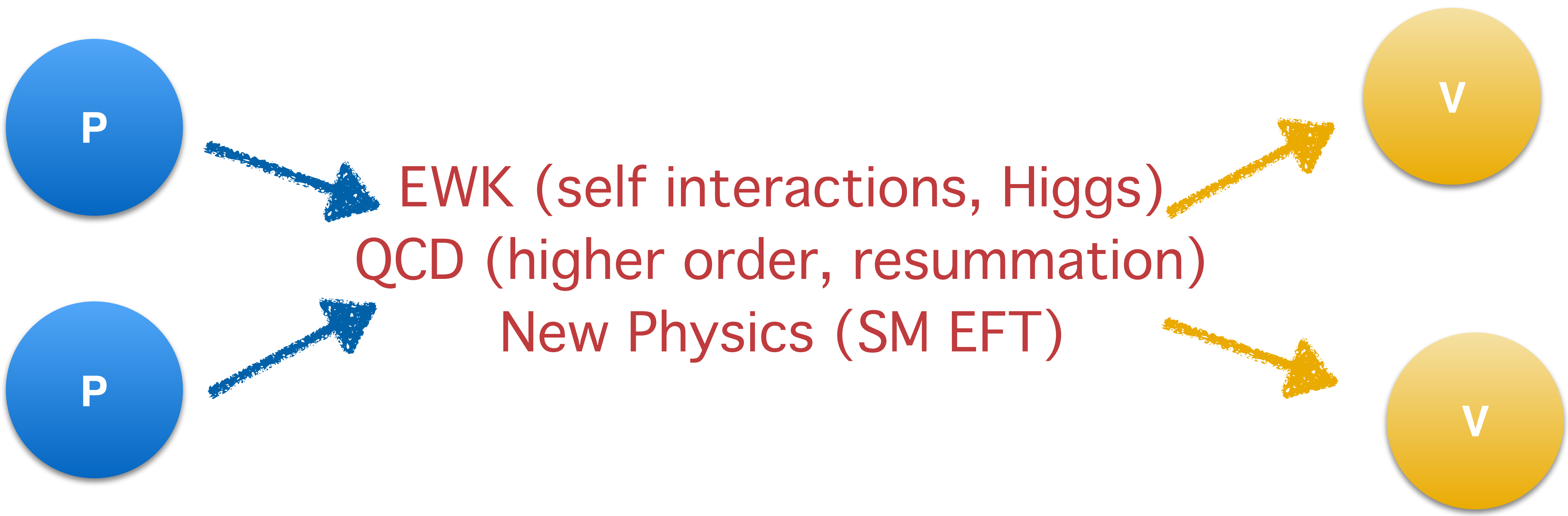
Multiboson production in final states with W and Z decays at CMS

Rafael Coelho Lopes de Sá (Fermilab)
For the CMS collaboration

ICHEP 2016: International Conference in High Energy Physics

Multiboson production with W and Z bosons in the final state



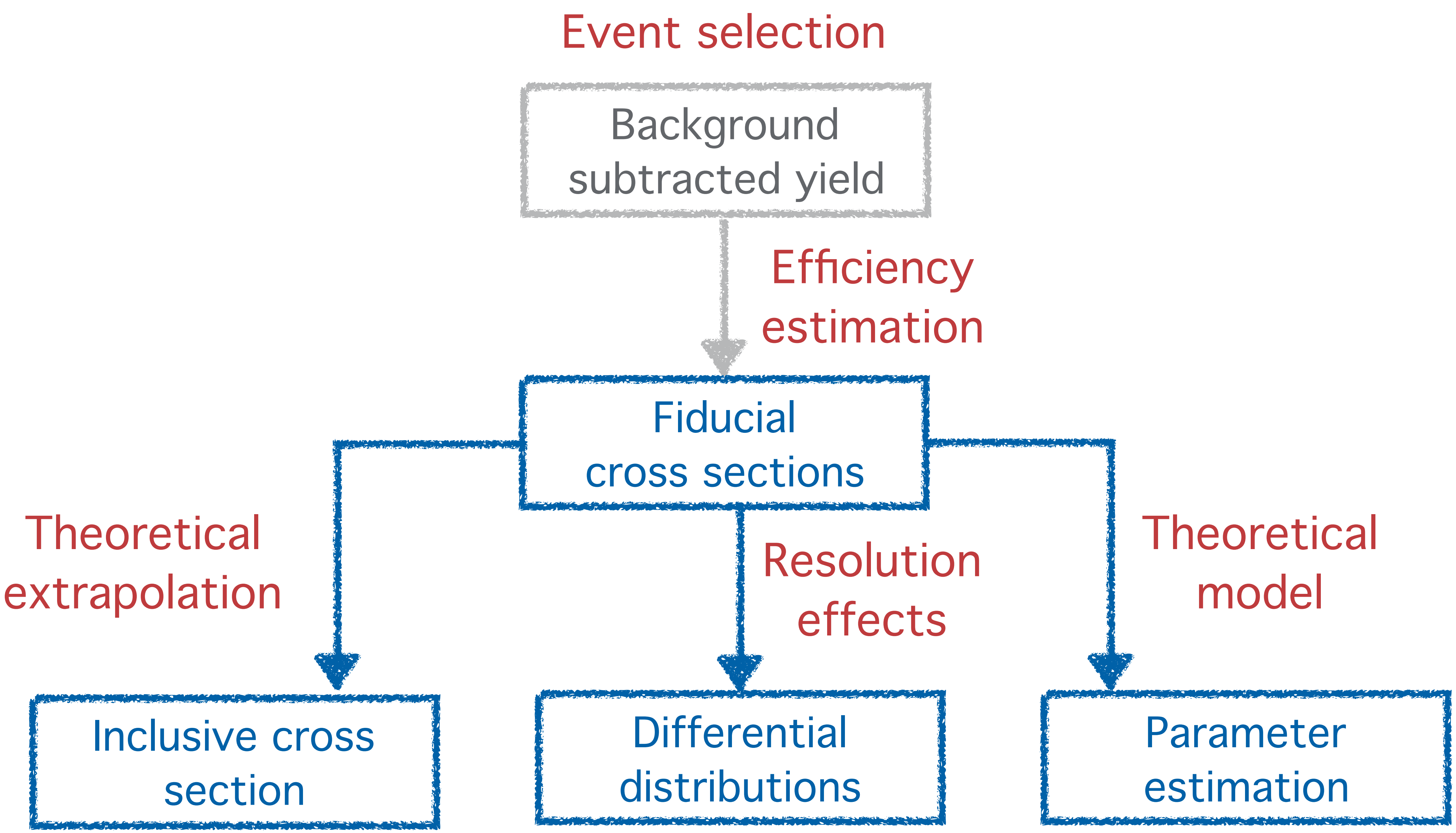
Recent results at 8 TeV

- $WW \to 2\ell 2\nu$
- $Z\gamma\gamma \to \ell\ell\gamma\gamma$
- $W\gamma\gamma \to \ell\nu\gamma\gamma$

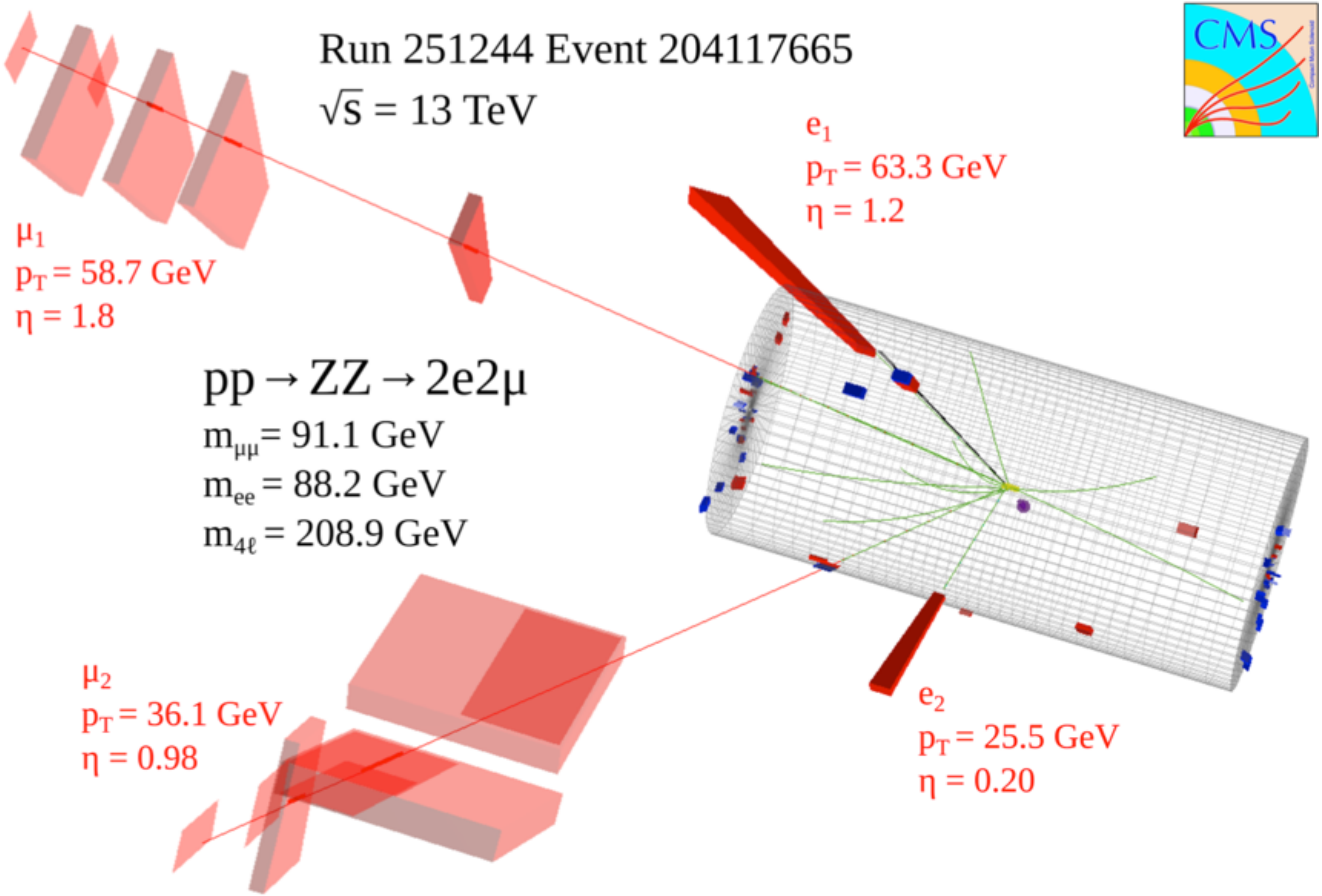
Recent results at 13 TeV

- $ZZ \to 4\ell$
- $WZ \to 3\ell\nu$
- $WW \to 2\ell 2\nu$
- $Z\gamma \to \nu\nu\gamma$

How measurements are presented...



