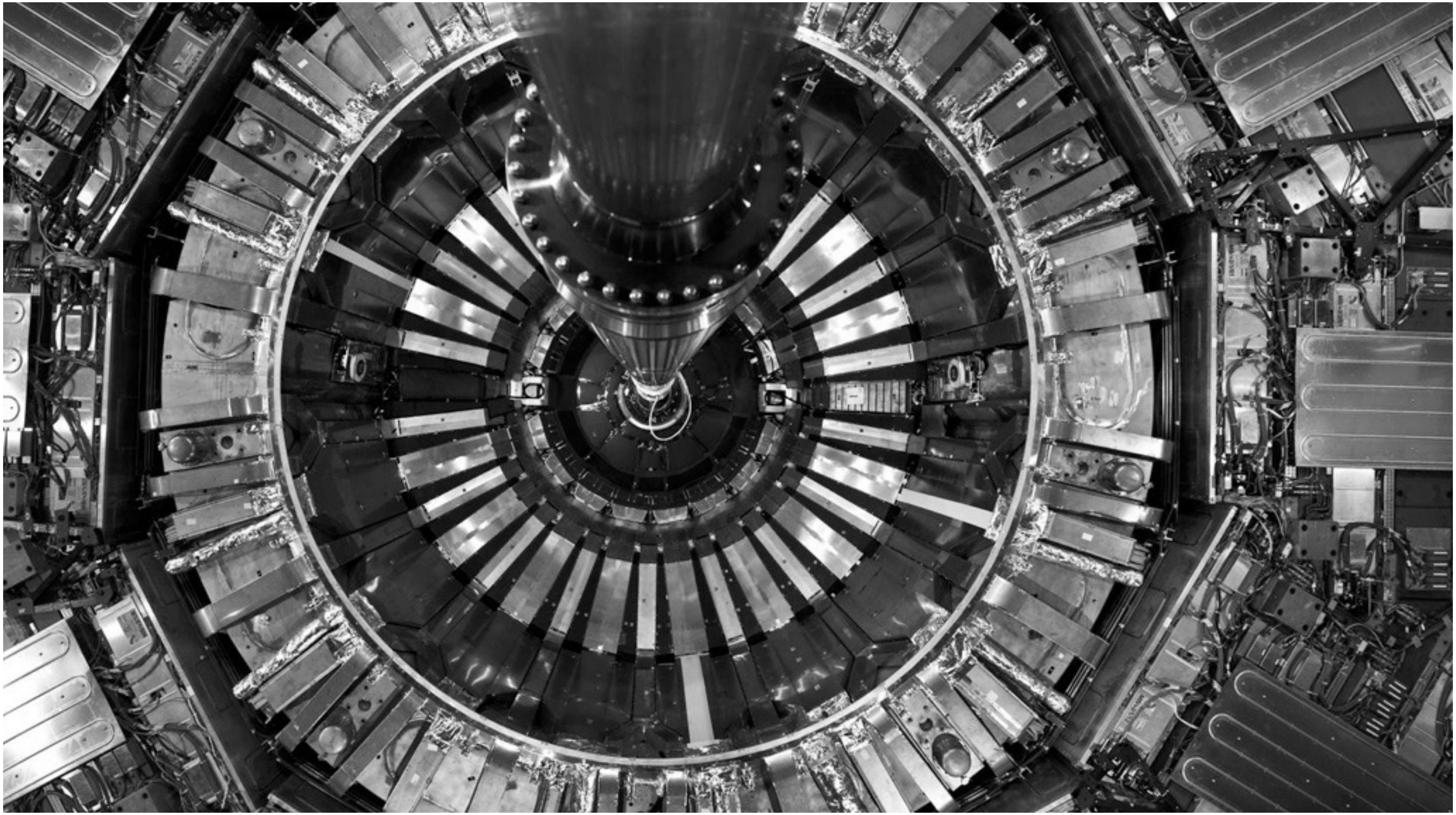
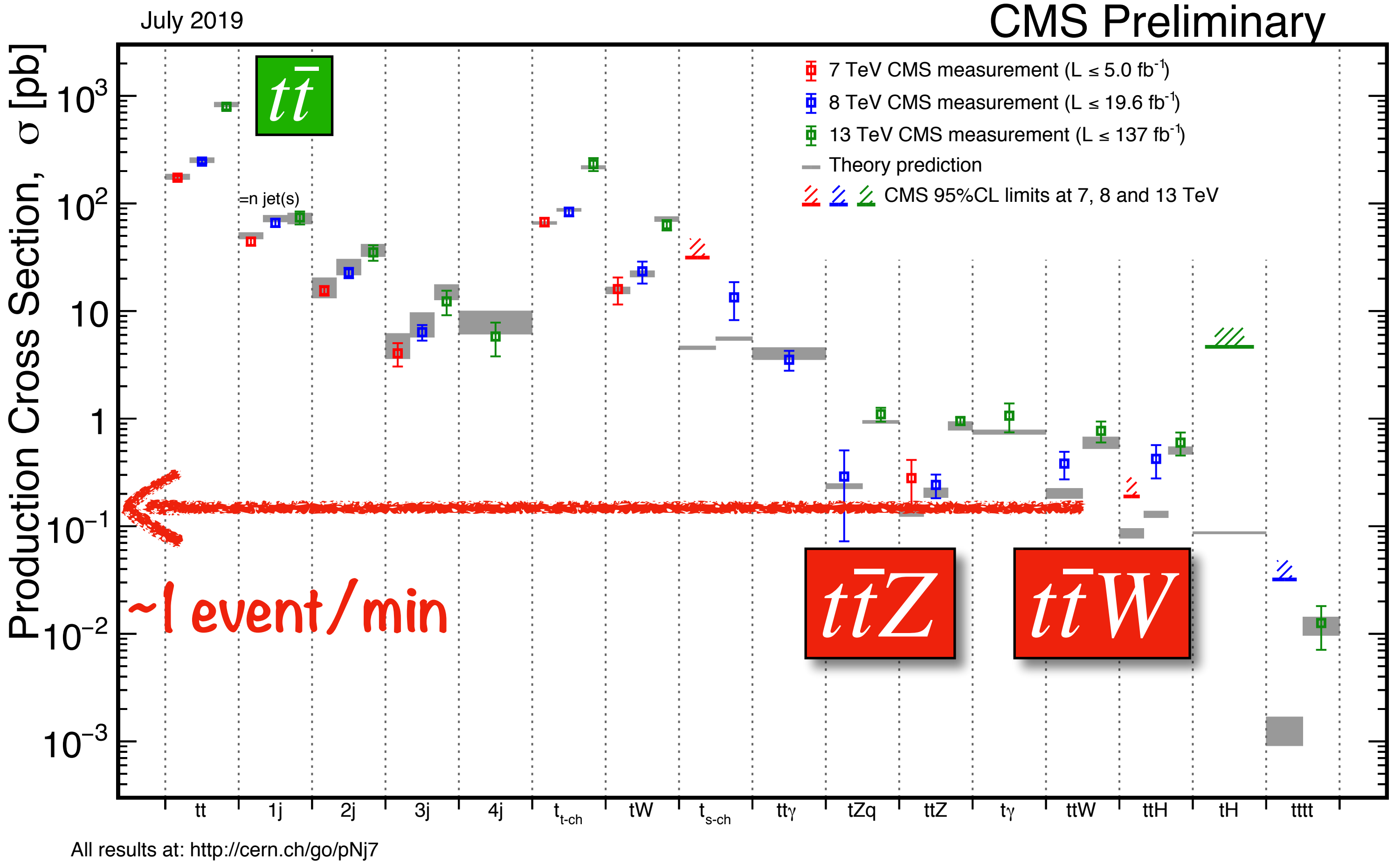
$t\bar{t} + Z/W$ in Atlas and CMS

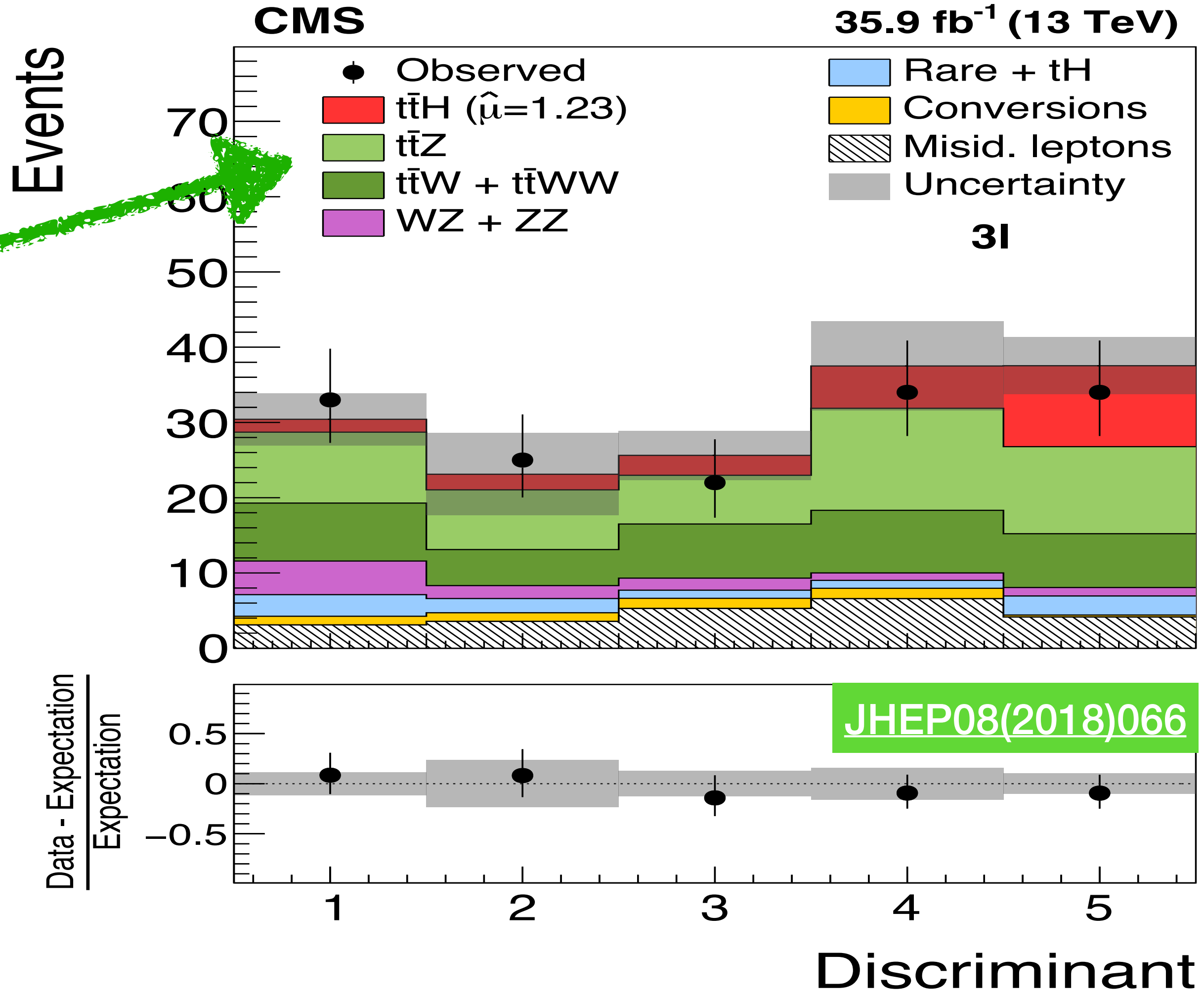


Francisco Yumiceva
Florida Institute of Technology
TOP2019, Beijing

Motivation



- Current datasets allow detail studies of the production of: $t\bar{t}+Z,\ t\bar{t}+W$
- Direct access to the *EWK coupling of the top quark* to the Z boson.
- These processes are *very sensitive to new physics*.
- ttW/Z are *important backgrounds* for $t\bar{t}H$ measurements and BSM searches
- Results presented in this talk:
  - CMS ttZ (78 fb^{-1}): arXiv:1907.11270
  - CMS ttW (36 fb^{-1}): JHEP 08(2018)011
  - Atlas ttW/Z (36 fb^{-1}): Phys. Rev. D 99 (2019) 072009

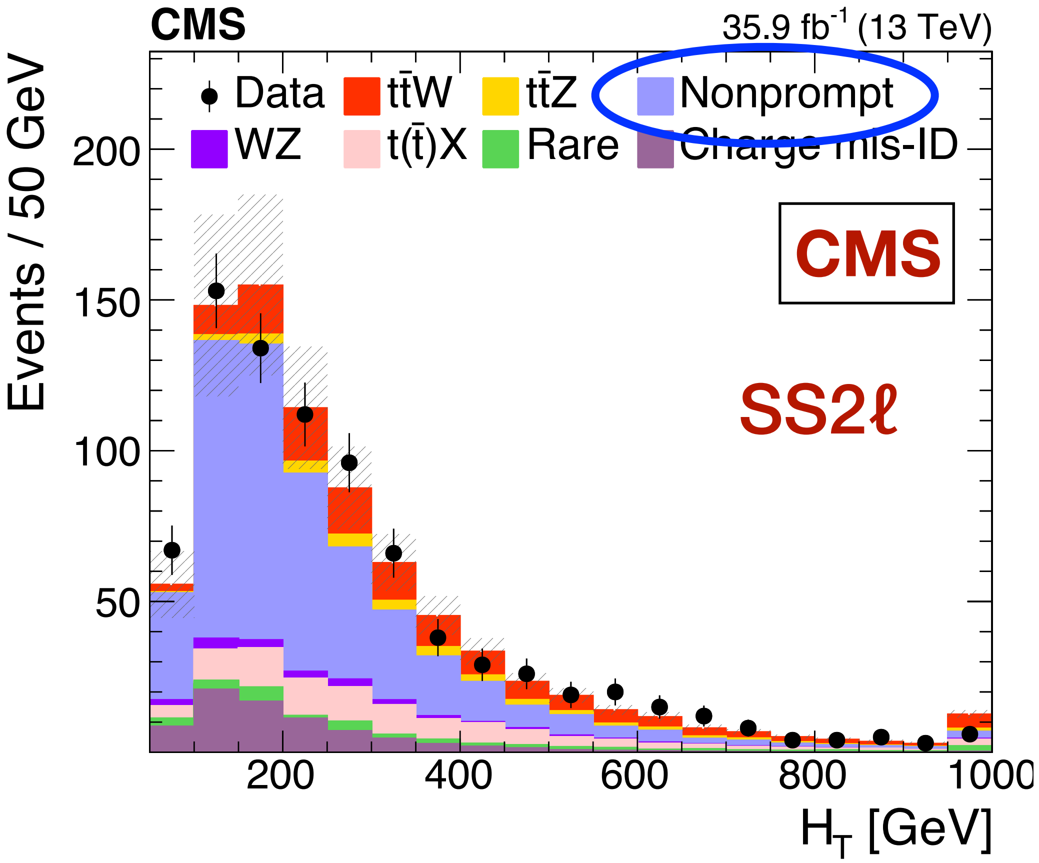


$t\bar{t}W$ and $t\bar{t}Z$ Signal Regions

Processes (ℓ=e,μ)		**Channel**	**Signal Regions**
$W \to \ell\nu$	$t\bar{t} \to \ell + j$	**SS2ℓ**	**12 (sign, flavor, N_b)**
	$t\bar{t} \to$ dileptons	**3ℓ**	**8 (sign, N_j, N_b)**
$Z \to \ell\ell$	$t\bar{t} \to$ jets	**OS2ℓ**	**4 (N_j, N_b)**
	$t\bar{t} \to \ell + j$	**3ℓ**	**8 (sign, N_j, N_b)**
	$t\bar{t} \to$ dileptons	**4ℓ**	**4 (flavor, Nj, N_b)**

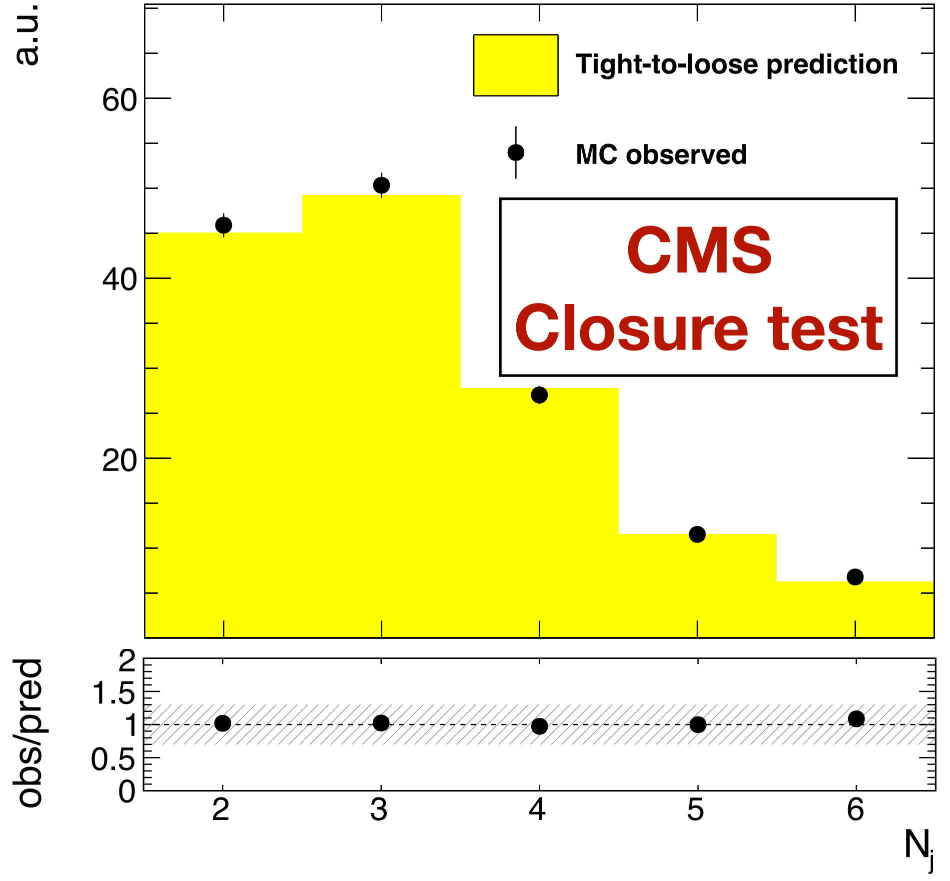
- Need good lepton (electron & muon) reconstruction and identification from soft p_T>10 GeV
- Important background from nonprompt ℓ (fake leptons) originating from hadron decays, γ conversions or misidentified jets.
- Construct MVA to increase efficiency of selecting prompt ℓ and reduce fakes.
- Use CRs enriched in multijet QCD events and apply the matrix method (tight-to-loose likelihood) to estimate nonprompt ℓ in SRs.
  - Fake rates & efficiencies parametrized as a function of ℓ p_T and η.
  - CMS compute probabilities using a *corrected* p_T for the energy in the lepton isolation cone.

