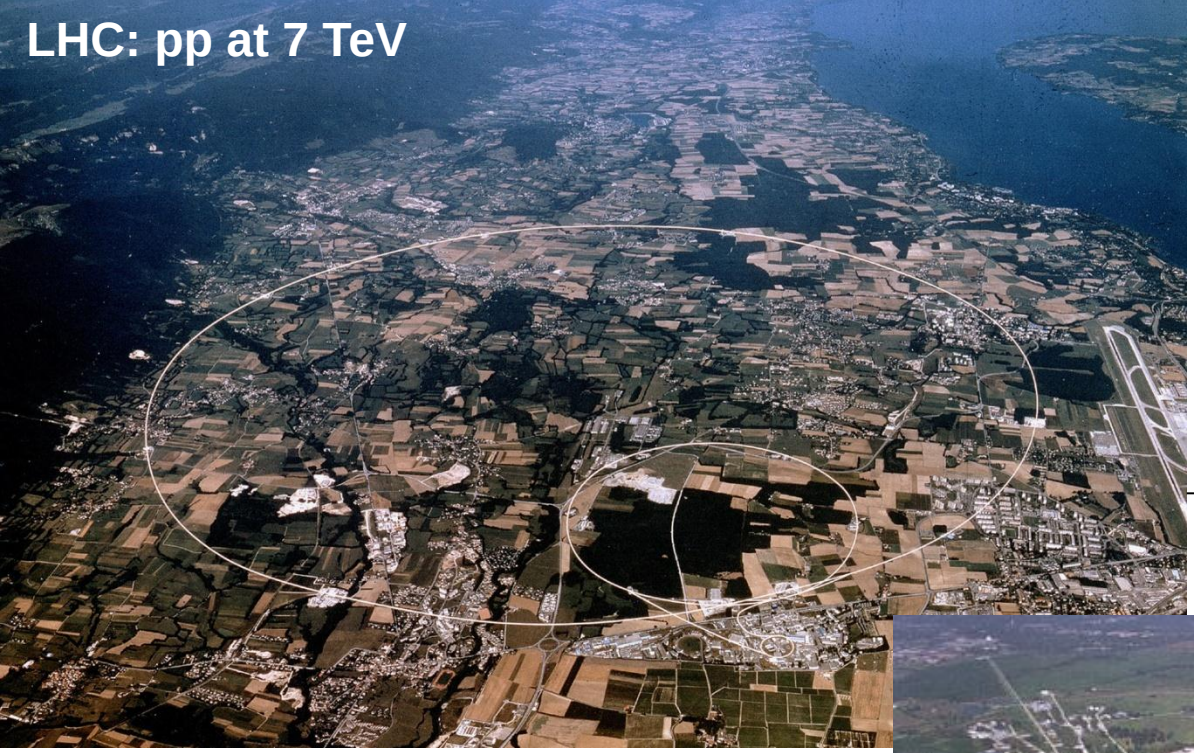


W/Z and Diboson production

S. Bolognesi (CMS-CERN)
on behalf of
ATLAS, CDF, CMS, D0 collaborations

Physics in Collision 2011
29 August 2011, Vancouver

Outline

- W,Z at hadron colliders (LHC, Tevatron)
  - their role and importance
  - their features: signature, main backgrounds

Note: leptonic decays only, no tau (see next-to-next talk)

- Inclusive cross section measurements
  - → status of theoretical calculations
  - impact of Parton Distribution Functions (PDF)
- Differential cross sections ($d\sigma/d\eta$, $d\sigma/dp_T$)
- V+jets measurement (also with Heavy Flavour)
- Diboson production: WW, WZ, ZZ, $Z\gamma$, $W\gamma$

Huge amount of results available → try to focus on most recent ones

Note: W/Z properties (W charge ratio, Z fwd-bwd asymmetry, W mass …) in next talk

W,Z role in hadron colliders

- **Commissioning:**

  clear signature and relatively well known physics → lepton scale/resolution, lepton efficiency, missing E_T scale/reso

- **Standard Model measurements:**

  - interesting by themselves (eg, Triple and Quadruple Gauge Couplings) and useful for global EWK fit (eg, m_W)
  - potential to constraint PDFs

  huge rate but in complex environment (eg initial state not completely known, Pileup, …)

  → real challenge for precision measurement is the control of systematics

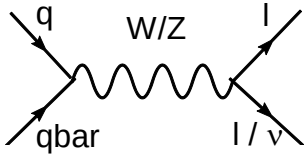
- **Background for New Physics searches**

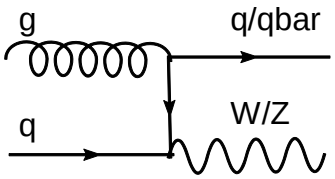
  eg, ewk WW, ZZ backgrounds to high mass Higgs

  eg, V+jets background to fully hadronic SuperSymmetry signals

W,Z production and decay

- Production:

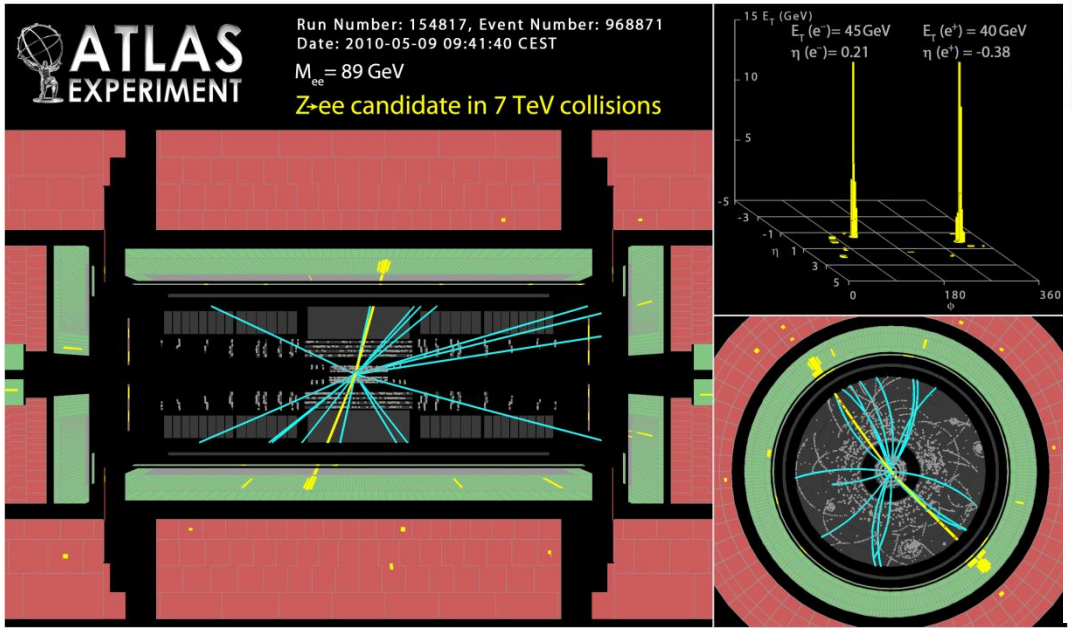


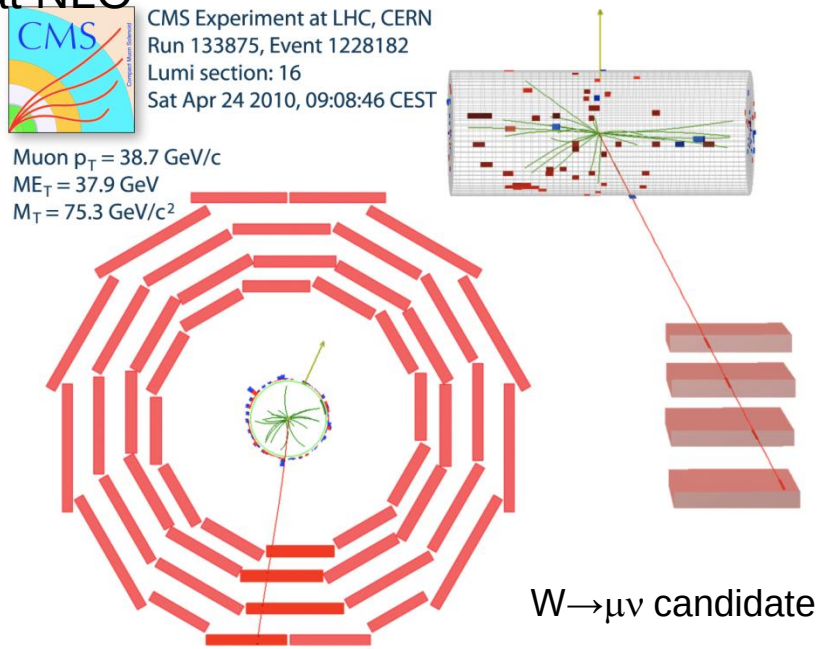


DY production at LO + NLO ….

- rate Tevatron: 3M W→ln per fb-1
- rate LHC: 10M W→ln per fb^{-1} (Z rate ~ 1/10 W rate)

- Signature: relatively high p_T, isolated leptons (trigger)
  missing E_T due to neutrino in W decay
  pileup / Underlying Event / jets at NLO

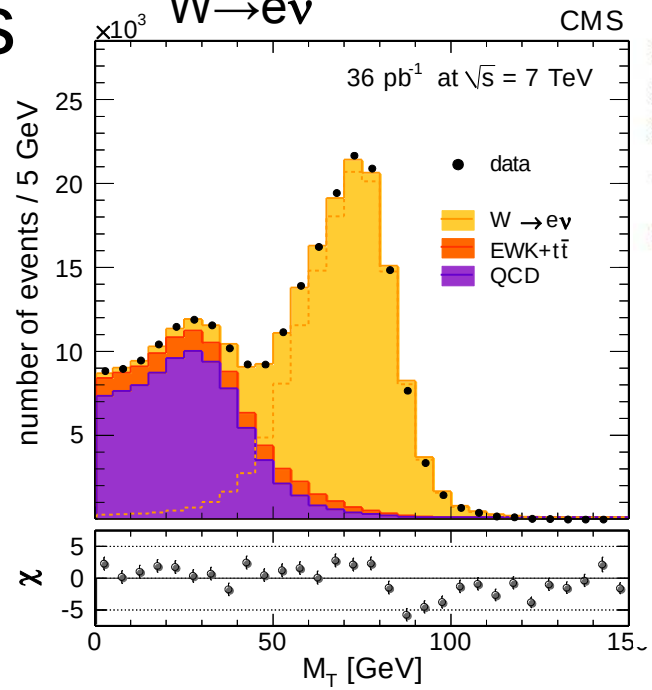




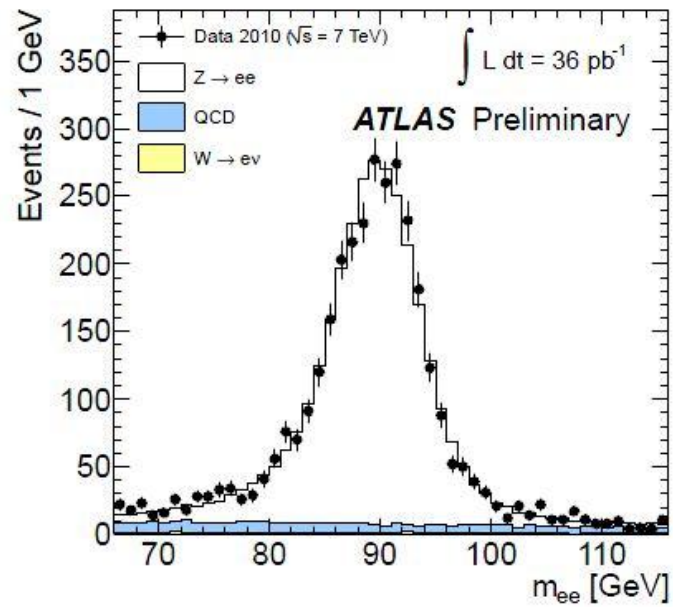
W→μν candidate

W, Z signal vs backgrounds

W→eν



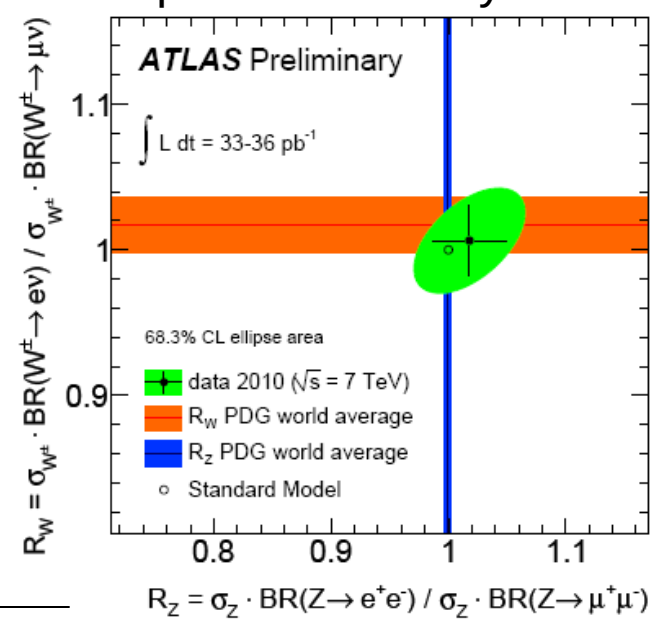
Z→ee



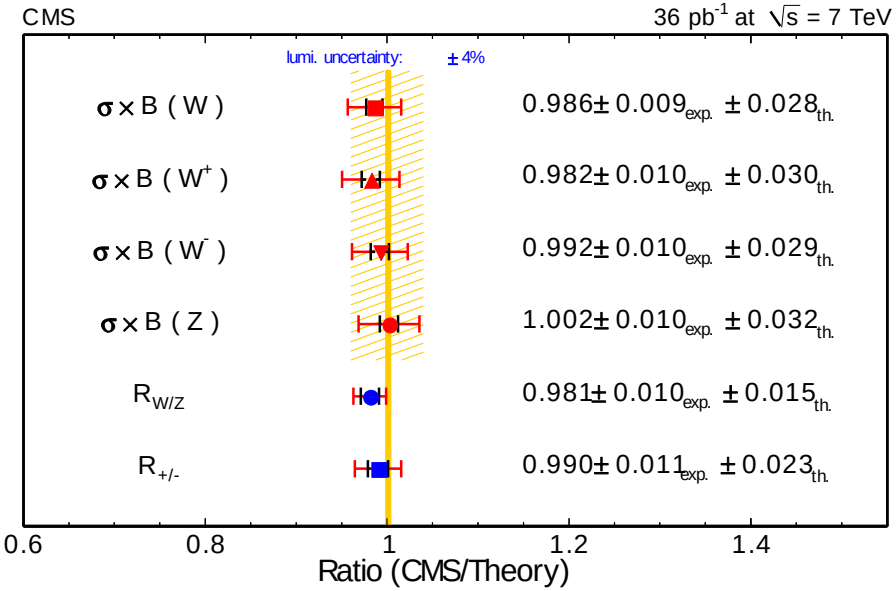
- **Signal extraction:**
  - W fit to missing ET or transverse mass
  - Z fit to dilepton invariant mass

