QCD at the Tevatron

Gavin Hesketh,
Northeastern University

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UK HEP Forum

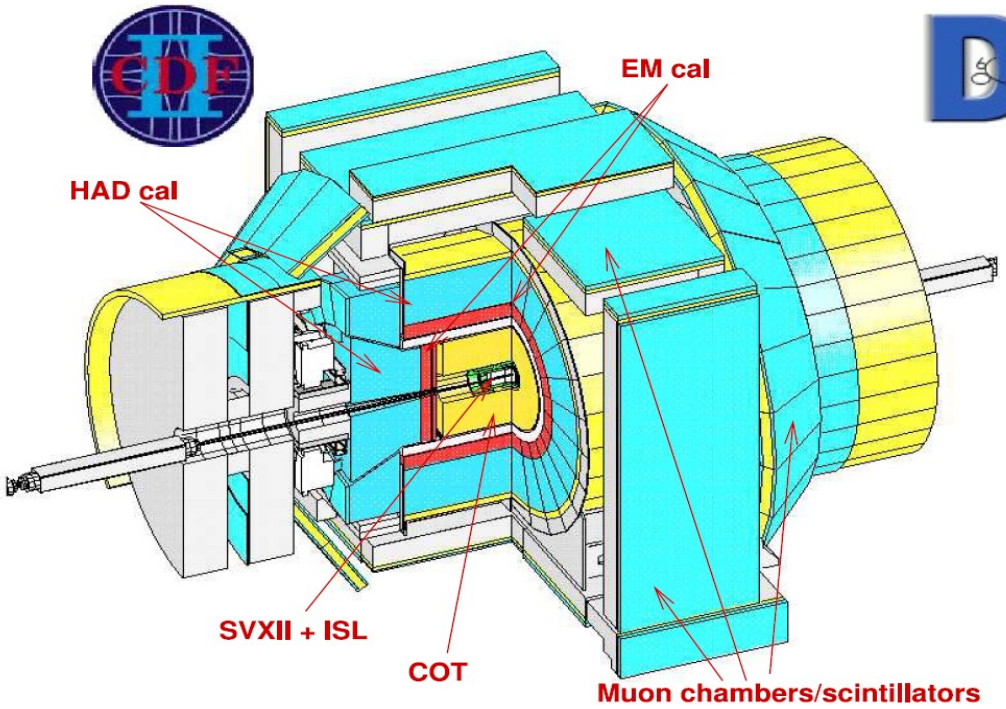
Introduction

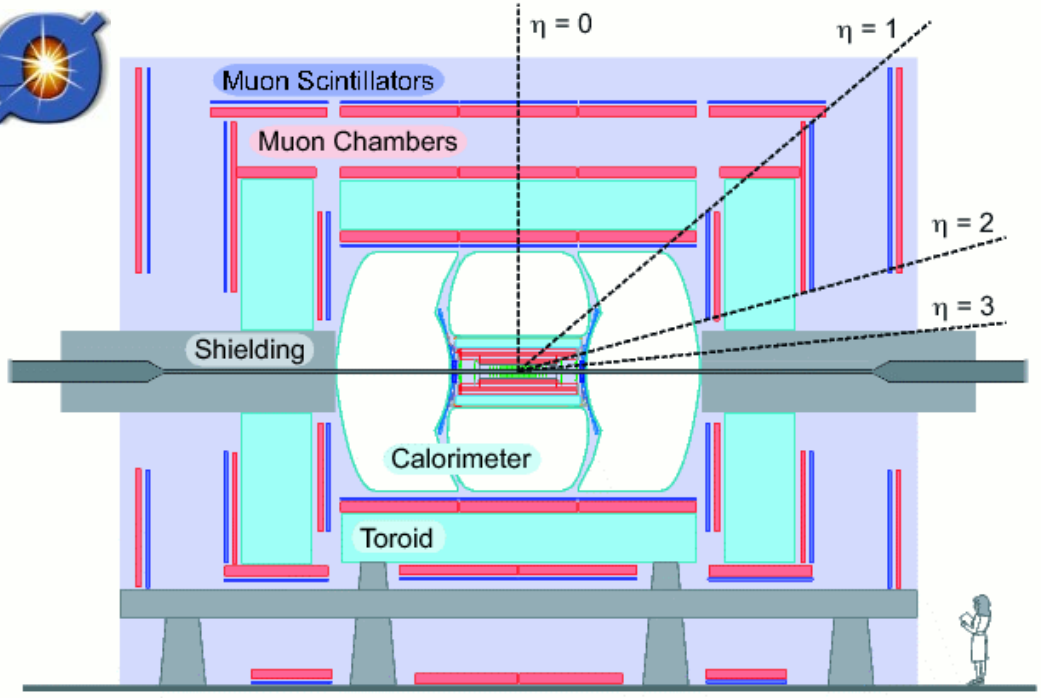
Inclusive Jets

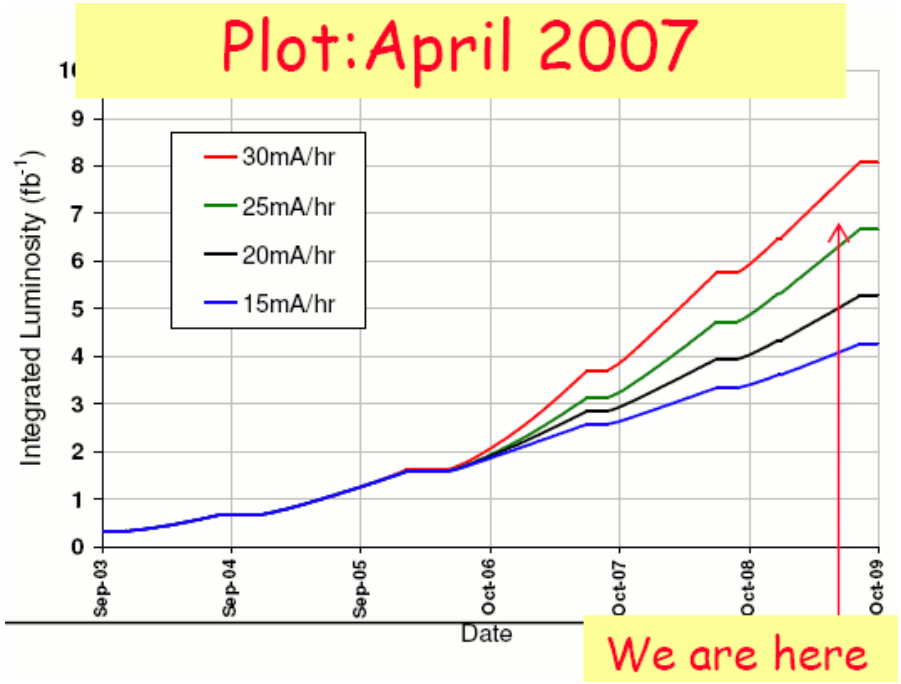
Photon (+jets)

W / Z + Jets

Tevatron & Experiments







Proton anti-proton collisions at 1.96 TeV

- currently highest centre of mass energy

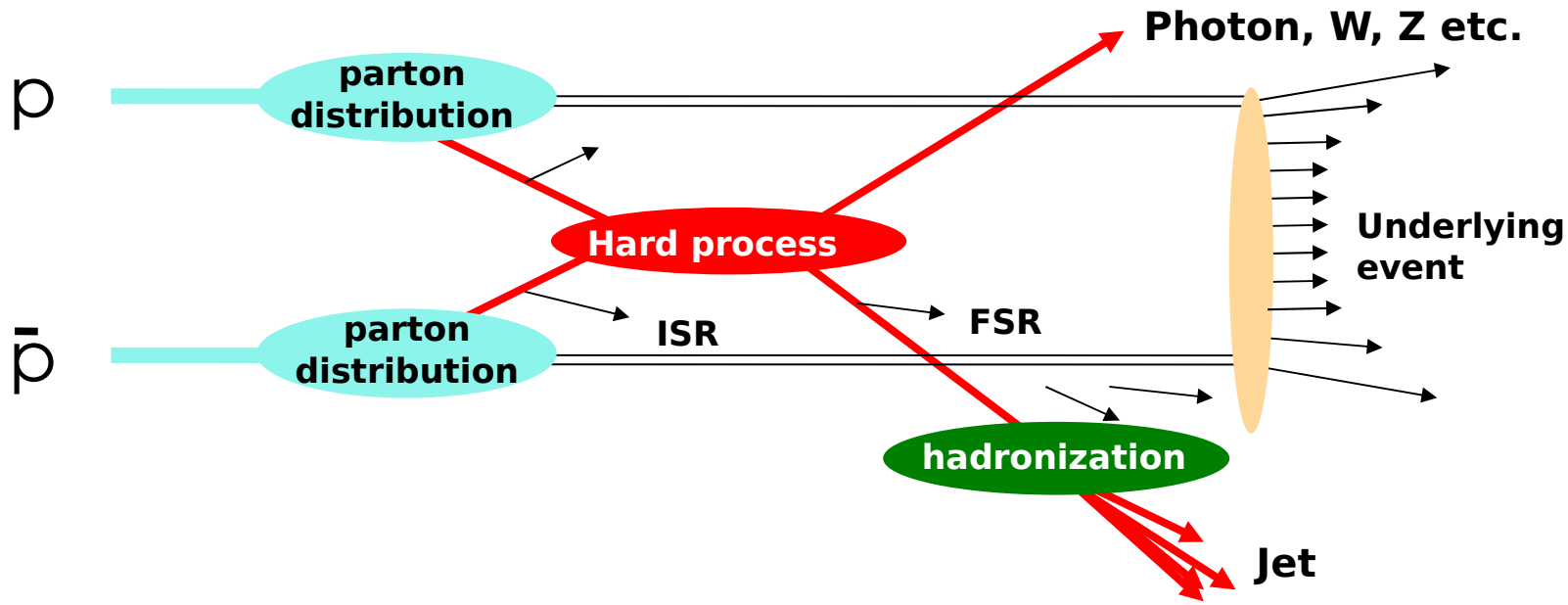
Tevatron performing very well

- 6.5 fb^{-1} delivered (per experiment)
- 2 fb^{-1} recorded in 2008 alone
- projection: > 9 fb^{-1} by end of 2010
- running in 2011 under discussion

Both experiments performing well

- data taking efficiency > 85 %

QCD at the Tevatron



Focus for this talk: testing the Standard Model using high energy hadron interactions

"Hard" QCD:

- NLO pQCD comparisons, constrain proton structure, search for new interactions
  - fundamental 2->2 processes
- study production of EW bosons (+jets)
  - more complex 2->2, 3, 4, 5, ... processes

"Soft" QCD:

- also need to understand the physics environment: underlying event, hadronisation

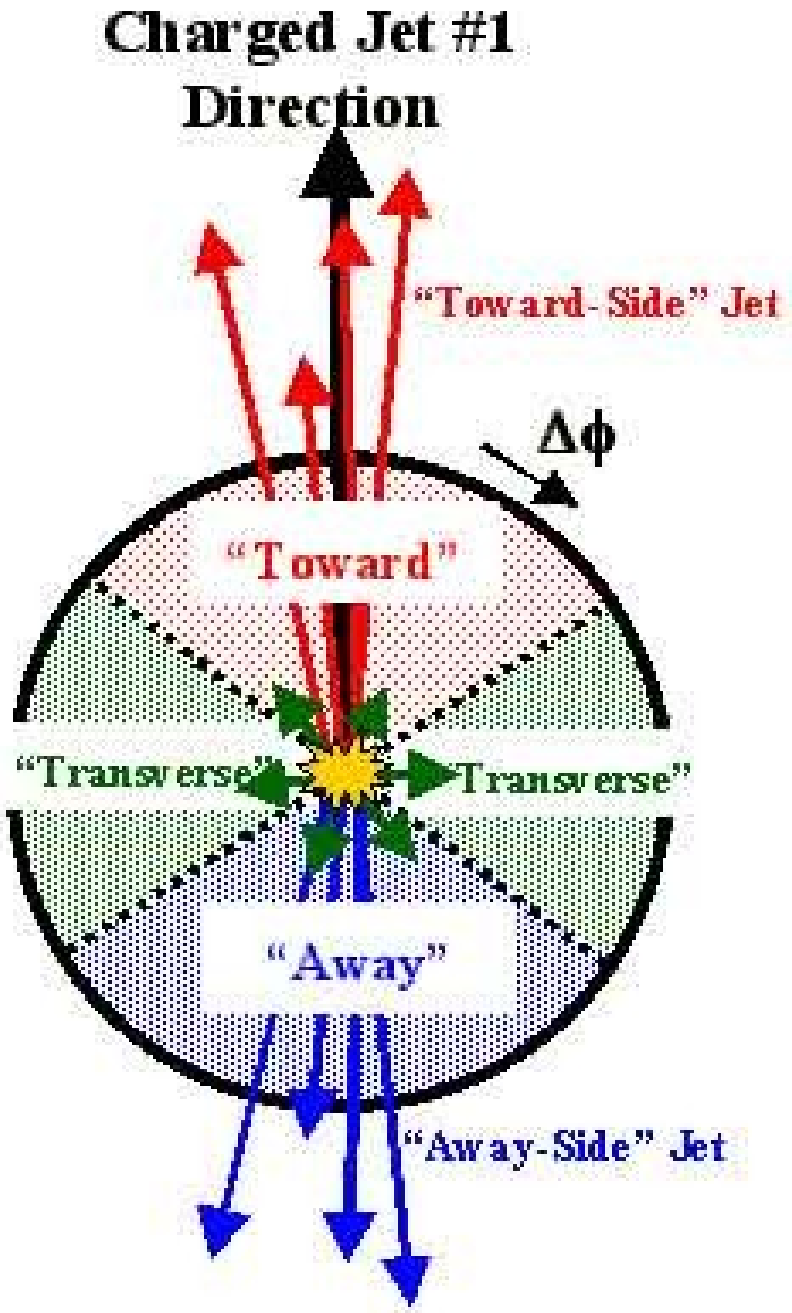
For more details, see CDF and D0 web pages. Apologies for all the results I cannot cover!

Underlying Event

Underlying Event

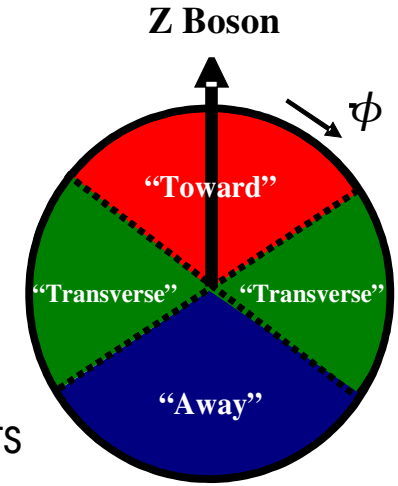
Techniques developed at CDF:

- look at charged particles in different regions
- transverse most sensitive to underlying event
- PYTHIA tune A (+ relatives) describe data

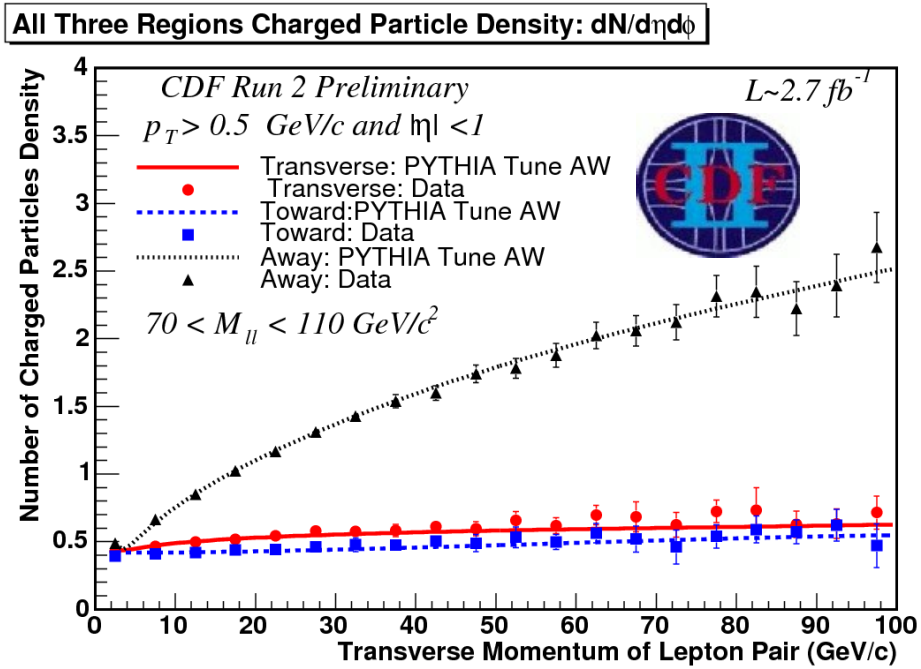


Underlying Event

Several studies at CDF
Update classic method:
- now use Z events



Compare to PYTHIA
- tuned on jet data
- good agreement in Z events



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- PYTHIA tunes describe data well
- b jet situation less clear, need more study

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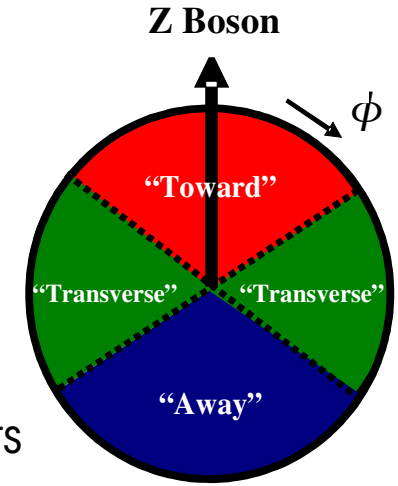

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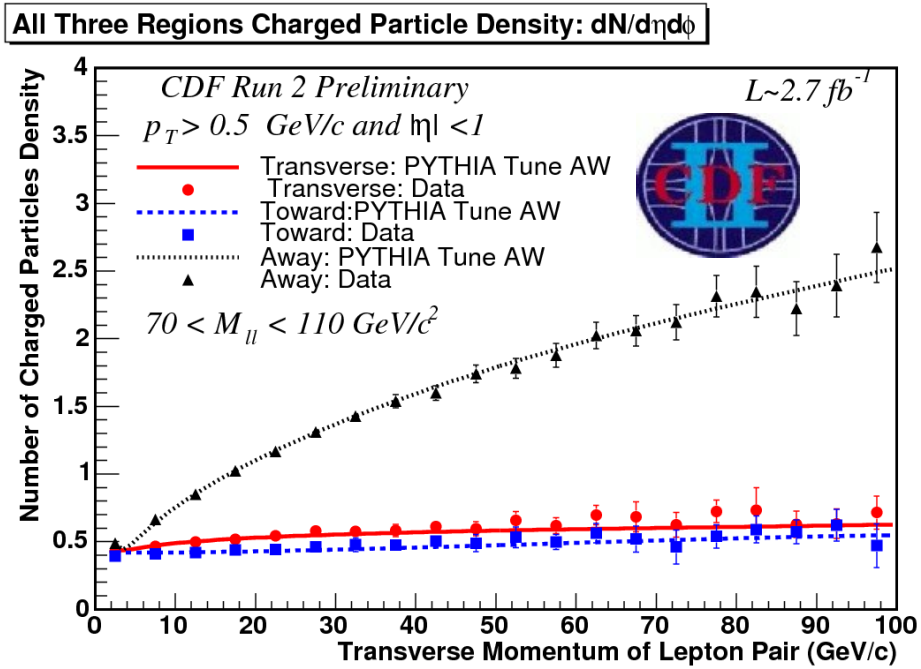

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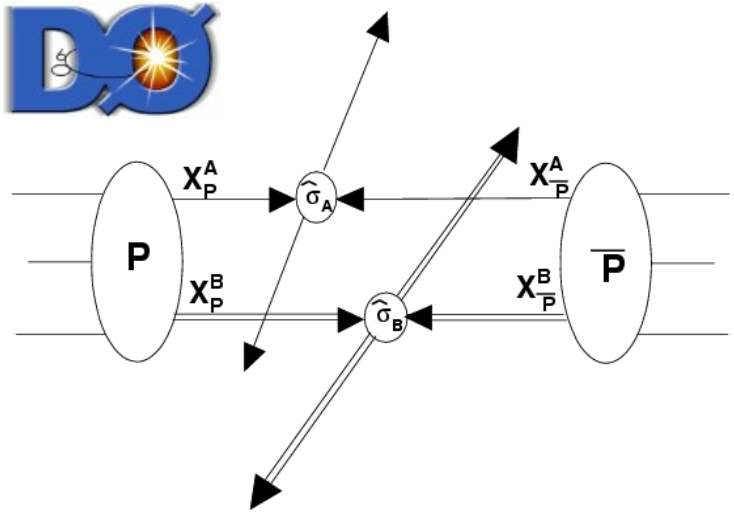
Double parton interactions:
- information about proton structure
- important background



Tag primary interaction A= γ+jet
Identify second interaction B=di-jets

Extract effective cross section:

$$\sigma_{DP} = m \cdot \sigma_A \cdot \frac{\sigma_B}{2\sigma_{eff}}$$

Measured: $\langle\sigma_{eff}\rangle$ = 15.1 ± 1.9 pb
Consistent with previous CDF result

Jets

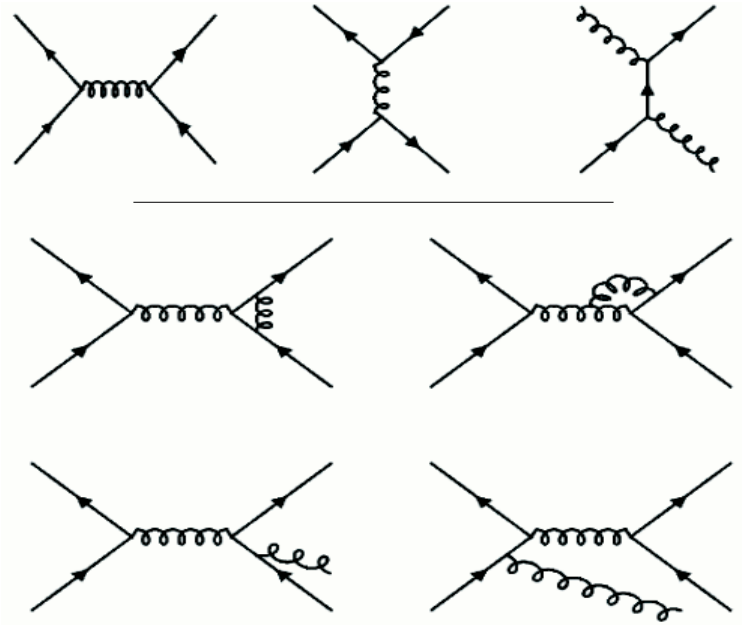
- inclusive jets
- di-jet mass, angles

Jet Production

Fundamental process at hadron collider!

