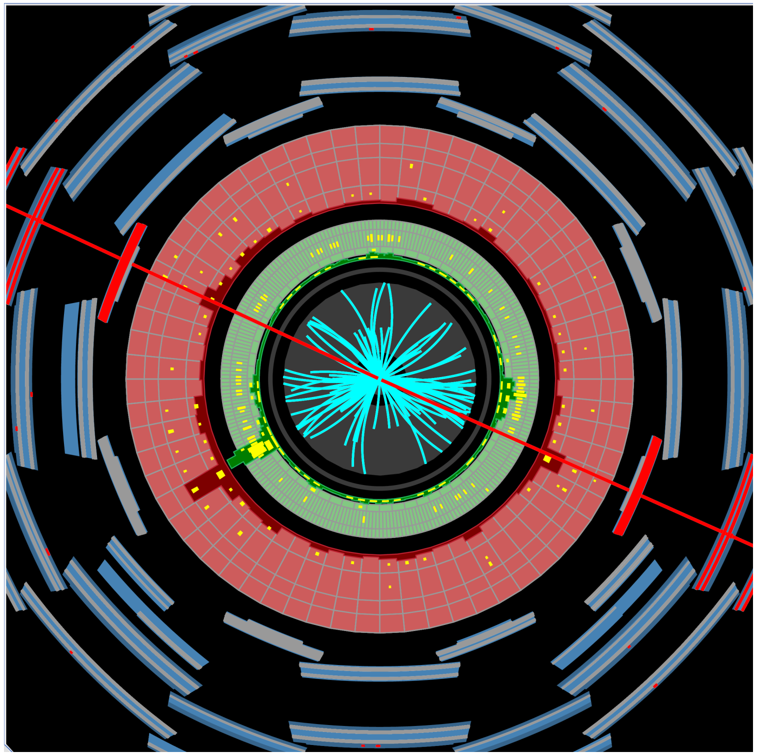
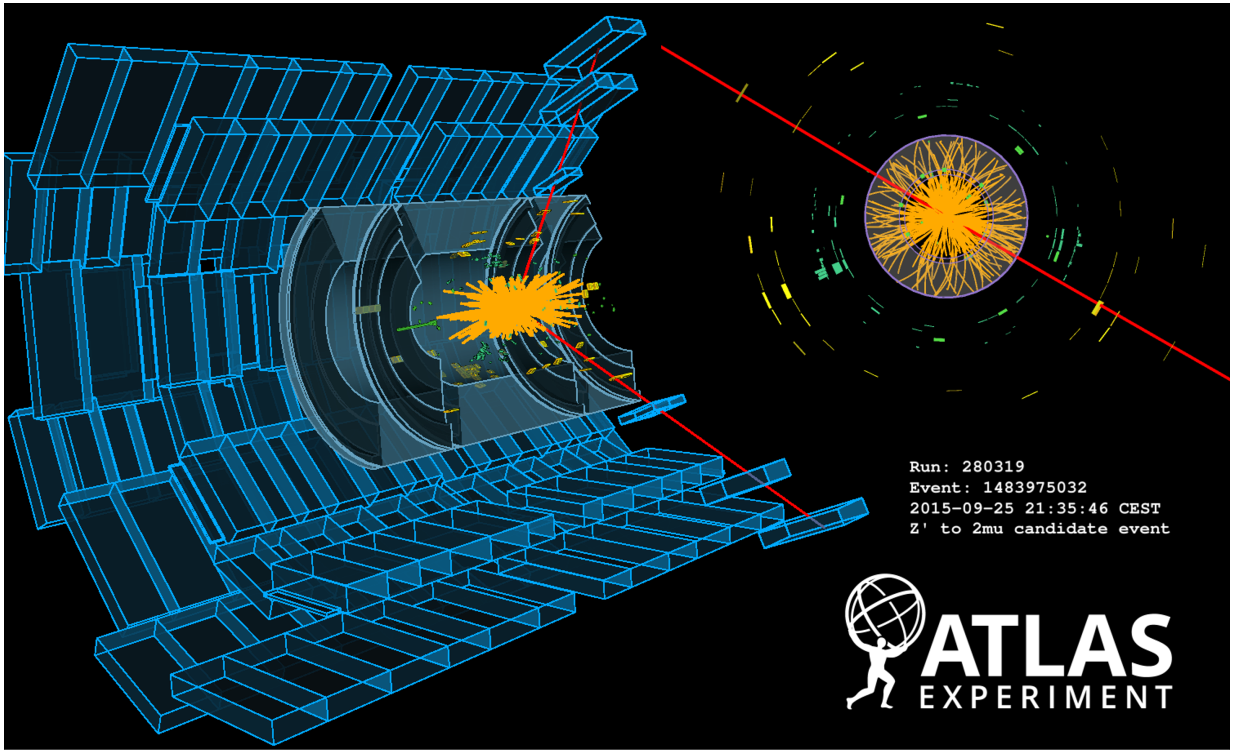
Searches for New s-channel Resonances with the ATLAS Detector at 13 TeV





Lake Louise Winter Institute
Chateau Lake Louise, Canada, 22 Feb. 2017

MICHIGAN STATE UNIVERSITY

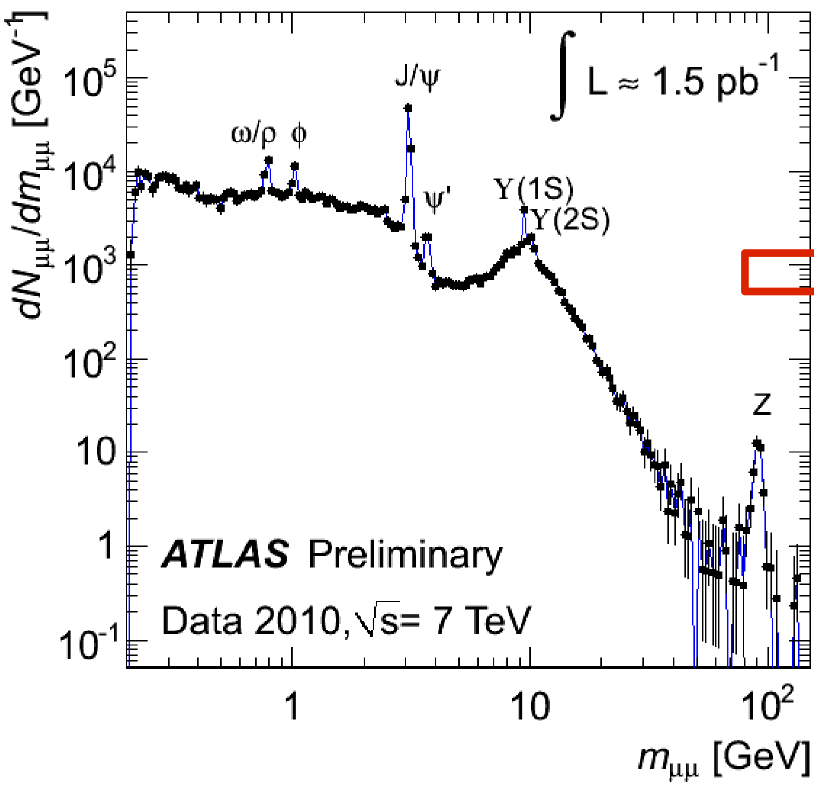
Christopher Willis on behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

Introduction

→ Brief overview of selected searches for new s-channel resonances in the 2015+2016 ATLAS dataset

→ s-channel process corresponds to the particles 1,2 joining into an intermediate particle that eventually splits into 3,4



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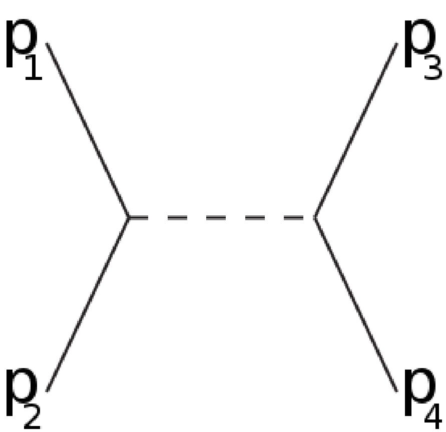


→ At LHC 1,2 are partons, 3,4 are SM Particles

→ Historically great place to look for evidence of New Physics

→ New resonances address big questions (unification, new forces, etc.)

ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8,\ 13$ TeV

W'
Z'

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	15.7	M_{th} 8.7 TeV	$n = 6$	ATLAS-CONF-2016-069
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	3.2	G_{KK} mass 3.2 TeV	$k/\overline{M}_{Pl} = 0.1$	1606.03833
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	13.2	G_{KK} mass 1.24 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	13.3	G_{KK} mass 360-860 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	13.3	Z' mass 4.05 TeV		ATLAS-CONF-2016-045
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	13.3	W' mass 4.74 TeV		ATLAS-CONF-2016-061
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e, μ	1 J	Yes	13.2	W' mass 2.4 TeV	$g_V = 1$	ATLAS-CONF-2016-082
	HVT $W' \to WZ \to qqqq$ model B	–	2 J	–	15.5	W' mass 3.0 TeV	$g_V = 3$	ATLAS-CONF-2016-055
	HVT $V' \to WH/ZH$ model B	multi-channel			3.2	V' mass 2.31 TeV	$g_V = 3$	1607.05621
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	15.7	Λ 19.9 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e, μ	–	–	3.2	Λ 25.2 TeV	$\eta_{LL} = -1$	1607.03669
	CI $uutt$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 250$ GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 150$ GeV	1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	VLQ $T_{5/3} T_{5/3} \to WtWt$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	3.2	$T_{5/3}$ mass 990 GeV		ATLAS-CONF-2016-032
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	3.2	q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \to qg$	–	2 j	–	15.7	q^* mass 5.6 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2016-069
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	8.8	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to ee$	2 e (SS)	–	–	13.9	$H^{\pm\pm}$ mass 570 GeV	DY production, BR($H_L^{\pm\pm} \to ee$)=1	ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1509.08059

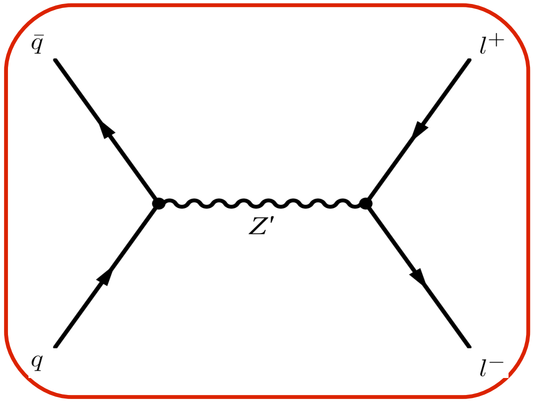
$\sqrt{s} = 8$ TeV (green) $\sqrt{s} = 13$ TeV (yellow)

Mass scale [TeV]: 10^{-1}, 1, 10

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Dilepton Analysis



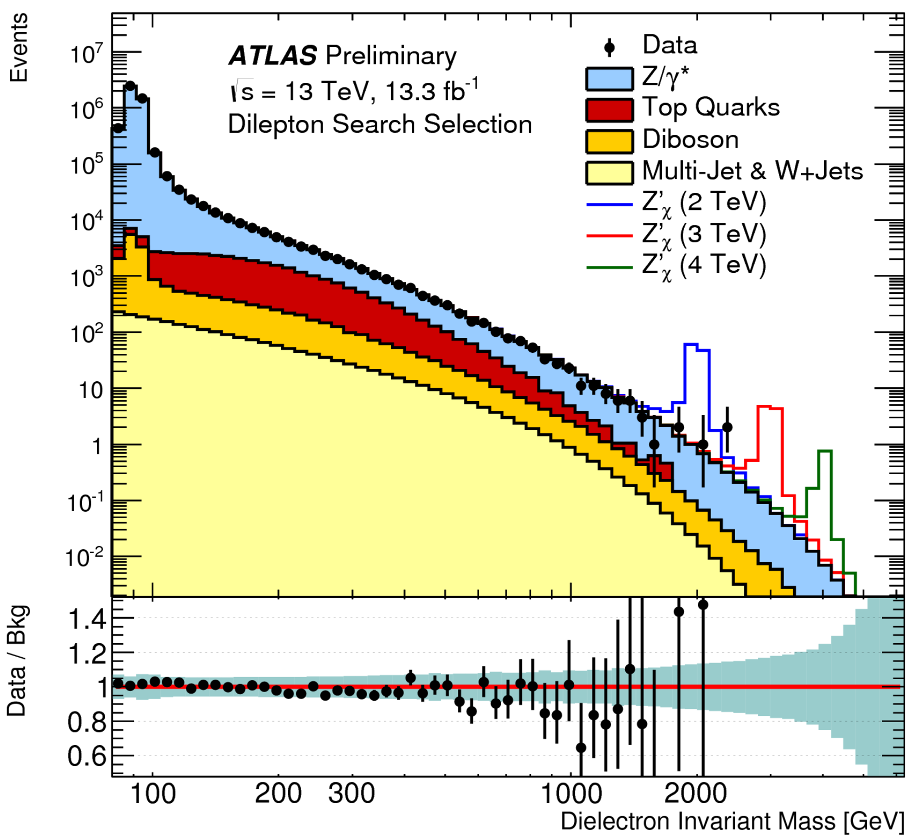
→ Search for both Resonant and Non-Resonant Phenomena

→ Selection designed for events with two high p_T, isolated leptons

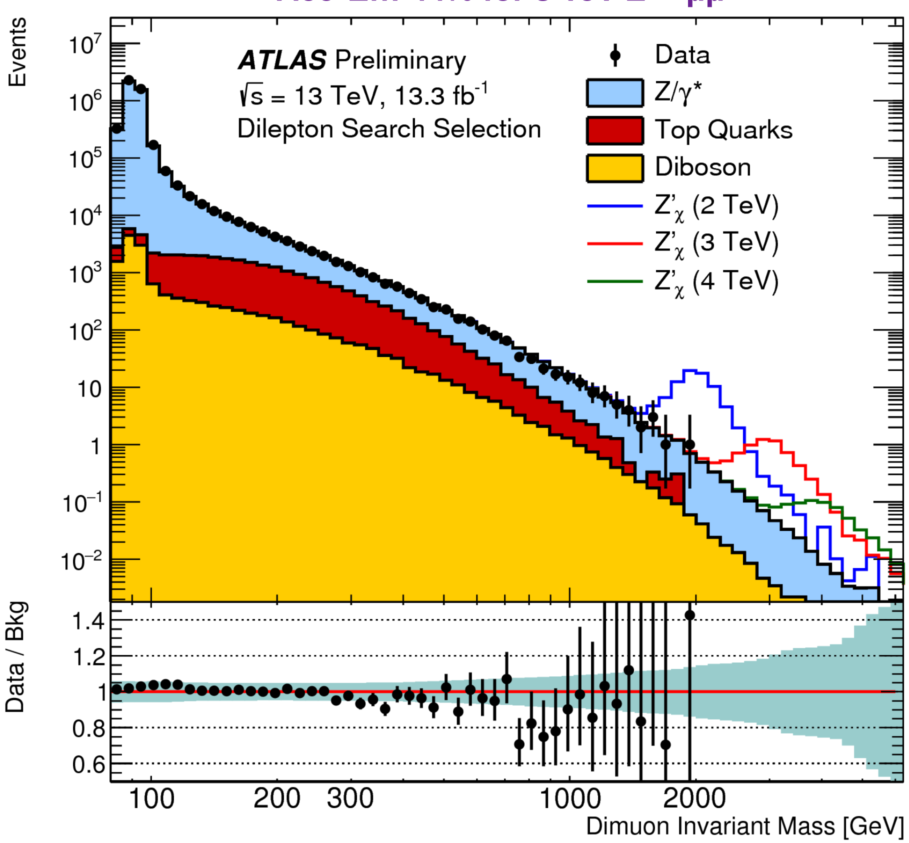
→ Backgrounds simulated with MC; fakes derived with data-driven method

→ Largest ee systematic: DY PDFs; largest μμ systematic: muon momentum resolution

