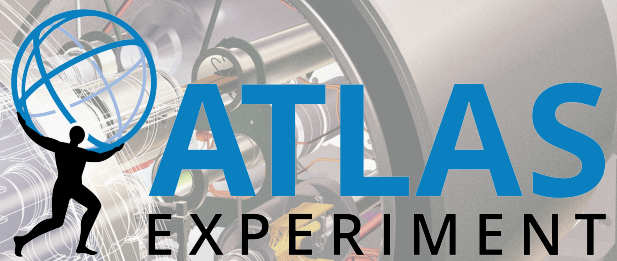
Results on Contact Interactions (mainly $bs\ell\ell$)

CKM Conference 2021

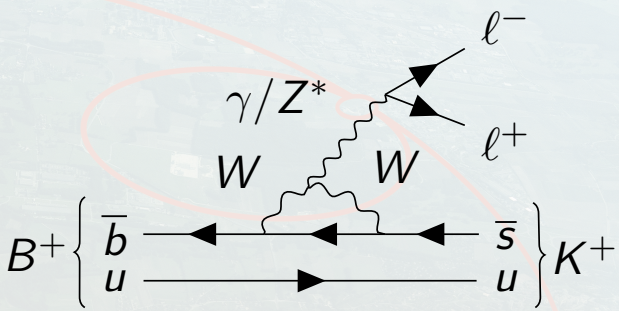
Yoav Afik (CERN)
On behalf of the ATLAS and the CMS collaborations

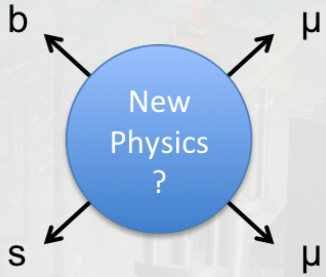
23.11.2021

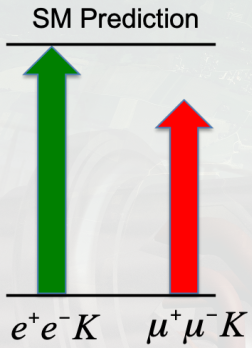


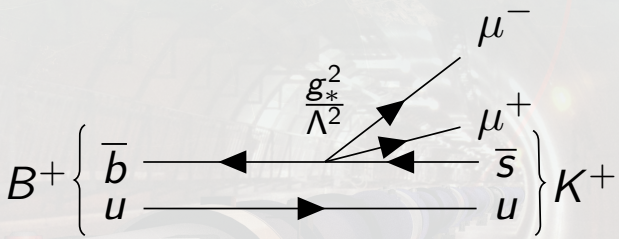
Motivation

- Hints of Lepton Flavour Universality (LFU) violation in rare B-meson decays:
  - $b \to s\ell\ell$ ($R_{K^{(*)}}$); $b \to c\ell\nu$ ($R_{D^{(*)}}$).









- Muon g-2 anomaly, possibly connected to the LFU anomaly.

Motivation

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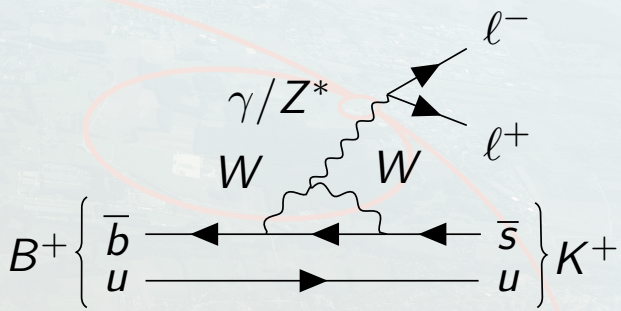
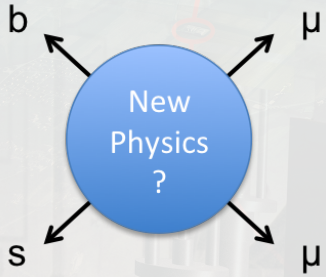
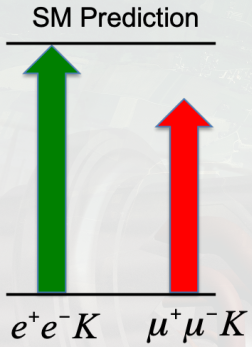
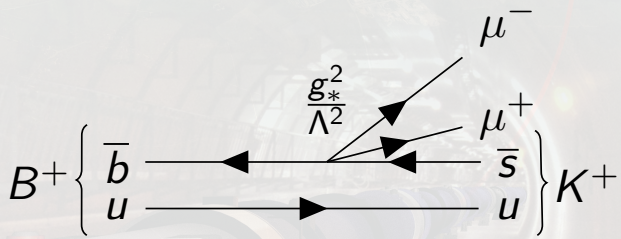






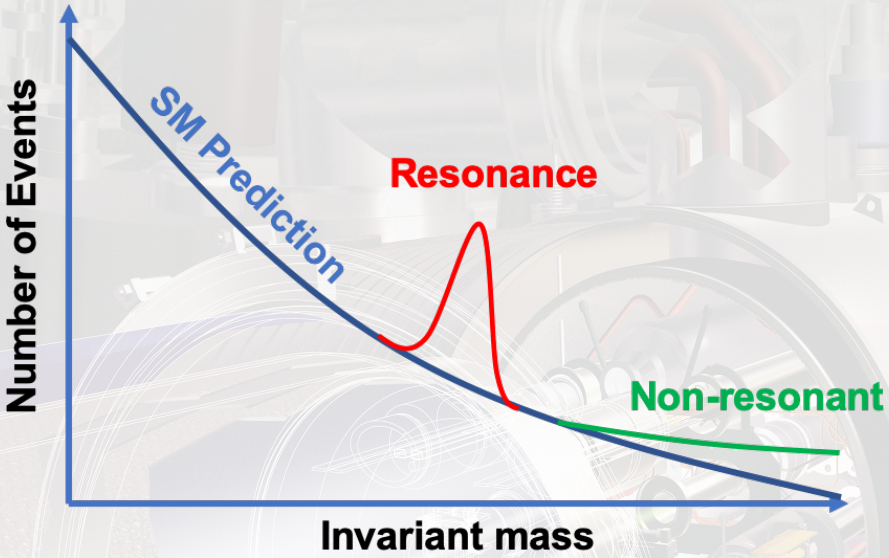


- Muon g-2 anomaly, possibly connected to the LFU anomaly.

- The solutions to the anomalies can be parametrized using Contact Interaction (CI)!
  - Cross-generational CIs are motivated.

Non-resonant Searches

- Assumption: heavy mass state are beyond of the LHC reach.
- Signal is modeled by using an Effective Field Theory (EFT).
- Heavy mass states are "integrated out".



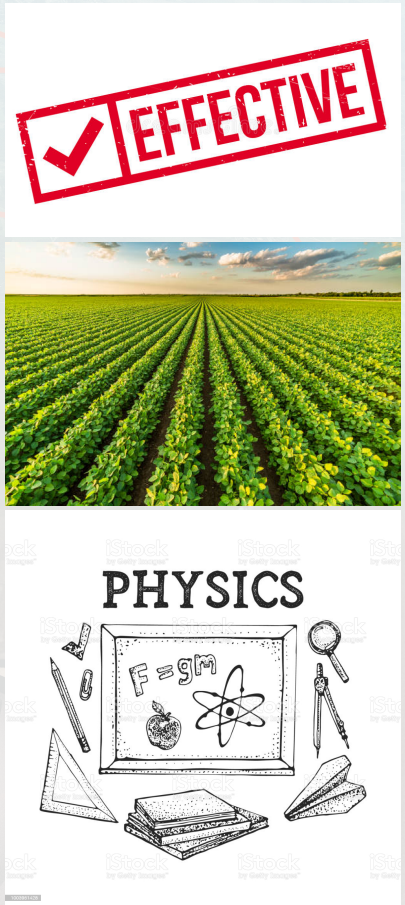


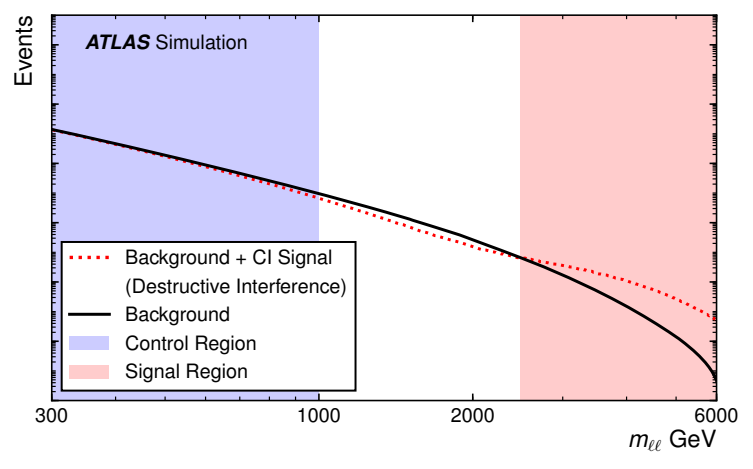
Figure: Effective + Field + Theory.

Inclusive Non-resonant Searches

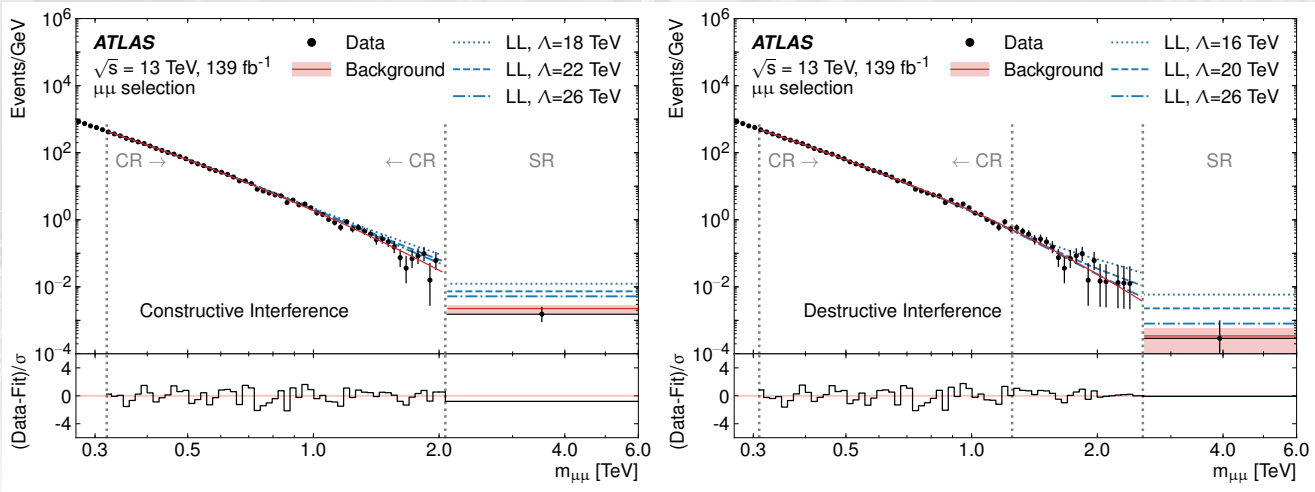
Search for $q\bar{q}\ell^+\ell^-$ CIs (ATLAS)

- Universal coupling between leptons and quarks:

$$\mathcal{L} = \frac{4\pi}{\Lambda^2}\{\eta_{LL}\,(\bar{q}_L\gamma_\mu q_L)\,(\bar{\ell}_L\gamma^\mu \ell_L) + \eta_{RR}\,(\bar{q}_R\gamma_\mu q_R)\,(\bar{\ell}_R\gamma^\mu \ell_R) + \eta_{LR}\,(\bar{q}_L\gamma_\mu q_L)\,(\bar{\ell}_R\gamma^\mu \ell_R) + \eta_{RL}\,(\bar{q}_R\gamma_\mu q_R)\,(\bar{\ell}_L\gamma^\mu \ell_L)\}$$

