QCD at D0: Jets and Bosons

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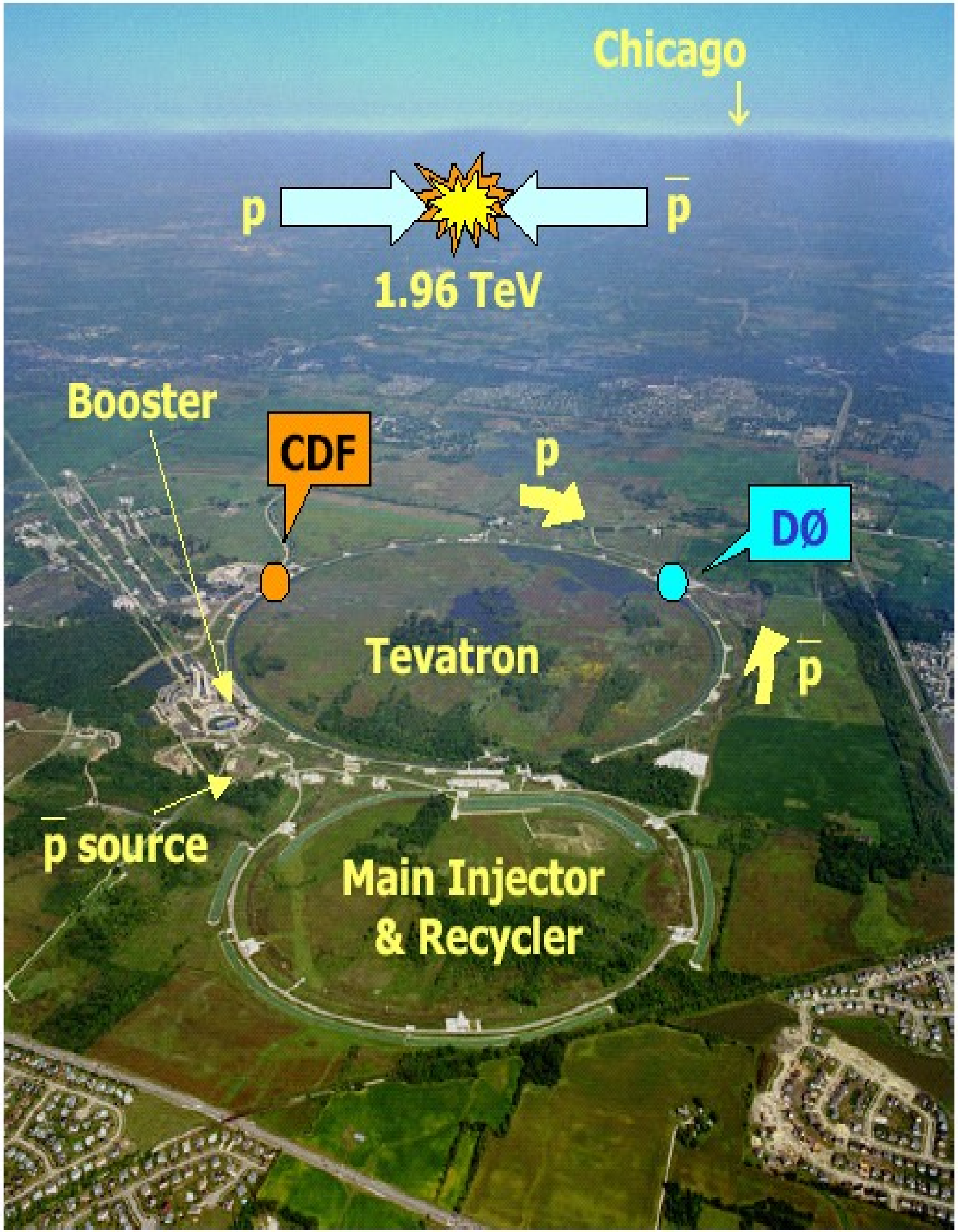
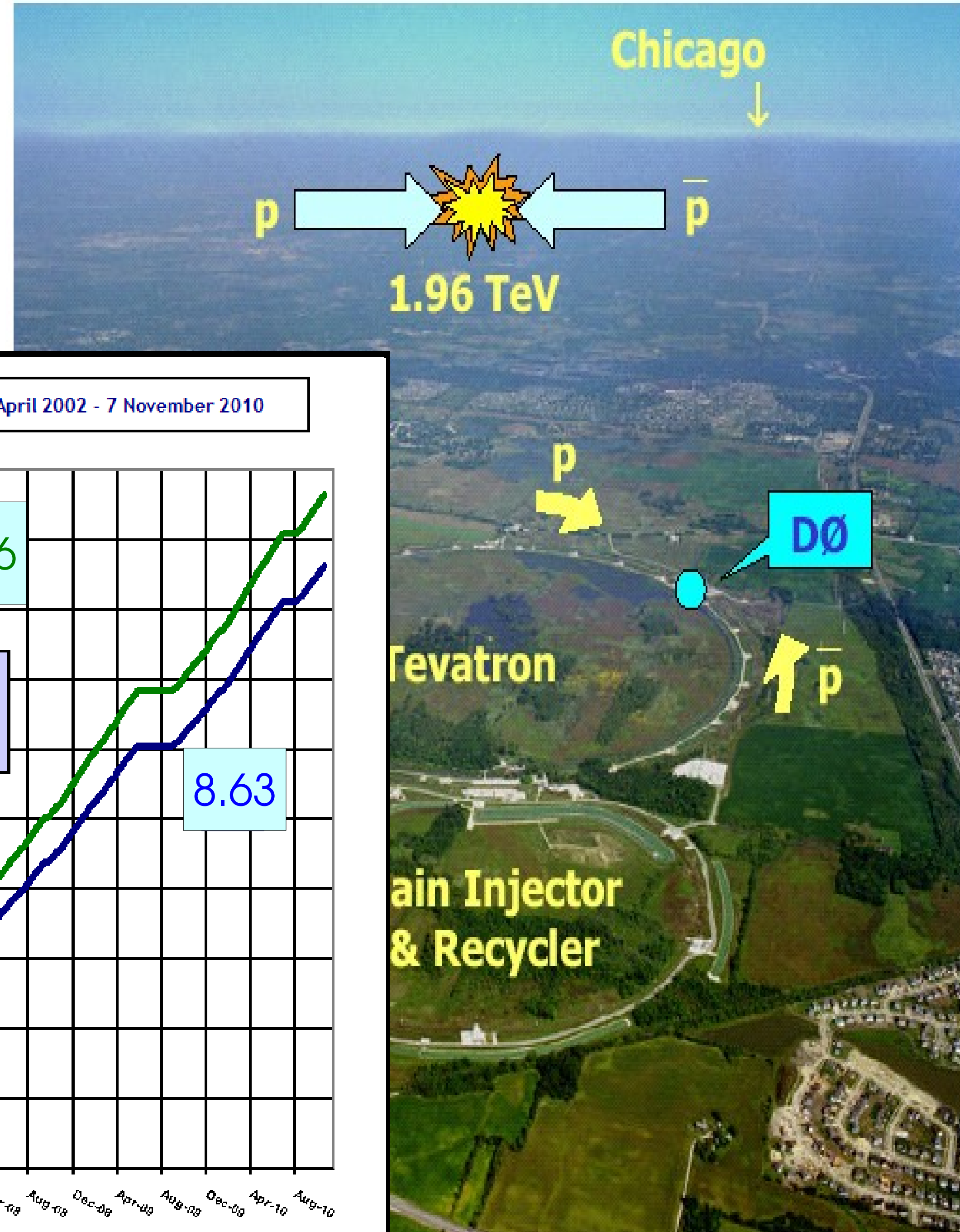
The Tevatron

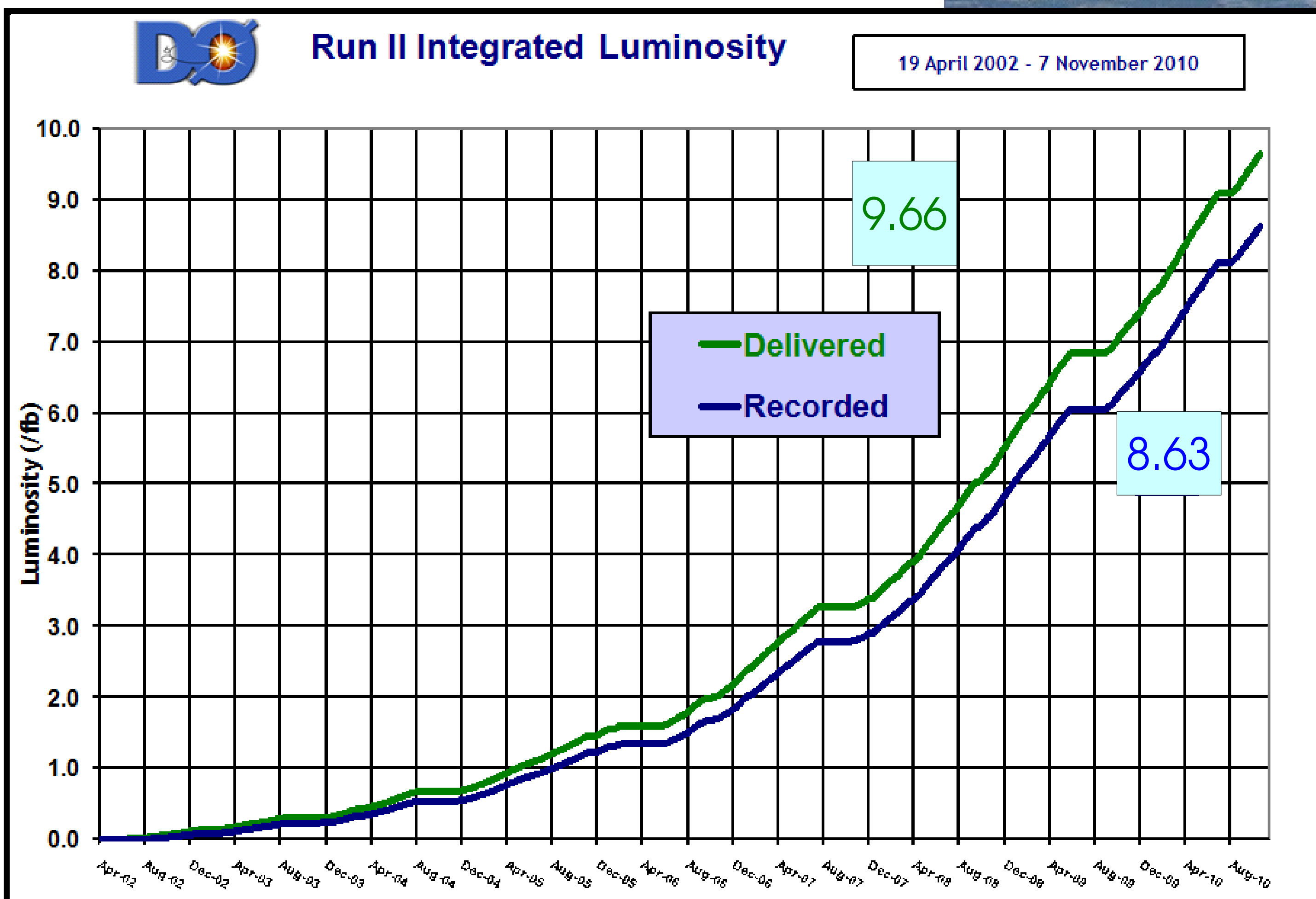
The Tevatron:
- proton anti-proton collider
- c.o.m energy 1.96 TeV
- RunII started in 2001
    - ending in 2011-14...
- Two general-purpose detectors:
    - D0 and CDF.



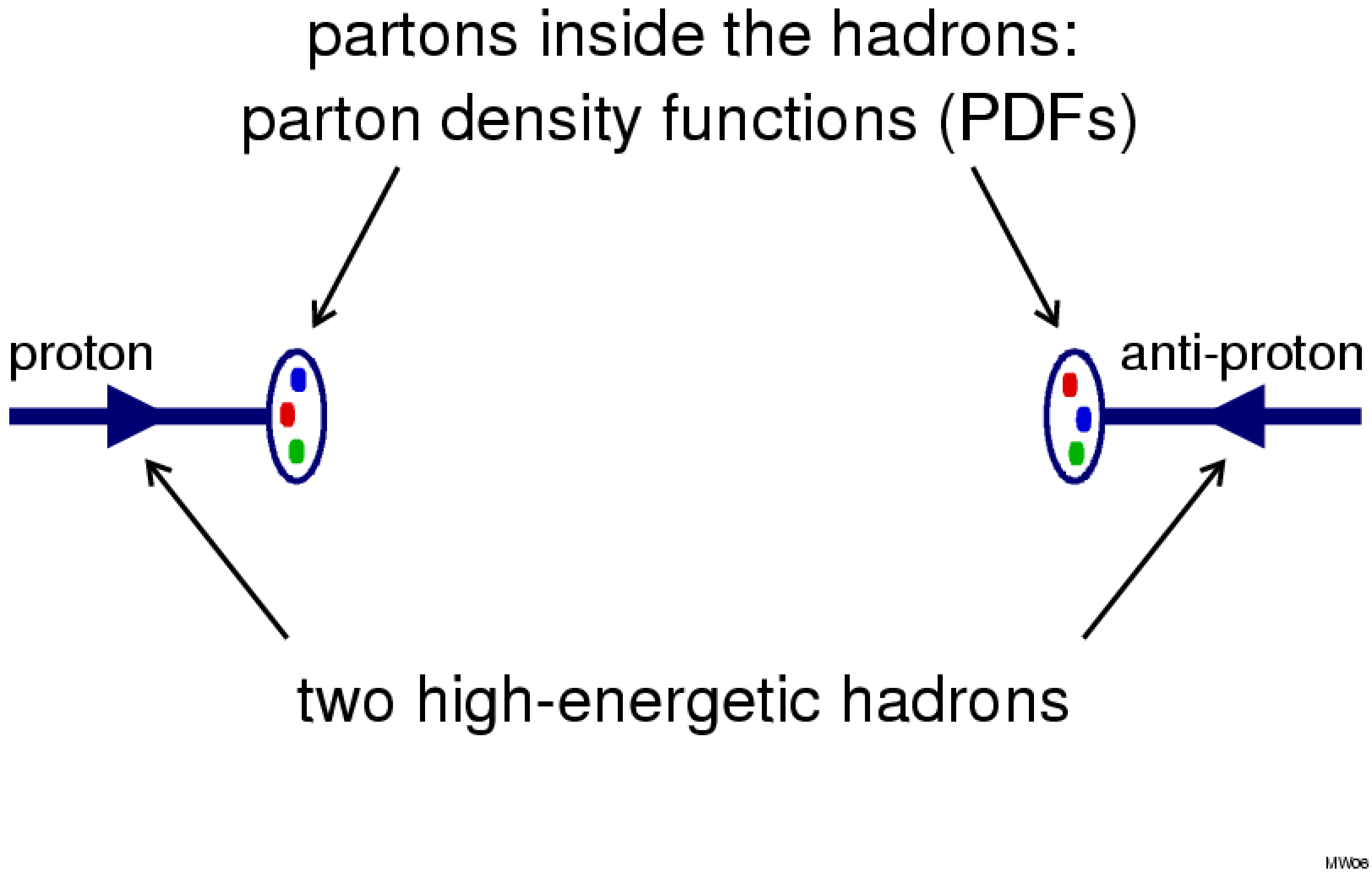
The Tevatron

Tevatron performing very well:
- 9.7 fb^{-1} delivered per experiment
- 2 fb^{-1} in 2009-10
- D0 efficiency >90% over the last 3 years





Hadron-Hadron Collisions



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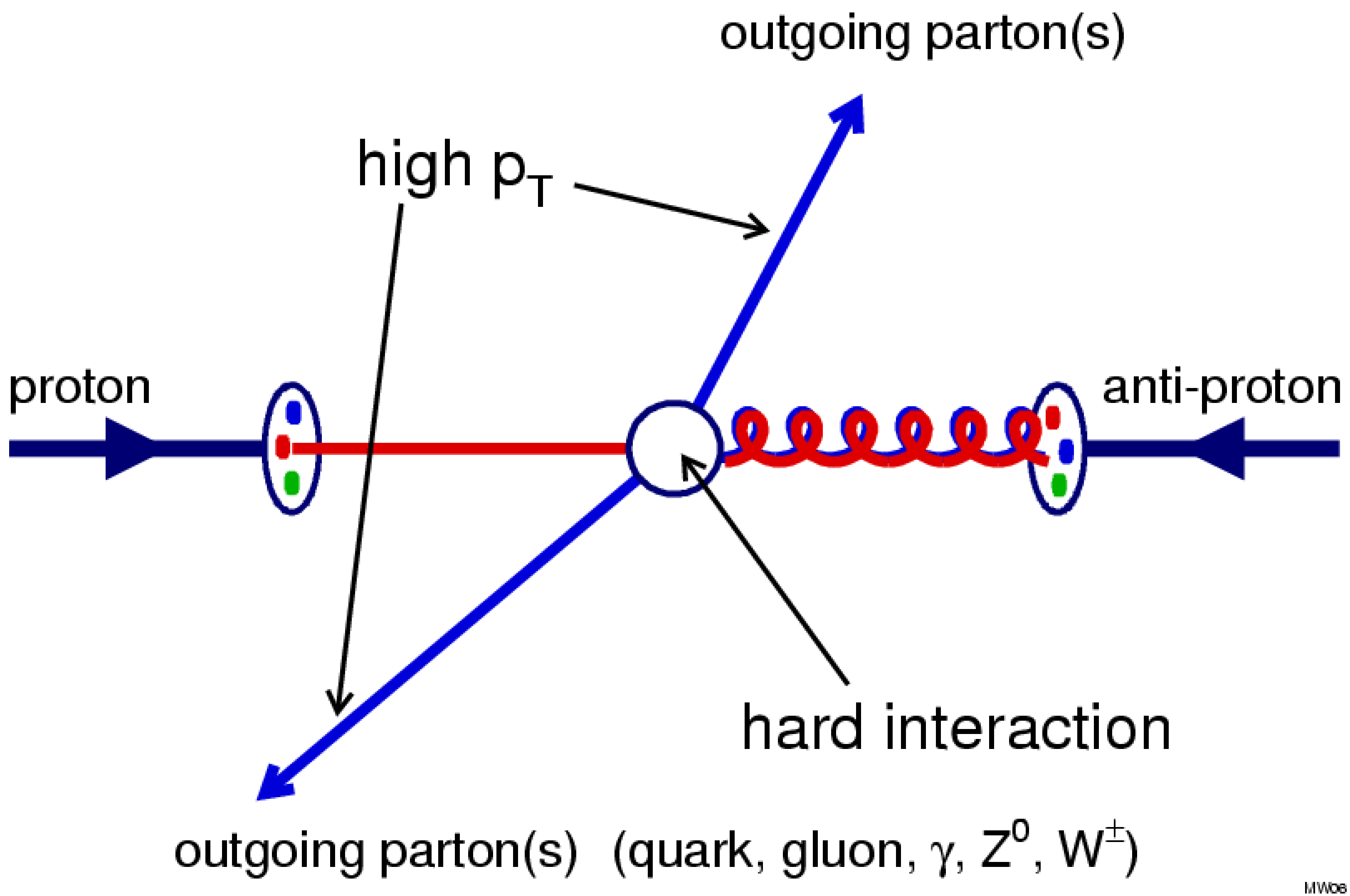

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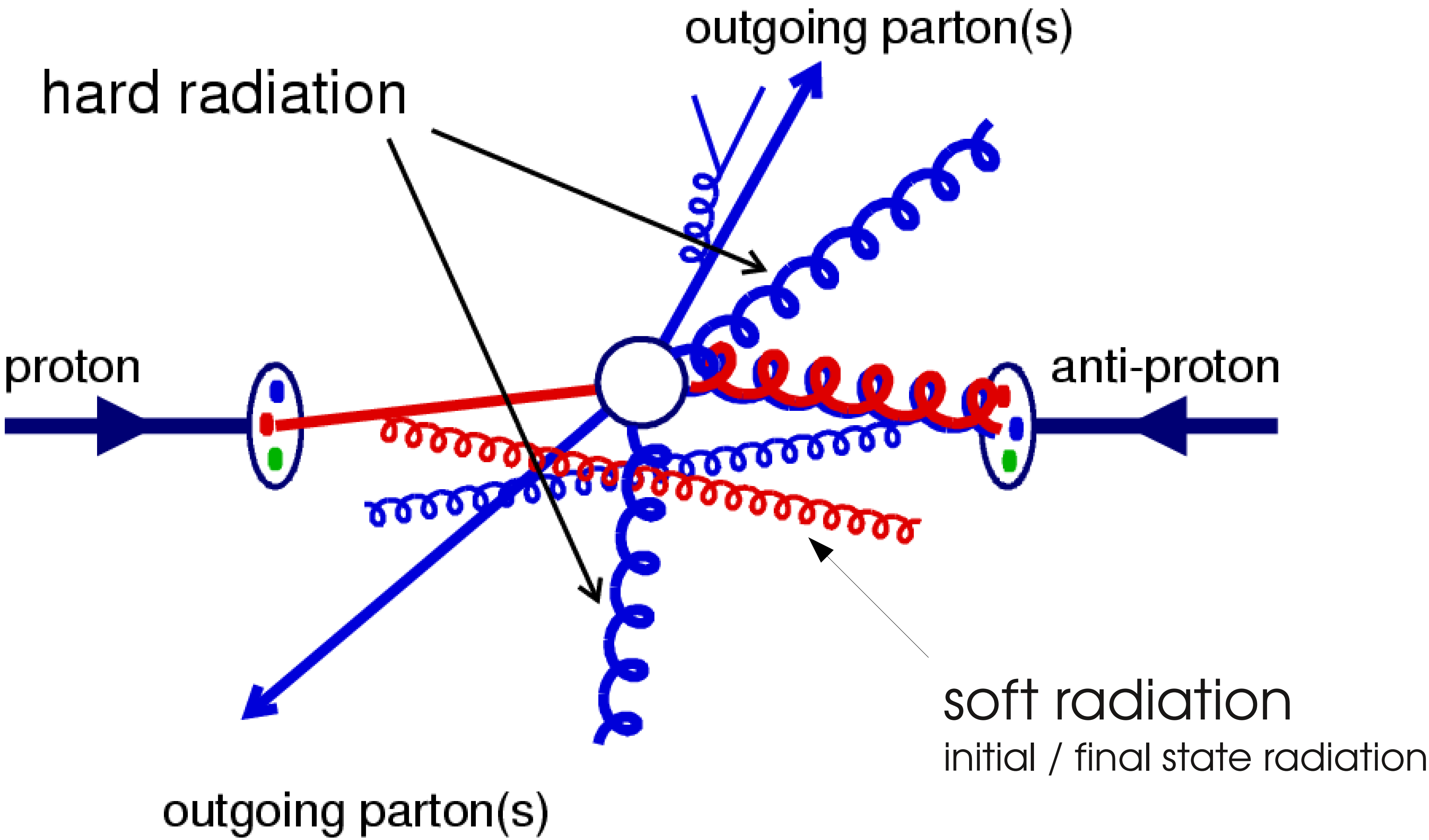

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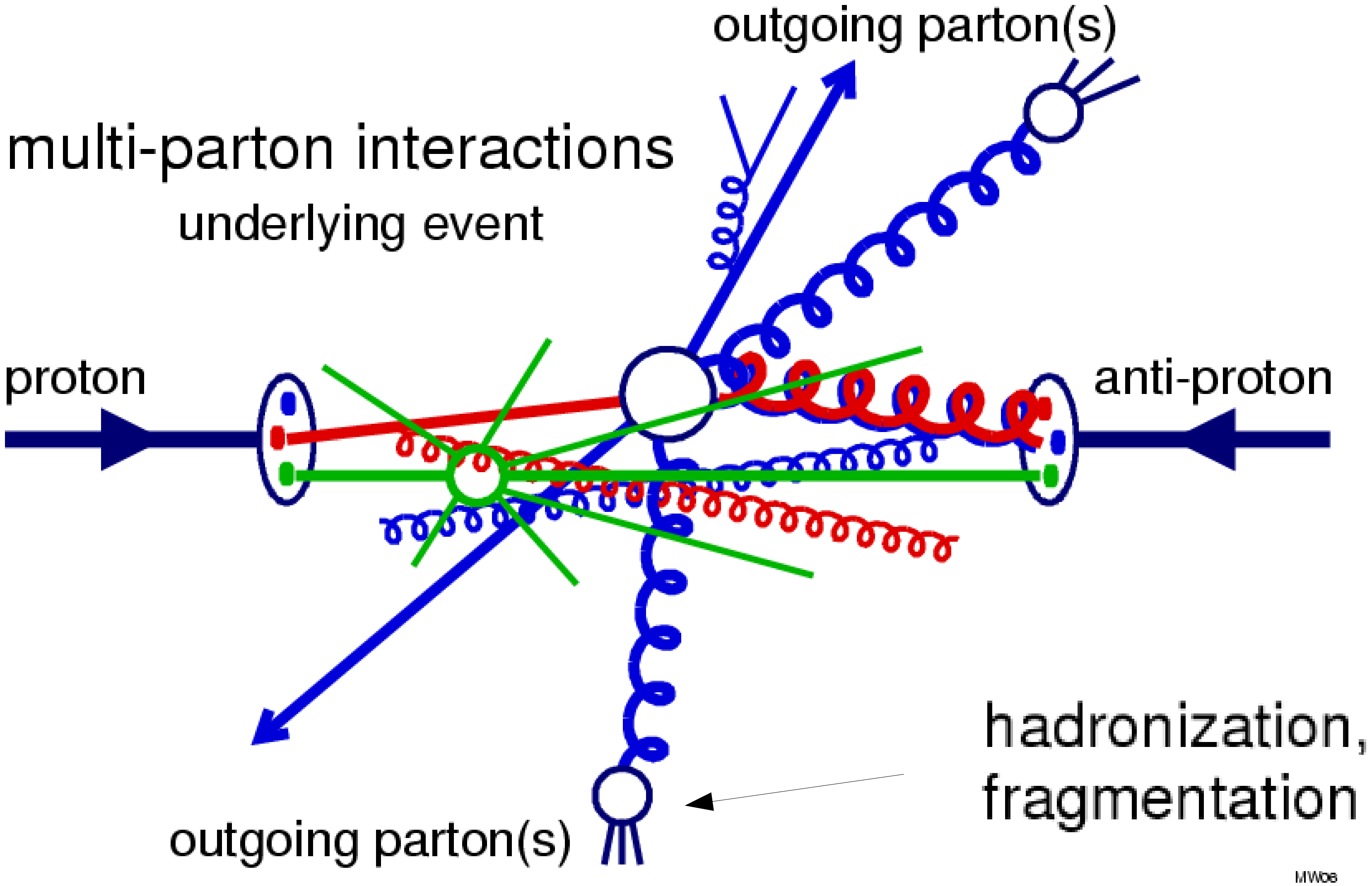

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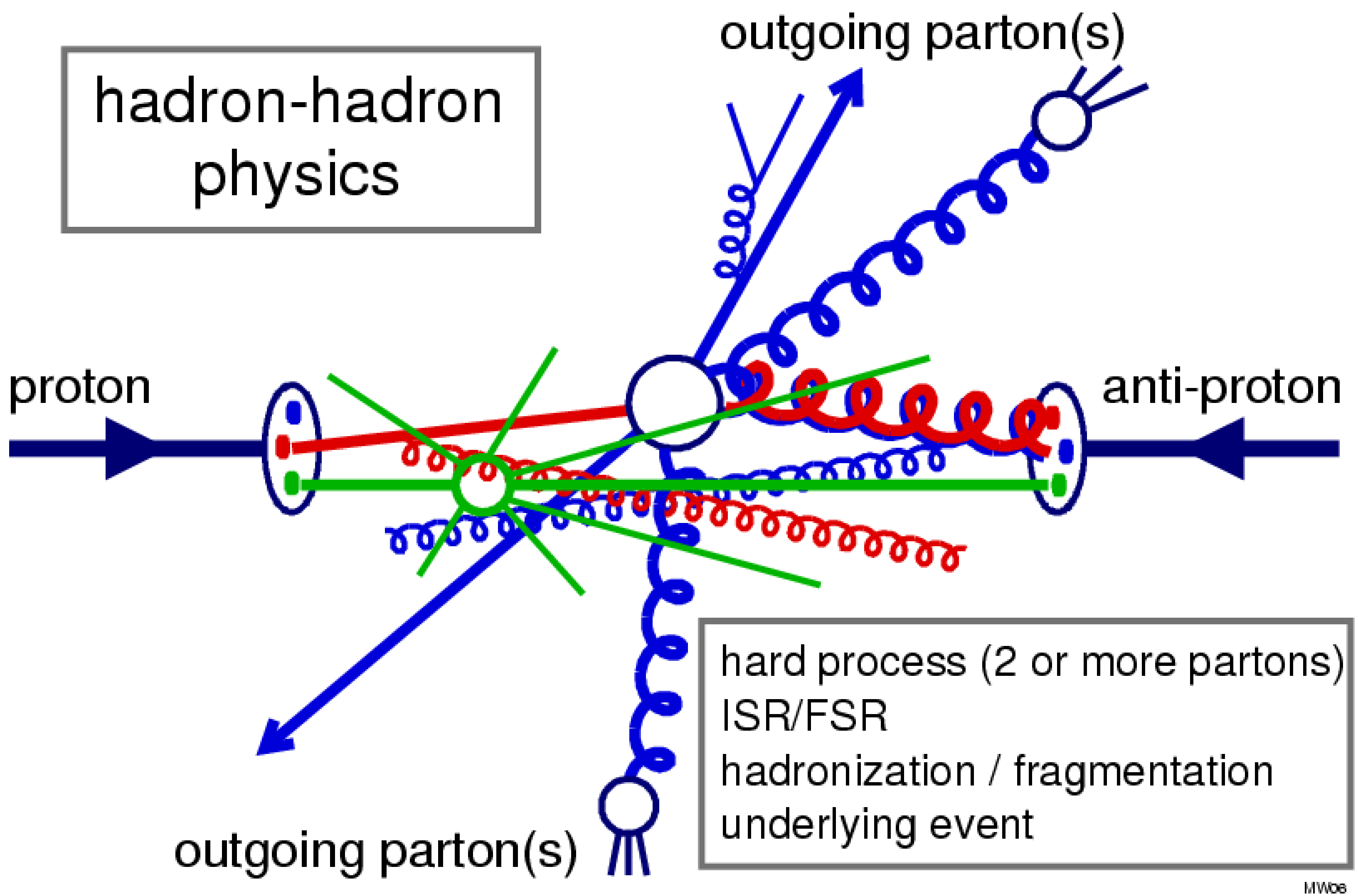
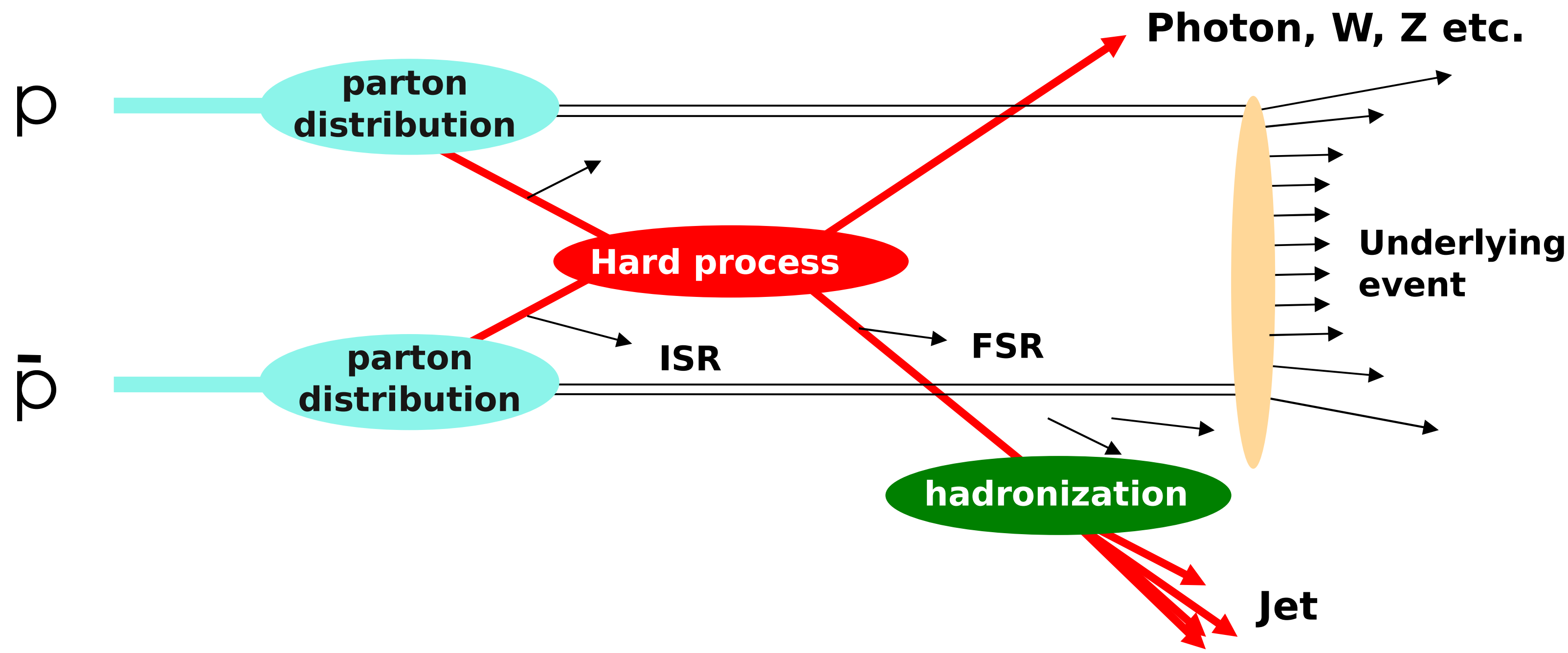




Part 1: basic parton scattering - jet production:

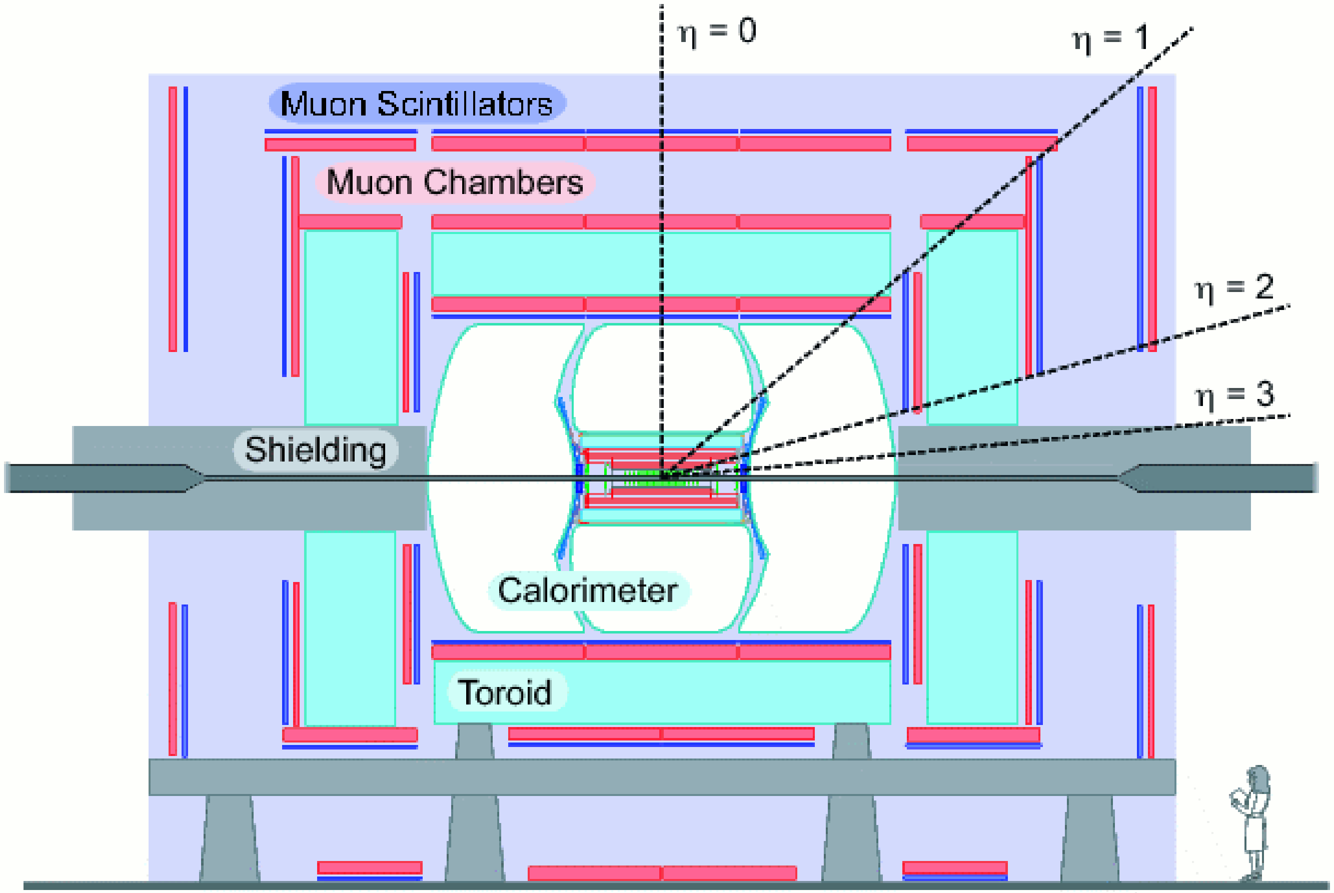
- test pQCD, constrain PDFs, search for new interactions

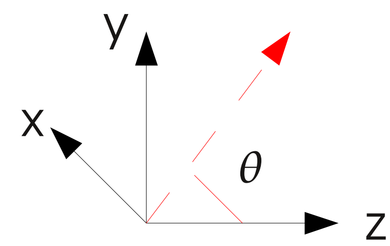
Part 2: using bosons as a probe of QCD:

- colourless probe of QCD – excellent testing ground for predictions
- using studies of known particles to predict dynamics of new signals
  - and their main backgrounds!

