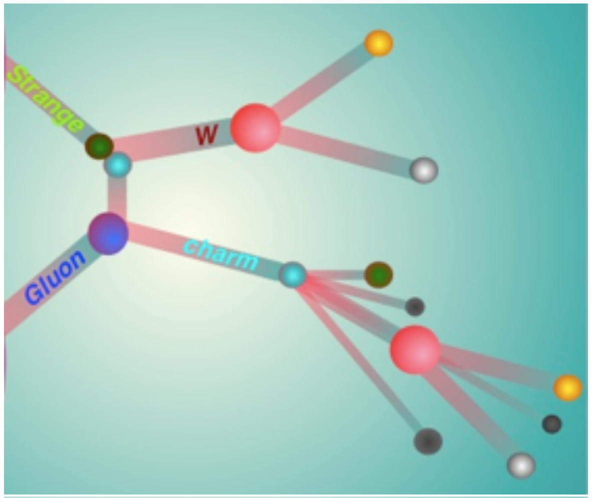
V+jets at the Tevatron



Lucio Cerrito
Queen Mary, University of London

(on behalf of the CDF and DØ Collaborations)

Top 2010
Bruges, June 2010

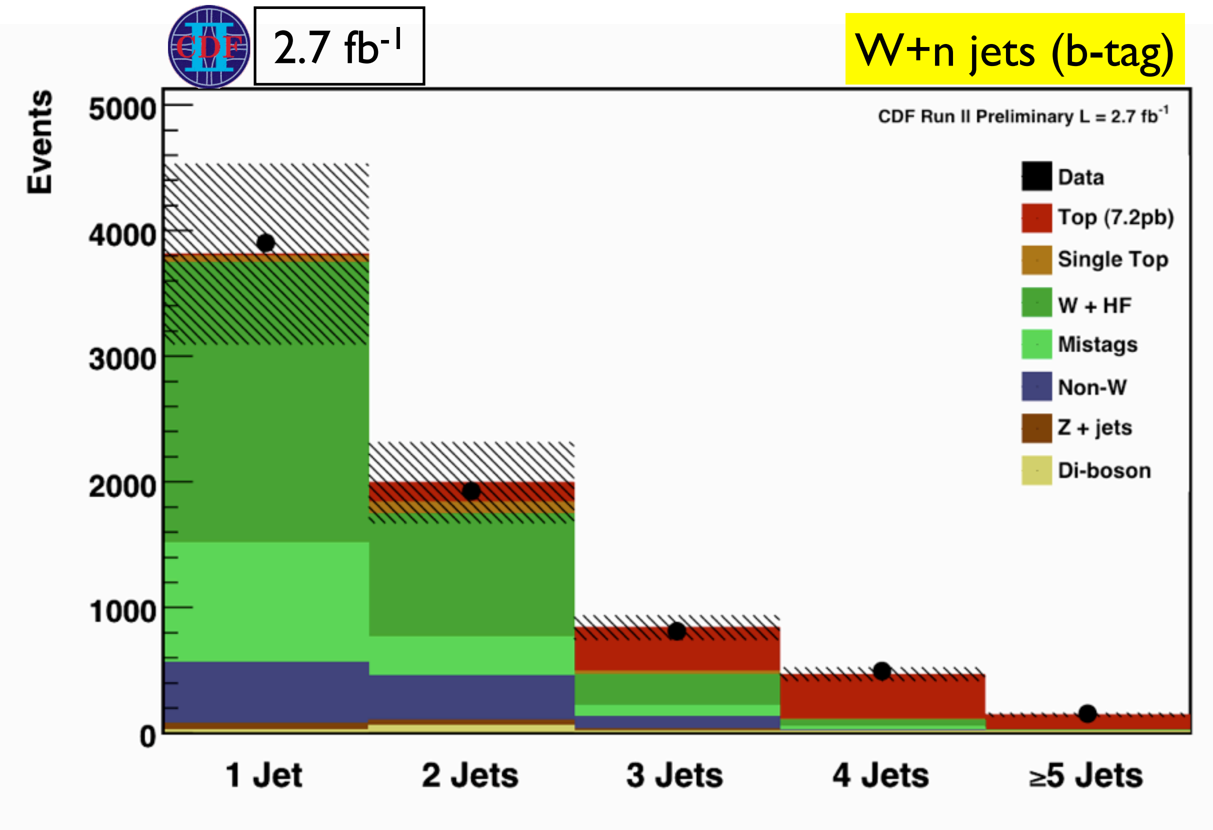
V+Jets Production

V+jets are critical for physics at the Tevatron and LHC: top, Higgs, searches.

W+HF normalisation amongst the main systematic uncertainties in measurements of *t*, b-tag *tt*,...

NLO pQCD calculations are available for lower jet multiplicities

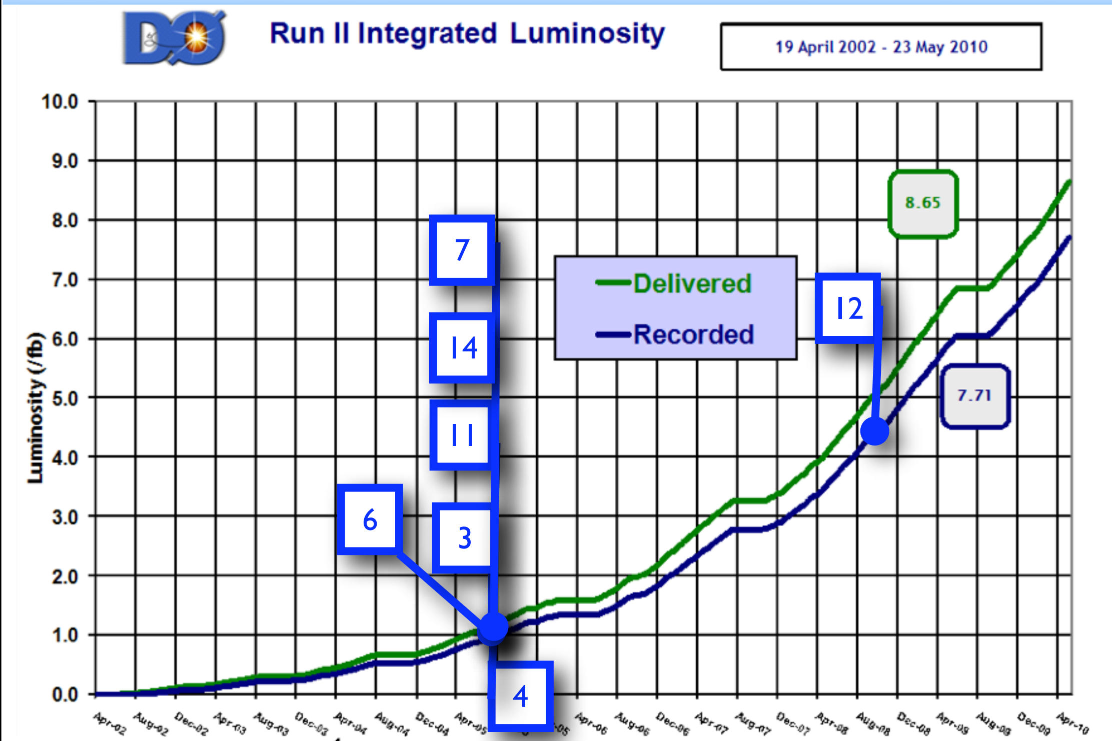
Many Monte Carlo tools are available:
- LO + Parton Shower (PYTHIA, HERWIG,)
- Matrix Element + Parton Shower: e.g. ALPGEN, SHERPA

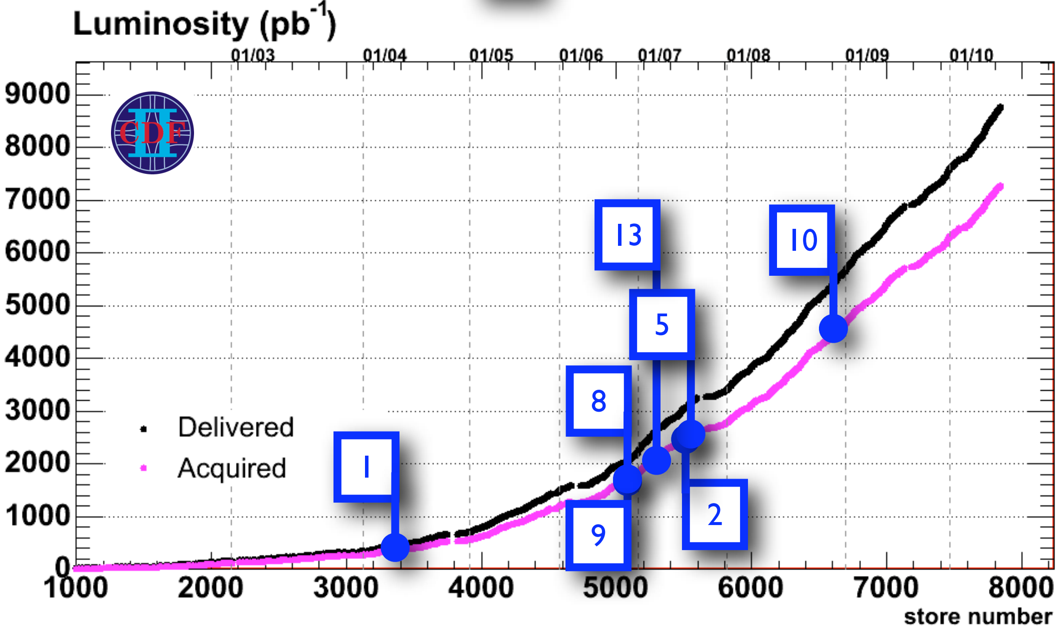


This review is from a top-physics perspective: V+jets measurements are of course important on their own for PDFs, parameters, pQCD testing....

Normalisation vs. shapes? What uncertainties are there?

V+Jets at the Tevatron





V+jets in Top analyses

"Method I, II, III" (CDF)

V+jets (inclusive)

- 1 — W+jets (CDF)
- 2, 3, 4 — Z(→μμ)+jets (DØ, CDF)
- 5, 6 — Z(→ee)+jets (DØ, CDF)
- 7 — γ+jets (DØ)

V+ heavy flavor jets

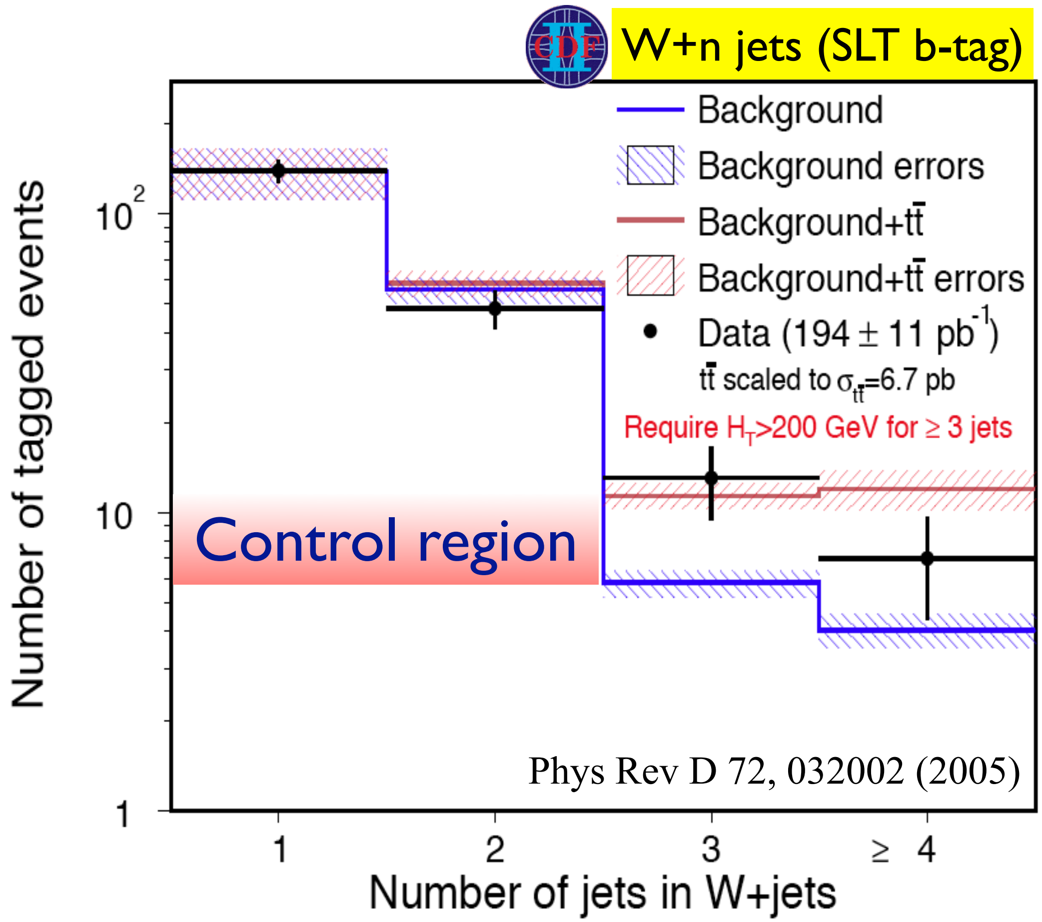
- 8 — W+bb+X (CDF)
- 9, 10 — W+c+X (CDF)
- 11 — W+c+X/W+jets (DØ)
- 12, 13 — Z+b+X (DØ, CDF)
- 14 — γ+b/c+X (DØ)

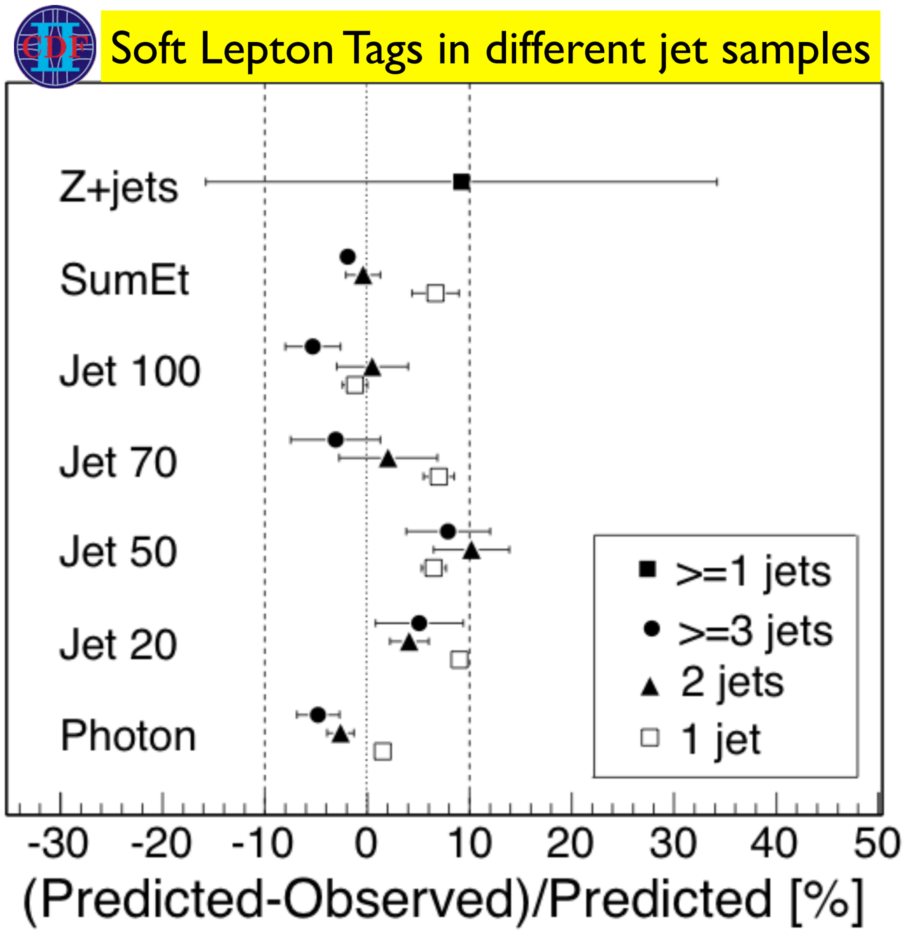
W+jets background in top

CDF Method I

Data-driven technique used in CDF I (~1995), but also in our CDF II (2005) Soft Lepton Tags cross section: an overall tag rate comprising heavy and light flavour is used to estimate W/Z +jets background