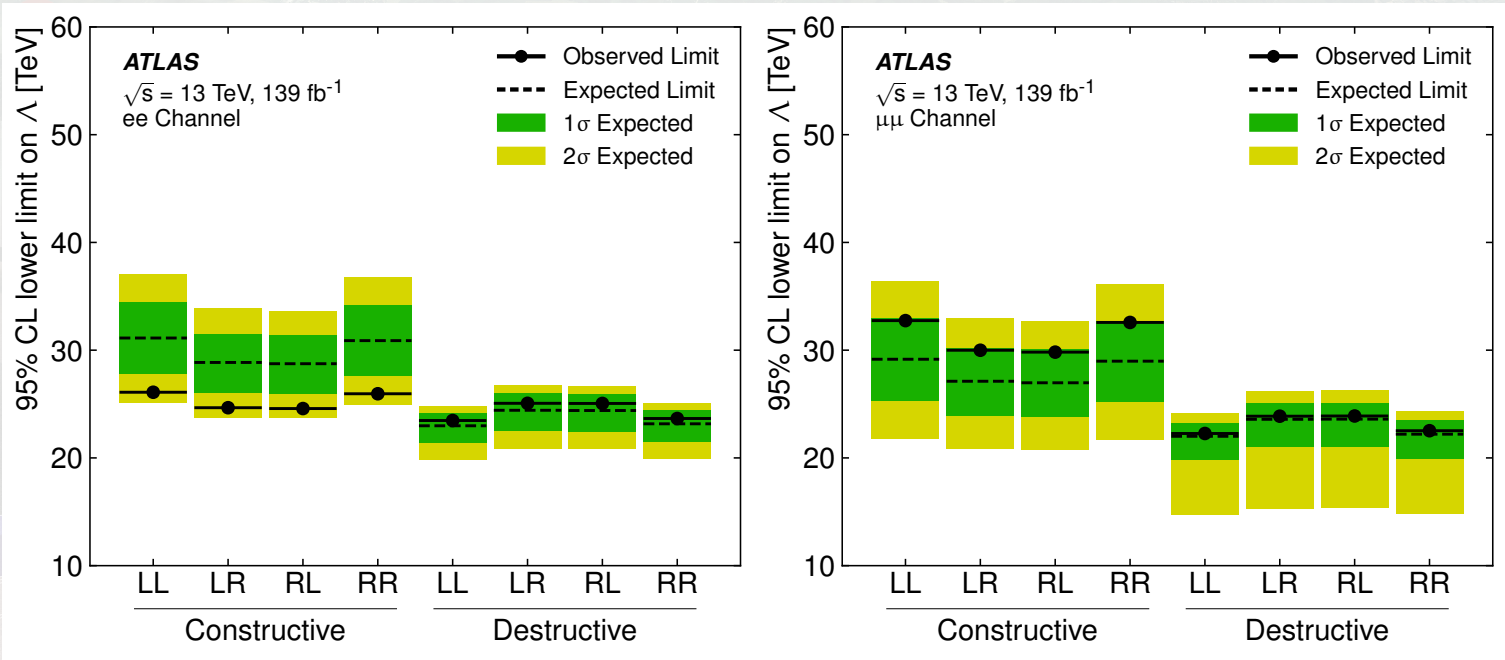


- Main background: $Z + jets$, normalized by data.



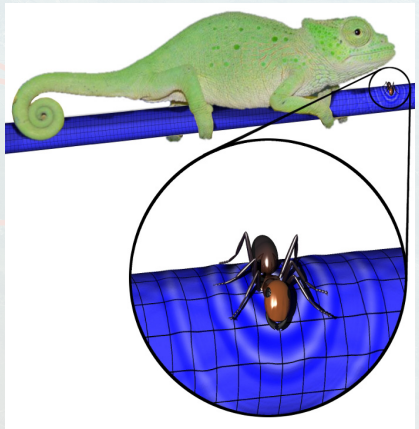
Search for $q\bar{q}\ell^+\ell^-$ CIs (ATLAS)

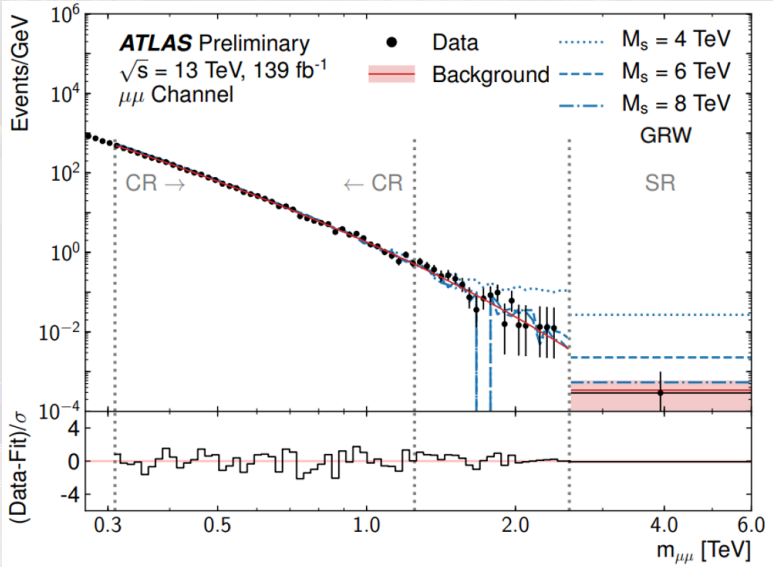
- Limits are set on the coefficients of the operators:
  - For different chirality structures.
  - For both destructive and constructive interference with the Standard Model.

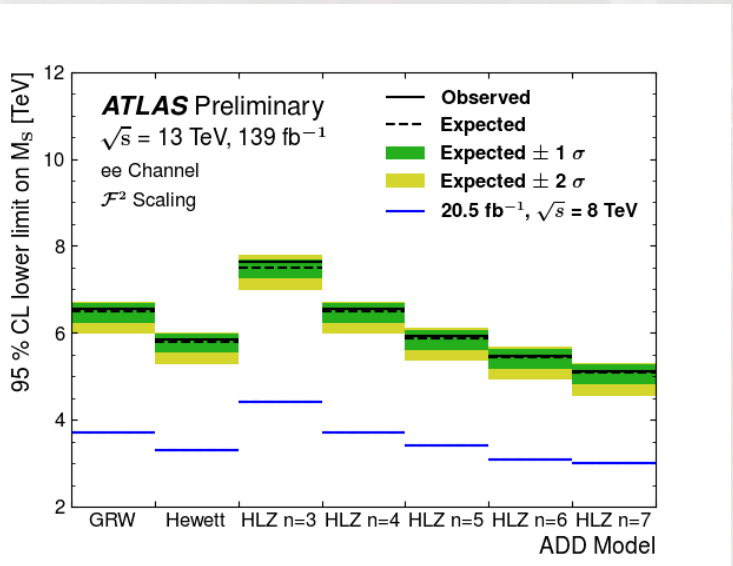


Search for Large Extra Dimensions (ATLAS)

- Re-interpretation of the $q\bar{q}\ell^+\ell^-$ non-resonant search.
- Limits on ADD model of large extra dimensions.
- M_S is the string scale of the theory.

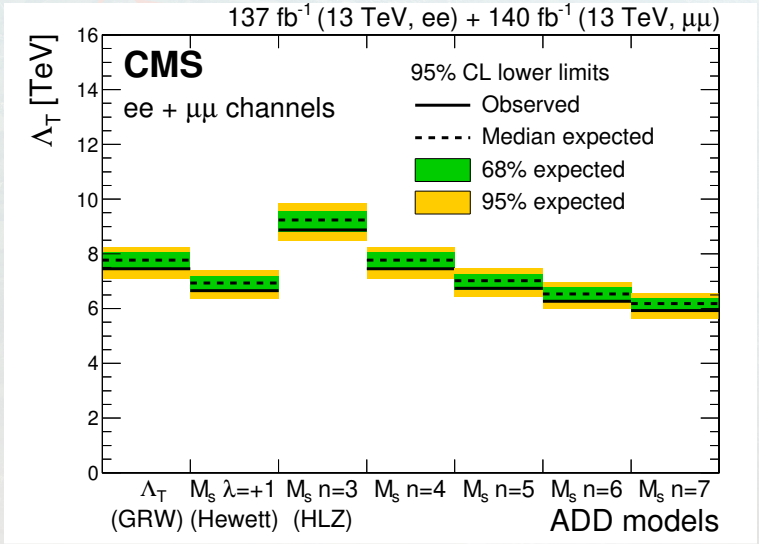


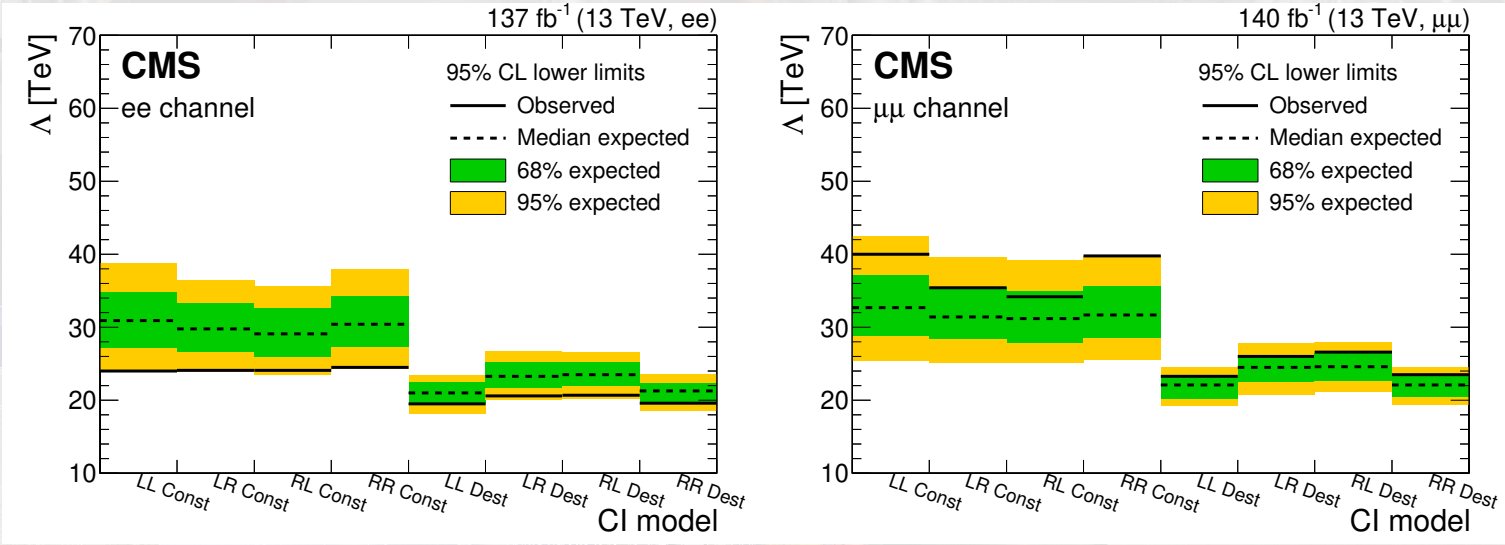




Search for $q\bar{q}\ell^+\ell^-$ CIs and Large Extra Dimensions (CMS)

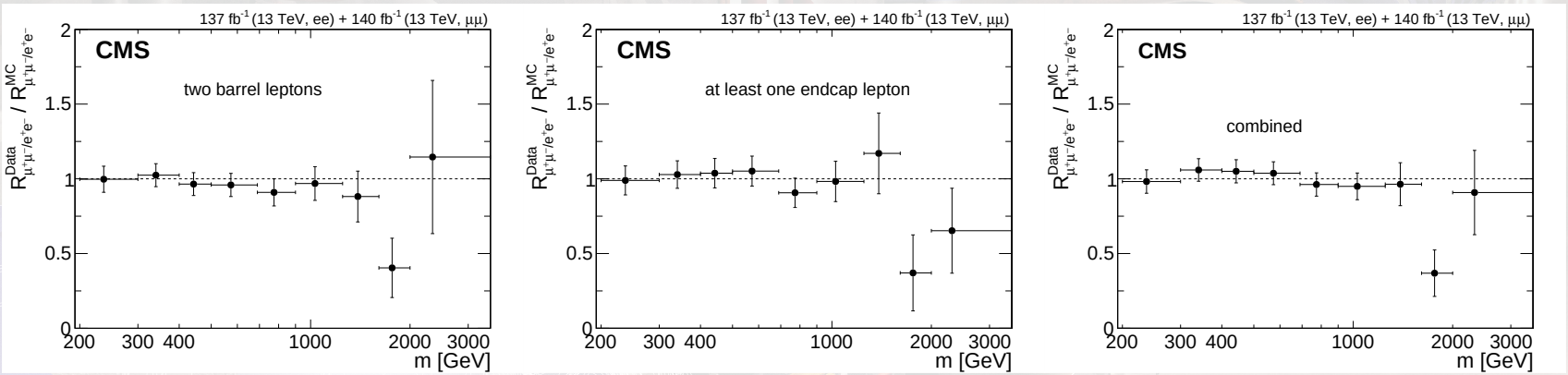
- Limits on similar CI operators.
- In addition ADD model of large extra dimensions.
- Normalizing the background in a dedicated CR with $60 < m_{\ell\ell} < 120$ GeV.





