SFU SIMON FRASER UNIVERSITY
ENGAGING THE WORLD

NSERC CRSNG

ATLAS EXPERIMENT

Searching for dilepton resonances at high mass in Run II data from ATLAS

Bumps on the horizon?

Congress 2019

Etienne Dreyer
etienned@sfu.ca

Preprint: *arXiv:1903.06248*
Material: *EXOT-2018-08*
HEPData: *record/88425*

Energy++

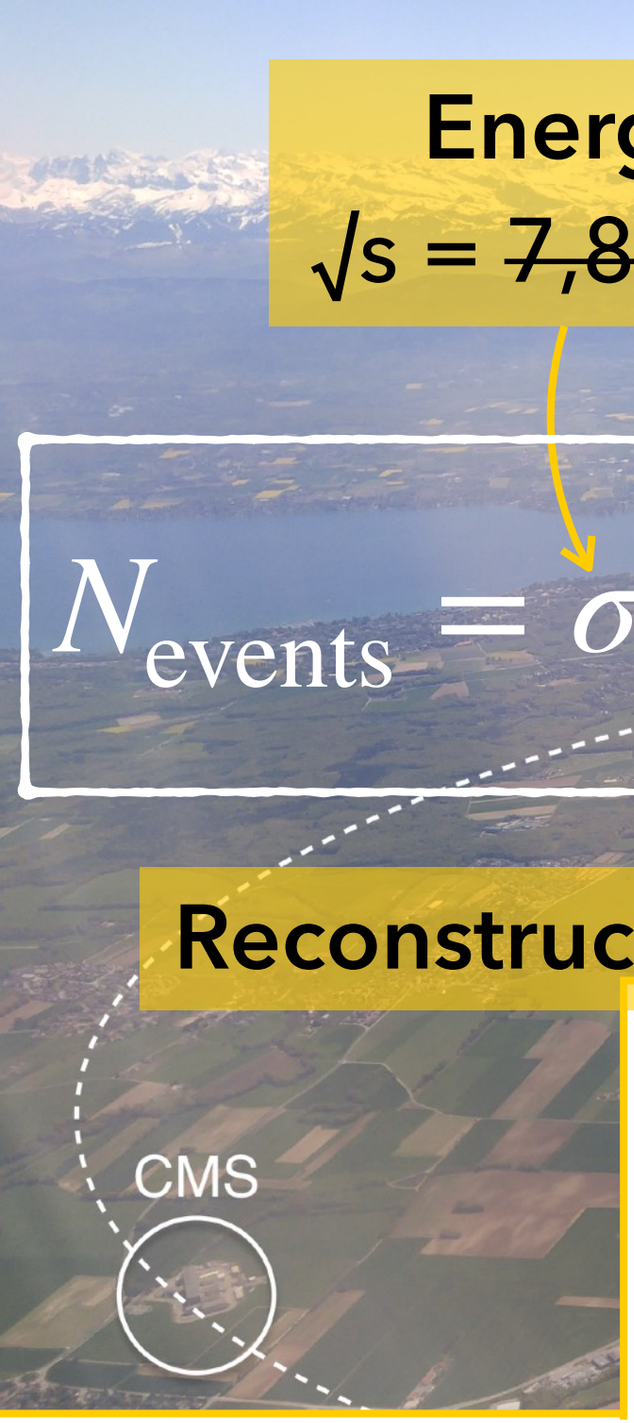
$\sqrt{s}$ = ~~7,8~~ ***13 TeV***

Luminosity++

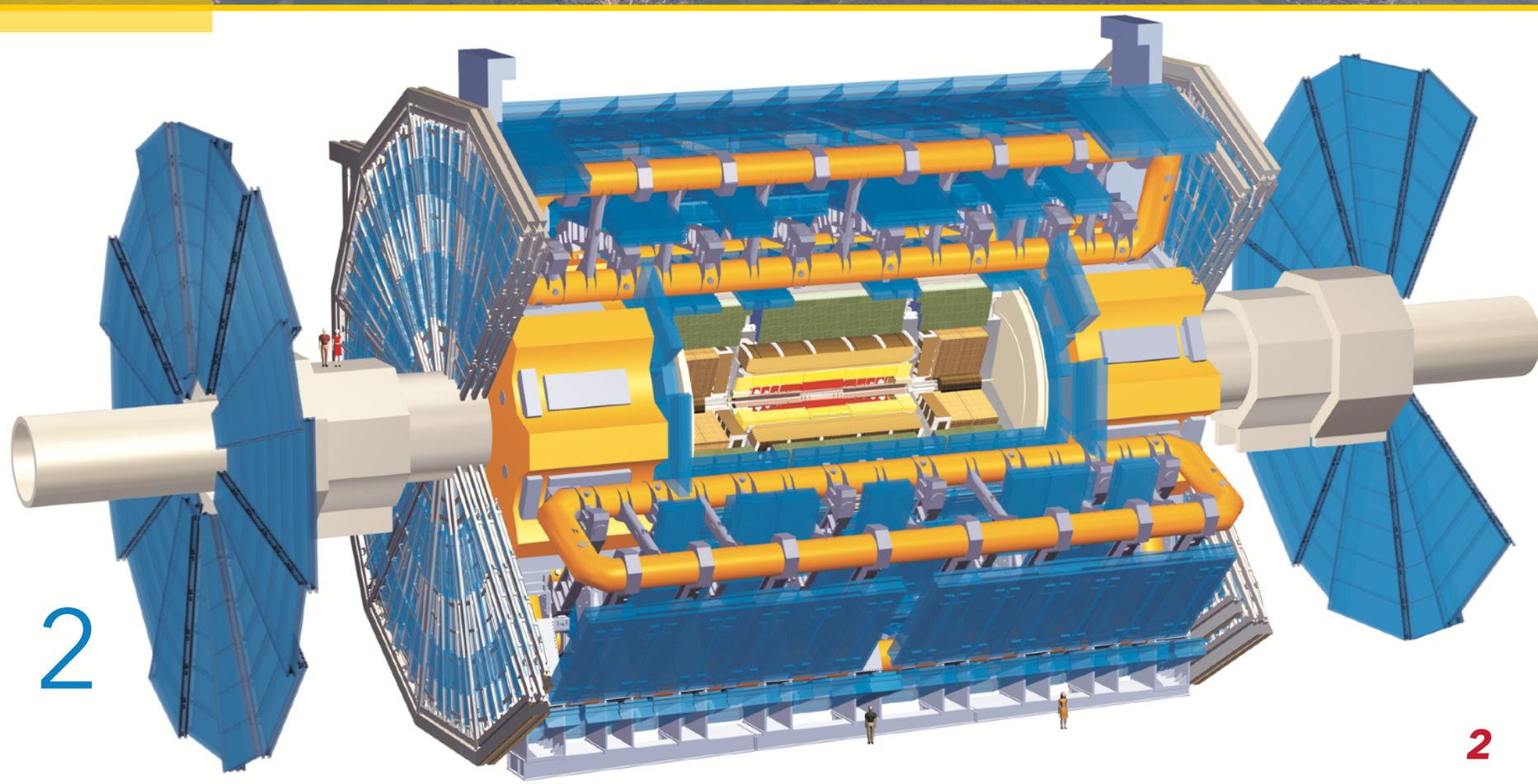
~~25~~ ***139 fb^{-1}***

$$N_{\text{events}} = \sigma \times A\epsilon \times \int L dt$$

Reconstruction++

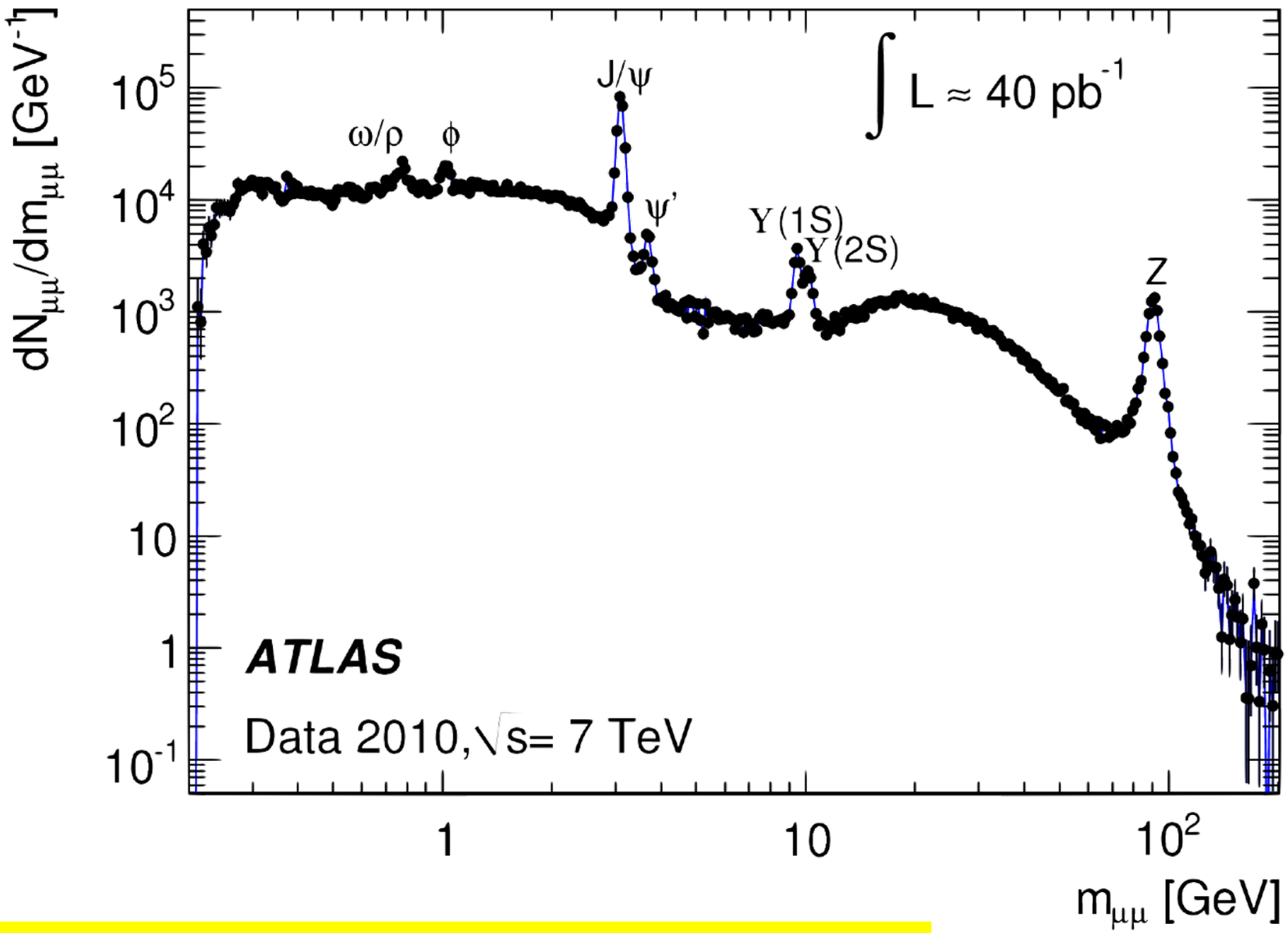


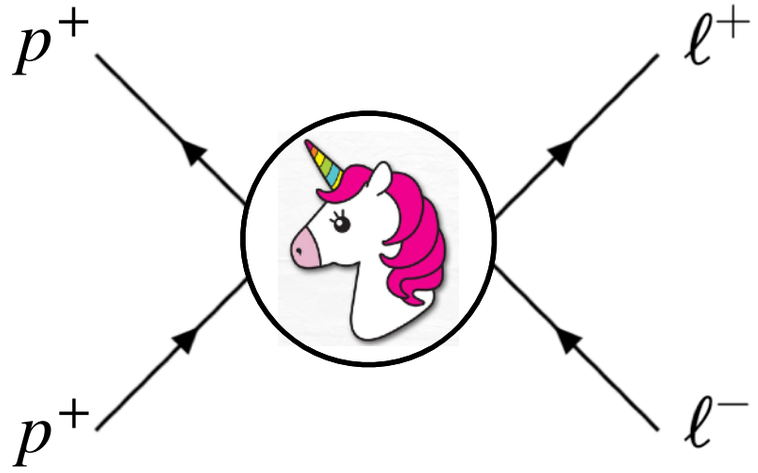
ATLAS @ LHC Run 2



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

2 muons 0.04 fb^{-1} (2010) [1]





. . .

here be dragons

Dilepton invariant mass:

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

[1] PERF-2011-01

Why more bumps?

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

Spin-1

- Superstring-inspired GUT:

$$E_6 \rightarrow SO(10) \times U(1)_\psi \quad \rightarrow Z'_\psi$$

or

$$SO(10) \rightarrow SU(5) \times U(1)_\chi \quad \rightarrow Z'_\chi$$

or

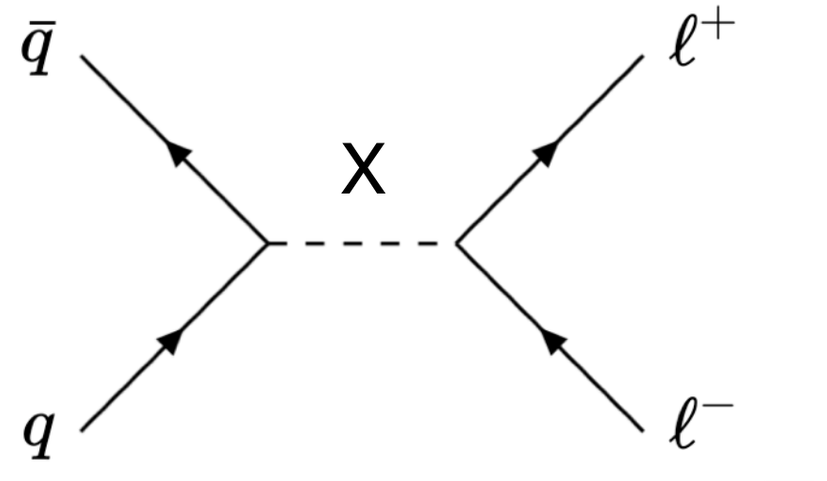
$$SO(10) \rightarrow SU(2)_R \times SU(2)_L \times U(1)_{B-L} \quad \rightarrow Z'_{LR}$$