Precision understanding of QCD is an essential part of the Tevatron (and LHC) program

The D0 Experiment

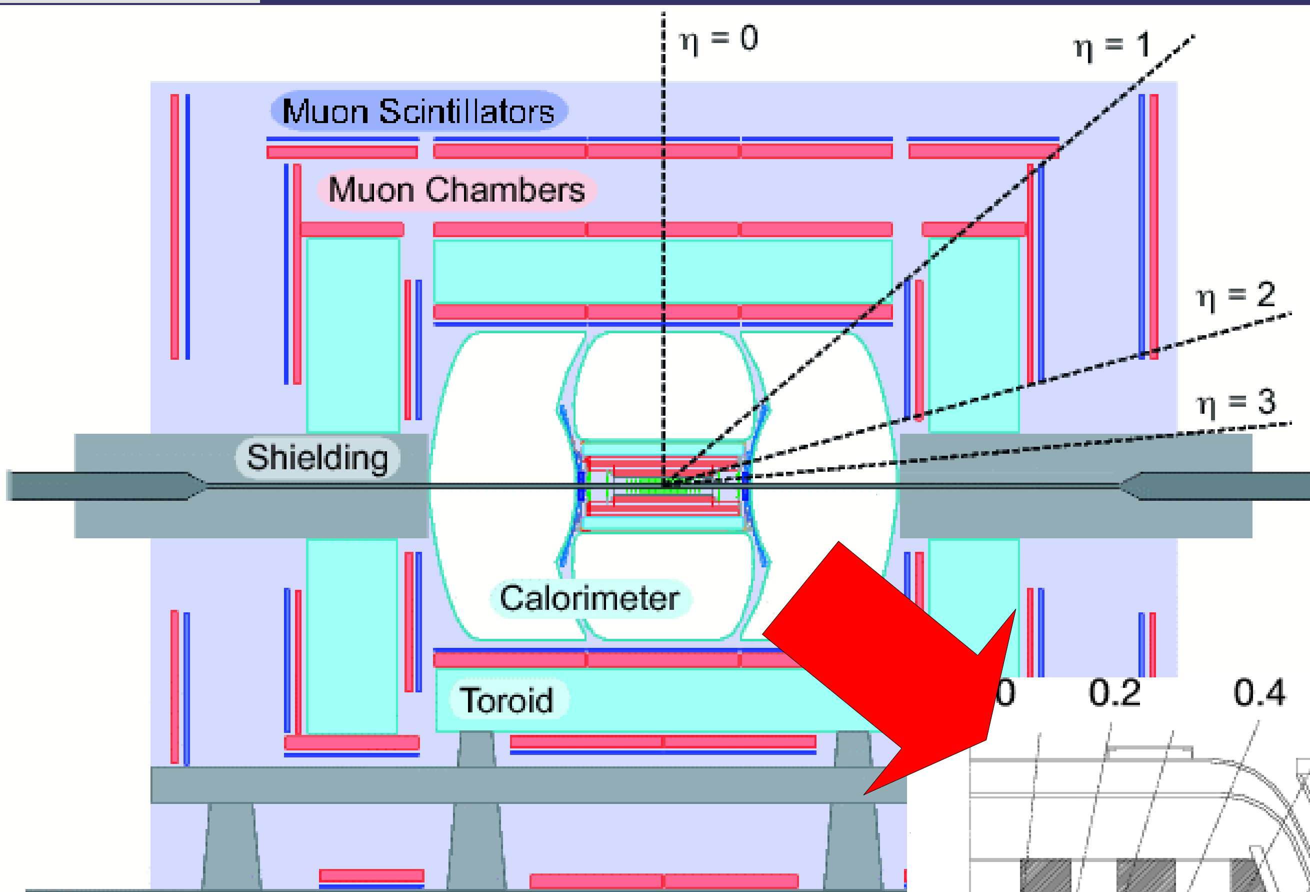


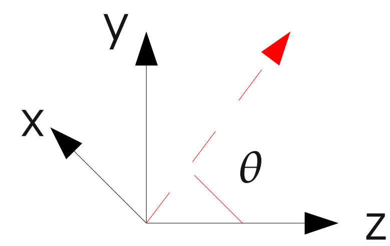


Some definitions:

- transverse momentum, p_T
- rapidity $y = ½ \ln((E+p_z)/(E-p_z))$
- pseudo-rapidity $\eta = -\ln (\tan \theta/2)$

The D0 Experiment





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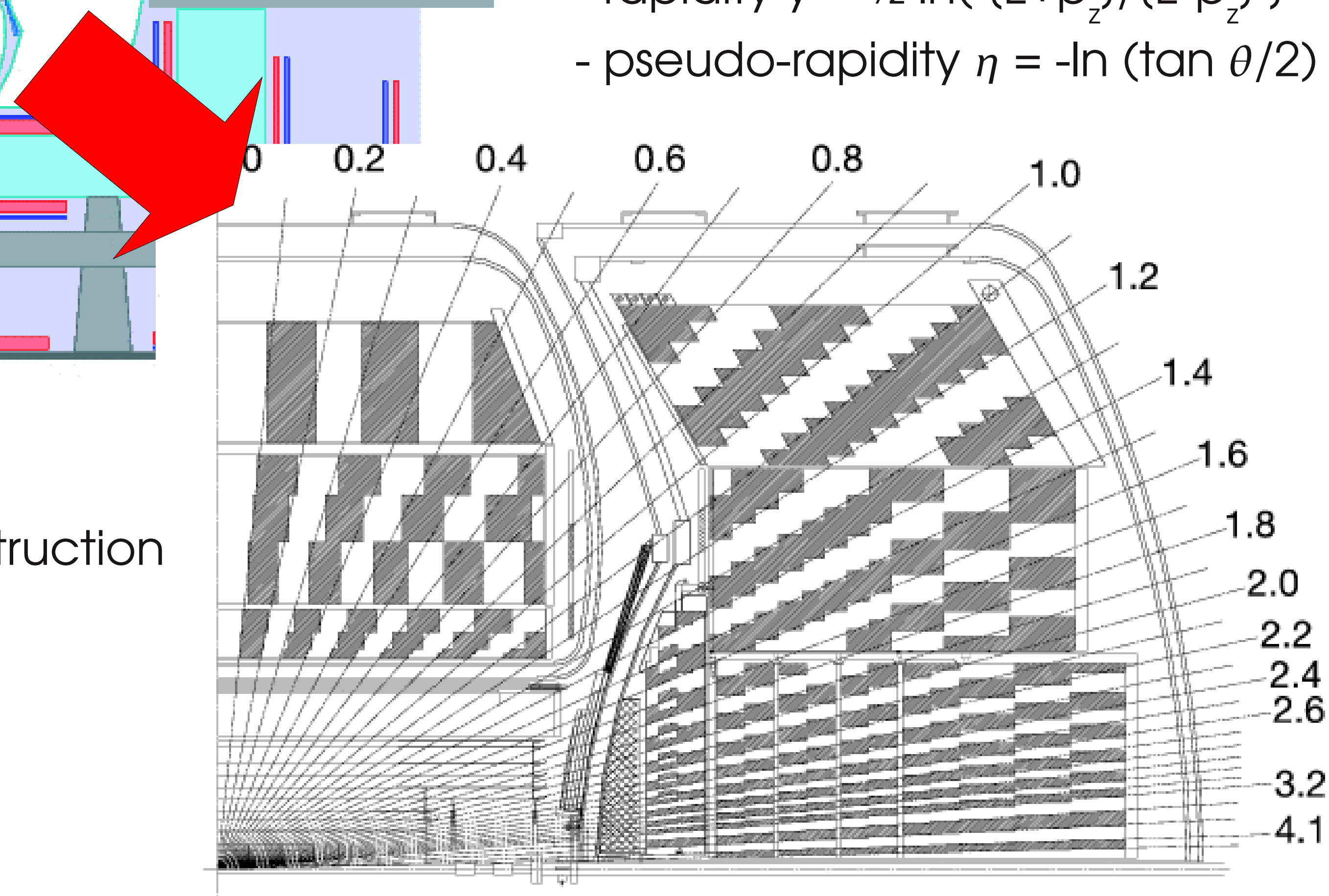
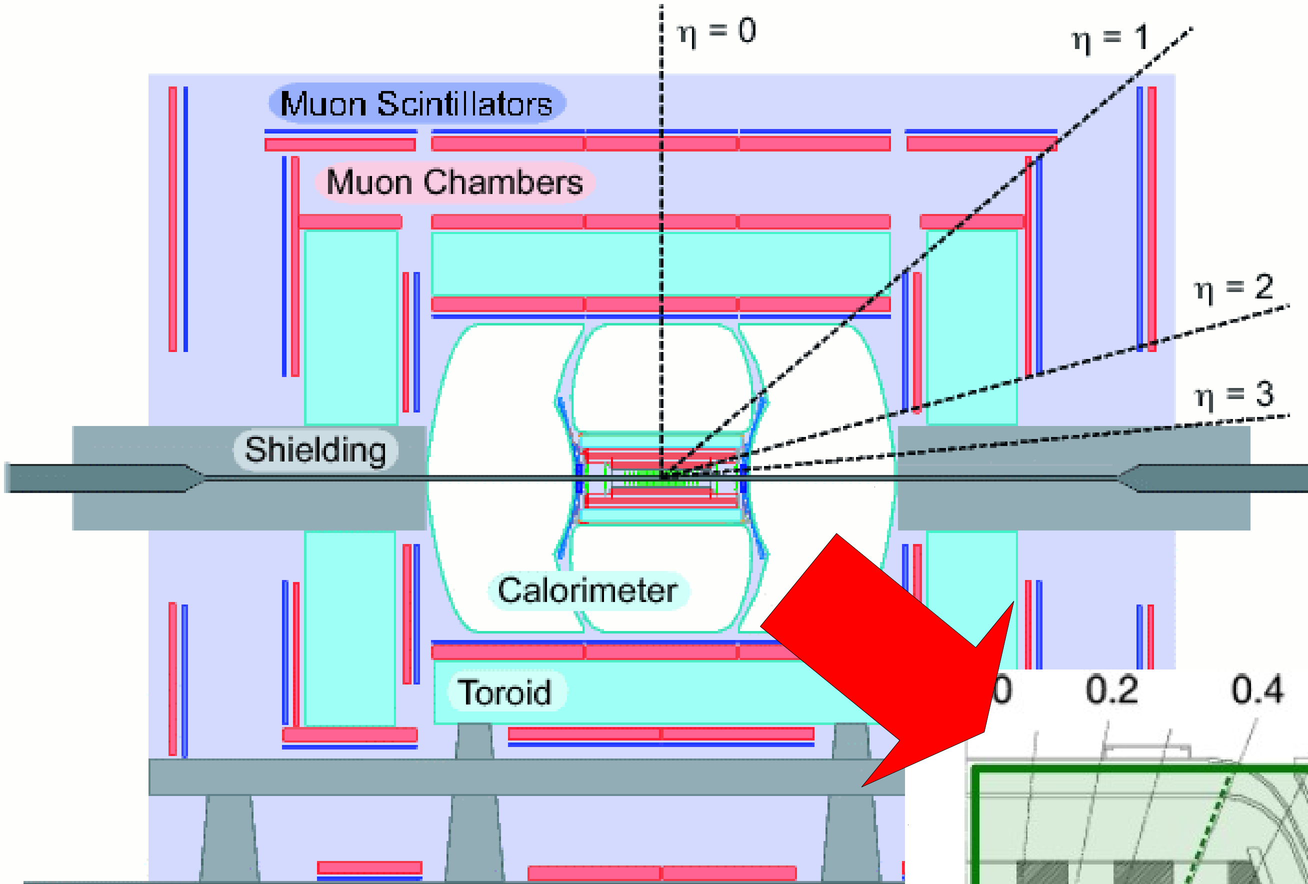
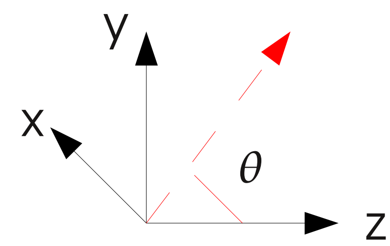


LAr – U calorimeter

- "Towers" of cells:
- used in triggering and reconstruction
- typically require $|z|<50$ cm

The D0 Experiment





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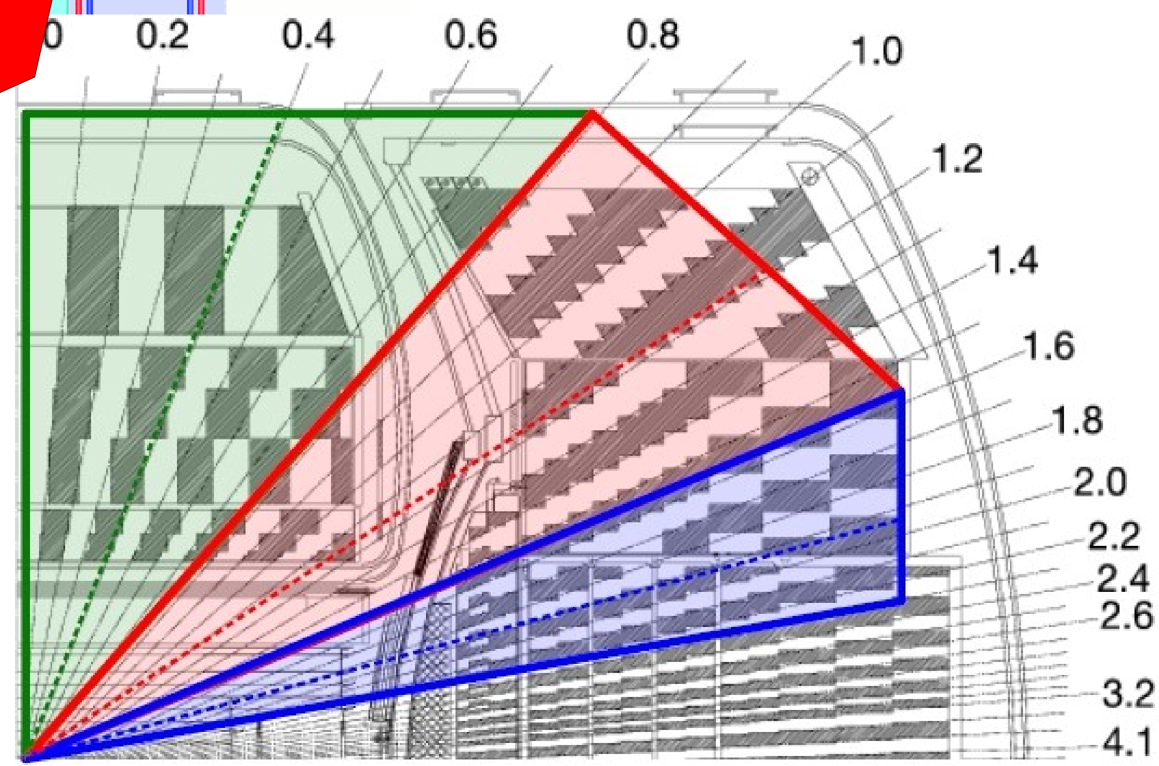
LAr – U calorimeter

- "Towers" of cells:
- used in triggering and reconstruction
- require $|z| < 50$ cm

Three distinct regions:

- central
- ICR
- forward




1) Jets
a) angles
b) cross sections

Defining a Jet

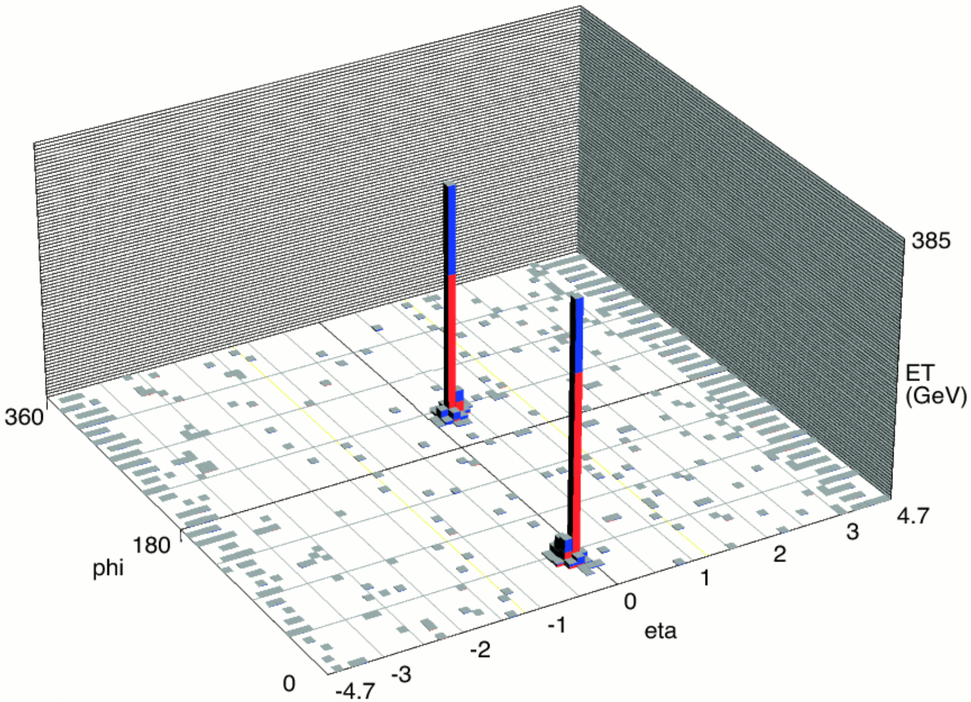
Use D0 RunII seeded, iterative, midpoint cone algorithm.

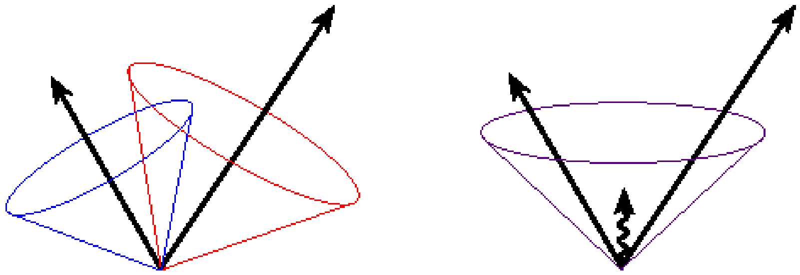
Run I algorithm:

- 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.





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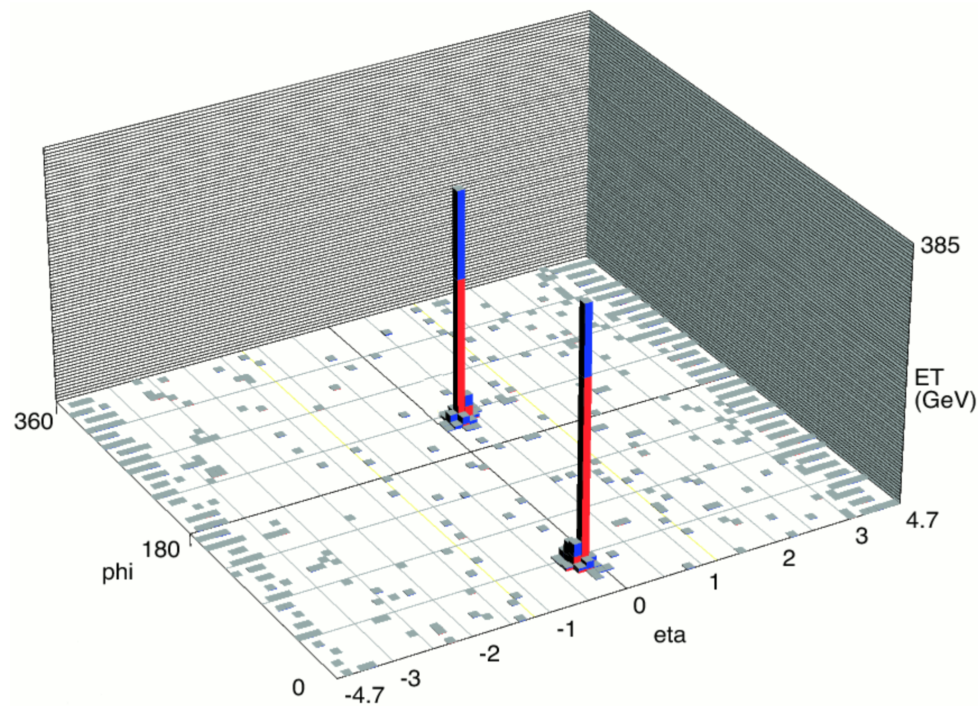
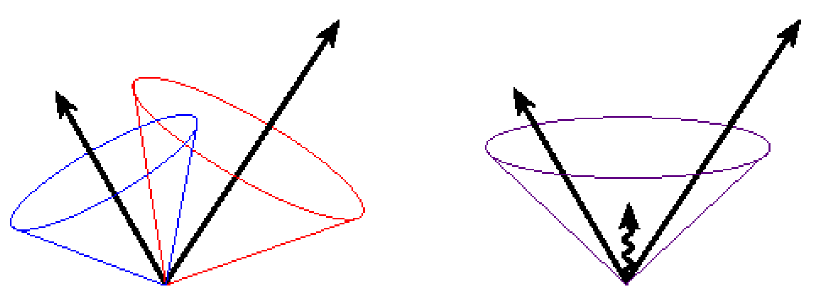


Algorithm sensitive to soft radiation:
- infra-red problem.

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

a) Jet Angles

First category: searches for new physics

- jet angles are a nice candidate:
  - angles are well measured, not limited by systematics

Focus on $\chi = \exp(|y_1 - y_2|)$

- in massless, 2→2 limit:
  - interaction with different kinematics to QCD → different dijet χ distribution
  - any deviation from QCD prediction → new physics!
- need good understanding of y dependence of JES

Dijet χ

Phys. Rev. Lett. 103, 191803 (2009)

Measurement of di-jet χ
- in 11 bins of di-jet mass
- first measurement above 1 TeV
    - ie > 50% of beam energy!
    - most sensitive to new physics

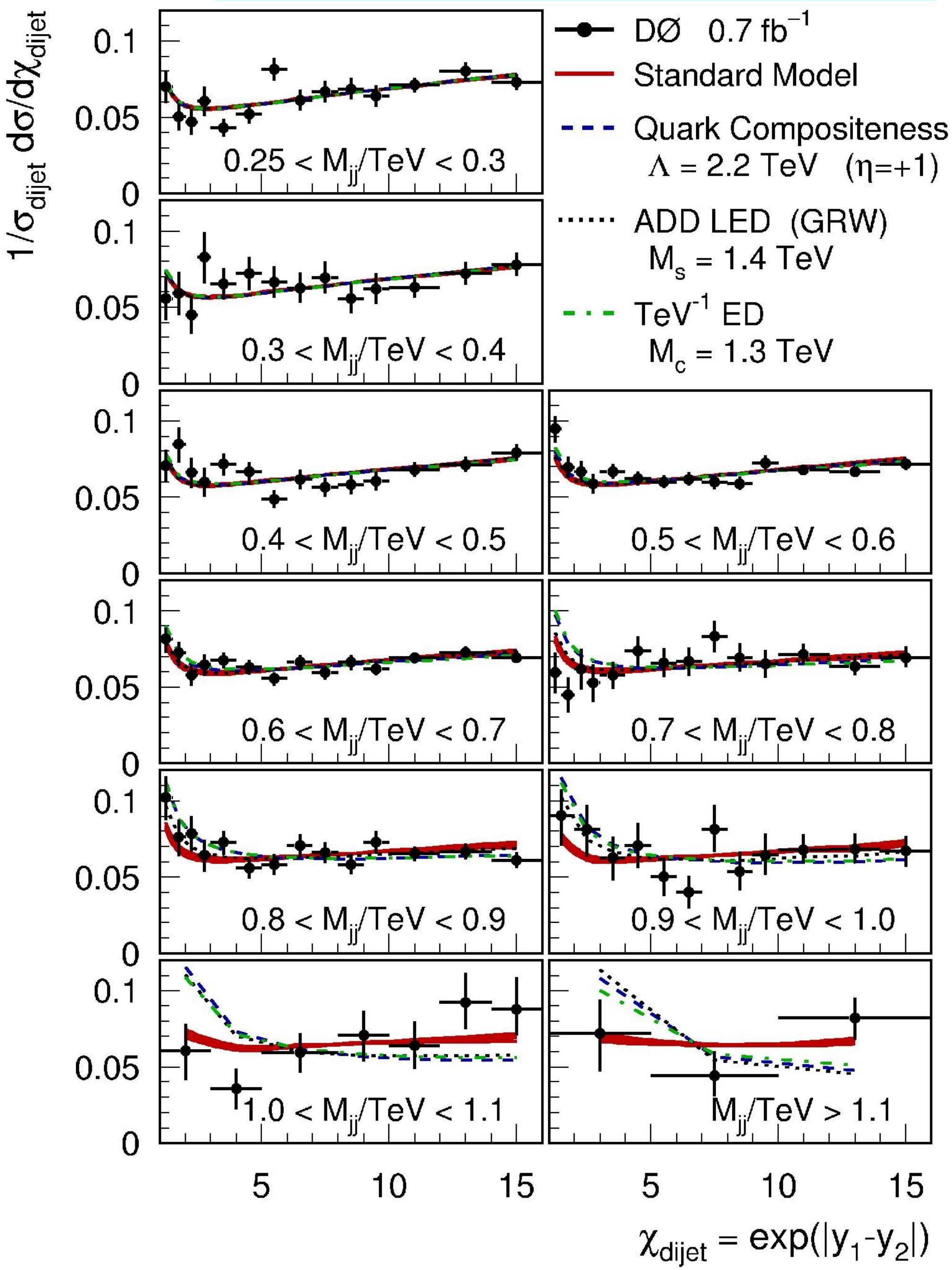
Result is 0.7 fb^{-1}, statistics limited!

Compared to NLO pQCD:
- very small theory uncertainty
- width of the red line!

In this game, beam energy wins!

D0 limits:
- exclude Λ < 1.3 – 2.2 TeV at 95% CL

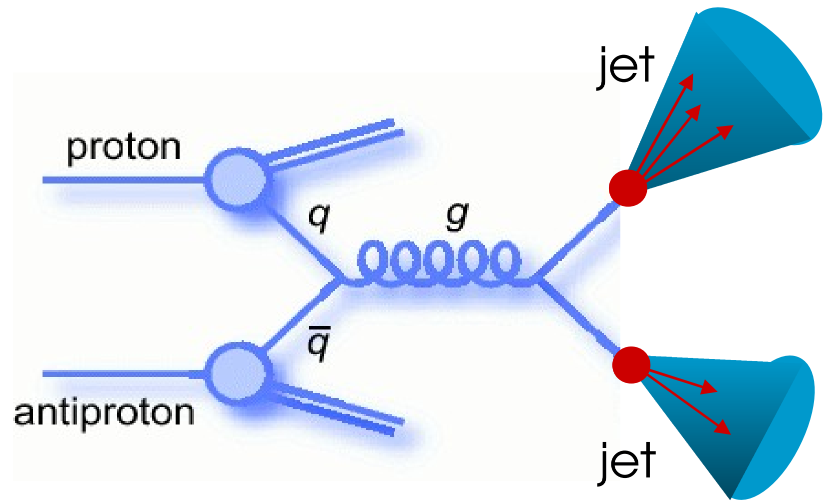
ATLAS: 3.1 pb-1, masses up to 2.8 TeV
- exclude Λ < 3.4 TeV at 95% CL



b) Jet Cross Sections

Second category: high pT cross sections

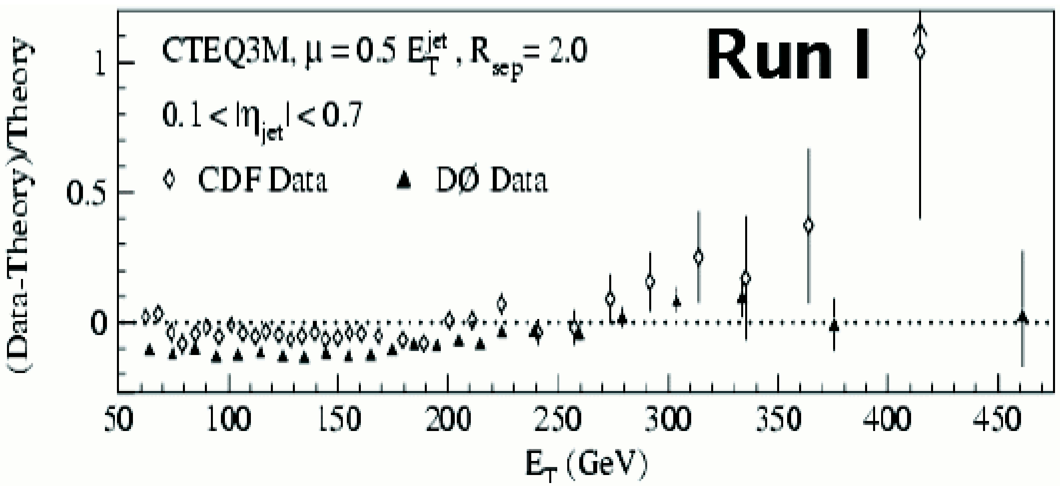
$$\sigma_{\text{pert}}(\alpha_s) = \left(\sum_n \alpha_s^n c_n\right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

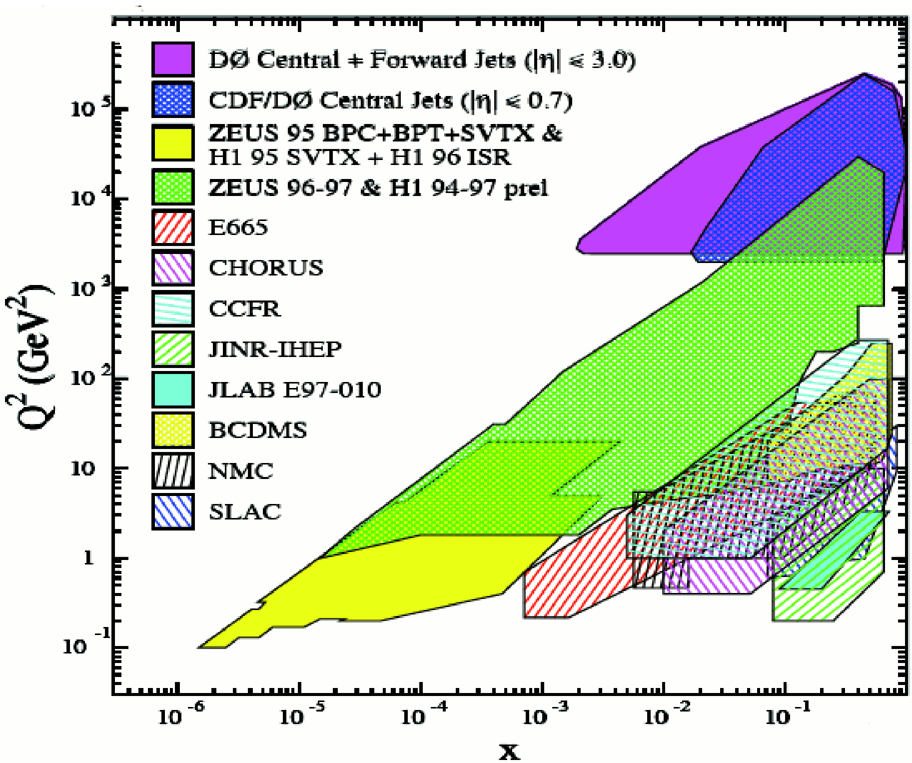


Matrix element known at NLO in pQCD
→ Inclusive jet cross section constrains PDFs

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

Tevatron complementary to ep, fixed target

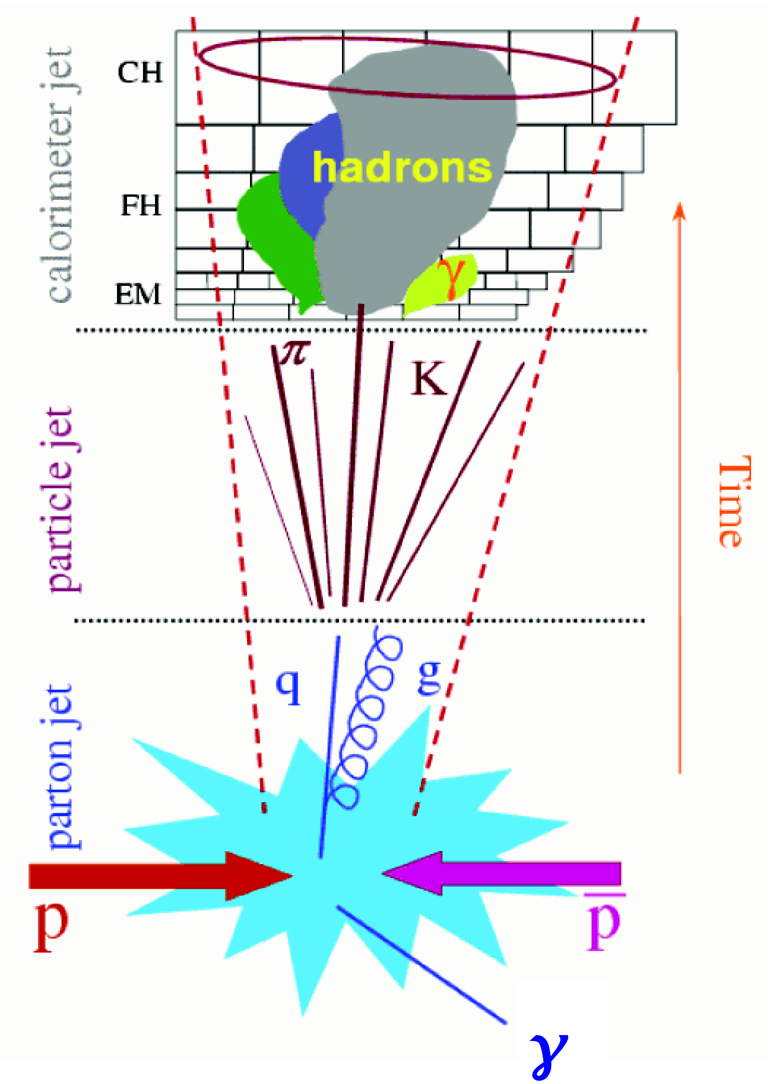




Jet Calibration Ia

Precision cross sections require calibrated objects

- Translate calorimeter jet energy to particle jet energy



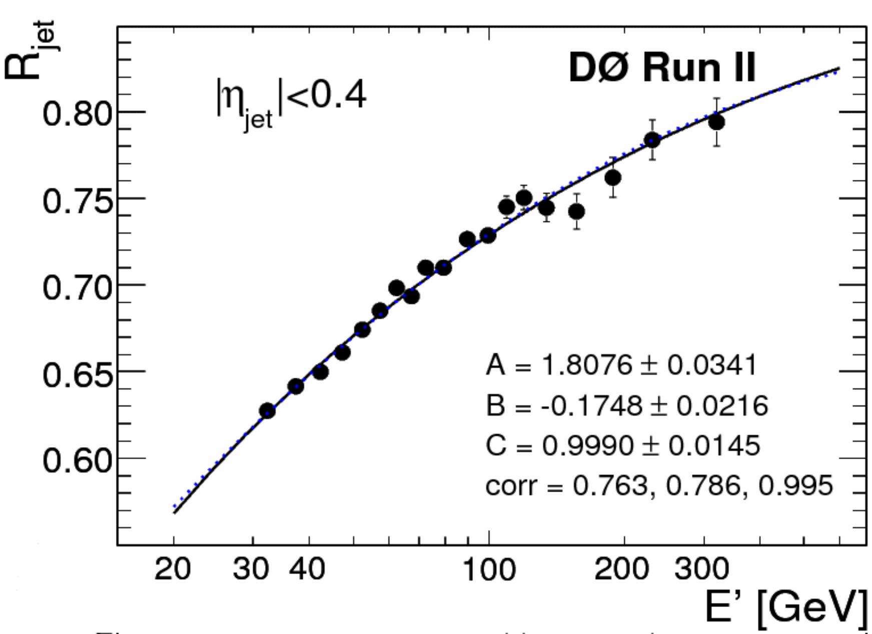
Jet Calibration Ia

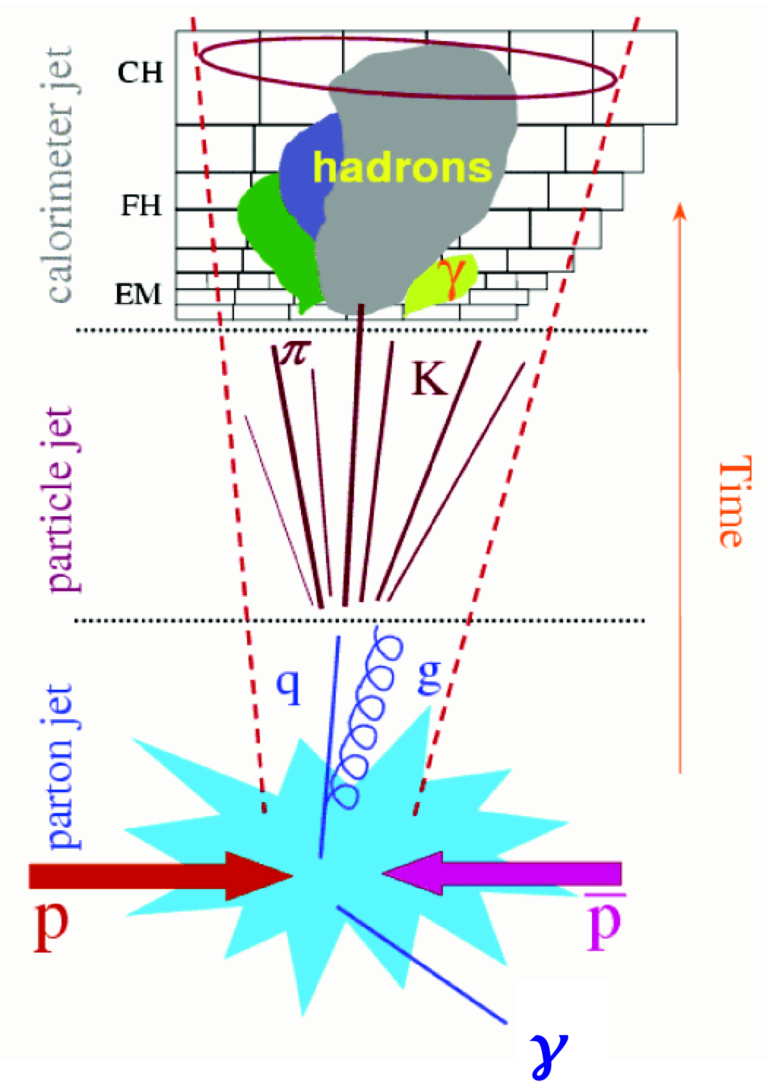
Precision cross sections require calibrated objects

- Translate calorimeter jet energy to particle jet energy

Main tool in energy scale calibration:

- p_T balance in back-to-back γ+jet
  - EM calibration from Z->ee

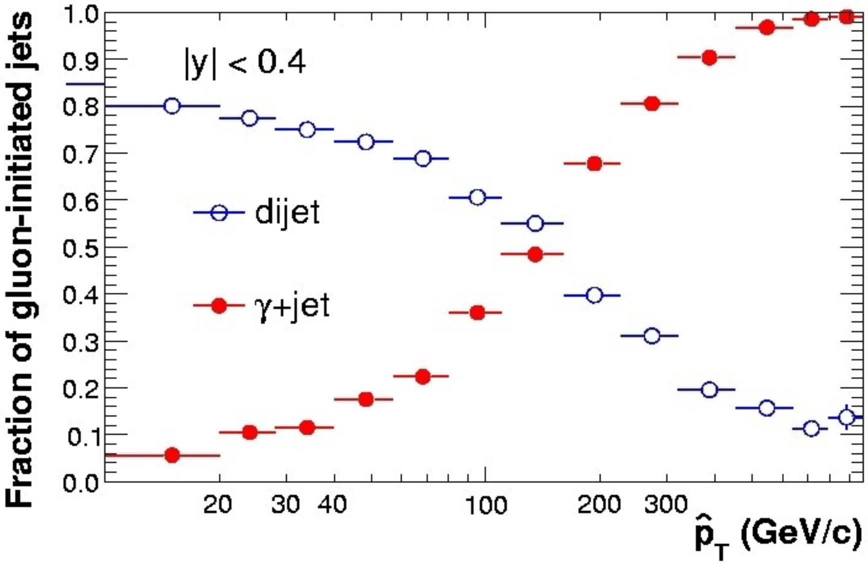




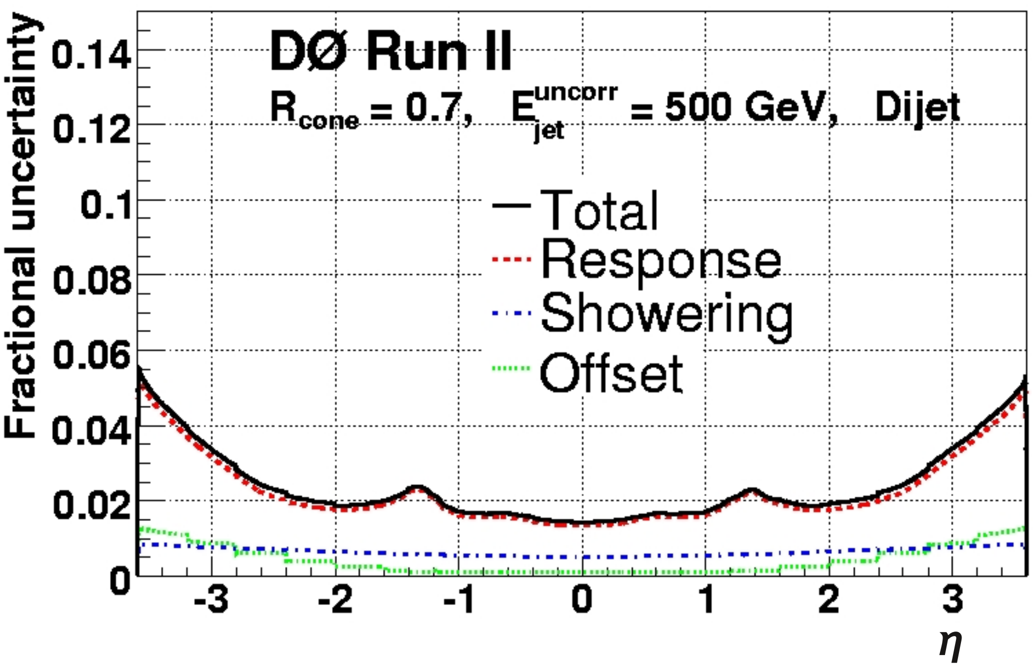
- further corrections for (detector) showering
- and for pile-up / min bias overlay

Jet Calibration Ib

Extend into forward calorimeter with dijets:
- account for quark/gluon jet differences
- gluon jet response ~ 5% lower.



