SFU SIMON FRASER UNIVERSITY
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NSERC CRSNG

ATLAS EXPERIMENT

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The search for high mass dilepton resonances in Run II data from ATLAS

A prime time for Z'

ALPS 2019

Obergurgl, April 24

Preprint: arXiv:1903.06248

Material: EXOT-2018-08

HEPData: record/88425

Energy++

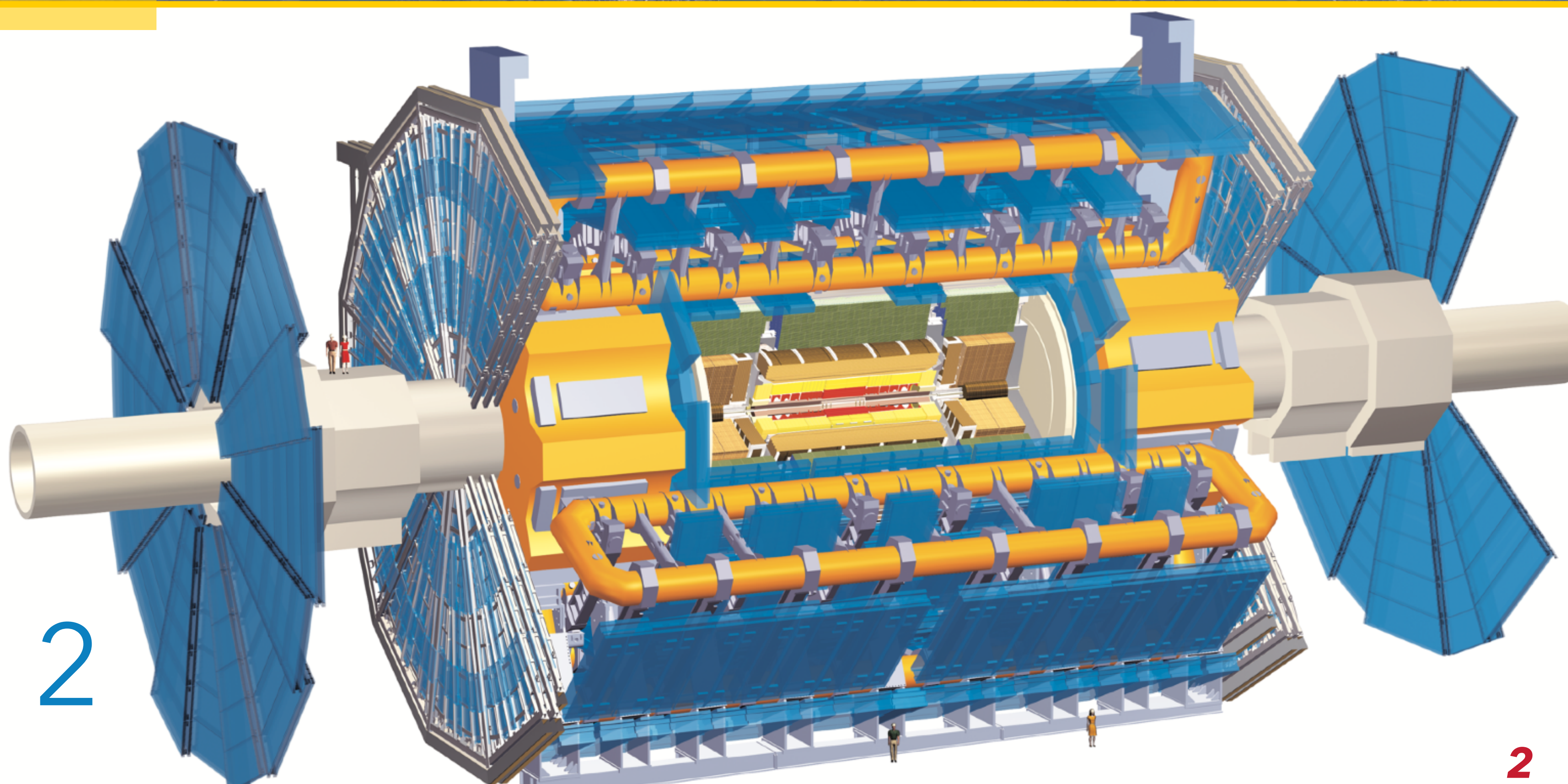
$\sqrt{s} = \cancel{7,8}$ **13 TeV**

Luminosity++

$\cancel{25}$ **139 fb^{-1}**

$$\boxed{N_{\mathrm{obs}} = \sigma \times A\epsilon \times \int L dt}$$

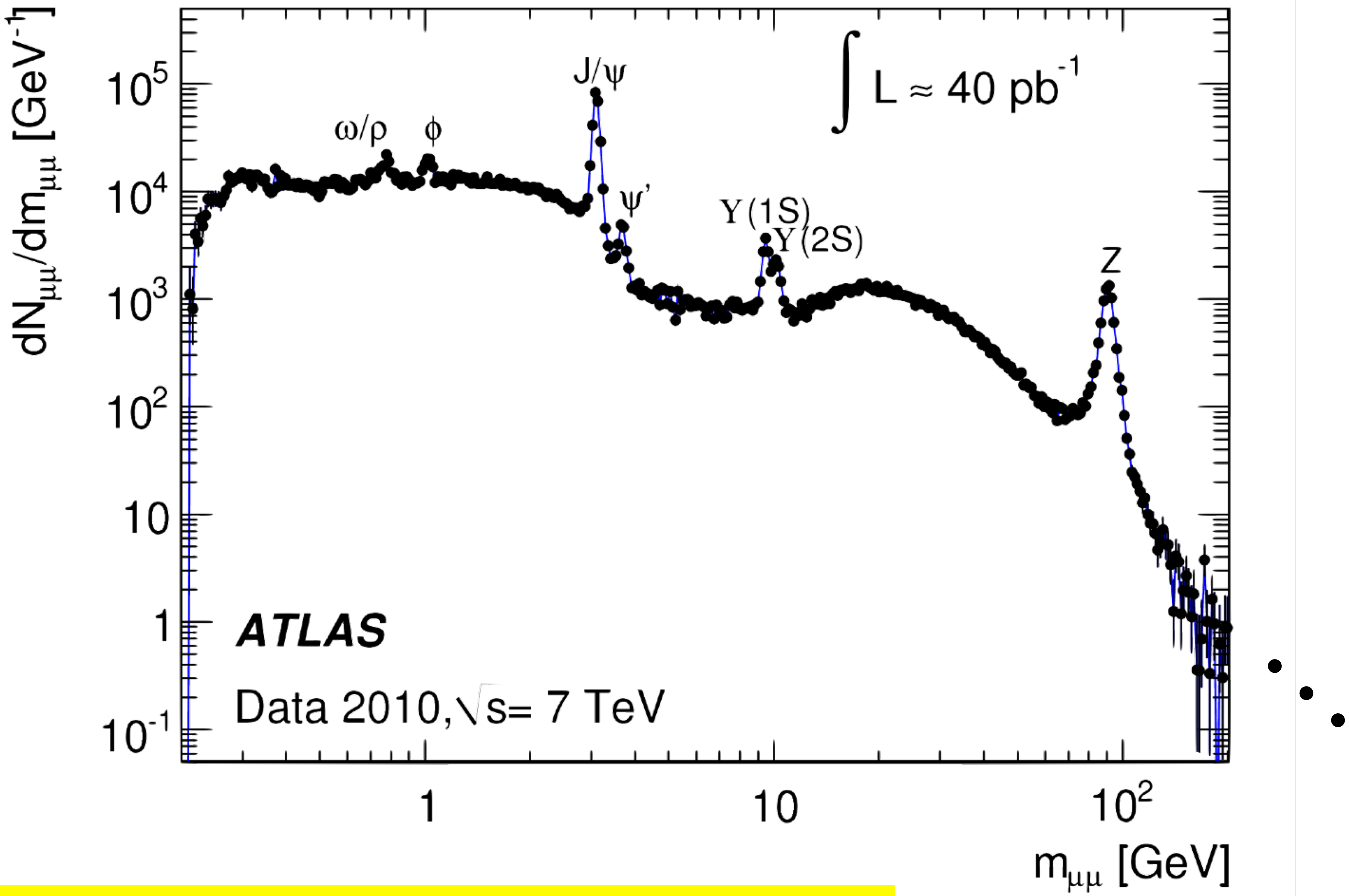
Reconstruction++



ATLAS
@ LHC Run 2

The $p^+p^+ \to \ell^+\ell^-$ high energy frontier

0.04 fb-1 (2010)



2 muons

here be dragons

Dilepton invariant mass:

$$m^2_{\ell\ell} = (P_{\ell_1} + P_{\ell_2})_\alpha (P_{\ell_1} + P_{\ell_2})^\alpha$$

Why more bumps?

1) Extension of SM gauge group with new U(1)′ or SU(2)′ Spin-1

- Superstring-inspired GUT:

$$E_6 \to SO(10) \times \boxed{U(1)_\psi} \qquad Z'_\psi$$

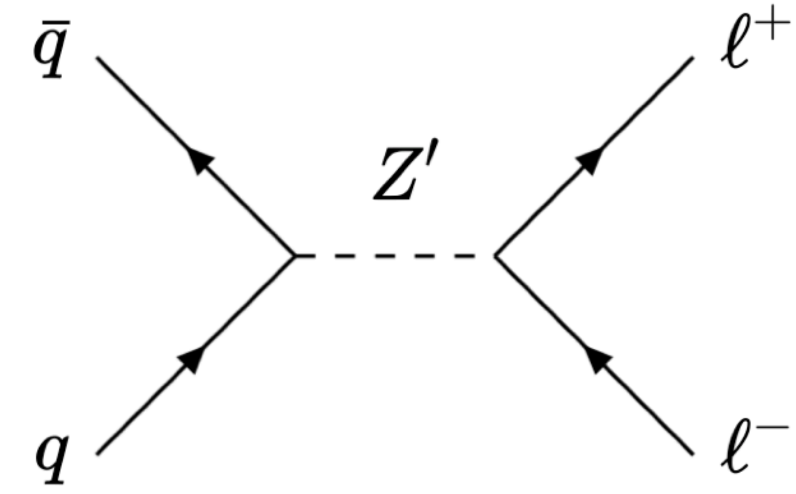
$$SO(10) \to SU(5) \times \boxed{U(1)_\chi} \qquad Z'_\chi$$

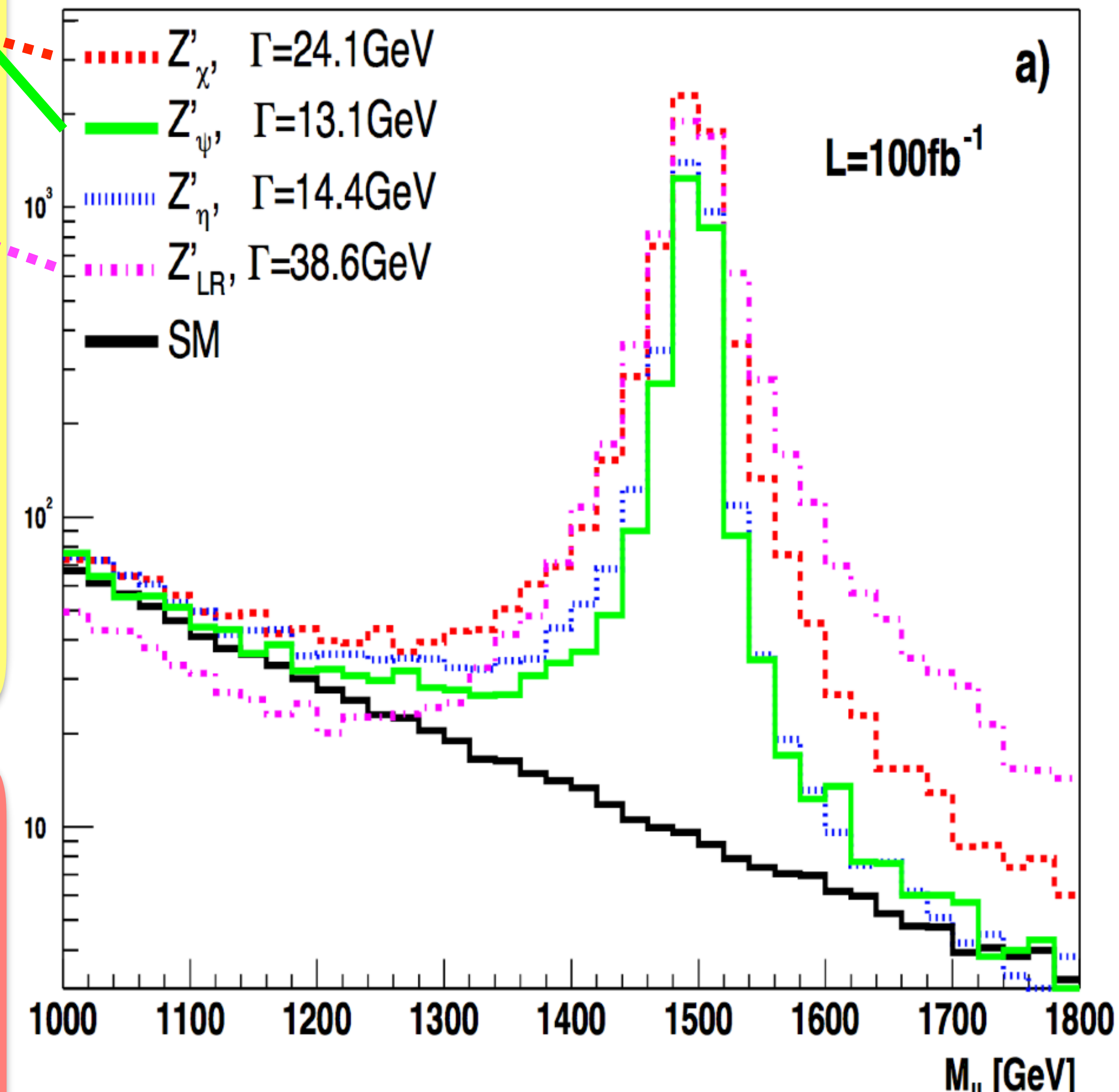
or

$$SO(10) \to SU(2)_R \times SU(2)_L \times \boxed{U(1)_{B-L}} \qquad Z'_{LR}$$

- Simplified dark matter mediator: Z'_{DM}
- Same fermion couplings as SM Z: Z'_{SSM}
- Neutral member of SU(2)′ triplet: Z'_{HVT}