Inclusive jet cross section constrains PDFs

- especially gluon at high x
- also probe for quark substructure



LO

NLO

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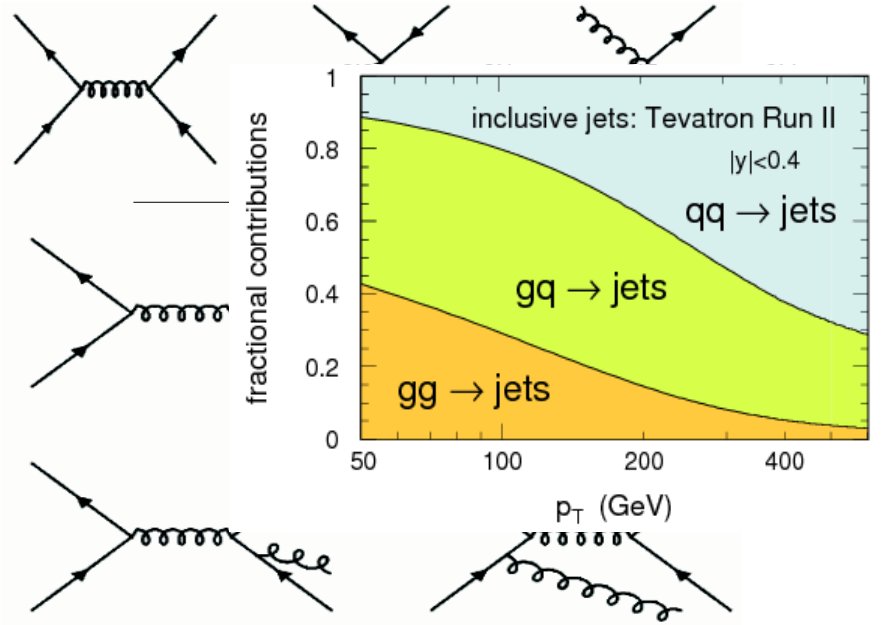

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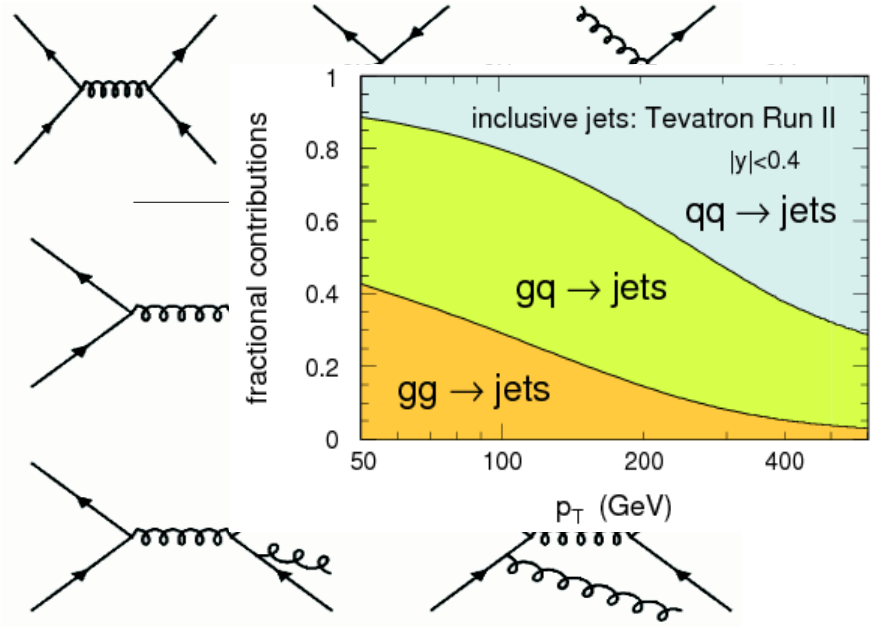
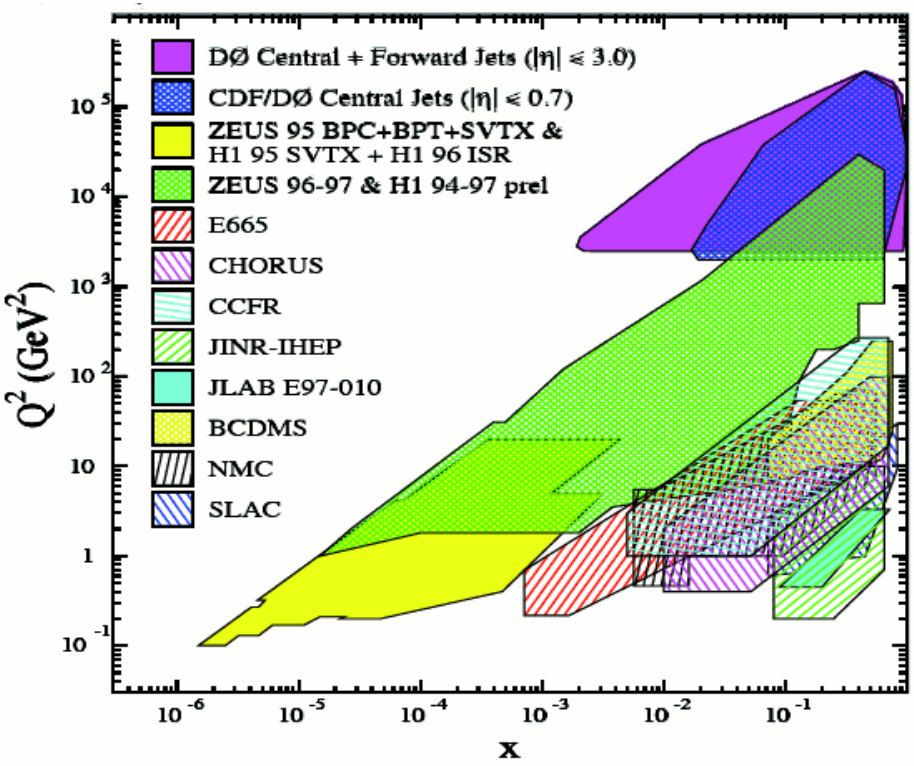
Tevatron complimentary to ep, fixed target





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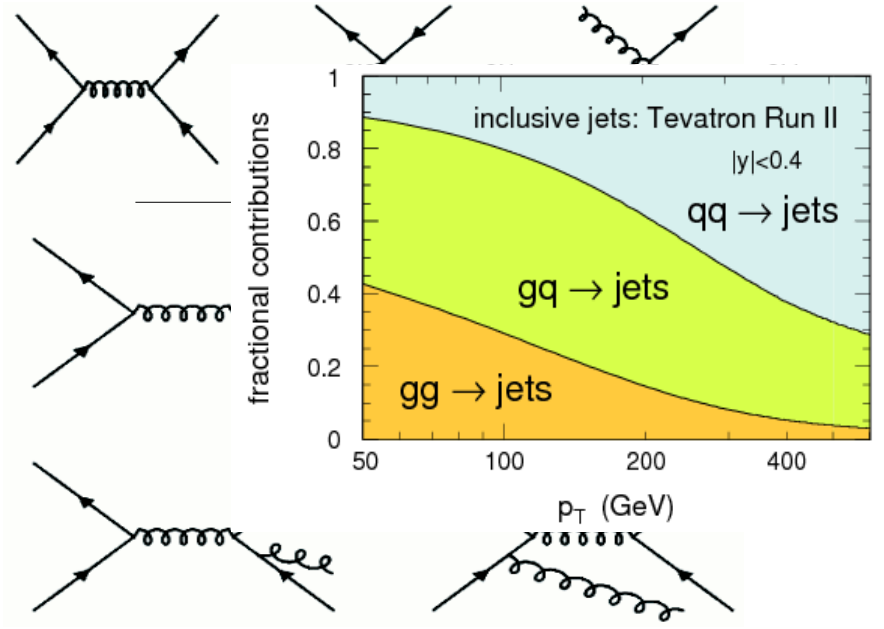
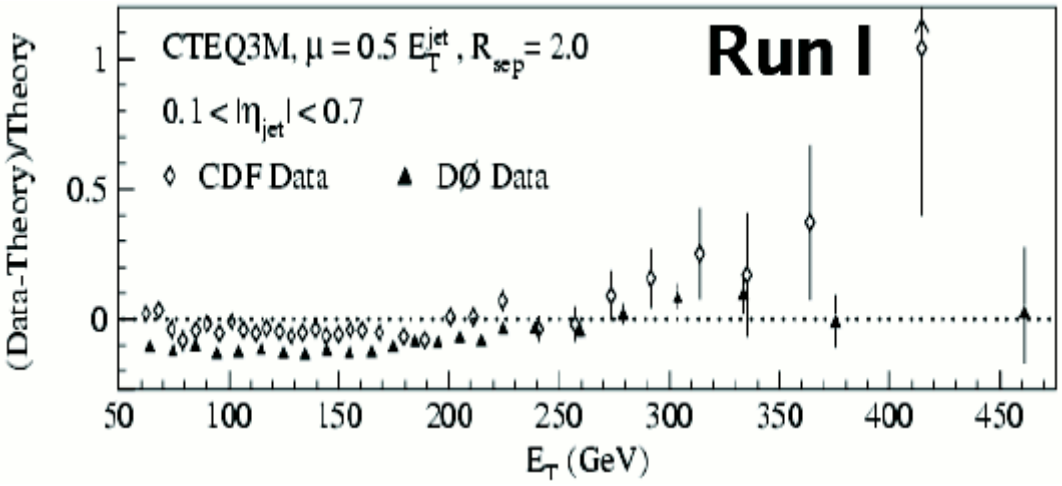
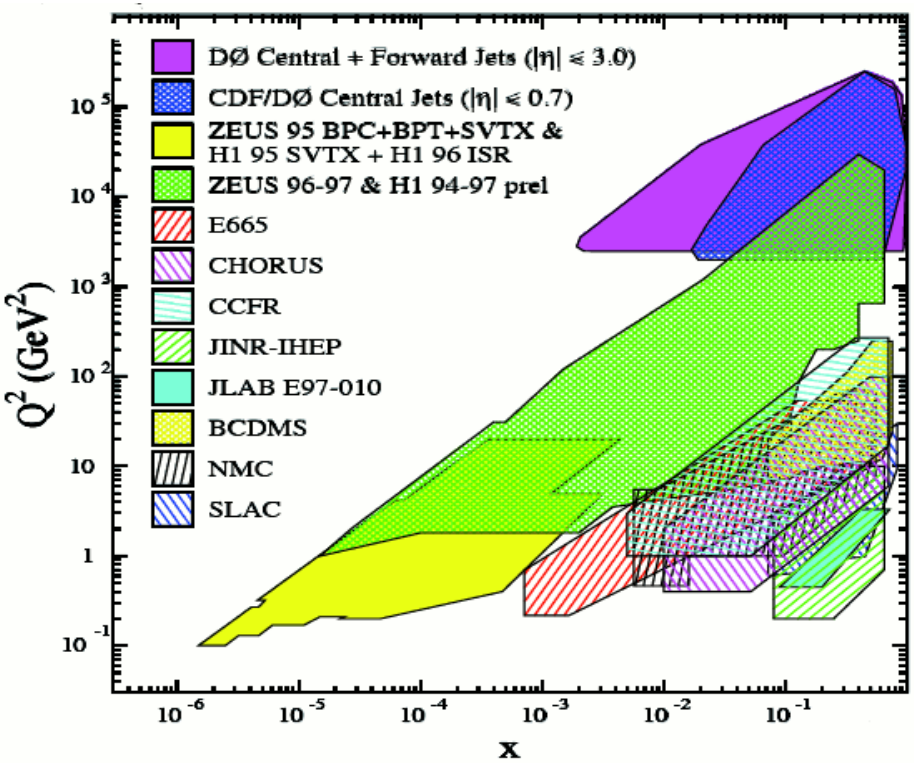
Run I measurements left lots of high-x freedom
- in Run II, analysed 10x the luminosity
- 5x higher cross section at p_T = 550 GeV







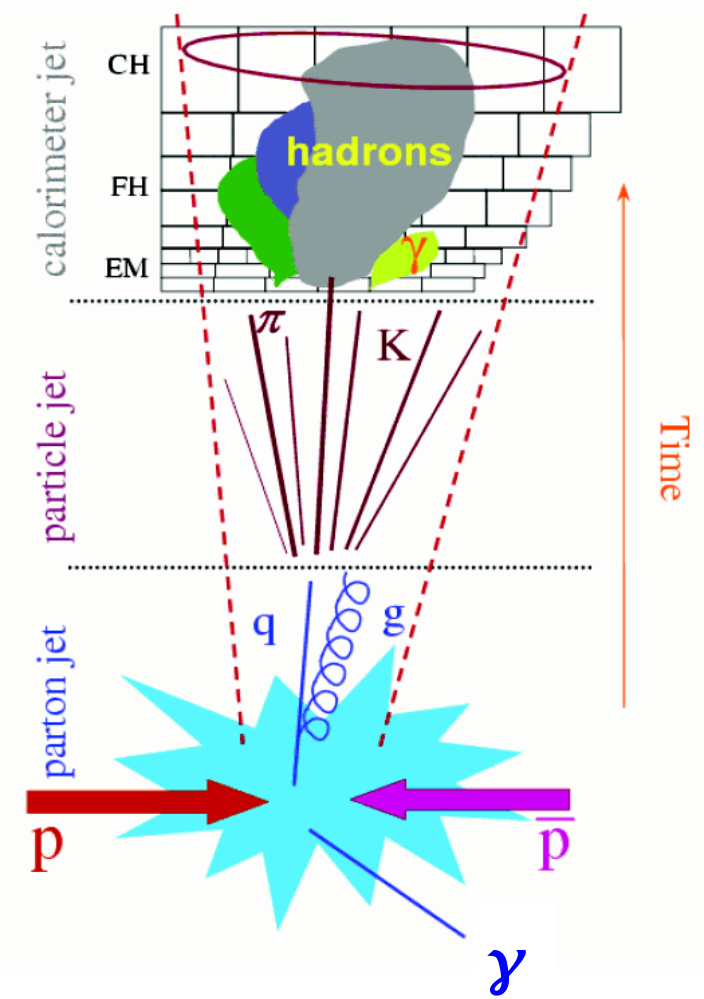
Jet Energy Scale

CDF and D0 use mid-point cone algorithms

- cone size 0.5 (0.4) D0 (CDF) or 0.7 (both)

Main steps in energy scale calibration:

- p_T balance in back-to-back γ+jet
  - EM calibration from Z->ee
  - relative η calibration with γ+jet and di-jet
  - account for quark/gluon jet response
- further corrections for (detector) showering
- and for pile-up / min bias overlay



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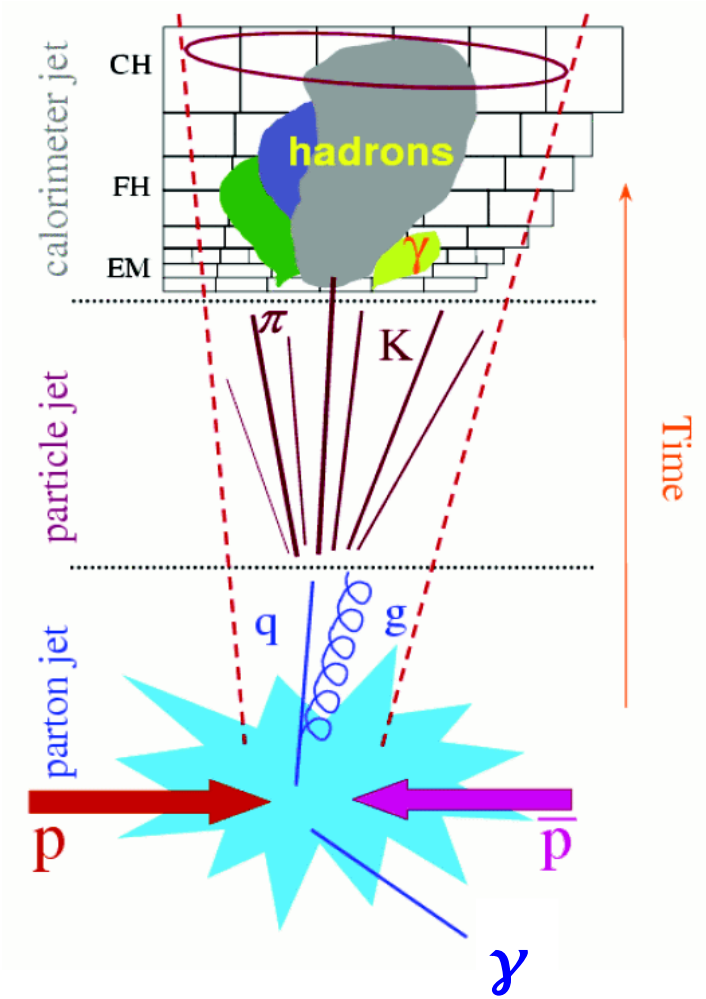

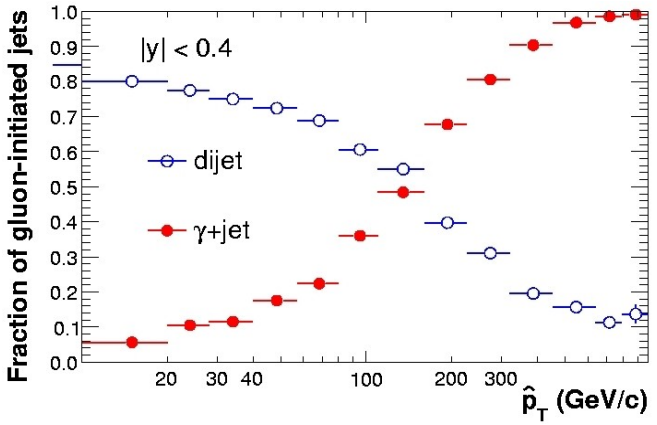

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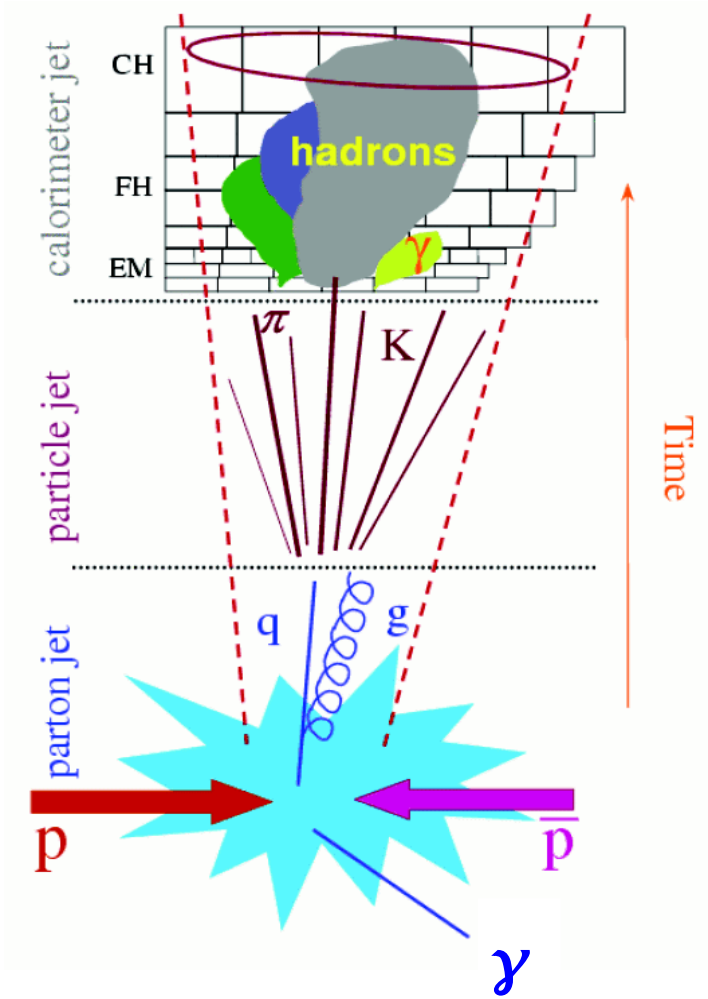
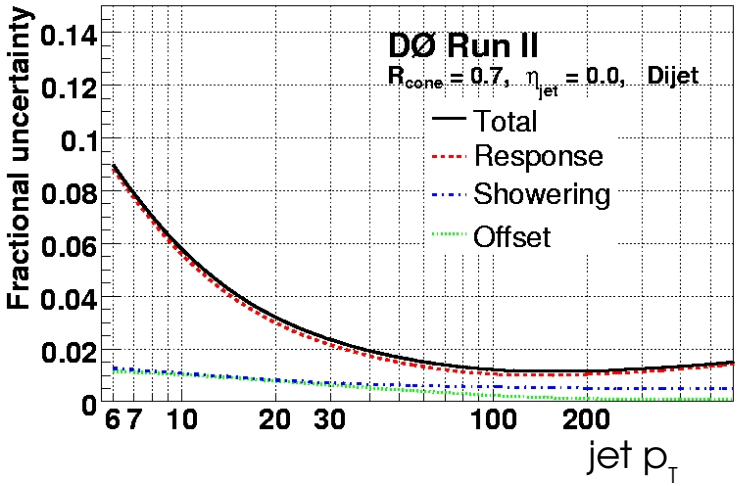
Huge amount of work:

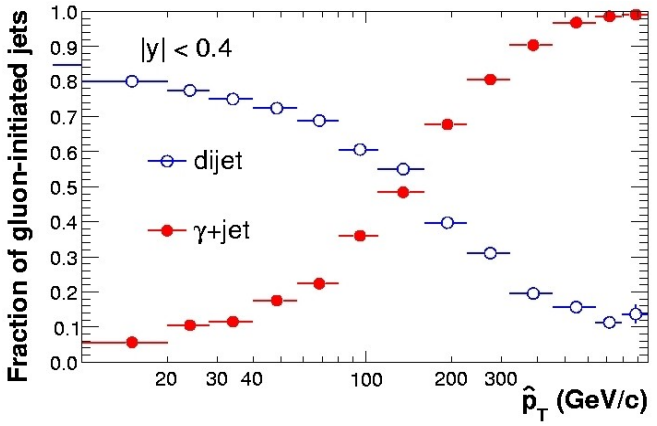
- data measurements, MC tuning

Remarkable achievement:

- uncertainties ~ 1-2 % (D0), 2-3 % (CDF)
- took 7 years!





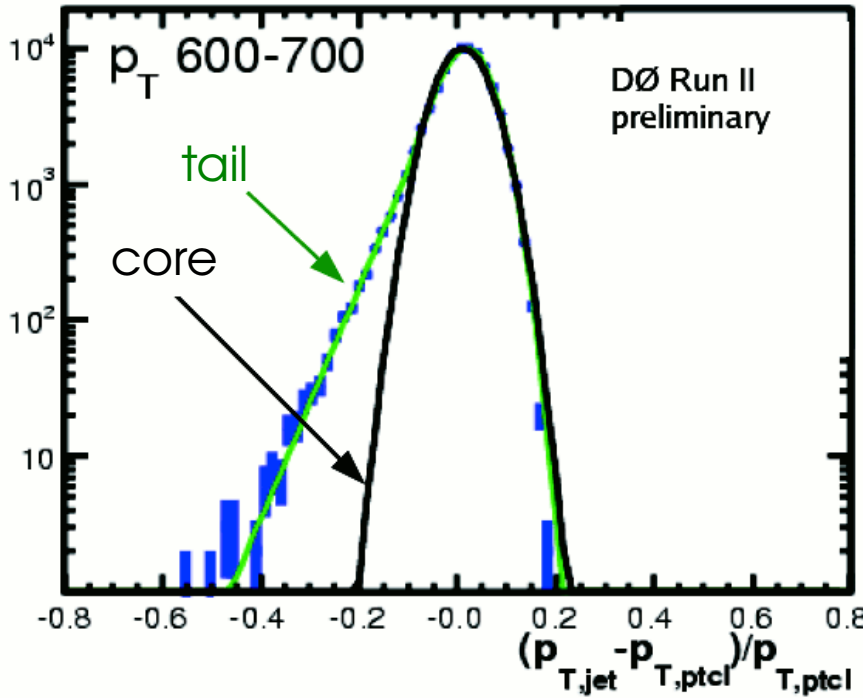


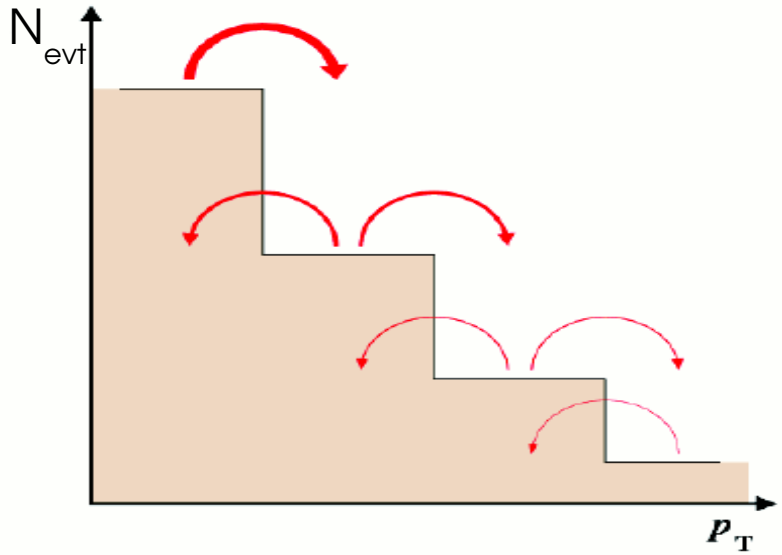
Inclusive Jets

Benchmark: inclusive jet cross section.

- essentially a counting experiment
- in bins of jet p_T and rapidity

$$\frac{d^2\sigma}{dp_T dy} = \frac{N}{\epsilon \cdot L \cdot \Delta p_T \Delta y} \cdot C_{smear}$$





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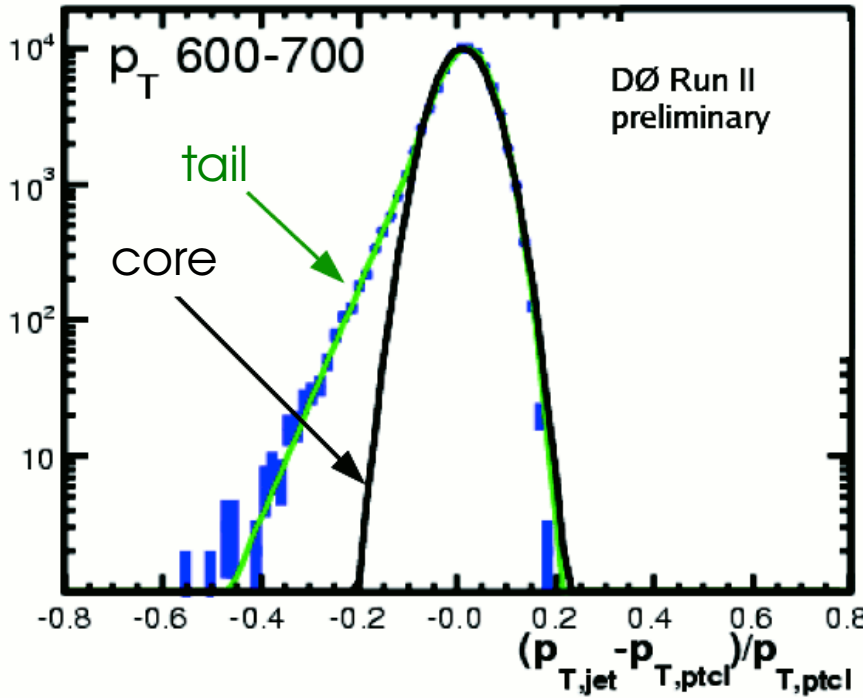
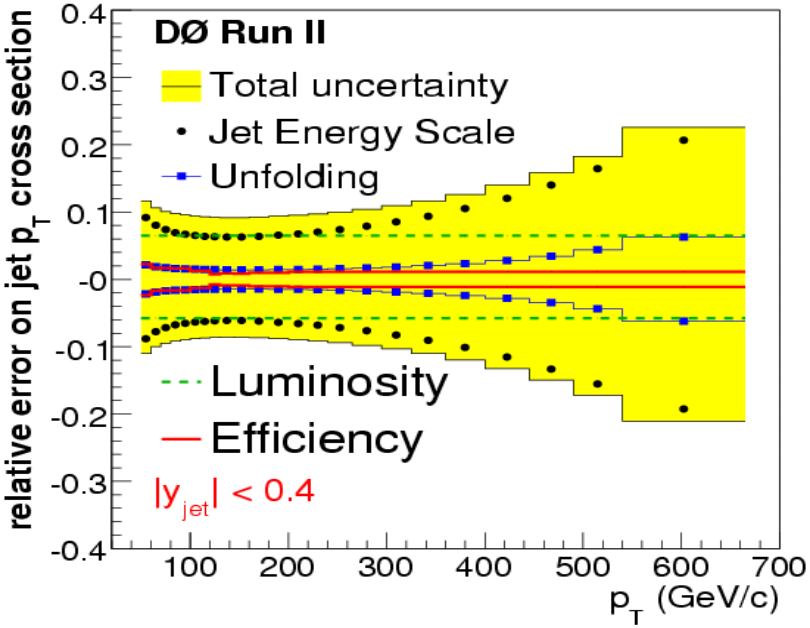
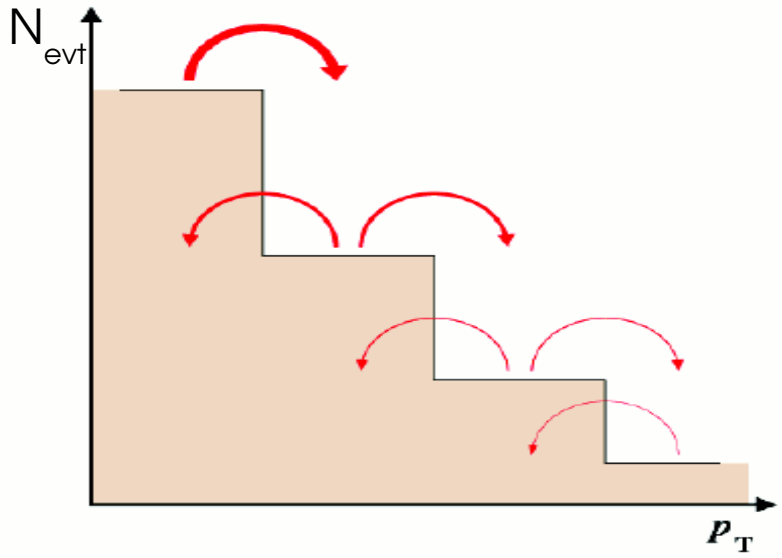