ZZ candidate event

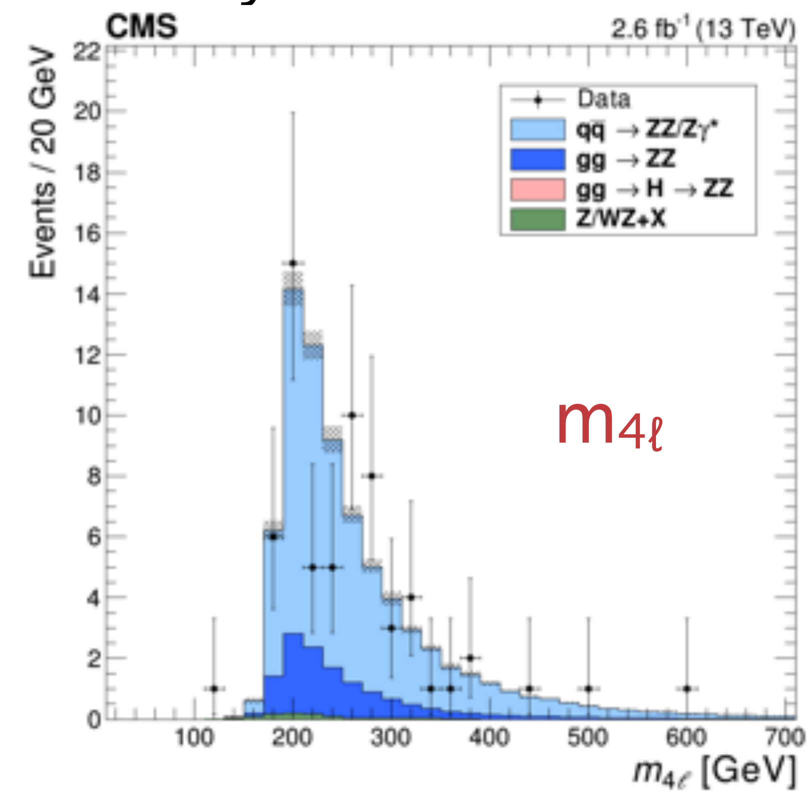


ZZ cross section @ 13 TeV [CMS SMP-16-001]

arXiv:1607.08834

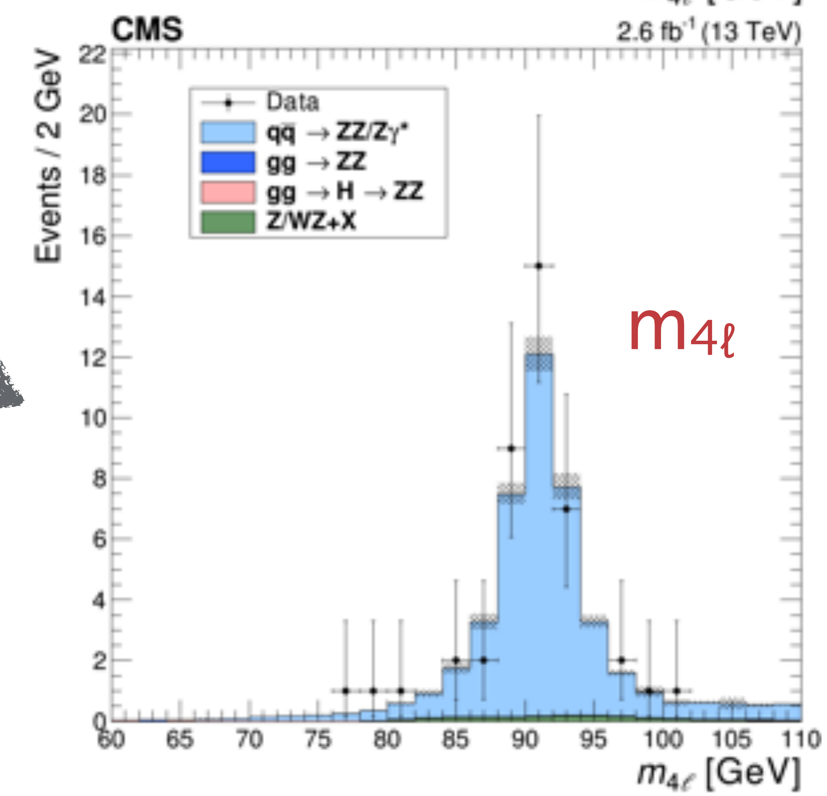
- Measurement performed with 2.6 fb^{-1} of integrated luminosity at 13 TeV.

Non-resonant ZZ->2ℓ2ℓ':
$60 < m_{Z1} < 120$ GeV
$60 < m_{Z2} < 120$ GeV



p_T(leading) > 20 GeV
p_T(subleading) > 10 GeV
p_T(e/μ) > 7/5 GeV
$|\eta$(e/μ)$|$ < 2.5/2.4
ΔR(ℓ,ℓ)>0.02, ΔR(e,μ)>0.05
$40 < m_{Z1}$(ℓ,ℓ) < 120 GeV
m_{Z2}(ℓ',ℓ') < 120 GeV

Resonant Z->2ℓ2ℓ':
80 < m(2ℓ2ℓ') < 100 GeV



ZZ cross section @ 13 TeV [CMS SMP-16-001]

arXiv:1607.08834

- p_T(leading) > 20 GeV
- p_T(subleading) > 10 GeV
- $p_T(e/\mu)$ > 7/5 GeV
- $|\eta(e/\mu)| < 2.5/2.4$
- $\Delta R(\ell,\ell)>0.02$, $\Delta R(e,\mu)>0.05$
- $40 < m_{Z1}(\ell,\ell) < 120$ GeV
- $m_{Z2}(\ell',\ell') < 120$ GeV

Non-resonant ZZ->2ℓ2ℓ':
$60 < m_{Z1} < 120$ GeV
$60 < m_{Z2} < 120$ GeV

ZZ fiducial region

- p_T(leading) > 20 GeV
- p_T(subleading) > 10 GeV
- $p_T(\ell)$ > 5 GeV
- $|\eta(\ell)| < 2.5$
- $60 < m_{Z1}, m_{Z2} < 120$ GeV

Resonant Z->2ℓ2ℓ':
$80 < m(2\ell 2\ell') < 100$ GeV

Z fiducial region

- p_T(leading) > 20 GeV
- p_T(subleading) > 10 GeV
- $p_T(\ell)$ > 5 GeV
- $|\eta(\ell)| < 2.5$
- $80 < m_{4\ell} < 100$ GeV
- $m_{Z1} > 40$ GeV

- Background-free measurement. Fiducial regions basically mimic the event selection.

$$\sigma_{\text{fid}}(\text{pp} \to \text{Z} \to \ell^+\ell^-\ell'^+\ell'^-) = 30.5^{+5.2}_{-4.7}\,(\text{stat})^{+1.8}_{-1.4}\,(\text{syst}) \pm 0.8\,(\text{lumi})\text{ fb},$$
$$\sigma_{\text{fid}}(\text{pp} \to \text{ZZ} \to \ell^+\ell^-\ell'^+\ell'^-) = 34.8^{+4.6}_{-4.2}\,(\text{stat})^{+1.2}_{-0.8}\,(\text{syst}) \pm 0.9\,(\text{lumi})\text{ fb}.$$

SM NLO prediction: $27.9^{+1.0}_{-1.5}$ fb (Z region) and $34.4^{+0.7}_{-0.6}$ fb (ZZ region) [POWHEG code]

ZZ cross section @ 13 TeV [CMS SMP-16-001]

arXiv:1607.08834

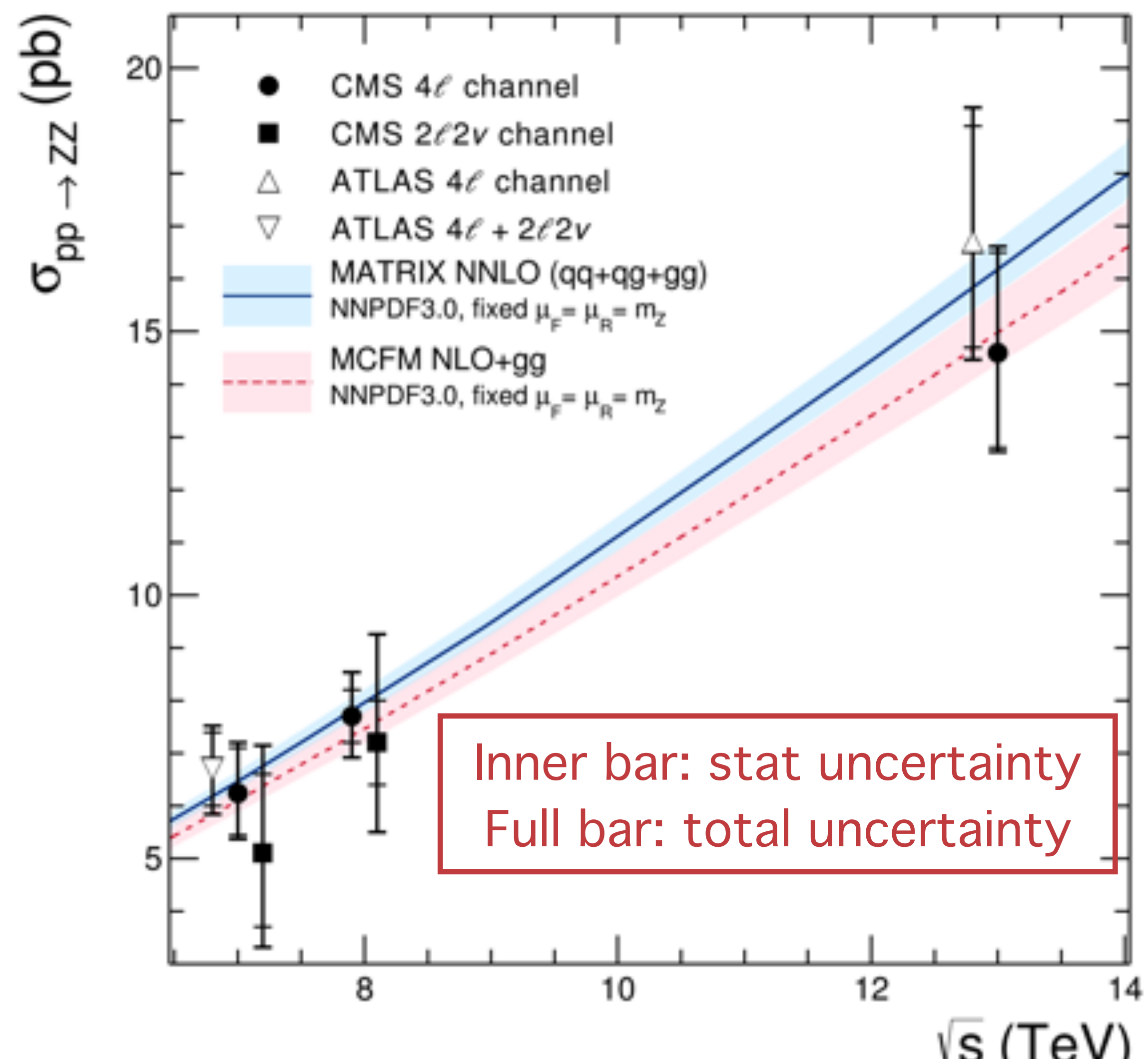
- The ZZ region measurement is used to extrapolate to the inclusive cross section ($60 < m_{Z1}, m_{Z2} < 120$ GeV, and Z BR from PDG). The Z region measurement is used to extract the $Z \rightarrow 4\ell$ BR measurement.

$$\sigma(\mathrm{pp} \rightarrow \mathrm{ZZ}) = 14.6^{+1.9}_{-1.8}\,(\mathrm{stat})^{+0.5}_{-0.3}\,(\mathrm{syst}) \pm 0.2\,(\mathrm{theo}) \pm 0.4\,(\mathrm{lumi})\ \mathrm{pb}.$$

