High-mass resonances searches with leptons

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ATLAS EXPERIMENT

CMS Compact Muon Solenoid

WEIZMANN INSTITUTE OF SCIENCE

LHCP 2019, Puebla, Mexico

Outline

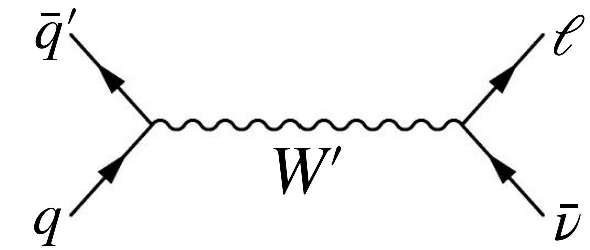
- Introduction

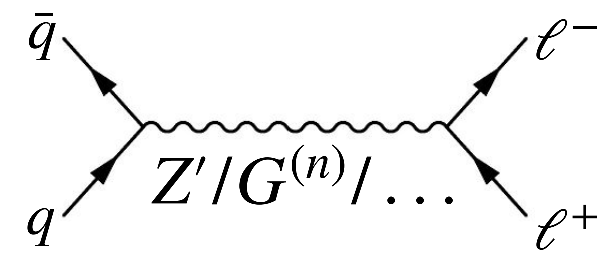
- Focus on Z', W', Heavy neutrinos and Multilepton searches
  - ATLAS $Z'\longrightarrow\ell\ell$ search, 139 fb^{-1} [arXiv:1903.06248] NEW!
  - CMS $Z'\longrightarrow\ell\ell$ search, 36 fb^{-1} [JHEP 06 (2018) 120, JHEP 04 (2019) 114]
  - ATLAS $W'\longrightarrow\ell\nu$ search, 139 fb^{-1} [soon] NEW!
  - ATLAS $W_R\longrightarrow\ell N_R\longrightarrow\ell\ell qq$ search, 80 fb^{-1} [arXiv:1904.12679] NEW!
  - CMS Multilepton search 137 fb^{-1} [CMS-PAS-EXO-19-002] NEW!

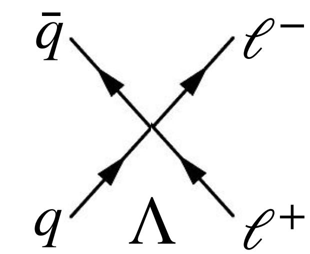
- Outlook

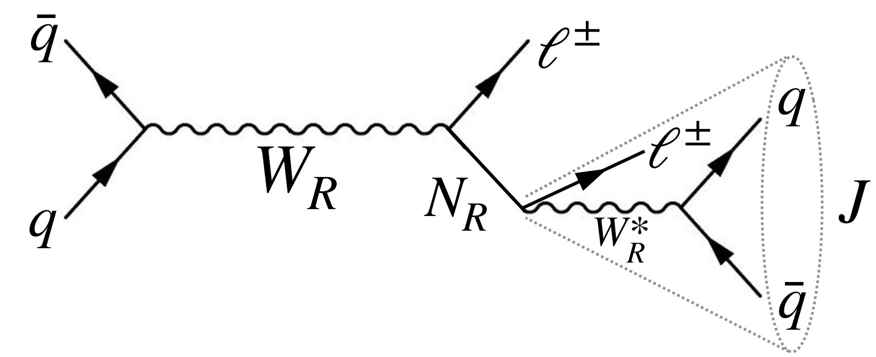
Motivation

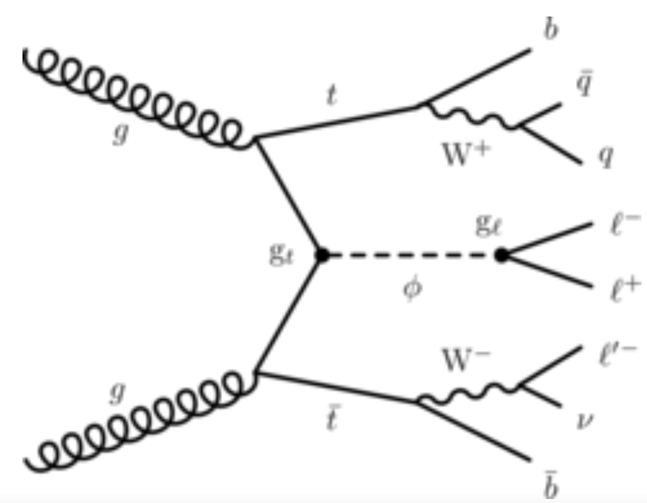
- Some well known SM extensions featuring new heavy resonances
- Also well known new types of non-resonant interactions
- Coupling to leptons provide the cleanest signatures for searches
  - selection *usually* straightforward
- Not many fresh models for “standard” resonances
  - several relatively new models motivated by the flavour-anomalies
- Recent models suggest completely new signatures, e.g. the *clockwork* theory [JHEP 1806 (2018) 009]

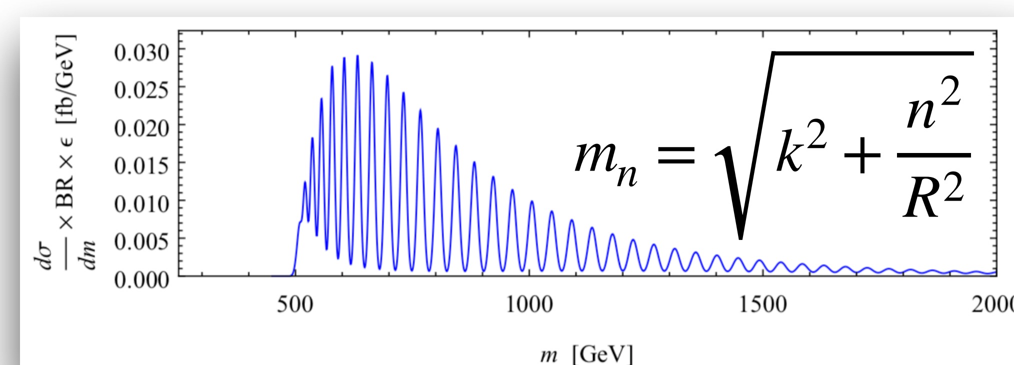












What’s new experimentally?

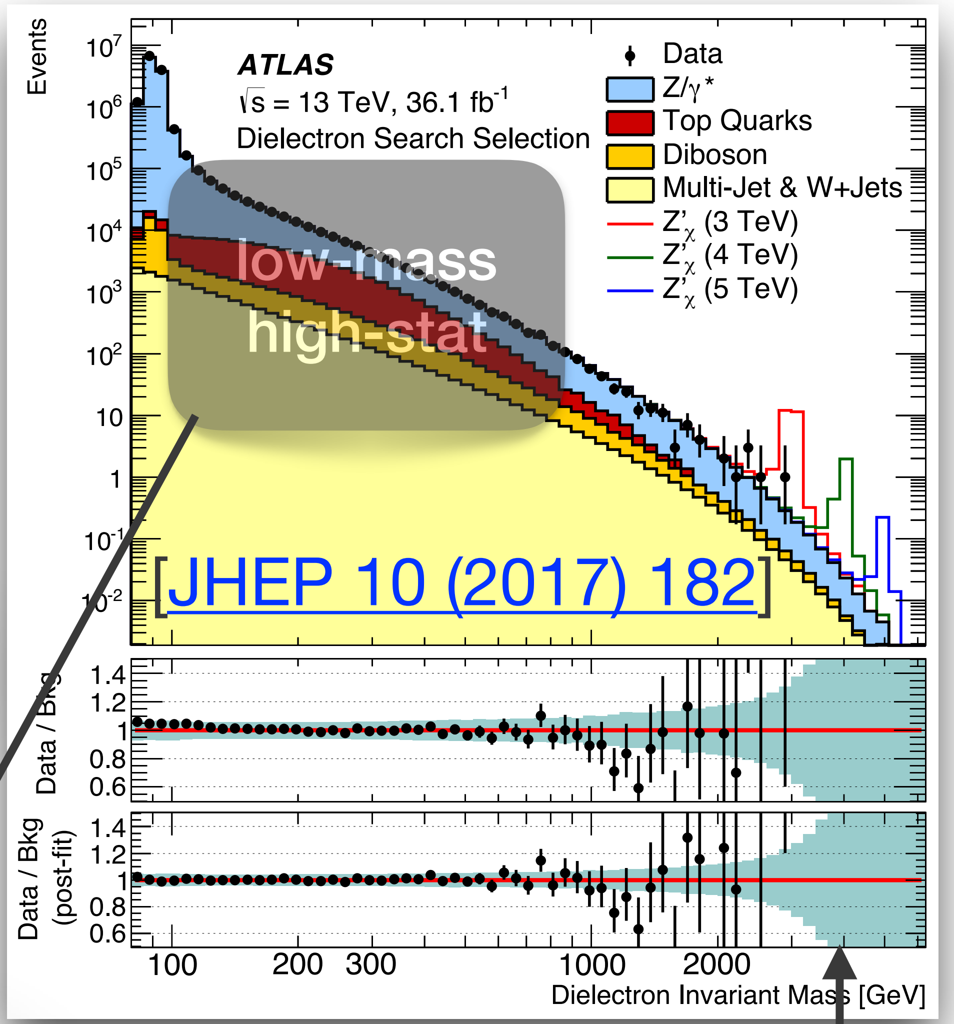
Yes, much more data plus some incremental improvements, but what’s besides that?

increased luminosity is great, but also poses some problems for searches!

- Keep the “high-stat end” in tune
- FullSim MC has to grow significantly
  - storage, processing, modelling…
- Can we work around that?

need at least $N_{MC} \gtrsim 100 \times N_{data}$ to keep the stat error ratio below 10% ⟶ difficult at low masses

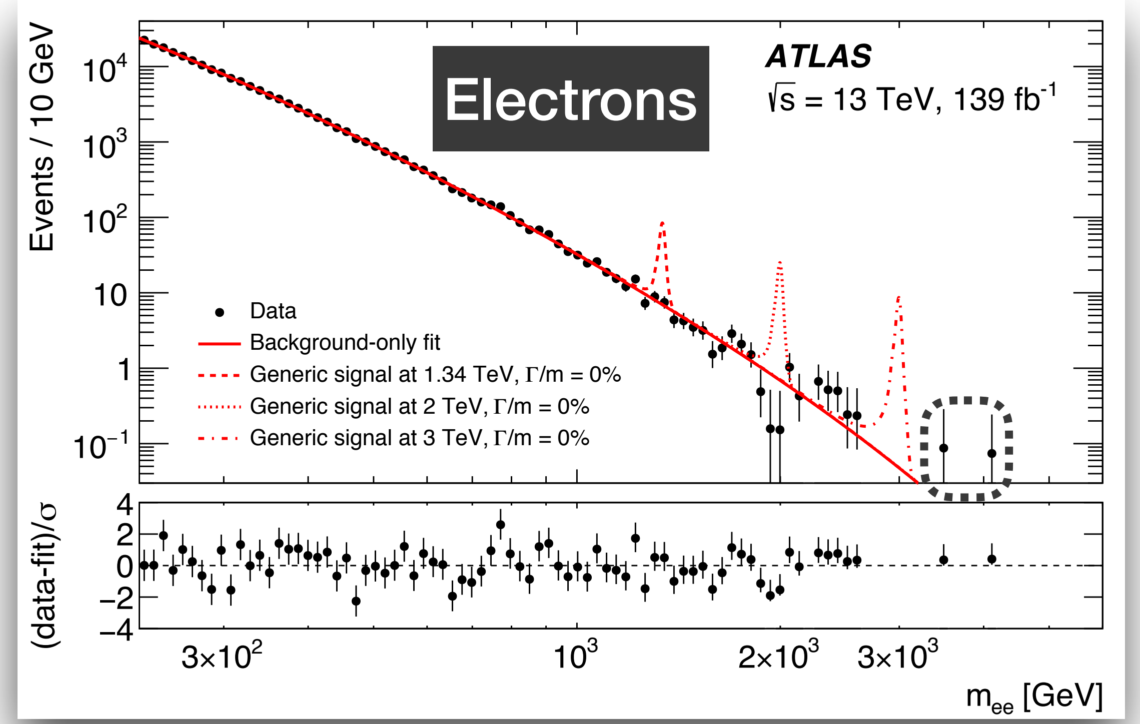
ATLAS dilepton, 36 fb^{-1}, 2015-2016

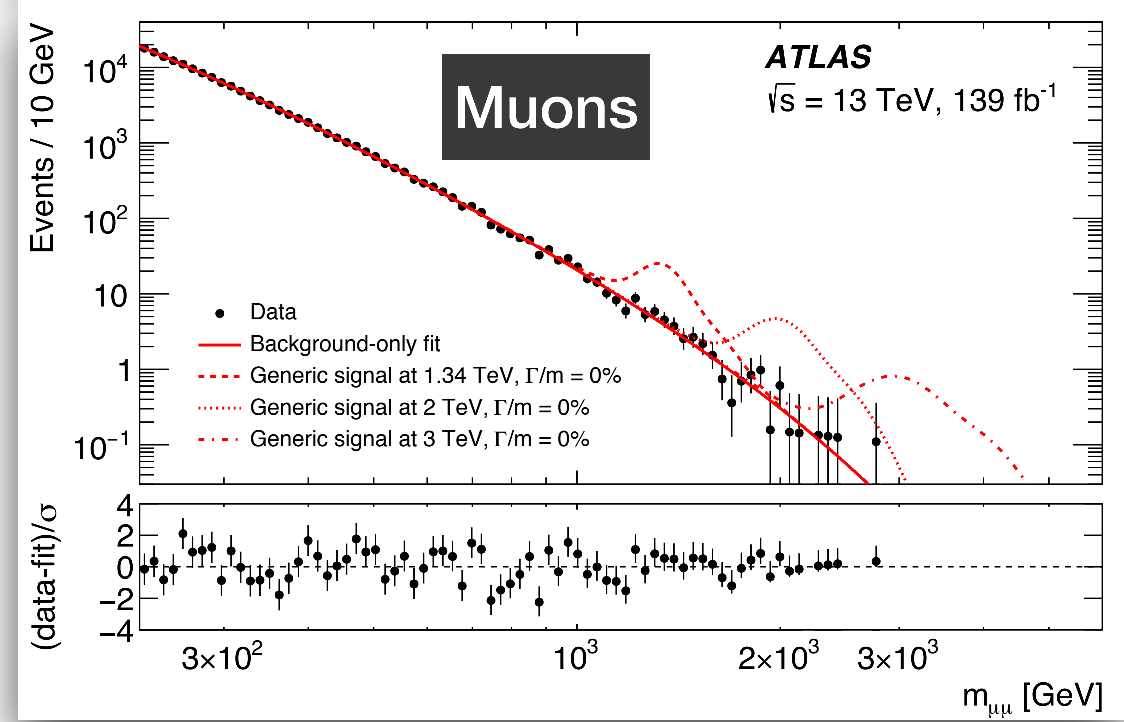


Limit on m(Z'_ψ) at ~3.8 TeV from both ATLAS & CMS

ATLAS $Z' \to \ell\ell$ search with 139 fb^{-1}

- **Bkg model: fit $m_{\ell\ell}$ spectra in data**
  - search from 250 GeV up to 6 TeV
  - MC is still used - see backup
- **Generic signal shapes**
  - Breit-Wigner⊗Resolution
- **Full response description**
  - efficiency and resolution vs $m_{\ell\ell}^{tru}$
  - allows easy reinterpretations
- **Limits** placed on the fiducial $\sigma \times \mathscr{B}$
  - for various widths
  - applicable to spin-0/1/2 signals
  - converted for a set of benchmarks (E6, HVT, SSM,…)