Remarkable achievement:
- uncertainties ~ 1-2 %
  - even into the forward region
- 7 years of work!
- still dominant uncertainty on jet measurements



Note:
- we use D0 Run II jet algorithm for detector and particle jets
- change jet algorithm:
  → must re-derive the JES!

Jet Calibration II

Jet Resolution measured in dijet events:

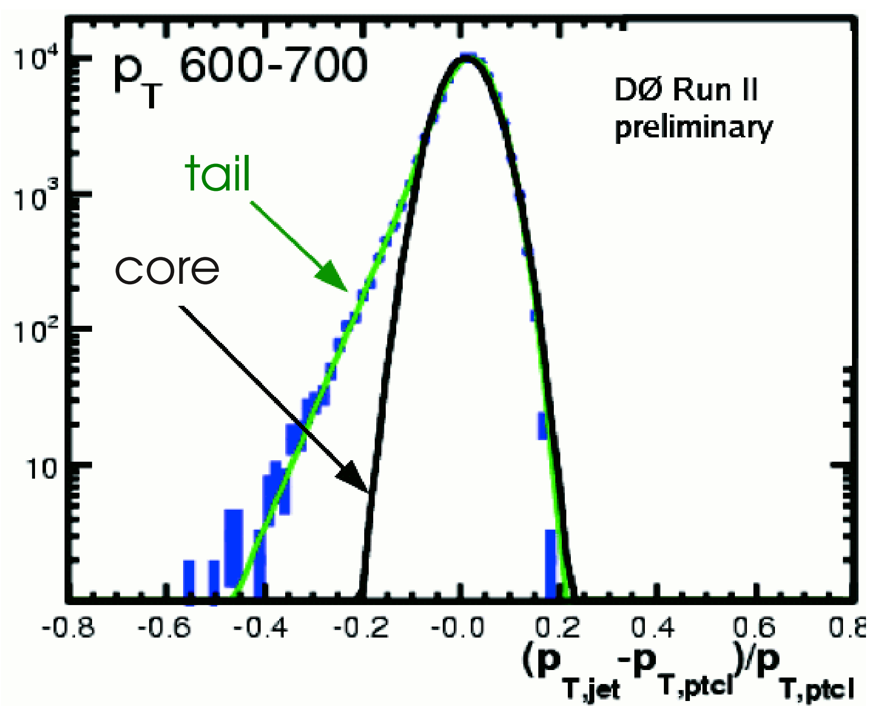
- attribute p_T imbalance to resolution
- after accounting for physics effects

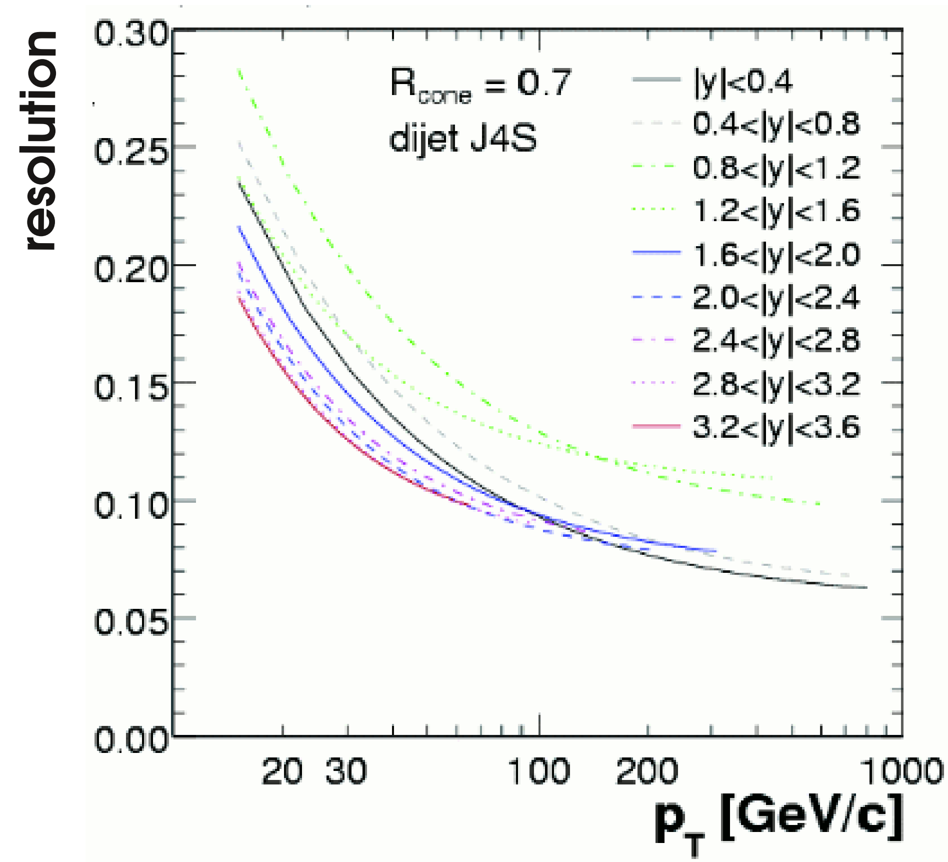
Raw asymmetry

$$A = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Raw resolution

$$\Rightarrow \frac{\sigma_{p_T}}{p_T} = \sqrt{2}\cdot RMS(A)$$





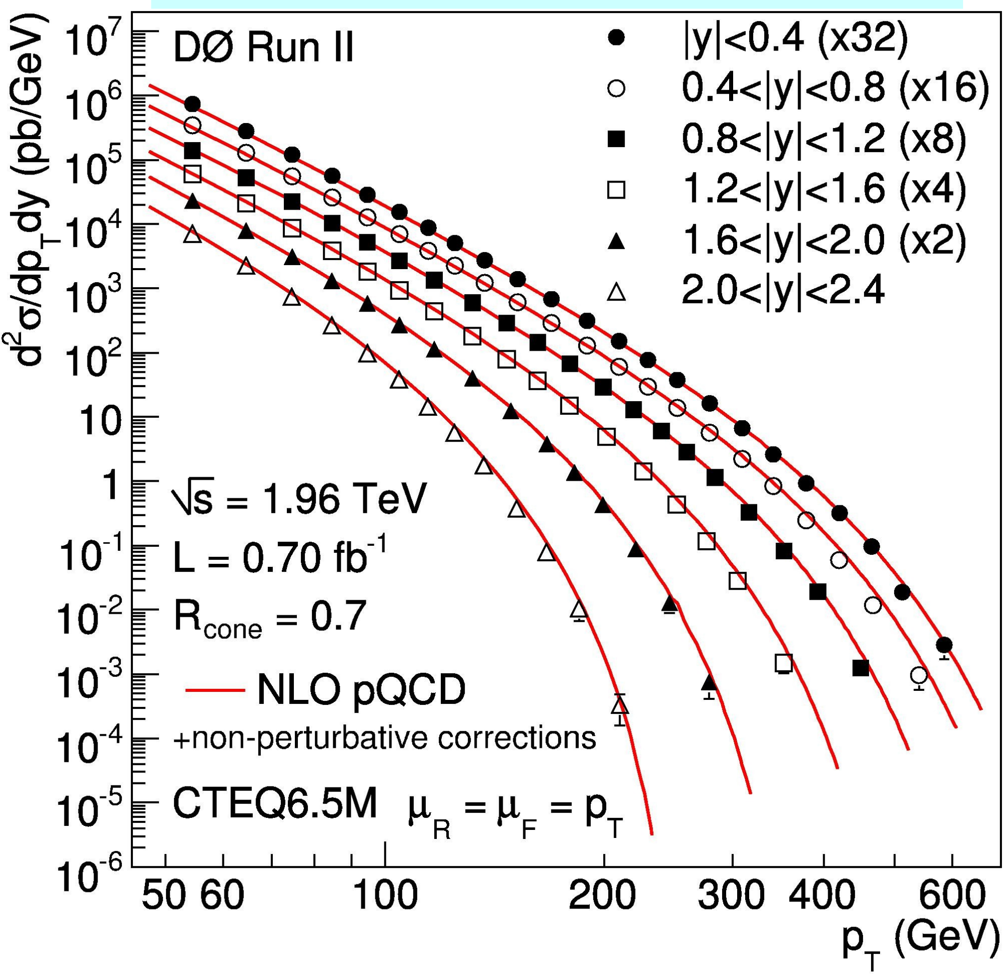
Jet p_T resolution:

- smears the measured p_T
- have to correct for this: **unfolding**

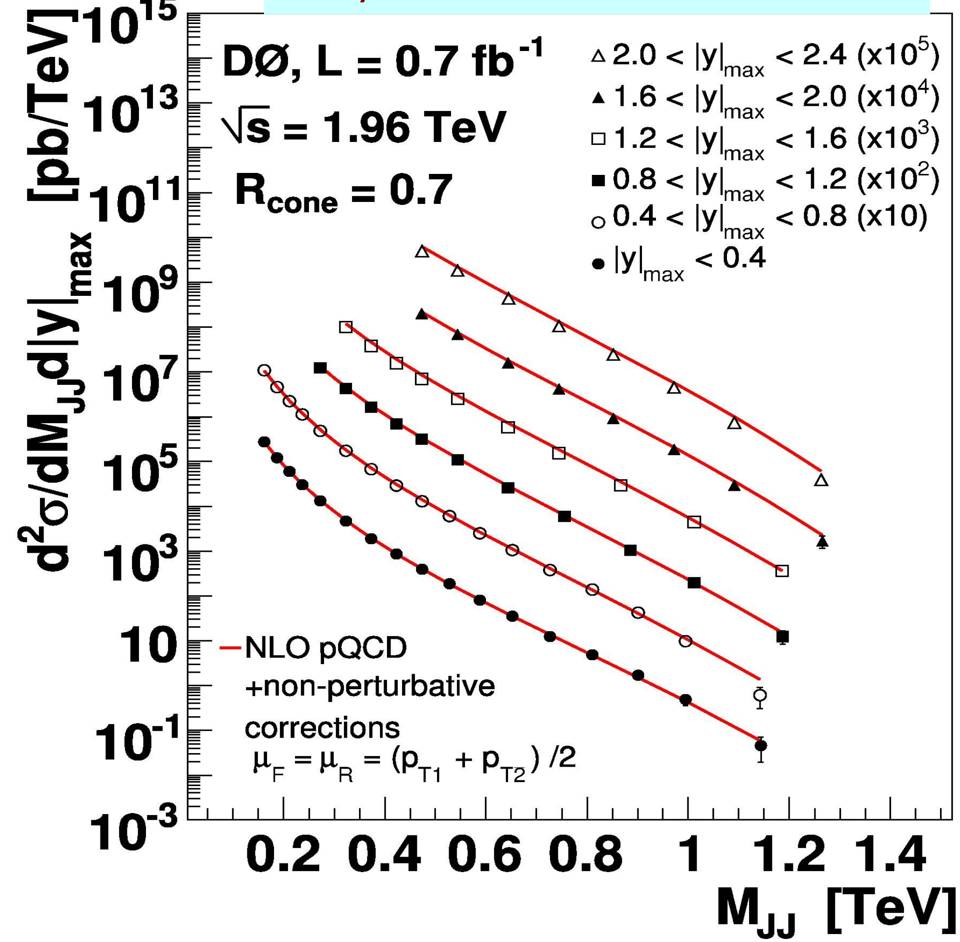
Jet Cross Sections

Two jet cross section results
- inclusive jets vs pT
- vs dijet mass
- both in bins of rapidity

Phys. Rev. Lett. 101, 062001 (2008)

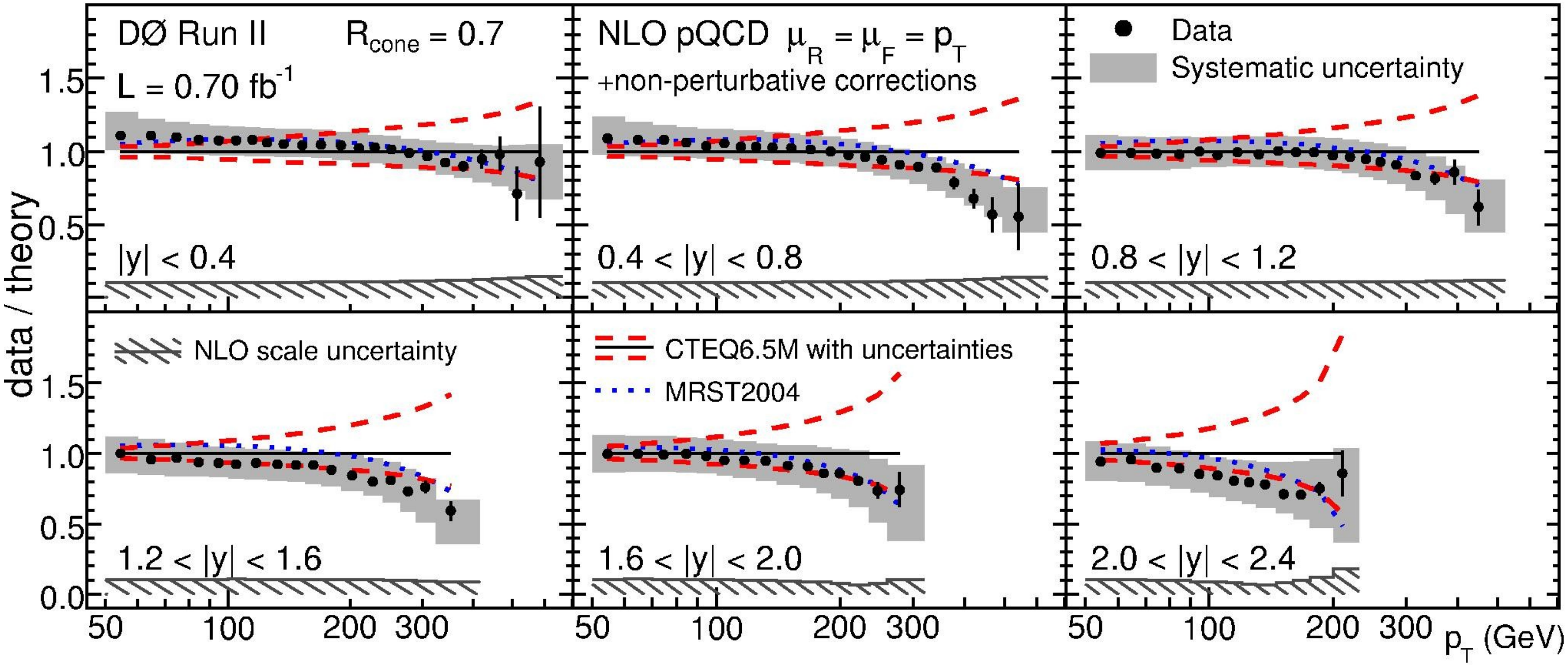


Phys. Lett. B 693, 531 (2010)



Comparison from NLO prediction
- with non-perturbative corrections
  - parton → particle level
  - underlying event
- typically ~5%

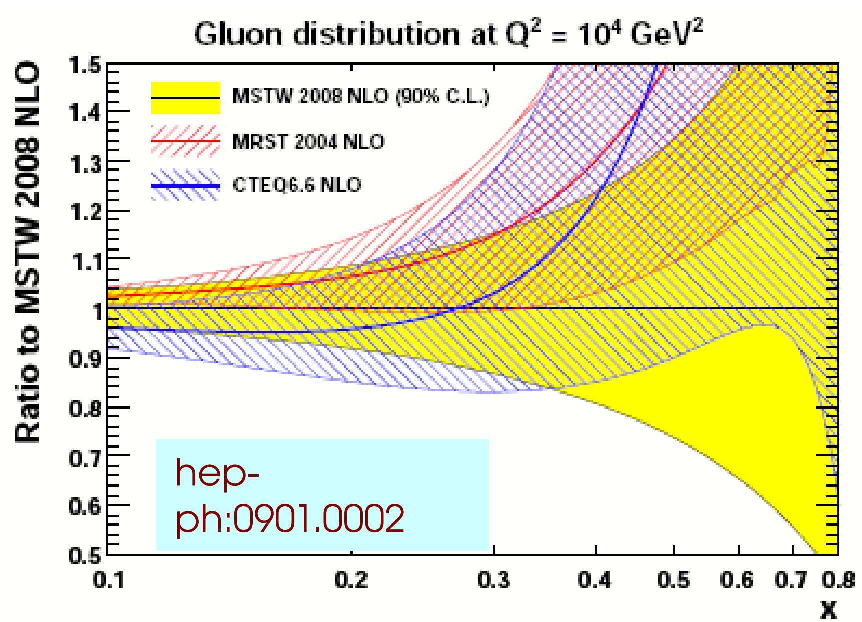
Impact on PDFs



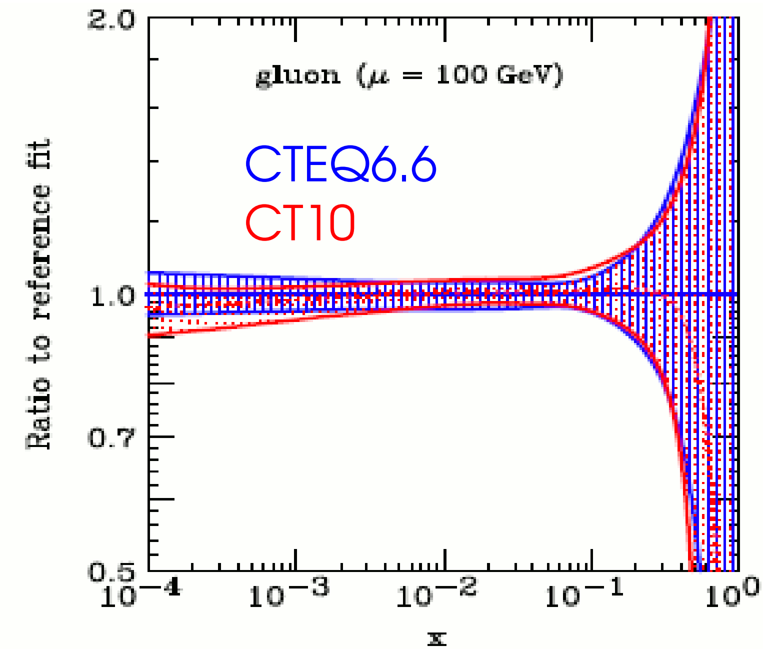
Data uncertainties
- JES ~5%

smaller than PDF unc!
- CTEQ6.5 here.

Used in MSTW 2008 PDF fits
- Run I jet data excluded



...and in CT10 fits

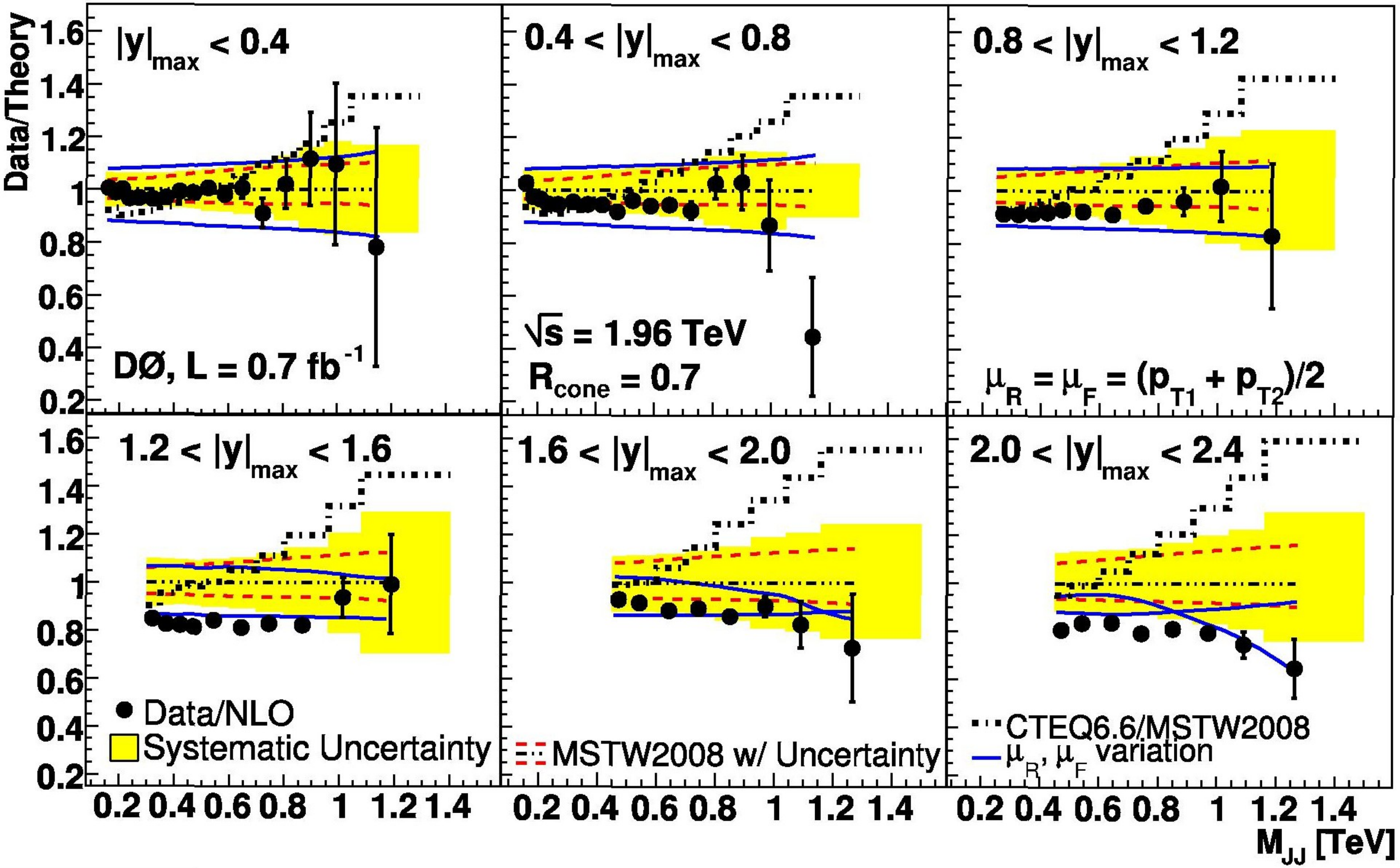


Impact on PDFs

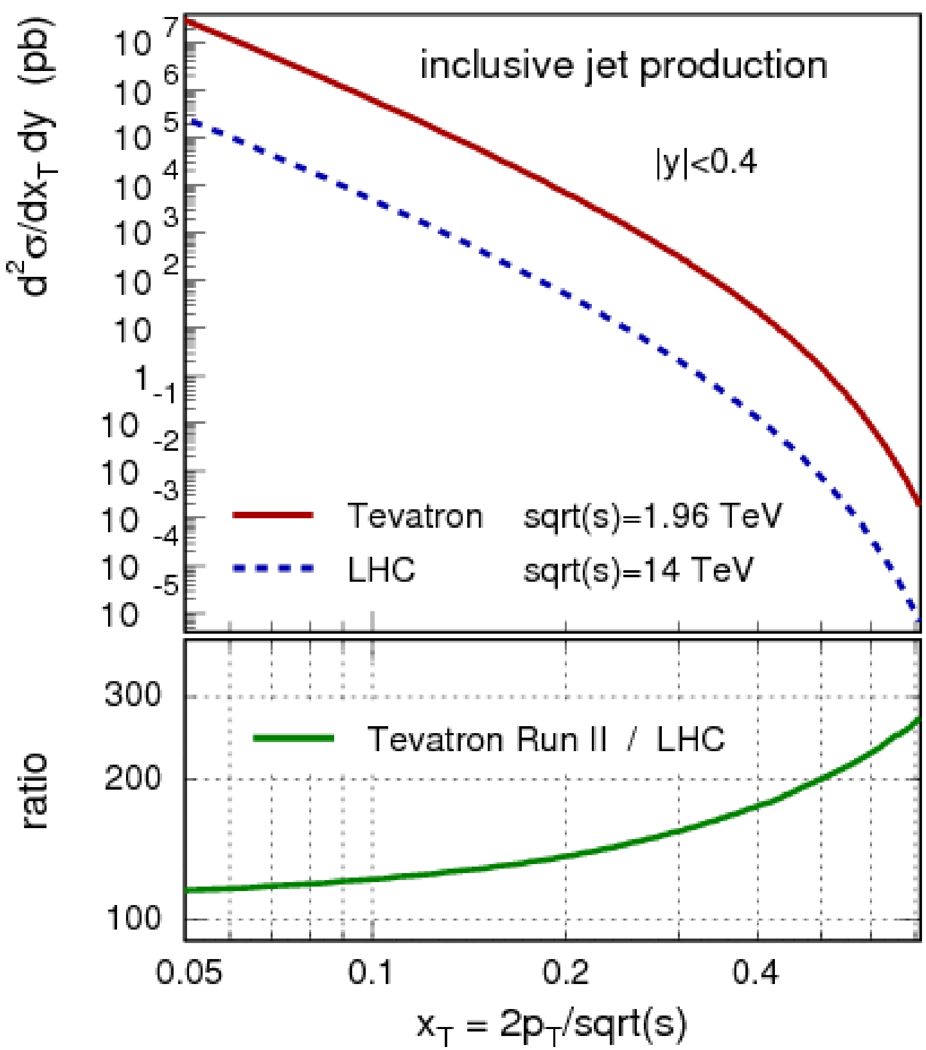
Dijet mass published in 2010 – compare to MSTW08 PDFs

- still not perfect
- can't use both in fits – datasets ~100% correlated.

Phys. Lett. B 693, 531 (2010)



Over to the LHC?



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:

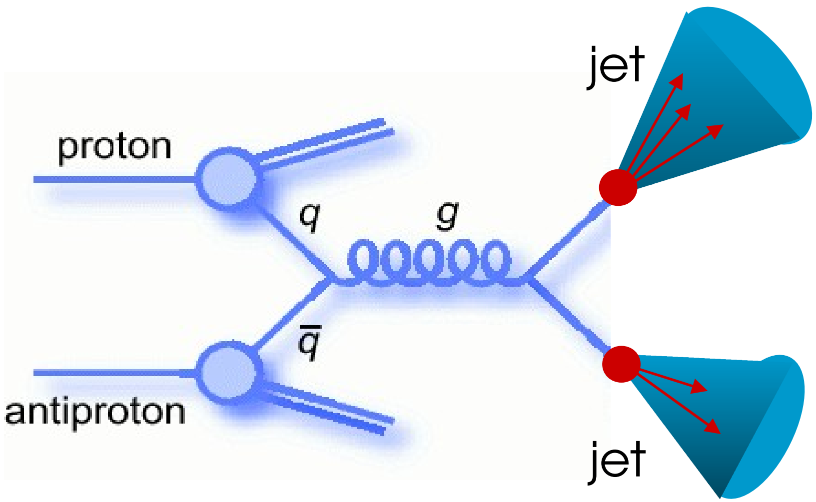
- need excellent jet energy scale
- out to very high p_T

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

Determining α_s

Phys. Rev. D 80, 111107 (2009)

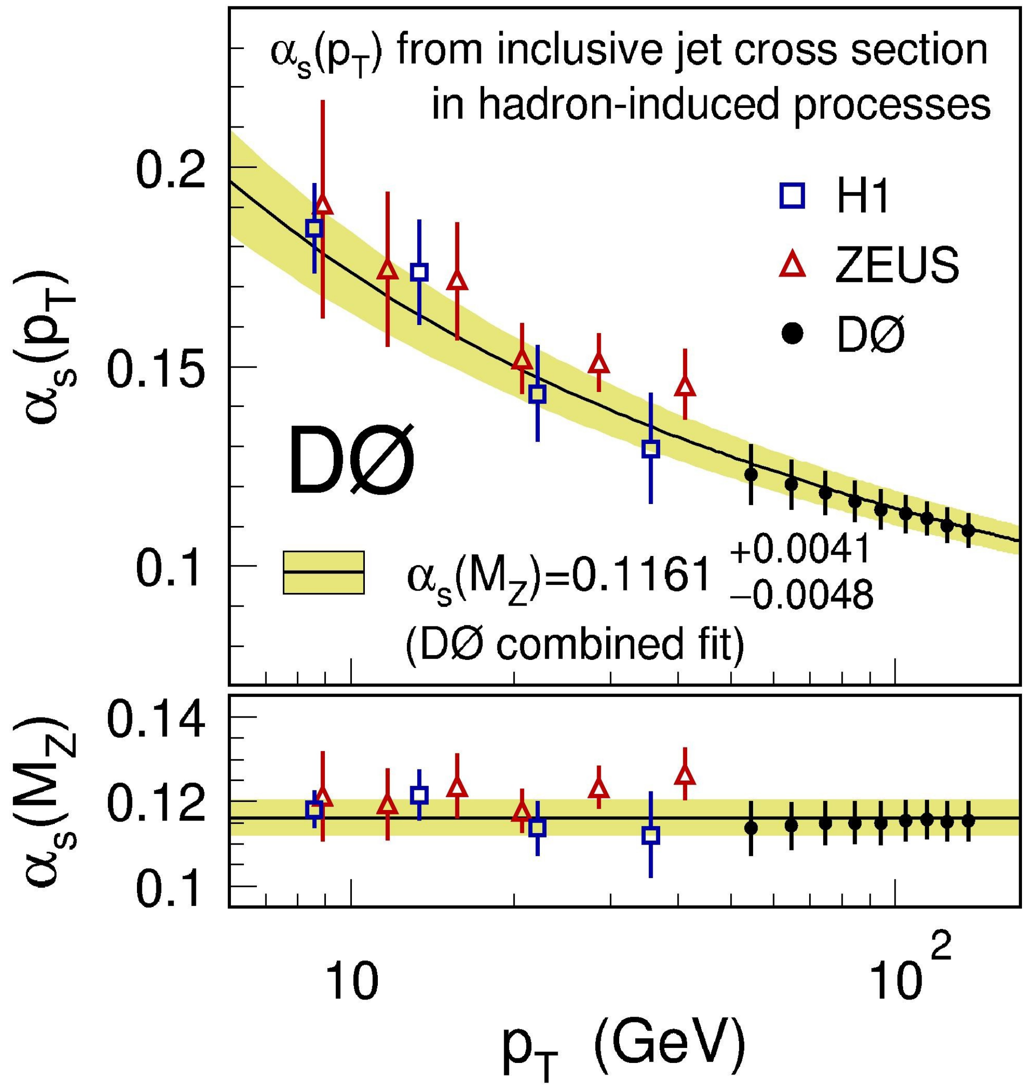
Can also turn into a measurement of α_s



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

- need PDFs for different α_s
  - 21 sets from MSTW08, 0.107 → 0.127
- NLO + 2-loop threshold corrections

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



result	uncertainty contributions				
$\alpha_s(M_Z)$	stat.	exp. syst.	non-pert.	PDF	scale $\mu_{r,f}$
0.1173	$^{+0.0001}_{-0.0001}$	$^{+0.0034}_{-0.0029}$	$^{+0.0010}_{-0.0010}$	$^{+0.0012}_{-0.0011}$	$^{+0.0021}_{-0.0029}$

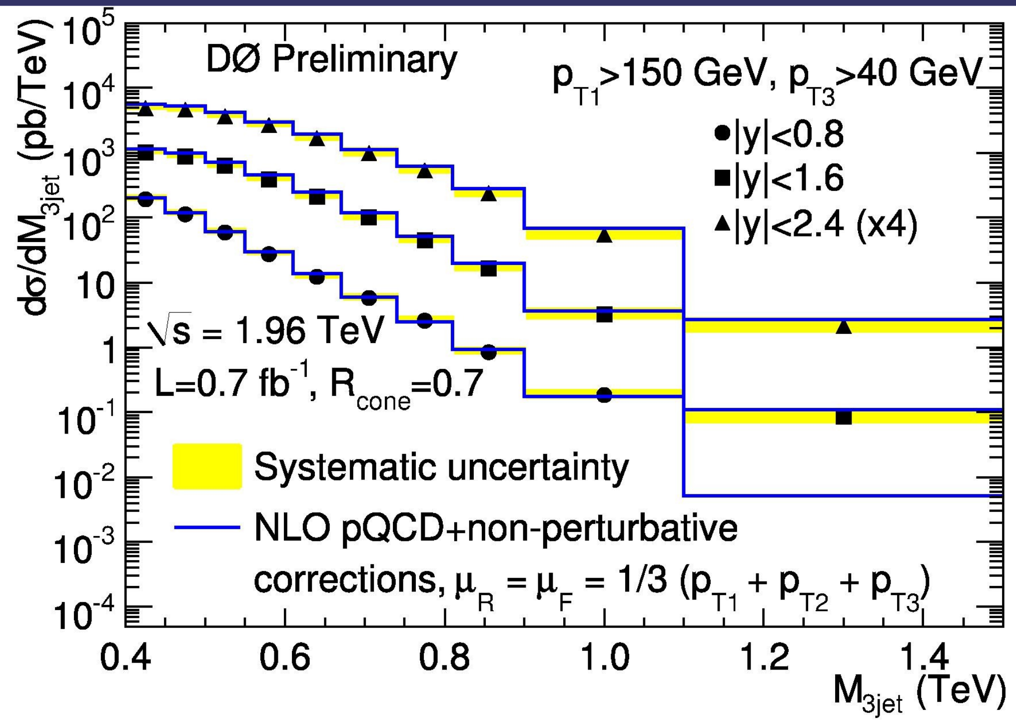
Near Future

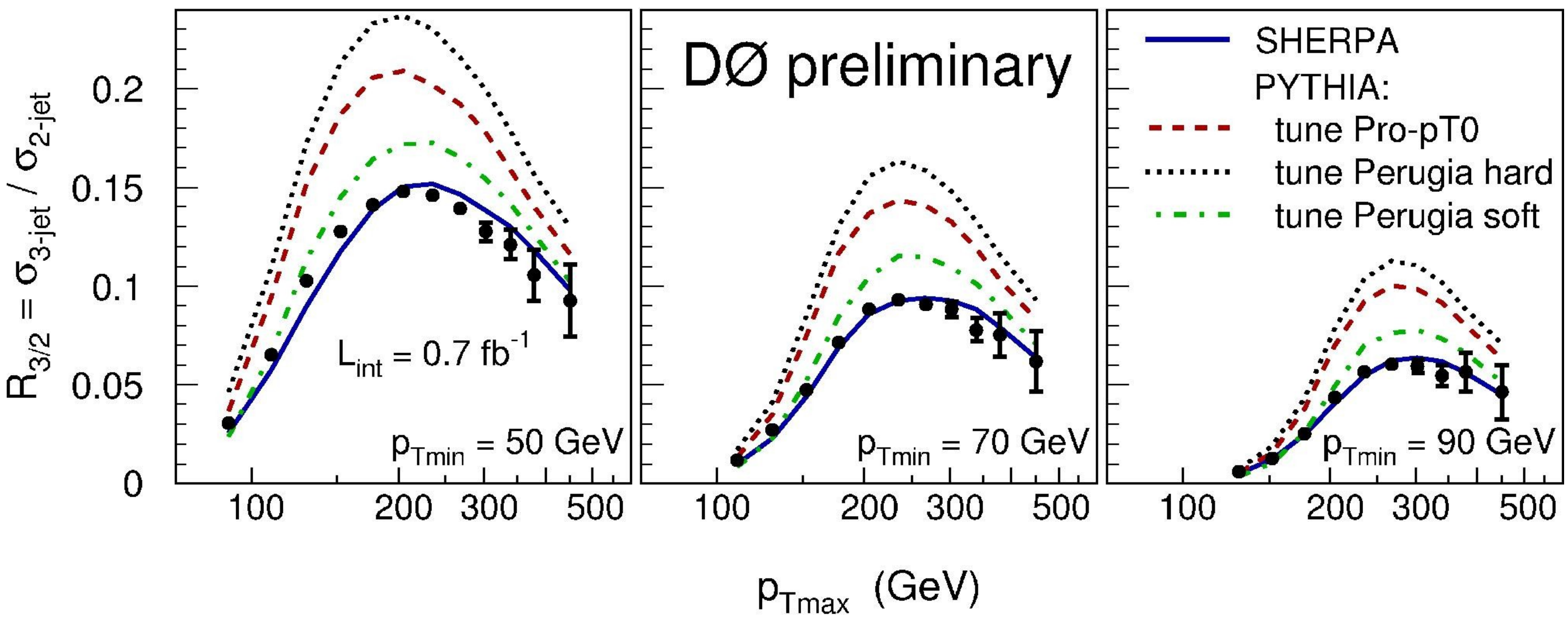
More jet studies on the way:

- 3 jet events
- R3/R2

Using 0.7 fb^{-1}

- driven by JES precision!

