Hunting for ‘Bumps’ in the Dilepton Invariant Mass spectrum using BUMPHUNTER with the ATLAS Detector

Winter Nuclear and Particle Physics Conference, 16-19th February 2017, Banff

Elham E Khoda

The University of British Columbia

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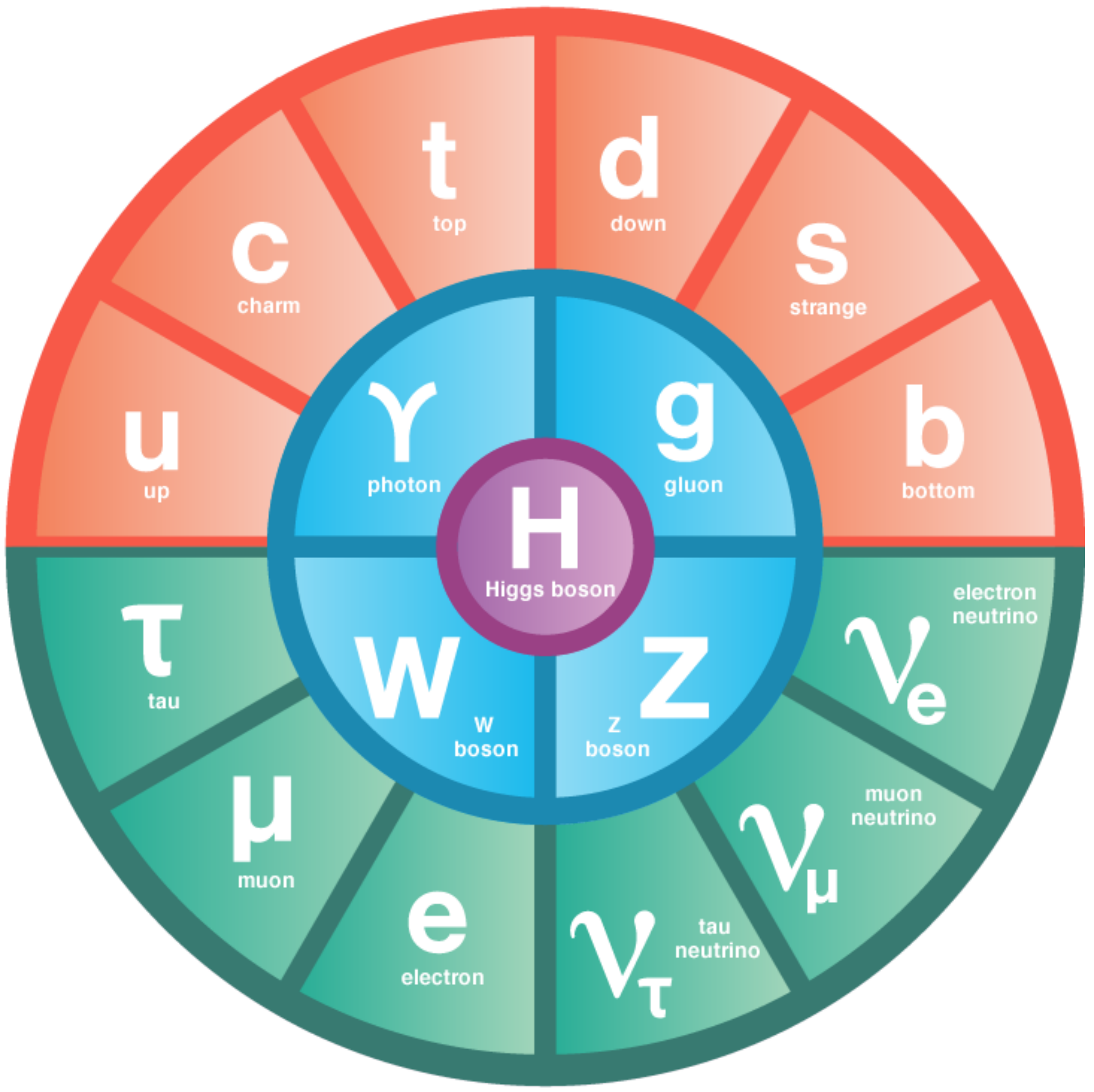


The Standard Model of Particle Physics

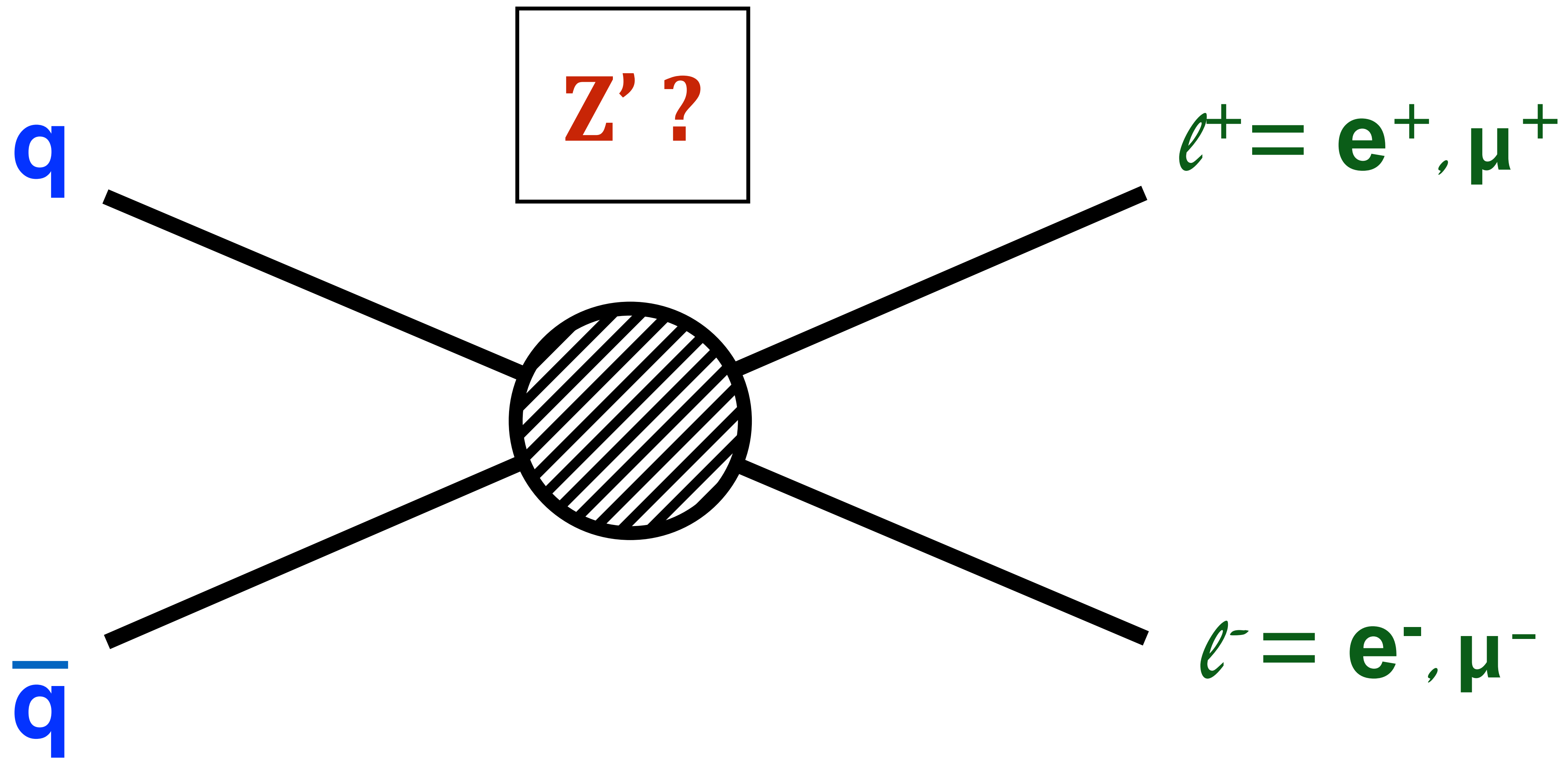
is not

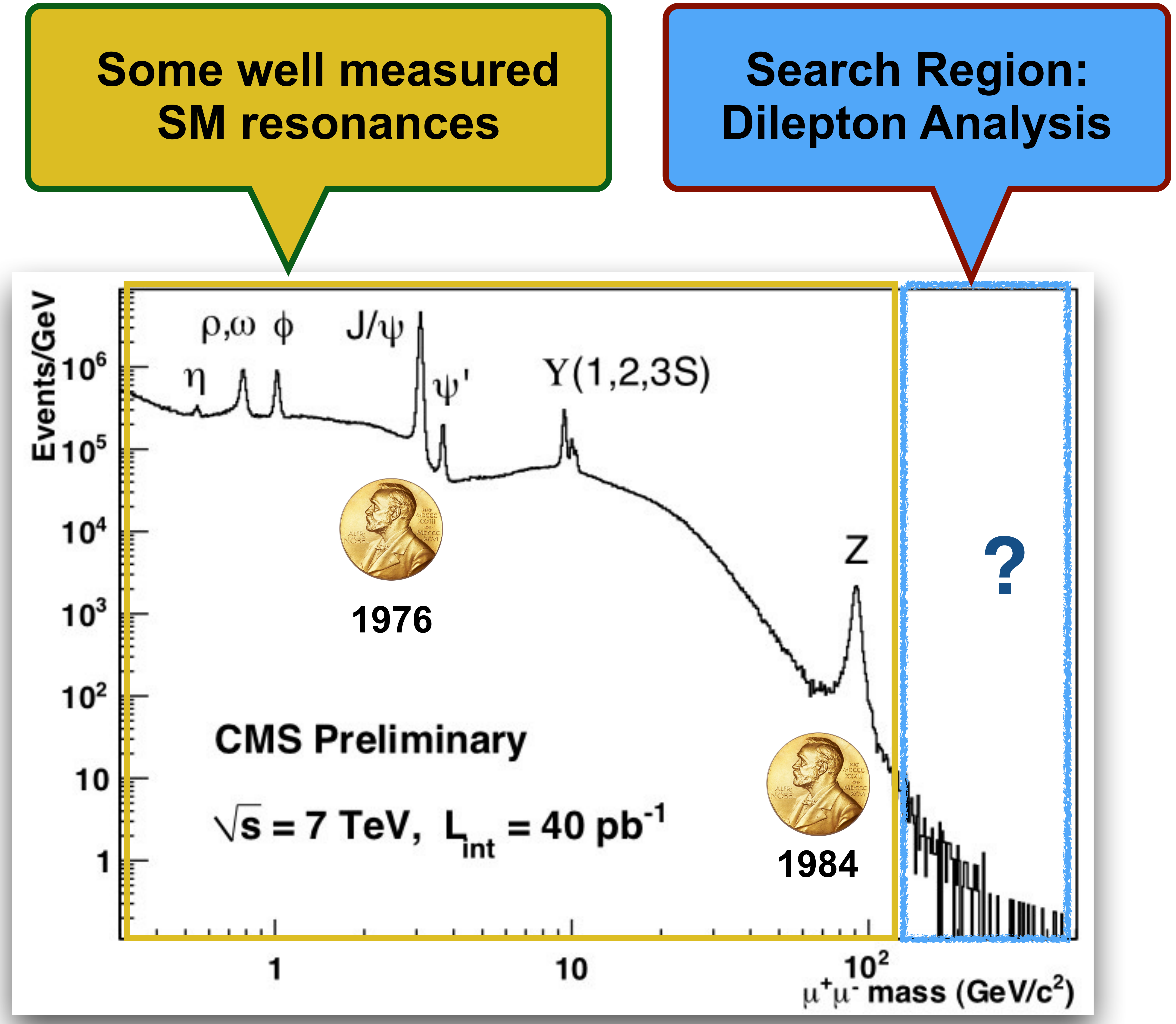
the complete theory of the nature *

*based on our several current observations

Many theories **Beyond the Standard Model (BSM)** predict new phenomena like:
➡ **narrow resonances**
over the SM in the **dilepton mass spectrum**

Observable: narrow peak



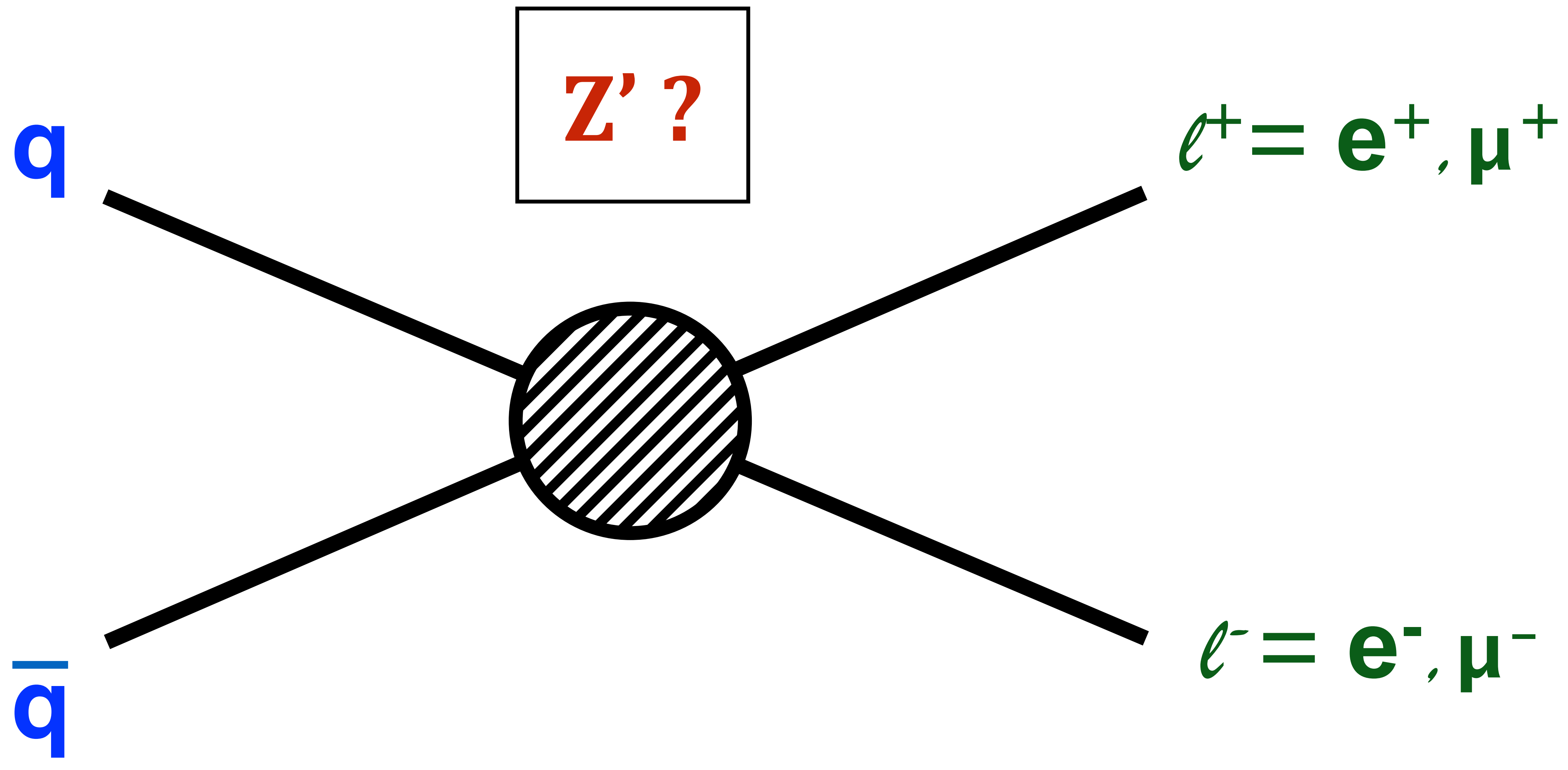


arXiv:1309.0721 [hep-ph]