Test of LFU at TeV Scale (CMS)

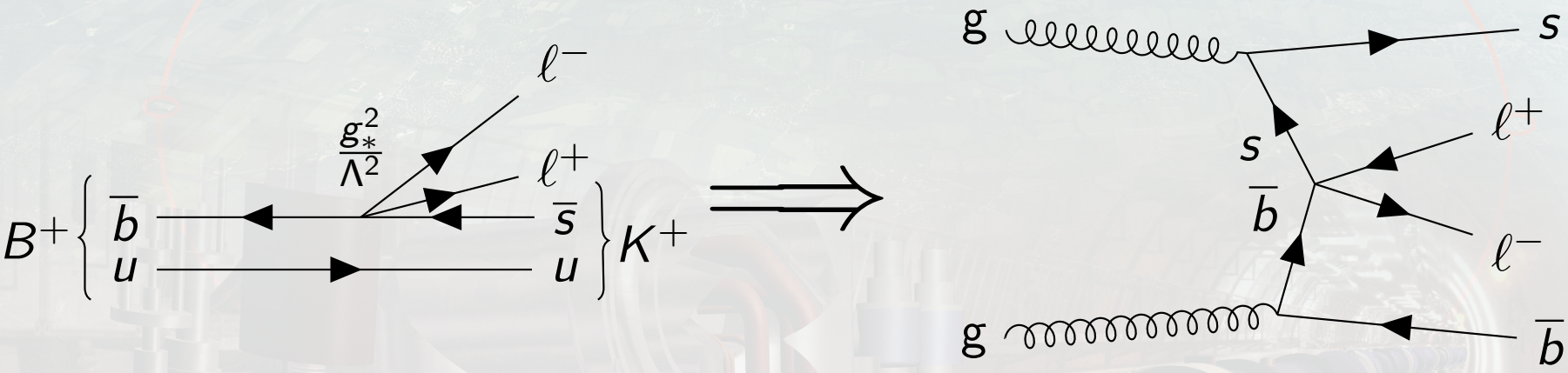
- First test of LFU at the TeV scale, inspired by Greljo, Marzocca, EPJC (2017).
- Ratio of the differential cross-section $R_{\mu^+\mu^-/e^+e^-}$:
  - Reducing all non-Z + *jets* backgrounds.
  - Correcting the reconstructed invariant mass spectra to particle level (unfolding).
- Resulting χ^2/dof yield p-values of 0.130, 0.225 and 0.012, respectively.



Exclusive Non-resonant Searches

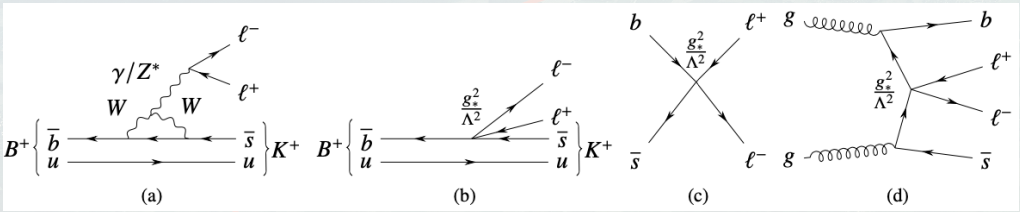
Search for $b\bar{s}\ell^+\ell^-$ CI (ATLAS)

- Generalizing the $bs\ell\ell$ interactions (4-fermion operator).
- Looking at direct production via pp collisions:



- We can search for BSM Physics in final states contain two opposite sign leptons and exactly one b-jet.
- Phenomenological framework established at YA, Cohen, Gozani, Kajomovitz, Rozen, JHEP (2018).
- The scale favored by the anomalies is $\Lambda/g_* \sim 40$ TeV.

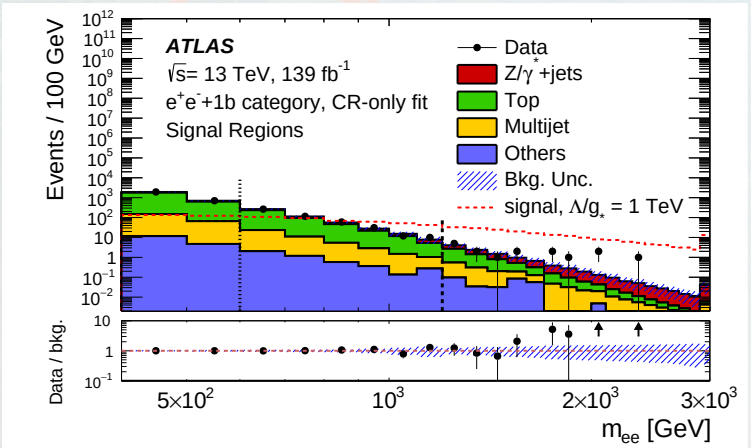
Search for $b\bar{s}\ell^+\ell^-$ CI (ATLAS)

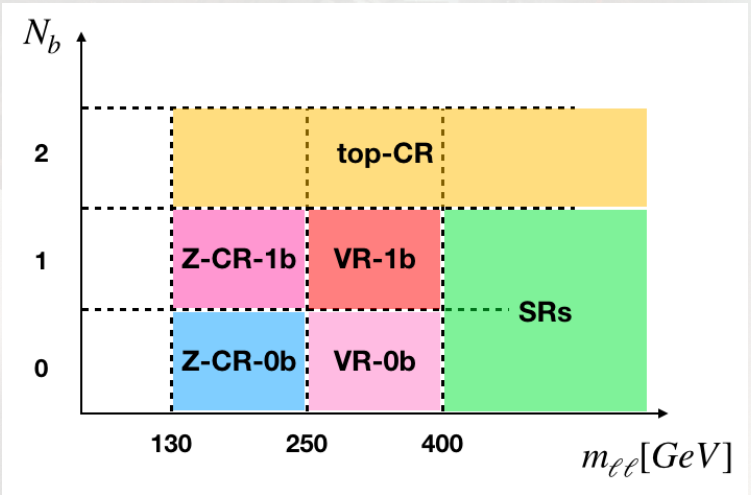


- General set of Signal Regions (SRs).

Region	top-CRs	Z-CRs	VRs	SRs
$m_{\ell\ell}$ [GeV]	> 130	130-250	250-400	$> 400 + n \cdot 100$
b-tagged jets	2		0/1	

- Enhanced sensitivity for many models as possible.
- Main backgrounds: $Z + jets$, di-leptonic $t\bar{t}$, normalized from data.



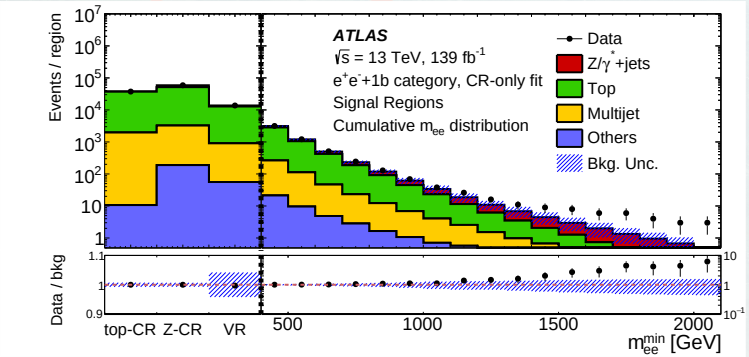


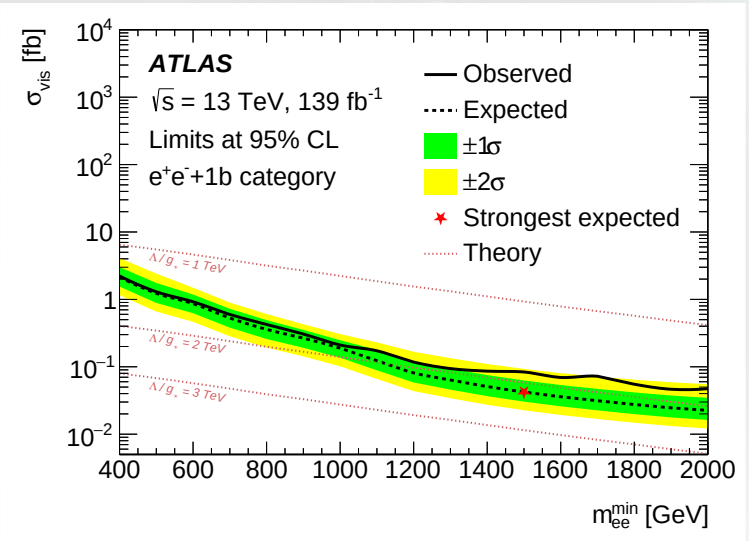
Search for $b\bar{s}\ell^+\ell^-$ CI (ATLAS)

- Many SRs are used for the statistical interpretation.
- Limits are set on the model-independent cross-section: $\sigma_{vis} = \sigma \cdot \epsilon \cdot \mathcal{A}$.
- Far below the scale favored by the anomalies:

electrons	$\Lambda/g_* > 2.0$ TeV
muons	$\Lambda/g_* > 2.4$ TeV

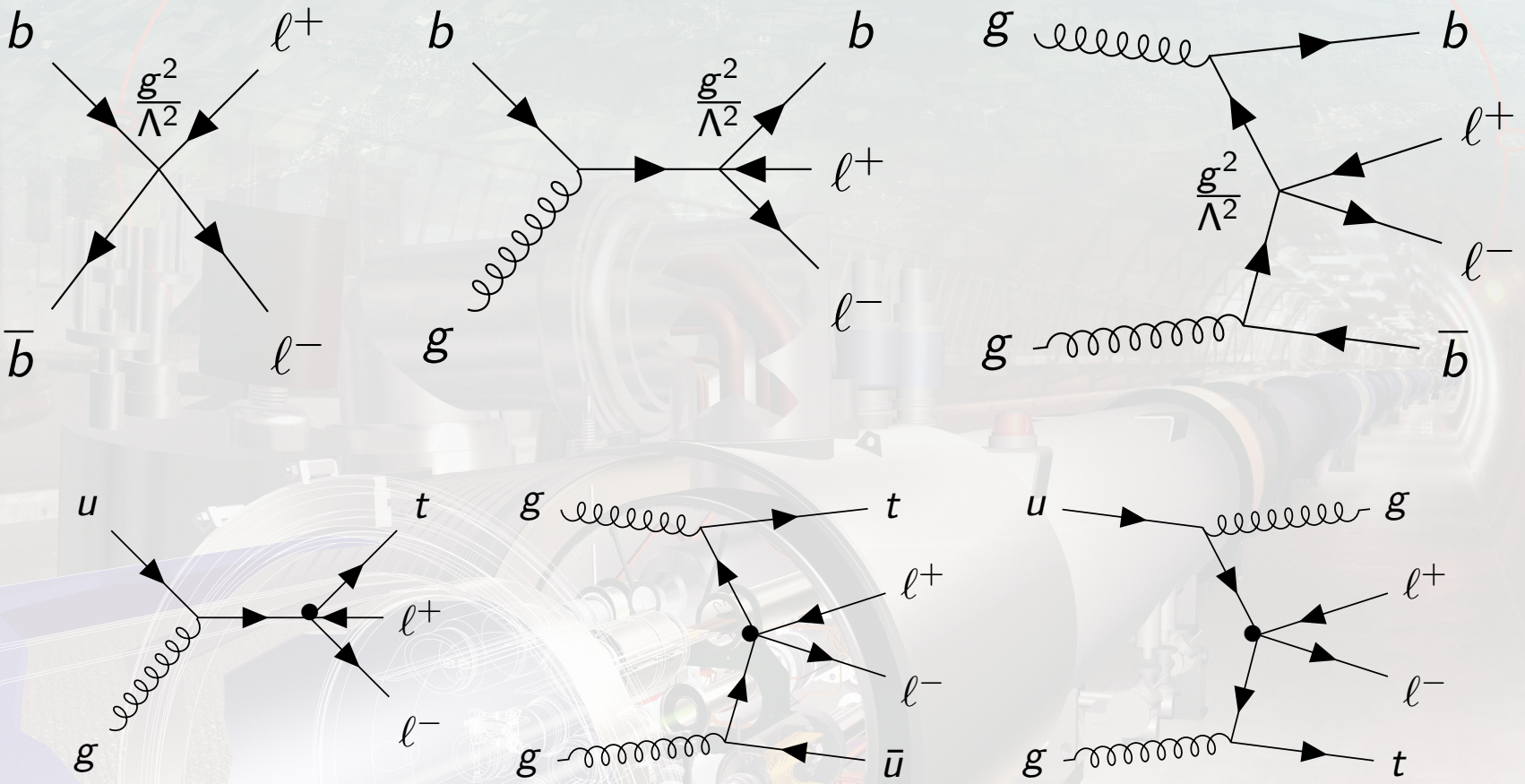
- Highest statistical deviation is observed at the $e^+e^- + 1b$ channel: 2.6σ local (1.5σ global).





