QCD results from the Tevatron

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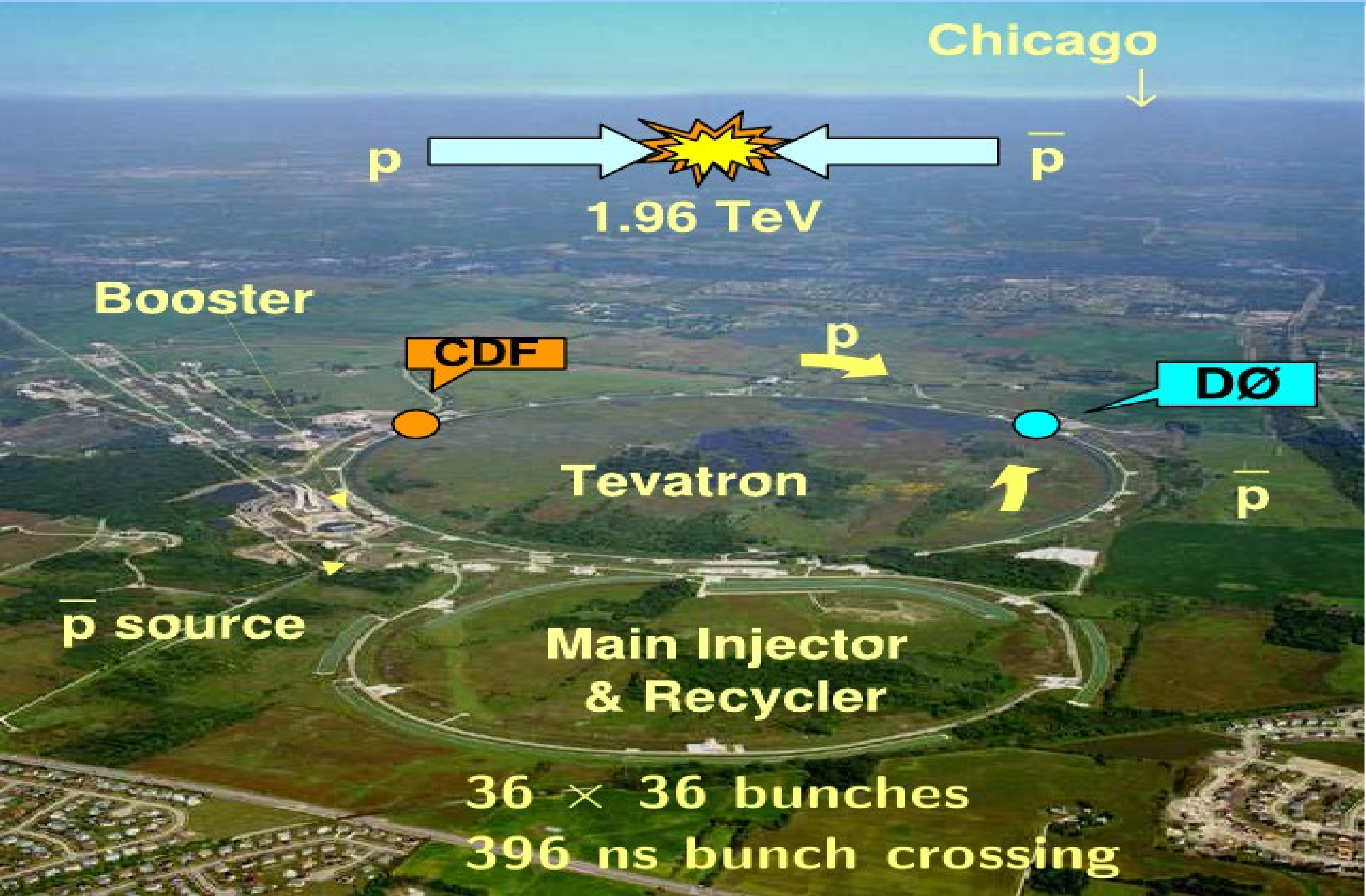
University of Virginia

QCD@LHC 2014, August 25, Suzdal, Russia

Tools


Chicago
p
$\bar{p}$
1.96 TeV
Booster
CDF
p
DØ
Tevatron
$\bar{p}$
$\bar{p}$ source
Main Injector
& Recycler
36 × 36 bunches
396 ns bunch crossing

Outline

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

- V + jets production
  - V + inclusive jets
  - V + heavy flavor jets

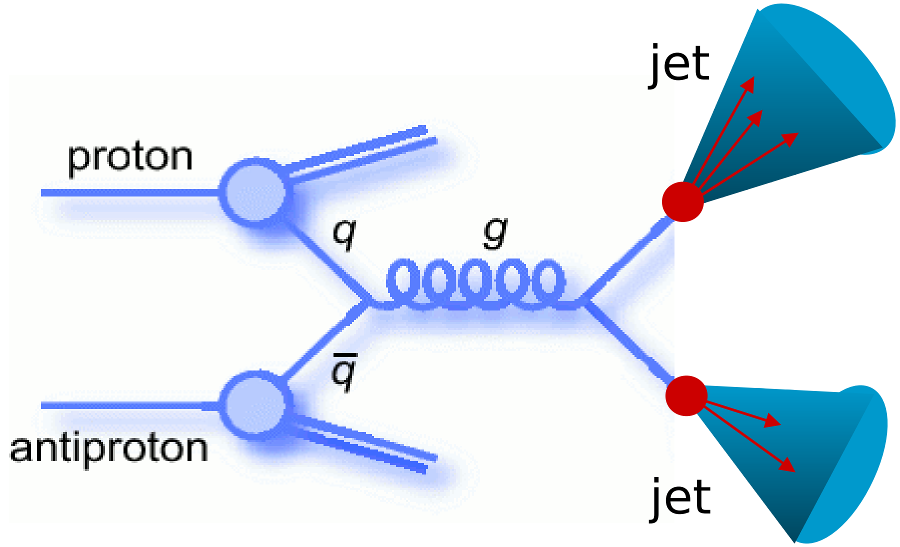
- Inclusive photon and di-photon production
- Underlying events and double parton interactions

Selected some of the latest results. More results can be found on:

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

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

Also, a detailed overview of QCD measurements at the Tevatron
should be published soon in RevModPhys.



Jet Results

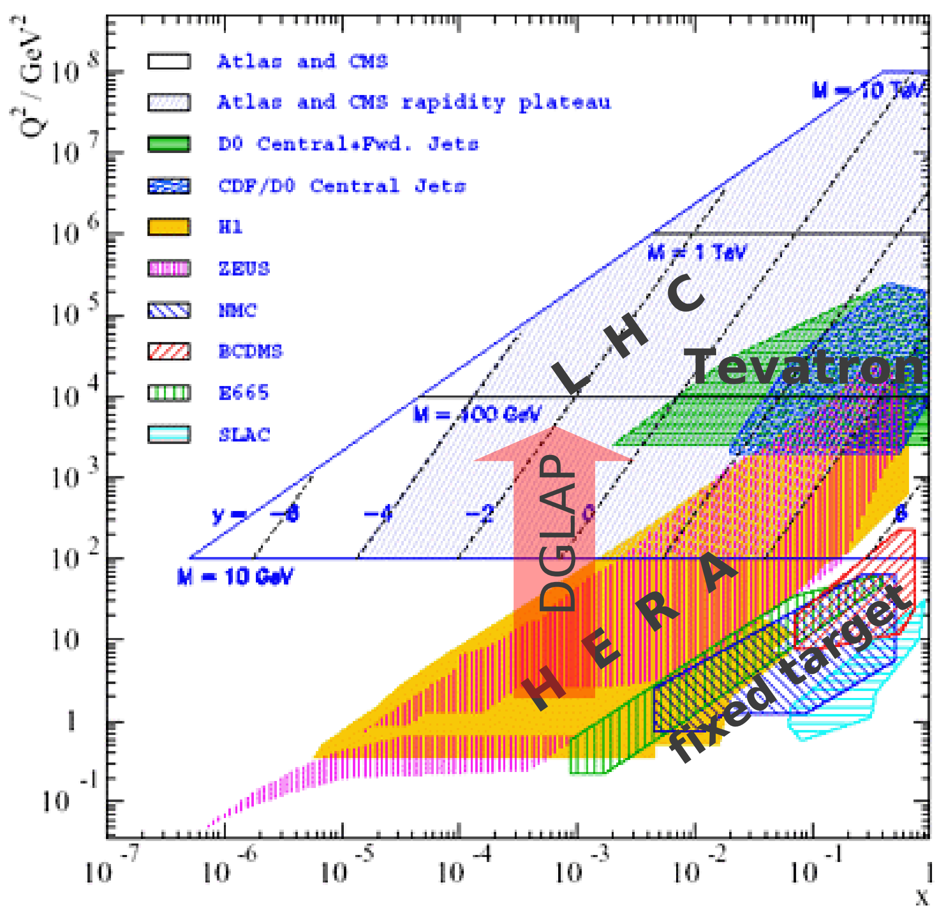
↕

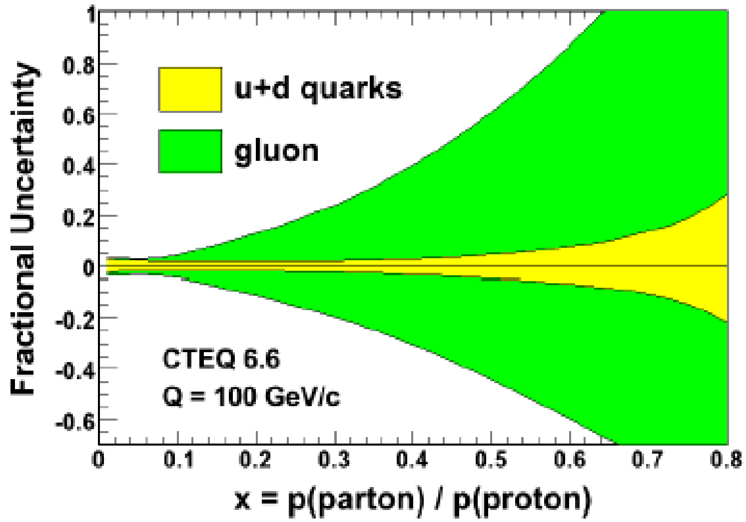
PDF, αs

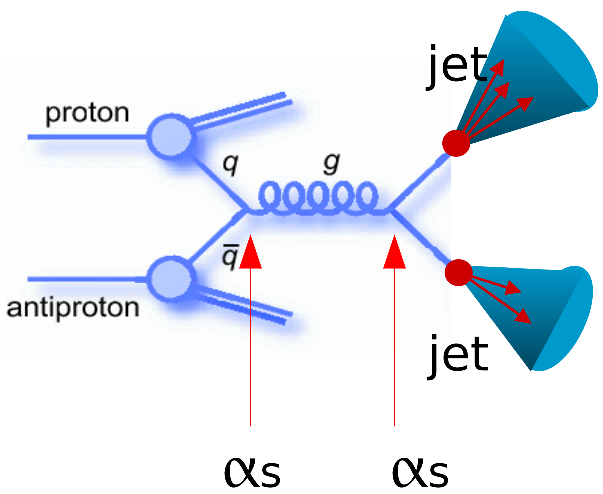
searches for New Physics

Motivations for jet measurements

- providing constraint on PDF:
  x-Q^2 regions accessible at fixed target, DIS, Tevatron and LHC are complementary to each other
- α_s extraction
- studying internal jet substructure
- searches for new phenomena are limited without proper understanding QCD background

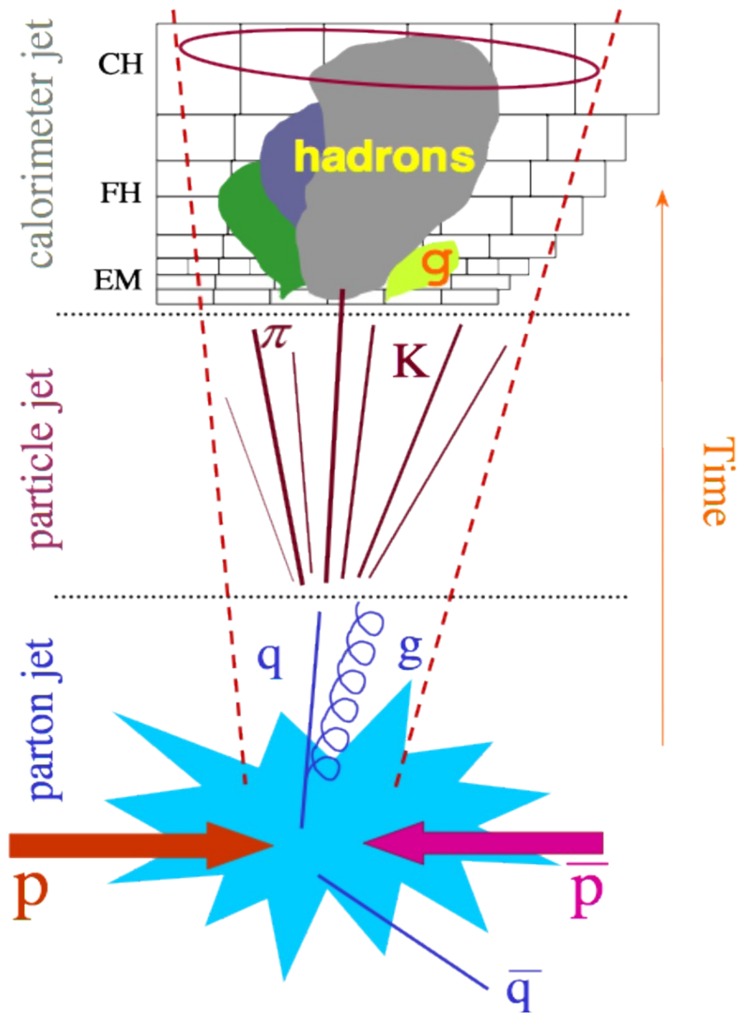


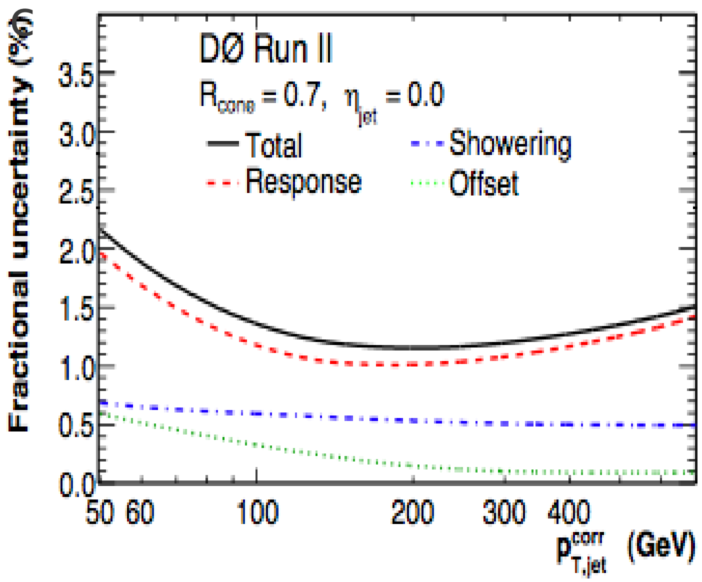


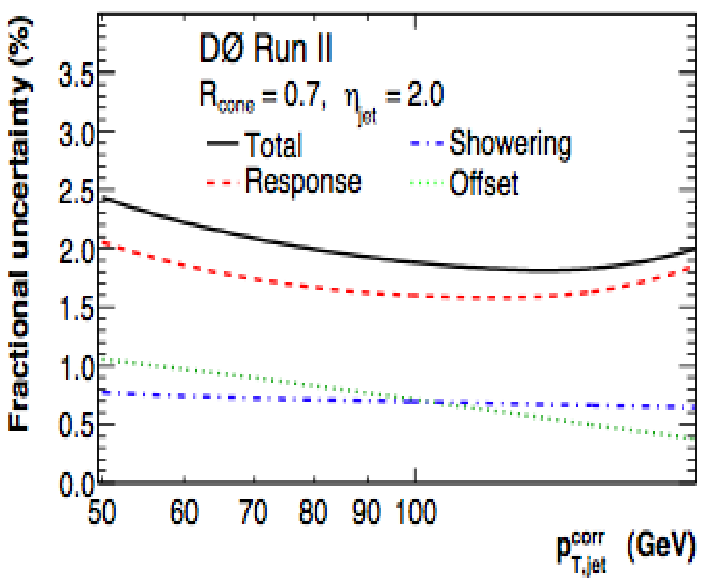


Jet Energy Scale

– Data and theory are corrected to the particle level: very challenging experimental issue, especially JES
– Getting precise (1-2%) JES results takes time. See detailed description at NIM A763, 442 (2014).



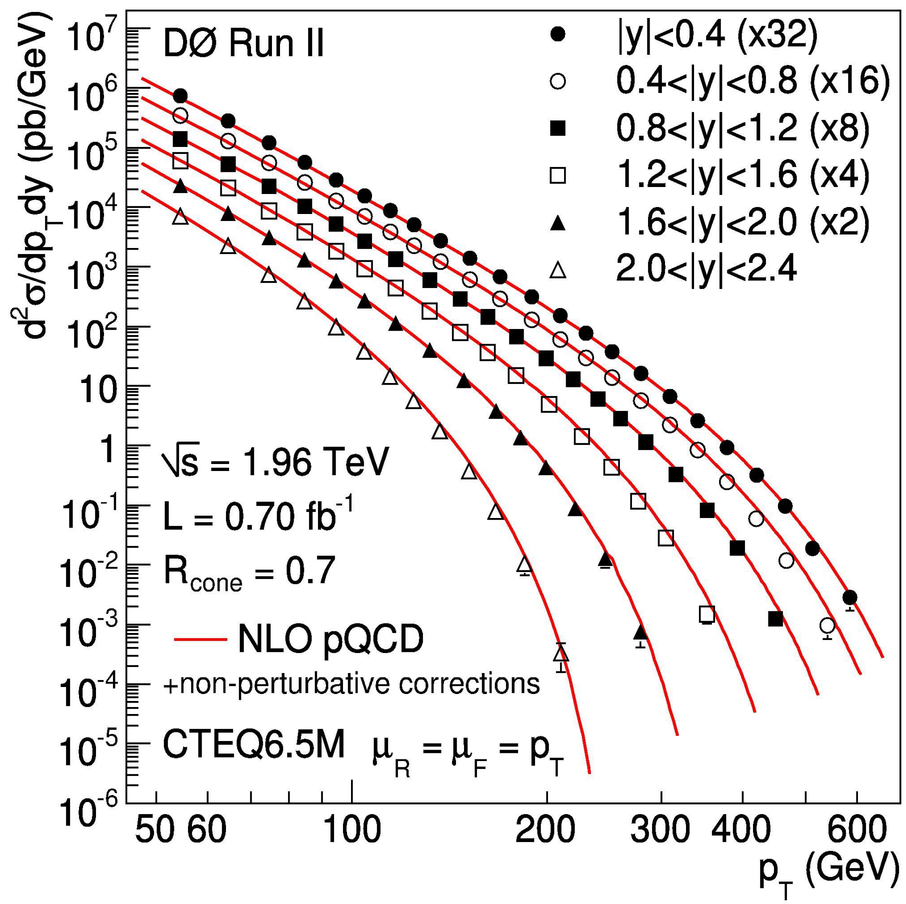




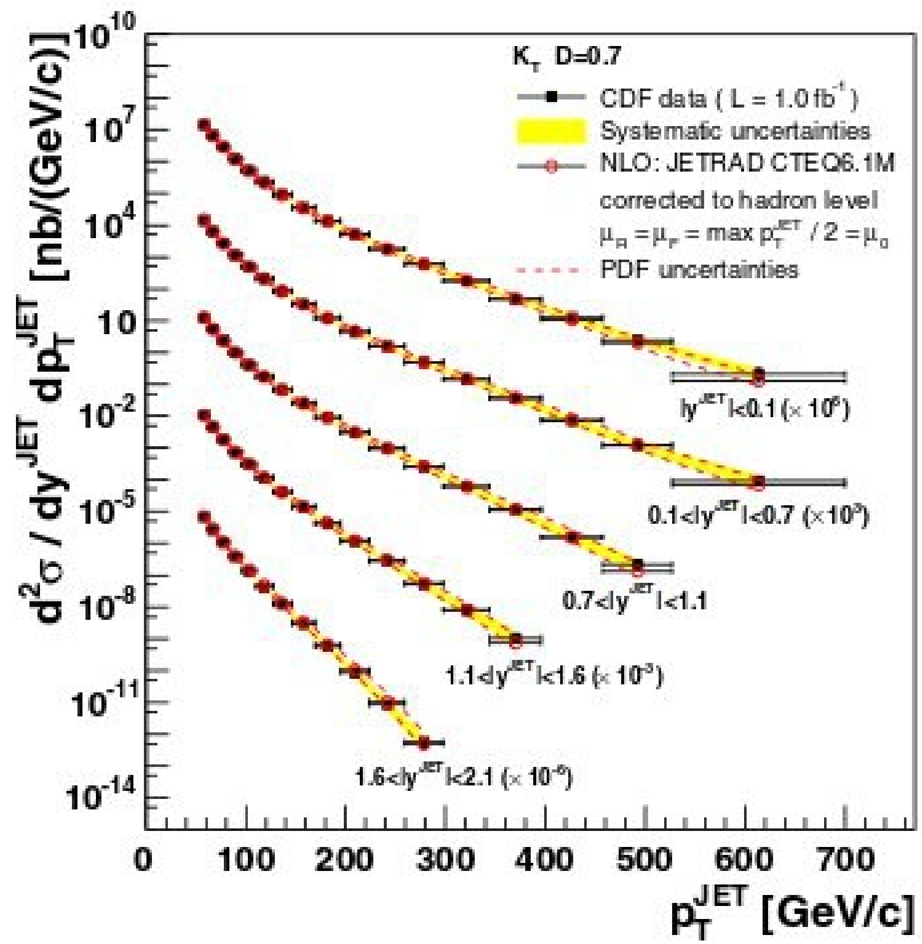
Inclusive jet production

- Inclusive is one of the most elementary measurements at hadron colliders.
- Inclusive jet cross sections at Tevatron test pQCD over 8-9 orders of magnitude up to 0.7 TeV
- Primary and powerful source of PDF constraint!

D0, Cone



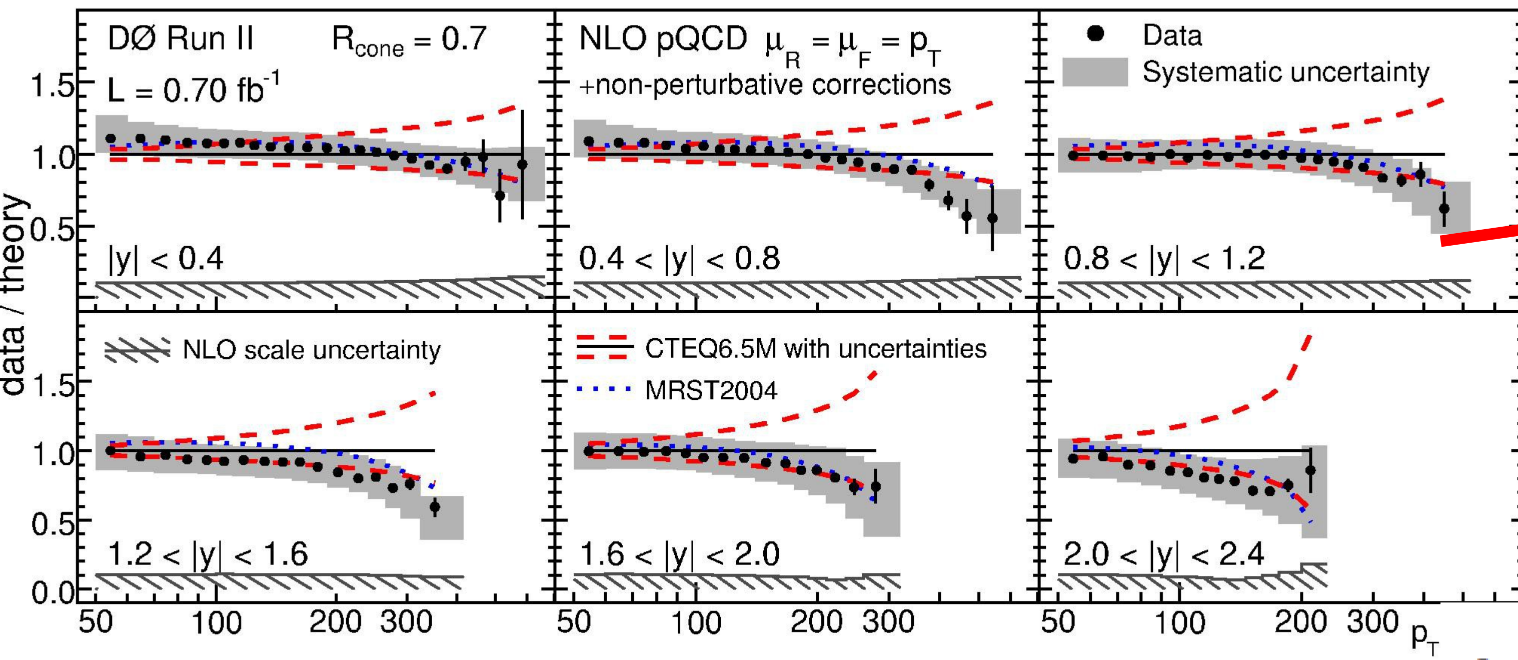
CDF, kT

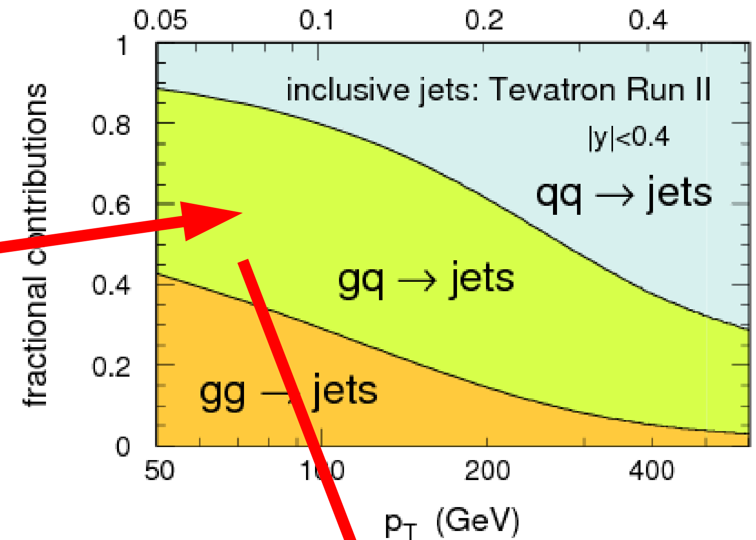


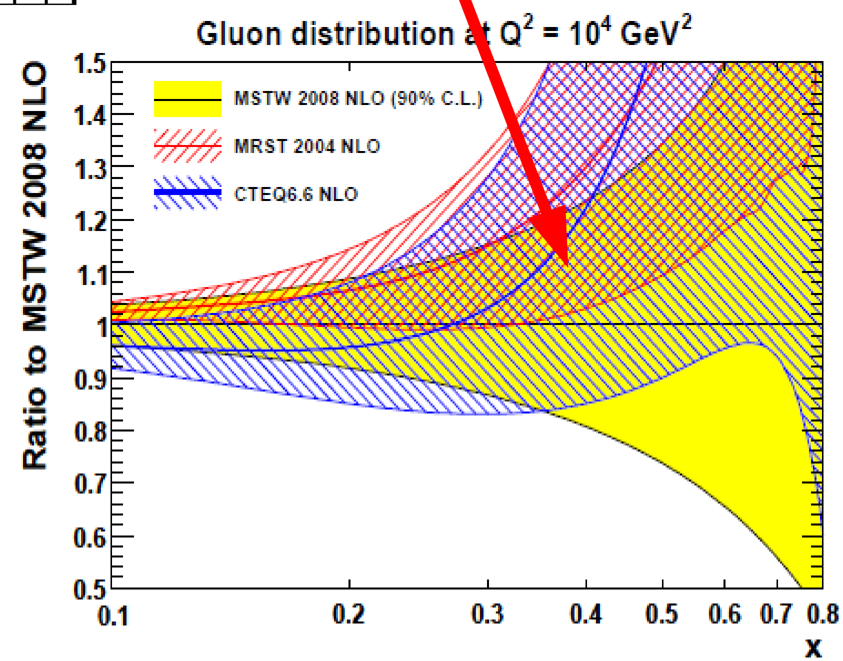
Constraints on PDF

D0&CDF jet 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

PRD75, 092006 (2007), PRL 101, 062001 (2008), PRD85, 052006 (2012)



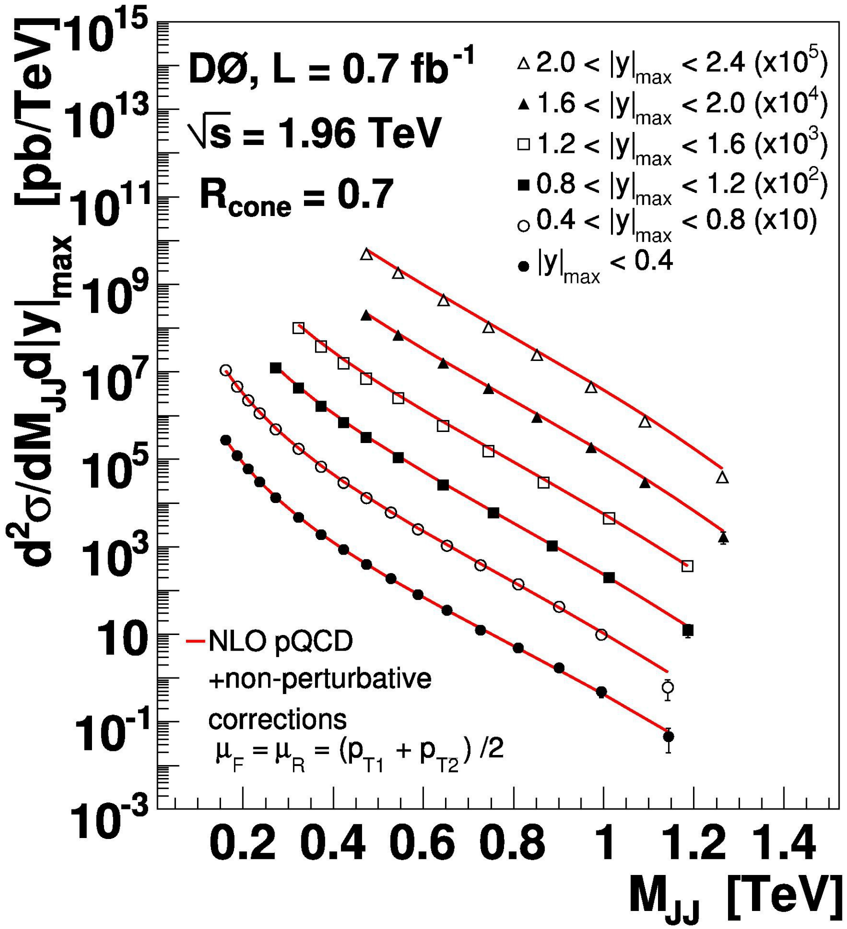




The measurements lead to modified gluon PDF (especially at x>0.25) and reduced PDF uncertainties.

MSTW 2008 uses CDF kT and D0 cone results.

