Electroweak measurements at CMS
(those sensitive to electroweak corrections)

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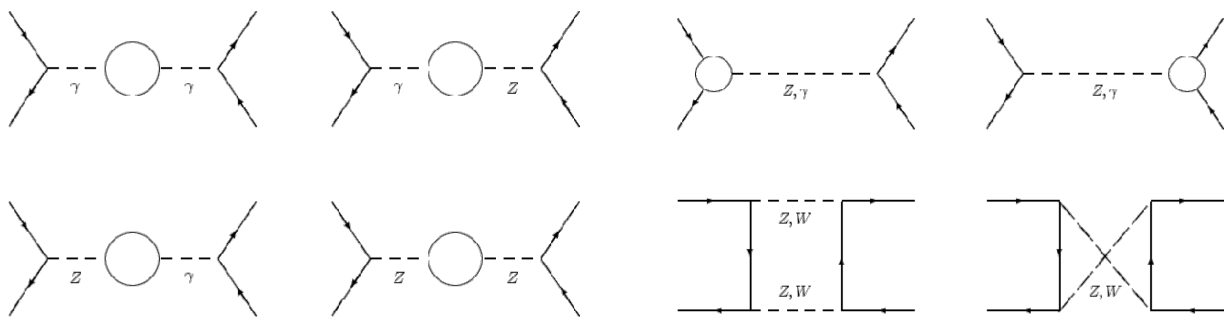
CMS Collaboration



Workshop on electroweak corrections for LHC physics
Durham, September 25, 2012

Outline

- Introduction
  - When electroweak corrections matter
  - Examples of such measurements

- W/Z measurements & sensitivity to EWK corrections

- W/Z+jets measurements & sensitivity to EWK corrections
  - Use of dressed (particle level) leptons

- Diboson measurements & sensitivity to EWK corrections

- Summary

When electroweak corrections are too strong

•EWK corrections become important in certain kinematic regimes.

•At the ~TeV scale, they significantly modify production cross sections through Sudakov logs of order $\alpha_W \log^2(\mu^2/M_W^2)$

= 25*αW @μ=1TeV

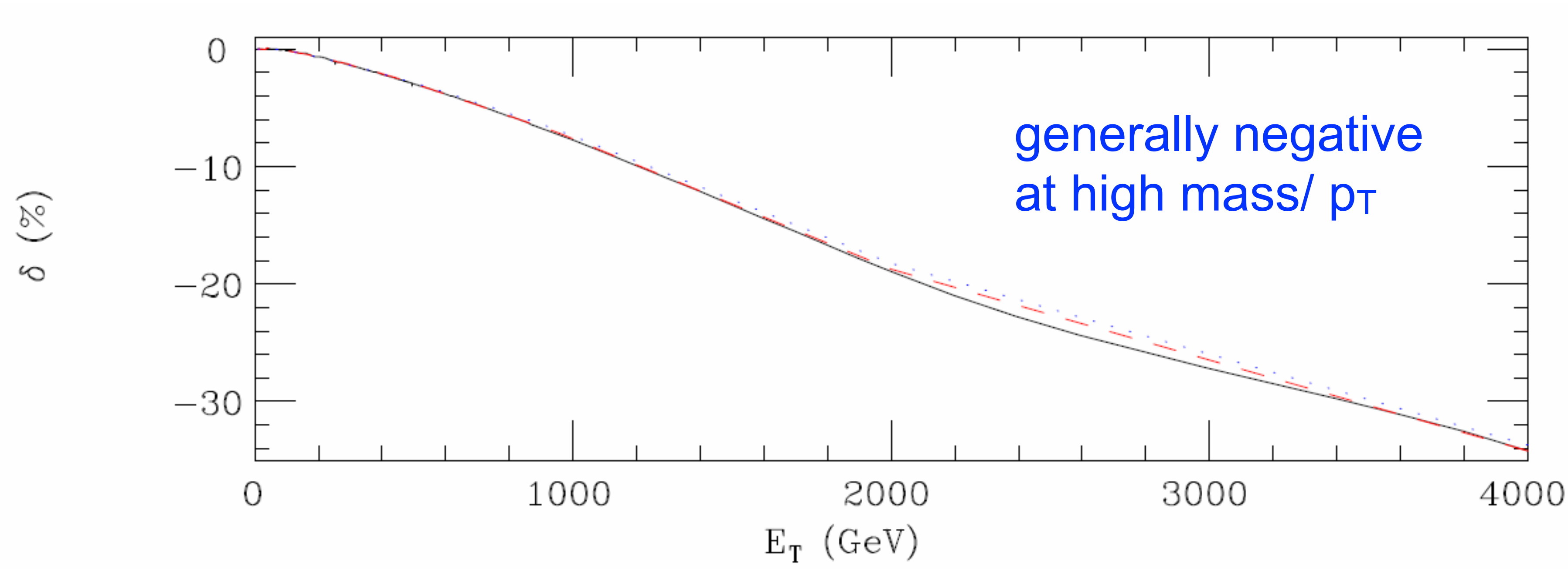
This typically exceeds ~10% of LO when mu is of order 1 TeV

•We are now encountering data where the precision at the TeV scale is of order 10%

•It is important not only for nominally electroweak processes, but for nominally QCD ones as well!

A classic example: when EWK corr. are too strong

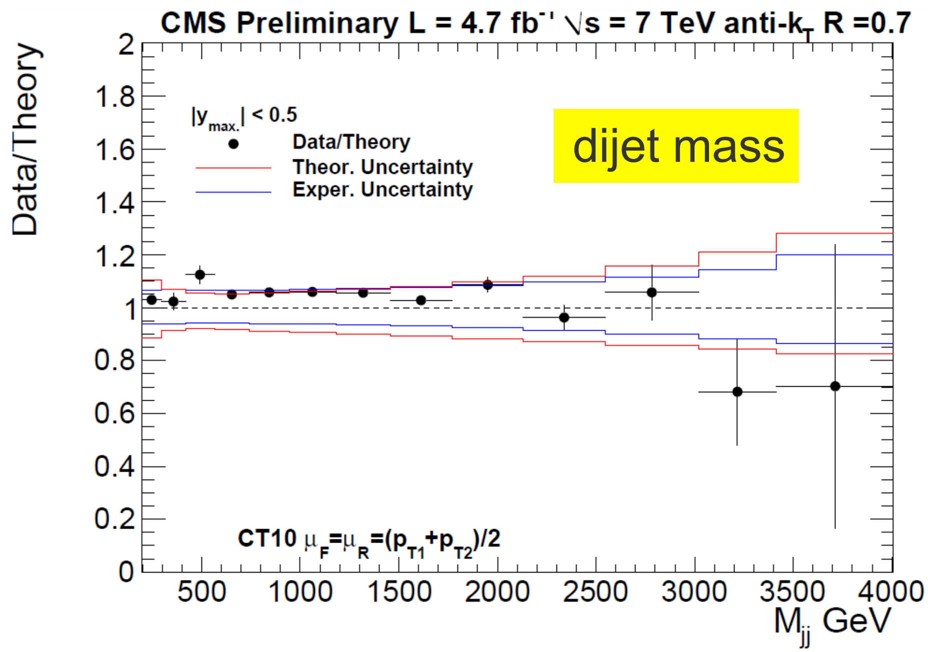
For inclusive jet production at 14 TeV, negative virtual contribution dominates over real emission at ~1 TeV and **cross section decreases from LO result** by ~20% at 2TeV, >30% at 4TeV

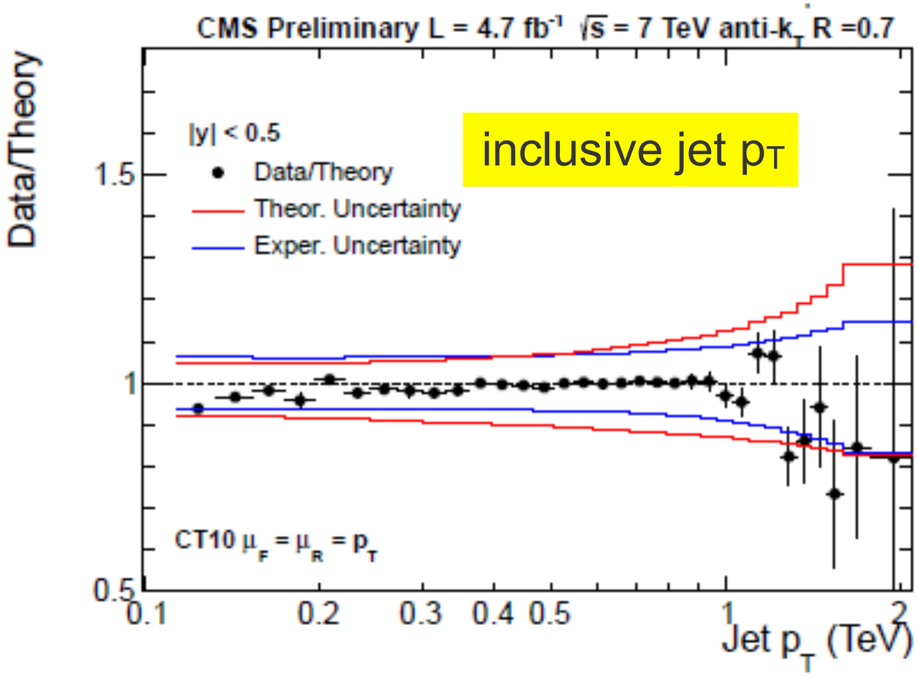


Moretti/Nolten/Ross, Nucl.Phys.B759:50-82,2006

Too strong for jets?: at today's precision, yes!

- CMS inclusive jet and dijet data/ theory comparisons with 5 fb^{-1}

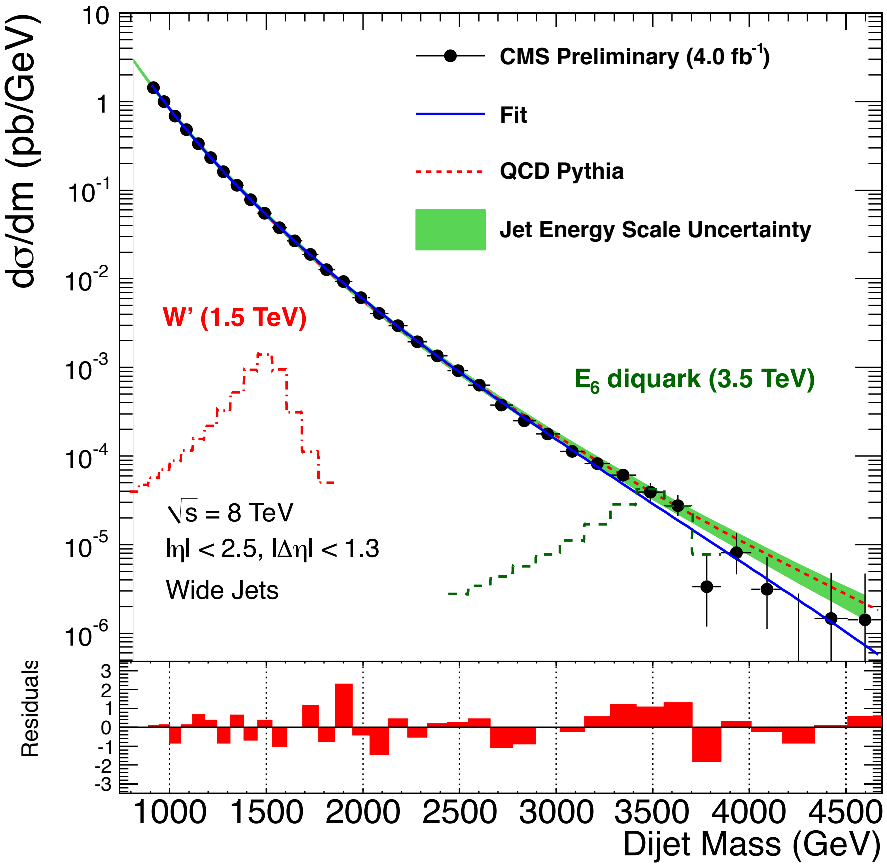


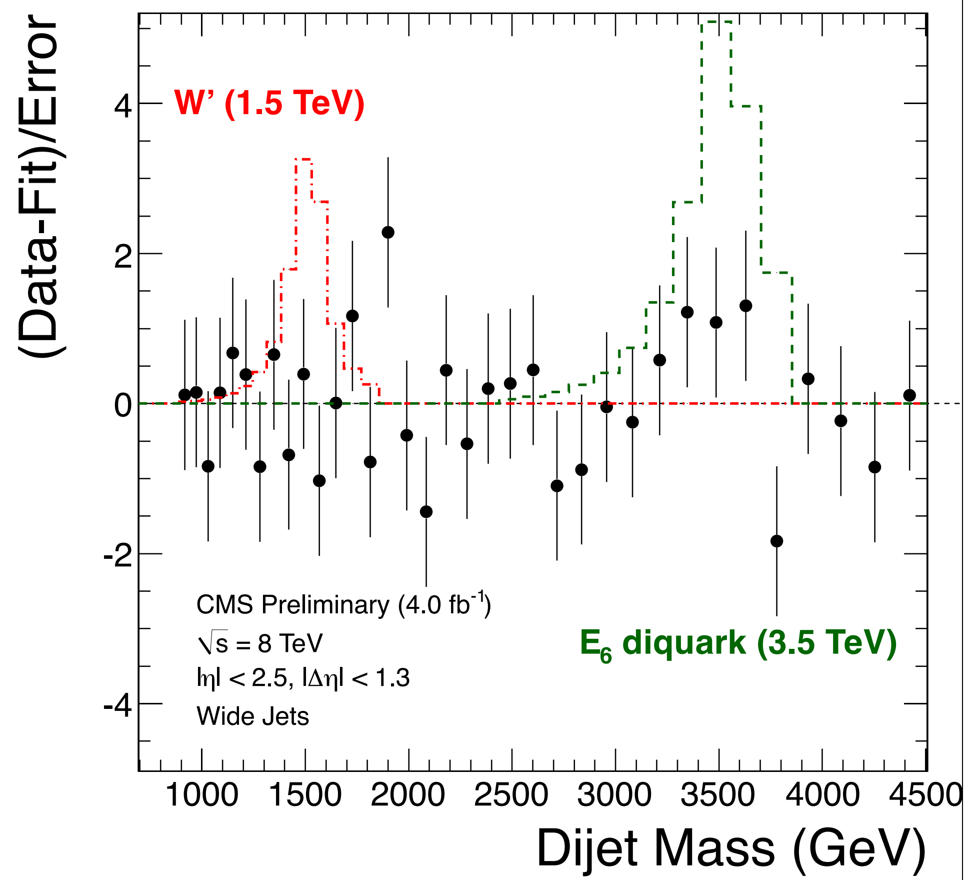


- Theory and exp. syst. error for ~2(4) TeV jets(dijets) is 25-30%
  - Comparable to the size of EWK corrections (~ -20%)

Dijet measurement at 8 TeV

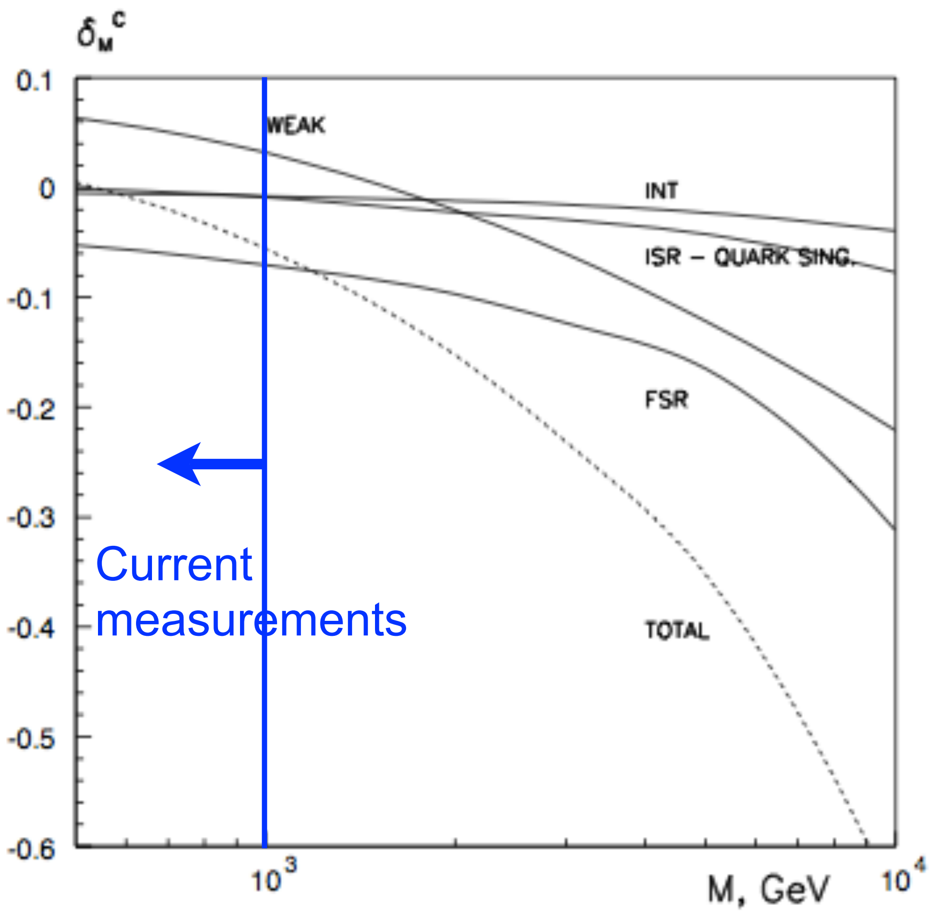
http://cdsweb.cern.ch/record/1462265





Cross section decreasing at high mass. Cannot rely on MC prediction.
For searches, use empirical parametrization to determine QCD yield.

What about electroweak processes



Zykunov, arXiv: hep-ph/0702-203

- EWK corrections for most processes at LHC are < the current experimental precision.

- However, most everything we could measure in 2010 (jets, photons, W, Z) will enter the "Sudakov zone" in 2012.

If experimental and PDF errors are < EWK corrections, then I'll call the measurement as being in the Sudakov zone. Typically need a few dozen events above 1 TeV to be in this zone.

Too strong for W,Z?: Yes, in some cases.

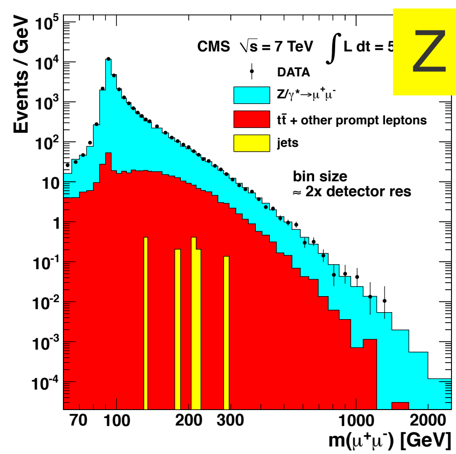
<u>Actually two cases:</u>

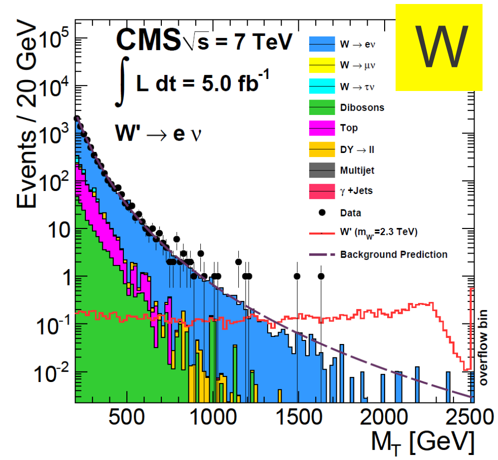
1. Super precise shape measurements which are not totally limited by PDF, e.g., W mass at Tevatron, or weak mixing angle

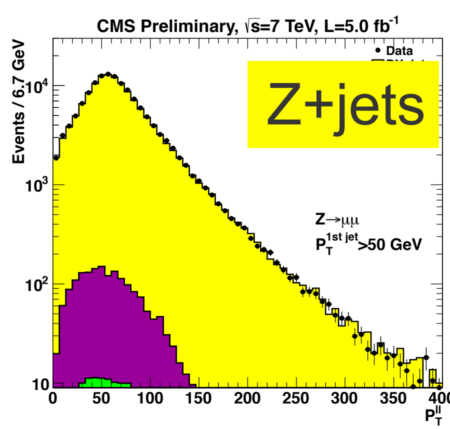
2. In the tails of the mass/ p_T distribution when we have ~ few dozen events at 1 TeV or beyond

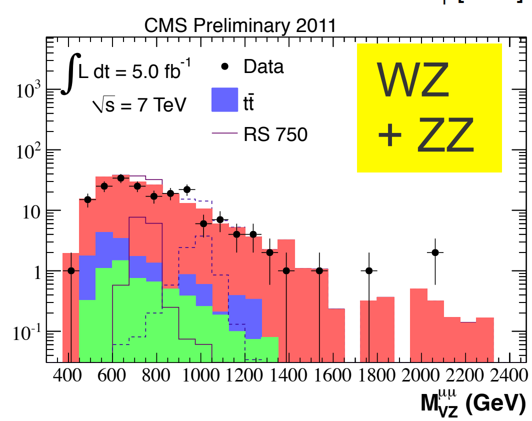
Presently don't have mature analyses of category 1.

So, in the following slides I'll survey CMS results where EWK corr. are relevant for 2012 data / 14 TeV run.



