ATLAS EXPERIMENT

The Hunt for the Z’ Boson in ATLAS:

A Statistical Perspective

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SFU SIMON FRASER UNIVERSITY
ENGAGING THE WORLD

Outline

1) Background

2) How do we search for a signal?

3) The *look-elsewhere* effect

4) Latest (public) search results

5) Summary

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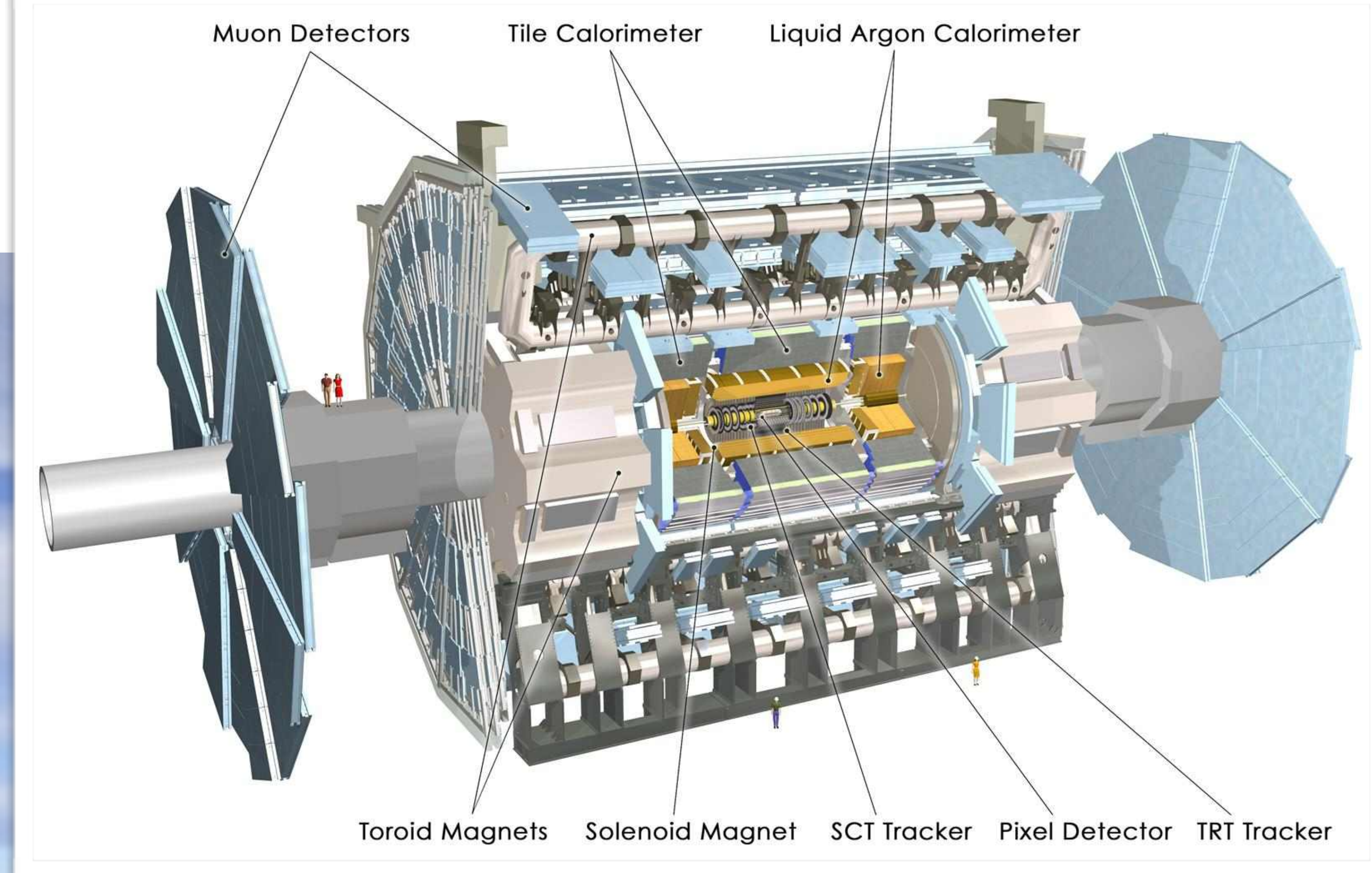
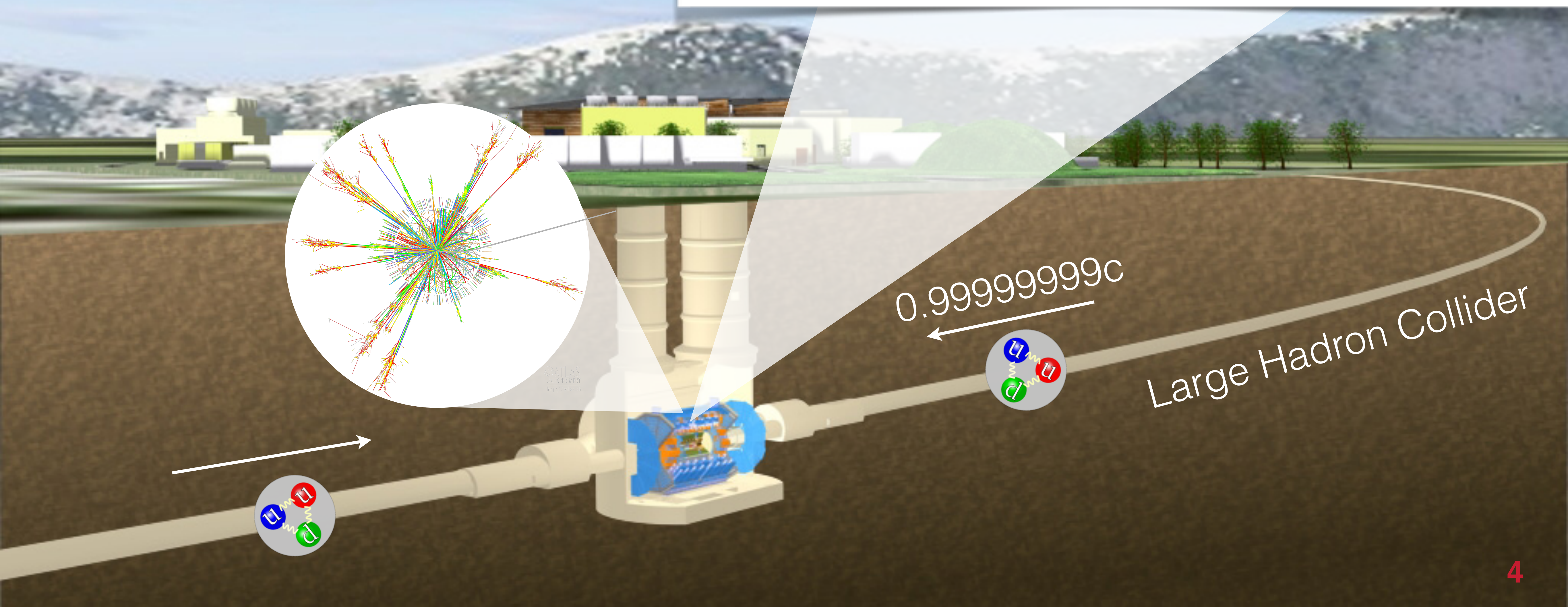
ATLAS

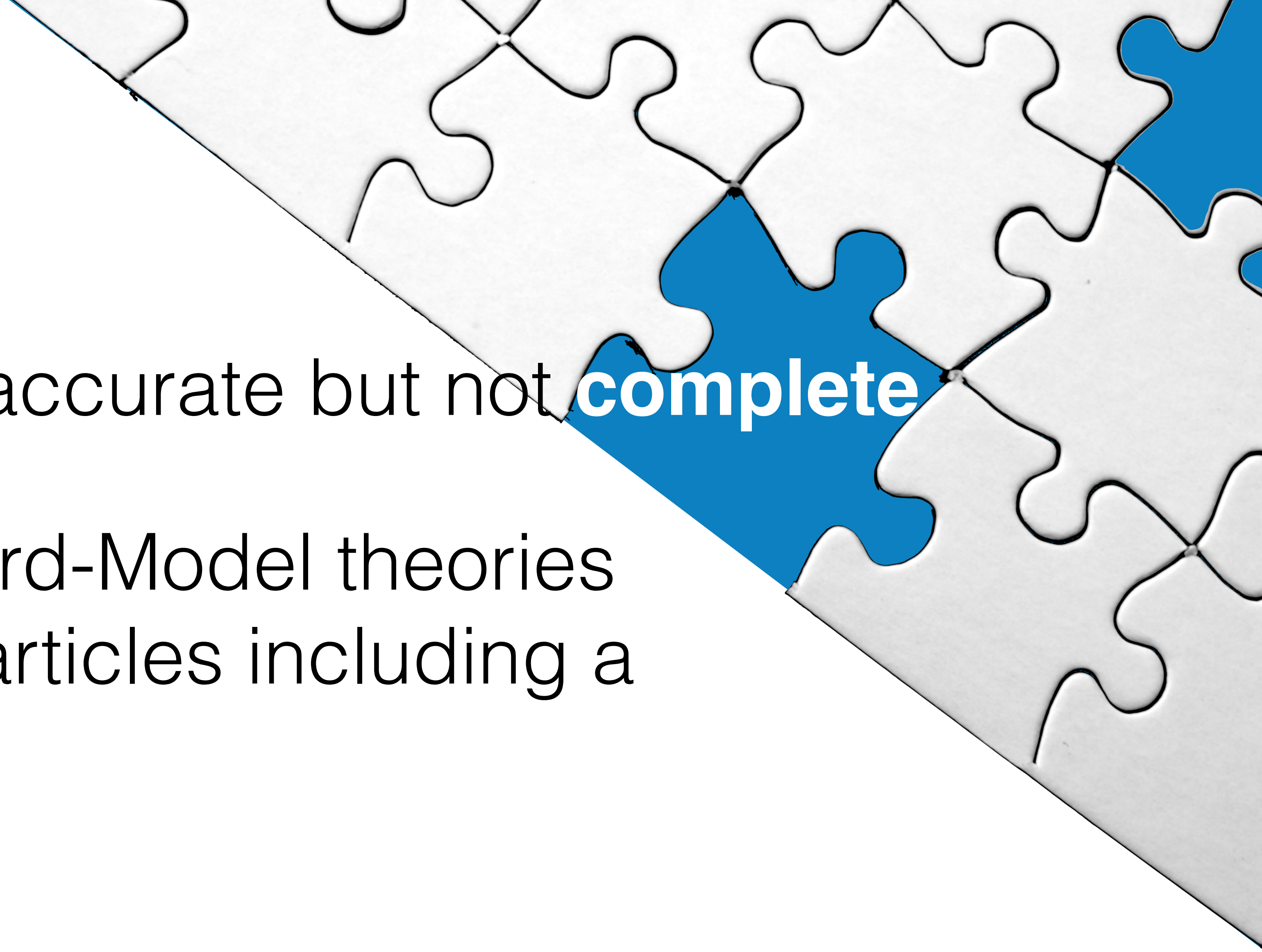
- 100MP camera
- Weight ~ Eiffel tower
- ~ 1 billion collisions/s





The Z’ Boson

- The *Standard Model* is accurate but not **complete**
- Several beyond-Standard-Model theories predict exotic gauge particles including a neutral *Z' boson*



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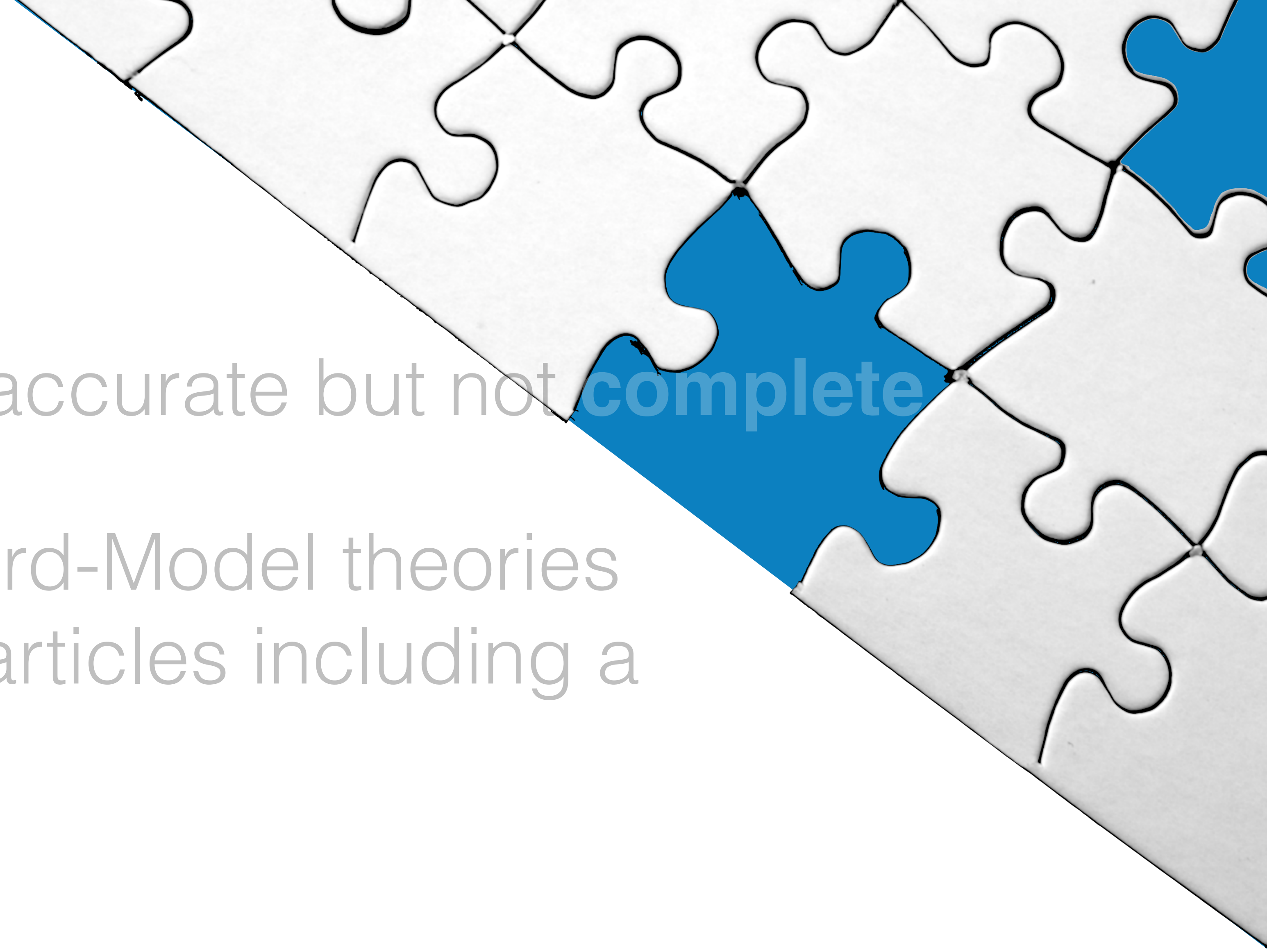

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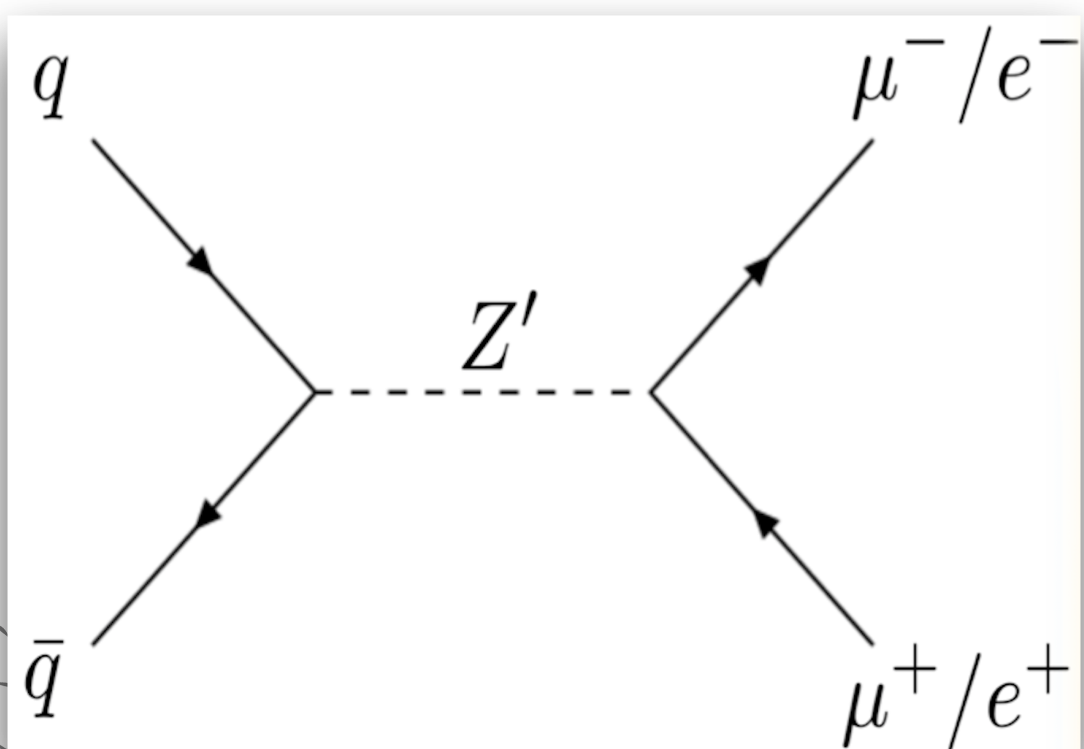
$$Z' \to \ell^+ \ell^-$$

