A short time ago, in a galaxy not so far away

- **Theorists having coffee, enters experimentalist.**

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- **Experimentalist:** *Let's go down and listen to the experiments?*

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A short time ago, in a galaxy not so far away

- **Theorists having coffee, enters experimentalist.**
- **Experimentalist**: *Let's go down and listen to the experiments?*
- **Prominent theorist**: *What for? There's nothing new they can tell us.*

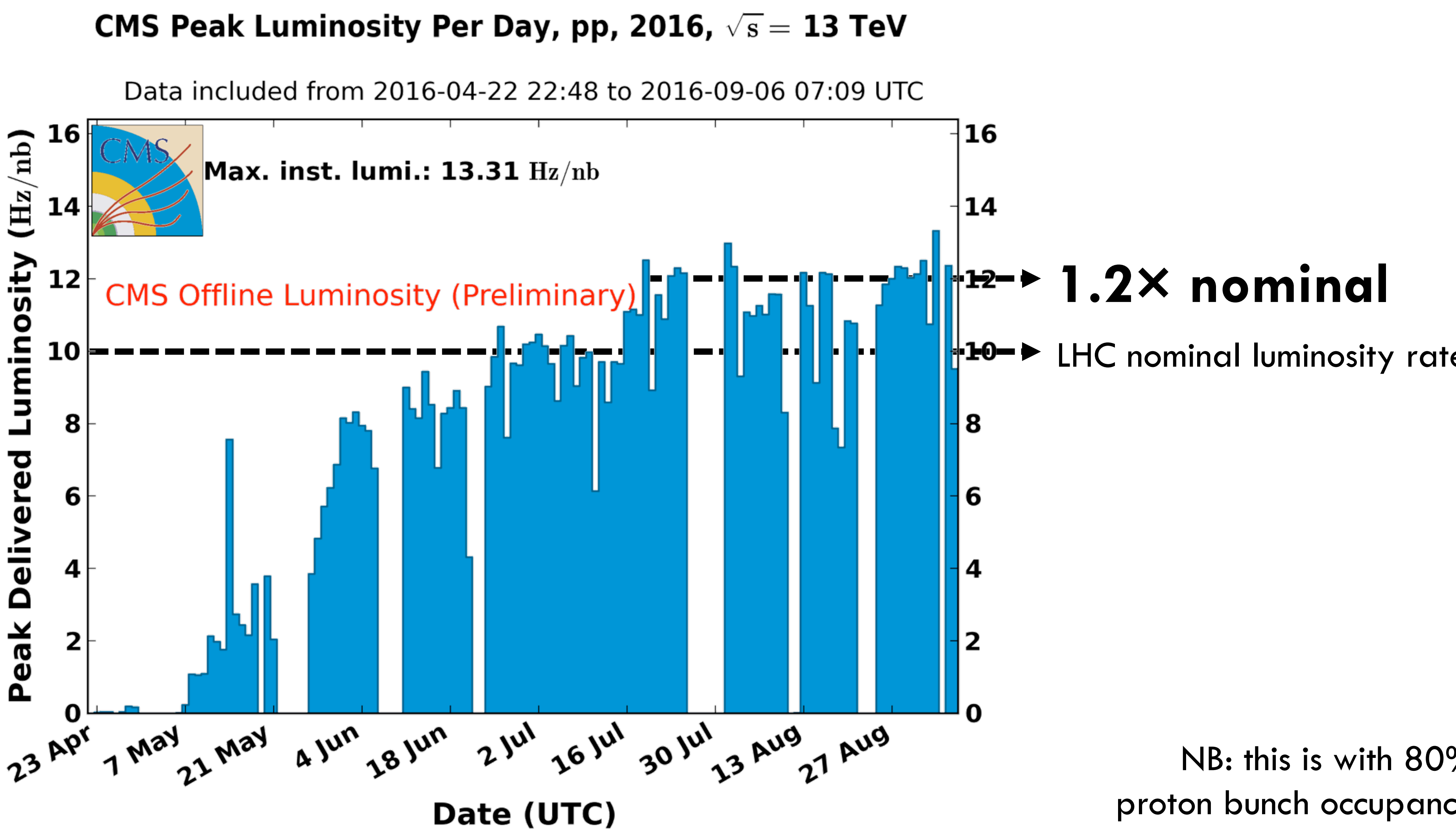
- I am happy to see **all** of them here.

WHEN **ONE** HIGGS IS **NOT** ENOUGH

Workshop on Multi-Higgs Models

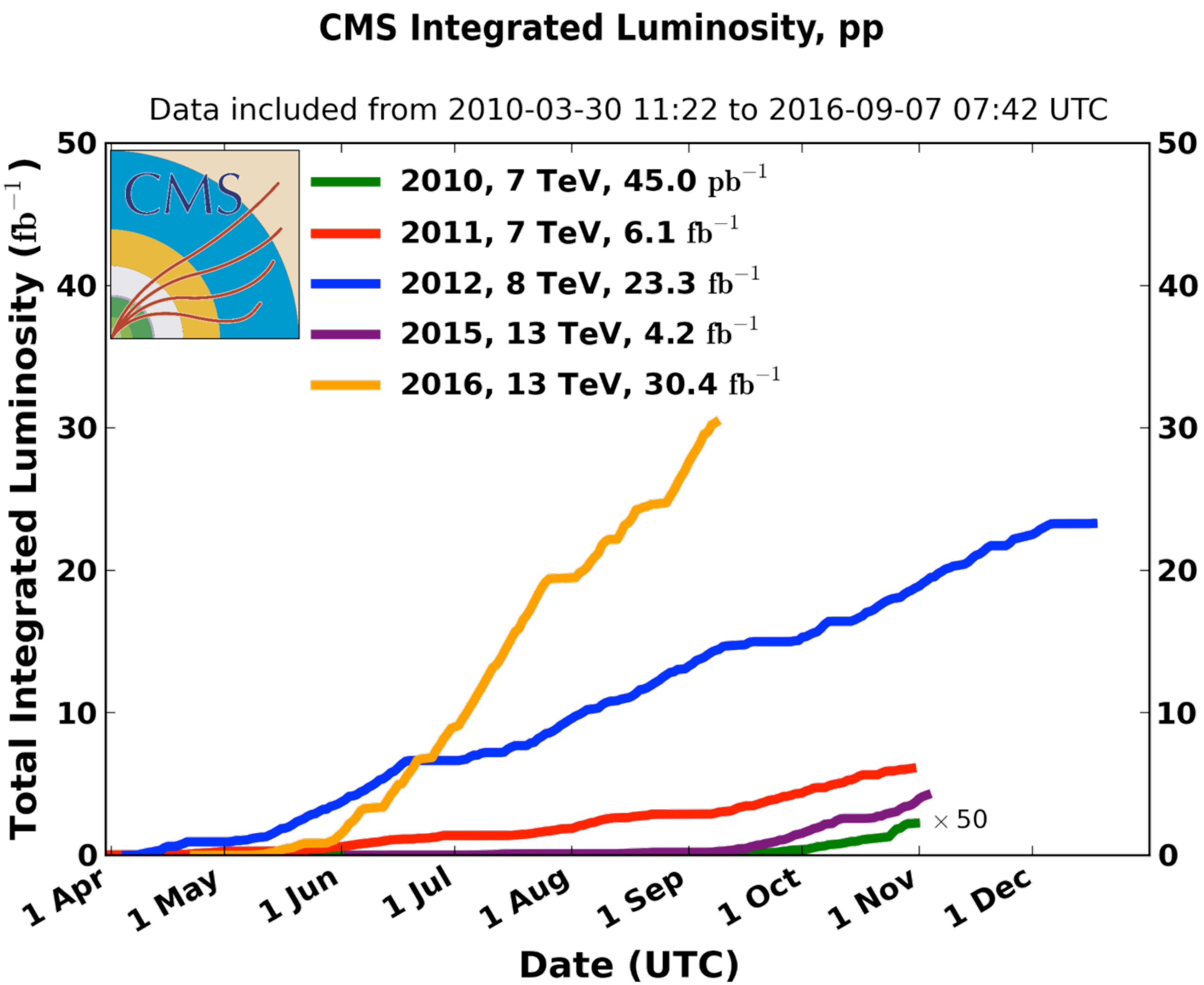
André David (CERN)

First, a word from the LHC

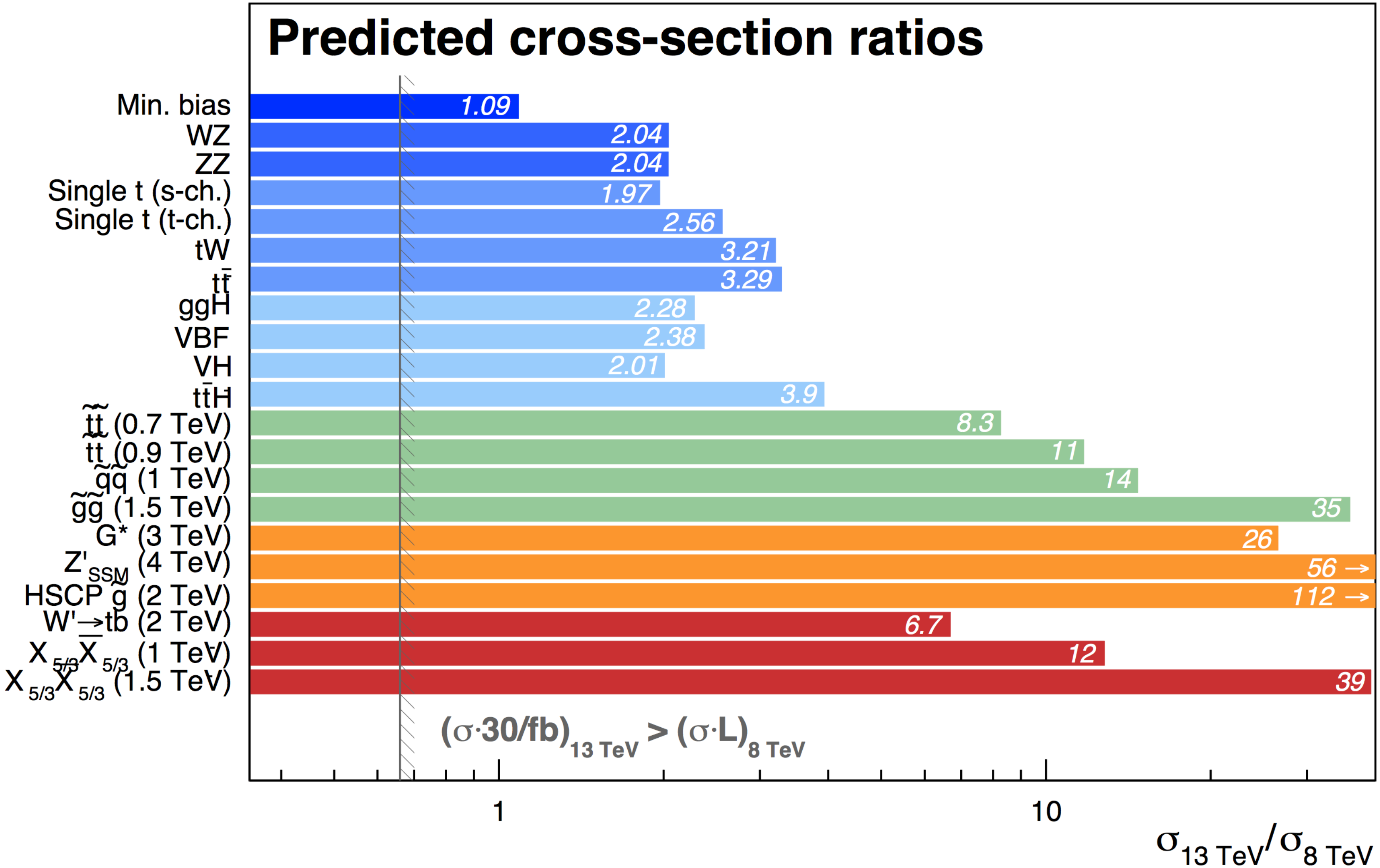


NB: this is with 80% proton bunch occupancy

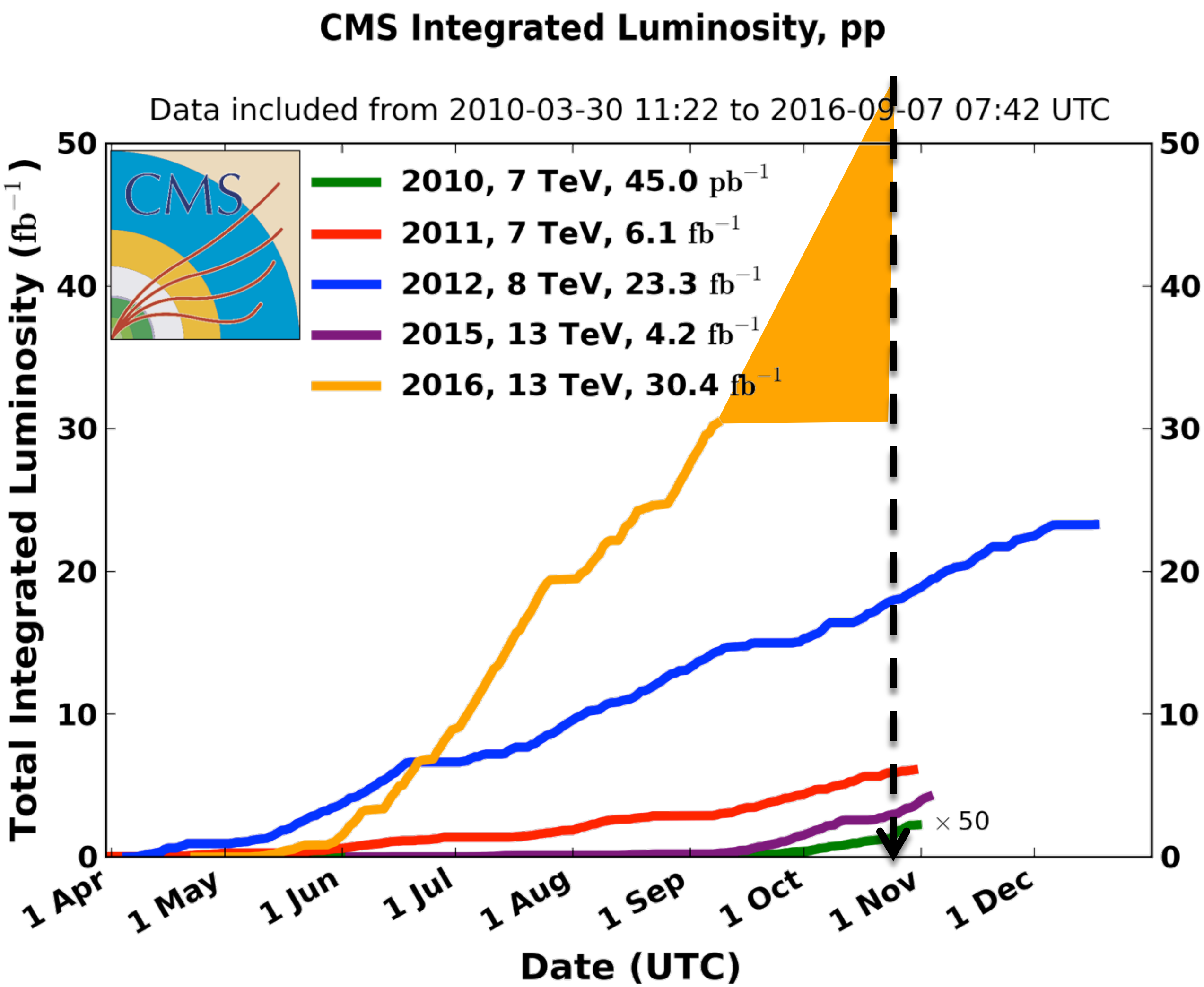
#MoarData


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:22 to 2016-09-07 07:42 UTC
CMS
2010, 7 TeV, 45.0 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
2015, 13 TeV, 4.2 fb⁻¹
2016, 13 TeV, 30.4 fb⁻¹
× 50
Total Integrated Luminosity (fb⁻¹)
0
10
20
30
40
50
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)

The ~~future~~ present is bright



#MoarData



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2010, 7 TeV, 45.0 pb^{-1}
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2016, 13 TeV, 30.4 fb^{-1}
× 50
Total Integrated Luminosity (fb^{-1})
0
10
20
30
40
50
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)

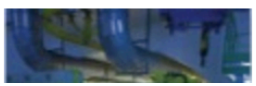
Let's go back a few years

[http://lhc2008.web.cern.ch/LHC2008/nobel/index.html]

CERN home > LHC 2008 > Nobel Expectations

Nobel expectations for new physics at the LHC

Home | LHC First Beam | News | **Events** | What is the LHC? | Nobel Expectations | Sponsors



What do leading figures in particle physics expect from the LHC?

2008 Nobel expectations for the LHC

[http://lhc2008.web.cern.ch/LHC2008/nobel/index.html]

David Gross: "a super world"

I expect new discoveries that will give us clues about the unification of the forces, and maybe solve some of the many mysteries that the Standard Model (SM) leaves open.

I personally expect supersymmetry to be discovered at the LHC; and that enormous discovery, if it happens, will open up a new world – a super world.

2008 Nobel expectations for the LHC

[http://lhc2008.web.cern.ch/LHC2008/nobel/index.html]

George Smoot: "the nature of dark matter”

I am looking forward to hearing about the Higgs, because I’d like to see the Standard Model completed and understood. I’m also hoping that the LHC will begin to unveil extra dimensions, and that will have huge applications across the board.

But what I am really looking forward to **is supersymmetry or something that shows what dark matter is made of**, so I have really high hopes, perhaps too high hopes.

2008 Nobel expectations for the LHC

[http://lhc2008.web.cern.ch/LHC2008/nobel/index.html]

Martinus Veltman: "the unexpected”

What I expect from the LHC? That’s a big problem.

What **I would like to see is the unexpected**. If it gives me what the Standard Model predicted flat out – the Higgs with a low mass – that would be dull. I would like something more exciting than that.