W+mistags here outnumber the rest by 4:1 (only ~20% W+HF component)





W+jets background in top

CDF Method II (many similarities for D0, see A. Heinson's Talk)

Data+MC technique widely used at CDF-II: W+jets normalised to data, W+hf fraction from ALPGEN (+PYTHIA) calibrated on data (earlier using multijets, because of stat., now W+1 jet).

$$N^{pretag}_{W\,+\,Jets} = N_{pretag} \cdot (1 - F^{pretag}_{QCD}) - N^{pretag}_{ewk} - N^{pretag}_{top}$$

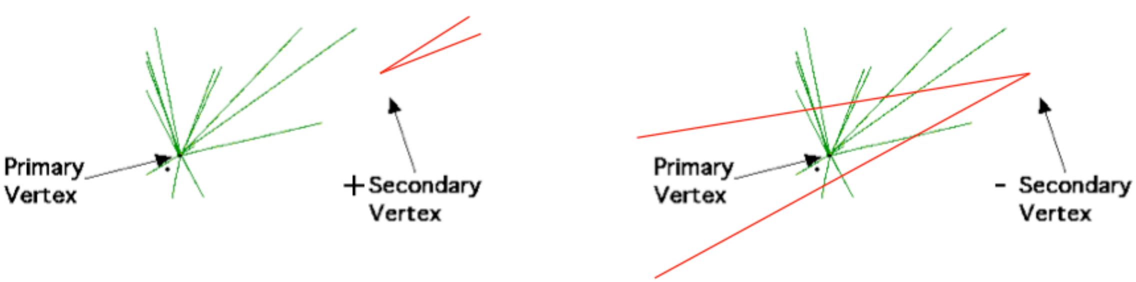
$$N^{tag}_{W\,+\,HF} = (N_{pretag} \cdot (1 - F^{pretag}_{QCD}) - N^{pretag}_{ewk} - N^{pretag}_{top}) \cdot F_{HF} \cdot K \cdot \epsilon_{tag}$$

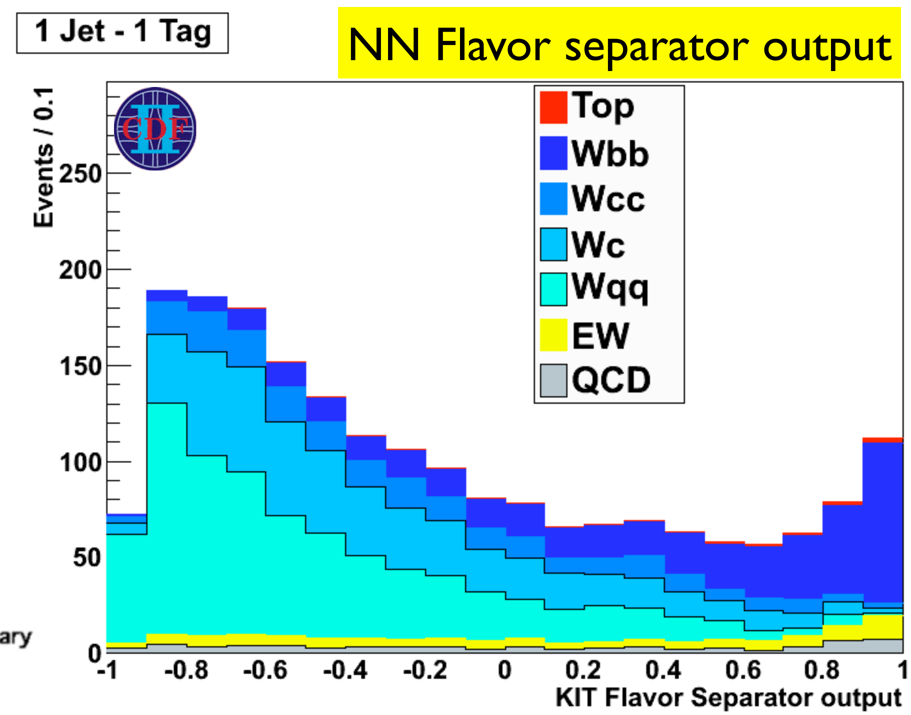
$$N^{tag}_{W\,+\,LF} = (N_{pretag} \cdot (1 - F^{pretag}_{QCD}) - N^{pretag}_{ewk} - N^{pretag}_{top} - N^{pretag}_{W\,+\,HF}) \cdot \frac{N_{-}}{N_{pretag}}$$

Initially an overall HF calibration term (given dataset, uncertainty includes b/c, n-Jet, systematics), e.g. $K=1.5\pm0.3$

More recently K different for Wbb, Wcc, Wc

Cross checked on Z+hf





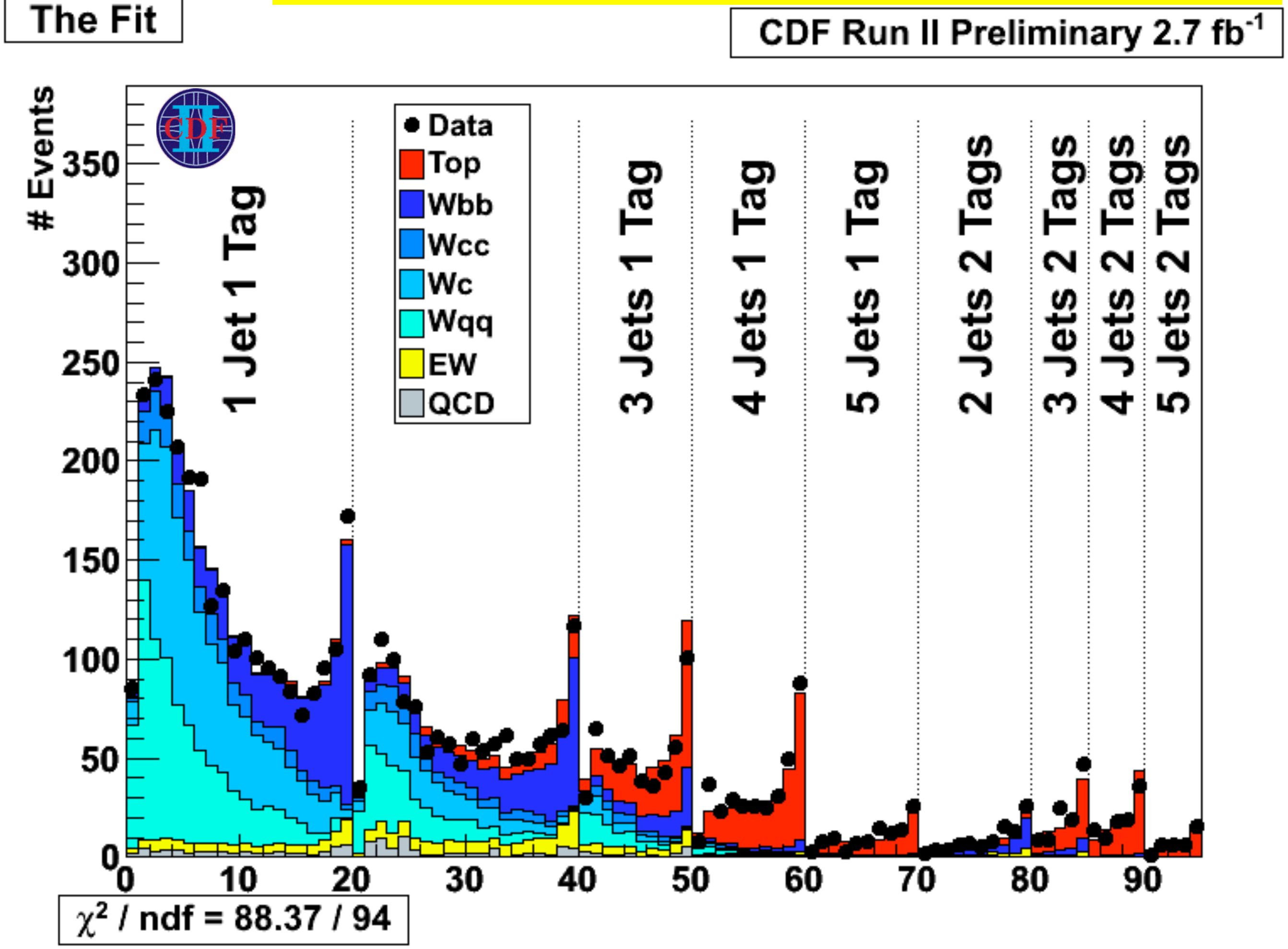
W+jets background in top

CDF Method III

Simultaneous measurement of the top cross section **and** the W+hf (K) fractions

NN Flavor separator output, different n-jets and b-tag

The Fit



Sample	Fit Value
$\sigma_{t\bar{t}}$	$7.64^{+0.57}_{-0.54}$
$K_{Wb\bar{b}}$	$1.57^{+0.28}_{-0.22}$
$K_{Wc\bar{c}}$	$0.94^{+0.90}_{-0.71}$
K_{Wc}	$1.90^{+0.34}_{-0.32}$
$K_{Wq\bar{q}}$	$1.10^{+0.34}_{-0.25}$
K_{EW}	$1.10^{+0.10}_{-0.10}$
K_{QCD}	$0.82^{+0.26}_{-0.26}$
R_{Btag}	$0.31^{+0.64}_{-0.64}$
R_{Mistag}	$-0.05^{+0.98}_{-0.98}$
R_{JES}	$0.47^{+0.63}_{-0.61}$
R_{Q^2}	$0.07^{+0.44}_{-0.44}$
R_{IFSR}	$0.13^{+0.90}_{-0.89}$

W+jets background in $t\bar{t}$

Background table for the tt+jets cross section in lepton+jets

Process	1jet	2jets	3jets	4jets	5jets
Pretag Events	7445	10947	6380	2724	782
Wbb	50.2 ± 15.5	176.2 ± 54.3	128.4 ± 39.8	50.9 ± 16.9	10.2 ± 6.9
Wcc	24.4 ± 7.7	76.9 ± 24.3	65.8 ± 20.8	27.3 ± 9.2	6.0 ± 4.0
Wc	32.6 ± 10.3	75.2 ± 23.7	41.6 ± 13.2	13.1 ± 4.4	2.4 ± 1.6
Mistags	111.4 ± 11.2	181.7 ± 26.8	101.2 ± 18.2	33.2 ± 9.4	6.2 ± 7.4
Non-W	41.6 ± 12.5	116.4 ± 34.9	71.7 ± 21.5	25.5 ± 20.4	9.3 ± 7.5
WW	2.9 ± 0.3	19.0 ± 2.5	14.8 ± 2.0	6.1 ± 0.8	2.0 ± 0.2
WZ	1.0 ± 0.1	7.1 ± 0.8	5.0 ± 0.6	1.9 ± 0.2	0.5 ± 0.1
ZZ	0.1 ± 0.0	0.9 ± 0.1	1.2 ± 0.2	0.5 ± 0.1	0.2 ± 0.0
Z+jets	3.8 ± 0.4	16.3 ± 1.9	16.7 ± 2.1	6.6 ± 0.8	1.8 ± 0.2
Single Top (s-channel)	1.2 ± 0.1	32.6 ± 3.2	16.5 ± 1.6	4.1 ± 0.4	0.8 ± 0.1
Single Top (t-channel)	0.4 ± 0.0	32.9 ± 2.9	18.7 ± 1.6	4.9 ± 0.4	0.9 ± 0.1
$t\bar{t}$ + 0j (5.5 pb)	8.6 ± 1.7	179.3 ± 35.0	534.4 ± 104.2	555.1 ± 108.1	105.7 ± 20.6
$t\bar{t}$ + j (1.6 pb)	0.5 ± 0.3	16.4 ± 10.3	86.7 ± 54.5	163.1 ± 102.6	182.1 ± 114.5
Total Prediction	278.6 ± 37.2	930.9 ± 117.3	1102.8 ± 144.6	892.3 ± 157.0	328.2 ± 118.1
Observed	304	917	1115	882	329

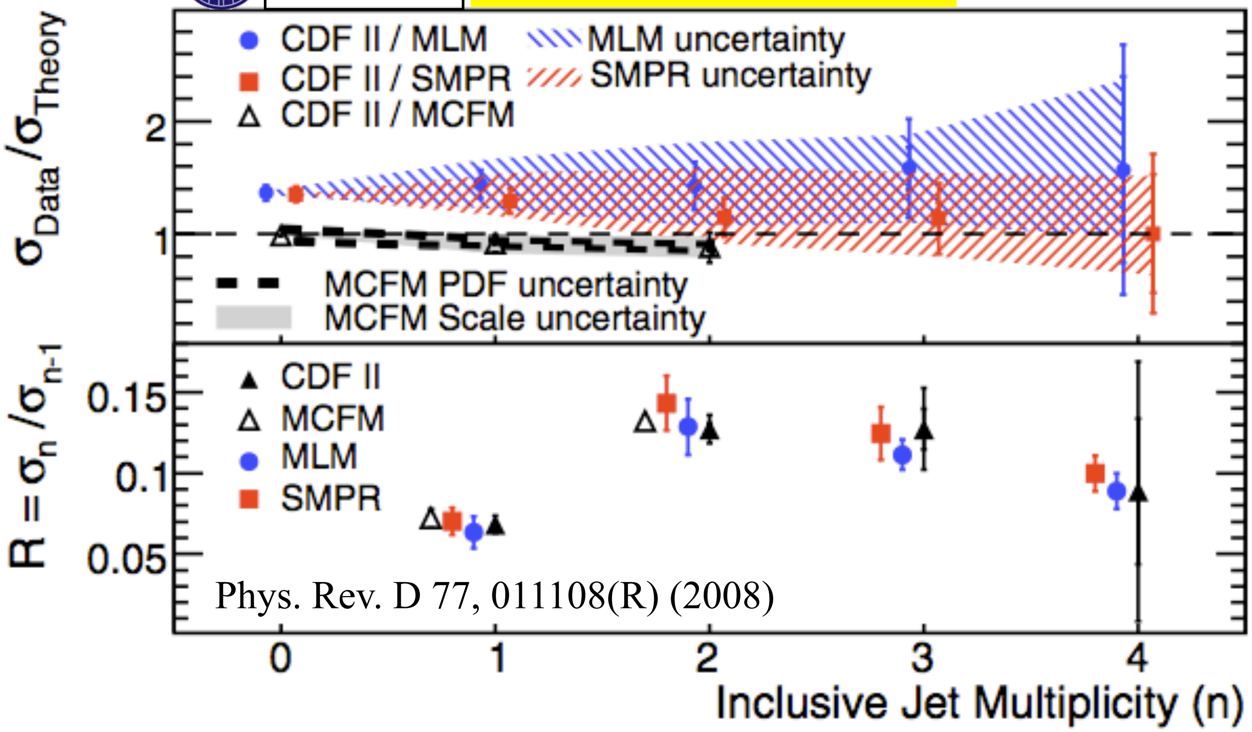
CDF Run II Preliminary $\mathcal{L} = 4.1\ \text{fb}^{-1}$