Steeply falling pT spectrum,

- correct for migrations between bins
- need excellent control of jet energy scale
  - at D0, 1 % error → 5 - 10% on central x-section
    →10 - 25% error on forward





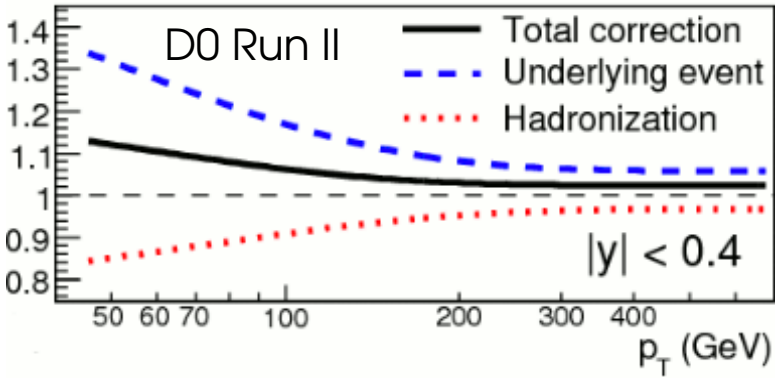
Inclusive Jets

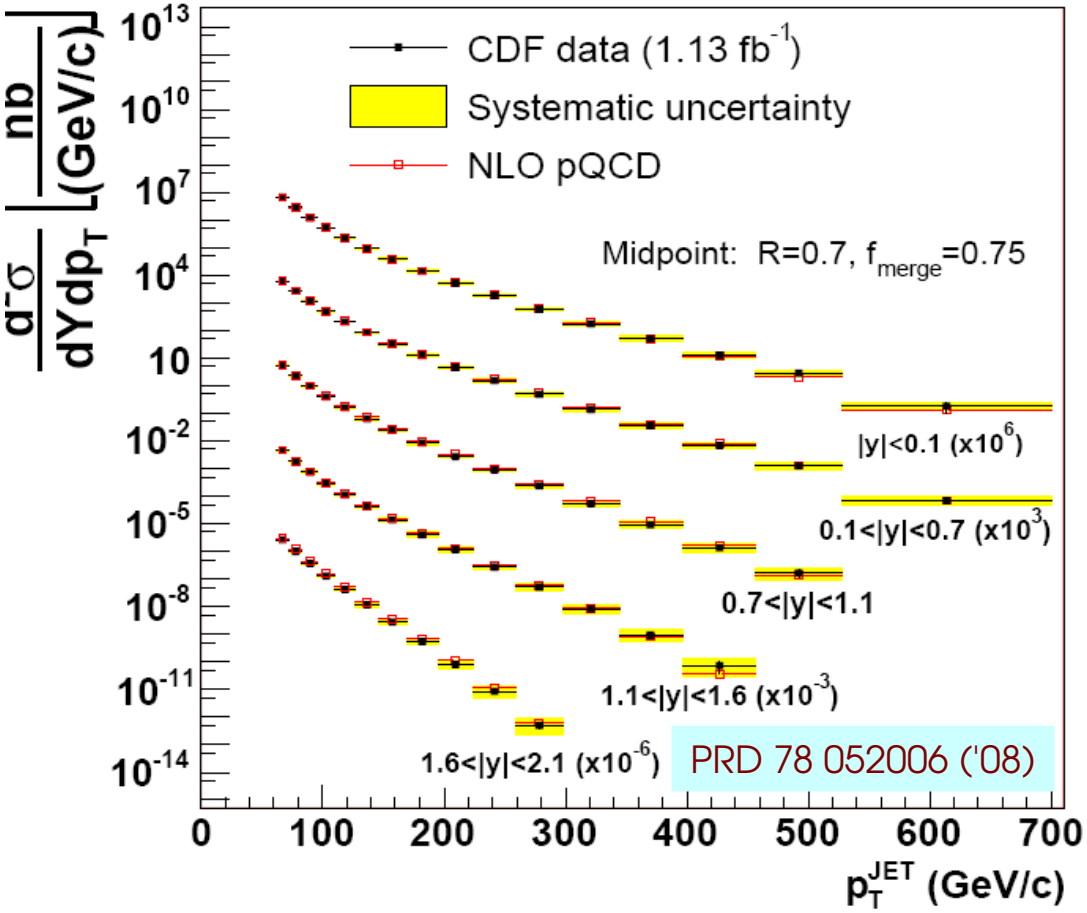
Measurements in 6 rapidity bins,

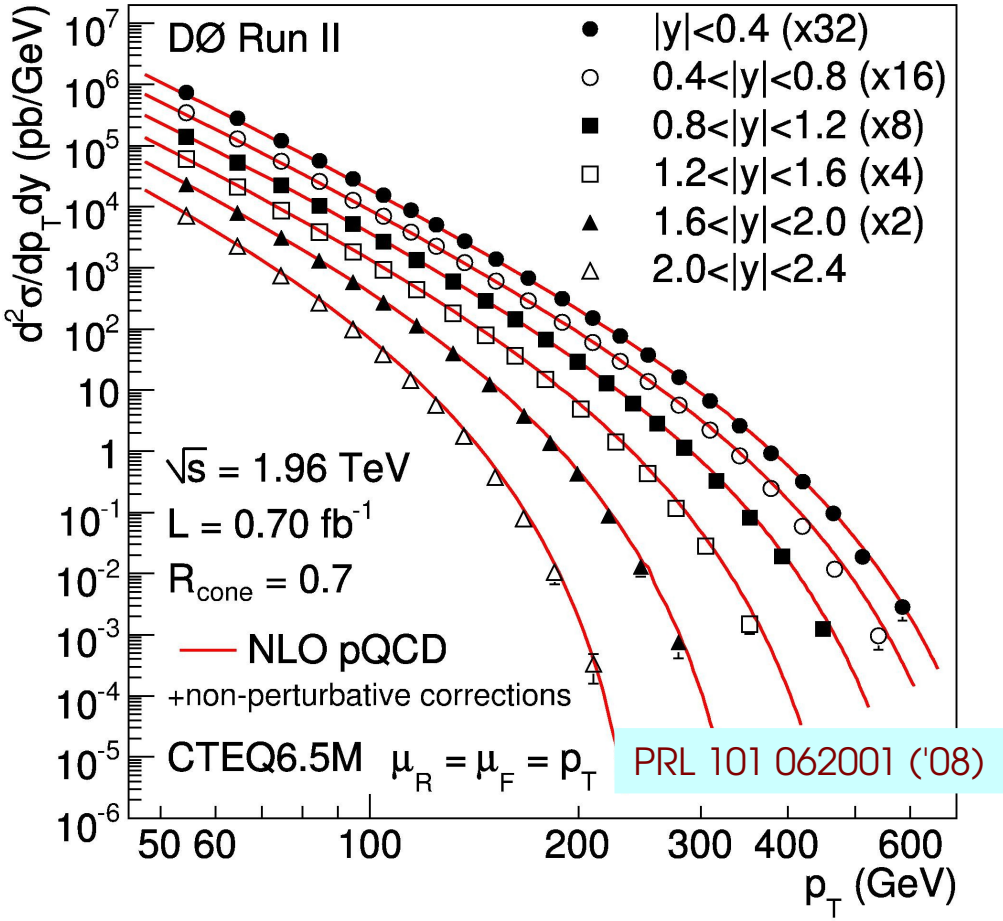
- over 9 orders of magnitude
- p_T up to 650 GeV

NLO prediction is parton level:

- must apply non-perturbative corrections
- derived from PYTHIA







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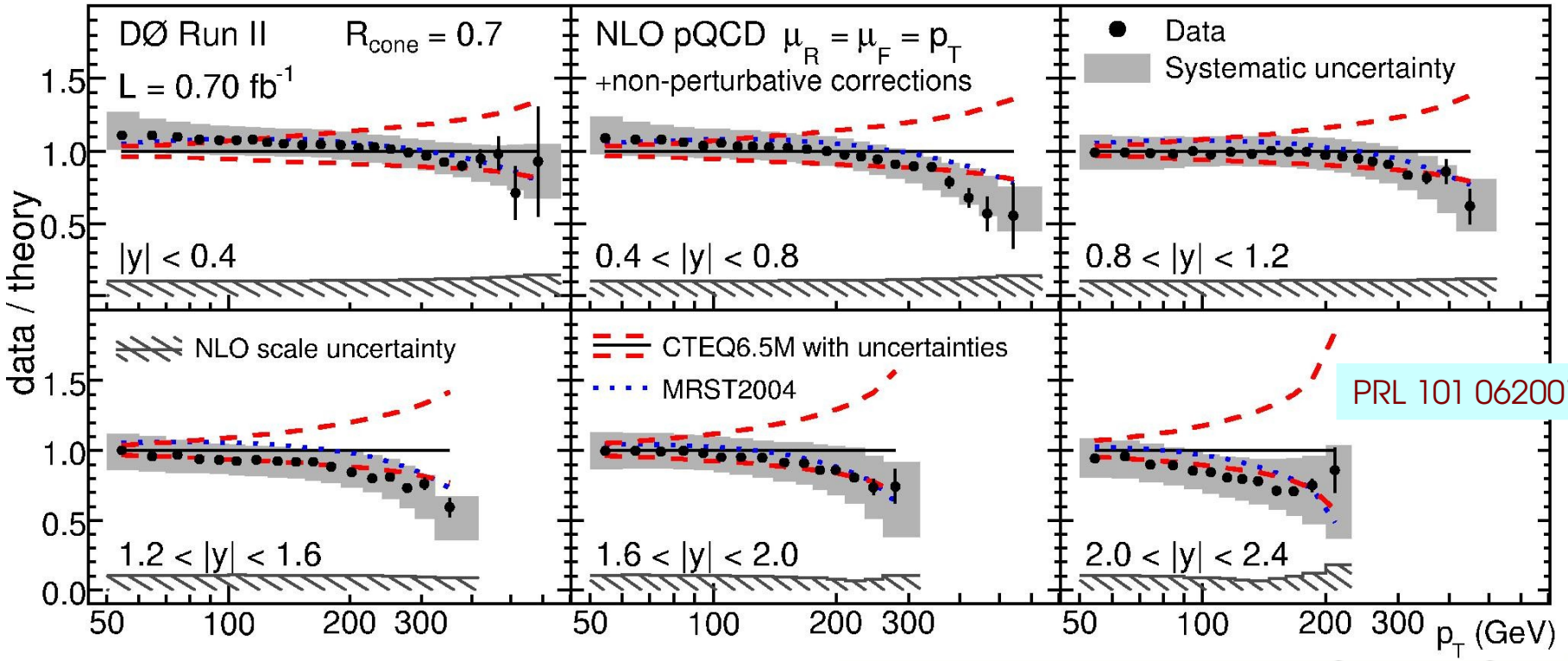
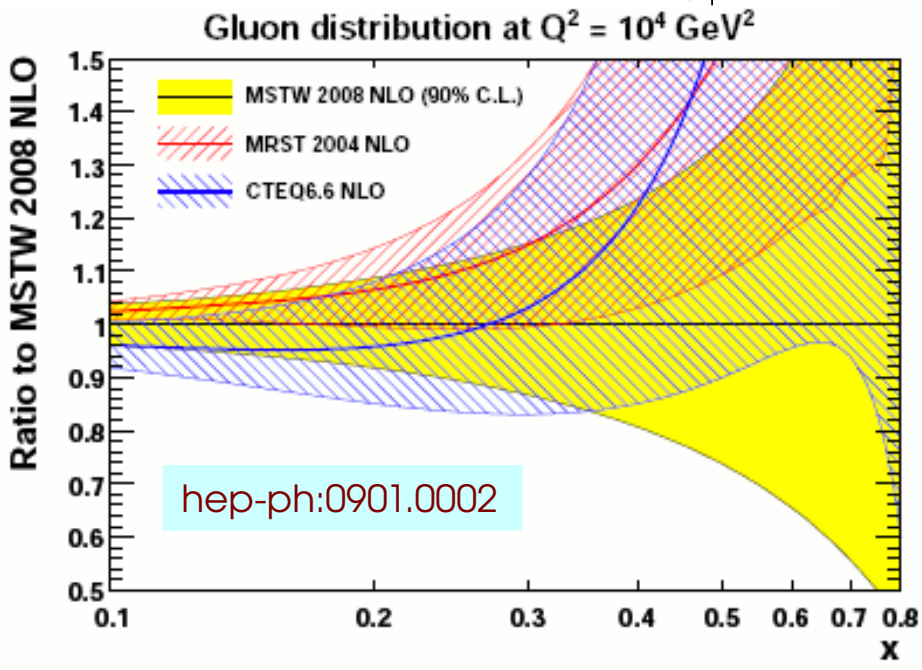


PRL 101 062001 ('08)

CDF and D0 Agree within uncertainties

Experimental unc. smaller than PDF unc.

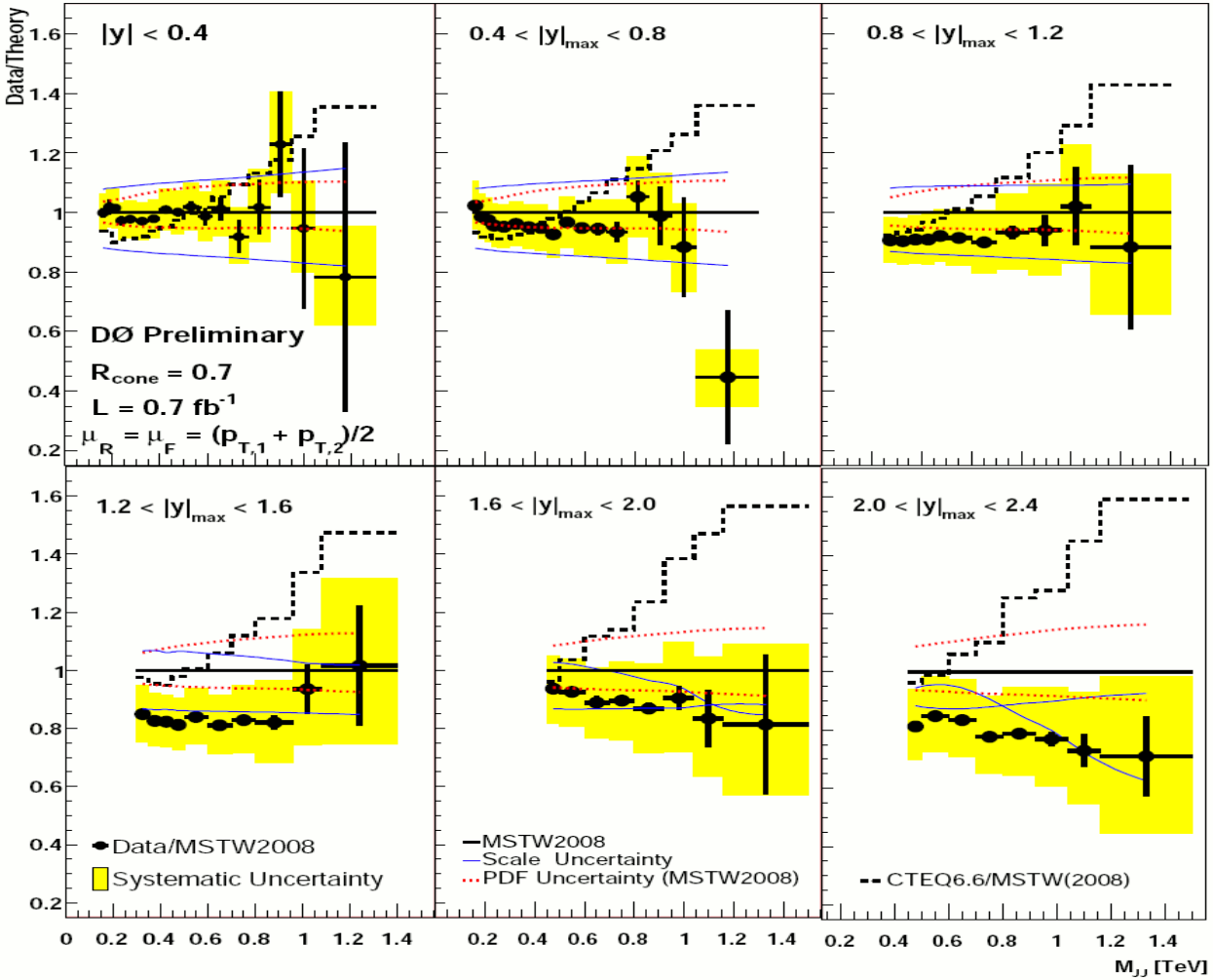
- used in MSTW 2008 PDF fits
  - Run I jet data excluded from fit
  - lower gluon at high x
- preliminary CTEQ09 PDF:
  - fit RunI & II results without softer gluon
  - error band overlaps with MRST08
  - waiting for final word...

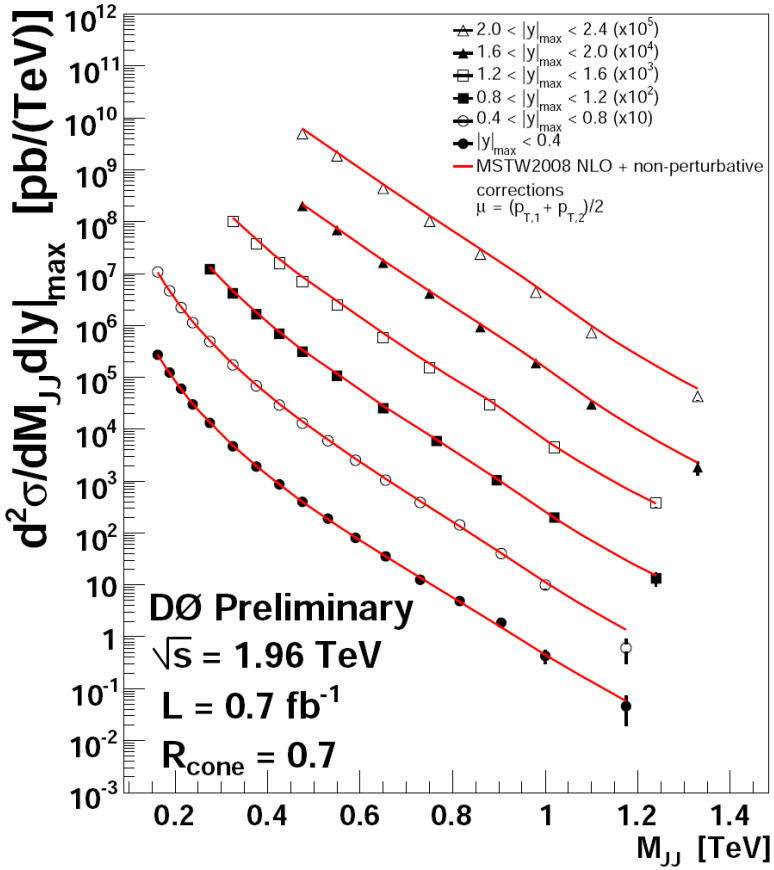


Di-jet Mass

With JES and resolutions, test QCD further:

- new D0 result, di-jet mass in six $|y_{jet}|$ regions
- NLO + MSTW2008 agrees within systematics
  ...but definite trend in forward region

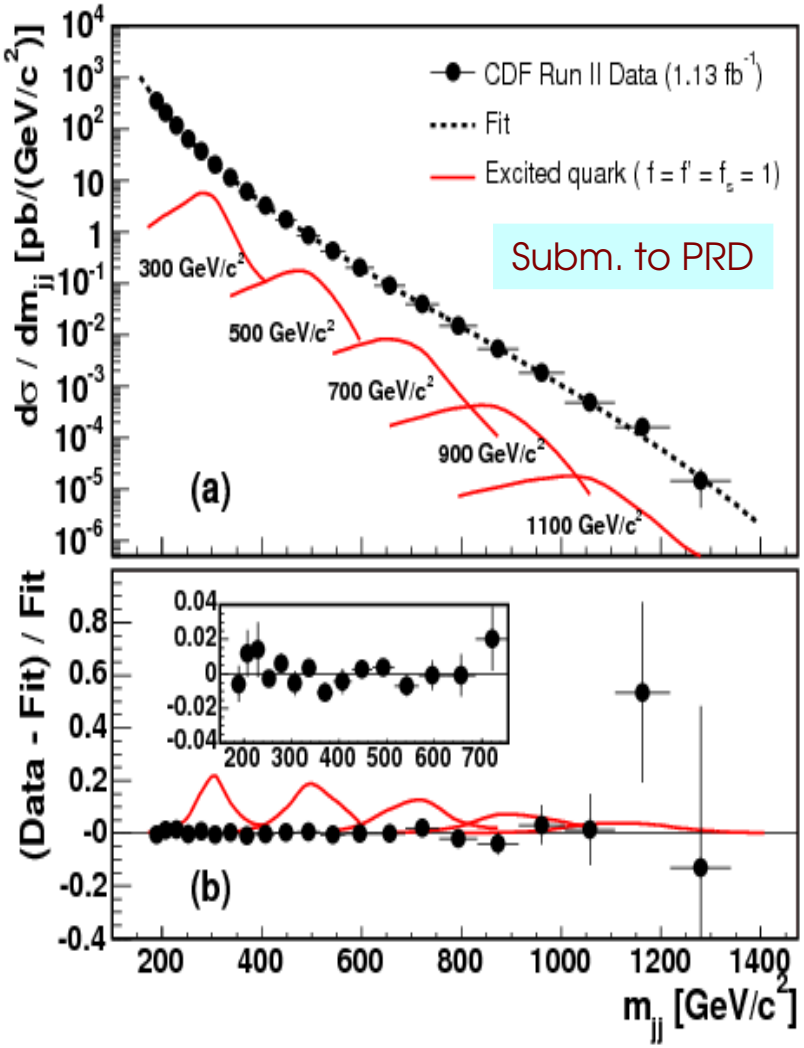




Di-jet Mass, Angles

Similar CDF analysis of di-jet mass:

- di-jet mass for $|y_{jet}|<1$
- also carry out a resonance search
- data out to 1300 GeV!



No new physics yet...