2008 Nobel expectations for the LHC

[http://lhc2008.web.cern.ch/LHC2008/nobel/index.html]

Gerardus 't Hooft: "a Higgs, or more"

The first thing we expect – we hope to see – is the Higgs. I am practically certain that the Higgs exists. My friends here say it is almost certain that if it exists, the LHC will find it.

So we're all prepared and we're very curious because there's little known about the Higgs except some interaction signs.

There could be more than one Higgs, several Higgs, and there could be a composite Higgs, but most of us think it should be an elementary particle…

My real dream is that the Higgs comes up with a set of particles that nobody has yet predicted and doesn't look in any way like the particles that all of us expect today. That would be the nicest of all possibilities. We would then really have work to do to figure out how to interpret those results.

See also arXiv:1609.01725

The good, the bad, and the ugly

The good, the bad, and the ugly

New poles

The good, the bad, and the ugly

Old poles

New poles

The good, the bad, and the ugly

Old poles	New poles	Tails

The good, the bad, and the ugly

Old poles	New poles	Tails
Precision measurements	Searches	

The good, the bad, and the ugly

Old poles	New poles	Tails
Precision measurements	Searches	

The good, the bad, and the ugly

Old poles	New poles	Tails
Precision measurements	Searches	
$Q^2 \sim m_X^2$		$Q^2 \sim s^2$

The good, the bad, and the ugly

New poles

Searches

$Q^2 \sim m_X^2$

Multi-Higgs Models

- HomePage
- Program
- Contacts & Registration
- Abstract Submission
- Accommodation
- Organizing Committee
- Intl Advisory Committee

2009 edition

2012 edition

2014 edition

edit

Sponsors

CFTP Centro de Física Teórica de Partículas

FCT Fundação para a Ciência e a Tecnologia

View Edit History Print

Main /

Welcome

Given LHC's Run 1, the ATLAS and CMS experiments at CERN could confidently announce the discovery a scalar particle of 125 GeV consistent with the Standard Model Higgs boson. François Englert and Peter W. Higgs have been awarded the Nobel Prize in Physics 2013 for the development of the symmetry breaking mechanism and its signature particle.

But there is no fundamental reason why there should be only one Higgs. And Multi-Higgs models open up a wonderful new world:

- the existence of charged scalars;
- mixing between neutral scalar particles;
- CP violation in the scalar sector;
- vacua where charge conservation is broken;
- substantial contributions to flavour-changing neutral currents;
- and the possibility of spontaneous CP violation.

These features become extremely relevant in the search for Higgs particles. Thus, Multi-Higgs models provide a very interesting testing ground for physics beyond the Standard Model in the electroweak symmetry breaking sector.

LHC's Run 2 is scrutinizing the properties of the 125 GeV scalar to unprecedentend precision and probing whether there is indeed only one Higgs scalar or, perhaps, more. Indeed, in December 2015 ATLAS and CMS announced tantalizing signals of a second scalar resonance around 750 GeV.

This Workshop brings together those interested in the theory and phenomenology of Multi-Higgs

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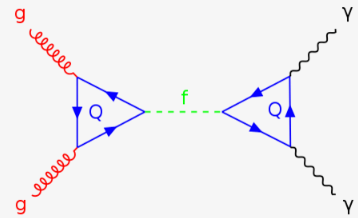
750 GeV diphoton excess

From Wikipedia, the free encyclopedia

The **750 GeV diphoton excess** in particle physics was an anomaly in data collected at the Large Hadron Collider (LHC) in 2015, which could have been an indication of a new particle or resonance.[8][9] The anomaly was absent in data collected in 2016, suggesting that the diphoton excess was a statistical fluctuation.[1][2] In the interval between the December 2015 and August 2016 results, the anomaly generated considerable interest in the scientific community, including about 500 theoretical studies.[10] The hypothetical particle was denoted by the Greek letter Ϝ (pronounced digamma) in the scientific literature, owing to the decay channel in which the anomaly occurred.[3] The data, however, were always less than five standard deviations (sigma) different from that expected if there was no new particle, and, as such, the anomaly never reached the accepted level of statistical significance required to announce a discovery in particle physics.[11] The digamma was refuted in August 2016 publications.

Digamma



Possible production and decay mechanism of the digamma resonance at LHC.

Composition	Elementary particle
Statistics	suspected bosonic
Status	Refuted; absent in August 2016 data[1][2]
Symbol	Ϝ,[3] Ϝ(750),[4] ϕ,[5] X,[6] η_{zy}[7]
Discovered	Resonance of mass ≈750 GeV decaying into two photons could have been seen by CERN in 2015[8][9] (though sufficient statistical significance never reached)
Mass	≈ 750 GeV/c^2 (CMS + ATLAS)[8][9]
Decay width	< 50 GeV/c^2[8][9]
Decays into	two photons (hinted in 2015 data;[8][9] absent in 2016 data[1][2]) two Z-bosons (predicted) one photon + one Z-boson (predicted) two W bosons (predicted) two gluons (predicted)

December 2015 data [edit]

On December 15, 2015, the ATLAS and CMS collaborations at CERN presented results from the second operational run of the Large Hadron Collider (LHC) at the center of mass energy of 13 TeV, the highest ever achieved in proton-proton collisions. Among the results, the invariant mass distribution of pairs of high-energy photons produced in the collisions showed an excess of events compared to the Standard Model prediction at around 750 GeV/c^2. The statistical significance of the deviation was reported to be 3.9 and 3.4 standard deviations (locally) respectively for each experiment.

The excess could have been explained by the production of a new particle (the digamma) with a mass of about 750 GeV/c^2 that decayed into two photons. The cross-section at 13 TeV centre of mass energy required to explain the excess, multiplied by the branching fraction into two photons, was estimated to be

$$\sigma(pp \to F) \times \mathrm{Br}(F \to \gamma\gamma) \approx 5\,\mathrm{fb}$$

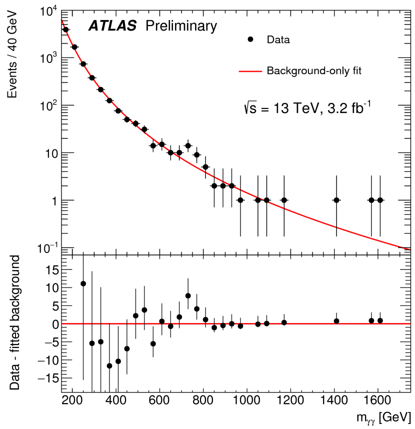
(fb=femtobarns)

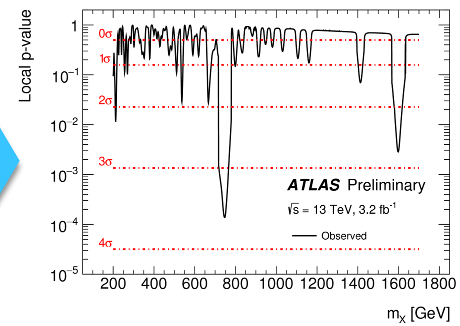
This result, while unexpected, was compatible with previous experiments, and in particular with the LHC measurements at a lower centre of mass energy of 8 TeV.

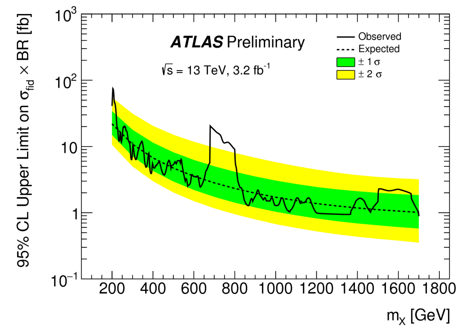
August 2016 data [edit]

Analysis of a larger sample of data, collected by ATLAS and CMS in the first half 2016, did not confirm the existence of the Ϝ particle, which indicates that the excess seen in 2015 was a statistical fluctuation.[1][2]

Diphoton resonances





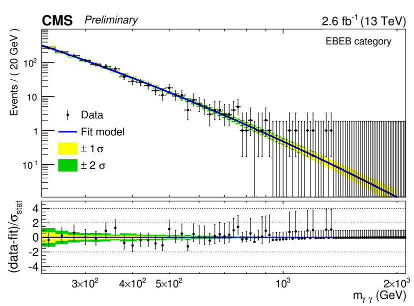


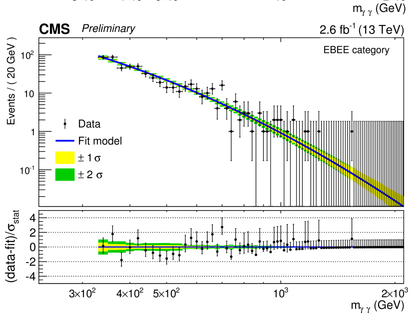
>90% prompt-prompt, $\sigma_m/m \sim 1\%$

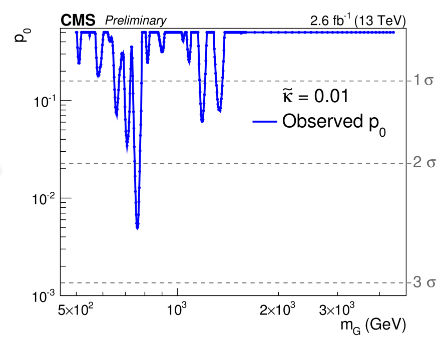
For $m_X = 750$ GeV

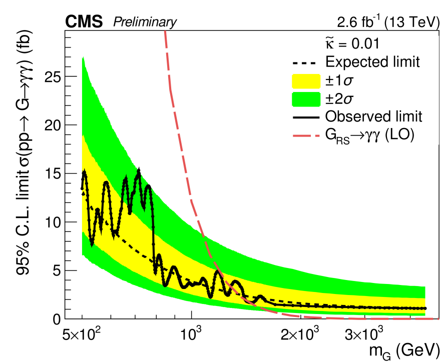
$3.6\sigma \rightarrow$ **2.0σ after LEE**

($3.9\sigma \rightarrow 2.3\sigma$ for $\Gamma = 6\%$)







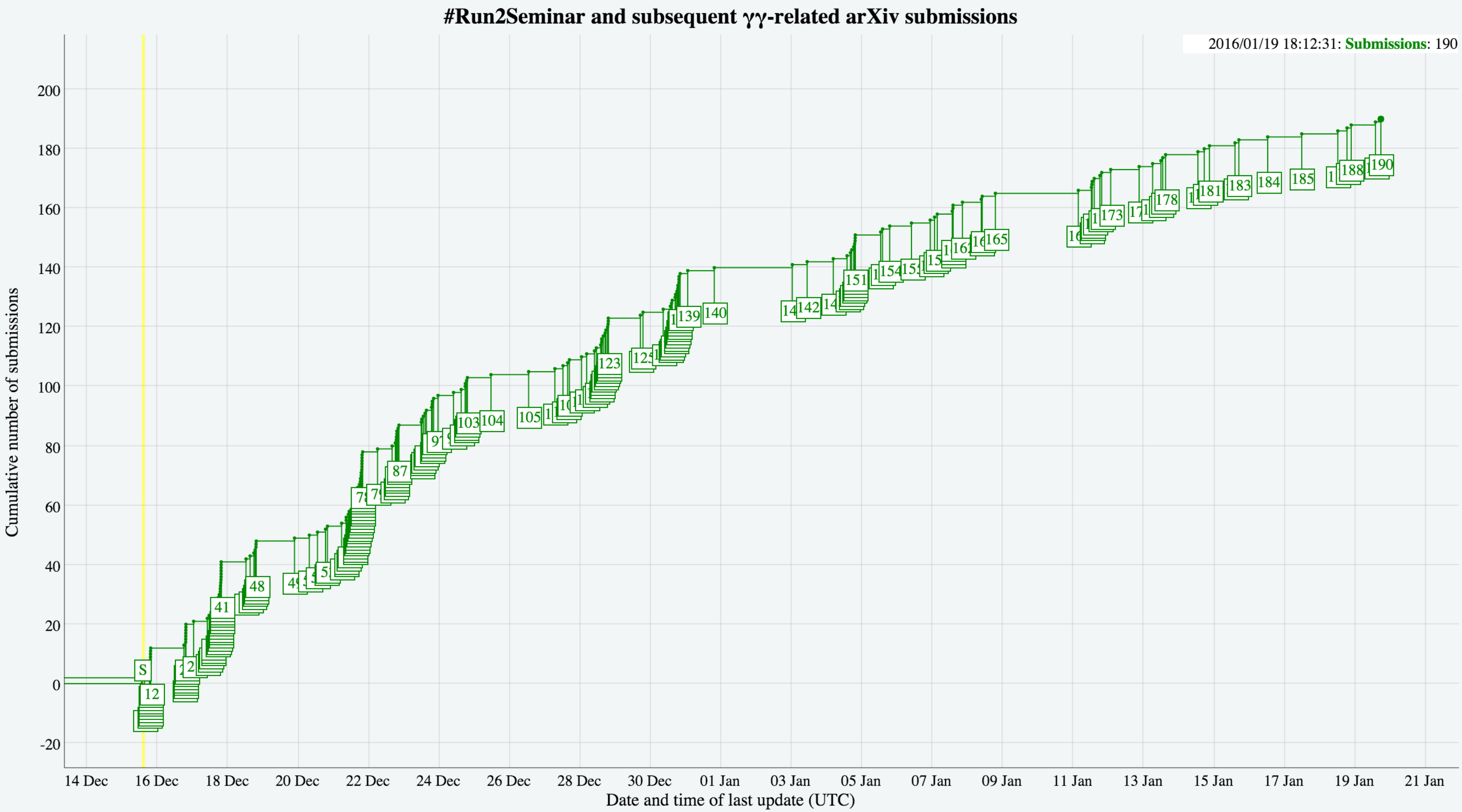


For $m_G = 760$ GeV

$2.6\sigma \rightarrow$ **1.2σ after LEE**

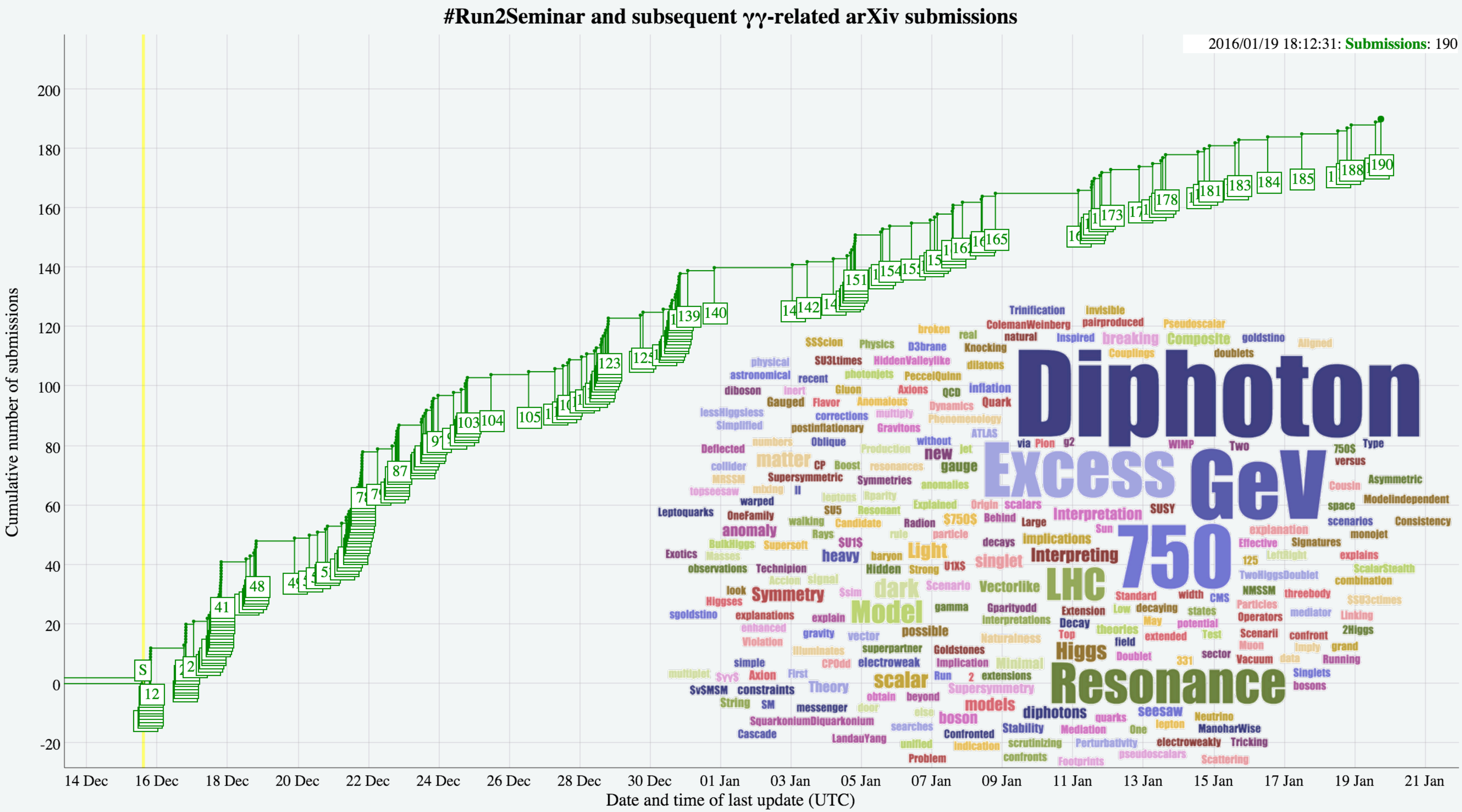
Post-seminar stampede

[http://cern.ch/go/DZt8]



