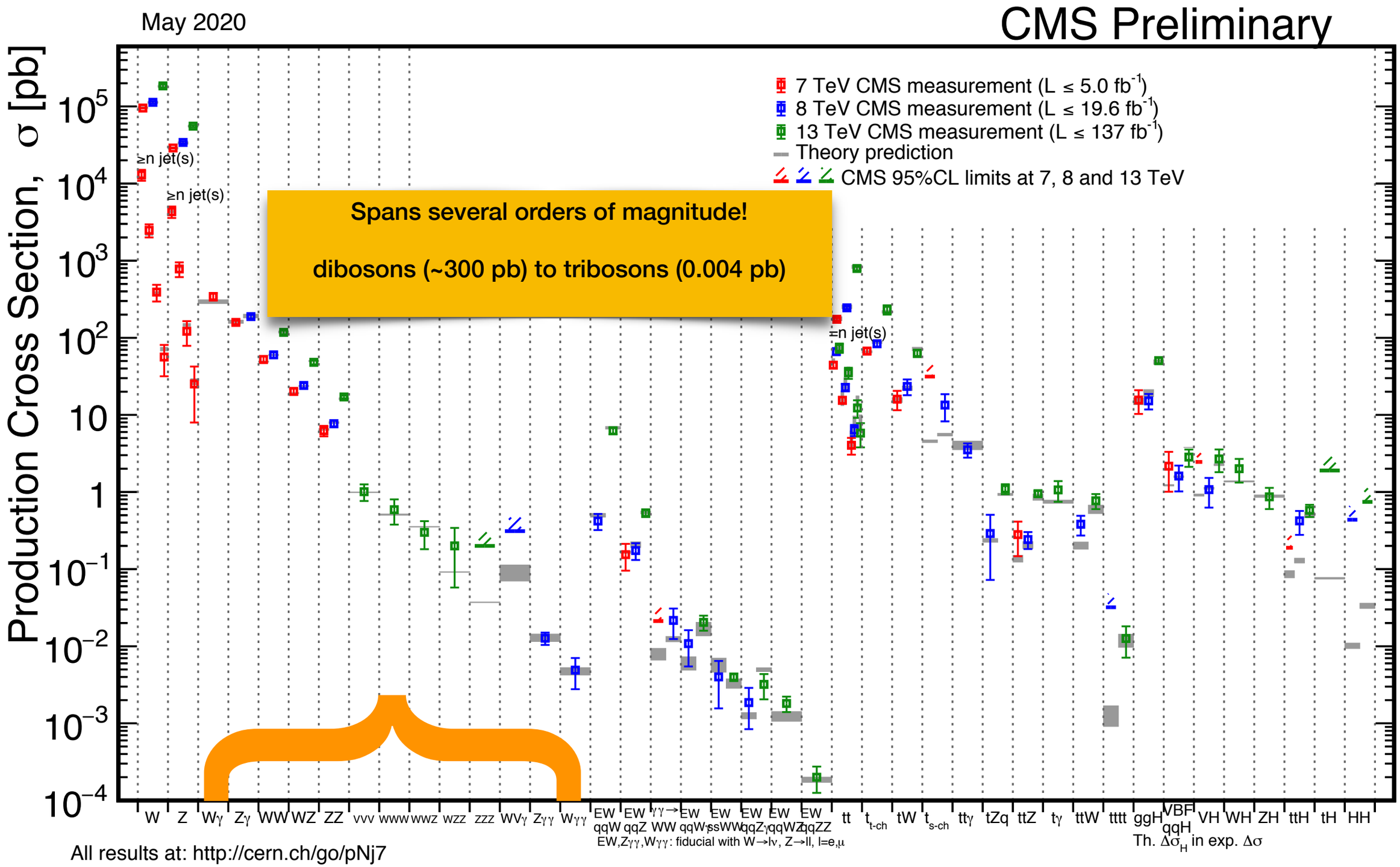
Multiboson Measurements in CMS and ATLAS

Saptaparna Bhattacharya
Northwestern University
LHCP, 2020

Multiboson Measurements

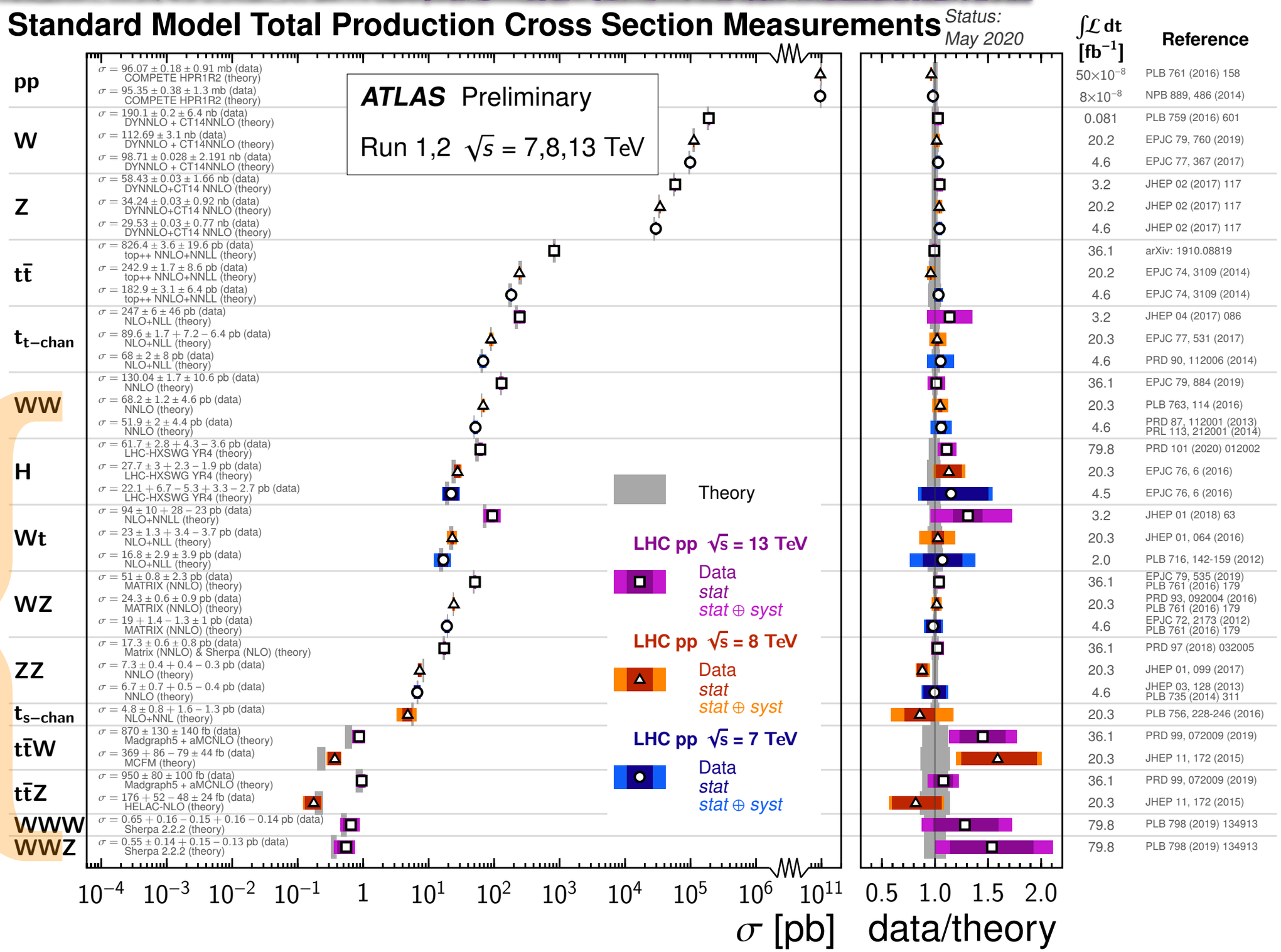


Spans several orders of magnitude!

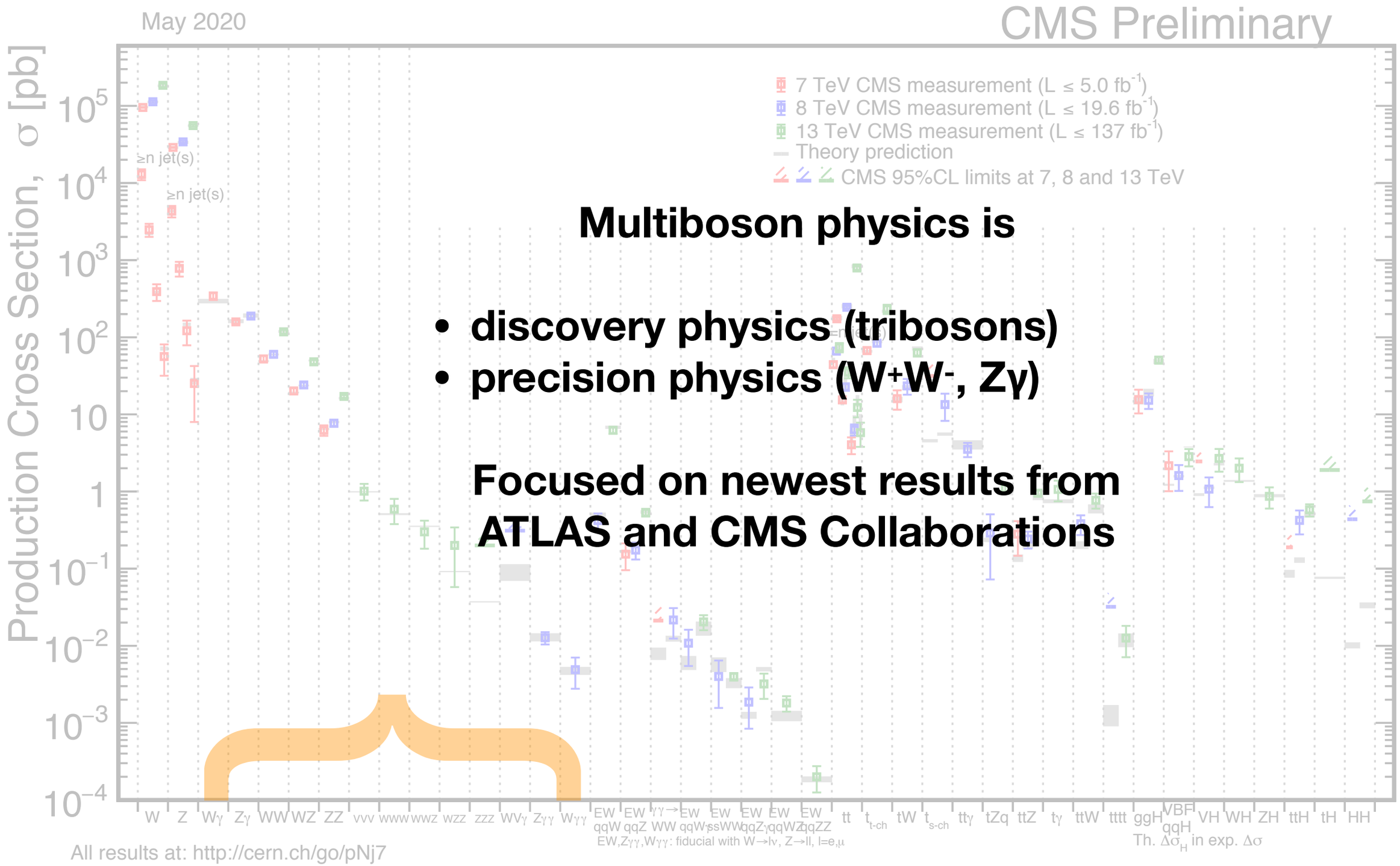
dibosons (~300 pb) to tribosons (0.004 pb)

Multiboson Measurements

- Production probability **lower by** factors of **2 - 100 (WZ - WWW)** wrt to Higgs production
- **Rare** and **difficult to isolate** from background processes



Multiboson Measurements



Multiboson physics is

- **discovery physics (tribosons)**
- **precision physics (W^+W^-, Zγ)**

Focused on newest results from ATLAS and CMS Collaborations

Observation of Heavy Tribosons with Run II data

Major milestone in Standard Model physics!

http://cms.cern/news/triple-treat-cms-observes-production-three-massive-vector-bosons

Information | Discussion (0) | Files

CMS Physics Analysis Summaries

Report number	CMS-PAS-SMP-19-014
Title	**Observation of heavy triboson production in leptonic final states in proton-proton collisions at $\sqrt{s} = 13$ TeV**
Corporate author(s)	CMS Collaboration
Collaboration	CMS Collaboration
Subject category	Particle Physics - Experiment
Accelerator/Facility, Experiment	CERN LHC ; CMS

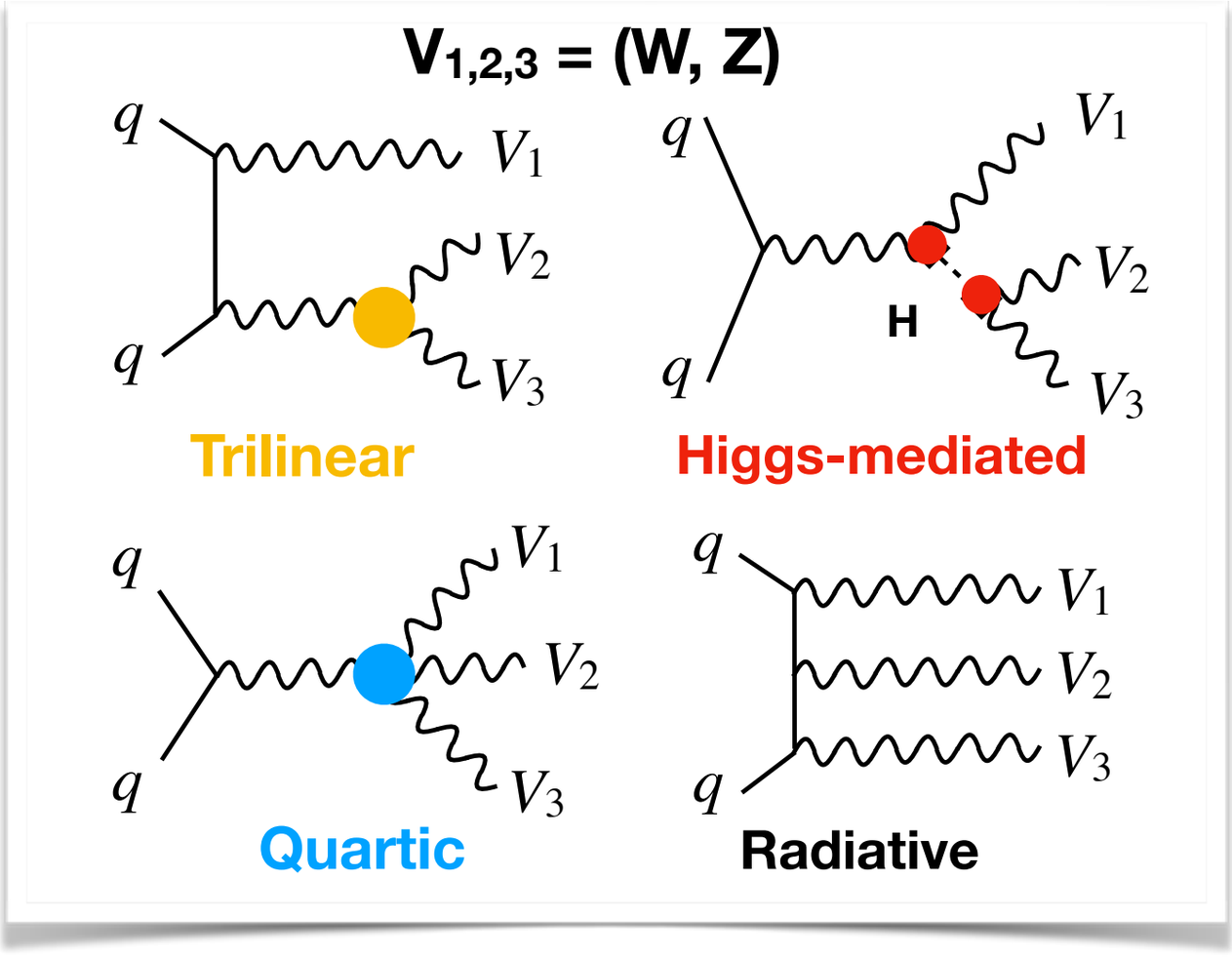
http://cds.cern.ch/record/2714899

Auxiliary material: https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-19-014/index.html