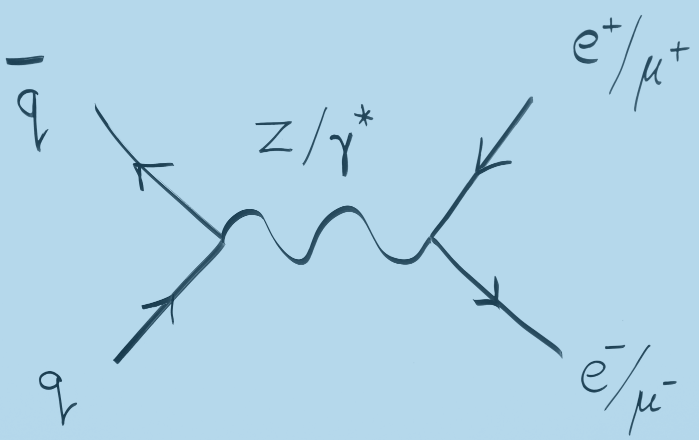


- Similar to the electroweak Z boson but heavier
- Should produce an excess number of lepton pairs with energies clustered around the Z’ mass (*resonance*)

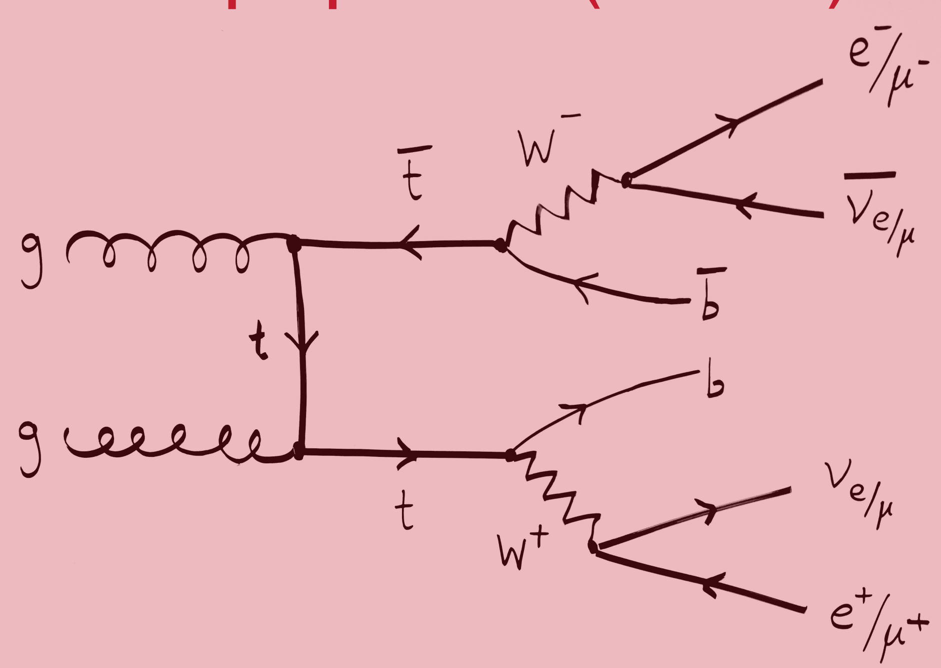
Hunting the Z’ in ATLAS

- *Background* processes also produce dilepton final states

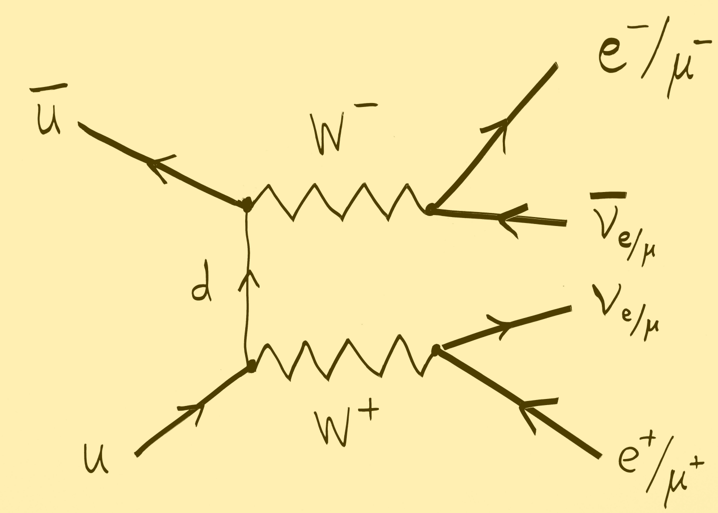
Drell-Yan (Z/γ^*)



Top quarks (t t-bar)



Diboson (WW, WZ, ZZ)

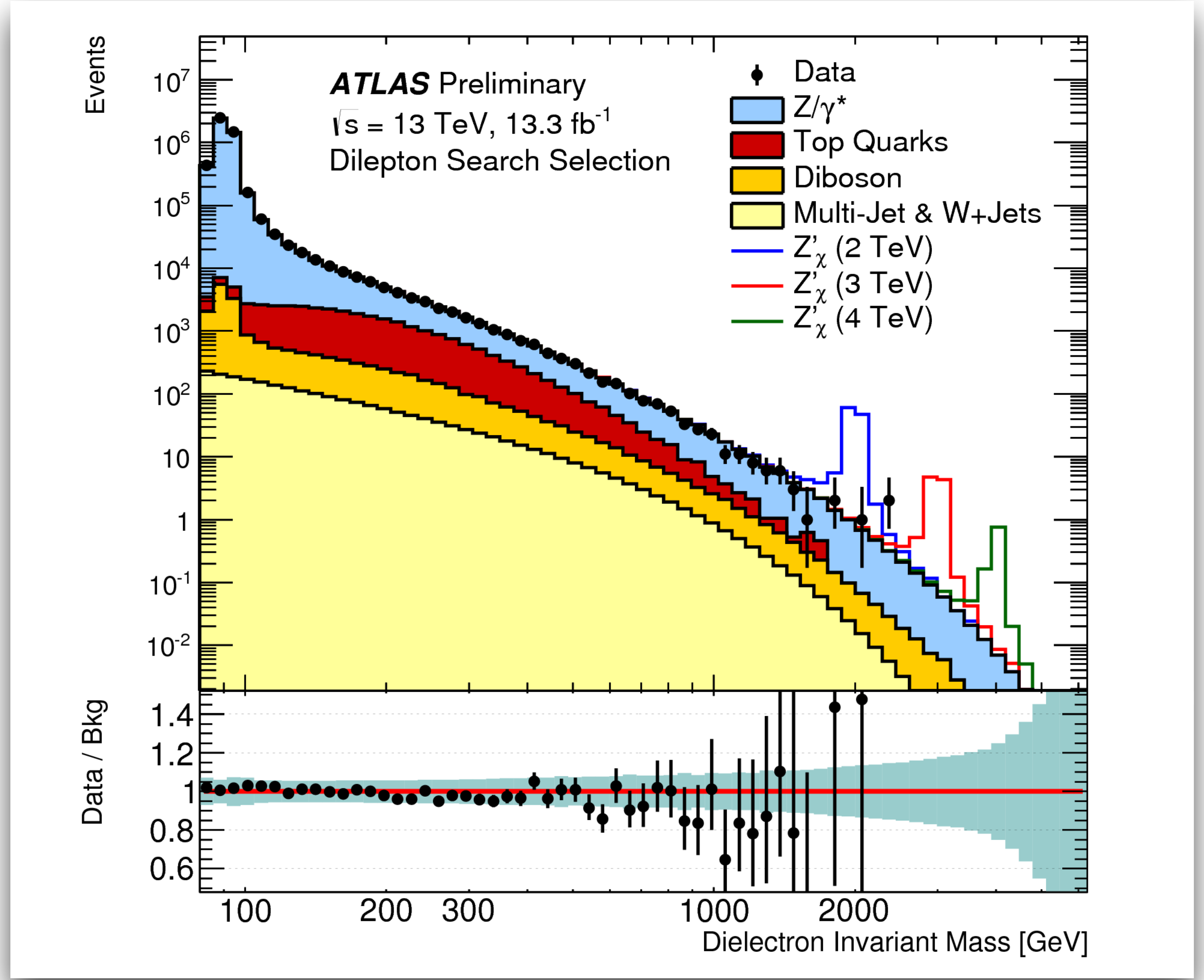


← Increasing cross section

also multi-jet and W+jets events where jets fake electrons (small)

- Simulate how many lepton pairs to expect as a function of their *invariant mass* and compare to the actual number recorded by ATLAS

Mass spectrum (ee channel)



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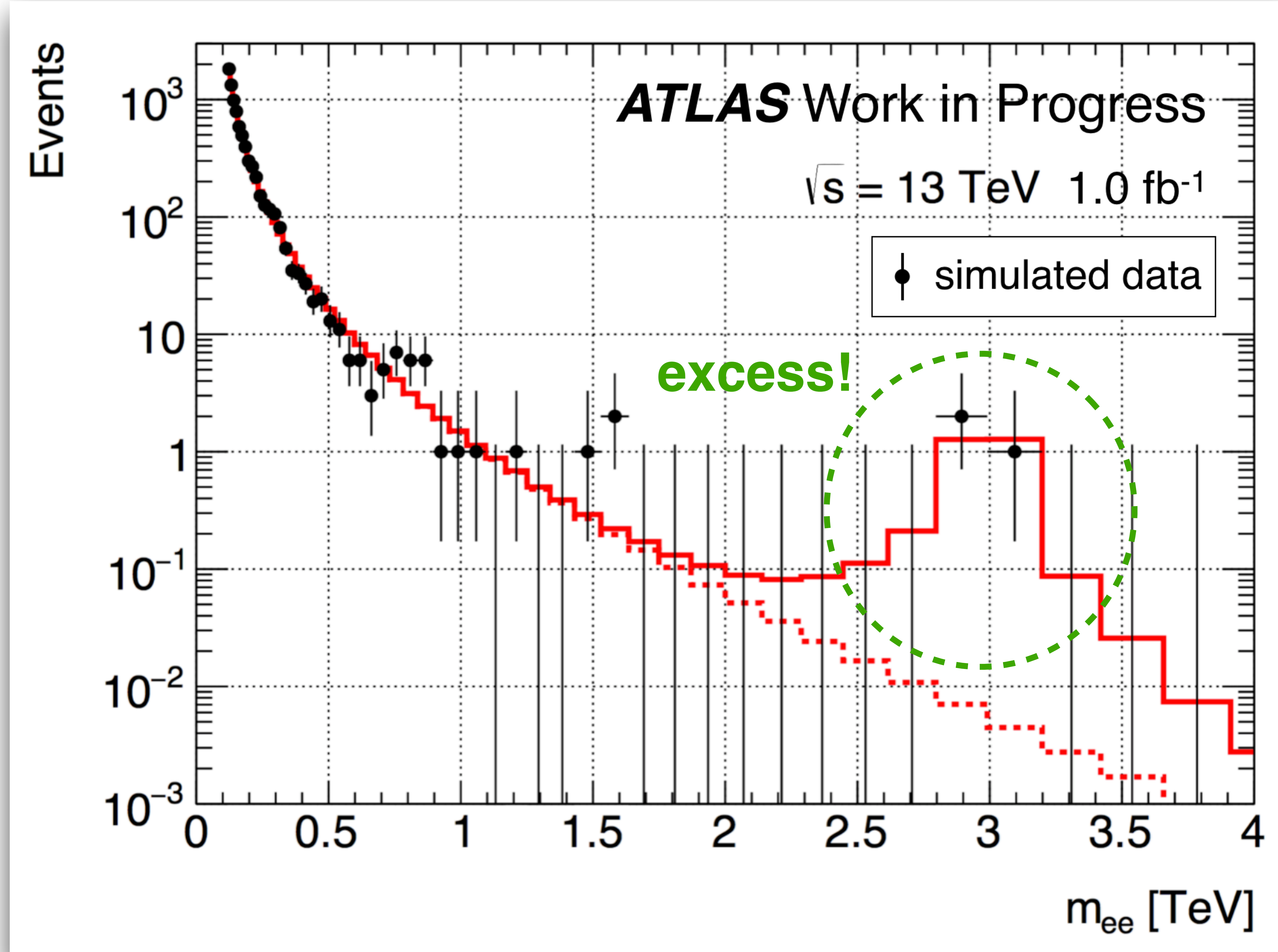
maybe in 2017...

Pseudodata with injected 3 TeV signal



Search for signals using templates

- What's the *likelihood* of getting these data under the background-only vs. the signal+background hypotheses?

$$\mathcal{L}(\mathrm{data}|H) = \prod_{i\in \mathrm{bins}} \frac{\left(N_i^{\mathrm{exp}}|H\right)^{N_i^{\mathrm{obs}}} e^{-(N_i^{\mathrm{exp}}|H)}}{\left(N_i^{\mathrm{obs}}\right)!}$$

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signal strength (μ)