Motivation: Benchmark Models

Many theories **Beyond the Standard Model (BSM)** predict new phenomena like:
➡ **narrow resonances** over the SM in the **dilepton mass spectrum**

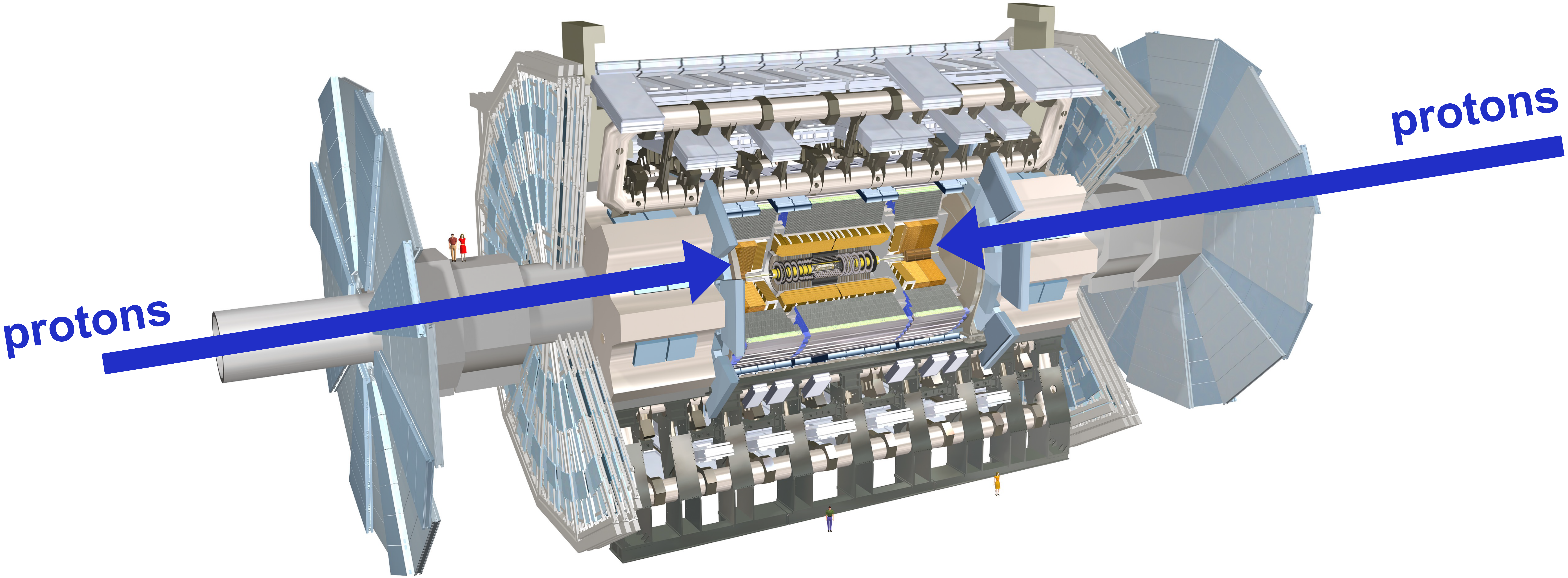
Observable: narrow peak



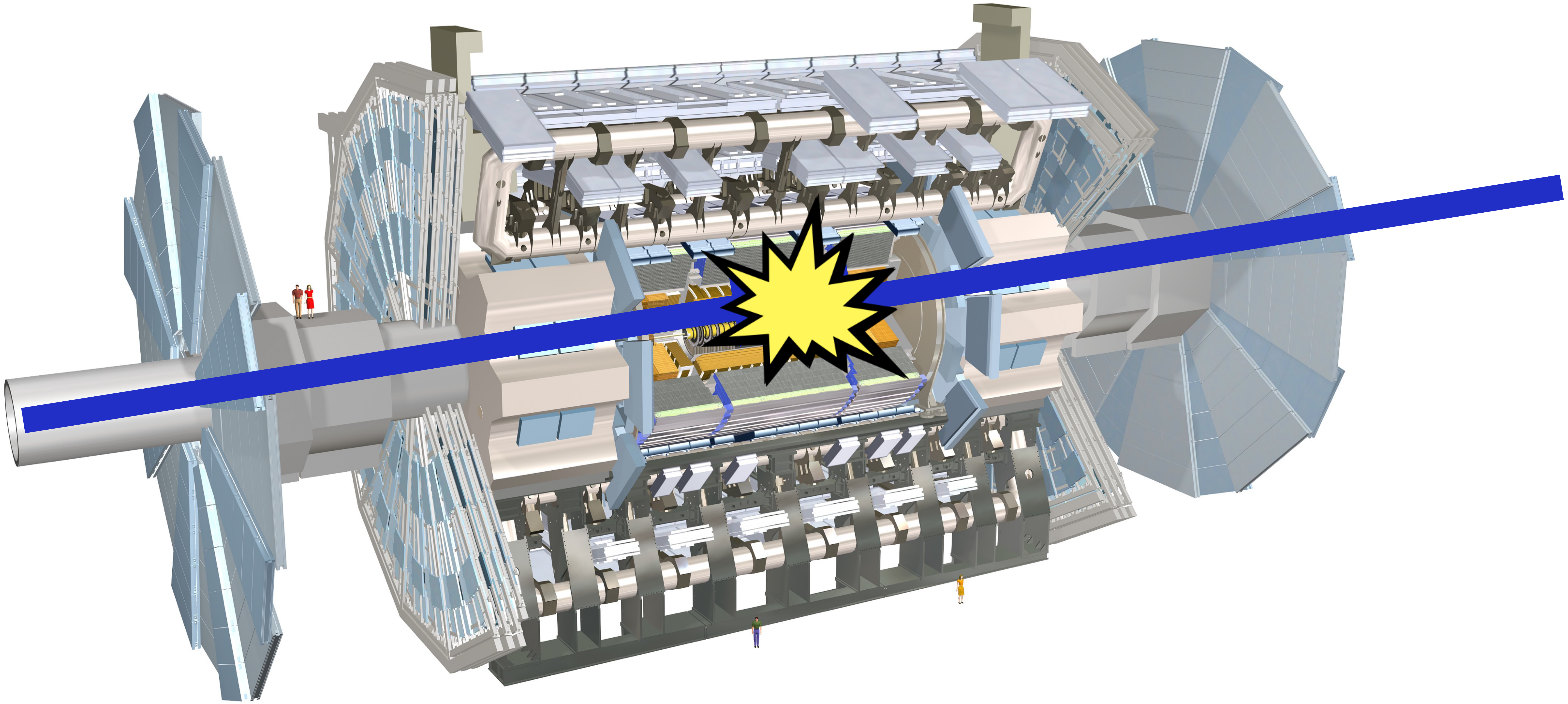
Z' Resonance

- Additional Spin-1 Gauge Boson
- **Sequential Model:** with same coupling to leptons (like SM Z)
- Also motivated by **Grand Unified Theories (GUT)**, such as $\mathbf{E_6}$
- Different models have different sizes and widths of resonances.
- Other models …

Invariant Mass

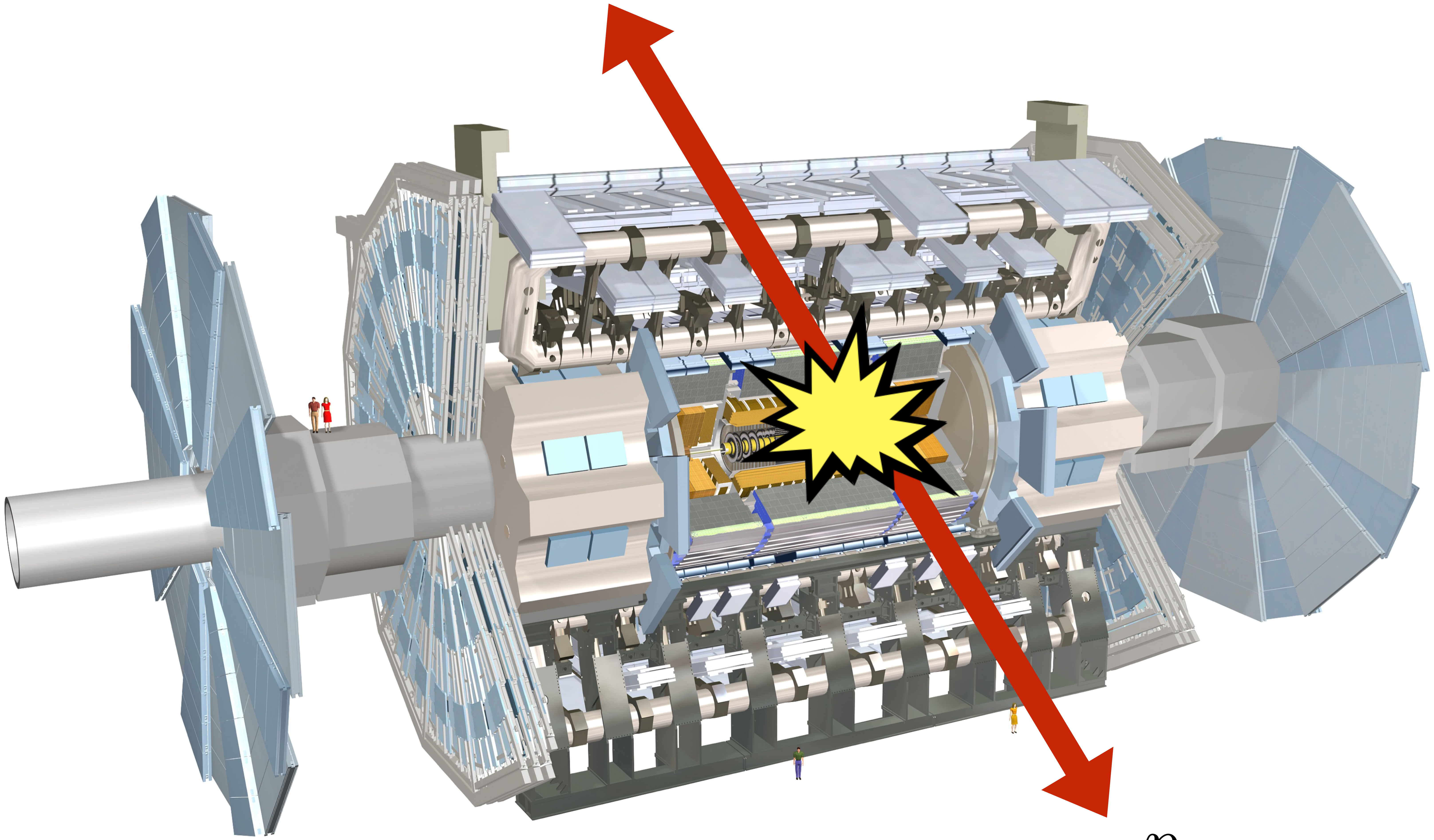


Invariant Mass



Invariant Mass

p_1 = 4-momentum of the final state lepton



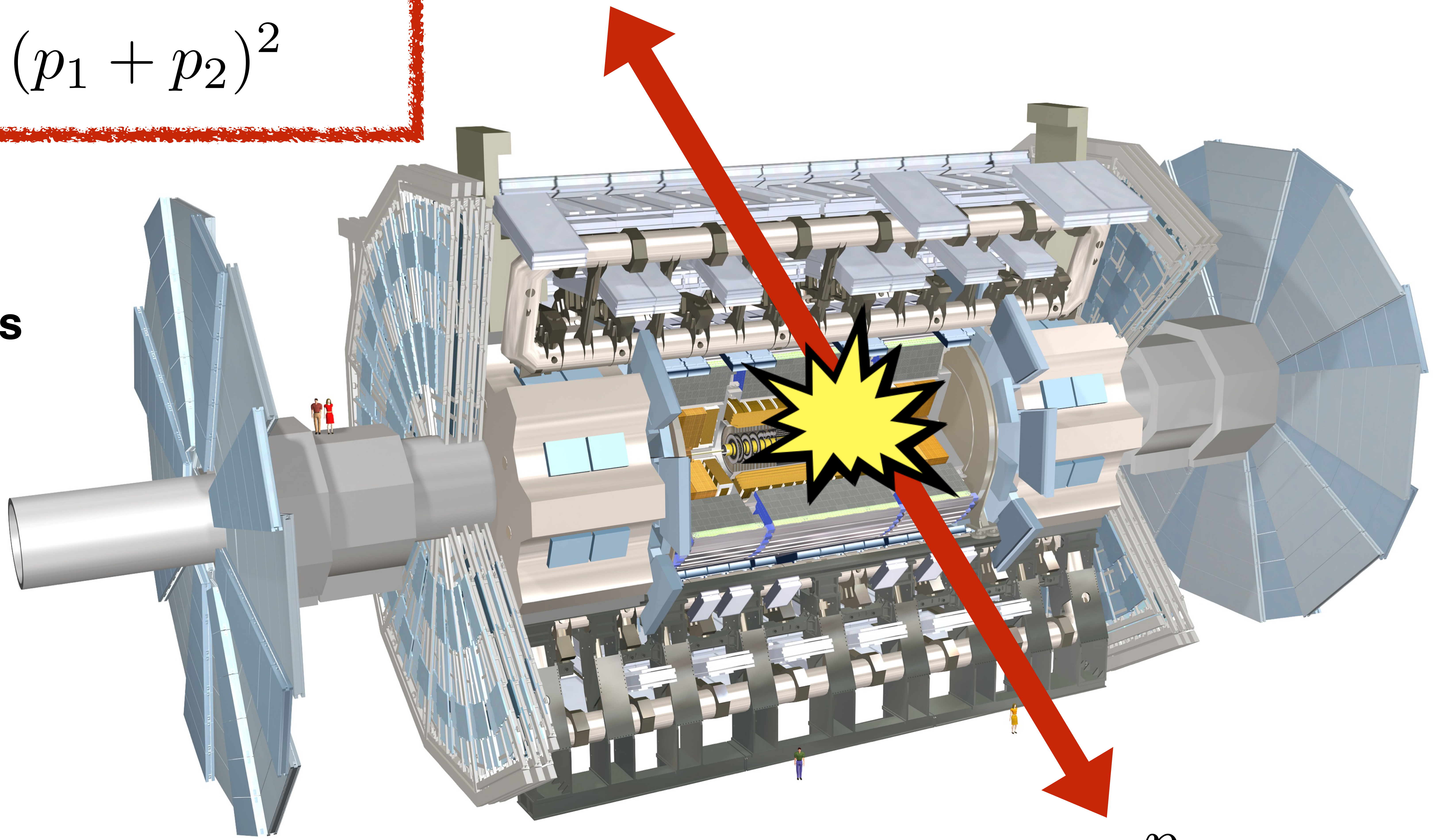
p_2 = 4-momentum of the final state anti-lepton