Observation of Heavy Tribosons with Run II data

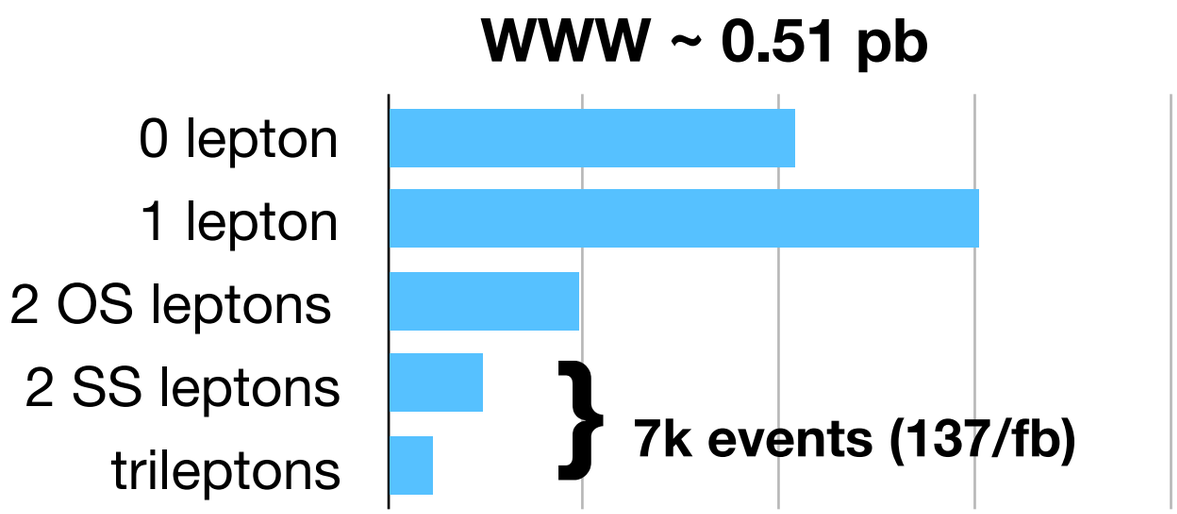
Combined observed significance at 5.7 σ
Observed significance for WWW and WWZ at 3.3 σ and 3.4 σ

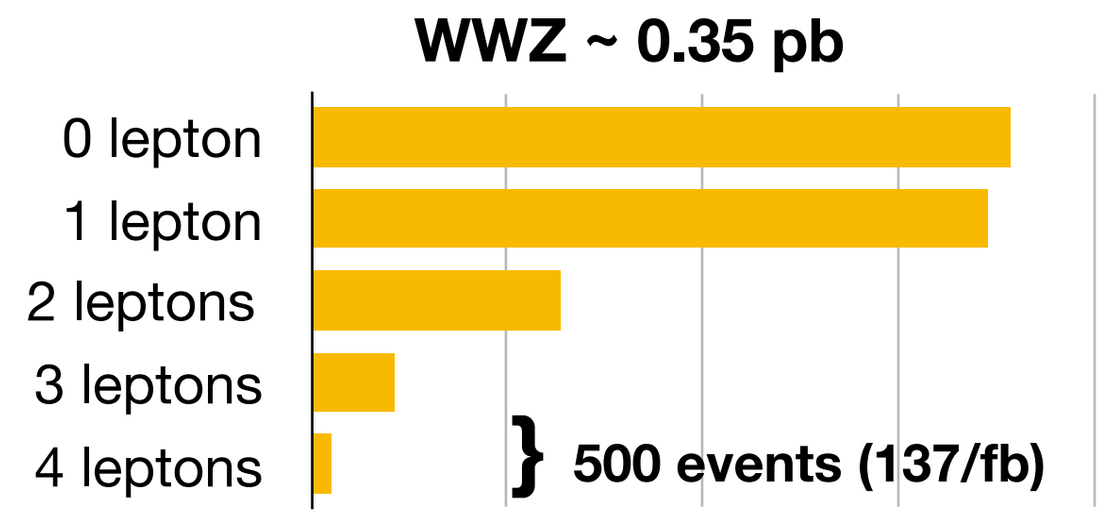
- Rich physics content in triboson final states
- Access to various couplings
- Evidence announced last year by ATLAS: arXiv:1903.10415, **WWW+WWZ** 4.0 (3.1) σ
- Search for **WWW** performed in CMS: arXiv:1905:04246, 0.6 (1.78) σ
- **New from CMS:** Explore leptonic final states, primarily geared toward:
  - **WWW:** same-signed dilepton and trilepton
  - **WWZ:** four leptons
  - **WZZ:** five leptons
  - **ZZZ:** six or more leptons

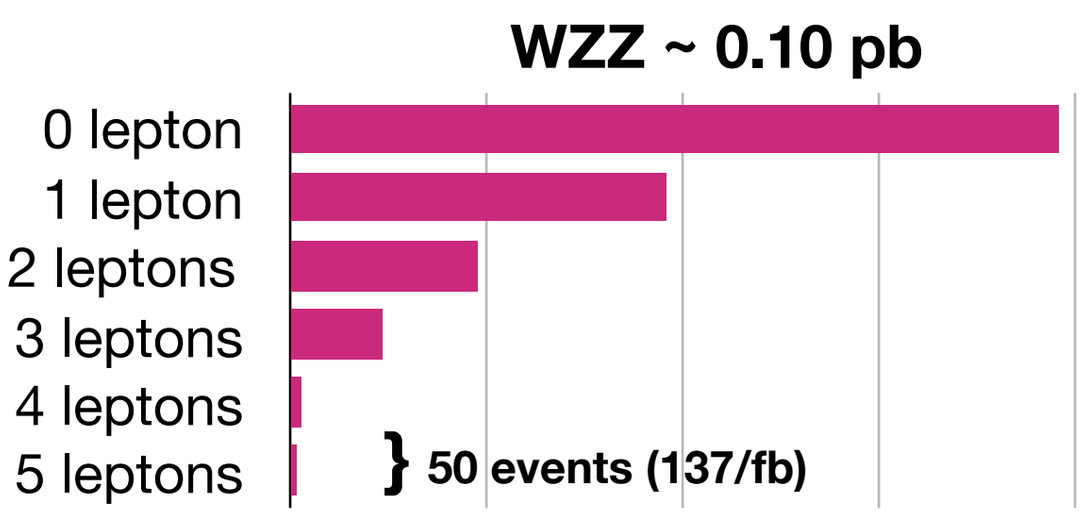


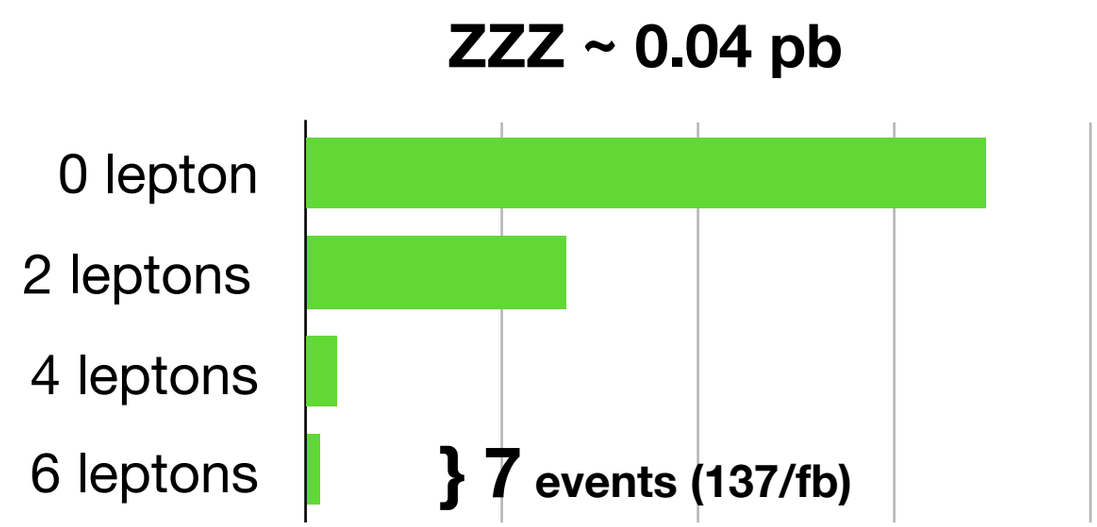
Search for WWW, WWZ, WZZ and ZZZ

Cross sections X Branching fractions

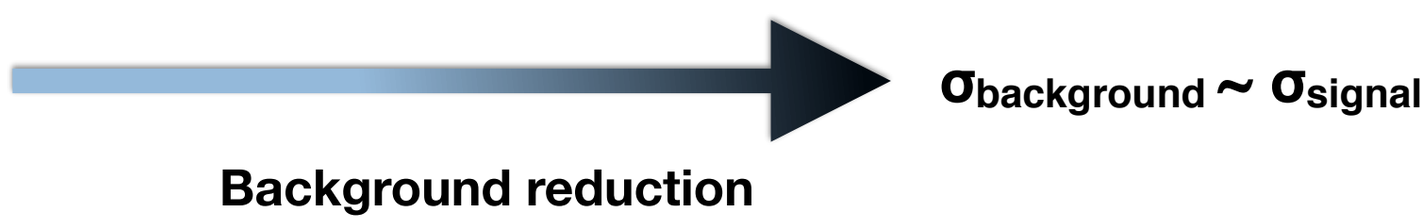






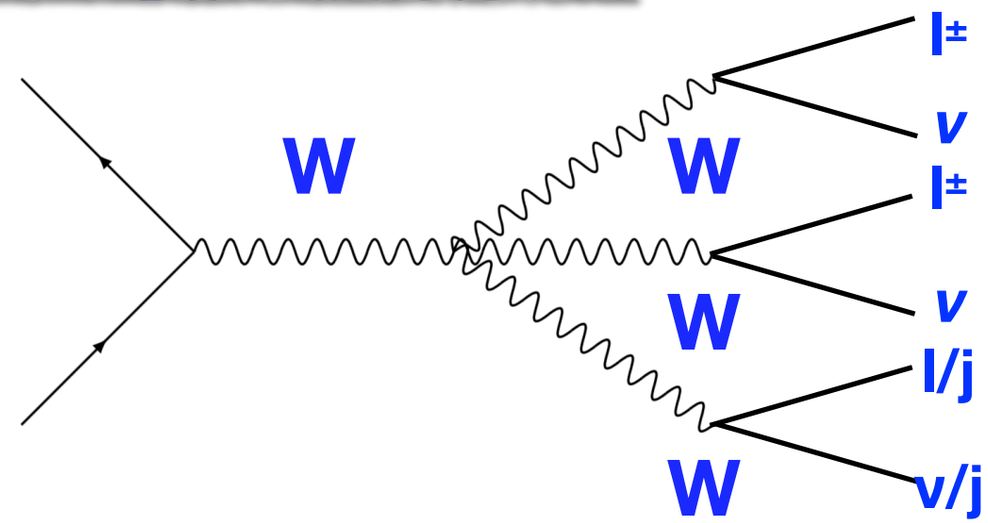


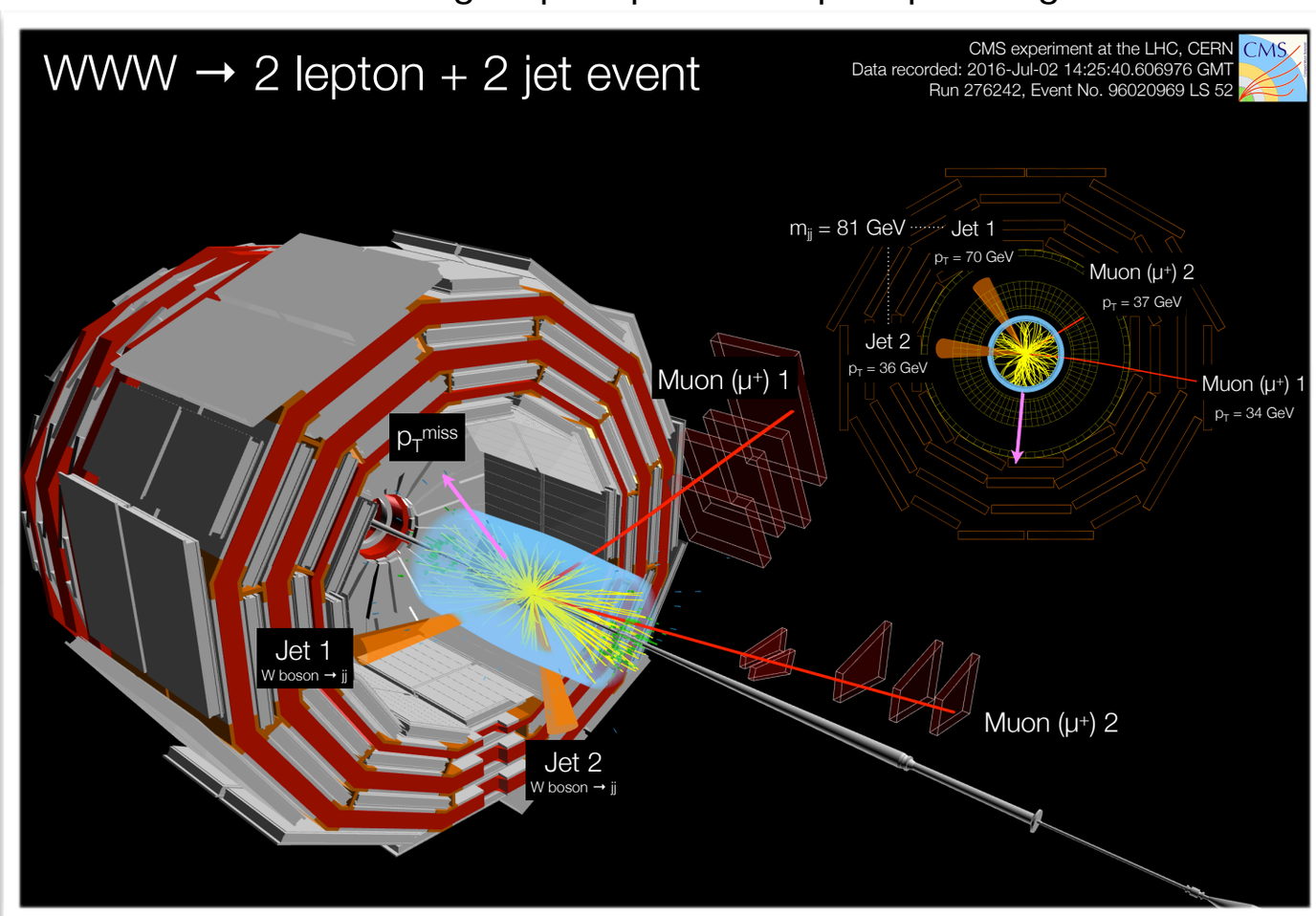
Explore leptonic final states; backgrounds reduced with a BDT based approach and complementary cut based analysis