Acc*Eff: 73% for 3 TeV Z'→ee



Acc*Eff: 44% for 3 TeV Z'→μμ

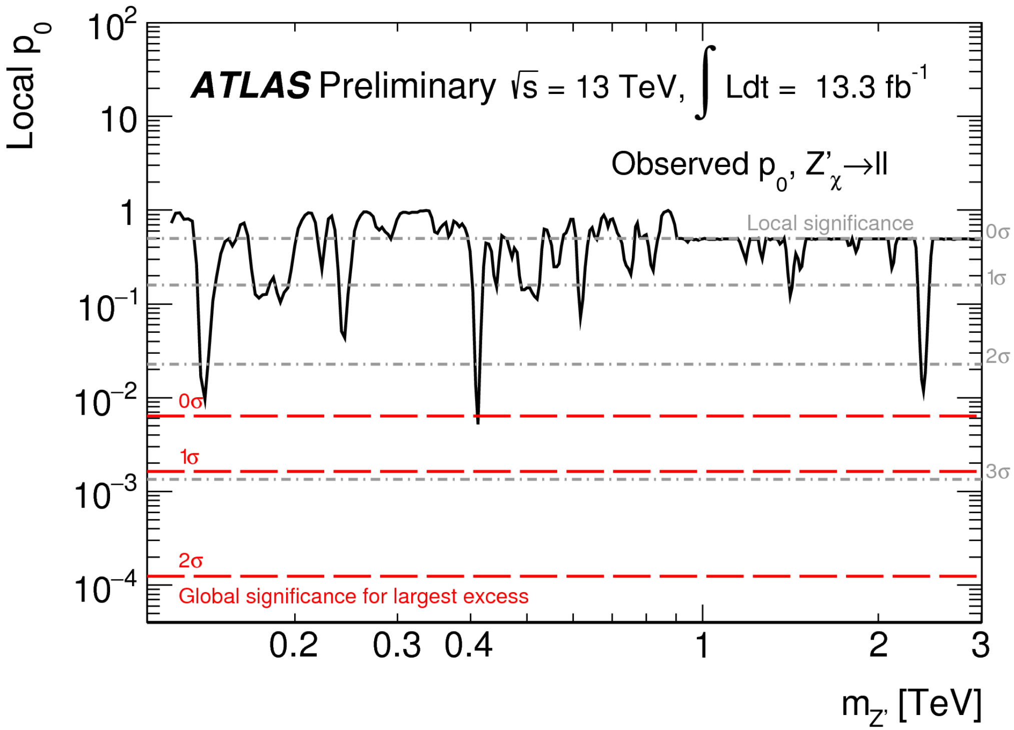


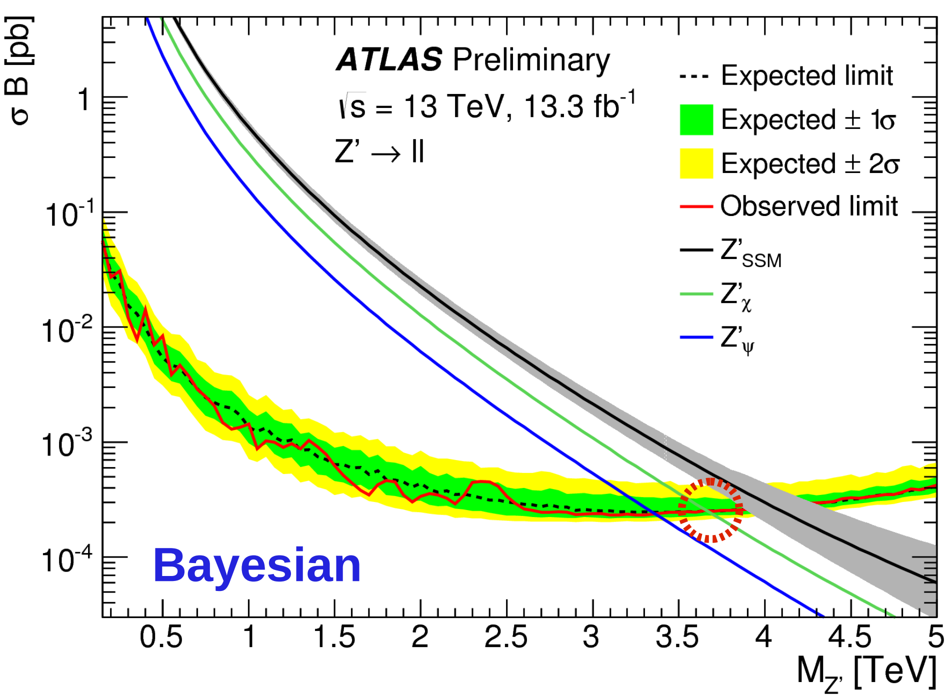
Dilepton Limits

→ ee/μμ channels combined for limits → ee dominates due to higher efficiency and better resolution

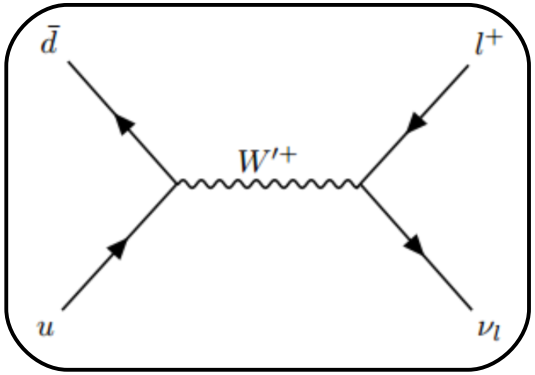
→ Reweighting scheme generates set of signal templates generated over search range

Model	Width [%]	θ_{E_6} [Rad]	Lower limits on $m_{Z'}$ [TeV]					
			ee		$\mu\mu$		$\ell\ell$	
			Obs	Exp	Obs	Exp	Obs	Exp
Z'_{SSM}	3.0	-	3.85	3.86	3.49	3.53	4.05	4.06
Z'_{χ}	1.2	0.50	3.48	3.49	3.18	3.19	3.66	3.67
Z'_{S}	1.2	0.63 π	3.43	3.44	3.14	3.14	3.62	3.61
Z'_{I}	1.1	0.71 π	3.37	3.37	3.08	3.08	3.55	3.55
Z'_{η}	0.6	0.21 π	3.25	3.25	2.96	2.94	3.43	3.42
Z'_{N}	0.6	-0.08 π	3.23	3.23	2.95	2.94	3.41	3.41
Z'_{ψ}	0.5	0 π	3.18	3.18	2.90	2.88	3.36	3.35





l+MET Analysis



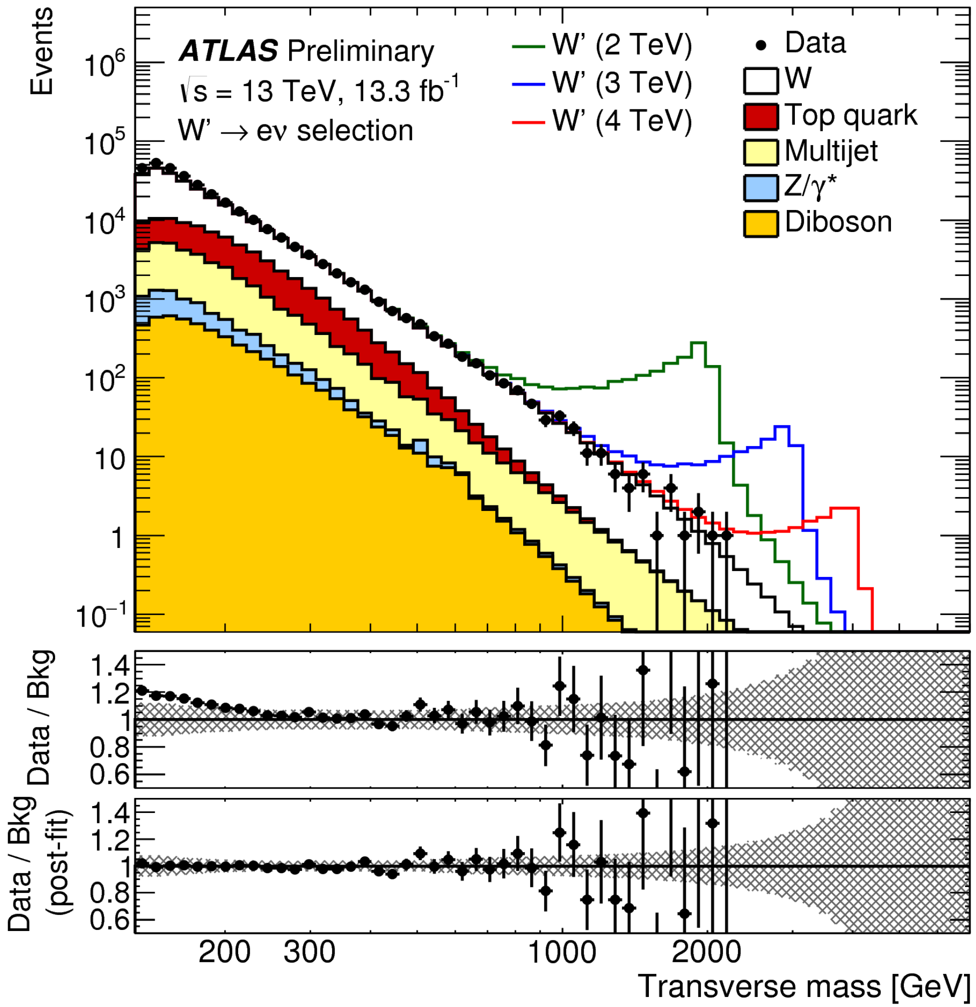
→ Search for Resonant Phenomena (SSM W', L-R symmetric models)

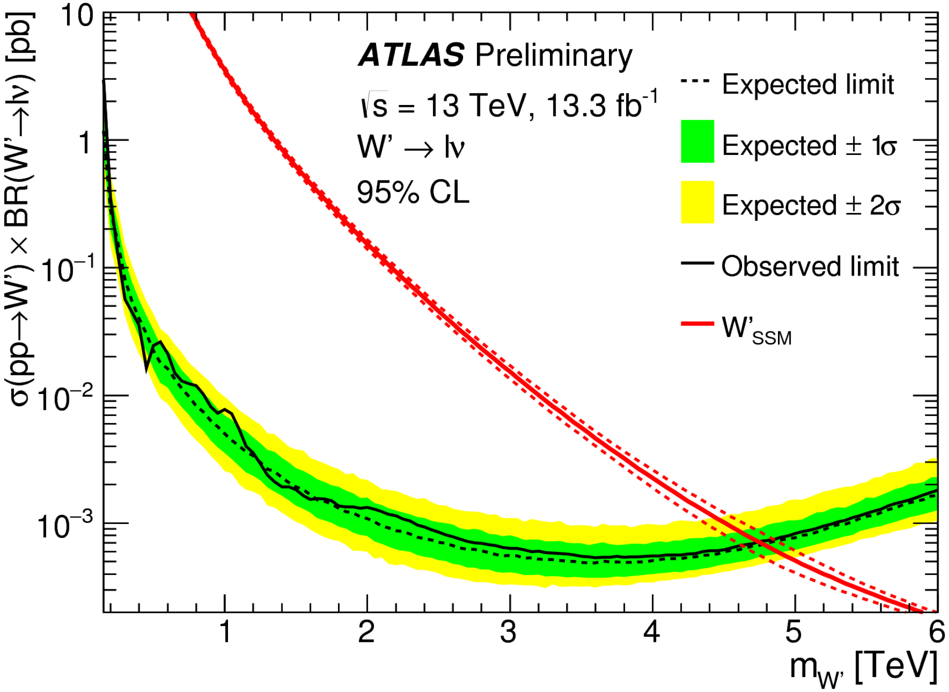
→ Selection designed for single high p_T, isolated lepton and MET

→ Backgrounds simulated with MC, fakes with data-driven method

→ Largest systematics from background extrapolations on m_T: eυ multijet; μυ: top, diboson

Acc*Eff: 74% (53%) for 2 TeV W'→ee (μμ)





Decay	$m_{W'}$ lower limit [TeV]	
	Expected	Observed
$W' \to e\nu$	4.59	4.64
$W' \to \mu\nu$	4.33	4.19
$W' \to \ell\nu$	4.77	4.74

High-Mass LFV Analysis

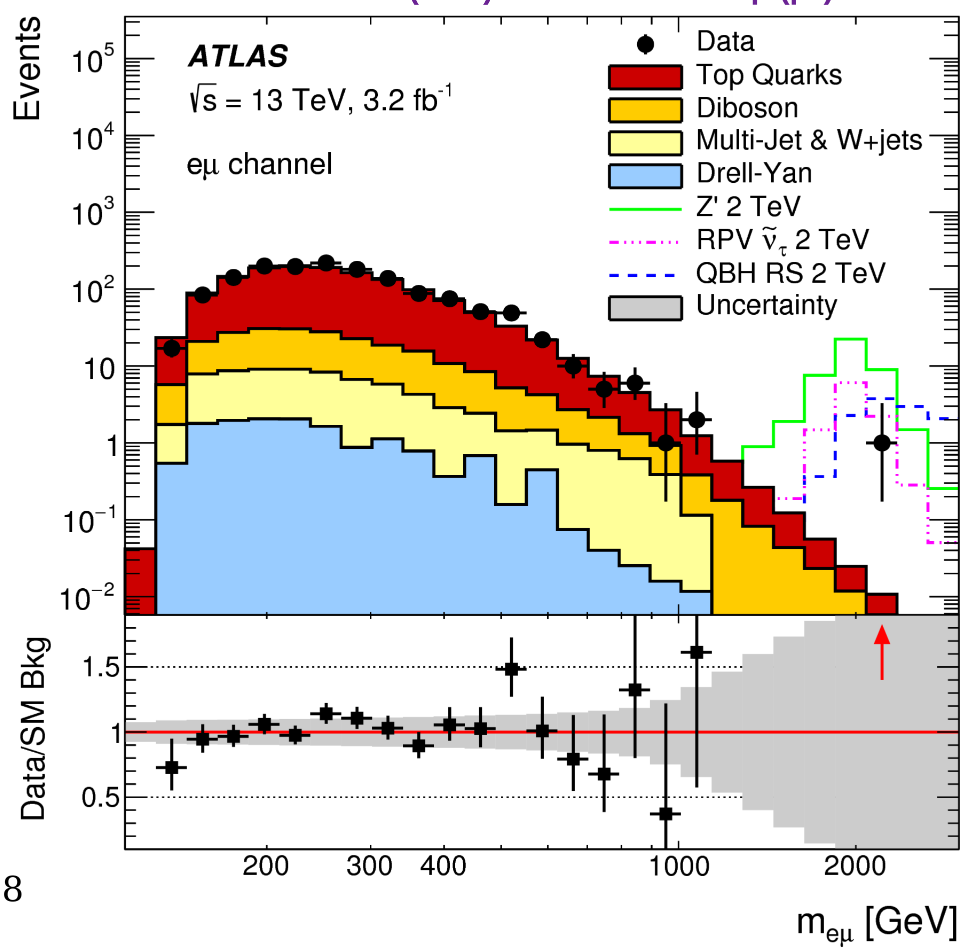
→ Direct production of different flavors lepton pairs in SM forbidden. Search performed for lepton flavor violating decays (LFV Z', QBH, SUSY) in $\mathbf{m_{e\mu}}$ /$m_{e\tau}$ /$m_{\mu\tau}$

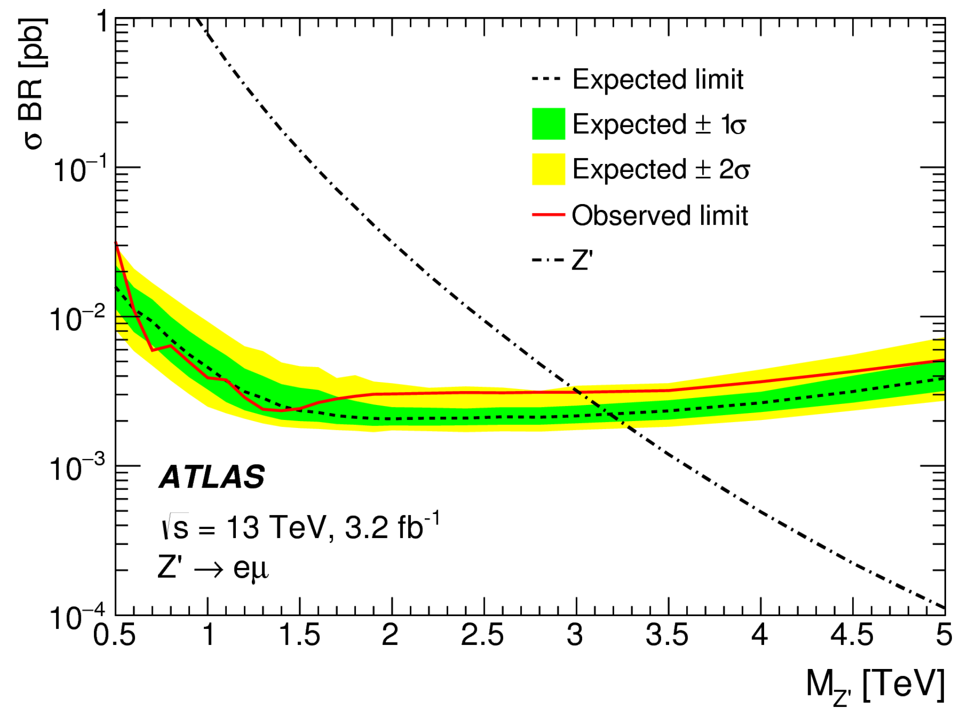
→ Select events with two high p_T, isolated different flavor lepton pairs

→ Backgrounds from final states with different flavor lepton pairs (e.g. qq → γ*/Z → $t\bar{t}$)

→ Largest Systematic is from $t\bar{t}$ high mass extrapolation, followed by PDFs.