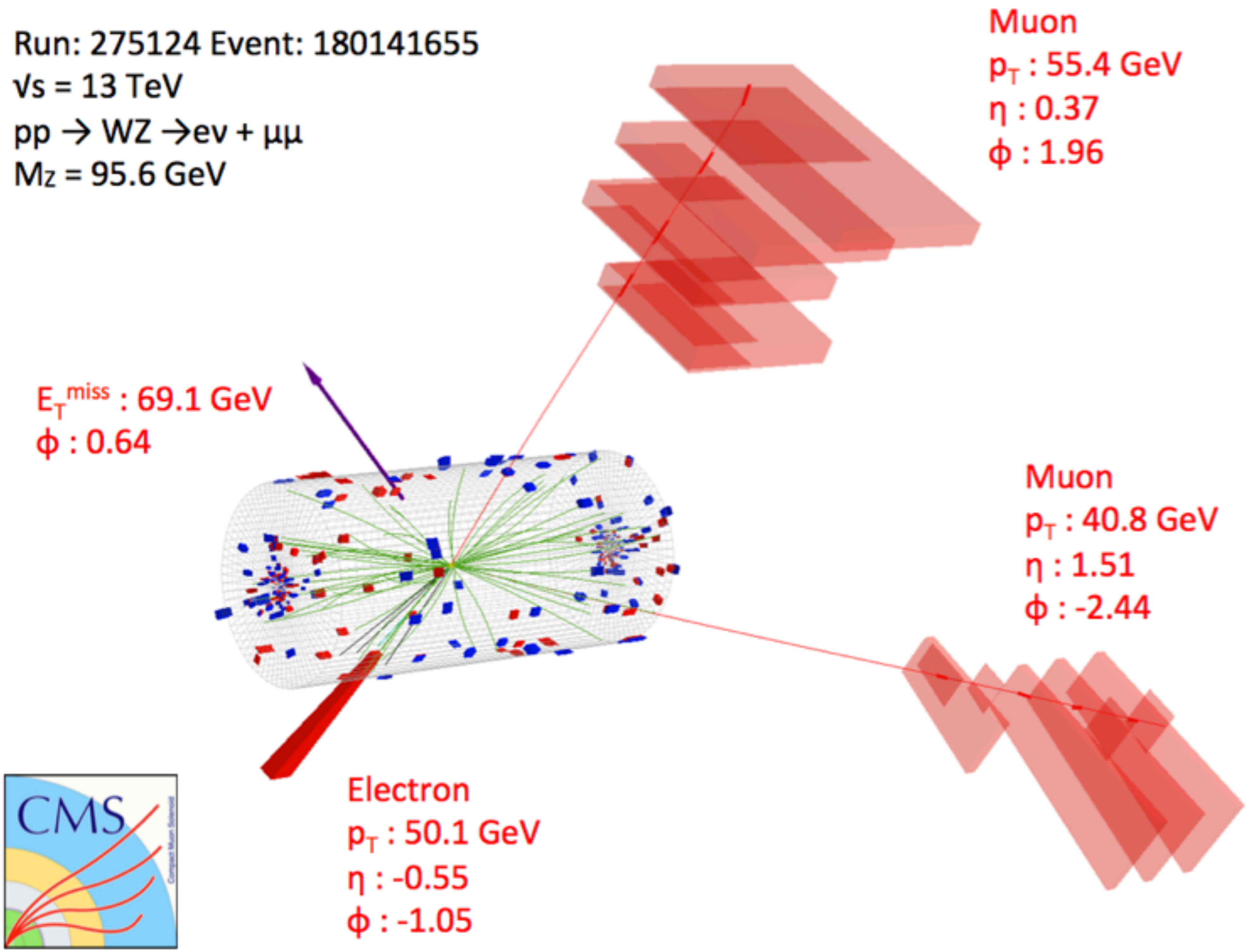
$$\mathcal{B}(\mathrm{Z} \rightarrow \ell^+\ell^-\ell'^+\ell'^-) = 4.9^{+0.8}_{-0.7}\,(\mathrm{stat})^{+0.3}_{-0.2}\,(\mathrm{syst})^{+0.2}_{-0.1}\,(\mathrm{theo}) \pm 0.1\,(\mathrm{lumi}) \times 10^{-6},$$

SM NNLO prediction for inclusive cross section: $16.2^{+0.6}_{-0.4}$ fb [MATRIX code]

Uncertainty	$Z \rightarrow 4\ell$	$ZZ \rightarrow 4\ell$
ID efficiency	2–6%	0.4–0.9%
Isolation efficiency	1–6%	0.3–1.1%
Trigger efficiency	2–4%	2%
MC statistics	1–2%	1%
Background	0.7–1.4%	0.7–2%
Pileup	0.4–0.8%	0.2%
PDF	1%	1%
Scale	1%	1%
Luminosity	2.7%	2.7%



WZ candidate event



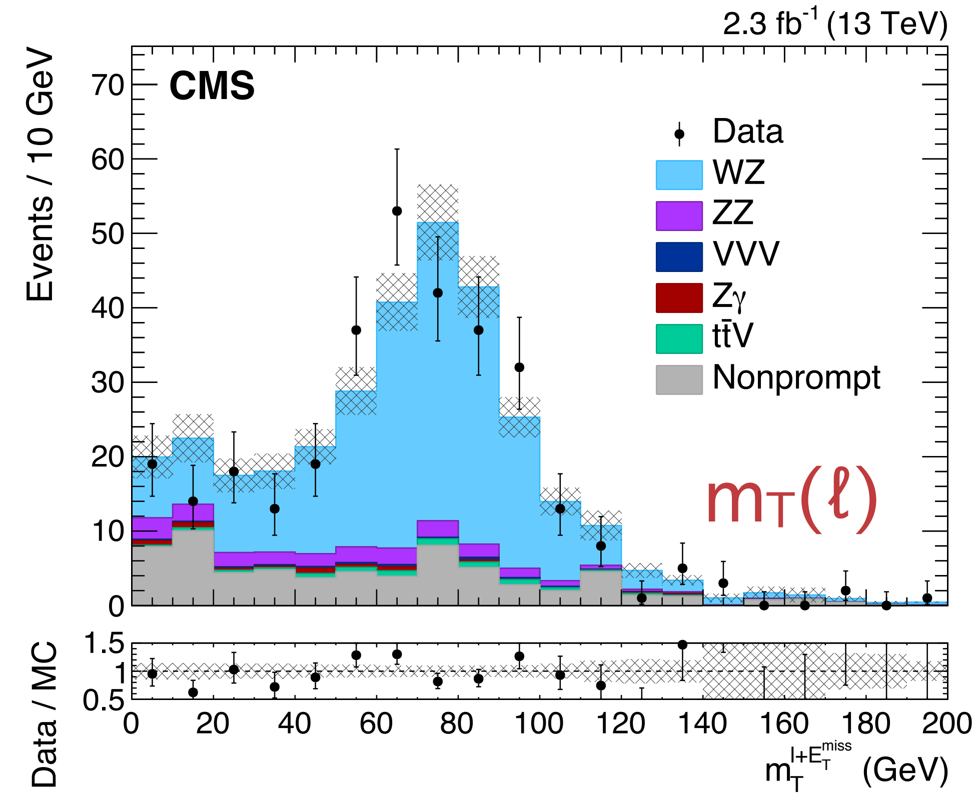
WZ cross section @ 13 TeV [CMS SMP-16-002]

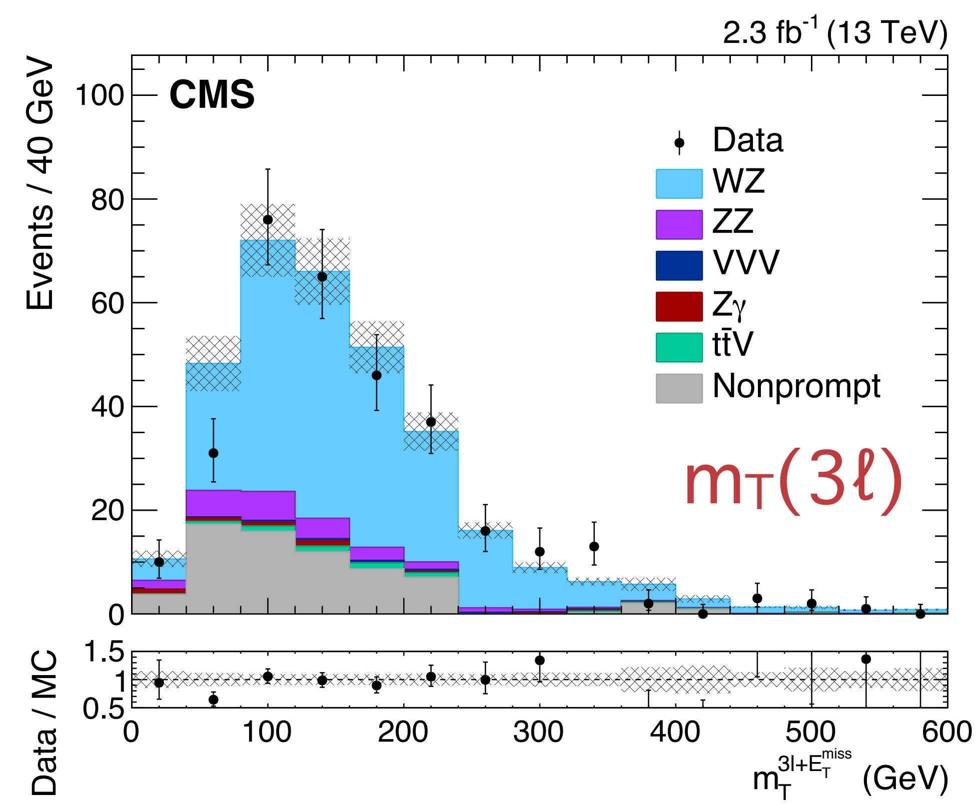
arXiv:1607.06943

- Measurement done with 2.3 fb^{-1} of integrated luminosity at 13 TeV

p_T(ℓ from W) > 20 GeV
p_T(leading ℓ from Z) > 20 GeV
p_T(subleading ℓ from Z) > 10 GeV
$|\eta(e/\mu)| < 2.5/2.4$
$76 < m_Z < 106$ GeV
MET > 30 GeV
m(ℓℓ) > 4 GeV
m(ℓℓℓ') > 100 GeV
0 b-quark jets with $p_T > 20$ GeV, $|\eta| < 2.4$

✦ ZZ background determined from MC
✦ Non-prompt background determined from isolation sidebands ('fake rate method')





WZ cross section @ 13 TeV [CMS SMP-16-002]

arXiv:1607.06943

Event selection

p_T(ℓ from W) > 20 GeV
p_T(leading ℓ from Z) > 20 GeV
p_T(subleading ℓ from Z) > 10 GeV
$|\eta(e/\mu)| < 2.5/2.4$
$76 < m_Z < 106$ GeV
MET > 30 GeV
m(ℓℓ) > 4 GeV
m(ℓℓℓ') > 100 GeV
0 b-quark jets with p_T > 20 GeV, $|\eta| < 2.4$

Fiducial region

p_T(ℓ from W) > 20 GeV
p_T(leading ℓ from Z) > 20 GeV
p_T(subleading ℓ from Z) > 10 GeV
$|\eta(\ell)| < 2.5$
$60 < m_Z < 120$ GeV

Inclusive cross section

$60 < m_Z < 120$ GeV
W and Z BR from PDG

$$\sigma_{\text{fid}}(\text{pp} \rightarrow \text{WZ} \rightarrow \ell\nu\ell'\ell') = 258 \pm 21\,(\text{stat})^{+19}_{-20}\,(\text{syst}) \pm 8\,(\text{lumi})\,\text{fb},$$

SM NLO prediction: 274^{+11}_{-8} fb [POWHEG code]

$$\sigma(\text{pp} \rightarrow \text{WZ}) = 39.9 \pm 3.2\,(\text{stat})^{+2.9}_{-3.1}\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 1.3\,(\text{lumi})\,\text{pb}.$$

SM NNLO prediction: $50.0^{+1.1}_{-1.0}$ pb [MATRIX code]

WZ cross section @ 13 TeV [CMS SMP-16-002]

arXiv:1607.06943

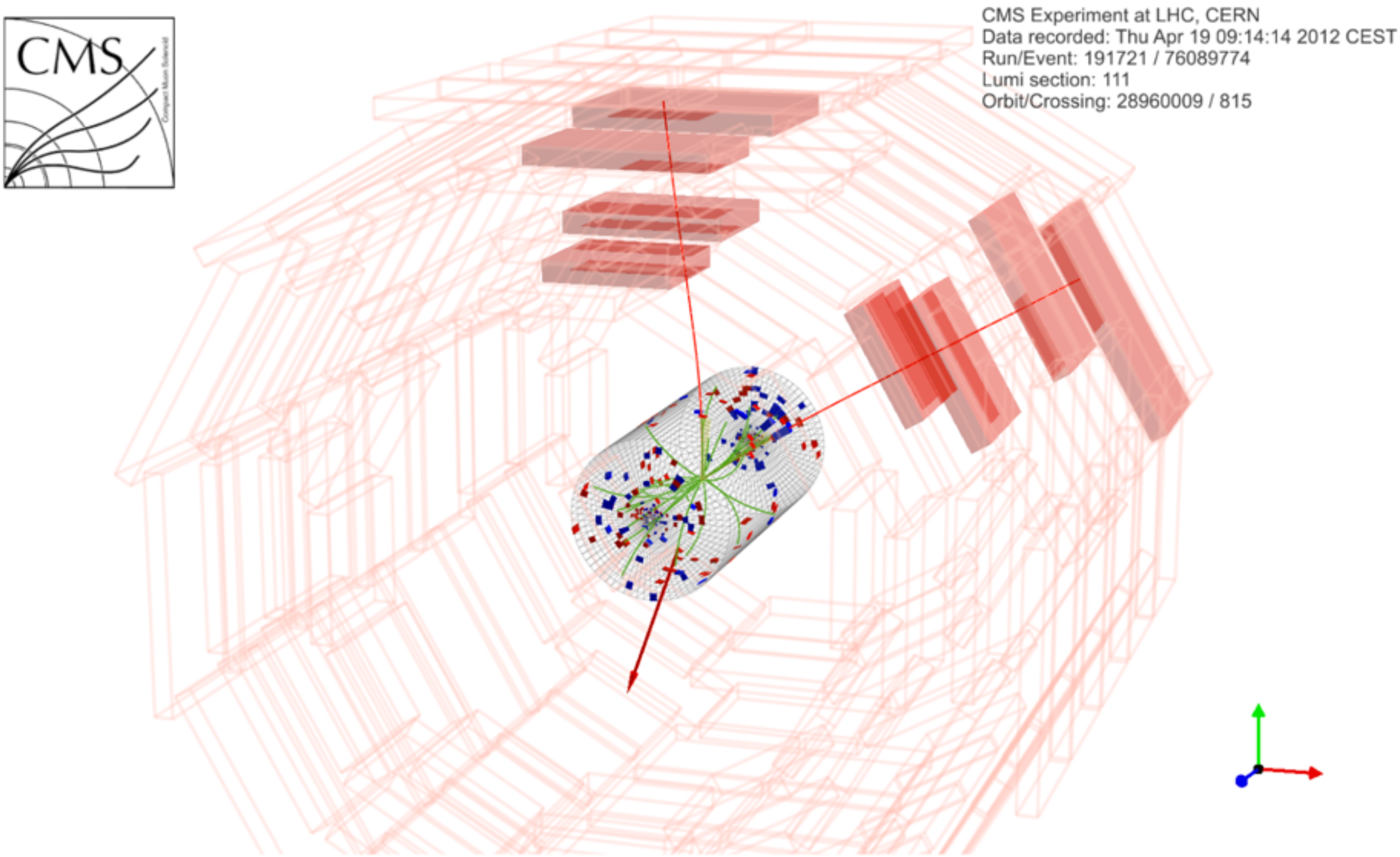
- With only 2.3 fb^{-1}, the inclusive cross section has large statistical and systematic uncertainties.
- Largest systematic uncertainty contribution from non-prompt background.