Search for $b\bar{s}\ell^+\ell^-$ CI (ATLAS)

- The same signature allows an enhanced sensitivity for other signal scenarios, e.g. YA, Bar-Shalom, Cohen, Rozen, PLB (2020) and YA, Bar-Shalom, Soni, Wudka, Phys. Rev. D 103, 075031.



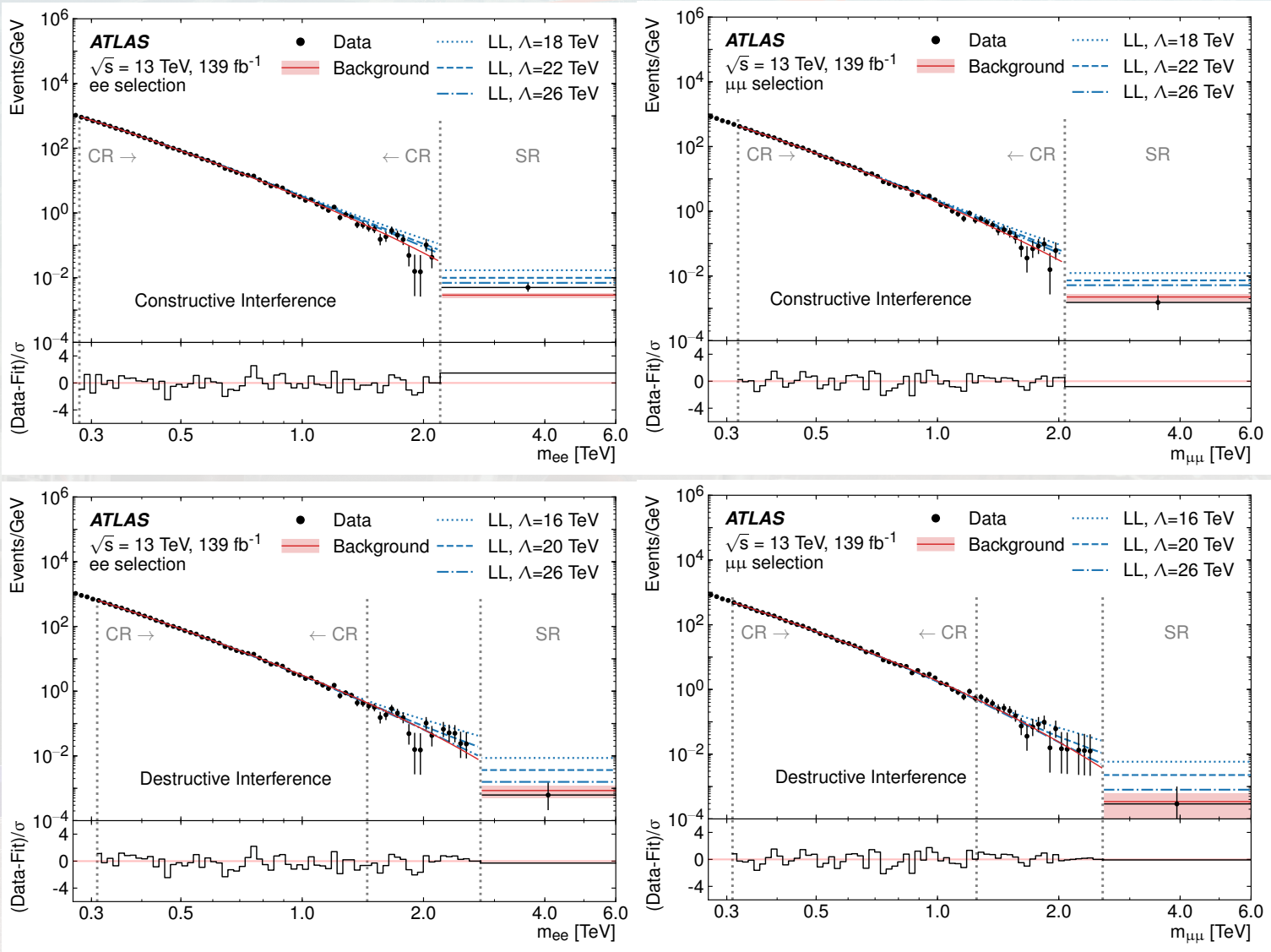
Summary

- A variety of CI related searches:
  - Inclusive di-lepton search.
  - Di-lepton search with b-tagged jet selections.
- Limits were set on $q\bar{q}\ell^+\ell^-$ CIs and ADD model, improving previous results by a few TeV.
- First ratio measurement of the differential cross-section at the TeV scale.
- First limits on $bs\ell\ell$ CI, still far from the value which is favored by the anomalies, which is ~ 40 TeV.

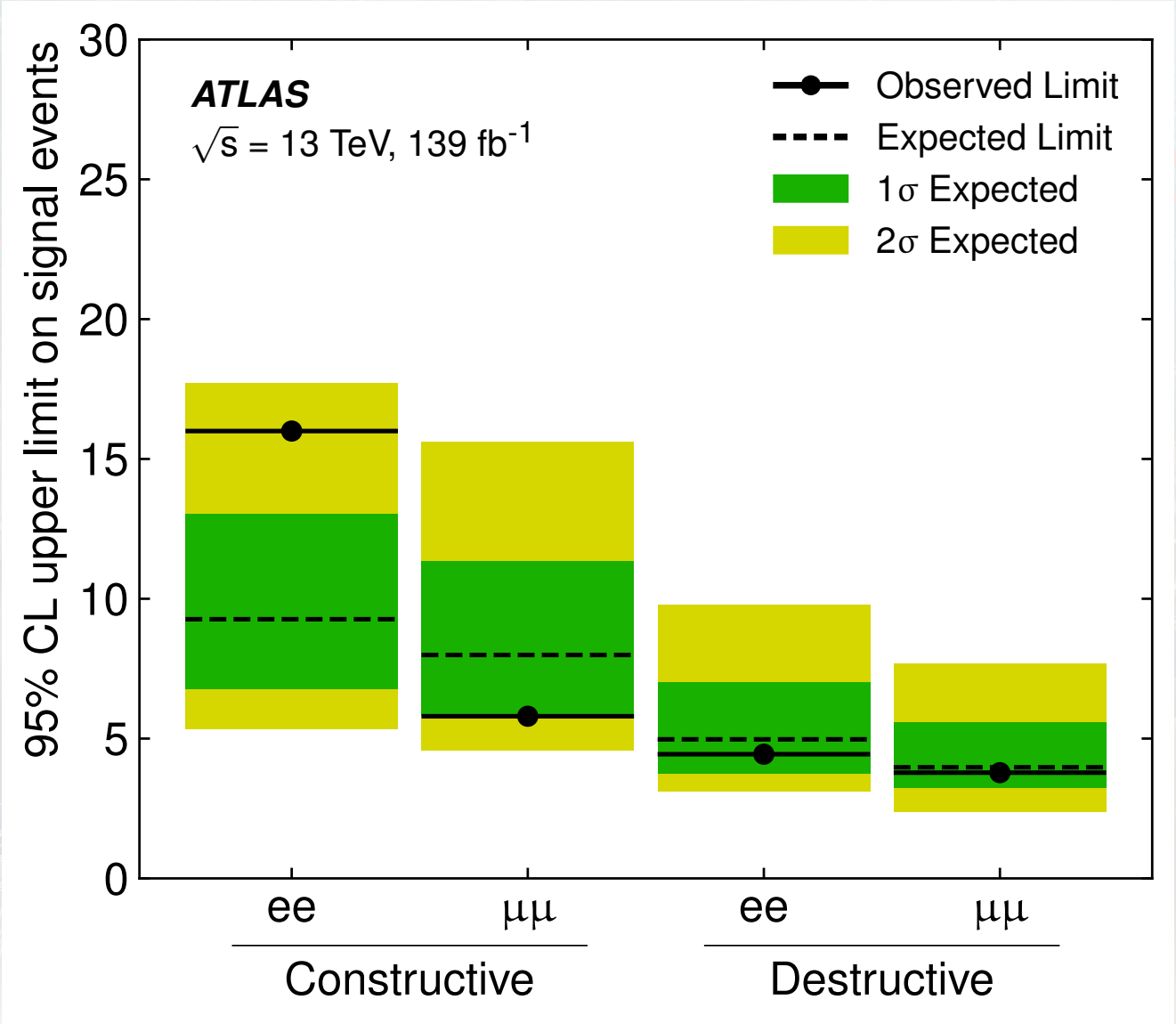
Thank You

Backup

Search for $q\bar{q}\ell^+\ell^-$ CIs (ATLAS)



Search for $q\bar{q}\ell^+\ell^-$ CIs (ATLAS)



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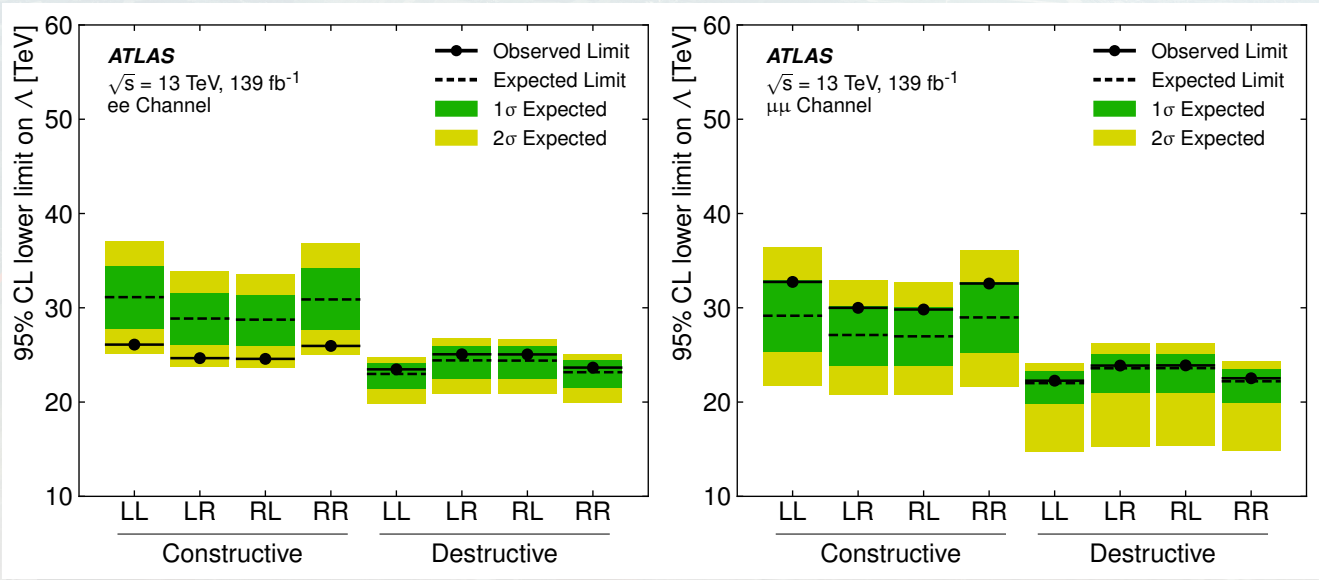
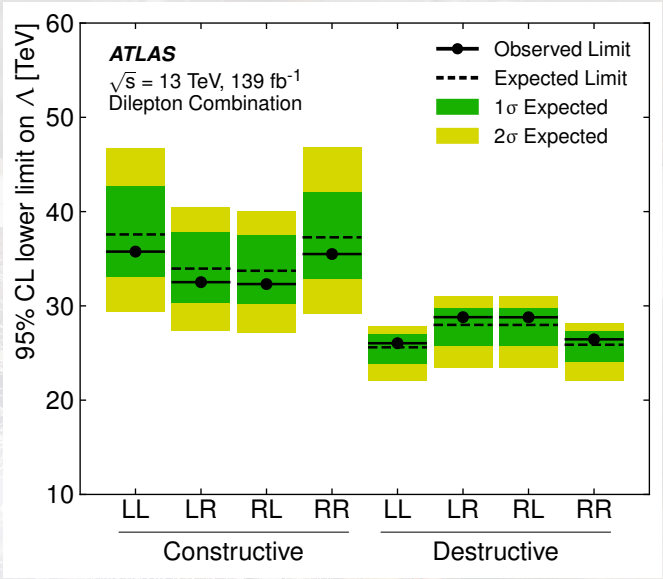




