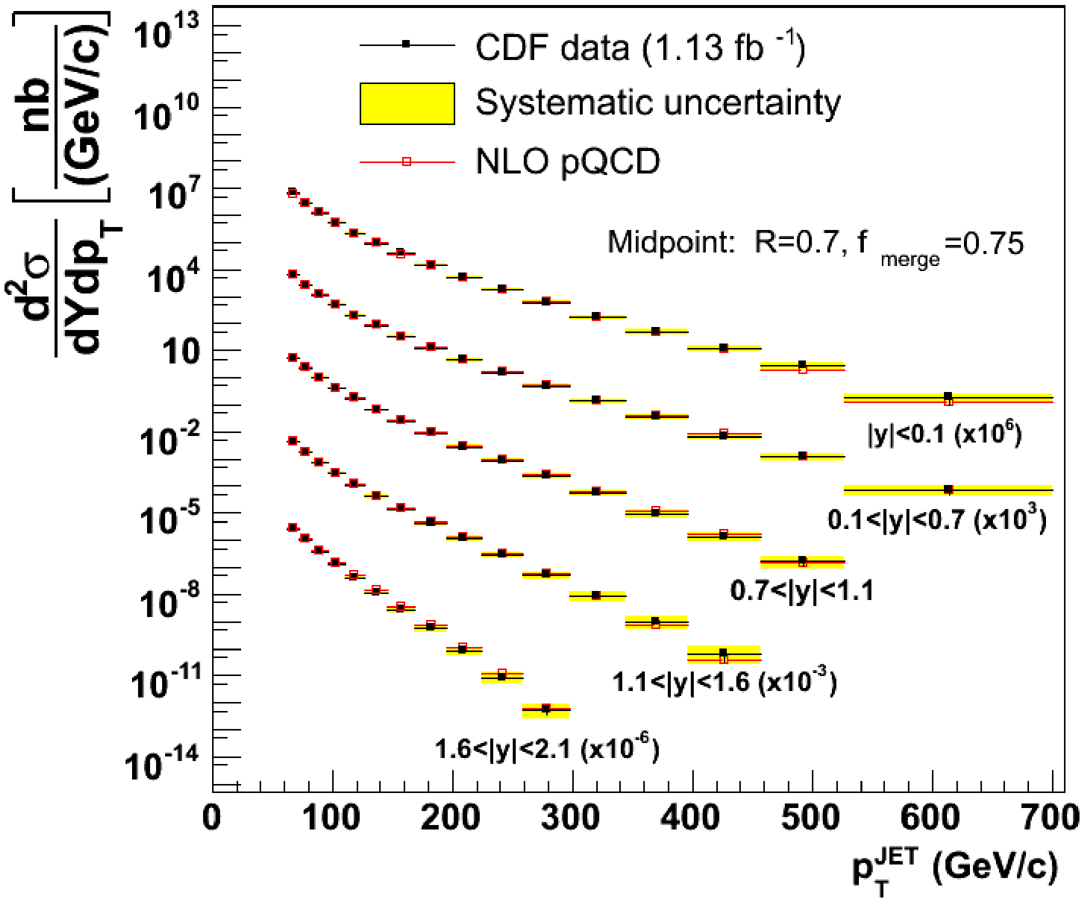


Inclusive jet production (CDF)

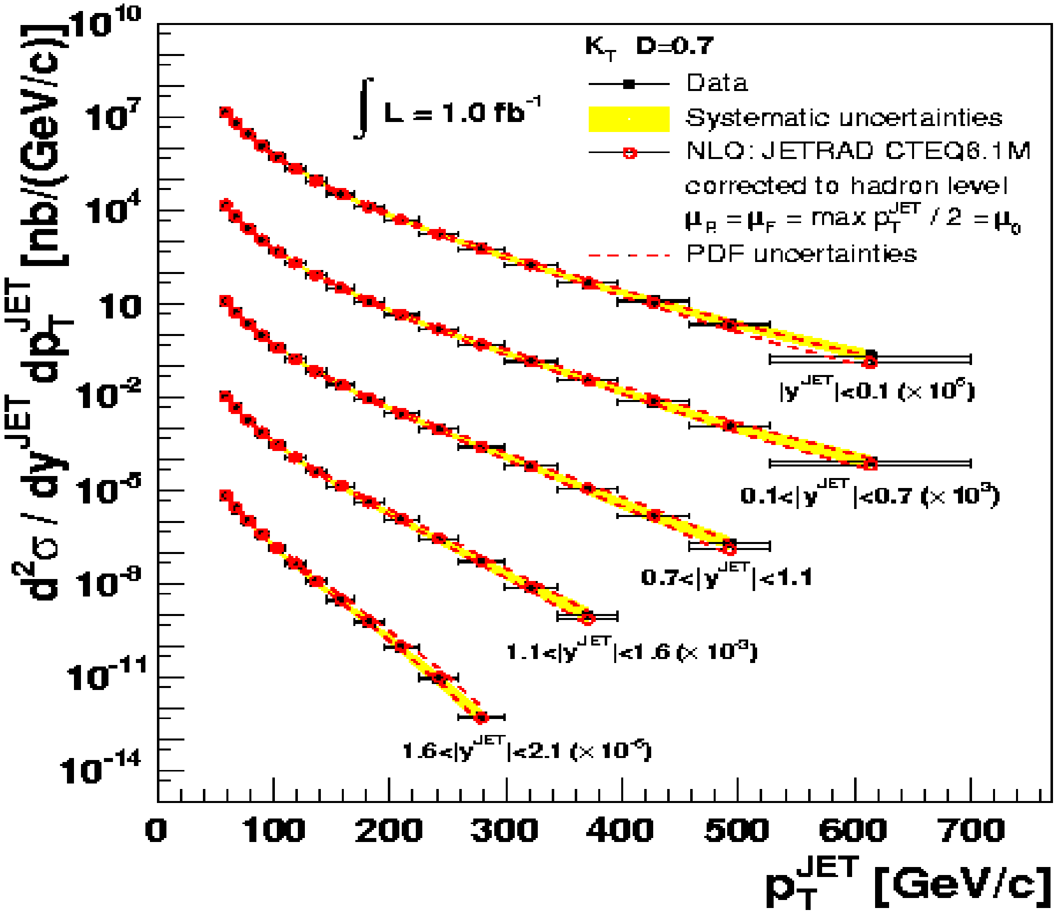
Inclusive jet measurements test pQCD over 8 orders of magnitude in 5 rapidity regions up to jet pT ~600 GeV.

- CDF measured inclusive jet cross section with Midpoint cone algorithm (R=0.7) and kT (D=0.4, 0.7, 1.0) algorithm.
- Data/Theory consistent for the cone and kT (for all D parameters) algorithms
  => both algorithms can be successfully used at hadron colliders.

PRD78, 052006 (2008)



PRD75, 092006 (2007)



Inclusive jet production (D0)

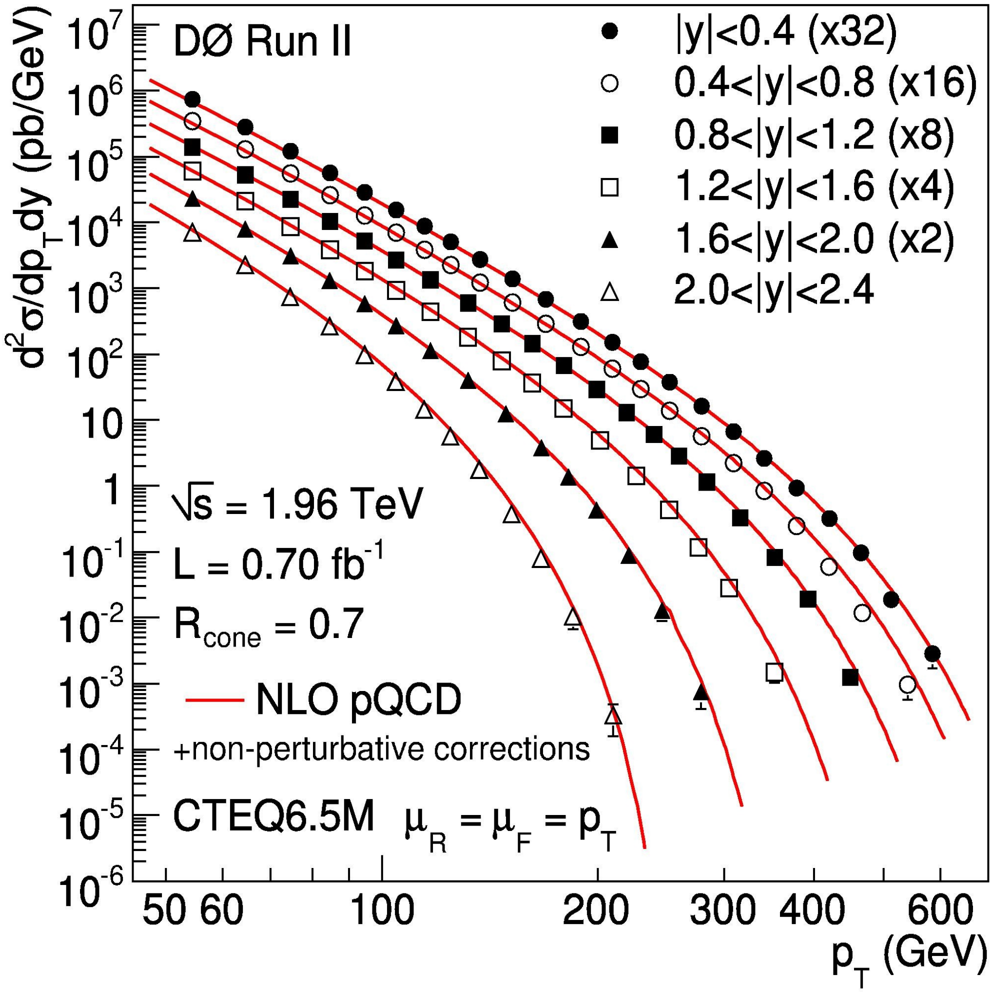
PRL 101, 062001 (2008)

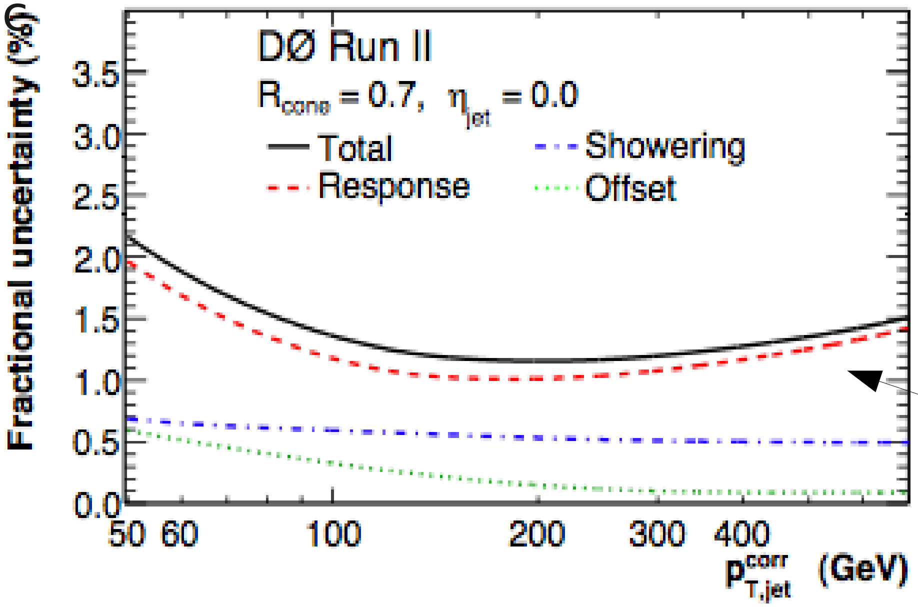
D0 also measured inclusive jet cross section using Midpoint algorithm in 6 rapidity regions.

Dominant systematic uncertainty is from JES:
Steeply falling spectrum:
=> Even small JES uncertainty leads to
large uncertainties on cross section

Typical JES uncertainty:
1-2% in D0, 2-3% in CDF

Total uncertainty on the cross sections:
15-30% in D0, 15-50% in CDF





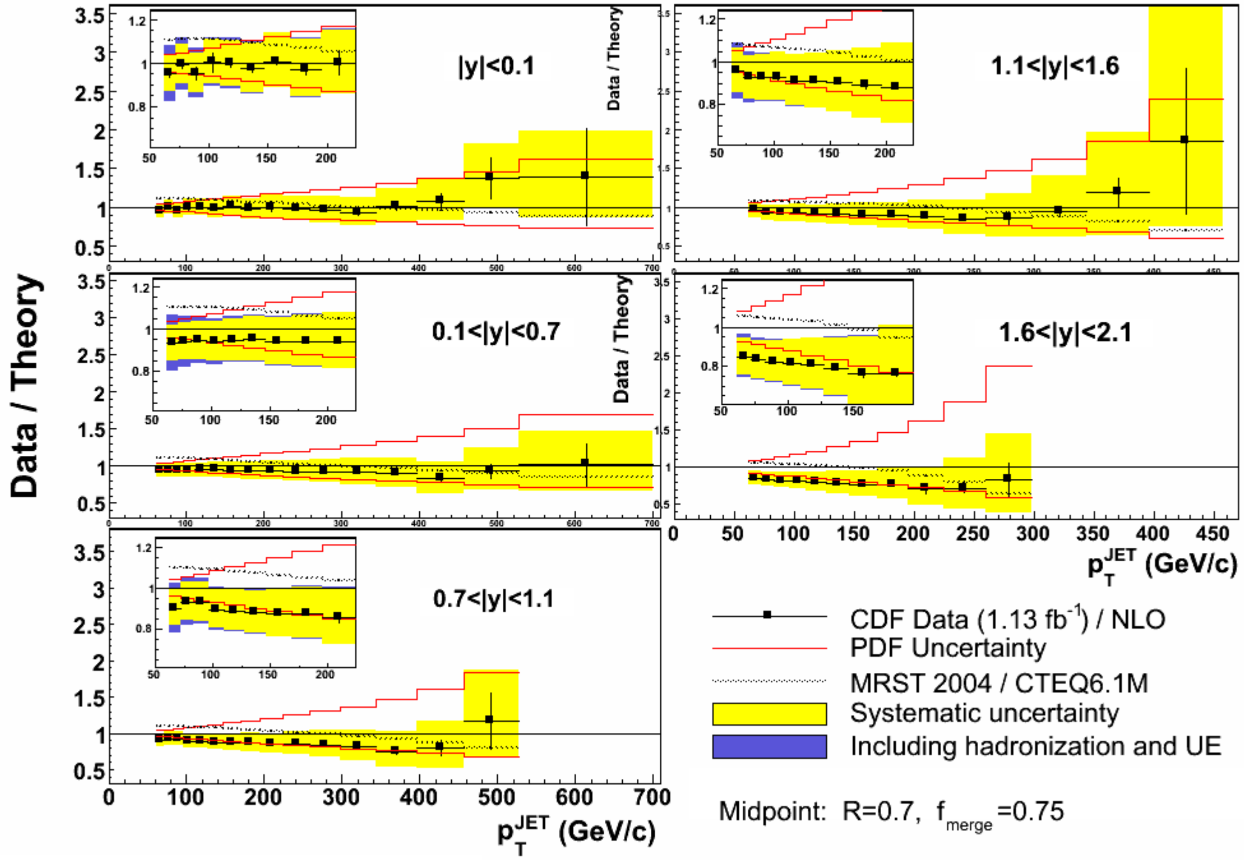
Energy scale uncertainty, D0

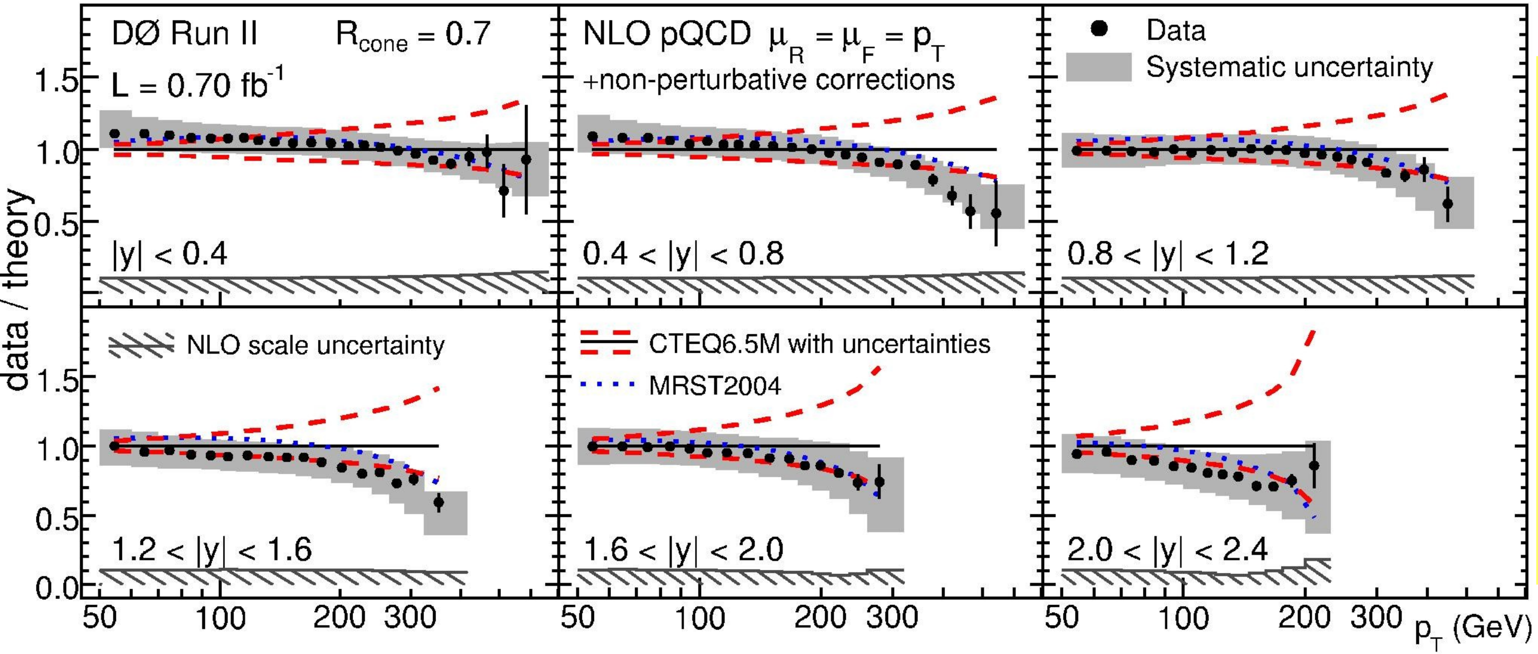
Inclusive jet production: Data/Theory (D0,CDF)

In general, CDF and D0 measurements are in agreement with QCD NLO predictions.

However, data favored lower bound of the theoretical (CTEQ6.5M PDF) predictions, with smaller gluon content at high x.

Experimental uncertainties at high pT are lower than theoretical (largely PDF ones): => constrain PDF





Leads to modified central values (esp. at x>0.3) and reduced PDF uncertainties.

D0 results are most precise measurement to date.

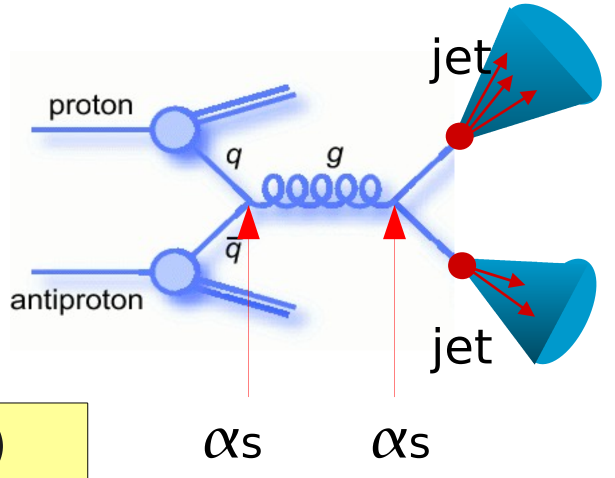
MSTW 2008 uses CDF kT and D0 cone results.

Measurement of α_s from inclusive jets (D0)

PRD 80, 111107 (2009)

- Cross section formula:

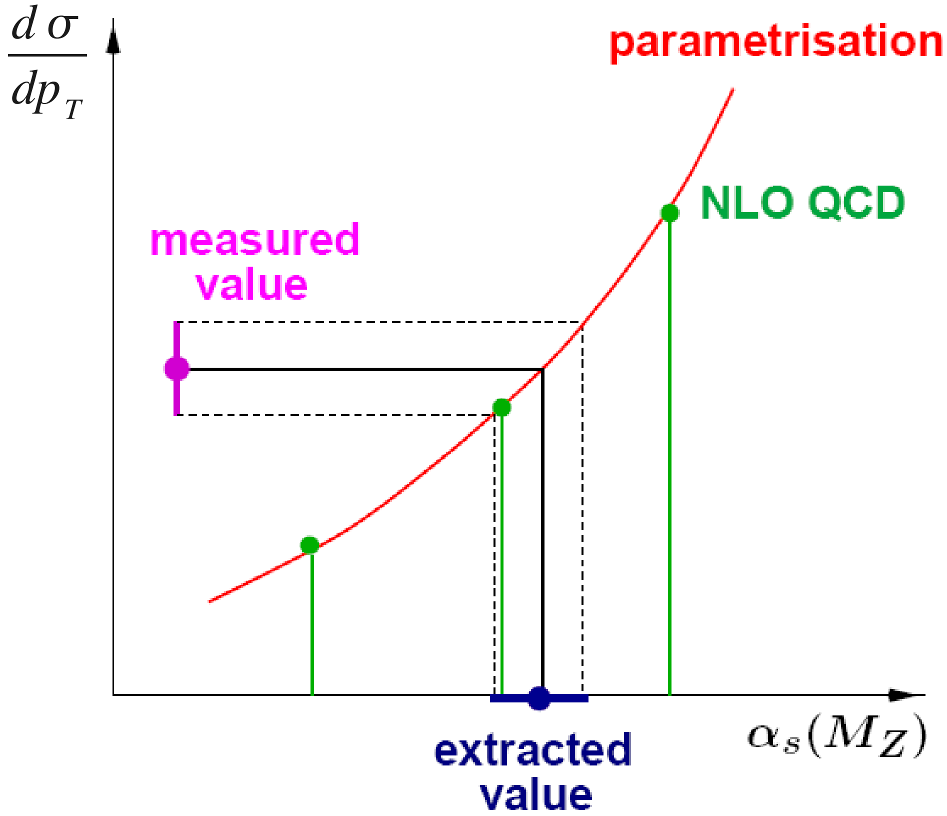
$$\sigma_{\text{theory}}(\alpha_s) = \left(\sum_n \alpha_s^n c_n \right) \otimes f_1 \otimes f_2$$



- c_n: perturbative coefficients (→ pQCD matrix elements)
- f_1, f_2: PDFs of colliding $p, \bar{p}$

Determine α_s from data:

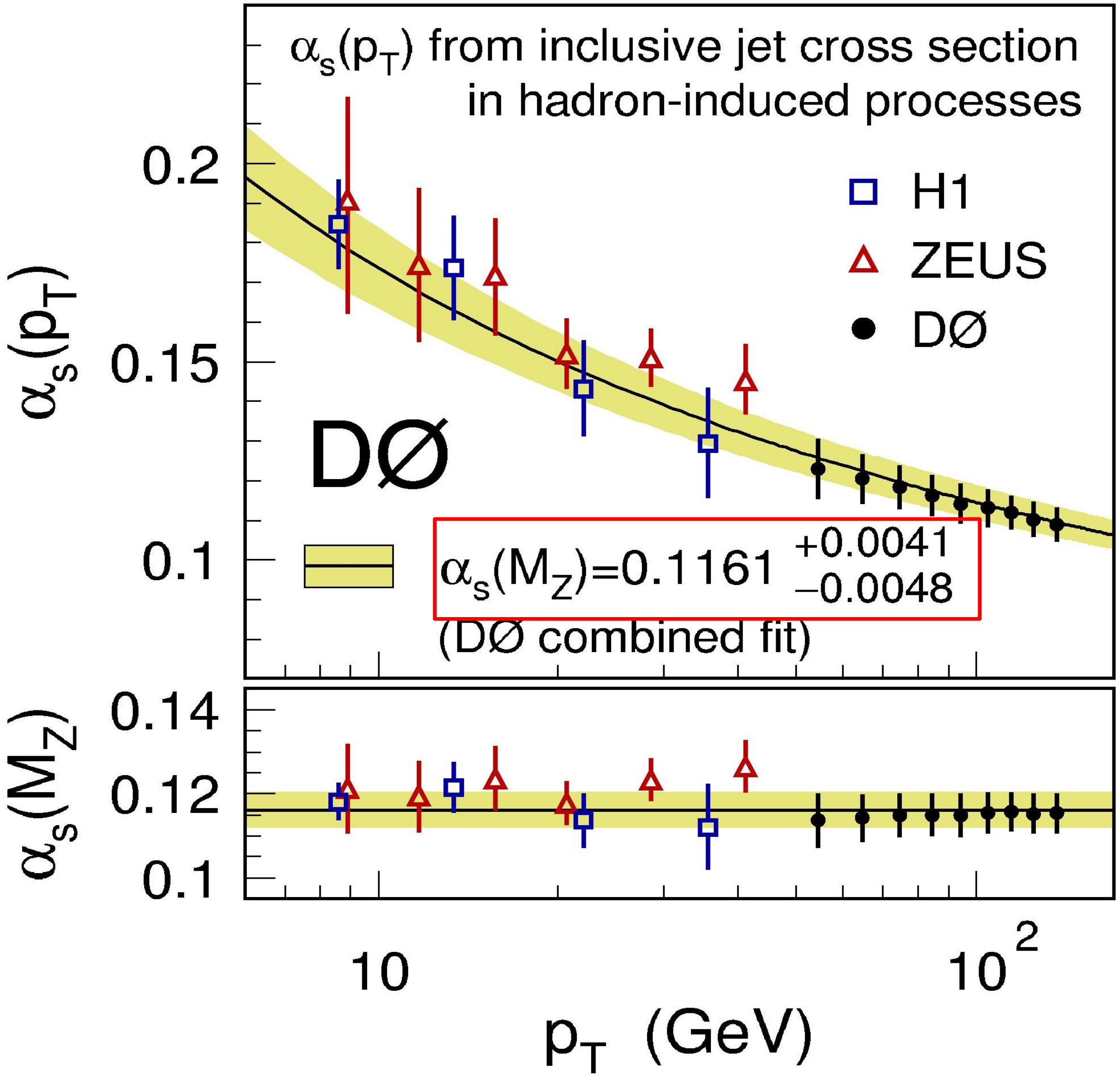
- Vary α_s until σ_{theory} agrees with σ_{exper}
- ...for each single bin →
- χ^2 fit of theory to data using 21 NNLO PDF sets from MSTW2008 with α_s within 0.107-0.127 in 0.001 steps
- 5 NLO CTEQ6.6M sets are also considered
- Only 22 points of 110 are used (with x<0.2)



Running of α_s(pT)

- Combine points in different |y| regions at same pT

→ Produce 9 α_s(pT) points from selected 22 data points



theory:NLO+2-loop threshold corrections

→ About same precision as HERA jets (**0.1189 ±0.0032**)

→ The only Run II result on α_s

→ Improvement as comp. with Run I

(**0.1178±0.0001**(stat)$^{\mathbf{+0.0081}}_{\mathbf{-0.0095}}$(syst))

Compare to HERA results:

→ consistency

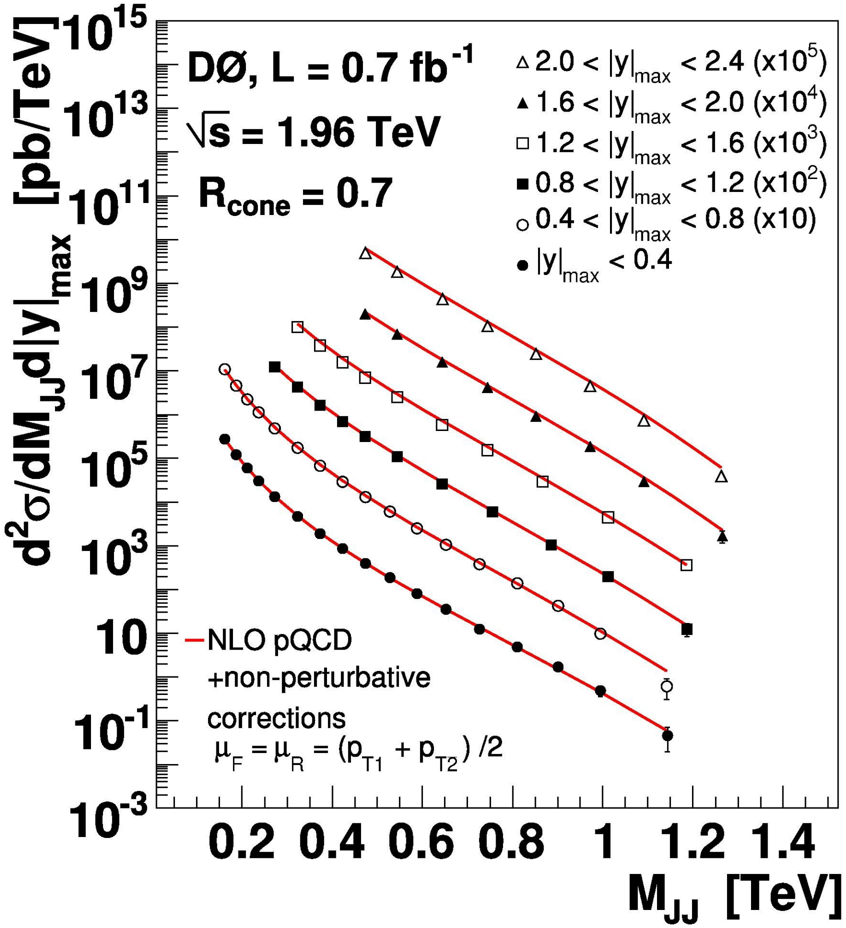
→ extend pT reach of HERA results to higher pT range of 50-145 GeV

