

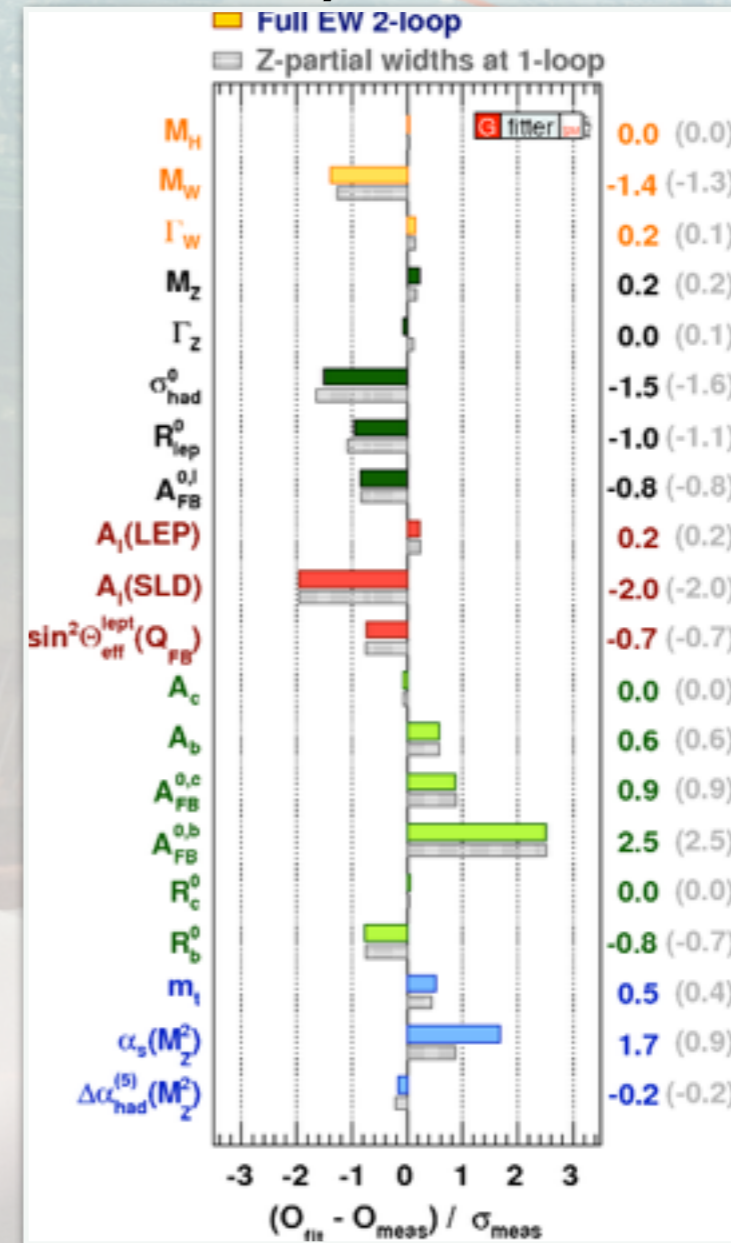
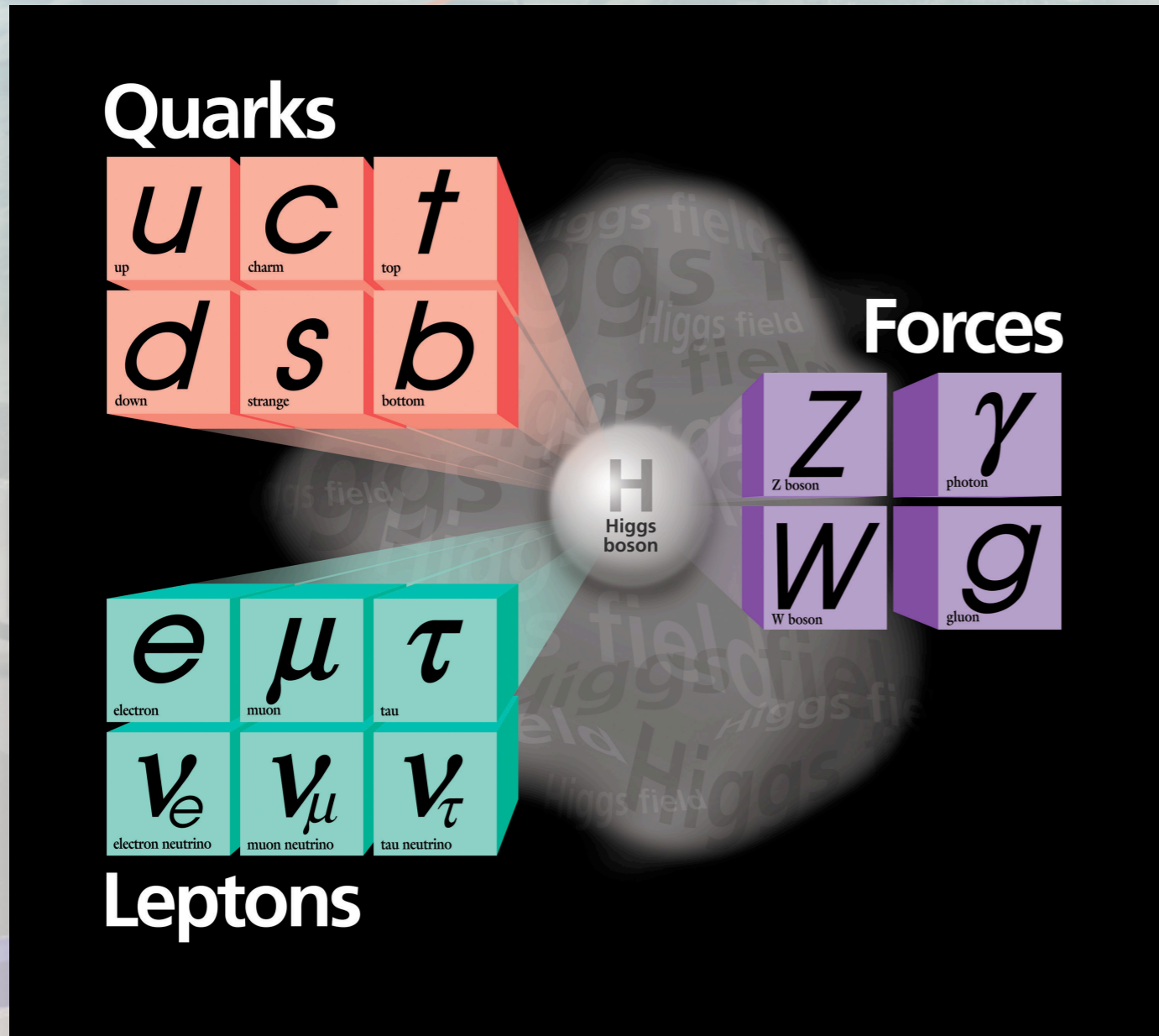


LHC Physics Highlights

Keti Kaadze
Kansas State University

The Standard Model

- Elementary particles and their interactions are described by the standard model



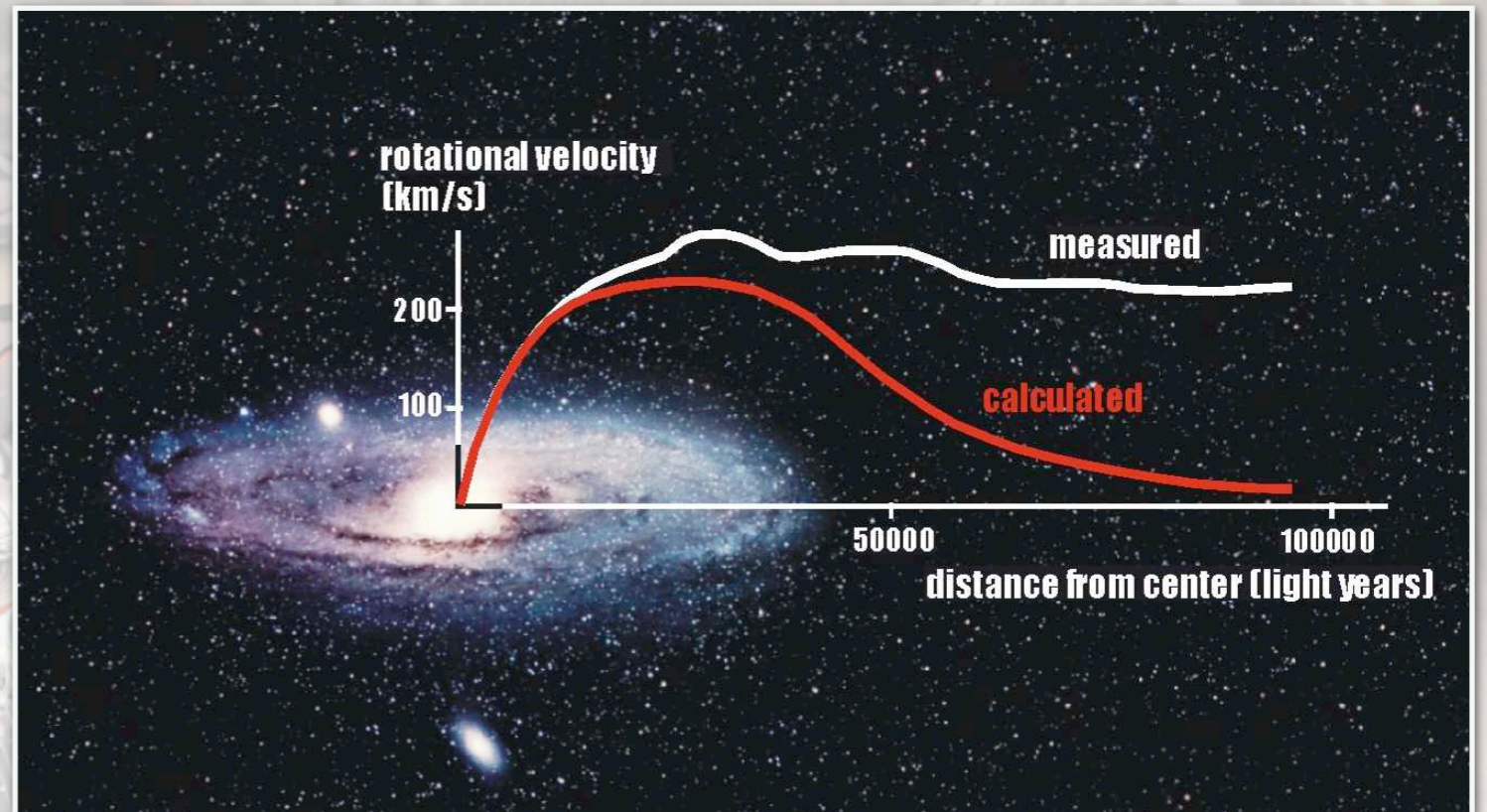
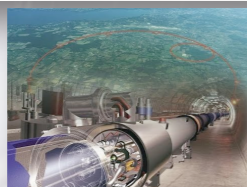
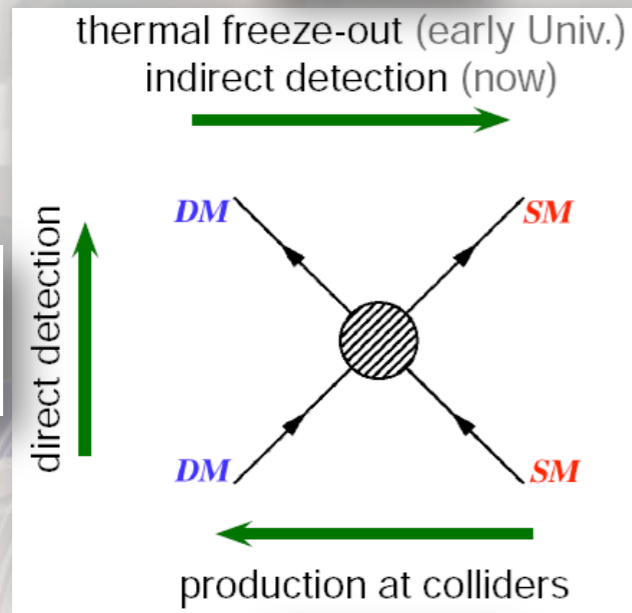
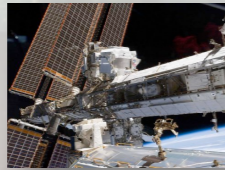
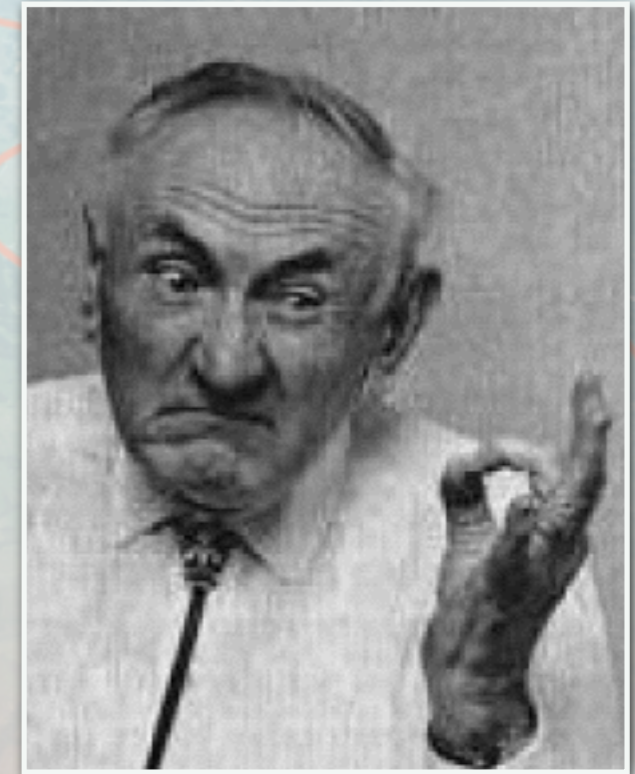
[arXiv:1407.3792](https://arxiv.org/abs/1407.3792)

Explains

- Structure of all matter on earth
- Interactions observed so far
- Mechanism of mass generation for particles*. However...

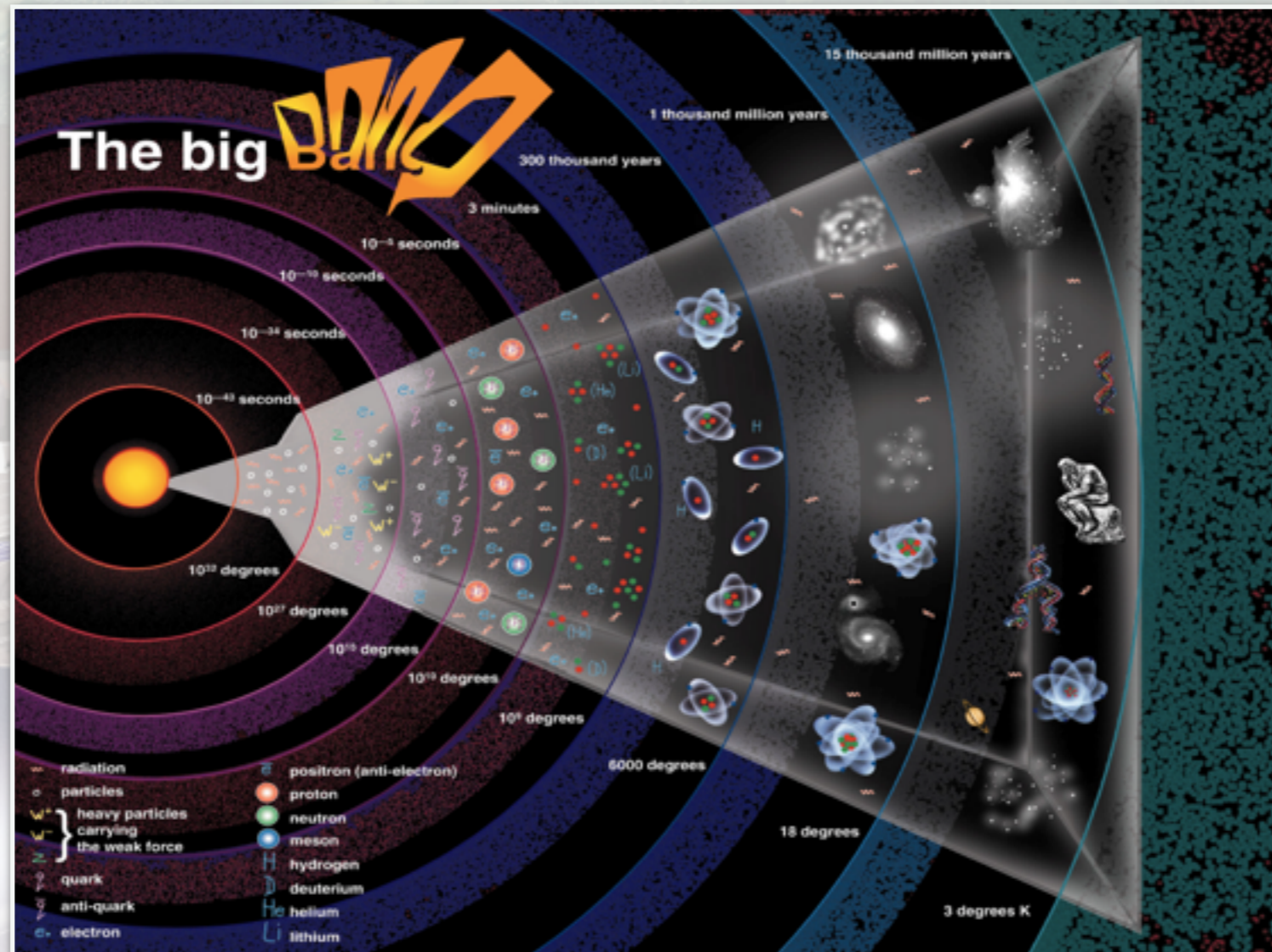
The SM is Incomplete

- In 1933 Zwicky inferred existence of “dunkle Materie”
- Later, in the measurements by different astronomers it was found that rotational velocities of the galaxies in large discrepancy to the expectation according to Newton’s law
- Today nature of dark matter is still unknown



More General Theory?

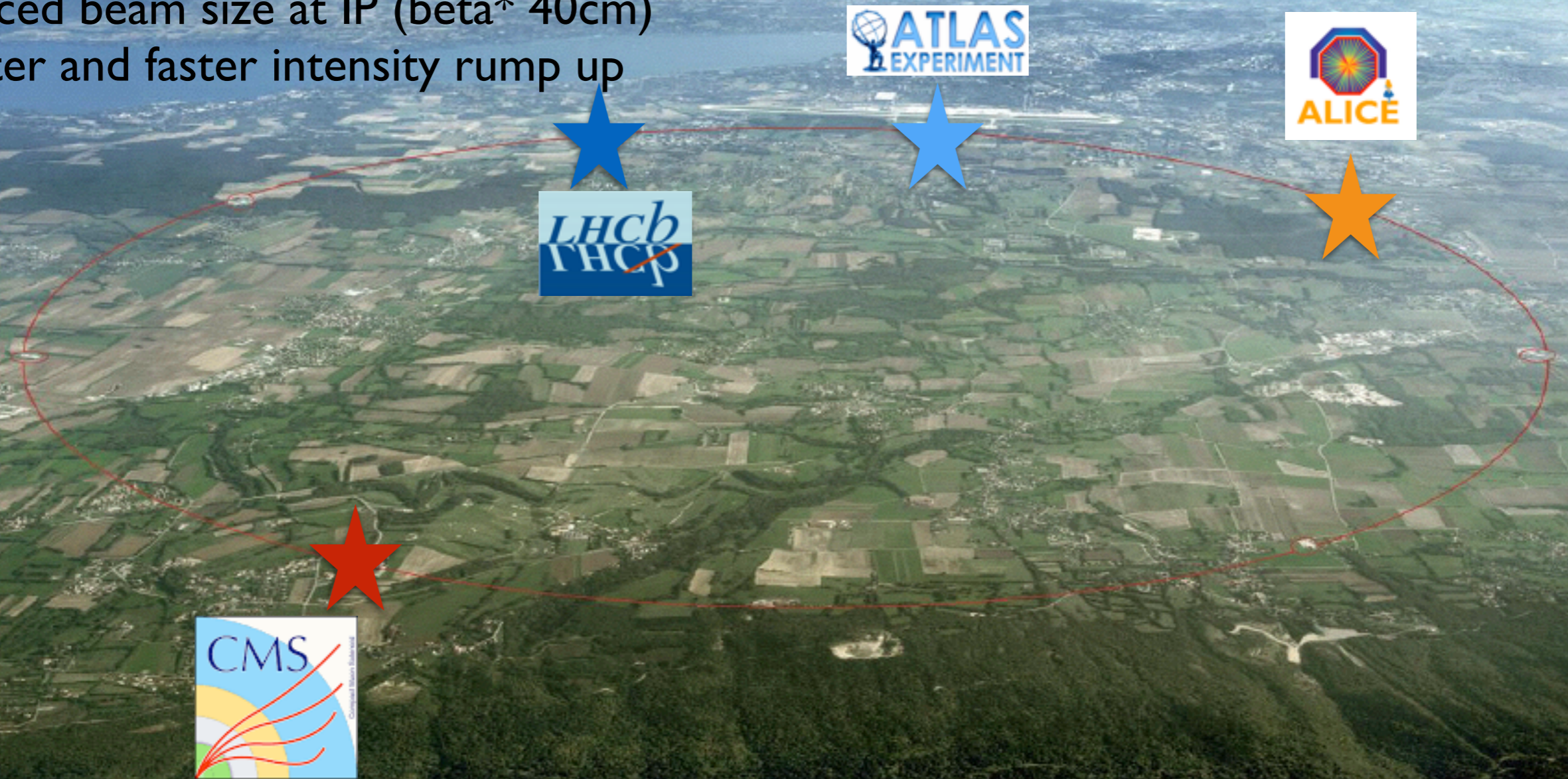
- How matter — antimatter asymmetry is explained?
- Why do we have three generations of quarks and leptons?
- Does Gravity enter the picture? How?
- Are there more interactions in nature?
- etc...