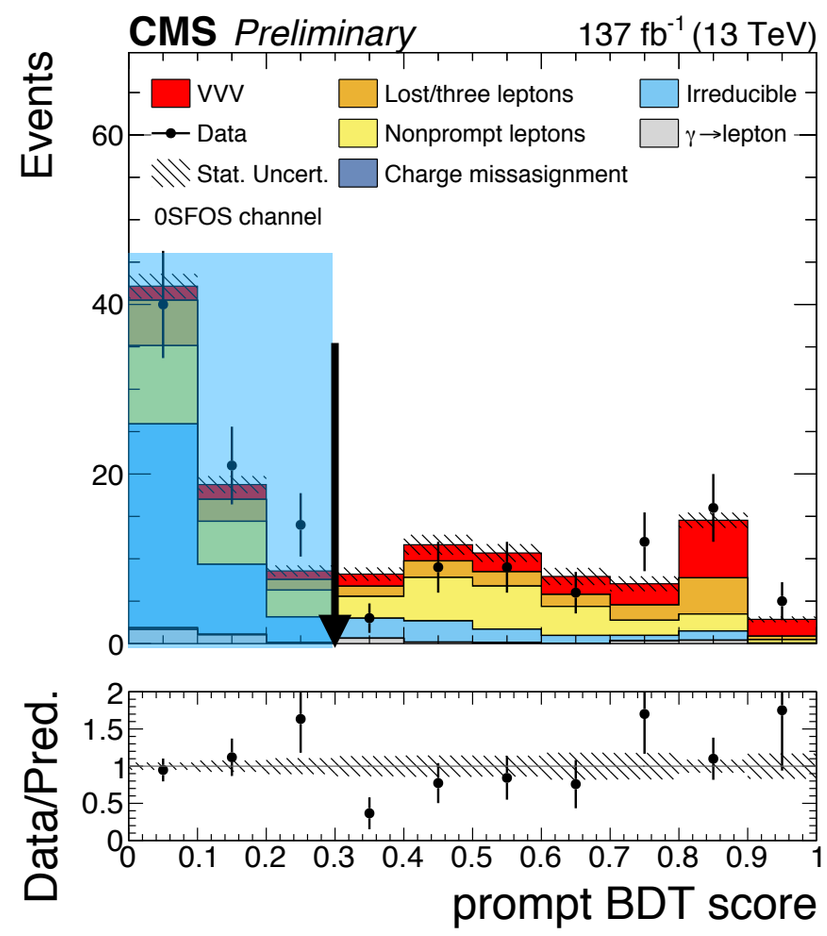


WWW → 2 same-signed leptons and 2 jets and WWW → 3 leptons

- Search for WWW in:
  - 2 same-signed leptons + 2 jets
    - further categorized based on $|M_{jj} - M_W| \leqslant 15$ GeV
  - 2 same-signed leptons + 1 jet
  - trileptons
    - subcategories based on number of opposite-sign same-flavor (OSSF) leptons
- Two BDTs trained to mitigate prompt and nonprompt backgrounds



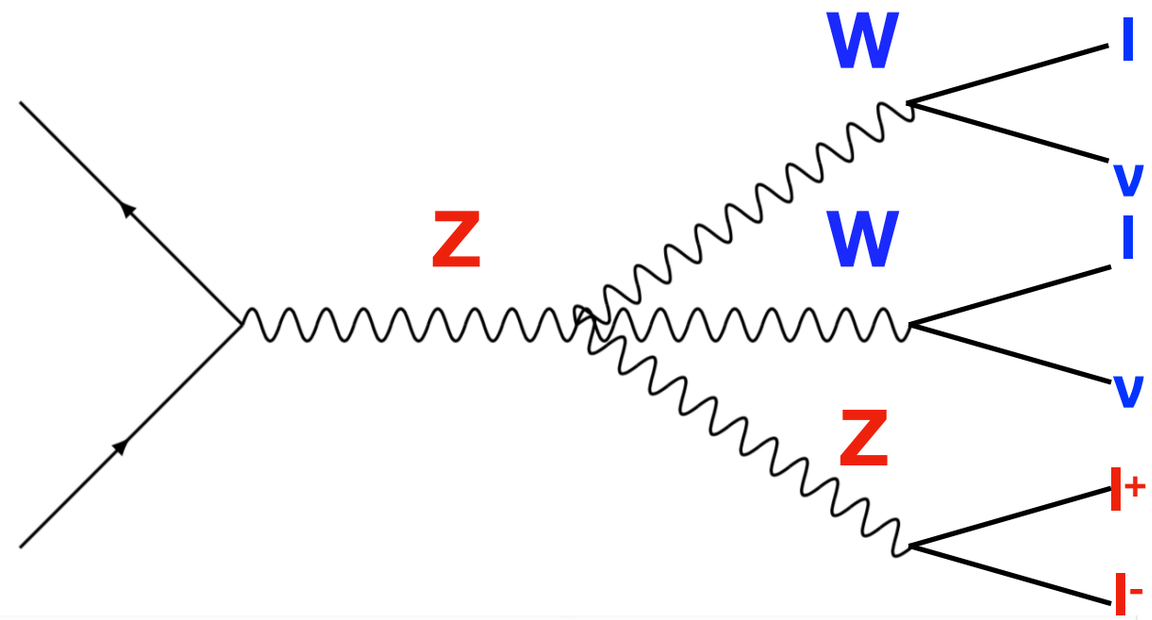




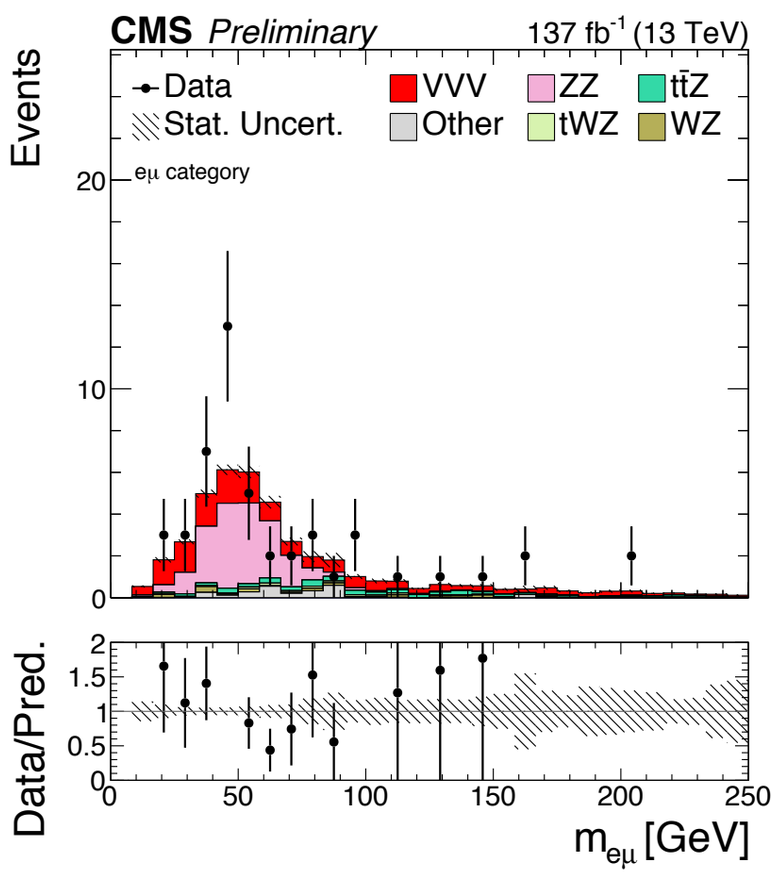
BDT trained with lepton p_Ts, jet p_Ts, p_T(miss), m_{jj} plus other kinematic variables

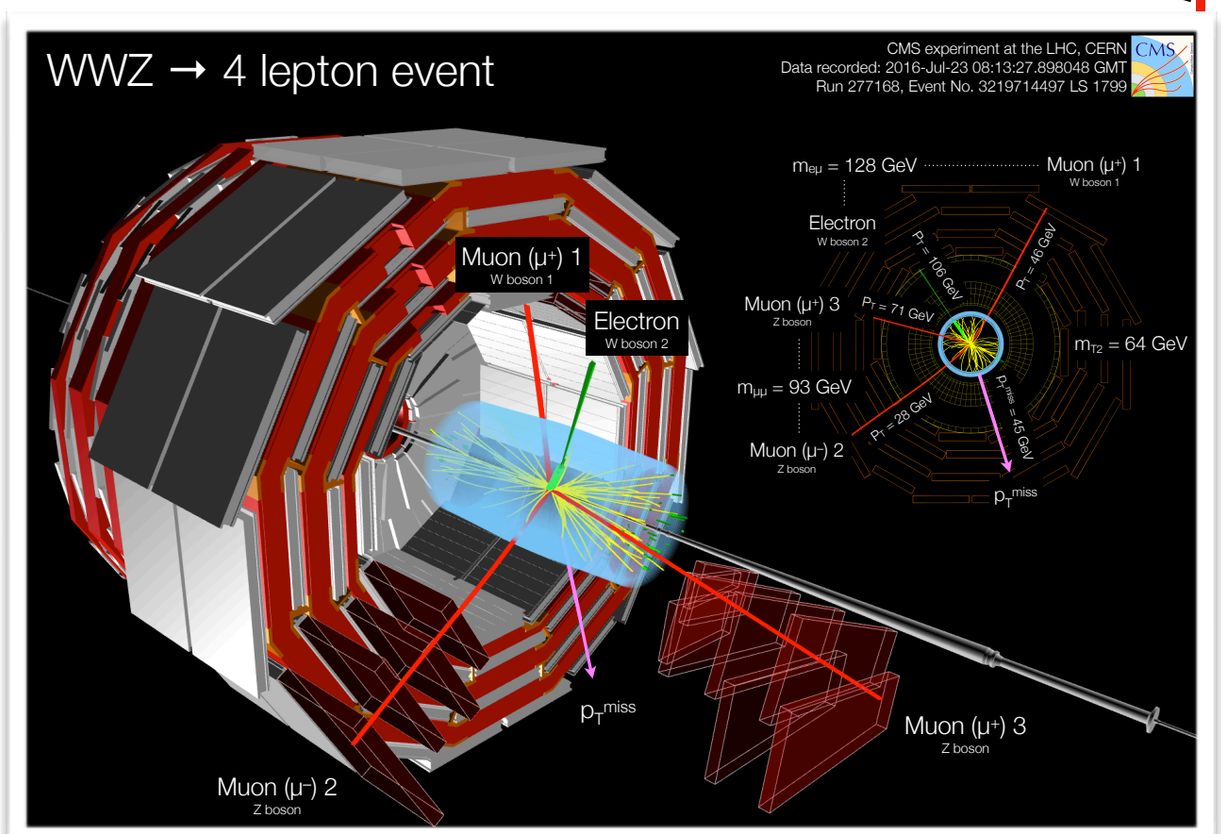
WWZ → 4 leptons

- **Search for WWZ in four lepton final state:**
  - Require one Z candidate
  - further splitting based on the **flavor of the W candidates (eμ or ee/μμ)**
- Major backgrounds from **ZZ** (dominant) and **ttZ**
- Two BDTs trained to mitigate ZZ and ttZ backgrounds: **used 2D plane of BDT scores to define signal region**



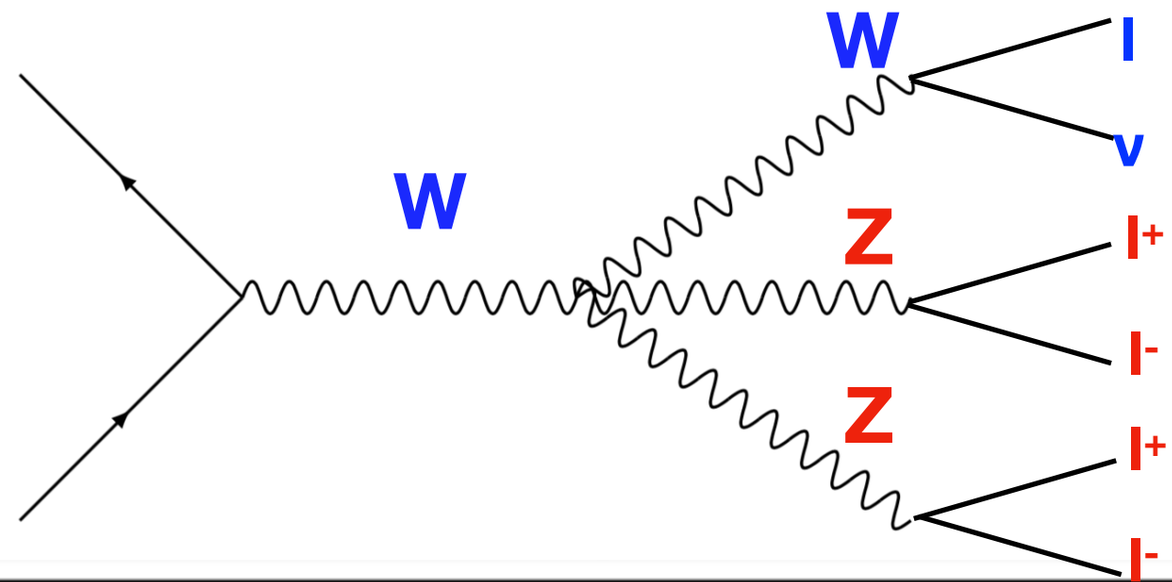
Main discriminant in the opposite-flavor channel

