DZero V+jets measurement

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Fermilab, Theoretical experimental workshop
on Higgs systematics

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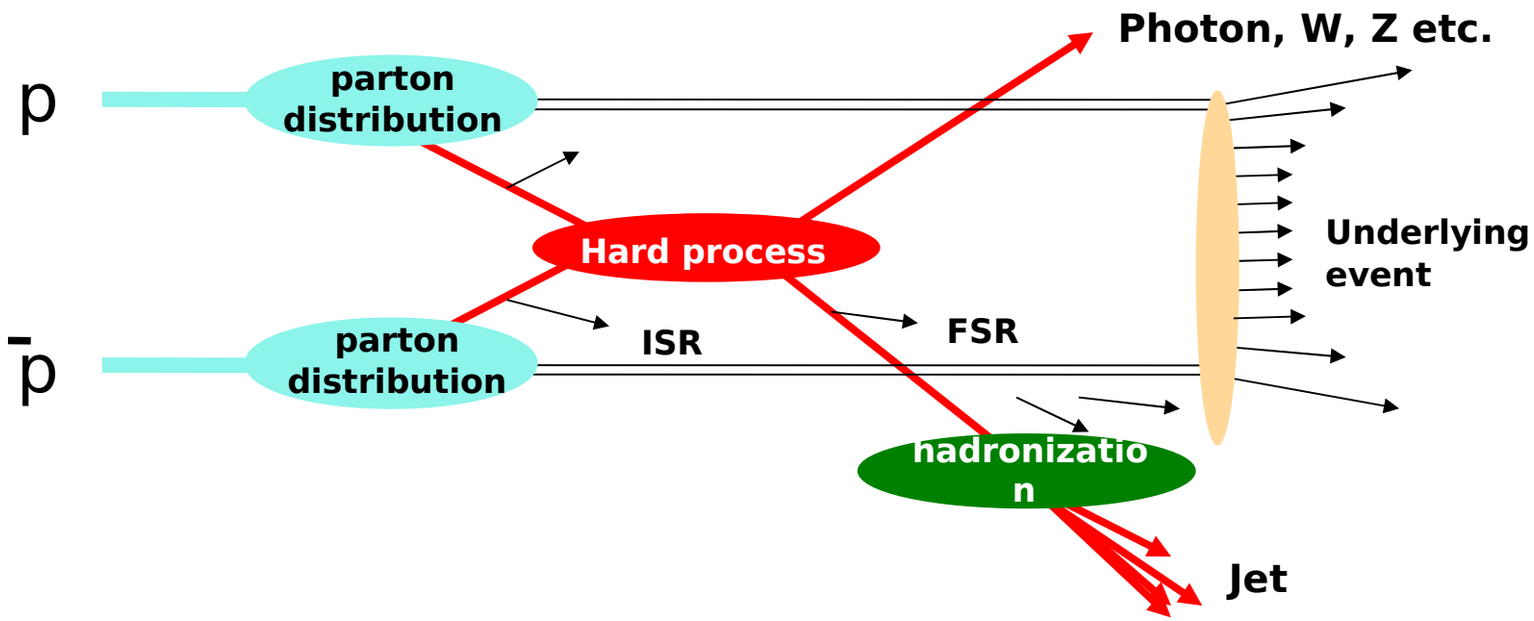
Precision QCD tests

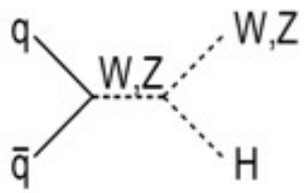


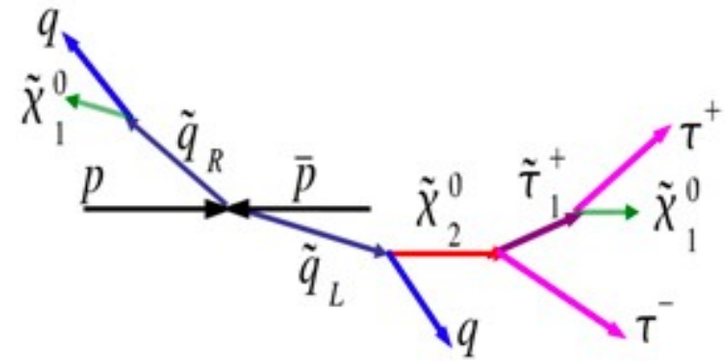
- Colorless probe of parton dynamics in V+jets final state
- Constraining the structure of the proton (gluon, s-, c- and b- quark PDFs)
- Constraining ISR/FSR and fragmentation models
- Search for new interactions

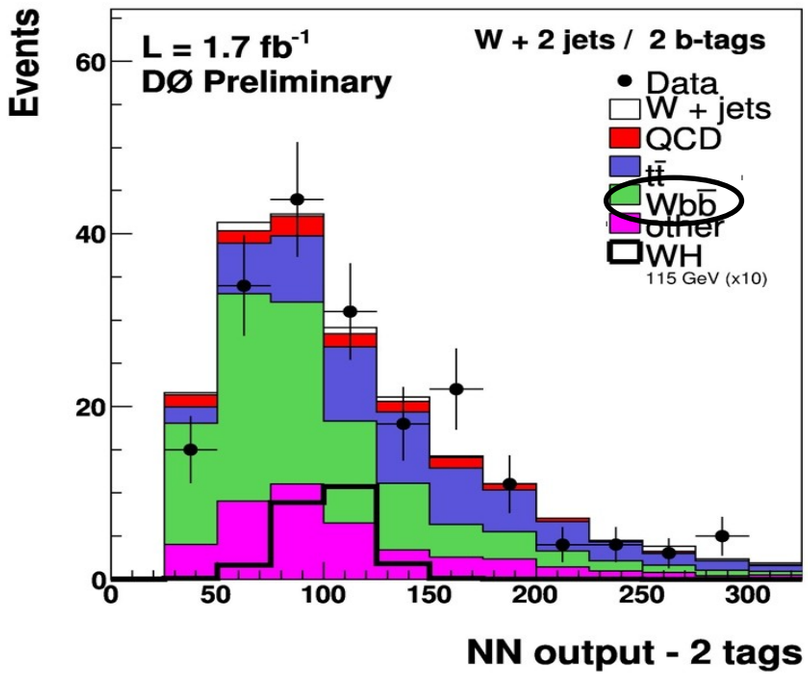
MC models are used extensively to simulate signal and backgrounds, particularly for multijet topologies. Tevatron dataset is now large enough and systematics are constrained well enough to test MC models.

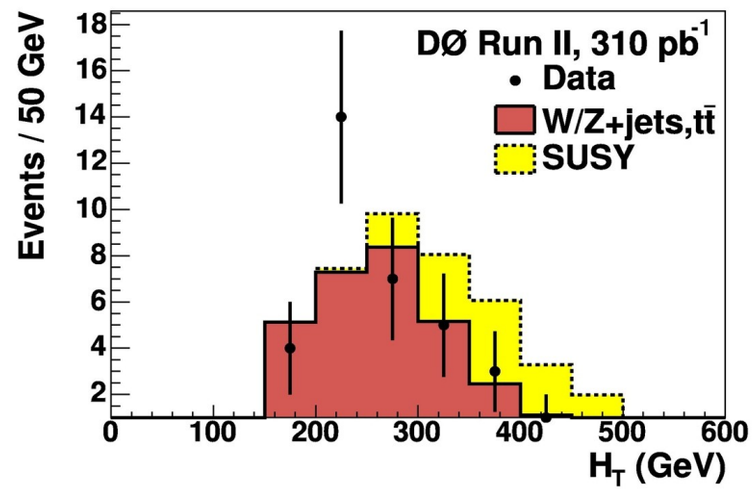
=> Precision understanding of QCD is an essential part of the Tevatron program

Backgrounds to new physics





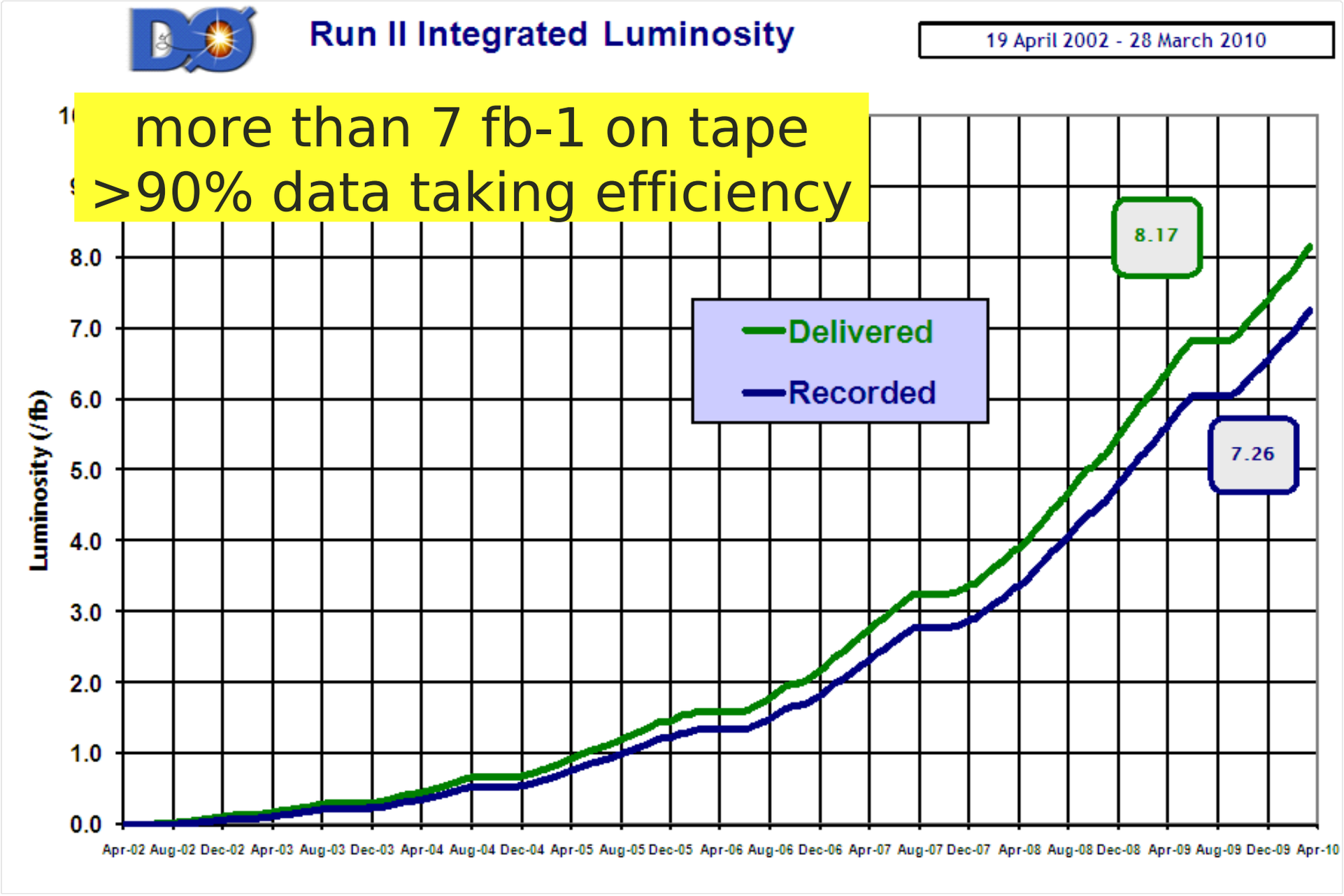




- Vector Bosons + jets events also constitute main backgrounds to top, Higgs, SUSY. SM Higgs and New Physics share signatures with irreducible V + jets backgrounds

- Interplay between fragmentation models, tunes, PDFs and scale choices needs to be understood to model SM backgrounds.

Collected D0 data



V+jets Tevatron measurements

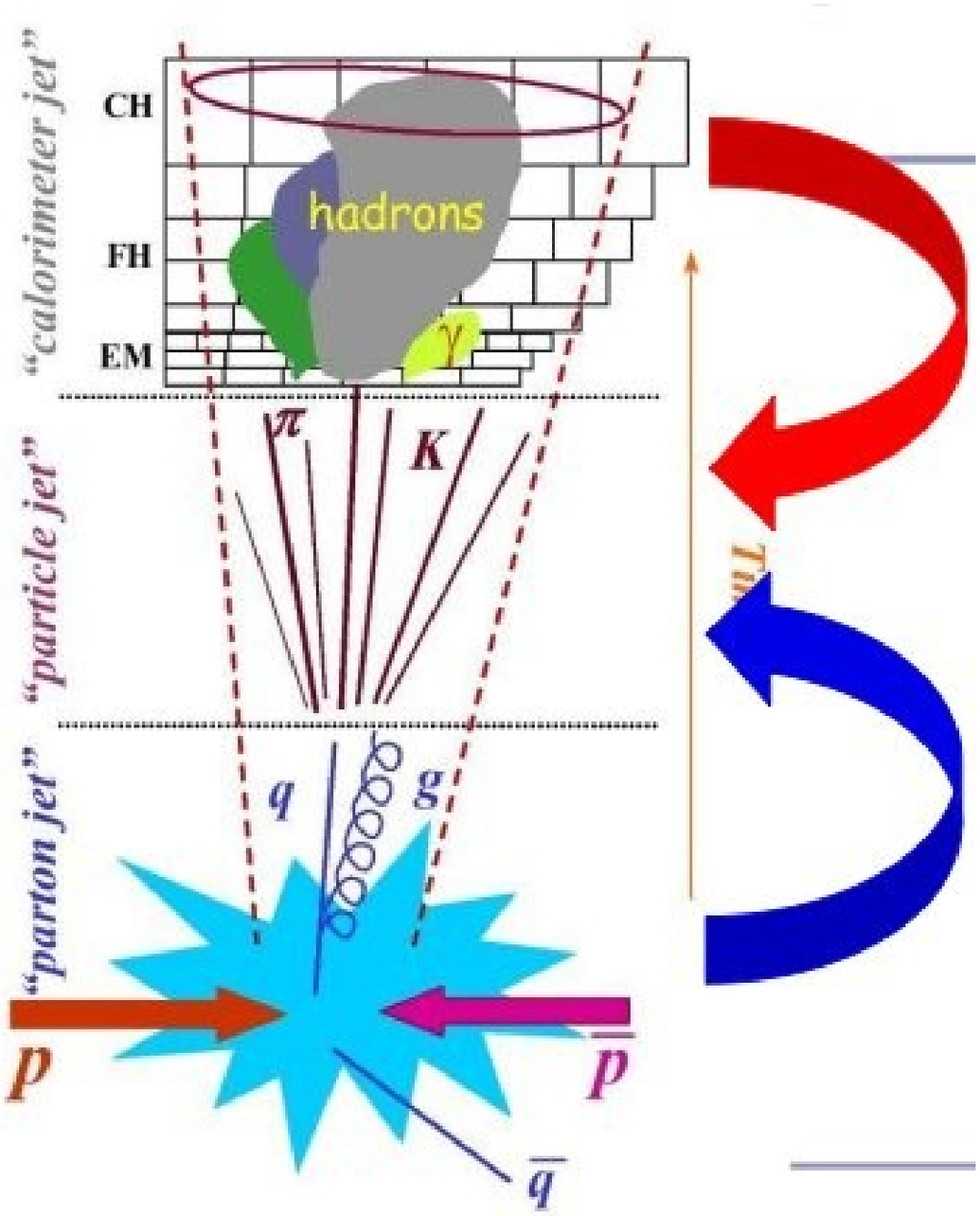
- W/Z/γ + light flavor jets
- W/Z/γ + heavy flavor jets