“World average”: **0.1184±0.0007**

PRD 80, 111107 (2009)

Dijet mass cross section measurement (D0)

PLB 693, 531 (2010)

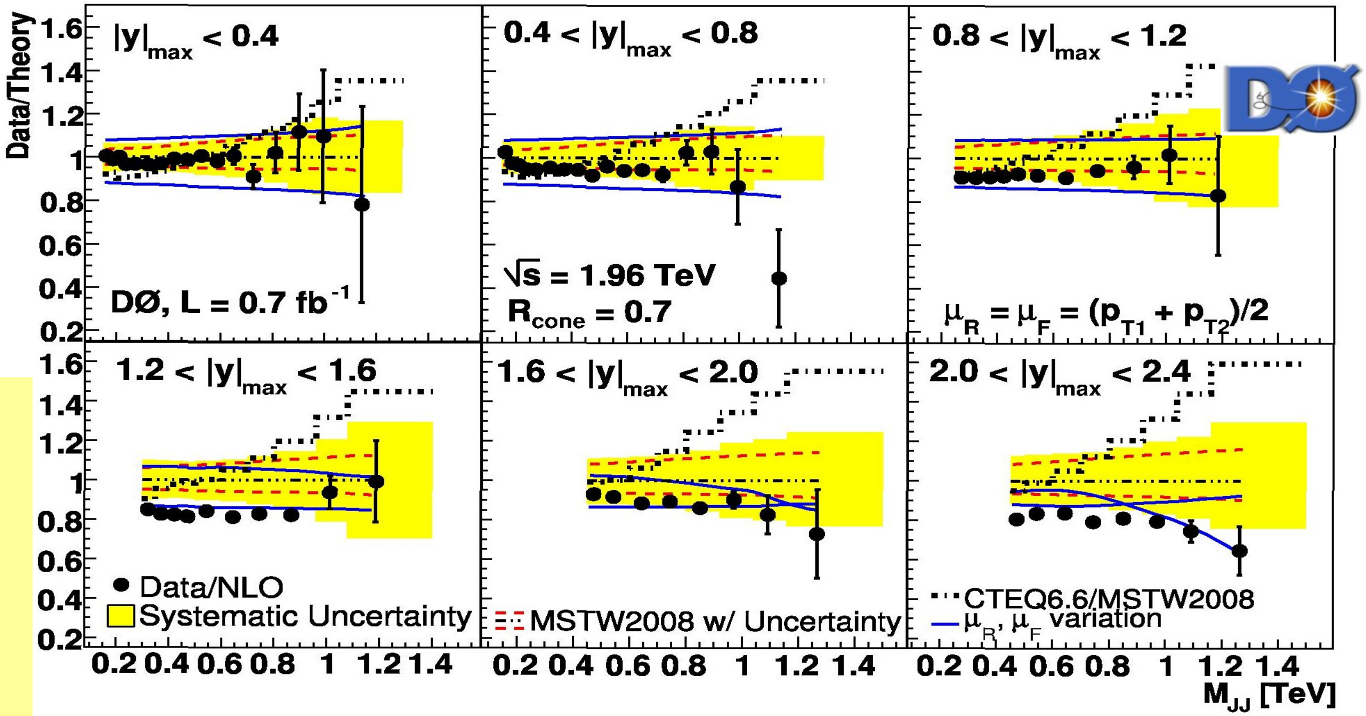


- Measurement of dijet mass in six rapidity bins, $|y|_{max} = \max(|y_1|, |y_2|)$

Non-perturbative corrections (-10%, 23%)

Comparison to NLO pQCD with MSTW2008 and

CTEQ6.6M NLO PDFs, $\mu_F=\mu_R=(pT_1+pT_2)/2$



- 40—60% difference between PDFs (MSTW2008/CTEQ6.6) at high masses

- Data/QCD in good agreement in central region
- Data are lower than central pQCD prediction at higher rapidities

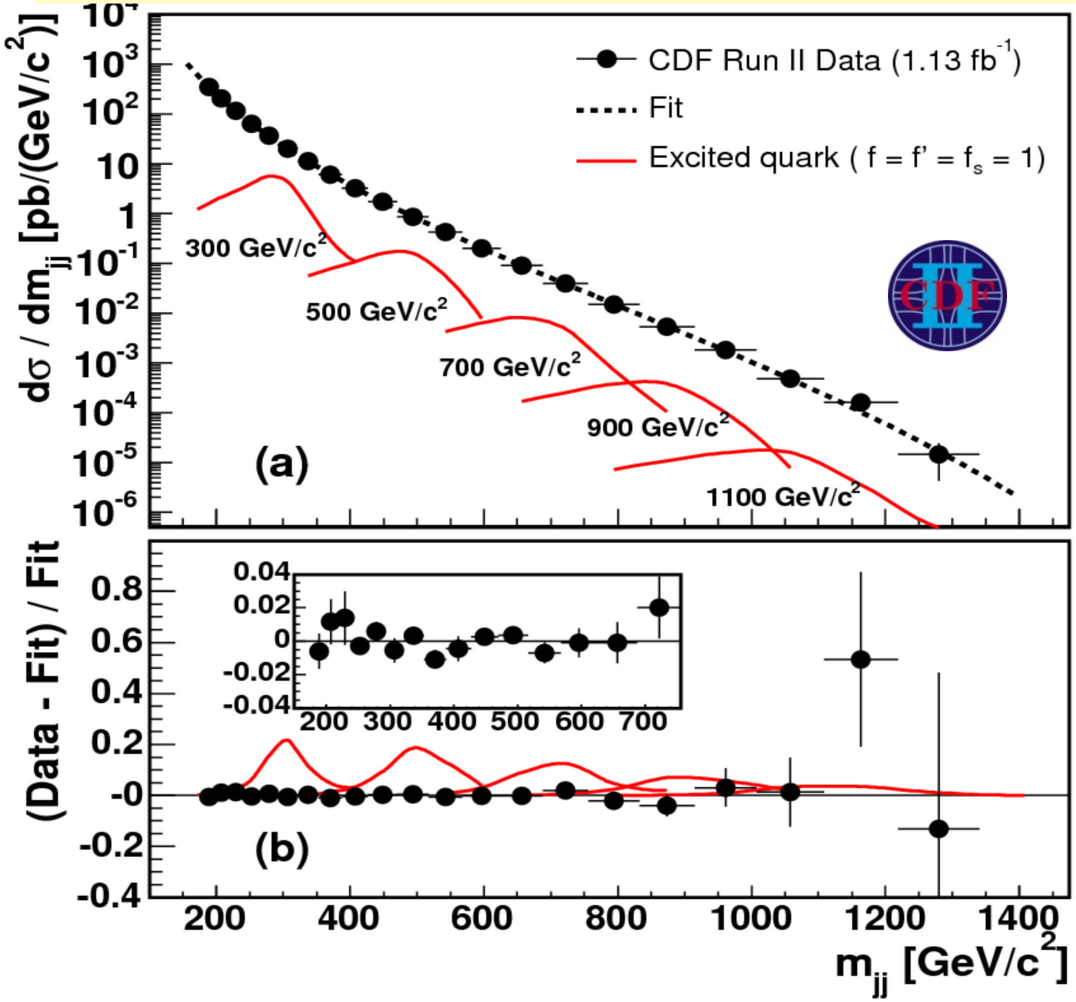
Last mass bin is at ~1.3 TeV!

Dijet mass: searches for new physics (CDF)

PRD 79, 112002 (2009)

Dijet mass tests pQCD but also sensitive to presence of new physics, resonances decaying to two jets
=> Use uncorrected jet data to maximize sensitivity to resonances

No significant evidence for resonant structure has been observed, so set limits



Observed mass exclusion range	Model description
260-870 GeV/c^2	Excited quark → qg (f=f'=f_s=1)
260-1100 GeV/c^2	ρ_{T8} techni-rho
260-1250 GeV/c^2	Axigluon/coloron
290-630 GeV/c^2	E_6 diquark
280-840 GeV/c^2	W' (SM couplings)
320-740 GeV/c^2	Z' (SM couplings)

D0 dijet χ: limits on q-compositeness, Extra Dim.: PRL 103, 191803 (2009) (slide 53 in backup)

Three jet mass cross section (D0)

Accepted by Phys.Lett.B

Differential measurements of 3-jet mass:

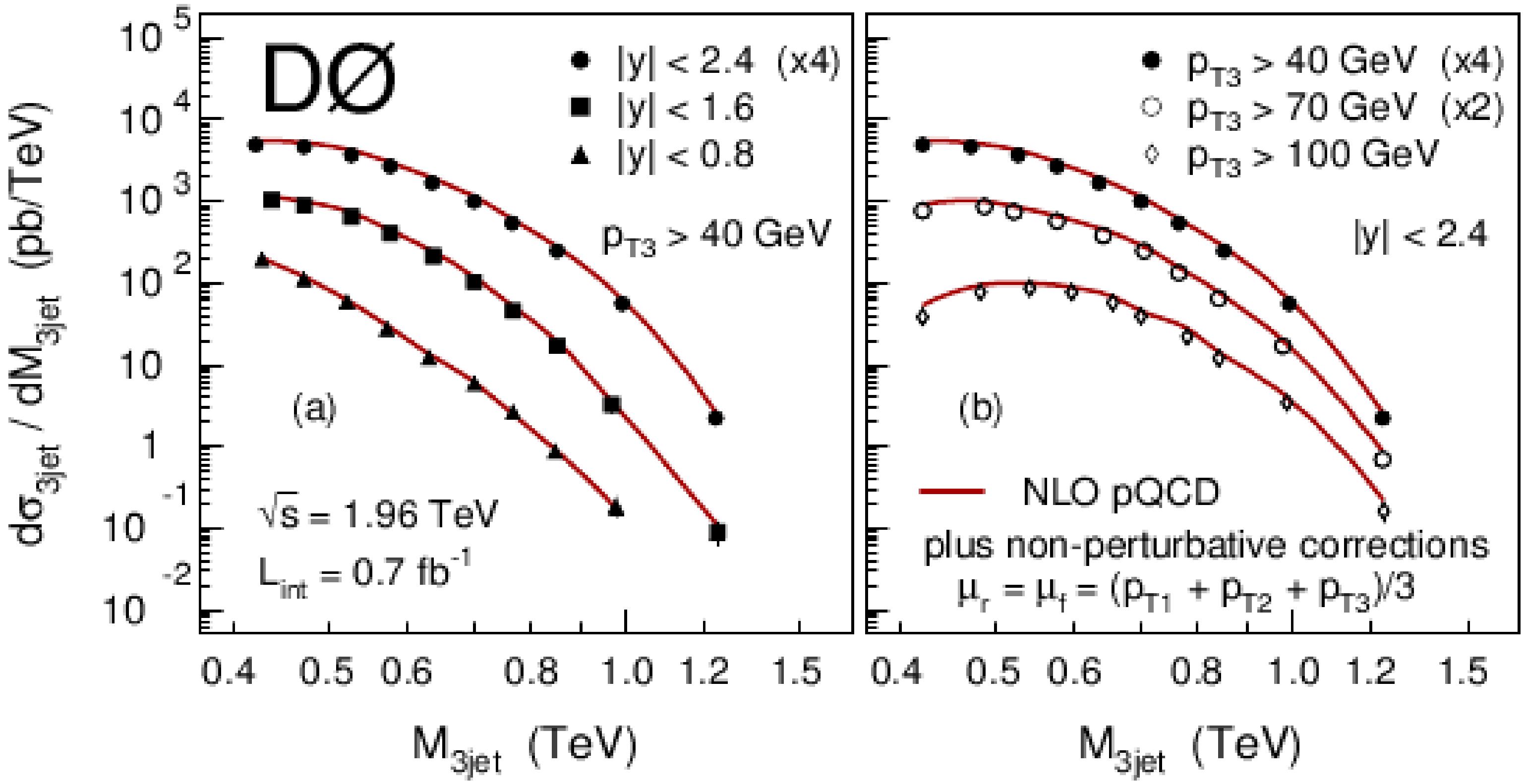
- $p_T^{lead}>150$ GeV, $p_T^{3rd}>40$ GeV; $\Delta R_{jj}>1.4$

– Measurement is done in 3 rapidity and 3 pT intervals of 3rd jet.

– Three-jet calculation available @NLO
  - Used fastNLO with MSTW2008
  - Default scale mu = 1/3(pT1+pT2+pT3)
  - Scale uncertainties: independent variations by *x*2 of renorm. and factor. scales

– NLO non-perturbative corr.: -3%,+6% (DW used as a default, x-checked with tunes A,BW, Z1,Perugia soft&hard)

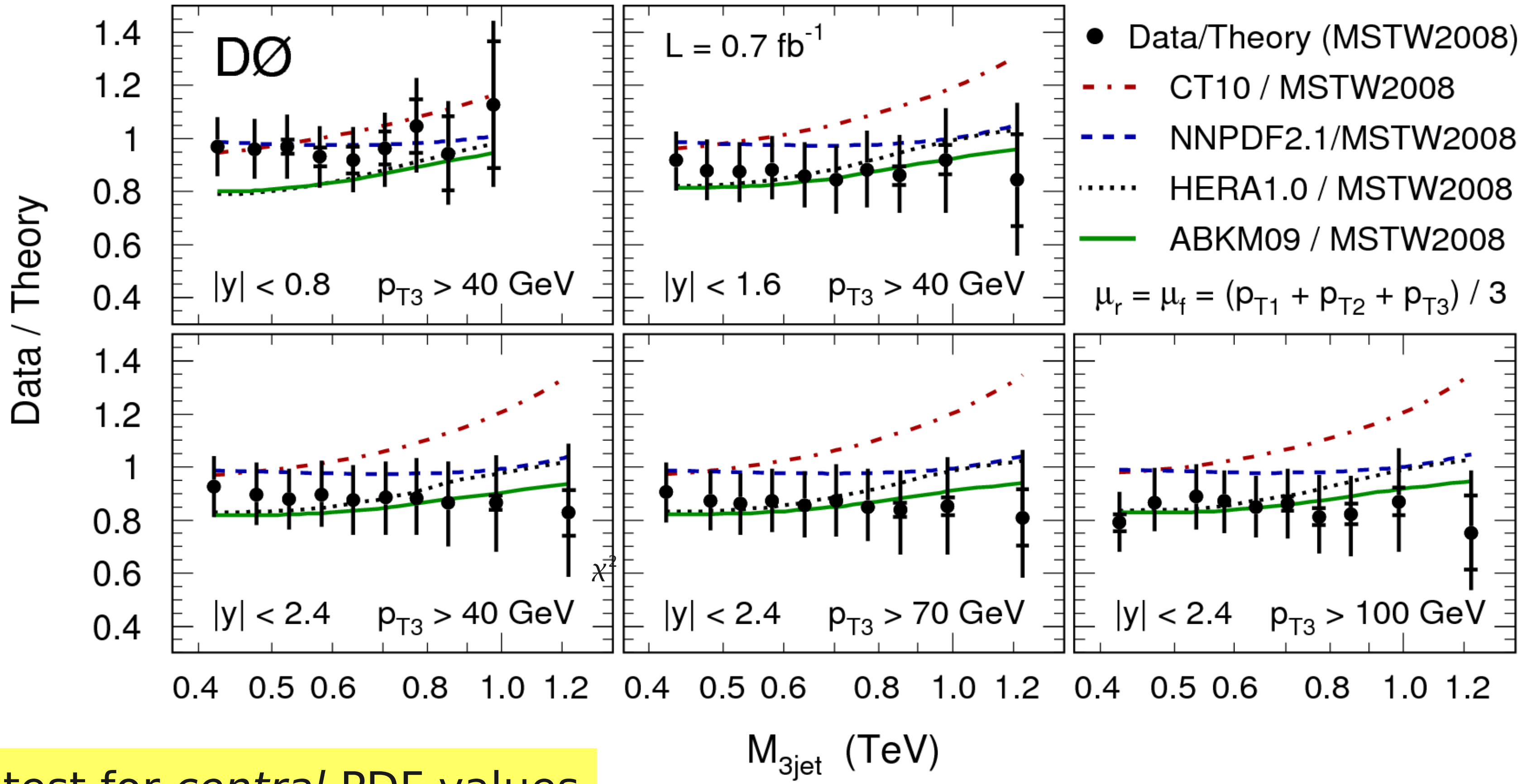
– Total systematic uncertainty: 20-30% (dominated by JES, p_T resolution and lumi)



Three jet mass cross section (D0)

Differential in y

Differential in p_T



χ^2 test for *central* PDF values

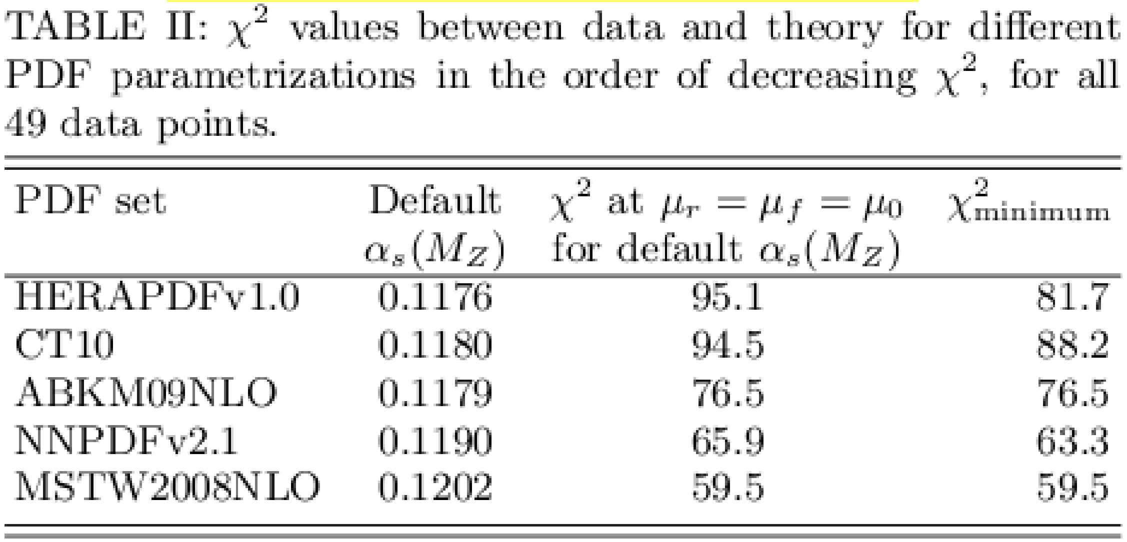


TABLE II: χ^2 values between data and theory for different PDF parametrizations in the order of decreasing χ^2, for all 49 data points.

PDF set	Default $\alpha_s(M_Z)$	χ^2 at $\mu_r = \mu_f = \mu_0$ for default $\alpha_s(M_Z)$	χ^2_{minimum}
HERAPDFv1.0	0.1176	95.1	81.7
CT10	0.1180	94.5	88.2
ABKM09NLO	0.1179	76.5	76.5
NNPDFv2.1	0.1190	65.9	63.3
MSTW2008NLO	0.1202	59.5	59.5

- Good agreement seen between data and NLO (MSTW2008) for all cases.
- Comparisons to ABKM09, NNPDF2.1, HERA1.0 are also provided.
- χ^2 test is done for 3 theor. scales and all α_s values available for a given PDF set (see slide 42 in backup)
- Best χ^2 results for MSTW2008, NNPDF2.1

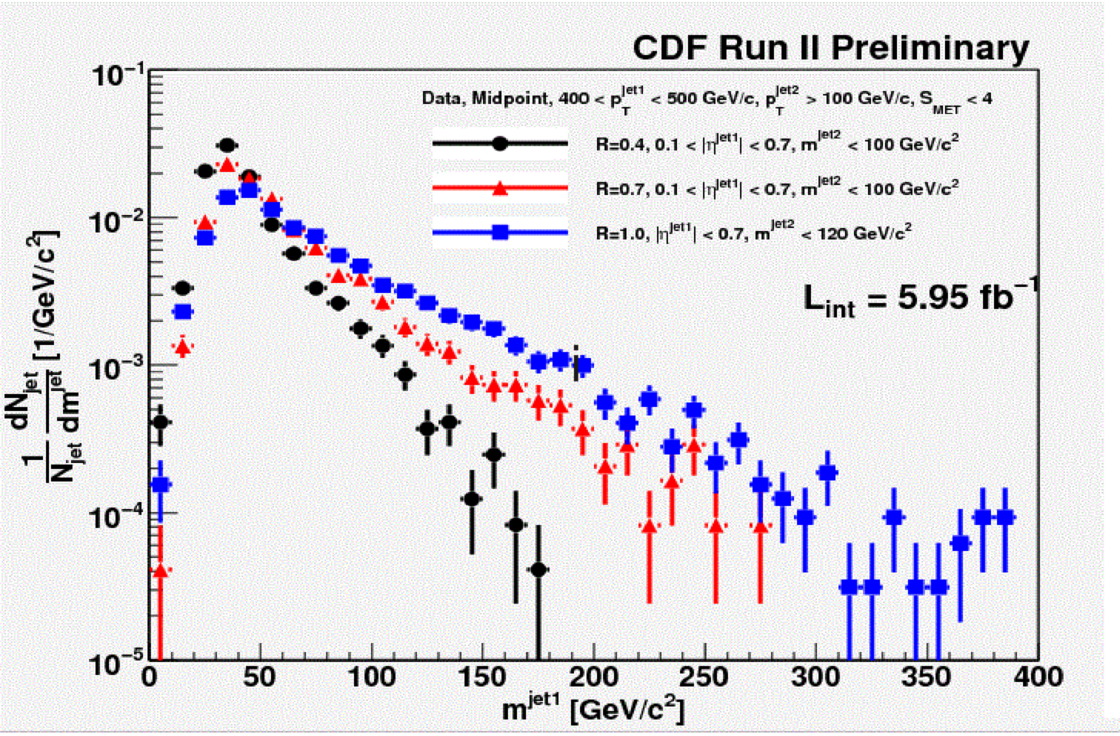
Structure of high pT jets (CDF)

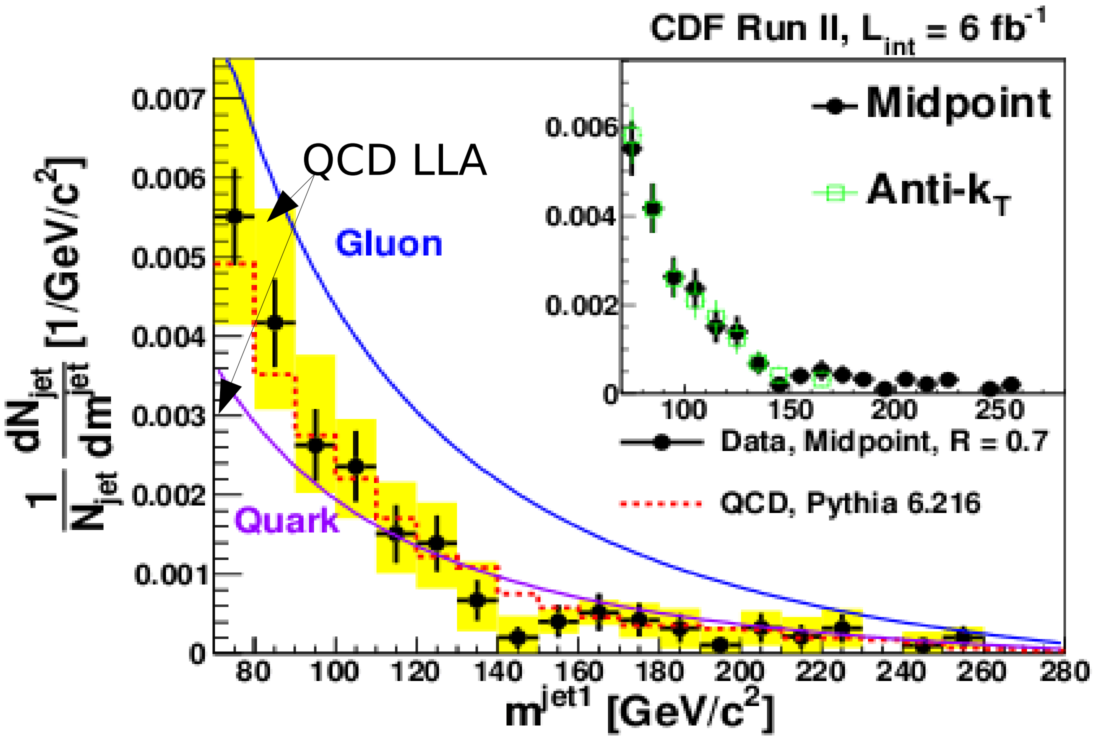
Submitted to PRL,
arXiv:1106.5952

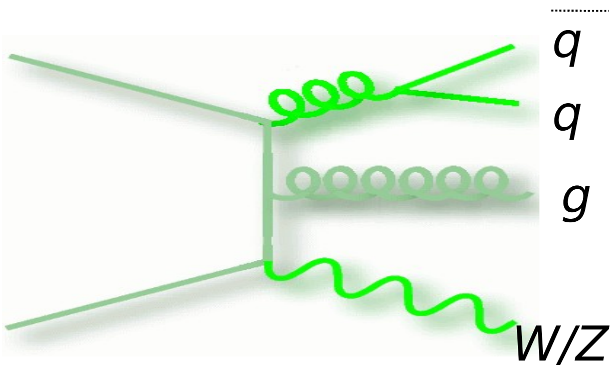
- Motivation: (a) test of QCD, tuning parton showering mechanism
  (b) can be used for new physics searches with
  a heavy resonance decay (Higgs, neutralinos, high pT top-quarks)
- Mass is calculated using standard E-scheme: 4-vector sum over towers in a jet, which gives (E,px,py,pz)
- Selections: ≥1 jet with pT>400 GeV, 0.1<|y|<0.7: 3136 (3621) events, jet R=0.4-1.0
  anti-top: m_jet2<100 GeV and S_met < 4 and pT_jet2>100 GeV

- Compared to QCD LLA and Pythia event generator.