Nonprompt Lepton Background



CMS

SS2ℓ



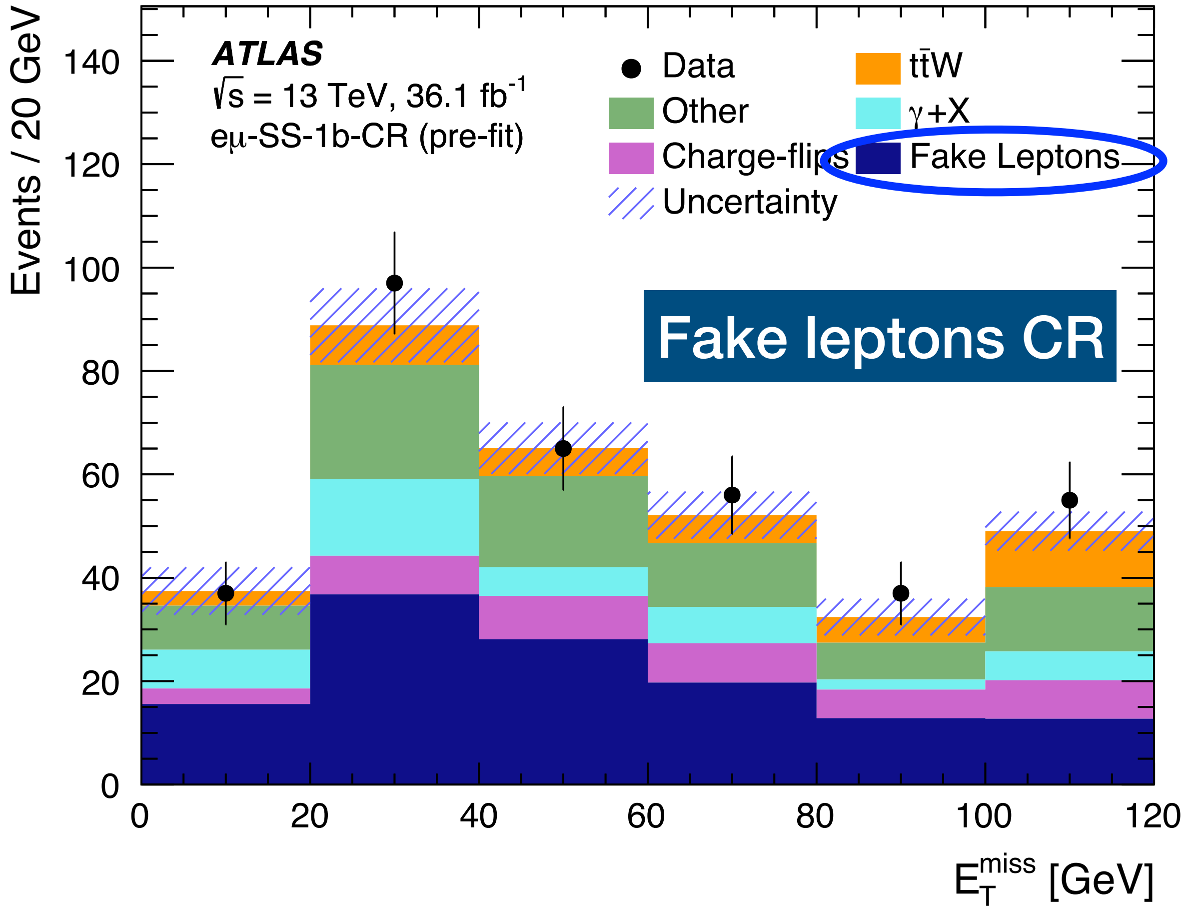
CMS Closure test

CMS

- Syst. uncertainty from differences in the closure test.

Atlas

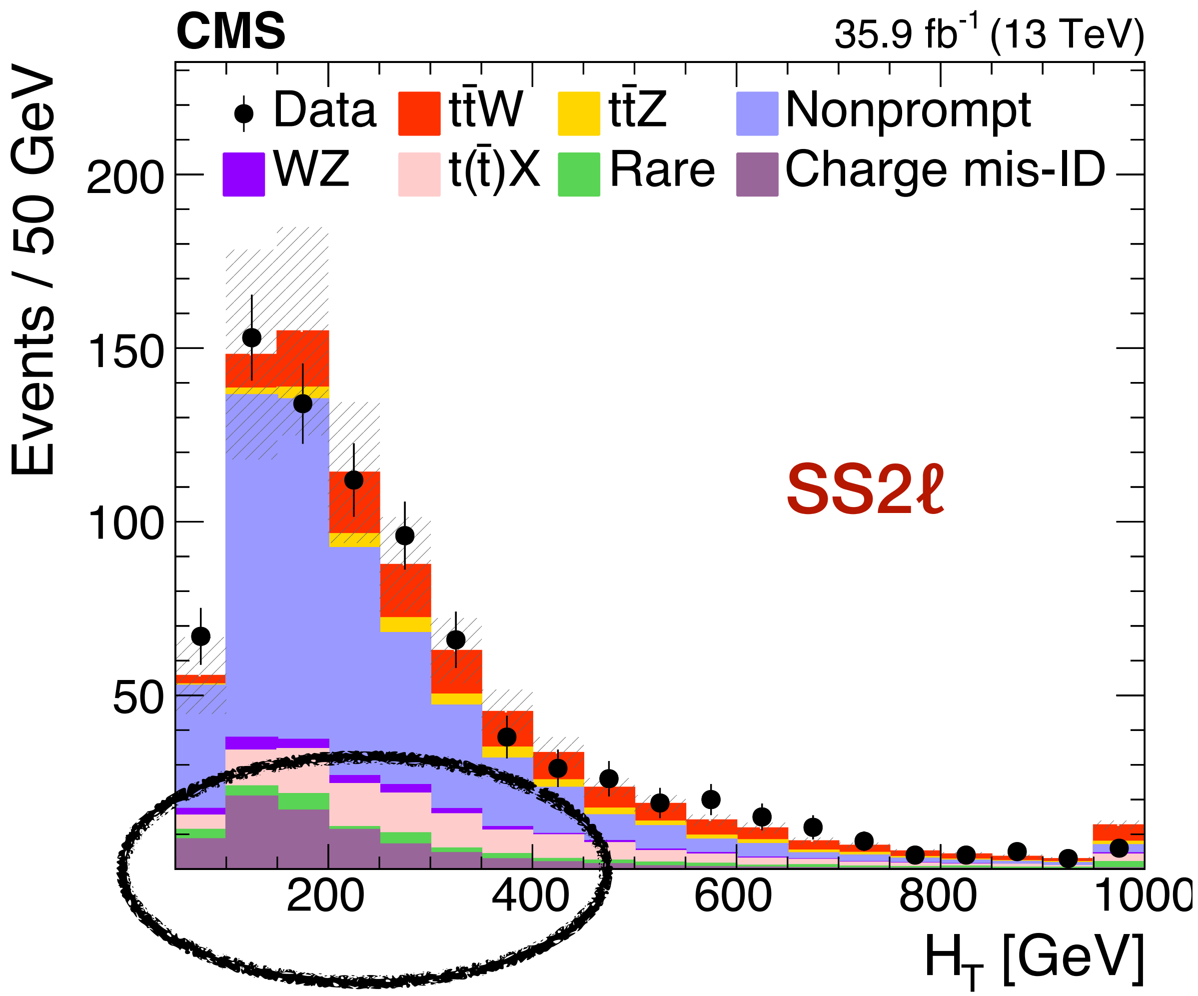
- Nuisance parameters corresponding to shifts from stat. uncertainties of the fake efficiency measurements.

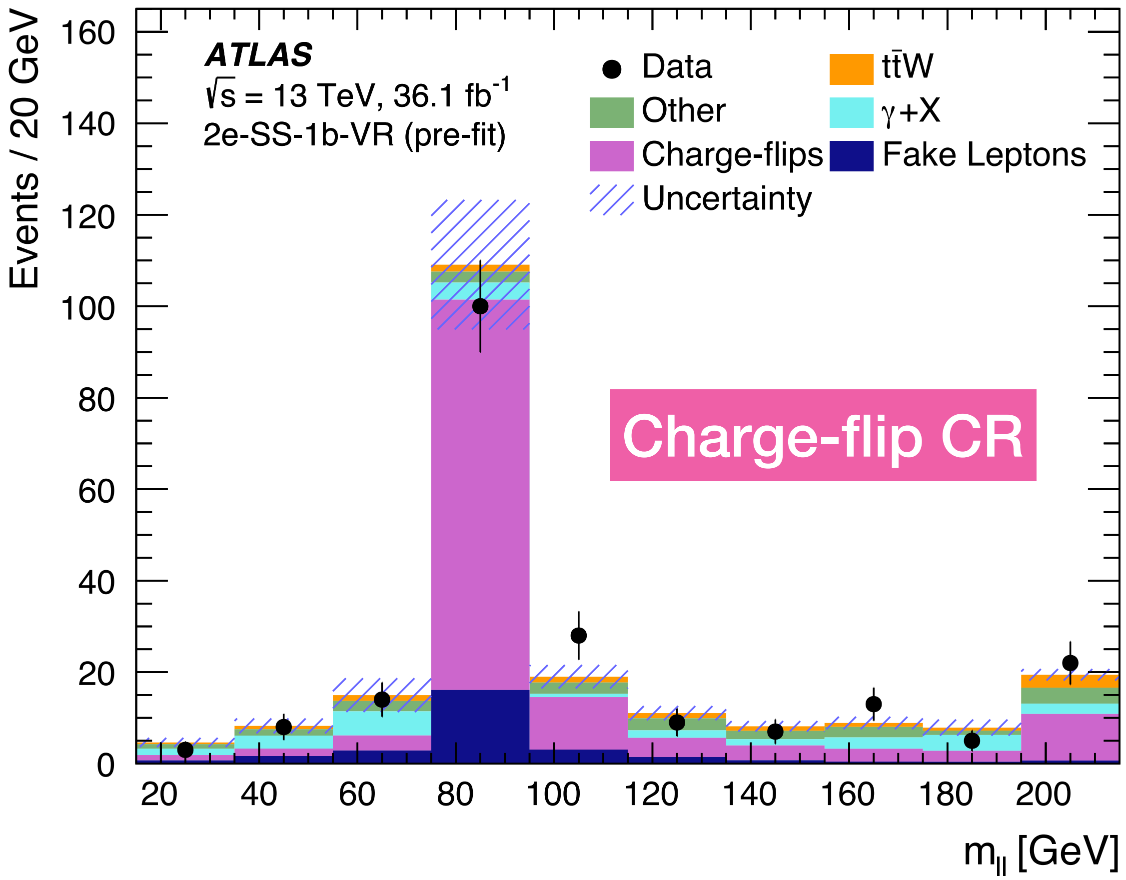


Fake leptons CR

Lepton Charge Misidentification (for $t\bar{t}W$)

- Background from lepton charge misidentification is significant in the **SS2ℓ region**
  - For muons this is negligible
  - For electrons could be up to < 2%
- The charge flip probability is estimated in an enriched $Z \rightarrow ee$ CR and parametrized as a function of lepton p_T and η.





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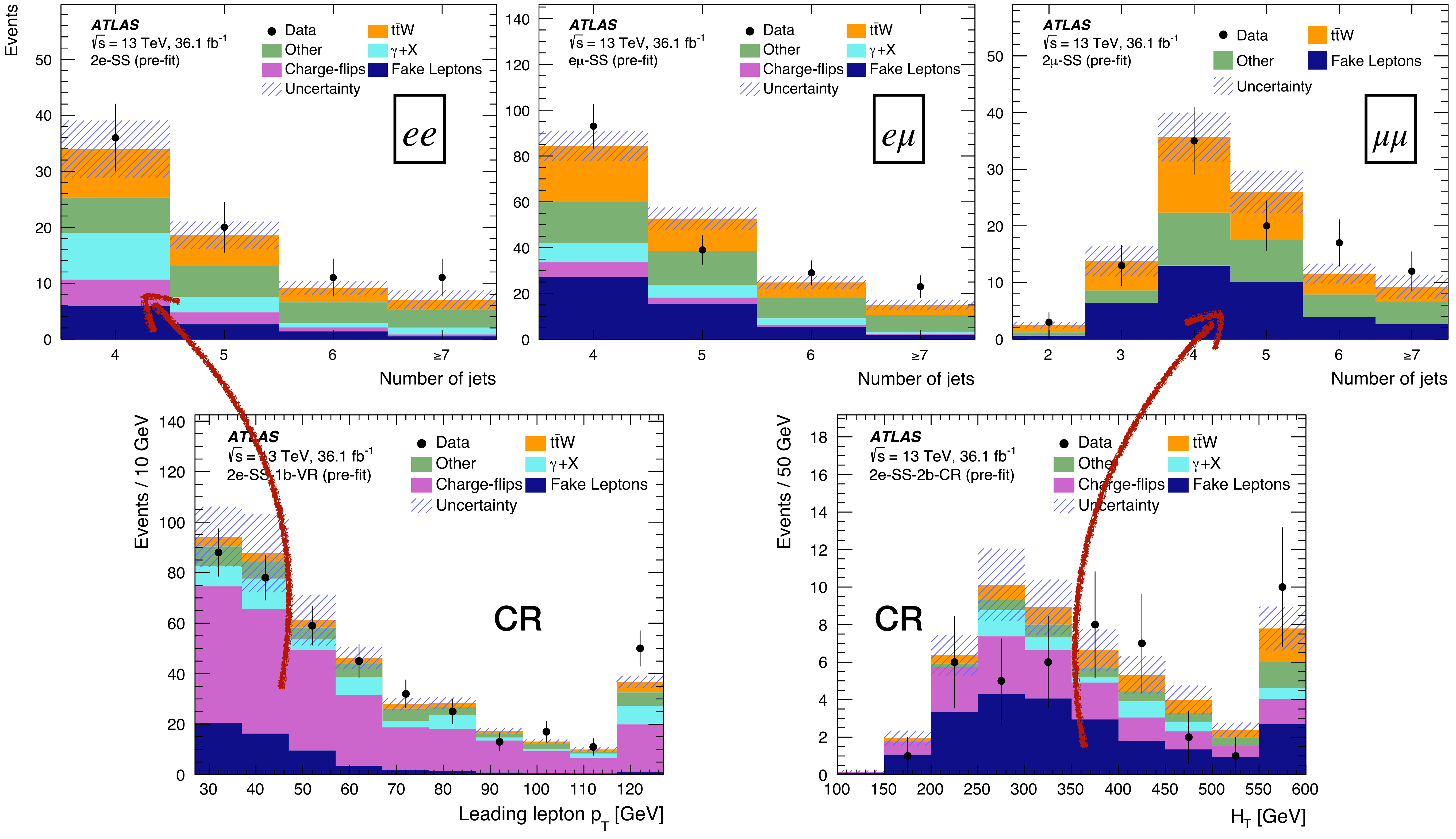
Same-Sign Dilepton (SS2ℓ) $t\bar{t}W$ Atlas

- **Data: 36.1 fb^{-1}. Use single lepton triggers.**
- MVA to suppress misidentified electron charge.
- **Other** backgrounds are from small SM processes



Opposite-Sign Dilepton (OS2ℓ, $t\bar{t}Z$)

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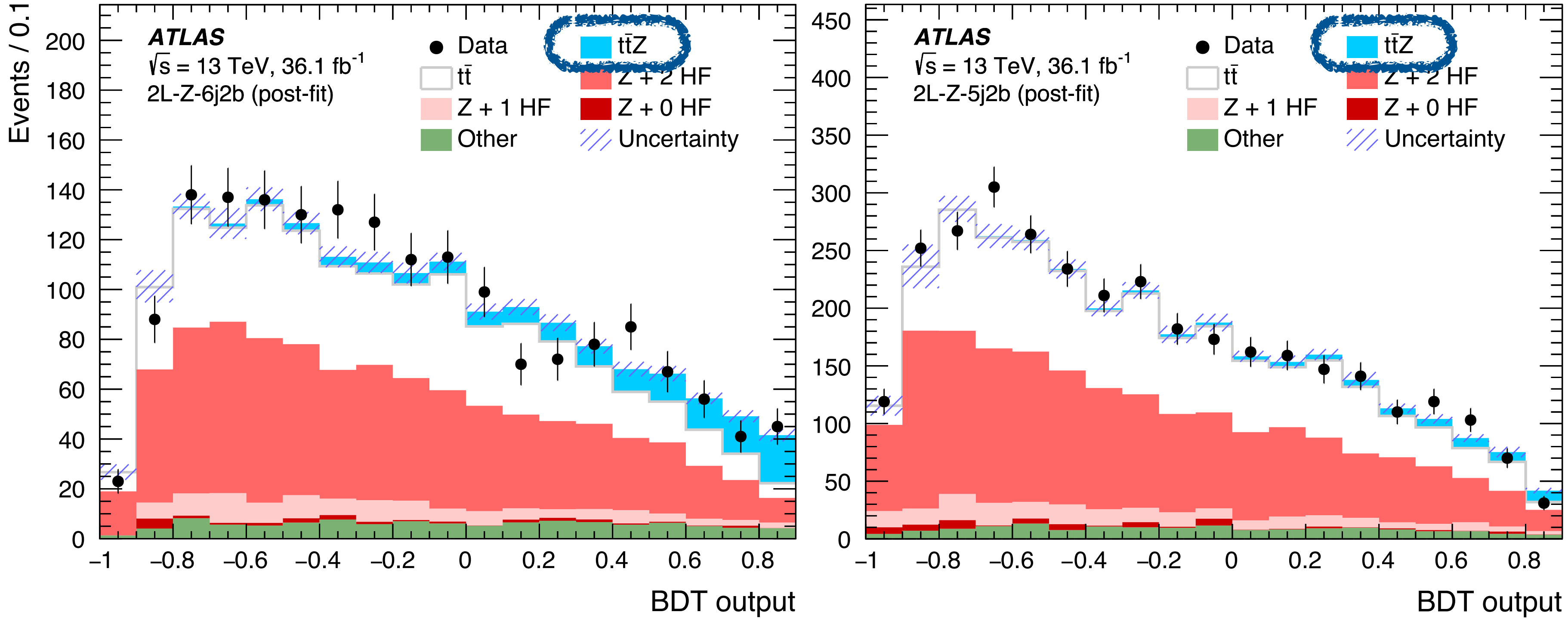
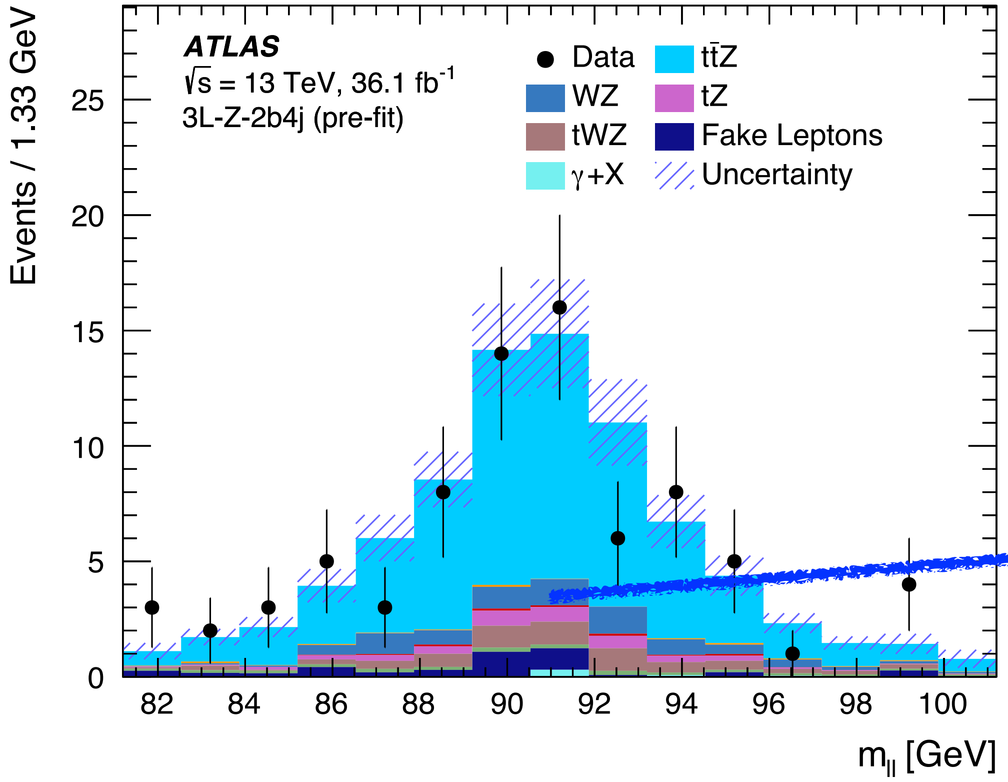
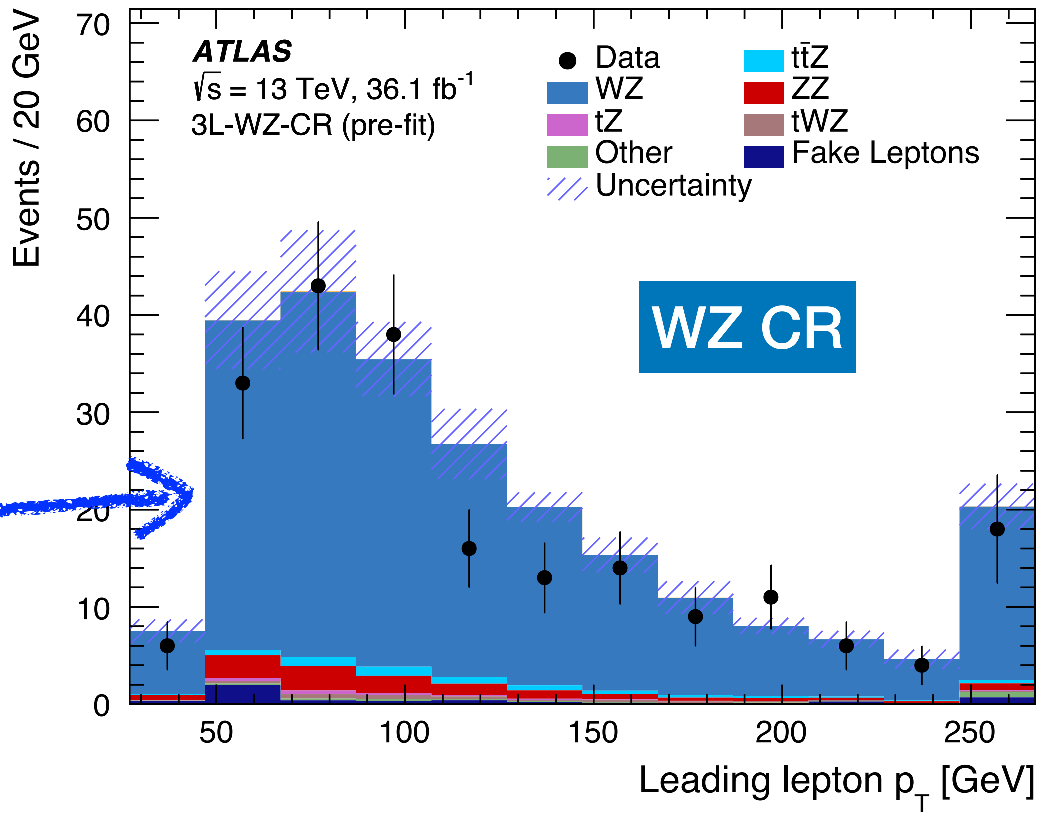