RunII measurements with associated luminosity

Final state	DØ	CDF
W+jets	--	0.32
Z+jets	1.0	2.5
W+b-jets	--	1.9
Z+b-jets	4.2	2.0
W+c-jets	1.0	1.8
γ+jets	1.0	--
γ+b/c jets	1.0	0.34

in black = preliminary
in red = published

Corrections to particle level



In most cases:

- data are corrected to particle level
- particle level measurements are compared to NLO theory
  NLO theory is corrected to particle level using parton shower MC

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

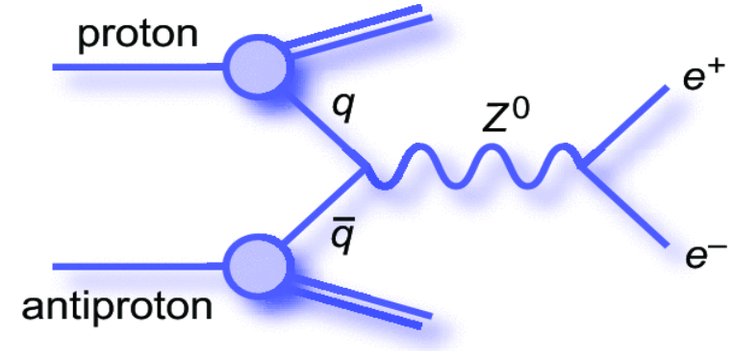
Outline

- Z+jets
- Z+b
- W+c
- γ+jets, γ+b/c

- Anticipate updates to Z+b and W+jets very soon.
- Some relevant CDF results are also mentioned.

Z+jets production (Z→$\mu\mu$)

Use leptonic (ee, $\mu\mu$) Z decays as probe of QCD
- high Q^2 (~M_Z or M_W)
- very small backgrounds, right down to very small p_T!

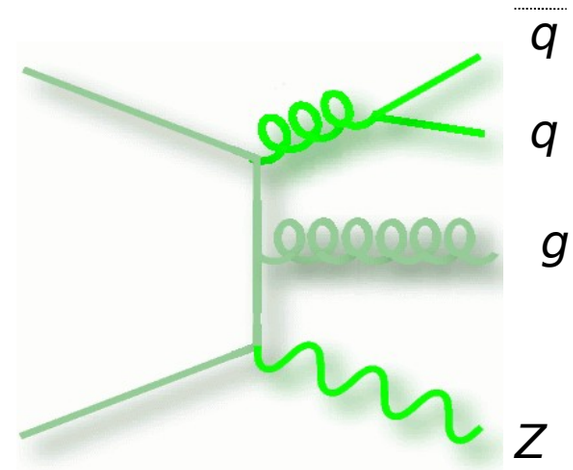


Concentrate on high pT final states: Z + jets
- regime of perturbative QCD

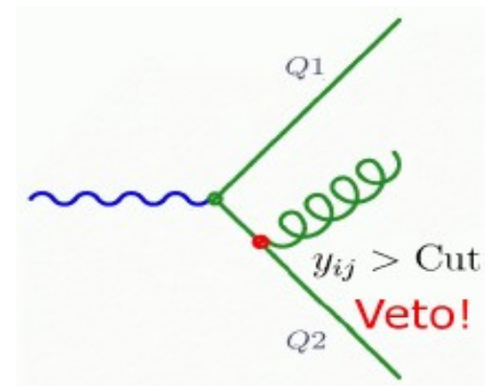
Theory predictions:

pQCD (+ corrections for underlying event & hadronization):
- LO Z(W) + 1 - 6 partons
- NLO Z(W) + 1, 2 (MCFM)

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



Event generators:
- LO 2 ->1, 2 + parton shower
  - PYTHIA, HERWIG (reweighted to Z+parton matrix element)
- LO 2 -> 1-6 + (vetoed) parton shower
  - ALPGEN (MLM ME-PS matching),
  - SHERPA (CKKW ME-PS matching)

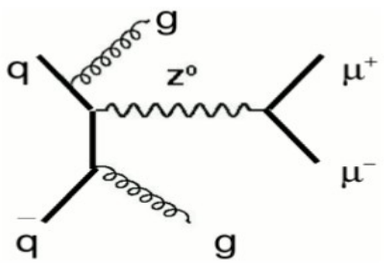


These generators are the main Tevatron and LHC tools,
- but, leading order → large uncertainties
- must to be tuned to data!

Z+jets production. Jet pT, data vs.NLO

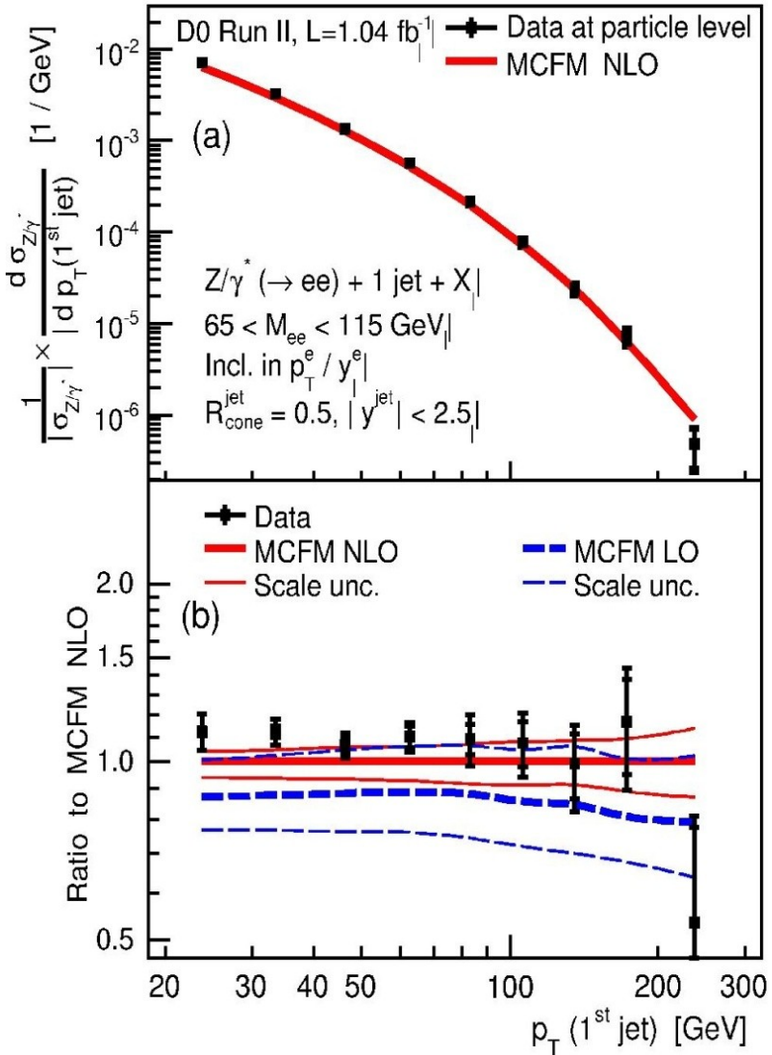
Measurement of 1st, 2nd and 3rd jet pT in Z events:

- 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



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 production. Jet pT, data vs.NLO

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

- Z→ee, jet p_T > 20 GeV, jet |y|< 2.5.
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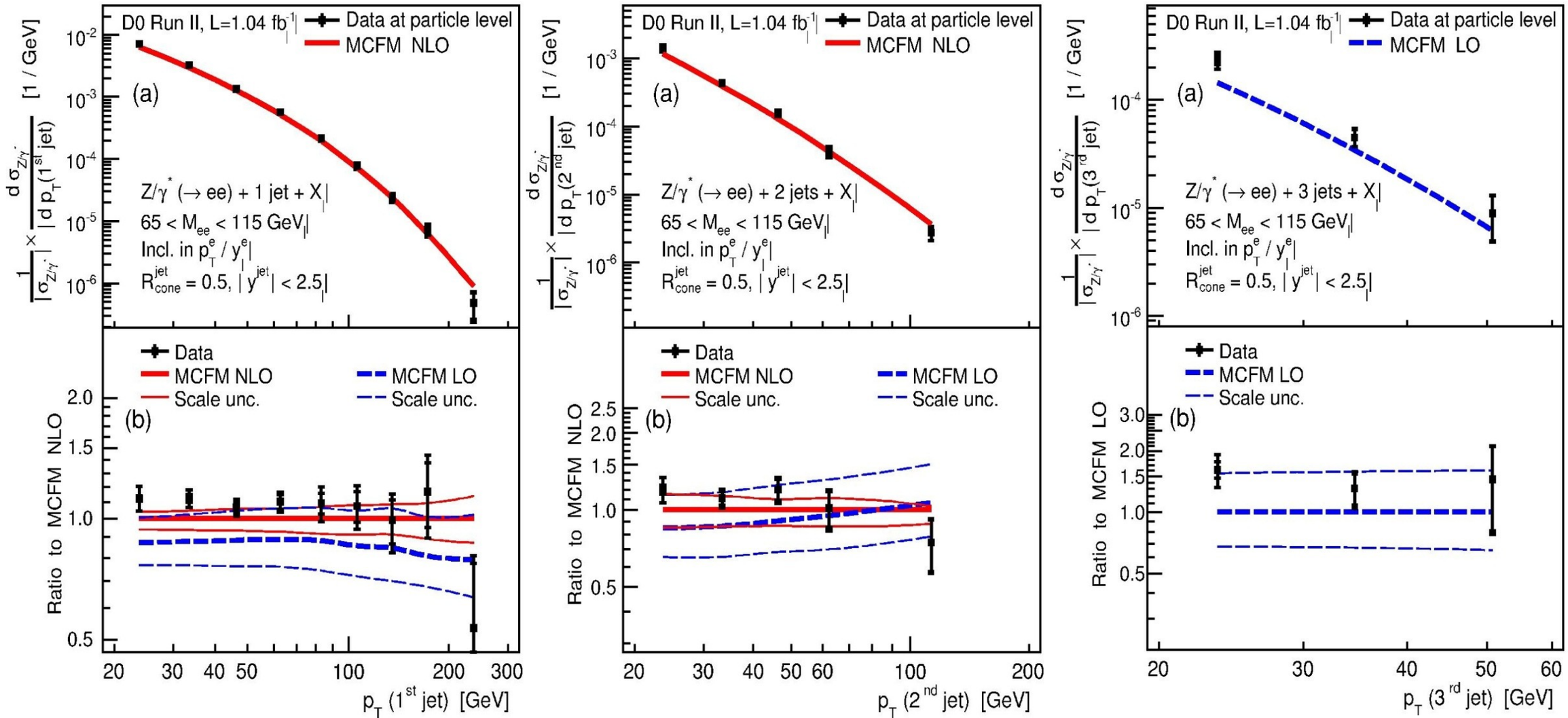
PLB 678, 45 (2009)

Leading jet in Z + jet + X **Second jet in Z + 2jet + X** **Third jet in Z + 3jet + X**

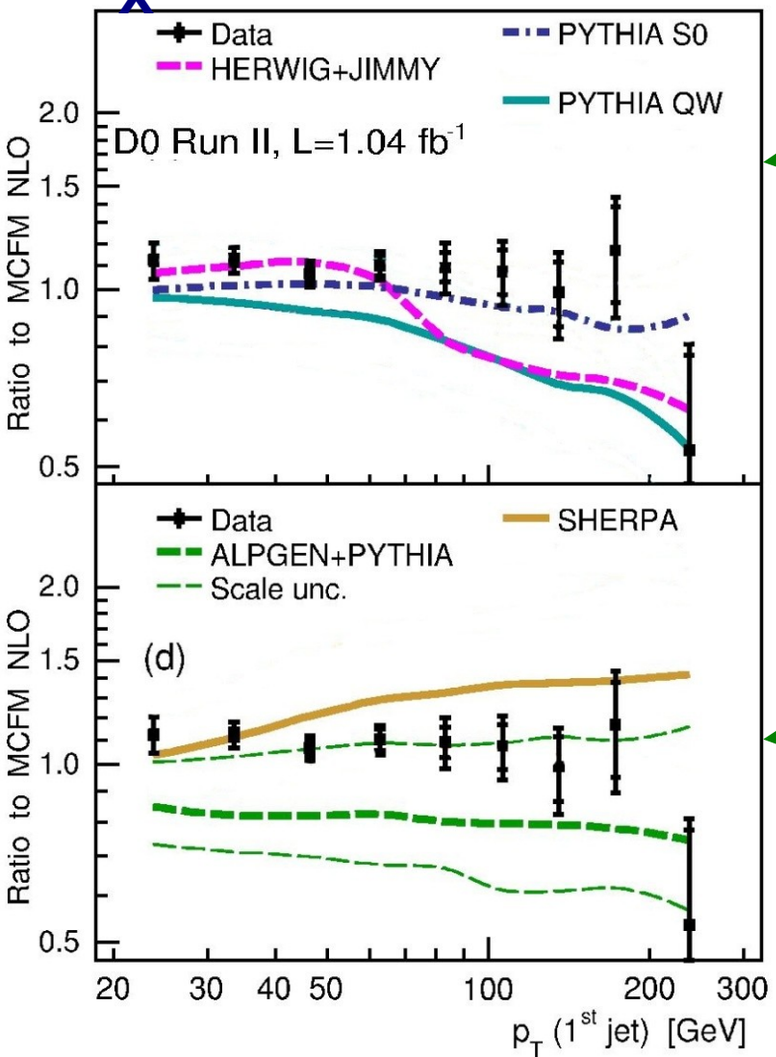


Z+jets production. Jet pT, data vs. MC

Now the event generators:

PLB 678, 45 (2009)

Leading jet in Z + jet + X



Parton Shower MC:

- **PYTHIA p_T ordered shower / NLO**
- **PYTHIA Q^2 ordered shower / NLO**
- **HERWIG / NLO**

Matrix element + Parton Shower MC:

- **ALPGEN+PYTHIA / NLO** + scale unc.