Large Hadron Collider

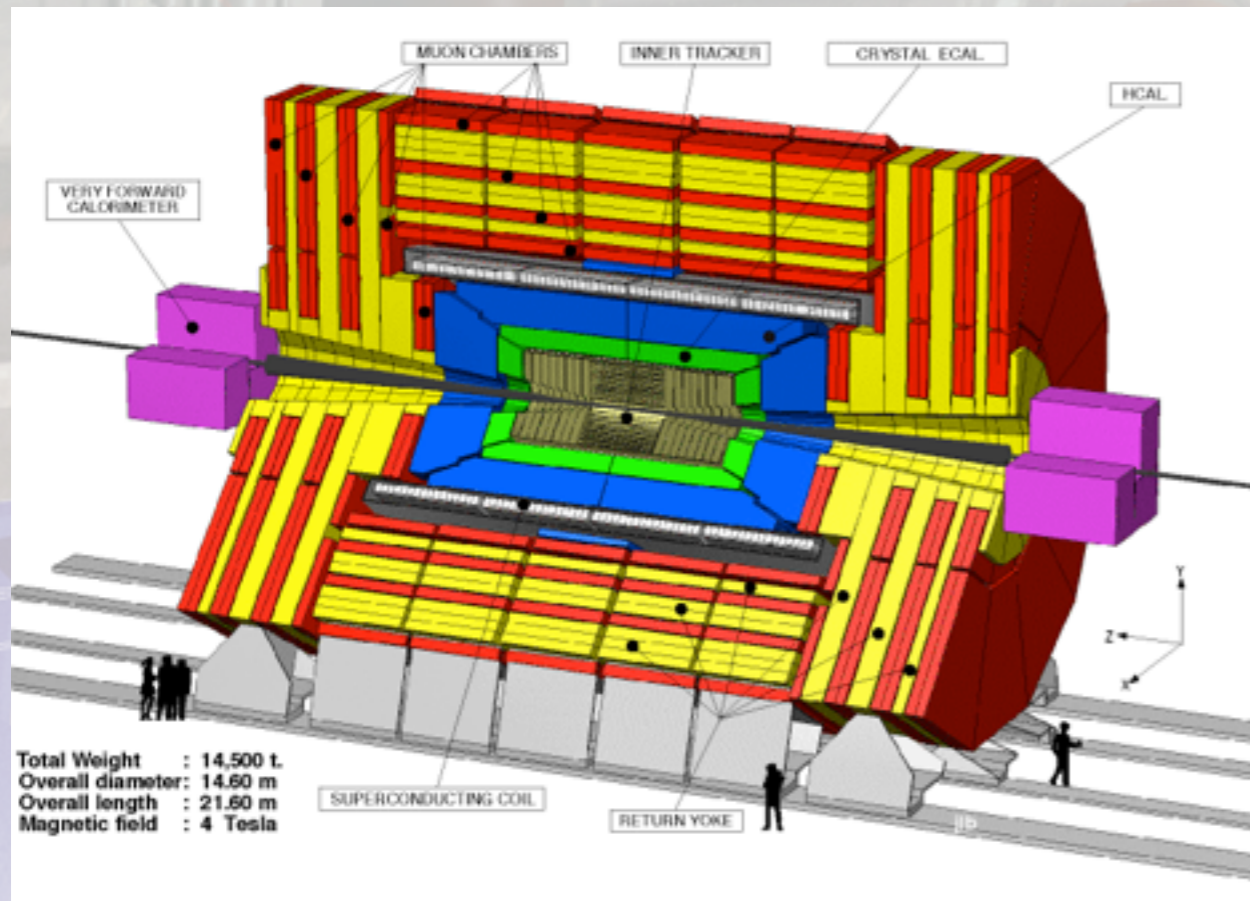
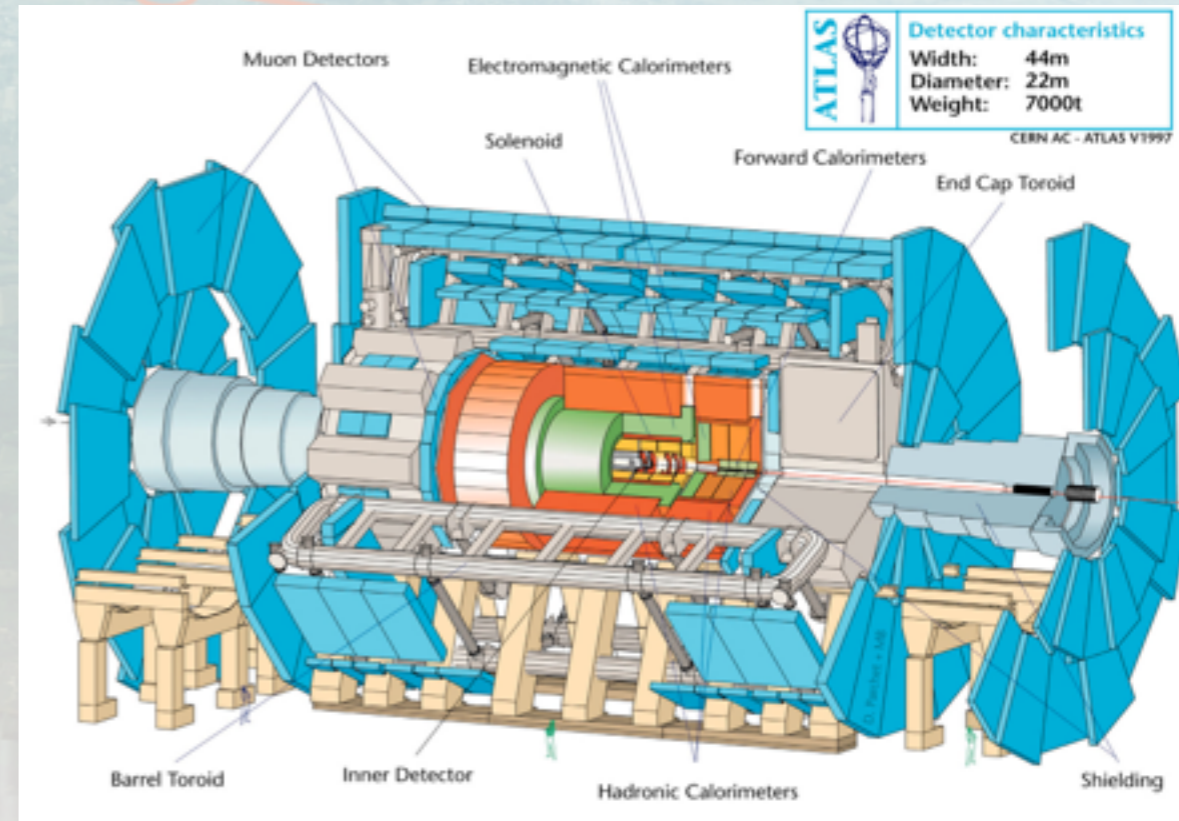
Run 2 for LHC:

- CME = 13 TeV
- Increased number of bunches (288b trains)
- 25 ns bunch spacing
- Reduced beam size at IP (beta* 40cm)
- Shorter and faster intensity rump up



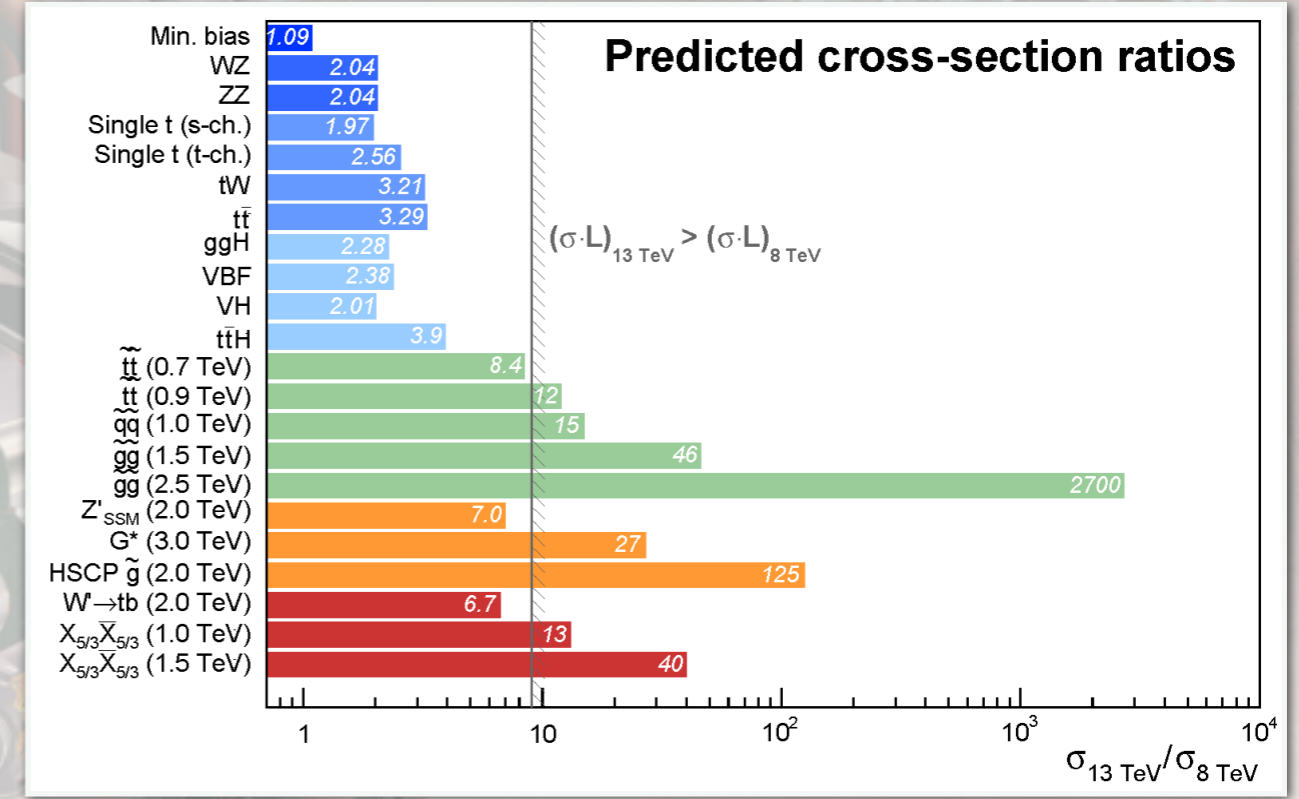
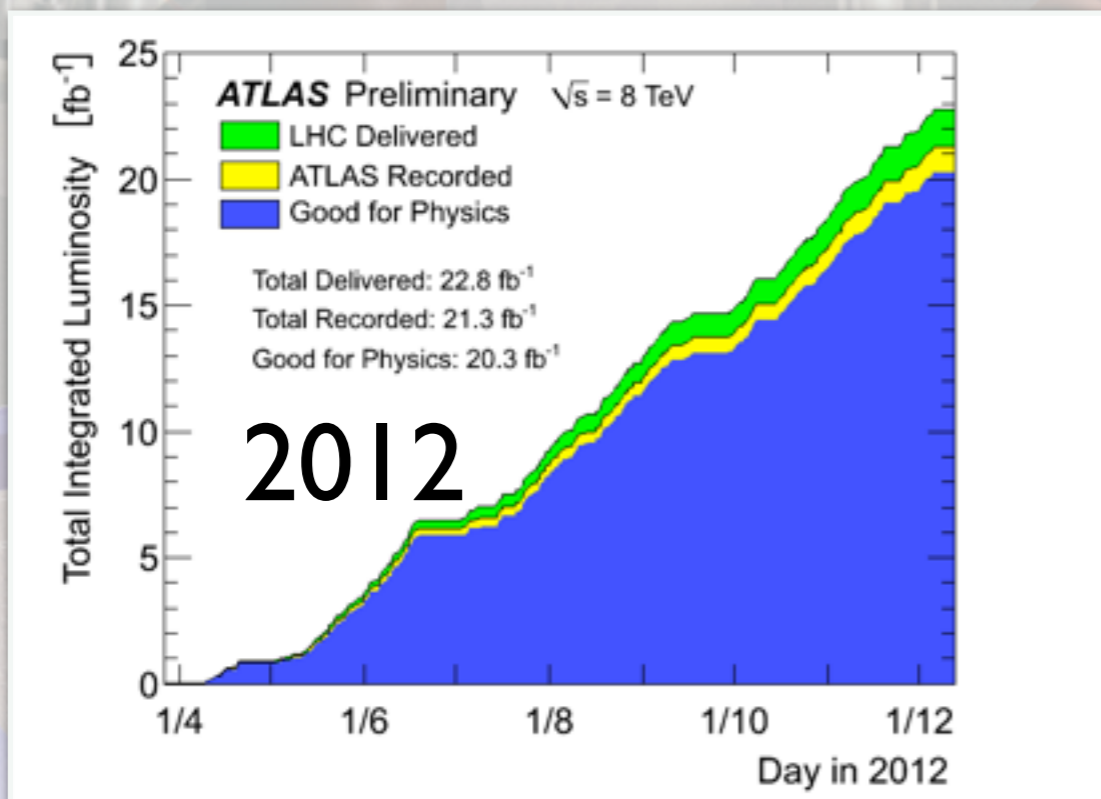
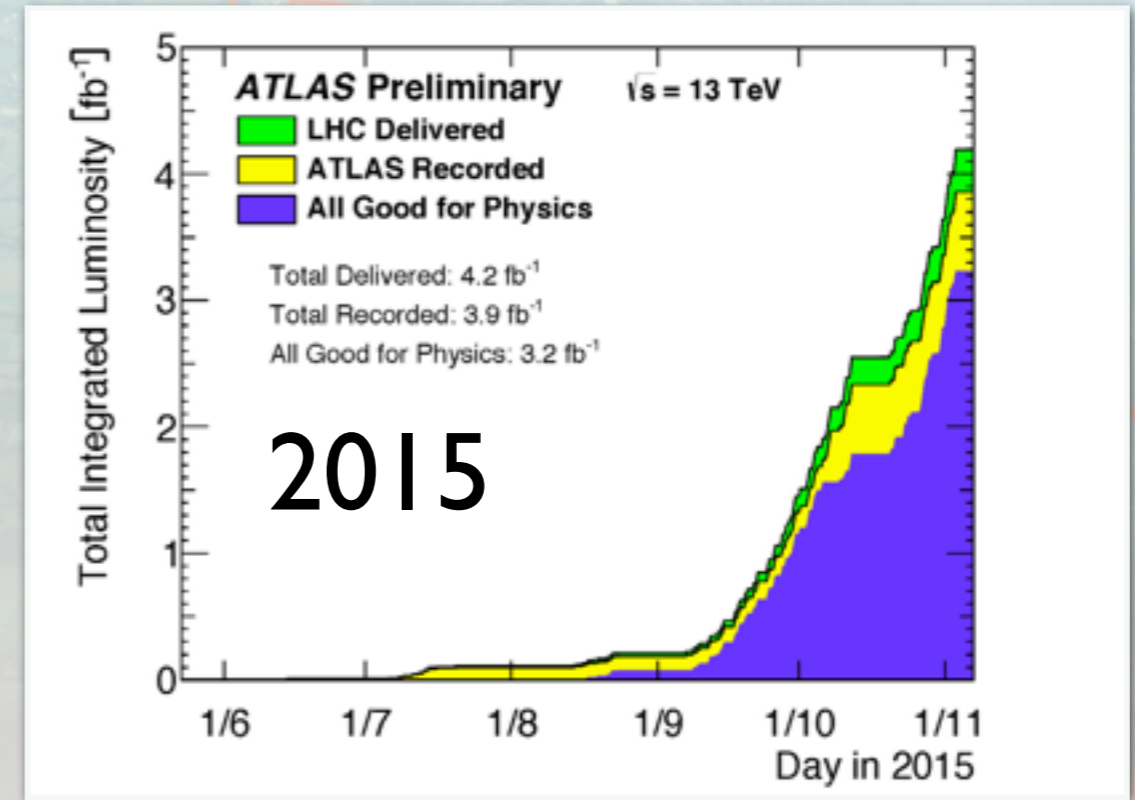
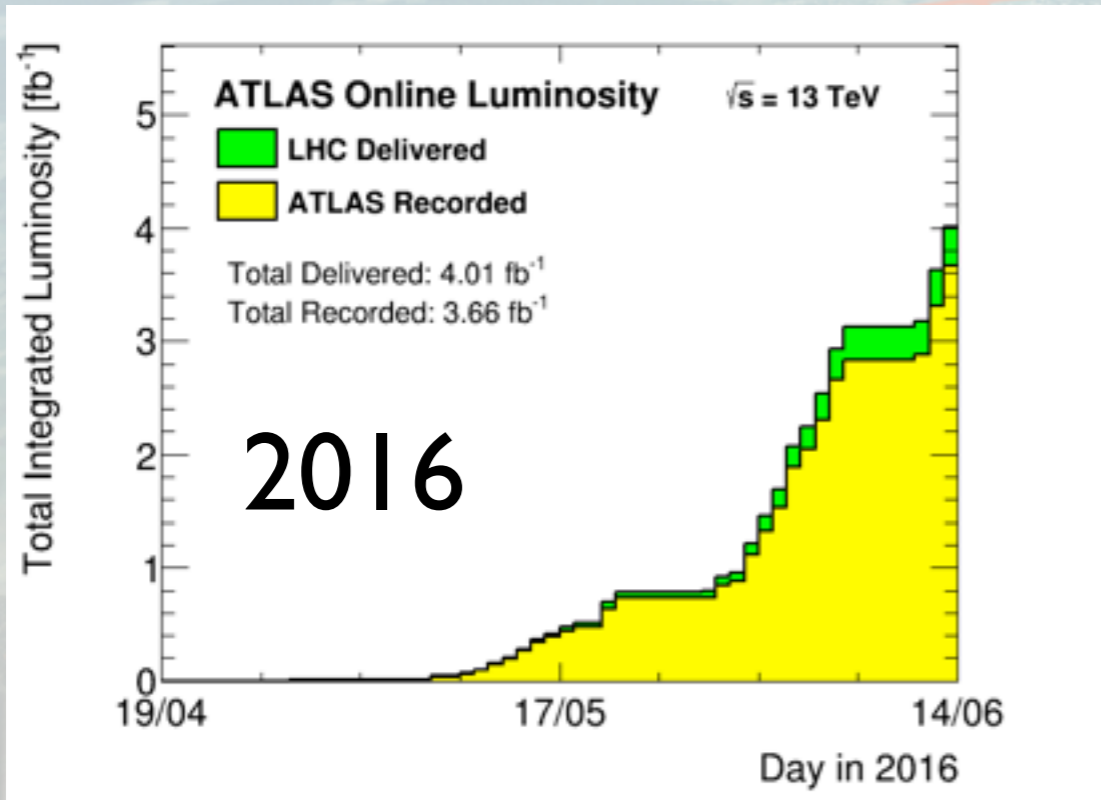
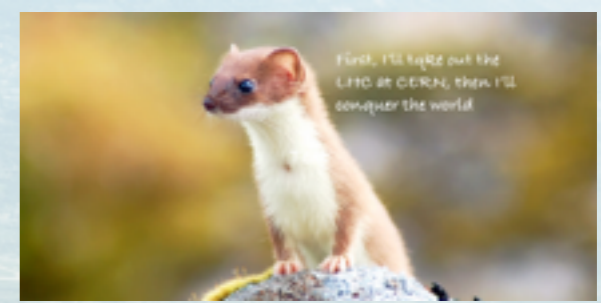
ATLAS and CMS Detectors

- Detectors are ready to tackle challenges of Run 2
 - Improved trigger menus for $5 \times 10^{33} - 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - Mitigation of pileup of $\sim 25\text{-}35$ inter.
 - Detector calibration/alignment and commissioning successfully achieved



Intense work was done on the CMS cryogenic system during winter technical stop. The CMS magnet operates at 3.8T since end of April, 2016

Luminosity



Higgs properties from Run I

- Properties of the discovered boson

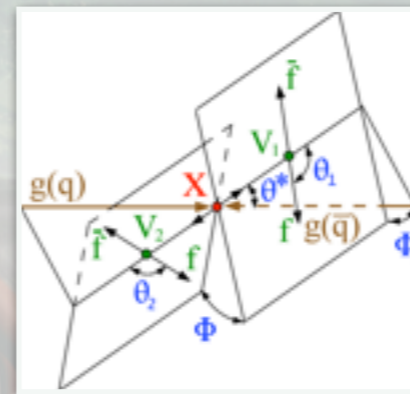
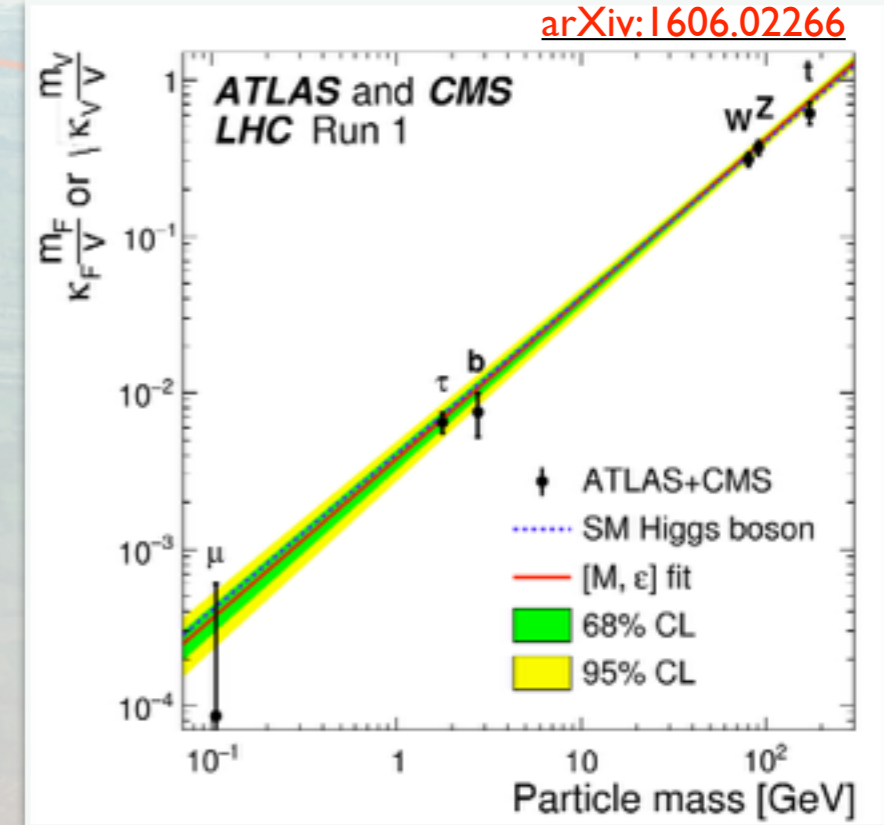
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$$M(H) = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV}$$

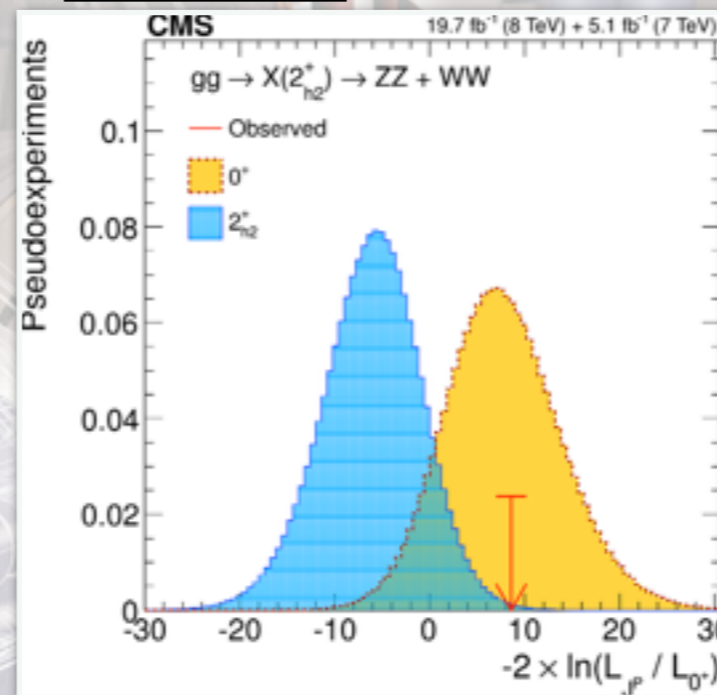
$$\Gamma_H < 13 \text{ MeV}(\text{obs.}), 26 \text{ MeV}(\text{exp.})$$

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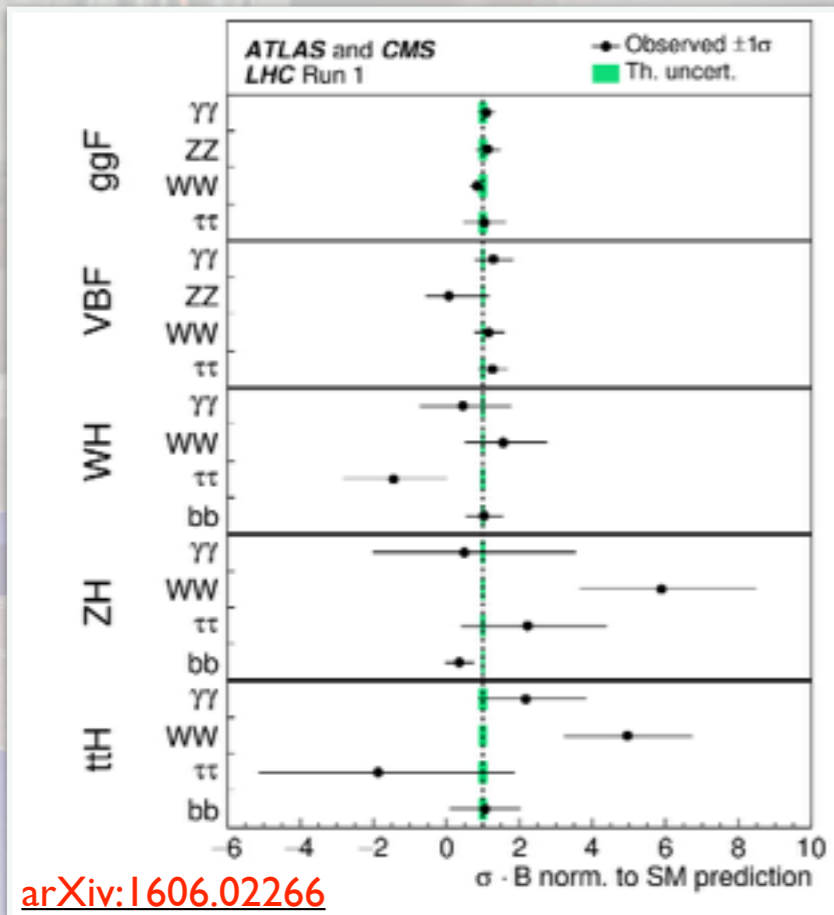
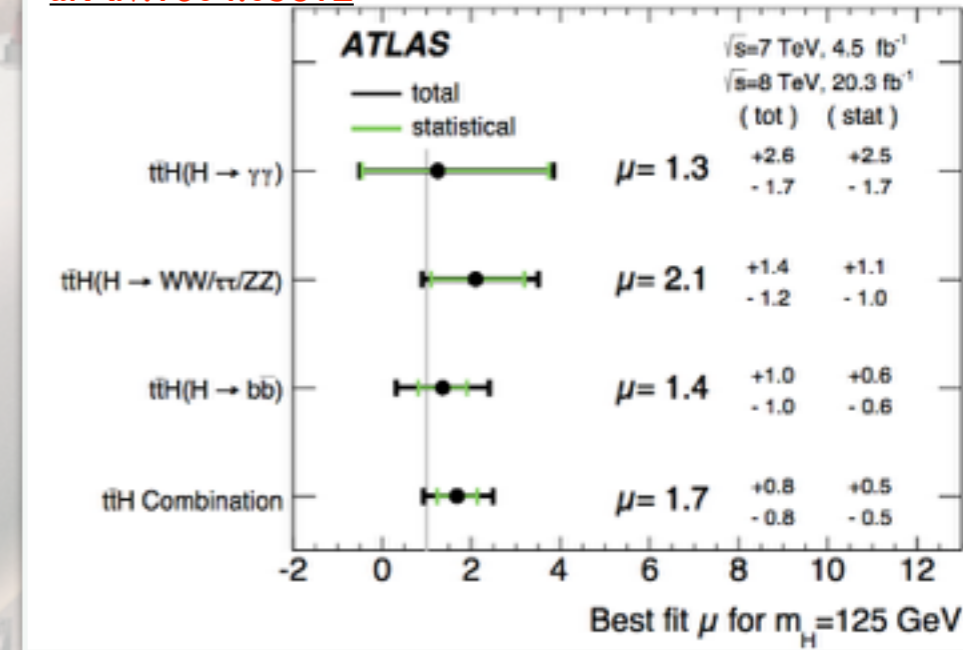
- All measurements are consistent with the SM Higgs boson hypothesis



[arXiv:1411.3441](https://arxiv.org/abs/1411.3441)