Acc*Eff: 50% (20%) for 1.5 TeV Z'→eμ (μτ)





Model	Expected Limit [TeV]			Observed Limit [TeV]		
	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$
Z'	3.2	2.7	2.6	3.0	2.7	2.6
RPV SUSY $\tilde{\nu}_\tau$	2.5	2.1	2.0	2.3	2.2	1.9
QBH ADD $n = 6$	4.6	4.1	3.9	4.5	4.1	3.9
QBH RS $n = 1$	2.5	2.2	2.1	2.4	2.2	2.1

Dijet Search

$$\chi = e^{2|y^*|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

→ Search for Excited Quarks, Z', W', QBH in mass, CI in angular distributions

→ Select events with at least 2 high p_T jets

→ Require $|y^*|<0.6$ for **Resonant Search** to reduce QCD; BSM peak $y^*=0$

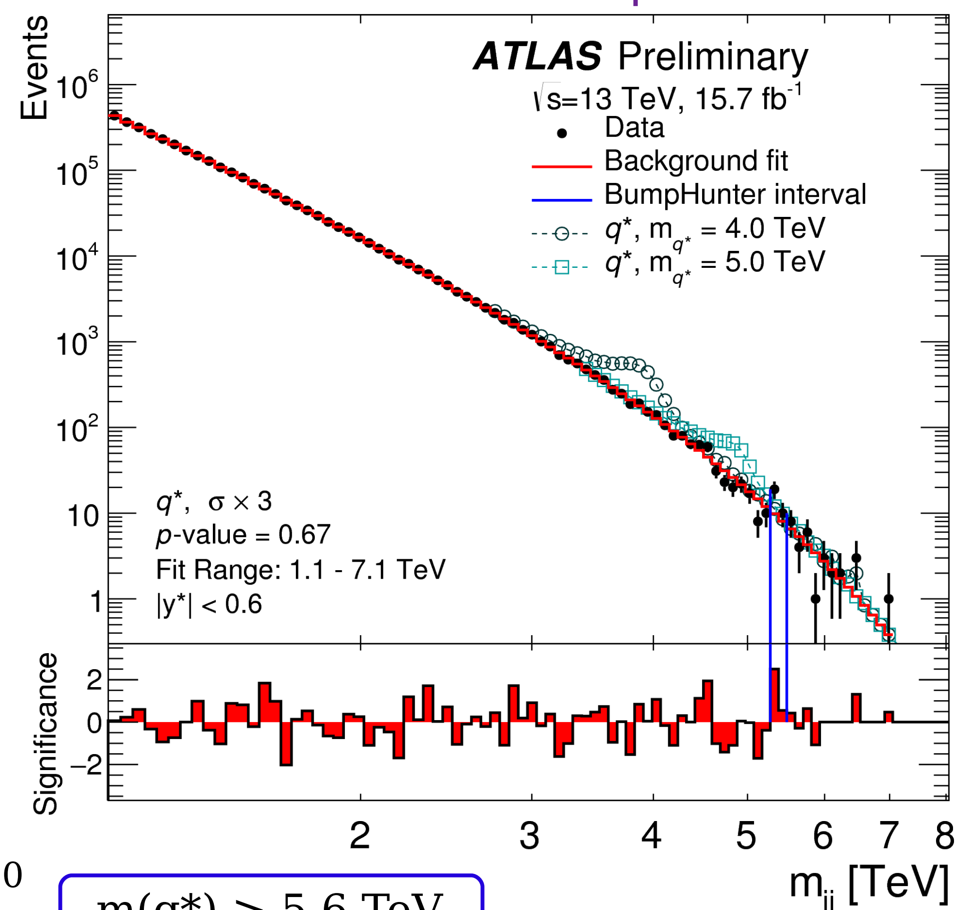
→ Functional form fit to data to estimate SM background

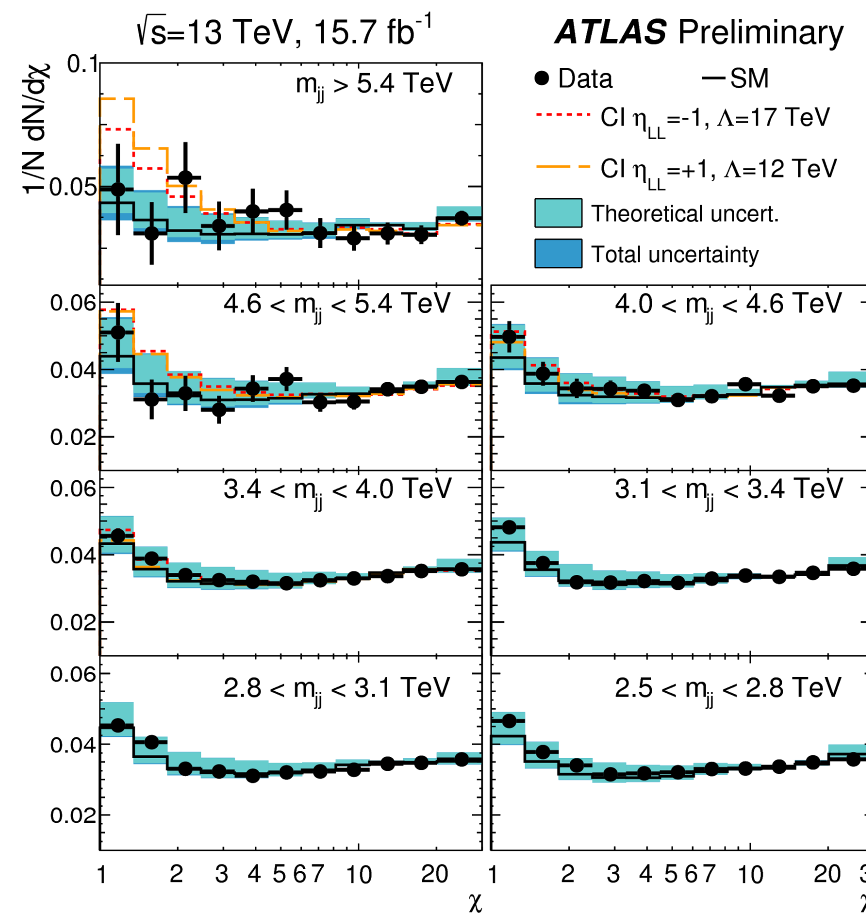
$$L_{qq} = \frac{2\pi}{\Lambda^2}\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L)$$

→ **Angular search** uses $|y^*|<1.7$, $|y_B|<1.1$

→ Uses LO MC + NLO QCD and LO EW corrections

Acc*Eff: 58% for 4 TeV q*





m(q*) > 5.6 TeV

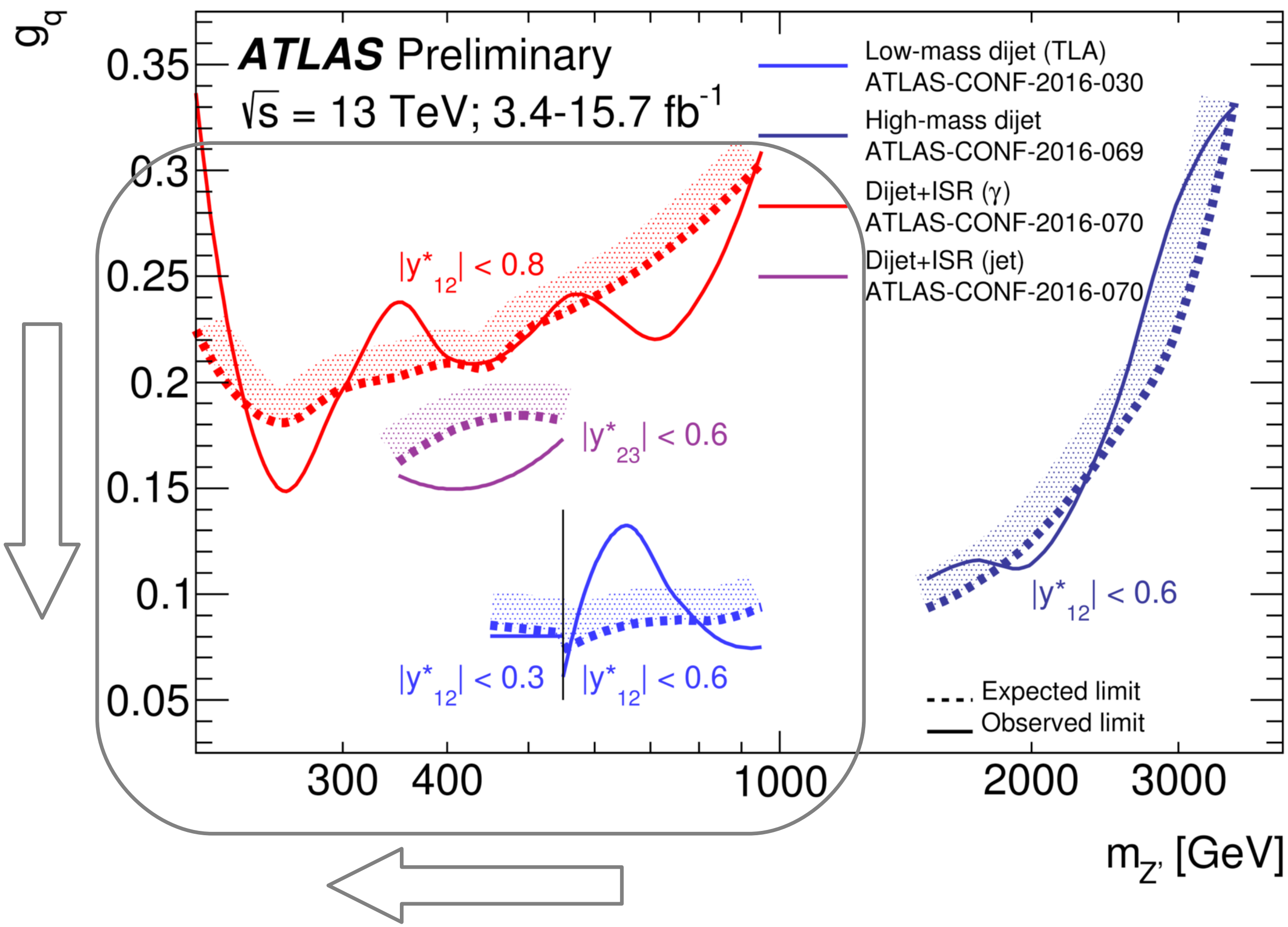
CI scale (η_{LL}=+1/-1) > 12.6 / 19.9 TeV

Summary Dijet Limits

→ Set limits on benchmark leptophobic Z' with gauge coupling g_q (dark-matter model)

→ Take advantage of **Dijet+ISR** to evade trigger limitations at low mass

→ Combination covers large mass range and parameter space

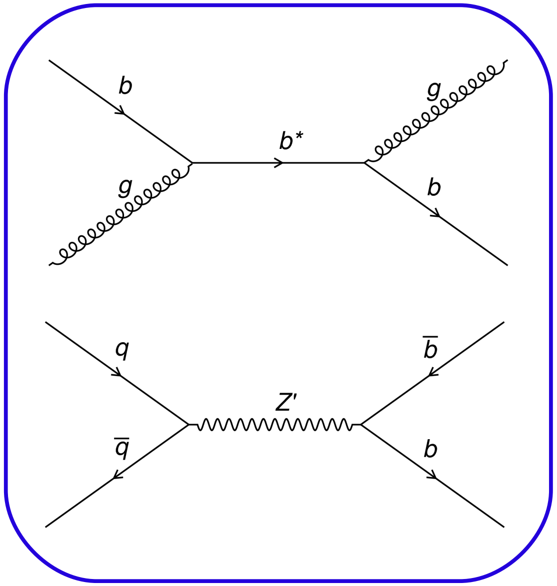


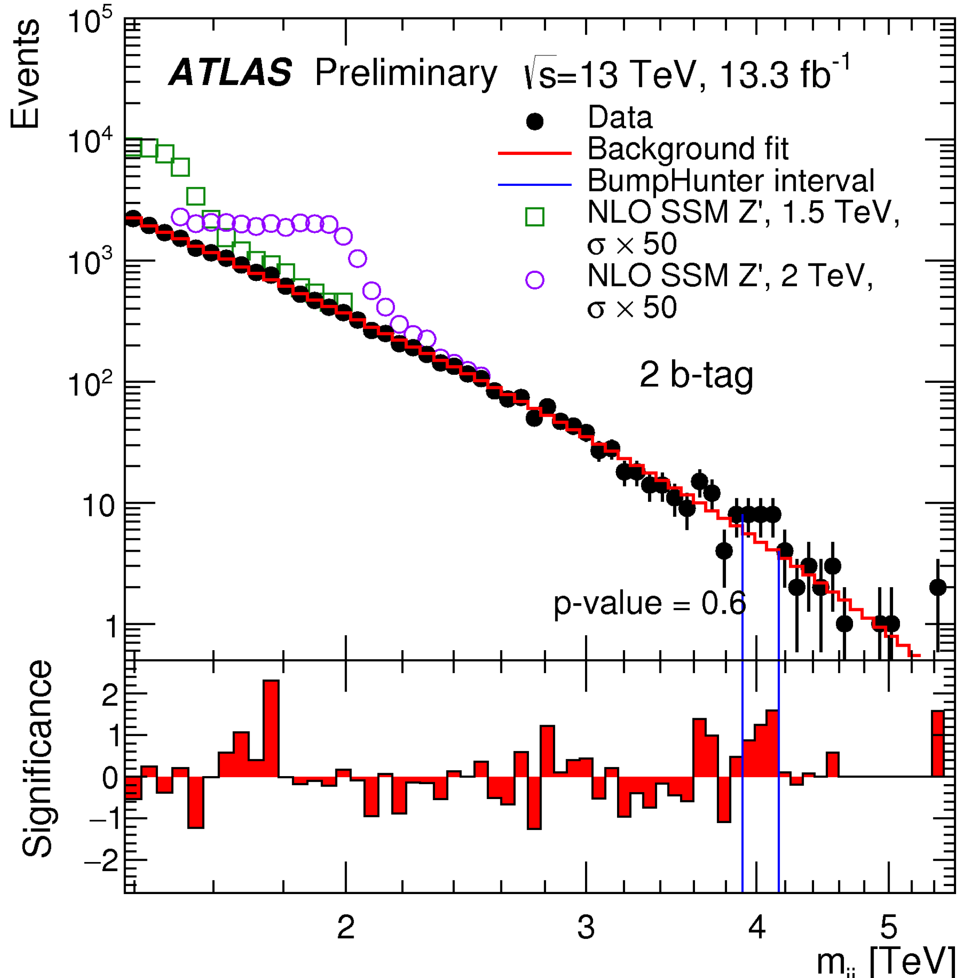
b-jet Search

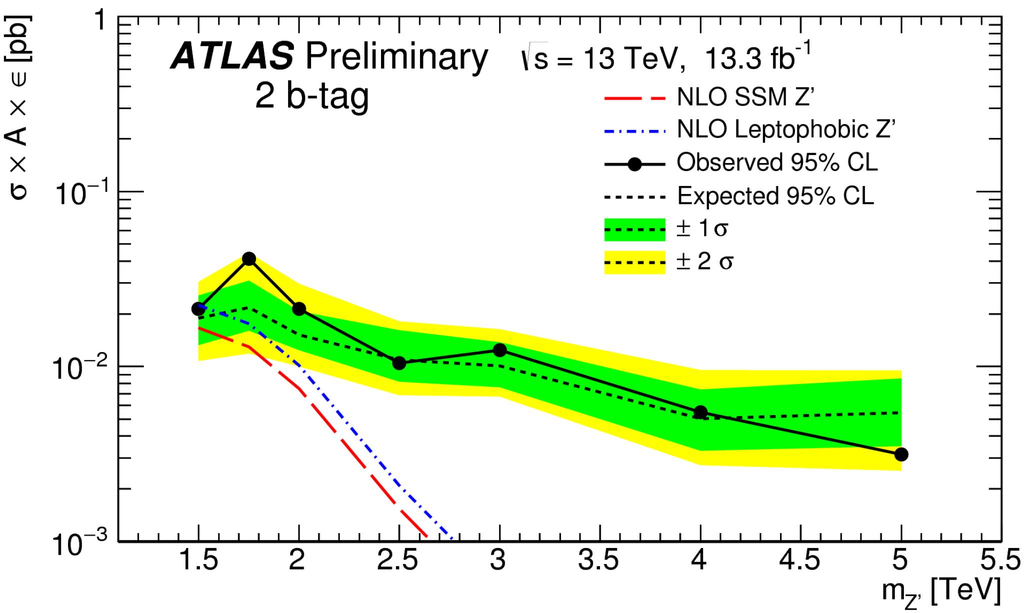
→ New particle couples to b-quark → decay to bb, bq or bg pairs
→ BSM Models: New Scalars, Leptophobic Z', b*

→ Search divides events into two channels: “1b” inclusive, and “2b”

→ Functional form fit to data to model SM background



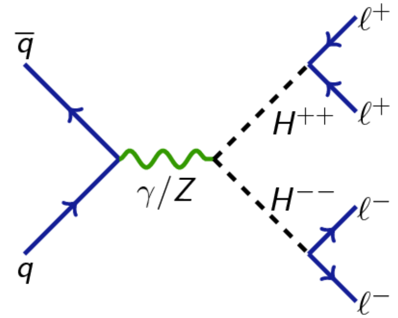




m(b*)>2.3 TeV, Br(b*→bg) = 0.85

m(Z'→bb) > 1.5 TeV

Doubly Charged Higgs



→ Search for Doubly charged Higgs (LRSM, Higgs triplets, Little Higgs, Seesaw, etc)