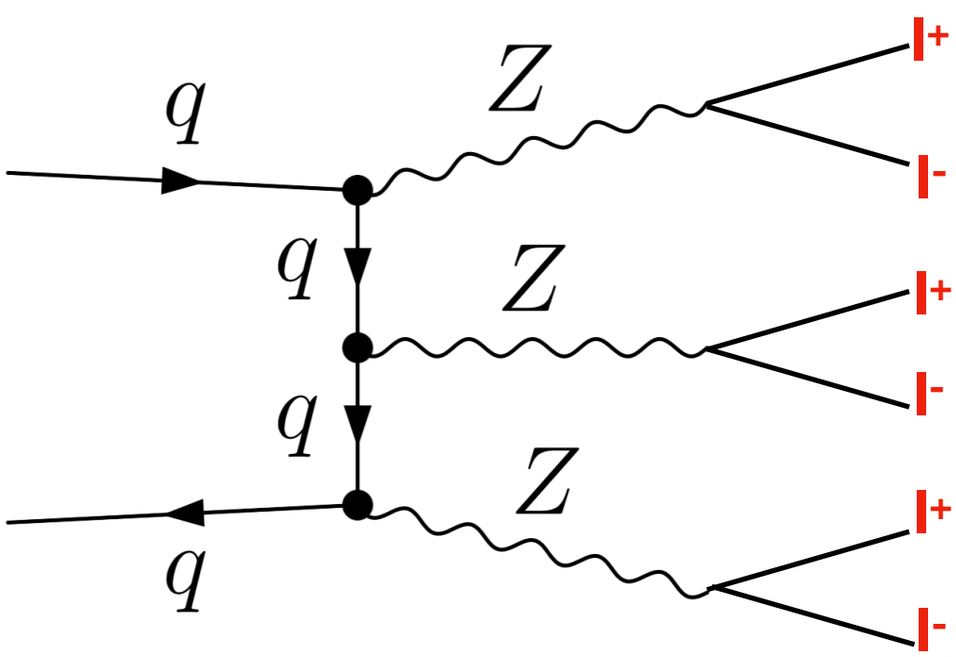


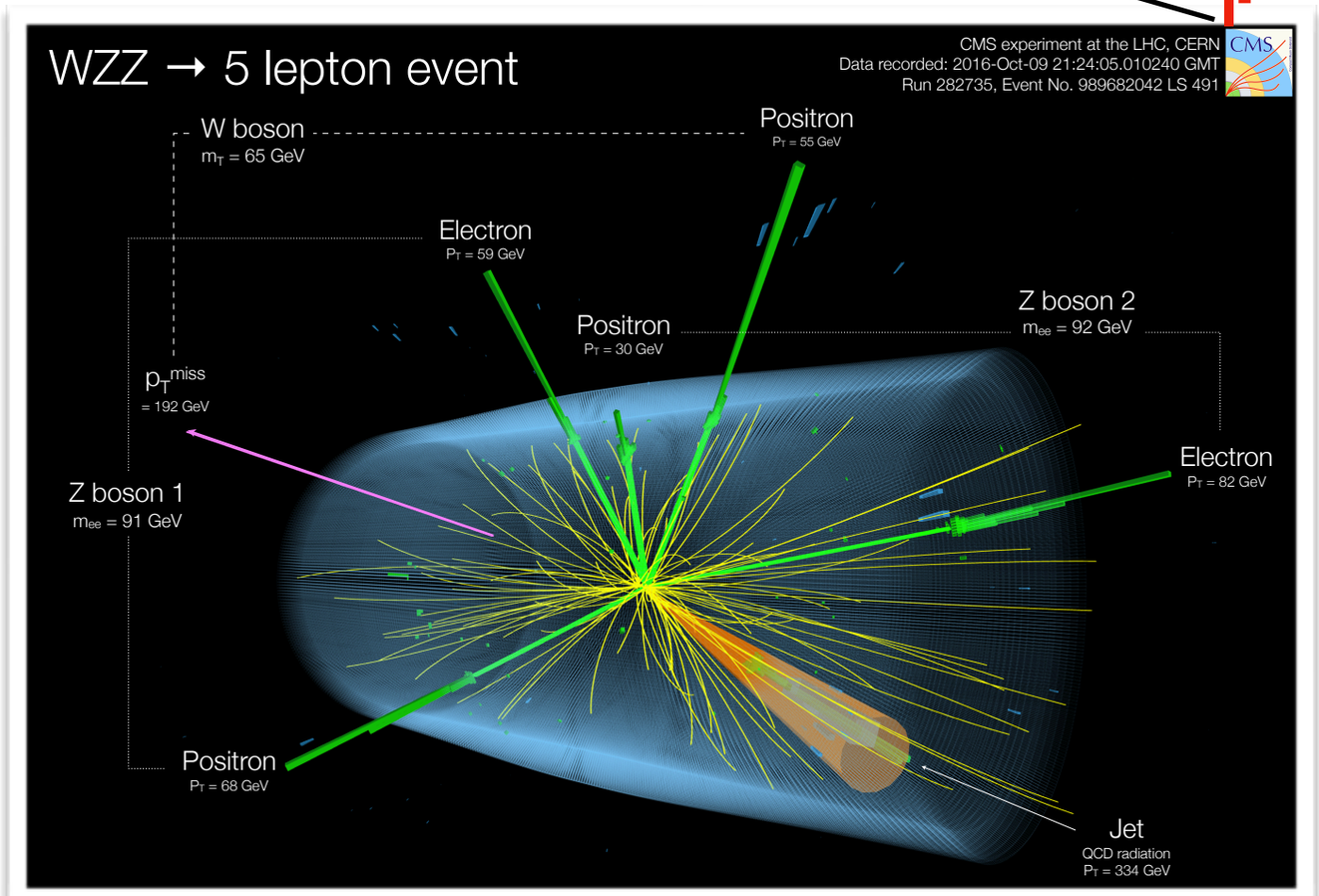


WZZ → 5 leptons and ZZZ → 6 leptons

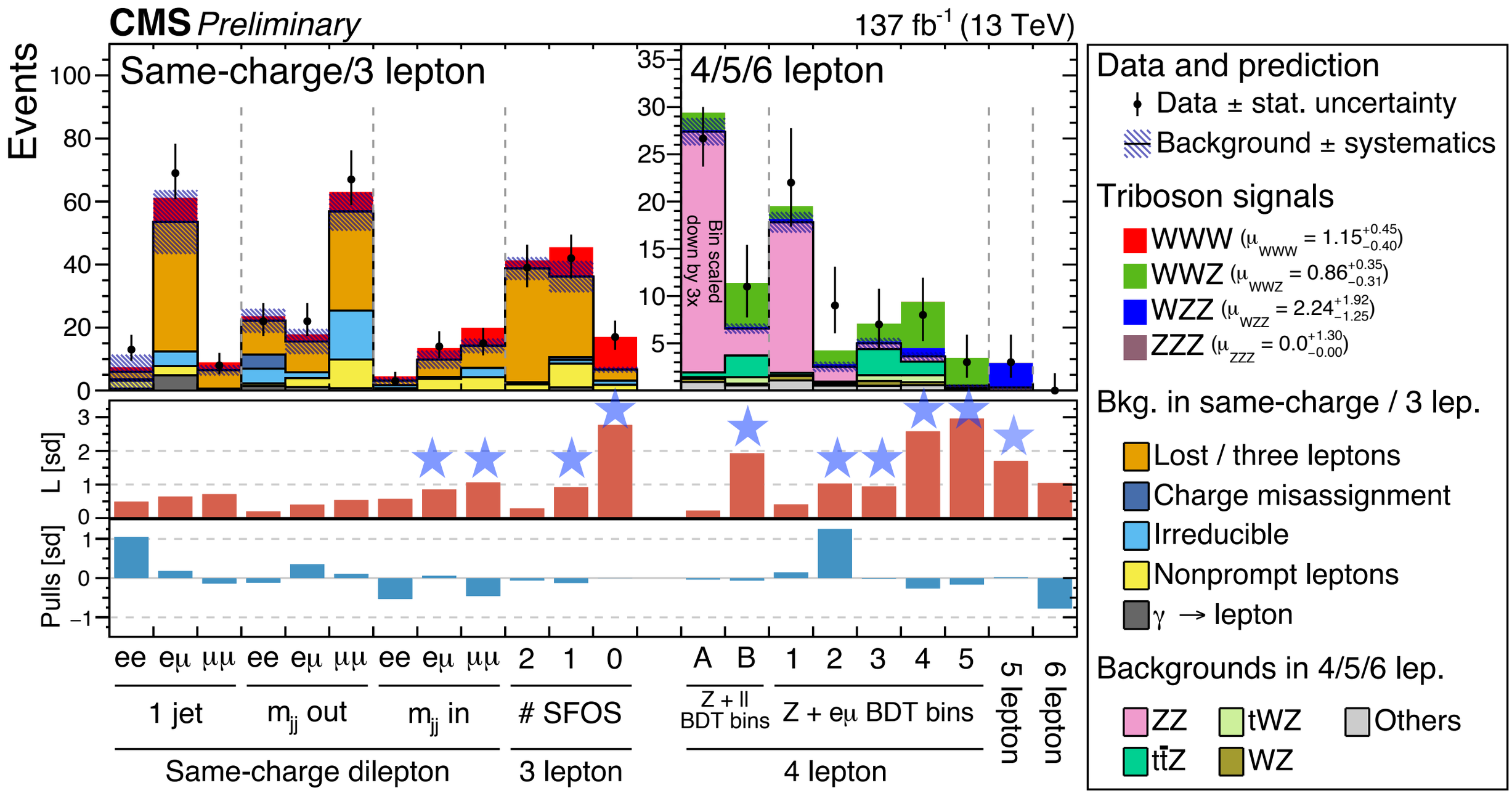
- Search for **WZZ and ZZZ in 5 and 6 lepton final** states
- **Low event yields**, backgrounds dominated by nonprompt leptons: cut based analysis pursued
- **In 5 lepton channel**: Require 2 Z boson candidates and associate remaining lepton with a W (require M_T > 50 GeV if electron)
- **In 6 lepton channel:** Require $\sum p_T$ of all leptons > 250 GeV, powerful against backgrounds, contribute at percent level







Results

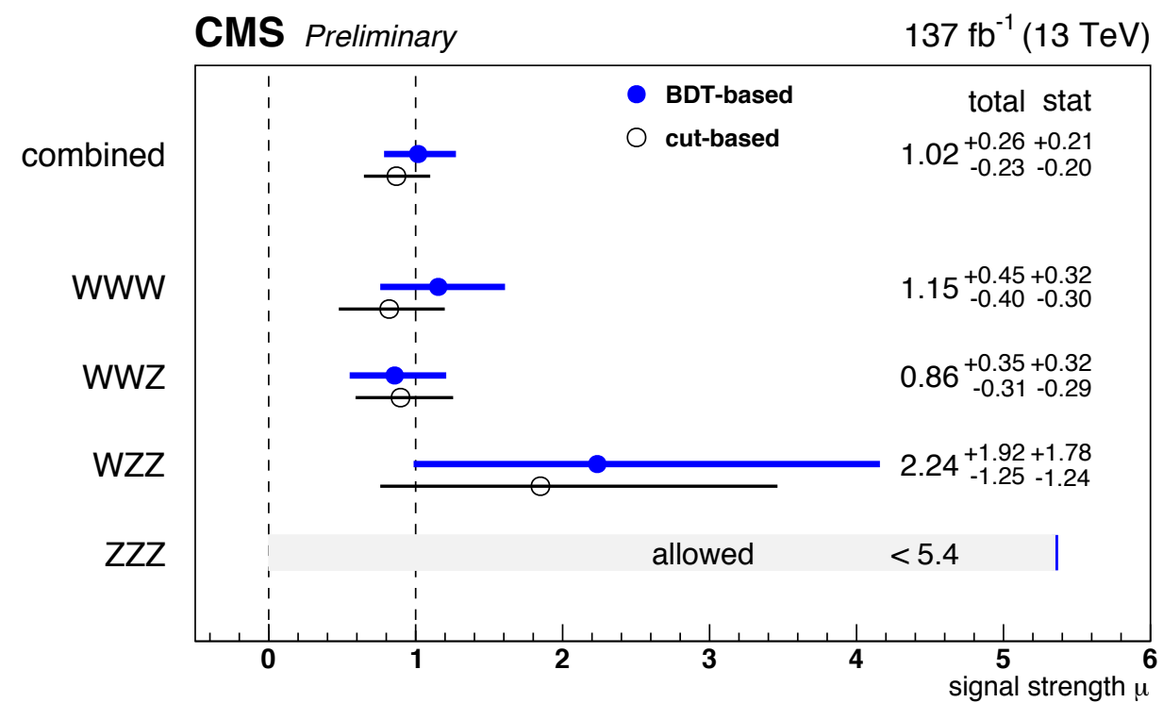


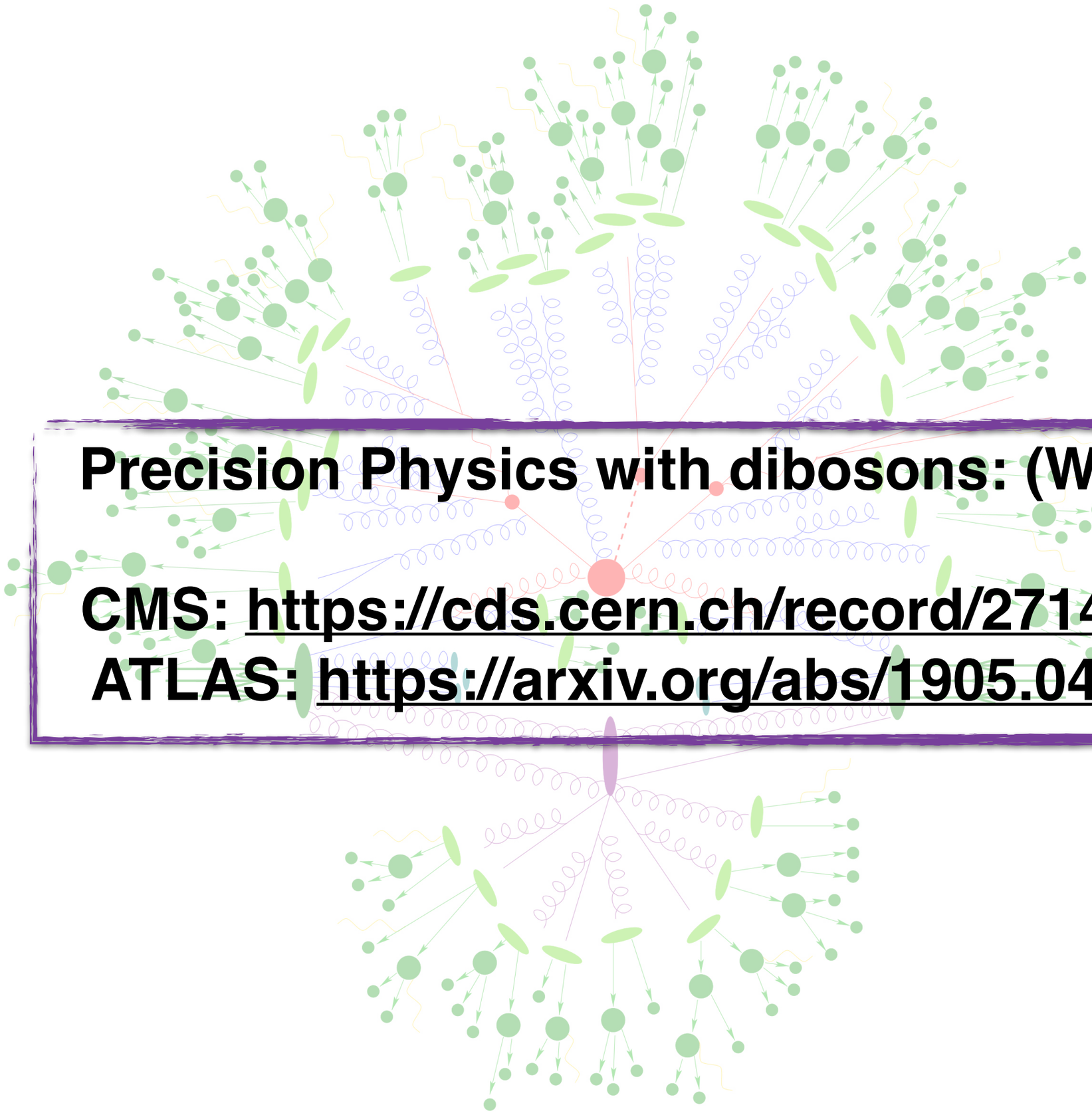
In the most sensitive signal regions (★) non-VH signal dominates with a 66% probability (33% VH)

Results

- Triboson (VVV) production **observed for the first time!**
- Observed significance for **WWW and WWZ at 3.3 σ and 3.4 σ**

Process	Observed (expected) significance
WWW	**3.3** (3.1)
WWZ	**3.4** (4.1)
WZZ	**1.7** (0.7)
ZZZ	**0.0** (0.9)
Combined	**5.7** (5.9)



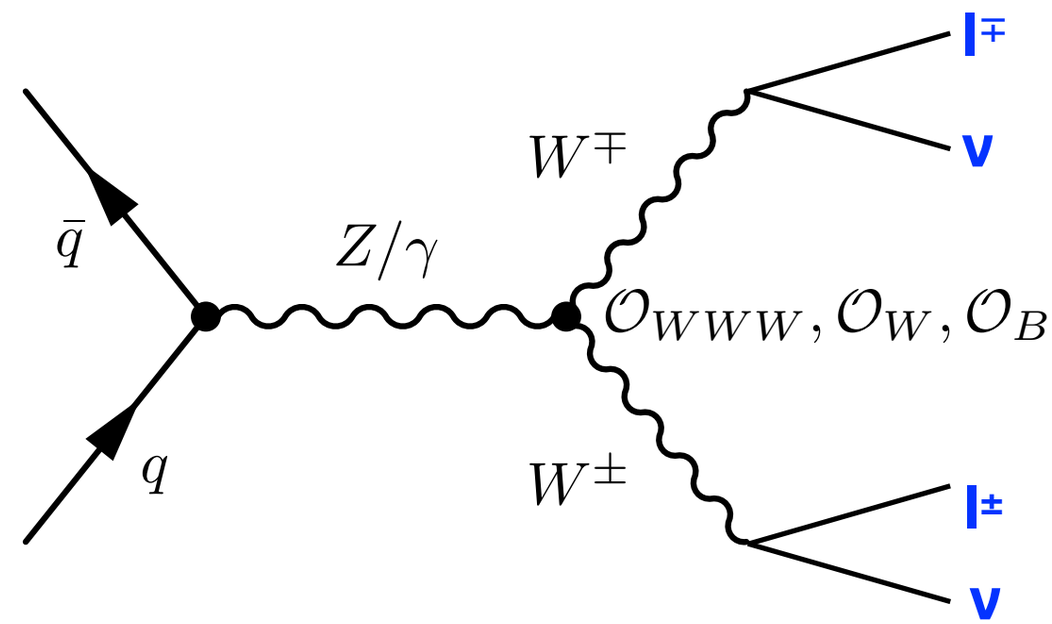


Precision Physics with dibosons: (W^+W^-)