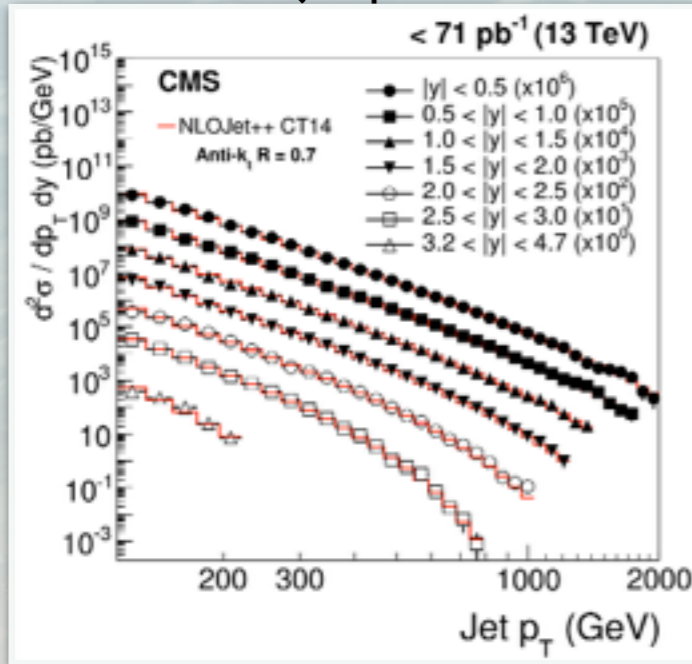


[arXiv:1604.03812](https://arxiv.org/abs/1604.03812)

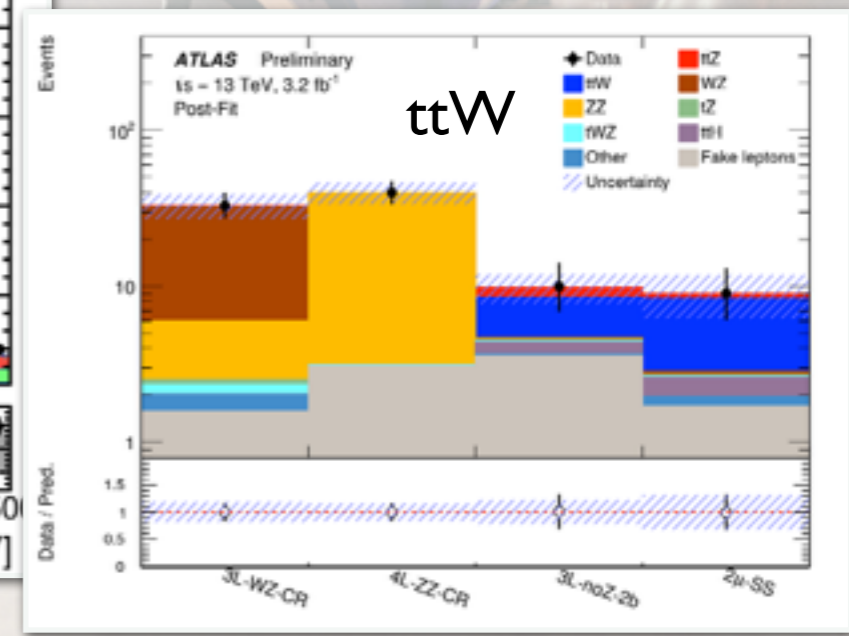
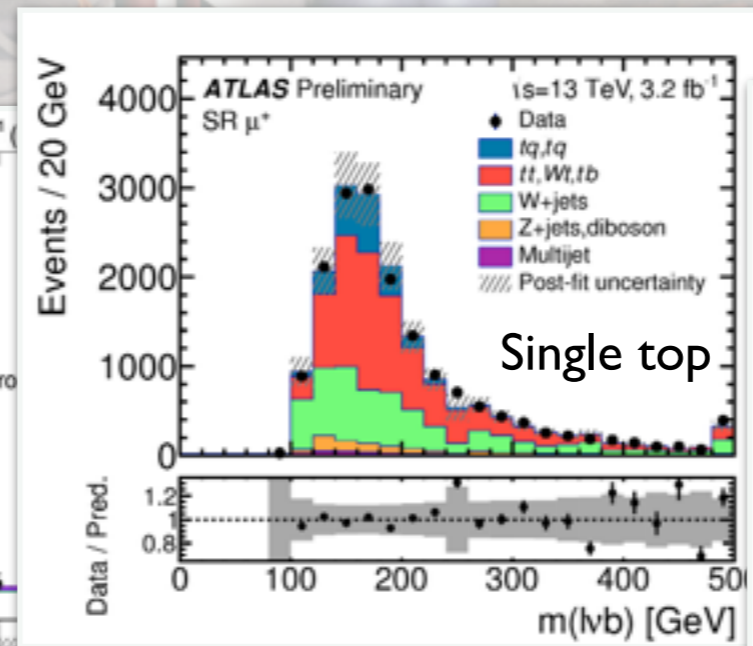
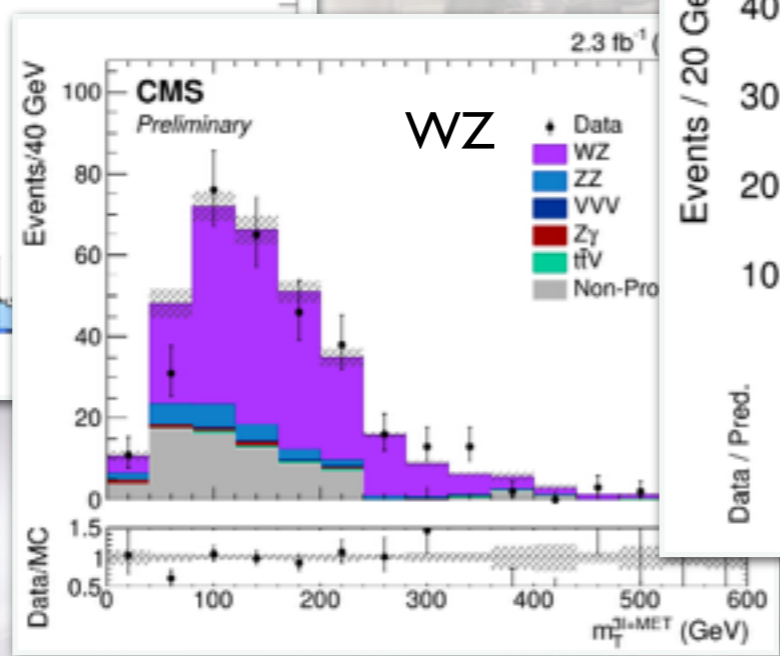
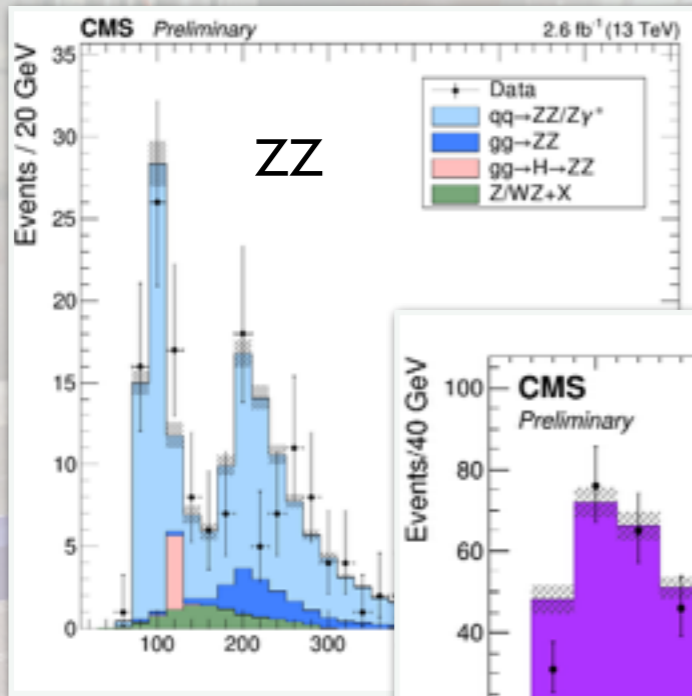
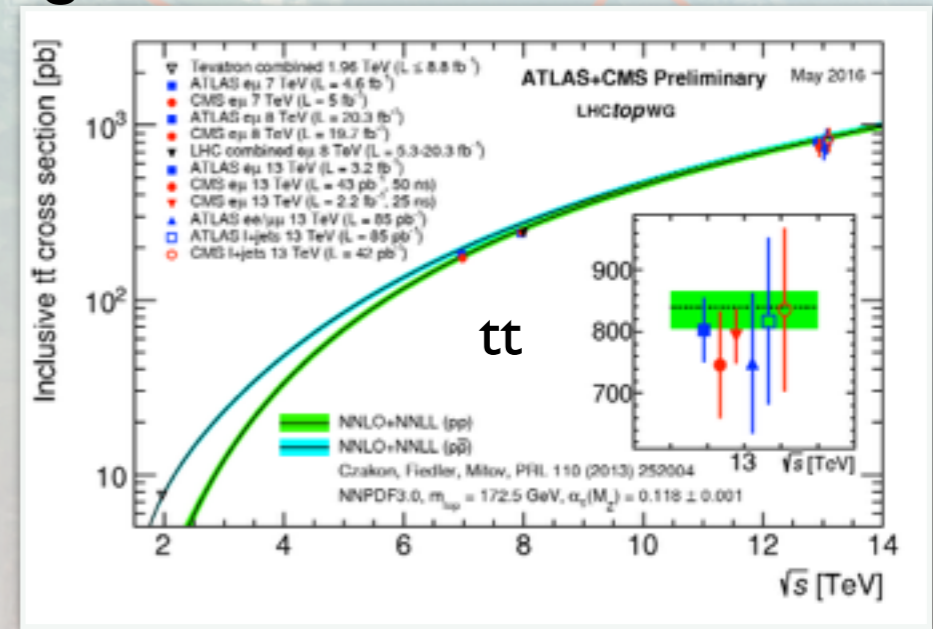
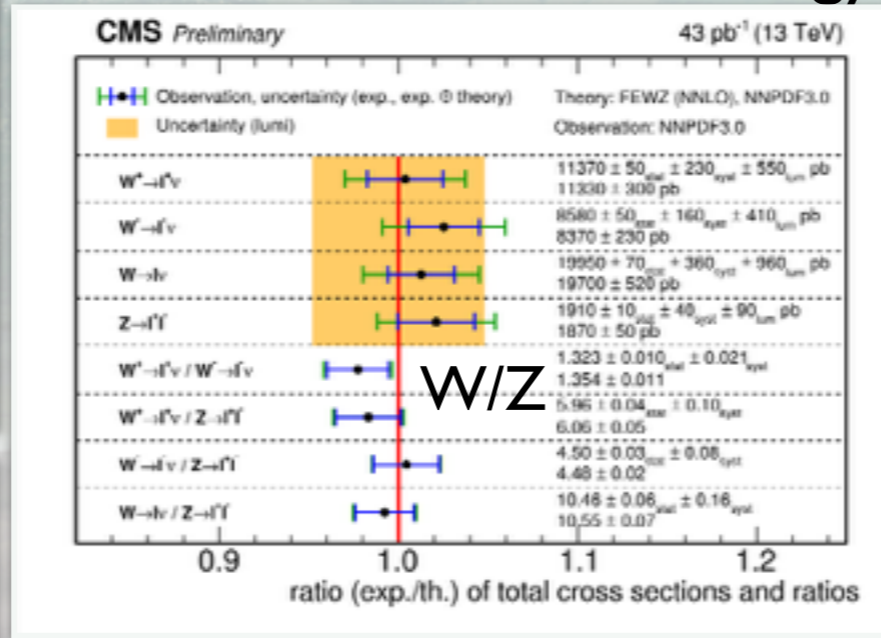


The SM revisited at 13 TeV

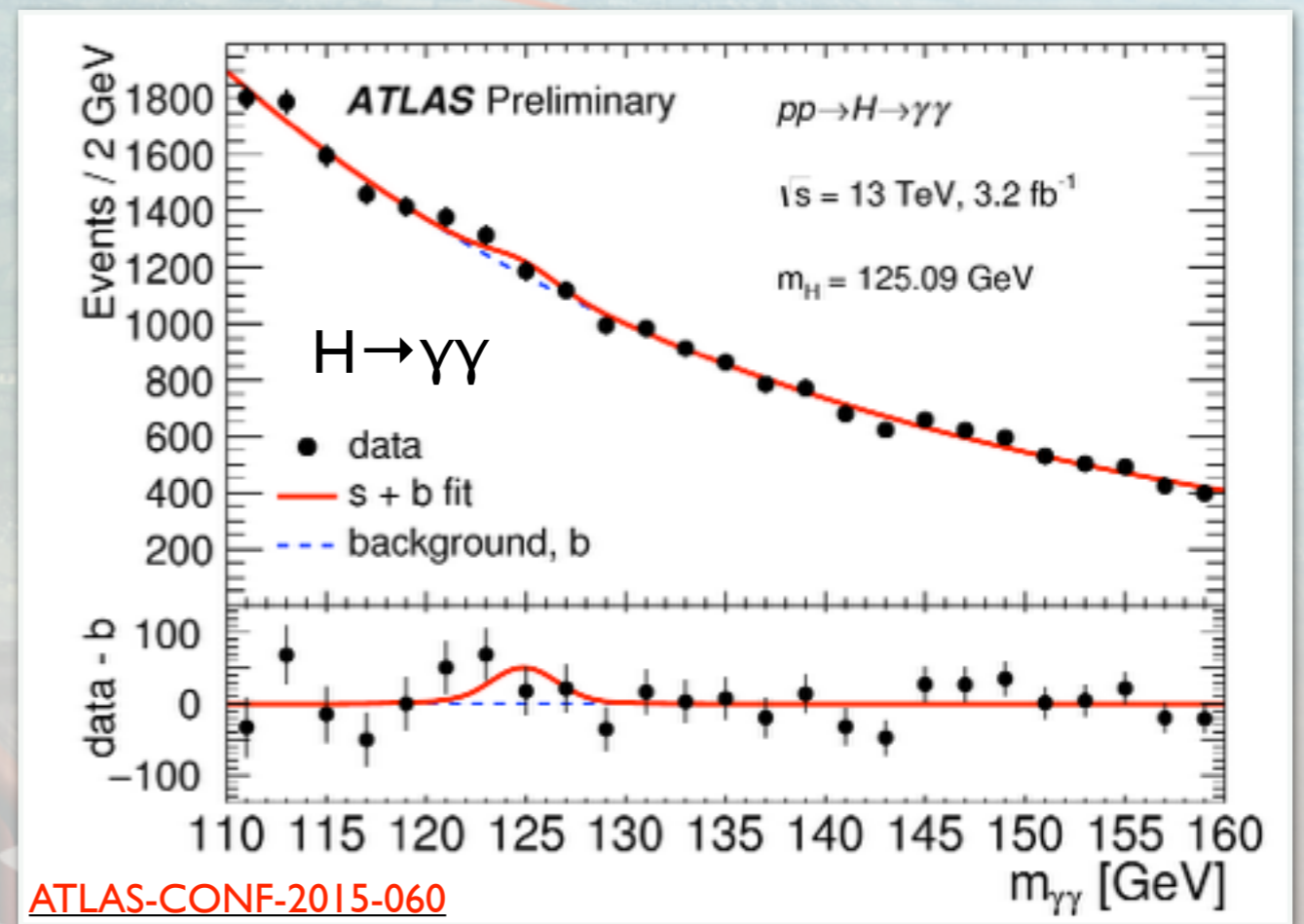
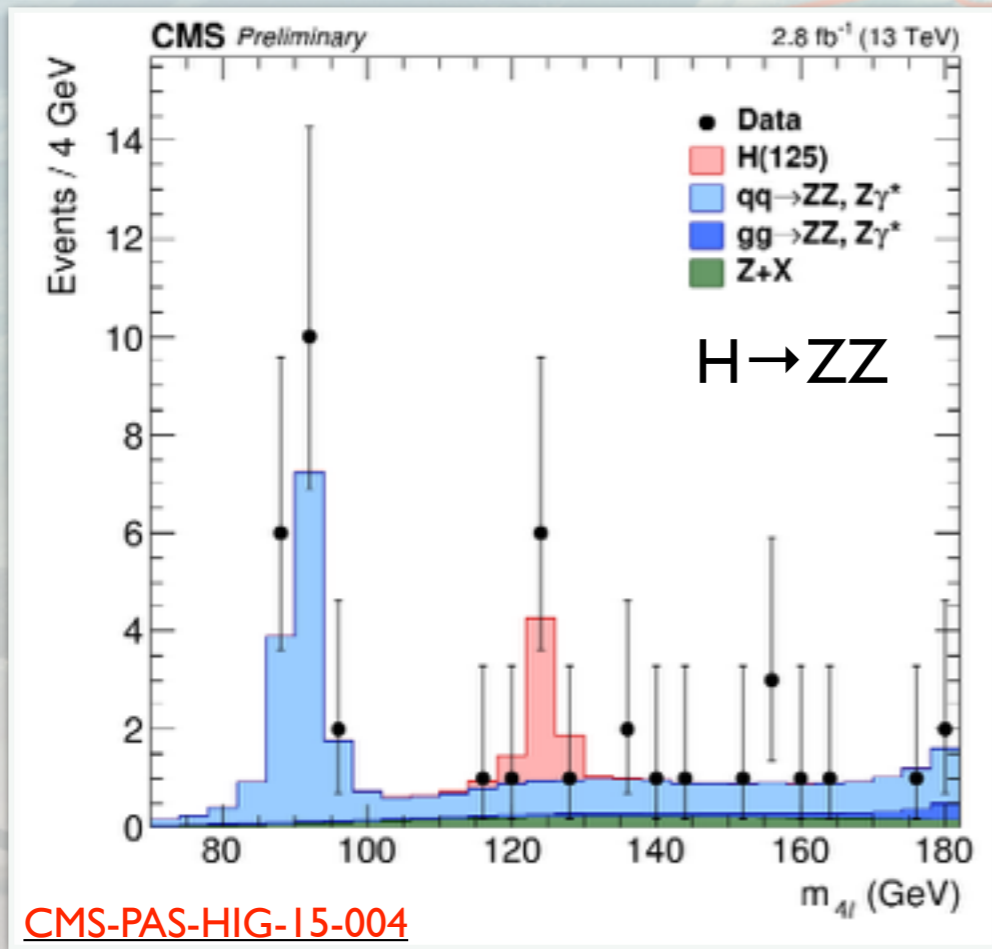
Inclusive jet production



- The SM process as background for searches
- Precise determination of the SM parameters
- Test the SM in new energy regime



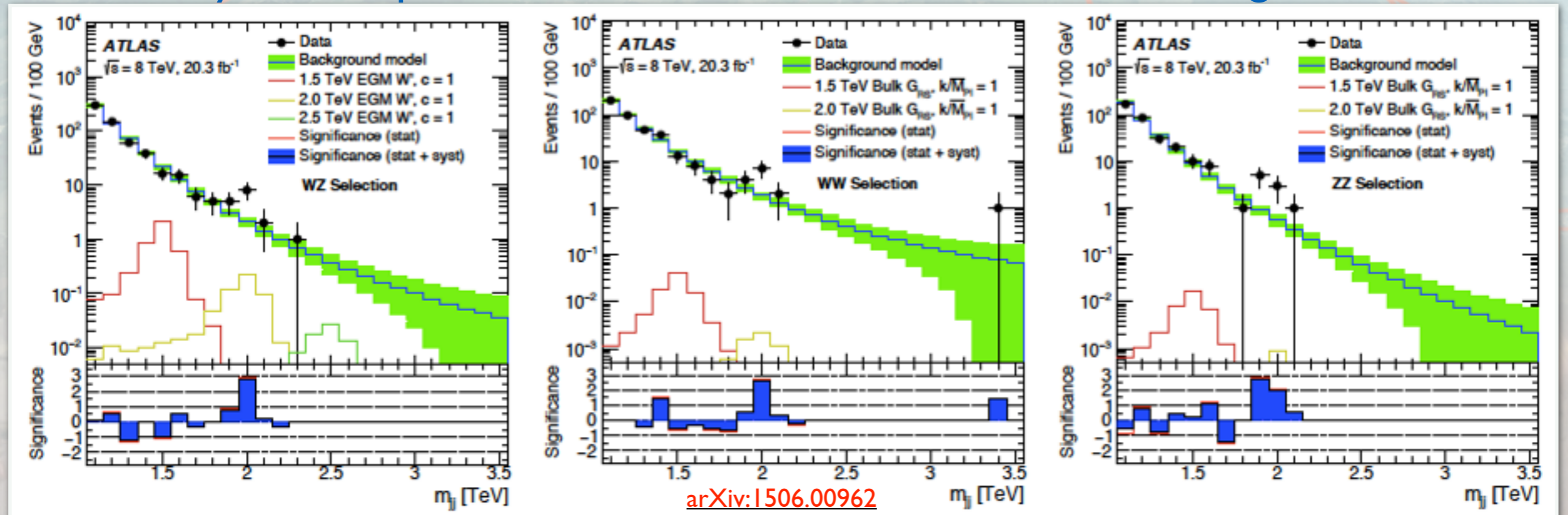
Higgs re-Discovery in Run 2



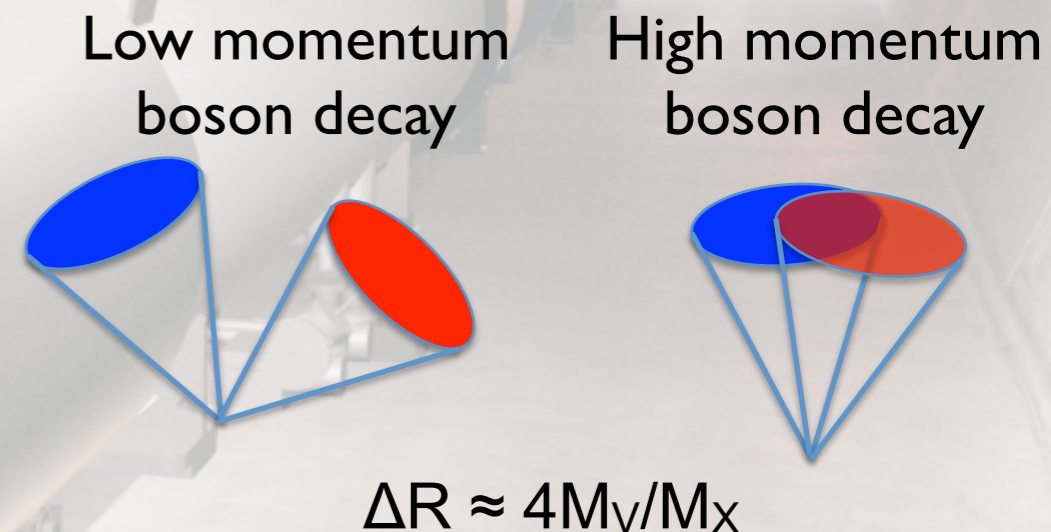
- First look at H → ZZ and H → γγ
 - Higgs signal is in agreement with the SM
 - Sensitivity is still smaller than in Run 1
 - Both experiments extract inclusive cross sections

Diboson Resonances

- Anomalies from Run I in $X \rightarrow VV$ searches: excess at ~ 2 TeV
 - Seen by both experiments; Seen in various channels; Global significance ~ 2 - 2.5σ

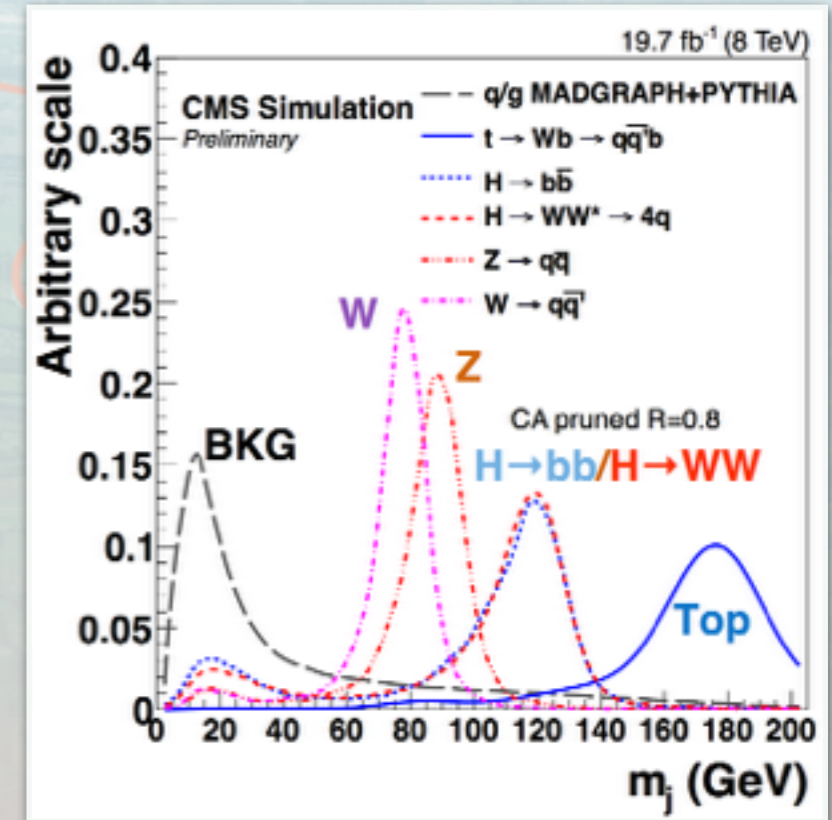
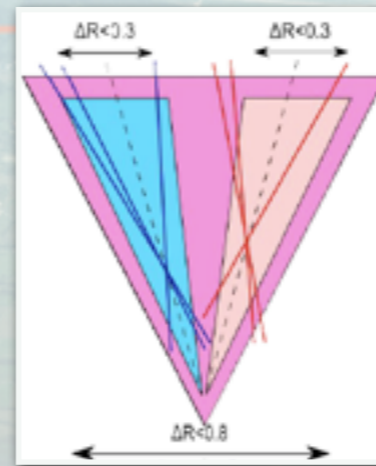


