High-p_T lepton final states at 13 TeV (W' and Z' searches)

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on behalf of the ATLAS and CMS Collaborations

51st Rencontres de Moriond EW 2016

W' and Z'

- Many BSM models predict the existence of massive spin-1 objects decaying into pairs of leptons
  - $W' \to l\nu_l$
  - $Z' \to ll : l \in \{e, \mu, \tau\}$
- Experimentally attractive: straightforward to trigger/reconstruct,
- SM backgrounds are either low or well understood
- Practically: **the differences between the models are largely in the natural widths**, ranging from around 0.5% to 3% (or non-resonant)

Sequential Standard Model

Applied to both $W' \to l\nu_l$ and $Z' \to ll$

Couplings to fermions are identical to those of the SM W and Z.

Used as a benchmark

Grand Unification Model

Applied to $Z' \to ll$

E6 gauge group breaks into SU(5) and two additional U(1) groups, physical states given by

$$Z'(\theta_{E_6}) = Z'_\psi \cos\theta_{E_6} + Z'_\chi \sin\theta_{E_6}$$

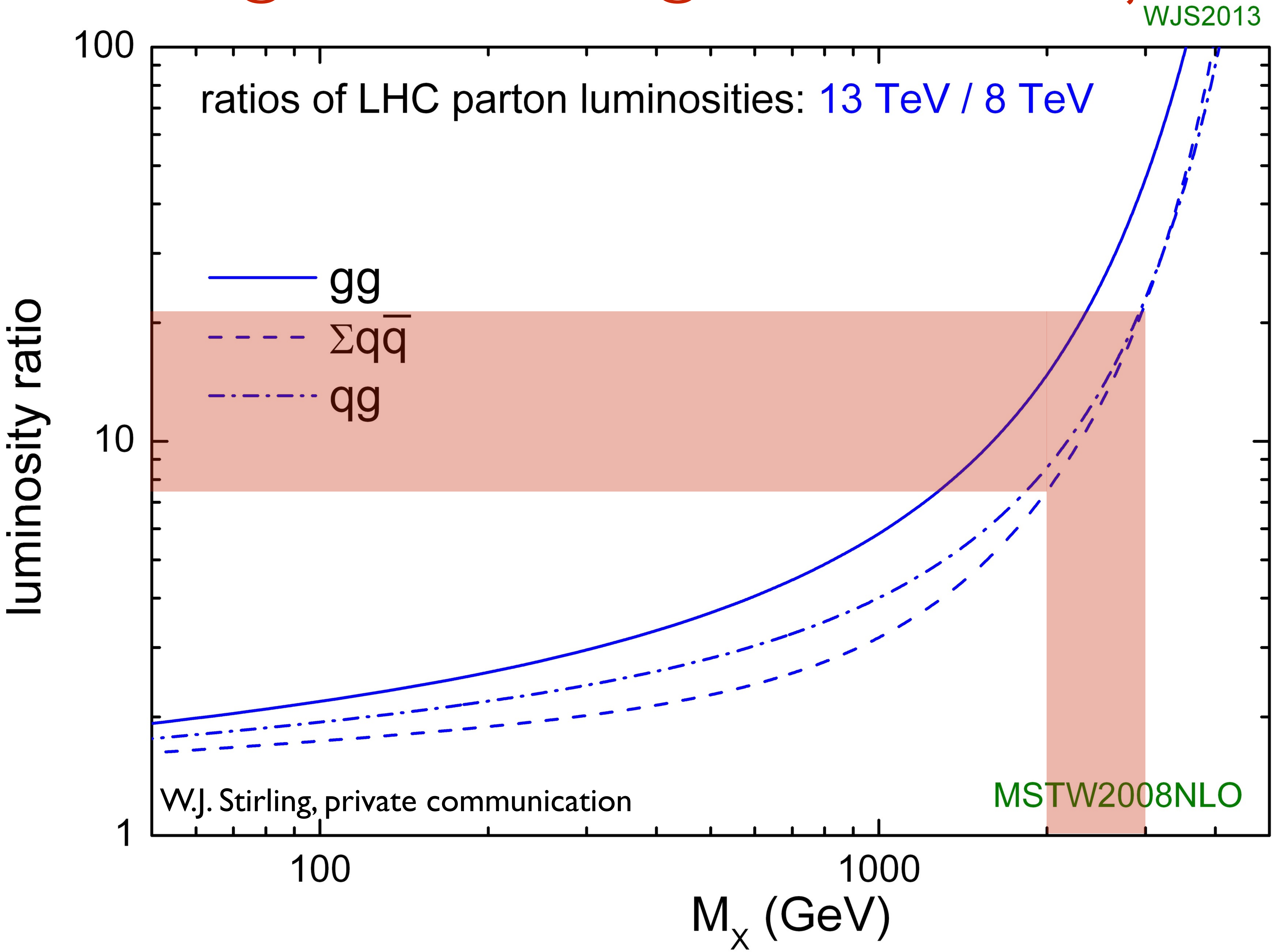
Six different values for mixing angle θ lead to specific Z' states $Z'_{\psi,\chi,\eta,I,S}$

Contact Interactions

Applied to di-lepton final state

Quark and lepton compositeness with a characteristic energy scale Λ corresponding to the binding energy between fermion constituent. Produces non-resonant excesses.

1fb^{-1} @ 13 TeV ~ 10-20fb^{-1} @ 8 TeV for a 2-3 TeV object



13 TeV results overview

- Z': search for narrow resonances in the di-lepton invariant mass distributions (M_{ee}, $M_{\mu\mu}$) or for non-resonant excesses above the SM background
- W': search for discrepancies above background in the transverse mass distribution: $$M_T = \sqrt{2 p_T^l E_T^{miss} (1 - \cos[\Delta\phi(\vec{p}_T^{\,l}, \vec{p}_T^{\,miss})])}$$
- ATLAS and CMS recently updated their 8TeV limits with 13TeV data; this talk reviews these 13 TeV results

	ATLAS	CMS
One-lepton (W')	ATLAS-CONF-2015-063 W' → {e, μ} + $\not{E}_T$	CMS-PAS-EXO-15-006 W' → {e, μ} + $\not{E}_T$
Two-leptons (Z')	ATLAS-CONF-2015-070 Z' → {ee, μμ} ATLAS-CONF-2015-072 Z' → {eμ}	CMS-PAS-EXO-15-005 Z' → {ee, μμ}

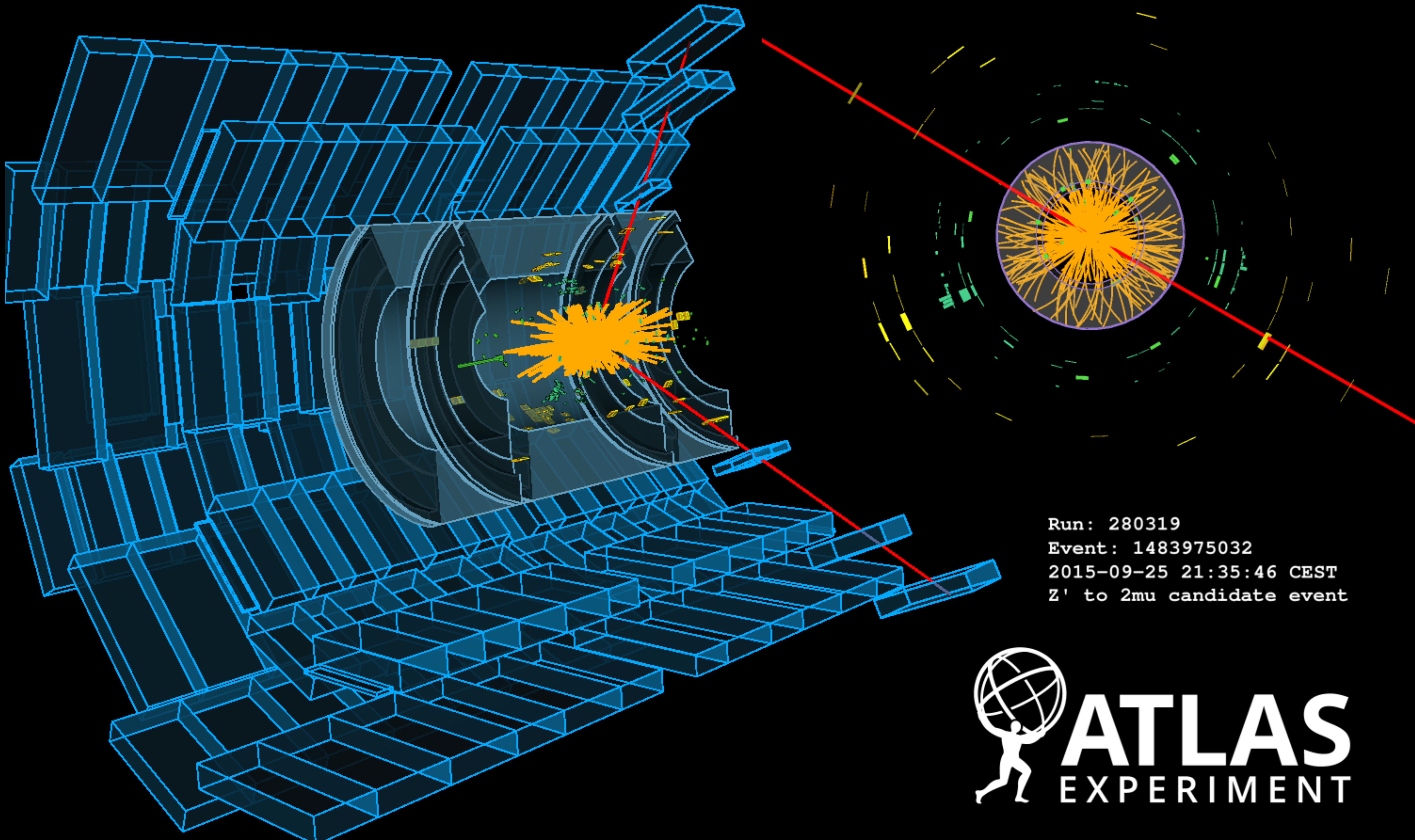
Event selection and main backgrounds

- Trigger: single e/μ (ee for Z')
- Offline event selection:
  - W': single e/μ plus missing transverse energy
  - Z': ee/μμ
- Indicative signal efficiencies (CMS)
  - 3 TeV W': **~75%** for e and μ
  - 1 TeV Z'→ee: **~75%** barrel-barrel, **70%** barrel-endcap
  - 1 TeV Z'→μμ: **~90%**
- Indicative dilepton resolutions
  - CMS (ee @ 1TeV): **1.8%** (barrel), **1.4%** (barrel+endcap)
  - CMS (μμ @ 1TeV): **4%**
  - ATLAS (ee > 200 GeV): **< 2%**
  - ATLAS (μμ @ 1TeV): **19-32%**

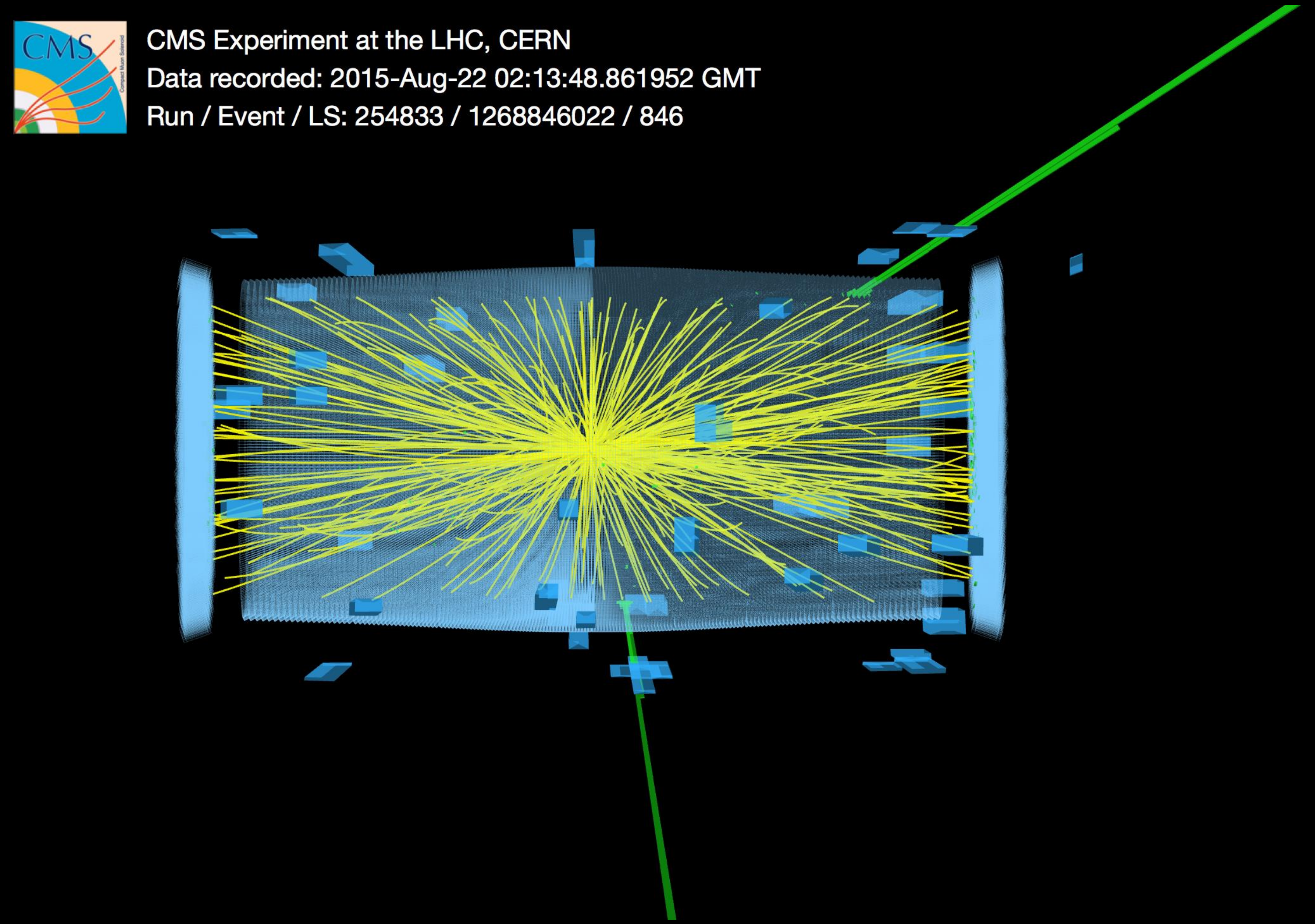
} Run-1 evaluation

		W'	Z'	Means of evaluation
Real leptons	DY (W, Z, γ*)	✓	✓	MC
	t/tbar, single top	✓	✓	MC
	Di-bosons (WW, WZ,ZZ)	✓	✓	MC
Fake leptons (hadronic jets)	With real leptons (W+jets)	✓	✓ (Electrons) ✕ (Muons)	Data
	With each other (multi-jets)	✓	✓ (Electrons) ✕ (Muons)	Data

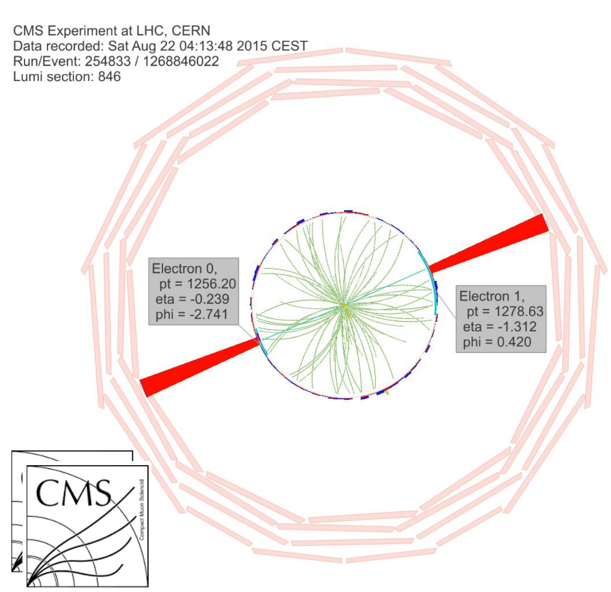
For the di-leptons: summed backgrounds are normalised to the level of the data in the region:
60/80 (CMS/ATLAS) <m_{ll}< 120 GeV
→ **mass independent systematics cancel**

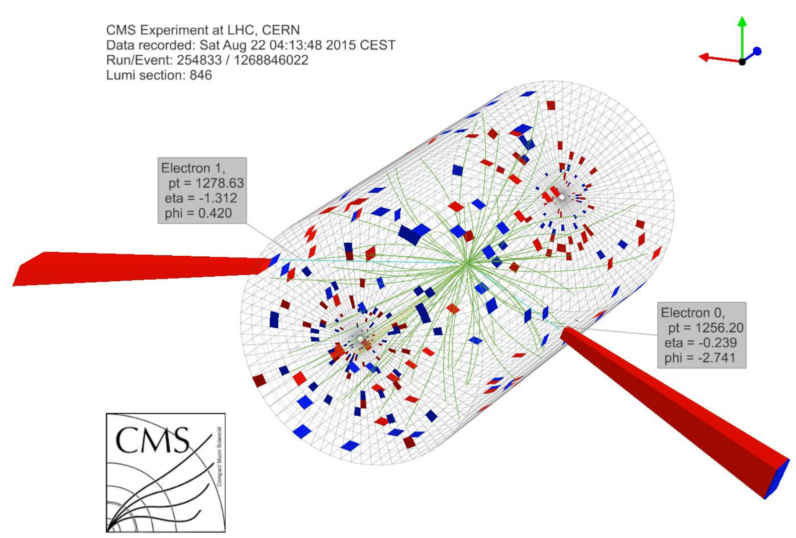


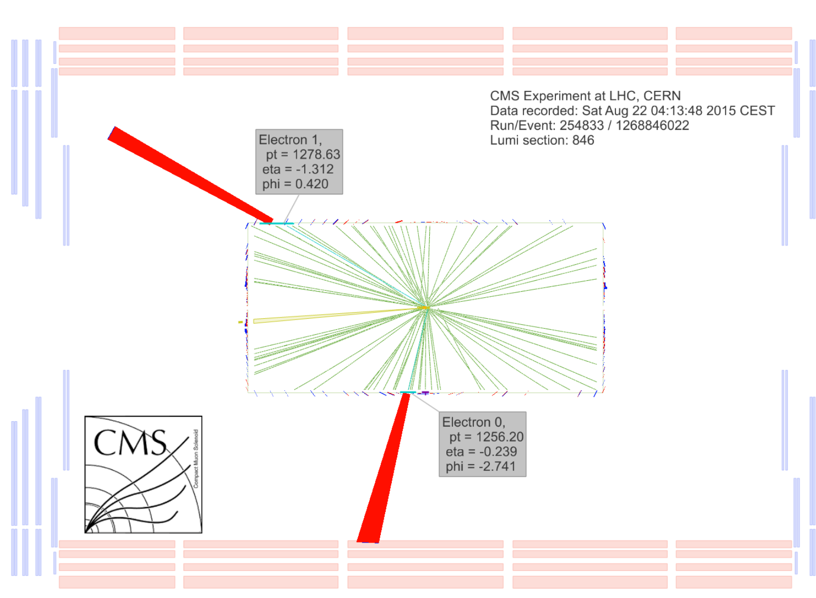
$M_{\mu\mu}$ event (1390 GeV) recorded by ATLAS @ 13TeV