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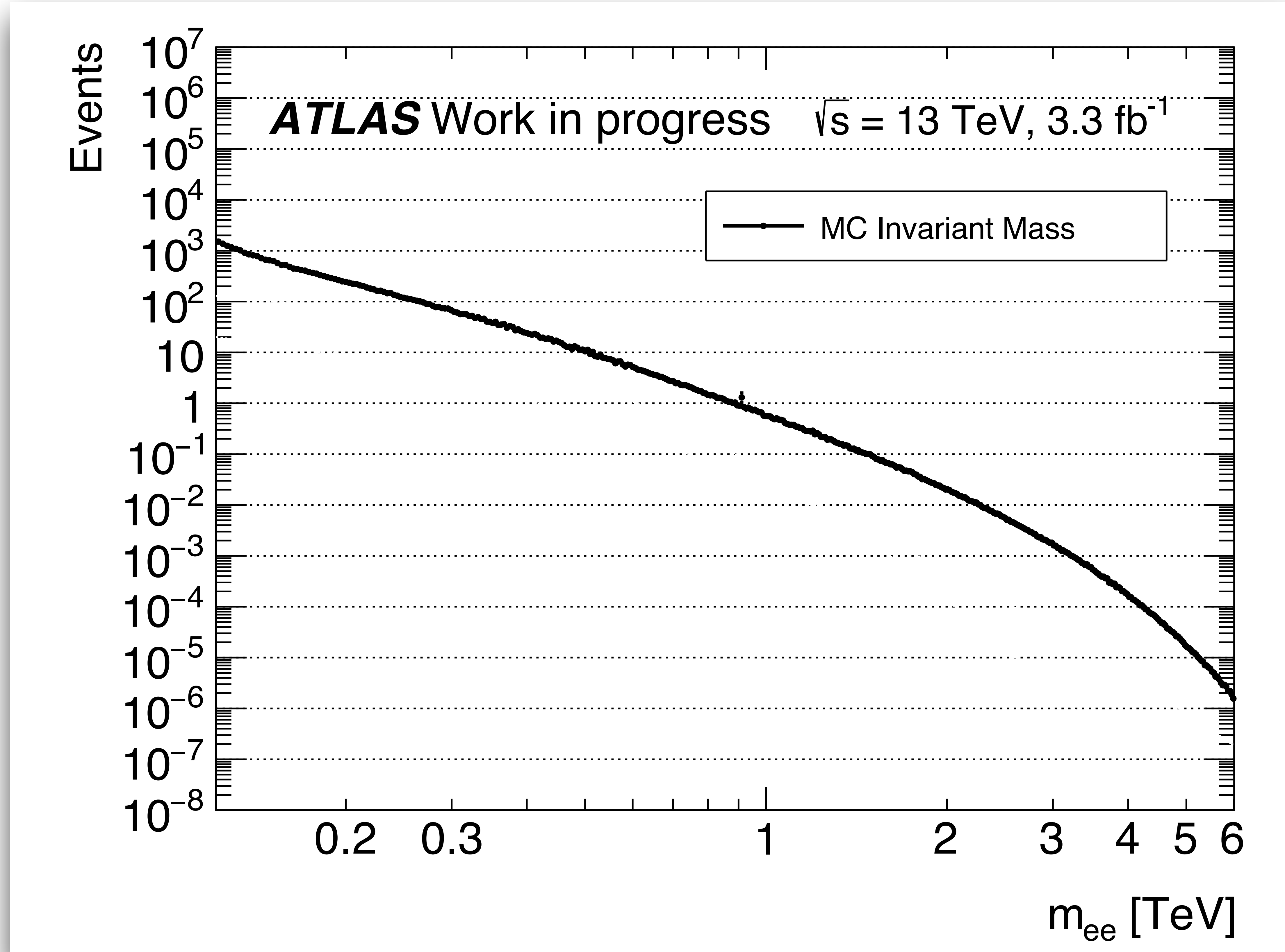
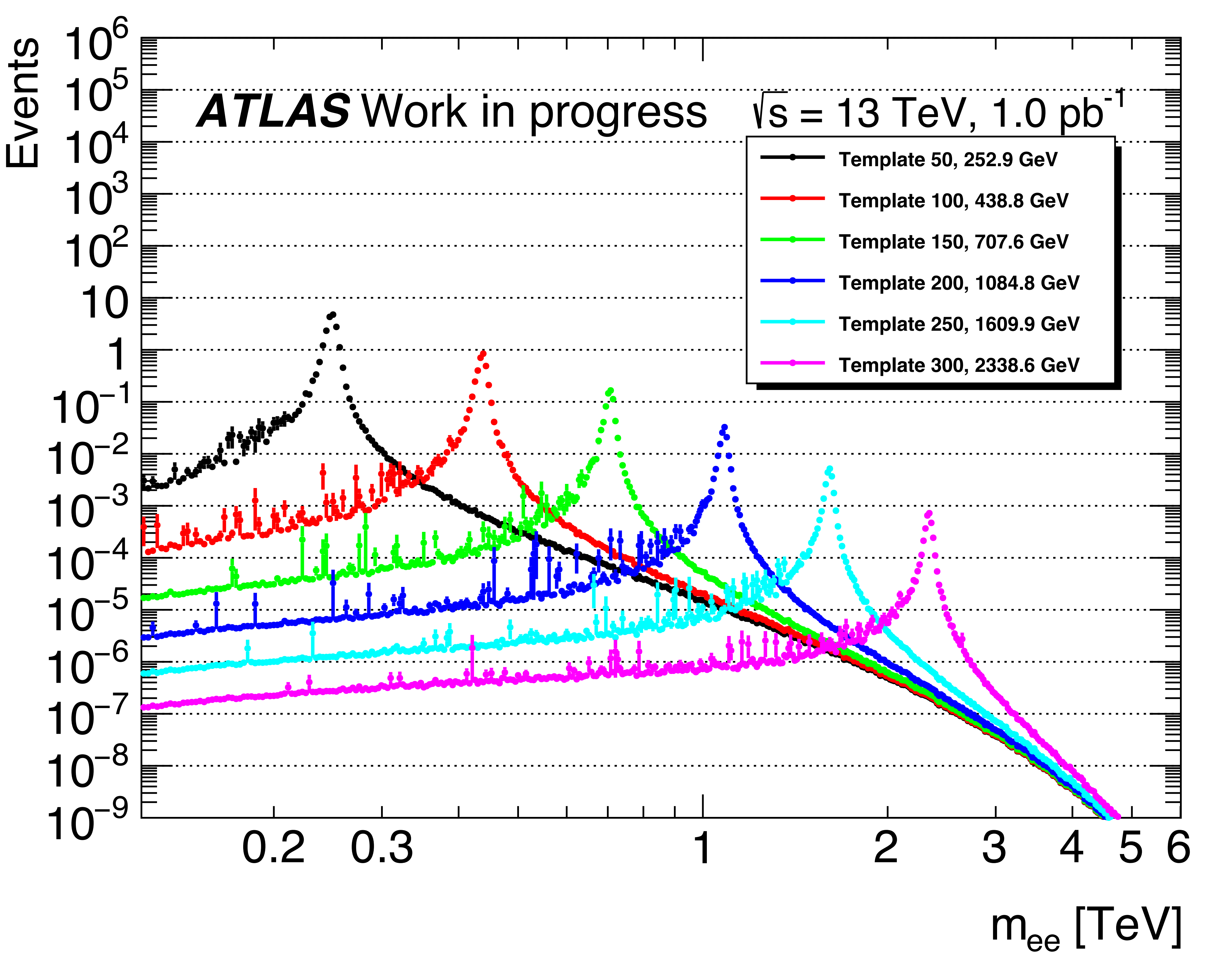
signal strength

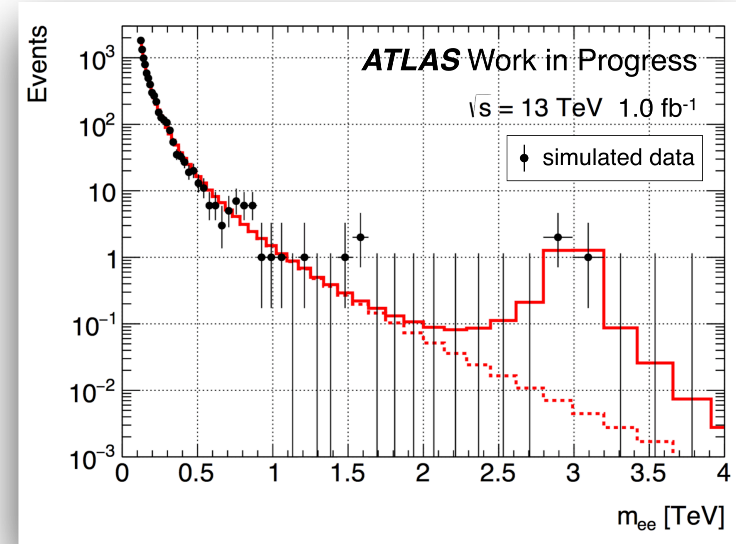
- We find the maximum likelihood under both hypotheses by fitting the data with *templates* of the background and signal distributions

ee background template



ee signal templates (sampler)



“data” = 

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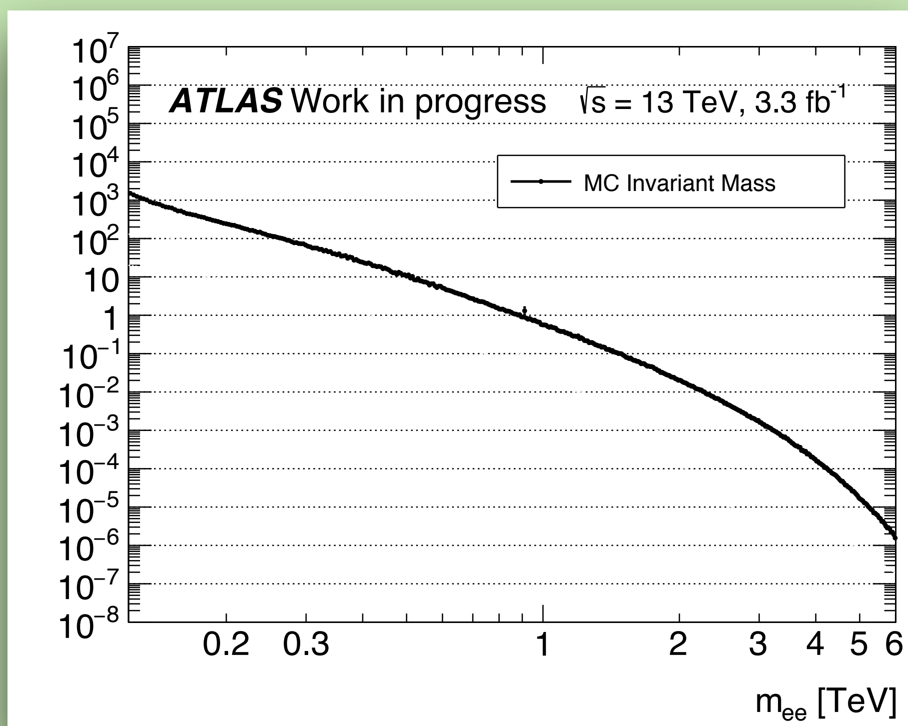
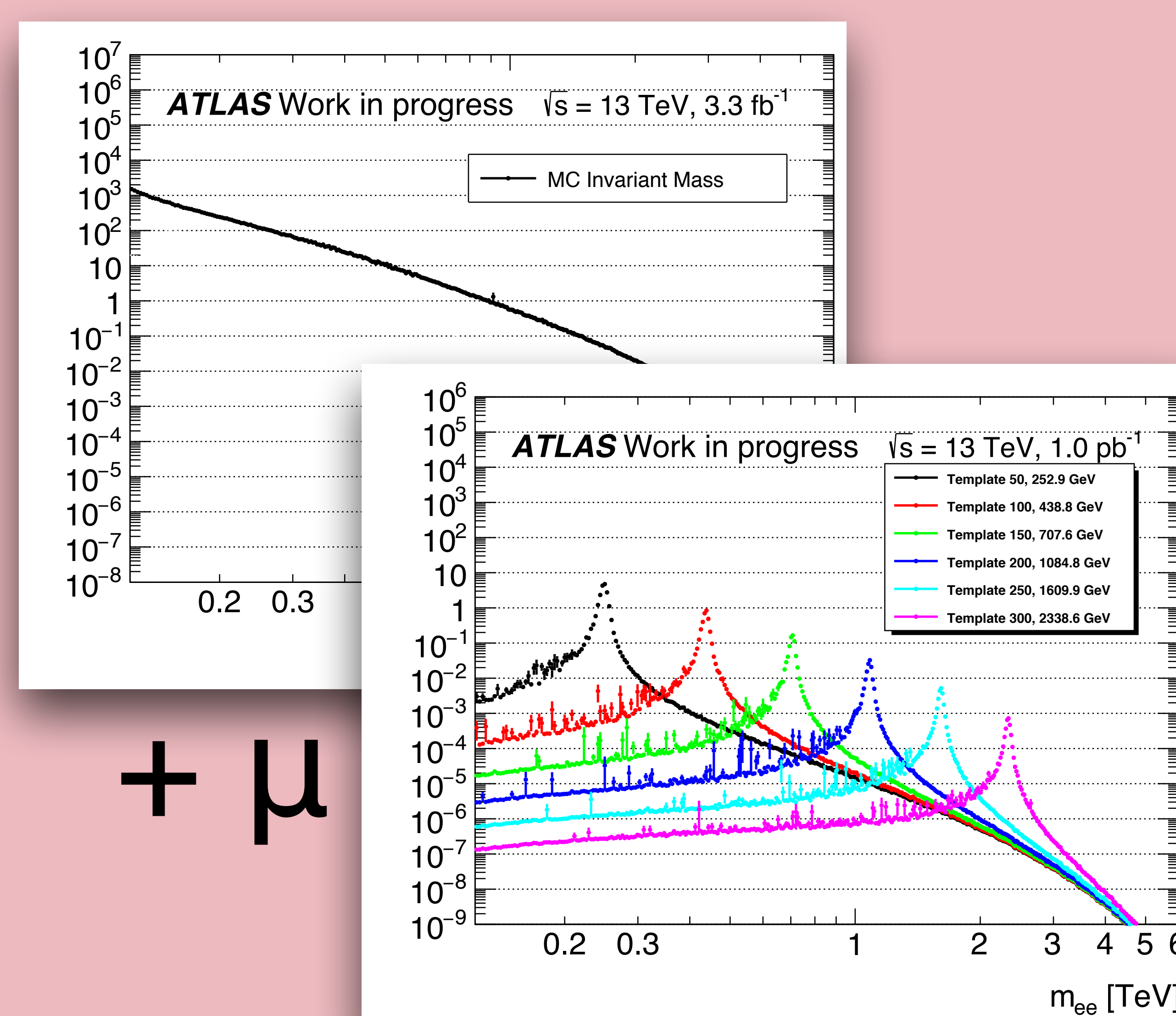
Background-only Hyp



$$\mathcal{L}(data|H_{\mathrm{B}})$$

OR

Background plus signal Hyp



+ μ

$$\mathcal{L}(data|H_{\mathrm{B+S}})$$

Deciding between hypotheses

- How should we evaluate the difference in the data's likelihood under the two hypotheses?

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- Neyman-Pearson Lemma:
  The optimal test statistic for distinguishing between hypotheses is the "log-likelihood-ratio" (*LLR*):

$$q_0 = \ln\left[\frac{\mathcal{L}(data|H_{\mathrm{B+S}})}{\mathcal{L}(data|H_{\mathrm{B}})}\right]^2 \times \mathrm{Sign}(\hat{\mu})$$

best-fit signal strength

Deficit	Nominal	Excess
$q_0 < 0$	$q_0 = 0$	$q_0 > 0$

The odds of being fooled

Q: What's the odds the observed $\hat{q}_0$ is a bkg fluctuation?

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- We can generate many bkg-only pseudo experiments (*toys*) and count how many fluctuate with $q_0 \geq \hat{q}_0$
- *Wilks' Theorem* ⇒ q_0 should asymptotically follow a χ^2 distribution with 1 degree of freedom[1] :

$$p_0 = \int_{\hat{q}_0}^{\infty} P_{\chi^2}(q_0) dq_0$$

[1]*Fine print: assuming the bin contents are gaussian-distributed and the two hypotheses differ by only 1 parameter*

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i.e. 5σ

- p-value often measured in *Gaussian significance*, aka z_0

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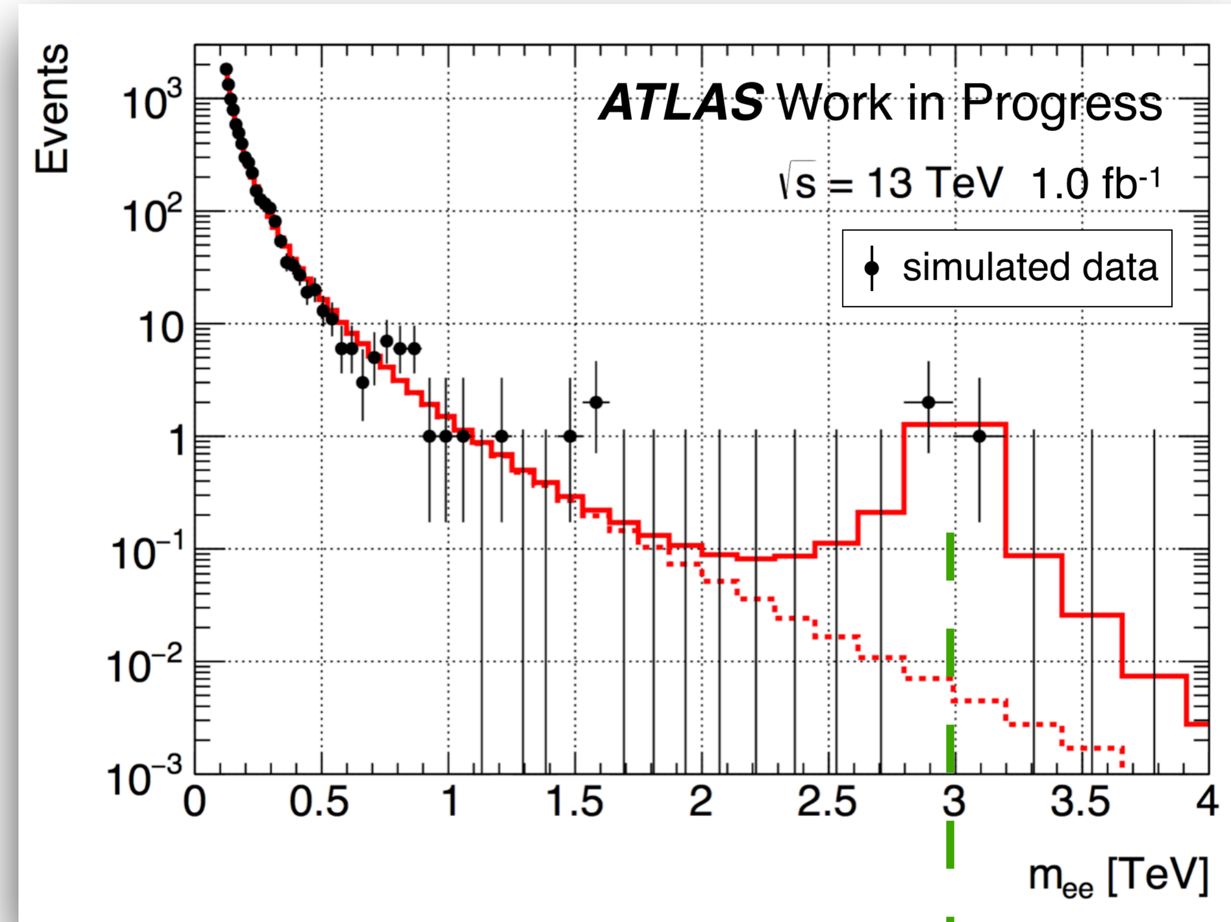
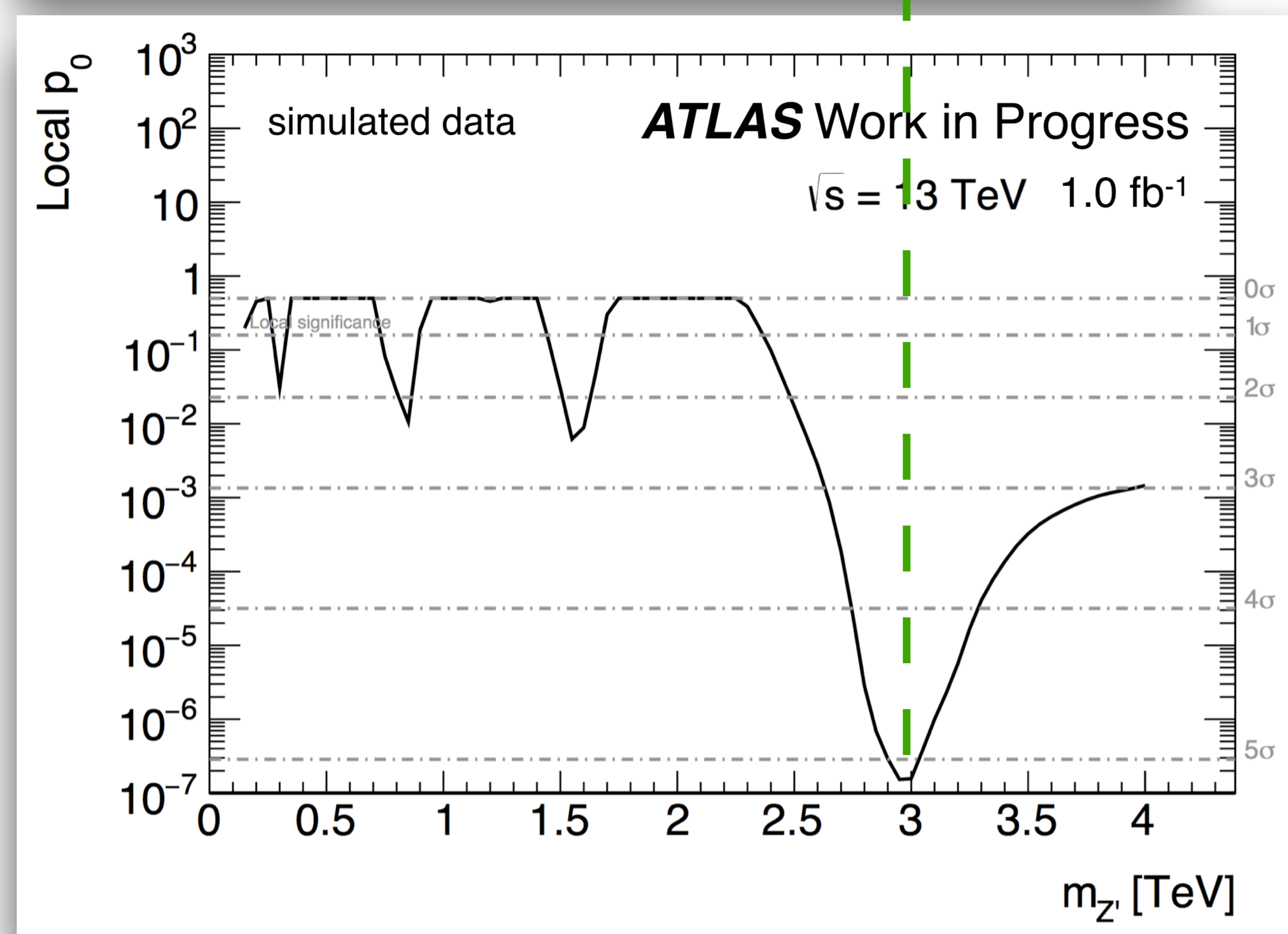
Pseudodata with injected 3 TeV signal