$$\sigma(\mathrm{pp} \to \mathrm{WZ}) = 39.9 \pm 3.2\,(\mathrm{stat})^{+2.9}_{-3.1}\,(\mathrm{syst}) \pm 0.4\,(\mathrm{theo}) \pm 1.3\,(\mathrm{lumi})\,\mathrm{pb}.$$

SM NNLO prediction: $50.0^{+1.1}_{-1.0}$ pb [MATRIX code]

Source of uncertainty	Uncertainty in the cross section
Background with nonprompt μ	5.4%
Background with nonprompt e	3.9%
b tagging	2.1%
$E_{\mathrm{T}}^{\mathrm{miss}}$	2.0%
Electron efficiency	1.9%
Muon efficiency	1.5%
Pileup	0.8%
ZZ cross section	0.4%
$\mathrm{t\bar{t}V}$ cross section	negligible
$\mathrm{Z}\gamma$ cross section	negligible
VVV cross section	negligible
Integrated luminosity	3.2%
PDF and scales	1.0%

WW candidate event

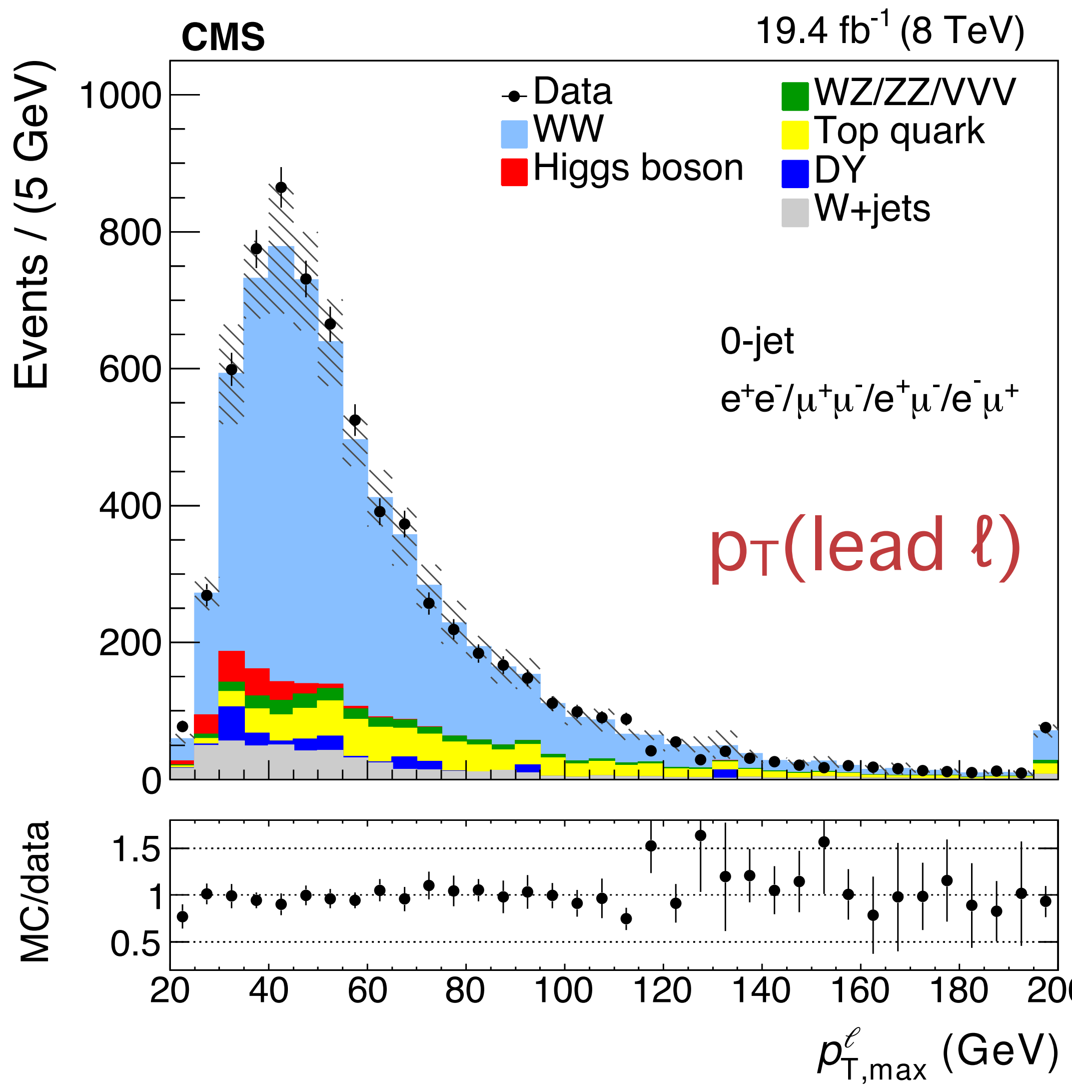


WW cross section @ 8 TeV [CMS SMP-14-016]

arXiv:1507.03268 [Eur. Phys. J. C76 (2016) nº7, 401]

- Measurement done with 19.4 fb^{-1} of integrated luminosity at 8 TeV.

$p_T(\ell)$ > 20 GeV
$|\eta(e/\mu)|$ < 2.5/2.4
MET > 20 GeV
$p_T(\ell\ell)$ > 30/45 GeV (different/same flavor)
$m(\ell\ell)$> 12 GeV
$|m(\ell\ell) - m_Z|$ > 15 (same flavor only)
DY MVA veto (same flavor only)
min(projMET, projTkMET) > 20 GeV
Top-quark veto (b-quark jets + soft muons)
0 or 1 jet (p_T > 30, $|\eta|$ < 4.7)



- ✦ Top background determined from data (inverting top and jet vetoes)
- ✦ DY background determined from data (inverting mass and MVA vetoes)
- ✦ Non-prompt background determined from isolation sidebands (‘fake rate method’)
- ✦ Higgs contribution removed using simulation (~4% after event selection)

WW cross section @ 8 TeV [CMS SMP-14-016]

arXiv:1507.03268 [Eur. Phys. J. C76 (2016) nº7, 401]

$p_T(\ell) > 20$ GeV
$|\eta(e/\mu)| < 2.5/2.4$
MET > 20 GeV
$p_T(\ell\ell) > 30/45$ GeV (different/same flavor)
$m(\ell\ell) > 12$ GeV
$|m(\ell\ell) - m_Z| > 15$ (same flavor only)
DY MVA veto (same flavor only)
min(projMET, projTkMET) > 20 GeV
Top-quark veto (b-quark jets + soft muons)
0 or 1 jet ($p_T > 30$, $|\eta| < 4.7$)

Jet veto p_T-dependent fiducial regions
(use events with 0 jets only)

$p_T(\ell) > 20$ GeV (different flavor only)
$|\eta(\ell)| < 2.5$
0 anti-kT 0.5 jets, $|\eta(j)| < 4.7$

0 anti-kT 0.5 jets, $|\eta(j)| < 4.7$
$W \to \ell\nu$ BR from PDG

p_T^{jet} (GeV)	$\sigma_{\text{zero-jet}, W\to\ell\nu}$ measured (fb)	$\sigma_{\text{zero-jet}, W\to\ell\nu}$ predicted (fb)
>20	$223 \pm 4\,(\text{stat}) \pm 13\,(\text{exp}) \pm 7\,(\text{theo}) \pm 6\,(\text{lumi})$	$228 \pm 1\,(\text{stat})$
>25	$253 \pm 5\,(\text{stat}) \pm 14\,(\text{exp}) \pm 8\,(\text{theo}) \pm 7\,(\text{lumi})$	$254 \pm 1\,(\text{stat})$
>30	$273 \pm 5\,(\text{stat}) \pm 15\,(\text{exp}) \pm 9\,(\text{theo}) \pm 7\,(\text{lumi})$	$274 \pm 1\,(\text{stat})$

p_T^{jet} (GeV)	$\sigma_{\text{zero-jet}}$ measured (pb)	$\sigma_{\text{zero-jet}}$ predicted (pb)
>20	$36.2 \pm 0.6\,(\text{stat}) \pm 2.1\,(\text{exp}) \pm 1.1\,(\text{theo}) \pm 0.9\,(\text{lumi})$	$36.7 \pm 0.1\,(\text{stat})$
>25	$40.8 \pm 0.7\,(\text{stat}) \pm 2.3\,(\text{exp}) \pm 1.3\,(\text{theo}) \pm 1.1\,(\text{lumi})$	$40.9 \pm 0.1\,(\text{stat})$
>30	$44.0 \pm 0.7\,(\text{stat}) \pm 2.5\,(\text{exp}) \pm 1.4\,(\text{theo}) \pm 1.1\,(\text{lumi})$	$43.9 \pm 0.1\,(\text{stat})$

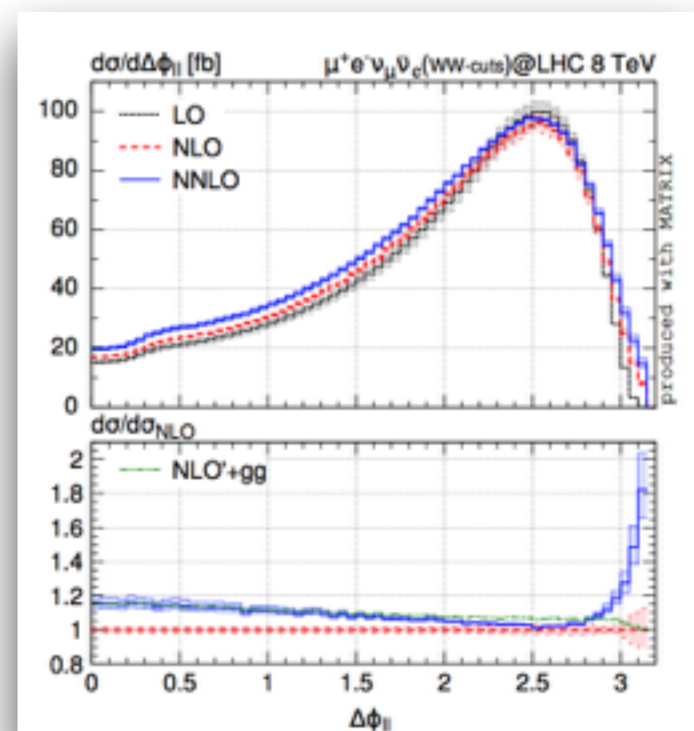
Allows direct comparison to resummed QCD calculation of jet veto efficiencies.