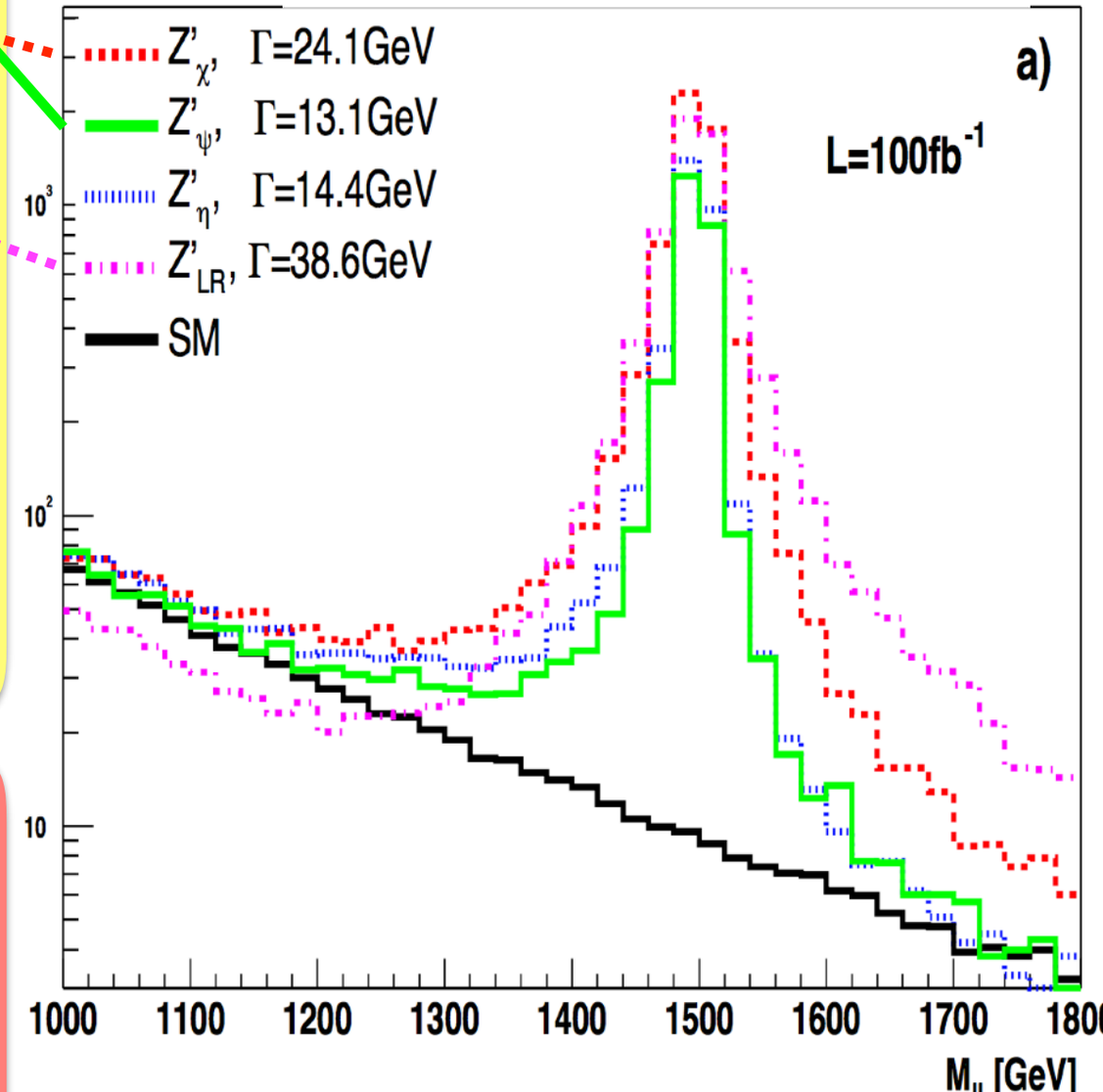
- Simplified dark matter mediator: Z'_{DM}
- Same fermion couplings as SM Z: Z'_{SSM}
- Neutral member of SU(2)′ triplet: Z'_{HVT}

Benchmarks

2) Other heavy neutral mediators

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





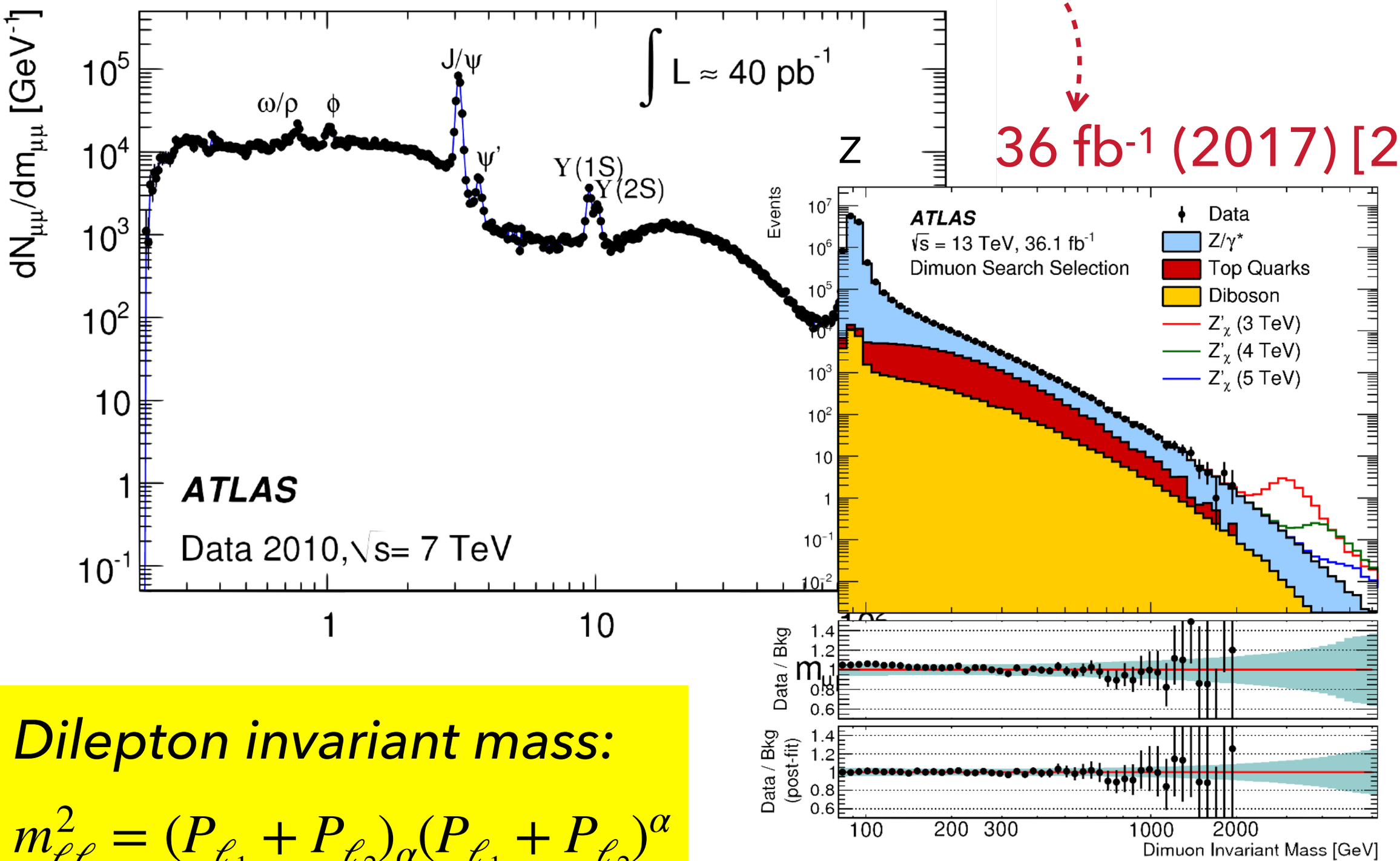
arXiv:hep-ph/0307020

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

2 muons

0.04 fb^{-1} (2010) [1]

36 fb^{-1} (2017) [2]



Dilepton invariant mass:

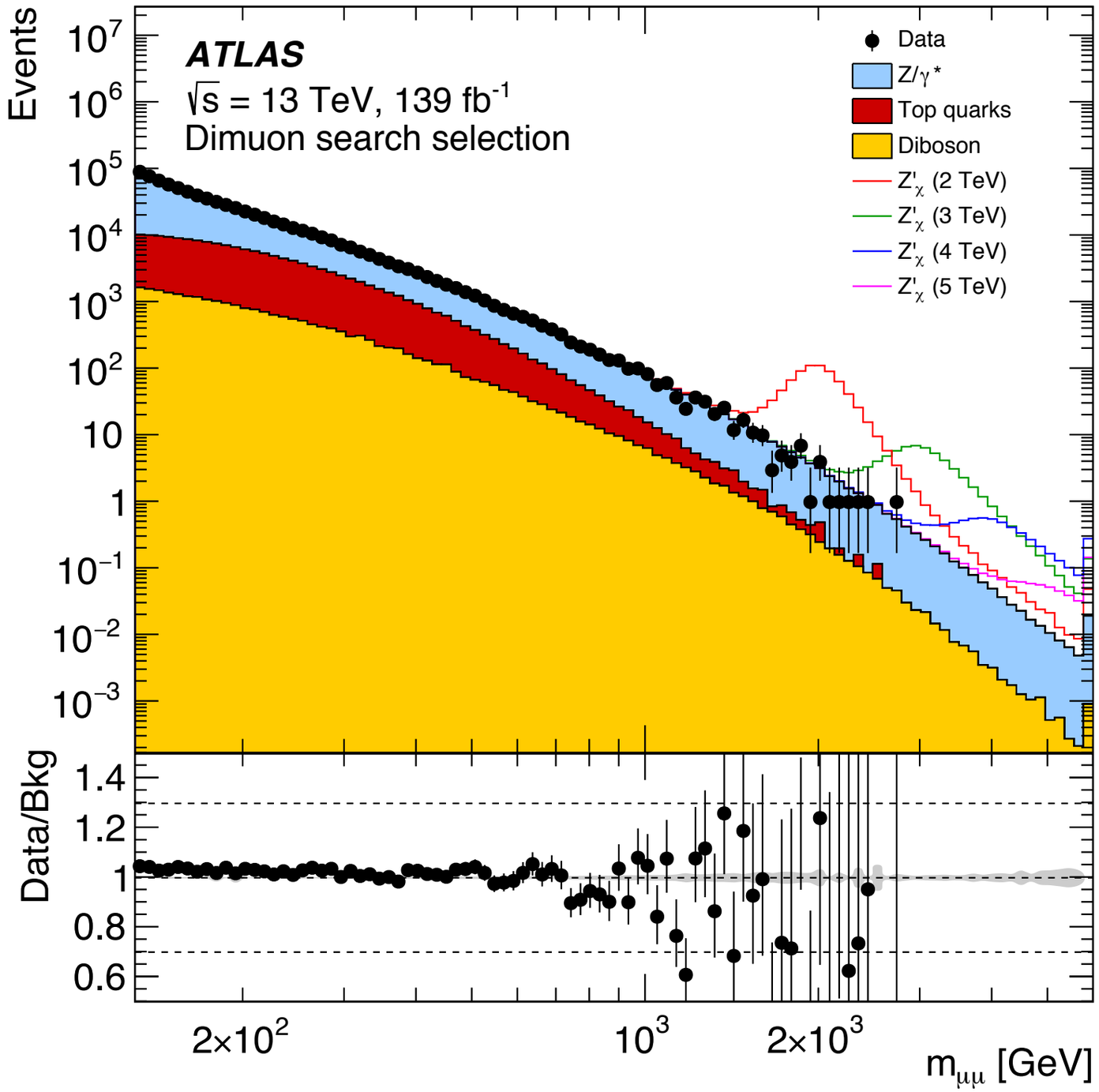
$$m^2_{\ell\ell} = (P_{\ell_1} + P_{\ell_2})_\alpha (P_{\ell_1} + P_{\ell_2})^\alpha$$

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

[1] PERF-2011-01 [2] EXOT-2016-05

Full Run-2 spectrum

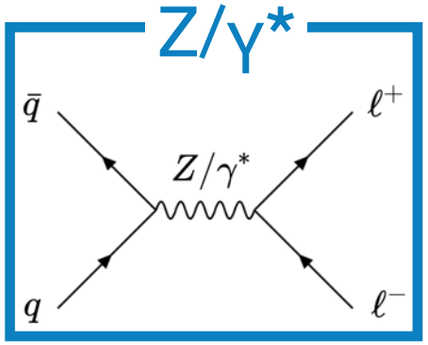
2 clean† ***muons****



† *full selection criteria in backup*

**opposite-charge required for muon pairs*

Data =



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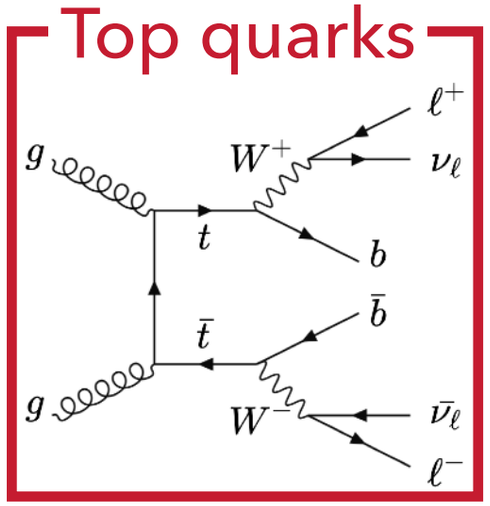

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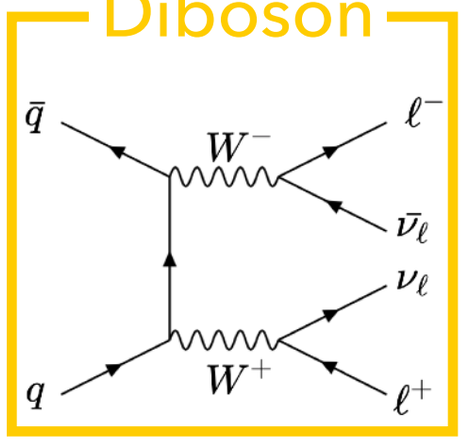
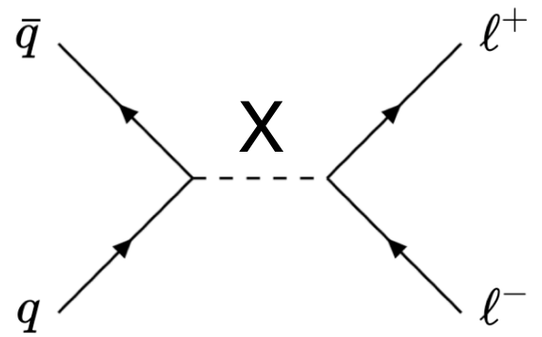
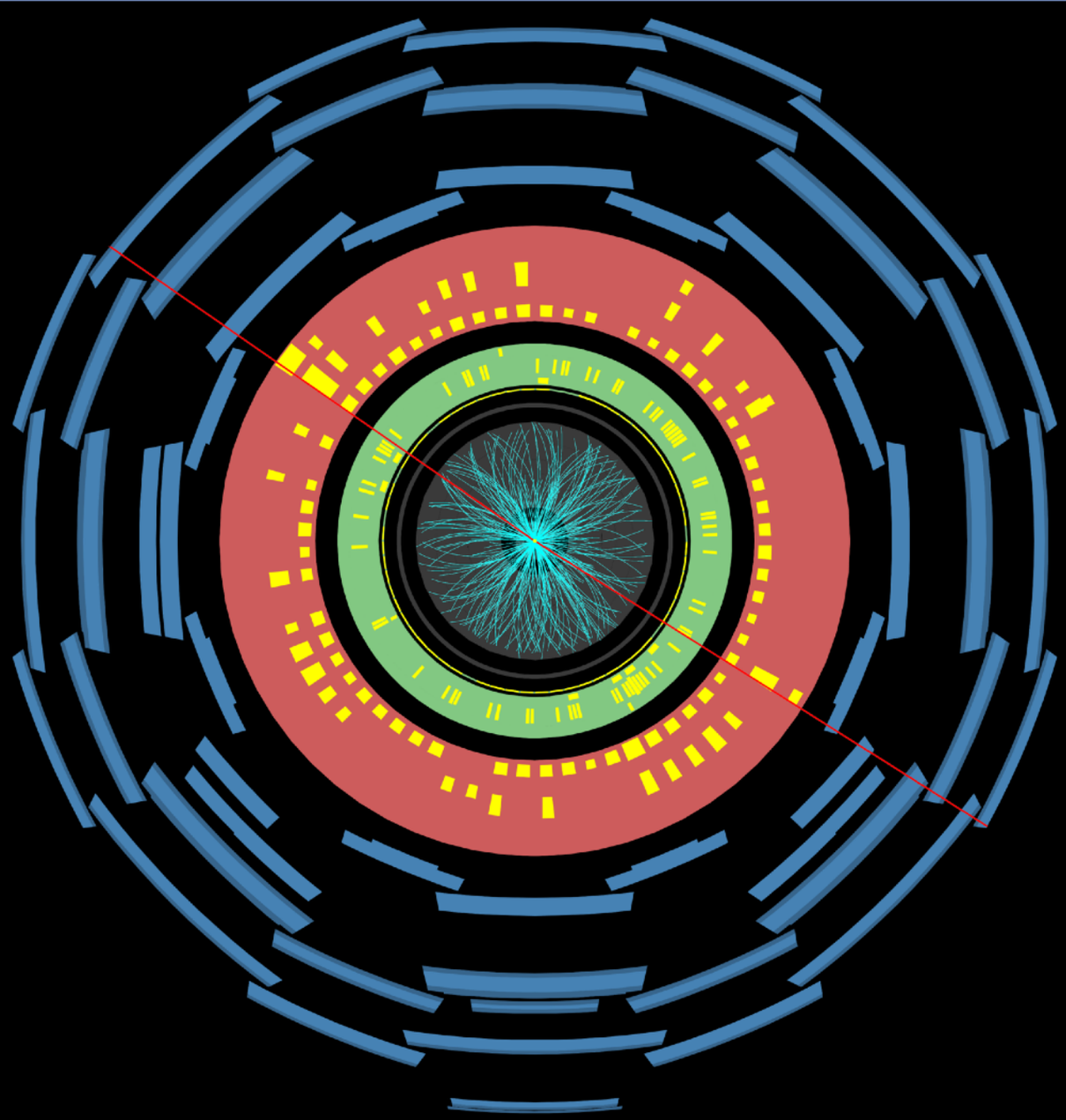