$\mathcal{L}(data|H_{\mathrm{B}})$

$\mathcal{L}(data|H_{\mathrm{B+S}})$

likelihood

log-likelihood ratio q_0

p-value p_0

significance z_0

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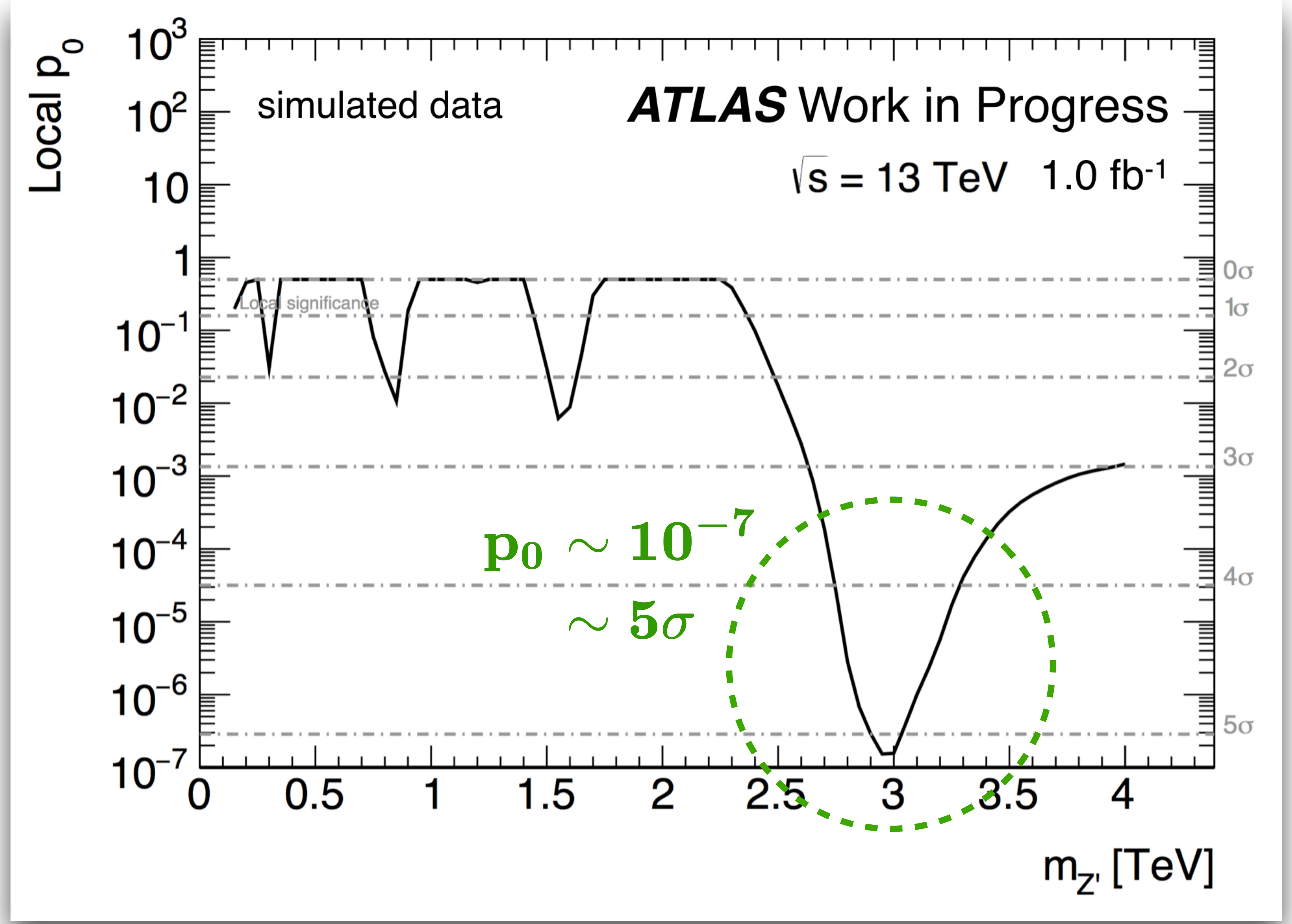
Looking around

- Since we don’t know the Z’ mass, we test many signal “locations” and find the largest excess



- HEP conventions for "evidence" & "discovery" are

$z_0 = 3\sigma \ \ (p_0 = 1.4 \times 10^{-3}) \qquad z_0 = 5\sigma \ \ (p_0 = 2.9 \times 10^{-7})$

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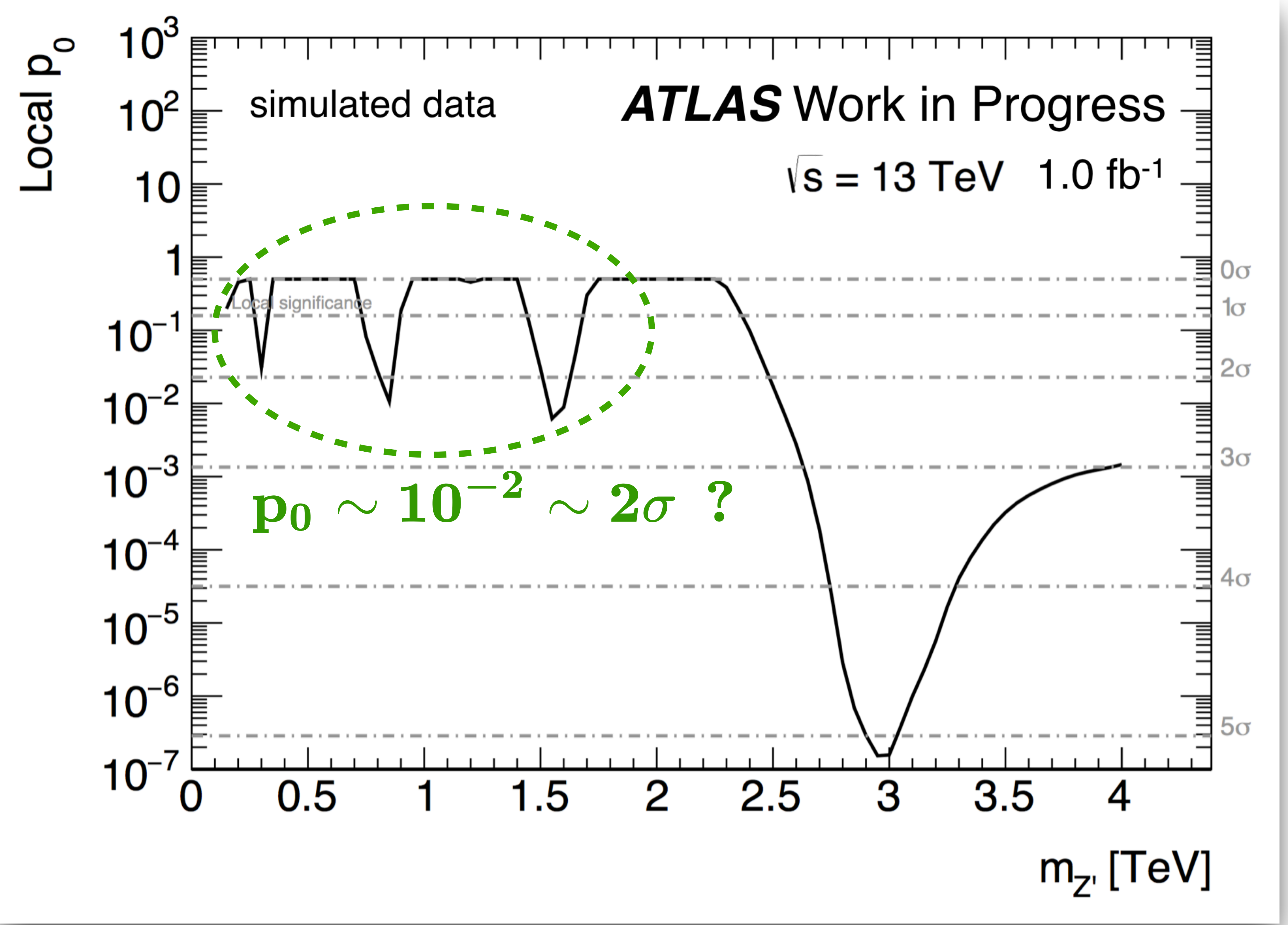
- This increases our chances of observing a fluctuation somewhere (*look-elsewhere effect*)



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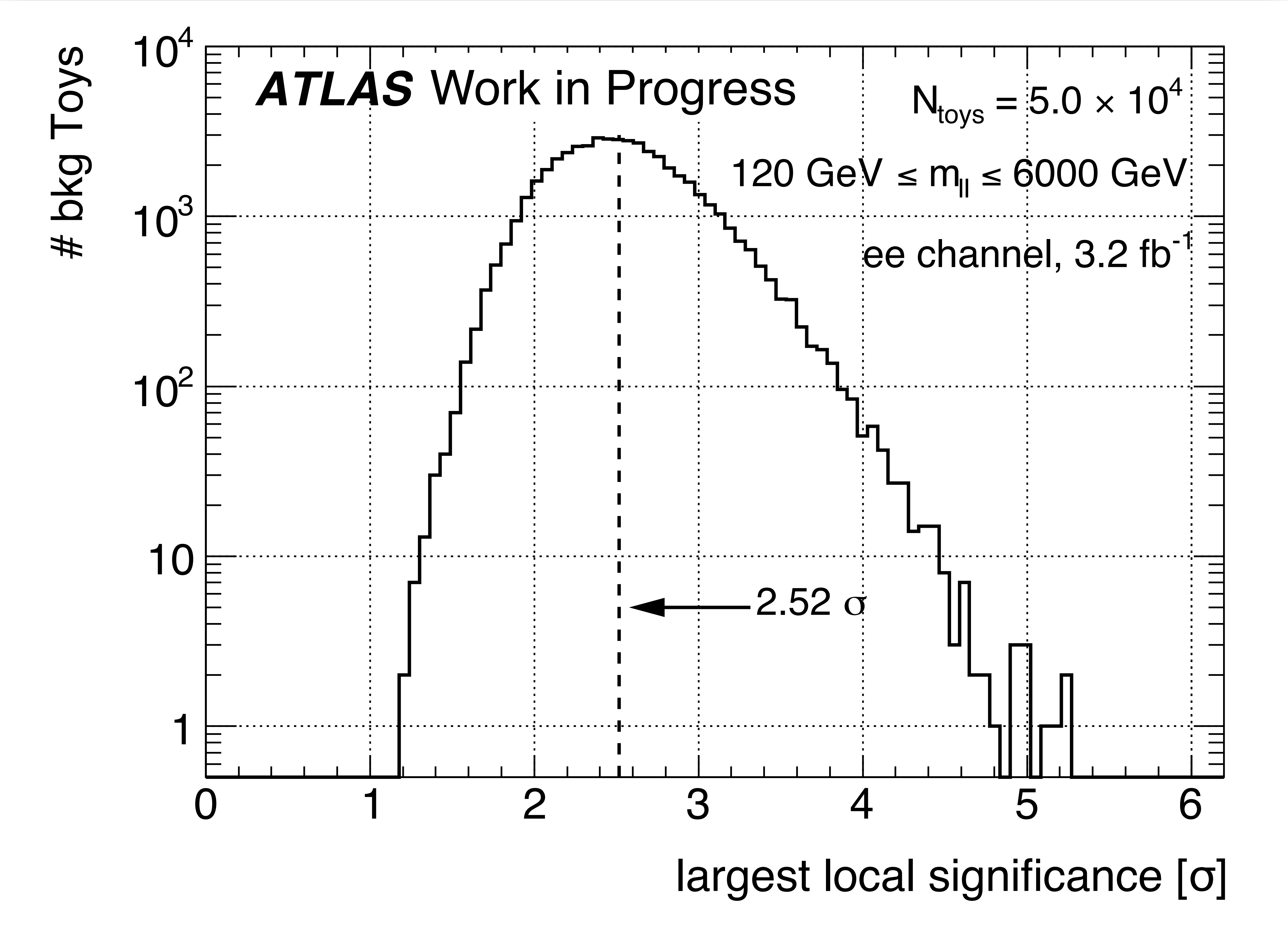
Looking around

- Since we don't know the Z' mass, we test many signal "locations" and find the largest excess
- This increases our chances of observing a fluctuation somewhere (*look-elsewhere effect*)
- The *global p-value* compensates by reporting the probability of observing a fluctuation at least as significant as the observed excess ***anywhere*** in the mass scan
- We can again generate many bkg toys and calculate the global p-value by brute force