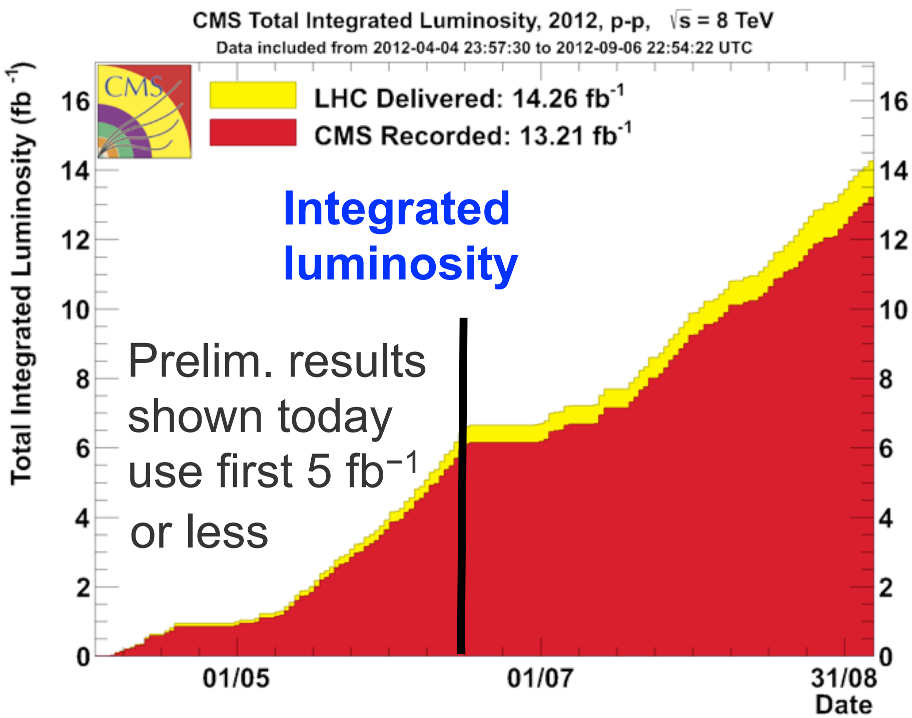


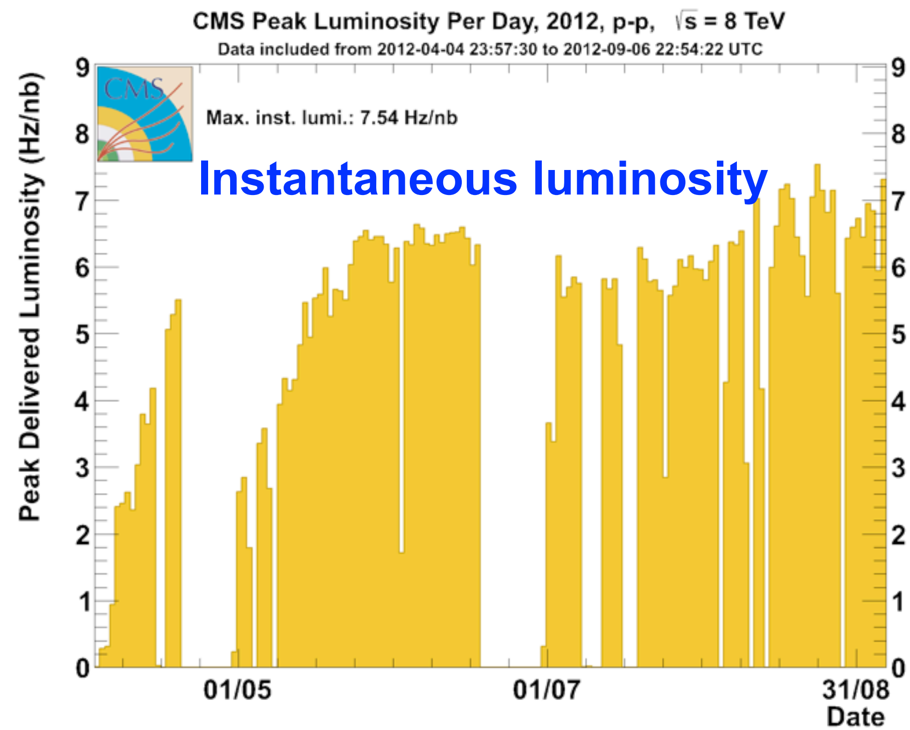




W and Z measurements

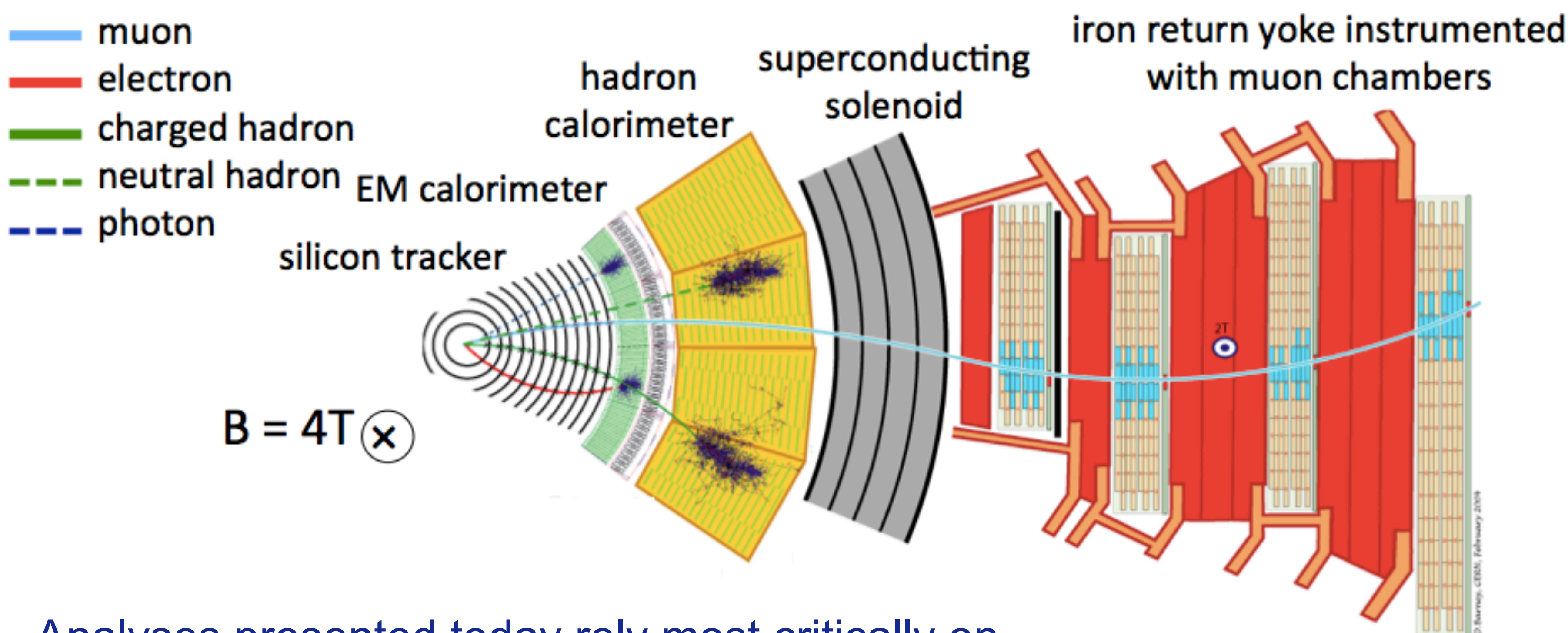
LHC data





- On target for 30 fb^{-1} by the end of 8 TeV run this year
- Routinely record 6−7 Hz/nb (i.e., 6−7 x 10^{33} $cm^{-2}s^{-1}$)

CMS detector

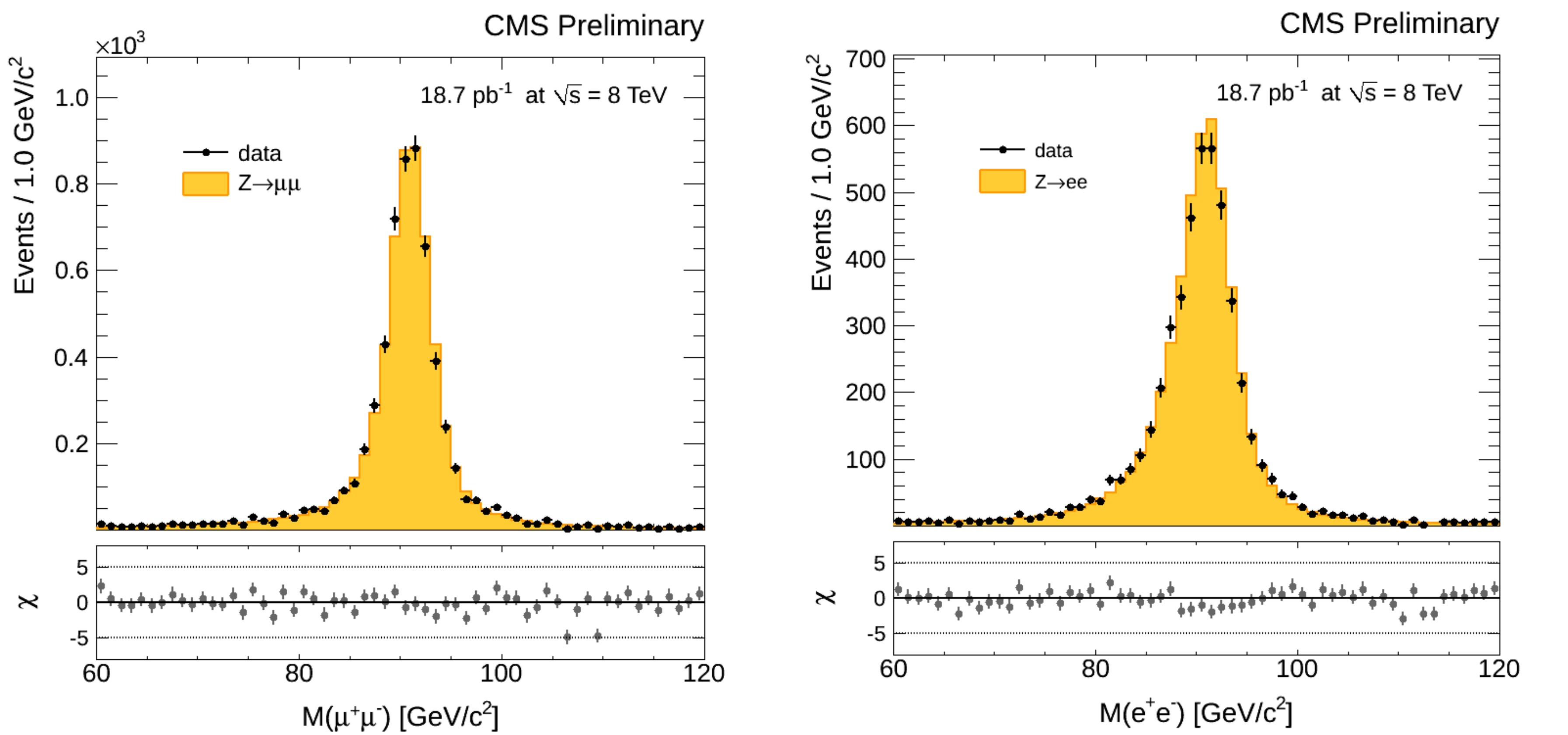


Analyses presented today rely most critically on

- **electrons**: tracks matched to clusters in EM calorimeter
- **muons**: minimum ionizing tracks, penetrate deep into muon system
- **jets / H_T**: constructed with combined tracking + calo info
- **MET**: constructed with combined tracking + calo info, hermetic detector

Inclusive Z cross section @8 TeV

https://cdsweb.cern.ch/record/1460098

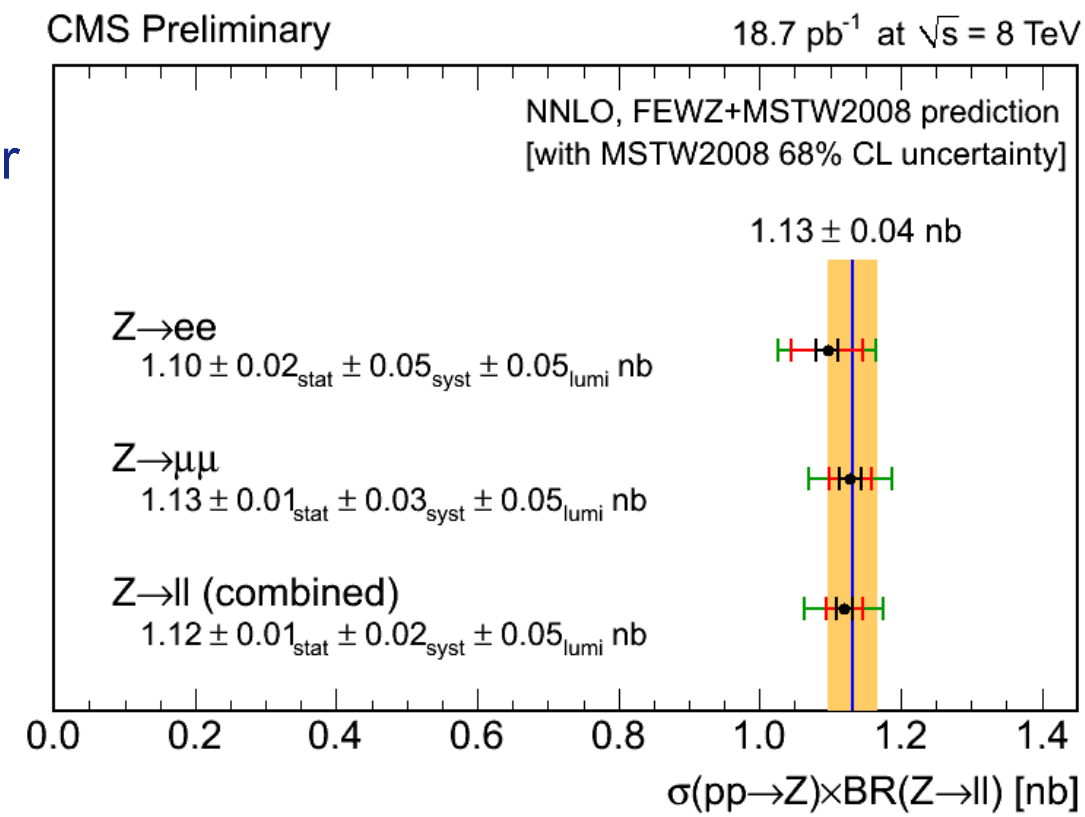


- Lepton p_T > 25 GeV, pair mass 60-120 GeV
- 11000 candidates, ~0 background, 1% stat.
- Excellent lineshape description from POWHEG+PYTHIA

Inclusive Z cross section @8 TeV

•Dominated by lumi (4.4%) and acceptance theory error (2-3%).

•Agreement with FEWZ + MSTW08 total NNLO cross section



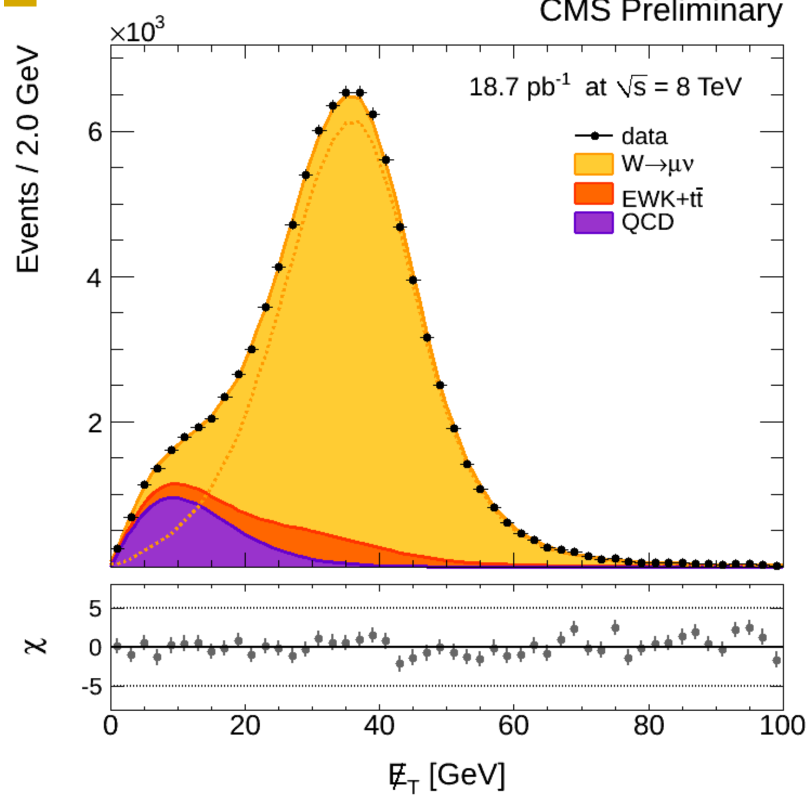
•EWK corrections is at the percent level

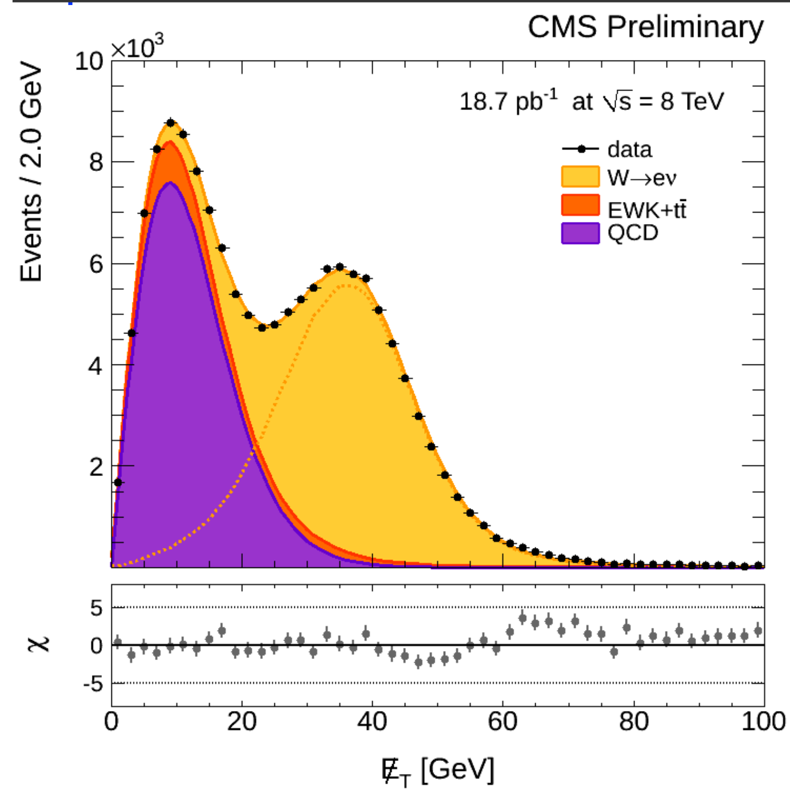
-Computed using Herwig (pseudo-NLO) + HORACE

•Will become important if luminosity & PDF uncertainties go below 1%

Inclusive W cross section @8 TeV

https://cdsweb.cern.ch/record/1460098



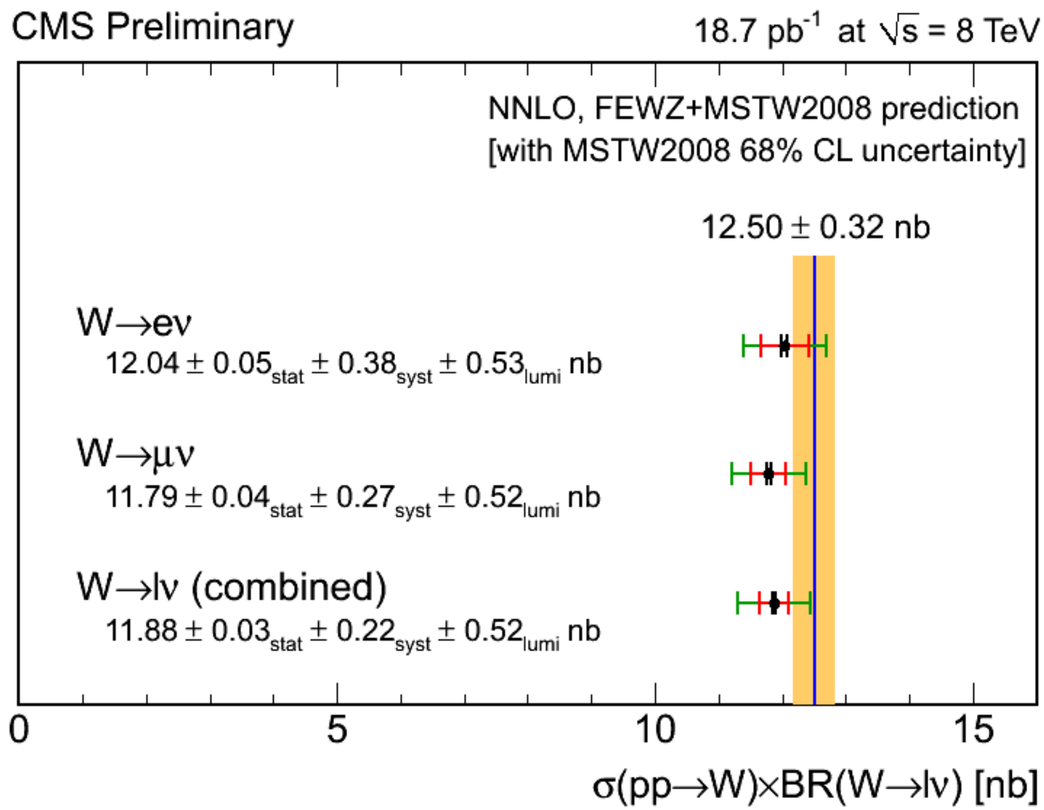


- =1 lepton p_T > 25 GeV, 156k W's
- No MET cut, signal extracted via binned MLH simultaneous fit of MET to isolated and non-isolated leptons
- W signal MET model corrected with Z recoil data

Inclusive W cross section @8 TeV

- W cross section dominated by lumi (4.4%) and acceptance theory error (2-3%).