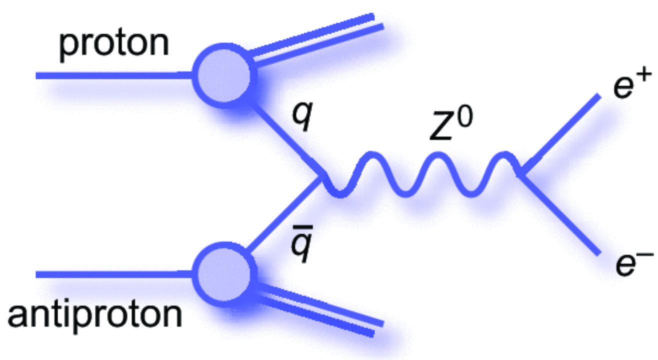




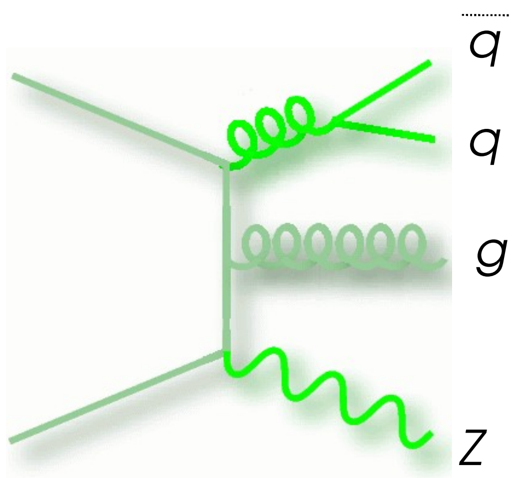
2) Bosons

- Z p_T, a_T, ϕ^*
- underlying event
- Z + jets

Vector Bosons



Focus on Z:
- leptonic decay modes provide very clean signal
- but much lower statistics than pure jet sample
- Z very well understood
    - colourless probe of QCD process
    → make precision QCD measurements!
- **very active area at D0**



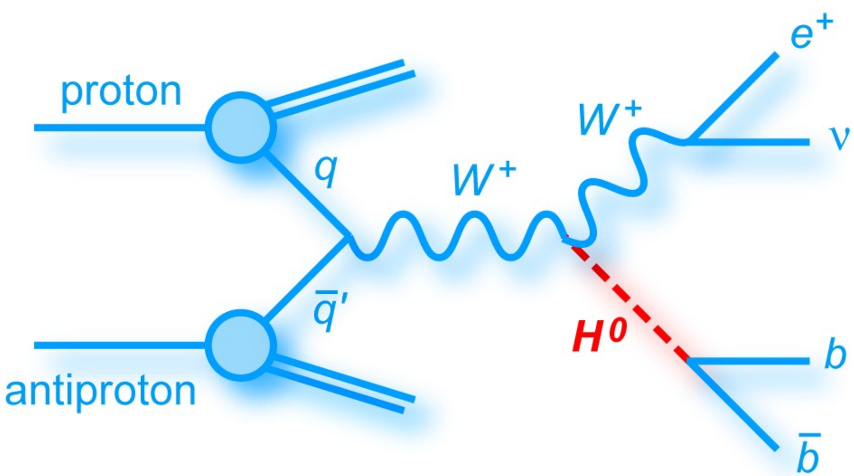
Beams have no transverse momentum:
- any Z pT caused by initial state radiation
- can reconstruct the Z right down to zero pT
    - soft (non-perturbative) QCD
- up to high pT (with identified jets)
    - pQCD

Excellent test of QCD predictions and models!

Knowledge Transfer

The other motivation:

- (W or) Z + jets is the main background to top, higgs, some SUSY models.
    - as well as the testing ground for the signal
- example: associated Higgs production: WH→lνbb, ZH→llbb



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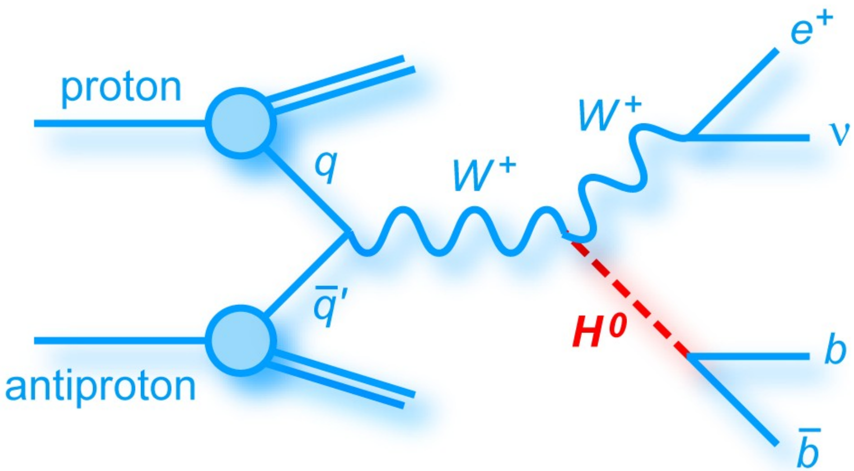
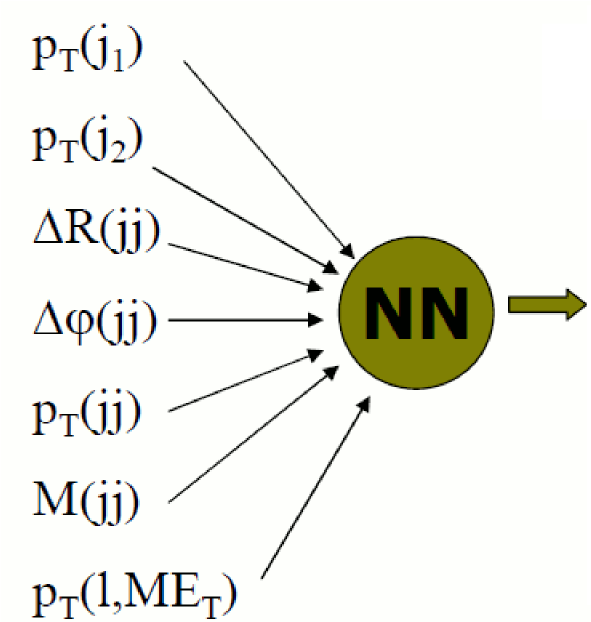
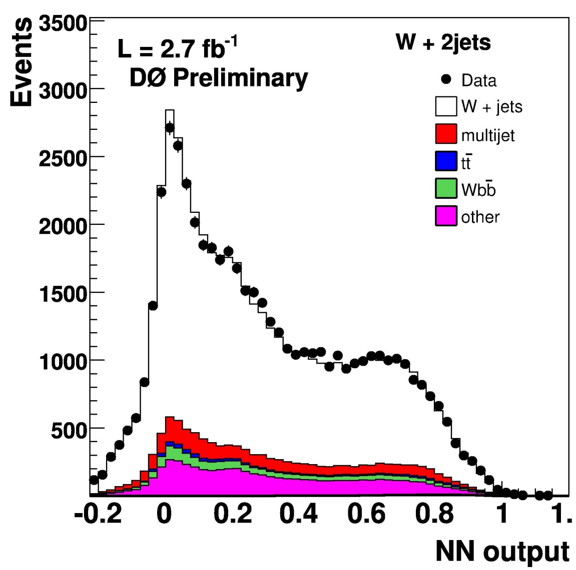


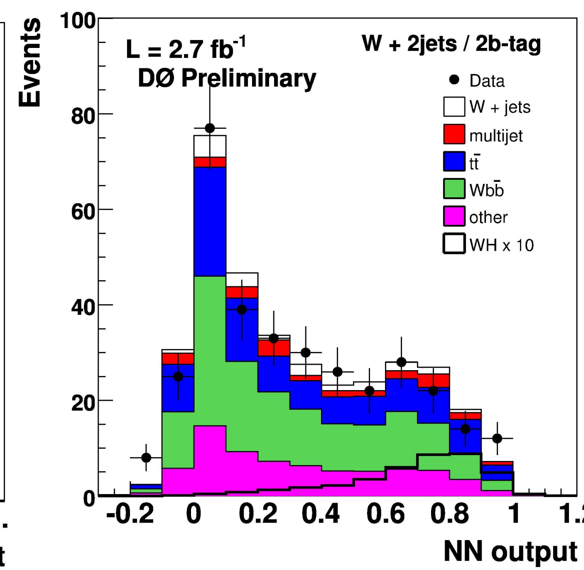
Tiny signal under huge background

- feed many variables to MVA
- need accurate descriptions of those variables
  - signal and background

Measure them for the first time!







Theory Status

1) Resummation: NNLL RESBOS-CP (+PHOTOS v2 for FSR)

- uses non-perturbative form factor at low pT, eg BLNY parameterisation:

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

- transitions to O(α_s) pQCD + k-factors at higher pT
- no jets!

2) Fixed order pQCD:

- W/Z+3 jets now available at NLO (blackhat, rocket); inclusive Z at NNLO.
- here, use MCFM v5.6, MSTW2008 PDFs
- apply FSR corrections derived from RESBOS+PHOTOS

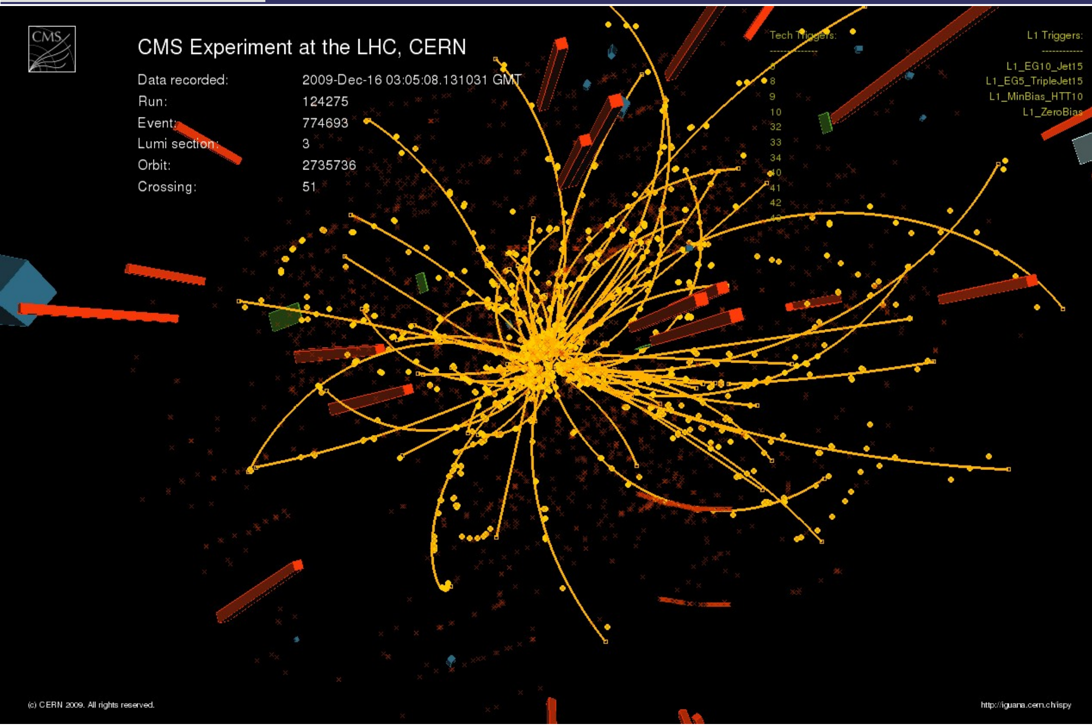
3) Full event generators, 2->1 ME + reweighted PS:

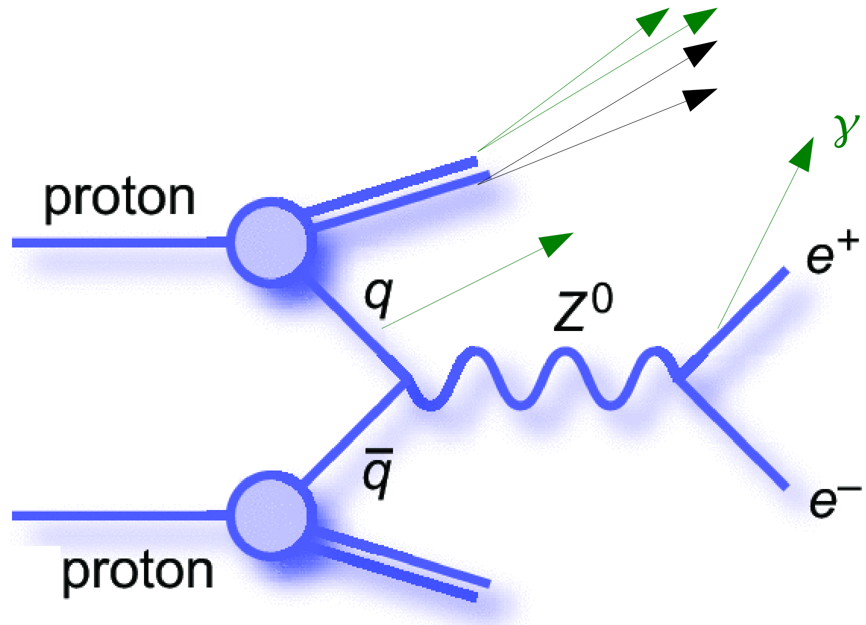
- various tunes available, here use:
    - PYTHIA (v6.423) Perugia 6 (p_T ordered)
    - PYTHIA (v6.423) D6 (Q^2 ordered)
    - HERWIG v5.1 (angular ordered)
- also NLO 2->1: MC@NLO, POWHEG

4) Full event generators, 2->N ME+PS:

- ALPGEN v2.13 and SHERPA v1.2.2, CTEQ6L1 PDF
- shower ALPGEN with PYTHIA and HERWIG

Phenomenological Issues





In published data measurements, typically:

1) correct observed leptons for detector resolution and efficiency
2) correct from the leptons the the (non-observable) Z
3) extrapolate from measured phase space to full 4pi coverage

The result is a mix of measurement and (significant) theory corrections

Publish data after step 1!

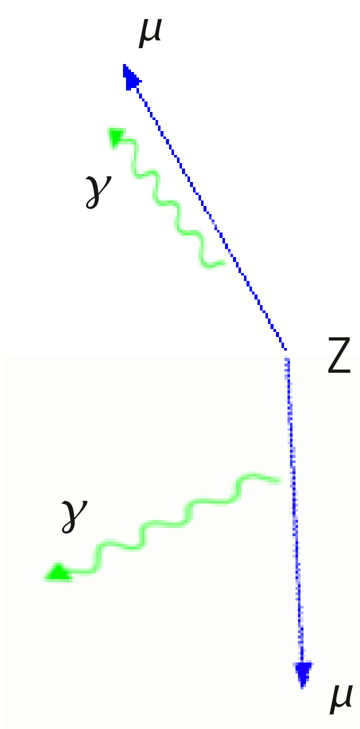
- minimal (zero?) model dependence, most useful for theory comparisons!
- also publish (best-guess) corrections to go to step 3 - or the data after step 3
  - to compare to other experiments

Phenomenological Issues

Present Z and W measurements at the level of particles entering the detector

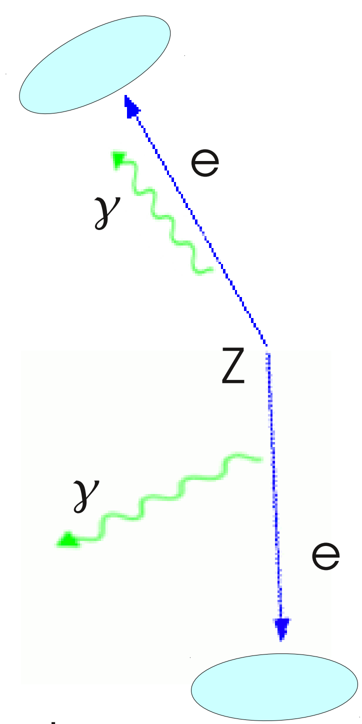
- define the Z and W in terms of these particles
- in a way that matches what we measure in the detector

arXiv:1003.1643, Section 14



A measured muon:

- curved track in tracking & muon systems
- underlying event has no effect
- all FSR “lost”



A measured electron:

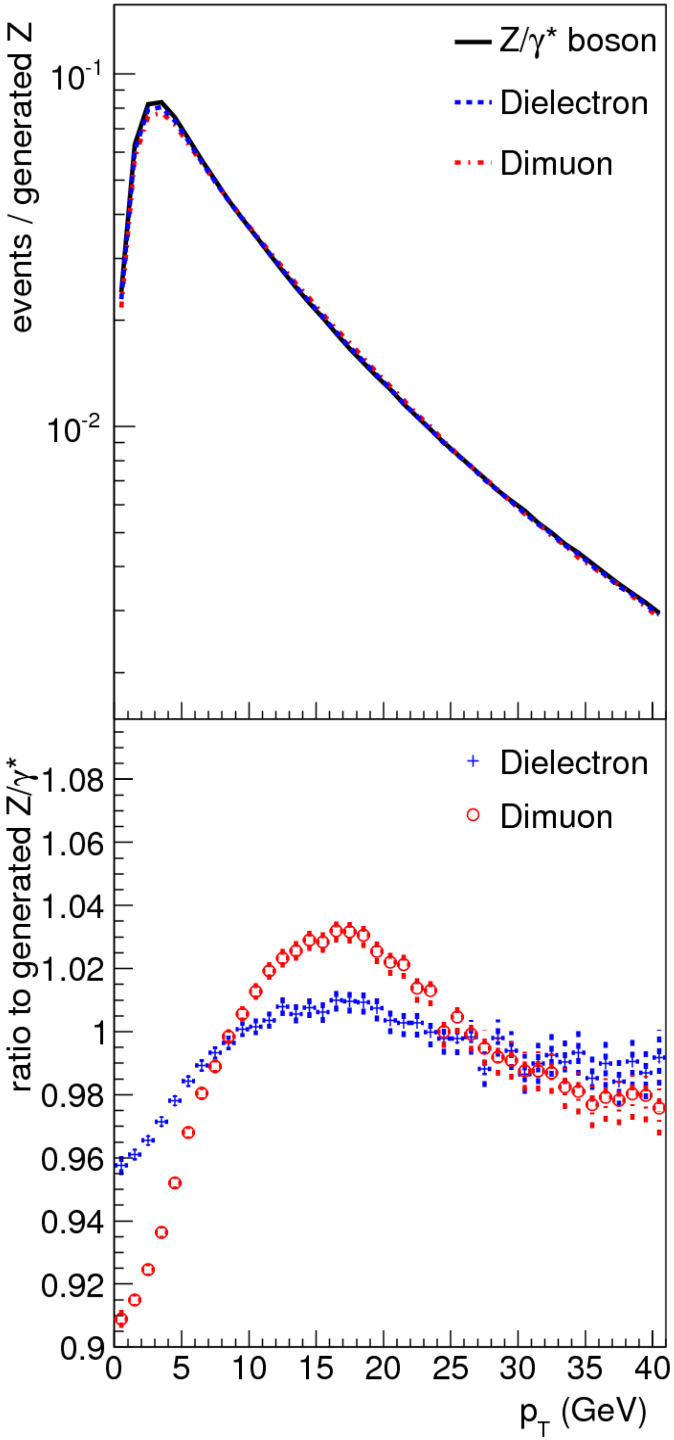
- sum of all EM energy in a cluster
  - electron + FSR (+ π^0 decays)
- wider angle FSR is “lost”
  - ie is not detected
  - or cannot be associated with electron

Impact

Main effect from not extrapolating in $|\eta|$

- corrections of x2 typical

- however, not correcting for FSR up to 5% in pT



Impact

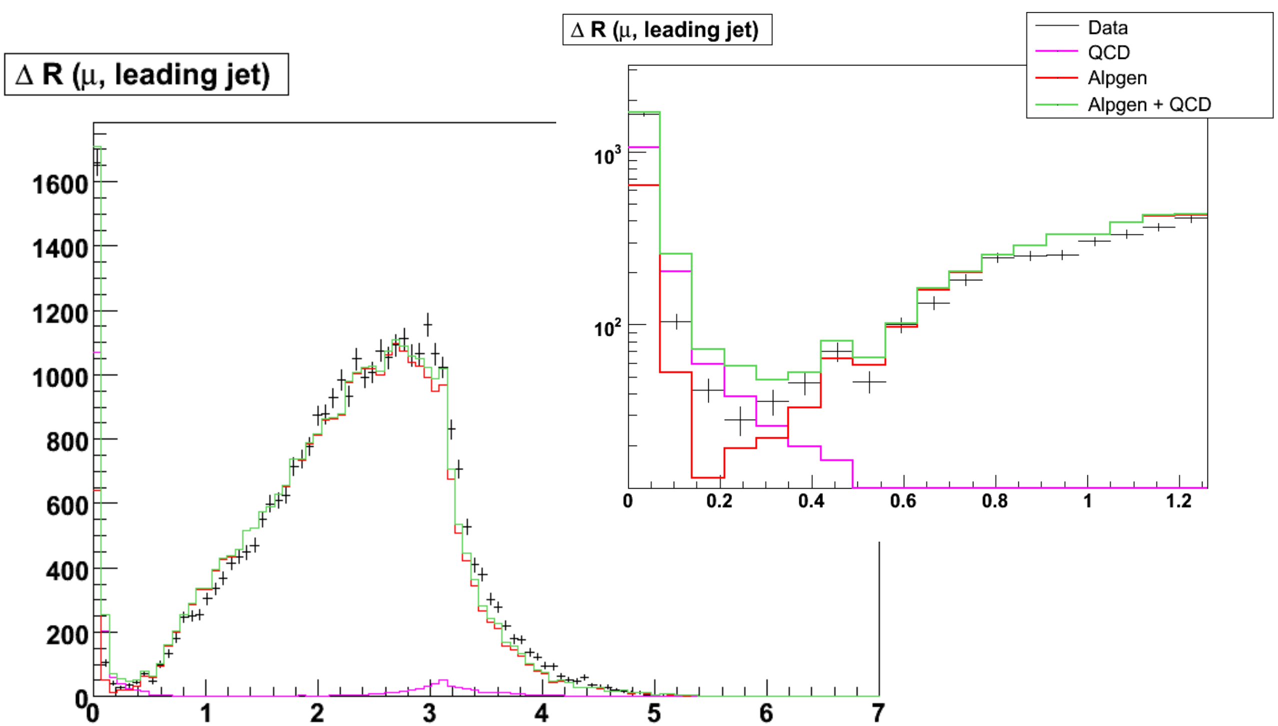
Main effect from not extrapolating in $|\eta|$

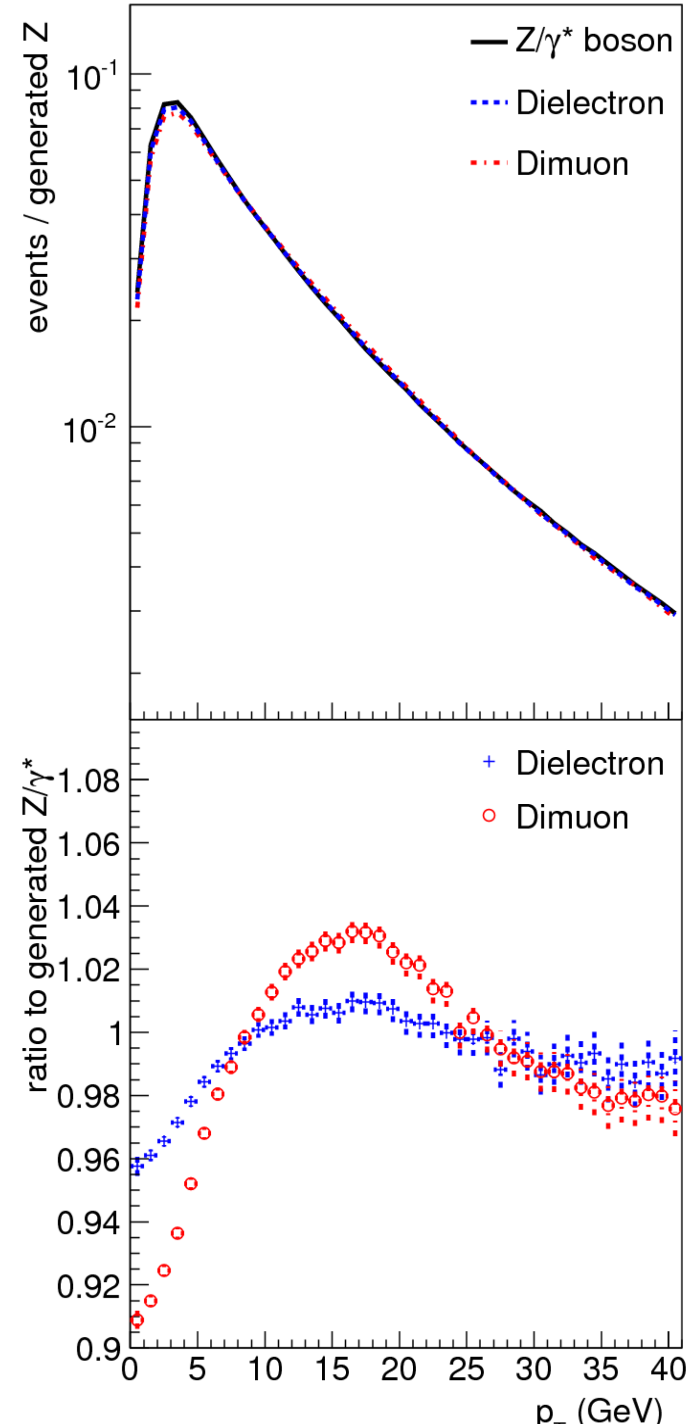
- corrections of x2 typical

- however, not correcting for FSR up to 5% in pT

Muon isolation is a grey area:

- FSR / brem can be reconstructed as jets
    - don't want to count / veto on these
- but multijet background looks similar
    - want to veto these events...

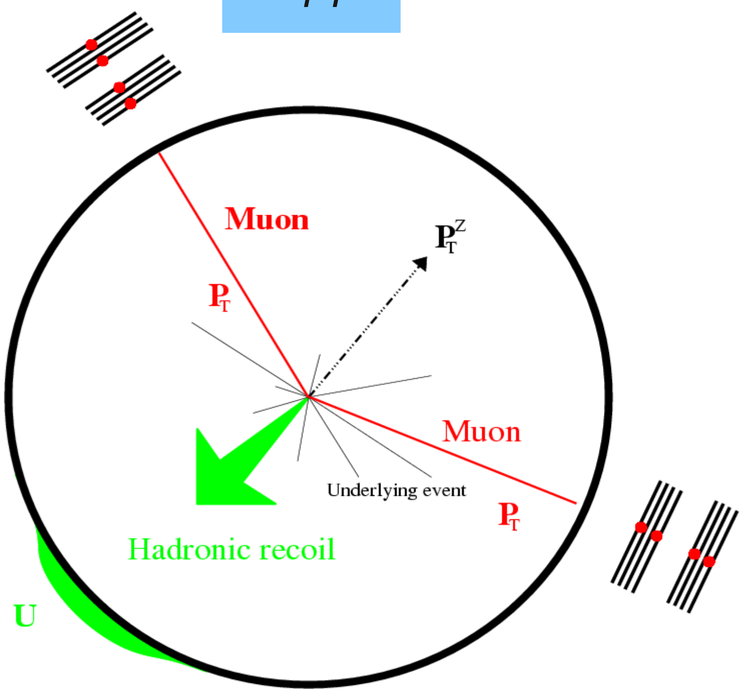




Experimental Issues

Gavin Hesketh

$Z \rightarrow \mu\mu$



Triggering and event selection:
- trigger & select high p_T (15 - 20 GeV)

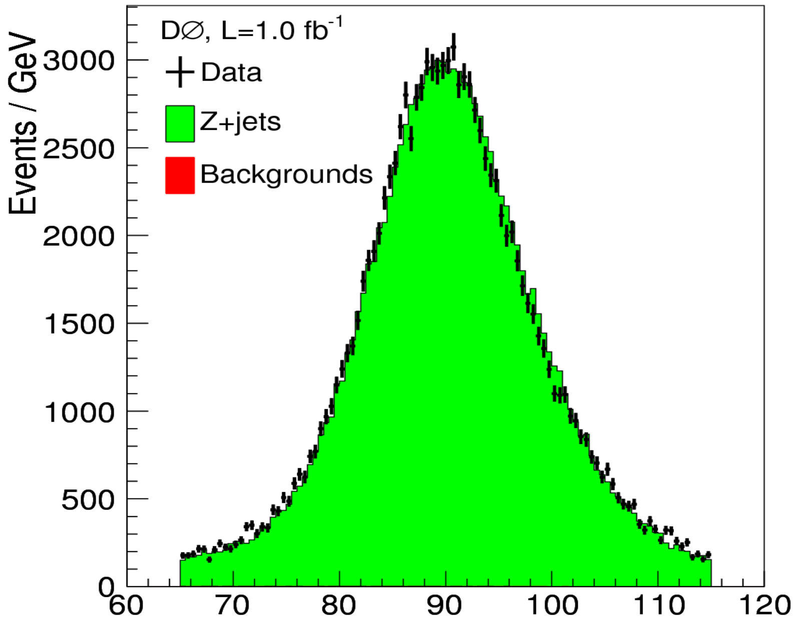
Z "Physics" Backgrounds:
- cosmic rays (μ, negligible)
- $Z \rightarrow \tau\tau$, WZ, WW, top pair (0.5% - 1%)

Z "instrumental" backgrounds:
- high EM fraction jets (~1%)
  - reject with shower shape cuts
- semi-leptonic decays (< ~0.5%)
  - reject with isolation criteria

Measure lepton efficiencies using "tag and probe"
- with Z events

Measure lepton resolution / energy scale:
- width and position of Z mass peak

Unfold using bin-corrections method, and matrix inversion



Inclusive Z pT

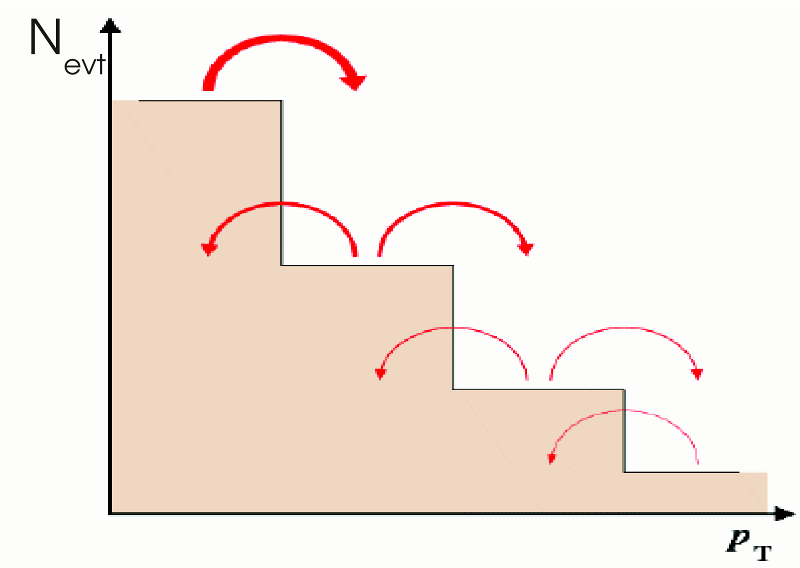
Principle is simple:
- reconstruct the Z, plot the pT

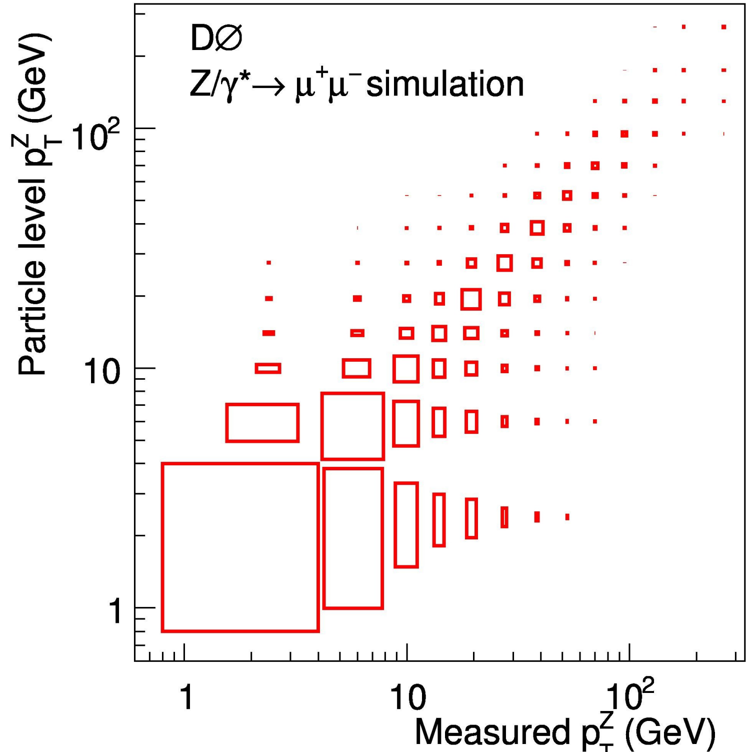
Have to correct for detector effects:
- efficiency and resolution (unfolding)

There are several unfolding techniques:
- regularized matrix inversion
- ansatz method
- bin corrections
- Bayesian unfolding
- ...