±~30%

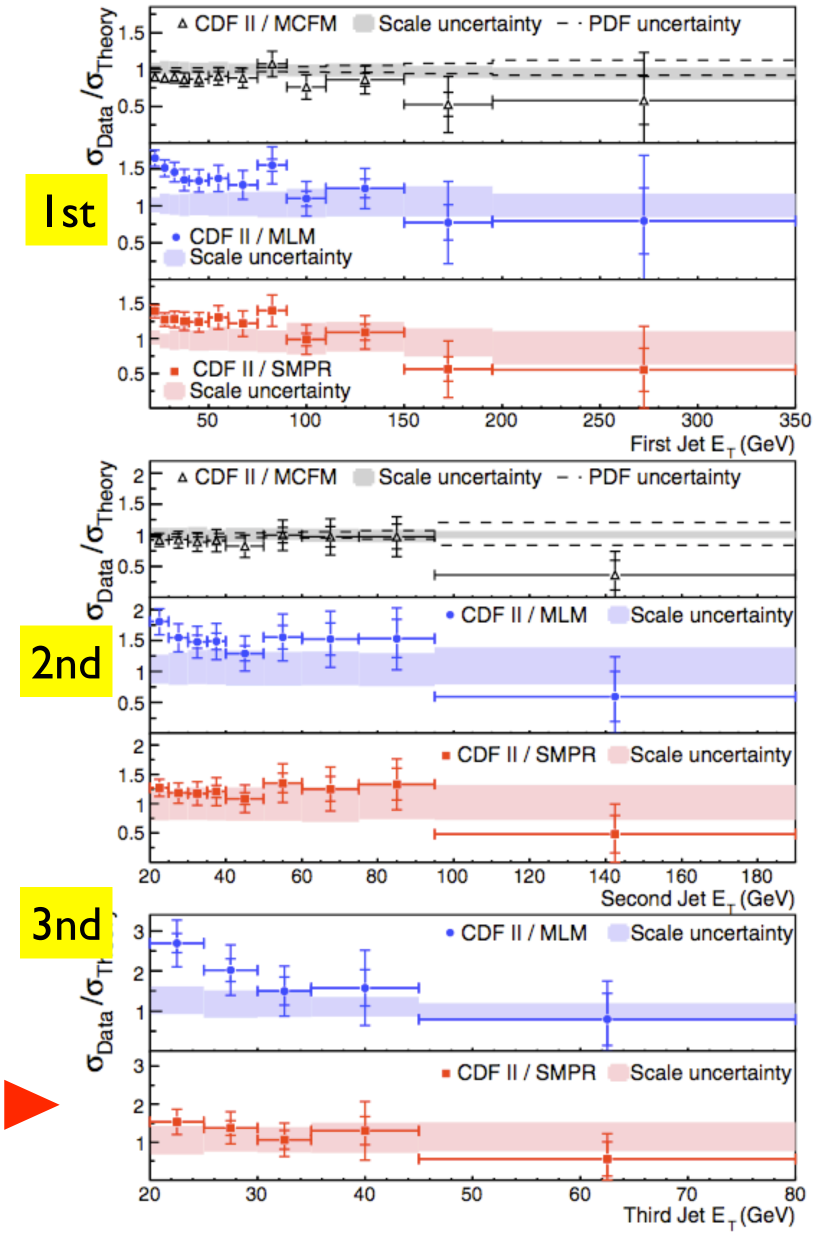
V+ jets (inclusive) Measurements

W+jets

320 pb^{-1} Cross section vs n-jets



Cross section vs jet E_T

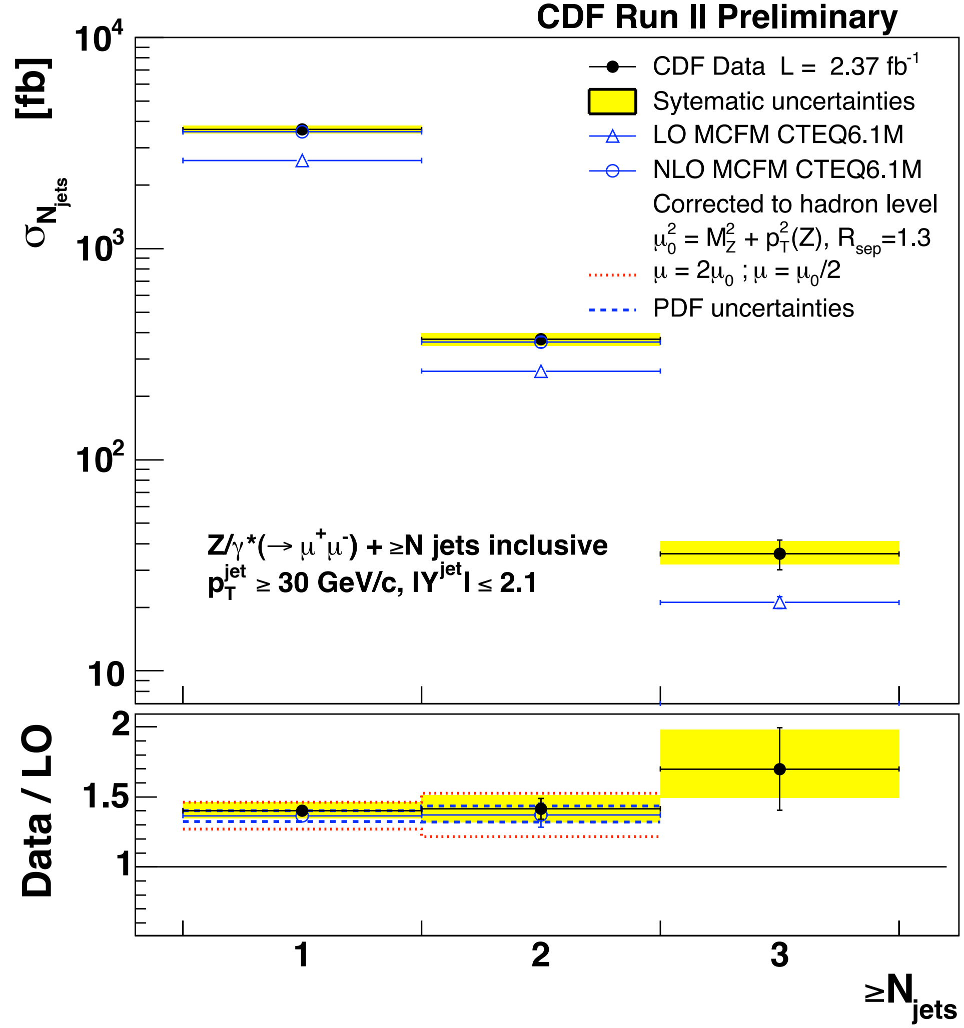


E_T(jet)>20 GeV, |η(jet)| < 2.0, cone 0.4
E_T(lep) > 20 GeV, |η(lep)| < 1.1
m_T(W)>20 GeV

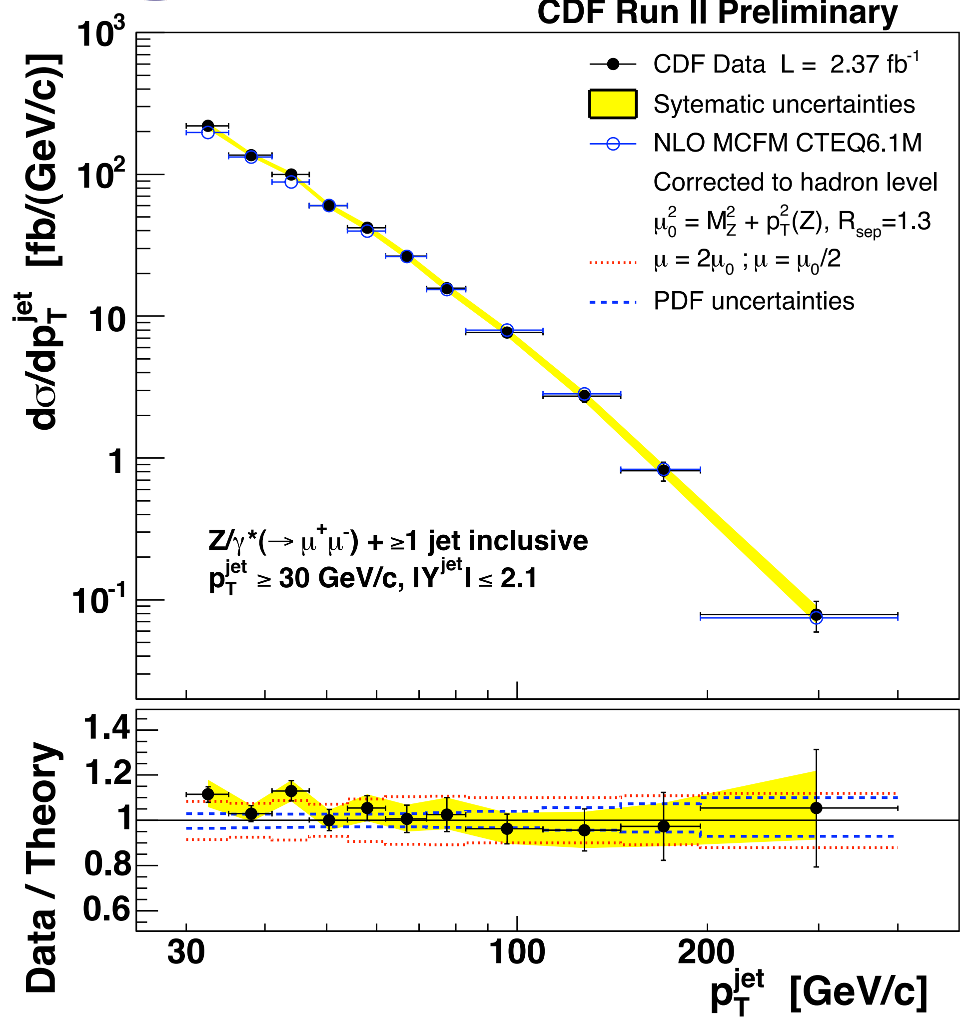
- Agreement with NLO better than 20%
- Agreement with ALPGEN+HERWIG or MADGRAPH +PYTHIA within 40−50%. Some shape distortions.
- Ratios σ_N/σ_{N-1} within 20%

Z(→μμ)+jets

2.4 fb^{-1} **new** Cross section vs n-jets



2.4 fb^{-1} **new** Cross section vs p_T^{jet}



- Data corrected to particle-jet
- Theory corrected for fragmentation and UE (PYTHIA)

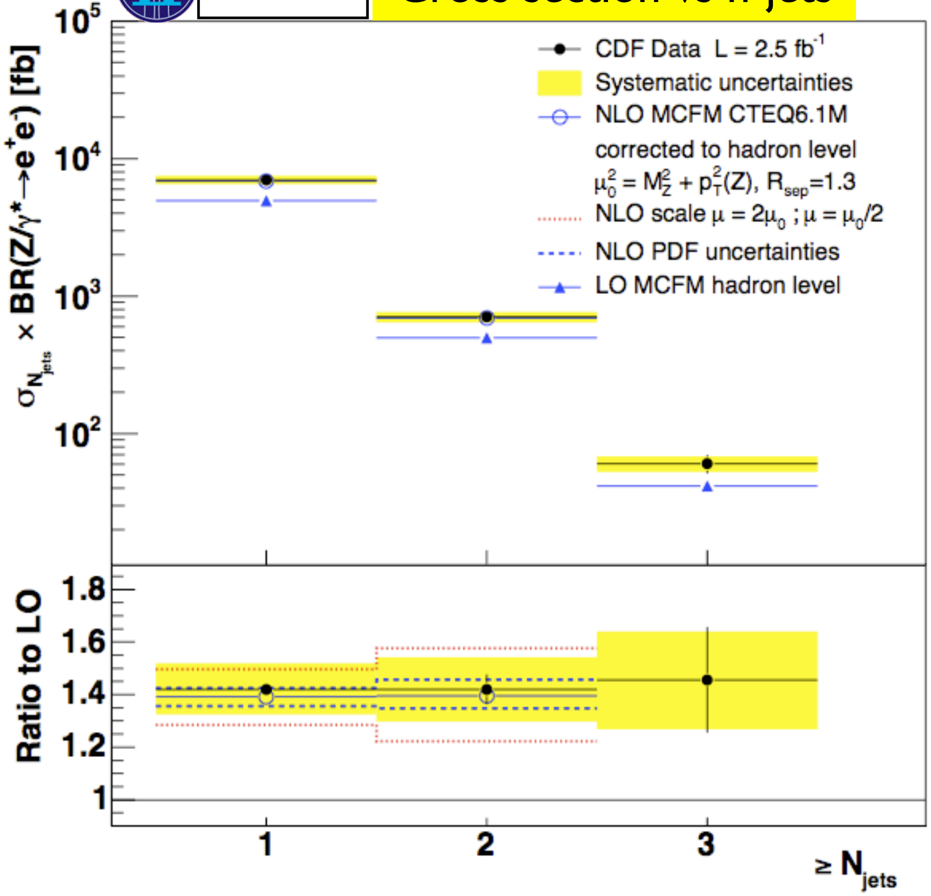
- Agreement with NLO within 10%
- LO factor (~1.4) independent on N jets

Z(→ee)+jets

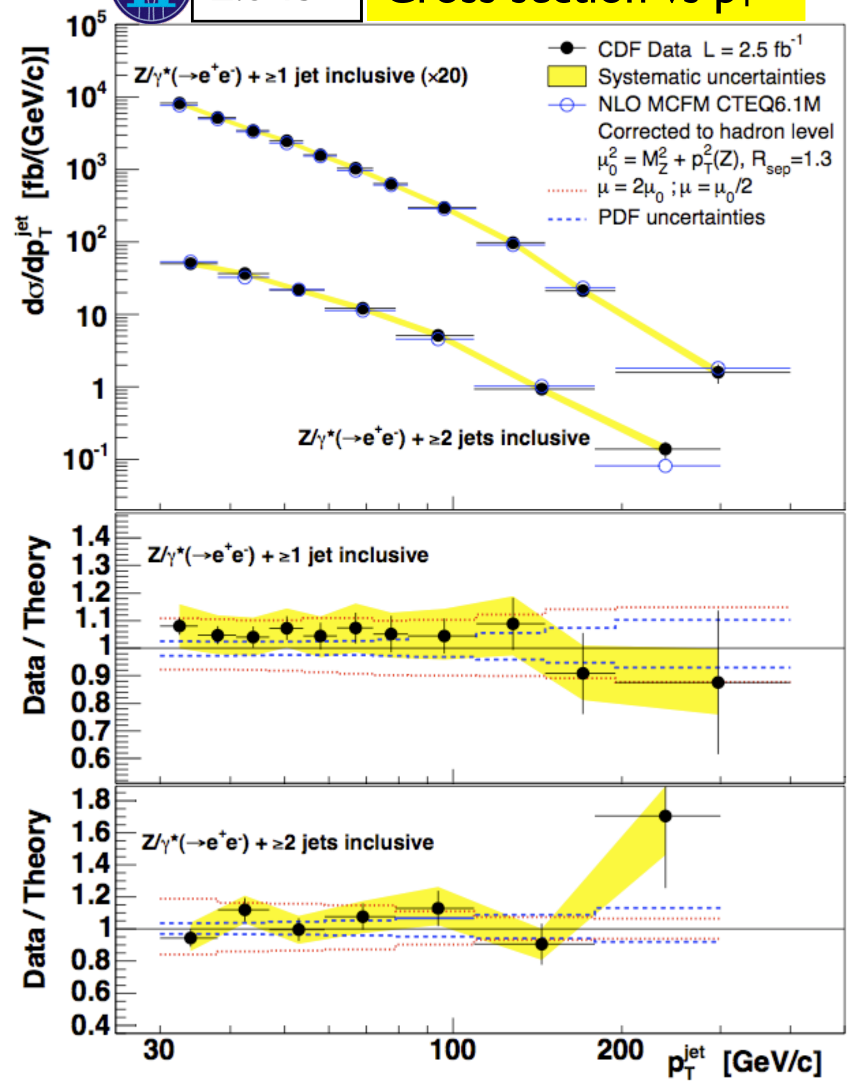
Update (2008) with 2.5 fb^{-1} on 1.7 fb^{-1} result:

Phys. Rev. Lett 100, 102001 (2008)

2.5 fb^{-1} Cross section vs n-jets



2.5 fb^{-1} Cross section vs p_T^{jet}

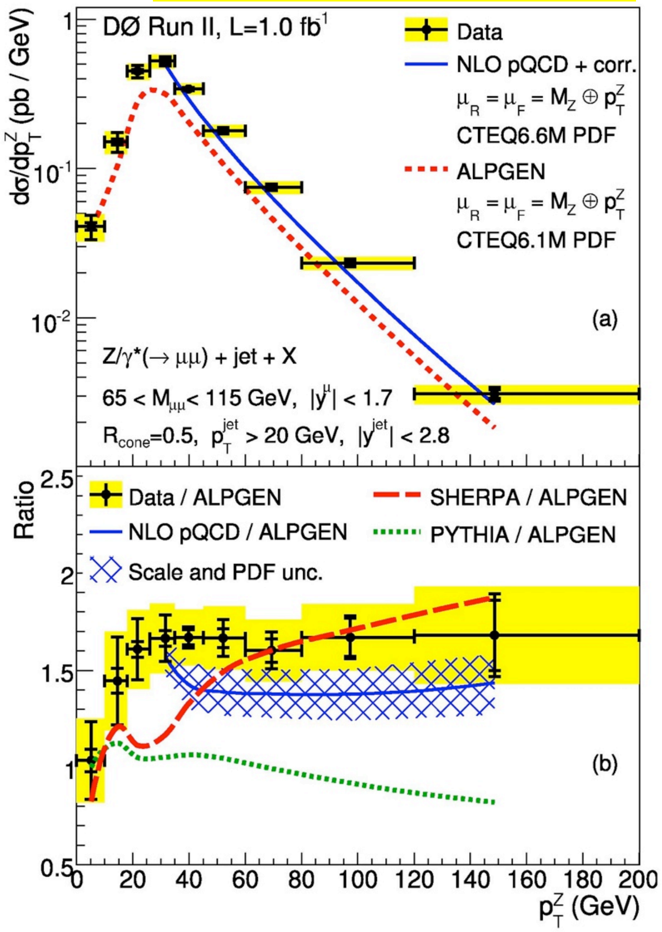


- Agreement with NLO within ~10%
- LO factor (~1.4) independent on N jets

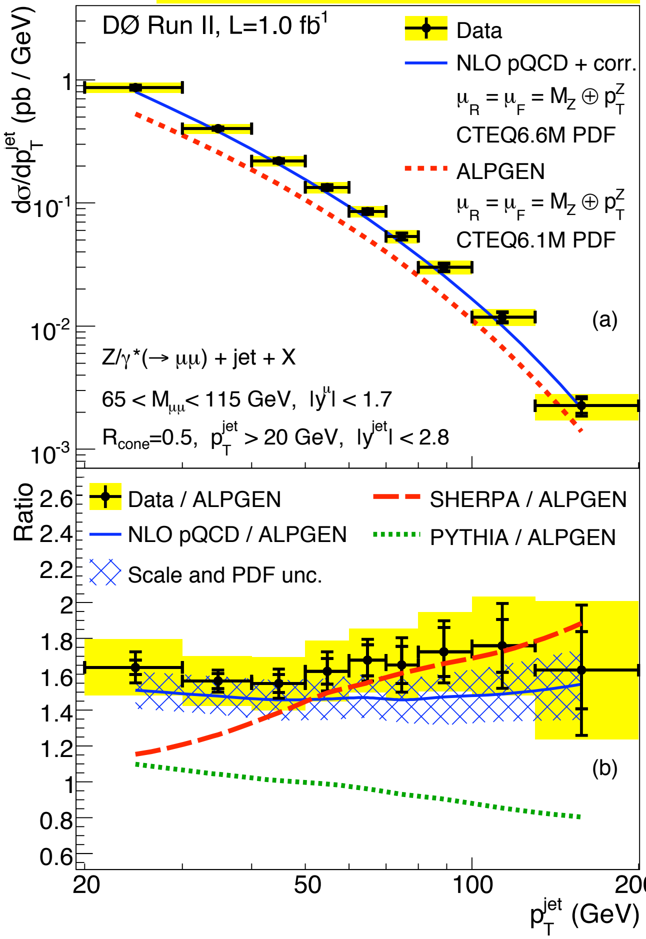
Z(→μμ)+jets

1.0 fb^{-1} Phys. Lett. B 669 (2008), 278

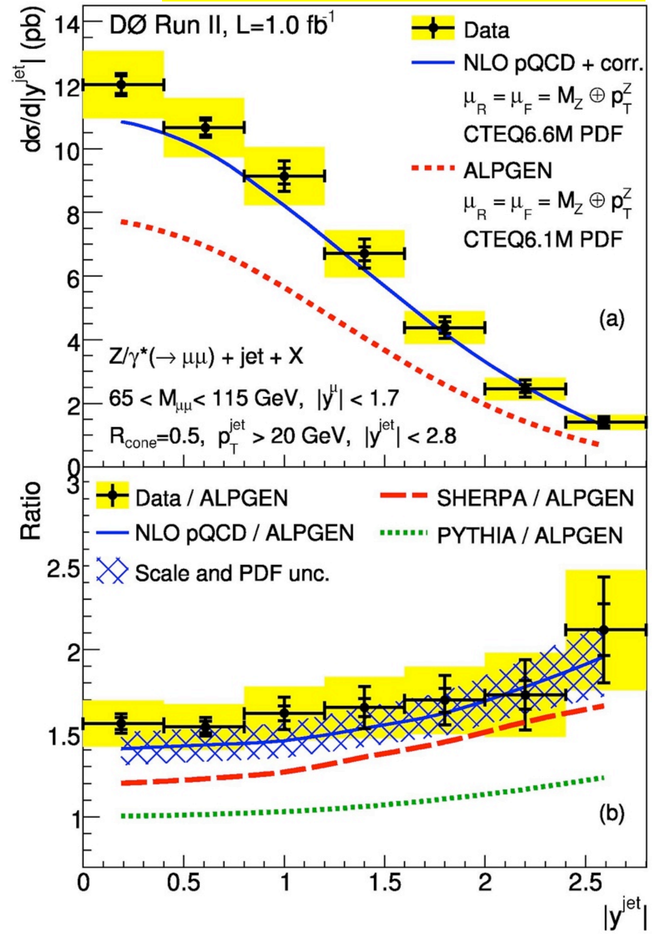
Cross section vs p_T^Z



Cross section vs p_T^{jet}



Cross section vs $|y^{jet}|$

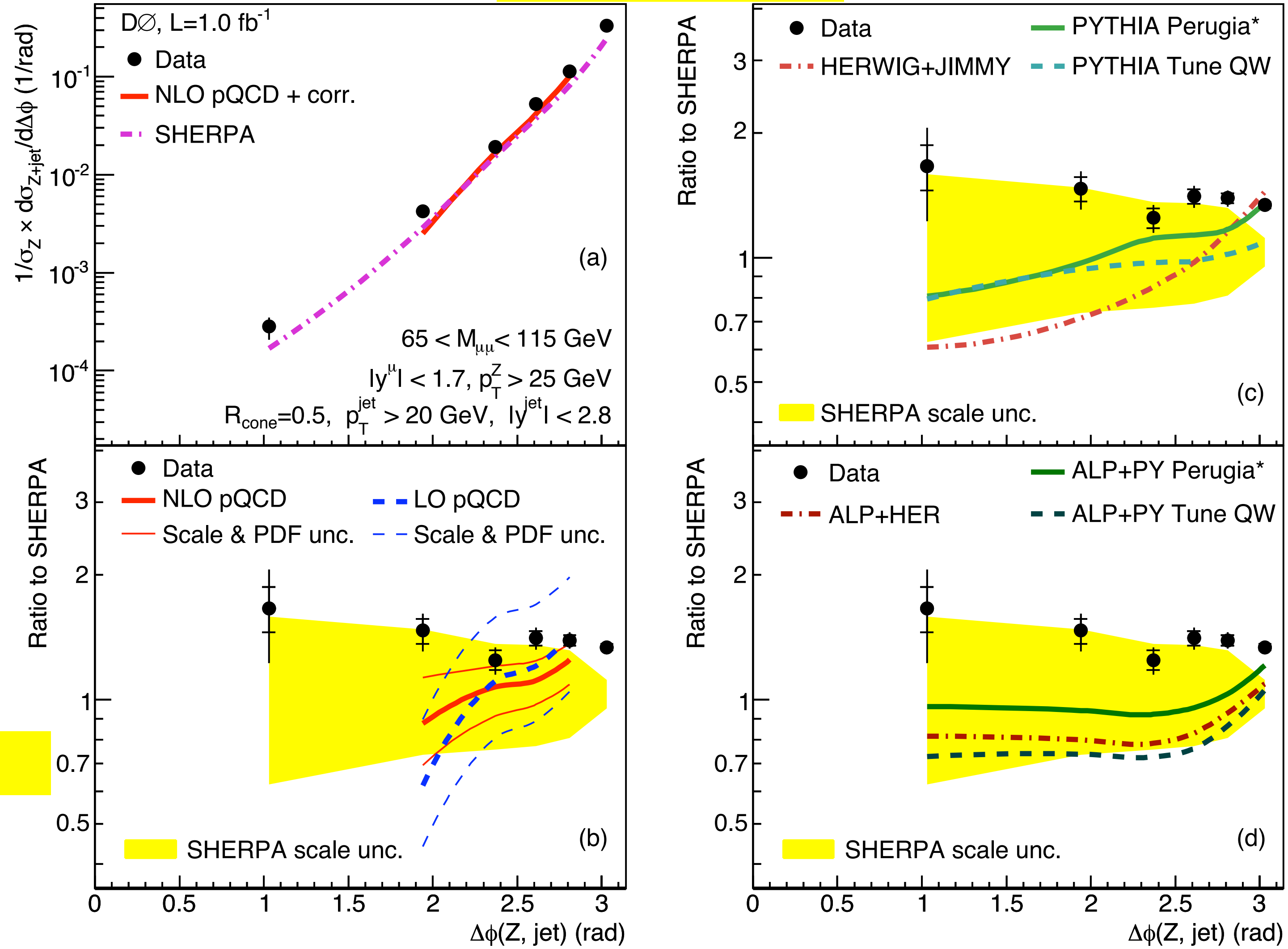


- Agreement with NLO within ~15% (! $p_{T,Z}$)
- ALPGEN & PYTHIA within ~60% but good for shapes
- SHERPA closer normalisation