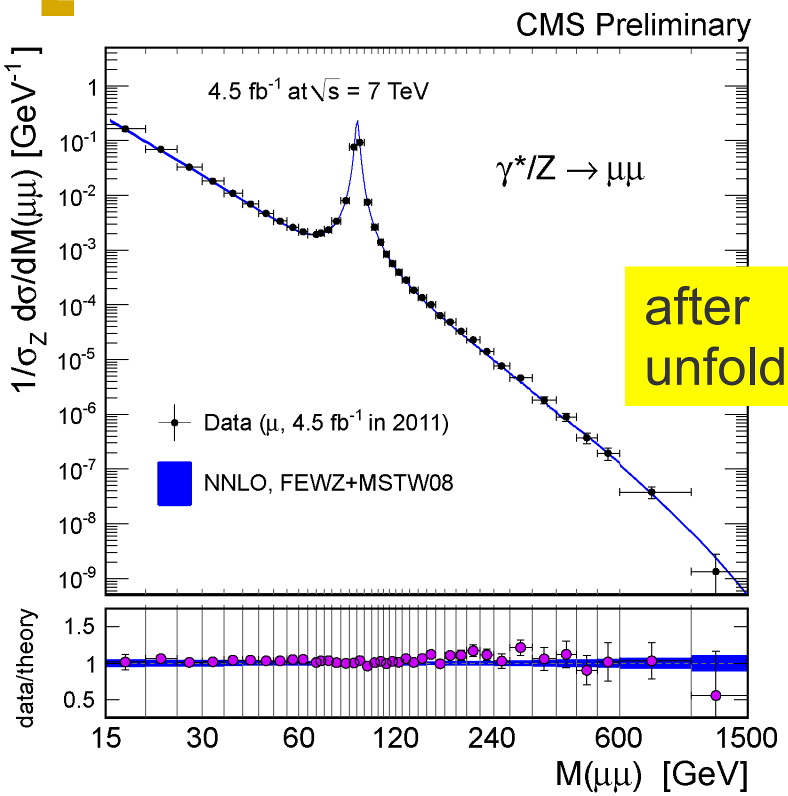
- Agreement with FEWZ + MSTW08 total NNLO cross section



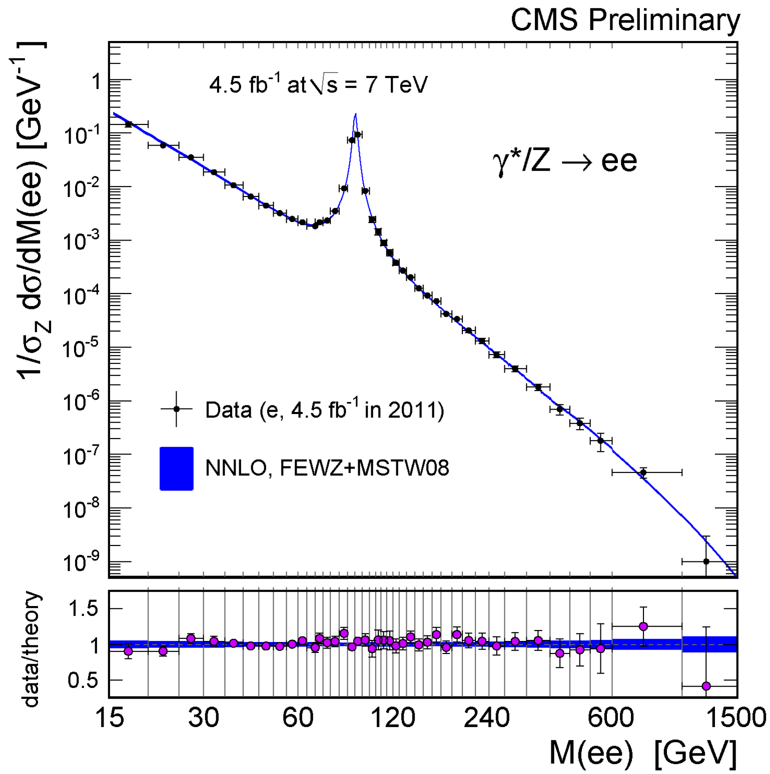
- EWK corrections is at the percent level
- Will become important if luminosity & PDF uncertainties go below 1%

Drell-Yan differential cross section

https://cdsweb.cern.ch/record/1439026



after unfolding

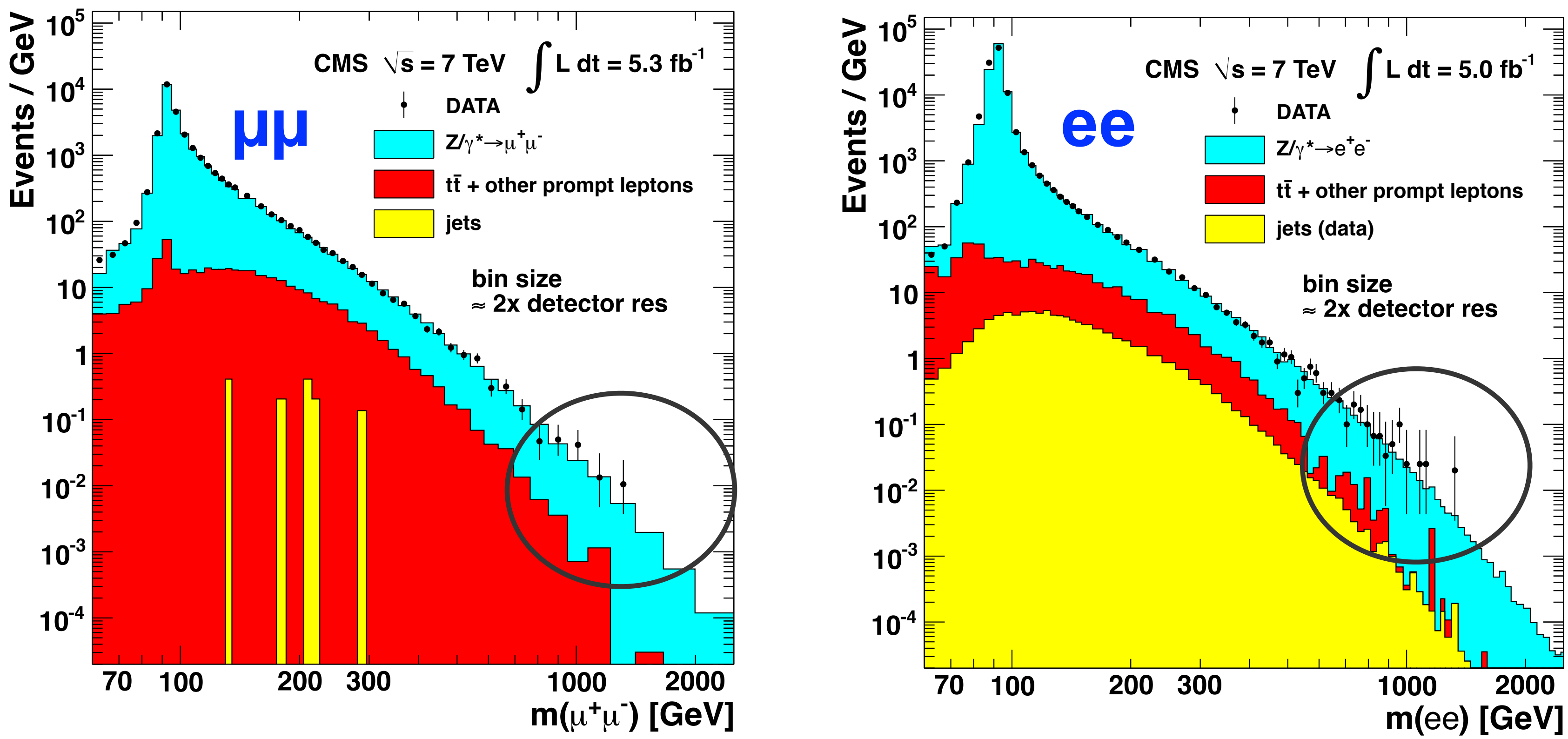


- Lepton pairs p_T > 14,9 GeV
- NNLO corrections important at low M (we select mostly boosted pairs), FSR effects unfolded
- Good agreement of Born level cross section with FEWZ+MSTW

Relevance of EWK corrections

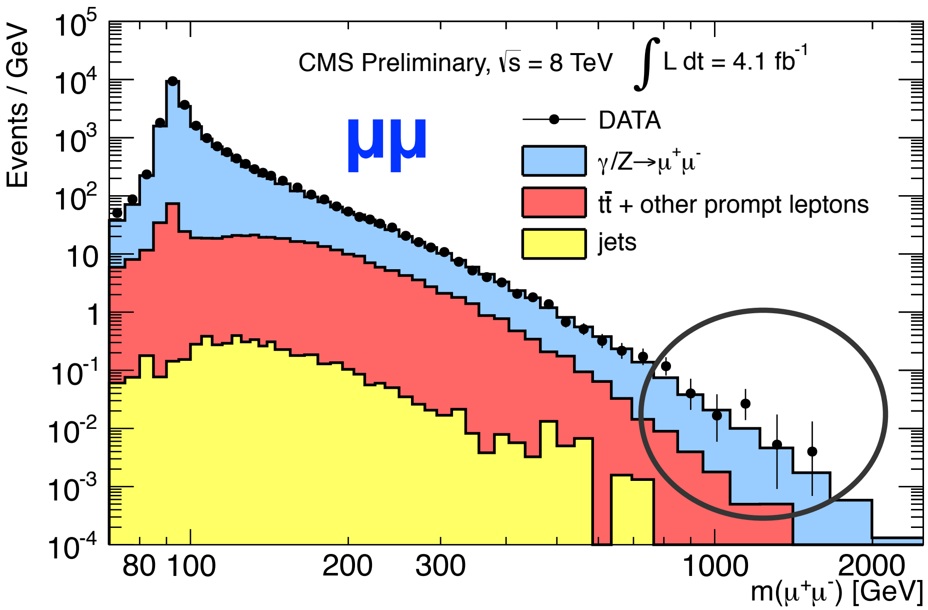
arXiv:1206.1849

7 TeV Drell-Yan data have 8 candidates above 1 TeV.



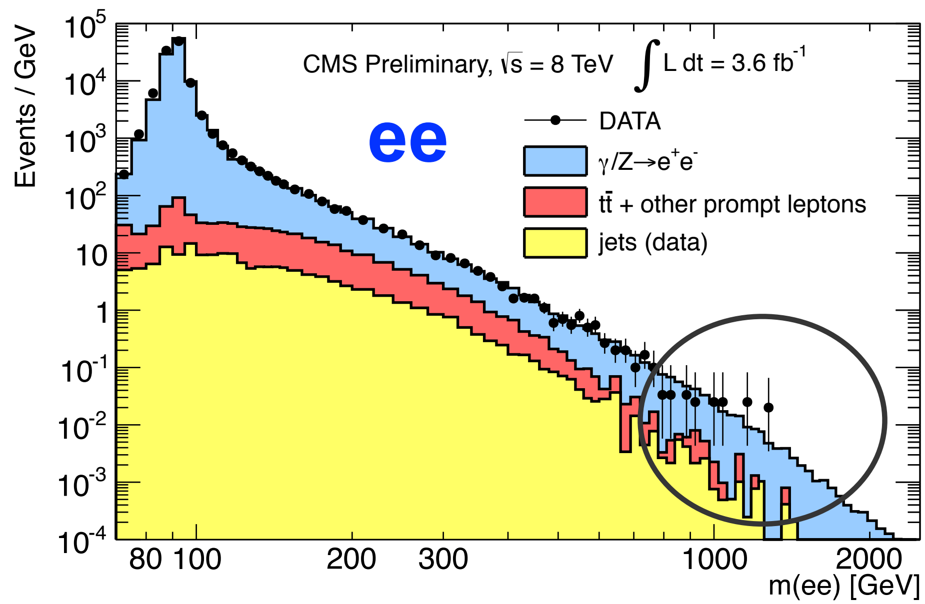
Almost in the Sudakov zone! Had to assign larger syst error to account for higher order corrections and PDF effects.

Dilepton distribution in 8 TeV data



http://cdsweb.cern.ch/record/1461216

A dozen candidates above 1 TeV!

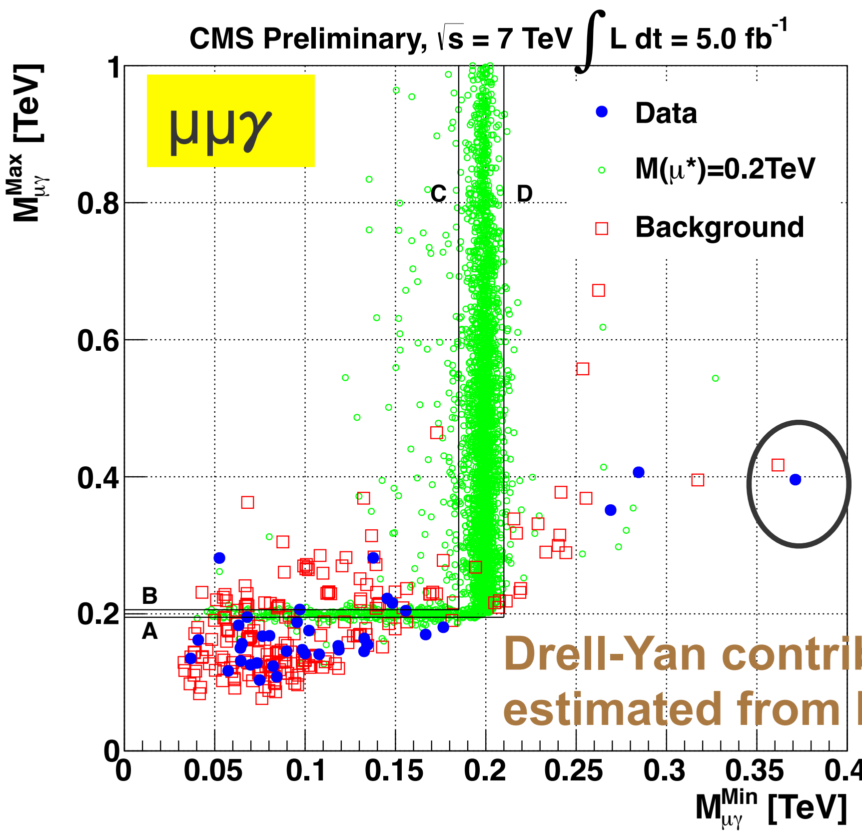


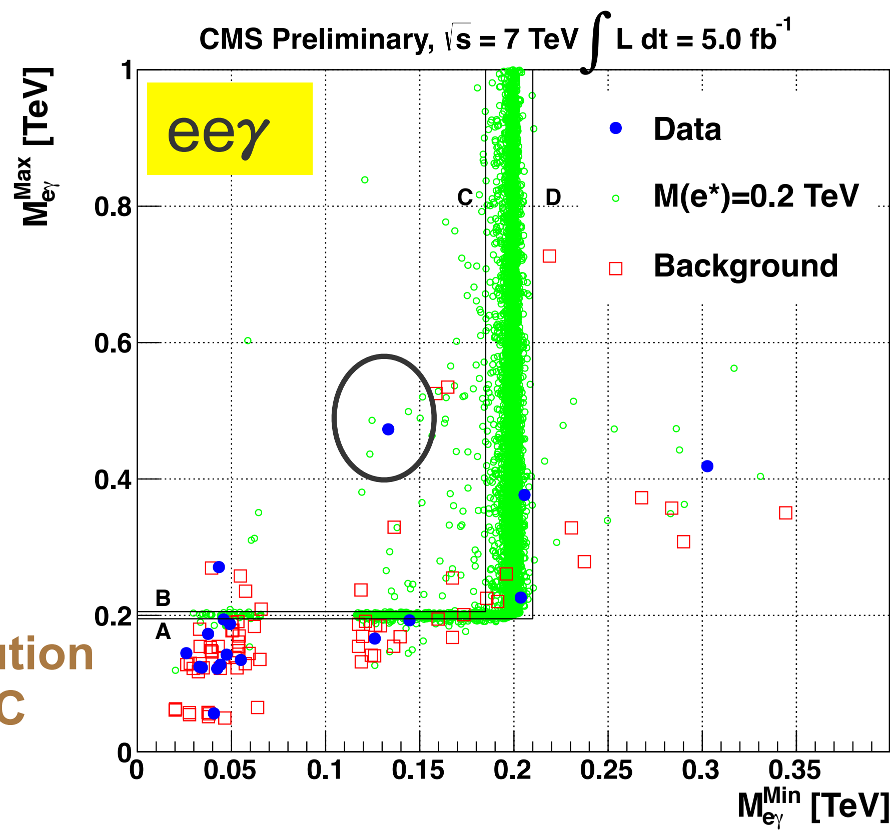
Stat. precision >1 TeV will improve to <15% by end of 2012.

Related measurements in the $\ell\ell\gamma$ final states

http://cdsweb.cern.ch/record/1460838

Plot $(M_{\ell\gamma})_{max}$ vs $(M_{\ell\gamma})_{min}$ to search for excited leptons





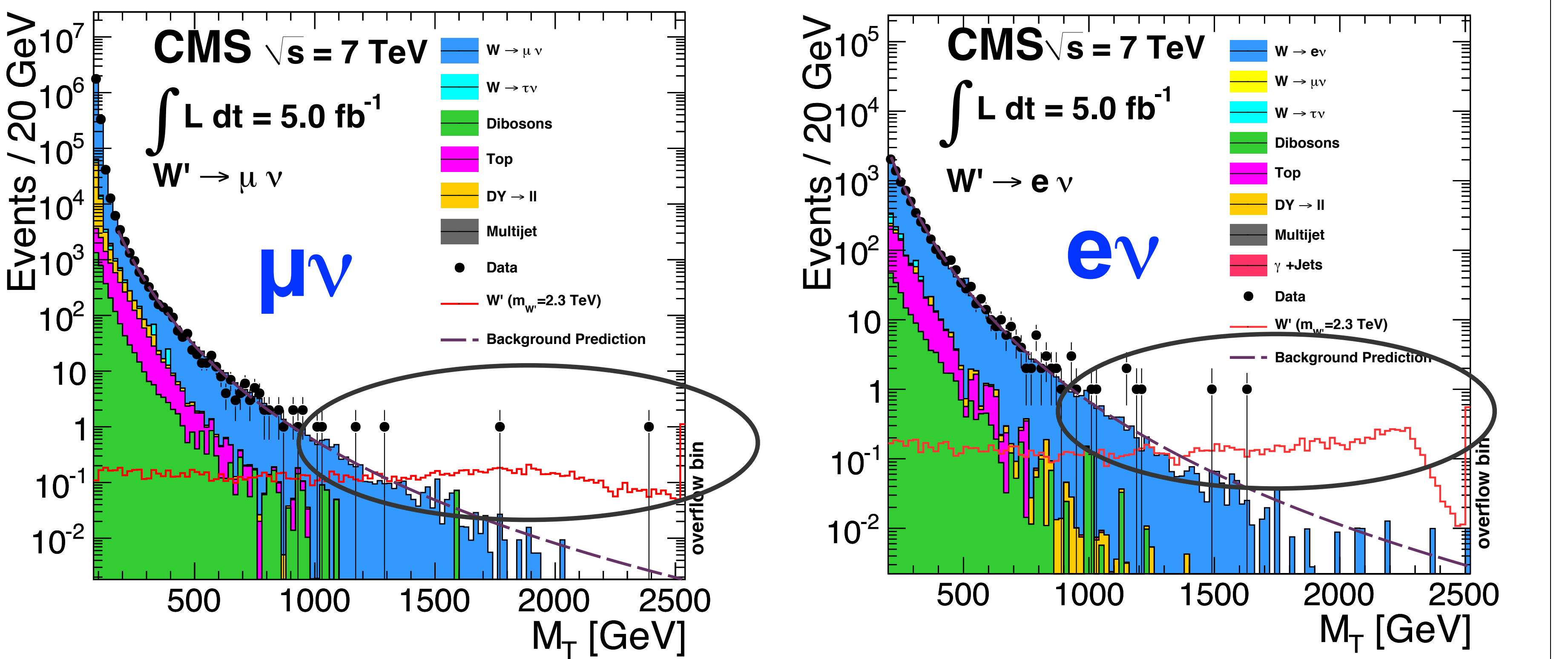
Drell-Yan contribution estimated from MC

Data upto 500 GeV in $M_{\ell\gamma}$ .Not yet in Sudakov zone. Perhaps in 2014.

W→ℓν tail

arXiv:1204.4764

CMS W' search has accumulated 14 events above 1 TeV



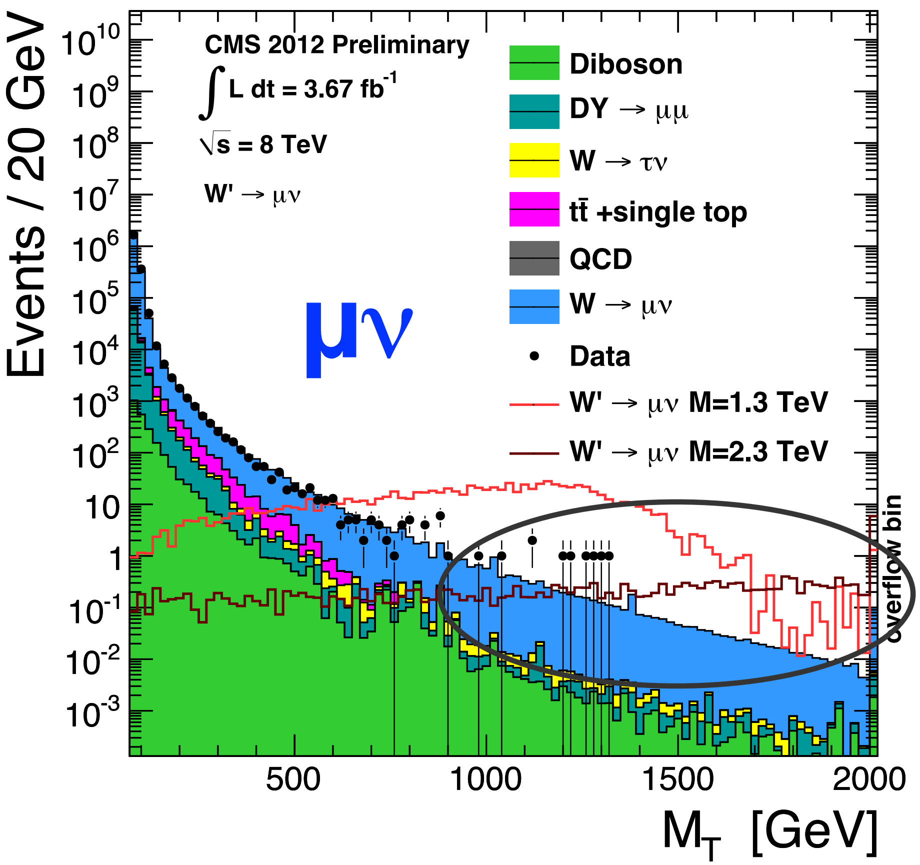
Approaching Sudakov zone! Cannot use NLO predictions blindly at high mass. Empirical parametrization to estimate W contribution.