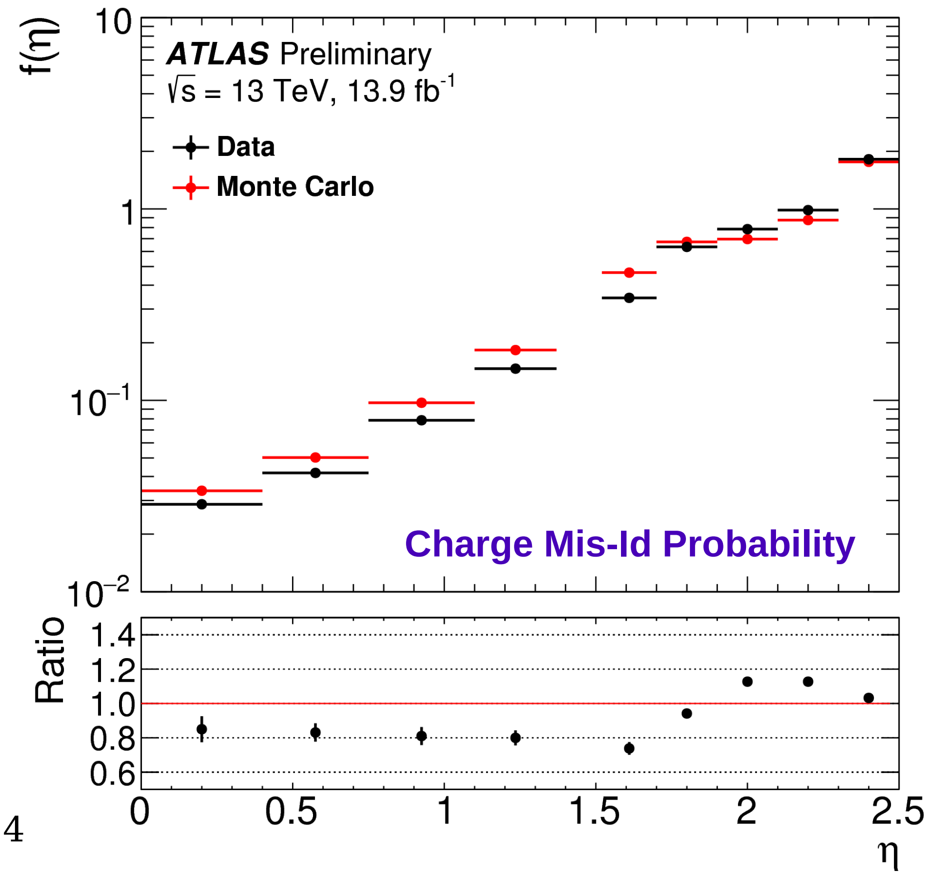
→ Background estimated using MC, data-driven for fake rate models light flavor jets

→ Selection requires two high p_T, isolated lepton pairs → split into orthogonal regions by sign

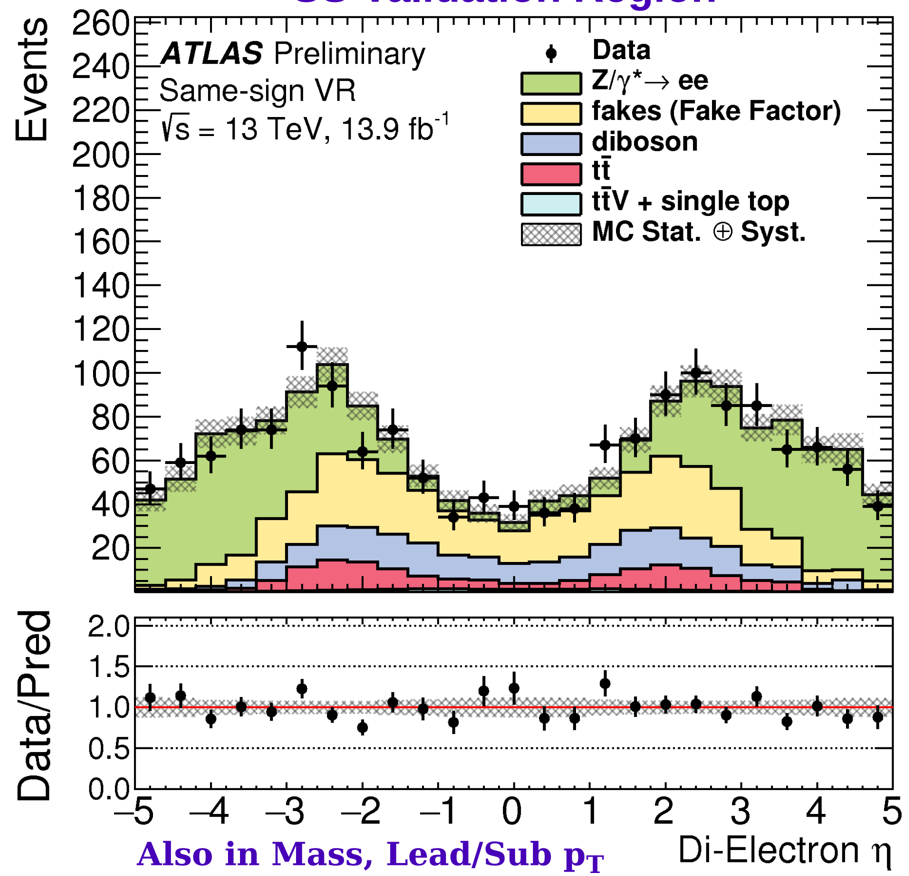
  → SS signal, two OS control, and SS validation

  → Derive SFs from OSCR, apply to SR to correct yields, check validity in SSVR

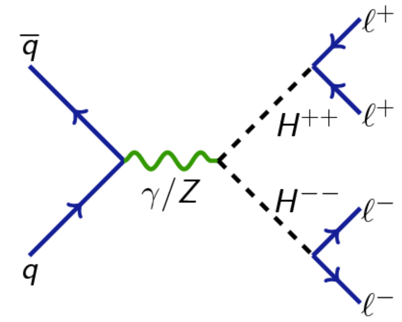
→ Charge Mis-Id probability derived from Z → ee events



SS Validation Region



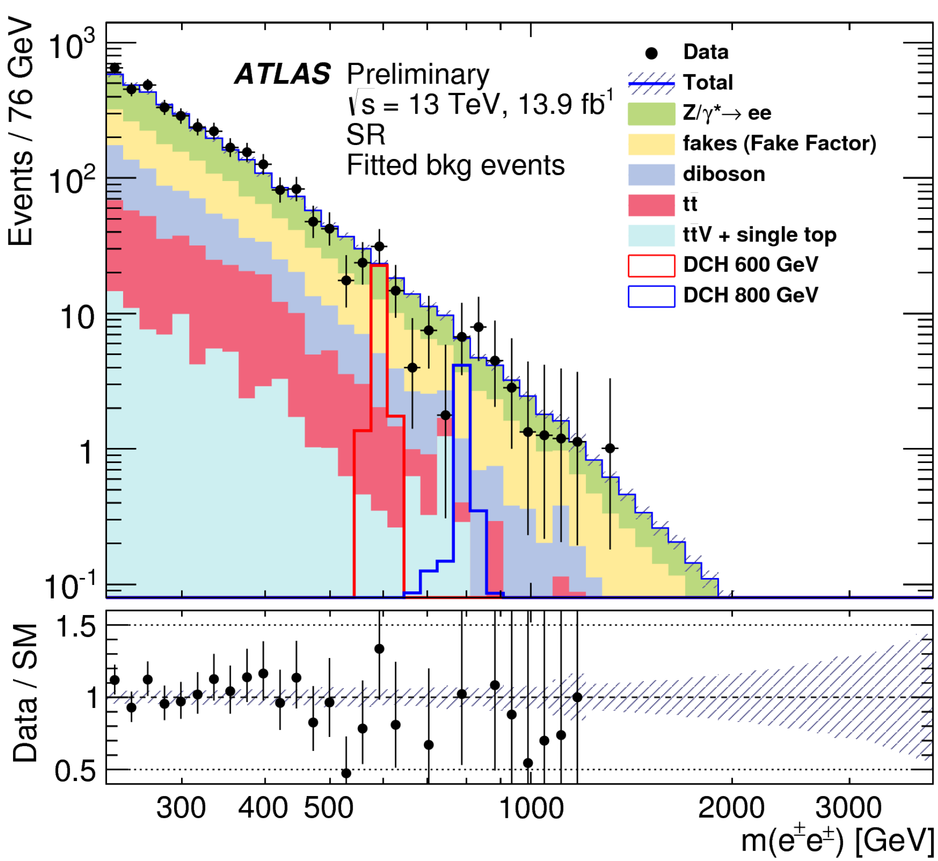
Doubly Charged Higgs

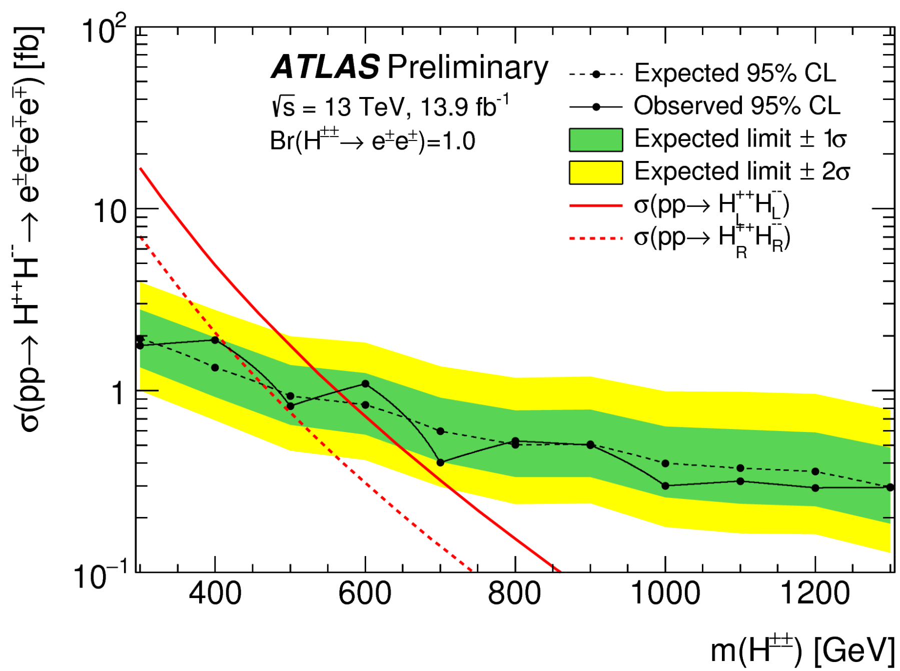


→ Theory Uncertainties considered on DY and ttbar, PDFs

→ Exp. Uncertainties account for Electron Efficiencies, charge Mis-ID

→ No signal observed, set 95% CL limits

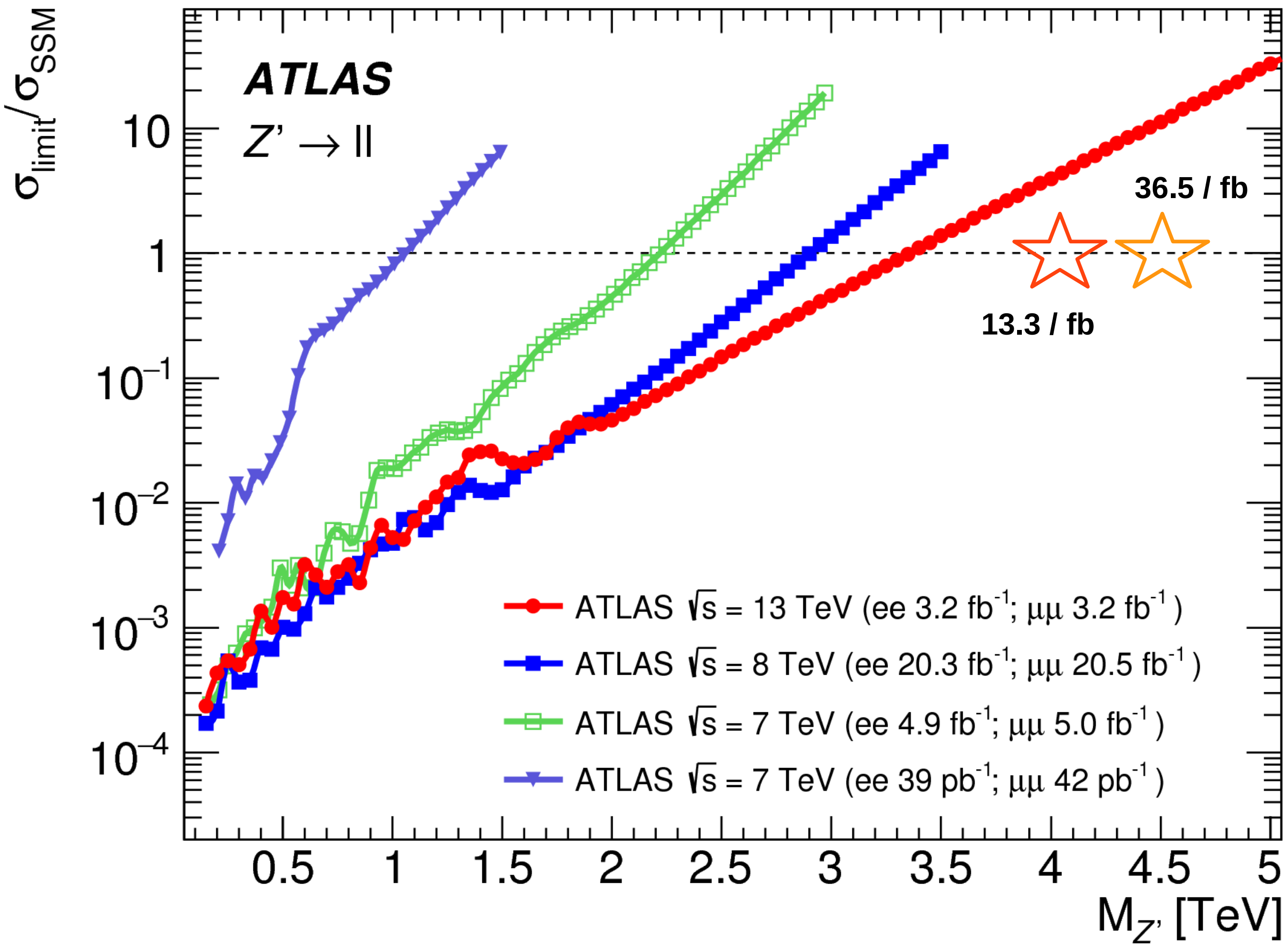




Taking BR($H^{\pm\pm}\rightarrow e^{\pm}e^{\pm}$) = 100%
→ 420 GeV on $H_R^{\pm\pm}$
→ 570 GeV on $H_L^{\pm\pm}$

Conclusion

→ Limits improved greatly for a wide range of models with Run-2 dataset



→ LHC performing extremely well

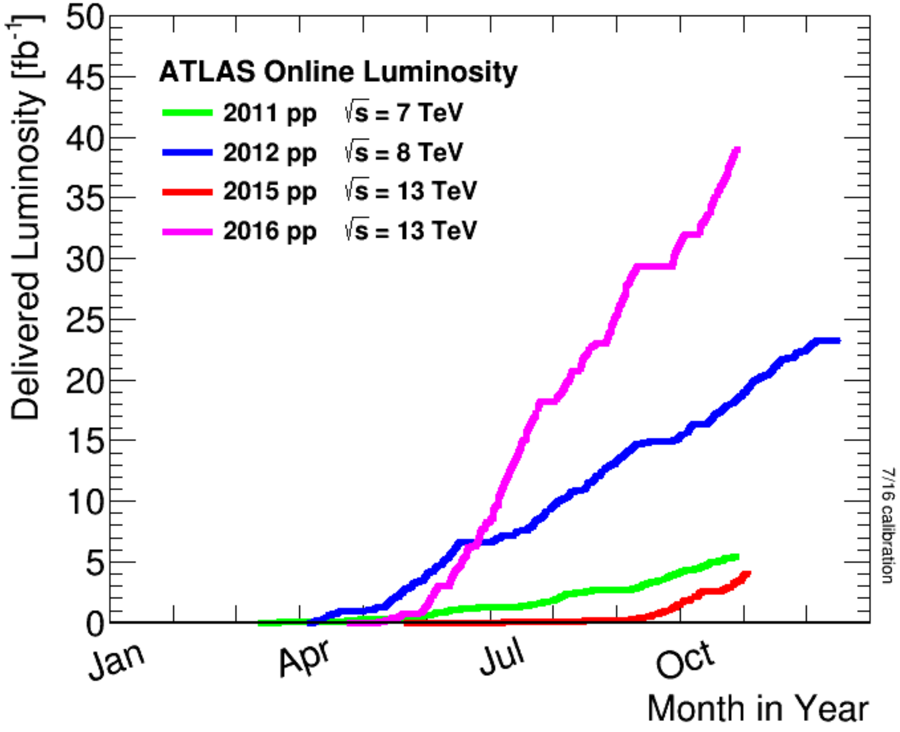
→ Stay tuned for updated results with the full 2016 data!