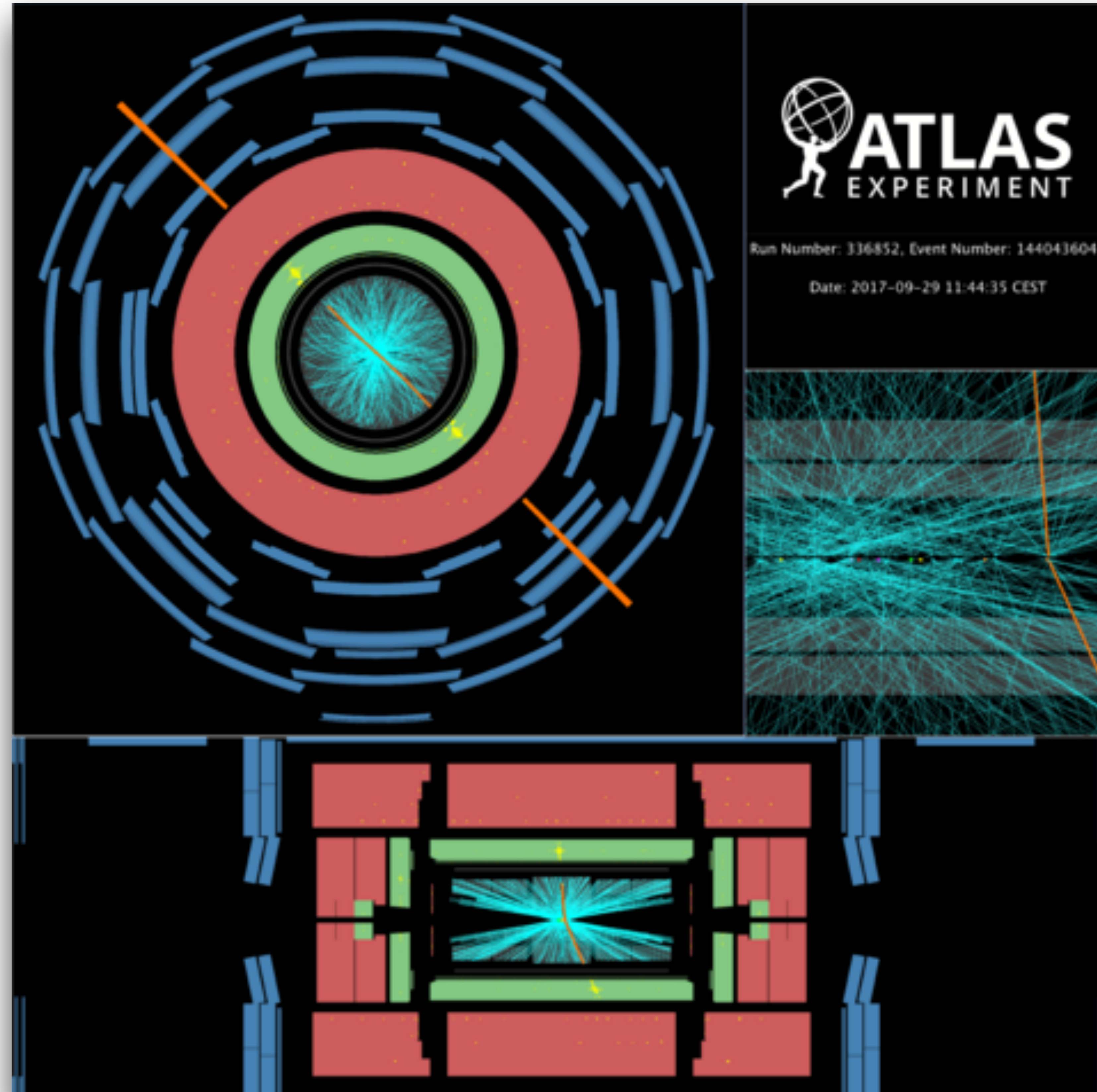


$$\mathscr{F} = Z_0(m_{\ell\ell}) \cdot \left(1 - x^c\right)^b \cdot x^{\sum p_n \log^n(x)}$$

$$x = m_{\ell\ell}/\sqrt{s},\ \ n = 0,\ldots,3$$

ATLAS $Z' \to \ell\ell$ search with 139 fb^{-1}

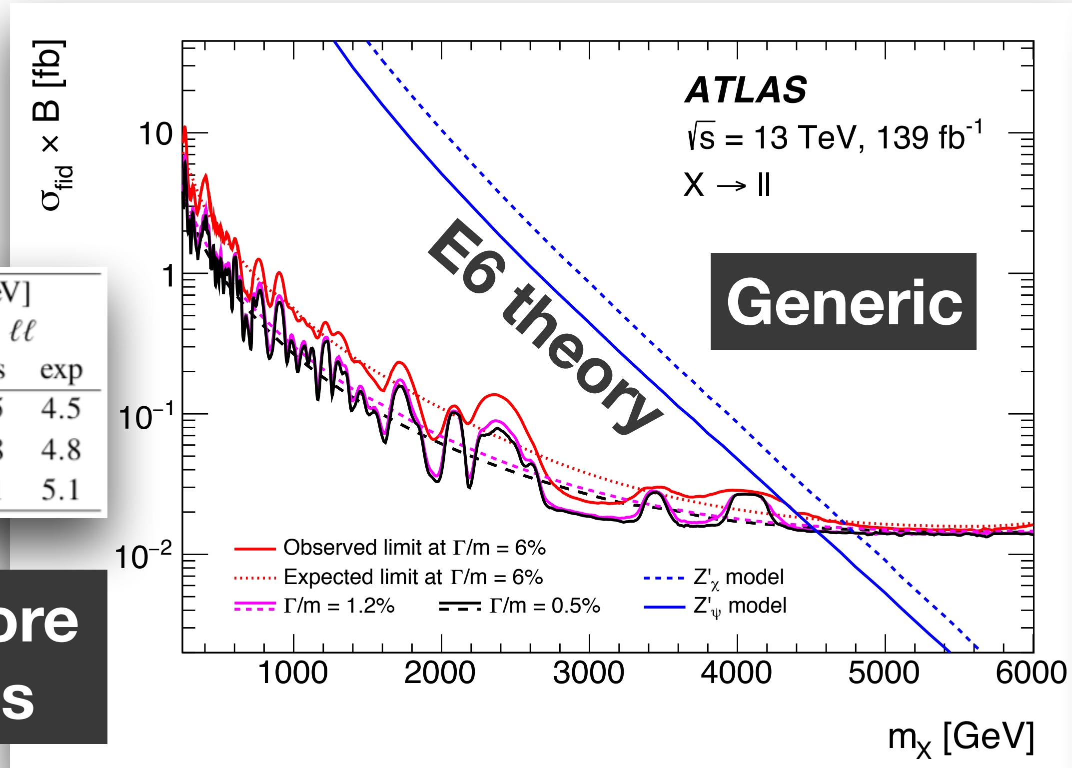
- **Most massive $\ell^+\ell^-$ event ever recorded!**
- m_{ee} = 4.06 TeV
- Leading electron
  - E_T = 2.01 TeV
  - η = 0.47
  - ϕ = -0.78
- Subleading electron
  - E_T = 1.92 TeV
  - η = -0.03
  - ϕ = 2.37

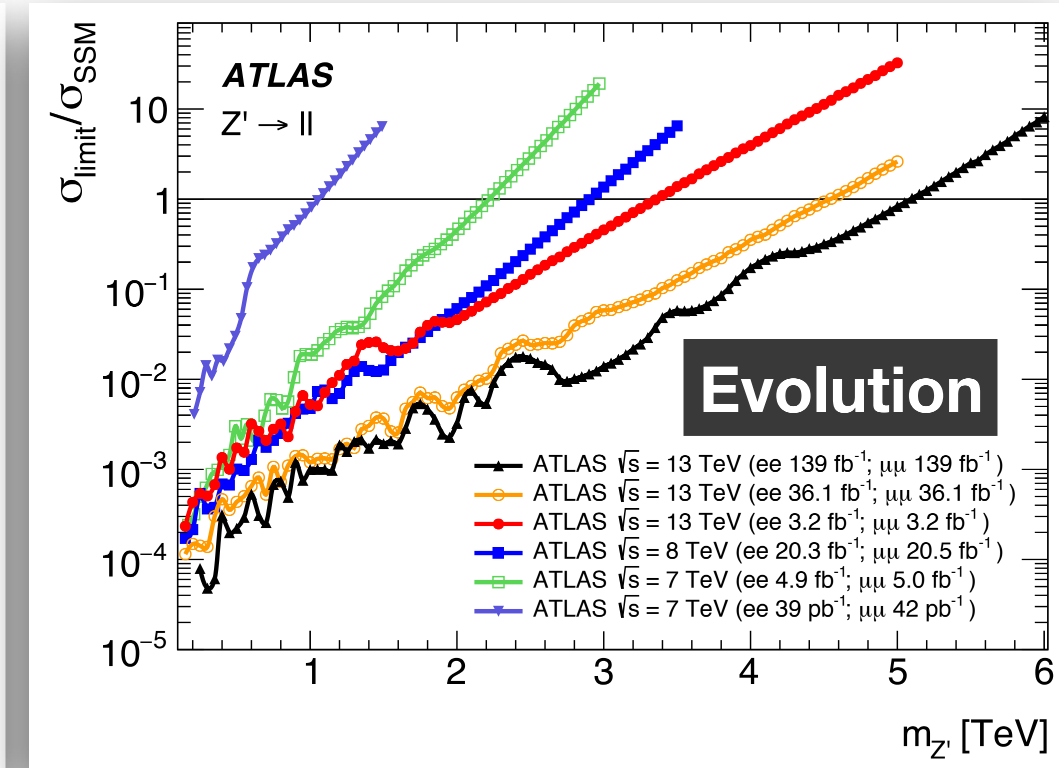


ATLAS $Z' \to \ell\ell$ search with 139 fb^{-1}

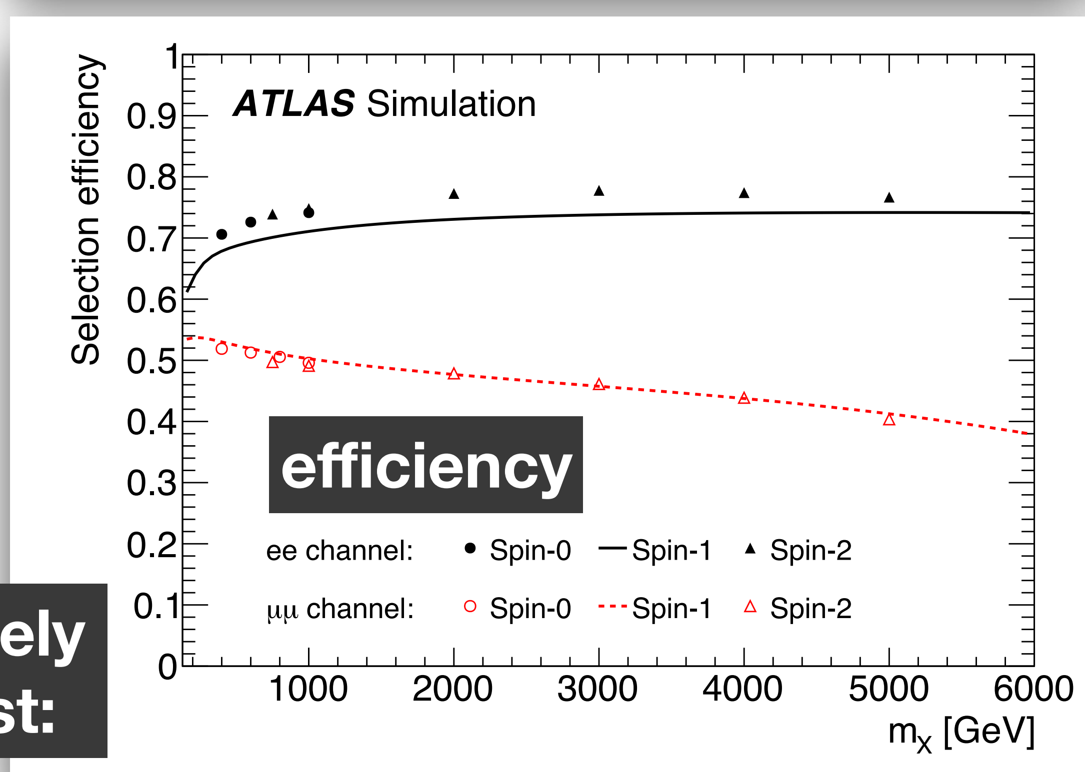
Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

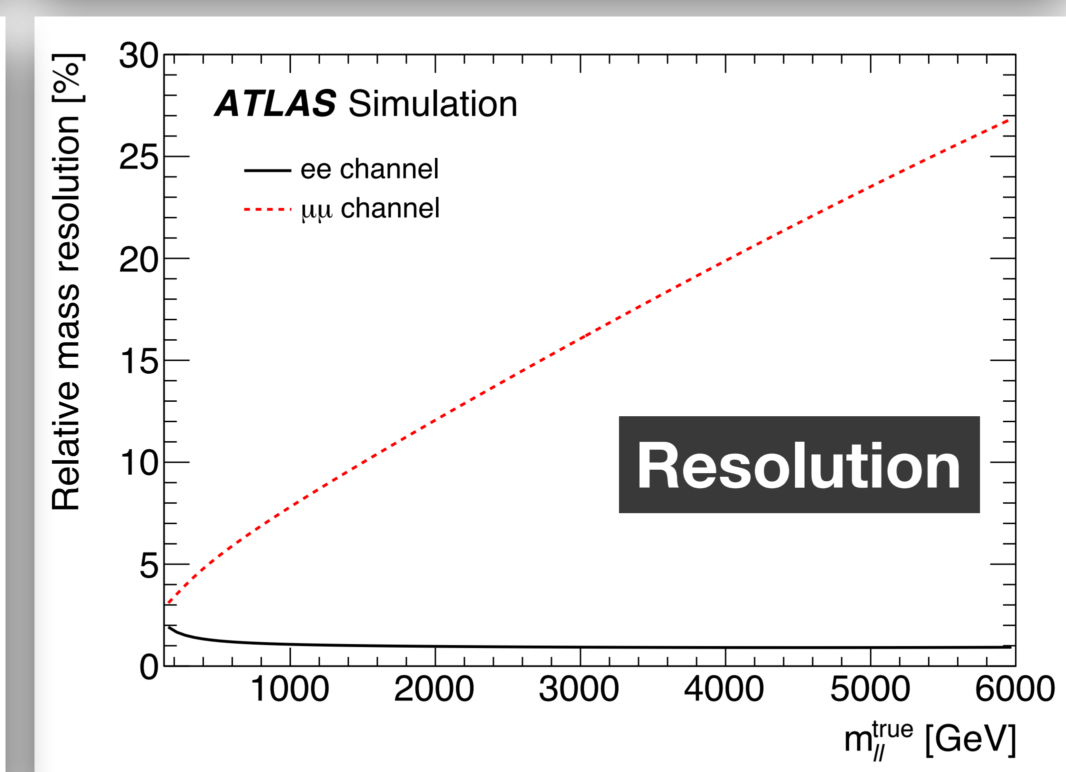
plus several more interpretations





but more uniquely than in the past:



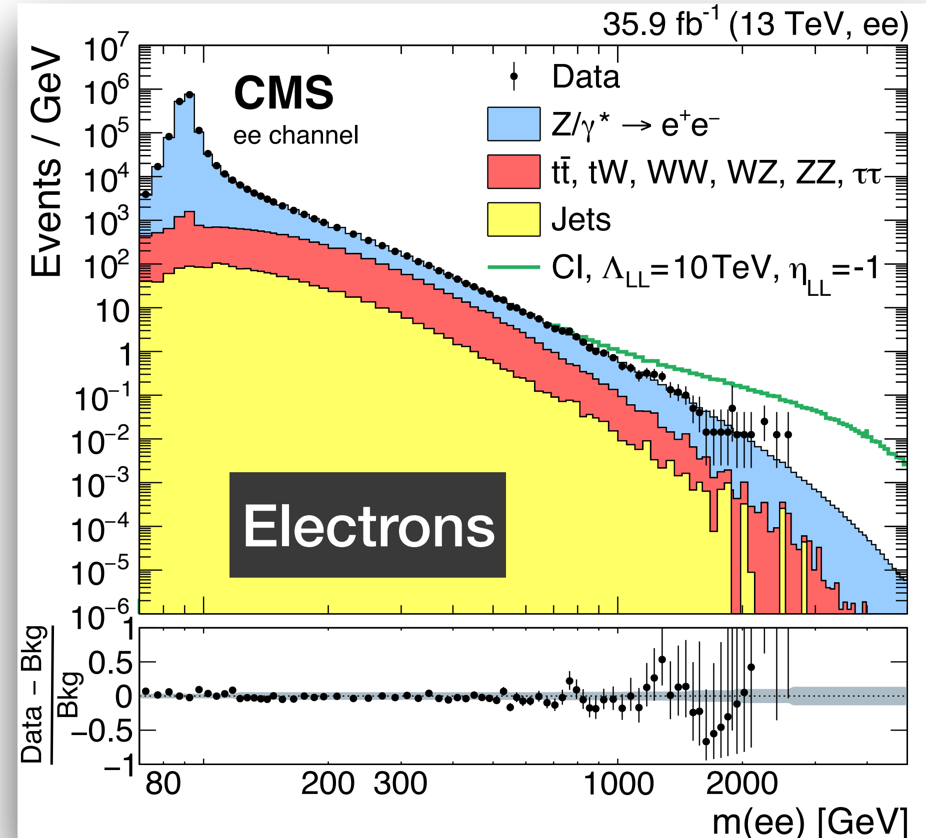


CMS $\ell\ell$ search with 36 fb^{-1}

- Based on MC
- **Resonant**
  - expect full Run2 result to be out soon
- **Non-resonant**

$$\frac{d\sigma_{X\to\ell\ell}}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} + \eta_X \mathcal{I}(m_{\ell\ell}) + \eta_X^2 \mathcal{S}(m_{\ell\ell})$$

$$\eta_X = -\frac{\eta_{ij}}{\Lambda_{ij}^2}$$



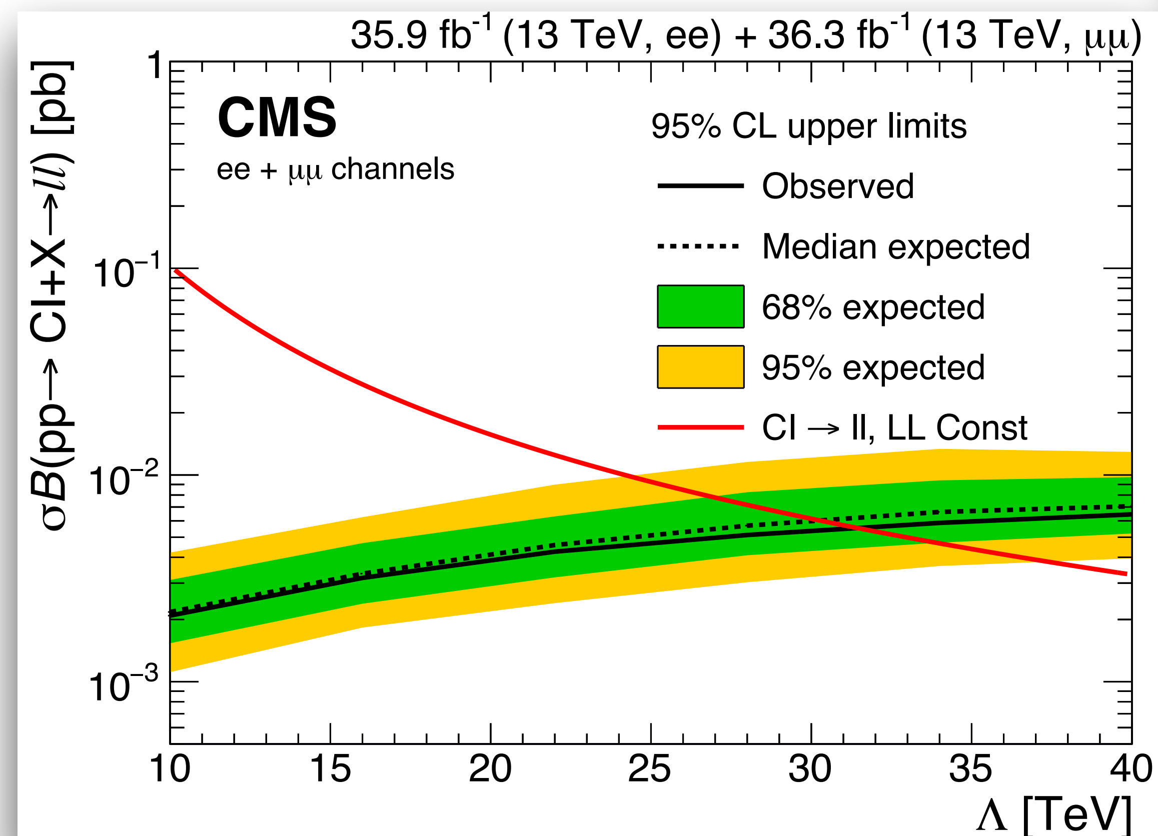
Limits:

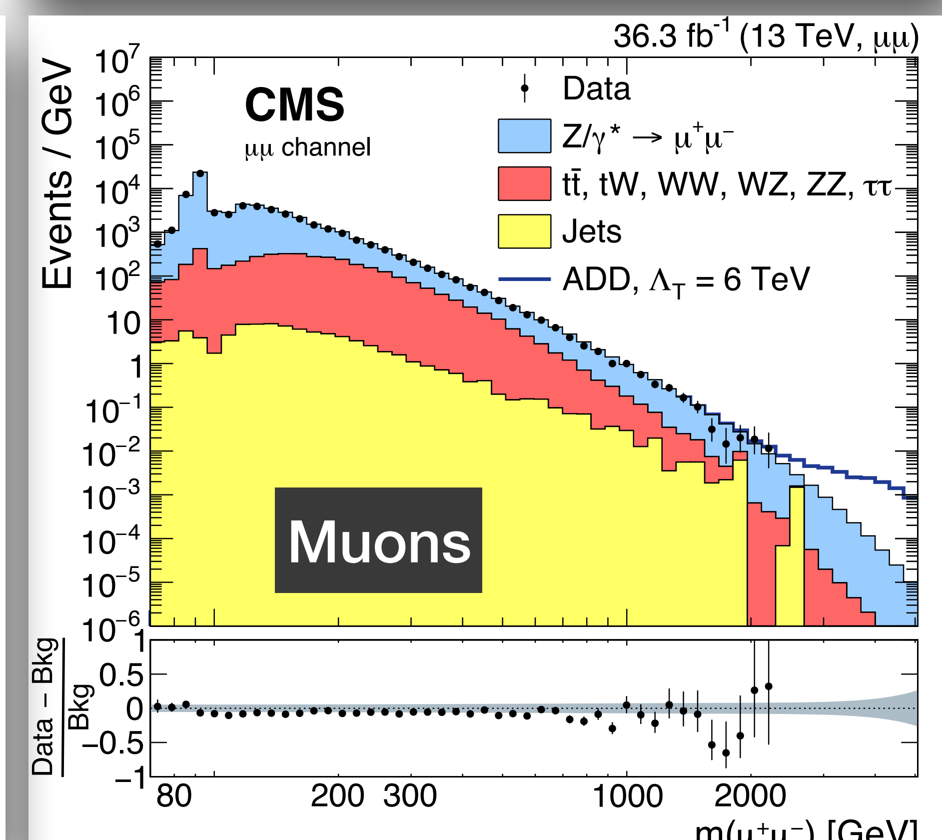
Λ_{LL}>20 TeV (destructive)

↓

Λ_{RR}>32 TeV (constructive)

and more! (ADD etc)



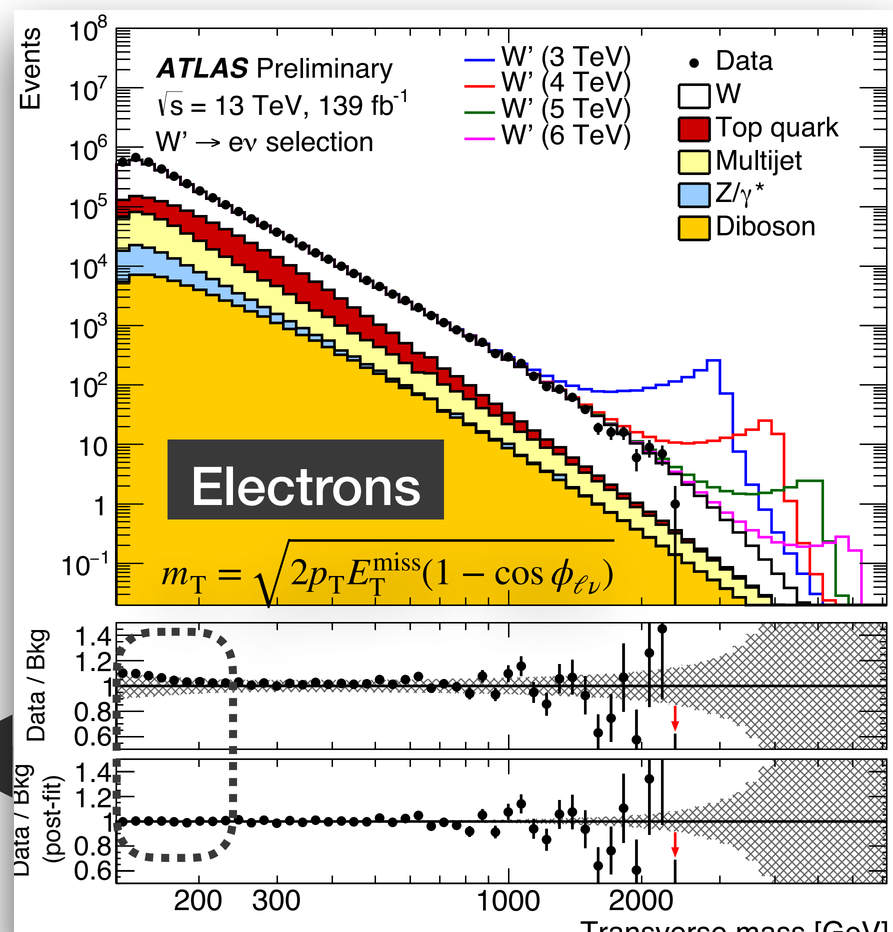


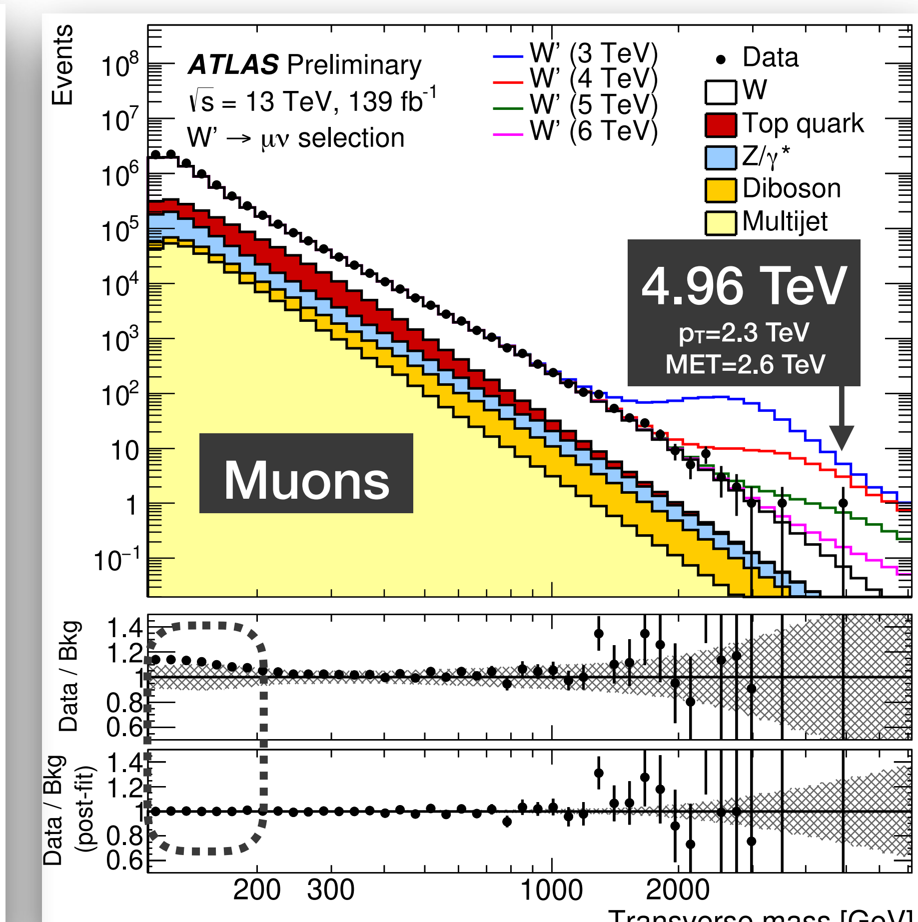
ATLAS $W' \to \ell\nu$ search with 139 fb^{-1}

- The low-m_T region re-included (was 300, now 150 GeV)
- Added single-bin (cross section) and generic (Γ/M=1-15%) limits
- MC used for all bkgs except for fake electrons contributions
  - ttbar and diboson smoothed and extrapolated
- E_T^{miss}: $|\Sigma_{vec} p_T$(signal leptons + photons + jets)$|$+(soft term)
- Large uncertainties in the bkg at high m_T have little impact (tiny stat…)

Reduce disagreement at low mass due to:

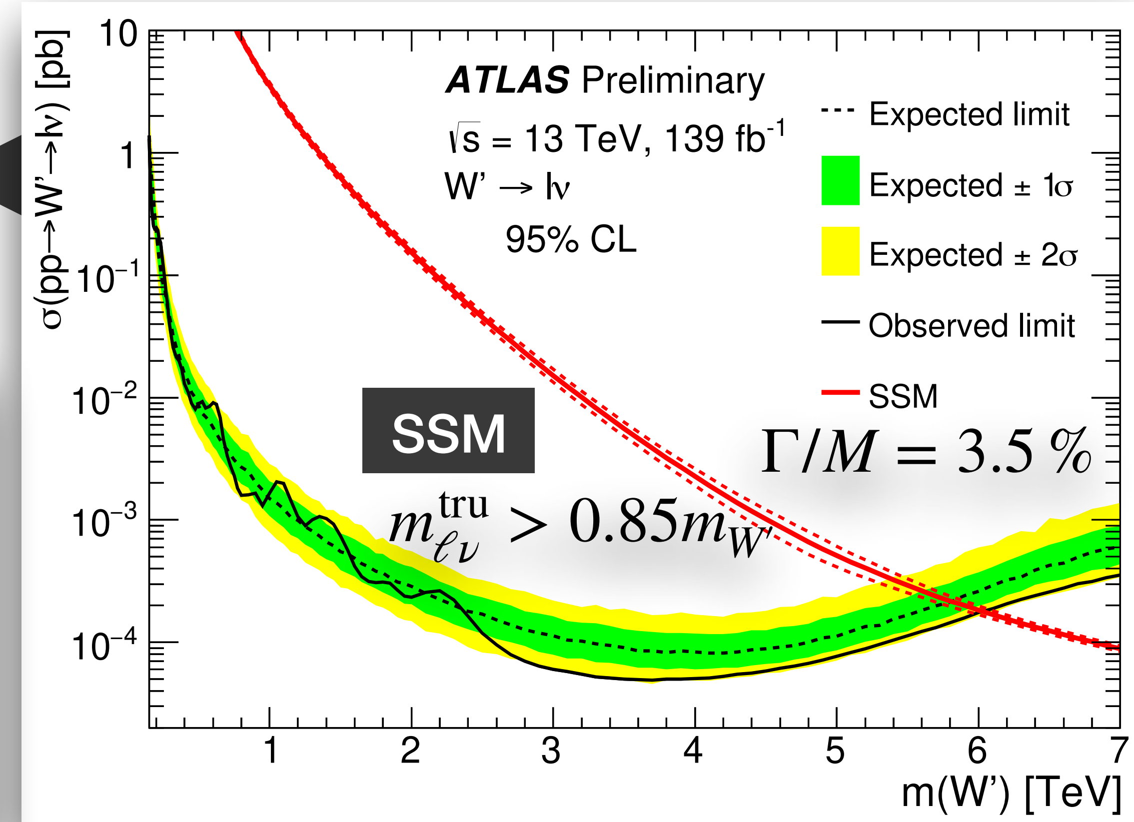
- jet energy resolution
- E_T^{miss} trk soft term