Search for $q\bar{q}\ell^+\ell^-$ CIs (ATLAS)

Channel	Constructive interference			Destructive interference		
	CR_{min}	CR_{max}	SR_{min}	CR_{min}	CR_{max}	SR_{min}
e^+e^-	280	2200	2200	310	1450	2770
$\mu^+\mu^-$	310	2070	2070	320	1250	2570

Search for $q\bar{q}\ell^+\ell^-$ CIs (ATLAS)

Channel	Interference	Background uncertainties			Signal uncertainties	
		σ_b^{Stat}	σ_b^{ISS}	σ_b^{CRB}	$\sigma_s^{Experiment}$	σ_s^{Theory}
e^+e^-	Constructive	14%	4%	2%	8%	$^{+11\%}_{-10\%}$
e^+e^-	Destructive	34%	7%	1%	8%	$^{+14\%}_{-13\%}$
$\mu^+\mu^-$	Constructive	21%	6%	2%	$^{+20\%}_{-17\%}$	$^{+10\%}_{-9\%}$
$\mu^+\mu^-$	Destructive	58%	24%	4%	$^{+27\%}_{-22\%}$	$^{+13\%}_{-12\%}$

Search for $q\bar{q}\ell^+\ell^-$ CIs (ATLAS)

SR	Data	Background	Significance
e^+e^- Const.	19	12.4±1.9	1.28
e^+e^- Dest.	2	3.1±1.1	−0.72
$\mu^+\mu^-$ Const.	6	9.6±2.1	−0.99
$\mu^+\mu^-$ Dest.	1	1.4±0.9	−0.58

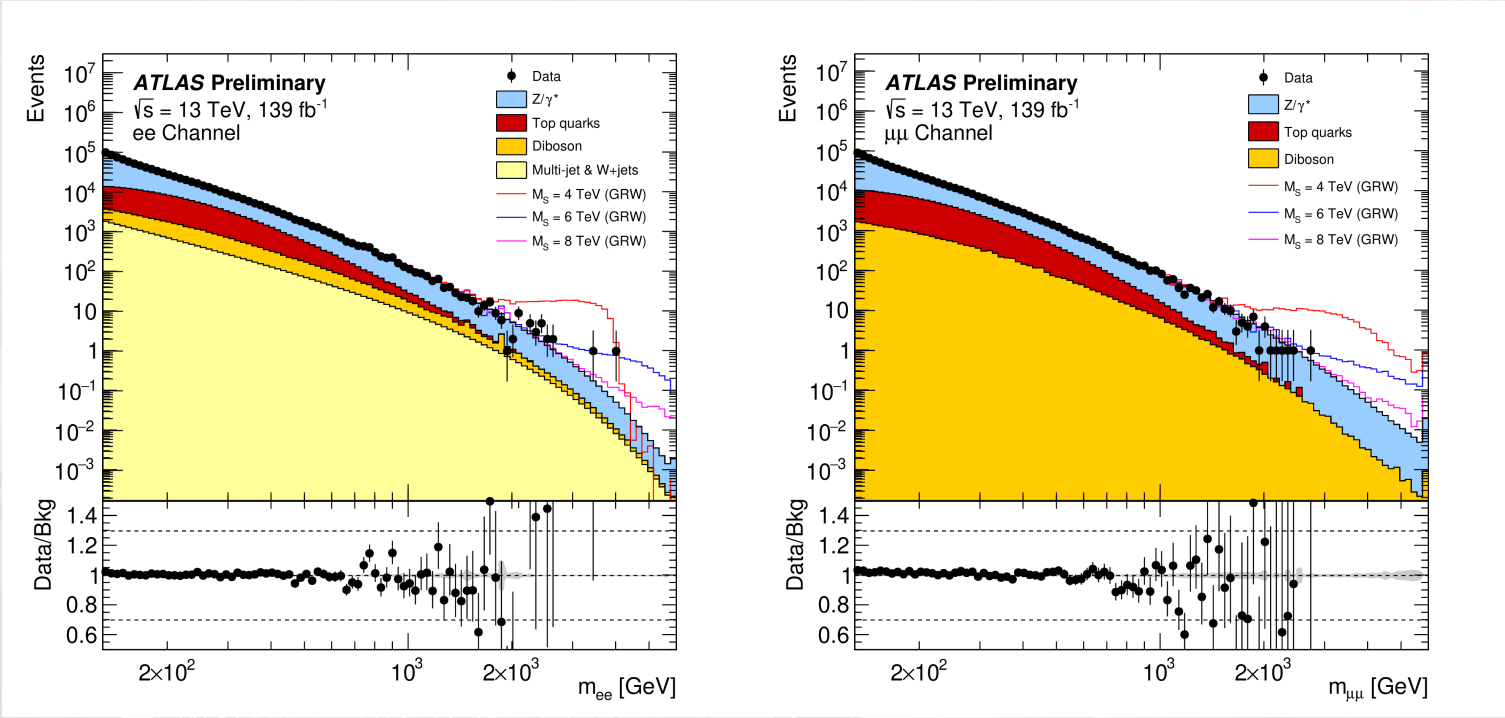
Search for $q\bar{q}\ell^+\ell^-$ CIs (ATLAS)

SR	Limit on $\sigma_{\text{vis}} \times \mathcal{B}$ [fb]		Limit on N_{sig}		Signal (LL chirality only)					
					Λ = 20 TeV		Λ = 30 TeV		Λ = 40 TeV	
	Exp.	Obs.	Exp.	Obs.	N_{sig}	$\mathcal{A} \times \epsilon_{\text{sig}}$ [%]	N_{sig}	$\mathcal{A} \times \epsilon_{\text{sig}}$ [%]	N_{sig}	$\mathcal{A} \times \epsilon_{\text{sig}}$ [%]
e^+e^- Const.	0.067	0.115	9.3	16.0	39.1	69	10.3	69	4.4	69
e^+e^- Dest.	0.036	0.032	5.0	4.4	9.6	70	1.0	70	−0.1	69
$\mu^+\mu^-$ Const.	0.057	0.042	8.0	5.8	28.5	43	7.7	43	3.4	43
$\mu^+\mu^-$ Dest.	0.029	0.027	4.0	3.8	7.1	43	0.6	42	−0.2	44

Search for $q\bar{q}\ell^+\ell^-$ CIs (ATLAS)

Int.	Channel	Exp./Obs.	LL	LR	RL	RR
Constructive	ee	Expected	31.1	28.9	28.7	30.9
		Observed	26.1	24.7	24.6	26.0
	$\mu\mu$	Expected	29.2	27.1	27.0	29.0
		Observed	32.7	30.0	29.8	32.6
	$\ell\ell$	Expected	37.6	34.0	33.7	37.3
		Observed	35.8	32.5	32.3	35.5
Destructive	ee	Expected	23.0	24.4	24.4	23.2
		Observed	23.5	25.1	25.1	23.7
	$\mu\mu$	Expected	22.0	23.6	23.6	22.2
		Observed	22.3	23.9	23.9	22.5
	$\ell\ell$	Expected	25.6	28.0	28.0	25.9
		Observed	26.0	28.8	28.8	26.5

Search for Large Extra Dimensions (ATLAS)



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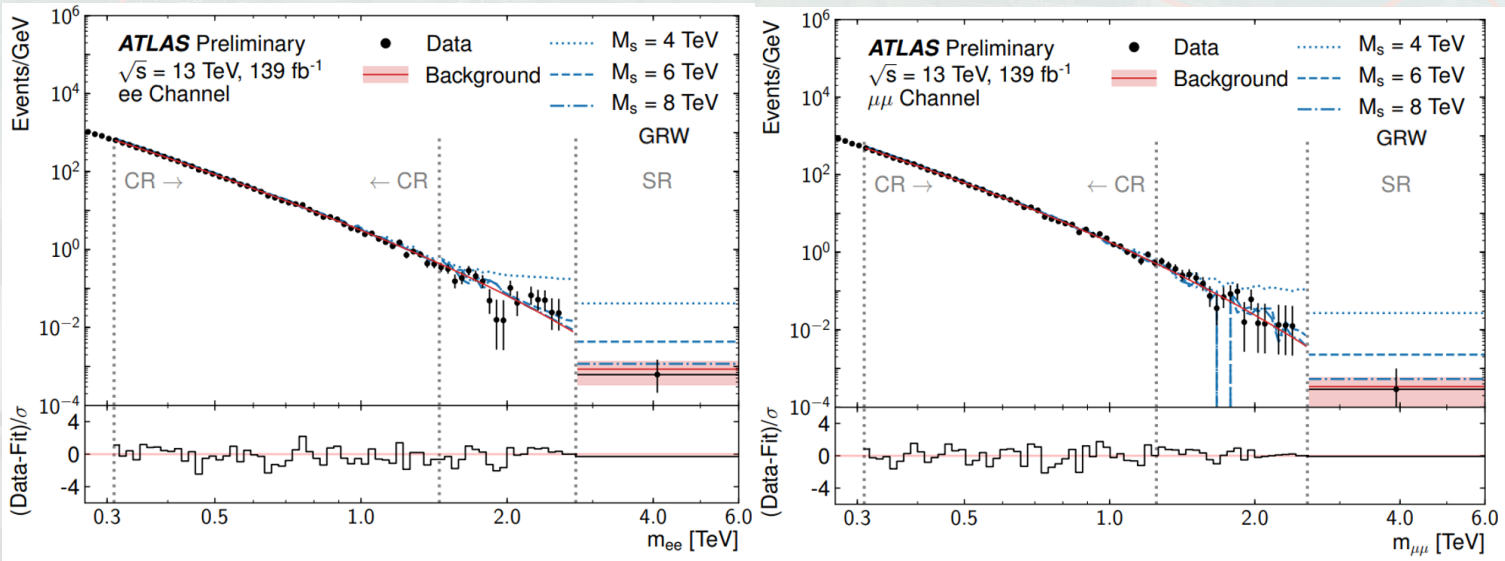