M_{ee} event (2910 GeV) recorded by CMS @ 13TeV



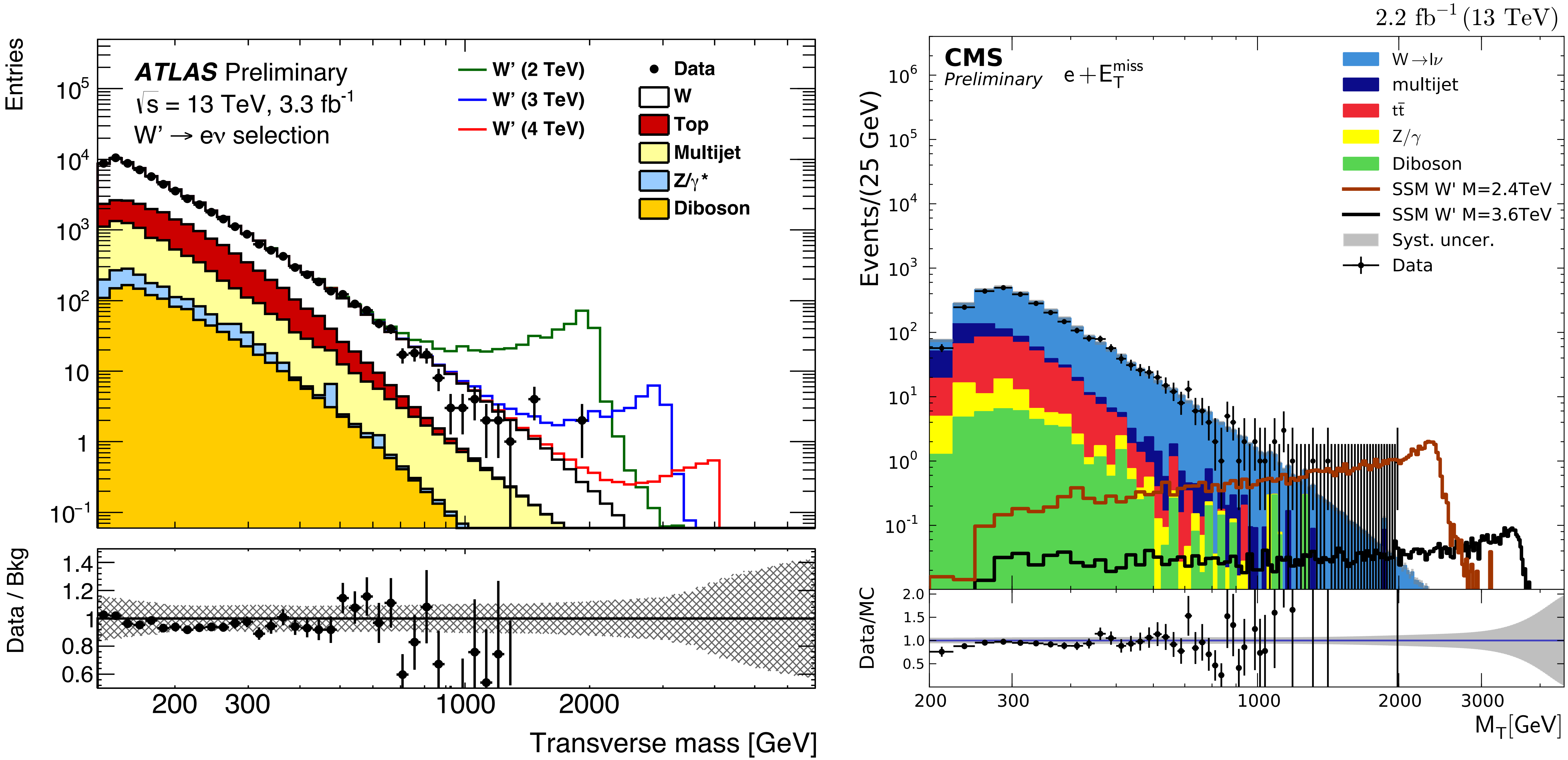




Systematics

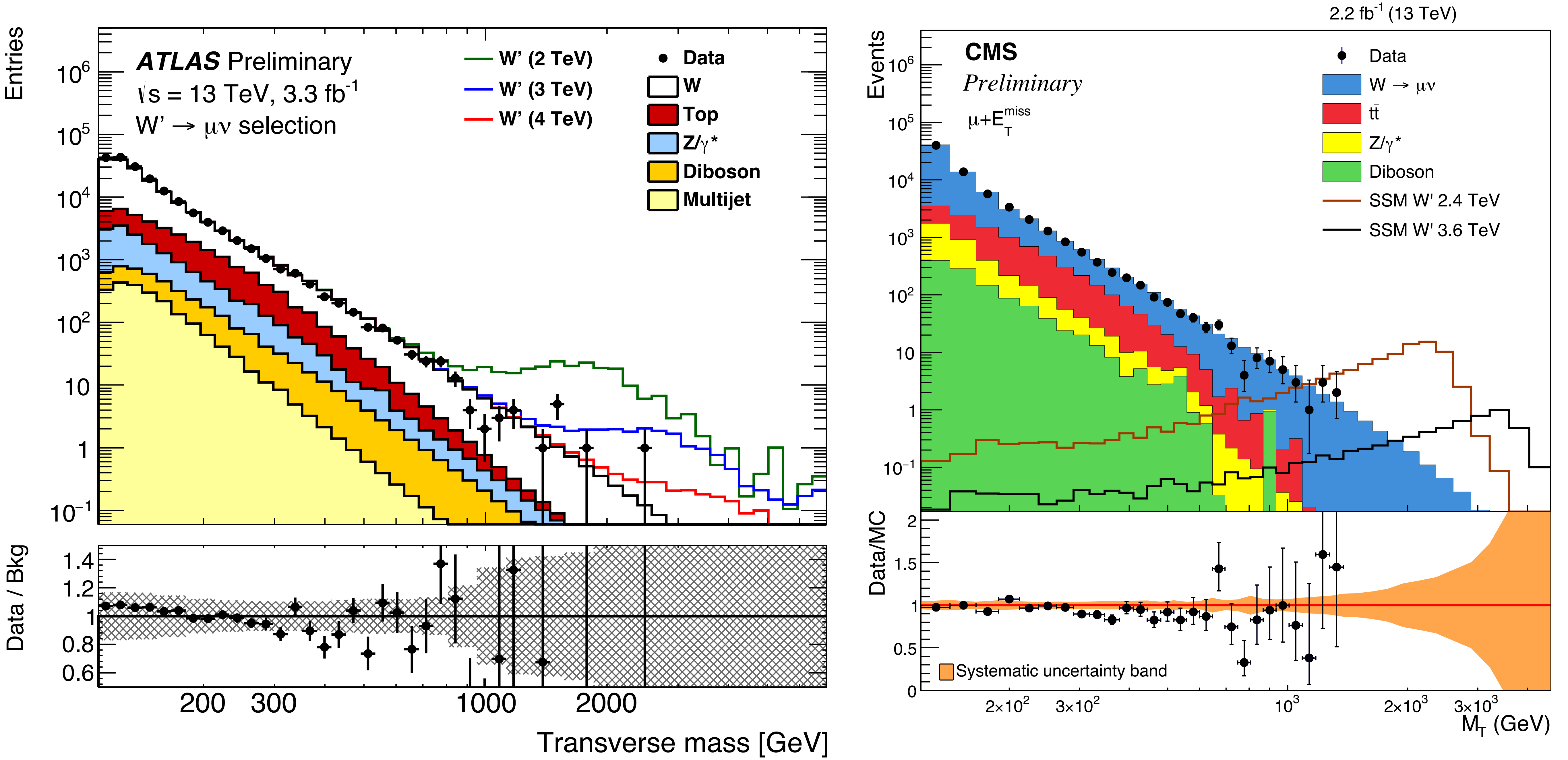
- Experimental uncertainties on the leptons and MET
  - Trigger (W')
  - Lepton reconstruction/identification efficiency (W', Z')
  - Lepton isolation (W', Z')
  - MET scale/resolution (W')
  - Jet scale/resolution (W')
  - MC statistics at high mass (W', Z') ← Extrapolation/interpolation needed to fill gaps and extend to the full search range
  - Normalisation (Z')
- Uncertainties on the MC background/signal
  - PDF-related for DY (W', Z')
  - Multi-jet and W+jets b/g (W')
- Luminosity (W')

W' searches: transverse mass distributions (eν)



Drell-Yan (W) dominates (e.g. ~90% at 1 TeV)
Multi-jet of secondary importance
Others largely irrelevant above 1TeV

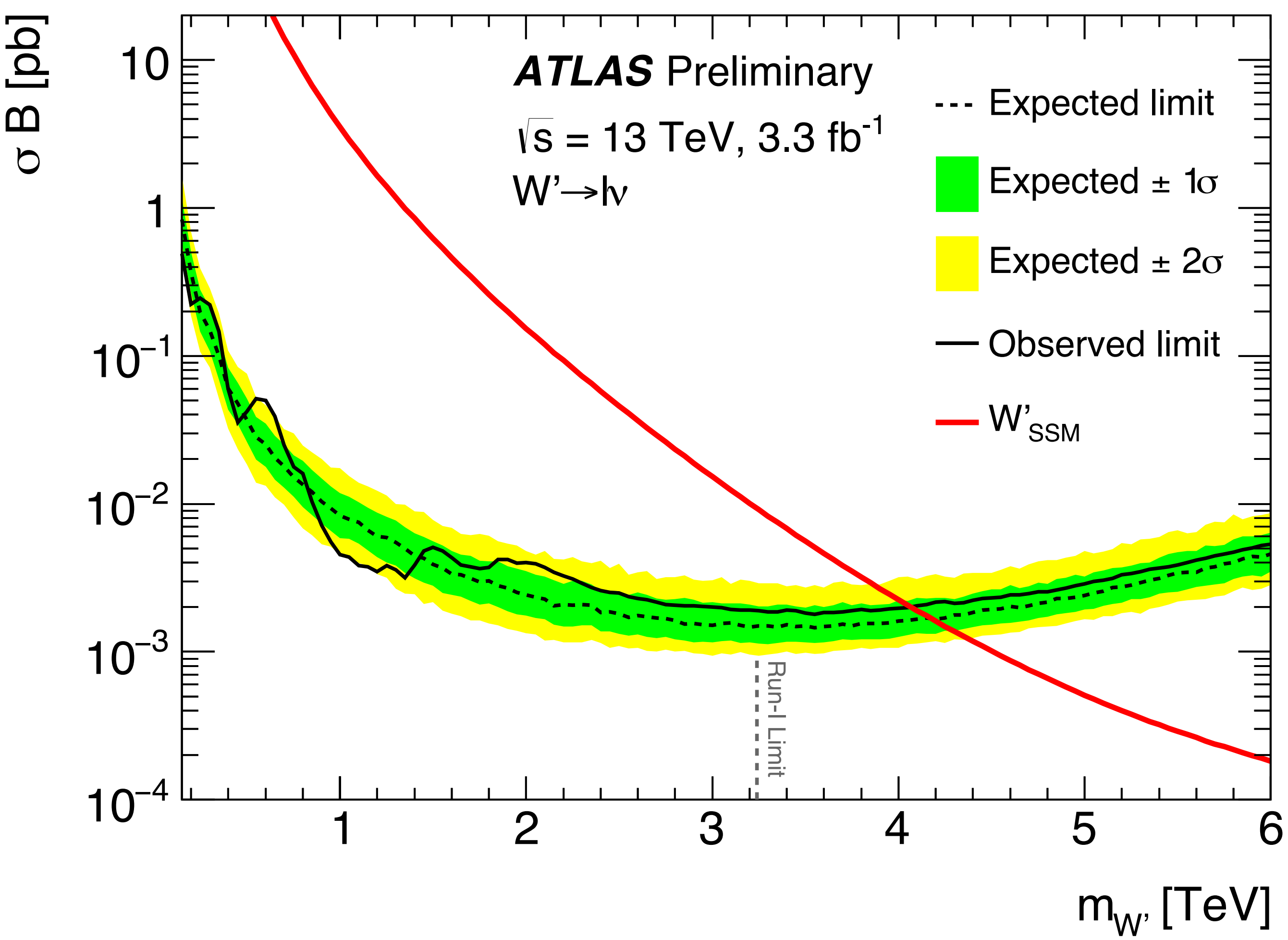
W’ searches: transverse mass distributions (μν)

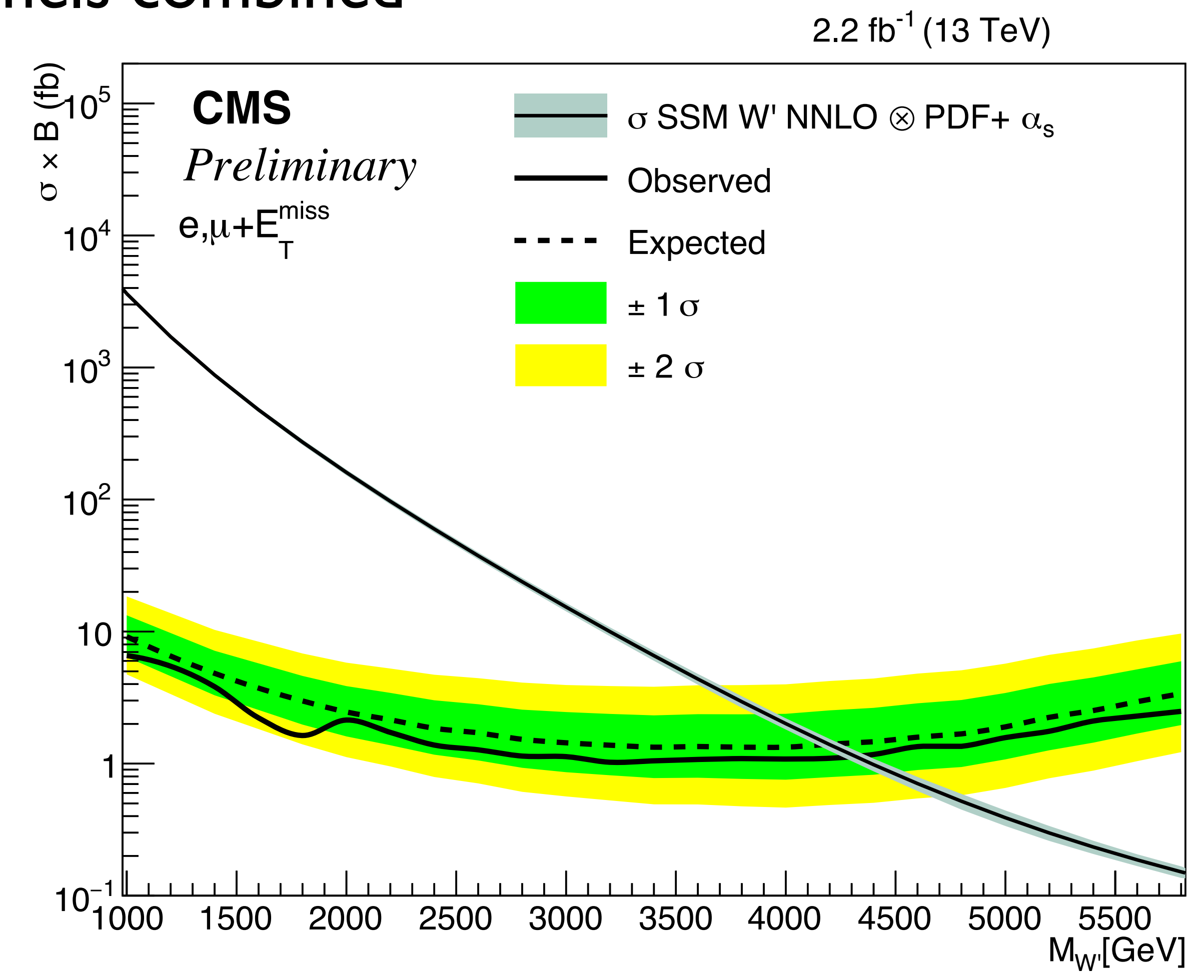


Drell-Yan (W) dominates (e.g. ~90% at 1 TeV)
Others of secondary (and equal) importance

W' searches: production and upper mass limits

Electron, muon channels combined



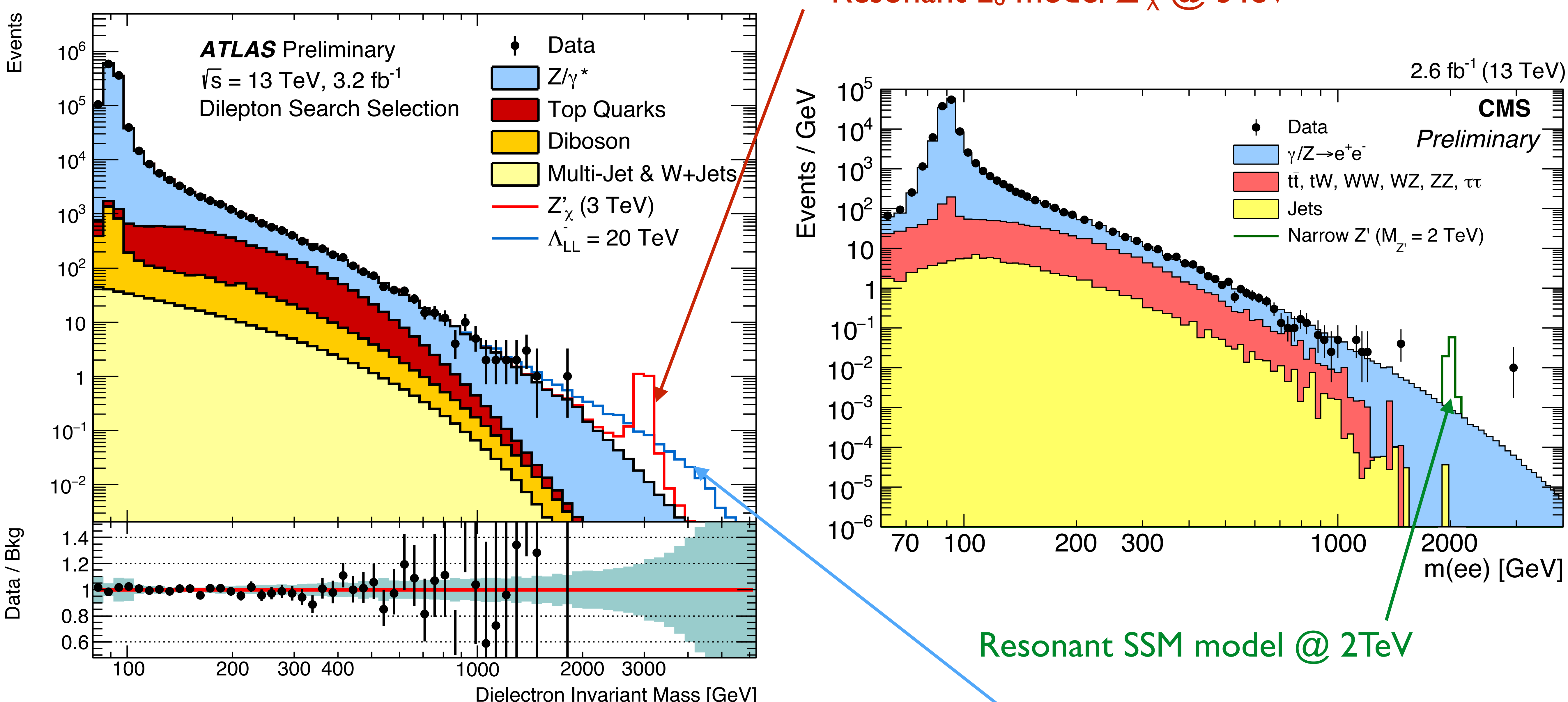


	Expected (TeV)		Observed (TeV)	
	ATLAS	CMS	ATLAS	CMS
eν	4.03	3.8	3.98	3.8
μν	3.66	3.8	3.42	4.0
combined	4.18	4.2	**4.07**	**4.4**
8 TeV	3.17	3.26	**3.24**	**3.28**