Z(→μμ)+jets: Angular Distributions

1.0 fb⁻¹ Phys. Lett. B 682 (2010), 370

Z-jet opening angle



HERWIG & PYTHIA

NLO

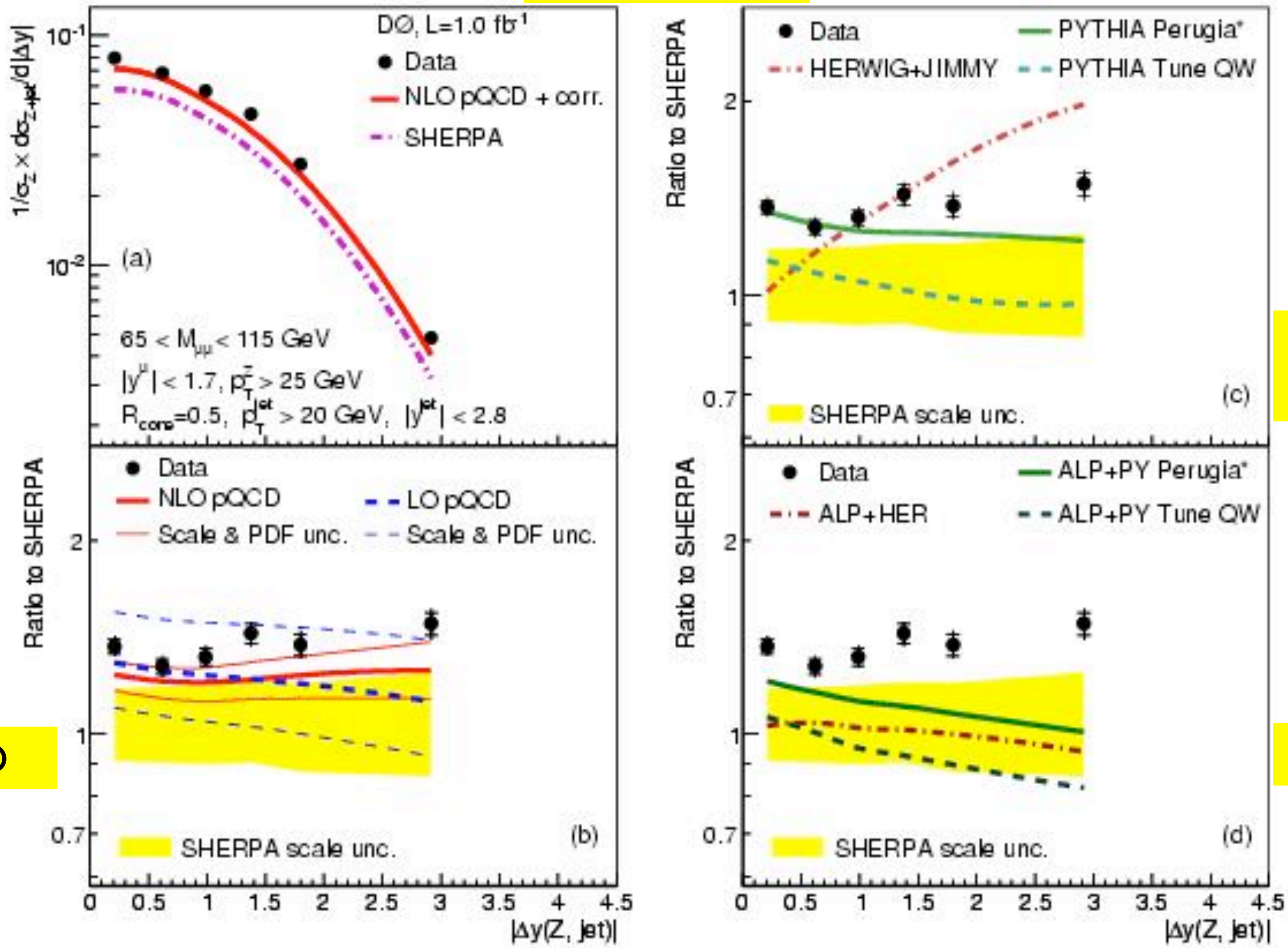
ALPGEN

‣ Variables particularly sensitive to QCD radiation

Z(→μμ)+jets: Angular Distributions

1.0 fb^{-1} Phys. Lett. B 682 (2010), 370

Z-jet opening



NLO

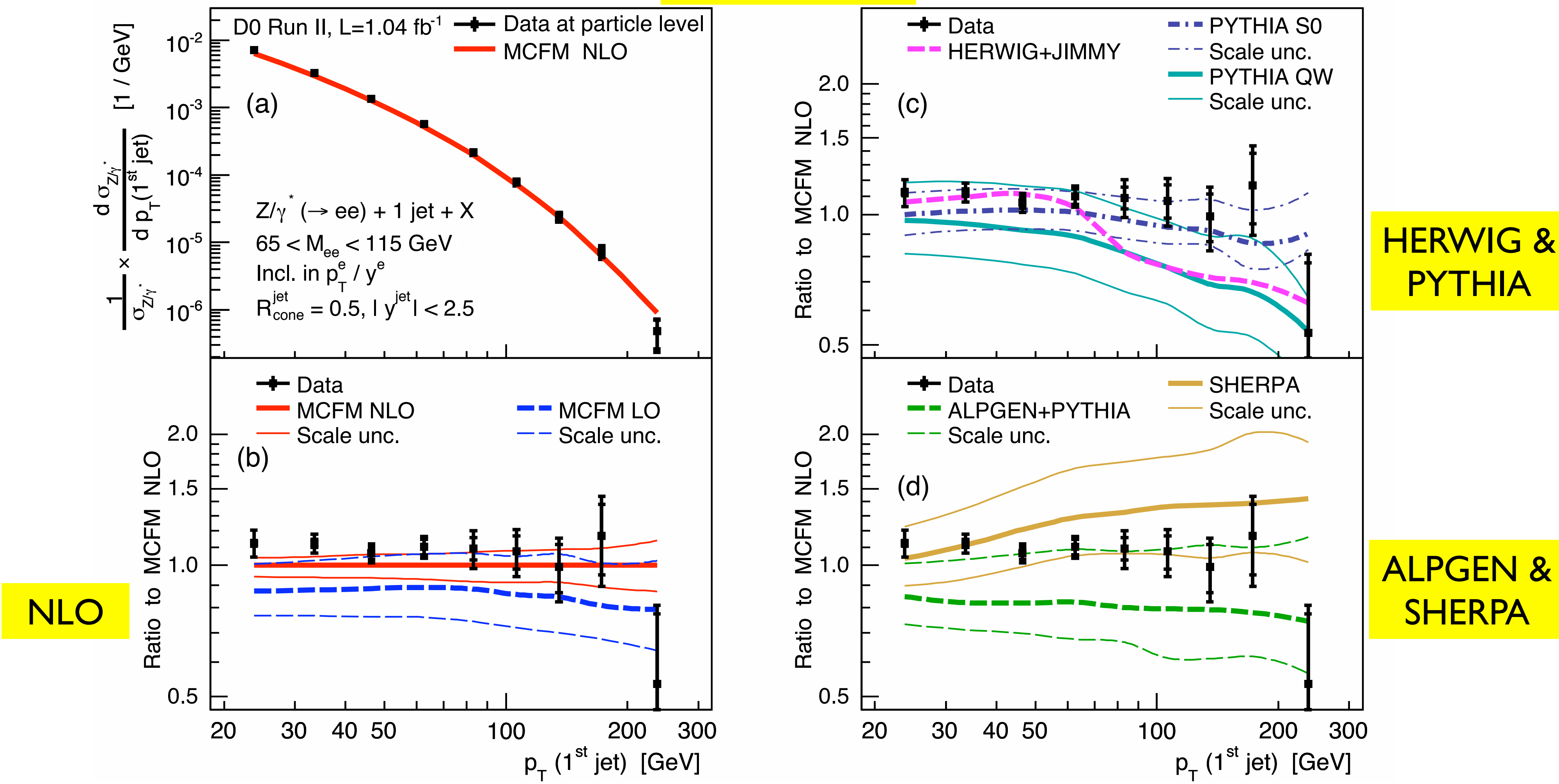
HERWIG & PYTHIA

ALPGEN

Z(→ee)+jets (1st jet)

1.0 fb⁻¹ Phys. Lett. B 678 (2009), 45

Jet pT (First Jet)

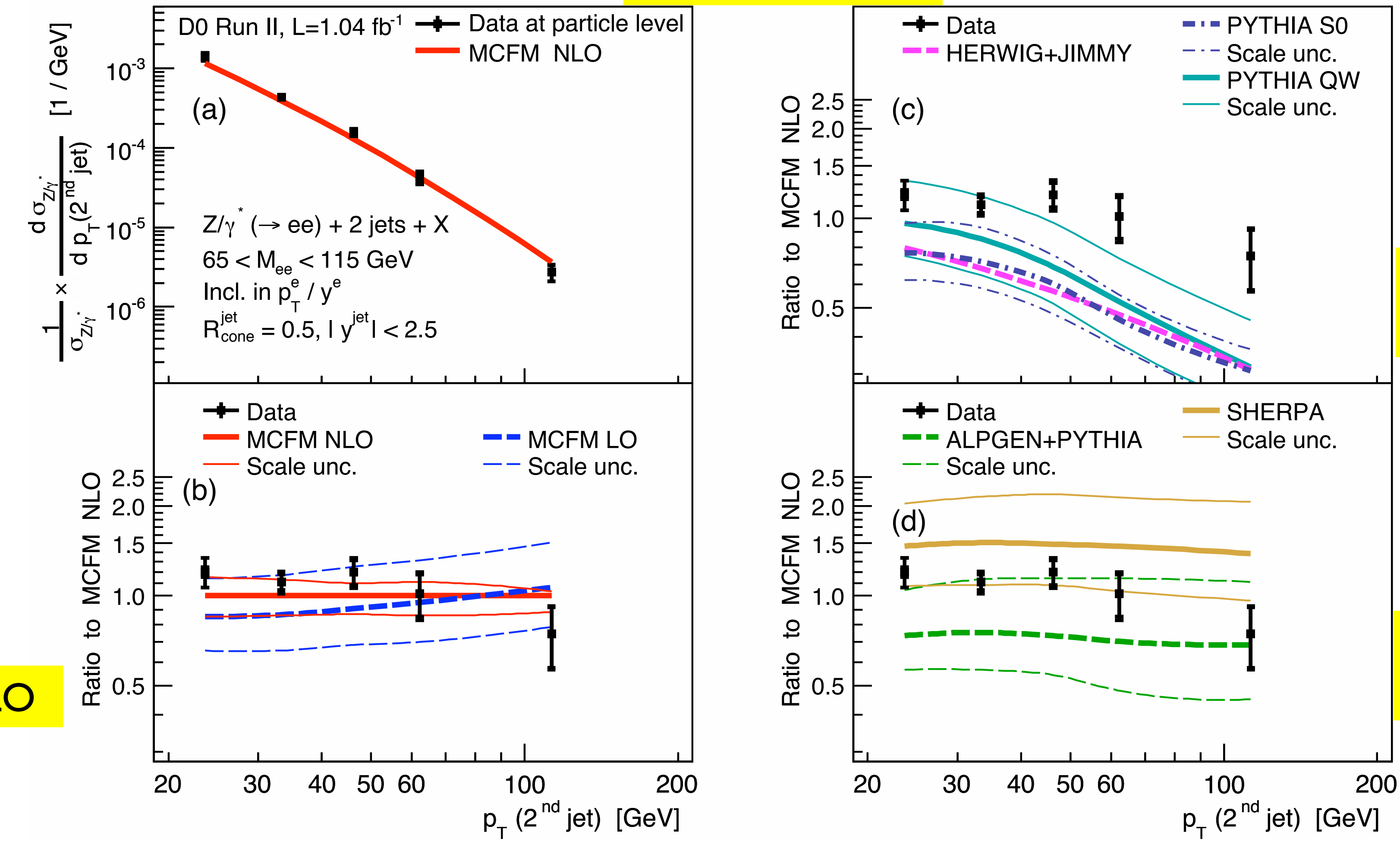


- Agreement with NLO within ~15%

Z(→ee)+jets (2nd jet)

1.0 fb^{-1} Phys. Lett. B 678 (2009), 45

Jet p_T (Second Jet)



NLO

HERWIG & PYTHIA

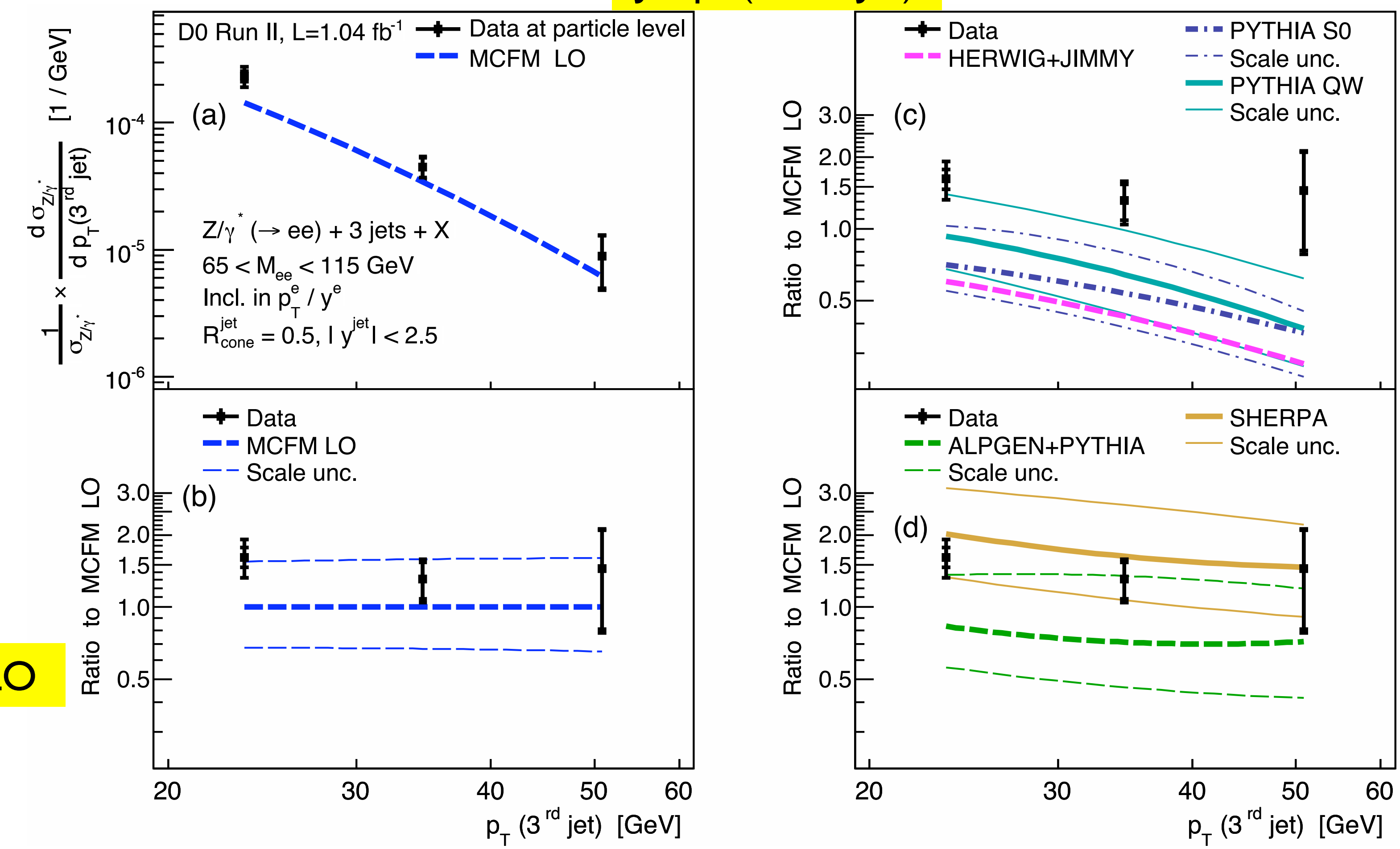
ALPGEN & SHERPA

- PYTHIA & HERWIG worsen for higher p_T
- ME+PS within ~40%

Z(→ee)+jets (3rd jet)

1.0 fb^{-1} Phys. Lett. B 678 (2009), 45

Jet p_T (Third Jet)



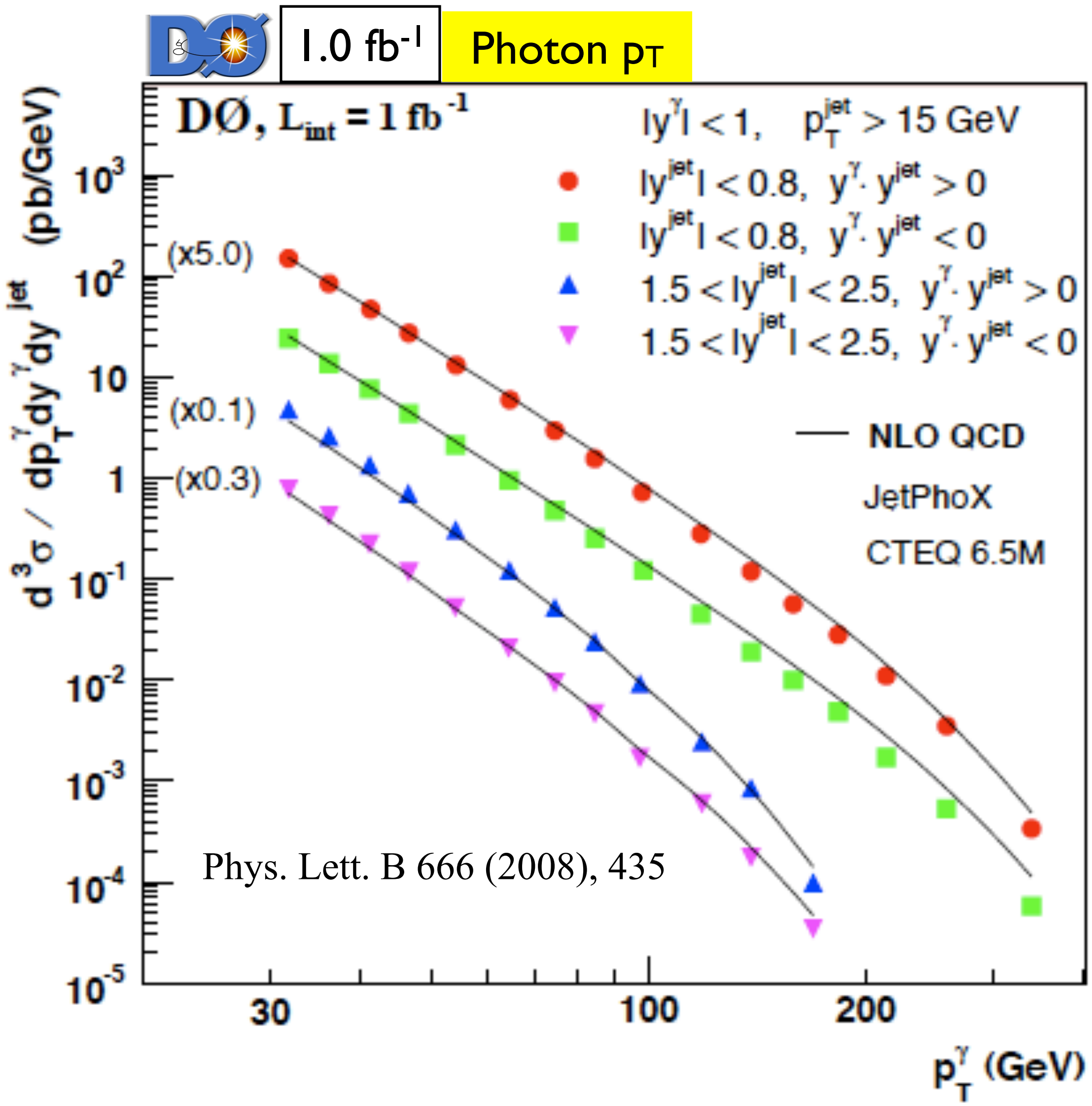
LO

HERWIG & PYTHIA

ALPGEN & SHERPA

‣ ME+PS within ~40%

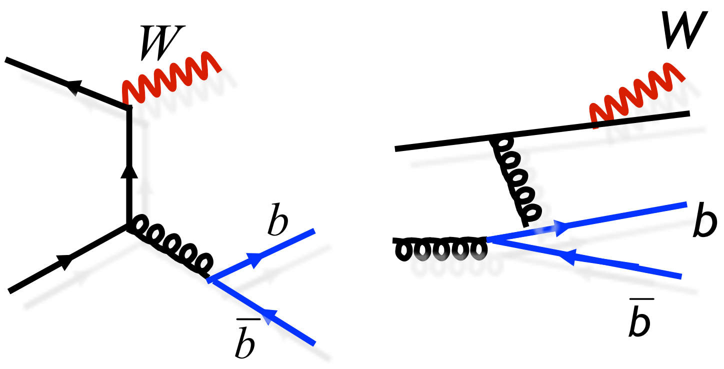
Photon+jets



- Good overall. Simultaneous description of these four regions in agreement only to within ~30-40%

