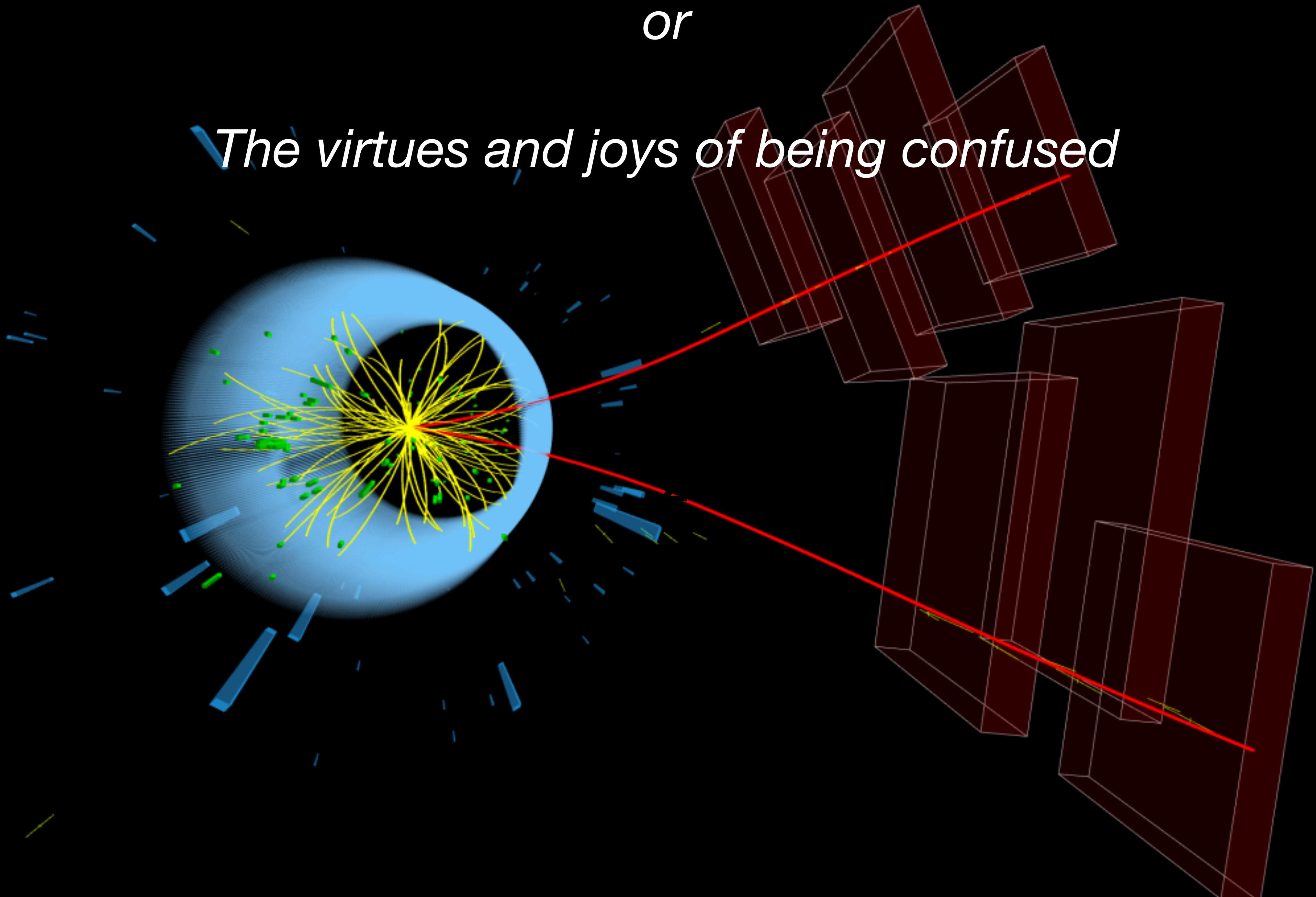
What do we learn from anomalies and tensions?

or

The virtues and joys of being confused



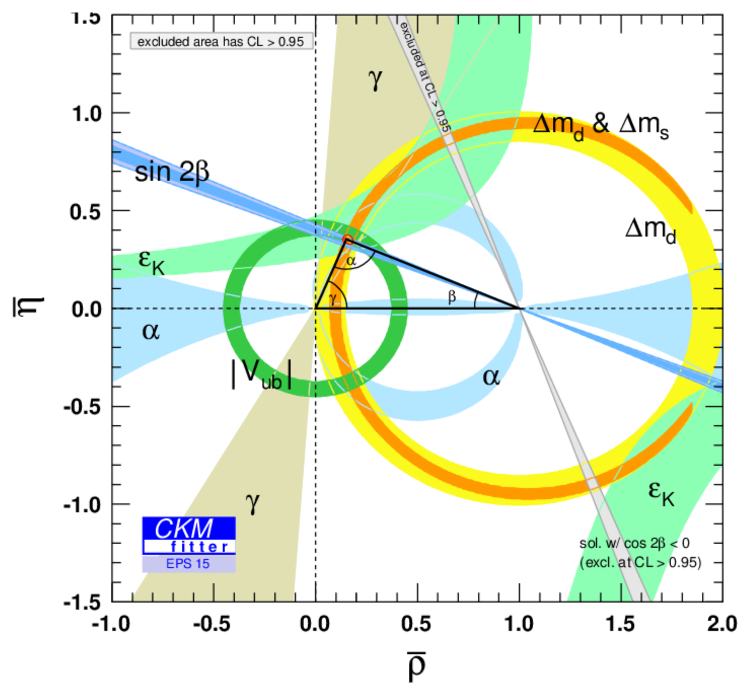
Simon Knapen

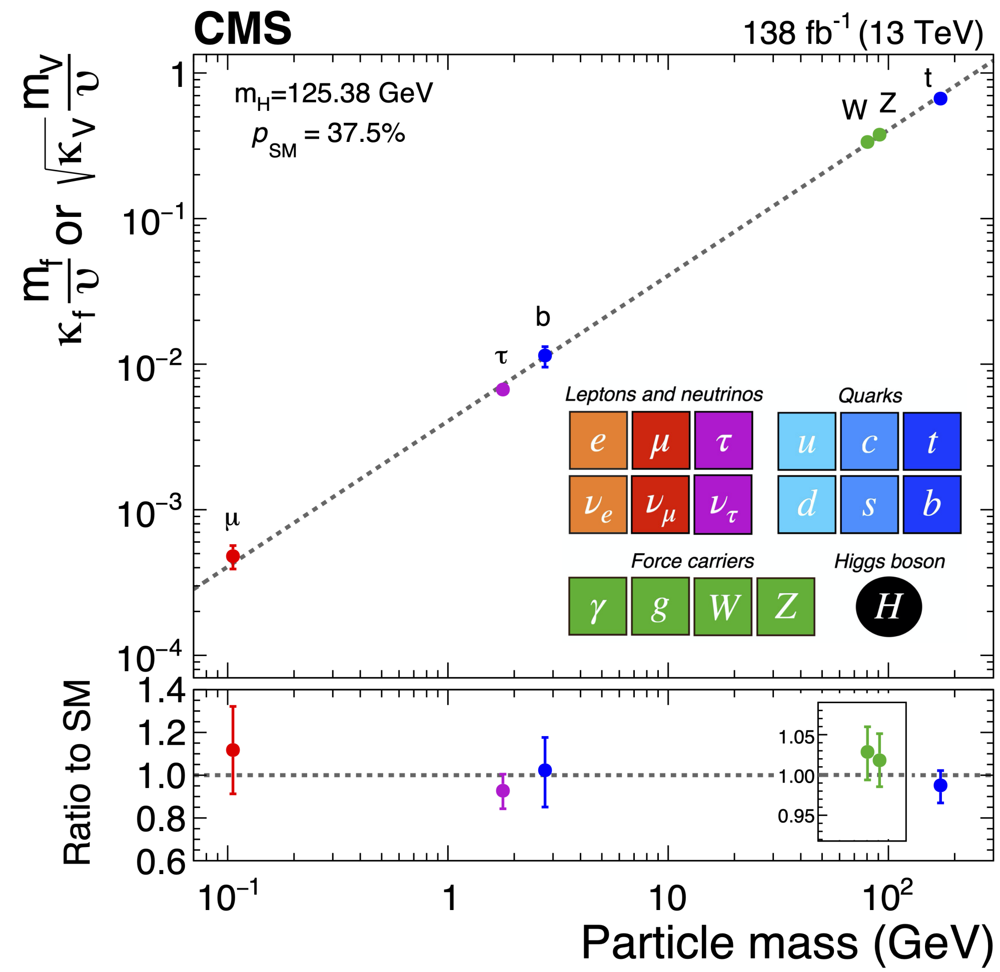
Lawrence Berkeley National Laboratory

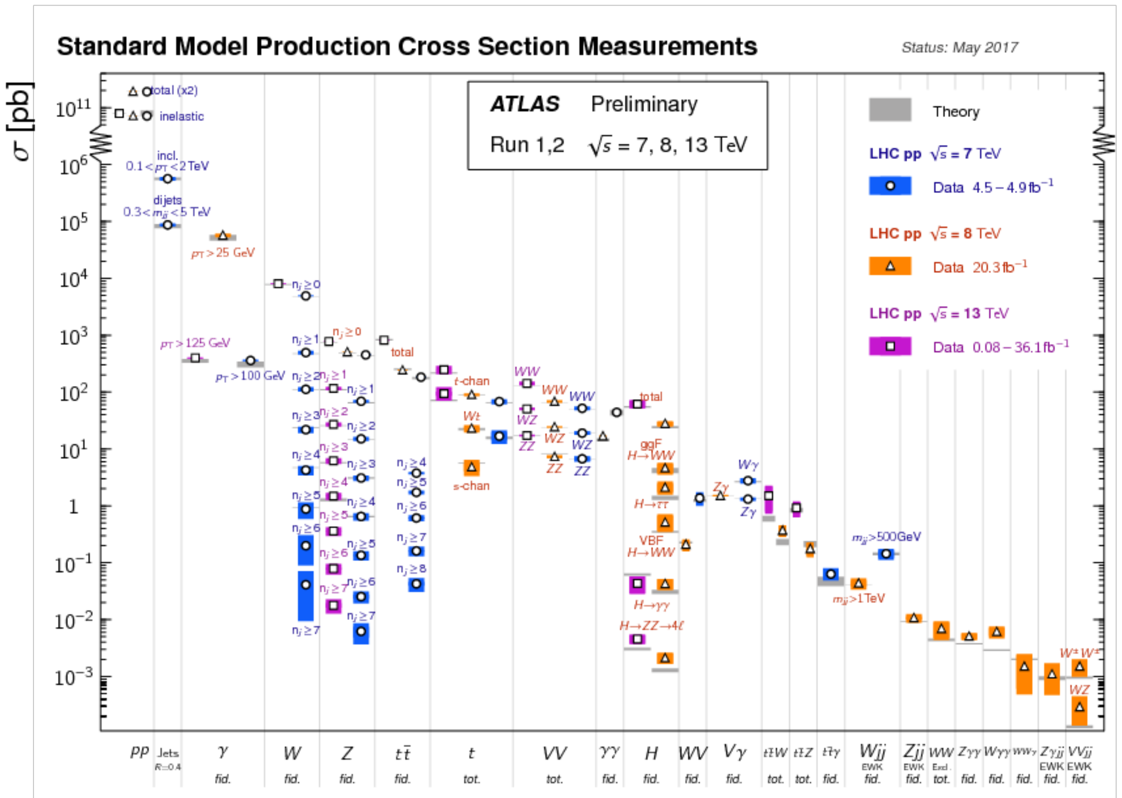
BERKELEY LAB

Particle physics is a unique field of science

Quantitative comparisons of theoretical predictions with experimental data are extraordinary







With this many measurements, large anomalies and tensions in data must occur

What to do about this is highly non-trivial

Outline

1. Why pay attention to anomalies?
2. How to judge an anomaly?
3. A case study
4. Some current anomalies

I will make no attempt at surveying and classifying all existing anomalies

I hope top provide you with tools / ideas to start tackling existing & future anomalies yourself

Why pay attention to anomalies?

Anomalies & tensions between data and theory are expected and important in how we make progress

Even if they end up “not being real”

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Even if they end up “not being real”

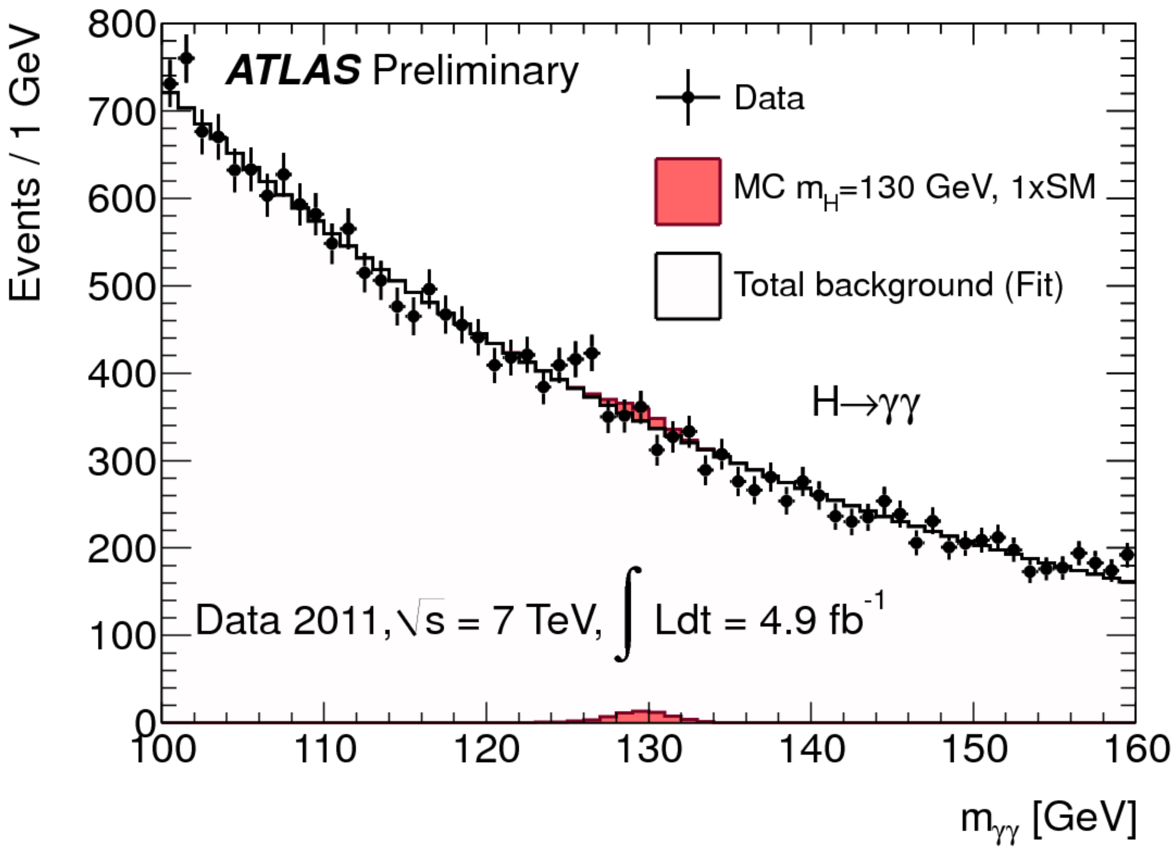
Why?

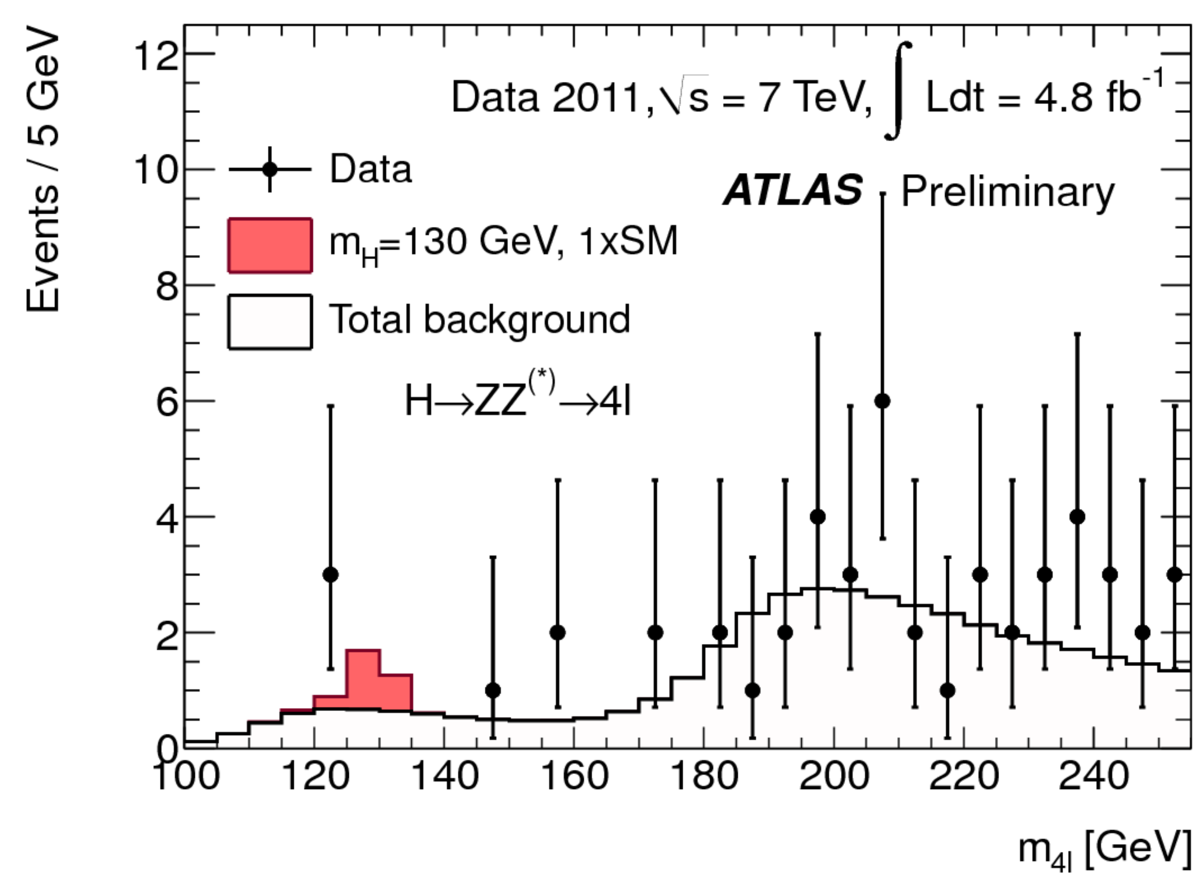
1. Discoveries often start as anomalies
2. Highlight sometimes lesser-known experiments / searches
3. Force us to re-examine theory predictions and / or experimental analysis
4. Thinking about them is a great way to stay in shape
5. Often lead to new research directions that persist long after the anomaly has been resolved

Why pay attention to anomalies?

1. Discoveries often start as anomalies

December 2011
4.9 fb^{-1} @ 7 TeV





ATLAS: 3.6σ (local), 2.5σ (global)
CMS: 2.6σ (local), 1.9σ (global)

ATLAS-CONF-2011-163/

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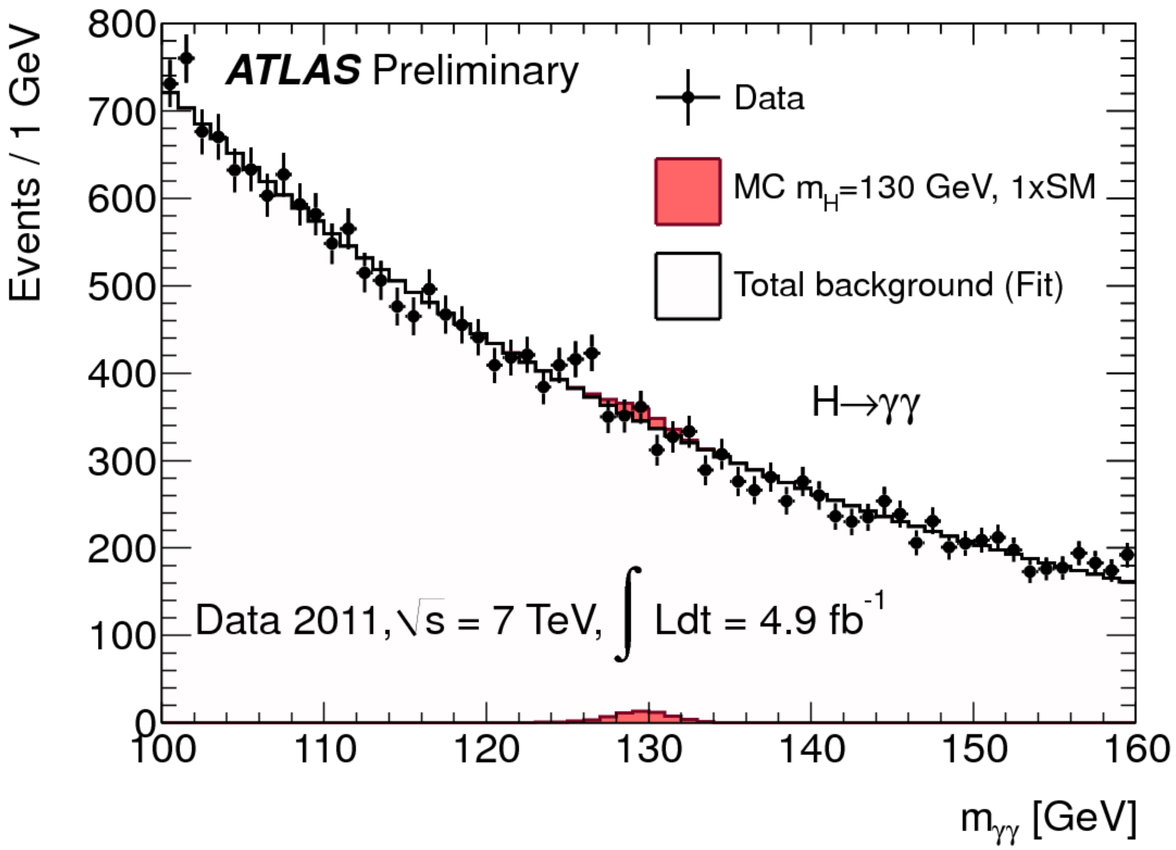
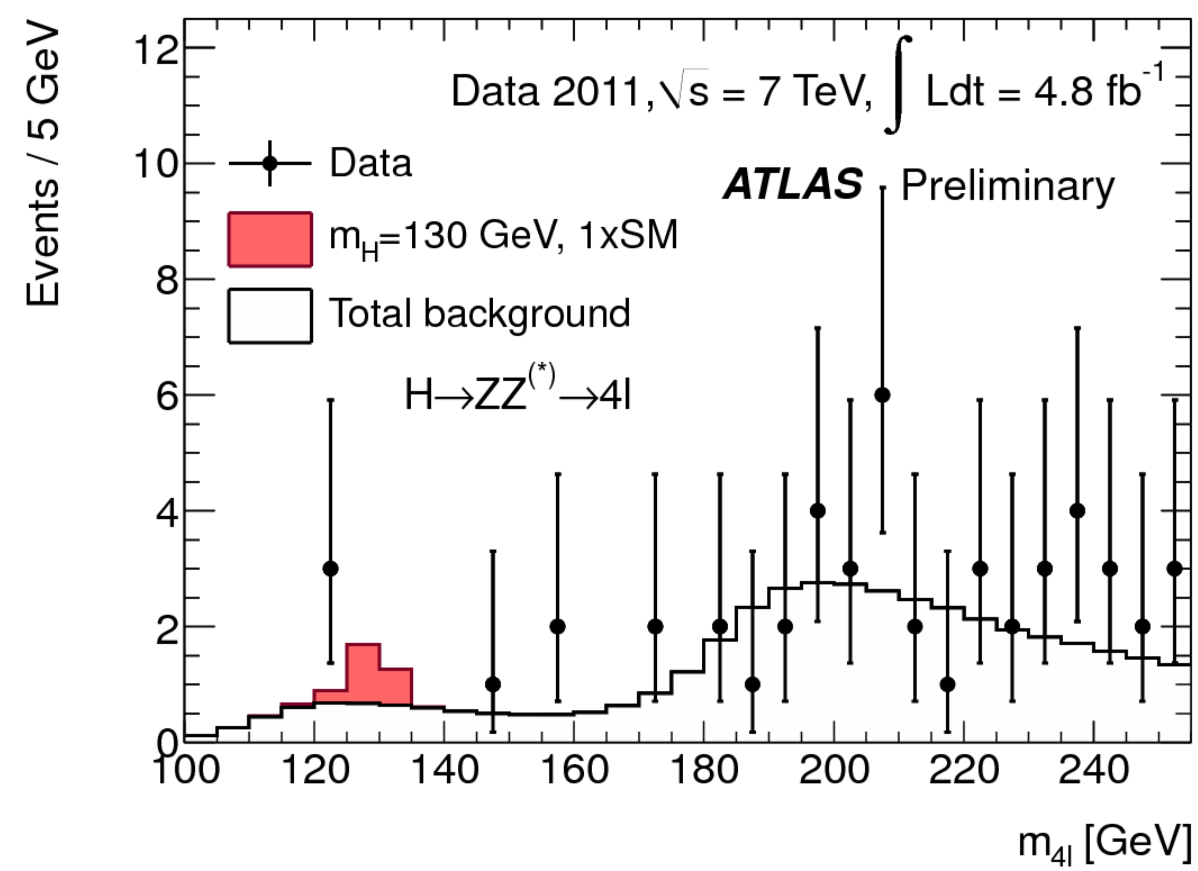




ATLAS: 3.6σ (local), 2.5σ (global)
CMS: 2.6σ (local), 1.9σ (global)