Invariant Mass

$$M^2 = (p_1 + p_2)^2$$

square of invariant mass

p_1 = 4-momentum of the final state lepton

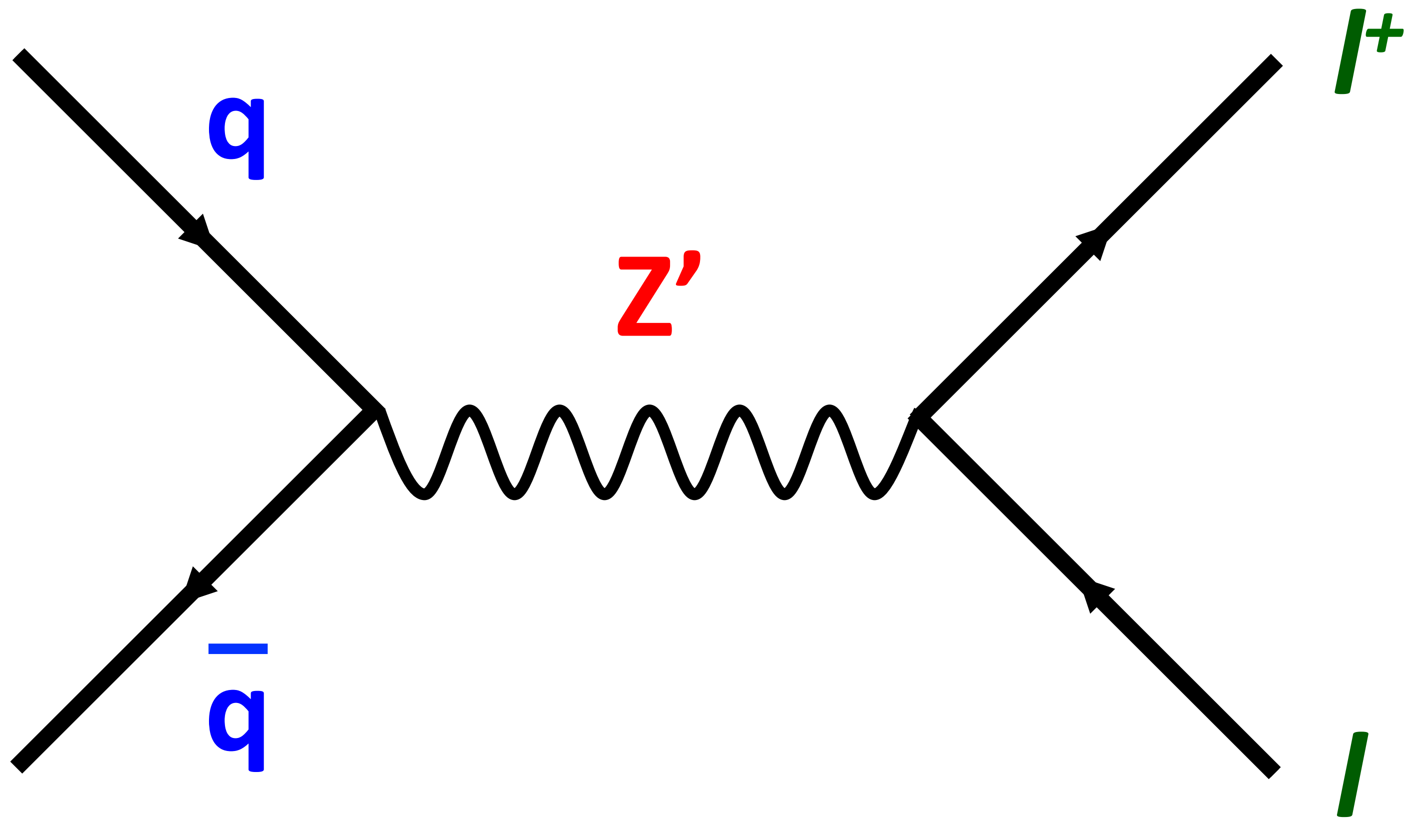


p_2 = 4-momentum of the final state anti-lepton

Data and MC Samples

Data: 2016+2015 data set (13.3/fb)

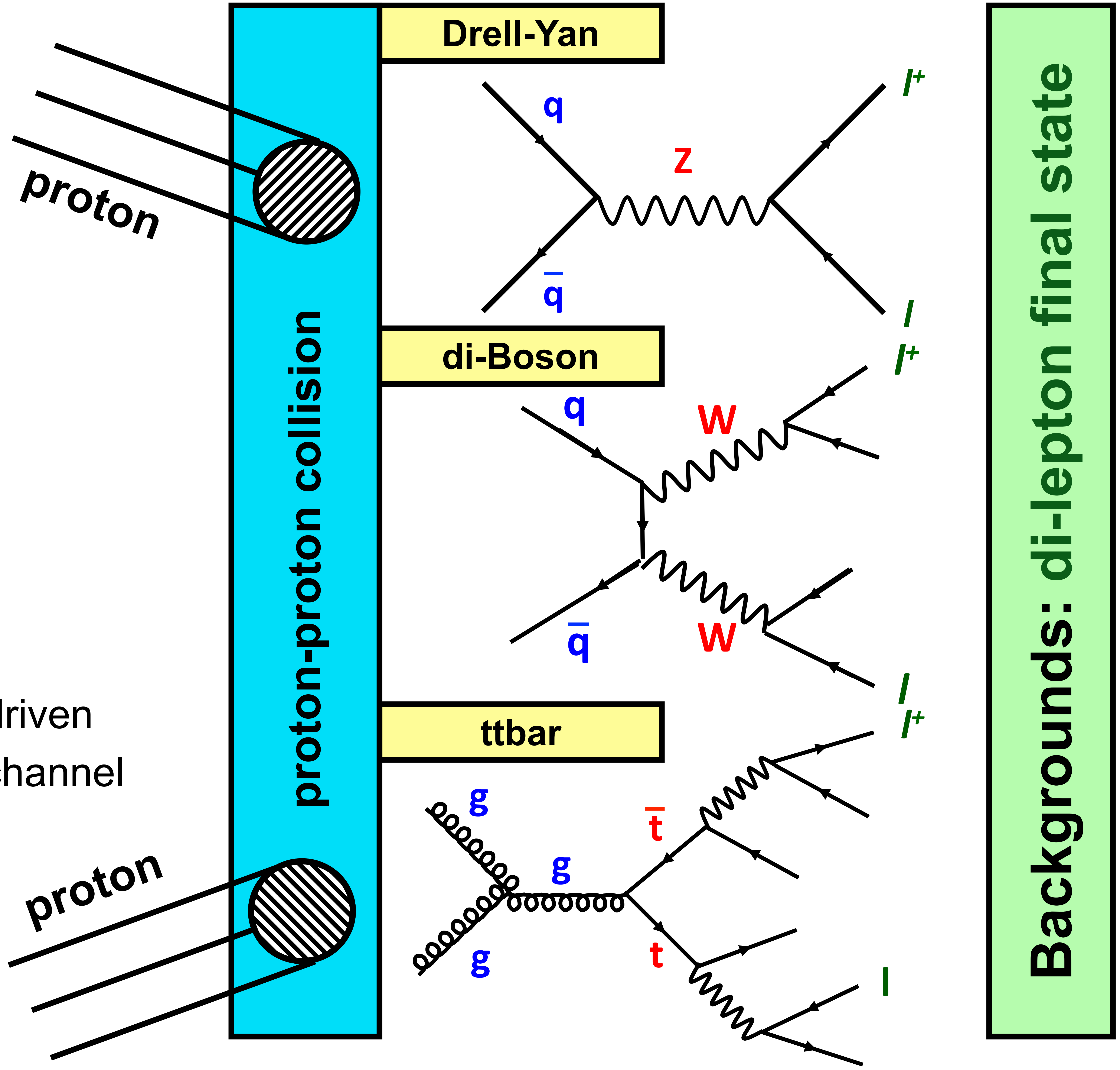
Largest Backgrounds: Monte-Carlo simulation



QCD & W+jets background: estimated using data-driven technique in electron channel → negligible in muon channel

➡ these events only have 1 actual lepton

➡ the other is a jet 'faking' a lepton



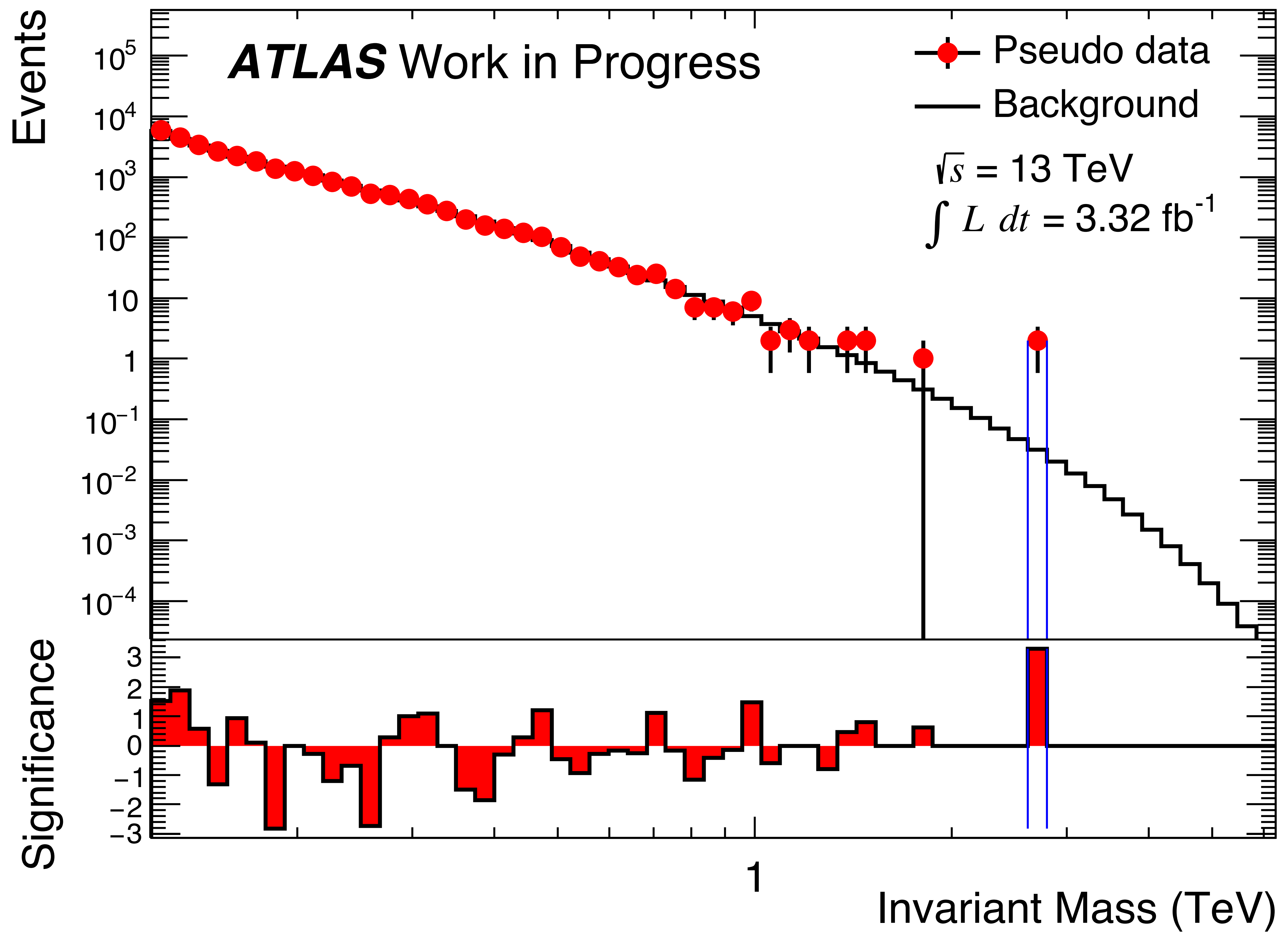
Searching new physics: BumpHunter

- Investigation any potential excess requires sophisticated search methods
- Different models predict different widths of resonances so want to search in a model independent way
- One such method: **BumpHunter**

The **BumpHunter** is a test that locates statistically significant deviations of data compared to the background null hypothesis

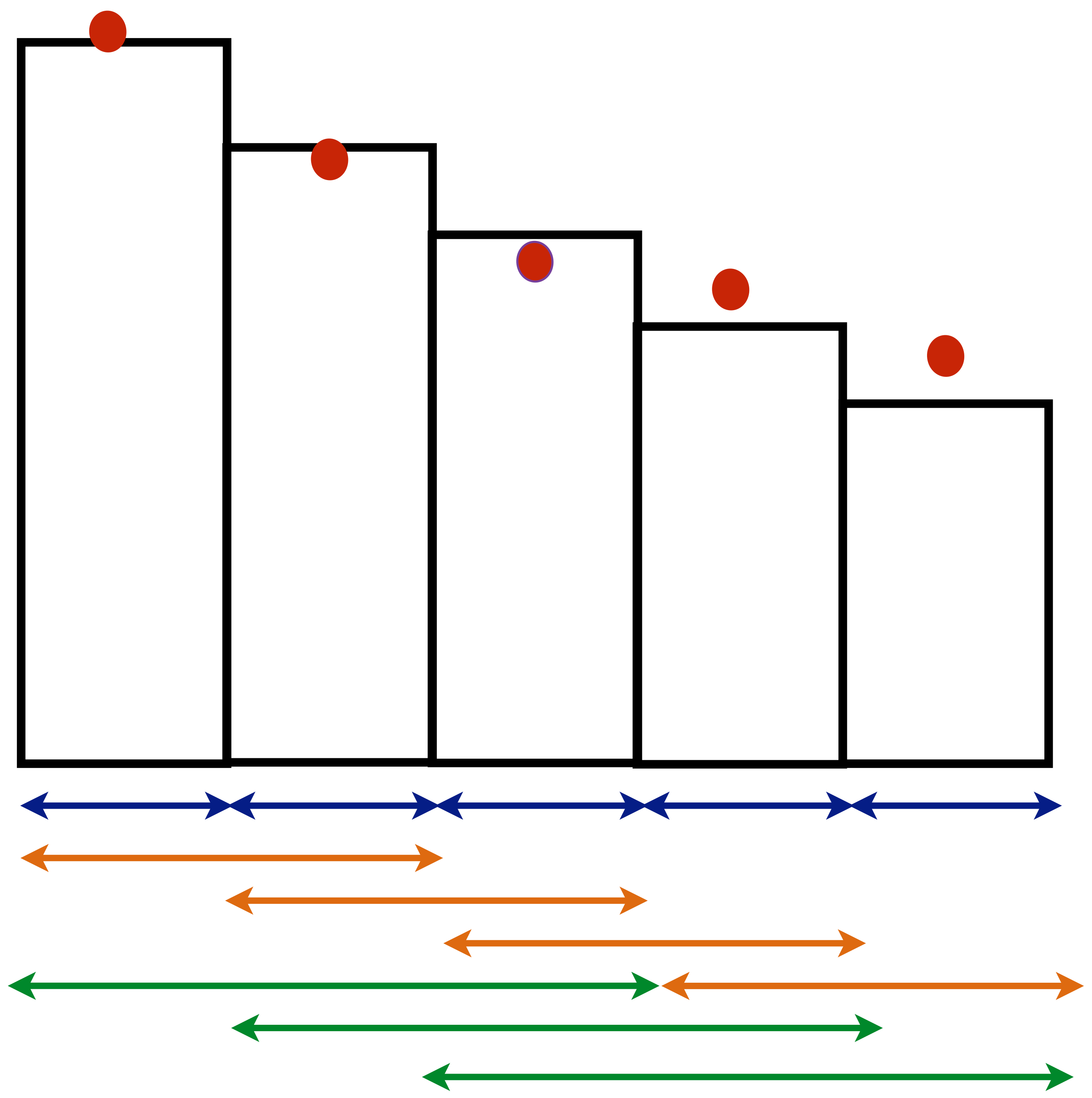
➡ **No signal model required**

https://arxiv.org/pdf/1101.0390v2.pdf by Georgios Choudalakis



pseudo-experiment:
signal injected at 2.65 TeV

BUMPHUNTER Intro



- **Searches in all contiguous bins:** 1 bin to half of the distribution
- local **p-value** = *p(n≥ d|b)*
- If bkg is poisson distributed