V+ heavy flavour jets Measurements

W+bb+X

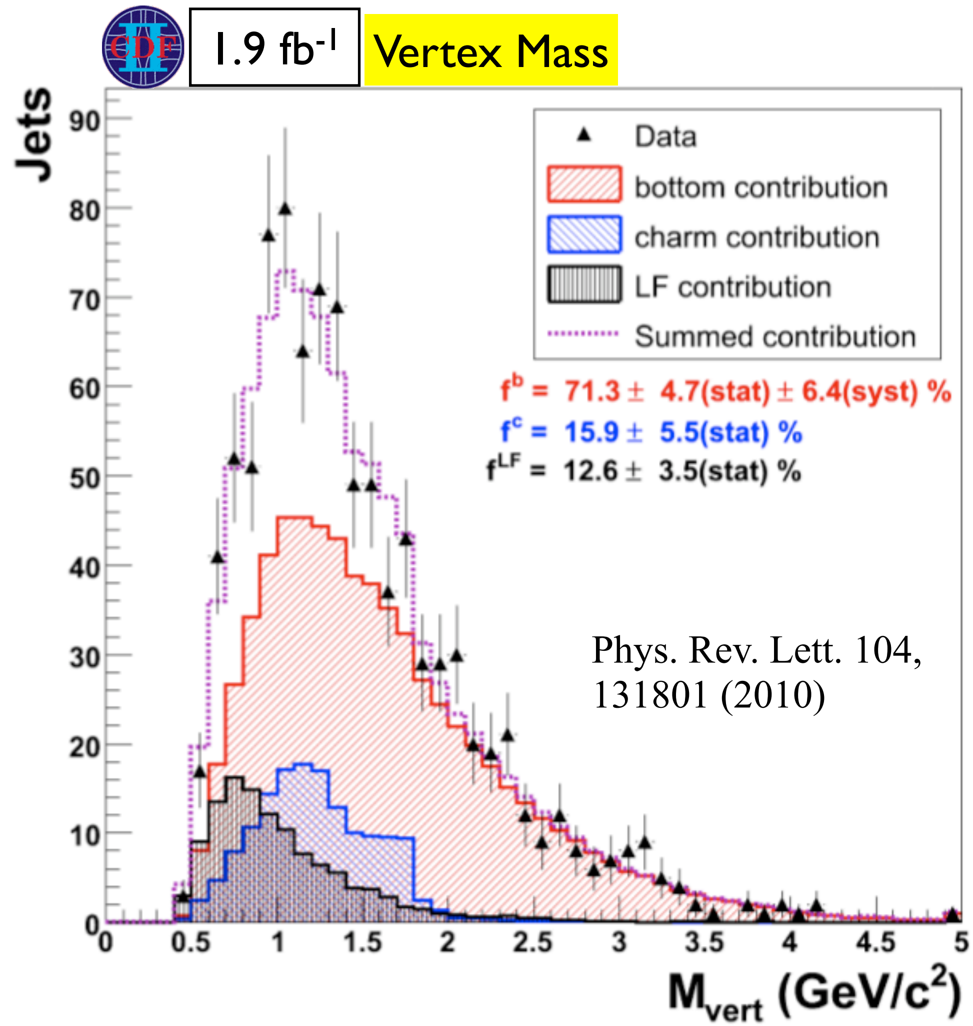


$$\sigma_{b\ \text{jets}} \times \mathcal{B}(W \to \ell\nu) = \frac{n_{\text{tag}} \cdot f^b - n^{b\ \text{jets}}_{\text{bkg}}}{\sum_{i=e,\mu} (\mathcal{L} \cdot \mathcal{A}^{b\ \text{jets}}_{W+b} \cdot \epsilon^b_{\text{tag}} \cdot \epsilon)_i}$$

S:B (*tt,t,non-W,..*) ~ 2.7

σ_{WbX}($p_{Te\mu}$>20 GeV/c, $|\eta_{e,\mu}|$<1.1, $p_{T\nu}$>25 GeV, $E_{T\,bjet}$ >20 GeV, $|\eta_{bjet}|$<2.0)×BR(W→lν) =

2.74 ± 0.27(stat) ± 0.42(syst) pb



Recent NLO calculation: σ·BR = 1.22±0.14 pb

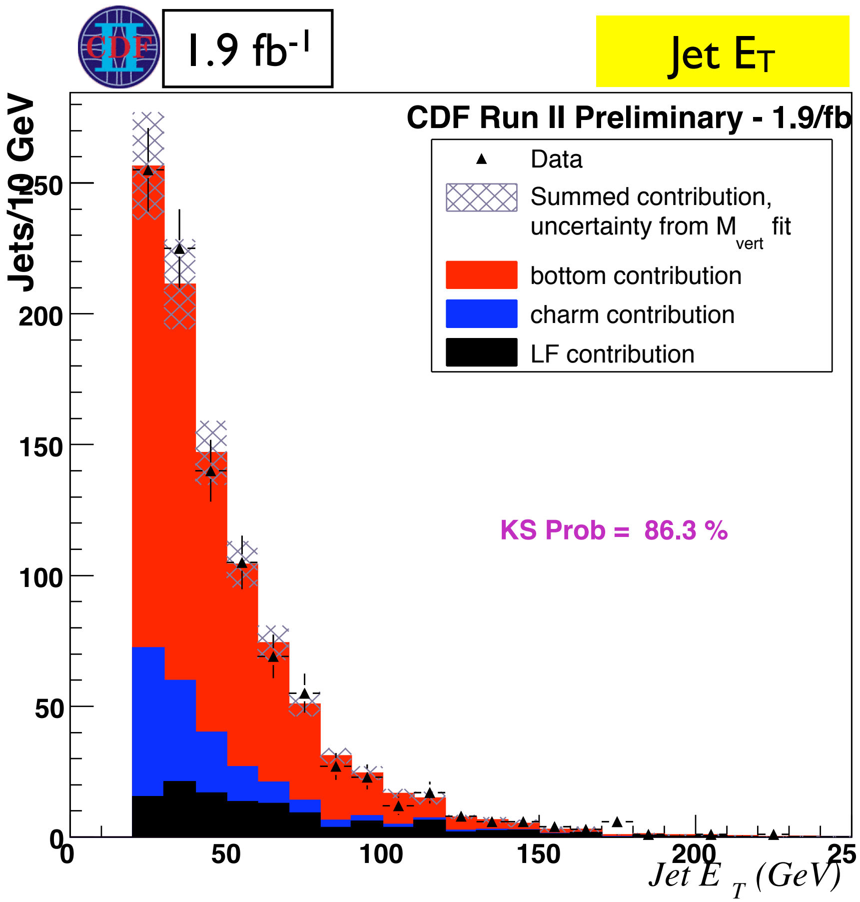
(J. Campbell, F. Febres Cordero, L. Reina, 2009)

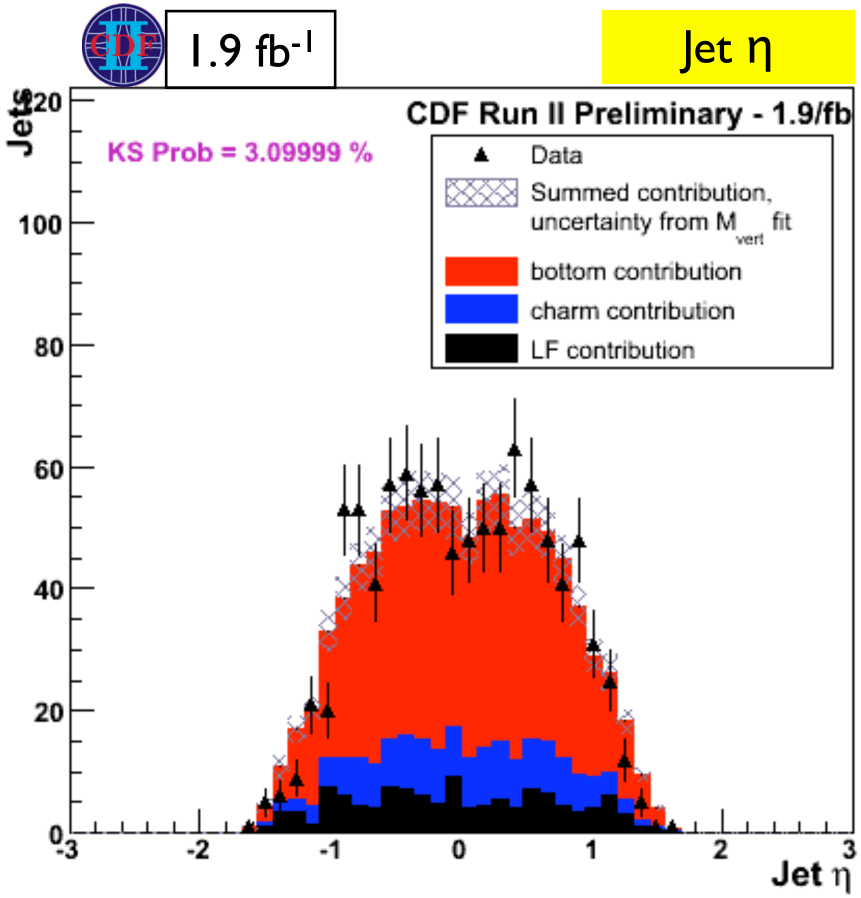
▸NLO and LO are factors of 2.5−3 (σ) lower

ALPGEN (LO): σ·BR = 0.78 pb

PYTHIA (LO): σ·BR = 1.10 pb

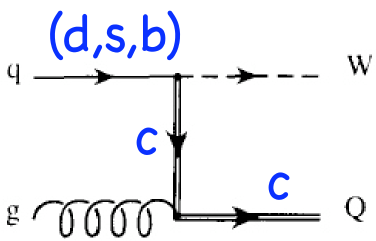
W+bb+X Shapes

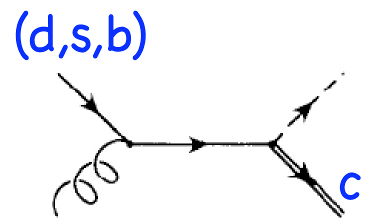




ALPGEN+PYTHIA shapes, good description

W+c+X





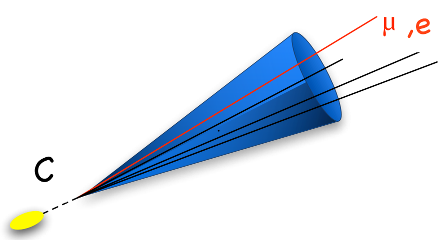
g+s~90%, g+d~10%

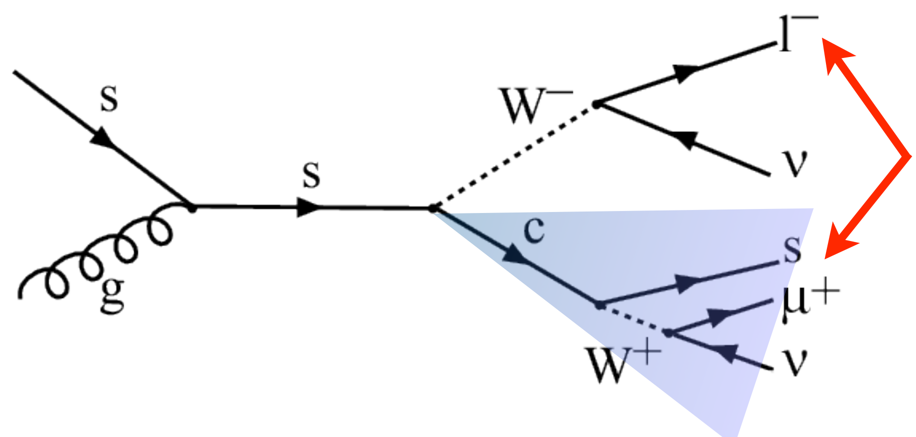
- Sensitivity to $|V_{cs}|$, s-PDF, scale: $\Delta\sigma_{TH} \approx \pm 30\%$
- Important background to top and Higgs analyses

We use the semileptonic decay (Soft Lepton Tag) of the charm:

1.8 fb^{-1} Phys. Rev. Lett 100, 091803 (2008)

Soft Lepton Tagging





W-SLT fully charge correlated

$P_T^\mu > 3$ GeV within $\Delta R < 0.6$ from the jet axis:

$$\sigma_{Wc} \times \mathrm{BR}(W \to \ell\nu) = \frac{N_{\mathrm{tot}}^{OS-SS} - N_{\mathrm{bkg}}^{OS-SS}}{Acc \cdot \int L \,\mathrm{dt}},$$

$\sigma_W \equiv \sigma_{W+c} + \sigma_{W-c}$

$p_{Tc} > 20$ GeV/c, $|\eta_c| < 1.5$

$\mathrm{BR}(W \to l\nu) = 0.108$

W+c+X - Backgrounds

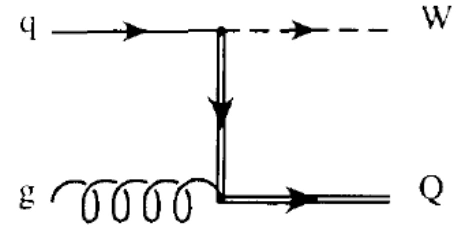
Backgrounds

TABLE I: Summary of data and charge-asymmetric background in the SLT-tagged $W + 1,\ 2$ jet sample.