400<pT<500 GeV, anti-top cuts







V + jet Results

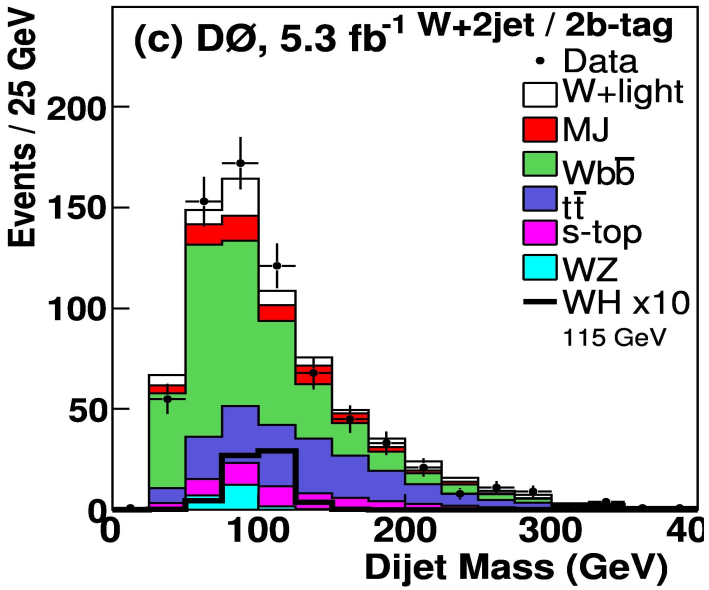
Fixed-order: NLO

LO + Parton Shower

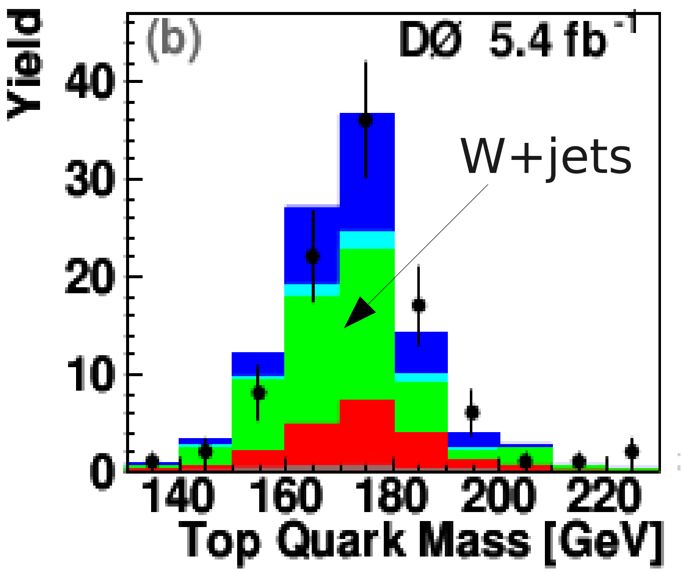
Backgrounds to New Physics

Vector Boson + Jet

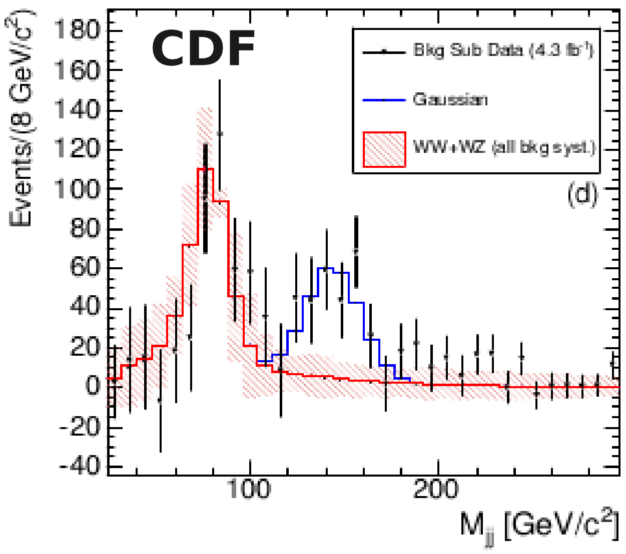
WH production



Single top production



W+dijet, M_{jj} “bump”



– Background to top-quark, Higgs, SUSY, other NP productions

– Provide detailed measurements of p_T and angular distributions of vector boson and jet

→ test of fixed order perturbative QCD, LO ME+PS predictions in Event Generators

→ testing and tuning of phenomenological models

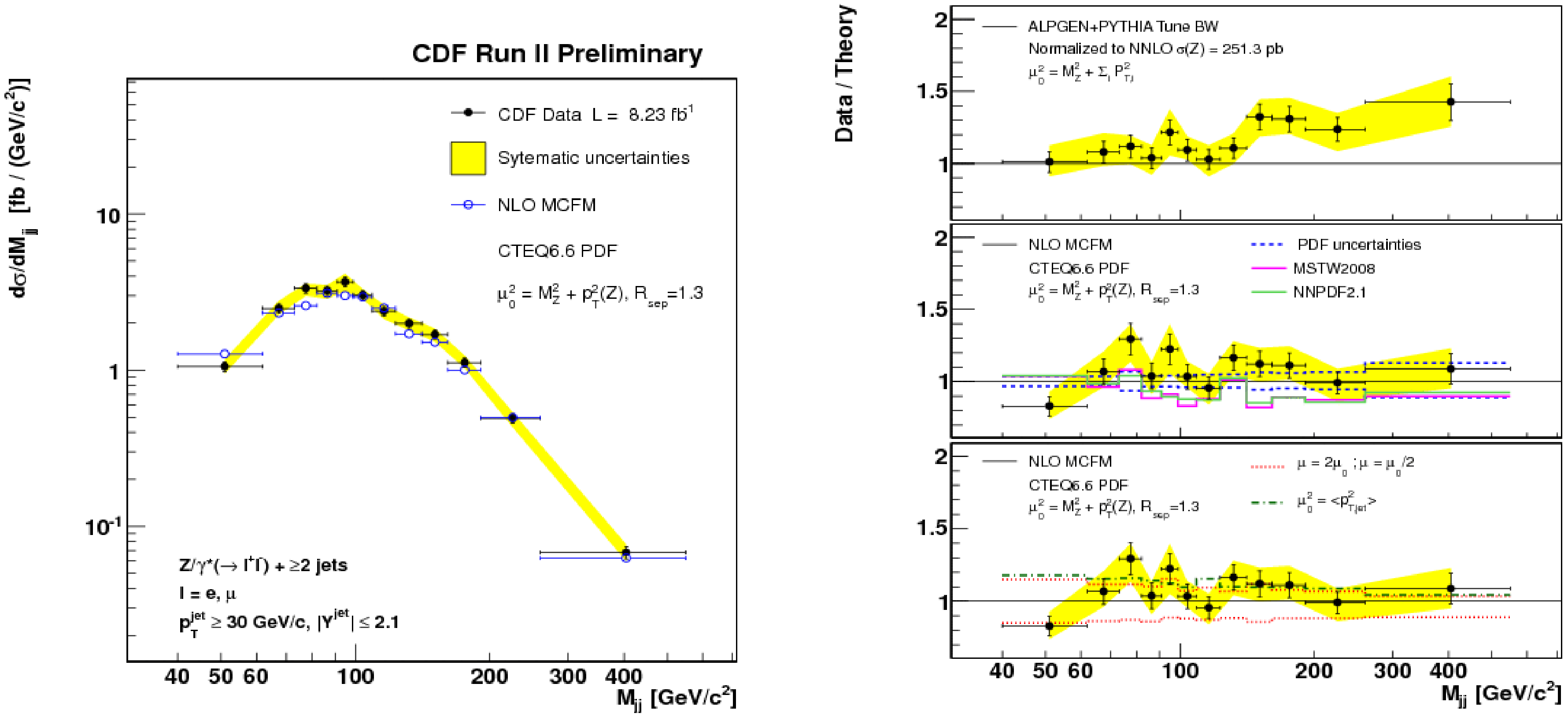
Z+jets production (CDF)

- The measurement tests Z+n-jet (n=1-4) production cross section vs jet pT, y, total jet HT, dijet pT, △y, $\Delta\Phi$, mass, Z+dijet mass
- Comparison to Alpgen+Pythia, LO&NLO MCFM and Blackhat+Sherpa

8.2 fb-1, ee and $\mu\mu$ channels, jet (R=0.7) pT>30 GeV and |y|<2.1

Preliminary (Aug, 2011)

Dijet Mass

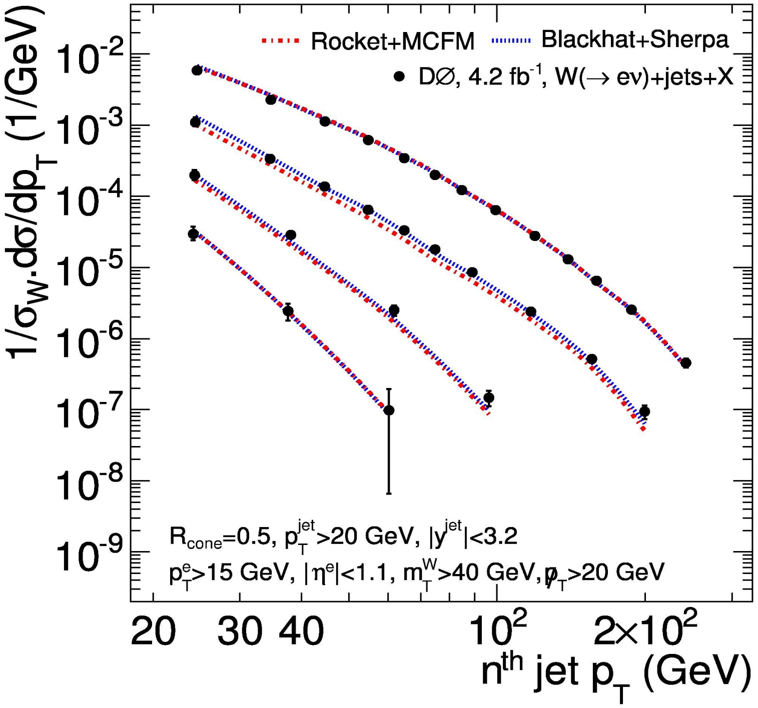


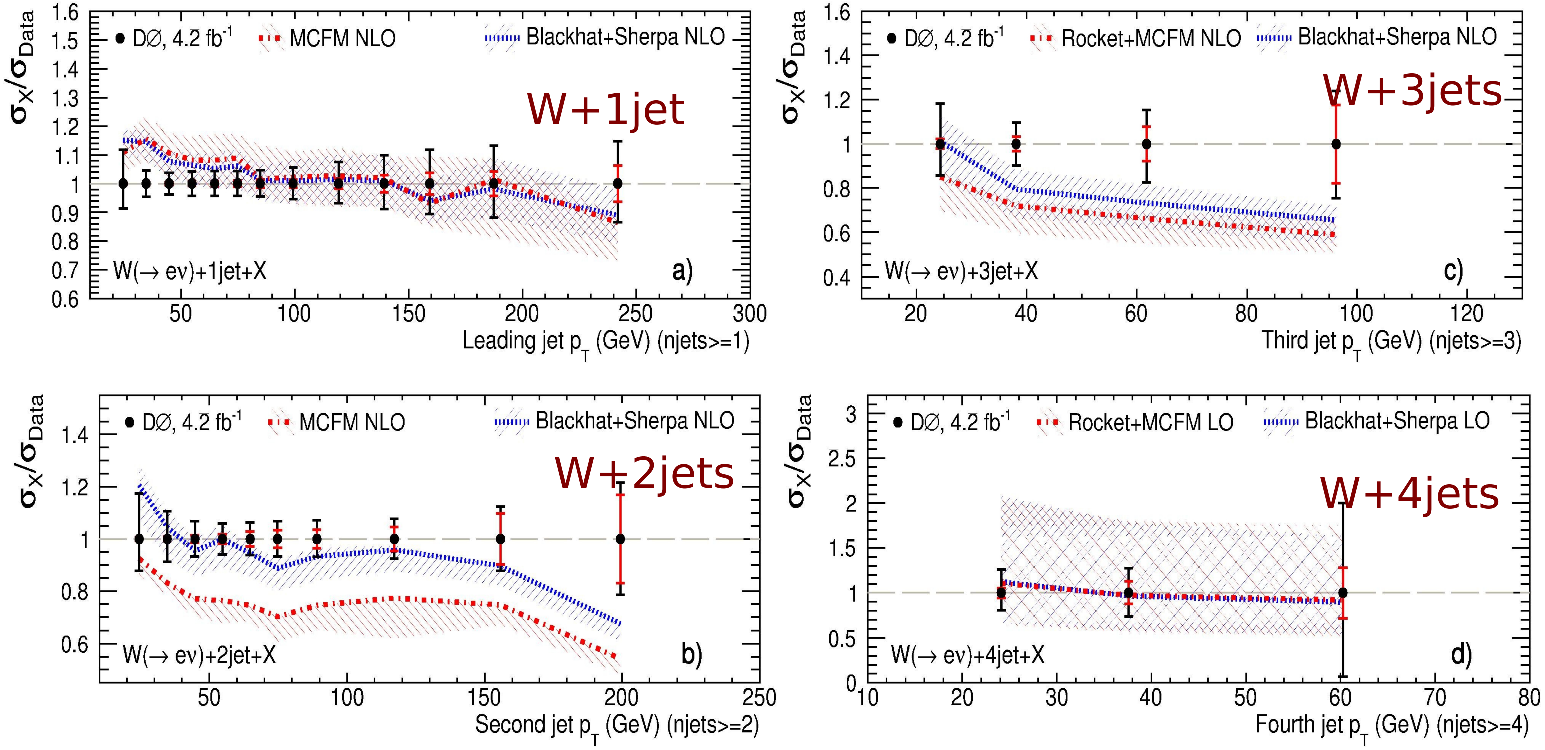
In general, good agreement with NLO QCD. However, there are discrepancies in some regions of phase space (eg. medium dijet pT, HT<150(≥3jets))

W+jets production: jet pT, #jets (D0)

Dominant background to the single top, ttbar, SM Higgs, many BSM searches

- The measurement tests W+n-jet (n=1-4) production cross section vs n-th jet pT
- Comparison to LO&NLO by Blackhat+Sherpa and Rocket+MCFM



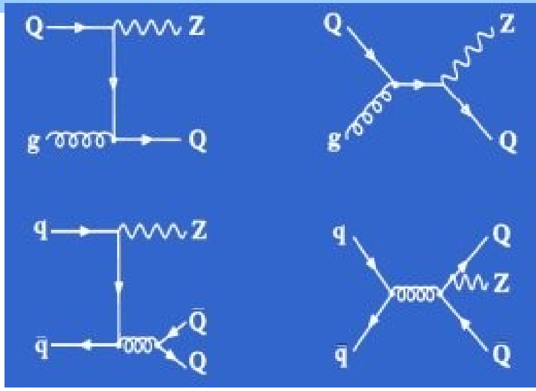


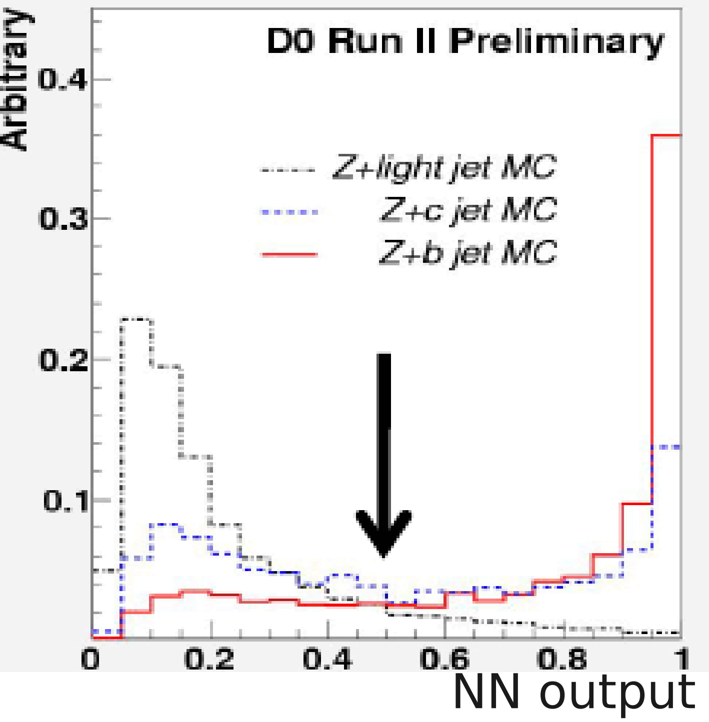
Submitted to PLB,
arXiv:1106.1457 (2011)

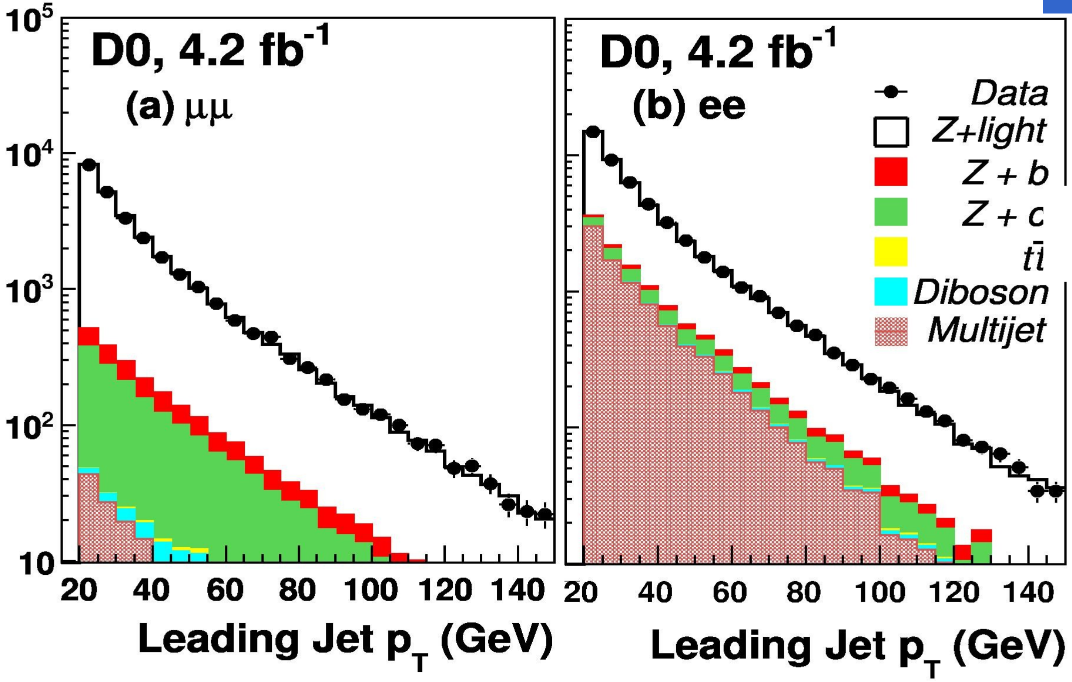
- In agreement with QCD NLO in jet pT and #jets
- Experimental uncertainties are lower than theoretical (scale) in many cases
  => tuning the theory
- First W+4jets result (only LO predictions)

σ(Z+b) / σ(Z+jet) (D0)

- Important background to the SM Higgs search in the ZH channel.
- Probe of b-quark PDF, important for gb → Hb & single-top studies
- Measurement of ratio σ(Z+b) / σ(Z+j) benefits from cancellation of many systematics => precise comparison with theory







PRD83, 031105 (2011)

- Measurement: **0.0193 ± 0.0022 (stat)± 0.0015 (syst)** [~8% syst]
  Most precise measurement of 'Z+b' fraction to date!
- Consistent with NLO theory**: 0.0192 +/- 0.0022**
  (MCFM, renorm. and factor. scales are at Mz)

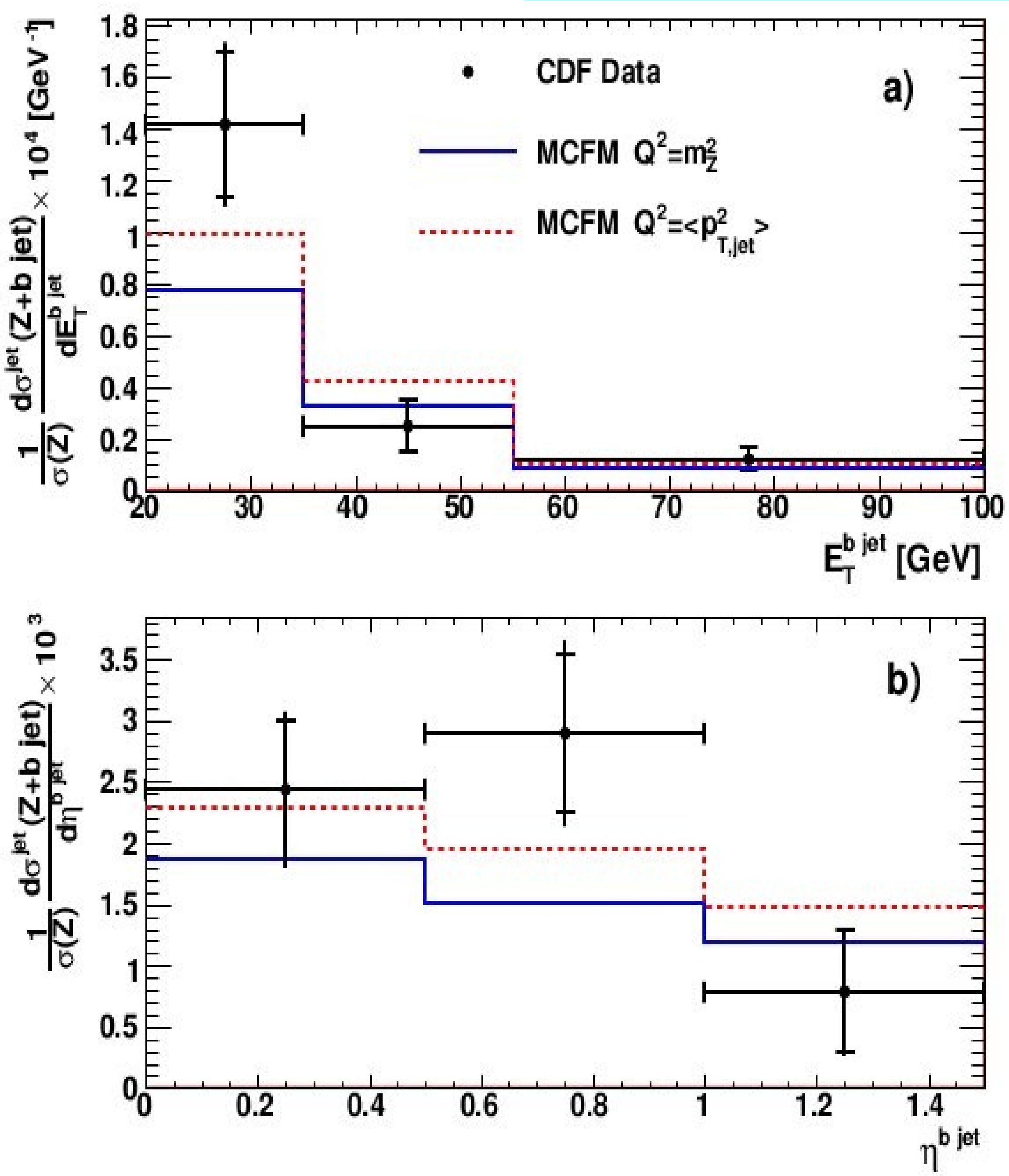
Z+b production (CDF)

PRD79, 052008 (2009)

- L=2 fb-1
- Z → ee/μμ + b + X
- jet p_T > 20 GeV, jet |η| < 1.5
- Jet track mass in the secondary vertex is used to discriminate between jet flavors

Theory:

- MCFM : all calculations are at $O(\alpha s^2)$
- Pythia, Alpgen



σ(Z+b) / σ(Z)

Data: $[3.32\pm 0.53(\text{stat})\pm 0.42(\text{syst})]x10^{-3}$

MCFM: 2.3 (2.8) $x10^{-3}, Q^2=Mz^2(jet\ p_T^2)$

Pythia: 3.5 $x10^{-3}$

Alpgen: 2.1 $x10^{-3}$

σ(Z+b) / σ(Z+jet)

Data: 2.08 ± 0.33(stat)±0.34(syst) %

MCFM: 1.8% / 2.2%

Pythia: 2.2%

Alpgen: 1.5%

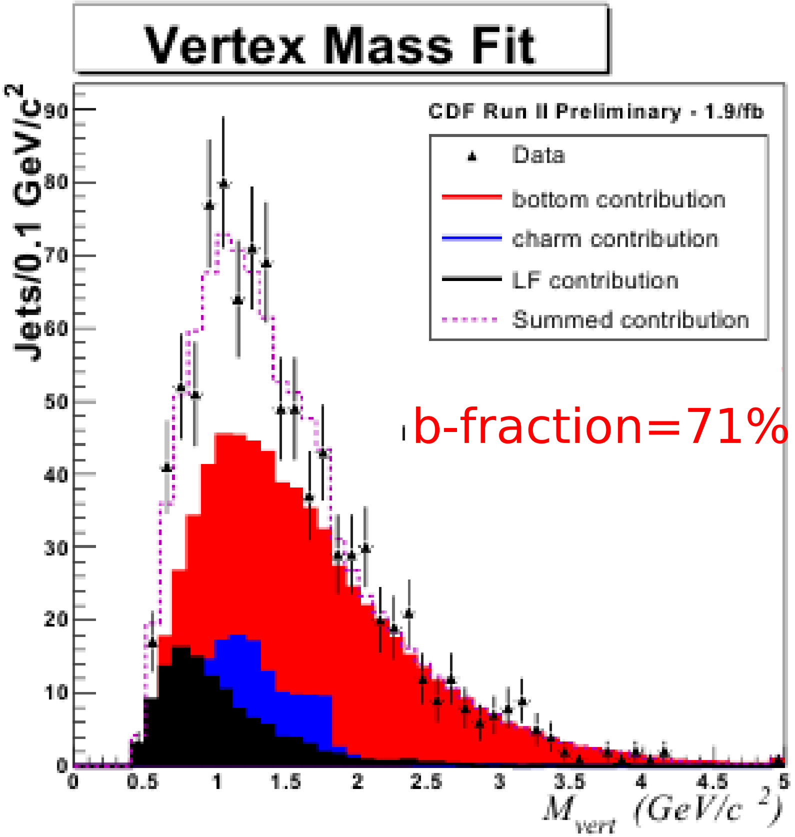
=> MCFM(μ= <jet p_T^2>), Pythia provide best agreement to data

σ(W+b) (CDF)

L= 1.9 fb-1

Phys.Rev.Lett.10,131801 (2010)

$p_T^{b\text{-jet}} > 20$ GeV, $|\eta_{b\text{-jet}}| < 2.0$, $(R_{\text{cone}} = 0.4)$, $p_T^{\ell} > 20$ GeV, $|\eta_{\ell}| < 1.1$, $p_T^{V} > 25$ GeV



- $$\sigma(W_{(\to \ell\nu)} + b) = \frac{N_{b\text{-tags}} \cdot f_{b\text{-jets}} - N_{\text{bkg}}^{b\text{-jets}}}{\mathcal{L} \times A \times \epsilon}$$

Major *b*-jet backgrounds:

$t\bar{t}$ (40% of total background)
single top (30%)
Fake *W* (15%)
WZ (5%)

Measured cross section larger than ALPGEN and NLO predictions ($\sim 3\sigma$)

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

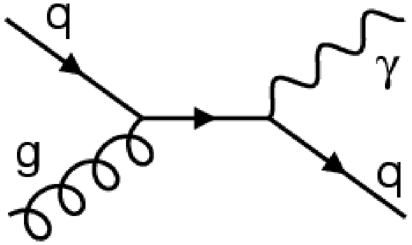
QCD NLO: 1.2 + 0.14 pb
Alpgen : 0.78 pb

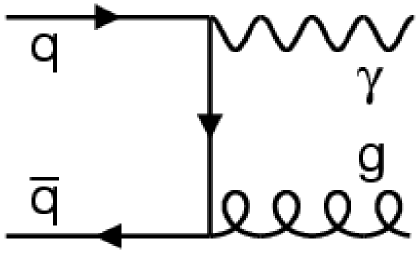
About a factor 2(3) of descrepancy with NLO (Alpgen)!

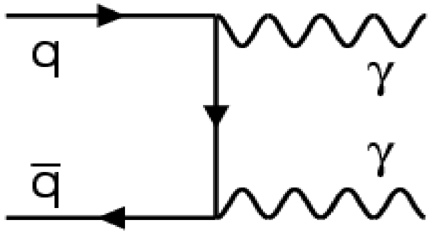
Photon production

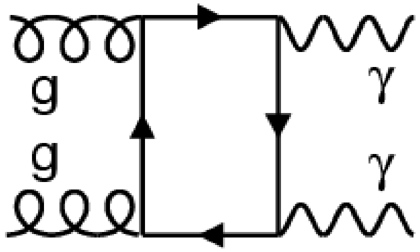
**Test fixed order NLO,
resummation, fragmentation, PDF**

Photon Production

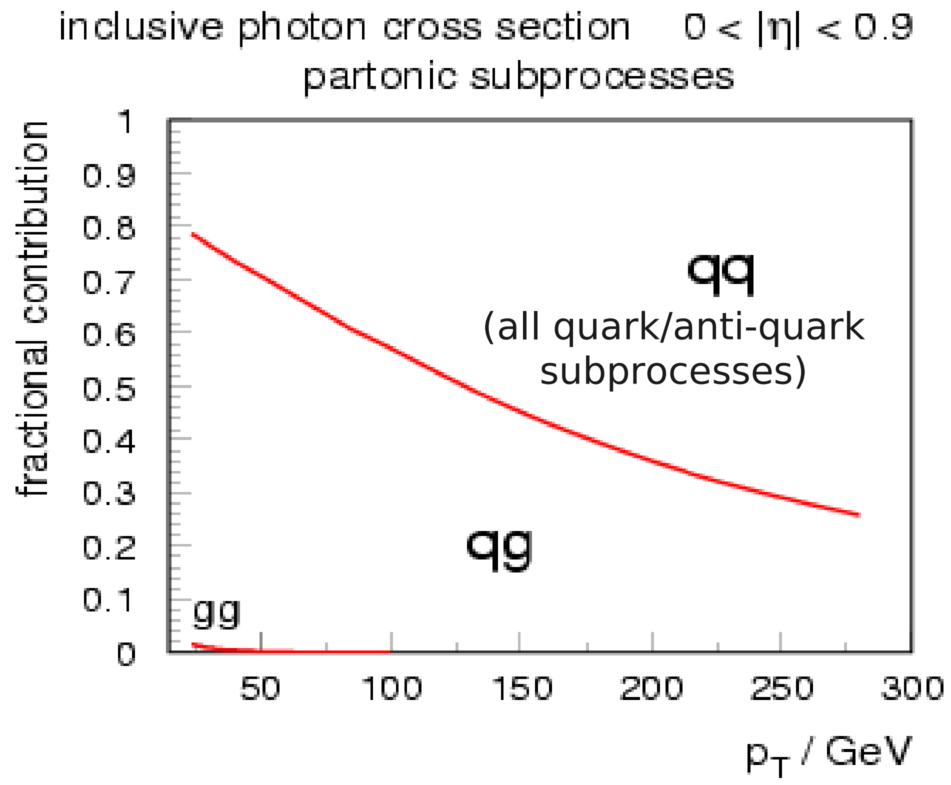




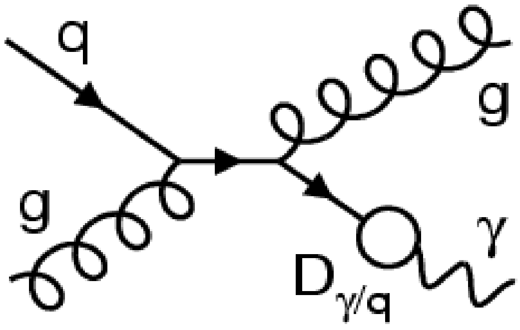




Direct photons emerge unaltered from the hard subprocess
→ direct probe of the hard scattering dynamics
→ potential sensitivity to PDFs (gluon!)
...but only if theory works



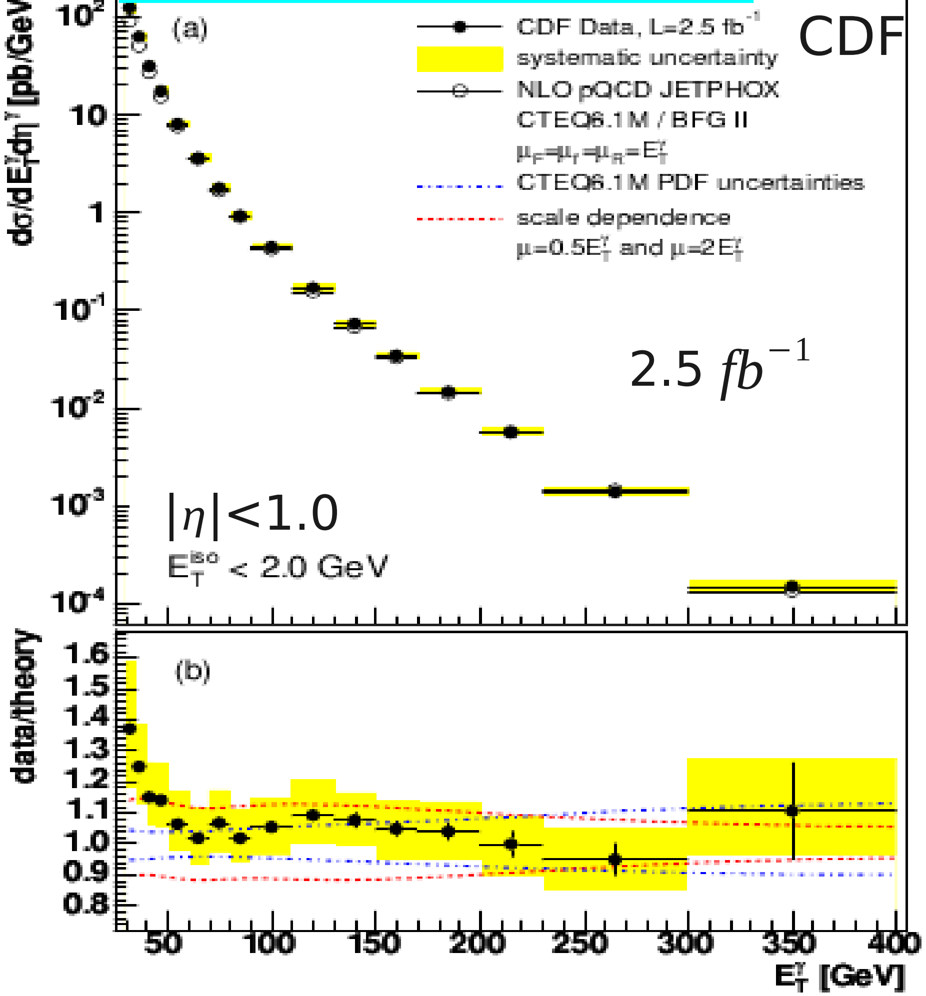
also fragmentation contributions:



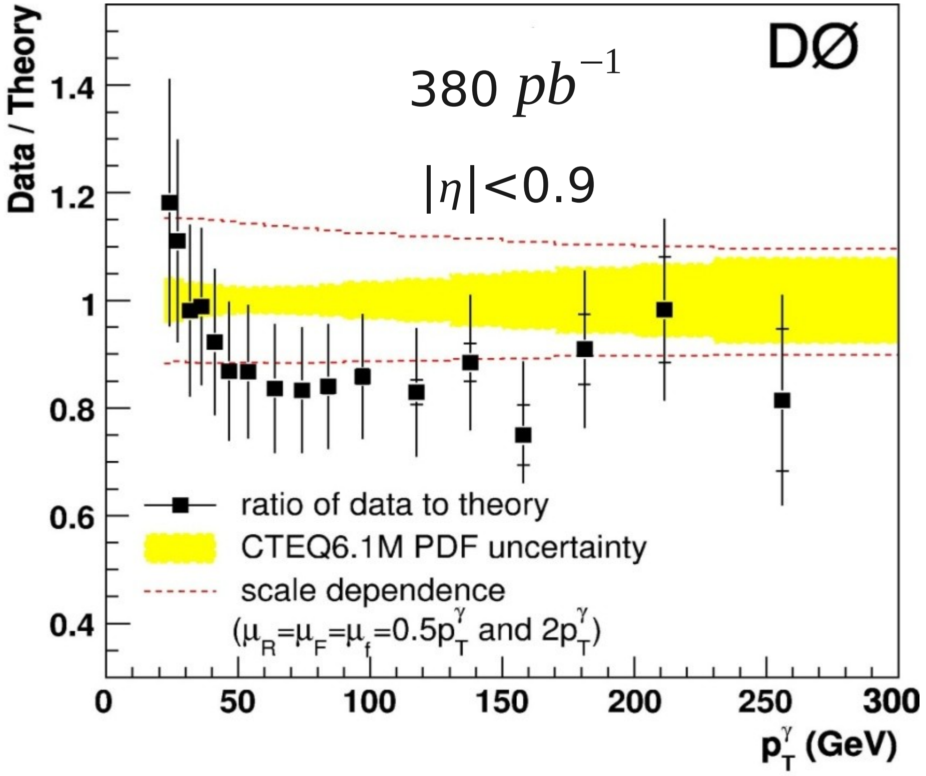
suppress by isolation criterion
→ observable: **isolated** photons

Inclusive Isolated Photons (CDF,D0)

Phys.Rev.D80,111106 (2009)



Phys. Lett. B 639, 151 (2006)



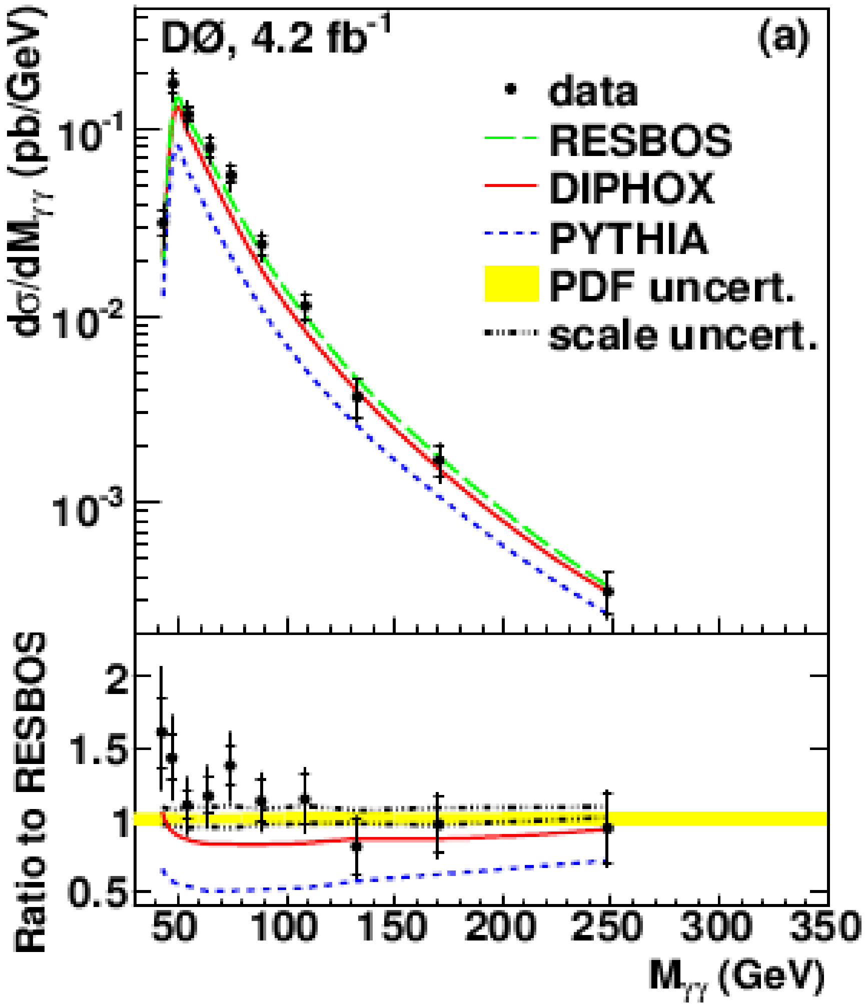
CDF and D0: 20< p_T <400 GeV, both results are for central rapidities, *same binning*

- D0/CDF: results in agreement
- Data/Theory: difference in low p_T shape
- experimental and theory uncertainties are larger than PDF uncertainty
  → no PDF sensitivity yet
- First: need to understand discrepancies in shape (similar to results of UA2, CDF Run 1)

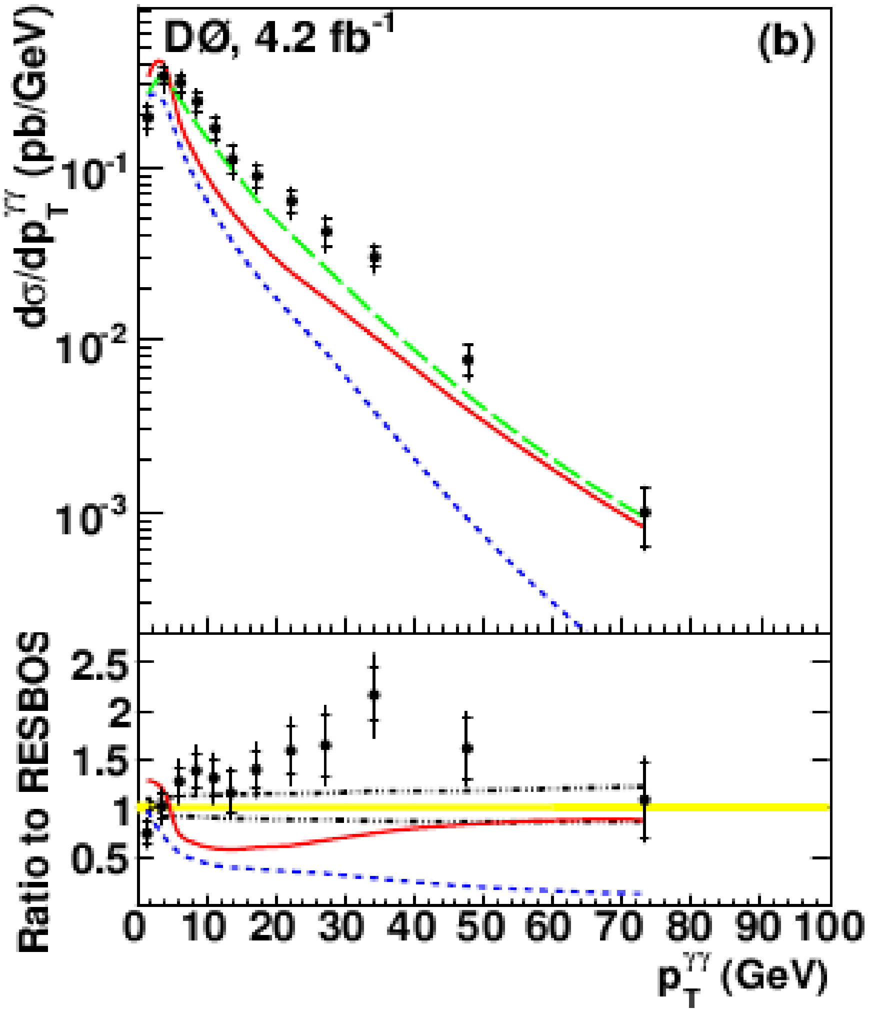
Photon Pair Production (D0)

- Almost irreducible background to H→ $\gamma\gamma$, other NP, => production XS should be understood
- Isolated (ETsum[R=0.4]< 2.5 GeV) photons with pT>20 and 21 GeV, |y|<0.9; 4.2 fb-1
- Data are compared with predictions by PYTHIA, DiPhoX, ResBos
- 1D cross sections in diphoton Mass, $p_T^{\gamma\gamma}$, $\Delta\phi$, cosθ^* and 2D ones ($p_T^{\gamma\gamma}$, $\Delta\phi$, cosθ^* in Mass bins)

Phys.Lett. B690,108(2010)



Good agreement between data and RESBOS for M>50-60 GeV

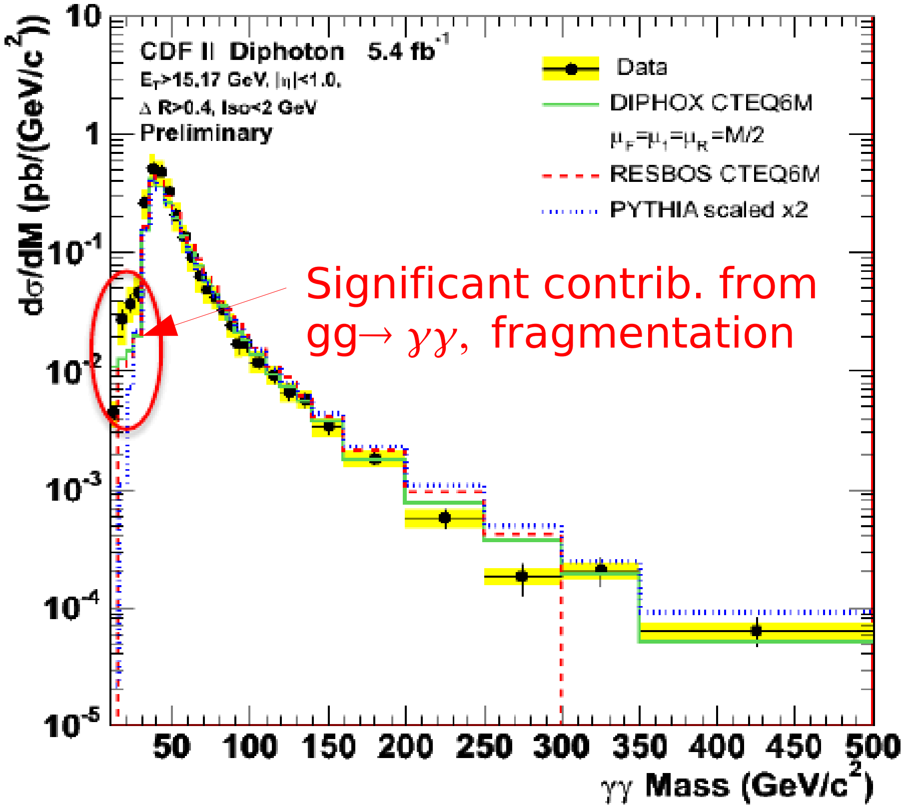


Data $p_T^{\gamma\gamma}$ spectrum is harder than predicted: need for NNLO? Unaccounted fragm. contribution?

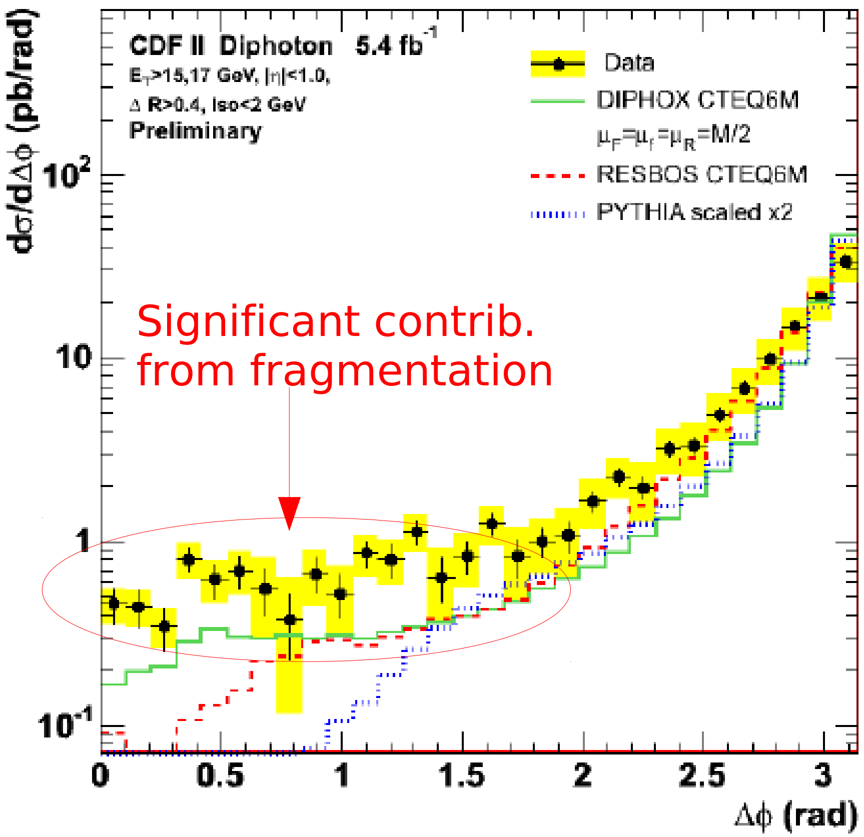
Photon Pair Production (CDF)

- Isolated (ETsum[R=0.4]< 2 GeV) photons with pT>15 and 17 GeV, |y|<1.0; 5.4 fb-1
- Data are compared with predictions by PYTHIA, DiPhoX, ResBos
- 1D cross sections vs. diphoton Mass, $p_T^{\gamma\gamma}$, $\Delta\phi$.

Submitted to PRL&PRD
arXiV 1106.5131

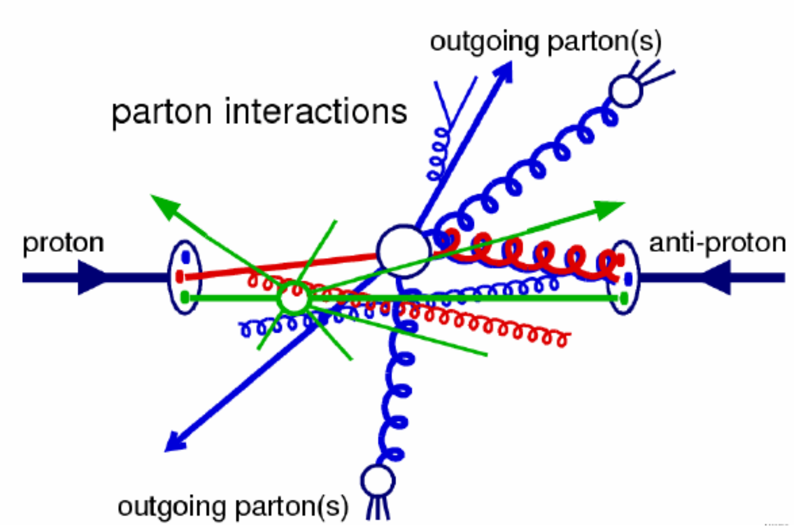


Significant contrib. from gg→ $\gamma\gamma$, fragmentation



Significant contrib. from fragmentation

- None of the models describe the data well in all kinematic regions, in particular at low diphoton mass (M<60 GeV), low $\Delta\phi$ (<1.7 rad) and moderate $p_T^{\gamma\gamma}$ (20-50 GeV)
- Data/Theory: similar conclusion to those from D0 results



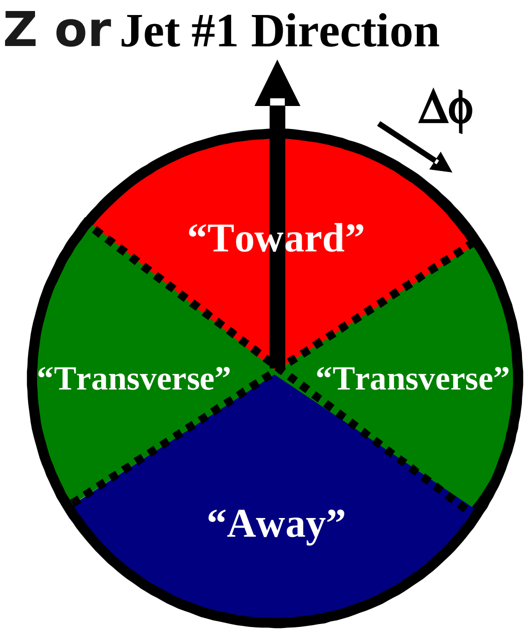
Underlying events
Double parton scattering

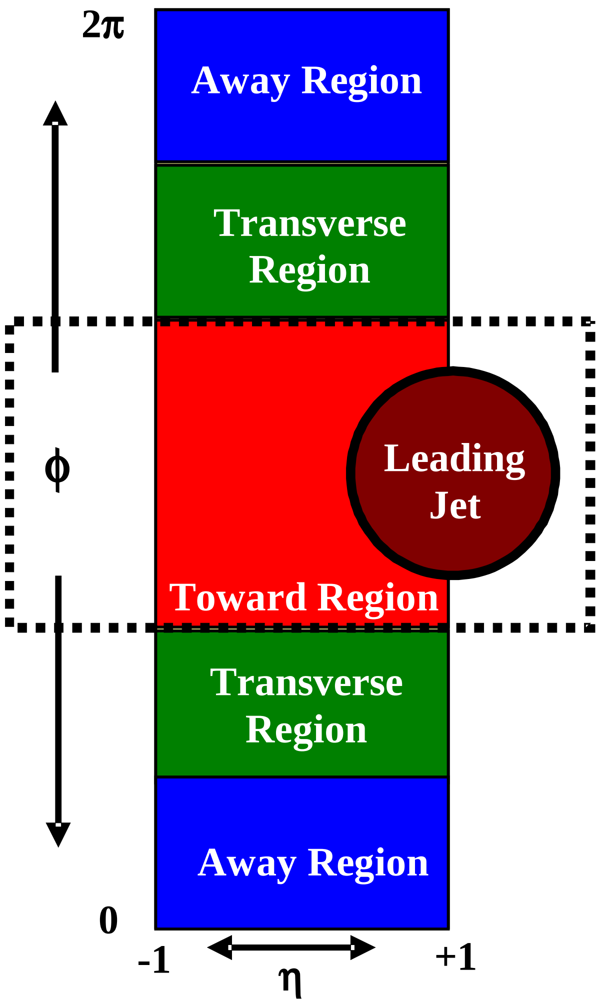
Tuning phenomenological models, MC Generators

Underlying Event in DY and Jet production (CDF)

UE events: multiple parton interactions (MPI) + beam remnants
Goal: improve understanding and modeling of high energy collider events

Define 3 regions in a jet/DY event,
based on the leading jet/dilepton pT
"toward"
"away"
"transverse"





"transverse" region

→ very sensitive to underlying event

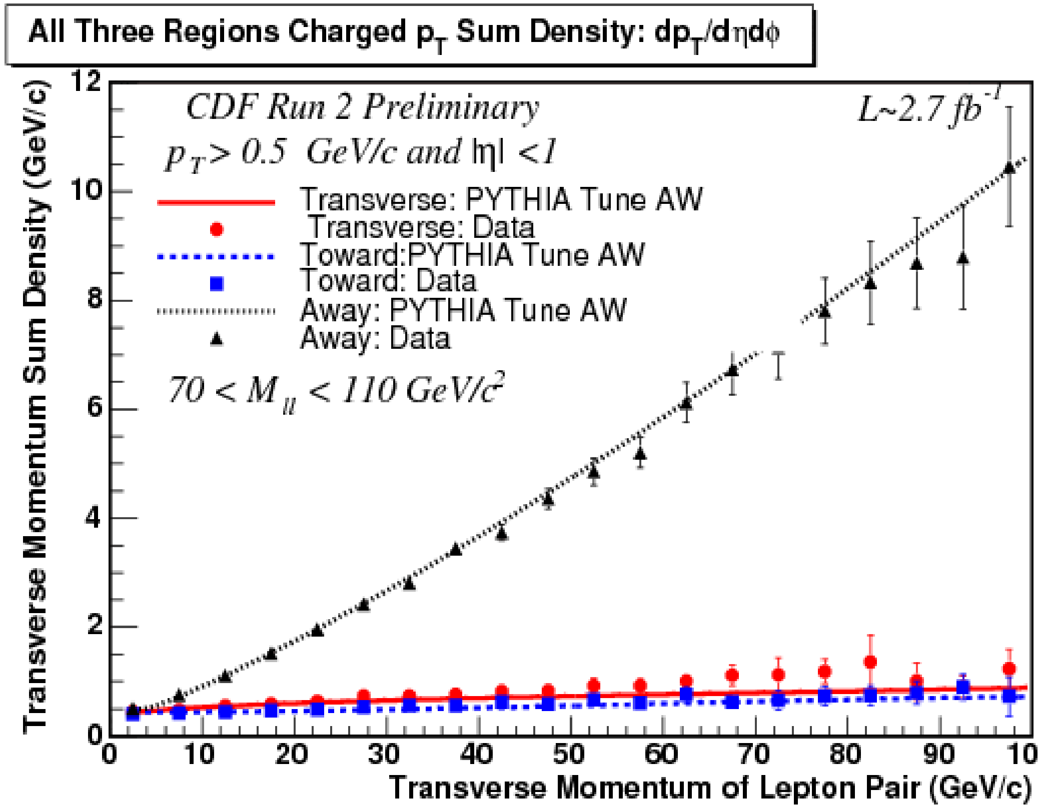
Study (in all regions)
- charged particle density (per $\Delta\eta\Delta\phi$)
- multiplicity
- p_T sum density

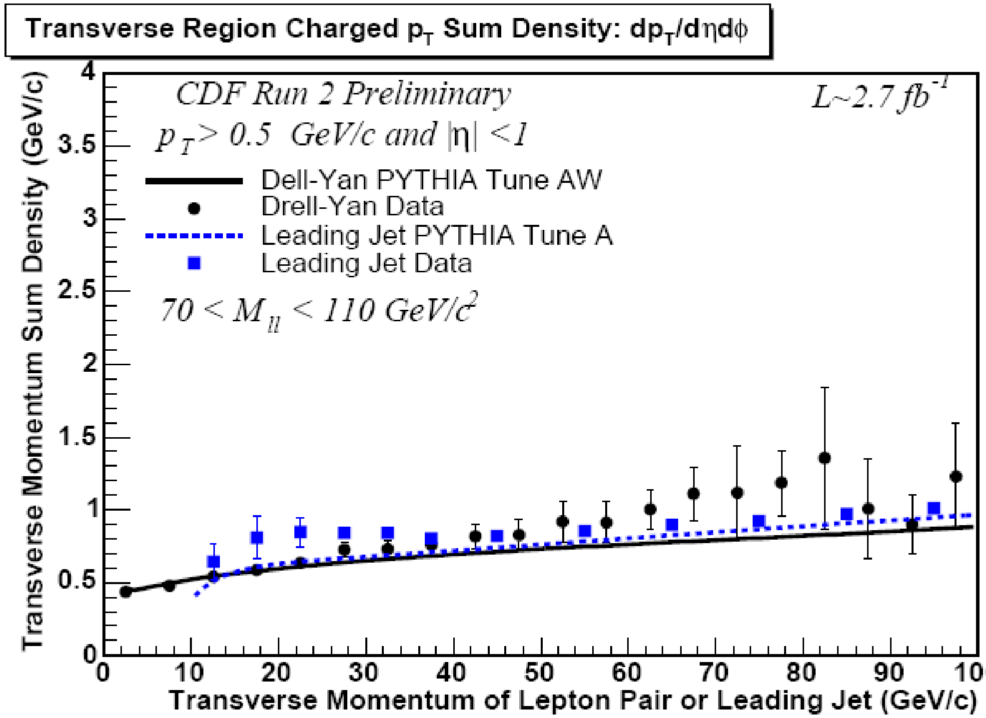
Underlying Event in DY and Jet production(CDF)

Phys.Rev.D82,034001 (2010)

Comparison of **three regions** in DY:

- "away" region: pT density increases with lepton pair (or jet) pT
- "transverse", "toward" regions: pT density is almost flat with lepton pair pT





Comparison of "transverse" region between **jets and DY**

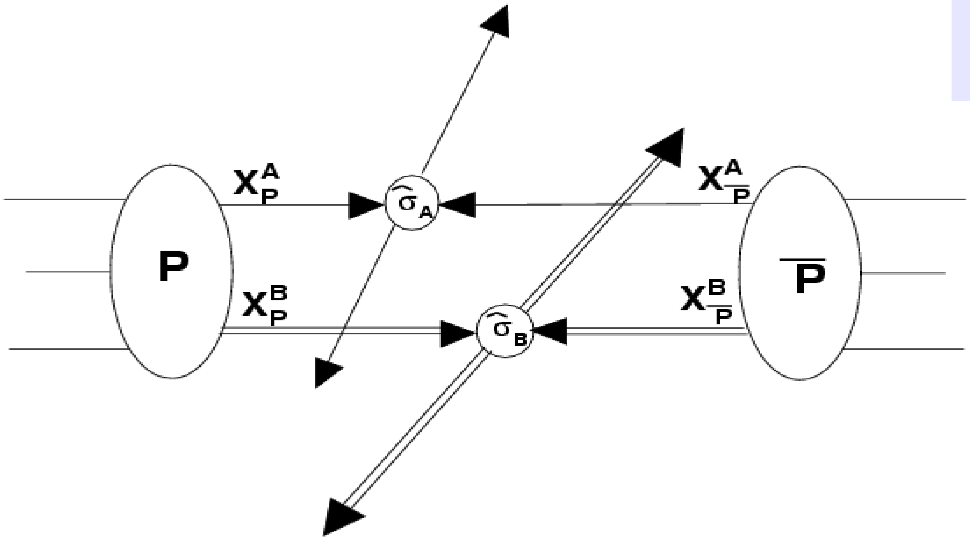
- similar trend in both (MPI universality?)
- tuned PYTHIA (A,AW) describes data

Double Parton Scattering in γ+3 jet events (D0)

- Study of MPI events in high pT regime (jet pT>15 GeV); complementary to CDF.
- Complementary information about proton structure: Spatial distribution of partons

  ⇒ Possible parton-parton correlations. Impact on PDFs?
- Needed for understanding multijet signal events and correct estimating backgrounds to many rare processes.