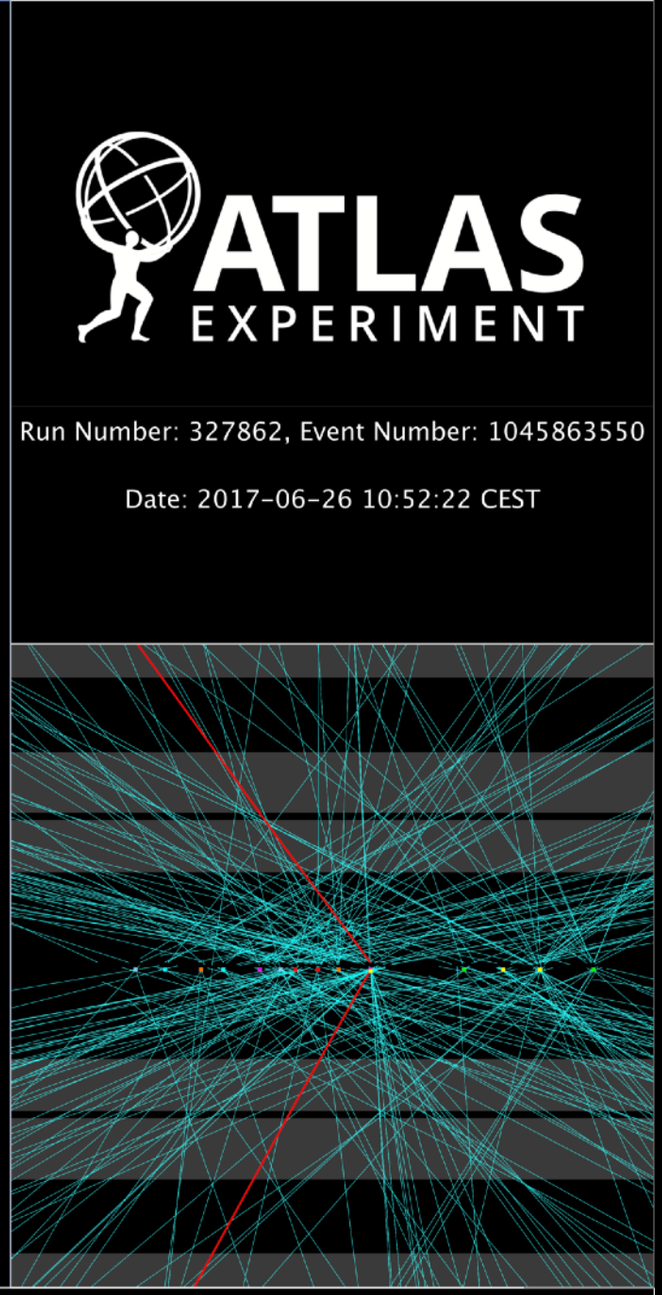
Background

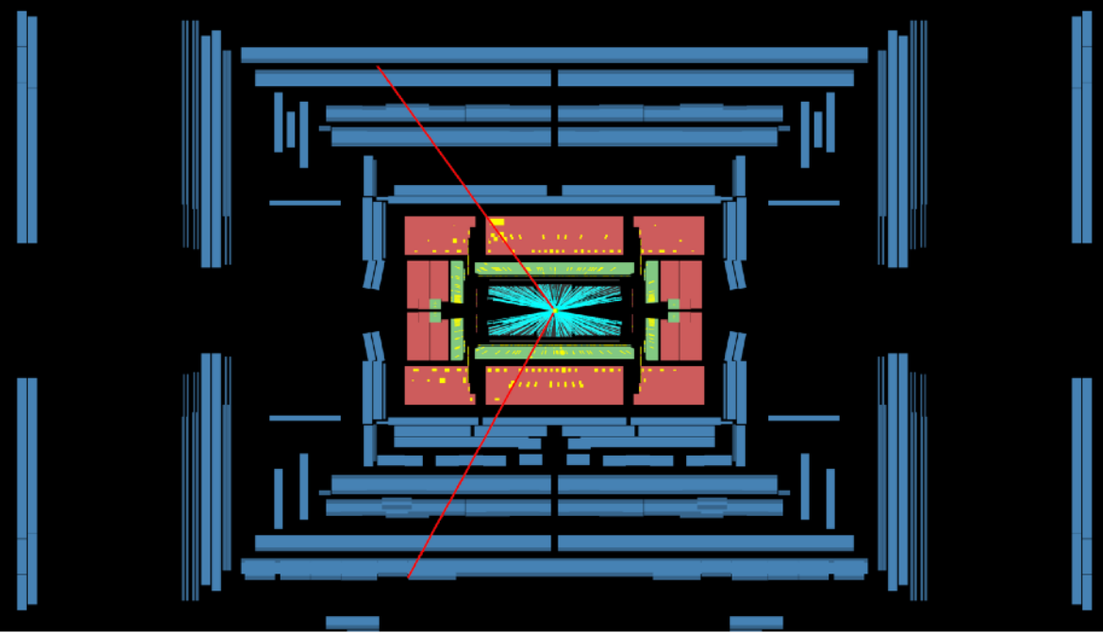
? +



Signal







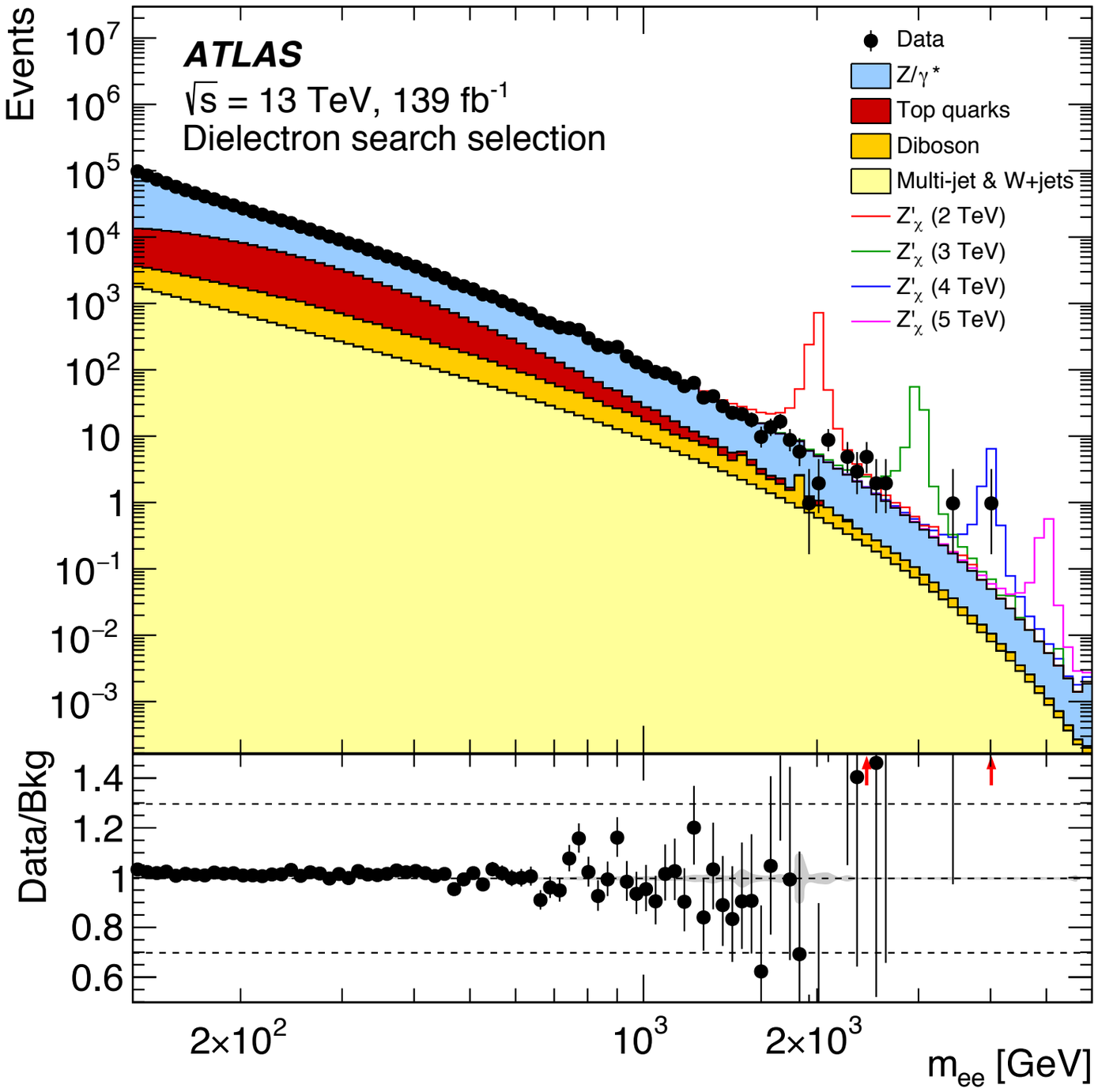
Highest inv. mass muon pair

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

2017

Full Run-2 spectrum

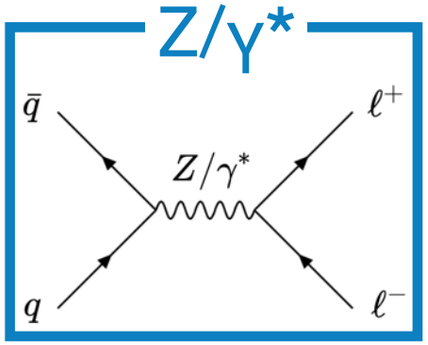
2 clean† ***electrons****



† *full selection criteria in backup*

**opposite-charge not required for electron pairs*

Data =



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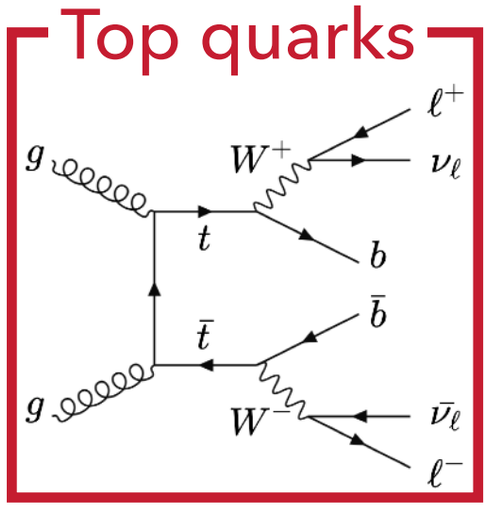

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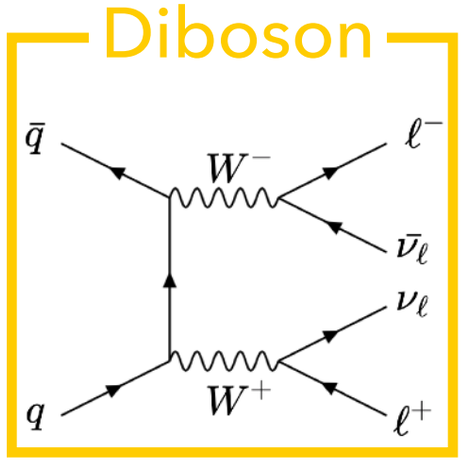
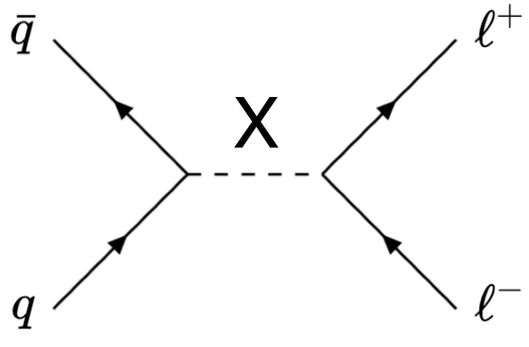