- Boosted boson decaying to two quarks is identified as a big merged jet
 - Mass of the jet is one of the main discriminators
 - Jet substructure variables provide further separation from background

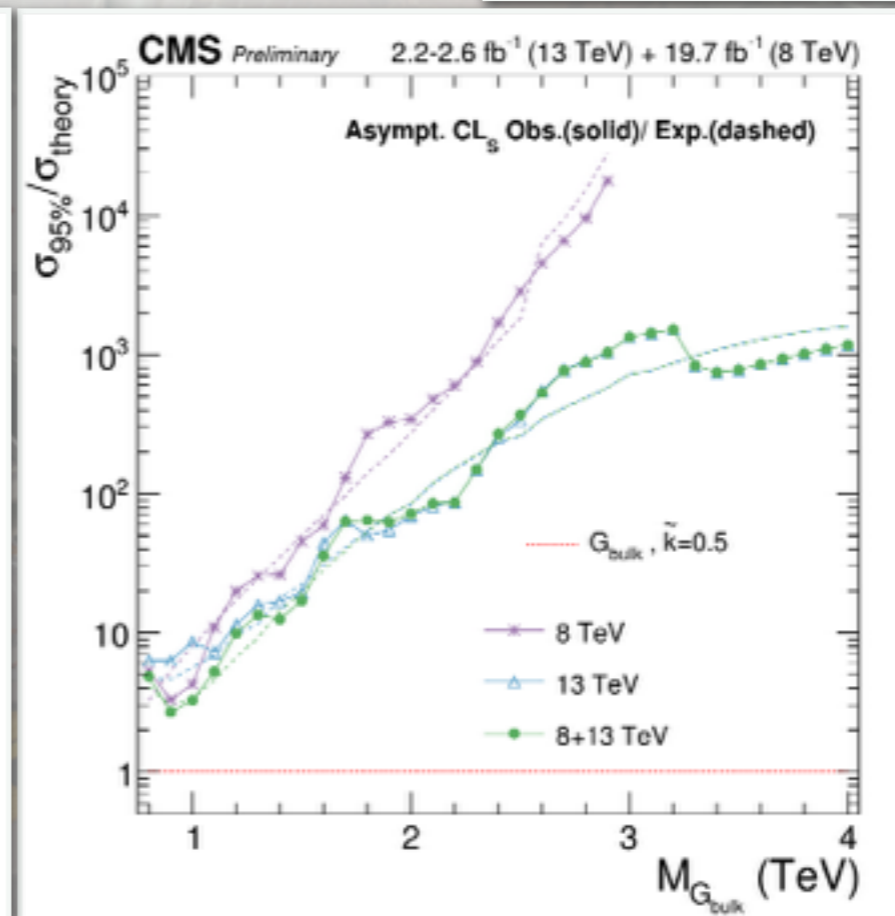
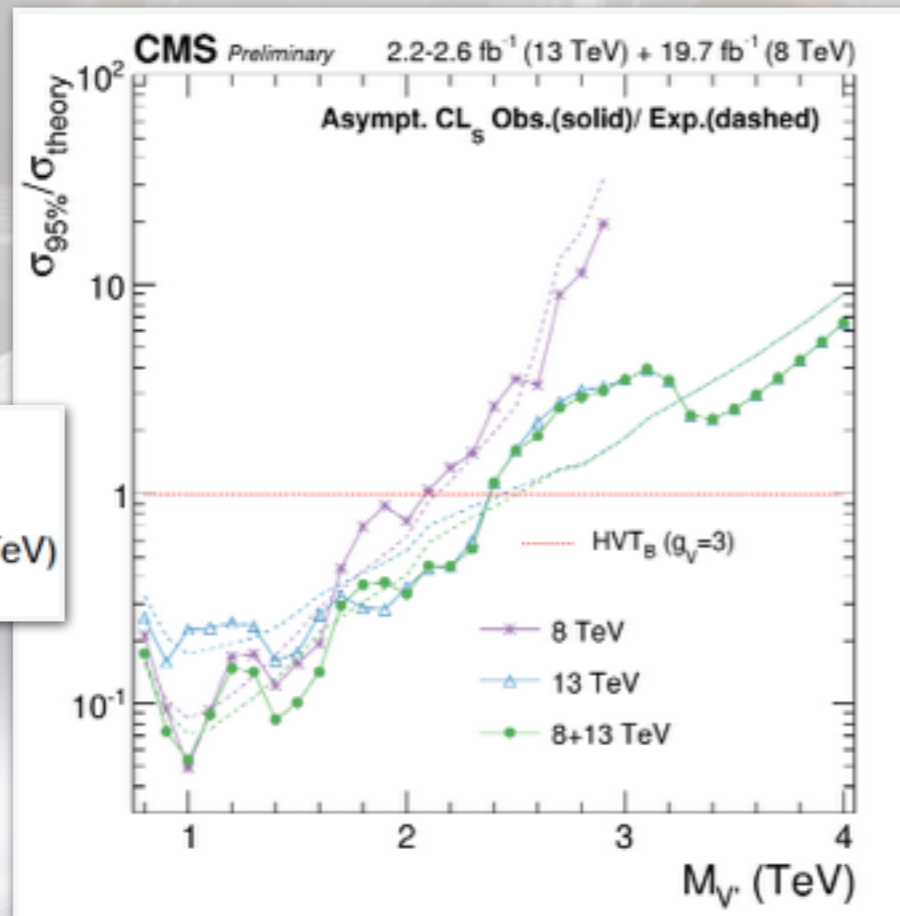


Diboson Resonances

- Adding boosted $H \rightarrow bb$
 - Large mass means less QCD
 - Possibility to tag one or two sub-jets
- Combine searches for $WW, WZ, ZZ, WH,$ and ZH resonances for 8 TeV and 13 TeV
 - 12 analyses exploring leptonic and hadronic modes

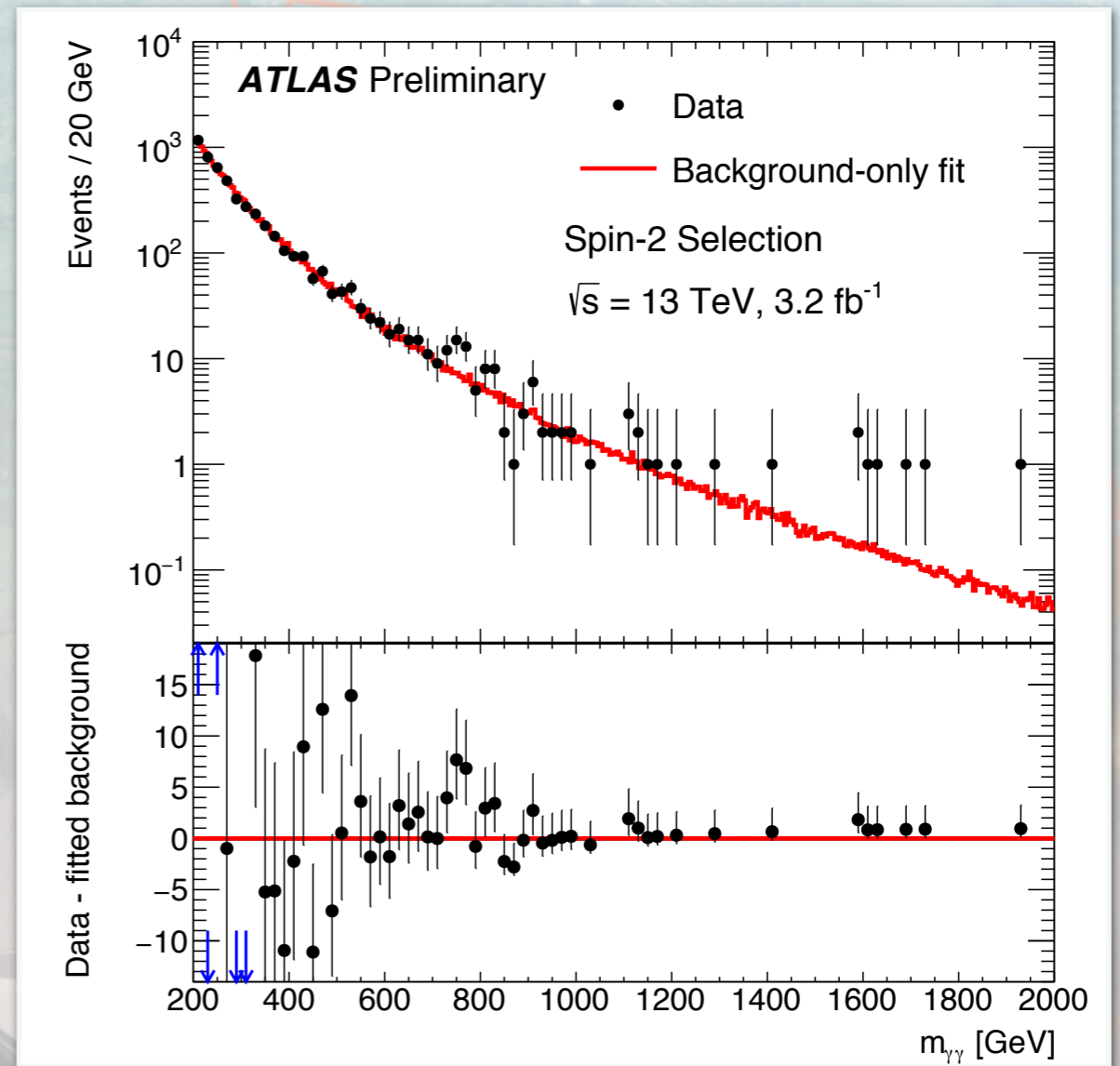
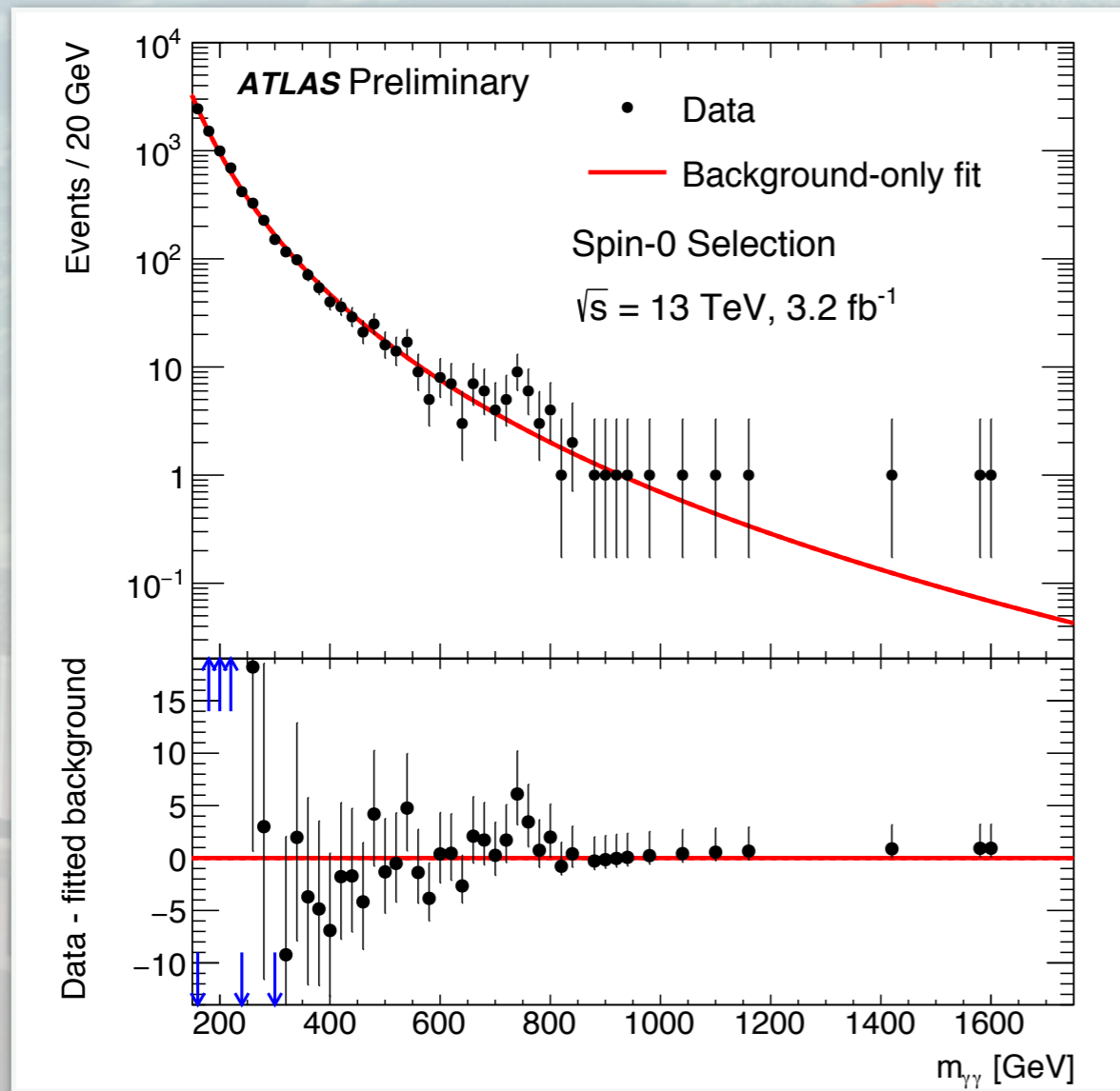


CMS-PAS-B2G-16-007



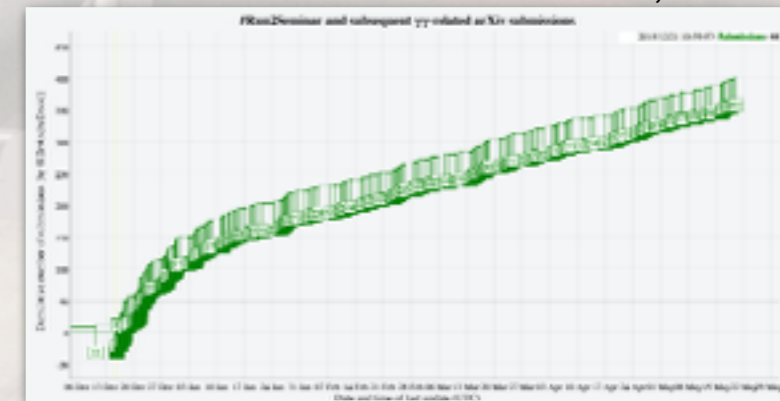
And, Diphoton Resonances

ATLAS-CONF-2016-018



- Seen in both experiments
 - ATLAS: local significance $> 3.5\sigma$, global significance $\sim 2\sigma$
 - CMS: local significance $\sim 2.6\sigma$, global significance $< 1.2\sigma$
 - ▶ CMS had $\sim 25\%$ less data than ATLAS with magnetic field

Number of theory papers as a function of time since seminar in December 15, 2015



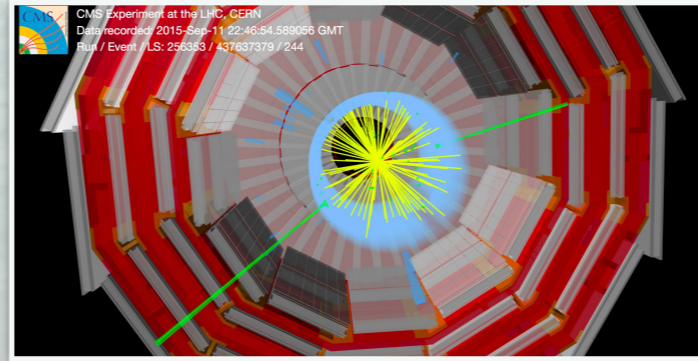
Improvements

CMS-PAS-EXO-16-018

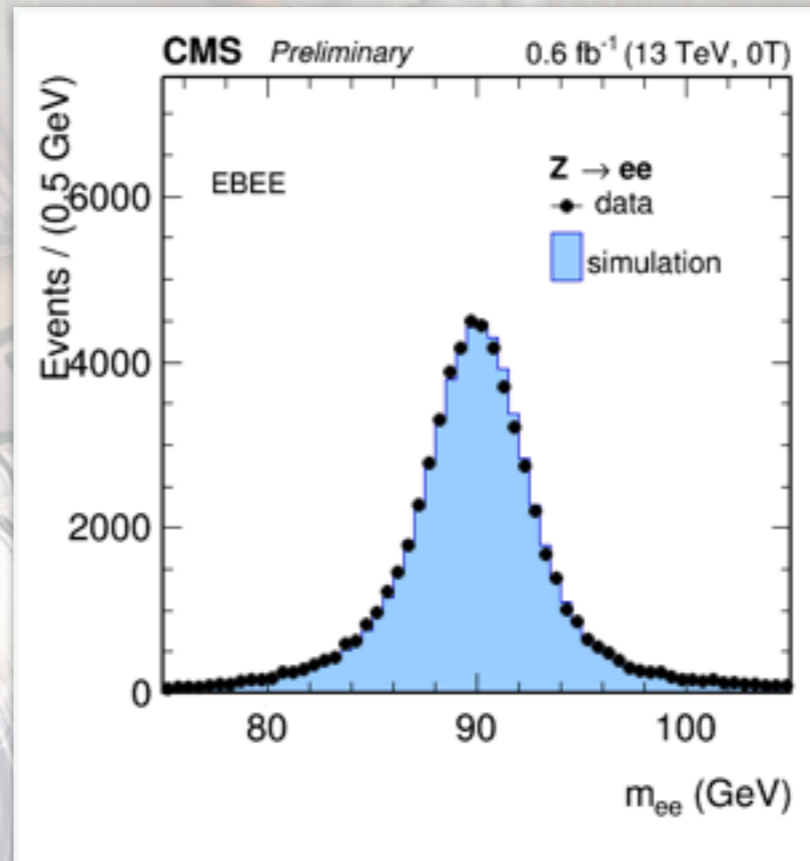
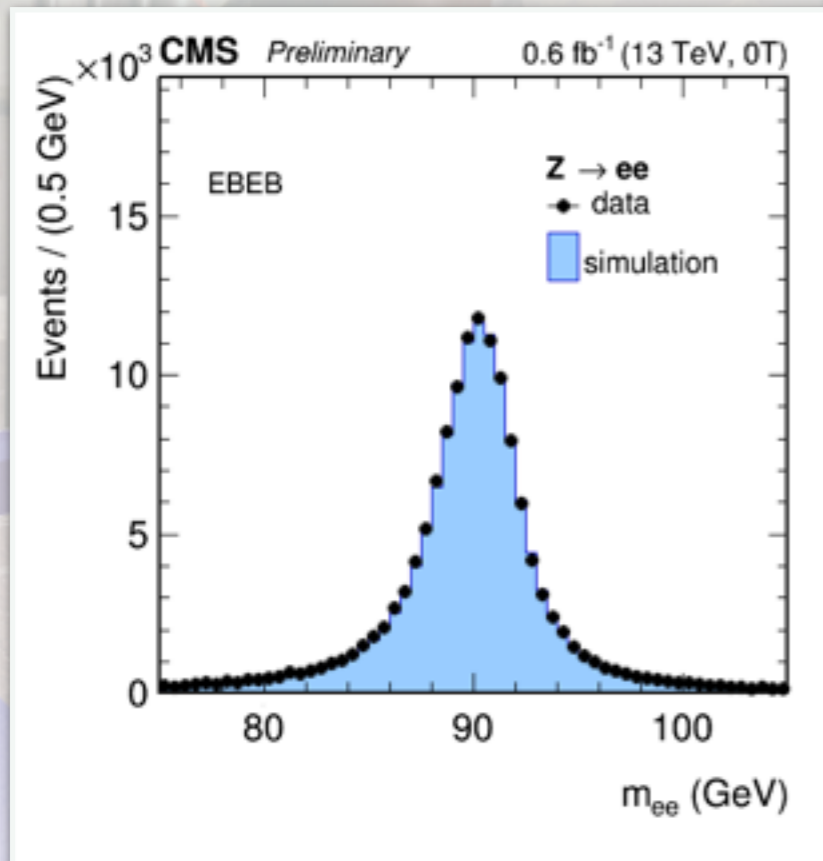
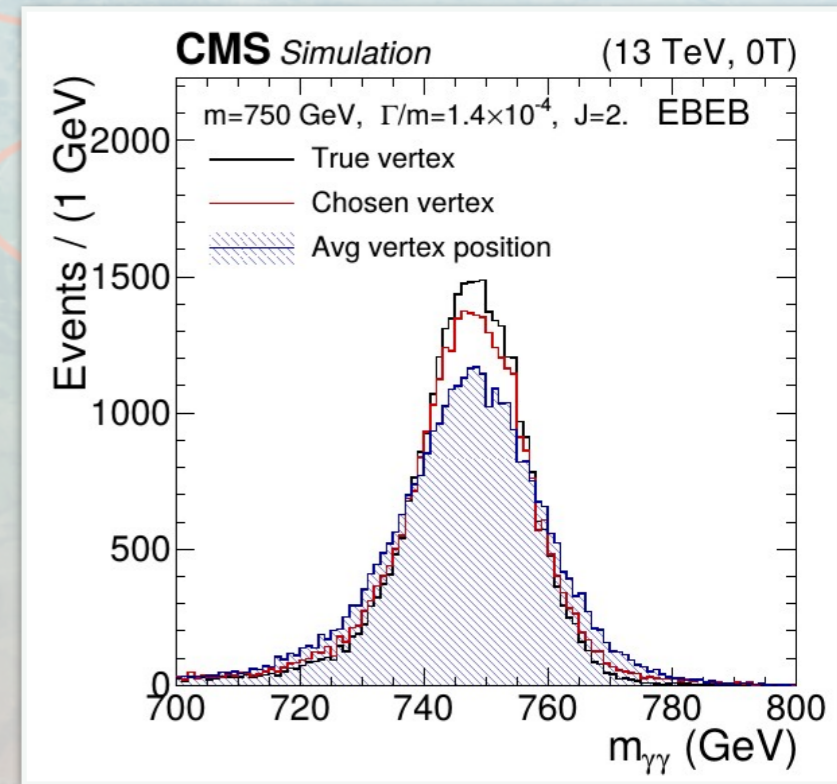
- Electromagnetic calorimeter calibration

- Including 0T data

- Con: No track momenta information
- Pro: No energy spread due to bremsstrahlung/conversion