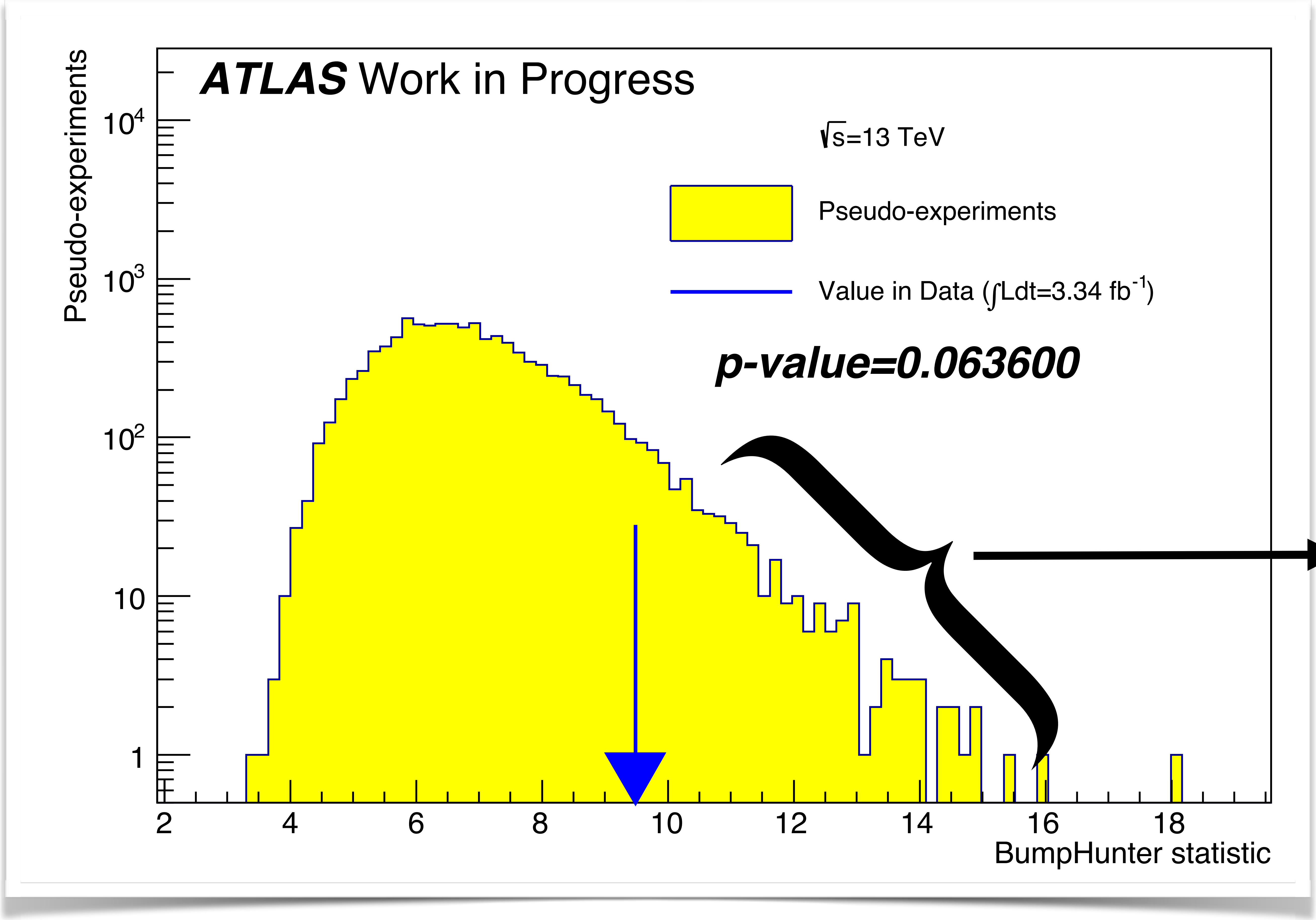
$$p(n \geq d|b) = \sum_{n=d}^{\infty} \frac{b^n}{n!} e^{-b}$$

- **BumpHunter statistic** = -ln(smallest local p-value)

But the more you search the larger the chance of getting statistically significant deviation due to bkg fluctuation

→ **look elsewhere-effect**

Generate many pseudo-experiments → calculate global p-value to compensate for this effect



Bkg-only pseudo-experiment (PE) =

Poisson fluctuation of nom bkg

global p-value =

$$\frac{\#\text{ of PEs where (bkg-only statistics } > \text{ observed statistics)}}{\text{Total }\#\text{ of pseudo-experiments}}$$

BumpHunter Intro

Algorithm

- Evaluate local p-value
- Select smallest p-value → BH Statistic
- Obtain global p-value

$$\frac{\#\text{ of PEs where (bkg-only statistics } > \text{observed statistics)}}{\text{Total }\#\text{ of pseudo-experiments}}$$