Backup

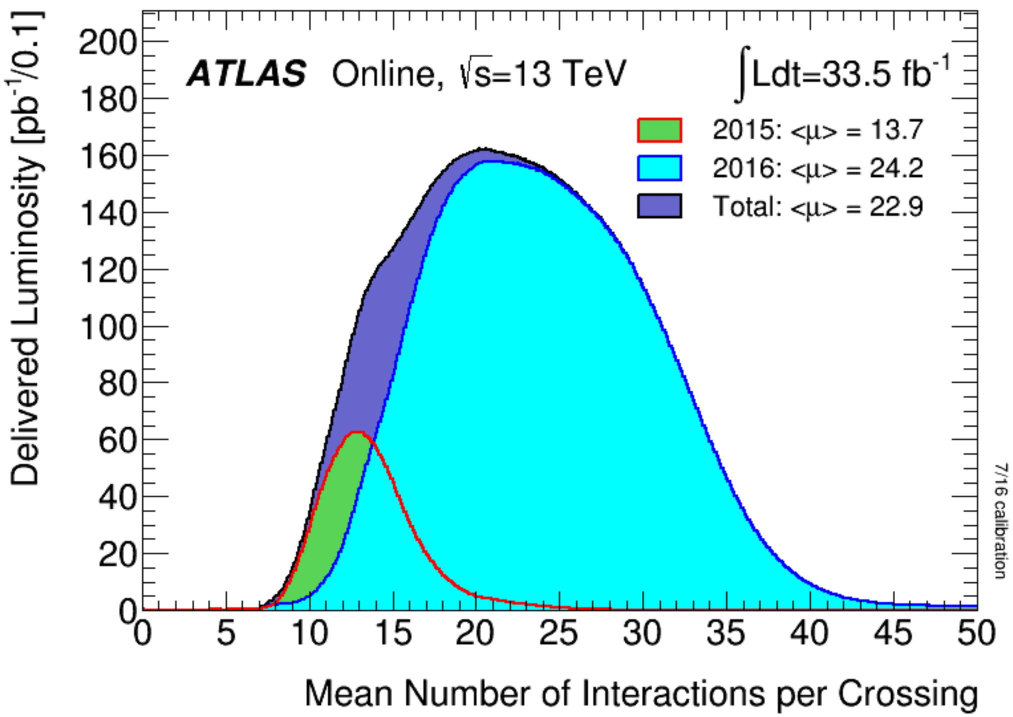
ATLAS Performance

→ Total collected good data is 36.5 fb^{-1} (3.2 fb^{-1} in 2015, 33.3 fb^{-1} in 2016)
ε > 90% usable for analysis

Exceptional LHC performance in 2016



Instantaneous luminosity now beyond design



→ Results presented here based on full 2015 dataset and partial 2016 dataset

arXiv:1607.08079

High-Mass LFV Analysis

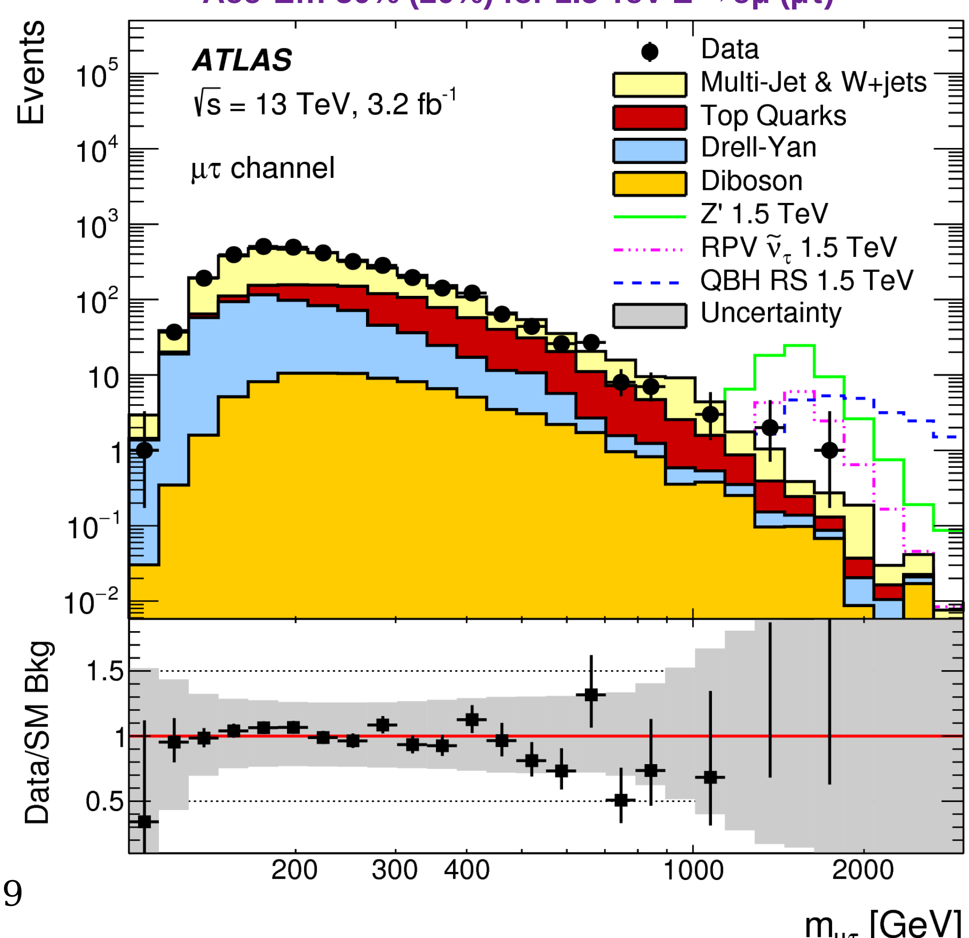
→ Direct production of different flavors lepton pairs in SM forbidden. Search performed for lepton flavor violating decays (LFV Z', QBH, SUSY) in $m_{e\mu}$ /$m_{e\tau}$ /$m_{\mu\tau}$

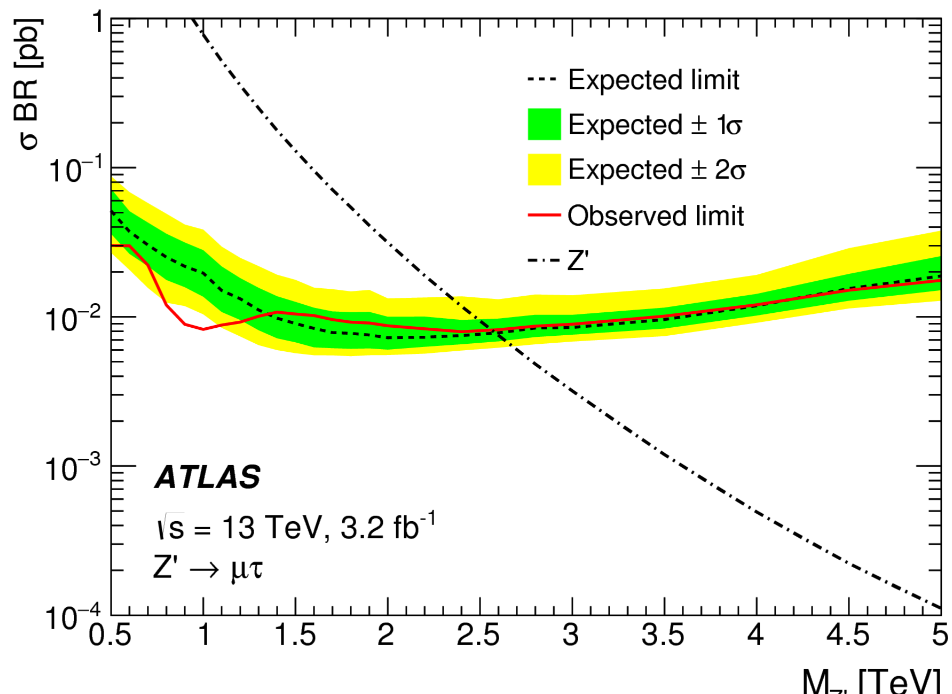
→ Select events with two high p_T, isolated different flavor lepton pairs

→ W+jets background dominant in $e\tau$ and $\mu\tau$ channels

→ Fake rate evaluated from data in W(→e/μ)+jets CR → weight W+jets MC

Acc*Eff: 50% (20%) for 1.5 TeV Z'→eμ (μτ)





Model	Expected Limit [TeV]			Observed Limit [TeV]		
	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$
Z'	3.2	2.7	2.6	3.0	2.7	2.6
RPV SUSY $\tilde{\nu}_\tau$	2.5	2.1	2.0	2.3	2.2	1.9
QBH ADD $n = 6$	4.6	4.1	3.9	4.5	4.1	3.9
QBH RS $n = 1$	2.5	2.2	2.1	2.4	2.2	2.1

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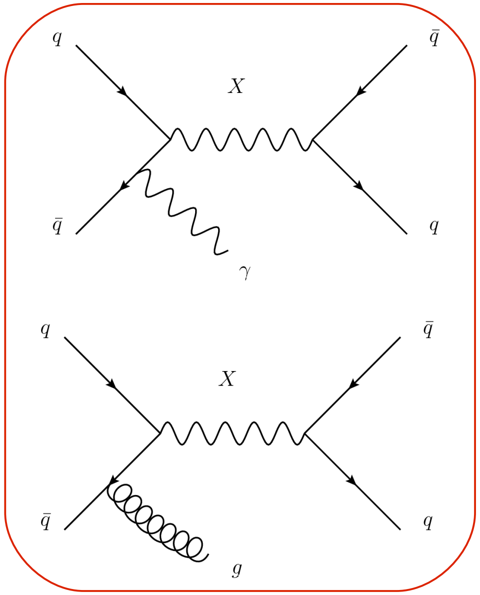
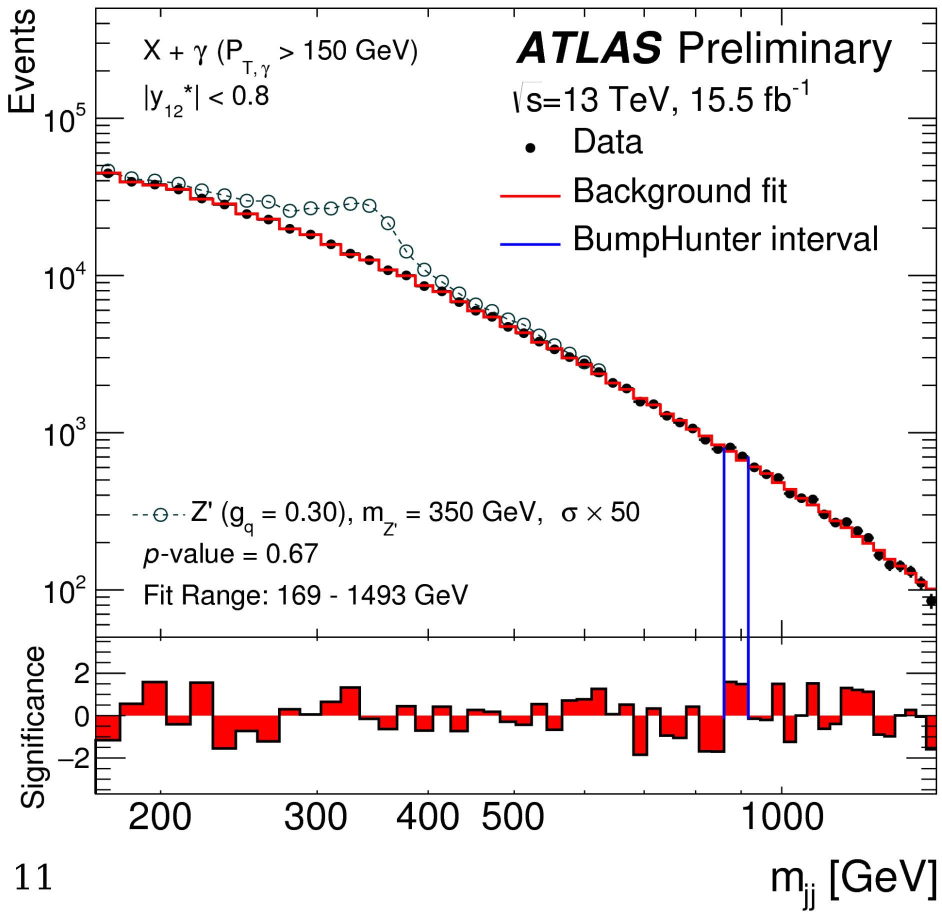
Dijet+ISR Search

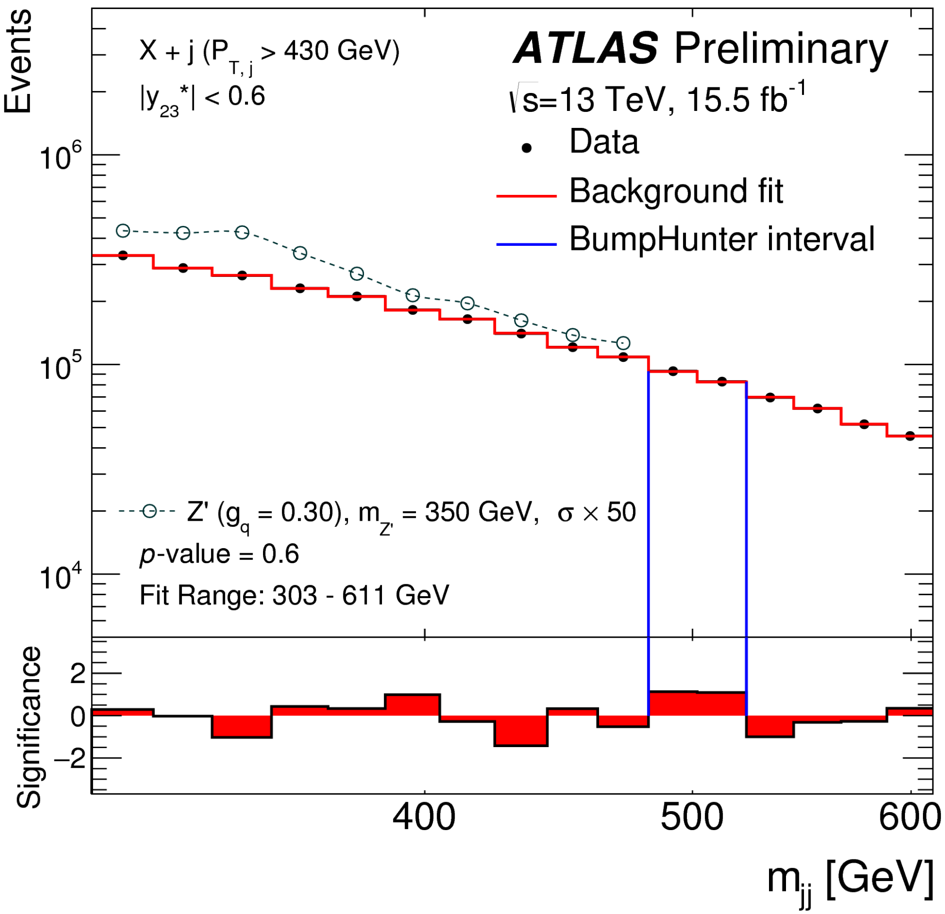


→ Sensitivity to light dijet resonances reduced by trigger limitations
→ Circumvent by requiring a hard ISR object in the final state

