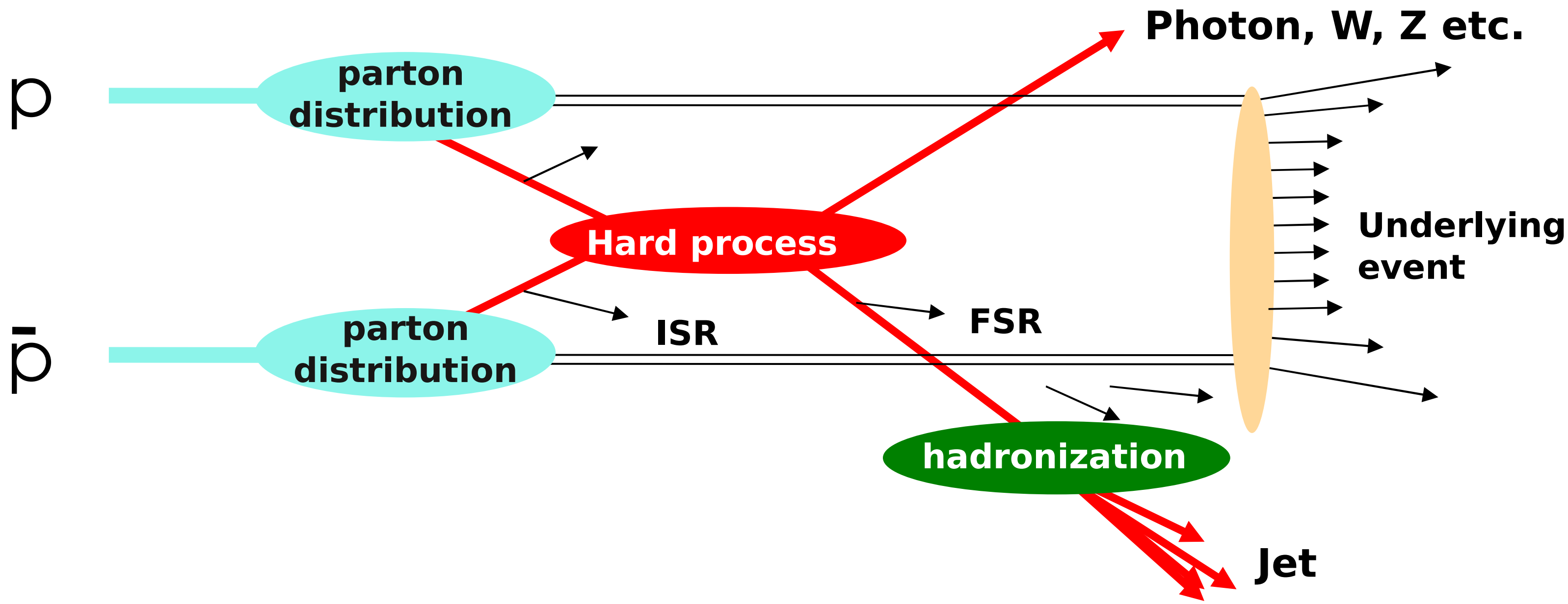
QCD at the Tevatron

Gavin Hesketh, University College London
On behalf of the CDF and D0 Collaborations

25th Recontres de Physique de la Vallee D'Aosta



Aims of the QCD programme at the Tevatron:

- understand the fundamental physics of hadron collisions
- precision tests of QCD, uncovering new physics

Today will focus on the latest results in "hard" QCD

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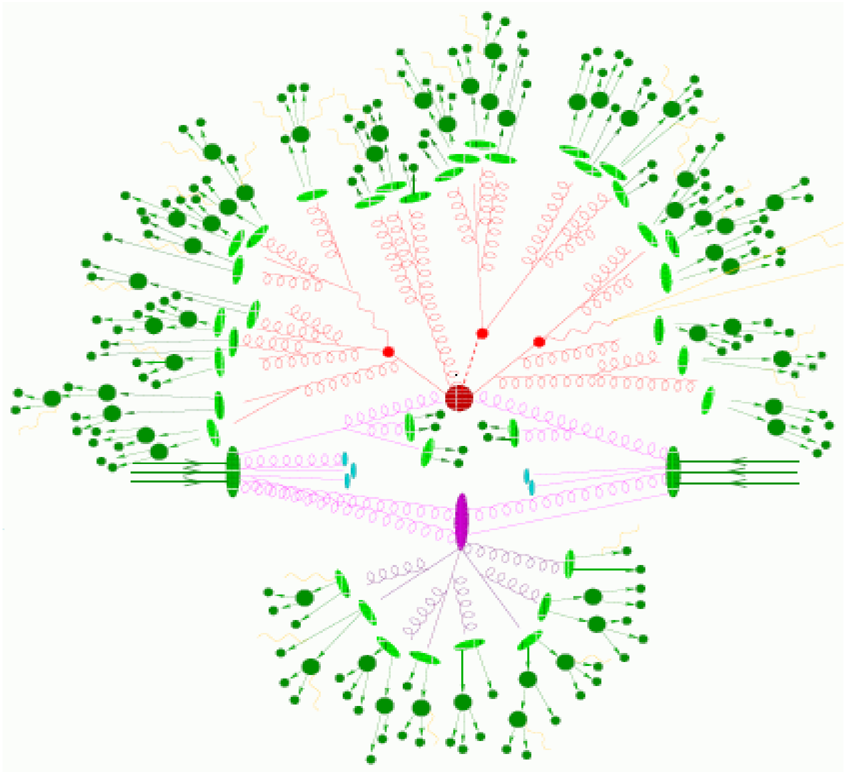

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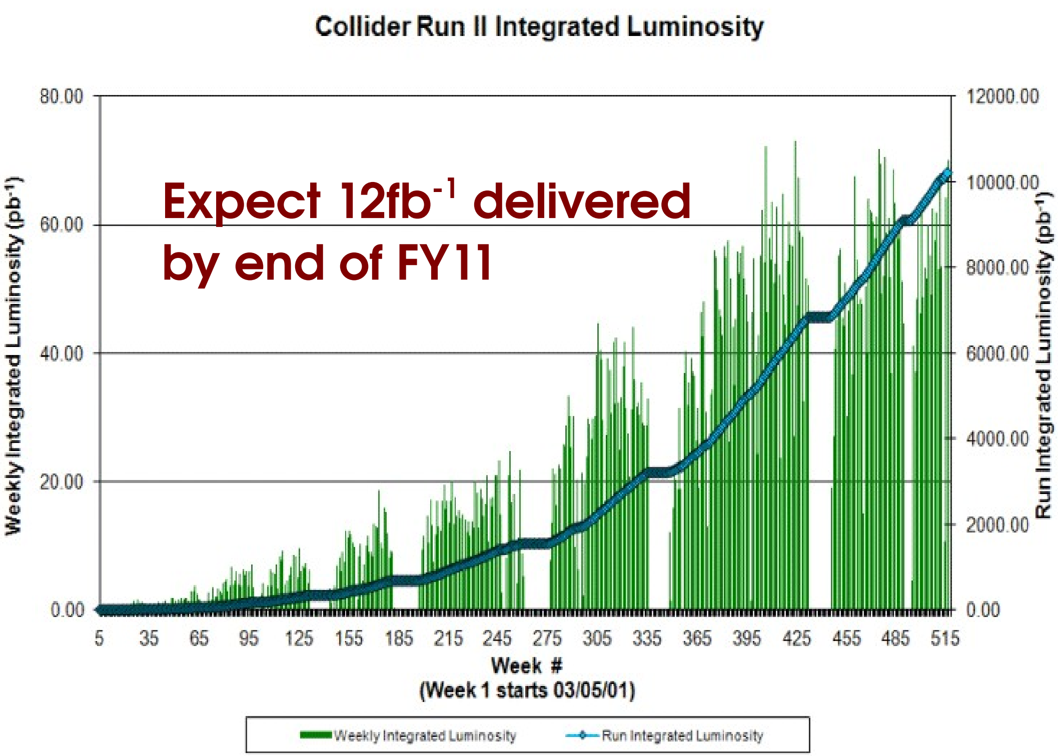
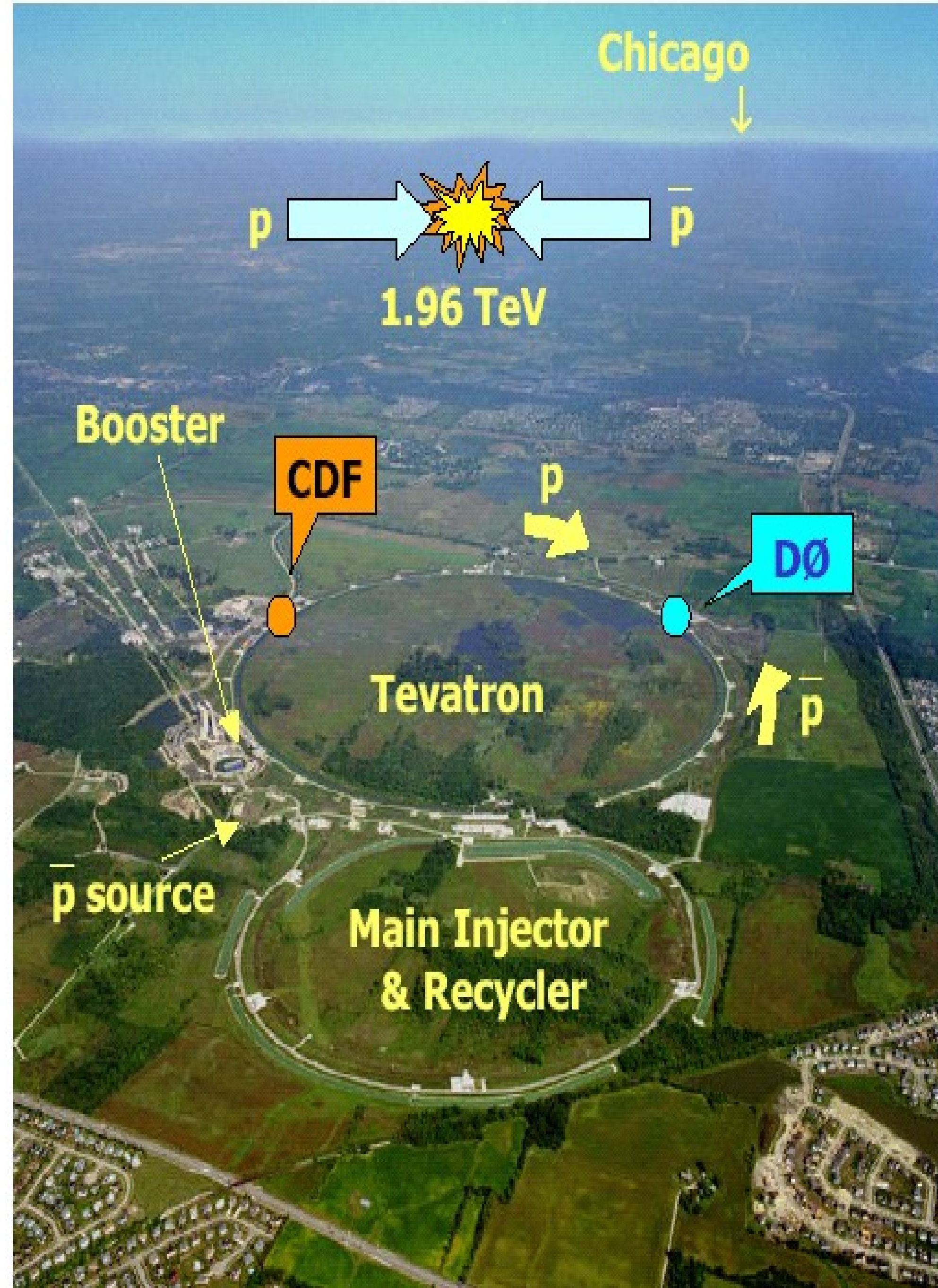
The Tevatron

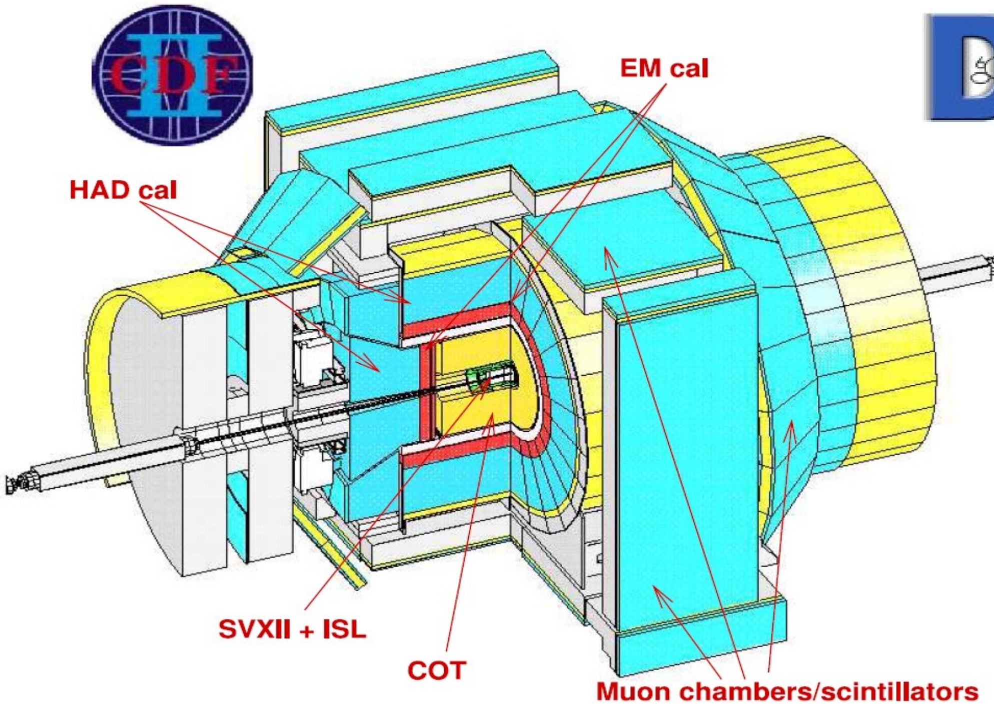
Tevatron performing very well:
- 10.3 fb^{-1} delivered per experiment
- 50 pb^{-1} per week
- experiment efficiency ~90%
- peak: 3.5 x 10^{32} $cm^{-2}s^{-1}$

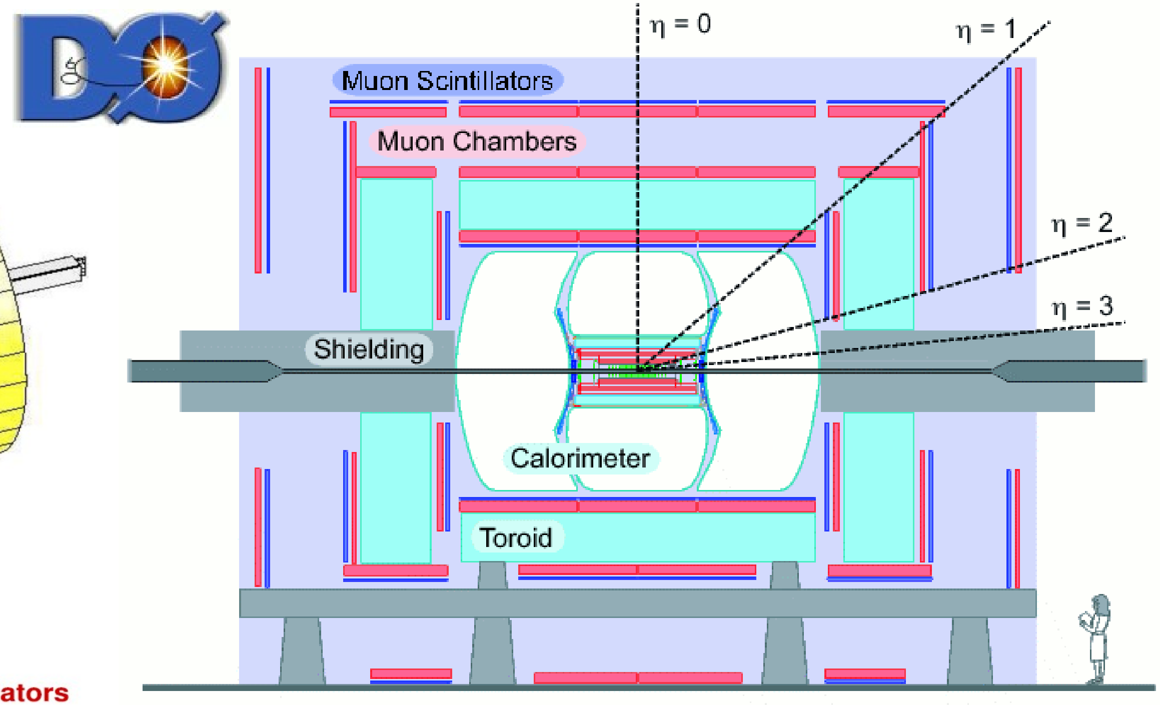
Results today use 0.7 – 6.2 fb^{-1}





CDF and D0





Two general purpose detectors: CDF and D0

- central tracking in a solenoid
- electromagnetic and hadronic calorimeters
- muon tracking (D0: with toroidal magnets)

Competitive advantages

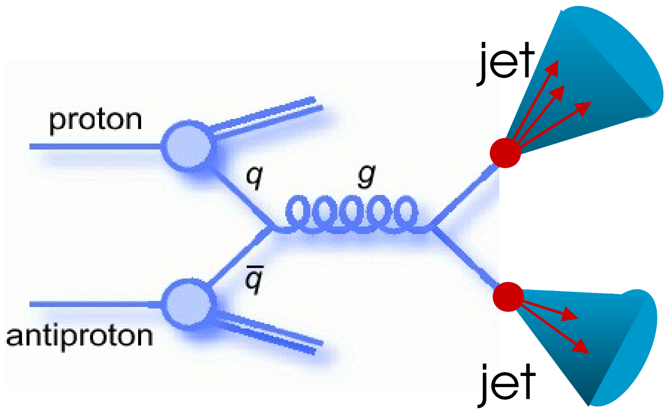
– CDF: better track momentum resolution & displaced track trigger at Level 1

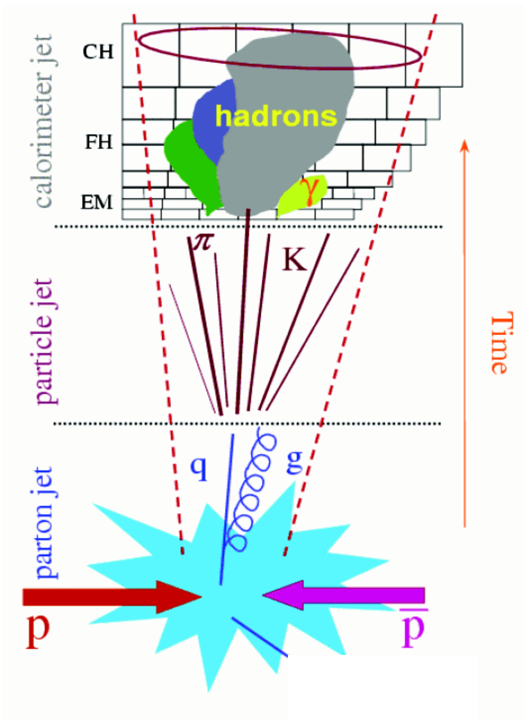
– D0: finer calorimeter segmentation, and muon coverage to $|\eta|<2.0$