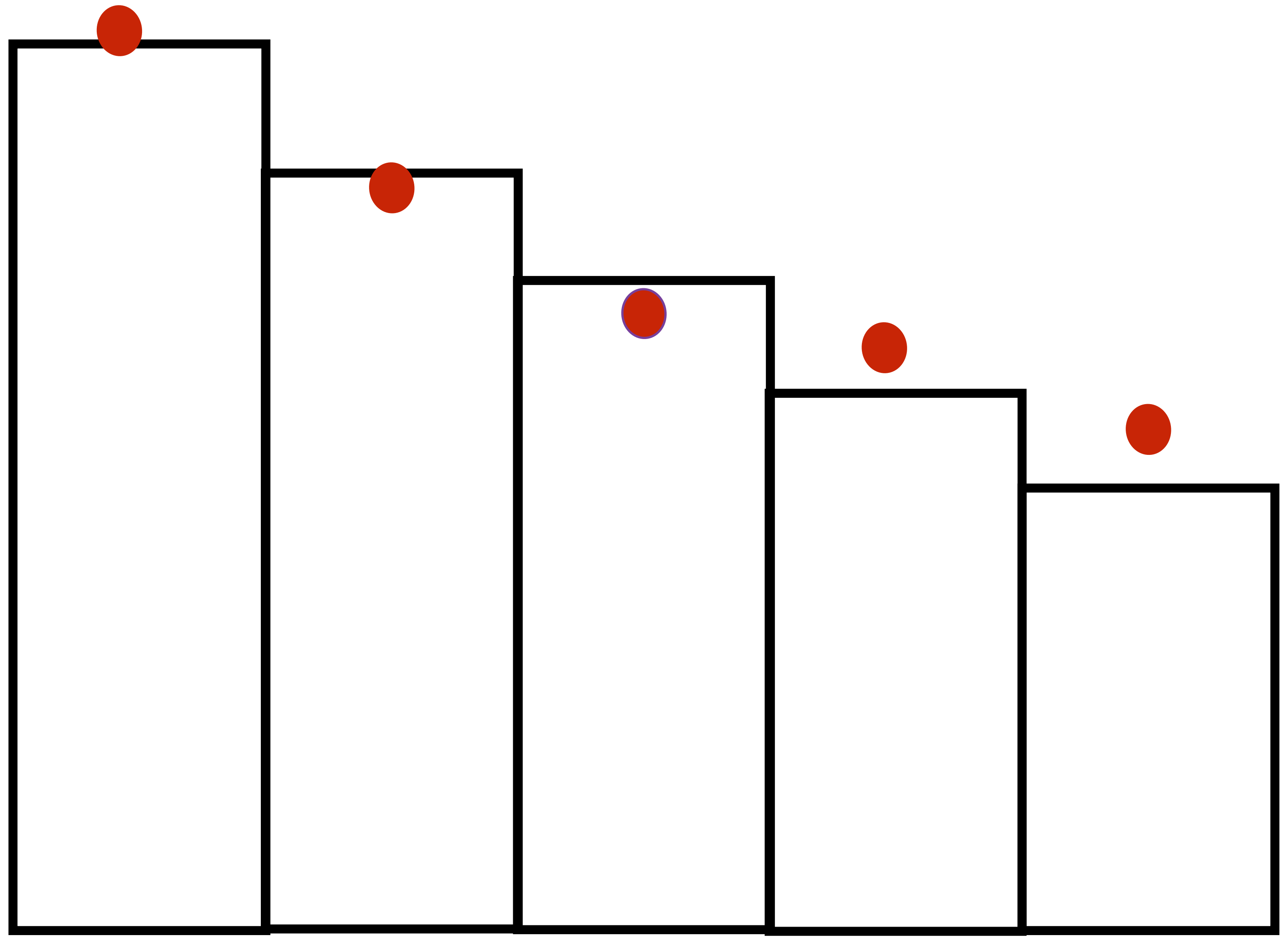
Effect of Systematic Uncertainties

In the absence of systematics

$$p(n_k|b_k) = \frac{b_k^{n_k}}{n_k!}e^{-b_k}$$

n_k : # of data events in k^{th} bin

b_k : # of background events in k^{th} bin



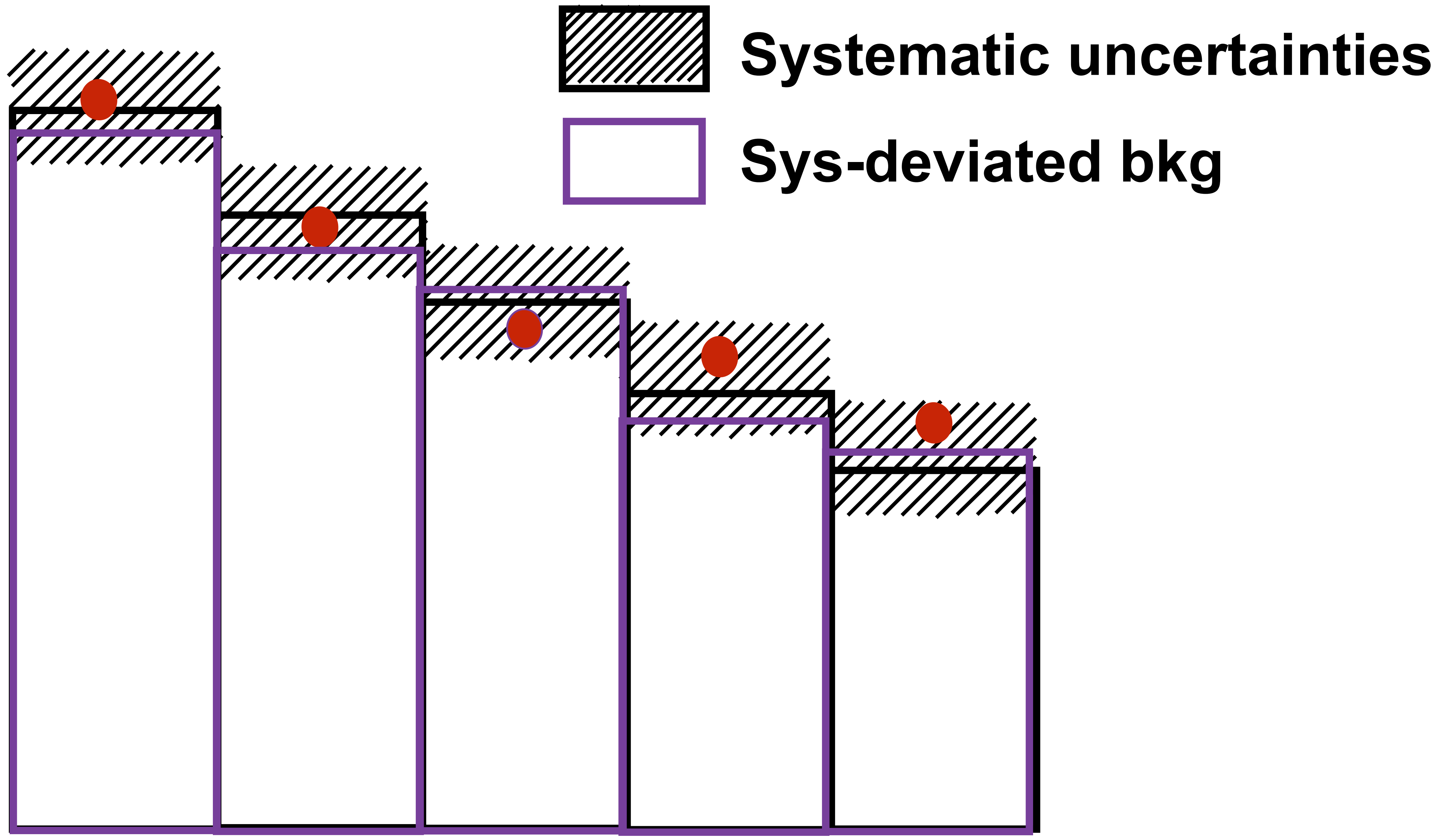
In presence of systematics

$$p(n_k|\mu_k) = \frac{\mu_k^{n_k}}{n_k!}e^{-\mu_k}$$

$$\mu_k = b_k(1 + \sum_{i=1}^{N_{sys}} \theta_i \sigma_{ik})$$

θ_i : nuisance parameter

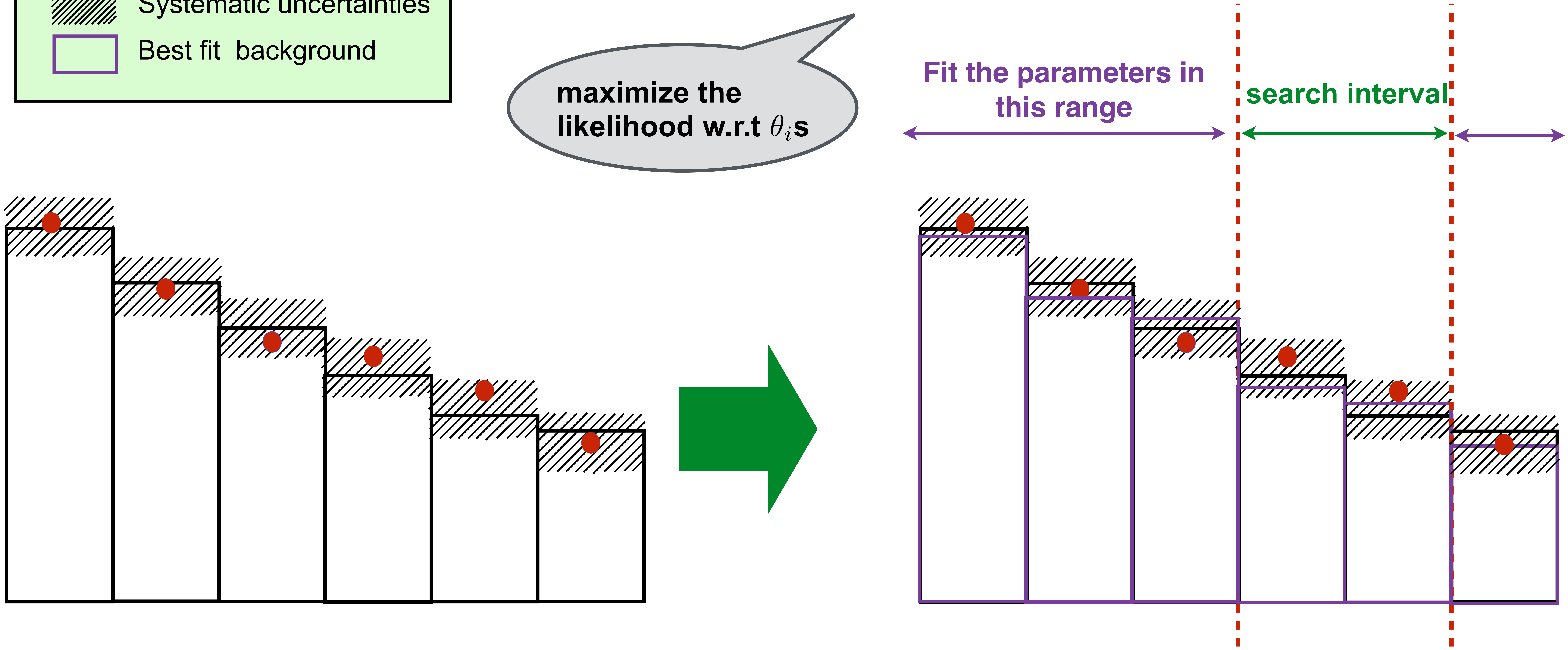
σ_{ik} : k^{th} bin content of i^{th} systematic



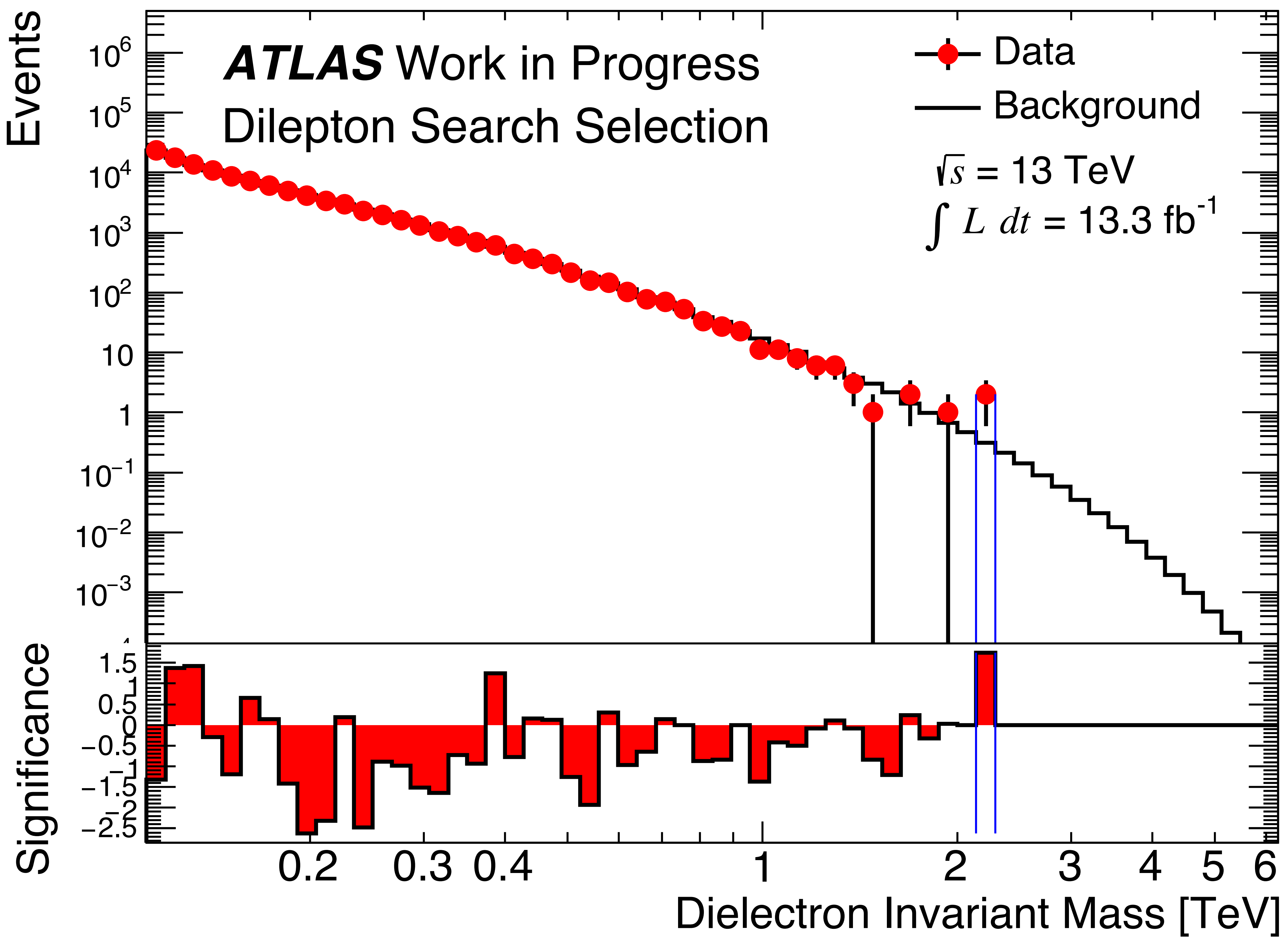
Search in presence of systematics

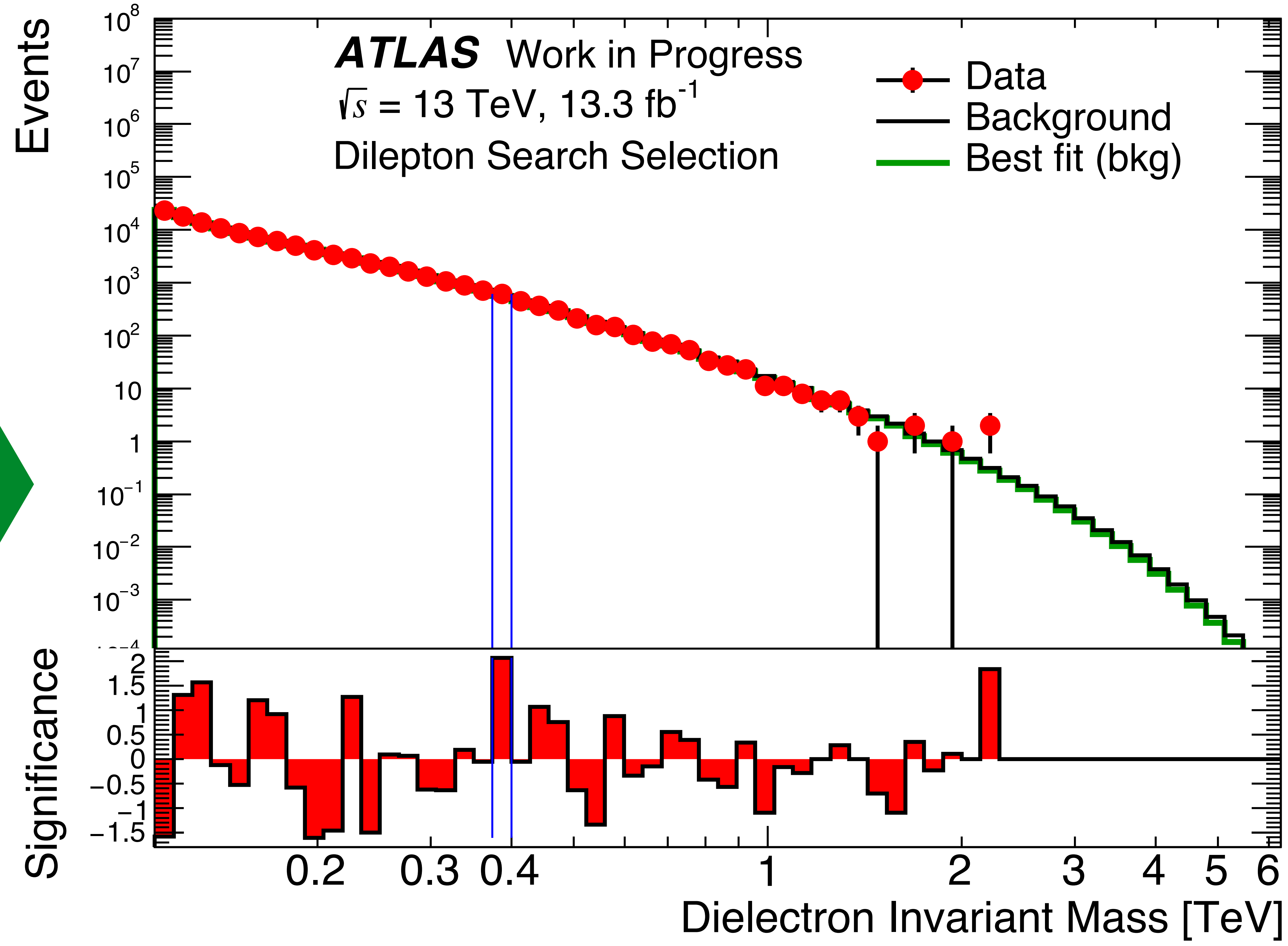
- ● **Pseudo data or data**
- ☐ Nominal background
- ▨ Systematic uncertainties
- ☐ Best fit background

$$\mathcal{L}(data|N_{exp}) = \prod_{k=1}^{N_{bin}} \frac{\mu_k^{n_k}}{n_k!} e^{-\mu_k} \prod_{k=1}^{N_{sys}} G(0,1;\theta)$$



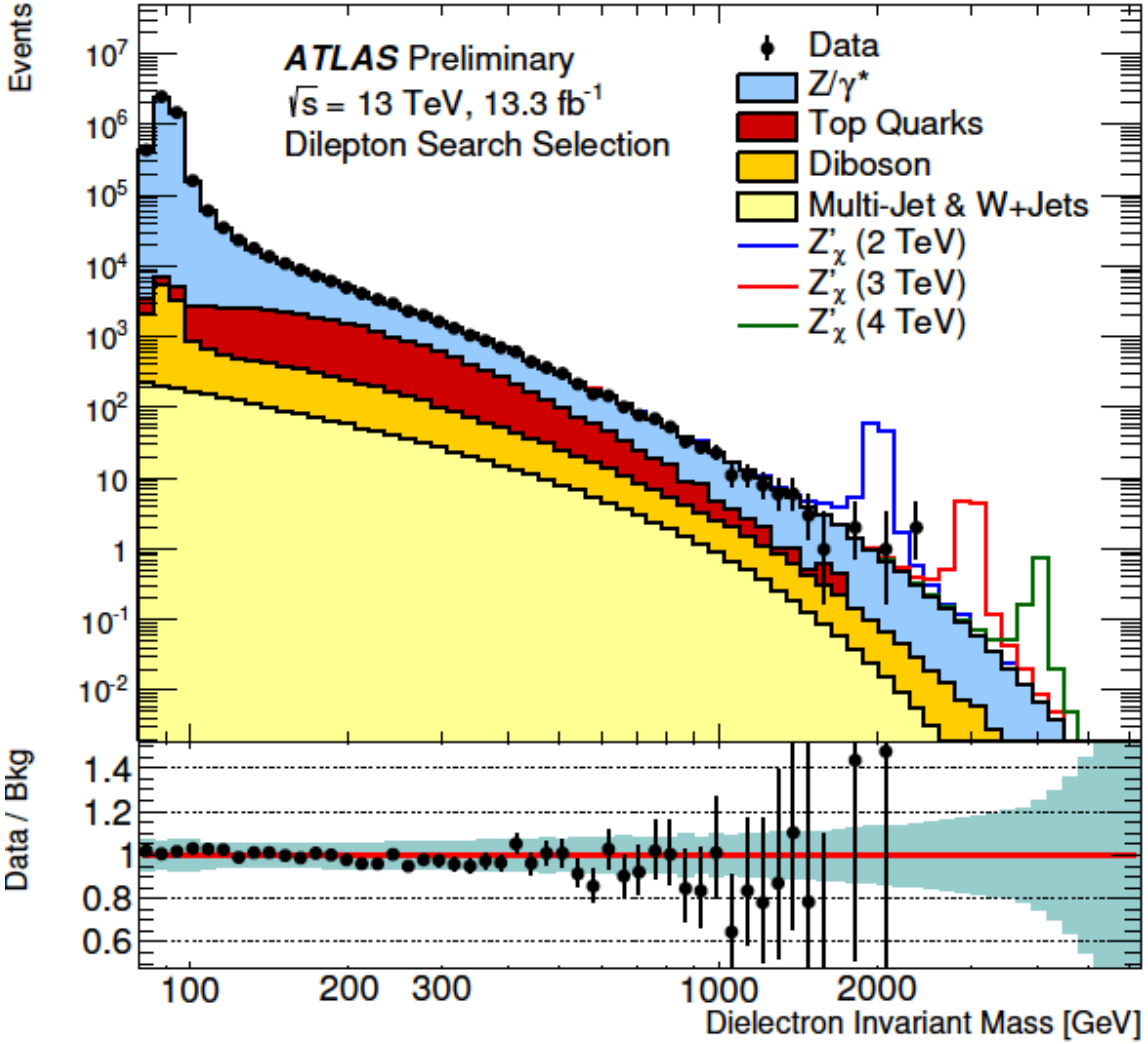
- After applying the systematics the significances are evenly distributed about zero
- The background with the best fit parameters are shown in **green**