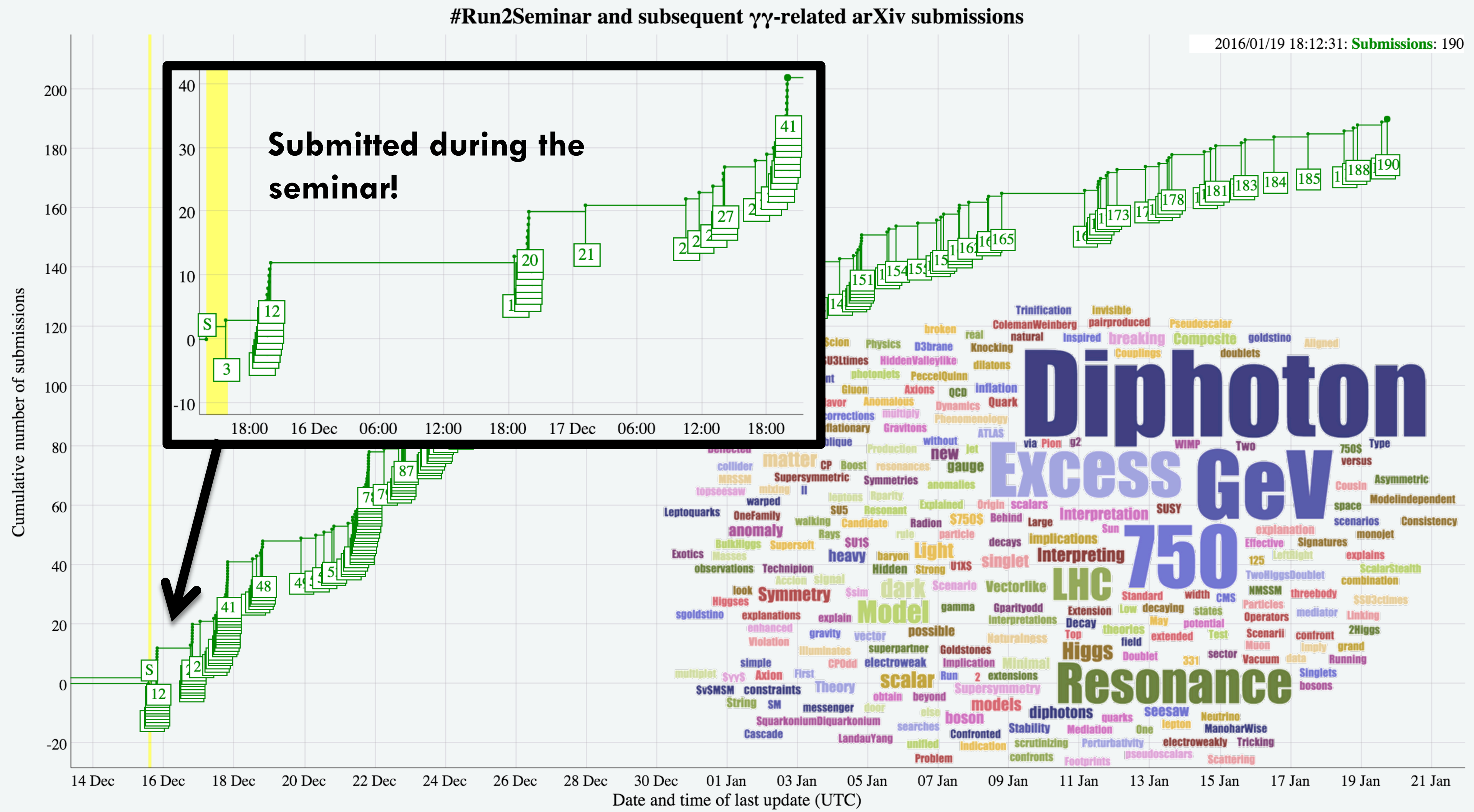
Post-seminar stampede

[http://cern.ch/go/DZt8]



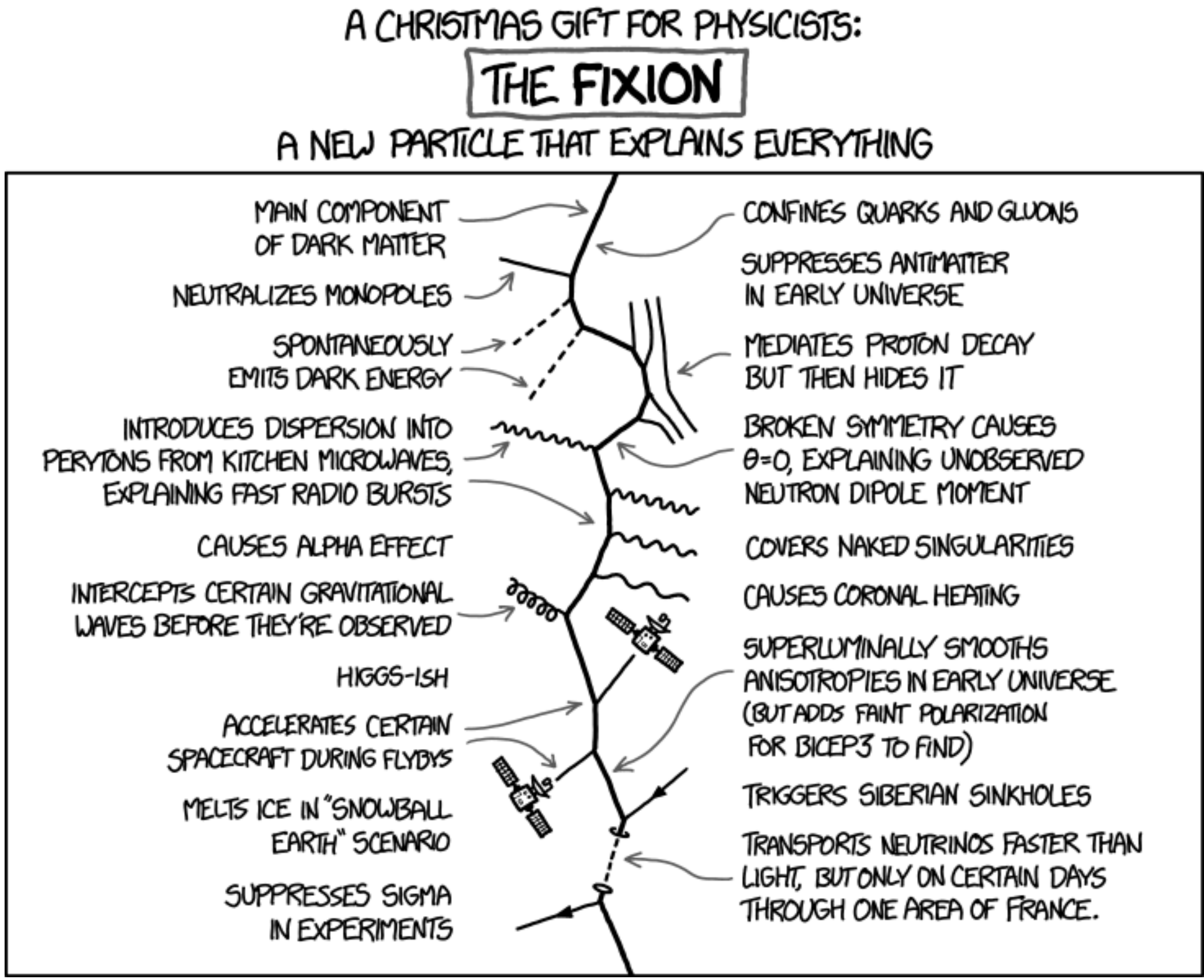
Post-seminar stampede

[http://cern.ch/go/DZt8]

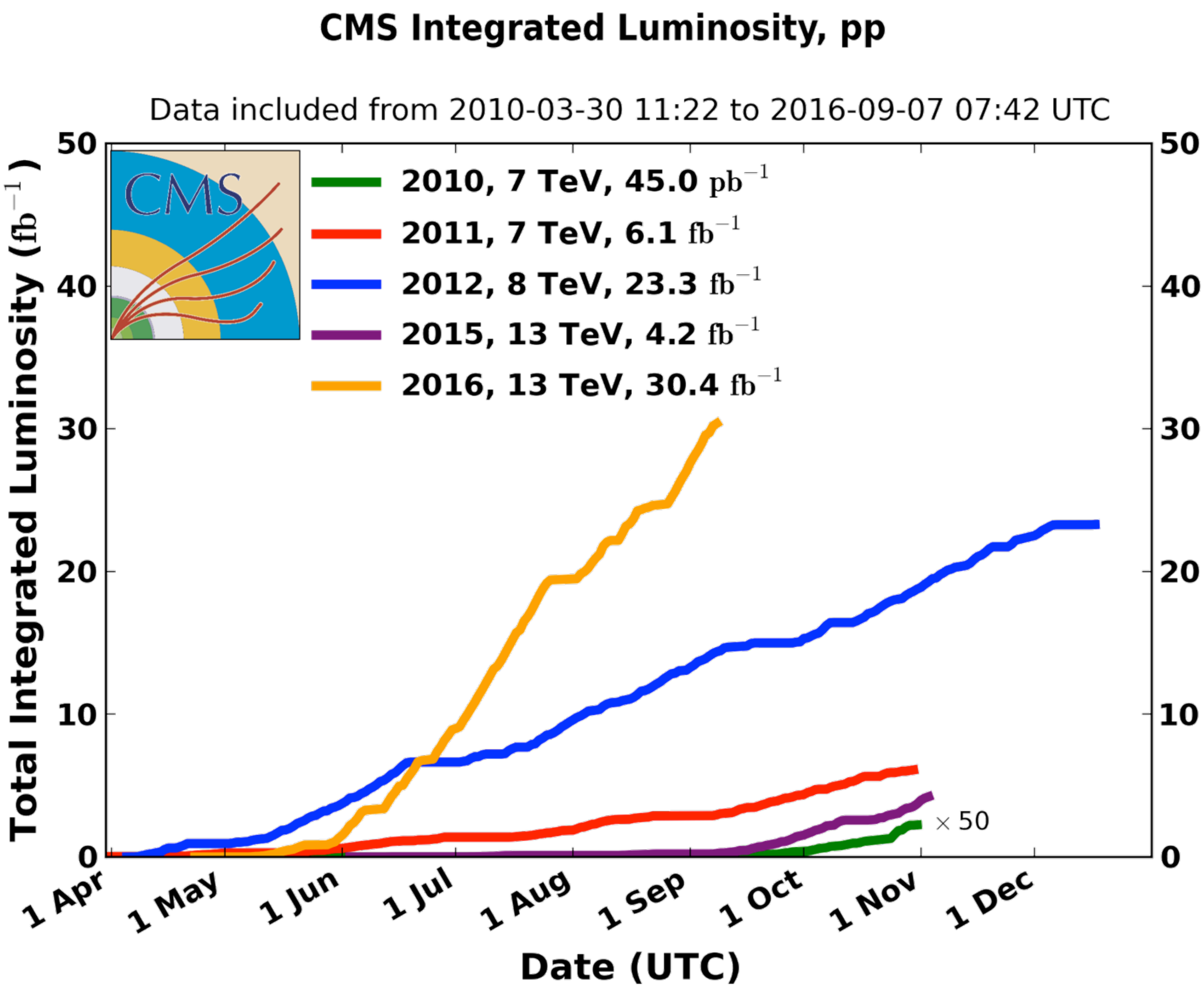


Perhaps a whole fixion sector?

[http://xkcd.com/1621]



#MoarData



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× 50
Total Integrated Luminosity (fb^{-1})
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1 Apr
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1 Jun
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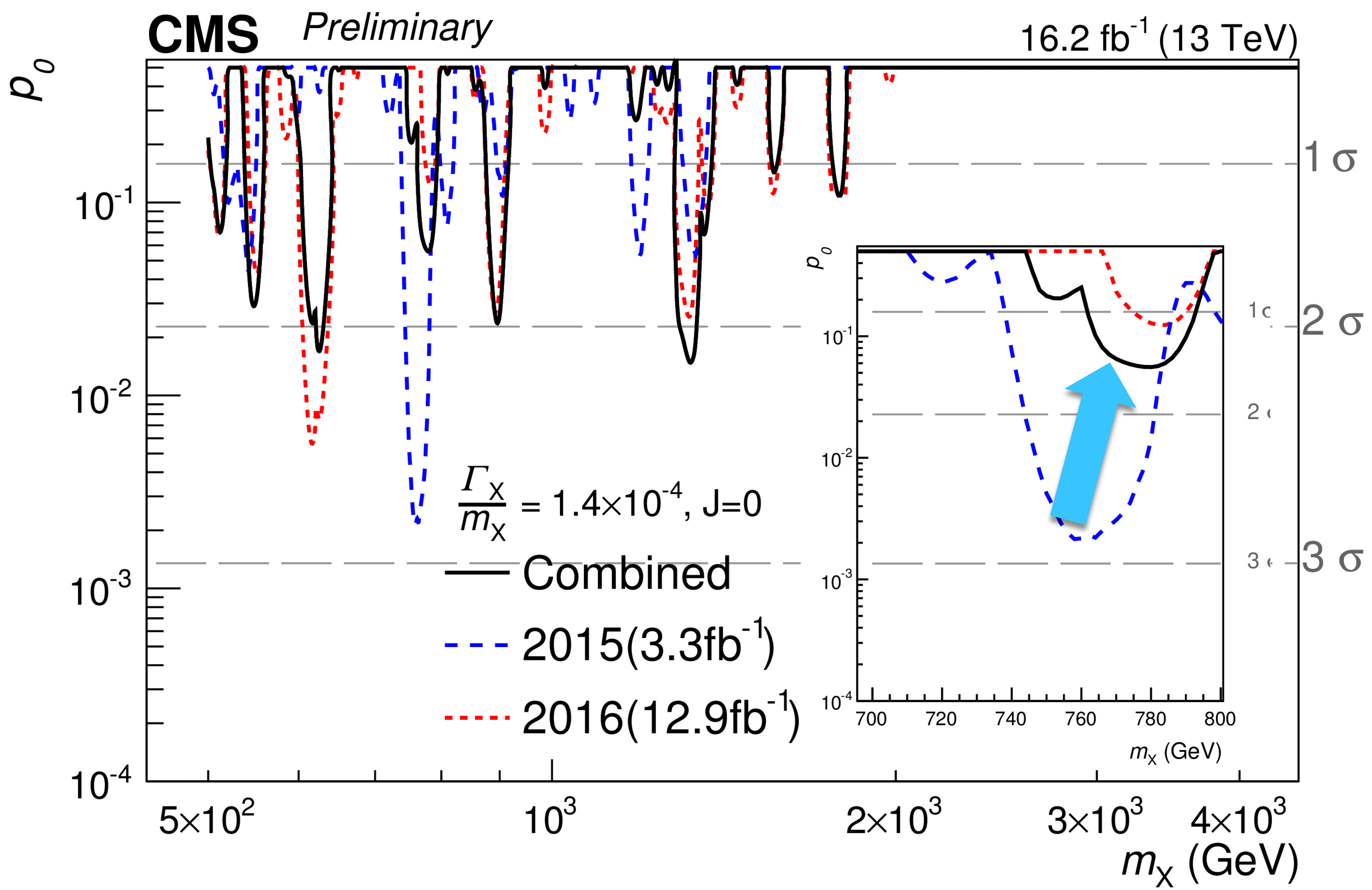
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)

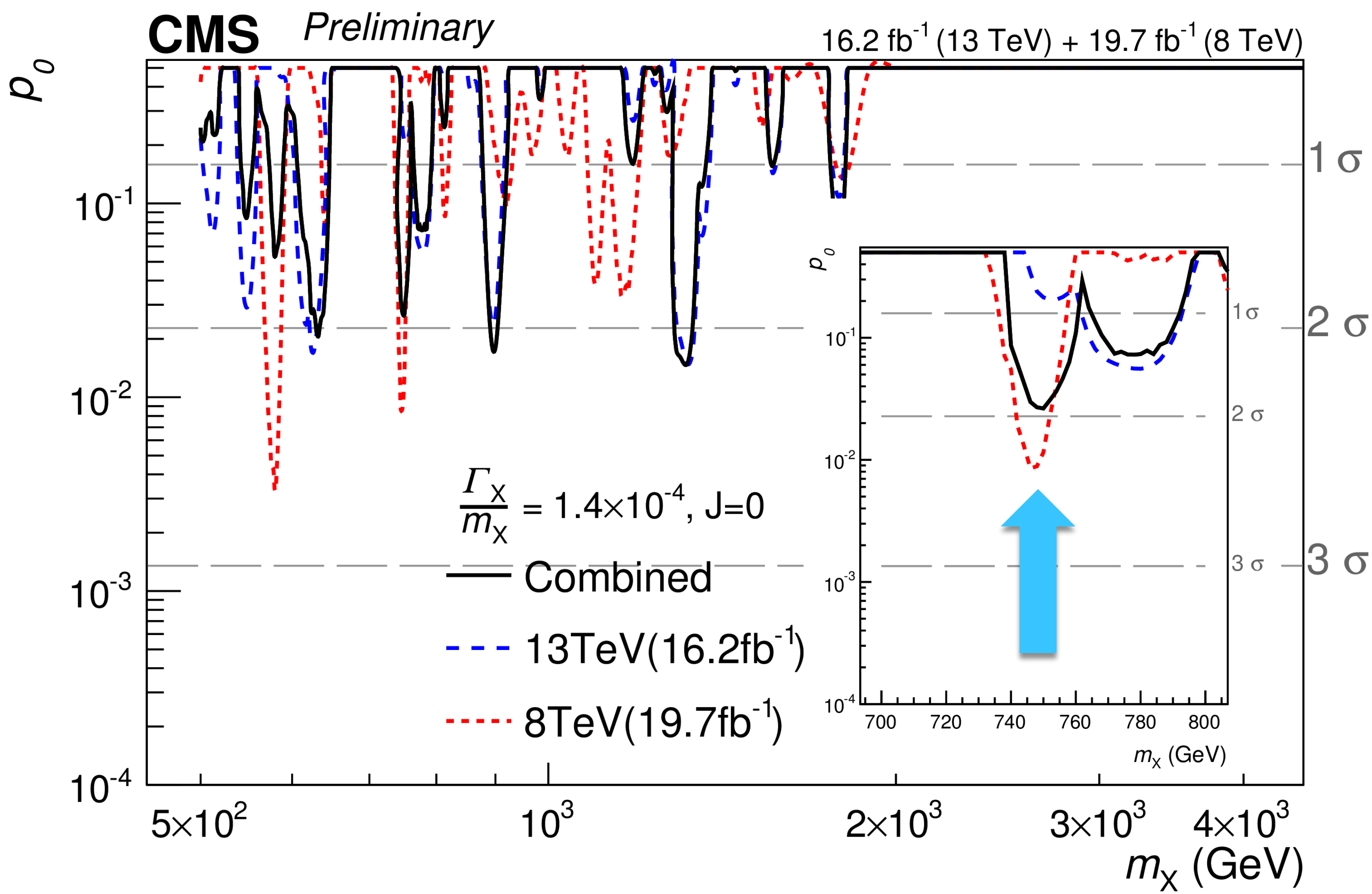
The effect of #MoarData

[CMS-PAS-EXO-16-027]