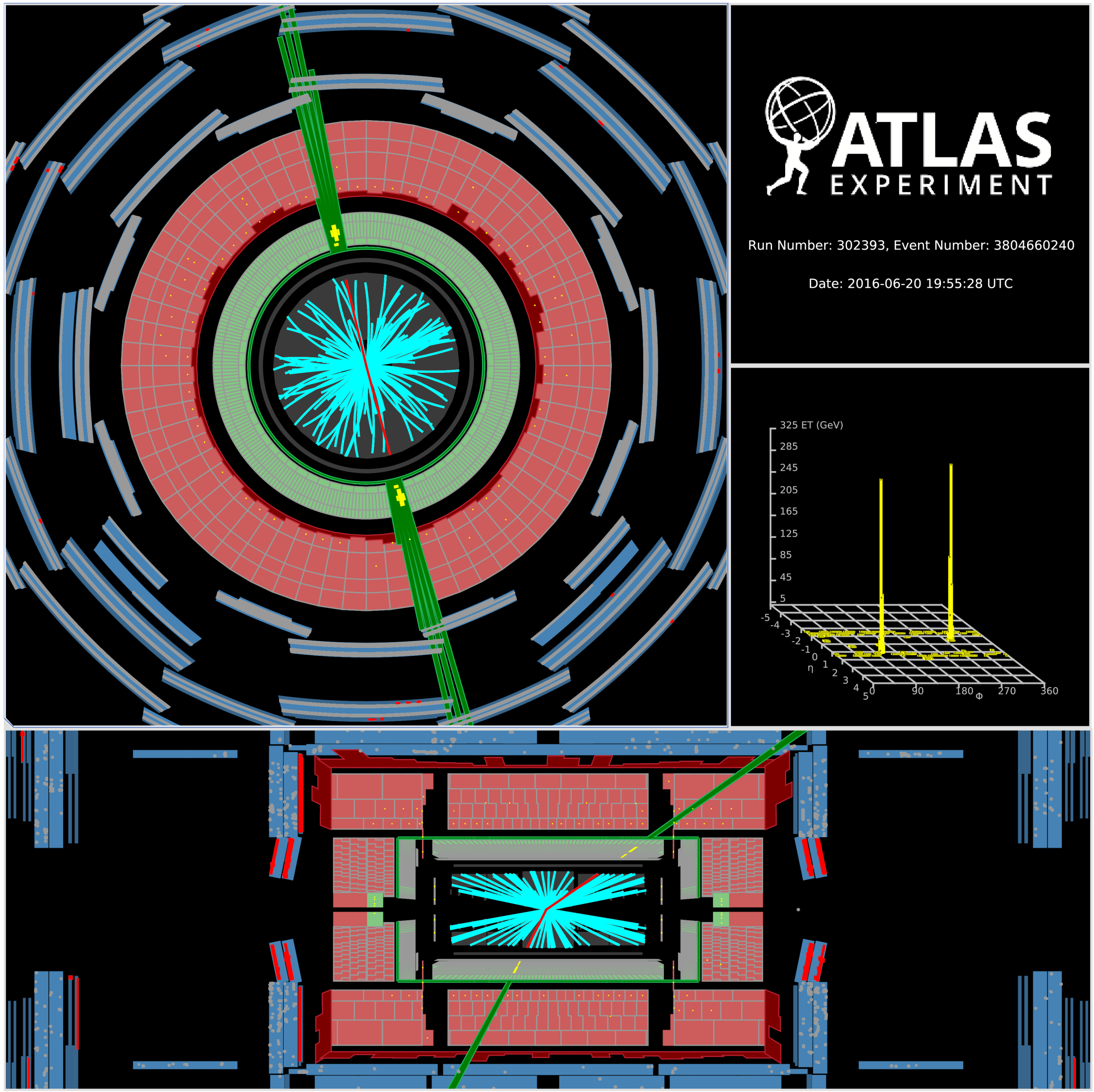
→ Same strategy as high-mass Dijet search

→ Two Channel: X+j (at least 1 jet), X+γ (at least 1 photon)





Dilepton Search

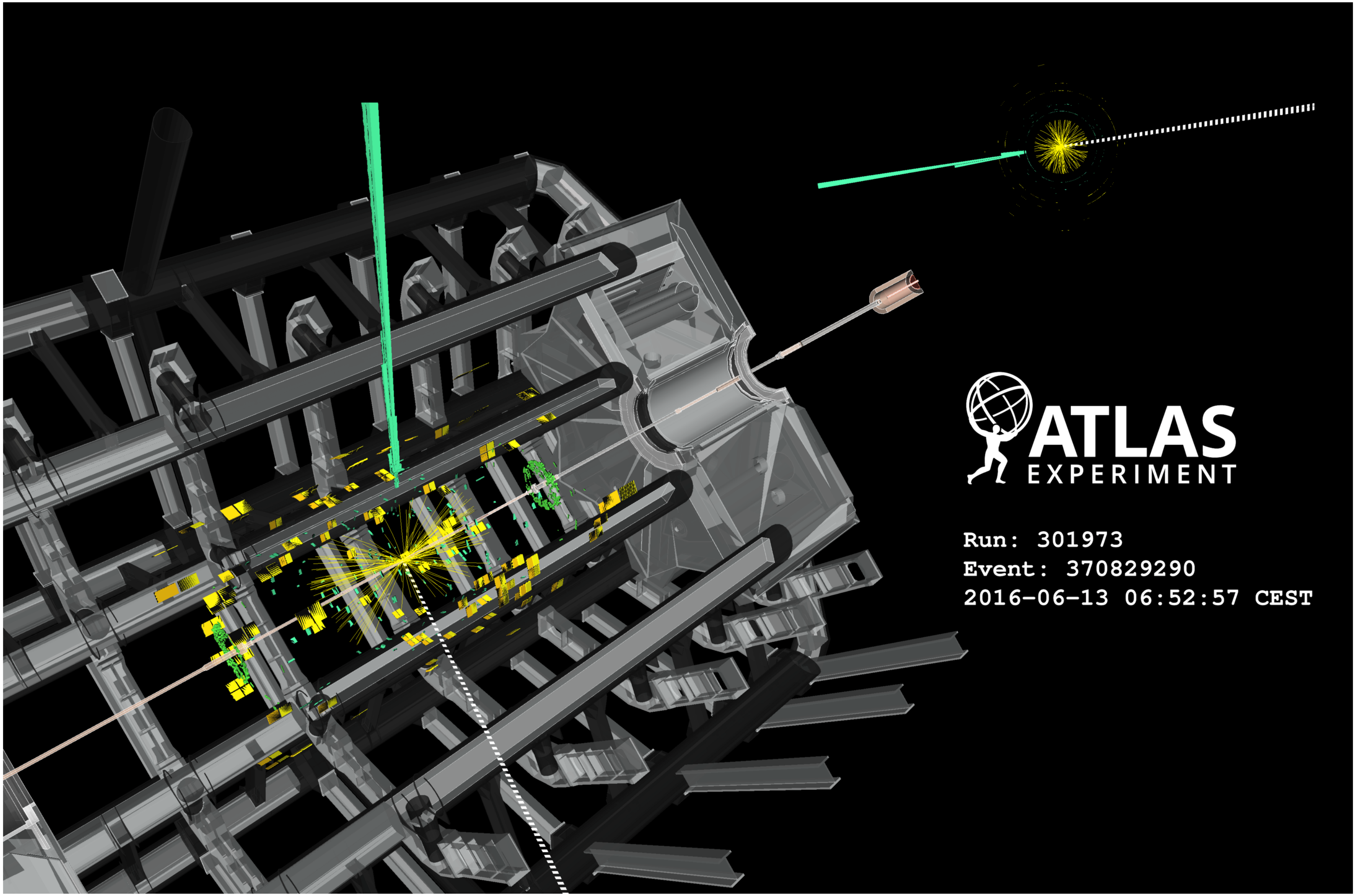


→ Highest Mass Dielectron Event: 2.38 TeV

→ Leading electron has an E_T of 889 GeV, and an η of -0.51

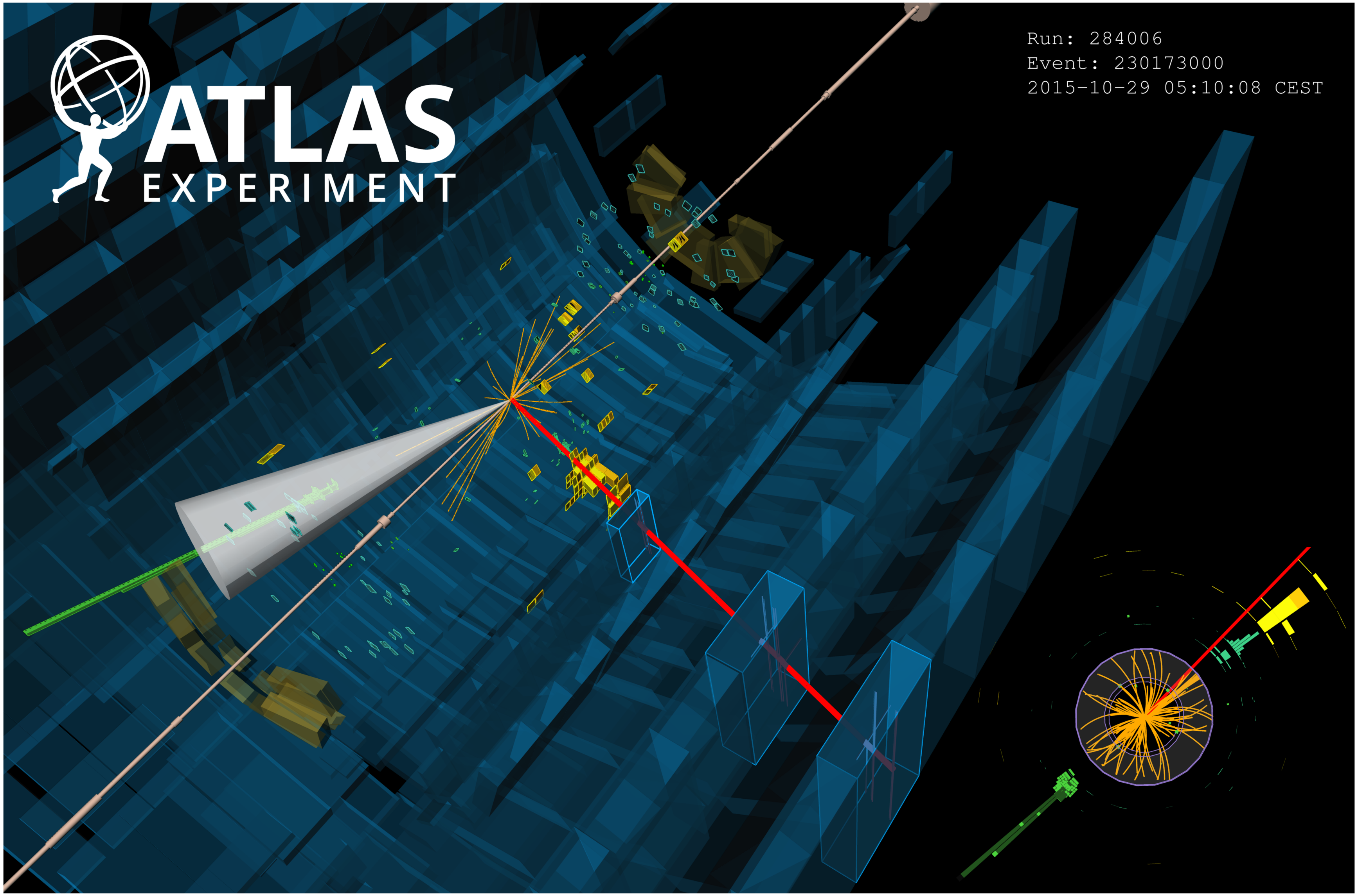
→ Subleading electron has an E_T of 868 GeV, and an η of 1.14

Lepton+MET Search



→ Electron with p_T = 1.09 TeV, η = 0.4, φ = −3.0,
→ Missing transverse energy with E_T = 1.09 TeV, φ = −0.02
→ Transverse Mass m_T = 2.19 TeV

High-Mass LFV Search

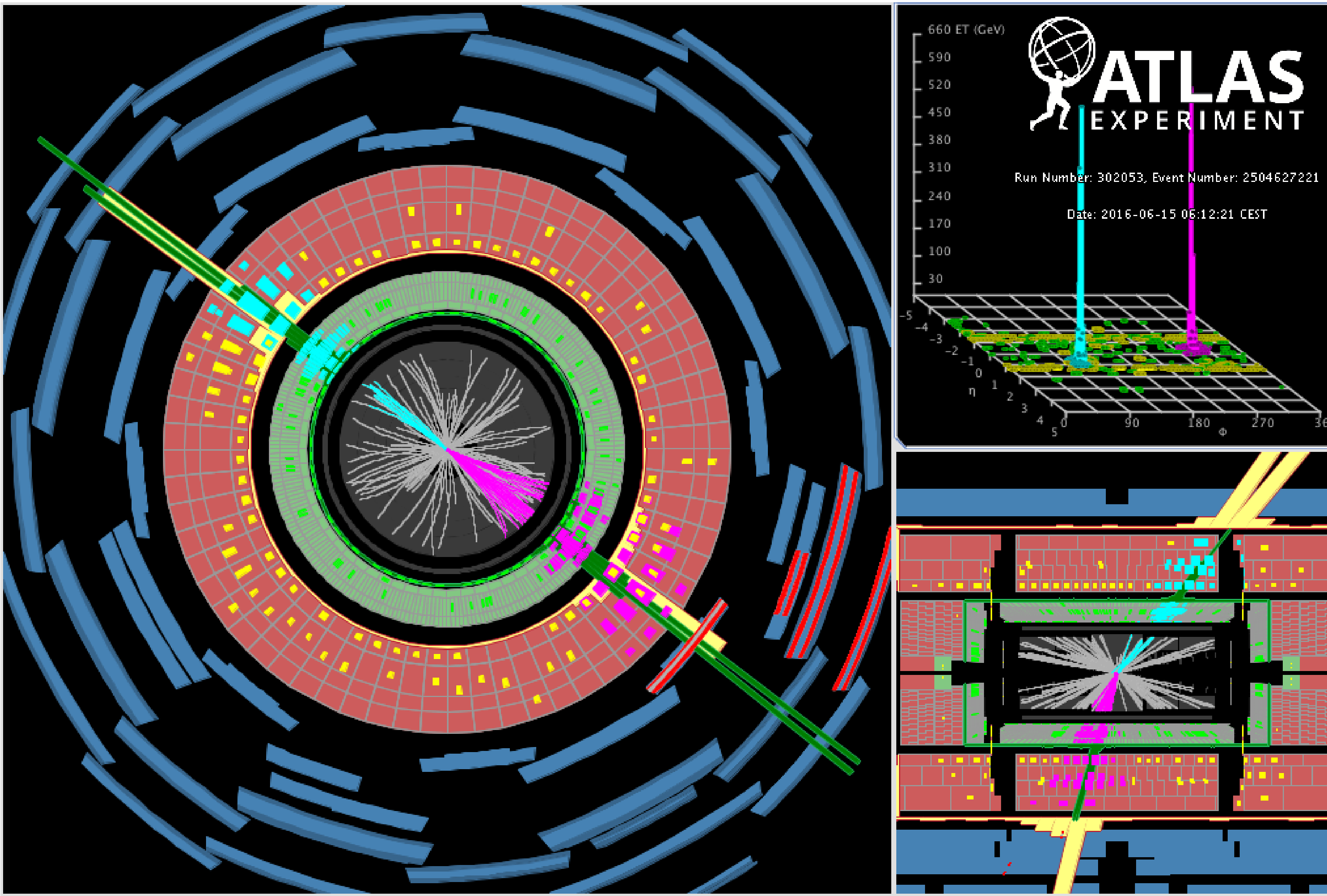


→ Highest Mass eμ Event: 2.09 TeV

→ Electron with E_T of 1164 GeV, and an η of 1.64, φ = −2.8

→ Antimuon with p_T of 617 GeV, and an η of 0.29, φ = 0.4

Dijet Search

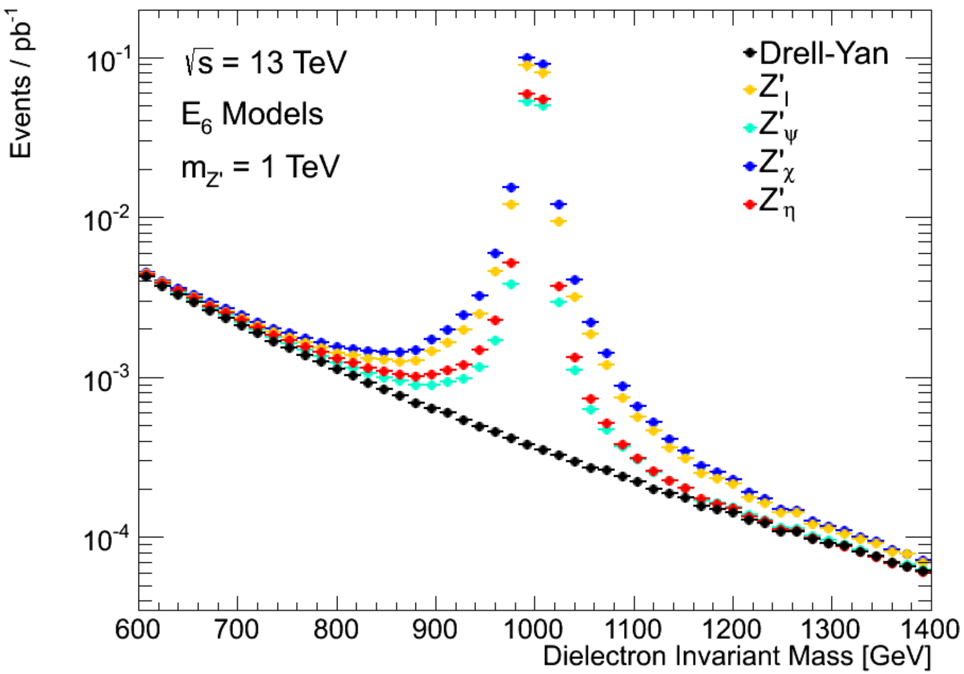


→ The two highest-mass central high-p_T jets:

→ Transverse momenta of 2.93 and 2.77 TeV, and a $|y*|$ of 0.51

→ Invariant mass is 6.46 TeV

Resonant Dilepton Models



Resonant Z'