  $\mu_F^2 = p_{TZ}^2 + M_Z^2$
- **SHERPA / NLO**

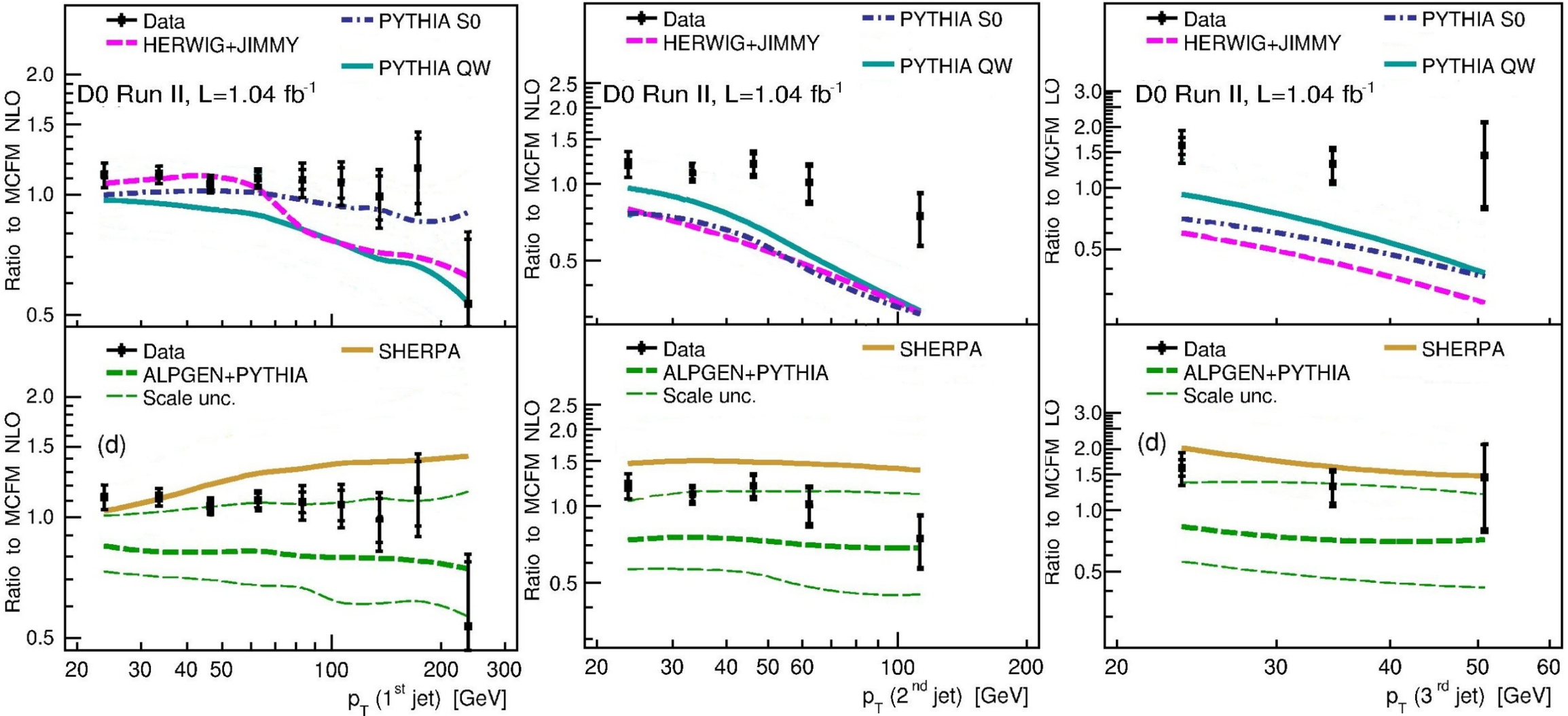
Z+jets production. Jet pT, data vs. MC

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

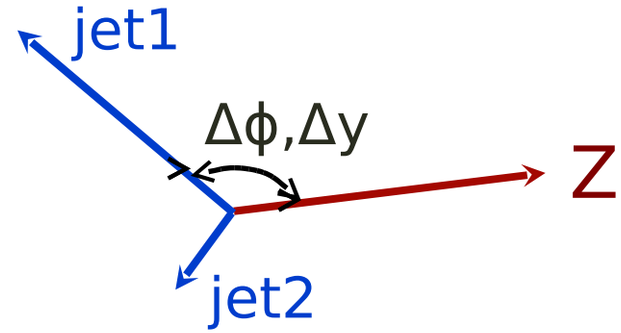
- best description from ALPGEN with lower scale (default: $\mu_F^2 = p_{TZ}^2 + M_Z^2$).

PLB 678, 45 (2009)

Leading jet in Z + jet + X **Second jet in Z + 2jet + X** **Third jet in Z + 3jet + X**



Z+jets production. Z-jet Angles



Further constrain the kinematics:

- look at angles between the Z and leading jet
- first measurements at a hadron collider of:
  - $\Delta\phi$(Z, jet), $|\Delta y$ (Z, jet)$|$, $|y_{boost}$(Z, jet)$| = |½ (y_1 + y_2)|$

Take a closer look at $\Delta\phi$(Z, jet):

- trivial in the absence of additional jets
- LO pQCD corrections come from Z + 2 jets (at LO)
- NLO pQCD corrections from Z + 3 jets

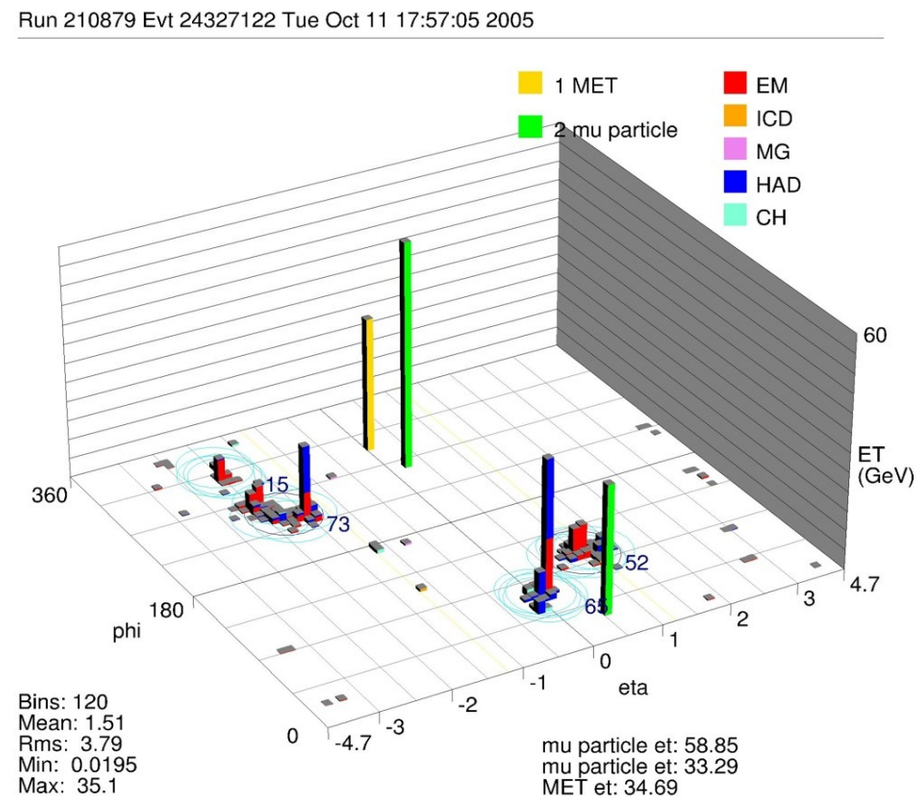
To get a meaningful measurement of ϕ(Z), require:

- Z p_T > 25 and > 45 GeV

(Below this, dominated by muon p_T resolution)

$|\Delta y$ (Z, jet)$|$, $|y_{boost}$(Z, jet)$|$ dominated by PDF contribution

- but still sensitive to additional radiation

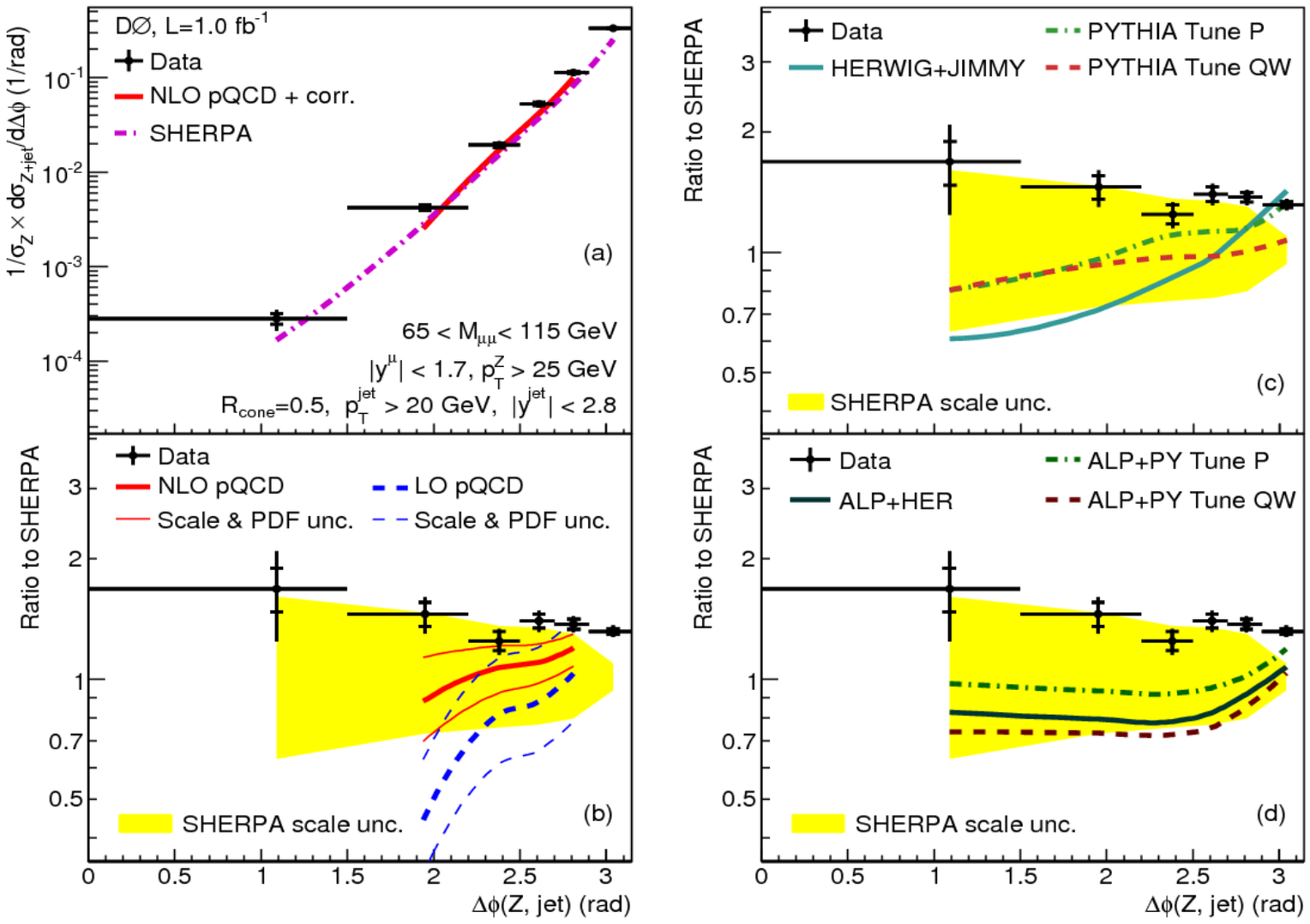


Z+jets production. Δϕ(Z,jet)

First measurement of $\Delta\phi$(Z, jet) !

- $Z \to \mu\mu$, $|y_\mu|<1.7$, $p_{TZ} > 25$ GeV
- jet $p_T>20$ GeV, |jet y| < 2.8

PLB 682, 370 (2010)



PYTHIA p_T ordered
- new "Perugia" tune
- MRST07 LO* PDF
PYTHIA Q^2 ordered
HERWIG

ALPGEN + PYTHIA p_T
ALPGEN + PYTHIA Q^2
ALPGEN + HERWIG

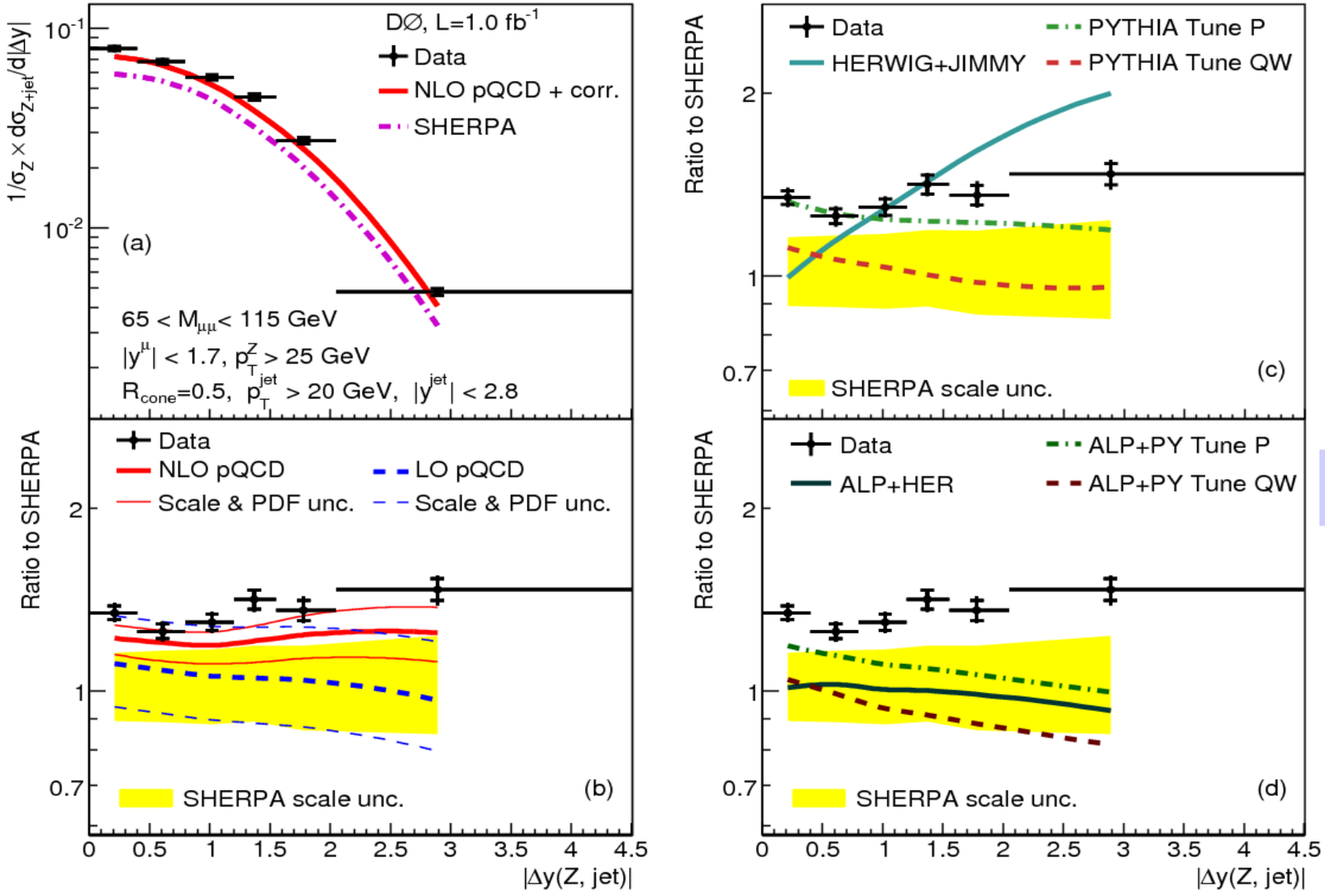
- Sherpa describes Δϕ(Z,jet) shape very well (but a normalization issue)

- Small values of Δϕ are excluded from MCFM due to significant non-perturbative contributions

Z+jets production. Δy(Z,jet)

First measurement of Δy(Z, jet) !