Largest local z-values found in 50,000 toys



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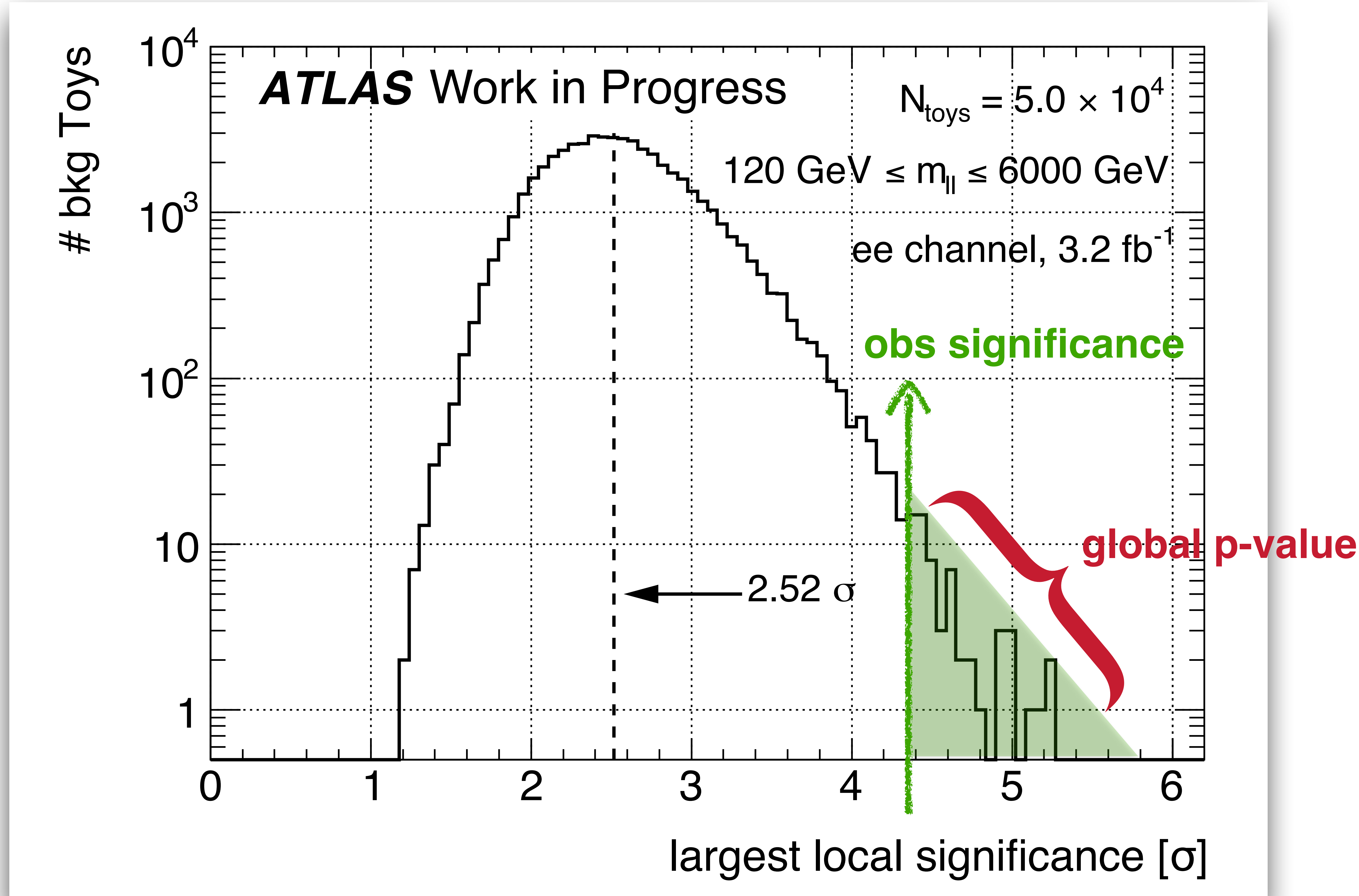
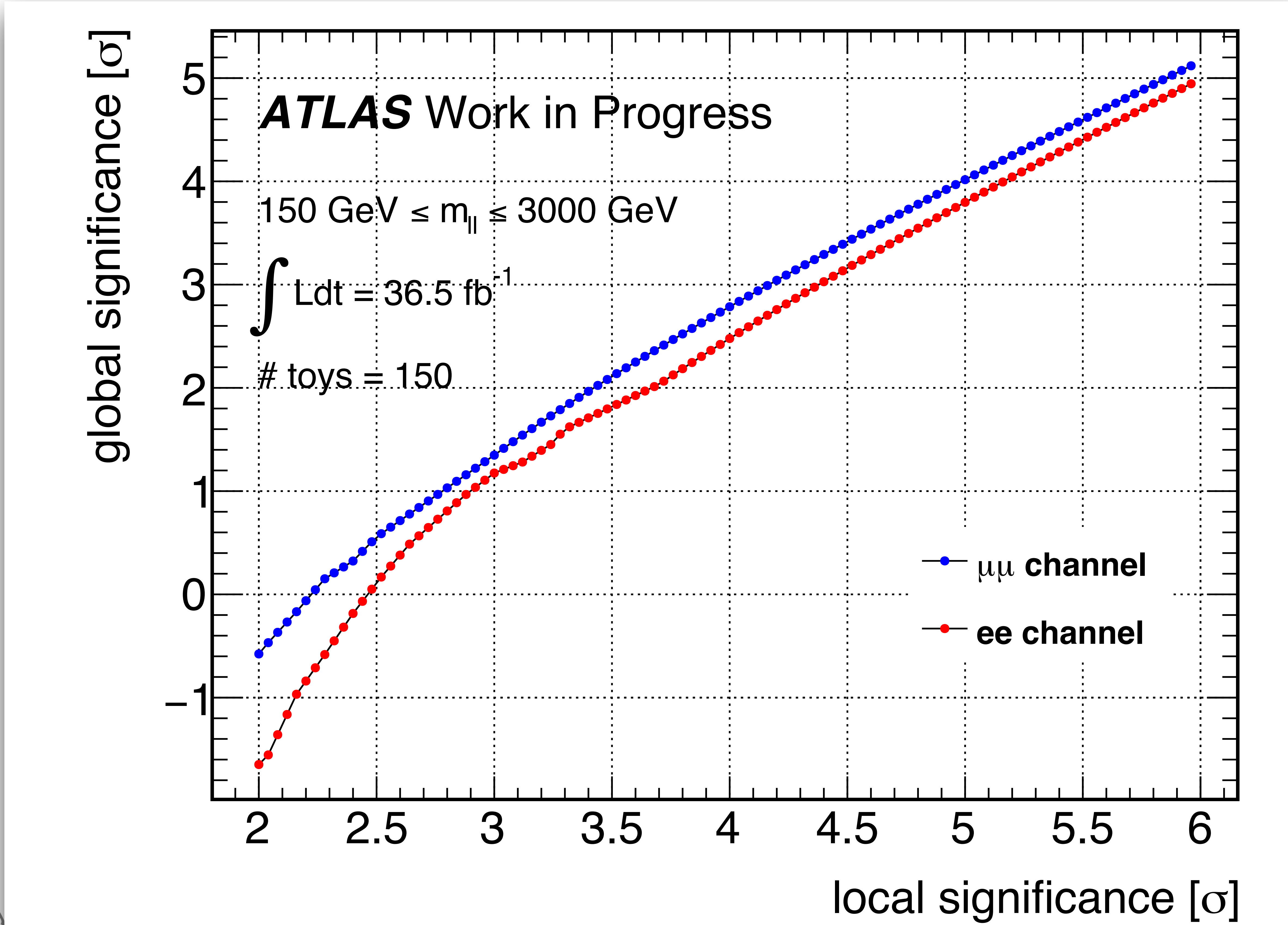


Global vs. Local Significance



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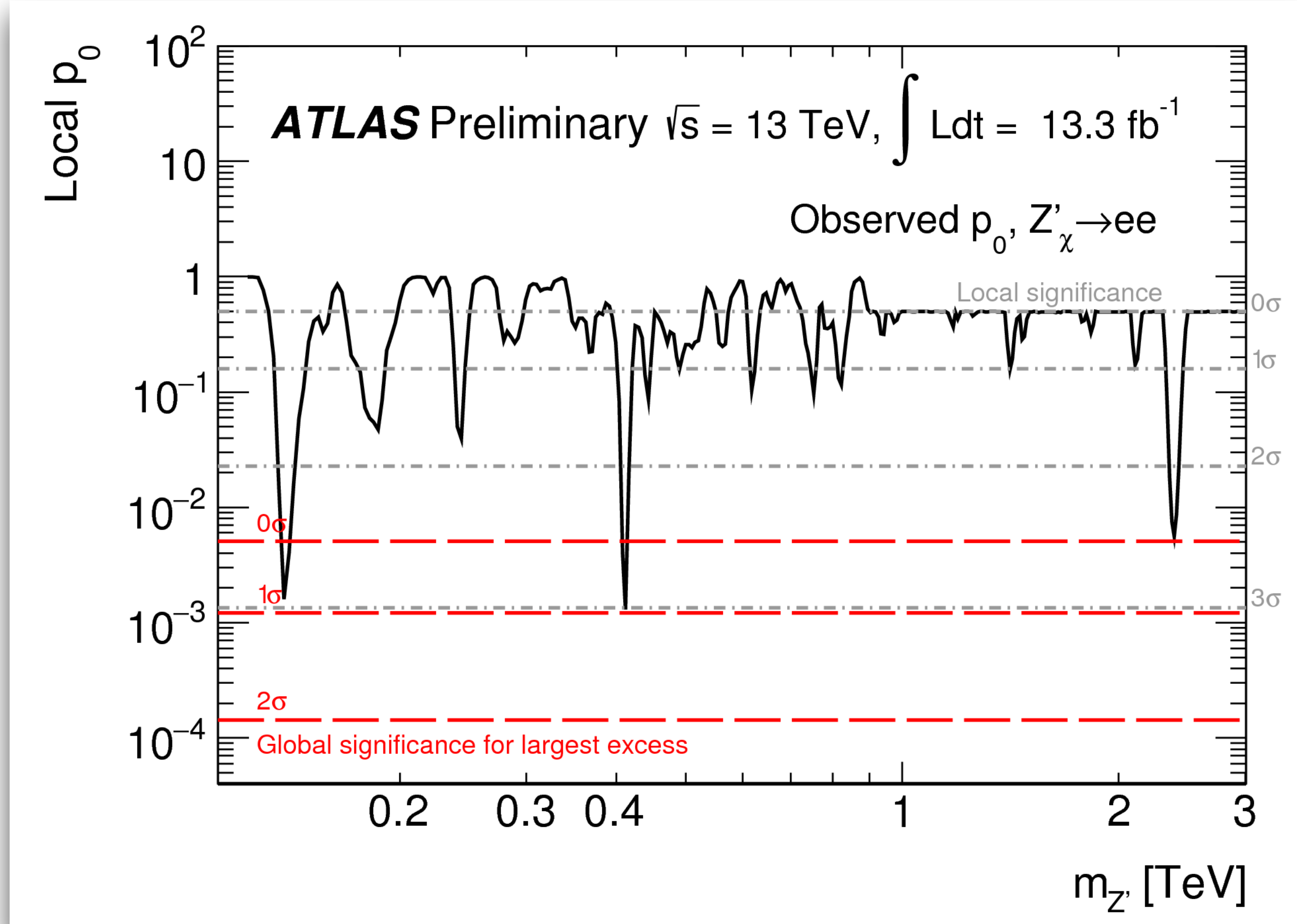
ee channel p-value scan



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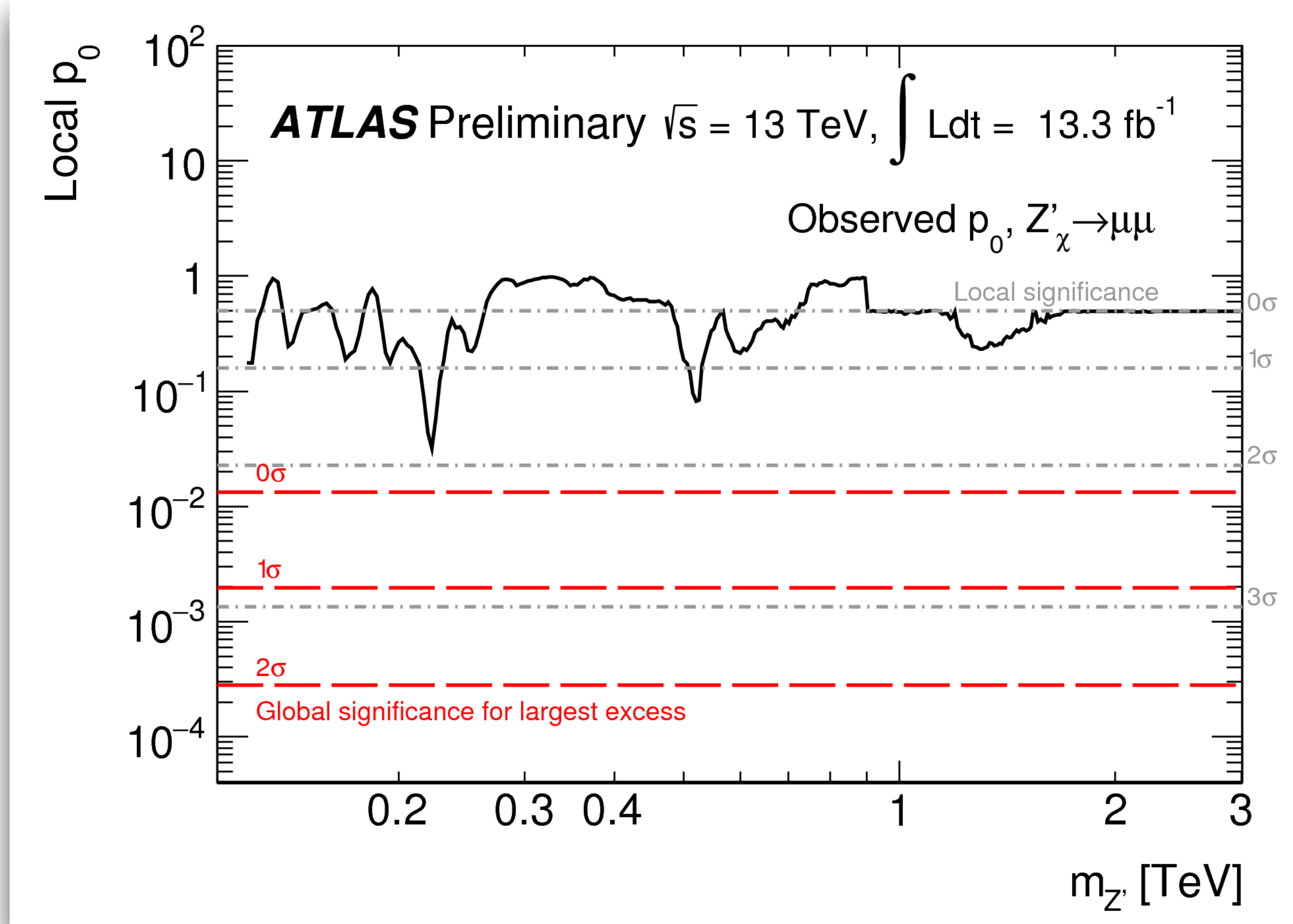
μμ channel p-value scan



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Summary

- We're looking for a localized excess of dilepton final states in ATLAS caused by a hypothetical *Z' boson*
- The *log-likelihood ratio* q_0 is the optimal test statistic for discriminating between H_B and H_{B+S}
- The *global p-value* of an observed excess is the probability that the bkg would produce a fluctuation at least as significant ***anywhere*** in the mass range
- No signal observed in ICHEP 2016 results (13.3 fb^{-1})

Questions?

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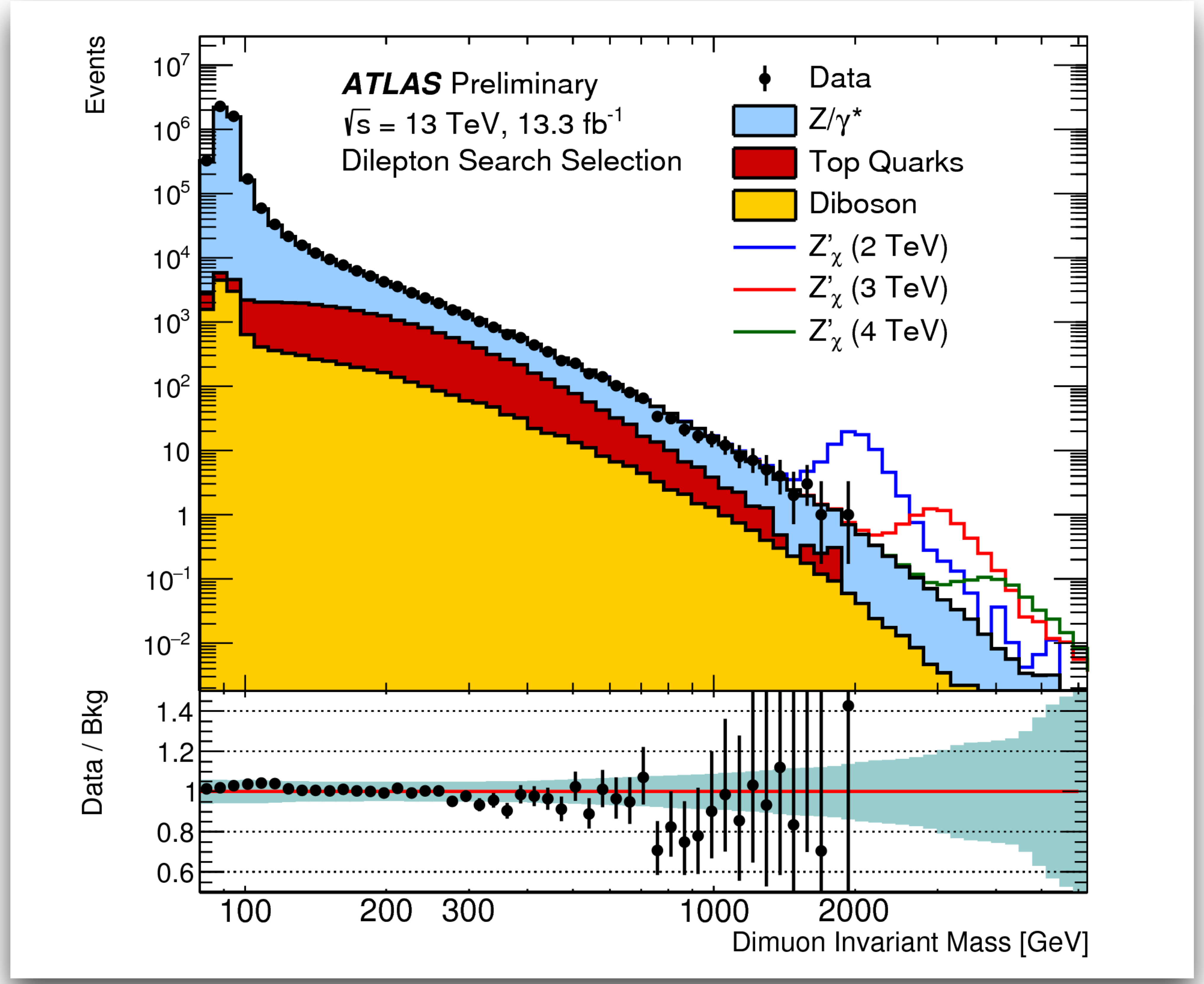
Bonus