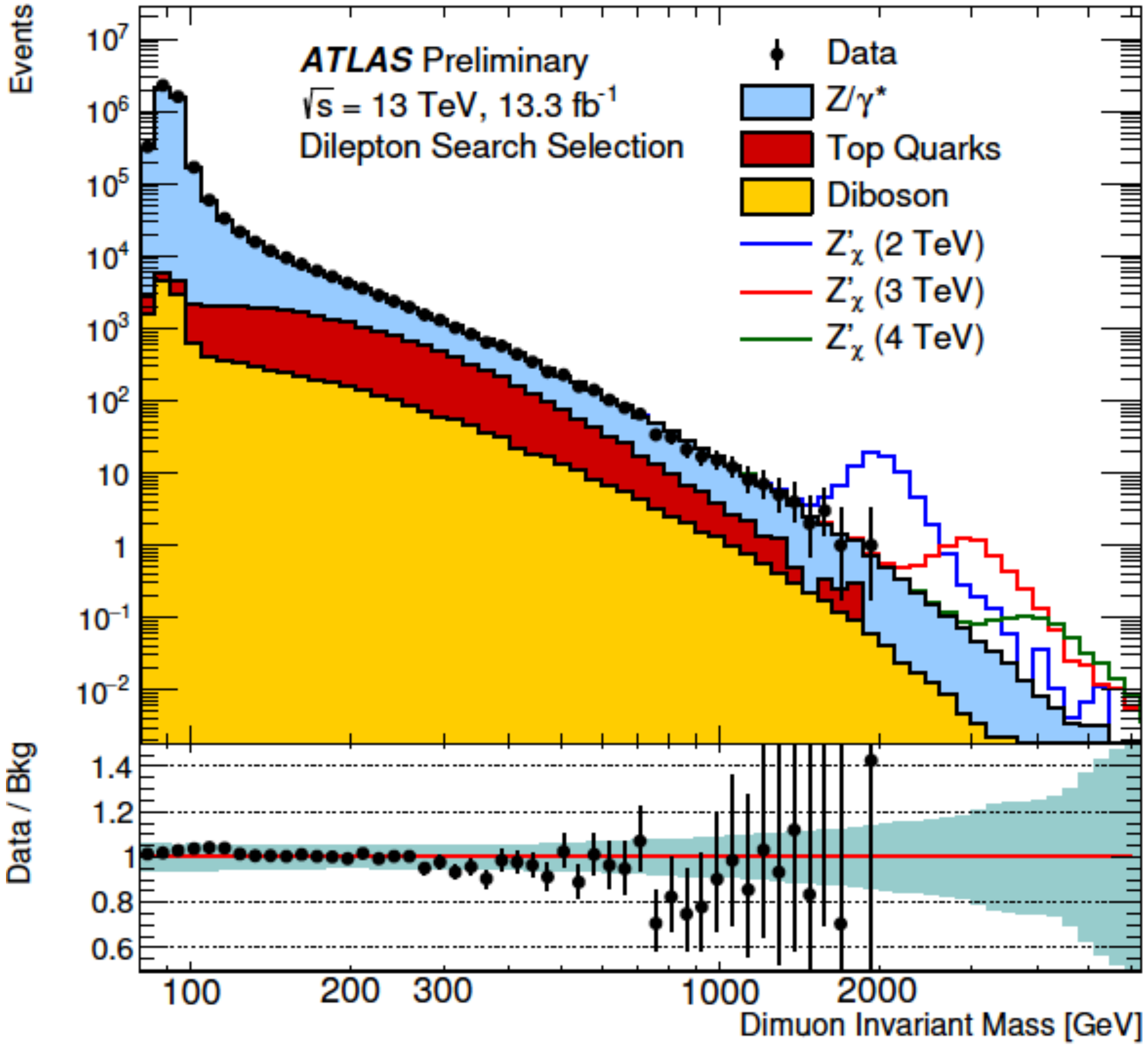


Invariant Mass distribution (data till July 2016)

Electron Channel



Muon Channel



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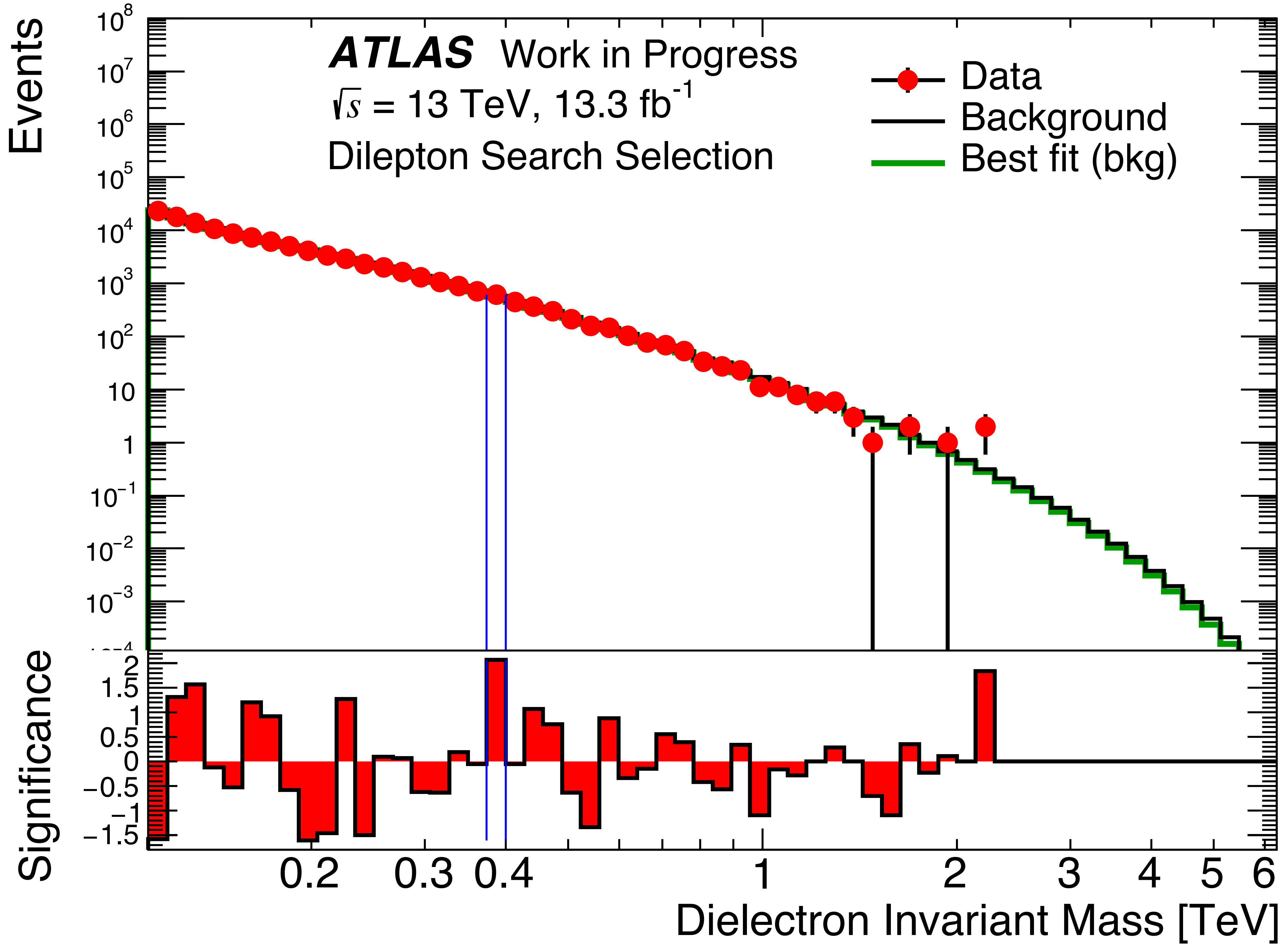
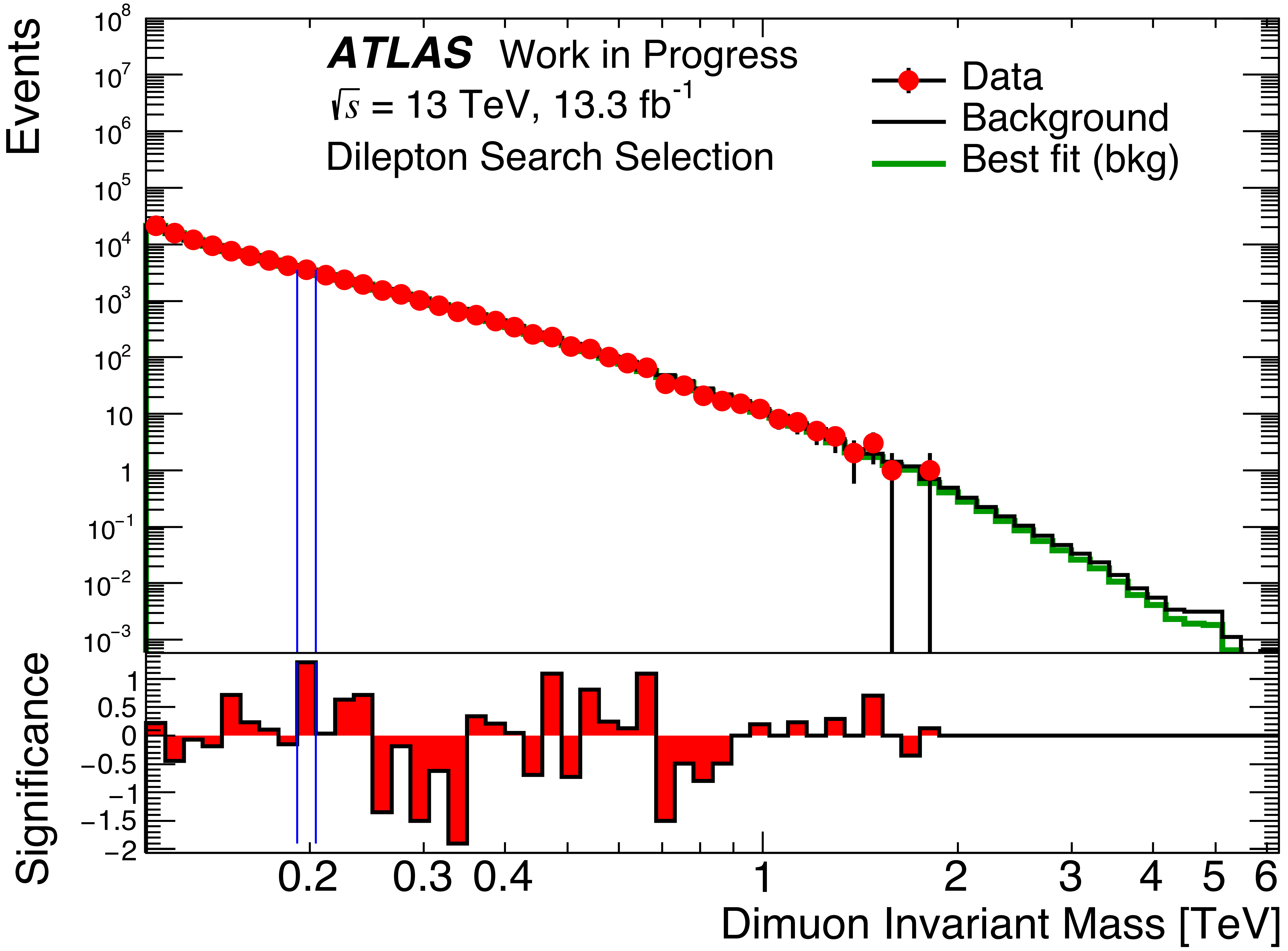
Electron Channel

Global p-value: 0.88 σ



Muon Channel

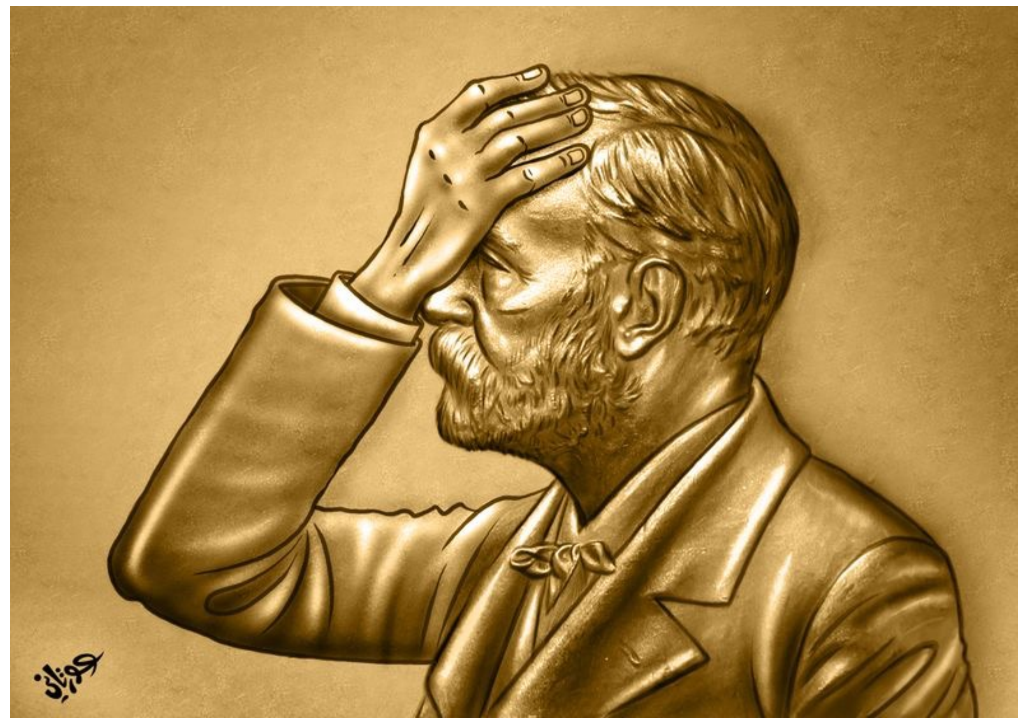
Global p-value: -0.26 σ



Conclusion and Outlook

- Many BSM theories predict high mass resonance with di-lepton final states

- **So far no new signal has been observed**
  - Overall good agreement between data and MC
  - Currently looking at full 2015+2016 data



- **BUMPHUNTER** used to search for model-independent signal
- Systematic uncertainties have been successfully implemented in the BUMPHUNTER framework
  - Need to reduce computation time!