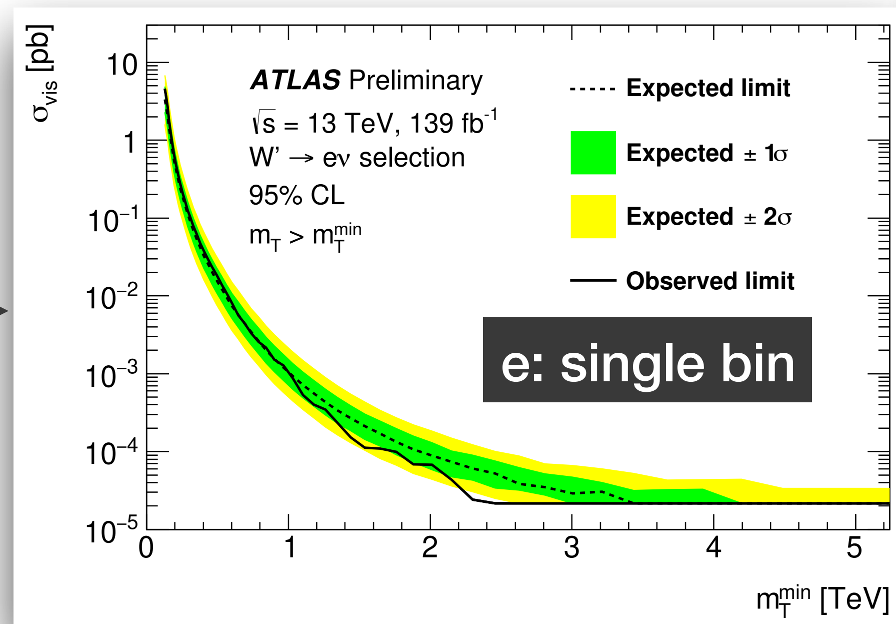


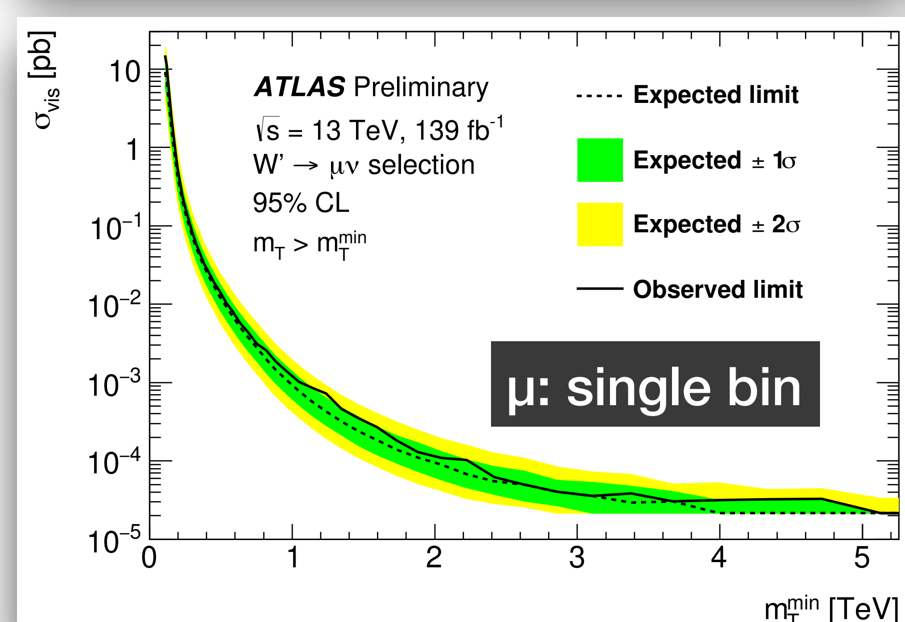
ATLAS $W'\to\ell\nu$ search with 139 fb^{-1}

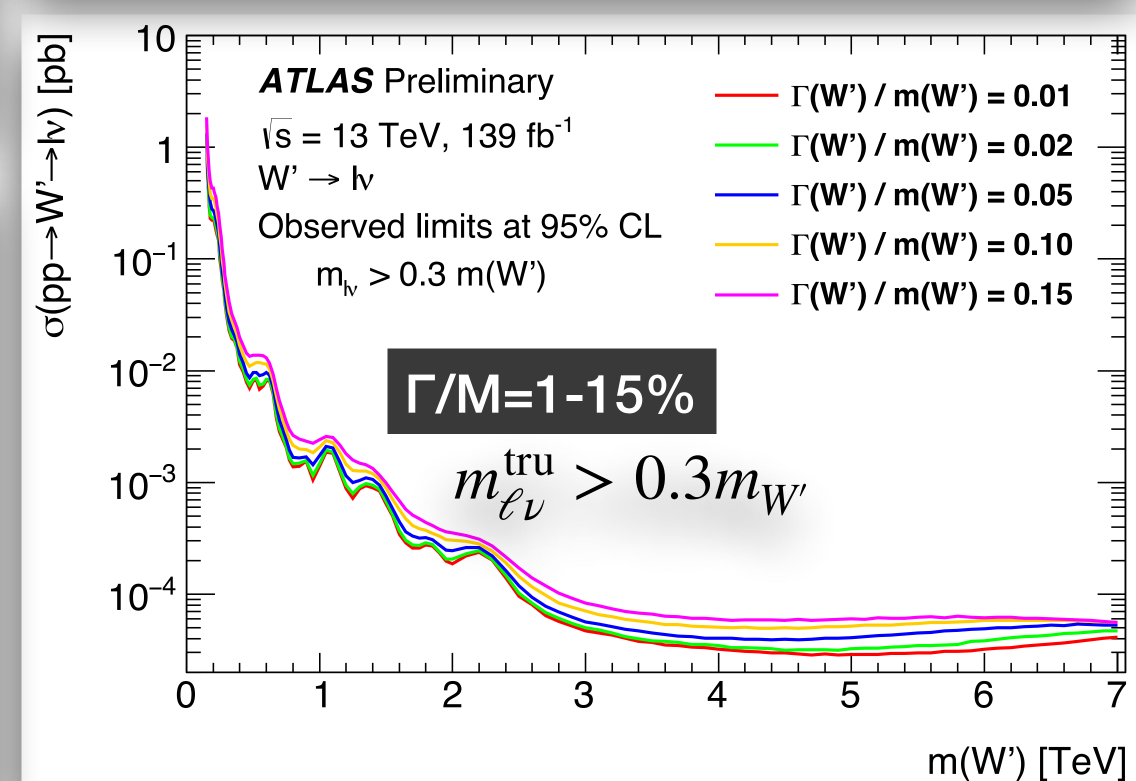
$m_{W'}$ > 6 (5.8) TeV, dominated by the electron channel



- Limits on $\sigma_{vis} = N_{sig}/L$
- different m_T^{min} thresholds
- different $\mathcal{A}\times\varepsilon$ (already in N_{sig})
- provide full binned info

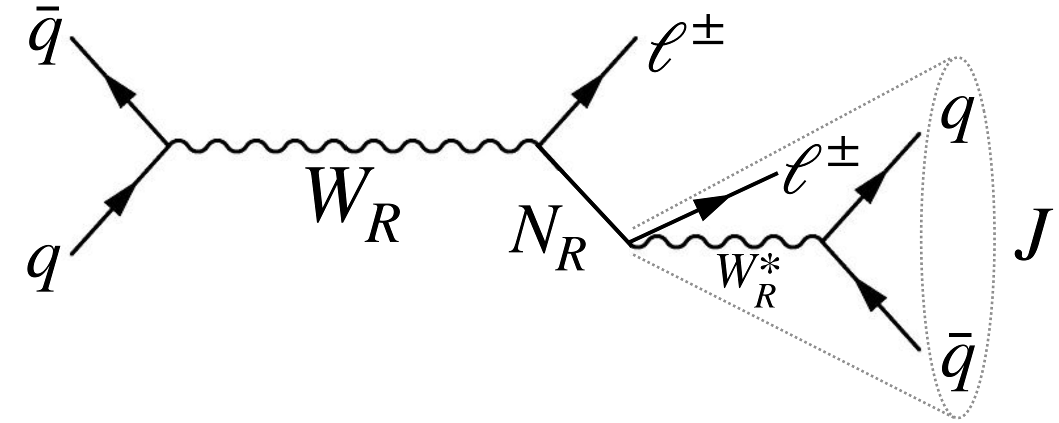




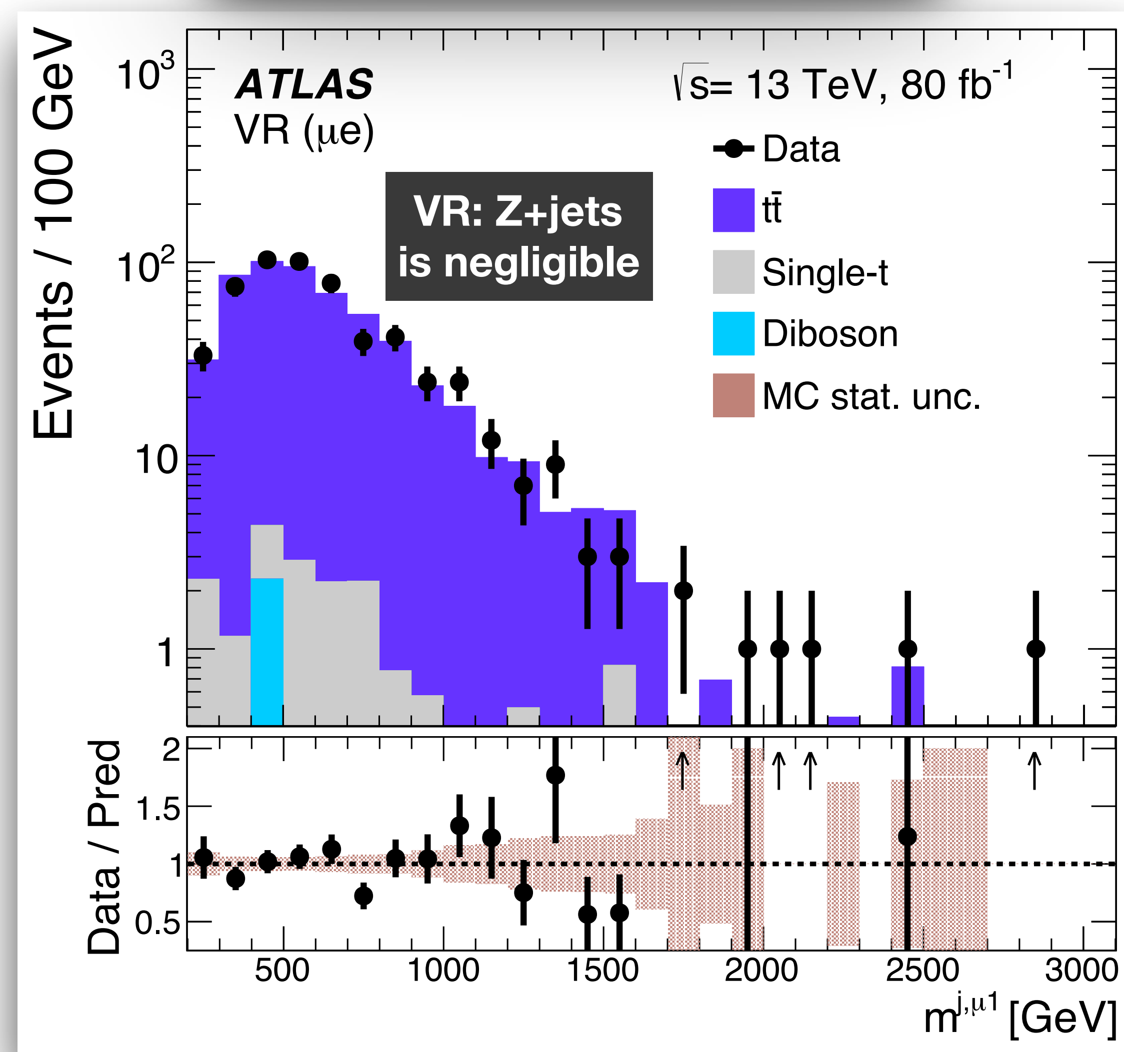


ATLAS $W_R \to \ell N_R \to \ell\ell qq$ with 80 fb^{-1}

- Framework of L-R symmetric models
  - SM-singlet heavy neutrinos N_R
- Focus on $m(N_R)/m(W_R) \leq 0.1$
  - N_R can be highly boosted
    - quarks merge $\Longrightarrow$ large-R jets
      - electrons: $m(N_R) = m(J)$
      - muons: $p(N_R) = p(J)+p(\mu_2)$
- SR: m_{WR}>2 TeV, same-flavour leptons
  - dominant bkg is ttbar
- Bkg MC is used for
  - optimise selection
  - electron-in-jet performance
  - estimate Z+jets contribution



VR: $W_R \to \mu + N_R \to \mu + eqq$

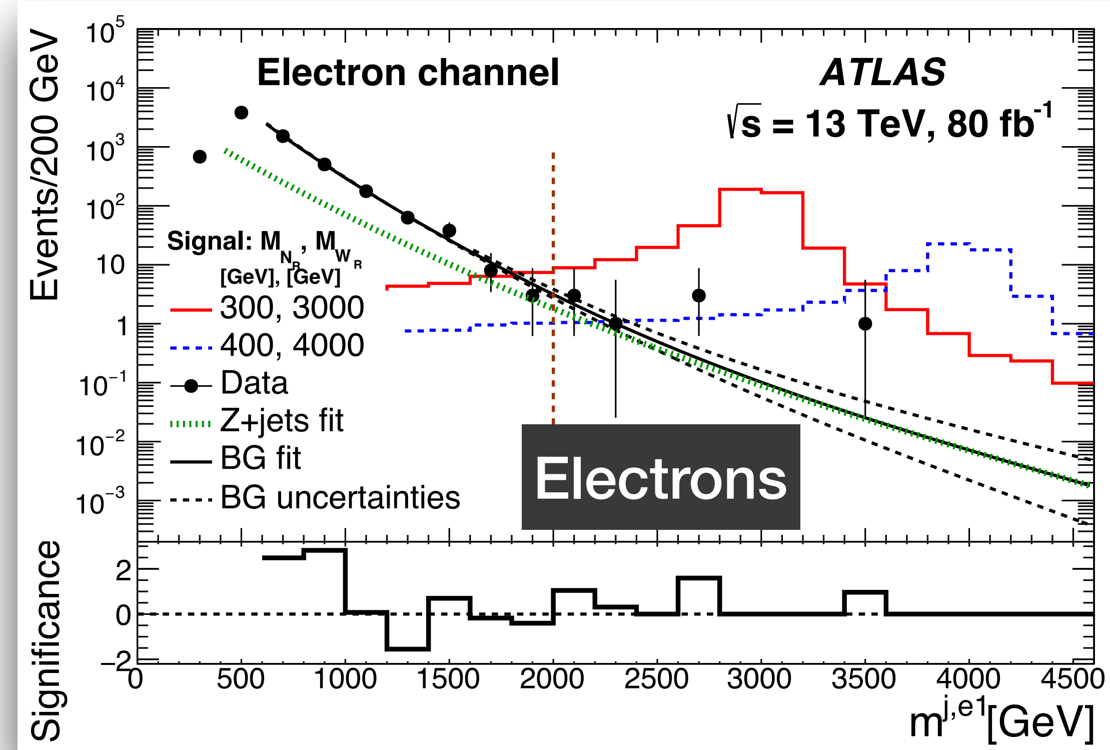


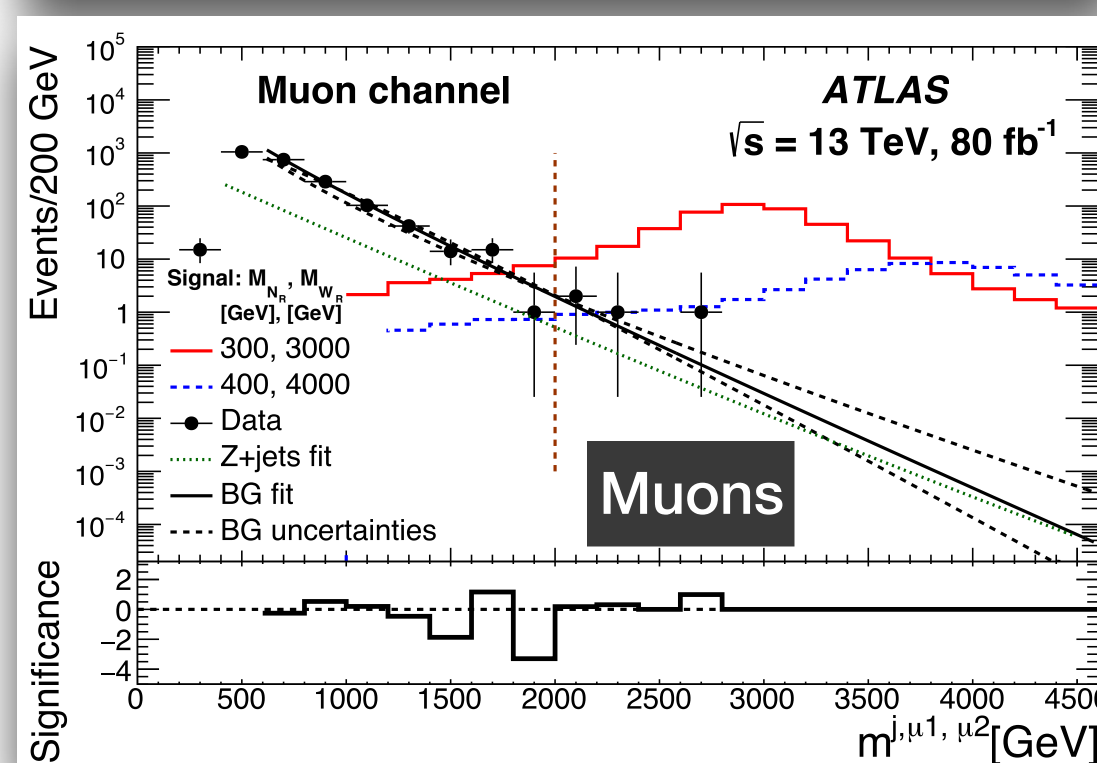
ATLAS $W_R \longrightarrow \ell N_R \longrightarrow \ell\ell qq$ with 80 fb^{-1}