Selections: 60 < photon pT < 80 GeV, lead. jet pT > 25, other 2 jets with pT > 15 GeV

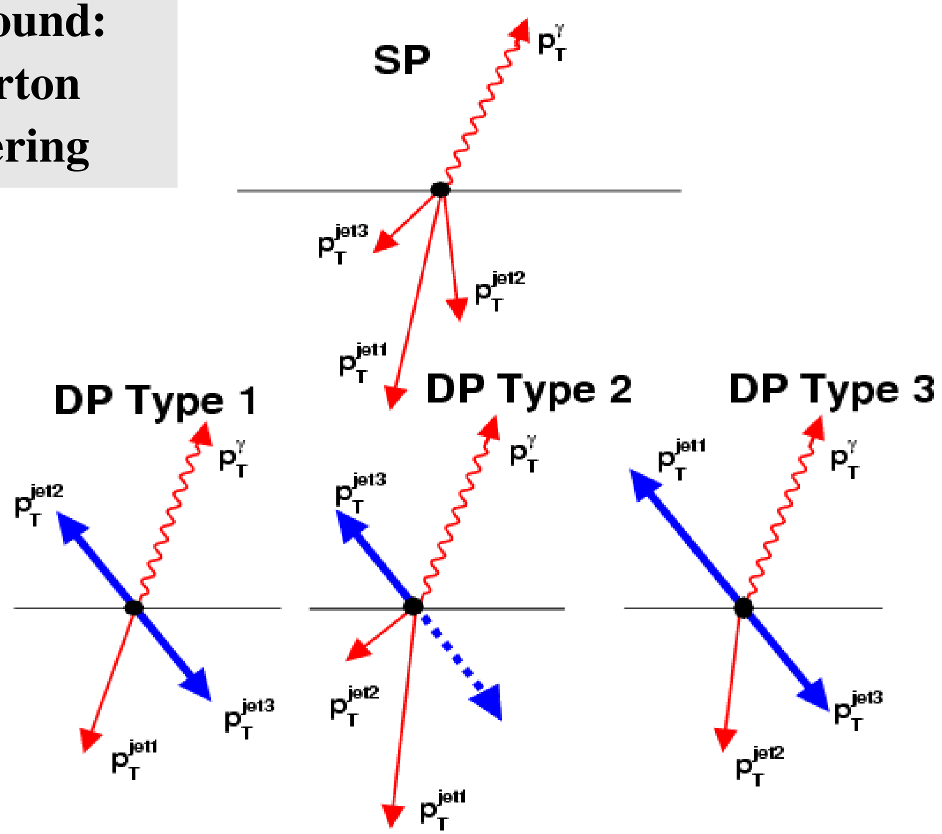


$$\boxed{\sigma_{DP} = \sigma_{\gamma j}\ \sigma_{jj}/\sigma_{eff}}$$

σ_{eff} is a scale parameter sensitive to the size of effective parton interaction region, and thus => to the parton spatial density

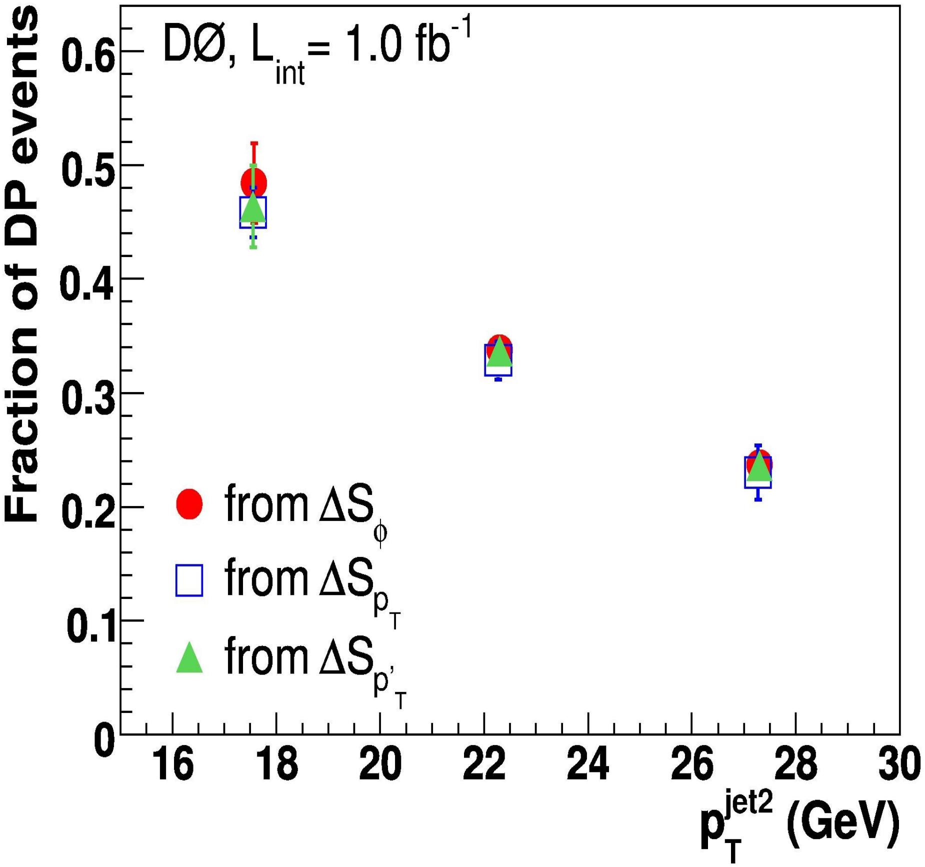
Main Background: Single Parton scattering

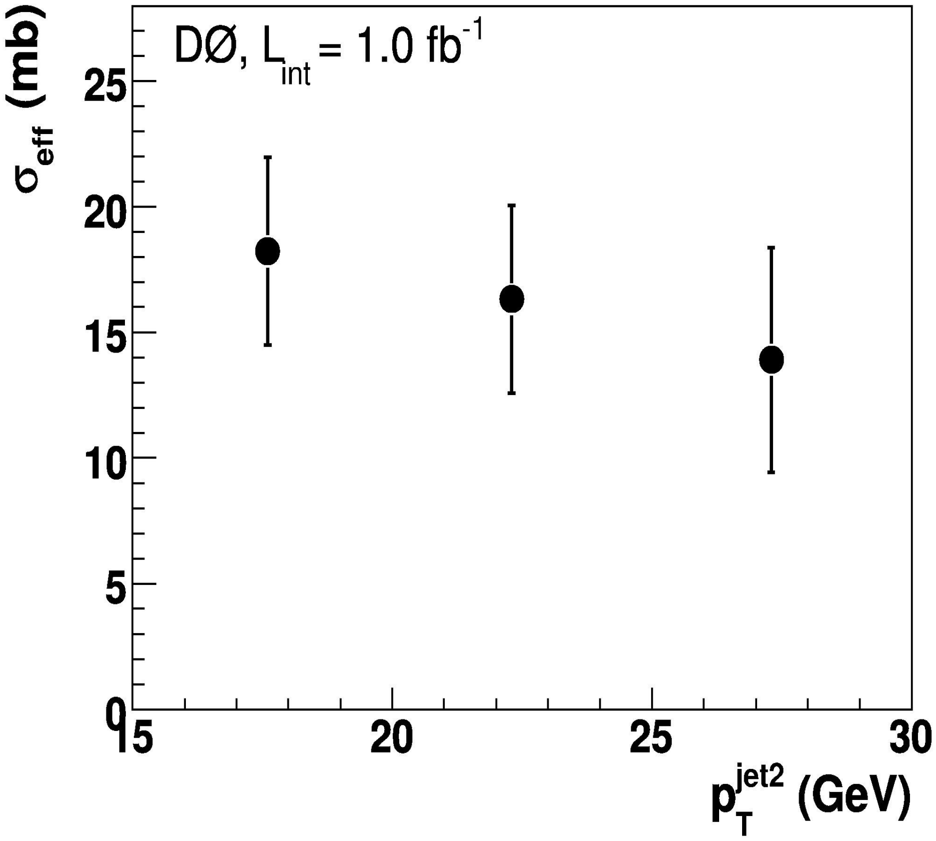
Three types of events with Double Parton scattering



Double parton results, γ+3 jet events (D0)

Phys.Rev.D81,052012 (2010)





- The measured double parton fraction drops from 0.47±0.04 at 15<p_{T2}<20 GeV to 0.23±0.03 at 25<p_{T2}<30 GeV
- Effective cross section averaged over 3 p_{T2} bins:

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

- Good agreement with Run I measurements by CDF („4 jets", $\sigma_{eff} = 12.1^{+10.7}_{-5.4}$ mb and "γ+3jets", $\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb)

Angular decorrelations in γ+2(3) jet events (D0)

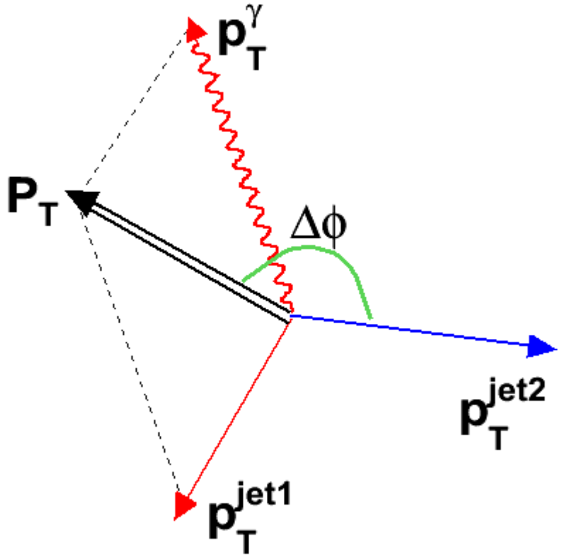
Motivations:

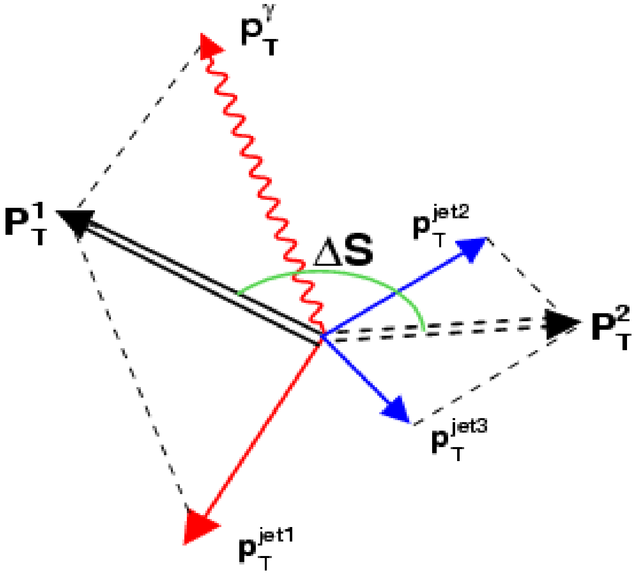
- By measuring **differential** cross sections vs. azimuthal angles in γ+3(2) jet events we can better tune (or even exclude some) MPI models in events with high pT jets.

- Differentiation in jet pT increases sensitivity to the models even further.

Four normalized differential cross sections are measured

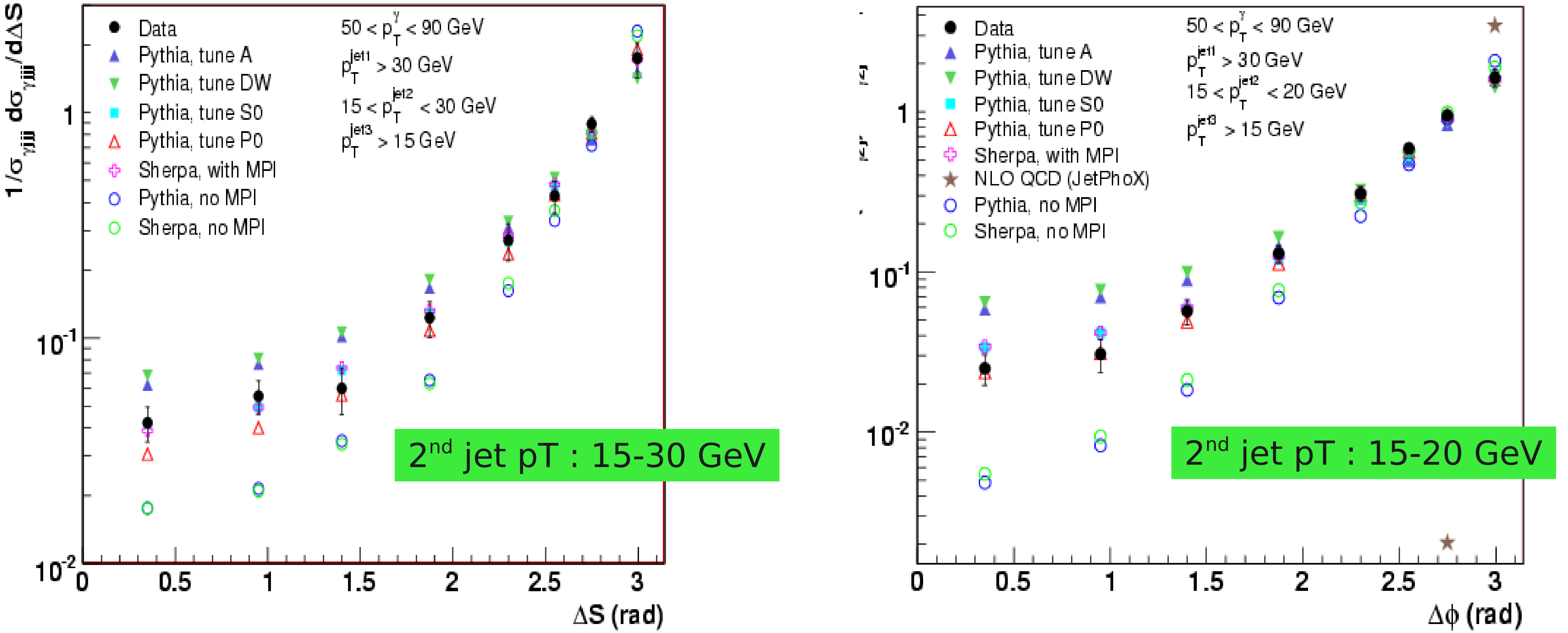
- $\Delta\phi(\gamma$+jet1, jet2) in 3 bins of 2nd jet pT: 15-20, 20-25 and 25-30 GeV
- ΔS(γ+jet1, jet2+jet3) for 2nd jet pT 15-30 GeV (larger for stat. reasons but still has good sensitivity to MPI models)





ΔS and $\Delta\phi$ cross sections

Phys.Rev.D83,052008 (2011)



2nd jet pT : 15-30 GeV

2nd jet pT : 15-20 GeV

- MPI models substantially differ from any prediction with single parton scattering only.
- Large difference between SP models and data confirm presence of DP events in the data sample.
- MPI models differ noticeably between each other, especially at small azimuthal angles => we can tune the MPI models or just choose the best one(s)
- Data are close to Perugia (P0), S0 and Sherpa with MPI tunes.
  N.B.: the conclusion is valid for both the considered variables and 3 jet pT intervals!

Summary

- Recent Tevatron results are presented: current level of understanding jet ID, systematics and jet energy scale leads in many cases to experimental uncertainties similar or lower than theory uncertainties.
=> Precision measurement of fundamental observables.

- Good consistency between D0 and CDF in most cases, complementarity.

- Jet results: good agreement with pQCD, sensitivity to PDF sets, strongest constraint on gluon PDF, extraction of α_s, detailed studies of the effect of different jet algorithms; jet substructure, limits on many NP models.

- Z/W results: extensive tests and tuning of pQCD and MC models

- Photon results: test fixed order NLO, resummation, fragmentation. Theory should be better understood.

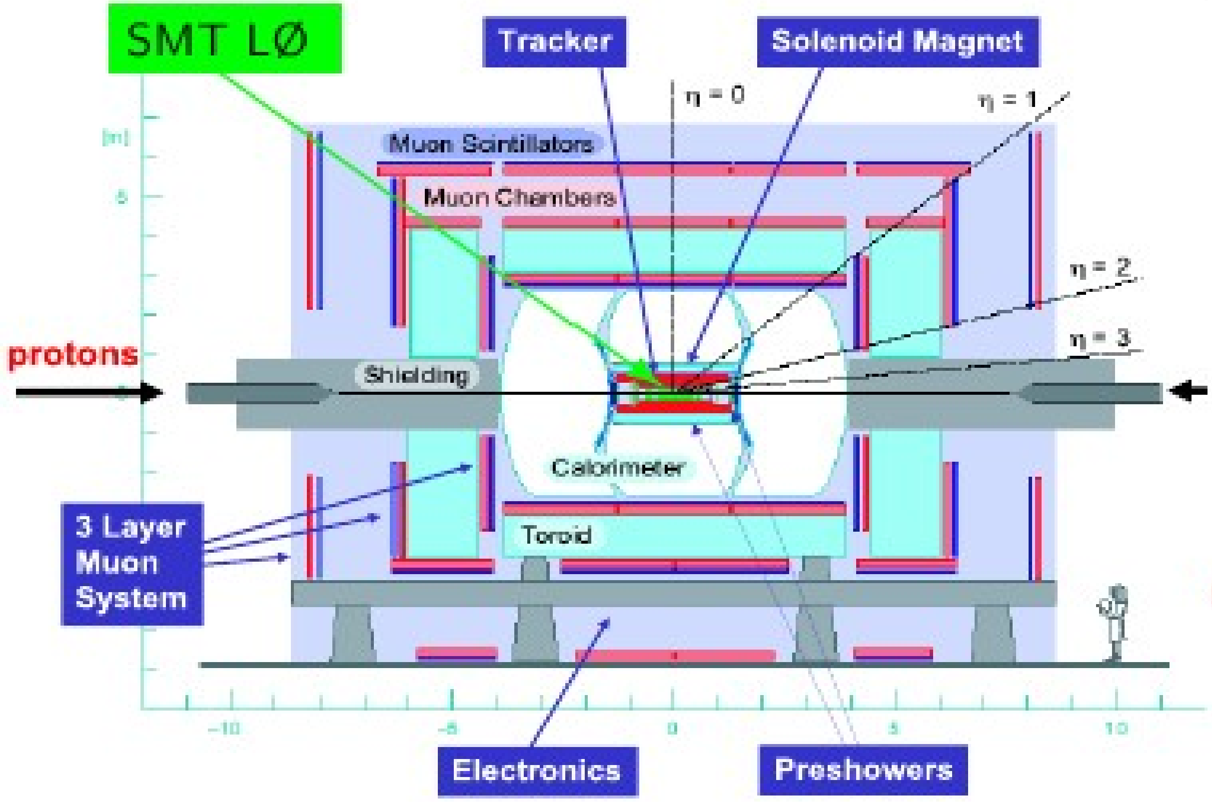
- Underlying/DP events: strong constraints/improving phenomenological models at low and high pT regimes.

See all current Run2 QCD results at
http://www-d0.fnal.gov/Run2Physics/qcd/D0_public_QCD.html
http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

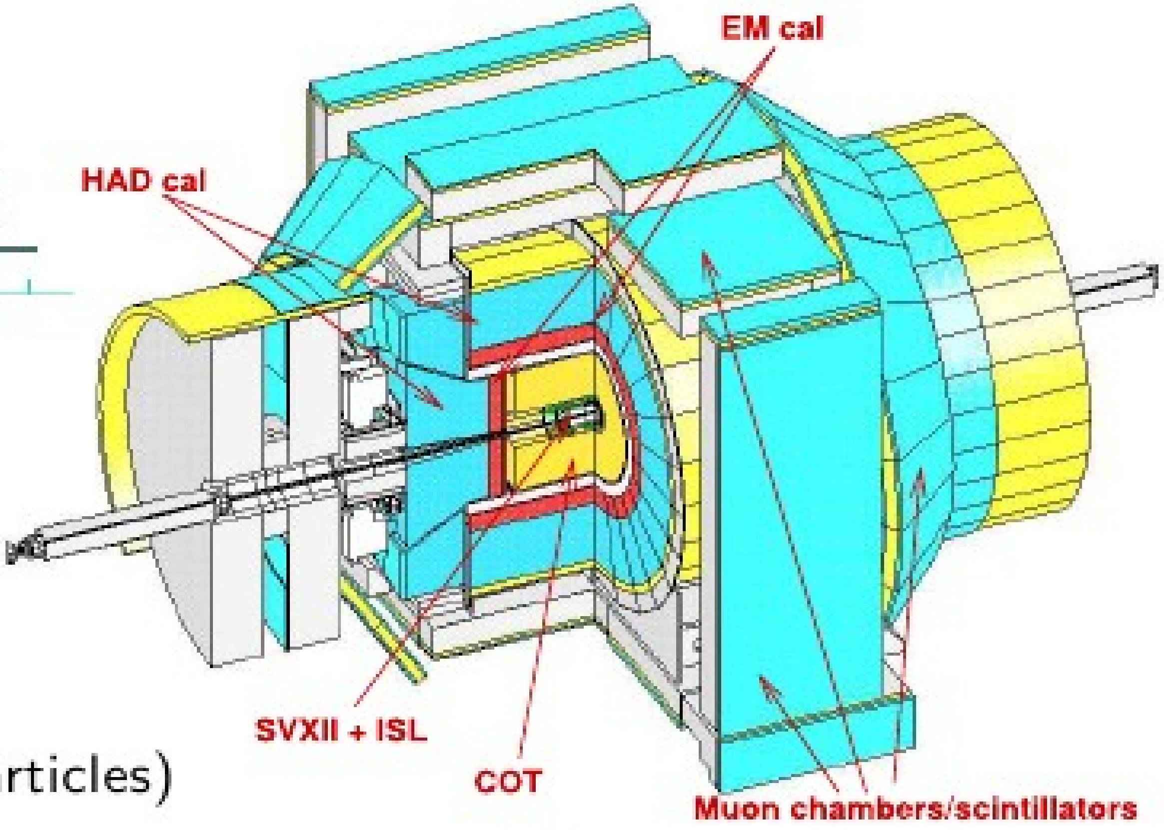
BACK-UP SLIDES

The DØ and CDF detectors

- Data taking efficiency (DØ & CDF) $\gtrsim$ 90%

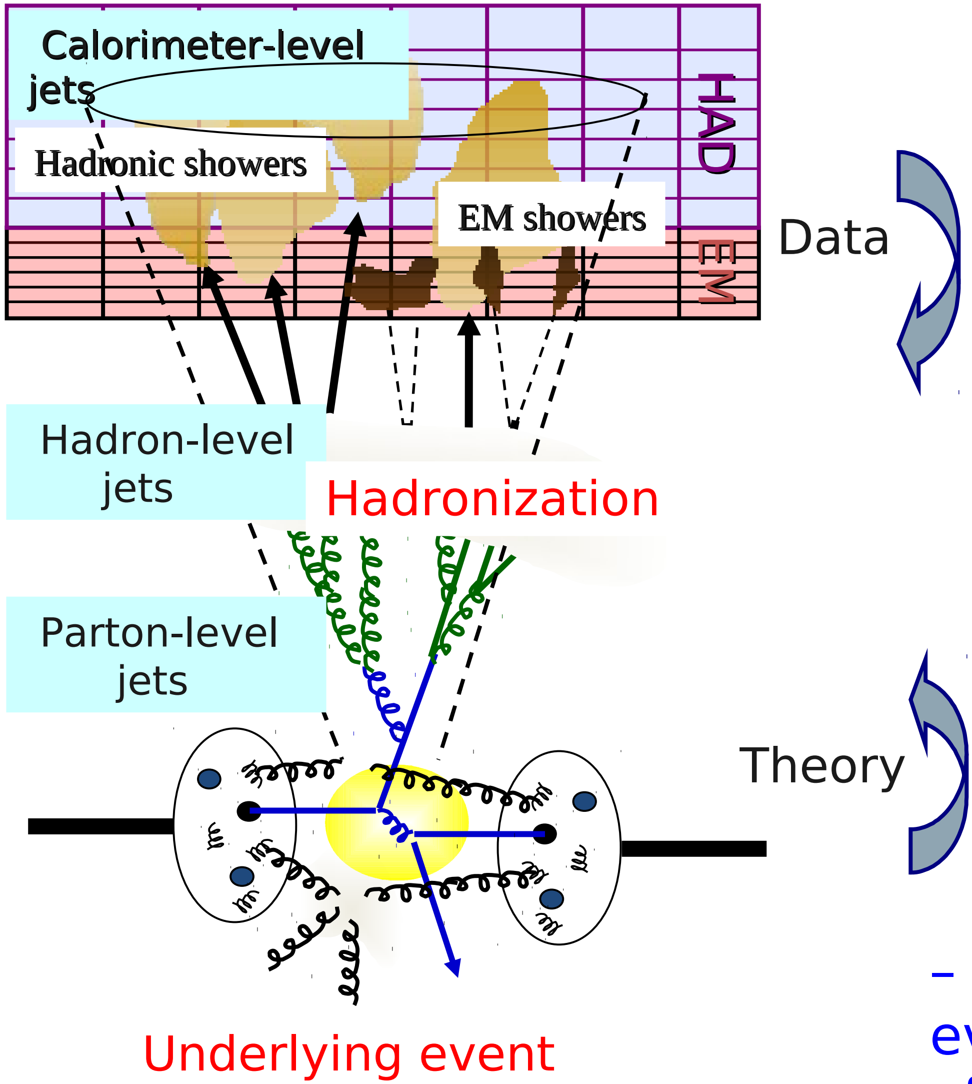


- Multi purpose detectors with broad particle ID capabilities
- Stable detectors and triggers



- Calorimeters (→ jets, e, γ): Fine granularity and good energy resolution
  DØ: $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$
  CDF: $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.26$
- Central tracking systems (→ charged particles)
- Muon spectrometers (→ muons)

Corrections to particle level

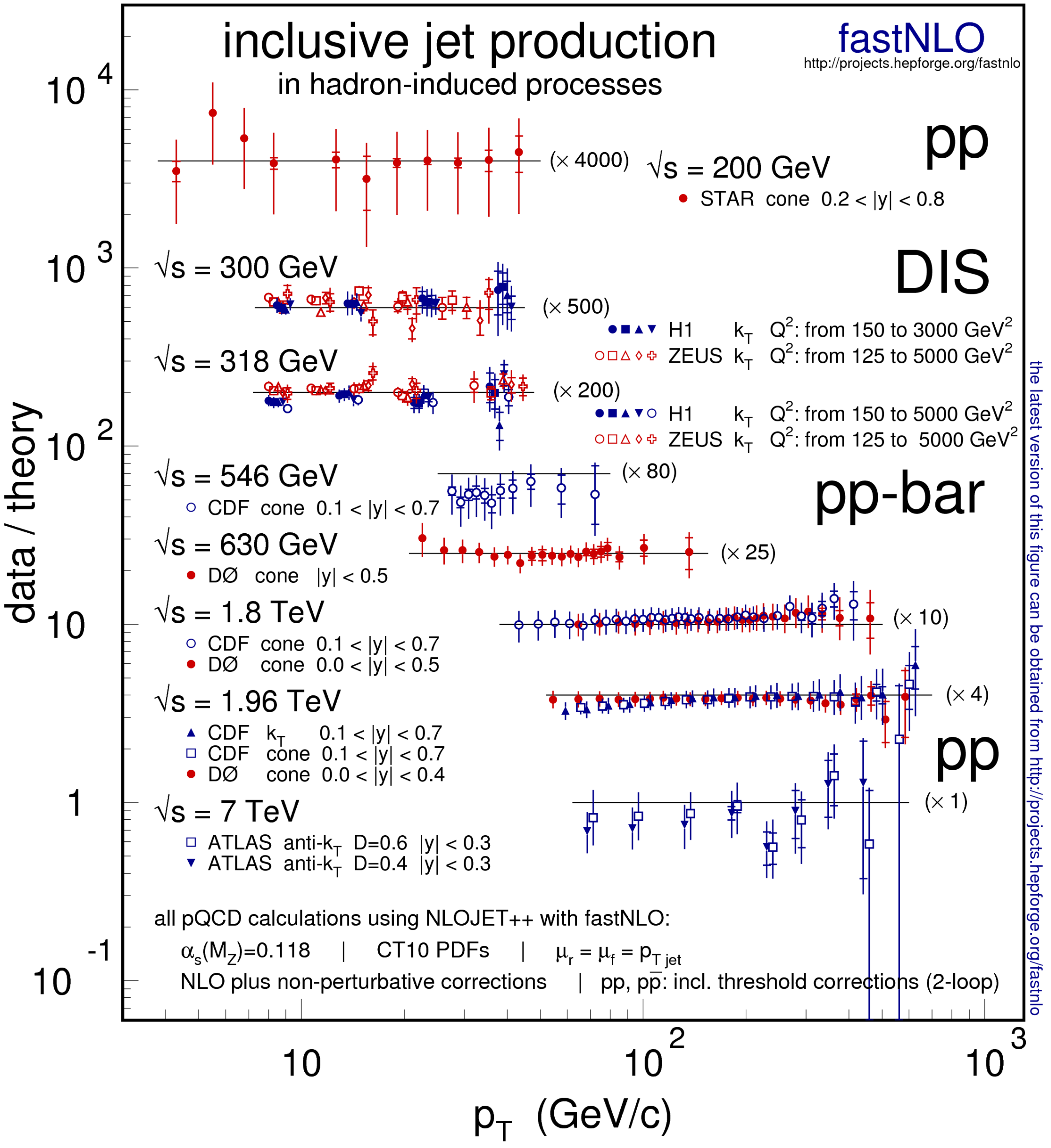


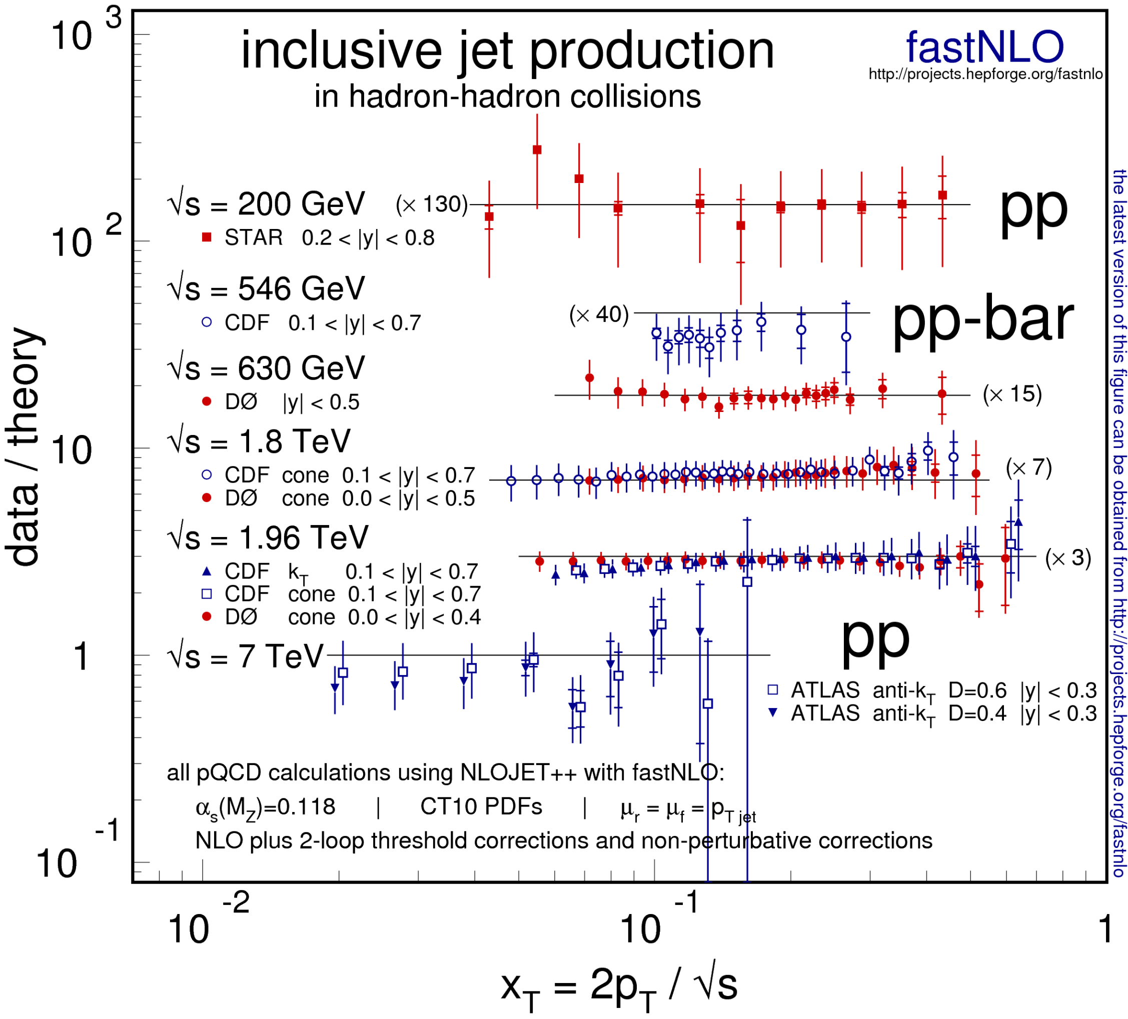
In Run II jet results, in most cases:
- data are corrected to particle level
- particle level measurements are compared to NLO theory
- NLO theory is corrected to particle level using parton shower MC

$$C_{had} = \frac{\text{observable (particle level)}}{\text{observable (parton level)}}$$

– There is also correction (C_{ue}) for the underlying events (MPI). Usually we run Pythia with a couple of Tunes, Herwig+Jimmy and correct predictions with MPI to that without.