Z’ searches: invariant mass distributions (ee)

Drell-Yan dominating background, others of secondary importance

Resonant E₆ model Z'_χ @ 3TeV

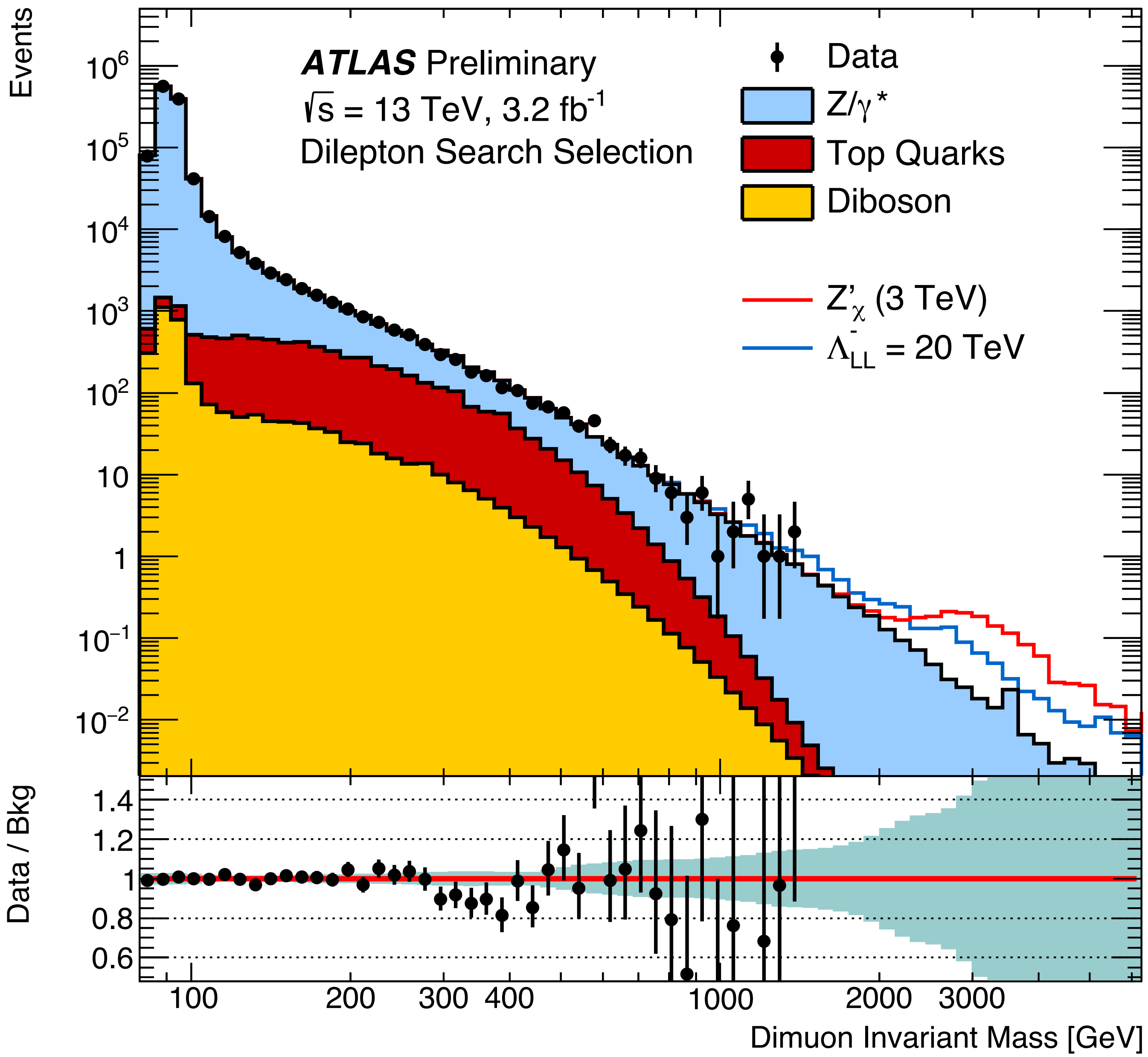


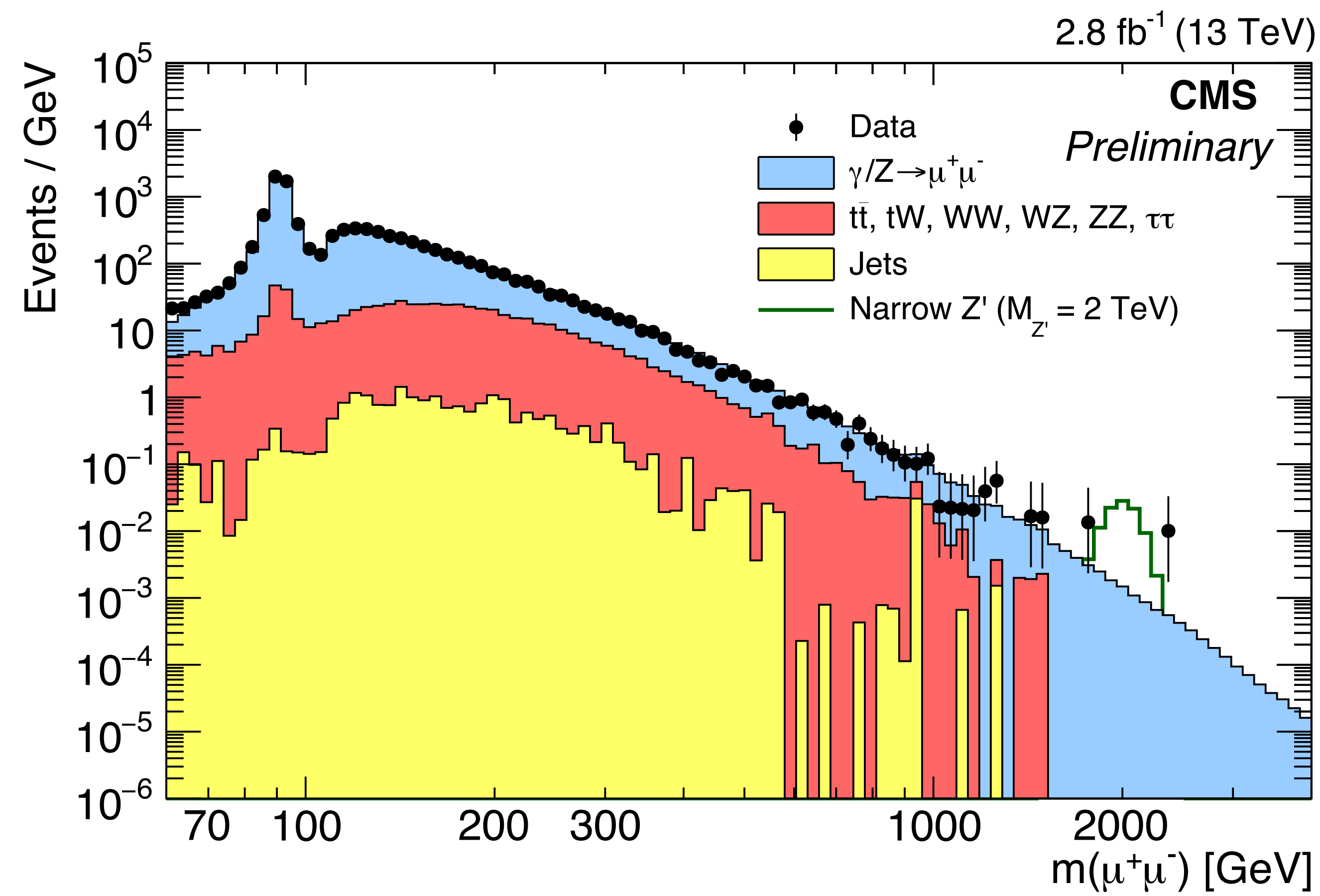
Resonant SSM model @ 2TeV

Non-resonant
contact interaction model @ 20TeV

Z' searches: invariant mass distributions (μμ)

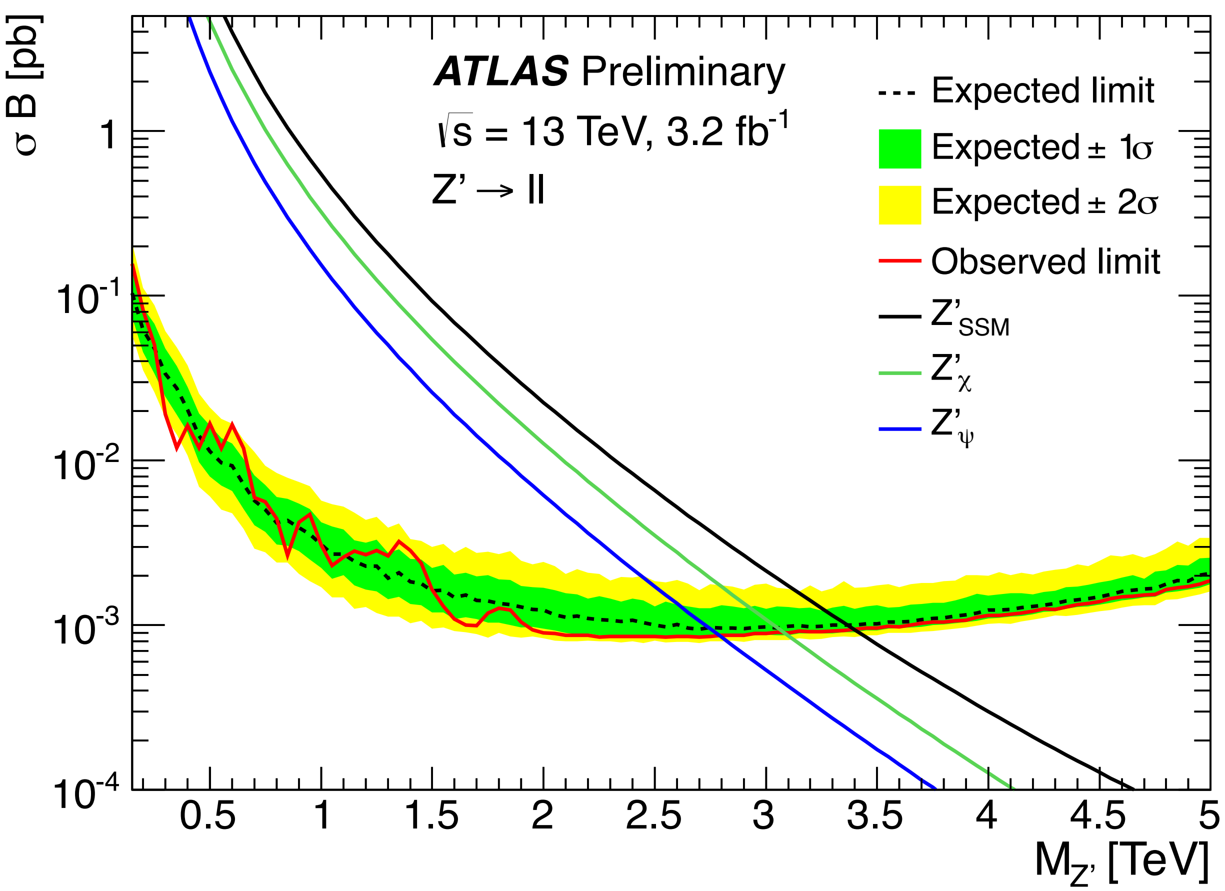
Drell-Yan dominating background around 1TeV, others of secondary importance
Fakes insignificant above ~500 GeV