Dijet mass cross section measurement

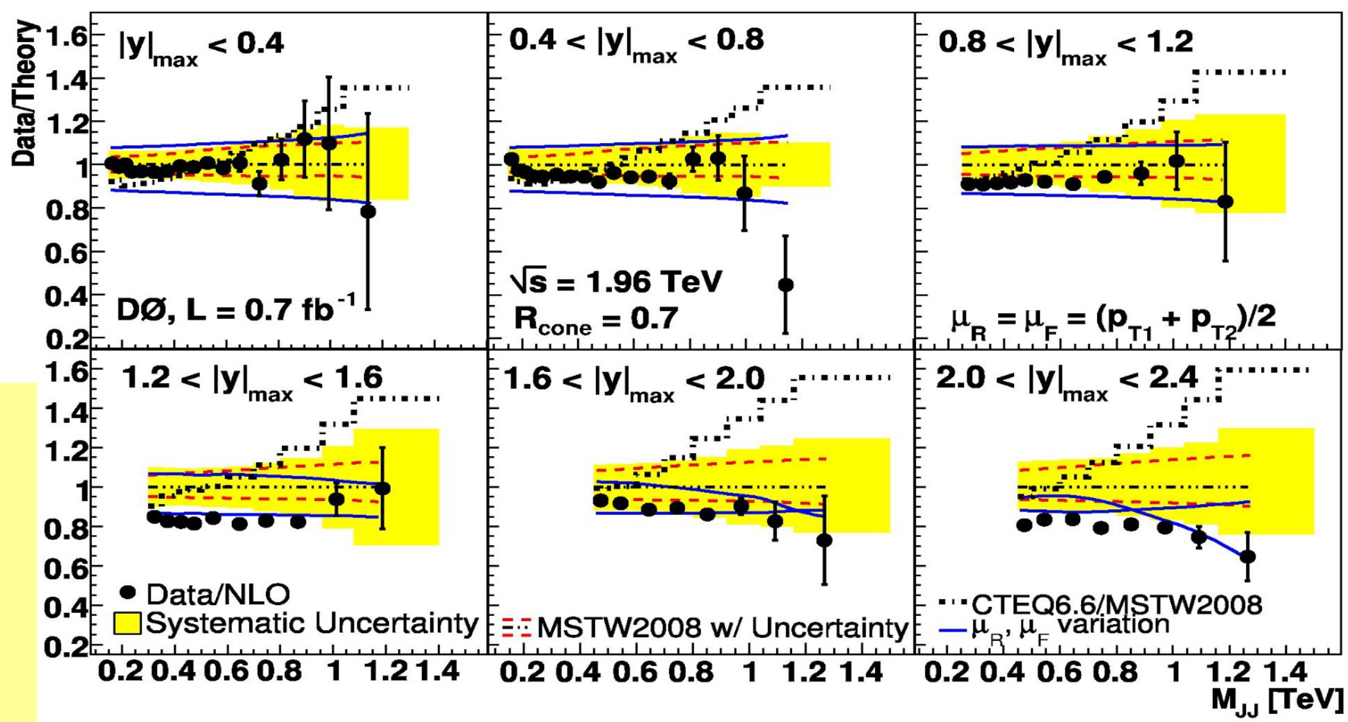


- Measurement of dijet mass in six rapidity bins, $|y|_{max} = \max(|y_1|, |y_2|)$

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

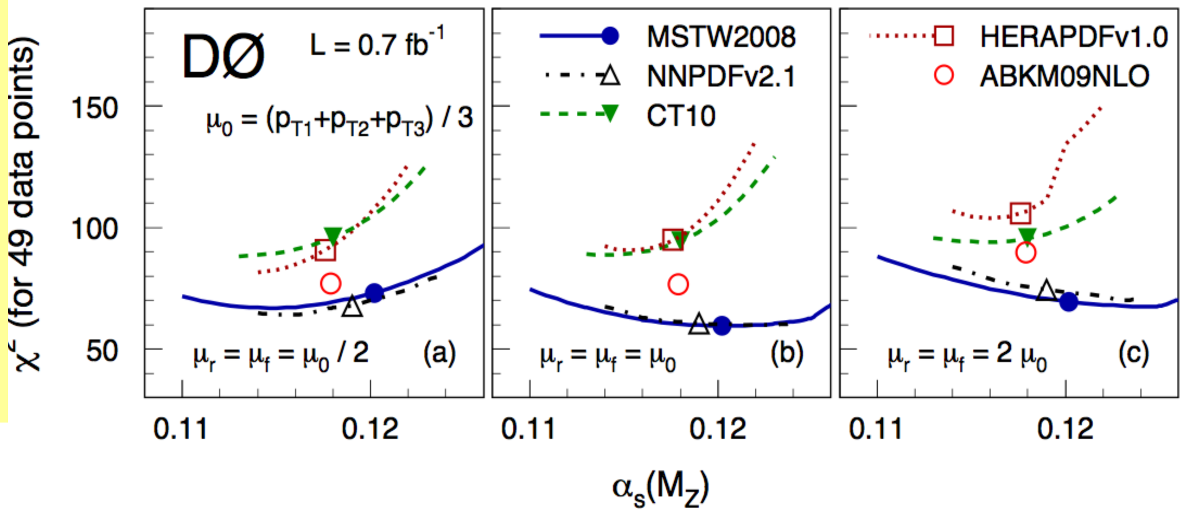
– Data are lower than central pQCD prediction at higher rapidities

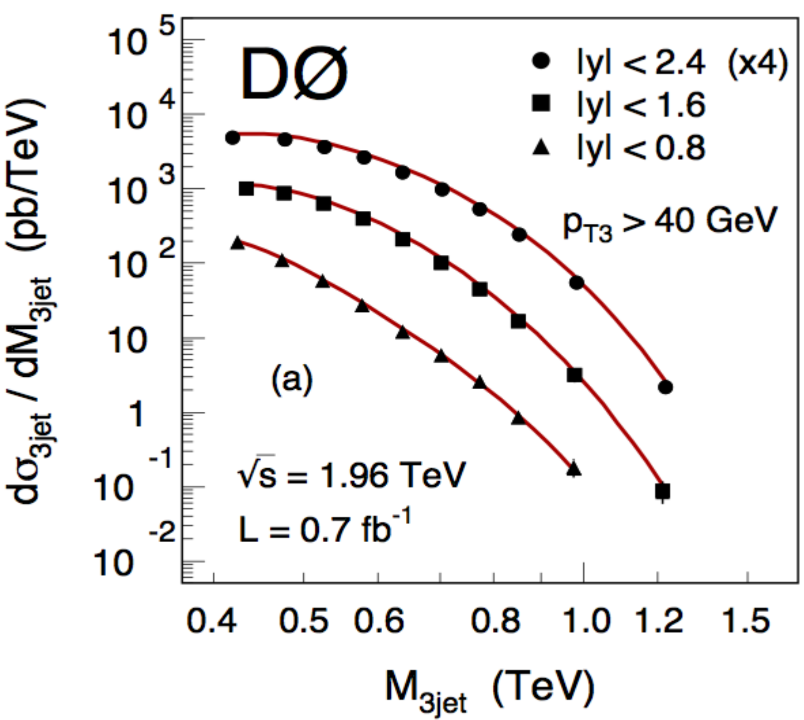
Last mass bin is at ~1.3 TeV!

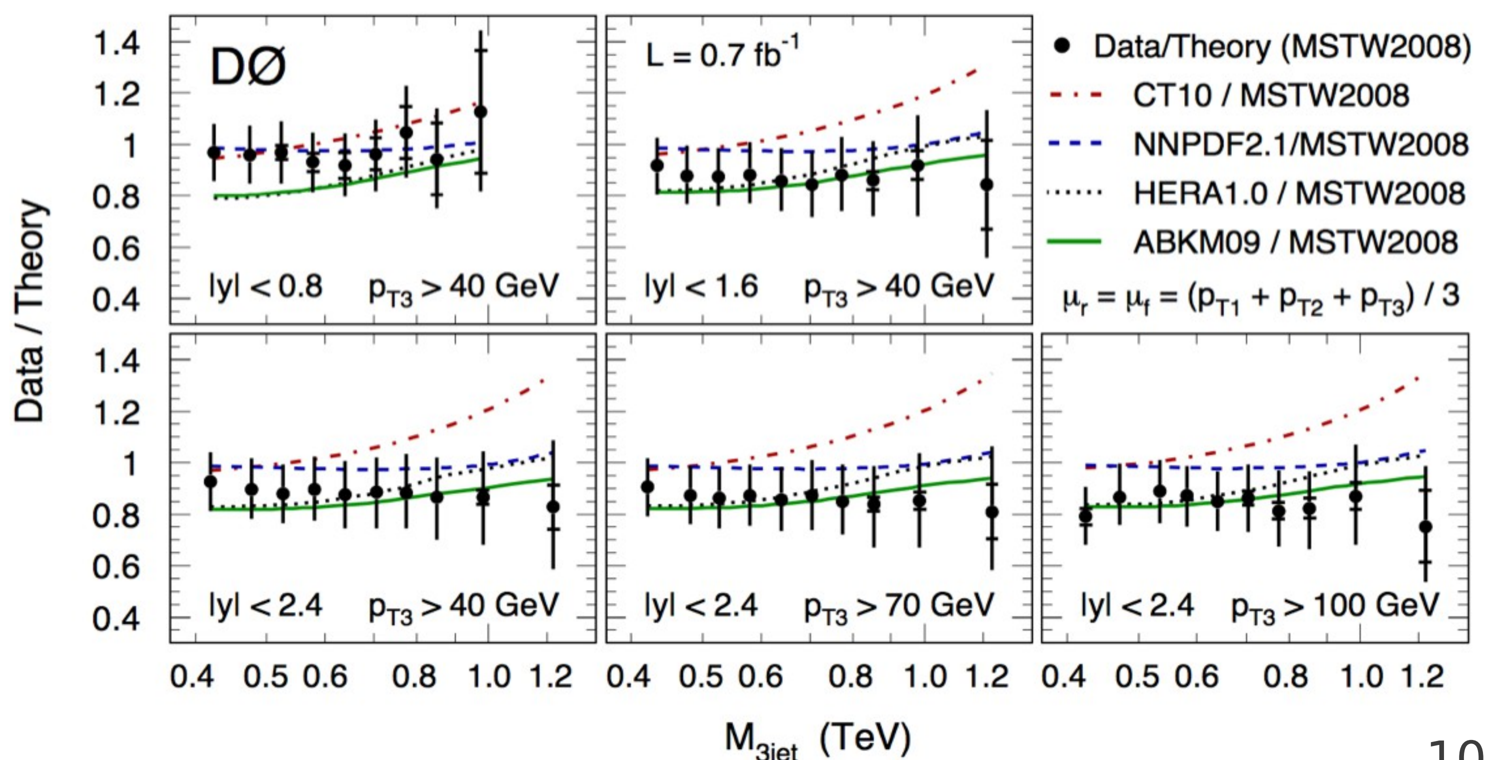
Three jet mass cross section

- 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
- Best χ^2 results for MSTW2008, NNPDF2.1

χ^2 test for *central* PDF values



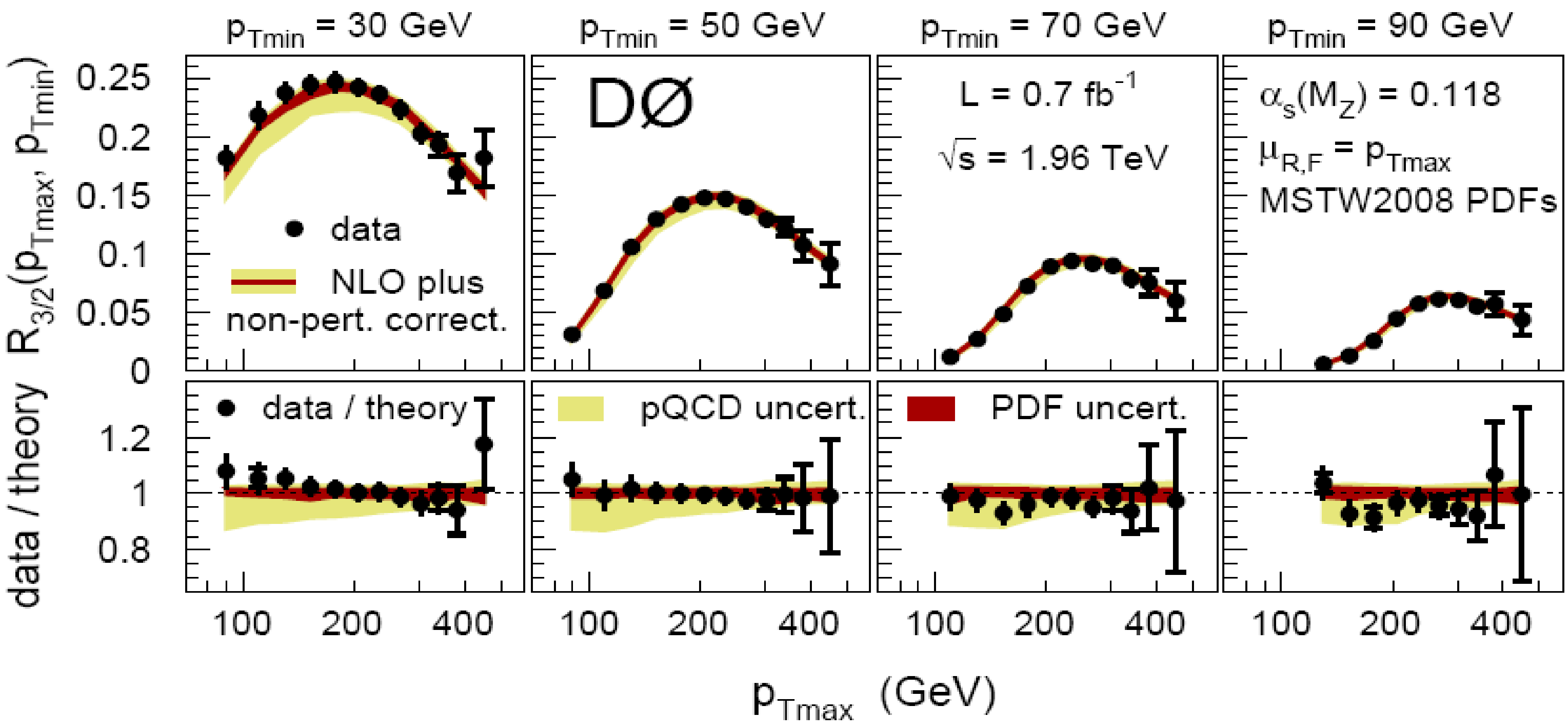




$R_{3/2}$ results

Ratio of inclusive 3 to 2 jet cross sections

Phys. Lett. B 720, 6 (2013)

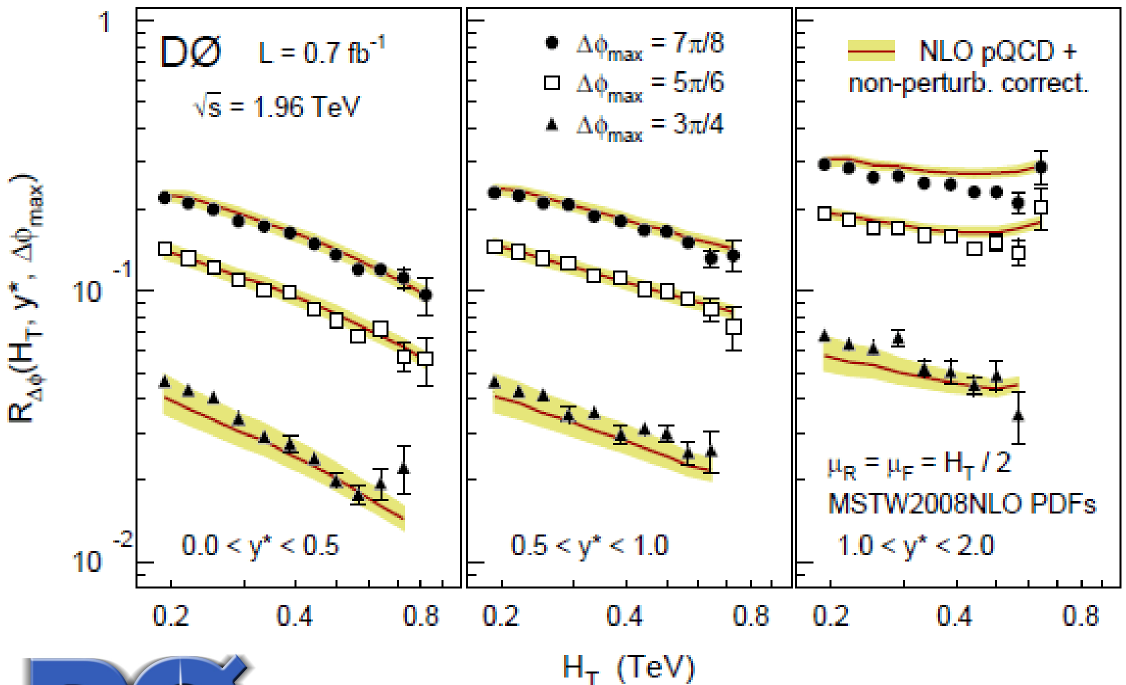


– Good agreement everywhere
– Some shape of data/theory at lowest p_{Tmin} = 30 GeV
– Best agreement is at scales=PTmax for PTmin≥50 GeV
– The results for CT10 and NNPDFv2.1 PDFs agree with those obtained
for MSTW2008NLO to better than 0.4%

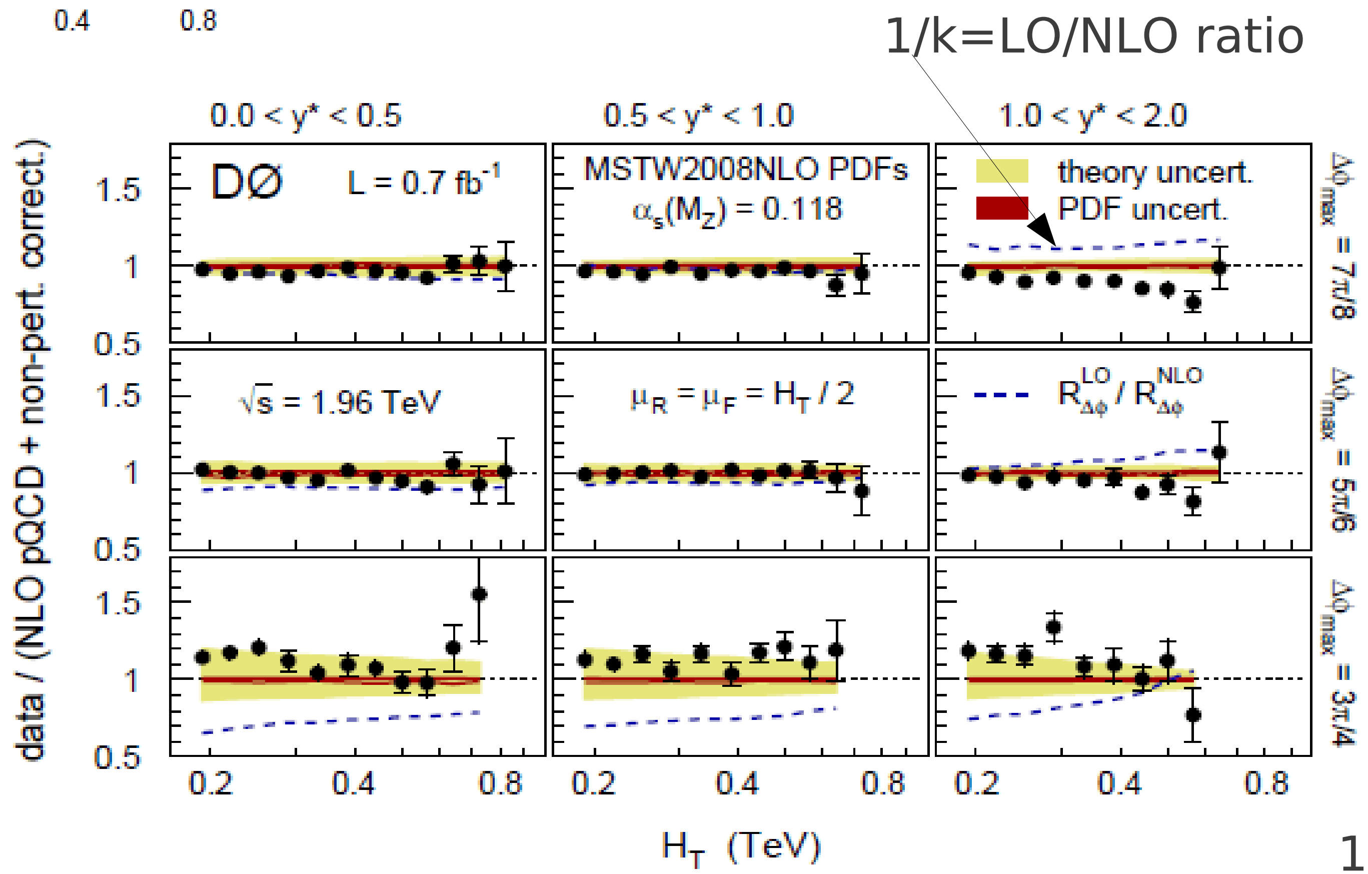
=> open road for α_s extraction

Azimuthal decorrelations

Phys. Lett. B 721, 212 (2013)



- $R_{\Delta\phi}$ (H_T, y^*, $\Delta\phi_{max}$)
- First measurement of rapidity dependence of Dijet azimuthal decorrelations



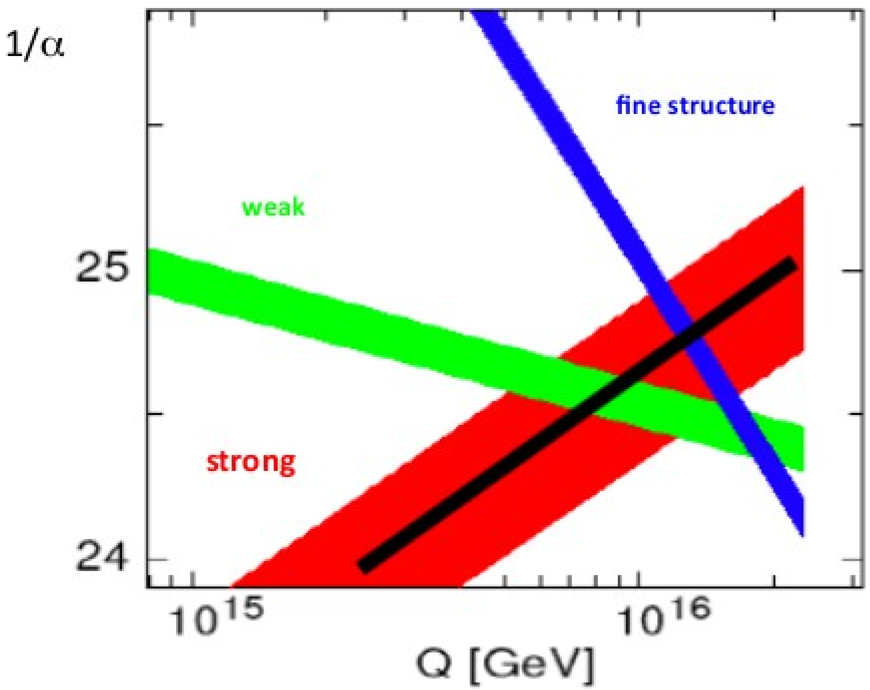
- Good agreement where non-pert. Corrections, and LO/NLO ratio are not too large

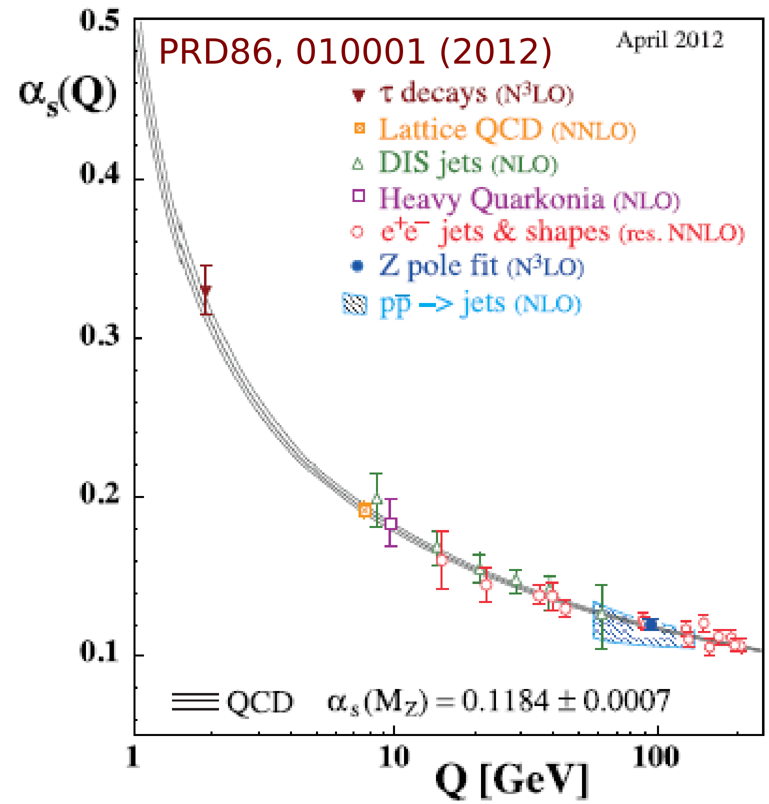
Strong Coupling Constant

α_S is the fundamental QCD quantity

α_S is the least known of the couplings ($\triangle\alpha_S$ (WA) = 0.6%)

α_S has influence on GUT and $\triangle\alpha_S$ translates into uncertainty on PDFs and cross sections



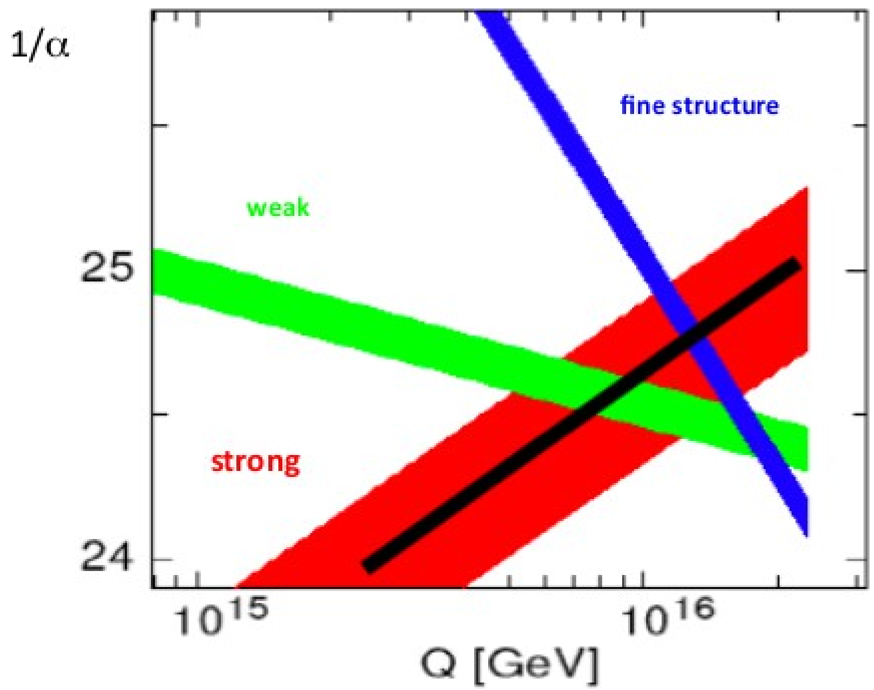


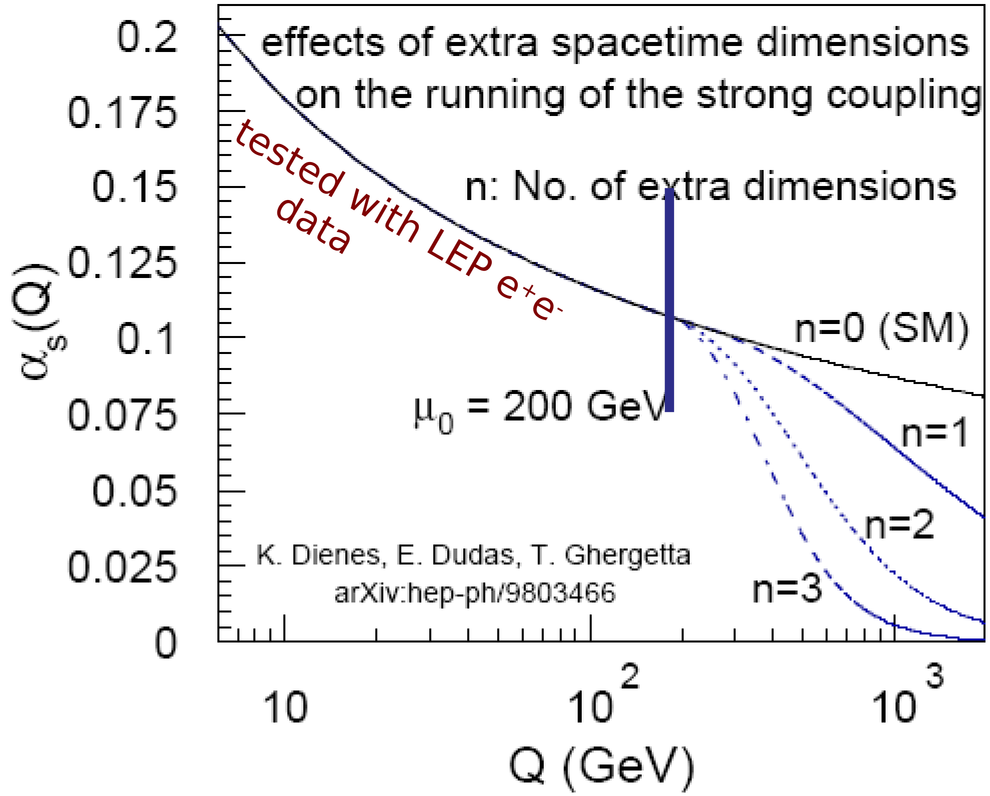
– Renormalization Group Equation (RGE) relates α_s values at different scales (Q)

– Predictions tested at LEP, HERA up to Q ≈ 208 GeV, +recently by Tevatron from inclusive Jets (54-145 GeV)

Strong Coupling Constant

α_s is the fundamental QCD quantity
α_s is the least known of the couplings ($\triangle\alpha_s$ (WA) = 0.6%)
α_s has influence on GUT and $\triangle\alpha_s$ translates into uncertainty on PDFs and cross sections
=> Jet data can be used to extract the running of α_s





Running of $\alpha_s(Q)$ can be modified for large Q, e.g. by extra dimensions
=> should be tested using variable free of RGE (PDF) dependence

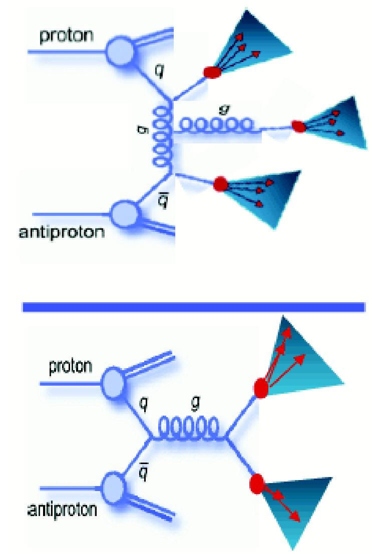
Strong Coupling Constant

Phys. Lett. B 721, 212(2013)