- **Backgrounds:**
  - QCD with real or fake leptons
    - isolation
    - measures from data (control region)
  - EWK mostly from MC:
    - ttbar→WWbbbar
    - WW,WZ,ZZ
    - W→τν, Z→ττ with leptonic tau decay
    - Z with one lepton outside acceptance as background to W

lepton universality



Inclusive cross-sections



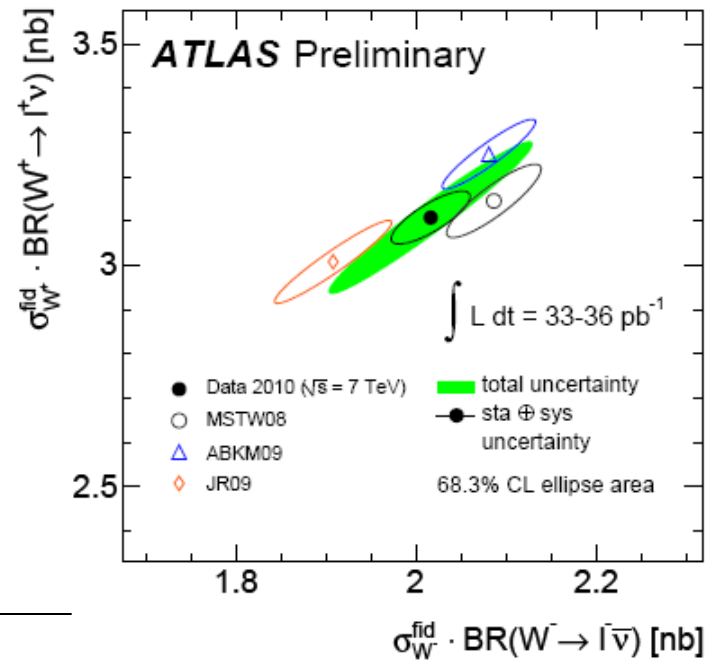
ATLAS (35 pb^{-1})

$$\sigma_W^{tot} \cdot BR(W \to l\nu) = 10.197 \pm 0.021(sta) \pm 0.127(syst) \pm 0.347(lum) \pm 0.165(acc) nb$$

$$\sigma_{Z/\gamma^*}^{tot} \cdot BR(Z \to ll) = 0.937 \pm 0.006(sta) \pm 0.009(syst) \pm 0.032(lum) \pm 0.016(acc) nb$$

- Measurement inside fiducial region gives constraints to PDF

- stat. error < experimental systematics < theoretical uncertainties
  - exp syst dominated by lepton efficiencies and missing E_T resolution
  - fixed order calculation:
    QCD NNLO, ISR-FSR, EWK NLO, scale
  - PDF syst on acceptance

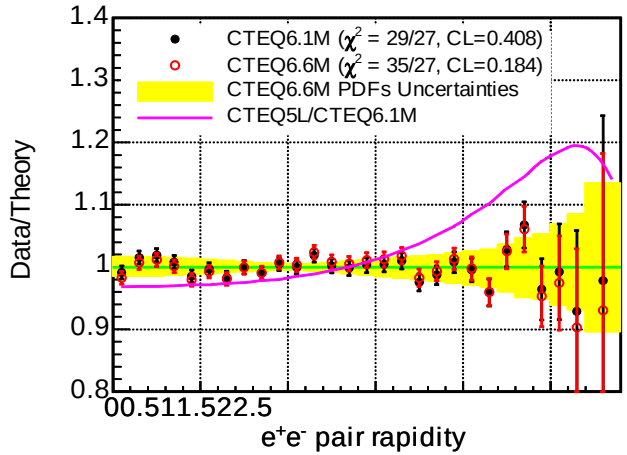


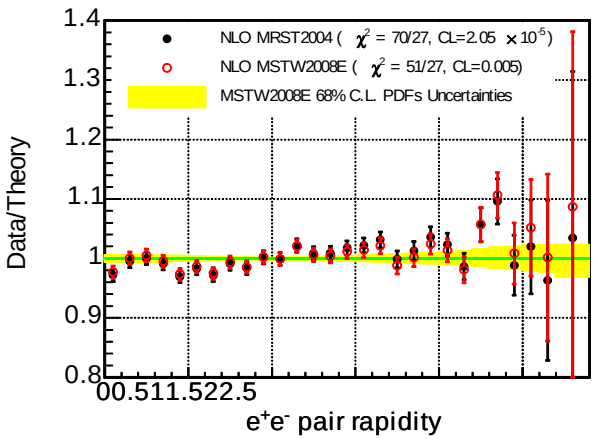
PDF: Z dσ/dy

$$m_{W/Z}^2 = s x_1 x_2 = \hat{s}$$

$$y_{W/Z} = 1/2 \ln(x_1/x_2)$$

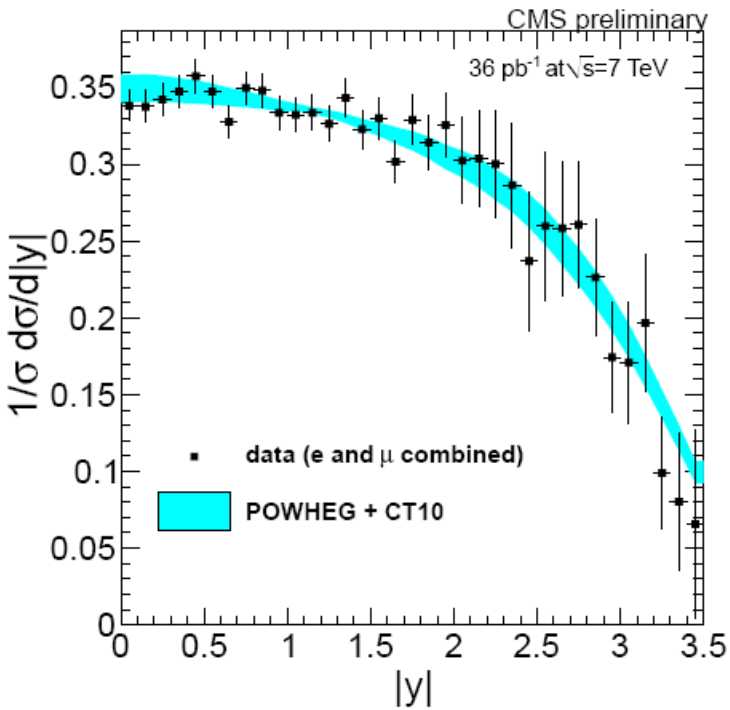
- **Tevatron** (ppbar @ 1.96 TeV): CDF 2fb-1 dataset

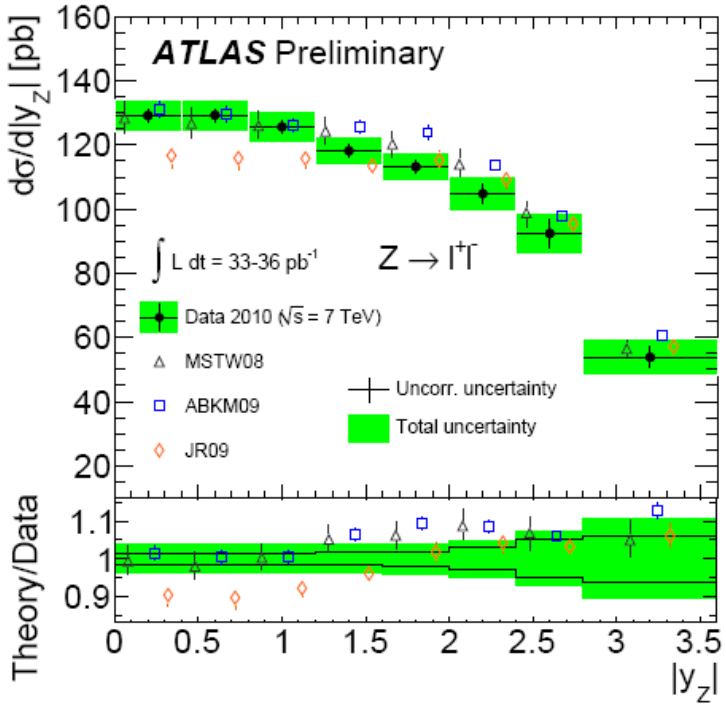


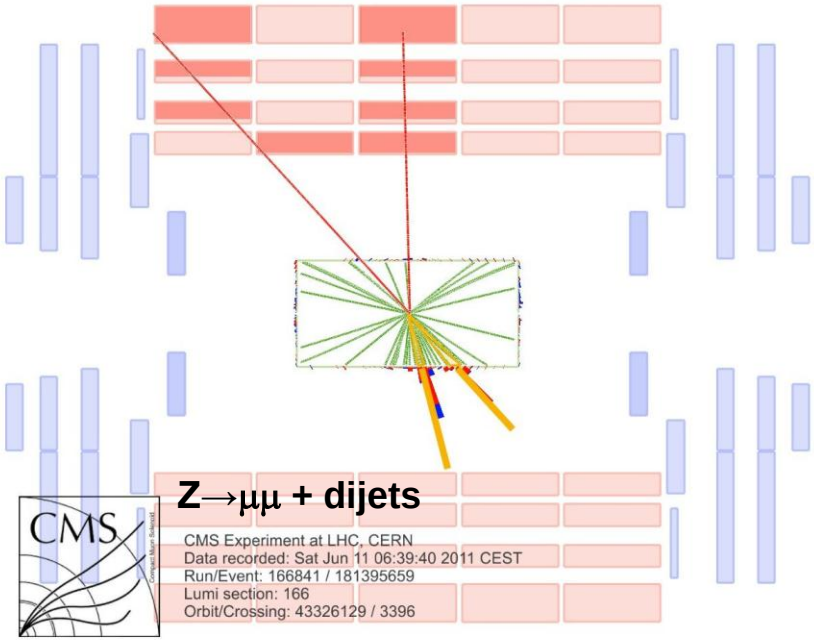


- **LHC** (pp @ 7 TeV):

10^{-3}<x<0.1 → gluon PDF dominate







Beyond Leading Order

- **Measurement of additional recoiling jets is direct probe of NLO and above**
- **P_T of the bosons is indirect measurement but more clean:**

- **low p_T**: dominated by non-perturb. effects and multiple soft gluon radiation
- **high p_T**: dominated by hard gluon emission well described by perturbative-QCD

- Available theoretical tools
  - Fixed order:

    Powheg, MC@NLO, MCFM: NLO
    FEWZ, DYNNLO : NNLO
    ResBos : NNLO (K factor) + NNLL
    Horace : EWK NLO
    BlackHat NLO up to 4 jets

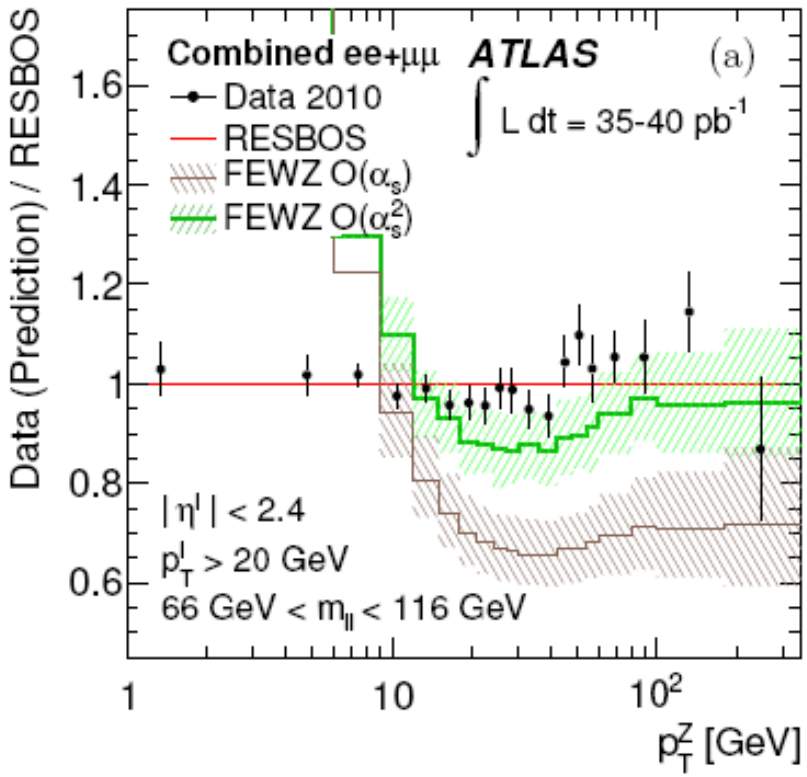
  - Matrix Element for hard/real emission up to high multiplicity
    Alpgen, Madgraph, Sherpa
    +
    matched with parton shower for soft/non-perturbative part
    (Pythia, Herwig)

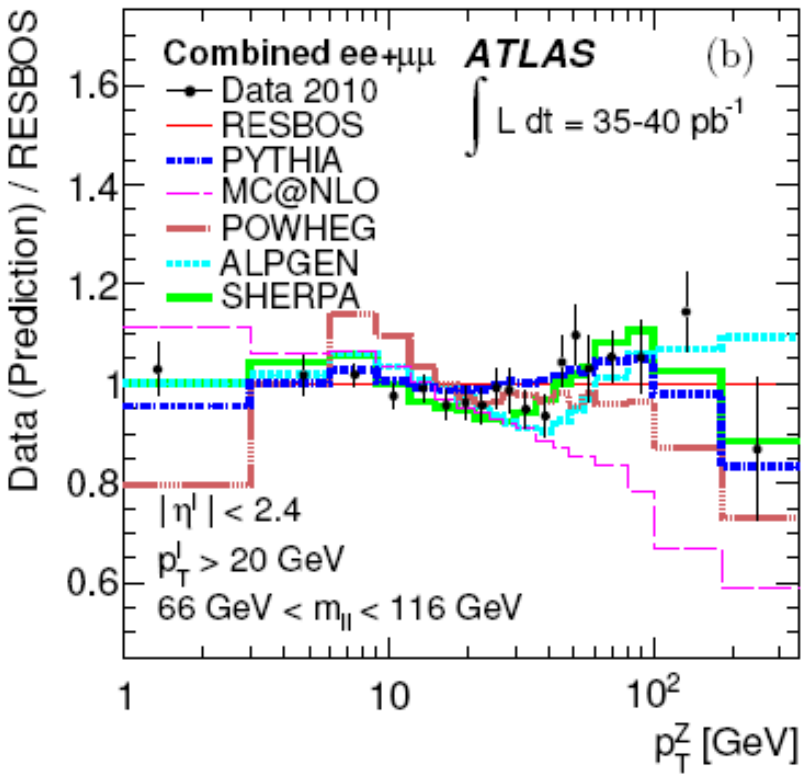
    TO BE TUNED from data

(matching with Photos for FSR, Pythia for shower and hadronization)

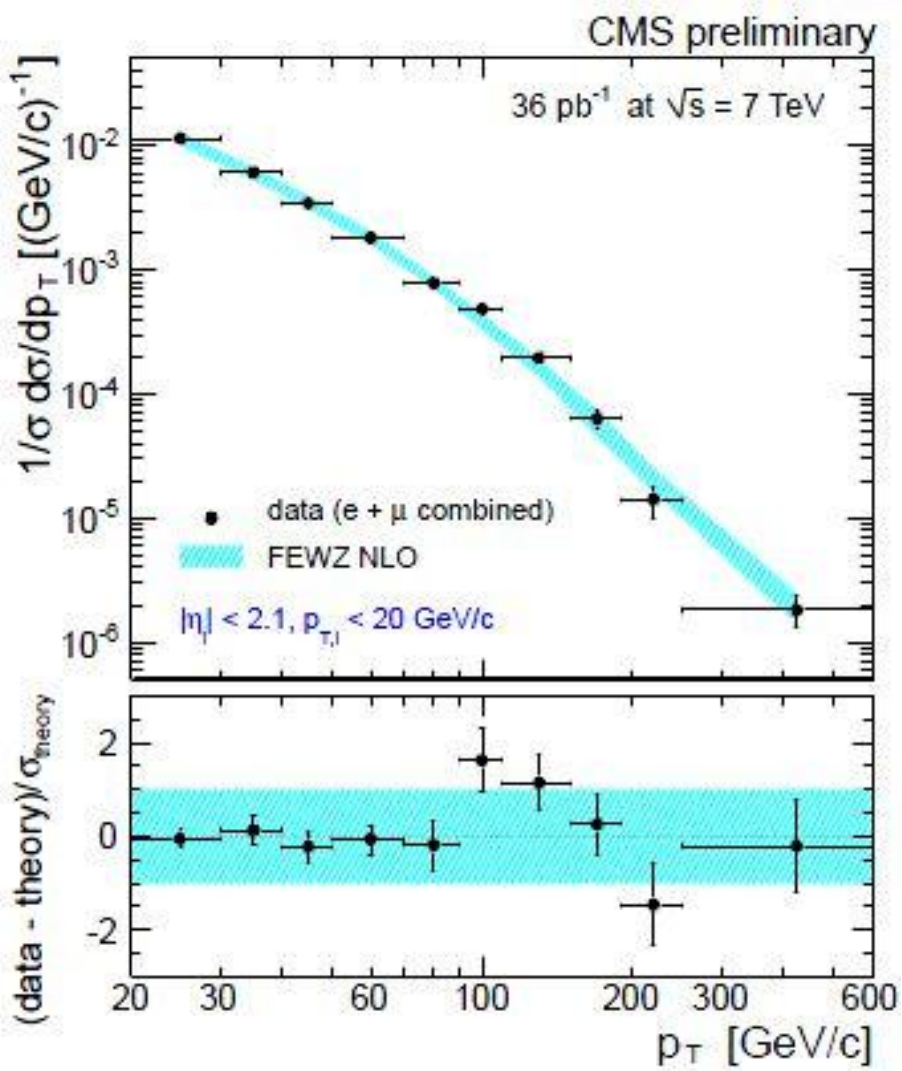
Z $1/\sigma\ d\sigma/dp_T$ measurement (ATLAS)