Inclusive jet production: hadron colliders

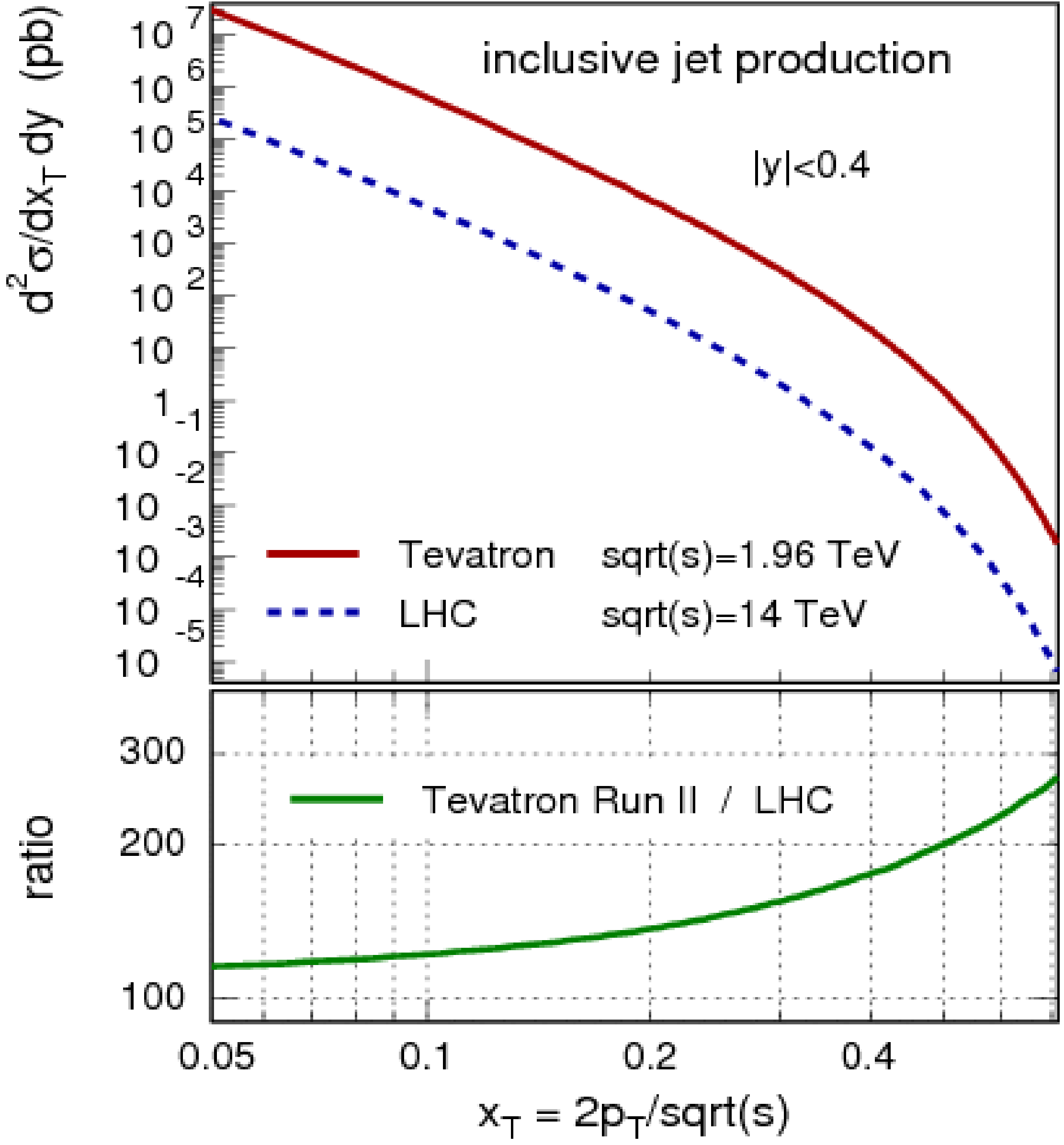




pT plot: the Tevatron pT reach is still about as good as the published LHC results
xT plot: the Tevatron data have far better high-x sensitivity

Inclusive Jets: Tevatron vs. LHC

fastNLO prediction



PDF sensitivity:

→ compare jet cross section at fixed $x_T = 2\ p_T$ / sqrt(s)

Tevatron (ppbar)

>100x higher cross section @ all x_T

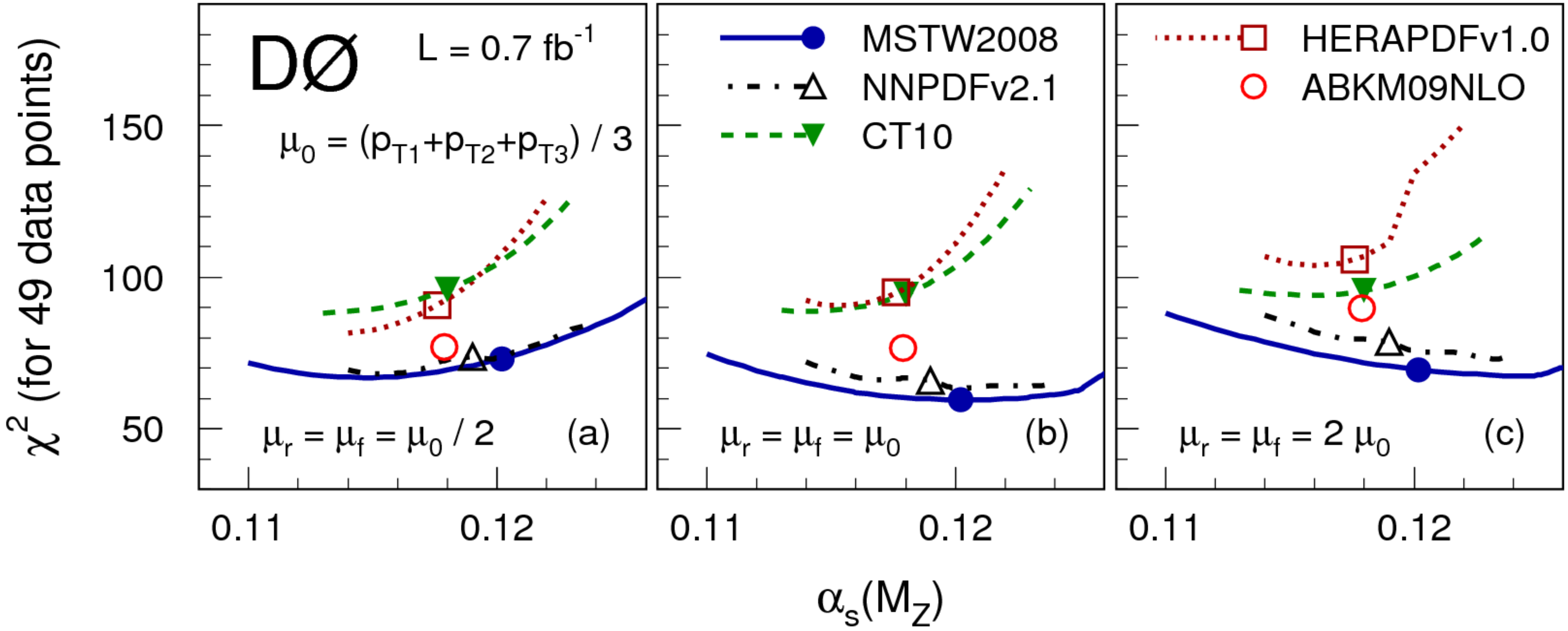
>200x higher cross section @ x_T>0.5

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)

→ Tevatron results should dominate high-x gluon for some years

Three jet mass: χ^2 test (D0)

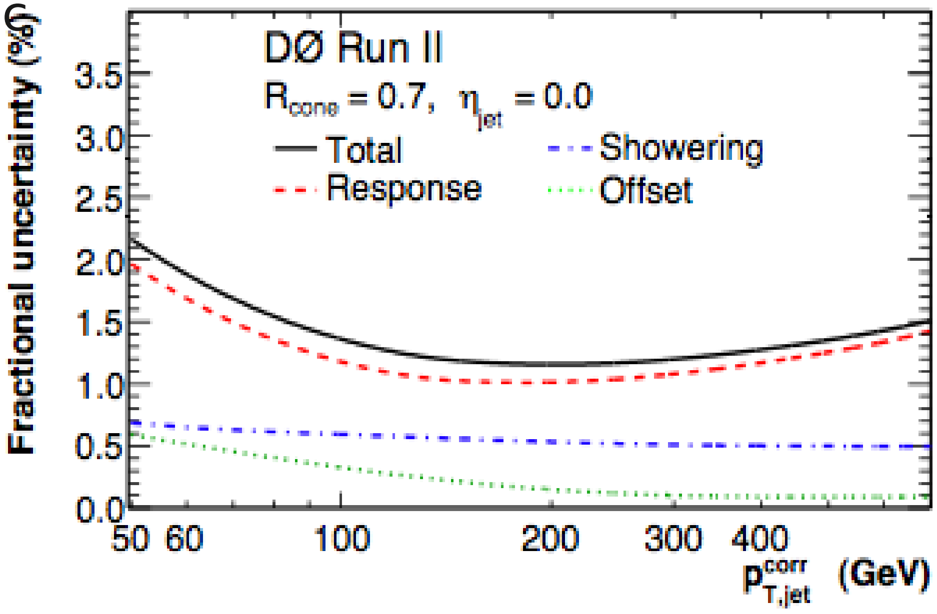


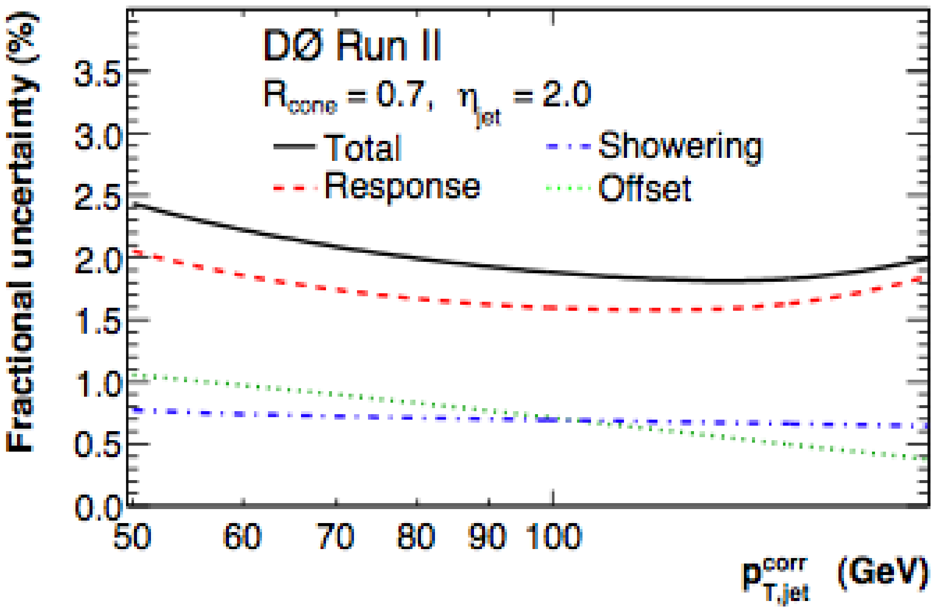
Jet energy scale calibration

- We do not “see” partons or particles in calorimeter, only ADC counts
- ADC counts --> cell energies
- Run jet cone algorithm (see Backup) with
  $\Delta R = \sqrt{(\Delta y^{2}+\Delta \Phi^{2})} < R_{\text{cone}}$

  Jet's E are corrected to the particle level using the Jet Energy Scale (JES) setting procedure :
- Calibrate using γ+jets (dijets and Z+jets)
- JES includes: Energy Offset (energy not from the main hard scattering process); Detector Response, Out-of-Cone showering; Resolution
- Responses in the calorimeter for quark and gluon jets are different: additional corrections are applied to convert γ+jet → dijet JES.

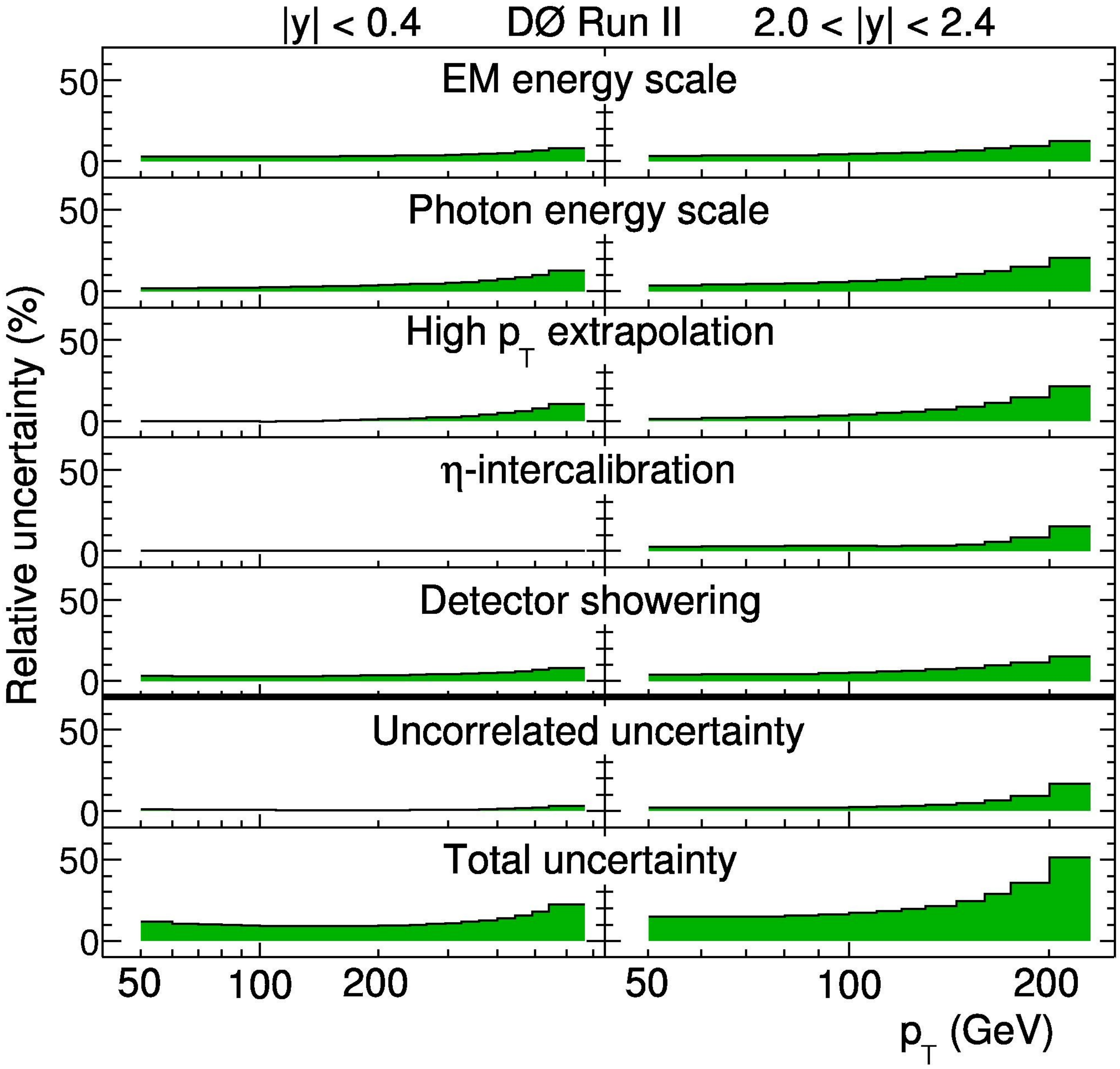
Energy scale uncertainty: 1-2.5% (a lot of hard work of many people)!





Inclusive jet production (D0): correlations study

- All systematic uncertainties in data compose 24 main groups
- Possibility to constrain PDF further using the provided correlation matrices
- Detailed paper on the measurement to be submitted soon to PRD



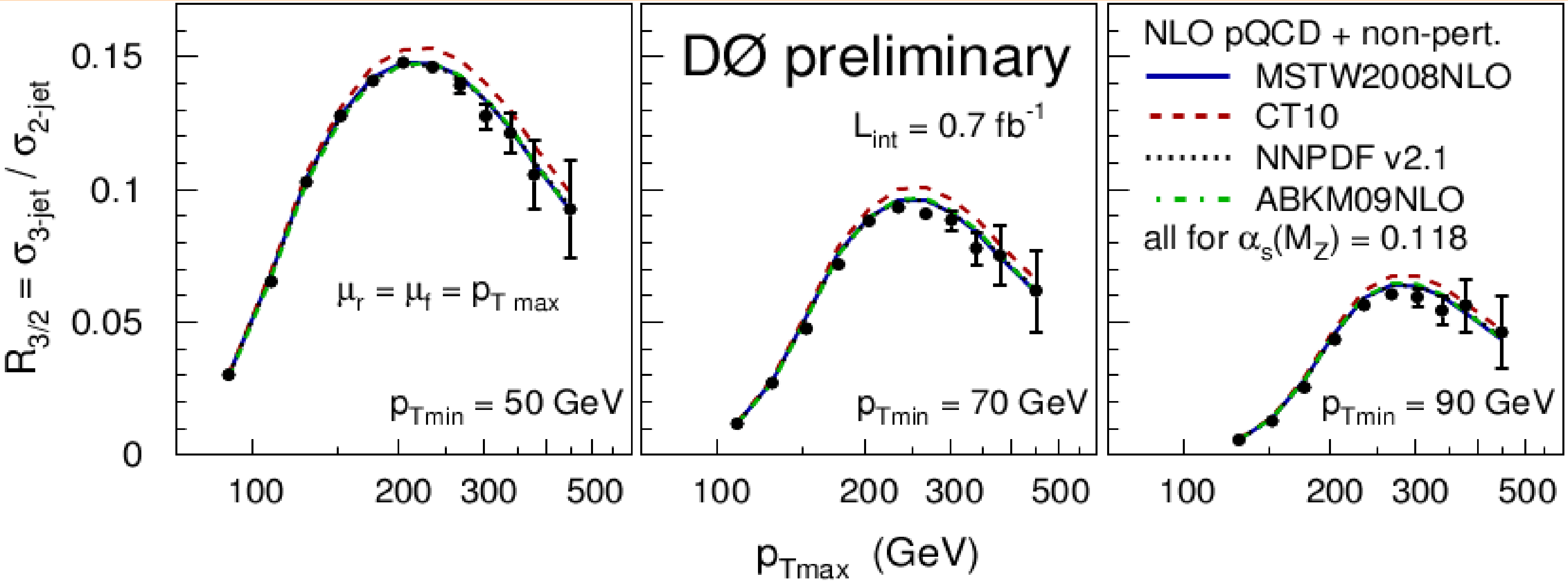
Main sources of systematic uncertainties

Ratio of 3 to 2 jet production cross sections (D0)

Preliminary

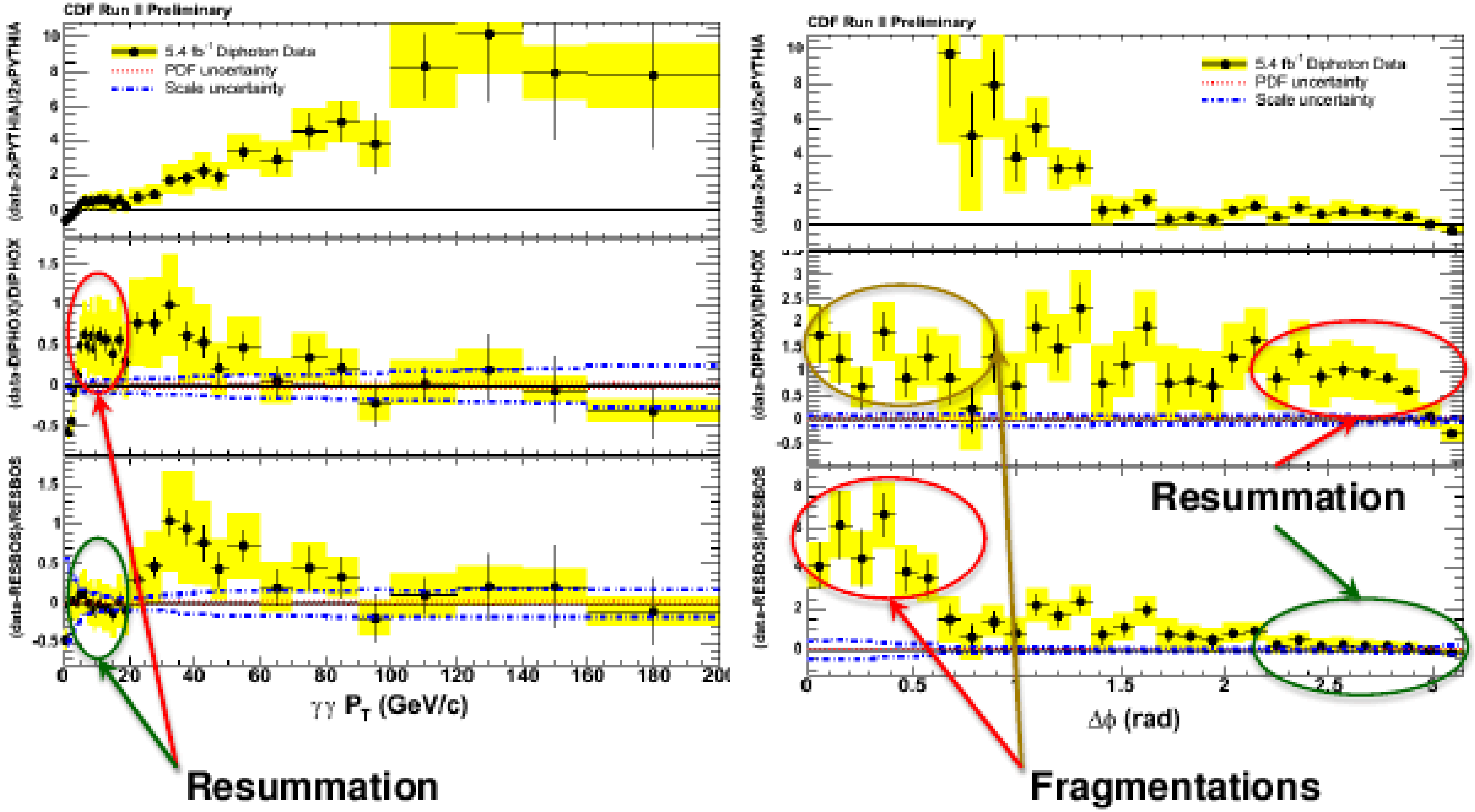
- First measurement of ratios of multijet cross-sections at Tevatron
- Test of QCD almost independent of PDFs
- Many experimental uncertainties also cancel in the ratio R3/2.
- Measure $R_{3/2}$= P(3rd jet | 2 jets) as a function of two momenta p_{Tmax}, p_{Tmin}:
  - p_{Tmax} – leading jet p_T (common between 2- and 3-jet productions)
  - p_{Tmin} – scale at which other 1-2 jets resolved
- Comparisons to NLO QCD, LO Sherpa and Pythia with a few tunes

- Shape of the ratios is well described by NLO theory and, as expected, practically independent on PDF set.
- Excellent agreement to Sherpa 1.1.3 (MSTW2008 LO), Pythia BW tune (tunes QW, DW [they worked for χ^2_i $\Delta\varphi$ data], Perugia are significantly off)
- Probes running of α_s up to p_T of 500 GeV



Photon Pair Production (CDF)

Direct Photon Pair Production Differential Cross Sections measured with the CDF Detector: Ratios of Data/Theories

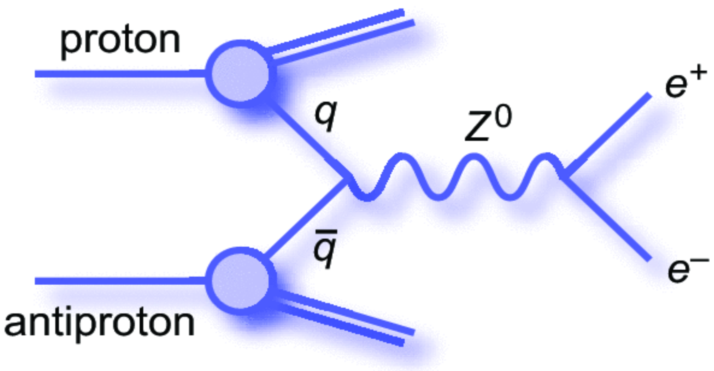


Resummation

Resummation

Fragmentations

Z/W+jets production



Use leptonic Z/W decays as most precise probe of QCD

- high Q^2 ($\sim M_Z$ or M_W)
- very small backgrounds, right down to very small p_T!

Concentrate on high pT final states

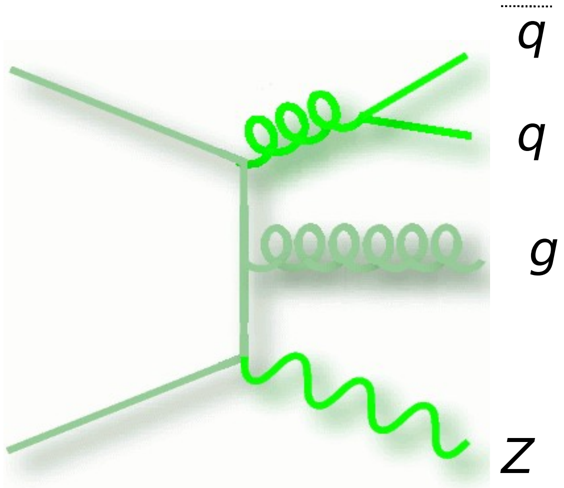
- regime of perturbative QCD

Theory predictions:

pQCD (+ corrections for underlying event & hadronization):

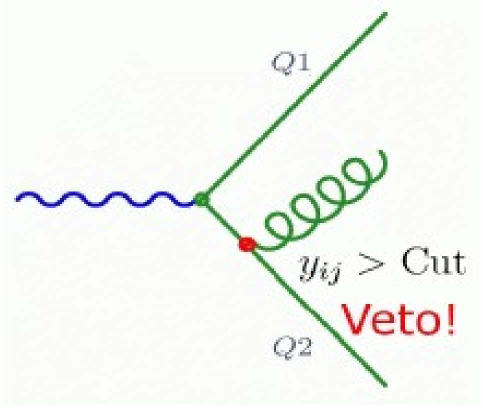
- LO Z(W) + 1 - 6 partons
- NLO Z(W) + 1, 2 (MCFM)

[NLO W+3 (Rocket, Blackhat+SHERPA) is also available now]



Event generators:

- LO 2 ->1, 2 + parton shower
  - PYTHIA, HERWIG
- LO 2 -> 1-6 + (vetoed) parton shower
  - ALPGEN (MLM ME-PS matching),
  - SHERPA (CKKW ME-PS matching)



These generators are the main Tevatron and LHC tools

- but, leading order → large uncertainties
- must to be tuned to data!