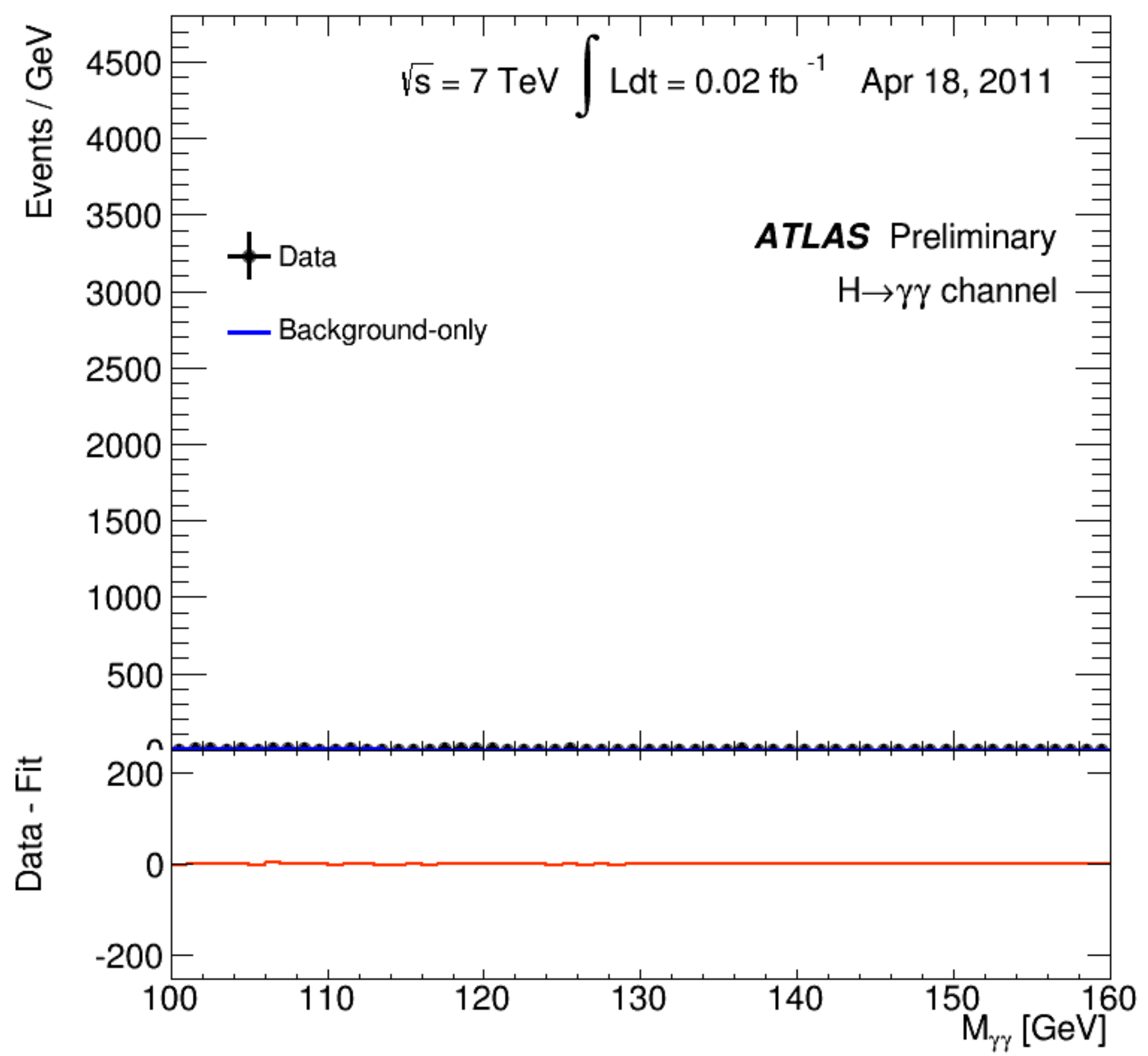
Context matters:

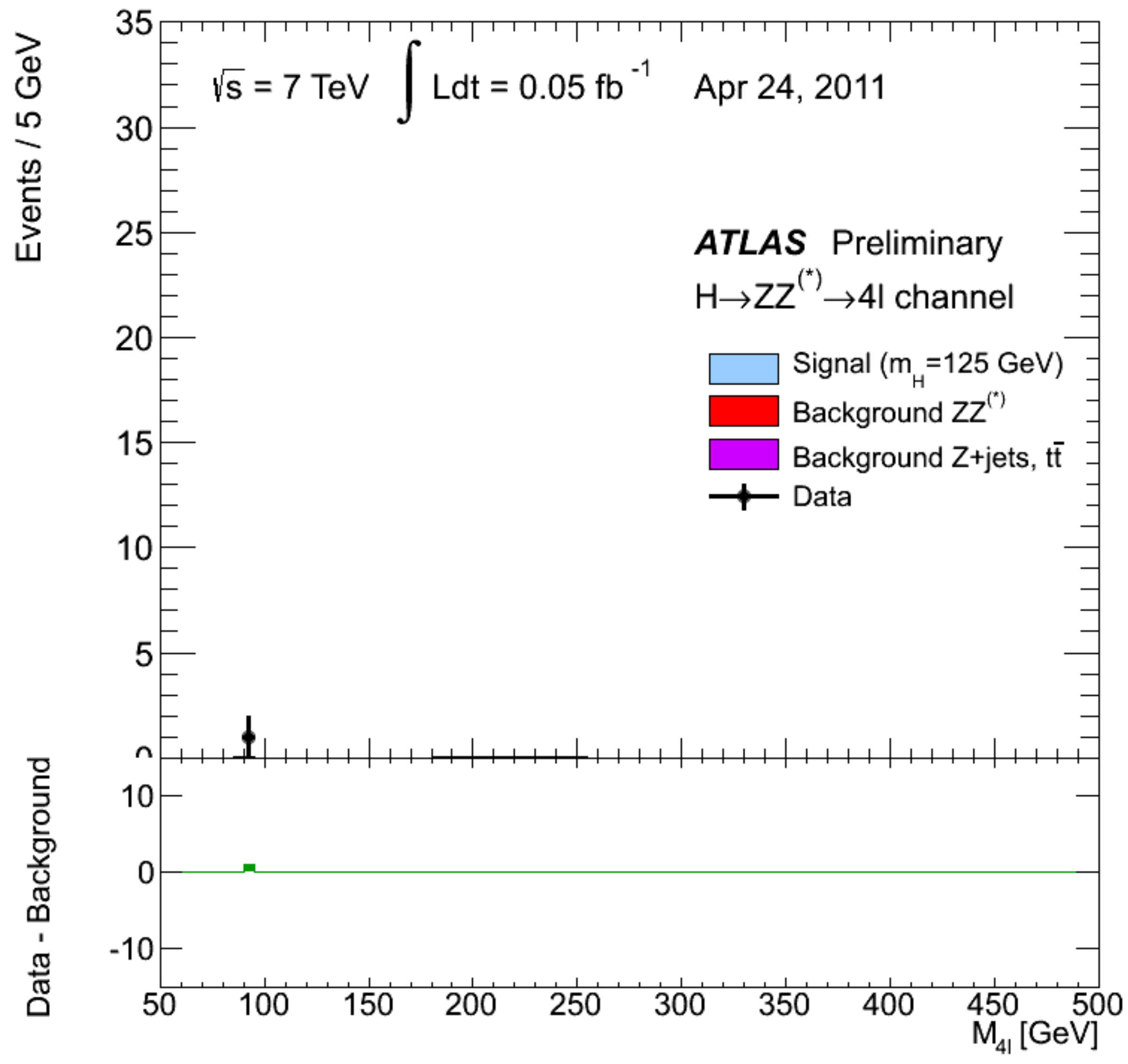
- Two experiments with compatible excess
- Multiple channels
- EXTREMELY strong theory prior

ATLAS-CONF-2011-163/

Just for fun

1. Discoveries often start as anomalies





https://cds.cern.ch/record/2230893

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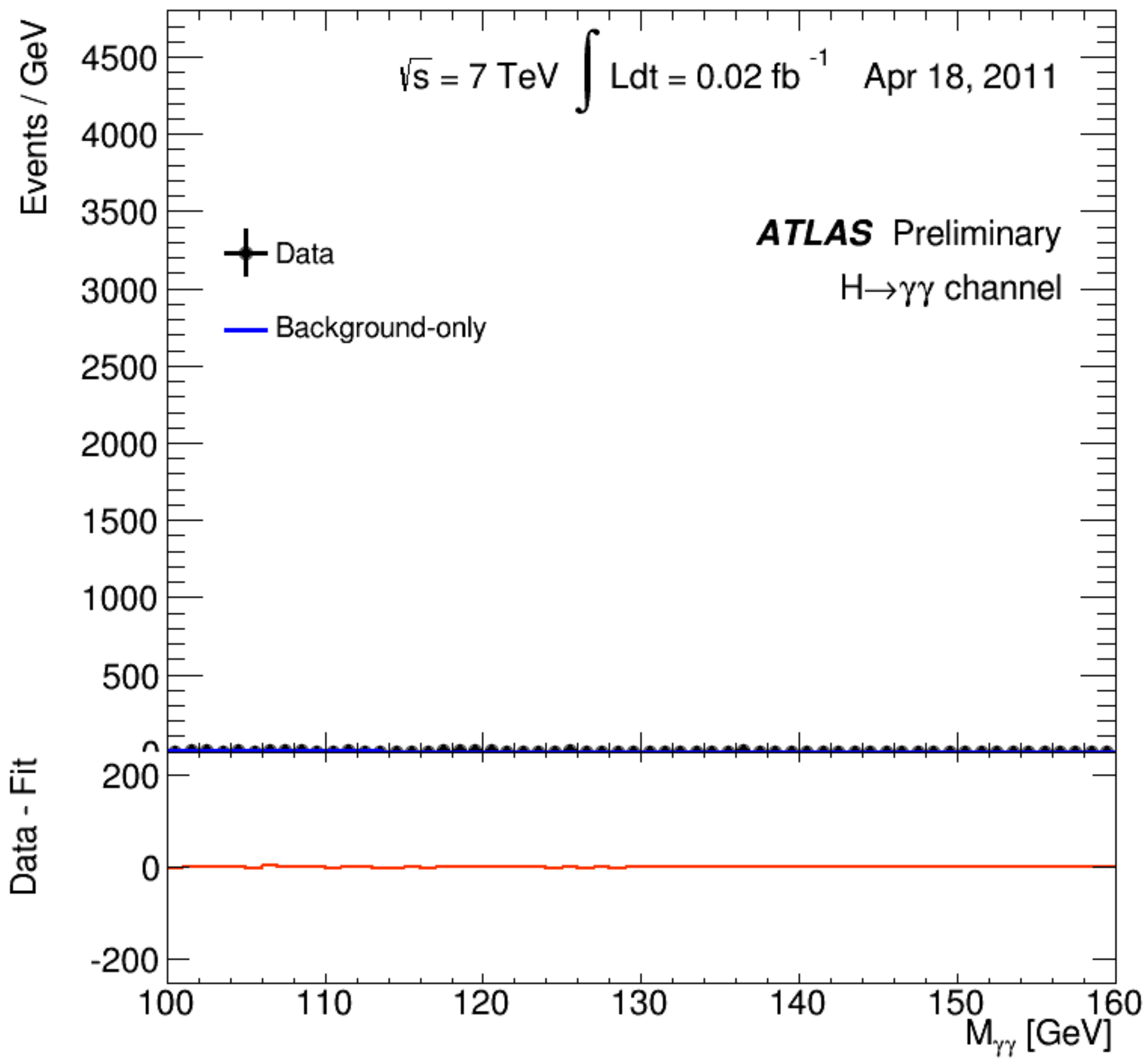

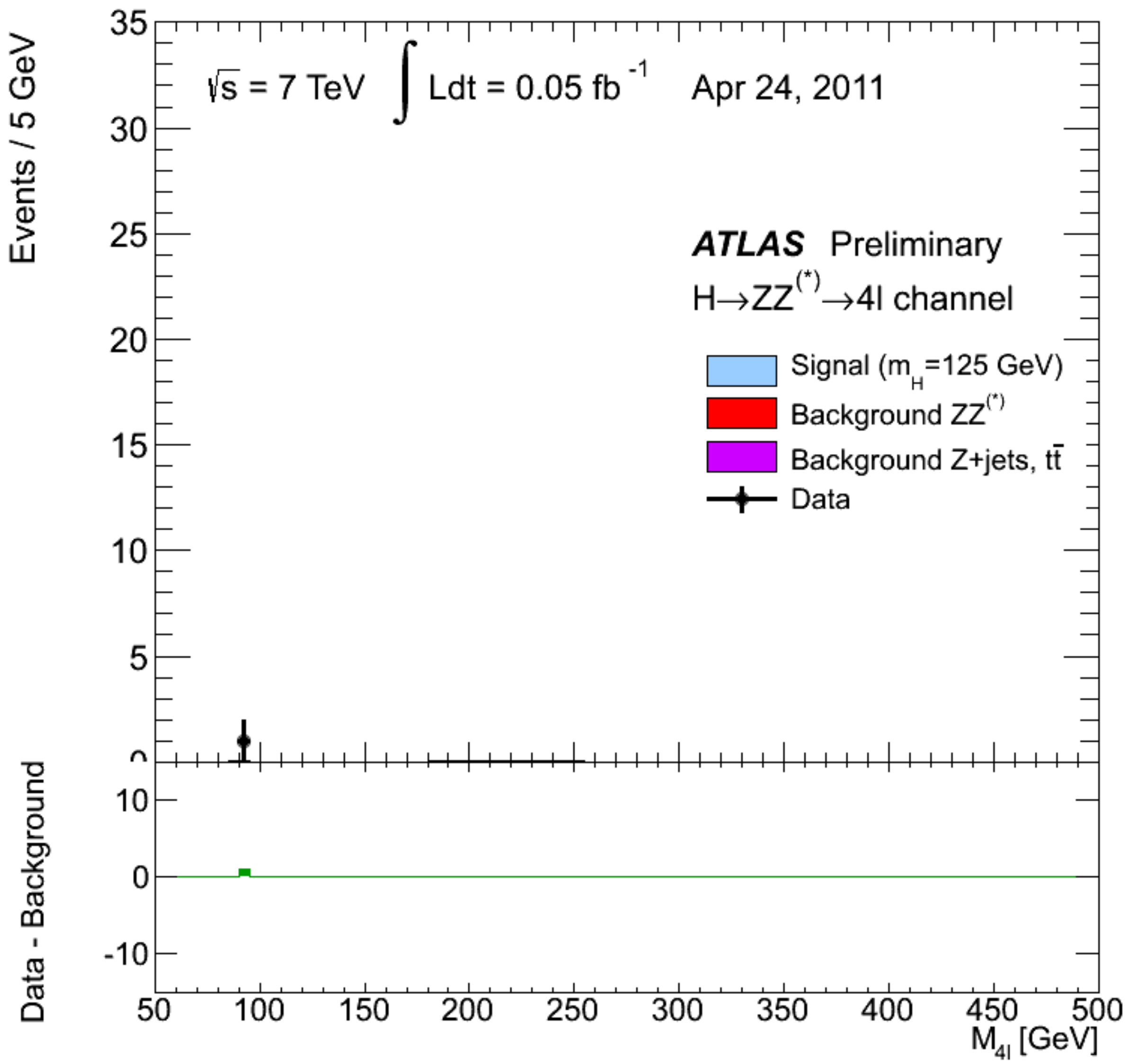

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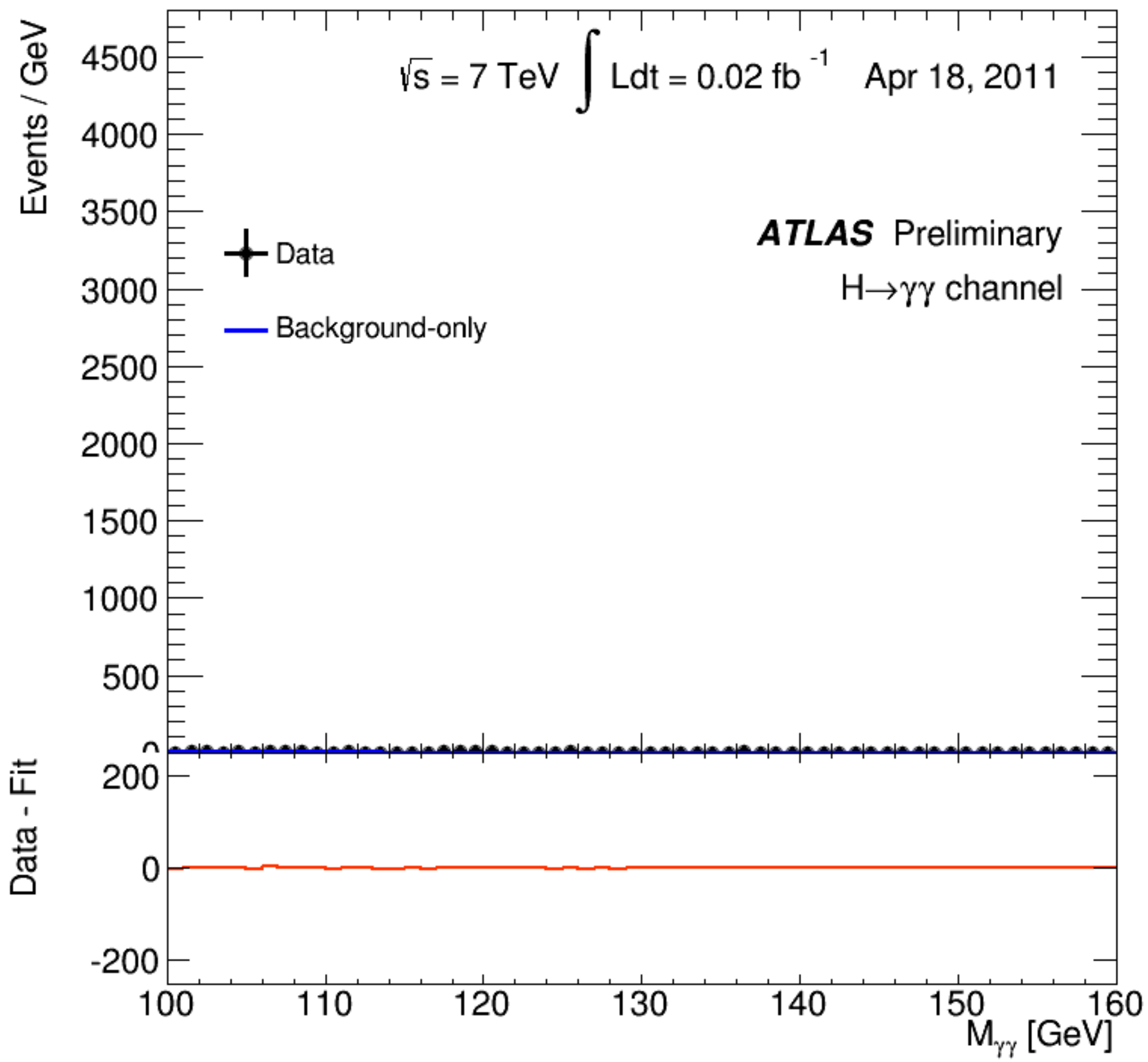

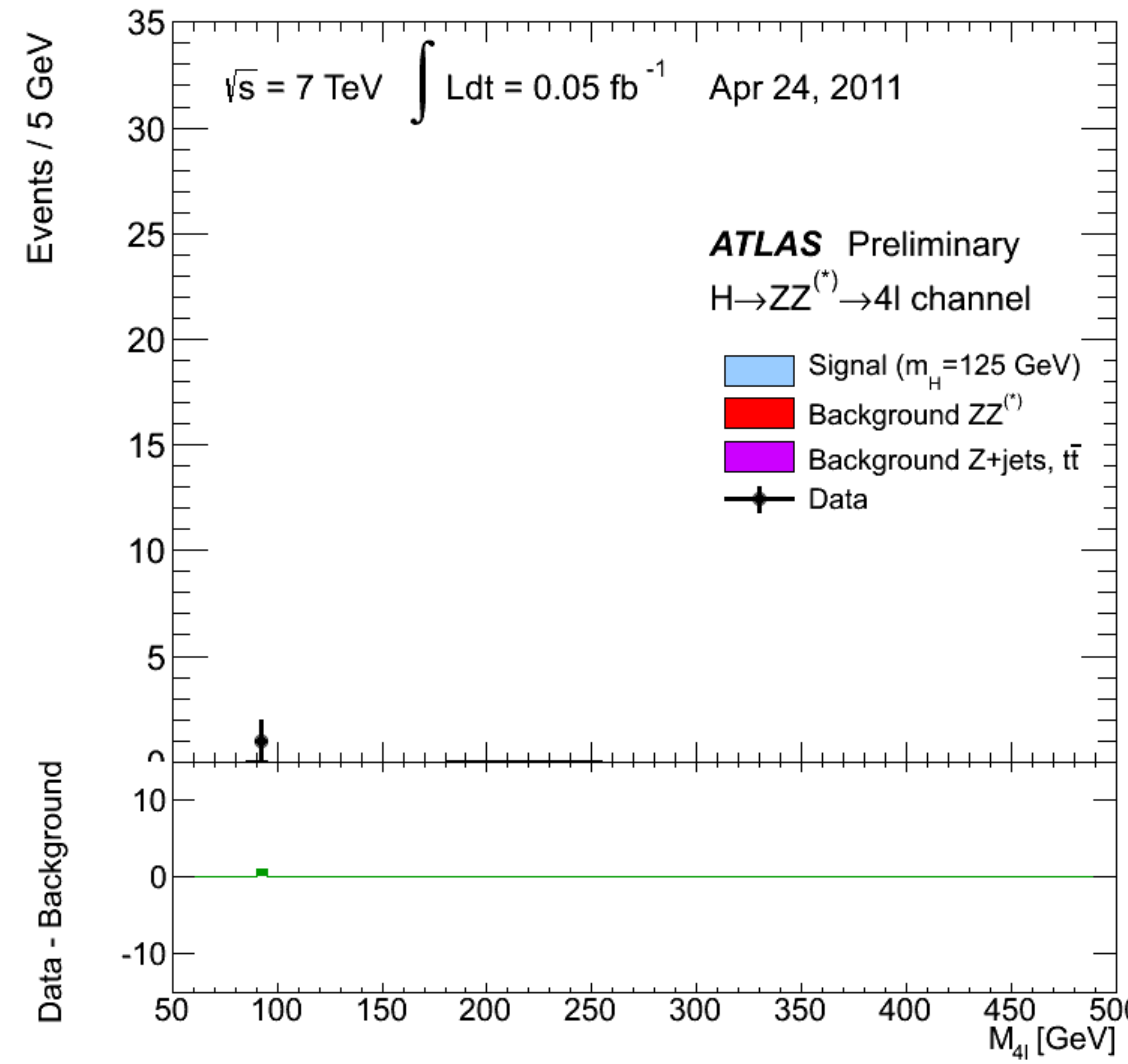

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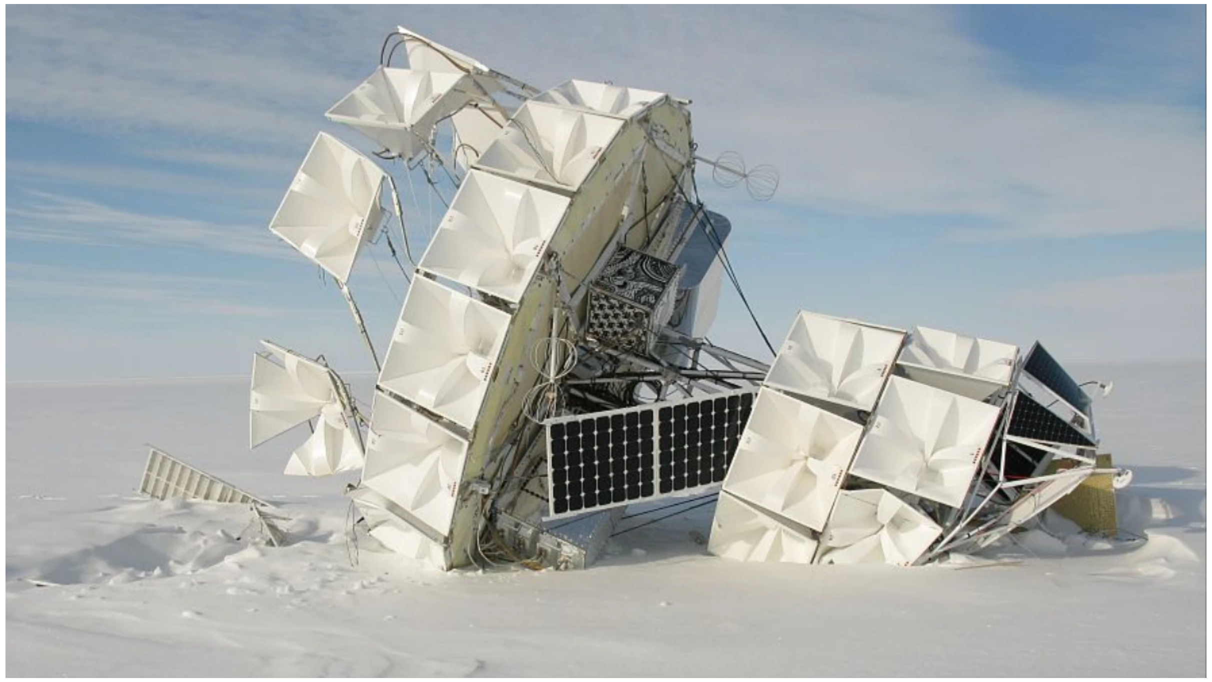
Why pay attention to anomalies?

2. Highlight sometimes lesser-known experiments / searches

Example: Antarctic Impulsive Transient Antenna (ANITA)

before



after

Balloon born experiment looking for ultra high energy neutrino's above the antarctic ice sheet

Saw 2 unexplained events with ~ 6 x 10^8 GeV energy pointing back to the earth
(remains unresolved afak)

arXiv: 1811.07261

Why pay attention to anomalies?