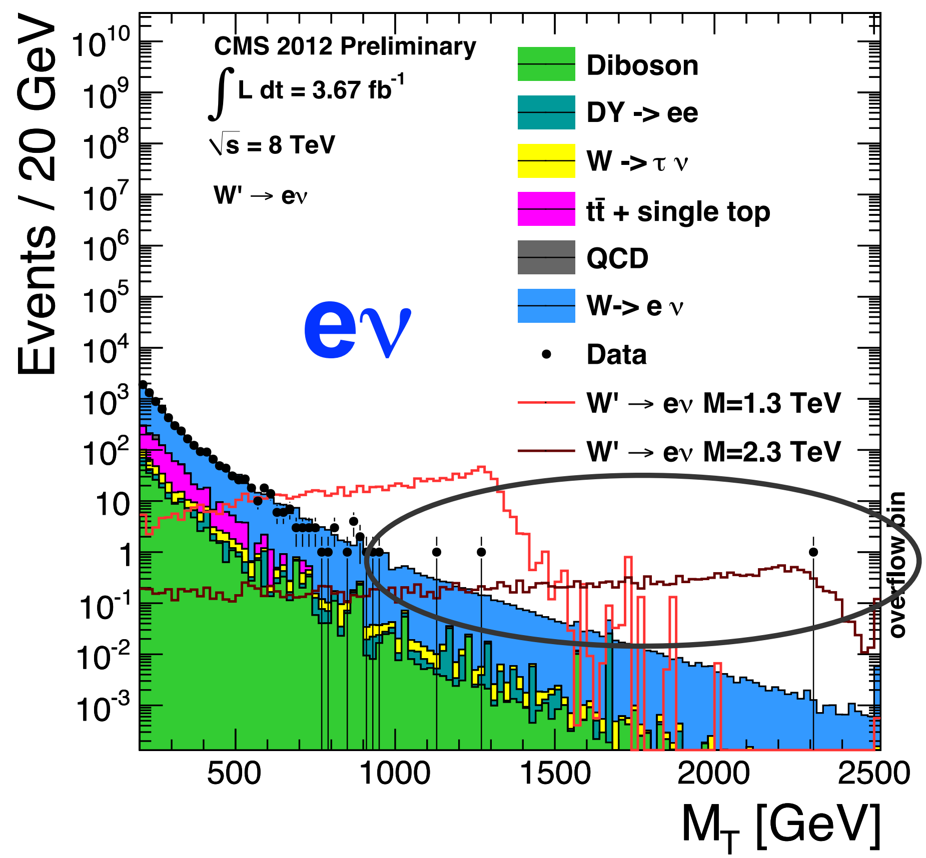
W→ℓν in 8 TeV data

http://cdsweb.cern.ch/record/1461725

12 events above 1 TeV in 3.7 fb^{-1} data

- Better than 10% precision expected in 2012



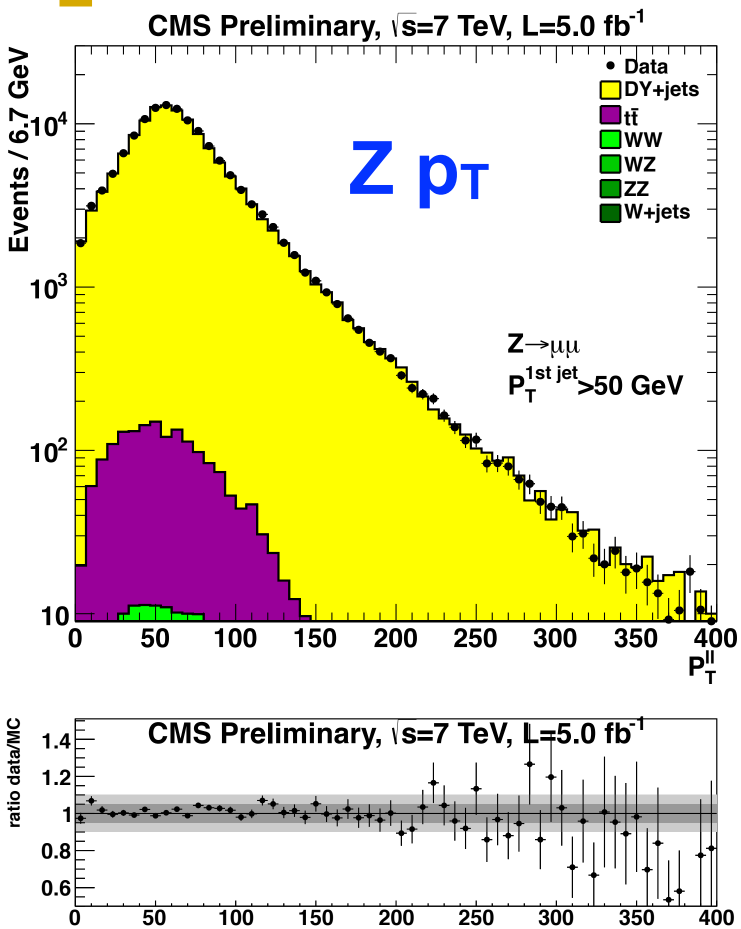


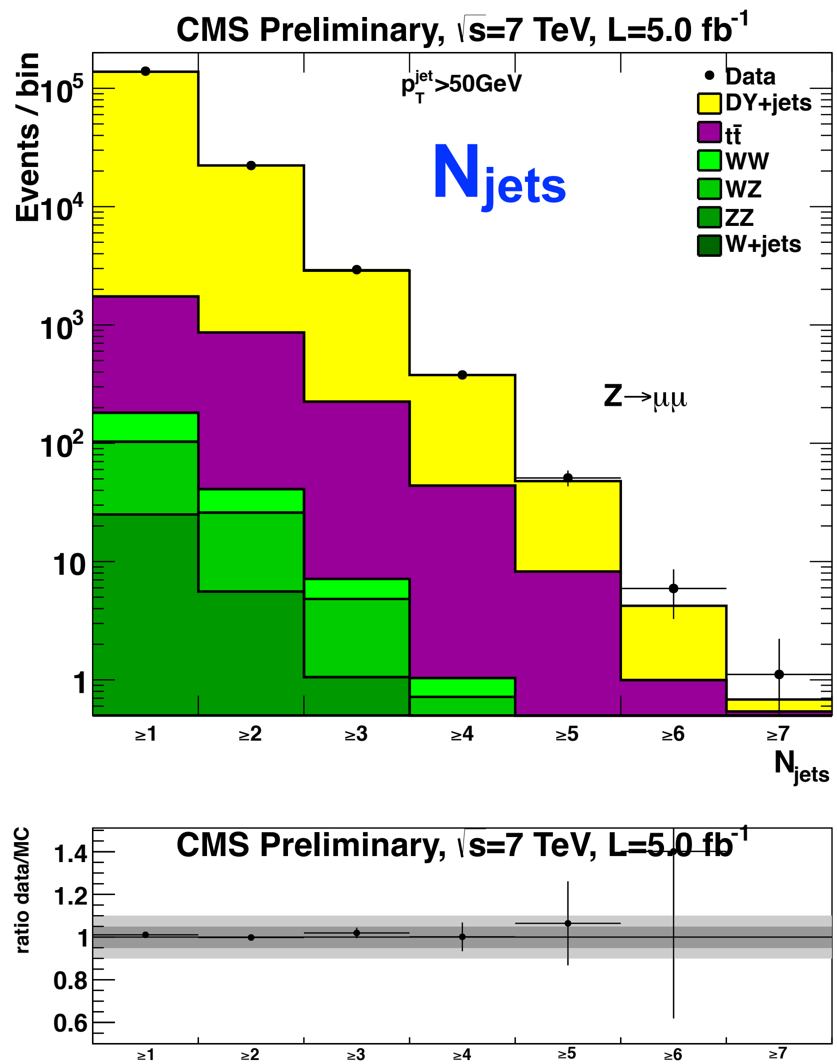
W/Z+jets measurements

Default MC versions used

Matrix element	Madgraph-5 1.3.30
Parton shower	Pythia 6.4.22
Matching threshold	20 GeV (MLM)
UE tune	Z2
Default PDF	CTEQ6L1
Fact./Renorm. scale	$\sqrt{m_V^2+p_{T,V}^2}$ dynamic

Z+jets @7 TeV





Data upto 500 GeV. Will reach Sudakov zone in 2014.

Lepton unfolding: "dressed leptons"

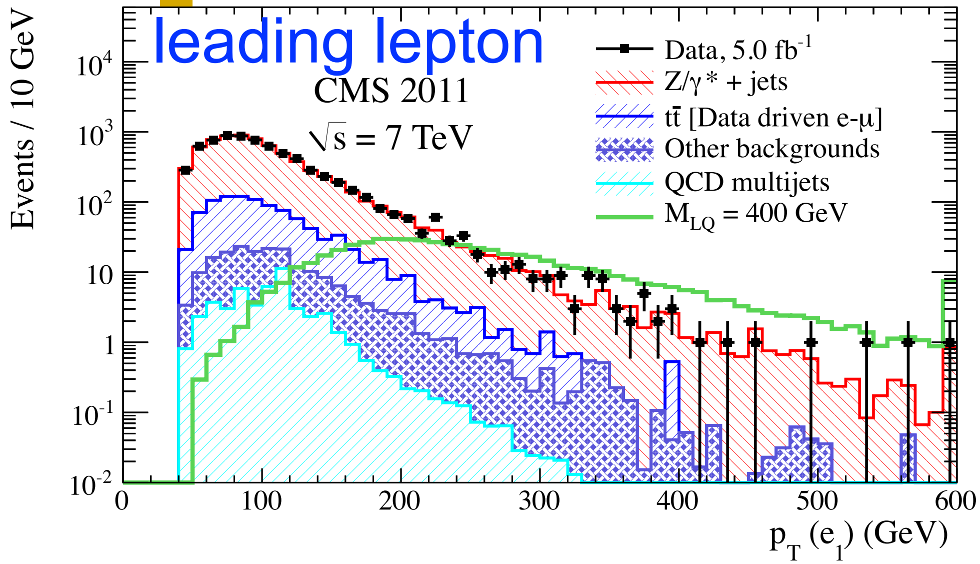
- The particle-level 4-vector of a lepton in MC is computed by adding to it the 4-vectors of all the photons within Δ= 0.1
  - -Thus, different FSR effects in Zμμ and Zee taken into account
  - -So that the two channels can be combined
  - -Similar in spirit to the particle response for jets

- Detector level effects corrected via response matrix:
  - -Using MadGraph (baseline) and Sherpa.
  - -Take half-difference between the two as systematics

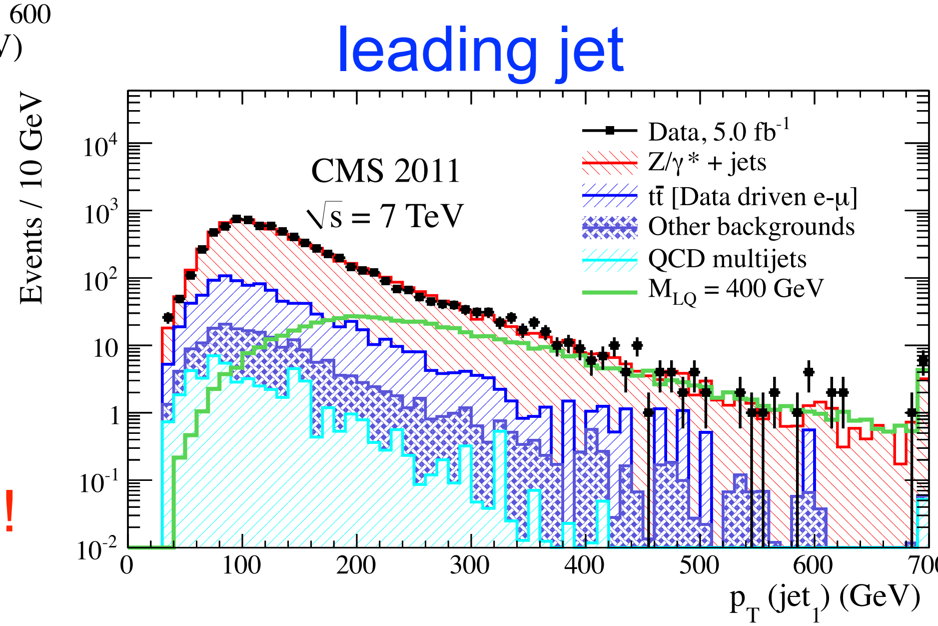
- Dressed-lepton makes it easier to compare to particle-level simulation. Bare lepton can be used for Born-level comparisons. Both CMS and ATLAS have adopted this procedure. Minimizes uncertainty from radiative corrections.

Unfolded particle-level event shape distributions in backup.

Related measurements in the ℓℓ+jj final states



arXiv:1207.5406



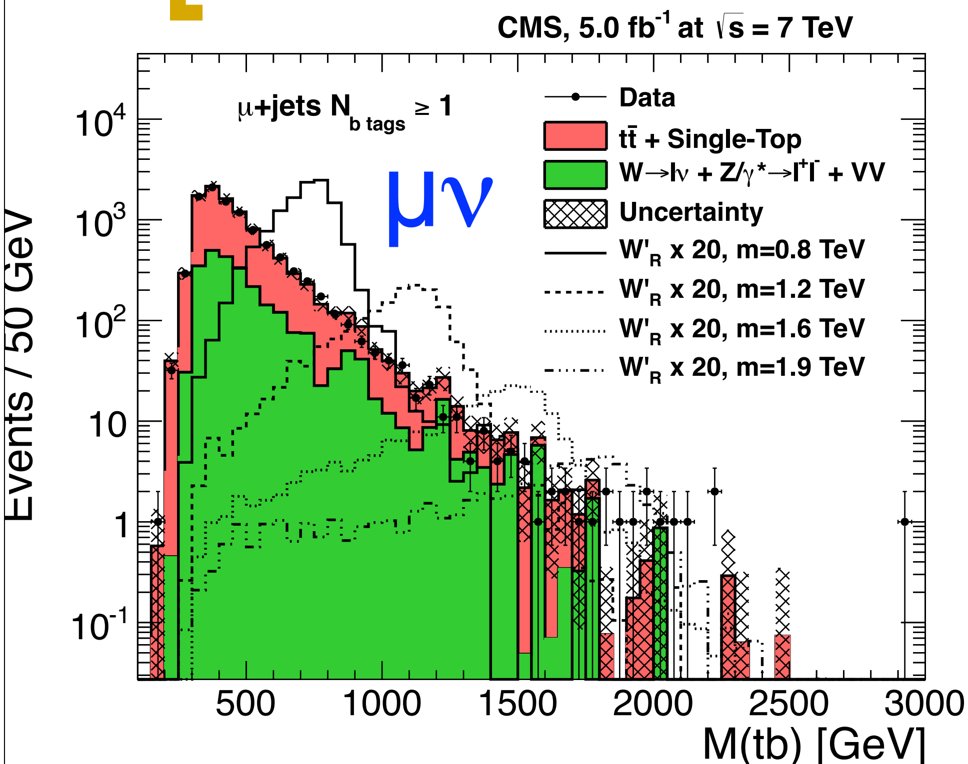
~15 events above 1 TeV

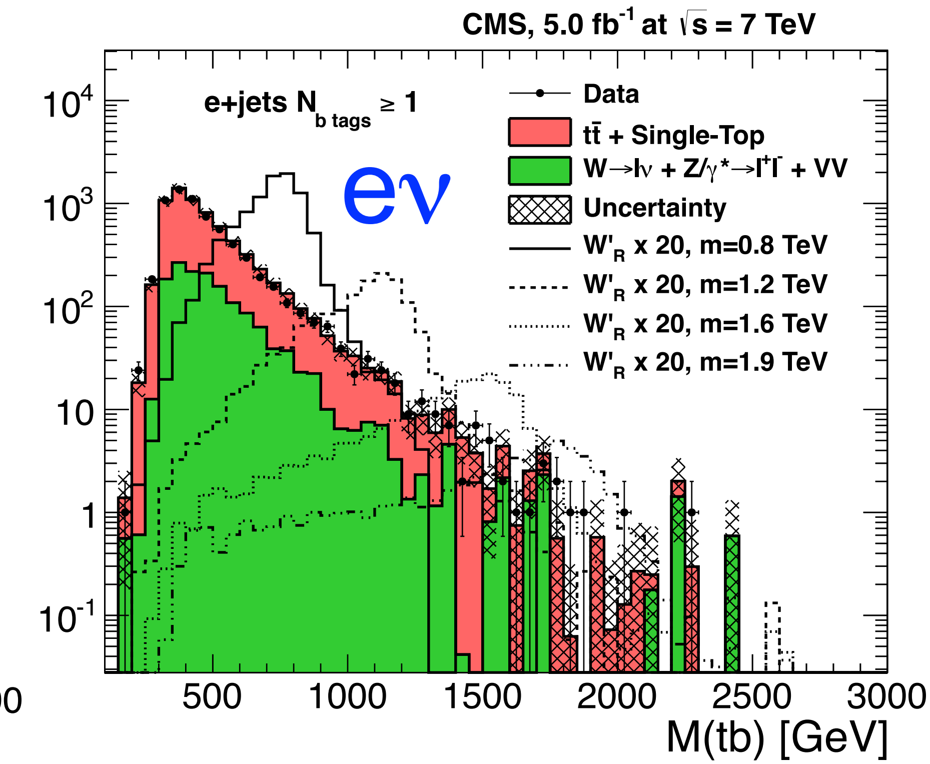
- Better than 10% precision expected in 2012

Approaching Sudakov zone in 2012!

W+jets with at least 1 b-tag

arXiv:1208.0956





Dozens of events above 1 TeV

Already in Sudakov zone!

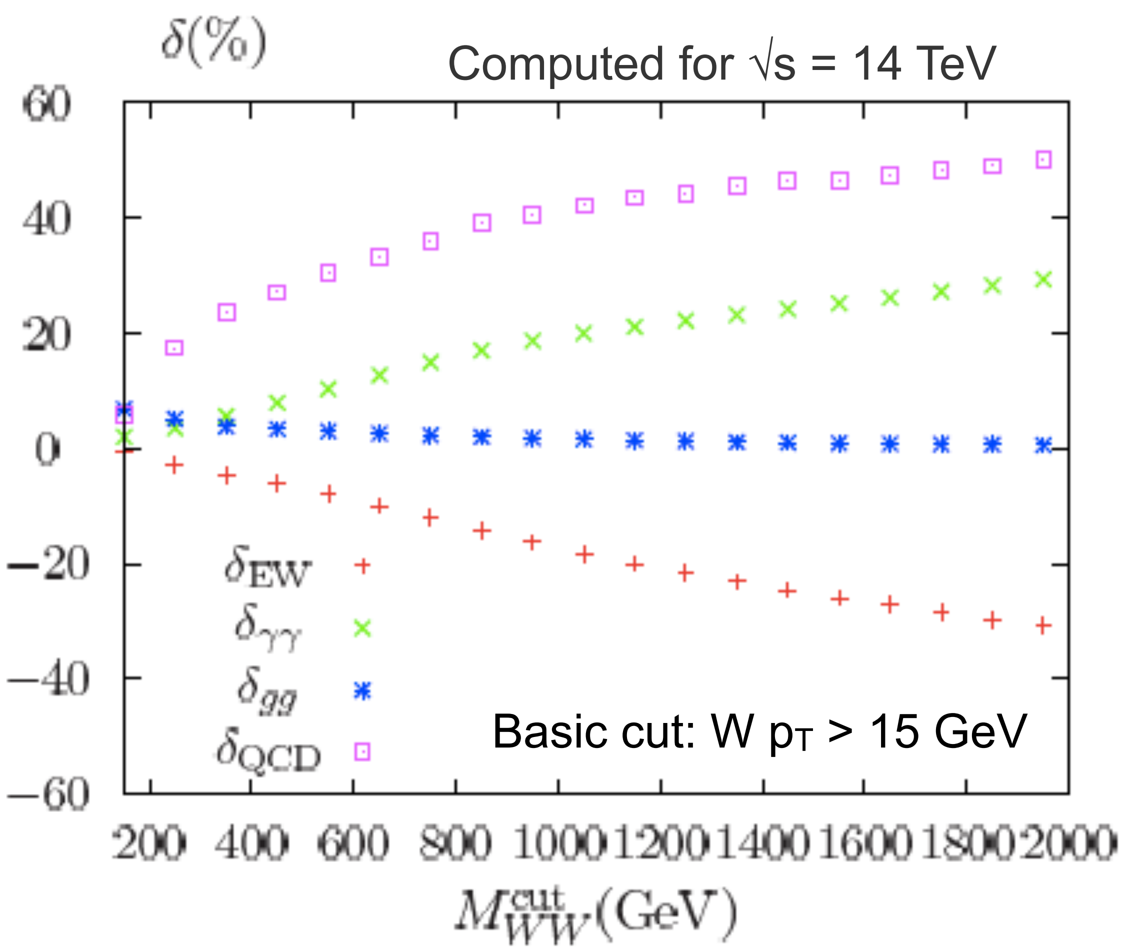
- Better than 5% precision expected in 2012

Validate W+jets shape using data: compare 0 b-tagged sample in data with W+jets MC; take difference as systematics.

Diboson measurements

Potentially large EWK corr. in WW production

See talk by T. Kasprzik at ICHEP 2012



EWK and QCD corrections partially cancel out, resulting in net positive enhancement at high WW invariant mass

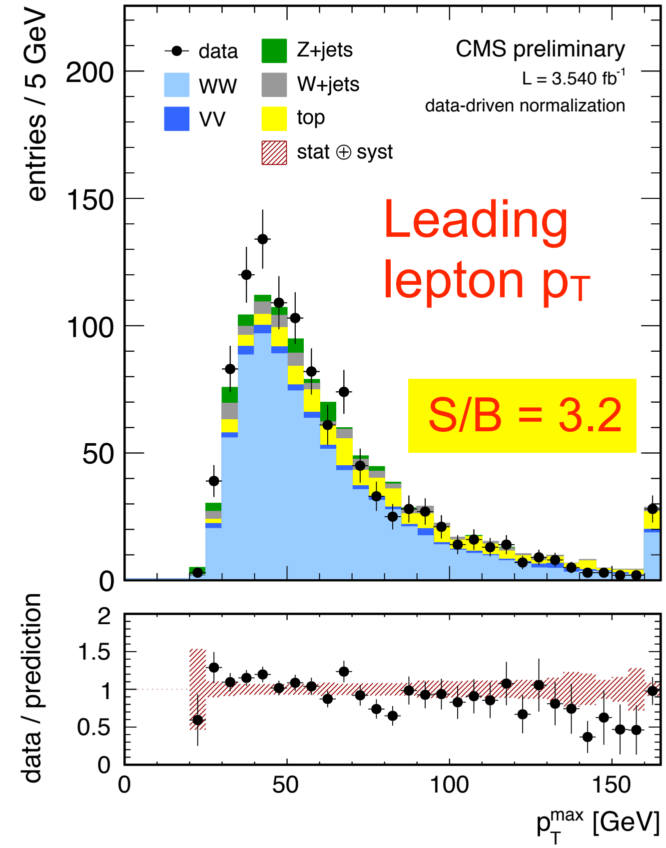
Important to understand the interplay of these cancellations, because we have experimental data up to moderately high masses.

WW→2ℓ2ν cross section at 7 TeV

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12005

Signal and background yields

Sample	Yield ± stat. ± syst.
$gg \to W^+W^-$	$46.0 \pm 0.6 \pm 14.2$
$q\bar{q} \to W^+W^-$	$750.9 \pm 4.1 \pm 53.1$
Total Background	$247.1 \pm 14.6 \pm 29.5$
Signal + Background	$1044.0 \pm 15.2 \pm 62.4$
Data	1134



Cross section measurement

σ = 52.4 ± 2.0 (stat) ± 4.5 (sys) ± 1.2 (lum) pb
NLO prediction (MCFM): 47.0 ± 2.0 pb

800 WW signal events

☑ Consistent with NLO

Campbell, Ellis, Williams. JHEP 07 (2011), 018.

Does not include EWK corrections!