Jets

- searches, precision measurements
- 3 jets, jet substructure

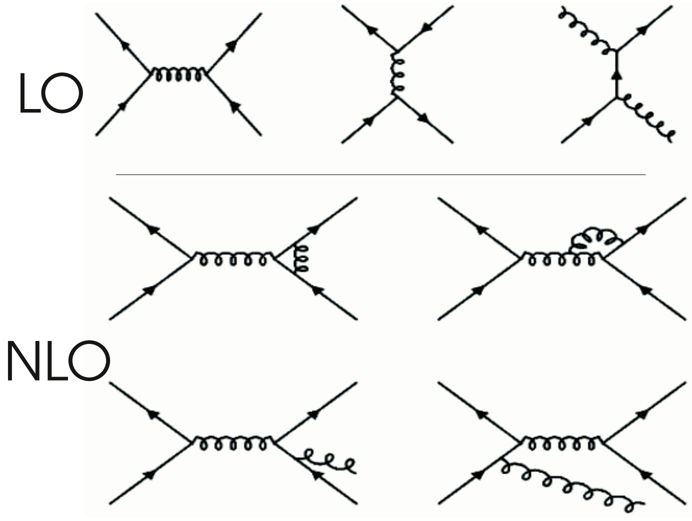
Jet Production



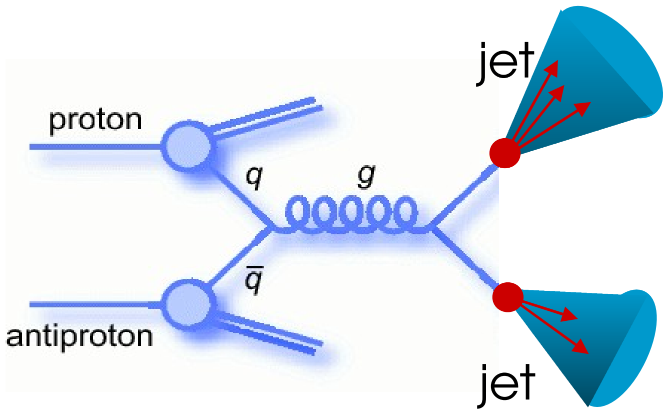


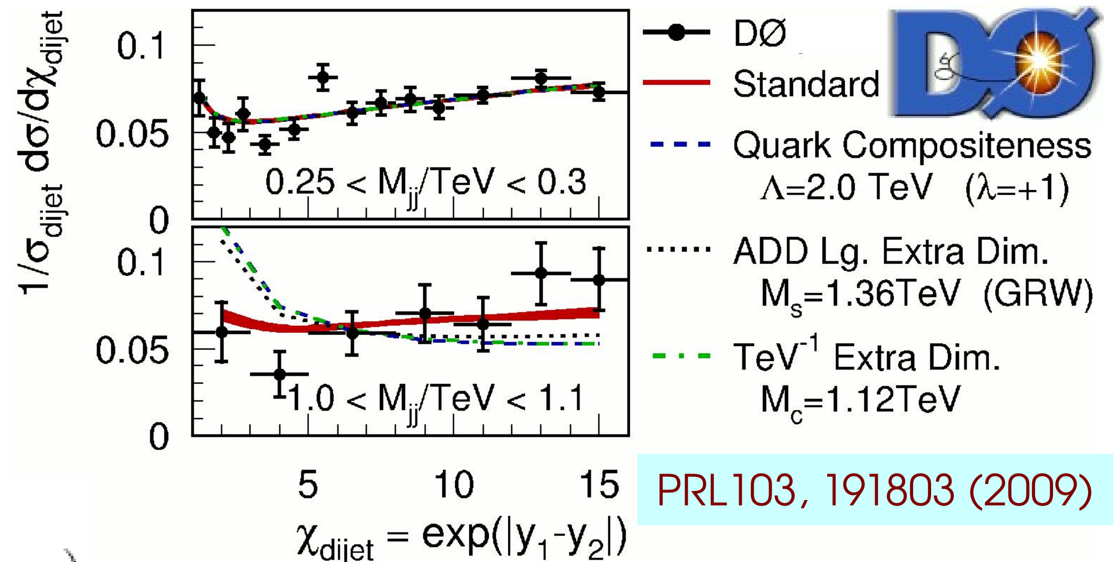
$$\sigma_{\text{pert}}(\alpha_s) = \left(\sum_n \alpha_s^n c_n \right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

Fundamental process at a hadron collider!



New Physics?





PRL103, 191803 (2009)

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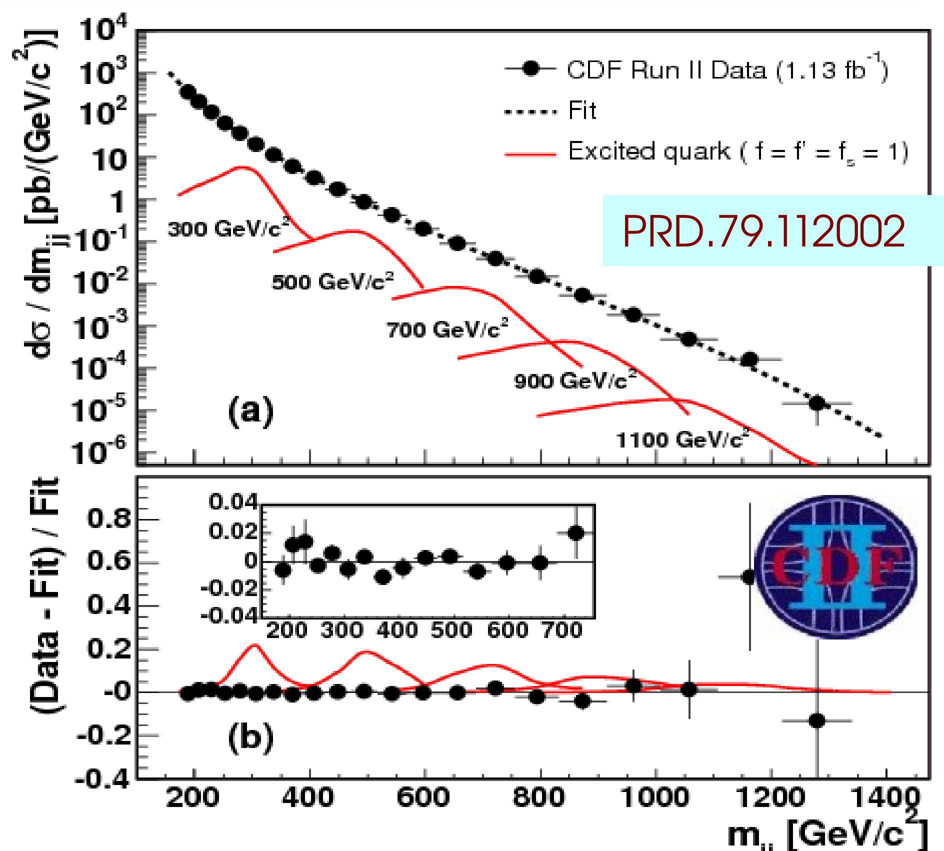


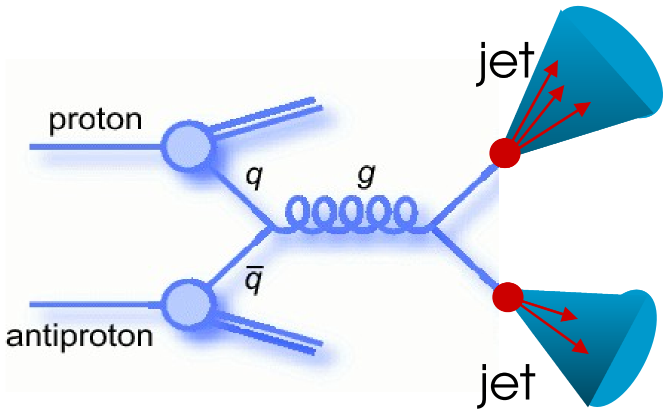
PRD.79.112002

Fundamental process at a hadron collider!

Any signs of new interactions?
- dijet angular distributions
- dijet mass resonances

No discovery, limits set
- limits depend on model, in 1-3 TeV range
- hard to compete with LHC!

Precision Measurements



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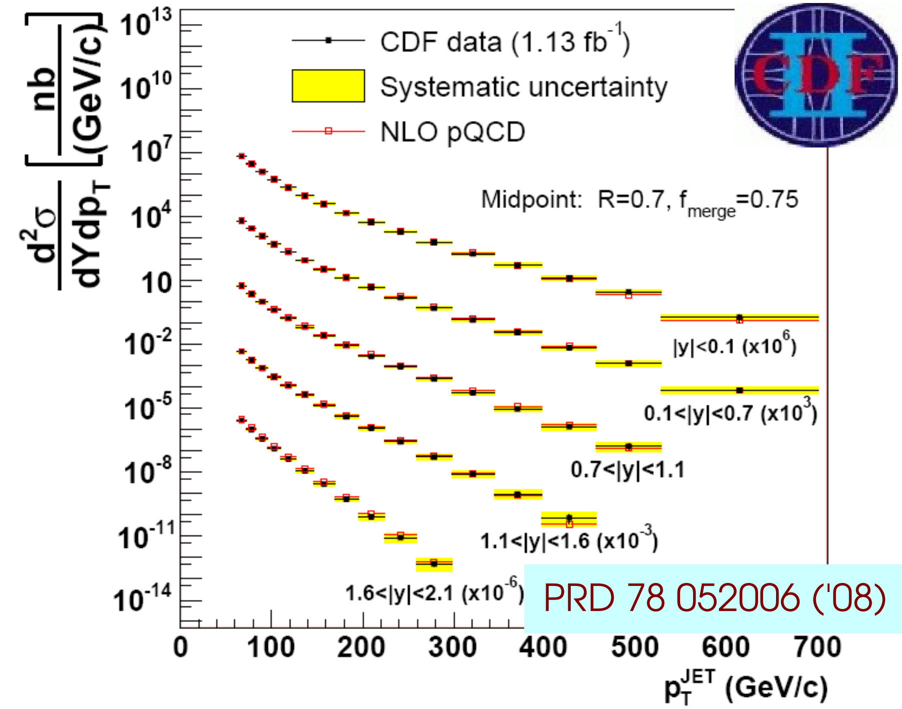


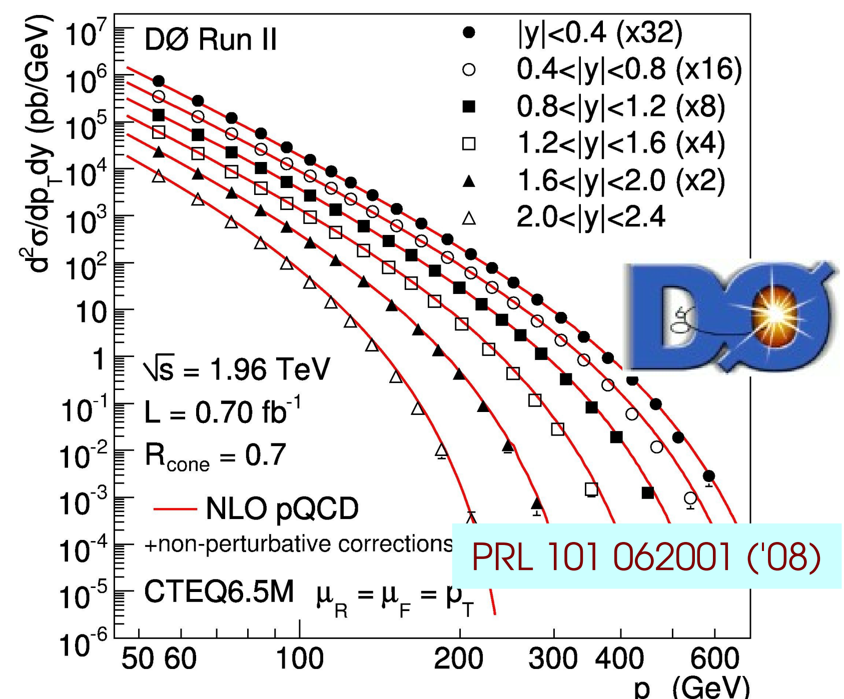
PRD 78 052006 ('08)

Precision test of QCD!

Benchmark: measurements of jet cross sections

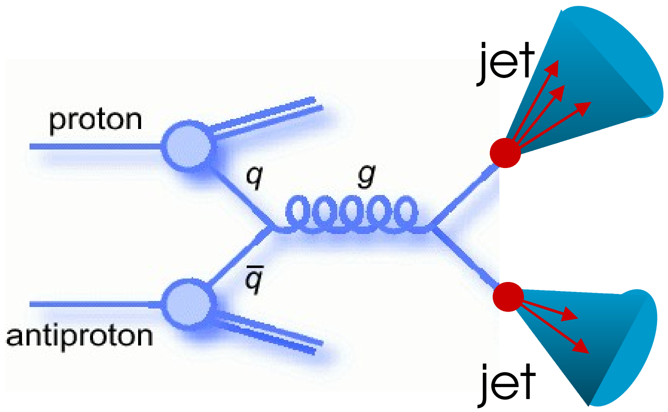
- driven by precise jet energy scale:
  - 1-2 % (D0)
  - 2-3 % (CDF)
- into forward region (| η | <2.4)

- also testing different jet algorithms
  - kT instead of cone: PRD 75, 092006 (2007)
- and jet shapes: PRD 71, 112002 (2005)



PRL 101 062001 ('08)

PDFs and α_s



Use inclusive jet data:
- constrain PDFs, particularly high-x gluon

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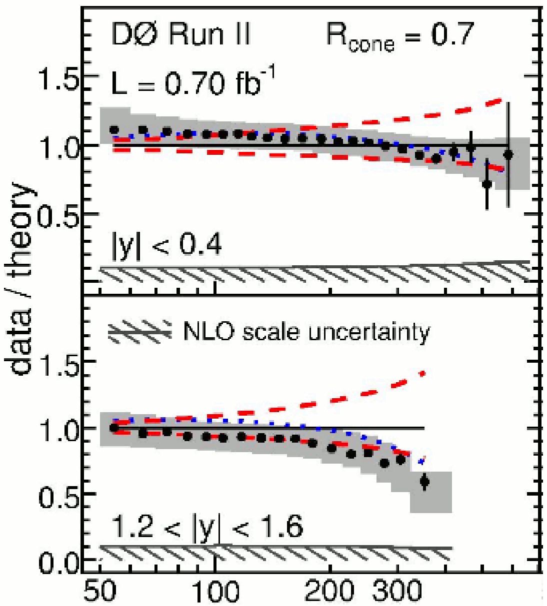
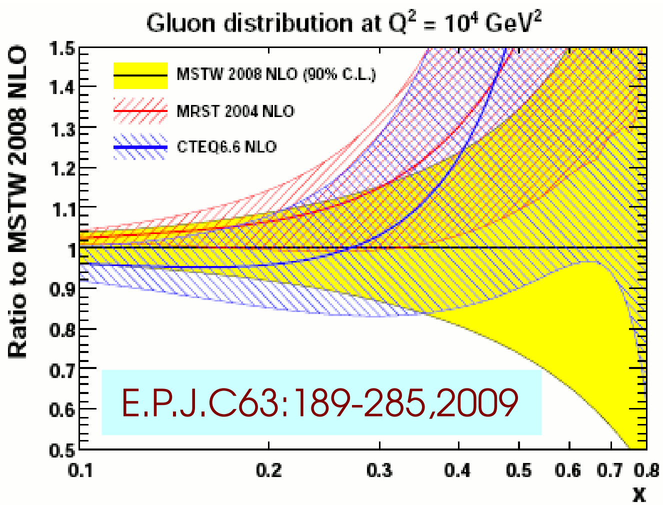
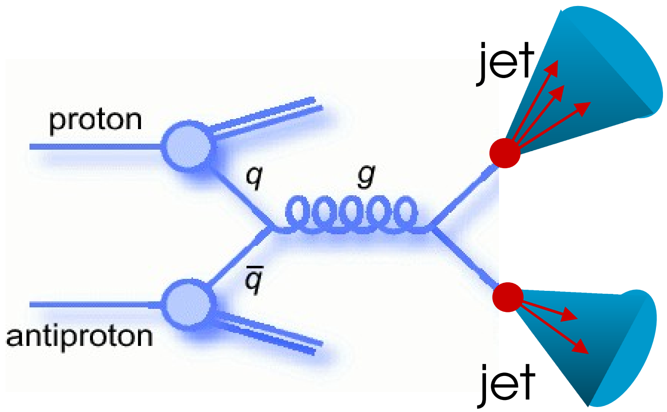




UCL

PDFs and α_s



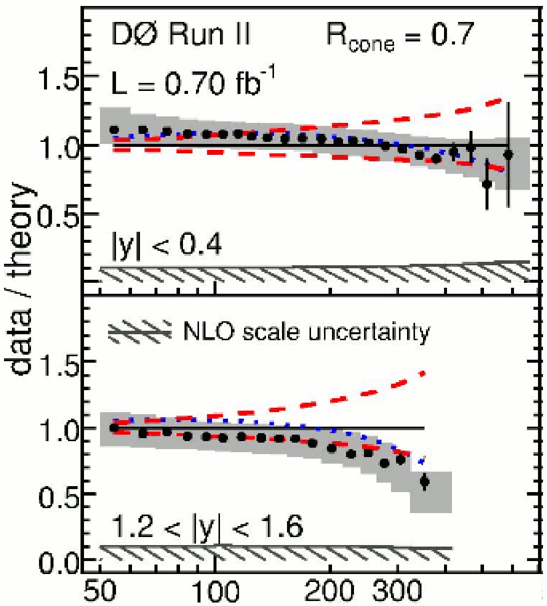
Use inclusive jet data:
- constrain PDFs, particularly high-x gluon
- and α_s

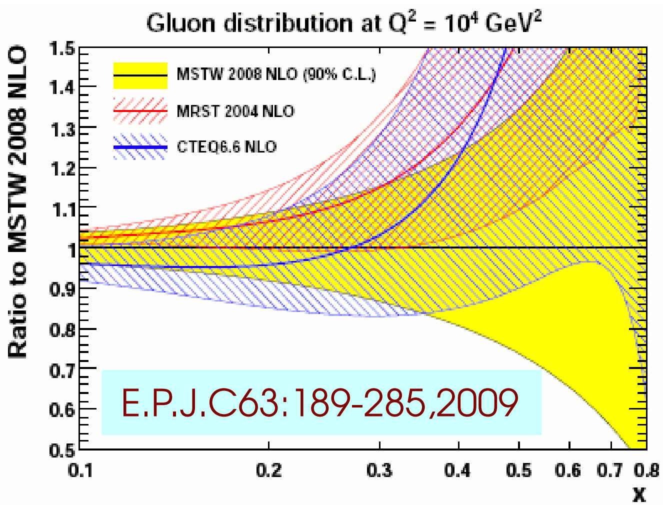
Legacy measurements from the Tevatron!