- 95 % limits on various resonances:
  - q* > 870 GeV, Z' > 740 GeV, techni-ρ> 1.1 TeV

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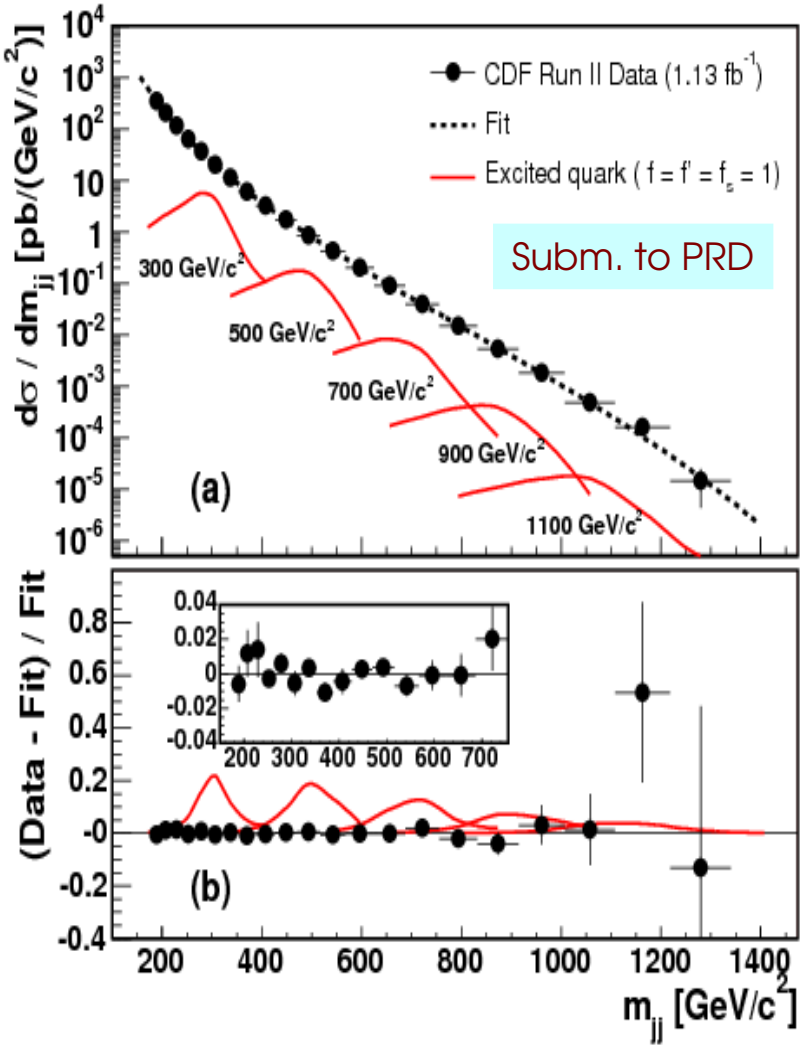
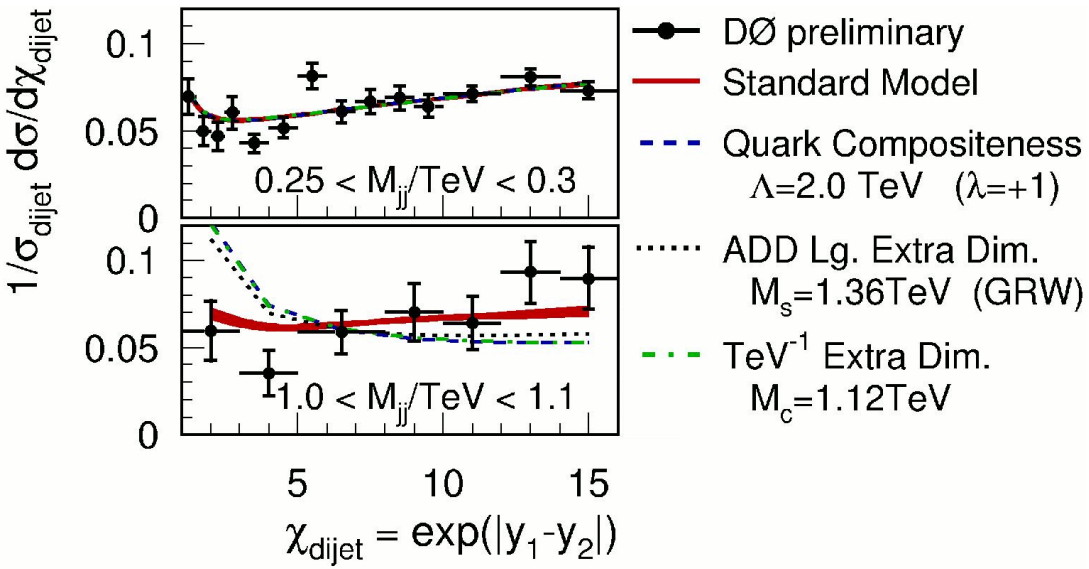




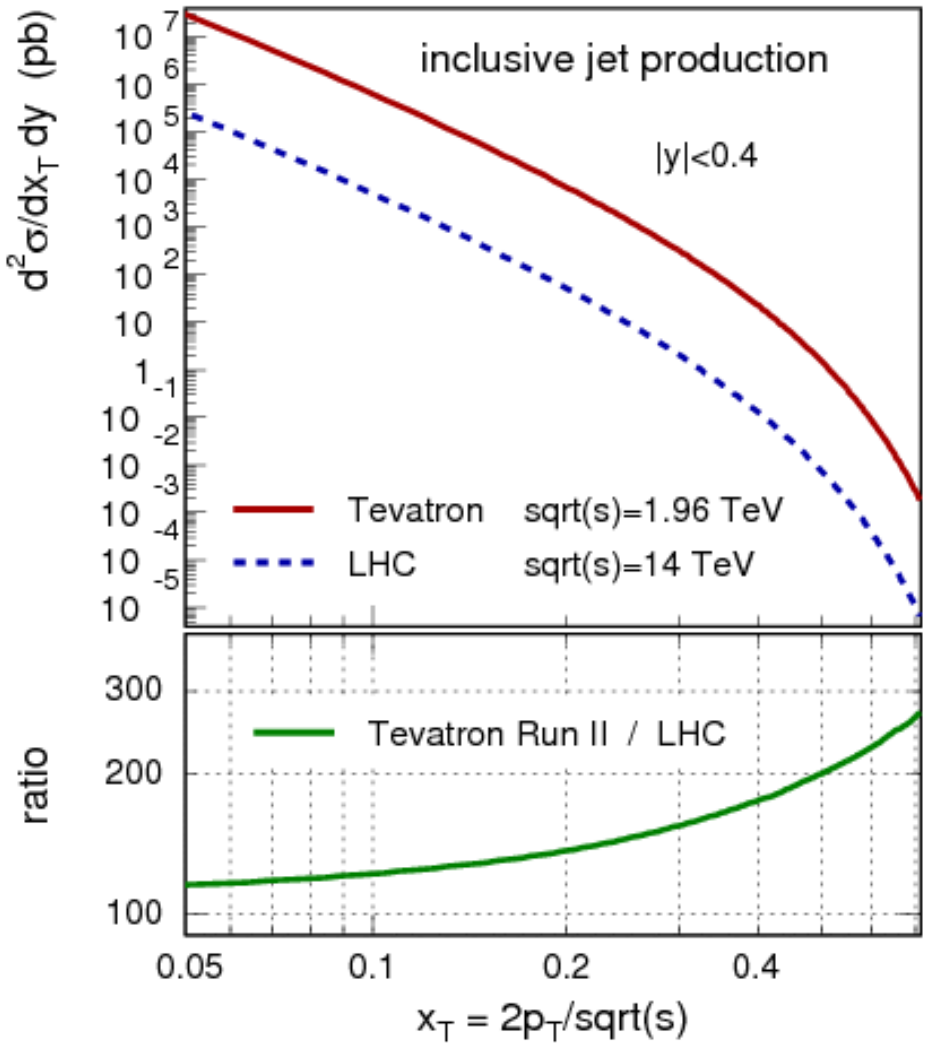
Di-jet chi in bins of di-jet mass:

- 11 bins of mass, 0.25 to 1.1 TeV!
- new interactions -> new matrix elements
- jet angles directly sensitive

No new physics yet...

- 95 % limits on various resonances:
  - q* > 870 GeV, Z' > 740 GeV, techni-ρ> 1.1 TeV
- and new interactions:
  - quark compositeness Λ > 2.58 TeV
  - ExDim M >1.56 TeV (ADD), >1.42 TeV (TeV^{-1})

Tevatron vs LHC



At the LHC:

- cross section vs p_T obviously much larger
- quickly pass Tevatron limits on new physics

BUT cross section vs x significantly smaller!

eg for $|y|<0.4$, factor of 200 at $x = 0.5$

Tevatron results with 1 fb^{-1}

→ need 200 fb^{-1} at LHC

Further, problem of steeply falling spectrum:

at D0, 1 % error on jet energy calibration

→ 5 - 10% error on central x-section

→10 - 25% error on forward x-section

At LHC, spectrum falls more steeply

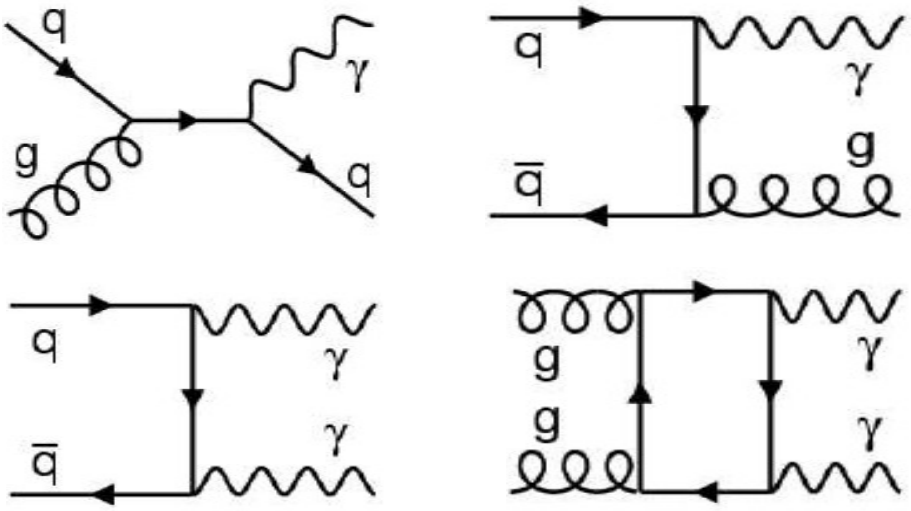
- need excellent jet energy scale
- out to very high p_T

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

Photons

- inclusive photons
- photon + jet
- photon + b/c jet
- di-photons in Higgs session

Inclusive Photon Production

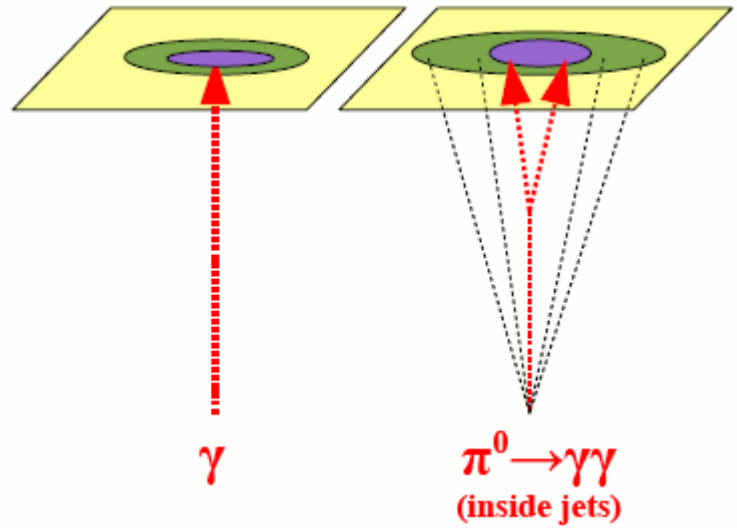


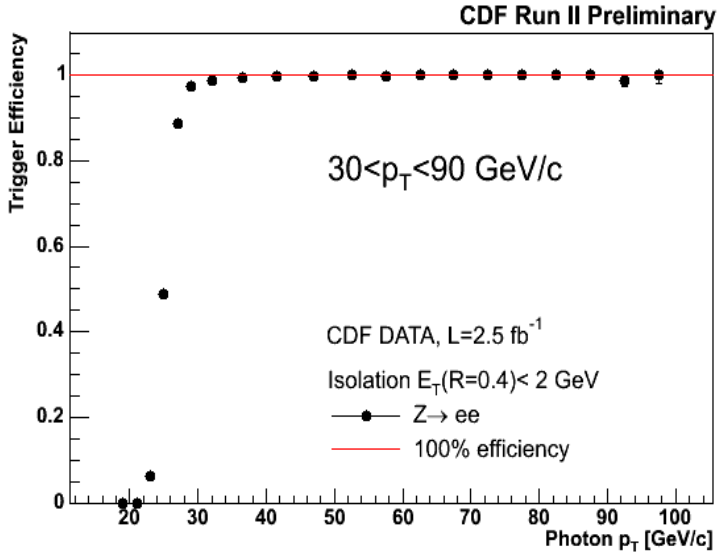
Measure photon directly
- colourless probe of hard process

Trigger on & select isolated EM clusters:
- low p_T triggers pre-scaled!

Photon ID based on:
- shower shapes, isolation, tracking
- $p_T > 30$ GeV, $|\eta| < 1.0$ (CDF)
- $p_T > 23$ GeV, $|\eta| < 0.9$ (D0)

"Instrumental background":
- non-prompt photons appear isolated
- energy overlay on prompt photons dilutes isolation



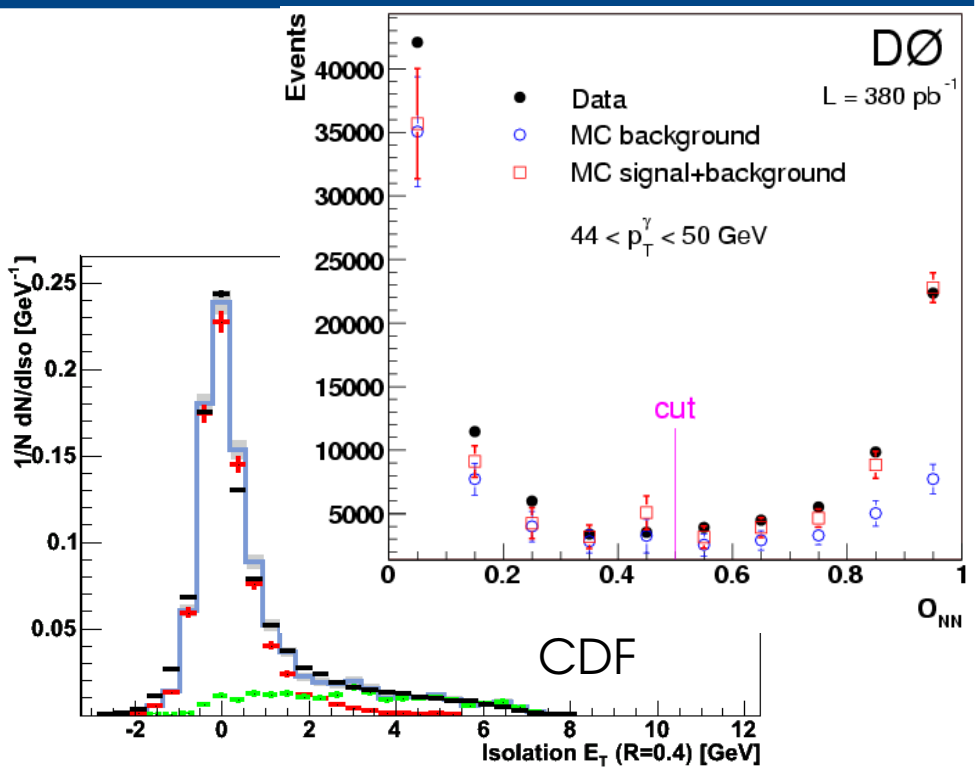


Photon ID

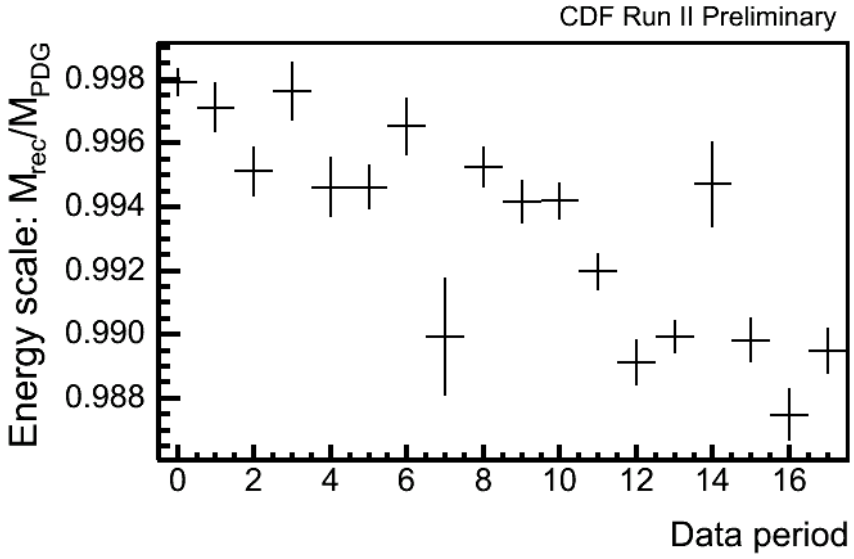
Photon Isolation and background:
- CDF: template fits to isolation in calorimeter
- D0: template fits to photon ID neural net

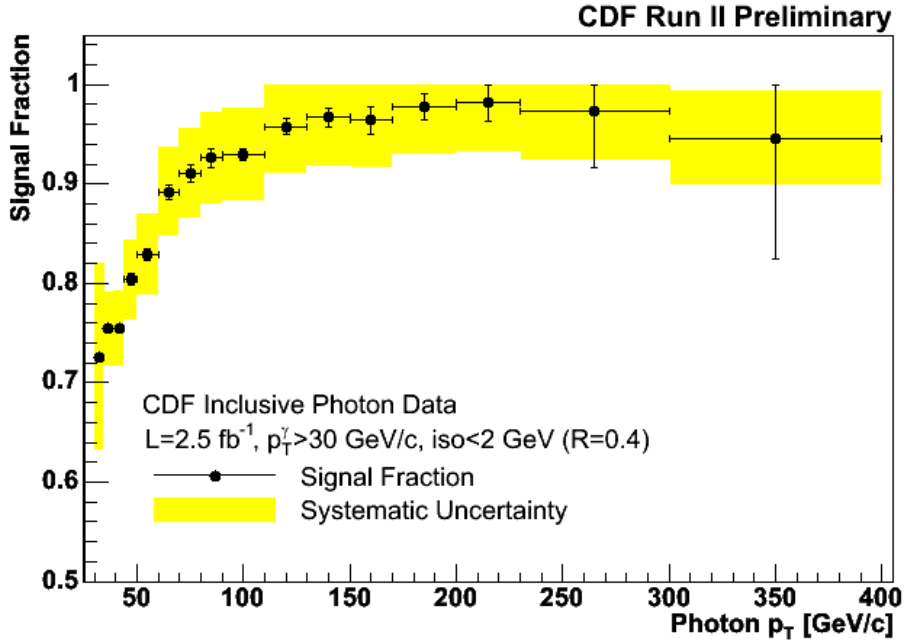
Simulation used for background templates
- must verify with data

Electron/photon energy scale:
- calibrate on Z mass peak
- e/γ differences from simulation
- simulation to extrapolate to high p_T



Photon p_T resolution corrections small





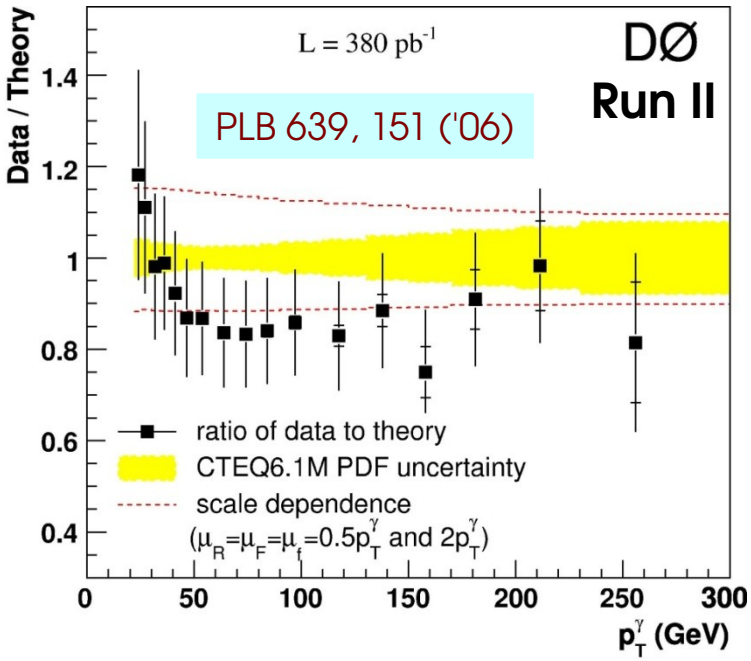
Inclusive Photon

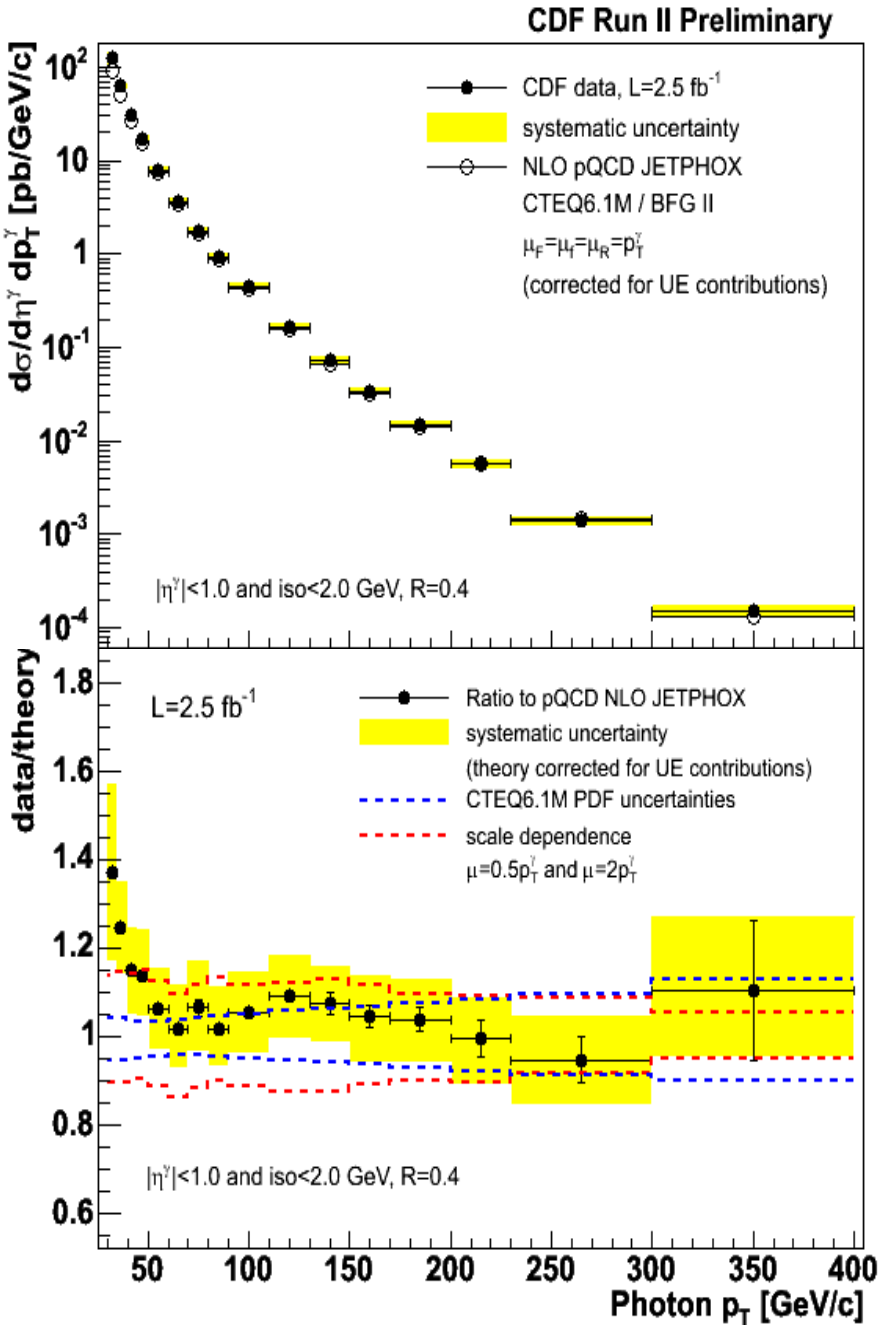
Dominant Systematics:

- 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, ...**



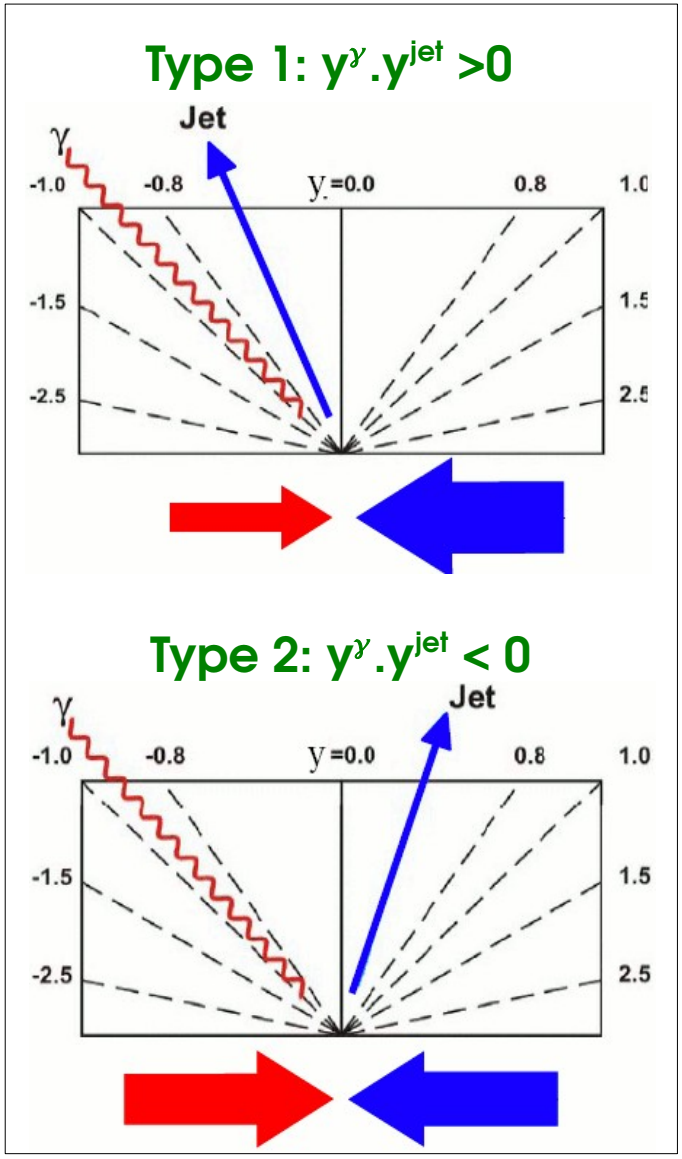


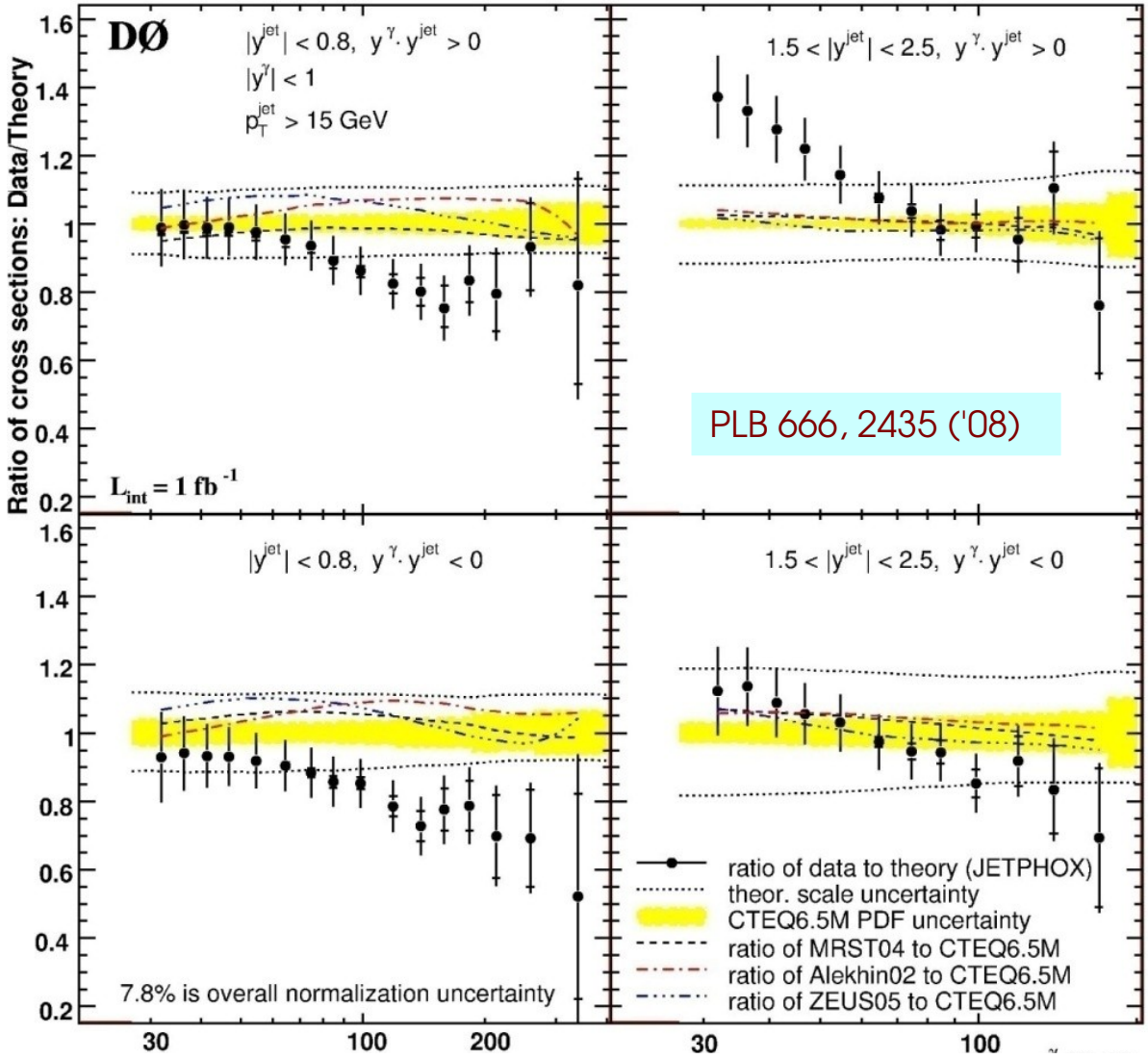
Photon + Jet Production

Investigate further: add a jet
- p_T>15 GeV, $|\eta_{jet}|$<0.8, 1.5 < $|\eta_{jet}|$ < 2.5

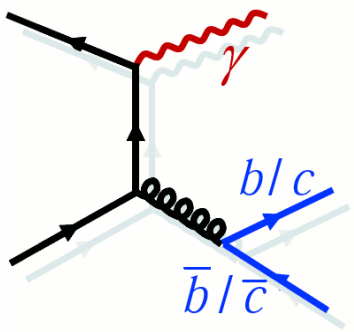
Triple differential:
- in jet η, photon η and photon p_T

Something missing in the theory?
- higher orders, resummation, ..?
- LHC measurements will be very interesting!