+

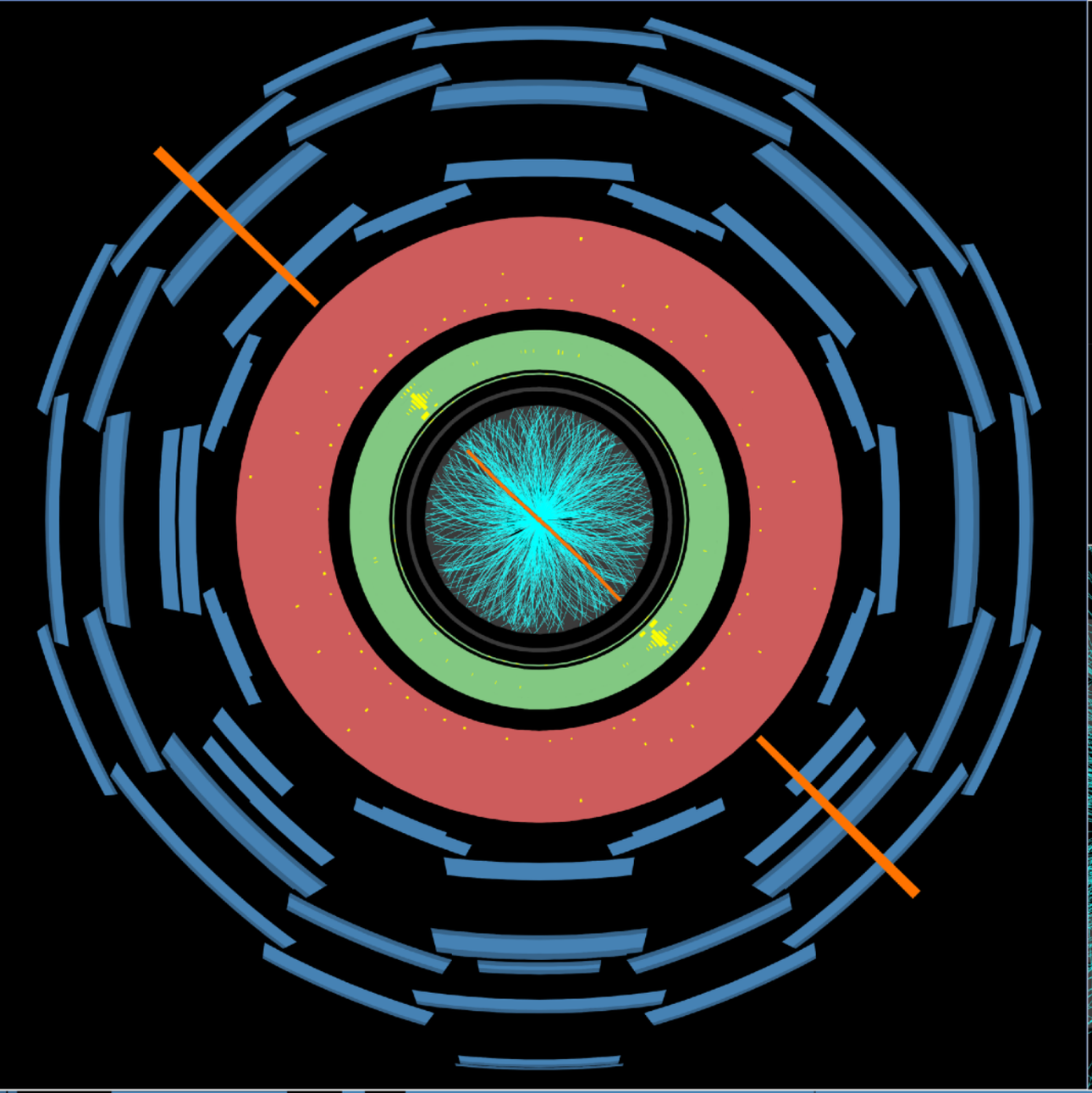
Jet(s) misidentified as electron(s)

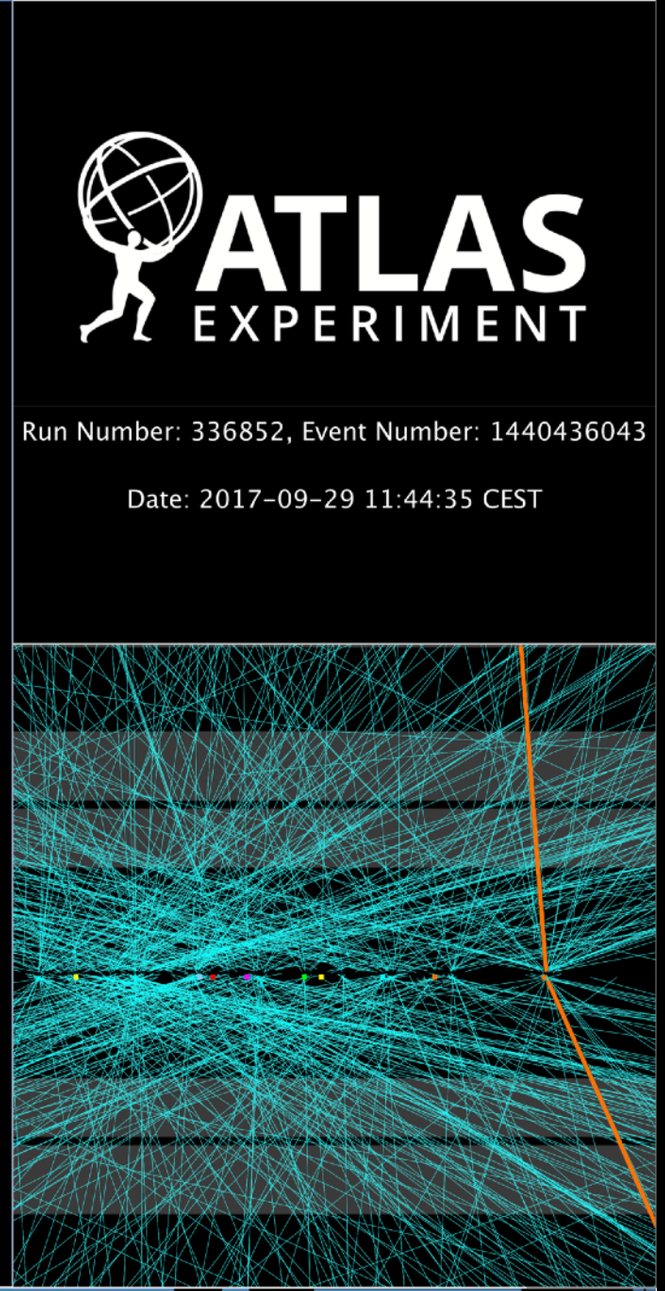
? +

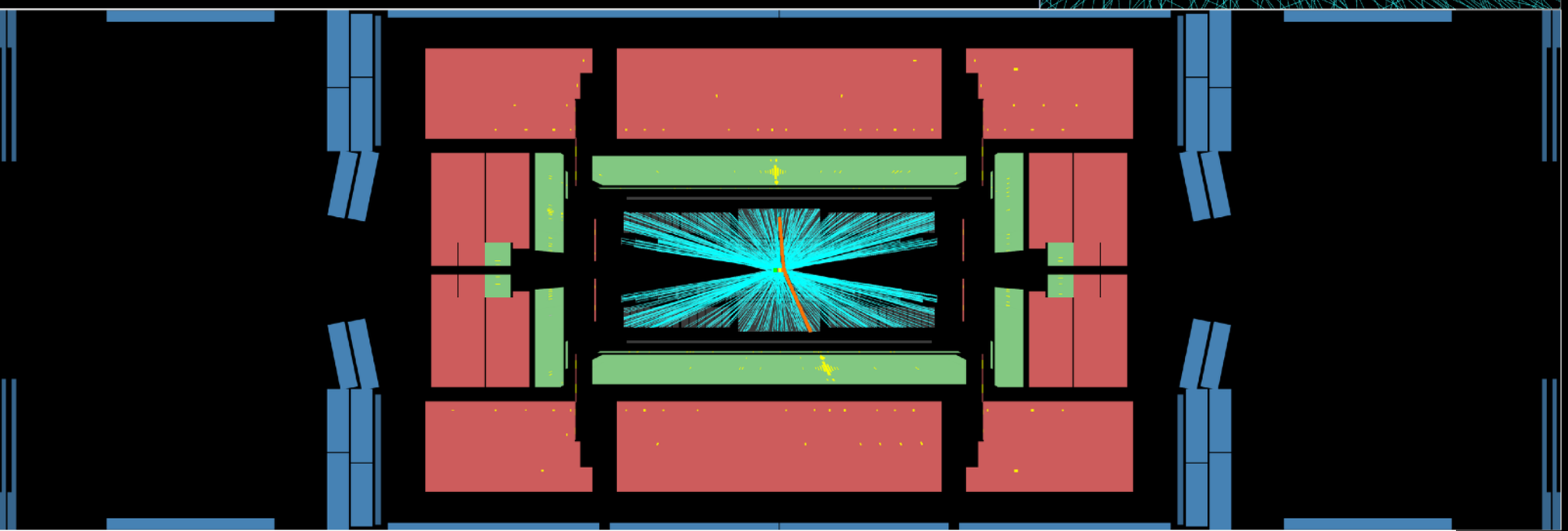


Background

Signal







Highest inv. mass electron pair

$m_{ee} = 4.06$ TeV

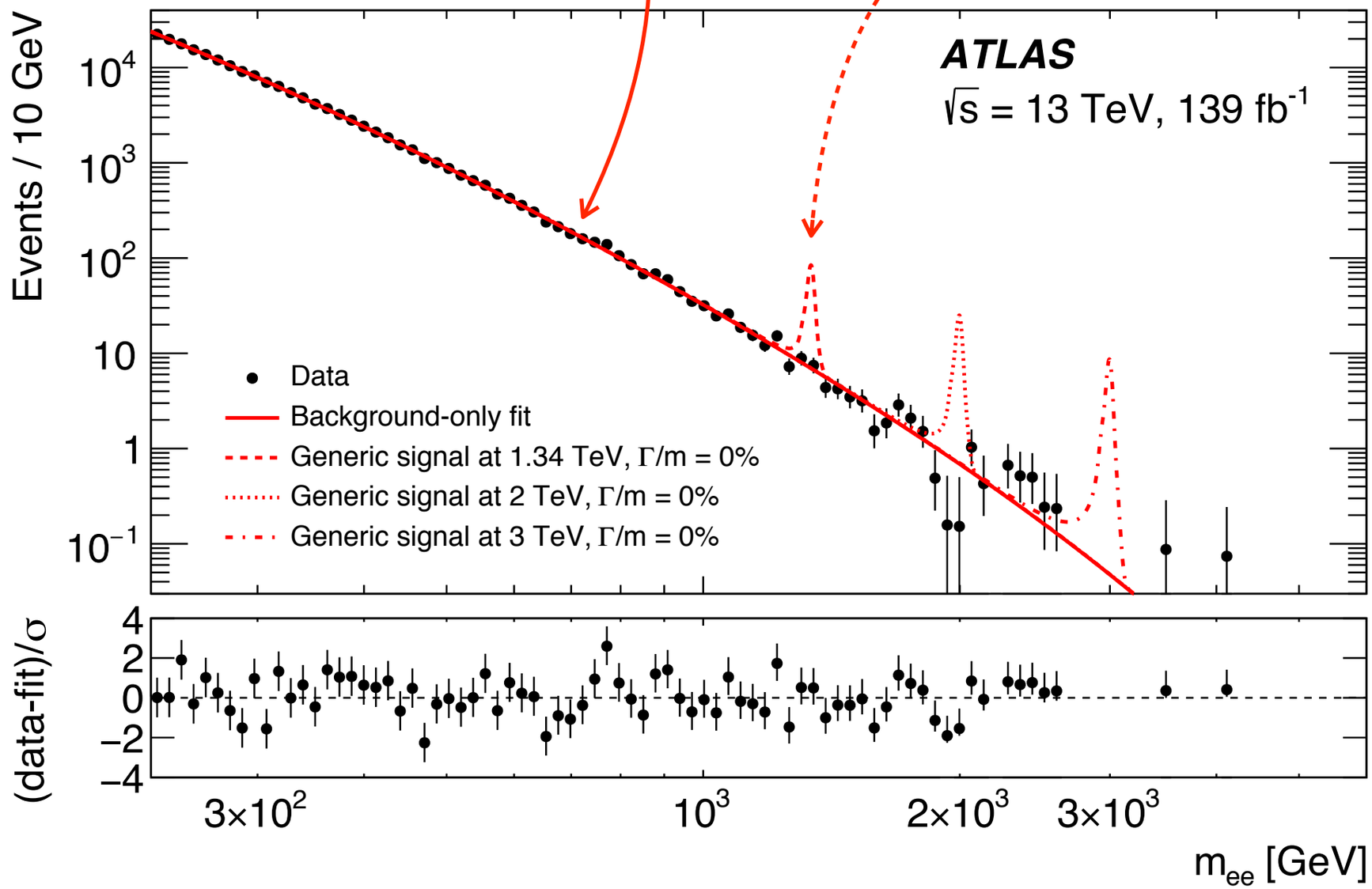
2017

Analysis strategy

Fit the observed dilepton invariant mass spectrum:

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

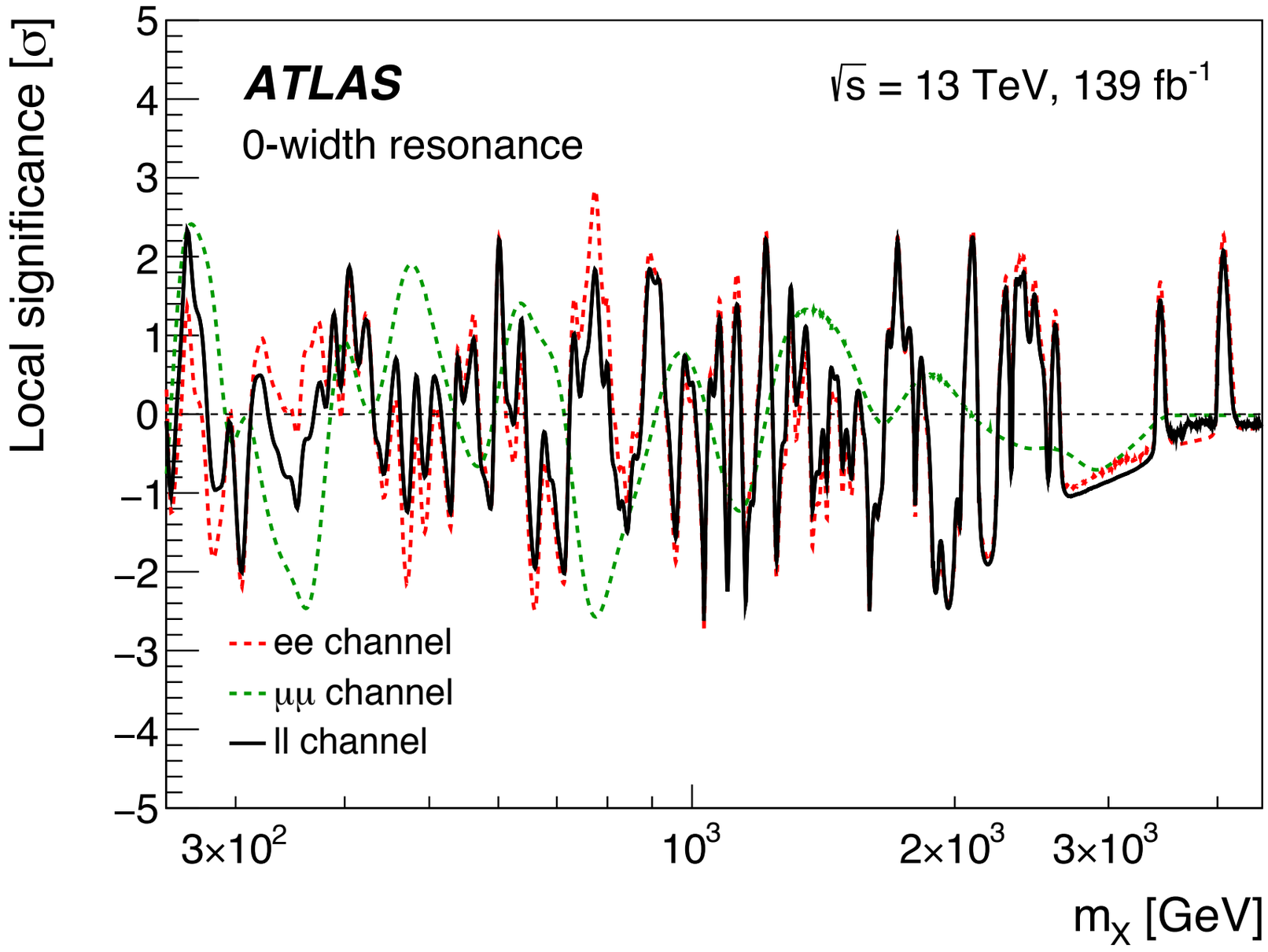
(theory) (detector)