Mostly use GURU, regularized SVD matrix inversion:
1) Use a Monte Carlo to populate the matrix
2) invert, apply some regualrisation
   - suppress statistical “noise”
   - ensure smooth solution
3) apply to the data, and correct for efficiency

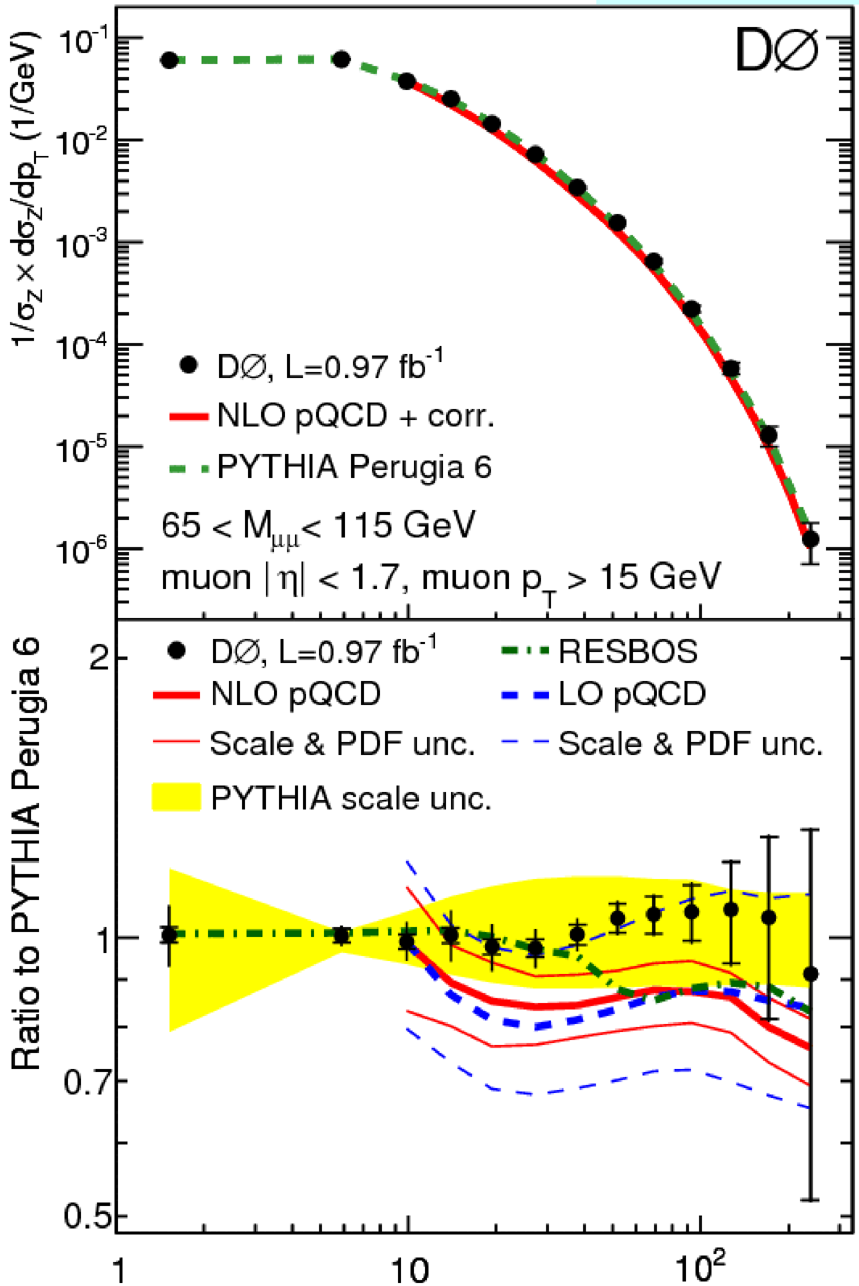
We also use bin corrections on some results.
- much more sensitive to the MC model.





Inclusive Z pT

Phys. Lett. B 693, 522 (2010)



Normalised cross section

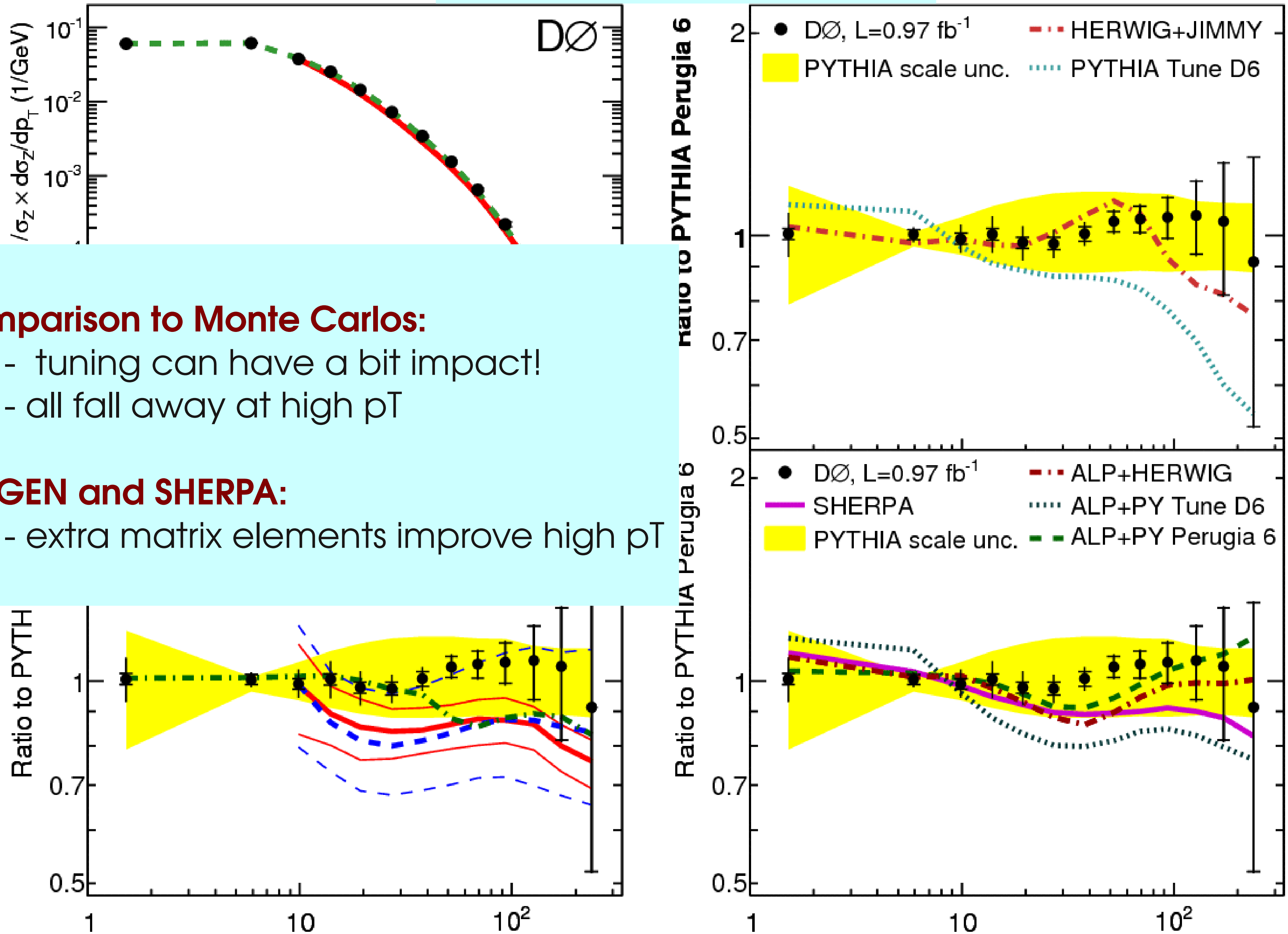
Limited by:
- muon resolution at low pT (~5%)
- and by stats. at high pT

Resbos falls away in transition region

pQCD consistently below the data!
- even with careful definition
- lower scale would help
- default $\mu^2 = M_Z^2 + p_{TZ}^2$

Inclusive Z pT

Phys. Lett. B 693, 522 (2010)



Comparison to Monte Carlos:

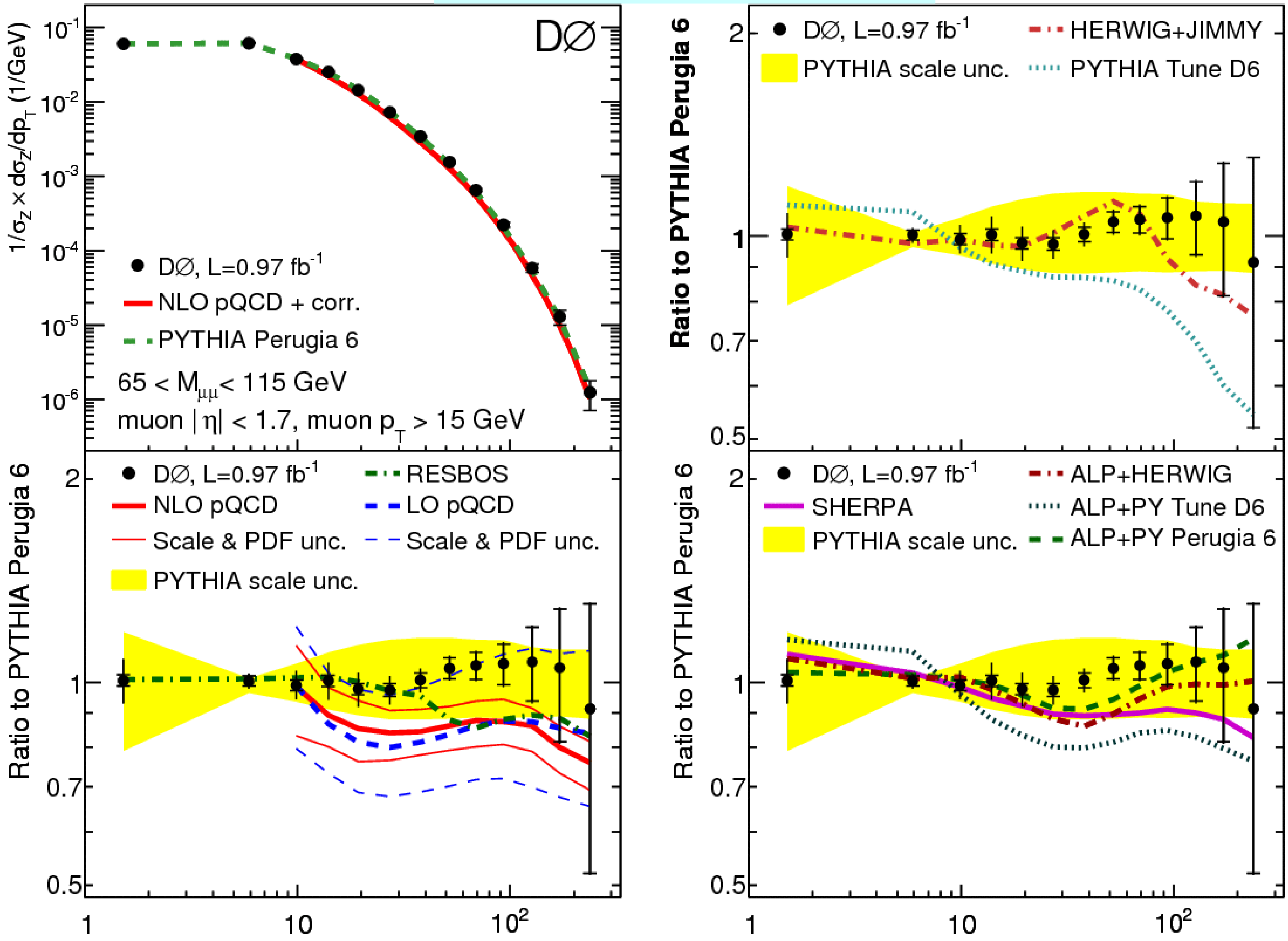
- tuning can have a bit impact!
- all fall away at high pT

ALPGEN and SHERPA:

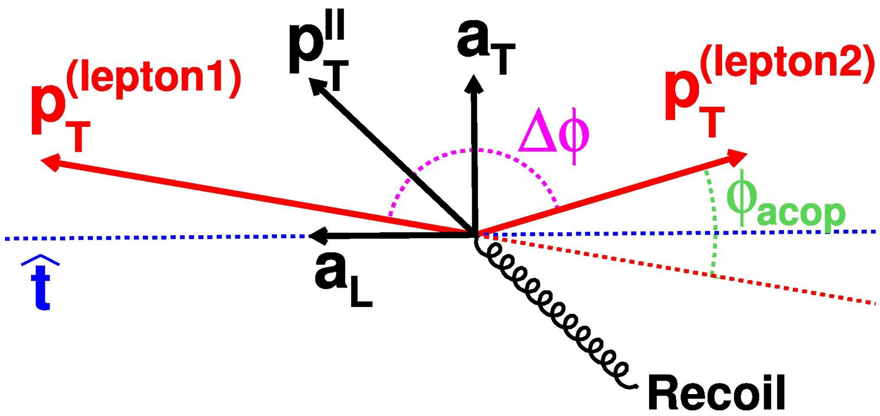
- extra matrix elements improve high pT

Inclusive Z pT

Phys. Lett. B 693, 522 (2010)



Z aT, ϕ^*

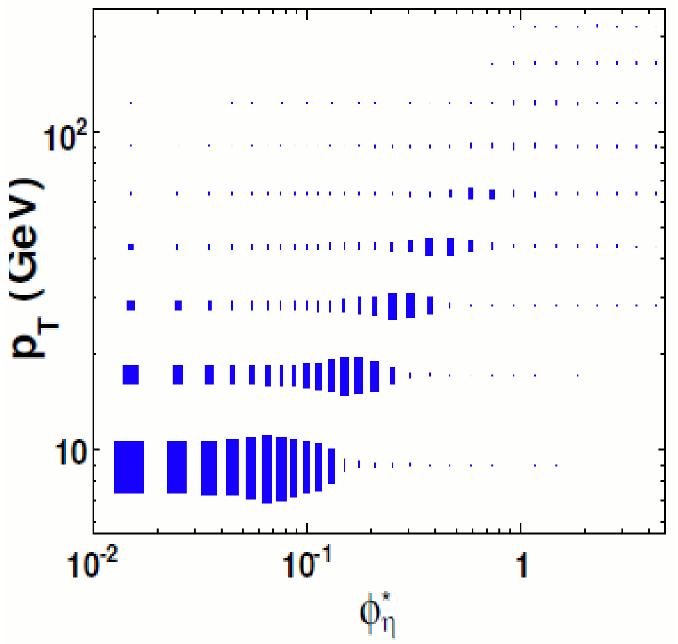


Resolution is a limitation:

- define a variable with ~no smearing!
- a_T = projection of p_T
- $\phi^*_\eta = \tan(\phi_{acop}/2)\sin(\theta^*_\eta)$

where: $\cos(\theta^*_\eta) = \tanh\left[(\eta^- - \eta^+)/2\right]$

- $\phi^* \sim a_T/M_{ll}$



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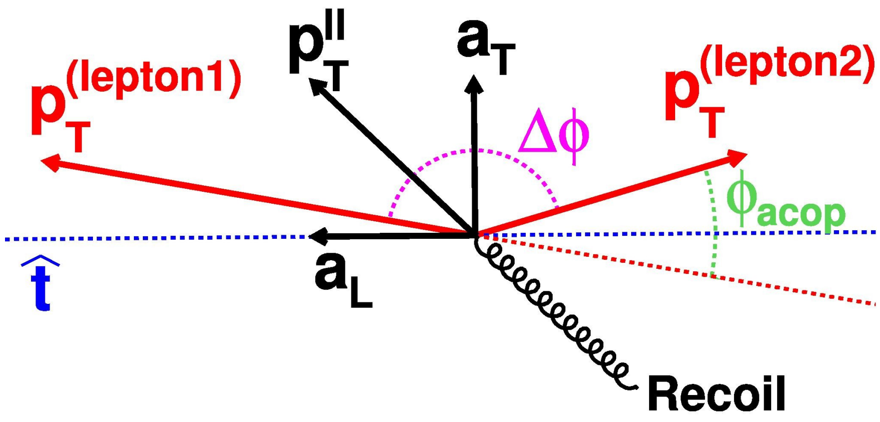
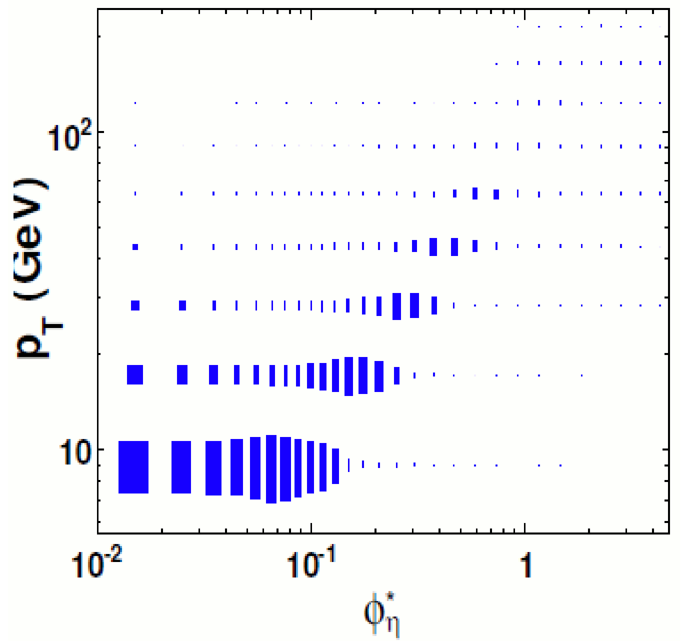


Analysis becomes stats. limited everywhere:

- use max lumi (7.3fb^{-1}), e and mu channels
- looser data quality
- 966k Z events!



New levels of precision at low pT:

- best measurement of g_2

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

Channel	$\lvert y\rvert < 1$	$1 < \lvert y\rvert < 2$	$\lvert y\rvert > 2$
ee	0.644 ± 0.013	0.619 ± 0.017	0.550 ± 0.048
$\mu\mu$	0.670 ± 0.012	0.645 ± 0.019	–

Can also look for “small x broadening”

Z ϕ^*

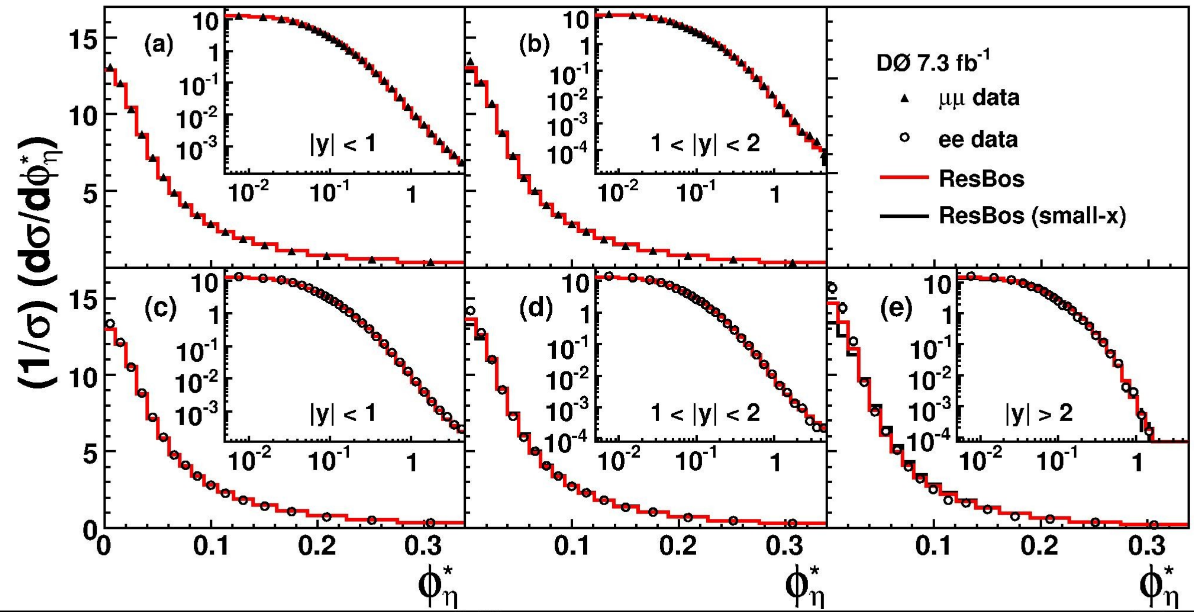
- **ResBos struggles at higher ϕ^***
  - as with Z p_T

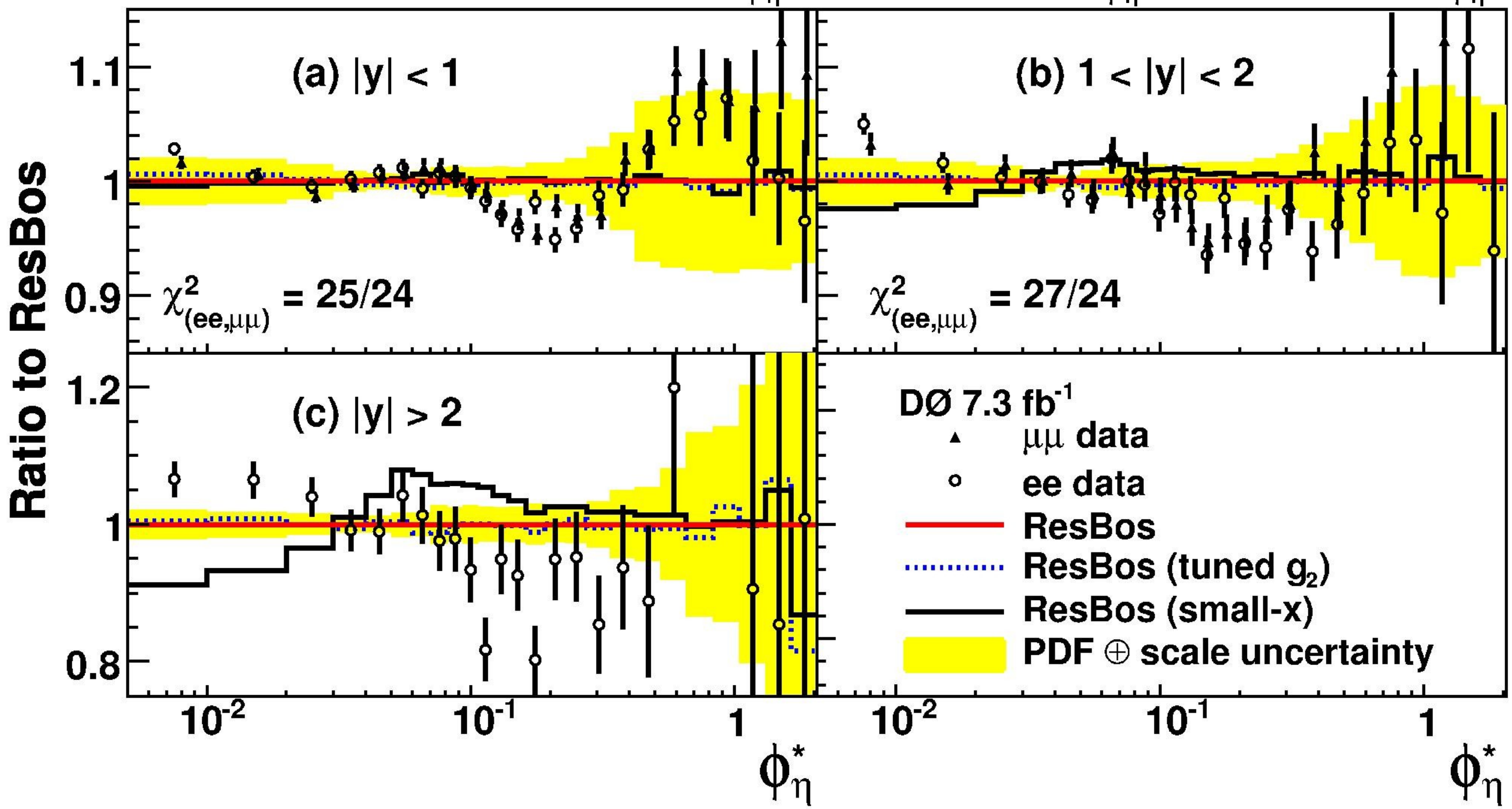
- **Data uncertainty < PDF unc.!**

- **Small-x broadening ruled out**

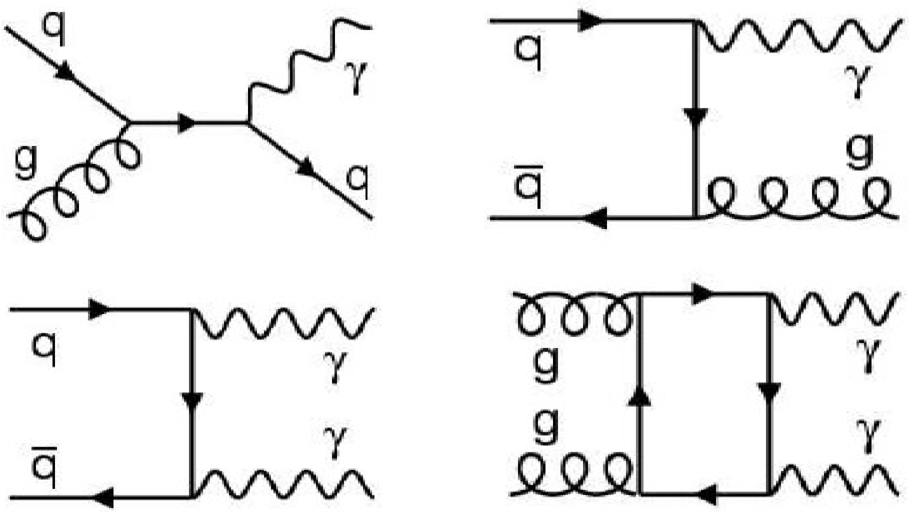
New standard of precision for Z recoil measurements
  - the end of Z p_T?

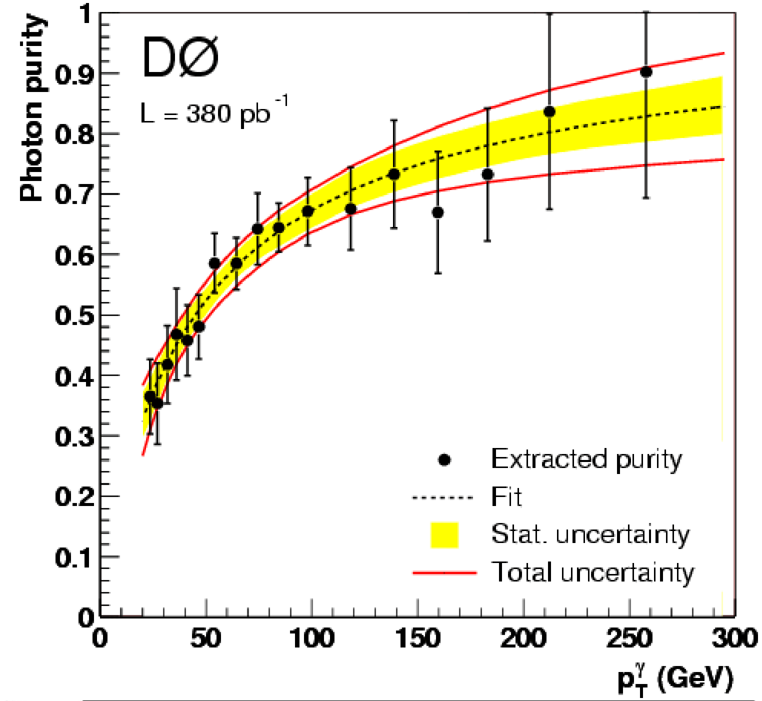
Subm. to PRL
arxiv:1010.0262



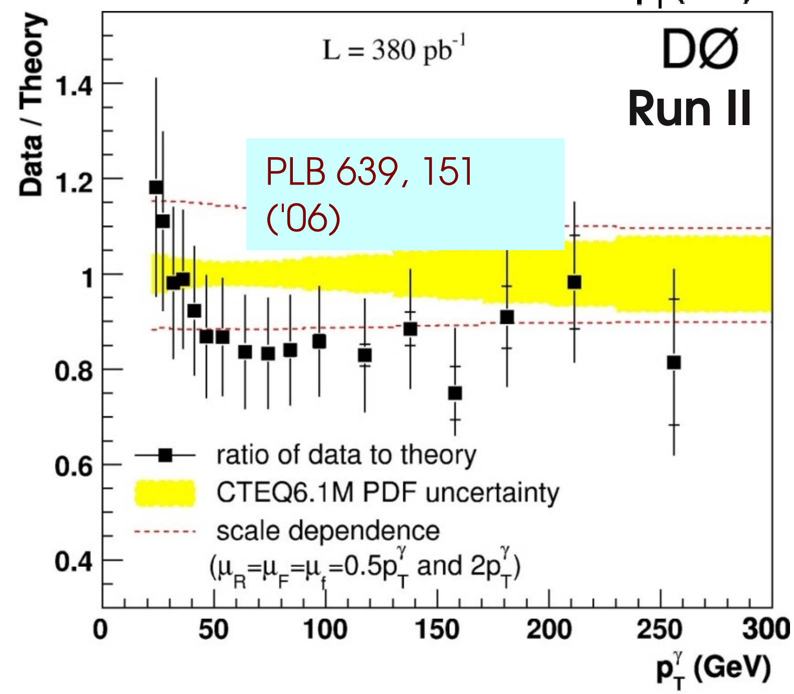


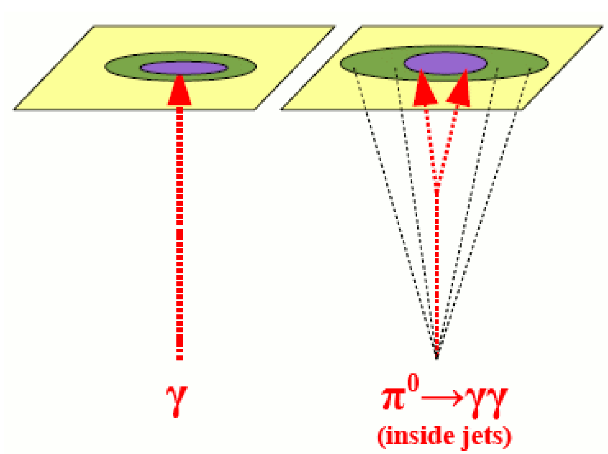
Photons





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

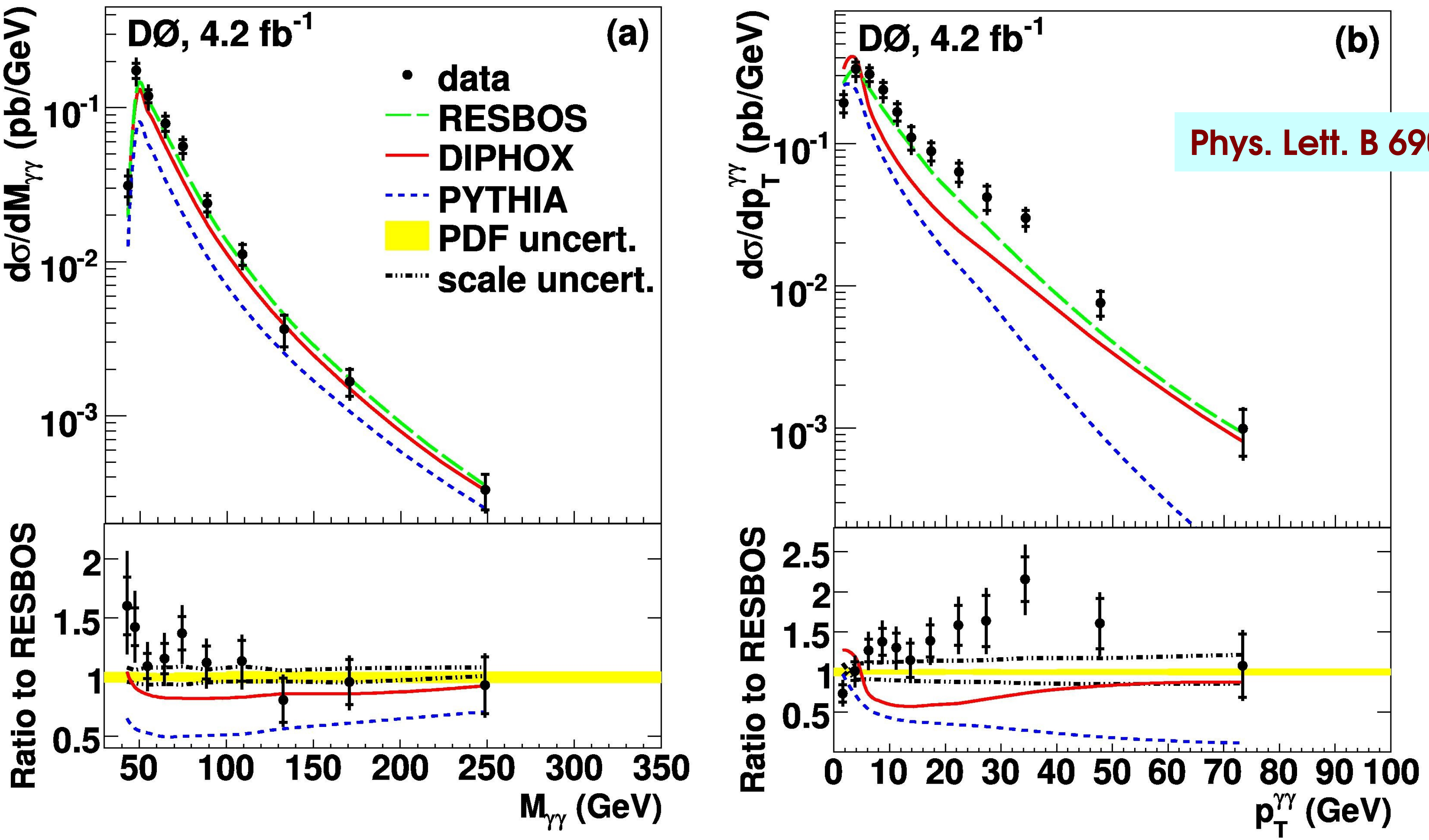




Diphotons

"spin-off" from the H→$\gamma\gamma$ search

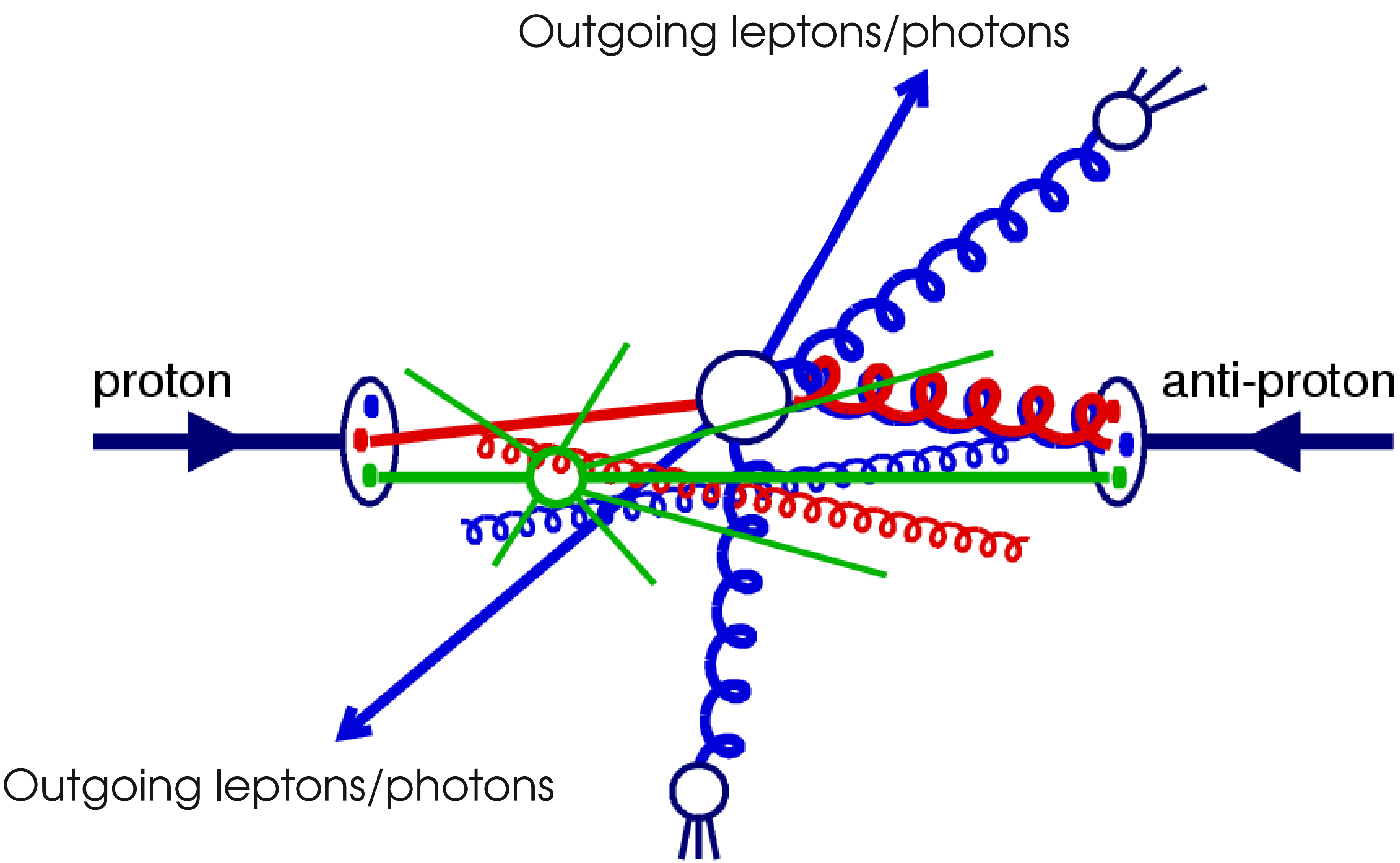
- two photons with pT>20 (21) GeV, $|\eta|$<0.9, pT($\gamma\gamma$) < M($\gamma\gamma$)
- measure mass, pT, $\Delta\phi$, cosθ*
  - and again, in bins of mass



Phys. Lett. B 690, 108 (2010)

The Next Step

Next step: take a closer look at what else is happening in these events
- extra activity from hard scatter, MPI, underlying event.
- can we disentangle?