Benchmarks





arXiv:hep-ph/0307020

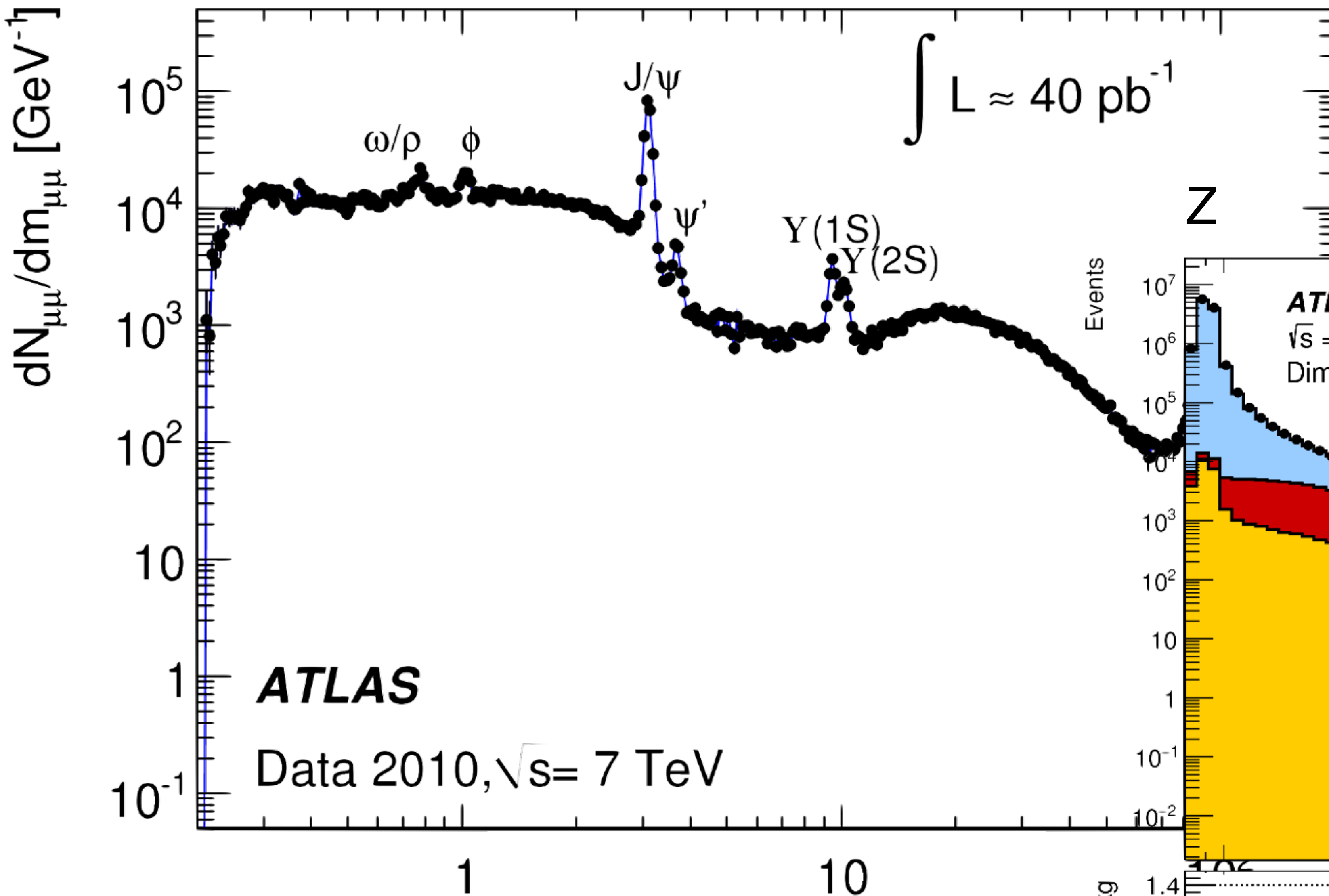
2) Other heavy neutral mediators

- Excitation of RS graviton Spin-2
- Extended scalar sector in MSSM Spin-0
- …

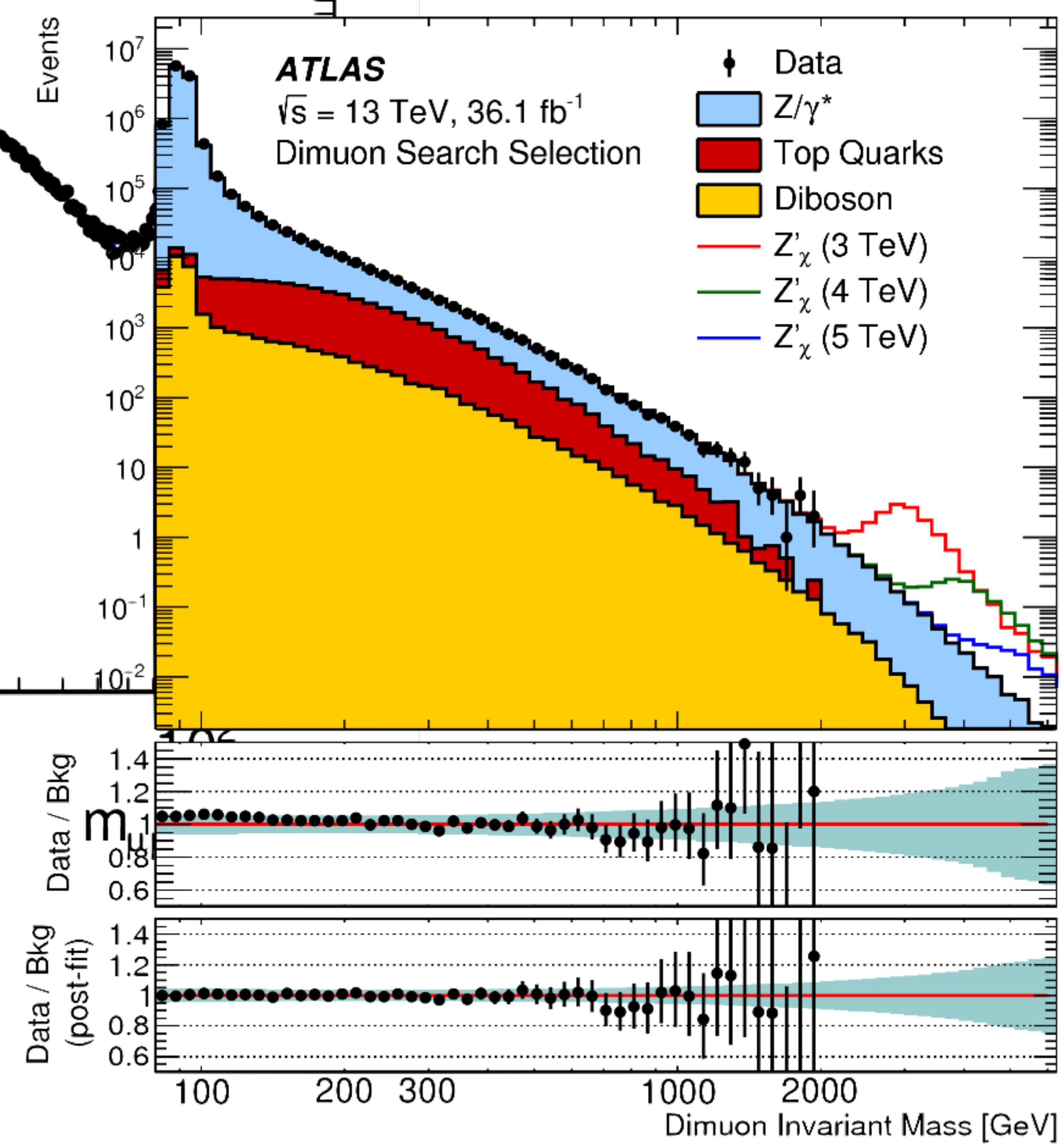
The $p^+p^+ \to \ell^+\ell^-$ high energy frontier

0.04 fb^{-1} (2010)

2 muons



36 fb^{-1} (2017)



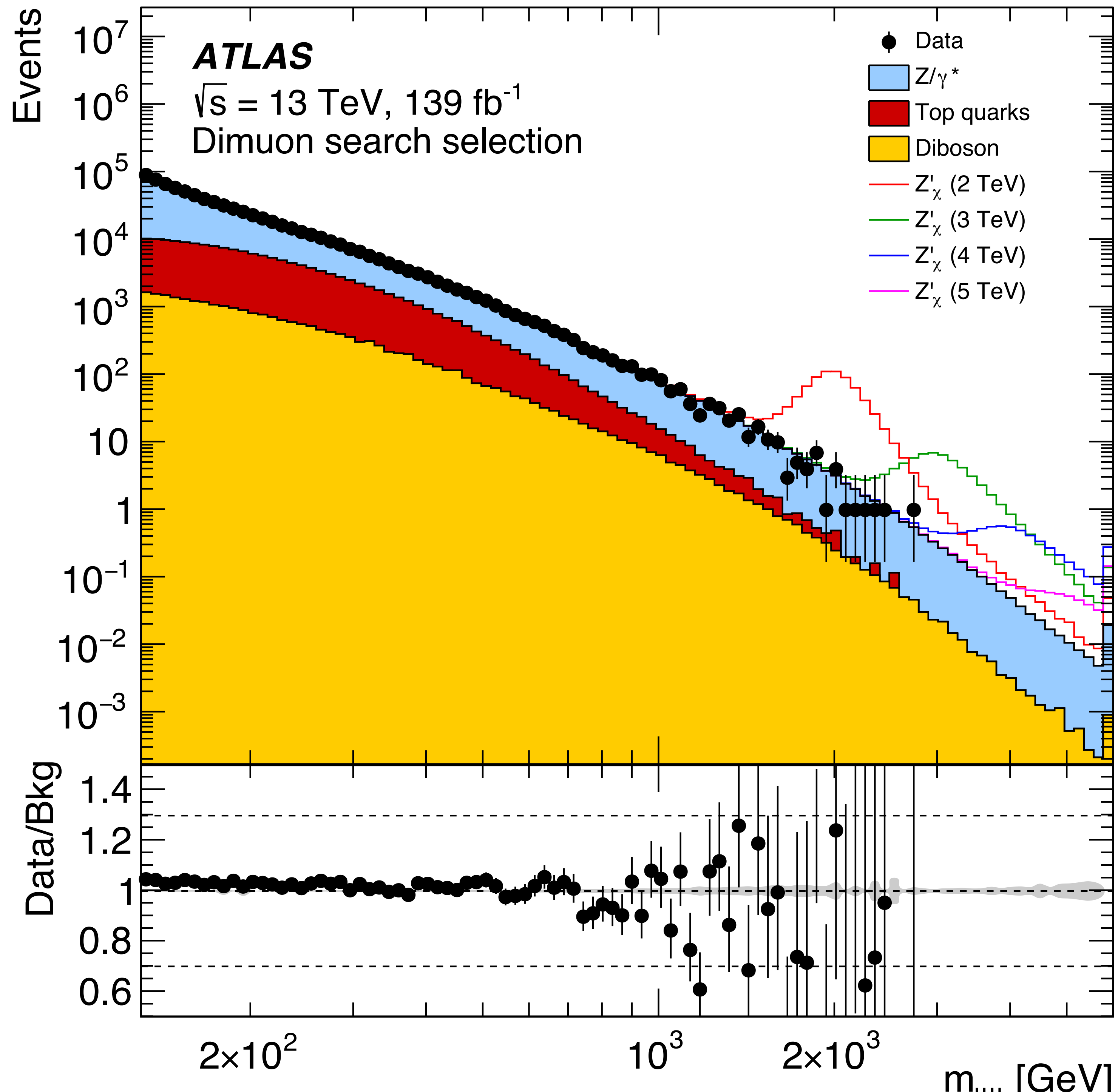
139 fb^{-1} (2019) ...