- $Z \to \mu\mu$, $|y_\mu|<1.7$, $p_{TZ} > 25$ GeV
- jet $p_T>20$ GeV, |jet y| < 2.8



PYTHIA p_T ordered
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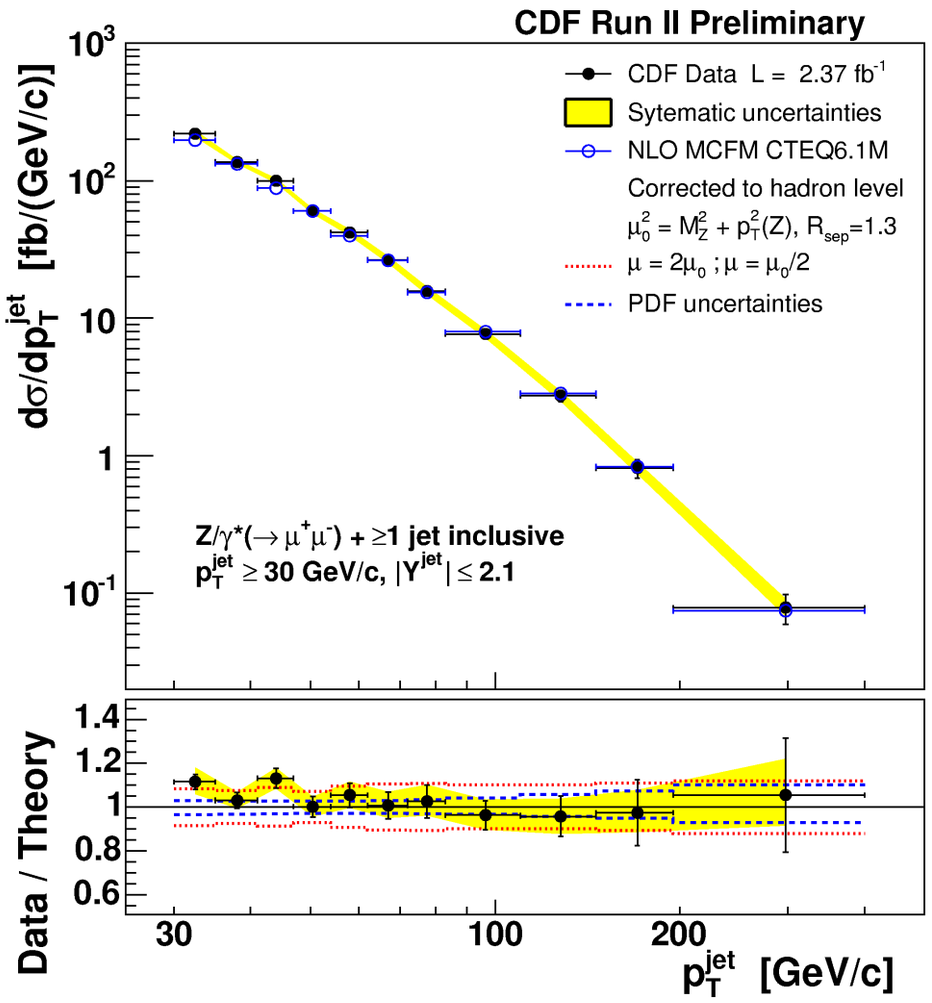
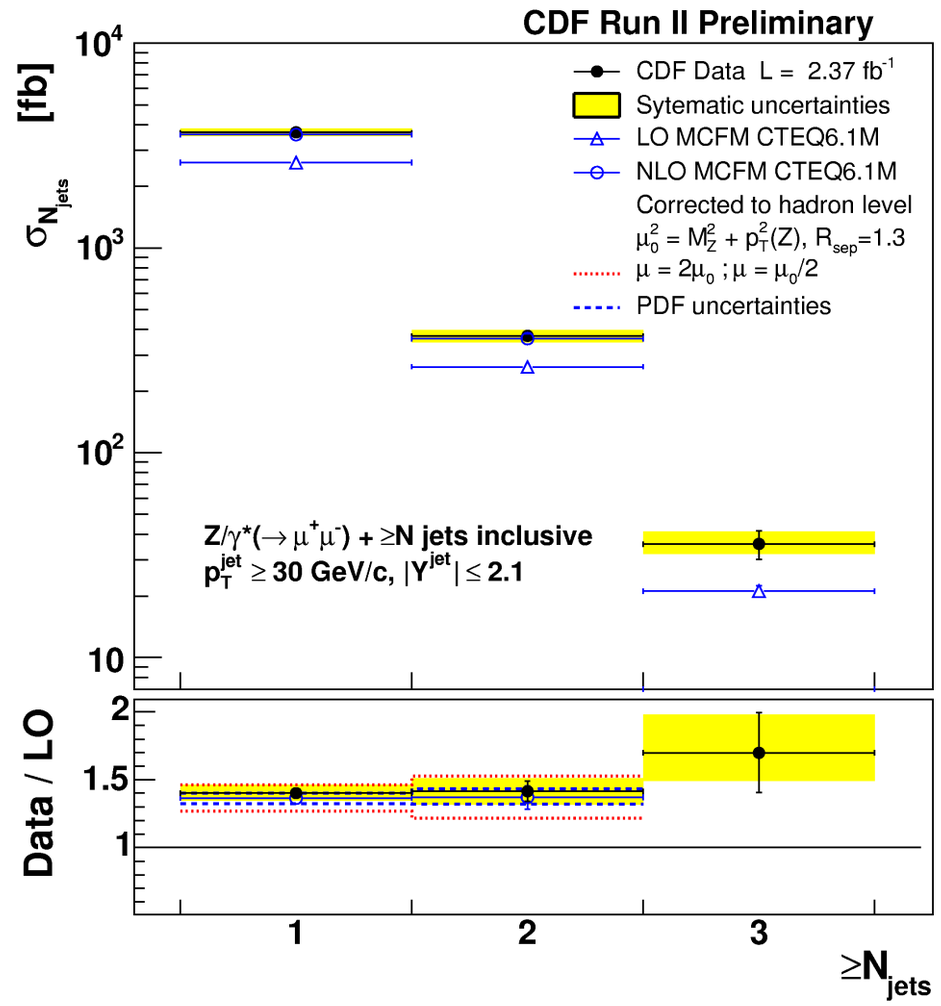
HERWIG

ALPGEN + PYTHIA p_T
ALPGEN + PYTHIA Q^2
ALPGEN + HERWIG

Sherpa, NLO describe Δy

Z+jets production, CDF

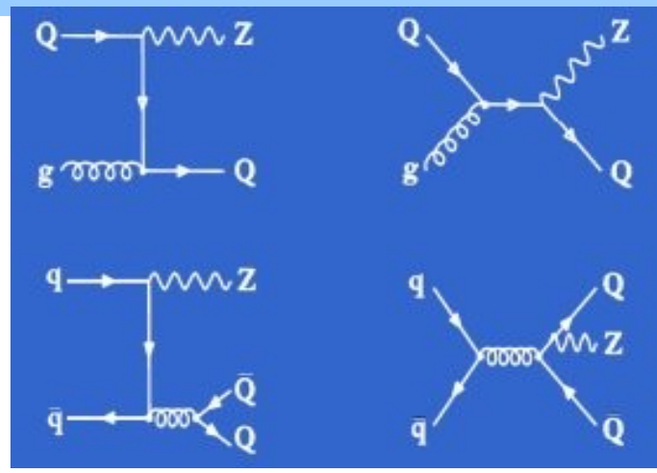




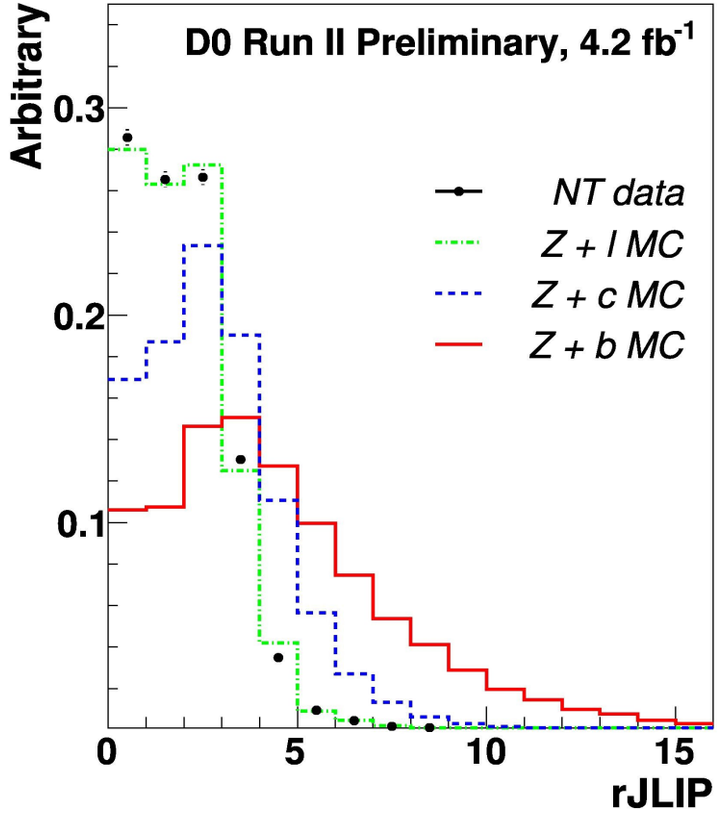
- These results complement previous ones at L=1.7 fb-1 (Z → ee)
- Good agreement with QCD NLO

σ(Z+b) / σ(Z+jet), D0

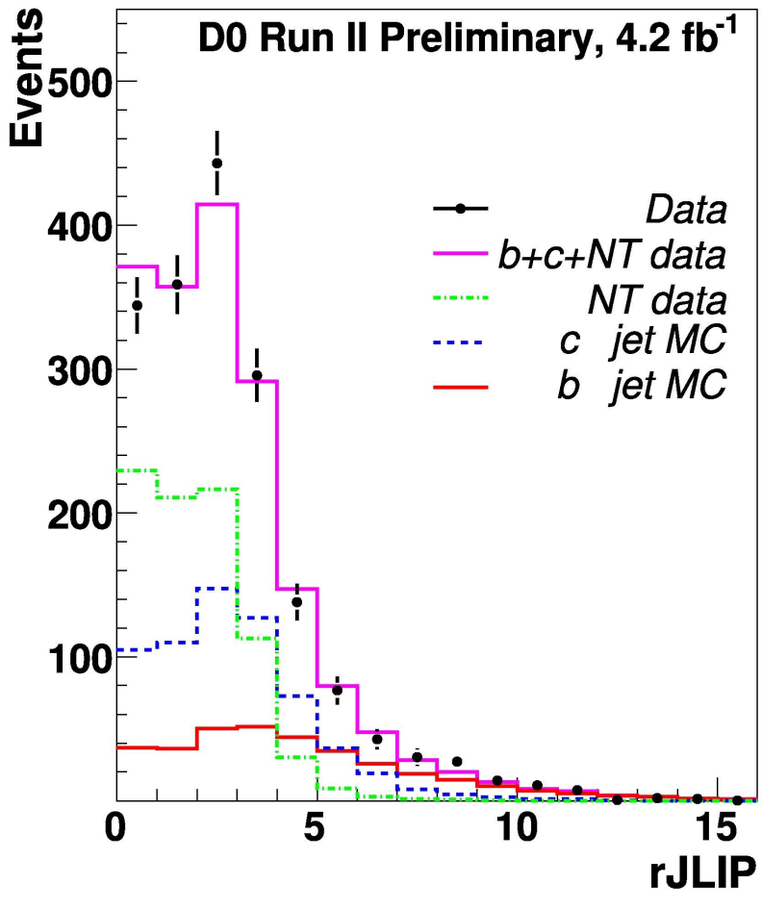
- Important background to the SM Higgs search in the ZH channel.
- Probe of b-quark PDF, important for gb → Hb & single-top studies
- Measurement of ratio σ(Z+b) / σ(Z+j) benefits from cancellations of many systematics => precise comparison with theory