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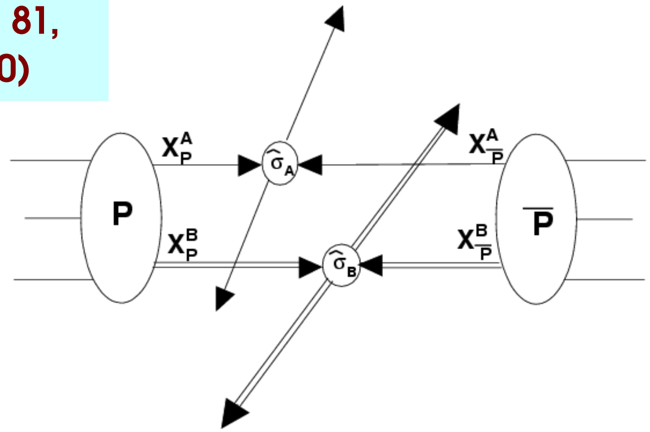
Phys. Rev. D 81, 052012 (2010)



Double parton interactions:
- important background (esp at LHC)

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: $<\sigma_{eff}> = 15.1 \pm 1.9$ pb
Consistent with previous CDF result

γ + jets: MPI; UE

Next step: take a closer look at what else is happening in these events

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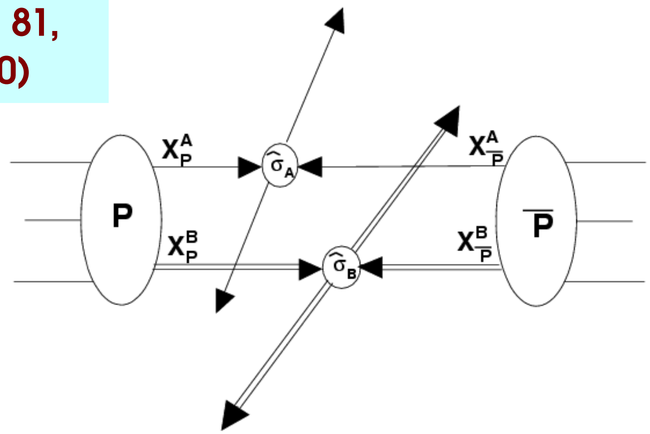
- can we disentangle?

Phys. Rev. D 81, 052012 (2010)



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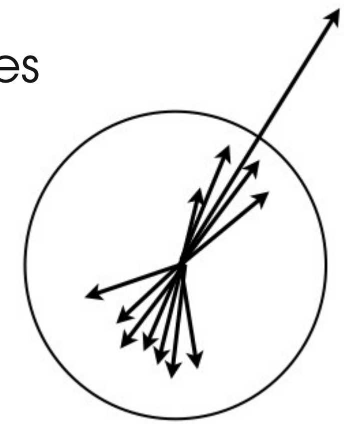
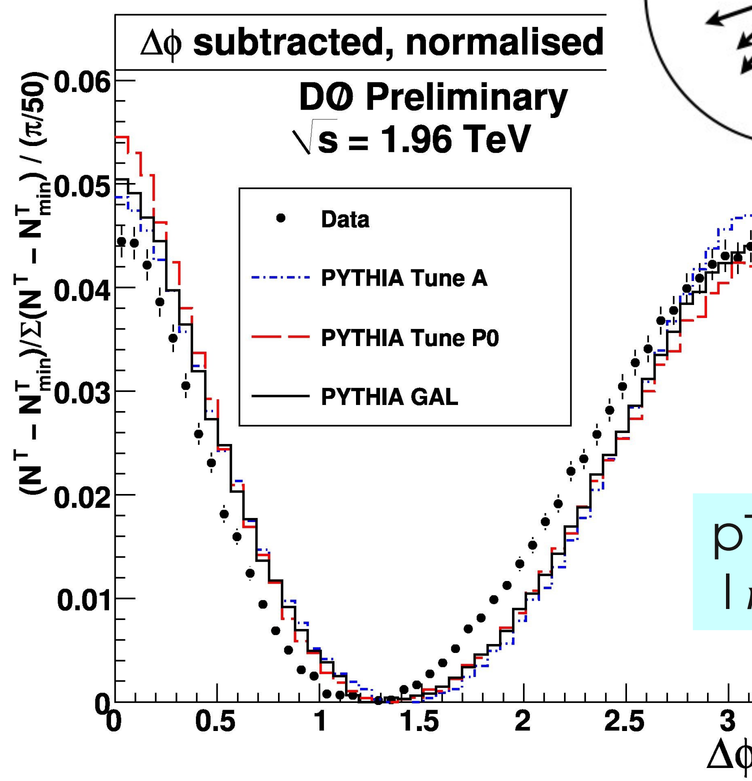
Measured: $<\sigma_{eff}> = 15.1 \pm 1.9$ pb
Consistent with previous CDF result

Also: a D0 min bias measurement!
- use dimuon triggers
- look for other vertices



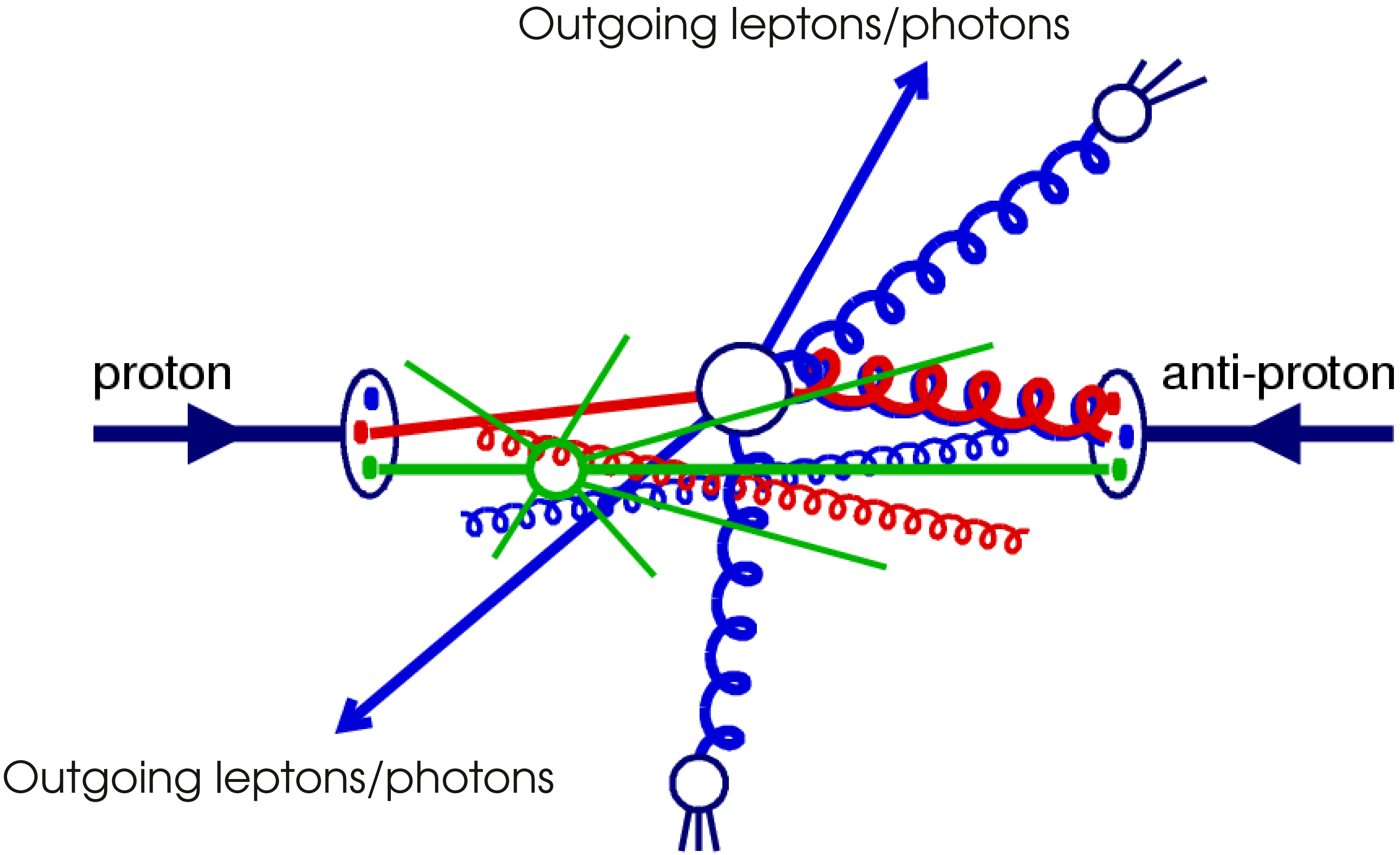
Preliminary



pT>0.5 GeV
$|\eta| < 2$

Z+jets

Back to the Z, focus on the jets:
- need differential distributions



Z+jets

Back to the Z, focus on the jets:

- need differential distributions

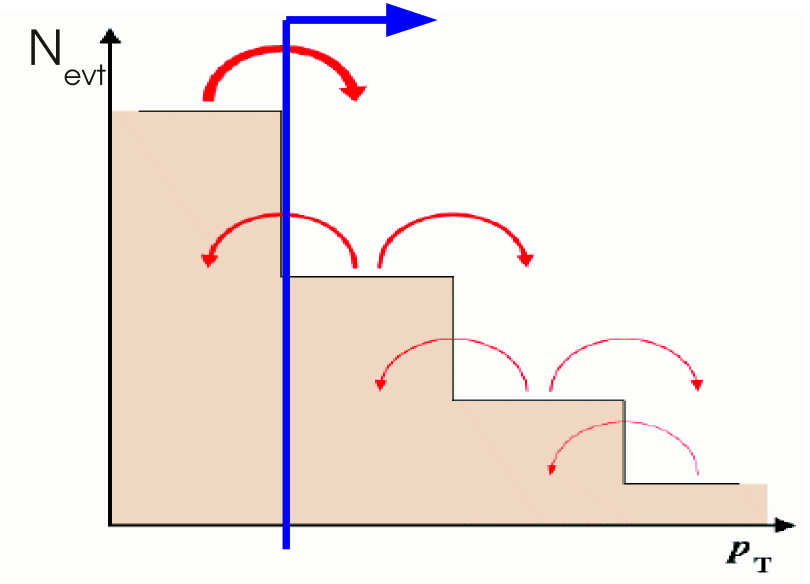
Unfolding problems become worse:

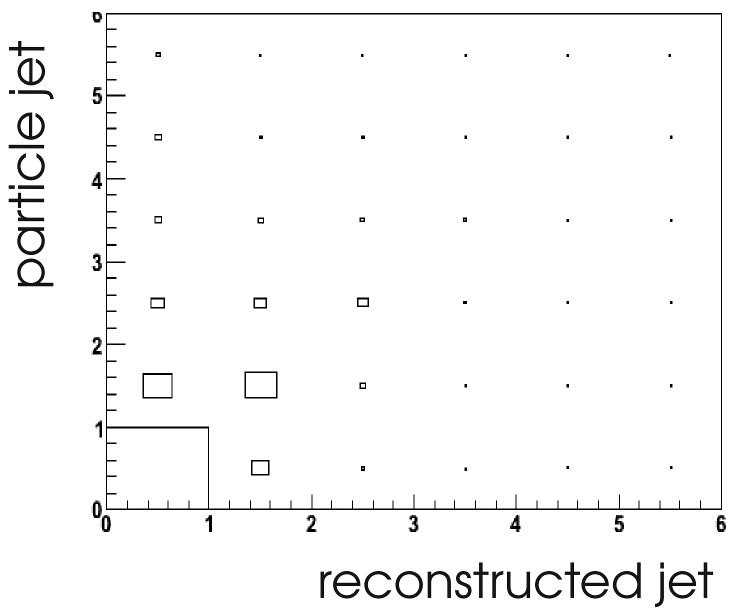
- detector resolution worse than leptons
- migrations across pT cut
- and changes in pT ordering...

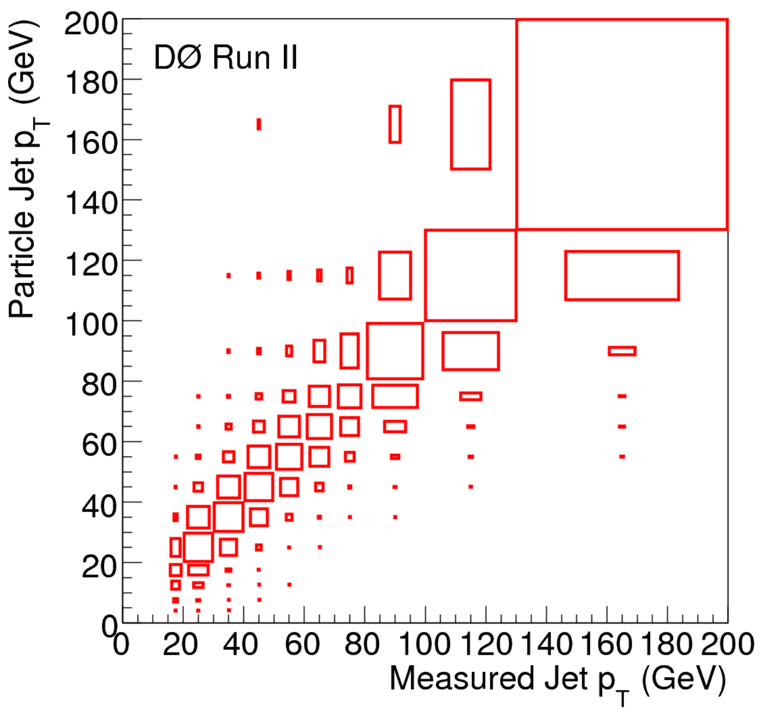
Looking at the 2nd, 3rd, …. jet is tough

- need to be very careful
- or have a MC which describes the data

  → lots of reweighting...







Z + 1,2,3 jets

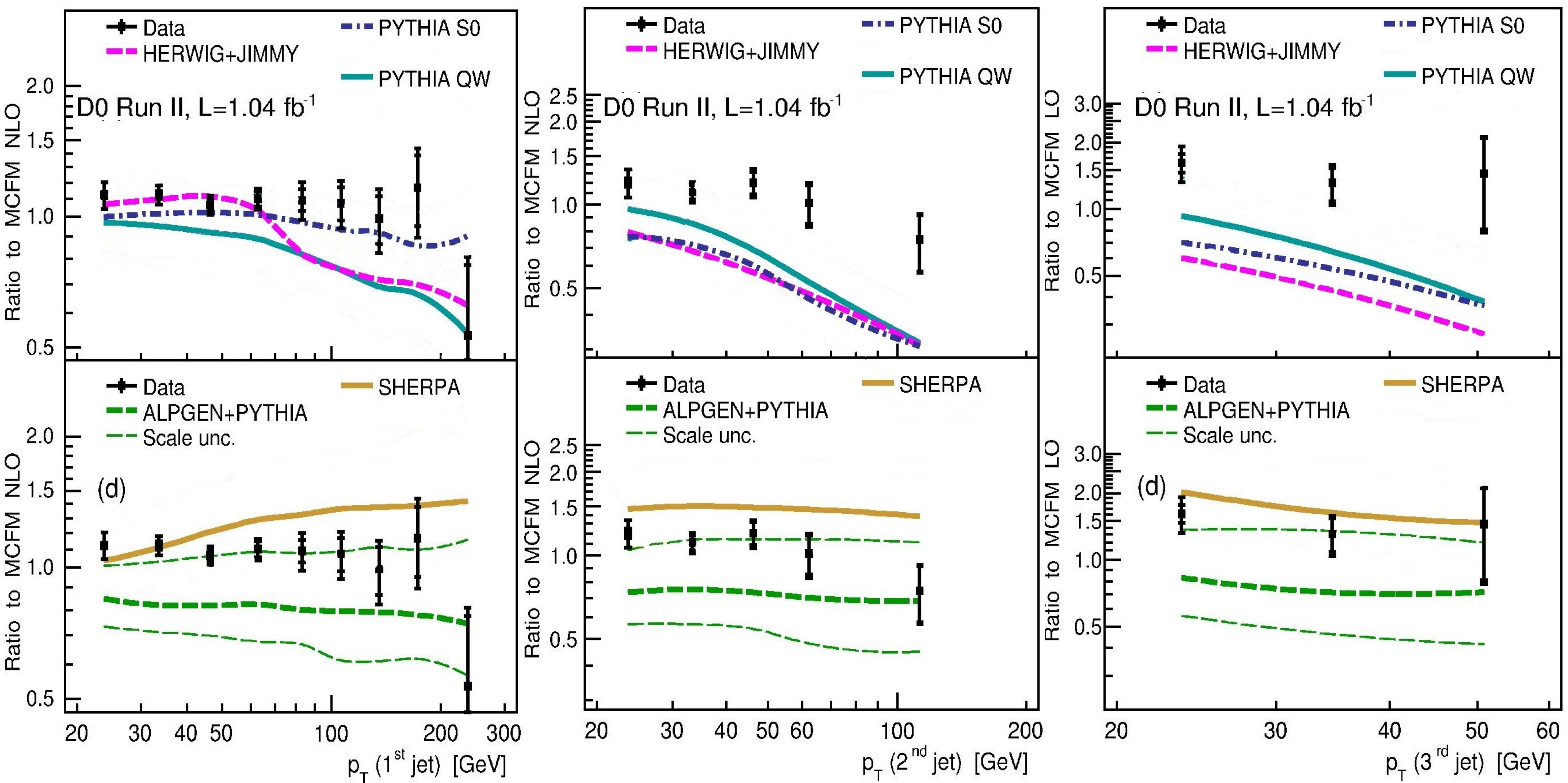
Measurement of 1st, 2nd and 3rd jet pT in Z events:

- 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

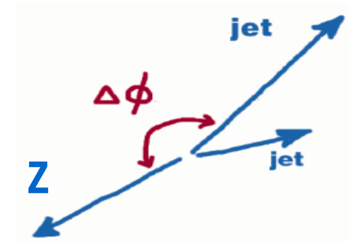
PLB 678, 45 (2009)

Leading Jet | **Second Jet** | **Third Jet**

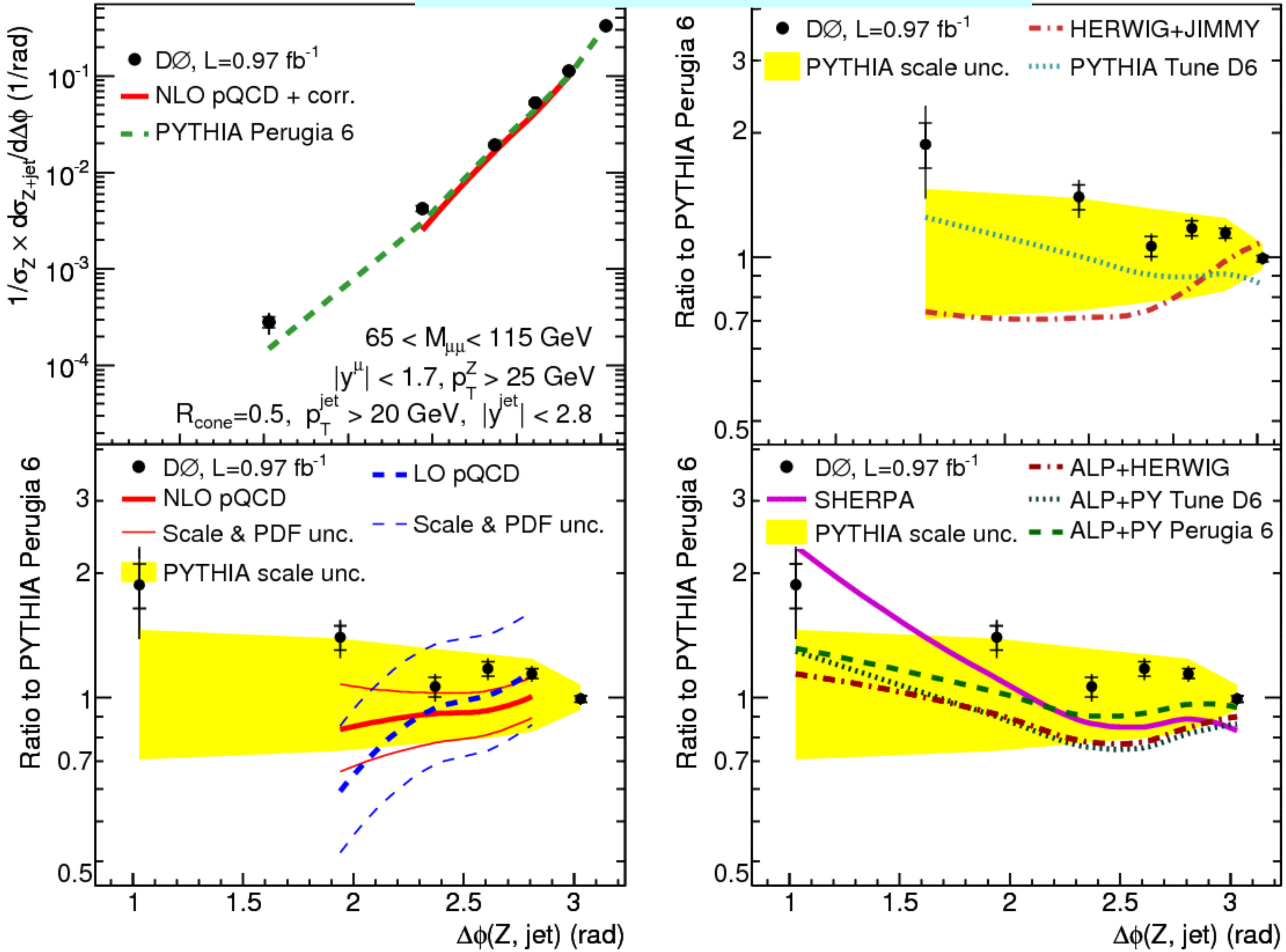


Z+jets: $\Delta\phi$

Another, simpler way to access higher jet multiplicities:
- similar to the dijet decorrelation measurement
- $\Delta\phi$(Z, leading jet), measured for the first time



Phys. Lett. B 682, 370 (2010)



Require $p_t(Z)$ > 25 GeV

LO = $O(\alpha_s^2)$
NLO = $O(\alpha_s^3)$

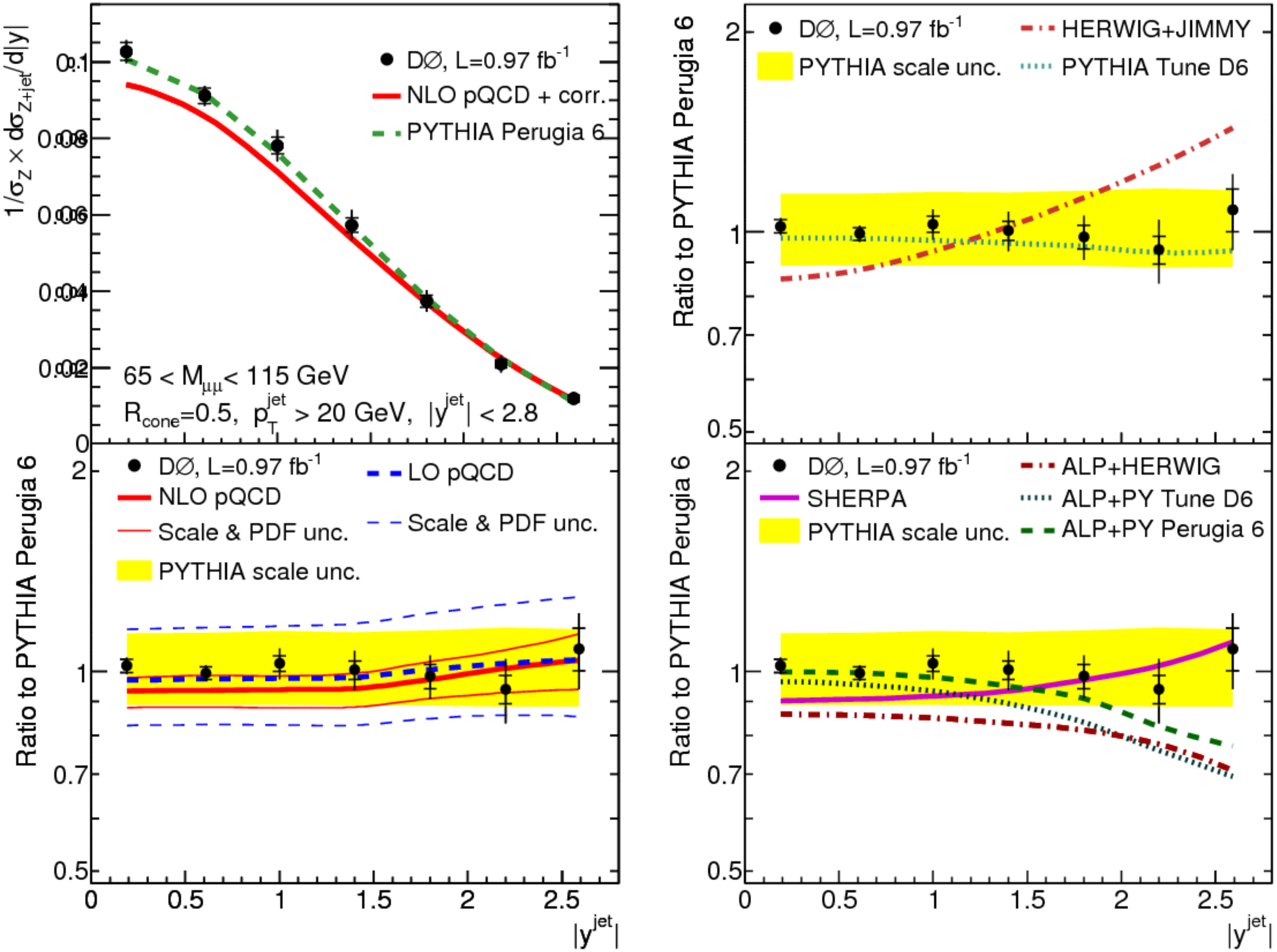
pQCD diverges as
$\Delta\phi \rightarrow \pi$

Corrections large as
$\Delta\phi \rightarrow 0$
(due to MPI)

Z+jets: jet y

Some simpler things also revealing: leading jet rapidity
- well modeled by pQCD
  - alpgen and (fortran) herwig diverge in opposite directions...

Phys. Lett. B 669, 278 (2008)

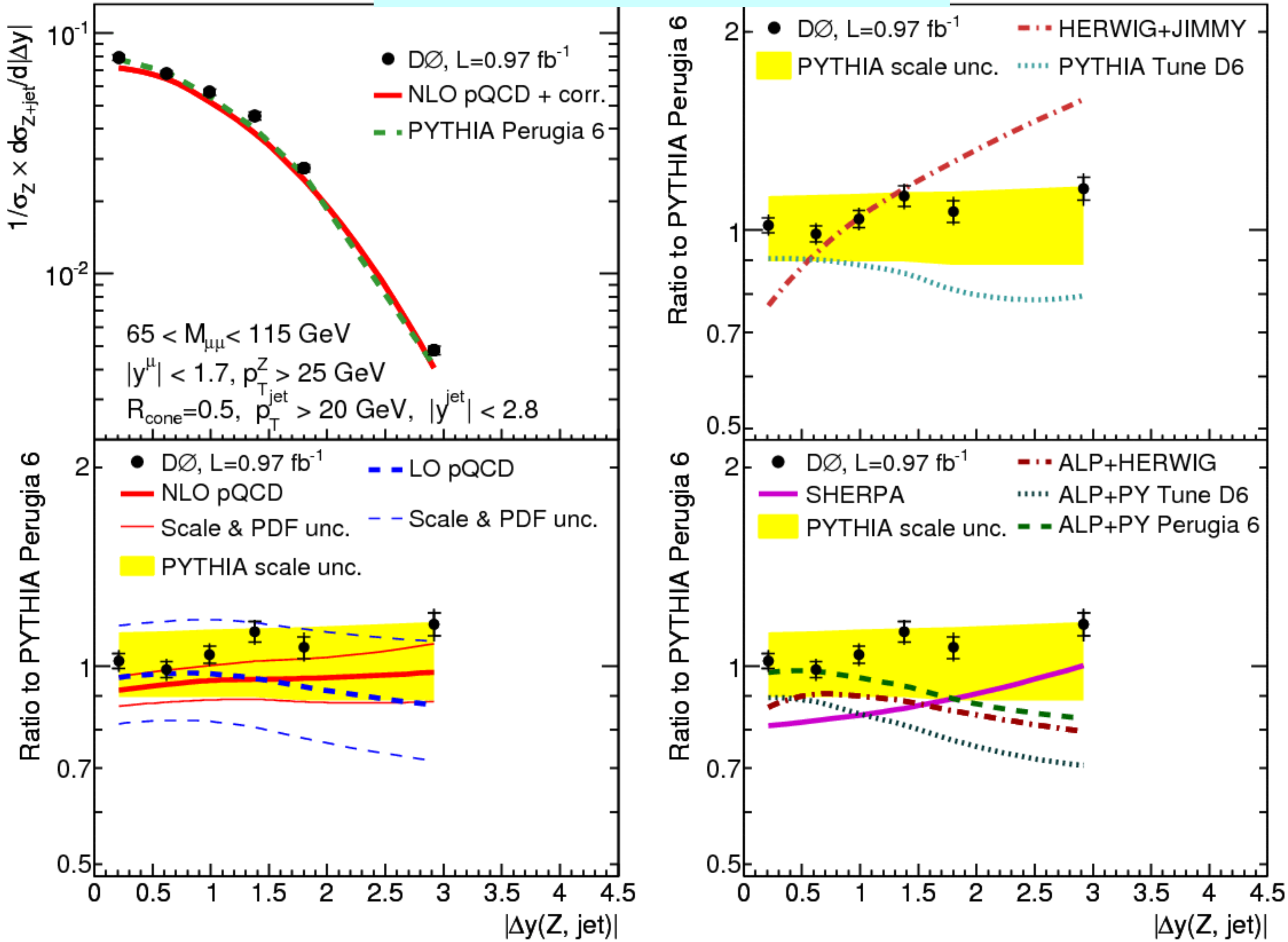


Z+jets: Δy

Gavin Hesketh

See same effect on Δy(Z, jet)

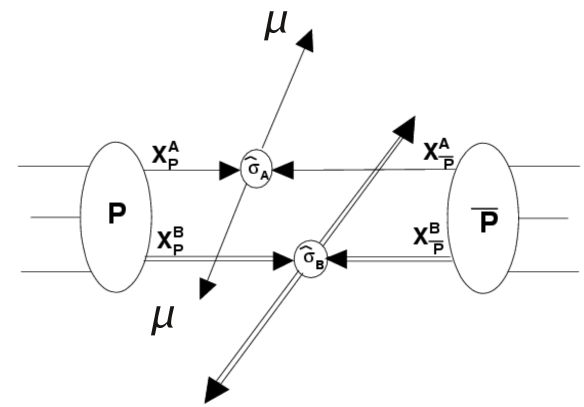
Phys. Lett. B 682, 370 (2010)



Z+jets

Z pT, >= 1 jet in the event

- never measured before
- interesting way to access MPI!



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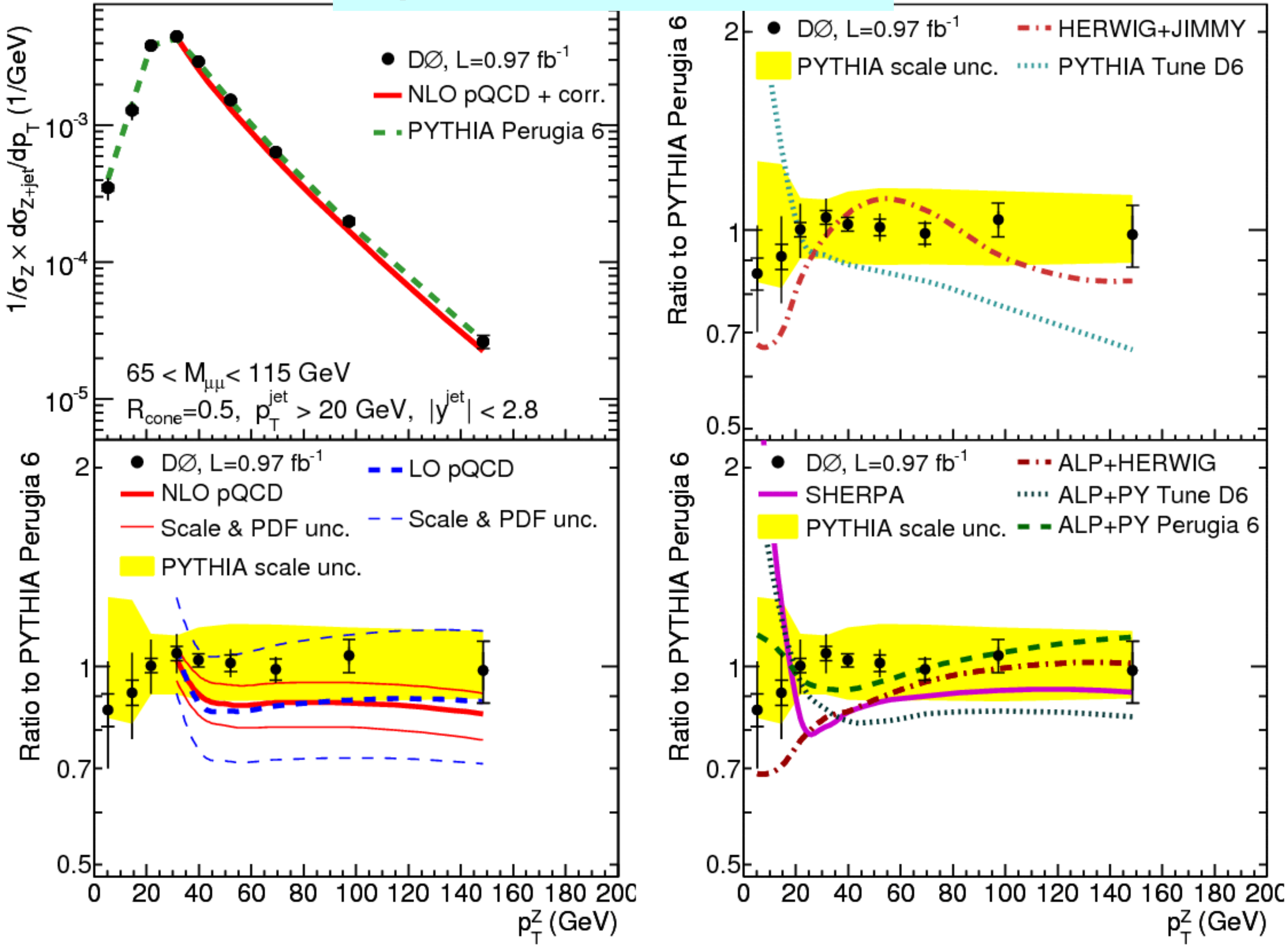

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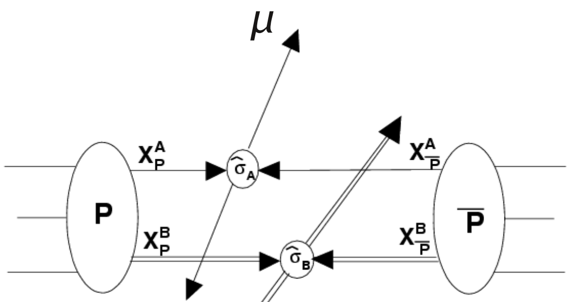
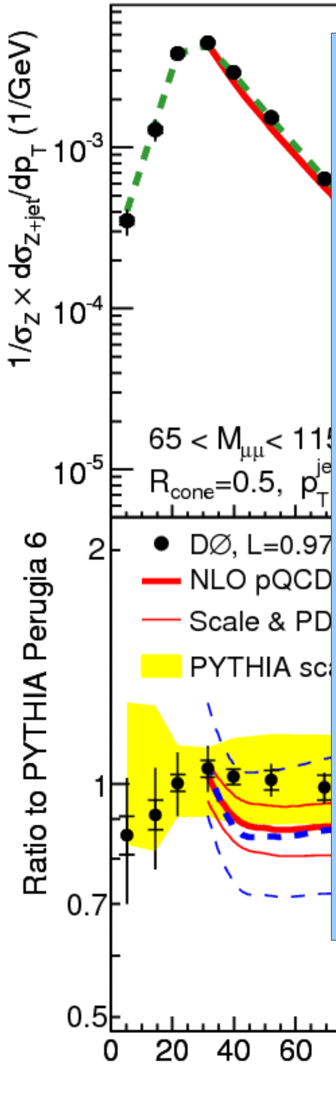
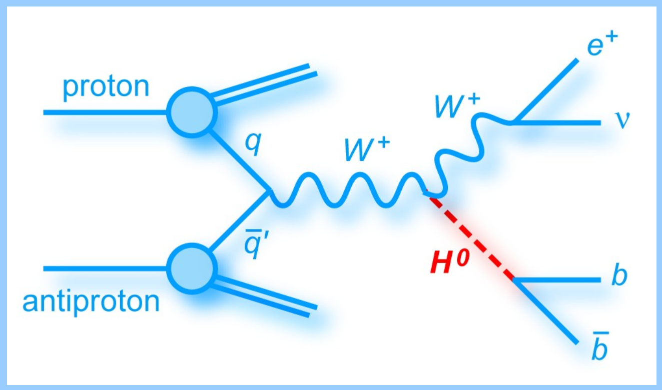
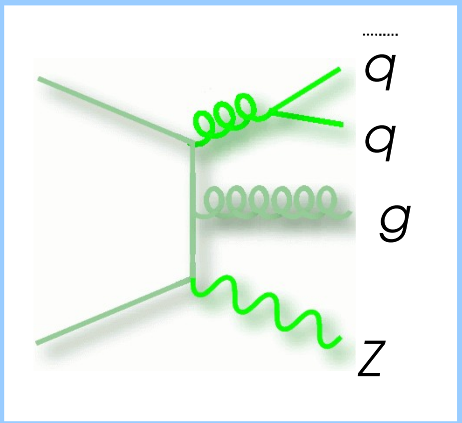


Phys. Lett. B 669, 278 (2008)







So far, no "perfect" Monte Carlo

- some good variables for future tuning
- LO Monte Carlos have LO accuracy...
  - how much should we expect from tuning?
  - some shape effects are not scale related
  - SHERPA v1.2.2 looks good overall

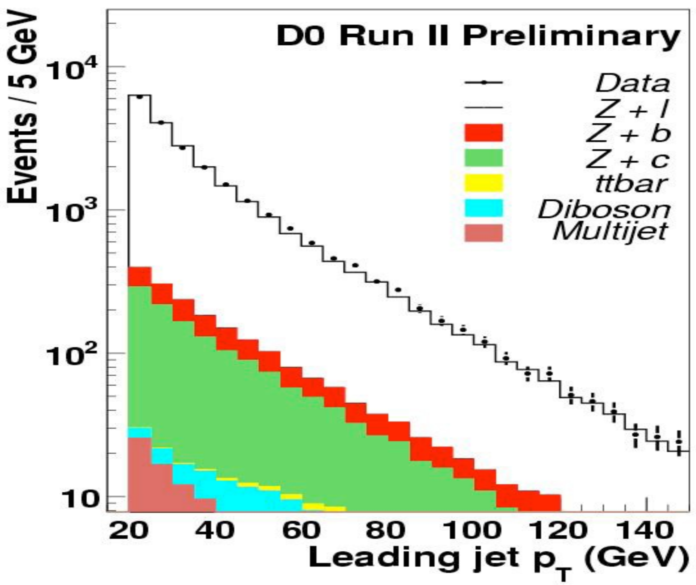
Z + Heavy Flavour

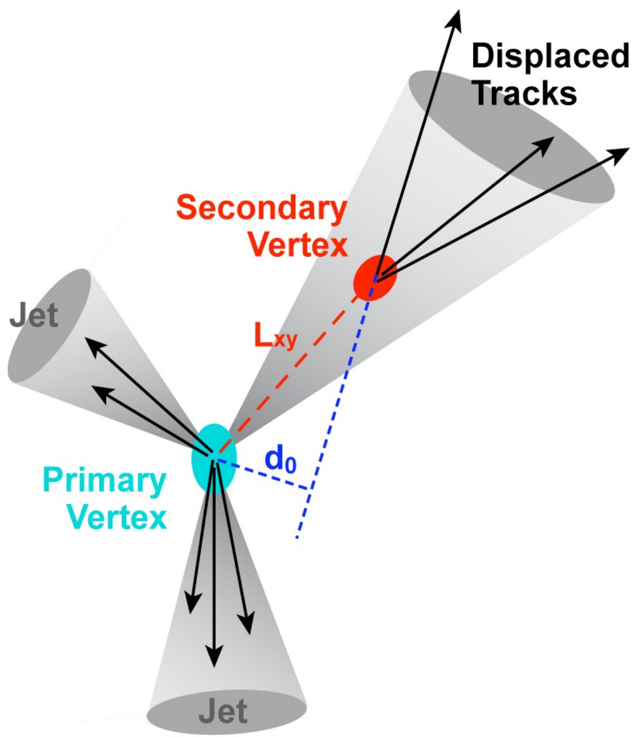
Much progress with Z+light flavour

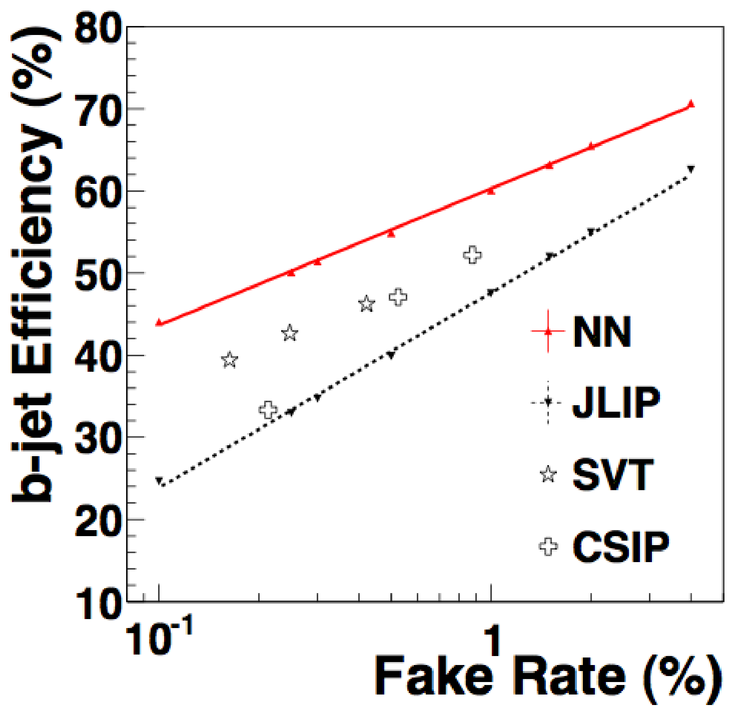
- also need to understand heavy flavour
- THE low mass Higgs background!