Naturalness

Z’ Models

- Sequential Standard Model (SSM)
  - Accessible as a benchmark but not very attractive theoretically
  - Fermion couplings identical to that of Standard Model Z
- E6 Grand Unified Theory
  - Physical Z’ states are a mixture of two residual U(1) after E6 breaking
- Randall-Sundrum Graviton
  - Z’ is an excitation of the spin-2 graviton propagating in bulk 5D space
- Little Higgs

Mass spectrum (μμ channel)



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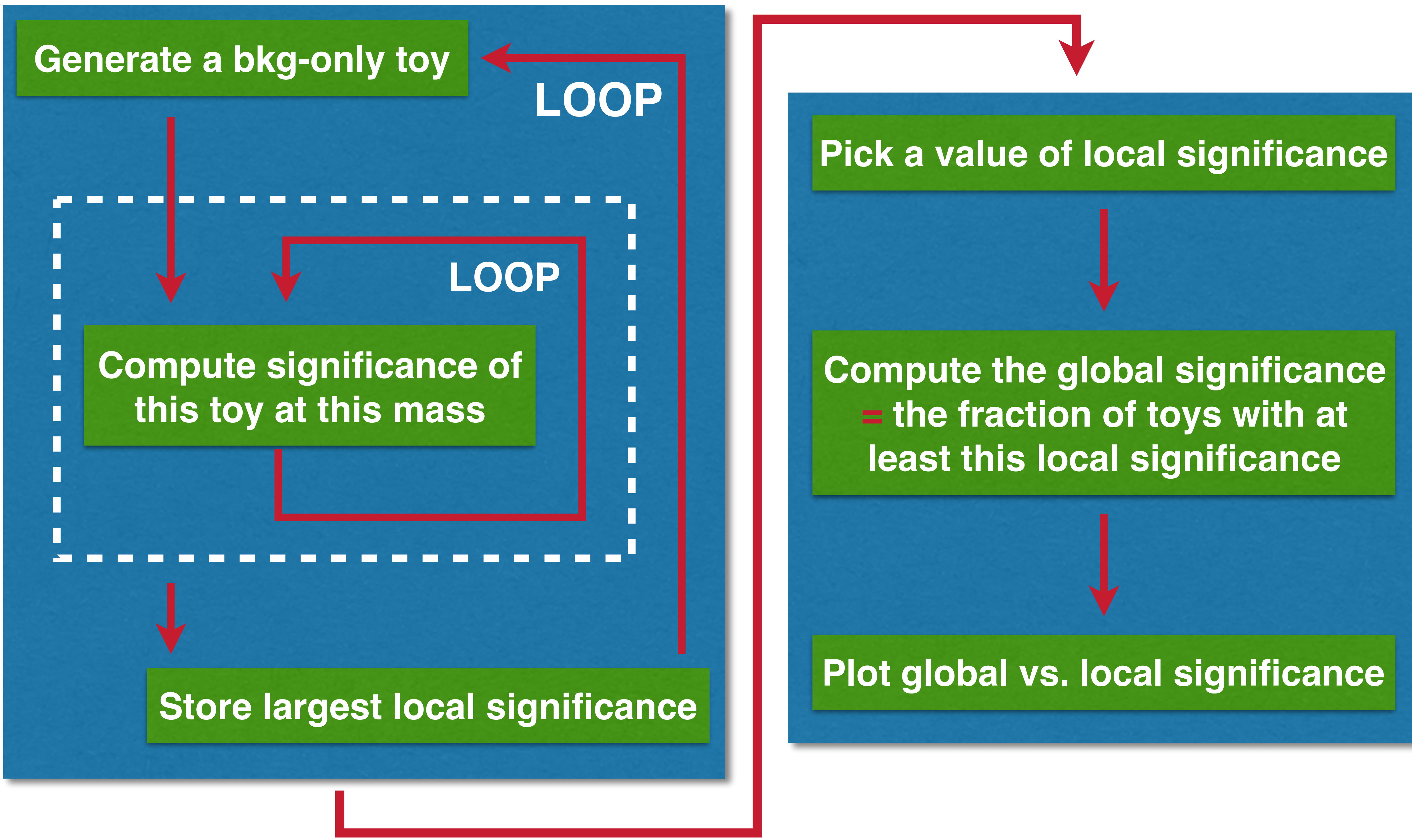
Brute-force global p_0 calculation



Global p-value from "upcrossings"

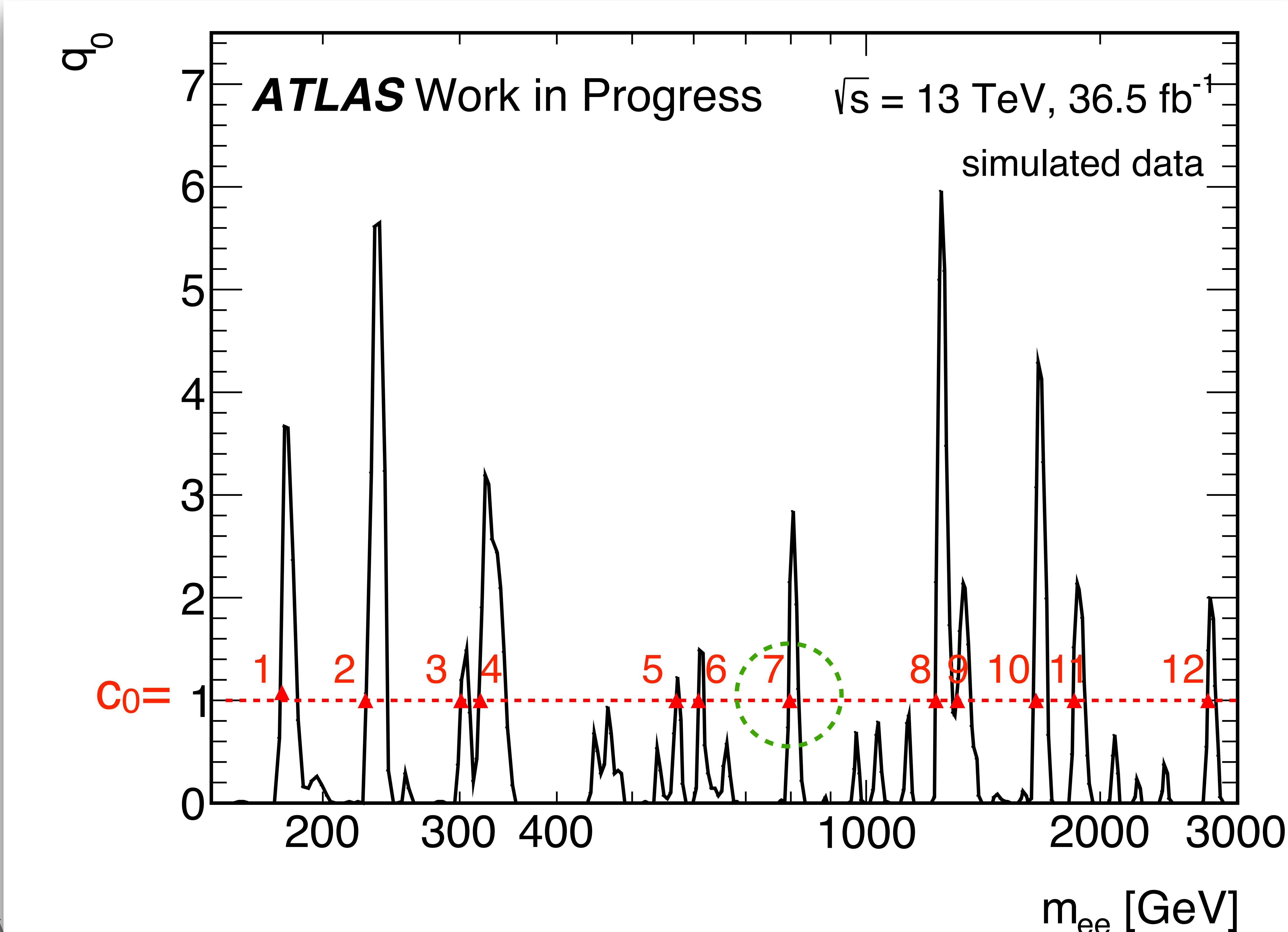
- Scanning toys takes a *long* time!

- *Gross & Vitells* derive an analytic description of the look-elsewhere effect which asymptotically approaches the slow "brute-force" method

Gross, Eilam, and Ofer Vitells. "Trial factors for the look elsewhere effect in high energy physics." *The European Physical Journal C - Particles and Fields* 70.1 (2010): 525-530.

Idea: the bkg's tendency to fluctuate is related to the average number of *upcrossings* where q_0 crosses above some threshold c_0 in pseudo-experiments

"▲" are upcrossings above $c_0=1$



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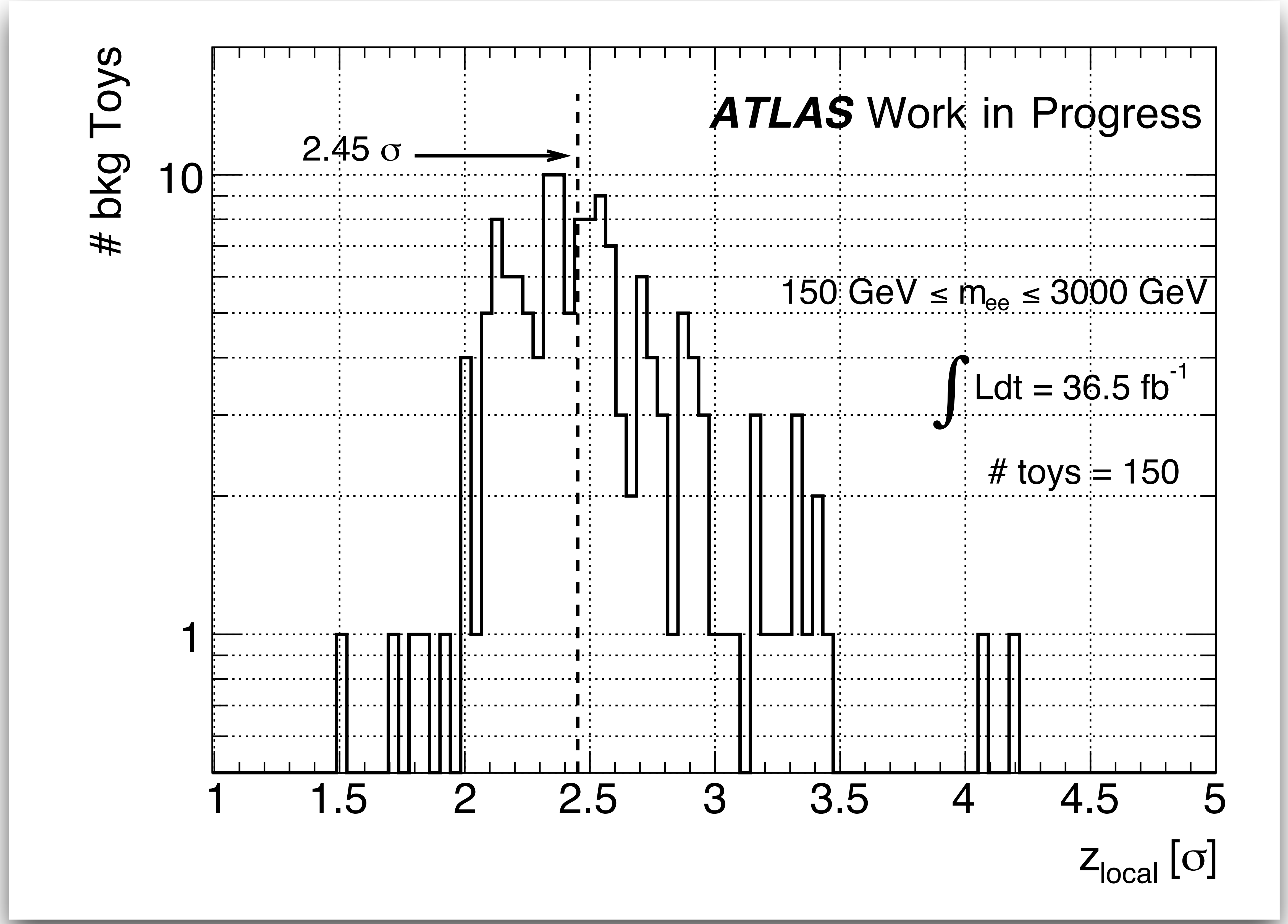
$$p_{\rm global} \leq P(\chi^2 > \hat{q}_0) + \langle N(c_0) \rangle e^{-(\hat{q}_0 - c_0)/2}$$