WW→$2\ell 2\nu$ at 8 TeV

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12005

Signal and background yields

Sample	yield ± stat. ± syst.
gg→WW	$43.3 \pm 1.0 \pm 13.4$
qq→WW	$640.3 \pm 4.9 \pm 47.4$
Total Background	$292.7 \pm 22.3 \pm 31.8$
Signal + Background	$976.3 \pm 22.9 \pm 63.9$
Data	1111

σ = 69.9 ± 2.8 (stat) ± 5.6 (sys) ± 3.1 (lum) pb
NLO prediction (MCFM): 57.3 ± 2.0 pb

1.8σ above NLO prediction

Could be a conspiracy of syst bias & upward fluctuation or something not included in theory calculation.

Does not include EWK corrections!

But has generated some buzz ...

Charginos Hiding In Plain Sight

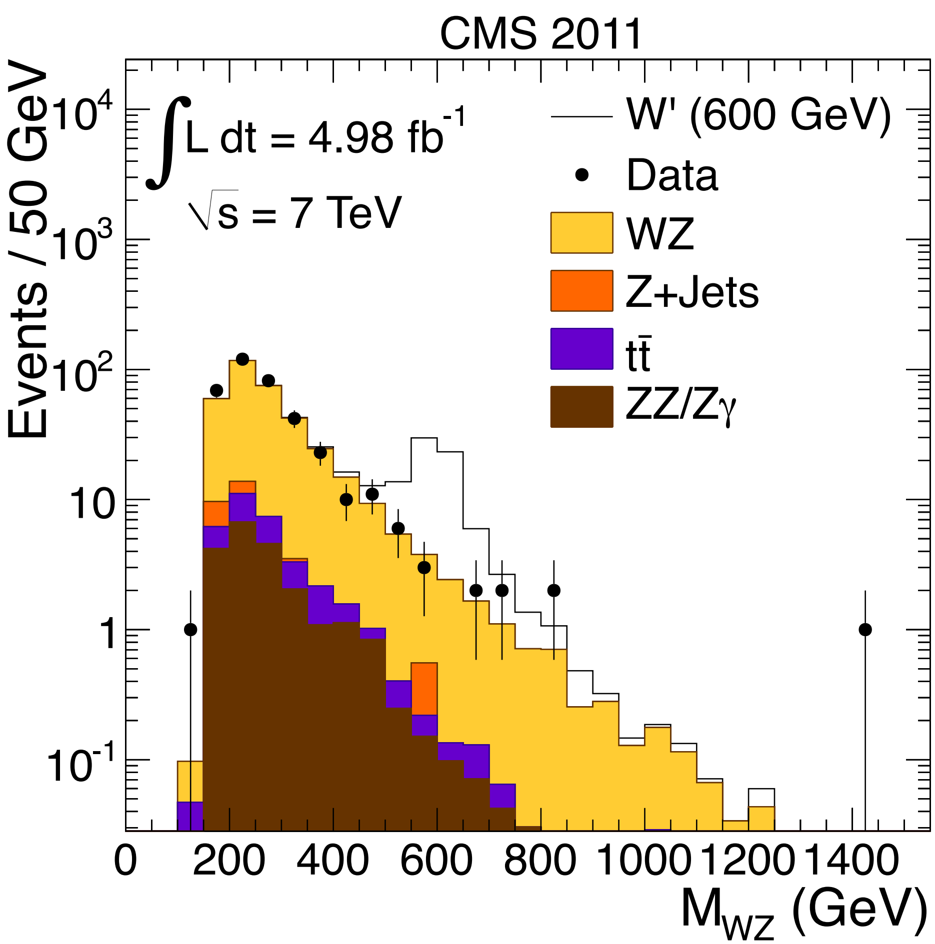
David Curtin,[1] Prerit Jaiswal,[1,2] and Patrick Meade[1]

arXiv:1206.6888v2

4% stat precision. Main systematics:
Theory (PDF & jet veto) 5%
Luminosity 4.4%.

Diboson production at 7 TeV: WZ→ℓℓℓ′ν

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11041



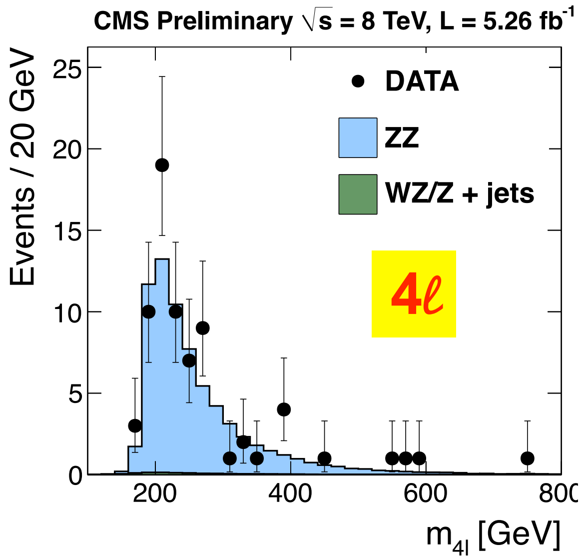
- 1 event above 1 TeV in 2011 data
- Expect about 5-10 events at the end of 2012
- Not in Sudakov zone, nor likely anytime soon!

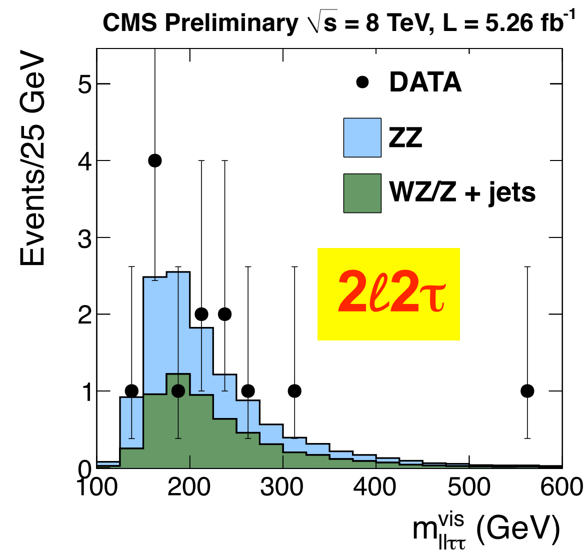
σ = 17.0 ± 2.4 (stat) ± 1.1 (sys) ± 1.0 (lum) pb
NLO prediction (MCFM): 17.5 ± 0.6 pb

☑ Consistent with NLO

Diboson production at 8 TeV: ZZ→4ℓ

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12014





Channel	ZZ expected	Backgr-d	Observed
4e	11.6	0.4	14
4mu	20.3	0.4	19
2e2mu	32.4	0.5	38
Total	→	65.6	71
2l2tau	6.5	5.6	13
4l+2l2tau	→	77.7	84

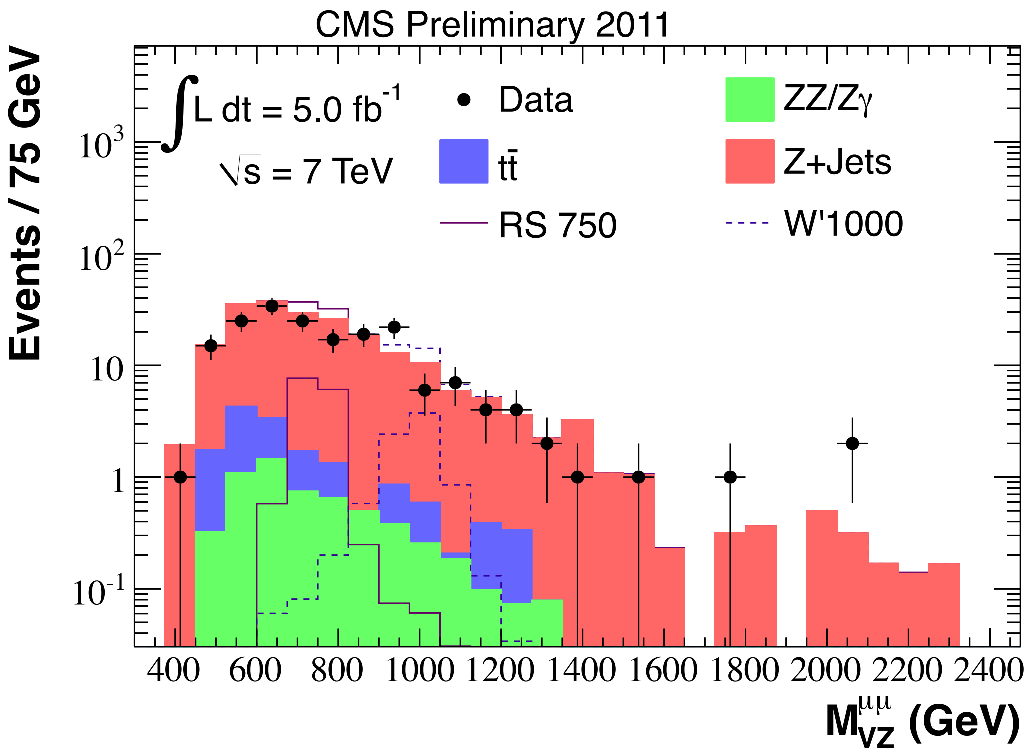
σ = 8.4 ± 1.0 (stat) ± 0.7 (sys) ± 0.4 (lum) pb
NLO (MCFM 6.0): 7.7 ± 0.4 pb

☑ Consistent with NLO

Not in Sudakov zone, nor likely any time soon.

Diboson at 7 TeV: WZ/ZZ→ℓℓ+j (boosted)

http://cdsweb.cern.ch/record/1444879



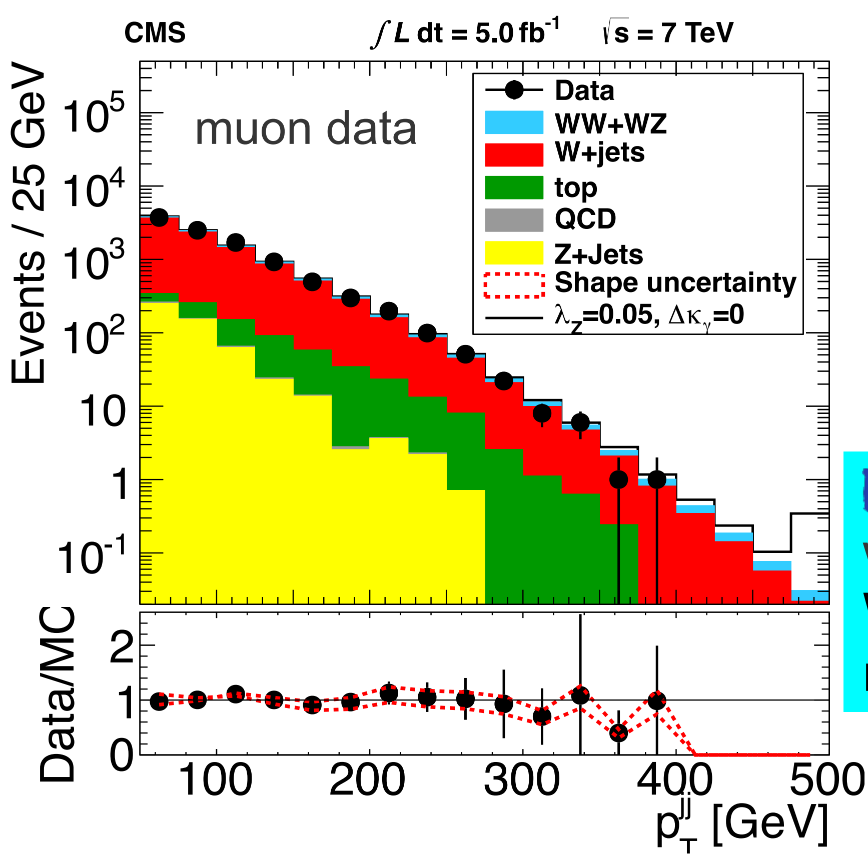
- ✦The other boson (W or Z) decays hadronically into a single (merged) jet
  - -anti-kT 0.7 jet
  - -highly boosted: p_T > 250 GeV
- ✦Plot invariant mass of the VZ system.

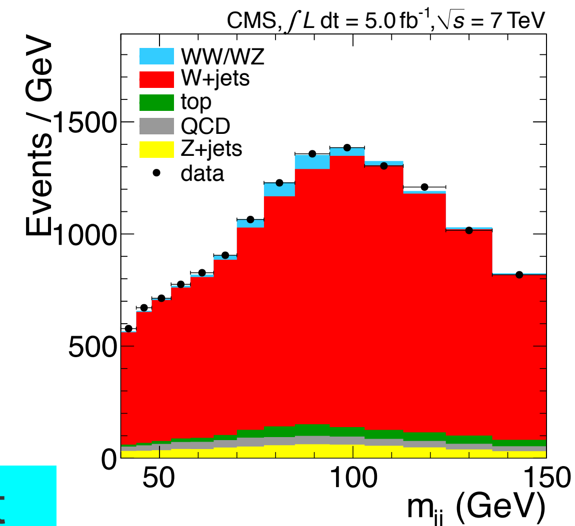
A dozen events beyond 1 TeV. Will be in the Sudakov zone in 2012.

Fit the smoothly falling spectrum to set limit.

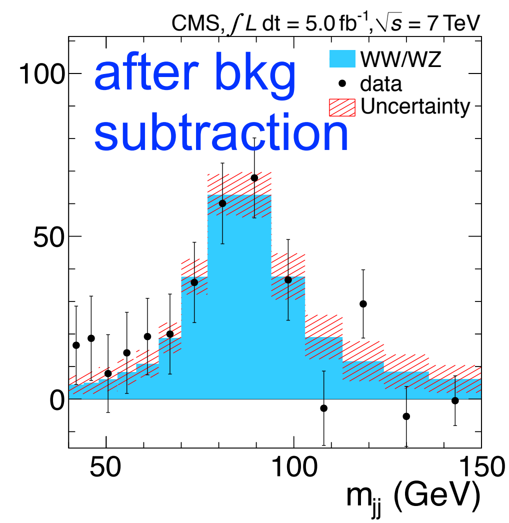
Diboson at 7 TeV: WW/WZ→ℓνqq

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12015





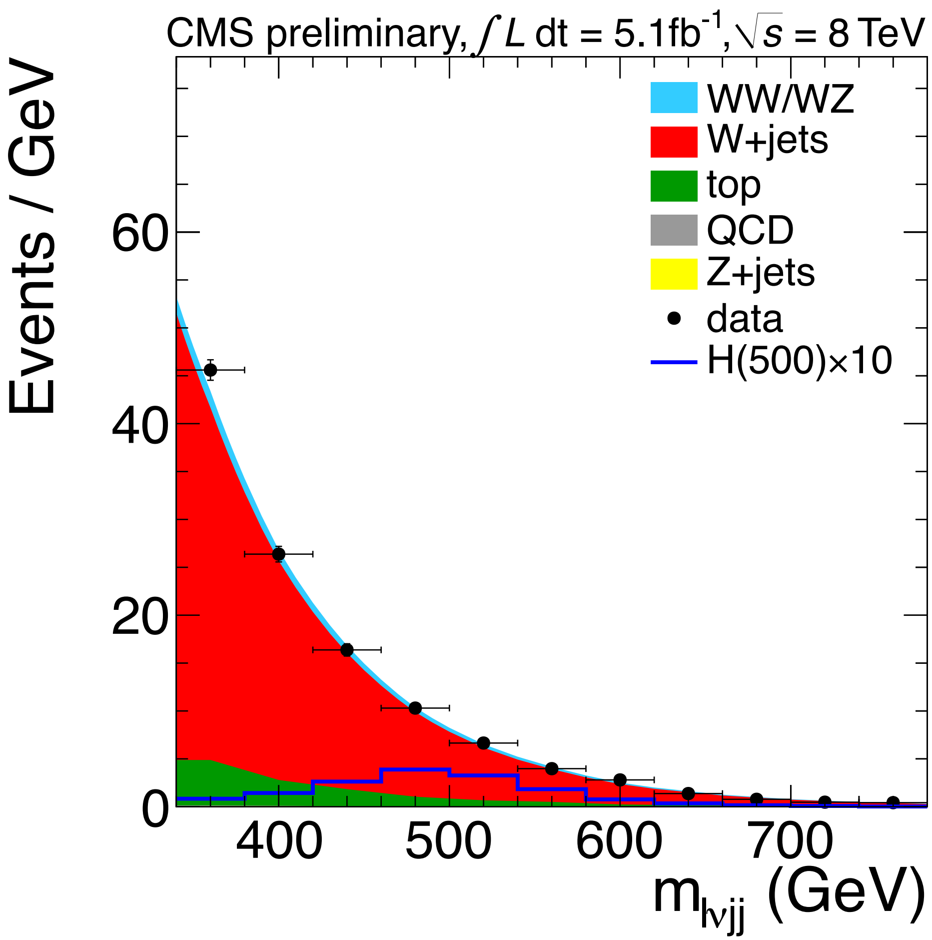
☑ Consistent with NLO. See WW mass on next slide.



σ = 68.9 ± 8.7 (stat) ± 9.7 (sys) ± 1.5 (lum) pb

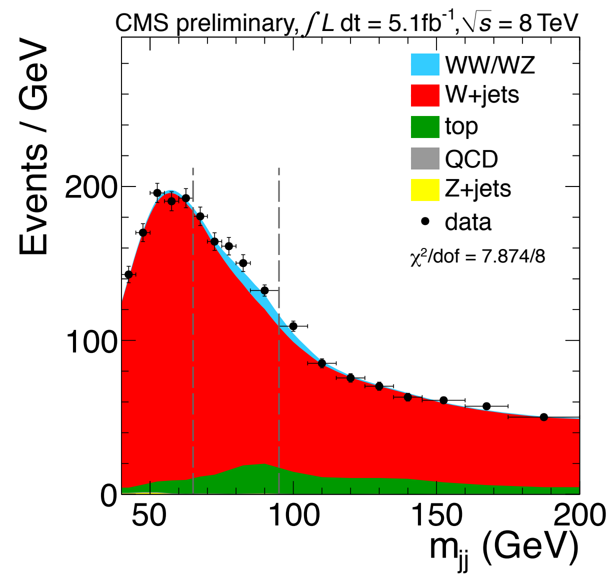
NLO prediction (MCFM): 65.6 ± 2.2 pb

Diboson at 8 TeV: WW/WZ→ℓνqq



http://cdsweb.cern.ch/record/1460660

A few dozen events above 1 TeV
(not shown here - see next slide).
Already in Sudakov zone.

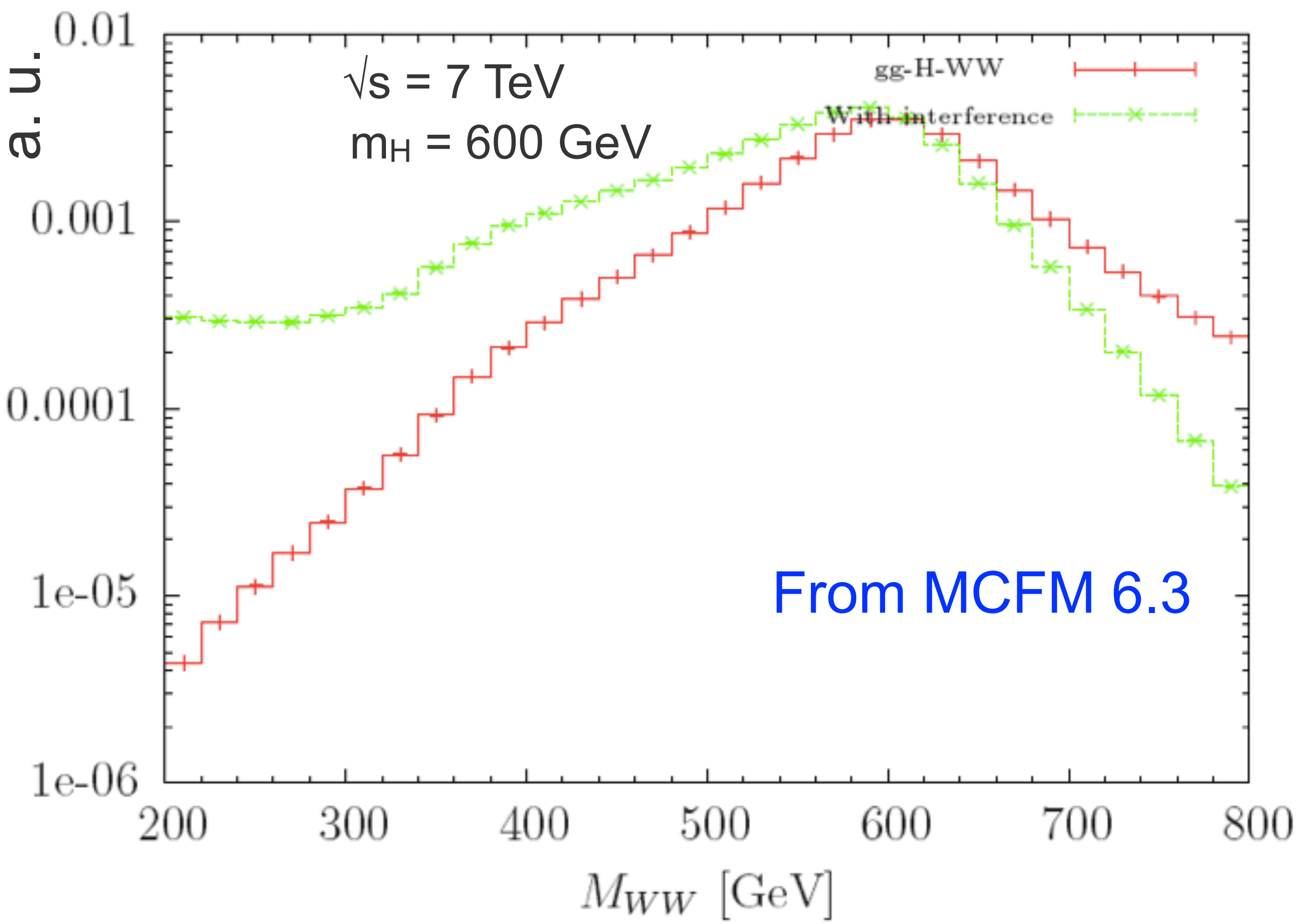


Model smoothly falling spectrum
using data sidebands.

The pesky interference

somewhat unrelated to EWK corr

Large interference between gg→WW and gg→H→WW for large H masses (valid for any broad resonance)



Magnitude & error of this interference not well understood. MCFM has LO computation of the interference. NLO effects large. Additional complexity due to resonance lineshape uncertainty.

Has prevented us from setting limits on m_H > 600 GeV

Quick recap of Sudakov zone survey

Are we in the Sudakov zone ?