CMS: https://cds.cern.ch/record/2714766
ATLAS: https://arxiv.org/abs/1905.04242

Precision Physics with Multibosons (W^+W^-)

- Diboson production, **W^+W^-**, occurs at the LHC via **s-channel, t-channel (dominant)**, sub-dominant $gg \rightarrow W^+W^-$
- Allows for **precise tests of the SM**
- Important **background** in many **New Physics (NP) searches**
- **Pursued in both CMS and ATLAS**



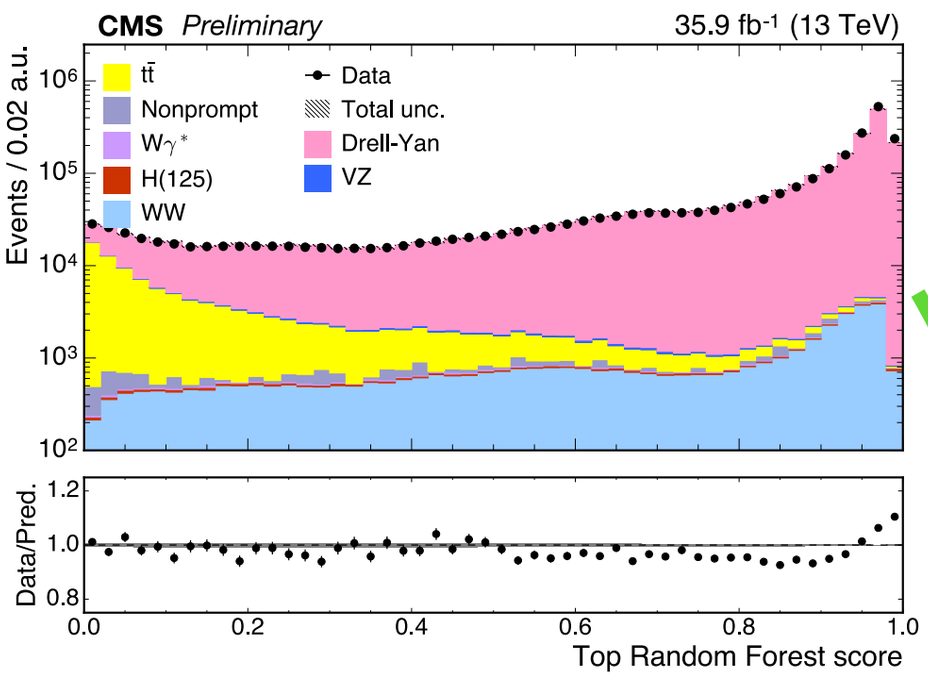
- **<u>ATLAS:</u> Cut based analysis in 0 jet bin**
- **<u>CMS:</u> Two different complementary search strategies** designed to reduce top and Drell-Yan backgrounds explored:
  - **sequential cut based analysis (in 0 and 1 jet bins)**
  - **Random forest classifier** trained on simulated events (incl. $n_{jet} \geq 2$)

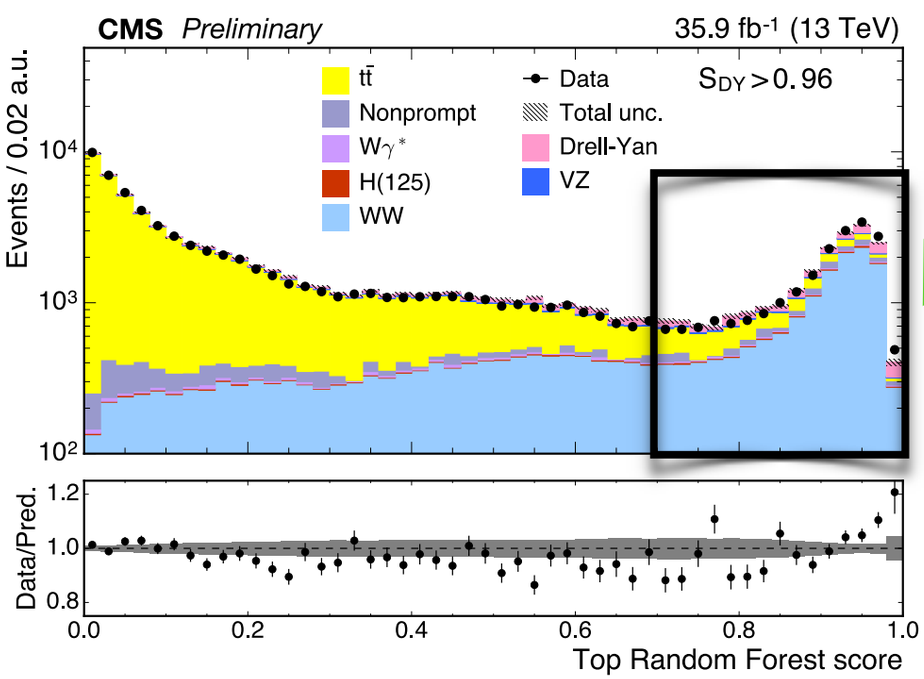
s-channel process could acquire contributions from higher dimensional operators

Analysis performed in oppositely charged leptonic final state

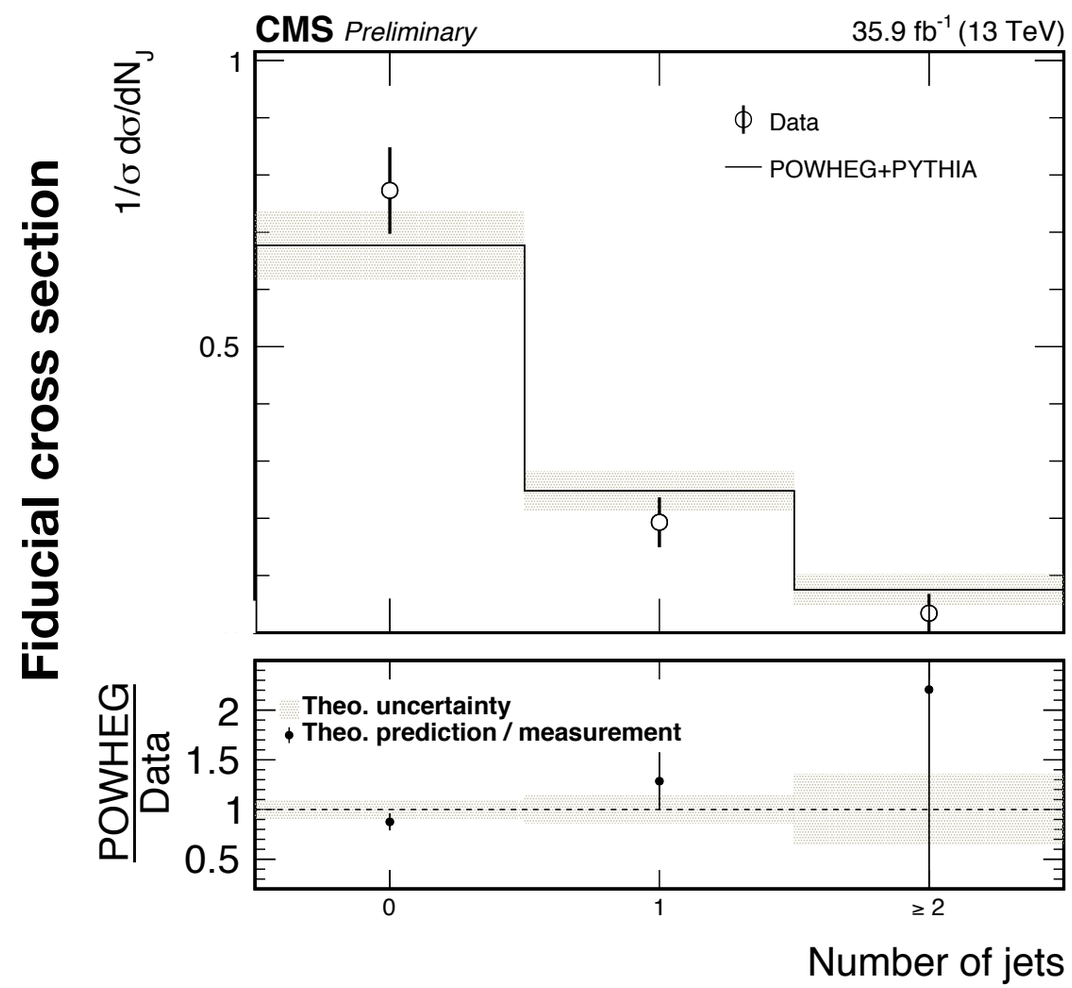
Higgs → W^+W^- considered:
- background (CMS)
- signal (ATLAS)

Using the Random Forest Discriminator





- Background contributions reduced by using novel method:
  - **Random Forest discriminator**
- Independently trained **collection of binary decision trees**
- Score defined as combination of **decisions of each tree**
- **Uses all jet categories**



Systematic Uncertainties

Theoretical Uncertainties

- Event selection in jet binned category (**cut based analysis**): sensitive to higher order QCD corrections
- Ascertained by varying factorization and renormalization scales (in some cases pT- resummation technique used)
- Additional theoretical uncertainties arise from α_s, PDFs

Total cross section:

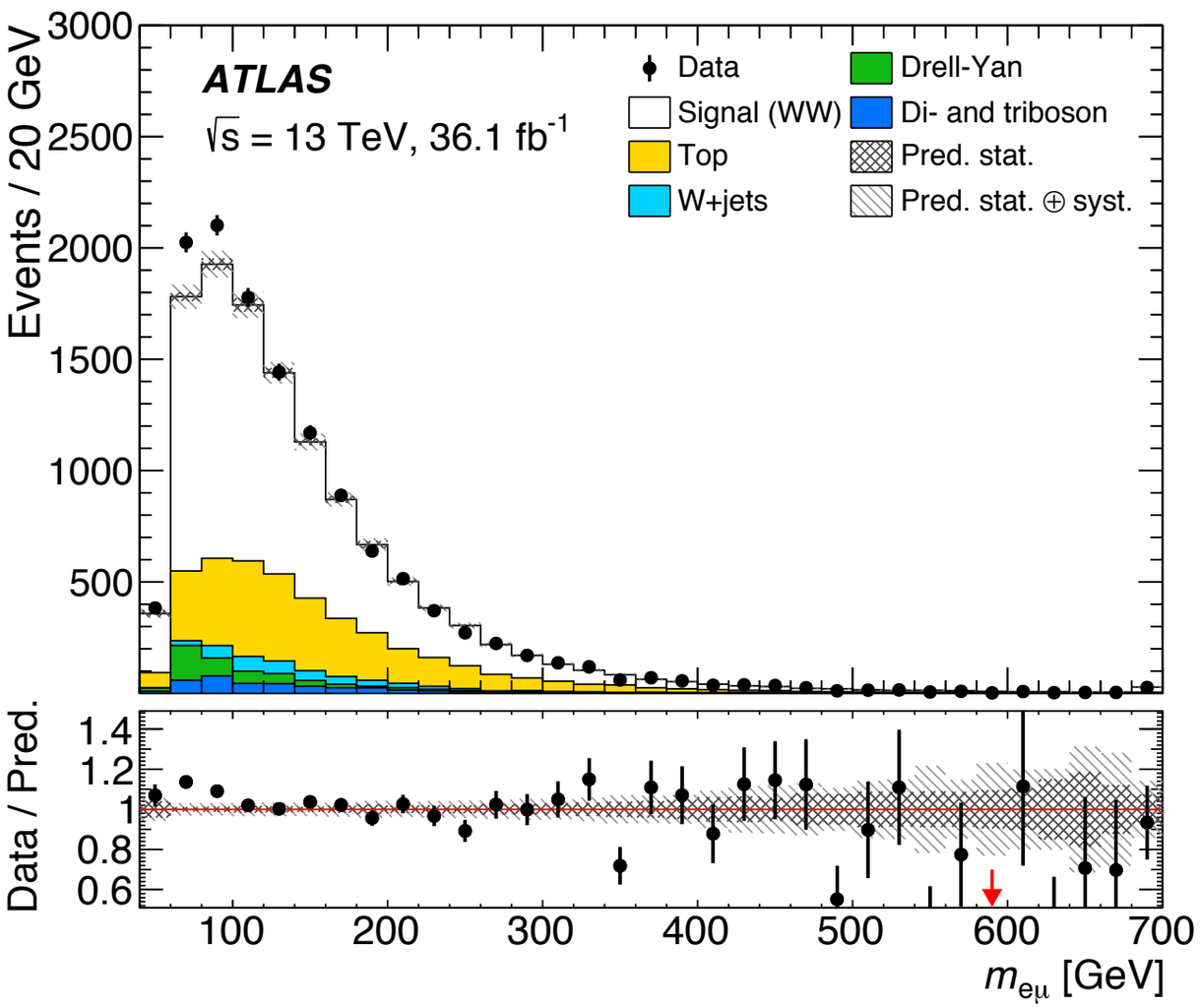
σ = 117.6 ± 1.4 (stat) ± 5.5 (syst) ± 1.9 (theo) ± 3.2 (lumi) pb

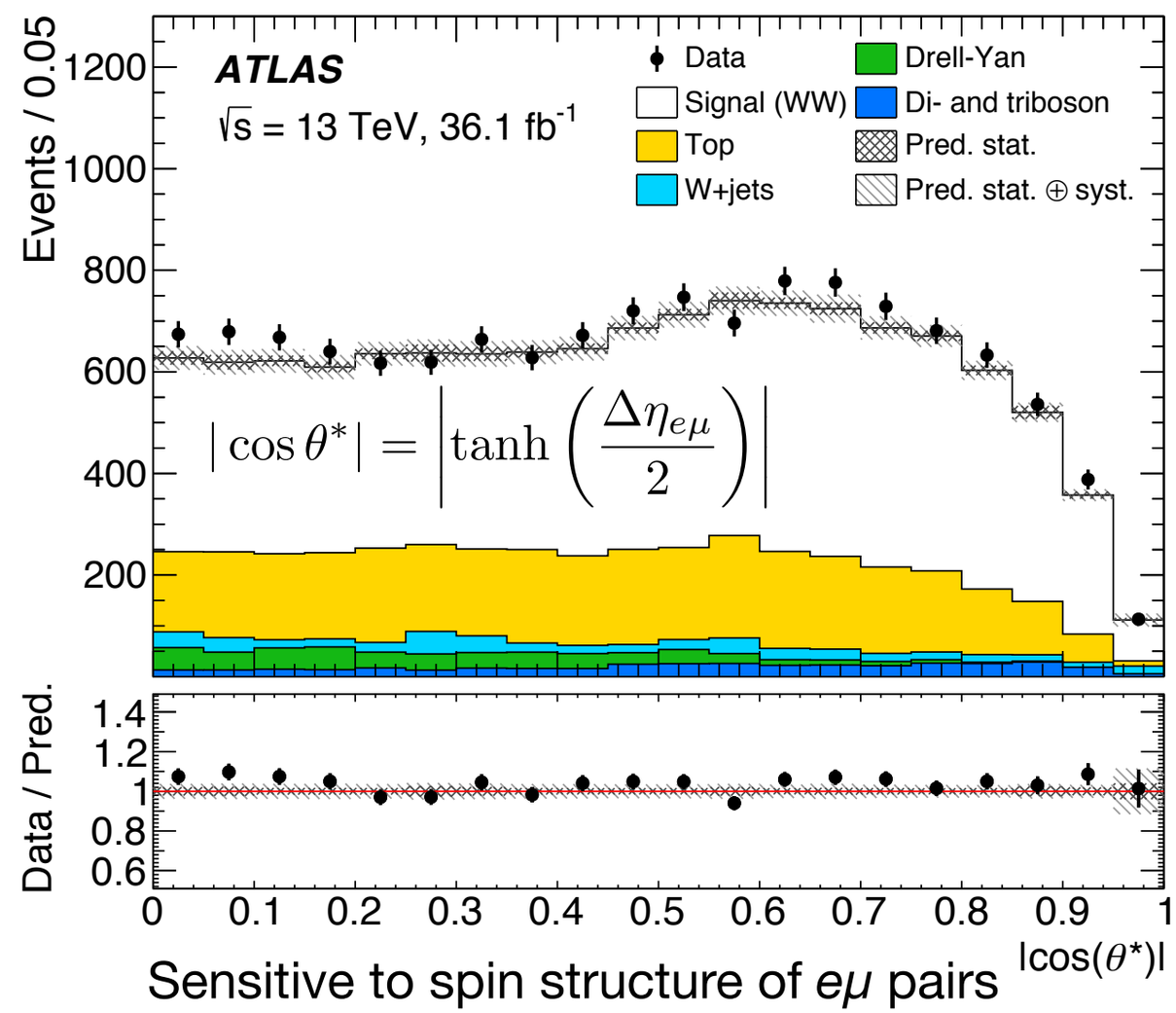
σ_{NNLO} = 118.7 + 3.0 -2.6 pb

Uncertainty source	(%)
Statistical uncertainty	1.2
$t\bar{t}$ normalization	2.0
Drell-Yan normalization	1.4
$W\gamma^*$ normalization	0.4
Nonprompt leptons normalization	1.9
Lepton efficiencies	2.1
b-tagging (b/c)	0.4
b-tagging (light)	1.0
Jet energy scale and resolution	2.3
Pileup	0.4
Simulation and data control regions sample size	1.0
Total experimental systematic uncertainty	4.6
QCD factorization and renormalization scales	0.4
Higher-order QCD corrections and p_T^{WW} distribution	1.4
PDFs	0.4
Underlying event modeling	0.5
Total theoretical systematic uncertainty	1.6
Luminosity	2.7
Total uncertainty	5.7