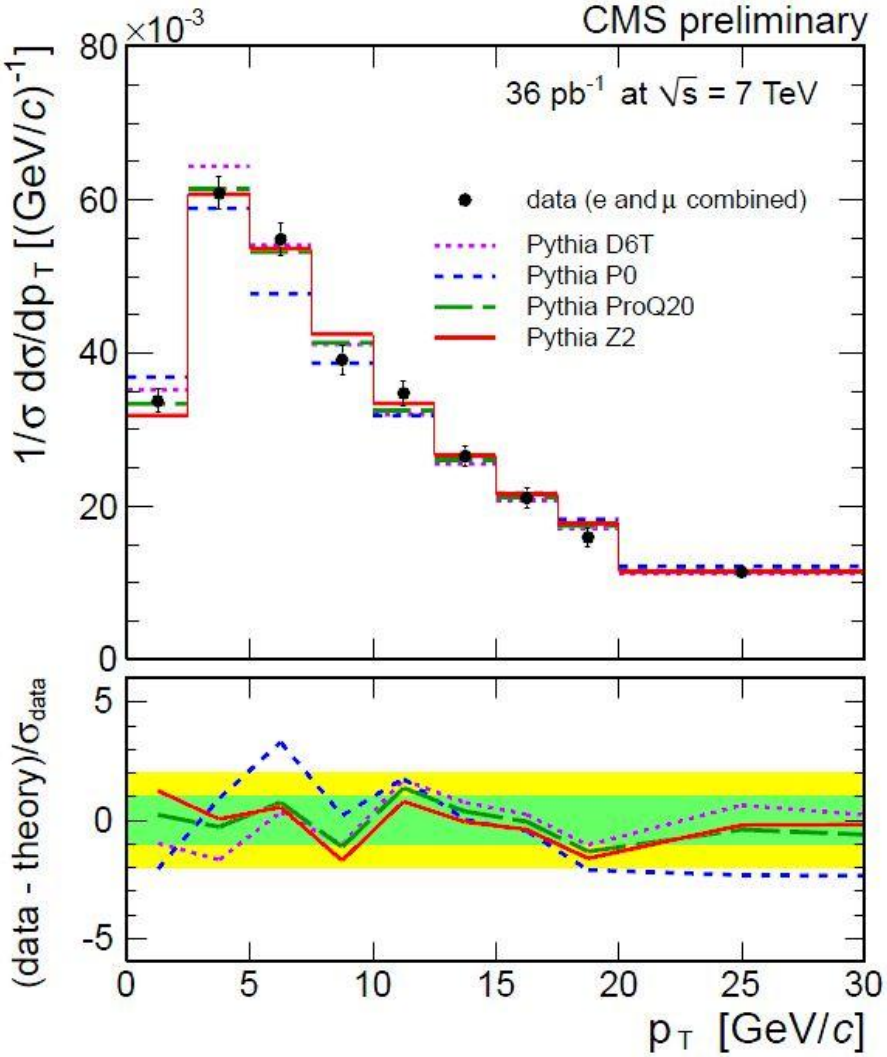
- Normalized differential xsec inside fiducial region (to minimize PDF uncertainty)
- Unfolded for detector effects and FSR





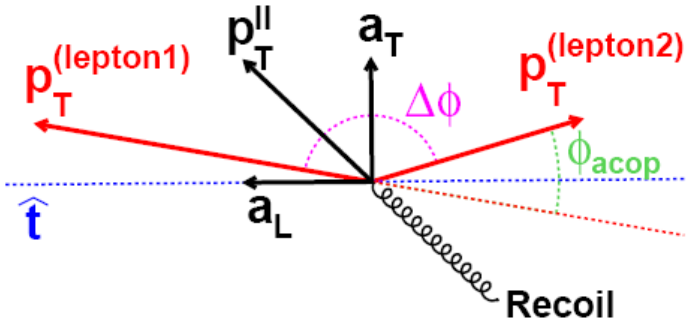
Z $1/\sigma\ d\sigma/dp_T$ measurement (CMS)





New D0 measurement

- Novel technique:



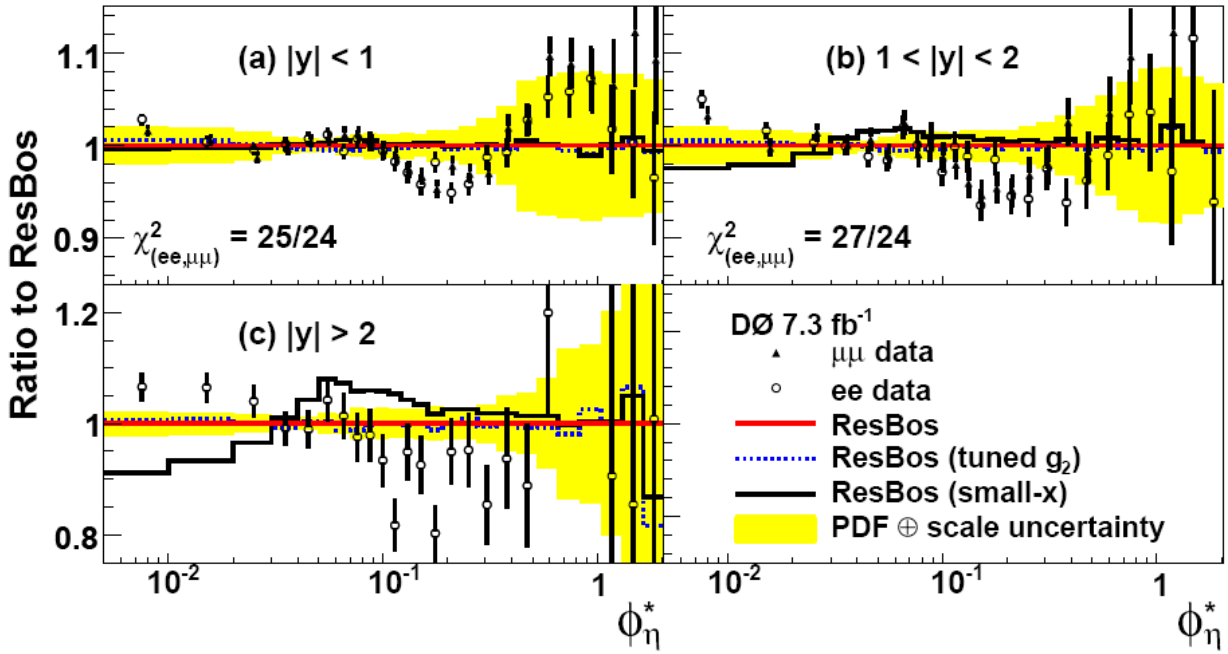
- a_T is most sensitive to Z production
- a_T/m(ll) to remove scale/resolution systematics

→ **pure angular variable**

$$\phi_\eta^* = \tan(\phi_{acop}/2)\cdot\sqrt{1-\tanh^2\left[\left(\eta^- - \eta^+\right)/2\right]}$$

- Maximum sensitivity with minimum systematics

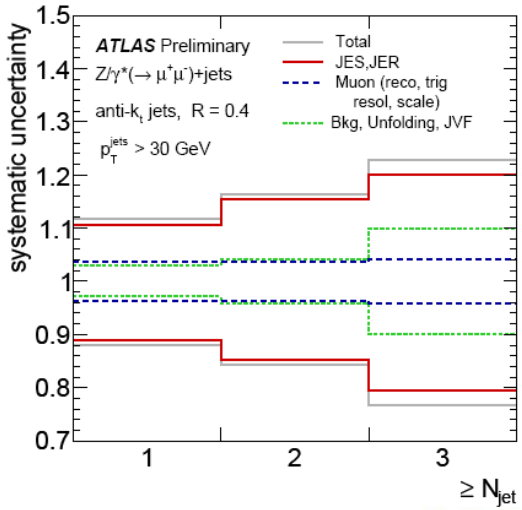
(angular resolution measured from cosmics)

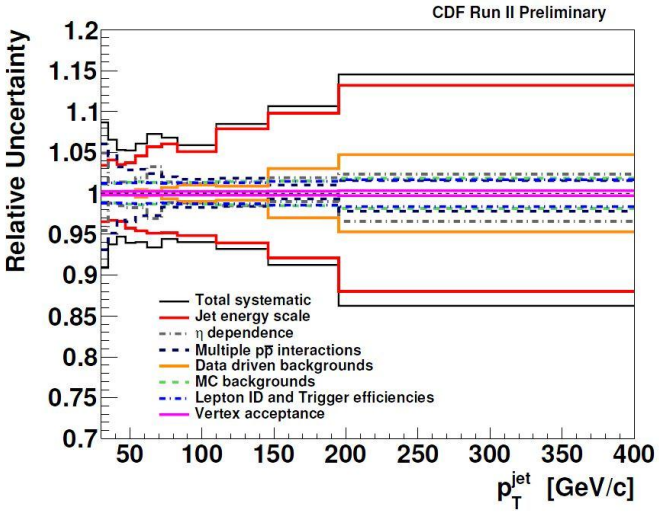


V+jets

- **QCD measurement** (jet p_T>20-30 GeV):

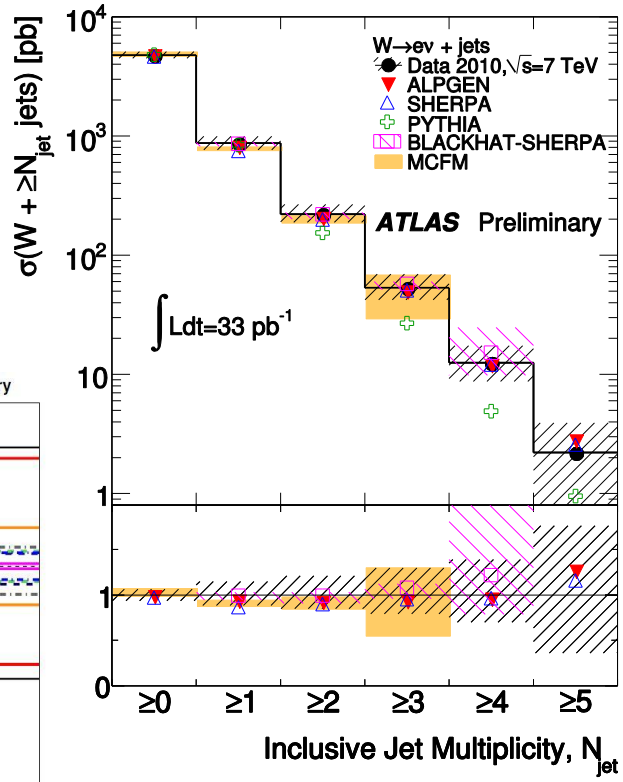
  → syst. dominated by jet scale, PileUp removal

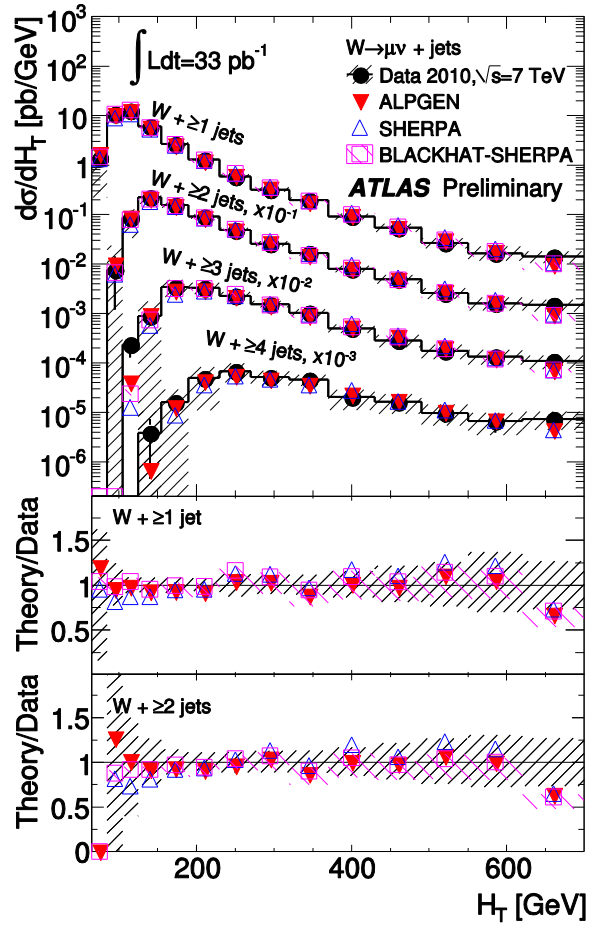




- Data unfolded for detector effects → compared to NLO("hadron level")

ATLAS:



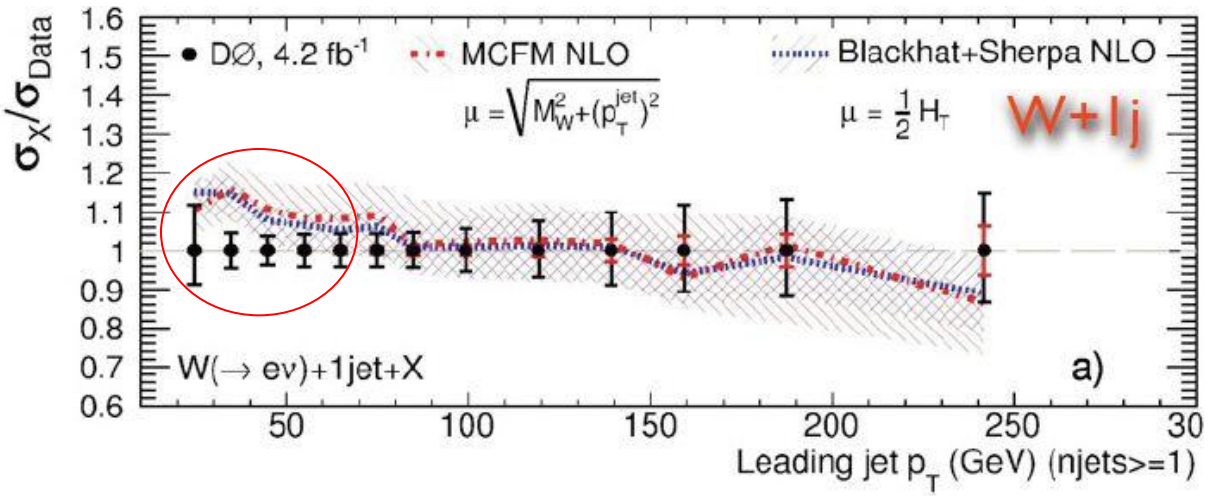


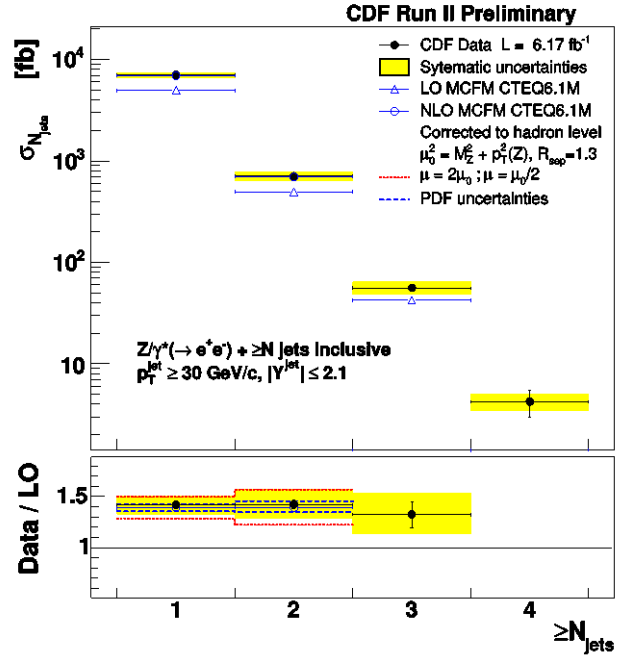
V+jets at Tevatron

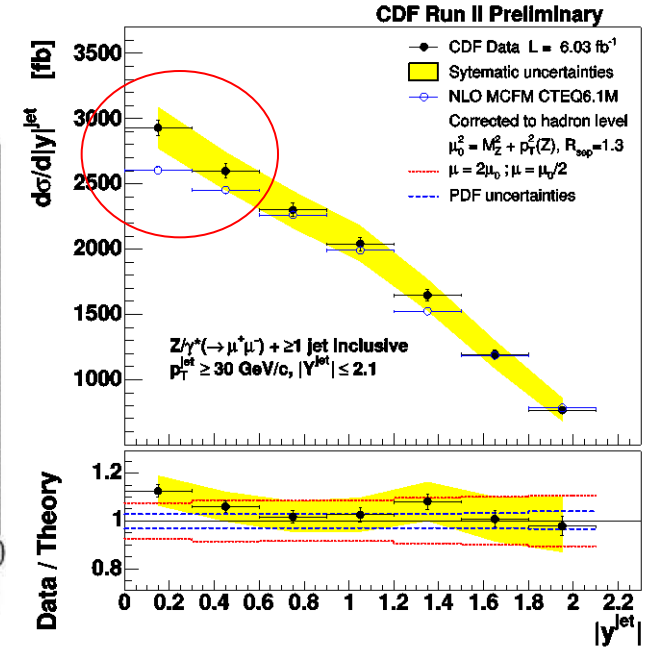
- **At high multiplicity**
  LHC has already collected higher statistics