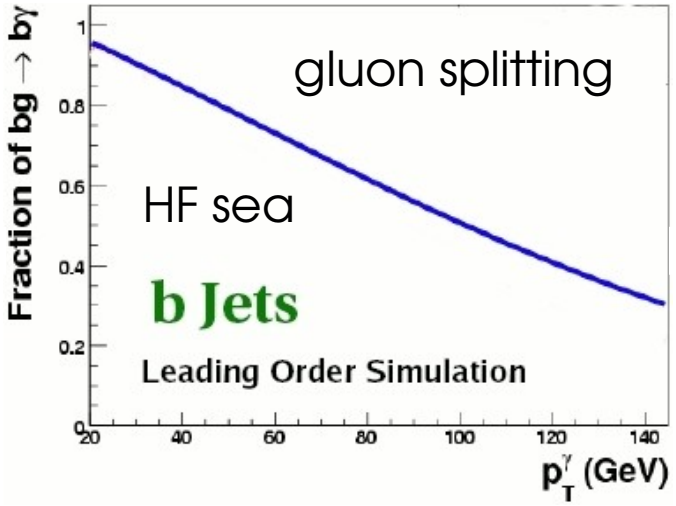


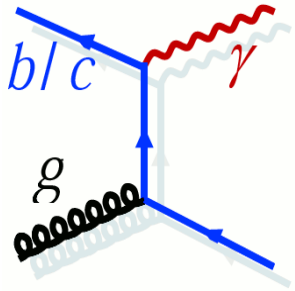
Photon + b/c



Gluon splitting contribution

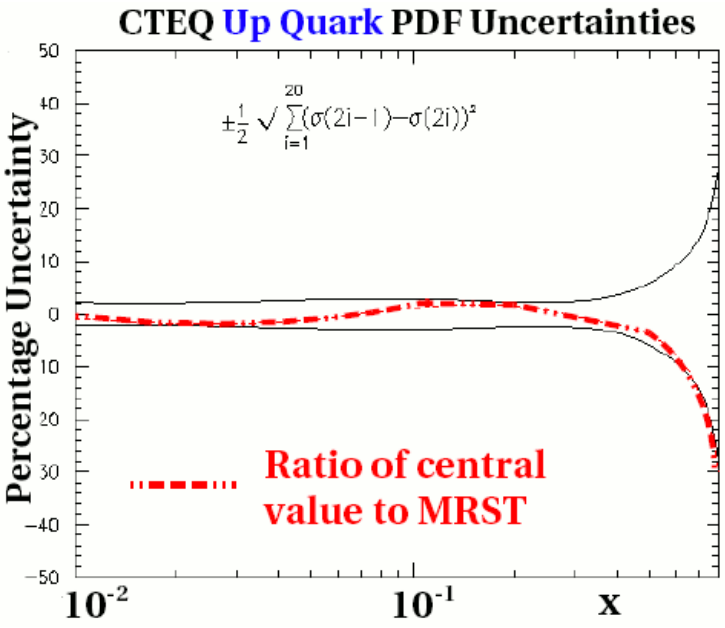
- dominates for high photon p_T
- important as background elsewhere

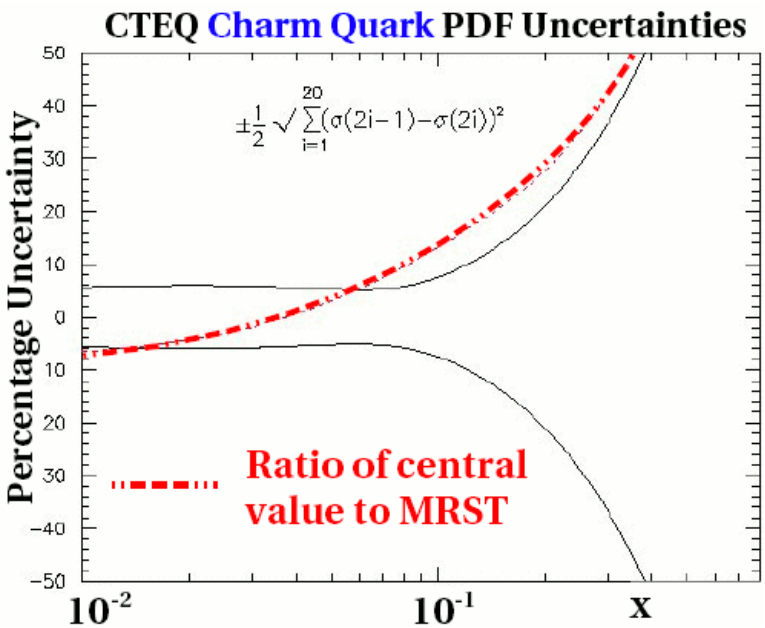




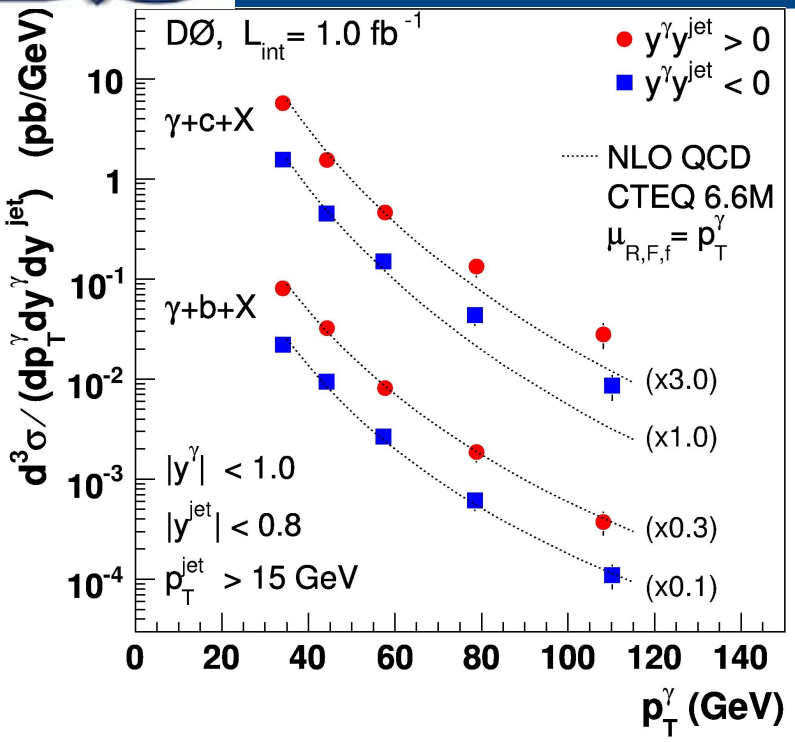
heavy flavour sea contribution

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





Photon + b/c



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?

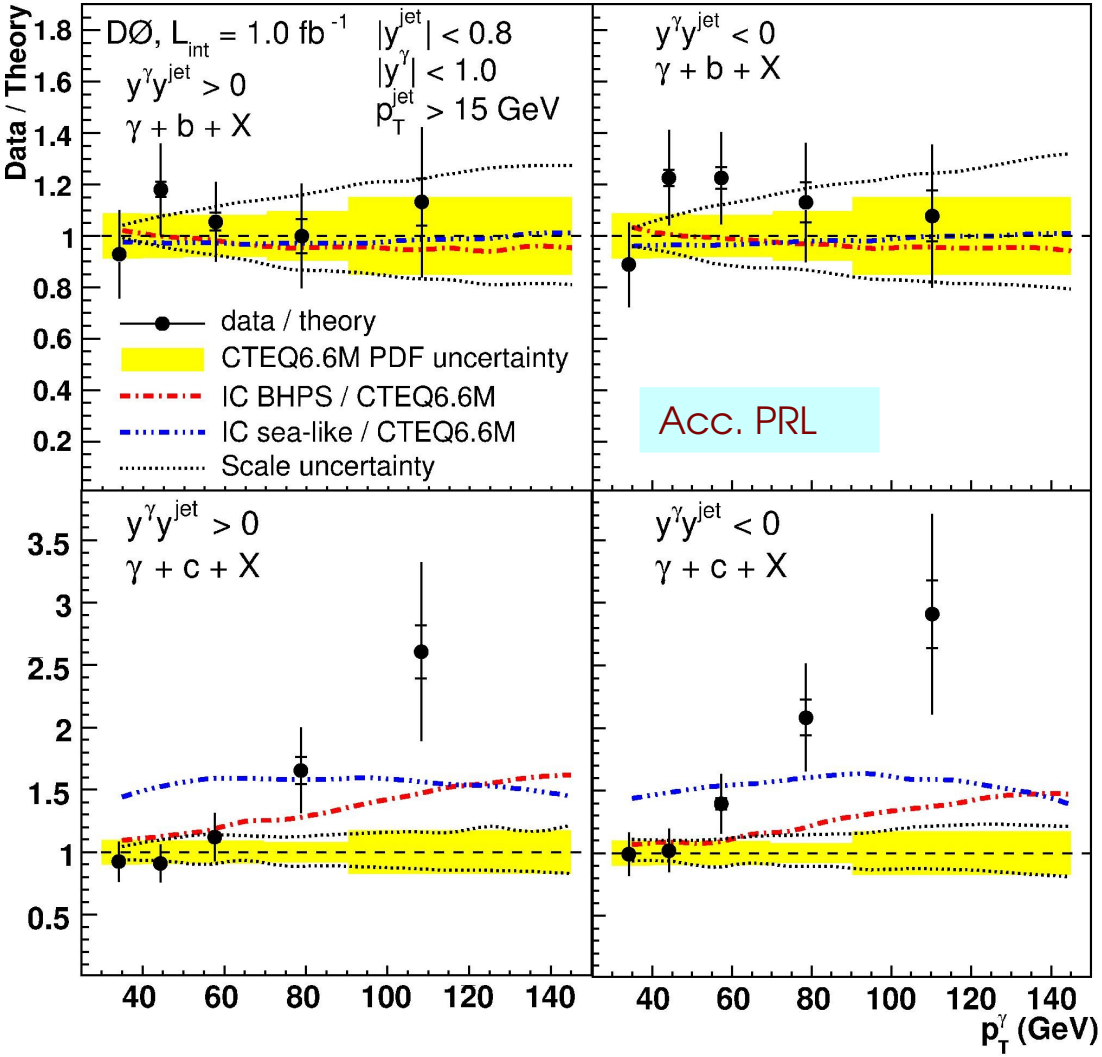
- more sensitive to heavy flavour sea

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



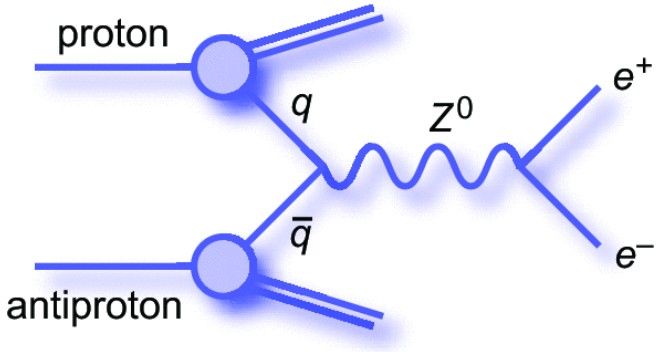
Heavy Bosons

- Z p_T, a_T
- Z + jets
- W / Z + b/c

W / Z Production

Use leptonic (ee, $\mu\mu$) Z decays as probe of QCD

- high Q^2 (~M_Z or M_W)
- ~zero backgrounds, right down to $p_T \geqslant 0$!
- but much lower cross section than photon



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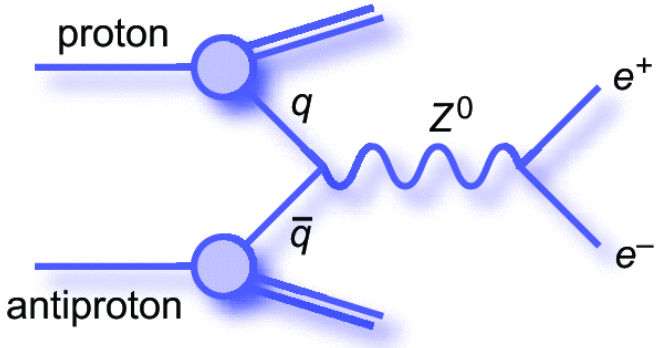


High multiplicity final states: W/Z + jets

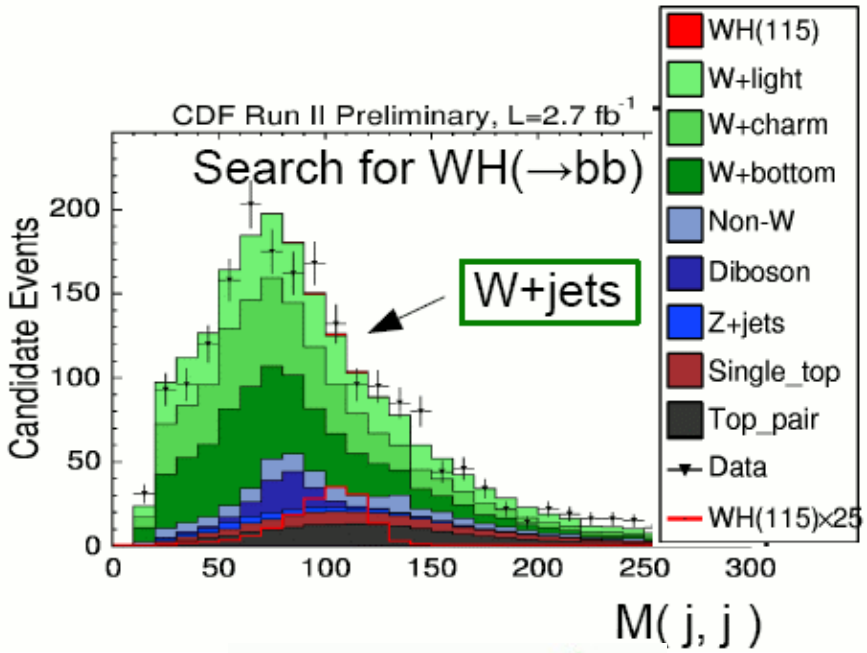
- main background to top, Higgs, SUSY, ...

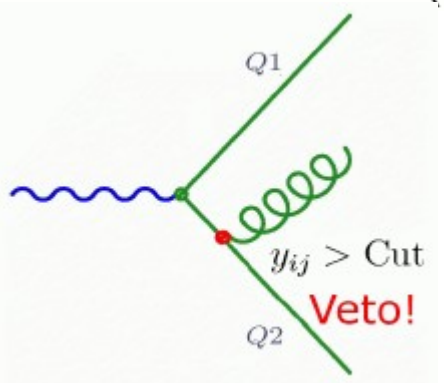
pQCD:

- LO W/Z + 1 - 6 partons
- NLO W/Z + 1, 2 (work on W+4)

Event generators:

- LO 2 ->1, 2 + parton shower
  - PYTHIA, HERWIG
- LO 2->N + (vetoed) parton shower
  - SHERPA, ALPGEN
- **main LHC tools, need to be tuned to data!**





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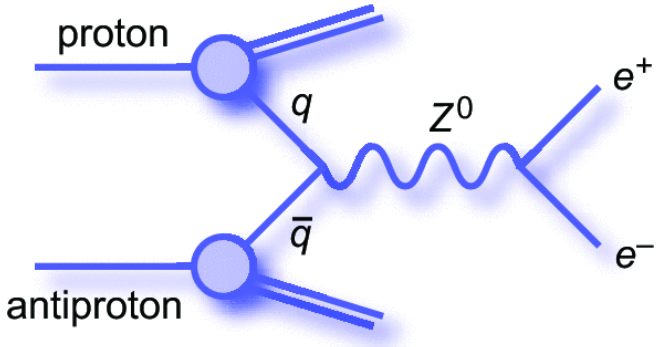

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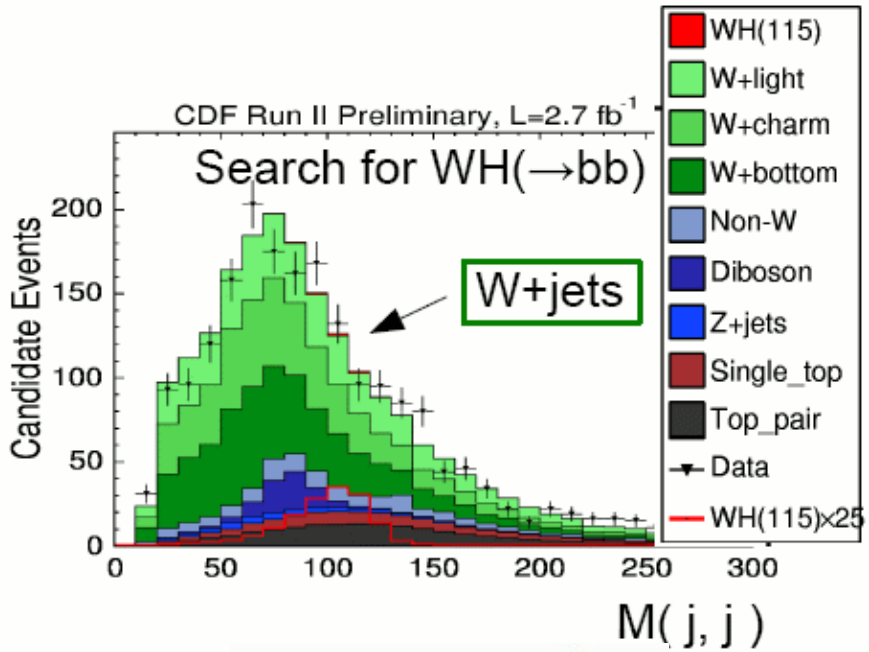
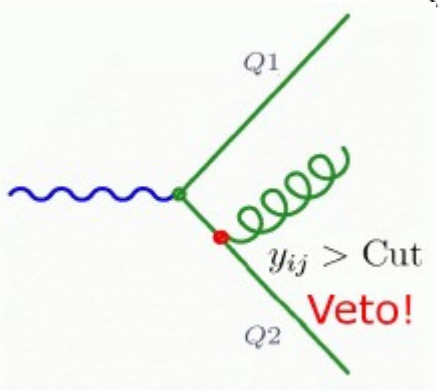


Experimental issues:

- see E. Nurse for details of W and Z selection

Jets:

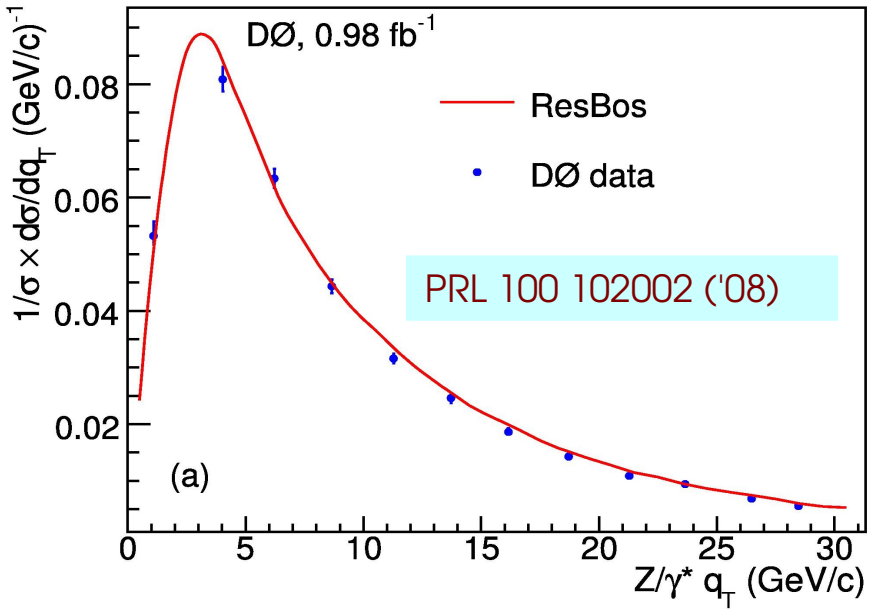
- unfolding is the main issue
- some residual sample dependence in JES



Z Boson p_T

Result using 1 fb^{-1}, Z→ee channel:

- differential cross section over wide Z p_T range
- normalised to inclusive Z cross section



Low Z p_T associated with soft ISR:

→ gluon re-summation, eg BLNY parameterisation:

$$S_{NP}(b,Q^2) = [g_1 + g_2 \ln(\frac{Q}{2Q_0}) + g_1 g_3 \ln(100 x_i x_j)]b^2$$

Implemented in RESBOS Monte Carlo

- extract **g_2 = 0.77 ± 0.06**

- also use forward Z to test small-x broadening

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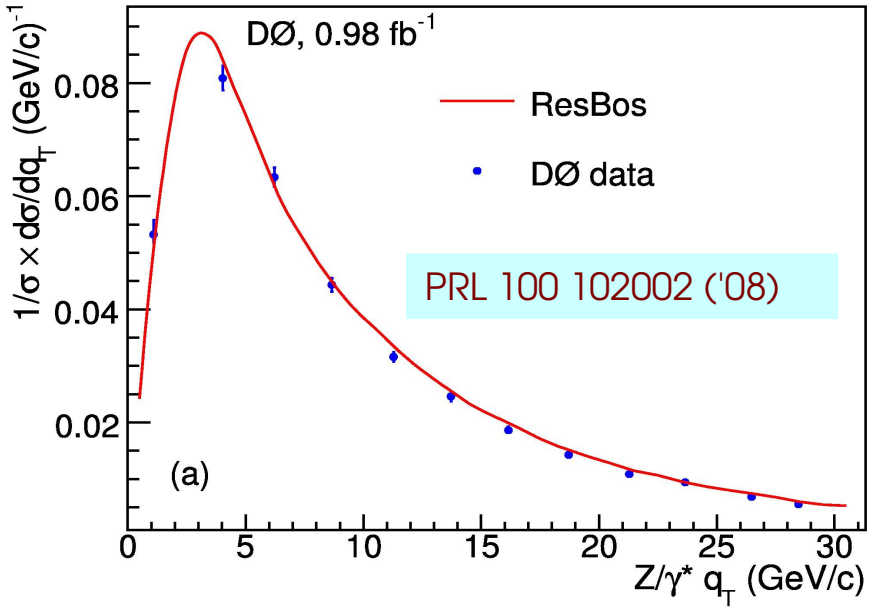

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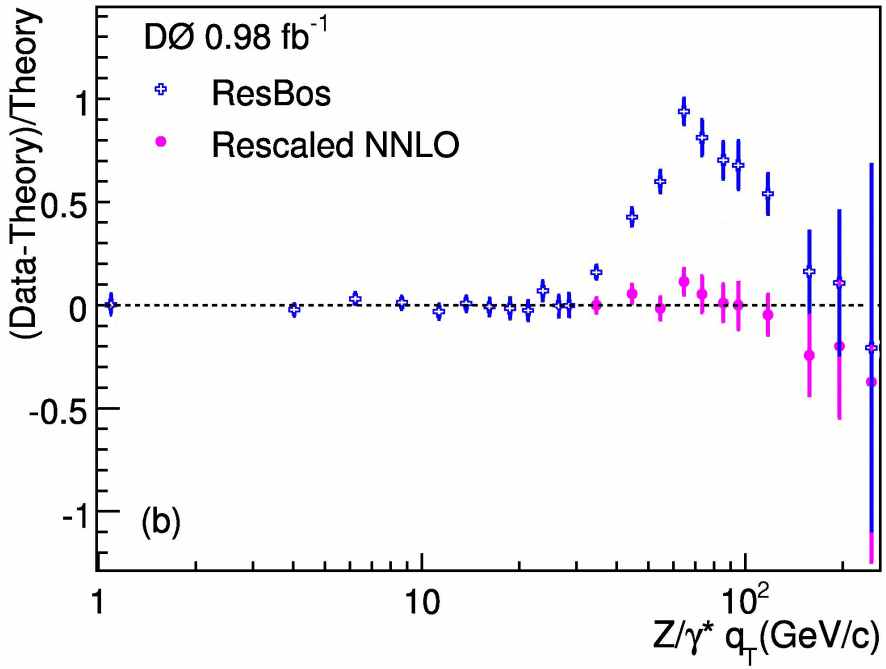


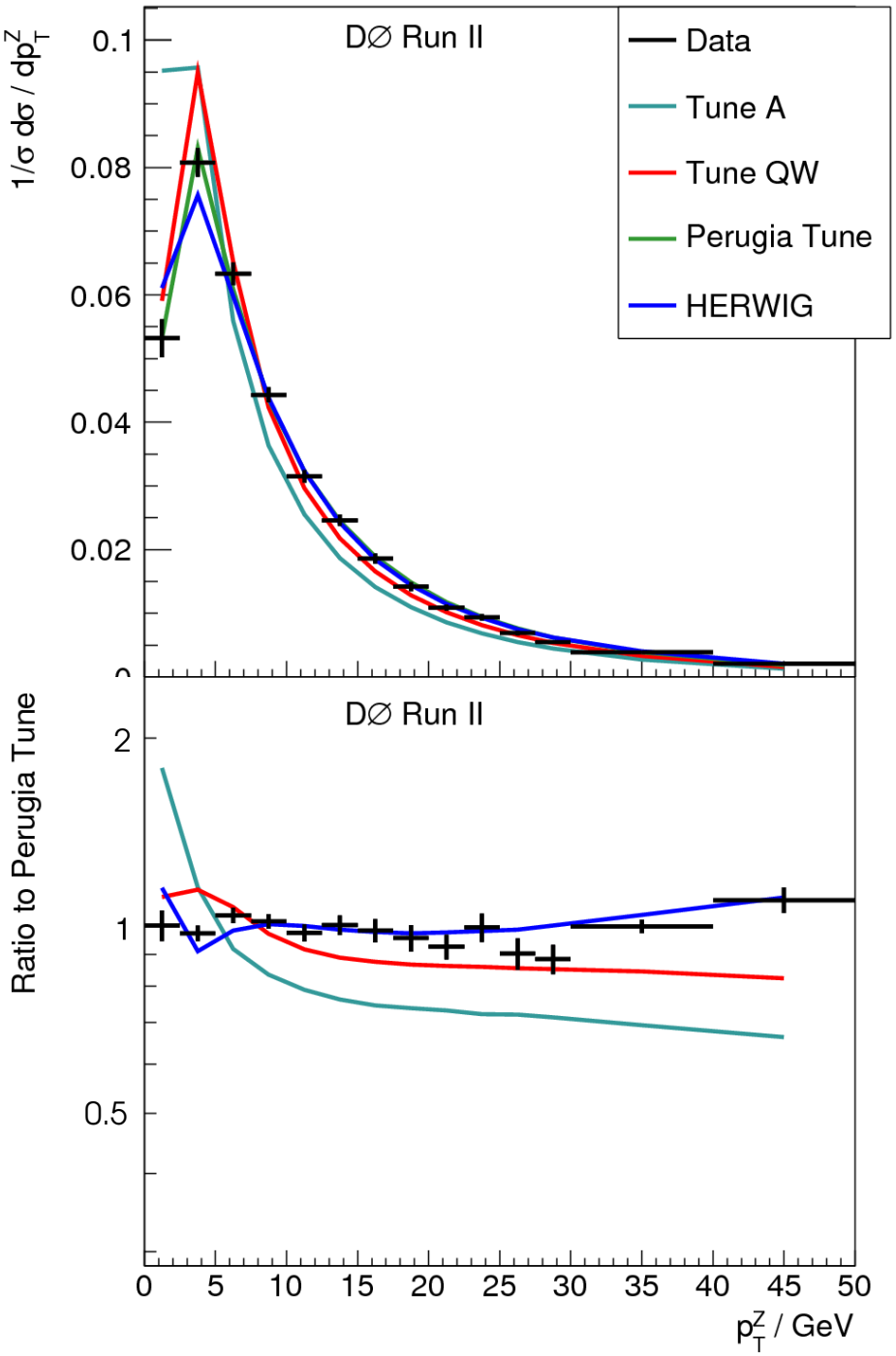
Higher p_T associated with hard ISR:

- well described by fixed order pQCD
- NNLO: Melnikov & Petrillo PRD 74, 114017 ('06)

Z p_T also very useful for generator tuning!