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

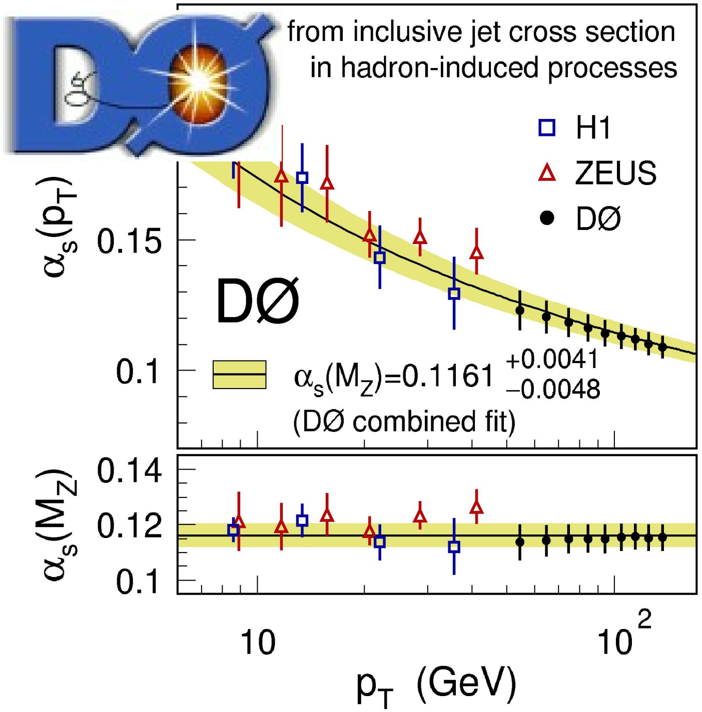
$$\alpha_s(M_Z) = 0.1173^{+0.0041}_{-0.0049}$$

Phys. Rev. D 80, 111107 (2009)





E.P.J.C63:189-285,2009



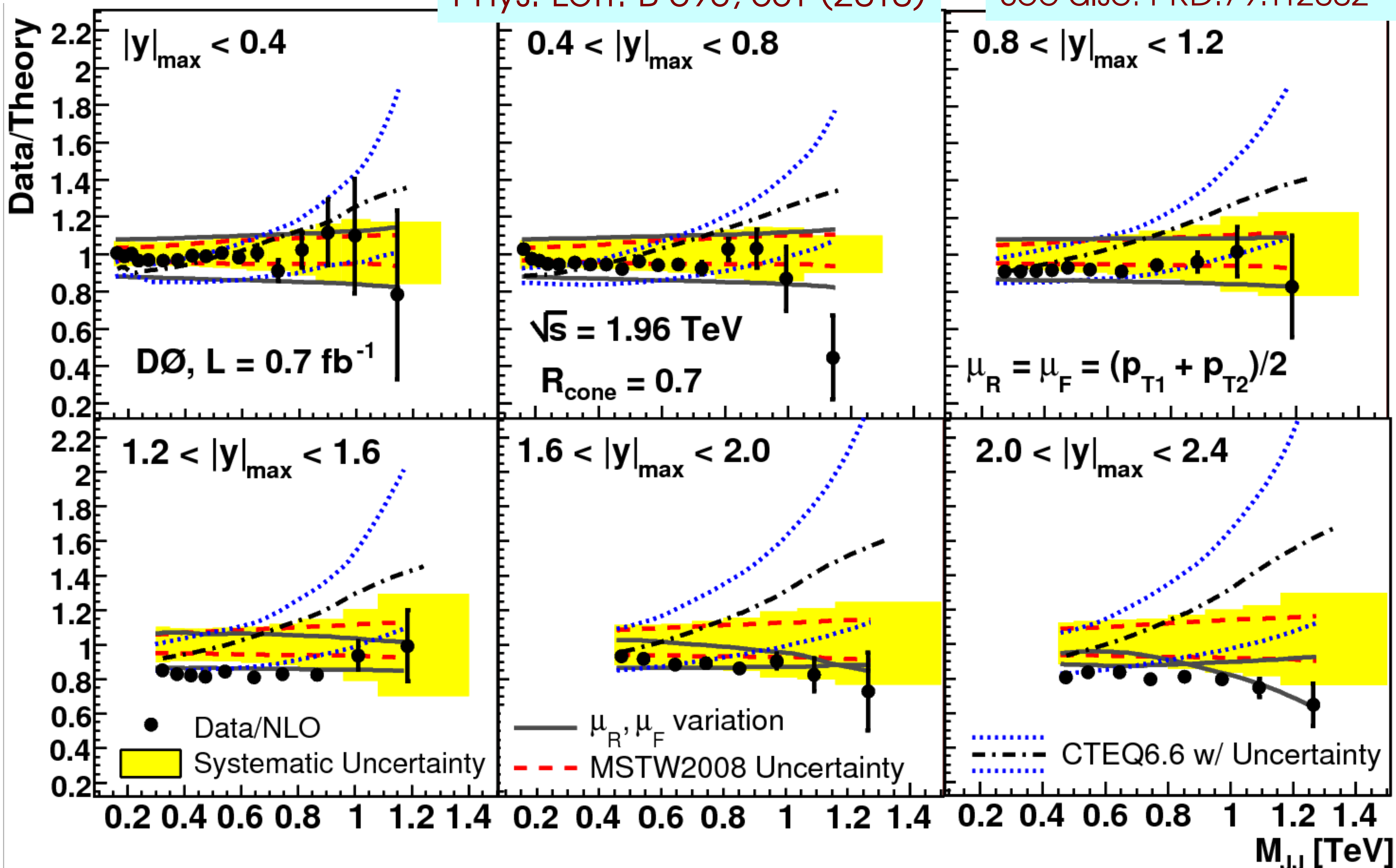
Dijet Mass

Further information in the di-jet mass distribution

- probe masses > 1.2 TeV!
- still shows some tension with latest PDF fits

Phys. Lett. B 693, 531 (2010)

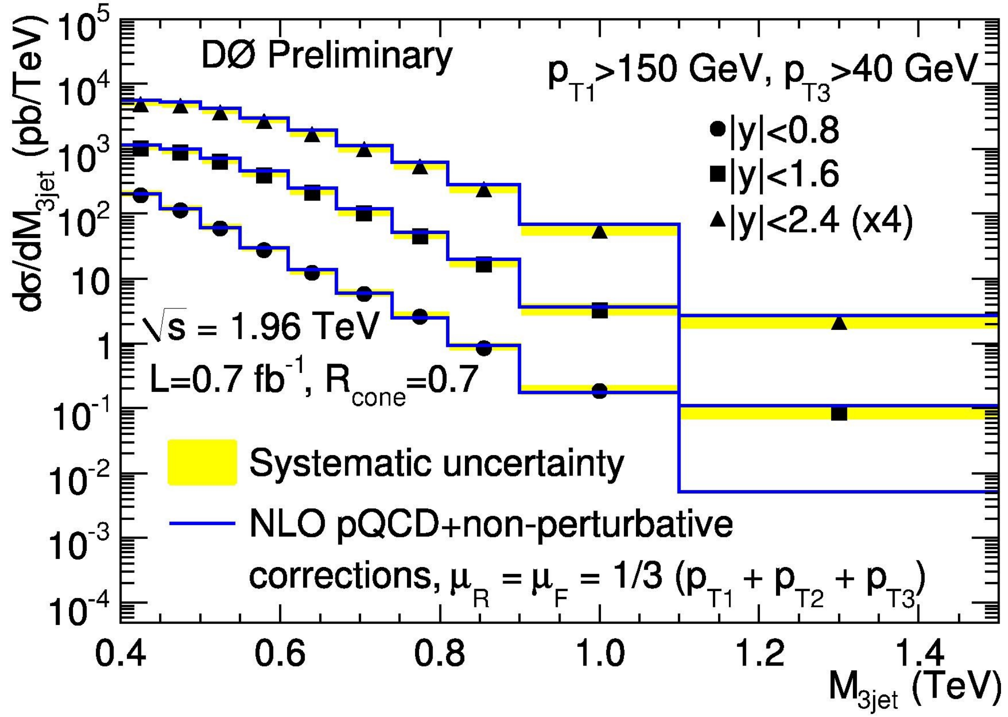
See also: PRD.79.112002



Three Jet Production

Preliminary results on 3 jet mass:

- leading jet pT>150 GeV
- three rapidity ranges, three pT selections
- test NLO in more complex events
- systematics limited: 20-30%, JES dominates



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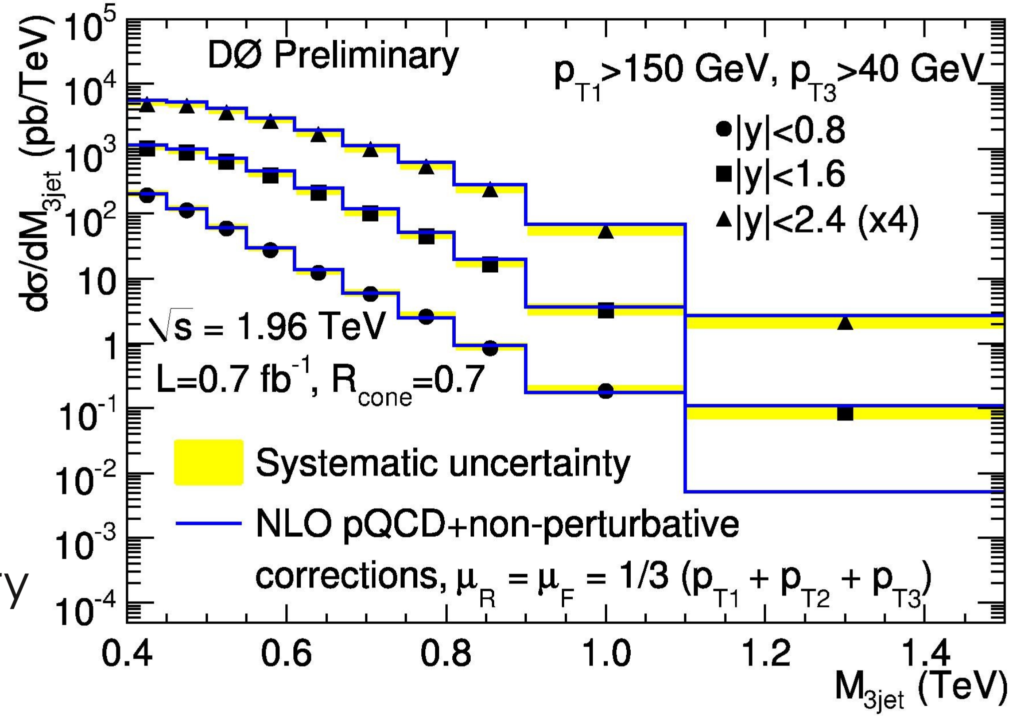
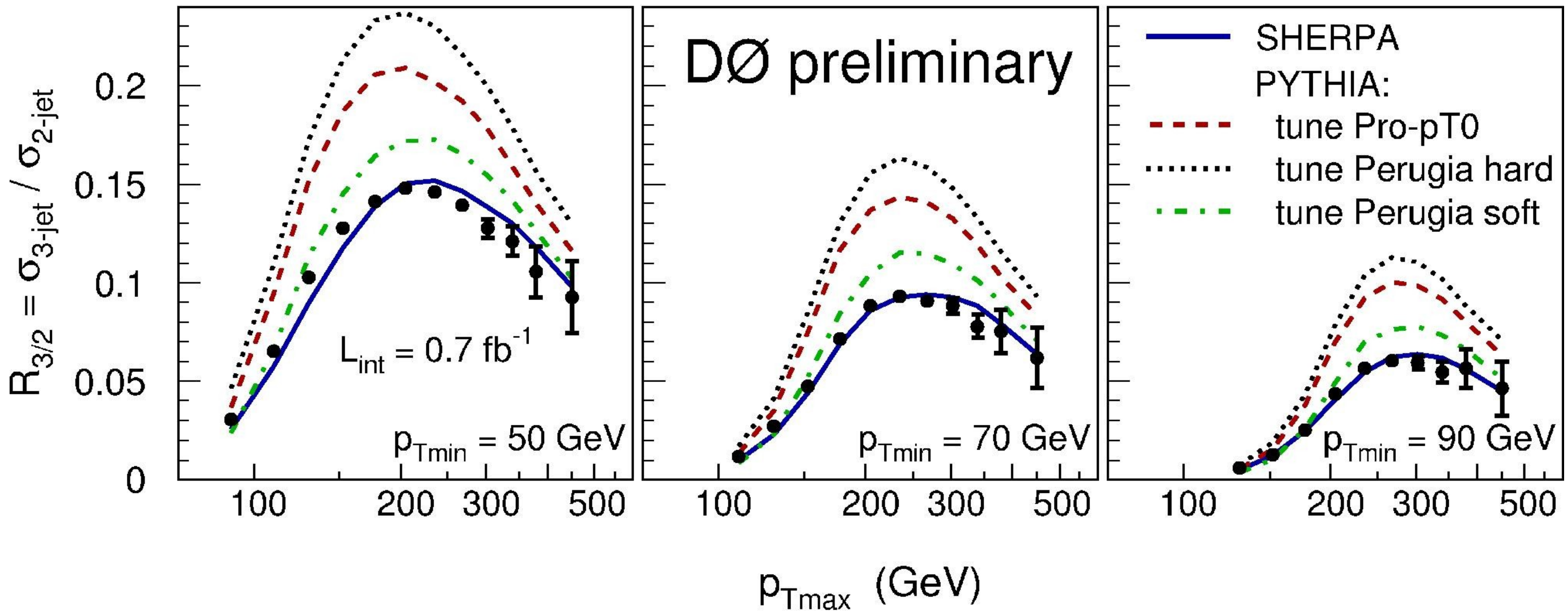
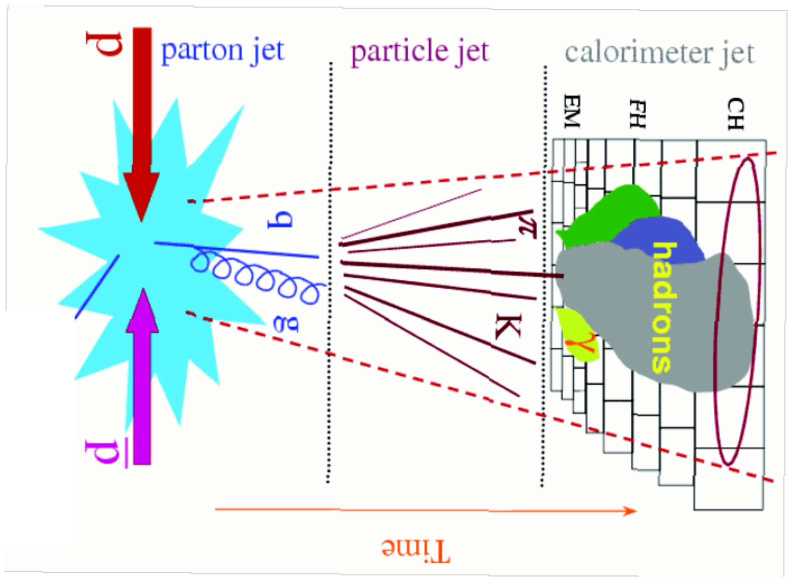
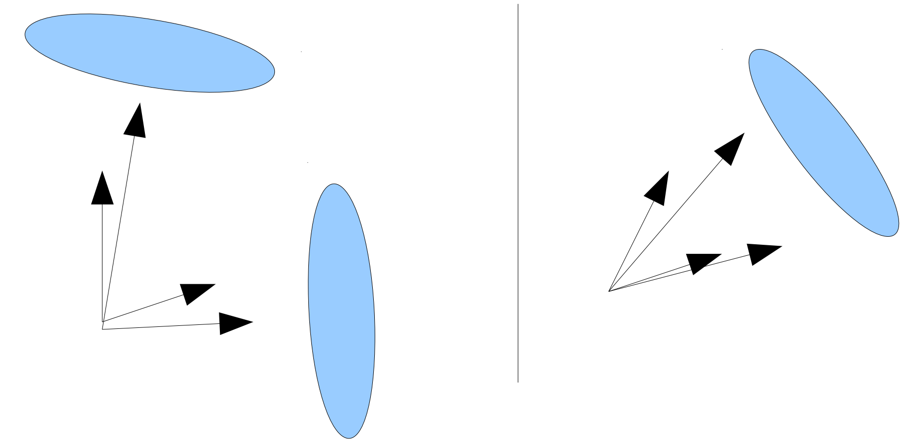


Also look at R3/2:
- cancels many experimental systematics
  - JES still dominates, at 3-5%
- and much of the PDF dependence in theory
- test QCD, and event generators
  - next: extract α_s



Jet Structure





Test QCD and parton shower models

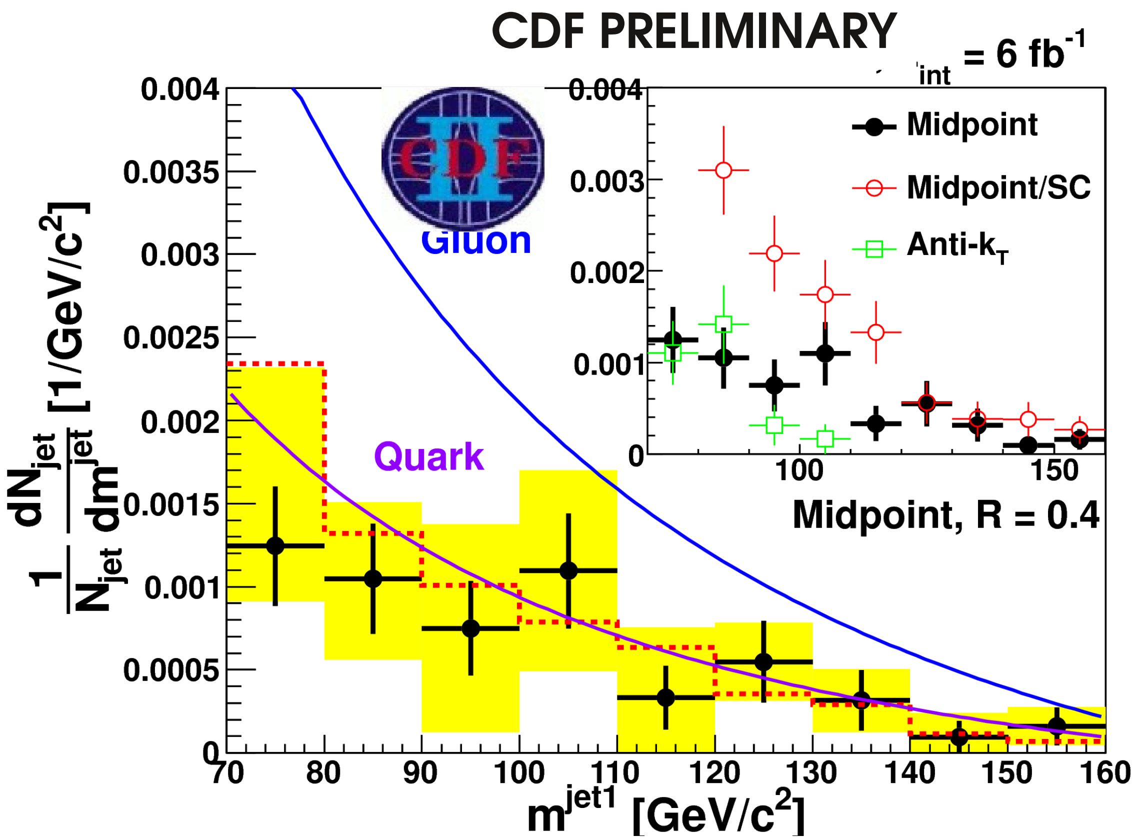
- using high energy jets (>400 GeV)
- also benchmark boosted objects

Jet mass

- E-scheme sum of tower 4-vectors)
- ~80% of jets originate from quarks

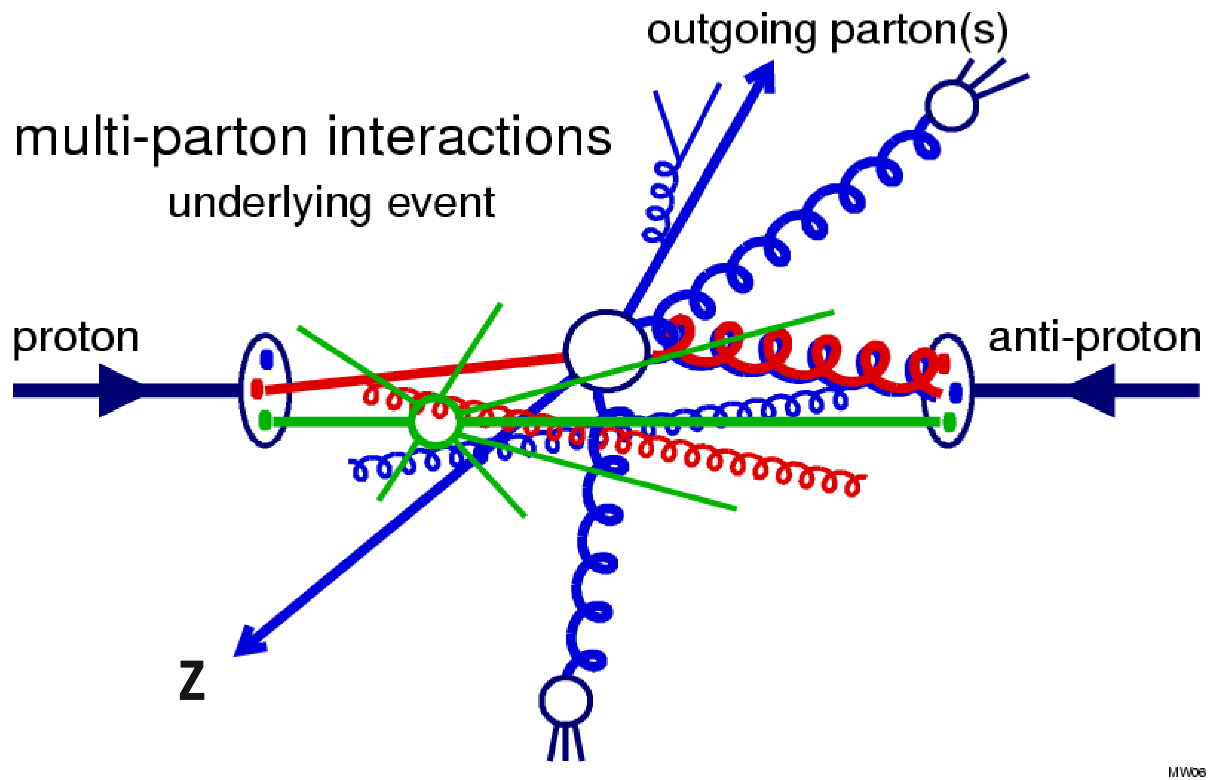
Angularity and planar flow

- better resolution
- less algorithm dependence



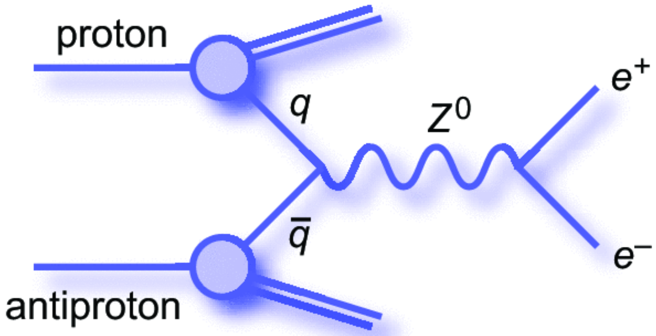

H
Z
2) Bosons
- diphotons
- photon + jets
- Z + jets
- heavy flavour

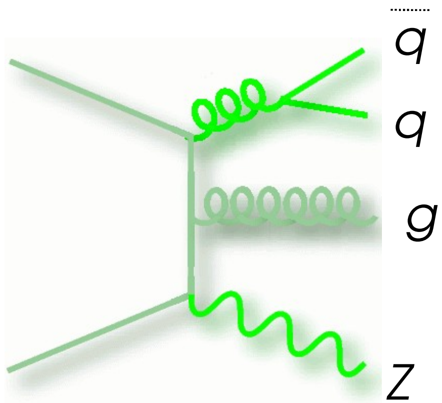
Photons, Z, W



Use the well-understood bosons as a colourless probe of QCD process!
- properties and intercations of the bosons well understood
- kinematics determined by hadronic recoil

Photons, Z, W





Use electron and muon decay modes of the Z

- clear experimental signature

Inclusive Z pT: soft and hard recoil

- see J. Sekaric on Electroweak, Thursday

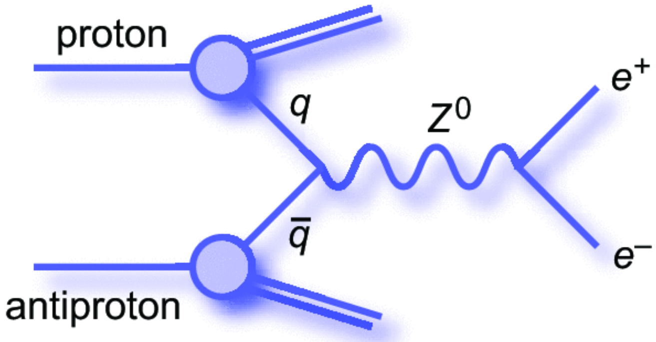
Identified jets:

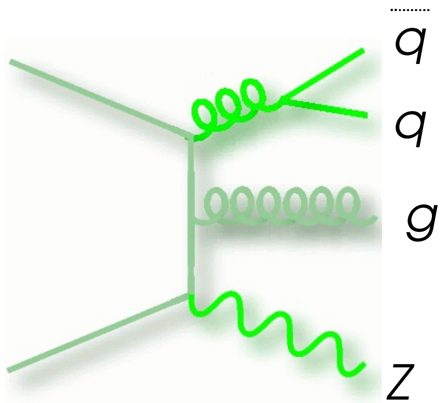
- complex events: recent NLO W/Z+3jets
- test QCD, understand search background!