- Z+HF separated in samples with 0, 1, and 2 HF
- tt estimated from CR BDT
- Others bkg from small SM

Trileptons (3ℓ, $t\bar{t}Z$)



- Bkg from dibosons and single top+X
- WZ estimated from CR (a lepton pair must be OSSF and no b-tagged jets)



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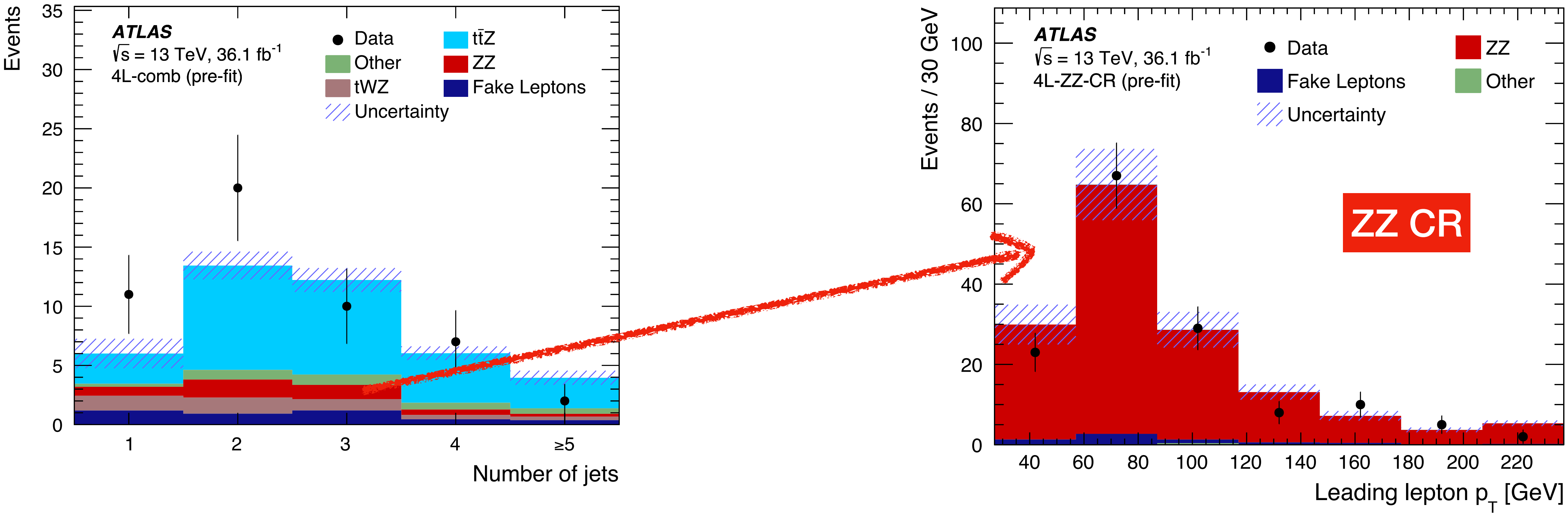
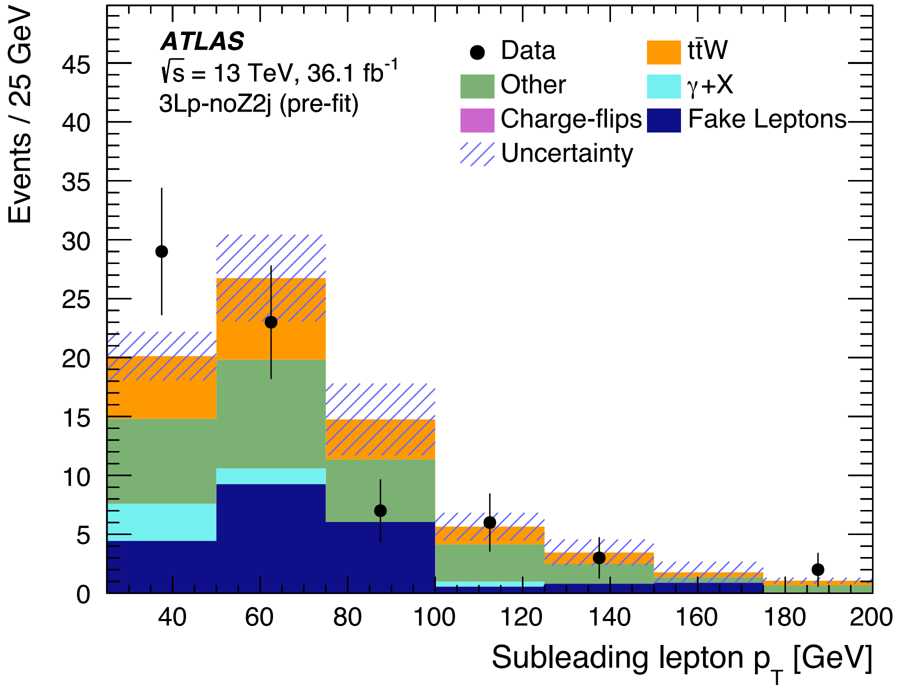
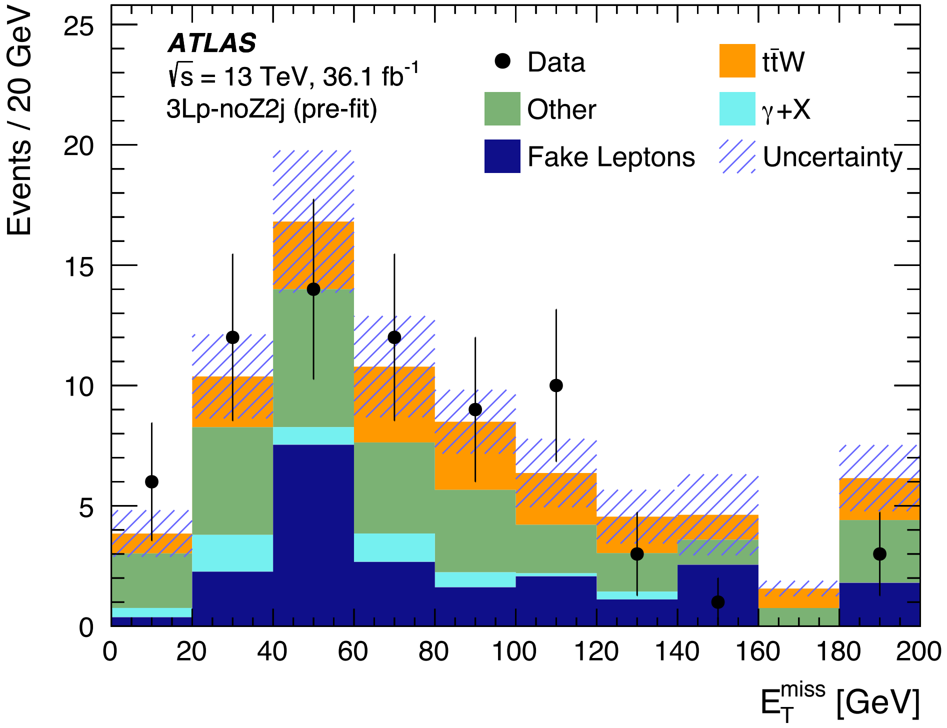
Tetraleptons ($t\bar{t}Z$)



Trileptons (3ℓ, $t\bar{t}W$)





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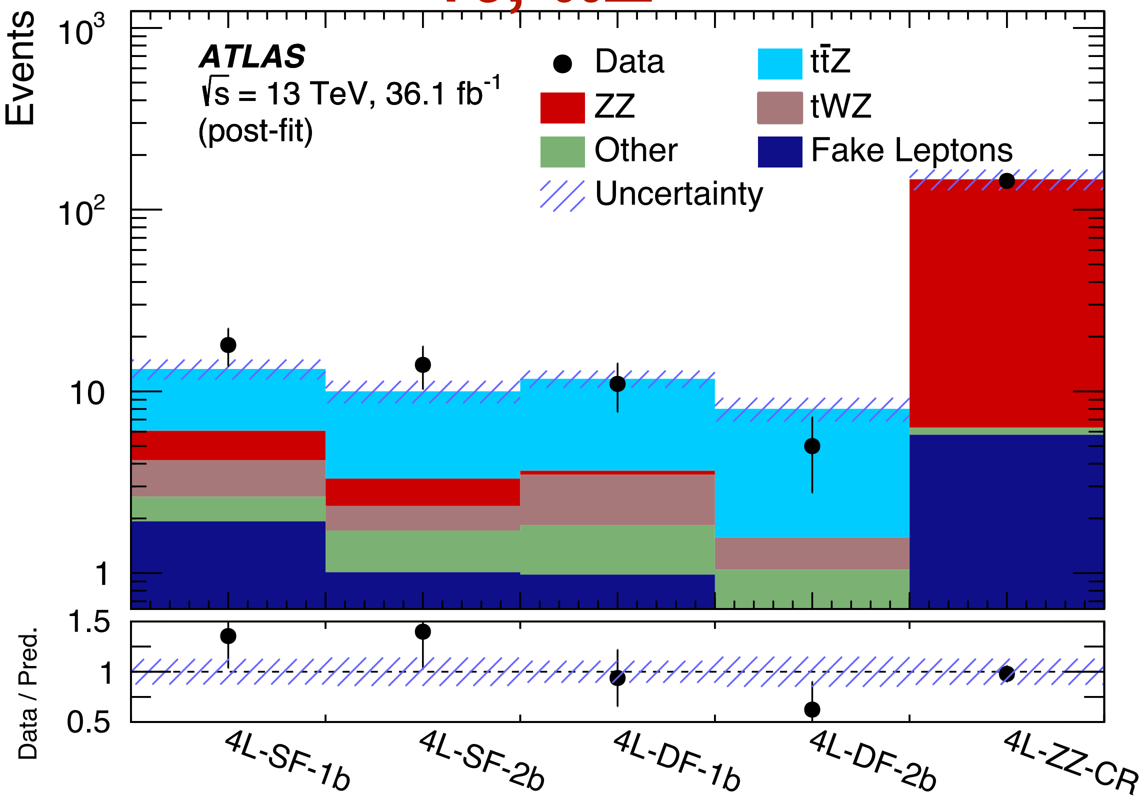
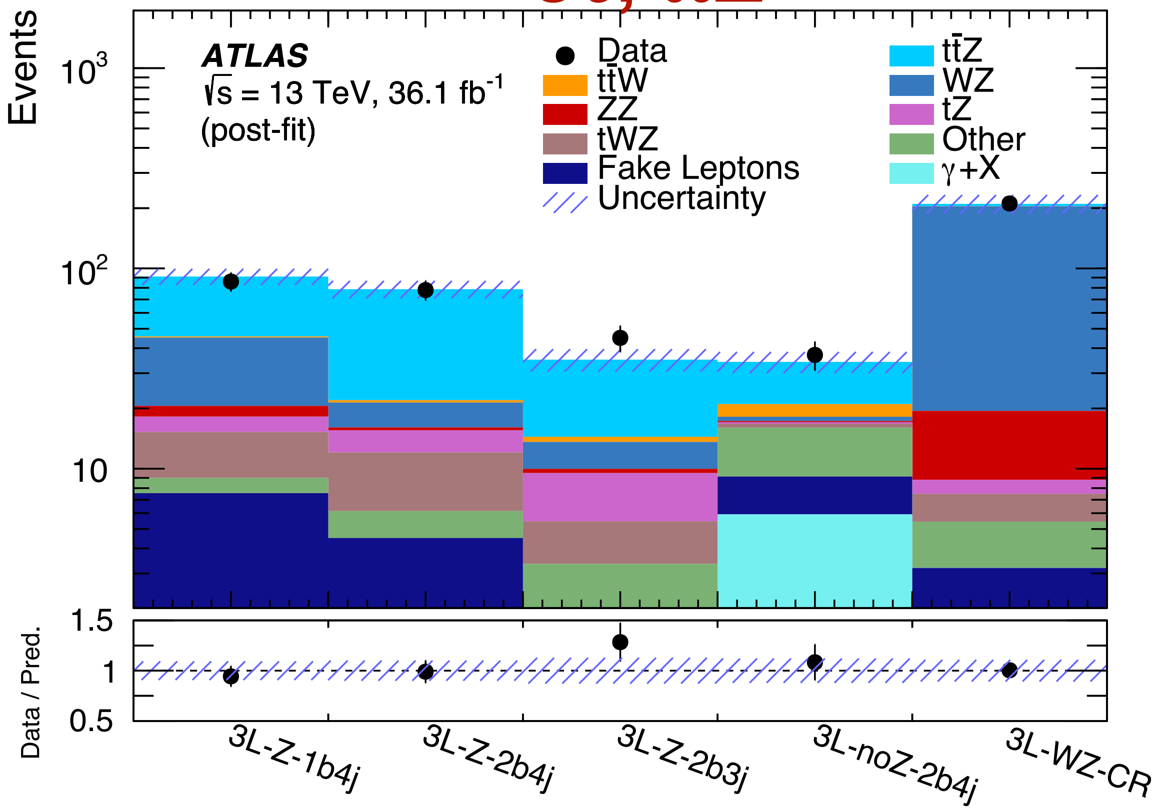
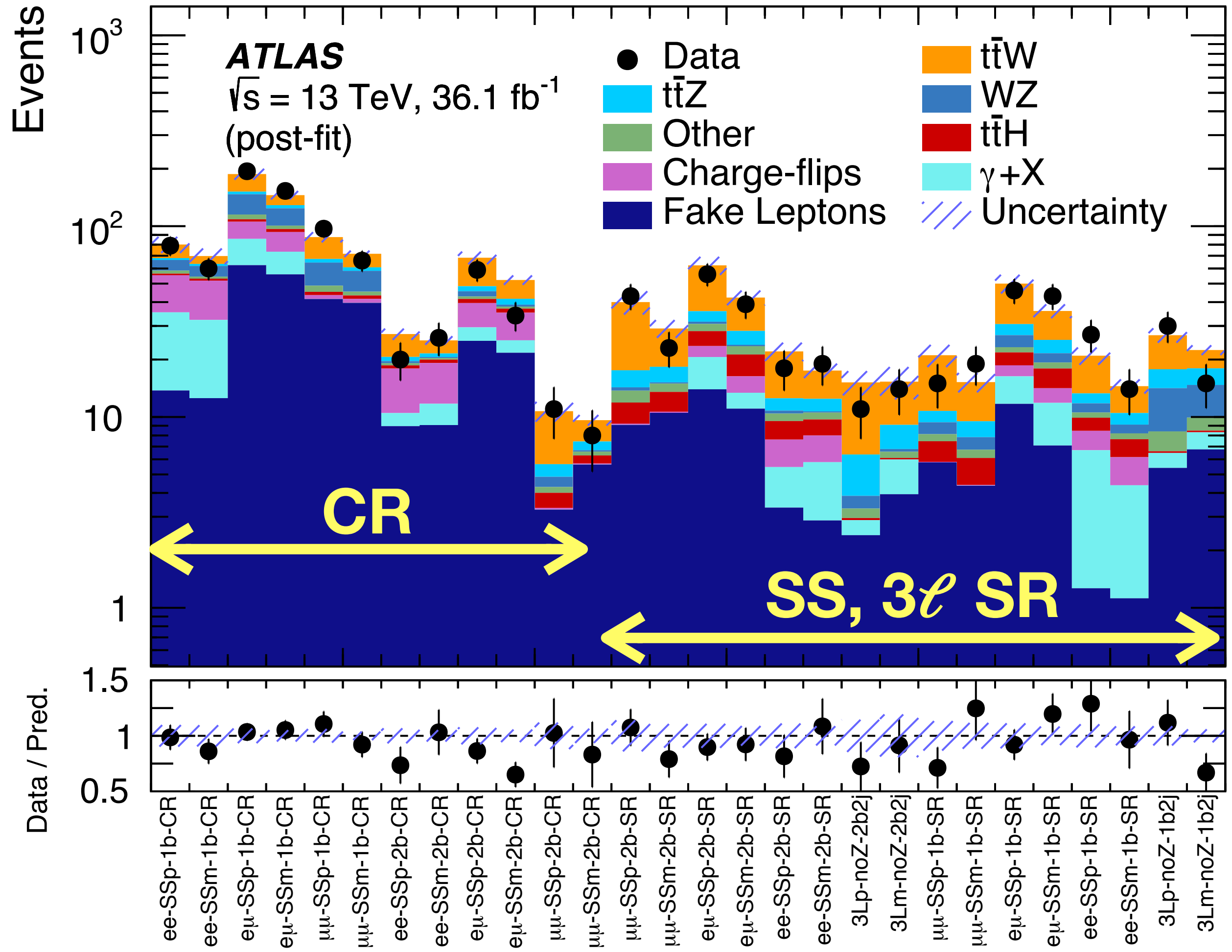
Results from Atlas