- D0 re-weight simulation to these data.

Generator Tuning



Important distribution for generator tuning:

- Tune A: CDF min-bias data
- Tune QW: added CDF Run I Z pT. D0 di-jet $\Delta\phi$
- Perugia tune: includes this distribution
  - and uses new pT-ordered shower

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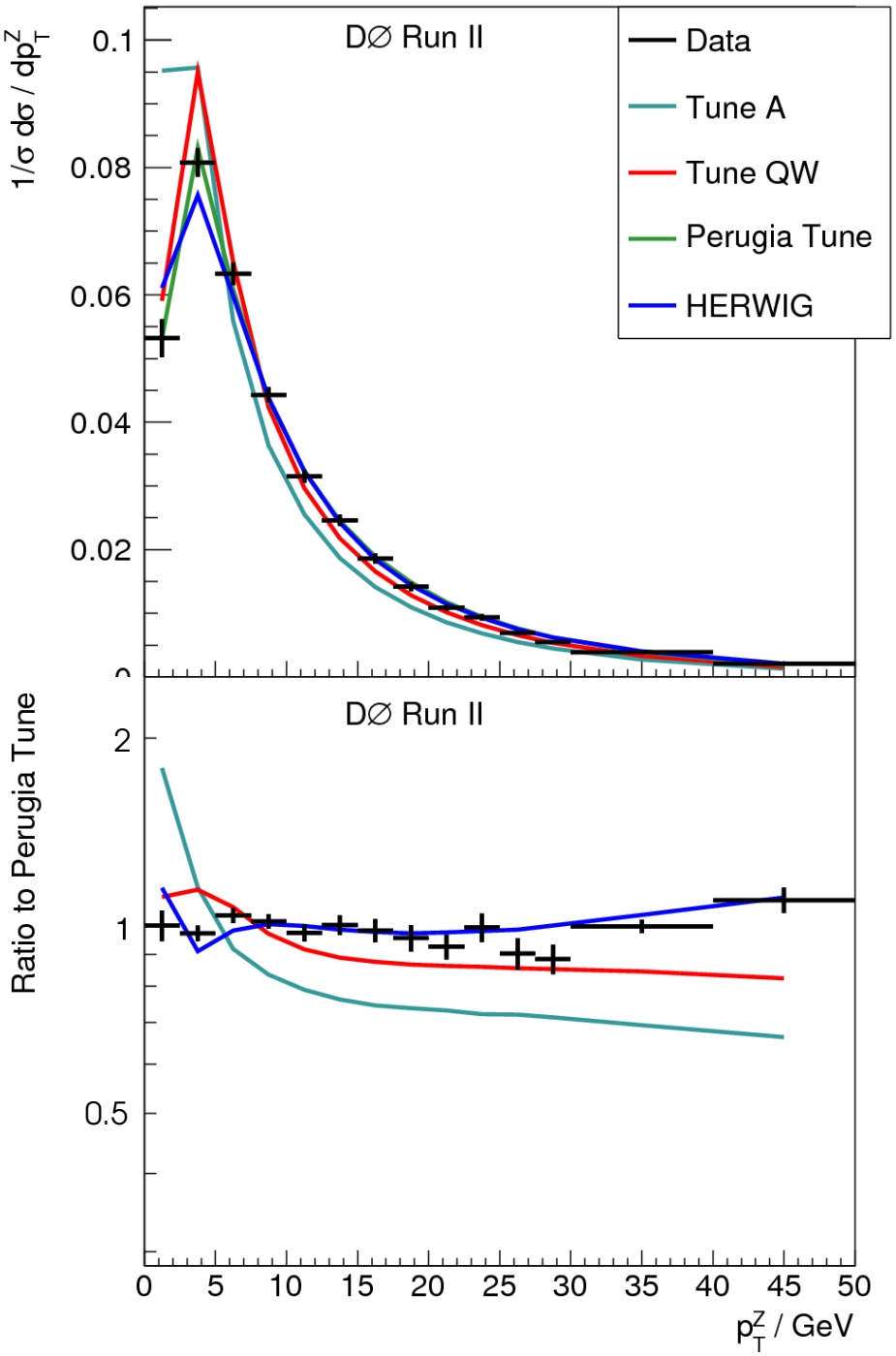
Generator Tuning



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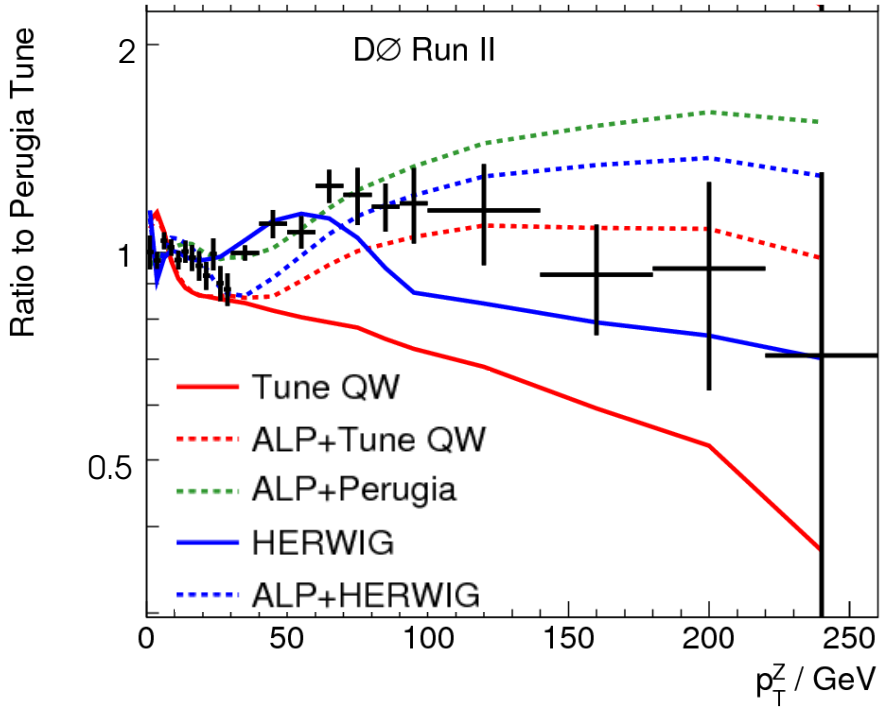
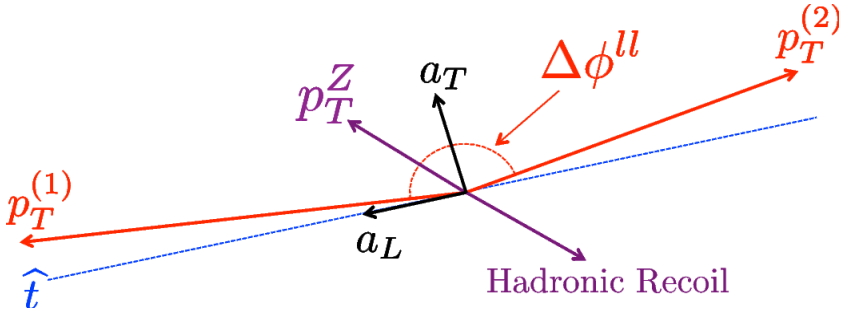
D0 re-weight Monte Carlo to these data.

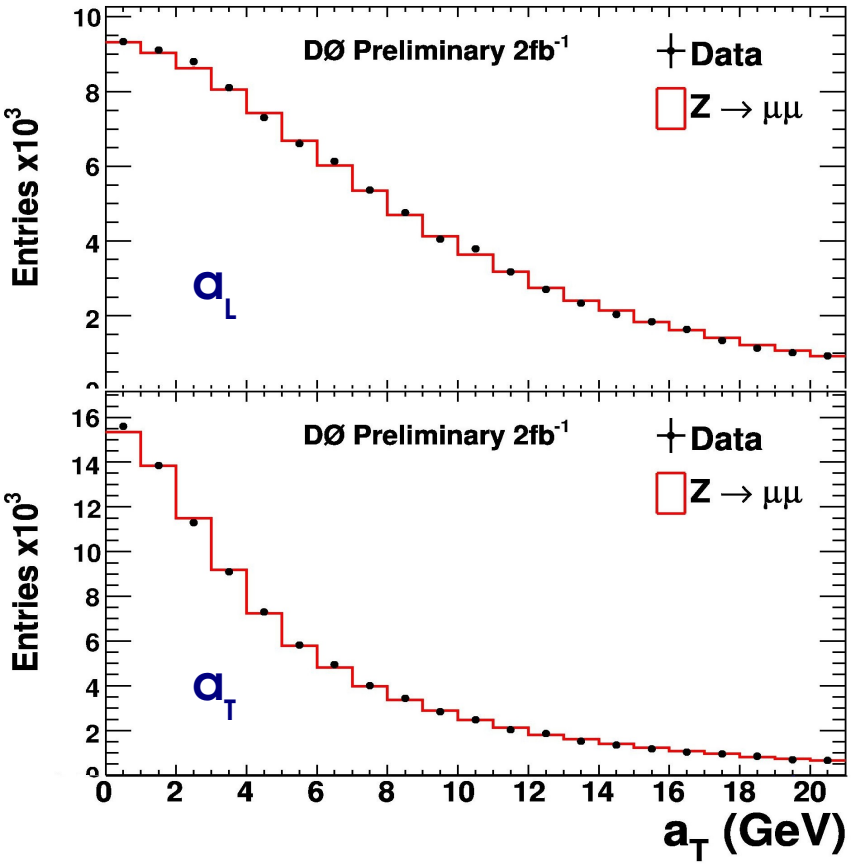
Adding ALPGEN (dashed lines):

- improves description at high p_T
- further tuning still possible



Z Boson a_T

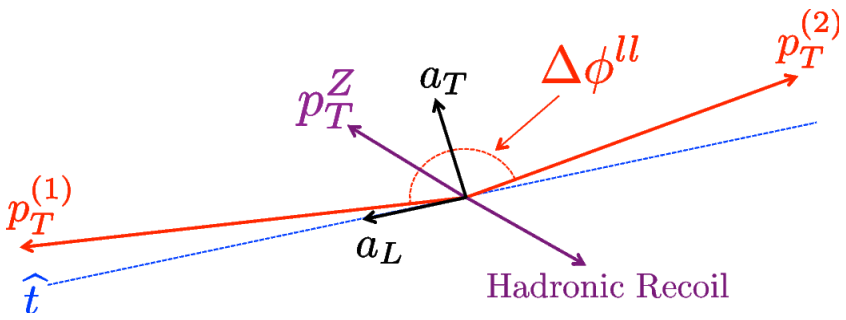


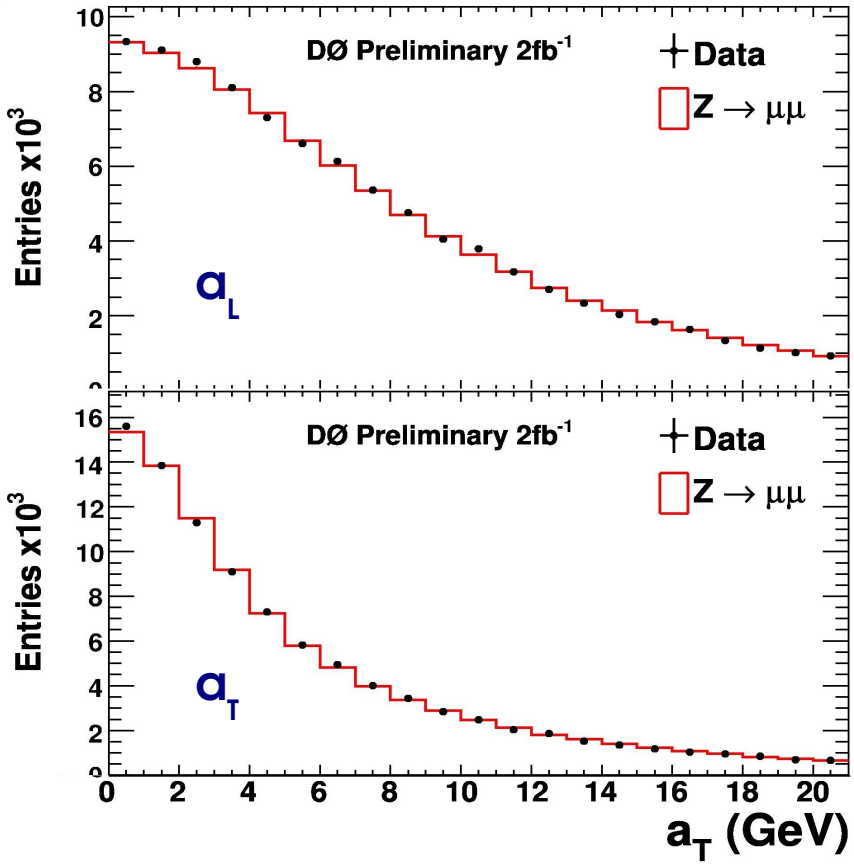


New variable avoids detector resolution issues

- a_T = p_T transverse to Z thrust axis.
- preliminary detector-level result e and μ channels

Z Boson a_T





New variable avoids detector resolution issues

- a_T = p_T transverse to Z thrust axis.
- preliminary detector-level result e and μ channels

Extract g_2:

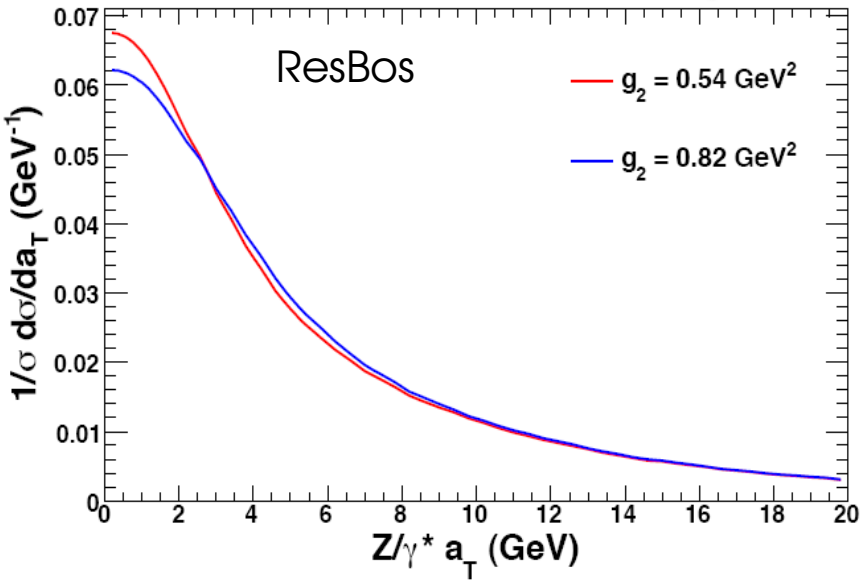
- generate RESBOS samples with various g_2 values
- reweight full detector simulation, fit to data

g_2 = 0.63 ± 0.02 (exp.) ± 0.04 (PDF)

- statistics limited!
- Best single measurement, comparable accuracy to world average: $0.68\ ^{+0.02}_{-0.01}$ (CTEQ3)

- Fully unfolded a_T distribution soon

- new calculations also available

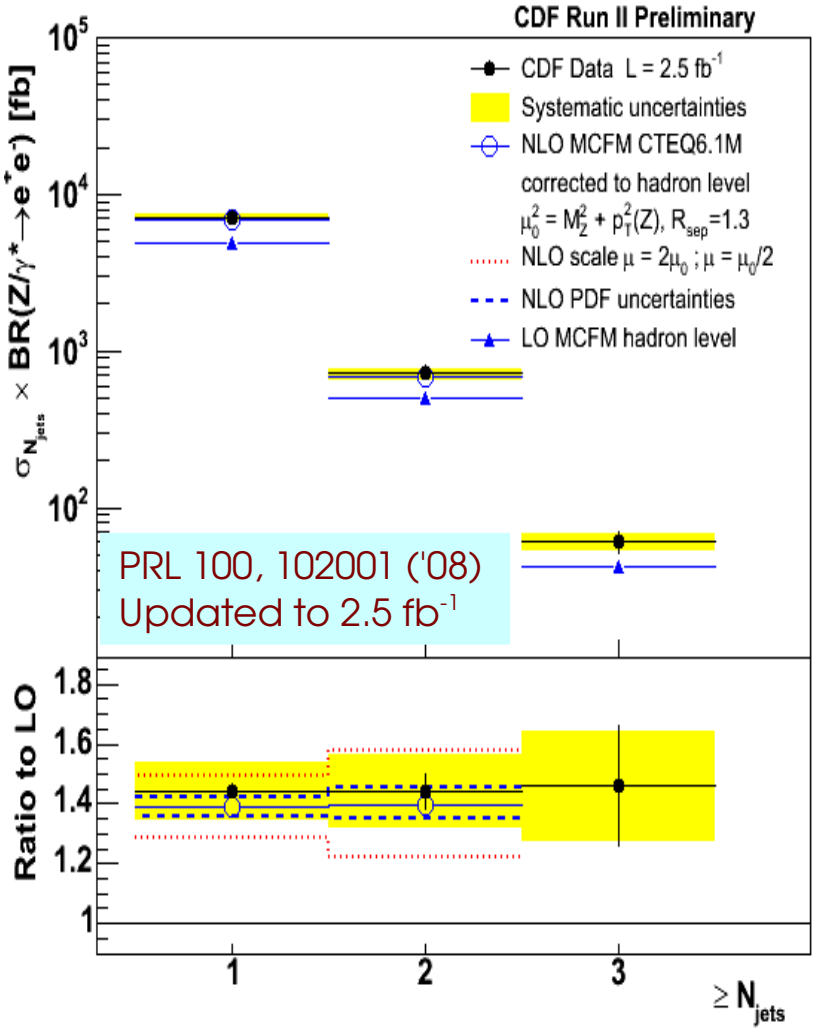


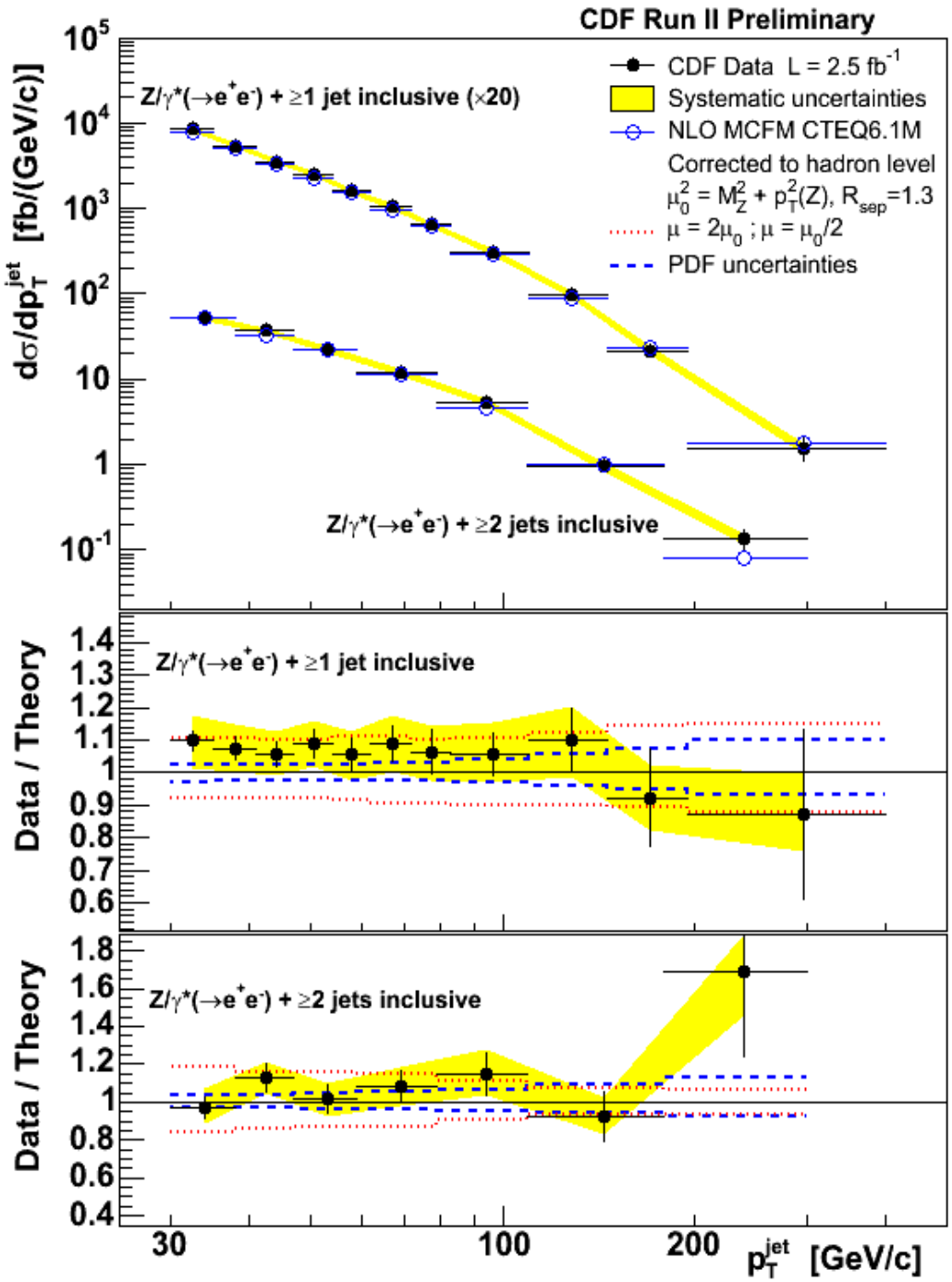
Z + Jets

CDF Z+jets analysis:

- Z→ee channel, jet $p_T > 30$, $|y| < 2.1$
- Differential cross section in jet p_T:
  - Z + ≥1 and Z + ≥2 jet events