WW cross section @ 8 TeV [CMS SMP-14-016]

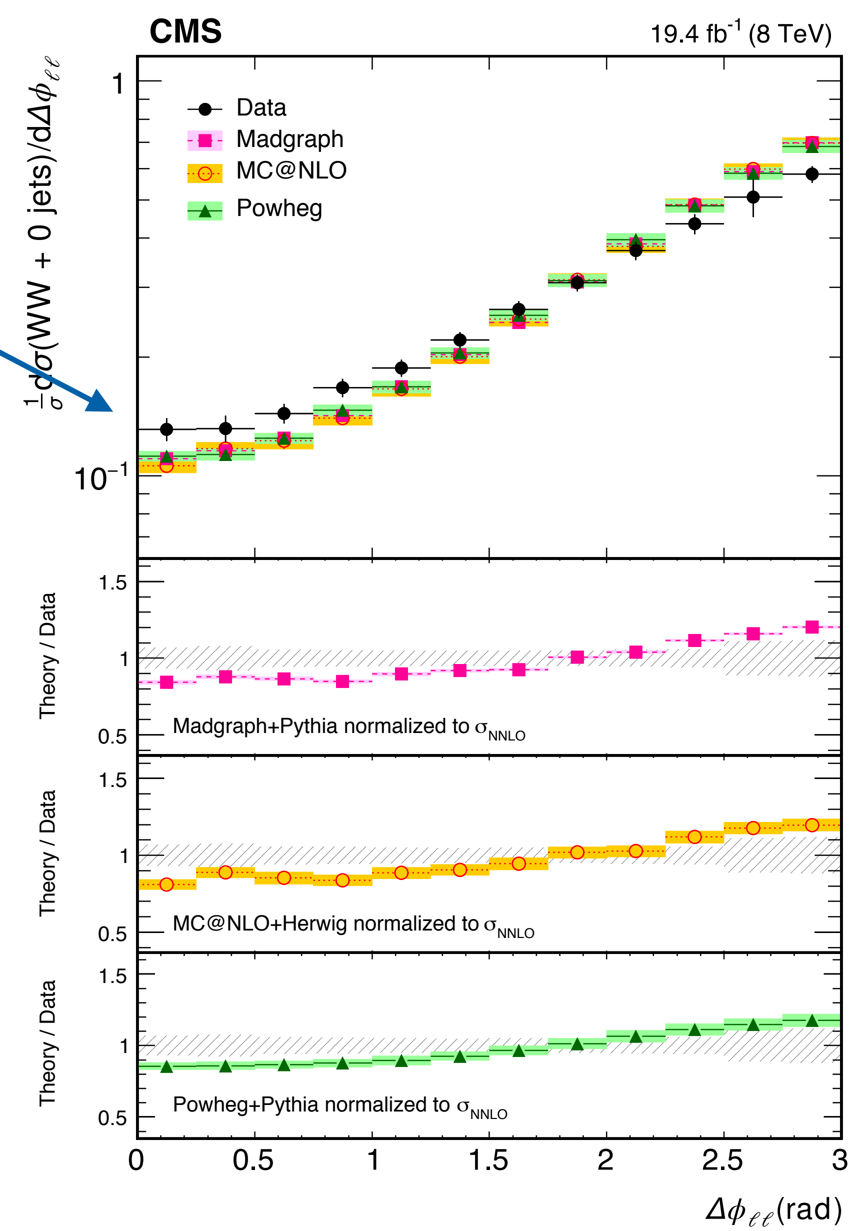
arXiv:1507.03268 [Eur. Phys. J. C76 (2016) nº7, 401]

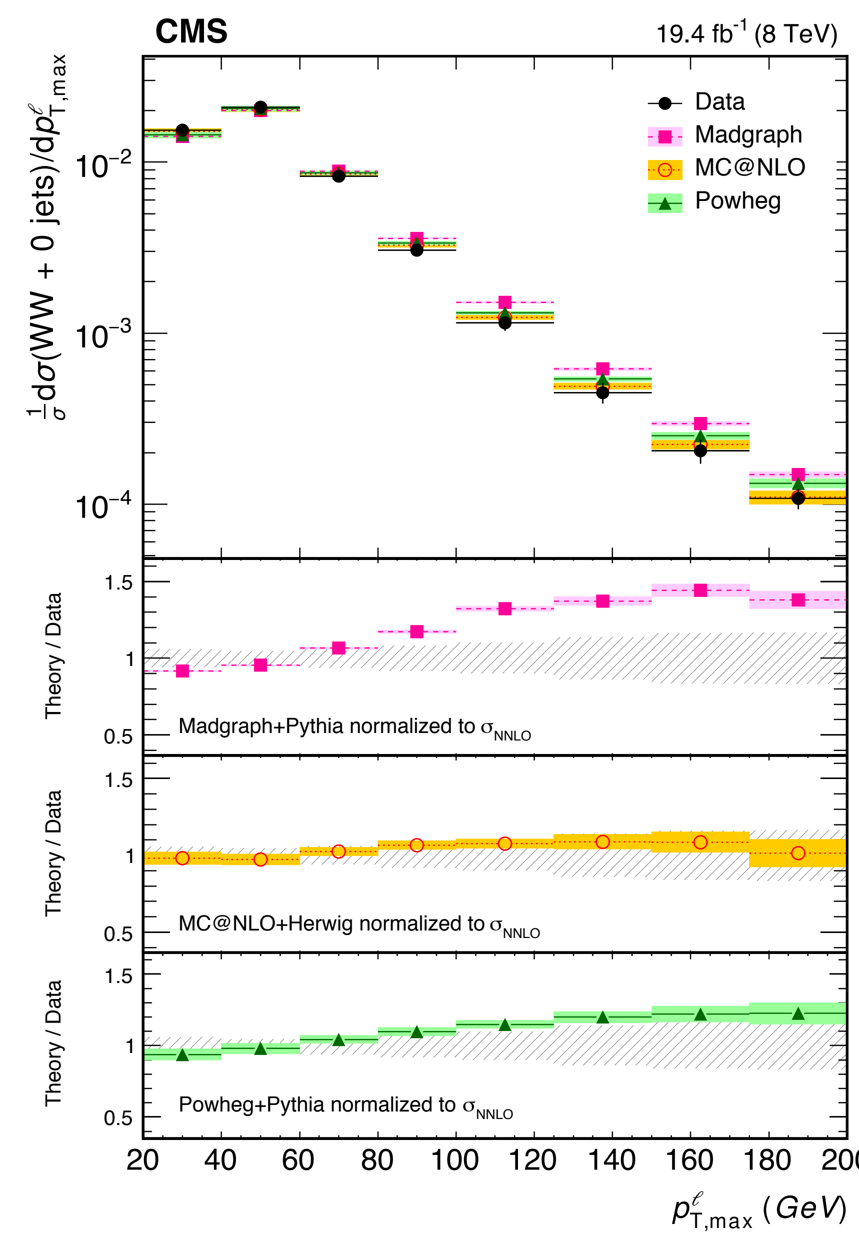
- Fiducial region with $p_T(\ell) > 20$ GeV, $|\eta(\ell)|<2.5$, and 0 jets is used to measure differential cross sections. We measured differential cross sections as a function of $\Delta\phi(\ell\ell)$, $m(\ell\ell)$, $p_T(\ell\ell)$ and p_T(leading lepton).

Visible higher order (2-loop) effects



[from arXiv:1605.02716]



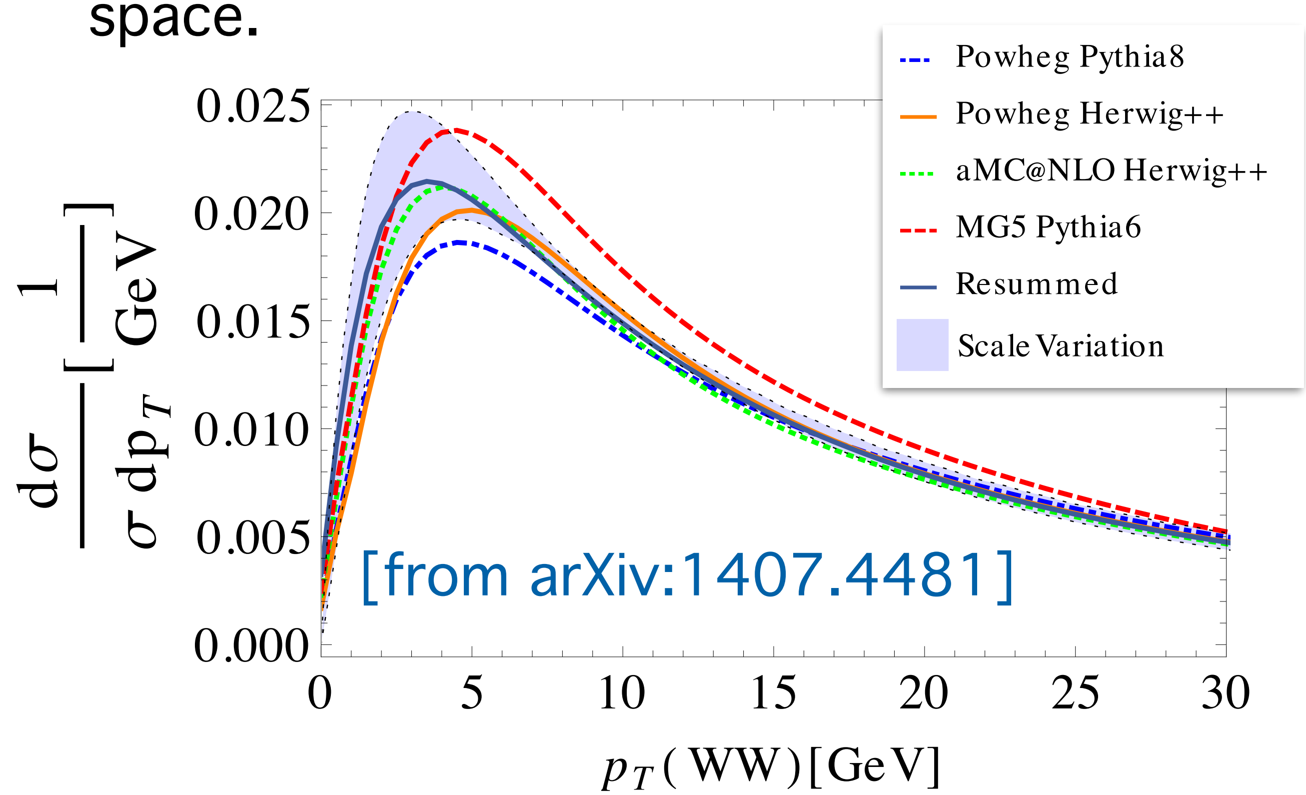


WW cross section @ 8 TeV [CMS SMP-14-016]

arXiv:1507.03268 [Eur. Phys. J. C76 (2016) nº7, 401]

Inclusive cross section

- Events with same-flavor and different-flavor lepton pair, with 0 and 1 associated jets, are used to measure the inclusive cross section.
- p_T^{WW}-resummed calculation used for extrapolation to the full W-boson decay phase space.