Dilepton invariant mass:

$$m^2_{\ell\ell} = (P_{\ell_1} + P_{\ell_2})_\alpha (P_{\ell_1} + P_{\ell_2})^\alpha$$

Full Run-2 spectrum

2 clean† ***muons****



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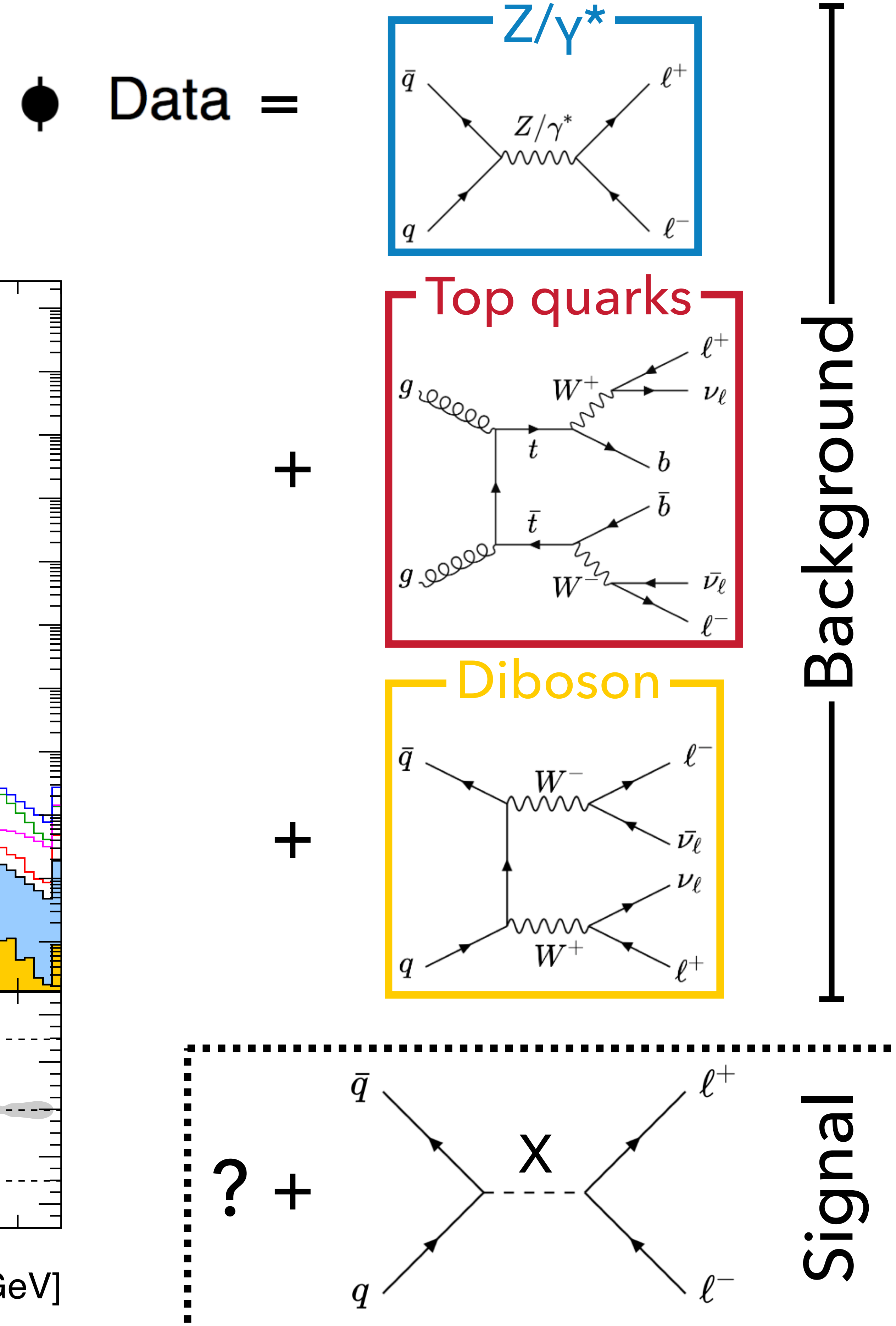
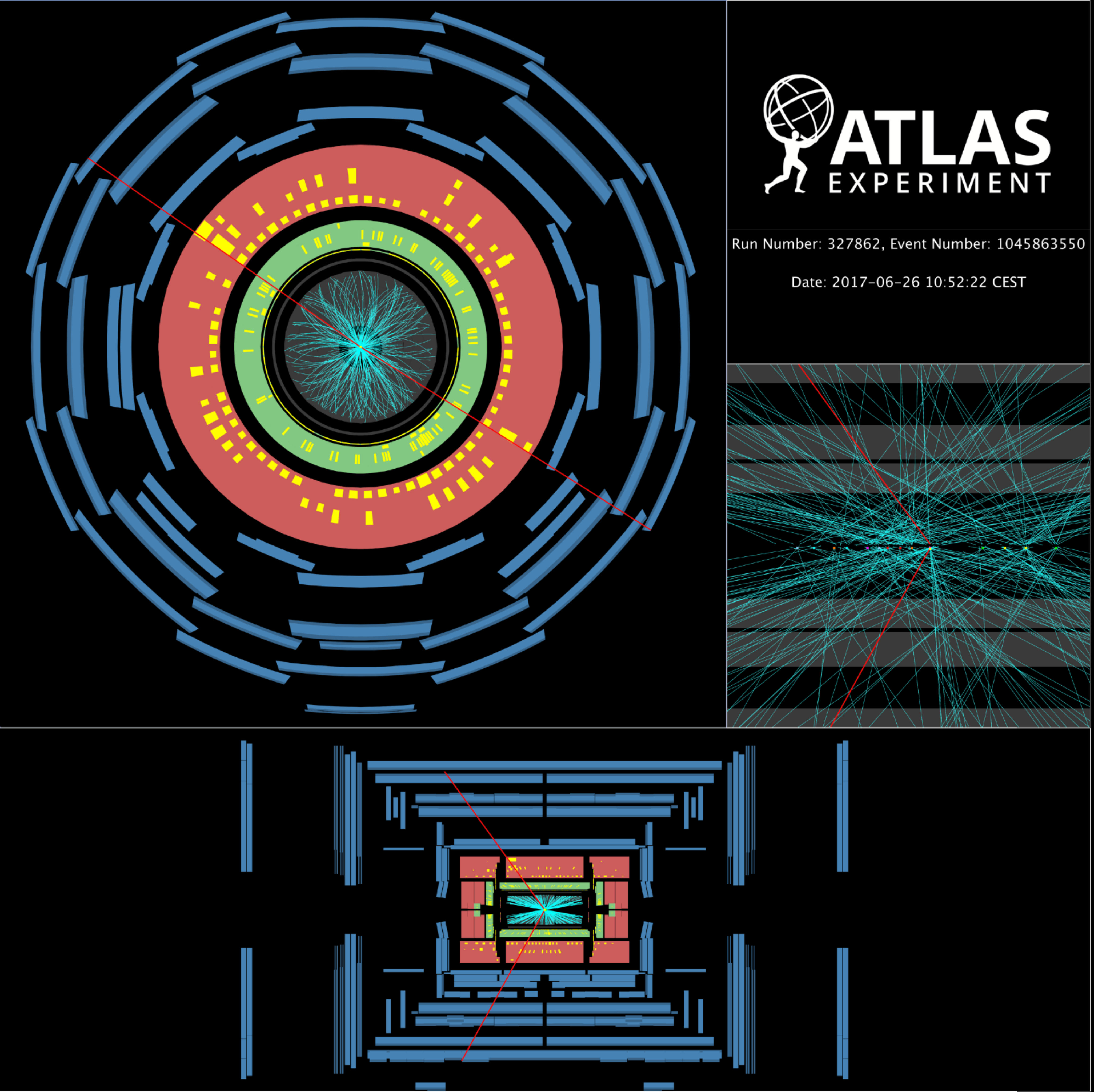


† *full selection criteria in backup*

**opposite-charge required for muon pairs*



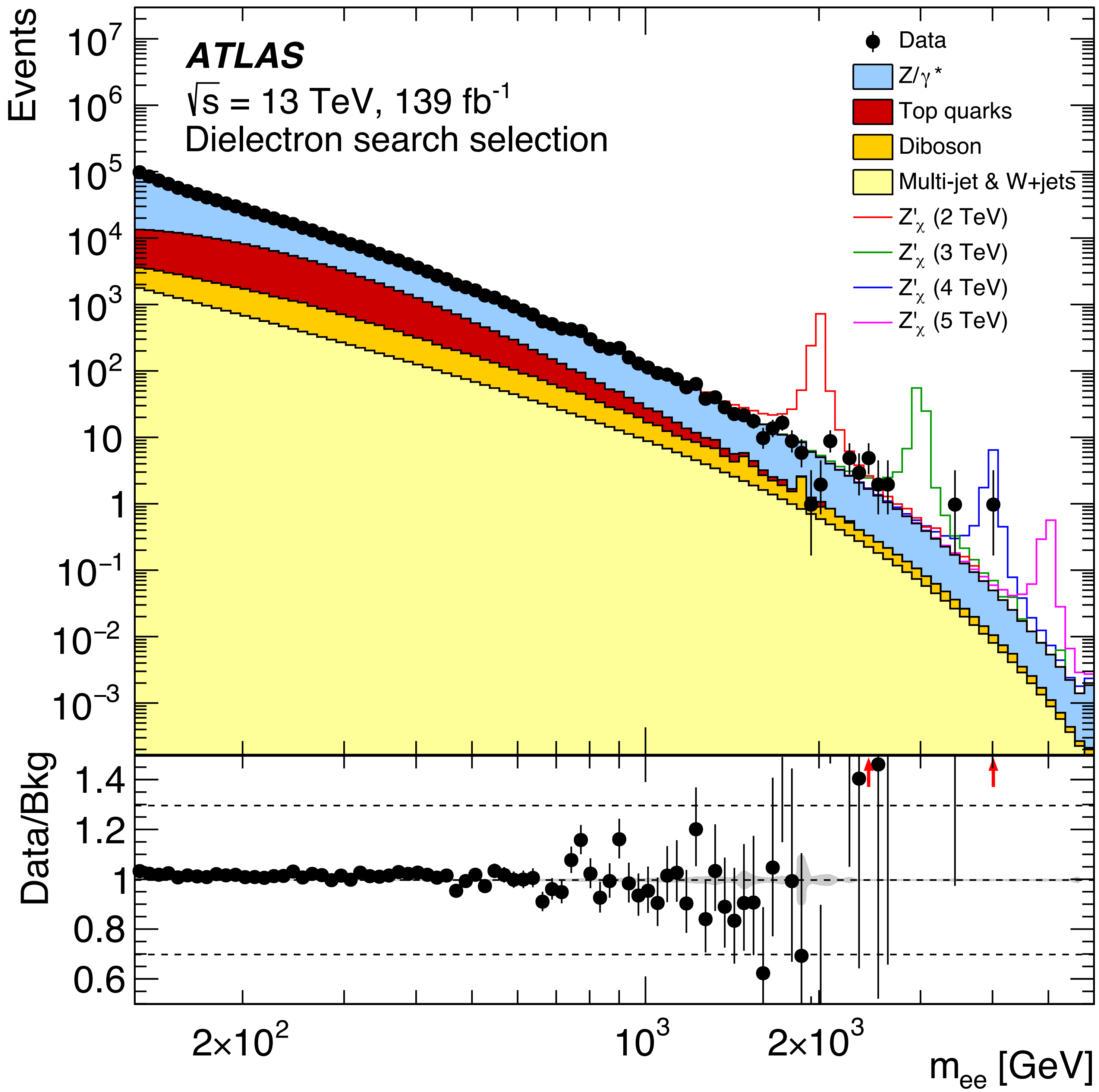
Highest inv. mass muon pair

$m_{\mu\mu} = 2.75$ TeV

2017

Full Run-2 spectrum

2 clean† ***electrons****



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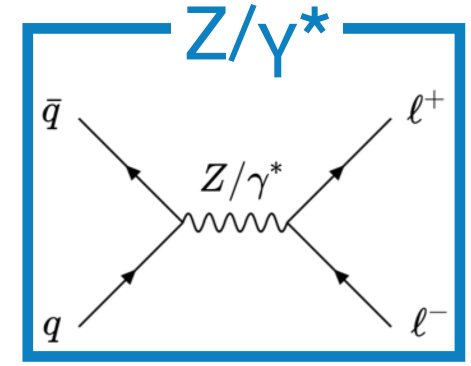
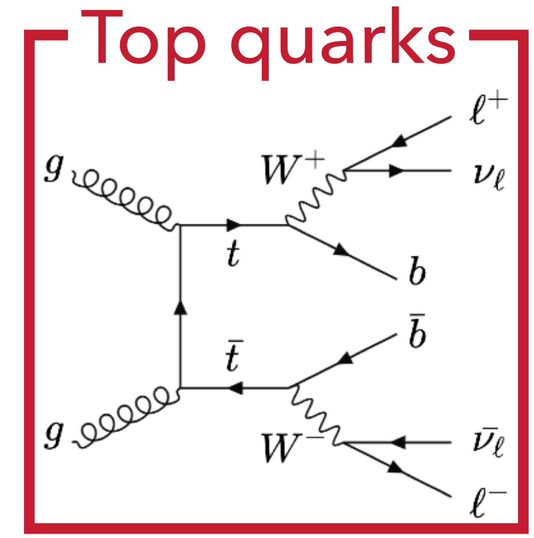