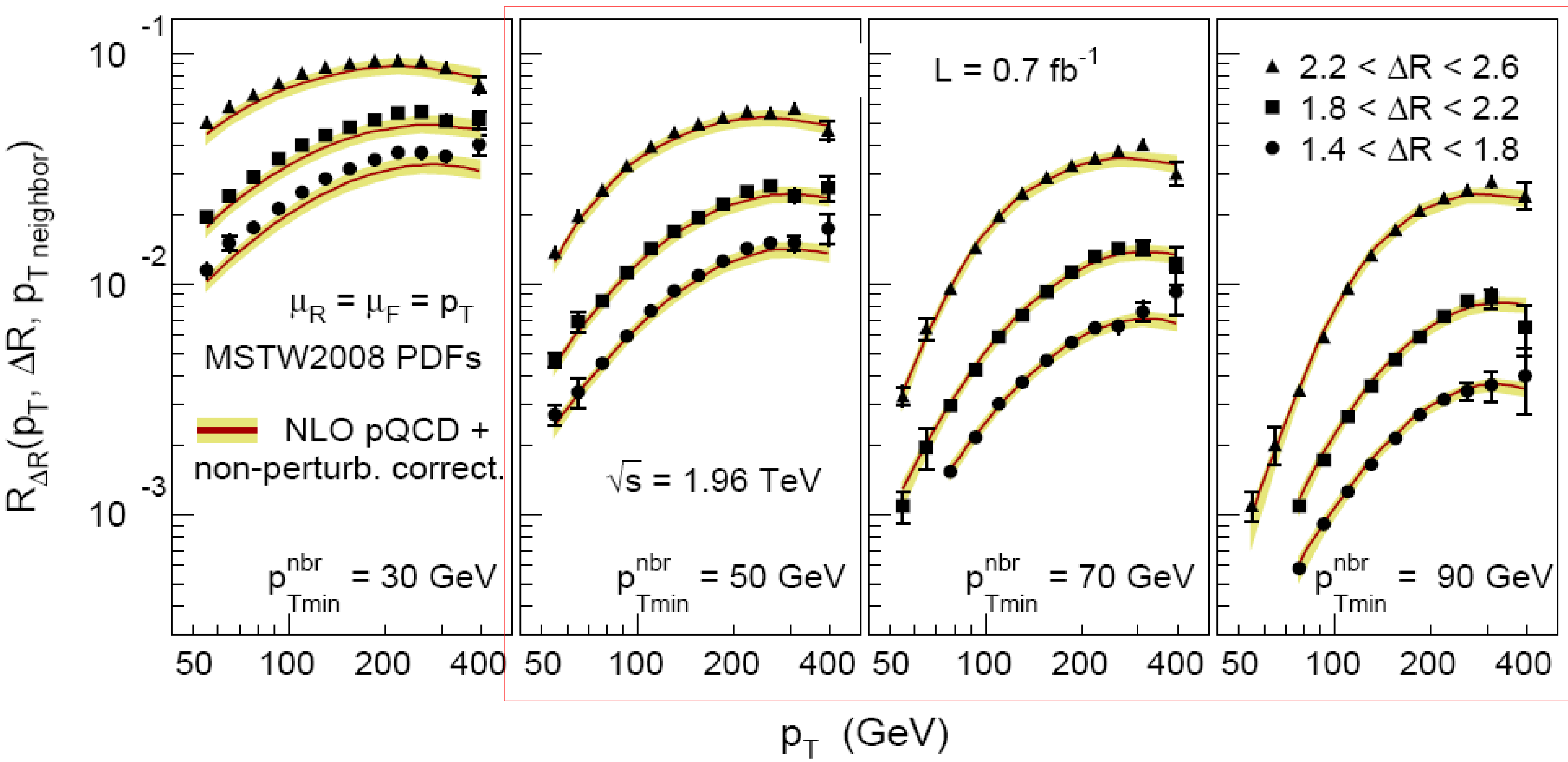
New variable introduced in D0 that characterizes angular correlations of jets and gives an average number of neighboring jets around a reference jet, measured triple differentially: $R_{\Delta R}$ $(p_T, \Delta R, p_{T\text{-nbr-min}})$:

Ratio $R_{\Delta R}$: sum of all neighboring jets / total number of inclusive jets

- For $\Delta R < \pi$ only contributions from ≥3-jet events
- RGE dependence and systematic uncertainties mostly cancel out in the ratio (PDF uncert. <3%)



⟺ α_s



used to extract α_s

Strong Coupling Constant

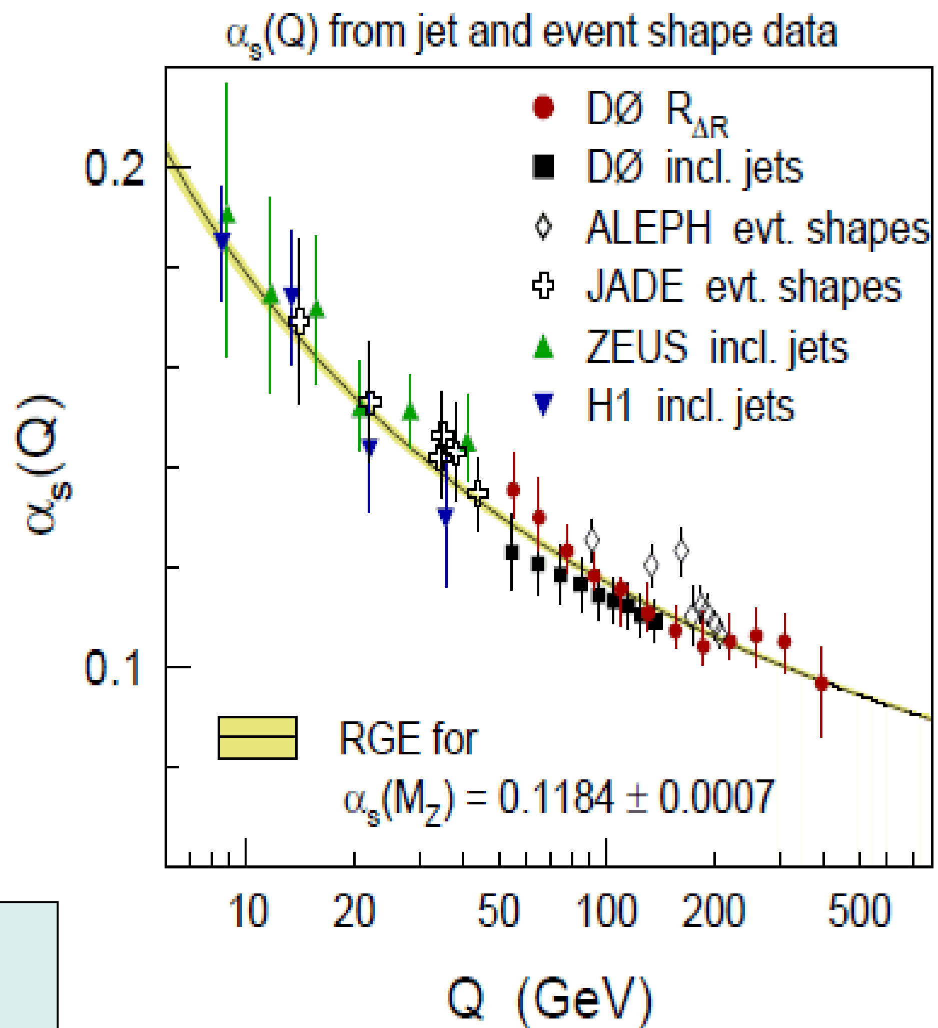
New variable introduced in D0 that characterizes angular correlations of jets and gives an average number of neighboring jets around a reference jet, measured triple differentially: $R_{\Delta R}$ (p_T, ΔR, $p_{T\text{-nbr-min}}$):

Ratio $R_{\Delta R}$: sum of all neighboring jets / total number of inclusive jets

- For $\Delta R < \pi$ only contributions from $\geq$3-jet events
- RGE dependence and systematic uncertainties mostly cancel out in the ratio (PDF uncert. <3%)

$$\alpha_s(M_z) = 0.1191^{+0.0048}_{-0.0071}$$

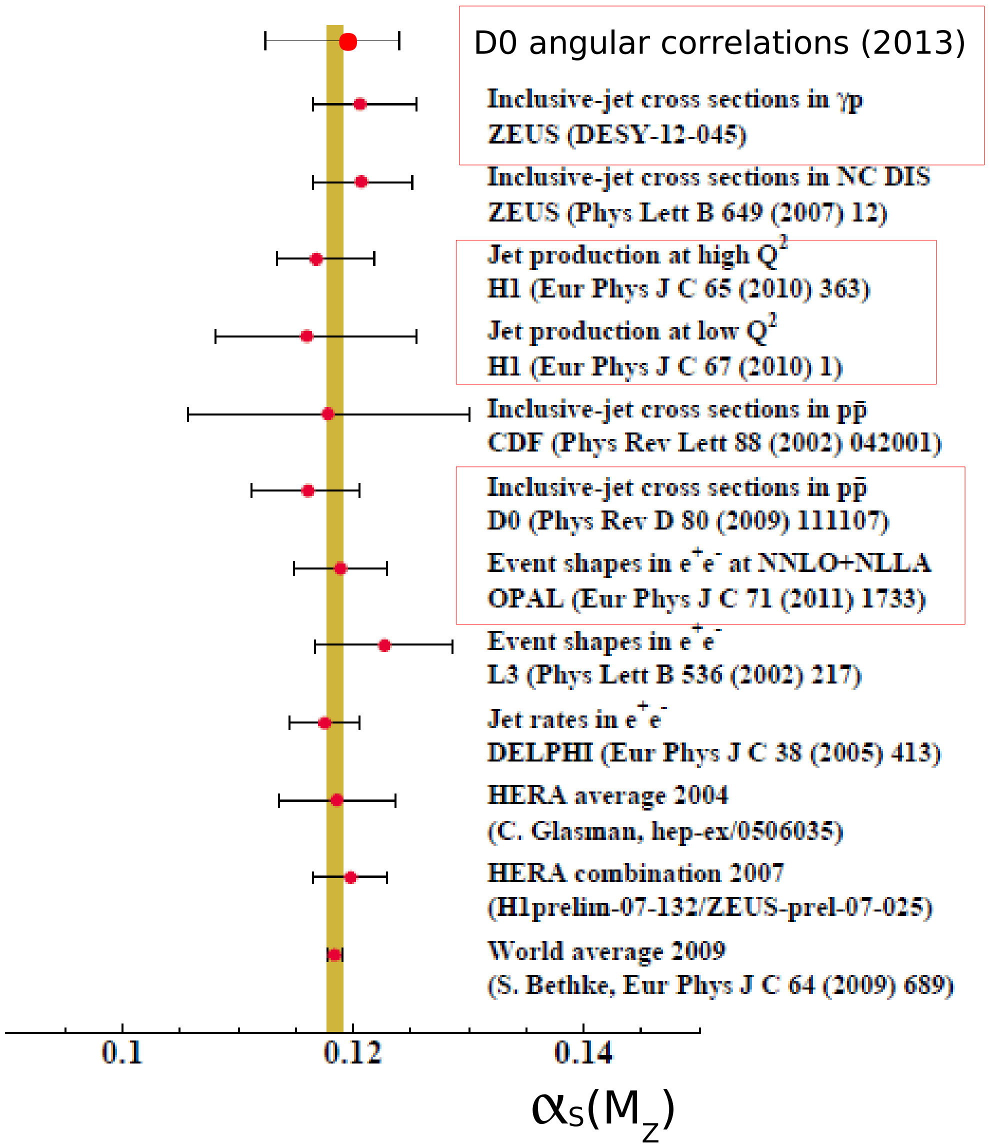
theor. scale uncertainty dominates



D0 data: 54.5 GeV to 395 GeV coverage

- → $\alpha_s(p_T)$ results up to 400 GeV
- → $\alpha_s(p_T)$ decreases with p_T as predicted by the RGE
- → In agreement with ALEPH,JADE,ZEUS,H1 and world average $\alpha_s(M_z)$=0.1184±0.0007

Compilation of α_S results

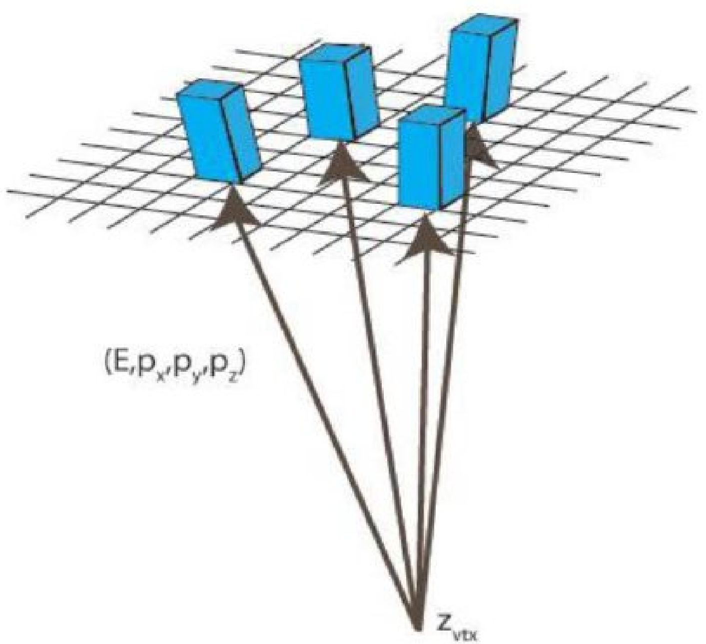


Results since 2009

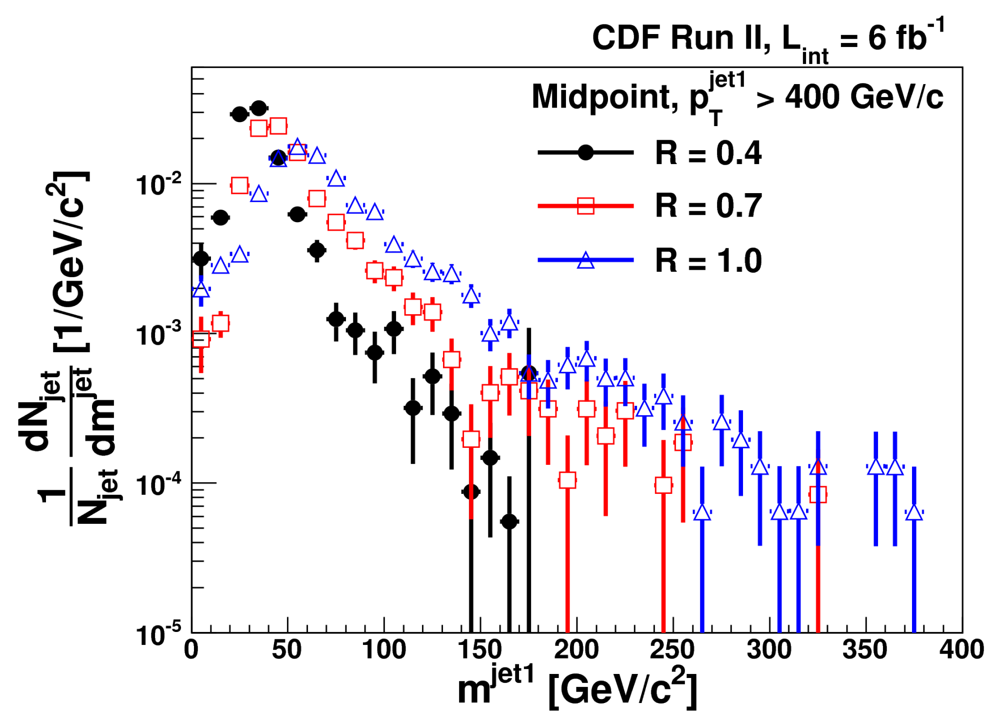
Structure of high pT jets (CDF)

- 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



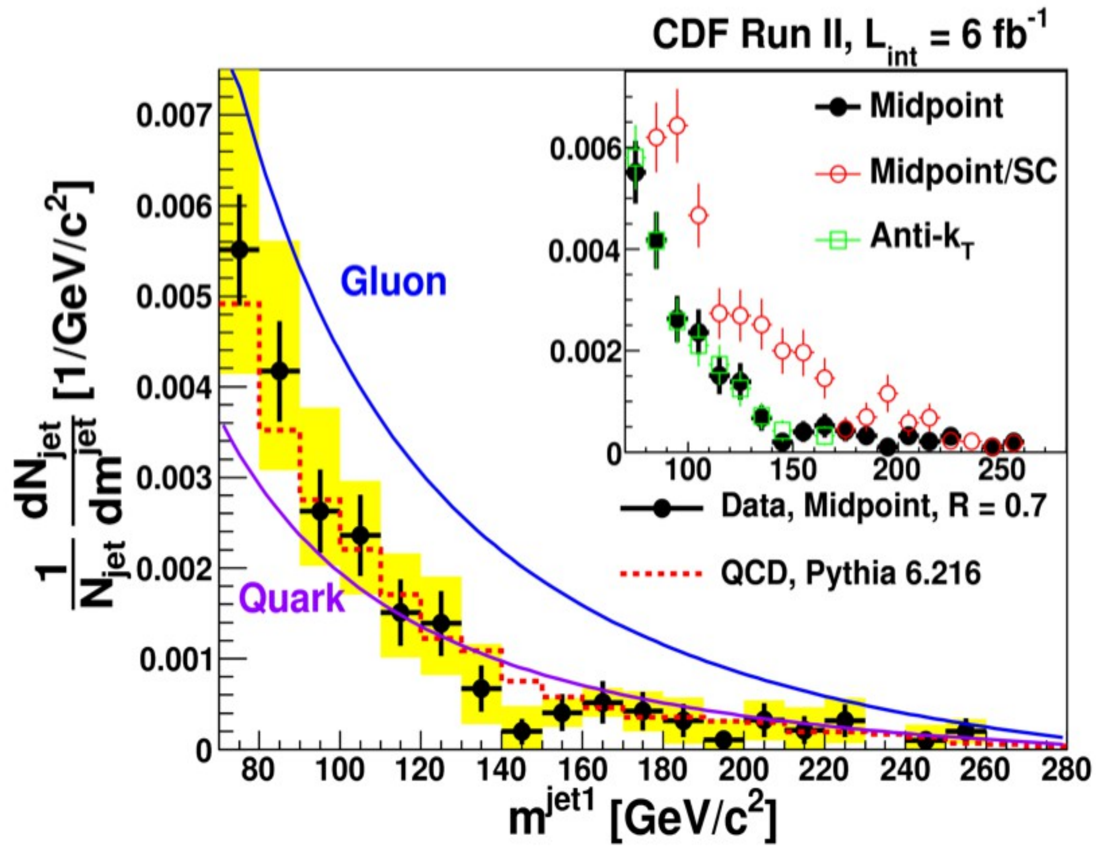
400<pT<500 GeV, anti-top cuts



Substructure of high pT jets

- 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) into a boosted/collimated jet
- Little studied in the past, but now gaining a lot of interest at hadron colliders
  - many variables: jet mass, subjet multiplicity, subjettiness, angularity, planar flow,..
  - Clear difference between quark and gluon jets

Jet pT>400 GeV (anti-top cuts applied)



Event shapes

- Geometric shape of the hadronic final state sensitive to details of QCD multijet production, but robust against experimental systematics, e.g. jet energy scale
- Test of high order pQCD corrections
- Source of precise α_s (traditionally used in e^+e^-)

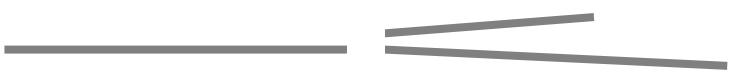
Transverse thrust:

$$T = \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i |\vec{p}_{T,i}|}, \quad \tau_\perp = 1 - T$$

$\hat{n}$: direction that maximizes T

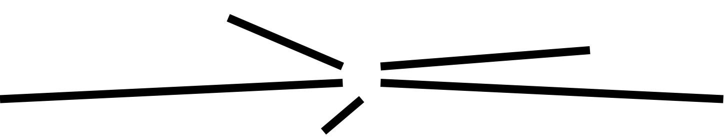
2-parton final state

T=1



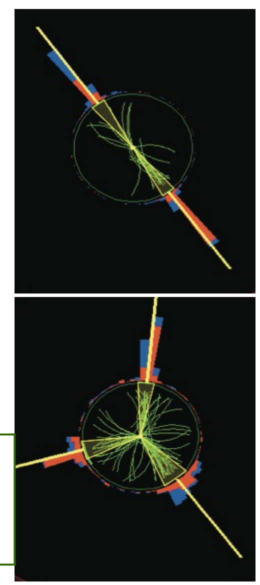
3-parton final state

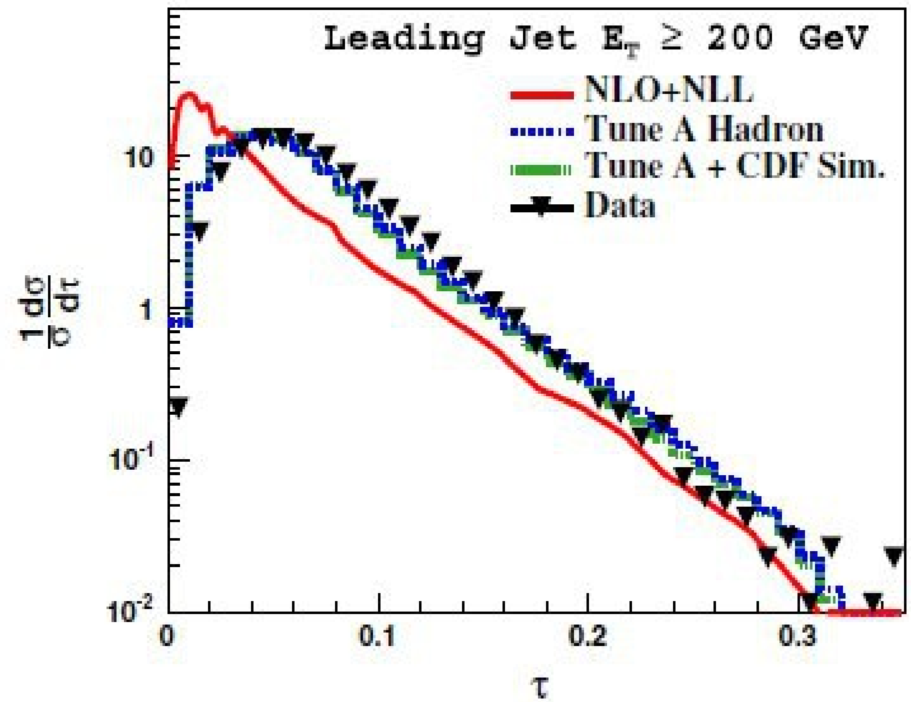
T=[2/3,1] (LO)



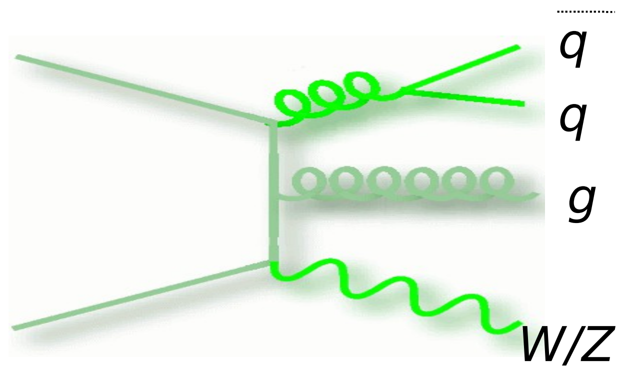
N-parton final state

T=[1/2,1] (N…NLO)





LO N..NLO

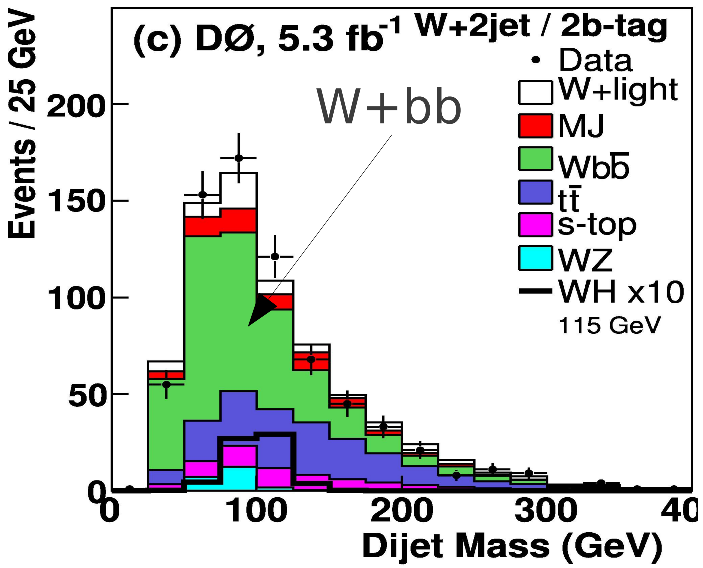


V + jet Results

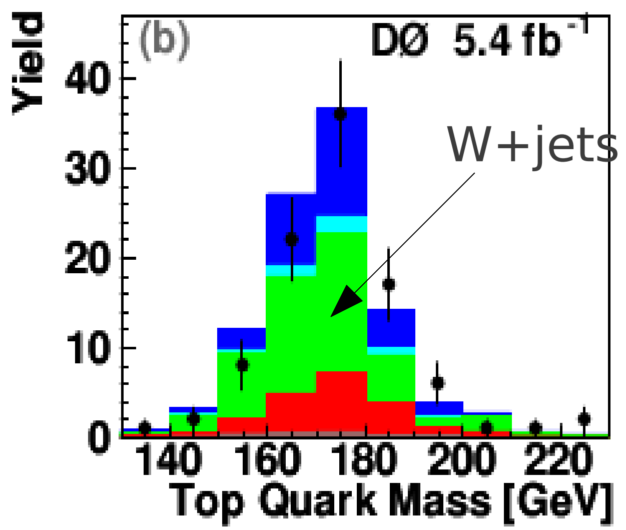
Fixed-order: NLO
LO + Parton Shower
Backgrounds to New Physics

V+jet production

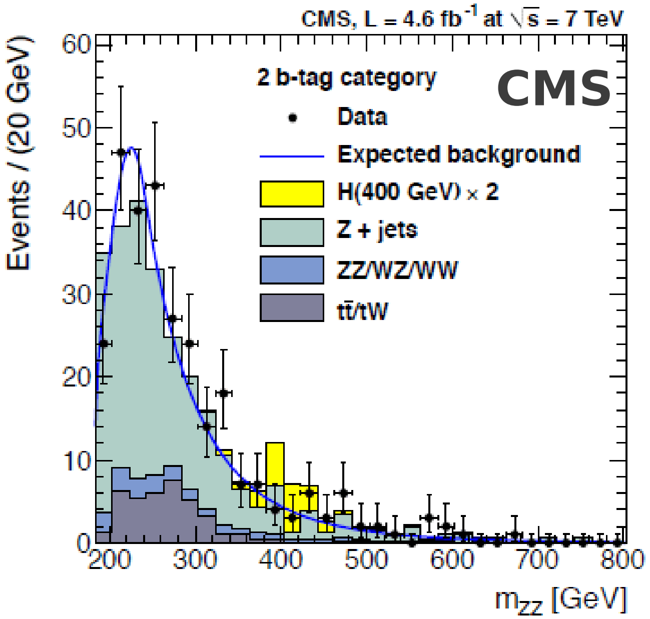
WH production



Single top production



H →ZZ→ 2l2q



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

– Provide detailed measurements of $p_{T,}$ mass and angular distributions of vector boson and jets

→ test of fixed order perturbative QCD (MCFM, Blackhat, Rocket, HEJ,..), LO ME+PS predictions in MC event generators (Alpgen,Sherpa,Madgraph,..)

→ testing and tuning of phenomenological models

→ All experiments are heavily involved in such tests

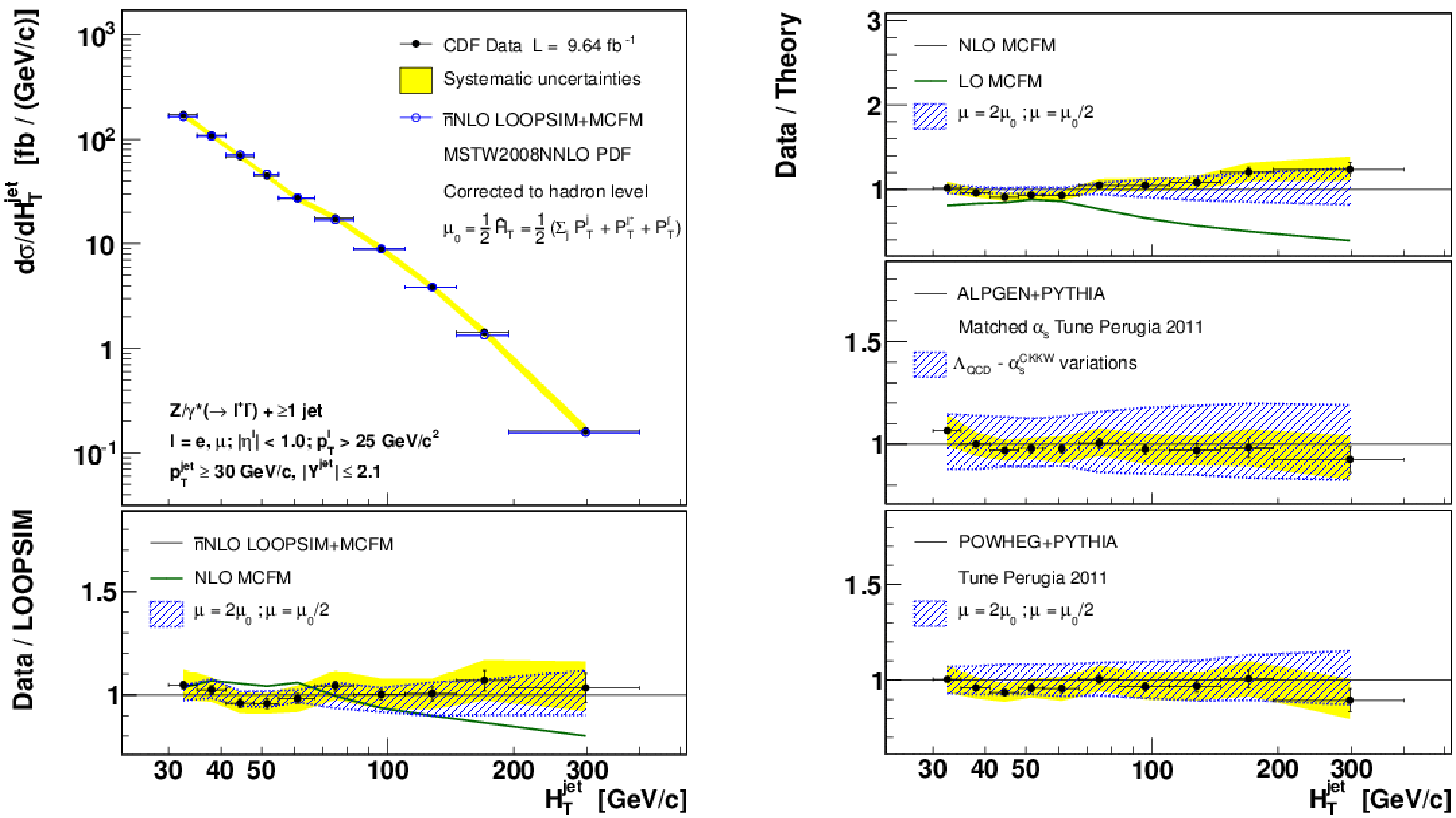
Z + jets

Detailed studies on Z(ll)+jet production coming out vs jet p_T, N_{jets}, H_T, etc

- comparisons with state-of-the-art theory calculations
- good agreement with NLO pQCD (BlackHat and MCFM)
- LO ME+PS (Alpgen), NLO+PS (Powheg) properly model data with large scale uncertainty
- Good modeling with approximate nNLO LOOPSIM with reduced scale uncertainty

CDF, jet H_T

Draft in preparation



W+jets

- Dominant background to ttbar production, Higgs boson, many non-SM processes

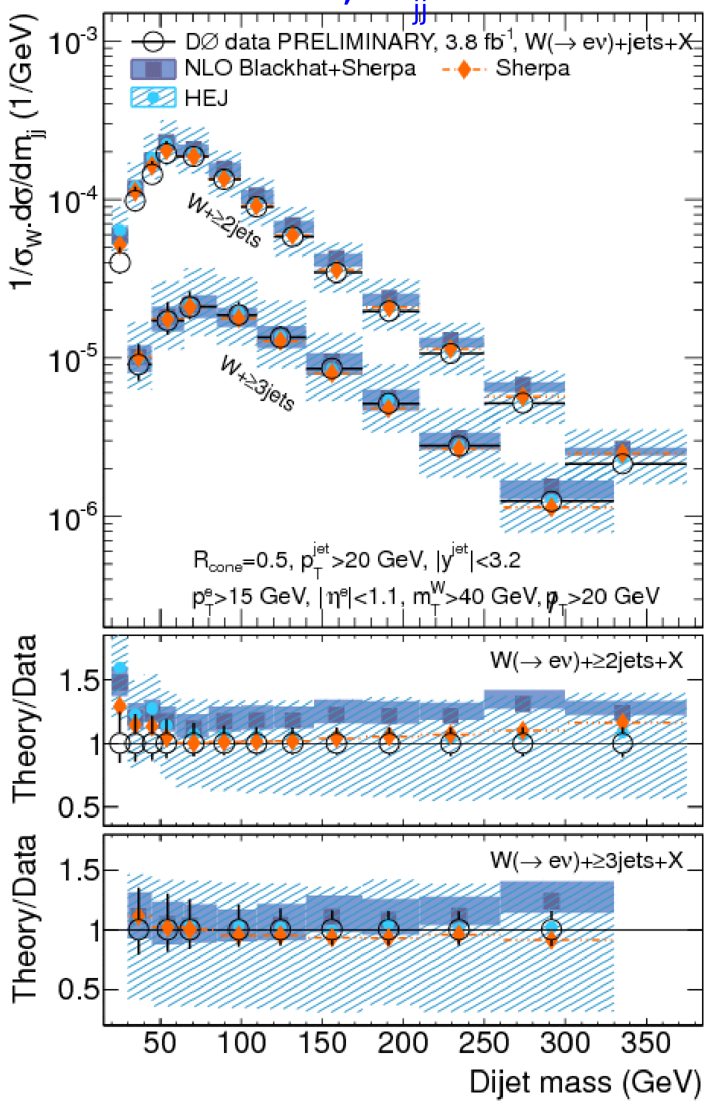
=> extensively studied in all Tevatron and LHC experiments:

jet p_T, H_T, #jets, jet angular, masses, 3rd jet emission prob, etc.