Process	Now	End 2012	14 TeV
Incl. W/Z	No	No	No
$\ell\ell\gamma$, $\ell\nu\gamma$	No	No	Yes
W/Z tail	No	Yes	Yes
W/Z+jets tail	Close	Yes	Yes
WW leptonic	No	Close	Yes
WZ,ZZ leptonic	No	No	No
WW semi-leptonic	Yes	Yes	Yes
WZ,ZZ semi-leptonic	No	Yes	Yes

Summary

- The size of EWK corrections for many processes at LHC are approaching the current precision of the measurement
  - Important at high mass/p_T tails beyond1 TeV
  - QCD inclusive jets/ dijet, W/Z, and diboson cross sections at high mass/p_T are already sensitive to EWK corrections

- Experimentalists are aware of the situation, 2 ways to cope with:
  - Either use data-driven/ empirical methods for shape & yields
  - Or live with larger theoretical syst. uncertainty for now

- Understanding kinematic phase space at high mass/p_T is an important benchmark for searches for new physics
  - Availability of dedicated theoretical calculation/ tools for applying EWK corrections will help in reducing syst. uncertainties

BACKUP SLIDES

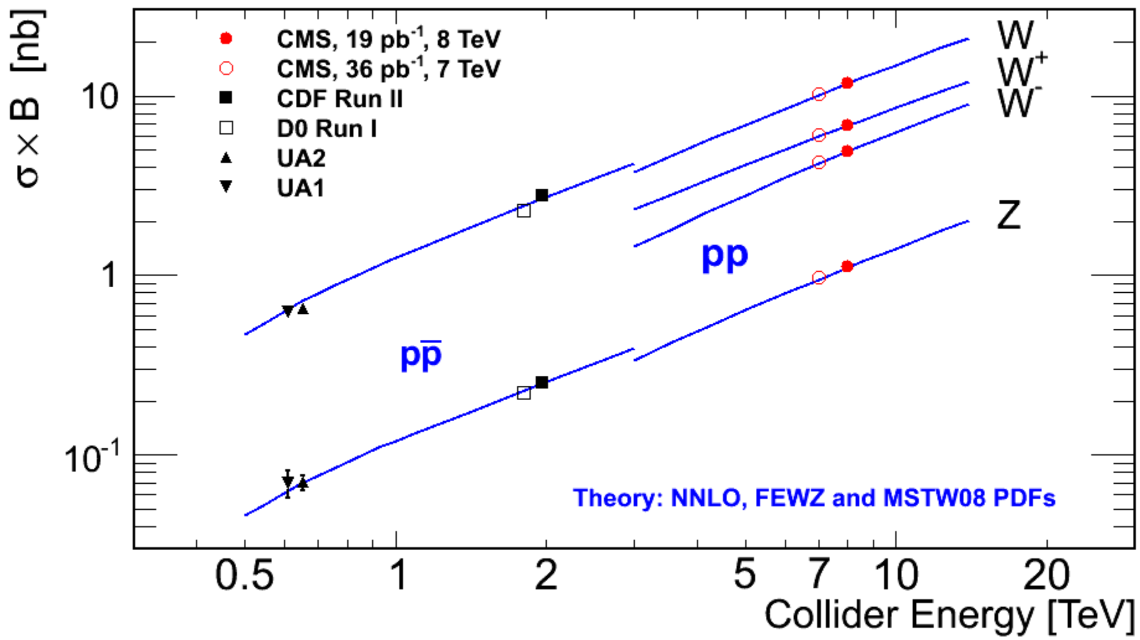
W and Z cross sections @8 TeV

https://cdsweb.cern.ch/record/1460098

- pQCD predicts a 15-20 % cross section increase as $\sqrt{s}$ = 7 →8 TeV

- W/Z and W^+/W^- cross section ratios (and 7/8 double ratios) are (sub-) percent predictions of pQCD

- Important initial experimental benchmarks for precision physics with leptons at 8TeV

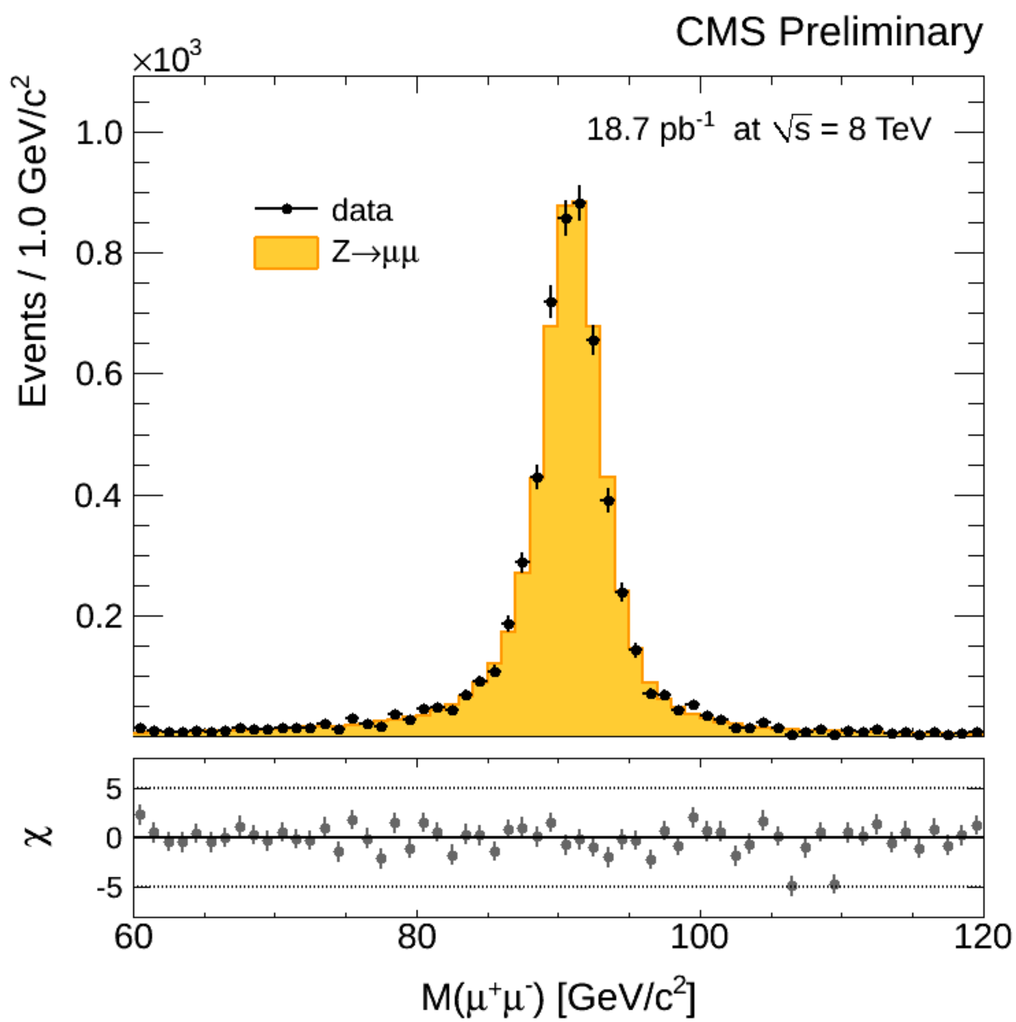


1% experimental (non-lumi, non-theory) precision achieved at 7 TeV with just 36/pb

J. High Energy Phys. 10 (2011) 132

Z cross section @8 TeV: Z→μμ

- Opp sign mu pairs with p_T > 25 GeV and $|\eta| < 2.1$, Pair mass 60-120 GeV
- 6000 candidates, ~0 background, 1.3% stat.
- Z reconstruction, ID, trigger efficiency known to 1.1% syst. from tag and probe methods
- Excellent lineshape description from POWHEG +PYTHIA



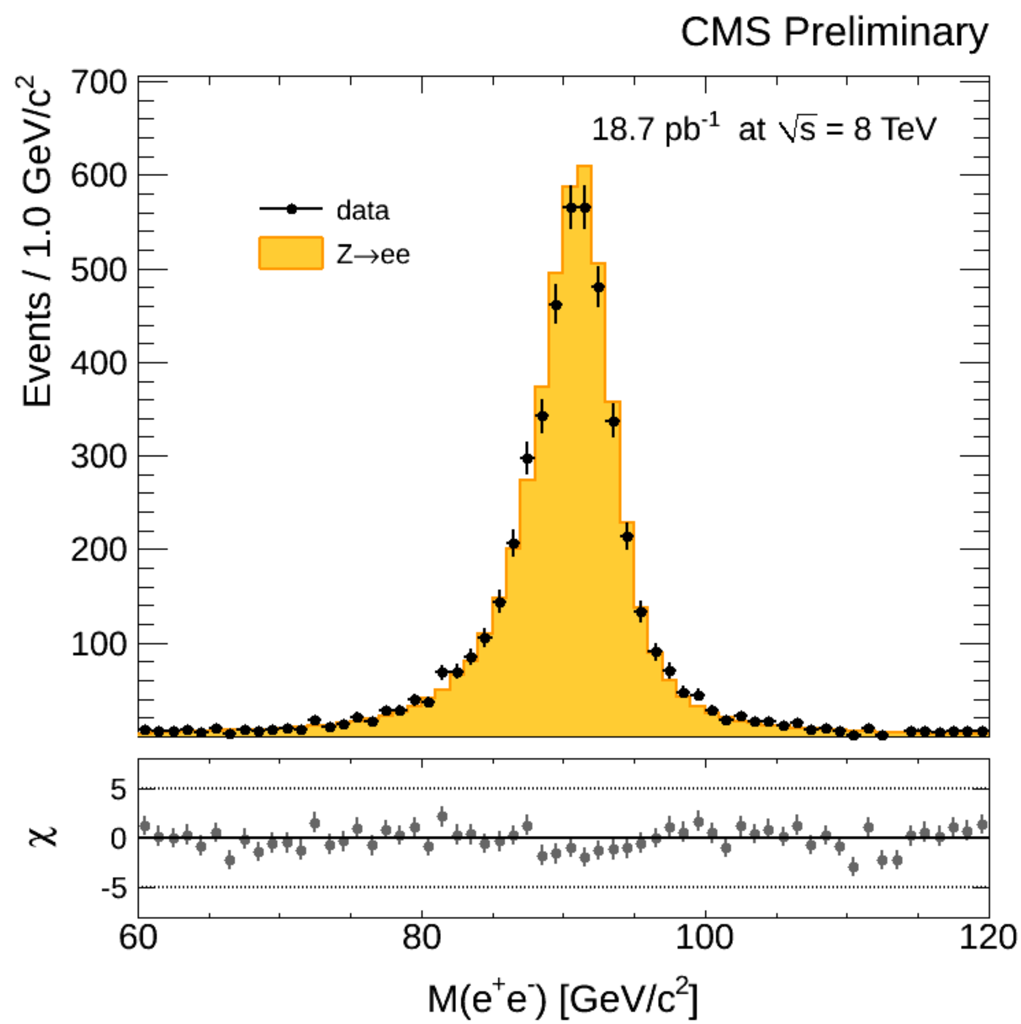
Z cross section @8 TeV: Z→ee

- Opp sign e pairs with $p_T >$ 25 GeV and $|\eta| < 2.5$, Pair mass 60-120 GeV

- 5000 candidates, ~0 background, 1.4% stat.

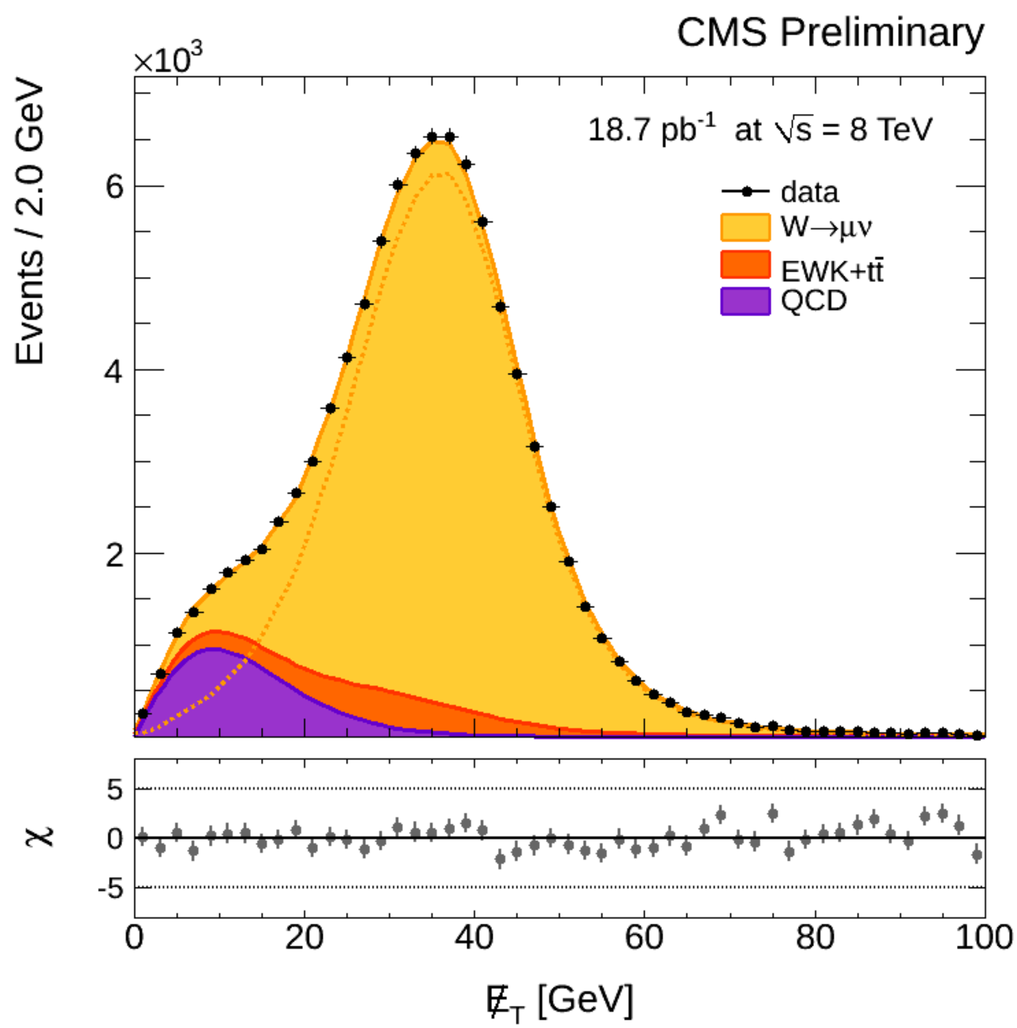
- Z reconstruction, ID, trigger efficiency known to 2.8% syst. from tag and probe methods

- Excellent lineshape description from POWHEG +PYTHIA



W cross section @8 TeV: W→μν

- =1 muon p_T > 25 GeV and $|\eta|$ < 2.1, 81k W's
- No MET cut, signal extracted via binned MLH simultaneous fit of MET to isolated and non-isolated muons. Signal,QCD yields + 2 QCD shape parameters floating.
- W signal MET model corrected with Z recoil data
- Lepton efficiency dominant exp. error (1%)



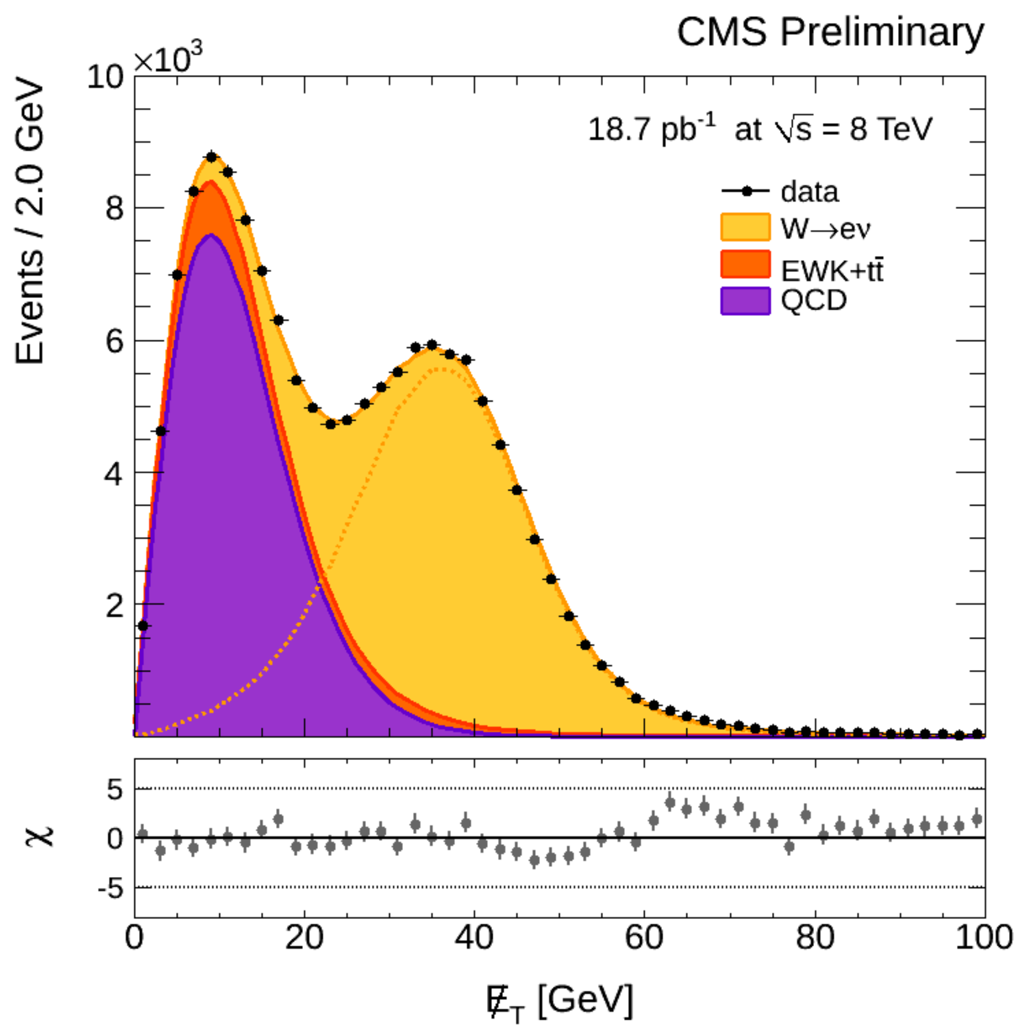
W cross section @8 TeV: W→eν

- =1 electron p_T > 25 GeV and |η| < 2.1, 75k W's

- No MET cut, signal extracted via binned MLH simultaneous fit of MET. Signal,QCD yields + 2 QCD shape parameters floating.

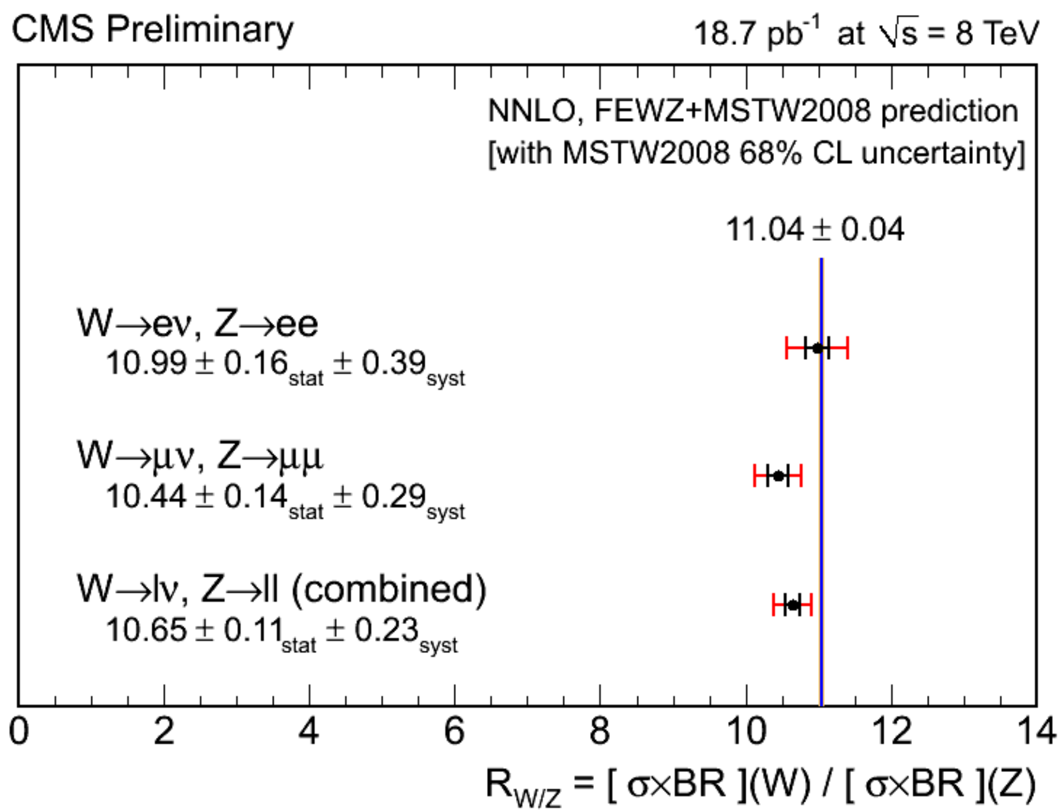
- W signal MET model corrected with Z recoil data (0.9% syst.)

- Lepton efficiency dominant exp. error (2.5%)



W and Z cross section ratios @8 TeV

- Acceptance ratio theory error: 2% (2.5%) for e (mu)
- Experimental error: 3.9% (1.7%) for e (mu)
- 1.5 sigma agreement with FEWZ + MSTW08 NNLO total cross section



EWK corrections will matter when lumi & PDF uncertainties go below 1%.