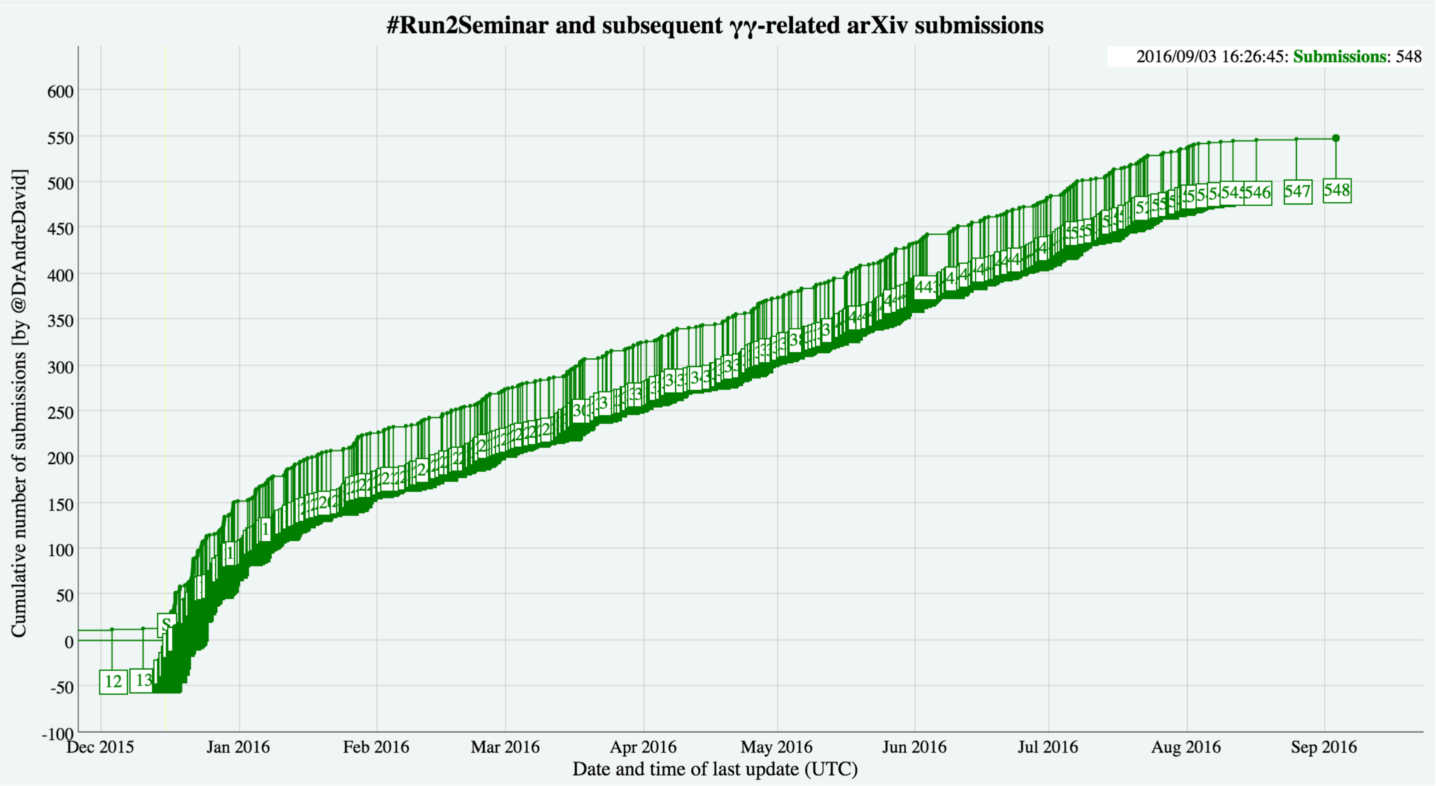
The effect of **even** #MoarData

[CMS-PAS-EXO-16-027]



Stampede no "moar"

[http://cern.ch/go/DZt8]



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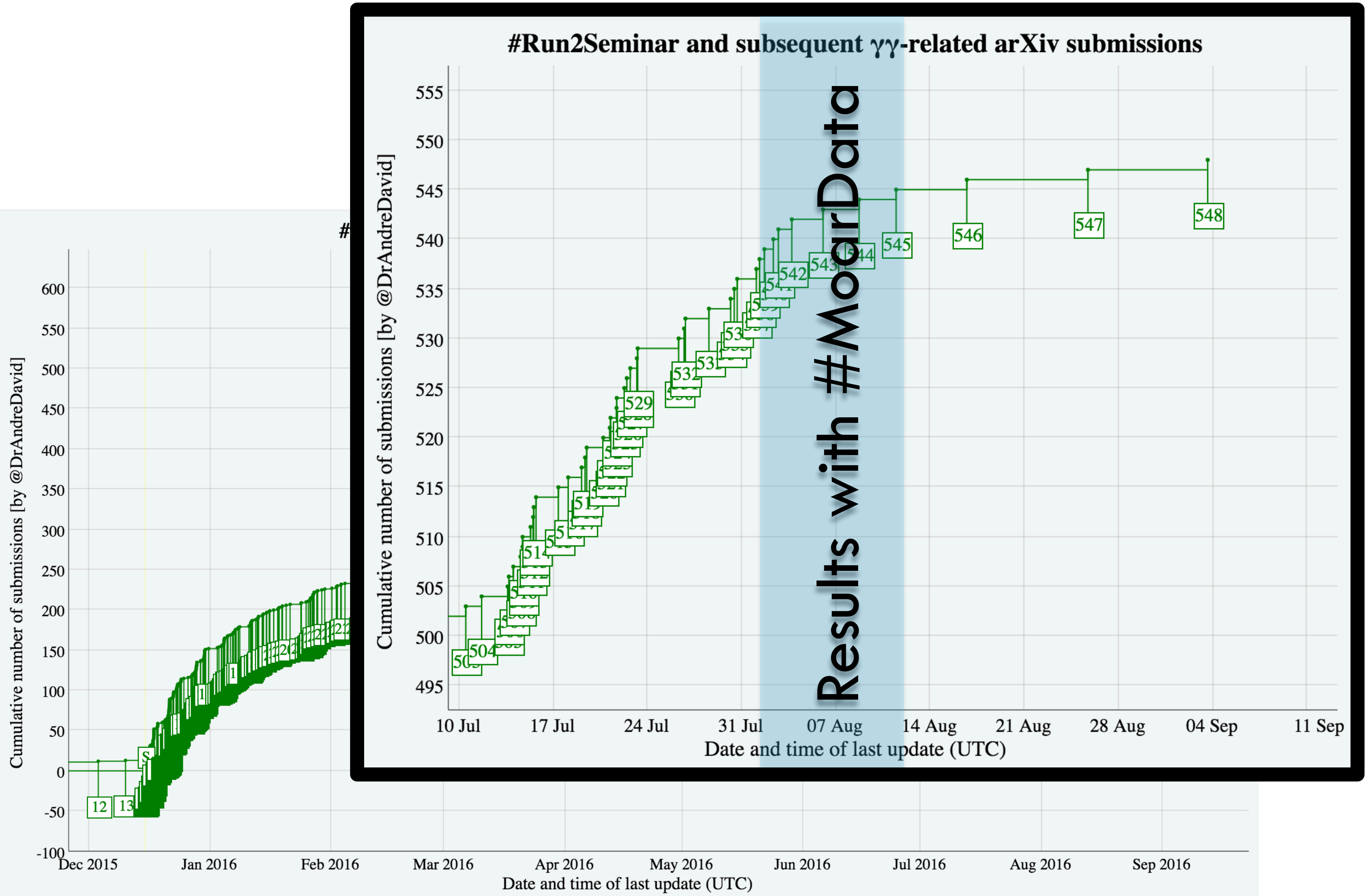

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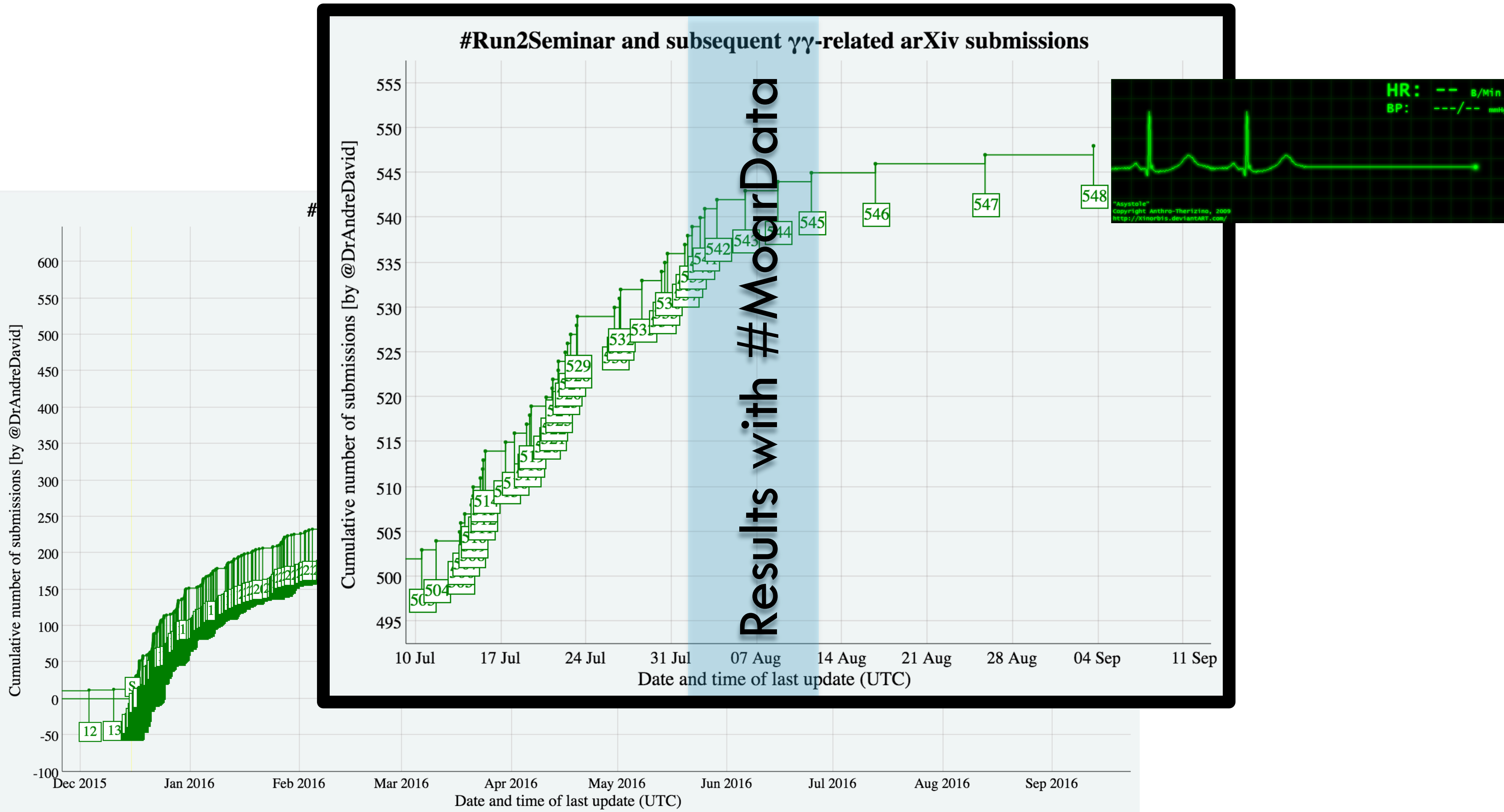


MultiHiggs is all about…

New poles

Searches

$Q^2 \sim m_X^2$

Run 1 summaries

[CMS-PAS-HIG-16-007]

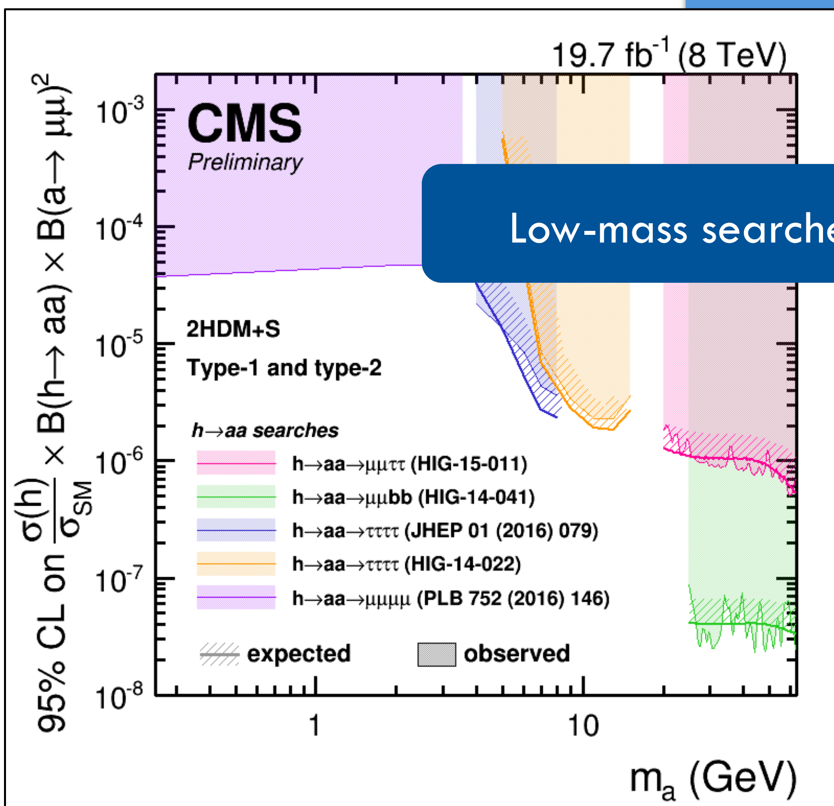
New poles

Low-mass searches

High-mass searches

Run 1 summaries

[CMS-PAS-HIG-16-007]



New poles

Low-mass searches

High-mass searches

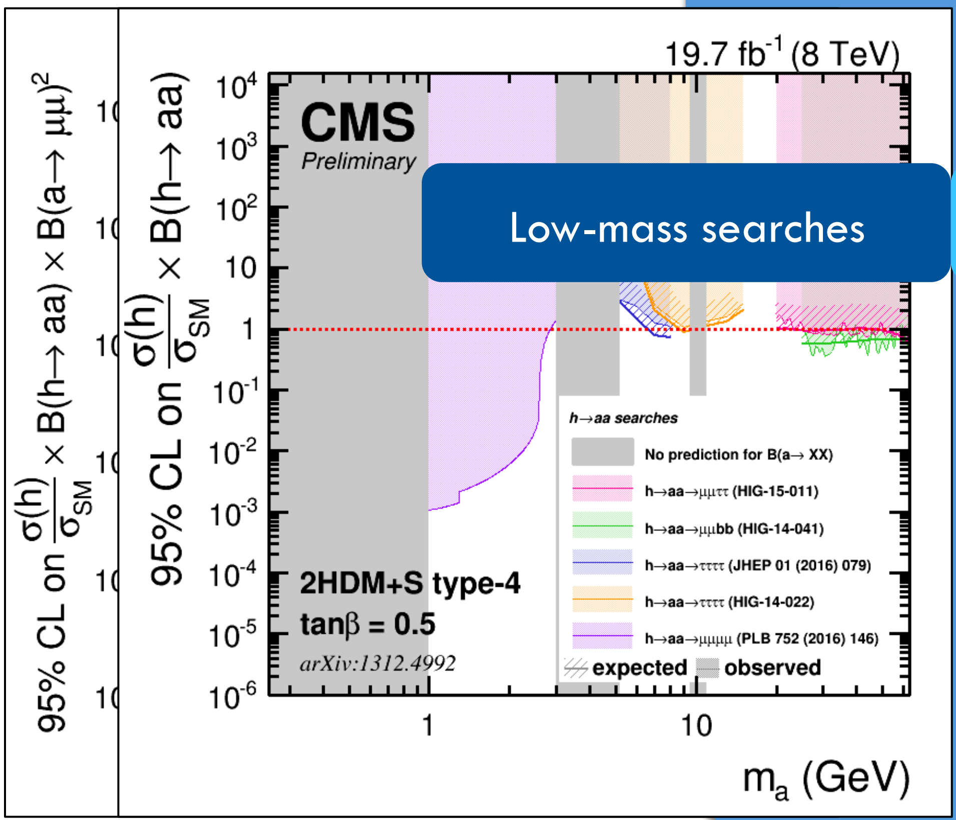
Run 1 summaries

[CMS-PAS-HIG-16-007]