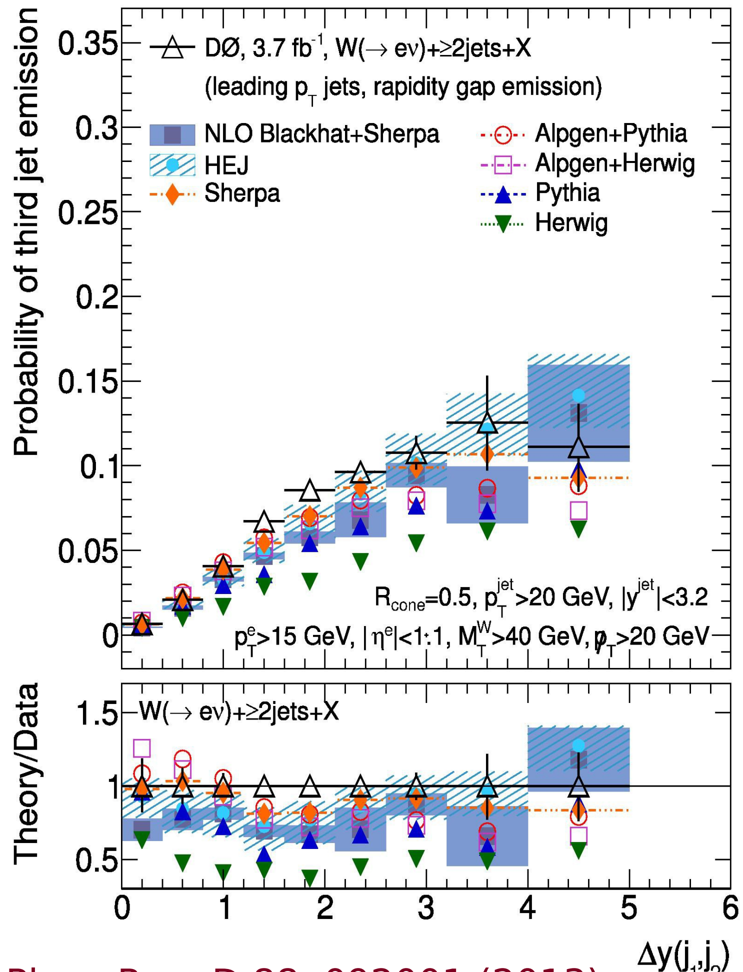
- Good agreement with NLO (Blackhat+Sherpa, HEJ) for most of phase space

(Blackhat: some tension for W+2jet in $M_{jj,}$ and high H_T)

D0, M_{jj}

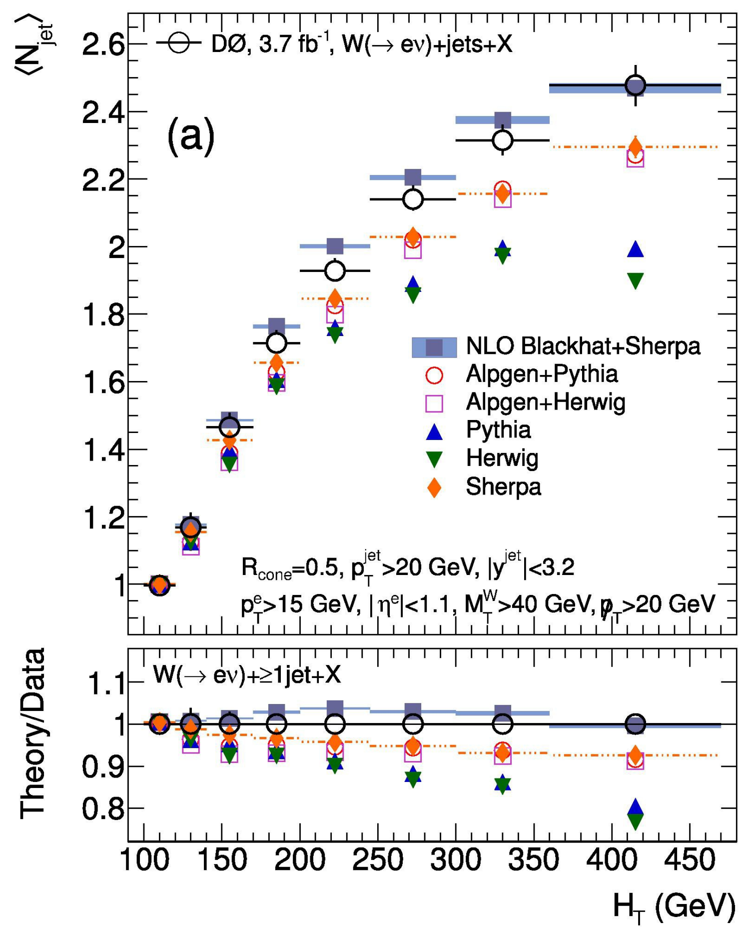


D0, 3rd jet emission



Phys. Rev. D 88, 092001 (2013)

D0, HT



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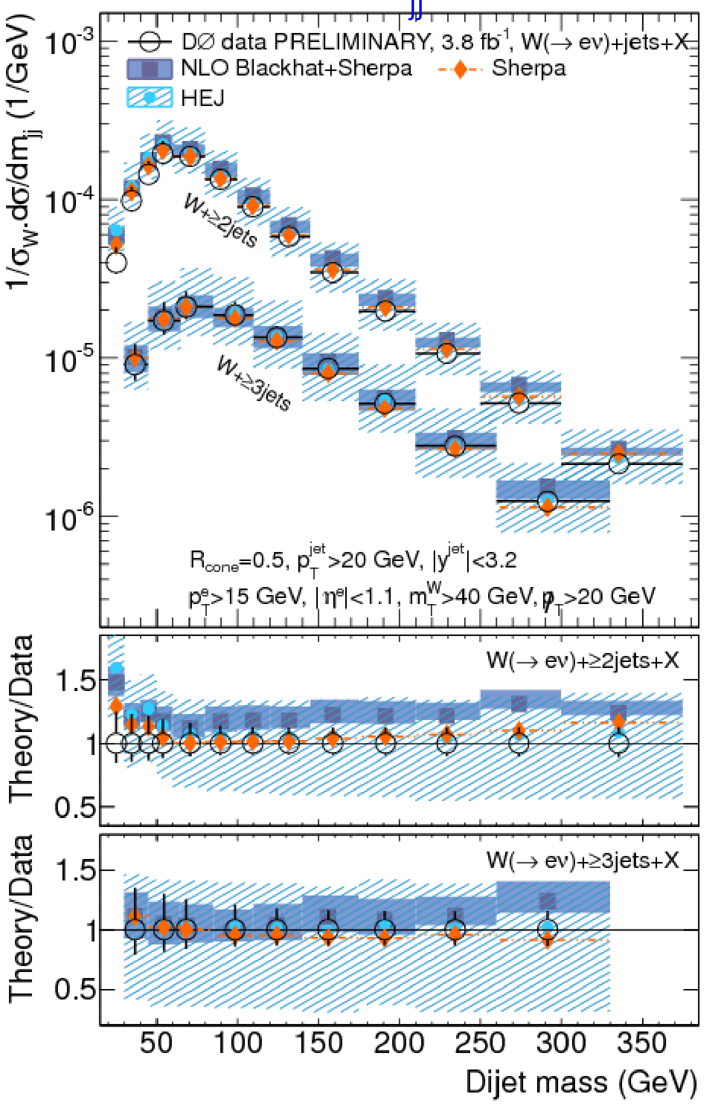
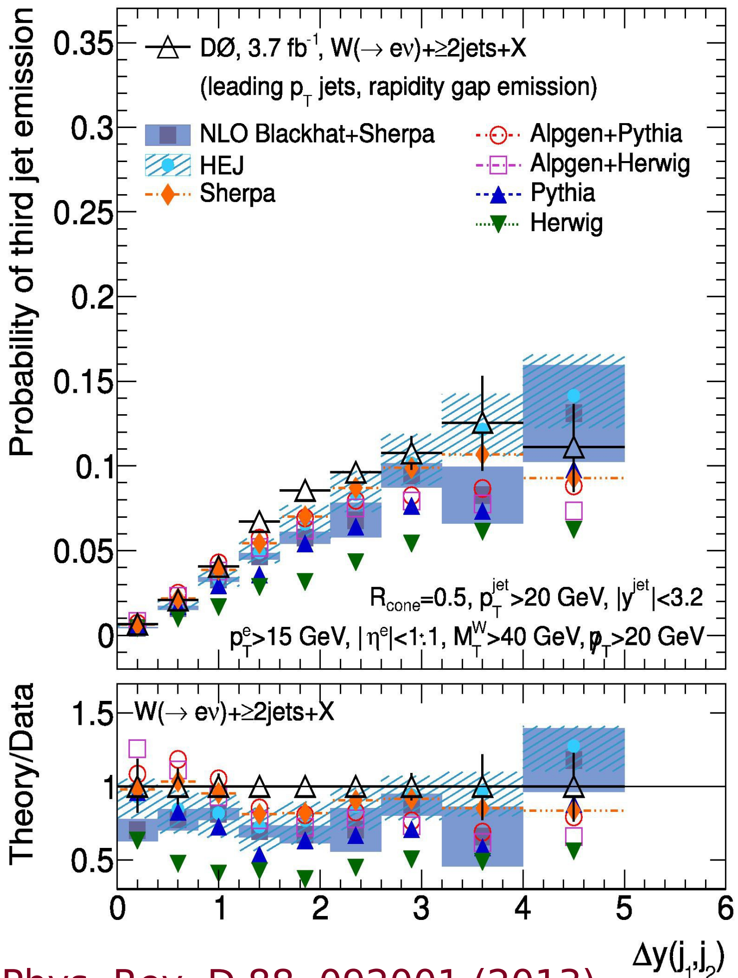
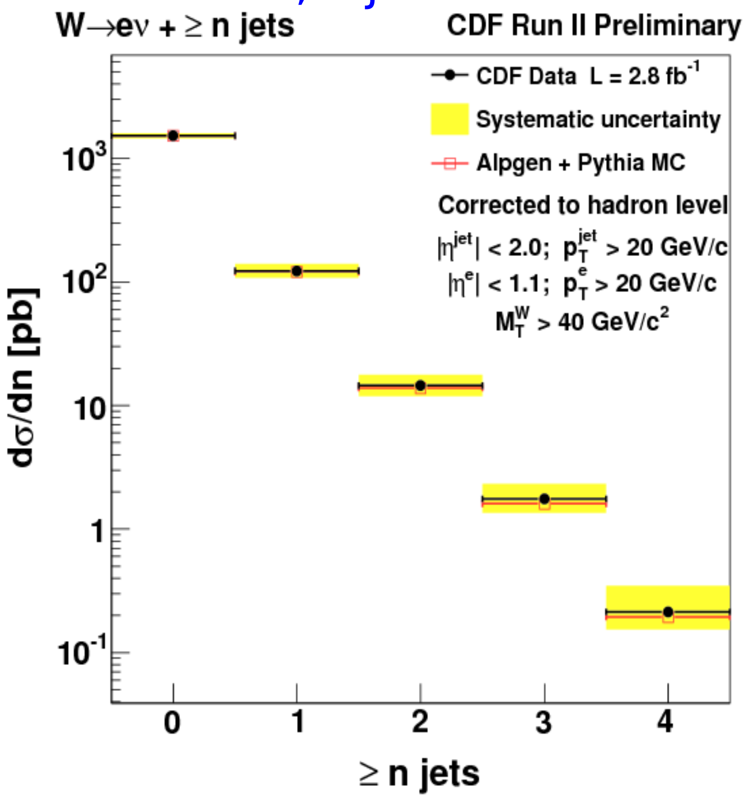
D0, M_{jj}



D0, 3[rd] jet emission



CDF, #jets

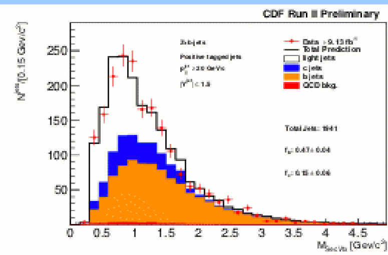


Phys. Rev. D 88, 092001 (2013)

Z+b

- Z+b-jets test of pQCD and b-quark fragmentation, PDF
- Z+b important background for single top, ZH, new phenomena
  - measure ratio with respect to inclusive Z and Z+jet
- Good agreement with NLO predictions (20-25% uncert.) in all experiments

PRD 87, 092010 (2013)

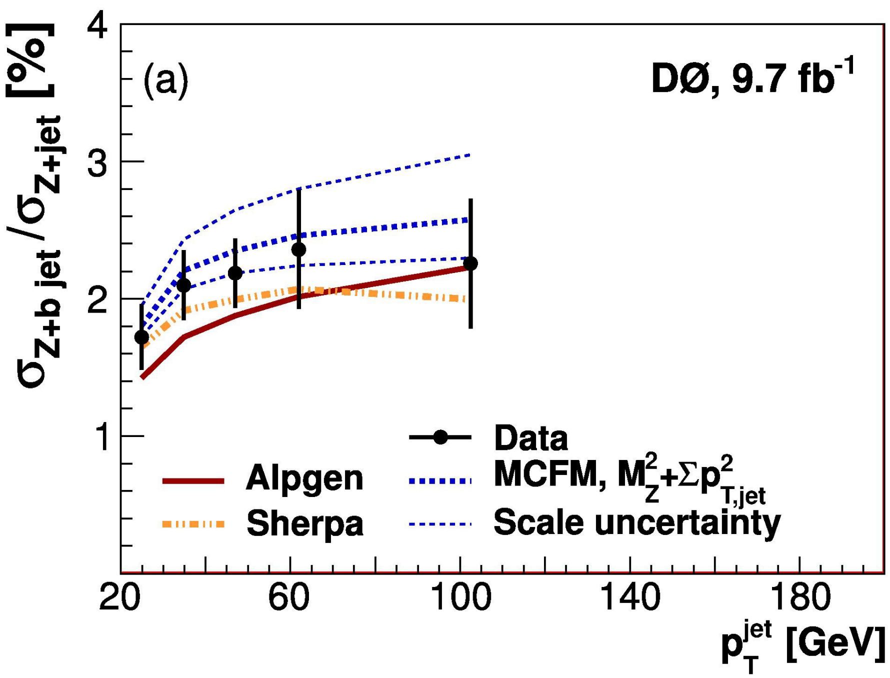


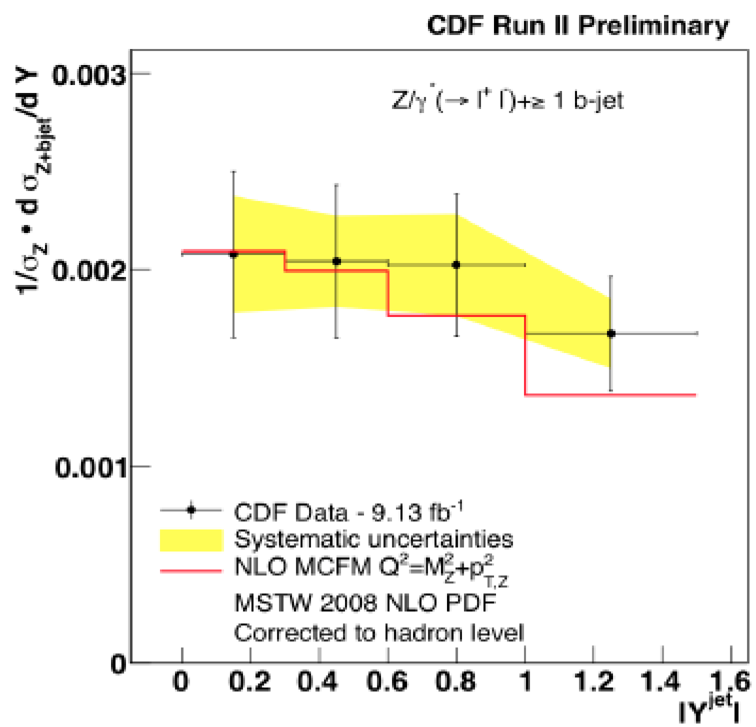
$$\frac{\sigma_{Z\_bjet}}{\sigma_Z} = 0.261 \pm 0.023^{stat} \pm 0.029^{syst}\%$$

$$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}} = 2.08 \pm 0.18^{stat} \pm 0.27^{syst}\%$$

To compare with NLO prediction with MCFM:

	$Q^2 = m_Z^2 + p_{T,Z}^2$	$Q^2 =< p_{T,jet}^2 >$
$\frac{\sigma_{Z\_bjet}}{\sigma_Z}$	0.23 %	0.29 %
$\frac{\sigma_{Z\_bjet}}{\sigma_{Zjet}}$	1.8 %	2.2%

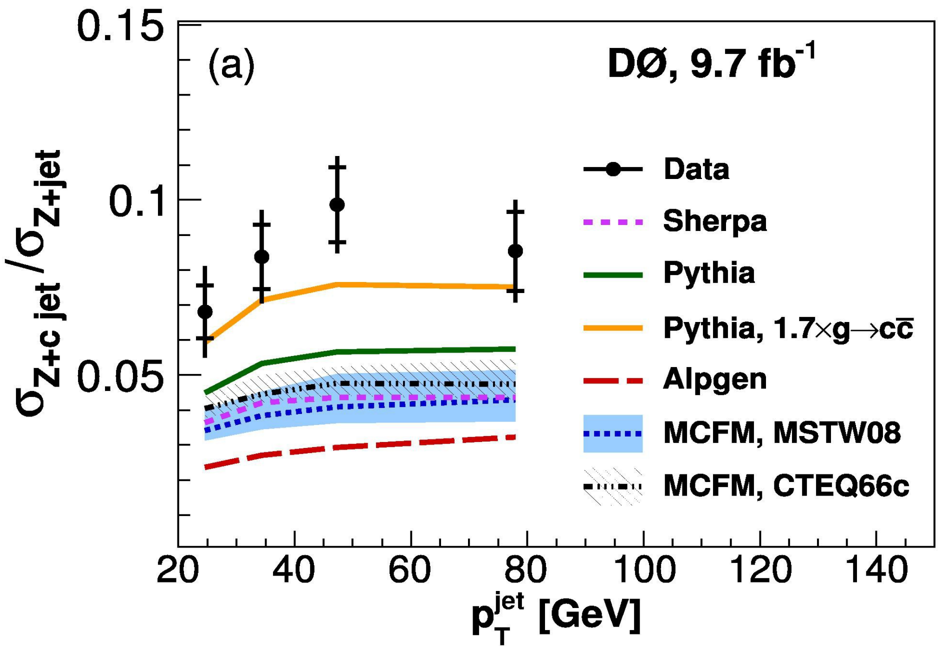




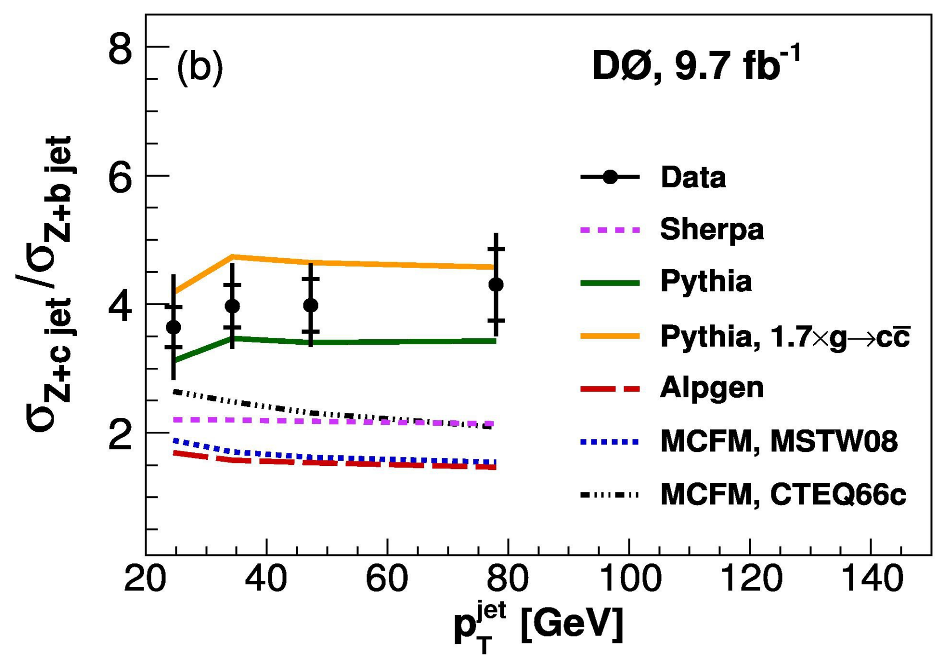
Z+c

PRL 112, 042001 (2014)

σ(Z+c)/σ(Z+jet)



σ(Z+c)/σ(Z+b)



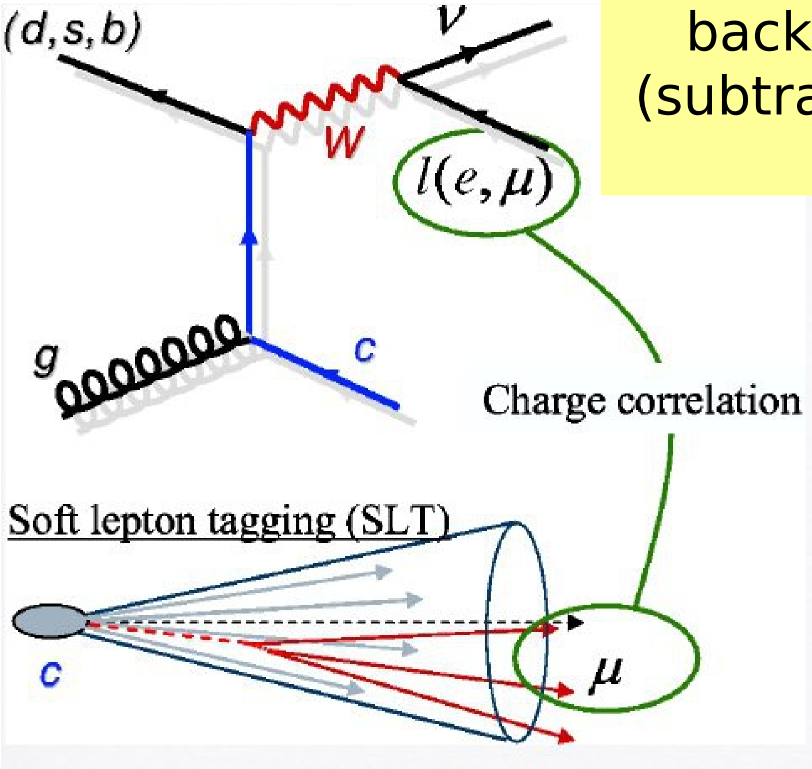
- D0 differential cross-sections measurements $\sigma_{Z+c\text{-}jet}/\sigma_{Z+jet}$ (*left*) and $\sigma_{Z+c\text{-}jet}/\sigma_{Z+b\text{-}jet}$ (*right*) as a function of p_T(jet) (p_T(jet) > 20 GeV, $|\eta_{jet}|$ < 2.5).
- Significantly higher than NLO (MCFM) prediction.
- Best agreement is with PYTHIA with 1.7 × enchanced g → cc rate.

W+c

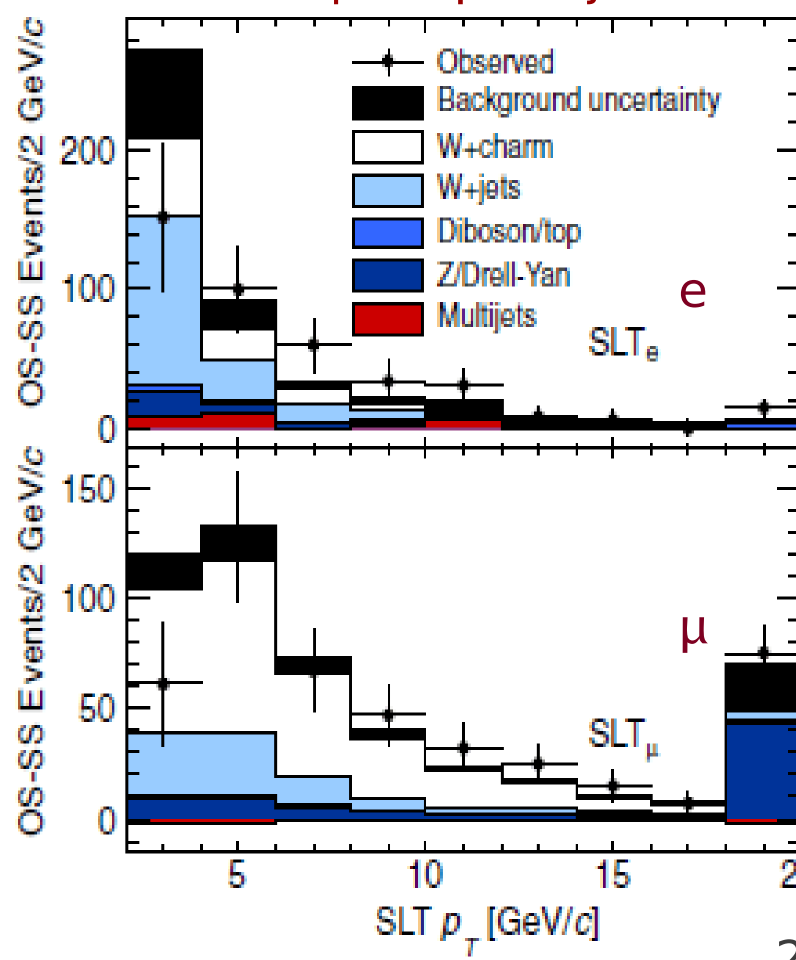
Sensitive to s-quark PDF: 90% s, 10% d

PRL 110, 071801 (2013)

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



Lepton pT in jet

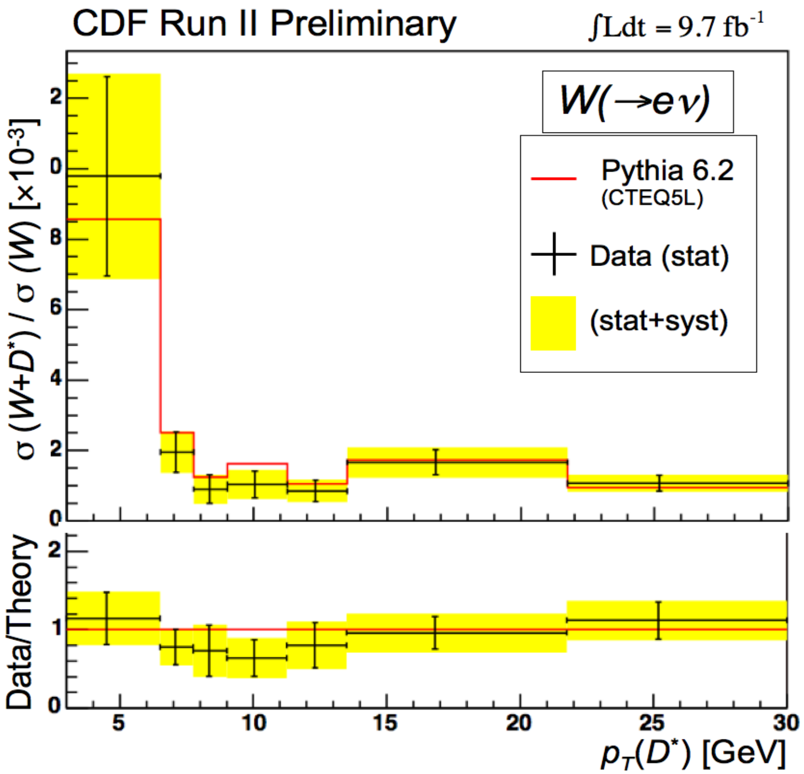


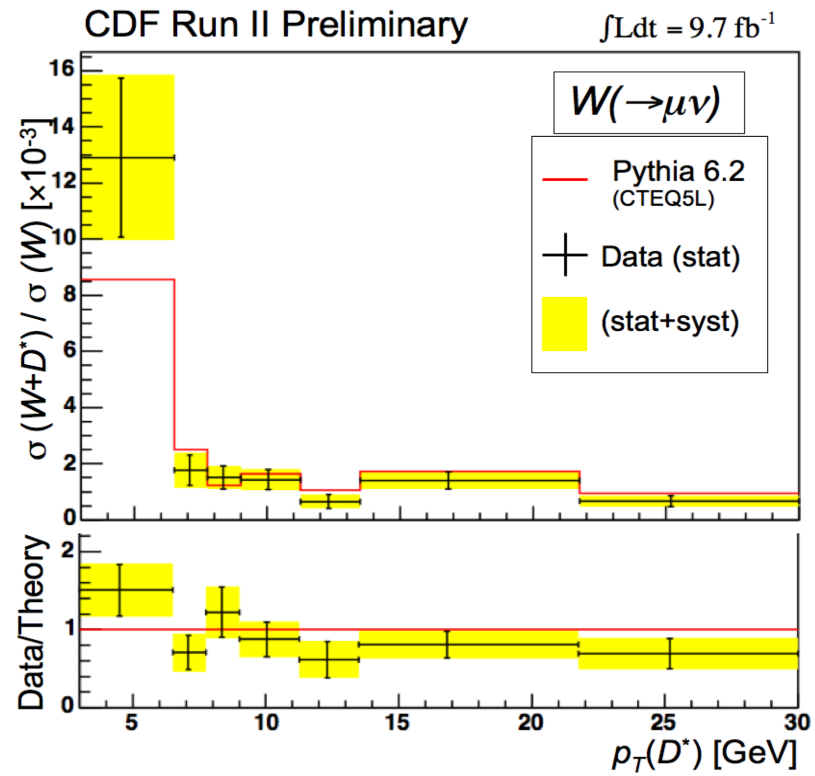
- Jet pT>20 GeV, $|\eta|<1.5$
- 5.7σ CL for W+single c-jet
- σ(W+c)*Br(W-> lnu):
  CDF Data: $13.6^{+3.4}_{-3.1}$ pb
  QCD NLO: 11.4±1.3 pb
- Also measured $|V_{cs}|=1.08\pm0.16$

Good agreement data/theory

Measurements of σ(V+D*)/σ(V)

Preliminary



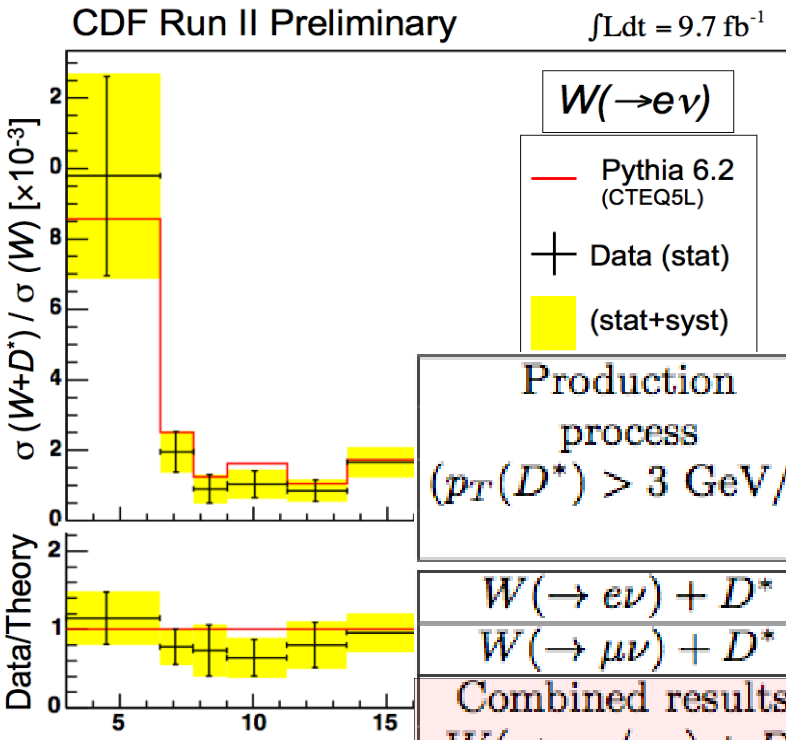


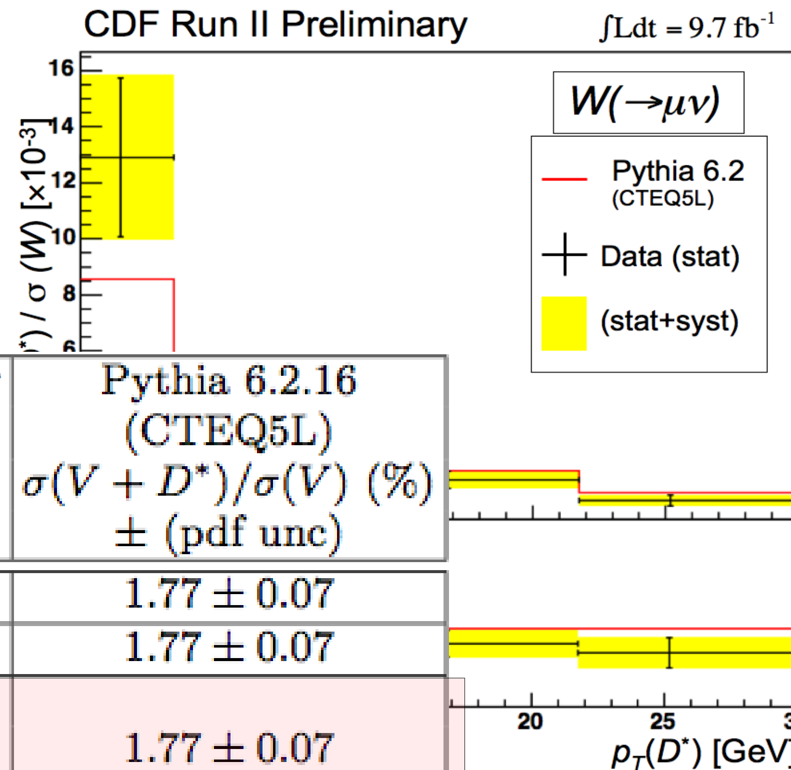
- CDF data for the differential rates of cross-section ratio σ(W + D*)/σ(W) as a function of p_T (D*), as measured by in the W → eν (*left*) and W → μν (*right*) decay channels.