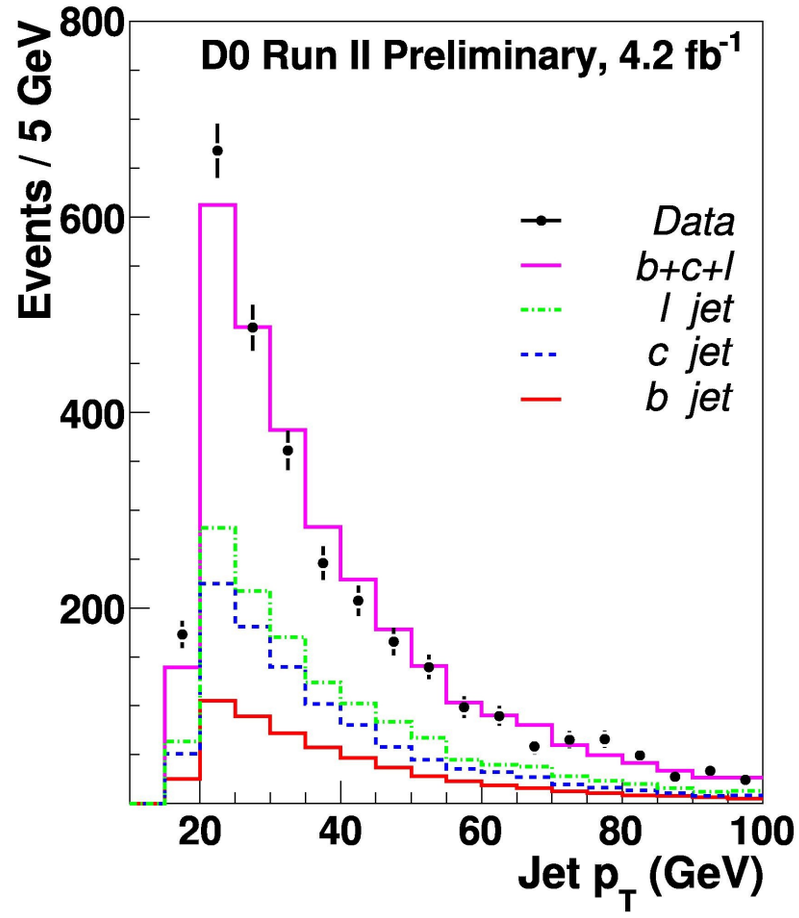


- L = 4.2 fb-1
- Z → ee/μμ + b + X
  70 < mZ < 110 GeV
- lepton p_T > 15 GeV
- D0 RunII Midpoint Cone jets with R=0.5
- jet p_T > 20 GeV
- jet |η| < 1.0
- Secondary vertex tagging
  → Apply Neural Network algorithm on jets to enrich with b-jets (NNout > 0.5)
  → Use a longer b-hadron lifetime to discriminate between b/c/light jets (rJLIP)
- Use data for light jet template, Pythya+Alpgen for b & c jets
- Use log likelihood fit to extract b- jets fractions



σ(Z+b) / σ(Z+jet)





Z+b/Z+jet ratio	0.0176±0.0024±0.0023

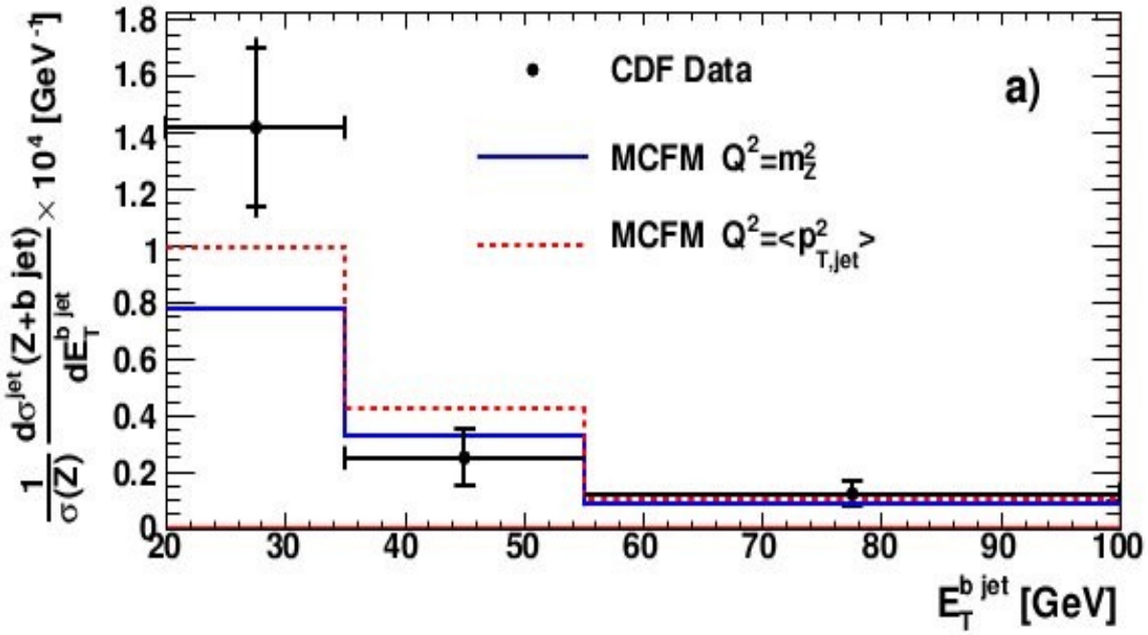
Consistent with NLO theory: 0.0184 +/- 0.0022 (MCFM)

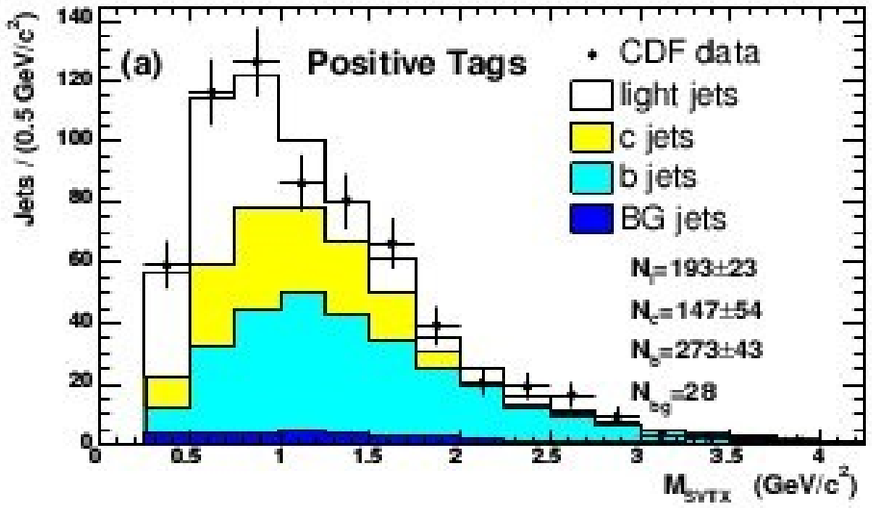
Z+b production, CDF

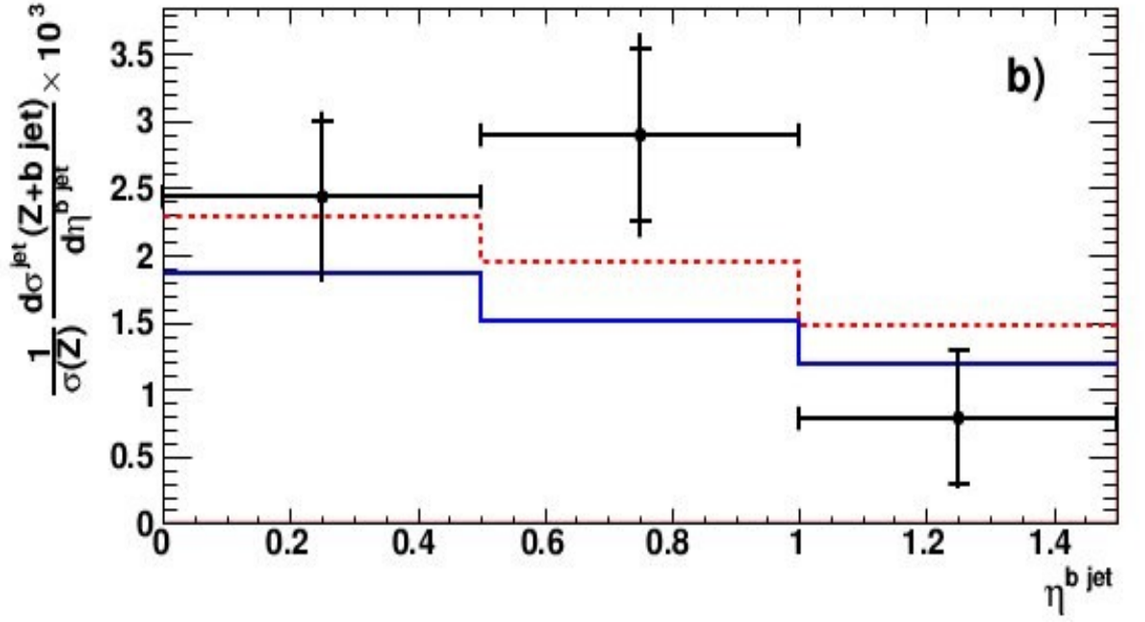
PRD79, 052008 (2009)

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

Theory:
- MCFM : all calculations are at O(a_s^2)
- Pythia, Alpgen







σ(Z+b) / σ(Z) and σ(Z+b) / σ(Z+jet), CDF

σ(Z+b) / σ(Z)

Data: [3.32± 0.53(stat)±0.42(syst)]*10^-3

MCFM
2.3*10^-3 / 2.8*10^-3
for Q^2=mZ^2 / <pTjet^2>
Alpgen: 2.1*10^-3
Pythia: 3.5 * 10^-5

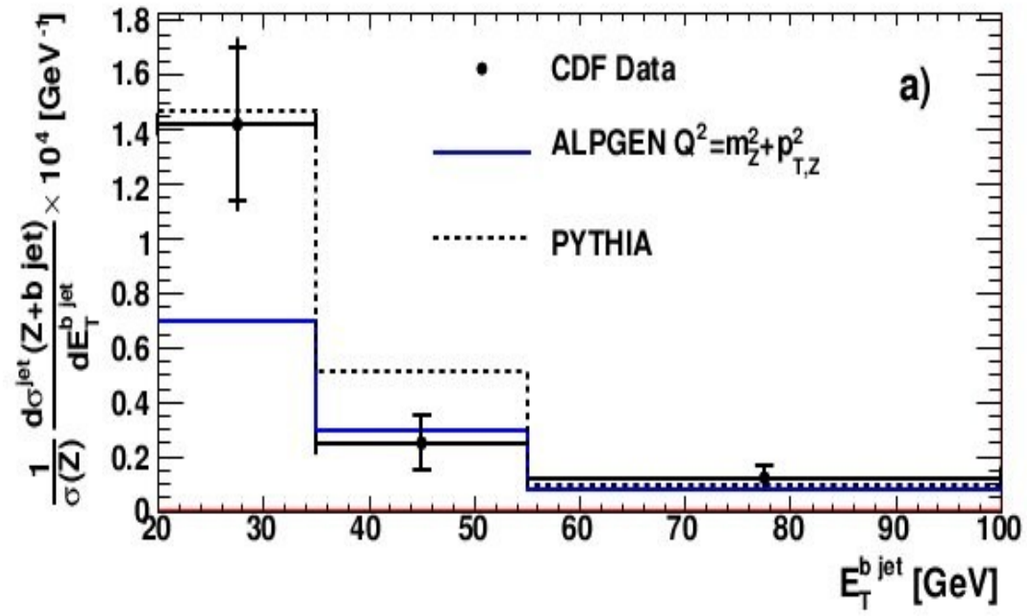
σ(Z+b) / σ(Z+jet)

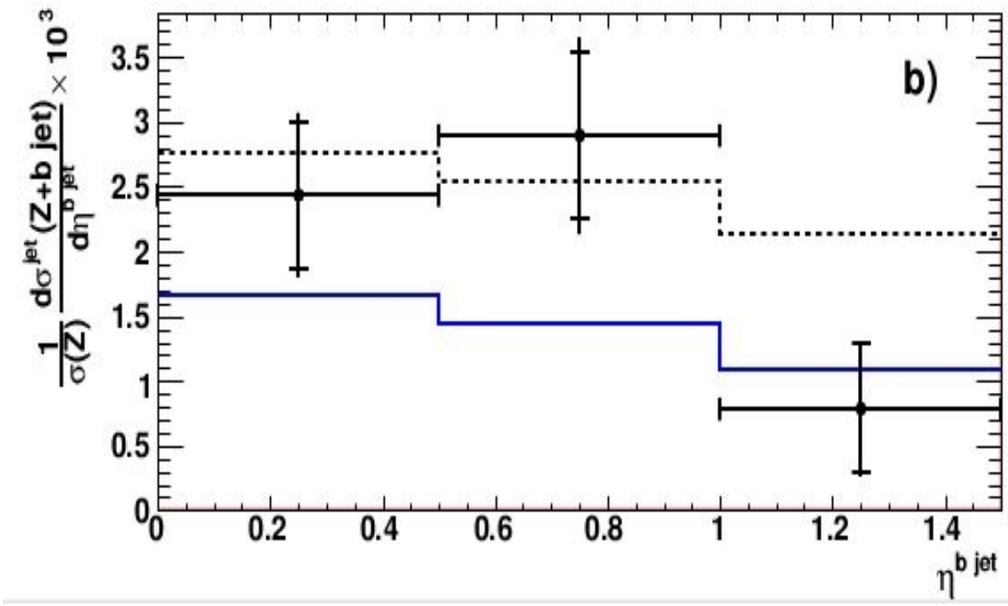
Data: 2.08 ± 0.33(stat)±0.34(syst)

MCFM: 1.8% / 2.2%
Alpgen: 1.5%
Pythia: 2.2%

σ(Z+b):

Data: 0.85 ±0.14(stat)±0.12(syst) pb
MCFM: 0.45±0.01 pb
(PRD69, 074021, 2004)



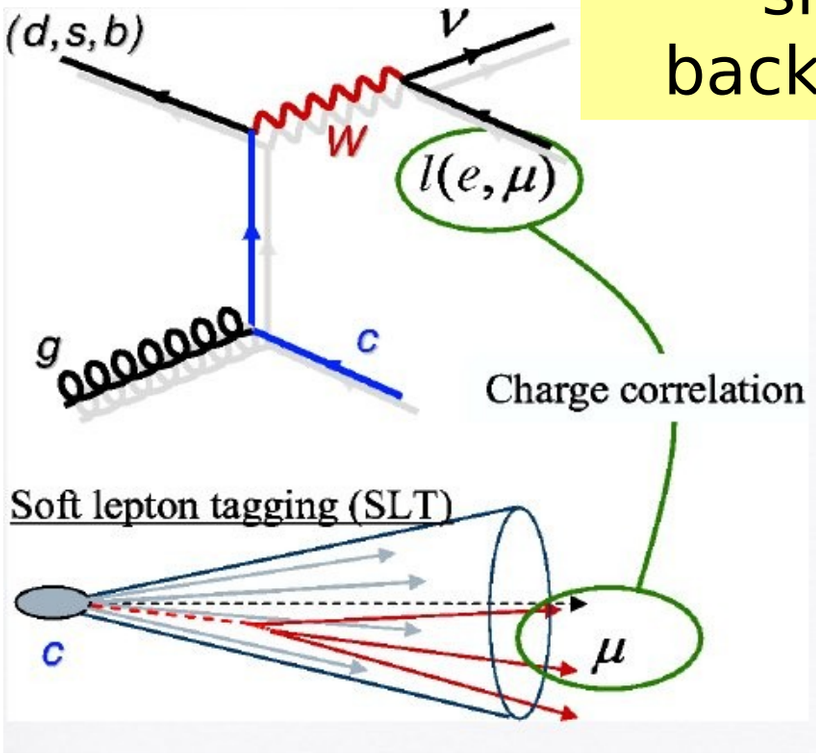


σ(W+c)/σ(W+jet)