Precision Physics with Multibosons (W^+W^-)

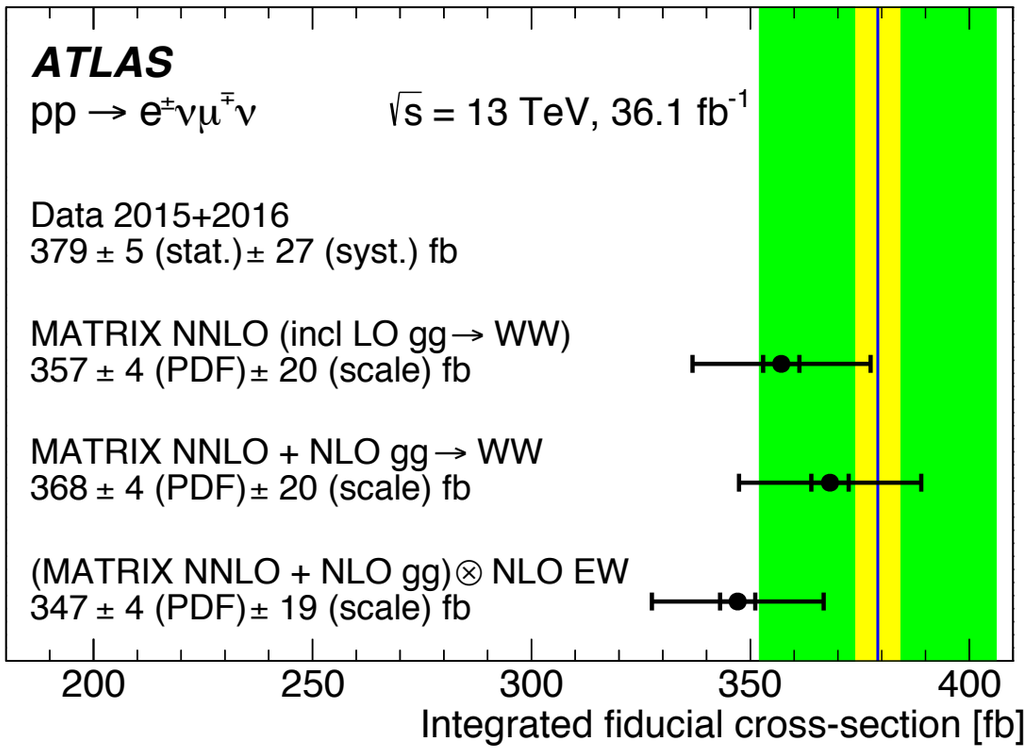
- $W^{\pm}W^{\mp} \rightarrow e^{\pm}\nu\mu^{\mp}\nu$ decay studied, with jet vet, includes b-veto
- Fiducial cross section computed (definition on slide 19)





Sensitive to spin structure of $e\mu$ pairs

Systematic Uncertainties



Total cross section:

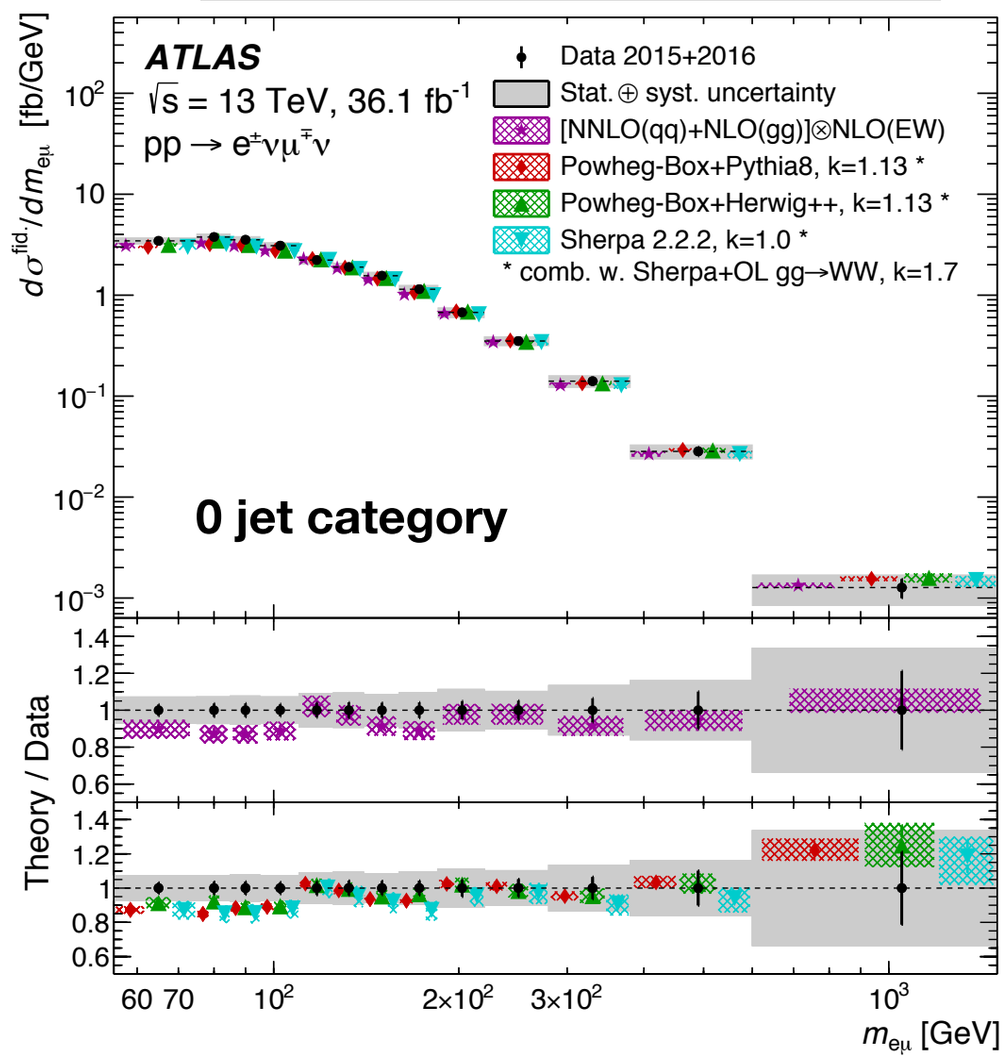
σ_{fid} = 379.1 ± 5.0 (stat) ± 25.4 (syst) ± 8.0 (lumi) fb

Systematic uncertainties associated with fiducial cross section:

Uncertainty source	Uncertainty [%]
Electron	0.7
Muon	0.9
Jets	3.0
b-tagging	3.4
$E_{\mathrm{T}}^{\mathrm{miss,track}}$	0.4
Pile-up	1.6
W+jets background modelling	3.1
Top-quark background modelling	2.6
Other background modelling	1.3
Unfolding, incl. signal MC stat. uncertainty	1.4
PDF+scale	0.1
Systematic uncertainty	6.7
Statistical uncertainty	1.3
Luminosity uncertainty	2.1
Total uncertainty	7.1

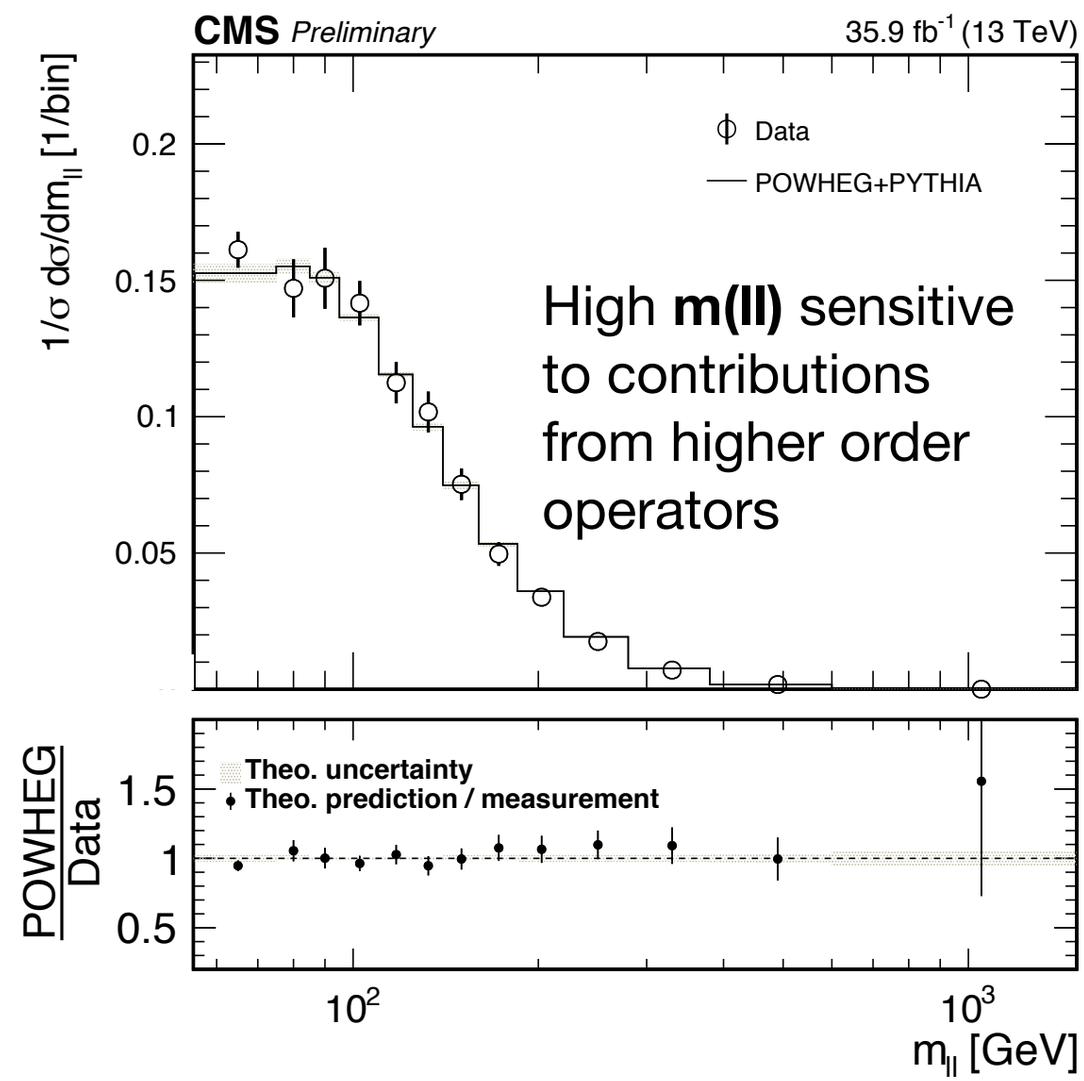
Differential cross sections

Fiducial selection requirements		
p_T^{ℓ}	>	27 GeV
$\lvert\eta^{\ell}\rvert$	<	2.5
$m_{e\mu}$	>	55 GeV
$p_T^{e\mu}$	>	30 GeV
E_T^{miss}	>	20 GeV
No jets with p_T	>	35 GeV, $\lvert\eta\rvert < 4.5$



Fiducial cross section computed in:

m(ll) > 20 GeV, p_T(ll) > 30 GeV and p_T(miss) > 20 GeV



EFT Interpretation

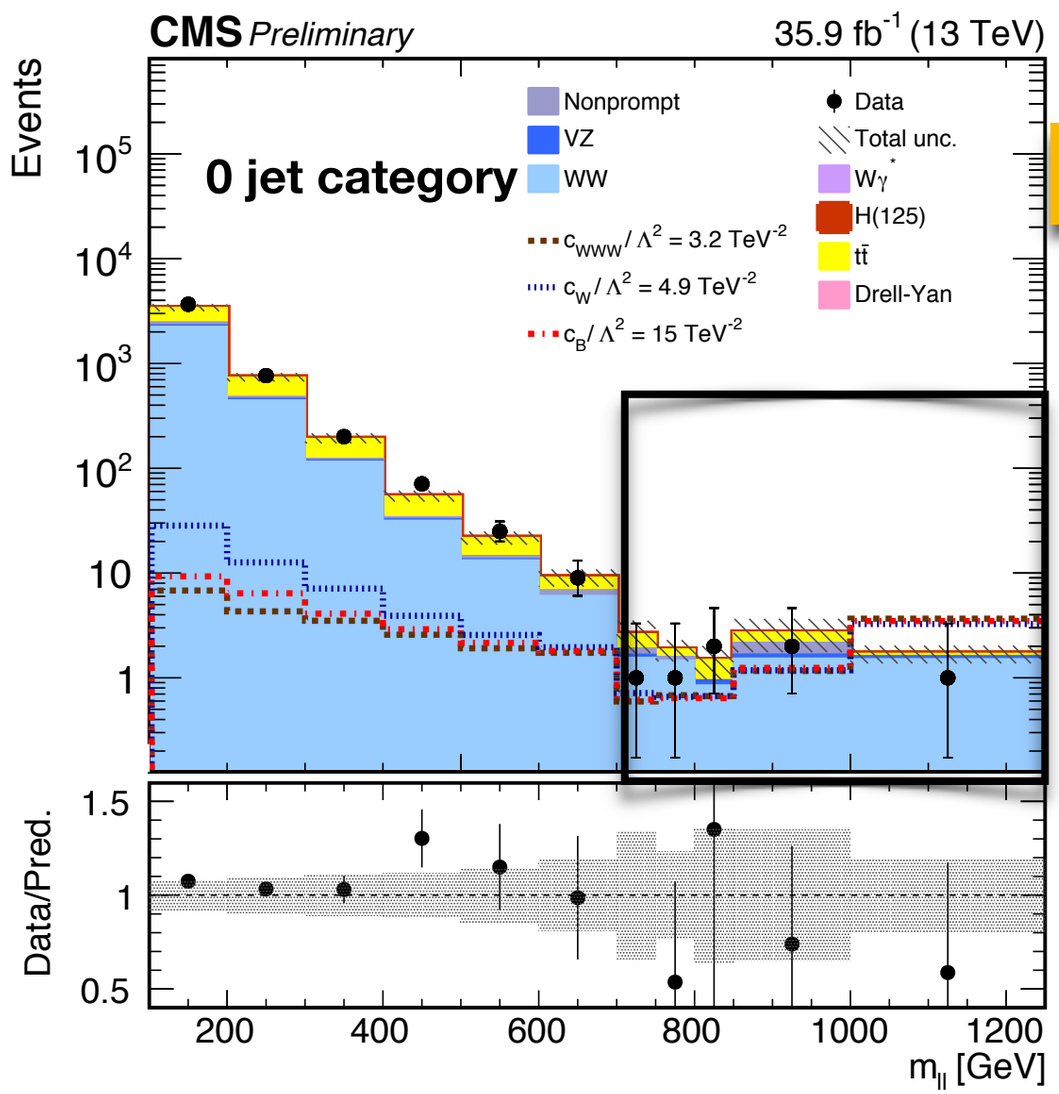
- **Limits set on Wilson coefficients associated with CP conserving operators:**