W:

- higher cross section
- neutrino adds complication

Photons, Z, W





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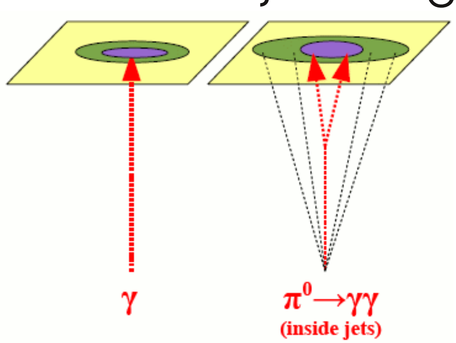
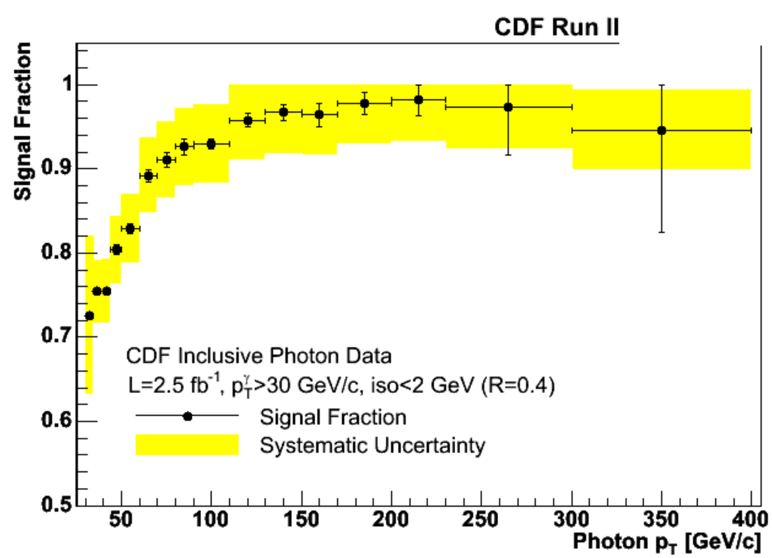
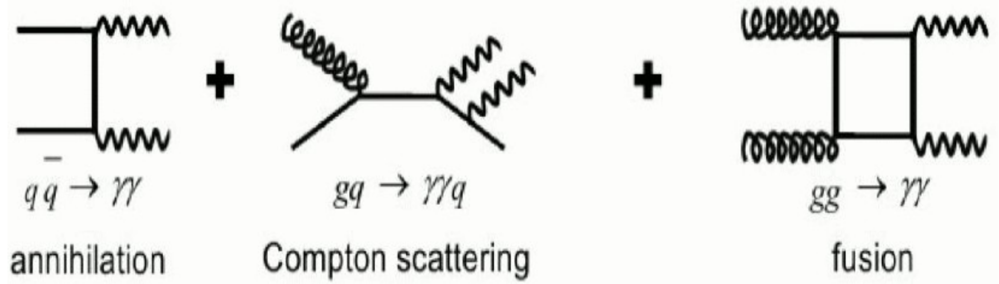
Photons:

- higher production cross section
- purity falls at low pT (>~70%)
- isolation cuts reject fragmentation





Di-photon Production



Extensive results from CDF and D0

- photon p_T>15-20 GeV, $|\eta| < 1.0$
- diphoton mass, pT, angles

Theoretical predictions:

DIPHOX: NLO, gg fusion @ LO
RESBOS: NLO + soft-gluon resummation
PYTHIA: LO + parton shower

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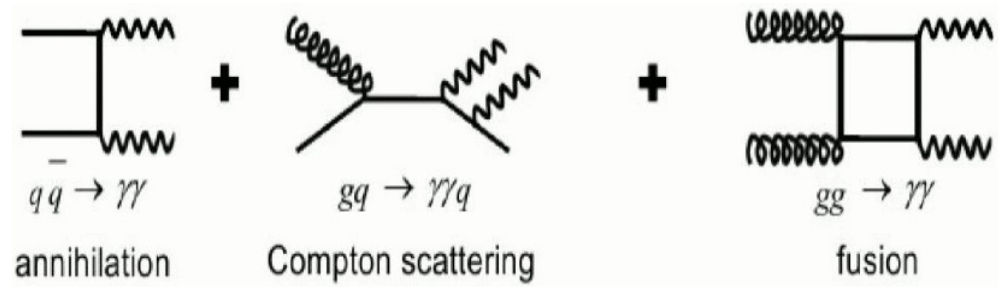
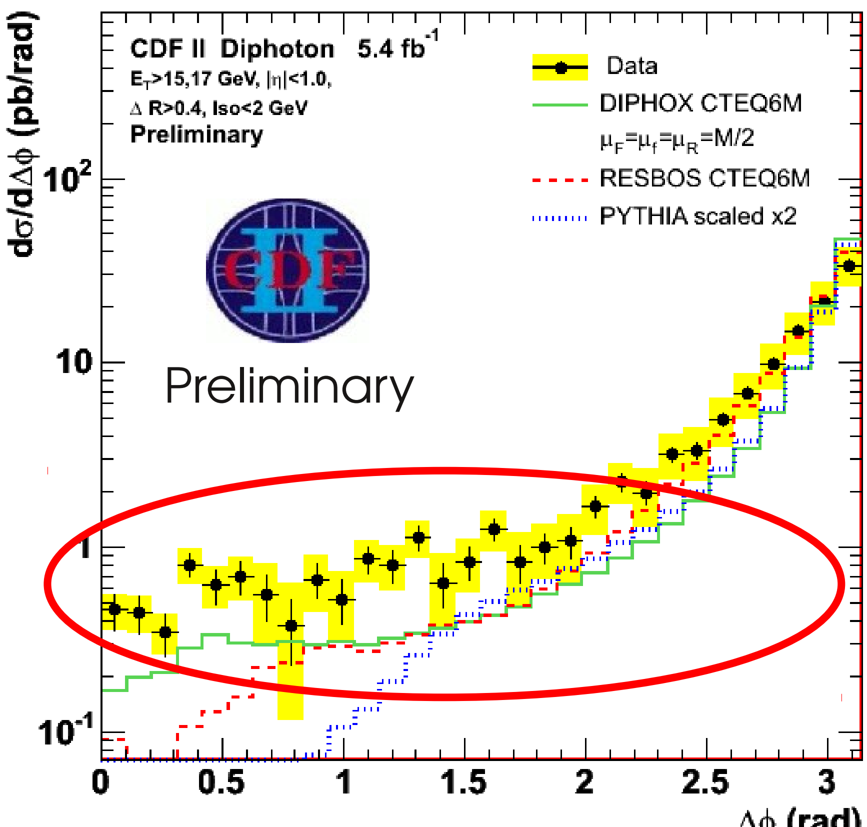
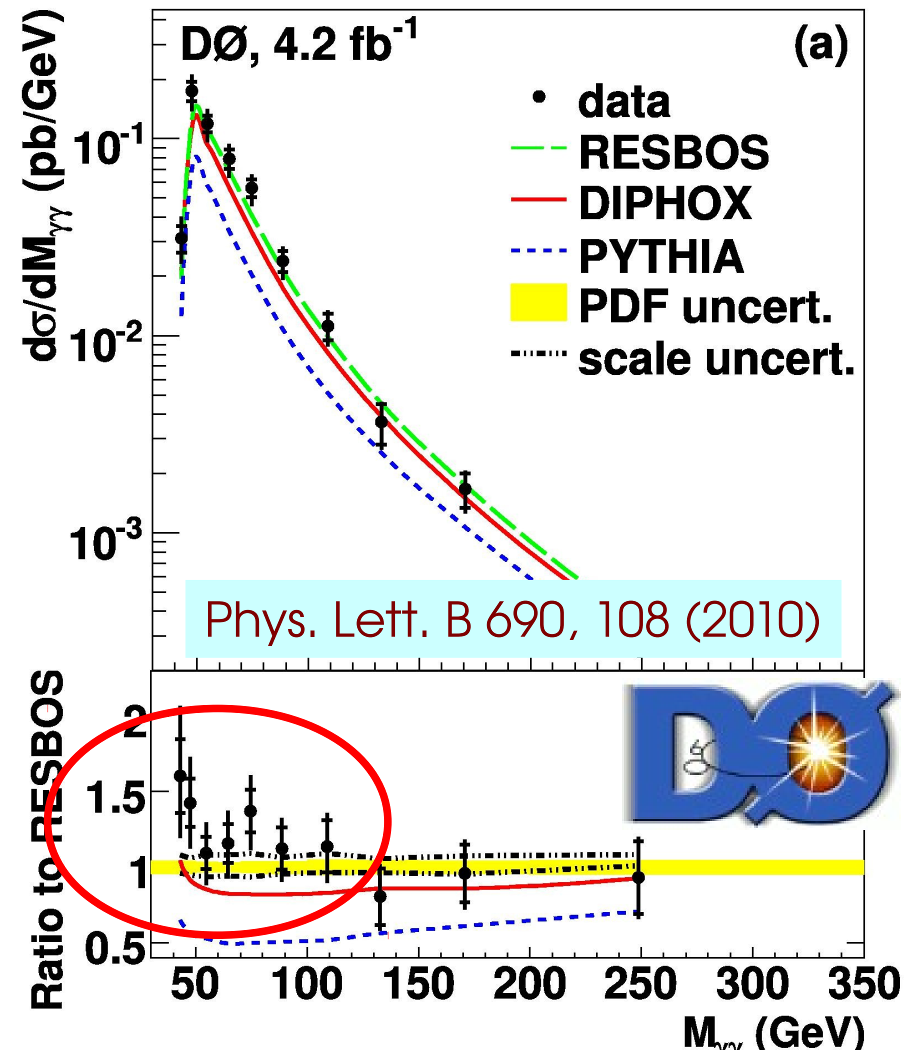


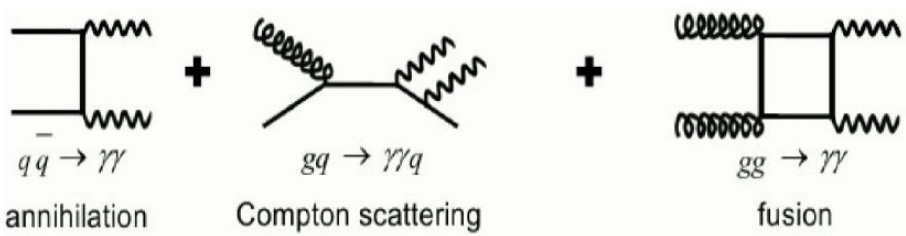


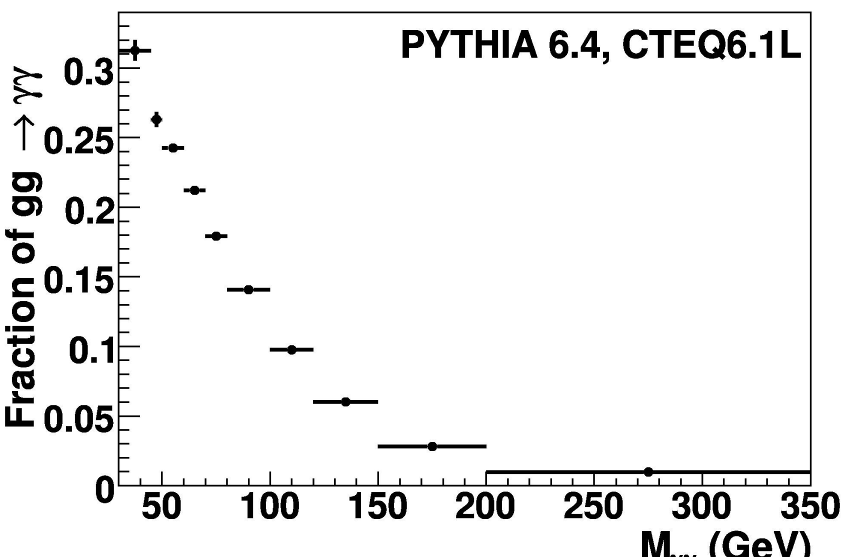


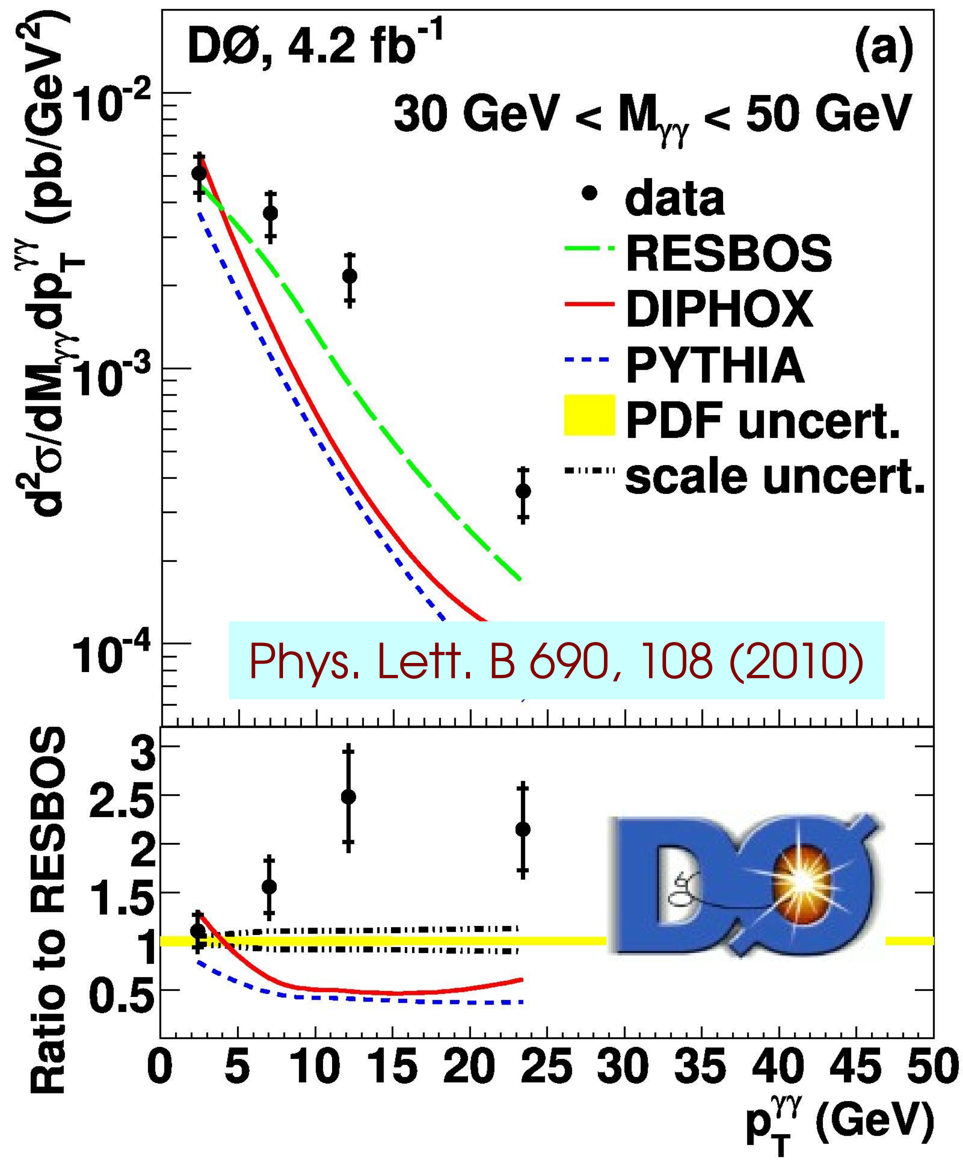
Good agreement at high mass

But, no model describes full range:

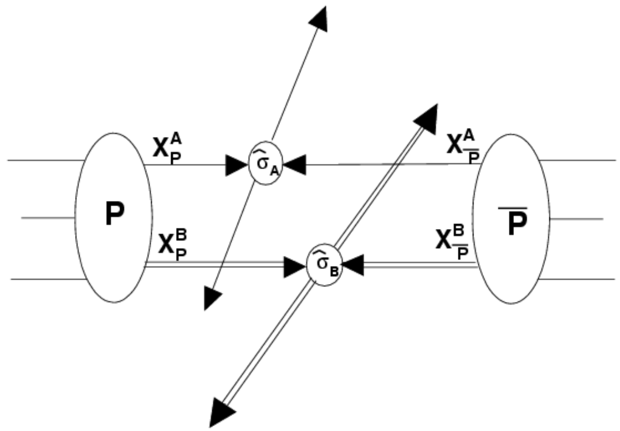
- low pT, mass regions difficult
    - double differential!
- large contribution from g-g
    - and fragmentation
- g-g more important at the LHC!