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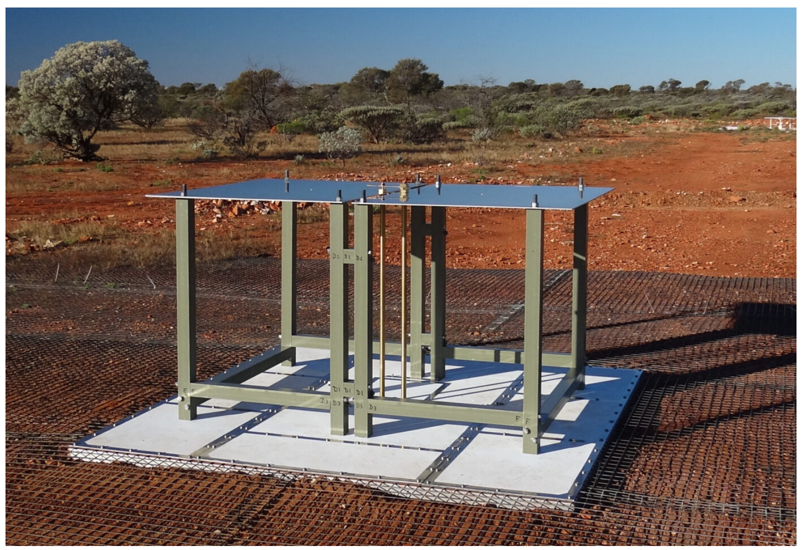
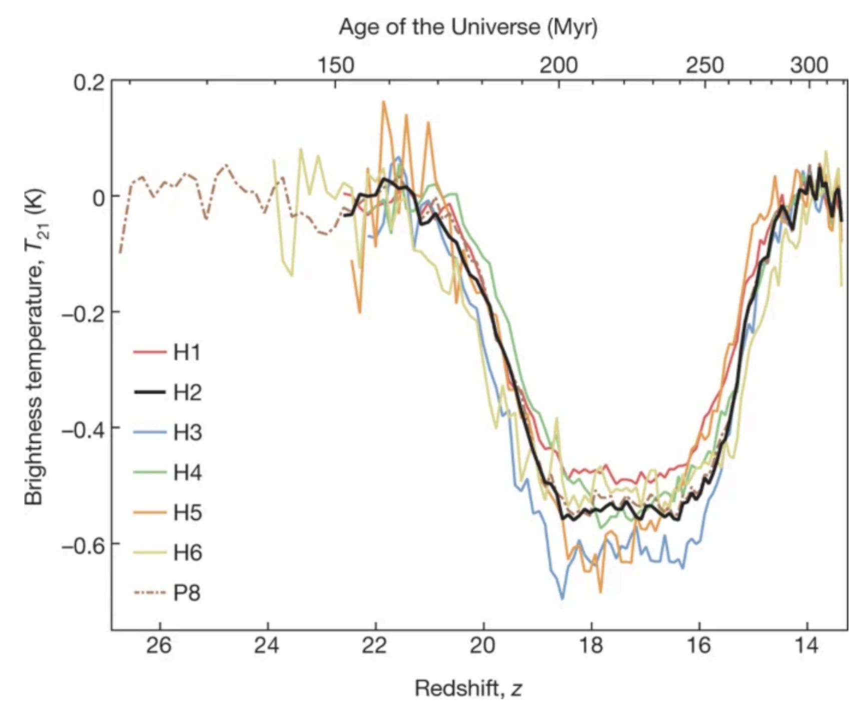
Example: EDGES experiment for 21cm cosmology





Radio antenna attempting to measure the absorption spectrum due to the hyperfine transition of hydrogen in early universe (21 cm).
This is a measurement of the H temperature before birth of first stars

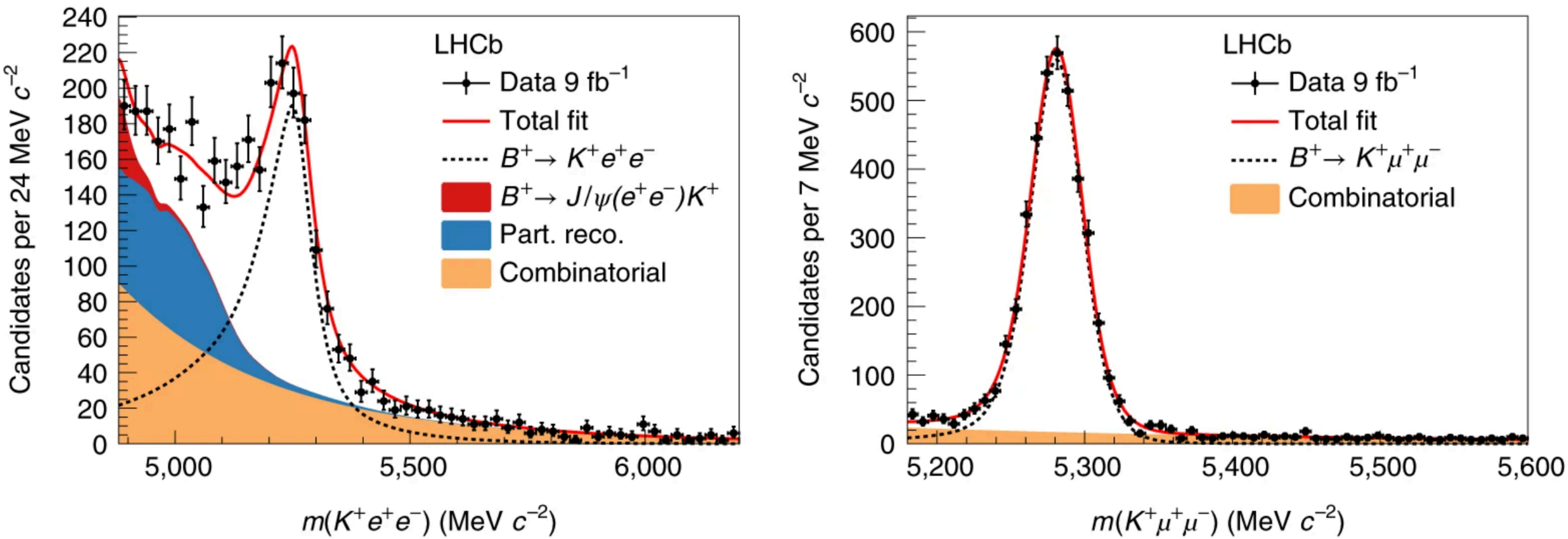
Saw deeper absorption spectrum than expected, indicating colder H gas than predicted.
(Not confirmed by later experiments, but started particle physics interest in 21 cm cosmology)

Nature volume 555, pages 67–70 (2018)

Why pay attention to anomalies?

3. Forces us to re-examine theory predictions and/or experimental analysis

Example: R_K



LHCb measured Br(B→Kee) / Br(B→Kμμ), as a test of lepton flavor universality

Nature Physics, volume 18, pages 277–282 (2022)

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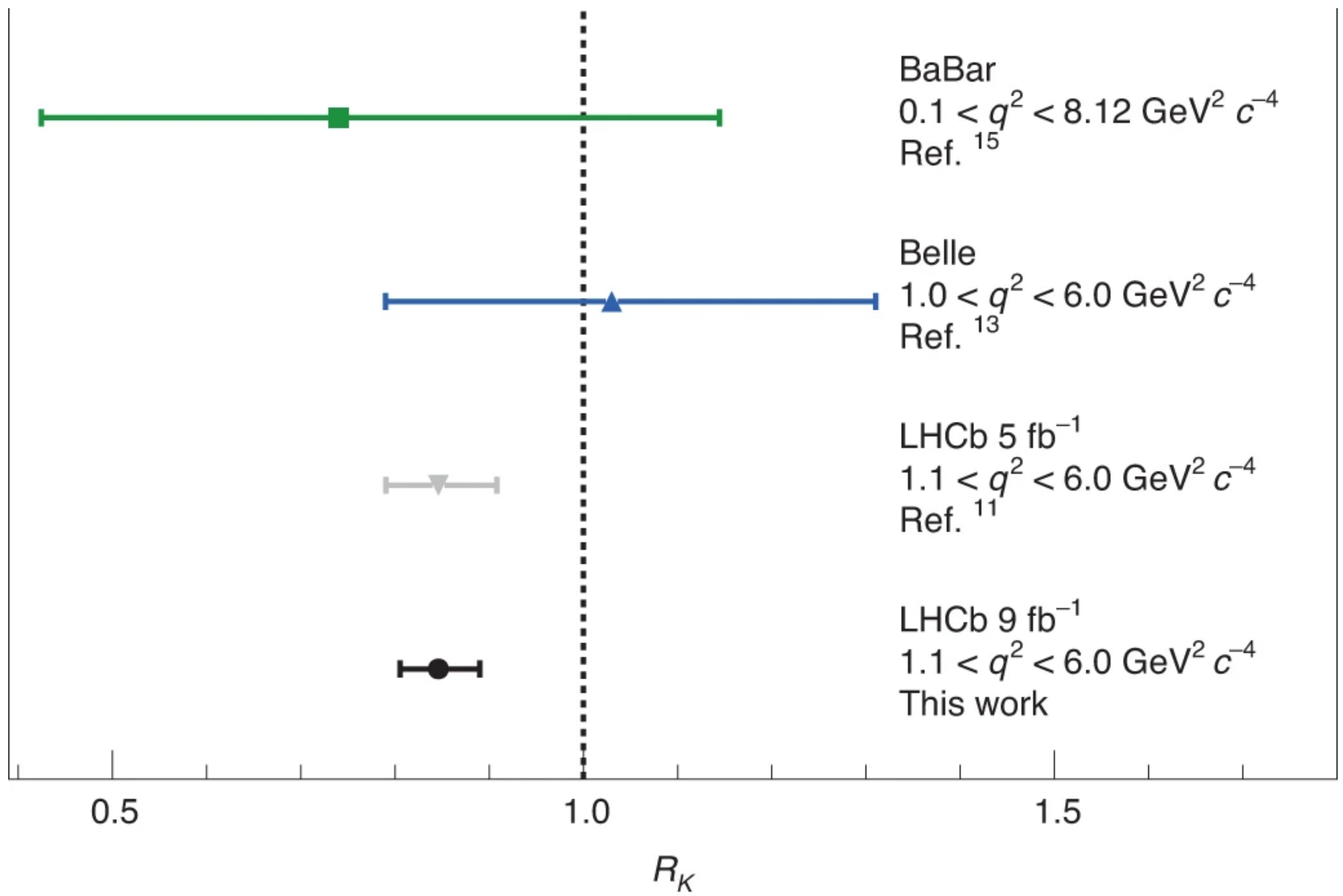

3.1σ tension with SM (statistics dominated)

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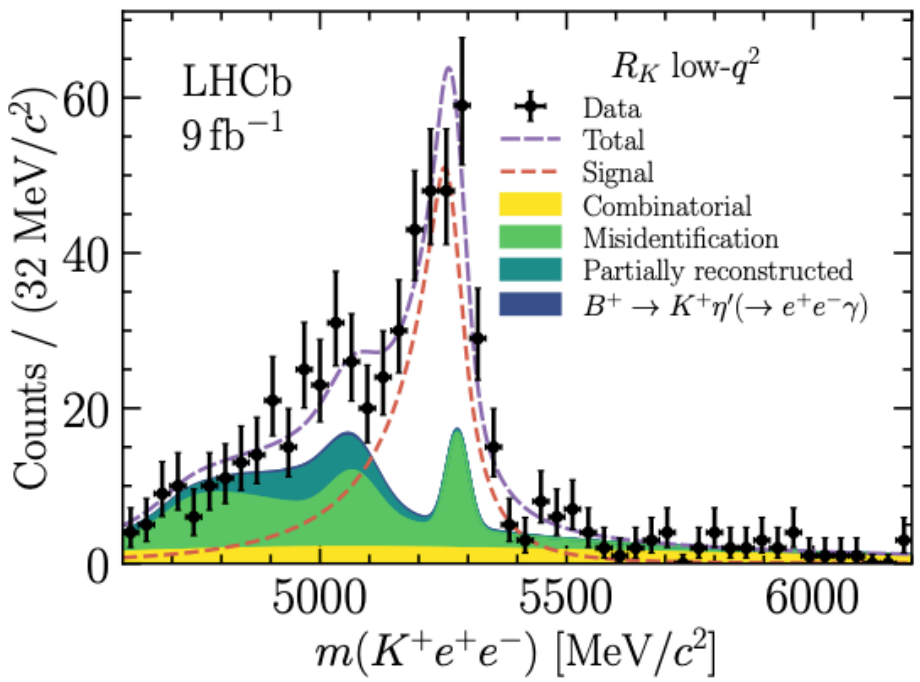
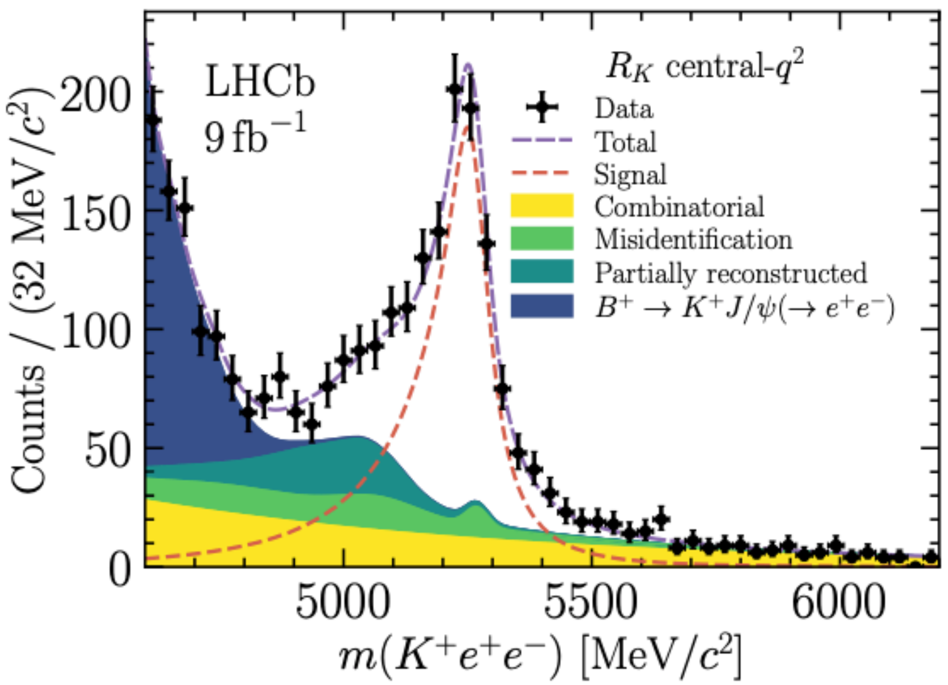
Example: R_K reanalysis





LHCb performed a very thorough reanalysis of their data, which revealed subtle contributions after improved electron identification and data driven determinations of the e^- misidentification rate

Phys.Rev.D 108 (2023)

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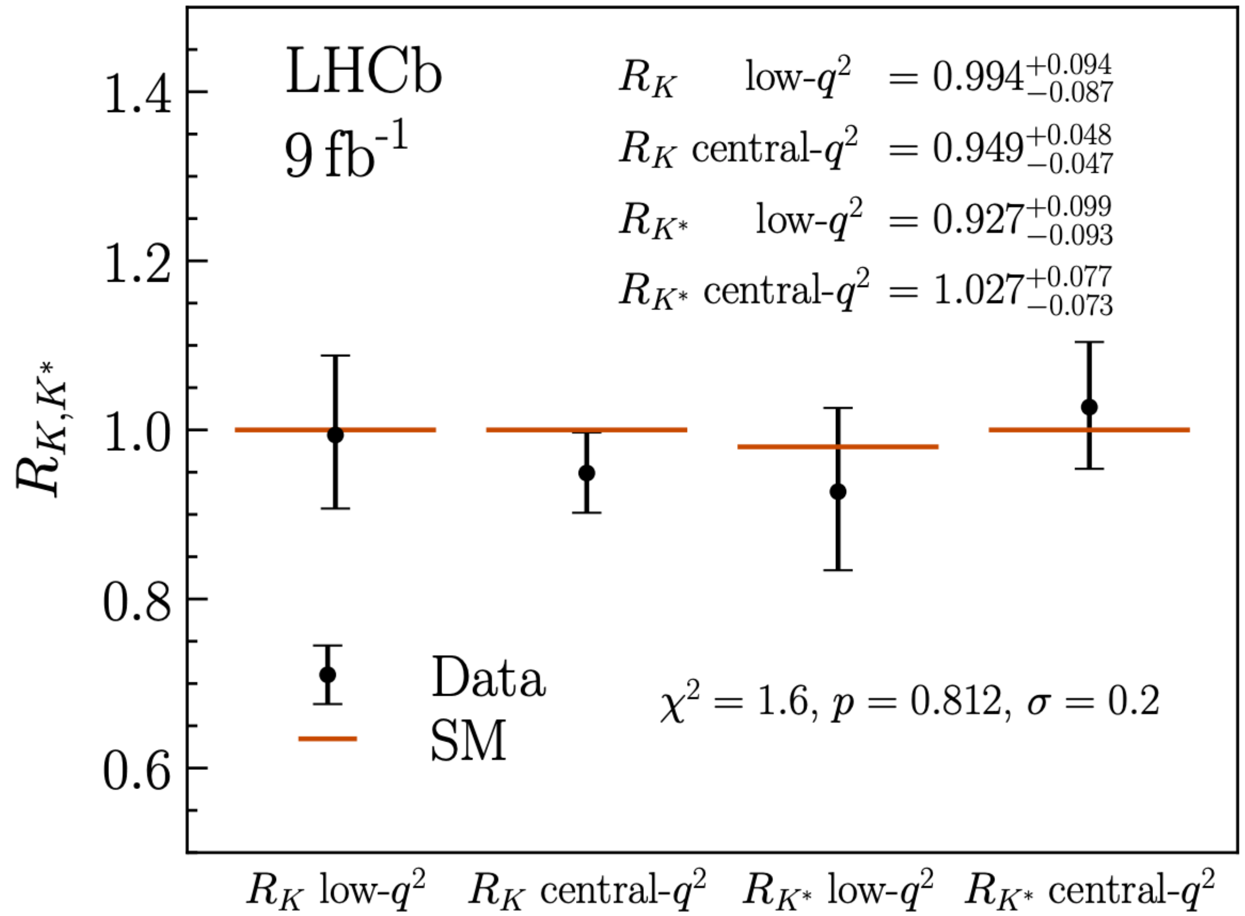

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Phys.Rev.D 108 (2023)

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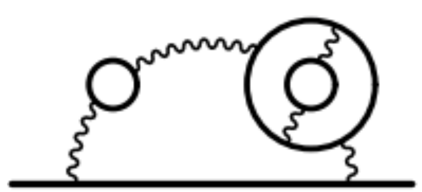
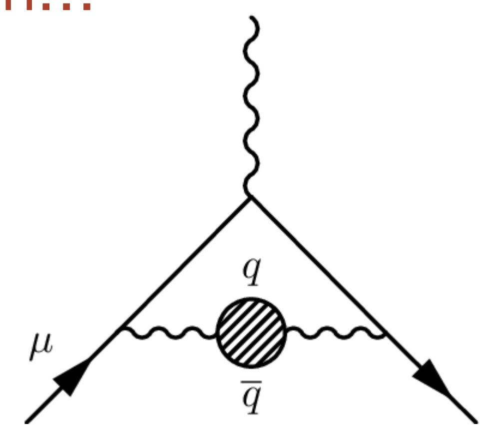
Example: muon g-2

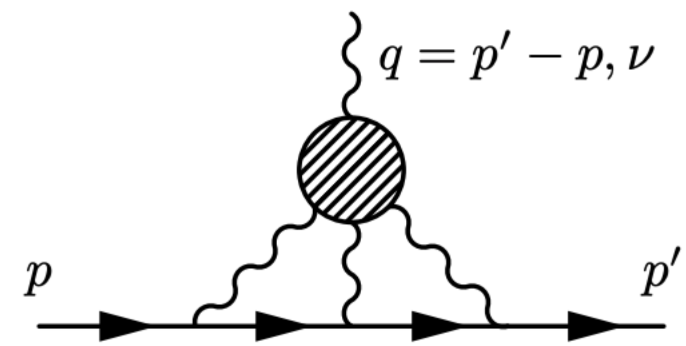
This is an extremely hard calculation…



QED computed to 10th order 😳



hadronic vacuum polarization calculated on lattice & with dispersion relations



Light-by-light calculated on lattice

g-2 theory initiative white paper arXiv: 2006.04822
(see Aida's lecture yesterday)

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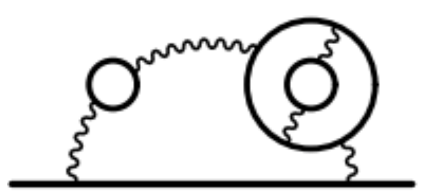

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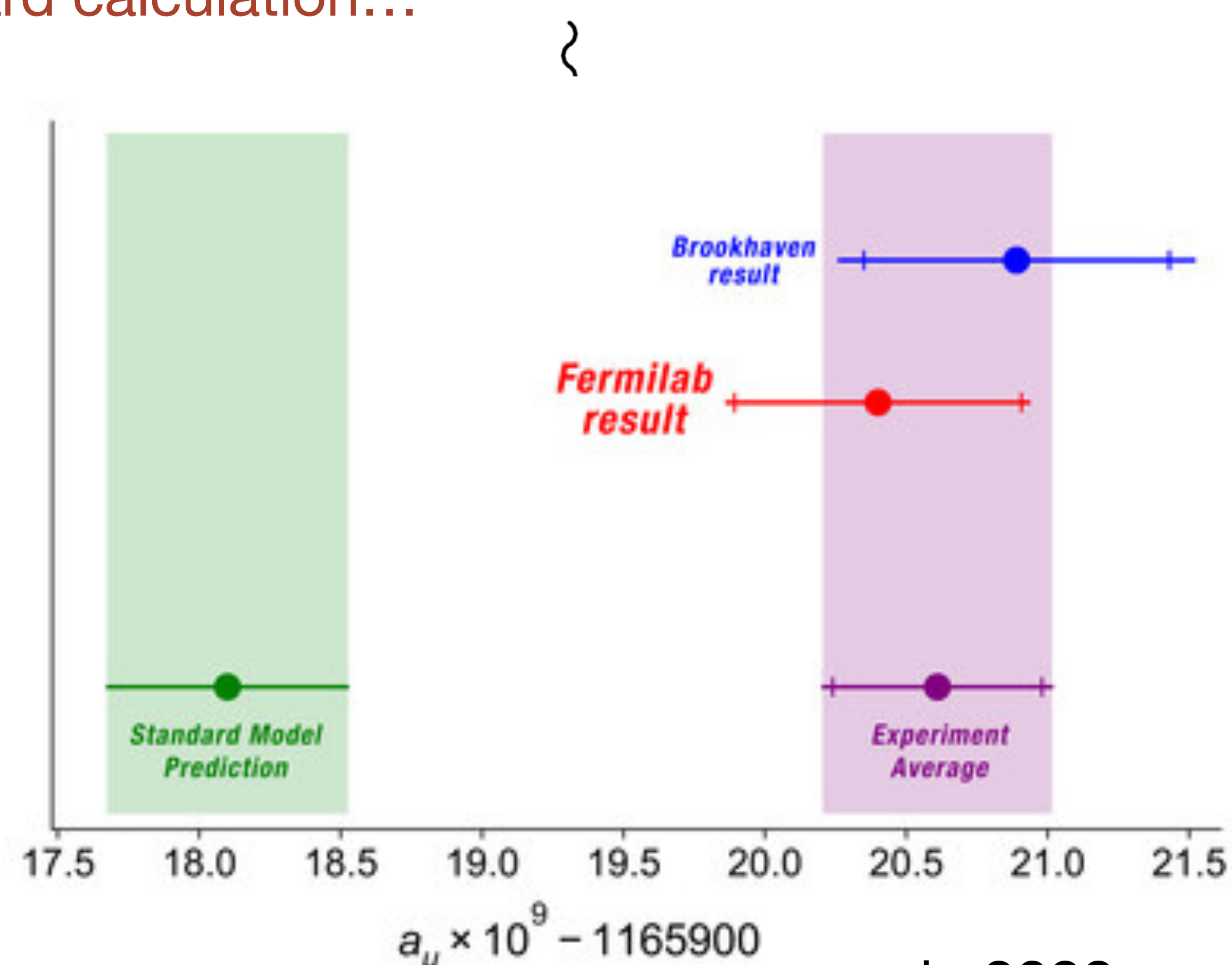
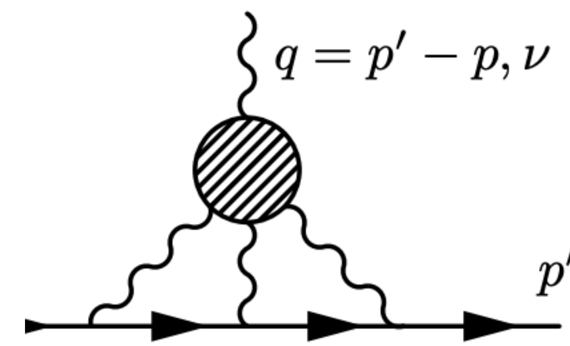


in 2022



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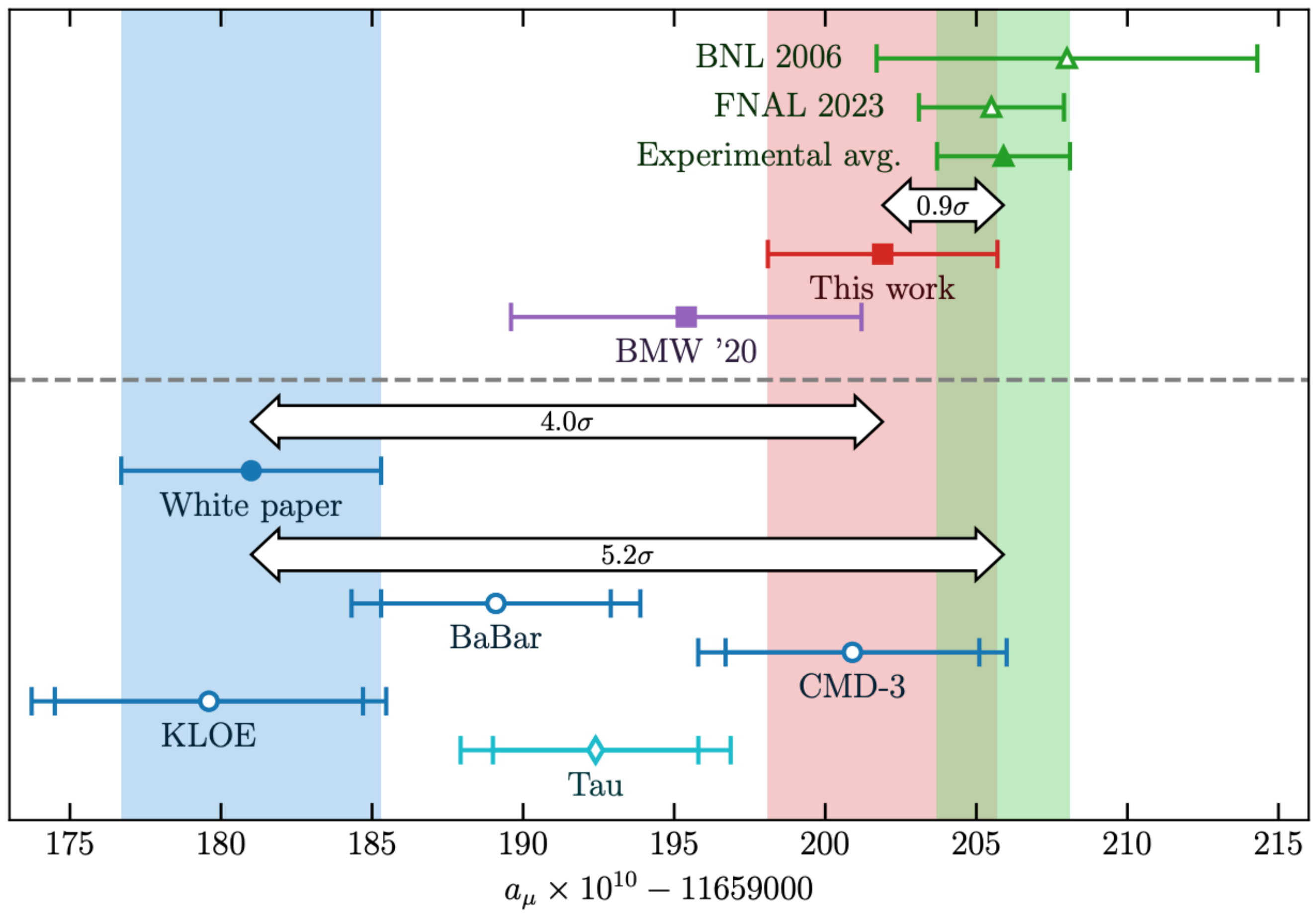


muon g-2 discrepancy looks like it will be resolved by extremely careful lattice calculations (see Aida's lecture)