"generic" signal model

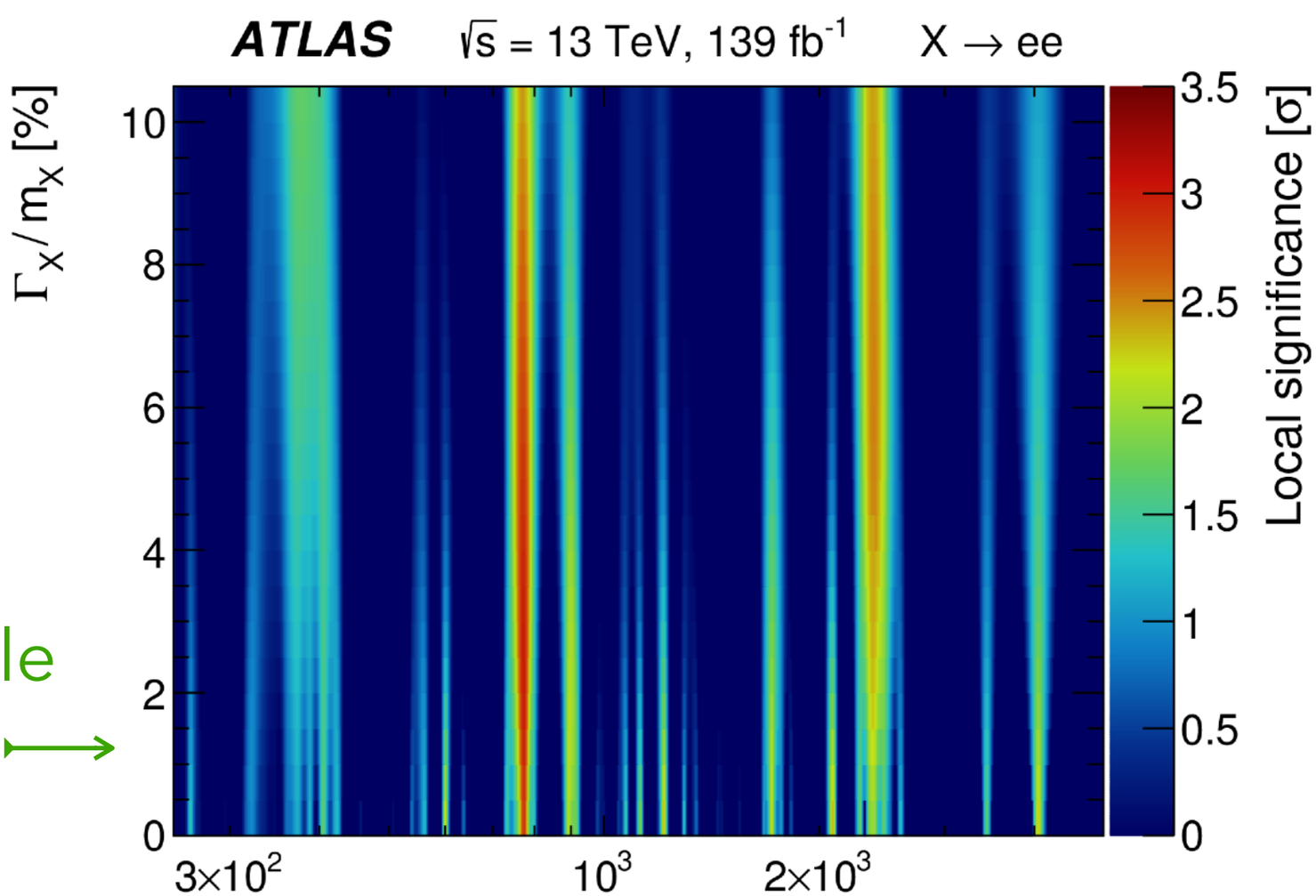
2 electrons

Local significance vs. mediator mass…



For very narrow ("zero width") resonances

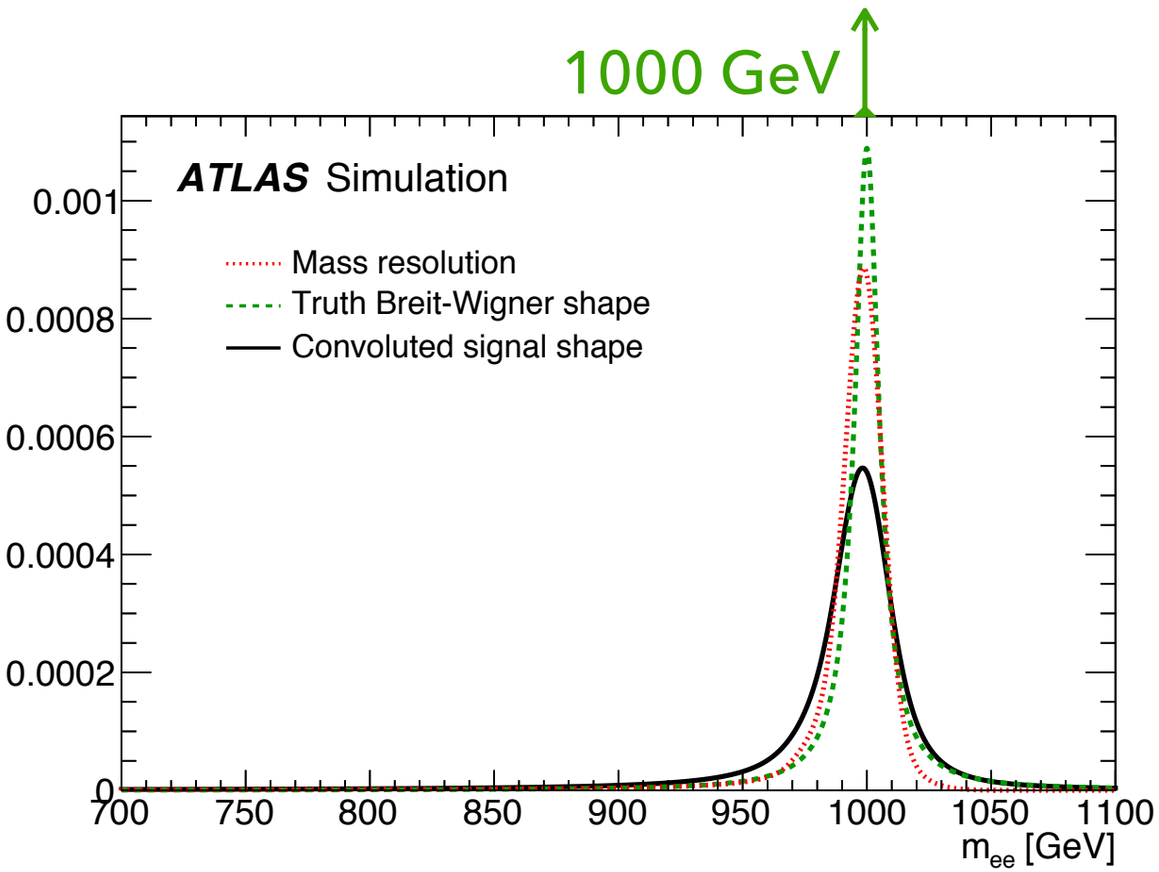
Channel	p_0 (local) $[\sigma]$	p_0 (global) $[\sigma]$	m_X[GeV]	Γ/m_X[%]
ee	2.9	0.1	774	0
$\mu\mu$	2.4	0.3	267	0
$\ell\ell$	2.3	$\lesssim 0$	264	0



example

1.2% ⟶

… testing significance of wide resonances

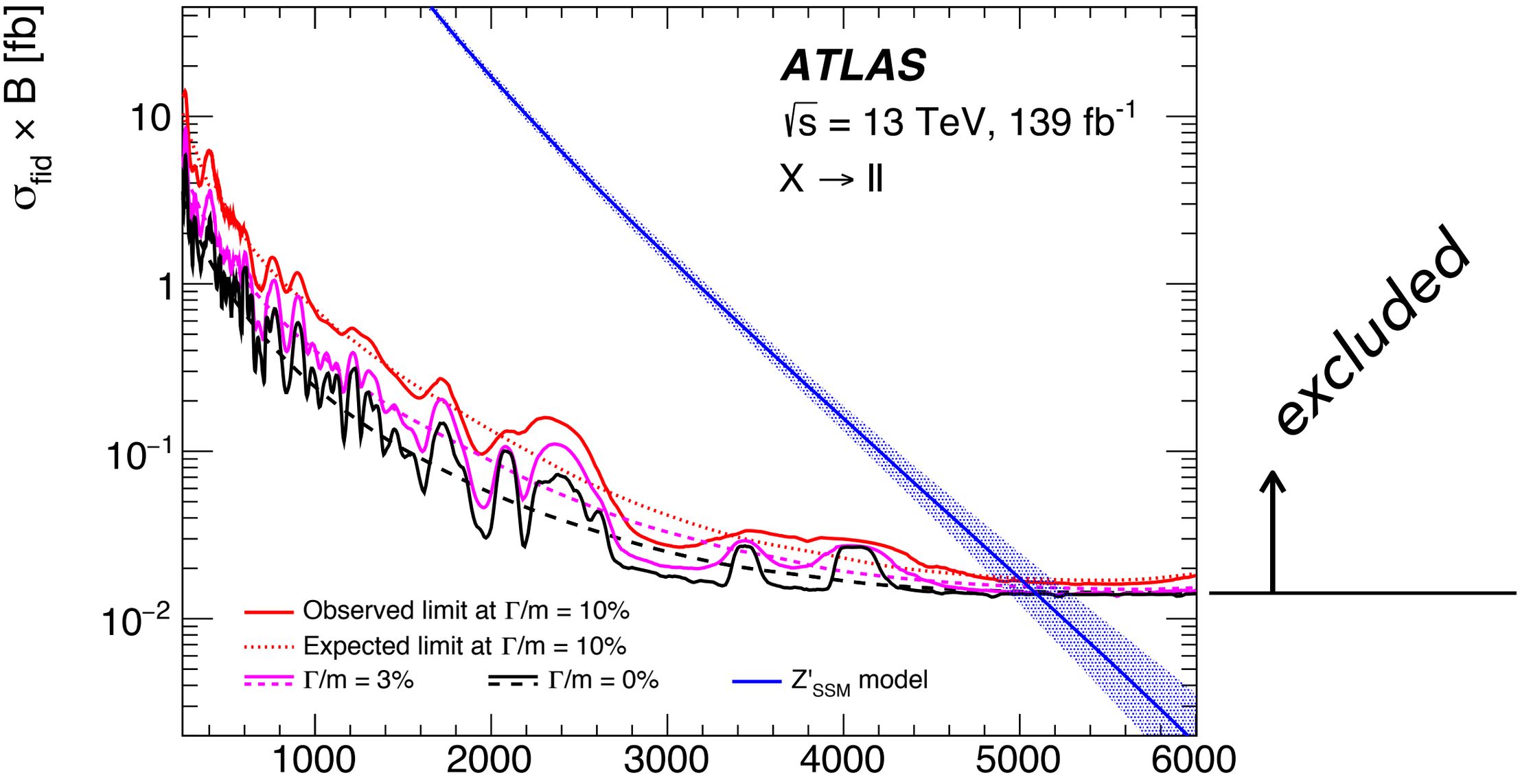


m_X [GeV]

<u>2 electrons</u>

Channel	Excess		
	p_0 [σ]	m_X [GeV]	Γ_X/m_X [%]
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

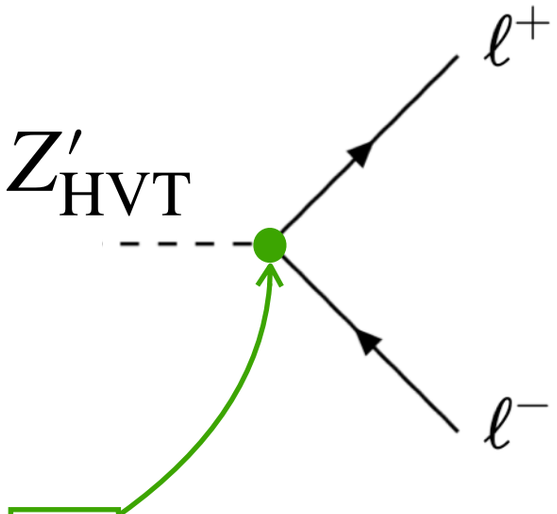
Cross section upper limits vs. mediator mass



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

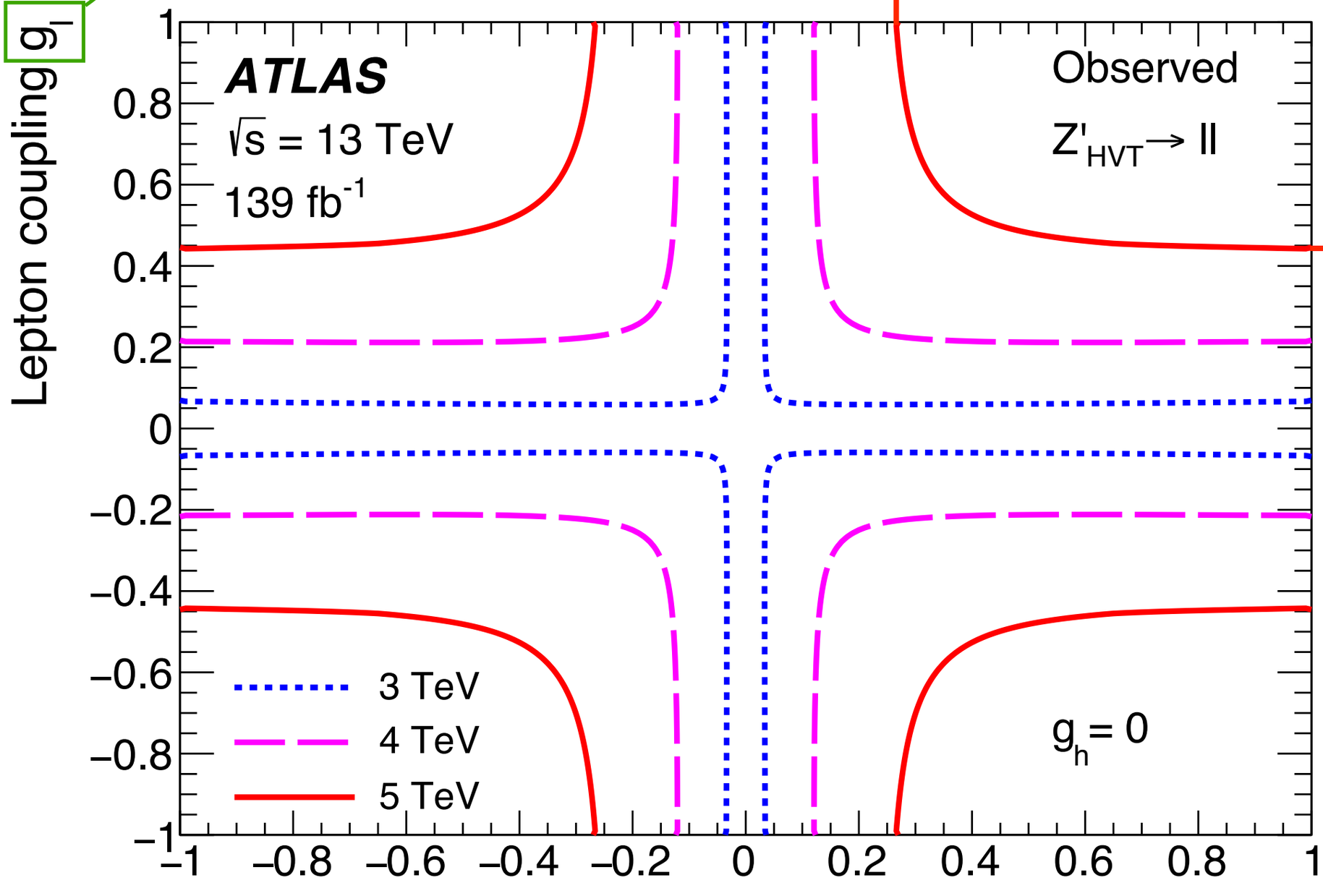
SSM mass limit = intersection with **3%** width generic cross section limit