- **Z+jets**: fit the MC prediction $\longrightarrow \mathscr{F}_{\text{Z+jets}}$
  - larger than ttbar at high m(WR)
- **Ttbar**: data fit in the CR, m(W_R)<2 TeV
  - $\mathscr{F} = \mathscr{F}_{\text{data,CR}} + \mathscr{F}_{\text{Z+jets}}$(fixed from MC)
  - validate in the eμ VR (Z+jets negligible)
- Extrapolate to the SR: m(W_R)>2 TeV
  - uncertainty on bkg yield: 25%
- Single-bin counting experiment in the SR

	Electron Channel	Muon Channel
Expected background	$2.8^{+0.5}_{-0.7}$	$1.9^{+0.5}_{-0.7}$
Observed events	8	4
Significance	2.4σ	1.2σ
p-value	0.0082	0.12

…small tension



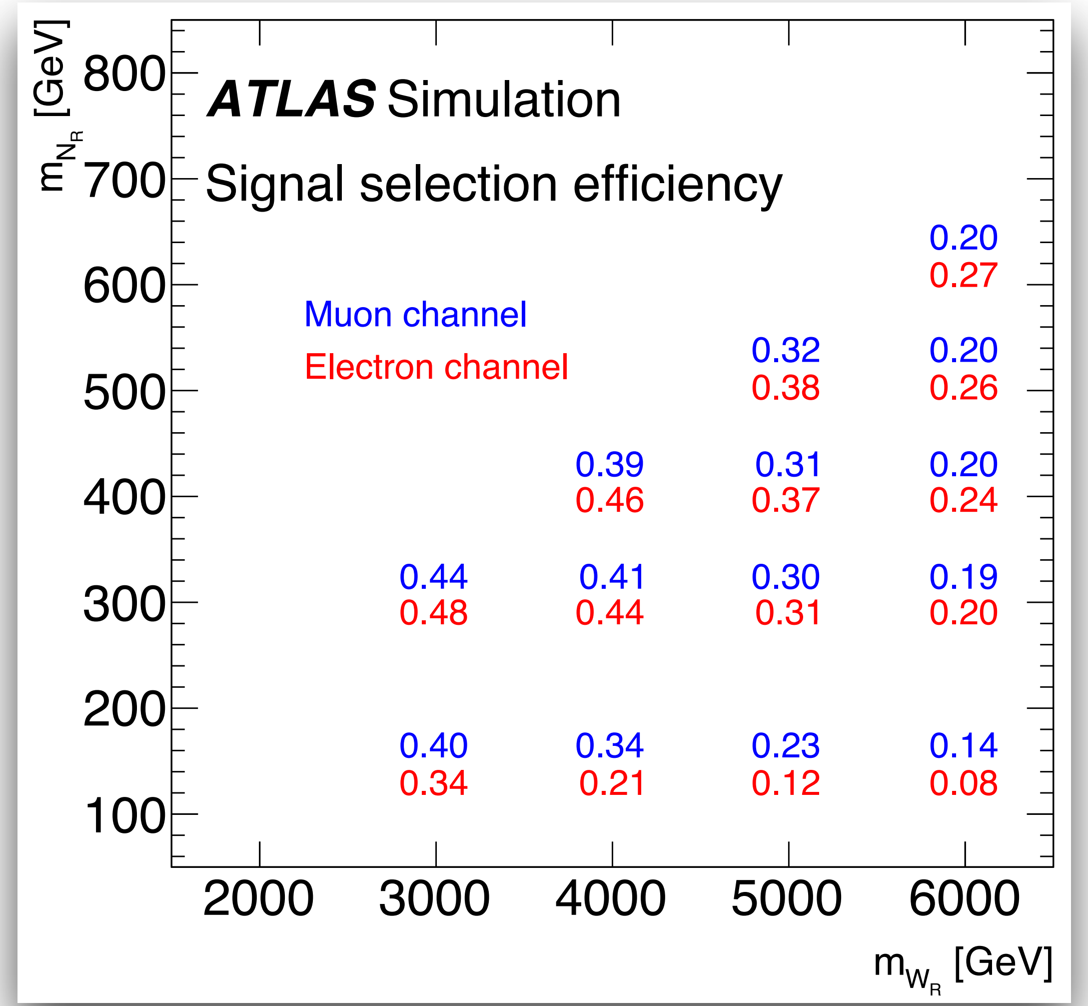


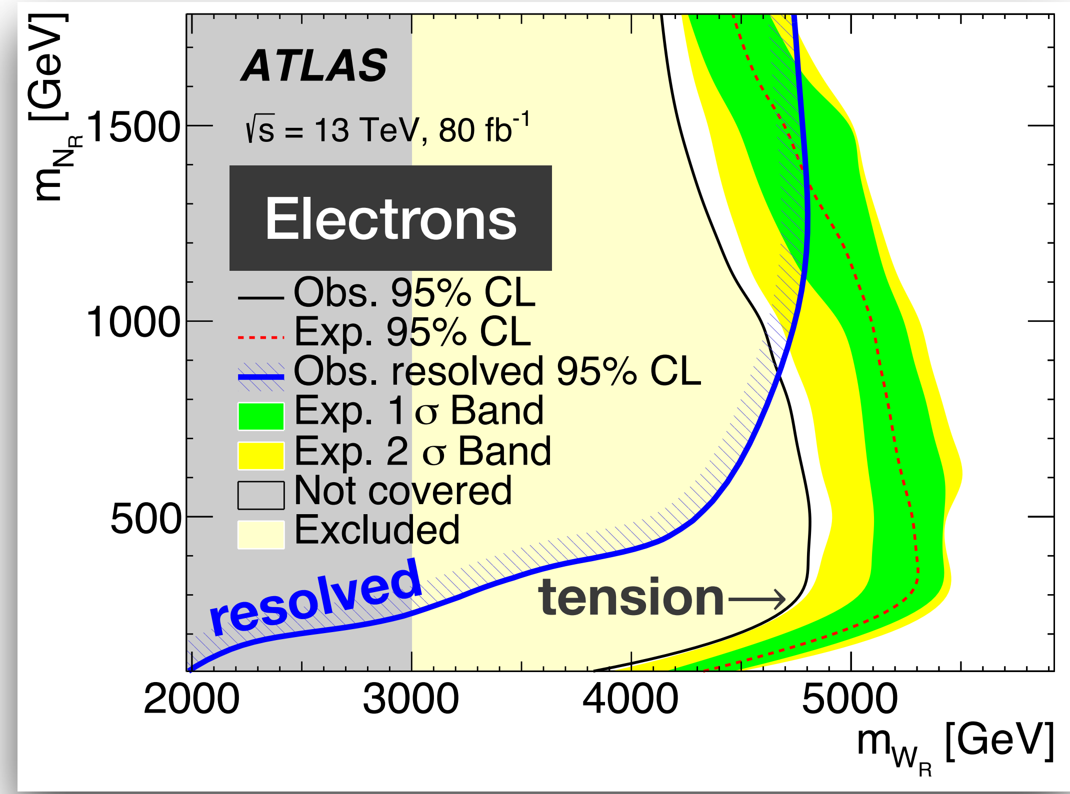
$$\mathscr{F}_{\text{data,CR}} = Ae^{-Bu}/u^C \qquad u = m_{W_R}/\sqrt{s}$$

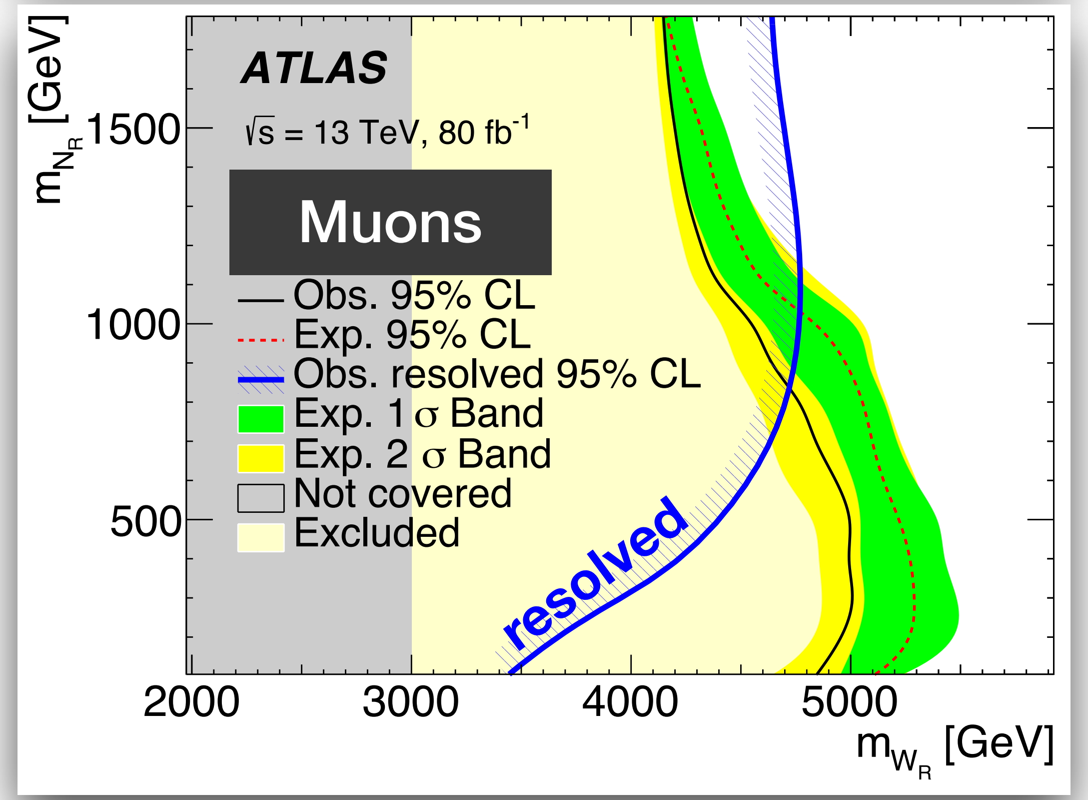
$$\mathscr{F}_{\text{Z+jets}} = A'(1-u)^{B'}(1+u)^{C'u}$$

ATLAS $W_R \longrightarrow \ell N_R \longrightarrow \ell\ell qq$ with 80 fb^{-1}

- Excluded region extends to m(W_R) of ~5 TeV for both channels, for m(N_R) of 0.4-0.5 TeV
- Much more sensitive wrt the resolved channel at small N_R masses

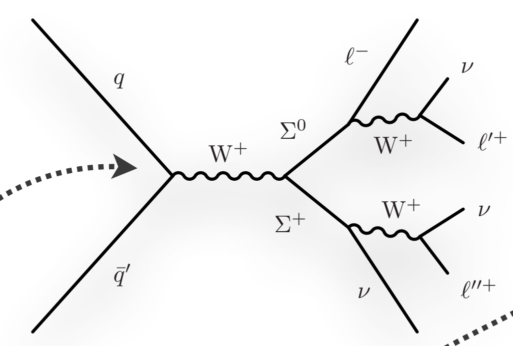


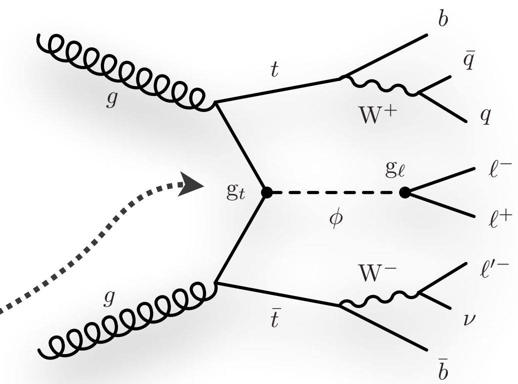




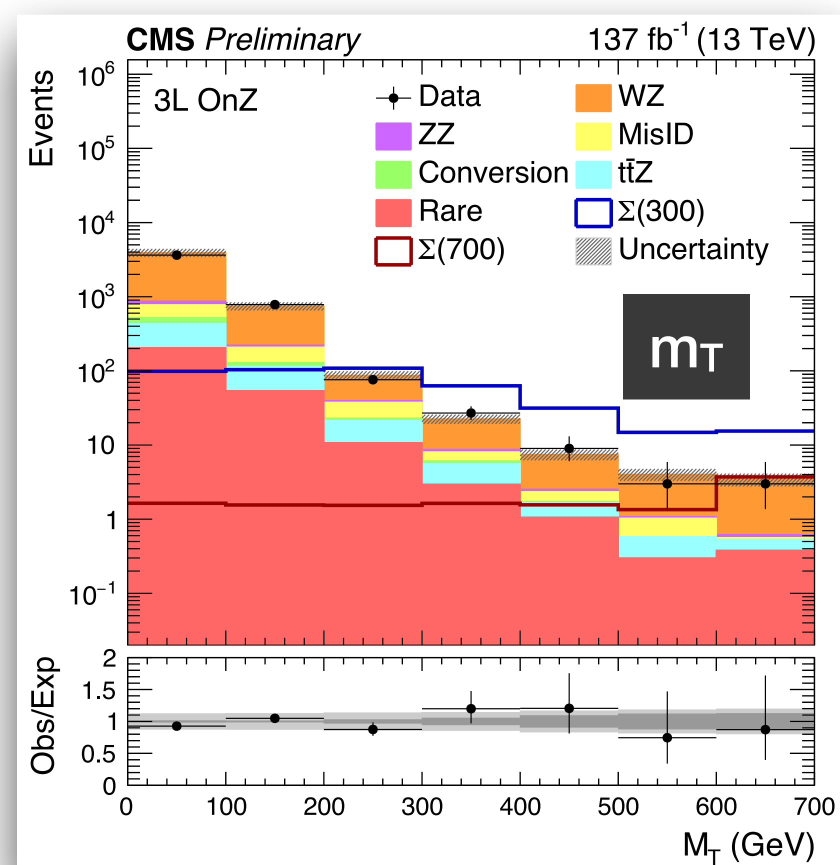
CMS Multileptons with 137 fb^{-1}

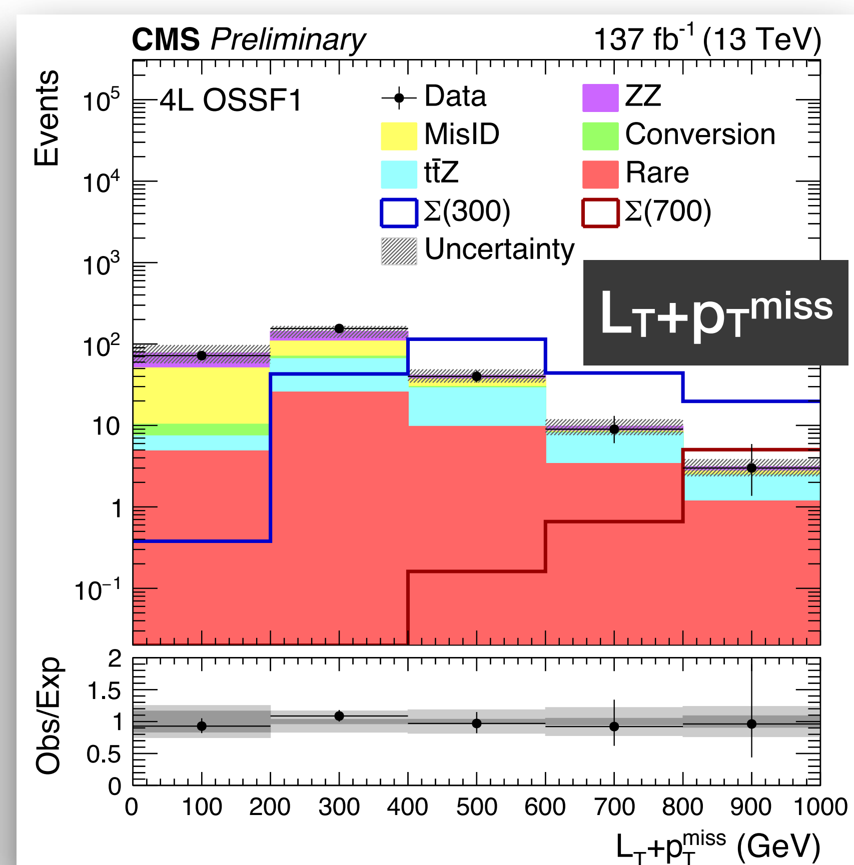
- Exactly 3 (3L) or 4 and more (4L) leptons
- Type-III seesaw pairs of heavy fermions
  - **non-resonant** tails in m_T or L_T+p_T^{miss}
- Light scalar top-associated production ($tt\phi$)
  - **resonant** in dilepton mass (first direct search!)
    - 15-75 GeV and 108-340 GeV (not onia/Z/$\phi \longrightarrow tt$)
- Bkgs: Diboson and ttZ (MC) and Z/ttbar+jets (data)