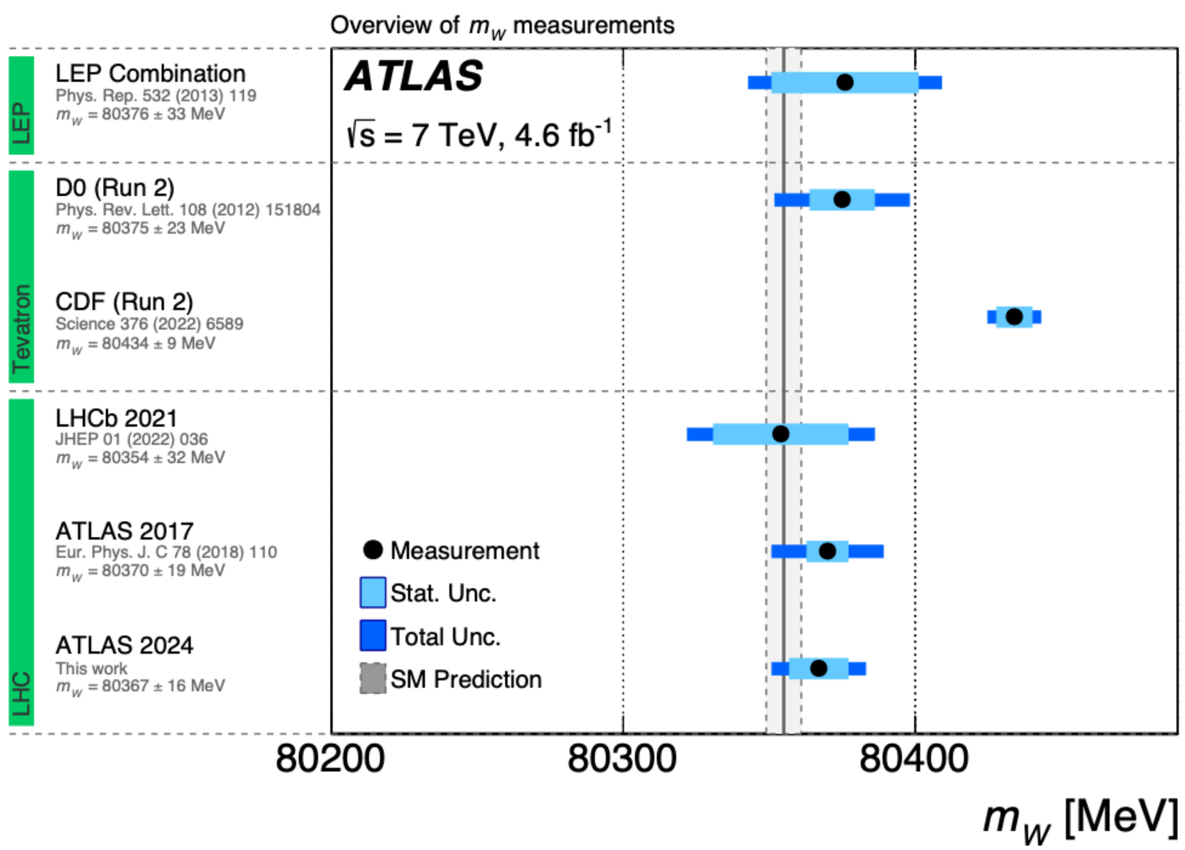
Discrepancy with dispersive calculations remains unresolved atm

BMW collaboration arXiv: 2407.10913

Why pay attention to anomalies?

4. Thinking about them is a great way to stay in shape

Example: m_W measurement



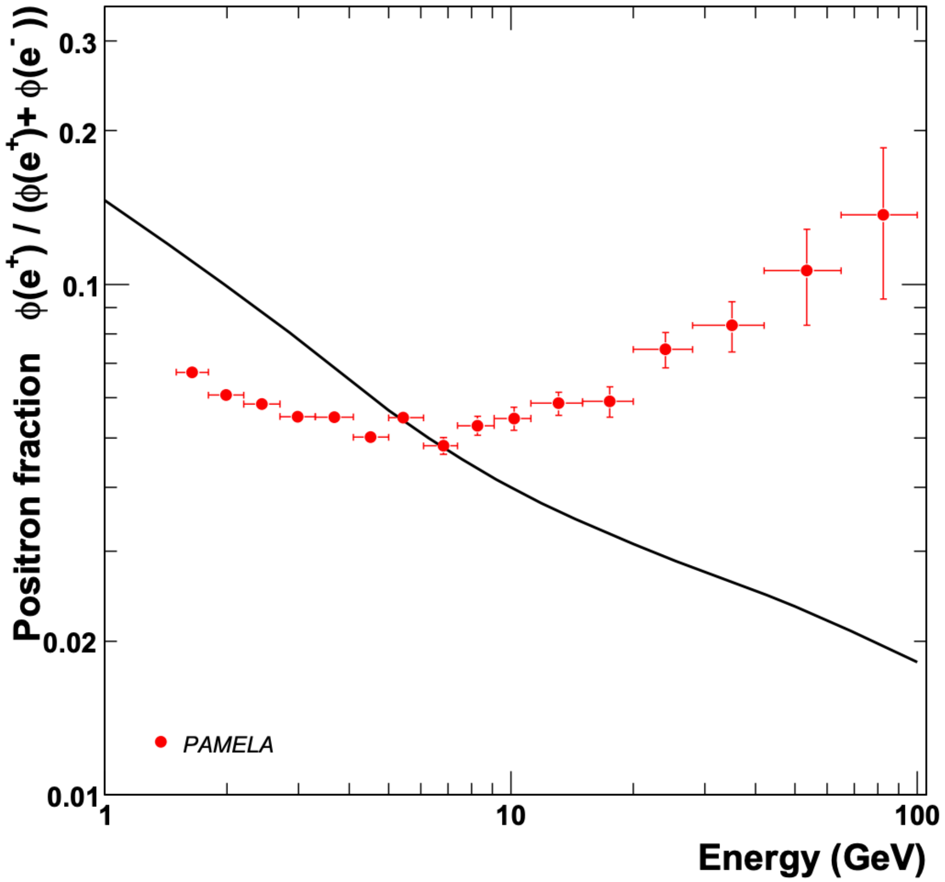
Excellent observable to look for new physics, though CDF result in modest tension with ATLAS, LHCb & LEP

Very difficult measurement. EW theory well understood, but measurement relies on precision QCD calculations of the W pT spectrum. BSM very interesting

Why pay attention to anomalies?

5. Often lead to new research directions that persist long after the anomaly has been resolved

Example: PAMELA positron excess



Positron fraction of cosmic rays much larger than expected

Nowadays we believe this likely due to pulsars rather than dark matter

Nature 458 (2009) 607-609

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Problem:

- Required dark matter annihilation cross section orders of magnitude higher than thermal annihilation cross section
- Seen in leptons only

"A theory of dark matter" N. Arkani-Hamed, D. Finkbeiner, T. Slatyer, N. Weiner arXiv 0810.0713 (1893 citations)

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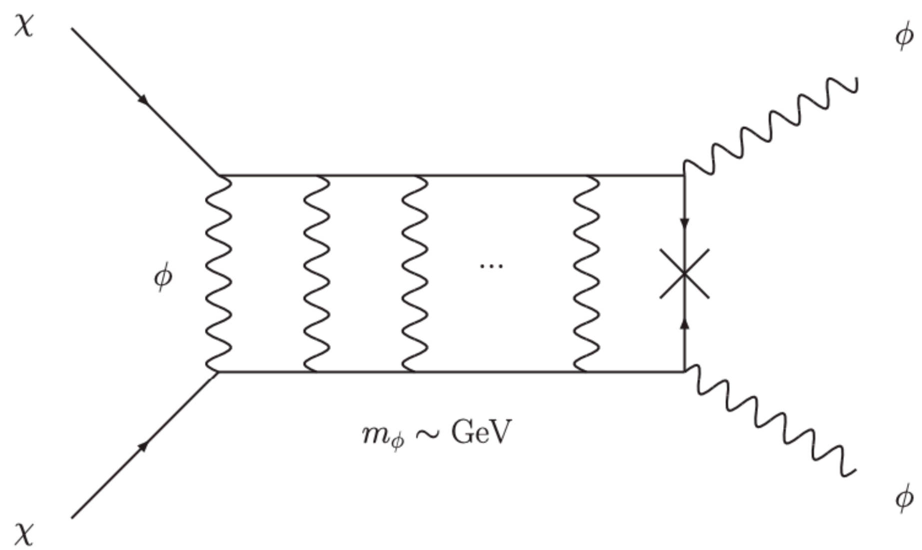
- Dark photon leading to Sommerfeld enhancement
- Dark photon allowing for leptophylic annihilation



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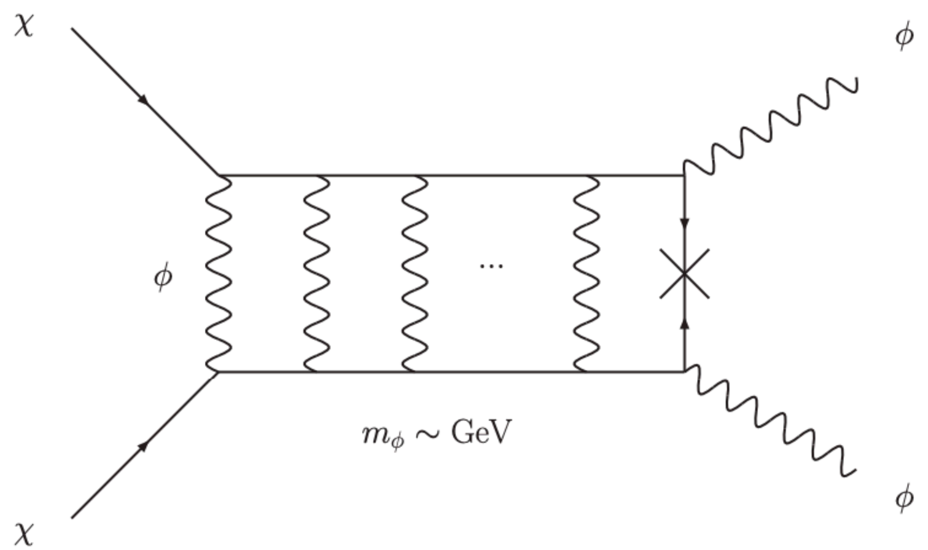

Started a new era of dark matter model building, beyond WIMPs

Indirectly contributed to the start of the light dark matter direct detection effort

(see Noah's talk)

"A theory of dark matter" N. Arkani-Hamed, D. Finkbeiner, T. Slatyer, N. Weiner arXiv 0810.0713 (1893 citations)

Outline

1. Why pay attention to anomalies?
2. How to judge an anomaly?
3. A case study
4. Some current anomalies

How to evaluate anomalies?

Not all anomalies are born equally. How to decide which one to invest time in?

Questions I think you should ask:

- Is it a “large” excess statistically?
- Are the errors statistics or systematics dominated?
- How difficult is the experimental measurement?
- How difficult is the theory prediction?
- Is it in tension with other measurements already?
- How difficult is it to build a plausible BSM model?

+ a good deal of personal preference: Does this physics excite you?

Statistical significance

Usually, experimentalists will define a likelihood ratio

$$\Lambda = \frac{P_0(b_i)}{P_1(b_i, s_i)}$$

With P_0 and P_1 the likelihood of the null/alternative hypotheses, which depends on some parameters b_i, s_i. Often these likelihoods involve approximations, Monte Carlo etc, and are thus a source of systematic uncertainties.

See arXiv 1007.1727 for a nice review on statistics

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Wilks theorem say that

$$-2\log\Lambda$$

Follows a χ^2-distribution if the null hypothesis is true. From this we compute a p-value. p-value is often reported as “nr of σ” on a standard gaussian

$$\begin{array}{ccc} 0.31 & \rightarrow & 1\sigma \\ 4.6\times10^{-2} & \rightarrow & 2\sigma \\ 2.7\times10^{-3} & \rightarrow & 3\sigma \\ 6.3\times10^{-5} & \rightarrow & 4\sigma \\ 5.7\times10^{-7} & \rightarrow & 5\sigma \end{array}$$

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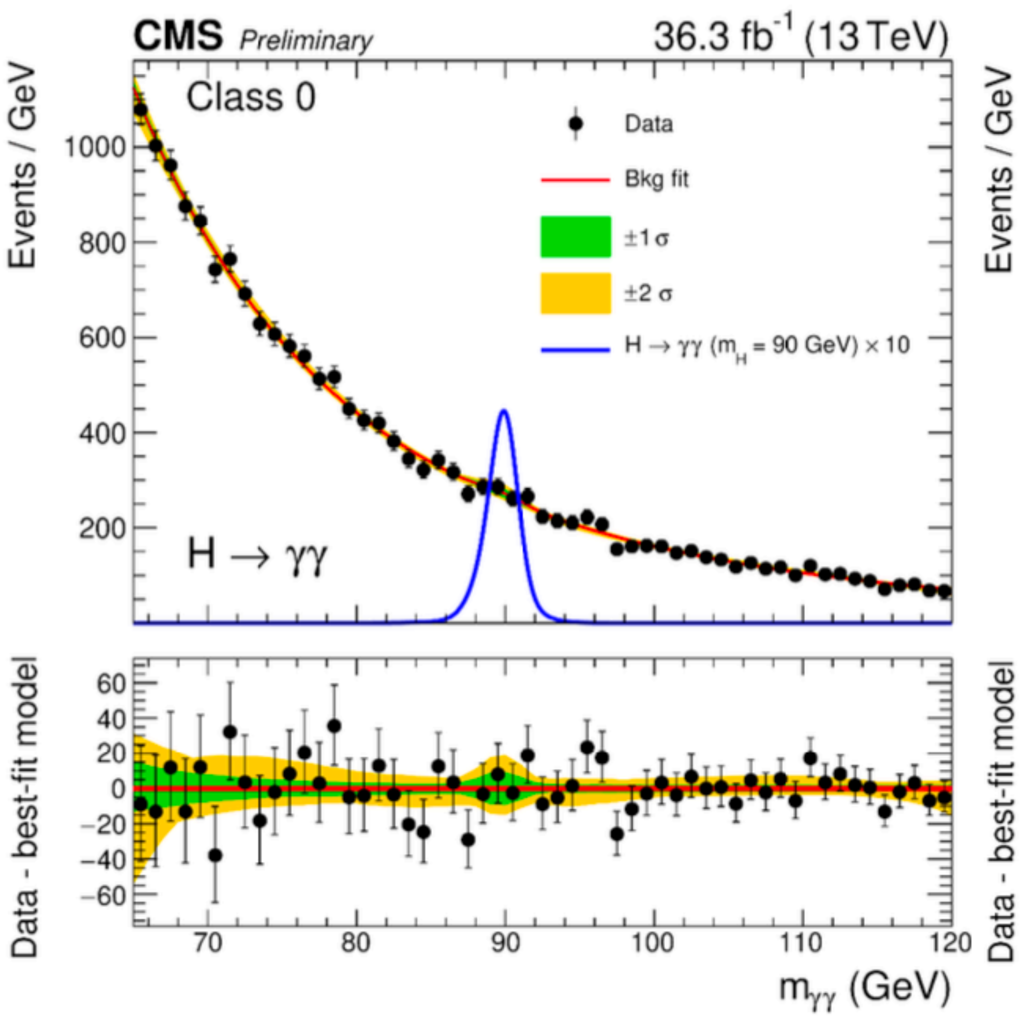
Look-else-where effect

Where is the excess?



See arXiv 2405.18149 for this excess

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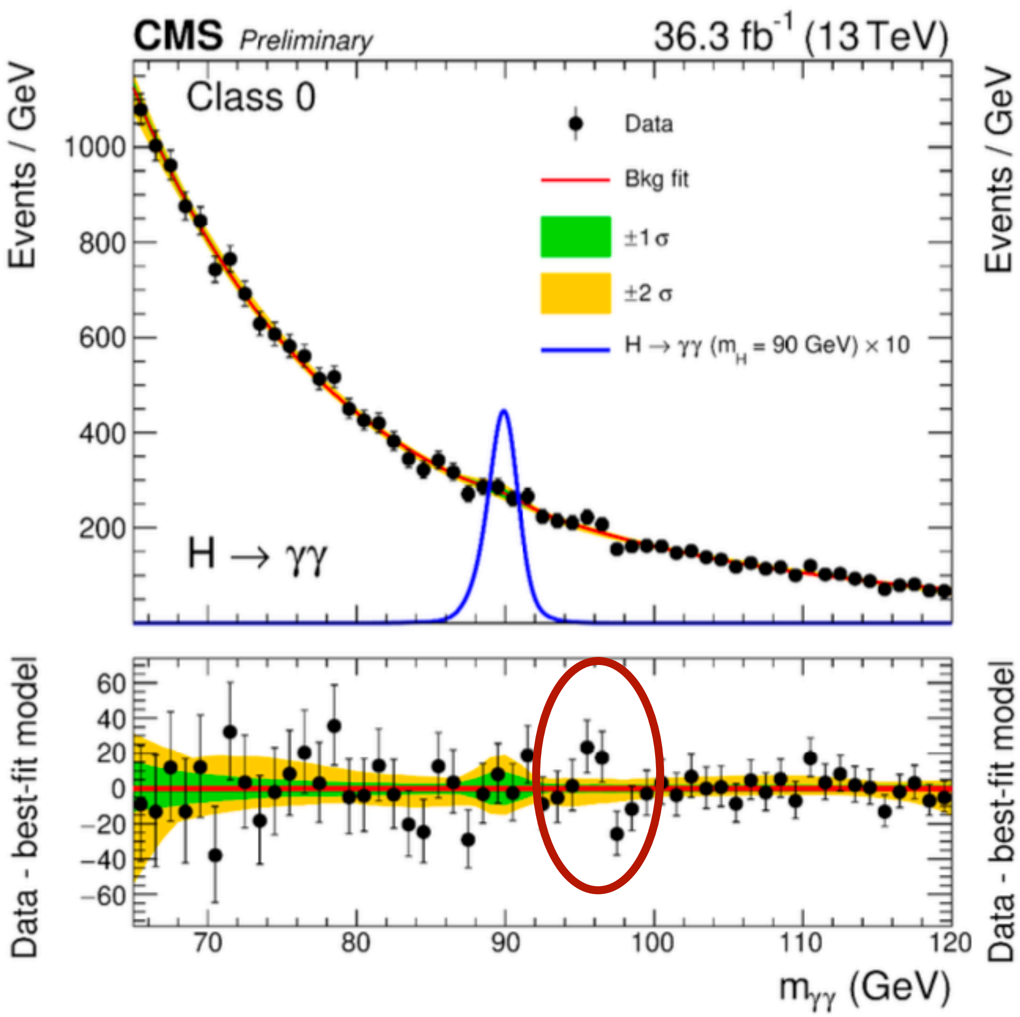

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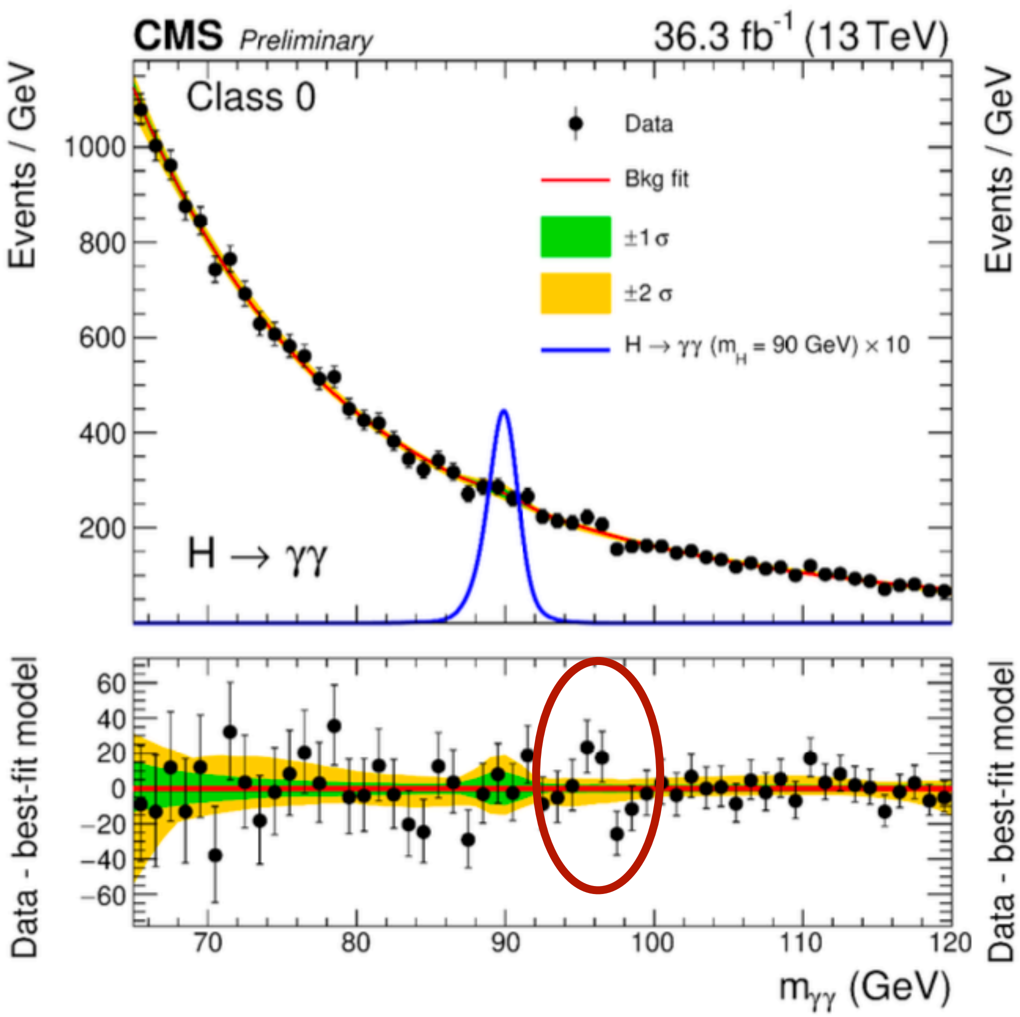