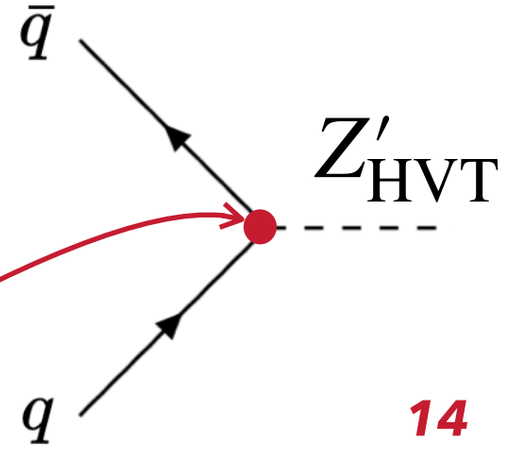
Implications for Heavy Vector Triplet Z′



Excluded cross sections imply

excluded couplings to SM





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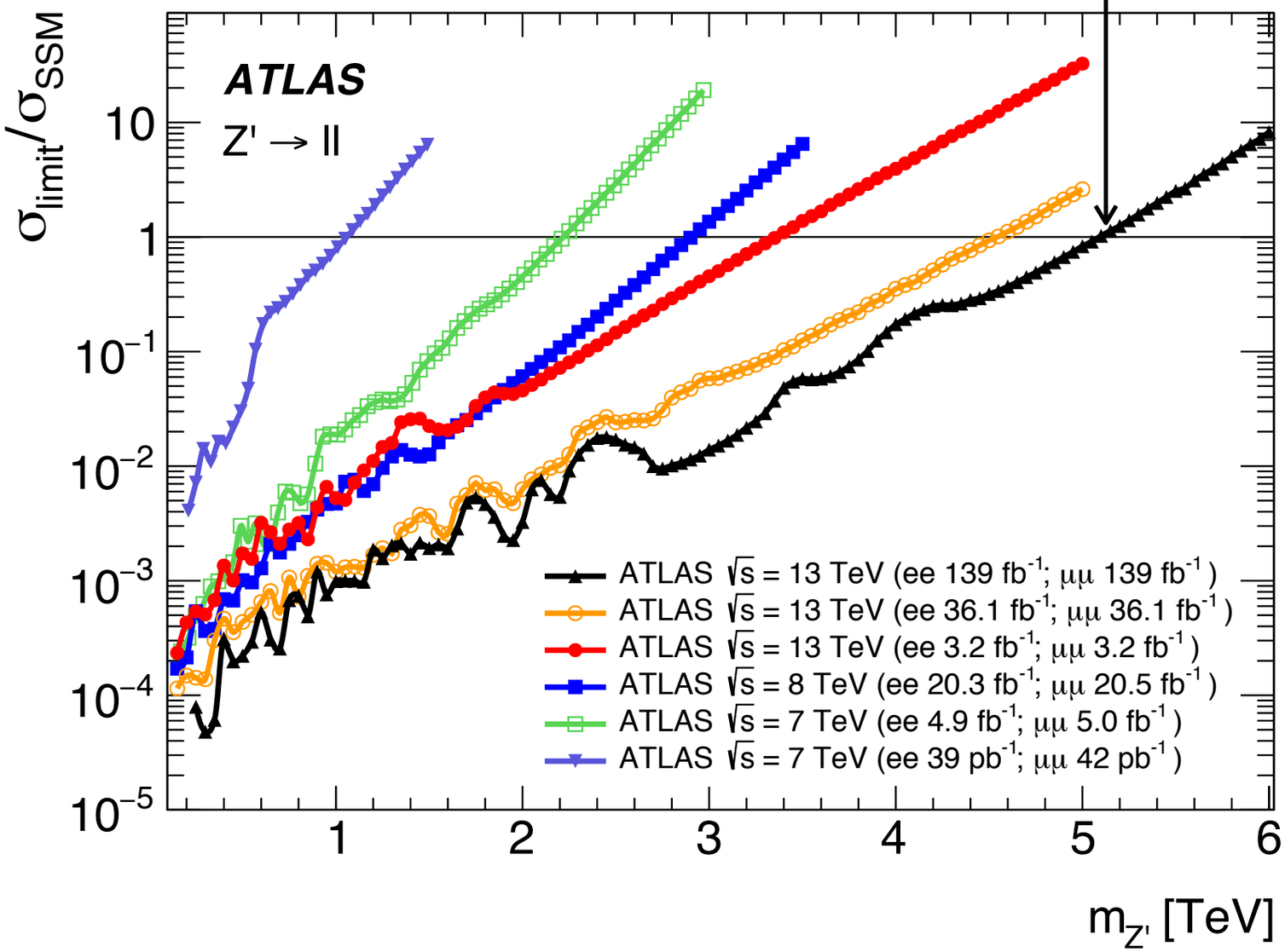
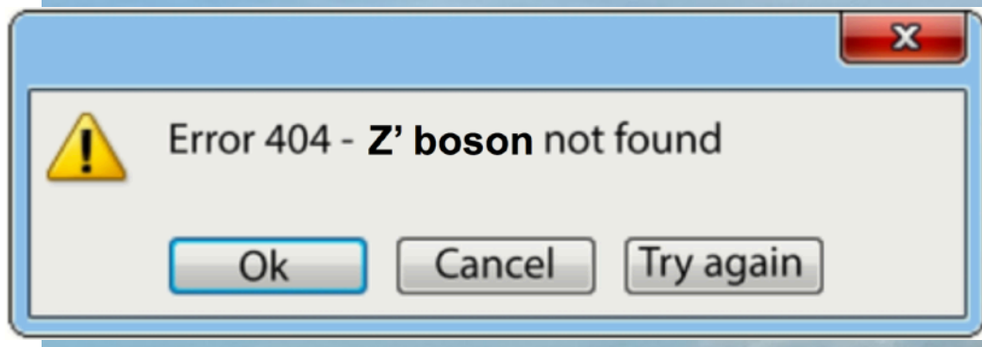


The end

- 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, ...)

Thank you…

... please come again

Bonus

Event selection

Electrons:

ID tracks + energy clusters in EMCal

no charge sign requirement

lowest unprescaled 2e trigger

$$E_T > 30 \text{ GeV}$$

$$|\eta| < 1.37 \text{ or } 1.52 < |\eta| < 2.47$$

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

$$|z_0 \sin\theta| < 0.5 \text{ mm}$$

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

$$p_T > 30 \text{ GeV}$$

$$|\eta| < 2.5$$

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

$$|z_0 \sin\theta| < 0.5 \text{ mm}$$

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

Background estimate

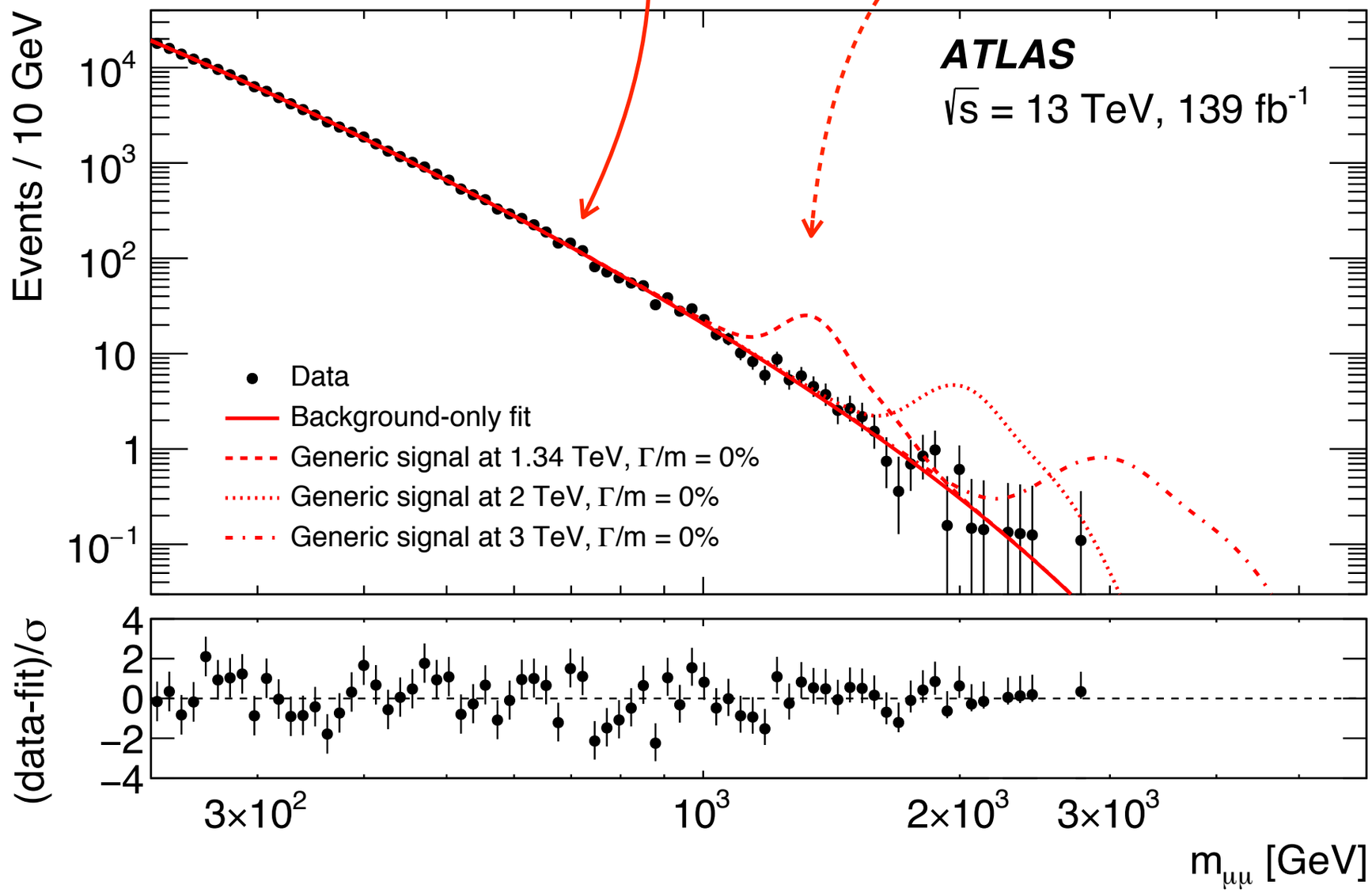
Fit the observed dilepton invariant mass spectrum:

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

smoothly falling function

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

(theory) (detector)



"generic" signal model

2 muons

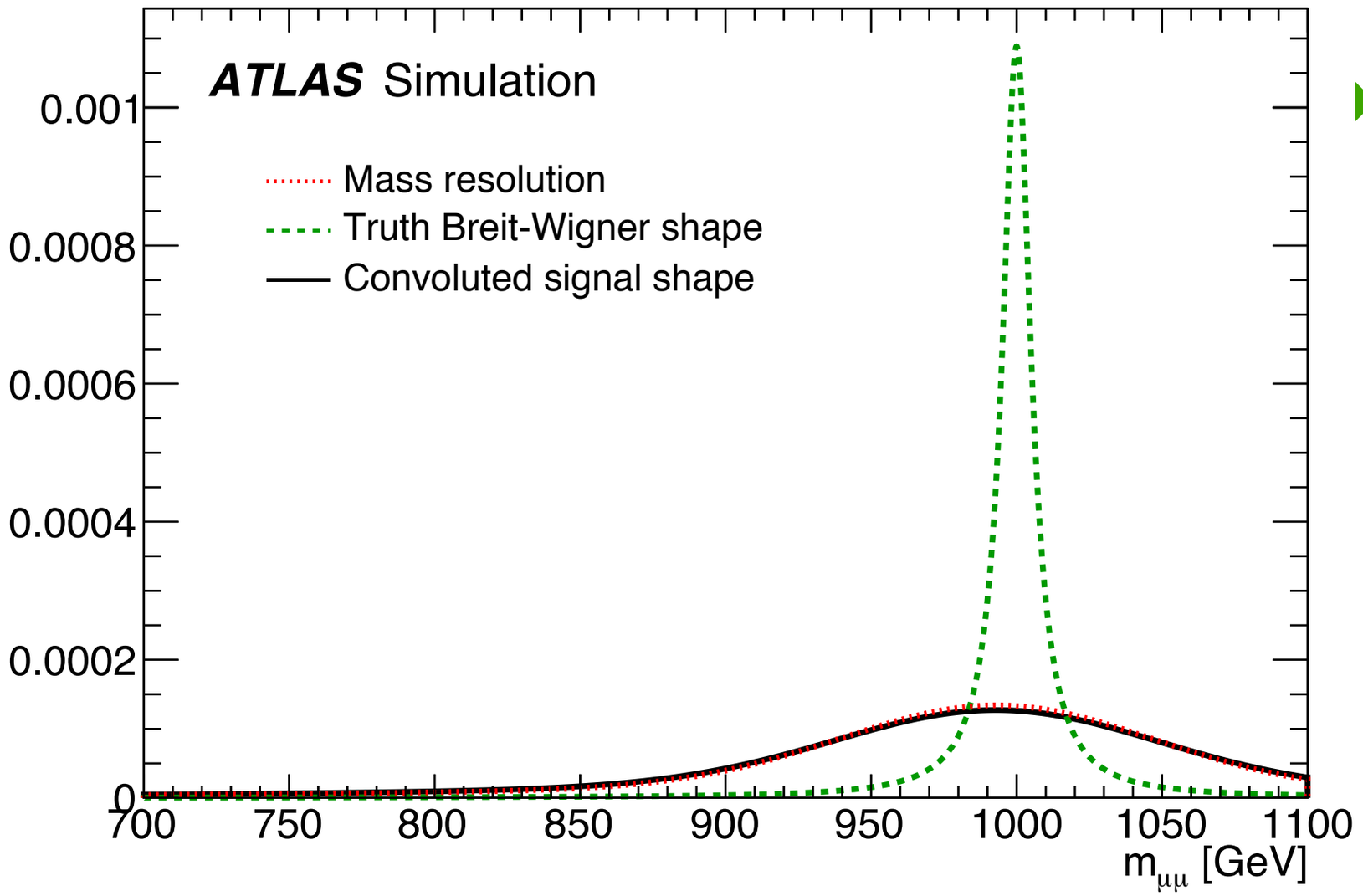
Signal model

convolution

non-relativistic

Generic signal = **Breit-Wigner** ⊗ **Relative $m_{\ell\ell}$ resolution**

(truth-level shape at given width) (modelled using simulated samples)



- Fiducial cuts:
  (for reinterpretation)