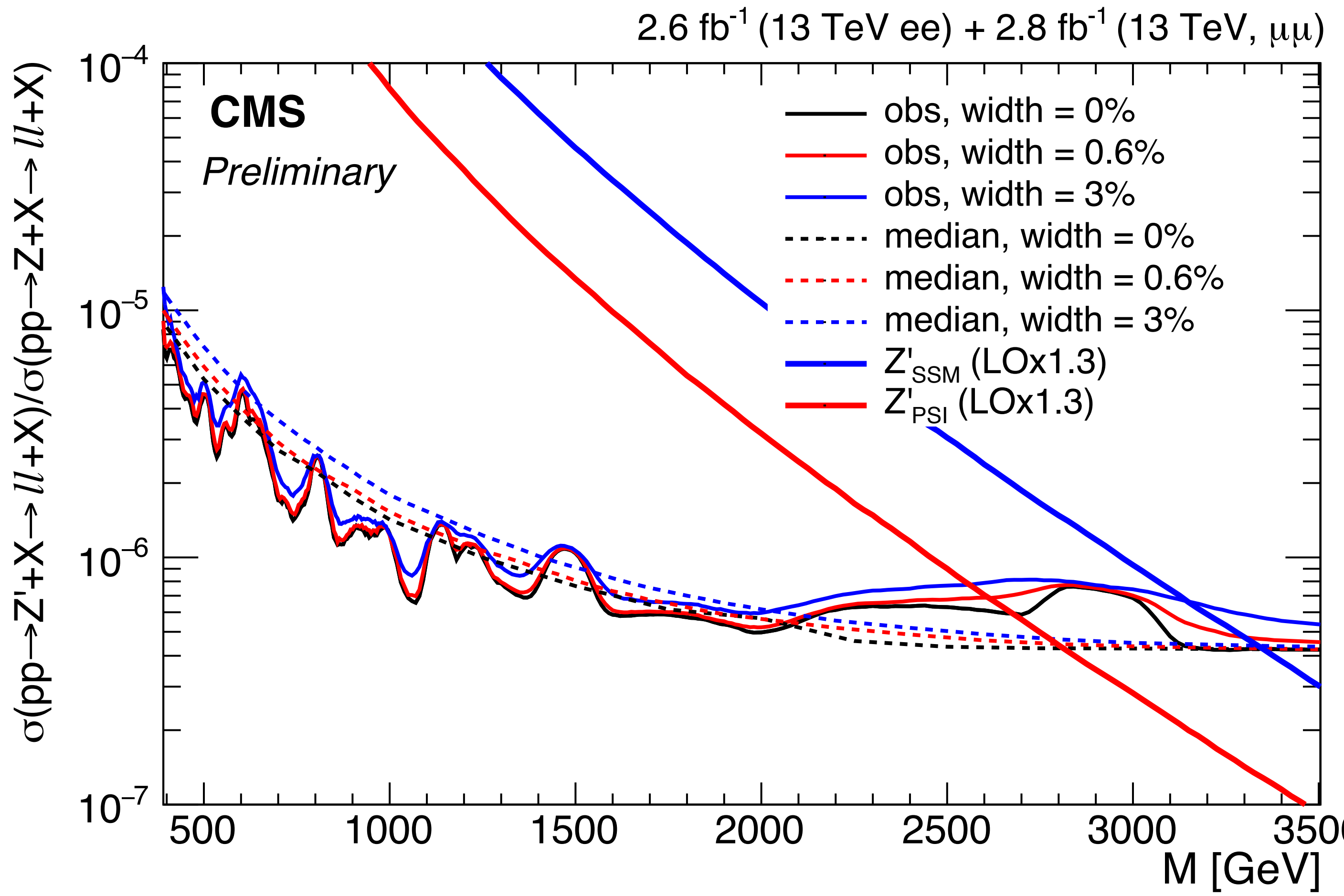




Z’ searches: production and upper mass limits

Electron, muon channels combined

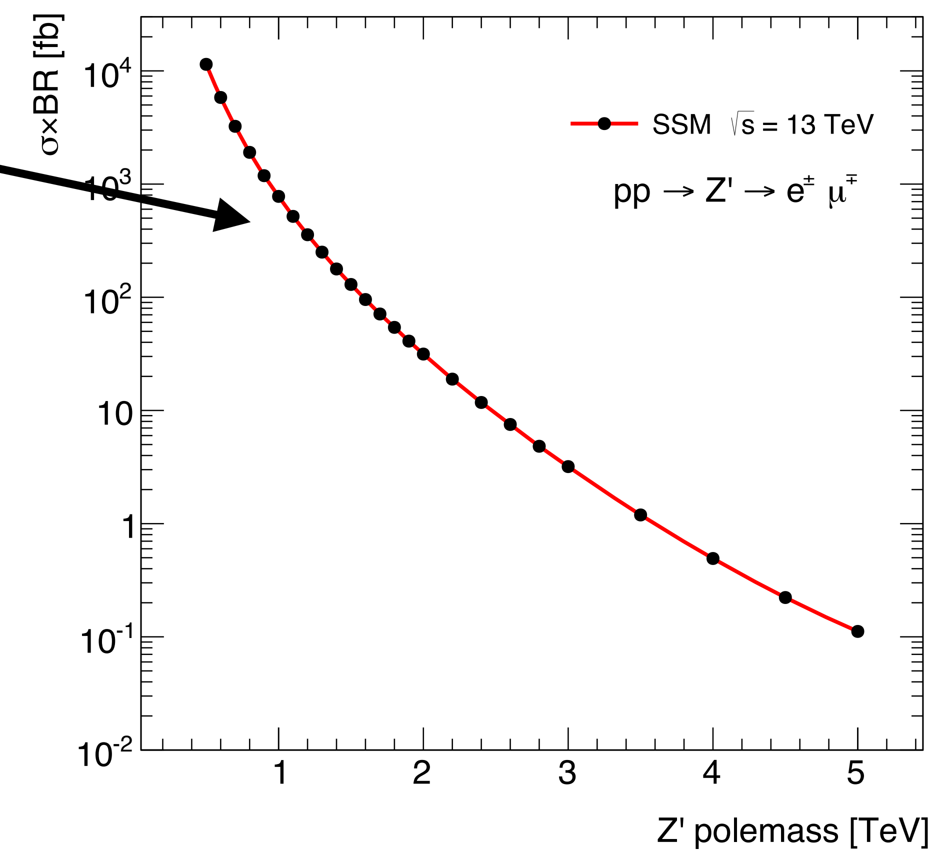


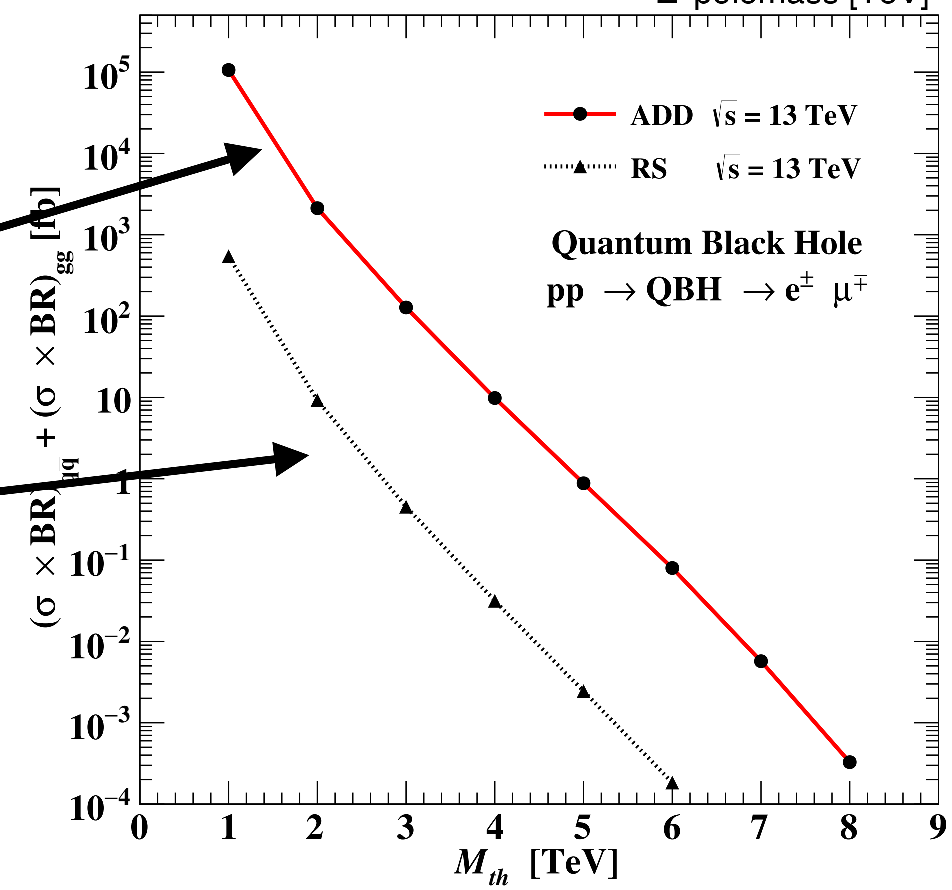


	Z'_ψ (width = 0.5% x M)				Z'_{SSM} (width = 3% x M)			
	Expected (TeV)		Observed (TeV)		Expected (TeV)		Observed (TeV)	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
ee	2.85	2.45	2.58	2.40	3.17	2.95	3.18	2.75
μμ	2.32	2.55	2.42	2.40	2.91	3.05	2.98	3.00
combined	2.74	2.80	**2.79**	**2.60**	3.37	3.35	**3.40**	**3.15**
8 TeV	2.82	2.57	**2.51**	**2.57**	2.87	2.90	**2.90**	**2.90**

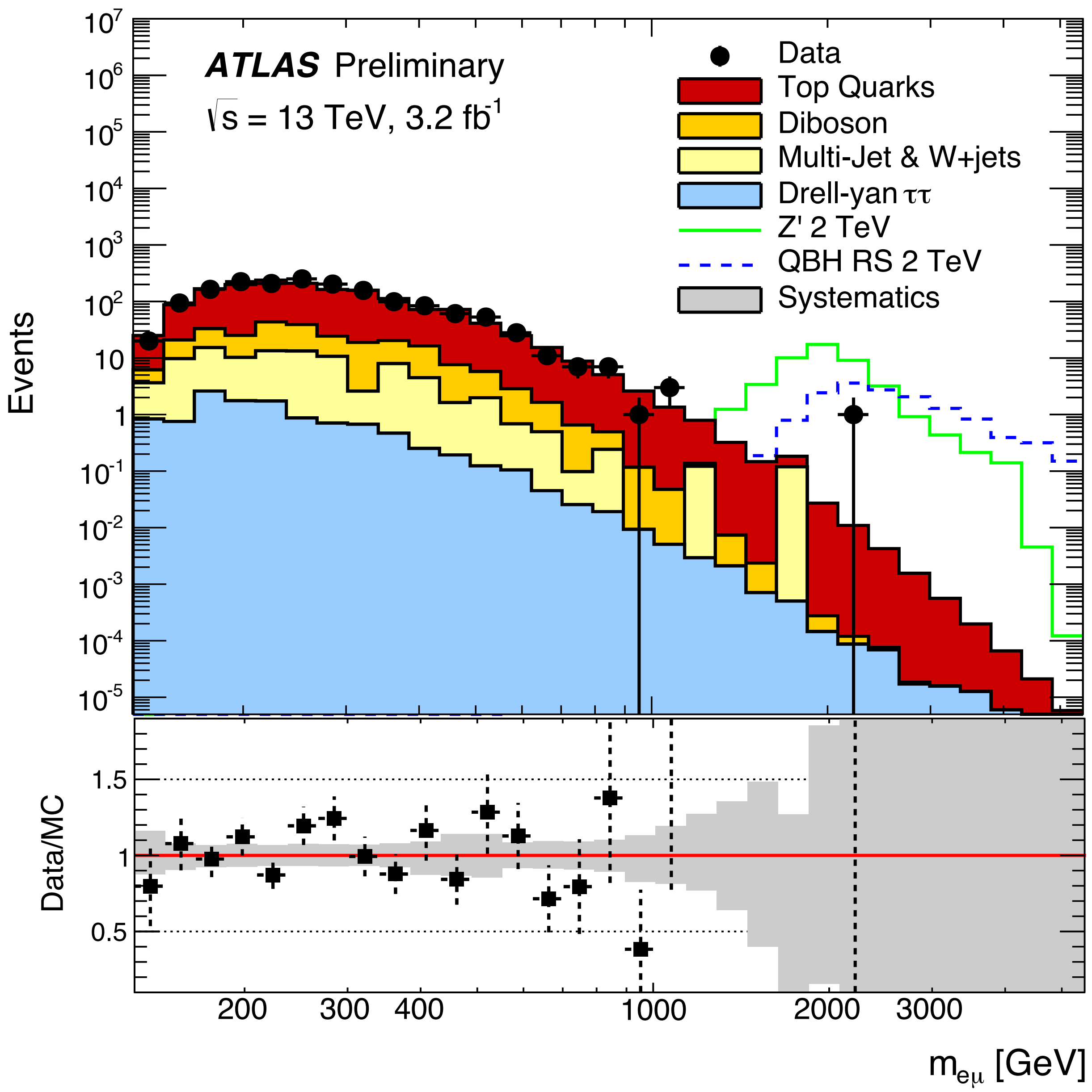
Lepton number violation through Z' and quantum gravity

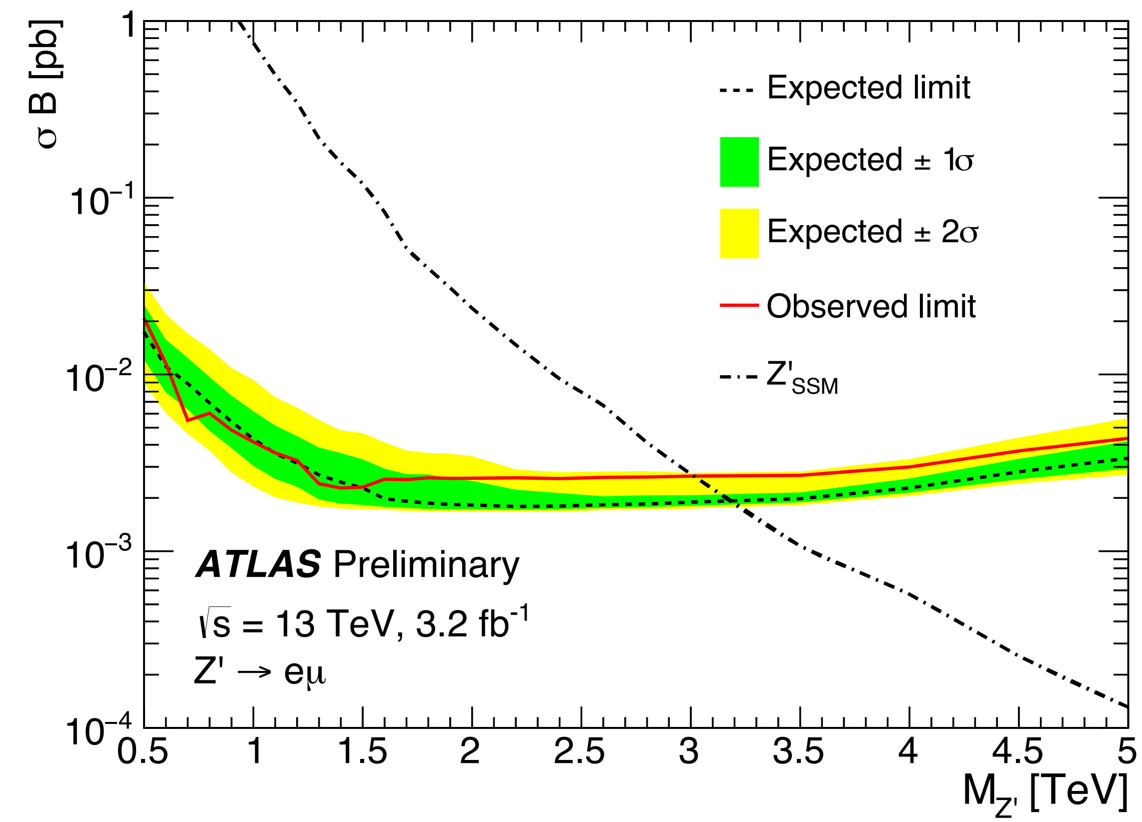
- Extensions to the SSM Z' model allow lepton-number violating decays to occur by introducing additional couplings
- Quantum black holes could fail to respect lepton number conservation in their decay, and produce eμ final states
  - Assume quantum gravity couples with equal strength to all SM particle degrees of freedom, allowing LFC violation but forbidding local symmetry violation (charge, colour)
  - Assume black hole predominantly decay into two-particle states
  - ADD model: six extra dimensions (n=6)
  - RS model: one highly warped extra dimension (n=1)
- Very similar to the lepton flavour conserving Z' analysis
- Low background, Drell Yan largely suppressed