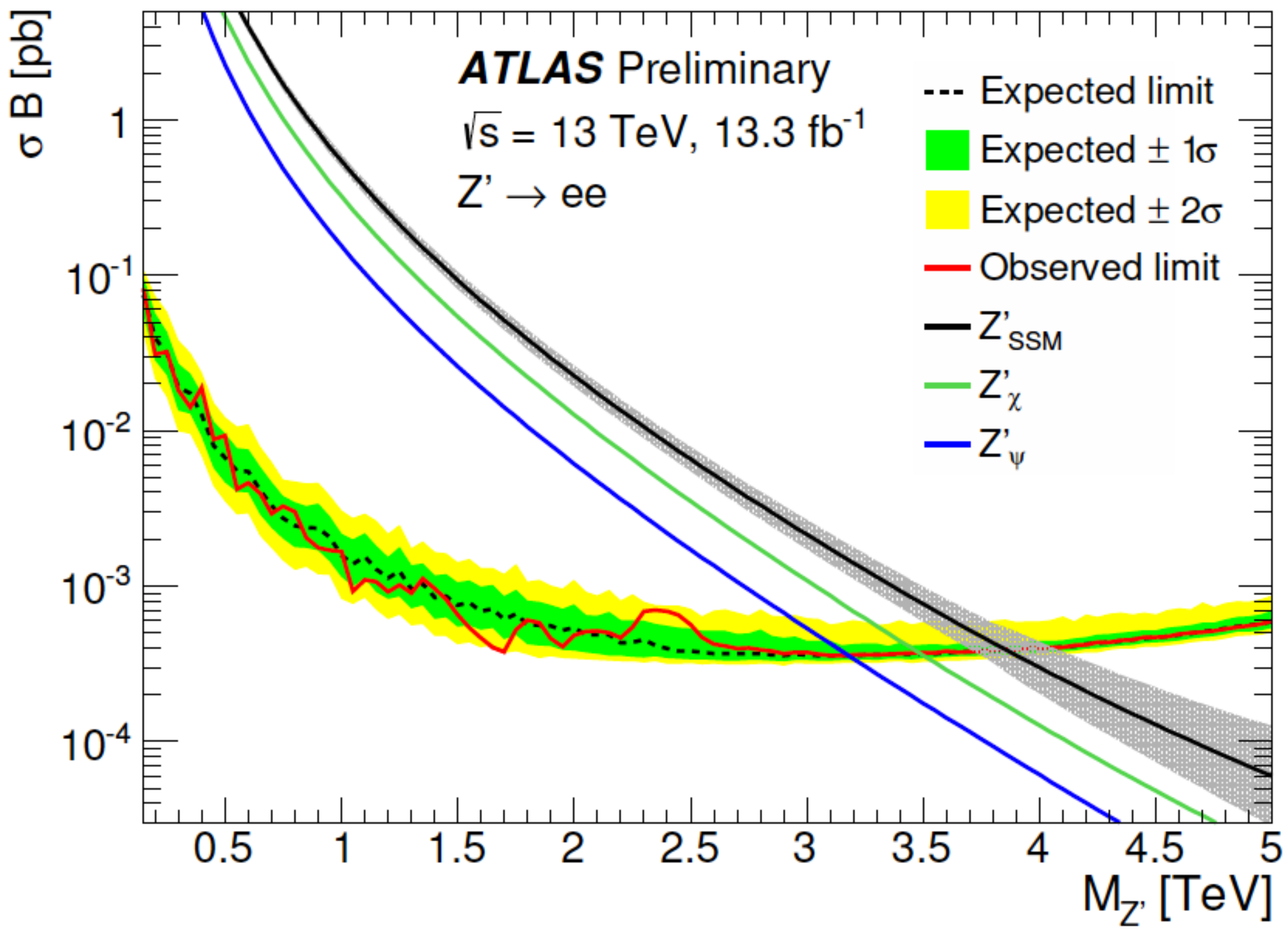
Current Status:

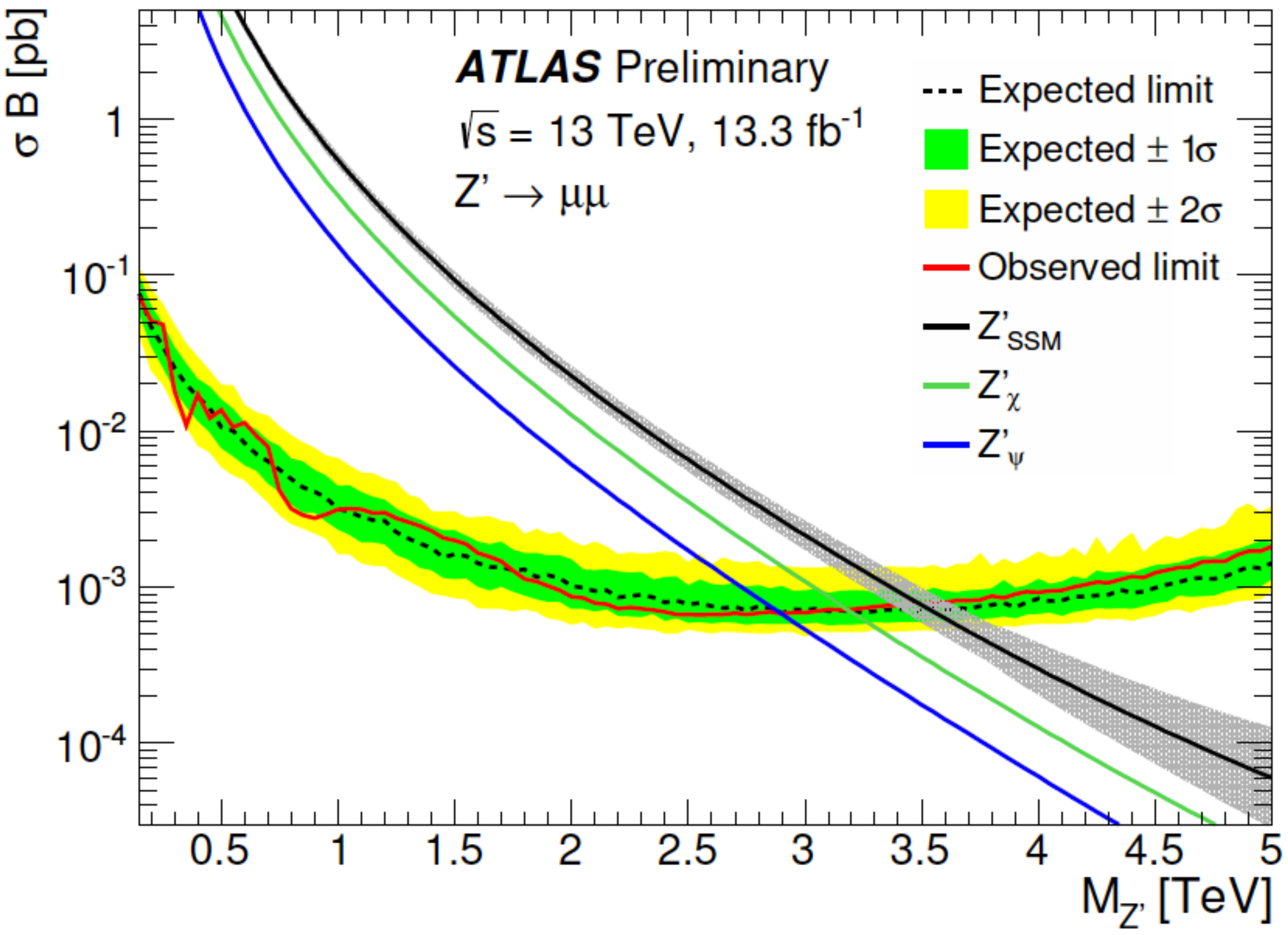
- Need to implement the method for combining several channels

Thank you !!

Back up

Current 95% Exclusion limits on mass





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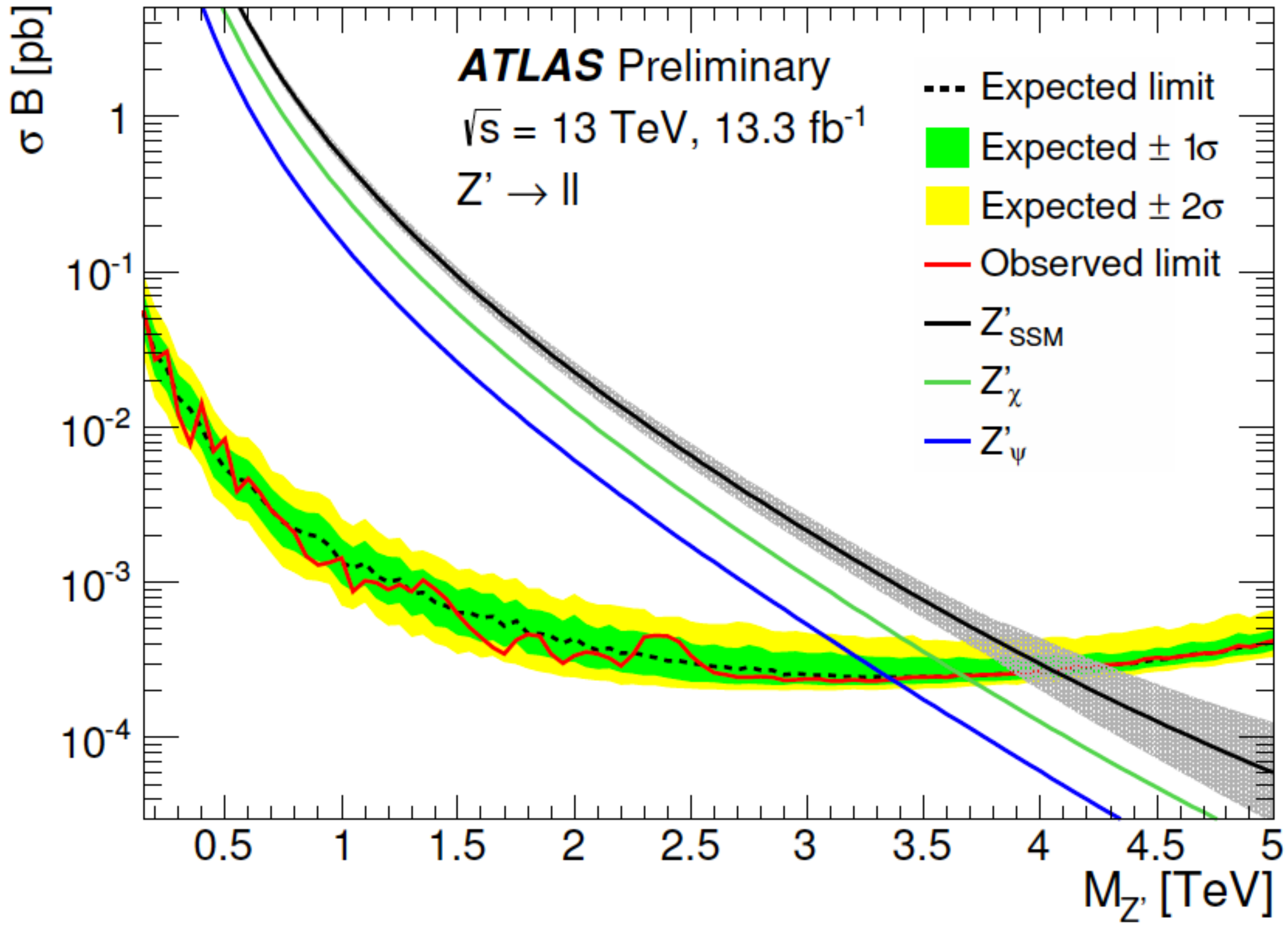
Current 95% Exclusion limits on mass



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Current 95% Exclusion limits on mass

Table 4: Observed and expected 95% C.L. lower mass limits for various Z' gauge boson models. The widths are quoted as a percentage of the resonance mass.

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

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Background Only PE

Nominal background

Systematic uncertainties

$$\mu_k = b_k(1 + \sum_{i=1}^{N_{sys}} \theta_i \sigma_{ik})$$

θ_i : random numbers from Gaussian(0,1)

Pseudo data:

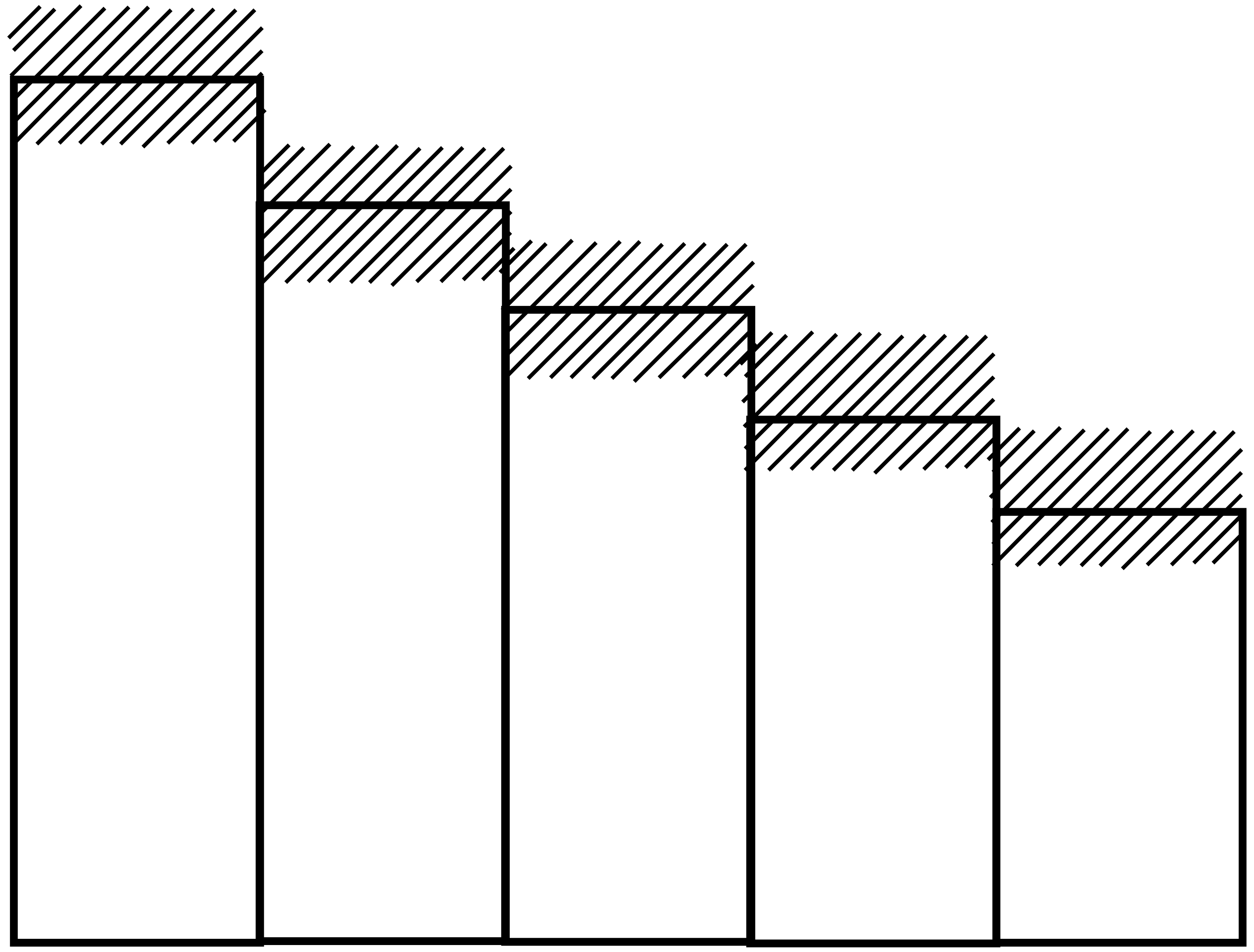
Poisson fluctuation around sys varied bkg