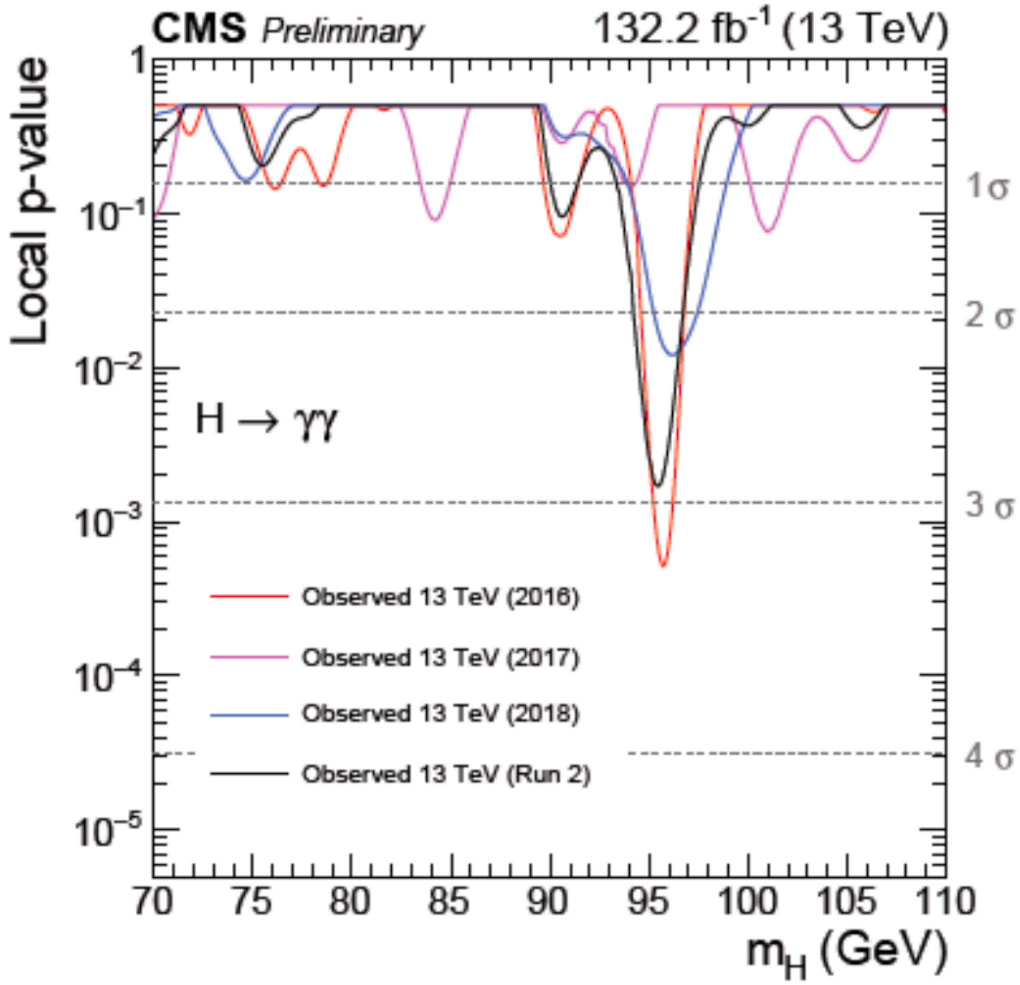

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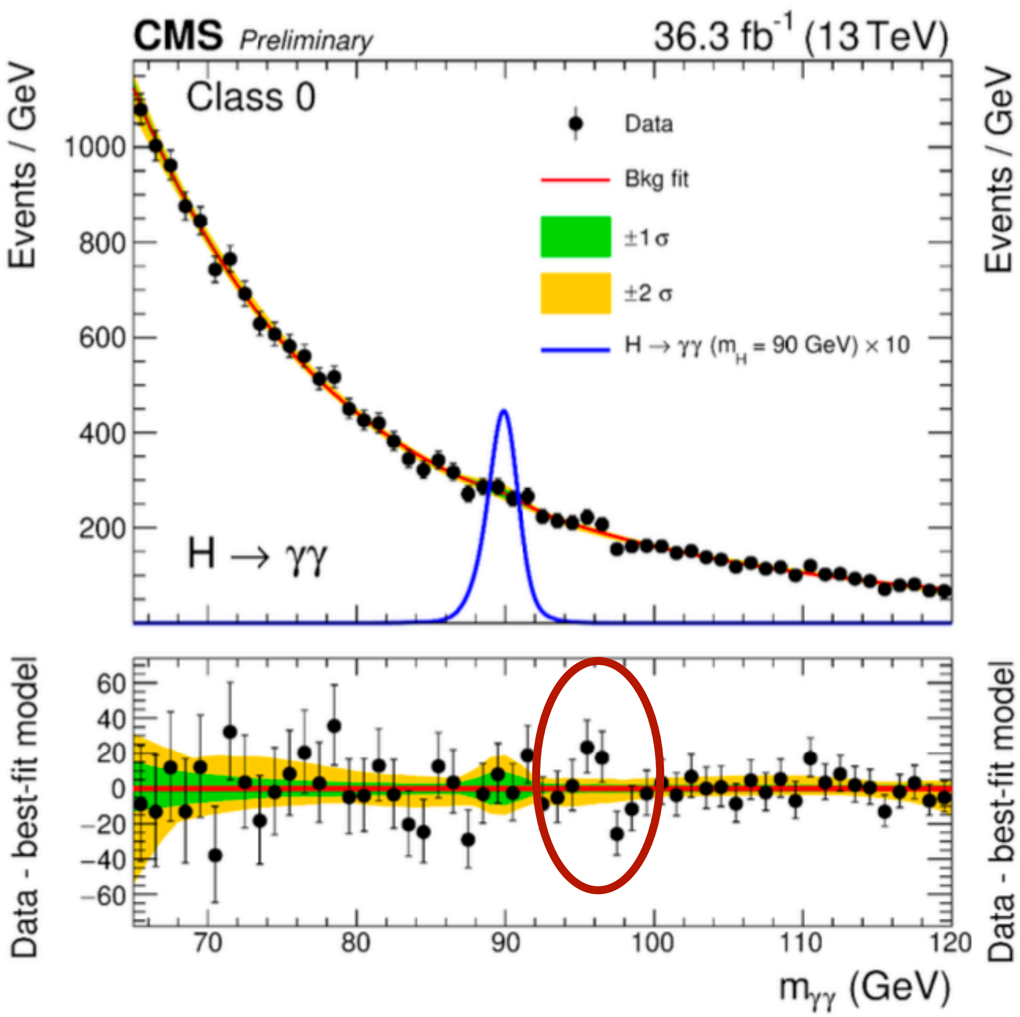
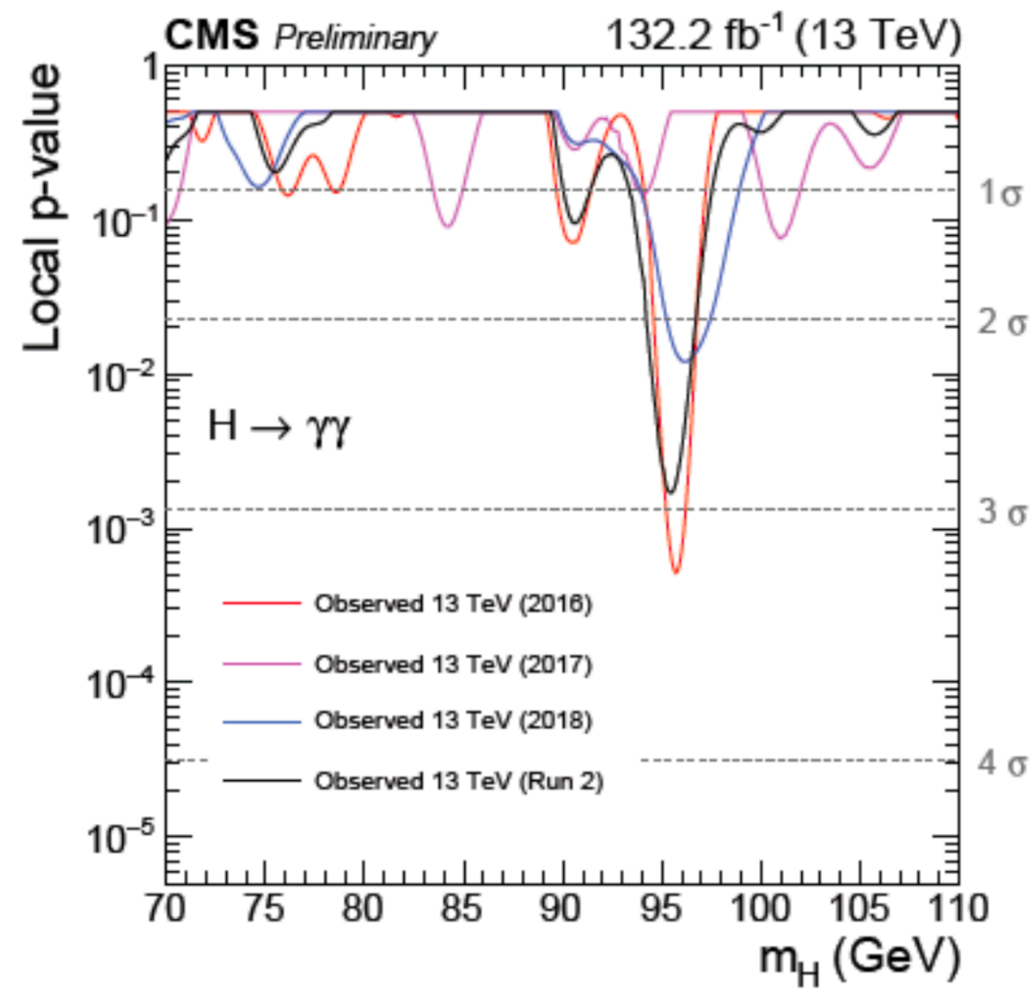




Problem: if you have many bins, chances are higher that there is an excess *somewhere*

Correction is needed: local (2.9σ) vs global (1.3σ) significance

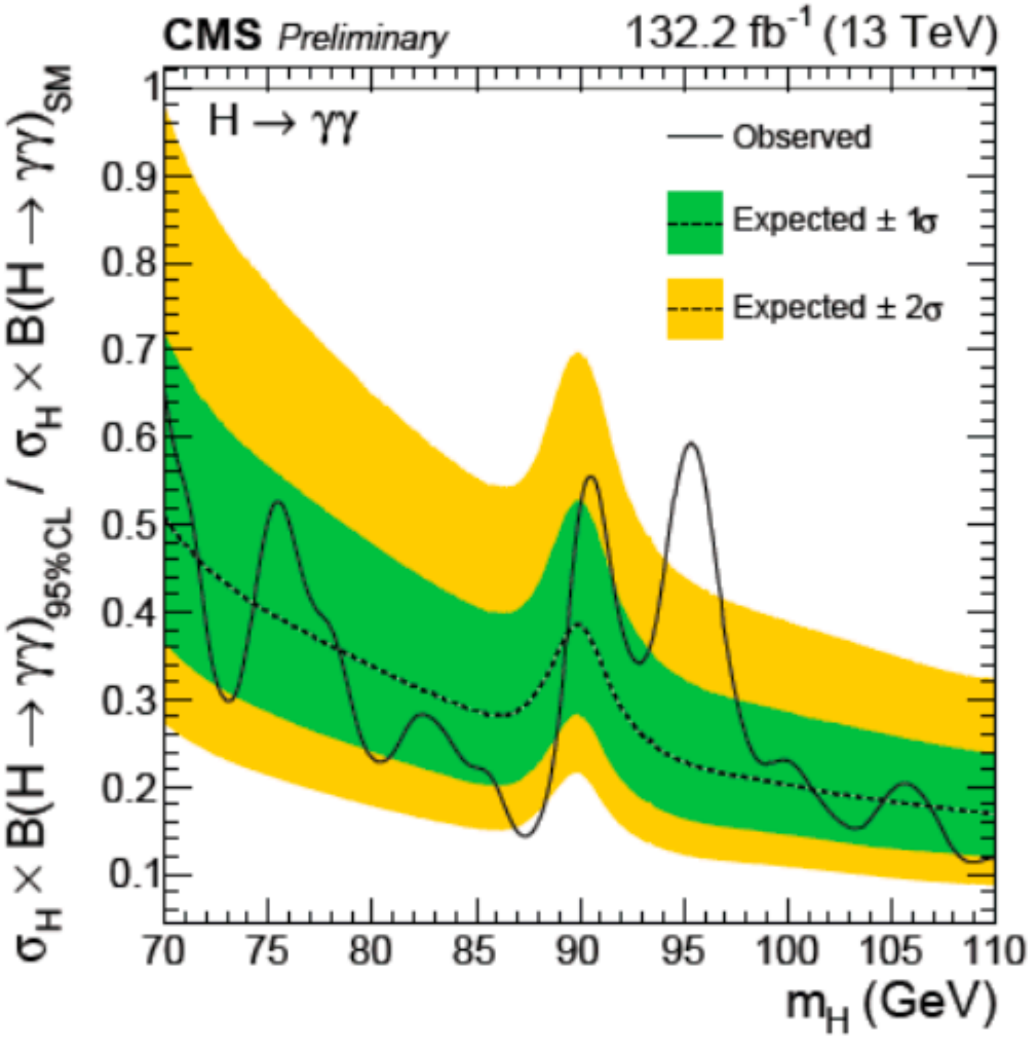
Does the excess show up in all data sets?

See arXiv 2405.18149 for this excess

Look-else-where effect

How to estimate the look-else-where effect:

- Multiply p-value with nr of bins
  (very rough, no correlations)
- Throw a lot of toys for the background and find largest excess in each one
  (correct, but CPU intensive)
- Semi-analytic approximations exist
  (see e.g. arXiv 1005.1891)



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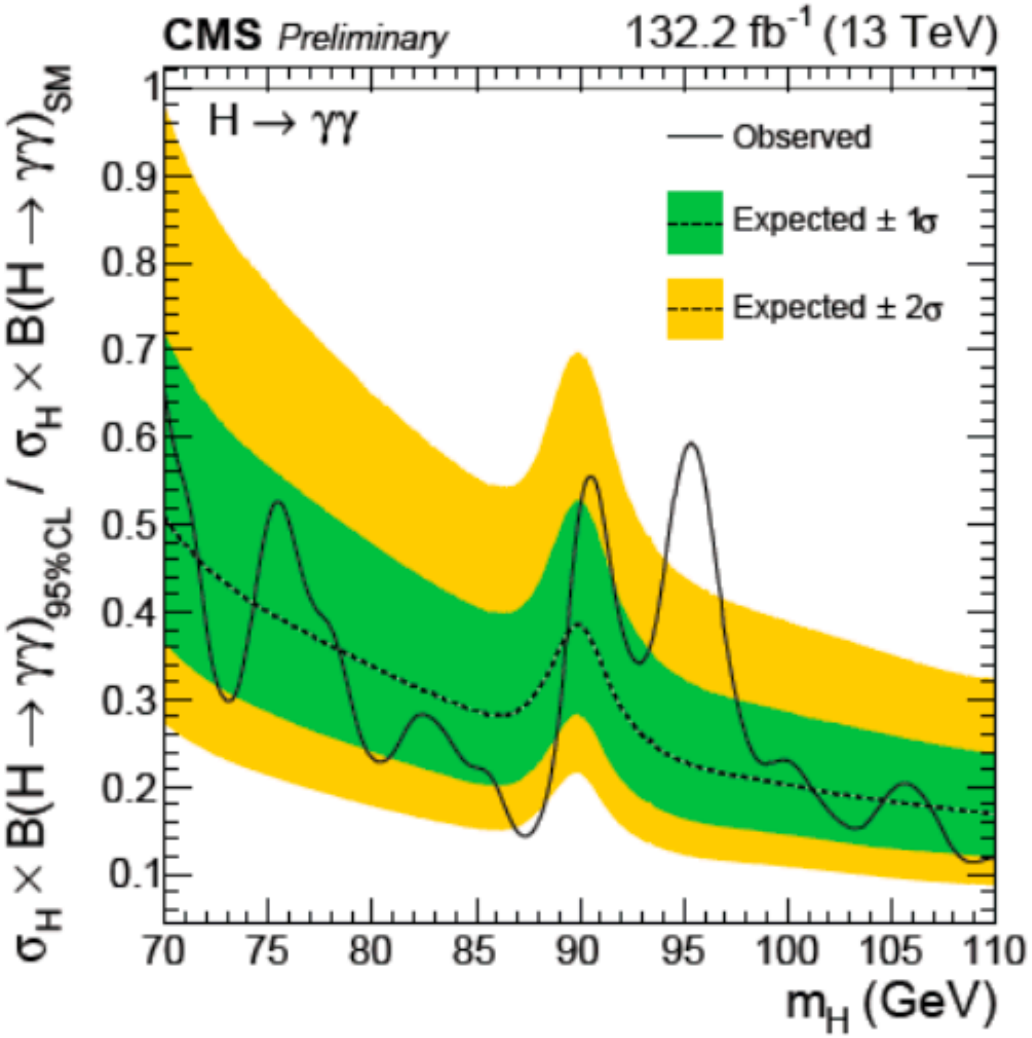


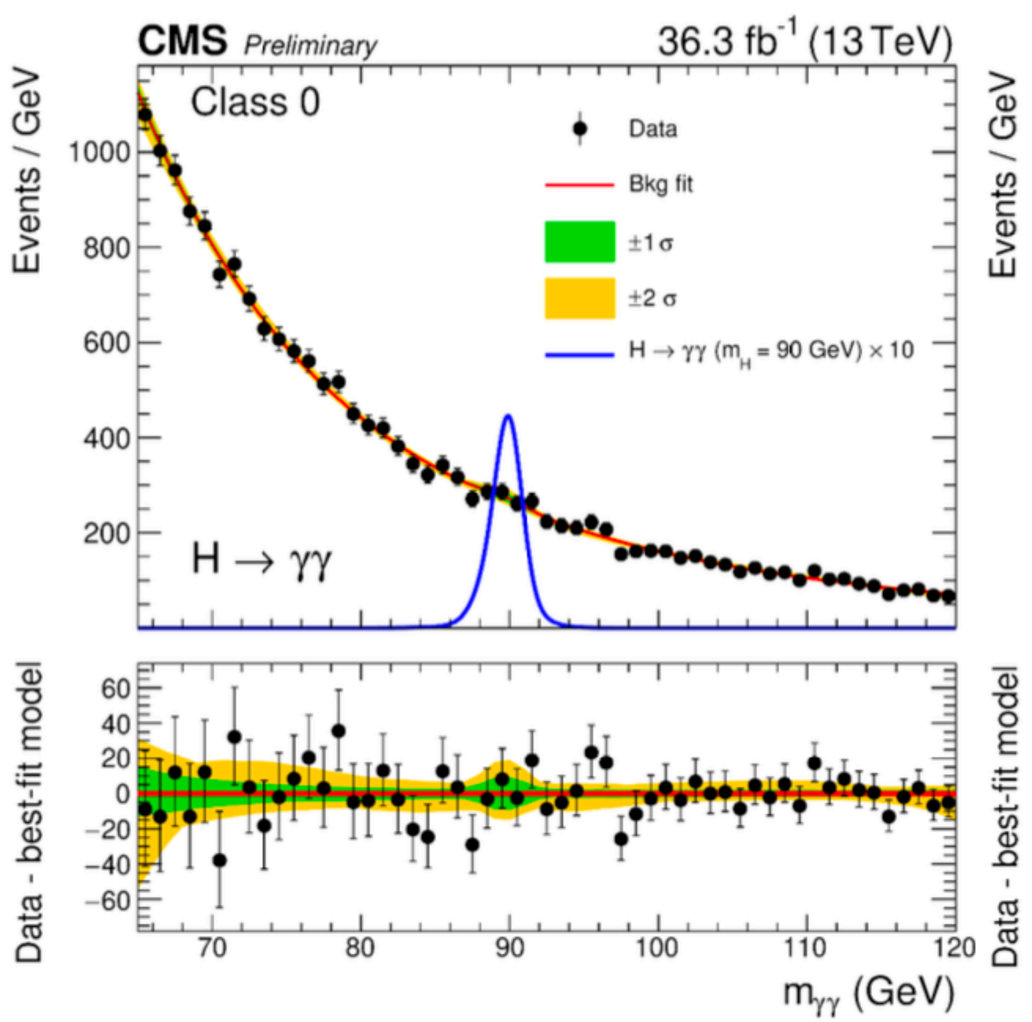
If two experiments see an excess in the same spot:

- Beware of combinations, correlations can be important! Best left to professionals
- My rule of thumb: Throw away the most significant experiment and treat the local significance of the weaker one as the global significance for both

Statistical vs systematic uncertainties

Many forms of systematic uncertainties, need to read the fine print

<u>Simple example:</u>



Sideband on smooth background
Low systematic uncertainty

arXiv 2307.14944

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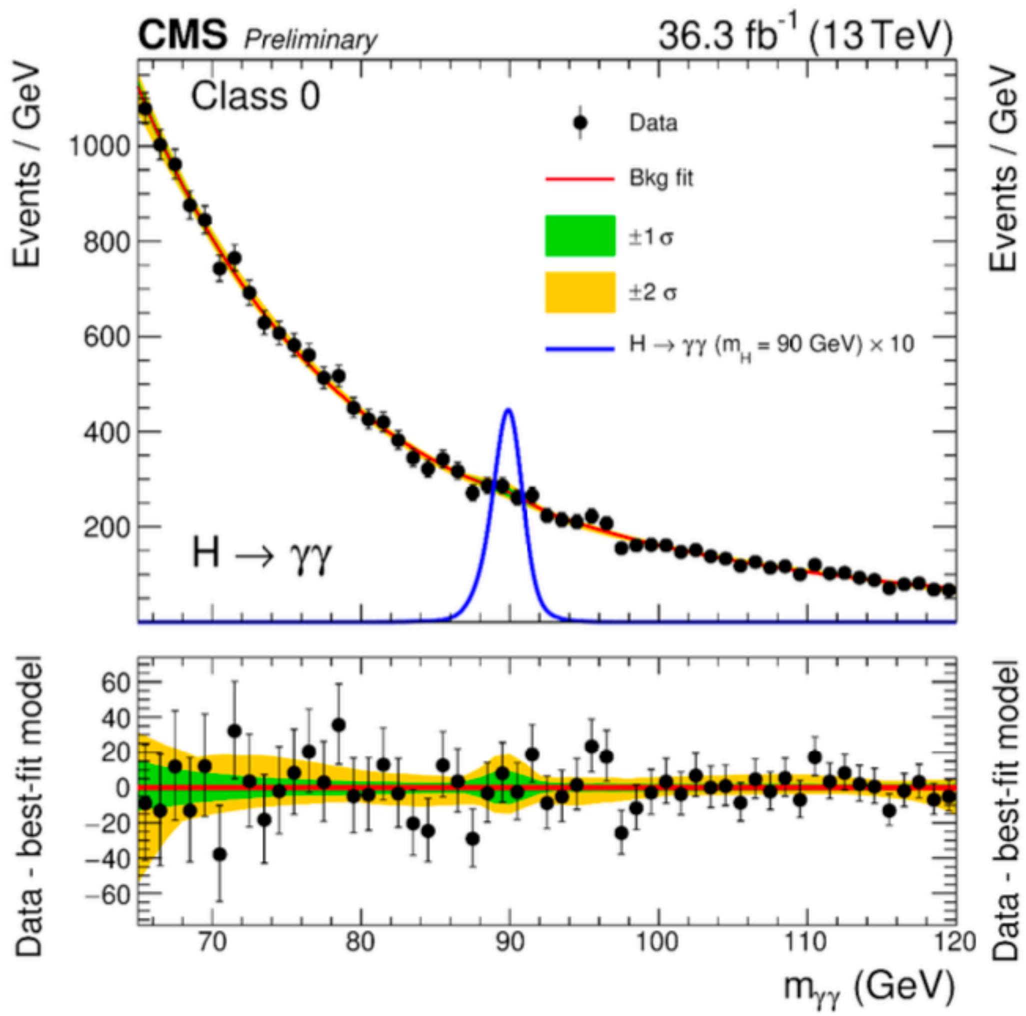

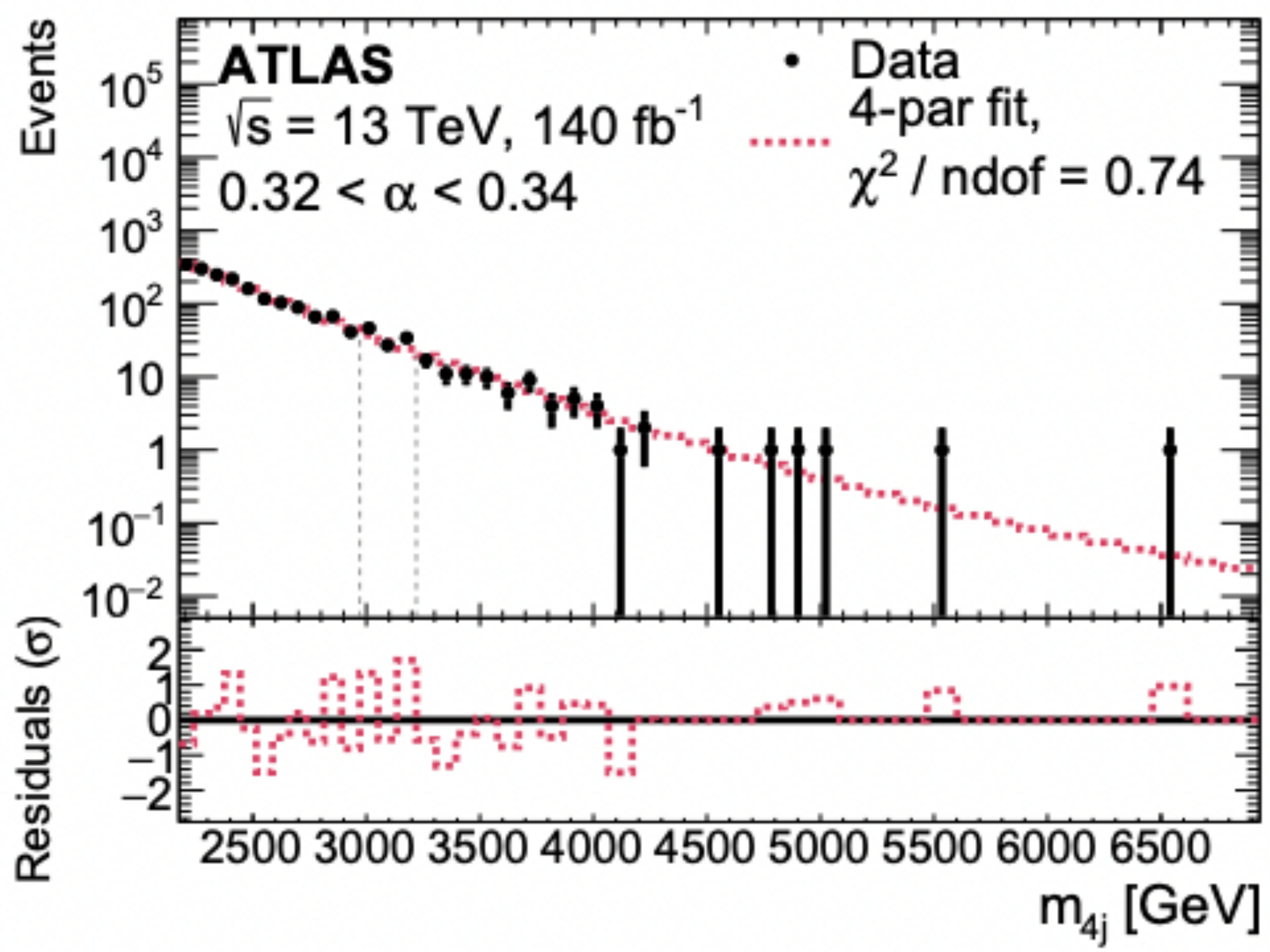

Sideband on smooth background
Low systematic uncertainty

Background extrapolation needed
High systematic uncertainty

arXiv 2307.14944

Theory uncertainties

Covered by other lectures in great detail -> Quick summary

There are a variety of theory uncertainties:

- Calculation to finite order in perturbation theory
- Processes/contributions which have not (yet) been calculated
- Uncalculable contributions which are estimated / bounded (e.g. powercorrections, hadronization uncertainties)
- Finite Monte Carlo statistics (e.g. in lattice calculations)
- Uncertainties related to extraction from experimental data (e.g. R-ratio)