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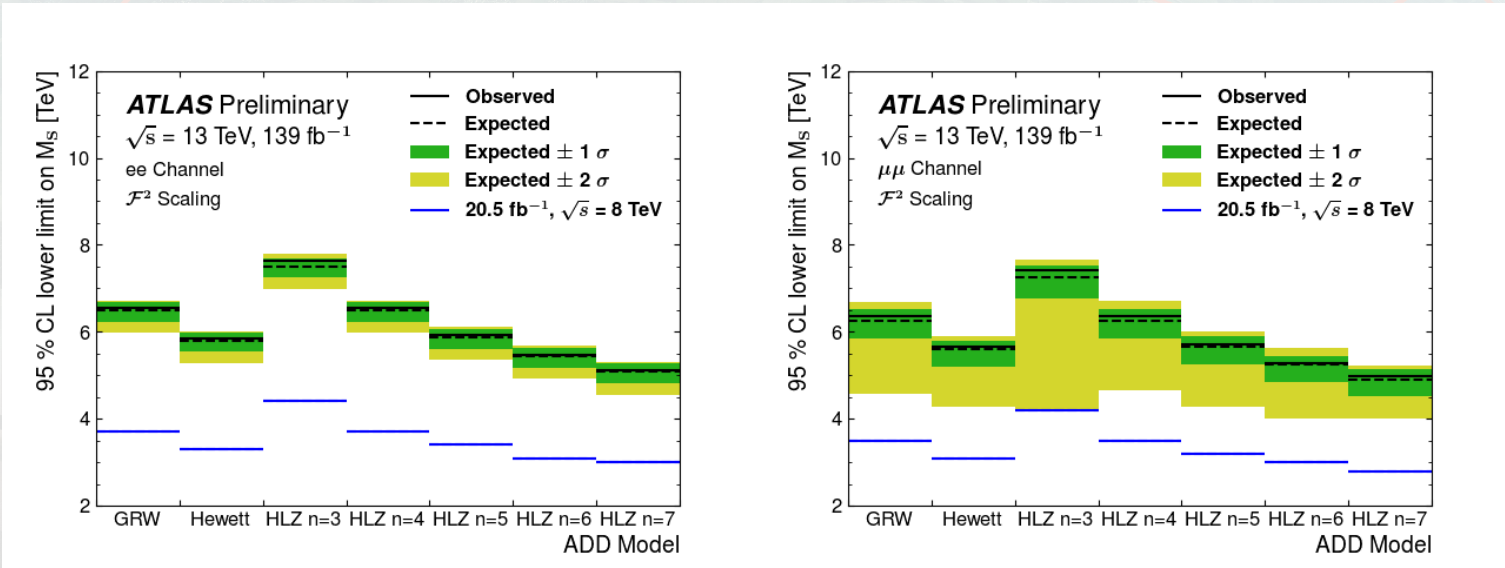


Search for Large Extra Dimensions (ATLAS)

Electron selection	**Muon selection**
Trigger	
2 e with $E_{\mathrm{T}} > 12$ - 24 GeV	1 μ with $p_{\mathrm{T}} > 50$ GeV
Acceptance	
$\lvert\eta\rvert < 2.47$ excluding region $1.37 < \lvert\eta\rvert < 1.52$ $E_{\mathrm{T}} > 30$ GeV	$\lvert\eta\rvert < 2.5$ excluding region $1.01 < \lvert\eta\rvert < 1.10$ $p_{\mathrm{T}} > 30$ GeV
Primary vertex (PV)	
Track from PV Longitudinal displacement near PV Transverse displacement near PV	
Quality selection	
Medium working point likelihood criteria Track isolation (variable cone size) Calorimeter isolation (E_{T} dependent, in cone $\Delta R = 0.2$)	High-p_T working point Track isolation (variable cone size) $(\frac{q}{p})$ requirement

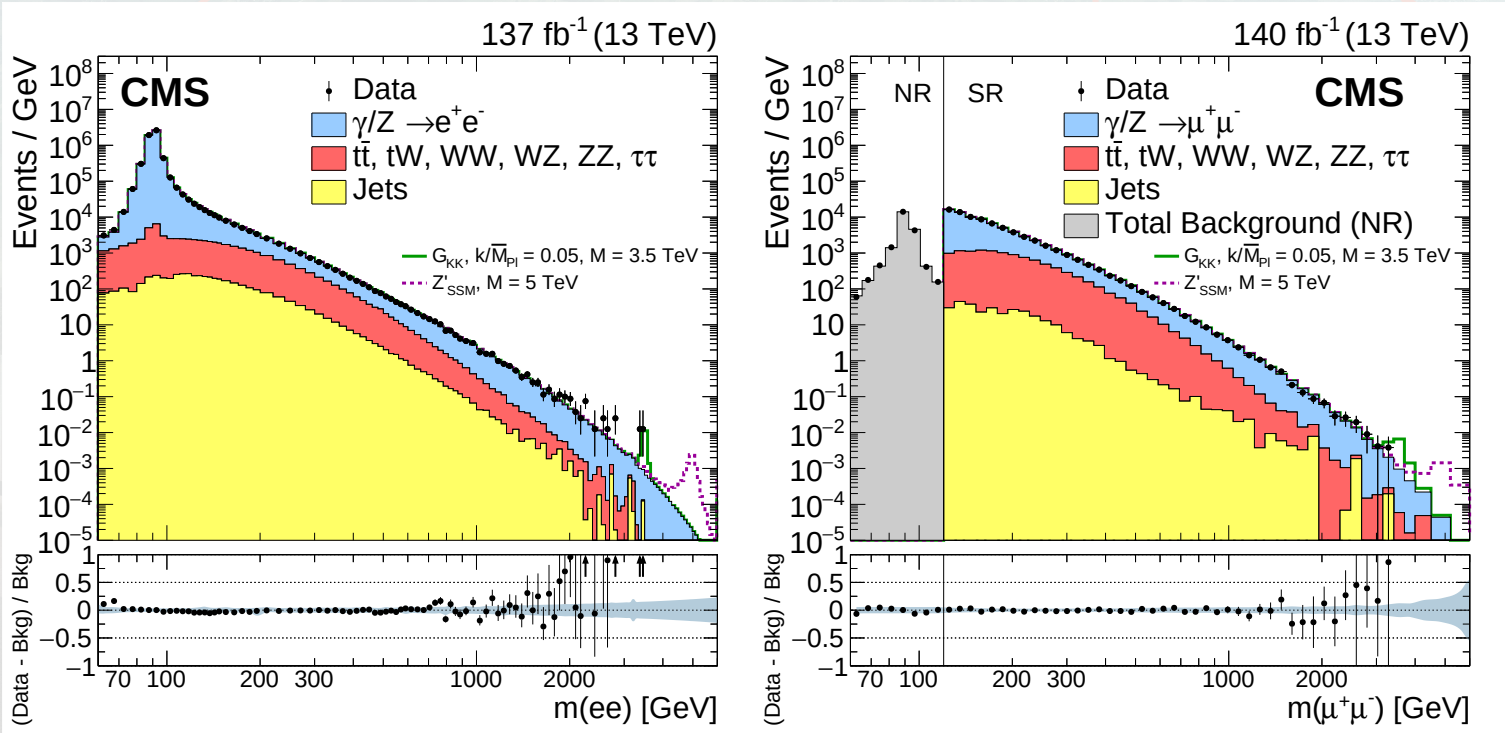
Search for Large Extra Dimensions (ATLAS)

ee Channel		$\mu\mu$ Channel	
String Scale, M_S (GeV)	N_{sig}^{SR}	String Scale, M_S (GeV)	N_{sig}^{SR}
3000	230	3000	230
4000	140	4000	99
5000	41	5000	26
6000	12	6000	6.9
7000	3.3	7000	2.1
8000	1.1	8000	0.65

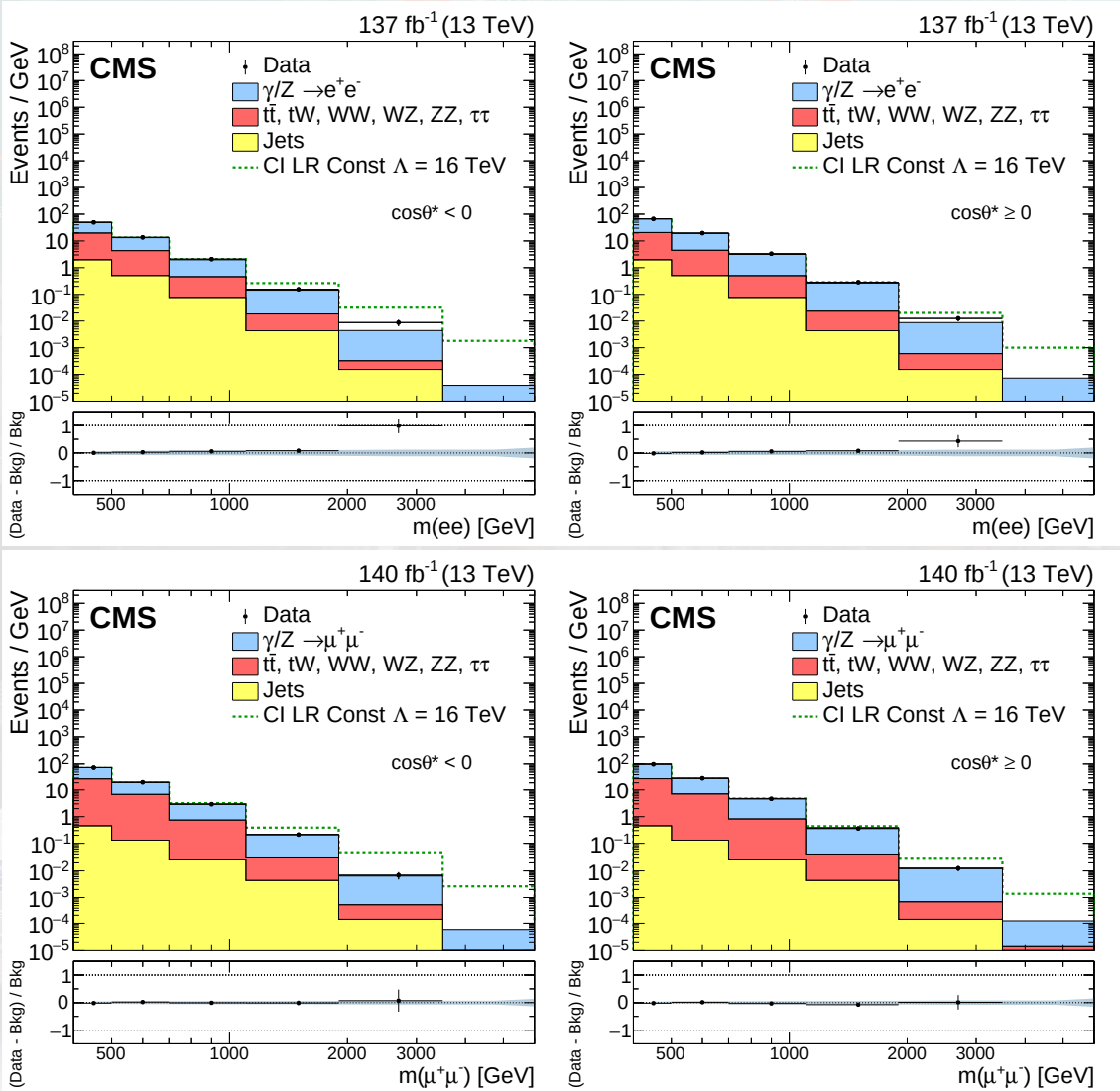
Search for Large Extra Dimensions (ATLAS)

Channel	Cross Section Scaling	GRW	Hewett	HLZ				
			$\lambda = +1$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
Exp: ee	$\mathscr{F}$	6.5	6.2	7.0	6.5	6.2	6.0	5.8
Obs: ee	$\mathscr{F}$	6.6	6.2	7.1	6.6	6.2	6.0	5.8
Exp: ee	$\mathscr{F}^2$	6.5	5.8	7.5	6.5	5.9	5.4	5.1
Obs: ee	$\mathscr{F}^2$	6.6	5.9	7.6	6.6	5.9	5.5	5.1
Exp: $\mu\mu$	$\mathscr{F}$	6.3	5.9	6.8	6.3	6.0	5.7	5.6
Obs: $\mu\mu$	$\mathscr{F}$	6.4	6.0	6.9	6.4	6.0	5.8	5.6
Exp: $\mu\mu$	$\mathscr{F}^2$	6.3	5.6	7.3	6.3	5.7	5.2	4.9
Obs: $\mu\mu$	$\mathscr{F}^2$	6.4	5.7	7.4	6.4	5.7	5.3	5.0