4ℓ, $t\bar{t}Z$



3ℓ, $t\bar{t}Z$





SS2ℓ, $t\bar{t}W$

3ℓ, $t\bar{t}W$

PRD 99 (2019) 072009

$t\bar{t}W$, $t\bar{t}Z$ Inclusive Cross Sections

Uncertainty	$t\bar{t}Z$ $\sigma_{t\bar{t}Z}$	$t\bar{t}W$ $\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
Simulated sample statistics	2.0%	5.3%
Data-driven background statistics	2.5%	6.3%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	3.2%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10%	16%
Statistical	8.4%	15%
Total	13%	22%

$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08$**(stat)** $\pm\, 0.10$**(syst) pb** 13%

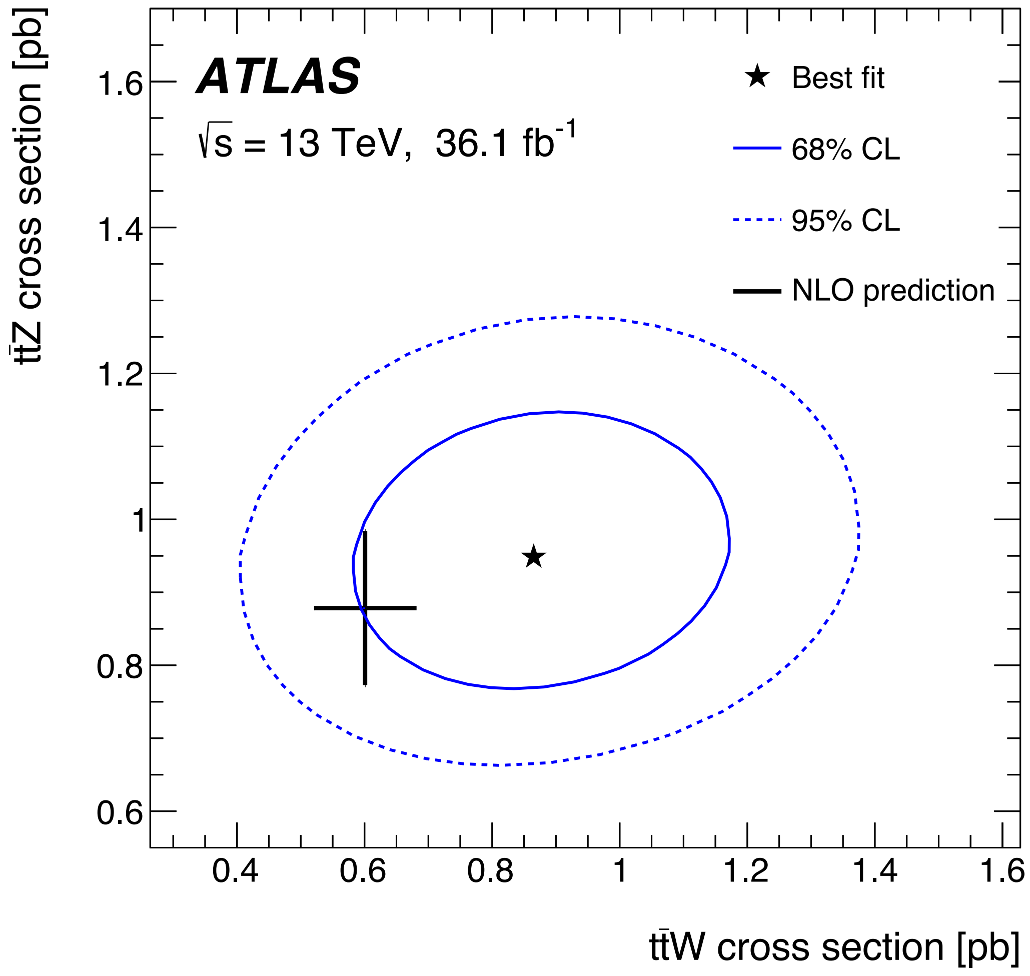
$\sigma_{t\bar{t}W} = 0.87 \pm 0.13$**(stat)** $\pm\, 0.14$**(syst) pb** 22%

$\sigma^{NLO}_{t\bar{t}Z} = 0.88^{+0.09}_{-0.11}$ **pb** $\sigma^{NLO}_{t\bar{t}W} = 0.6^{+0.08}_{-0.07}$ **pb** 13%

Use a profile likelihood fit

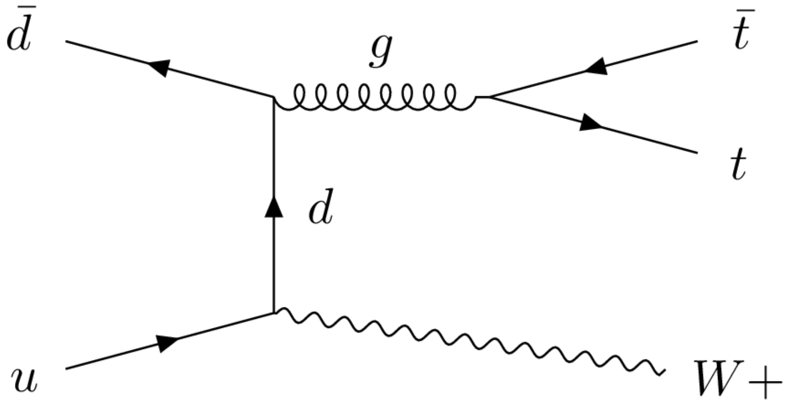
Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	–
3ℓ $t\bar{t}Z$	1.08 ± 0.18	–
2ℓ-SS and 3ℓ $t\bar{t}W$	–	1.41 ± 0.33
4ℓ	1.21 ± 0.29	–

Leading syst. are from ISR/FSR and generator comparisons

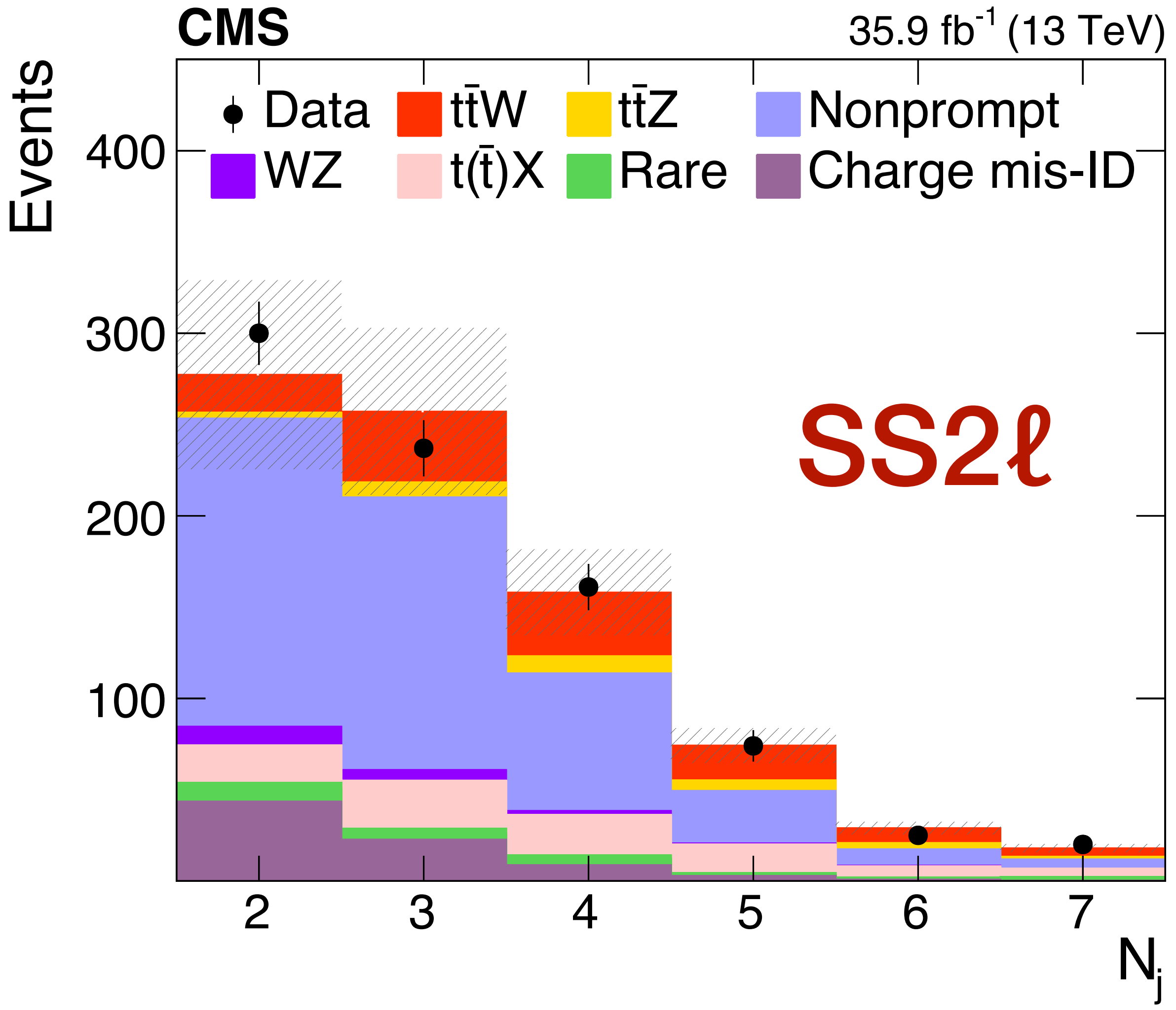


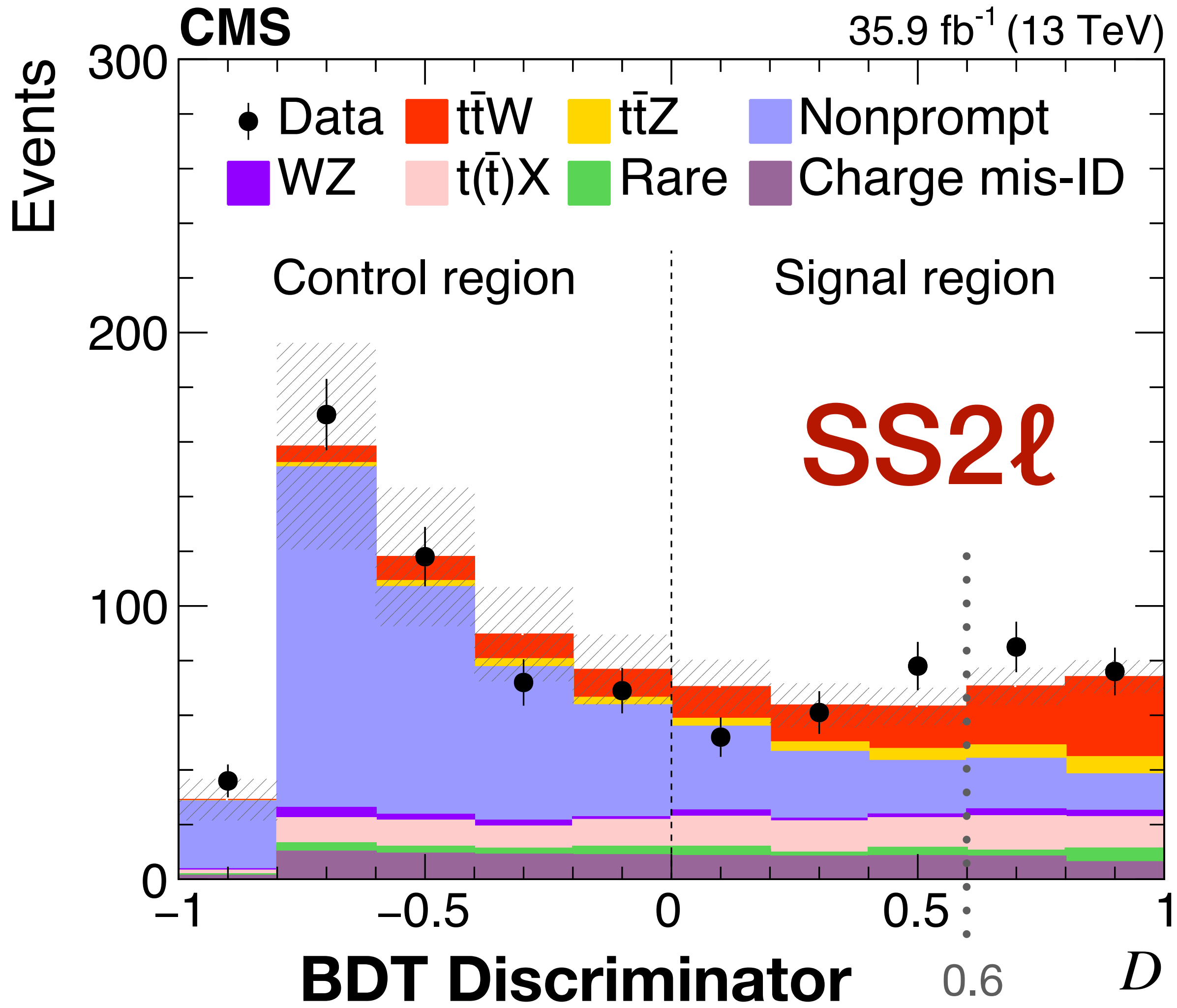
JHEP 08(2018)011

$t\bar{t}W$ from CMS



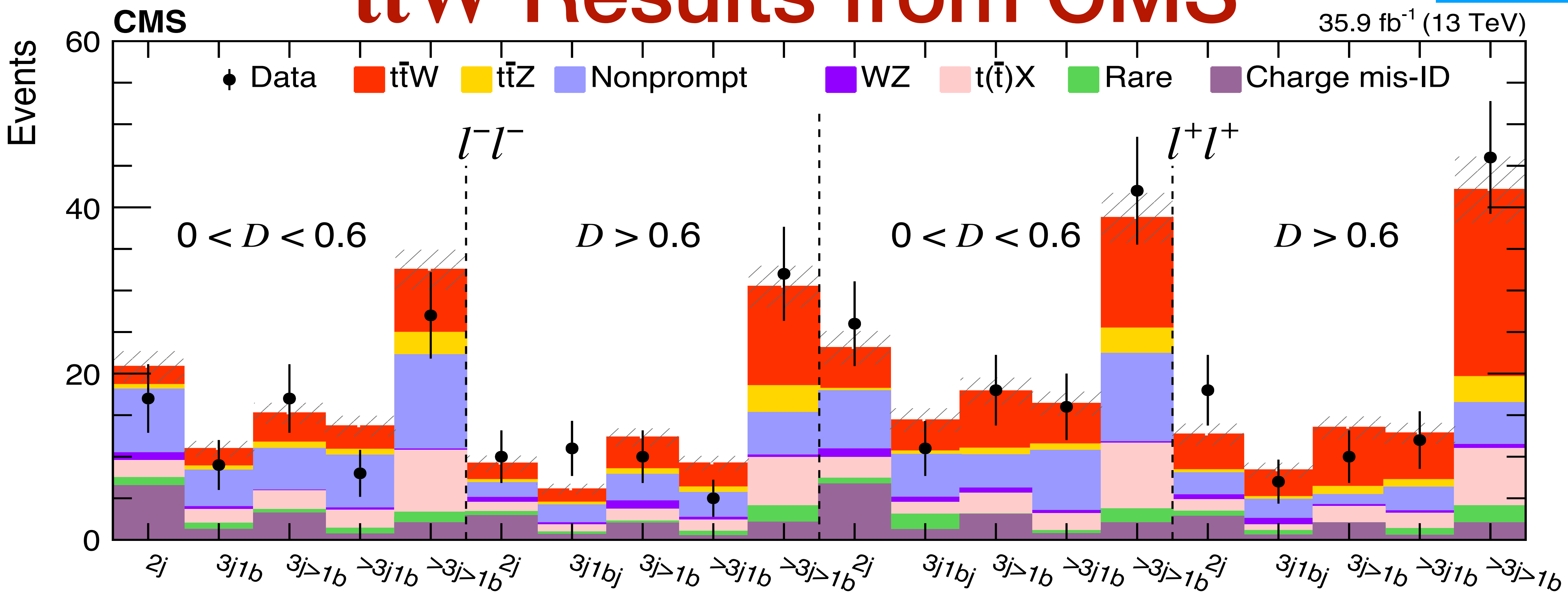
- **Data 35.9 fb^{-1} with single lepton triggers.**
- BDT constructed with N_{jets}, N_b, H_T, p_T^{miss}, p^{ℓ}_T, M_T, $\Delta R(\ell,j)$
- Fake leptons estimated using the tight-to-loose method with a corrected lepton p_T and parametrized in p_T and η.
- Charge misID and WZ also extracted with data driven methods.
- t(t)X=ttH, tqZ, tWZ, rare=multiboson





$t\bar{t}W$ Results from CMS

JHEP 08(2018)011



Source	Uncertainty from each source (%)	Impact on the measured $t\bar{t}W$ cross section (%)
Integrated luminosity	2.5	4
Jet energy scale and resolution	2–5	3
Trigger	2–4	4–5
B tagging	1–5	2–5
PU modeling	1	1
Lepton ID efficiency	2–7	3
Choice in μ_R and μ_F	1	<1
PDF	1	<1
Nonprompt background	30	4
WZ cross section	10–20	<1
ZZ cross section	20	—
Charge misidentification	20	3
Rare SM background	50	2
$t(\bar{t})X$ background	10–15	4
Stat. unc. in nonprompt background	5–50	4
Stat. unc. in rare SM backgrounds	20–100	1
Total systematic uncertainty	—	14

$$\sigma_{t\bar{t}W} = 0.77^{+0.12}_{-0.11}\textbf{(stat)}^{+0.13}_{-0.12}\textbf{(syst) pb}$$ 23%

$$\sigma_{t\bar{t}W^+} = 0.58 \pm 0.09\textbf{(stat)}^{+0.09}_{-0.08}\textbf{(syst) pb}$$

$$\sigma_{t\bar{t}W^-} = 0.19 \pm 0.07\textbf{(stat)} \pm 0.06\textbf{(syst) pb}$$