- **At low p_T, low multiplicity:**
  interesting discrepancy data-NLO observed
  but results limited by systematics

→ new variables (next slide)

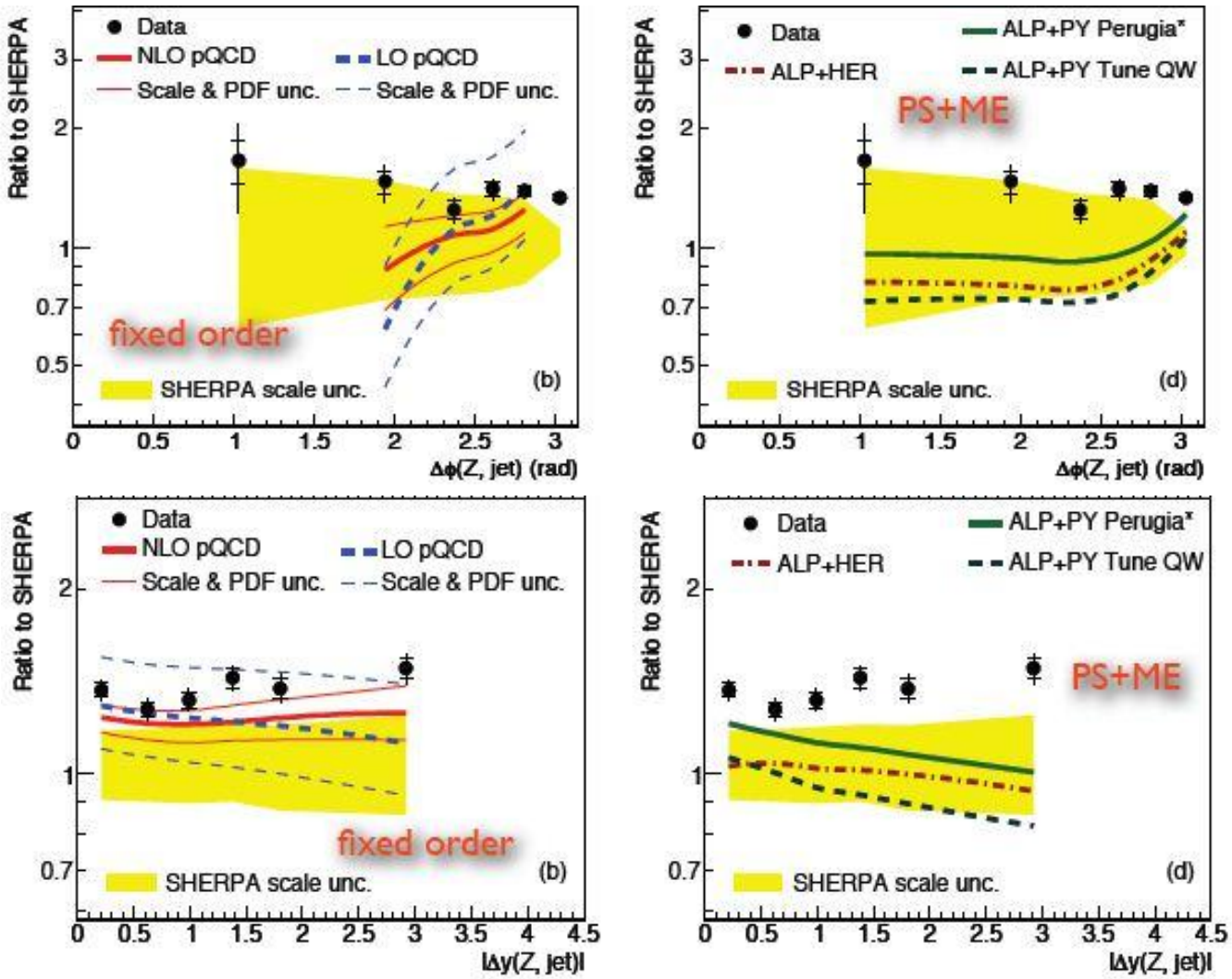






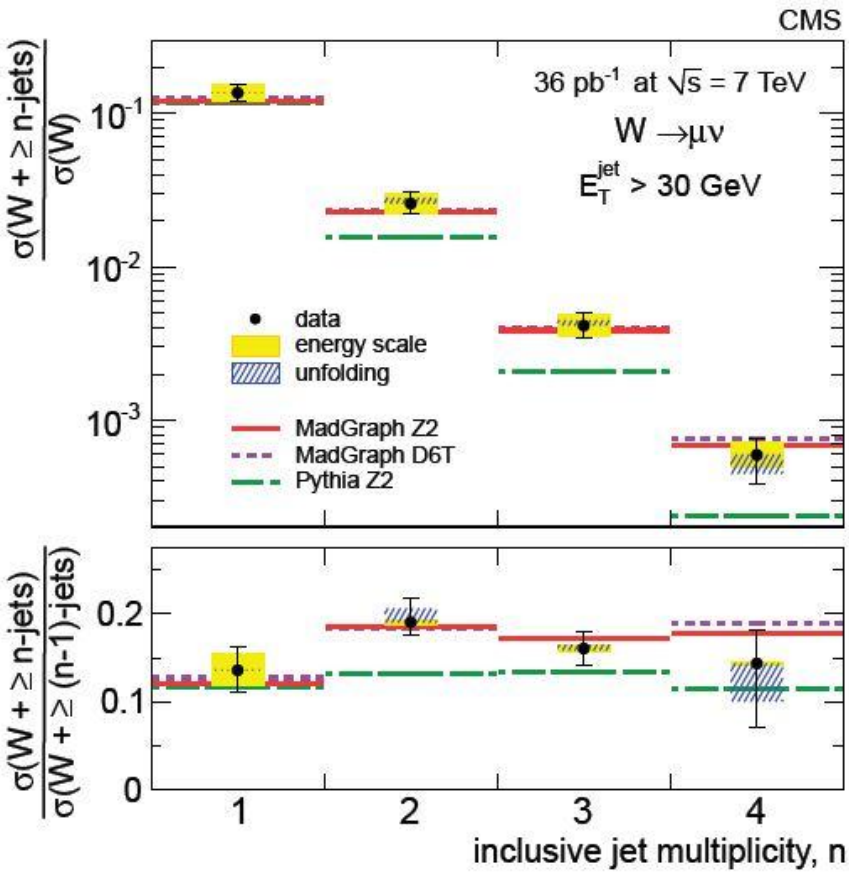
V+jets: alternative variables

- D0 novel measurement: angular correlations (lower systematics)



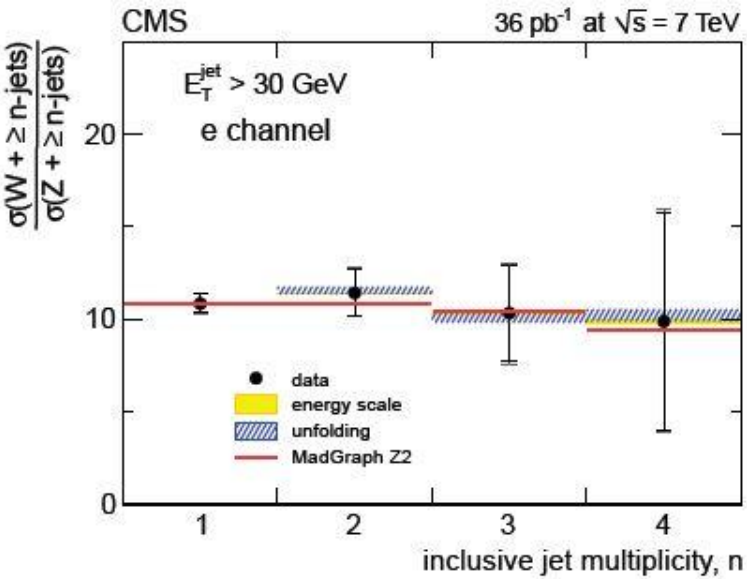
V+jets: ratios

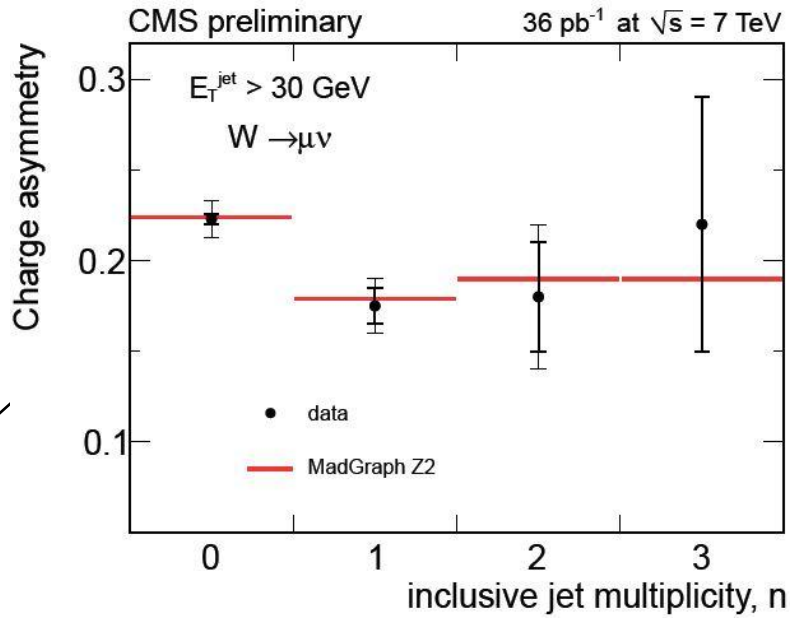
- Many systematics cancel out



- Very well known theoretically
→ any deviation is hint of NP

- Use high statistics W sample to predict Z+jets background for NP





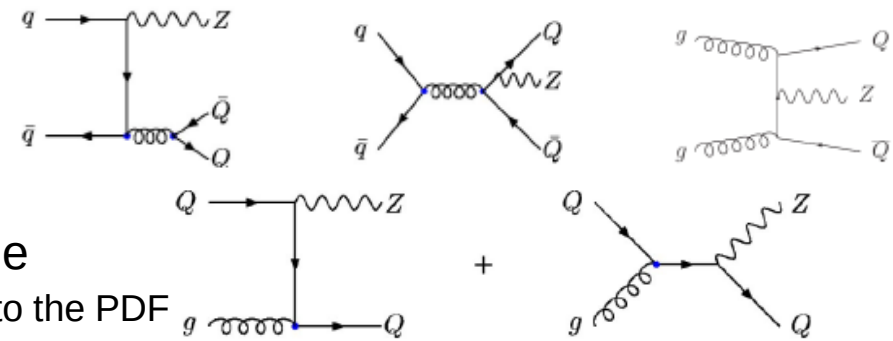
Z+b jets

- **PDF of b quarks**

fixed flavor scheme
b only from gluon splitting

variable flavor scheme
gluon splitting integrated into the PDF

(expected to coincide at NLO)

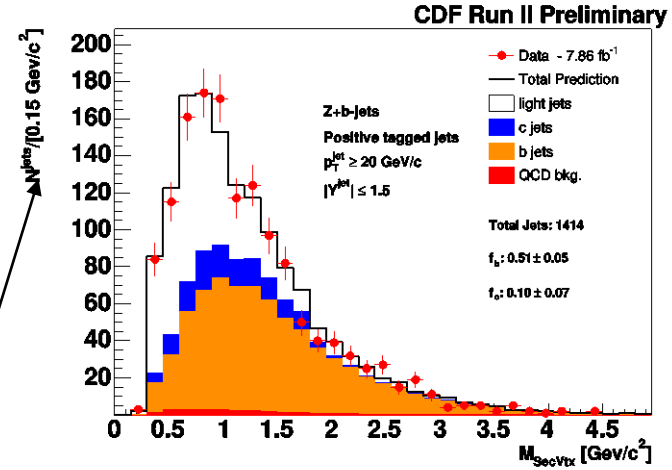


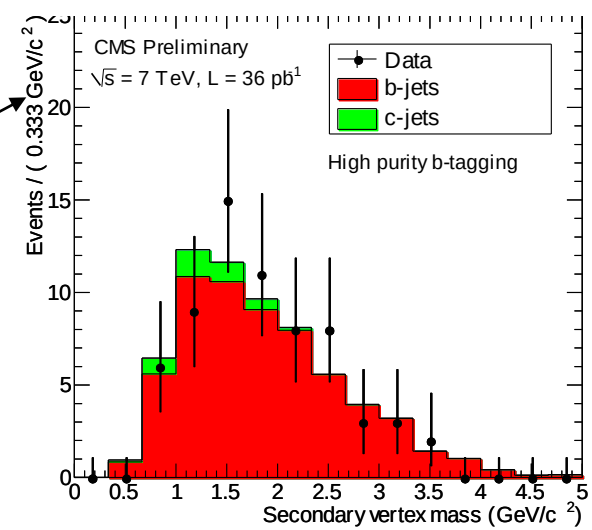
- Benchmark for MSSM Higgs: ϕbbbar
(large theoretical uncertainty on xsec)

Background to ZH(H→bbar), NP search with lept+b-jets

- **b-jets analysis:**
  - b-tagging with Secondary Vertex requirement
  or more sophisticated (eg Neural Network in D0)
  - b-tag eff. measured separately from data
  - b-tag purity extracted from data (eg SV mass fit)

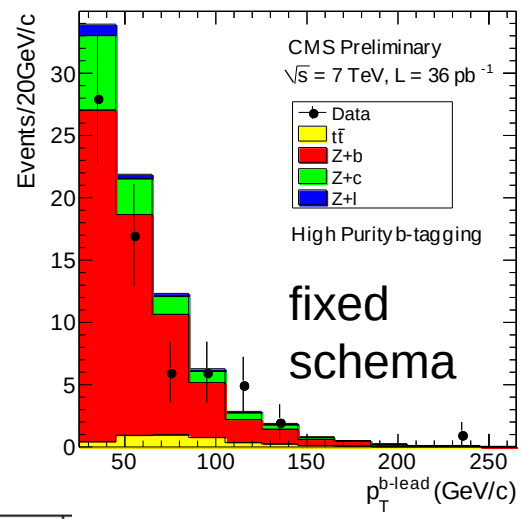
→ measurement of Z+b / Z+jets to cancel other (non-btag) systematics

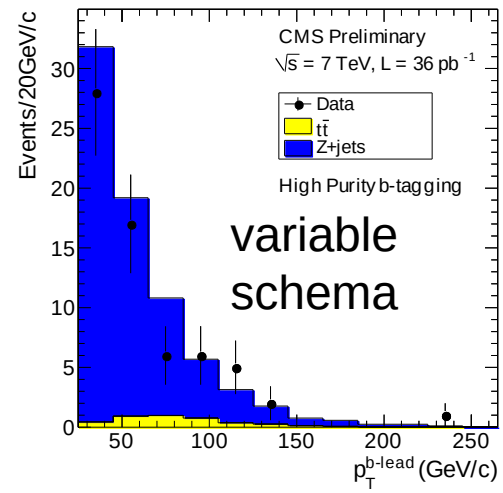




Z+b results

0.9 data/MC b-tag eff.