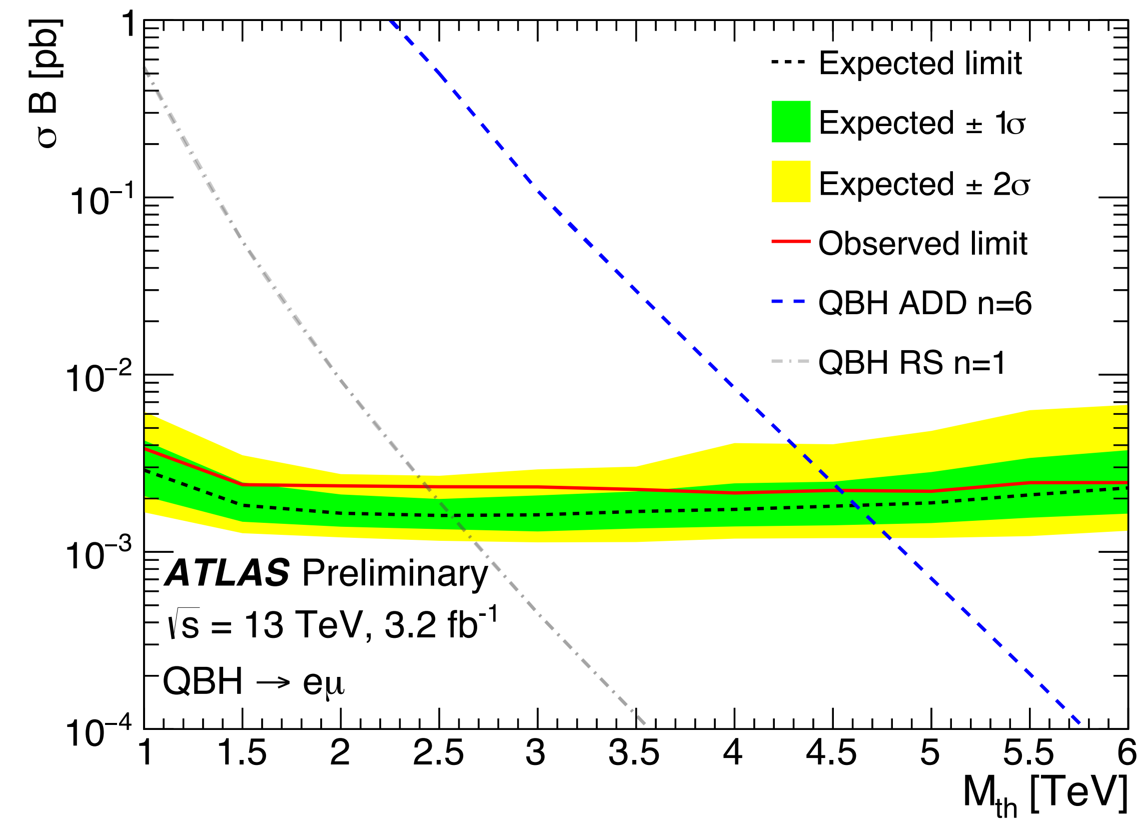




Lepton number violation through Z' and quantum gravity





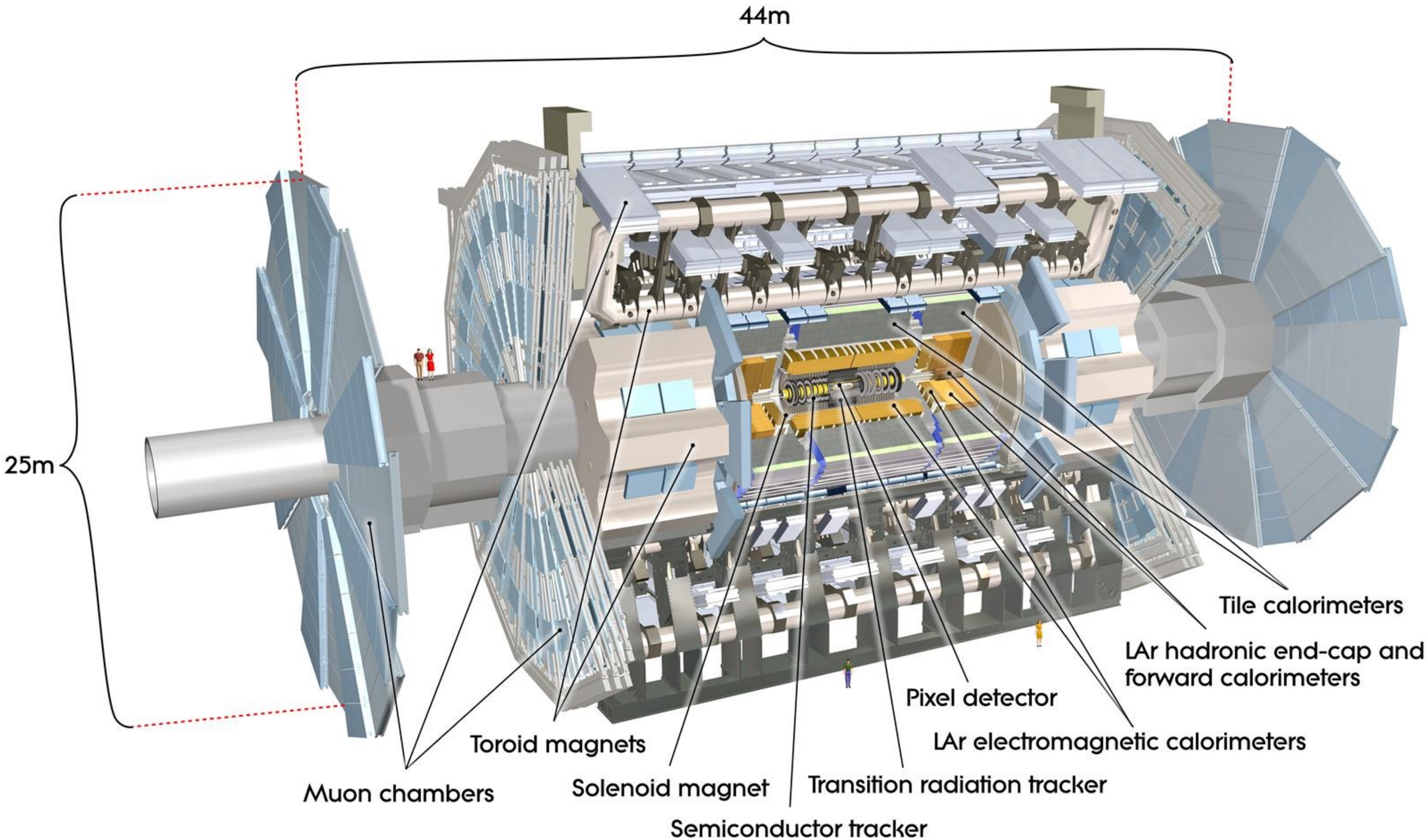


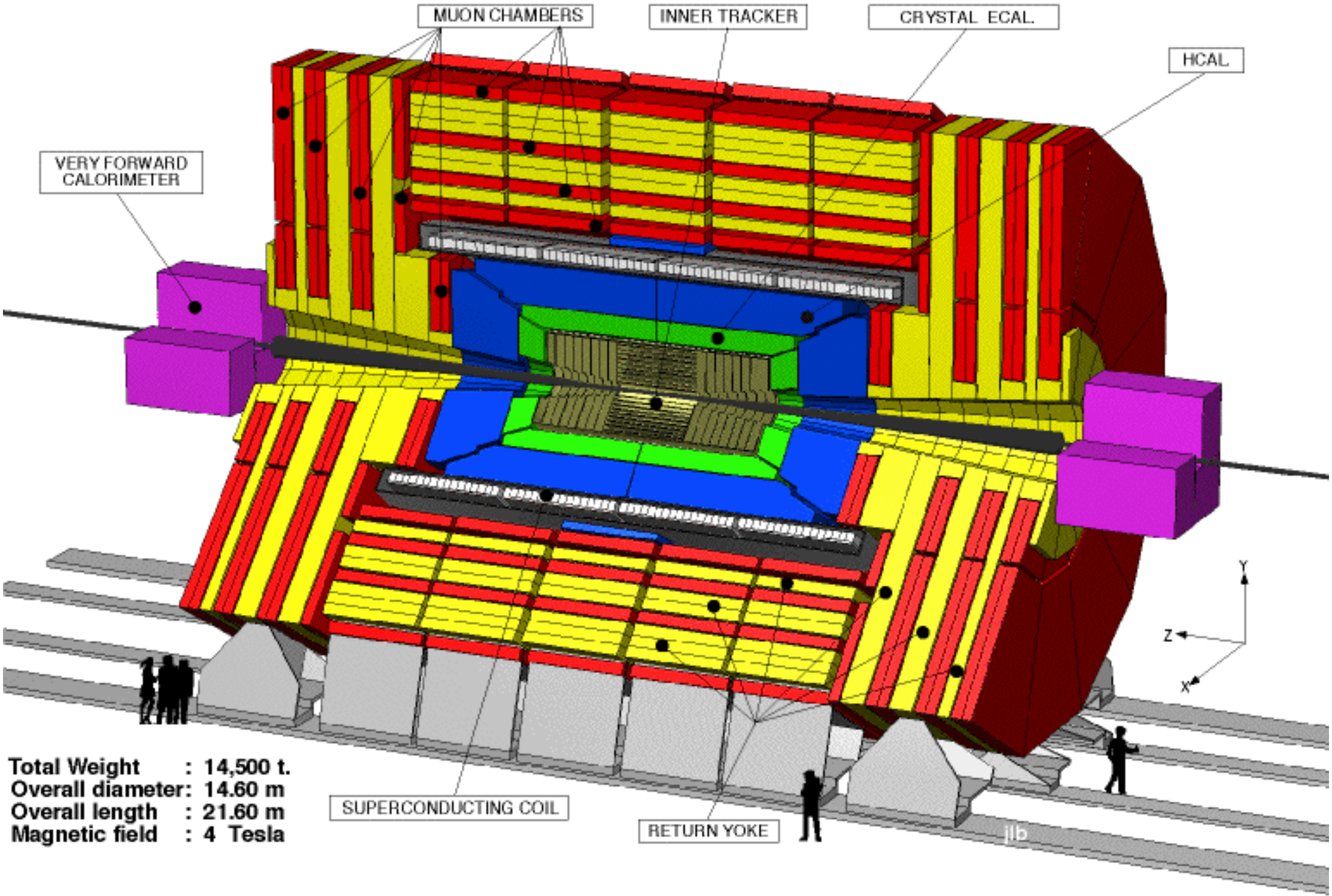
	Expected (TeV)	Observed (TeV)
Z' SSM	3.19	**3.01**
ADD n=6	4.62	**4.54**
RS n=1	2.56	**2.44**

Outlook and conclusions

- ATLAS and CMS have well-developed searches in place for heavy counterparts of the W and Z boson
  - Both detectors demonstrate excellent performance in the relevant object reconstruction, and complement each other's strengths
- 2-3 inverse femtobarns of data at 13TeV has already allowed us to push the limits beyond Run-1 for W' and Z' over 1TeV
- In 2016 we expect ~10 times more data
  - *What might we see this year? Some very interesting results ahead of us!*

Back-up slides


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker


MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL
HCAL
VERY FORWARD CALORIMETER
SUPERCONDUCTING COIL
RETURN YOKE
Y
Z
X
jlb
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

Triggers

		ATLAS	CMS
W'	eν	1e > 50 GeV, HCAL isolation at L1 or nonisolated > 60, 120 GeV	1e > 105 GeV or 1e > 115 GeV
	μν	1μ > 50 GeV	1μ > 50 GeV, |η| < 2.4 or 1μ > 45 GeV, |η| < 2.1
Z'	ee	2e > {17 GeV, 17 GeV} E_T	2e > {33 GeV, 33 GeV} E_T Hadronic calo deposits in cone centred around electron of size ΔR=0.14 must be less than 15% (barrel) or 10% (endcaps) of the electron energy
	μμ	1μ > 26 (isolated) || 50 GeV	1μ > 50 GeV, |η| < 2.4

Offline selections (W’)

		ATLAS	CMS
W’	eν	1e p_T > 65 GeV “Tight” for pT< 125, “Medium” otherwise Isolated E_{Tmiss} > 65 GeV m_T >130 GeV	1e p_T > 130 GeV Isolated Events with additional electrons > 35 GeV rejected
	μν	1μ p_T > 55 GeV Isolated E_{Tmiss} > 55 GeV m_T > 110 GeV	1μ p_T > 53 GeV σ_{pT}/p_T < 0.3 Isolated Events with additional muons > 25 GeV rejected
	Both	Event must have a primary vertex	$\|\Delta\phi\|(p_T , p_{Tmiss}\|$ > 2.5 0.4 < p_T/E_{Tmiss} < 1.5

Offline selections (Z')

		ATLAS	CMS
Z'	ee	2e $E_T > 30$ GeV Primary vertex Isolated No opposite charge requirement	2e $E_T > 35$ GeV $\|\eta_{det}\| < 1.4442$ (barrel) $1.566 < \|\eta_{det}\| < 2.5$ (endcap) At least one in the barrel Isolated No opposite charge requirement
	μμ	2μ $p_T > 30$ GeV Primary vertex Isolated Opposite charge requirement	2μ > 53 GeV, $\|\eta\| < 2.4$ Isolated Common vertex fit χ^2/dof < 20 Opposite charge requirement

- Used to calculate contamination from hadronic jets which are wrongly identified as leptons ("fakes")
  - Singly for W'
  - Together or in combination with a real lepton for Z'
- Idea of the matrix method: express the unknown quantities (number of fake candidates) in terms of quantities that can be measured from data
  - Loosen the lepton ID criteria to produce a "loose lepton" sample
  - Measure how many loose leptons pass the signal selection, use matrix method to link back to the actual fake yield
  - e.g. for W' (similar for Z' but 4x4 matrix due to paired combinations)

Measurable (Tight leptons: N_T; Loose leptons: N_L) — Unknown (Real leptons: N_R; Fake leptons: N_F)

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} \epsilon_R & \epsilon_F \\ 1-\epsilon_R & 1-\epsilon_F \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix}$$

$$\epsilon_R = \frac{N^{\rm real}_{\rm tight}}{N^{\rm real}_{\rm loose}} \qquad \epsilon_F = \frac{N^{\rm fake}_{\rm tight}}{N^{\rm fake}_{\rm loose}}$$

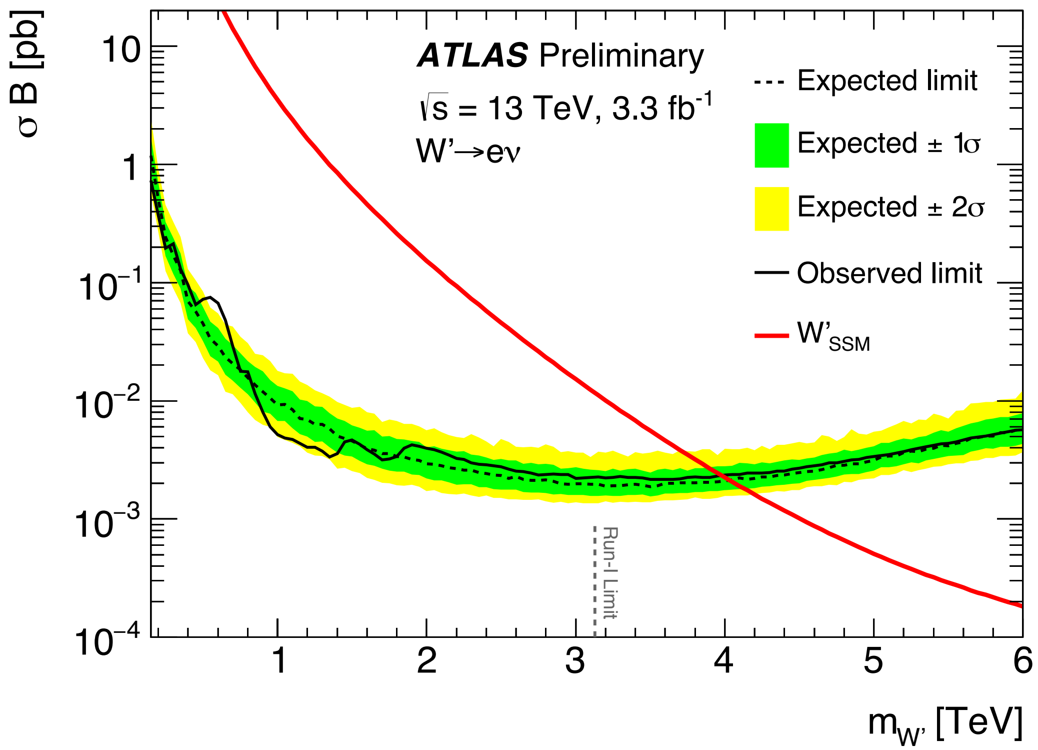
Invert matrix: $$\epsilon_F N_F = \frac{\epsilon_F}{\epsilon_R - \epsilon_F}\left(\epsilon_R (N_L + N_T) - N_T\right)$$

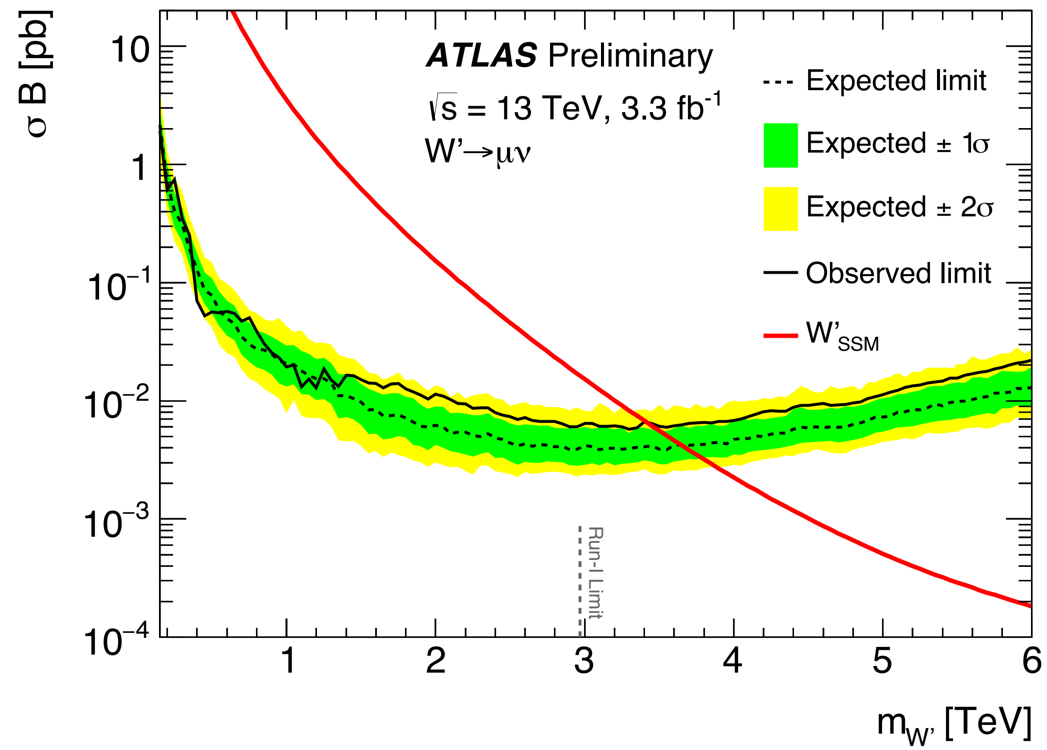
ε_F and ε_R are measured independently (using data driven methods such as tag-and-probe for efficiencies and enriched background samples for fake rates)

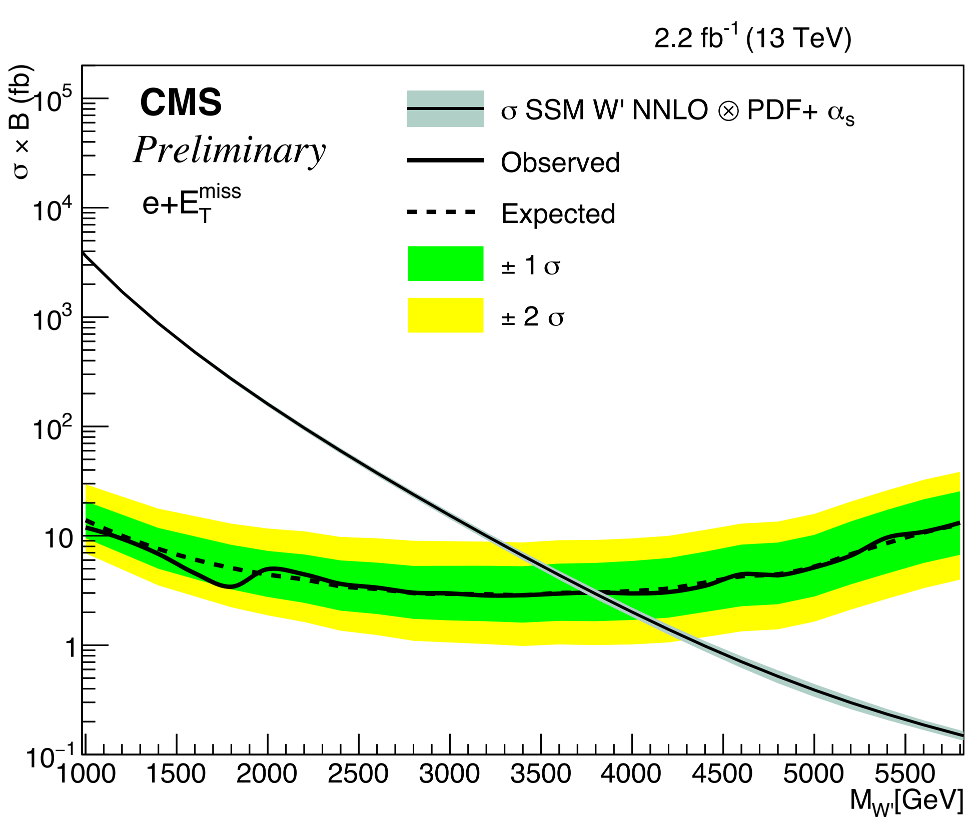
W’ supplementary results

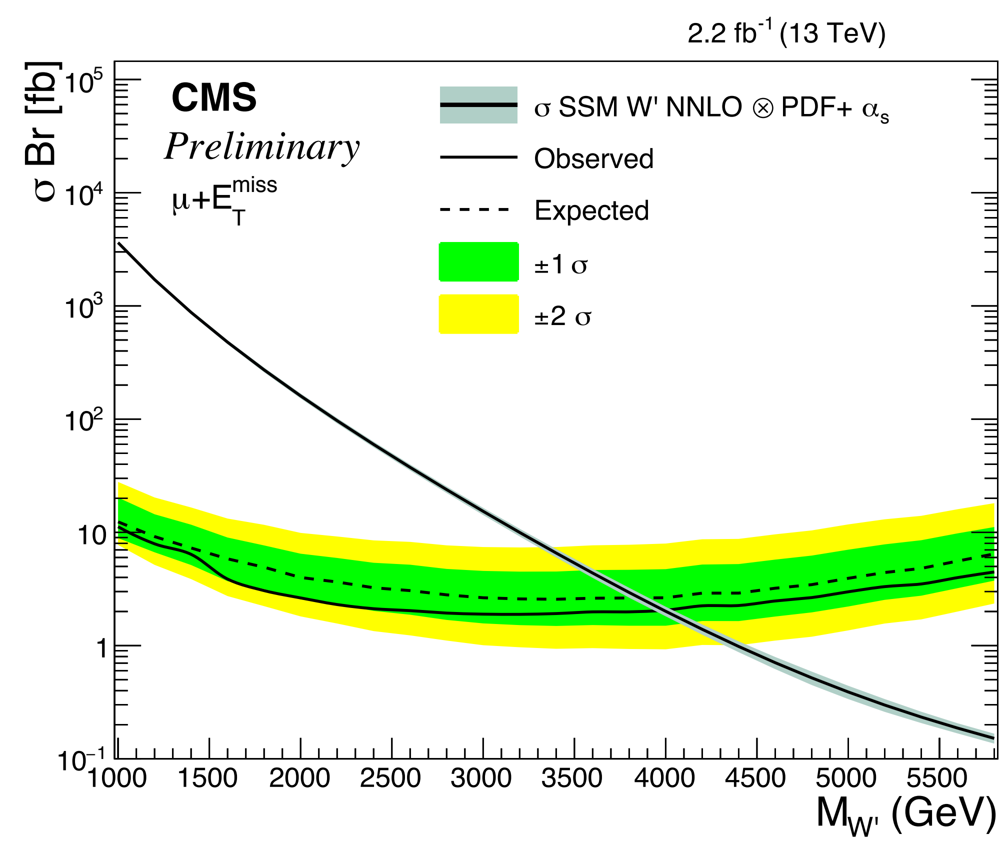
W' searches: production limits

Electron, muon channels separately









ATLAS systematics

Source	Electron channel		Muon channel	
	Background	Signal	Background	Signal
Trigger	negl. (negl.)	negl. (negl.)	3% (3%)	3% (4%)
Lepton reconstruction and identification	negl. (negl.)	negl. (negl.)	6% (10%)	5% (8%)
Lepton isolation	negl. (negl.)	negl. (negl.)	5% (5%)	5% (5%)
Lepton momentum scale and resolution	3% (3%)	11% (6%)	49% (69%)	5% (21%)
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution and scale	$< 0.5\%$ ($< 0.5\%$)	$< 0.5\%$ ($< 0.5\%$)	1% (1%)	1% (2%)
Jet energy resolution	$< 0.5\%$ ($< 0.5\%$)	$< 0.5\%$ (1%)	1% (1%)	1% (1%)
Multijet background	3% (19%)	N/A (N/A)	negl. (negl.)	N/A (N/A)
PDF choice for DY production	3% (13%)	N/A (N/A)	2% (2%)	N/A (N/A)
PDF variation for DY production	8% (10%)	N/A (N/A)	6% (8%)	N/A (N/A)
Luminosity	8% (4%)	9% (9%)	9% (9%)	9% (9%)
Total	12% (26%)	14% (11%)	51% (71%)	13% (25%)

CMS event yields

Electrons

	M_T >500 GeV	M_T >1000 GeV	M_T >1500 GeV
Data	230	11	1.0
SM Background	246 ± 18	14.3 ± 1.2	1.9 ± 0.2
SSM W' M=2.4TeV	66.1 ± 5.5	58.4 ± 5.2	46.3 ± 4.4
SSM W' M=3.6TeV	5.5 ± 0.7	4.9 ± 0.7	4.3 ± 0.6