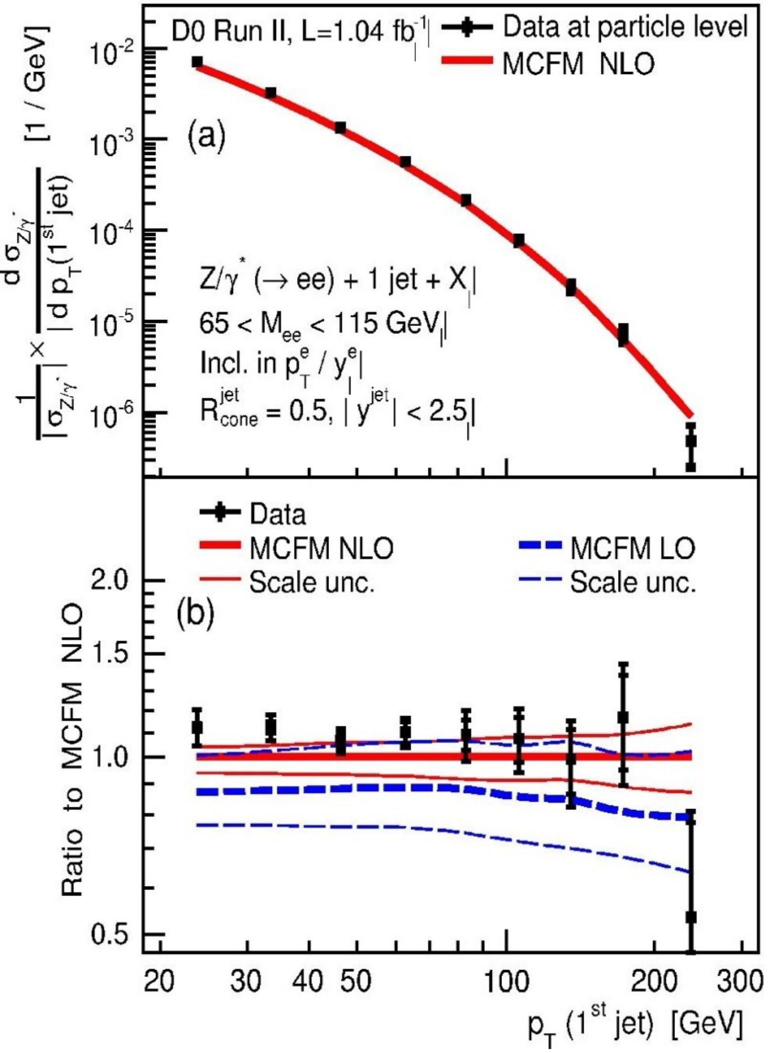
Z+jets production: jet pT, data/NLO (D0)

Measurement of 1st, 2nd and 3rd jet pT in Z events:

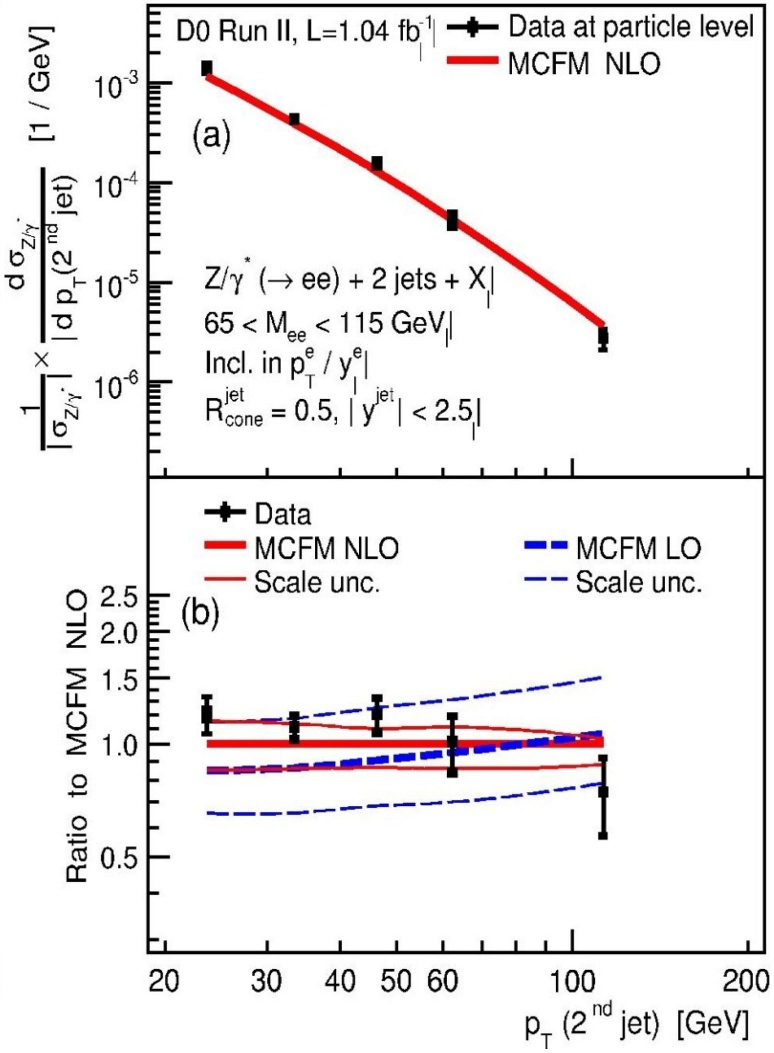
PLB 678, 45 (2009)

- Z→ee, jet p_T > 20 GeV, jet |y|< 2.5.
- Normalized to inclusive Z production x-section (cancel some uncertainties)

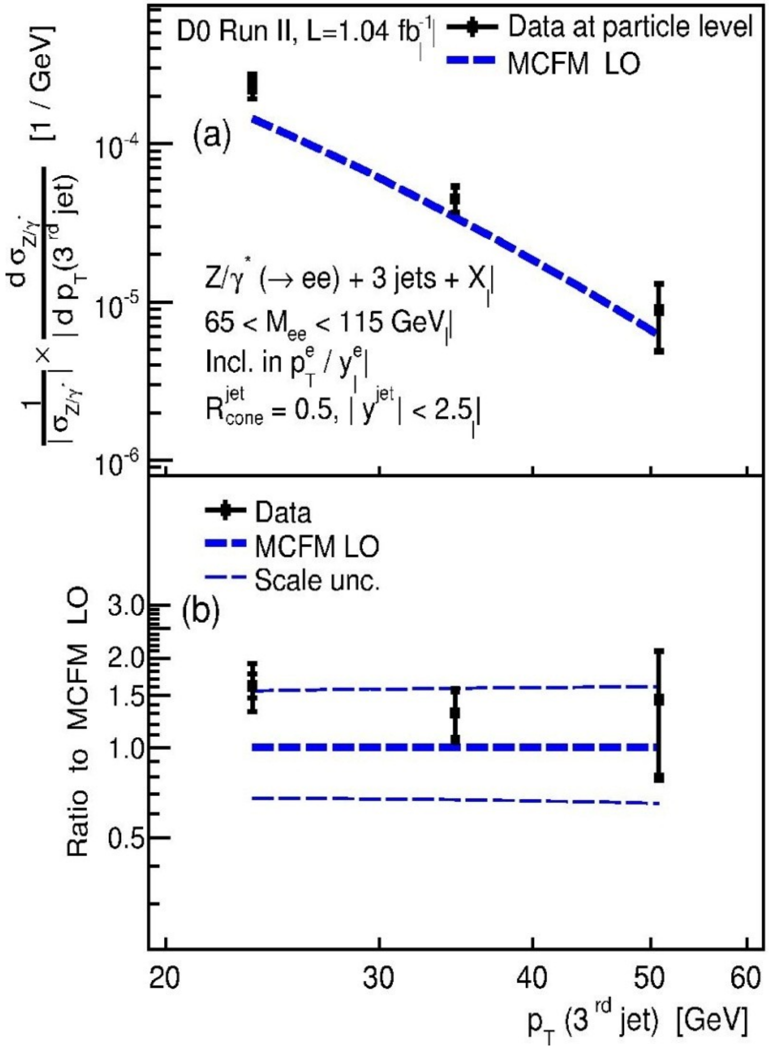
1st jet in Z + jet + X



2nd jet in Z + 2jet + X



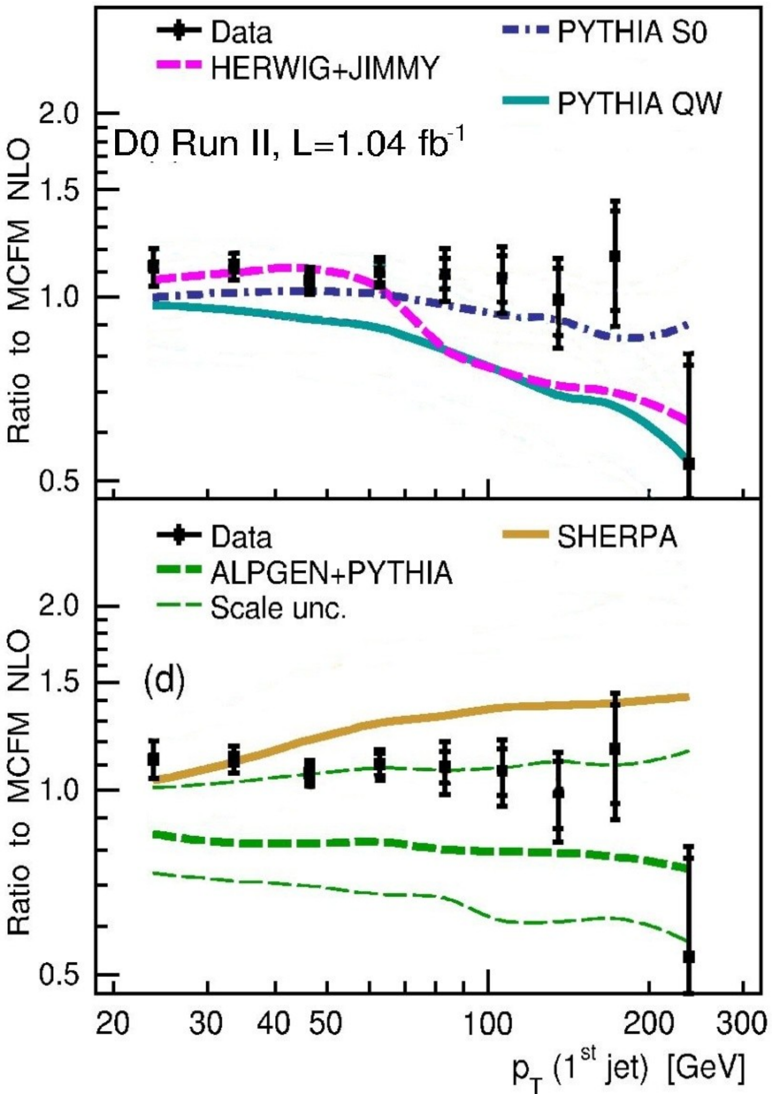
3rd jet in Z + 3jet + X



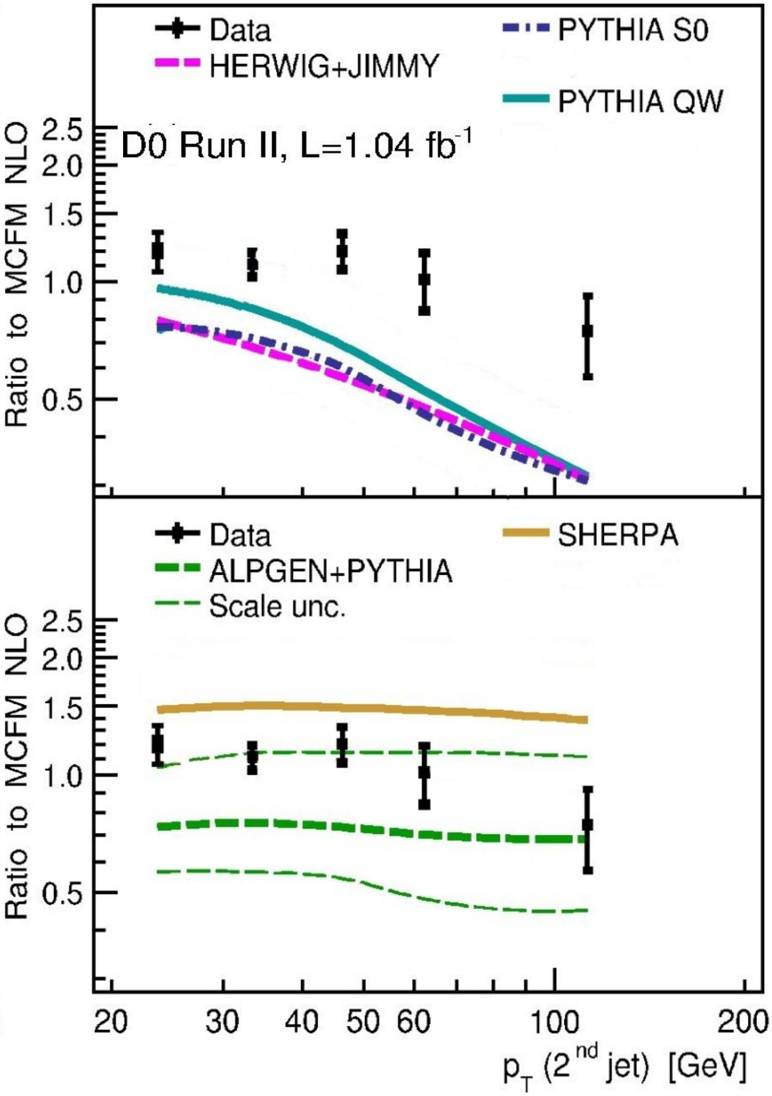
Z+jets production; jet pT, data/MC (D0)

Comparison to Pythia, Herwig, Alpgen and Sherpa
Treating the scale choice as a tuneable parameter:
best description from Alpgen with lower scale (default: $\mu_F^2 = p_{TZ}^2 + M_Z^2$).

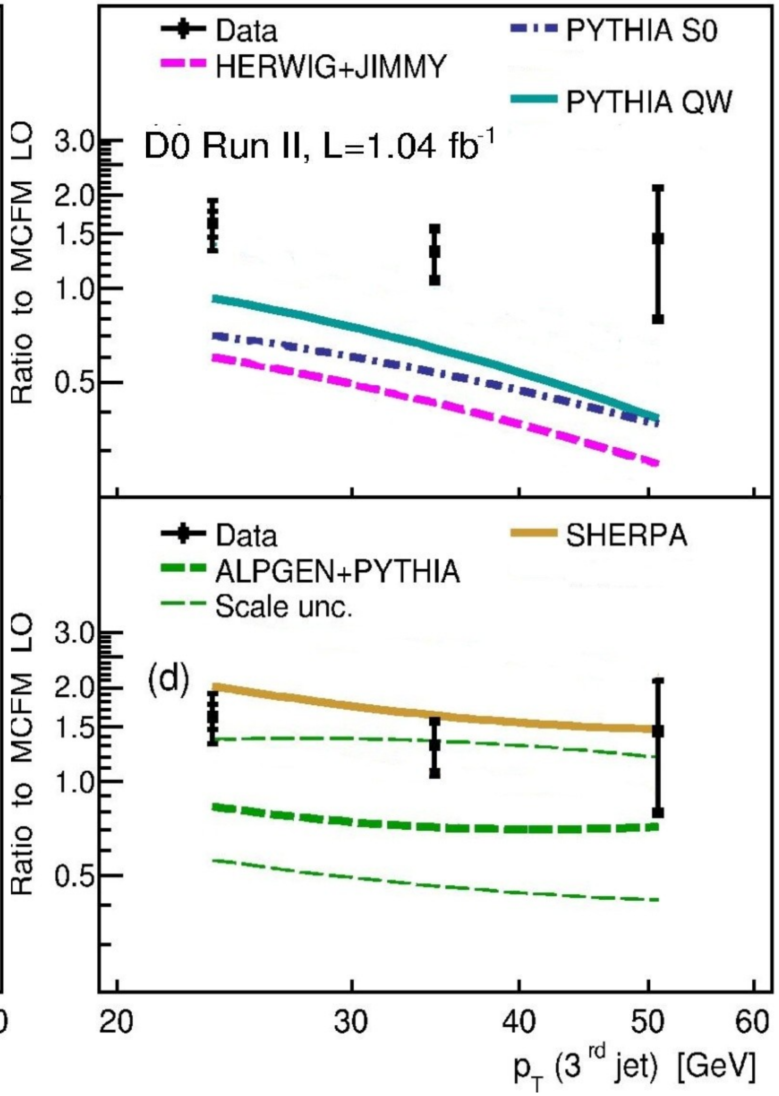
Leading jet in Z + jet + X



2nd jet in Z + 2jet + X



3rd jet in Z + 3jet + X

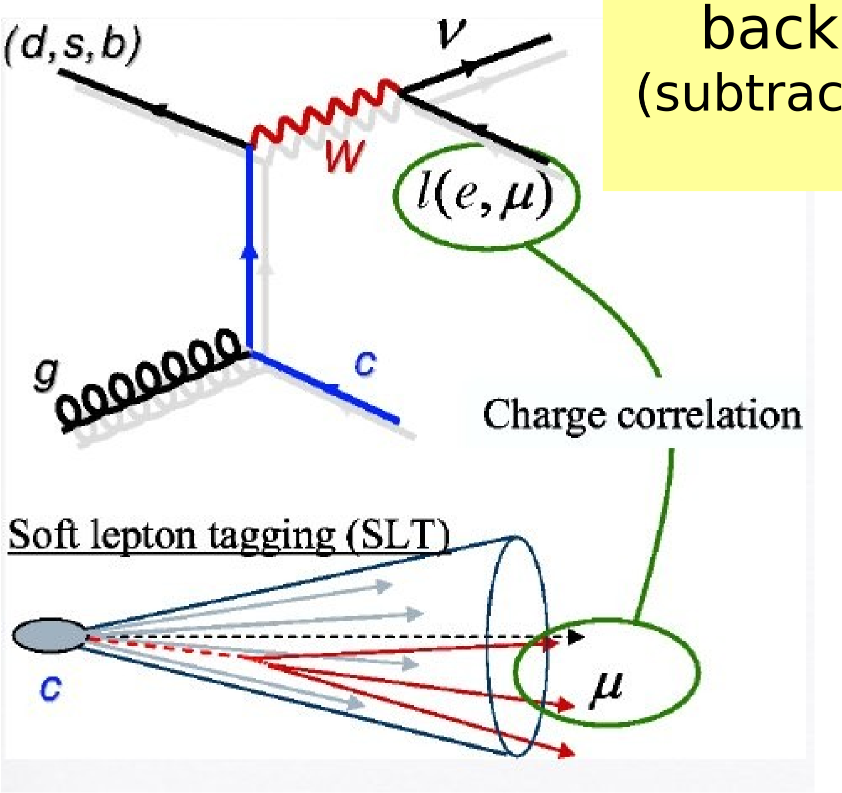


σ(W+c)/σ(W+jet) at D0 and σ(W+c) at CDF

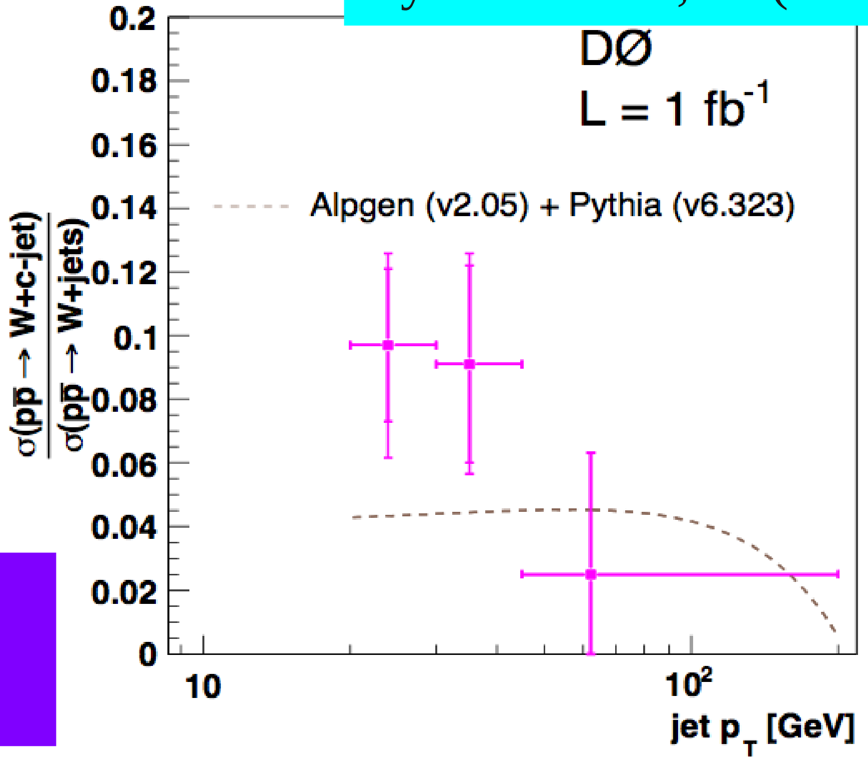
Sensitive to s-quark PDF: 90% s, 10% d

signal: OS>>SS
backgrounds: OS~SS
(subtracted in the diff. 'OS-SS')

Measurement cuts:
lepton p_T > 20 GeV
missing E_T > 20 GeV
D0 midpoint jet R_{cone}=0.5,
p_T^{jet} > 20 GeV,$|\eta^{jet}|$ < 2.5(1.5)



Phys.Lett.B666, 23 (2008)



D0 Data: 0.074 ± 0.019 (stat) ± $^{+0.012}_{-0.014}$ (sys)
Alpgen+Pythia: 0.044±0.003

CDF: σ(W+c)*Br(W-> lnu), L=1.8 fb-1 :
CDF Data: 9.8±3.2 pb
QCD NLO: 11.0 +1.4/ -3.0 pb

Good agreement data/theory

Phys.Rev.Lett.100,091803 (2008)

Angularity and planar flow (CDF)

- Angularity and planar flow variables study the jet substructure; quite robust against soft radiation, less dependent on the jet algorithm used.

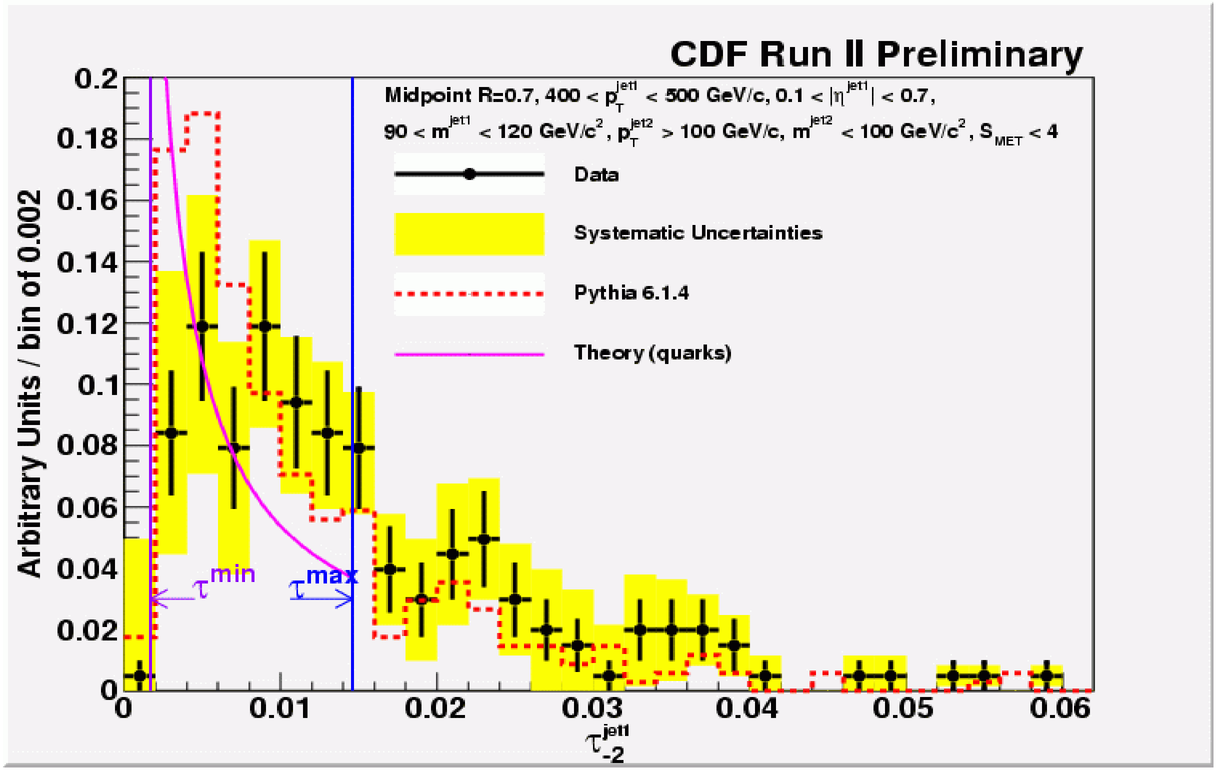
– Angularity: sum over calorimeter towers:

$$\tau_a(R,p_T) = \frac{1}{m_J}\sum_{i\in jet}\omega_i \sin^a\theta_i\,[1-\cos\theta_i]^{1-a} \sim \frac{2^{a-1}}{m_J}\sum_{i\in jet}\omega_i\,\theta_i^{2-a}$$

where ω_i is energy of a jet tower (particle)

– It is sensitive to the degree of symmetry in the energy deposition inside a jet: can distinguish jet originating from regular QCD production of light quarks and e.g. gluons from boosted heavy particle decay.

– Data show fewer jets at lower angularity, i.e. prefer more 'spherical' jets.



Angularity and planar flow (CDF)

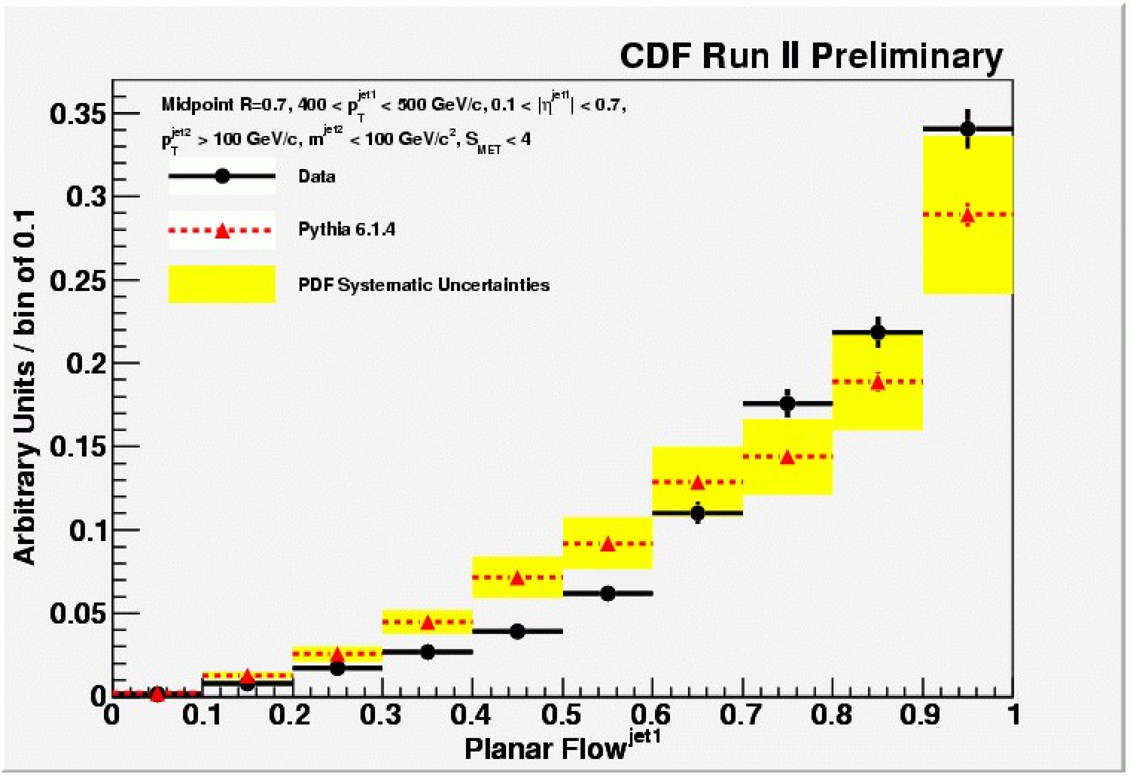
– Planar flow is another jet substructure variable:

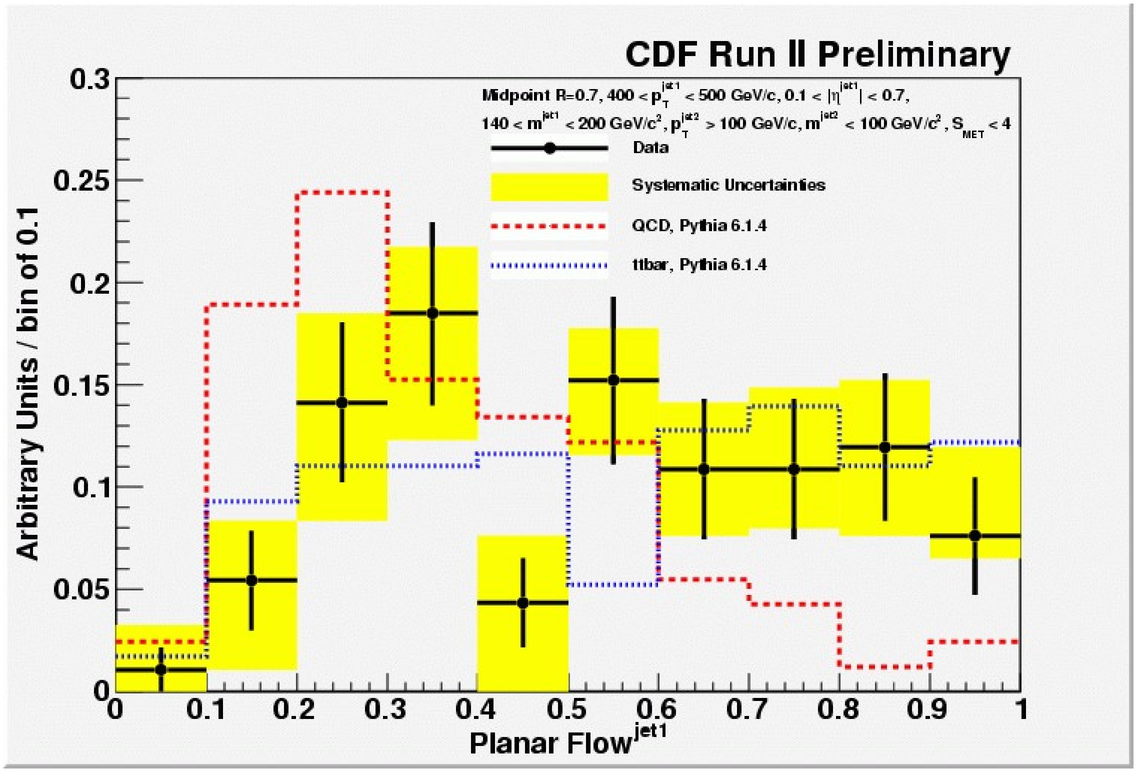
$$I_w^{kl} = \frac{1}{m_J} \sum_i w_i \frac{p_{i,k}}{w_i} \frac{p_{i,l}}{w_i} \qquad Pf = 4\frac{\det(\mathrm{I_w})}{\mathrm{tr}(\mathrm{I_w})^2} = \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2}$$

where w_i is energy of a jet tower (particle), p_i,k is a k-th component of transverse momentum relative to the jet momentum axis; λ_1,2 is eigenvalue of the matrix I_w.

– ***Pf*** should vanish for linear shapes and close to unity for isotropic depositions of energy.

– At high jet masses (140-200 is considered) data prefer more aplanar configuration than QCD prediction (anti-top cuts are applied).