  D* is fully reconstructed at the track level [D*(2010)→ D0(→ Kπ)πs]

Measurements of σ(V+D*)/σ(V)

Preliminary





Production process ($p_T(D^*) > 3$ GeV/c)	CDF Run II Preliminary $\int \mathcal{L}dt = 9.7$ fb^{-1} $\sigma(V+D^*)/\sigma(V)$ (%) $\pm$(stat) $\pm$ (syst)	Pythia 6.2.16 (CTEQ5L) $\sigma(V+D^*)/\sigma(V)$ (%) $\pm$ (pdf unc)
$W(\to e\nu) + D^*$	$1.74 \pm 0.21 \pm 0.17$	1.77 ± 0.07
$W(\to \mu\nu) + D^*$	$1.75 \pm 0.17 \pm 0.05$	1.77 ± 0.07
Combined results: $W(\to e\nu/\mu\nu) + D^*$	$1.75 \pm 0.13 \pm 0.09$	1.77 ± 0.07
$Z(\to ee) + D^*$	$1.0 \pm 0.6 \pm 0.2$	1.36 ± 0.05
$Z(\to \mu\mu) + D^*$	$1.8 \pm 0.5 \pm 0.2$	1.36 ± 0.05
Combined results: $Z(\to ee/\mu\mu) + D^*$	$1.5 \pm 0.4 \pm 0.2$	1.36 ± 0.05

- CDF data for the differential rates of cross-section ratio σ(W + D*)/σ(W) as a function of p_T (D*), as measured by in the W → eν (*left*) and W → μν (*right*) decay channels.

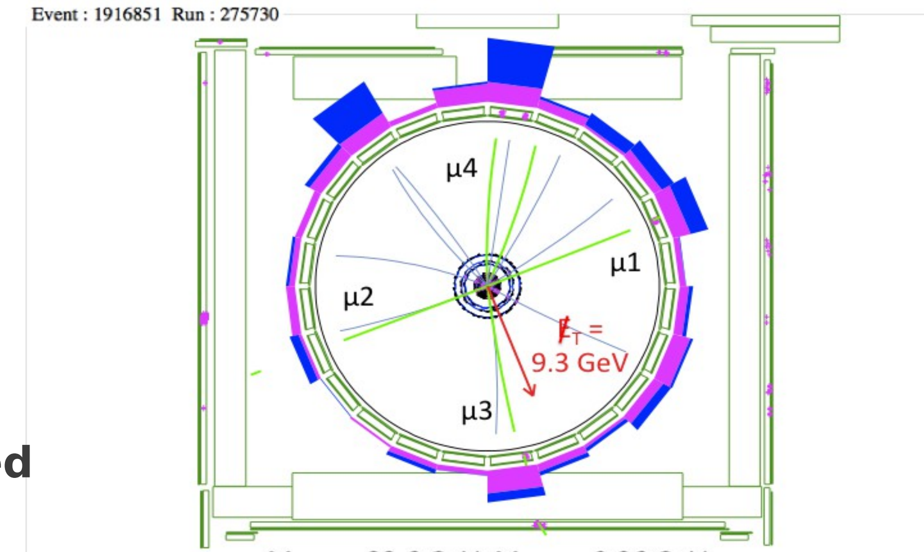
  D* is fully reconstructed at the track level [D*(2010)→ D0(→ Kπ)πs]
- The measurements show good agreement with PYTHIA 6.2 Tune A with in all bins.

W/Z+Upsilon Search

Preliminary

- CDF search for the production of the Upsilon (1S) meson in association with a vector boson.
- 9.7 fb^{-1} data set

Υ+Z Candidate at CDF



$M_{\mu1\mu2}$ = 88.6 GeV, $M_{\mu3\mu4}$ = 9.26 GeV

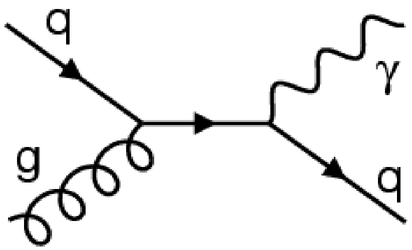
Observe one Upsilon + W candidate over an expected background of 1.2 ± 0.5 events, and one Upsilon + Z candidate over an expected background of 0.1 ± 0.1 events.

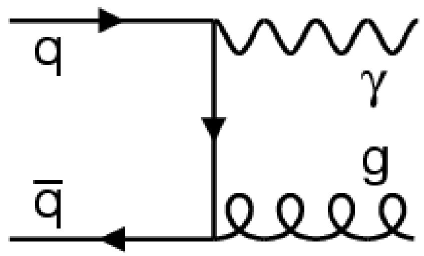
	$\Upsilon + W \to e\nu$	$\Upsilon + W \to \mu\nu$	$\Upsilon + W \to \ell\nu$	$\Upsilon + Z \to ee$	$\Upsilon + Z \to \mu\mu$	$\Upsilon + Z \to \ell\ell$
N_{sig}	0.019±0.004	0.014±0.003	0.034±0.006	0.0048±0.0009	0.0037±0.0007	0.0084±0.0016
N_{bg} (fake Υ)	0.7±0.4	0.4±0.3	1.1±0.5	0.07±0.07	0.04±0.04	0.1±0.1
N_{bg} (fake W/Z)	0.06±0.04	negl.	0.06±0.04	negl.	negl.	negl.
N_{bg} ($\Upsilon + Z$)	0.0006±0.0001	0.0033±0.0006	0.0039±0.0007			
N_{bg} (total)	0.8±0.4	0.4±0.3	1.2±0.5	0.07±0.07	0.04±0.04	0.1±0.1
N_{obs}	0	1	1	0	1	1

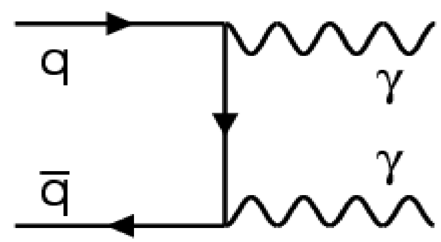
95% C.L. Cross Section Limits

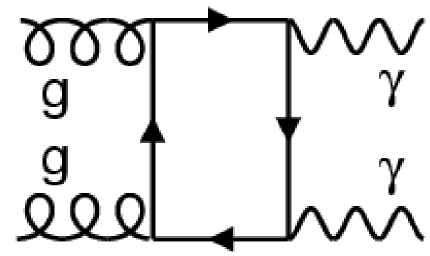
	$\Upsilon + W$	$\Upsilon + Z$
expected limit (pb)	5.5	13
observed limit (pb)	5.5	20

Photon Production









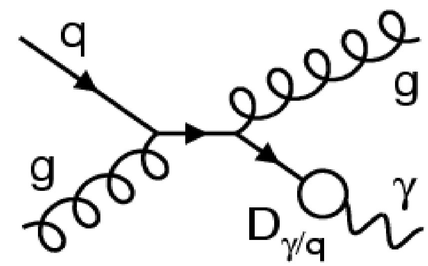
Direct photons emerge unaltered from the hard subprocess

→ direct colorless probe of the hard scattering dynamics

→ observable: **isolated** photons (typically in R=0.4)

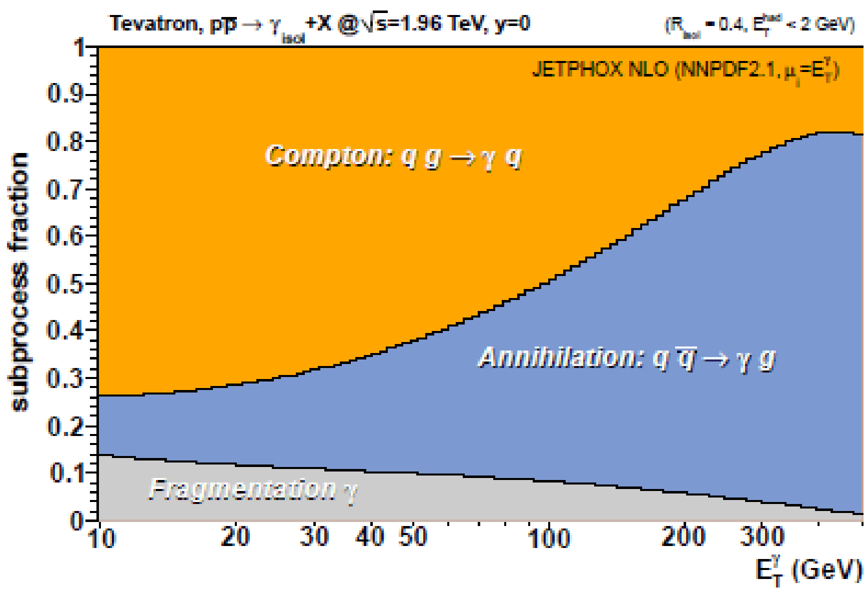
→ potential sensitivity to PDFs (gluon!)

+also fragmentation contributions (suppressed by isolation criterion)

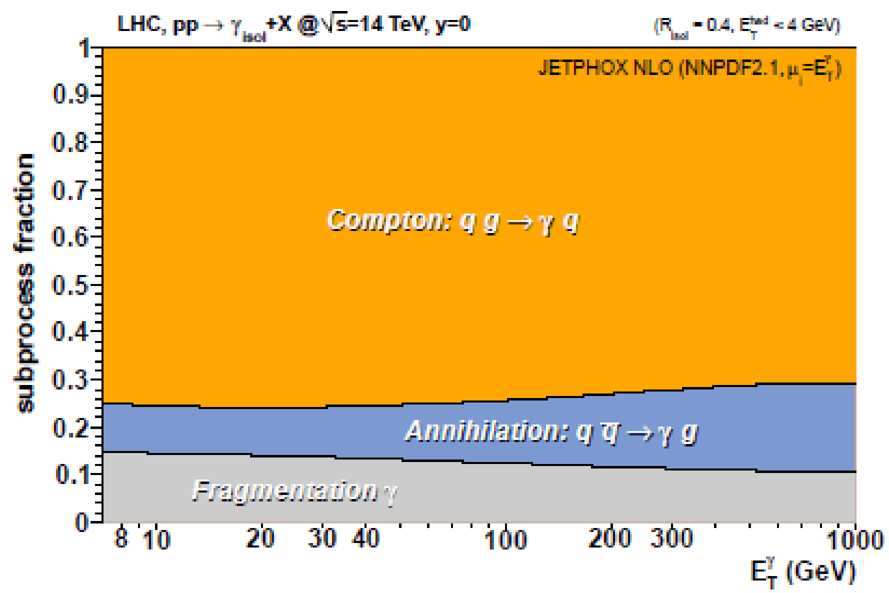


Isolated inclusive γ: process composition

Tevatron



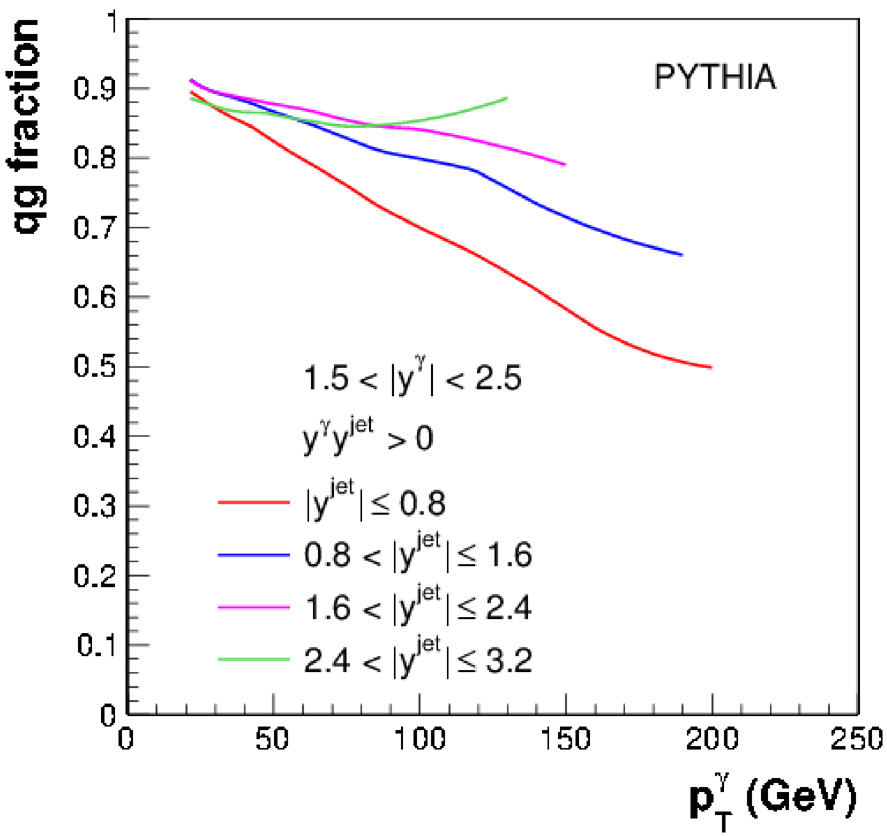
LHC

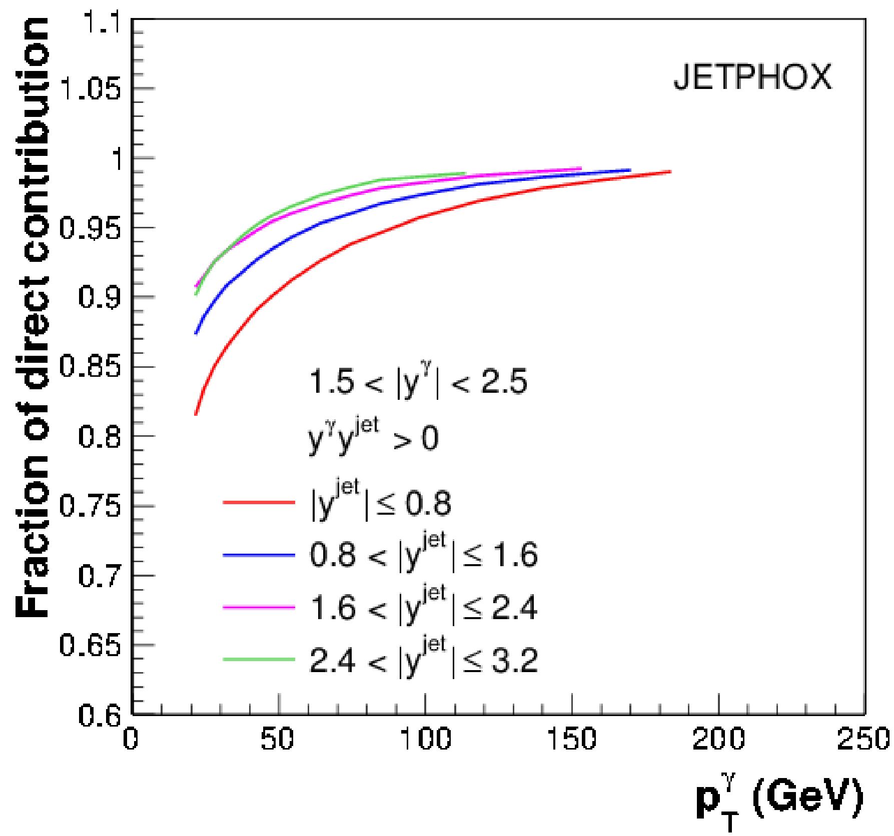


Triple photon+jet differential

Phys. Rev. D 88, 072008 (2013)

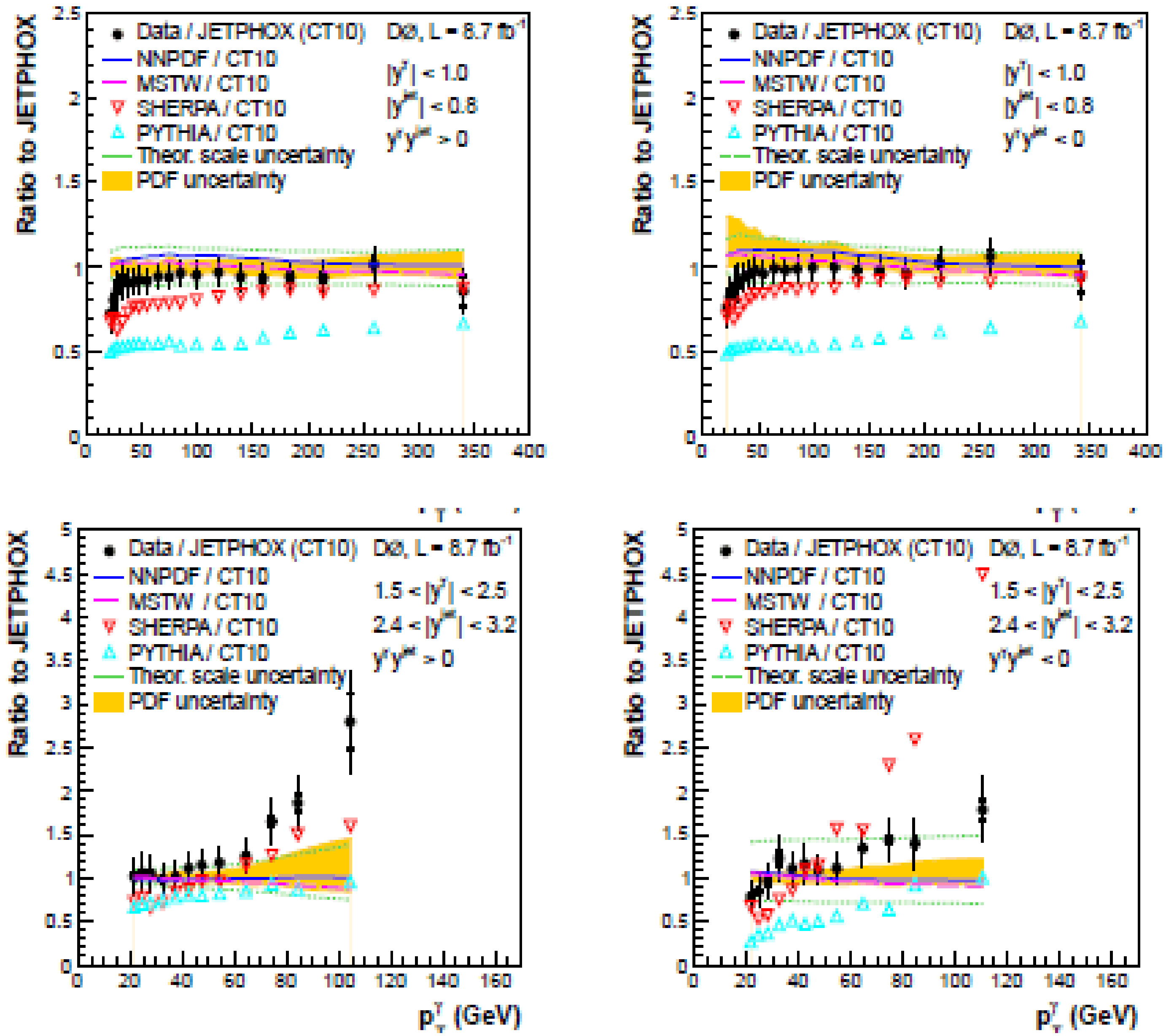
- Measurements of diff. cross section in photon pT in 8 regions: $|y^{\gamma}|$: {0-1, 1.5-2.5}; $|y^{jet}|$: {0-0.8, 0.8-1.6, 1.6-2.4, 2.4-3.2}
- … with same sign and opposite sign photon and jet rapidities
- Sensitive to parton x from 0.007 to 0.4





Triple photon+jet differential

SS OS



Central photons
Central jets

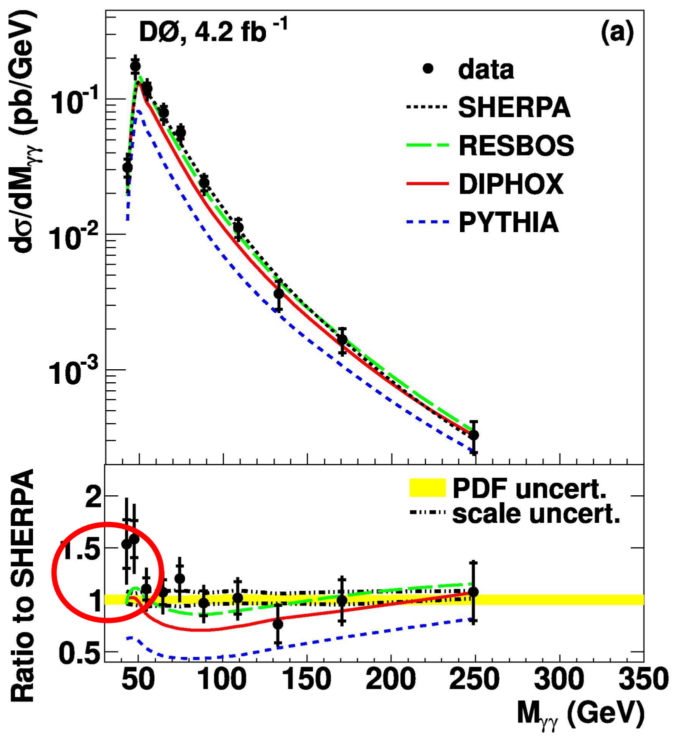
Forward photons
Forward jets

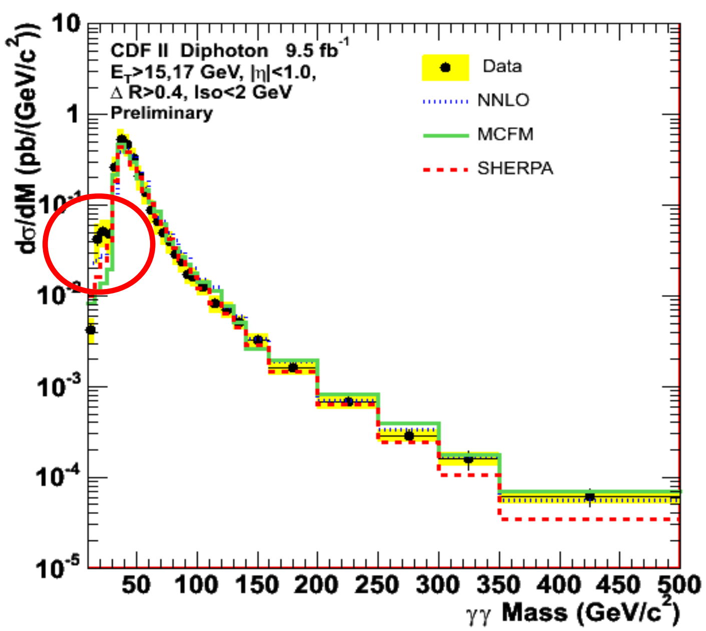
Disagreement to NLO at pT<40 GeV, and pT>70 GeV with very forward jets.

Photon Pair Production

– Almost irreducible background to H→ γγ, other new phenomena => should be understood
– Isolation: ETsum[R=0.4] <2-2.5 GeV (CDF,D0), <4-5 GeV (Atlas, CMS)
– Min photon pT varies as 16-20 GeV
– Data are compared with predictions: PYTHIA, SHERPA, DiPhoX, ResBos, NNLO
– 1D cross sections in diphoton Mass, $p_T^{\gamma\gamma}$, $\Delta\phi$, $\cos\theta^*$ and 2D ones ($p_T^{\gamma\gamma}$, $\Delta\phi$, $\cos\theta^*$ in Mass bins)

Diphoton Mass





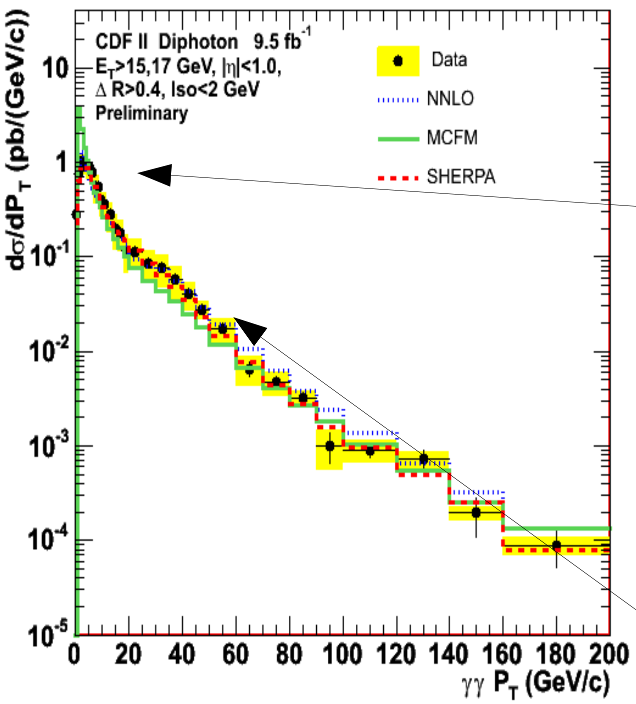
Small masses: Significant contrib. from gg→ γγ (30-40%), fragmentation

Good agreement with most theories at Mass>50 GeV, but data are higher than theory up to a factor 1.5-2 at smaller masses.

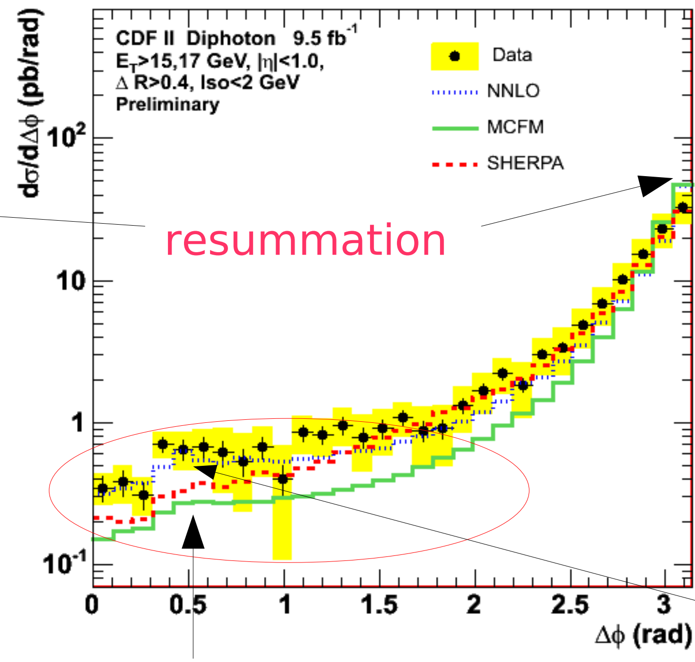
Photon Pair Production

- Almost irreducible background to H→ γγ, other new phenomena, => should be understood
- Isolation: ETsum[R=0.4] <2-2.5 GeV (CDF,D0), <4-5 GeV (Atlas, CMS)
- Min photon pT varies as 16-20 GeV
- Data are compared with predictions: PYTHIA, SHERPA, DiPhoX, ResBos, NNLO
- 1D cross sections in diphoton Mass, $p_T^{\gamma\gamma}$, $\Delta\phi$, $\cos\theta^*$ and 2D ones ($p_T^{\gamma\gamma}$, $\Delta\phi$, $\cos\theta^*$ in Mass bins)

$p_T^{\gamma\gamma}$



$\Delta\phi$



resummation

Significant contrib. from fragmentation photons

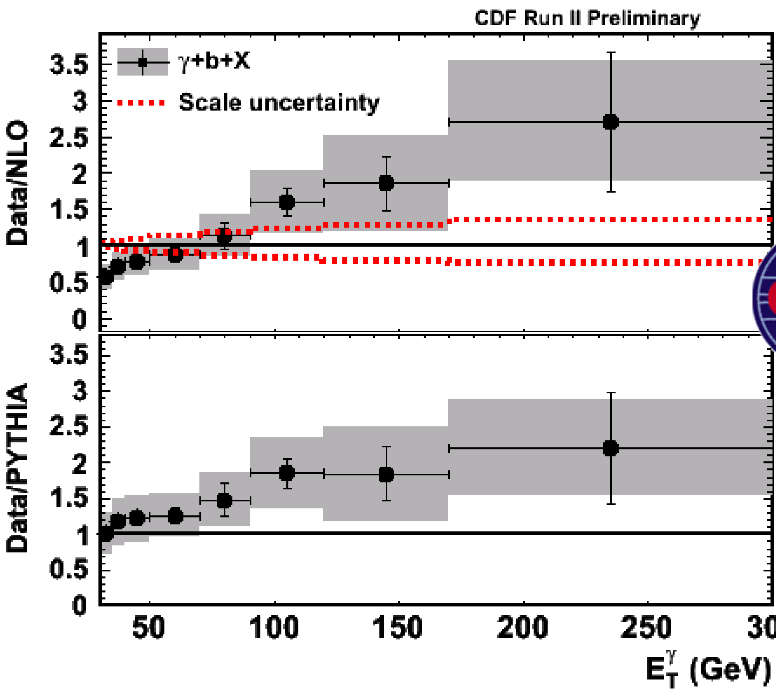
NNLO is doing good job, big NNLO/NLO ratio

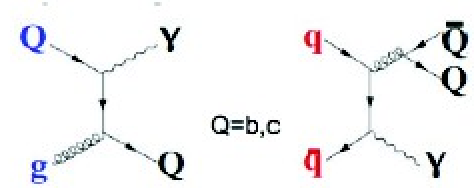
D0, PLB 690, 108 (2010)
D0, PLB 725, 6 (2013)
CDF, PRL 110, 101801(2013)
CDF, PRD 84, 052006 (2011)

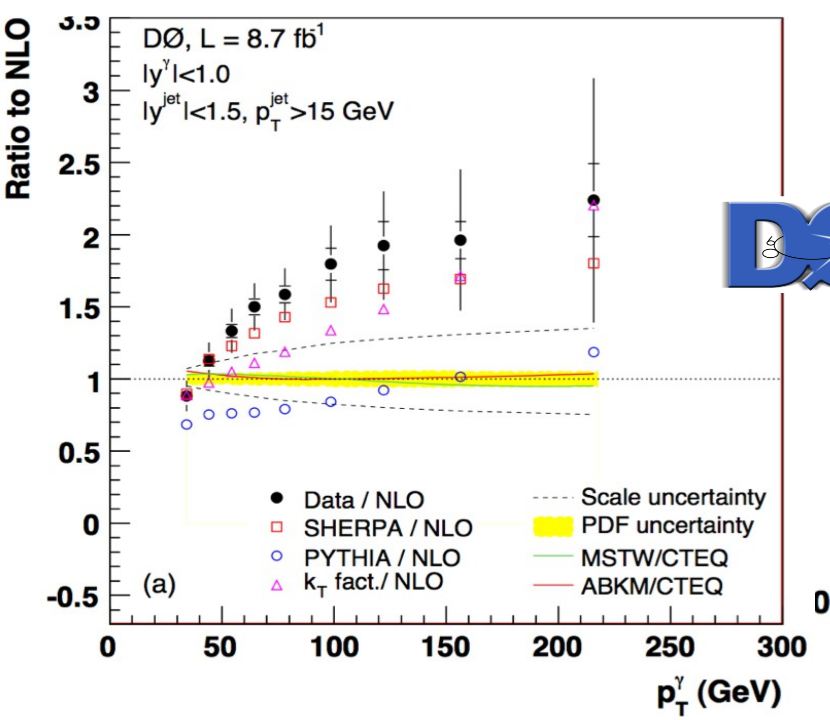
- None of theories describe the whole phase space: small masses, small $\Delta\phi$ and $\Delta\phi \approx \pi$, moderate $p_T^{\gamma\gamma}$ are most problematic for theories.
- NNLO: good description $p_T^{\gamma\gamma}$, $\Delta\phi$ at CMS, CDF; still should be added the "*gg* box" HO corrections, resummation (fragm. functions?)