Muons

	$M_T > 500$ GeV	$M_T > 1000$ GeV	$M_T > 1500$ GeV
Data	220	10	0
SM Background	251.5 ± 8.8	13.0 ± 1.2	1.8 ± 0.3
SSM W' M=2.4TeV	94.6 ± 5.2	83.9 ± 4.6	65.8 ± 3.6
SSM W' M=3.6TeV	6.3 ± 0.3	5.7 ± 0.3	5.0 ± 0.3

MC sample details

- Drell-Yan
  - NLO Powheg-Box v2, CT10 PDF + Pythia8.186 + Photos FSR
  - Normalised as function of mass to NNLO pQCD using VRAP + CT14NNLO PDF
  - Generated in slices to ensure full coverage
- Top
  - Powheg-Box v2 (ttbar), Powheg-Box v1 (single top), CT10 PDF + Pythia6.428
  - Normalised to cross section as calculated by Top++2.0
- Diboson
  - Sherpa2.1.1, CT10 PDF
- Signal
  - Pythia8.183, NNPDF23 LO. No interference. WZ decay forbidden.
  - Normalised as per DY samples

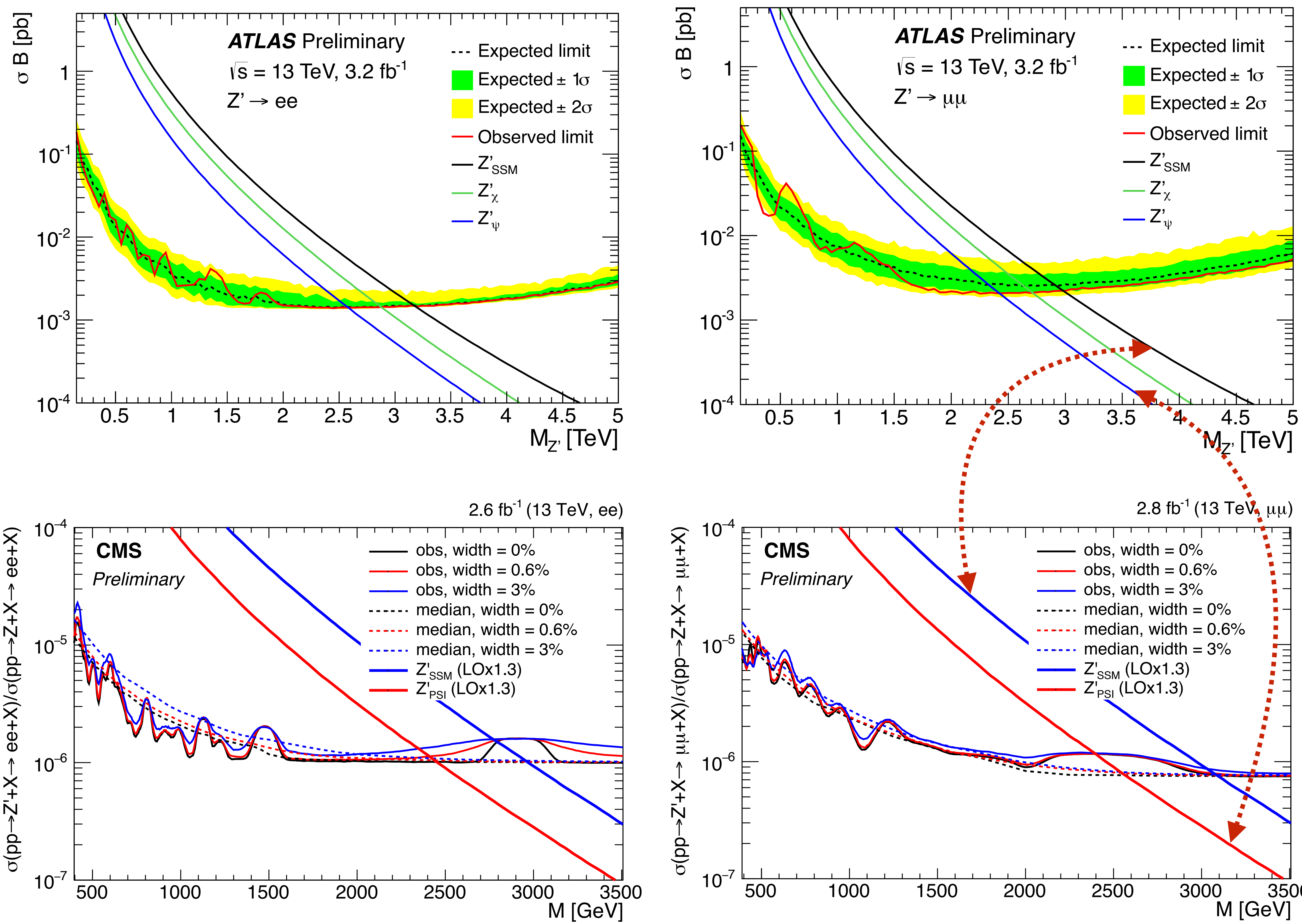
W' MC details

	ATLAS	CMS
DY	NLO Powheg-Box v2, CT10 PDF + Pythia8.186 + Photos FSR Normalised as function of mass to NNLO pQCD using VRAP + CT14NNLO PDF Generated in slices to ensure full coverage	W: inclusive in mass - Madgraph 5_aMC@NLO W: high mass slices - Pythia8.2, tune CUETP8M1, NNPDF3.0 PDF Mass dependent k-factor for high MT tails: NNLO QCD using FEWZ 3.2β2, NLO E/W corrections using MSC_{ANC} High mass DY: Powheg
Top	Powheg-Box v2 (ttbar), Powheg-Box v1 (single top), CT10 PDF + Pythia6.428 Normalised to cross section as calculated by Top++2.0	ttbar: Powheg Single top: Powheg in in t- and tW-channels, aMC@NLO in s-channel
Diboson	Sherpa2.1.1, CT10 PDF	Pythia8.2, tune CUETP8M1, CT10 PDF
Signal	Pythia8.183, NNPDF23 LO. No interference. WZ decay forbidden. Normalised as per DY samples	Pythia8.2, tune CUETP8M1, NNPDF3.0 PDF K-factors to NNLO via FEWZ 3.2β2

Z’ supplementary results

Z' searches: production limits

Electron, muon channels separately



ATLAS results for all resonant models

Model	Width [%]	ee [TeV]		$\mu\mu$ [TeV]		$\ell\ell$ [TeV]	
		Exp	Obs	Exp	Obs	Exp	Obs
Z'_{SSM}	3.0	3.17	3.18	2.91	2.98	3.37	3.40
Z'_{χ}	1.2	2.87	2.88	2.64	2.71	3.05	3.08
Z'_{S}	1.2	2.83	2.84	2.59	2.67	3.00	3.03
Z'_{I}	1.1	2.78	2.78	2.53	2.62	2.95	2.98
Z'_{N}	0.6	2.64	2.64	2.38	2.48	2.81	2.85
Z'_{η}	0.6	2.64	2.65	2.38	2.48	2.81	2.85
Z'_{ψ}	0.5	2.58	2.58	2.32	2.42	2.74	2.79

ATLAS systematics

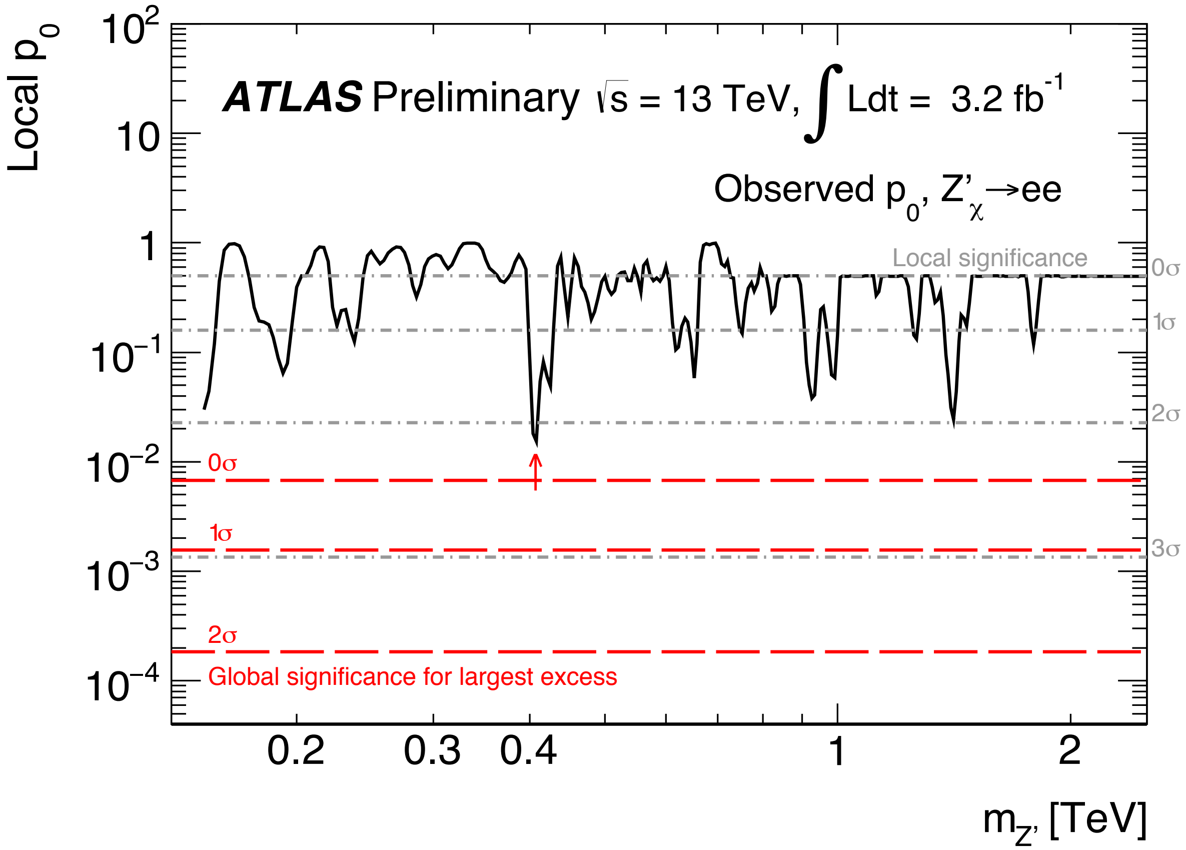
Source	Dielectron		Dimuon	
	Signal	Background	Signal	Background
Normalisation	4.0% (4.0%)	N/A	4.0% (4.0%)	N/A
PDF Choice	N/A	9.1% (17%)	N/A	5.3% (7.4%)
PDF Variation	N/A	5.3% (11%)	N/A	4.4% (6.5%)
PDF Scale	N/A	1.8% (2.3%)	N/A	1.7% (1.9%)
Photon-induced corrections	N/A	3.4% (5.4%)	N/A	3.2% (3.8%)
Efficiency	5.1% (5.0%)	5.1% (5.0%)	13% (19%)	13% (19%)
Scale & Resolution	<1.0% (<1.0%)	7.8% (9.1%)	20% (26%)	20% (46%)
Multi-jet & W+jets	N/A	<1.0% (<1.0%)	N/A	N/A
MC Statistics	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Total	6.5% (6.4%)	15% (24%)	25% (32%)	26% (51%)

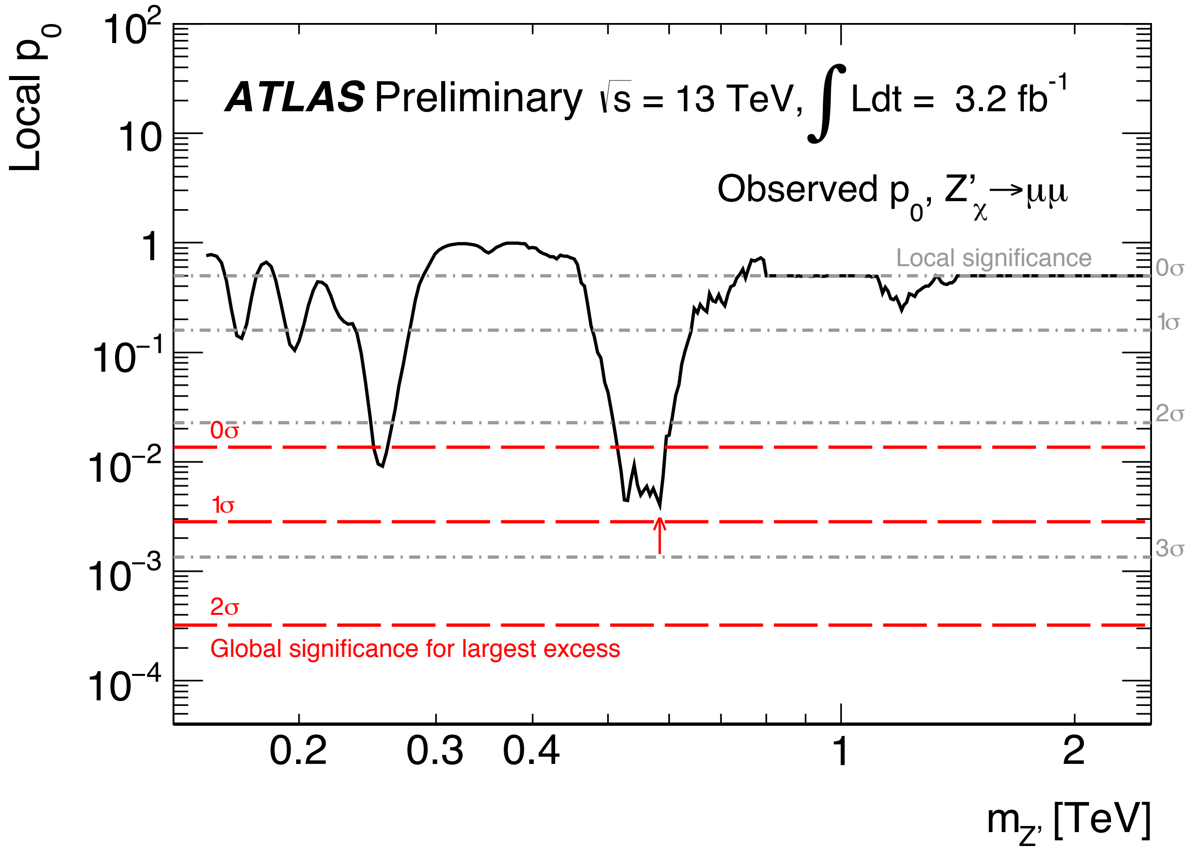
ATLAS full yields

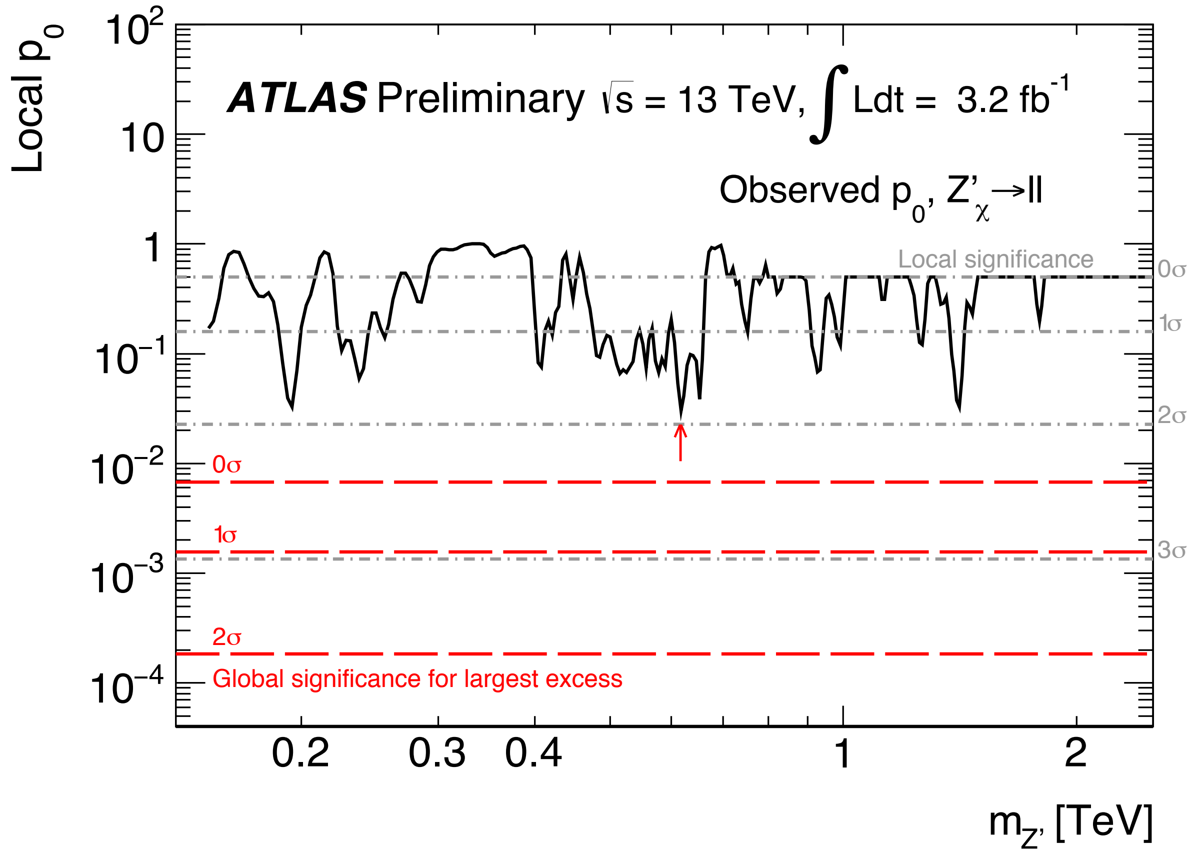
m_{ee} [GeV]	500-700	700-900	900-1200	1200-1800	1800-3000	3000-6000
Drell–Yan	145 ± 30	38 ± 6	16 ± 4	5.6 ± 1.6	0.87 ± 0.26	0.026 ± 0.012
Top Quarks	43.8 ± 2.9	5.4 ± 1.2	0.9 ± 0.5	0.09 ± 0.11	0.002 ± 0.006	$<$ 0.001
Diboson	7.7 ± 1.1	1.4 ± 0.5	0.39 ± 0.26	0.08 ± 0.12	0.005 ± 0.030	$<$ 0.001
Multi-Jet & W+Jets	4 ± 4	1.1 ± 0.8	0.40 ± 0.16	0.089 ± 0.019	0.0042 ± 0.0014	$<$ 0.001
Total SM	201 ± 31	46 ± 7	17 ± 4	5.8 ± 1.6	0.88 ± 0.26	0.026 ± 0.012
Data	202	44	17	9	0	0
SM+Z' ($m_{Z'}$ = 3 TeV)	201 ± 31	46 ± 7	17 ± 4	5.9 ± 1.6	2.6 ± 1.1	1.44 ± 0.34
SM+CI ($\Lambda^{-}_{\mathrm{LL}}$ = 25 TeV)	207 ± 31	49 ± 7	20 ± 4	8.0 ± 1.6	2.11 ± 0.27	0.251 ± 0.019