W and Z cross section ratios @8 TeV

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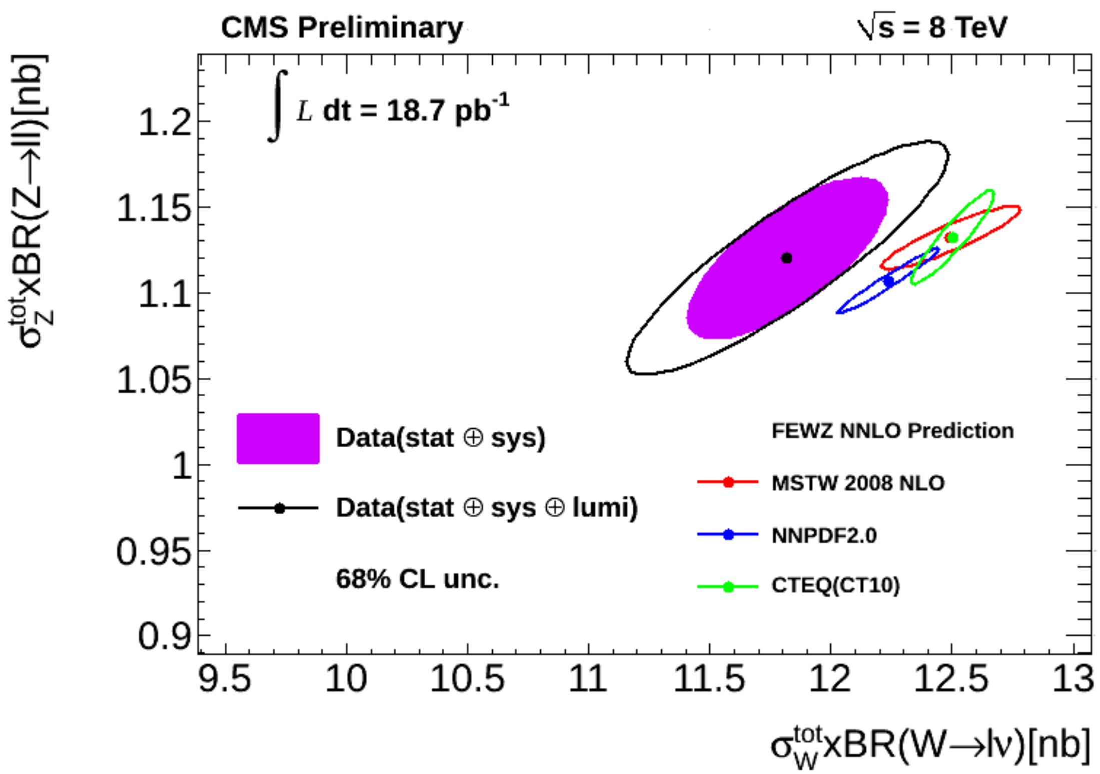


EWK corrections will matter when lumi & PDF uncertainties go below 1%.

Drell-Yan differential cross section vs mass: μμ

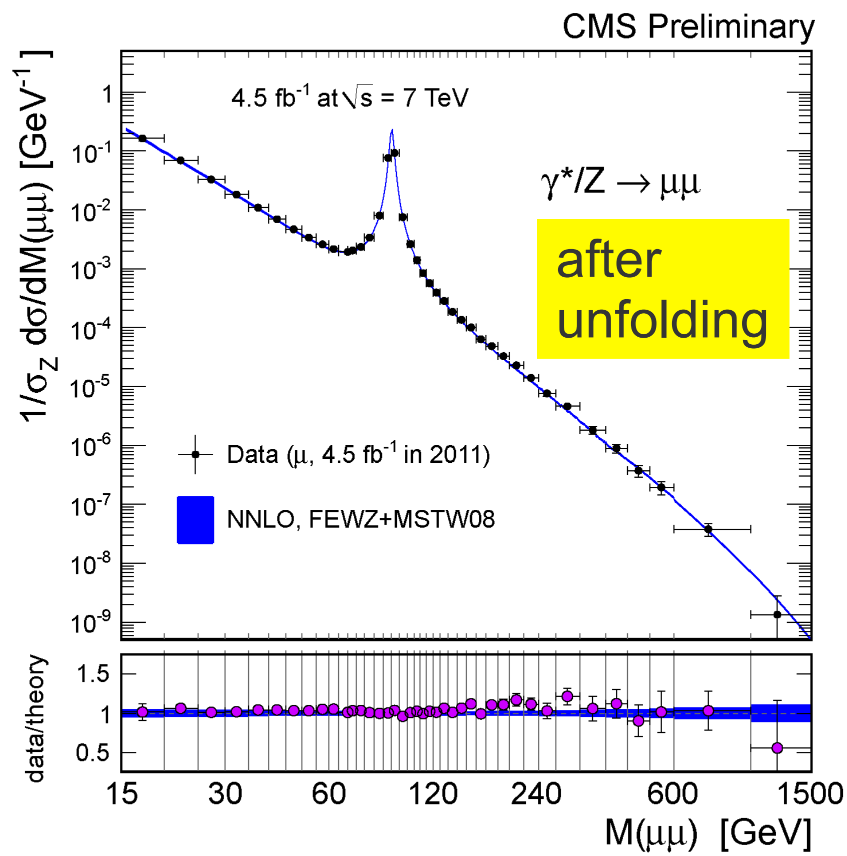
- With full 2011 data set, 1D differential Drell-Yan cross section vs. mass for M=20-1500 GeV

- Mu pair analysis:
  - Mu p_T > 14,9 GeV, $|\eta(\mu)| < 2.4$

- NNLO corrections important at low M (we select mostly boosted pairs)
- FSR effects unfolded

- Good agreement of total Born level cross section with FEWZ+MSTW

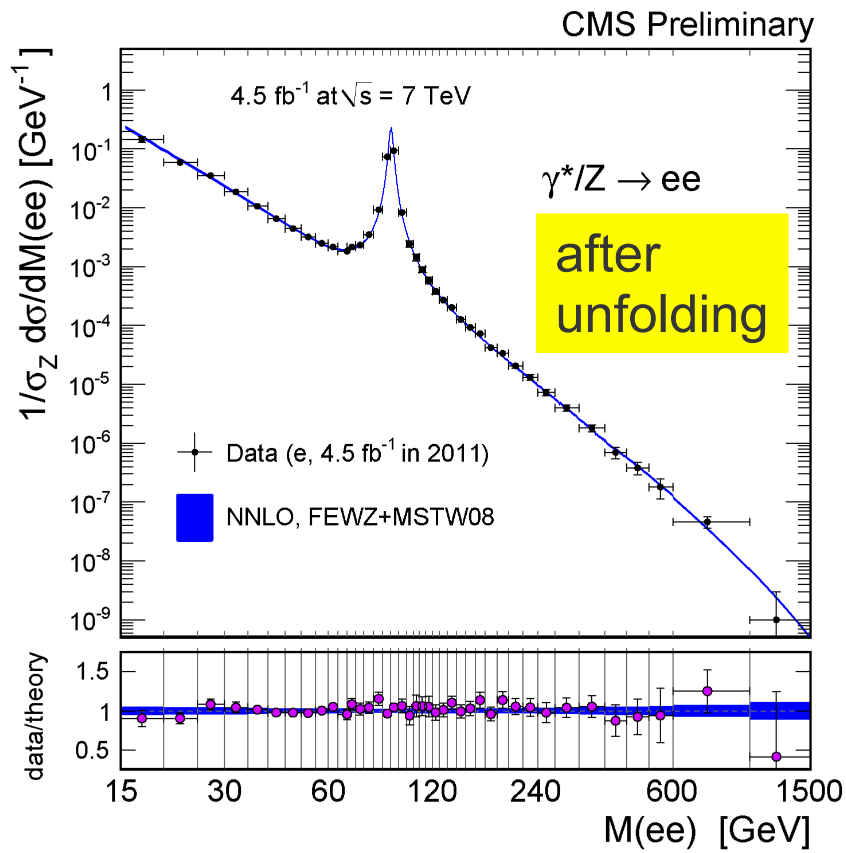
https://cdsweb.cern.ch/record/1439026



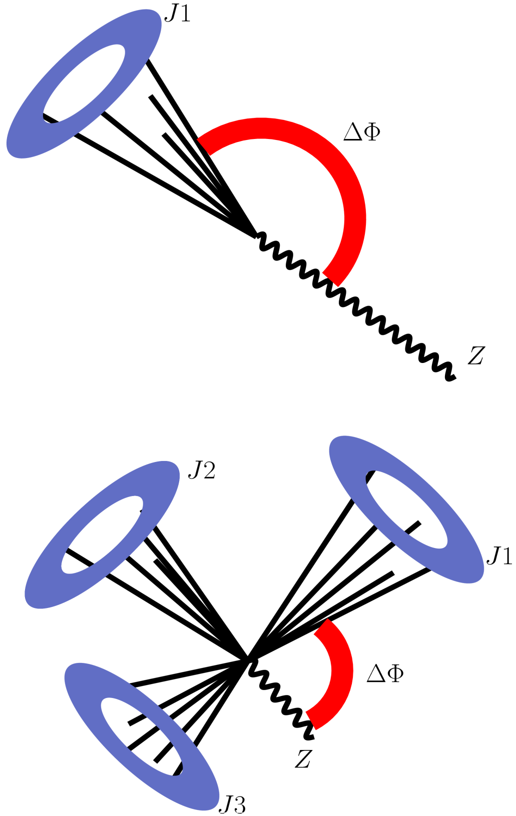
Drell-Yan differential cross section vs mass: ee

- Electron pair analysis:
  - -E p_T > 14,9 GeV, |η(e)| < 2.5
  - -QCD background estimated from e+anti-select e convolved with fake rate

- Good agreement of total Born level cross section with FEWZ +MSTW



Z+jets azimuthal correlation @7 TeV



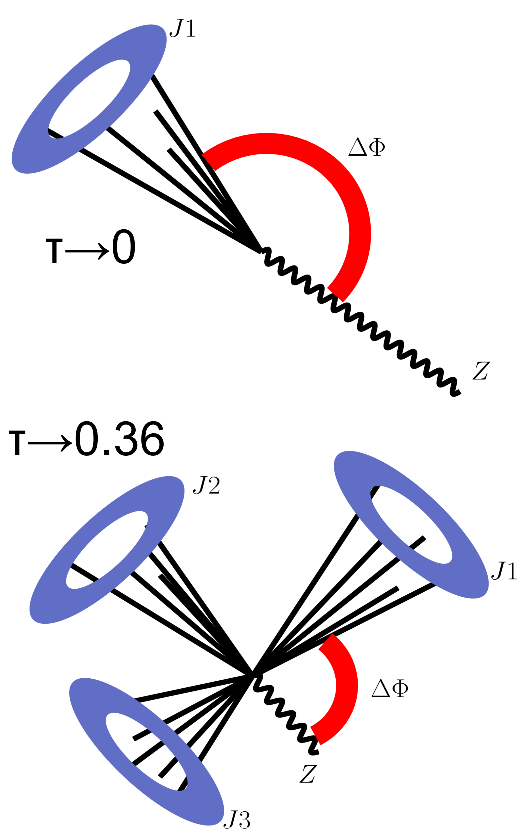
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11021

- In depth characterization of the topology of Z+jets (2011 data, 5 fb^{-1})
  - $\Delta\phi$(Z, lead jet), $\Delta\phi$(j,j)
  - inclusively and in boosted regime $p_T(Z)>150$ GeV
- Event selection:
  - ≥ 1 jet with $p_T>50$ GeV, $|\eta|<2.5$
  - 71 GeV $< m_{\ell\ell} <$ 111 GeV
- Results unfolded at particle level

Z+jets azimuthal correlation & event shape @7 TeV

Transverse thrust:

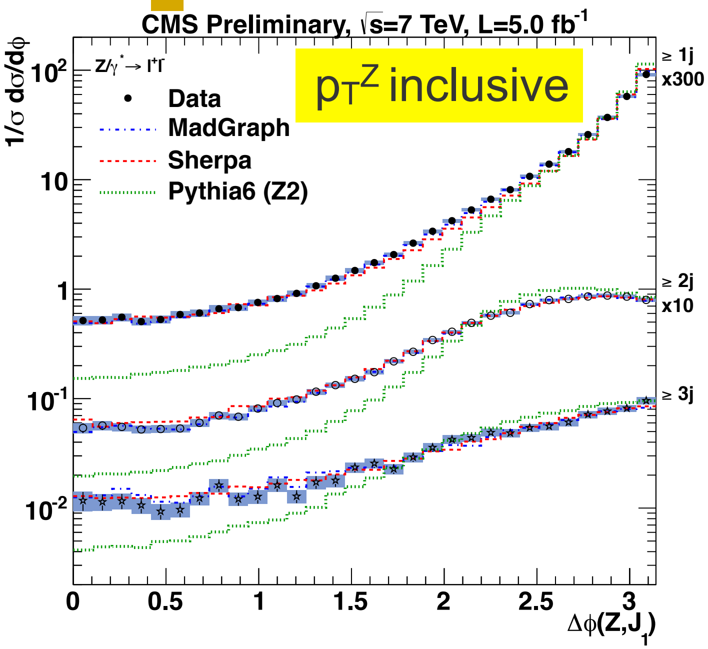
$$\tau_\perp \equiv 1 - \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$

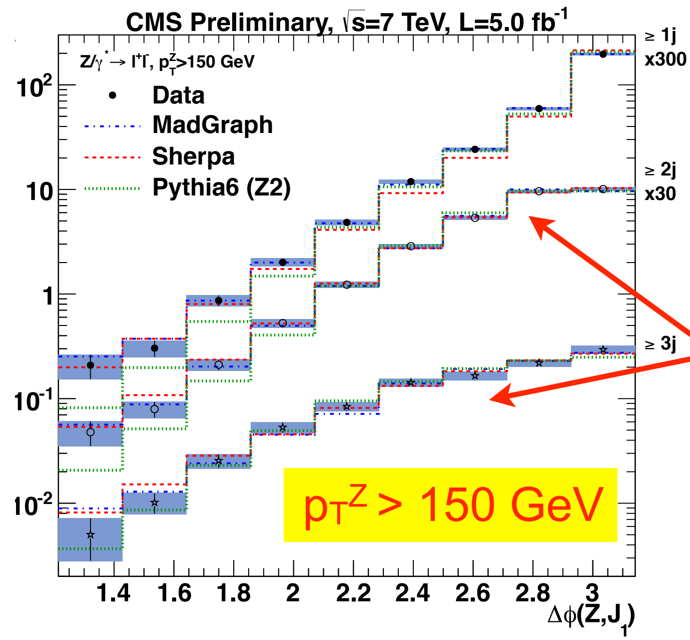


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11021

- ✦In depth characterization of the topology of Z+jets (2011 data, 5 fb^{-1})
  - -ΔΦ(Z, lead jet), ΔΦ(j,j), and thrust
  - -inclusively and in boosted regime $p_T(Z)>150$ GeV
- ✦Event selection:
  - ≥1 jet with $p_T>50$ GeV, $|\eta|<2.5$
  - 71 GeV < $m_{\ell\ell}$ < 111 GeV
- ✦Results unfolded at particle level

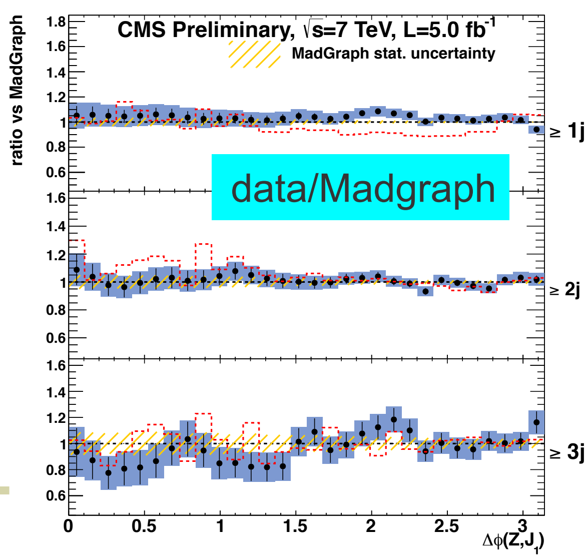
Δϕ(Z, leading jet)

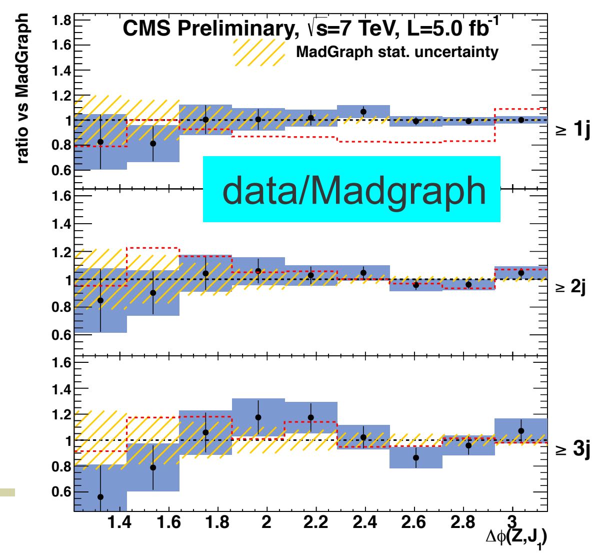




Error bars: data stat
Shaded: data syst
Hatched: MC stat

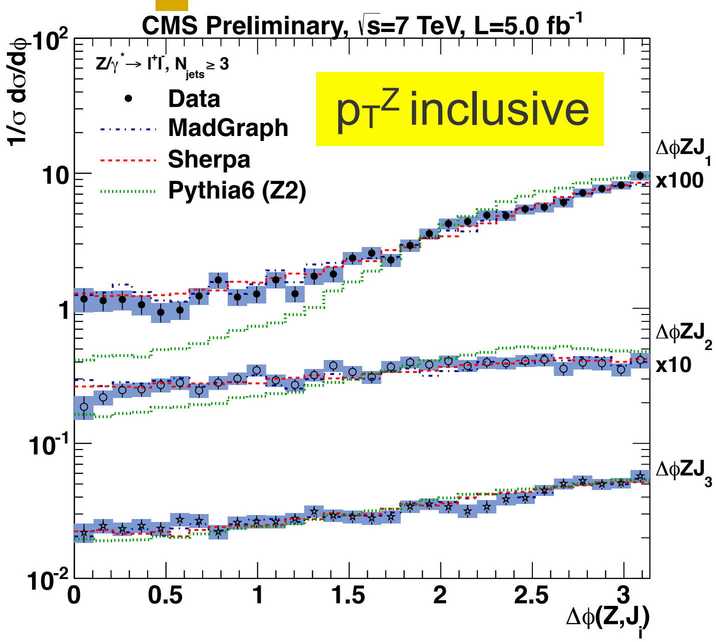
Distribution gets flatter with increase in N_{jets}

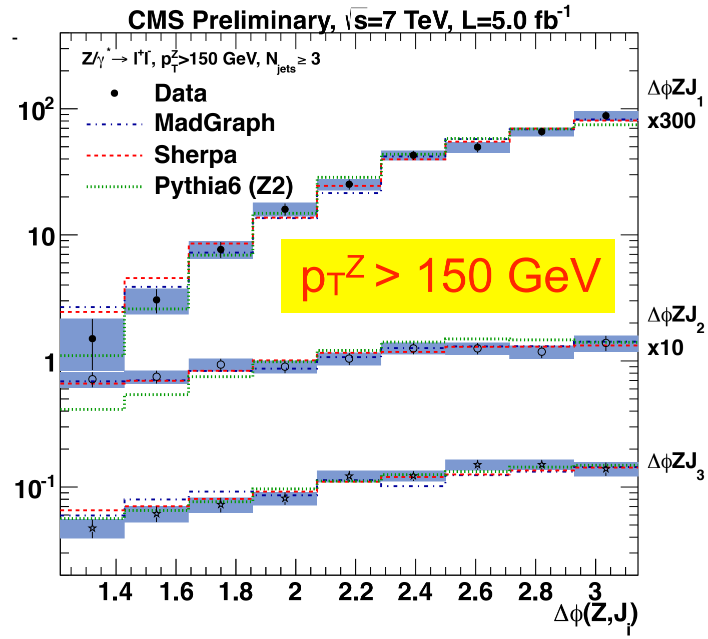




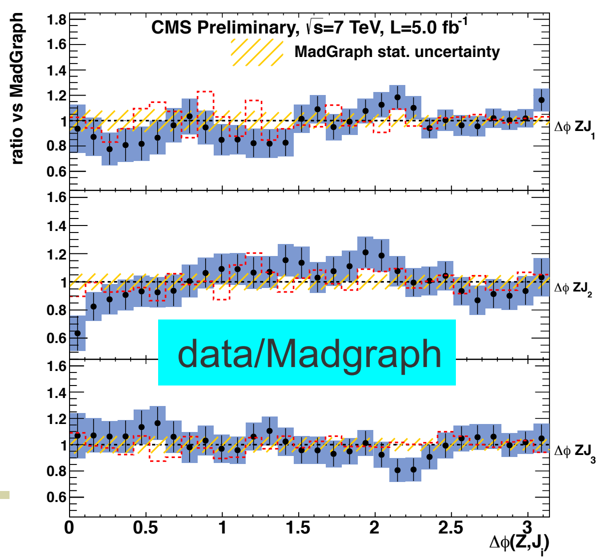
Both Sherpa and Madgraph give a good description of data. Pythia unable to describe multi-jet configurations.

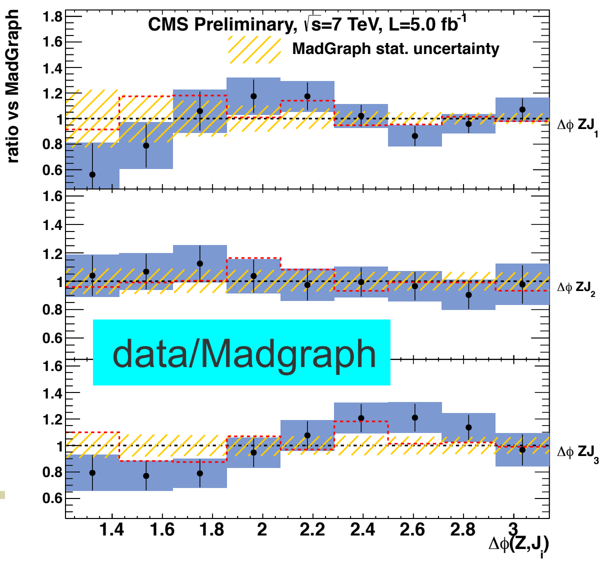
Δϕ(Z, J_i) in events with high hadronic activity





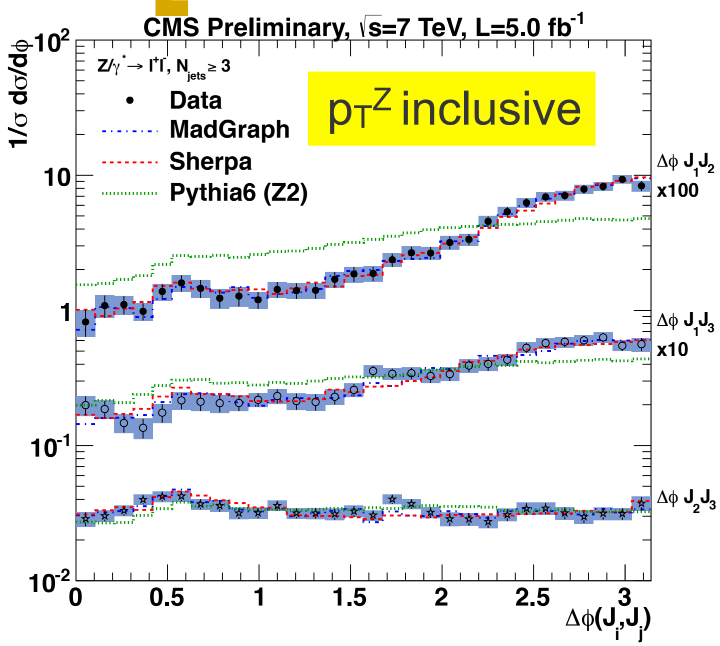
- ≥3 jets. Typically Z & a sub-leading jet balance the leading jet.