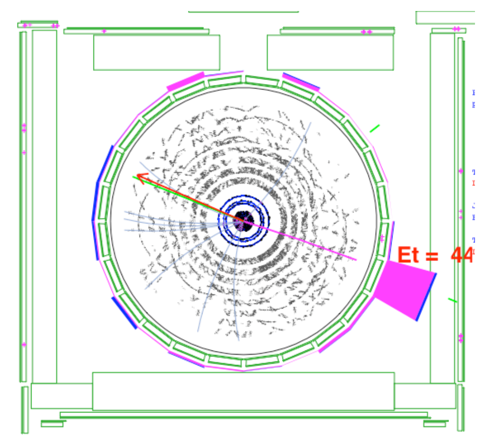
Source	Events	Asymmetry	OS–SS events
Drell-Yan			41.6 ± 5.4
Non-W (e PL)	200.0 ± 41.5	0.179 ± 0.046	35.8 ± 11.8
Non-W (μ PL)	30.2 ± 6.5	0.252 ± 0.066	7.6 ± 2.6
W + LF (e PL)	695.5 ± 75.7	0.057 ± 0.002	39.6 ± 4.9
W + LF (μ PL)	491.4 ± 53.3	0.019 ± 0.002	9.3 ± 2.0
Single top			7.6 ± 1.1
$Z \to \tau\tau$, WW			7.2 ± 1.2
Total Background			148.7 ± 15.4
Data	1824		298

Main OS−SS backgrounds

- Fake W
- W+light flavor jets



- Drell-Yan

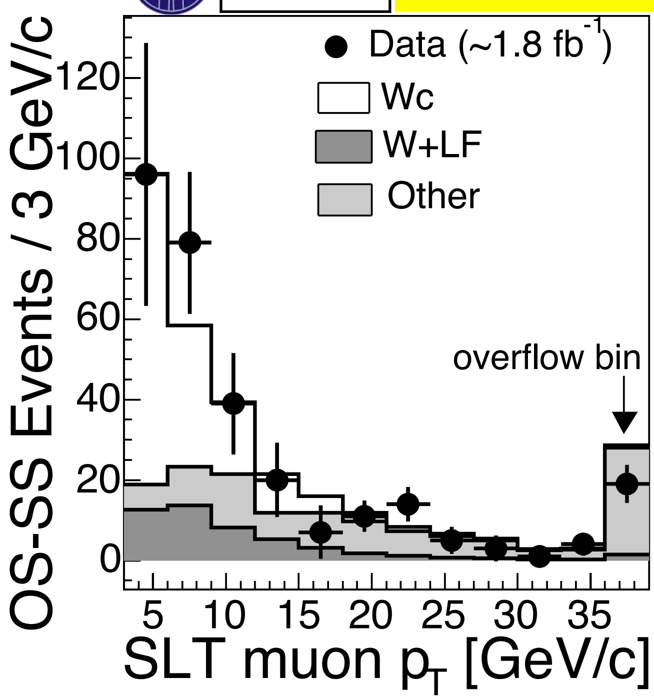


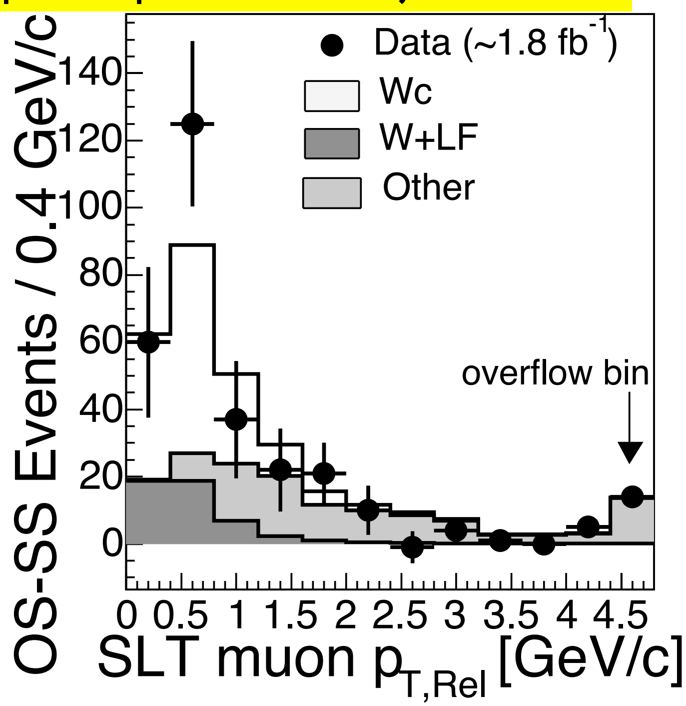
Wbb, Wcc etc. ~OS/SS symmetric

W+c+X - Results

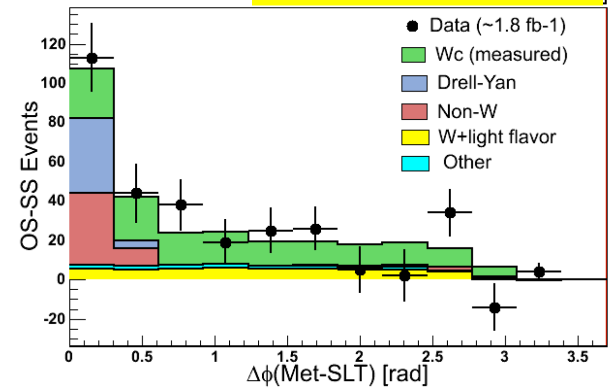
1.8 fb^{-1}

SLT muon p_T and p_T relative to jet axis

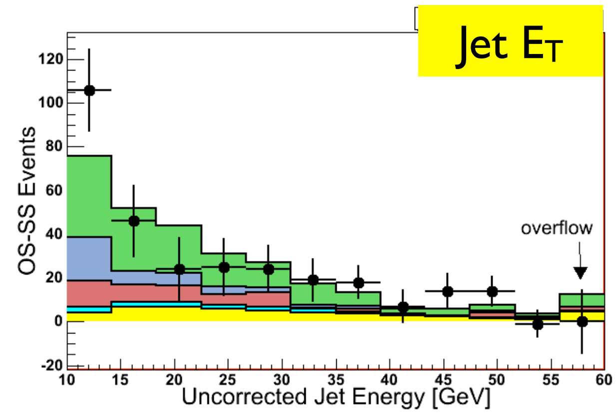




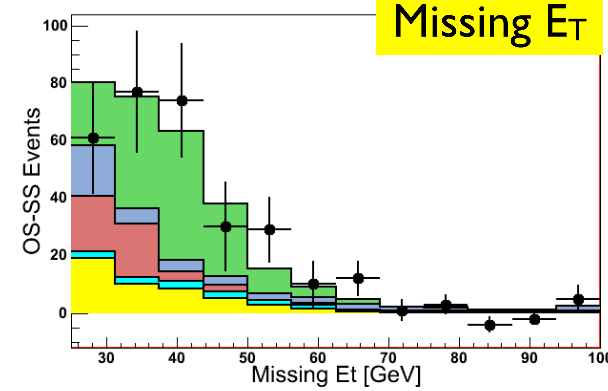
MET-SLT opening



Jet E_T



Missing E_T



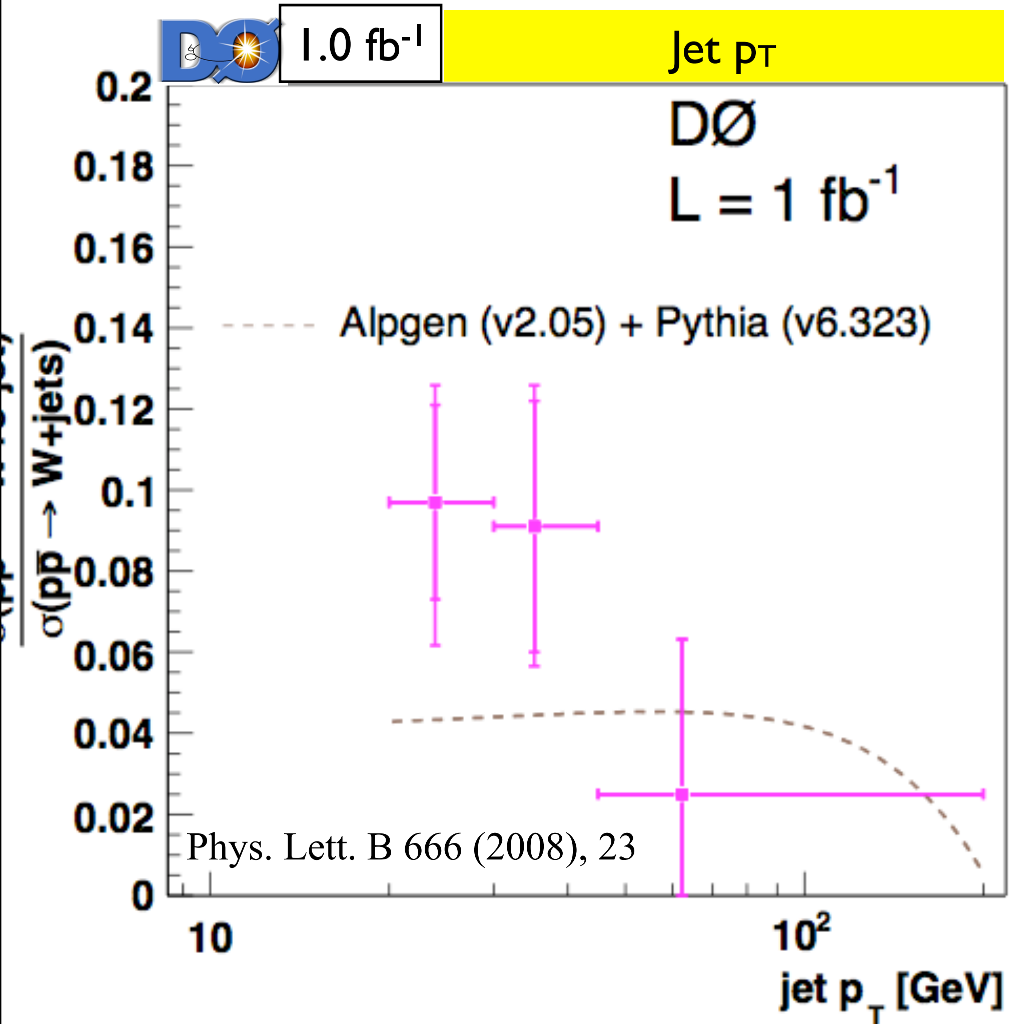
$\sigma_{Wc}(p_{Tc}>20\ \text{GeV/c}, |\eta_c|<1.5) \times BR(W\rightarrow l\nu)=$

$=9.8\pm2.8(\text{stat})^{+1.4}_{-1.6}(\text{syst})\pm0.6(\text{lum})$ pb

NLO (MCFM): $11.0^{+1.4}_{-3.0}$ pb

- Agreement with NLO within the uncertainty ($\Delta\sigma$~30%)
- ALPGEN+PYTHIA shapes, good description

W+c+X



D0 uses both e and muon soft leptons
For jets with p_T > 20 GeV, $|\eta|$<2.5

Measure the ratio $\sigma_{W+c}/\sigma_{W+jets}$.

$$\frac{\sigma\,[W + c\text{-jet}]}{\sigma\,[W + \text{jets}]} = 0.074 \pm 0.019(\text{stat.})^{+0.012}_{-0.014}(\text{syst.}).$$

LO (Alpgen+Pythia): 0.044 ± 0.003

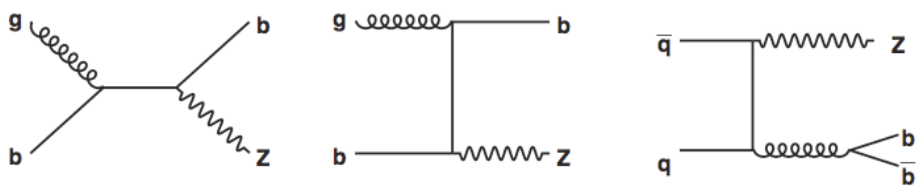
- Agreement within the uncertainty ($\Delta\sigma$~30%)

4.3 fb-1 **new** **SLT-e CDF Run II Preliminary**

$\sigma_{Wc}(p_{Tc}$>20 GeV/c, $|\eta_c|$<1.5)×BR(W→lν)=
=21.1 ± 7.1 (stat) ± 4.6(syst) pb

- Agreement with NLO within $\Delta\sigma$~30%

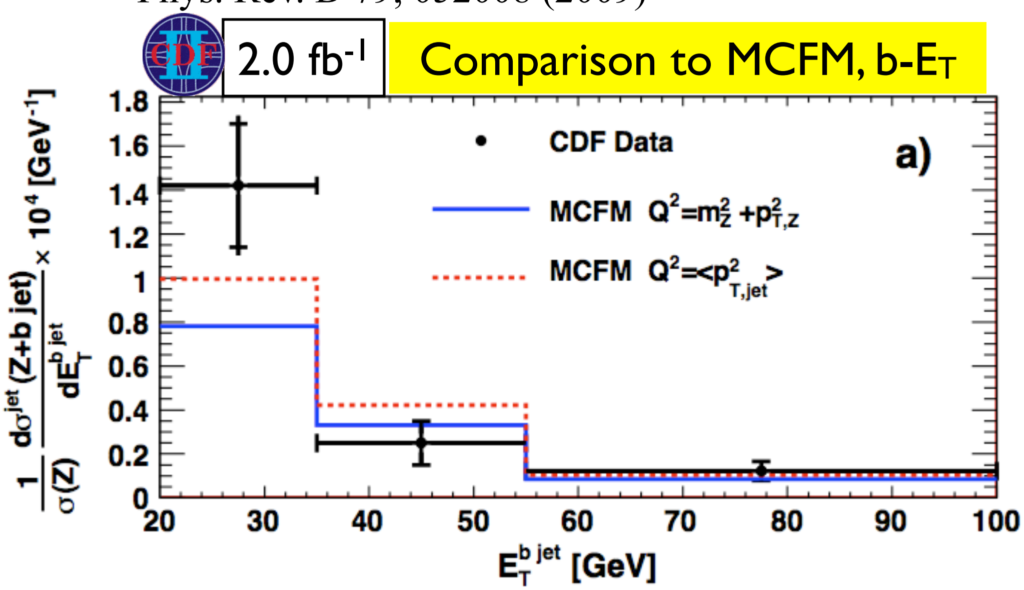
Z+b+X

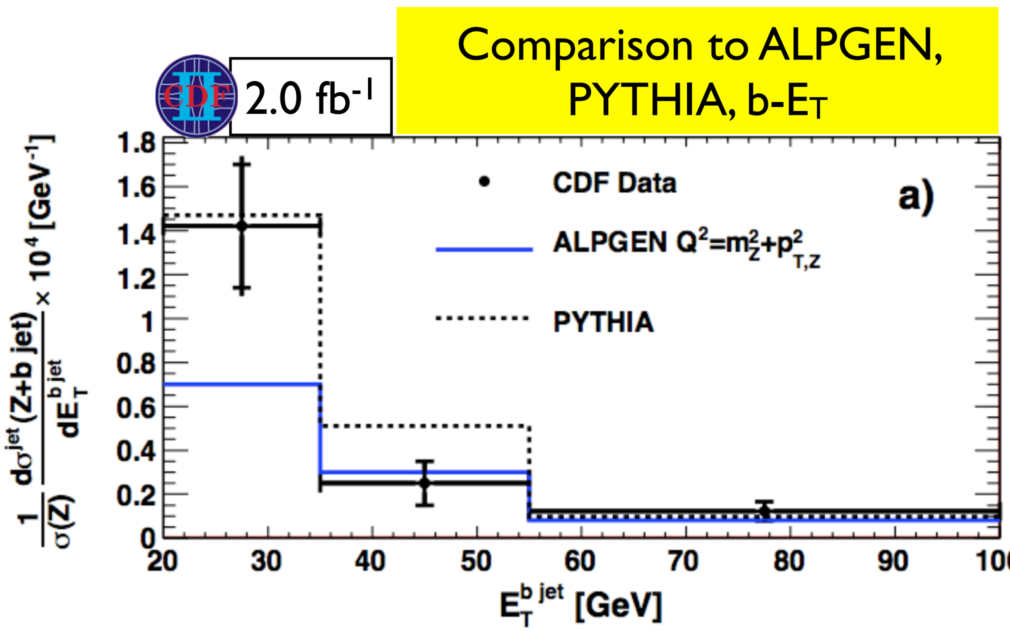


⇐ ~50%

jets with Et > 20 GeV
and |η| < 1.5, R=0.7

Phys. Rev. D 79, 052008 (2009)





$$\frac{\sigma^{jet}(Z+bjet)}{\sigma^{jet}(Z+jet)} = (2.08 \pm 0.33 \pm 0.34)\%$$