- **CMS**

  No statistical power yet to disentangle fixed VS variable flavor scheme

b-tag eff. corrected results:

Sample	$\frac{pp\to ee+b+X}{pp\to ee+j+X}$ (%) $p_T^e > 25$ GeV, $\lvert\eta^e\rvert < 2.5$
Data SSVHE	$4.3 \pm 0.6(stat) \pm 1.1(syst)$
Data SSVHP	$5.4 \pm 1.0(stat) \pm 1.2(syst)$
MADGRAPH	$5.1 \pm 0.2(stat) \pm 0.2(syst) \pm 0.6(theory)$
MCFM	$4.3 \pm 0.5(theory)$

Similar results for muons

(variable flavor)
(fixed flavor)

TO BE UPDATED soon with 1fb^{-1} → much better precision!

- **D0** (4.2 fb-1)

$$\frac{\sigma(Z+b\,\text{jet})}{\sigma(Z+\text{jet})} = 0.0193 \pm 0.0022(\text{stat}) \pm 0.0015(\text{syst})$$

NLO (m_Z^2) 0.0192 +/- 0.0022

- **CDF** (7.86 fb-1)

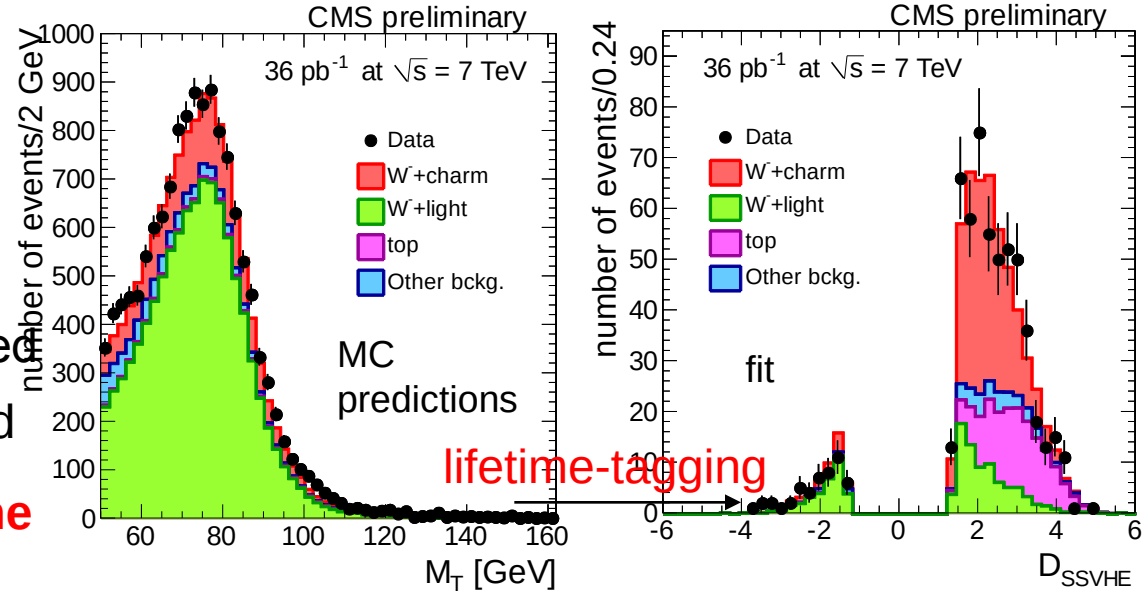
	Measured	NLO $Q^2 = m_Z^2 + p_{T,Z}^2$	NLO $Q^2 = < p_{T,jet}^2 >$
$\frac{\sigma(Z+b)}{\sigma(Z)}$	$2.84 \pm 0.29 \pm 0.29 \times 10^{-3}$	2.3×10^{-3}	2.8×10^{-3}
$\frac{\sigma(Z+b)}{\sigma(Z+\text{jet})}$	$2.24 \pm 0.24 \pm 0.26 \times 10^{-2}$	1.8×10^{-2}	2.2×10^{-2}

(corrected for geometrical acceptance)

W+c

- Dominated by sg→Wc
  - dg→Wc Cabibbo suppressed
  - W+b even more suppressed

→ **Wcbar (Wc) measures the sbar (s) PDF**



lifetime-tagging

LHC: W+c ~ 10% W+jets (W+b negligible)

- **CMS** (unexpected! just a first go):

$$R_c^{\pm} = 0.92 \pm 0.19\ (stat.) \pm 0.04\ (syst.)$$
$$R_c = 0.143 \pm 0.015\ (stat.) \pm 0.024\ (syst.)$$

Ratio	MCFM (CT10)	MCFM (MSTW08)	MCFM (NNPDF21)
$R_c^{\pm}$	$0.915^{+0.006}_{-0.006}$	$0.881^{+0.022}_{-0.032}$	0.902 ± 0.008
R_c	$0.125^{+0.013}_{-0.007}$	$0.118^{+0.002}_{-0.002}$	0.103 ± 0.005

- Tevatron: W+c ~ 5% W+jets

semileptonic charm decay + opposite charge W and c

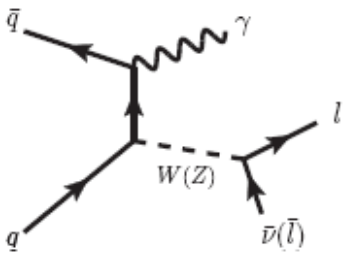
CDF (4.3 fb^{-1}): $\sigma(Wc) \cdot BR(W \to l\nu) = 33.7 \pm 11.4(stat) \pm 4.7(syst)\, pb$

(NLO calculation $16.5 \pm 4.7\, pb$)

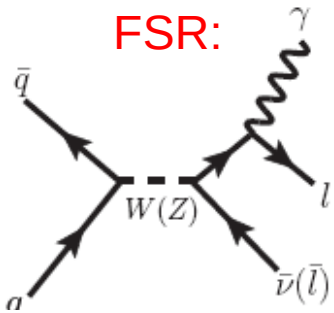
Wγ, Zγ

- **Photon reco**: isolated EM calo deposit with correct shape and no track associated
- **Production mechanism:**

ISR:

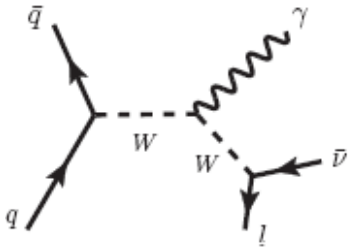


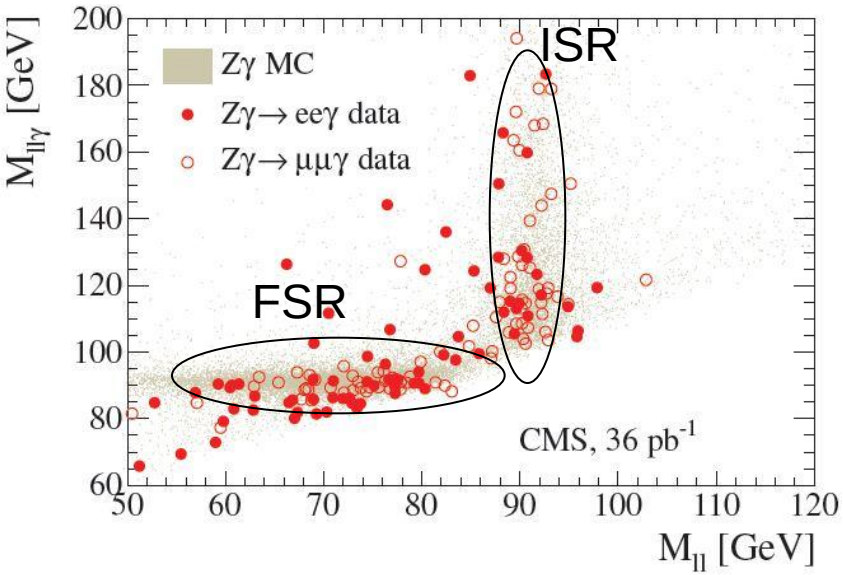
FSR:



TGC:

$Z\gamma\gamma$ and $ZZ\gamma \sim 0$
(only through loops)



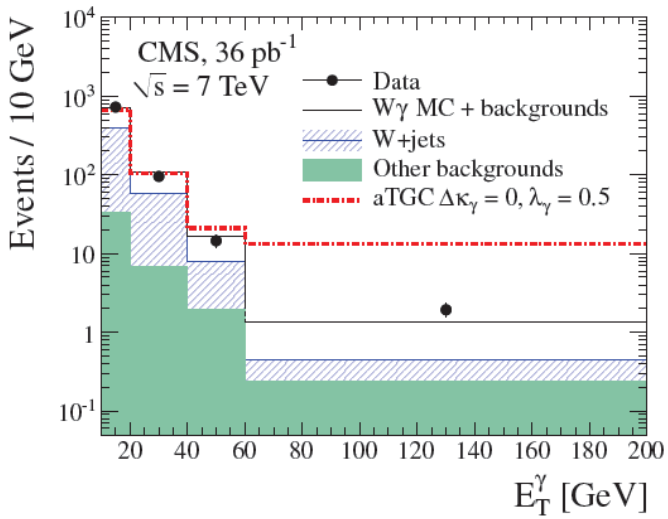


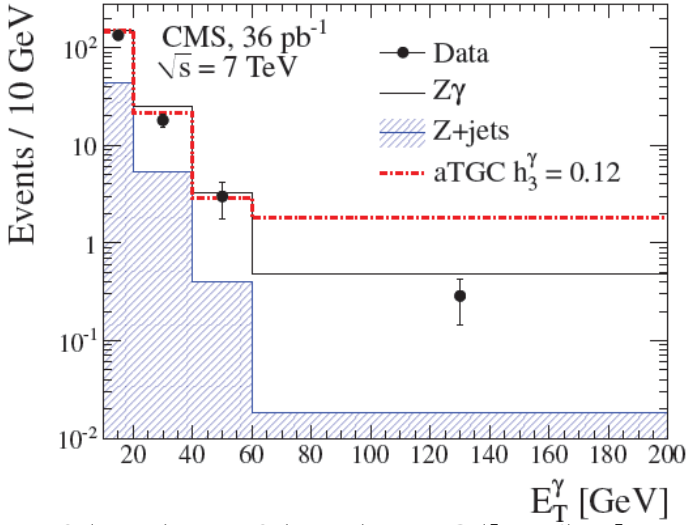
→ measurement of TGC
(next talk)

- **Fiducial region:** $E_T\ \gamma > 10$ GeV, $\Delta R(\text{lep-}\gamma) > 0.7$ } to avoid LO xsec divergence

  photon isolation (to remove γ from fragmentation)

Vγ: LHC results

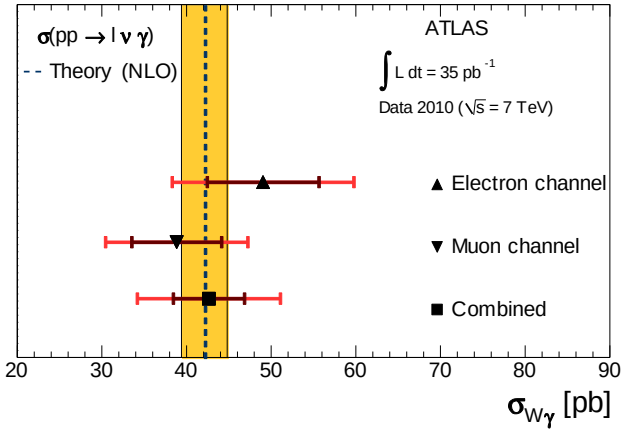


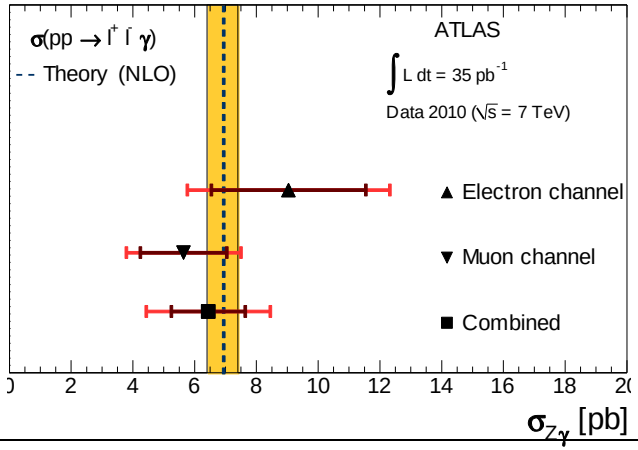


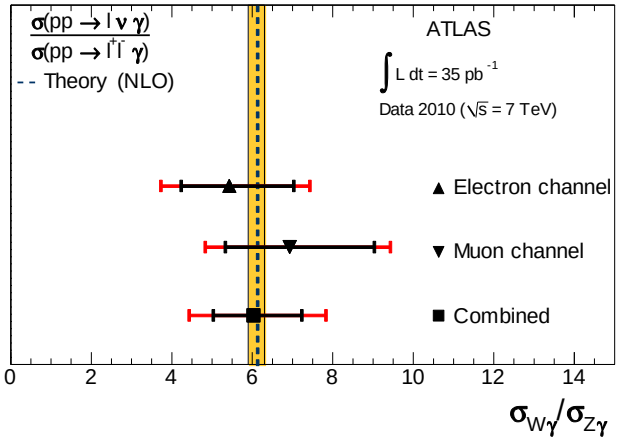
- Main backgr. V+jets from data
- Prediction NLO (QED,QCD)

CMS: $\sigma(W\gamma)\cdot BR(W\to l\nu) = 56.3\pm5.0(stat)\pm5.0(syst)\pm2.3(lumi)\,pb$ $\quad 49.4\pm3.8\,pb$

$\sigma(Z\gamma)\cdot BR(Z\to ll) = 9.4\pm1.0(stat)\pm0.6(syst)\pm0.4(lumi)\,pb$ $\quad 9.6\pm0.4\,pb$