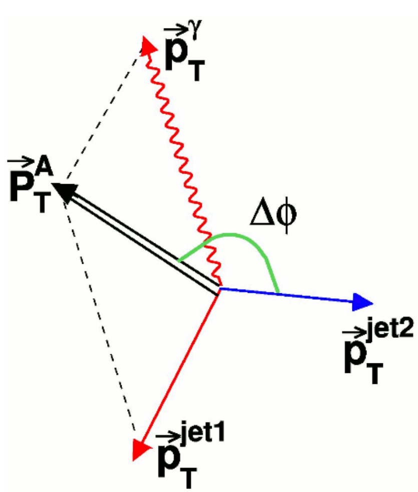


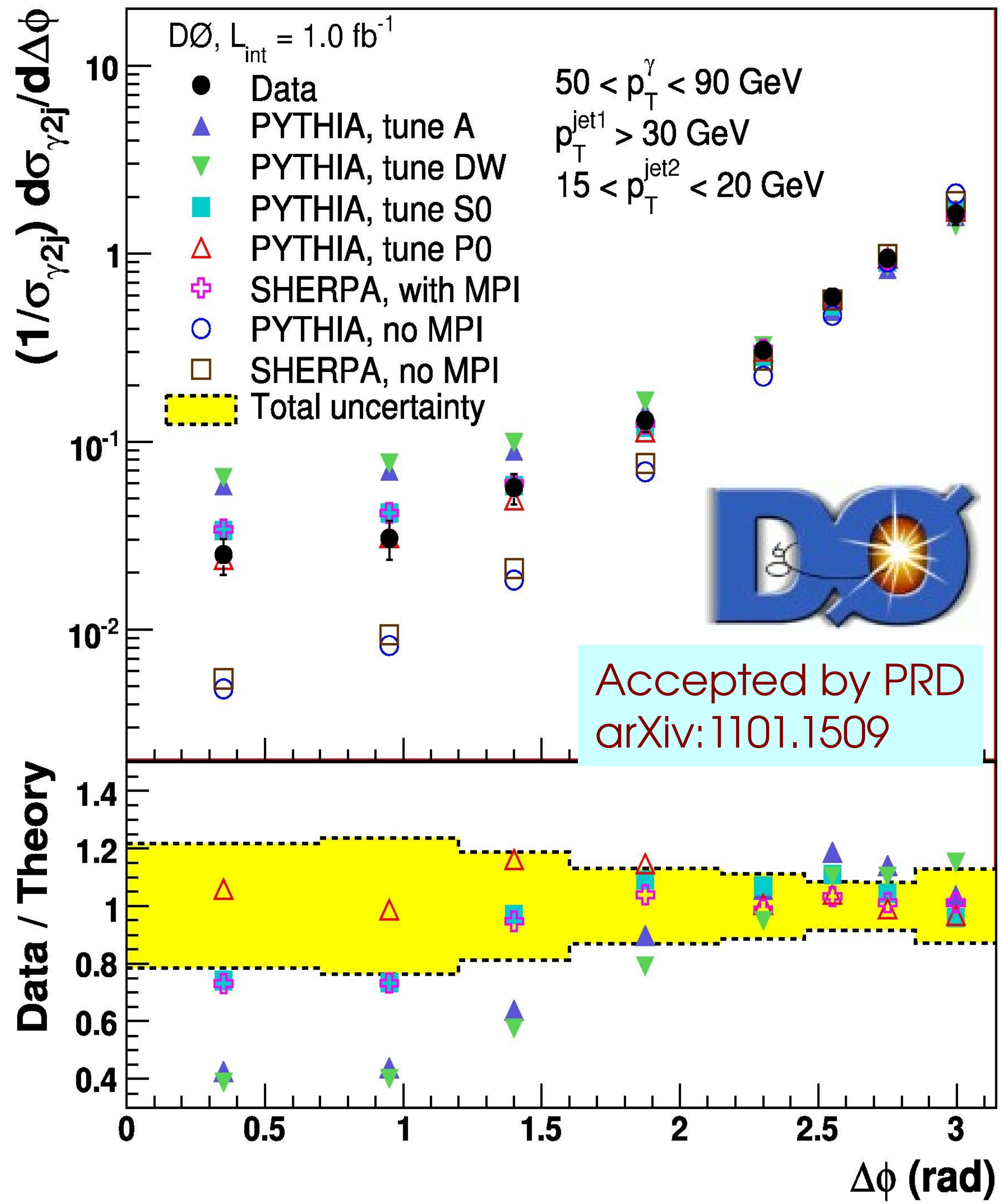
Photon + jets: MPI



Use photon + jet production:
- look for multiple interactions

Divide event into two systems:
  - photon + jet
  - additional jets in event
- check for balance/correlation





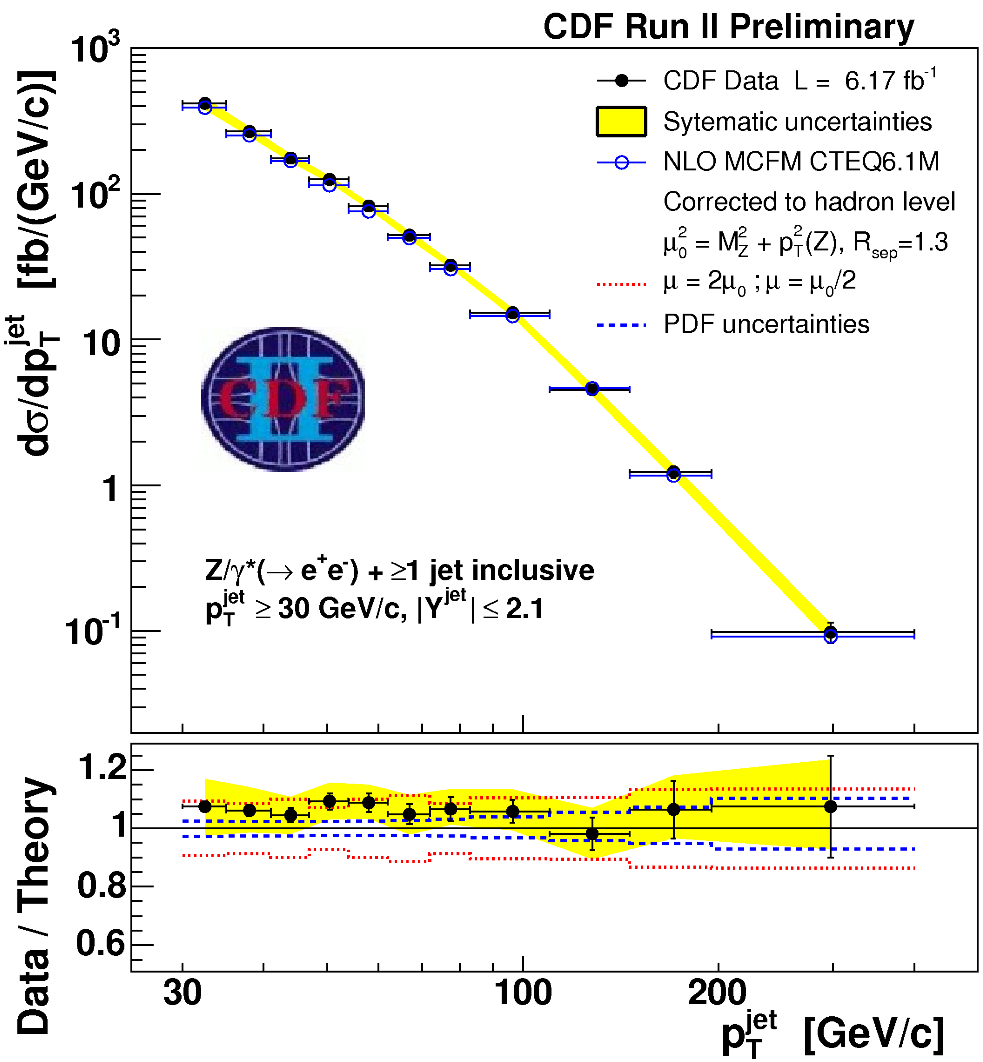
Accepted by PRD
arXiv:1101.1509

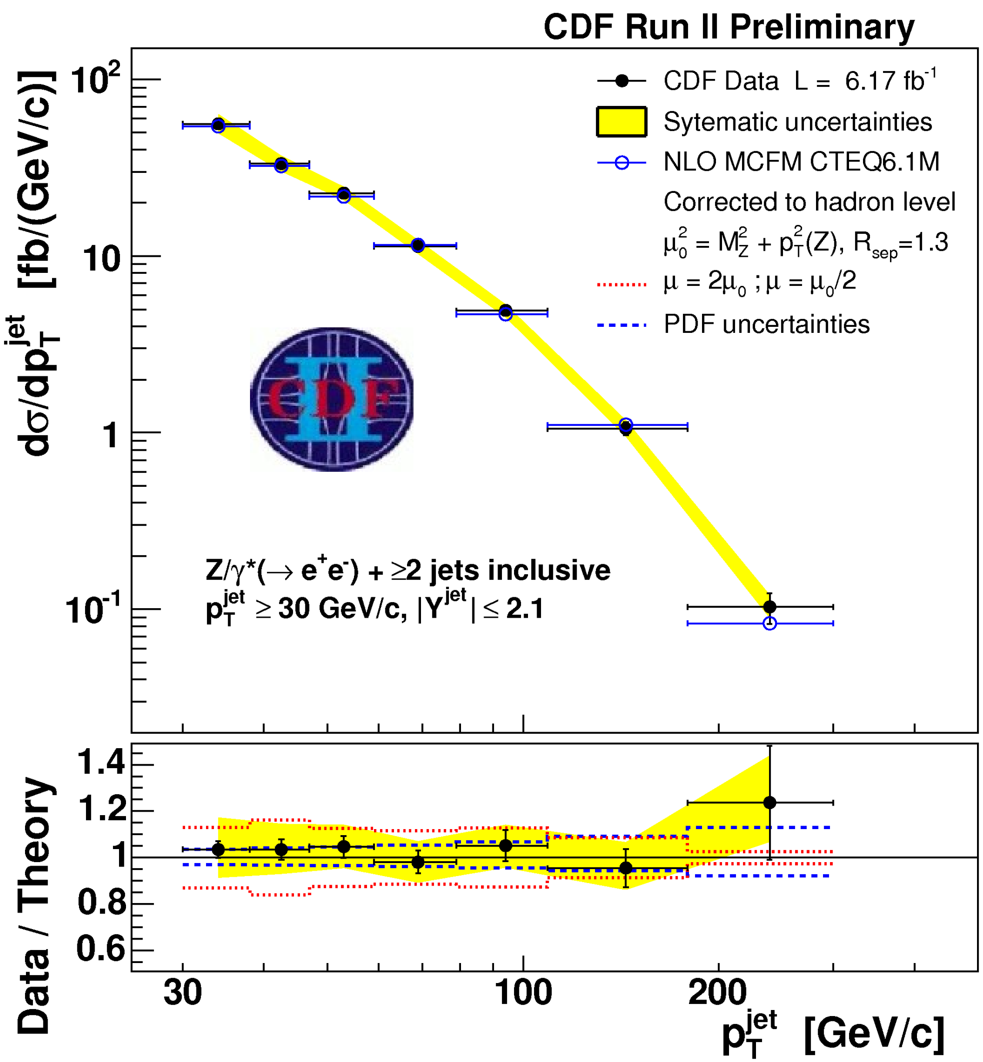
Z + Jets

Updated result from CDF:

- electron and muon channels, now with **6.2 fb^{-1}**
- leading and second jet pT, rapidity
  - compared to LO and NLO pQCD
  - theory describes data well!

Update to PRL 100, 102001 (2008)

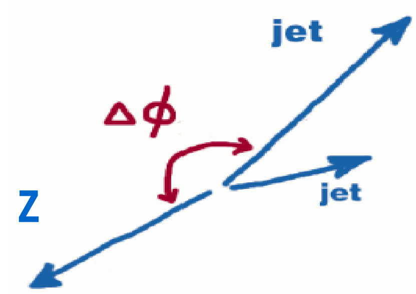




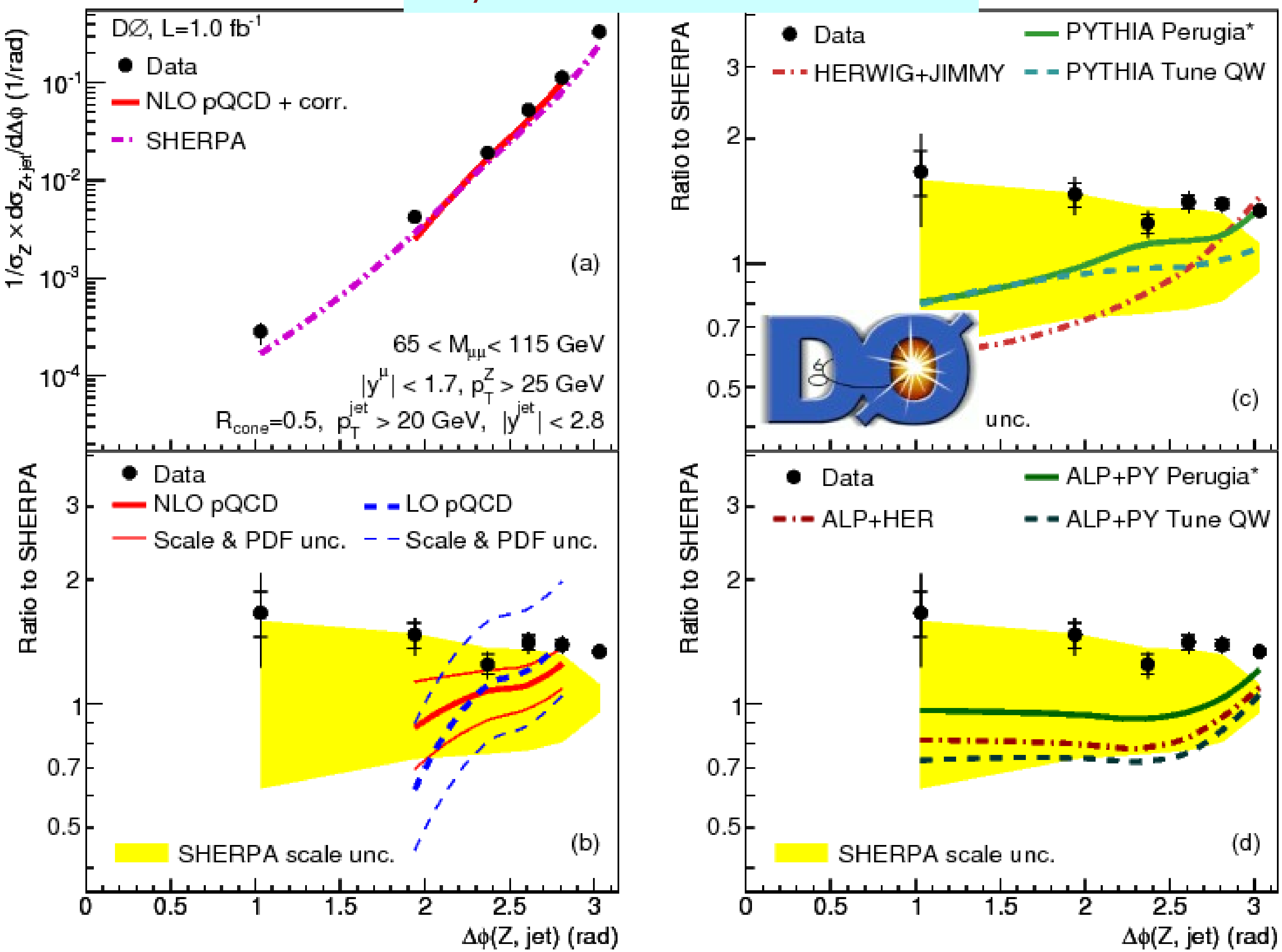
Z + Jets

Another, way to access higher jet multiplicities:

- $\Delta\phi$(Z, leading jet), measured for the first time
- compared to pQCD and several event generators



Phys. Lett. B 682, 370 (2010)



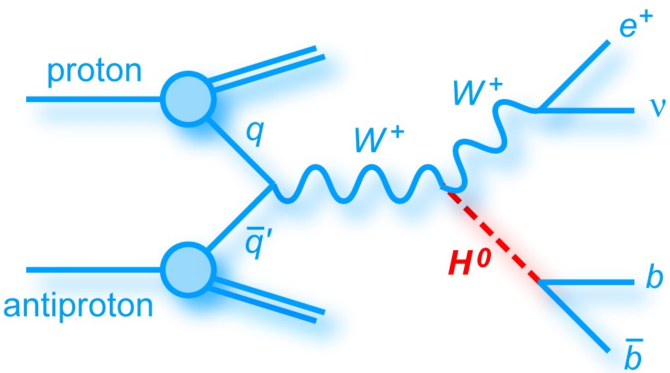
See also:
PLB 669, 278 (2008)
PLB 678, 45 (2009)

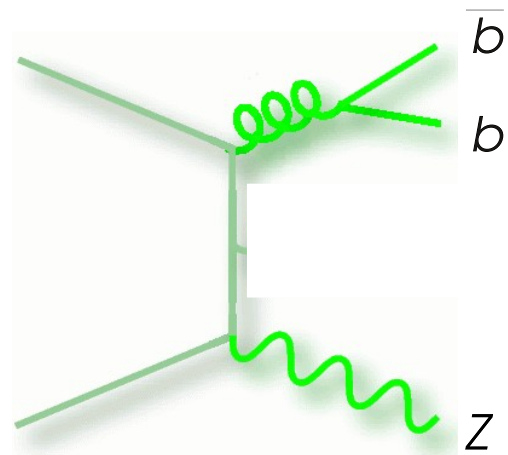
1st, 2nd, 3rd jet pT
Z pT and rapidity (>= 1 jet)
1st jet rapidity
Δy(Z,jet)
y_{boost}(Z,jet)

W / Z +b

Much progress with Z+light flavour

- also need to understand heavy flavour
- THE low mass Higgs background!





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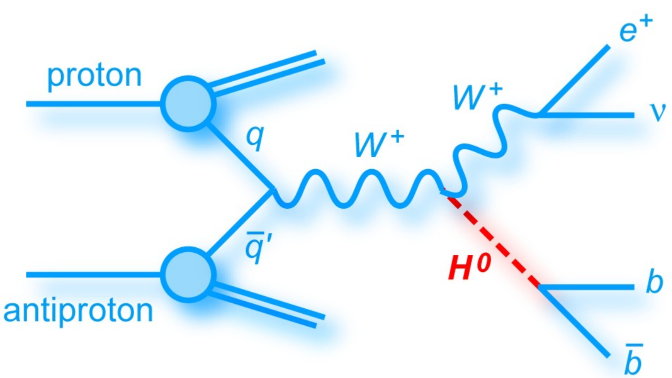
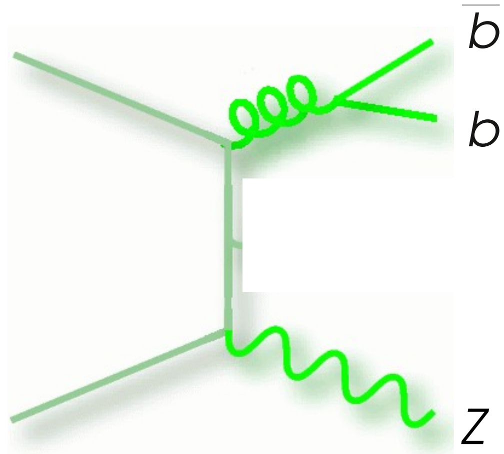
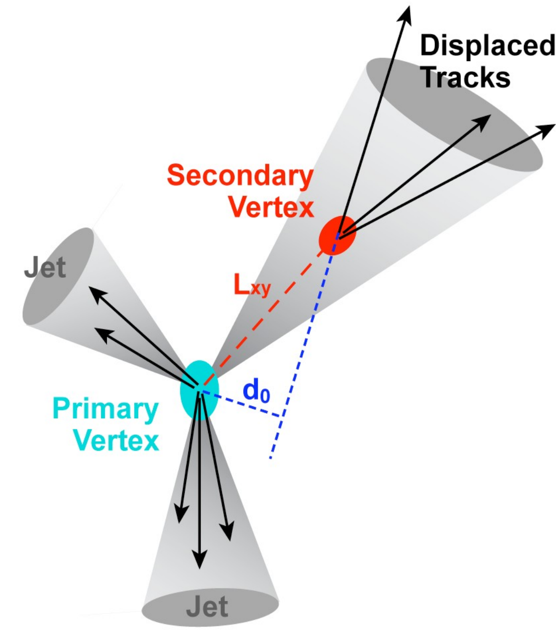