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

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

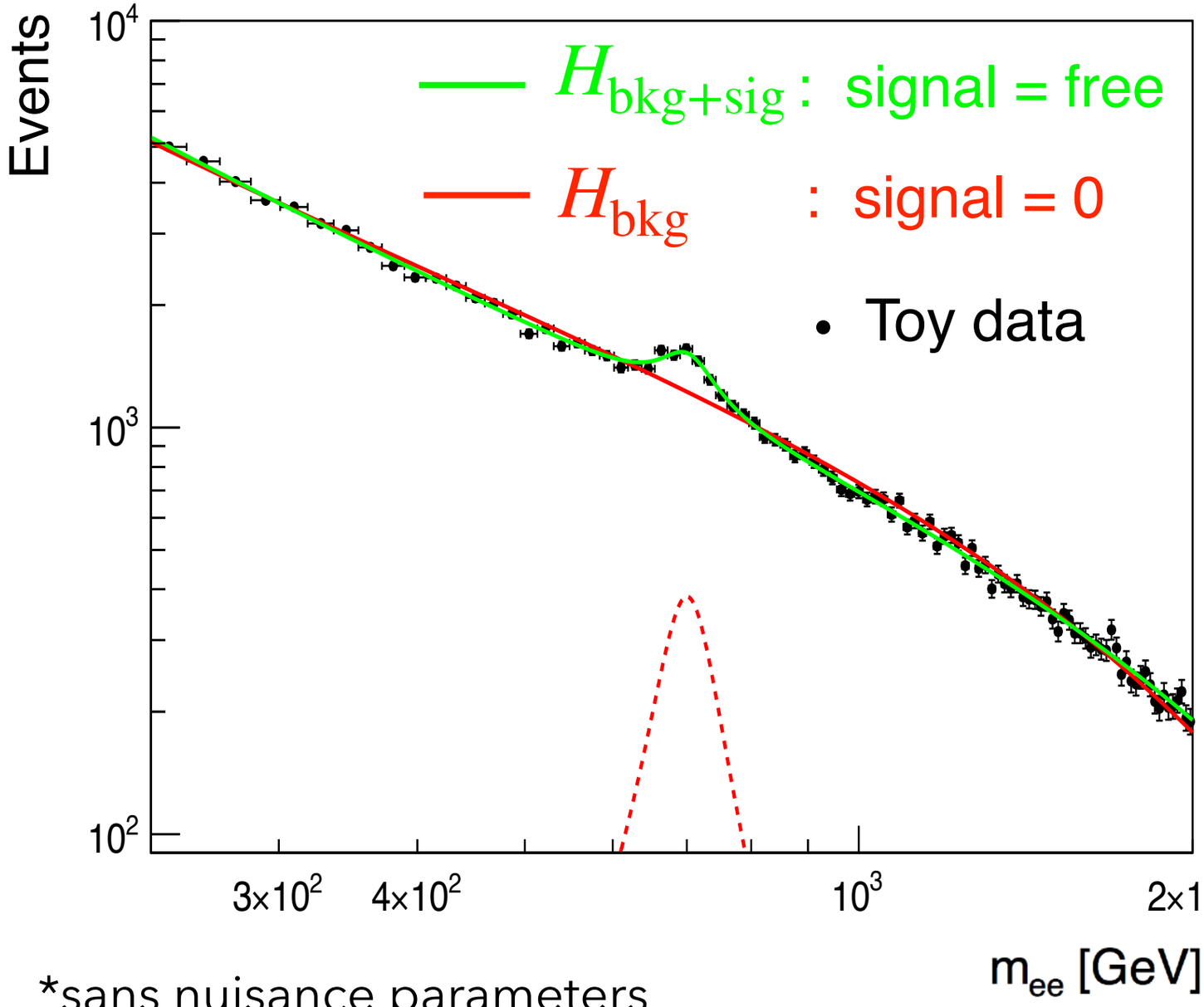
$$\left|\eta^{\text{lead}}\right|, \left|\eta^{\text{sublead}}\right| < 2.5$$

2 muons

Statistical analysis

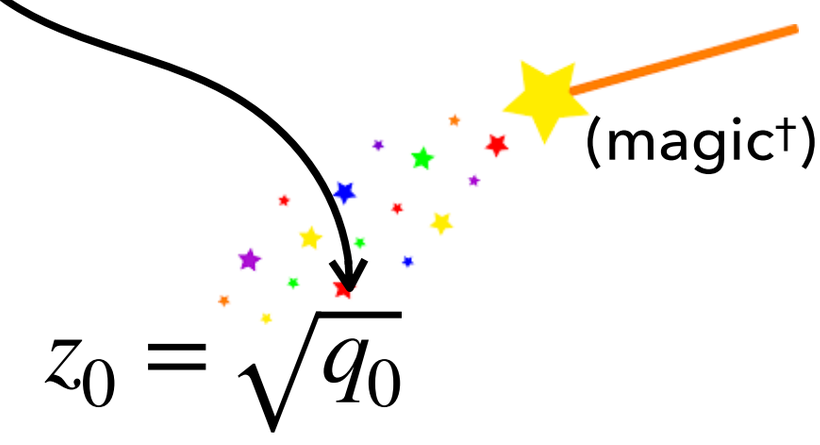
1) Likelihood*

$$\prod_{i \in \text{bins}} \text{Poisson}(n^i_{\text{obs}}, n^i_{\text{exp}} | H) = L(\text{data} | H)$$



$$q_0 = \ln \left[\frac{L(\text{data} | H_{\text{bkg+sig}})}{L(\text{data} | H_{\text{bkg}})} \right]^2$$

2) Test-statistic



$$z_0 = \sqrt{q_0}$$

3) Local significance

*sans nuisance parameters

†magic: G. Cowan et al., Eur. Phys. J. C 71 (2011) 1554

Background model details

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

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

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

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

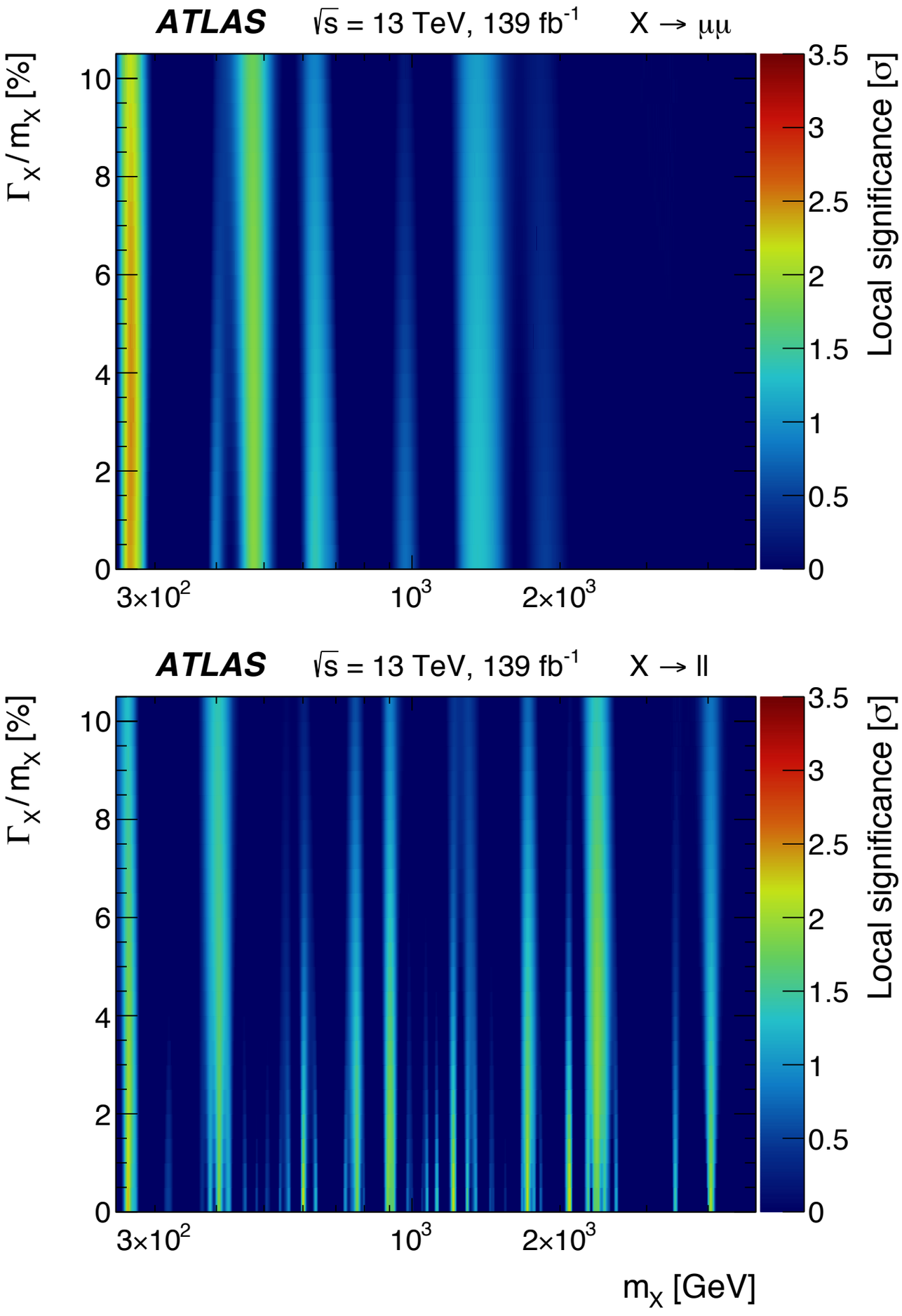
← normalization

- 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

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	$^{-1.7}_{-4.0}$ $\left(^{+1.0}_{-1.8}\right)$	$^{+0.1}_{-0.4}$ (± 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)	$^{+55}_{-35}$ $\left(^{+55}_{-35}\right)$

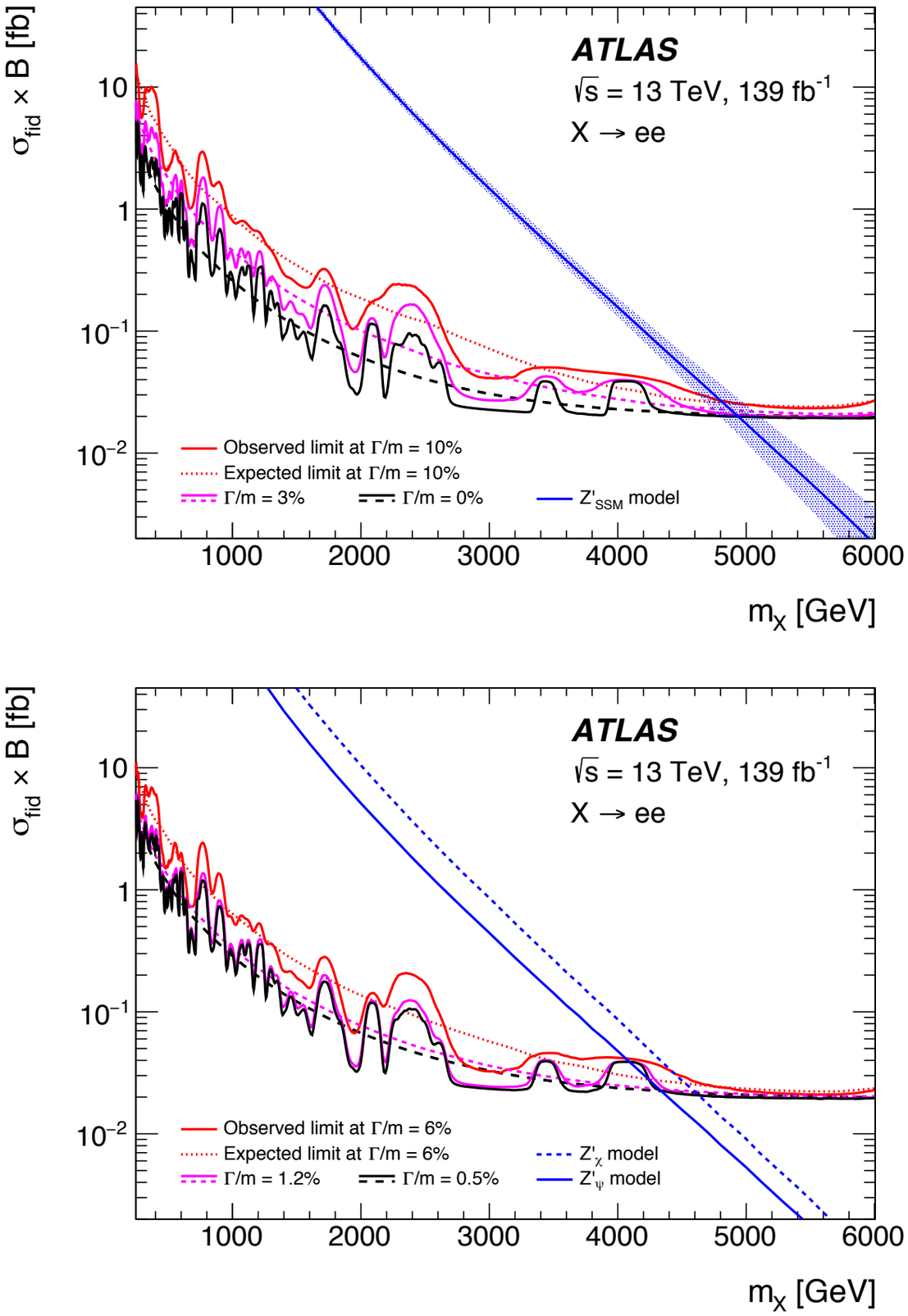
- Impact on signal strength from ±1σ pull on nuisance parameter