NLO matches data, within uncertainties





Z + Jets

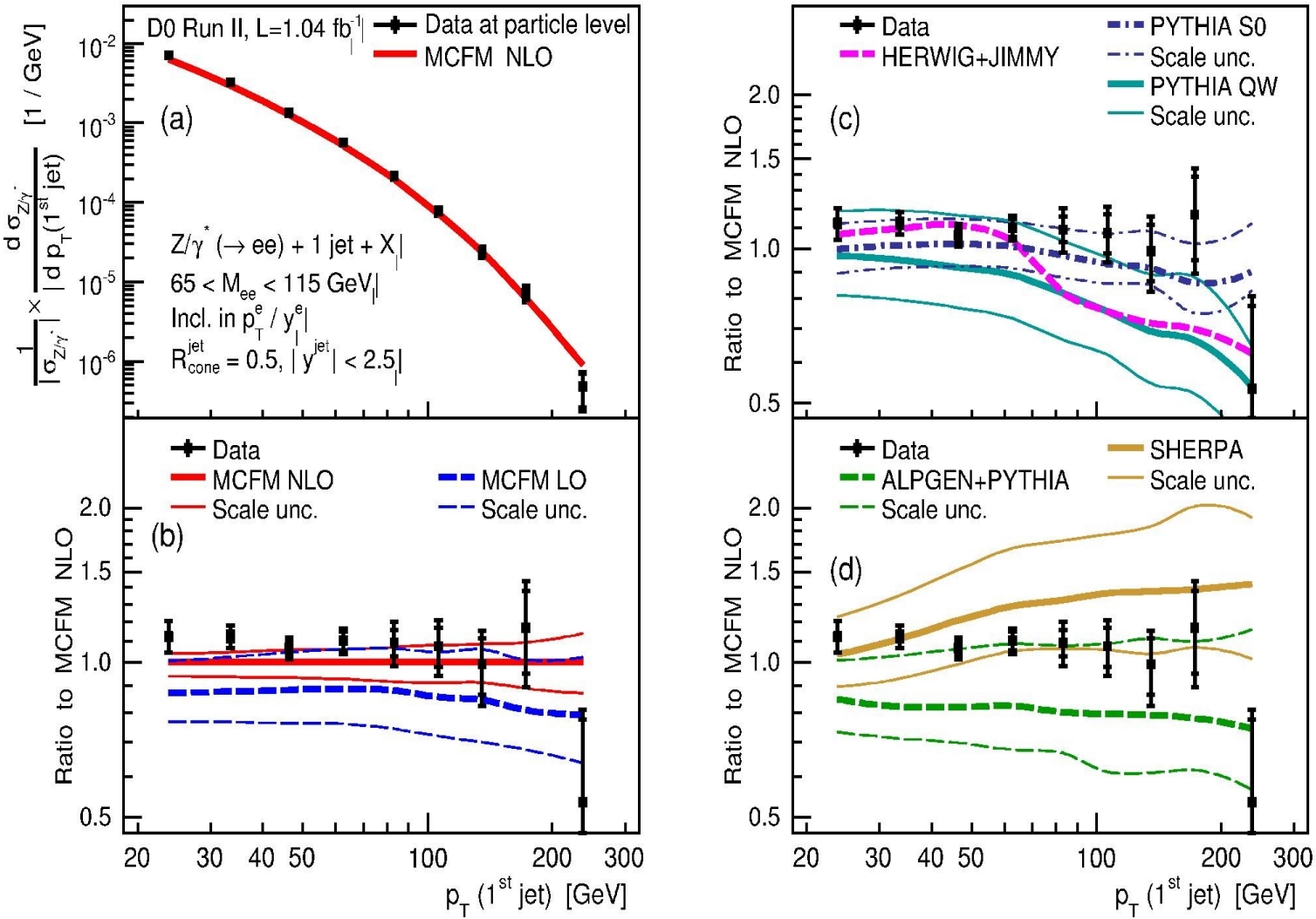
D0 measurement of 1st, 2nd and 3rd jet pT in Z events:

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

Carry out extensive event generator comparisons

Leading jet in Z + jet + X

Subm. to PLB



Parton Shower

- PYTHIA Q^2 ordered
- PYTHIA p_T ordered
- HERWIG

Matched ME + PS

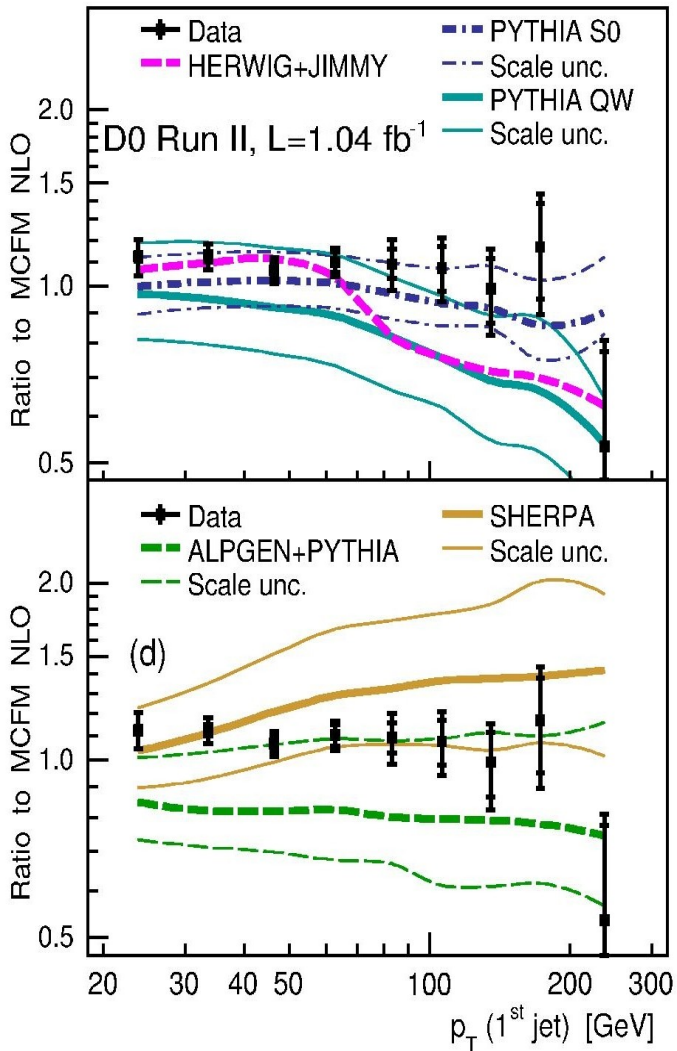
- ALPGEN+ PYTHIA (Q^2)
- SHERPA 1.1.1, old tune
  - new tune better!

Z + Jets

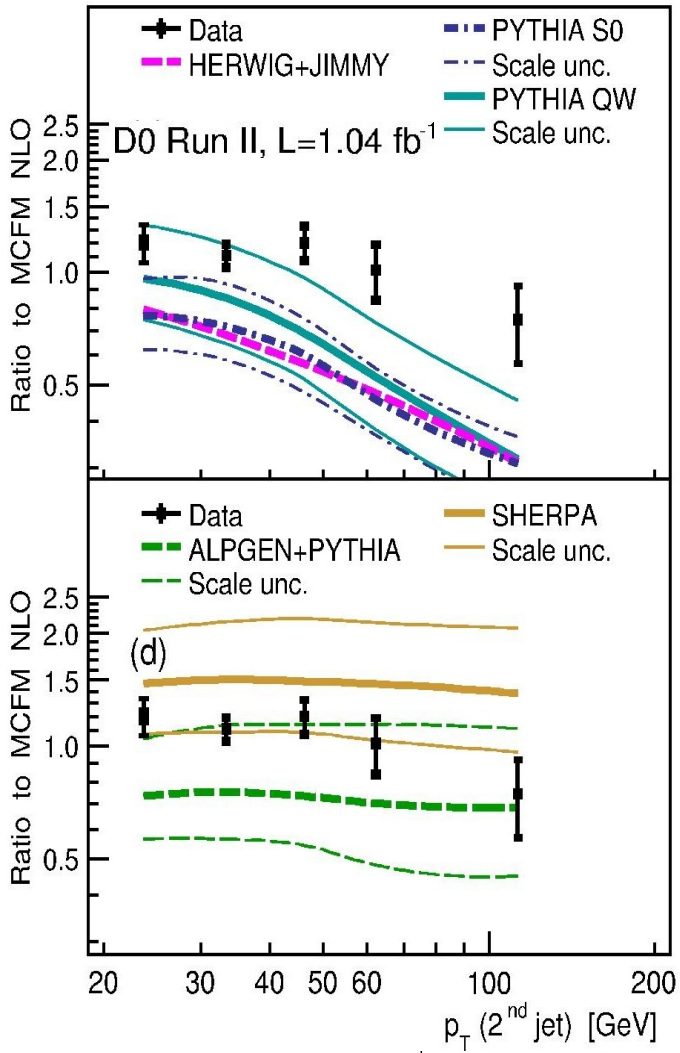
Including the higher order matrix elements pays off for second, third jet
Treating the scale as a tuneable parameter:

- **ALPGEN and SHERPA can describe data for all three jets.**

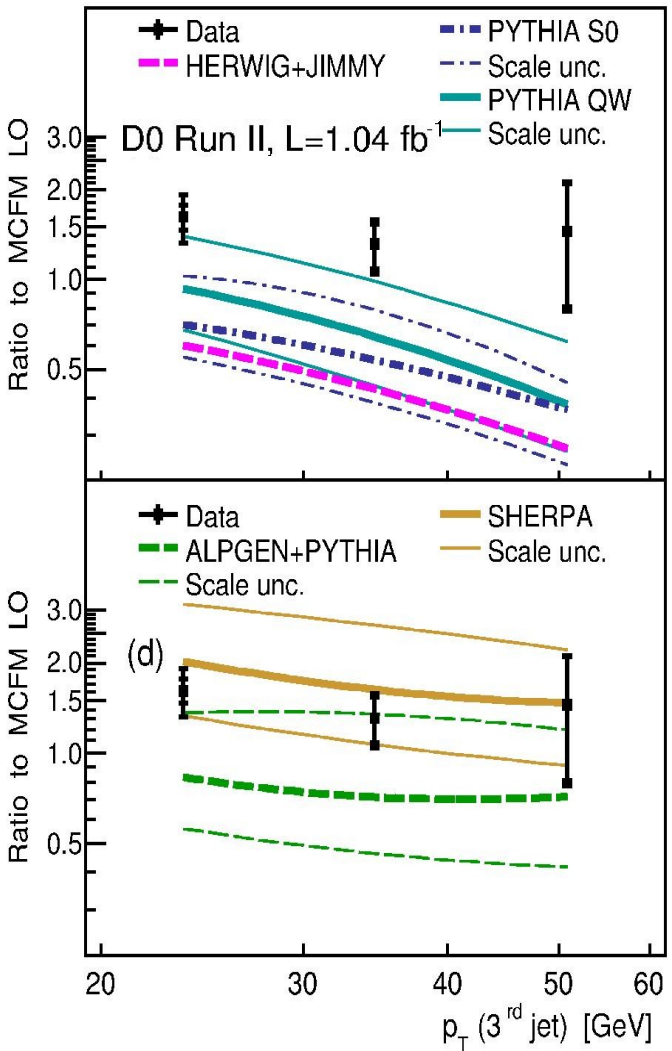
Leading Jet



Second Jet



Third Jet



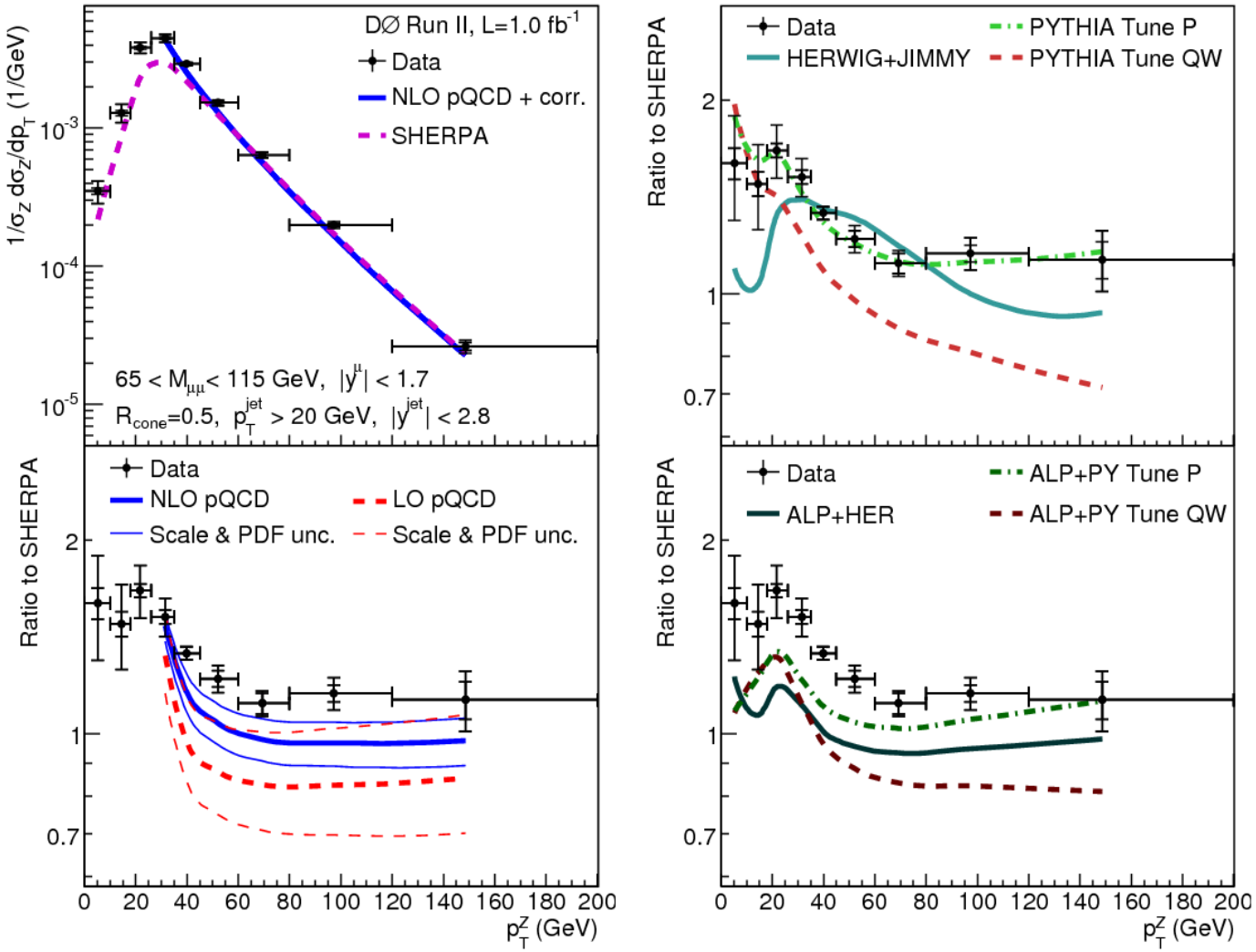
Z + Jet + X

Take a more detailed look at Z(→ $\mu\mu$) + ≥ 1 jet

- Z p_T < 20 GeV significant contributions from underlying event / MPI
  - not described by fixed order calculation
- Leading jet rapidity too narrow in ALPGEN

Z p_T in Z + jet + X

PLB 669, 278 ('08)



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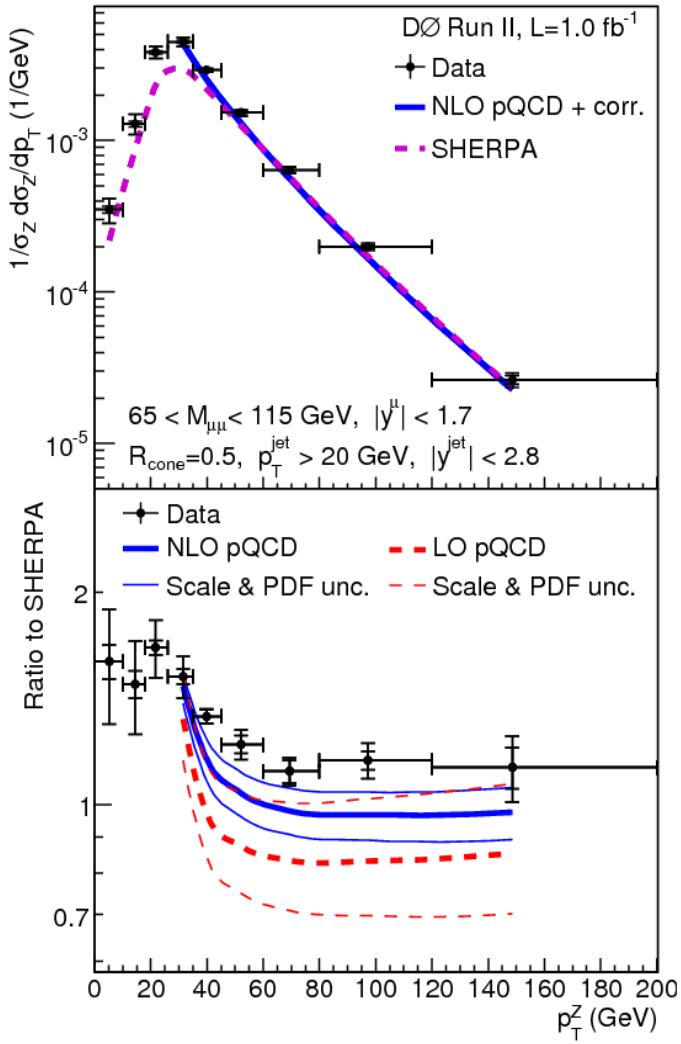
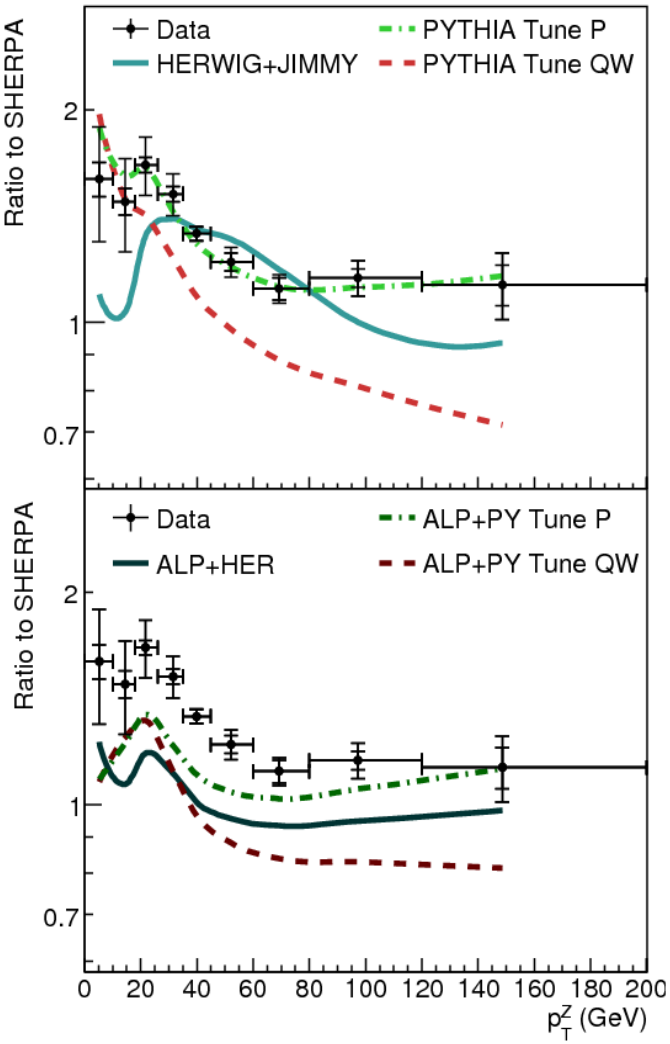
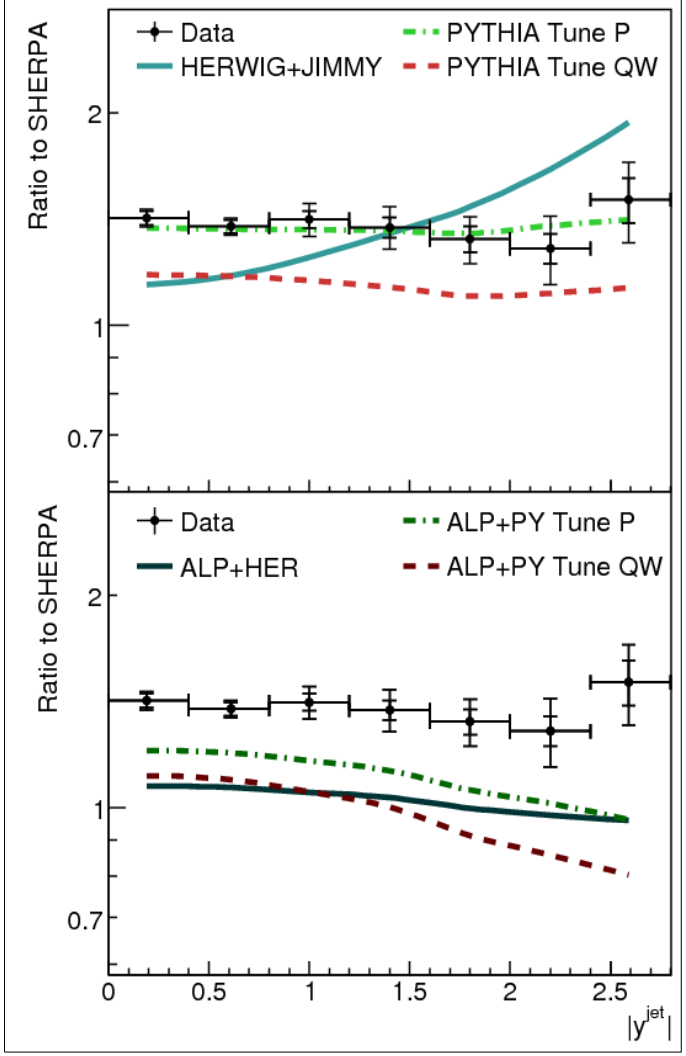




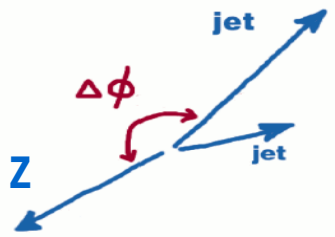
Leading jet y



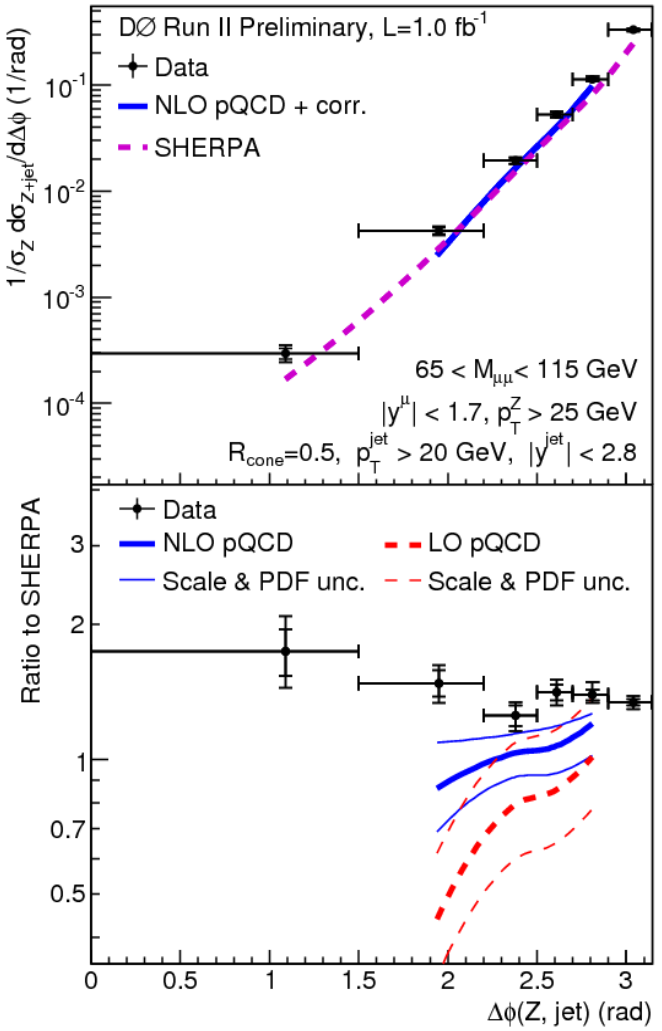
Z + Jet + X

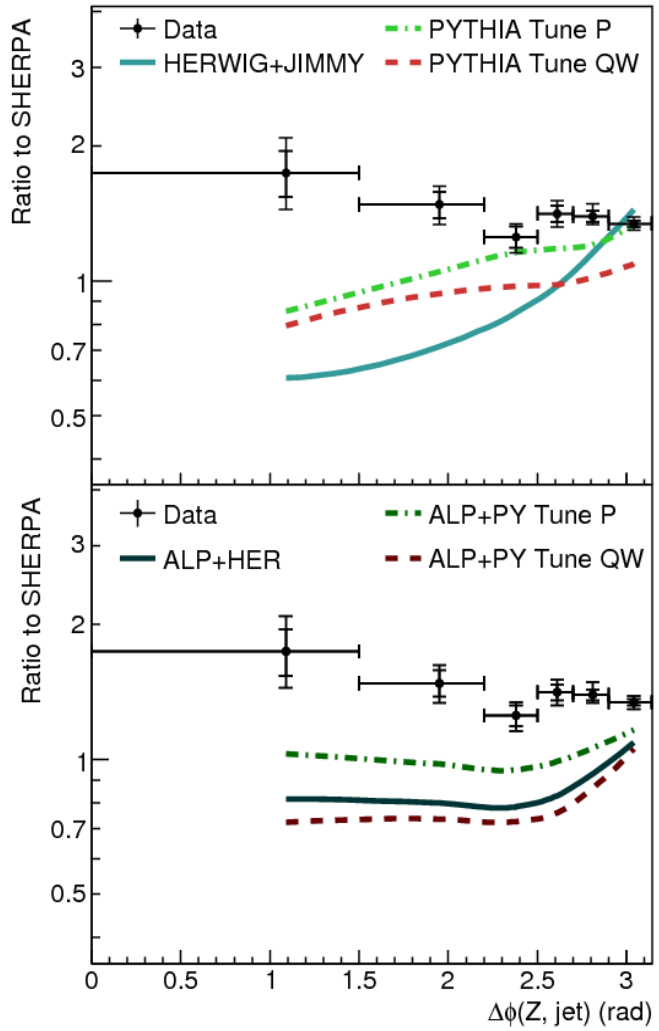
$\Delta\phi$ (Z, jet) sensitive to additional radiation

- low $\Delta\phi$ very sensitive to multi jet, underlying event



$\Delta\phi$ (Z, leading jet)