As for experimental systematics, theory errors reflect the best judgement of the team performing the work at the time, and may be revised as understanding grows

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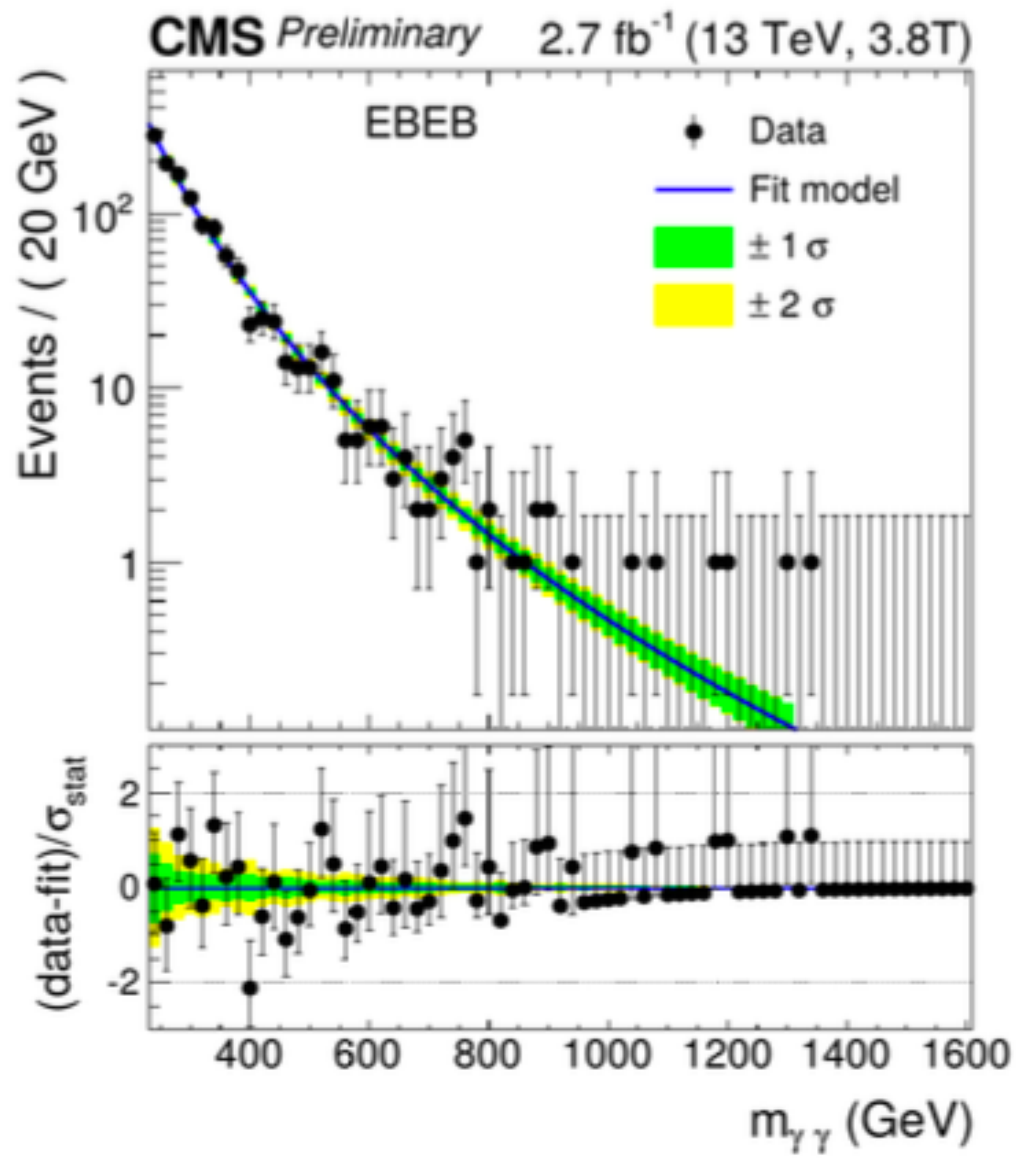
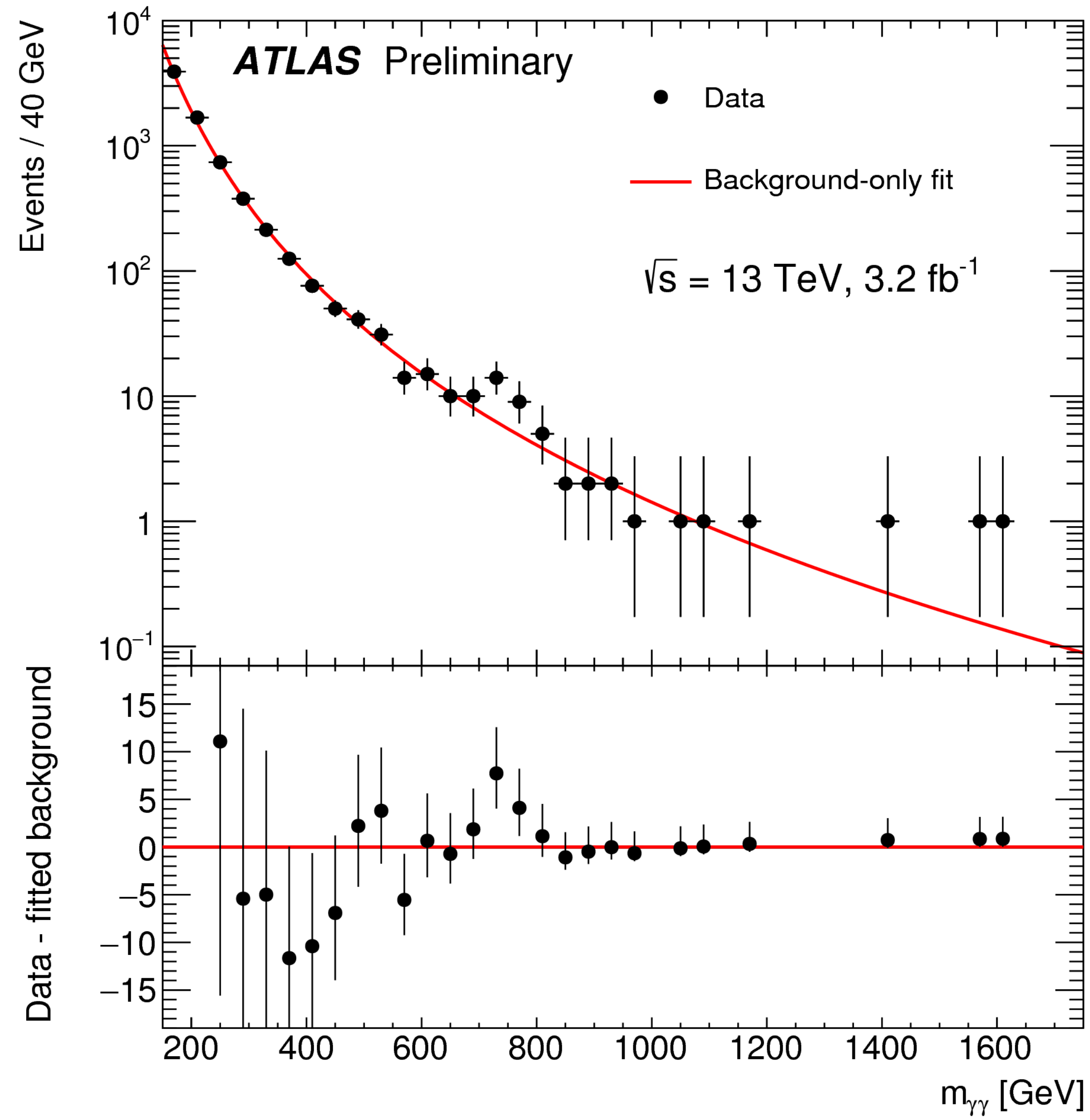
Case study: $\gamma\gamma$ resonance @ 750 GeV (2015)

Both ATLAS and CMS saw an excess in early 13 TeV data





This was the first serious batch of 13 TeV data, community was already on edge

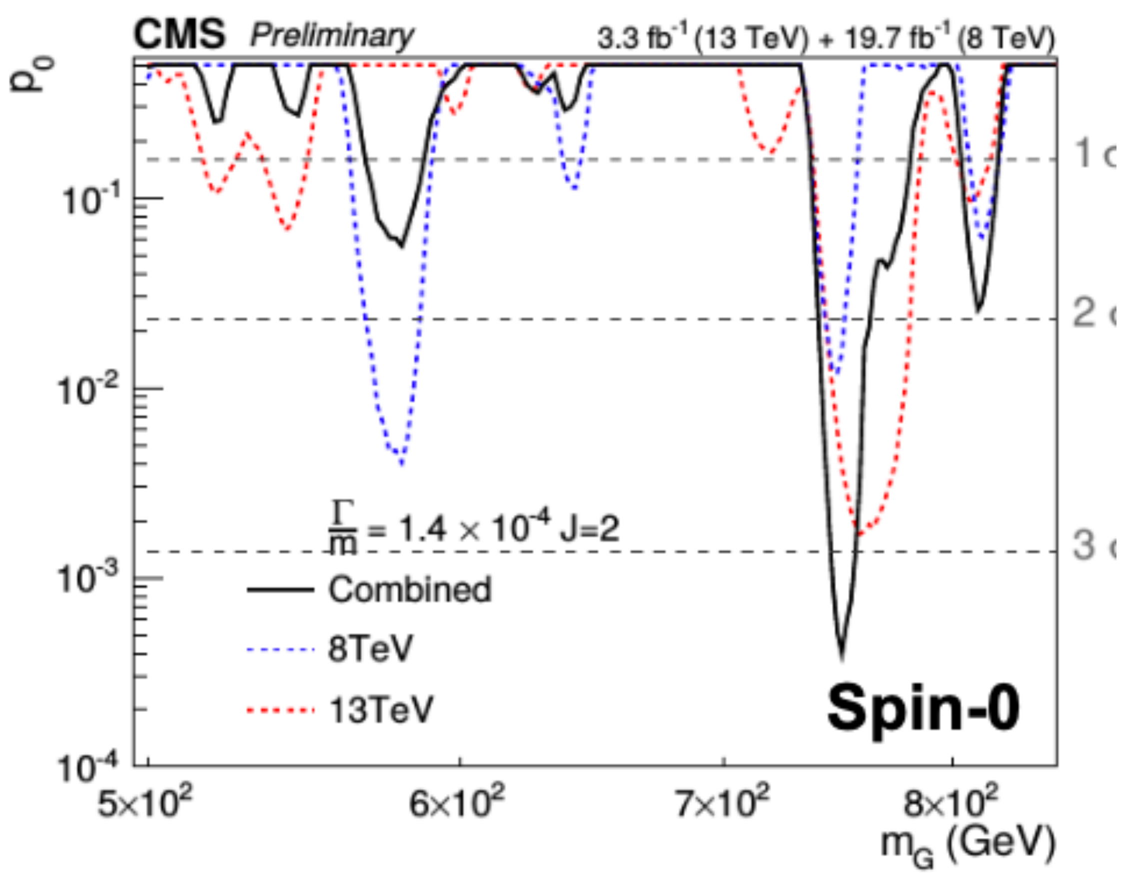
CMS-PAS-EXO-15-004
ATLAS-CONF-2015-081

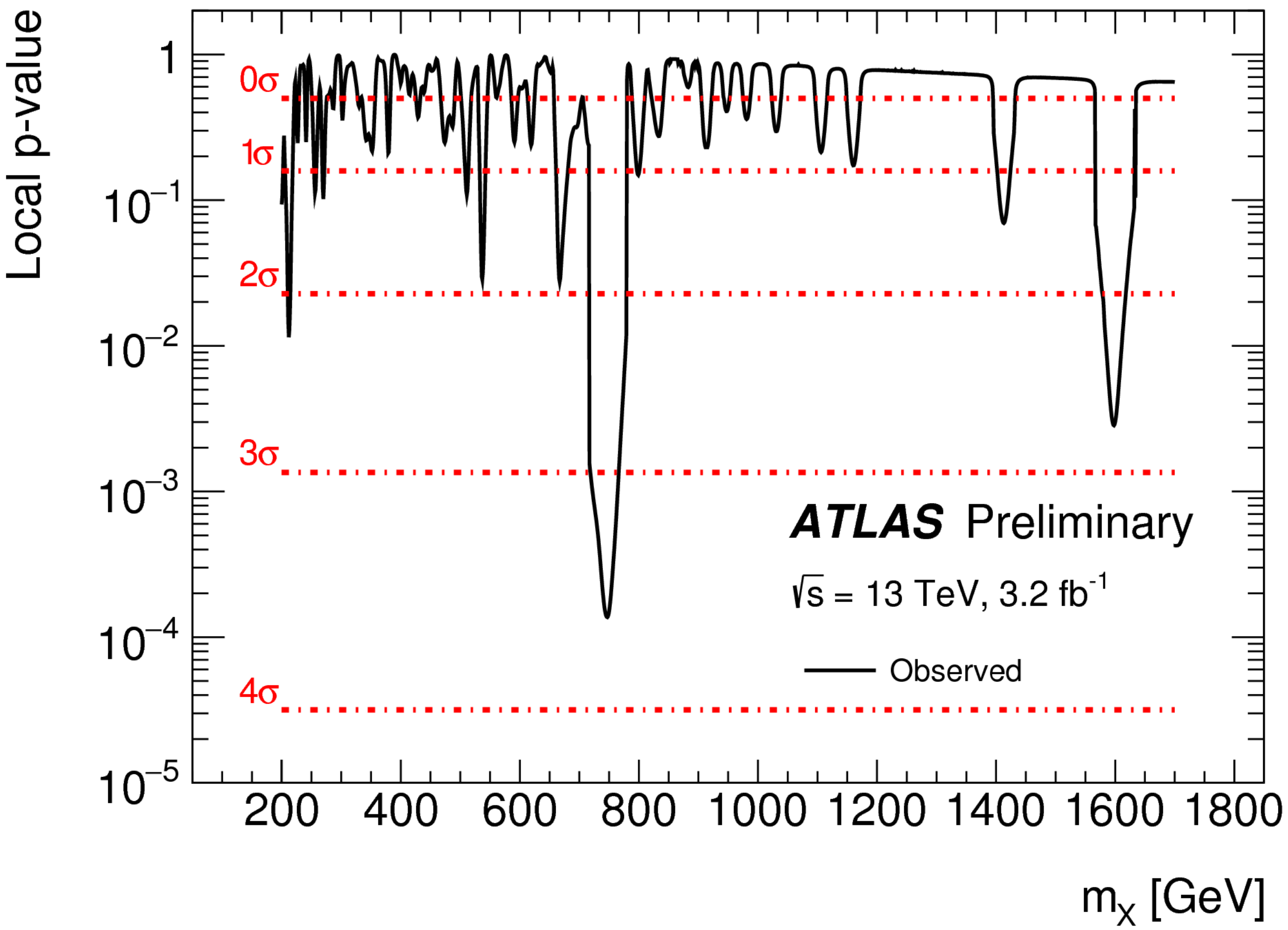
Case study: $\gamma\gamma$ resonance @ 750 GeV (2015)

Questions, in order of priority:

- How statistically significant is it?
- Is it compatible with other data?
- Do we understand the background?
- Is there a decent theoretical framework? (simplified model)
  What other predictions does it make?
- Does it fit into a bigger theoretical context?
- What other lessens were learned? (after anomaly demise)

p-values





Local: 2.6σ

Global: 1.2σ

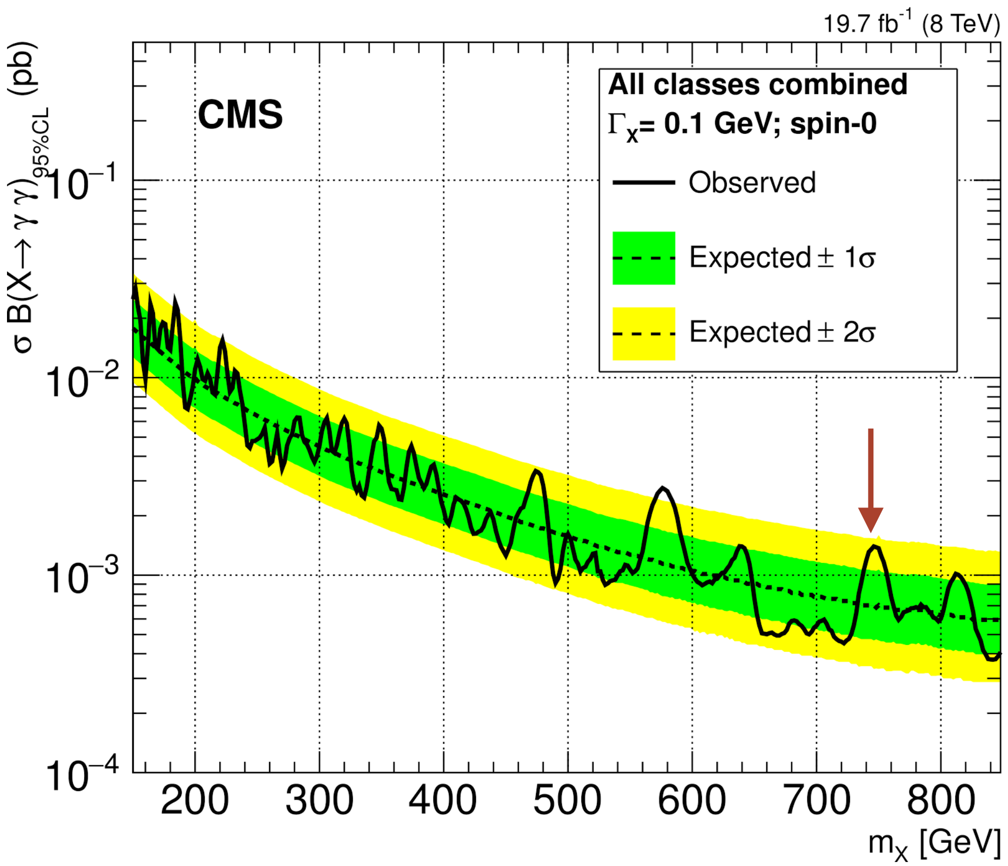
Local: 3.6σ

Global: 2.0σ

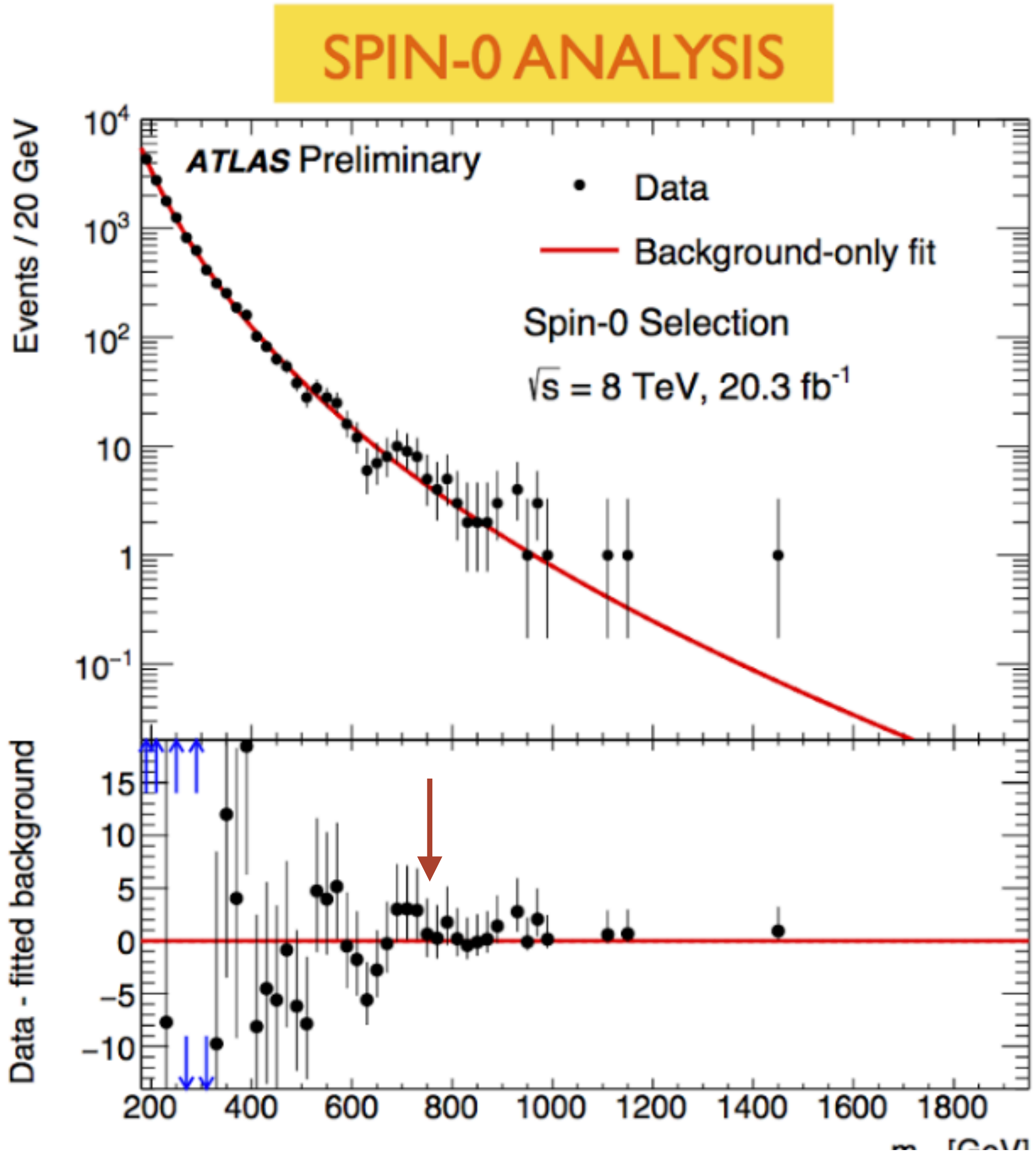
My rule of thumb: throw away ATLAS, take CMS local significance as global for both experiments

CMS-PAS-EXO-15-004
ATLAS-CONF-2015-081

8 TeV vs 13 TeV



Very mild excess at CMS 8 TeV



Nothing at ATLAS 8 TeV

Does this kill it?

Not yet, because the cross section should be lower at 8 TeV than at 13 TeV

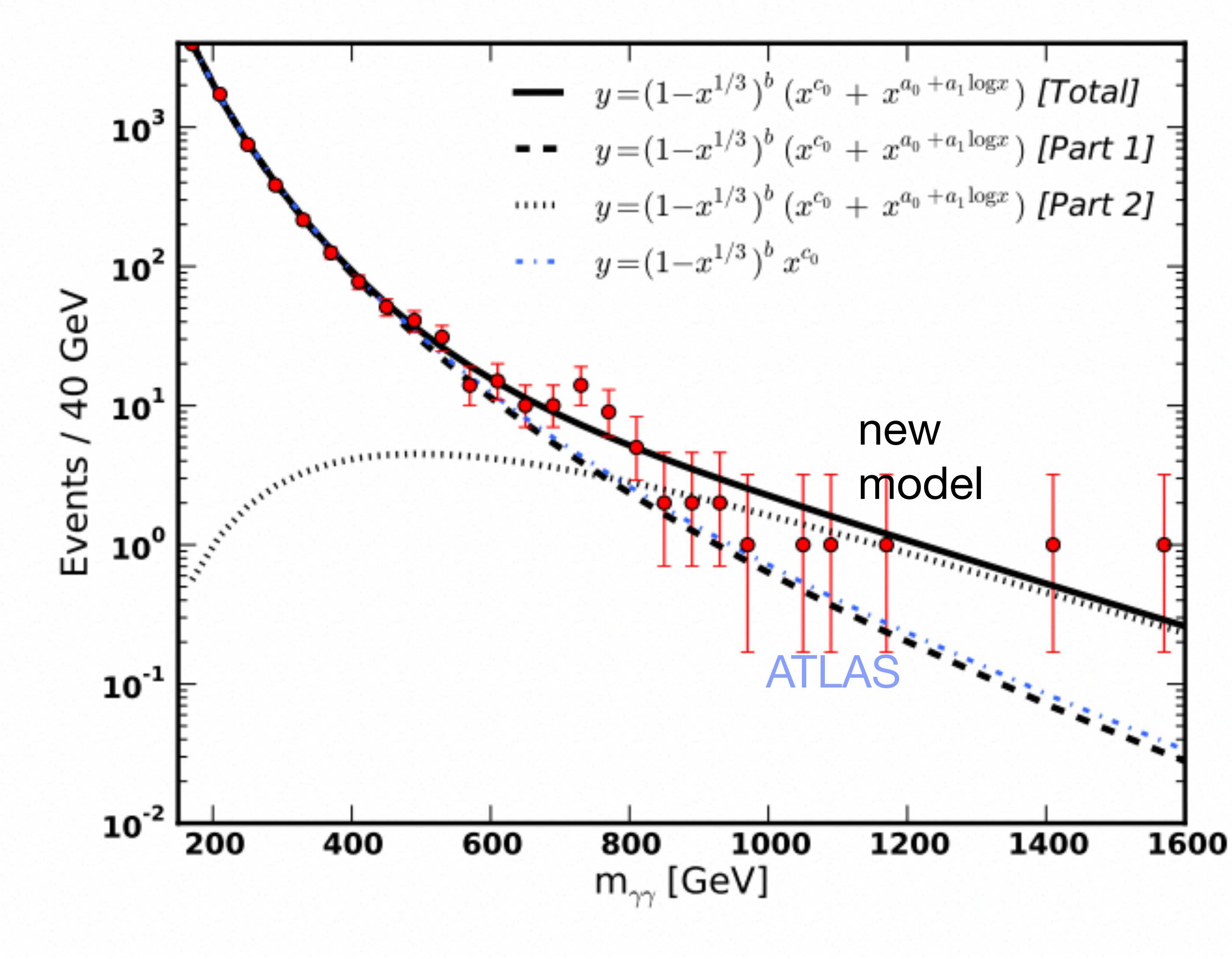
Gluon fusion initial state was best fit, with a mild tension with ATLAS 8 TeV

$q\bar{q}$ initial state was disfavored

Do we understand the background?

It’s just a side band, what could go wrong?