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]$$

$$\mathcal{O}_W = (\mathcal{D}_\mu\Phi)^\dagger W^{\mu\nu}(\mathcal{D}_\nu\Phi) \qquad \mathcal{O}_B = (\mathcal{D}_\mu\Phi)^\dagger B^{\mu\nu}(\mathcal{D}_\nu\Phi)$$

CP conserving

CP non-conserving



ATLAS

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

CMS

Coefficients (TeV^{-2})	68% CL interval		95% CL interval	
	expected	observed	expected	observed
c_{WWW}/Λ^2	$[-1.78, 1.82]$	$[-0.93, 0.99]$	$[-2.67, 2.71]$	$[-1.78, 1.84]$
c_W/Λ^2	$[-3.67, 2.68]$	$[-2.03, 1.33]$	$[-5.28, 4.22]$	$[-3.56, 2.78]$
c_B/Λ^2	$[-9.45, 8.40]$	$[-5.14, 4.30]$	$[-13.9, 12.8]$	$[-9.35, 8.46]$

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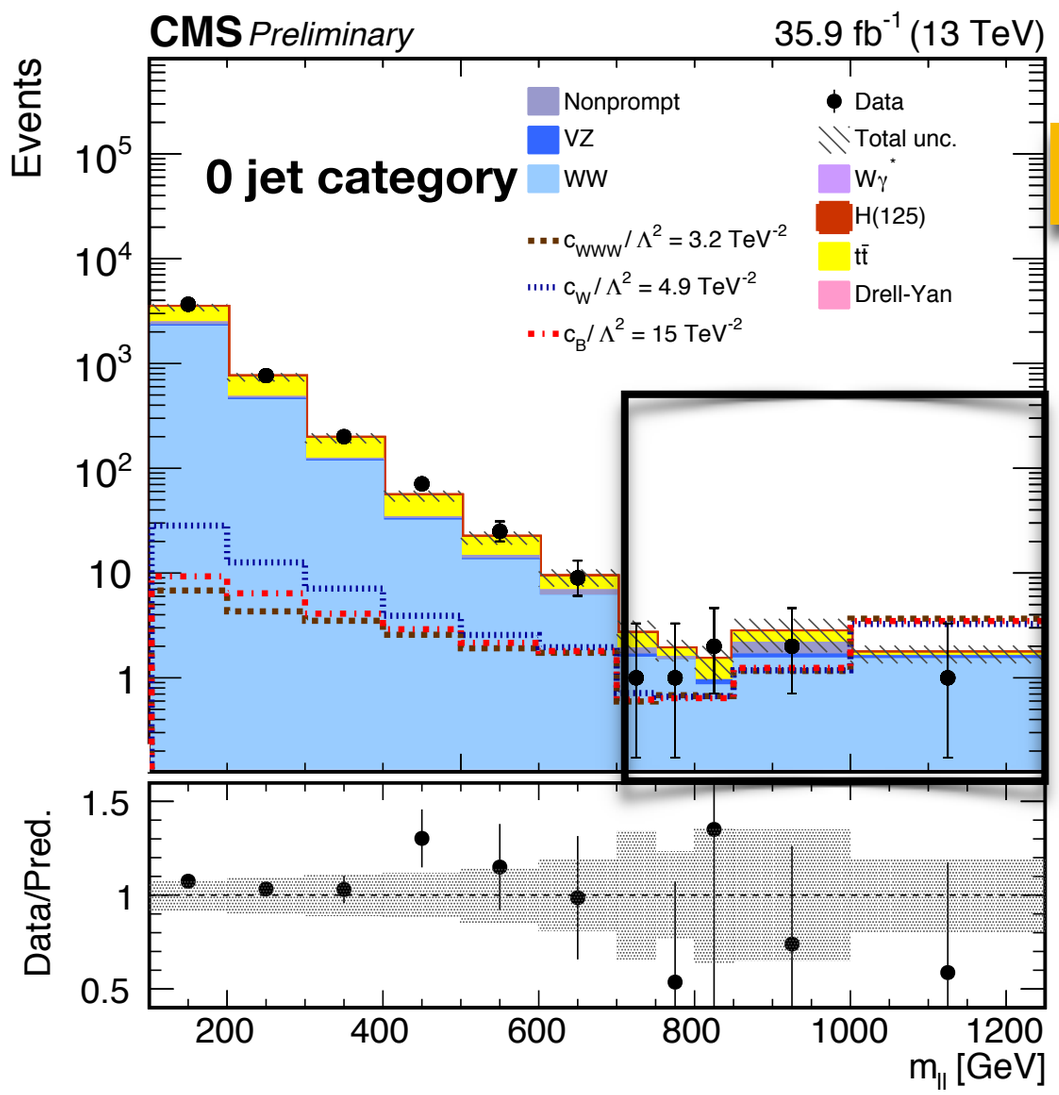
CP conserving

CP non-conserving



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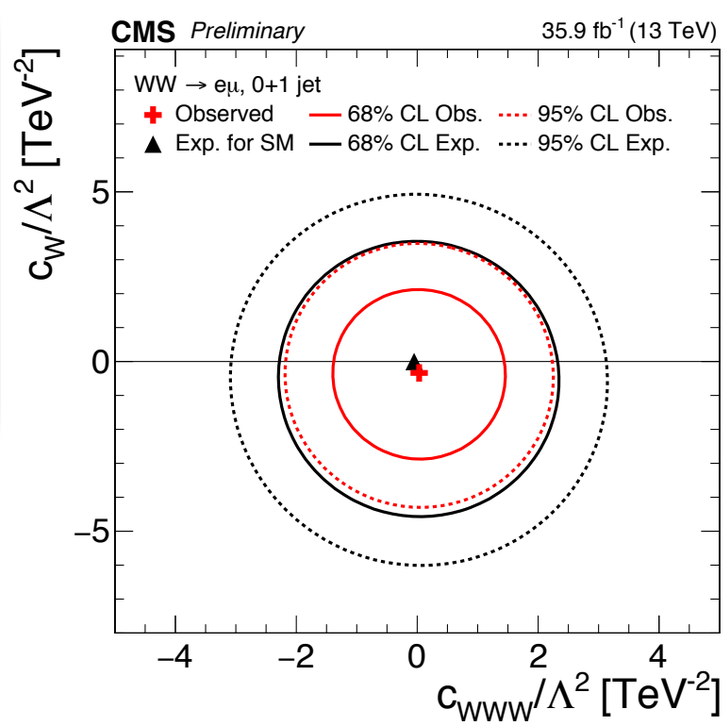
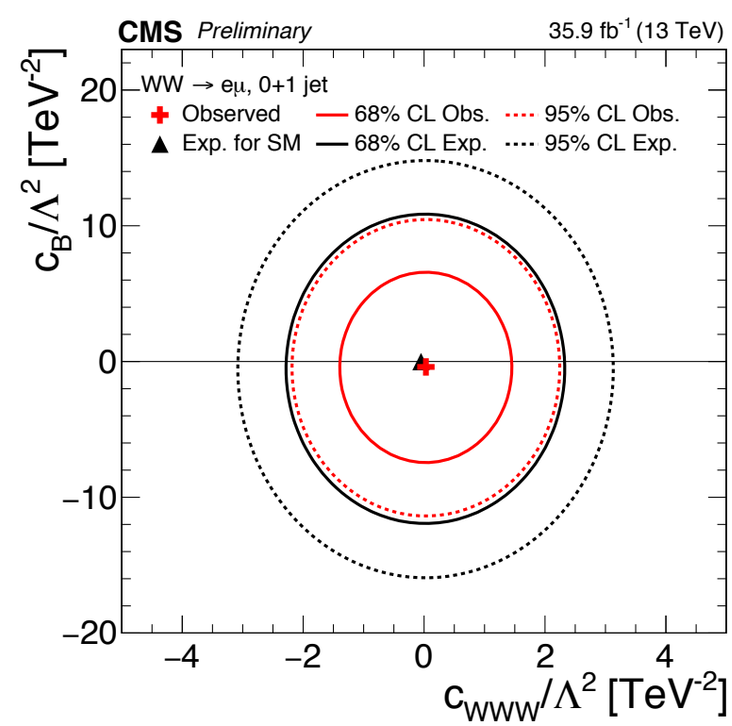
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]



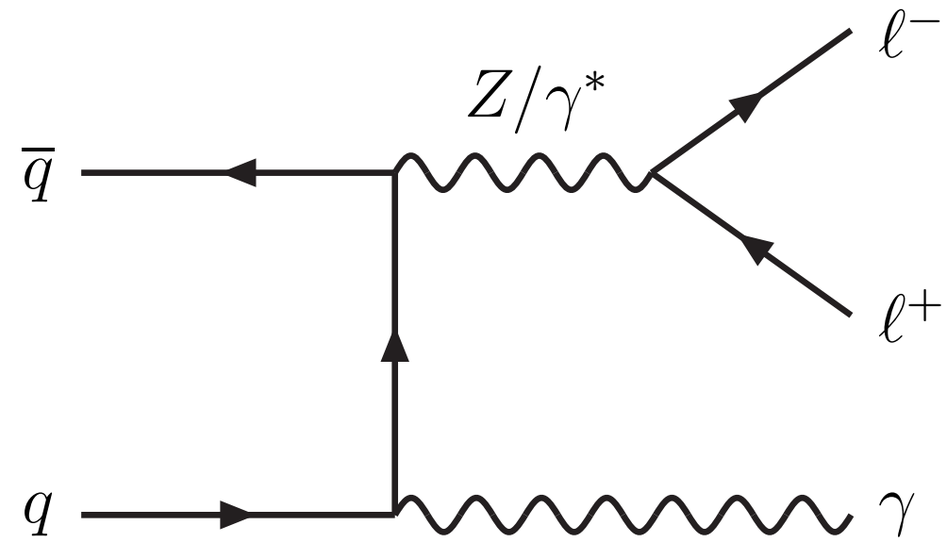


Precision Physics with dibosons: (Zγ)

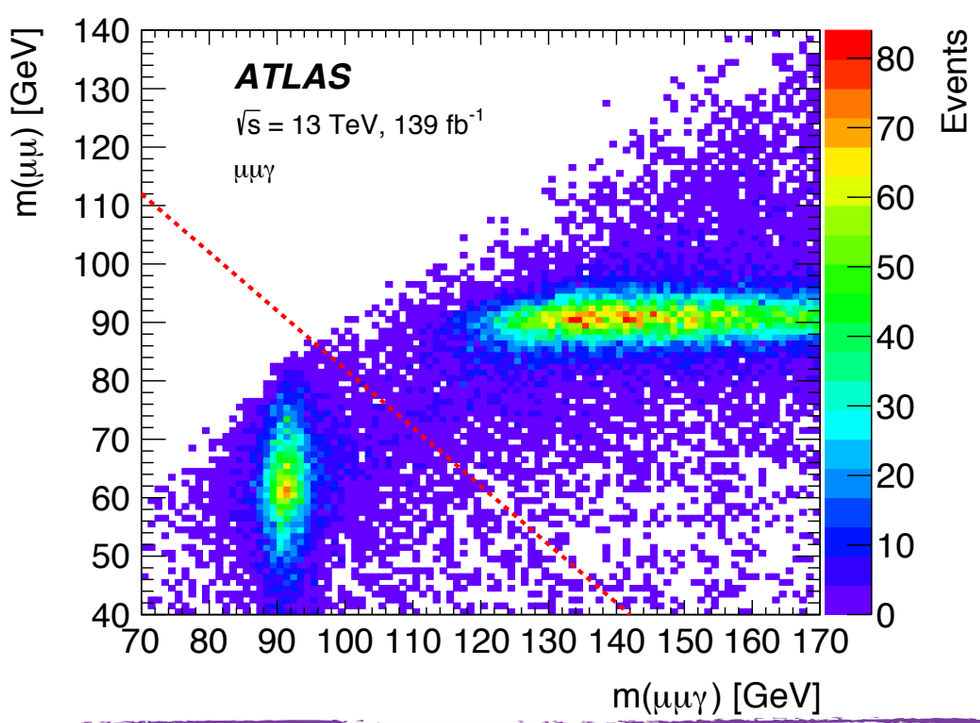
ATLAS: https://arxiv.org/abs/1911.04813

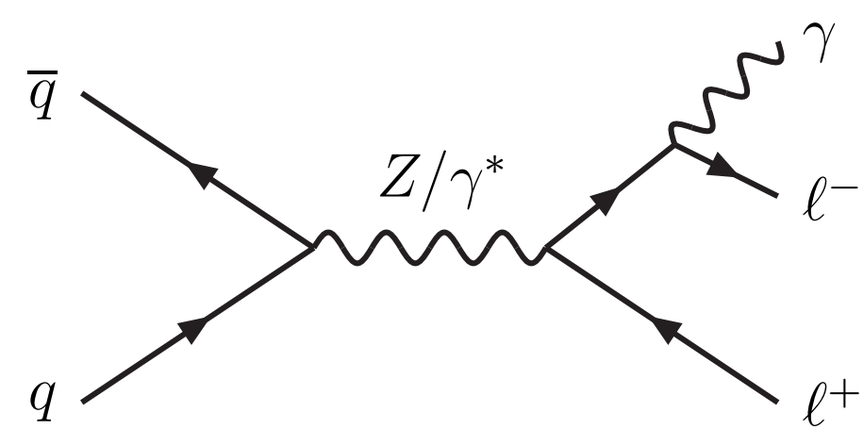
Precision Physics with Multibosons: Zγ

- **Production of Z in association with a photon (γ)** offers important probe of the **electroweak sector of the SM**
- **Major background** in Higgs → Zγ channel
- Previous exploration focused on large photon E_T: $Z\gamma \rightarrow \nu\nu\gamma$ ($E_T > 150$ GeV) and $Z\gamma \rightarrow bb\gamma$ ($E_T > 175$ GeV), designed to be sensitive to higher dimensional operators
- This analysis **explored an E_T range of 30-1200 GeV**
- **Photons arising from final state radiation (FSR) suppressed by requiring m(*ll*) + m(*llγ*) > 182 GeV**
- **Highly precise measurement of fiducial cross section achieved**