+



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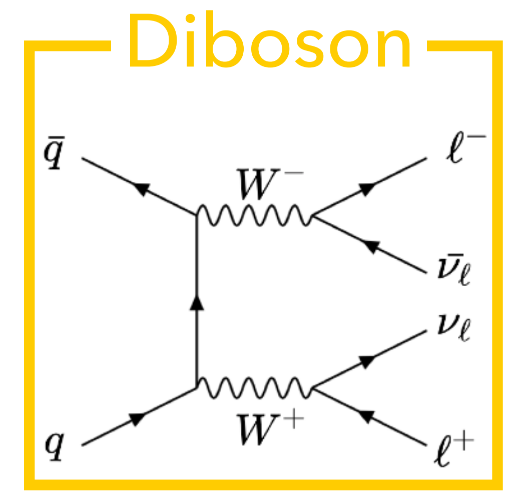
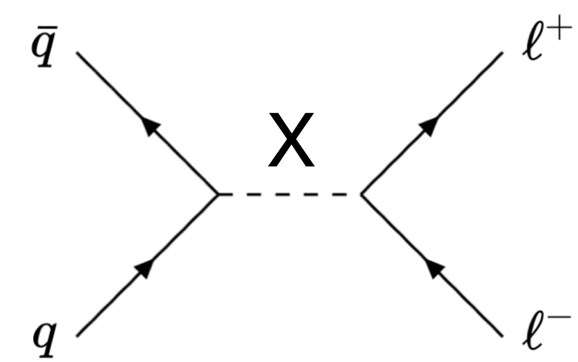


+

Jet(s) misidentified as electron(s)

Background

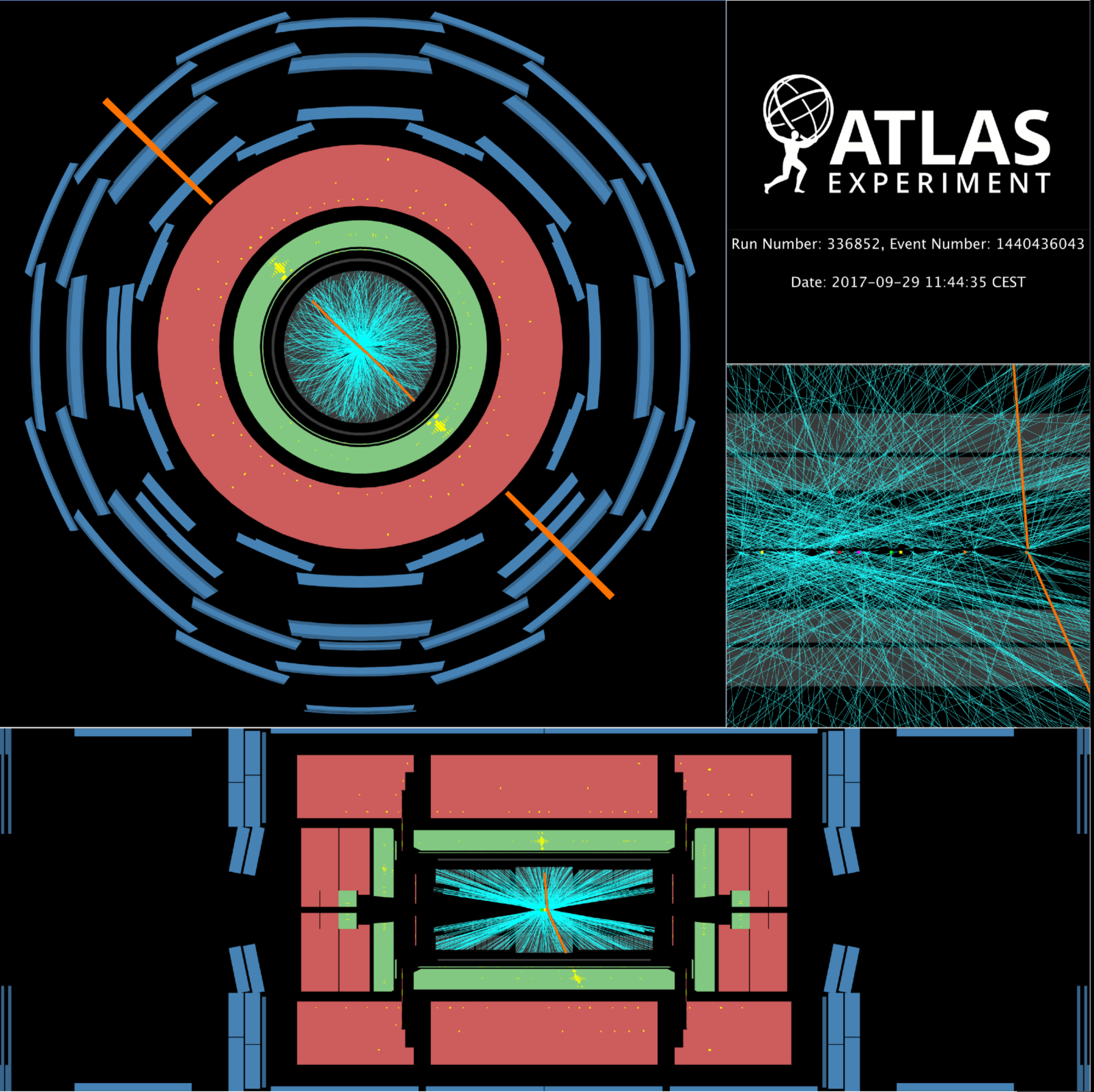
? +



Signal

† full selection criteria in backup

***opposite-charge not required for electron pairs**



Highest inv. mass electron pair

$m_{ee} = 4.06$ TeV

2017

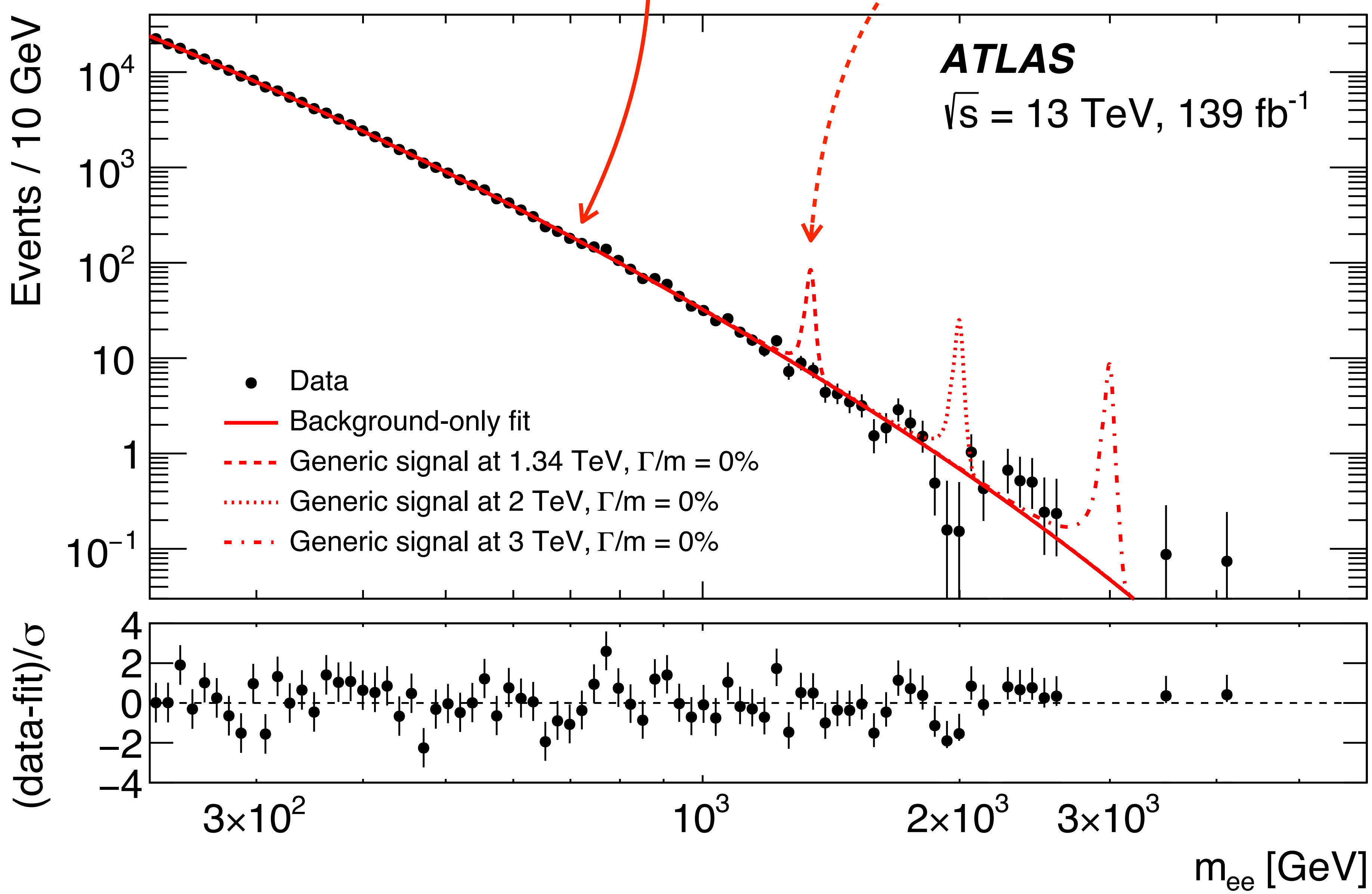
Analysis strategy

Fit the observed dilepton invariant mass spectrum:

$$\text{data distribution} = \underbrace{f_{\text{bkg}}(m_{\ell\ell})}_{\text{smoothly falling function}} + \underbrace{f_{\text{sig}}(m_{\ell\ell})}_{\text{Breit-Wigner} \otimes m_{\ell\ell}\ \text{resolution}}$$

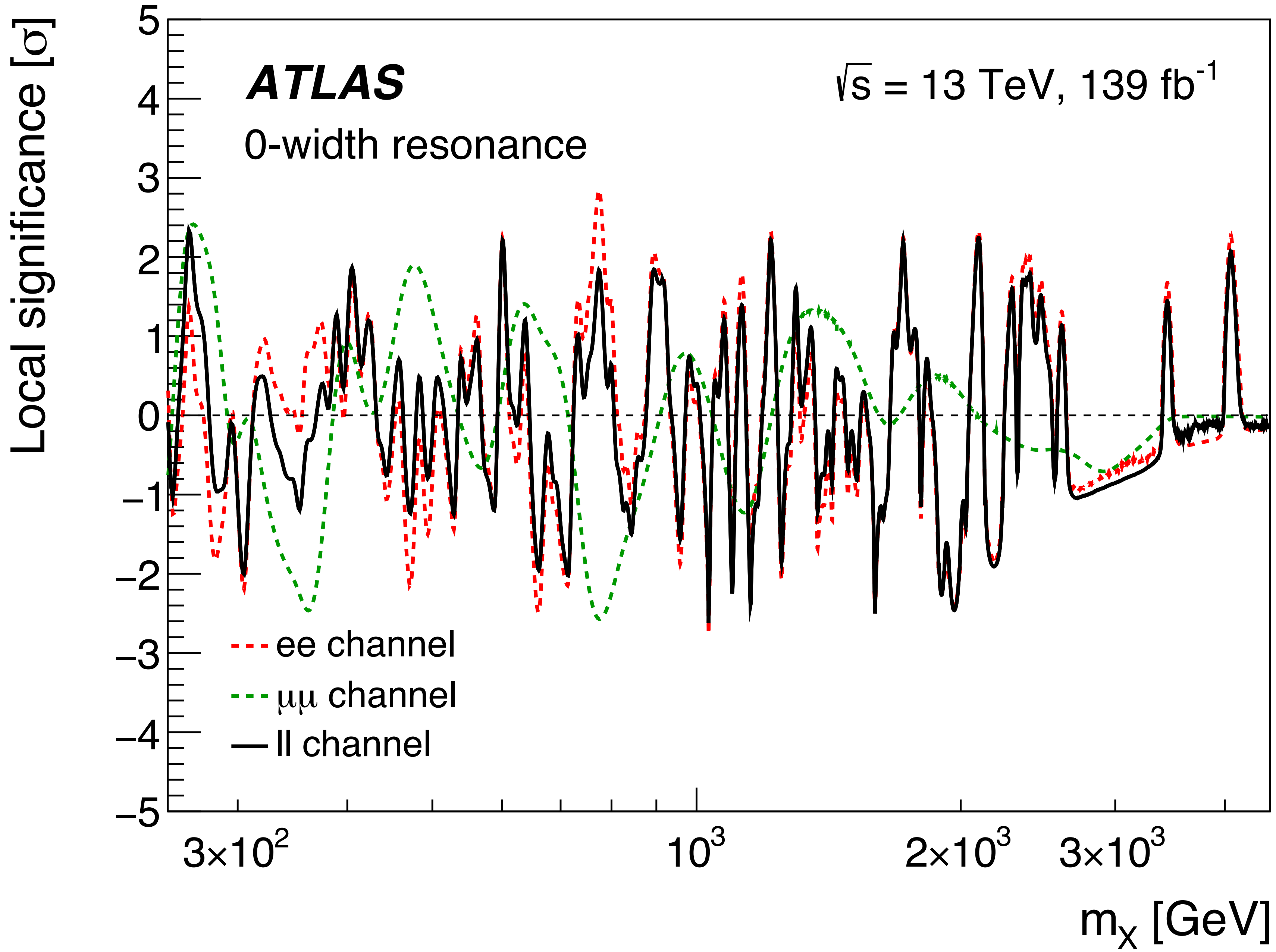
(theory) (detector)