local p-value

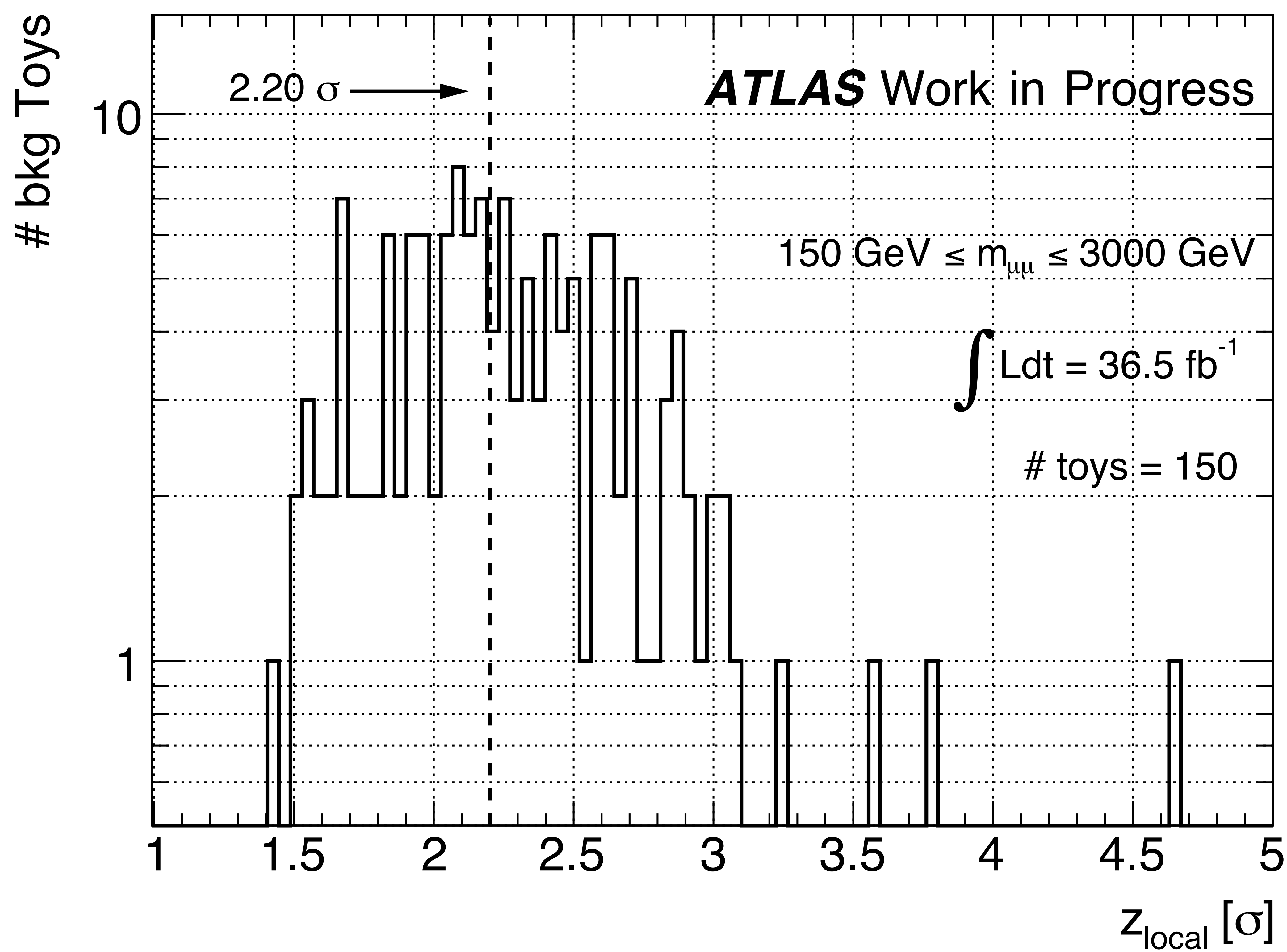
avg # of upcrossings/toy

scaling law for threshold c_0

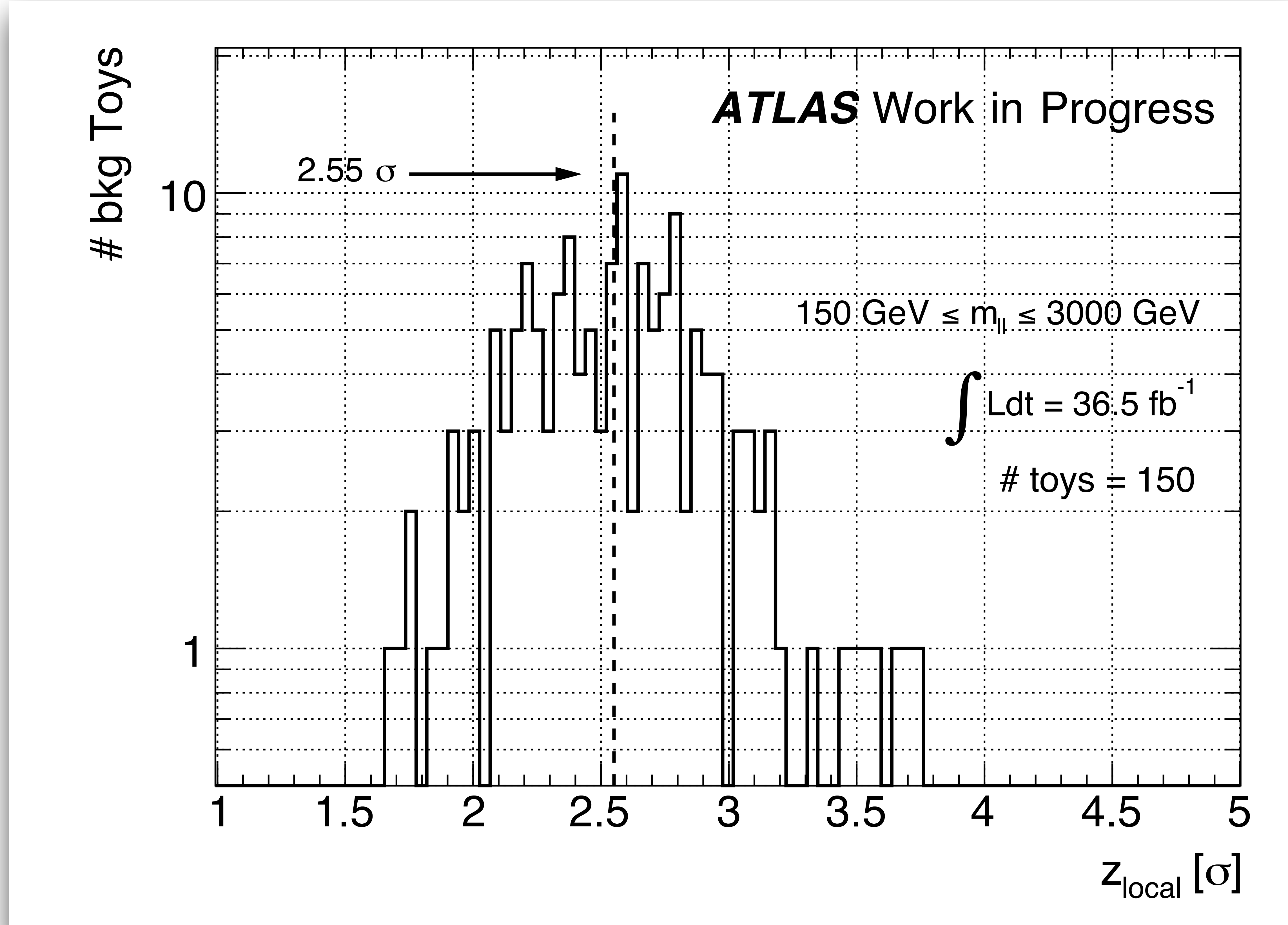
Largest local z-values (ee)



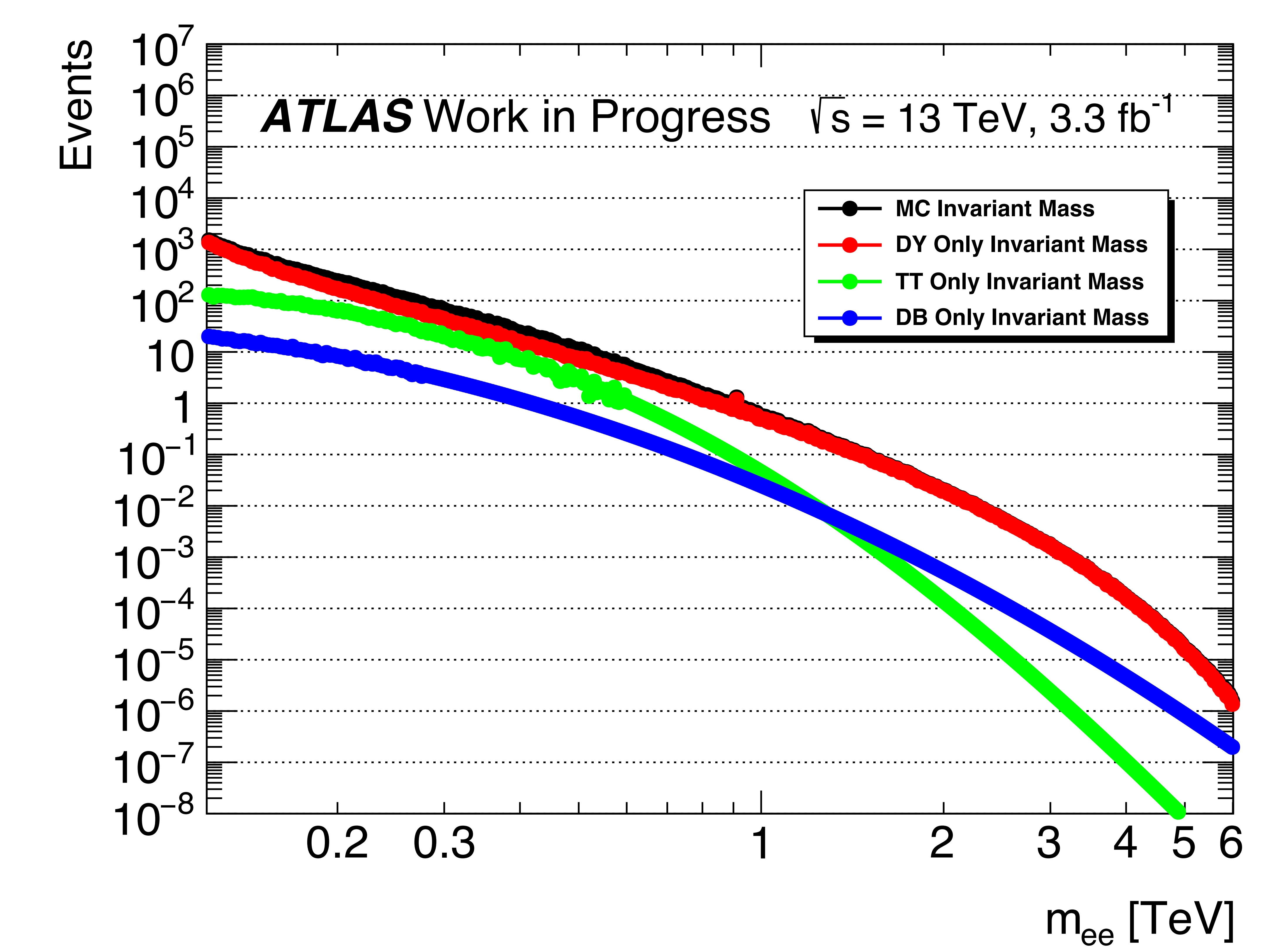
Largest local z-values (μμ)



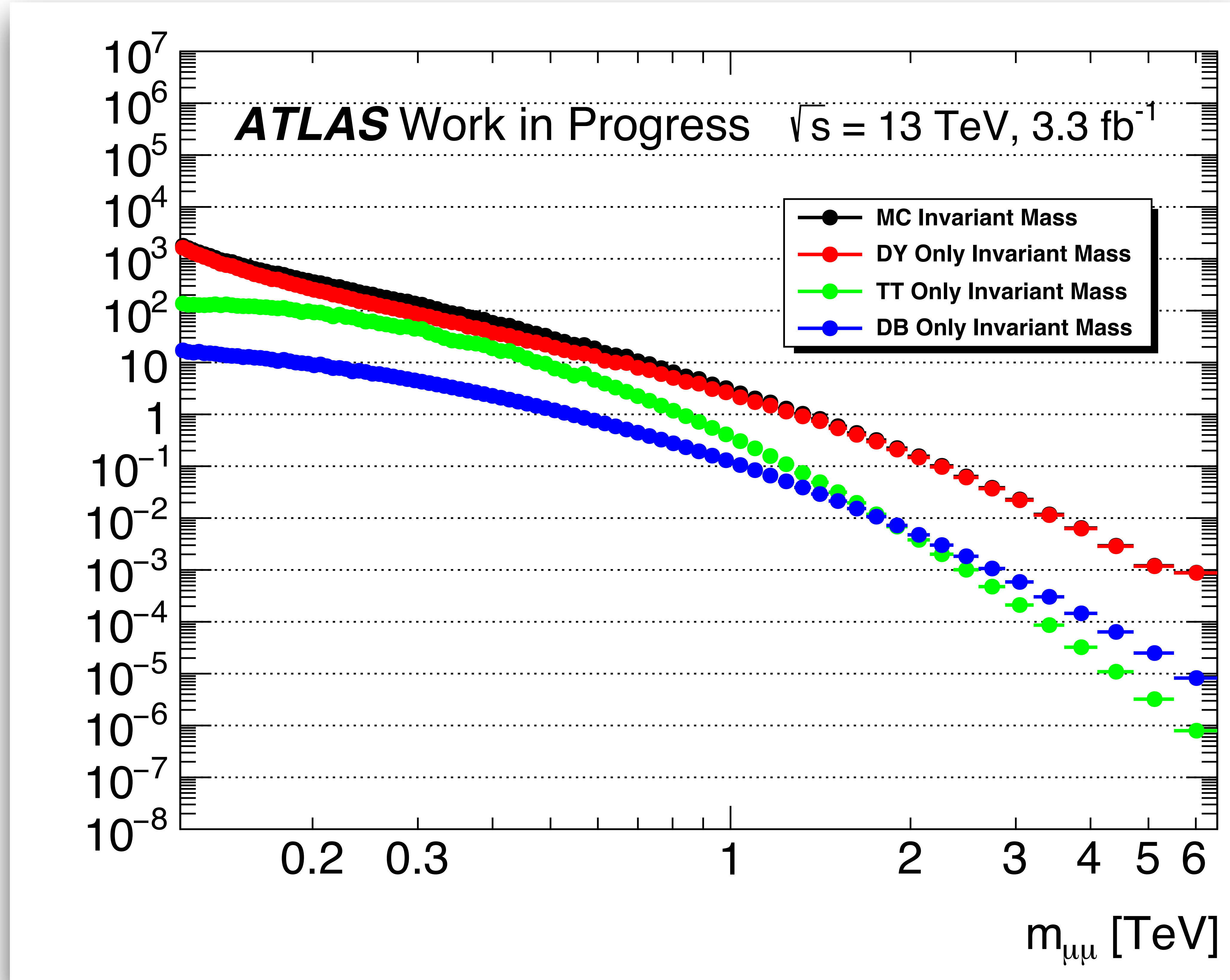
Largest local z-values (comb)



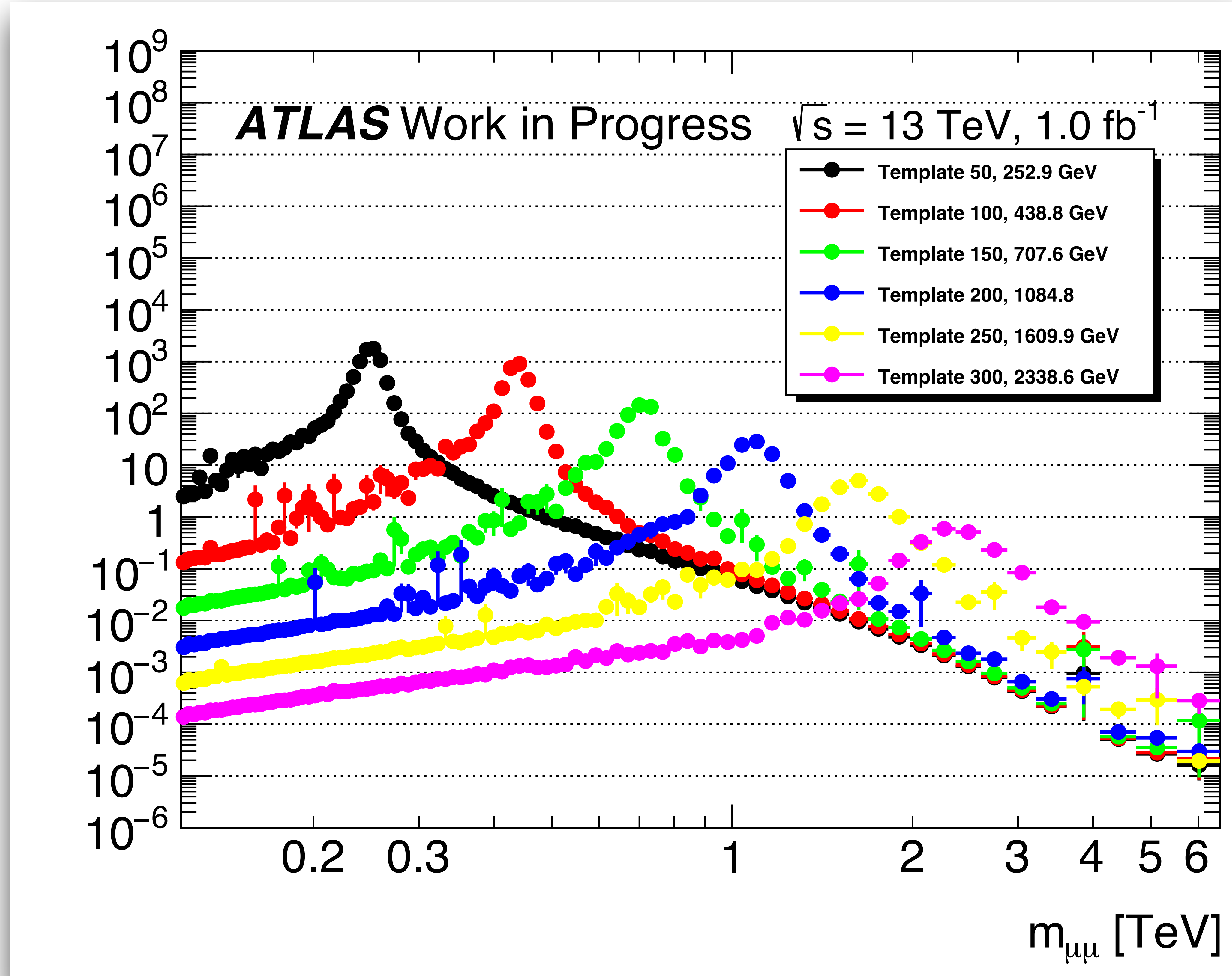
ee background templates



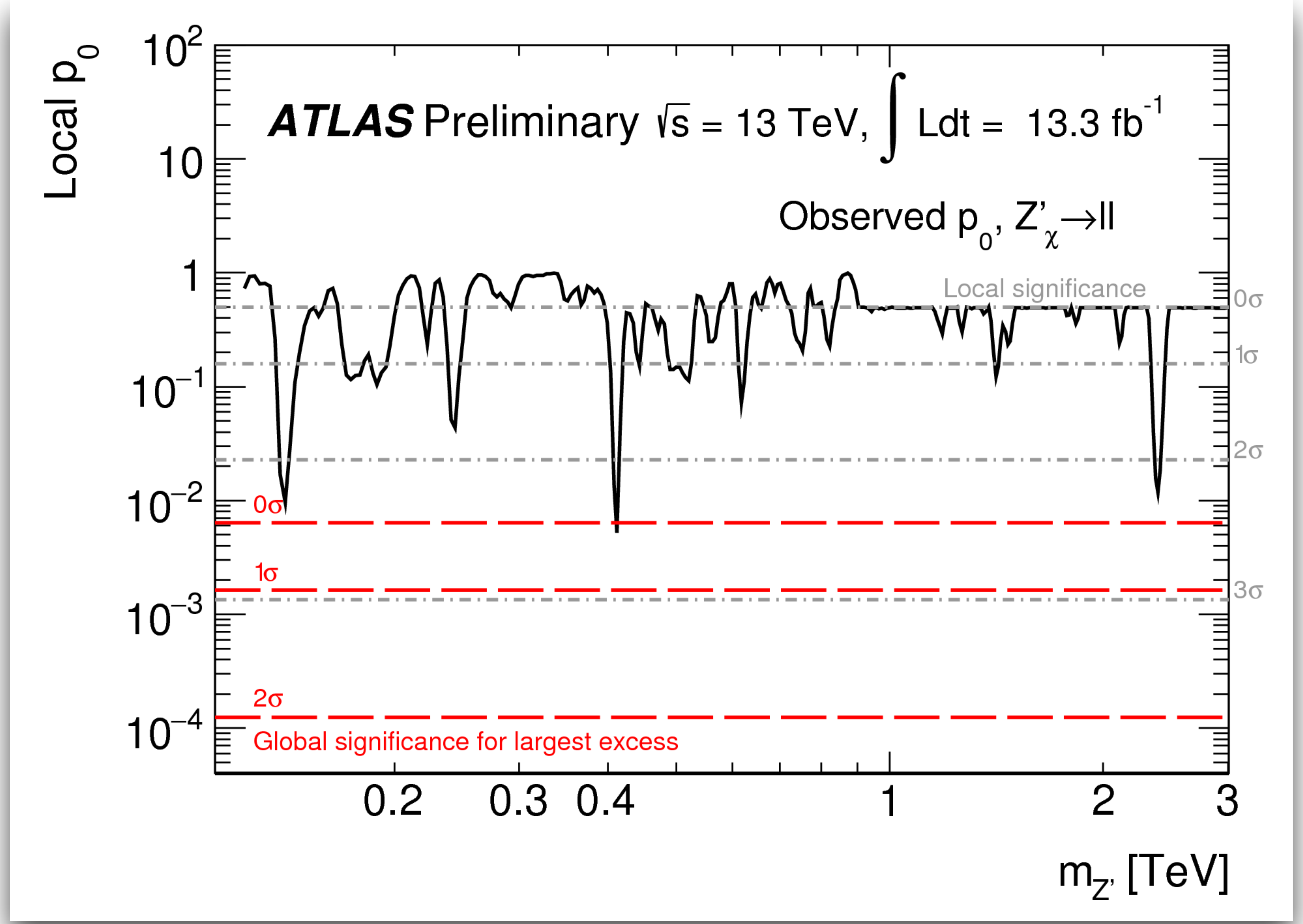
μμ background templates



Signal templates (μμ)