Signal: ISR photon

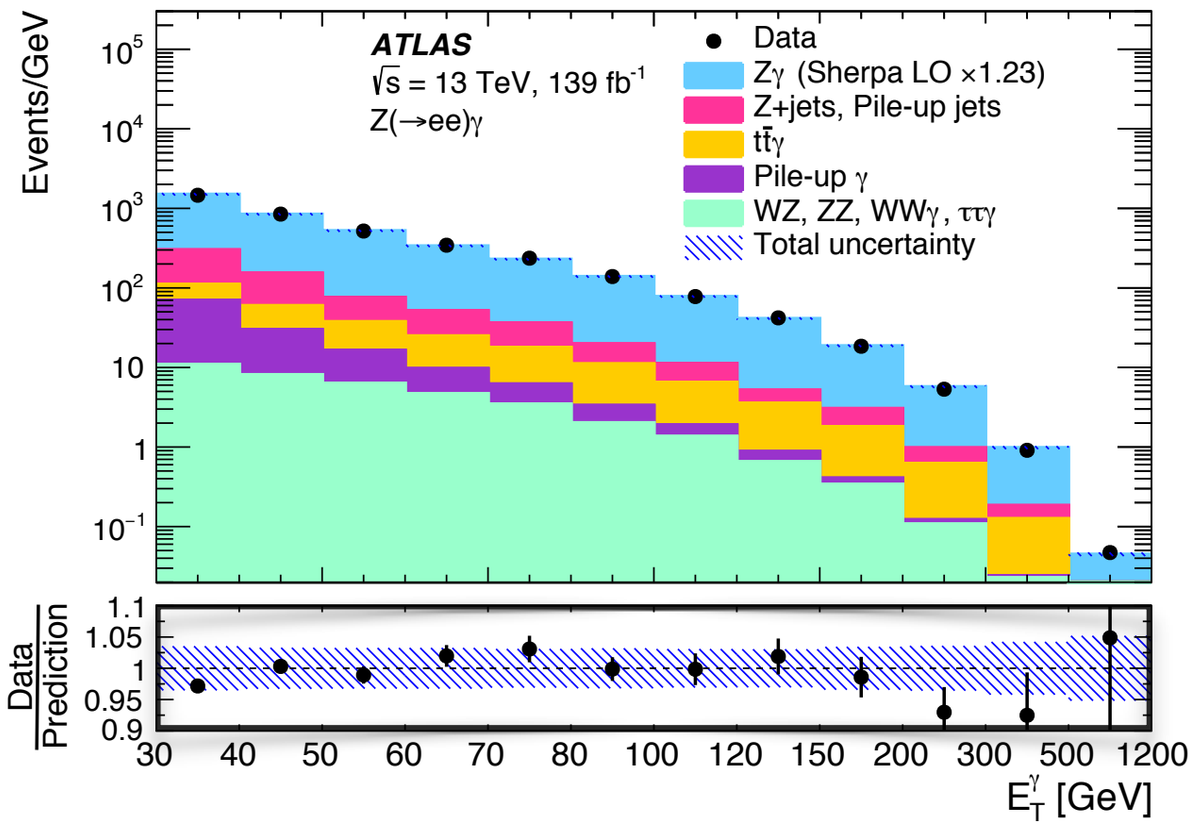


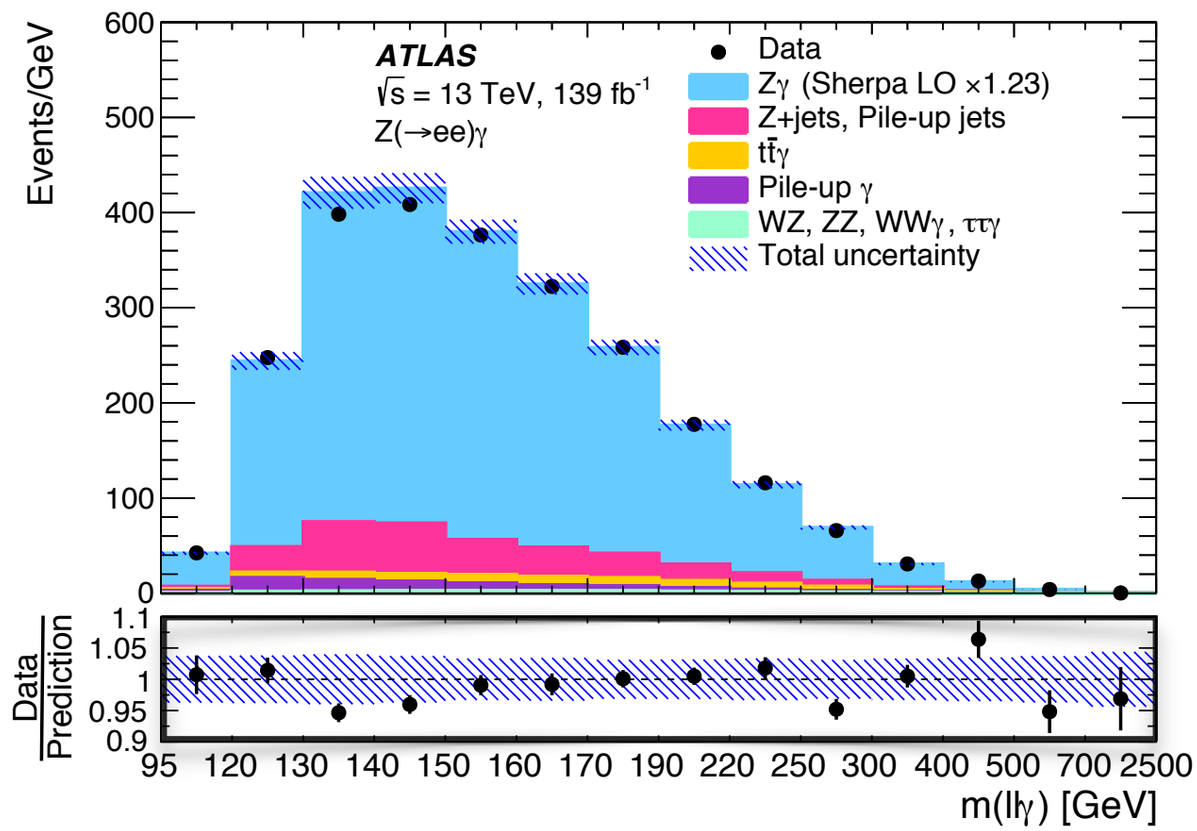


Need to suppress FSR photon

Precision Physics with Multibosons: Zγ

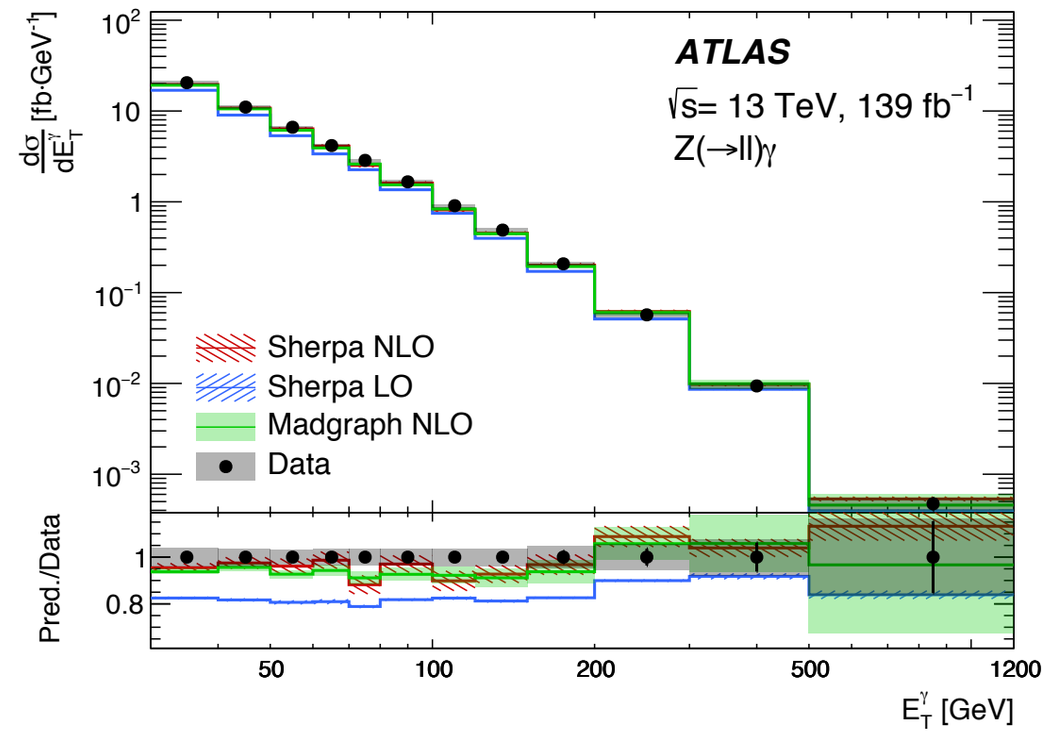
- **Z+jets** where a **jet is misidentified as a photon** constitutes the **largest background:** estimated from sidebands
- Background arising from **pileup:** photon and lepton pair from different pp collisions in one LHC bunch crossing
  - **Novel** method used to determine this background by **correlating z-coordinates of the Z and the γ**
- All other backgrounds determined from simulations

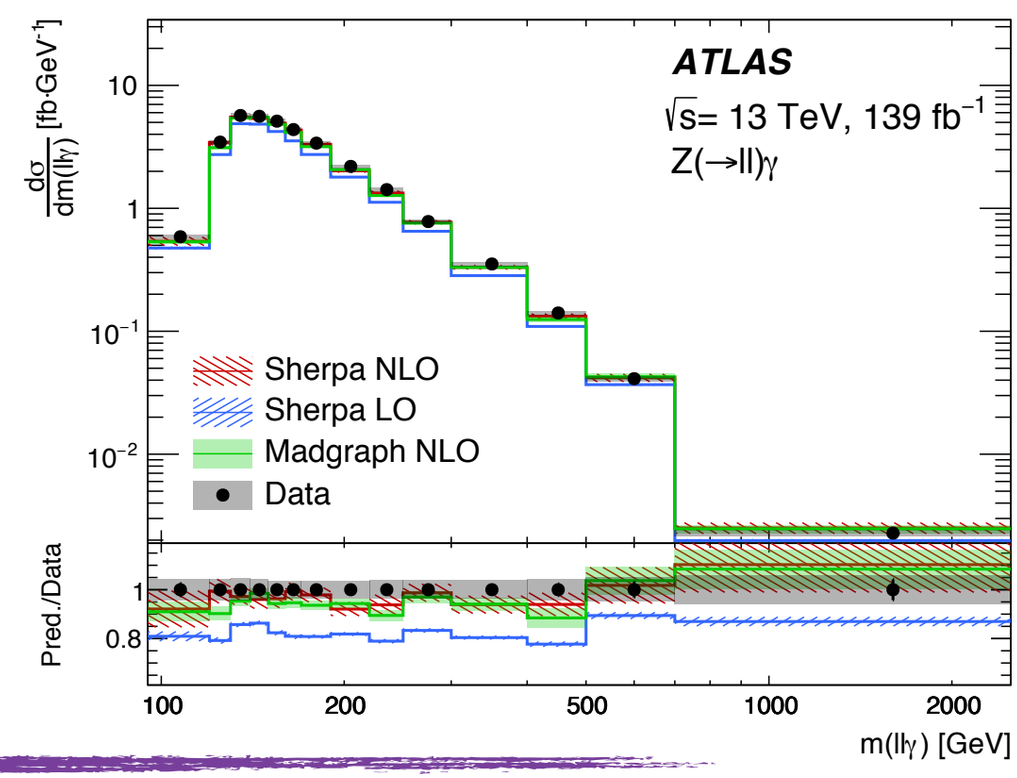




Differential cross sections

- **Relative precision of the cross section is 2.9%**
- Fiducial cross section defined by:
  - **m(*ll*) > 40 GeV**
  - **m(*ll*) + m(*llγ*) > 182 GeV**
- **Computed in bins of γ E_T, m(*llγ*), $|\eta^\gamma|$, p_T(*llγ*), p_T(*llγ*)/ m(*llγ*), ΔΦ(*ll, γ*)**
- Low systematic uncertainty, major contributors associated with:
  - photon identification (1%)
  - electron identification (1.4%)
  - Z+jets background (1.3%)
  - luminosity (1.7%)
- Total **statistical uncertainty** lower by a **factor of ~6**
- **$\sigma_{fiducial}$ = 533.7 ± 2.1 (stat) ± 12.4 (syst) ± 9.1 (lumi) fb**





Conclusion

- **Three different analysis presented** that highlight the myriad possibilities of exploration in multiboson final states
- While, **new processes being discovered**, **precision physics is being concurrently carried out:**
  - **New processes:**
    - **VVV**
  - **Precision analysis:**
    - **W^+W^-**
    - **Zγ**
- I'll be in the zoom room after the talk: https://cern.zoom.us/j/95764014445 (session password)

Full list of Standard Model analyses performed by ATLAS and CMS Collaborations can be found here:

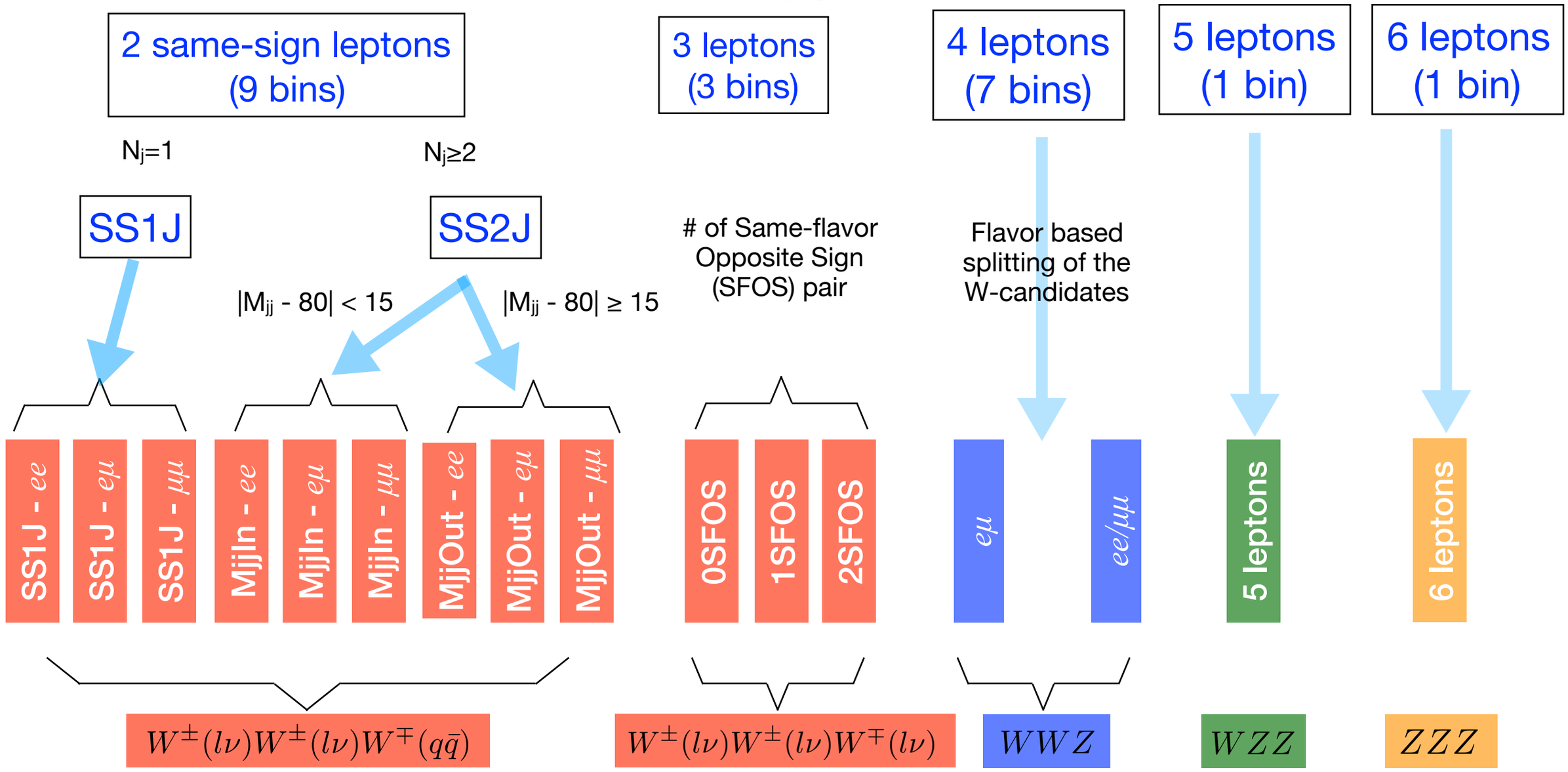
- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
- CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

Additional Material

Analysis Strategy

Probe WWW, WWZ, WZZ, ZZZ processes by counting number of leptons

21 bins in total



- **For cut-based, further split into 4 M_{T2}-M_{ll} (eμ) and 3 MET-p_T^{4l} (ee/μμ) bins**
- **For BDT, further split into 5 bins in eμ and 2 in ee/μμ**