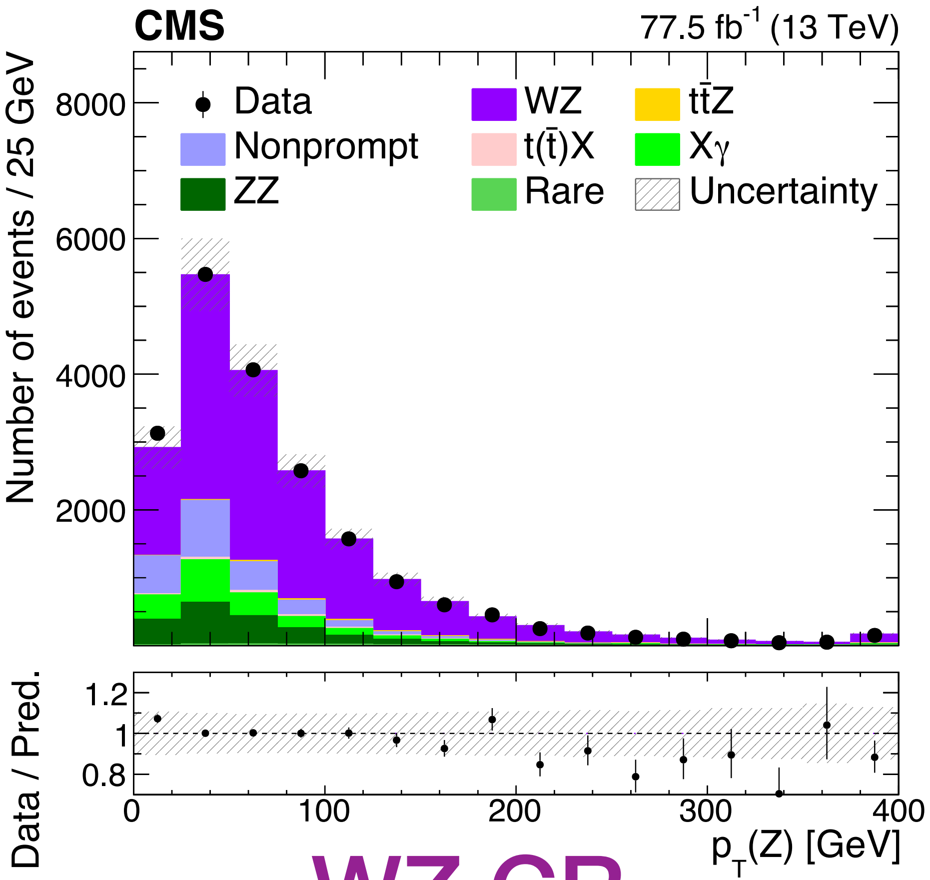
$$\sigma^{NLO}_{t\bar{t}W} = 0.6^{+0.08}_{-0.07}\ \textbf{pb}$$

$t\bar{t}Z$ from CMS

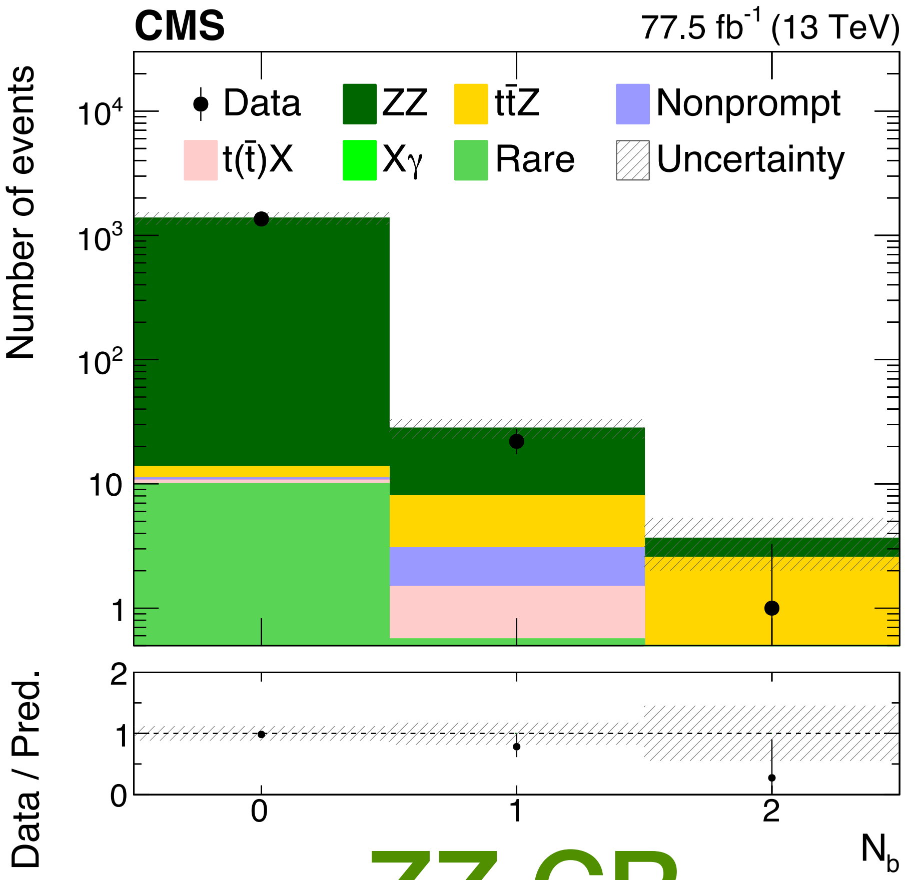
arXiv:1907.11270

- **Data 77.5 fb^{-1} (2016, 2017).**
- Use trilepton and tetralepton channels.
- **Improvements** from previous analysis:
  - More inclusive lepton triggers: combination of single, dilepton, and trilepton triggers.
  - Dedicated MVA for lepton selection: 15% increase in prompt ℓ efficiency and fake ℓ efficiency reduced by 2-4 wrt old selection.

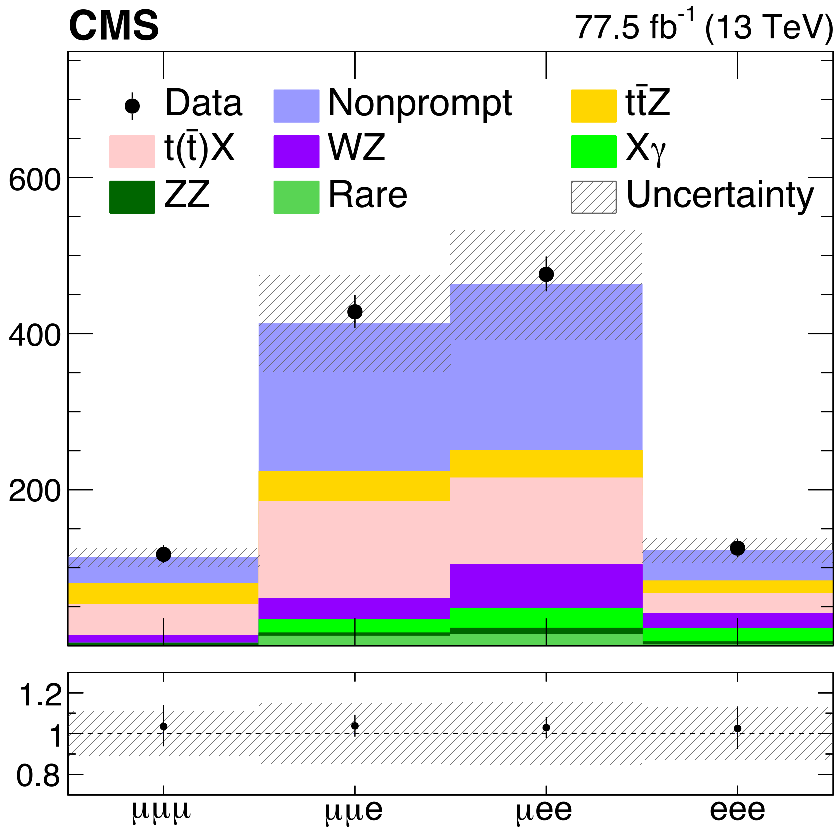
- Backgrounds:
  - t(t)X, X=H,W,WZ,Zq,Hq,HW,VV,tt are taken from simulation.
  - WZ(3ℓ) CR with $N_b=0$.
  - ZZ(4ℓ) CR with reconstructed ZZ.
  - Fake leptons with CR with veto Z(3ℓ)
  - Rare = VVV, Xγ events from simulation.



WZ CR



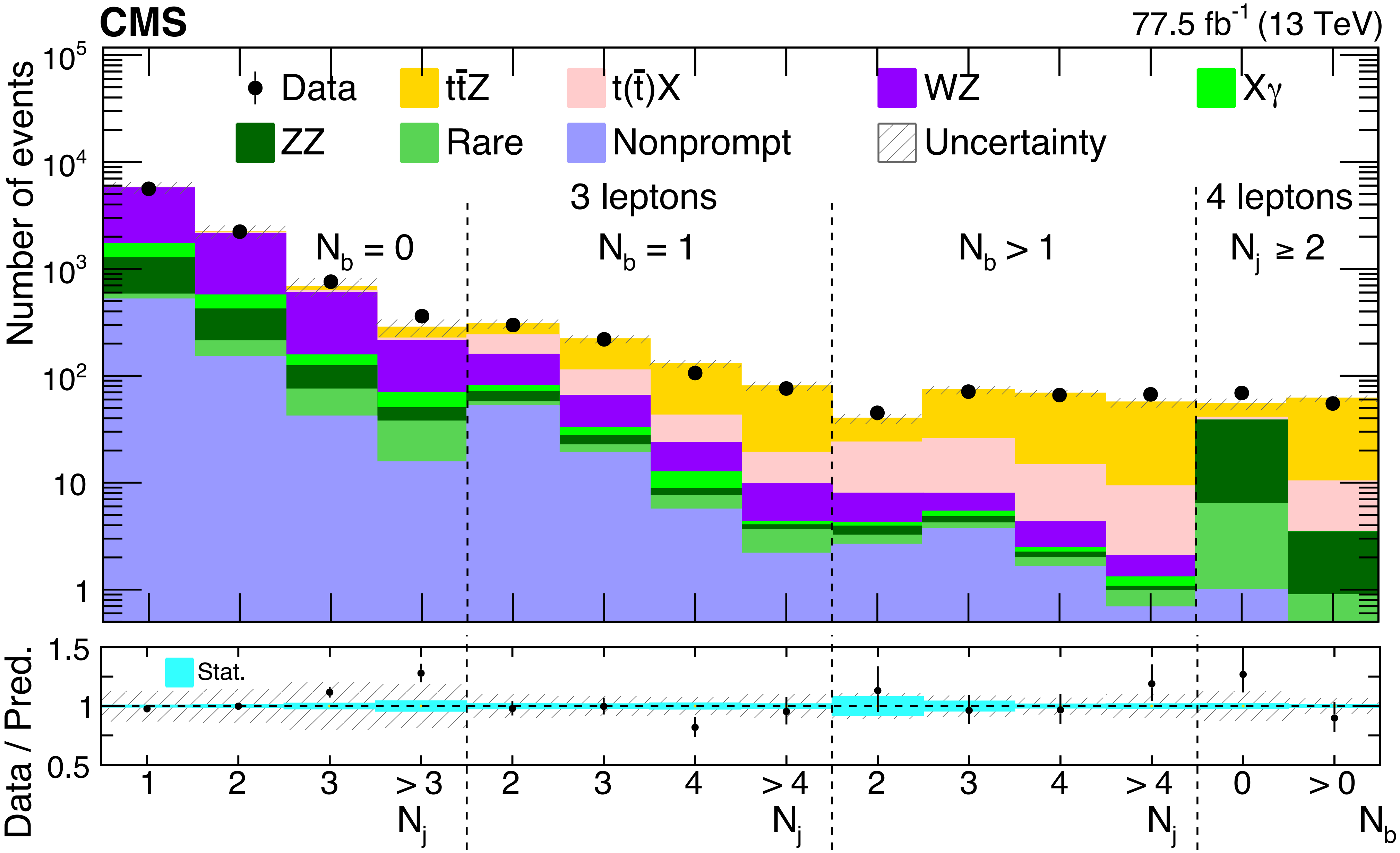
ZZ CR



Fake leptons CR

CMS Inclusive $t\bar{t}Z$ Cross Section

arXiv:1907.11270



Systematic Uncertainties

arXiv:1907.11270

Source	Uncertainty range (%)	Correlated between 2016 and 2017	Impact on the $t\bar{t}Z$ cross section (%)
Integrated luminosity	2.5	×	2
PU modeling	1–2	✓	1
Trigger	2	×	2
Lepton ID efficiency	4.5–6	✓	4
Jet energy scale	1–9	✓	2
Jet energy resolution	0–1	✓	1
btagging light flavor	0–4	×	1
btagging heavy flavor	1–4	×	2
Choice in μ_R and μ_F	1–4	✓	1
PDF choice	1–2	✓	1
Color reconnection	1.5	✓	<1
Parton shower	1–8	✓	1
WZ cross section	10–20	✓	3
WZ + heavy flavor	8	✓	1
ZZ cross section	10	✓	1
$t(\bar{t})$X background	10–15	✓	3
Xγ background	20	✓	1
Nonprompt background	30	✓	<1
Rare SM background	50	✓	2
Stat. unc. in nonprompt bkg.	5–50	×	<1
Stat. unc. in rare SM bkg.	5–100	×	<1
Total systematic uncertainty			6
Statistical uncertainty			5
Total			8

Lepton requirement	Measured cross section
3ℓ	$0.97 \pm 0.06\,(\text{stat}) \pm 0.06\,(\text{syst})$ pb
4ℓ	$0.91 \pm 0.14\,(\text{stat}) \pm 0.08\,(\text{syst})$ pb
Total	$0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})$ pb

Precision

Measurement at 8%

Th. NLO at 12%

Th. NLO+NNLL at 9%

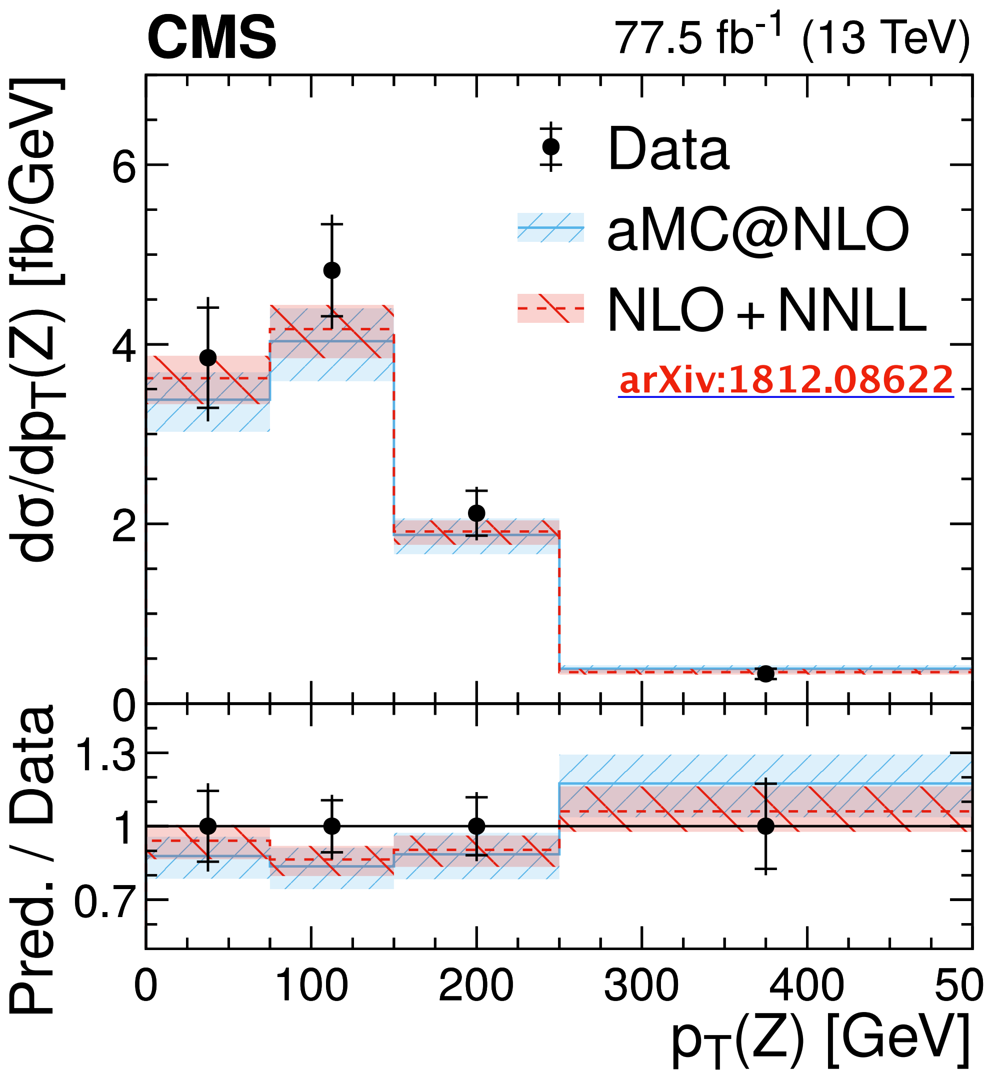
arXiv:1812.08622

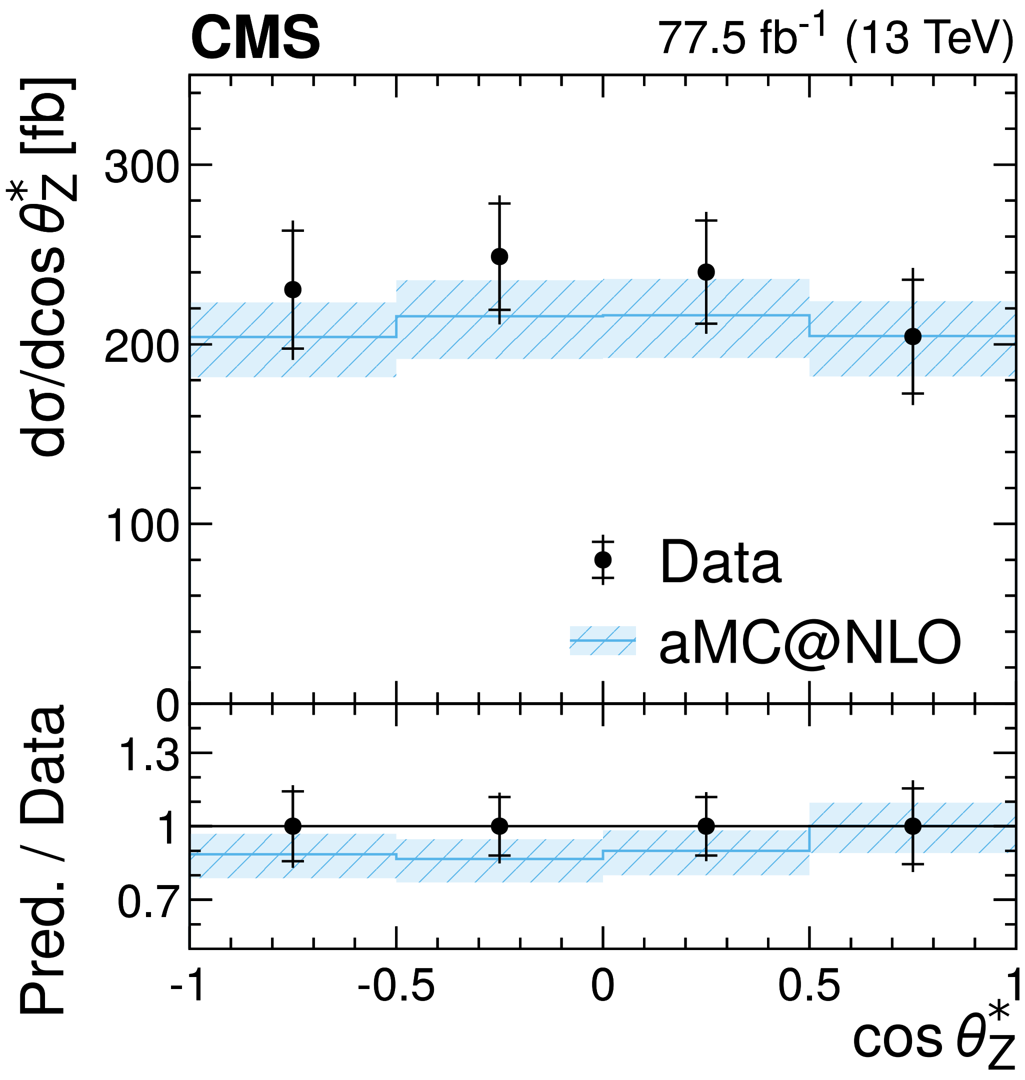
$$\sigma^{NLO}_{t\bar{t}Z} = 0.88^{+0.09}_{-0.11}\ \textbf{pb}$$

arXiv:1907.11270

$t\bar{t}Z$ Differential Cross Section

- Calculated wrt leptonic observables that have very good resolution.
- The detector response matrix is mostly diagonal. Unfolding done without regularization.
- Measurement done in an enriched signal sample 3ℓ, $N_j \geq 1$, $N_b \geq 1$.
- Limited by statistics (4 bins). **(normalized in backup)**