comb channel p-value scan



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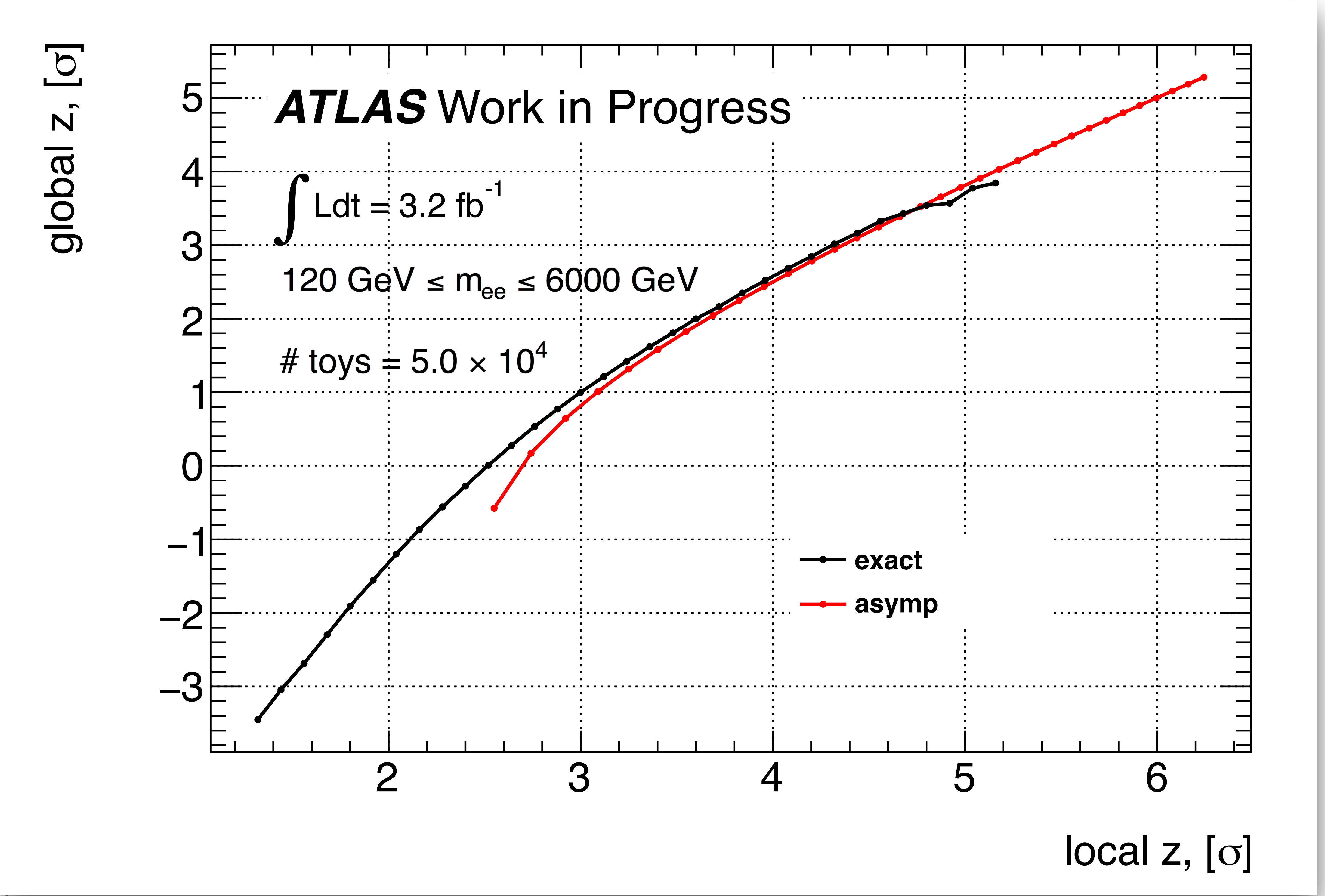
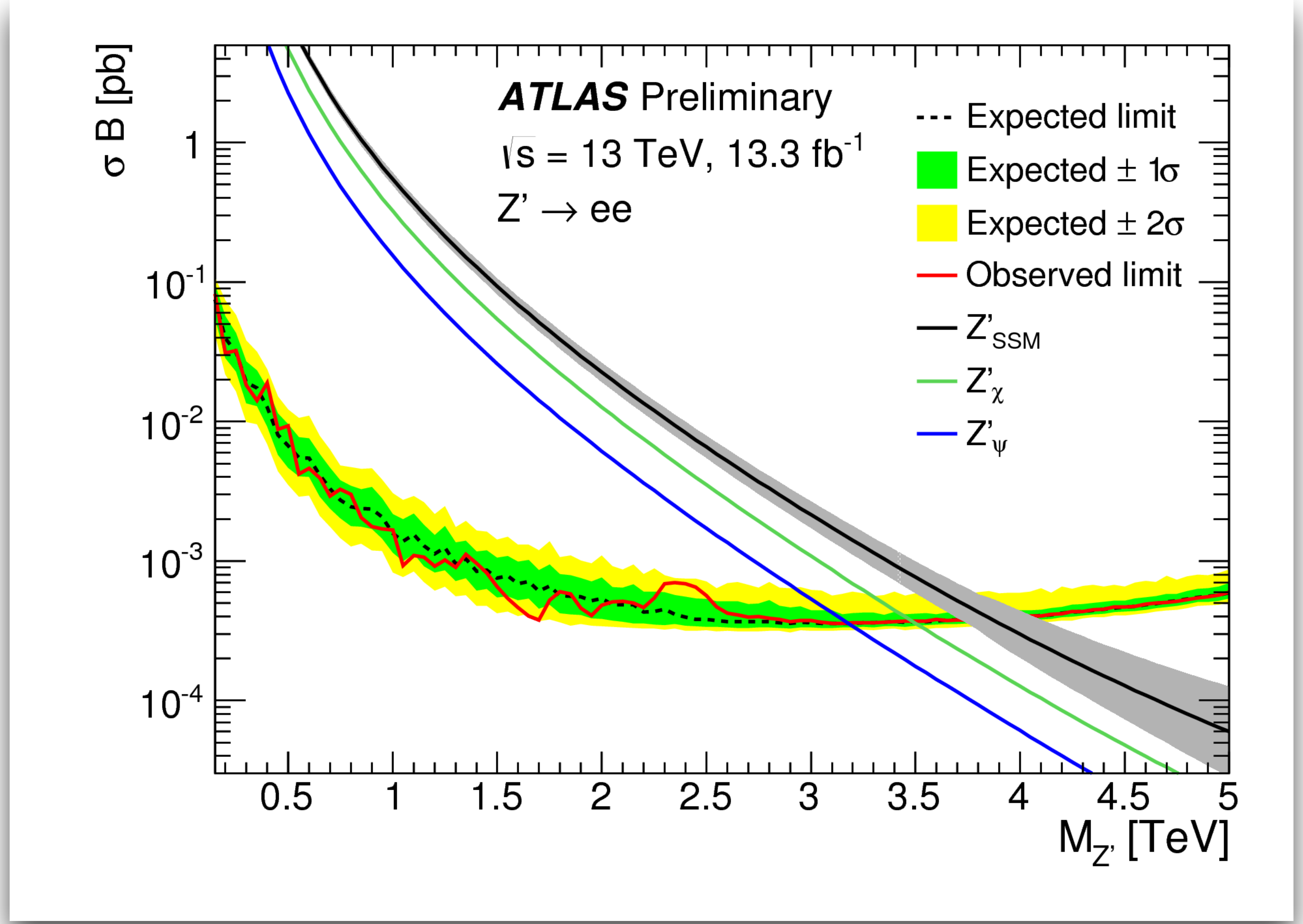
Validation without systematics



Exclusion limits (ee)



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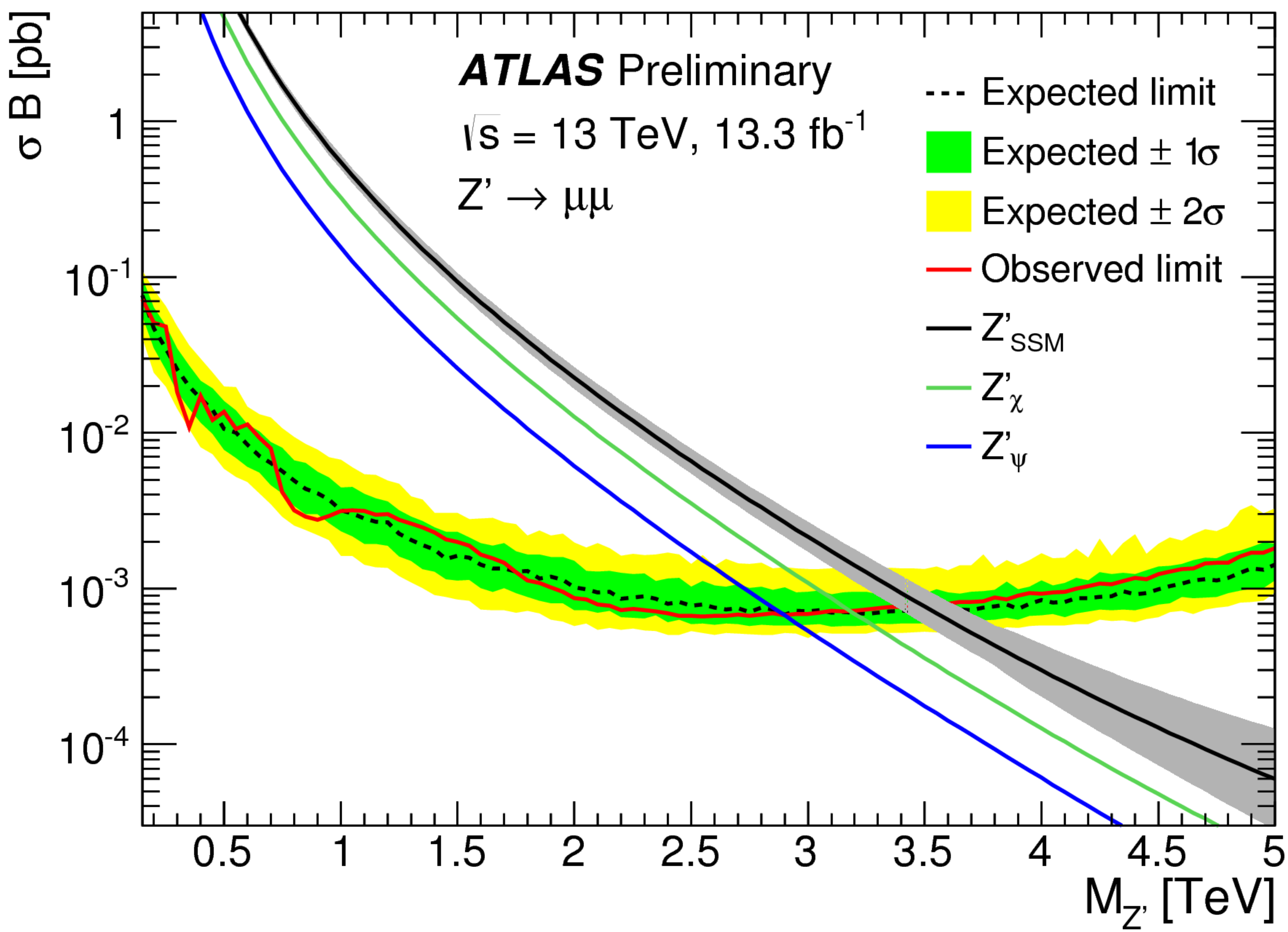
Exclusion limits (μμ)



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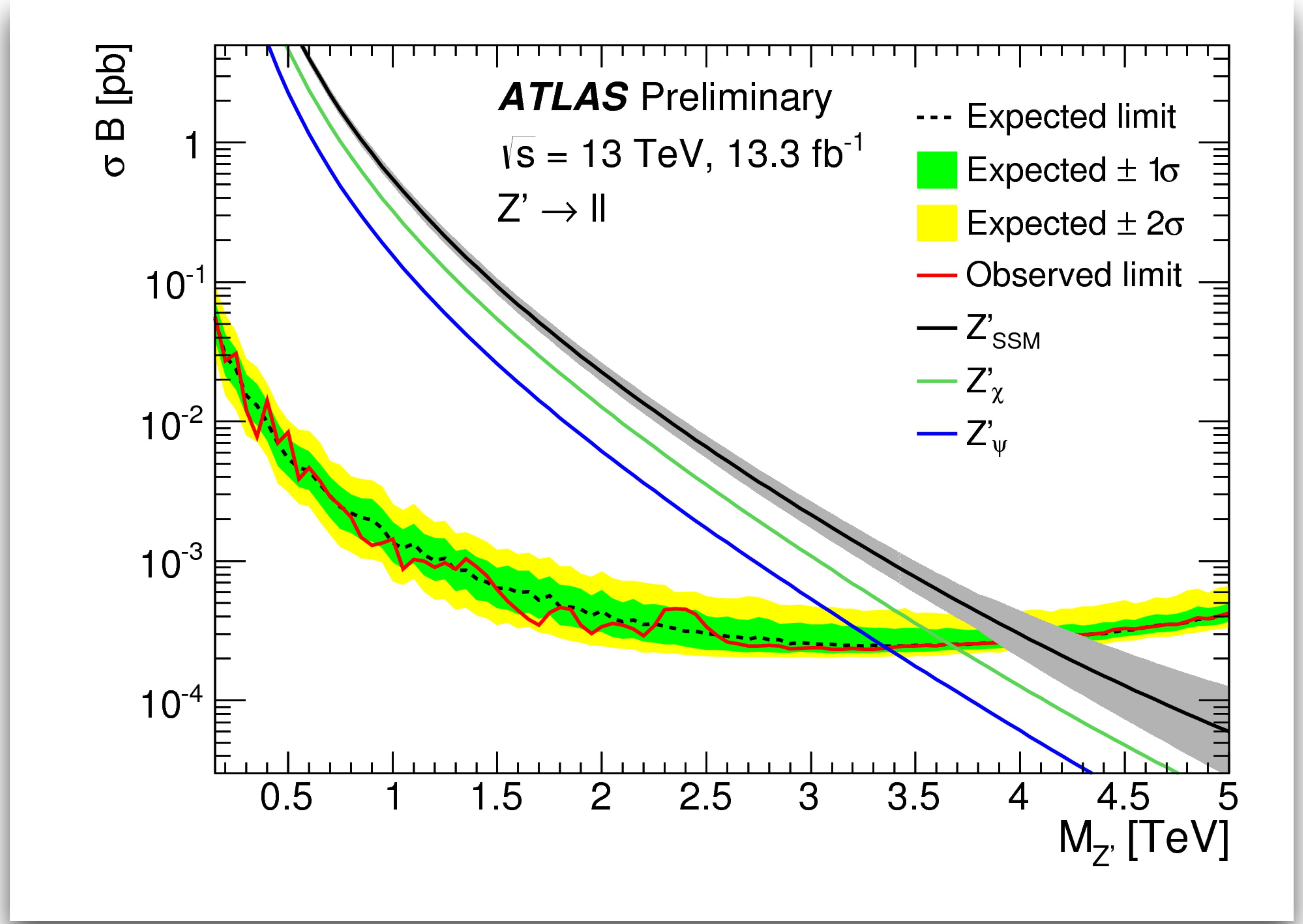
Exclusion limits (comb)



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