Source	Uncertainty (%)
Statistical uncertainty	1.5
Lepton efficiency	3.8
Lepton momentum scale	0.5
Jet energy scale	1.7
E_T^{miss} resolution	0.7
$t\bar{t}$+tW normalization	2.2
W+jets normalization	1.3
$Z/\gamma^* \to \ell^+\ell^-$ normalization	0.6
$Z/\gamma^* \to \tau^+\tau^-$ normalization	0.2
$W\gamma$ normalization	0.3
$W\gamma^*$ normalization	0.4
VV normalization	3.0
$H \to W^+W^-$ normalization	0.8
Jet counting theory model	4.3
PDFs	1.2
MC statistical uncertainty	0.9
Integrated luminosity	2.6
Total uncertainty	7.9

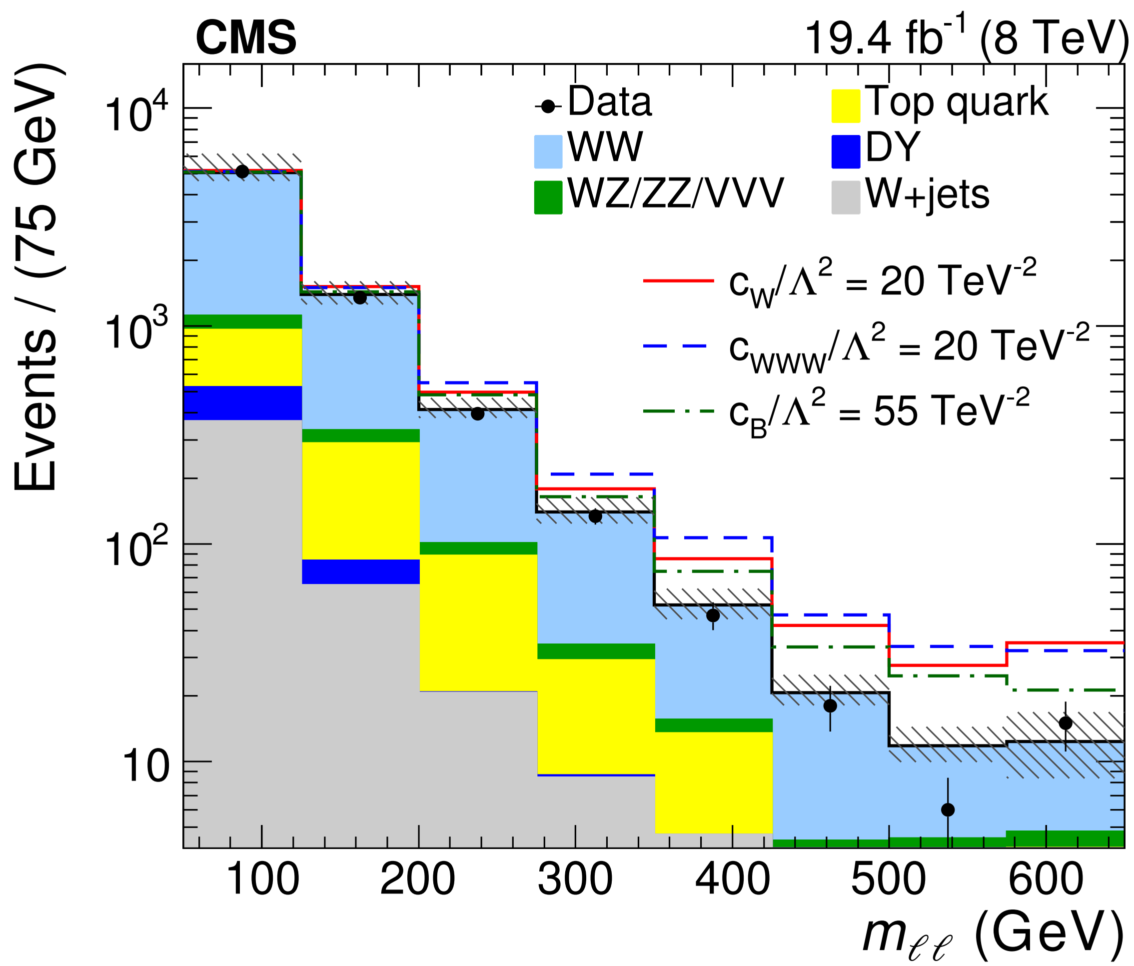
$$\sigma_{W^+W^-} = 60.1 \pm 0.9\,(\mathrm{stat}) \pm 3.2\,(\mathrm{exp}) \pm 3.1\,(\mathrm{theo}) \pm 1.6\,(\mathrm{lumi})\,\mathrm{pb}$$

SM NNLO prediction: $59.8^{+1.3}_{-1.1}$ pb [Phys. Rev. Lett. 113 (2014) 212001]

WW cross section @ 8 TeV [CMS SMP-14-016]

arXiv:1507.03268 [Eur. Phys. J. C76 (2016) nº7, 401]

- Events with high m(ℓℓ) are used to measure SMEFT dimension-6 operators.

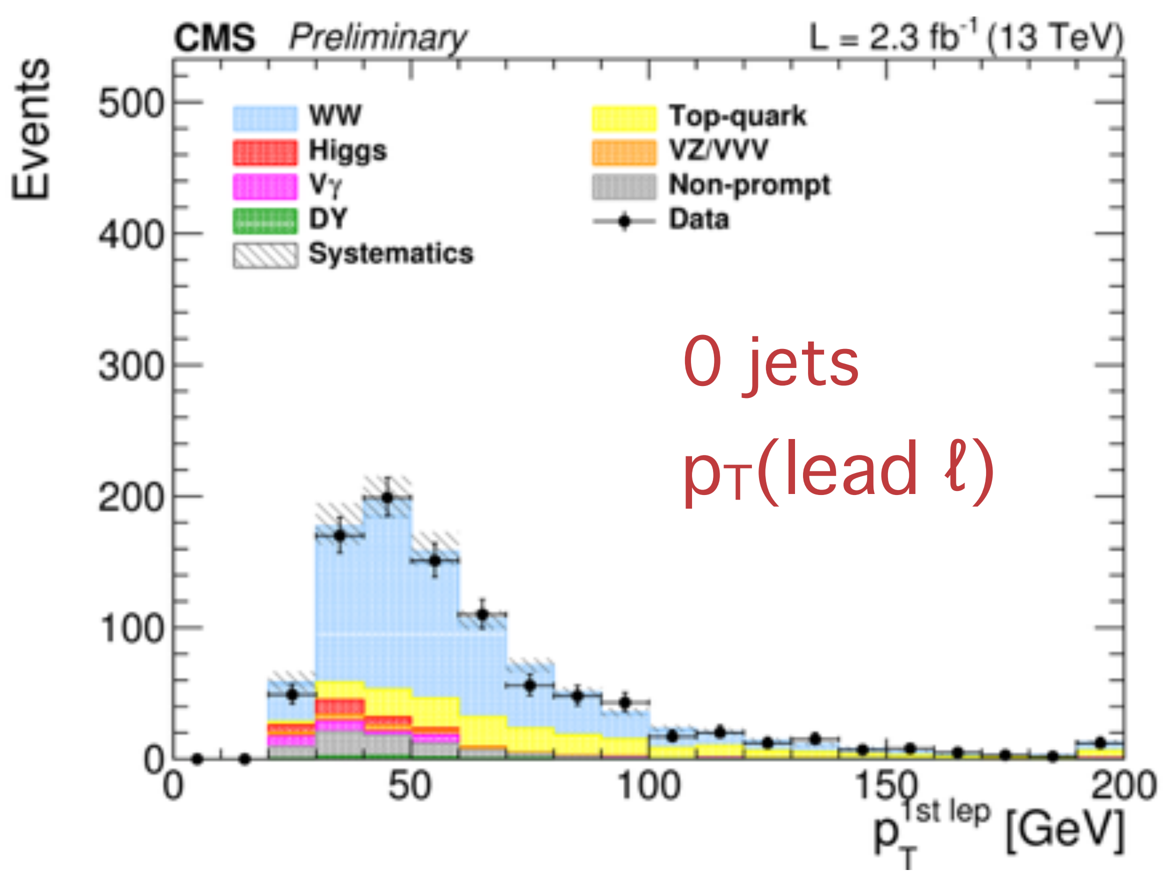


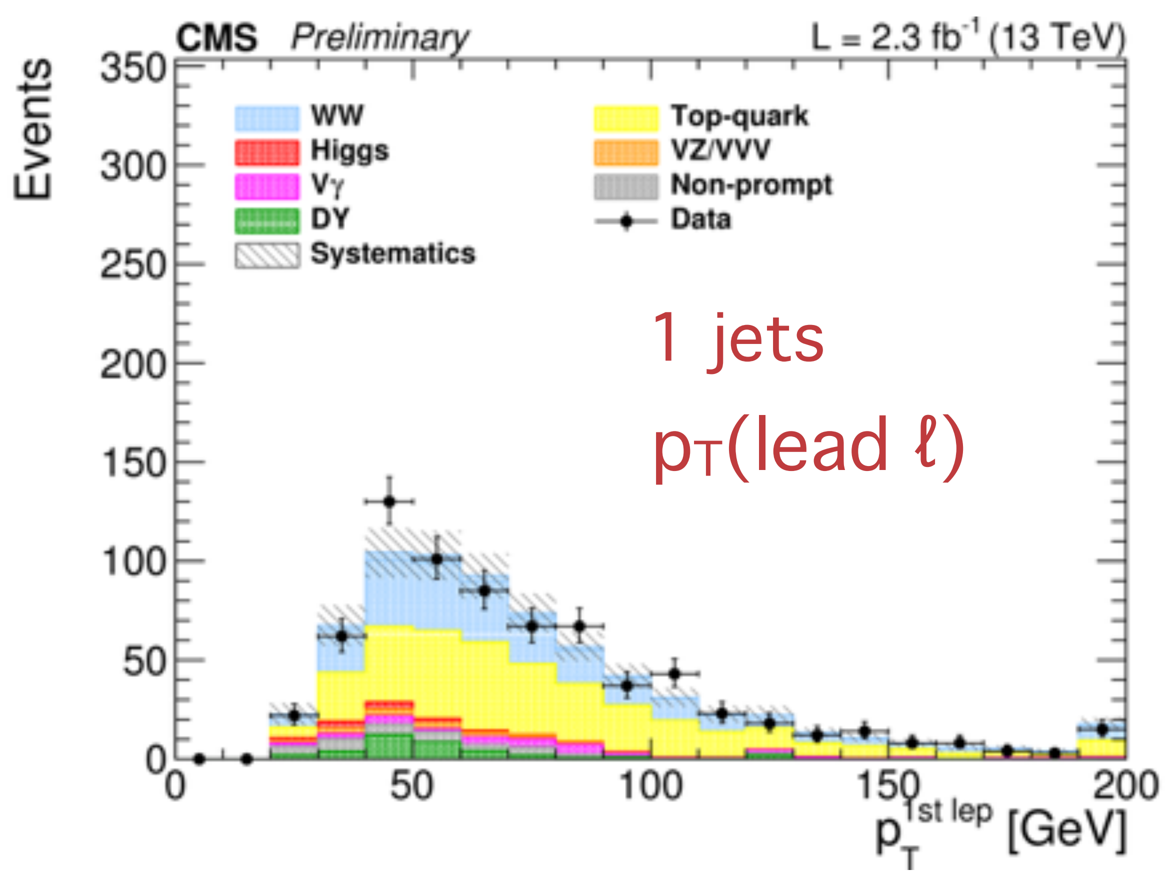
Coupling constant	This result (TeV^{-2})	Its 95% CL interval (TeV^{-2})	World average (TeV^{-2})	
c_{WWW}/Λ^2	$0.1^{+3.2}_{-3.2}$	$[-5.7, 5.9]$	-5.5 ± 4.8	(from λ_γ)
c_W/Λ^2	$-3.6^{+5.0}_{-4.5}$	$[-11.4, 5.4]$	$-3.9^{+3.9}_{-4.8}$	(from g_1^Z)
c_B/Λ^2	$-3.2^{+15.0}_{-14.5}$	$[-29.2, 23.9]$	$-1.7^{+13.6}_{-13.9}$	(from κ_γ and g_1^Z)

WW cross section @ 13 TeV [CMS SMP-16-006]

cds:CMS-PAS-16-006

- Measurement performed with 2.3 fb^{-1} of integrated luminosity at 13 TeV.
- First 13 TeV WW cross section measurement.
- Similar, but simplified event selection with respect to the 8 TeV measurement
  - Different-flavor channel only
  - Simplified Top-quark veto (b-quark jet veto with p_T > 20 and $|\eta|$ < 2.4)
  - Identical background estimation methods.





WW cross section @ 13 TeV [CMS SMP-16-006]

cds:CMS-PAS-16-006

- Preliminary result with only inclusive cross section.
- Measurement limited by small data sample and large b-tagging uncertainty.