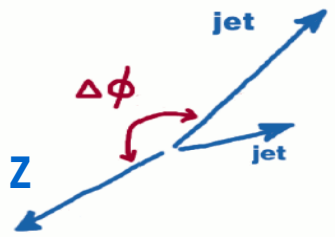




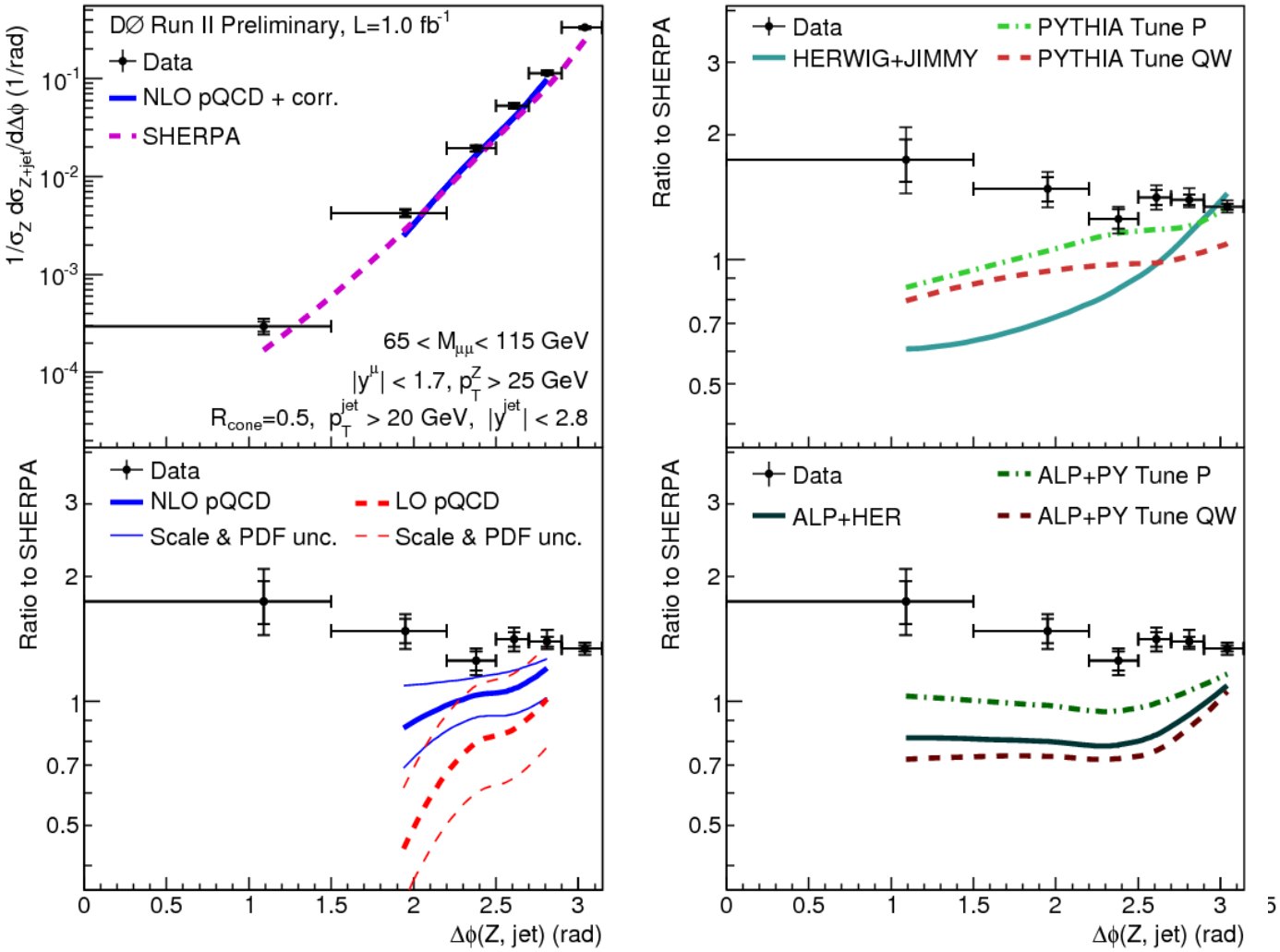
Z + Jet + X

$\Delta\phi$ (Z, jet) sensitive to additional radiation

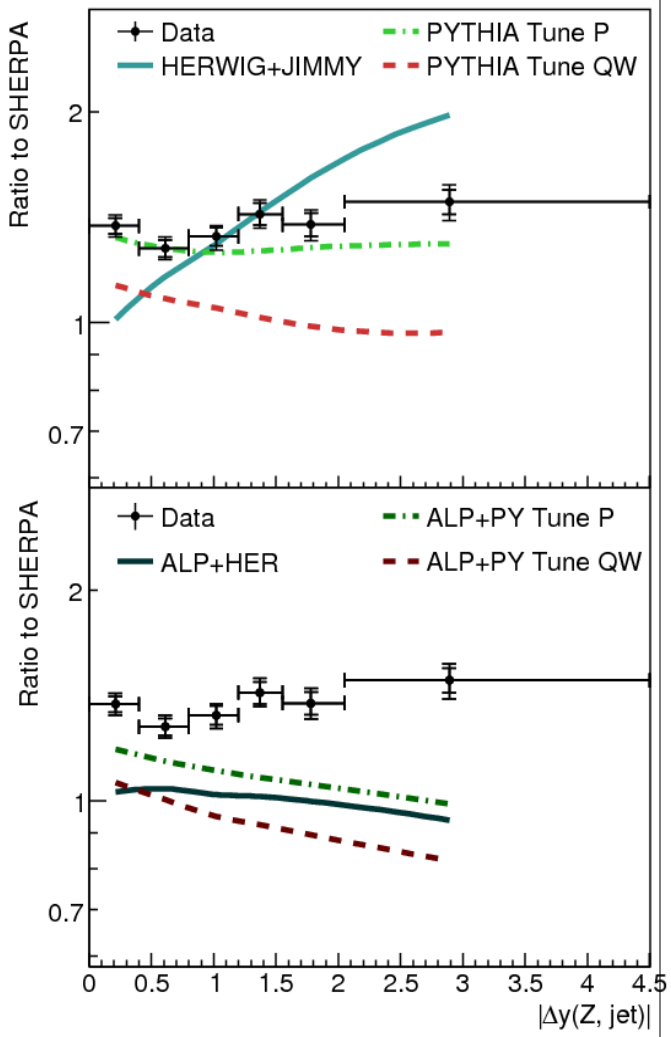
- low $\Delta\phi$ very sensitive to multi jet, underlying event



$\Delta\phi$ (Z, leading jet)



Δy (Z, leading jet)



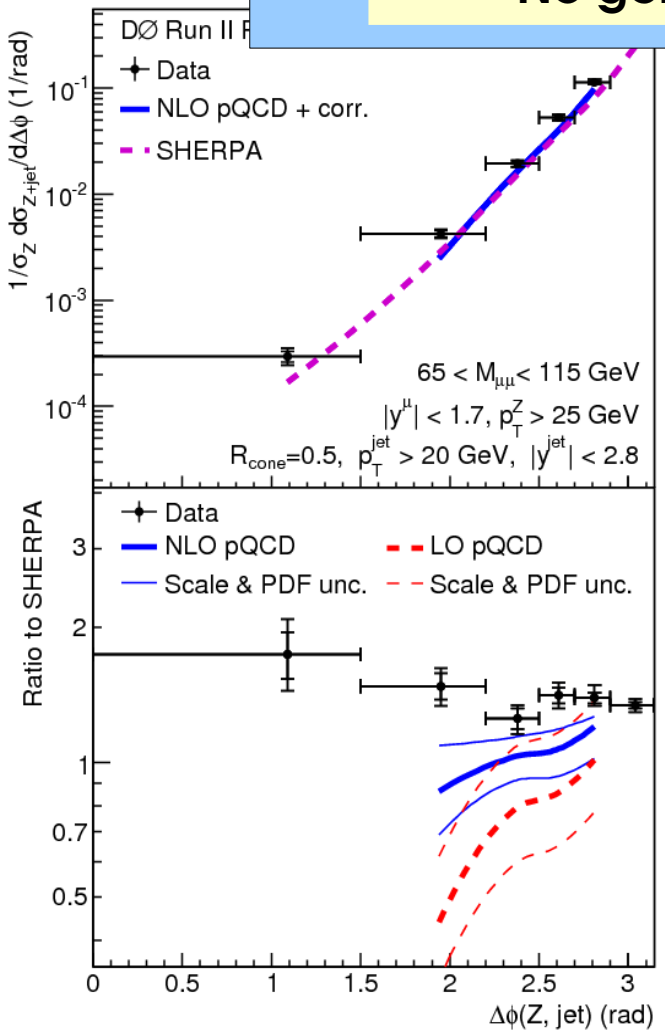
That's a lot of MC curves... Emerging picture:

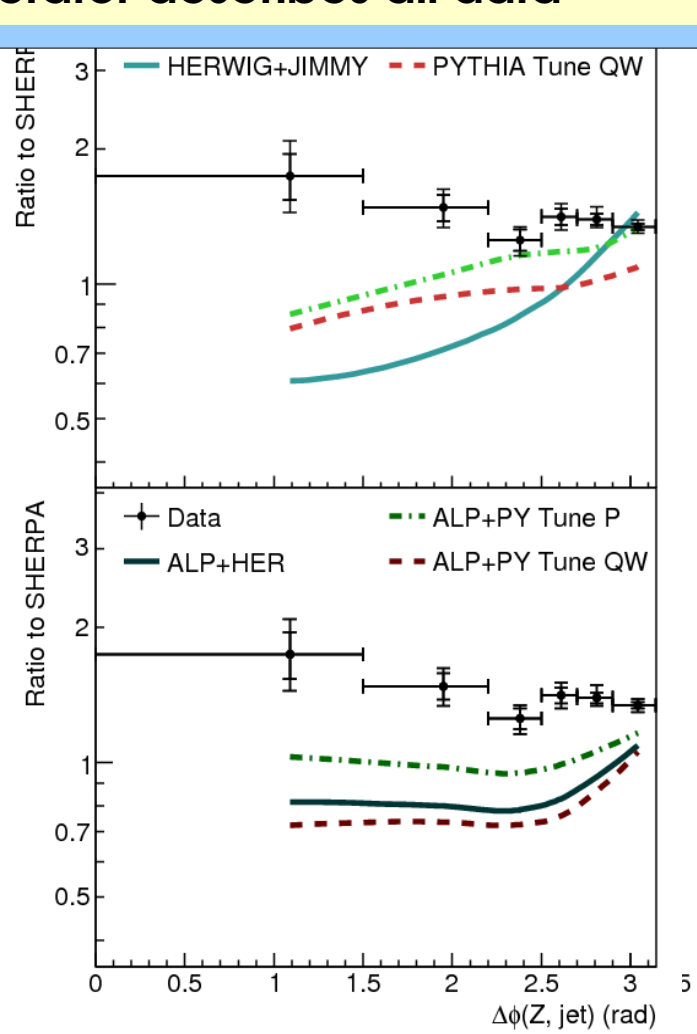
- NLO performs well (where available)
- generators improve with new tunes: SHERPA 1.1.3, PYTHIA "perugia", ALPGEN+PYTHIA (p_T ordered)
- need ME+PS (ALPGEN/SHERPA) beyond 1st jet
- ALPGEN performs best for p_Ts,
- SHERPA performs best for angles
- **No generator describes all data**

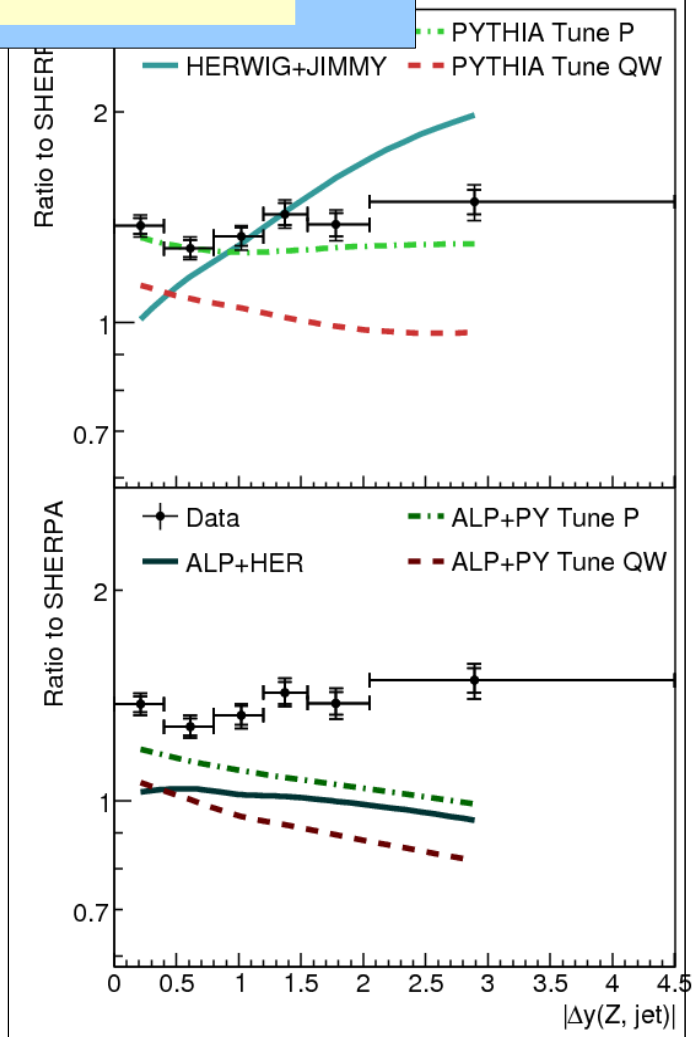
$\Delta\phi$ (Z, je

- low $\Delta\phi$

ng jet)







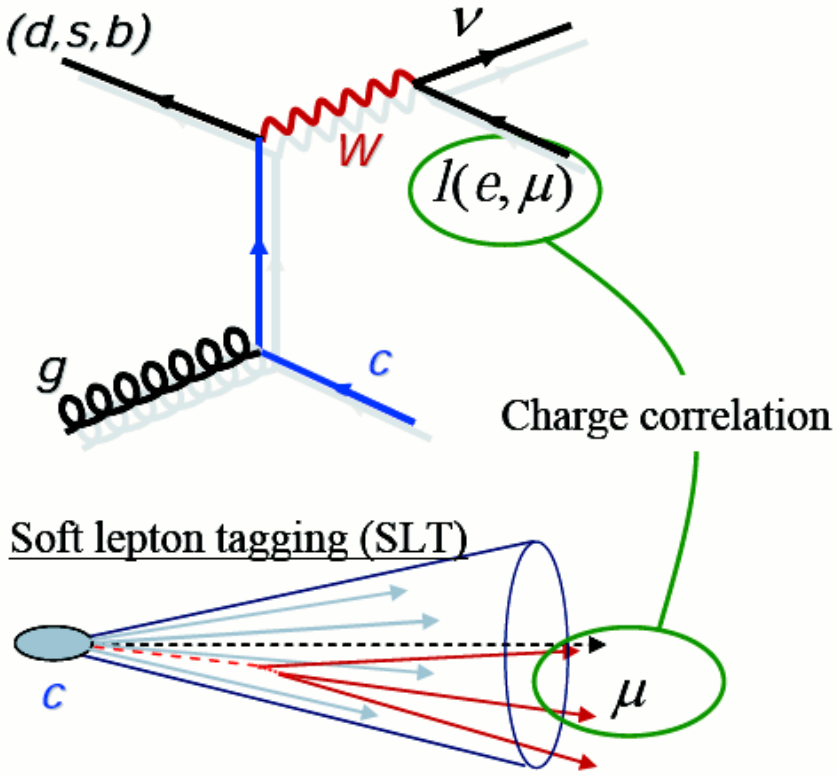
W + c

Probe strange PDF at high Q^2 (~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)



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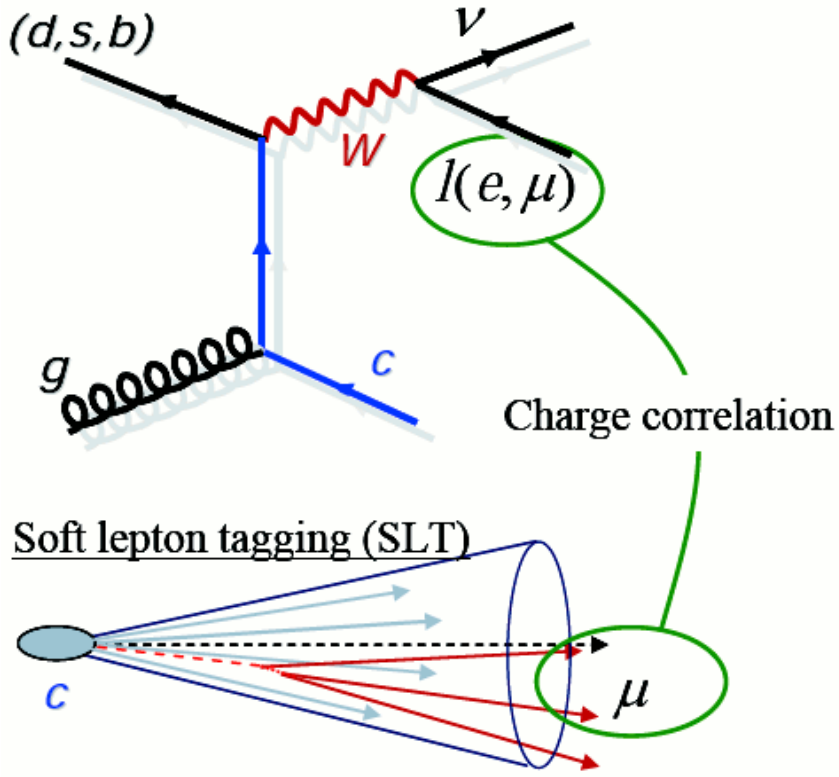
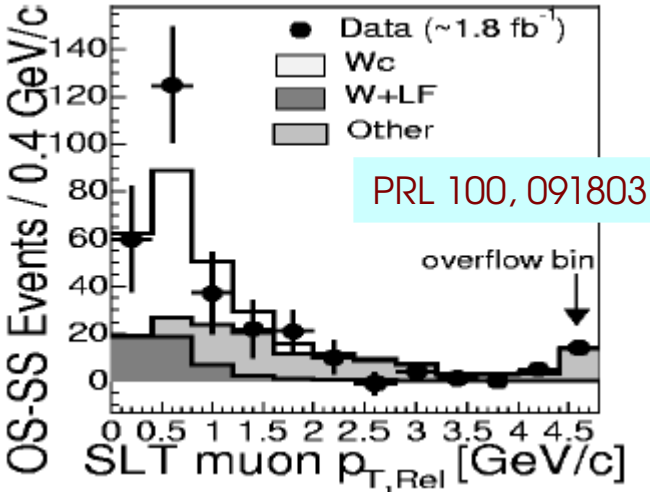


Good agreement between NLO & data:

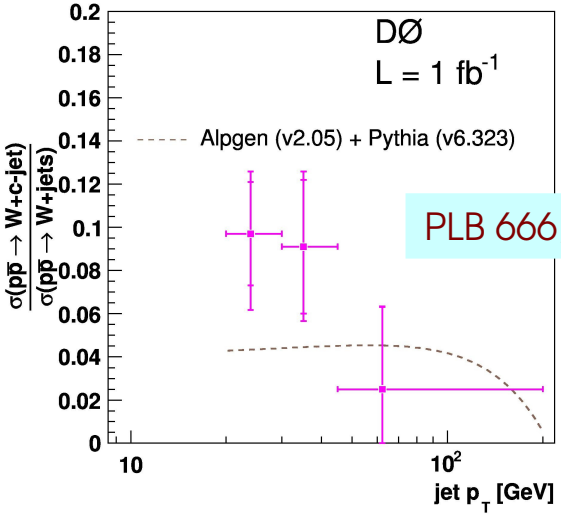
$$\sigma_{W+c} \cdot BR = 9.8 \pm 2.8\,(\text{stat})\,^{+1.4}_{-1.6}\,(\text{syst})\ \text{pb}$$

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

W+c / W+jets agrees with ALPGEN+PYTHIA



PRL 100, 091803 ('08)



PLB 666, 23 ('08)

W / Z + b jets

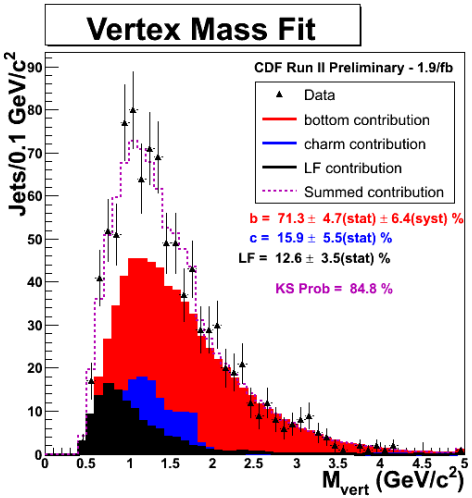
W: e, μ p_T > 20 GeV, $|\eta|$ <1.1, MET > 20 GeV

Z: e, μ p_T >18 GeV, $|\eta|$ <1.1, 66 < M_{ll} < 116 GeV

Jets: E_T>20, $|\eta|$ <2 ($|\eta|$ <1.5 for Z analysis)

b-fraction based on template fits to vertex mass:

- ultra-tight: ~ 70 % b-jets (W)
- tight operating point: ~40 % b-jets (Z)



b-shape, tagging ϵ and luminosity

$\sigma_{W(\to l\nu)+b}$ = 2.78 ± 0.27 (stat) ± 0.42 (syst) pb

ALPGEN: 0.78 pb; No NLO prediction yet

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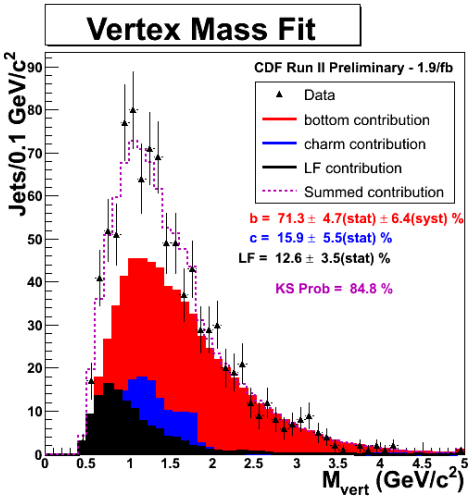

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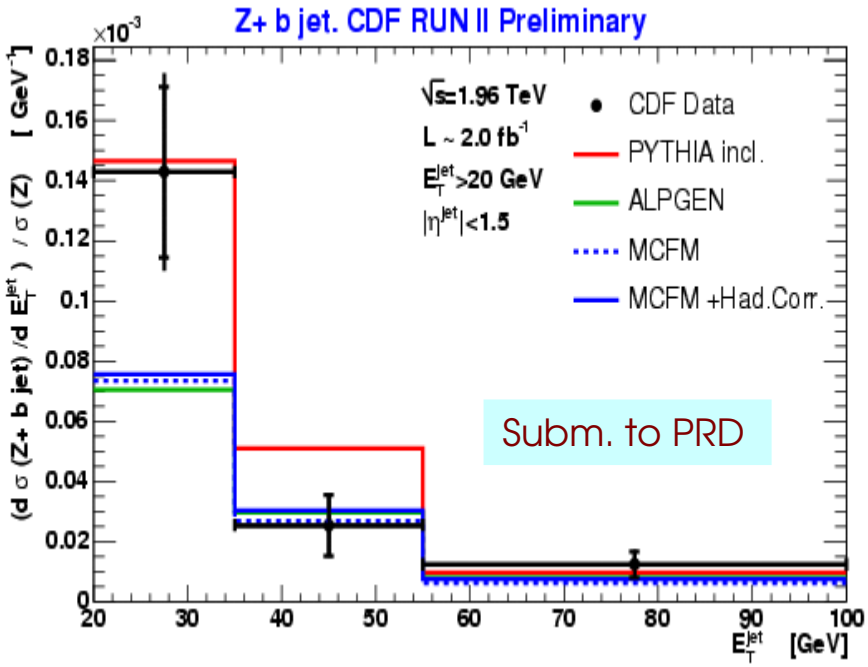
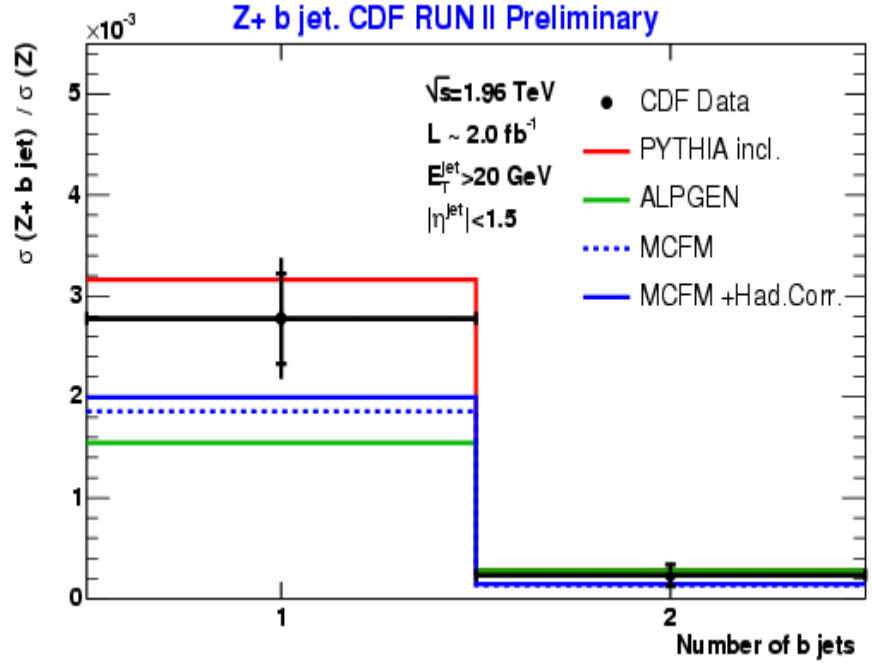
Z+b: agreement with NLO

Factor of 2 difference ALPGEN ↔ PYTHIA

First differential distributions available:

- b-jet p_T, b-jet η, Z p_T, # jets, # b-jets





Conclusions

Many Interesting QCD results from the Tevatron!

Underlying event: how will the models scale to LHC?

Jets:

- unprecedented jet energy scale precision: 1-3 %
- expect Tevatron results to dominate high-x gluon for some time
- no signs of new interactions yet...

Photons:

- inclusive and photon+jet: missing component of theory?
- photon + b/c: charm sea or gluon splitting problem?

W / Z + jets:

- range of differential cross sections:
  - p_T of 1st, 2nd, 3rd jet; 1st jet $|y|$, Z p_T, $|y|$ ($\geq$1 jets); $\Delta\phi$, Δy, y_{boost}(Z, 1st jet)
- compare pQCD predictions, and the current best V + jet(s) event generators
  - tuning needed to describe the data: must be fixed for LHC (& Tevatron!)

W / Z + heavy flavour:

- first differential Z + b-jet distributions now available
- need more data, and resolution to theory issues
- hear more in the Higgs session!


Thanks, that's all!
Apart from the backups.