Sensitive to s-quark PDF

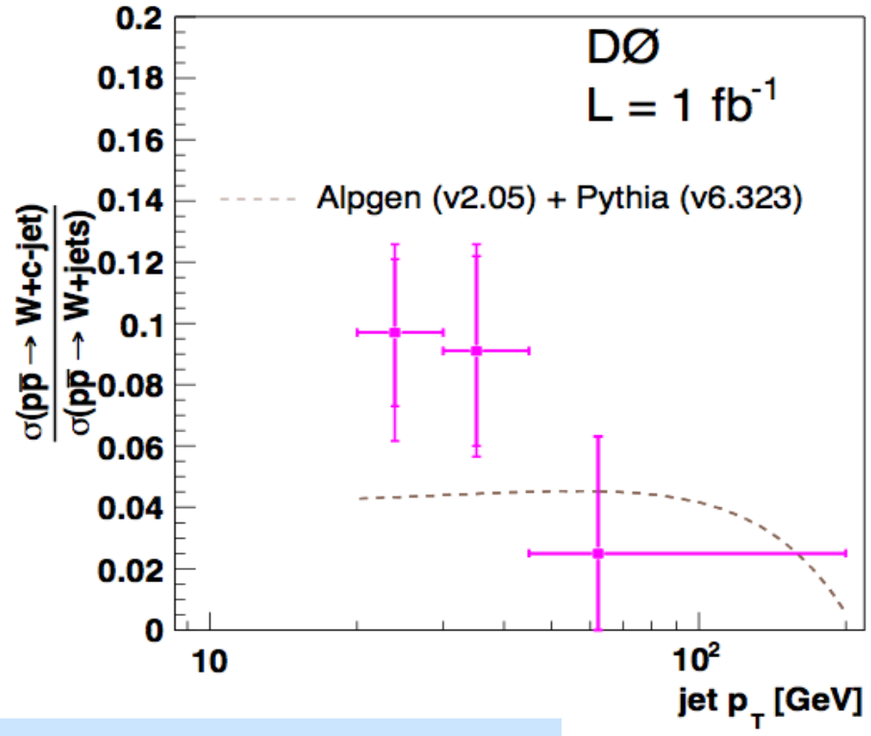
90% s, 10% d

signal: OS>>SS
backgrounds: OS~SS



Phys.Lett.B666:23-30 (2008)

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



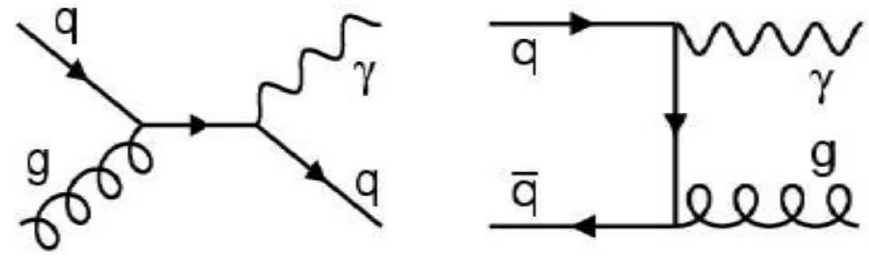
Data: 0.074 ± 0.019 (stat) ± $^{+0.012}_{-0.014}$ (sys)
Alpgen+Pythia: 0.044±0.003

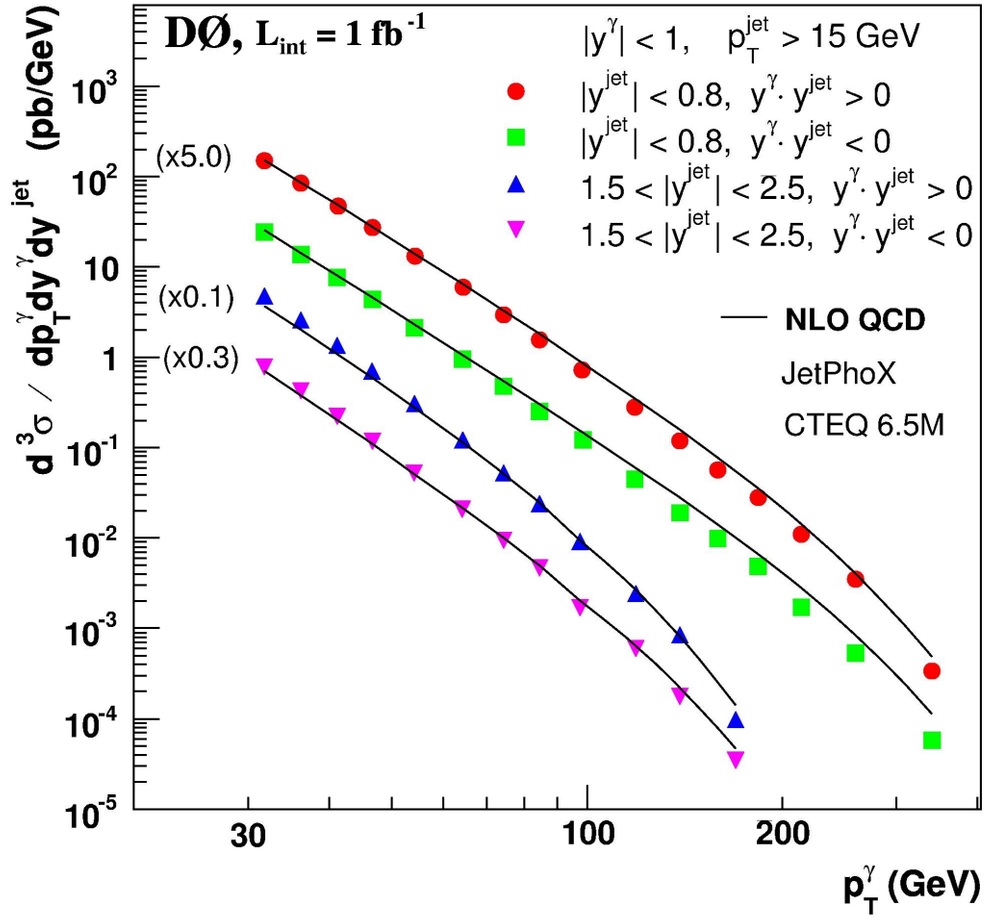
CDF: σ(W+c)*Br(W-> lnu):
9.8±3.2 pb with QCD NLO: 11.0 +1.4/ -3.0 pb (1.8 fb-1, PRL 2008)
However, preliminary recent 2010 result for a larger phase space:
33.7±11.4 (stat)±4.7 (syst) pb with QCD NLO: 17.8 +1.7 pb (4.3 fb-1)

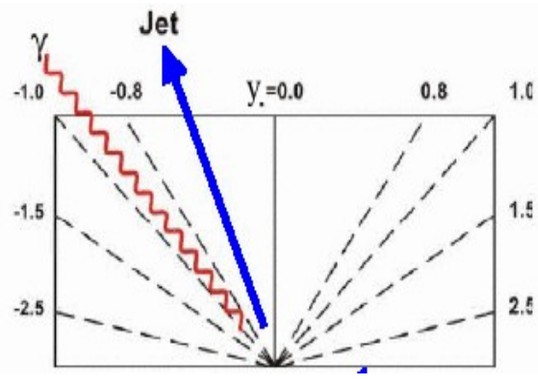
Photon+jet production

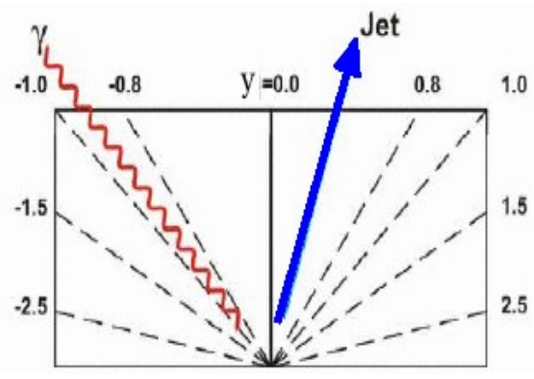
Phys.Lett.B666, 2008

- Much higher statistics than in W/Z+jets final state allows to measure triple differential cross sections:
  - in photon pT and jet & photon y
  - tag photon and jet
  - reconstruct full event kinematics
- measure in 4 regions of y_γ, y_{jet}
  - photon: central ($|\eta|<1$)
  - jet: central / forward
  - same side / opposite side
- Dominant production at low p_T^γ (< 120 GeV) is through Compton scattering: $qg \rightarrow q+g$
- Probe PDF's in **0.007<x< 0.8** and **900<Q²<1.6x10⁵ GeV²**