Angle of leptons in rest frame of the Z boson/dilepton system

Joscha Knolle's YSF talk

Anomalous Couplings and EFT Interpretation

- Use ttZ events for a model independent BSM search using two approaches:
- Modified coupling coefficients (C_i^Z):

$$\mathcal{L}_{t\bar{t}Z}^{SM} = e\bar{u}(p_t)\left[\gamma^\mu(C_{1,V}^Z + C_{1,A}^Z) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}(C_{2,V}^Z + C_{2,A}^Z)\right]v(\bar{p}_t)Z_\mu$$

Vector & Axial-vector Couplings

Magnetic & Electric Dipole Moments ~10^{-3}

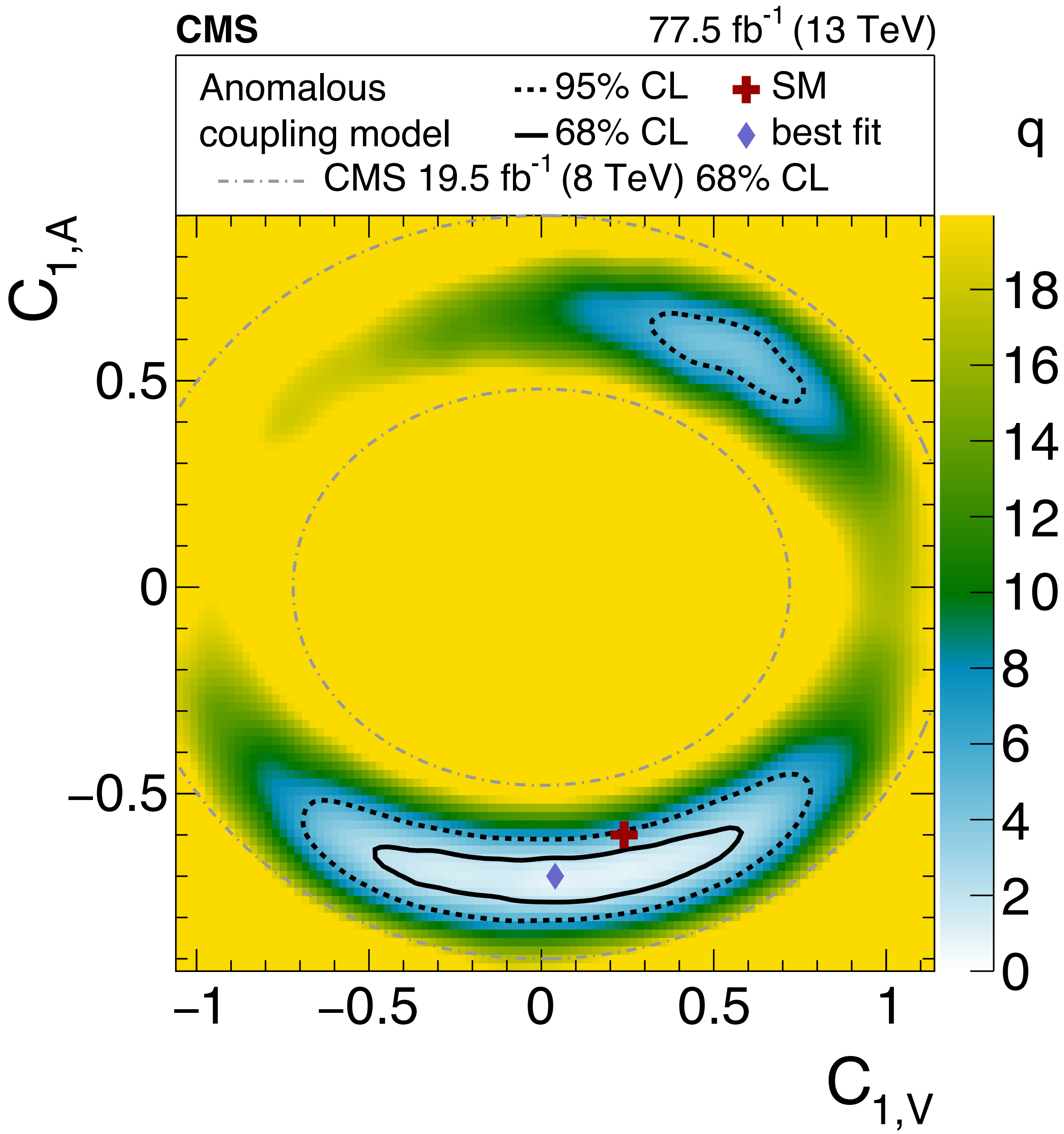
- and using the EFT approach:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \cancel{\frac{1}{\Lambda}\sum_i c_i\mathcal{O}_i} + \frac{1}{\Lambda^2}\sum_j c_j\mathcal{O}_j$$

- Four Wilson coefficients ($c_{tZ}, c_{tZ}^{[I]}, c_{\phi t}, c_{\phi q}^{-}$) out of 15 within the dim6top EFT model are relevant for ttZ.
- Found that the best observables are the $p_t(Z)$ and $\cos\theta^*$ distributions.
- Weights $w(p_t(Z), \cos\theta^*) = \dfrac{w_i^{BSM}}{w_i^{SM}}$ are computed to map the large BSM phase space.

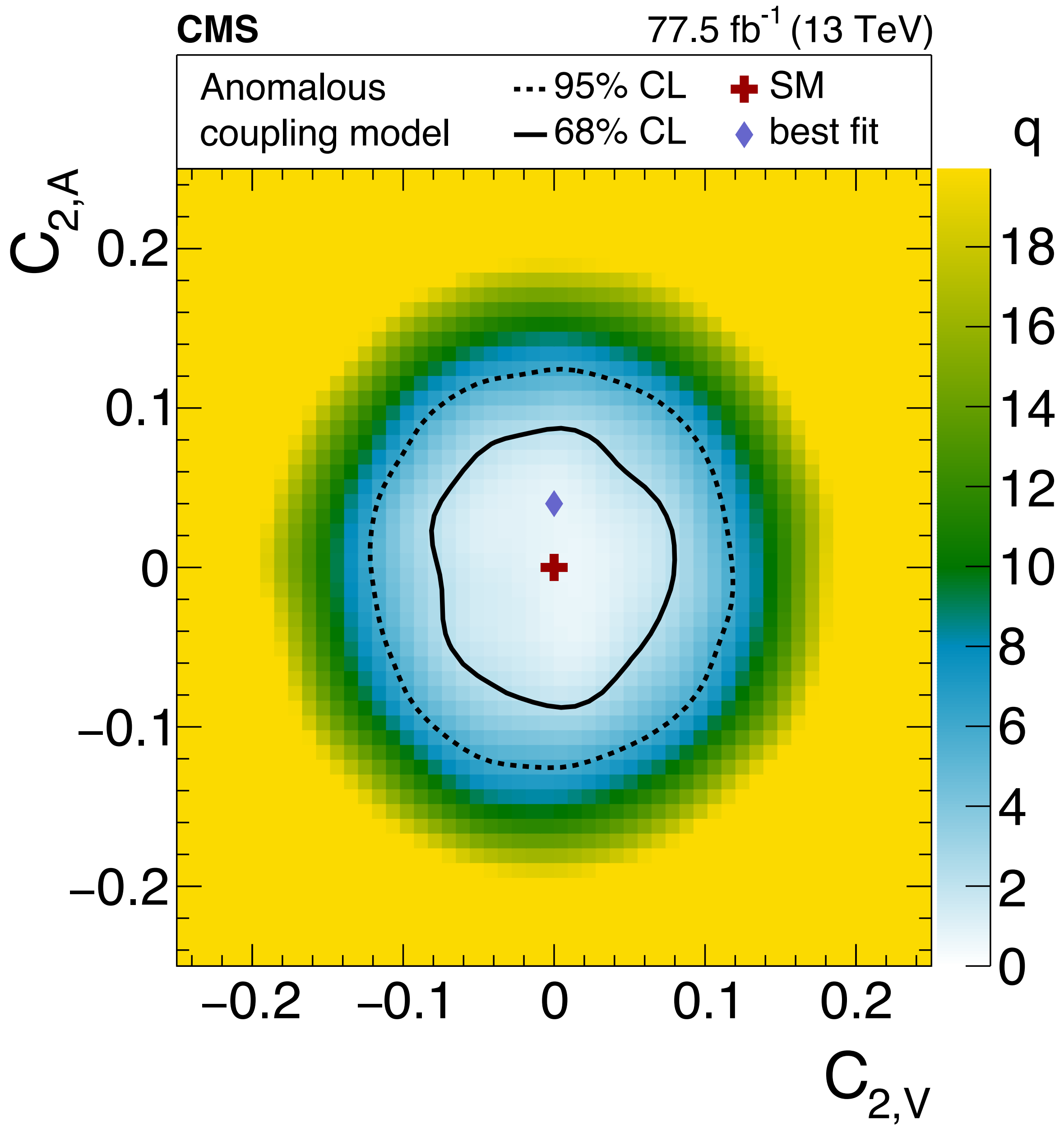
Anomalous Coupling Results

Axial Vector Couplings



Best fit is ~2σ from SM

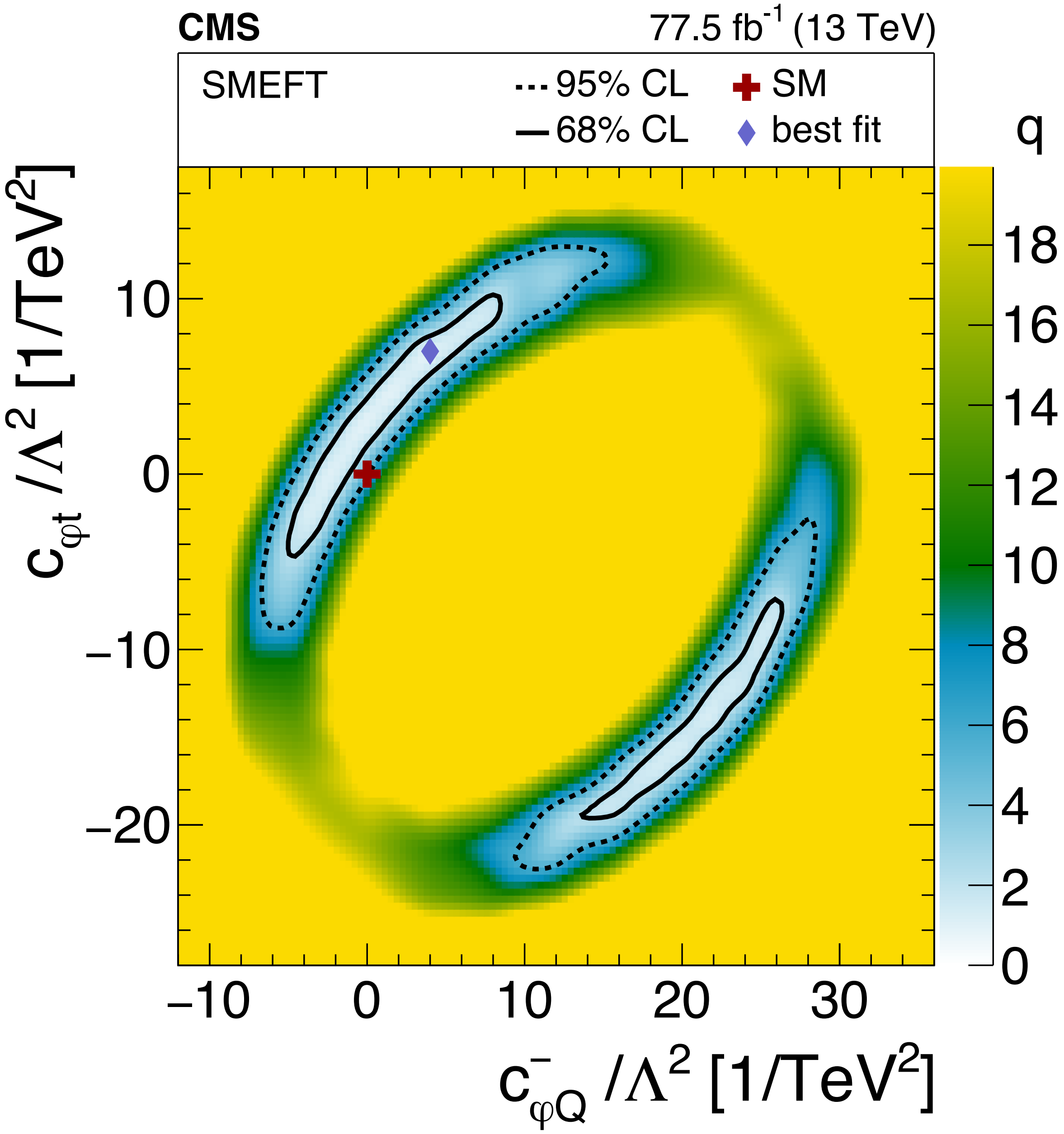
EW Dipole Moments



q= log-likelihood ratio with respect to the best-fit value (diamond) arXiv:1907.11270