"generic" signal model



2 electrons

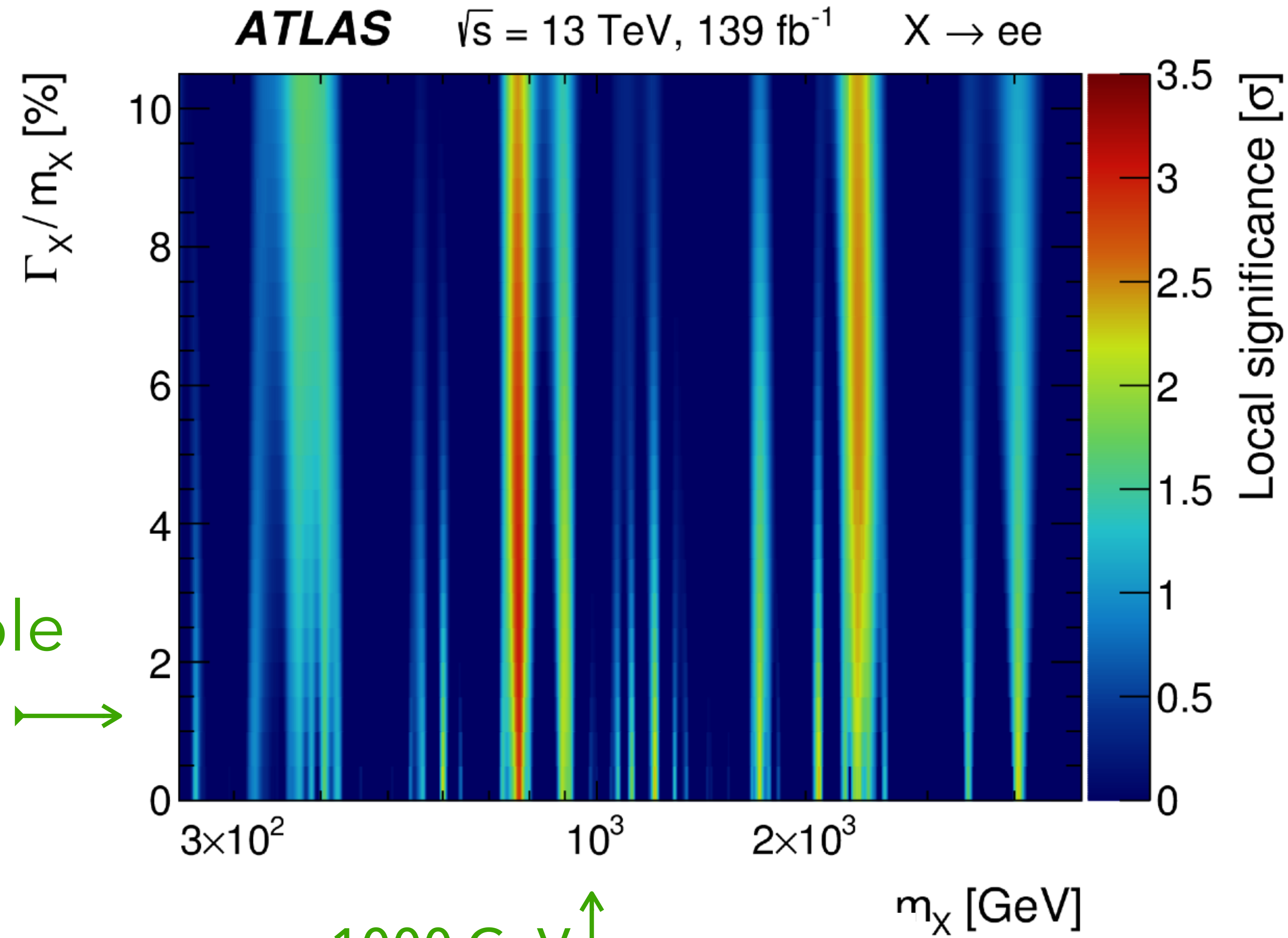
Statistical significance vs. mediator mass…



For very narrow ("zero width") resonances

Channel	p_0 (local) [σ]	p_0 (global) [σ]	m_X[GeV]	Γ/m_X[%]
ee	2.9	0.1	774	0
$\mu\mu$	2.4	0.3	267	0
$\ell\ell$	2.3	$\lesssim 0$	264	0

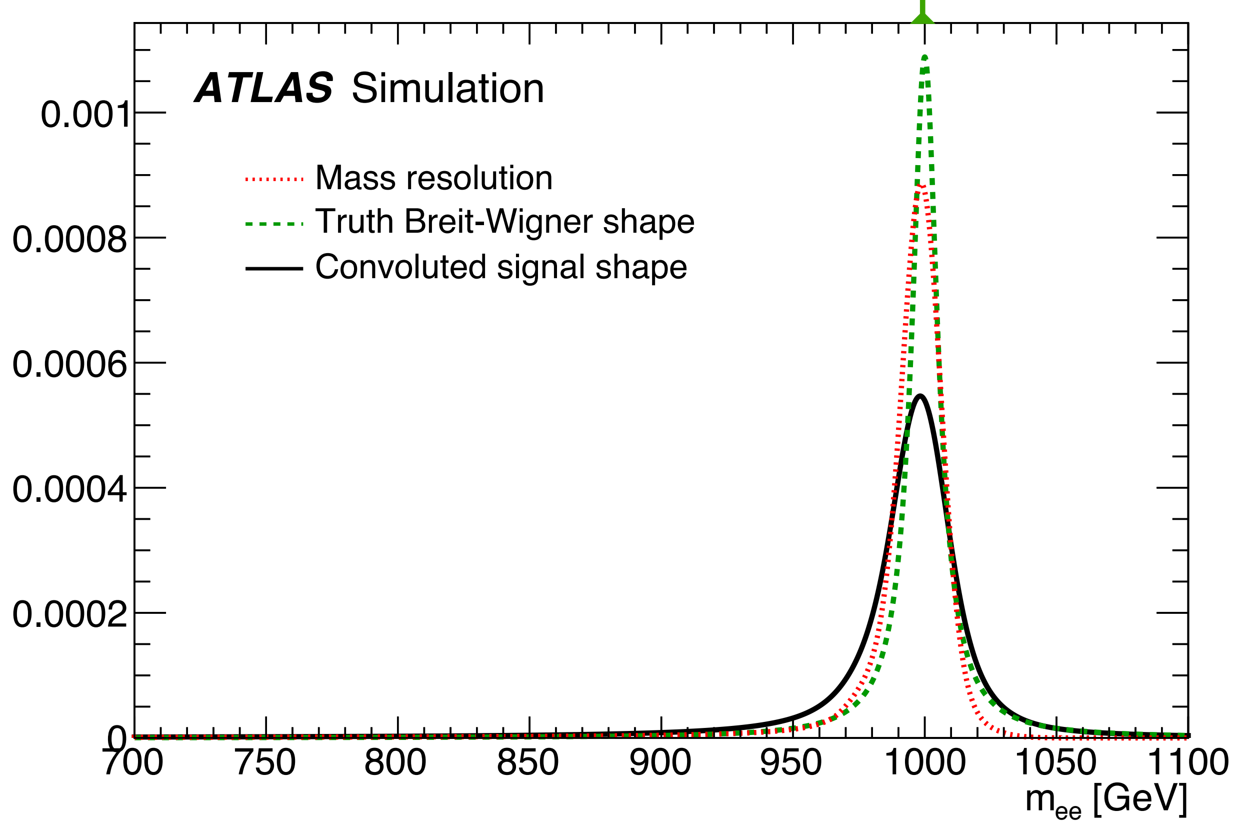
… testing significance of wide resonances



example

1.2% ⟶

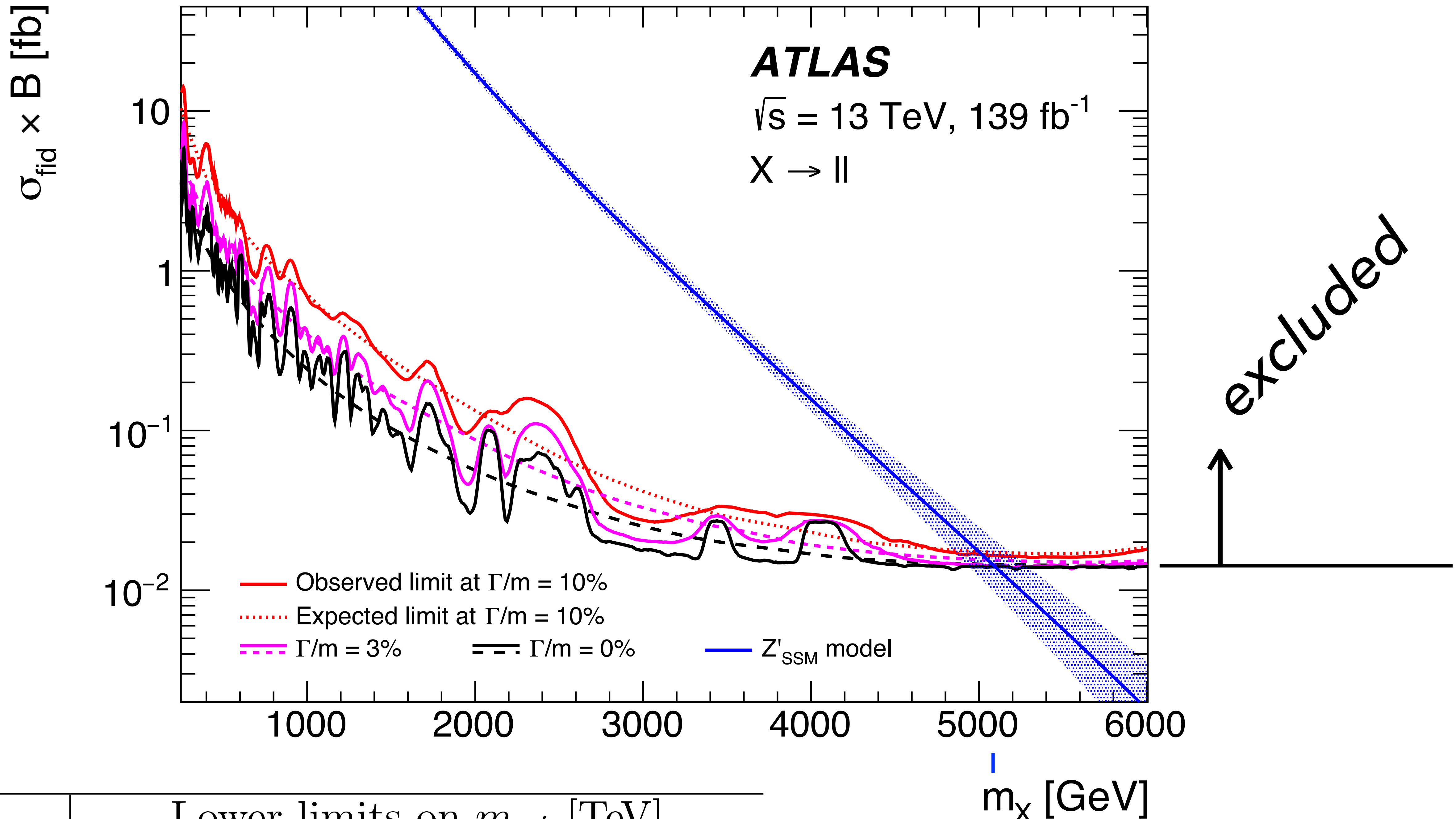
1000 GeV ↑



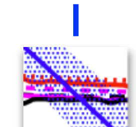
2 electrons

Channel	p_0 [σ]	m_X [GeV]	Γ_X/m_X [%]
	Excess		
ee	3.0	773	2.5
$\mu\mu$	2.5	268	2.5
$\ell\ell$	2.3	264	0
	Deficit		
	p_0 [σ]	m_X [GeV]	Γ_X/m_X [%]
ee	−3.2	1957	4.0
$\mu\mu$	−2.8	349	8.5
$\ell\ell$	−2.9	1958	3.0