Uncertainty source	Propagation to cross section (%)
Experimental uncertainties	4.9
QCD scales and higher order effects	3.2
PDFs	0.4
Underlying event and parton shower	3.7
Non-prompt normalization	3.0
Top-quark normalization	2.0
$W\gamma^*$ normalization	0.3
Simulation and data control regions sample size	1.4
Total systematic uncertainty	7.4
Total statistical uncertainty	5.0
Luminosity	3.0
Total uncertainty	9.5

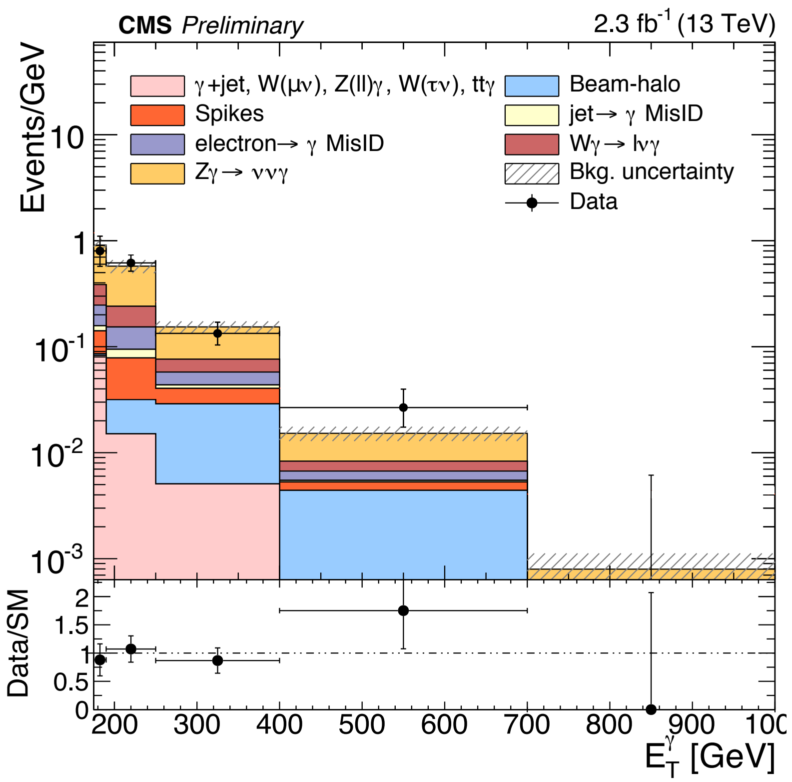
Category	Value $\pm$ stat. $\pm$ exp. syst. $\pm$ theo. syst. $\pm$ lumi. [pb]
0-jet	$113.6 \pm 6.3 \pm 5.1 \pm 6.5 \pm 3.3$
1-jet	$135.3 \pm 15.4 \pm 34.0 \pm 14.4 \pm 6.0$
Combination	$115.3 \pm 5.8 \pm 5.7 \pm 6.4 \pm 3.6$

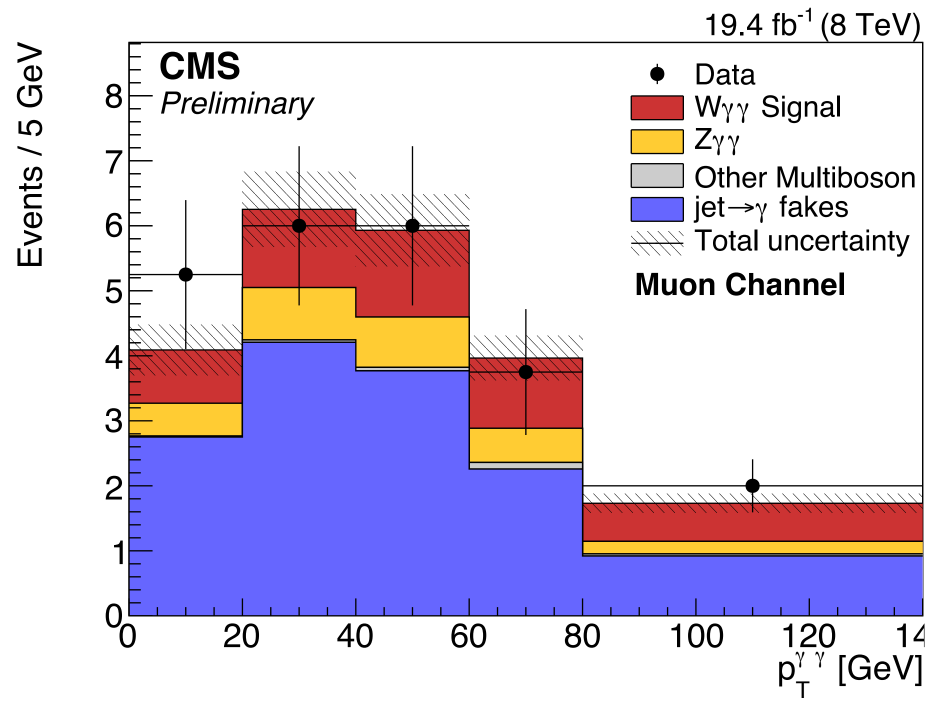
SM NNLO prediction: 120.3±3.0 pb

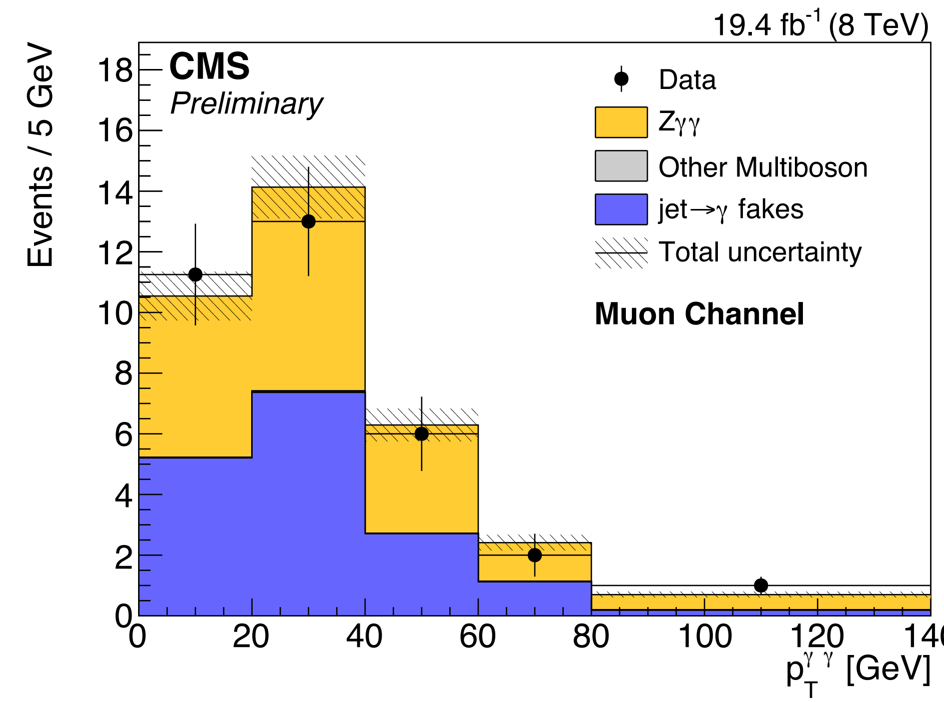
[Phys. Rev. Lett. 113 (2014) 21201 and Phys. Lett. B754 (2016) 275-280]

Measurements with photons in the final state

Z(→νν)γ	W(→ℓν)γγ	Z(→ℓℓ)γγ
2.3 fb^{-1} @ 13TeV	19.4 fb^{-1} @ 8TeV	19.4 fb^{-1} @ 8TeV





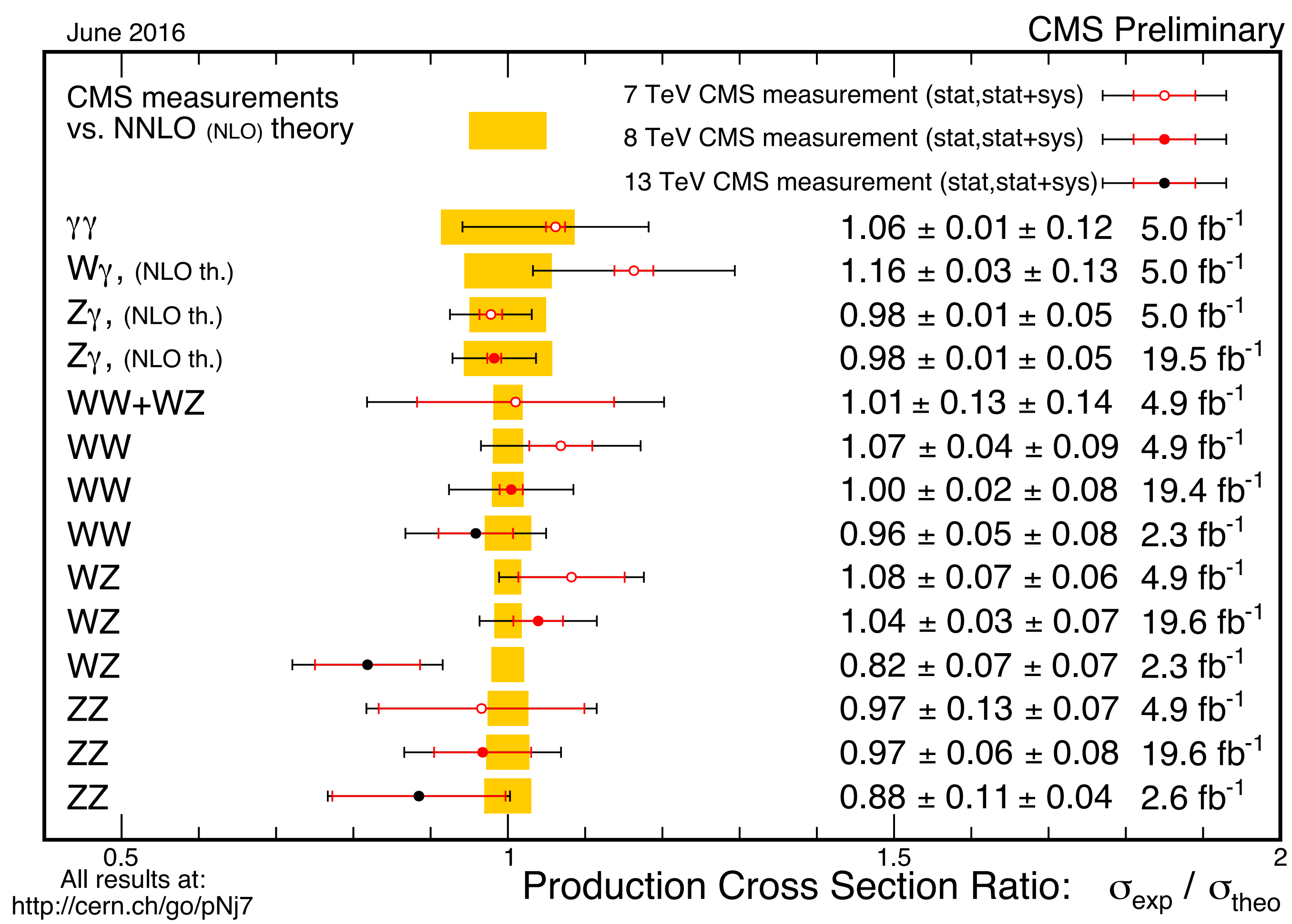


Z(→νν)γ	W(→ℓν)γγ	Z(→ℓℓ)γγ
$p_T(\gamma) > 175$ GeV, $|\eta(\gamma)|<1.44$	$p_T(\gamma) > 25$ GeV	$p_T(\gamma) > 15$ GeV
$\sigma_{exp} = 66.5 \pm 19.9$ fb	$\sigma_{exp} \times BR = 6.0 \pm 2.9$ fb	$\sigma_{exp} \times BR = 12.7 \pm 2.3$ fb
$\sigma_{NNLO} = 65.5 \pm 3.3$ fb	$\sigma_{NLO} \times BR = 4.76 \pm 0.53$ fb	$\sigma_{NLO} \times BR = 12.95 \pm 1.47$ fb

More details in J. Kunkle's talk

Summary

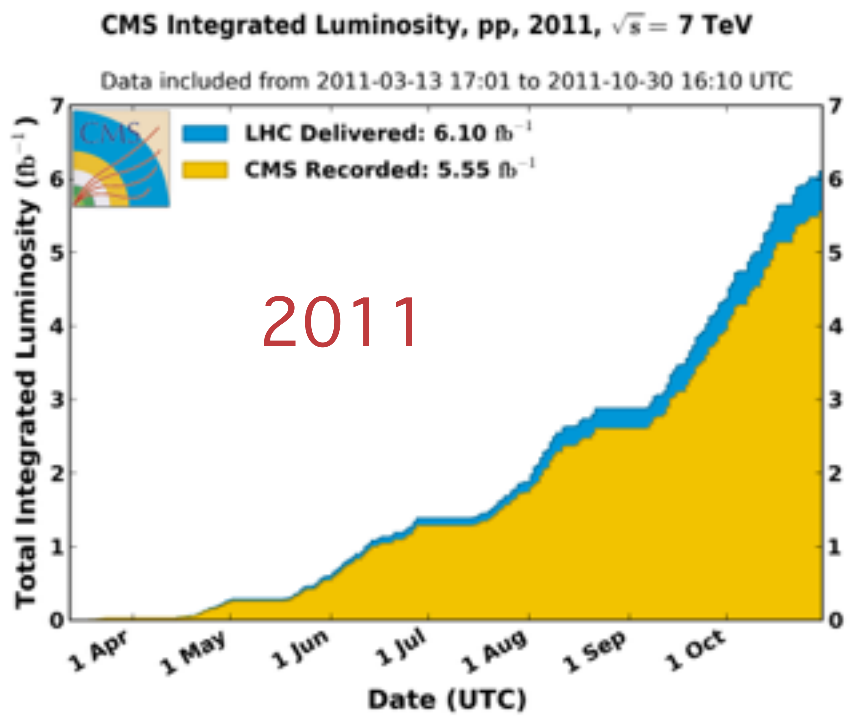
- CMS has a broad program of multiboson production cross section measurements at the LHC. Production cross sections have been measured at 7, 8, and 13 TeV.
- Inclusive, fiducial, and differential measurements are performed. The experimental precision of these results requires, in many cases, 2-loop and resummed QCD calculations to accurately describe the results.
- Rich program of SMEFT measurements performed at 8 TeV. Single channels at 13 TeV already surpass the combined precision of these measurements. Stay tuned!