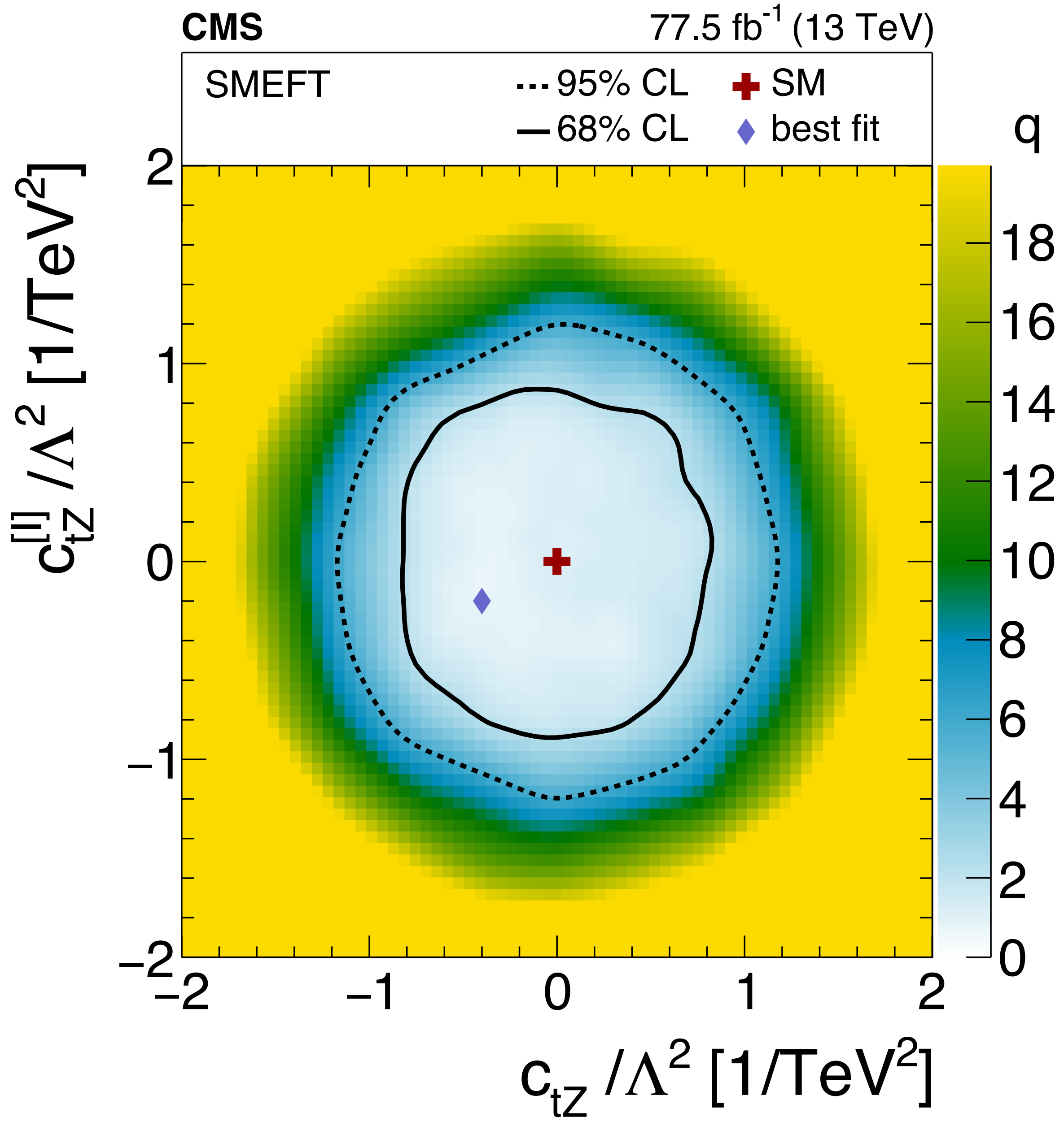
EFT Interpretation

Induce Anomalous NC interactions



Best fit is ~2σ from SM

Induce EW Dipole Moments



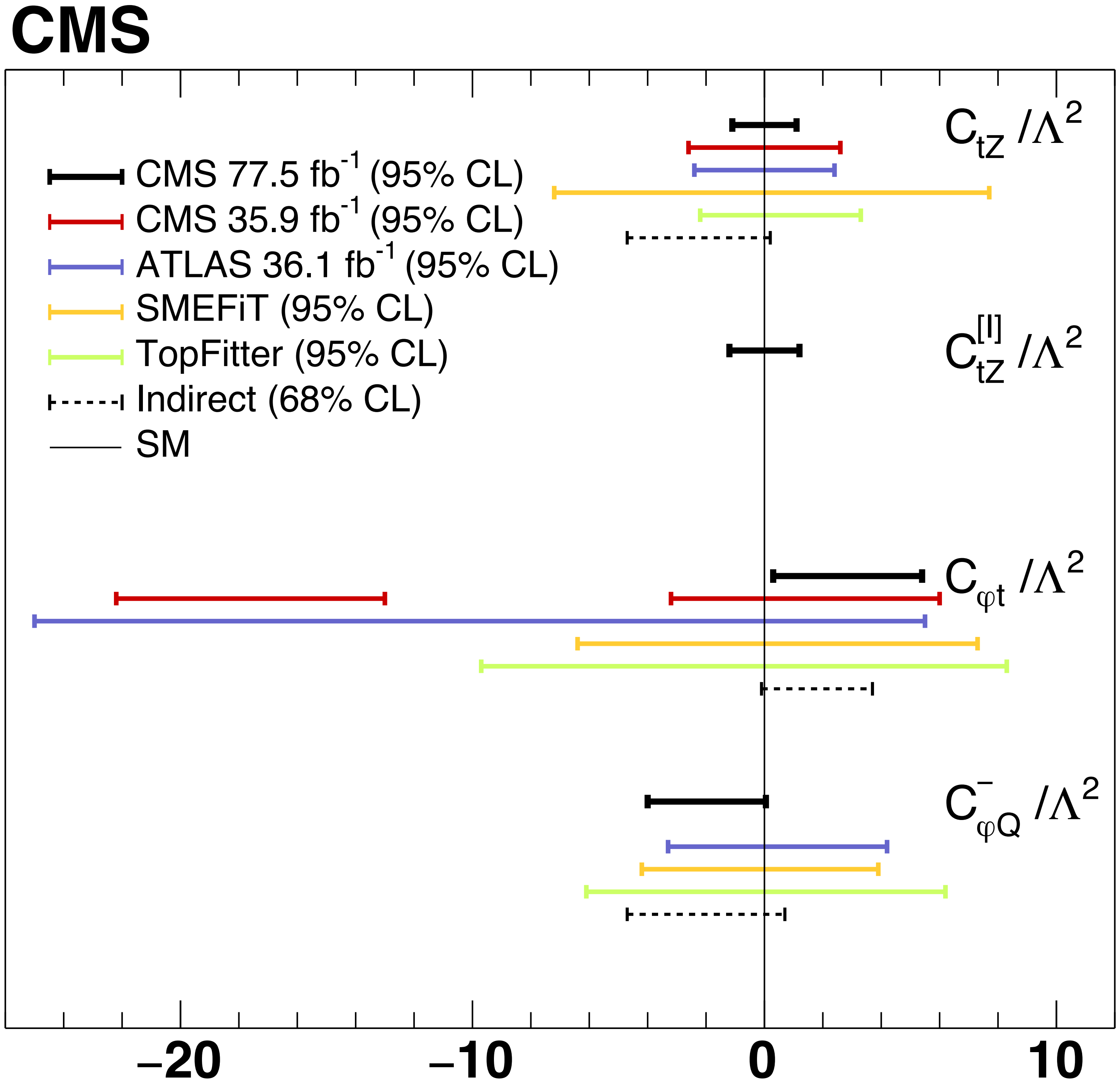
q= log-likelihood ratio with respect to the best-fit value (diamond)

Summary EFT Results

SMEFiT
arXiv:1512.03360

TopFitter
arXiv:1901.05965

EWK data
arXiv:1201.6670



Summary

- Atlas results
  - ttW: $\sigma_{t\bar{t}W} = 0.87 \pm 0.13$**(stat)** $\pm\, 0.14$**(syst) pb**
  - ttZ: $\sigma_{t\bar{t}Z} = 0.95 \pm 0.08$**(stat)** $\pm\, 0.10$**(syst) pb**
- CMS results
  - ttW: $\sigma_{t\bar{t}W} = 0.77^{+0.12}_{-0.11}$**(stat)**$^{+0.13}_{-0.12}$**(syst) pb**
  - ttZ: $\sigma_{t\bar{t}Z} = 0.95 \pm 0.05$**(stat)** $\pm\, 0.06$**(syst) pb**
- Ongoing work to analyze the full Run2 data and expand the differential cross sections.
- Experimental precision challenging the current theory predictions.
- Sensitive ttZ observables allow us to probe a large BSM phase space.
- References:
  - CMS ttZ (78 fb^{-1}): arXiv:1907.11270
  - CMS ttW (36 fb^{-1}): JHEP 08(2018)011
  - Atlas ttW/Z (36 fb^{-1}): Phys. Rev. D 99 (2019) 072009

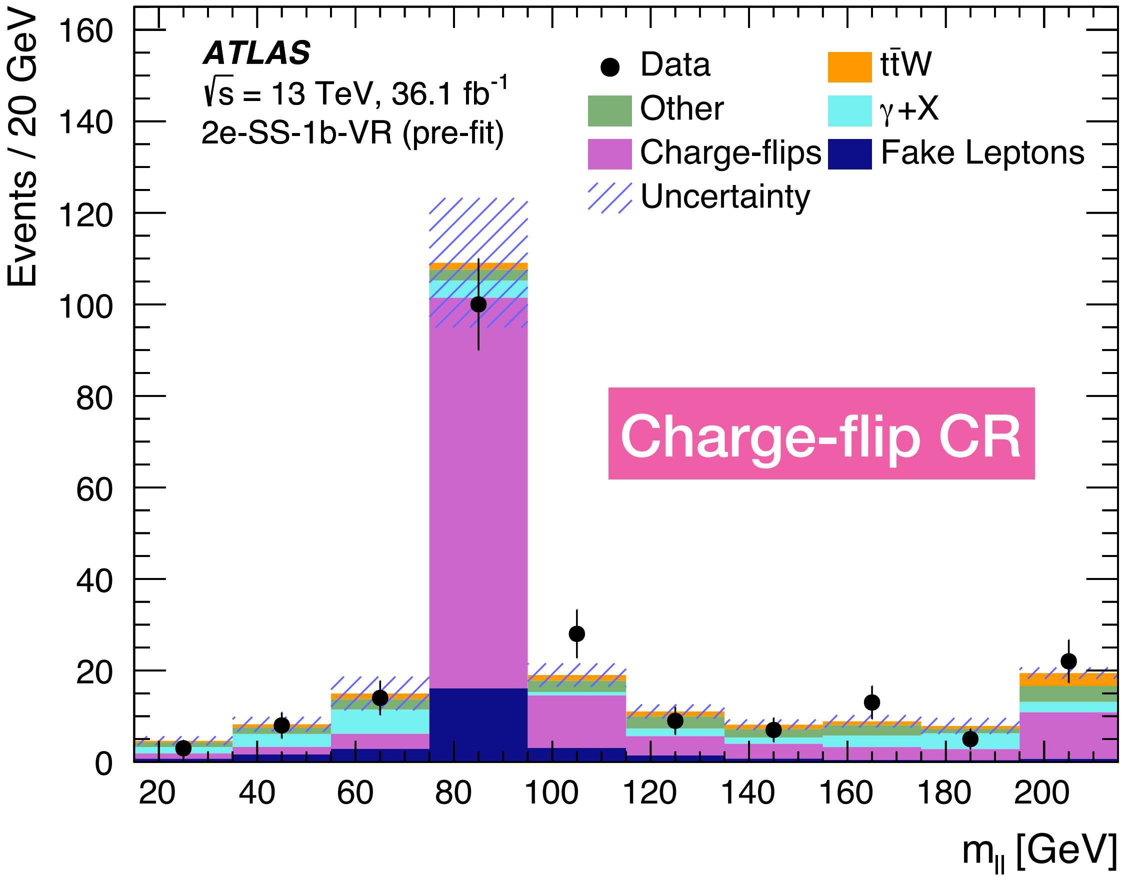
Backup Slides

$t\bar{t}W$ and $t\bar{t}Z$ from Atlas

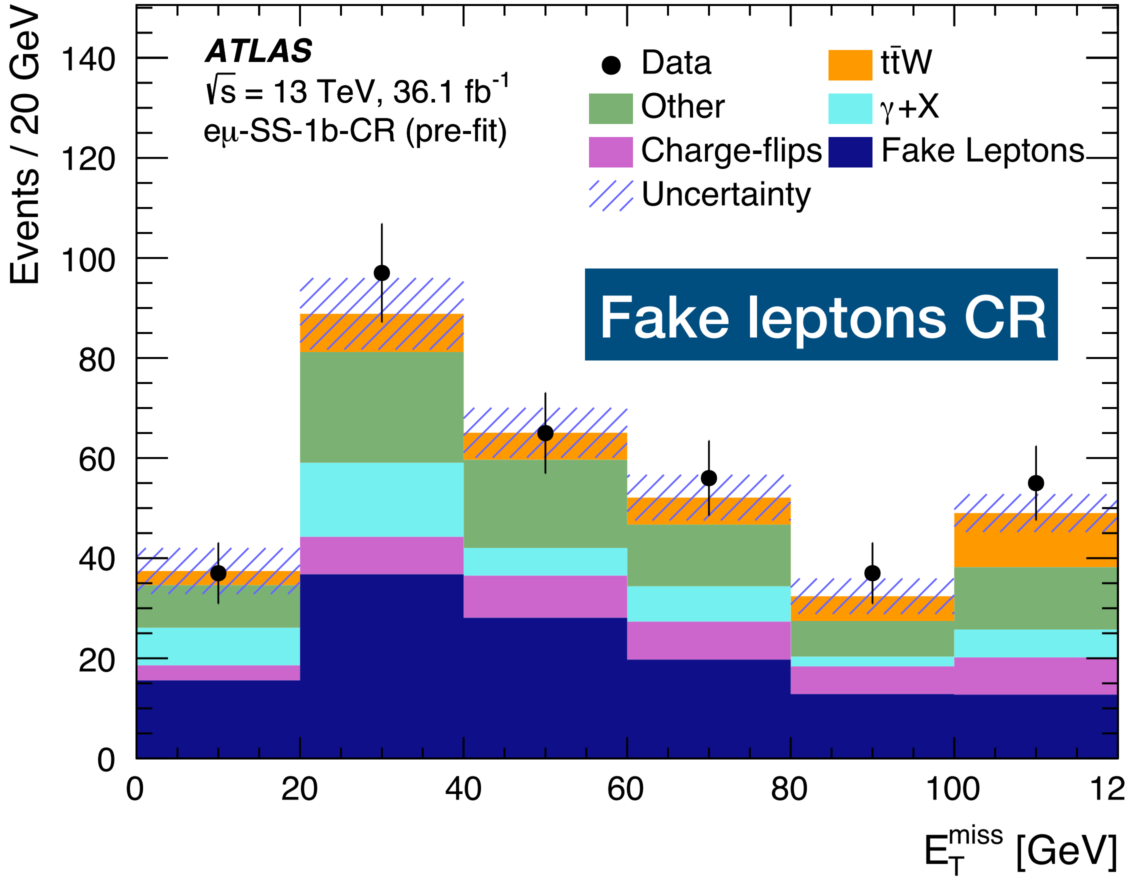
PRD 99 (2019) 072009

- **Data: 36.1 fb^{-1}. Use single lepton triggers.**
- MVA to distinguish prompt ℓ from nonprompt ℓ originating from hadron decays, γ conversions or jets misidentified.
- MVA to suppress misidentified electron charge (SS channel).
- Control regions to characterize backgrounds:
  - **Charge-flip CR**: remove charge requirement.
  - **Fake leptons CR**: matrix method (tight-to-loose likelihood)
  - Several orthogonal samples produced by inverting lepton charge or flavor, and N$_{\text{jets}}$
- Signal regions separated by N$_{\text{jets}}$, N$_{\text{b-jets}}$, lepton charge and flavor.

Processes (ℓ=e,μ)		Channel	Signal Regions
$W \rightarrow \ell\nu$	$t\bar{t} \rightarrow \ell + j$	SS2ℓ	12 (sign, flavor, N$_b$)
	$t\bar{t} \rightarrow$ dileptons	3ℓ	8 (sign, N$_j$, N$_b$)
$Z \rightarrow \ell\ell$	$t\bar{t} \rightarrow$ jets	OS2ℓ	4 (N$_j$, N$_b$)
	$t\bar{t} \rightarrow \ell + j$	3ℓ	8 (sign, N$_j$, N$_b$)
	$t\bar{t} \rightarrow$ dileptons	4ℓ	4 (flavor, Nj, N$_b$)

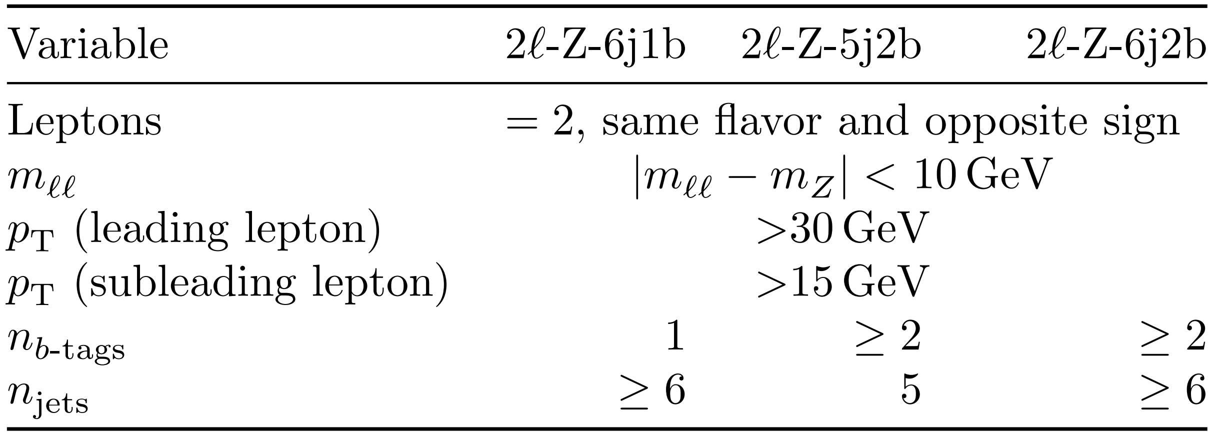


Charge-flip CR

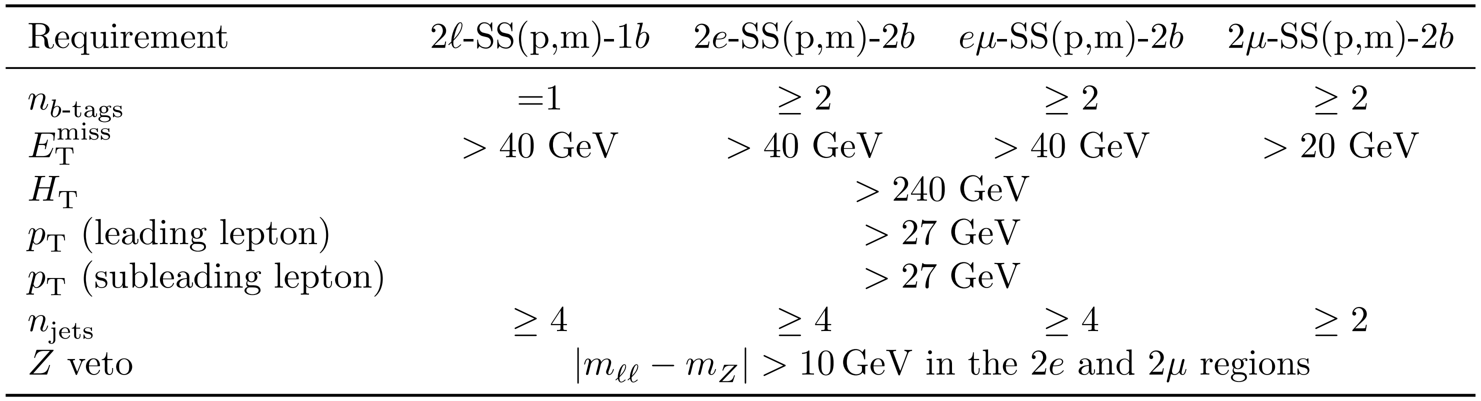


Fake leptons CR

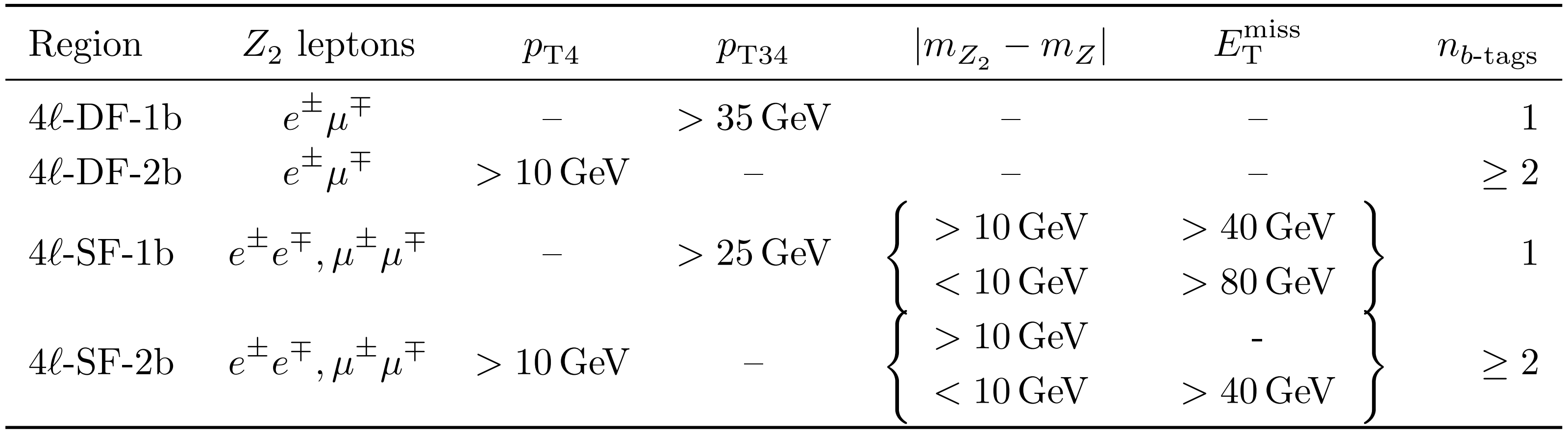
Atlas



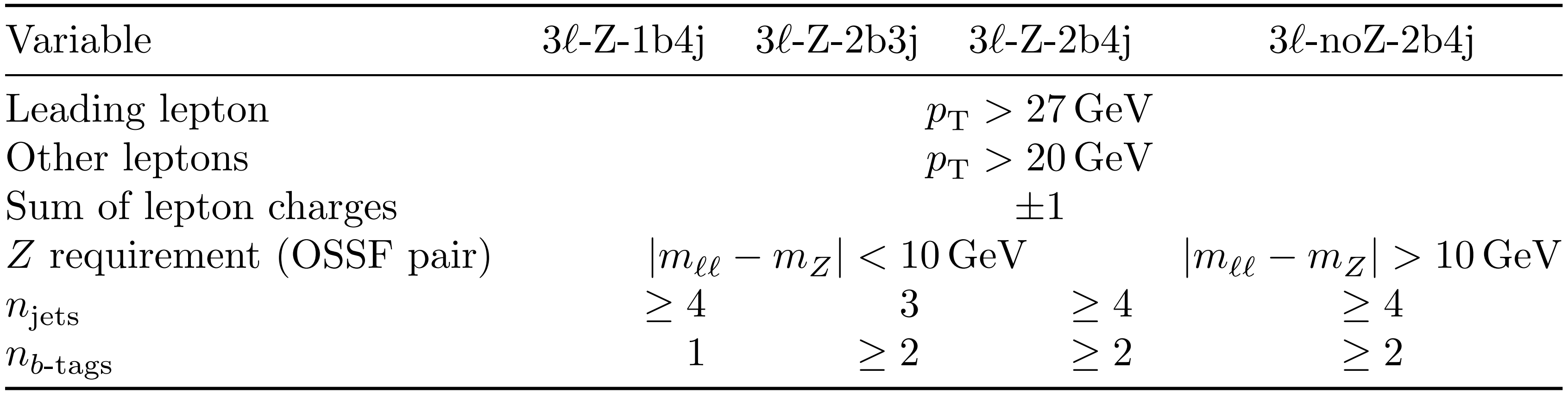
Variable	2ℓ-Z-6j1b	2ℓ-Z-5j2b	2ℓ-Z-6j2b
Leptons	$= 2$, same flavor and opposite sign		
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert < 10\,\mathrm{GeV}$		
p_{T} (leading lepton)	$>30\,\mathrm{GeV}$		
p_{T} (subleading lepton)	$>15\,\mathrm{GeV}$		
$n_{b\text{-tags}}$	1	≥ 2	≥ 2
n_{jets}	≥ 6	5	≥ 6