Cross section upper limits vs. mediator mass



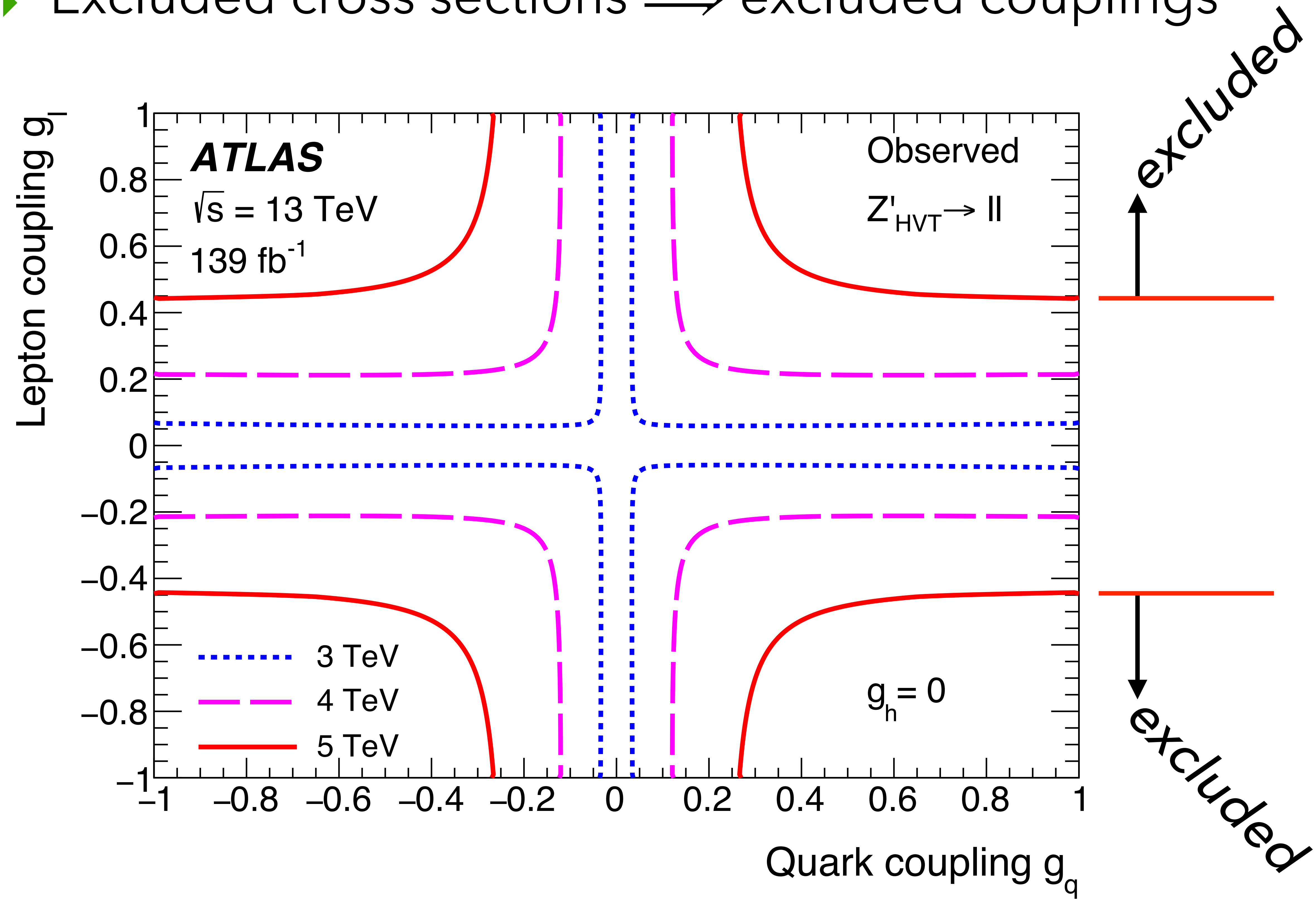
Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1



SSM mass limit = intersection with **3%** width generic cross section limit

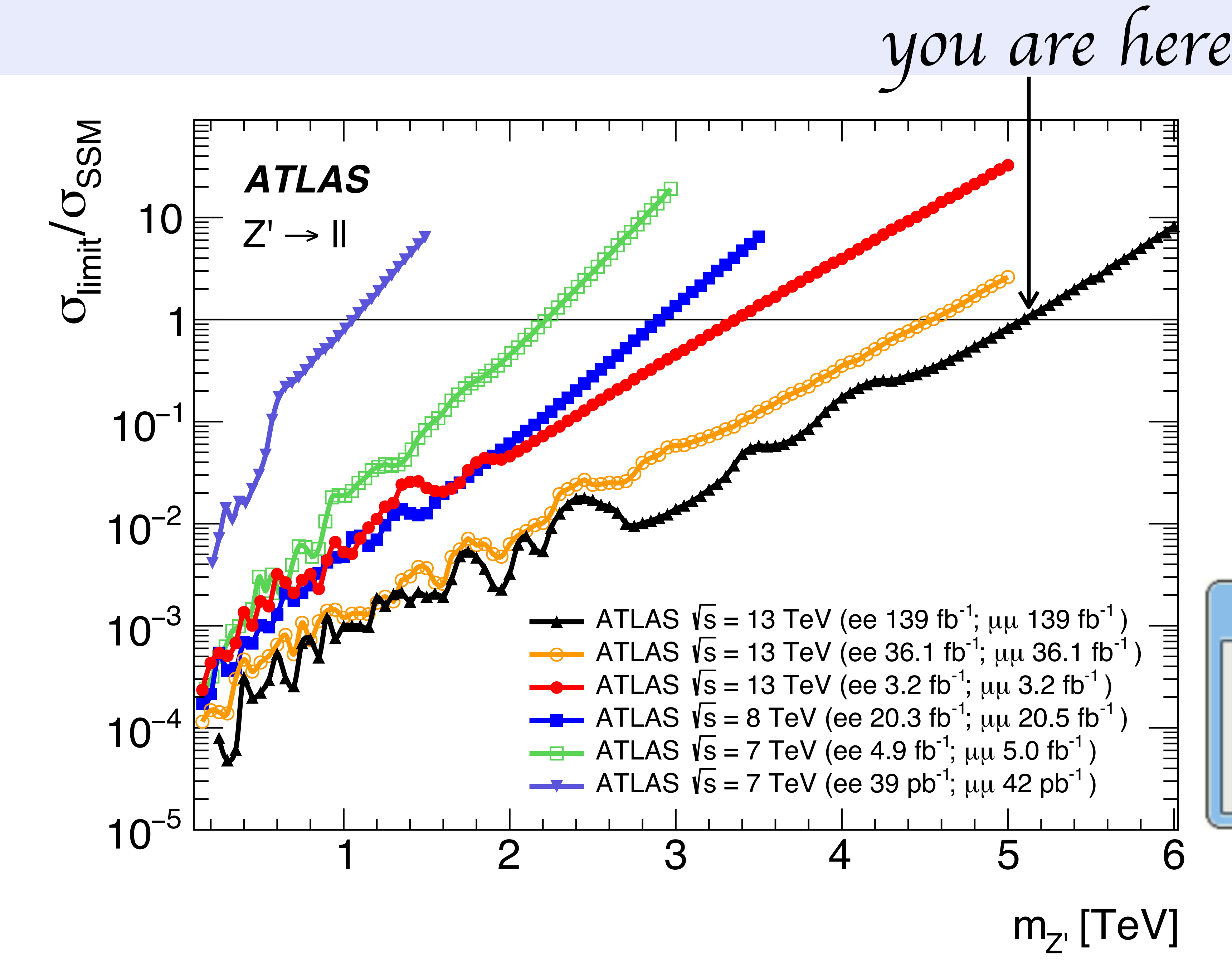
Implications for a Heavy Vector Triplet Z′

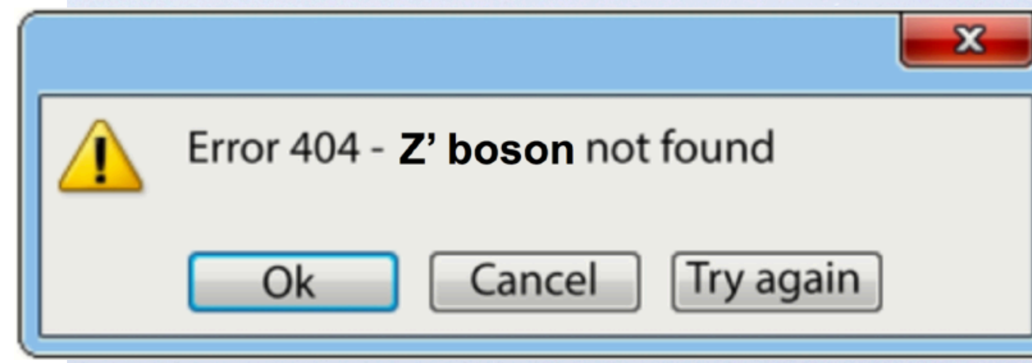
- Excluded cross sections $\Longrightarrow$ excluded couplings



The end

- ATLAS full Run-2 dataset has been combed for high mass dilepton resonances





😭 No significant deviation from the SM observed

😍 Limits on cross section of generic signal can be readily reinterpreted to constrain various models (Z'_{DM}, spin-0, spin-2, …)

Bonus

Event selection

Electrons:

ID tracks + energy clusters in EMCal

no charge sign requirement

lowest unprescaled 2e trigger

$E_T > 30$ GeV

$|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$

$|d_0/\sigma(d_0)| < 5$

$|z_0 \sin\theta| < 0.5$ mm

medium identification working point

(>92% efficient for $E_T > 80$ GeV)

"gradient" isolation working point

Muons:

ID tracks + MS tracks

muons opposite charge

lowest unprescaled 1μ trigger

$p_T > 30$ GeV

$|\eta| < 2.5$

$|d_0/\sigma(d_0)| < 3$

$|z_0 \sin\theta| < 0.5$ mm

high-pT identification working point

(require 3 hits in precision MS tracking layers)

(69% – 64% efficient from 1.0 TeV – 2.5 TeV)

require σ(q/p) below "good muon" threshold

(from ~100% efficient at 1 TeV to 93% at 2.5 TeV)

"fixed cut tight track only" isolation working point

Event-level: Make pair out of highest p_T (same flavour) leptons in event

Analysis strategy

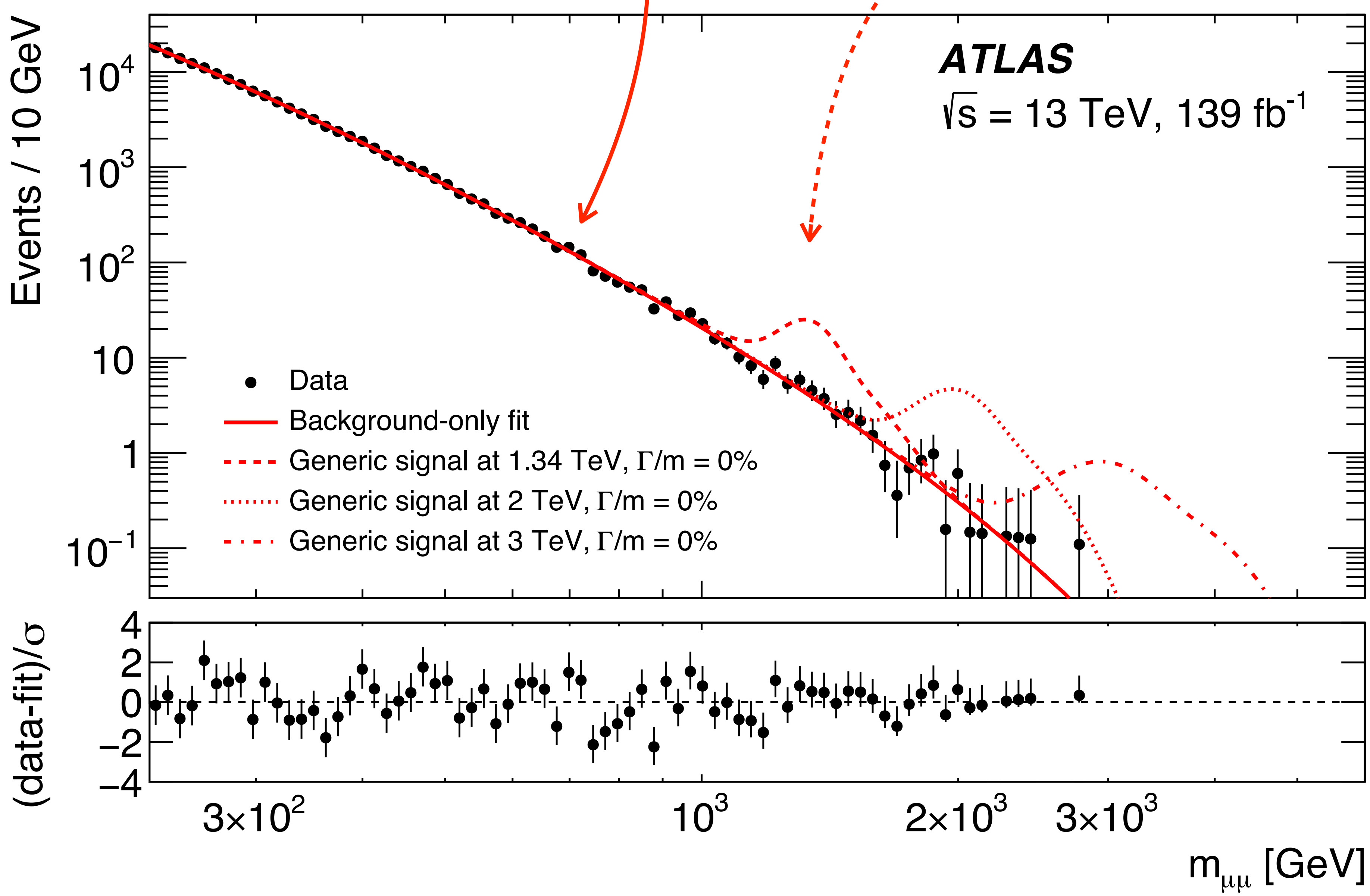
Fit the observed dilepton invariant mass spectrum:

$$\text{data distribution} = \underbrace{f_{\text{bkg}}}(m_{\ell\ell}) + \underbrace{f_{\text{sig}}}(m_{\ell\ell})$$

smoothly falling function

Breit-Wigner $\otimes$ $m_{\ell\ell}$ resolution

(theory) (detector)