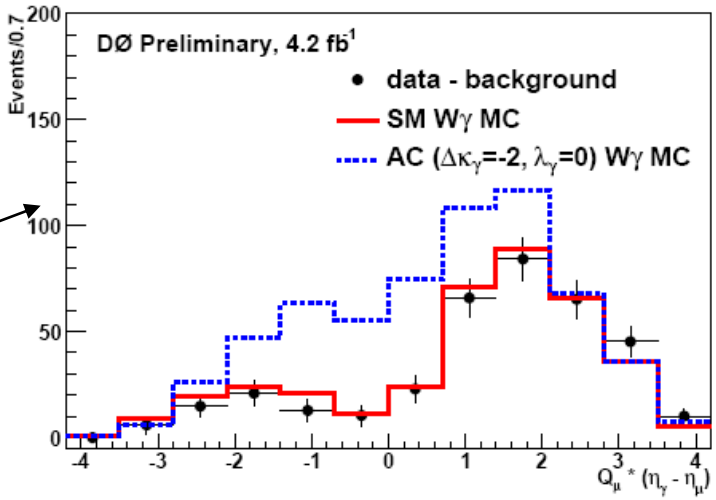
Vγ Tevatron results

- **D0: Wγ→μνγ with 4.2 fb-1**

$$\sigma(W\gamma)\cdot BR(W\to\mu\nu)=15.2\pm0.4(stat)\pm1.6(syst)\,pb$$

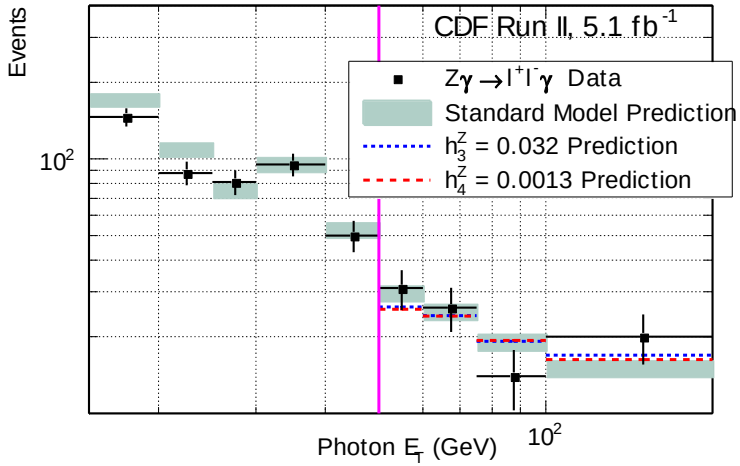
NLO: $16.0\pm0.4\,pb$

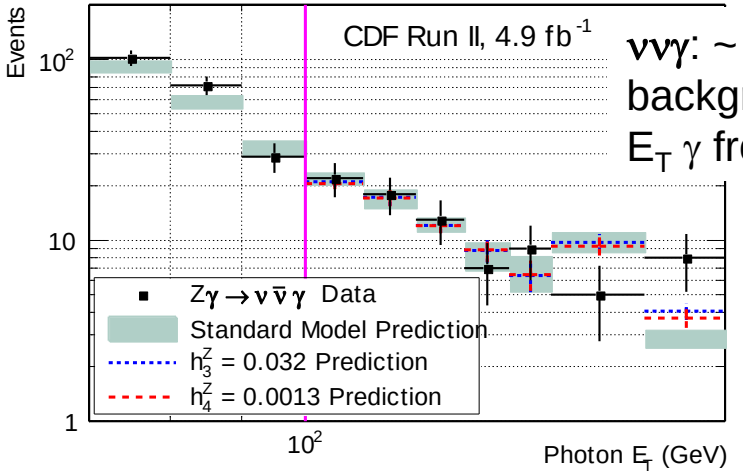
Diagrams interference → amplitude suppressed for given lept-photon angle



- **CDF: Zγ→llγ (5.1 fb.1) + ννγ (4.9 fb-1)**

M(llγ) > 100 GeV → FSR removed



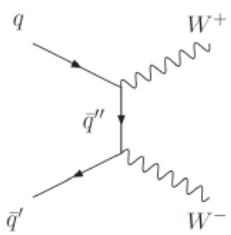


ννγ: ~ main background is high E_T γ from cosmics

Diboson production (WW,WZ,ZZ)

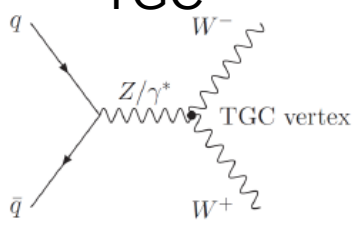
(TGC, QGC limits in next talk)

qqbar → VV



WW,WZ,ZZ

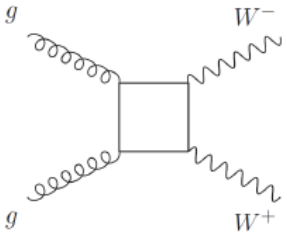
TGC



forbidden for ZZ

+ NLO qqbar +

gg→ VV



forbidden for ZW

(LHC: few % of xsec with ~50% uncertainty)

- SM test: TGC fixed by ewk gauge structure

  → any deviation from SM in VV xsec is direct hint of NP in bosonic sector

- Backgrounds for high mass Higgs→VV

  → test to establish Higgs search techniques

WW→lνlν at LHC

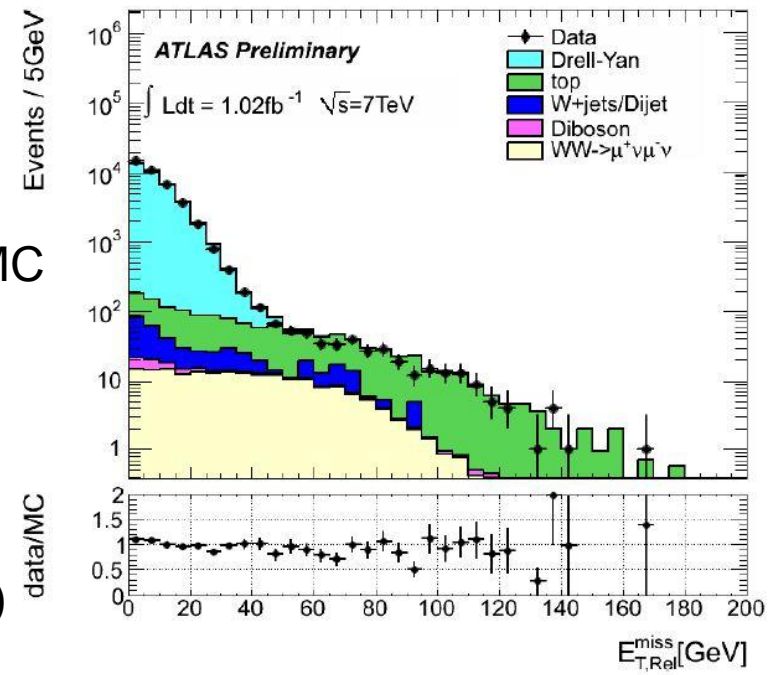
- Complex analysis (no mass peak→counting experiment, many backgrounds)
- Main systematics:
  - background estimate:

Background	Cuts
W+jets	tight lepton quality
top	(b-)jet veto
Drell-Yan	Z mass veto missing E_T
WZ, ZZ, Wγ	2 leptons → estimated from MC

estimated from data

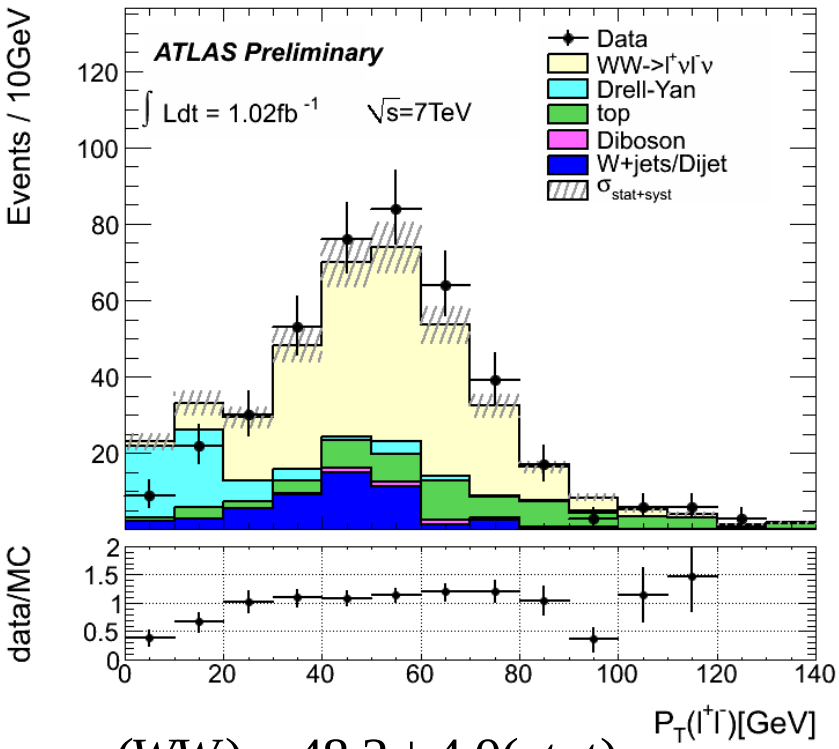
  - signal acceptance: jet-veto efficiency
    leptonic efficiency
    missing E_T uncertainty
    theoretical (gg box, PDF)

Sample	Yield
$qq \to W^+W^-$	349.7 ± 30.3
$gg \to W^+W^-$	17.2 ± 1.6
$W + \text{jets}$	106.9 ± 38.9
$t\bar{t} + tW$	63.8 ± 15.9
$Z/\gamma^* \to \ell\ell + WZ + ZZ$	12.2 ± 5.3
$Z/\gamma^* \to \tau\tau$	1.6 ± 0.4
WZ/ZZ not in $Z/\gamma^* \to \ell\ell$	8.5 ± 0.9
$W + \gamma$	8.7 ± 1.7
signal + background	568.6 ± 52.2
Data	626



WW LHC results (1 fb^{-1})

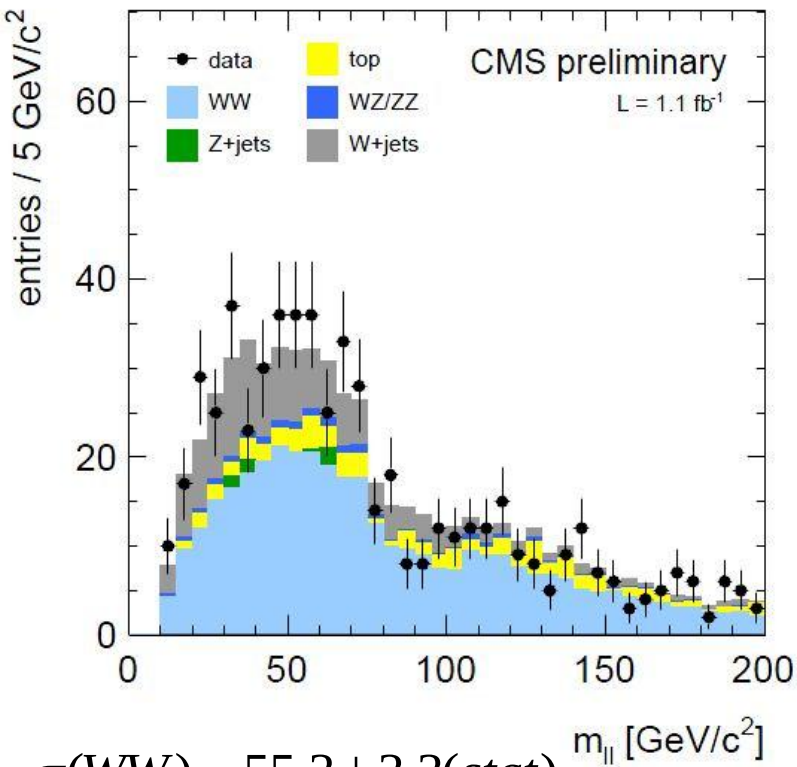
ATLAS



$$\sigma(WW) = 48.2 \pm 4.0(stat) \pm 6.4(syst) \pm 1.8(lumi)\, pb$$

(NLO expected $46 \pm 3\, pb$)

CMS



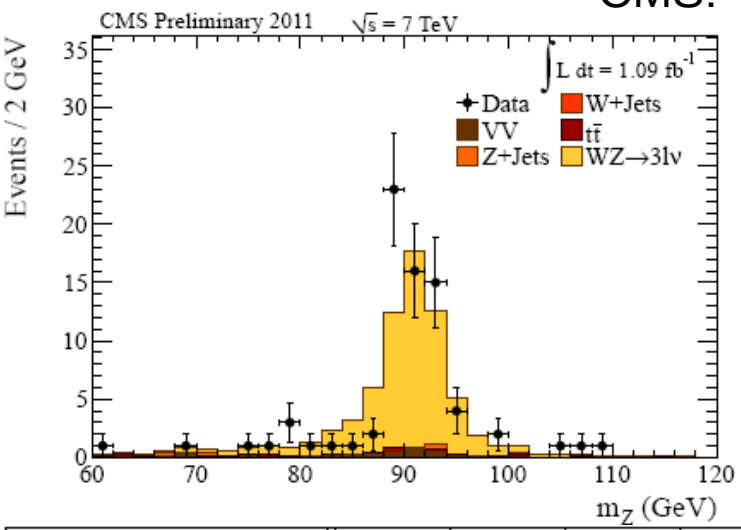
$$\sigma(WW) = 55.3 \pm 3.3(stat) \pm 6.9(syst) \pm 3.3(lumi)\, pb$$

(NLO expected $43 \pm 2\, pb$)

WZ→3l+ν at LHC

- Very clean, low background

CMS:

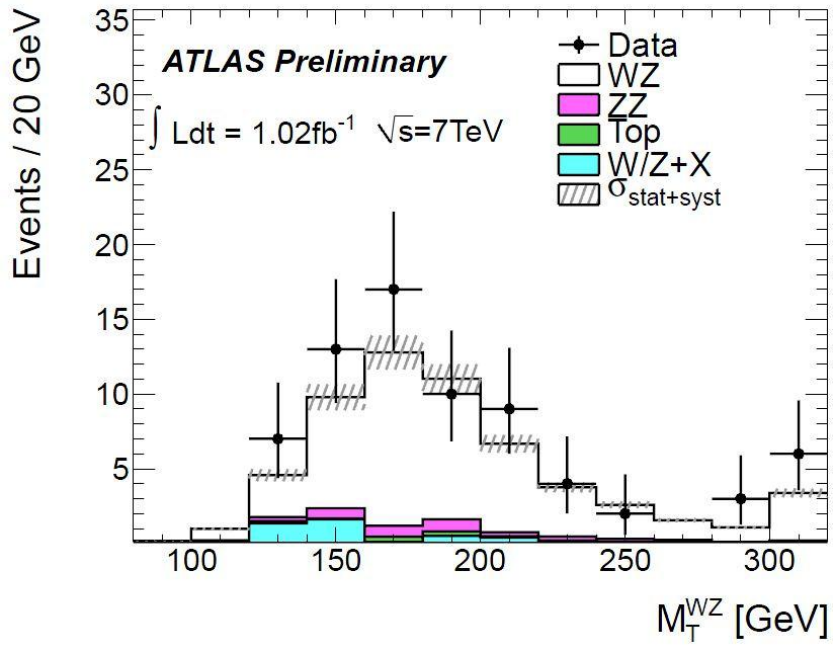


Sample	$3e0\mu$	$2e1\mu$	$1e2\mu$	$0e3\mu$
Background	2.95	2.14	1.31	1.72
$WZ \to 3\ell\nu$	14.47	17.49	13.95	18.56
All MC	17.42	19.62	15.26	20.28
Data	22	20	13	20

$$\sigma(WZ) = 17.0 \pm 2.4(stat) \pm 1.1(syst) \pm 1.0(lumi)\, pb$$

(NLO expected $18.75^{+1.1}_{-0.8}\, pb$)

ATLAS:



$$\sigma(WZ) = 21.1^{+3.1}_{-2.8}(stat) \pm 1.2(syst)^{+0.9}_{-0.8}(lumi)\, pb$$

(NLO expected $17.2^{+1.2}_{-0.8}\, pb$)

Recent WZ→3l+ν at Tevatron

- Possible only at hadron colliders (charged final state)
  - **D0 with 4.1 fb-1**

    statistics 2 times smaller than LHC, while xsec is 6 times smaller

    $$\sigma(WZ) = 3.90^{+1.06}_{-0.90}\, pb$$

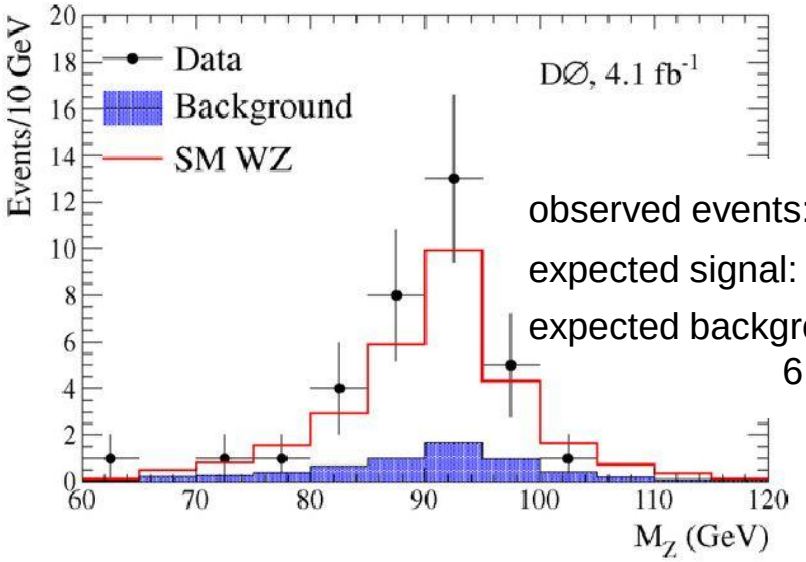
    (NLO expected $3.25 \pm 0.19\, pb$)