MCFM	1.8	$Q^2 = m_Z^2 + p_{T,Z}^2$
MCFM	2.2	$Q^2 = < p_{T,jet}^2 >$
ALPGEN	1.5	
PYTHIA	2.2	

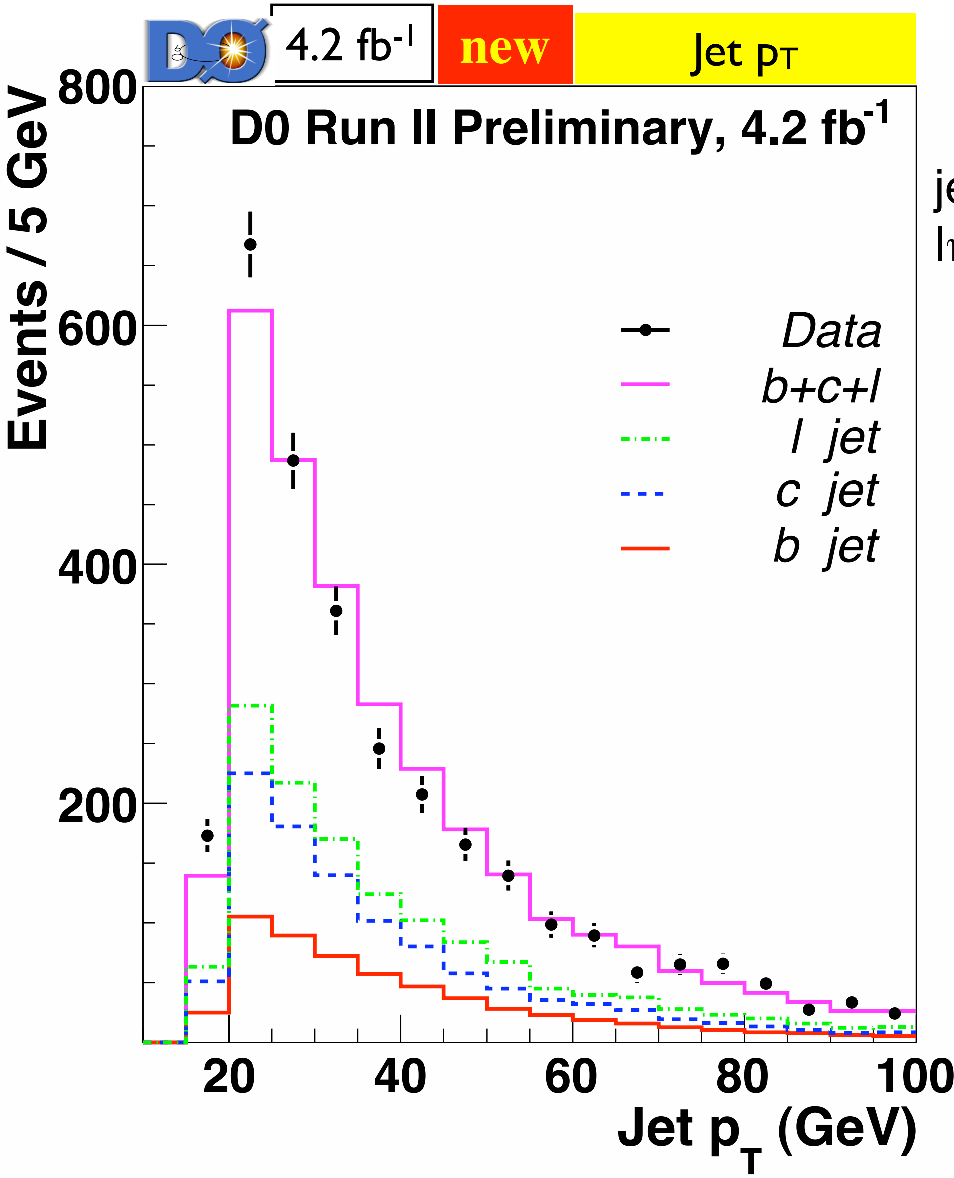
$$\frac{\sigma^{jet}(Z+b\,\text{jet})}{\sigma(Z)} = (3.32 \pm 0.53(\text{stat}) \pm 0.42(\text{syst})) \times 10^{-3}$$

MCFM	2.3×10^{-3}	$Q^2 = m_Z^2 + p_{T,Z}^2$
MCFM	2.8×10^{-3}	$Q^2 = < p_{T,jet}^2 >$
ALPGEN	2.1×10^{-3}	
PYTHIA	3.5×10^{-3}	

- NLO ok, low scale preferred. ALPGEN not so well

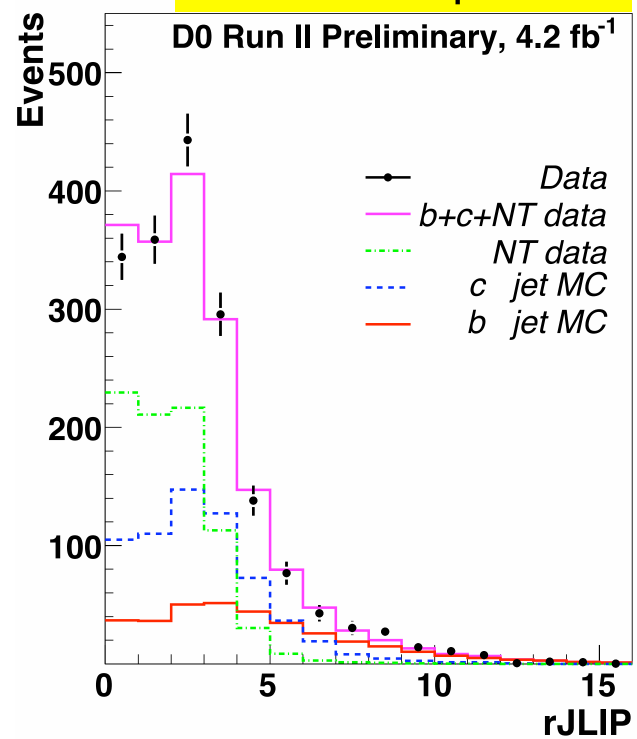
Z+b+X

supersedes Phys. Rev. Lett. 94, 161801 (2005)



jets with Et > 20 GeV
|η| < 1.1 R=0.5

NN Flavor separation

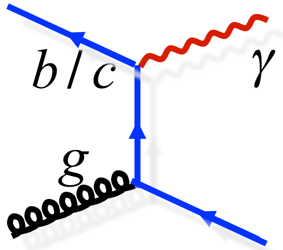


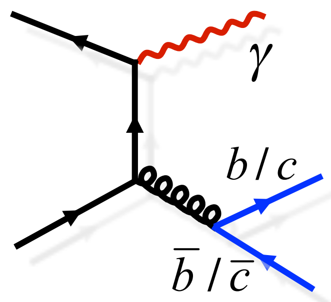
$$\frac{\sigma^{jet}(Z+bjet)}{\sigma^{jet}(Z+jet)} = (1.76 \pm 0.24 \pm 0.17)\%$$

MCFM $(1.84 \pm 0.22)\%$

- Agreement with NLO within Δσ~15%

ϒ + HF jets





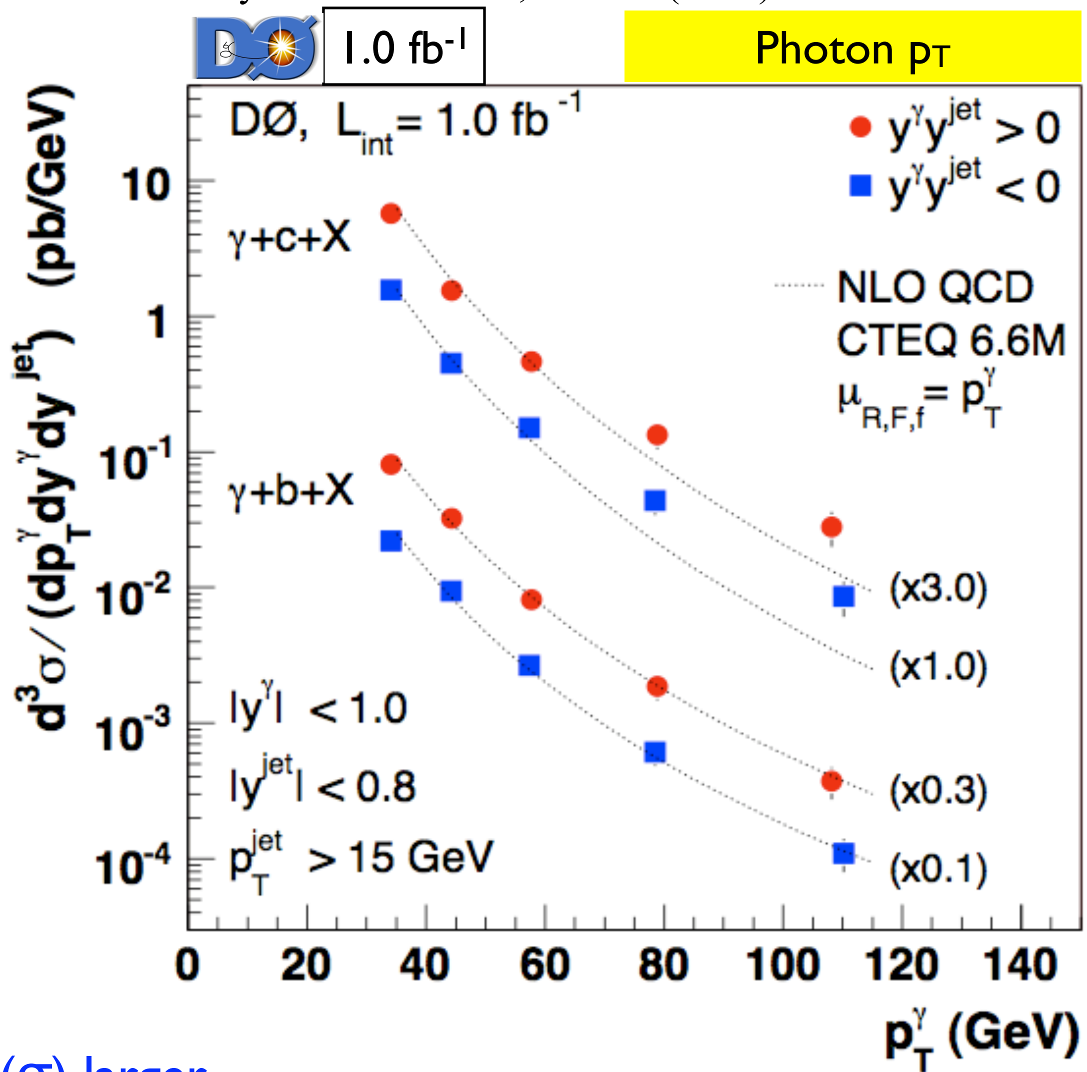
Sensitive to HF-content of proton
Bkgd for many BSMs

Photon p_T: 30 – 150 GeV
Jet p_T >15 GeV, cone 0.5, b-ANN
Rapidities: $|y^{\gamma}|<1.0$, $|y^{jet}|<0.8$

Photon+b:
Agreement over full p_T^{γ} range

Photon+c:
Agree only at $p_T^{\gamma}<50$ GeV, then a factor 2 (σ) larger
Disagreement increases with p_T^{γ}.

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



Summary

- All V+jets measurements agree with NLO pQCD to within the calculation uncertainties (15-20%) and for most relevant distributions
- Many shapes (not all) of ME+PS are in agreement, normalisation typically lower by ~40-60%
- Working to improve the Wbb and Wc cross section measurements

V+jets in Top analyses

"Method I, II, III" ±~30%

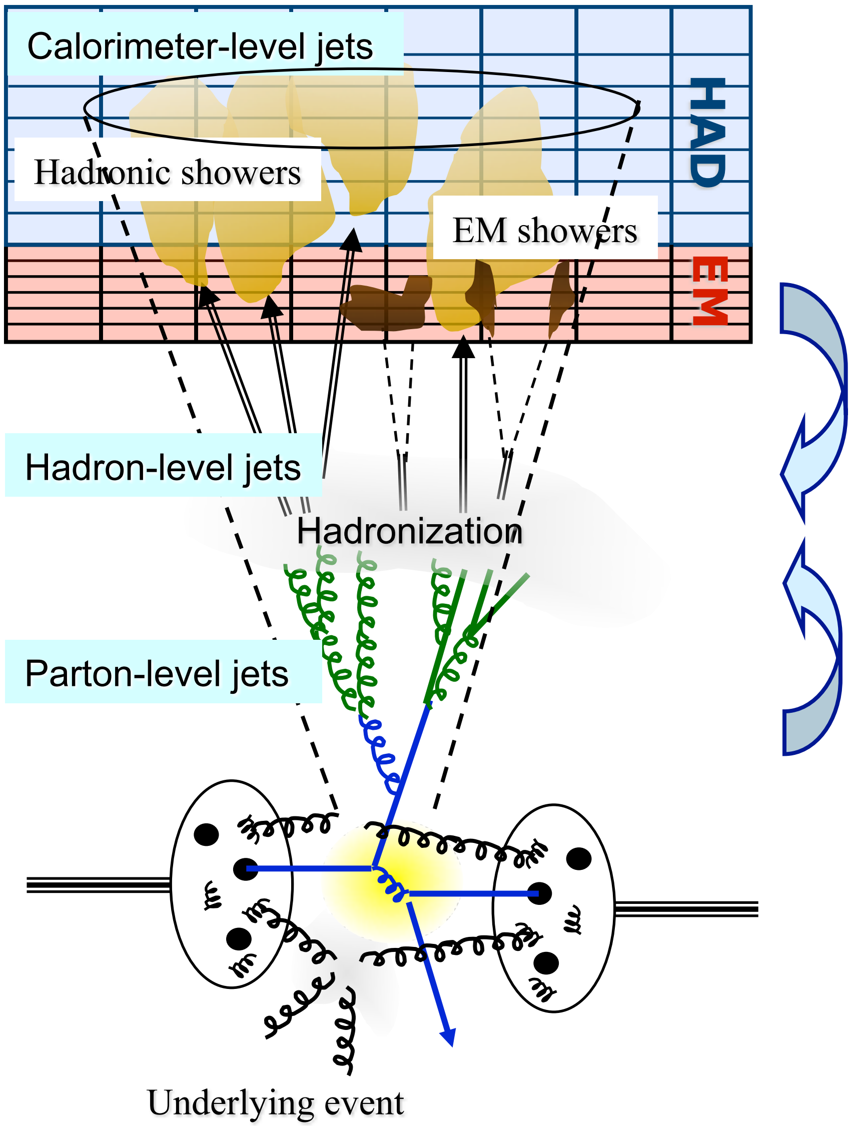
V+jets (inclusive)

1	W+jets	NLO within ~10-15%
2 3 4	Z(→μμ)+jets	NLO within ~10-15%
5 6	Z(→ee)+jets	NLO within ~10-15%
7	γ+jets	NLO good; $y_l \cdot y_j$ 40-50%

V+ heavy flavor jets

8	W+bb+X	NLO x2-3 (σ) low
9 10	W+c+X	NLO within $1\sigma_{exp}$ (~30%)
11	W+c+X/W+jets	NLO within $1\sigma_{exp}$ (~30%)
12 13	Z+b+X	NLO within $1\sigma_{exp}$ (~15%)
14	γ+b/c+X	NLO *b* ok, *c* x2 (σ) larger

Jet production and measurement



Unfold measurements to the hadron (particle) level (+dead material - MI energy)

Correct parton-level theory for non-perturbative effects
(hadronization & underlying event)

Jets are collimated spray of particles originating from parton fragmentation.
->To be defined by an algorithm