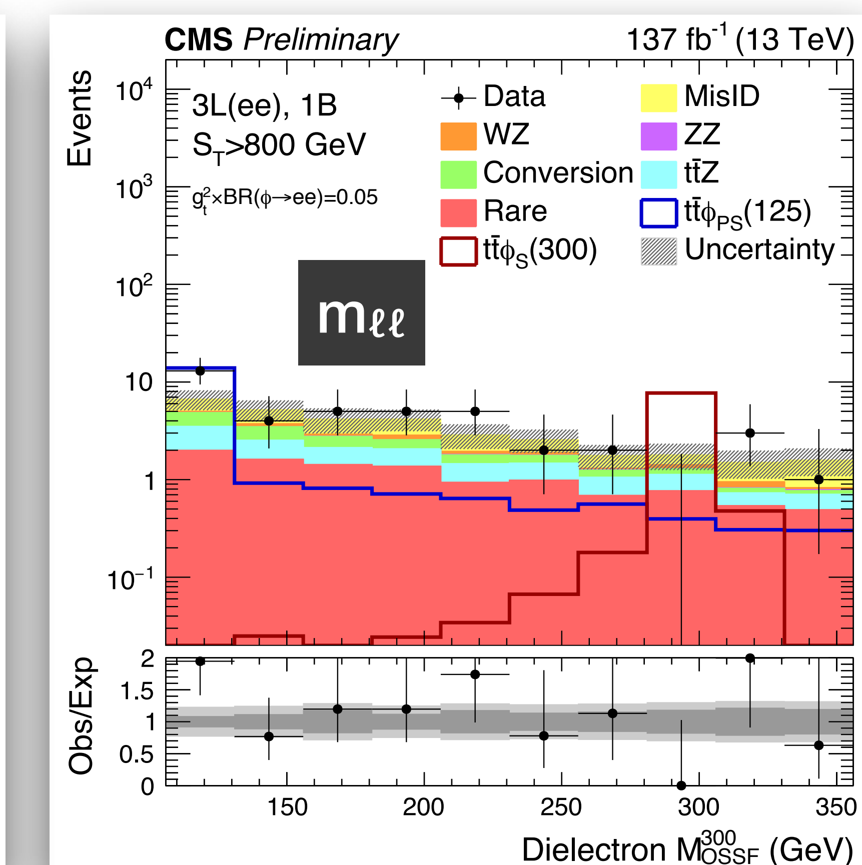




Multiple SRs!



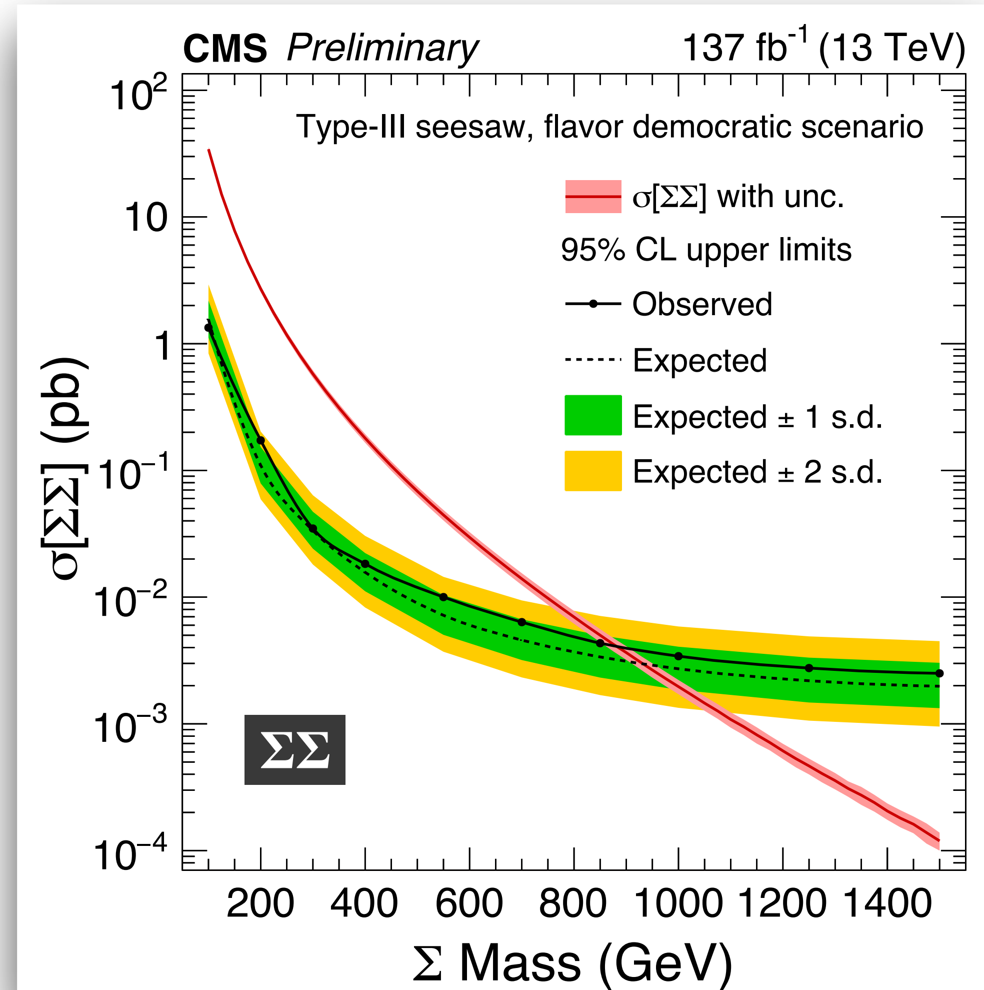




ΣΣ

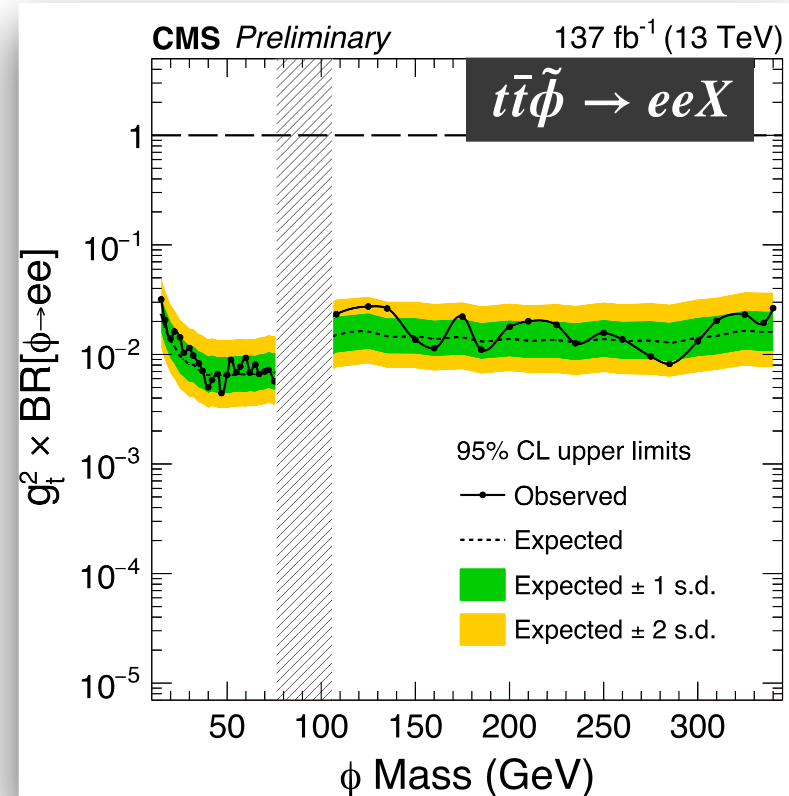
$tt\phi$

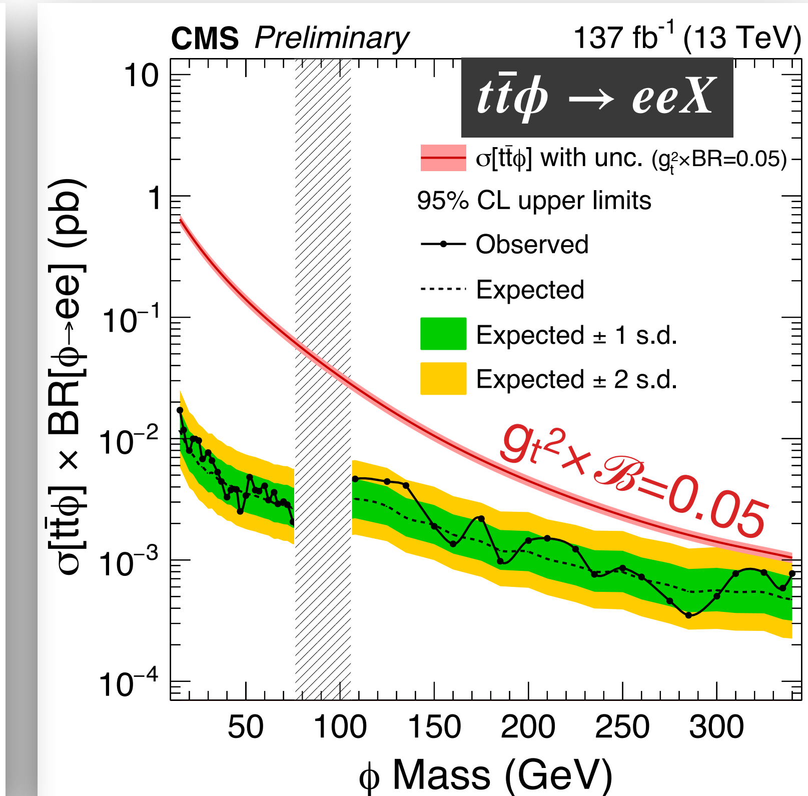
CMS Multileptons with 137 fb^{-1}

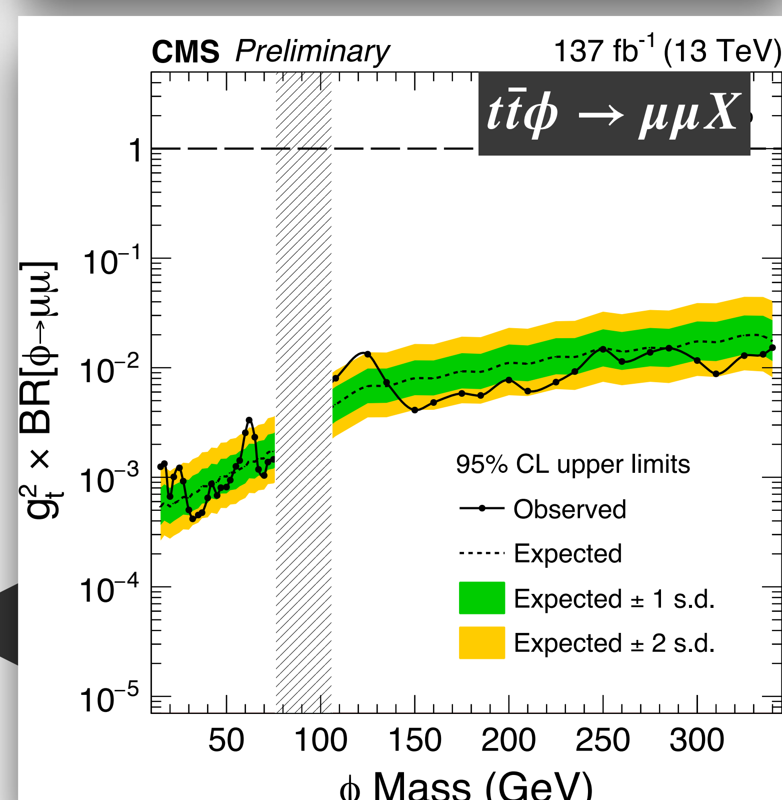


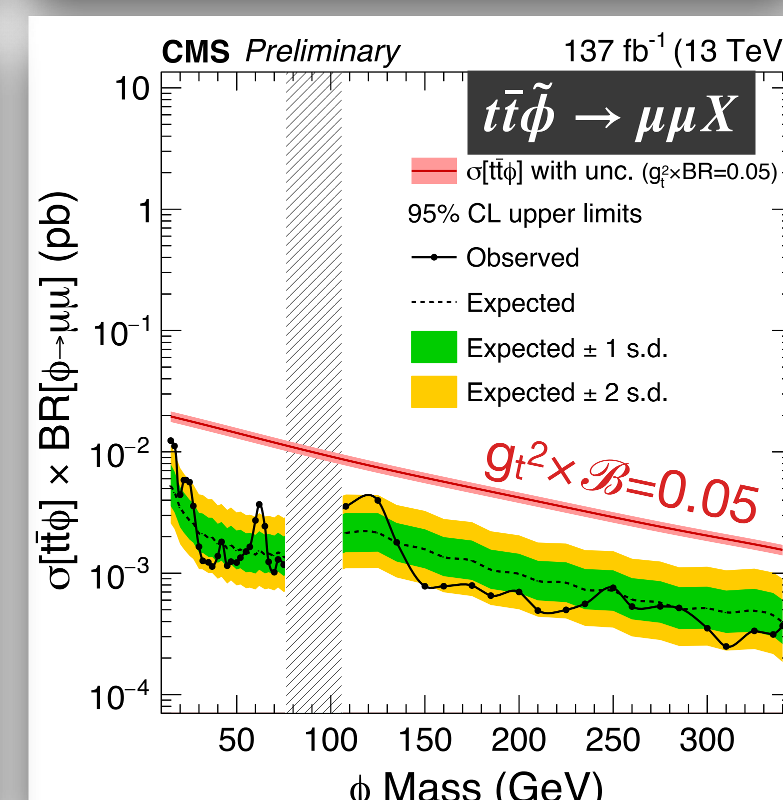
Heavy fermions excluded below 880 GeV (case of lepton flavour democratic decay)

$\mathscr{B}(\phi\to\ell\ell)$ excluded above 0.04 for scalar (0.03 pseudoscalar) mass in 108-340 GeV, for g_t^2~1.









g_t^2: Yukawa coupling of φ to tops

Summary

- A few recent cutting-edge direct searches with leptons
  - some refreshments in long-standing strategies
  - no significant evidence of such physics yet
    - new/stronger exclusions from both experiments
- However,
  - what we usually exclude is a class of very strong signals
  - recall that we haven't observed the $H\longrightarrow\mu\mu$ signal yet
  - weakly coupled resonances could still be anywhere above the Z
- We need more luminosity and more energy!