"generic" signal model

2 muons

Background model details

$$f_{\ell\ell}(m_{\ell\ell}) = f_{\mathrm{BW,Z}}(m_{\ell\ell}) \cdot \left(1 - x^c\right)^b \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i}$$

$x = \dfrac{m_{\ell\ell}}{\sqrt{s}}$

$c = \begin{cases} 1, & ee \\ 1/3, & \mu\mu \end{cases}$

b, p_i free

Parameter	ee channel	$\mu\mu$ channel
a	178000 ± 400	138700 ± 400
b	1.5 ± 1.0	11.8 ± 0.5
p_0	-12.38 ± 0.09	-7.38 ± 0.12
p_1	-4.295 ± 0.014	-4.132 ± 0.017
p_2	-0.9191 ± 0.0027	-1.0637 ± 0.0029
p_3	-0.0845 ± 0.0005	-0.1022 ± 0.0005

← normalization

- Function chosen based on performance on smoothed simulated SM background
- Potential mismodelling is accounted for by measuring difference between functional fit and smoothed simulated SM background
- The magnitude of this "spurious signal" then defines the 1σ pull of a nuisance parameter multiplying the signal component
- Extra function parameter p_4 available if it significantly improves (> 2σ) likelihood of fit to data ⇒ not needed in 139 fb^{-1} fit

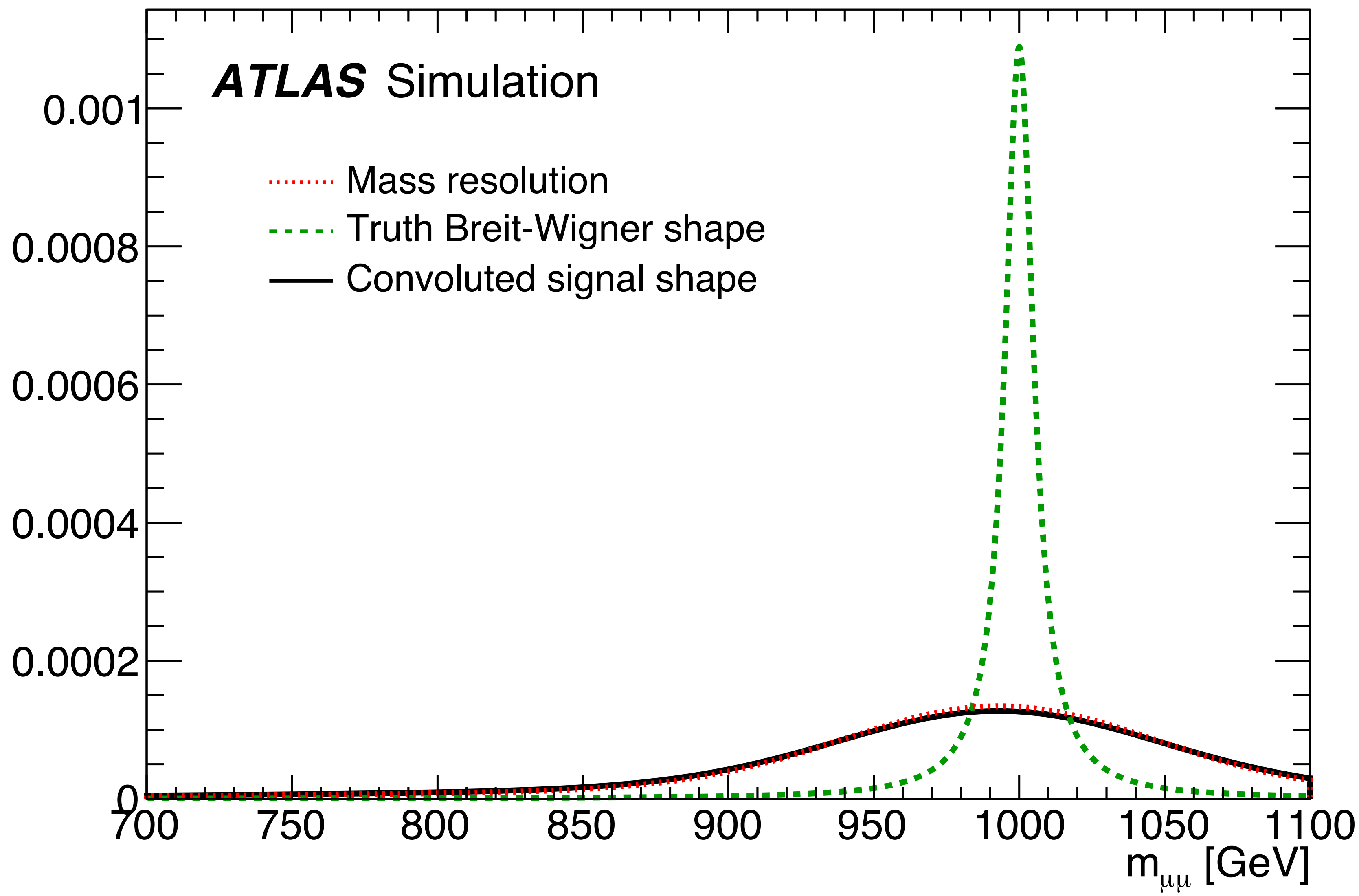
Signal modeling

convolution

non-relativistic

$$\boxed{\text{Generic signal}} = \text{Breit-Wigner} \otimes \text{Relative } m_{\ell\ell} \text{ resolution}$$

(parametric, model-indep.) (truth-level shape at given width) (modelled using simulated samples)



- Fiducial cuts:
  (for reinterpretation)

$$m_{\ell\ell} > m_X - 2\Gamma\ ,$$

$$p_T^{\text{lead}}, p_T^{\text{sublead}} > 30\ \text{GeV}$$

$$\left|\eta^{\text{lead}}\right|, \left|\eta^{\text{sublead}}\right| < 2.5$$

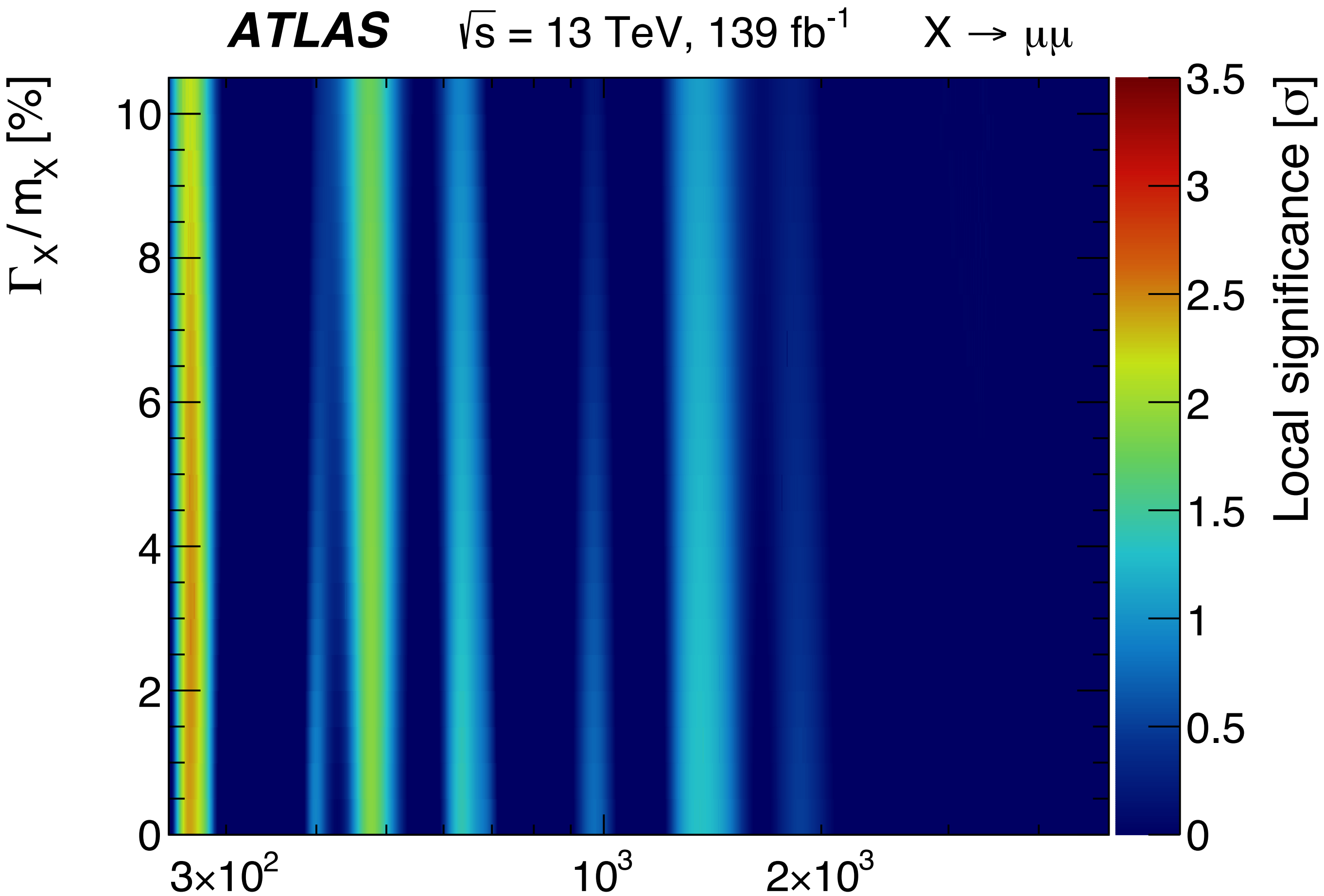
2 muons

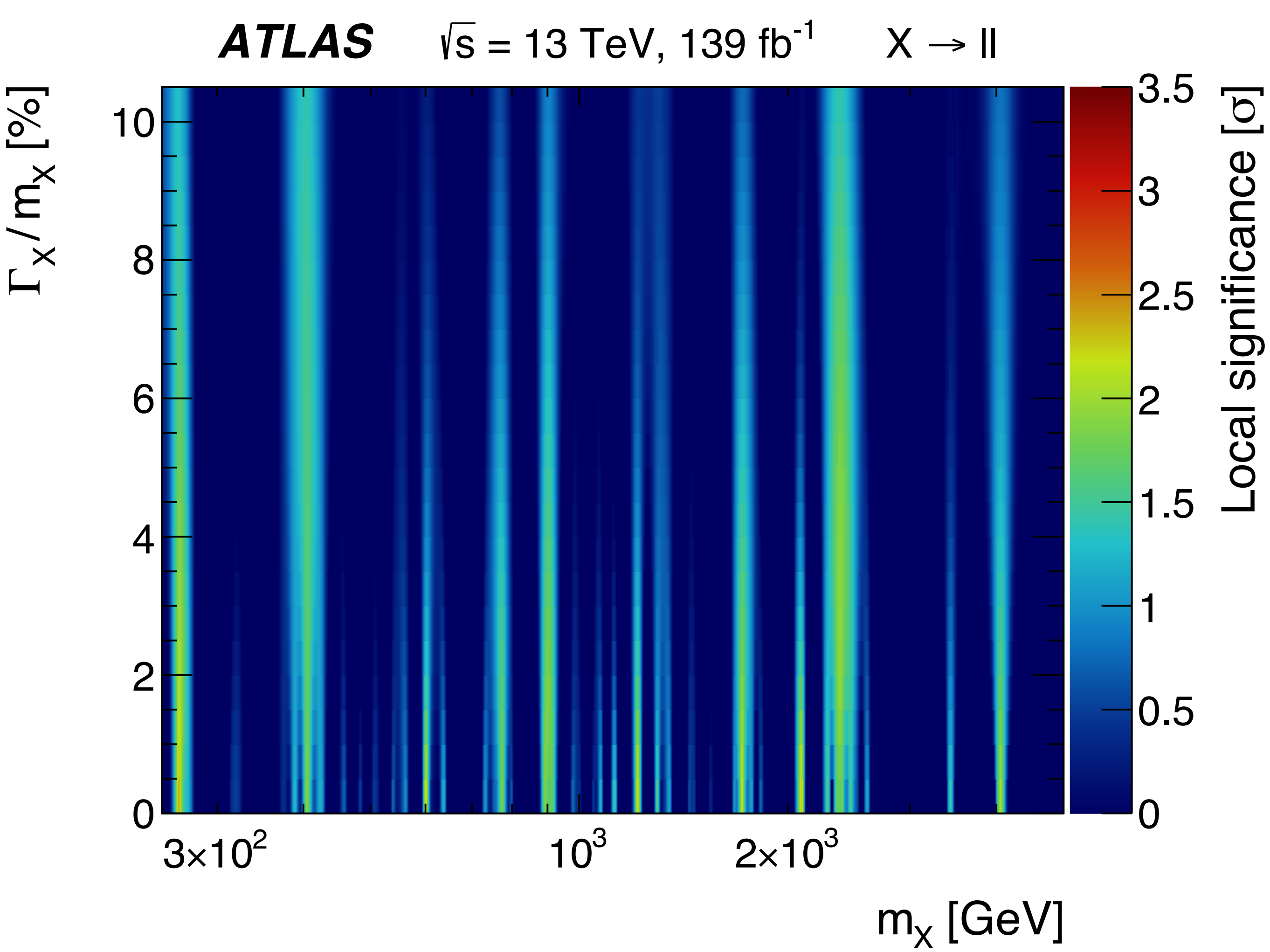
Systematics

Uncertainty source for m_X [GeV]	Dielectron 300	Dielectron 5000	Dimuon 300	Dimuon 5000
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)
Electron energy scale	${}^{-1.7}_{-4.0}\ \left({}^{+1.0}_{-1.8}\right)$	${}^{+0.1}_{-0.4}\ (\pm 0.8)$	-	-
Electron energy resolution	${}^{+7.9}_{-8.3}\ \left({}^{+1.1}_{-0.9}\right)$	${}^{+0.4}_{-0.9}\ (\pm 0.1)$	-	-
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)	${}^{+55}_{-35}\ \left({}^{+55}_{-35}\right)$