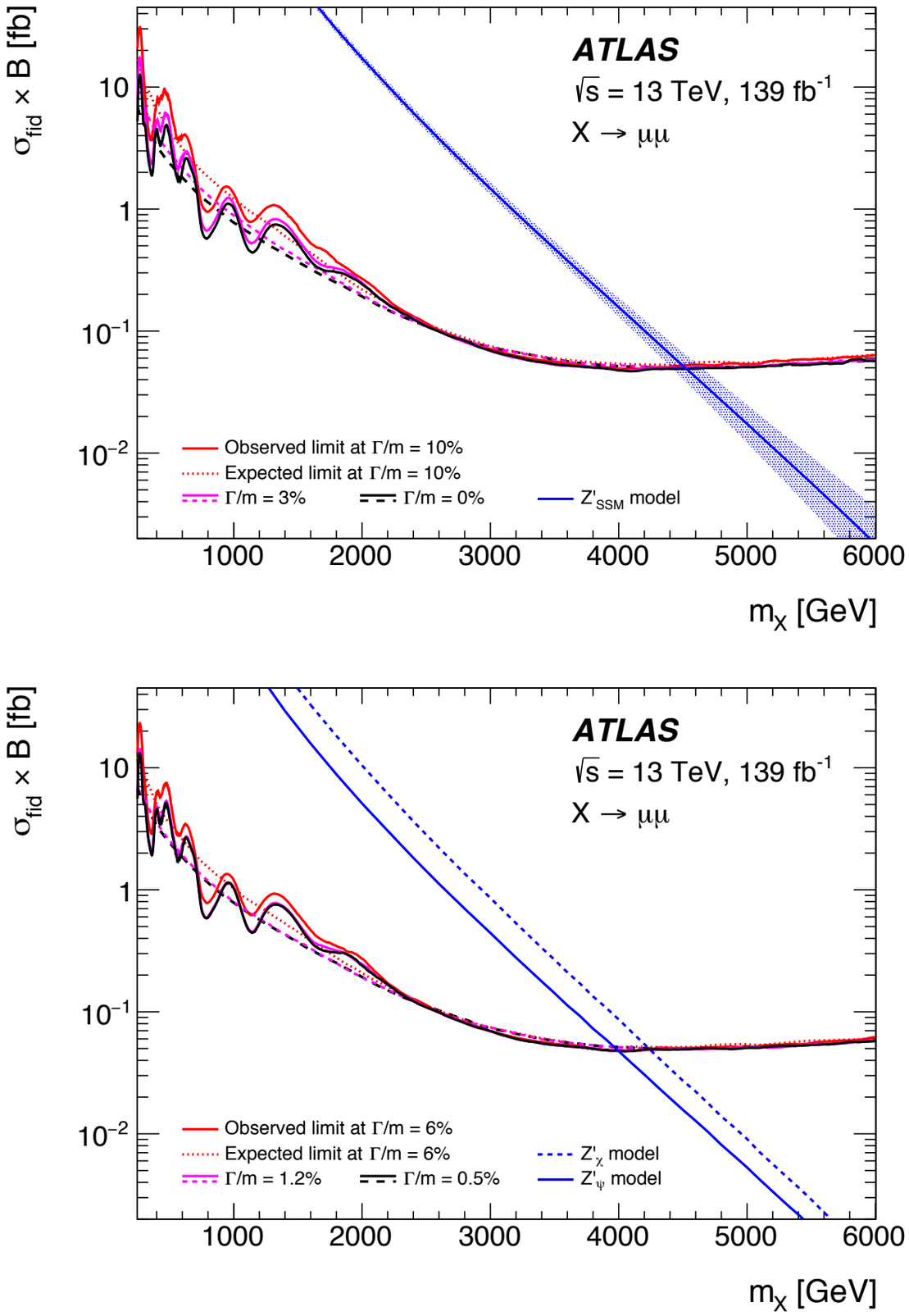


Additional 2D p-value scans

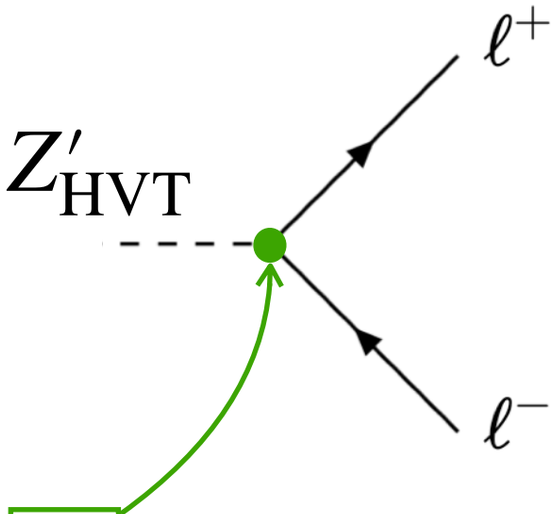
Channel	Excess		
	p_0 [σ]	m_X [GeV]	Γ_X/m_X [%]
ee	3.0	773	2.5
$\mu\mu$	2.5	268	2.5
$\ell\ell$	2.3	264	0
	Deficit		
	p_0 [σ]	m_X [GeV]	Γ_X/m_X [%]
ee	-3.2	1957	4.0
$\mu\mu$	-2.8	349	8.5
$\ell\ell$	-2.9	1958	3.0

Channel-wise cross section limits



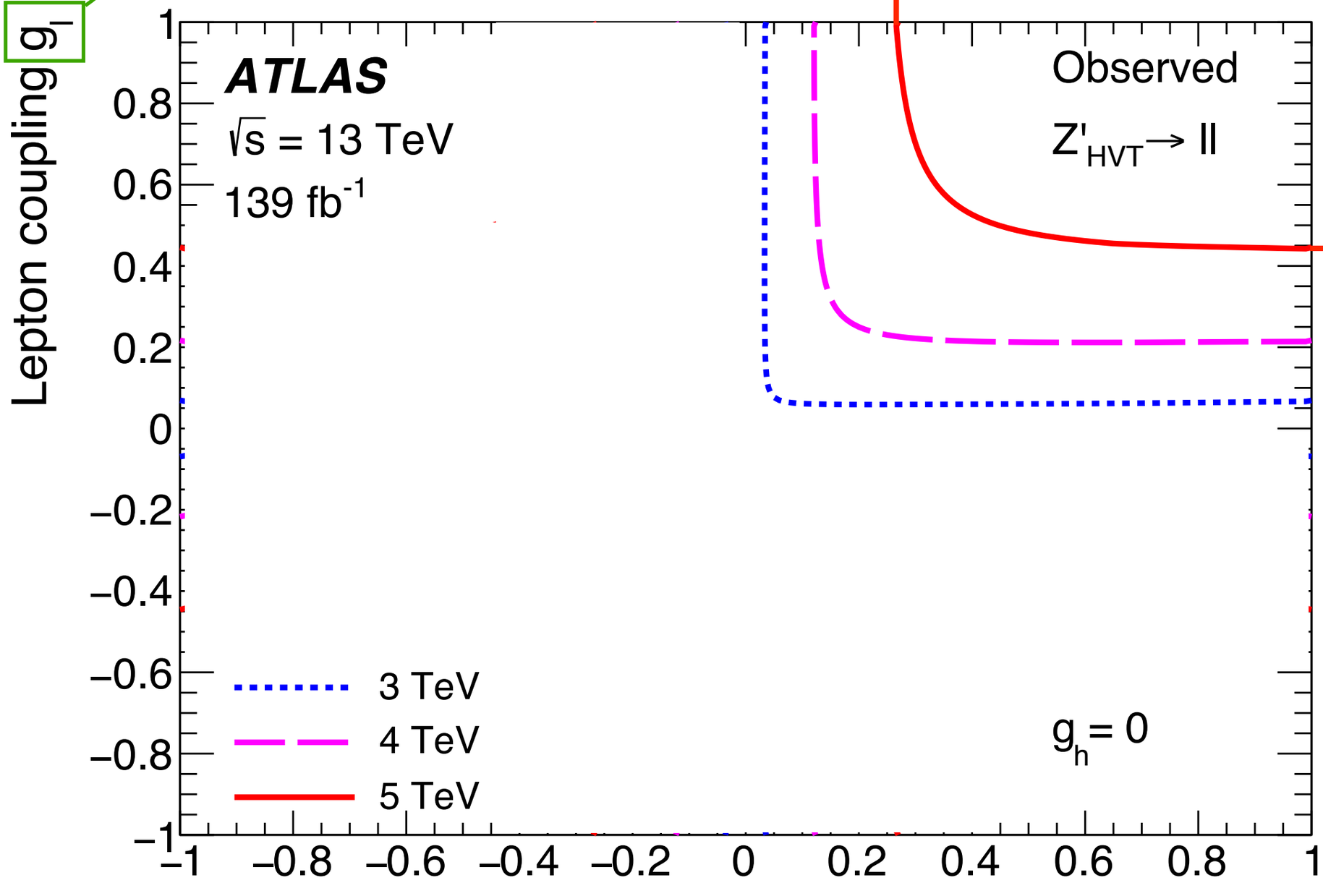


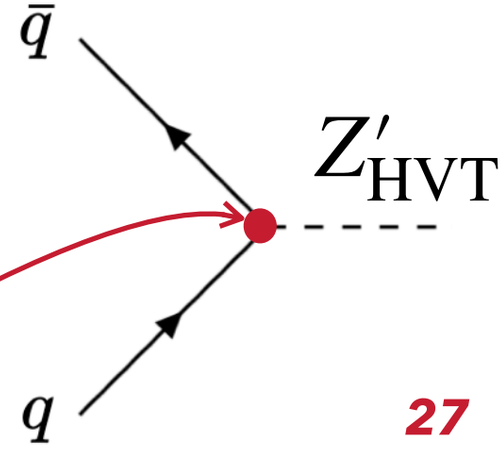
Implications for Heavy Vector Triplet Z′



Excluded cross sections imply

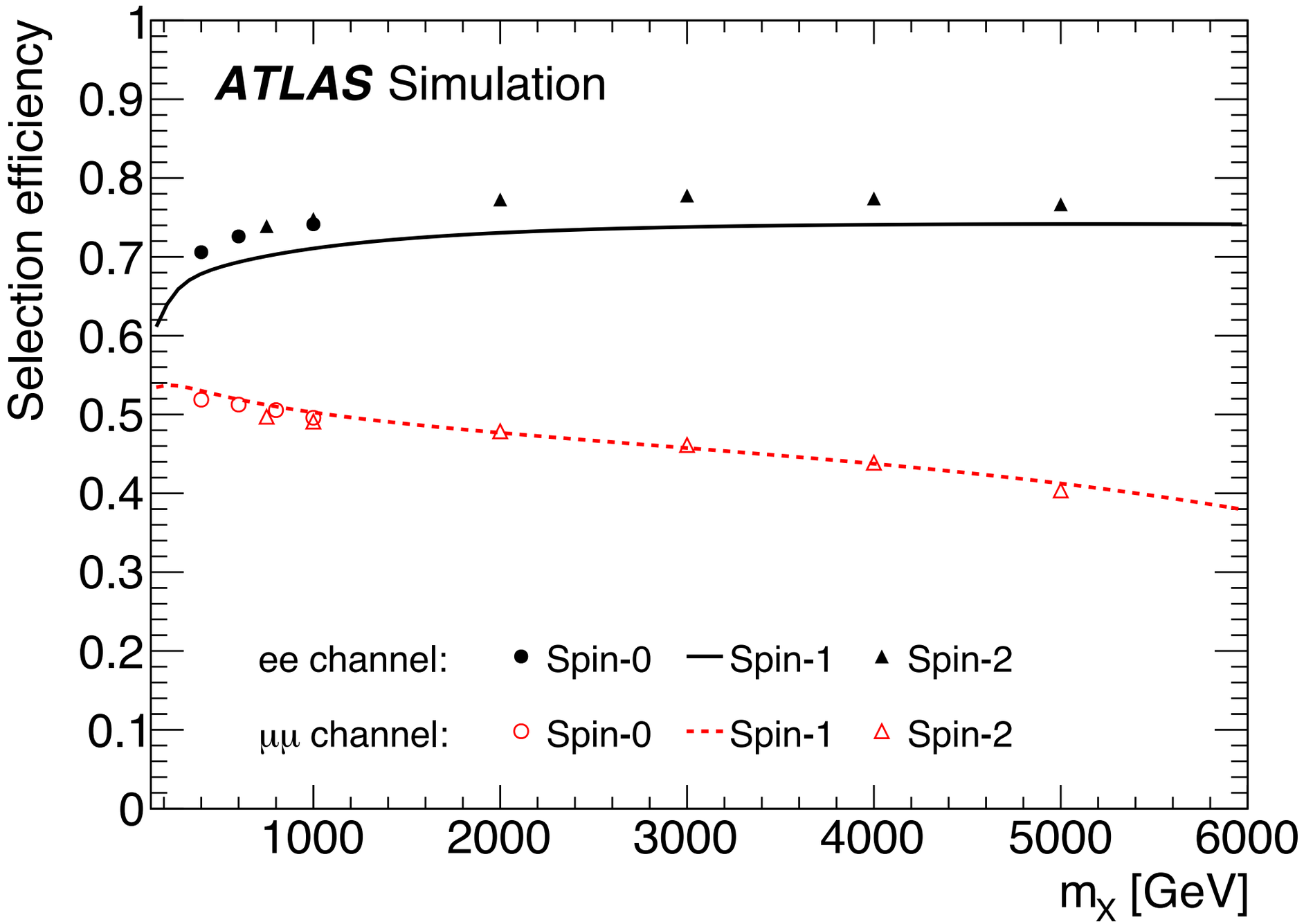
excluded couplings to SM



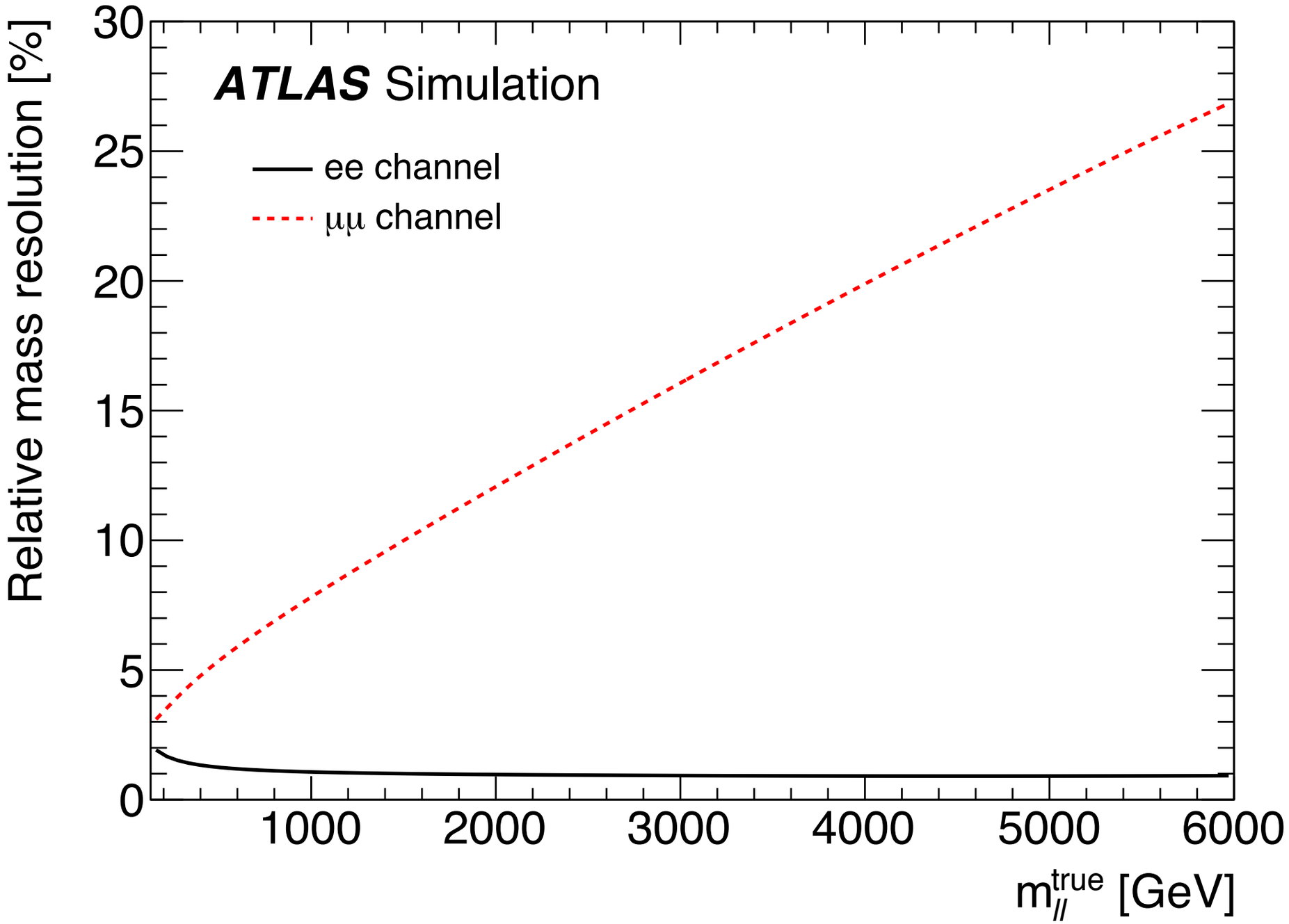


Selection efficiency

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



Relative invariant mass resolution



Implications for a Heavy Vector Triplet Z′

- Excluded cross sections ⟹ excluded couplings