THANK YOU

BACKUP

ATLAS Z' selection

Event Selection

- At least one *pp* interaction vertex is reconstructed
- Primary vertex: highest $\sum p_T^2$ using tracks with p_T >0.5 GeV

Electrons

- $E_T > 30$ GeV
- $|\eta| < 1.37$ or $|\eta| > 1.52$
- *medium* ID (93% efficient for $E_T > 80$ GeV)

Muons

- $p_T > 30$ GeV
- $|\eta| < 2.5$
- *high-pt* ID: three hits required in MS, some veto areas (69% η averaged efficiency at 1 TeV)
- *good muon* selection: q/p uncertainty passes p_T-dependent threshold

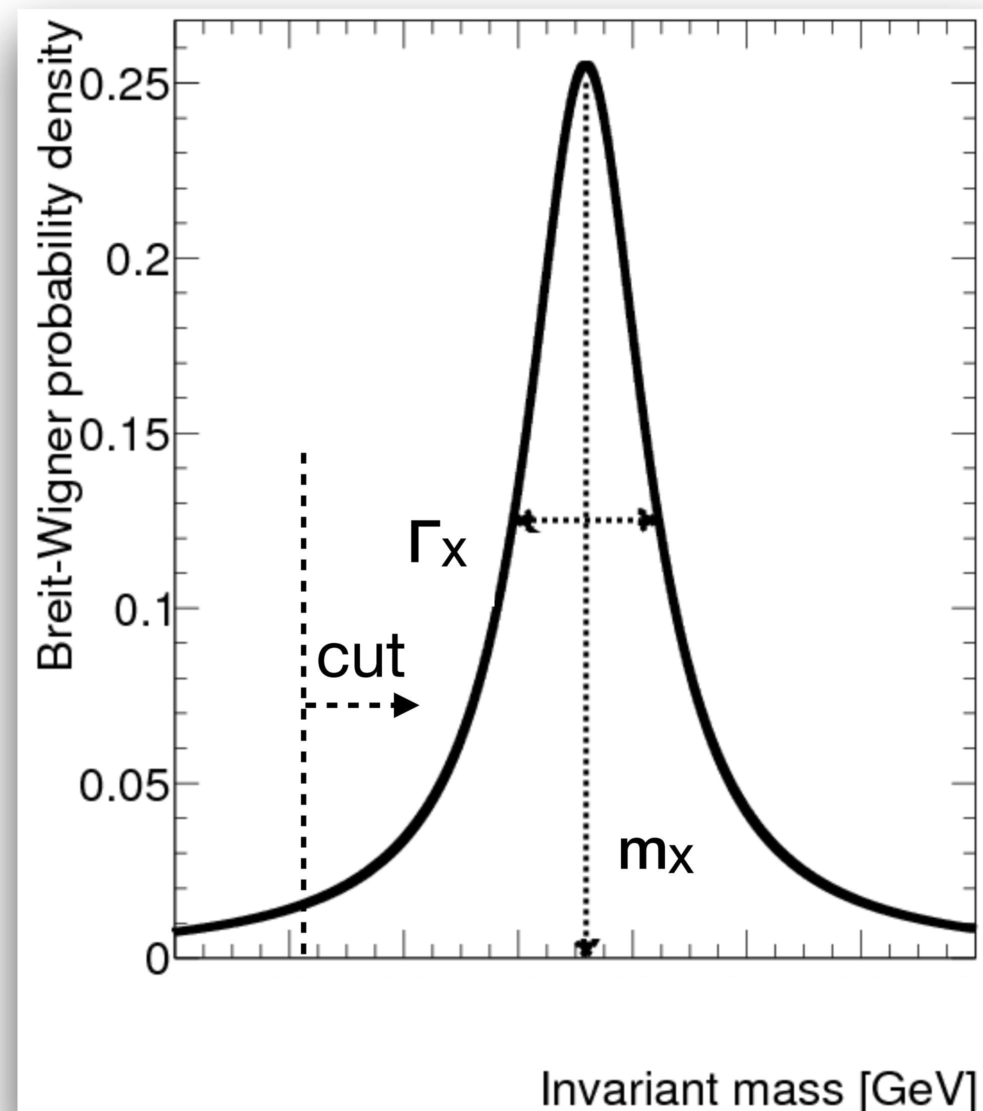
- $|z_0 \sin(\theta)| < 0.5$ mm constraint on the longitudinal impact parameter
- $|d_0/\sigma(d_0)| < 5(3)$ for $e(\mu)$ constraint on the traverse impact parameter
- Both e and μ pass a 99% efficient isolation requirement

Event selection

- Must have two same-flavor leptons
- If additional leptons, pick same-flavor pair with largest E_T (p_T) for *ee* ($\mu\mu$)
- If two different flavors are found, *ee* is used because of the better resolution
- For dimuon pairs, an opposite charge requirement is applied

ATLAS Z' Fiducial region

- Done to reduce model-dependencies from off-shell effects
- Requirements at particle level (for resonance X)
  - $|\eta(\ell)|<2.5$
  - $p_T(\ell)>30$ GeV
  - $m_{\ell\ell}(\text{tru})>(m_X-2\Gamma_X)$



ATLAS Z’ uncertainties

Table 2: The relative impact of $\pm 1\sigma$ variation of systematic uncertainties on the signal yield in percent for zero (10%) relative width signals at the pole masses of 300 GeV and 5 TeV for dielectron and dimuon channels. A signal is injected at the cross-section limit.

	Uncertainty source	Dielectron		Dimuon	
	for m_X [GeV]	300	5000	300	5000
bkg	Spurious signal	±12.5 (12.0)	±0.1 (1.0)	±11.7 (11.0)	±2.1 (2.2)
	Lepton identification	±1.6 (1.6)	±5.6 (5.6)	±1.8 (1.8)	$^{+25}_{-20}\left(^{+25}_{-20}\right)$
	Isolation	±0.3 (0.3)	±1.1 (1.1)	±0.4 (0.4)	±0.4 (0.5)
	Luminosity	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)
signal	Electron energy scale	$^{-1.7}_{-4.0}\left(^{+1.0}_{-1.8}\right)$	$^{+0.1}_{-0.4}$ (±0.8)	-	-
	Electron energy resolution	$^{+7.9}_{-8.3}\left(^{+1.1}_{-0.9}\right)$	$^{+0.4}_{-0.9}$ (±0.1)	-	-
	Muon ID resolution	-	-	$^{+0.8}_{-2.3}\left(^{+0.3}_{-0.8}\right)$	$^{+0.6}_{-0.4}\left(^{+0.5}_{-0.3}\right)$
	Muon MS resolution	-	-	$^{+2.8}_{-3.8}\left(^{+1.0}_{-1.3}\right)$	±2.4 (2.1)
	‘Good muon’ requirement	-	-	±0.6 (0.6)	$^{+55}_{-35}\left(^{+55}_{-35}\right)$

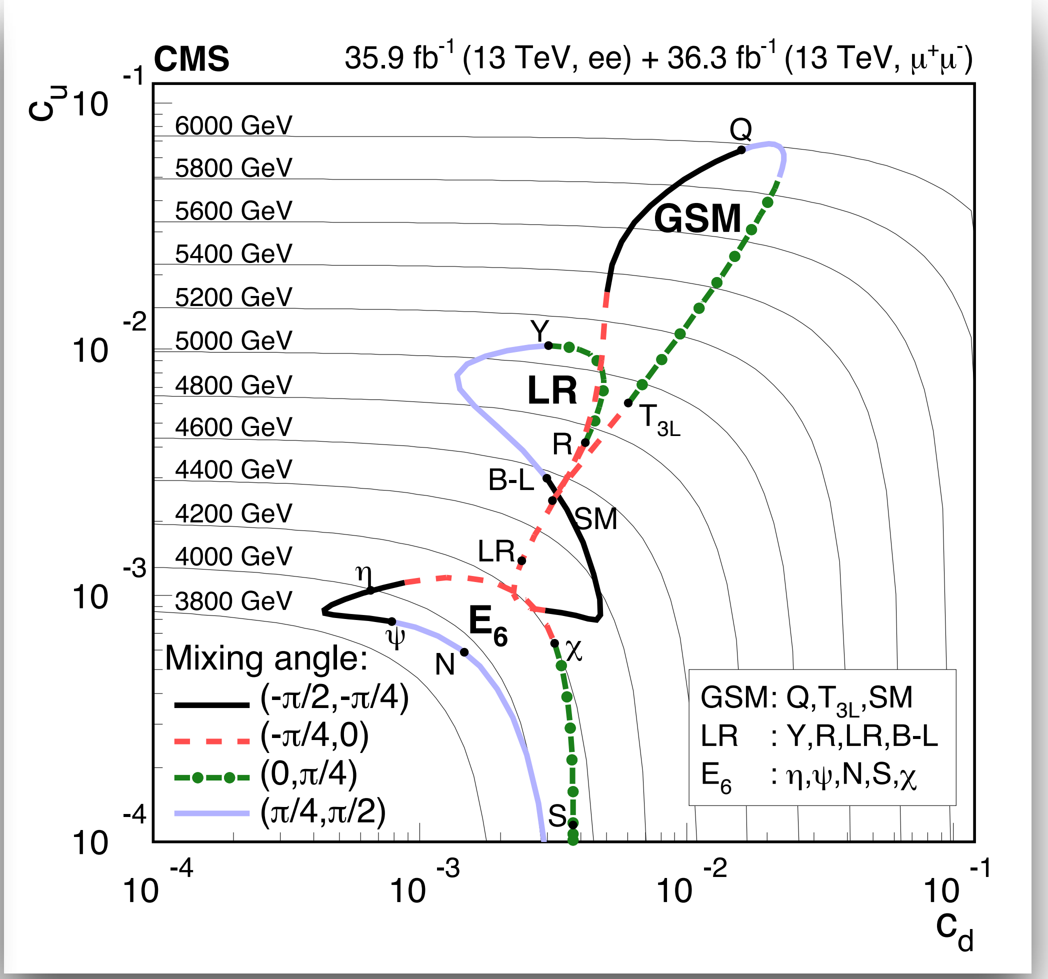
ATLAS Z' MC's?

- Non-huge MC samples still used to
  - explore fit functions
  - study bkg compositions
  - evaluate efficiency & resolution
  - derive spurious signal uncertainty
    - for each Γ_X assumptions in: 0%,0.5%,…,10%
- Main backgrounds are DY and ttbar
  - produced from large-stat generator level
  - smeared by the $m_{\ell\ell}$ resolution
  - corrected by $m_{\ell\ell}$-dependent $\mathcal{A}\times\varepsilon$

CMS's Z' search

- Cross section can, in the narrow-width approx', be expressed as $c_u\omega_u + c_d\omega_d$
- c_u (c_d) contains information about the model-dependent Z′ couplings to the up-type (down-type) quarks, while ω_u (ω_d) depends on the respective PDFs
- The parameterisation of the linear mixing of the relevant U′(1) generators produces a contour in the c_d-c_u plane that represents each class of models

$U'(1)$ model	Mixing angle	$\mathcal{B}(\ell^+\ell^-)$	c_u	c_d	c_u/c_d	$\Gamma_{Z'}/M_{Z'}$
E_6						
$U(1)_\chi$	0	0.061	6.46×10^{-4}	3.23×10^{-3}	0.20	0.0117
$U(1)_\psi$	0.5π	0.044	7.90×10^{-4}	7.90×10^{-4}	1.00	0.0053
$U(1)_\eta$	-0.29π	0.037	1.05×10^{-3}	6.59×10^{-4}	1.59	0.0064
$U(1)_S$	0.129π	0.066	1.18×10^{-4}	3.79×10^{-3}	0.31	0.0117
$U(1)_N$	0.42π	0.056	5.94×10^{-4}	1.48×10^{-3}	0.40	0.0064
LR						
$U(1)_R$	0	0.048	4.21×10^{-3}	4.21×10^{-3}	1.00	0.0247
$U(1)_{B-L}$	0.5π	0.154	3.02×10^{-3}	3.02×10^{-3}	1.00	0.0150
$U(1)_{LR}$	-0.128π	0.025	1.39×10^{-3}	2.44×10^{-3}	0.57	0.0207
$U(1)_Y$	0.25π	0.125	1.04×10^{-2}	3.07×10^{-3}	3.39	0.0235
GSM						
$U(1)_{SM}$	-0.072π	0.031	2.43×10^{-3}	3.13×10^{-3}	0.78	0.0297
$U(1)_{T3L}$	0	0.042	6.02×10^{-3}	6.02×10^{-3}	1.00	0.0450
$U(1)_Q$	0.5π	0.125	6.42×10^{-2}	1.60×10^{-2}	4.01	0.1225

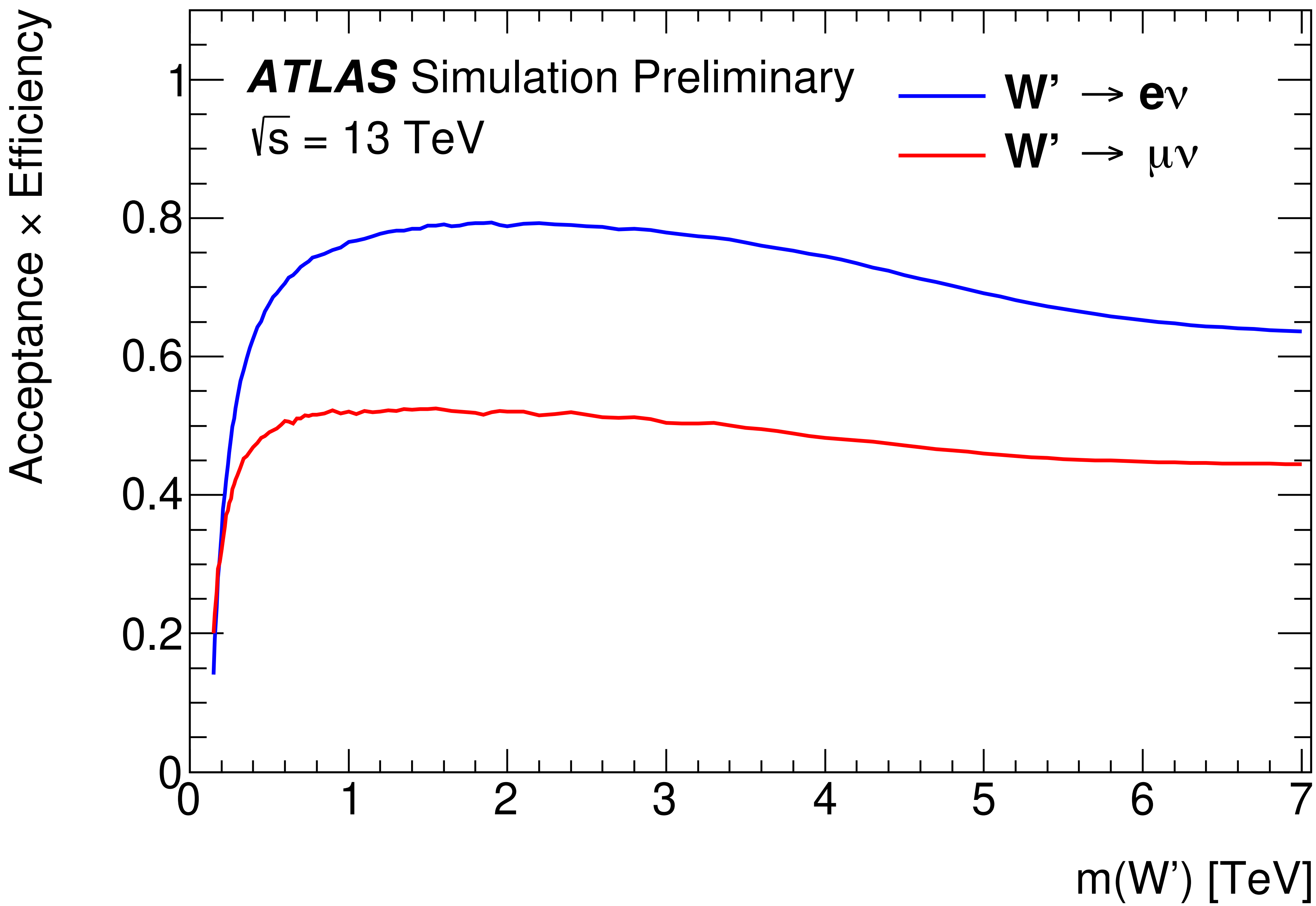


CMS's CI uncertainties

Uncertainty	Electrons $m_{ee} > 2\,\mathrm{TeV}$	Electrons $m_{ee} > 4\,\mathrm{TeV}$	Muons $m_{\mu\mu} > 2\,\mathrm{TeV}$	Muons $m_{\mu\mu} > 4\,\mathrm{TeV}$
Electron trigger + selection efficiency BB (BE)	6 (8)%		—	—
Electron energy scale BB (BE)	12.0 (6.7)%	21.7 (11.0)%	—	—
Muon trigger efficiency BB (BE)	—	—	0.3 (0.7)%	
Muon ID efficiency BB (BE)	—	—	0.8 (4.6)%	1.7 (7.6)%
Muon p_T resolution BB (BE)	—	—	0.8 (1.4)%	1.5 (2.3)%
Muon p_T scale BB (BE)	—	—	0.8 (2.8)%	4.1 (12.1)%
$t\bar{t}$/diboson cross section	7%		7%	
Z boson peak normalization	1%		5%	
PDF	5.7%	17.1%	5.7%	17.1%
Multijet BB (BE)	0.1 (1.3)%	0.1 (0.1)%	<0.1 (4.8)%	<0.1 (<0.1)%
Pileup reweighting BB (BE)	0.5 (0.7)%	0.4 (0.7)%	0.2 (0.1)%	0.2 (0.2)%
MC statistics BB (BE)	1.0 (1.8)%	0.7 (1.7)%	1.1 (1.3)%	1.0 (2.0)%

Table 1. Systematic uncertainties in the predicted SM yields for the electron and the muon channels, for two dilepton mass thresholds. Where noted, uncertainties are provided separately for events where both leptons are in the barrel region (BB), or where at least one of the leptons is in the endcap region (BE). Uncertainties that are mass-dependent affect both the event yield and the shape of the invariant mass distribution. The systematic uncertainties in the signal yields are largely the same as for the background, with a few exceptions as discussed in the text.