New poles

Low-mass searches

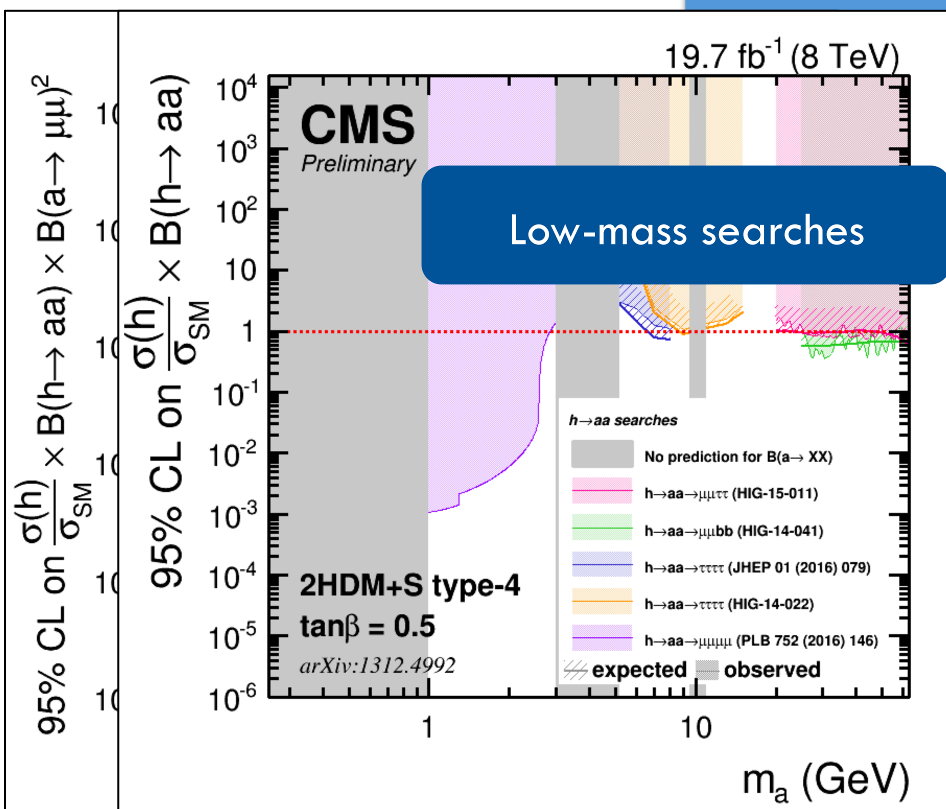
High-mass searches



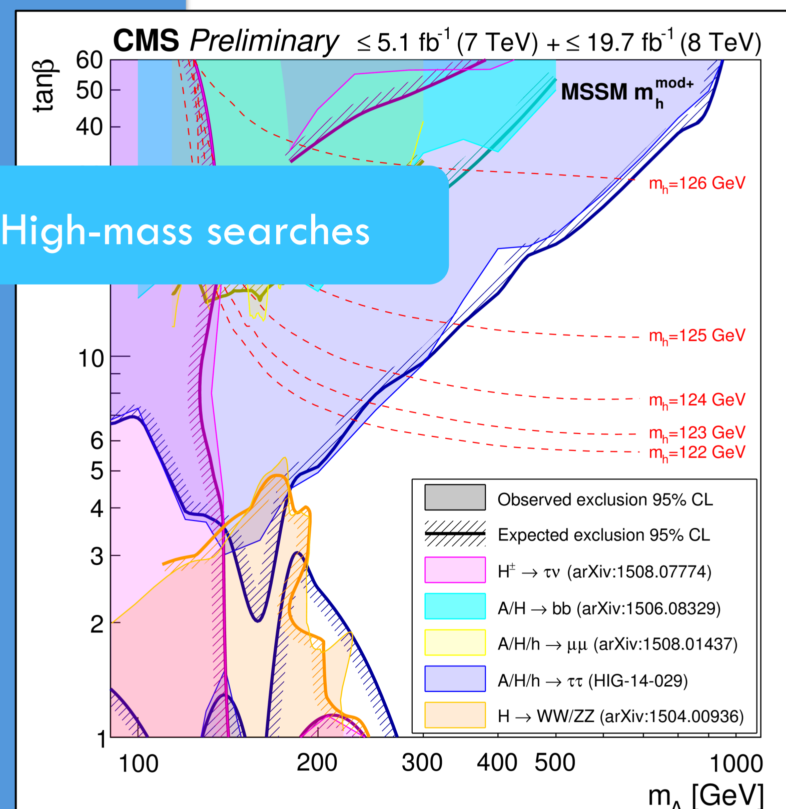
Run 1 summaries

[CMS-PAS-HIG-16-007]

New poles



Low-mass searches

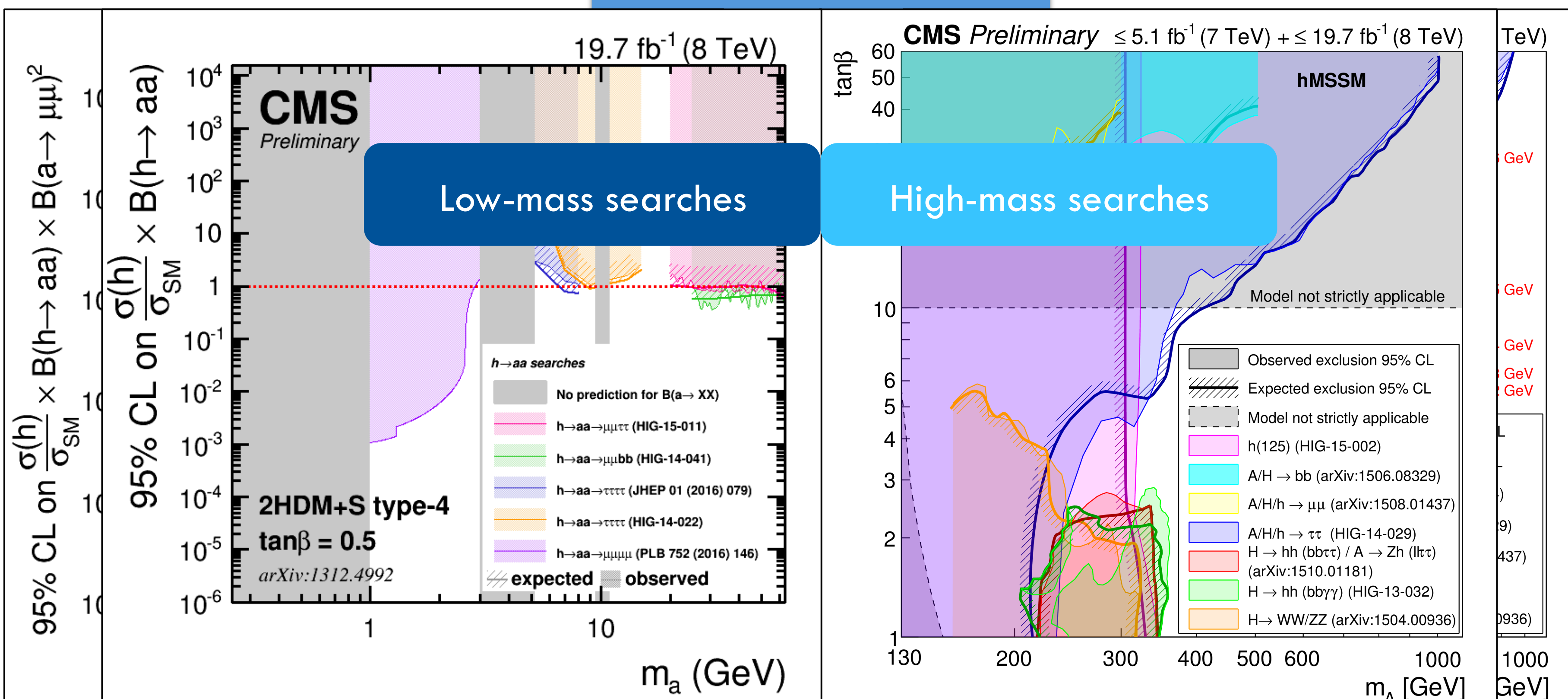


High-mass searches

Run 1 summaries

[CMS-PAS-HIG-16-007]

New poles



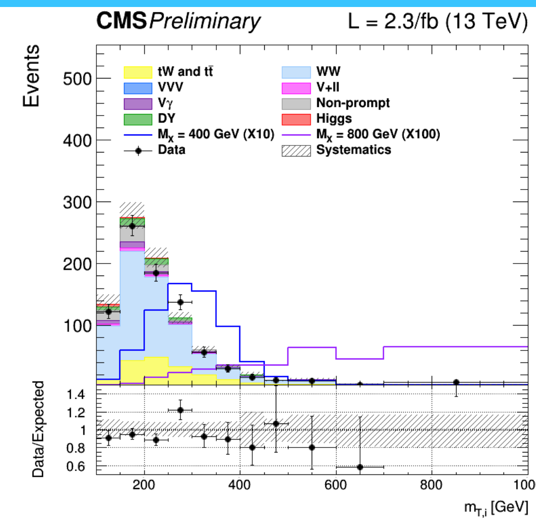
Low-mass searches

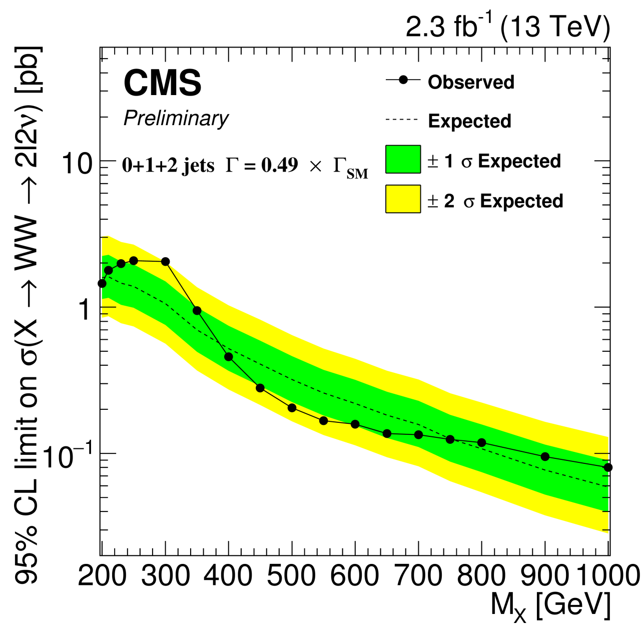
High-mass searches

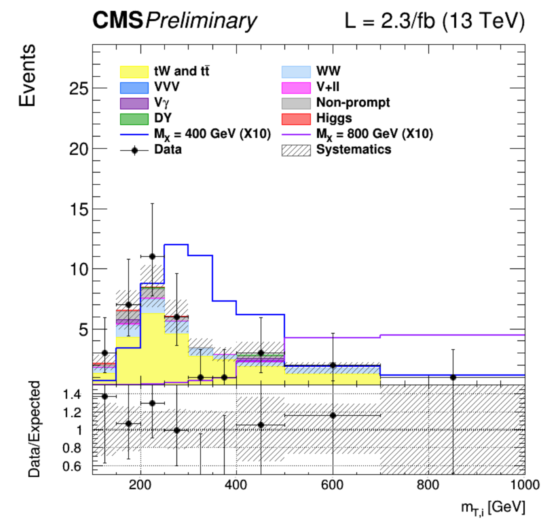
High mass H→WW (2015)

[CMS-PAS-HIG-16-023]

- Signal/gg→WW interference accounted for.
- 0-jet, 1-jet, and 2-jet VBF categories.
- Final discriminant used: m_T.
- Result for different widths.



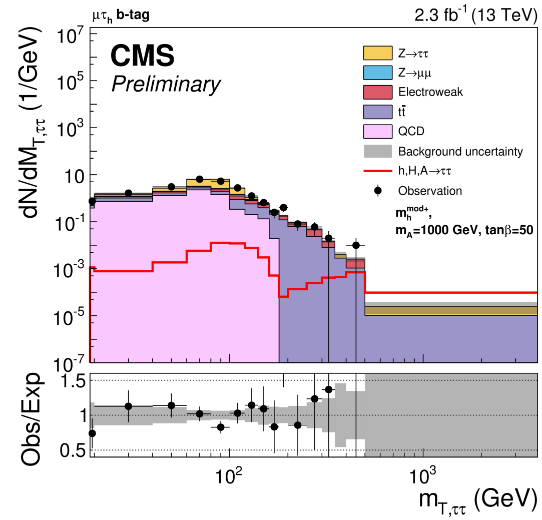


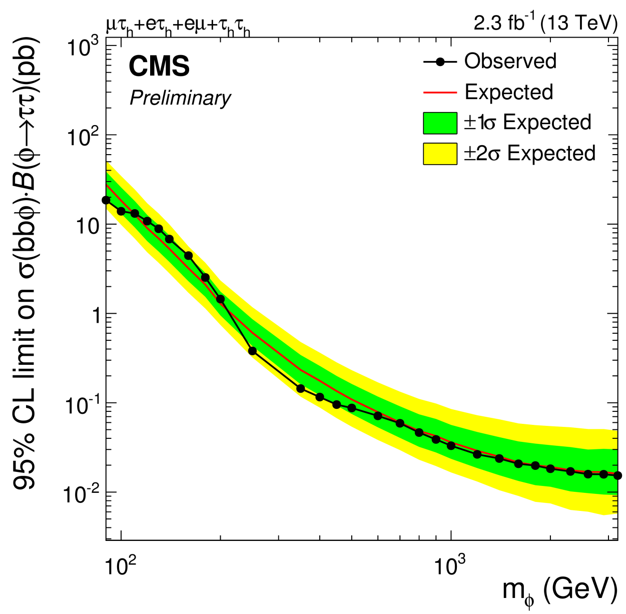


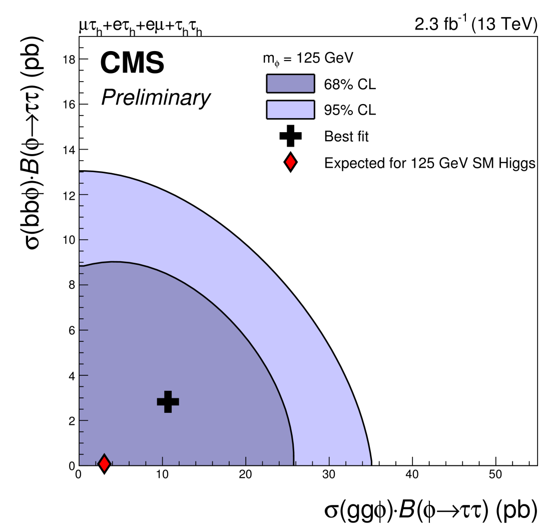
MSSM H→ττ (2015)

[CMS-PAS-HIG-16-006]

- Coupling enhanced for high tan β.
- Different tau decays used.
- Separating ggϕ and bbϕ.



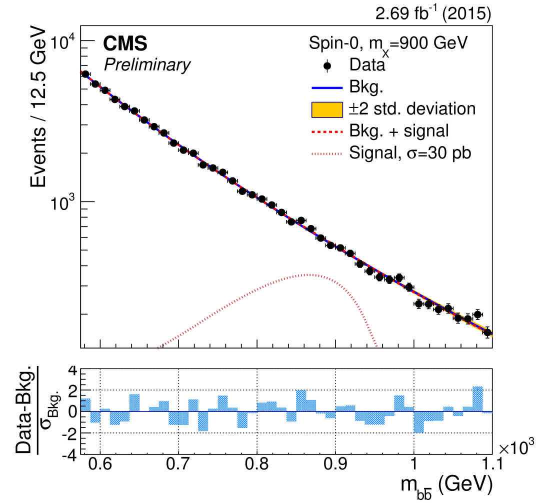


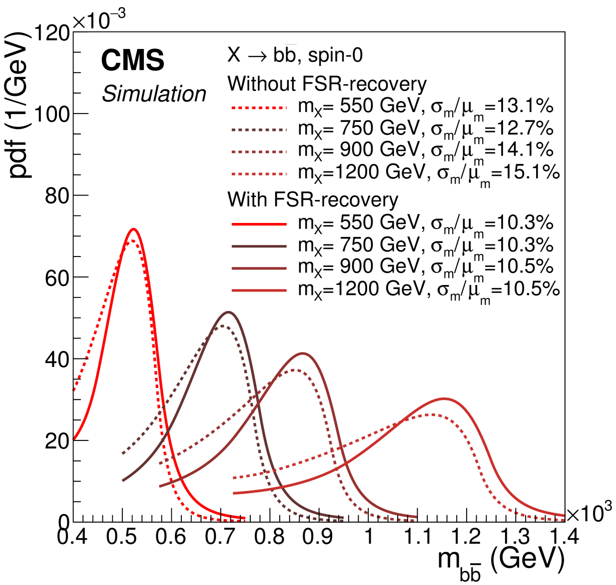


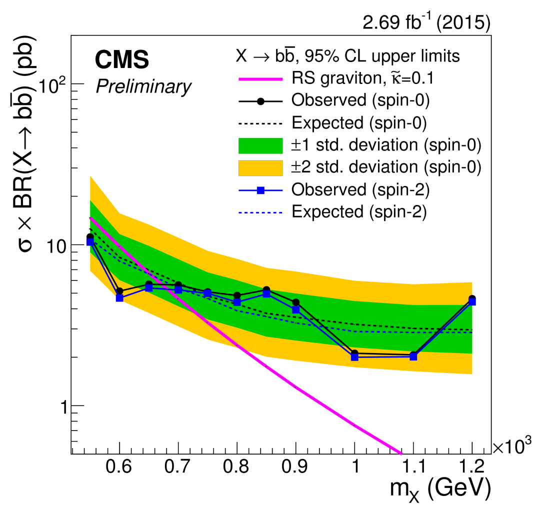
High-mass H→bb (2015)

[CMS-PAS-HIG-16-025]

- Inclusive search.
- Veto events with isolated e, μ, or γ.
- FSR recovery adds jets close to b-jets.
- Mass-fit in window around m_X.