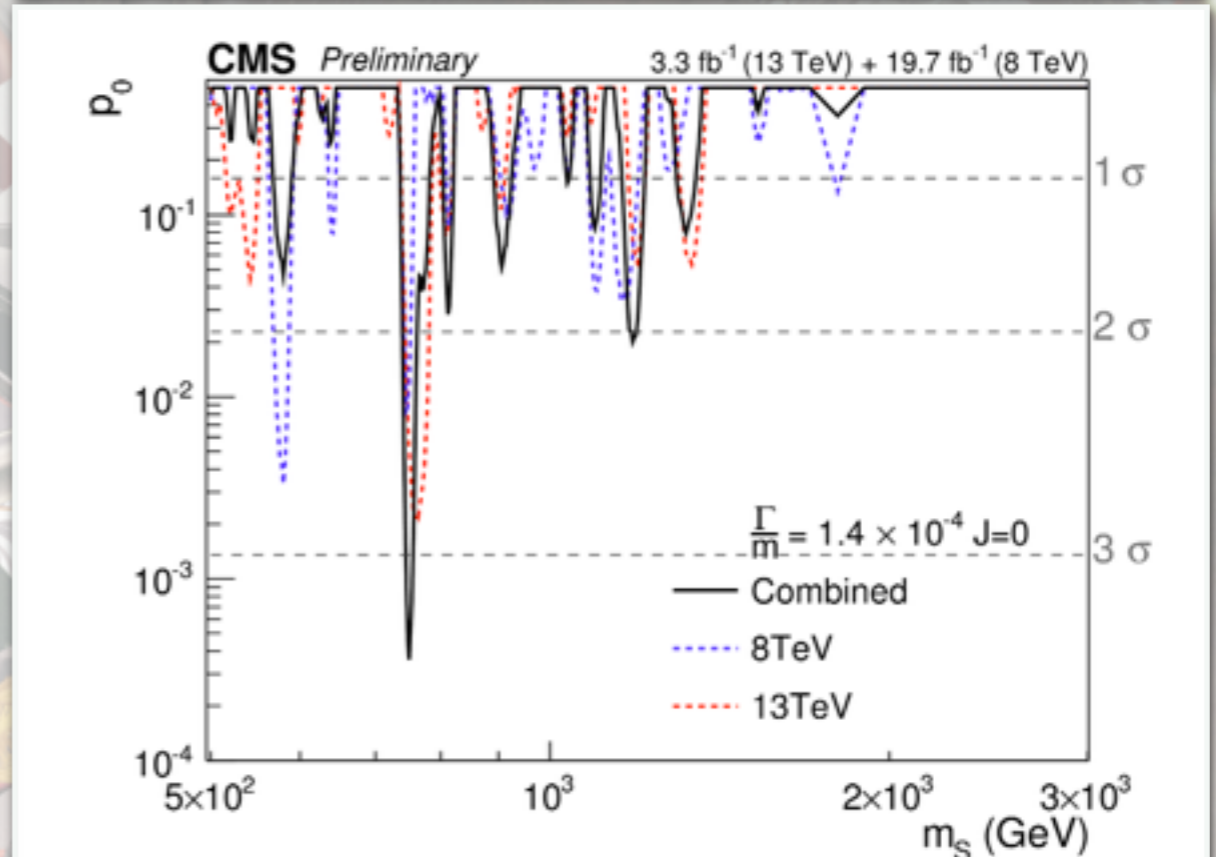
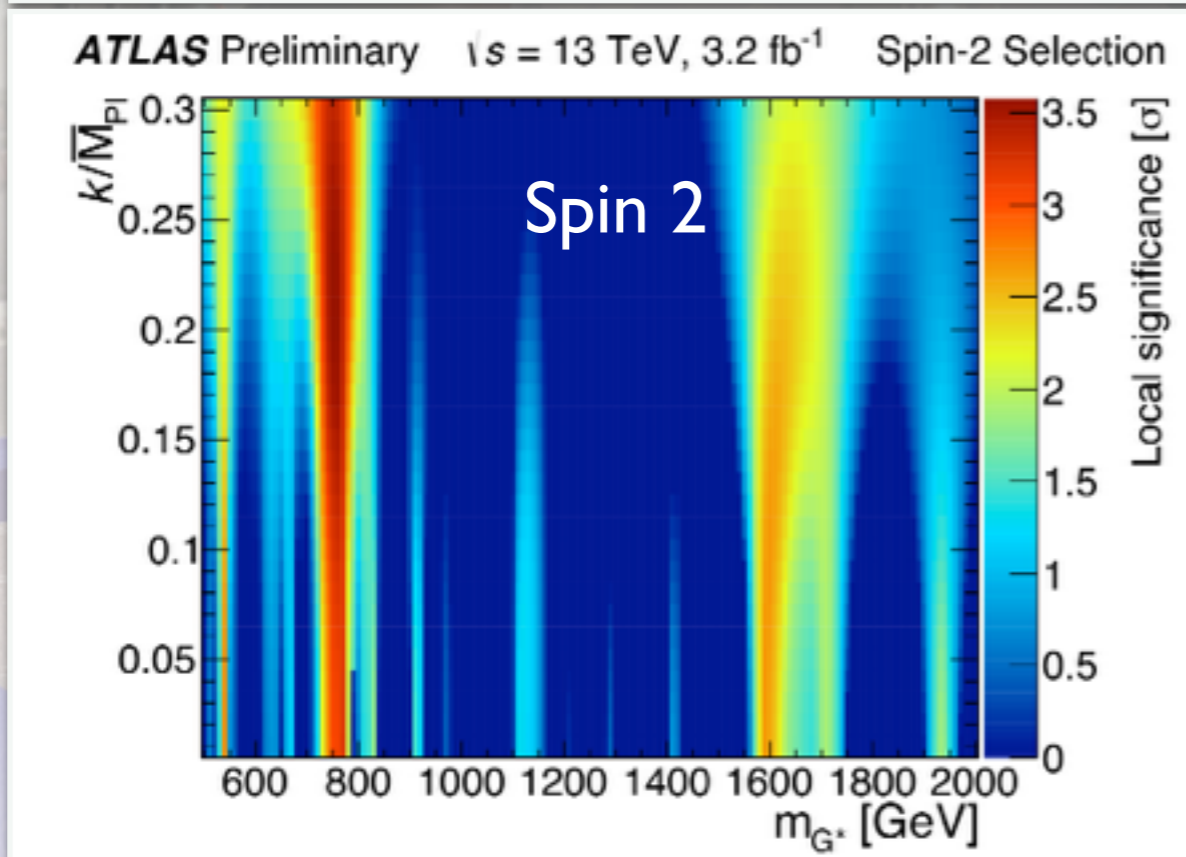
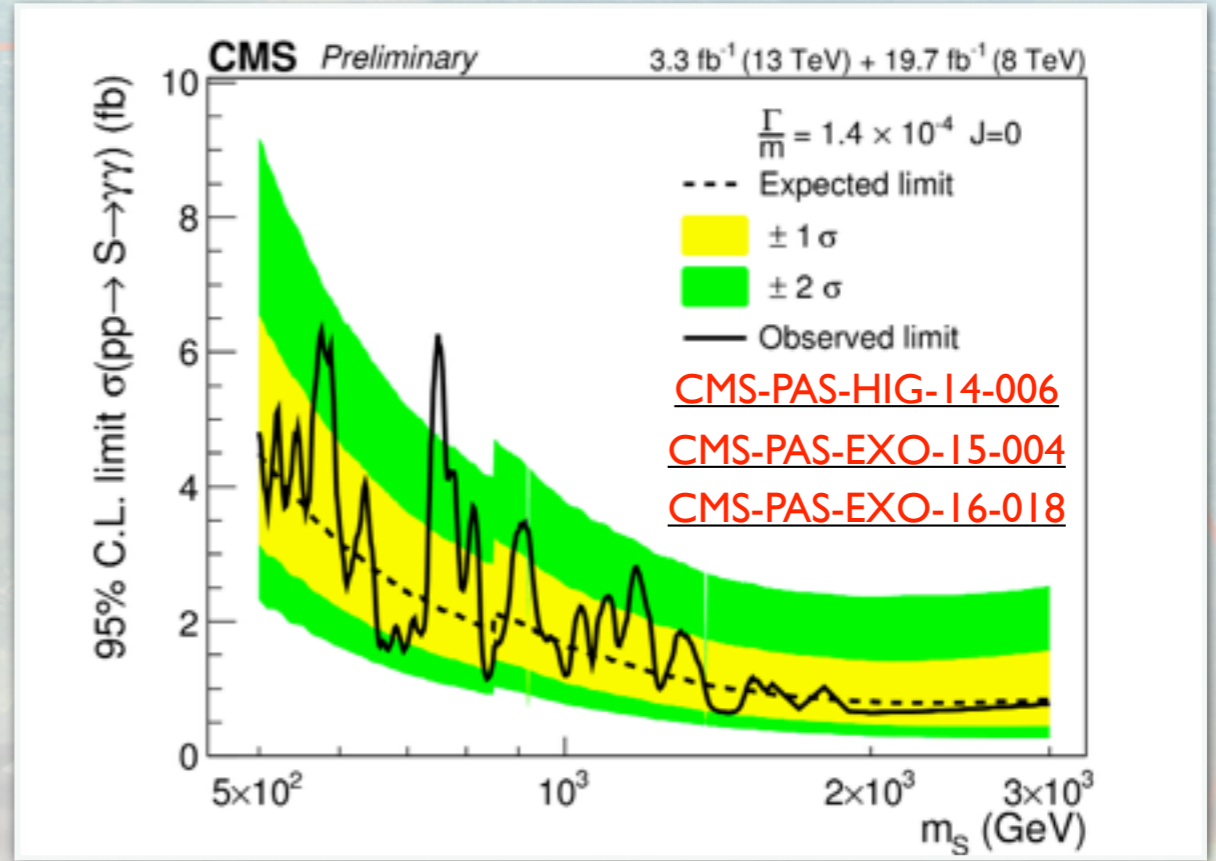
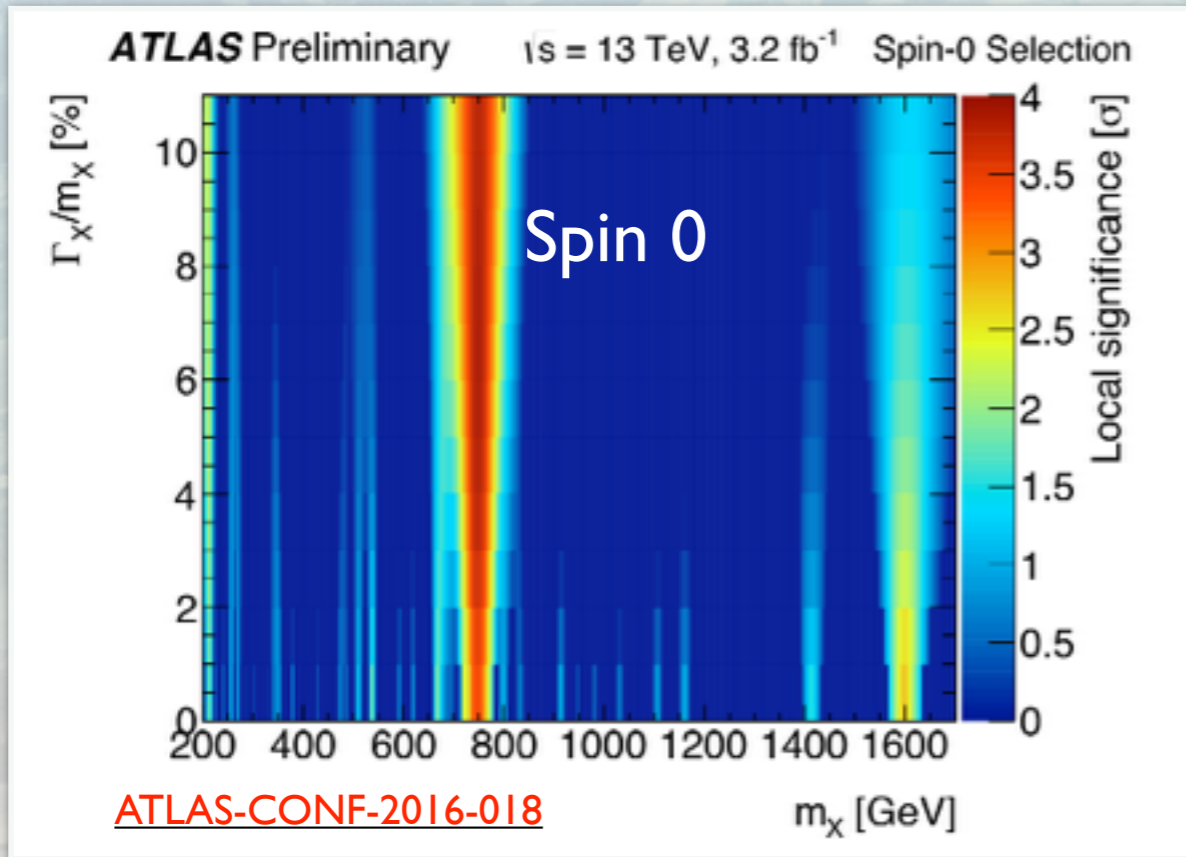


Simple track counting algorithm



Dedicated energy scale calibration with 0 T $Z \rightarrow ee$ events

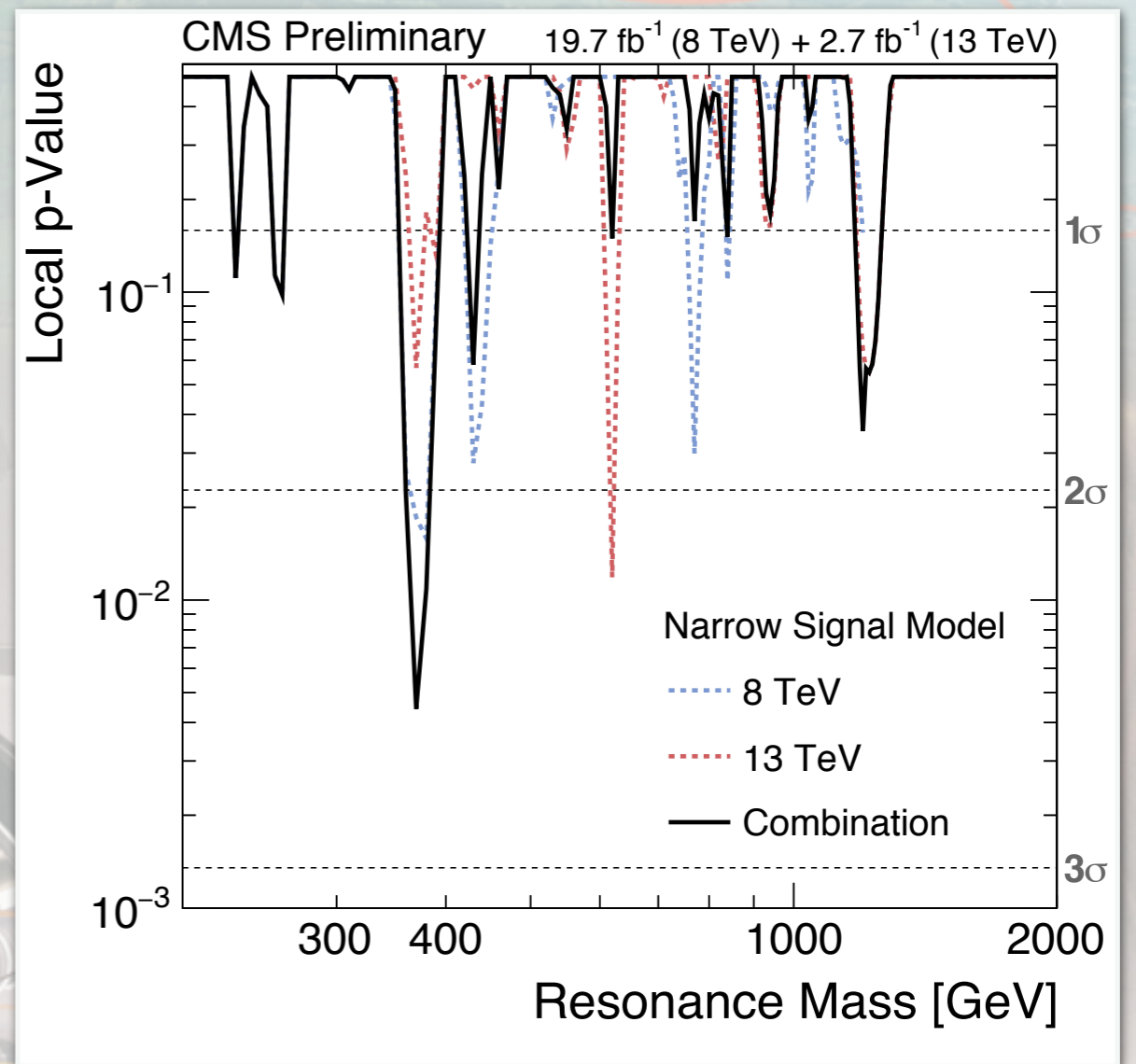
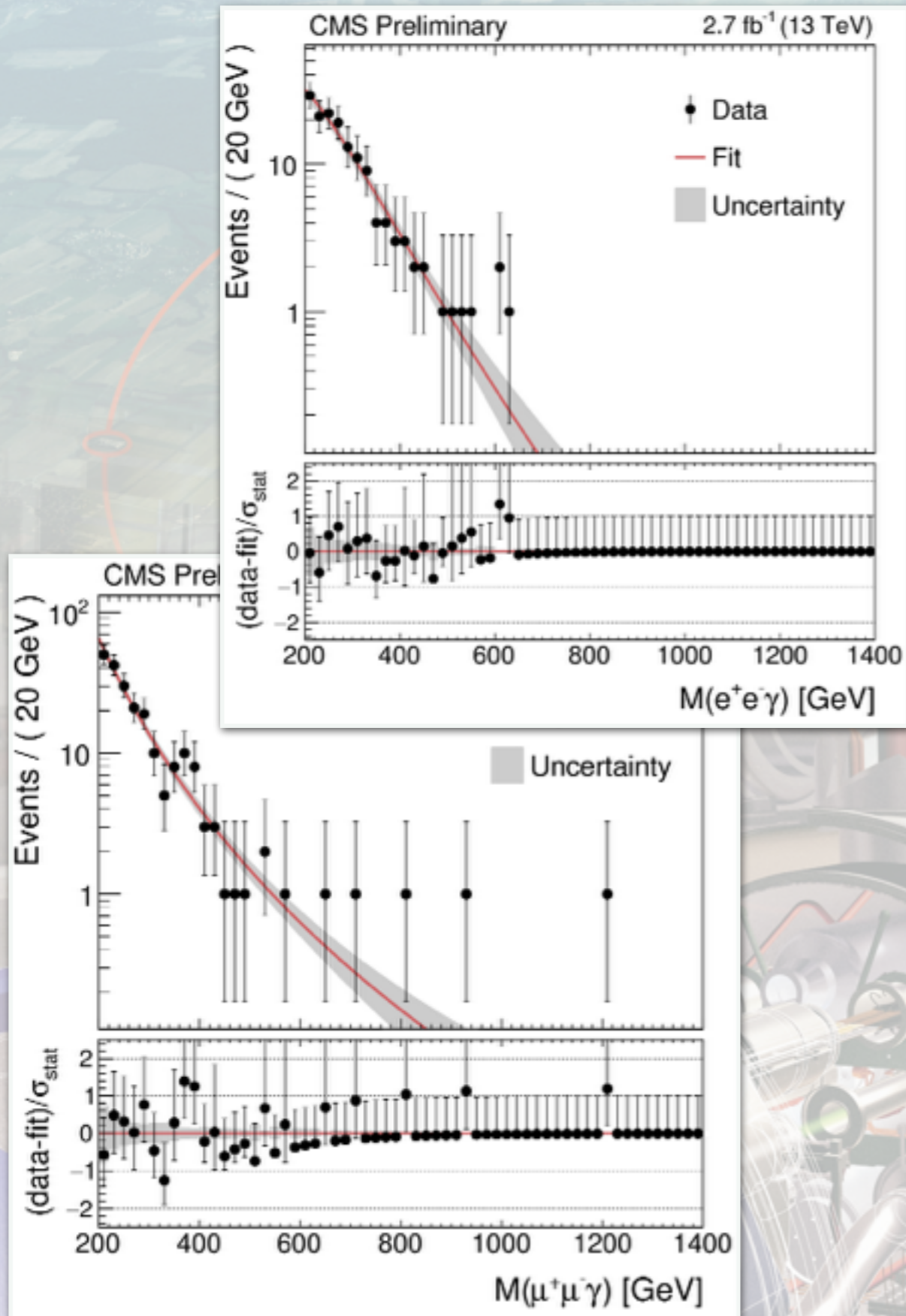
Current Picture of the Excess



What about $X \rightarrow Z\gamma$?

Leptonic Z decay

8TeV and 13TeV results are combined
Fluctuation at $\sim 370\text{GeV}$ corresponds to 2.6σ (local) and $< 1\sigma$ (global) significance



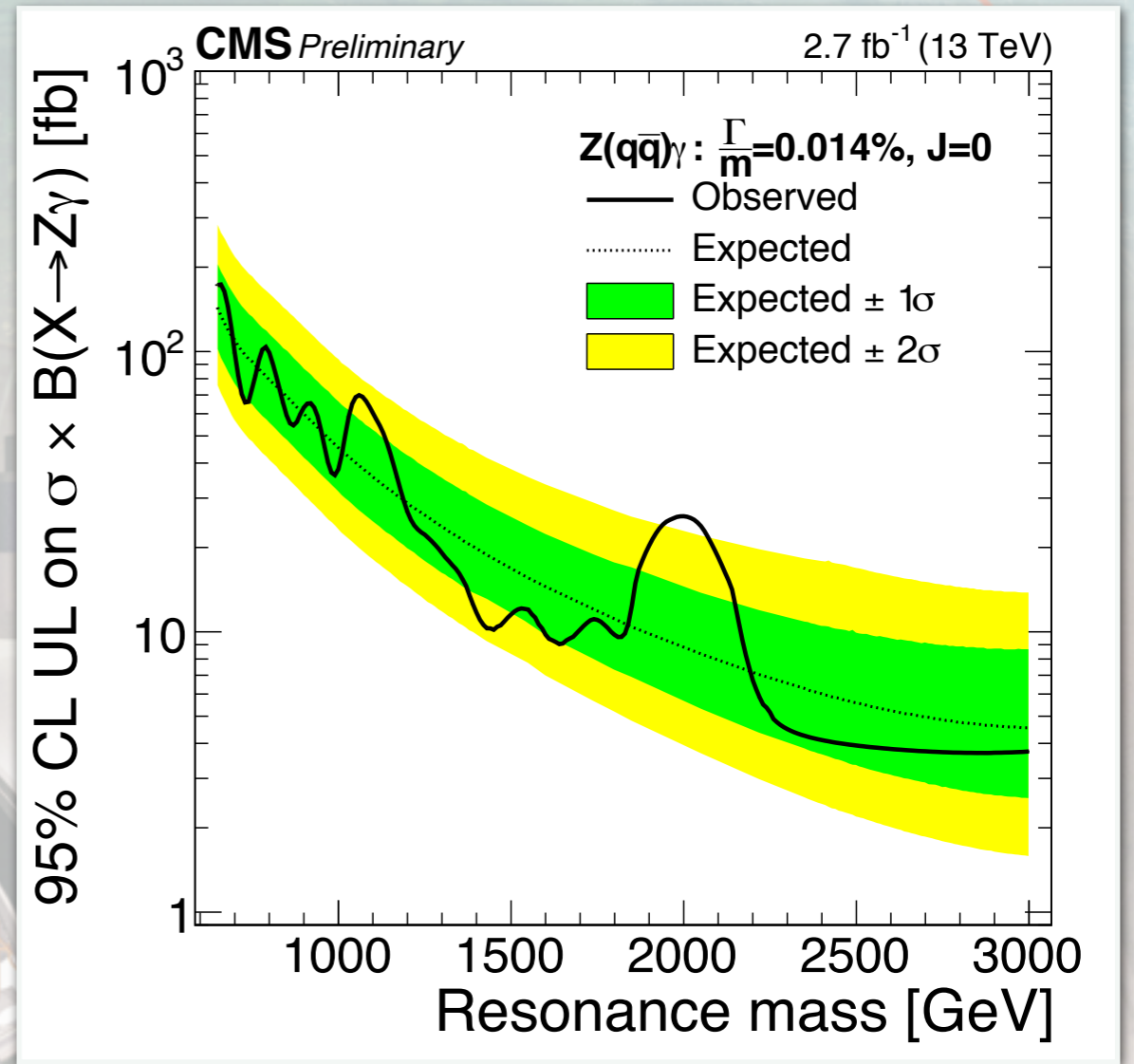
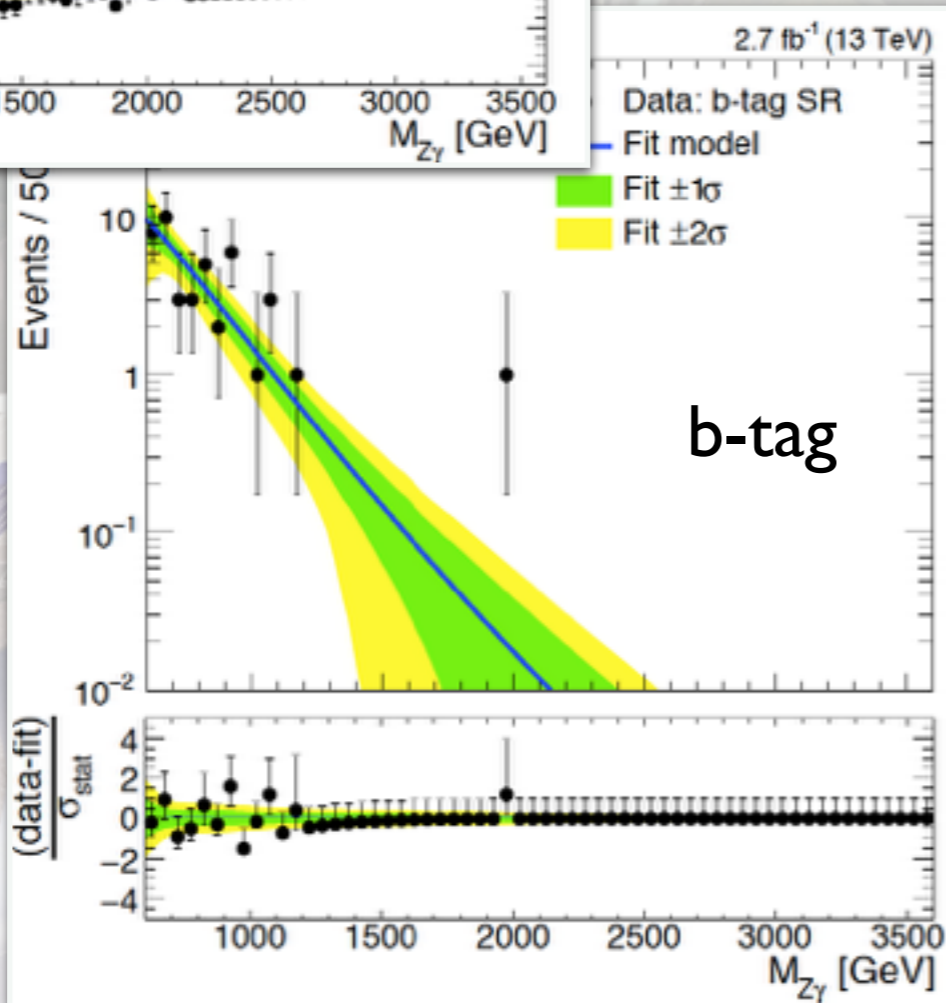
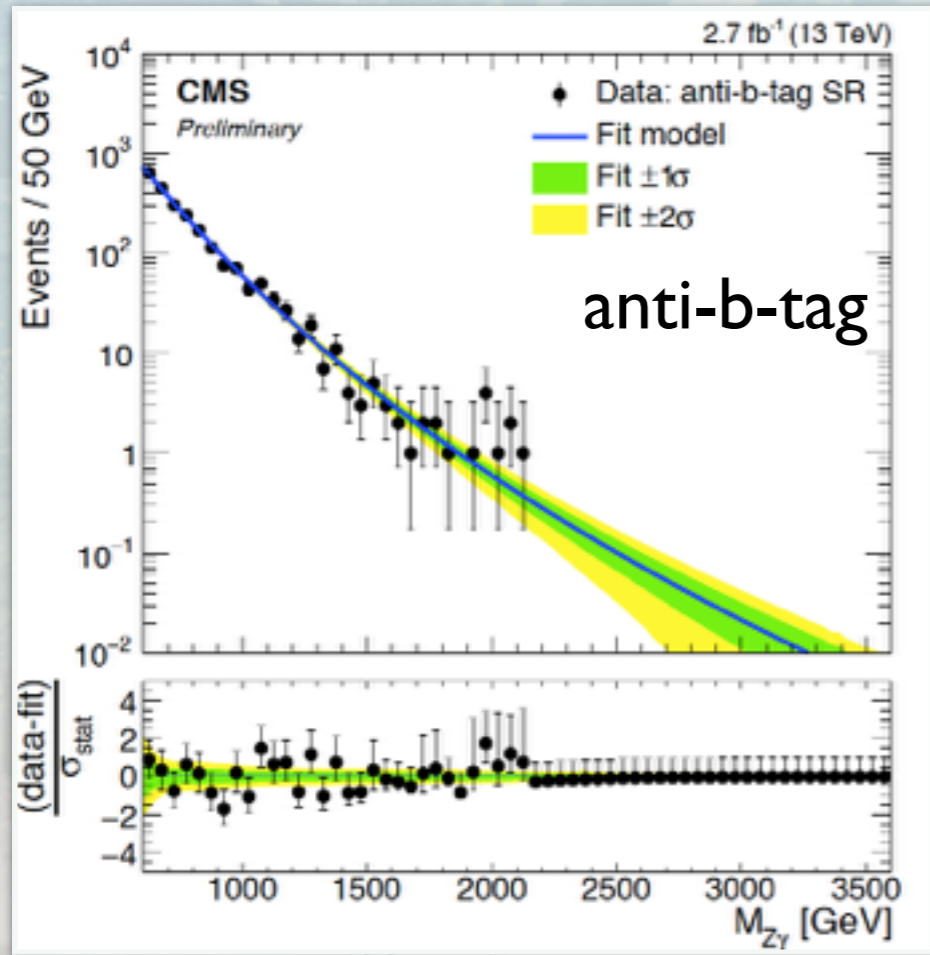
[CMS-PAS-EXO-16-019](#)

[CMS-PAS-EXO-16-021](#)

What about $X \rightarrow Z\gamma$?