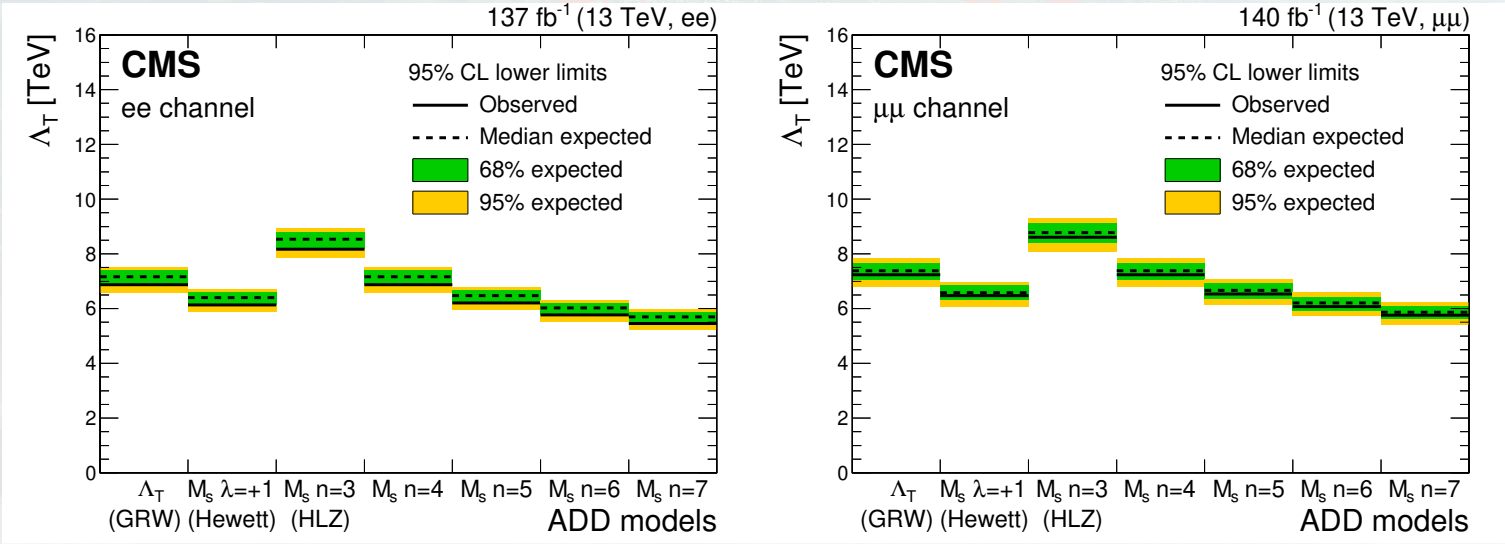
Search for $q\bar{q}\ell^+\ell^-$ CIs (CMS)

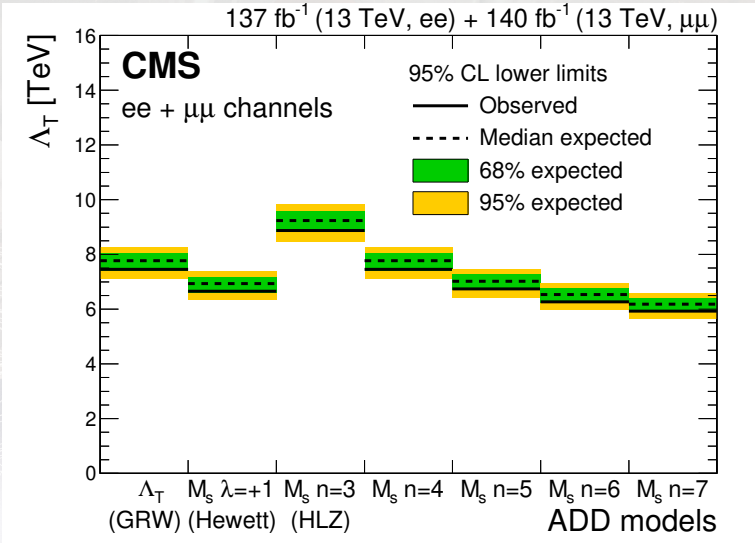


Search for $q\bar{q}\ell^+\ell^-$ CIs (CMS)

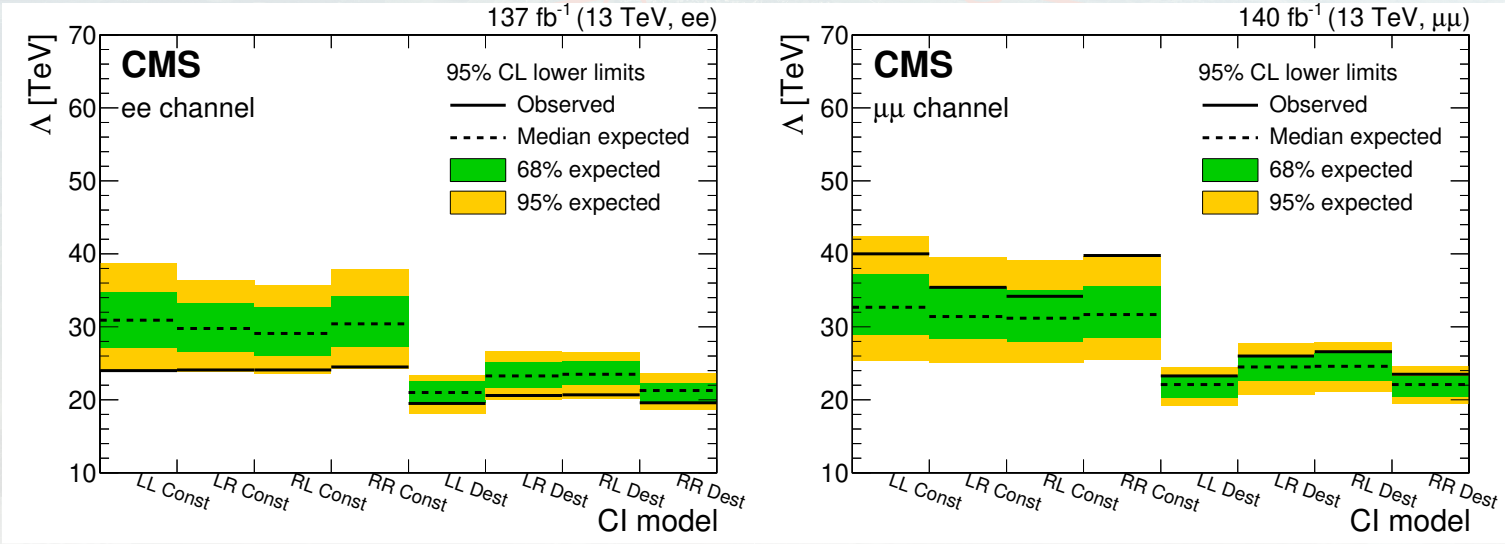


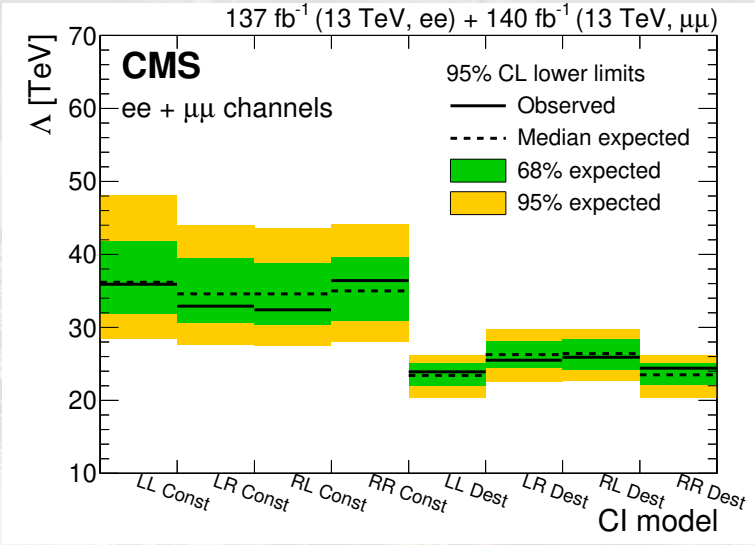
Search for $q\bar{q}\ell^+\ell^-$ CIs (CMS)





Search for $q\bar{q}\ell^+\ell^-$ CIs (CMS)





Search for $q\bar{q}\ell^+\ell^-$ CIs (CMS)

Uncertainty source	Impact on background [%]			
	$m_{\ell\ell} > 1$ TeV		$m_{\ell\ell} > 3$ TeV	
	ee	μμ	ee	μμ
Lepton selection efficiency	6.8	0.8	6.4	1.3
Muon trigger efficiency	—	0.9	—	0.9
Mass scale	7.0	2.7	15.4	2.4
Dimuon mass resolution	—	0.1	—	0.6
Pileup reweighting	0.3	—	0.5	—
Trigger prefiring	0.5	—	0.2	—
PDF	3.7	3.0	9.4	10.2
Cross section for other simulated backgrounds	0.6	0.8	0.2	0.4
Z peak normalization	2.3	5.0	2.0	5.0
Simulated sample size	0.4	0.4	1.3	1.6

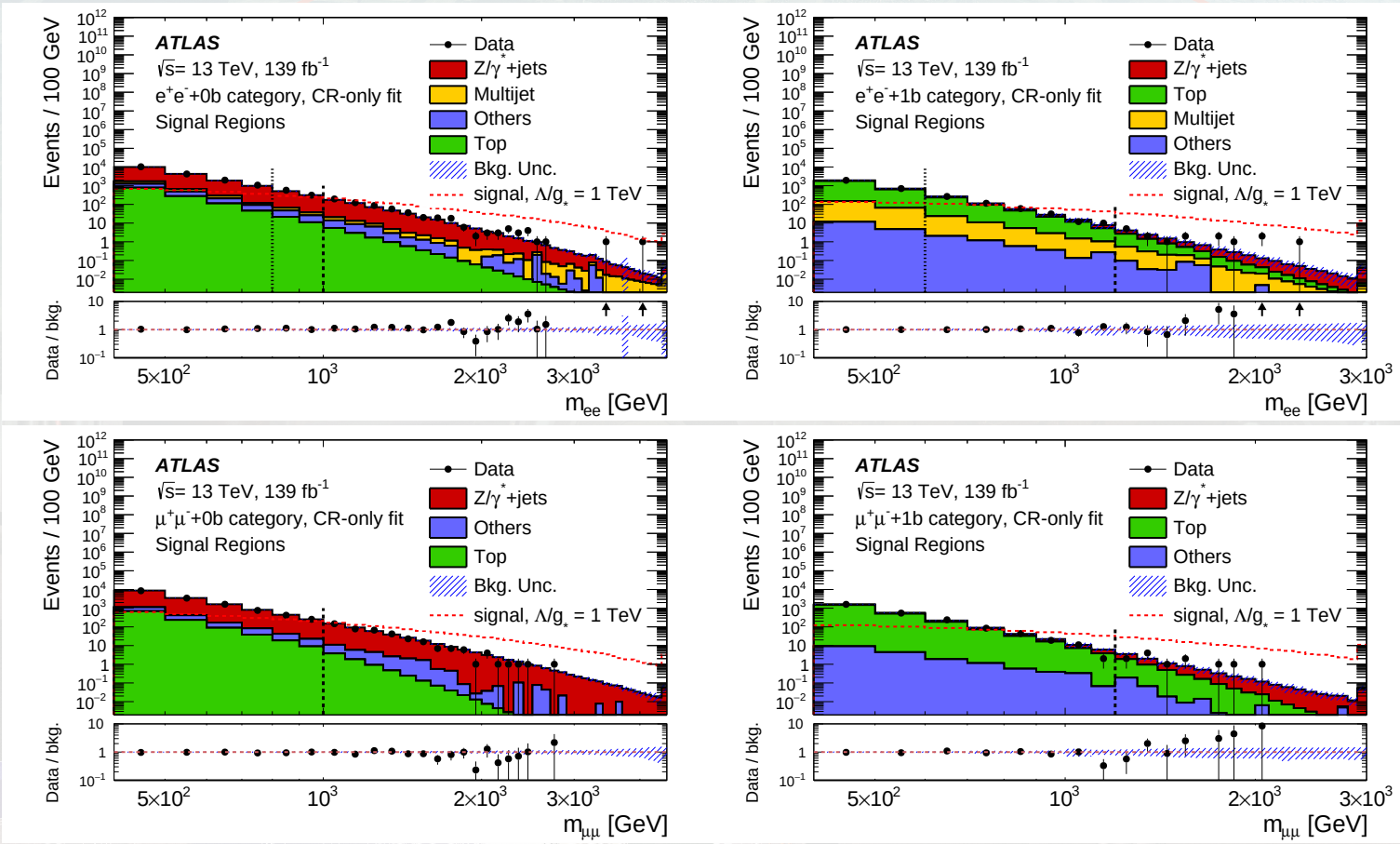
Search for $q\bar{q}\ell^+\ell^-$ CIs (CMS)