- Impact on signal strength from $\pm 1\sigma$ pull on nuisance parameter

Additional 2D p-value scans





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ee	-3.2	1957	4.0
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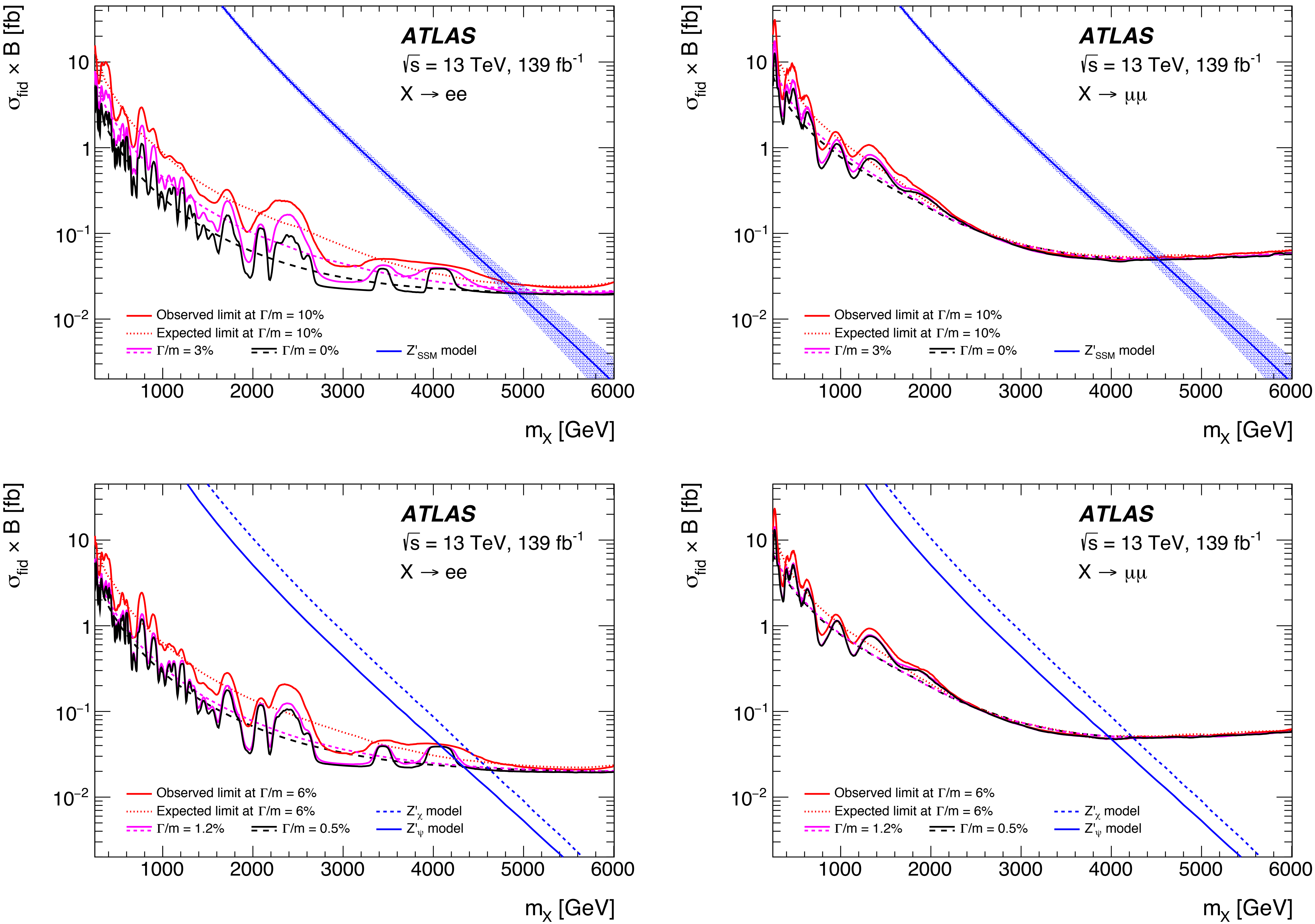
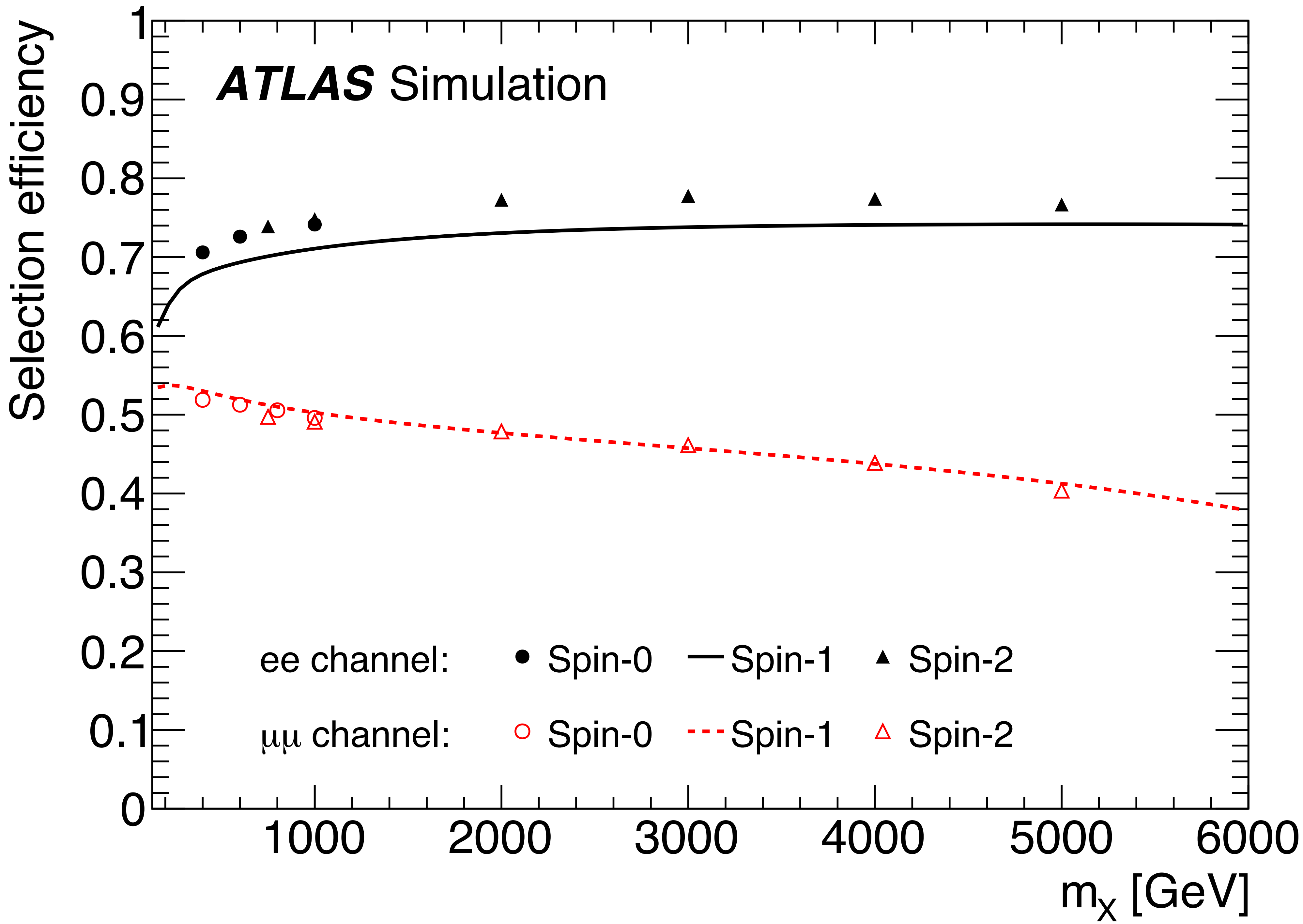
$\ell\ell$	-2.9	1958	3.0

Channel-wise cross section limits

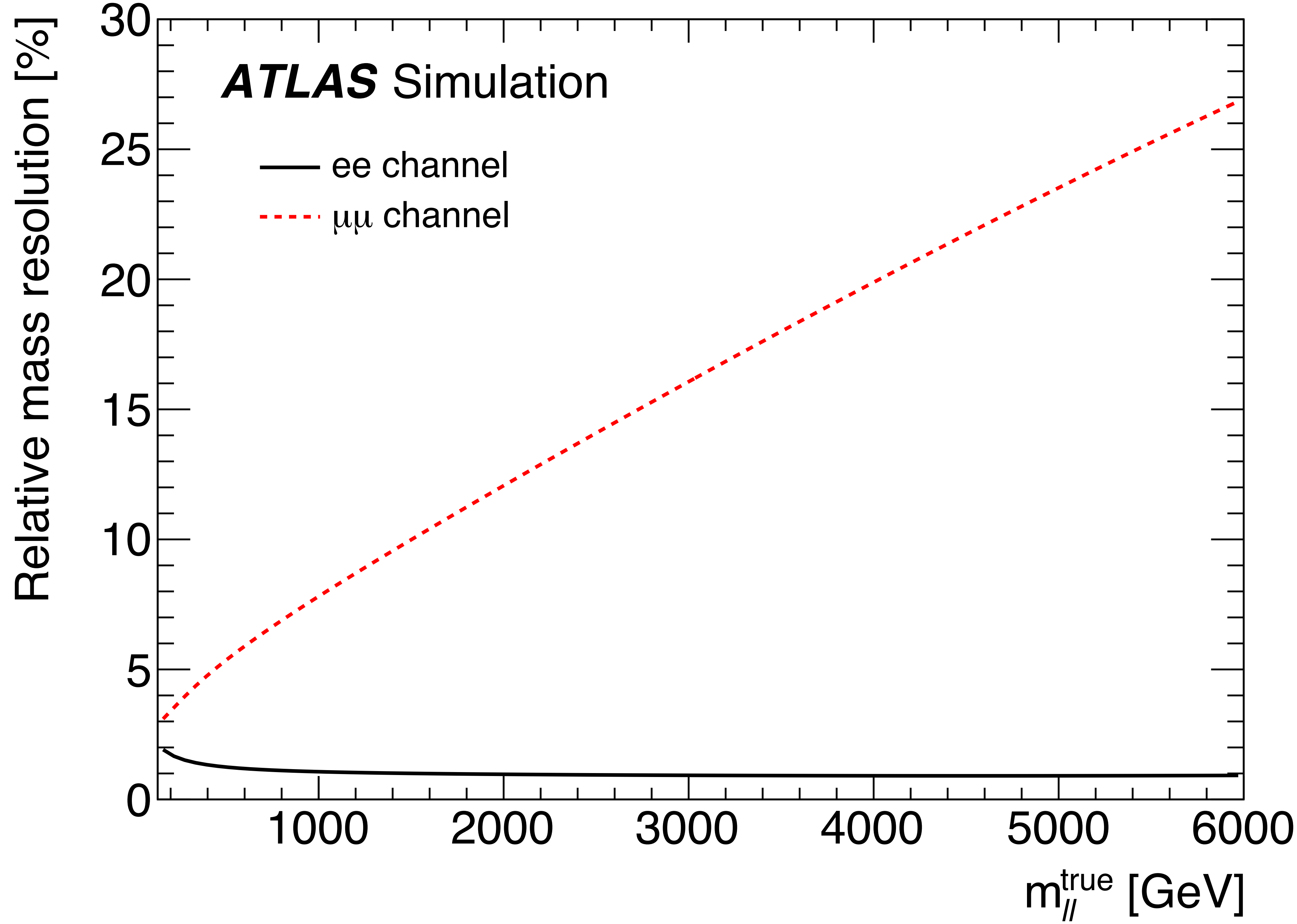


Selection efficiency

- Efficiency consistent across spin cases within 4% (absolute)



Relative invariant mass resolution



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