Hadronic Z decay

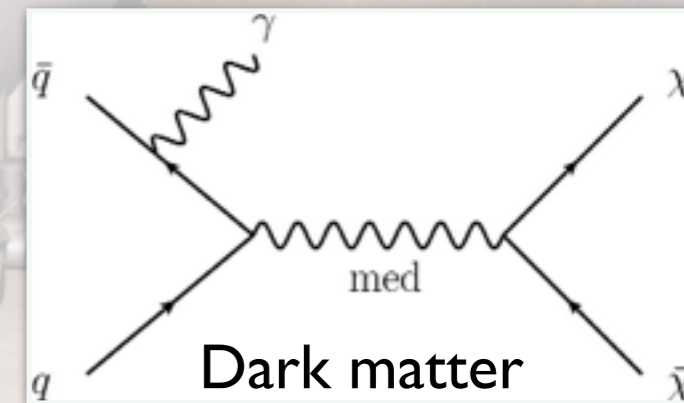
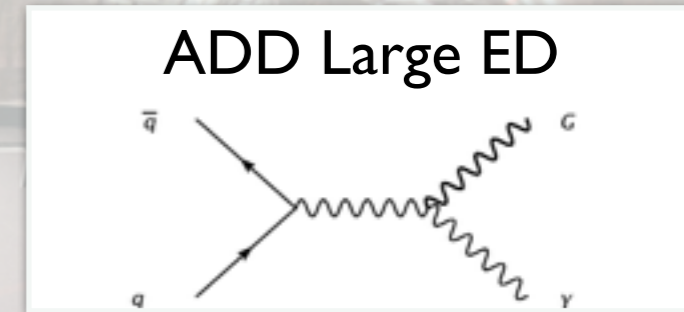
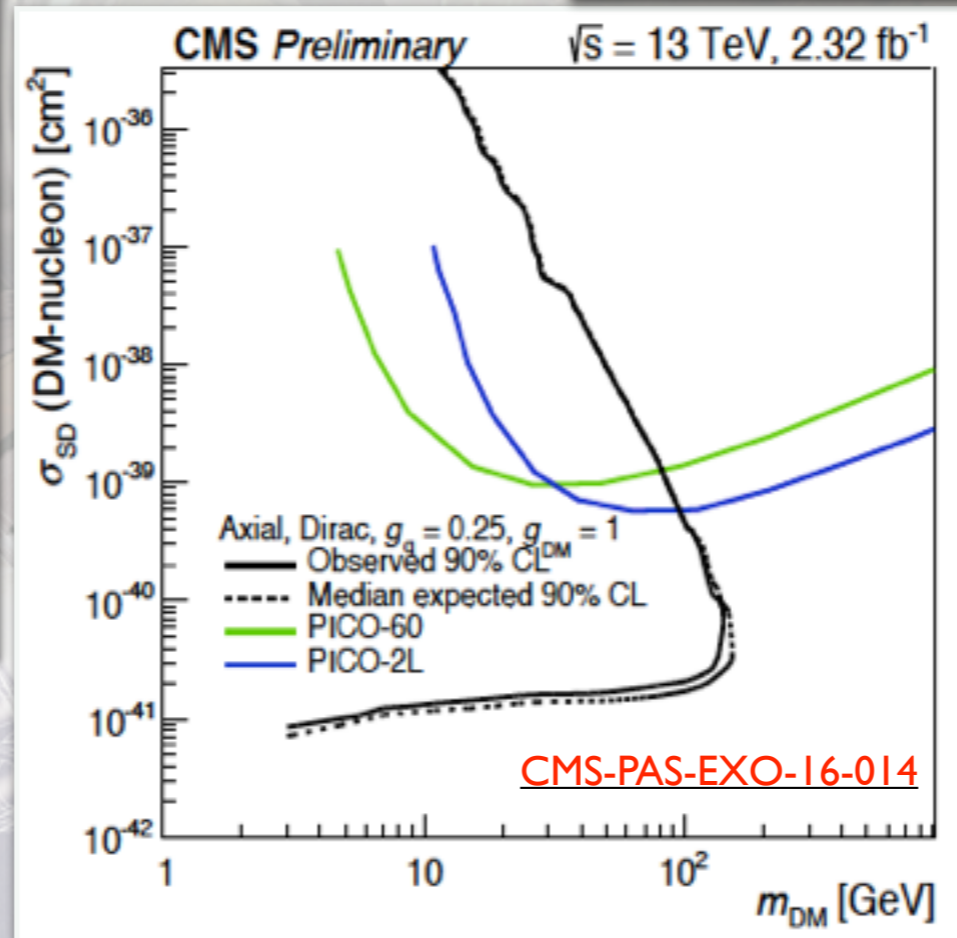
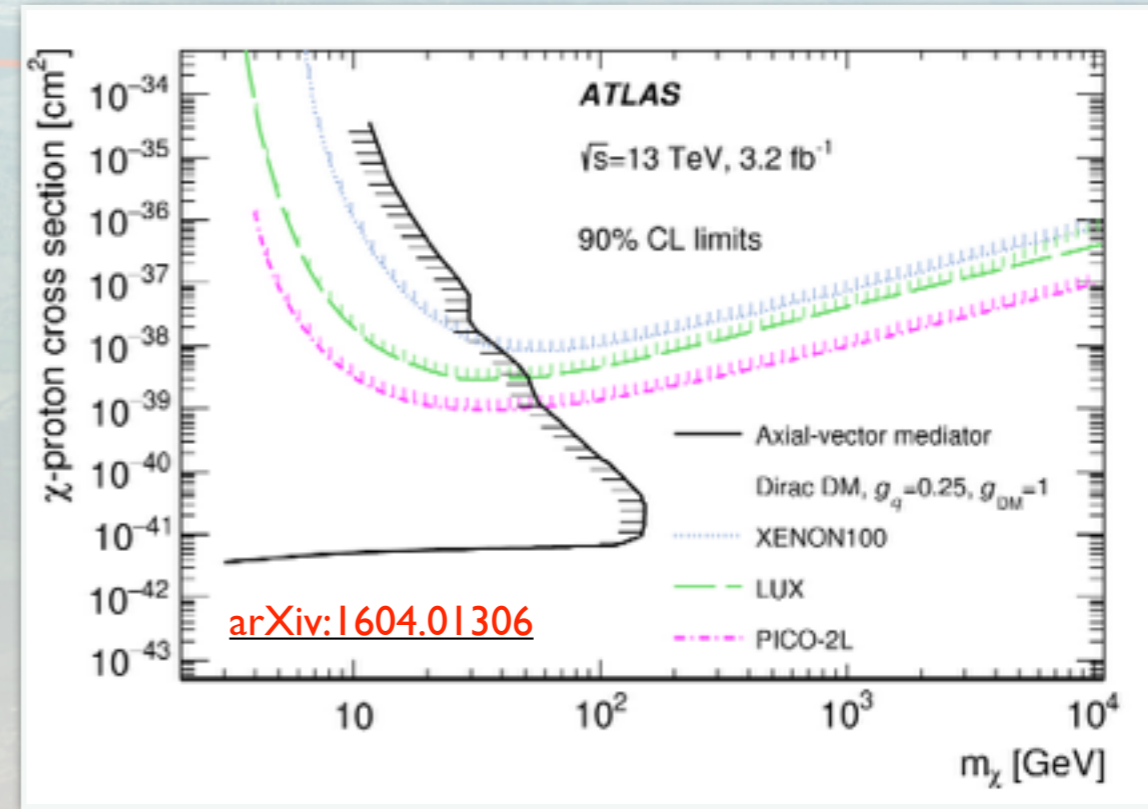
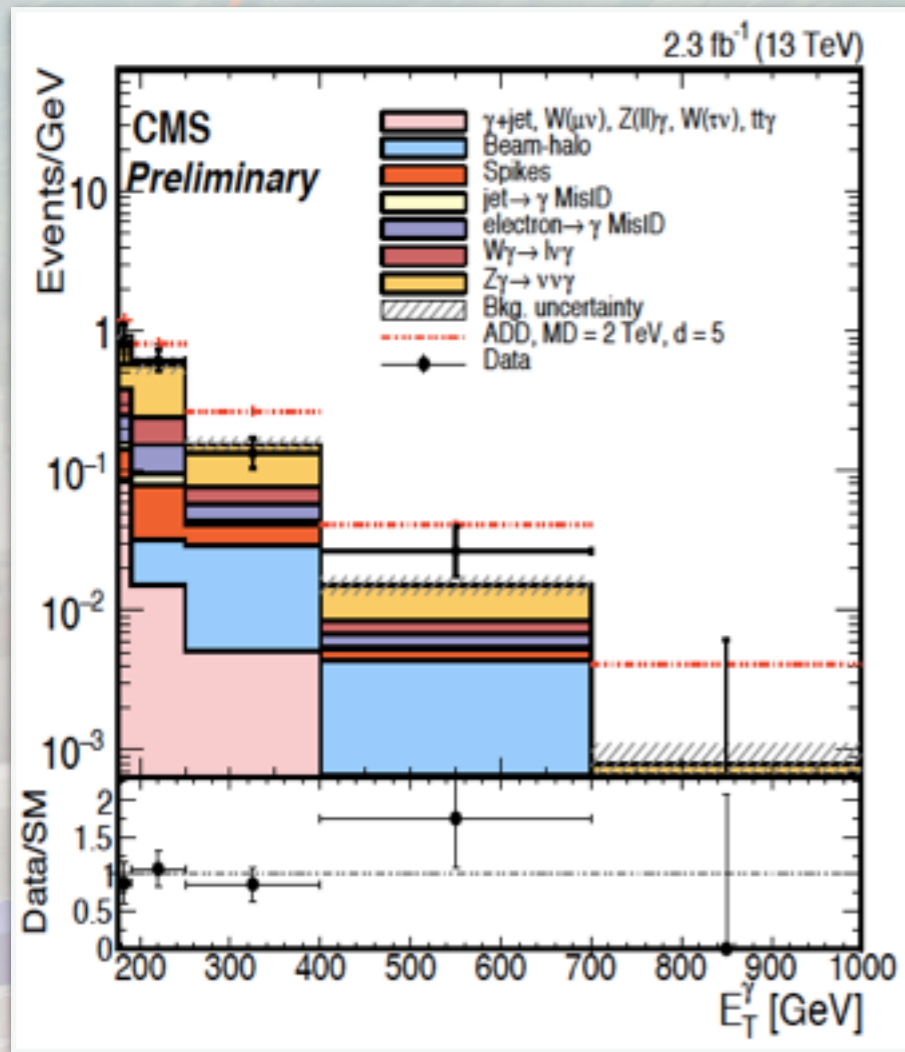
Anti-b-tag and b-tag categories are combined



CMS-PAS-EXO-16-020

Mono-photon Search

- Sensitive to
 - Extra dimensions and dark matter search
 - Also, $X \rightarrow Z\gamma \rightarrow \nu\nu\gamma$ search



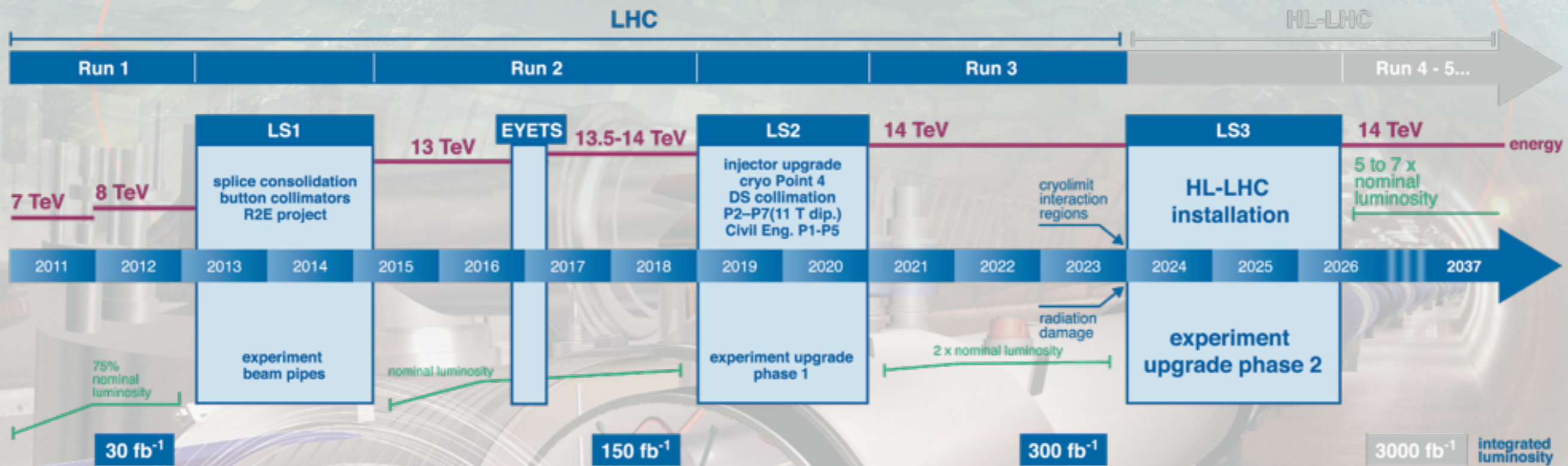
Outlook

- Successful startup in 2016
 - The LHC has successfully resumed colliding protons at 13 TeV CME
 - The ATLAS and CMS detectors are in great shape to collect delivered data
- First 13 TeV data from 2015 ($\sim 3/\text{fb}$) analyzed to large extent
 - The SM still in good shape
 - Search for BSM physics is ongoing with the full speed
 - Excesses from Run I searches are not (yet?) confirmed or fully disproved
 - New interesting, mild excess in diphoton mass spectrum seen by both experiments
- It is going to be very exciting year — the most important is to stay calm and keep working!

Additional Material

Future Plans

LHC / HL-LHC Plan



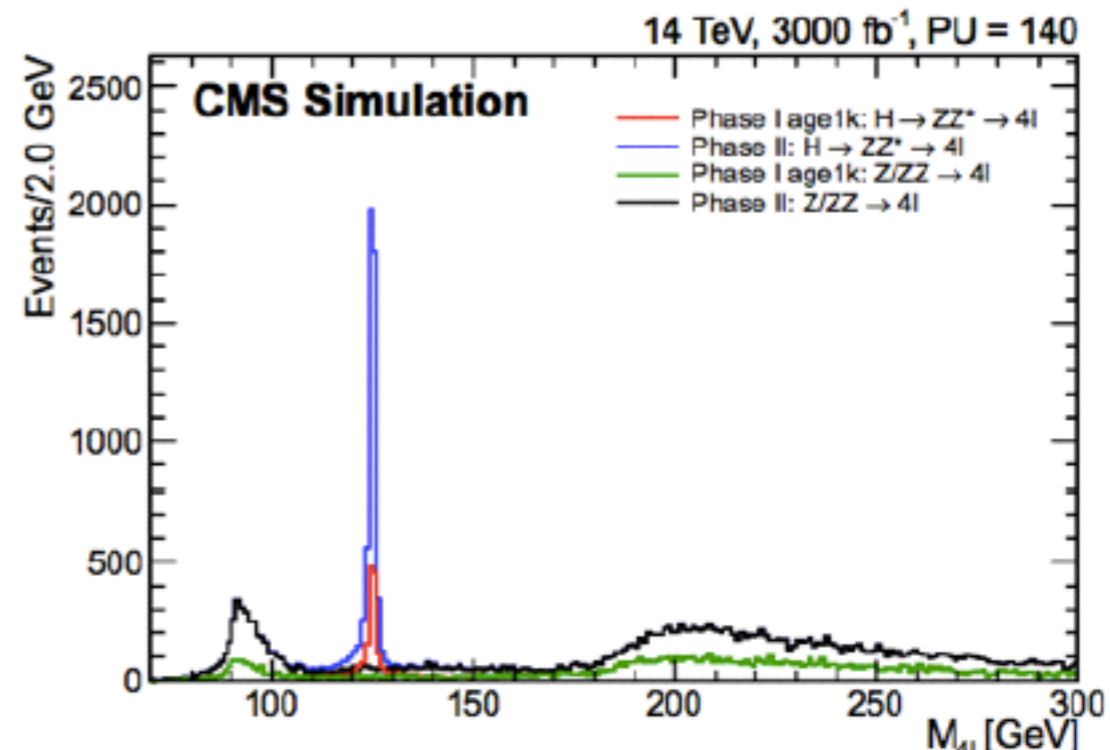
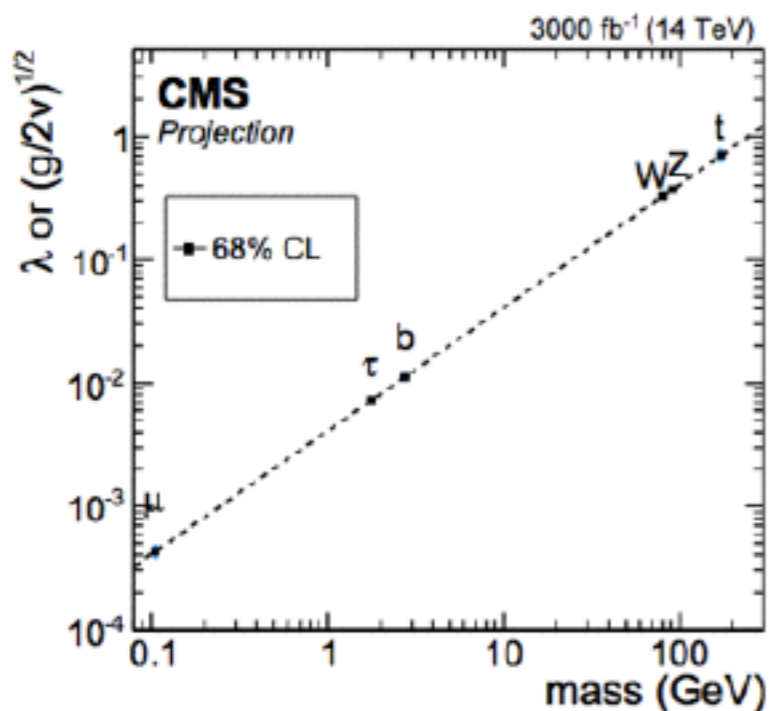
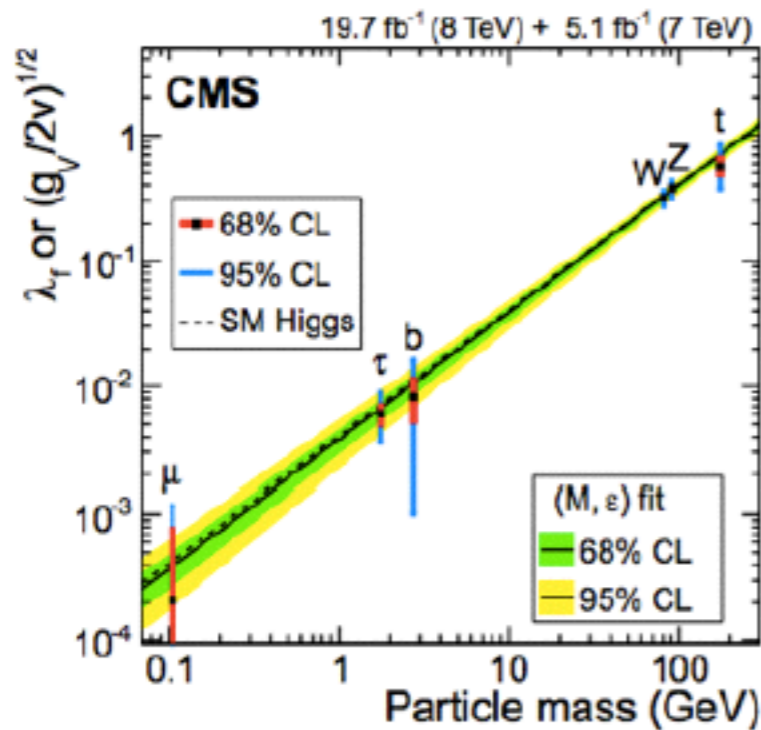
Phase I Upgrade
2015-2020

Phase II Upgrade
2024-2026

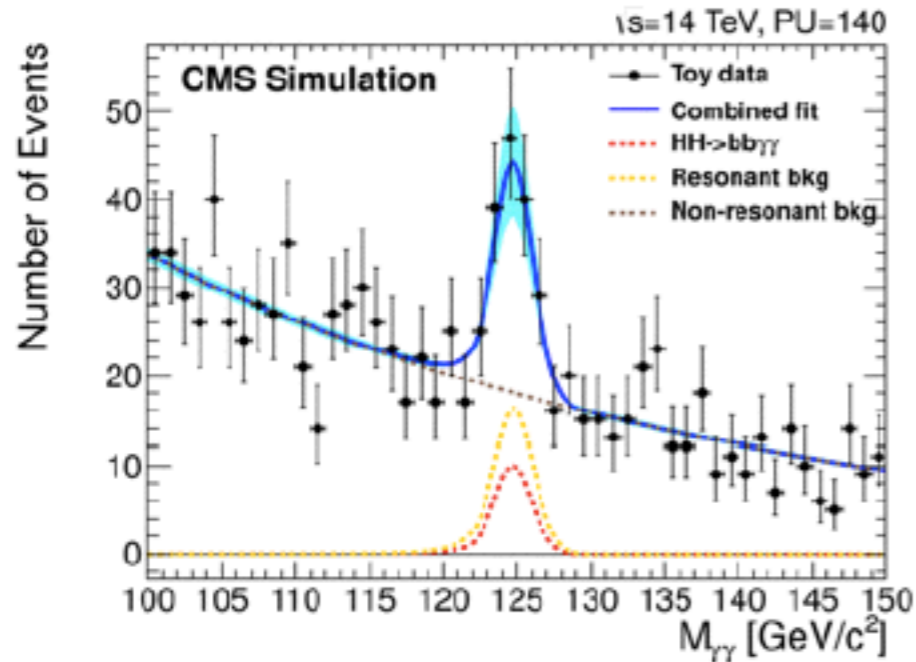
Physics opportunities at 3000/fb

Higgs

- 2-10% precision on Higgs couplings.
- Coupling to the 2nd generation fermions will be probed for the first time by measuring the Higgs boson decays to two muons.
- Evidence of di-Higgs production (allow to study Higgs boson self coupling).