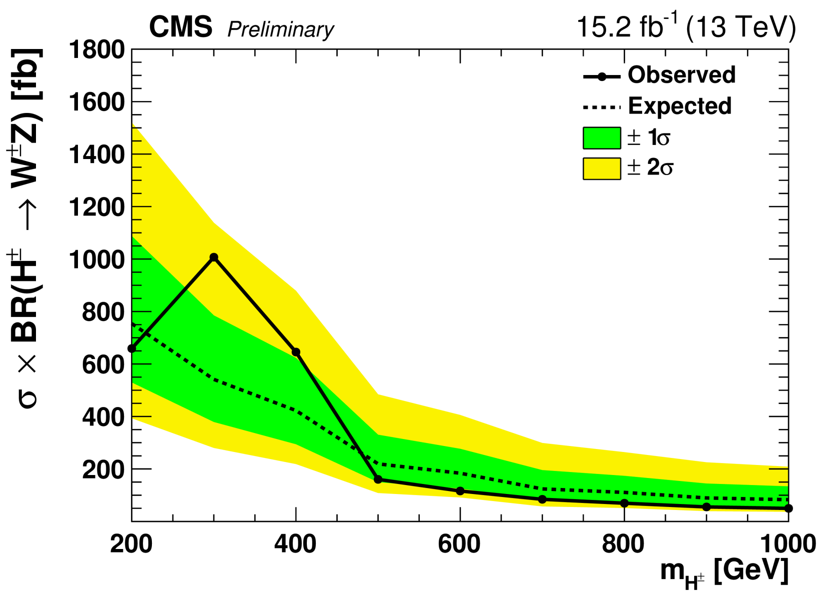


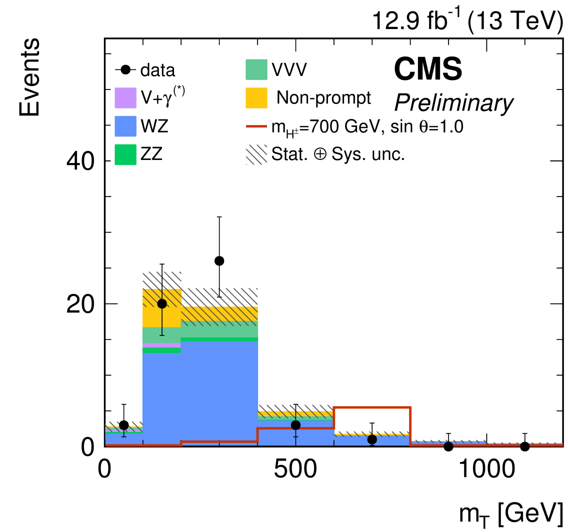


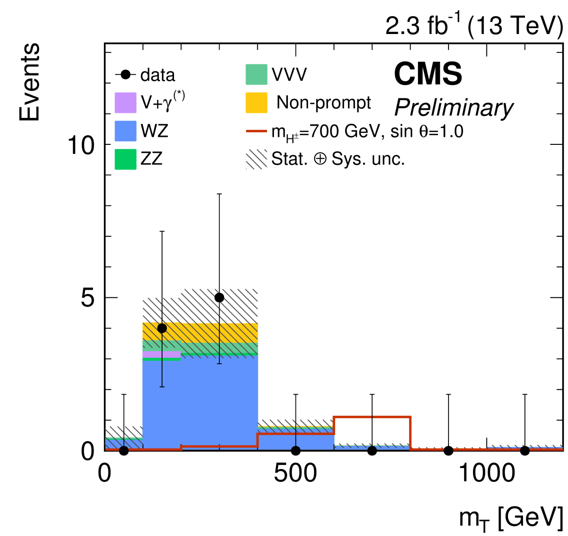
VBF $H^{\pm} \to W^{\pm}Z \to 3\ell\nu$

[CMS-PAS-HIG-16-027]

- Georgi-Machacek Higgs Triplet Models.
- Select WZ events with VBF-like dijet.
- First time done in CMS.

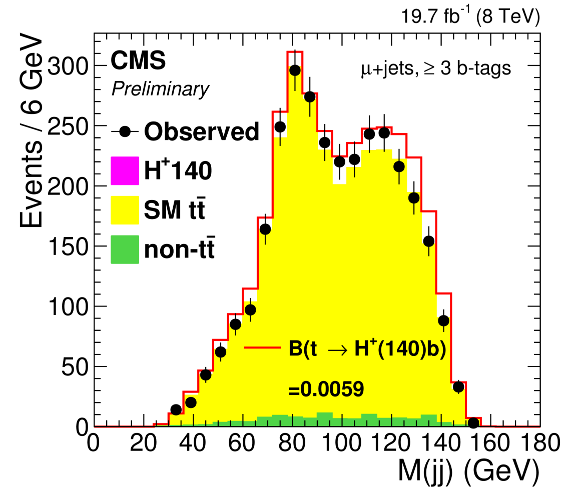


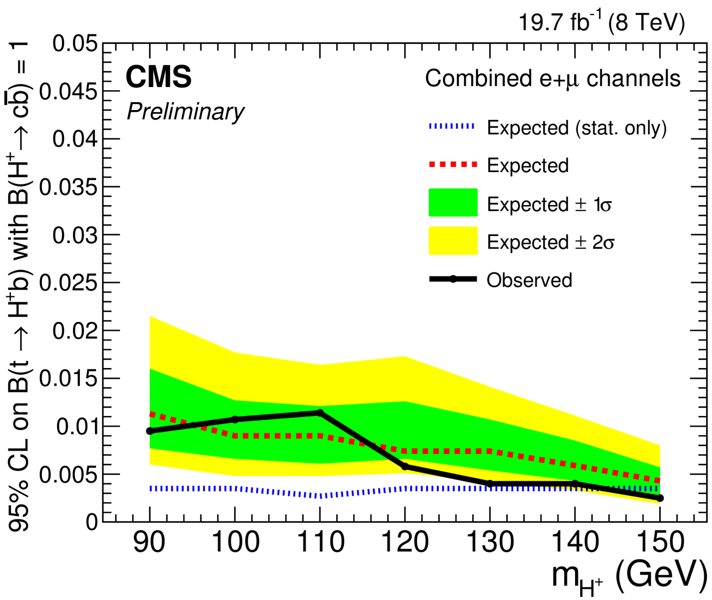


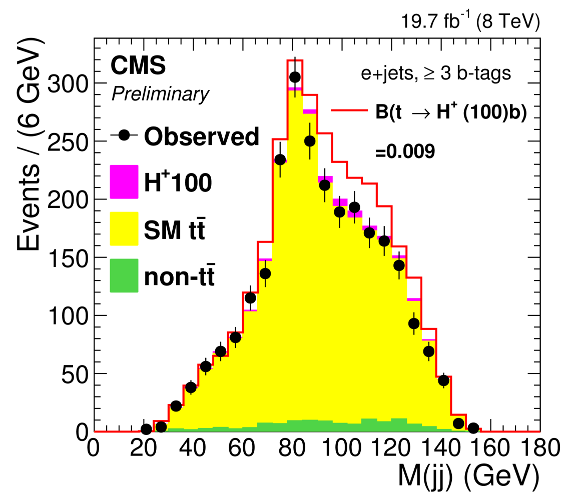


$H^{\pm} \to cb$

- Search $tt \to (H^+b)(W^-b) \to (cbb)(\ell\nu b)$
- Bump hunt.
- Dijet pair selected by kin. fitter from at least four jets in an event.







HH searches

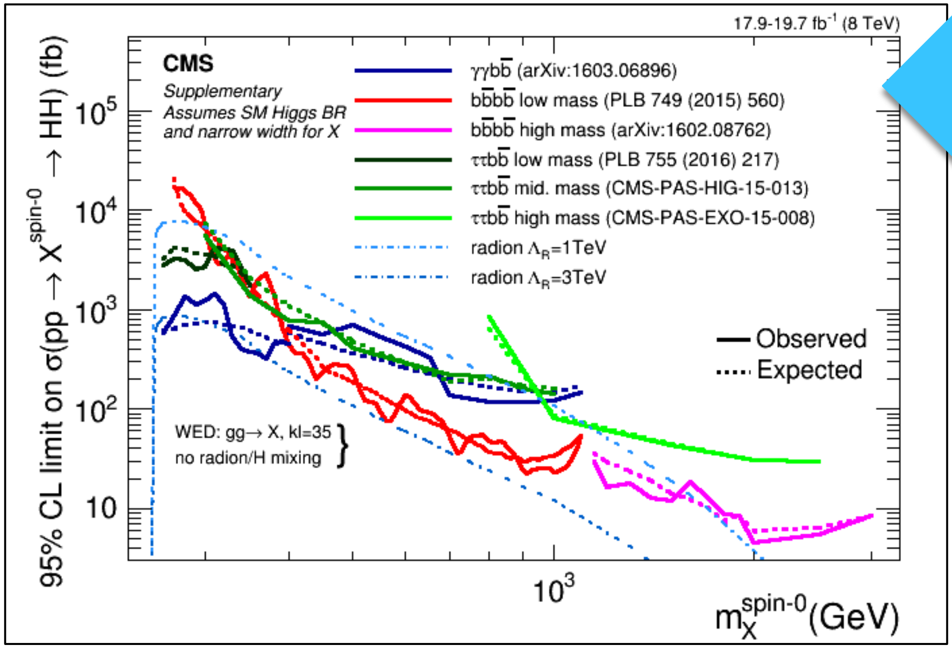
 [CMS-PAS-HIG-16-007]

New poles

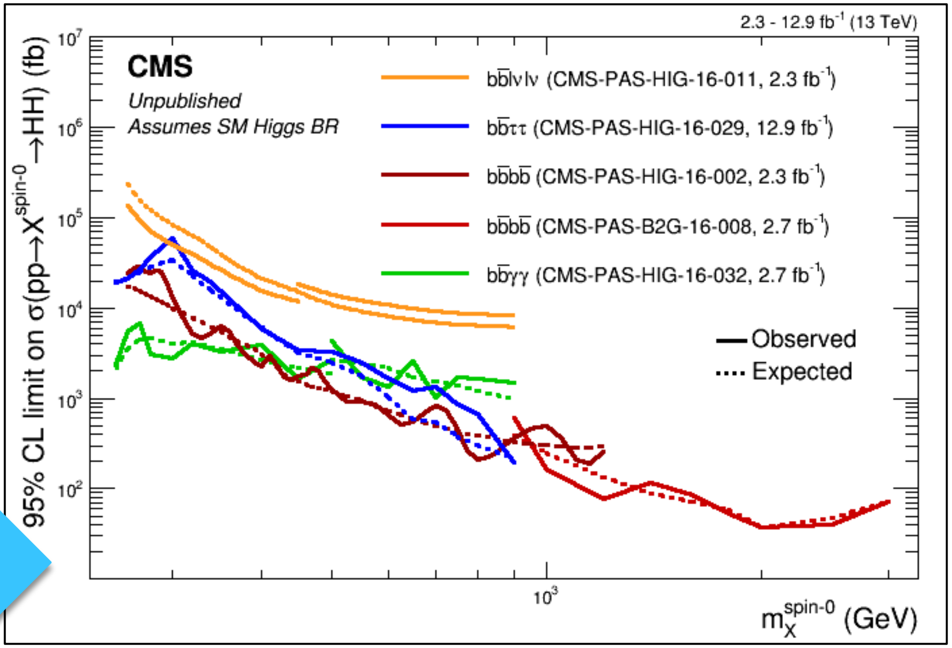
Final state	Resonant 8 TeV	*Non-resonant 8 TeV*	Resonant 13 TeV	*Non-resonant 13 TeV*
bbbb	**HIG-14-013**	-	**HIG-16-002**	*HIG-16-026*
bbWW	-	-	**HIG-16-011**	*HIG-16-024*
bbττ	**HIG-15-013**		**HIG-16-013** **HIG-16-028**	*HIG-16-012* *HIG-16-029*
bbγγ	**HIG-13-032**		**HIG-16-032**	

X→HH search summaries (spin-0)

[CMS-PAS-HIG-16-007]

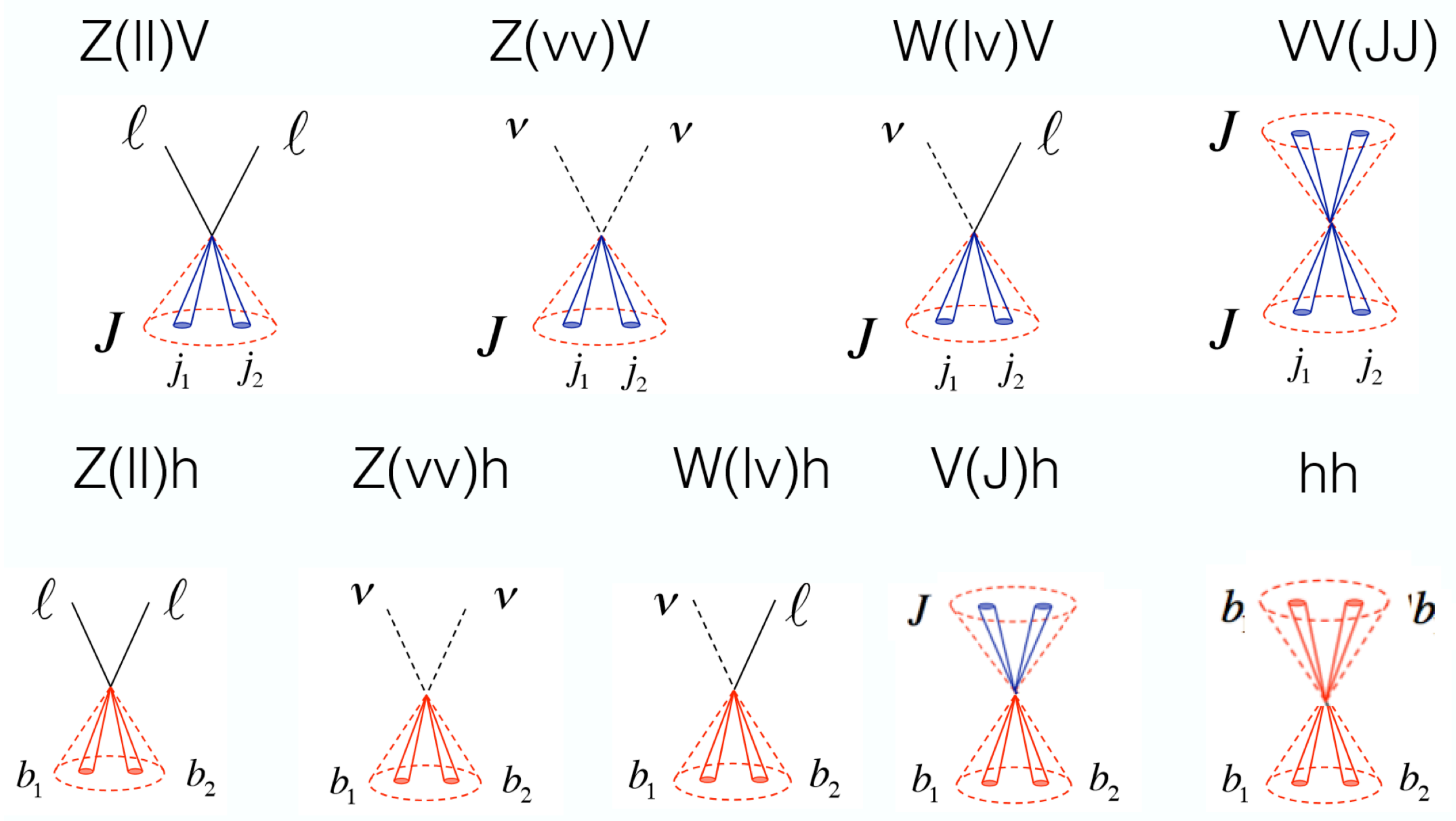


8 TeV



13 TeV

And many more results I cannot cover…



If interested, you can find more (spin-0) results at:

- http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html

The good, the bad, and the ugly

Old poles

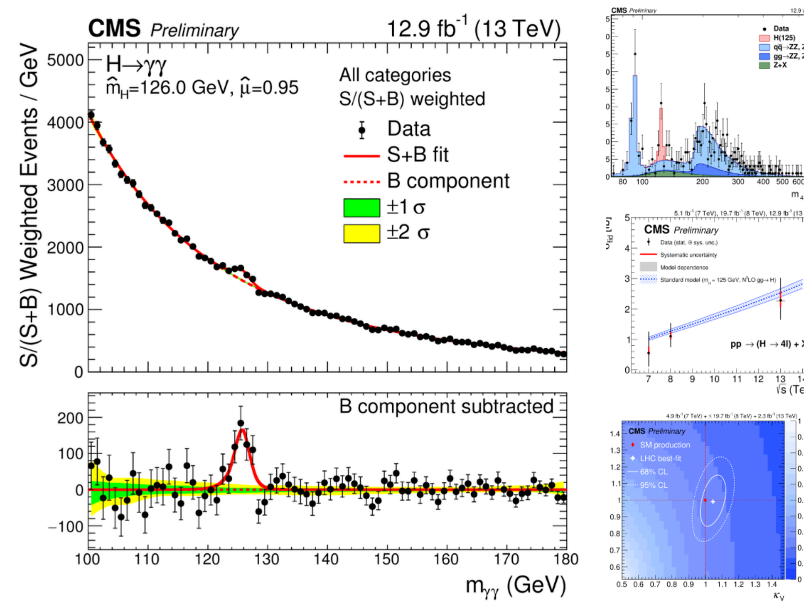
Precision measurements

$Q^2 \sim m_X^2$

Old faithful

André David
@DrAndreDavid

Very proud of the #Higgs #physics results from @CMSexperiment presented at #ICHEP2016!