$m_{\mu\mu}$ [GeV]	500-700	700-900	900-1200	1200-1800	1800-3000	3000-6000
Drell–Yan	110 ± 7	27.5 ± 2.2	11.8 ± 1.1	4.5 ± 0.7	0.70 ± 0.08	0.079 ± 0.023
Top Quarks	39.5 ± 0.8	6.7 ± 0.4	0.89 ± 0.15	0.046 ± 0.032	$<$ 0.001	$<$ 0.001
Diboson	3.98 ± 0.32	0.65 ± 0.11	0.229 ± 0.028	0.022 ± 0.006	0.00104 ± 0.00034	$<$ 0.001
Total SM	151 ± 7	35.5 ± 2.3	14.2 ± 1.1	4.6 ± 0.7	0.71 ± 0.08	0.079 ± 0.024
Data	169	28	13	4	0	0
SM+Z' ($m_{Z'}$ = 3 TeV)	151 ± 7	35.5 ± 2.3	14.2 ± 1.1	4.6 ± 0.7	2.13 ± 0.26	0.8 ± 0.4
SM+CI ($\Lambda^{-}_{\mathrm{LL}}$ = 25 TeV)	162 ± 8	38.1 ± 2.4	15.3 ± 1.2	5.5 ± 0.8	0.87 ± 0.09	0.099 ± 0.035

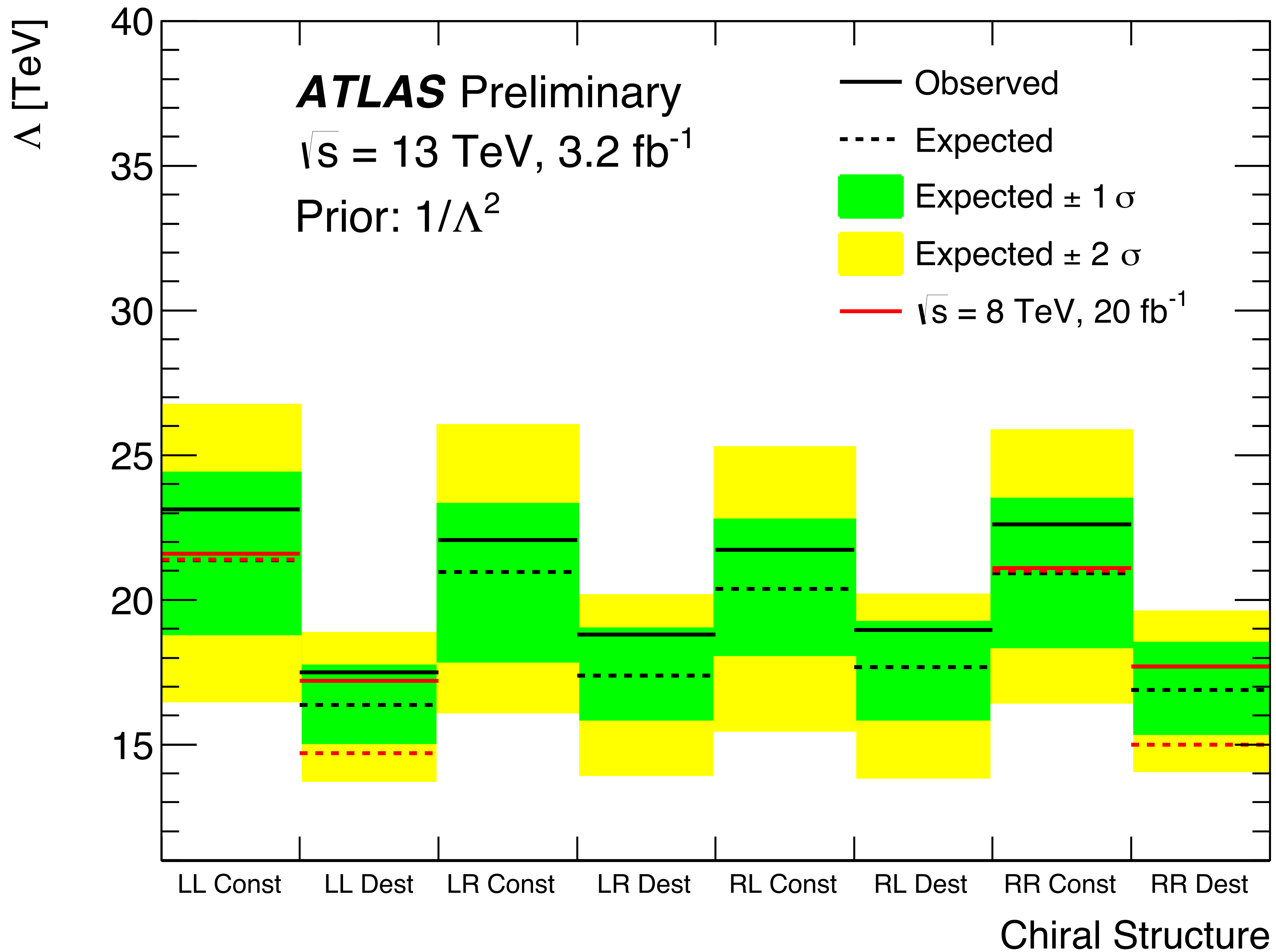
ATLAS p-value distributions







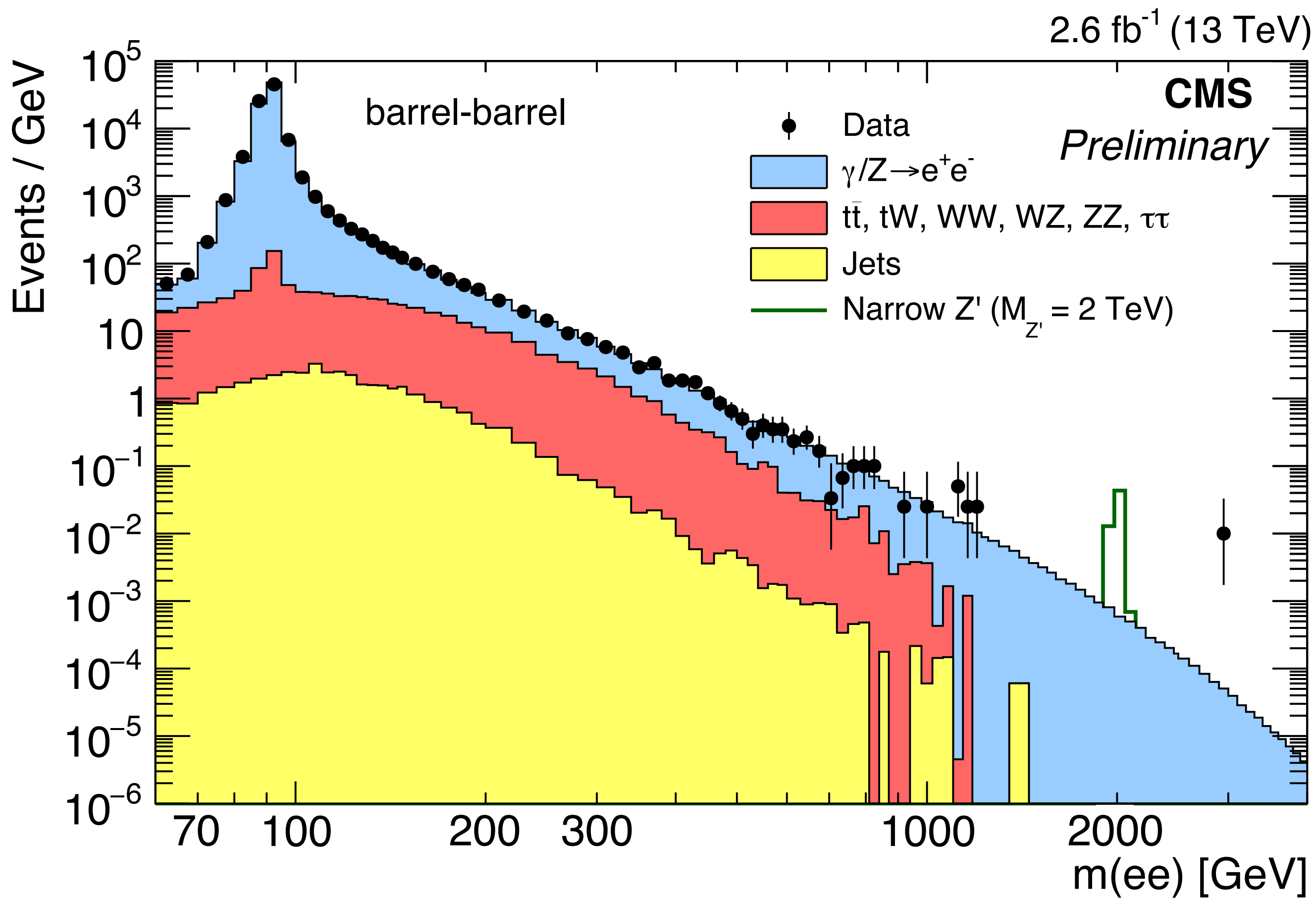
ATLAS limits for non-resonant (CI) production

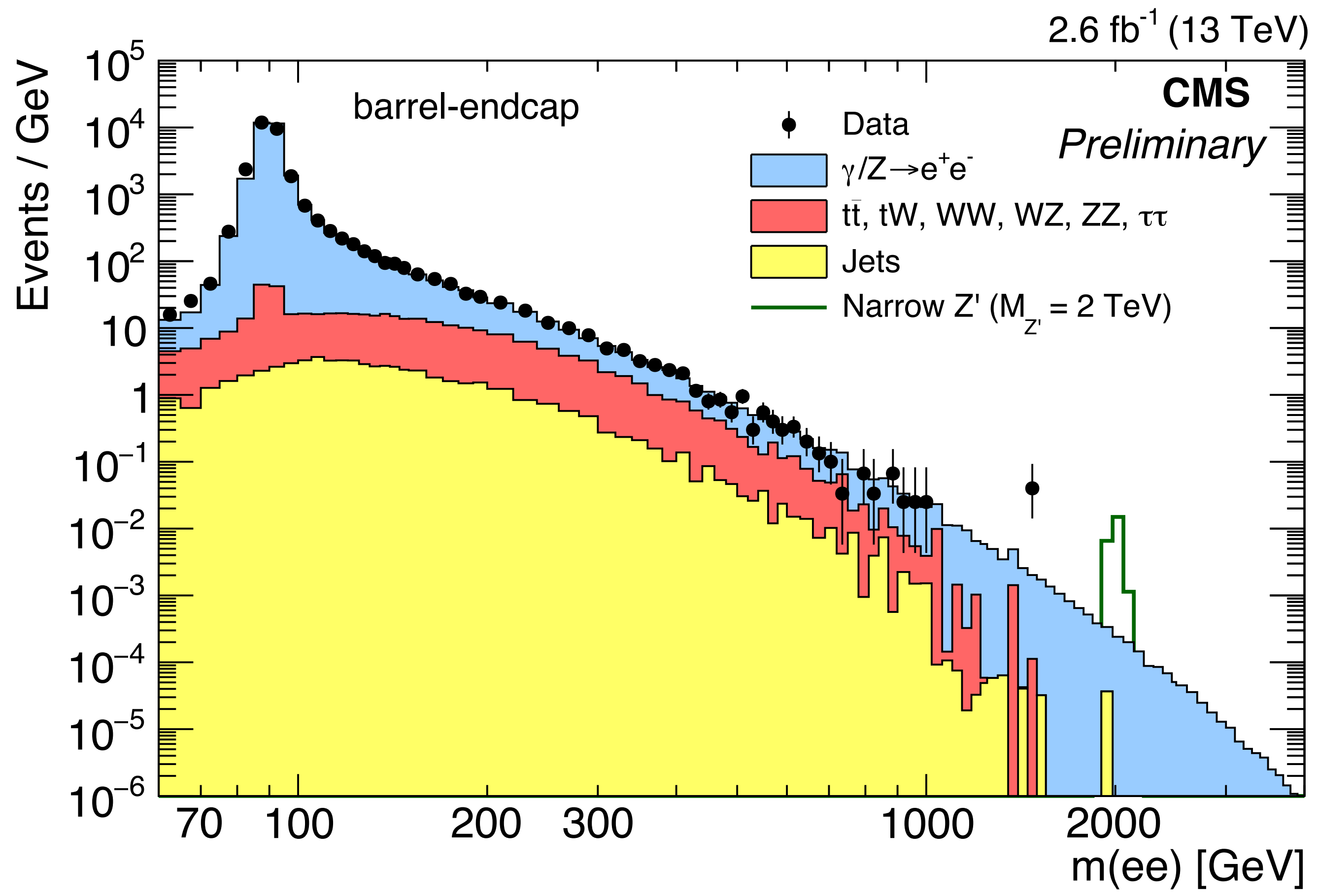


ATLAS limits for non-resonant (CI) production

Channel	Prior	Left-Left [TeV]		Left-Right [TeV]		Right-Left [TeV]		Right-Right [TeV]	
		Const.	Destr.	Const.	Destr.	Const.	Destr.	Const.	Destr.
Exp: ee	$1/\Lambda^2$	18.5	15.2	18.1	15.8	17.7	16.1	17.9	15.9
Obs: ee		18.3	15.3	17.6	15.8	17.5	15.9	17.5	15.8
Exp: ee	$1/\Lambda^4$	16.9	14.3	16.6	14.8	16.4	14.8	16.5	14.7
Obs: ee		16.7	14.1	16.2	14.5	16.1	14.6	16	14.6
Exp: $\mu\mu$	$1/\Lambda^2$	18.2	14.5	17.5	15.1	17.4	15.4	18.1	14.5
Obs: $\mu\mu$		20.2	15.8	19.7	17.0	19.4	17.1	20.4	15.8
Exp: $\mu\mu$	$1/\Lambda^4$	16.6	13.8	16.3	14.4	16.1	14.5	16.6	13.9
Obs: $\mu\mu$		18.1	15.0	17.7	15.8	17.4	15.9	18.1	15.0
Exp: $\ell\ell$	$1/\Lambda^2$	21.4	16.4	21.0	17.4	20.4	17.7	20.9	16.9
Obs: $\ell\ell$		23.1	17.5	22.1	18.8	21.7	19.0	22.6	17.7
Exp: $\ell\ell$	$1/\Lambda^4$	19.9	15.6	19.0	16.6	18.7	16.6	19.4	16.0
Obs: $\ell\ell$		20.7	16.4	20.0	17.5	19.8	17.6	20.3	16.6

CMS M_{ee} distributions in barrel and endcaps



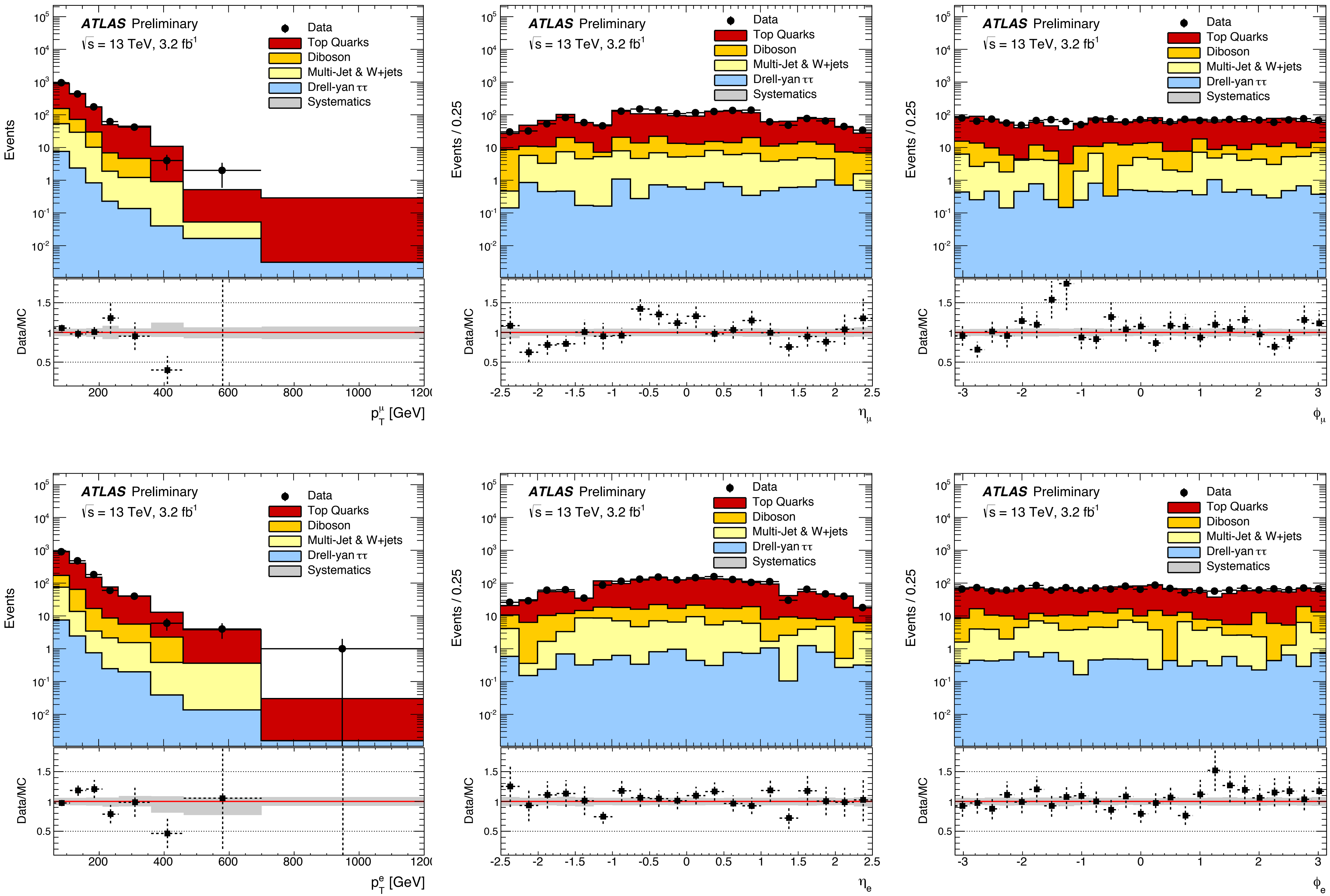


Z' MC details

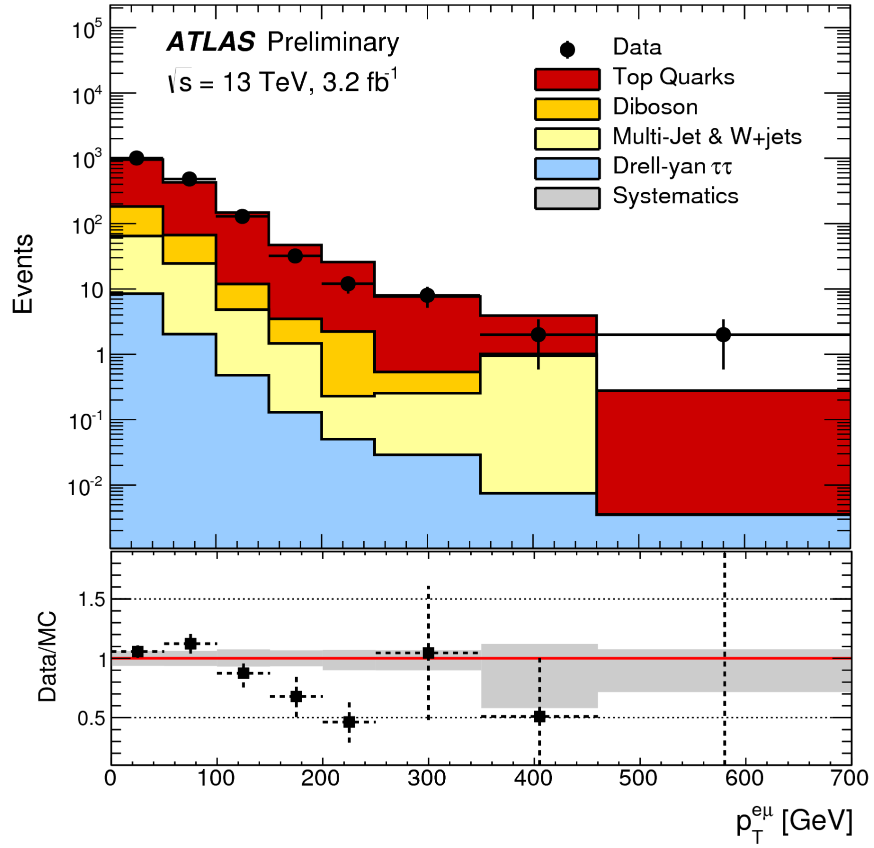
	ATLAS	CMS
DY	NLO Powheg-Box v2, CT10 PDF + Pythia8.186 + Photos FSR Mass dependent k-factor to NNLO using VRAP + CT14NNLO PDF Mass-dependent EW corrections at NLO using mcsanc and CT14 PDF set	Powheg2.0, NNPDF3.0 PDF + Pythia8
Top	Powheg-Box v2 (ttbar), Powheg-Box v1 (single top), CT10 PDF + Pythia6.428 Normalised to cross section as calculated by Top++2.0	Powheg 2.0
Diboson	Sherpa2.1.1, CT10 PDF	Pythia8
Signal	Pythia8.183, NNPDF23 LO. No interference for resonant. For non-resonant, both DY and CI samples generated to account for interference.	Pythia8