Heavy flavour tagging:

- based on many variables in a NN
- different operating points
- extra complication in unfolding

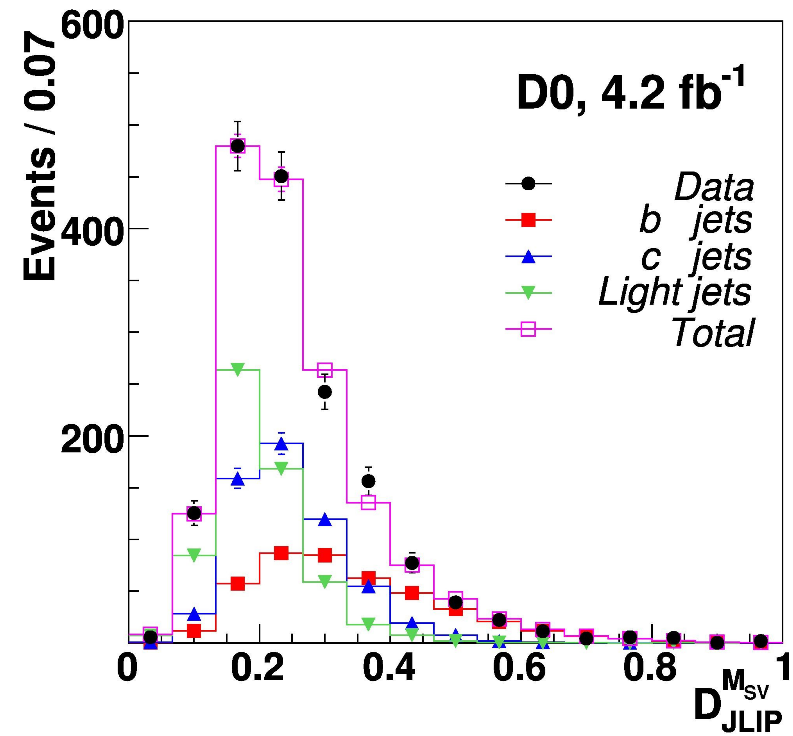






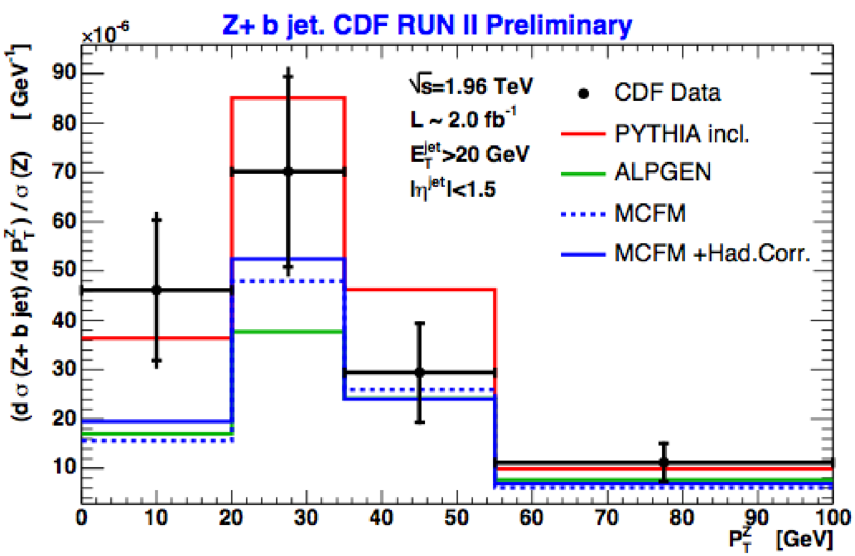
Z + Heavy Flavour

Final discriminant: rJLIP
- reduced jet lifetime probability
- confidence level that all tracks in a jet originate from same vertex.
- reduced? discard the least likely track.
- fit templates to extract b-jet fraction



Z+b/Z+jet = 0.0176 ± 0.0024(stat) ± 0.0023 (syst)
- in agreement with NLO pQCD (which has 20-25% scale uncertainty)

Subm to PRL, arXiv.org:1010.6203



CDF result: 0.0208 ± 0.0033(stat) ± 0.0034 (syst)
2 sigma over pQCD in first bin

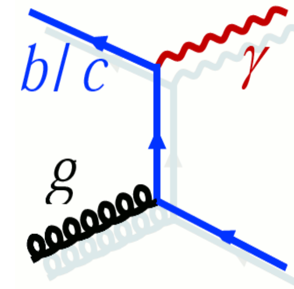
γ + Heavy Flavour

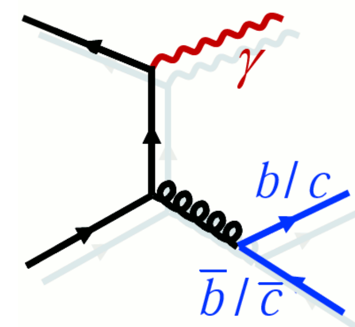
Similar analysis to photon + jet:

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

Systematics dominated by flavour fractions

- from template fit to jet lifetime probability





Phys. Rev. Lett. 102, 192002 (2009)

b-jet cross section well modeled

Deficit in c-jet at high p_T:

- region dominated by gluon splitting

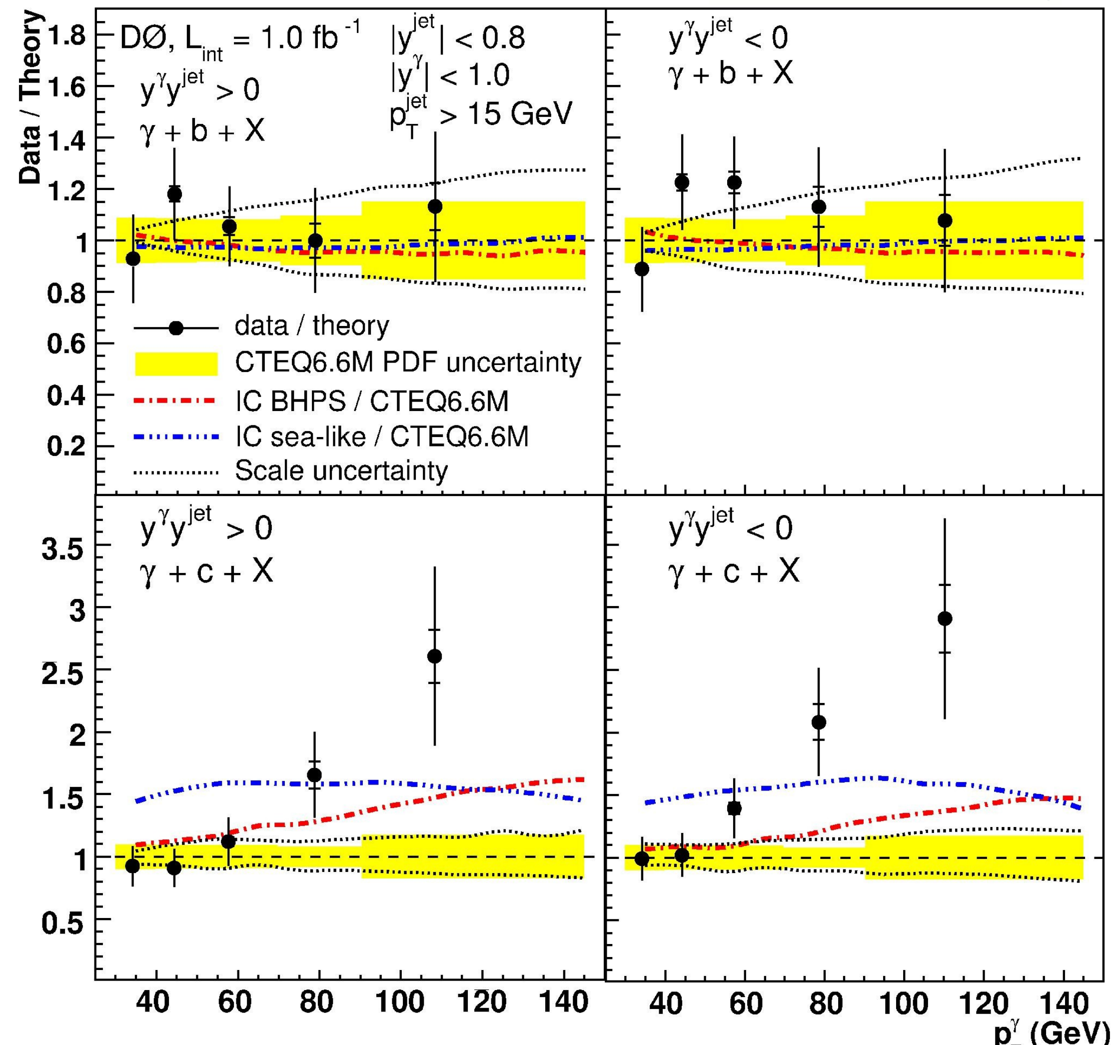
Increased charm sea models:

- move in direction, but not enough

What will the LHC observe?

- more sensitive to heavy flavour sea

How will this look for Z?



Conclusions

Understanding QCD is essential at a hadron collider!

QCD programme at D0 very successful

- solid methods, precision results!

Jet results building on the precise JES:

- no new physics, but...
- improving knowledge of PDFs
- new measurement of α_s
- more results to come

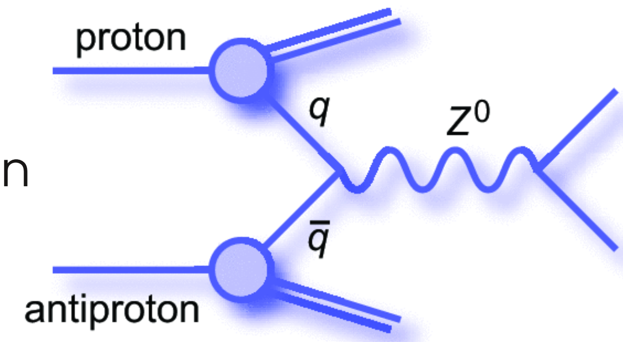
Boson (+ jet) production:

- excellent test of QCD predictions, essential for discoveries!
- developed new techniques, new variables
- extensive study of Z+jets
  - and updated MC tunes
- Z/W + heavy flavour is next!

Backup

Inclusive Z pT

Z transverse momentum:
- no pT in the initial state (incoming protons)
- any Z pT must be balanced by initial state QCD radiation
- here, measure the shape: $(1/\sigma)\times(d\sigma/dpT)$
    - cancel many uncertainties
    - accessing different physics to σ measurement

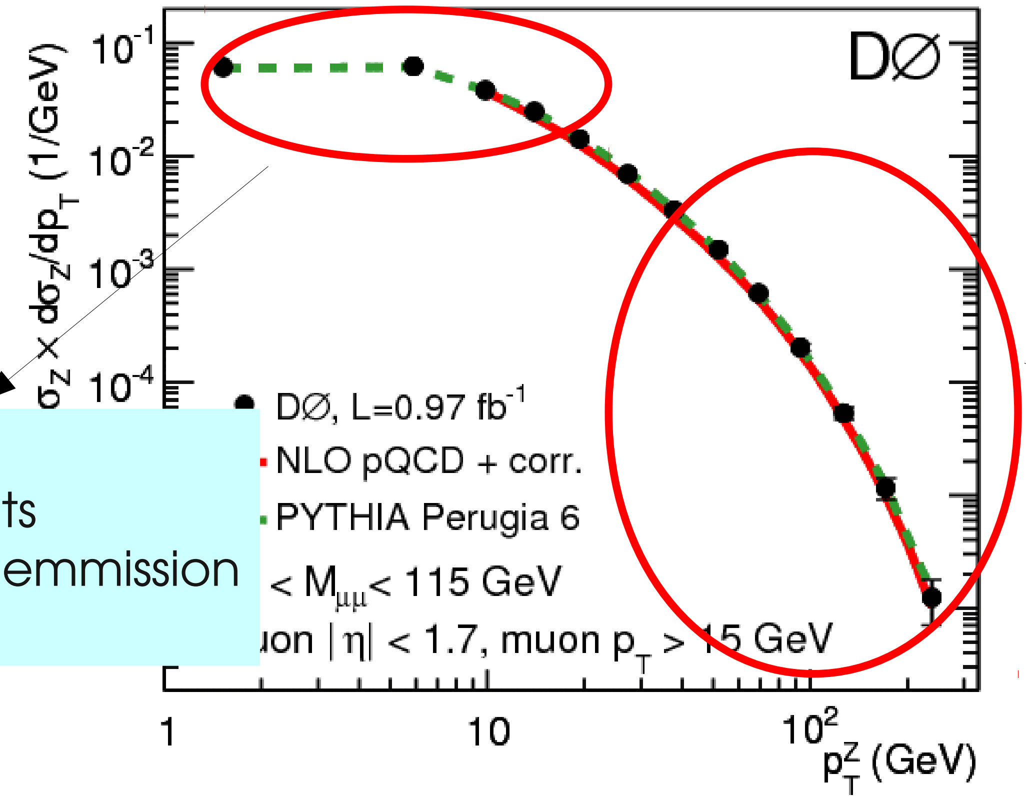


$\bar{q}$

q

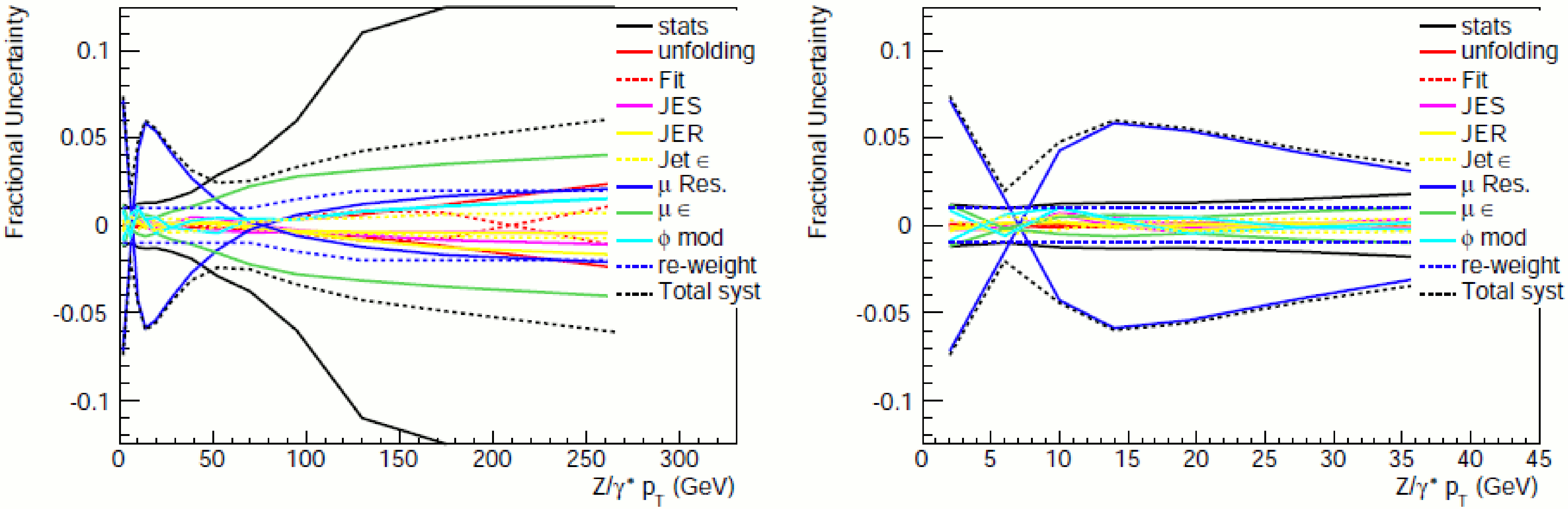
g

Z



Low pT
- most of the stats
- multiple gluon emmission
→ resummation

High pT
- hard emmission
→ perturbative QCD
→ Z+jets



Fractional Uncertainty
0.1
0.05
0
-0.05
-0.1
0
50
100
150
200
250
300
Z/γ* p_T (GeV)
stats
unfolding
Fit
JES
JER
Jet ∈
μ Res.
μ ∈
ϕ mod
re-weight
Total syst
Fractional Uncertainty
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
25
30
35
40
45
Z/γ* p_T (GeV)
stats
unfolding
Fit
JES
JER
Jet ∈
μ Res.
μ ∈
ϕ mod
re-weight
Total syst

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**

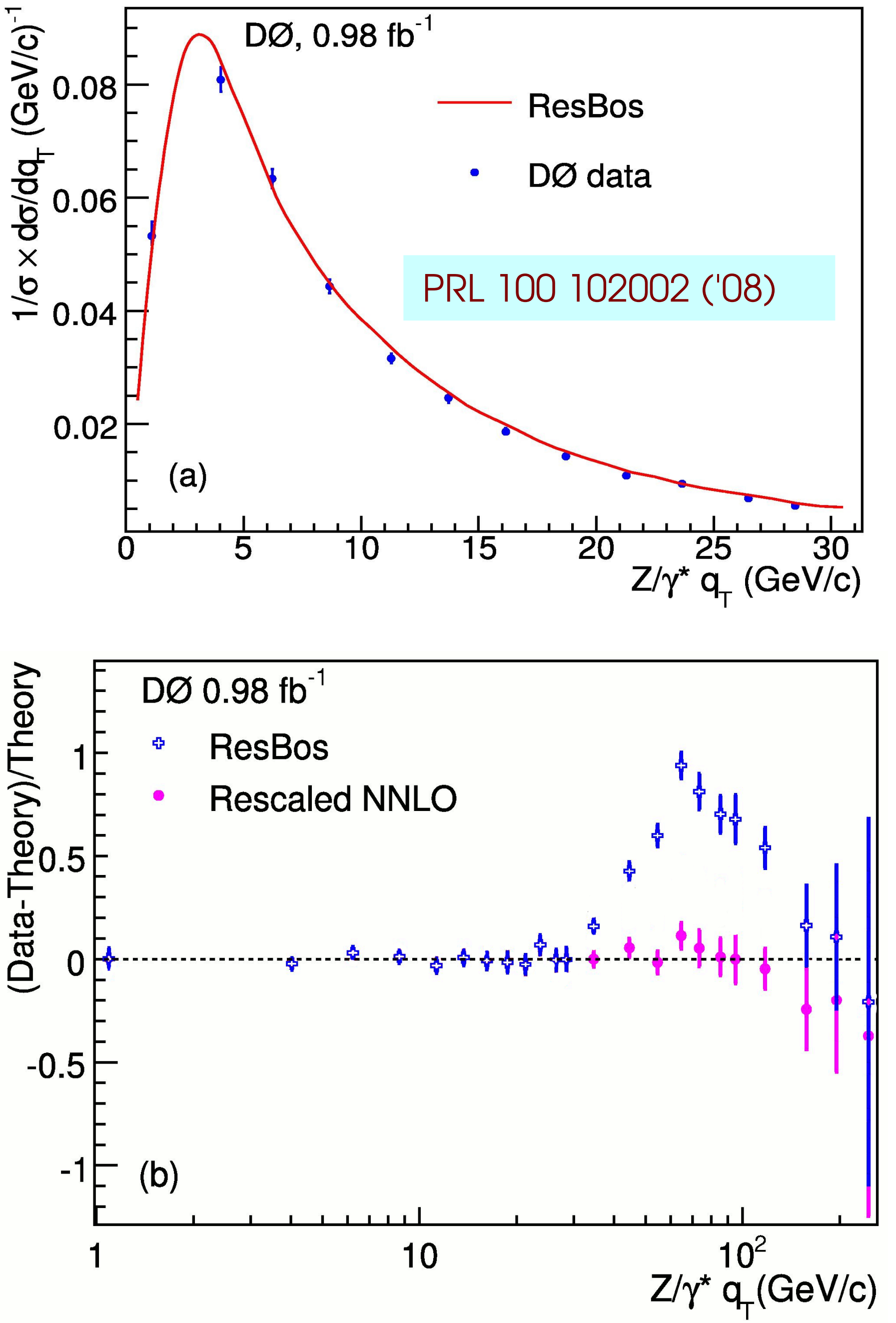
- also use forward Z to test small-x broadening

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!

- re-weight simulation to these data.



Jet Energy Scale

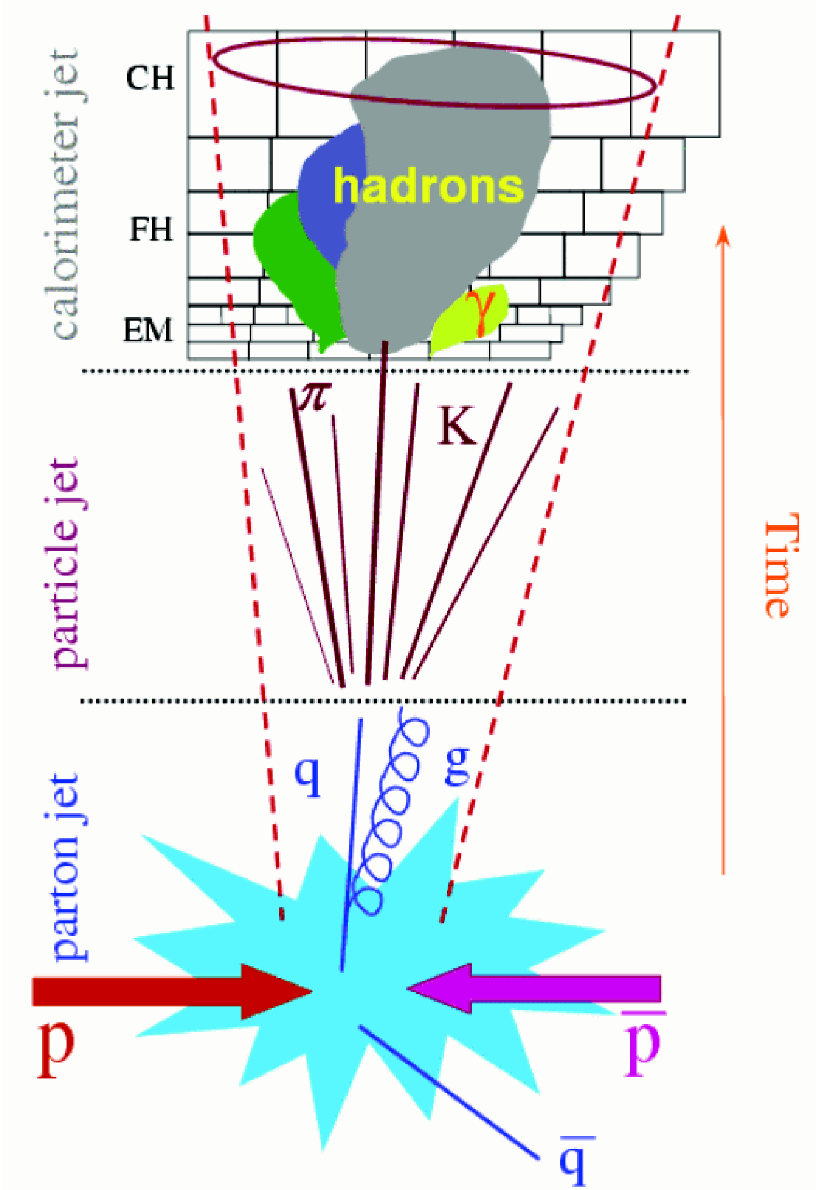
$$\langle E_{ptcl} \rangle = \frac{E_{cal} - \text{Offset}}{R \times A \times S} k_{bias}$$

Offset: energy not from hard scatter
- noise, pile-up
- measure in min bias events, 1-3 % effect

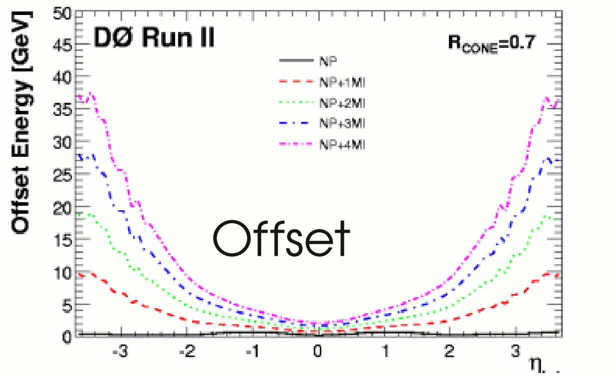
R x A: Relative and absolute response corrections
- fraction of total particle energy seen
- primarily in back-to-back photon+jet
- extrapolate forward with di-jets

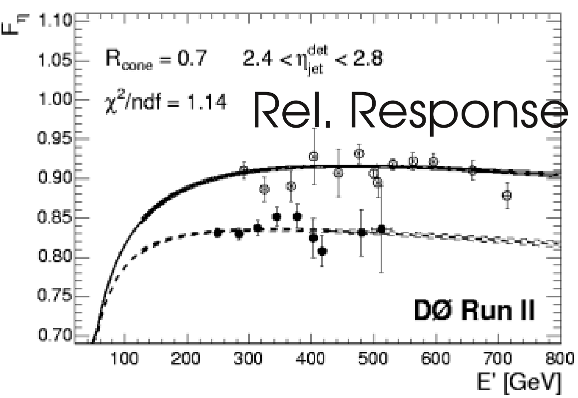
S: (detector) showering effects
- finite calorimeter tower size;
- magnetic field
- hadron shower size
- 1-5 % effect, function of η
- again, measure in photon +jet

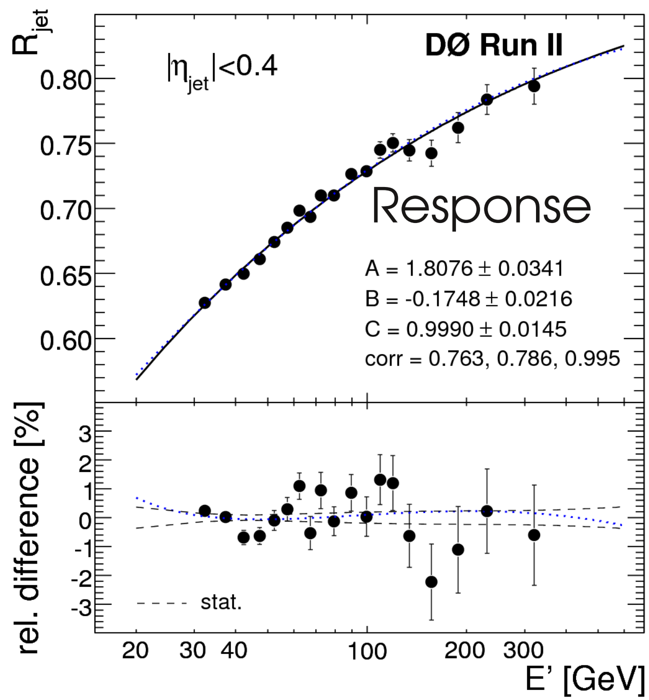
k: any remaining biases:
- effects of cell zero suppression
- response sample selection bias

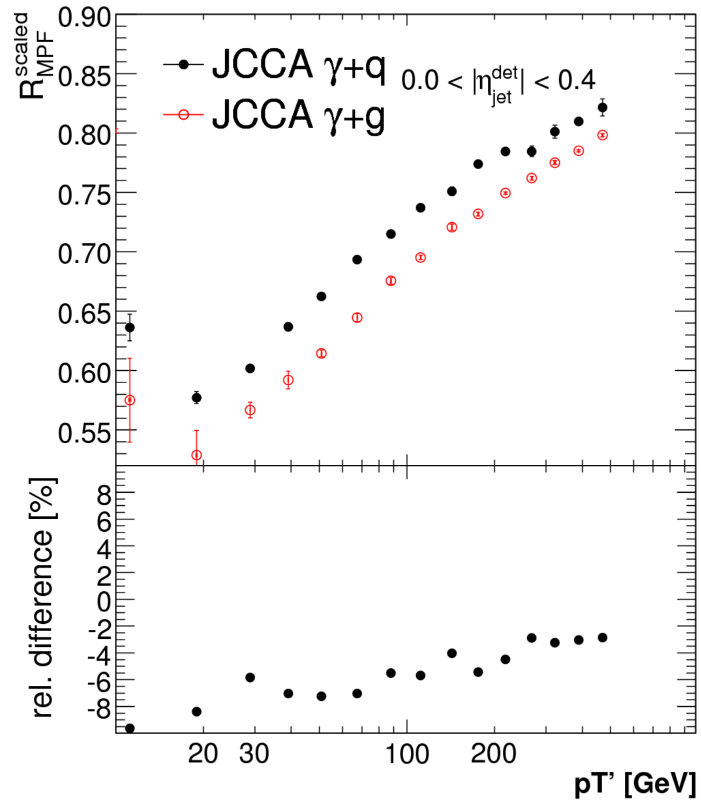


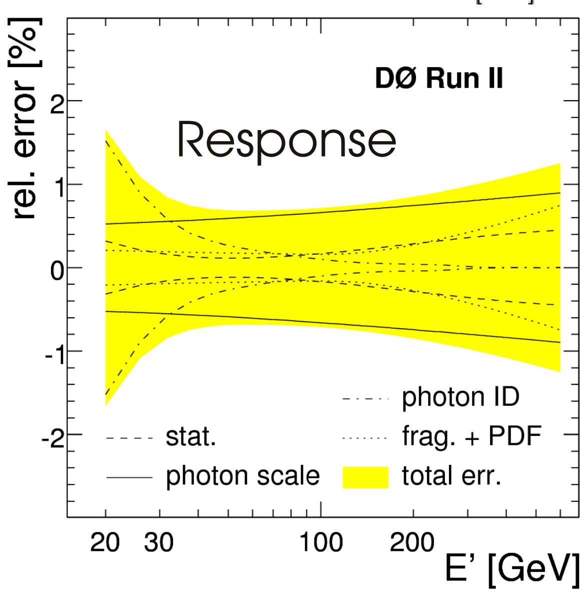
Jet Energy Scale

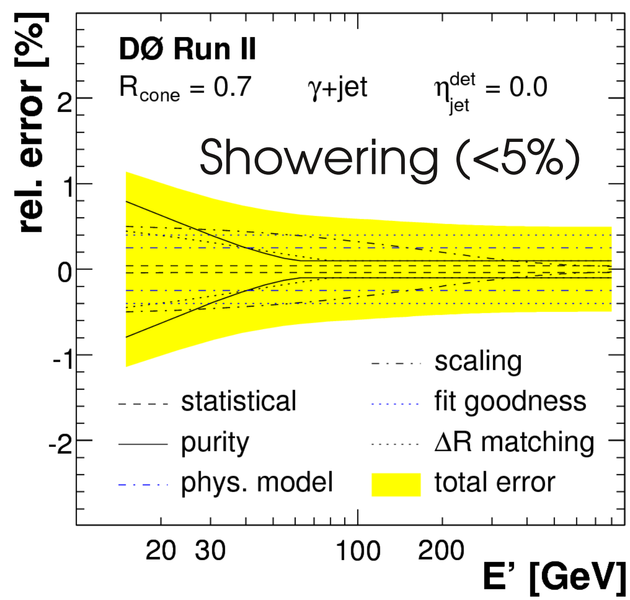


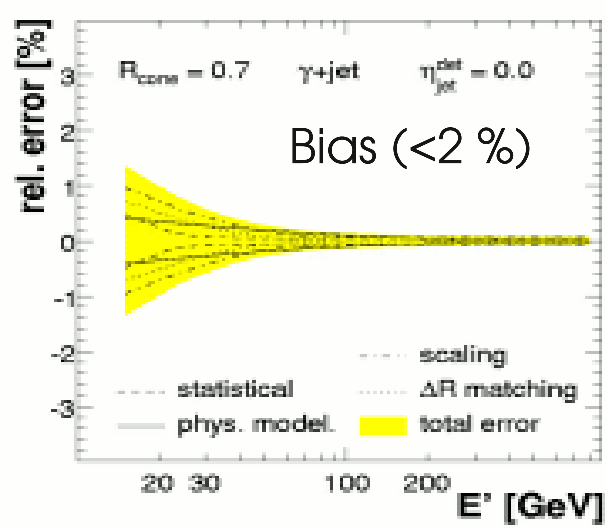












Particle Level

In simulation, construct "Z" and "W" from the particles entering the detector:

1) Consider all particles with ctau > 10 mm as "stable" (ie reach the detector)

2) Muon: any stable muon. ie after QED FSR, to mirror a tracking detector

3) Electron: combine EM energy in a cluster, to mirror a calorimeter
   - eg, a cone with R=0.2 suitable for Tevatron, but not LHC

4) Missing ET: vector sum of all neutrinos in event

5) Dilepton (Z) selection should mirror data:
   - consider all leptons in acceptance range (eg |eta| <2.5)
   - make opposite sign pairs, keep those in mass range (eg 65 < M <115 GeV)
   - when >1 pair, pick "best" in same way as for data
     - eg closest to Z mass

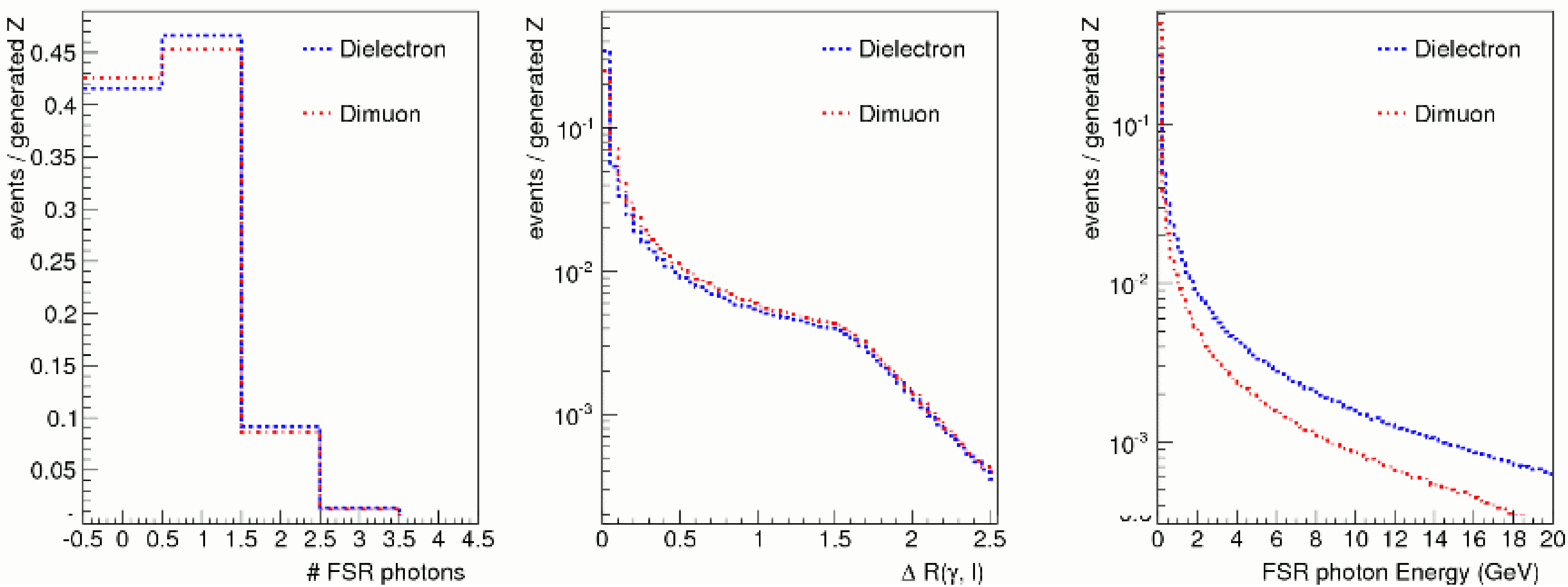
5) Lepton + MET (W) selection should mirror data:
   eg highest pT lepton inside acceptance, combined with MET

Data must still be corrected for detector resolution and efficiency
"unfolding", a difficult subject worthy of several talks...