Physics opportunities at 3000/fb

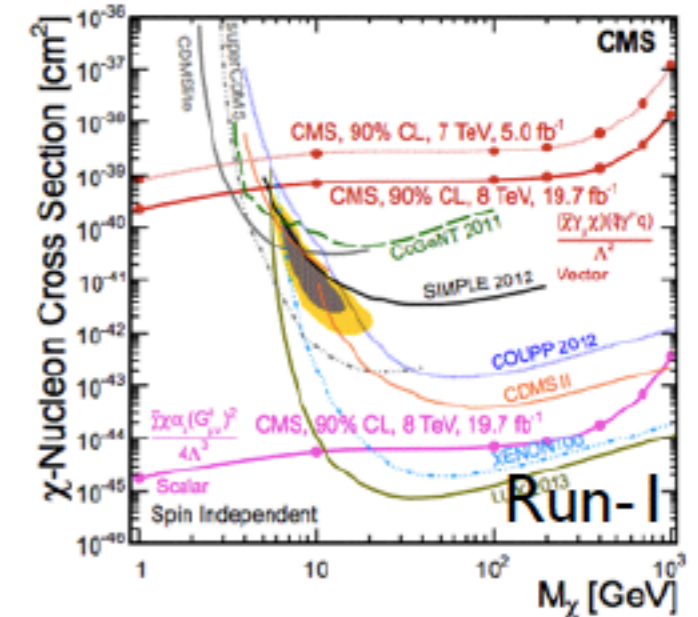
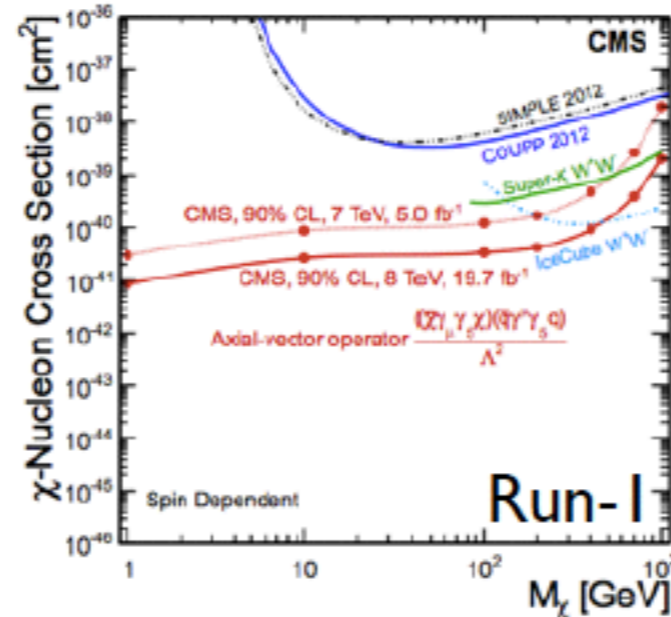
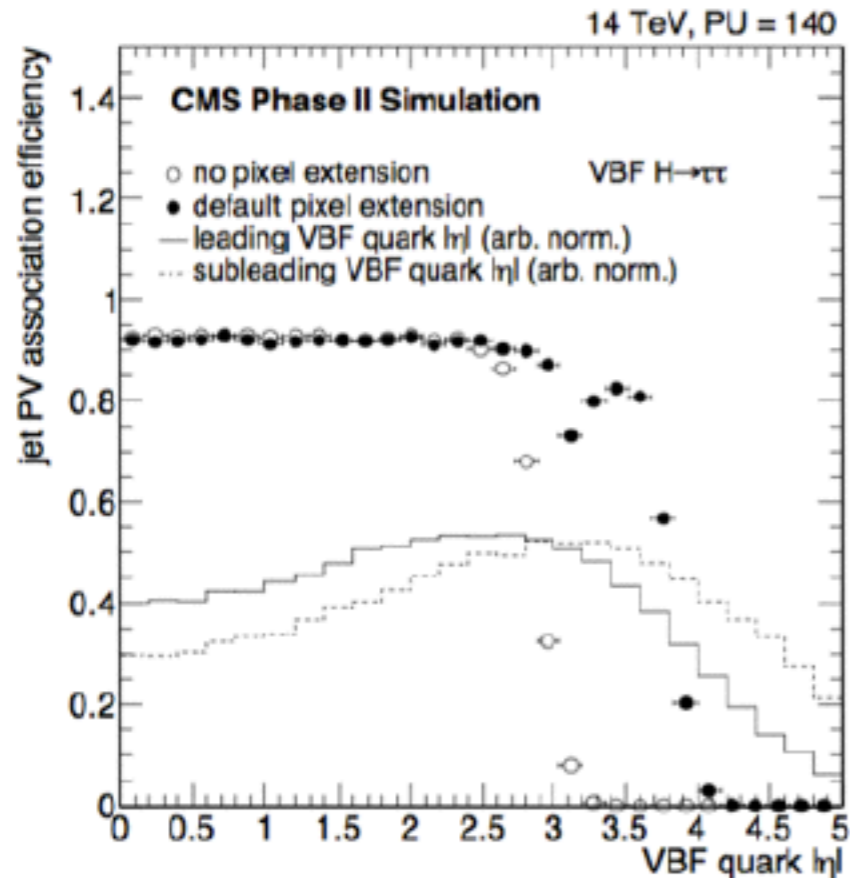


Higgs

- HH \rightarrow bb $\gamma\gamma$ with background from ZH, ttH, bbH
- VBF H \rightarrow $\tau\tau$: enabled by VBF jet tagging, τ -ID, MET resolution

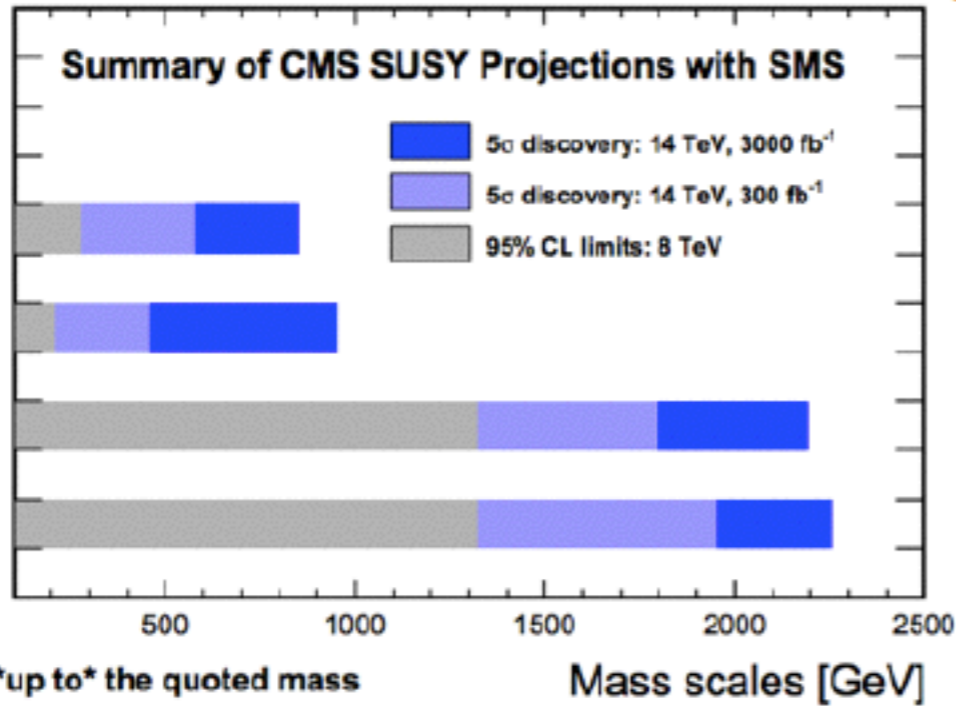
EXO

- Mono-channel to search for the Dark Matter, including MonoHiggs.

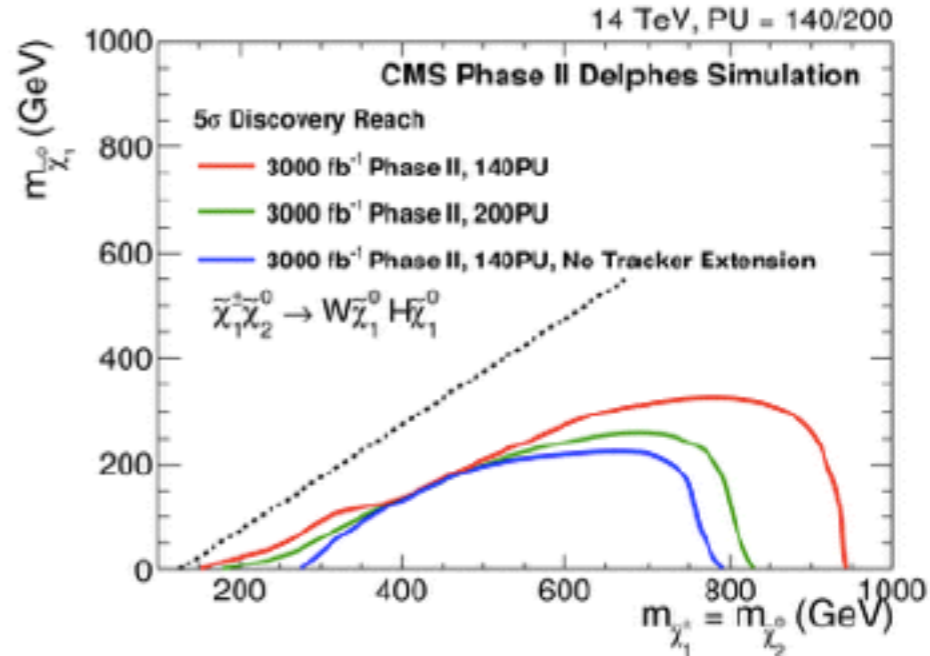


Physics opportunities at 3000/fb

SUSY

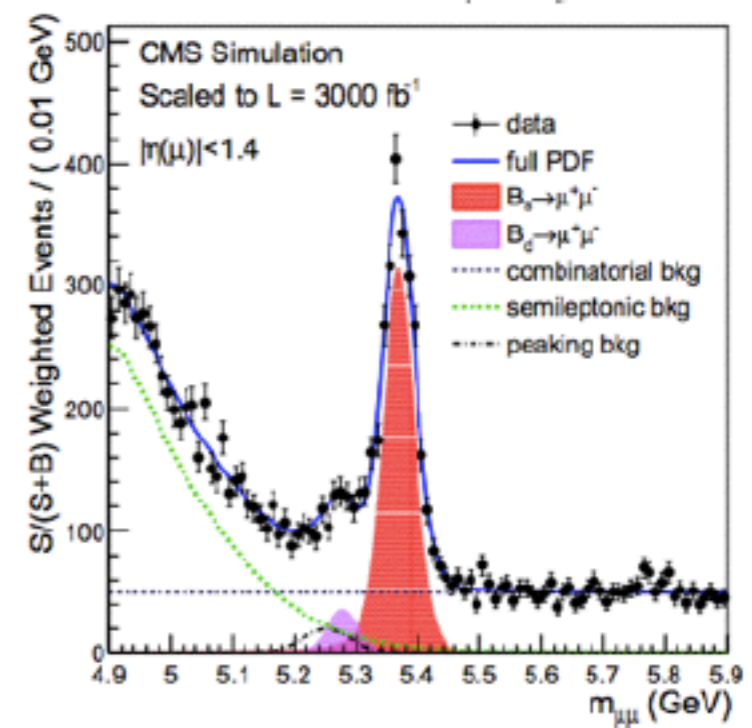
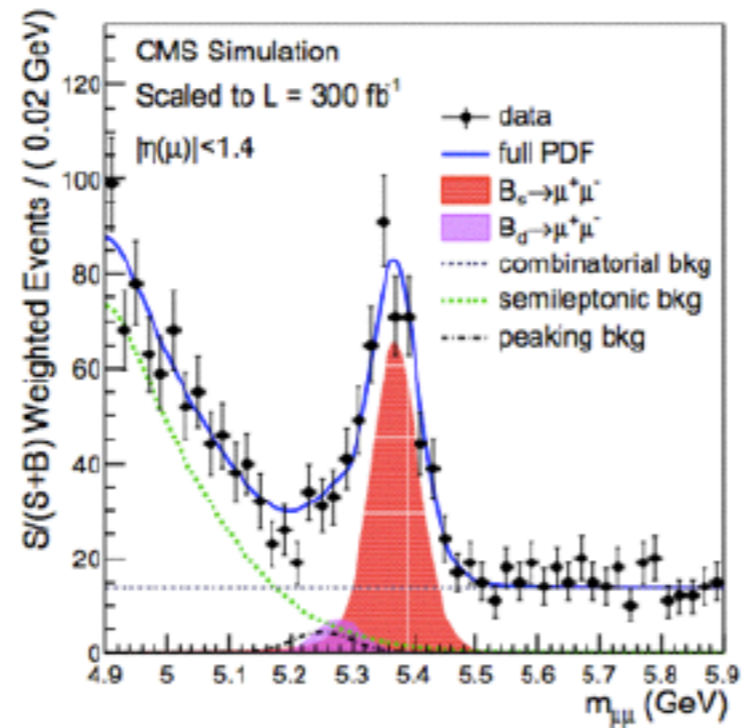


- Neutralino mass range increase - enabled by Tracker extension, b-tagging, MET



SMP

- Study rare-decay with reasonable accuracy, significance of the Bd, predicted to be 2.2σ after 300 fb^{-1} , will improve to 6.8σ with 3000 fb^{-1} .



Higgs properties from Run I

- Properties of the discovered boson

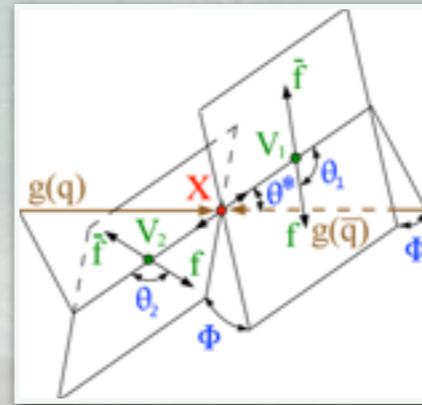
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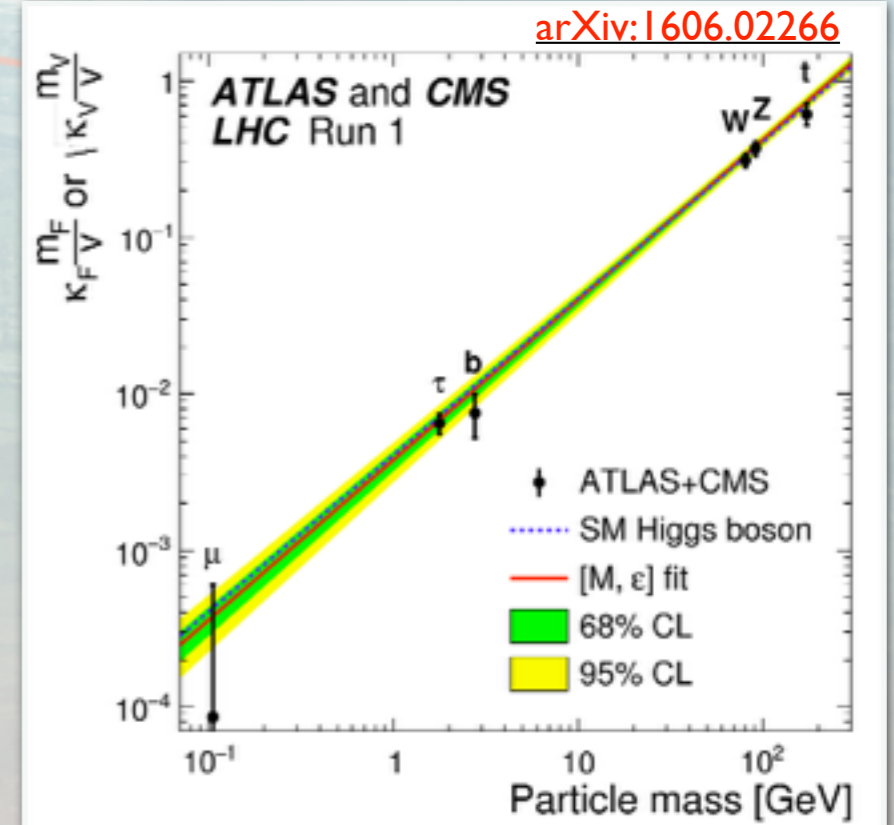
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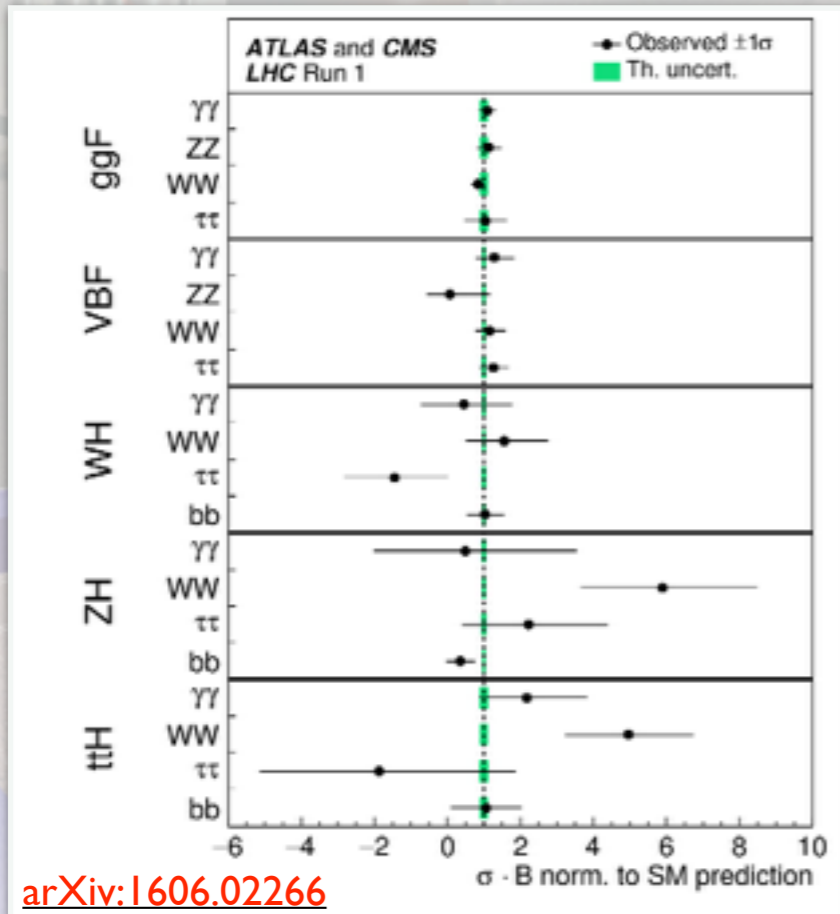
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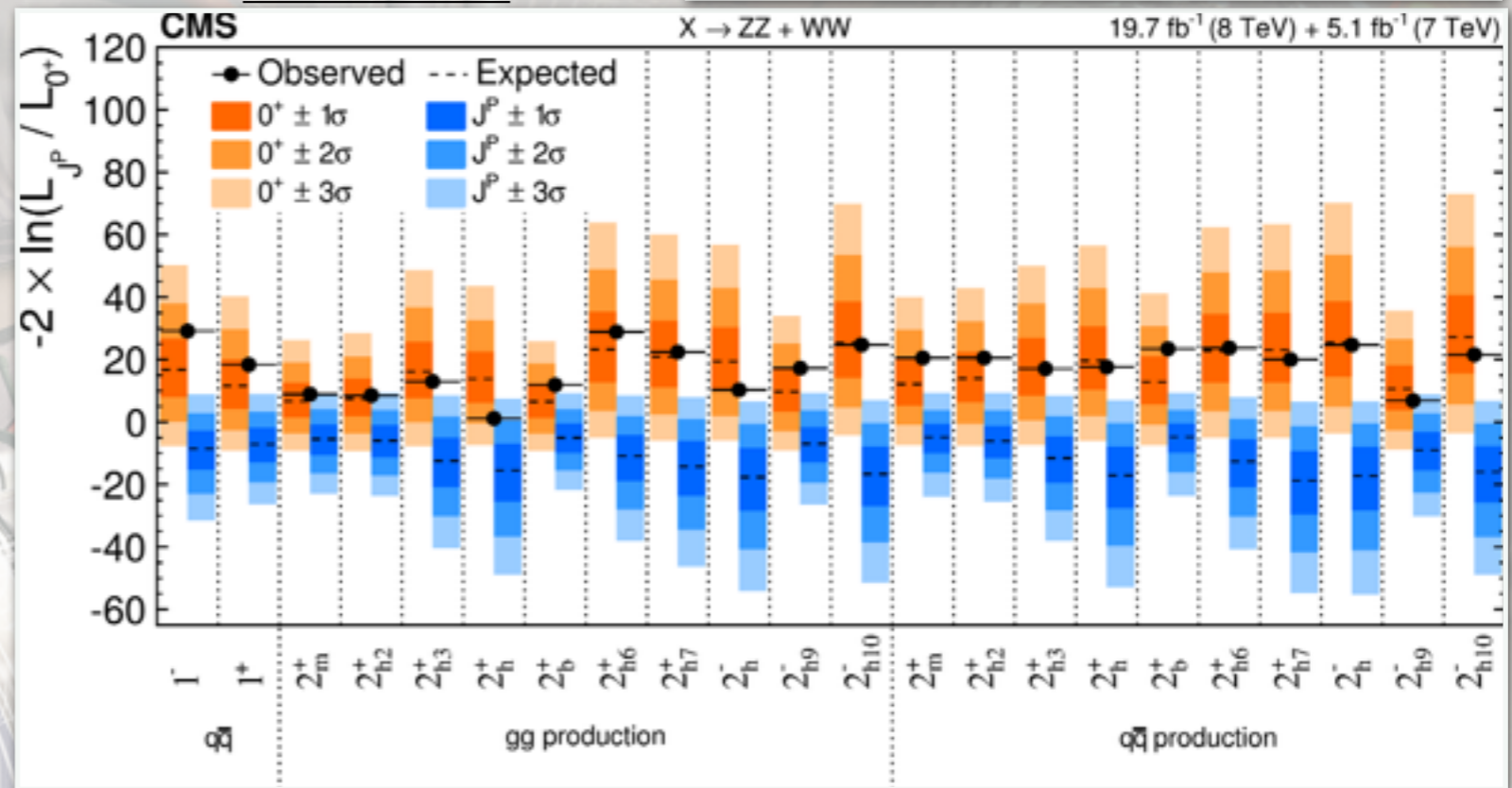
[arXiv:1411.3441](https://arxiv.org/abs/1411.3441)



[arXiv:1606.02266](https://arxiv.org/abs/1606.02266)



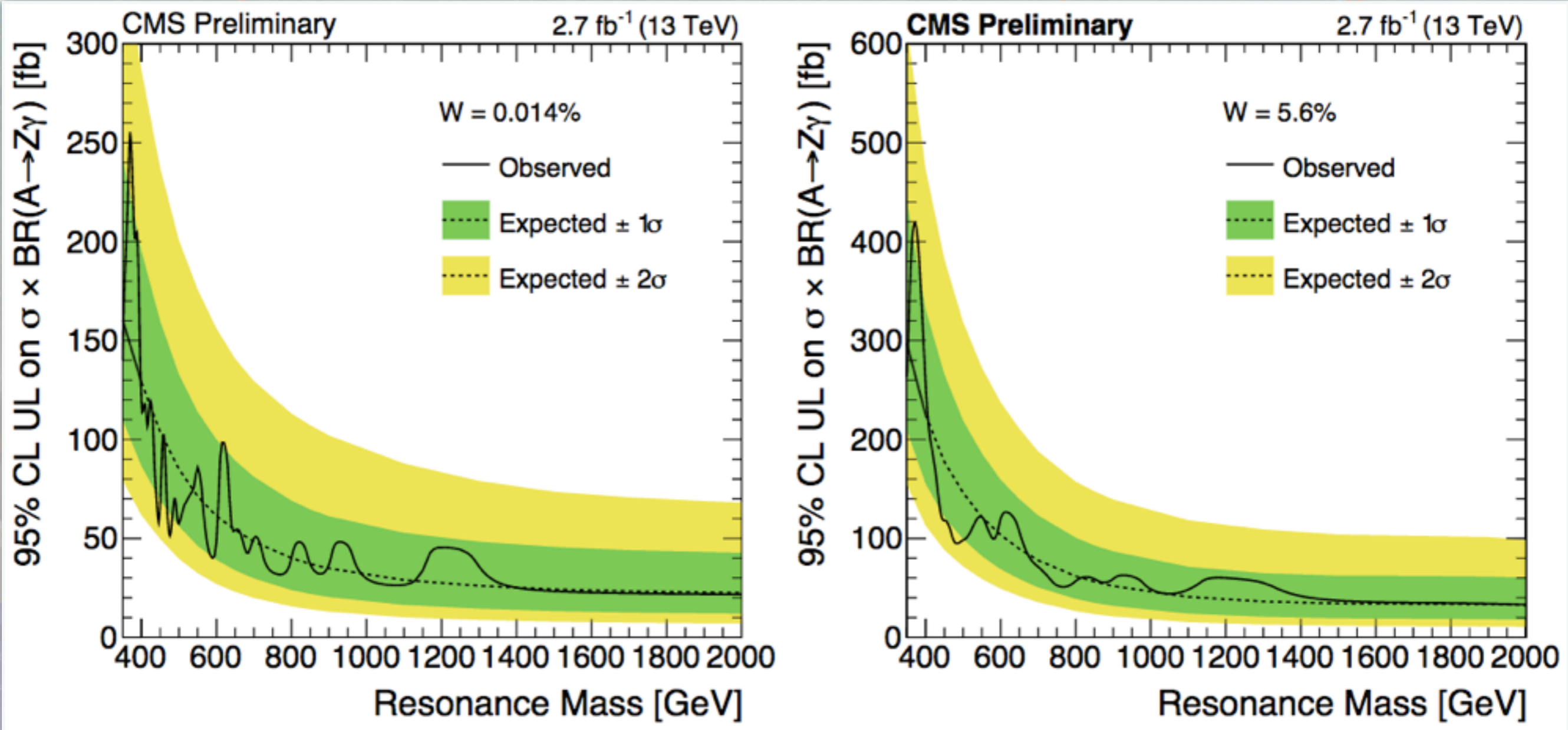
[arXiv:1606.02266](https://arxiv.org/abs/1606.02266)