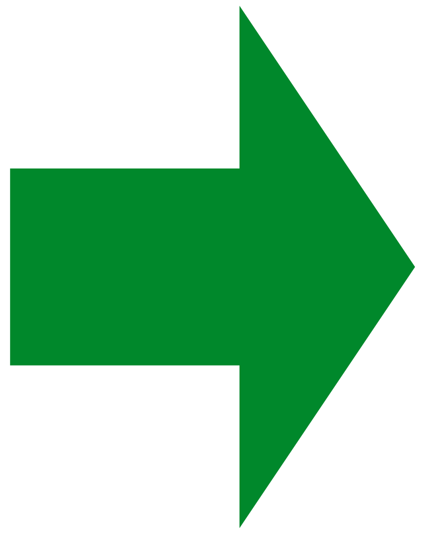
Pseudo data

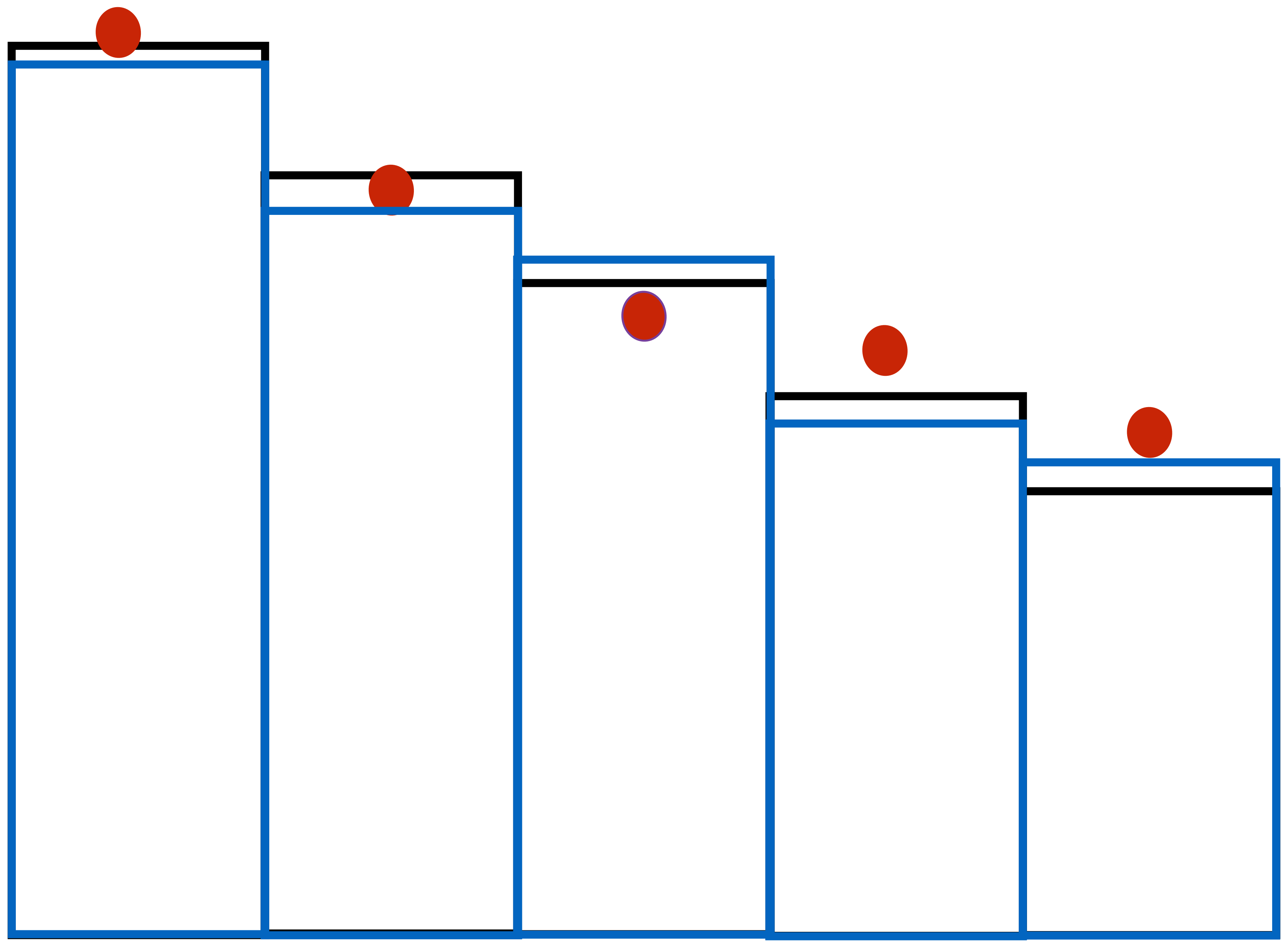
Nominal background

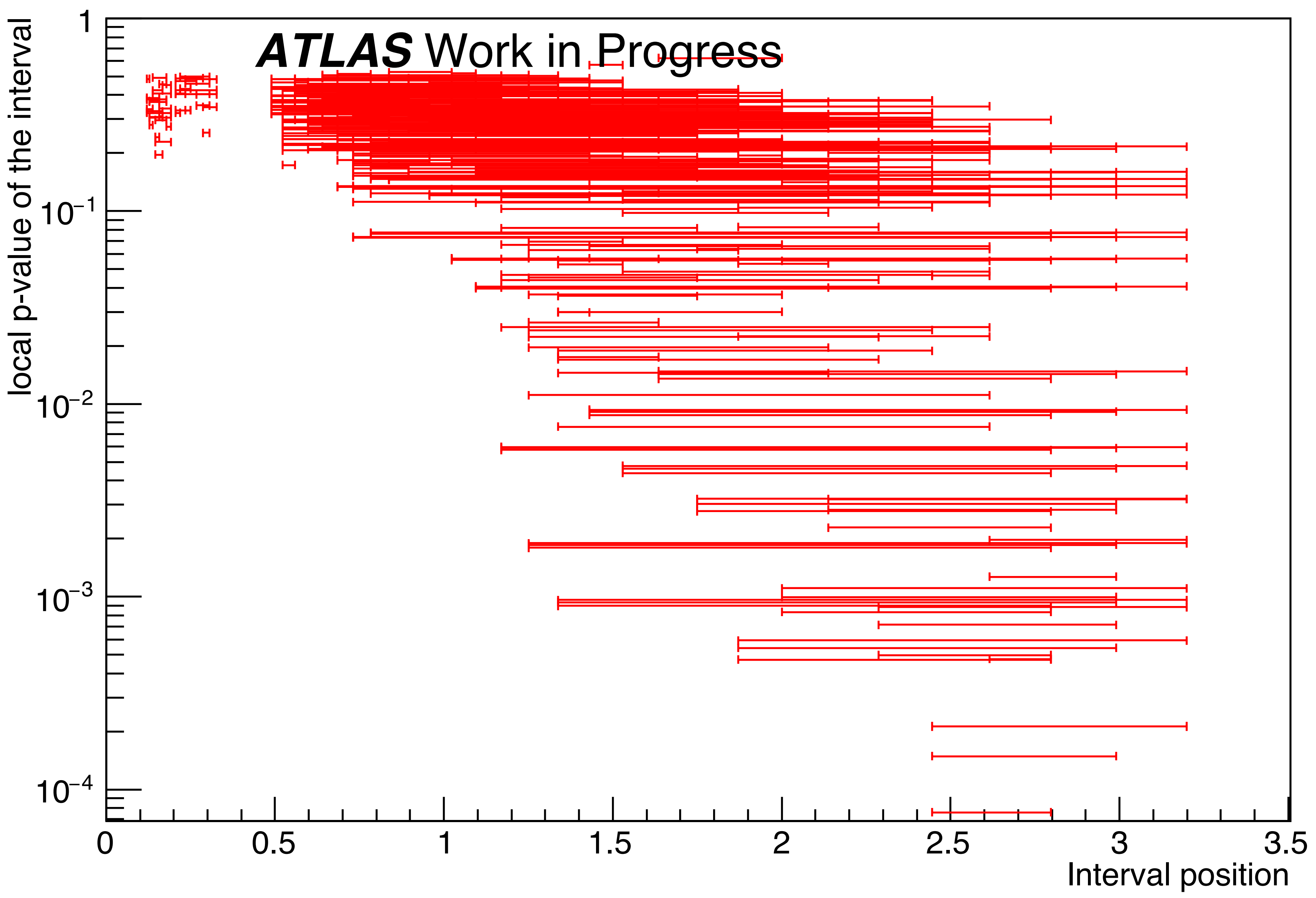
Systematic uncertainties

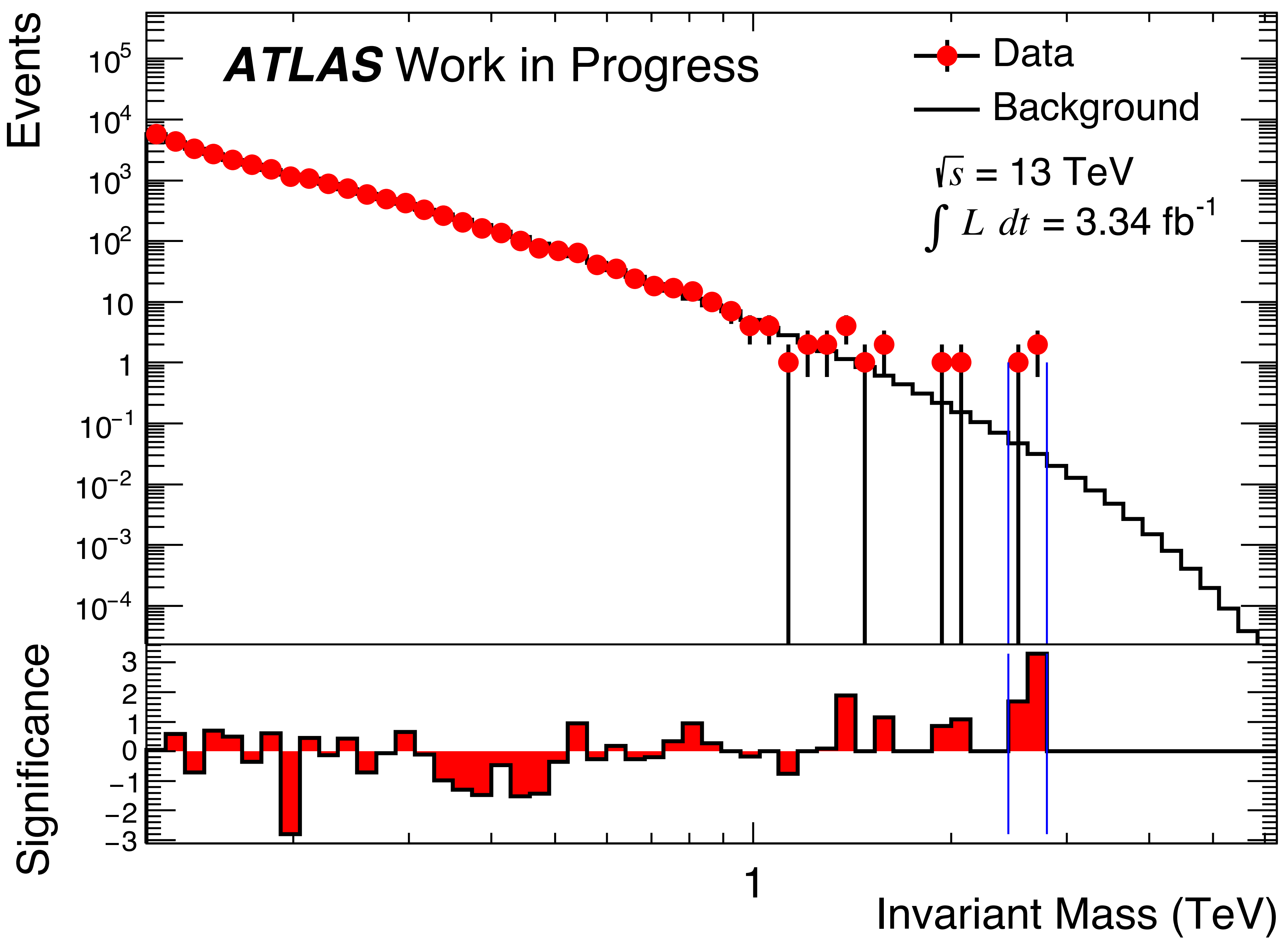
Sys varied background








ATLAS Work in Progress
local p-value of the interval
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.5
1
1.5
2
2.5
3
3.5
Interval position


ATLAS Work in Progress
Data
Background
$\sqrt{s}$ = 13 TeV
$\int L\ dt$ = 3.34 fb^{-1}
Events
Significance
1
Invariant Mass (TeV)

Event Selection

Electron Channel

- Event passes di-electron trigger
- >= 2 electron
- Well reconstructed isolated electrons with E_T >30 GeV

- Two highest E_T leptons
  - mass > 80 GeV

Muon Channel

- Event passes single muon trigger
- >= 2 muons
- Well reconstructed isolated muons with p_T >30 GeV

- Two highest p_T leptons with opposite charge
  - mass > 80 GeV

Event Selection

Electron Channel	Muon Channel
Event-level criteria	
Trigger: 2e17_lhloose	Trigger: mu26_ivarmedium || mu50
Event Cleaning	Event Cleaning
>=2 electrons	>=2 muons
Lepton-level selection	
$\|\eta\|$< 2.47, exclude crack region	p_T >30 GeV
Good Object Qualty	High p_T Muon Working Point
E_T >30 GeV	bad-muon veto
$\|d_0(\sigma)\| < 5$	$\|d_0(\sigma)\| < 3$
$\|\Delta z_0 \sin\theta\| < 0.5$ mm	$\|\Delta z_0 \sin\theta\| < 0.5$ mm
Electron-ID: Likelihood Medium	Isolation WP: Loose Track Only
Isolation WP: Loose	Opposite Charge
Select Highest E_T/p_T Pair	
m_{ee} > 80 GeV	$m_{\mu\mu}$ > 80 GeV

Data and MC Samples

Data: All 2016+2015 data set (36.5/fb)

Largest Backgrounds: from Monte-Carlo simulation

QCD & W+jets background: estimated using data-driven technique in electron channel → negligible in muon channel

these events only have 1 actual lepton, the other is a jet 'faking' a lepton

Additional **Theory Corrections** (QCD, ElectroWeak, Photon Induced) applied to Drell-Yan (Z/γ^*)

Backgrounds	Generator	Order	Parton Shower	PDF	Sample
NC Drell-Yan	Powheg v2	NLO	Pythia 8.186	CT10	Unbinned & Mass-Binned: 120 – 5000+ GeV
Top	Powheg v2	NLO	Pythia 6.428	CT10	Unbinned
Diboson	Sherpa 2.1.1	NLO	Sherpa 2.1.1	CT10	Mass-binned
Signals	**Generator**	**Order**	**Parton Shower**	**PDF**	**Sample**
NC Drell-Yan	Pythia 8.186	LO	Pythia 8.186	NNPDF23LO	Mass-Binned: 70 – 5000+ GeV (for signal reweighting)
Z' (E6 Chi)	Pythia 8.186	LO	Pythia 8.186	NNPDF23LO	Unbinned, no interference: 2, 3, 4, 5 TeV
CI(LL,LR,RL,RR)	Pythia 8.186	LO	Pythia 8.186	NNPDF23LO	Mass-Binned: 300 – 3000+ GeV