Does any of this actually make a difference?

Some test studies: ppbar->Z->ee and Z->mumu in Pythia 6.421, tune Perugia 6

- Tevatron example as we have the data, and know this tune does well
- simple analysis:
  - build the particle level leptons, require:
    - | lepton eta | <1.7
    - di-lepton mass 65<M<115 GeV
  - compare to the generated Z, with the same cuts on the leptons **before FSR**



Recovering Old Results?

Gavin Hesketh

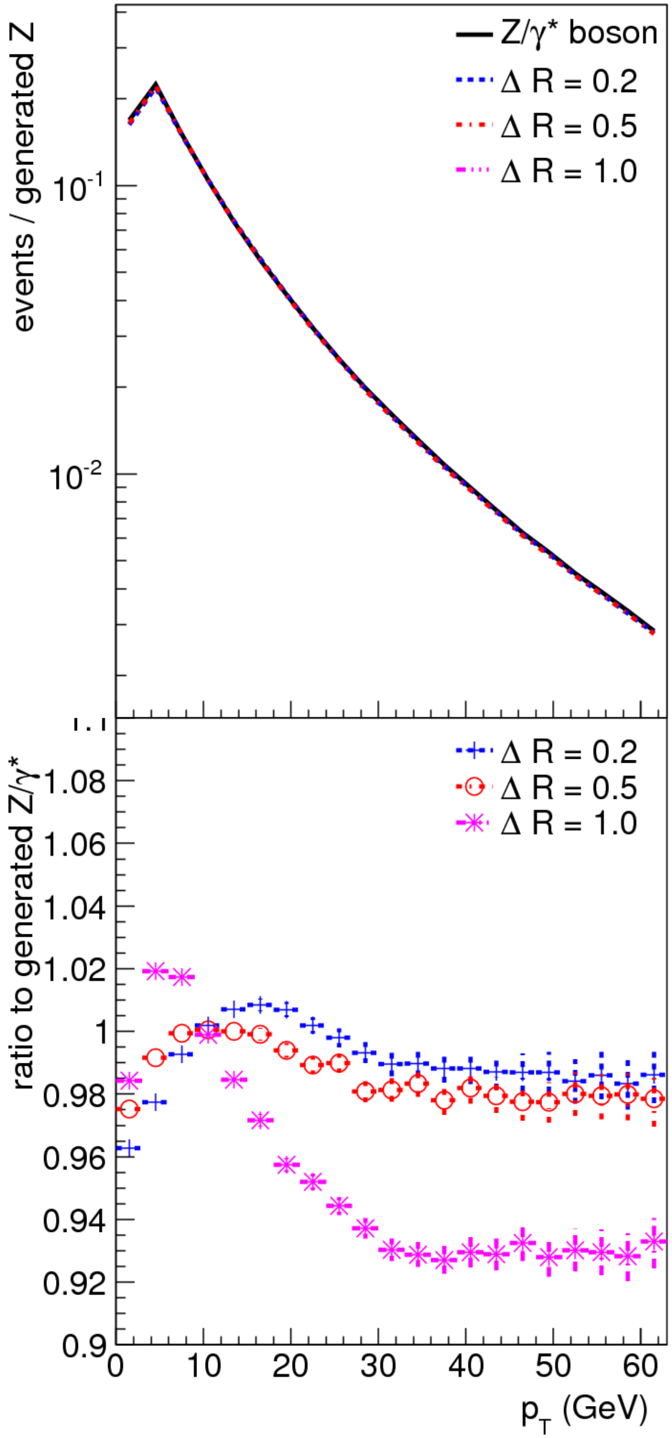
Previous publications of Z pT:
- corrected from measure leptons to Z
- corrected to 4pi acceptance

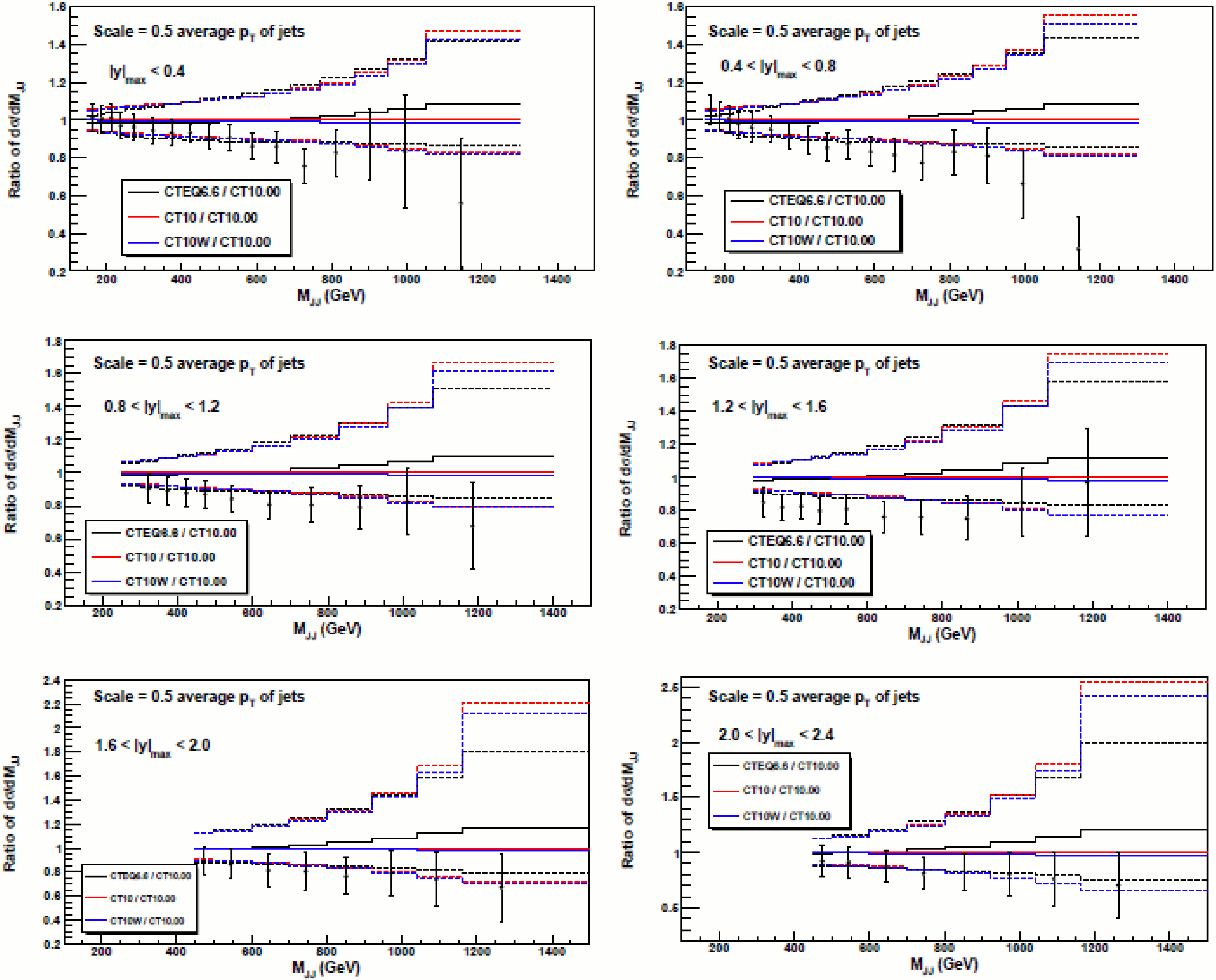
Is it possible to reproduce these using stable particles?
- ie in RIVET?

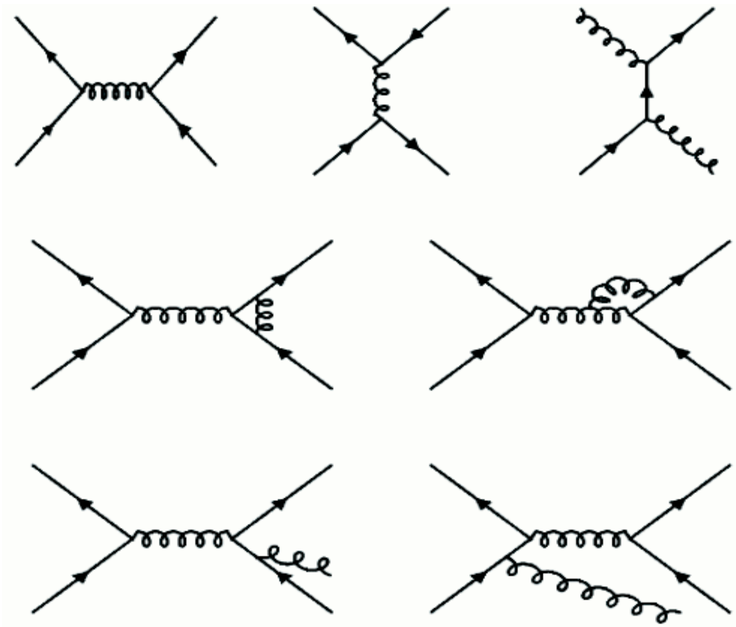
Try to catching more FSR:
- increase the electron cone size: 0.5 and 1.0
- 0.5 cone moves closer to Z
- 1.0 goes too far
  - catch too many underlying event photons

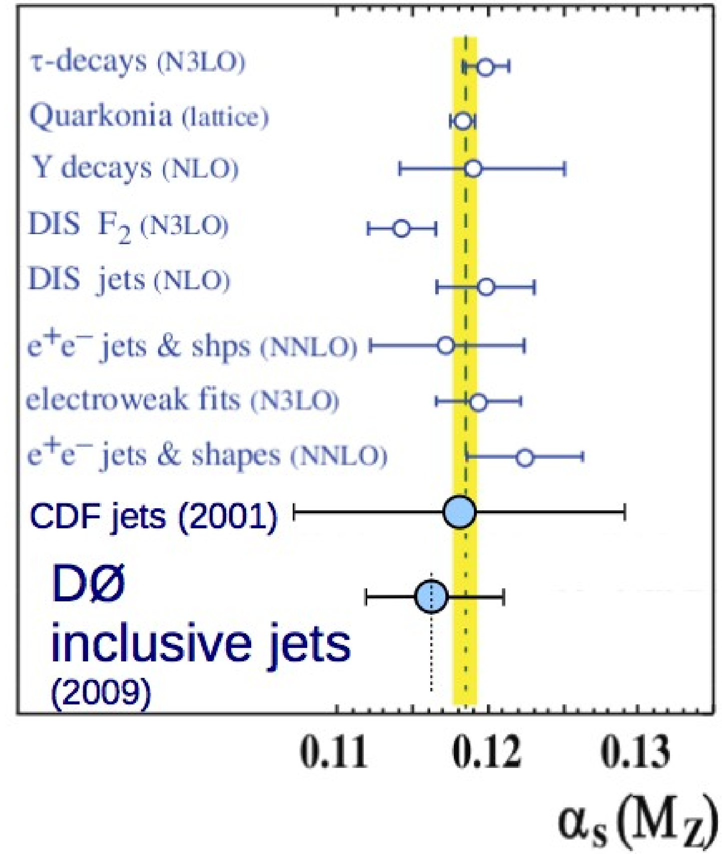
note: neither of these are observables!

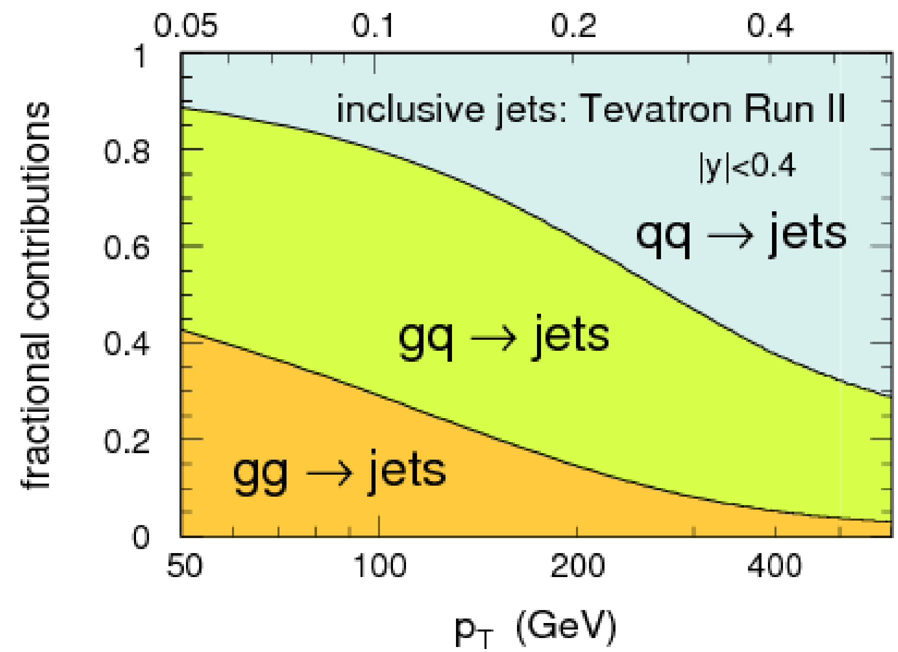
Cannot reproduce previous measurements!
- without "cheating"




Scale = 0.5 average p_T of jets
|y|_max < 0.4
0.4 < |y|_max < 0.8
0.8 < |y|_max < 1.2
1.2 < |y|_max < 1.6
1.6 < |y|_max < 2.0
2.0 < |y|_max < 2.4
CTEQ6.6 / CT10.00
CT10 / CT10.00
CT10W / CT10.00
Ratio of dσ/dM_JJ
M_JJ (GeV)




τ-decays (N3LO)
Quarkonia (lattice)
Υ decays (NLO)
DIS F2 (N3LO)
DIS jets (NLO)
e+e− jets & shps (NNLO)
electroweak fits (N3LO)
e+e− jets & shapes (NNLO)
CDF jets (2001)
DØ
inclusive jets
(2009)
0.11
0.12
0.13
αs(MZ)


0.05
0.1
0.2
0.4
1
0.8
0.6
0.4
0.2
0
fractional contributions
inclusive jets: Tevatron Run II
|y|<0.4
qq → jets
gq → jets
gg → jets
50
100
200
400
pT (GeV)

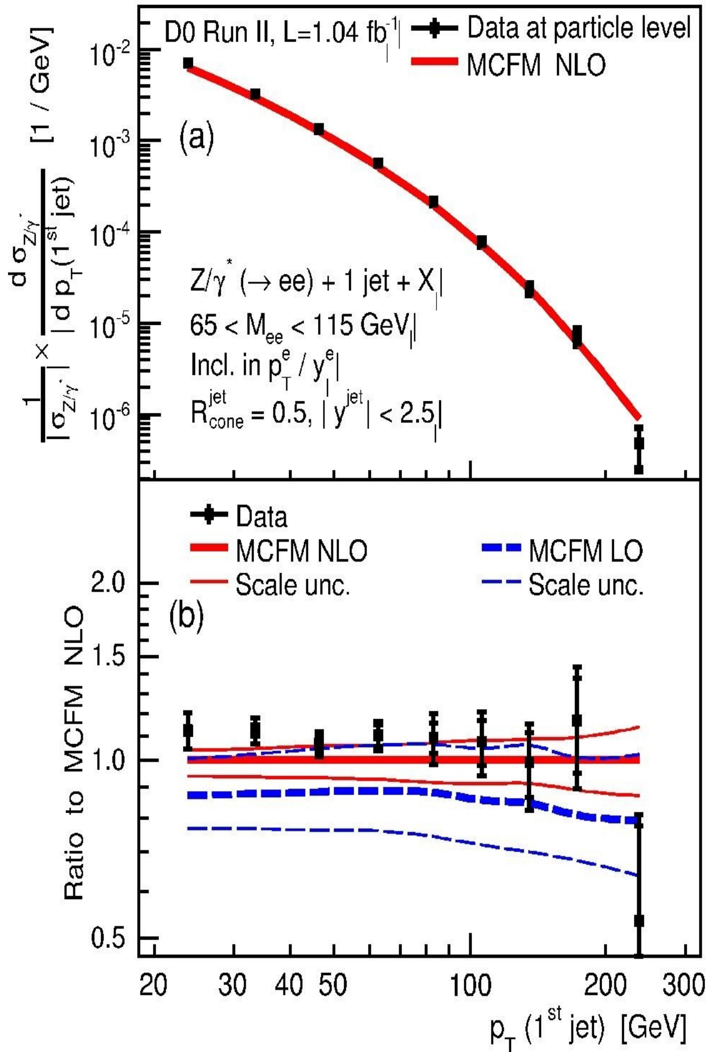
Z + jets

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

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

PLB 678, 45 (2009)

Leading jet in Z + jet + X



The differential cross section, normalised to inclusive Z production

NLO: MCFM
- CTEQ6.6M PDF
- $\mu_R^2 = \mu_F^2 = p_{TZ}^2 + M_Z^2$

Data / NLO
LO / NLO + scale uncertainties
NLO scale uncertainties

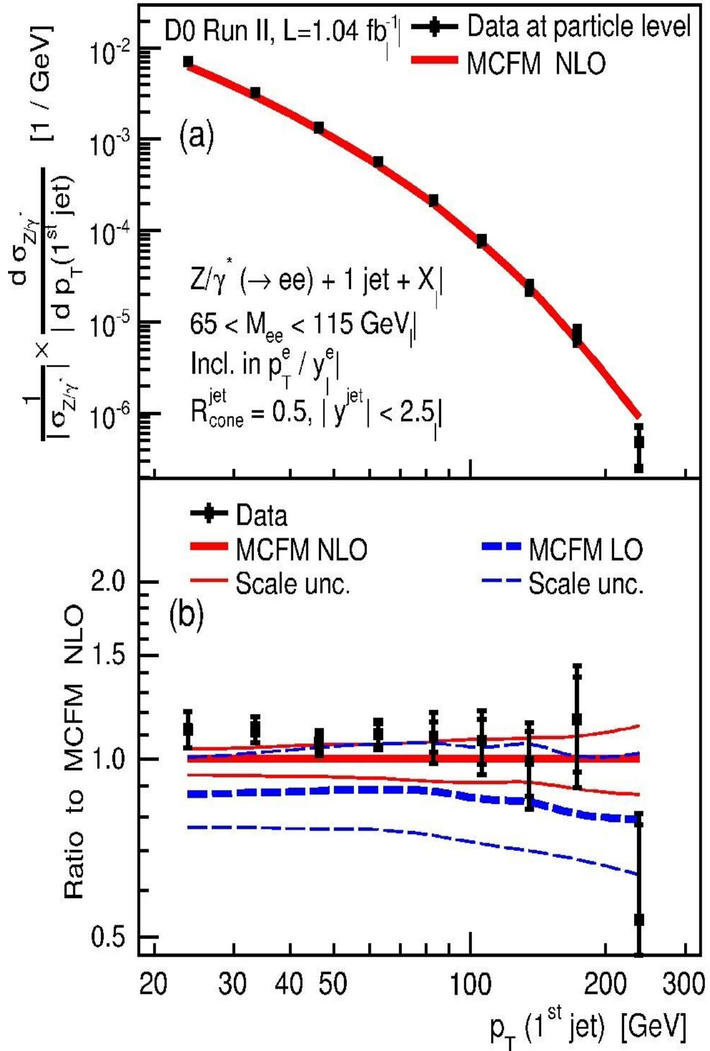
Z + jets

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

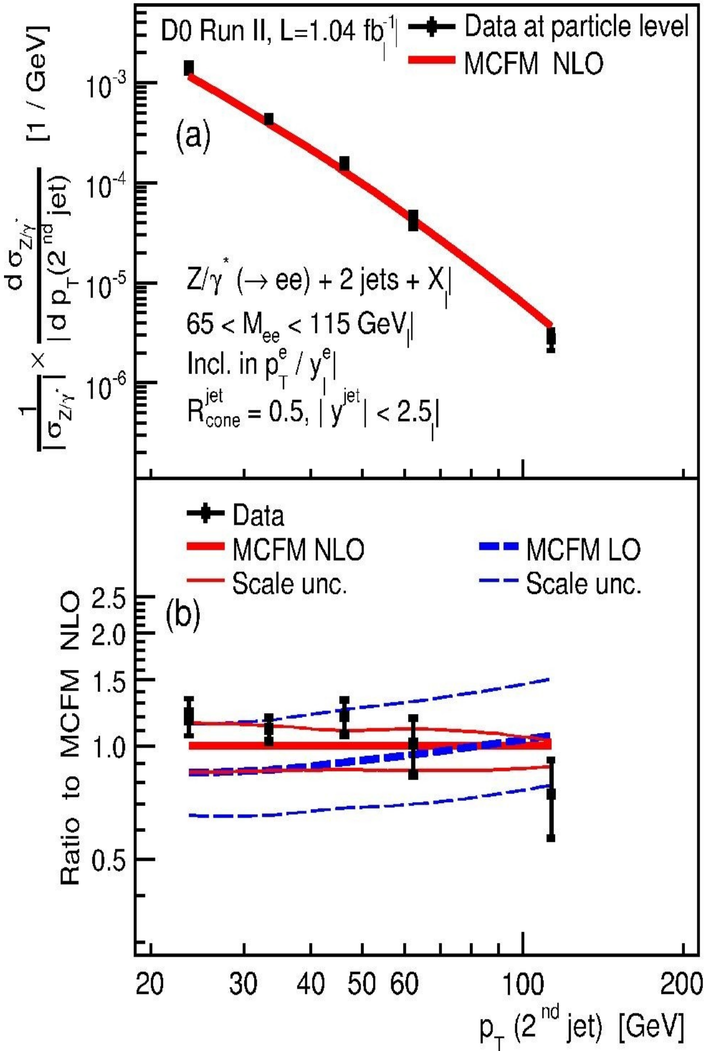
- Z→ee, jet p_T > 20 GeV, jet |y| < 2.5.
- normalize to inclusive Z production (cancel some uncertainties)

PLB 678, 45 (2009)

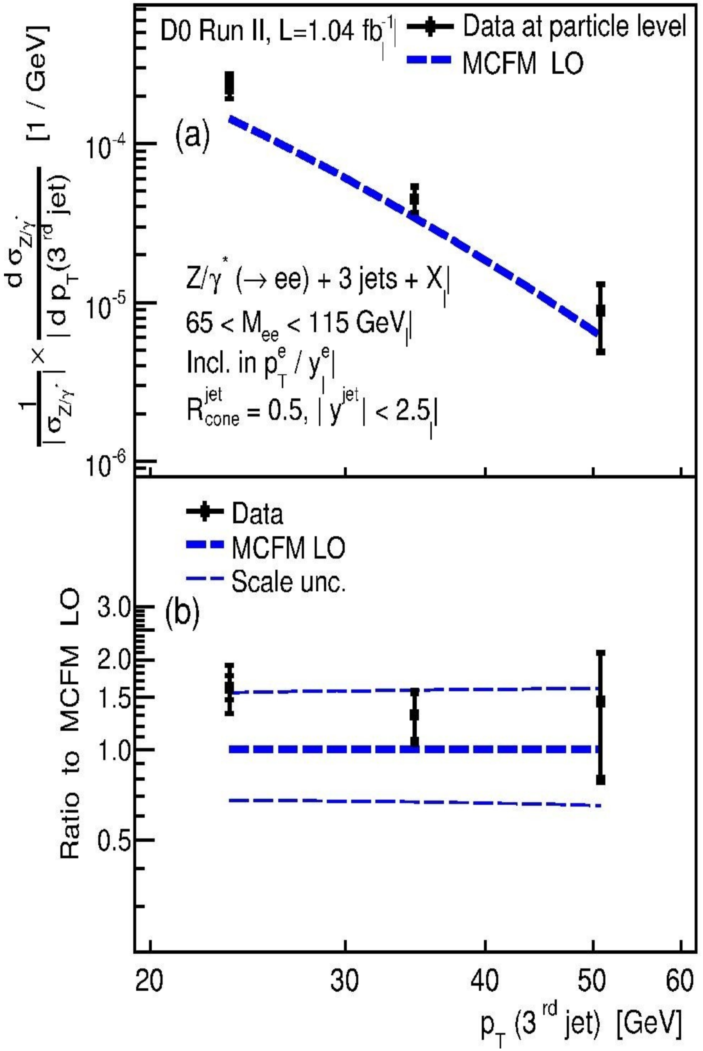
Leading jet in Z + jet + X

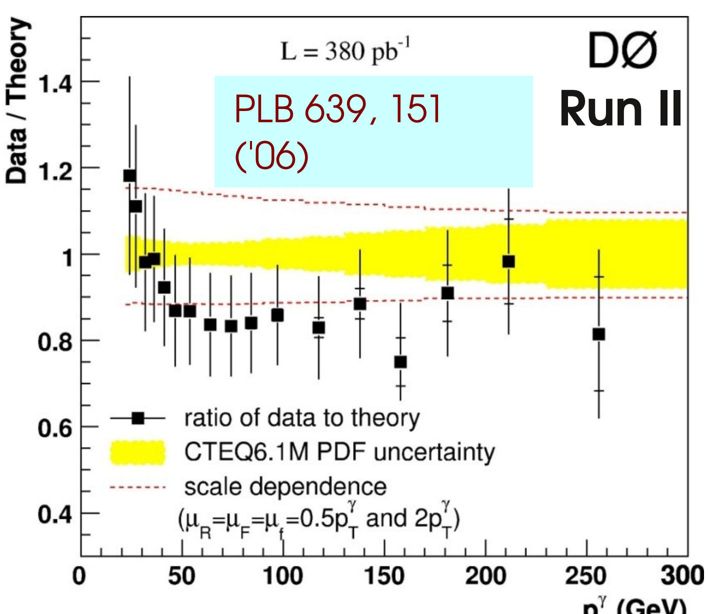


Second jet in Z + 2jet + X

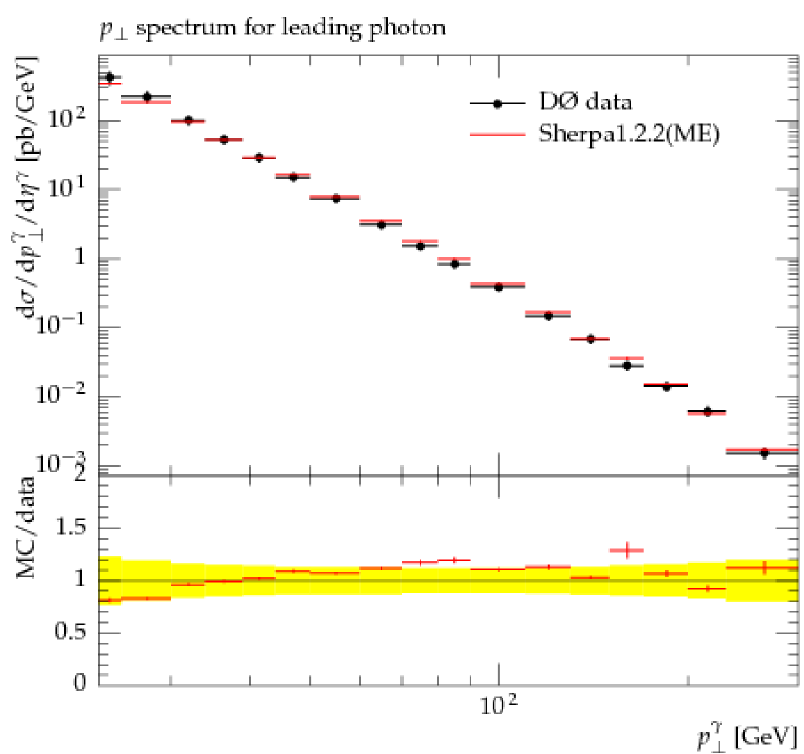


Third jet in Z + 3jet + X





Data / Theory
L = 380 pb^{-1}
DØ
Run II
PLB 639, 151 ('06)
ratio of data to theory
CTEQ6.1M PDF uncertainty
scale dependence
($\mu_R=\mu_F=\mu_f=0.5p_T^\gamma$ and $2p_T^\gamma$)
p_T^γ (GeV)



$p_\perp$ spectrum for leading photon
$d\sigma/dp_\perp^\gamma/d\eta^\gamma$ [pb/GeV]
DØ data
Sherpa1.2.2(ME)
MC/data
$p_\perp^\gamma$ [GeV]

γ + jet

Investigate further: add a jet

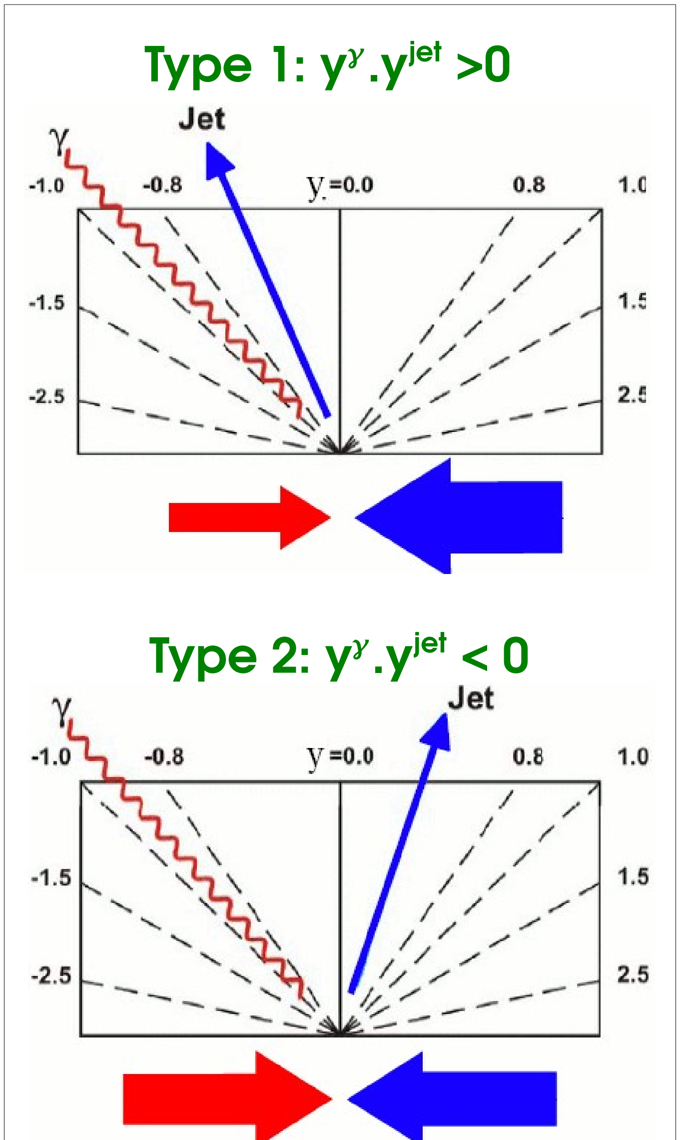
- p_T>15 GeV, $|\eta_{jet}|$<0.8, 1.5 < $|\eta_{jet}|$ < 2.5

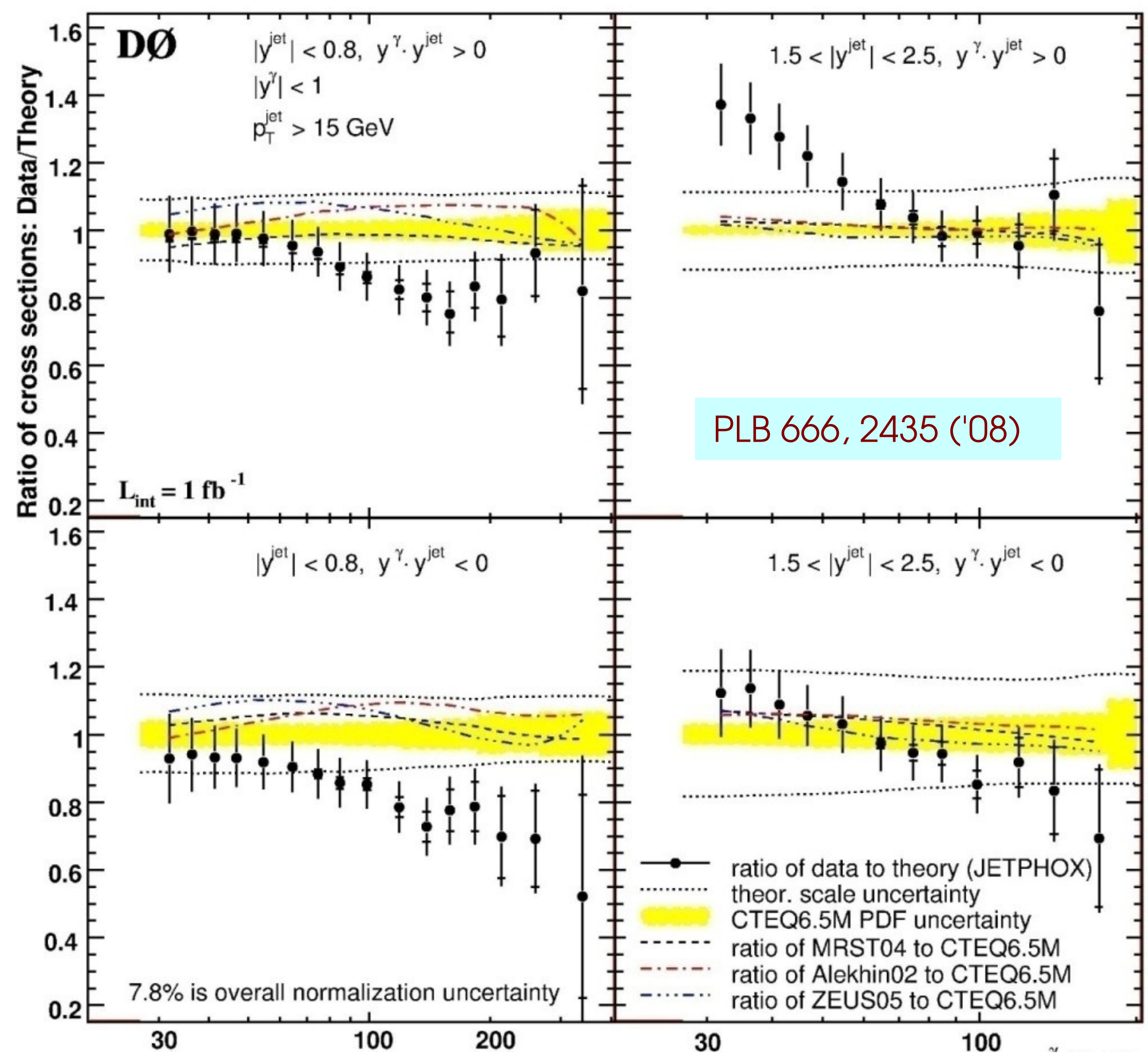
Triple differential:

- in jet η, photon η and photon p_T

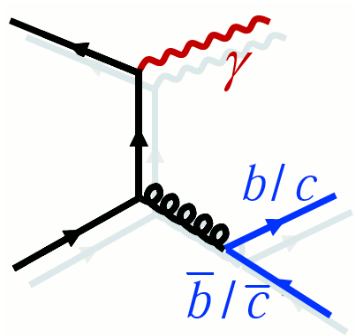
Something missing in the theory?

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



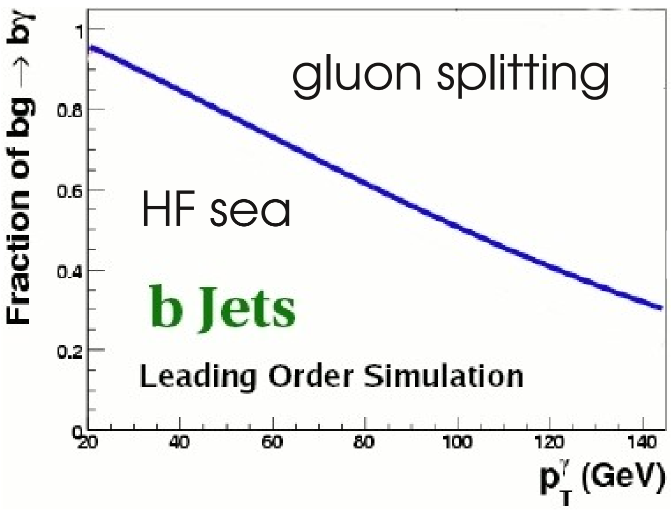


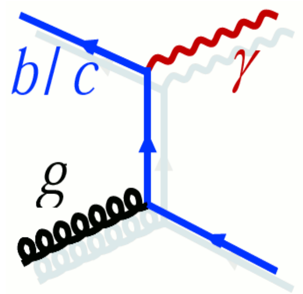
γ + Heavy Flavour



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