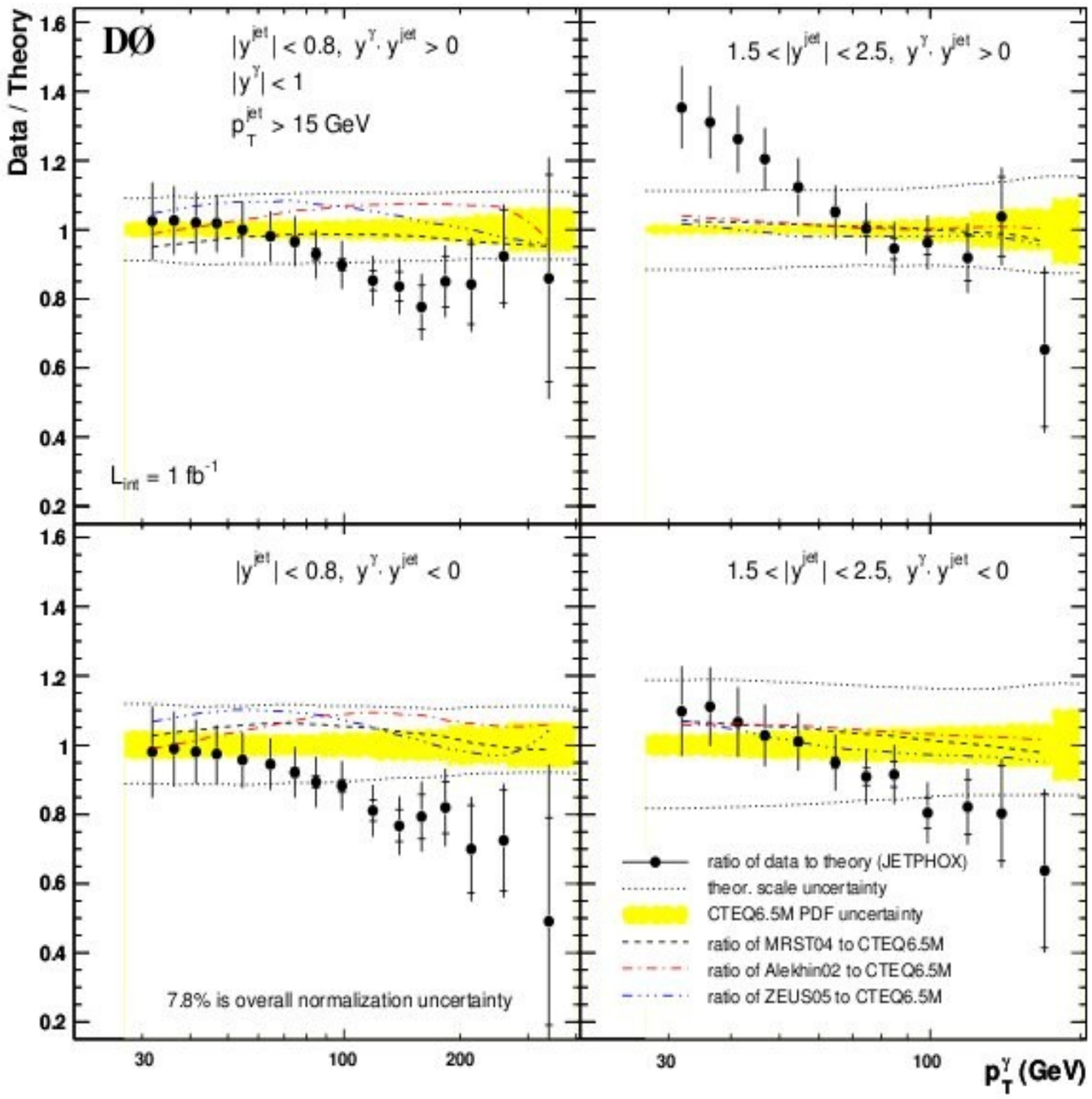






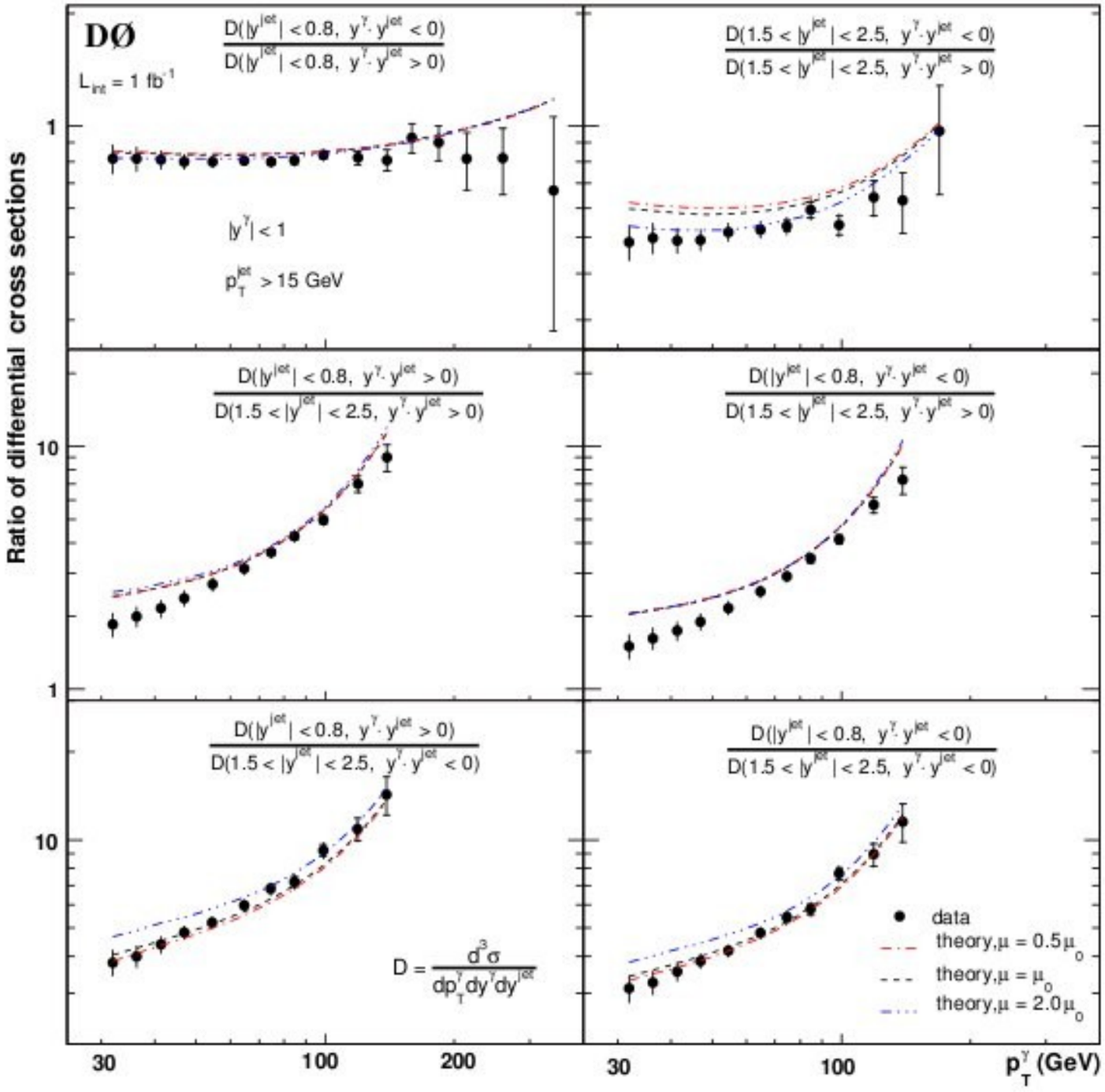


Photon+jet production



All shapes cannot be easily accommodated by any single theory

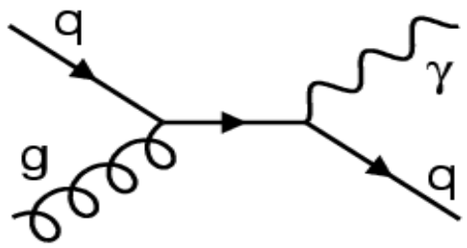
Photon+jet production

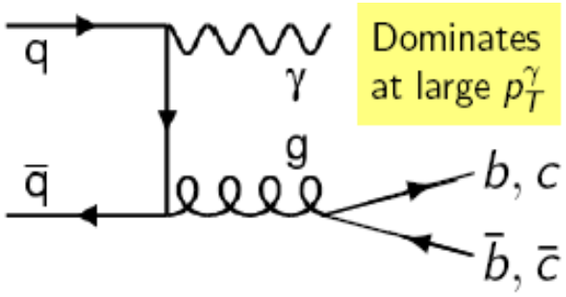


- Most errors cancel in ratios between regions (3-9% across most p_T^{γ} range)
- Data & Theory agree qualitatively
- A quantitative difference is observed in the central/forward ratios

=> Need improved and consistent theoretical description for γ+ jet

Photon+b & c jet production



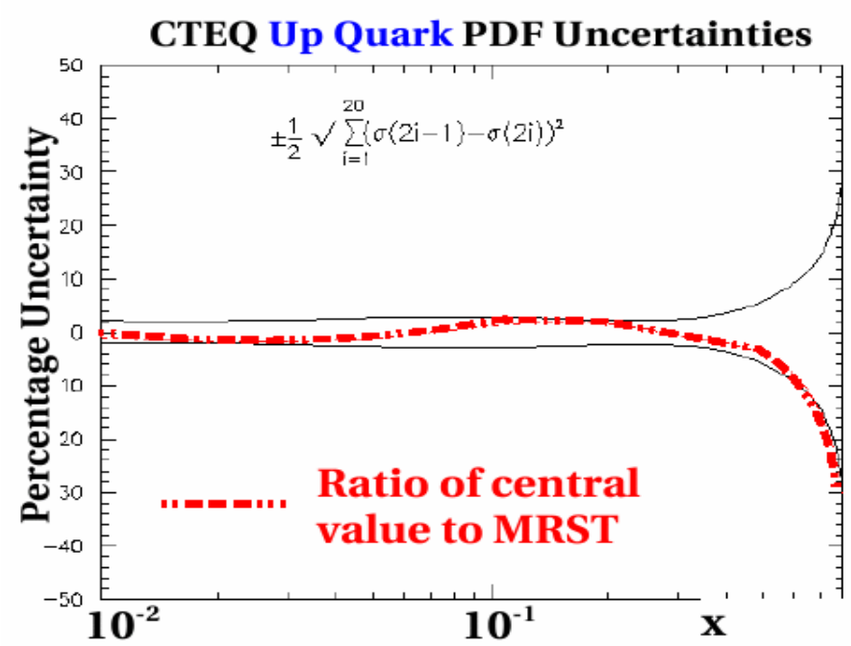


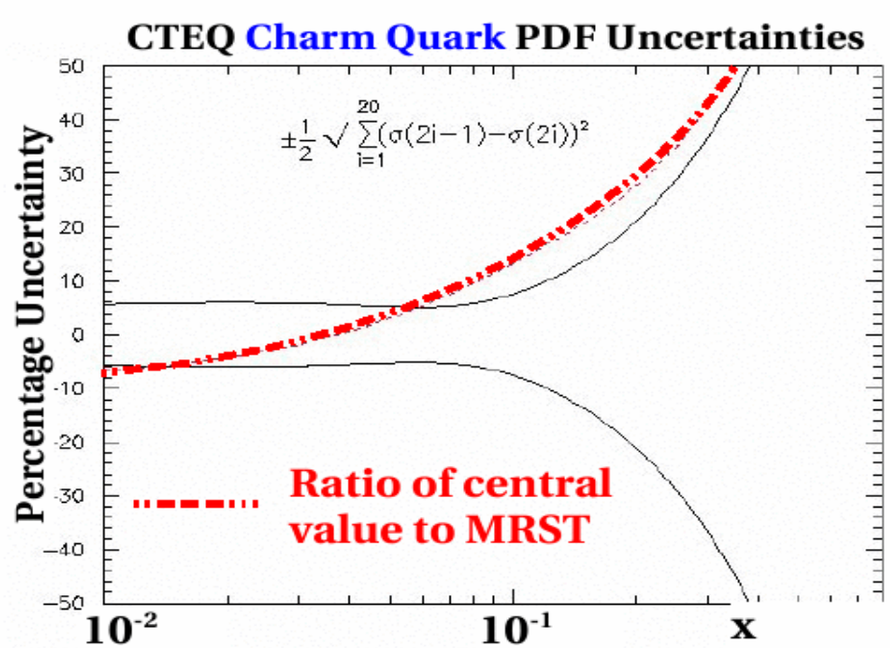
Phys.Rev.Lett. 102, 192002 (2009)

- QCD Compton-like scattering dominates for b(c) production up to 90(120) GeV
- Outgoing = incoming quark

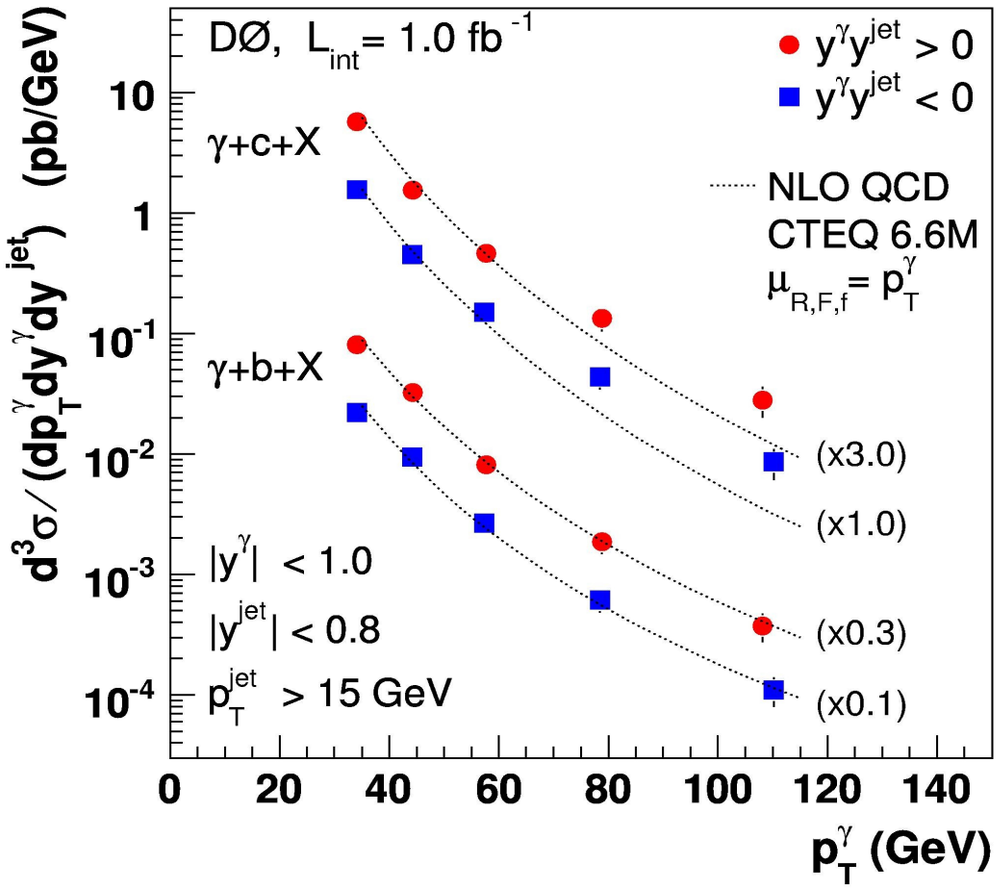
⇒ Constraints on HF PDF

- Triple differential with two photon-HF jet rapidity regions => better splitting of parton x intervals.

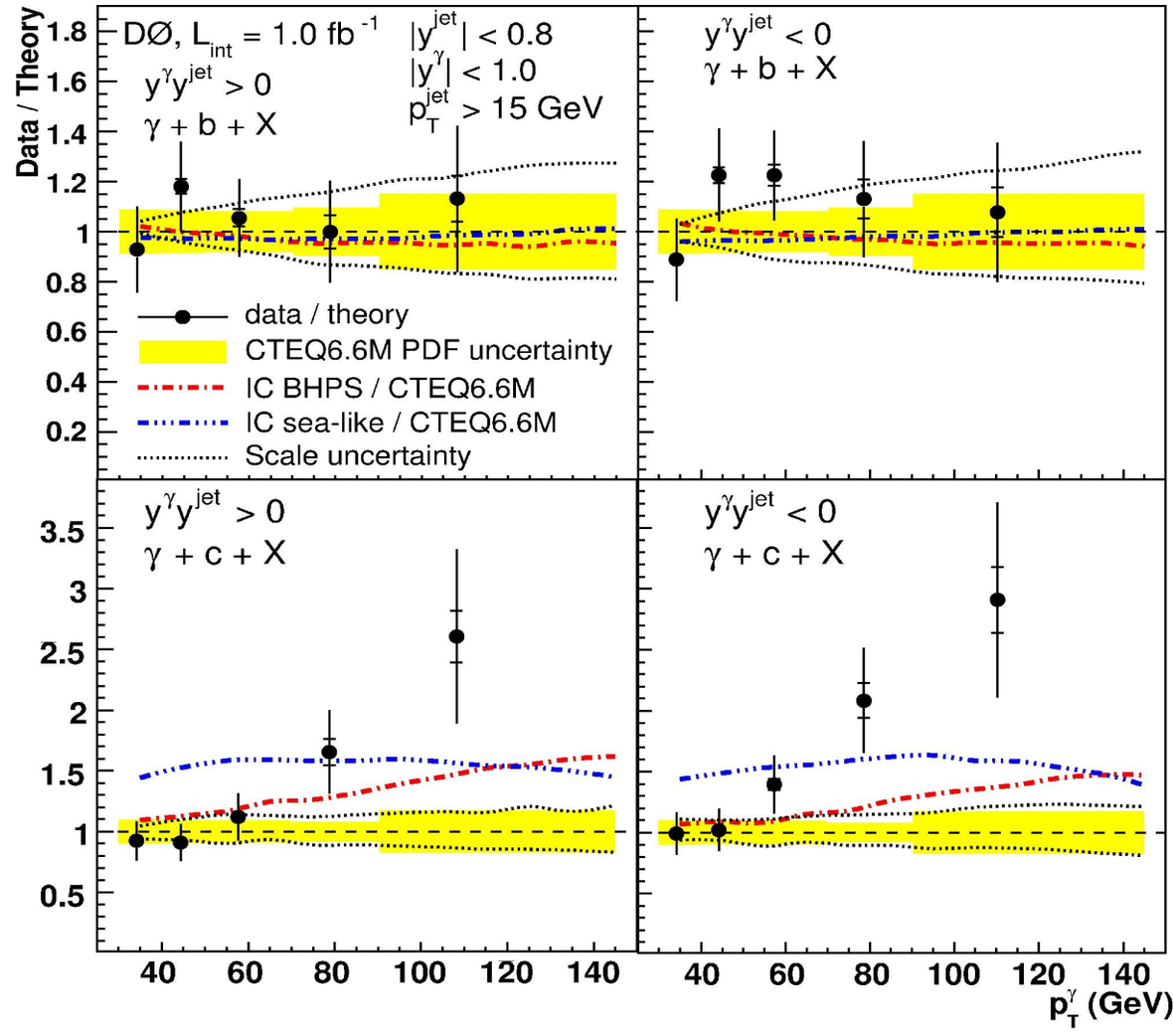




Photon+b & c jet production



Data/theory comparison



$\sigma(\gamma$+b) agrees with theory in the whole range, but disagrees at p_T^γ> 70 GeV

Too little intrinsic charm in proton, or not enough charm in gluon splitting from annihilation process?

Summary

- Many new, interesting results coming from the Tevatron in Vector Boson + jet measurements

=>Crucial for understanding backgrounds to NP and SM Higgs searches

=> Understanding of W/Z/γ + b/c jet is extremely important

- Discrepancies with theory suggest HO corrections and some theory components may need study: tuning of scale choices, PDFs, heavy quark fragmentation, etc

- New results on W+n-jets, Z+b are coming soon, W+b(b) is in progress.