m_{ee} range [GeV]	Observed yield	Total background	DY	Other prompt lepton backgrounds	Jet mis-identification
60–120	28194452	28200000 ± 710000	28000000 ± 710000	153000 ± 8000	11300 ± 5700
120–400	912504	942000 ± 37000	744000 ± 31000	179000 ± 11000	18900 ± 9500
400–600	16192	16400 ± 770	10900 ± 477	4910 ± 340	534 ± 267
600–900	3756	3660 ± 190	2800 ± 150	757 ± 52	103 ± 51.4
900–1300	704	696 ± 47	590 ± 42	89.8 ± 6.8	16.0 ± 8.0
1300–1800	135	131 ± 12	118 ± 11	11.0 ± 1.0	2.82 ± 1.41
>1800	44	29.2 ± 3.6	26.8 ± 3.5	1.60 ± 0.22	0.82 ± 0.41
$m_{\mu\mu}$ range [GeV]	Observed yield	Total background	DY	Other prompt lepton backgrounds	Jet mis-identification
60–120	164075	166000 ± 9360	165000 ± 9300	994 ± 89	—
120–400	977714	1050000 ± 60400	836000 ± 47000	210000 ± 19000	3070 ± 1540
400–600	24041	26100 ± 1580	16700 ± 970	9120 ± 820	212 ± 106
600–900	5501	5610 ± 337	4170 ± 250	1370 ± 120	74.0 ± 37.0
900–1300	996	1050 ± 65	863 ± 52	169 ± 15	19.9 ± 10.0
1300–1800	183	195 ± 13	169 ± 10	19.9 ± 1.8	6.7 ± 3.4
>1800	42	44.3 ± 3.4	38.7 ± 2.5	3.3 ± 0.3	2.2 ± 1.1

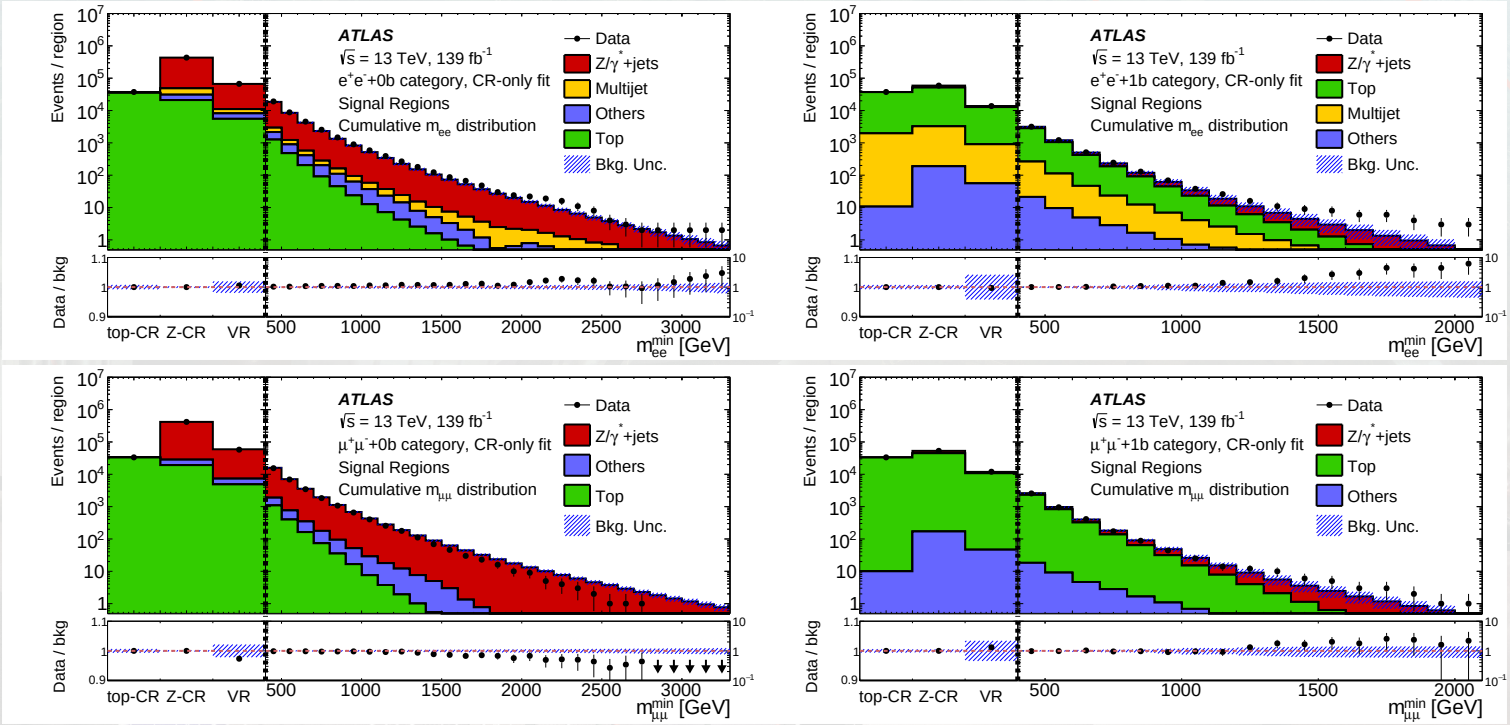
Search for $q\bar{q}\ell^+\ell^-$ CIs (CMS)

Order	GRW Λ_T [TeV]	Hewett M_S [TeV] $\lambda = +1$	HLZ M_S [TeV] $n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
			ee				
LO	6.7 (6.9)	5.9 (6.2)	7.9 (8.2)	6.7 (6.9)	6.0 (6.3)	5.6 (5.8)	5.3 (5.5)
LO $\times$1.3	6.9 (7.2)	6.1 (6.4)	8.2 (8.5)	6.9 (7.2)	6.2 (6.5)	5.8 (6.0)	5.5 (5.7)
			$\mu\mu$				
LO	7.0 (7.1)	6.2 (6.4)	8.3 (8.5)	7.0 (7.1)	6.3 (6.4)	5.9 (6.0)	5.6 (5.7)
LO $\times$1.3	7.2 (7.4)	6.5 (6.6)	8.6 (8.8)	7.2 (7.4)	6.5 (6.7)	6.1 (6.2)	5.8 (5.9)
			Combined ee and $\mu\mu$				
LO	7.3 (7.5)	6.5 (6.7)	8.6 (8.9)	7.3 (7.5)	6.6 (6.8)	6.1 (6.3)	5.8 (6.0)
LO $\times$1.3	7.5 (7.8)	6.7 (6.9)	8.9 (9.2)	7.5 (7.8)	6.7 (7.0)	6.3 (6.5)	5.9 (6.2)

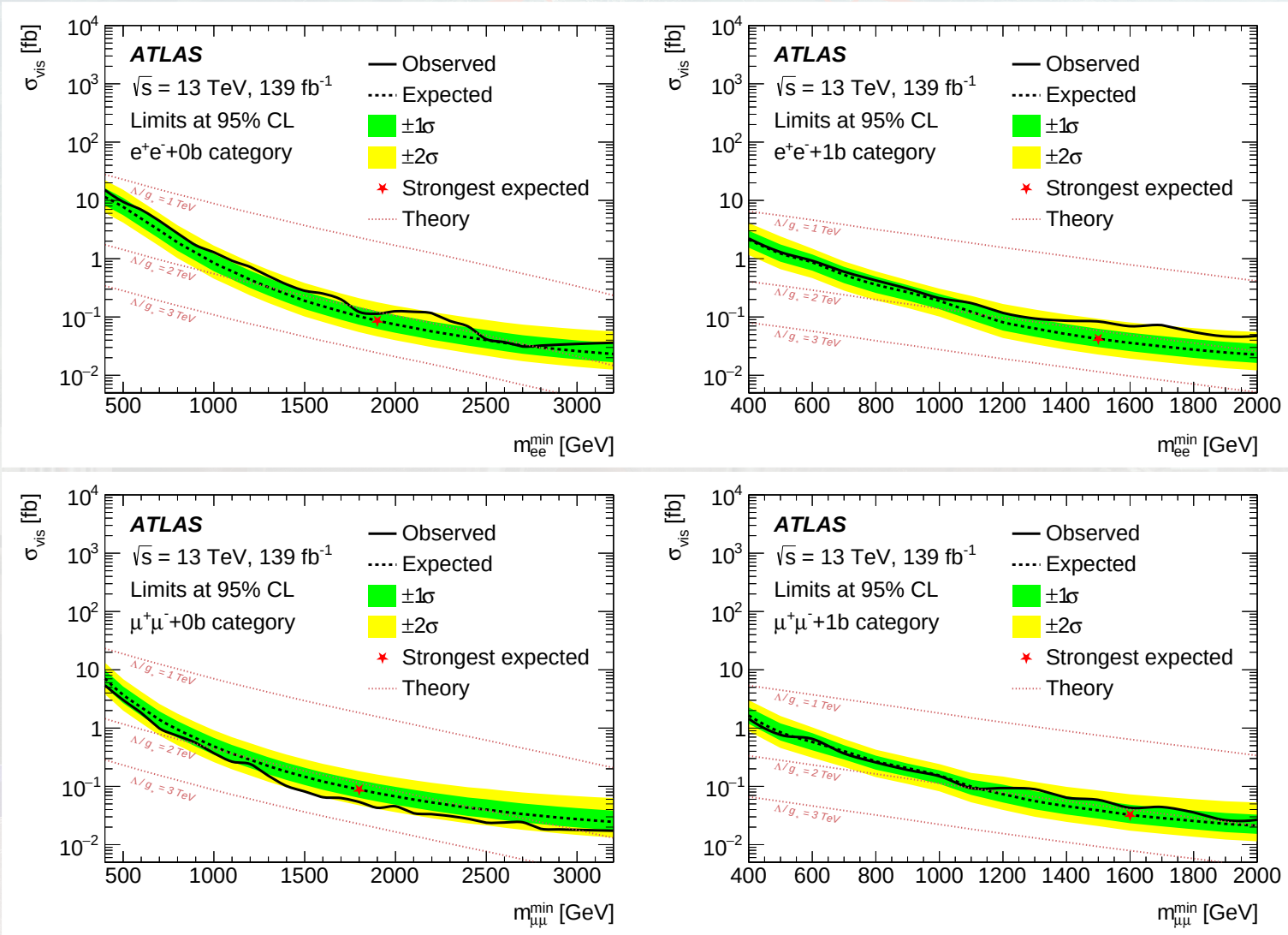
Search for $b\bar{s}\ell^+\ell^-$ CI (ATLAS)



Search for $b\bar{s}\ell^+\ell^-$ CI (ATLAS)



Search for $b\bar{s}\ell^+\ell^-$ CI (ATLAS)



Search for $b\bar{s}\ell^+\ell^-$ CI (ATLAS)

Source	e^+e^- + 0b (1b) [%]		$\mu^+\mu^-$ + 0b (1b) [%]	
	Signal 0b (1b)	Background 0b (1b)	Signal 0b (1b)	Background 0b (1b)
Luminosity	1.7 (1.7)	1.6 (1.5)	1.7 (1.7)	1.7 (1.7)
Pileup	<0.5 (<0.5)	<0.5 (0.7)	<0.5 (<0.5)	<0.5 (<0.5)
Leptons	8.7 (8.6)	8.6 (6.3)	8.5 (6.5)	9.1 (4.2)
Jets	<0.5 (1.8)	<0.5 (3.4)	<0.5 (1.6)	<0.5 (1.9)
b-tagging	<0.5 (1.4)	<0.5 (2.0)	<0.5 (1.4)	<0.5 (2.2)
Top bkg. extrapolation	-	3.5 (32.0)	-	<0.5 (36.0)
Multijet extrapolation	-	7.5 (15.0)	-	-
Top bkg. modeling	-	<0.5 (<0.5)	-	<0.5 (<0.5)
Z/γ^*+jets bkg. modeling	-	9.4 (4.3)	-	10.0 (5.5)
MC statistics	0.6 (0.8)	1.9 (3.5)	0.7 (1.0)	1.7 (2.4)
Total	8.9 (9.1)	15.0 (37.0)	8.7 (7.1)	14.0 (37.0)