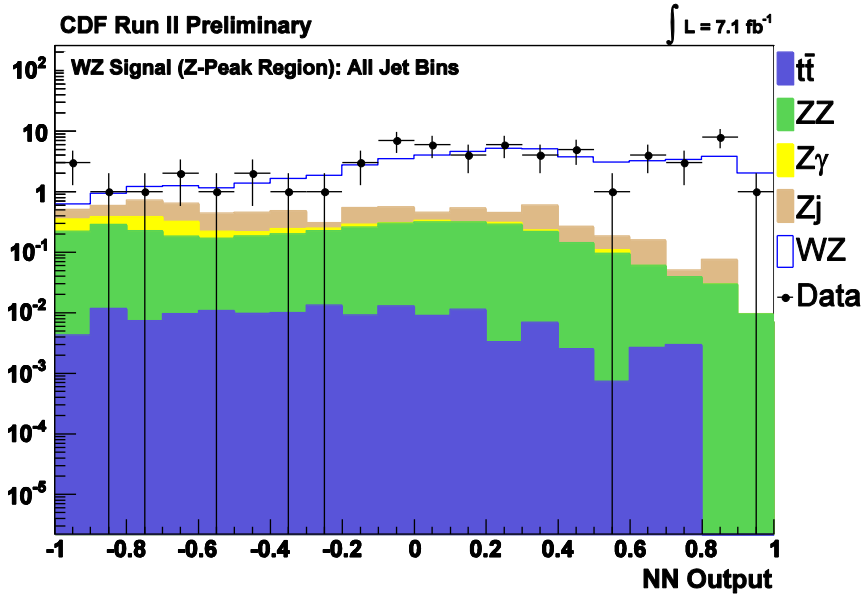
  - **CDF with 7.1 fb-1**

    Shape analysis with fit to neural network

    $$\sigma(WZ) = 3.9^{+0.6}_{-0.5}(stat)^{+0.6}_{-0.4}(syst)\, pb$$

    (NLO expected $3.46 \pm 0.21\, pb$)

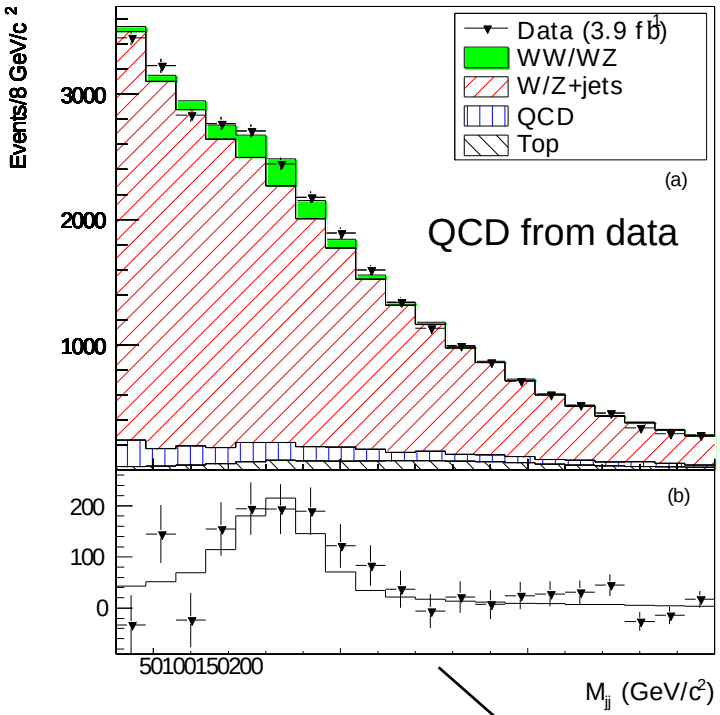




WW/WZ→lν2j at CDF

- First observation: 5.4σ (first evidence at D0 with 4.4σ in 2008)
- Much larger backgrounds, no resolution to distinguish W/Z→jj

fit to Mjj (3.9 fb-1)



+ matrix element method: (2.7 fb-1)

- discriminant exploiting full kinematic information, based on calculations of differential xsec of signal and background
- data-MC validation of input kinematic variables
- fit to shape of discriminant

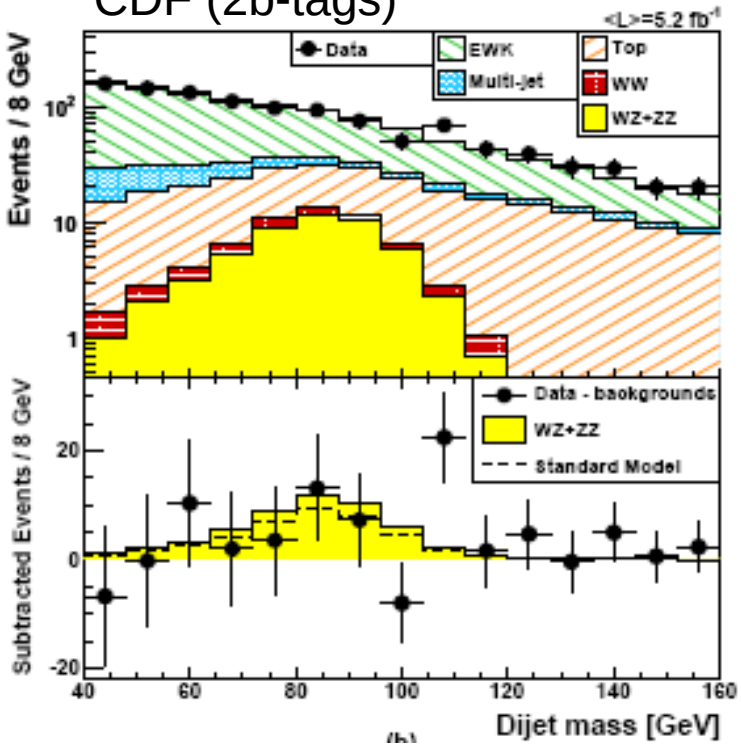
$$\sigma(WW+WZ) = 16.0 \pm 3.3(stat+syst)\,pb$$ (NLO expected $16.1 \pm 0.9\,pb$)

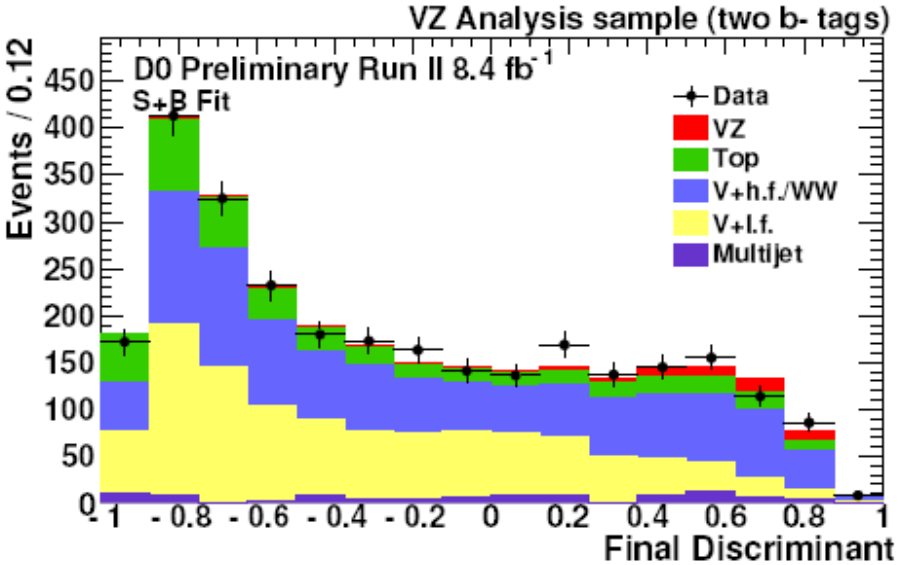
WZ/ZZ→lν/νν+2b at Tevatron

- Crucial for Higgs search (ZH→ννbb). Very complex analysis!
  - WZ → lνbb + ZZ → ννbb ⇨ b-tag jets + missing E_T (+ topological cuts)
  - No leptons! → huge background: multijets QCD, V+jets (from data)
  - very sophisticated techniques: b-tag probability with Boosted Decision Tree or Neural Network which exploits much info and different variables

different channels combined (0,1,2 b-tag)

CDF (2b-tags)





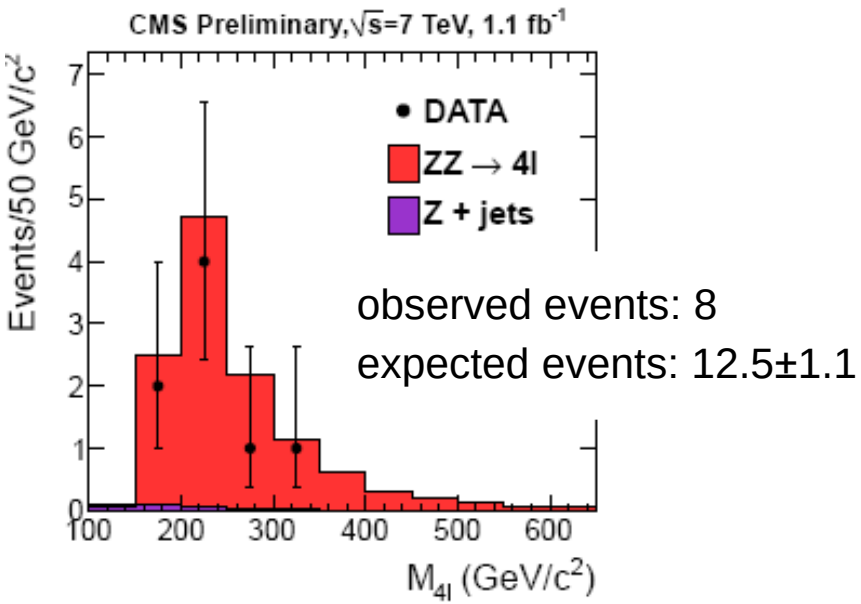
D0: $\sigma(WZ, ZZ) = 6.9 \pm 1.3(stat) \pm 1.8(syst)\, pb$ (expected 4.6 pb)

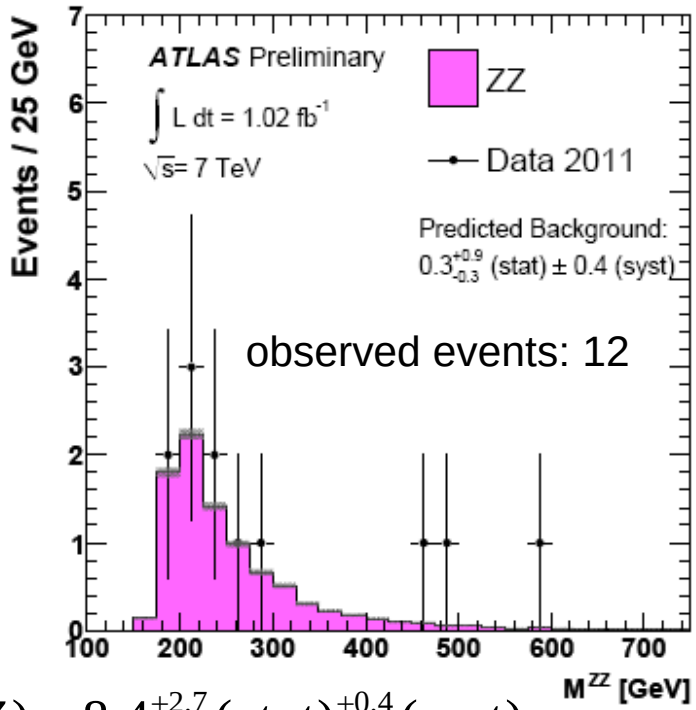
CDF: $\sigma(WZ, ZZ) = 5.8^{+3.6}_{-3.0}\, pb$ (expected 5.1 pb)

ZZ→4l

- 4l is 0.5% of xsec but very clean (Higgs search golden channel at LHC)

Negligible backgrounds: Z+(c,b)jets, top





$$\sigma(ZZ) = 3.8^{+1.5}_{-1.2}(stat) \pm 0.2(syst) \pm 0.2(lumi)\,pb$$

(NLO expected $6.4 \pm 0.6\,pb$)

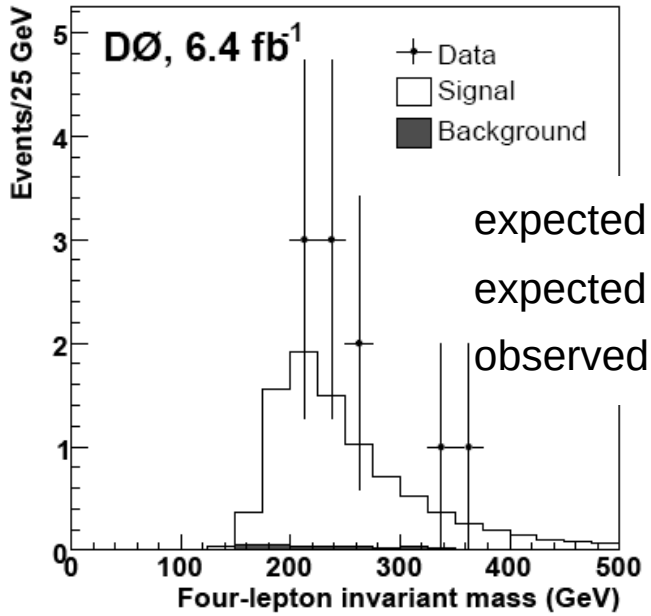
$$\sigma(ZZ) = 8.4^{+2.7}_{-2.3}(stat)^{+0.4}_{-0.7}(syst) \pm 0.3(lumi)\,pb$$

(NLO expected $6.5^{+0.3}_{-0.2}\,pb$)

- High statistical uncertainty (still true also at Tevatron →)

ZZ at D0

- **New ZZ→4l** with more data (6.4 fb-1) and more inclusive cuts → reduced statistical uncertainty



expected signal events: 8.73 + 1.22

expected background events: 0.37 + 0.13

observed 10 events

- Combination 4l with 2l2ν → **most precise ZZ xsec measurement**

$$\sigma(ZZ) = 1.40^{+0.43}_{-0.37}(stat) \pm 0.14(syst)\,pb$$

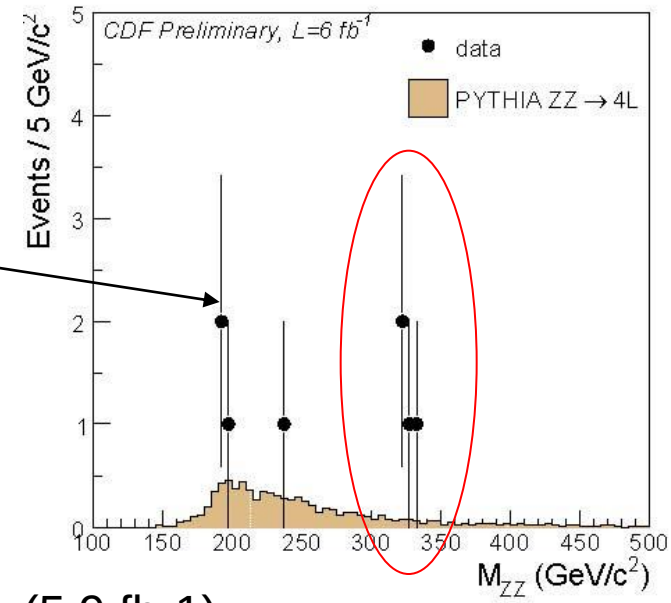
ZZ at CDF

- **ZZ→4l** (6 fb-1) excess of events at high M_{ZZ} (eg Randall Sundrum Graviton)
  - But xsec still compatible with SM