- QCD will continue to be a rich field of study and extremely important in the LHC era

- Be tuned by looking at

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

BACK-UP SLIDES

D0 RunII Midpoint Jet Cone Algorithm

"particle" = {experiment: calorimeter towers / MC: stable particles / pQCD: partons}

three parameters: $R_{\text{cone}} = 0.7$, $p_{T\,\text{min}} = 8\,\text{GeV}$, overlap fraction $f = 50\%$

- Use all particles as **seeds**
  — make cone of radius $\Delta R = \sqrt{(\Delta y^2 + \Delta\phi^2)} < R_{\text{cone}}$ around seed direction
  — proto jet: add particles within cone in the "E-scheme" (adding four-vectors)
  — iterate until stable solution is found with: cone axis = jet-axis
- Use all **midpoints** between pairs of jets as **additional seeds** $\Longrightarrow$ infrared safety!!!
  — (repeat procedure as described above)

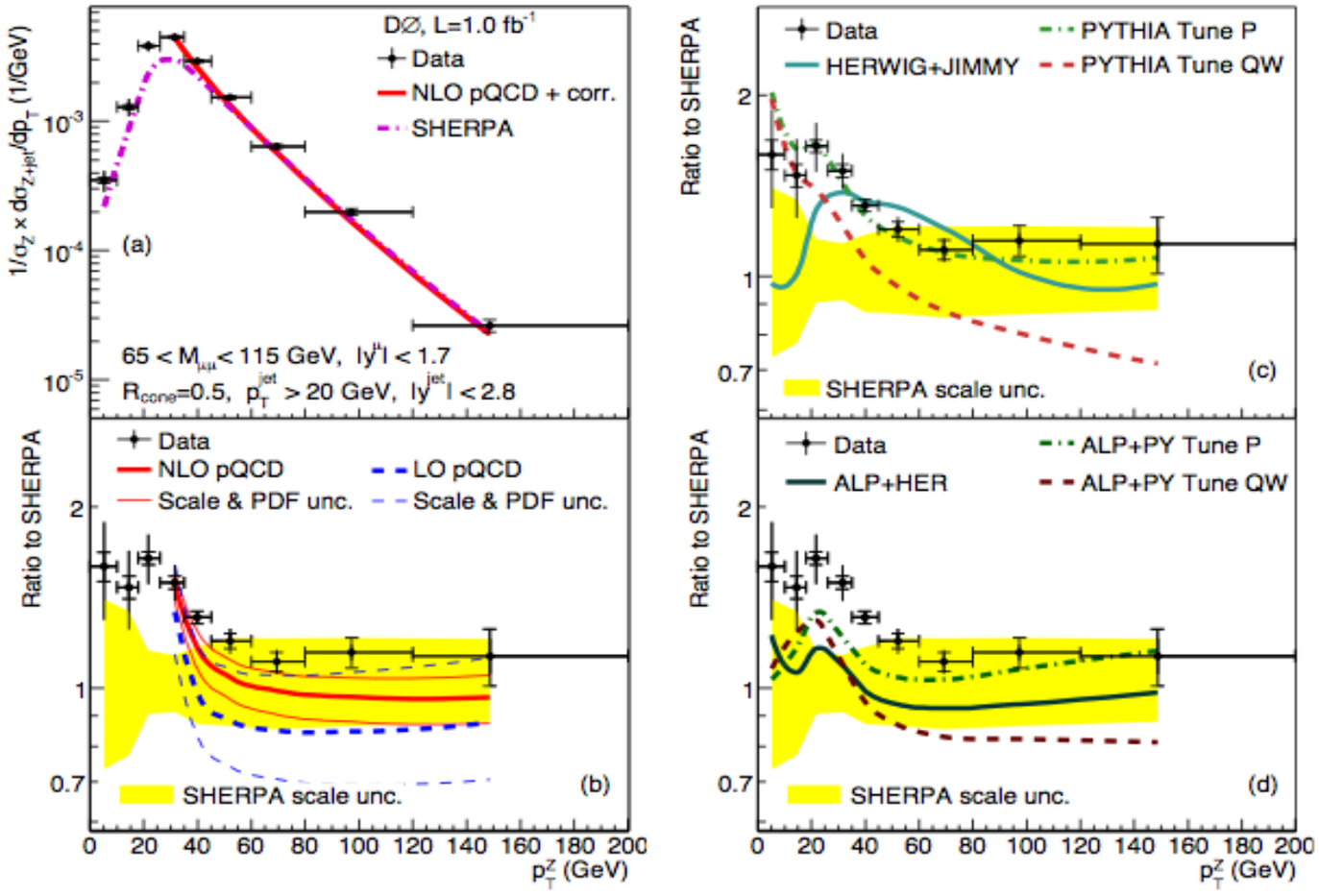
- Take all solutions from the first two steps:
  — remove identical solutions
  — remove proto-jets with $p_{T\,\text{jet}} < p_{T\,\text{min}}$
- Look for jets with **overlapping cones**:
  — merge jets, if more than a fraction f of $p_{T\,\text{jet}}$ is contained in the overlap region
  — otherwise split jets: assign the particles in the overlap region to the nearest jet
  ($\rightarrow$ and recompute jet-axes)

Z+jets production. Z pT

Particle level phase space:
65 GeV< $M_{\mu\mu}$ < 115 GeV,
jet R_{cone}=0.5, p_T^{jet} > 20 GeV
$|y^{jet}|$ < 2.8, $|y^{\mu}|$ < 1.7
muons include QED radiation

theory predictions updated since publication

ratios relative to Sherpa 1.1.3



PLB 669, 278 (2008)

MCFM v5.4 PDF: MSTW2008
$\mu_r^2 = \mu_f^2 = p_{T,Z}^2 + M_Z^2$

PYTHIA v6.420
Pythia Tune P
Pythia Tune QW
HERWIG v6.510 + JIMMY v4.31

ALPGEN v2.13+PYTHIA v6.420
ALPGEN v2.13+HERWIG v6.510

- Z p_T<30 GeV sensitive to underlying event
- All LO predictions underestimate data
- Pythia can be tuned to reproduce data

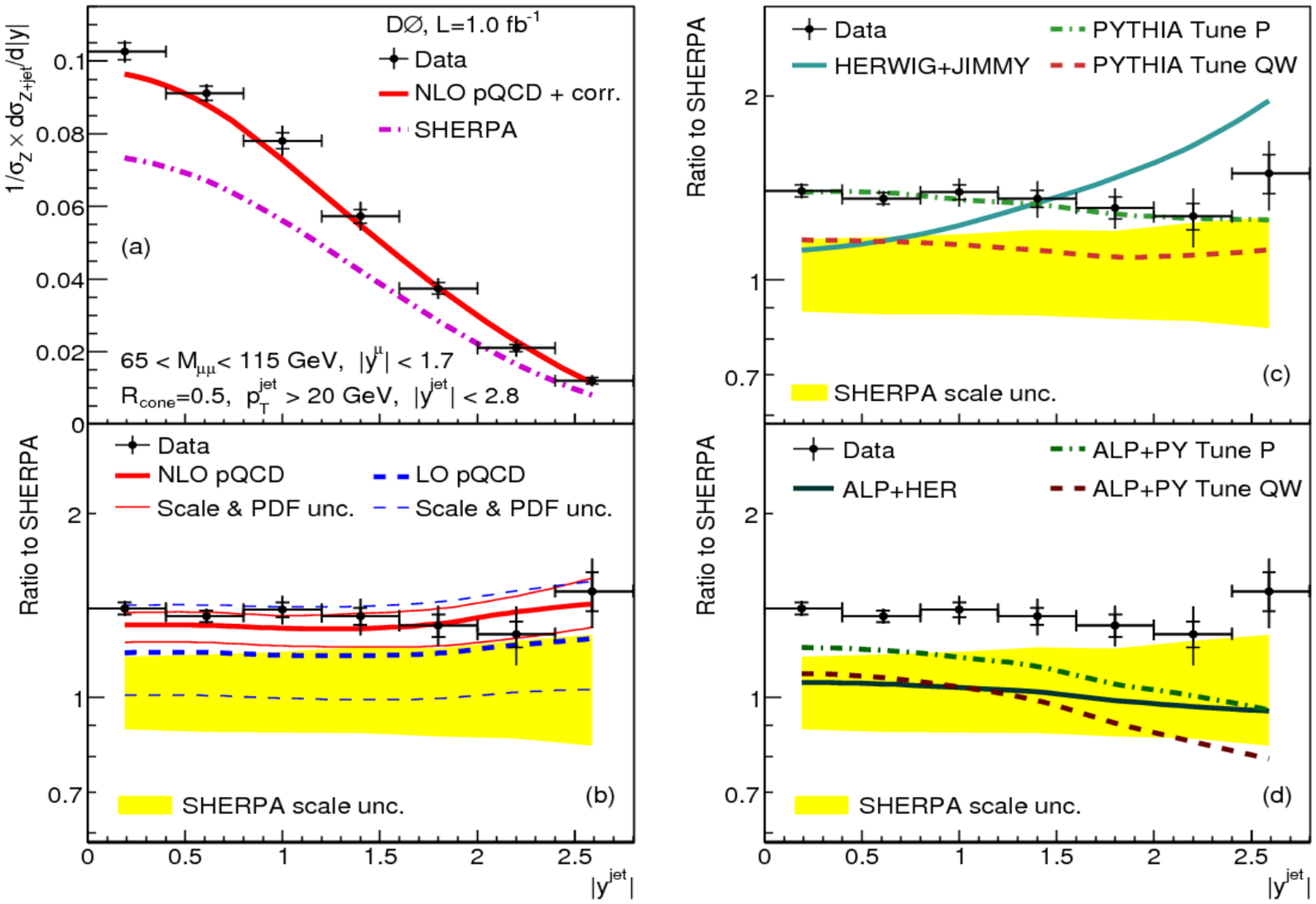
Z+jets production. Jet rapidity

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

PLB 669, 278 (2008)

- we also need good description of jet angles: look at leading jet rapidity

Jet rapidity in Z + jet + X



PYTHIA p_T ordered
- new "Perugia" tune
- MRST07 LO* PDF
PYTHIA Q^2 ordered
HERWIG

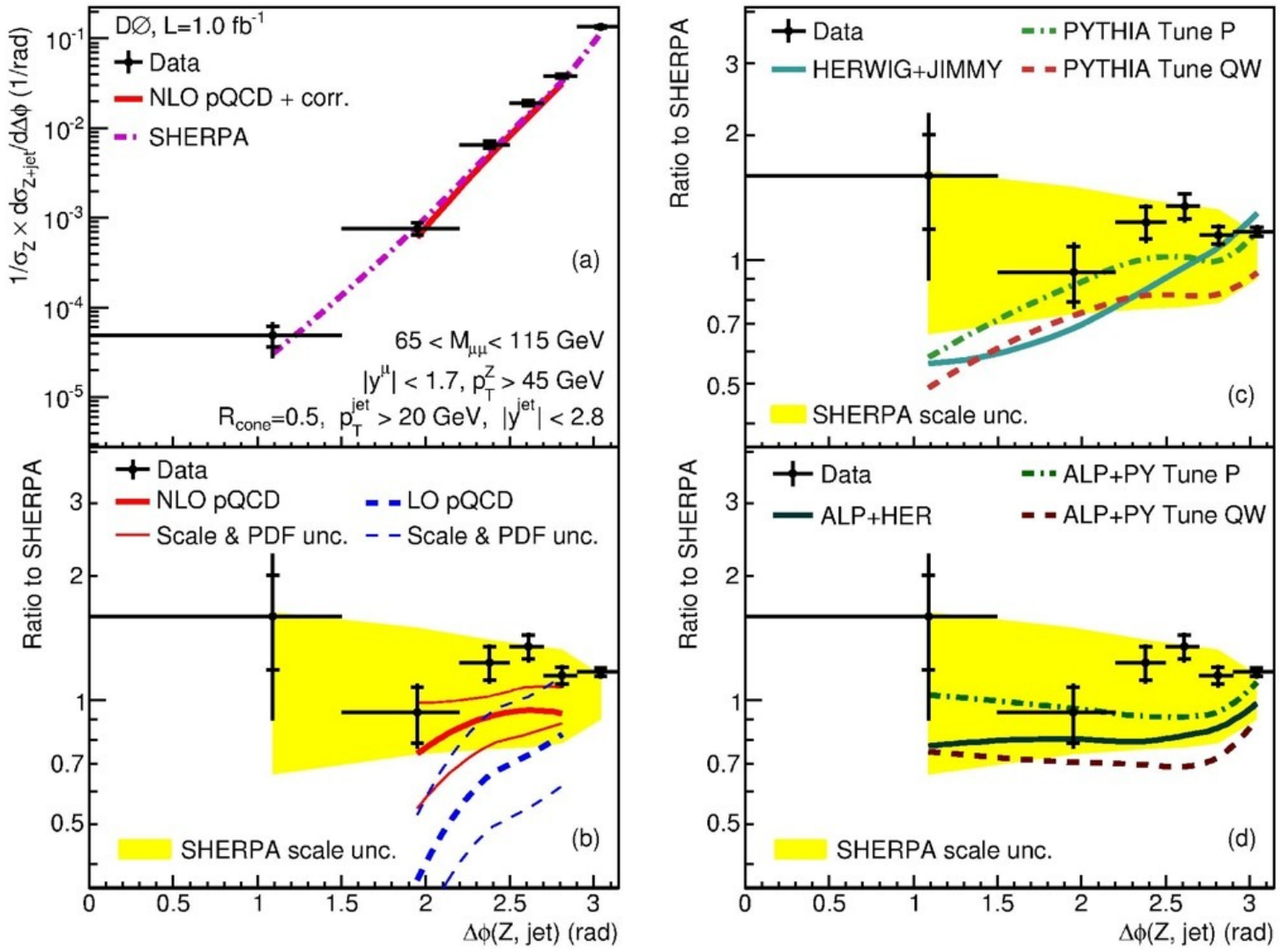
ALPGEN + PYTHIA p_T
ALPGEN + PYTHIA Q^2
ALPGEN + HERWIG

Z+jets production. Δϕ(Z,jet)

First measurement of $\Delta\phi$(Z, jet) !

- $Z \to \mu\mu$, $|y_\mu|<1.7$, $\mathbf{p_{TZ} > 45}$ **GeV**
- jet p_T>20 GeV, |jet y| < 2.8

PLB 682, 370 (2010)



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HERWIG

ALPGEN + PYTHIA p_T
ALPGEN + PYTHIA Q^2
ALPGEN + HERWIG

- Sherpa describes Δϕ(Z,jet) shape very well

- Small values of Δϕ are excluded from MCFM due to significant non-perturbative contributions

Photon+jet production

DØ Collab., Phys. Lett. **B 666**, 435 (2008)

$\mathcal{L} = 1.0\ \mathrm{fb}^{-1}$

$p\bar{p} \to \gamma + \mathrm{jet} + X$: Event selection

- $p_T^\gamma > 30$ GeV (up to 400 GeV), $|y^\gamma| < 1.0$
- Isol< 0.07, frac$(EM) > 0.96$, $O_{NN} > 0.7$
- $\not{E}_T < 12.5\ \mathrm{GeV} + 0.36 p_T^\gamma$ (cosmics, $W \to e\nu$)
- $p_T^{\mathrm{jet}} > 15$ GeV
- $|y^{\mathrm{jet}}| < 0.8$ (central), $1.5 < |y^{\mathrm{jet}}| < 2.5$ (forward)

4 regions: $y^\gamma \cdot y^{\mathrm{jet}} \lesseqgtr 0$, central and forward jets