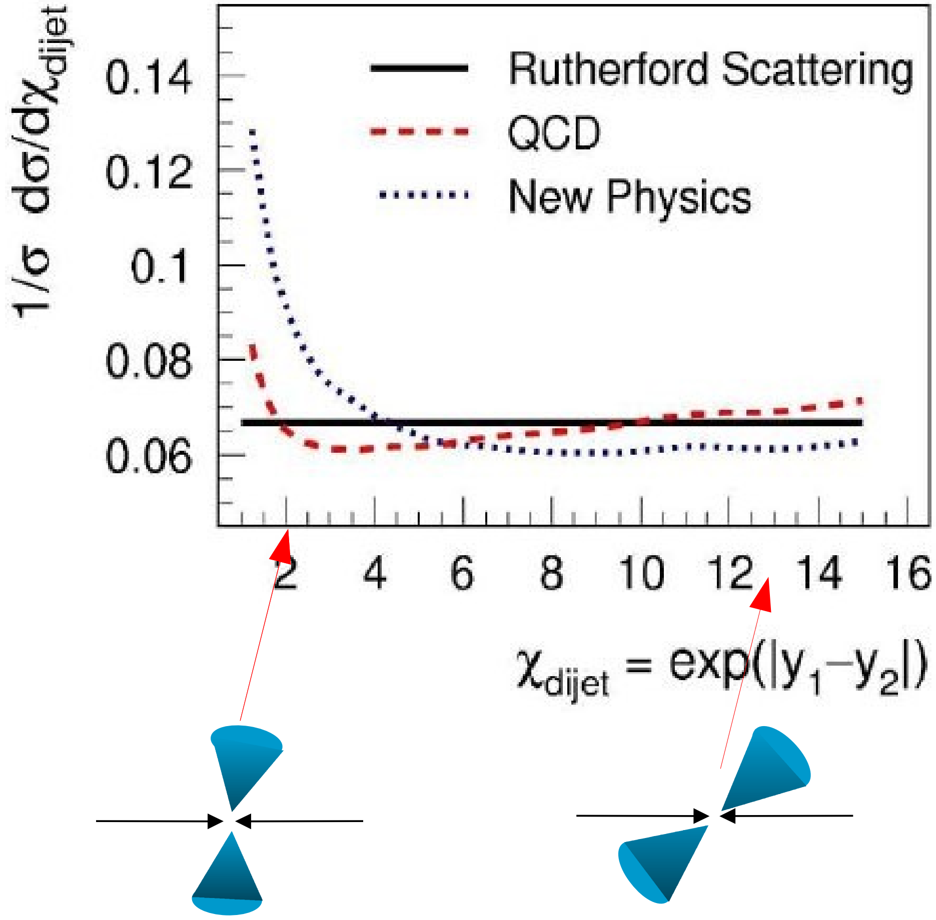


Angular distributions: dijet χ (D0)

- Measure χ = exp(|y1 – y2|) in 10 regions of dijet mass with M_{jj} >250 GeV (last bin: >1.1TeV!)
- Good agreement with NLO pQCD(MSTW2008)
- Data are used to set limits on the models of

Quark compositeness: ~ 3 TeV
TeV-1 extra dim. : ~1.6 TeV
ADD extra dim. :~1.3-1.9 TeV (dep. on Ned)

Large excess at small △y is expected in QC and ED models



Small △y

Large △y

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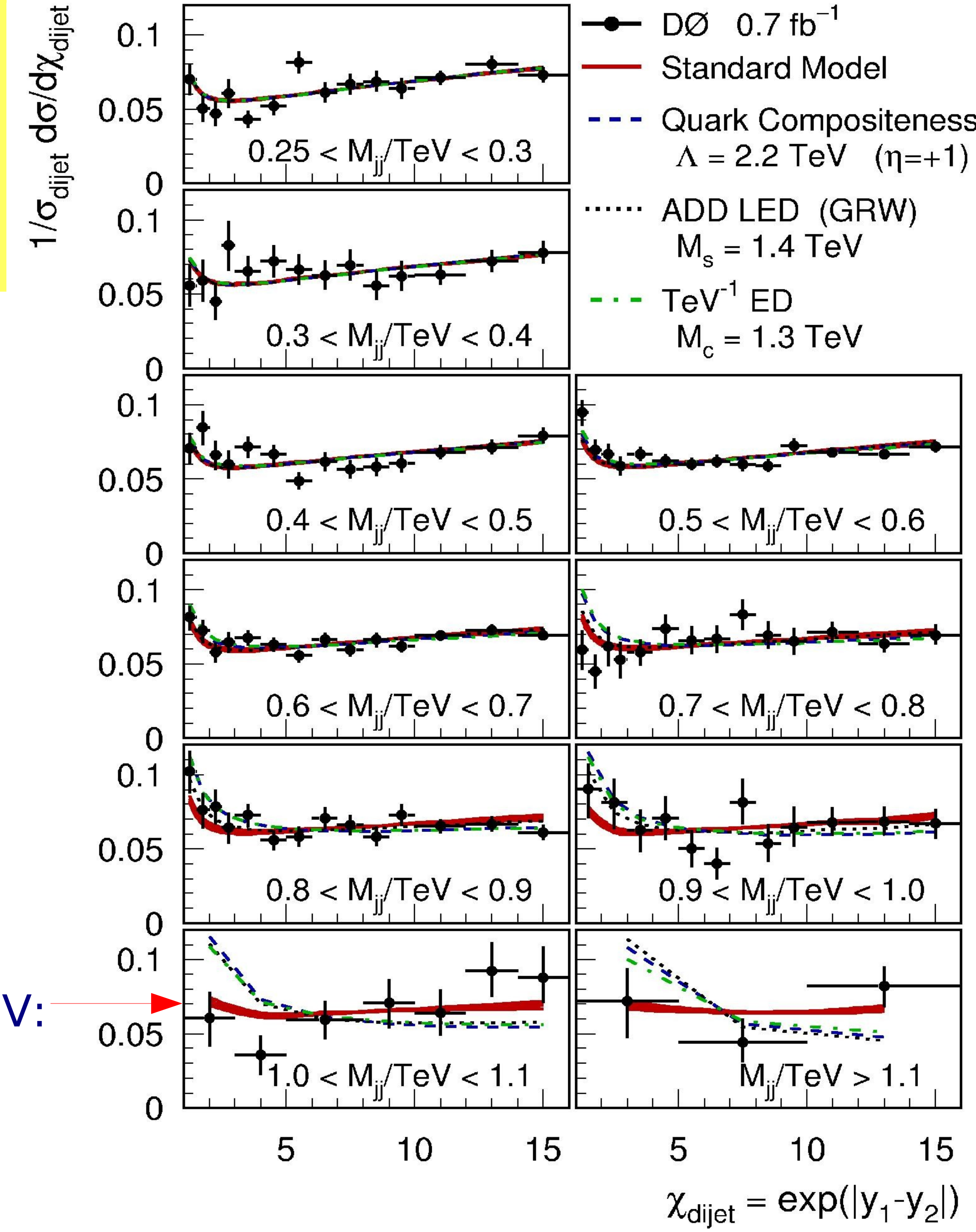
M>1 TeV:



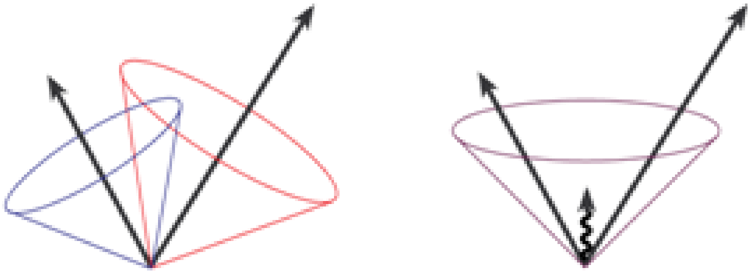
Jet “Definitions” - Jet Algorithms

Midpoint cone-based algorithm

- Cluster objects based on their proximity in y-ϕ space
- Starting from seeds (calorimeter towers/particles above threshold), find stable cones (kinematic centroid = geometric center).

Infrared unsafety:

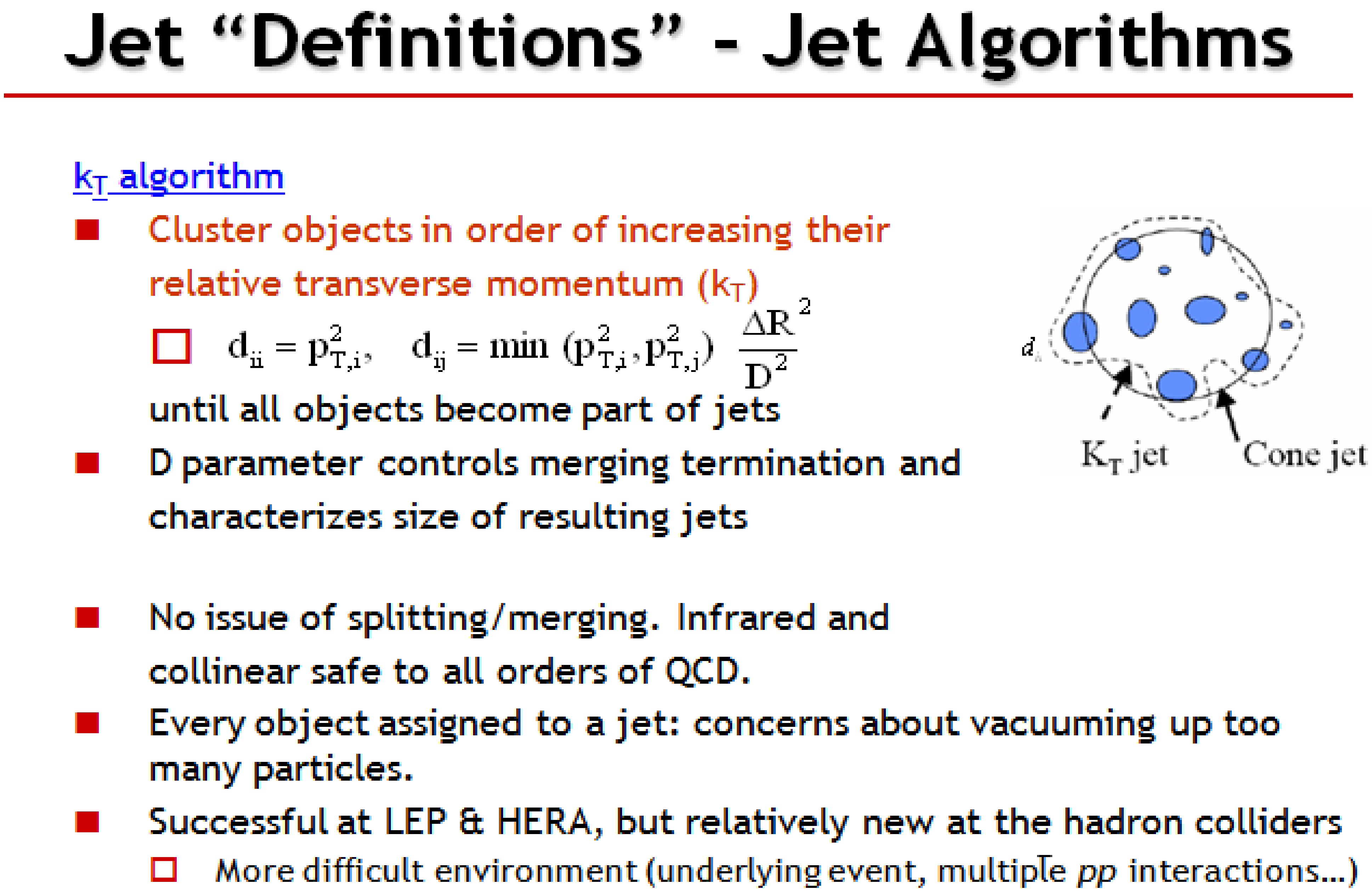
soft parton emission changes jet clustering



- Seeds necessary for speed, however source of infrared unsafety.
- In recent QCD studies, we use “Midpoint” algorithm, i.e. look for stable cones from middle points between two adjacent cones
- Stable cones sometime overlap
  → merge cones when p_T overlap > 75%

More advanced algorithm(s) available now, but negligible effects on this measurement.

Inclusive jets



Jet “Definitions” - Jet Algorithms

k_T algorithm

- Cluster objects in order of increasing their relative transverse momentum (k_T)
  - ☐ $d_{ii} = p_{T,i}^2, \quad d_{ij} = \min(p_{T,i}^2, p_{T,j}^2)\,\frac{\Delta R^2}{D^2}$

  until all objects become part of jets
- D parameter controls merging termination and characterizes size of resulting jets

- No issue of splitting/merging. Infrared and collinear safe to all orders of QCD.
- Every object assigned to a jet: concerns about vacuuming up too many particles.
- Successful at LEP & HERA, but relatively new at the hadron colliders
  - ☐ More difficult environment (underlying event, multiple *pp* interactions…)

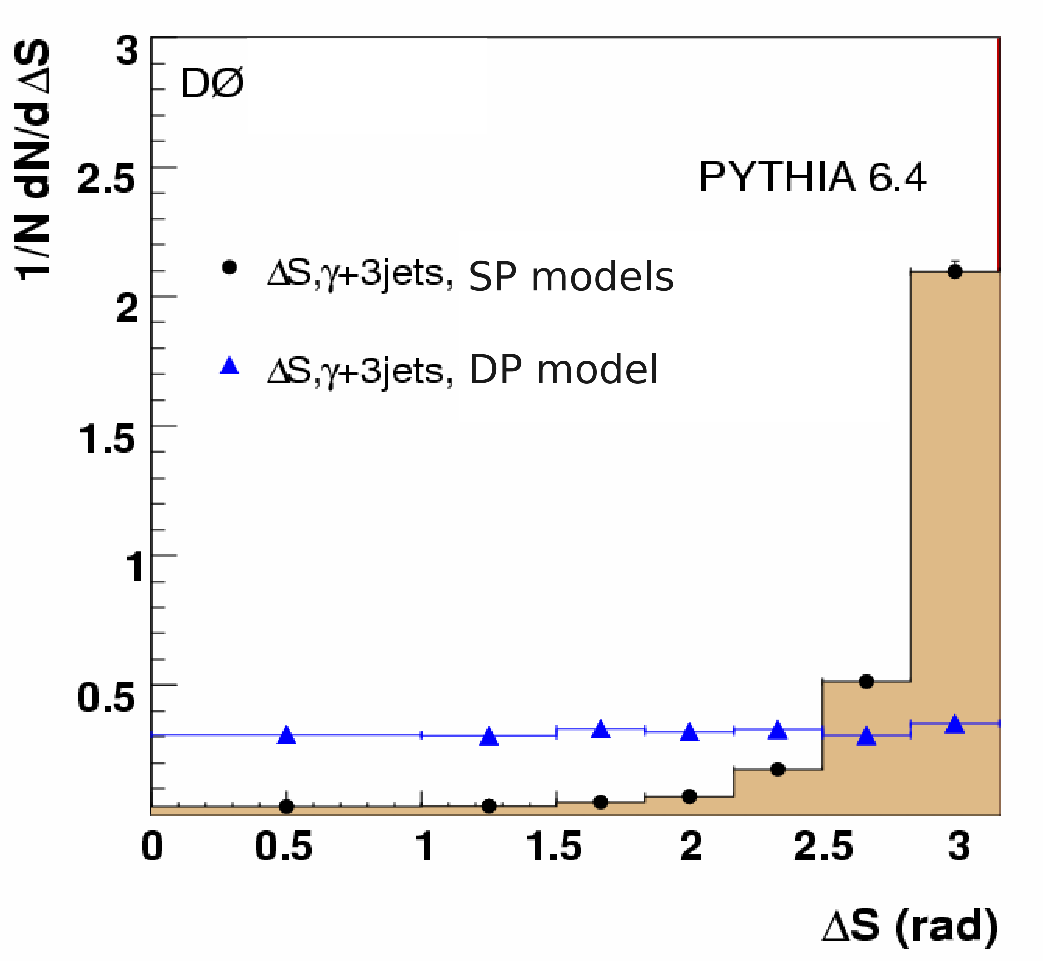
DP Signal variables

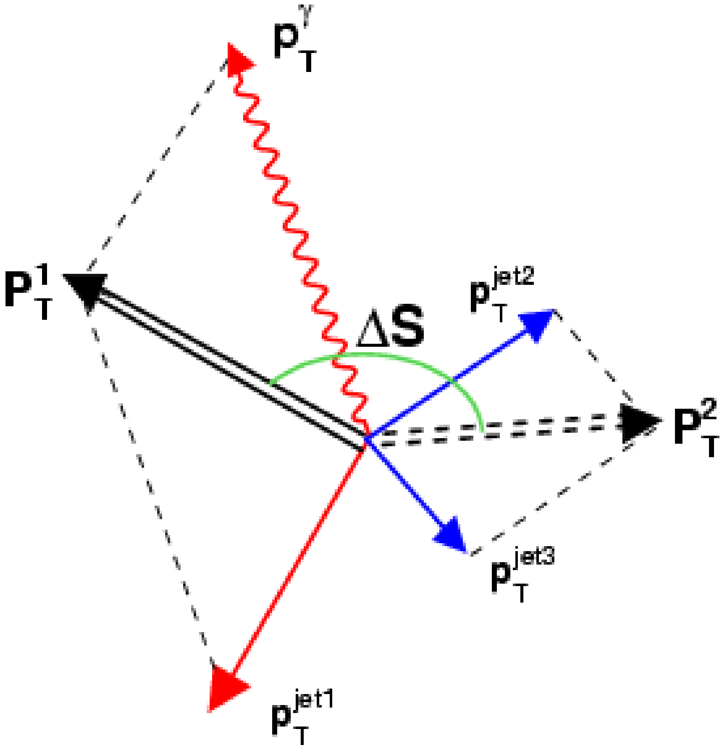
Calculate the azimuthal angle for the pair that gives the minimum value of *S*:

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

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

$$\Delta S=\Delta\phi\left(\mathrm{p}_{\mathrm{T}}^{\gamma,jet_i},\ \mathrm{p}_{\mathrm{T}}^{jet_j,jet_k}\right)$$





Minimum bias track multiplicities and pT (CDF)

→ Sensitive distribution to QCD perturbative/non-perturbative effects, MPI.

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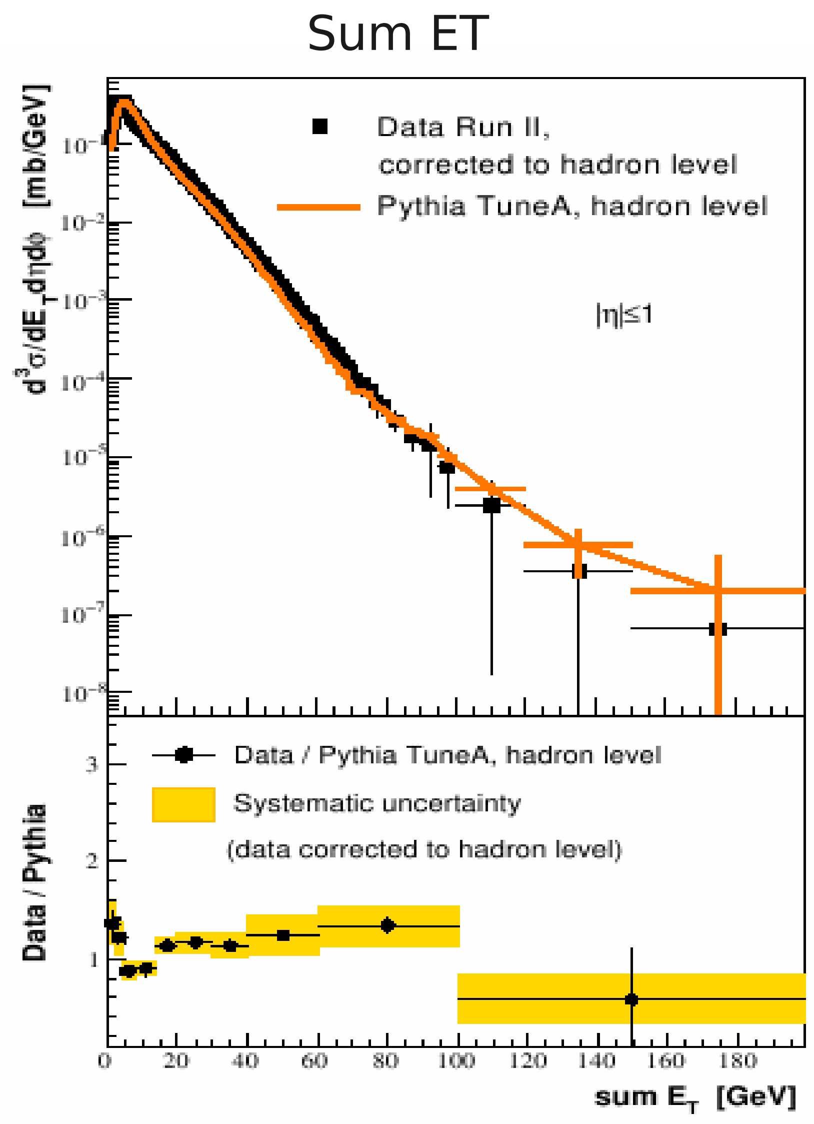
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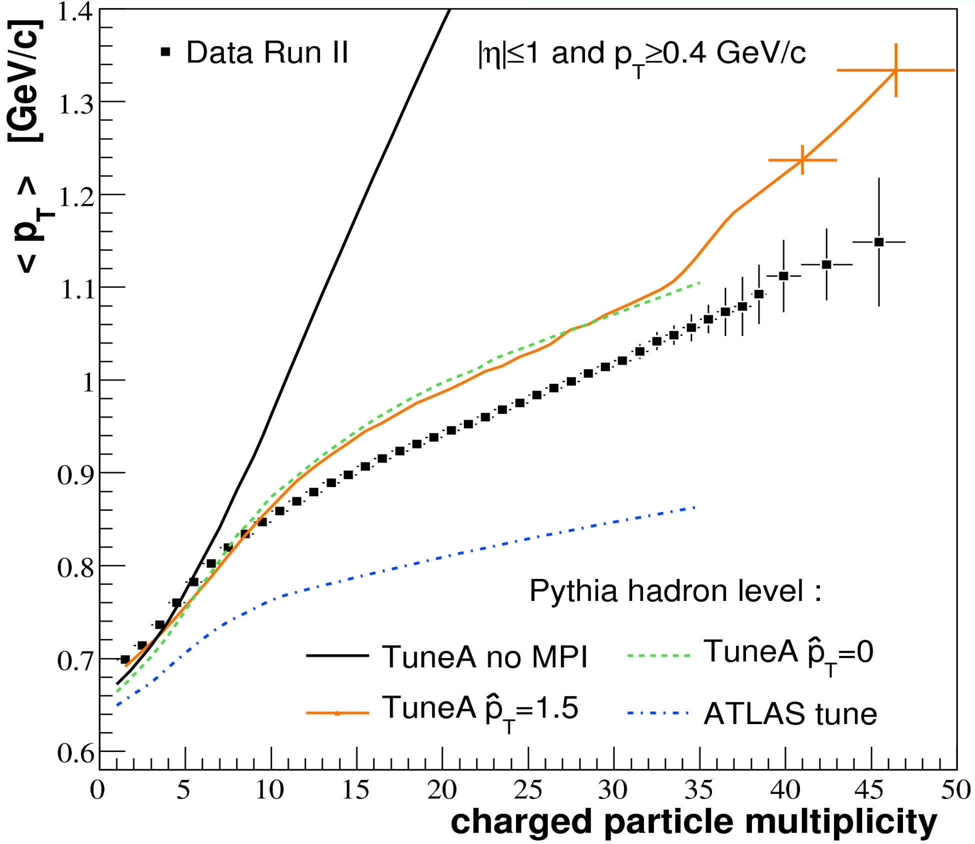
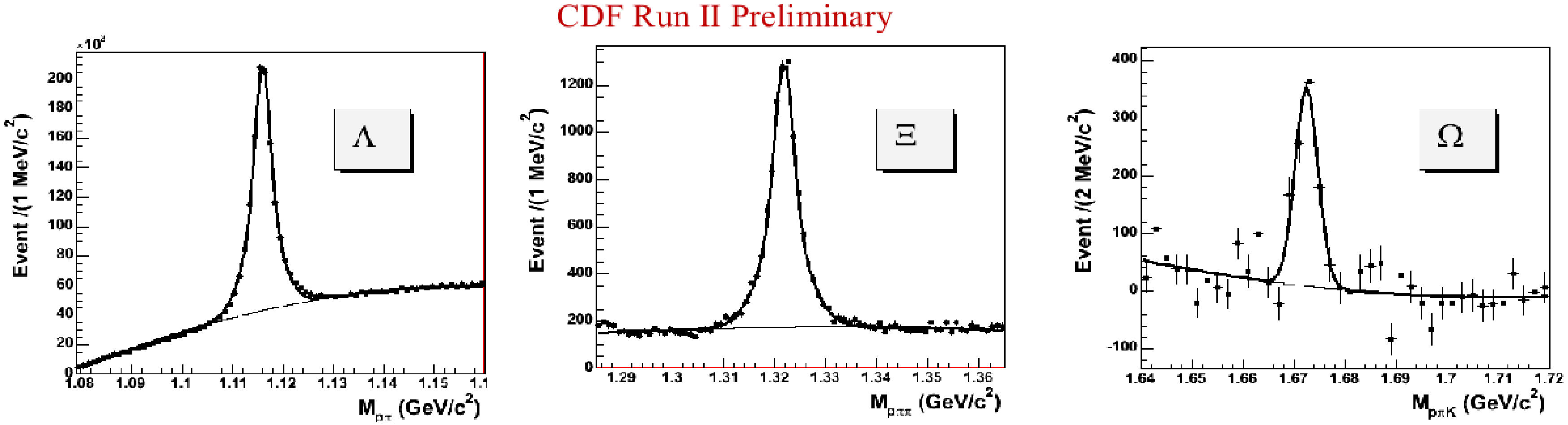


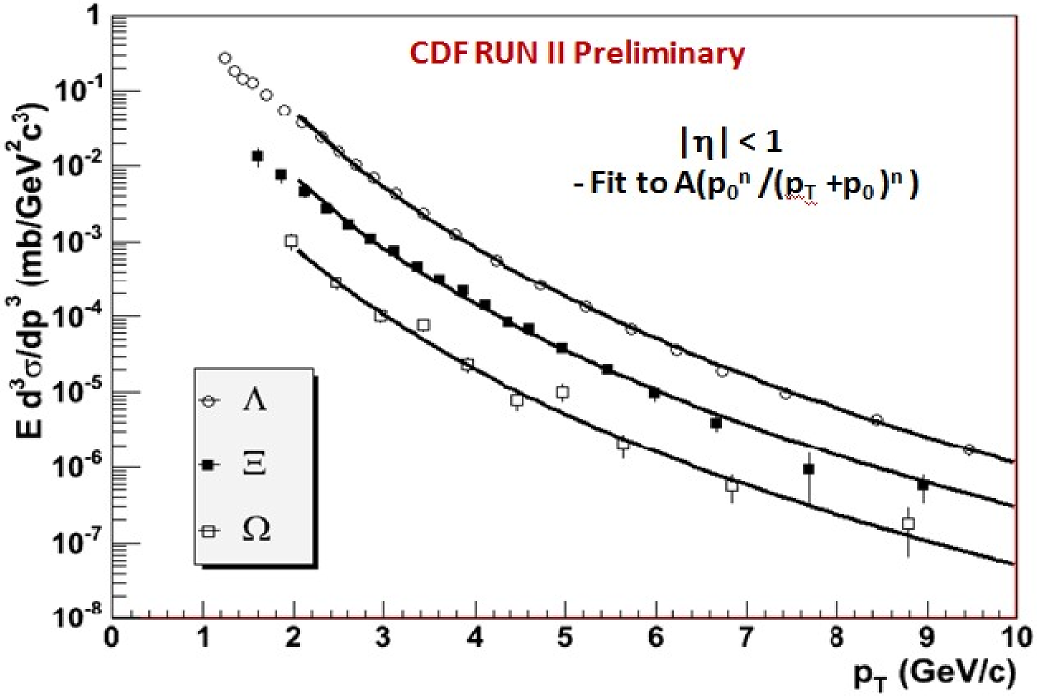
→ Well described by "Tune A" MPI model

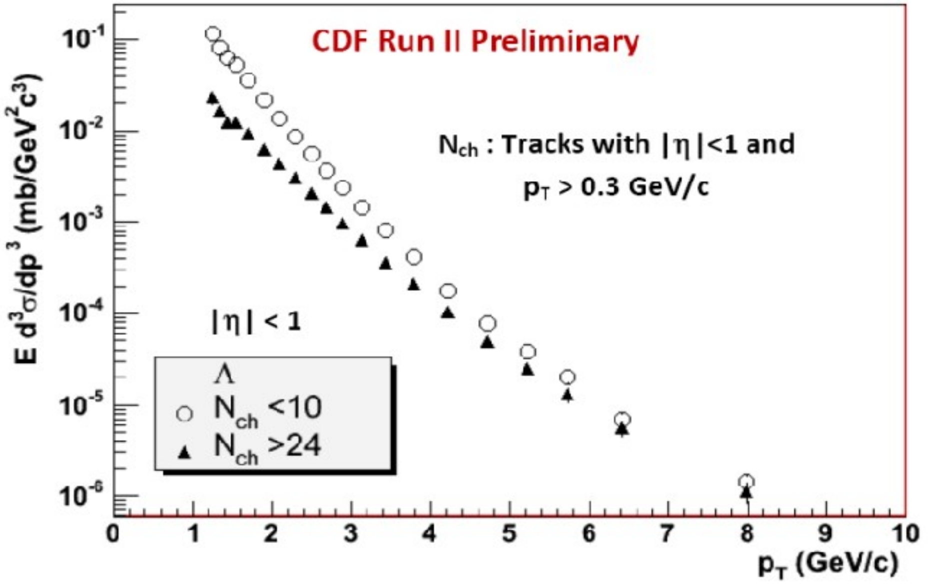
→ Data favors the presence of multiple parton interactions (MPI) and can be used to constrain MPI models. (MPI lead to larger Nch that are harder than the beam remnants but not as hard in pT as for the primary hard 2→2 scattering.)

MINIMUM BIAS – HYPERON PRODUCTION (CDF)

→ Strange particle production can reveal mechanisms from the collision.







→ Cross sections are measured in pT bins, accessing previously unexplored high pT regions.

→ Cross sections are also measured in different multiplicity regions.

http://www-cdf.fnal.gov/physics/new/qcd/hyperons_10/hyperon_public_note.pdf