Some folks proposed an alternative fitting function for background and claimed much lower significance for excess



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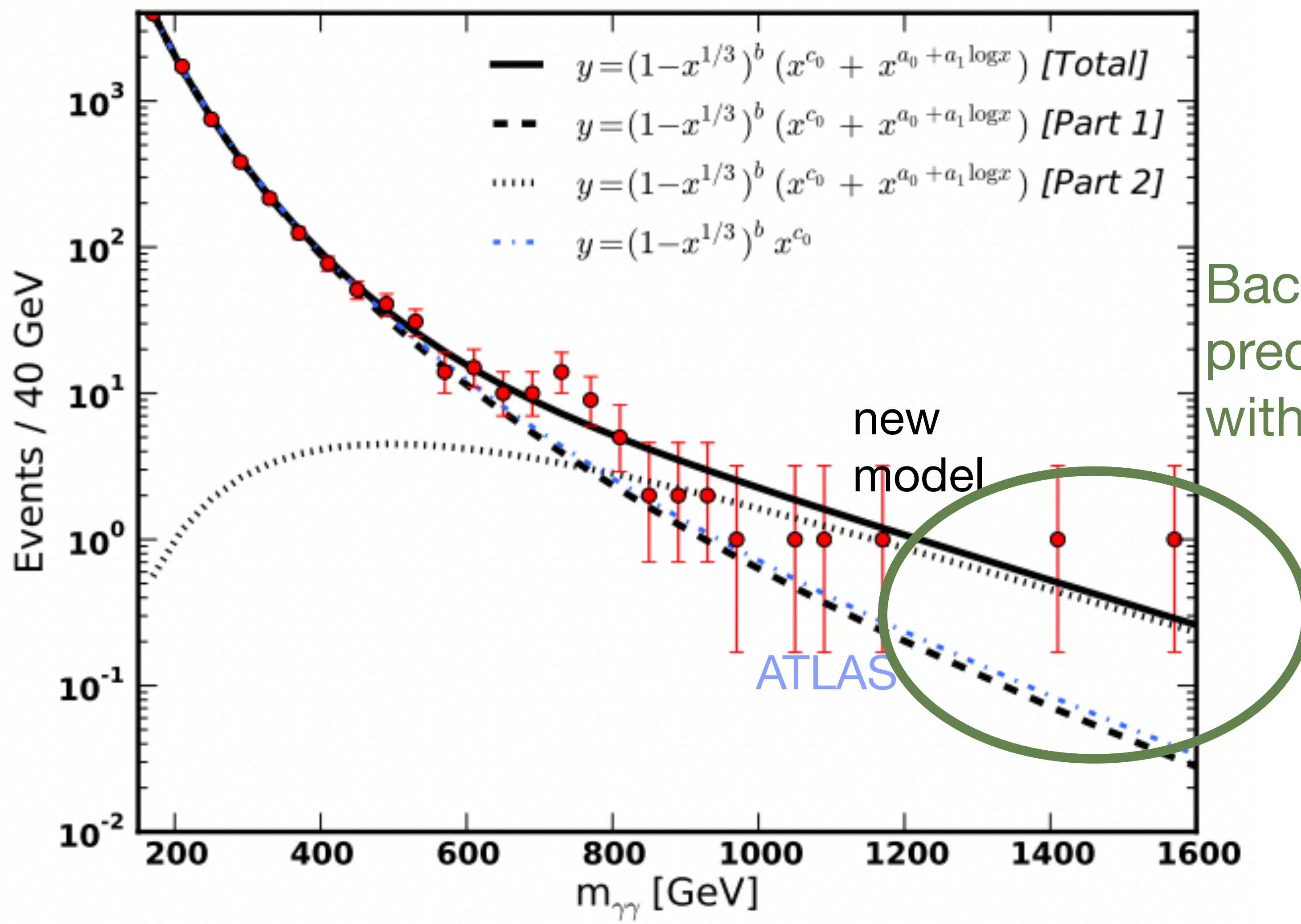


Background model over predicts the tail of the data with ~ 3 σ

Always account for bins with 0 events in fit

Is there a decent theory framework?

In the meanwhile, in theory land…

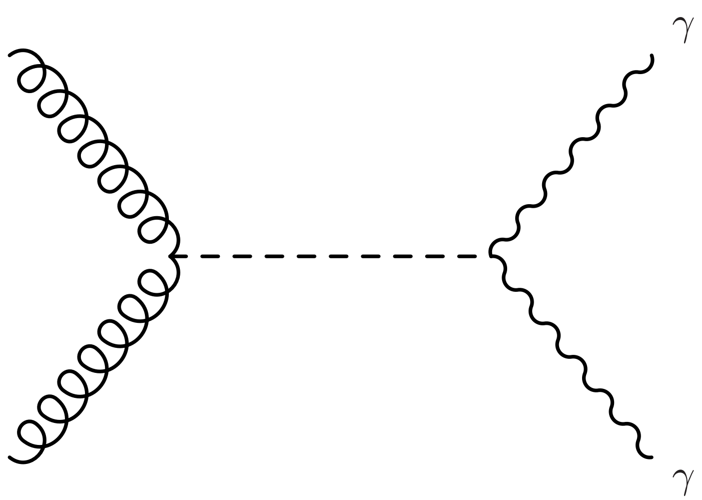
540 citations in ~ 6 months
120 citations in ~ first month

I will make no attempt to fairly cite all this work here…

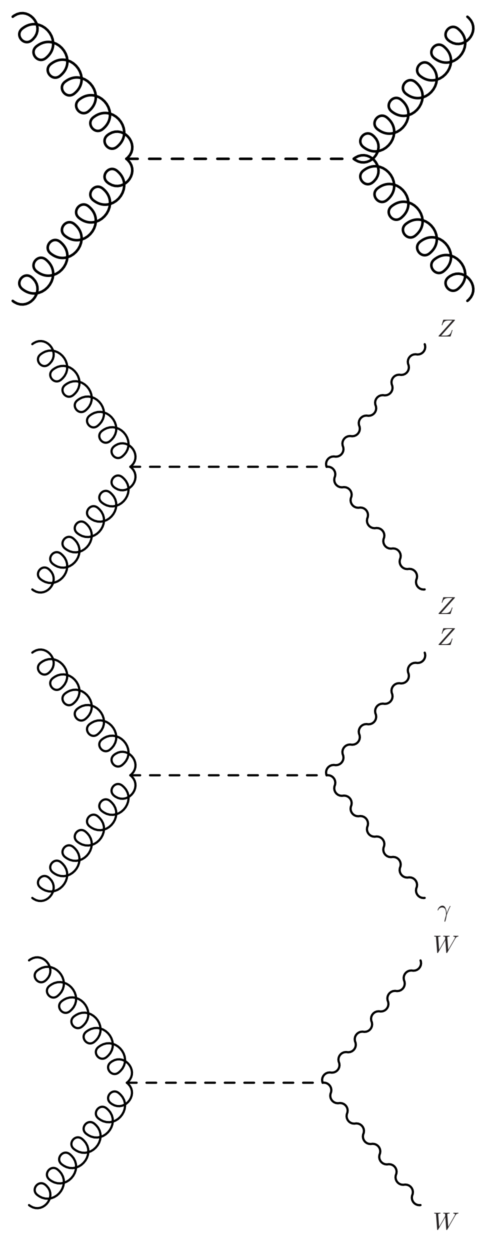
Simplified models (aka “the first few hours”)

What do we know:

- It decays to photons (obviously)
- Cross section ~ 5 - 10 fb
- Gluon fusion preferred over $q\bar{q}$ initial state
- Spin 0 or spin 2 (spin 1 forbidden by the Landau-Yang theorem)

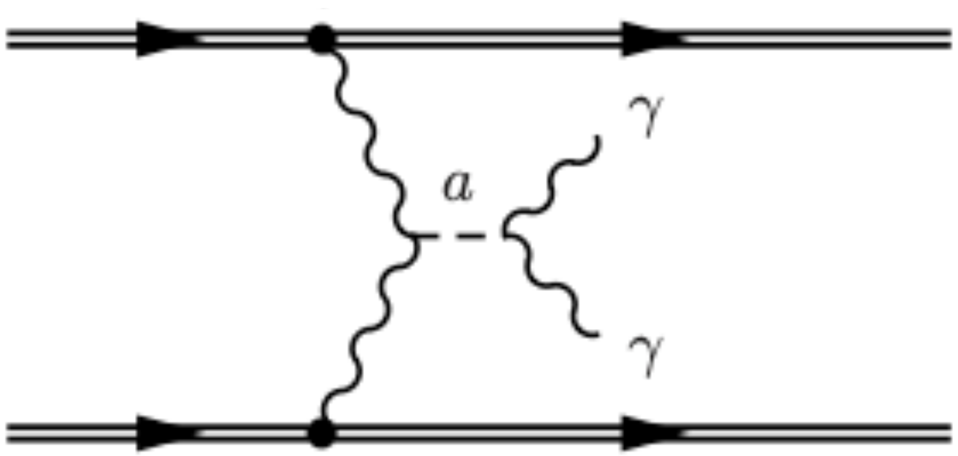


Suggests existence other decay channels, but more assumptions needed to predict their rate



Photon fusion

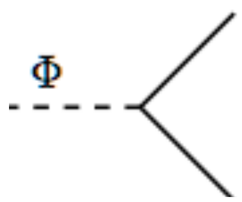
Gluon coupling not strictly necessary



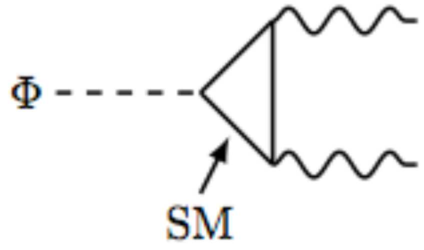
- Gluon fusion would typically produce some additional jets
- Photon fusion would tend to be more forward
- Photon fusion in mild tension with ATLAS 8 TeV data
- Issues found with photon pdf's (more on that later)

More complete models (aka “the first few days”)

Cannot be Higgs-like:

$\Bigg|$  $\Bigg|^2$

$\sim 10^5$

$\Bigg|$  $\Bigg|^2$

Already excluded

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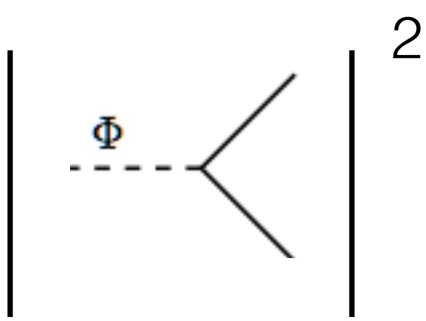

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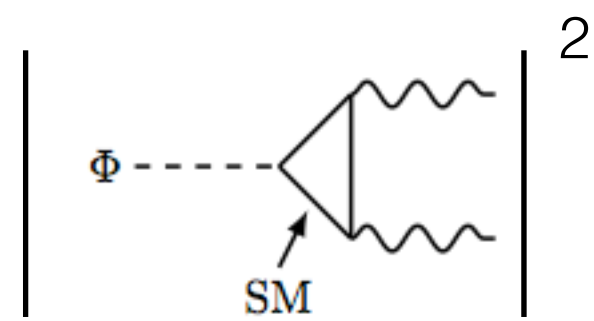
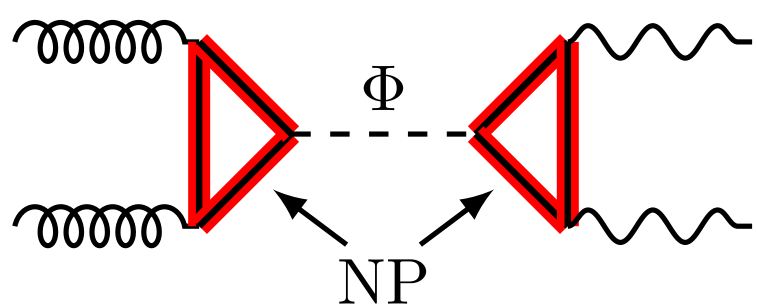


Already excluded

Need new colored & charged fermions or scalars:



With mass around ~ 1 TeV and fairly large Yukawa couplings

More complete models (aka “the first few days”)

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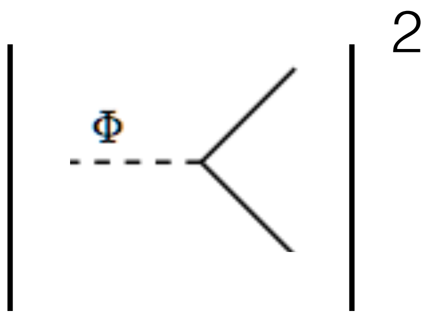
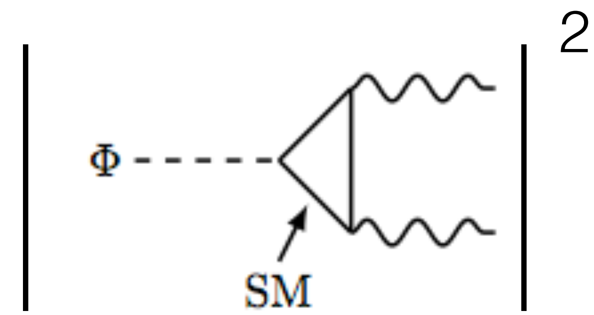


~ 10^5



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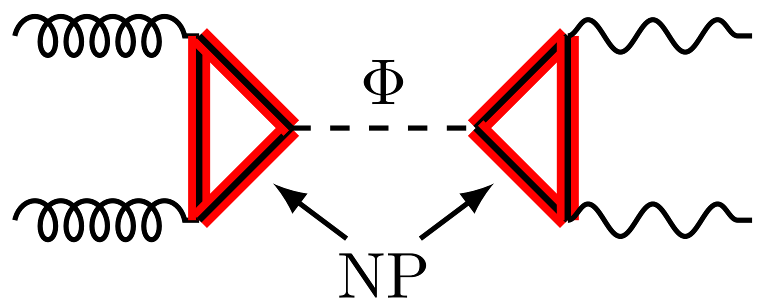


With mass around ~ 1 TeV and fairly large Yukawa couplings

→

- New search strategies
- Implications for grand unification
- Implications for dark matter
- Implications for composite Higgs models etc

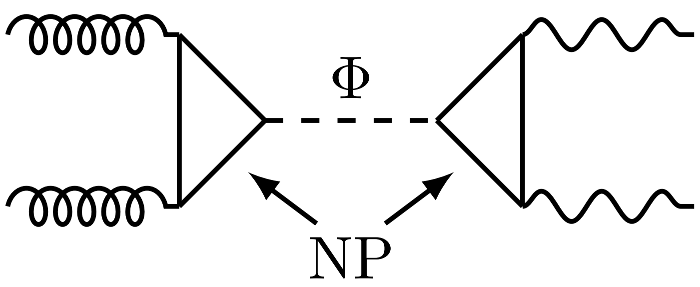
It all kinda worked, but it looked weird.

No good argument was provided *why* these particles needed to exist

Sidebar for theorists: beware of perturbativity

Perturbativity for scalars cubic coupling is straightforward, but often forgotten

fermions



$$\mathcal{L} \supset y\Phi\bar{\psi}\psi$$

From our QFT course we know

$$y \ll 4\pi$$

Sidebar for theorists: beware of perturbativity

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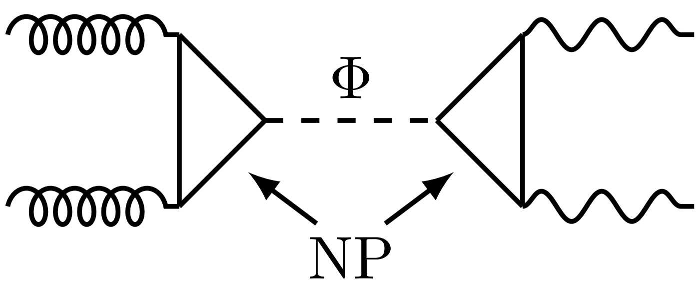

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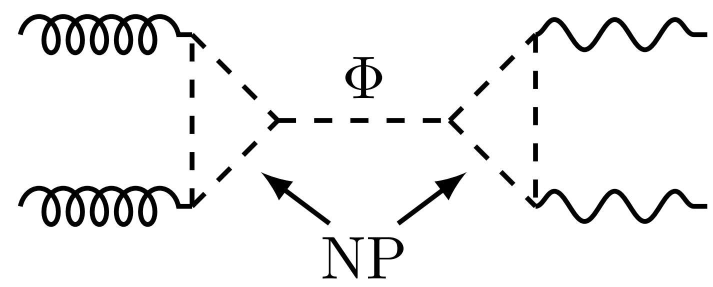
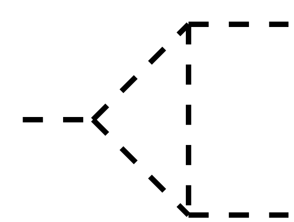


$$\mathcal{L} \supset A\Phi\phi^\dagger\phi$$

Compute the correction



$$= \frac{1}{8\pi^2}\frac{A^3}{m_\phi^2} \ll A$$

$$\longrightarrow \frac{A}{m_\phi} \ll 4\pi$$

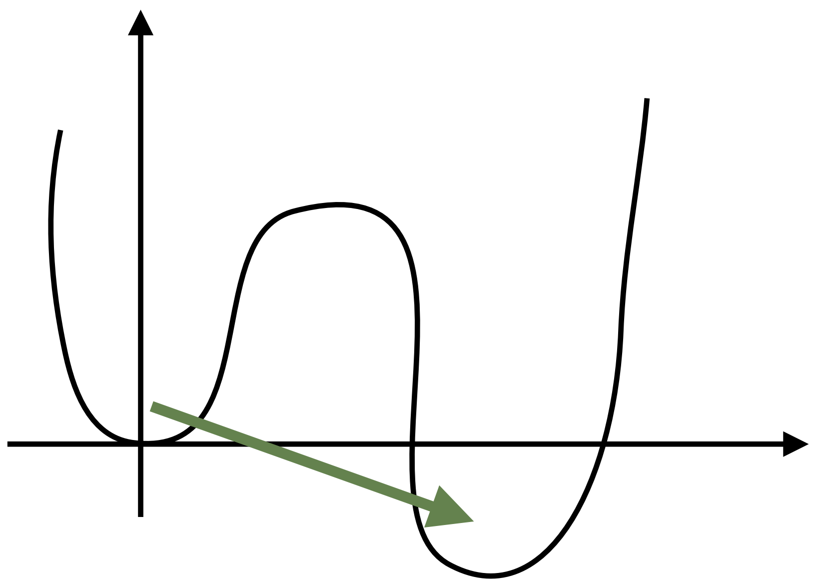
Sidebar for theorists: beware of perturbativity

Perturbativity for scalars cubic coupling is straightforward, but often forgotten

Moreover beware of vacuum stability

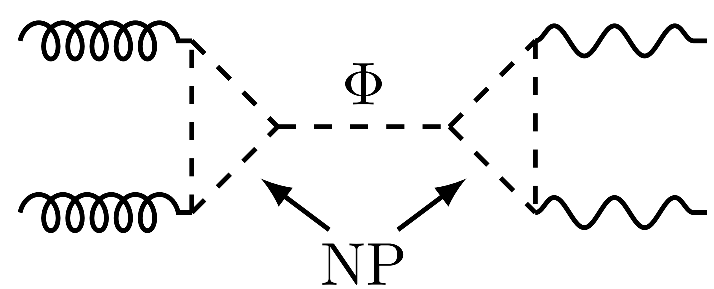
For $A \gtrsim m_\phi, m_\Phi$

A false vacuum can open up in the potential



Need to check that your universe hasn't already tunneled into a different ground state!

scalars



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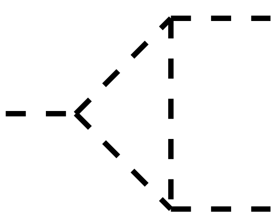

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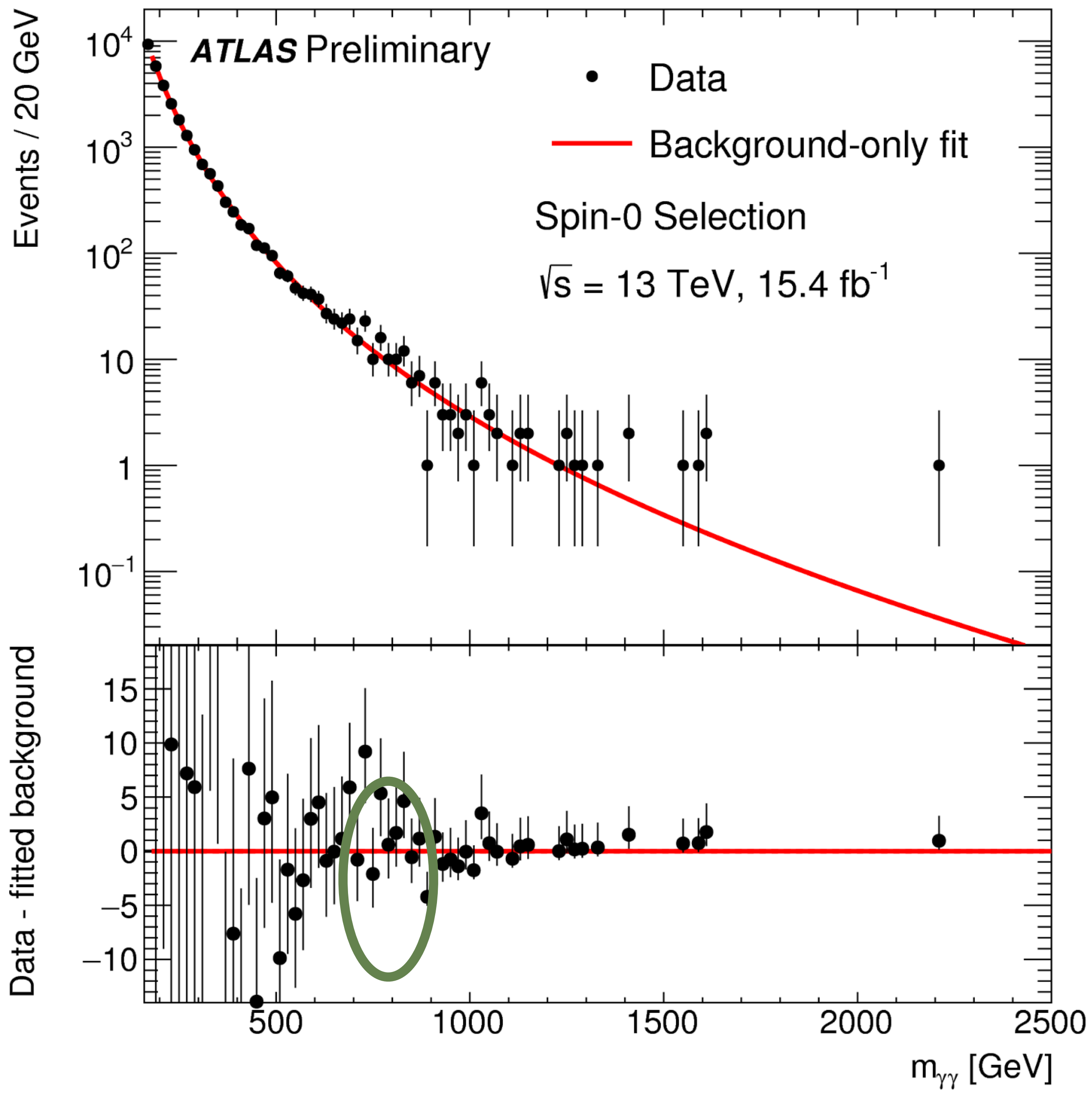
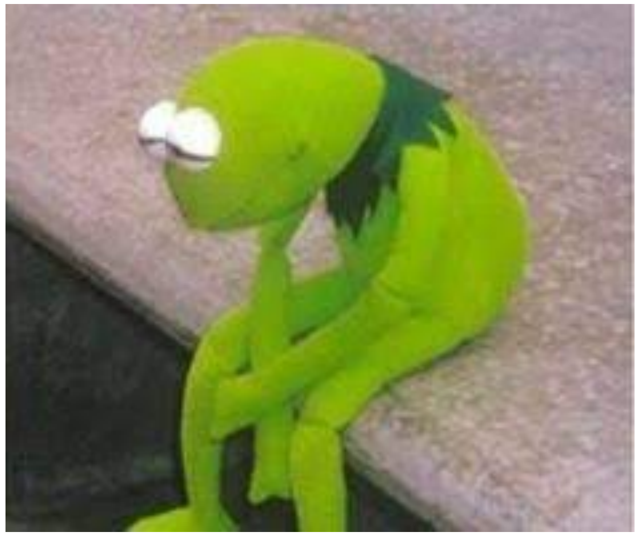
$$\longrightarrow \quad \frac{A}{m_\phi} \ll 4\pi$$

The death of the excess

Summer of 2016





In the spring of 2016, combined ATLAS + CMS local significance was about 4.4σ (p-value ~ 10^{-5})

It just went away with more data

The LHC does so many observations that fluctuations can produce an seemingly extremely significant excess once in a while!