RETWEETS 8 LIKES 19

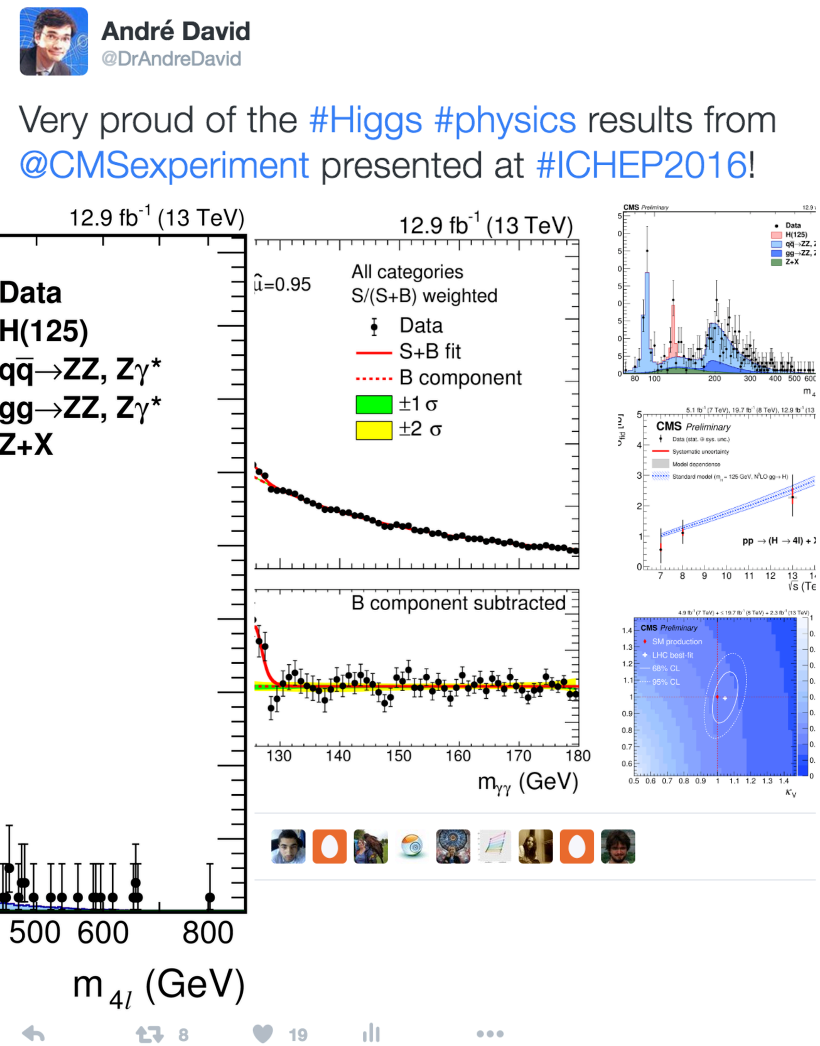
12:43 AM - 6 Aug 2016

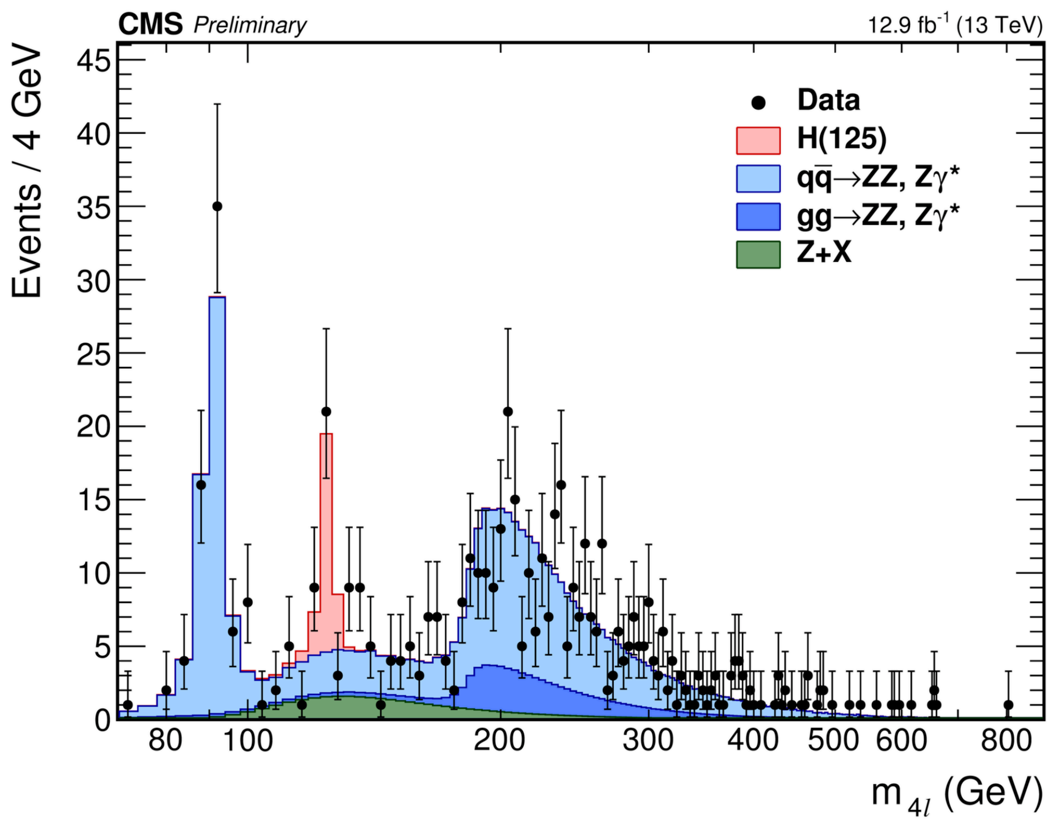
Lisbon, Portugal

CMS Experiment CERN

8 19

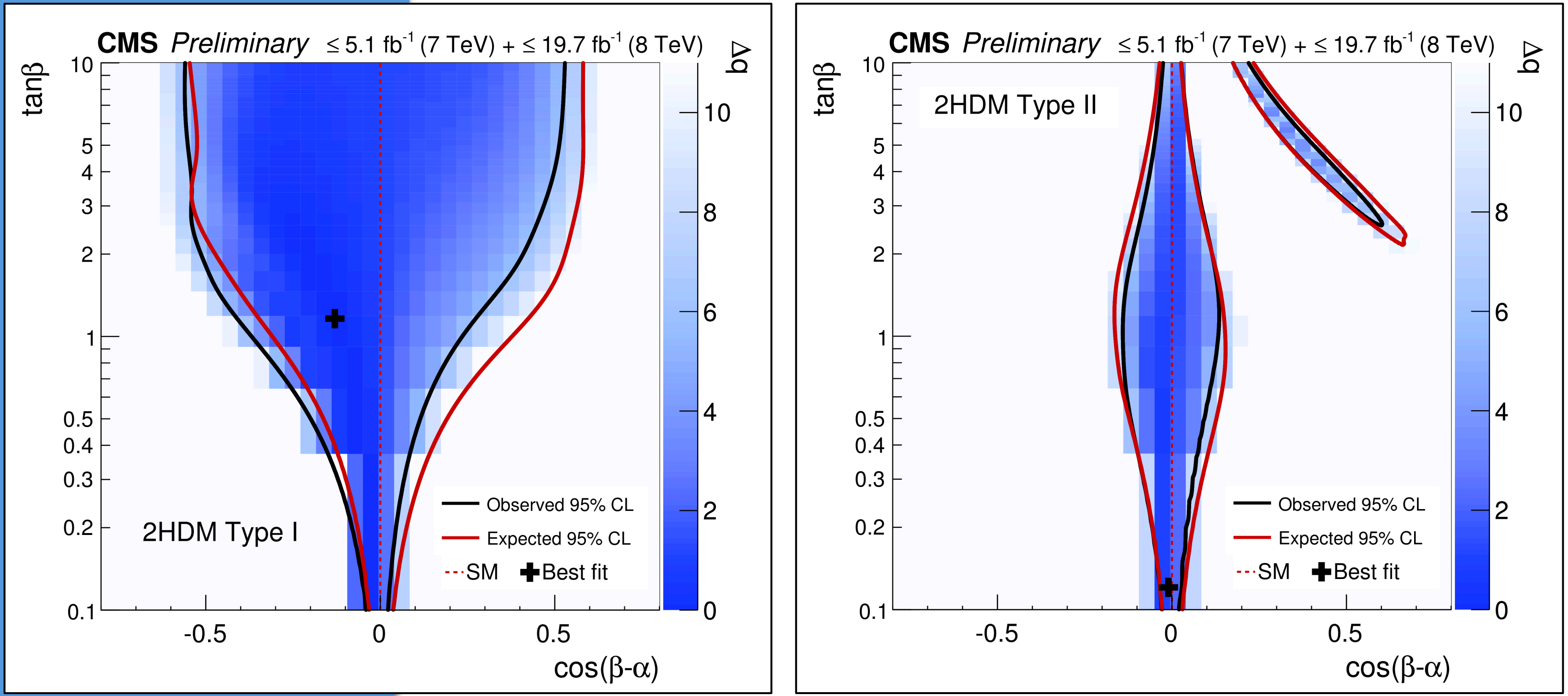
Old faithful





Run 1 2HDM summaries

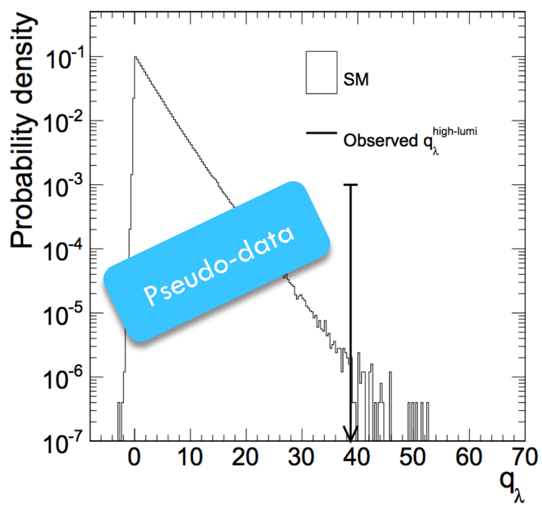
Old poles



Two states at 125 GeV?

[EPJC 75 (2015) 49]

- Treat production×decay as matrix.
  - Single state ⇒ rank 1matrix **(1.)**
- Test single state against completely free values **(2.)**
- Calculate p-value for data under SM hypothesis.



1. A general rank 1 matrix with eight parameters μ_j, λ_{VBF}, λ_{VH}, and λ_{ttH}:

	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to \tau\tau$	$H \to bb$
ggH	$\mu_{\gamma\gamma}$	μ_{WW}	μ_{ZZ}	$\mu_{\tau\tau}$	μ_{bb}
VBF	$\lambda_{\text{VBF}} \cdot \mu_{\gamma\gamma}$	$\lambda_{\text{VBF}} \cdot \mu_{WW}$	$\lambda_{\text{VBF}} \cdot \mu_{ZZ}$	$\lambda_{\text{VBF}} \cdot \mu_{\tau\tau}$	$\lambda_{\text{VBF}} \cdot \mu_{bb}$
VH	$\lambda_{\text{VH}} \cdot \mu_{\gamma\gamma}$	$\lambda_{\text{VH}} \cdot \mu_{WW}$	$\lambda_{\text{VH}} \cdot \mu_{ZZ}$	$\lambda_{\text{VH}} \cdot \mu_{\tau\tau}$	$\lambda_{\text{VH}} \cdot \mu_{bb}$
ttH	$\lambda_{\text{ttH}} \cdot \mu_{\gamma\gamma}$	$\lambda_{\text{ttH}} \cdot \mu_{WW}$	$\lambda_{\text{ttH}} \cdot \mu_{ZZ}$	$\lambda_{\text{ttH}} \cdot \mu_{\tau\tau}$	$\lambda_{\text{ttH}} \cdot \mu_{bb}$

2. The most general 5×4 matrix with twenty parameters μ_j, λ^j_{VBF}, λ^j_{VH}, and λ^j_{ttH}:

	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to \tau\tau$	$H \to bb$
ggH	$\mu_{\gamma\gamma}$	μ_{WW}	μ_{ZZ}	$\mu_{\tau\tau}$	μ_{bb}
VBF	$\lambda^{\gamma\gamma}_{\text{VBF}} \cdot \mu_{\gamma\gamma}$	$\lambda^{WW}_{\text{VBF}} \cdot \mu_{WW}$	$\lambda^{ZZ}_{\text{VBF}} \cdot \mu_{ZZ}$	$\lambda^{\tau\tau}_{\text{VBF}} \cdot \mu_{\tau\tau}$	$\lambda^{bb}_{\text{VBF}} \cdot \mu_{bb}$
VH	$\lambda^{\gamma\gamma}_{\text{VH}} \cdot \mu_{\gamma\gamma}$	$\lambda^{WW}_{\text{VH}} \cdot \mu_{WW}$	$\lambda^{ZZ}_{\text{VH}} \cdot \mu_{ZZ}$	$\lambda^{\tau\tau}_{\text{VH}} \cdot \mu_{\tau\tau}$	$\lambda^{bb}_{\text{VH}} \cdot \mu_{bb}$
ttH	$\lambda^{\gamma\gamma}_{\text{ttH}} \cdot \mu_{\gamma\gamma}$	$\lambda^{WW}_{\text{ttH}} \cdot \mu_{WW}$	$\lambda^{ZZ}_{\text{ttH}} \cdot \mu_{ZZ}$	$\lambda^{\tau\tau}_{\text{ttH}} \cdot \mu_{\tau\tau}$	$\lambda^{bb}_{\text{ttH}} \cdot \mu_{bb}$

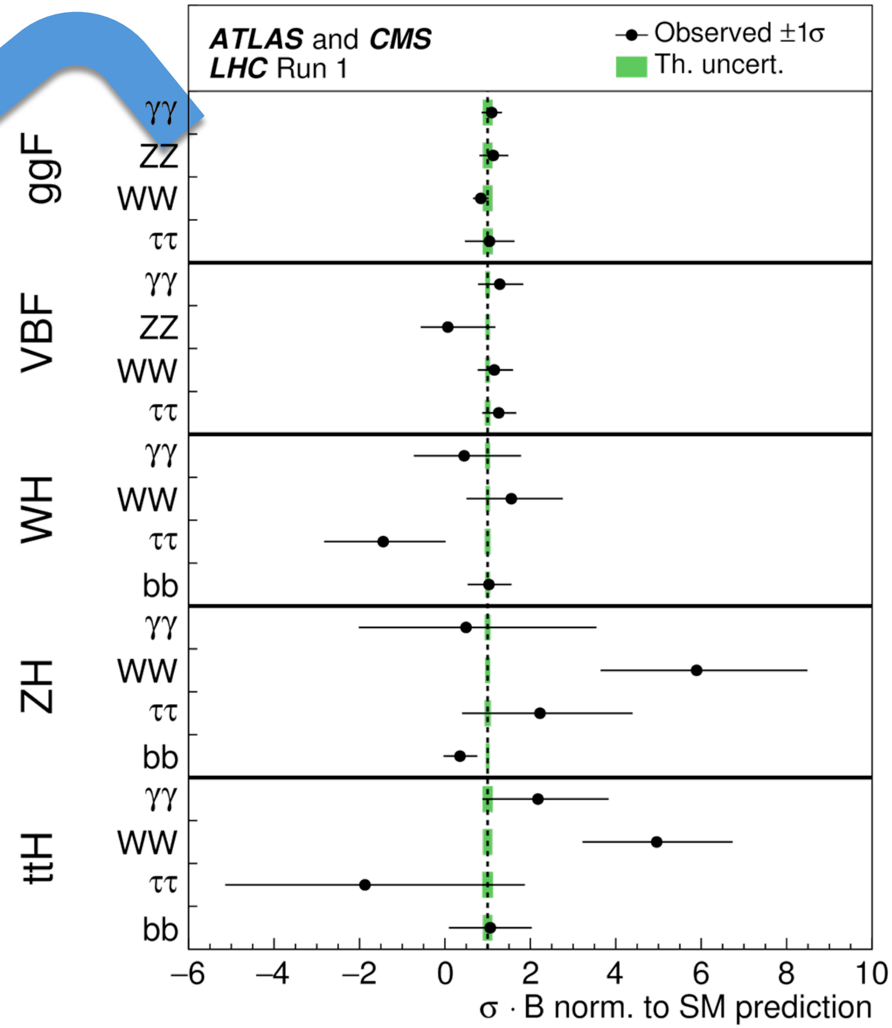
Two states at 125 GeV?

[JHEP 08 (2016) 045]

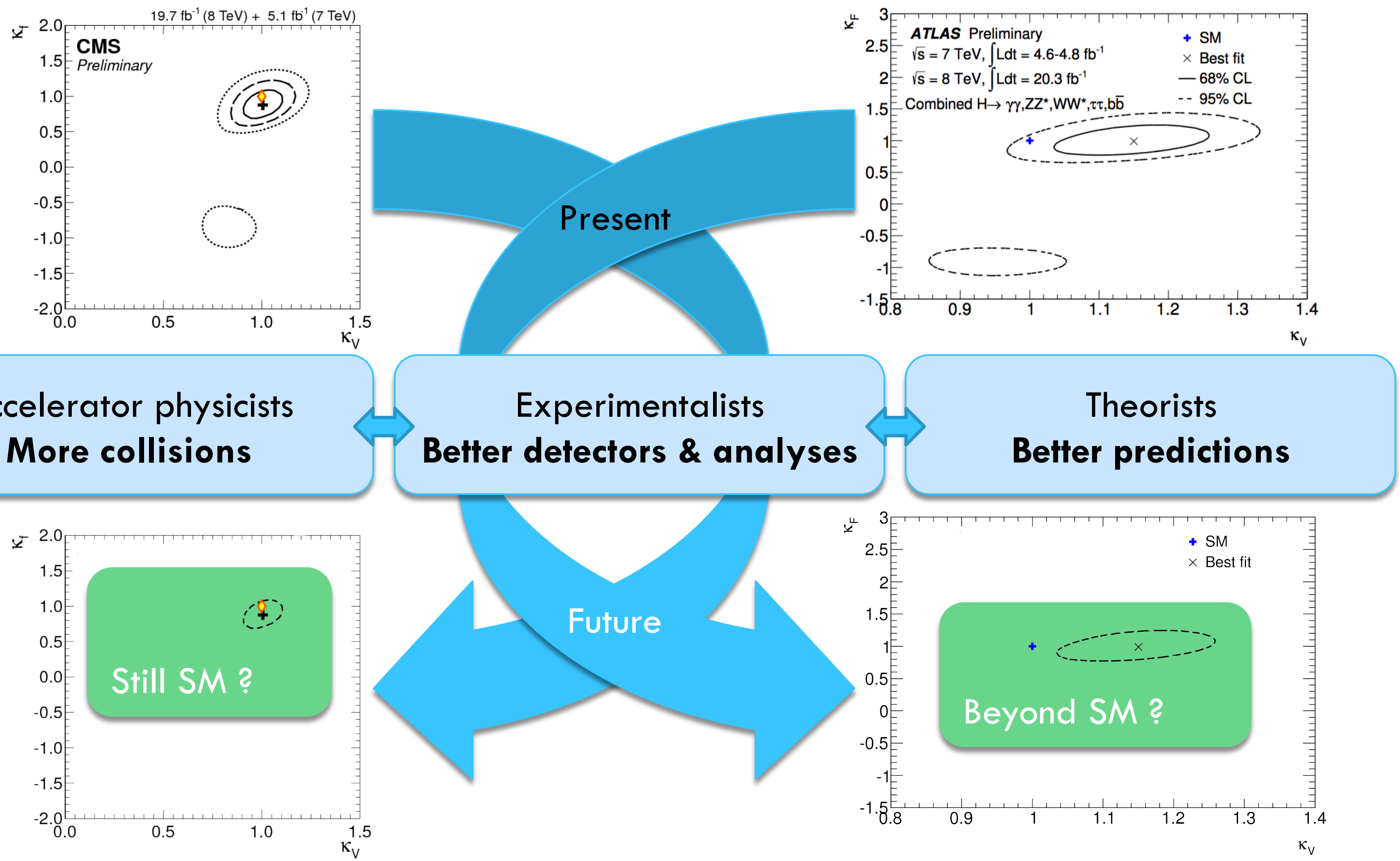
- Tested for Run1:

	p(data | SM)
ATLAS	0.58
CMS	0.33
ATLAS+CMS	**0.29 ± 0.02**

- With concrete BSM predictions, we could directly test SM vs. concrete BSM model.