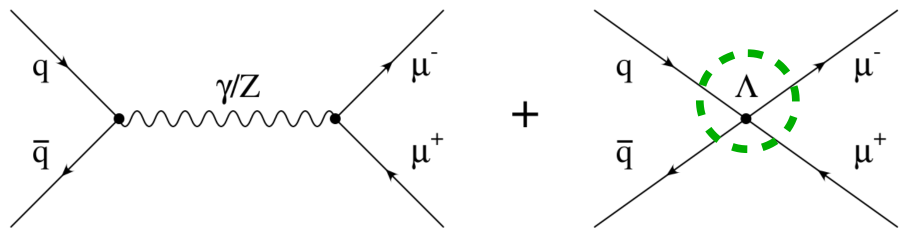
- Additional Spin-1 Gauge Bosons
- **E_6** GUT Models
  - $E_6 \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$
  - $Z'(\theta_{E_6}) = Z'_\psi \cos\theta_{E_6} + Z'_\chi \sin\theta_{E_6}$
  - Six different values of mixing angle θ lead to observable Z' states: $Z'_\psi, Z'_{\mathrm{N}}, Z'_\eta, Z'_I, Z'_{\mathrm{S}}$ and Z'_χ
- **SSM** Benchmark Model
  - Z'_{SSM} assigned same Fermion couplings as SM Z Boson

Additional Resonances

- **RS** Graviton Models
  - Spin-2 Resonance
  - Predicts excited KK modes of Graviton → first excitation G*
  - k/M_{Pl} sets scale of spacetime curvature and resonance width

Non-Resonant Dilepton Models

$$\frac{d\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} - \eta_{XY}\frac{F_I}{\Lambda^2} + \frac{F_C}{\Lambda^4}$$



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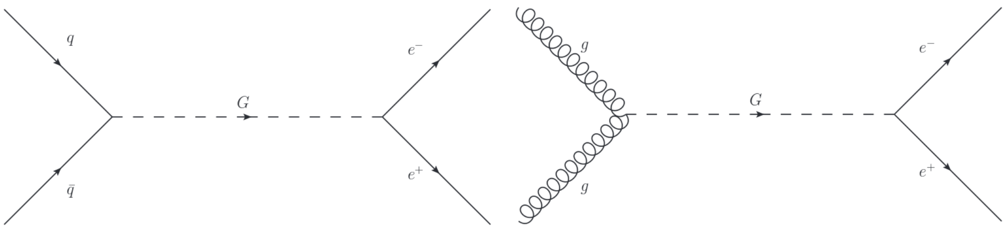
Non-Resonant CI

- Quark and Lepton Compositeness
  - **Λ** defines Compositeness Scale
  - $\boldsymbol{\eta_{xy}}$ defines the chiral structure of interaction → interference
  - Signal appears as broad excess above SM expectation

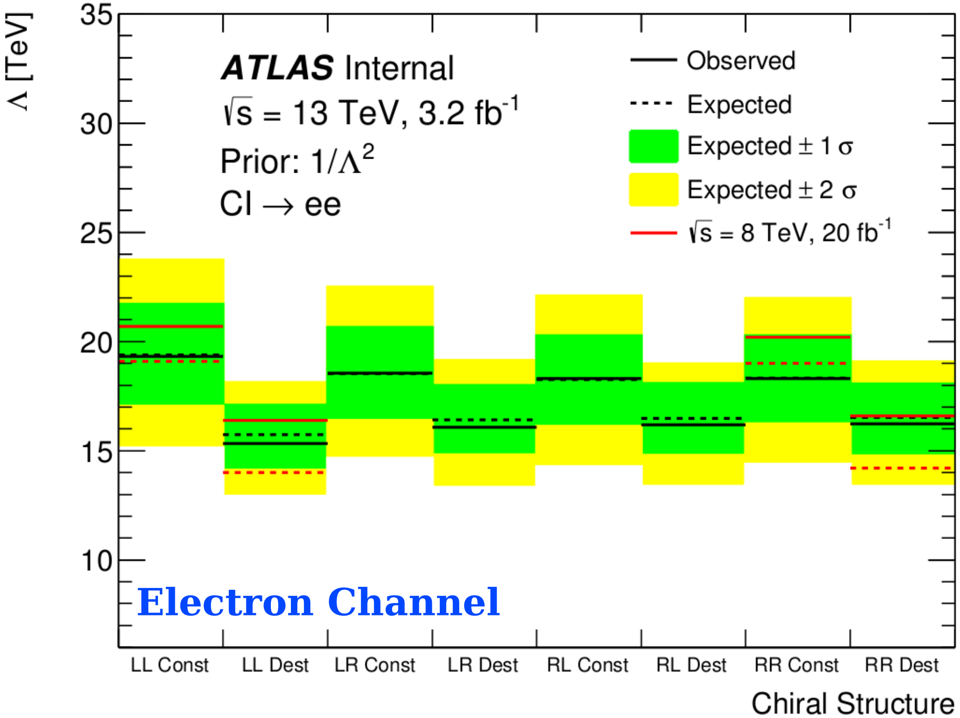
ADD Graviton

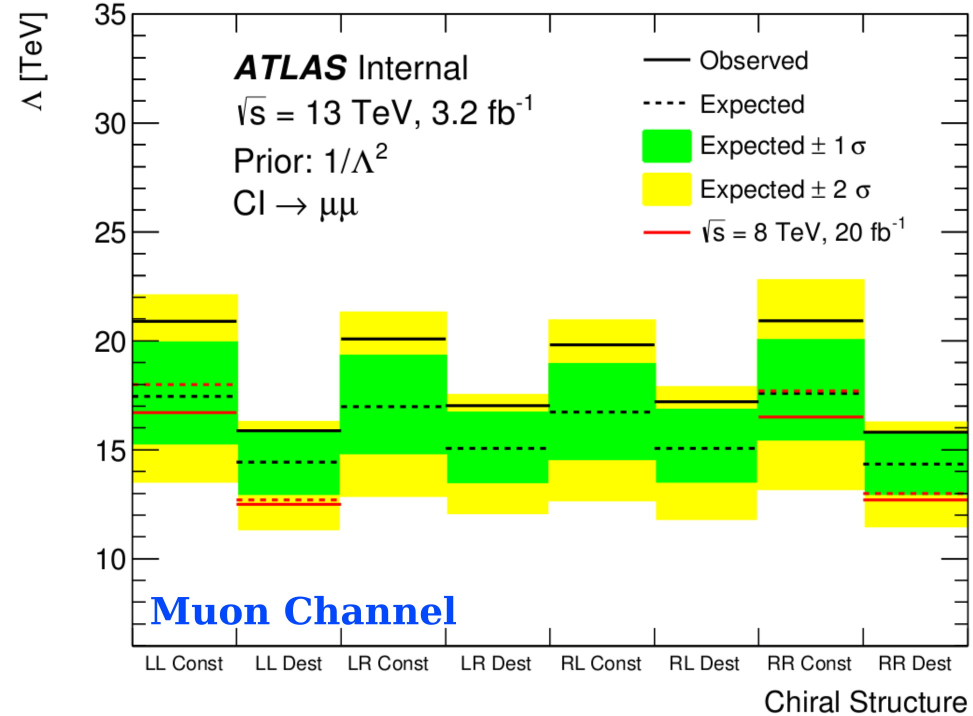
- Solution to Hierarchy Problem
  - Large extra dimensions
  - KK modes → almost continuous spectrum
  - $\mathbf{M_S}$ sets scale of quantum gravity
  - **F** is dependence on extra dimension assumptions

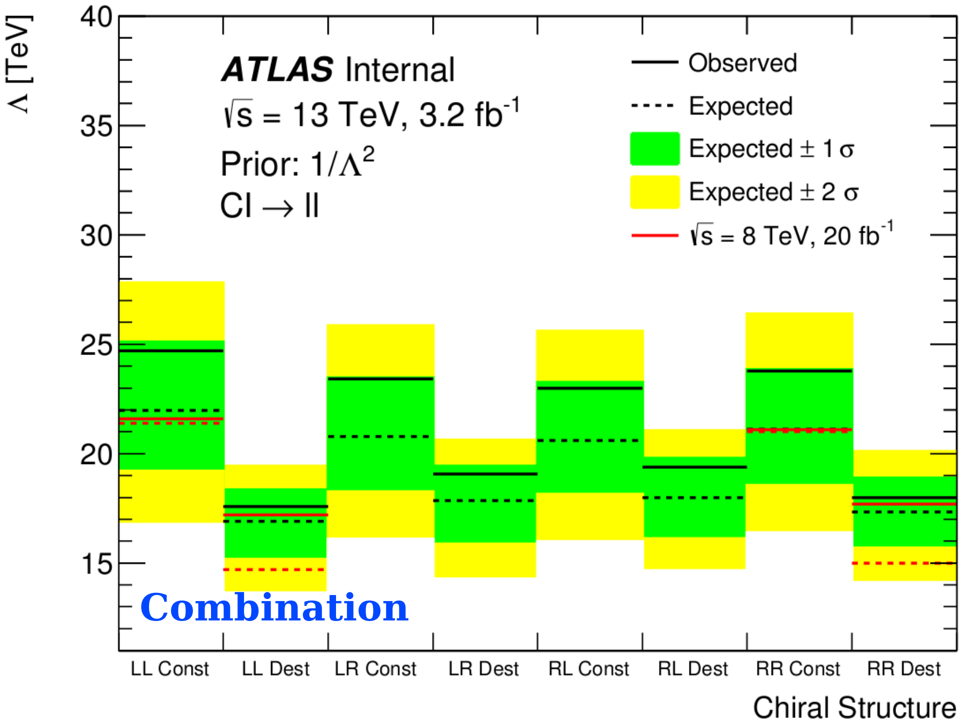


$$\frac{d\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} + \mathcal{F}\frac{F_I}{M_S^4} + \mathcal{F}^2\frac{F_G}{M_S^8}$$