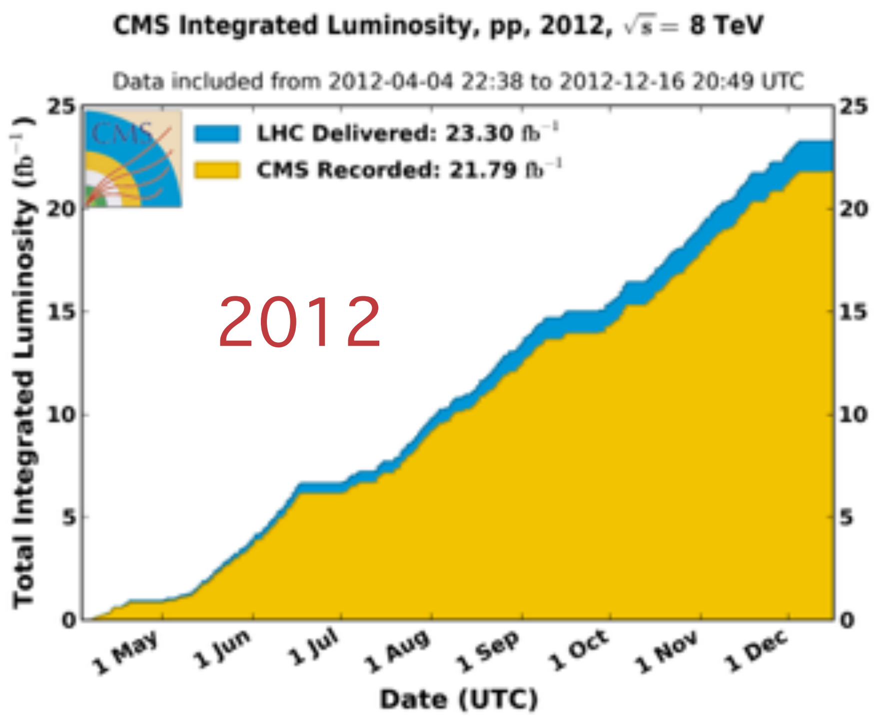


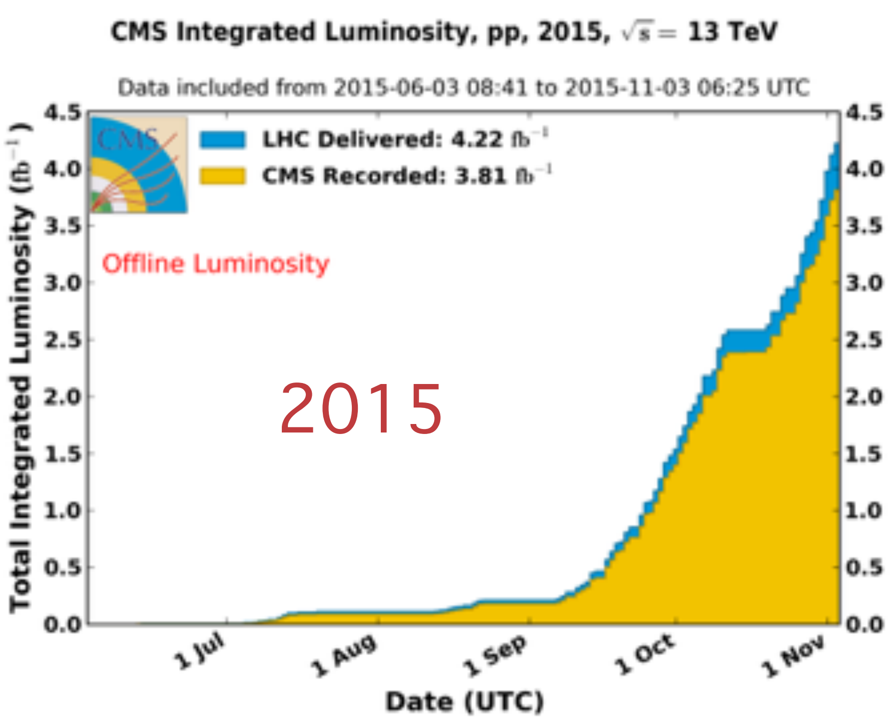
Backup slides

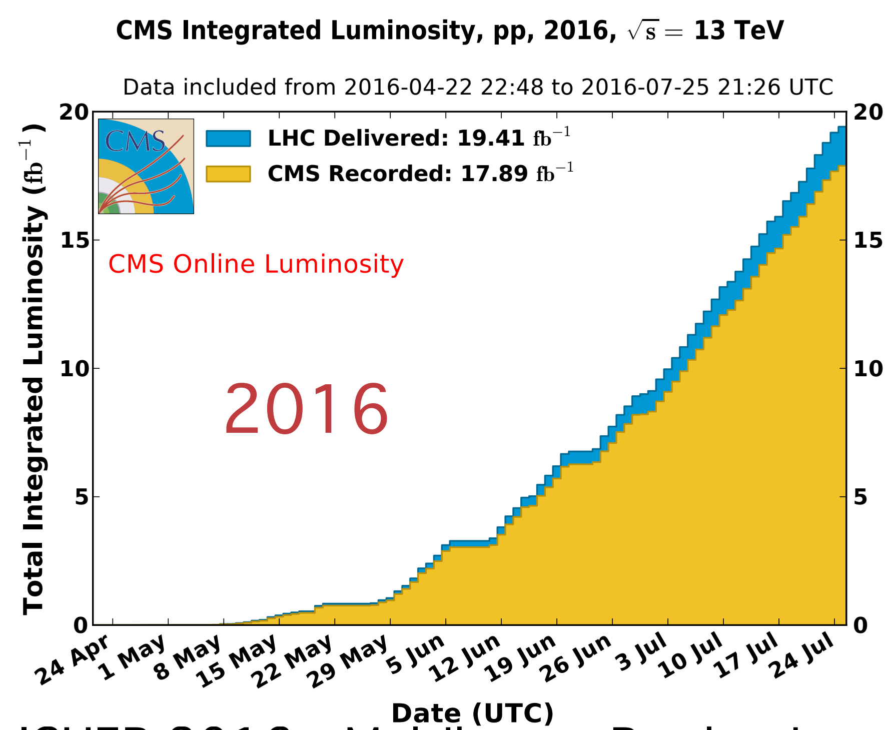
Data collected by the CMS detector

CMS has efficiently collected data at 7, 8 and 13 TeV. This extensive dataset allows us to explore production cross section measurements in different energy regimes, providing stringent tests of the theories describing these processes.





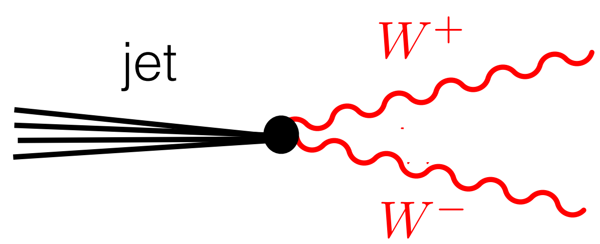




WW p_T resummation

(arXiv:1407.4481, arXiv:1507.06937)

✦ Resums logs of the type $\log(m_{WW}/p_T^{WW})$



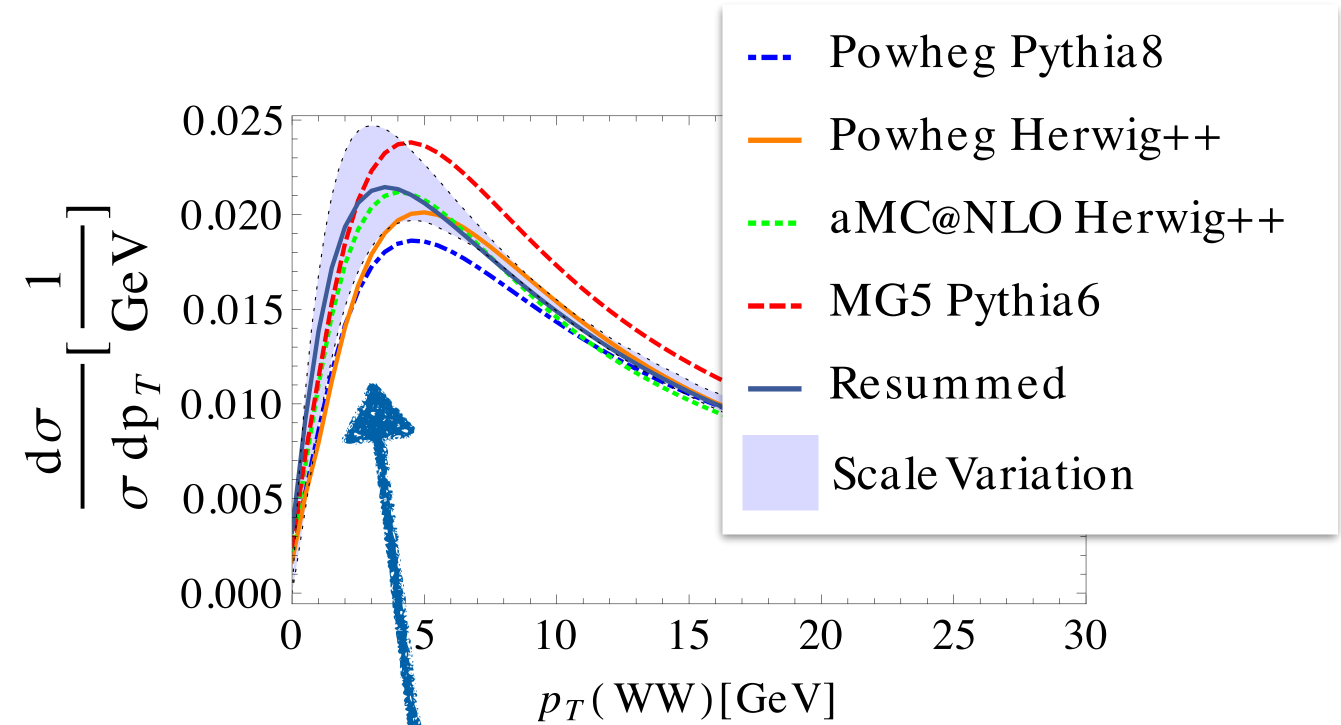
✦ Resummed p_T^{WW} distribution is used to reweight parton shower MC generators and obtain exclusive distributions.

✦ The uncertainty is estimated by varying the resummation (Q), renormalization and factorization scales in the intervals:

$$\frac{M_W}{2} < Q < 2M_W$$

$$M_W < \mu_f < 4M_W$$

$$M_W < \mu_r < 4M_W$$



Resummation predicts softer spectrum ⇒ higher jet veto efficiency⇒ smaller inclusive cross section

Smaller corrections at NNLL