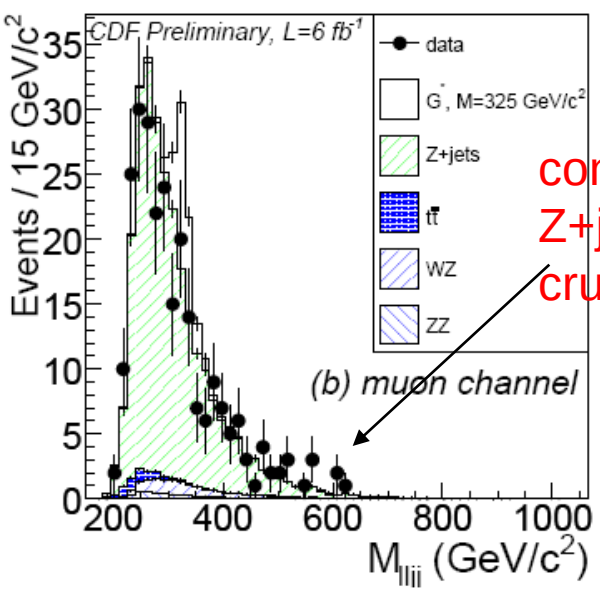
$$\sigma(p\bar{p} \to ZZ) = (2.8\ ^{+1.2}_{-0.9}\ (\text{stat.}) \pm 0.3\ (\text{syst.}))\,\text{pb}$$

$$(1.4 \pm 0.1)\,\text{pb}$$

  - No excess in other final states



- **ZZ→2l2j**



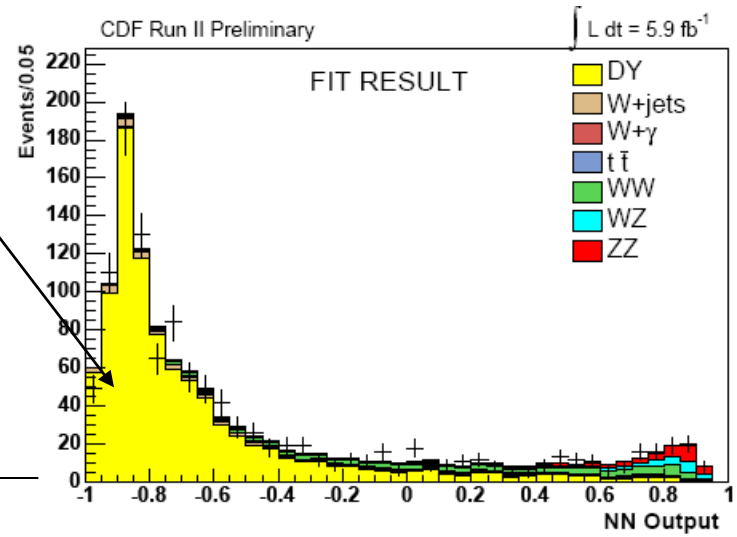
control of Z+jets is crucial

- **ZZ→2l2ν** (5.9 fb-1)

Shape analysis with fit to neural network

$$\sigma(p\bar{p} \to ZZ) = 1.45^{+0.45}_{-0.42}(stat.)^{+0.41}_{-0.30}(syst.)\ \text{pb}$$

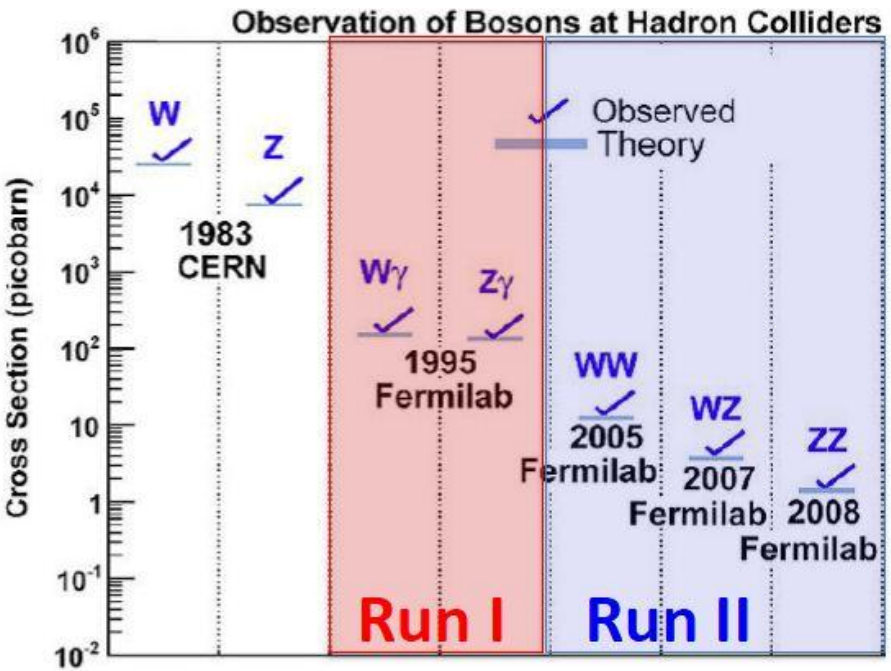
$$\sigma(ZZ) = 1.21^{+0.05}_{-0.04}(scale)^{+0.04}_{-0.03}(PDF)\ \text{pb.}$$

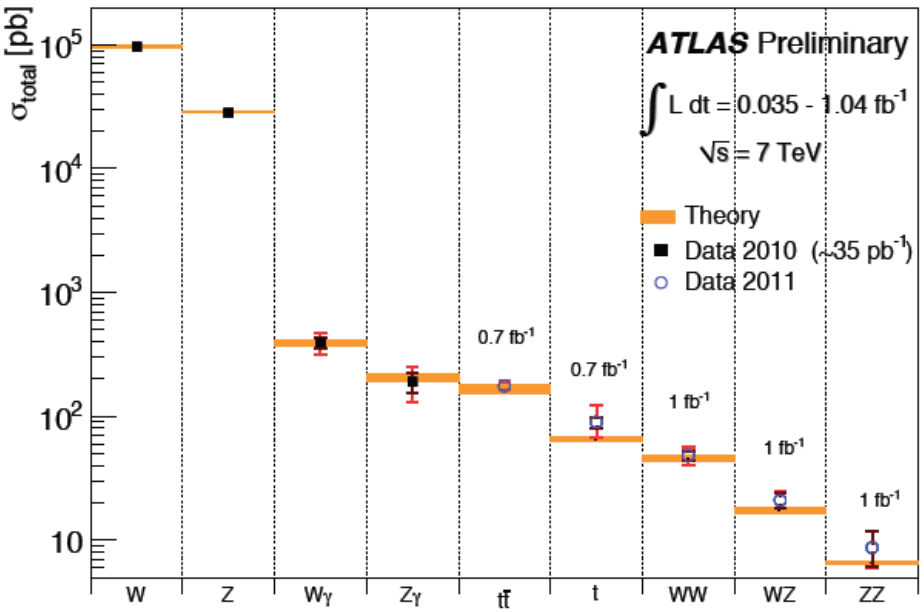


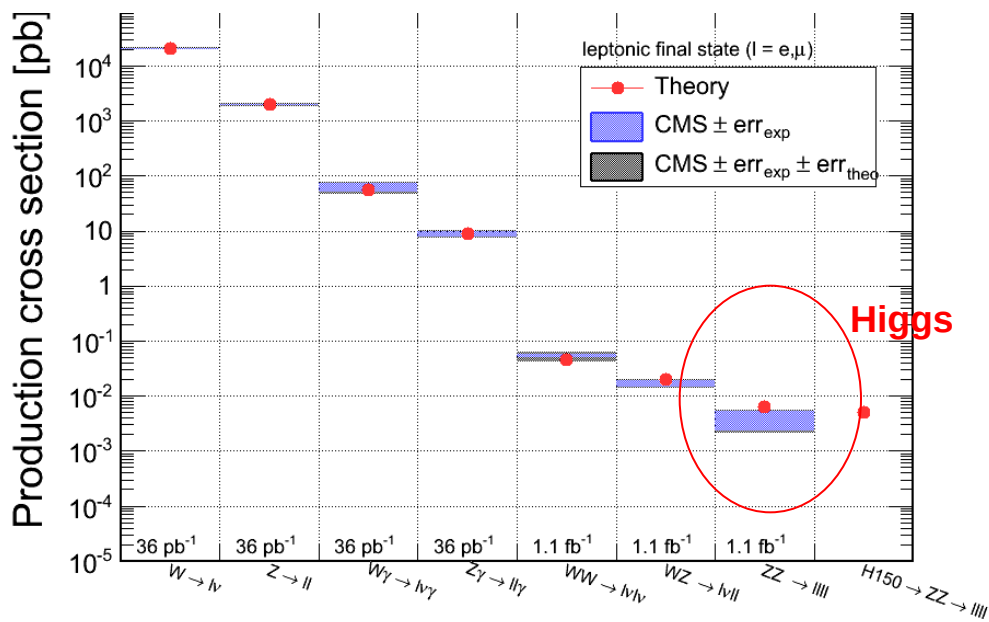
Conclusions

- **LHC:** first results → much room for improvement
  - V, V+jets, Vγ results with ~ 35 pb^{-1}
    VV results with ~ 1 fb^{-1}
    } expected 10 fb^{-1} in next months !
  - control systematics expected to improve further (2 years only from LHC startup!)
- **Tevatron:**
  - maximum statistics (10 fb^{-1} available, 5-7 fb^{-1} analyzed)
  - control of systematics at best
  - new techniques (angular variables, Matrix-Element, Neural Network…) under study
- **What's next ?**
  - Improve V, V+jets, Vγ results ⇒
    - SM test and measurement (precision physics is challenging at hadron colliders)
    - PDF constraints
  - Improve VV measurement ⇒
    - **background to Higgs search**
    - **benchmark test for Higgs analyses !**

THE LONG ROAD TO THE EWK SYMMETRY BREAKING







References:

ATLAS

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

CDF

http://www-cdf.fnal.gov/physics/ewk/

CMS

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK

D0

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

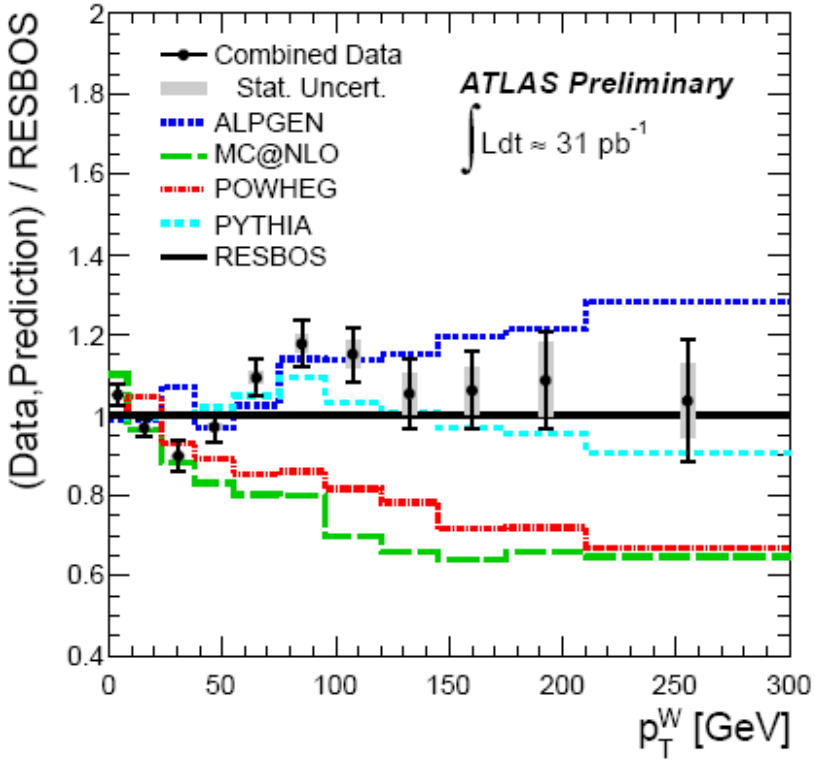
W/Z and Diboson production

Back-up

S. Bolognesi (CMS-CERN)
on behalf of
ATLAS, CDF, CMS, D0 collaborations

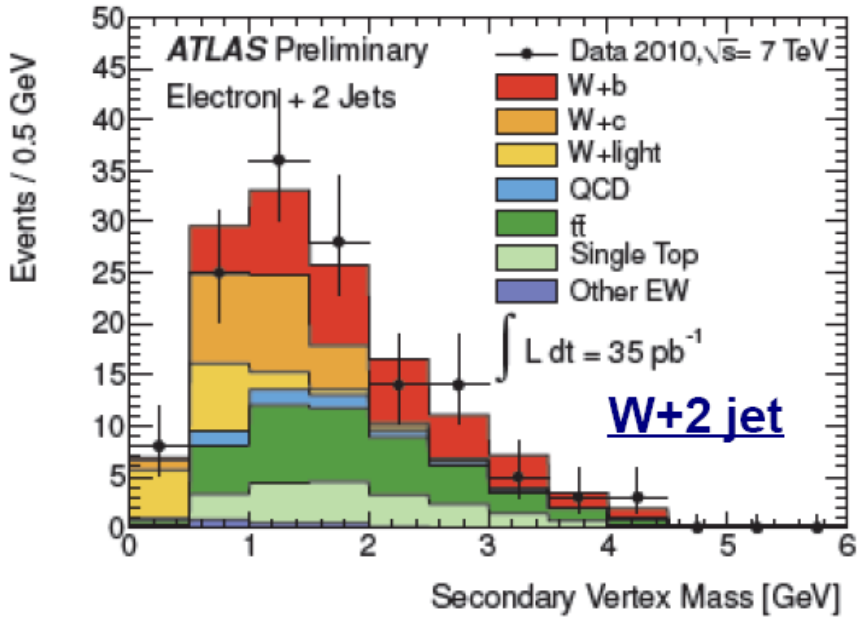
Physics in Collision 2011
29 August 2011, Vancouver

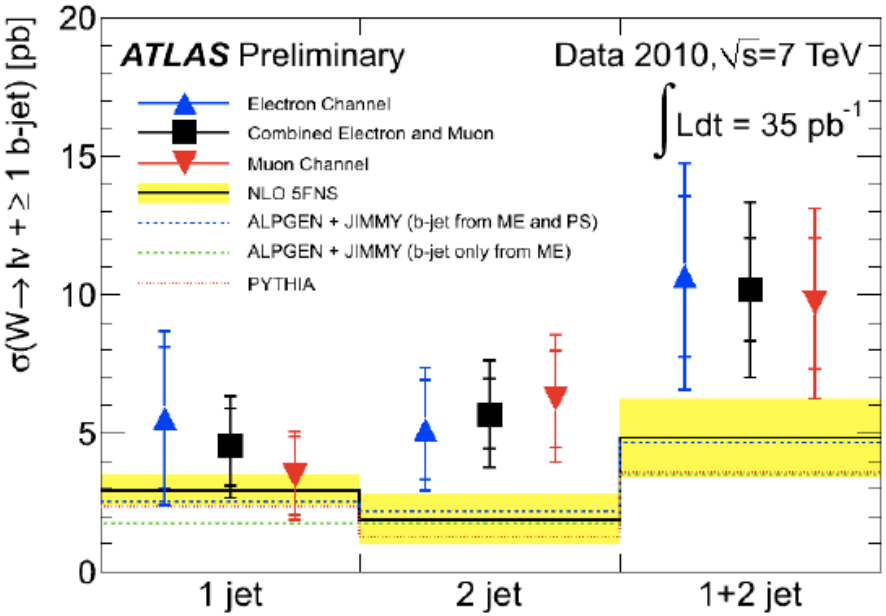
W p_T measurement at LHC



- Unexpected discrepancy with respect to ResBos to be investigated

W+b at LHC





- Complex analysis: it needs control of W+c