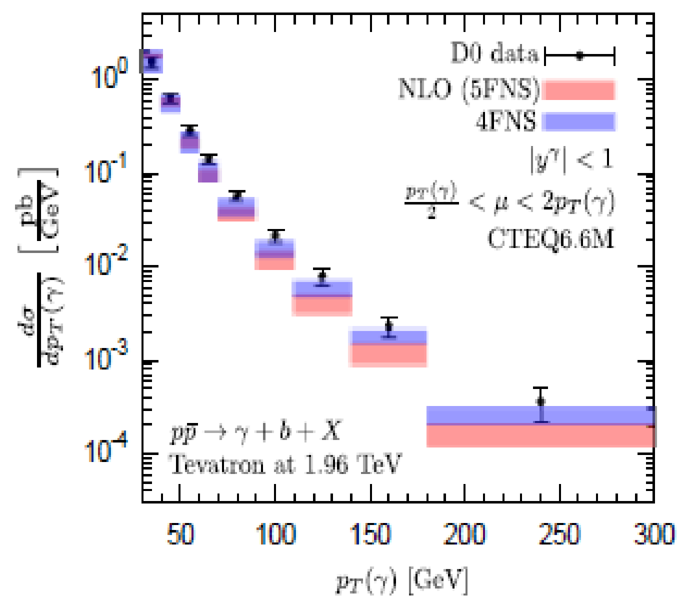
Photon+b

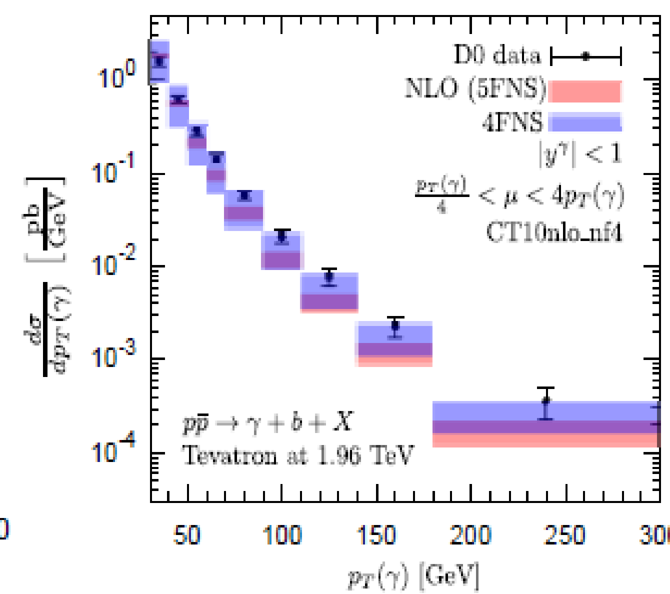
- Disagreement with NLO 5FNS predictions at $p_T > 70$ GeV
- D0 and CDF agree at $p_T > 70$ GeV
- NLO 4FNS describes data within uncertainties.









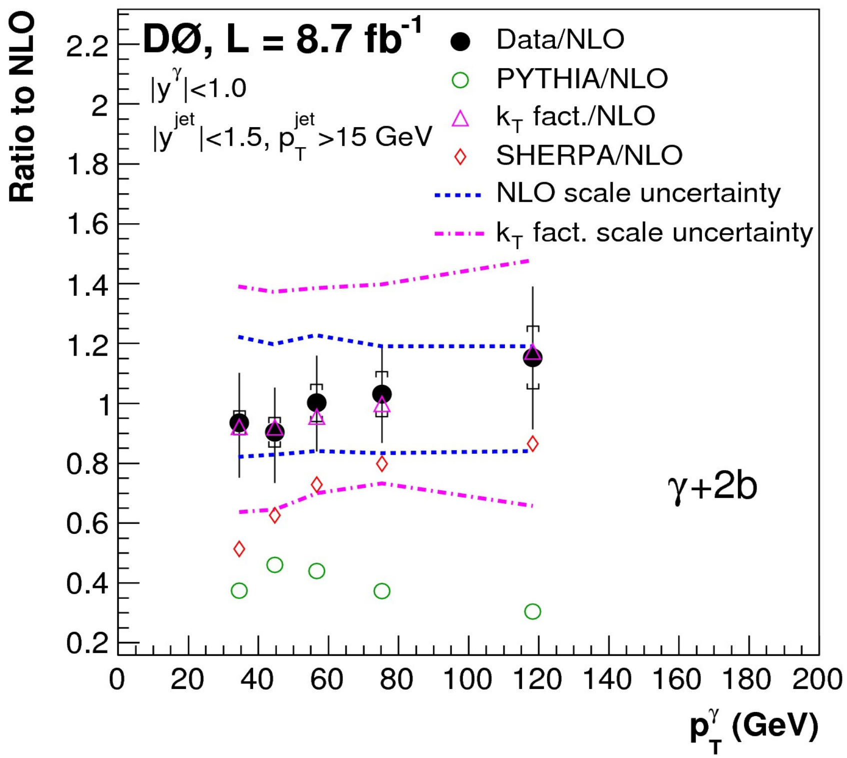


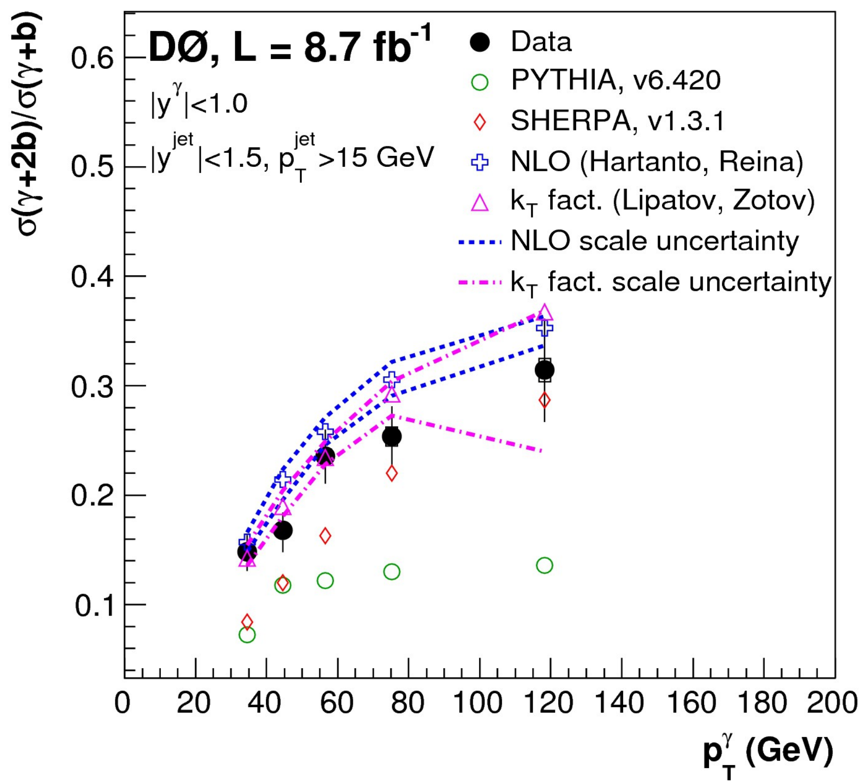
Tevatron: $q\bar{q} \to \gamma g\,(g \to b\bar{b})$ dominates at pT>80 GeV
LHC: $bg \to b\gamma$ dominates at most pT

Photon+bb

Submitted to PLB, arXiv:1405.3964

- Measurement of photon+2 b-jet differential cross section vs photon pT with b-jet pT>20 GeV, |y|<1.5
- Measurement of ratio $\sigma(\gamma bb)/\sigma(\gamma b)$





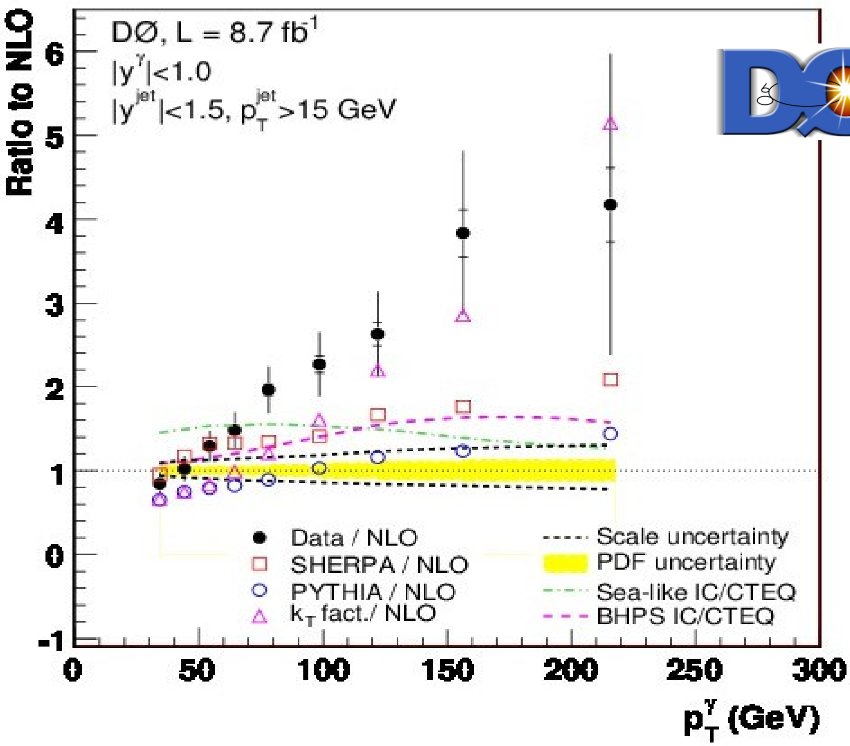
- Good agreement with NLO (4FNS) and kT factorization
- Sherpa underestimates the $\sigma(\gamma bb)/\sigma(\gamma b)$ ratio at low pT; Pythia is significantly lower.

Photon+c

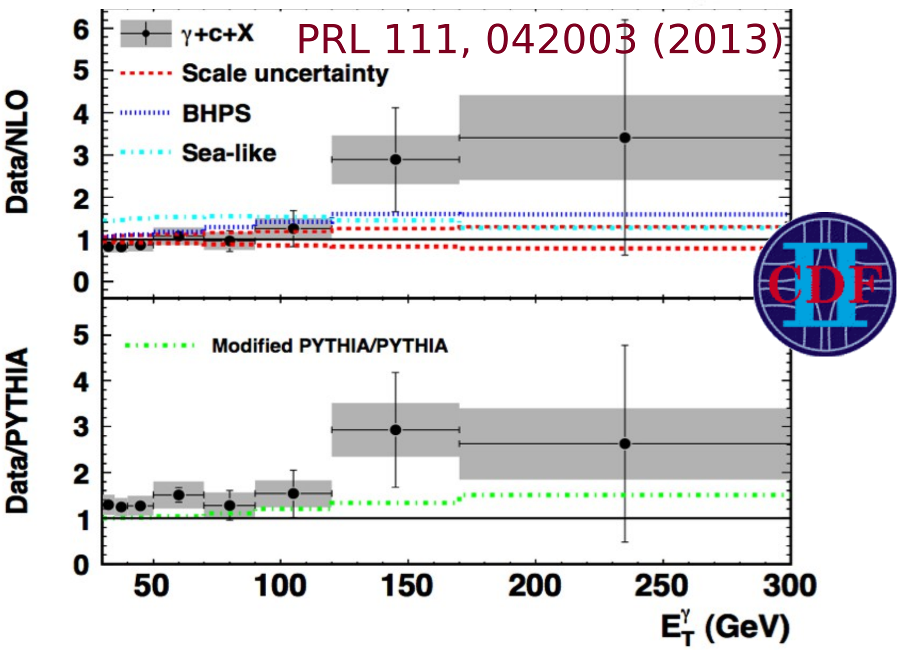
– Intrinsic charm models predict higher cross sections. BHPS model favored with rise in photon p_T.

– Pythia describes photon+c/photon+b ratio with increased g-->cc rate (annihilation process)

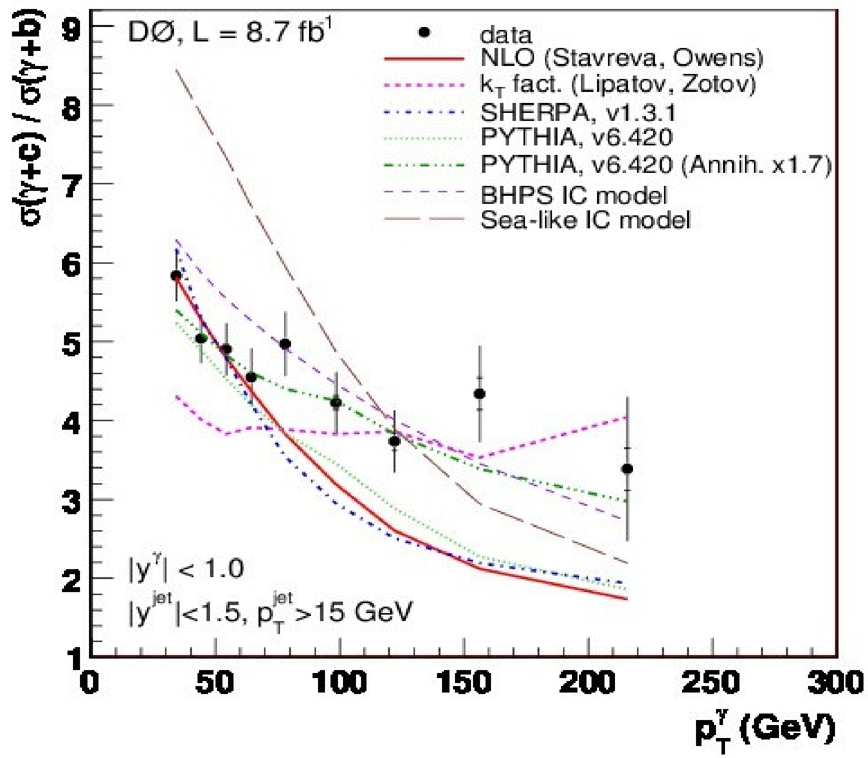
PLB 719, 354 (2013)

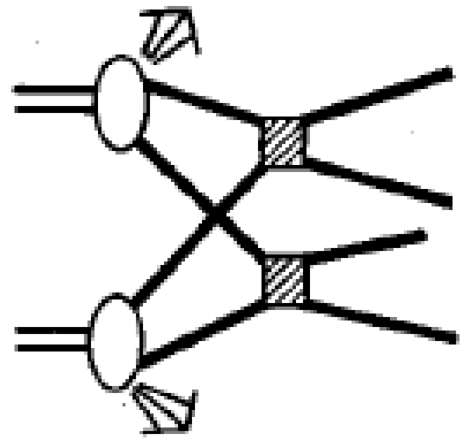


PRL 111, 042003 (2013)



PLB 719, 354 (2013)



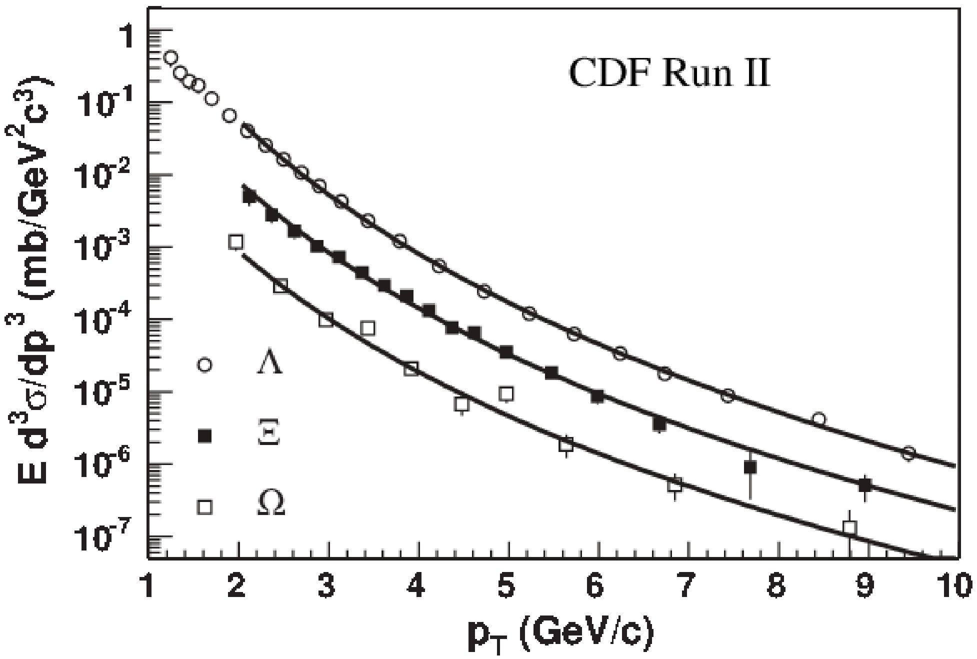


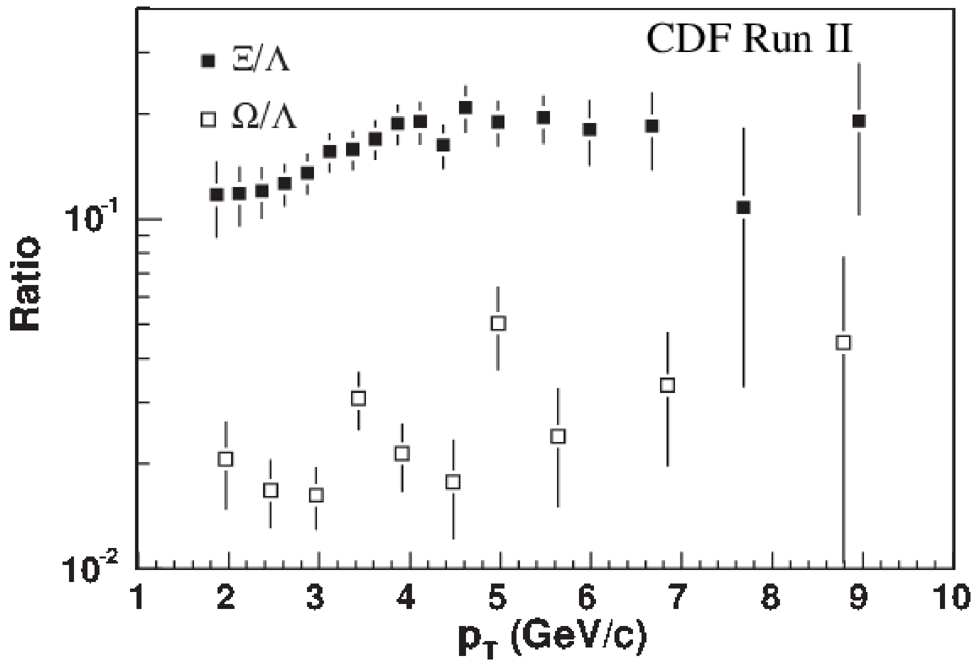
Soft physics

Phenomenological nucleon models

Strange particle production

– Strangeness production is used for refining phenomenological models and parameters of the Monte Carlo models.
– Enhanced production of the strange particle has been frequently suggested as a manifestation of the formation of quark-gluon plasma.
– Measured production cross section of Λ(uds), $\Xi^{\pm}$(.ss) and $\Omega^{\pm}$(sss)

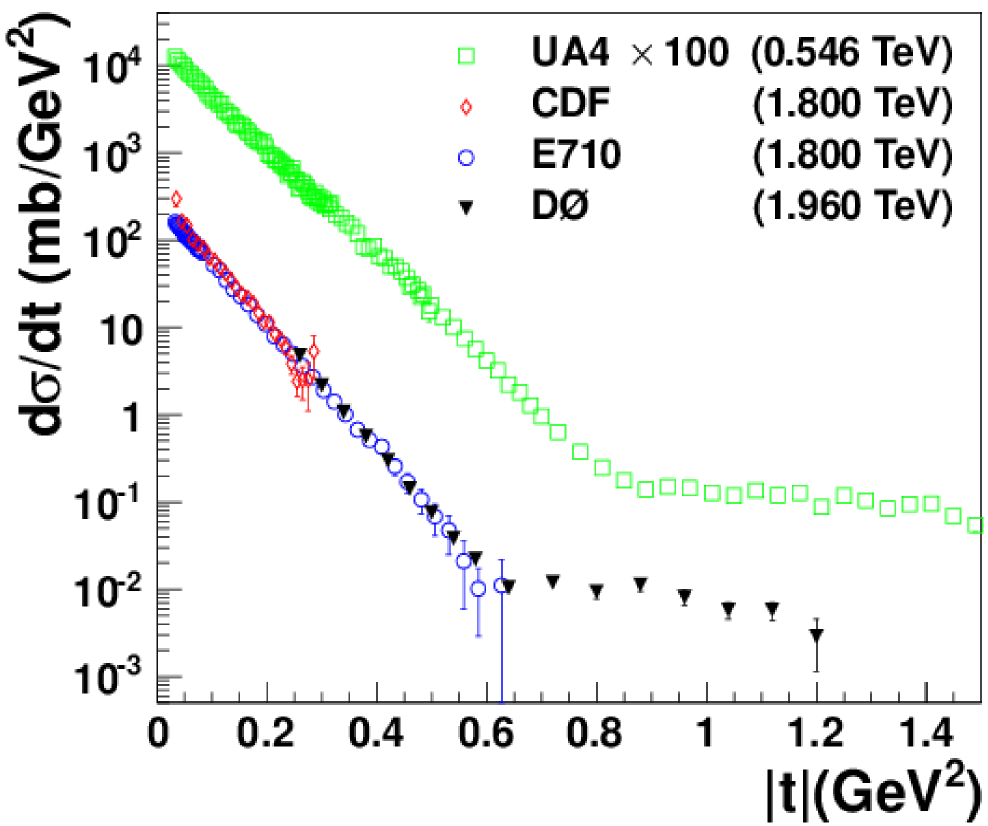


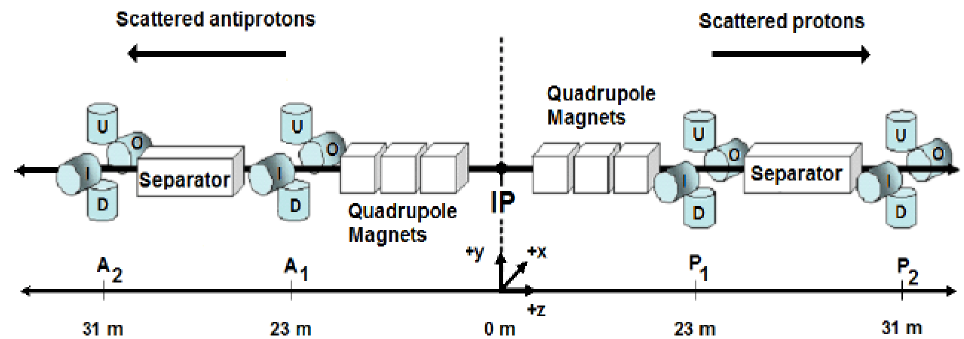


Cross sections depend on the number of strange quarks, however very similar pT slopes indicate an universality in particle production.

Elastic cross-section

- Measurement of dσ/d|t| for 0.25<|t|<1.2 GeV: information on nucleon structure and non-perturbative effects, tests of many phenomenological models.
- Previous measurements: UA4 (546), E710 (1800), CDF (1800)
- Uses a special run with one bunch of p+pbar.





$$d\sigma/dt = A\exp(-b|t|)$$

$$b = 16.86 \pm 0.10(stat) \pm 0.20(syst)$$

- Measured fundamental parameter ***b*** (tightly related with effective nucleon radius)
- The position of the dip is identified, $|t|=0.6$ GeV^2; TOTEM result: dip at $|t|=0.5$ GeV^2: diffractive minimum keeps moving to lower |t| values (UA4-->Tevatron-->LHC)

Exclusive di-photons

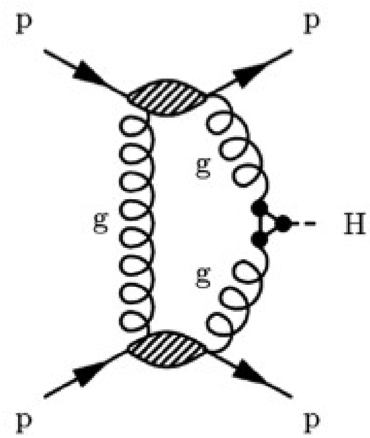
Search for exclusive $\gamma\gamma$ production via $p\bar{p} \to p + \gamma\gamma + \bar{p}$ and compare to theory

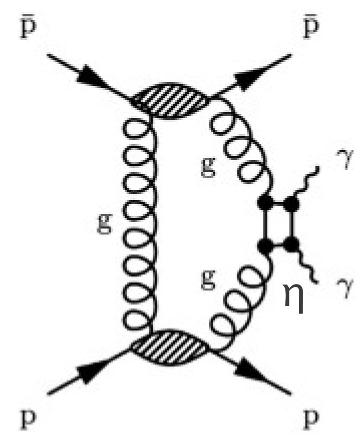
Motivation: instrinsically interesting QCD process;
tightly related with excl. Higgs boson production $p\bar{p} \to p + H + \bar{p}$

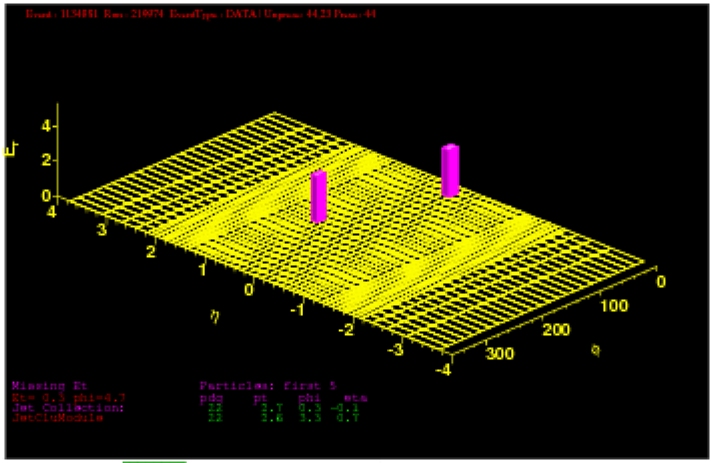
Features:
a) proton and antiproton emerge intact with no hadrons produced
b) .. have pT<1 GeV, having emitted a pair of gluons (in CS mode)

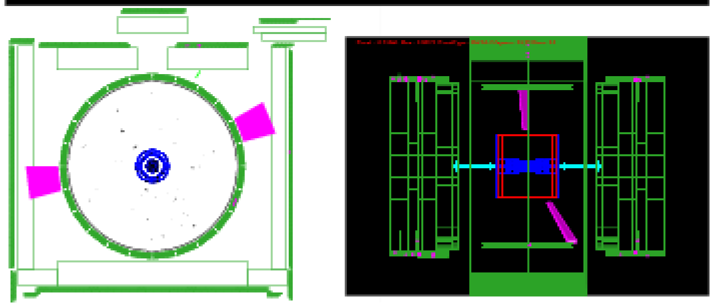
Event selection:
- two central photons with pT>2.5 GeV
- No other activity in the detector

Background: irreducible ($q\bar{q} \to \gamma\gamma$) <5%
reducible ($\pi^0\pi^0$, $\eta\eta$) are <16%

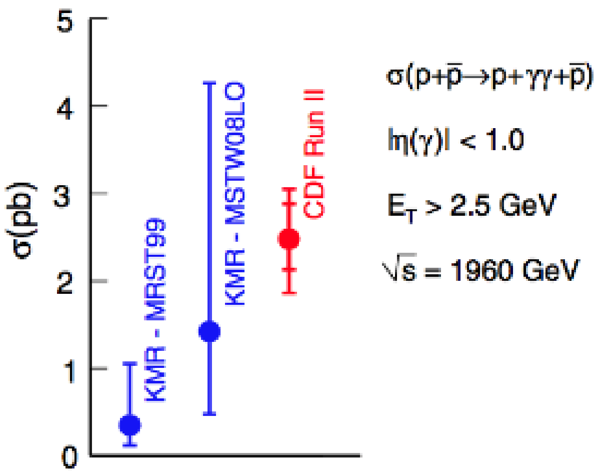








PRL 108, 081801 (2012)



Regge theory: diffractive scattering via pomeron exchange

Data: $2.48^{+0.40}_{-0.35}(stat)^{+0.40}_{-0.51}(syst)$

Good agreement with theory

Exclusive di-photons

Search for exclusive $\gamma\gamma$ production via $p\bar{p} \rightarrow p + \gamma\gamma + \bar{p}$ and compare to theory

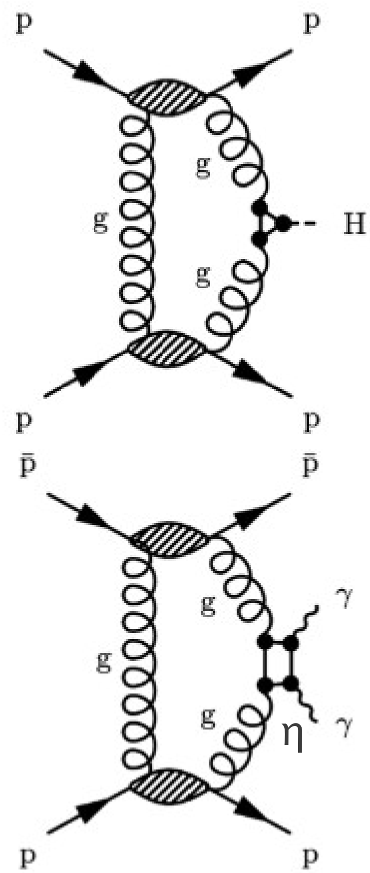
Motivation: instrinsically interesting QCD process;
tightly related with excl. Higgs boson production $p\bar{p} \rightarrow p + H + \bar{p}$

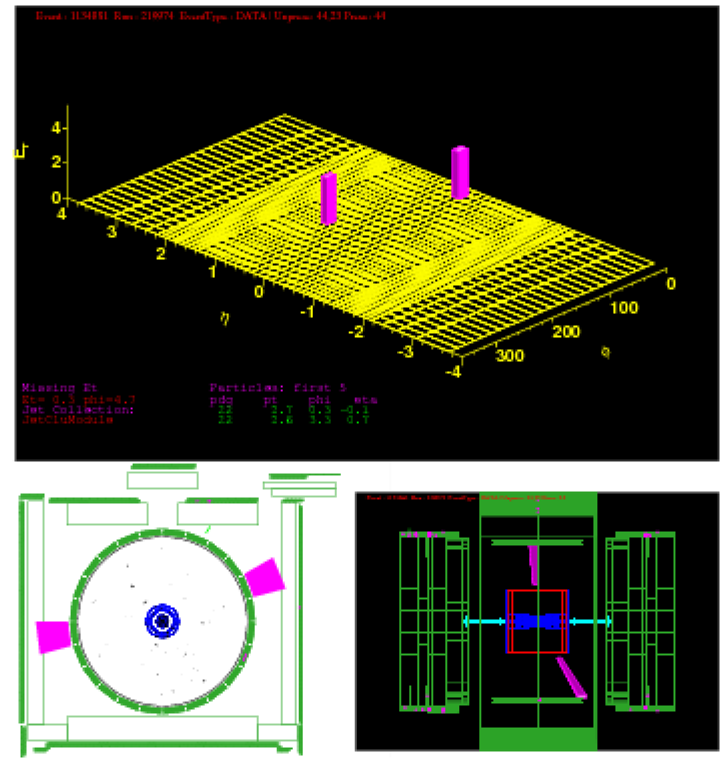
PRL 108, 081801 (2012)