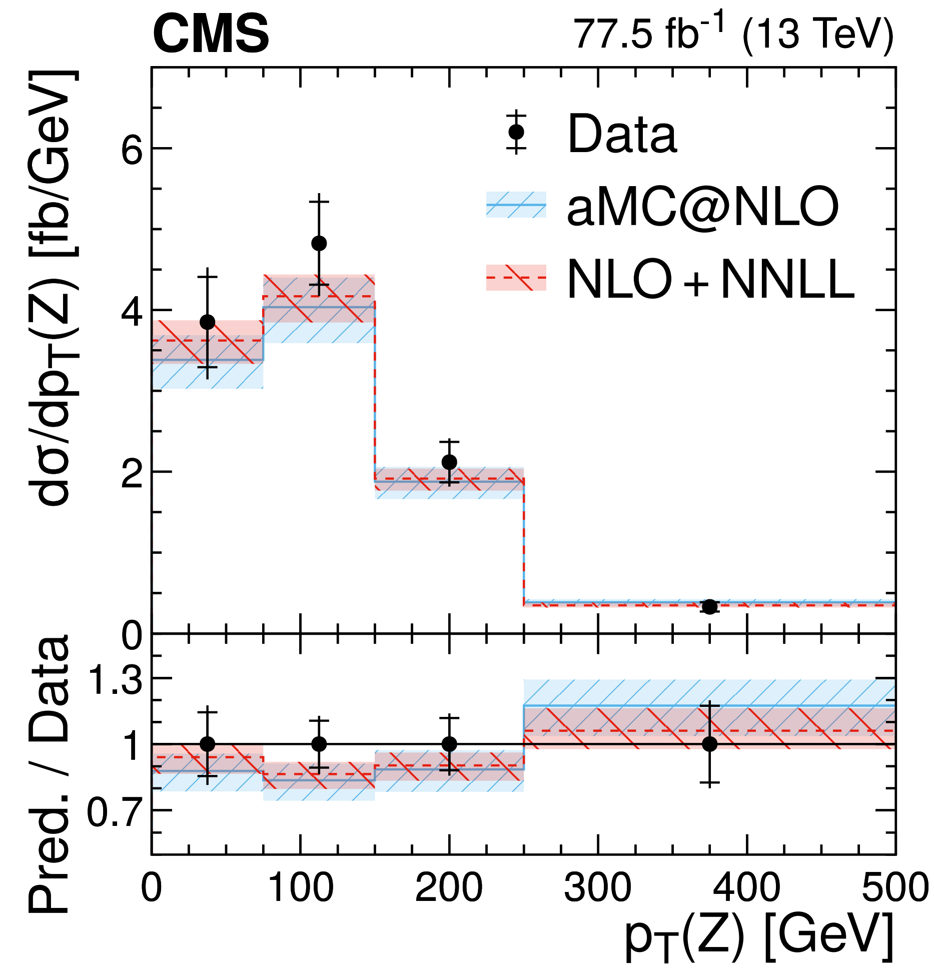
Requirement	2ℓ-SS(p,m)-1b	$2e$-SS(p,m)-2b	$e\mu$-SS(p,m)-2b	2μ-SS(p,m)-2b
$n_{b\text{-tags}}$	=1	≥ 2	≥ 2	≥ 2
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 40 GeV	> 40 GeV	> 40 GeV	> 20 GeV
H_{T}	> 240 GeV			
p_{T} (leading lepton)	> 27 GeV			
p_{T} (subleading lepton)	> 27 GeV			
n_{jets}	≥ 4	≥ 4	≥ 4	≥ 2
Z veto	$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\mathrm{GeV}$ in the $2e$ and 2μ regions			

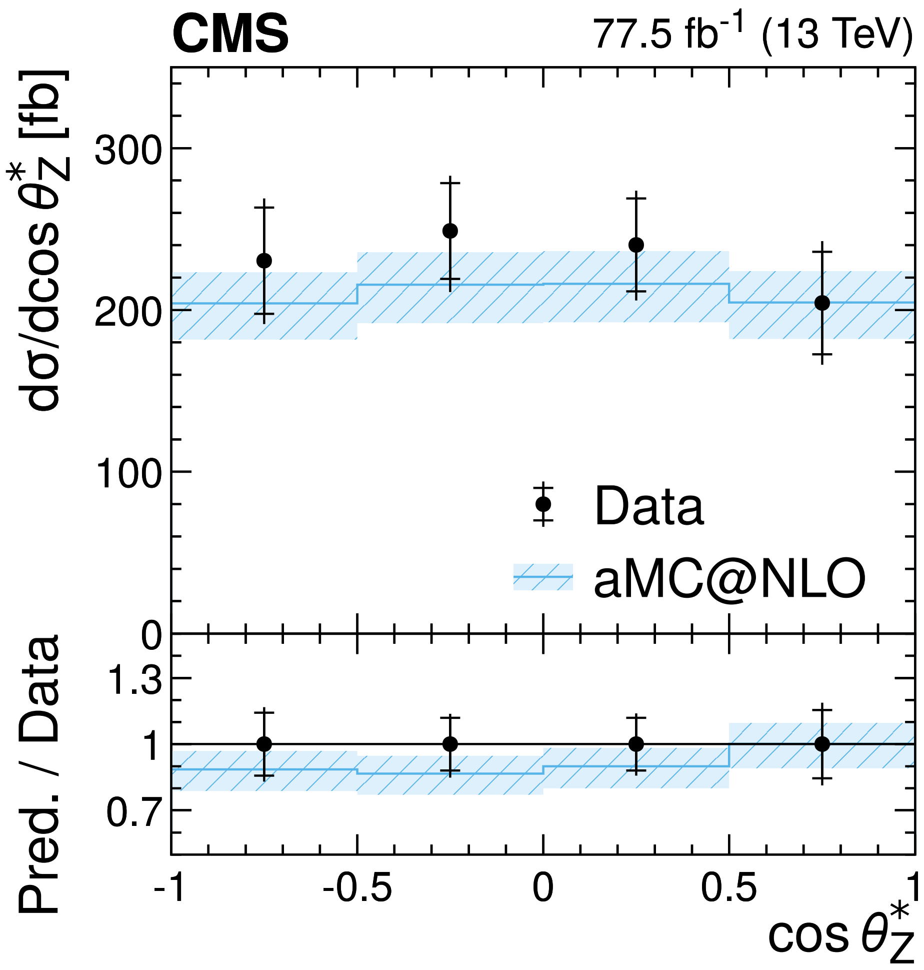


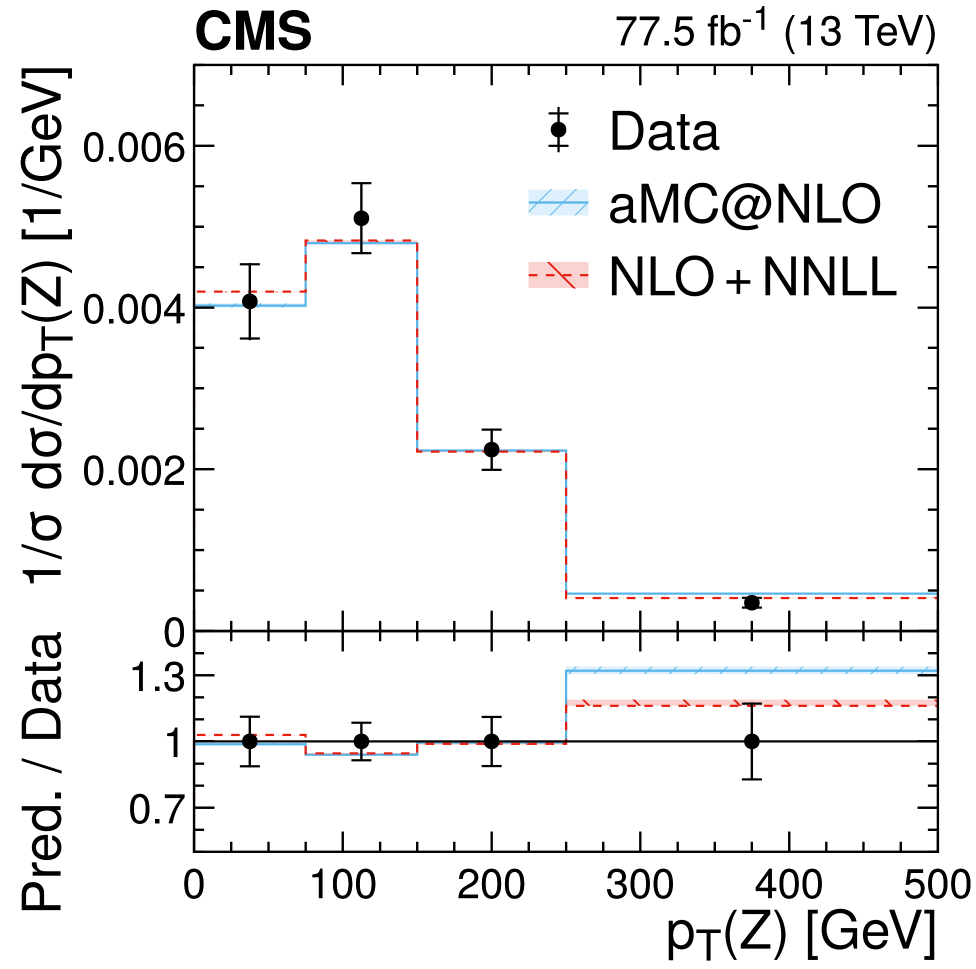
Region	Z_2 leptons	p_{T4}	p_{T34}	$\lvert m_{Z_2} - m_Z \rvert$	$E_{\mathrm{T}}^{\mathrm{miss}}$	$n_{b\text{-tags}}$
4ℓ-DF-1b	$e^{\pm}\mu^{\mp}$	–	> 35 GeV	–	–	1
4ℓ-DF-2b	$e^{\pm}\mu^{\mp}$	> 10 GeV	–	–	–	≥ 2
4ℓ-SF-1b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	–	> 25 GeV	> 10 GeV < 10 GeV	> 40 GeV > 80 GeV	1
4ℓ-SF-2b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	> 10 GeV	–	> 10 GeV < 10 GeV	- > 40 GeV	≥ 2

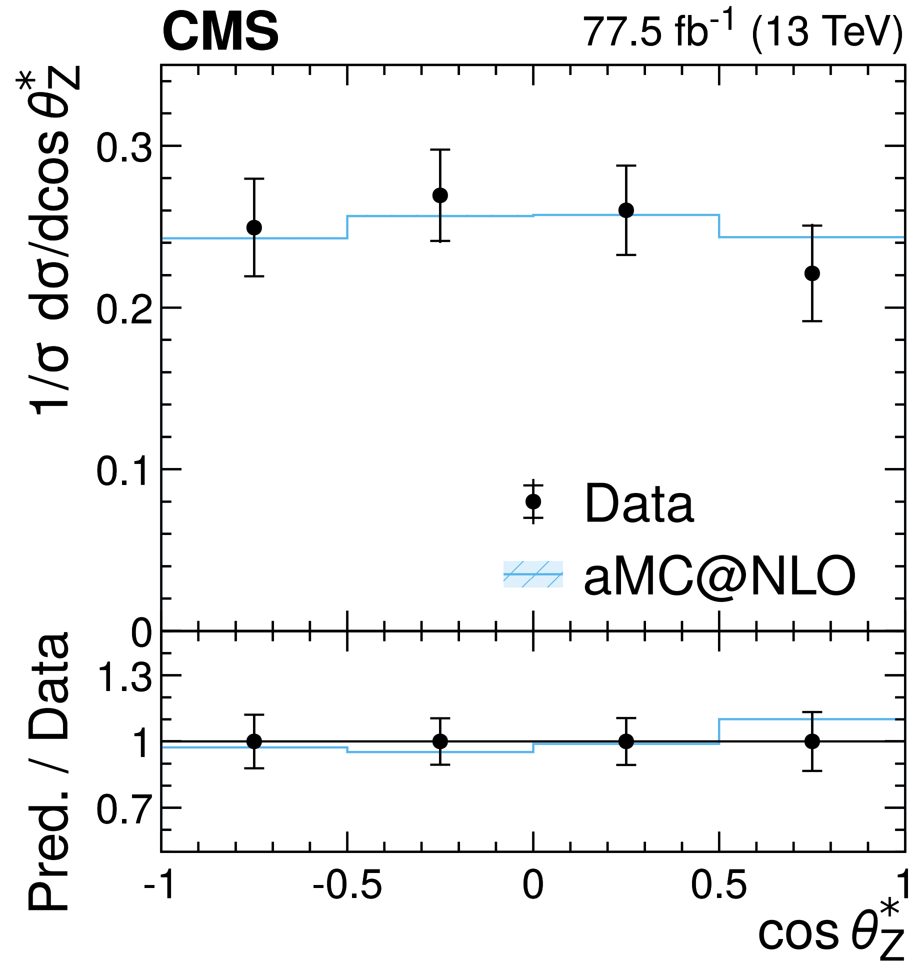


Variable	3ℓ-Z-1b4j	3ℓ-Z-2b3j	3ℓ-Z-2b4j	3ℓ-noZ-2b4j
Leading lepton	$p_{\mathrm{T}} > 27\,\mathrm{GeV}$			
Other leptons	$p_{\mathrm{T}} > 20\,\mathrm{GeV}$			
Sum of lepton charges	± 1			
Z requirement (OSSF pair)	$\lvert m_{\ell\ell} - m_Z \rvert < 10\,\mathrm{GeV}$			$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\mathrm{GeV}$
n_{jets}	≥ 4	3	≥ 4	≥ 4
$n_{b\text{-tags}}$	1	≥ 2	≥ 2	≥ 2

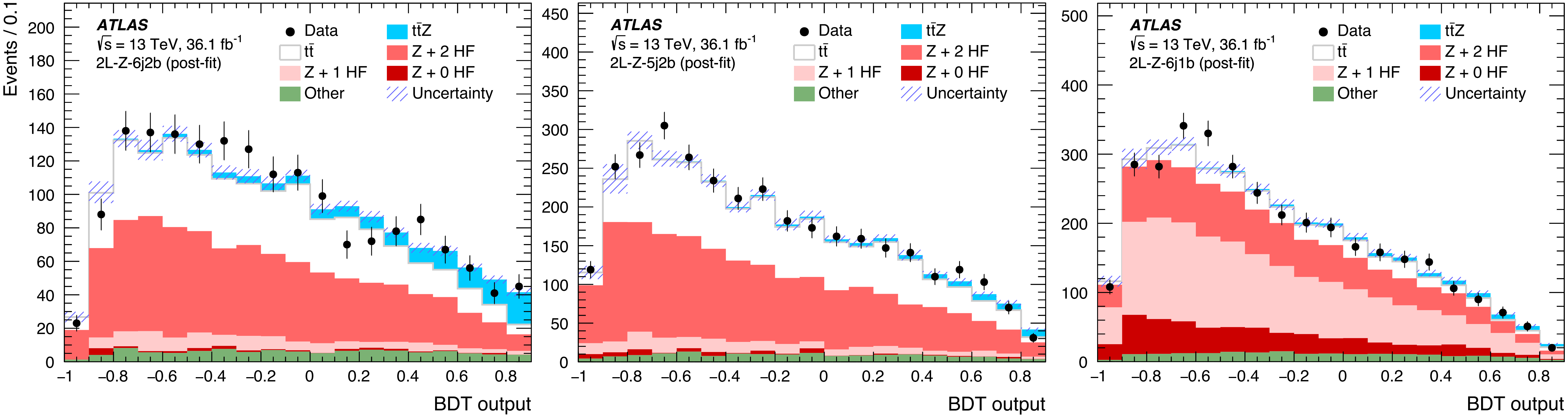

CMS
77.5 fb^{-1} (13 TeV)
Data
aMC@NLO
NLO + NNLL
$d\sigma/dp_T(Z)$ [fb/GeV]
Pred. / Data
0
2
4
6
0.7
1
1.3
0
100
200
300
400
500
$p_T(Z)$ [GeV]


CMS
77.5 fb^{-1} (13 TeV)
Data
aMC@NLO
$d\sigma/d\cos\theta^*_Z$ [fb]
Pred. / Data
0
100
200
300
0.7
1
1.3
-1
-0.5
0
0.5
1
$\cos\theta^*_Z$


CMS
77.5 fb^{-1} (13 TeV)
Data
aMC@NLO
NLO + NNLL
$1/\sigma\ d\sigma/dp_T(Z)$ [1/GeV]
Pred. / Data
0
0.002
0.004
0.006
0.7
1
1.3
0
100
200
300
400
500
$p_T(Z)$ [GeV]


CMS
77.5 fb^{-1} (13 TeV)
Data
aMC@NLO
$1/\sigma\ d\sigma/d\cos\theta^*_Z$
Pred. / Data
0
0.1
0.2
0.3
0.7
1
1.3
-1
-0.5
0
0.5
1
$\cos\theta^*_Z$

Opposite-Sign Dilepton (OS2ℓ, ttZ)



- Slides in progress ….