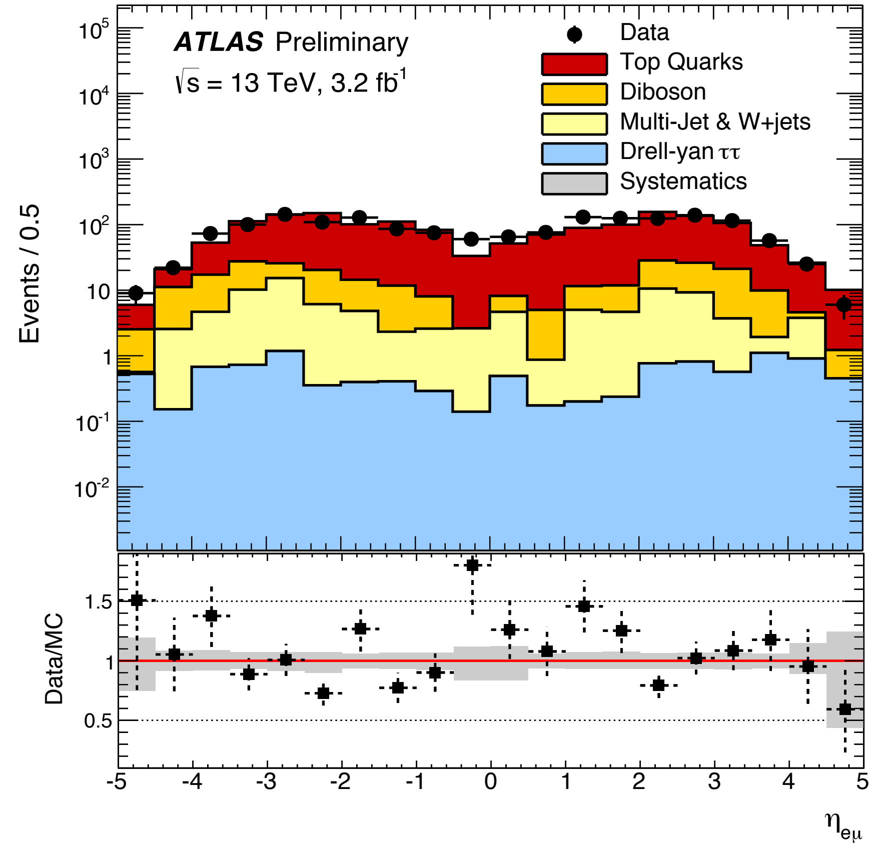
$Z' \to e\mu$ supplementary results

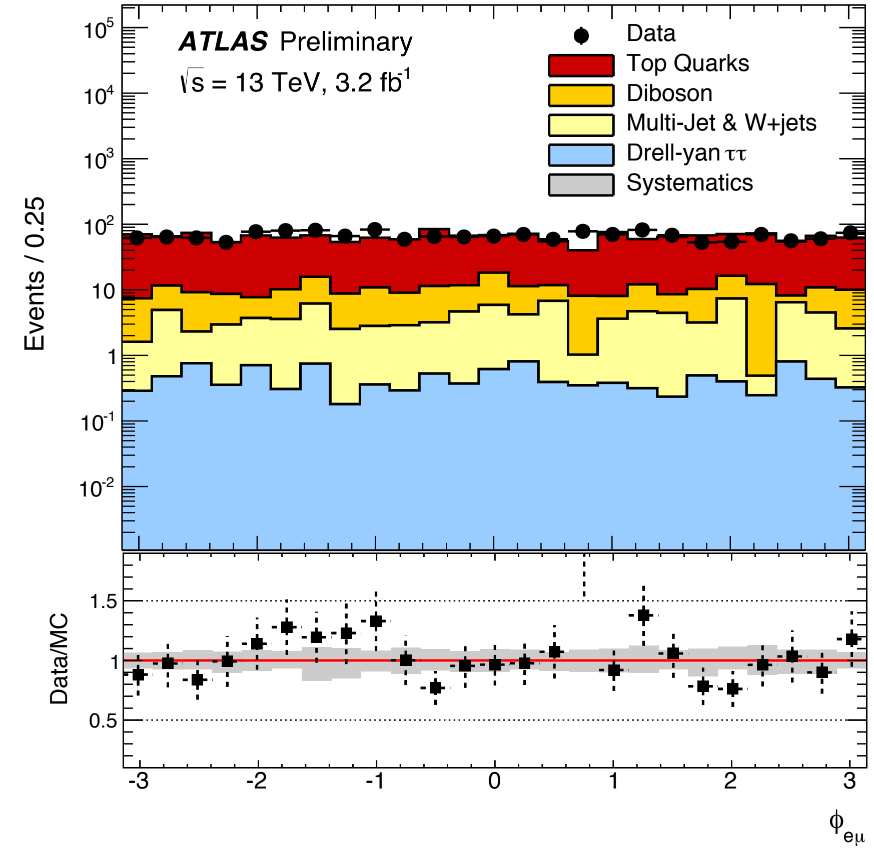
Kinematic variables of e, μ for selected pairs



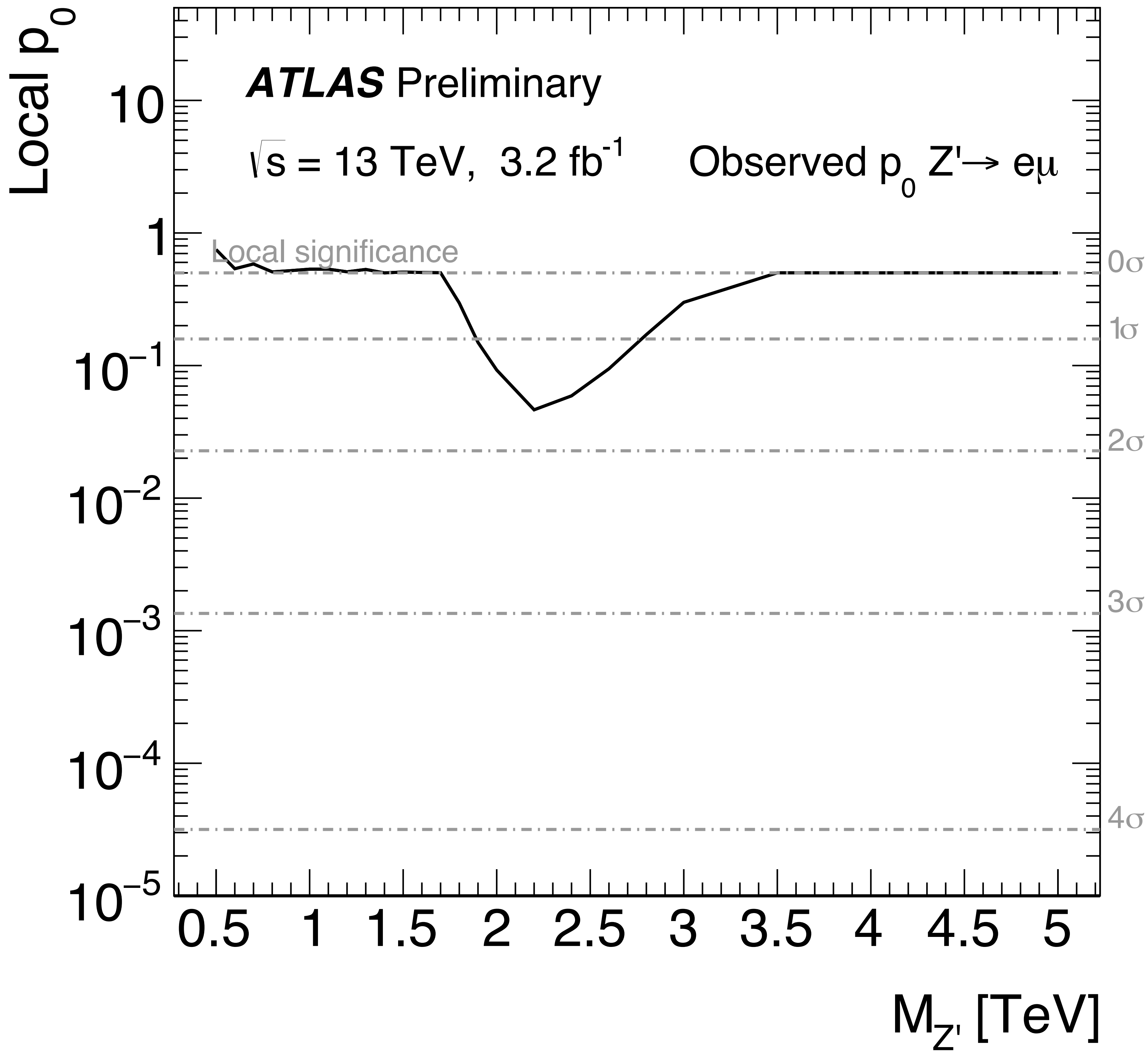
Kinematic variables of eμ for selected pairs



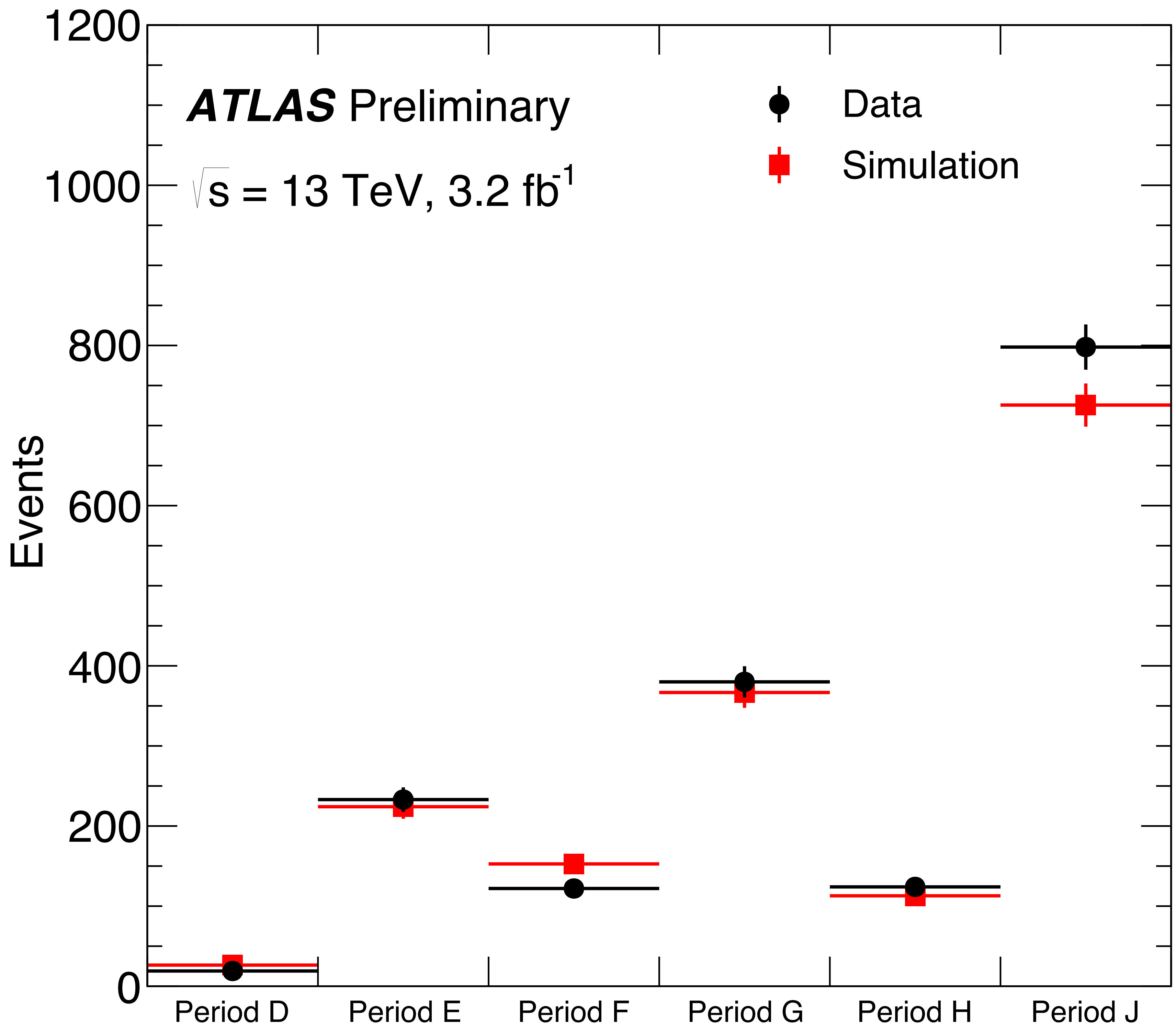




Local p-value



Expected and observed candidates by data-taking period



Systematics

Source	$m_{e\mu}$=1.0 TeV		$m_{e\mu}$=2.0 TeV		$m_{e\mu}$=3.0 TeV	
	Signal	Background	Signal	Background	Signal	Background
PDF uncertainties	N/A	11.0%	N/A	27%	N/A	41%
Luminosity	5%	5%	5%	5%	5%	5%
Electron Trigger Efficiency	5%	5%	5%	5%	5%	5%
Electron ID	5%	5%	5%	5%	5%	5%
Muon Reconstruction Efficiency	1%	1%	2%	2%	3%	3%
Electron energy scale and resolution	1%	1%	4%	4%	5%	5%
Muon scale and resolution	7%	7%	15%	15%	20%	20%
Muon Trigger Efficiency	2%	2%	2%	2%	2%	2%
Instrumental backgrounds	N/A	1%	N/A	1%	N/A	1%
Background Extrapolation	N/A	25%	N/A	90%	N/A	400%
MC Statistics	2%	N/A	2%	N/A	2%	N/A
Total	12%	32%	17%	100%	23%	400%

Expected and observed yields

Process	$m_{e\mu} < 300$ GeV	$300 < m_{e\mu} < 600$ GeV
Top	900 ± 80	404 ± 50
Diboson	116 ± 13	52 ± 7
QCD and W+jets	67 ± 10	17 ± 4
$Z/\gamma^* \to \tau\tau$	9.3 ± 1.3	1.79 ± 0.21
Total background	1092 ± 90	476 ± 50
Data	1164	475

Process	$600 < m_{e\mu} < 1200$ GeV	$1200 < m_{e\mu} < 2000$ GeV
Top	36 ± 4	0.55 ± 0.31
Diboson	2.6 ± 0.4	$(7 \pm 5\ ) \cdot 10^{-3}$
QCD and W+jets	1.0 ± 0.9	0.12 ± 0.35
$Z/\gamma^* \to \tau\tau$	0.13 ± 0.01	$(3.5 \pm 1.4) \cdot 10^{-3}$
Total background	40 ± 4	0.67 ± 0.34
Data	36	0

Process	$2000 < m_{e\mu} < 3000$ GeV	$m_{e\mu} > 3000$ GeV
Top	$(1.7 \pm 3.4) \cdot 10^{-2}$	$(0.3 \pm 2.6) \cdot 10^{-3}$
Diboson	$(4 \pm 6) \cdot 10^{-5}$	$(0.3 \pm 1.5) \cdot 10^{-7}$
QCD and W+jets	0	0
$Z/\gamma^* \to \tau\tau$	$(1.9 \pm 2.6) \cdot 10^{-4}$	$(2 \pm 10\ ) \cdot 10^{-5}$
Total background	$(1.7 \pm 3.4) \cdot 10^{-2}$	$(0.3 \pm 2.7) \cdot 10^{-3}$
Data	1	0

Z'→eμ MC details

- Z' signal: Pythia8, NNPDF23LO PDF
  - 25 mass points from 500 GeV to 5TeV
  - No interference
- QBH signal: QBH, CTEQ6L1 PDF + Pythia8
  - ADD and RS models
  - 11 threshold mass points in 500 GeV steps, from 3-8TeV
- Single top and ttbar: Powheg-Box v2 CT10 PDF + Pythia6.4.28
- Di-bosons: Sherpa2.1.1, CT10 PDF
- Drell-Yan: Pythia8, NNPDF2.3 PDF
  - k-factors for QCD and EW corrections to NNLO with FEWZ and CT14NNLO PDF