The future is in precision and accuracy



2008 Nobel expectations for the LHC

[http://lhc2008.web.cern.ch/LHC2008/nobel/index.html]

Carlo Rubbia: "Nature will tell"

I think Nature is smarter than physicists. **We should have the courage to say: "Let Nature tell us what is going on."**

Our experience of the past has demonstrated that in the world of the infinitely small, it is extremely silly to make predictions as to where the next physics discovery will come from and what it will be.

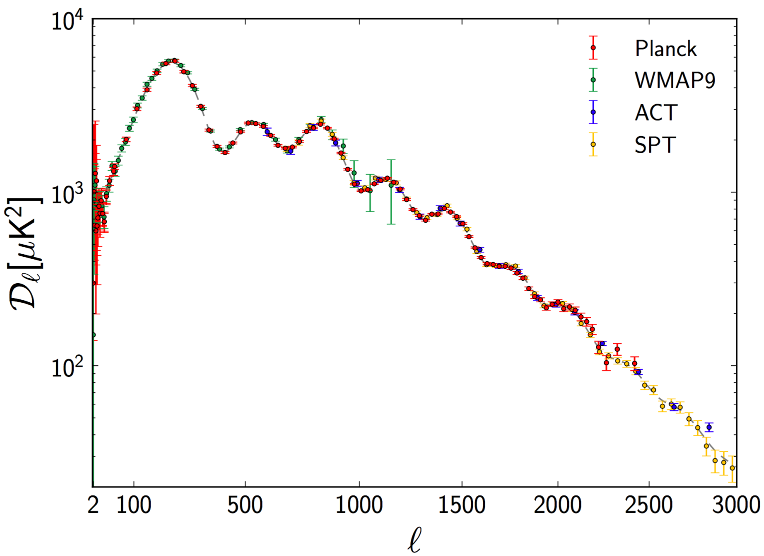
In a variety of ways, this world will always surprise us all. **The next breakthrough might come from beta decay, or from underground experiments, or from accelerators.**

We have to leave all this spectrum of possibilities open and just enjoy this extremely fascinating science.

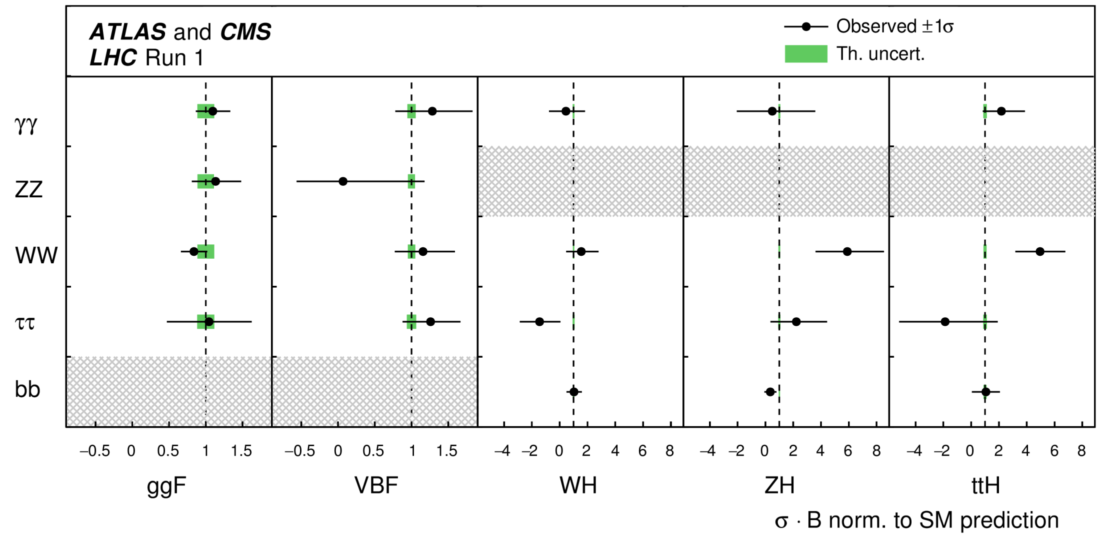
The ~~beautiful~~ ~~boring~~ Universe today

[arXiv:1303.5062][JHEP 08 (2016) 045]

- **Up above:**
  (Simple) 6-parameter ΛCDM.



- **Down below:**
  (Not-as-simple) ~20-parameter Standard Model of Particle Physics.

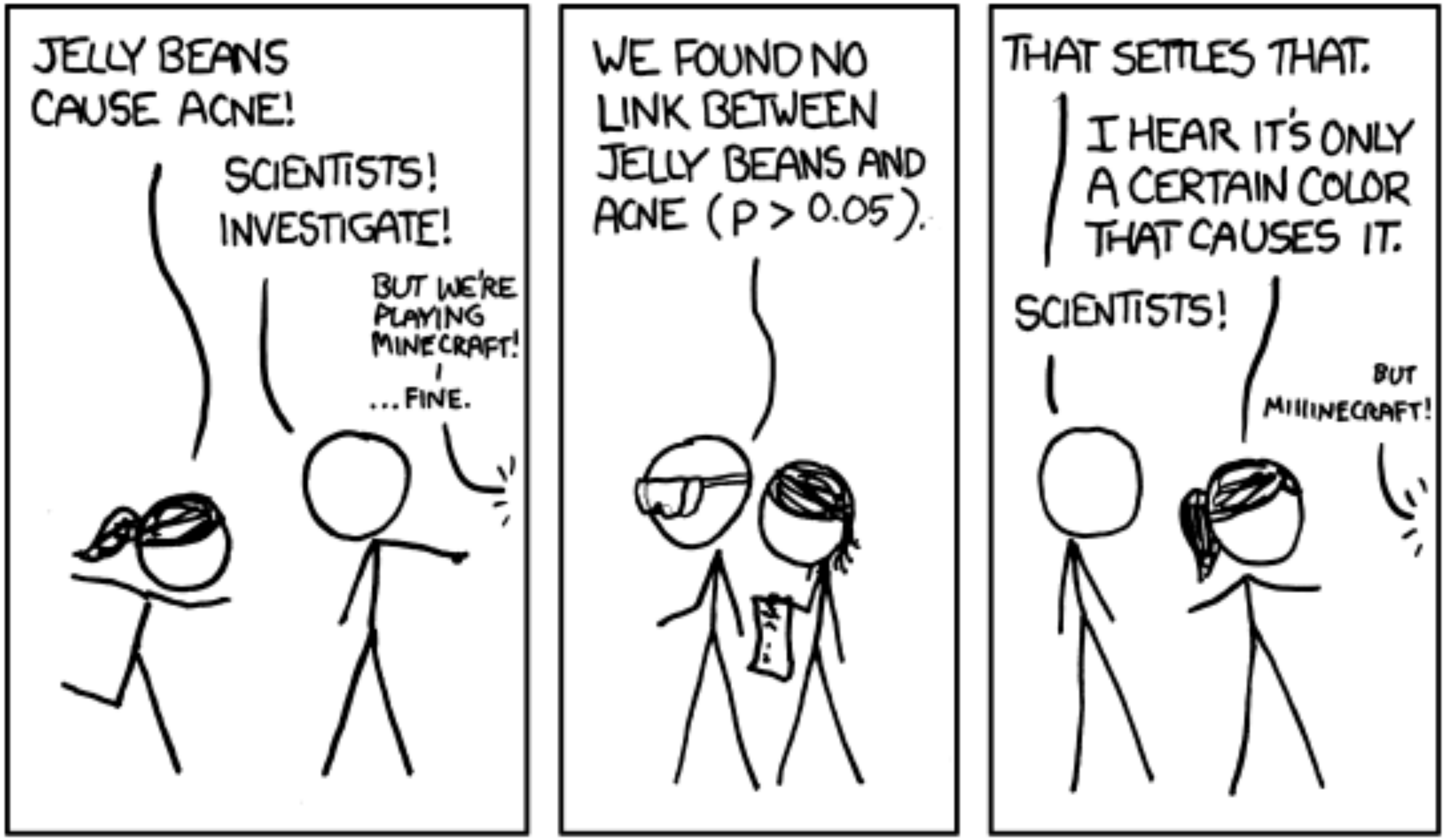


Looking forward to surprises at higher energy: PeV neutrinos, #MoarData at LHC 13 TeV, …

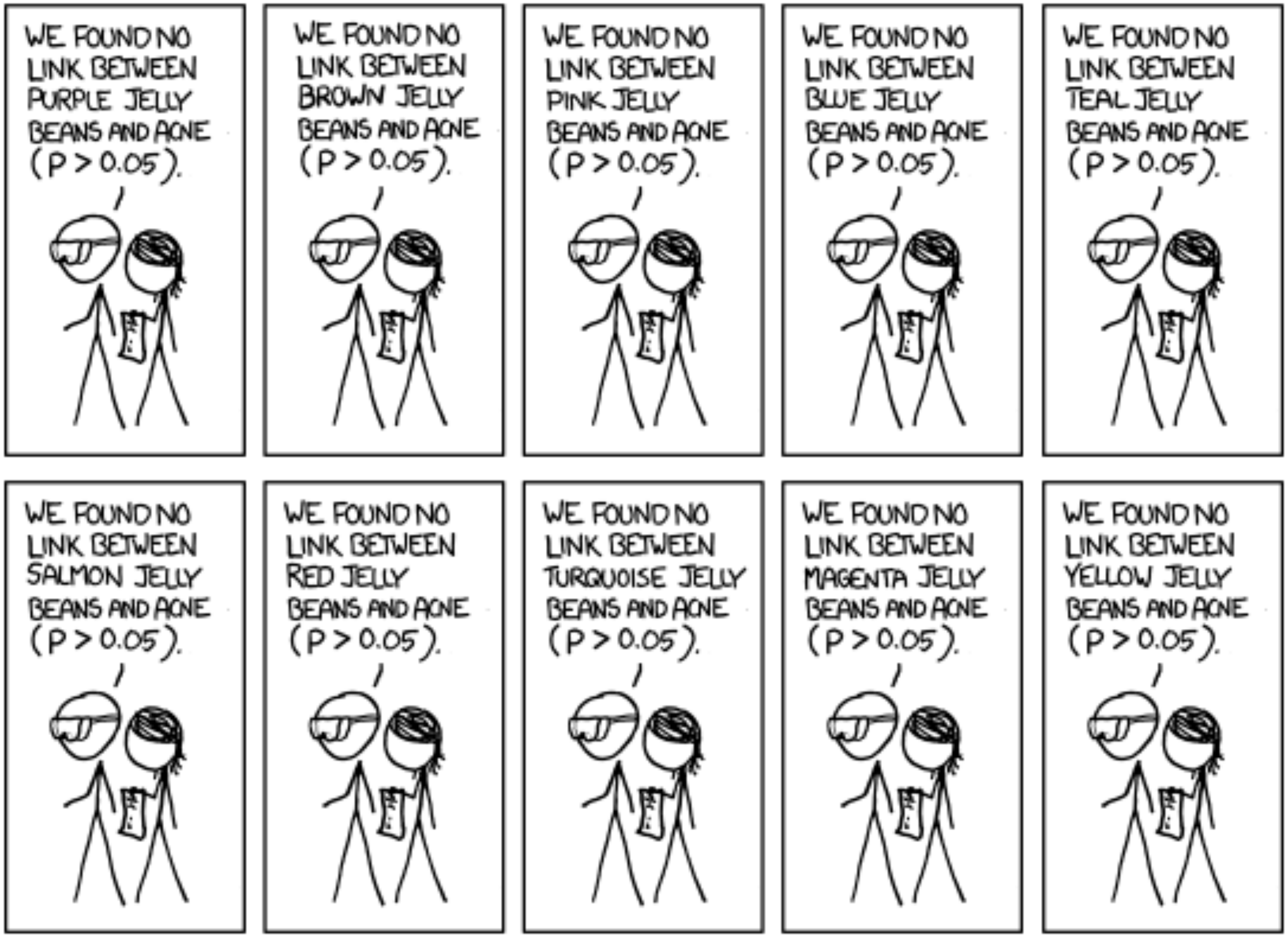
"…and references therein."

- Experiments' pages on Higgs results:
  - ATLAS: http://cern.ch/go/7IDT
  - CMS: http://cern.ch/go/6qmZ

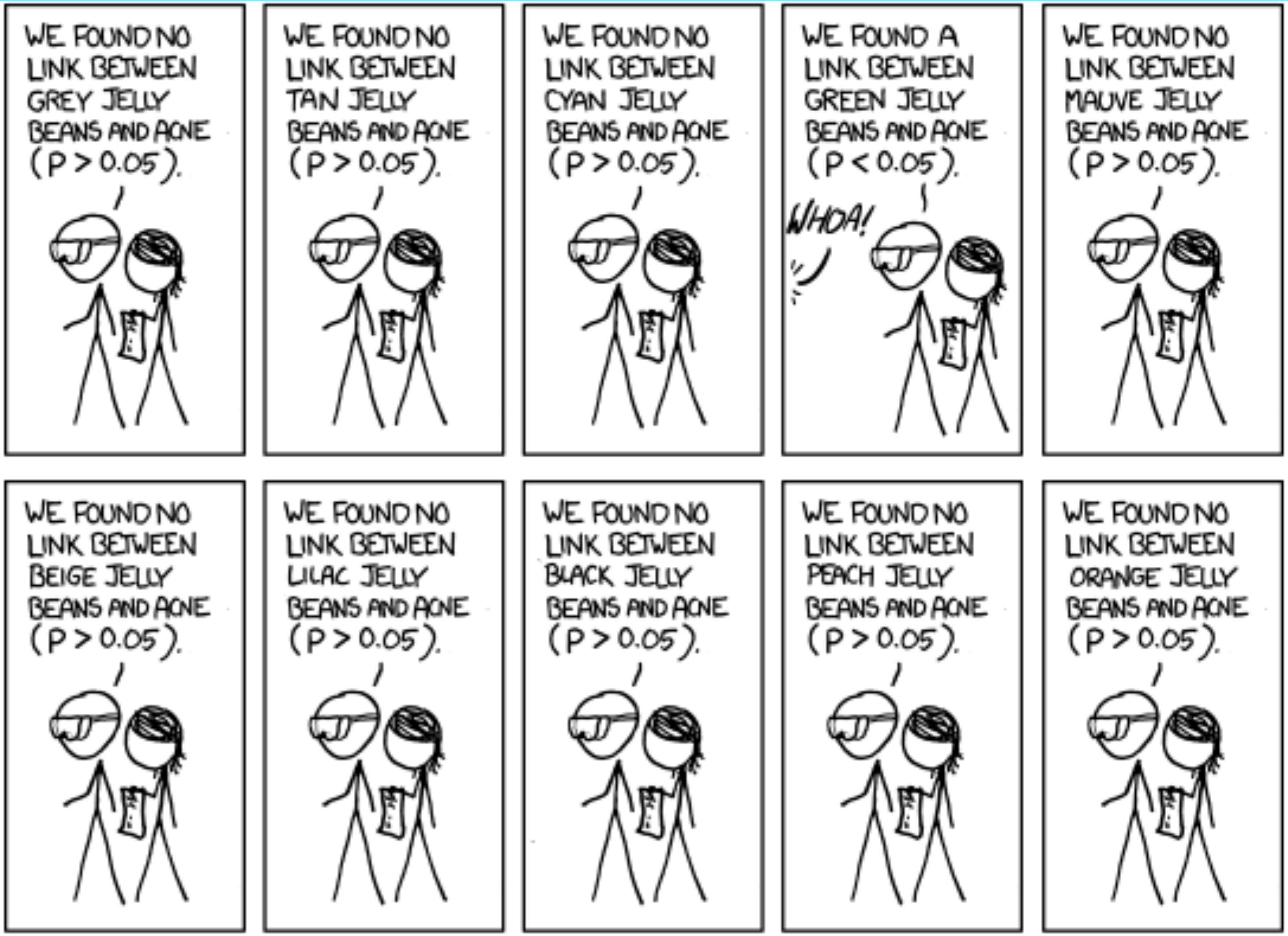
Significant – xkcd.com/882



Significant – xkcd.com/882



Significant – xkcd.com/882



Significant – xkcd.com/882