ATLAS W' search



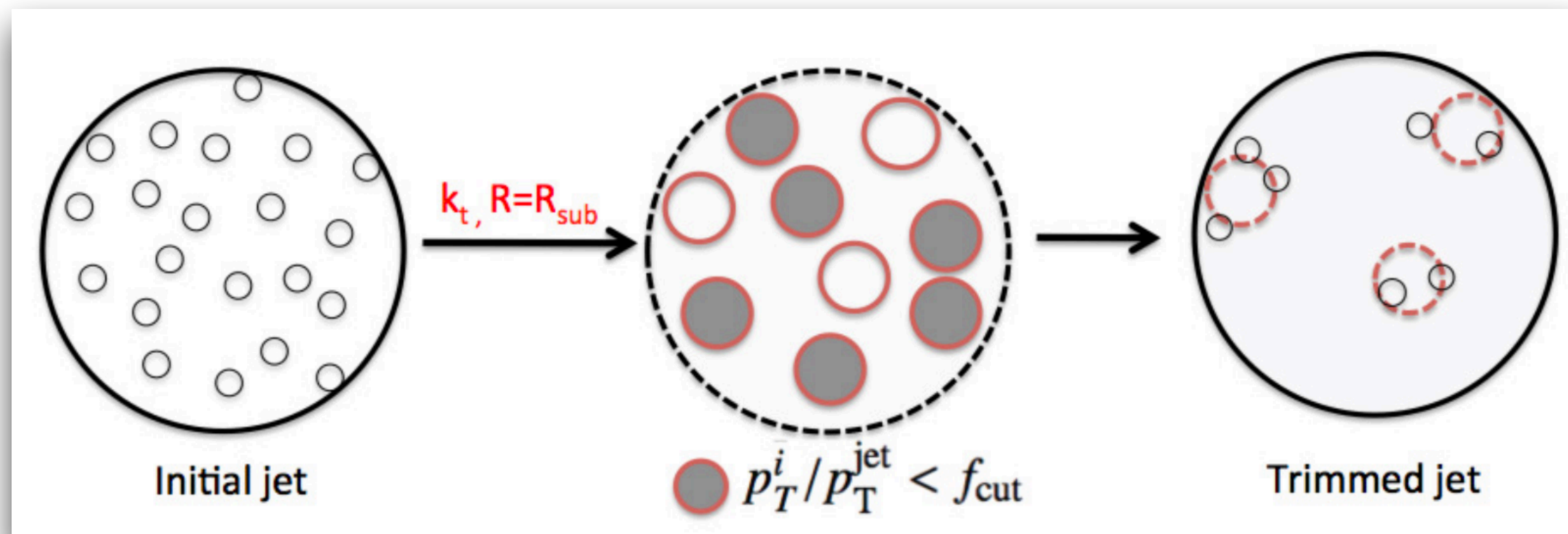
ATLAS N_R search

Table 2: Object selection criteria. The significance of the transverse impact parameter is defined as the transverse impact parameter d_0 divided by its uncertainty, σ_{d_0}, of tracks relative to the primary vertex with the highest sum of track p_T. The longitudinal impact parameter z_0 is multiplied by $\sin\theta$, where θ is the polar angle of the track.

	Electron channel	Muon channel
Lepton:		
p_T	> 26 GeV	> 28 GeV
$\|\eta\|$	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	< 2.5
Leading lepton quality	Medium [61], isolated [61]	Medium [62], isolated [62]
Subleading lepton quality	Medium, no isolation	Medium, no isolation
Transverse impact parameter significance	$\|d_0\|/\sigma_{d_0} < 5.0$	$\|d_0\|/\sigma_{d_0} < 3.0$
Longitudinal impact parameter	$\|z_0\| \sin\theta < 0.5$ mm	
Trimmed large-*R* jet:		
p_T	> 200 GeV	
$\|\eta\|$	< 2.0	
Mass	> 50 GeV	None

Large-R jet trimming

- Decays of boosted massive particles (t,Z,W) appear merged in the detector
- Average angular separation between the decay products is $\Delta R \sim 2m/p_T$
- Different grooming algorithms, input variables, tagging approaches etc.
- Jet grooming (e.g. trimming) is used to remove soft contaminations from PU, UE and ISR
- Trimming: Jets built with the anti-kt algorithm using R~1, trimmed using R~0.2 subjets, removing those whose pT fraction is e.g. <5% of the jet pT



ATLAS heavy neutrinos

Table 4: Relative systematic uncertainties of the signal yield in the signal region, in percentage for each source. The ranges indicate the different signal samples. The systematic uncertainties with sub-percent contributions are not shown.

Component	Electron channel [%]	Muon channel [%]
Lepton identification	4–20	4–8
Lepton isolation	4–5	1.0–1.5
Lepton reconstruction	4–5	1–4
Lepton trigger	4–5	0.5
Pile-up	< 0.5	2–3
Luminosity	2	2
Theory	10	10

- Ttbar fit uncert.: variations of the fit range⟶largest change in the SR yield
- Z+jets fit uncert.: same as ttbar + fit alternative Z+jets MC samples after varying the scale and using alternative PDF sets (all in quadrature)
- The uncertainty of the background yield in the SR is 25% for both channels
- Fits statistical uncertainties: use pseudo-experiments while varying the input data points within their statistical uncertainties

CMS Multileptons

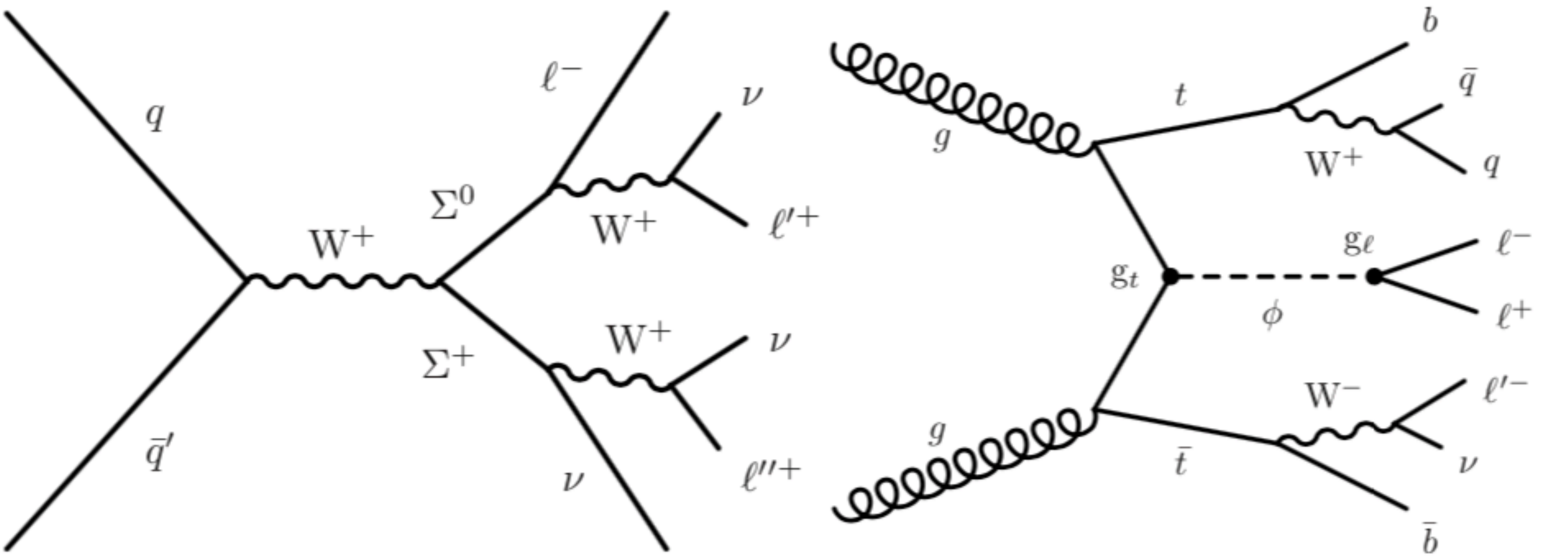


Figure 1: Leading order Feynman diagrams for the type-III seesaw (left) and $t\bar{t}\phi$ (right) signal models, depicting example production and decay modes in pp collisions.

CMS Multileptons

Table 1: Multilepton signal region definitions for the signal models. All events containing a same-flavor lepton pair with mass below 12 GeV, and 3L events containing an OSSF lepton pair with mass below 76 GeV when the trilepton mass is within a Z boson mass window (91 ± 15 GeV) are vetoed.

Label	N_ℓ	N_{OSSF}	M_{OSSF}	N_b	p_T^{miss}	Variable		Binning scheme		
Signal model: type-III seesaw										
3L below-Z	3	1	< 76 GeV	–	–	$L_T + p_T^{miss}$	$0 - 1200$ GeV	6 bins		
3L on-Z	3	1	$76 - 106$ GeV	–	> 100 GeV	M_T	$0 - 700$ GeV	7 bins		
3L above-Z	3	1	> 106 GeV	–	–	$L_T + p_T^{miss}$	$0 - 1600$ GeV	8 bins		
3L OSSF0	3	0	–	–	–	$L_T + p_T^{miss}$	$0 - 1200$ GeV	6 bins		
4L OSSF1	≥4	1	–	–	–	$L_T + p_T^{miss}$	$0 - 1000$ GeV	5 bins		
4L OSSF2	≥4	2	–	–	> 100 GeV if double on-Z	$L_T + p_T^{miss}$	$0 - 1200$ GeV	6 bins		
Signal model: $t\bar{t}\phi$								S_T (GeV)		
								$0 - 400$	$400 - 800$	> 800
3L($\ell\ell$)* 0B	3	1	off-Z	0	–	M_{OSSF}^{20}	$12 - 77$ GeV	13 bins	13 bins	5 bins
						M_{OSSF}^{300}	$106 - 356$ GeV	10 bins	10 bins	10 bins
3L($\ell\ell$)* 1B	3	1	off-Z	≥1	–	M_{OSSF}^{20}	$12 - 77$ GeV	13 bins	13 bins	5 bins
						M_{OSSF}^{300}	$106 - 356$ GeV	10 bins	10 bins	10 bins
								$0 - 400$	> 400	
4L($\ell\ell$)* 0B	≥4	≥ 1	off-Z	0	–	M_{OSSF}^{20}	$12 - 77$ GeV	3 bins	2 bins	
						M_{OSSF}^{300}	$106 - 356$ GeV	3 bins	2 bins	
								inclusive		
4L($\ell\ell$)* 1B	≥4	≥ 1	off-Z	≥1	–	M_{OSSF}^{20}	$12 - 77$ GeV	3 bins		
						M_{OSSF}^{300}	$106 - 356$ GeV	3 bins		

* ℓ = e or μ

CMS Multileptons

Table 2: Sources of systematic uncertainties, affected background and signal processes, relative variation on the affected processes, and correlation model across years in signal regions.

Uncertainty source	Signal/Background process	Variation (%)	Correlation
Luminosity	Signal/Rare/Non-Zγ conversion	$2.3 - 2.5$	No
Lepton reco, ID and iso. efficiency	Signal/Background*	$4 - 5$	No
Lepton displacement efficiency (only in 3L)	Signal/Background*	$3 - 5$	Yes
Trigger efficiency	Signal/Background*	< 3	No
B tag efficiency	Signal/Background*	< 5	No
Minbias cross section (pileup)	Signal/Background*	< 3	Yes
Factorization/renormalization scale & PDF	Signal/Background*	< 10	Yes
Jet energy scale	Signal/Background*	< 5	Yes
Unclustered energy scale	Signal/Background*	< 5	Yes
Muon energy scale and resolution	Signal/Background*	< 5	Yes
Electron energy scale and resolution	Signal/Background*	< 2	Yes
WZ normalization (0/1/2/$\geq$3 jets)	WZ	$5 - 10$	Yes
ZZ normalization (0/1/$\geq$2 jets)	ZZ	$5 - 10$	Yes
$t\bar{t}Z$ normalization	$t\bar{t}Z$	$15 - 20$	Yes
Conversion normalization	Conversion	$20 - 50$	Yes
Rare normalization	Rare	50	Yes
Lepton misidentification rates	Misidentified lepton	$30 - 40$	Yes
Electron charge misidentification	WZ/ZZ†	< 20	No

*WZ, ZZ, $t\bar{t}Z$, rare, and conversion background processes.
†Only in 3L OSSF0 and 4L OSSF1 signal regions.

CMS Multileptons

Table 3: Acceptance times efficiency values in 3 and 4 lepton channels for the signal models at various mass hypotheses.

Signal model	Acceptance × efficiency (%)														
Type-III seesaw															
Σ mass (GeV)	100	200	300	400	550	700	850	1000	1250	1500					
Flavor democratic	0.32	1.82	2.63	3.02	3.29	3.34	3.29	3.21	2.99	2.82					
$t\bar{t}\phi$															
ϕ mass (GeV)	15	20	25	30	40	50	60	70	75	108	125	150	200	250	300
Scalar $\phi(\to ee)$	0.85	1.29	1.67	2.02	2.74	3.44	4.25	5.16	4.95	5.53	8.32	9.00	10.3	11.1	11.5
Scalar $\phi(\to \mu\mu)$	1.54	2.16	2.81	3.35	4.38	5.29	6.40	7.69	7.56	8.74	11.6	12.3	14.0	14.8	15.3
Pseudoscalar $\phi(\to ee)$	0.96	1.81	2.69	3.45	4.88	5.82	6.62	7.35	6.83	6.8	9.77	10.4	11.0	11.4	11.9
Pseudoscalar $\phi(\to \mu\mu)$	1.69	2.95	4.24	5.38	7.14	8.46	9.73	10.4	9.93	10.3	13.4	14.0	14.9	15.2	15.9

Clockwork theory

- [JHEP 1806 (2018) 009]
- Multiple copies of gravity
- Multiple massless gravitons

Clockwork Fierz-Pauli:

$$\mathcal{L} = -\frac{m^2}{2}\sum_{j=0}^{N-1}\left([h_j^{\mu\nu} - q h_{j+1}^{\mu\nu}]^2 - [\eta_{\mu\nu}(h_j^{\mu\nu} - q h_{j+1}^{\mu\nu})]^2\right)$$

Massless graviton from gauge symmetry:

$$h_j^{\mu\nu} \to h_j^{\mu\nu} + \frac{1}{q^j}(\partial^\mu A^\nu + \partial^\nu A^\mu)$$