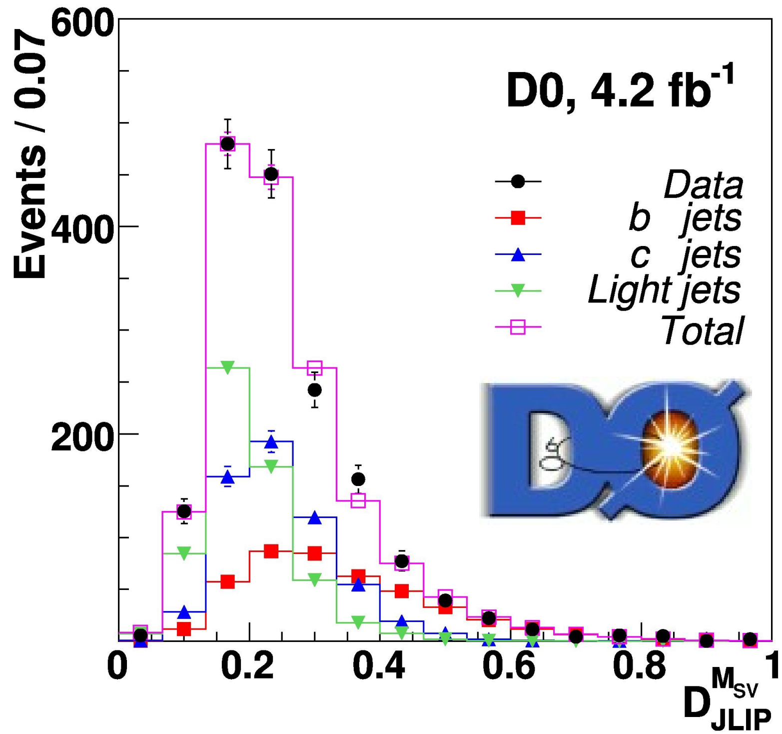


Heavy flavour tagging:

- based on many variables in a NN
- cut on discriminant output

Extract flavour fractions:

- fit templates to jet lifetime, vertex mass
- templates from MC (heavy flavour) data (light flavour).
- both experiments require p_T > 20 GeV



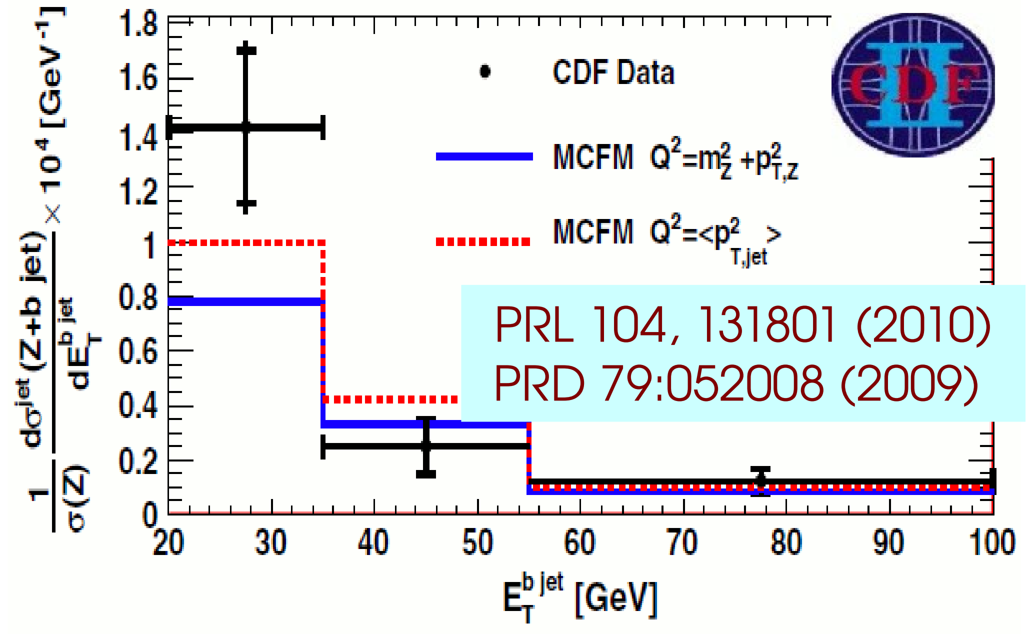
W / Z +b

CDF results, based on 2 fb^{-1}:

W+b jets: 2.74 ± 0.27 ± 0.42 pb
NLO: 1.22 ± 0.14 pb

Z+b / Z: 0.332 ± 0.053 ± 0.042 %
NLO: 0.23% (0.28%)

Z+b / Z+jet: 2.08 ± 0.33(stat) ± 0.34 (syst) %
NLO 1.8% (2.2%)



PRL 104, 131801 (2010)
PRD 79:052008 (2009)

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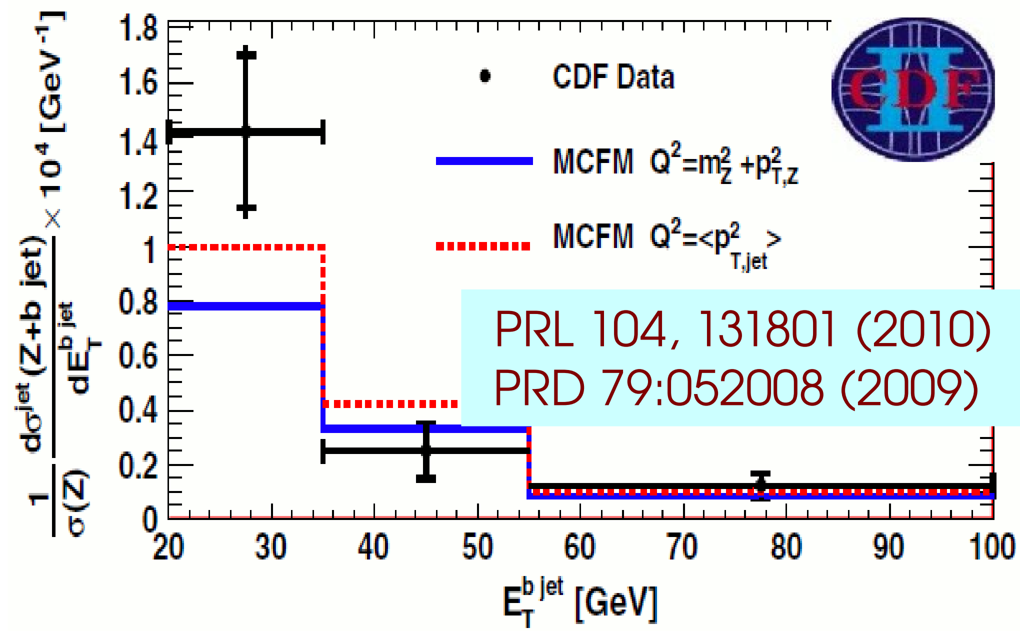

PRL 104, 131801 (2010)
PRD 79:052008 (2009)

New D0 result, using 4.2 fb^{-1}:

- electron and muon channels
- jet $|\eta|$<2.5 (1.5 for CDF)

PRD 83, 031105(R) (2011)

Z+b/Z+jet: 1.93 ± 0.22 (stat) ± 0.15 (syst) %
NLO: 1.85 ± 0.22 % ($Q^2 = m_Z^2$)

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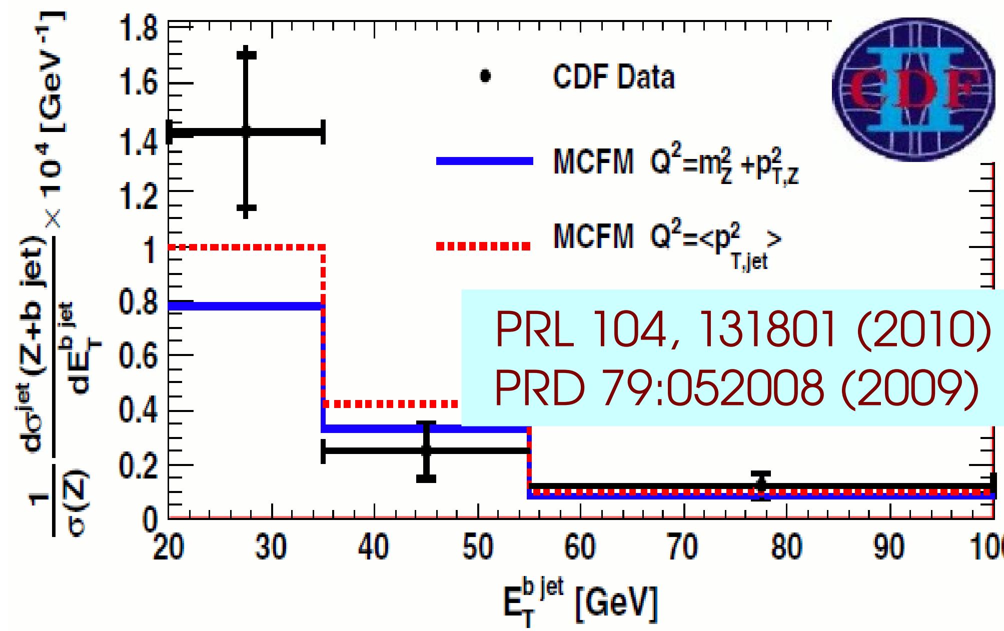

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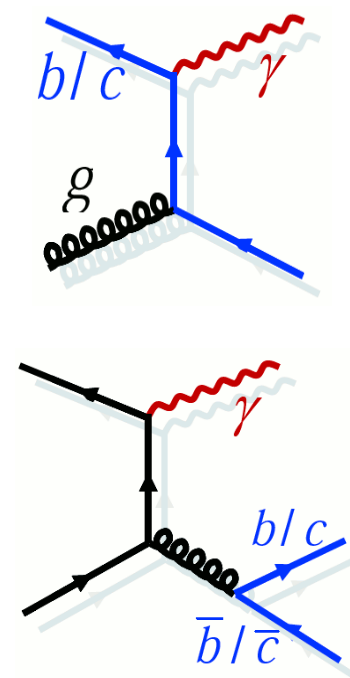


Previous results for photon + heavy flavour:
- theory matches photon + b
- but underestimates photon + c

Phys. Rev. Lett. 102, 192002 (2009), Phys. Rev. D81, 052006 (2010)

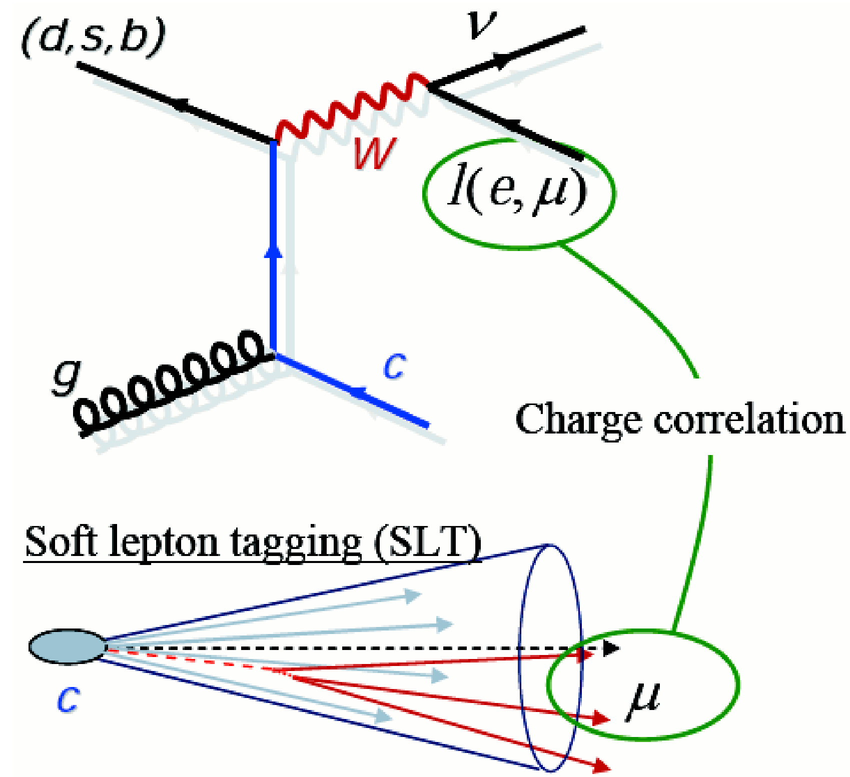
W+c

Probe strange PDF at high Q^2 ($\sim M_W$)

Background to top, Higgs, SUSY

Strategy:

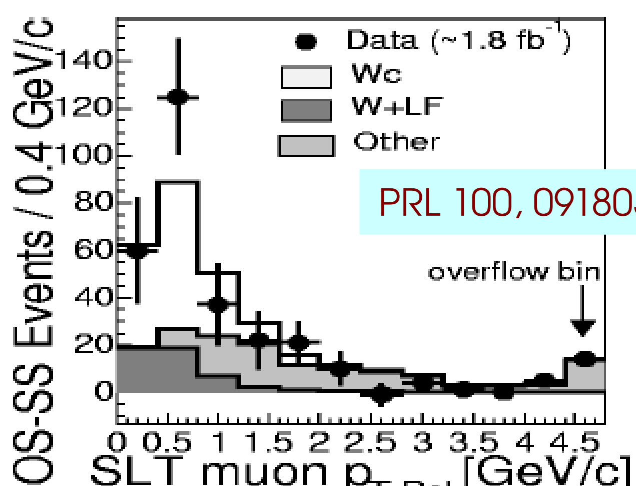
- select high pT e, μ & soft lepton tagged jet
- for W+c, opposite sign (OS) > same sign (SS)
    - multijet, DY, W+bb/cc, OS~SS
- count N(OS) - N(SS)



Good agreement between NLO & data:

$$\sigma_{W+c} \cdot BR = 9.8 \pm 2.8\,(\text{stat})\,^{+1.4}_{-1.6}\,(\text{syst})\,\text{pb}$$

NLO pQCD: $11.0\,^{+1.4}_{-3.0}\,\text{pb}$



PRL 100, 091803 ('08)

New Preliminary result using soft-e tag:

σ x BR = 33.7 ± 11.4 (stat) ± 4.7 (syst) pb

NLO: 17.8 ±1.7 pb

And analysis from D0:

- PLB 666, 23 (2008)

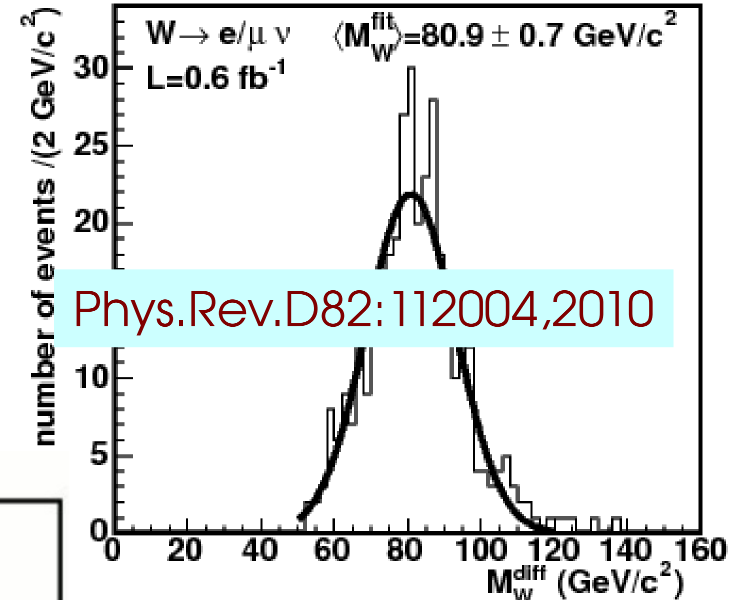
Also consistent with NLO.

Other New Results

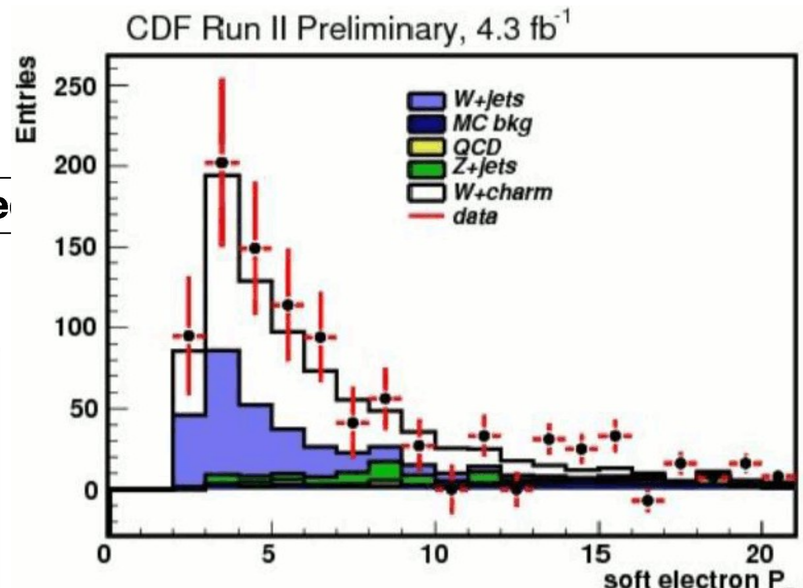
Other new results in:

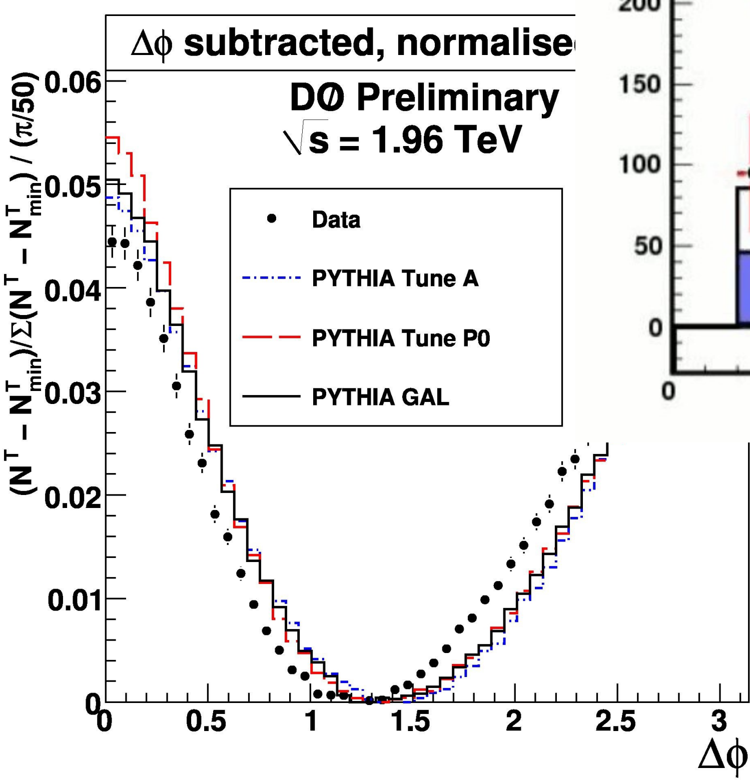
- diffractive W and Z production
- elastic scattering
- underlying event
- strangeness production in min-bias

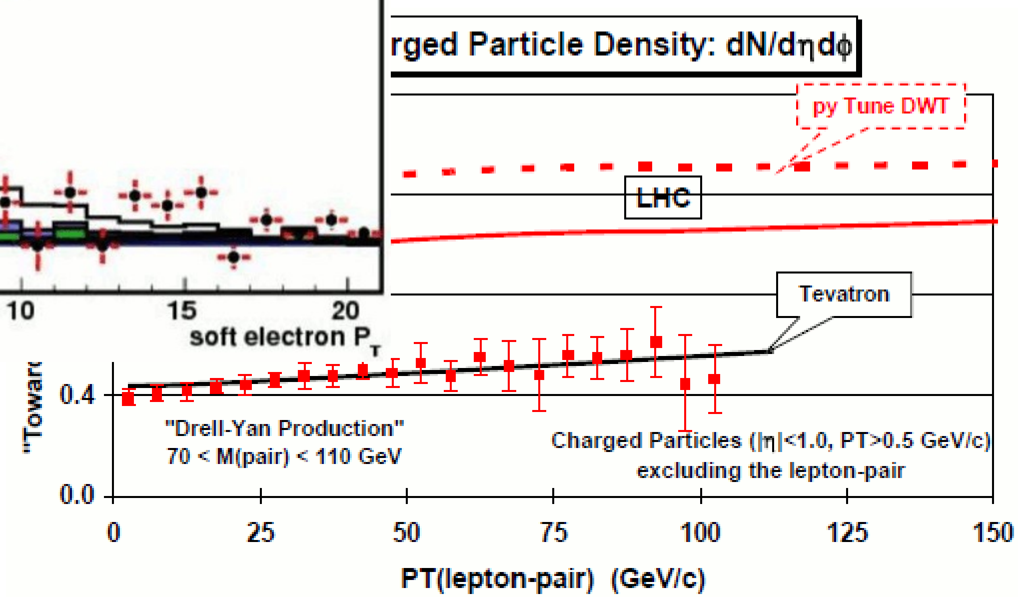
… and many more published results



Phys.Rev.D82:112004,2010







Phys. Rev. D82, 034001 (2010)

Conclusion

Jet results build on the precise JES:

- legacy measurements from the Tevatron
  - improving knowledge of PDFs
  - new measurement of α_s
- will remain competitive for years to come

Boson (+ jet) production:

- excellent test of QCD predictions, essential for discoveries!
- extensive study of photons and Z+jets
- interesting new results on Z/W + heavy flavour

Analyses today used up to half of the Tevatron data set

- lots more to come from the Tevatron QCD programme!

http://www-cdf.fnal.gov/physics/new/qcd/QCD.html
http://www-d0.fnal.gov/Run2Physics/qcd/

Backup

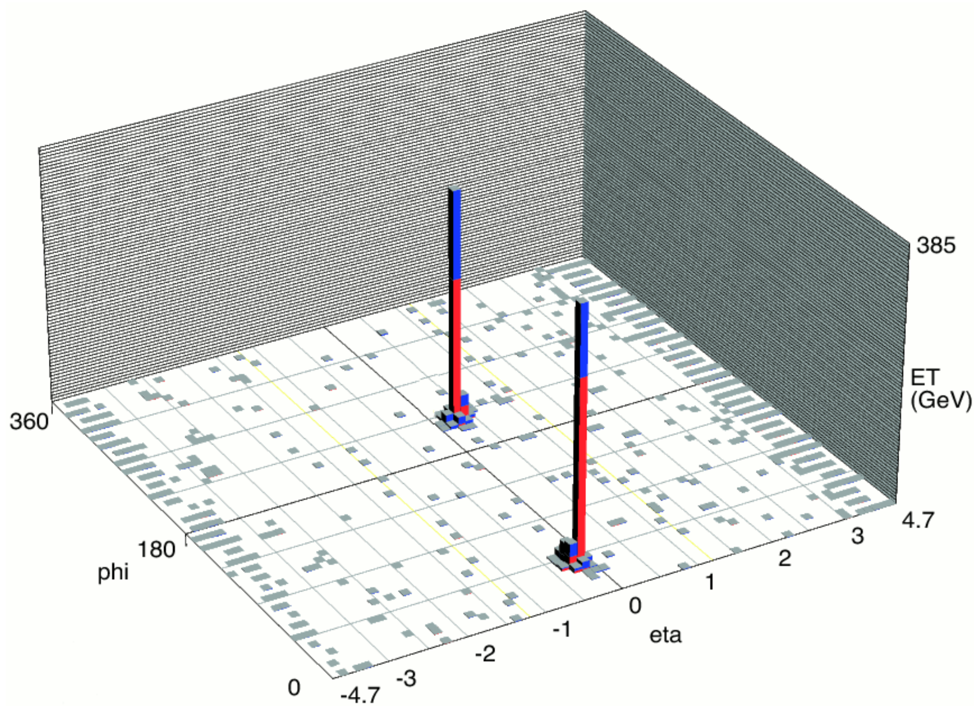
Defining a Jet

G. Hesketh

The D0 RunII seeded, iterative, midpoint cone algorithm.