Dilepton CI Limits

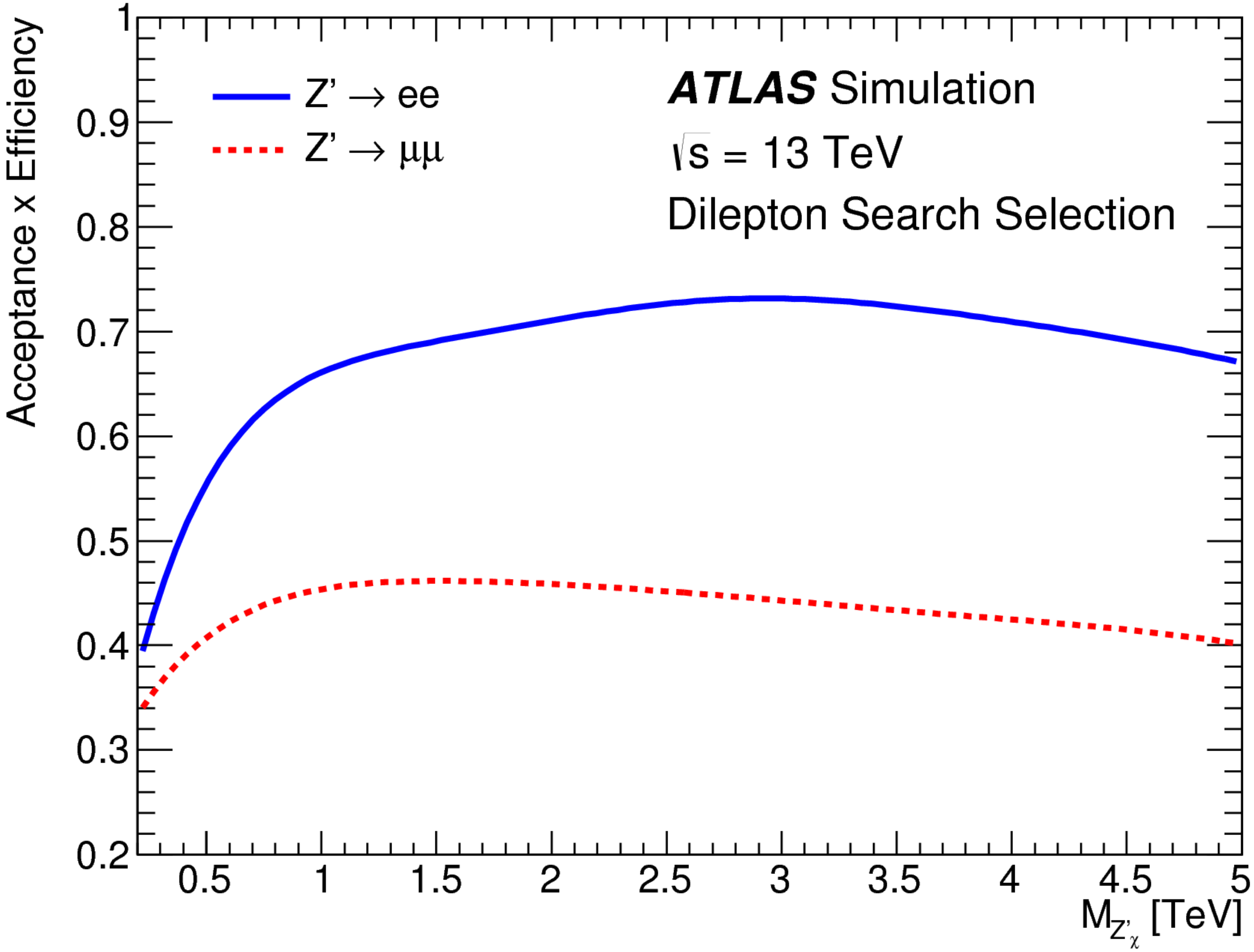




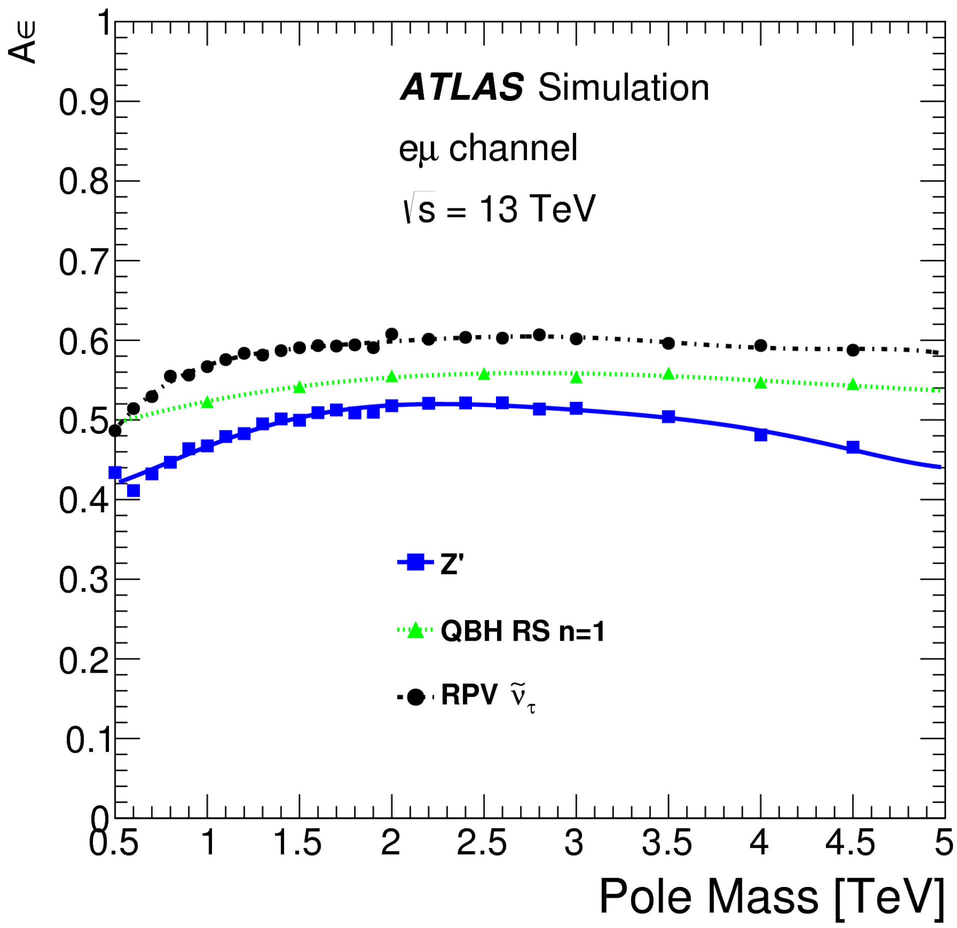


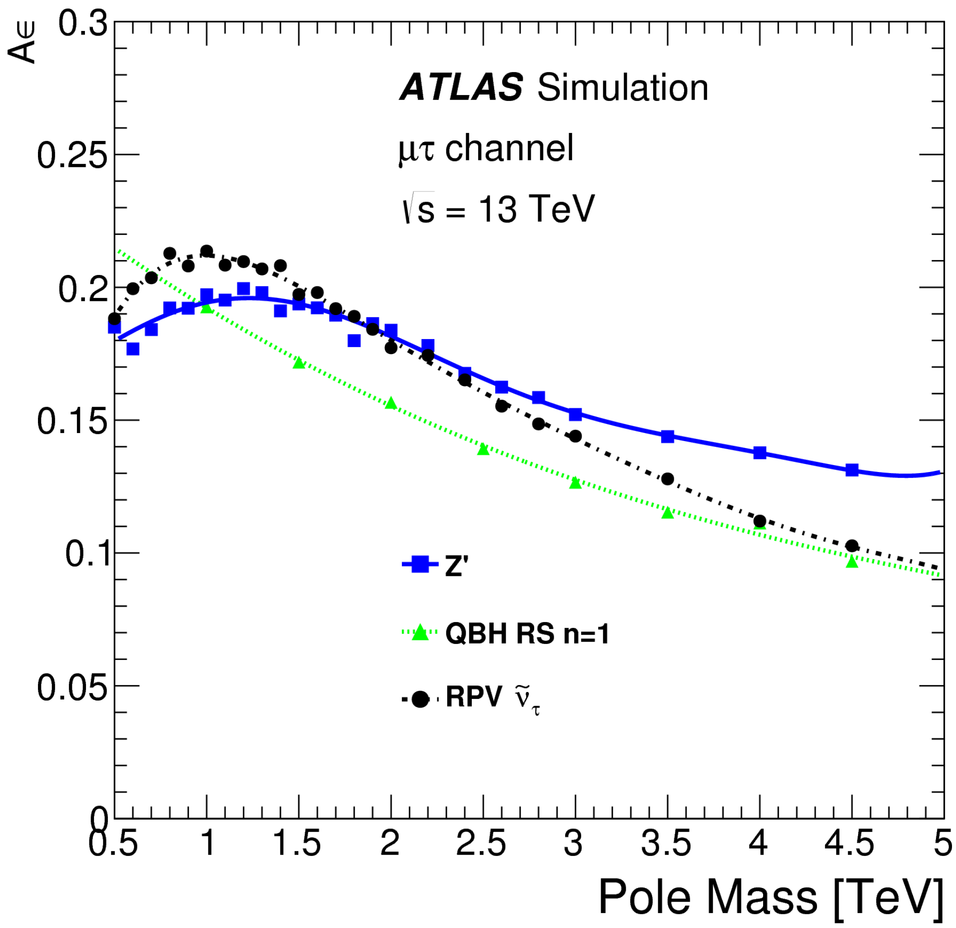
Channel	Prior	Left-Left [TeV]		Left-Right [TeV]		Right-Left [TeV]		Right-Right [TeV]	
		Const.	Destr.	Const.	Destr.	Const.	Destr.	Const.	Destr.
Exp: ee	$1/\Lambda^2$	19.4	15.7	18.5	16.4	18.3	16.5	18.3	16.5
Obs: ee		19.3	15.3	18.6	16.1	18.3	16.2	18.3	16.2
Exp: ee	$1/\Lambda^4$	17.6	14.6	16.8	15.1	16.7	15.2	16.8	15.3
Obs: ee		17.5	14.2	16.9	14.9	16.6	15	16.6	15
Exp: $\mu\mu$	$1/\Lambda^2$	17.4	14.4	17	15.1	16.7	15.1	17.6	14.3
Obs: $\mu\mu$		20.9	15.9	20.1	17	19.8	17.2	20.9	15.8
Exp: $\mu\mu$	$1/\Lambda^4$	15.8	13.8	15.5	14.3	15.5	14.3	16	13.7
Obs: $\mu\mu$		18.2	14.9	17.9	15.9	17.7	16	18.5	15
Exp: $\ell\ell$	$1/\Lambda^2$	22	16.9	20.8	17.9	20.6	18	21.1	17.3
Obs: $\ell\ell$		24.7	17.6	23.4	19.1	23	19.4	23.8	18
Exp: $\ell\ell$	$1/\Lambda^4$	20	16	19.2	16.8	19	17	19.4	16.3
Obs: $\ell\ell$		21.9	16.5	21	17.7	20.6	18	21.2	16.9

Dilepton Search Acc*Eff

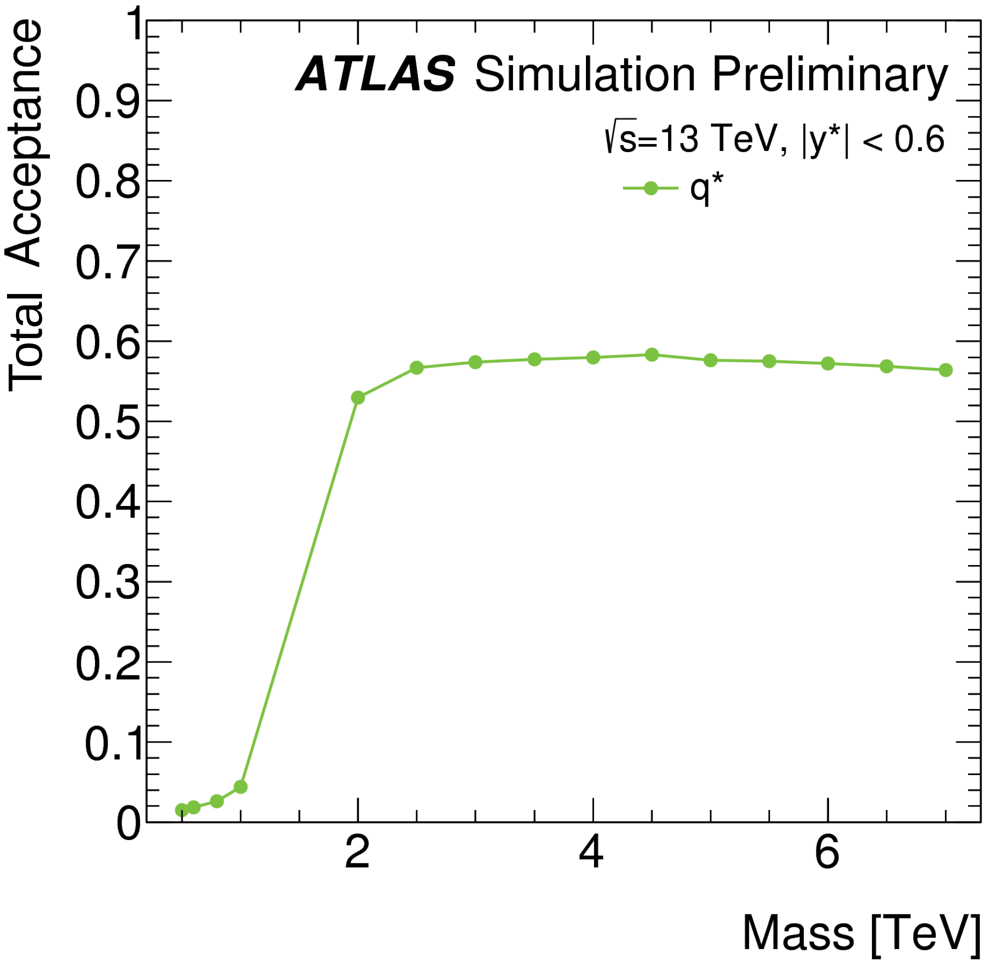


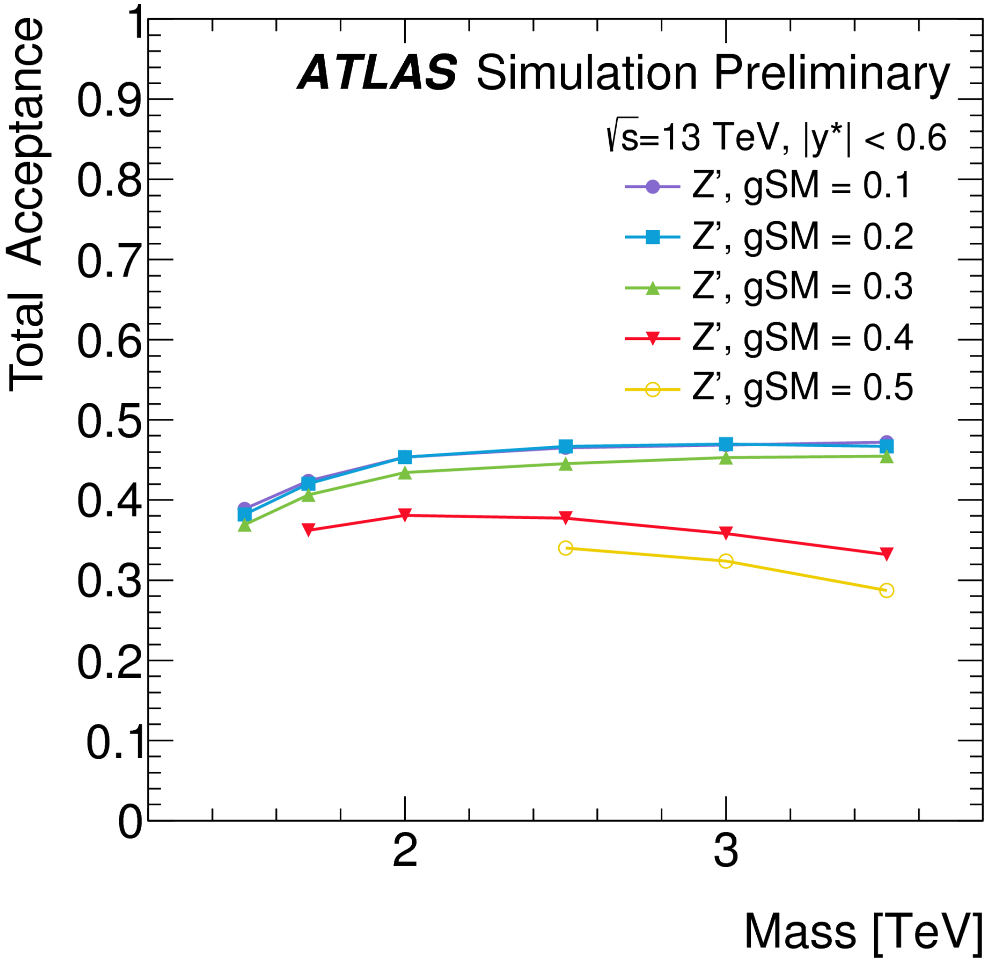
High-Mass LFV Acc*Eff



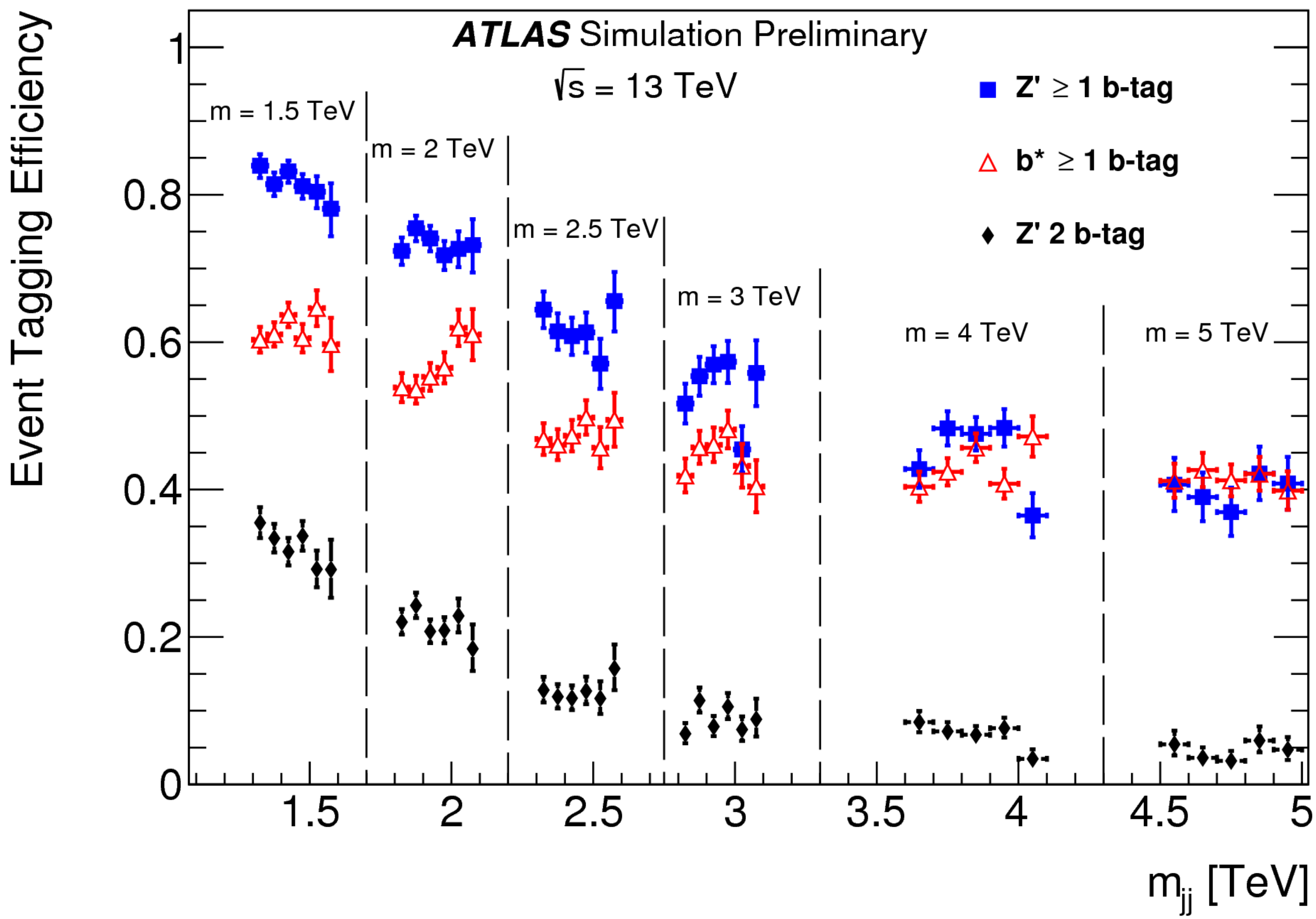


Dijet Search Acc*Eff

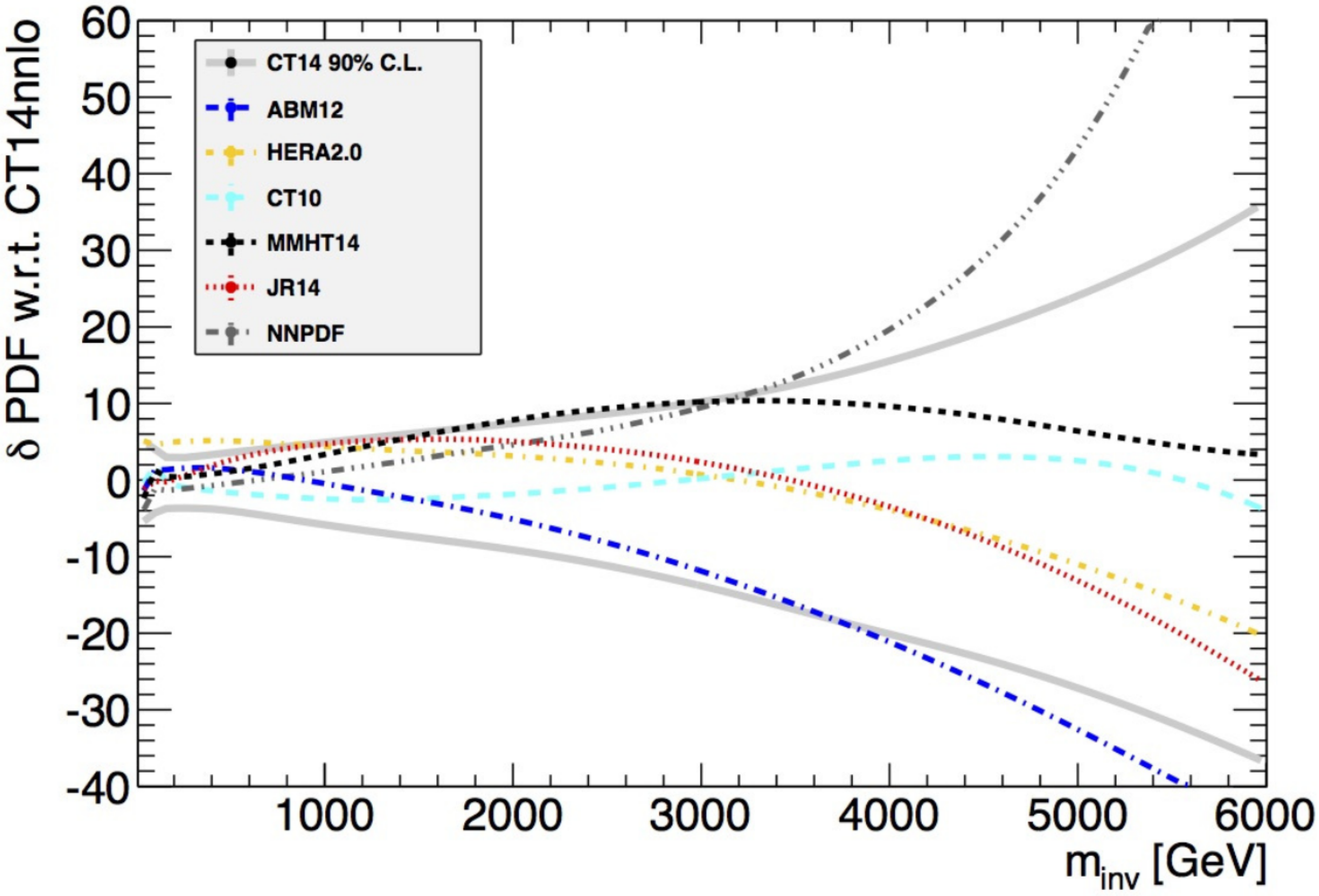




b-jet Search b-tagging Efficiency



Dilepton PDF Systematic Uncertainty



- PDF Uncertainty becomes ever more dominant at high mass
  - → will not affect resonant dilepton limits
  - → but loose ability to differentiate between models in discovery scenario

Diboson Summary Limits