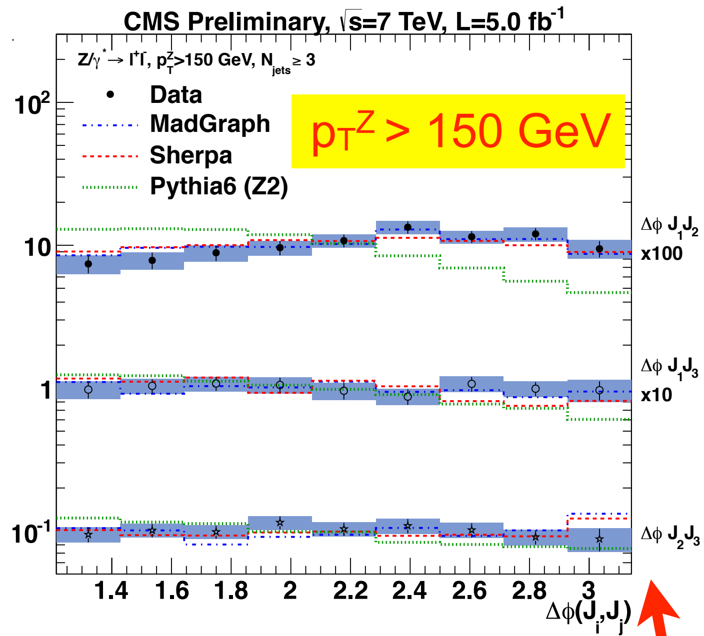


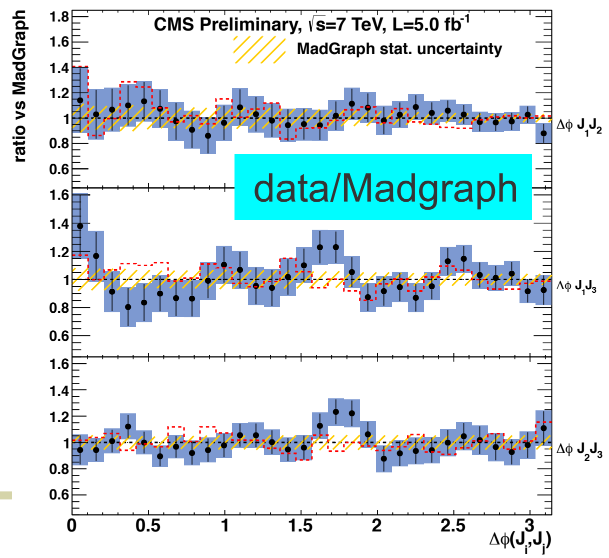


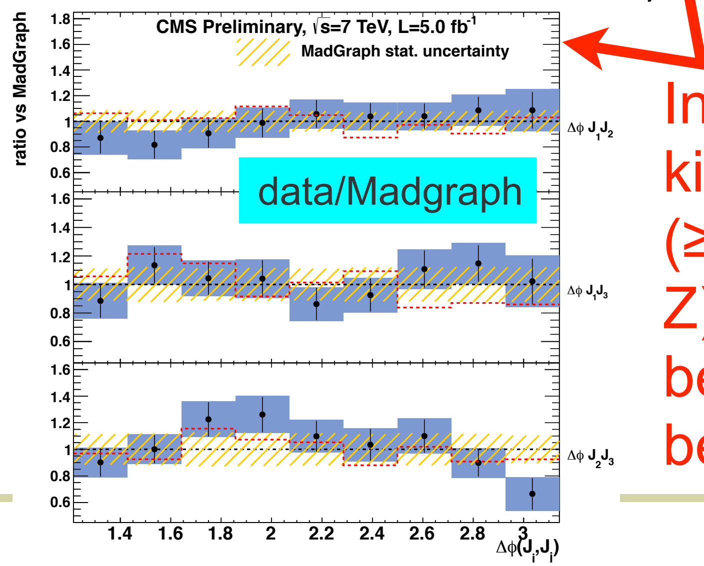
- Good agreement with data.

$\Delta\phi(J_i, J_j)$ in events with high hadronic activity



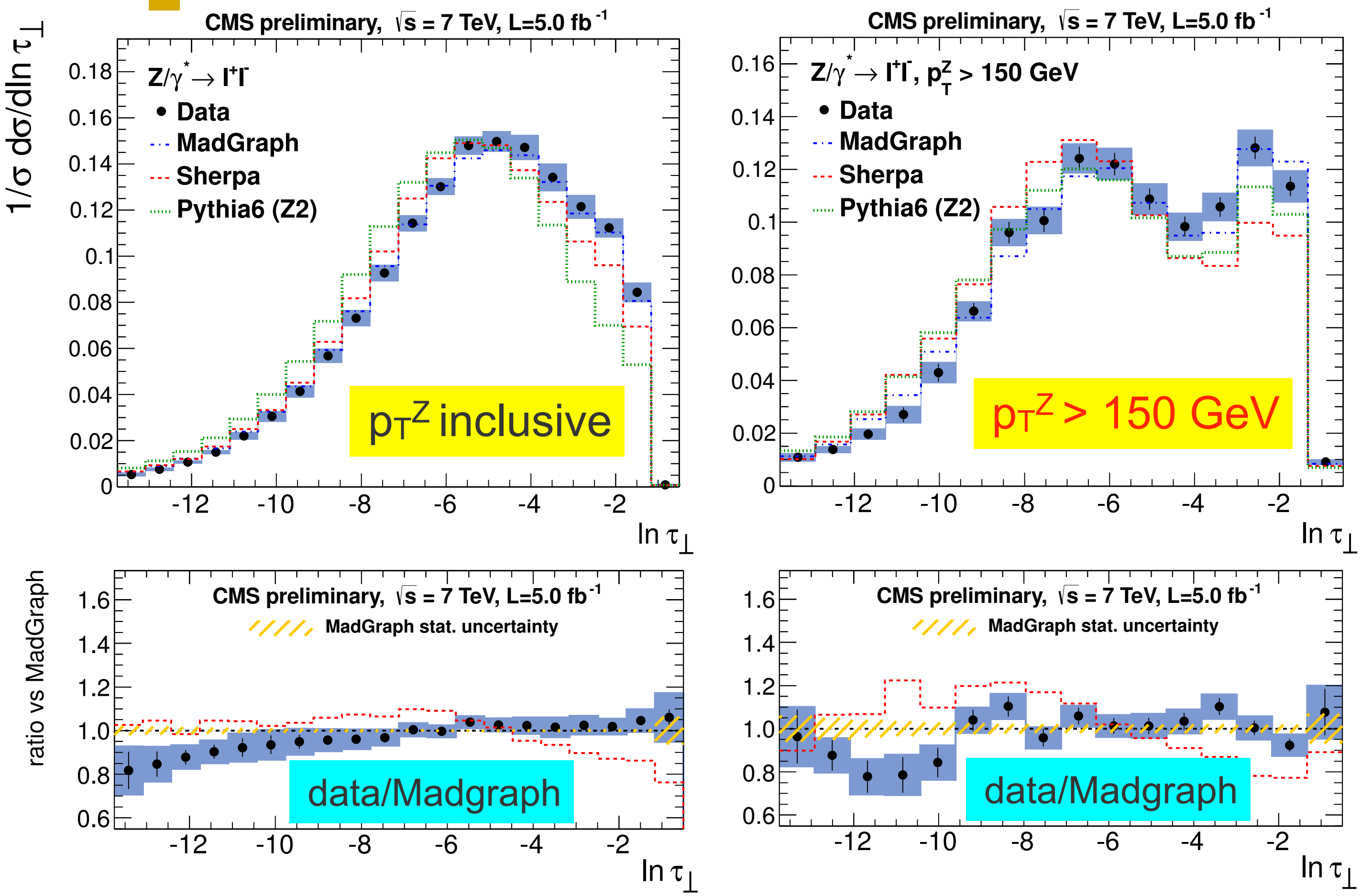






In this extreme kinematic regime (≥3 jets & a boosted Z), the correlation between the jets becomes flat.

Z+jets event shape

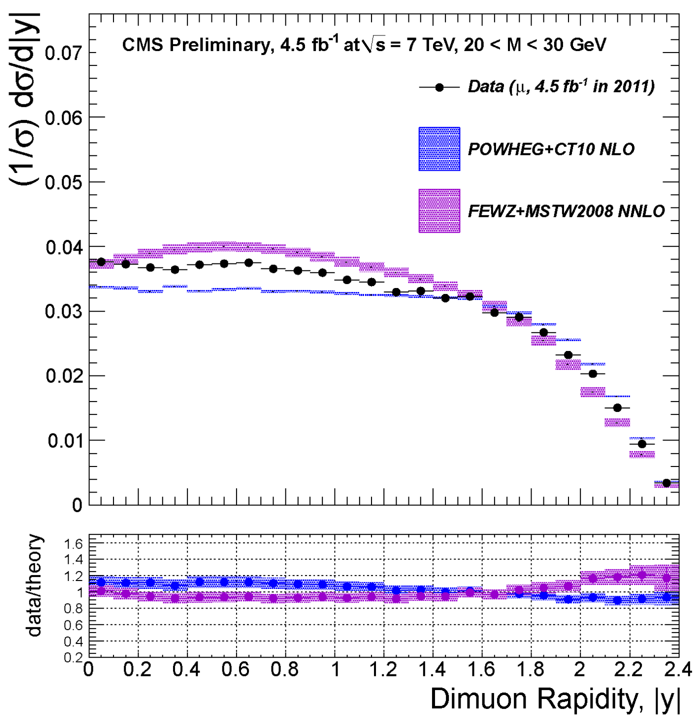


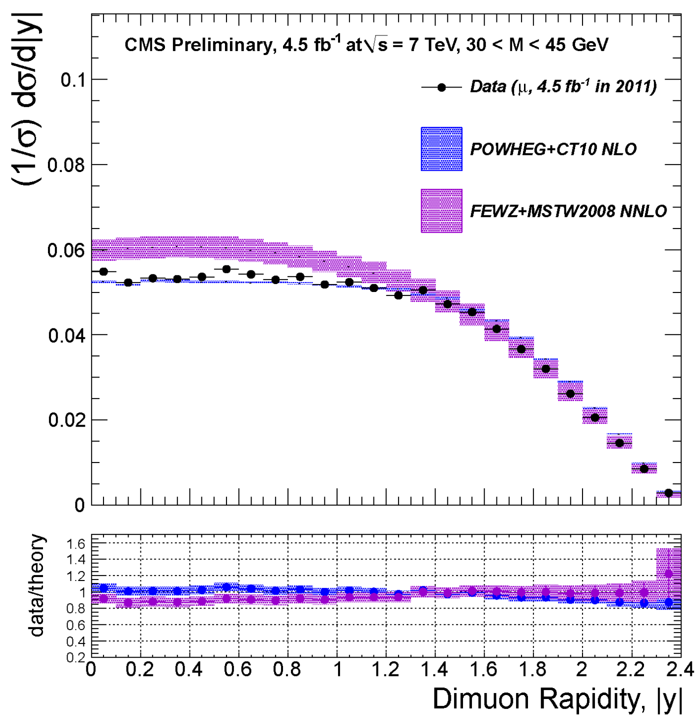
- Madgraph shows good agreement
- Sherpa is shifted left
  - -Consistent w/ the pattern observed in $\Delta\phi$ distributions

- The requirement on p_T^Z shifts the distribution towards lower values
- Enhances Z+1 jet topology

Drell-Yan double differential cross section vs M, y

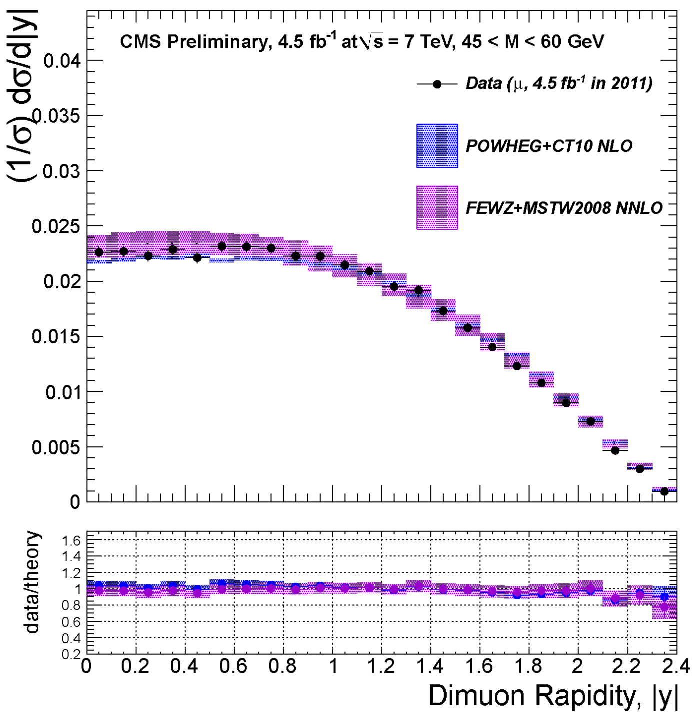
- For μ pairs, in detector fiducial, normalized to total cross section
  - Six bins in M and varying bins in y.
- Low-mass bins (20-30, 30-45): NNLO important here
  - preliminary disagreement with POWHEG, FEWZ and data (FEWZ theory value/errors being revisited)

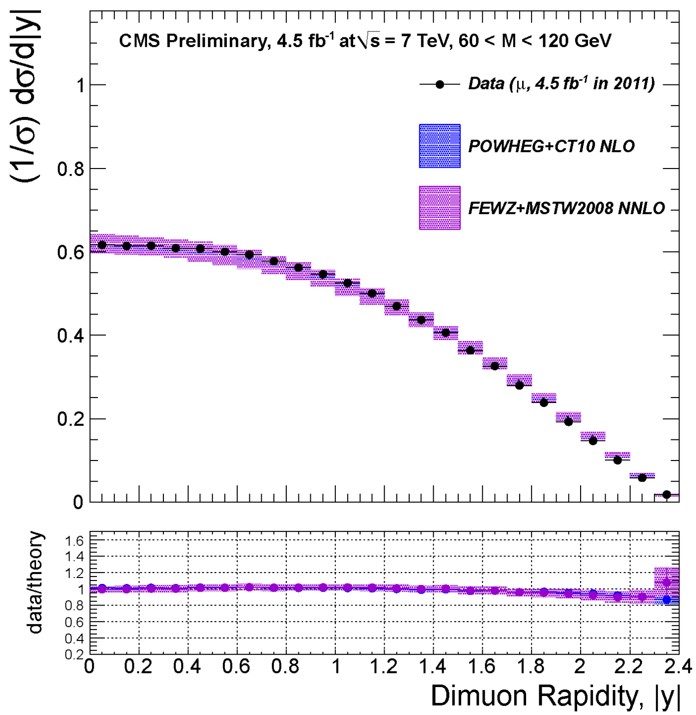




Drell-Yan double differential cross section vs M, y

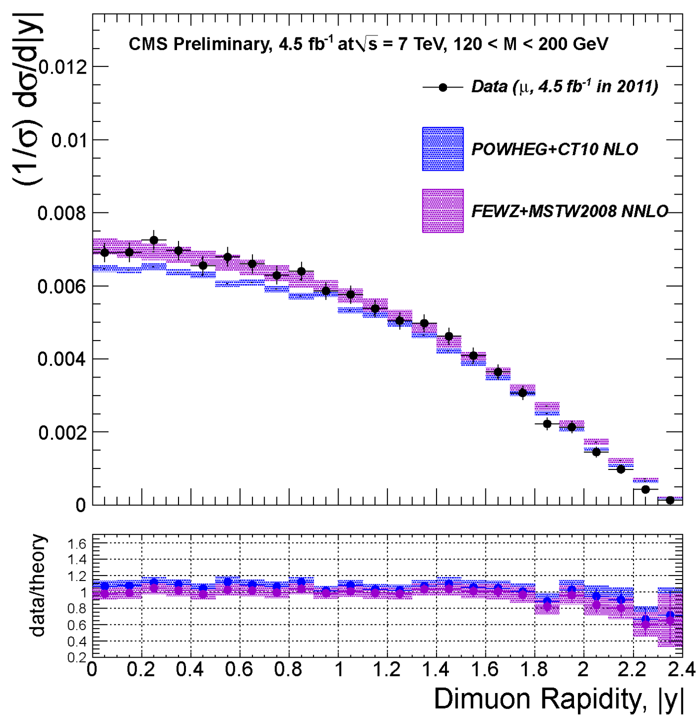
- On-peak bins (45-60, 60-120):
  - -Excellent agreement with POWHEG and FEWZ
- 60-120 (aka "Z rapidity") systematics limited
  - -Consistent with 2010 result

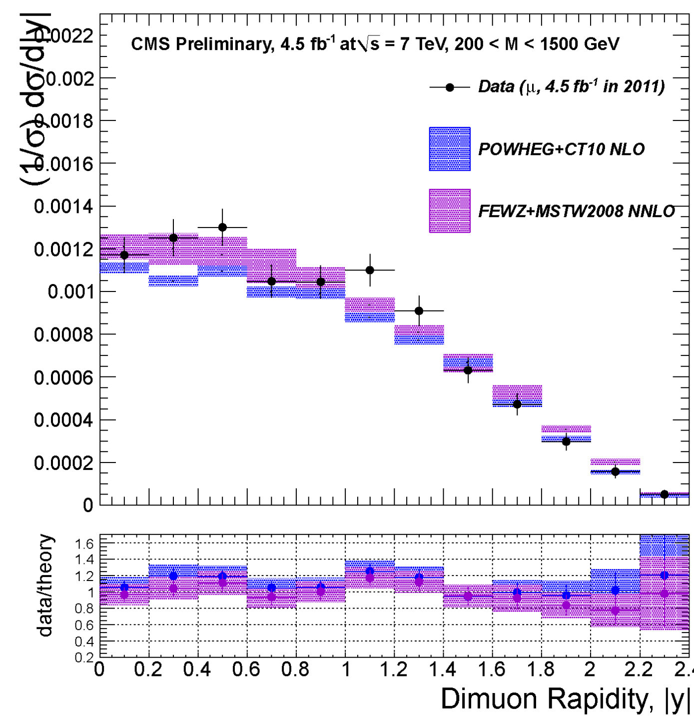




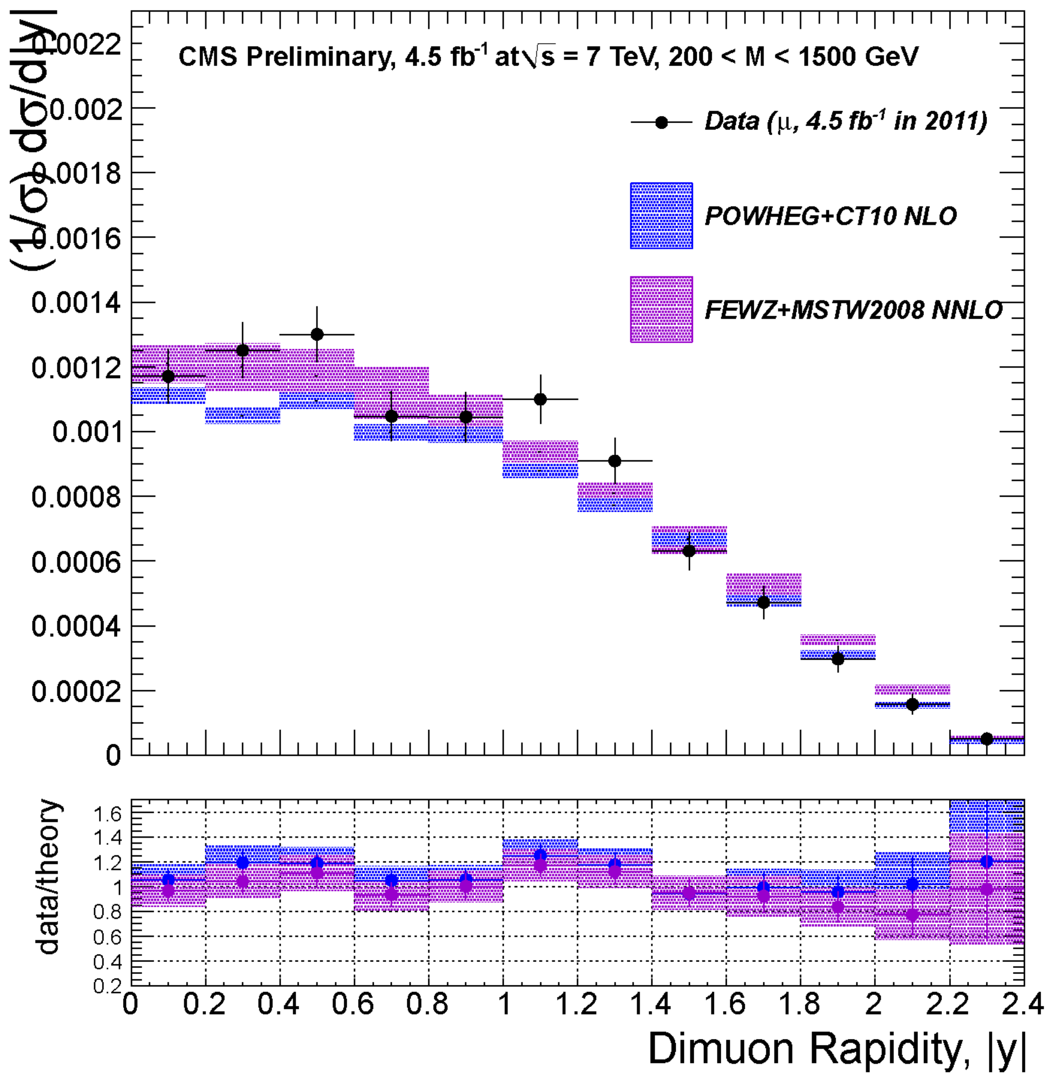
Drell-Yan double differential cross section vs M, y

- High mass bins (120-200, 200-1500):
  - Excellent agreement with POWHEG and FEWZ
- Statistics limited
  - 8 TeV data will extend the mass reach and improve statistics at high mass





Drell-Yan double differential cross section vs M, y



- High mass bins 200-1500:
  - Good agreement with POWHEG and FEWZ
- Statistics limited
  - 8 TeV data will extend the mass reach and improve statistics at high mass

Getting close to Sudakov zone.