Run I algorithm:

- draw cone axis around seed (tower)
- split/merge after proto-jet finding
- recompute axis using E_T weighted mean
- re-draw cone
- iterate until stable.

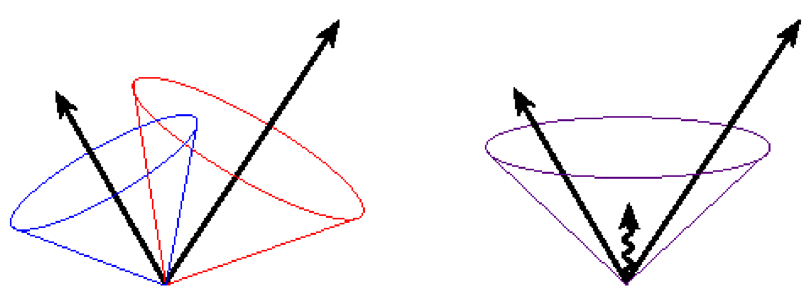


Algorithm sensitive to soft radiation:

- infra-red problem.

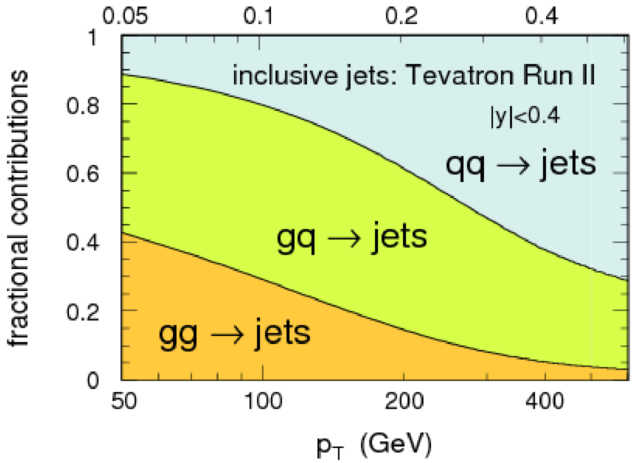
D0 Run II algorithm:

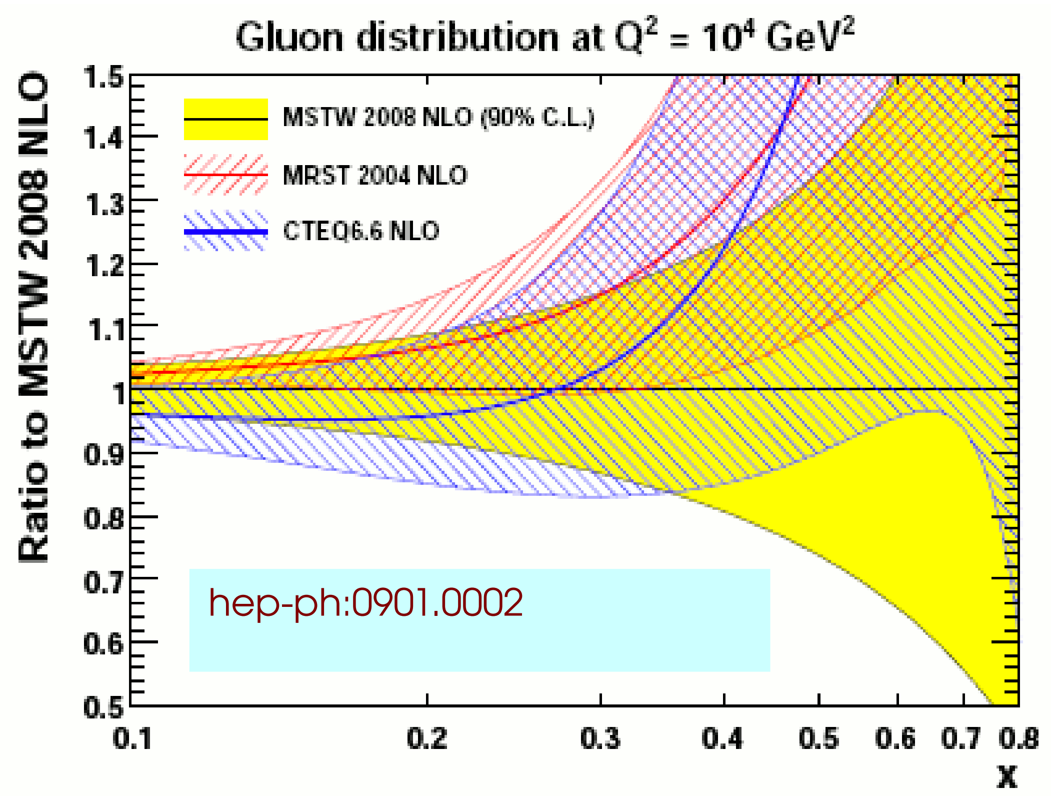
- add additional seeds between jets
- use 4-vectors instead of E_T
    - Jets characterised in terms of p_T and y.

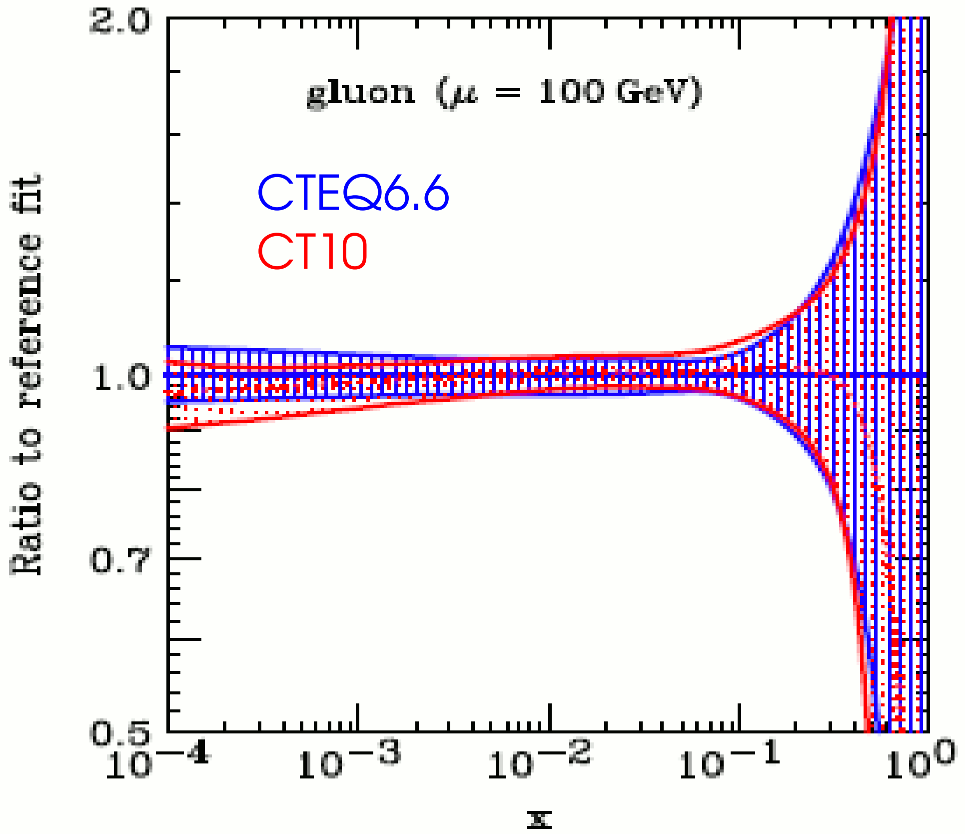


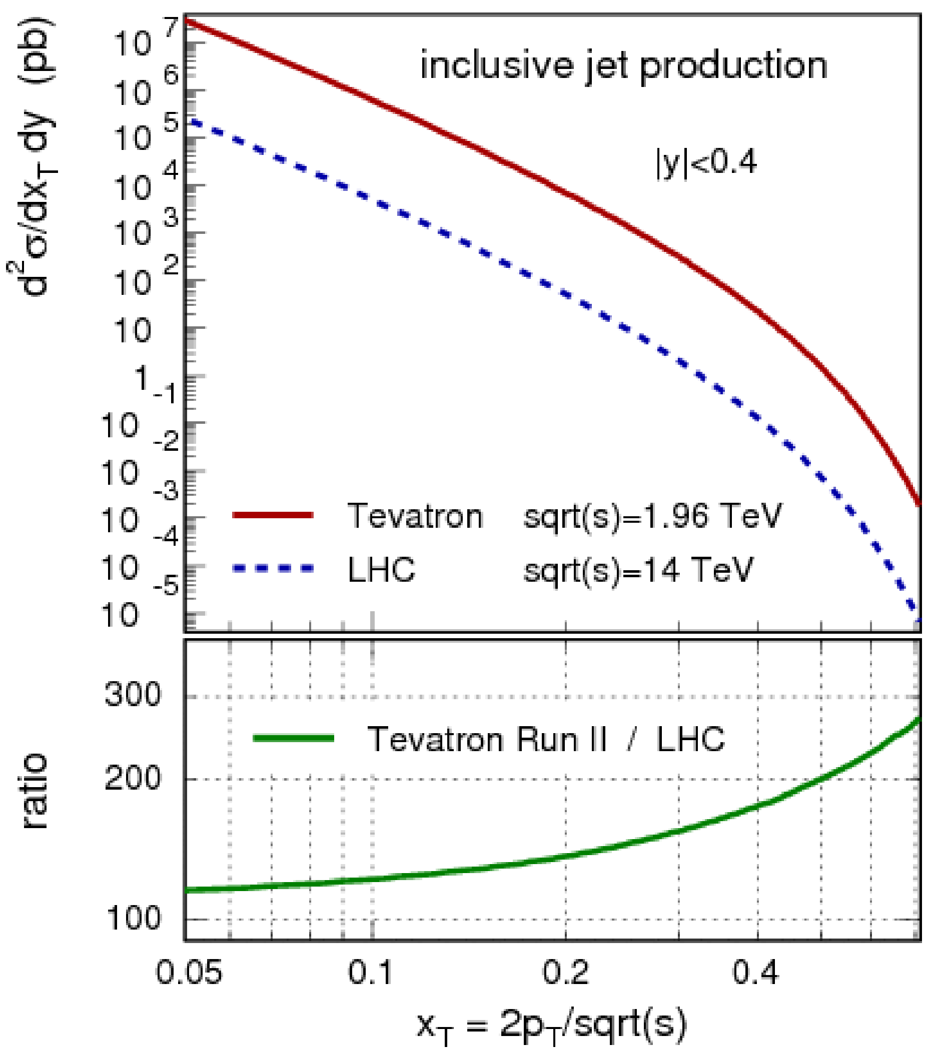
Improved infra-red stability

Algorithm available in fastjet v2.4


inclusive jets: Tevatron Run II
|y|<0.4
qq → jets
gq → jets
gg → jets
fractional contributions
pT (GeV)


Gluon distribution at Q² = 10⁴ GeV²
MSTW 2008 NLO (90% C.L.)
MRST 2004 NLO
CTEQ6.6 NLO
Ratio to MSTW 2008 NLO
hep-ph:0901.0002
x


gluon (μ = 100 GeV)
CTEQ6.6
CT10
Ratio to reference fit
x



At the LHC:

- cross section vs p_T obviously much larger

BUT cross section vs *x* significantly smaller!

e.g. for $|y|<0.4$, factor of 200 at x = 0.5

D0 results with 0.7 fb^{-1}

→ need 140 fb^{-1} at LHC

Further, problem of steeply falling spectrum:

at D0, 1% error on jet energy calibration

→ 5 - 10% error on central σ

→10 - 25% error on forward σ

At LHC:

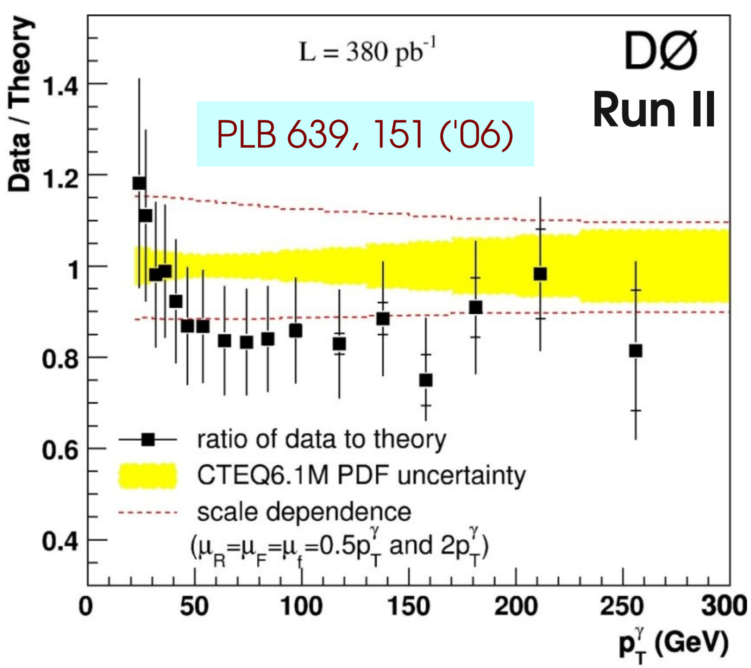
- need excellent jet energy scale
- out to very high p_T

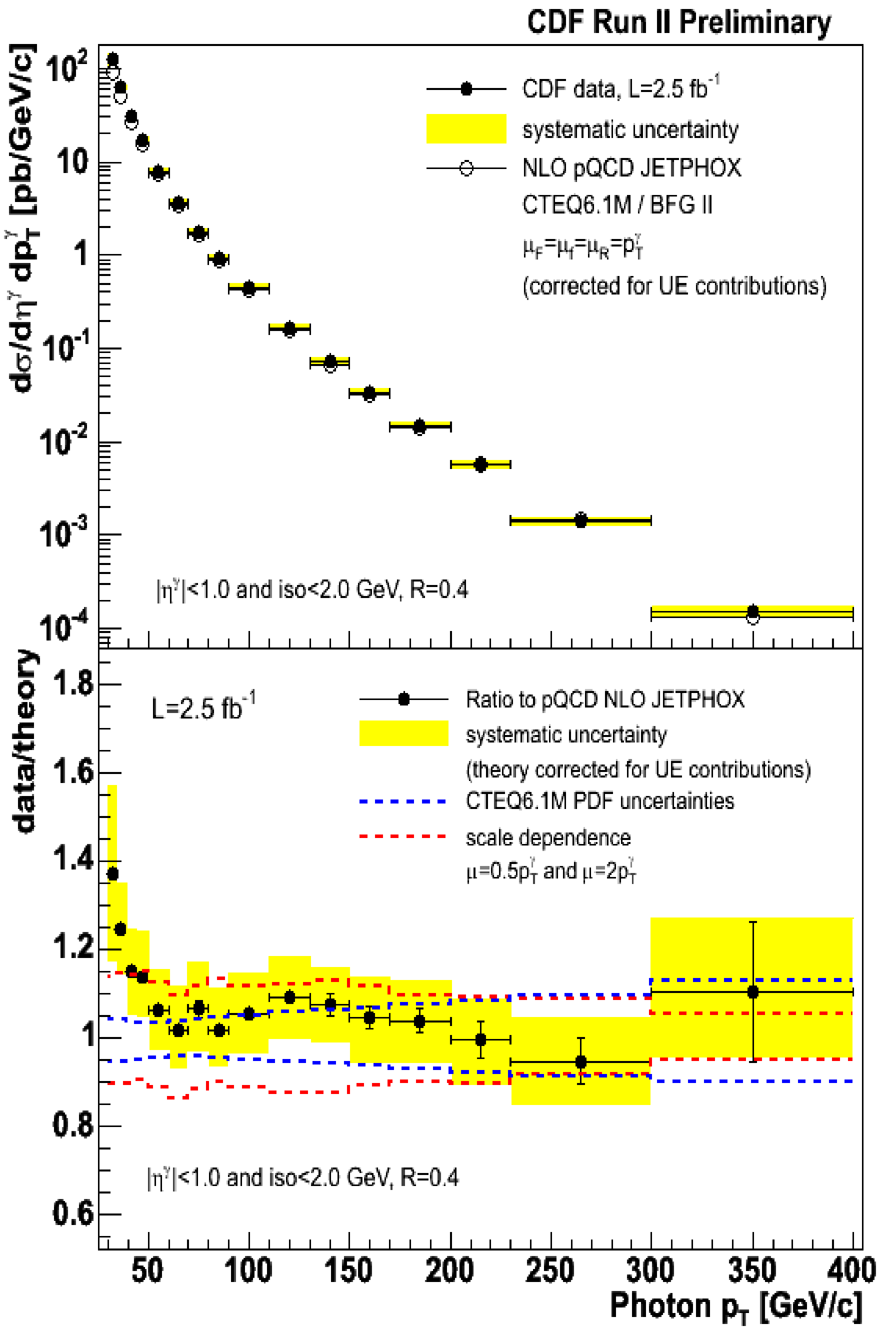
Expect Tevatron to dominate high-x gluon PDF for some years!

Inclusive Photons

Dominant Systematics:
- photon fraction at low pT (5%)
- photon energy scale at high pT (5-15 %).