Features:

a) proton and antiproton emerge intact with no hadrons produced

b) .. have pT<1 GeV, having emitted a pair of gluons (in CS mode)

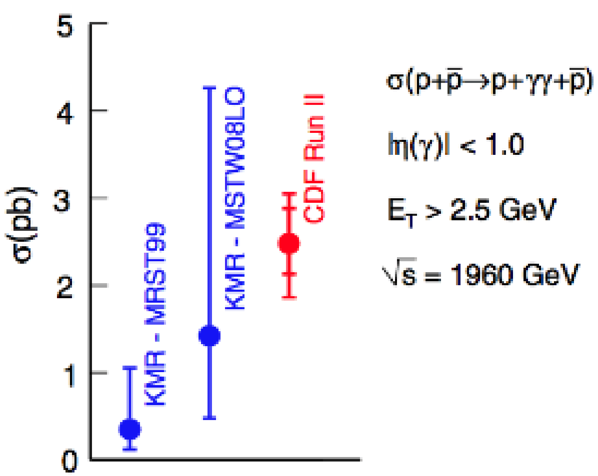




Event selection:

- two central photons with pT>2.5 GeV
- No other activity in the detector

Background: irreducible ($q\bar{q} \rightarrow \gamma\gamma$) <5%
reducible ($\pi^0\pi^0$, $\eta\eta$) are <x%



Other exclusive diffractive productions:

dijets, D0: PLB 705, 193 (2011)

dijets, CDF: PRD 86, 032009 (2012)

W/Z, CDF: PRD82, 112004 (2010)

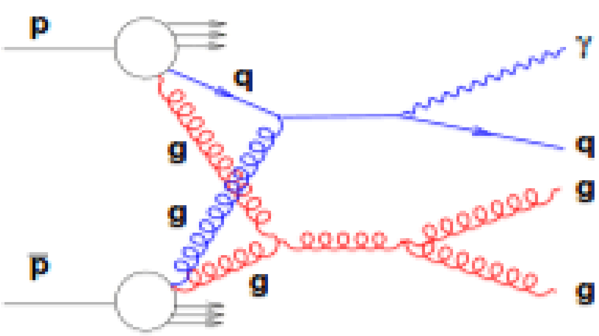
Charmonium, CDF: PRL, 102, 242001 (2009)

e+e-, CDF: PRL 98, 112001 (2007)

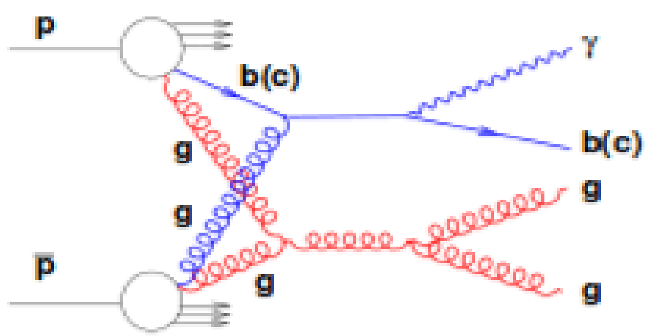
Double parton scattering: Photon+HF+dijet

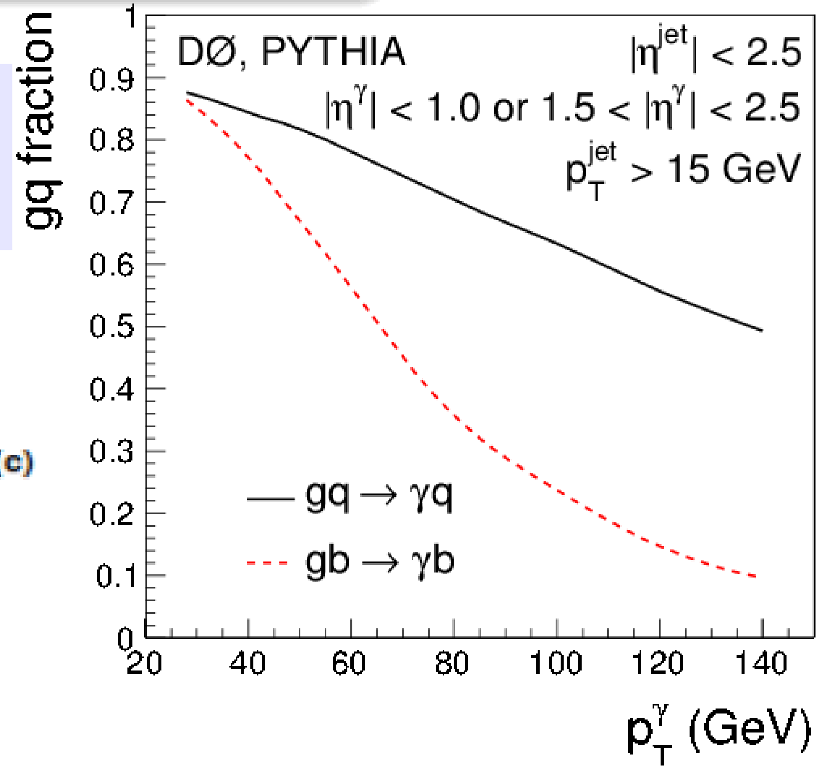
- Photon: $p_T^{\gamma} > 26$ GeV, $|\eta| < 1.0$ or $1.5 < |\eta| < 2.5$
- At least 3 jets with $p_T^{jet} > 15$ GeV and $|\eta| < 2.5$
  $15 < p_T^{jet2} < 35$ GeV
- Topology: $\Delta R(\gamma, jet) > 0.7$, $\Delta R(jet, jet) > 1.0$

Case 1: No leading jet flavor requirement (Inclusive sampe)



Case 2: Leading jet Heavy flavor requirement (HF sample)





Check dependence on initial parton flavor!

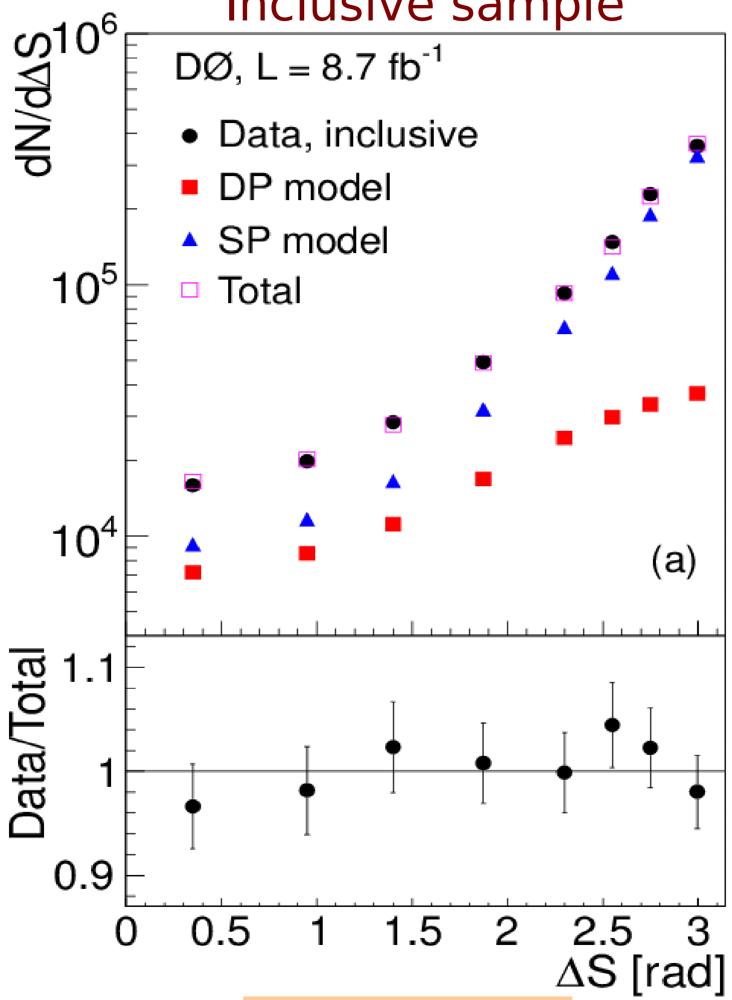
$$\sigma_{DP} = \sigma_A \sigma_B / \sigma_{eff}$$

Data Sample	1Vtx	2Vtx
inclusive	218686	269445
HF	5004	5811

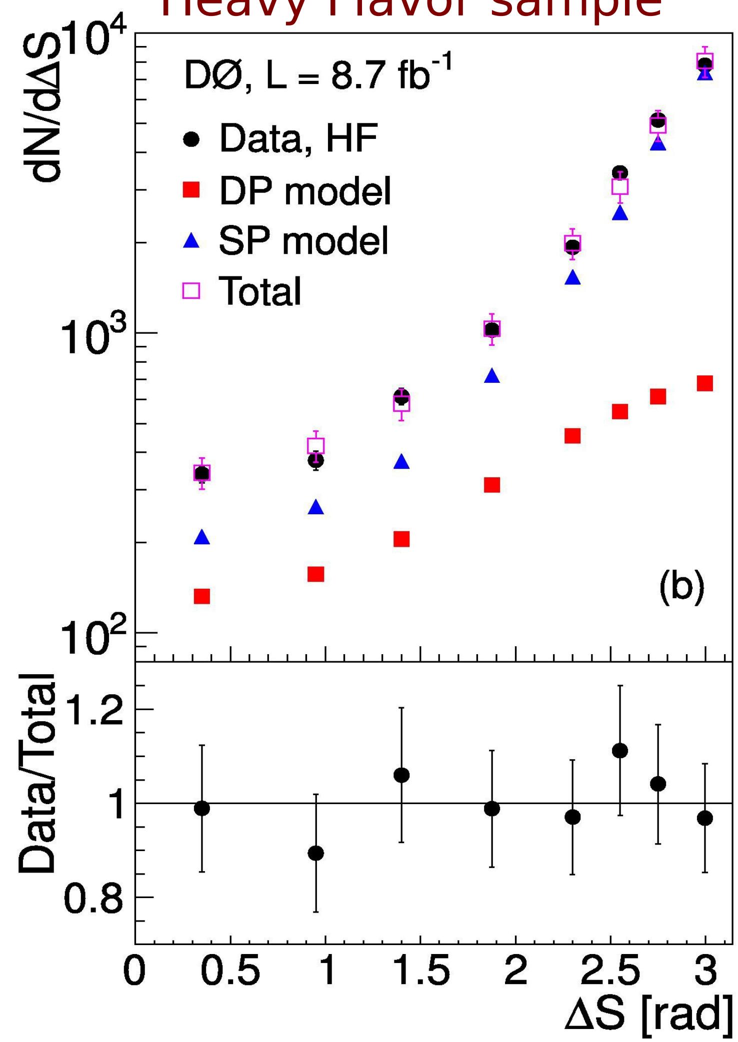
Fractions of Double Parton events

DP event fraction is found by maximul likelihood fitting Single Parton event model (Sherpa) and Double Parton signal event model (MixDP) to data.

Inclusive sample



Heavy Flavor sample



DP fractions

γ+HF+dijet	γ+3 jet
0.171 ± 0.020	0.202 ± 0.007

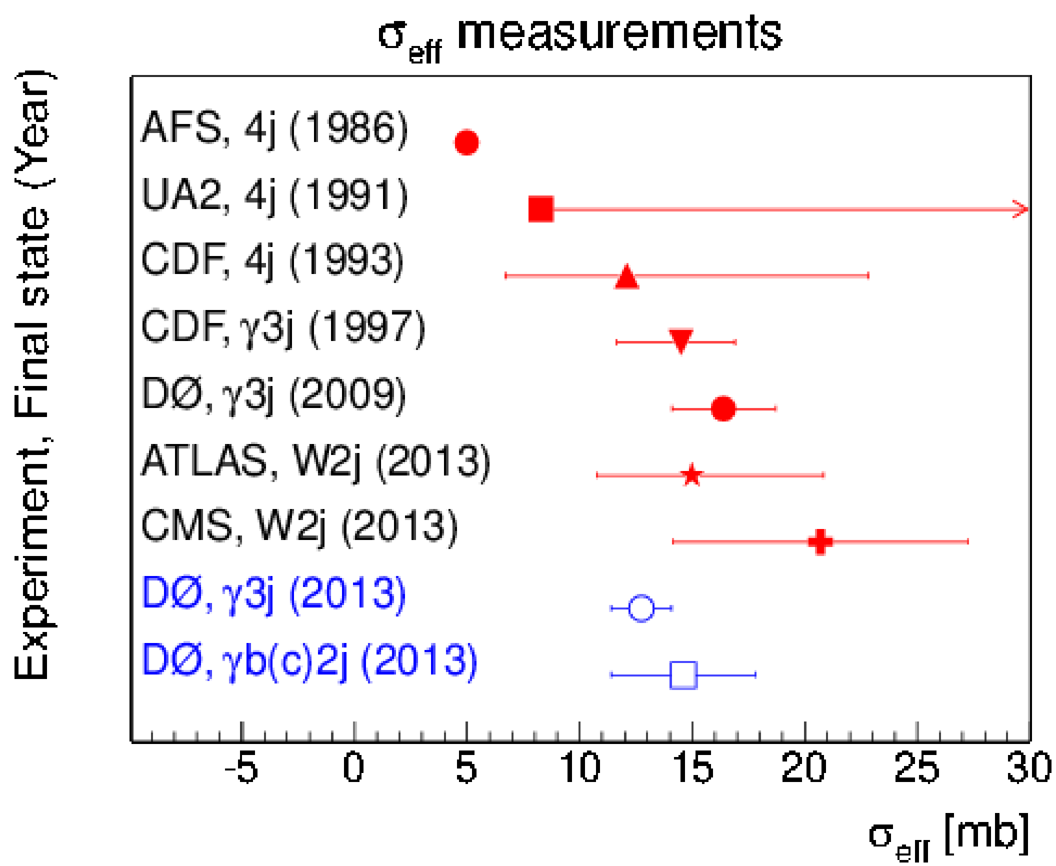
Effective cross section

Phys.Rev.D89, 072006 (2014), arXiv:1402.1550

- Having measured number of DP events and corresponding acceptances and efficiencies one can calculate $\boldsymbol{\sigma_{eff}}$ for both final states.

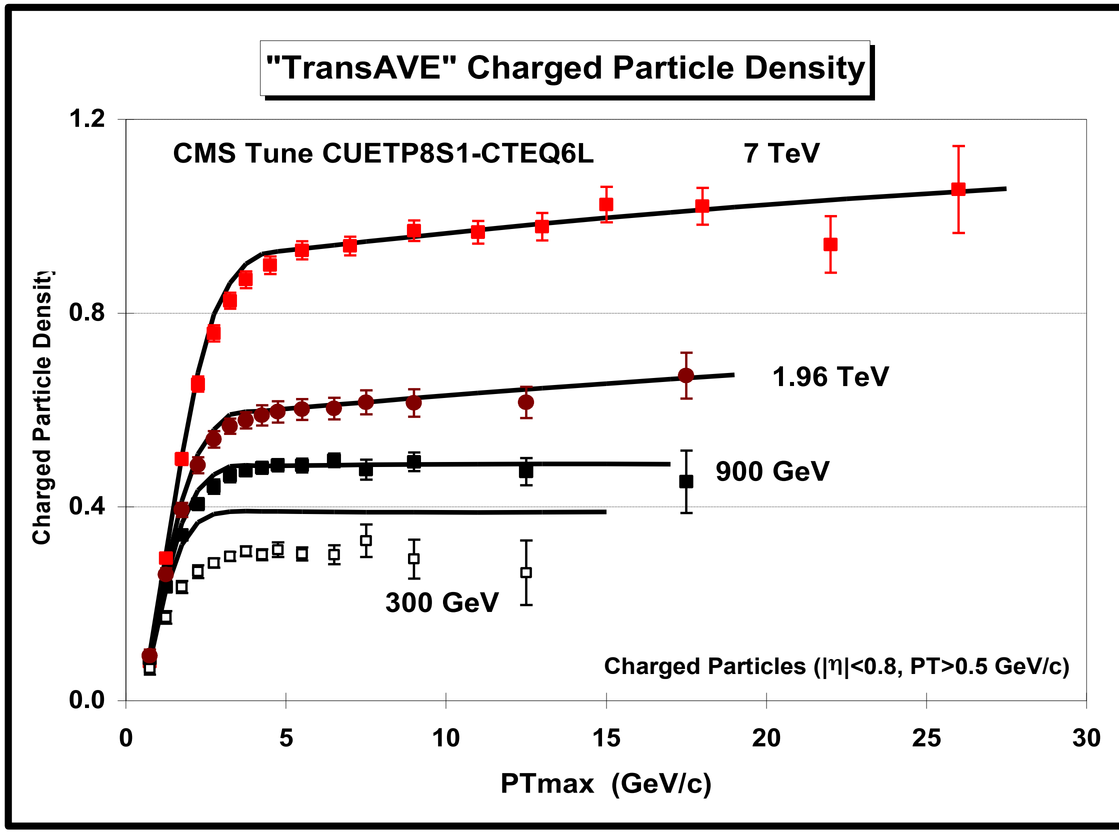
- Measured σ_{eff} is in agreement with all Tevatron and LHC measurements, but the new values is more precise.

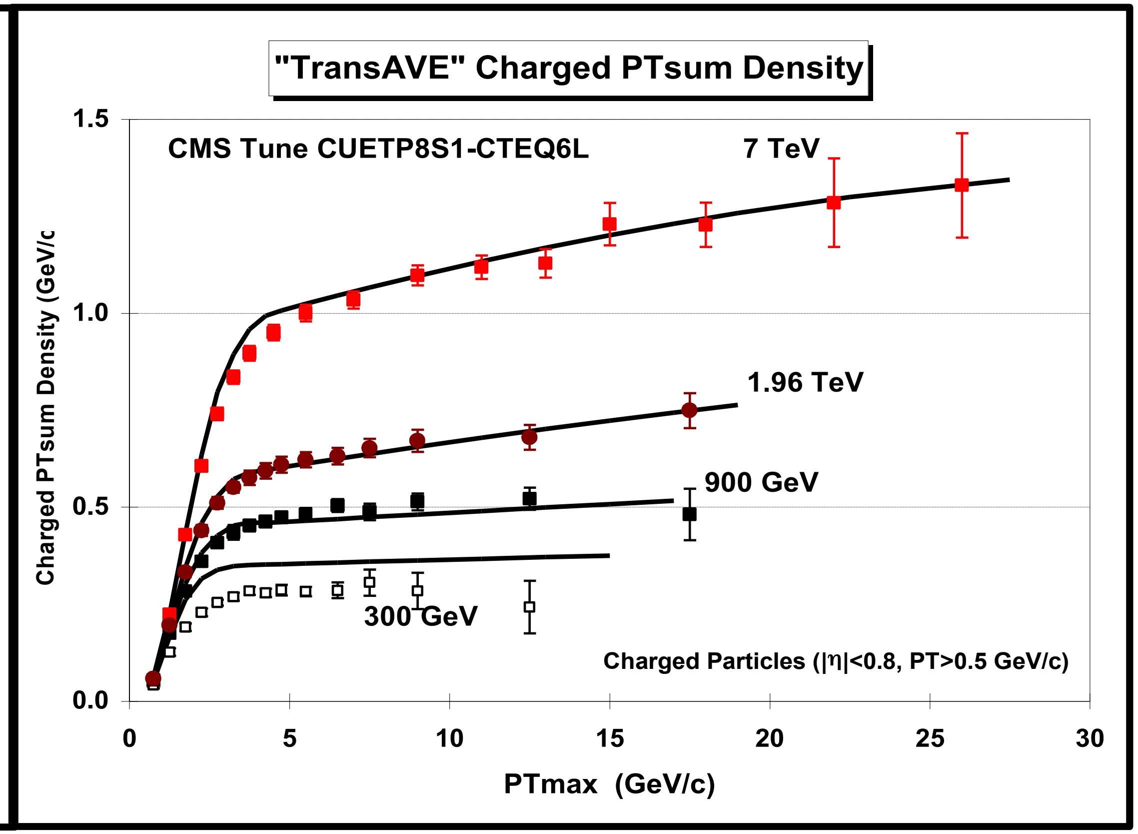
- No dependence of $\boldsymbol{\sigma_{eff}}$ on initial quark flavor has been observed.



Final state	γ+HF+dijet	γ+3 jet
$\sigma_{eff}\,(mb)$	14.6 ± 3.26	12.7 ± 1.32

“Tevatron” to the LHC





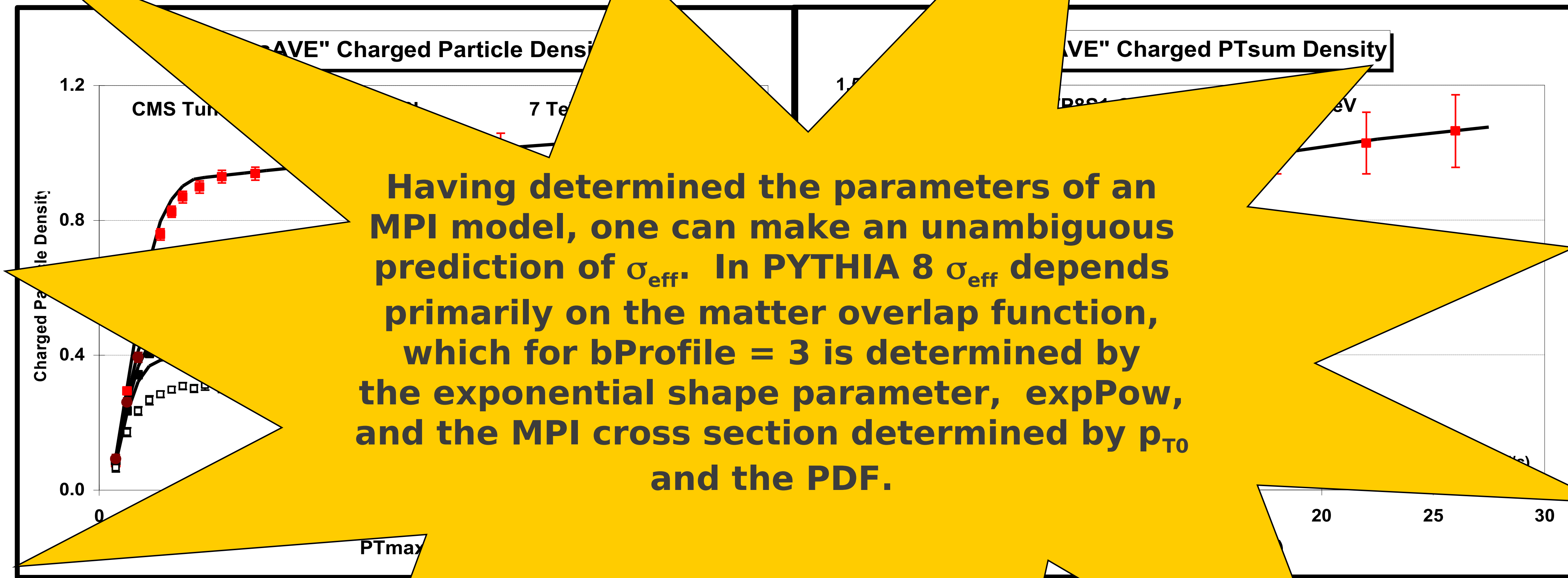
- Shows the “transAVE” **charged particle density** as defined by the leading charged particle, PTmax, as a function of PTmax at sqrt(s)=300 GeV, 900 GeV, 1.96 TeV, and 7 TeV compared with the CMS PYTHIA 8 tune CUETP8S1-CTEQ6L.

➔ Shows the “transAVE” **charged PTsum density** as defined by the leading charged particle, PTmax, as a function of PTmax at sqrt(s)=300 GeV, 900 GeV, 1.96 TeV, and 7 TeV compared with the CMS PYTHIA 8 tune CUETP8S1-CTEQ6L.

What we are learning should allow for a deeper understanding of MPI which will result in more precise predictions at the future LHC energies of 13 & 14 TeV

from R.Field's talk at LHCP'14

"Tevatron" to the LHC

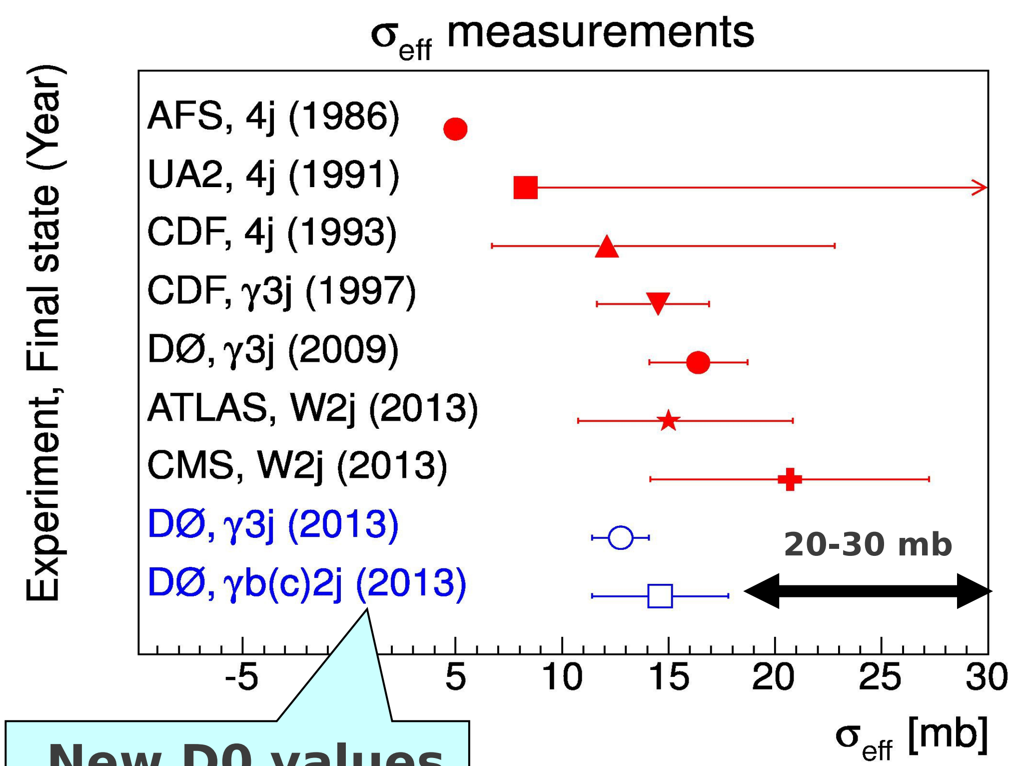


Having determined the parameters of an MPI model, one can make an unambiguous prediction of σ_{eff}. In PYTHIA 8 σ_{eff} depends primarily on the matter overlap function, which for bProfile = 3 is determined by the exponential shape parameter, expPow, and the MPI cross section determined by p_{T0} and the PDF.

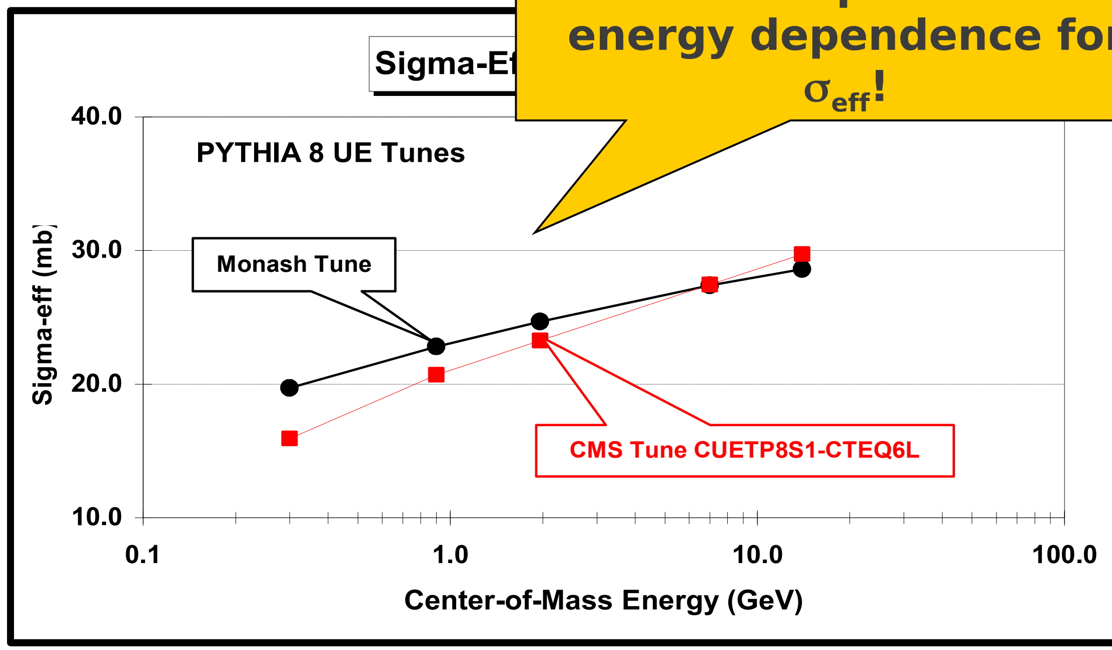
- Shows the "transAVE" … as defined by the lea… charged … PTmax, as a functio… PTmax at 3… 900 GeV, 1.96 TeV, and 7 TeV compare… e CMS PYTHIA 8 tune CUETP8S1-CTEQ…
- …ansAVE … PTsum density as … e leading ch… particle, PTmax, as … of PTmax at 30… V, 900 GeV, 1.96 TeV, … eV compared with th… CMS PYTHIA 8 tune C… 8S1-CTEQ6L.