The aftermath: what did we learn?

example 1: Photon pdf's:

Extracted from $pp \to \ell^+\ell^-$

This contains $\gamma\gamma \to \ell^+\ell^-$ but need to subtract dominant $q\bar{q} \to \ell^+\ell^-$ piece
This lead to large errors

A. Manohar, P. Nason, G. Salam, G. Zanderighi *Phys.Rev.Lett.* 117 (2016) 24, 242002 • arXiv: 1607.04266

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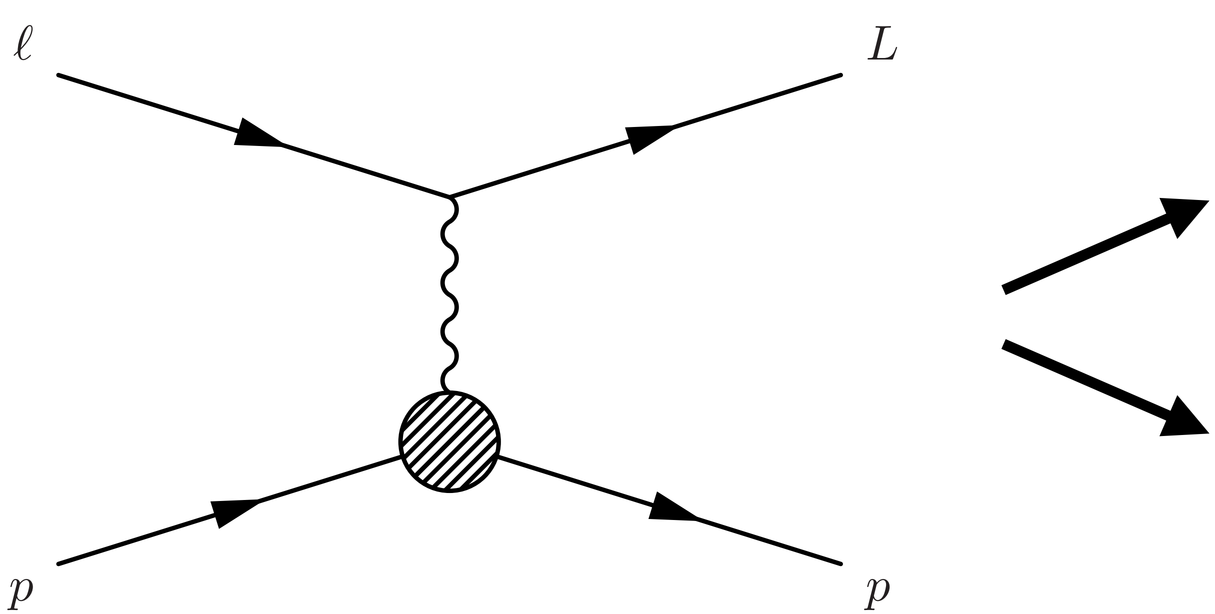
This lead to large errors

Idea: consider hypothetical lepton upscattering to heavier lepton through photon interaction



Calculate using proton electromagnetic form factors

Calculate using photon pdf of the proton

These calculations are equivalent

A. Manohar, P. Nason, G. Salam, G. Zanderighi *Phys.Rev.Lett.* 117 (2016) 24, 242002 • arXiv: 1607.04266

The aftermath: what did we learn?

example 1: Photon pdf's:

$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \Bigg\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2)$$

$$\left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right]$$

$$- \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z}, \mu^2\right) \Bigg\}, \quad (6)$$

A. Manohar, P. Nason, G. Salam, G. Zanderighi *Phys.Rev.Lett.* 117 (2016) 24, 242002 • arXiv: 1607.04266

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electromagnetic form factors of the proton

Can be extracted from $pe^- \to pe^-$ data

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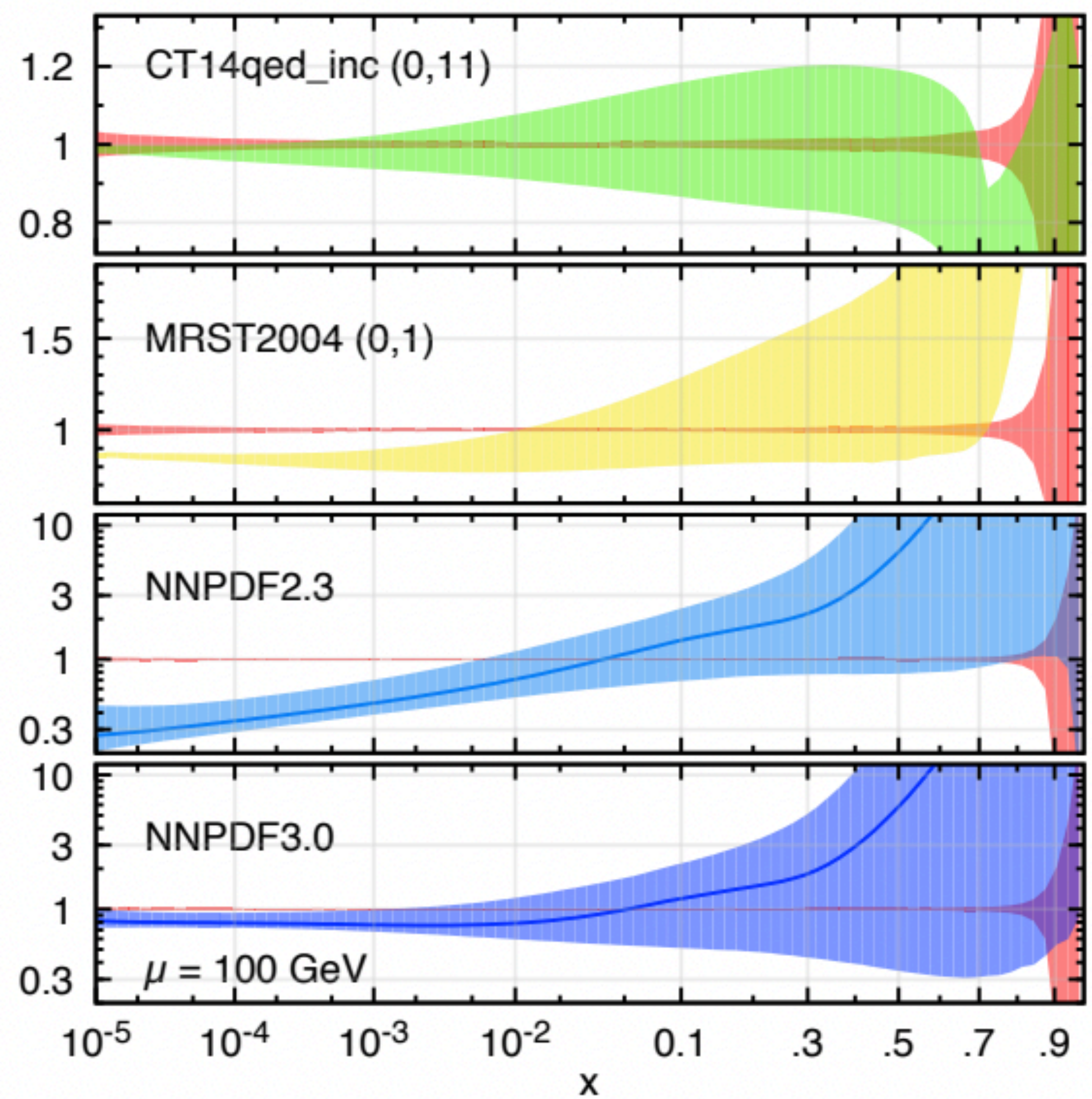


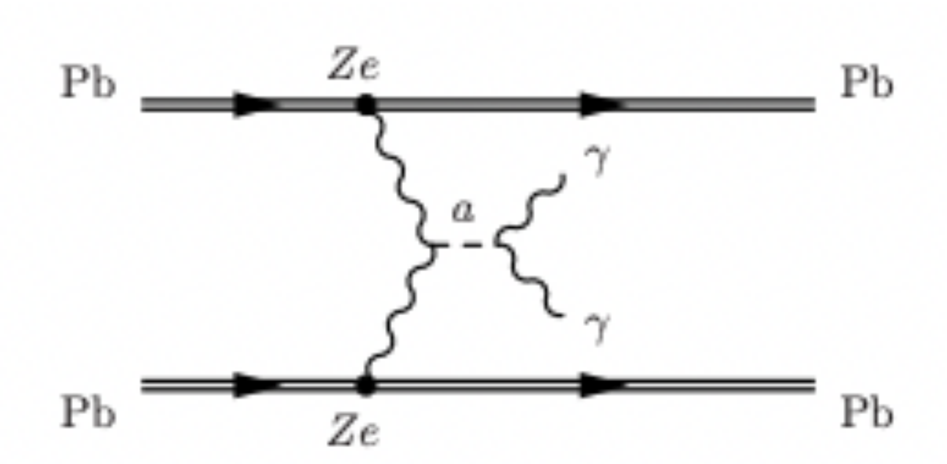
Tiny uncertainties!

A. Manohar, P. Nason, G. Salam, G. Zanderighi *Phys.Rev.Lett.* 117 (2016) 24, 242002 • arXiv: 1607.04266

The aftermath: what did we learn?

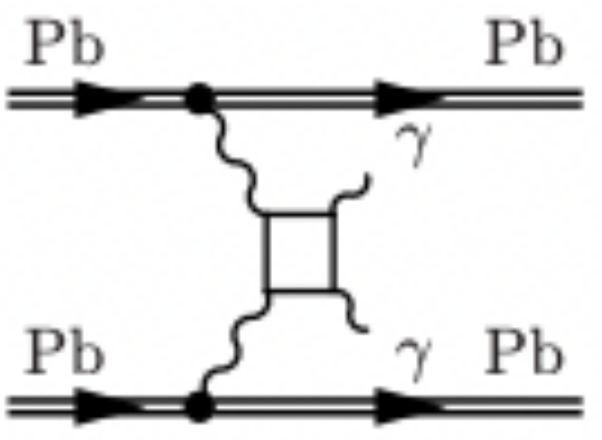
ALPs at heavy ion collisions:

Signal



enhanced with Z^4

Background



light-by-light scattering

SK, T. Lin, H. Lou, T. Melia *Phys.Rev.Lett.* 117 (2016) 24, 242002 • arXiv: 1607.04266

The aftermath: what did we learn?

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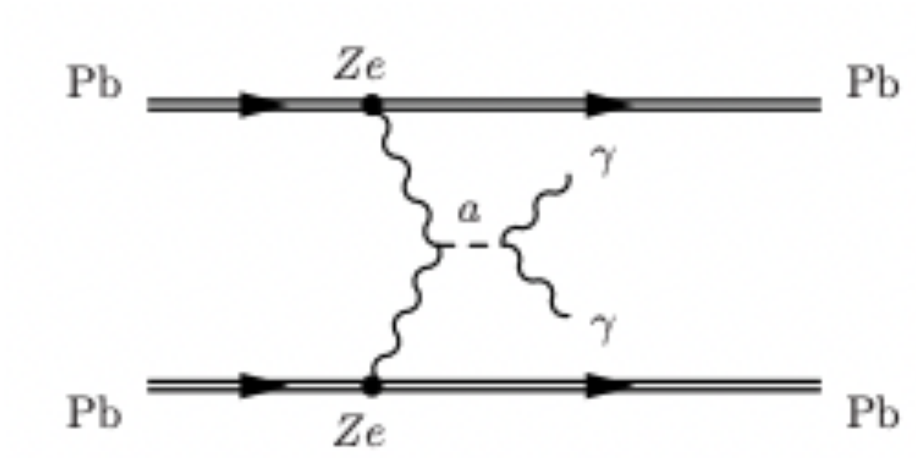

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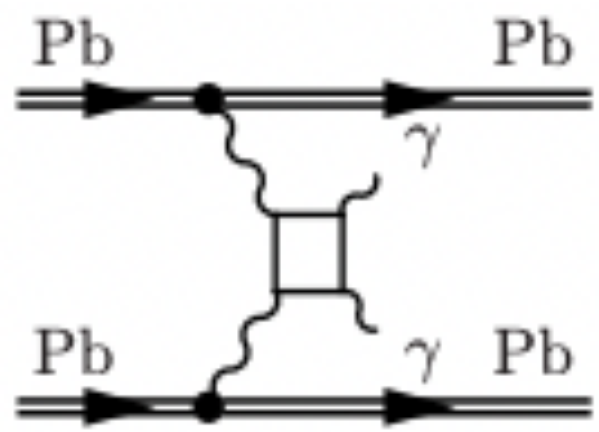

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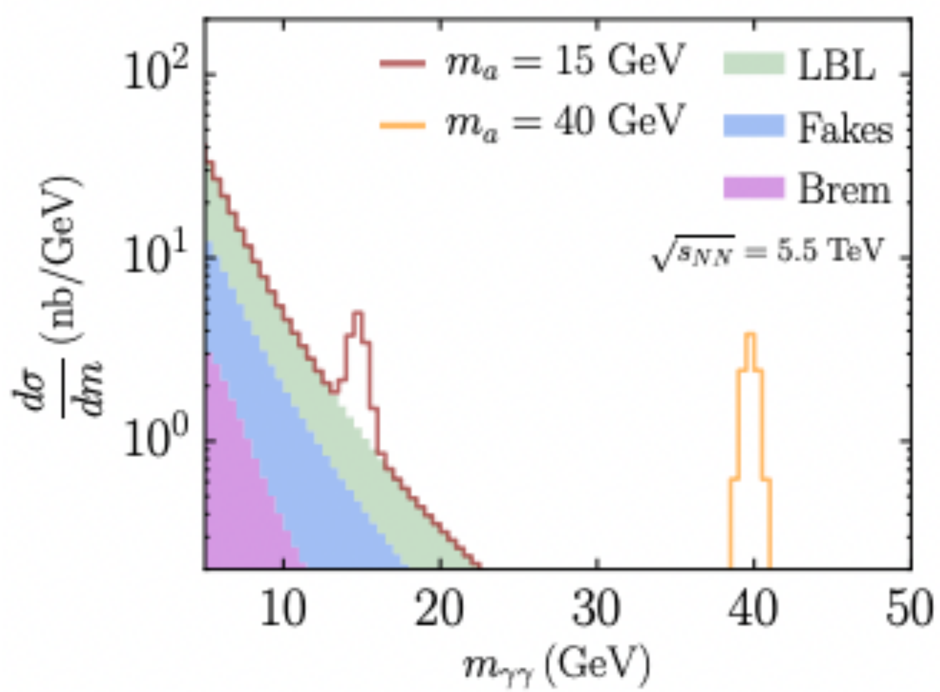


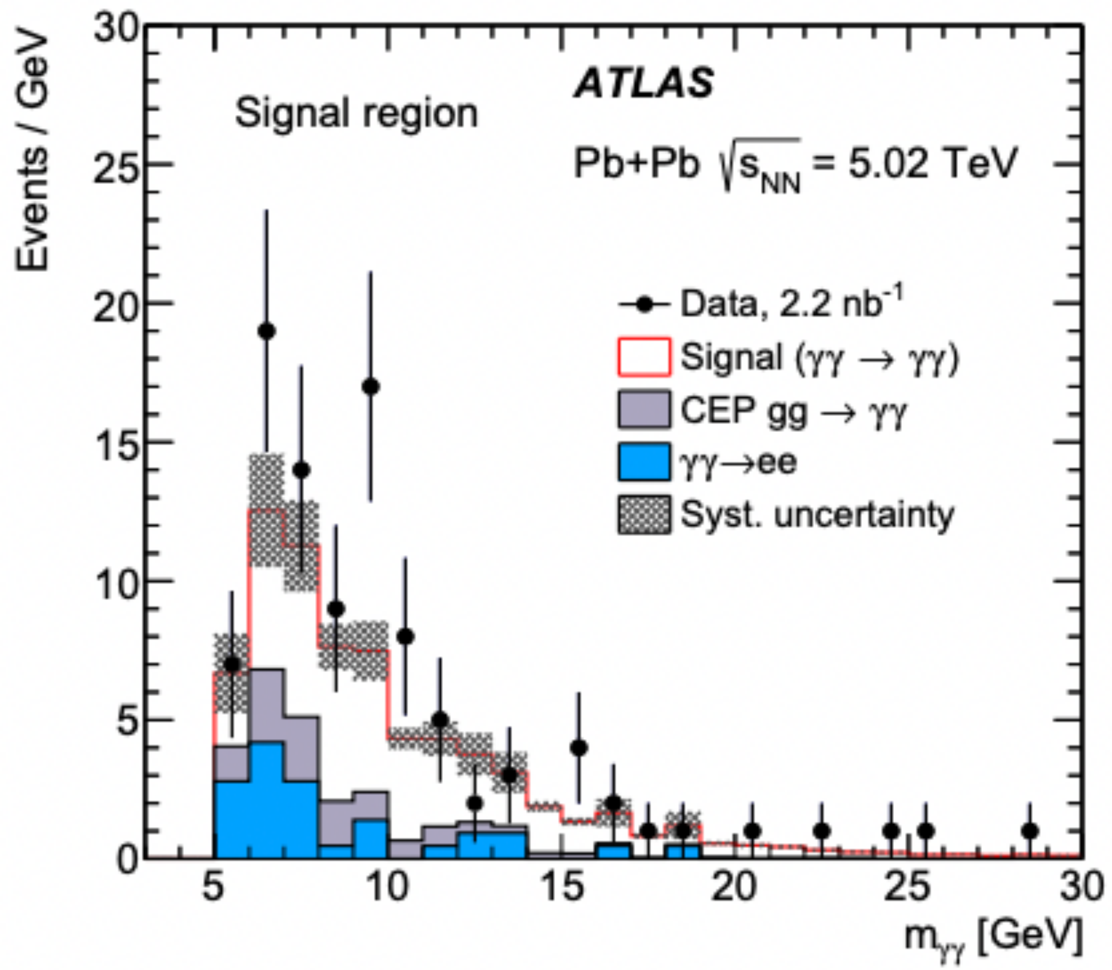
Use ultraperipheral collisions, where both Pb remain intact experimentally very clean

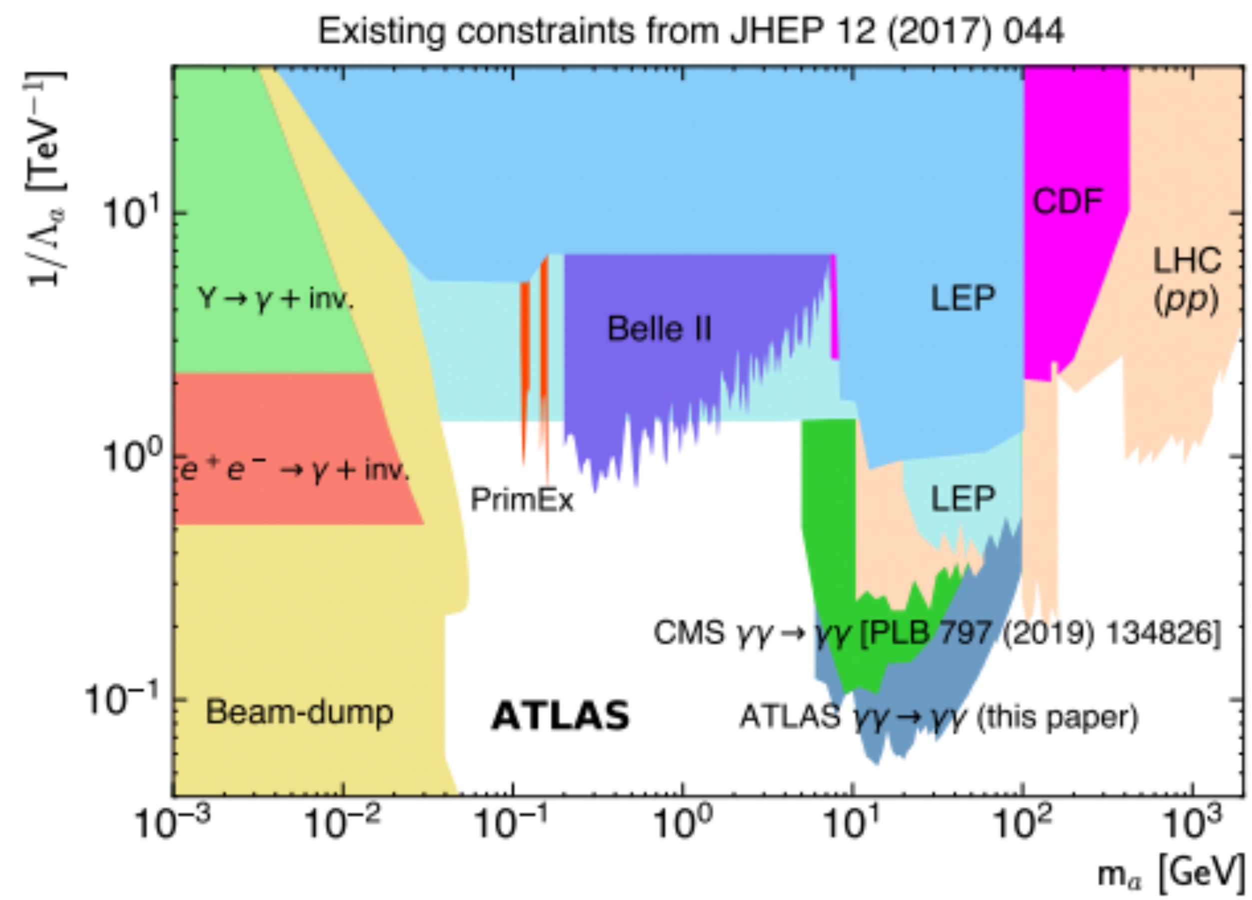
Viable BSM search in Pb-Pb collisions

SK, T. Lin, H. Lou, T. Melia *Phys.Rev.Lett.* 117 (2016) 24, 242002 • arXiv: 1607.04266

The aftermath: what did we learn?

ALPs at heavy ion collisions:





Limits from both ATLAS and CMS now

Still best limits in this mass range

ATLAS • arXiv: 2008.05355
CMS • arXiv: 1810.04602

Outline

1. Why pay attention to anomalies?
2. How to judge an anomaly?
3. A case study
4. Some current anomalies

Current anomalies

There are many, but at the moment none extremely compelling for BSM imo

Here are two recent review articles with fairly comprehensive lists

“Anomalies in Particle Physics” A. Crivellin, B. Mellado • arXiv: 2309.03870

“Dark Matter” M. Cirelli, A. Strumia, J. Zupan • arXiv: 2406.01705

I’ll list a few examples, with a bias towards non-LHC anomalies

Some current anomalies

Anomaly	"Cleanliness"	Model building	Comment
CDF m_W	difficult	easy	in tension with all other data
DAMIC low energy excess	difficult	need isospin violation	likely unknown background
3.5 keV γ ray	difficult	moderate	May be due to missmodeling
Galactic center excess	difficult systematics	easy	pulsars?
muon g-2	theory difficult	easy	appears to be going away
Hubble tension	difficult	very hard	no totally satisfactory BSM atm
neutron lifetime	moderate	hard	SM agrees with bottle method
pulsar timing arrays	convincing	moderate	likely black hole mergers
galactic anomalies	simulations very difficult	easy	self-interacting DM?
ATOMSKI 17 MeV	nuclear physics uncertainties	hard	Will be tested soon

How can we discover anything?

The bar for a discovery will be extremely high:

- Statistical significance needs to be extreme (~ 5σ global?)
- Need confirmation from a second experiment
- Needs to be compatible with all relevant data sets
- Systematic uncertainties & theory will be scrutinized in extreme detail
- A compelling theory interpretation
- Ideally more than 1 channel (e.g. Higgs discovery)

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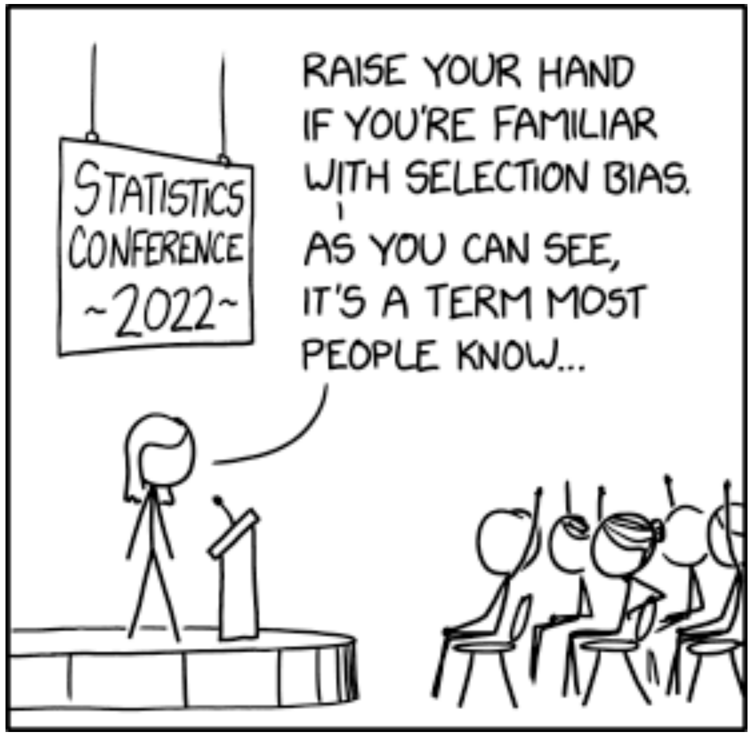
This would probably be an impossible standard in any other field

But we have the experimental and theoretical capabilities to meet these criteria

Conclusions

Anomalies and tensions in the data are normal and important in how we make progress

Because they shake up the status quo and force us to think in a new ways



www.xkcd.com

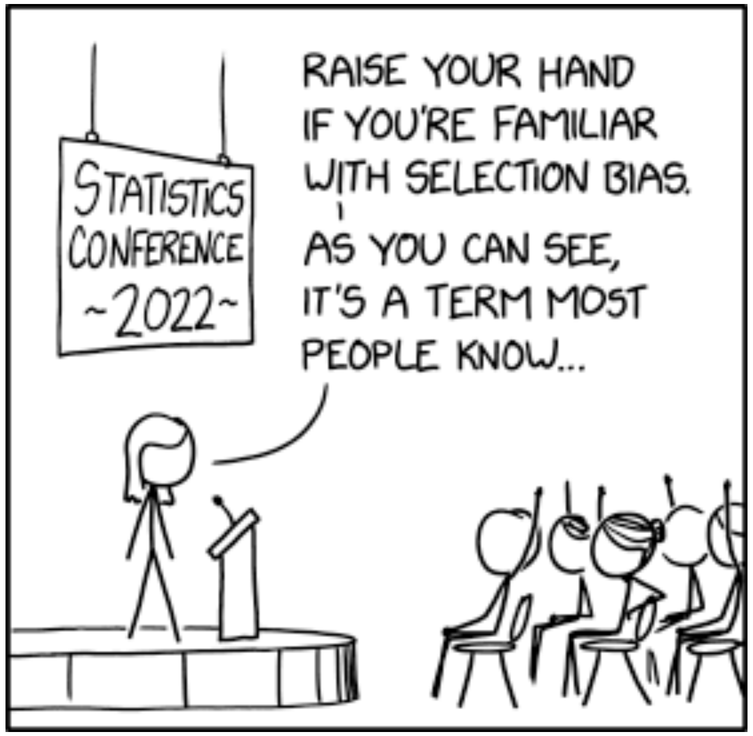
Conclusions

Anomalies and tensions in the data are normal and important in how we make progress

Because they shake up the status quo and force us to think in a new ways

<u>My advice:</u>

- Allow yourself to get excited
- Don't loose your head however, and check your biases. Listening to others with different views is essential.
- Be prepared to be disappointed. It's fine, you will learn many new things and another batch of data will come



www.xkcd.com