New CDF result (2.5 fb^{-1})
- extends measured photon p_T range
- agreement within systematics
- shape features at low p_T seen at D0 and CDF
    - **- similar feature seen in Run I, UA2, ...**





Photon + Jet

Investigate further: add a jet

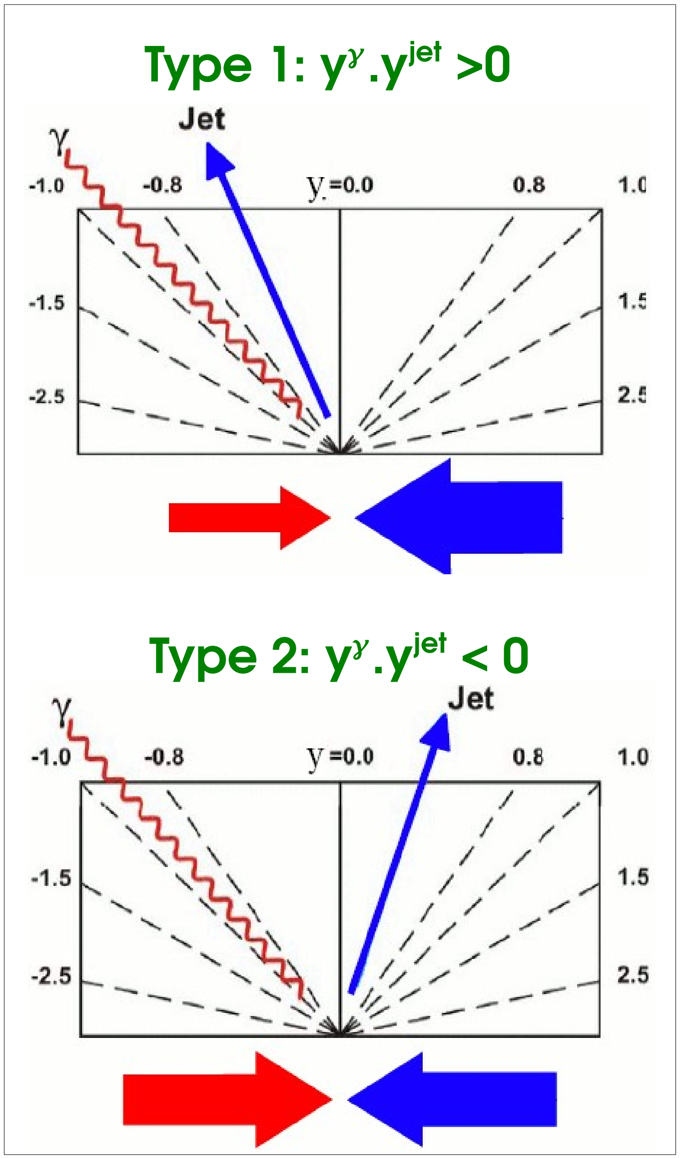
- p_T>15 GeV, $|\eta_{jet}|$<0.8, 1.5 < $|\eta_{jet}|$ < 2.5

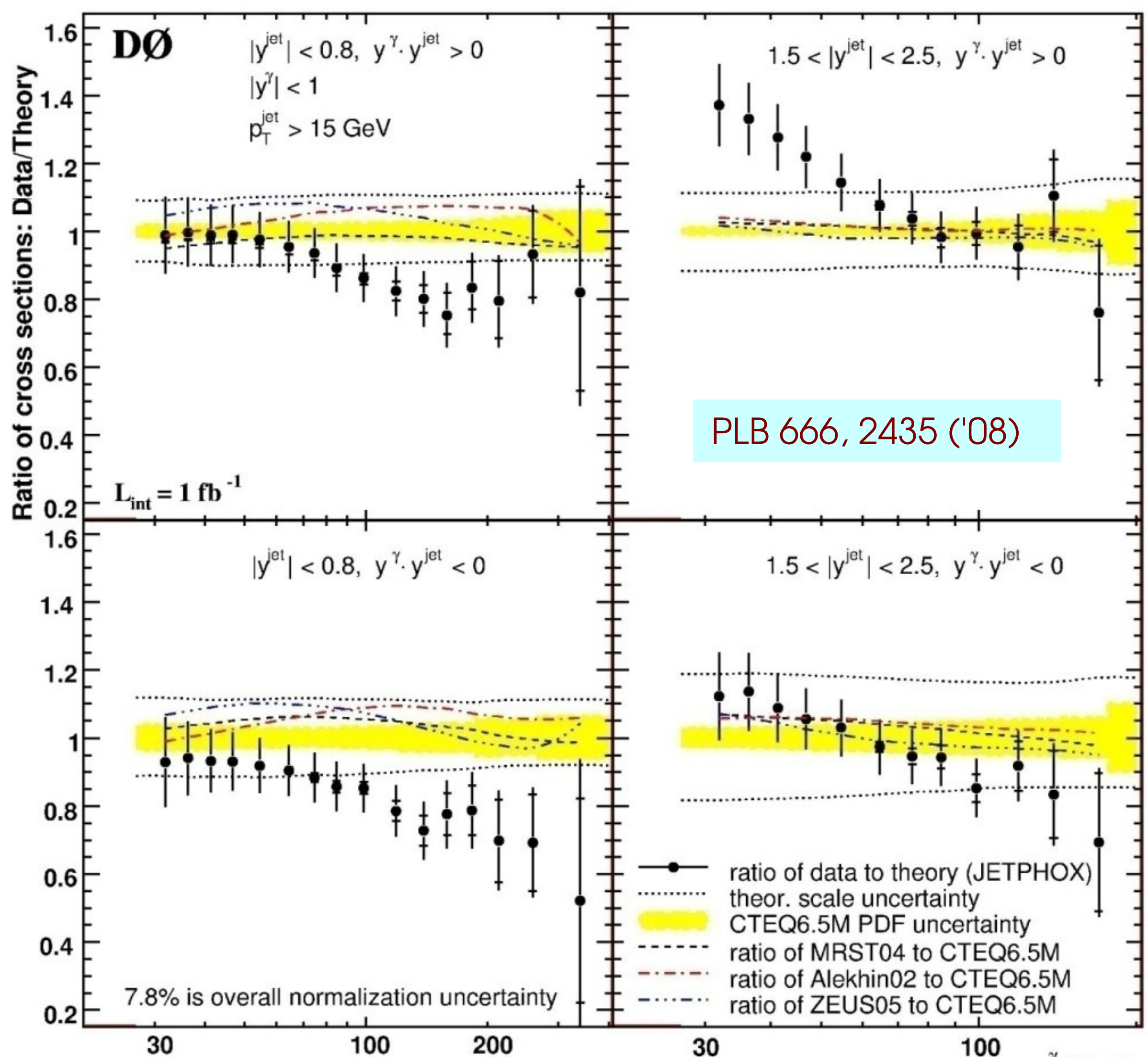
Triple differential:

- in jet η, photon η and photon p_T

Something missing in the theory?

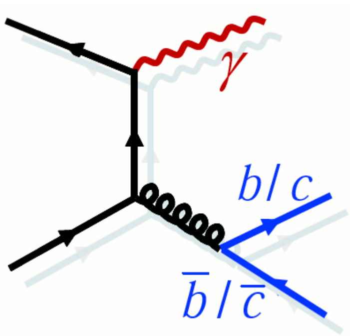
- higher orders, resummation, ..?
- LHC measurements will be very interesting!





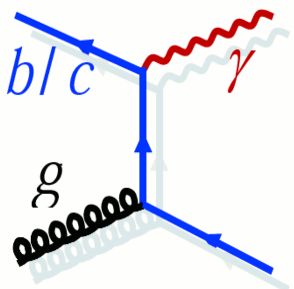
PLB 666, 2435 ('08)

Photon + b / c



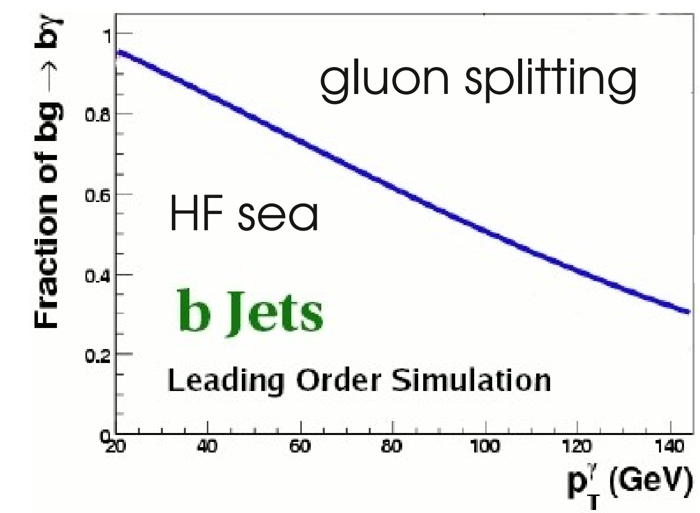
Gluon splitting contribution

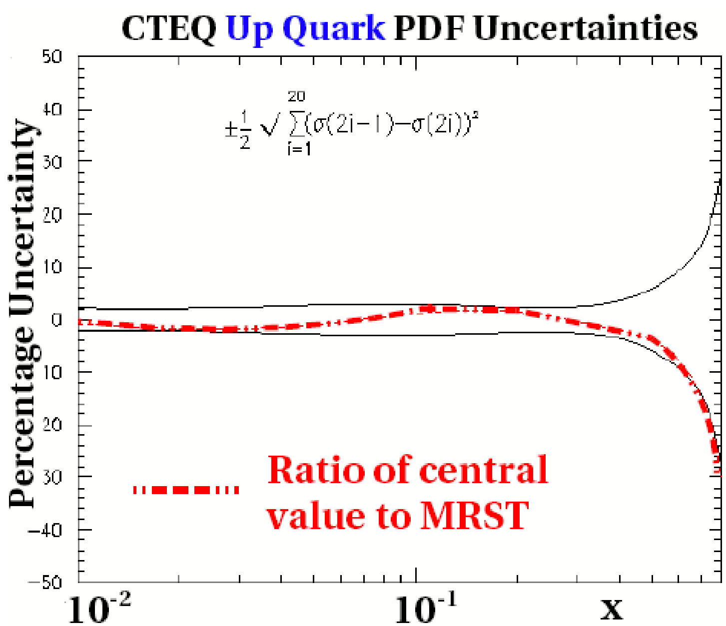
- dominates for high photon p_T
- important as background elsewhere

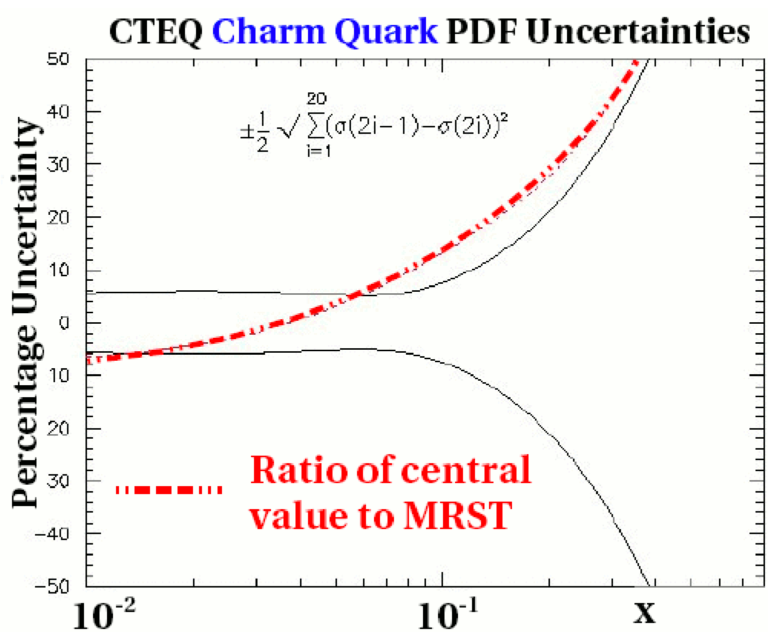


heavy flavour sea contribution

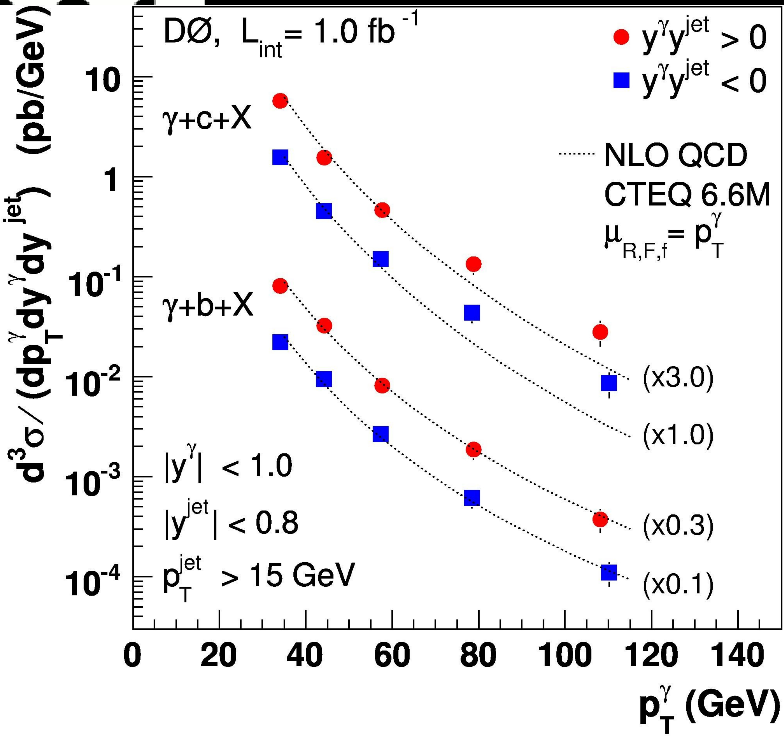
- dominates at low photon p_T
- LHC: larger contribution over all p_T
- charm PDF has significant uncertainties







Photon + b / c

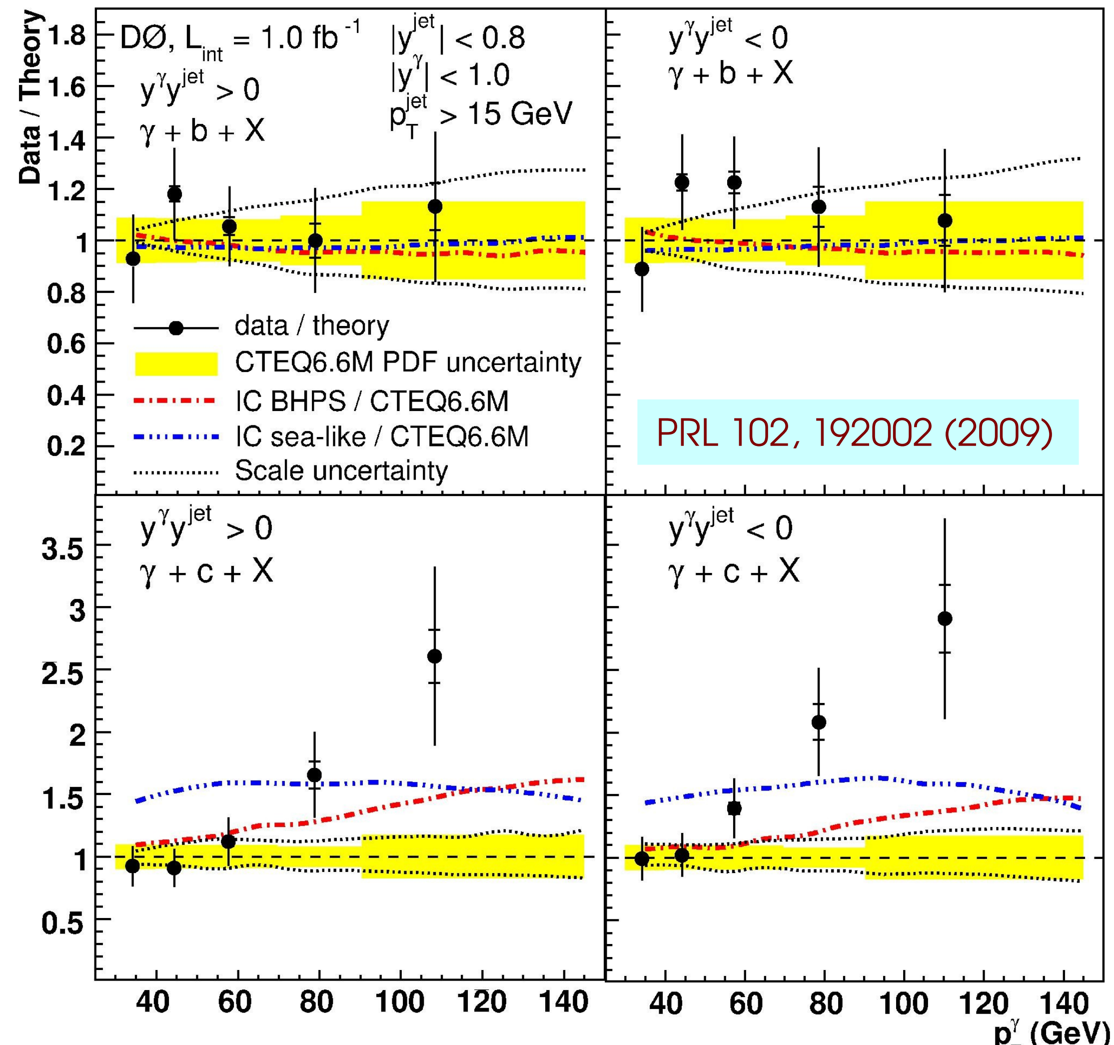


Similar analysis to photon + jet:

- $p_{Tjet} > 15$ GeV, $|\eta_{jet}| < 0.8$, $|\eta_{\gamma}| < 1$

Systematics dominated by flavour fractions

- from template fit to jet lifetime probability



b-jet cross section well modeled

Deficit in c-jet at high p_T:

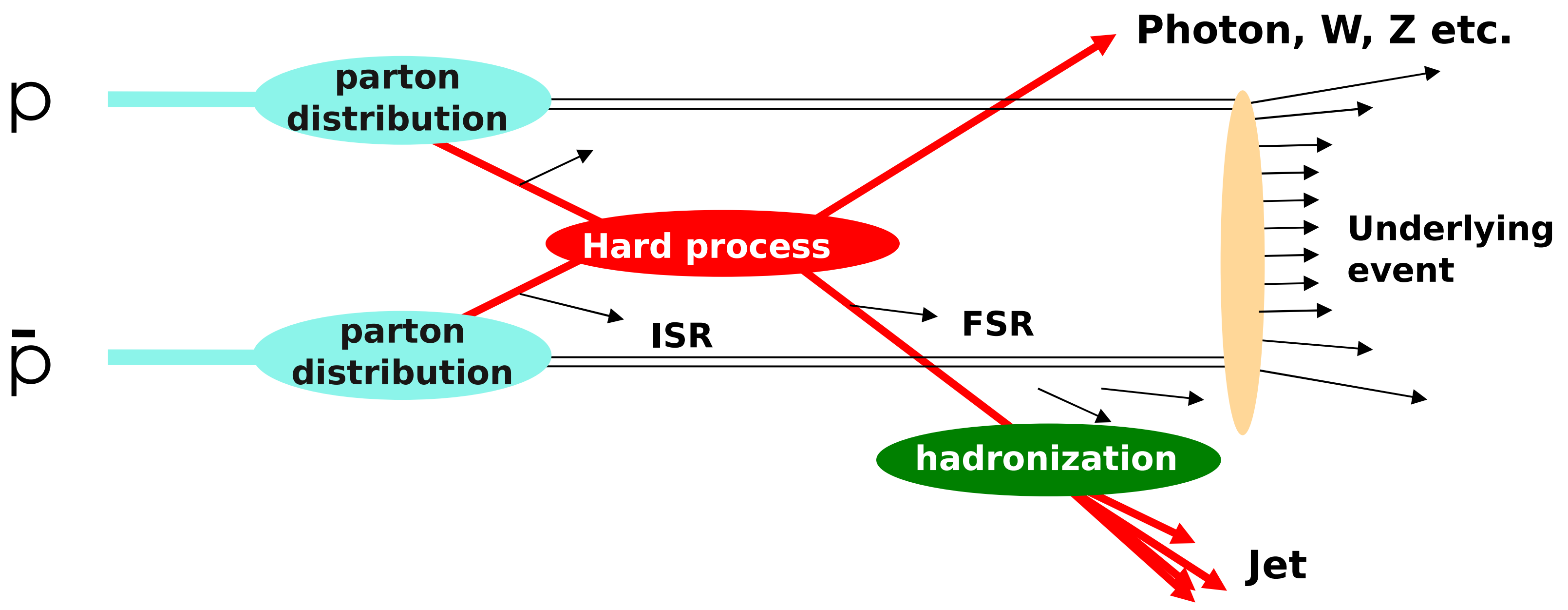
- region dominated by gluon splitting

Increased charm sea models:

- move in direction, but not enough

What will the LHC observe?

- more sensitive to heavy flavour sea


p
parton distribution
p̄
parton distribution
Hard process
Photon, W, Z etc.
ISR
FSR
Underlying event
hadronization
Jet