What we are learning should allow for a deeper understanding of MPI which will result in more precise predictions at the future LHC energies of 13 & 14 TeV

Sigma-Effective



New D0 values

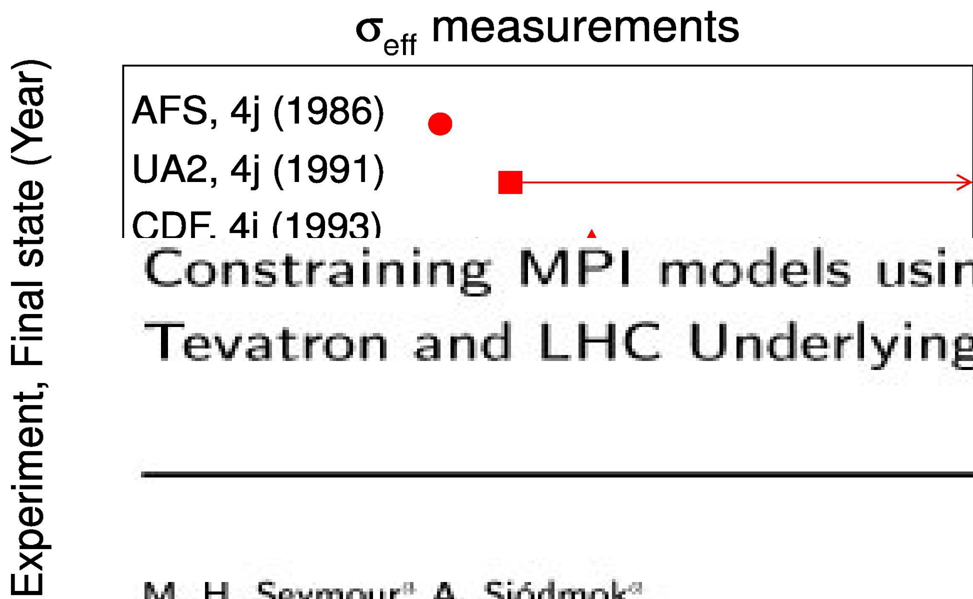


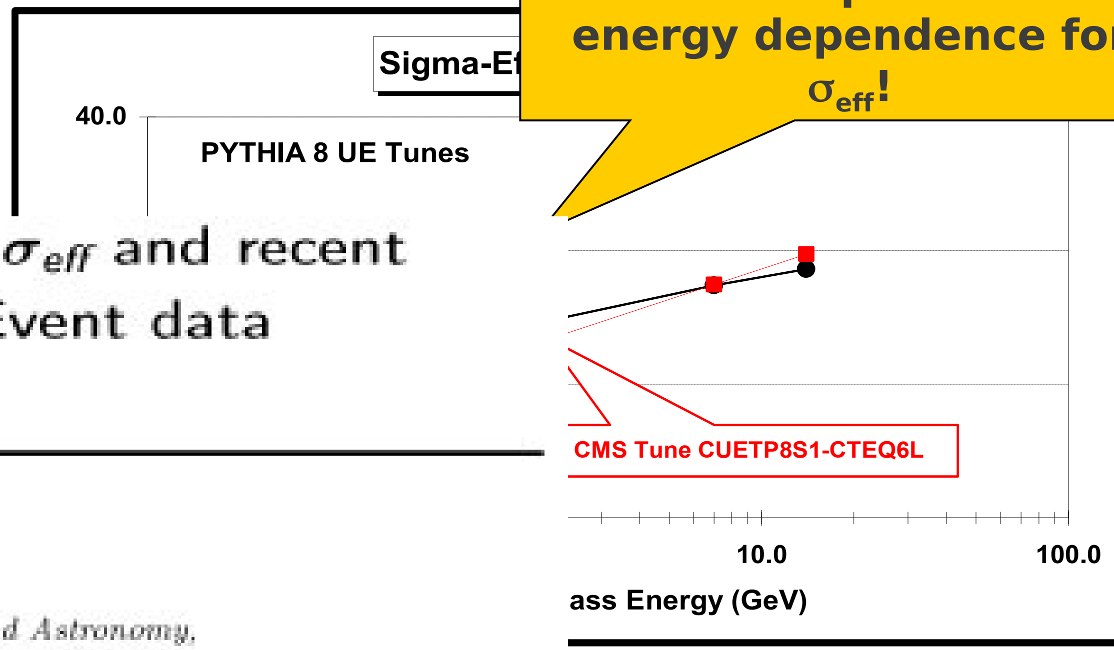
PYTHIA 8 predicts an energy dependence for σ_{eff}!

- Shows the σ_{eff} values calculated from the PYTHIA 8 Monash and CMS tune CUETP8S1-CTEQ6L.

The σ_{eff} predicted from the PYTHIA 8 UE tunes is slightly larger than the direct measurements!

Sigma-Effective





PYTHIA 8 predicts an energy dependence for σ_{eff}!

Constraining MPI models using σ_{eff} and recent Tevatron and LHC Underlying Event data

M. H. Seymour[a] A. Siódmok[a]

[a] *Consortium for Fundamental Physics, School of Physics and Astronomy, The University of Manchester, Manchester, M13 9PL, U.K.*

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Abstract: We review the modelling of multiple interactions in the event generator Herwig++ and study implications of recent tuning efforts to Tevatron and LHC data. It is often said that measurements of the effective cross section for double-parton scattering, σ_{eff}, are in contradiction with models of the final state of multi-parton interactions, but we show that the Herwig++ model is consistent with both and gives stable predictions for underlying event observables at 14 TeV.

Ne

; calculated from the
d CMS tune CUETP8S1-

T

Summary

- Good consistency and complementarity for most of experimental data

- Current level of understanding jet ID, systematics and jet energy scale leads in many cases to experimental uncertainties similar or lower than theoretical uncertainties.

- Jet results: Precision measurement of fundamental observables.
  => sensitivity to PDF sets, strongest constraint on gluon PDF, extraction of α_s and test of its running up to 400 GeV, detailed studies of the effect of different jet algorithms, study of jet substructure, limits on many NP models.

- Z/W results: extensive tests of pQCD and MC models; in most cases, a triumph of NLO and ME-PS MC predictions.

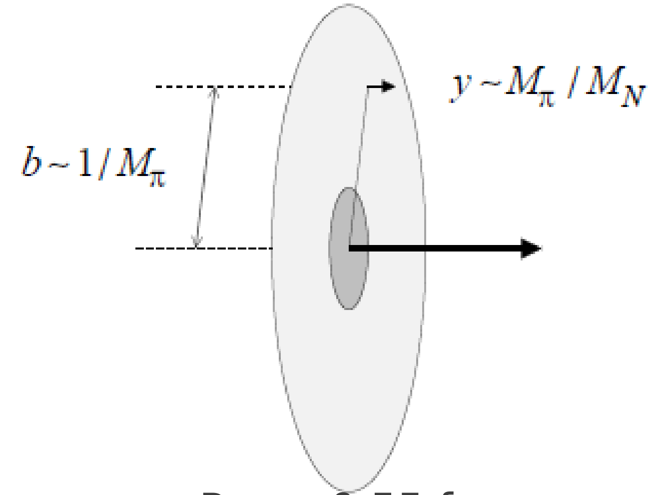
- Photon results: test of fixed order NLO, resummation, fragmentation. Theory should be better understood. First NNLO results look very promising.

- UE/DP events: improving phenomenological models, good knowledge is required in multijet studies/searches.

BACK-UP SLIDES

Pion cloud model

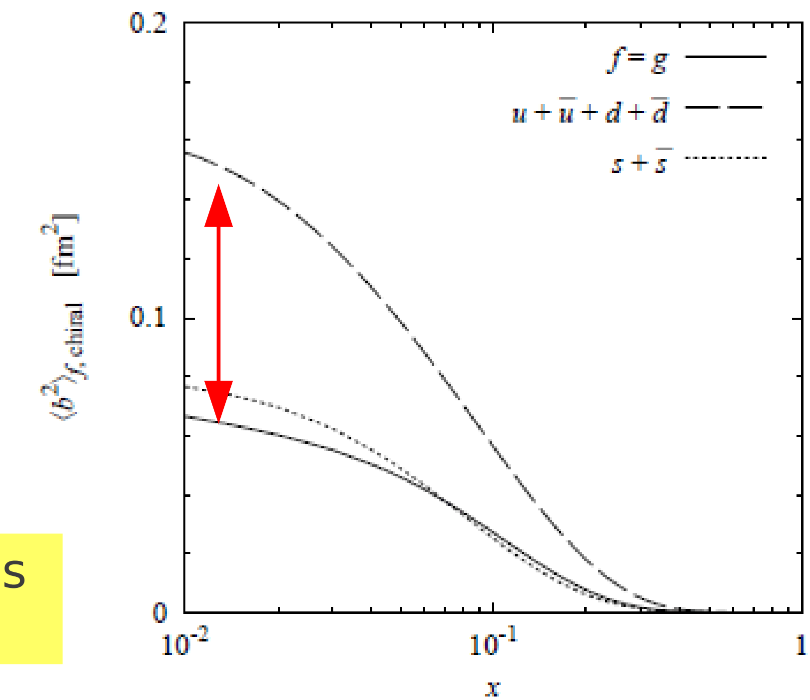
– For details please see e.g. PRD80:114029,2009, PRD83:054012,2
– In this model, there can be interactions of gluons and quarks in the proton "core" with soft pions in the "cloud". The "bare" parton can make transition to a virtual state containing a pion, $p \to n\pi^+$ (more likely), $p \to \Delta^{++}\pi^-$. (excess of π^+ vs π^-, => |dbar-ubar|>0 for the "sea" quarks). The pion is a "slow parton", with a momentum $y = M_\pi/M_p$



$R_{core} \approx 0.55$ fm
$\langle b^2 \rangle_{core} \approx 0.3\ \mathrm{fm}^2$

Due to these interactions, u and d quarks size grows more rapidly than gluonic radius

$$\langle b^2 \rangle_f = \frac{\int d^2b\, b^2\ [f(x,b)_{\rm core} + \Theta(b > b_0)\, f(x,b)_{\rm chiral}]}{f(x)}$$
$$\equiv \langle b^2 \rangle_{f,\,\rm core} + \langle b^2 \rangle_{f,\,\rm chiral}. \qquad (56)$$



In numbers, for x ~ 0.01, we get about 30% larger $\langle b^2 \rangle_{q+qbar}$ than $\langle b^2 \rangle_g$

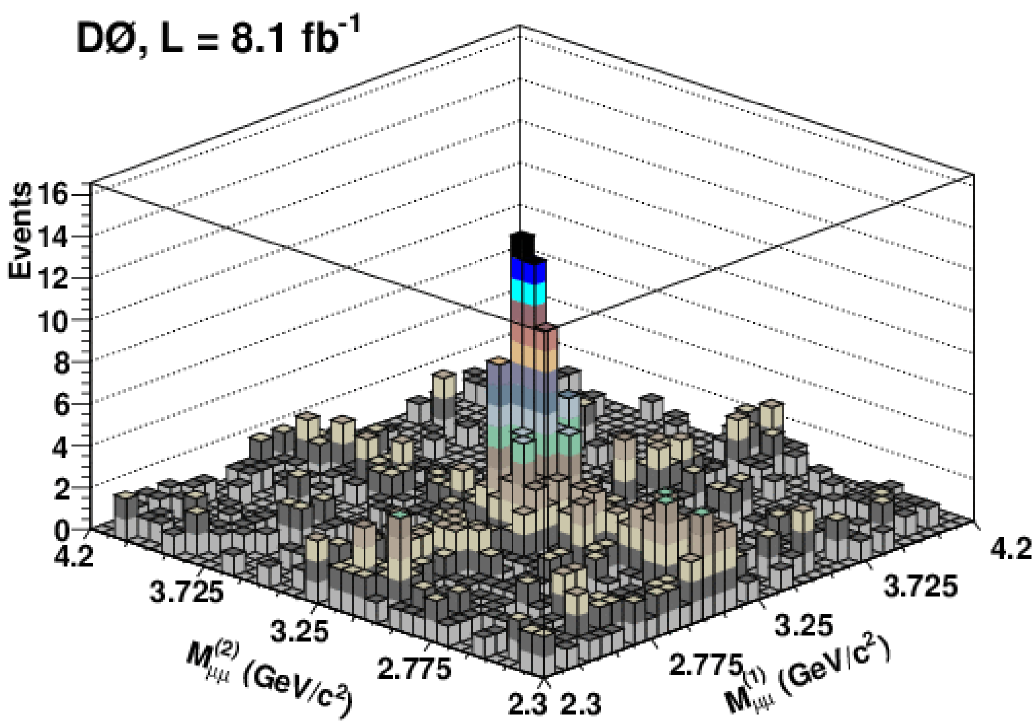
Assumption made: transverse sizes of quarks and gluons in the core are the same (is it true?).

Double J/psi production

- Dominant production channel: gg → J/ψ J/ψ
- Signal: prompt direct J/ψ (S-wave) and (P-waves) χ_{1c} and χ_{2c}, $\chi_{1(2)c}$ → J/ψ+γ
- Background: non-prompt B-hadron decays, non-resonant DY, π/K decays.
- Single and Double parton scatterings may contribute

  => Test of σ_{eff} energy dependence: from high energies to 4-5 GeV, with gg initial state only

Prediction for the Tevatron at pT(J/ψ)>4 GeV, |η|<0.6: expected DP fraction is ~15%



p J/ψ

SP

$\bar{p}$ J/ψ

p J/ψ

DP

$\bar{p}$ J/ψ

Single Parton and Double Parton contributions

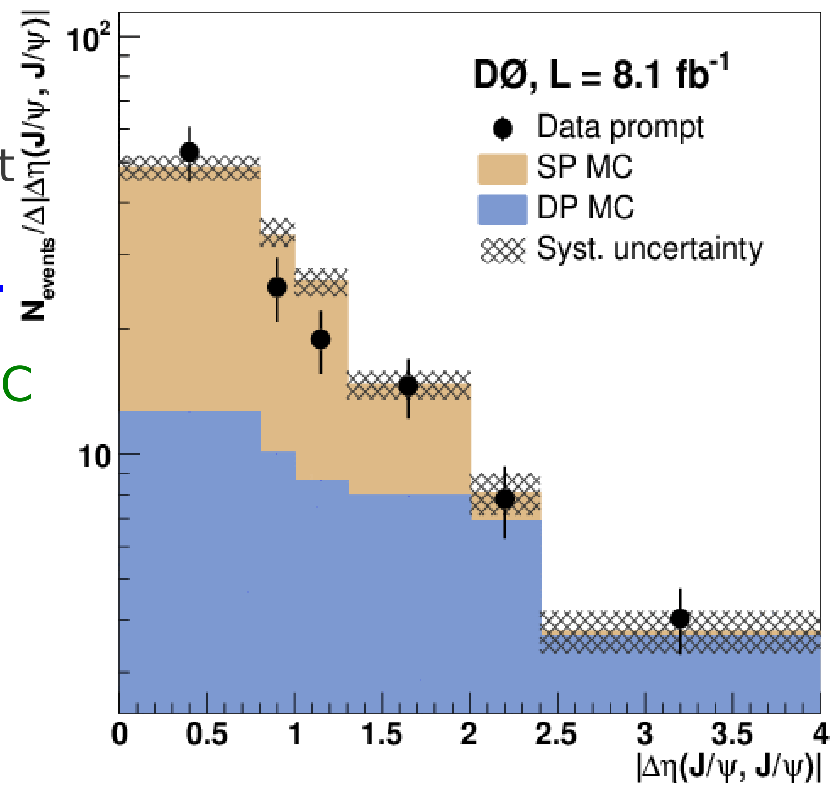
– We measure the Double J/ψ production cross section for Double Parton and Single Parton scatterings separately. To discriminate between the two mechanisms, we use $\triangle\eta(J/\psi, J/\psi)$ difference.

DP dominates at $|\triangle\eta(J/\psi\ J/\psi)| > 2$

– Contributions from double non-prompt, prompt+non-prompt and accidental backgrounds are subtracted from data
=> data should contain just prompt SP and DP events.

SP template: DJ events simulated with Herwig++ /DJPsiFDC
DP template: Pythia-8 or data-like DP model.

Systematics: fit and variation between the 2+2 models; prompt+non-prompt origin (either 100% SP- or DP-like). DP double non-prompt is highly suppressed to 0.7–2 fb.



$$\sigma_{eff} = \frac{\sigma(J/\psi)^2}{\sigma(J/\psi\, J/\psi)}$$

$f_{SP} = 0.70 \pm 0.11$, $f_{DP} = 0.30 \pm 0.10$

$$\sigma_{eff} = 5.0 \pm 0.5(stat) \pm 2.7(syst)\ fb$$

Pion cloud model: GPD and experiment

In GPD formalism, the transverse quark/gluon sizes are related to the corresp. GPD:

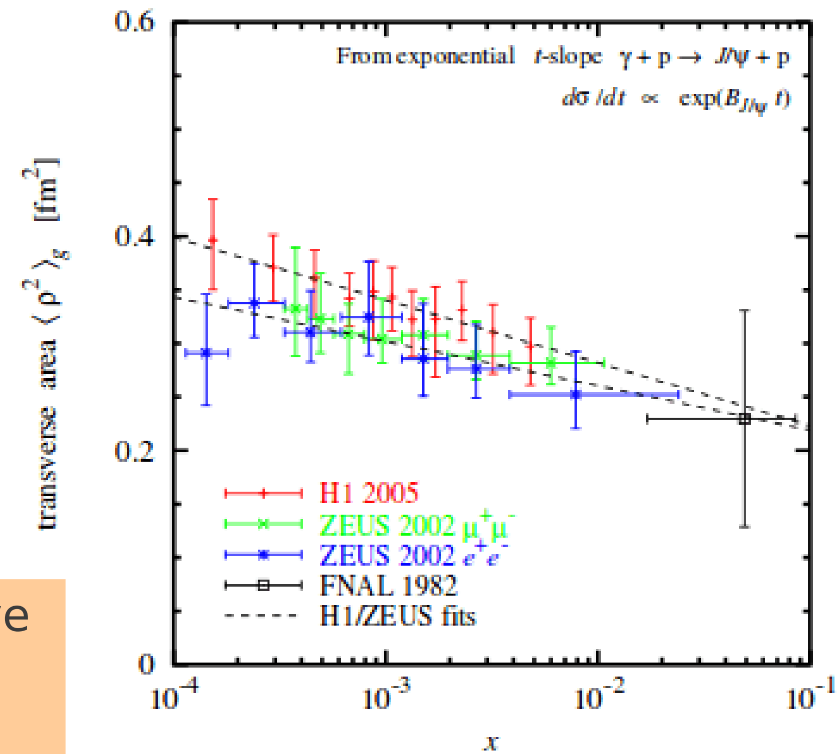
GPD

$$\langle b^2 \rangle_f(x) \equiv \frac{\int d^2b\, b^2\, f(x,b)}{f(x)} \qquad (f = q, \bar{q}, g)$$

$$\langle b^2 \rangle_g = 4 \frac{\partial}{\partial t} \left[\frac{d\sigma/dt\,(t)}{d\sigma/dt\,(0)} \right]^{1/2}_{t=0} \qquad (d\sigma/dt)^{\gamma N \to J/\psi + N} \propto \exp(B_{J/\psi} t)$$

$$\langle b^2 \rangle_g = 2 B_{J/\psi}$$

J/ψ photoproduction



t-dependence of J/ψ photoproduction cross section is sensitive to the transverse gluon size. H1, ZEUS data:
$B_{J/\psi} \approx 4.1 – 4.6\ \mathrm{GeV}^{-2}$ or $\langle b^2 \rangle_g = 0.32\text{-}0.35\ \mathrm{fm}^2$

t-dependence of deeply-vertual Compton scattering cross section is sensitive to the transverse quark size. H1 data:
$B_\gamma \approx 5.2 – 5.8\ \mathrm{GeV}^{-2}$ or $\langle b^2 \rangle_{q+\bar{q}} = 0.42\text{-}0.46\ \mathrm{fm}^2$

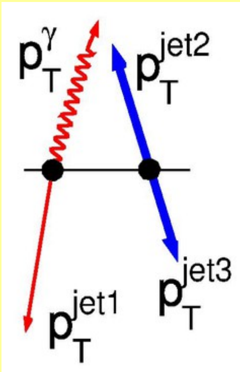
See PRD80:114029,2009, C.Weiss, DIS2011.

Measurement of σ_{eff}

Same approach as in $1fb^{-1}$ measurement, PRD81, 052012 (2010)

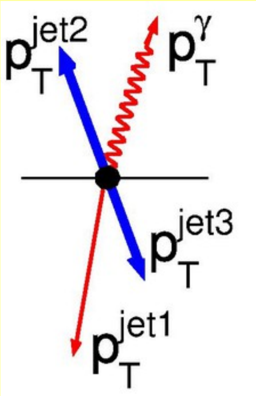
For two hard scattering events at two separate $p\bar{p}$ collisions:

$$P_{DI} = 2\left(\frac{\sigma^{\gamma j}}{\sigma_{hard}}\right)\left(\frac{\sigma^{jj}}{\sigma_{hard}}\right)$$



The number of Double Interaction events:

$$N_{DI} = 2\frac{\sigma^{\gamma j}}{\sigma_{hard}}\frac{\sigma^{jj}}{\sigma_{hard}} N_C(2) A_{DI}\,\epsilon_{DI}\,\epsilon_{2vtx}$$



For two hard interactions: at one $p\bar{p}$ collision:

$$P_{DP} = \left(\frac{\sigma^{\gamma j}}{\sigma_{hard}}\right)\left(\frac{\sigma^{jj}}{\sigma_{eff}}\right)$$

Then the number of Double Parton events:

$$N_{DP} = \frac{\sigma^{\gamma j}}{\sigma_{hard}}\frac{\sigma^{jj}}{\sigma_{eff}} N_C(1) A_{DP}\,\epsilon_{DP}\,\epsilon_{1vtx}$$

Therefore from N_{DP}/N_{DI} ratio one can extract:

$$\sigma_{eff} = \frac{N_{DI}}{N_{DP}}\frac{N_C(1)}{2N_C(2)}\frac{A_{DP}}{A_{DI}}\frac{\epsilon_{DP}}{\epsilon_{DI}}\frac{\epsilon_{1vtx}}{\epsilon_{2vtx}}\sigma_{hard}$$

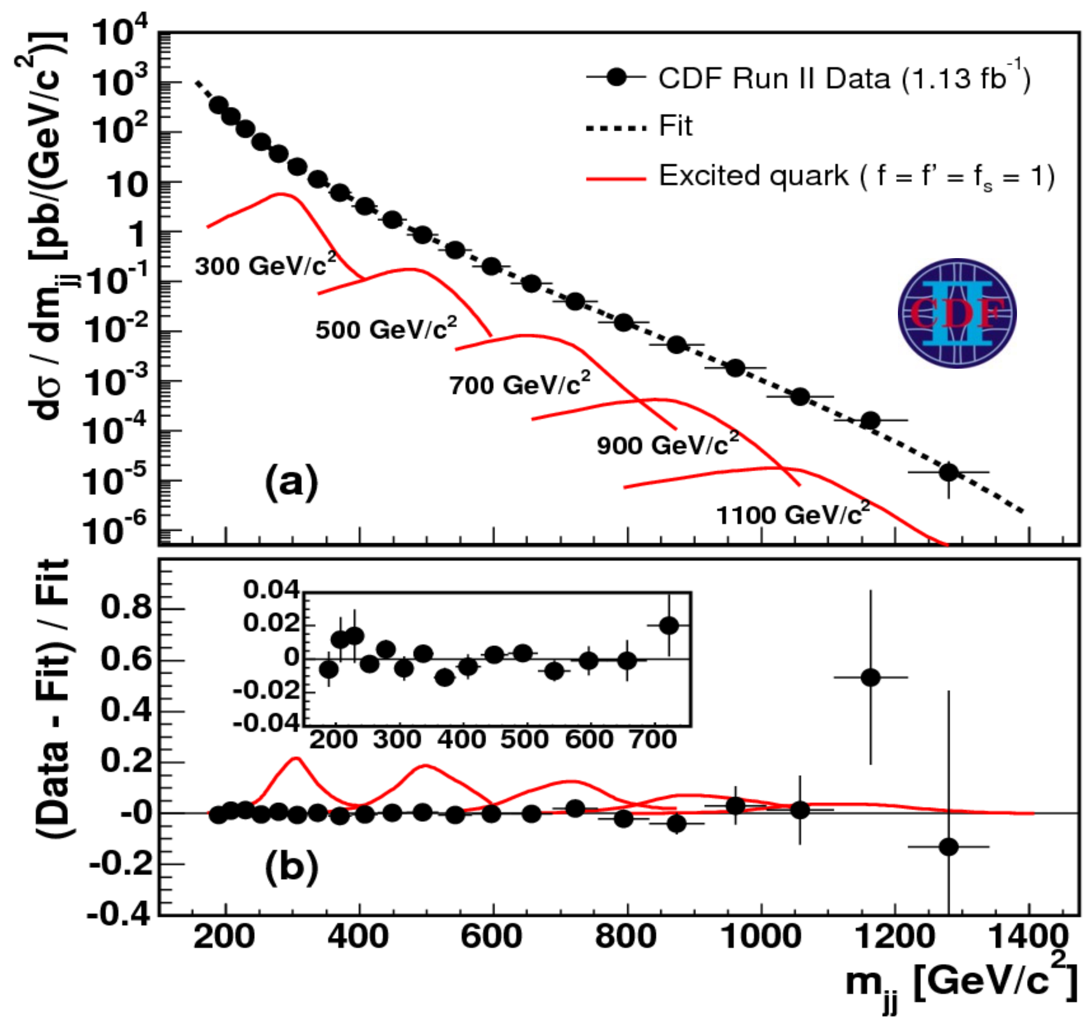
=> Data-driven method
=> reduces dependence on Monte-Carlo and NLO QCD theory predictions.

Dijet mass: searches for new physics

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

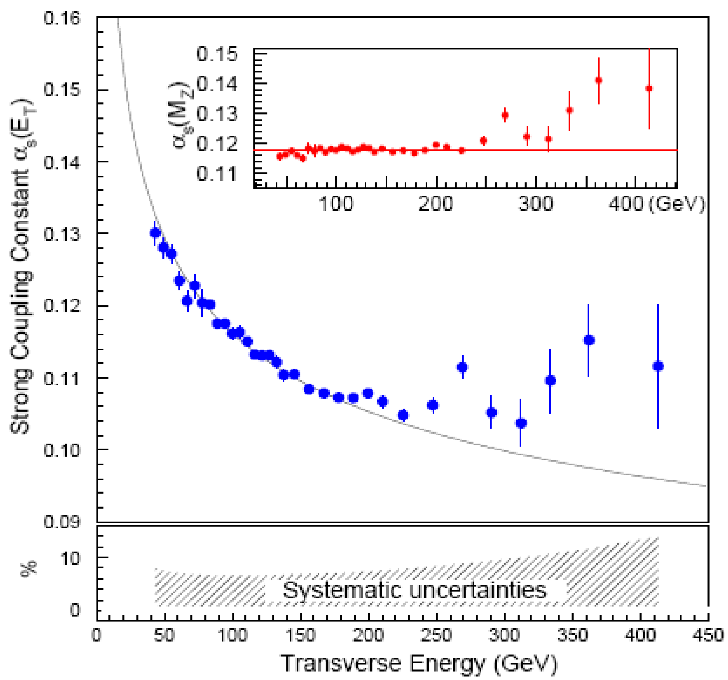


Observed mass exclusion range	Model description
260-870 GeV/c²	Excited quark → qg ($f=f'=f_s=1$)
260-1100 GeV/c²	ρ_{T8} techni-rho
260-1250 GeV/c²	Axigluon/coloron
290-630 GeV/c²	E_6 diquark
280-840 GeV/c²	W' (SM couplings)
320-740 GeV/c²	Z' (SM couplings)

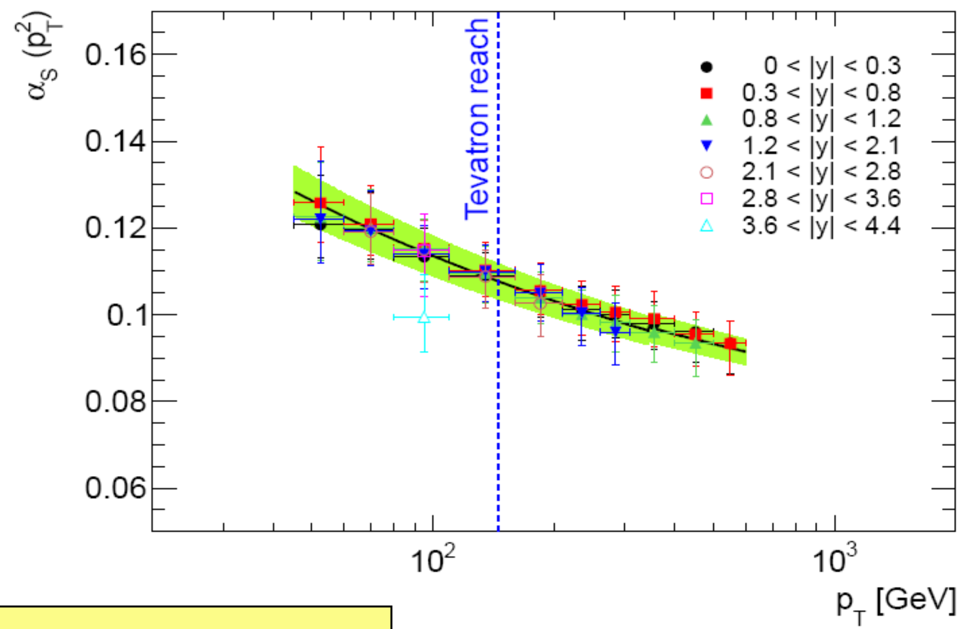
D0 dijet χ: limits on q-compositeness, Extra Dim.: PRL 103, 191803 (2009)

α_s results from inclusive jet cross section data

CDF Collaboration, T. Affolder et al.,
Phys. Rev. Lett. 88, 042001 (2002)



B. Malaescu, P. Starovoitov, arXiv:1203.5416



Statements:

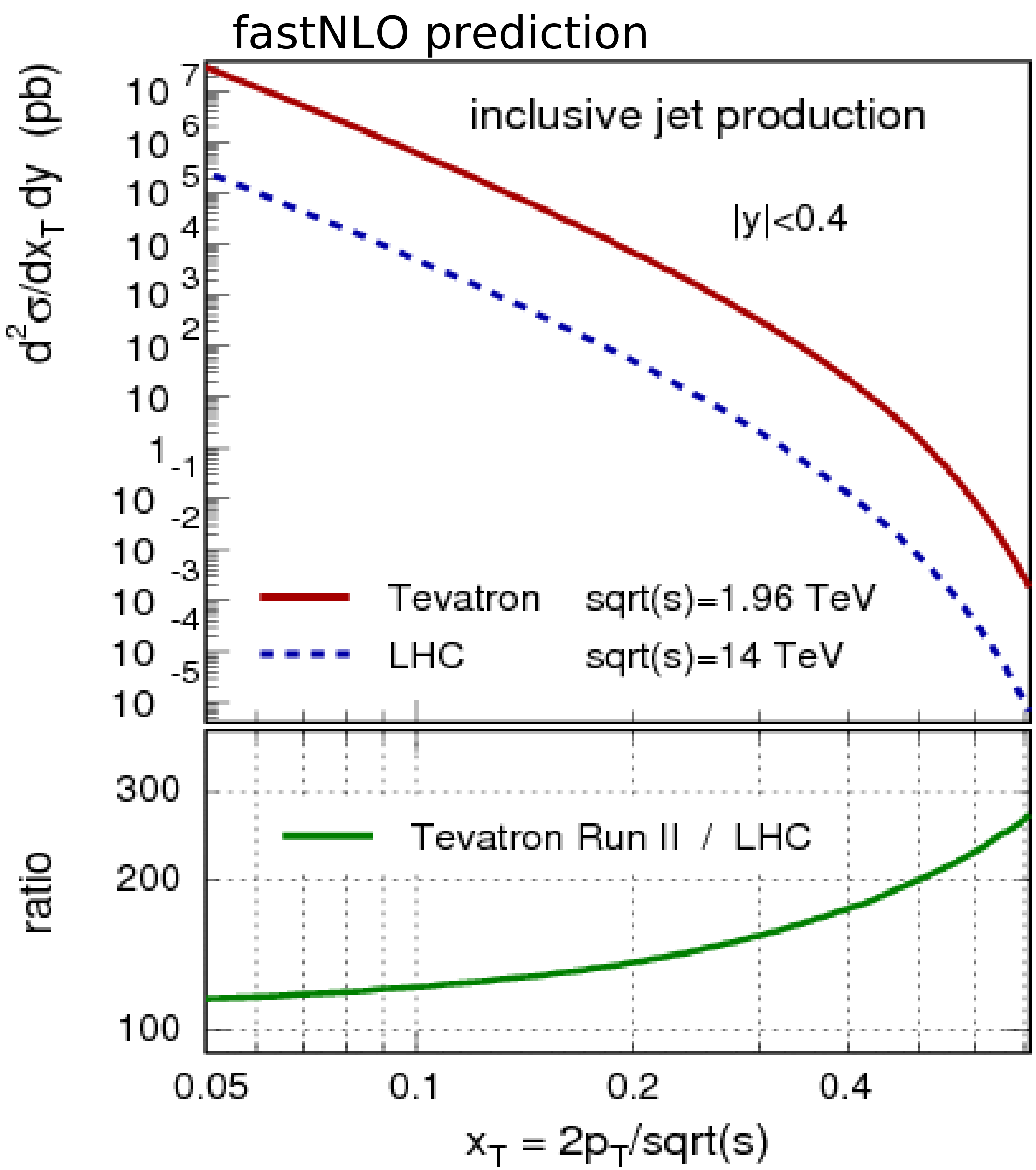
"Test running over 40< E_T< 440 GeV"

"Test running up to p_T → 600 GeV"

But analyses use PDF for which DGLAP evolution is already done under assumption of running $\alpha_s(Q)$ according to the RGE

→ RGE was already assumed
→ Not an independent test

Inclusive Jets: Tevatron vs. LHC



PDF sensitivity:

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

Tevatron (ppbar)

>100x higher cross section @ all x_T

>200x higher cross section @ x_T >0.5

LHC (pp)

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