$X \rightarrow Z\gamma$ in leptonic decay mode

[CMS-PAS-EXO-16-019](#)

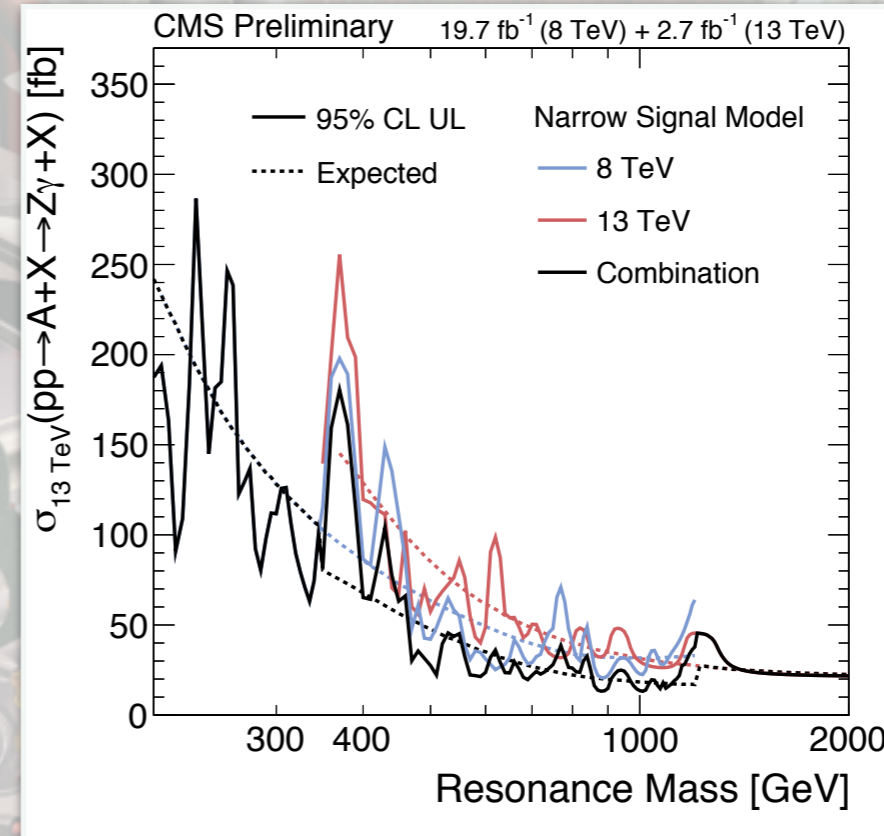
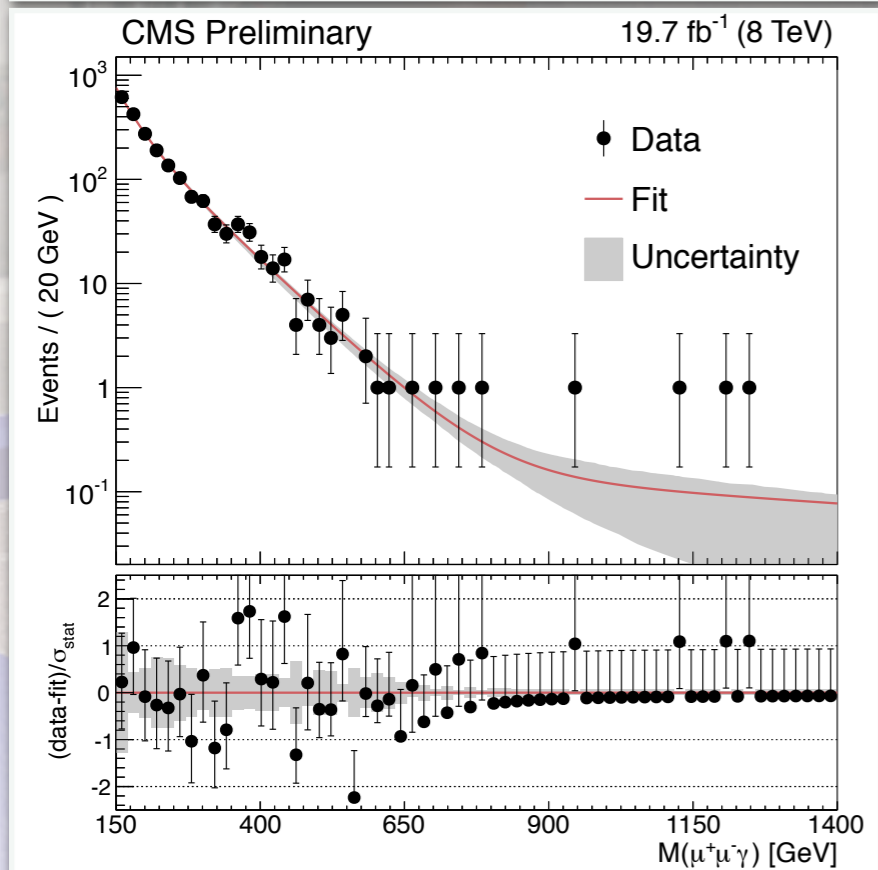
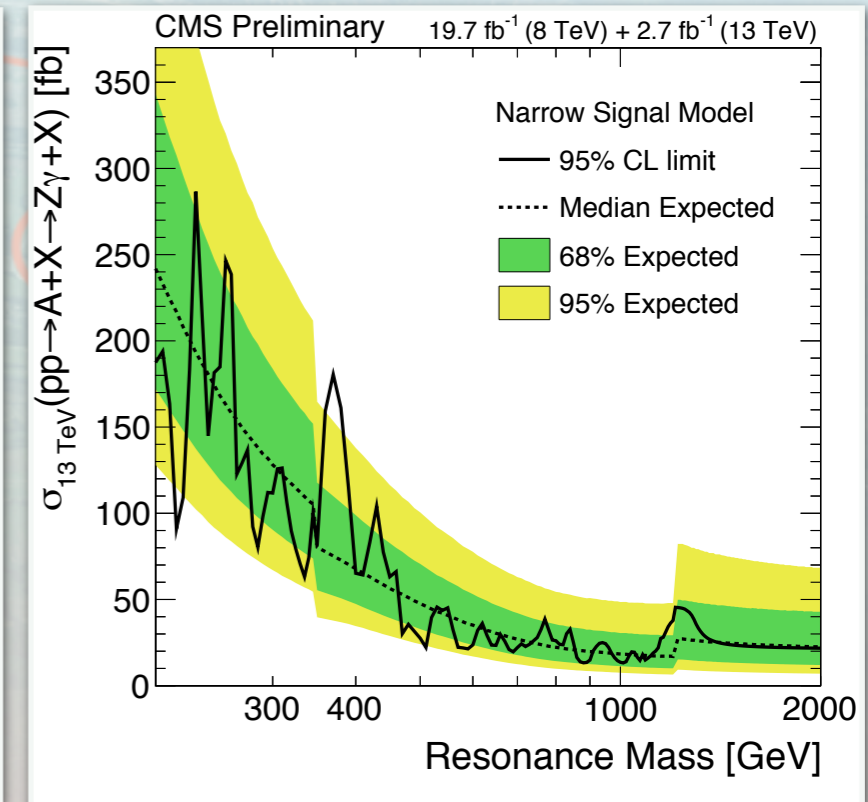
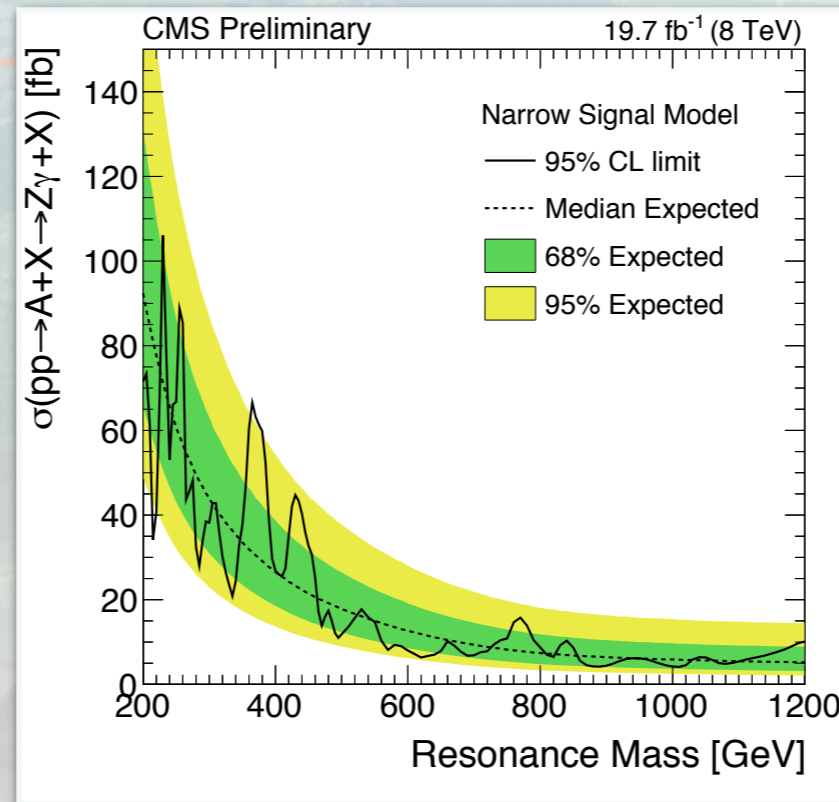
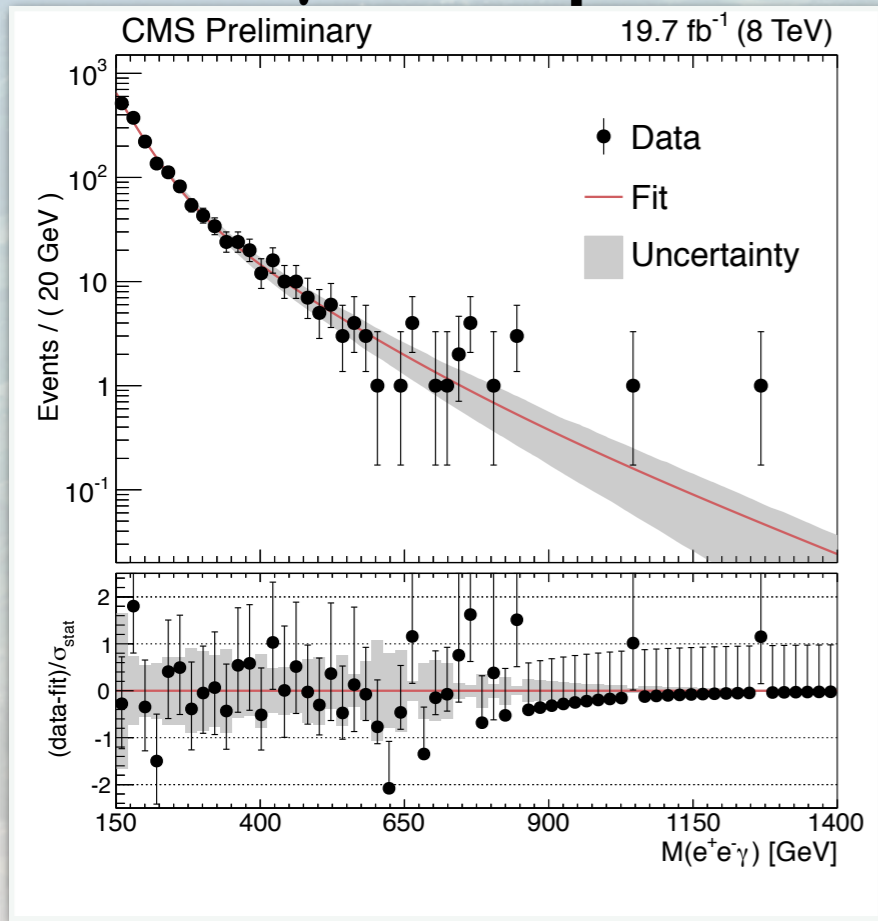
[CMS-PAS-EXO-16-021](#)



$X \rightarrow Z\gamma$ in leptonic decay mode

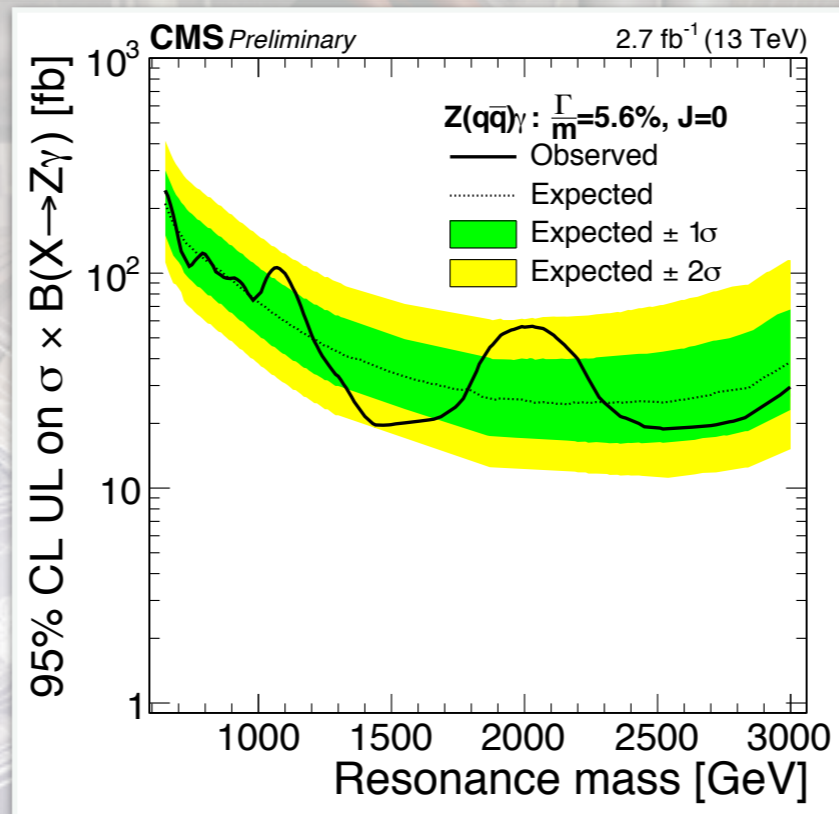
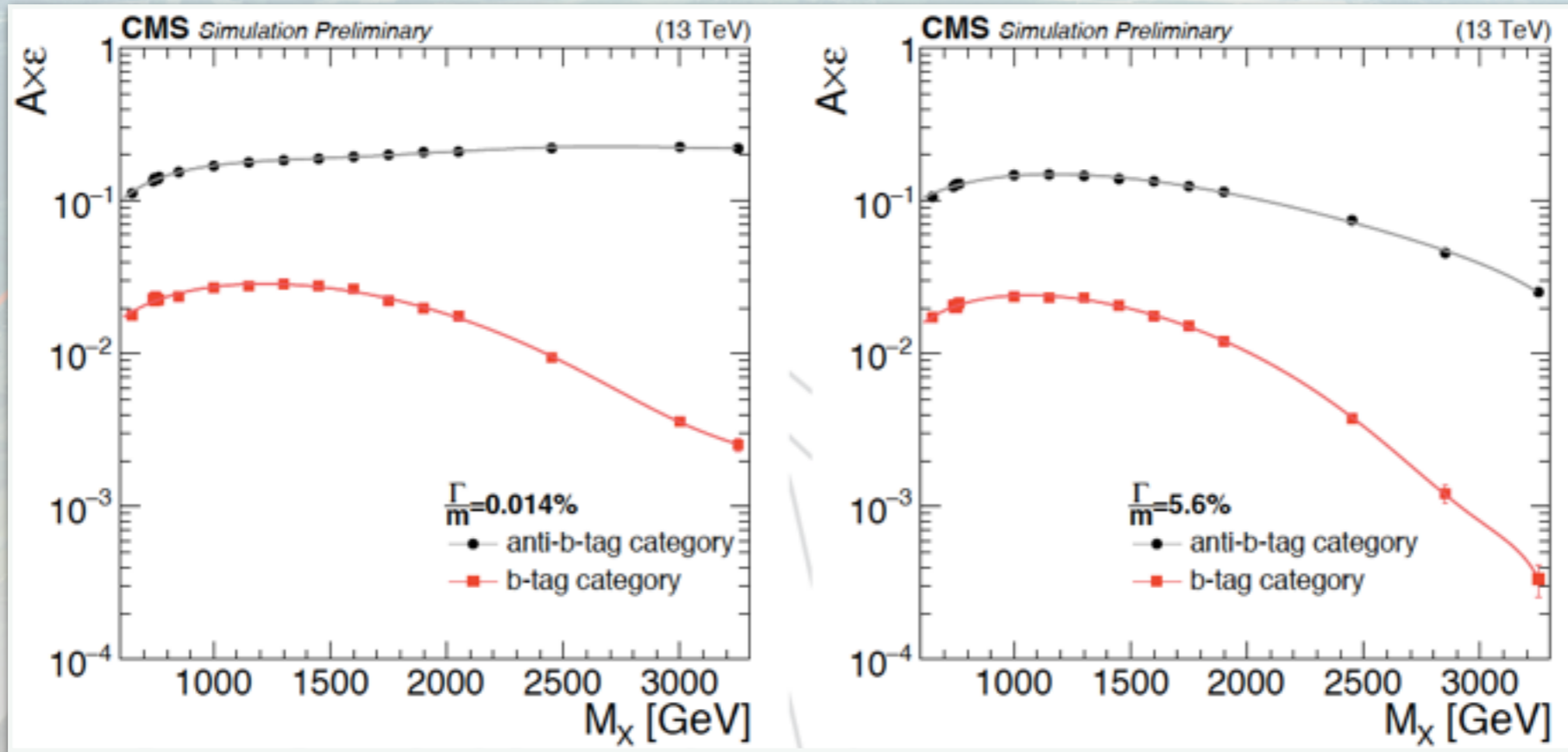
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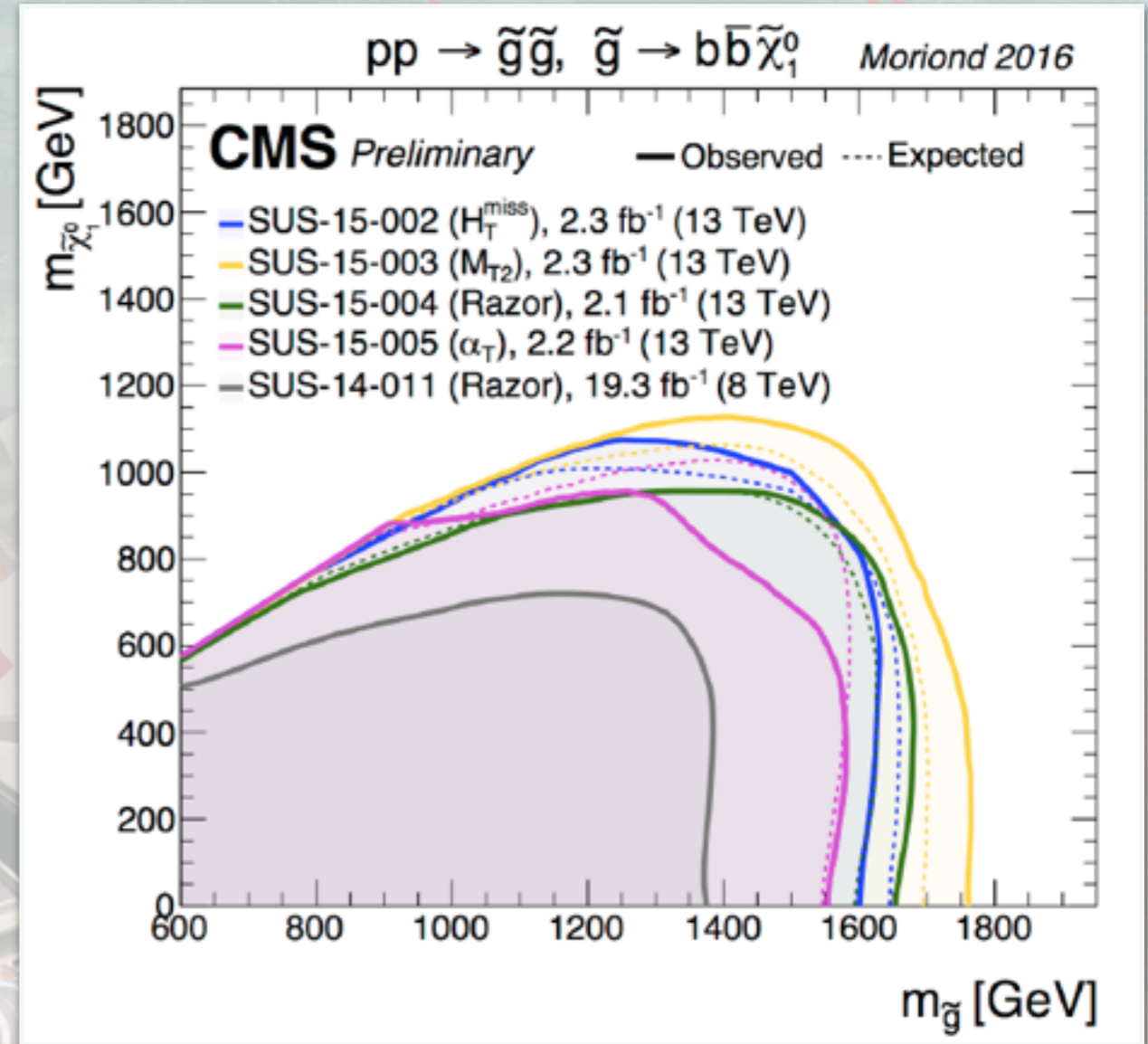
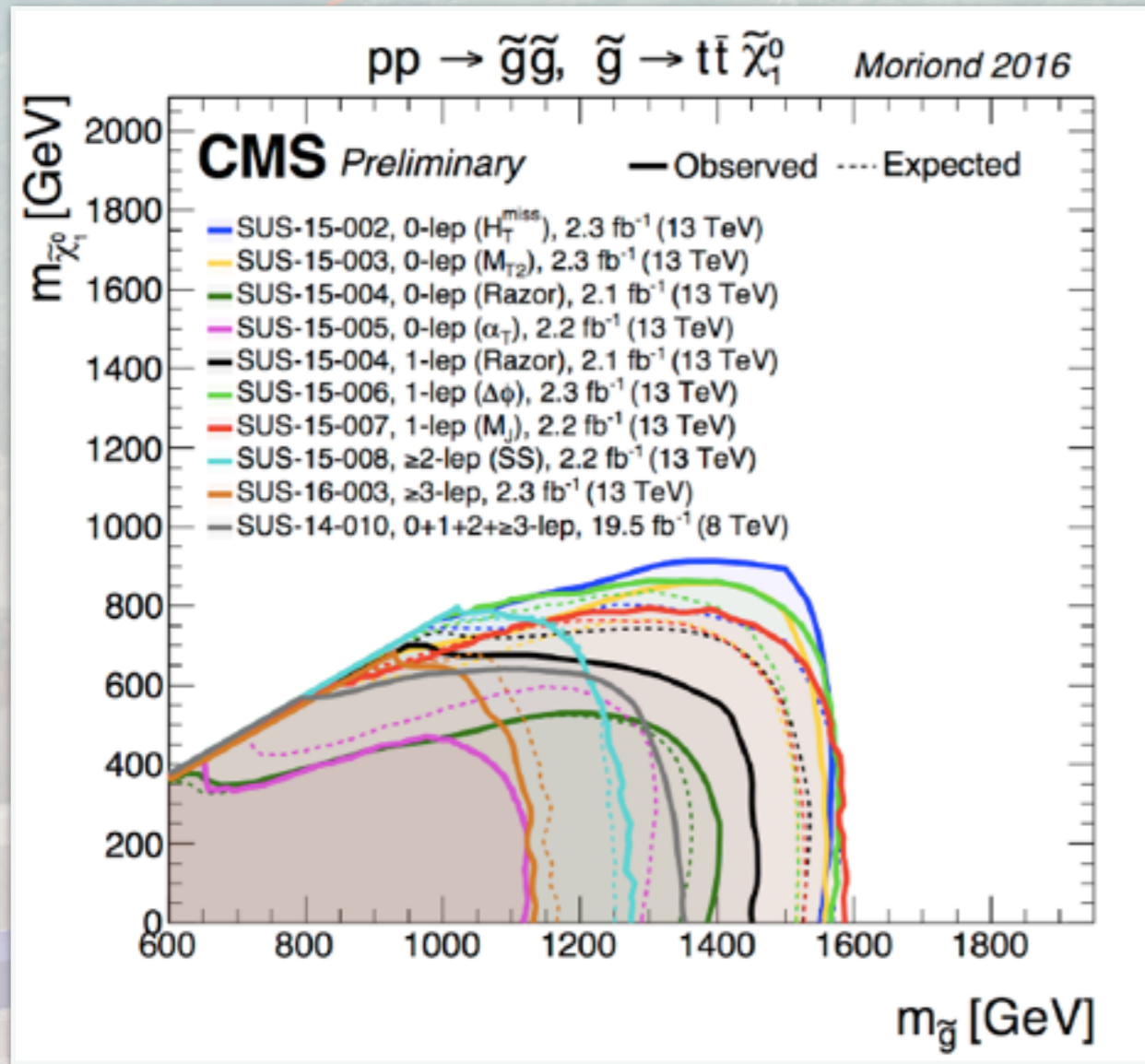
Including 8TeV

$X \rightarrow Z\gamma$ in hadronic decay mode

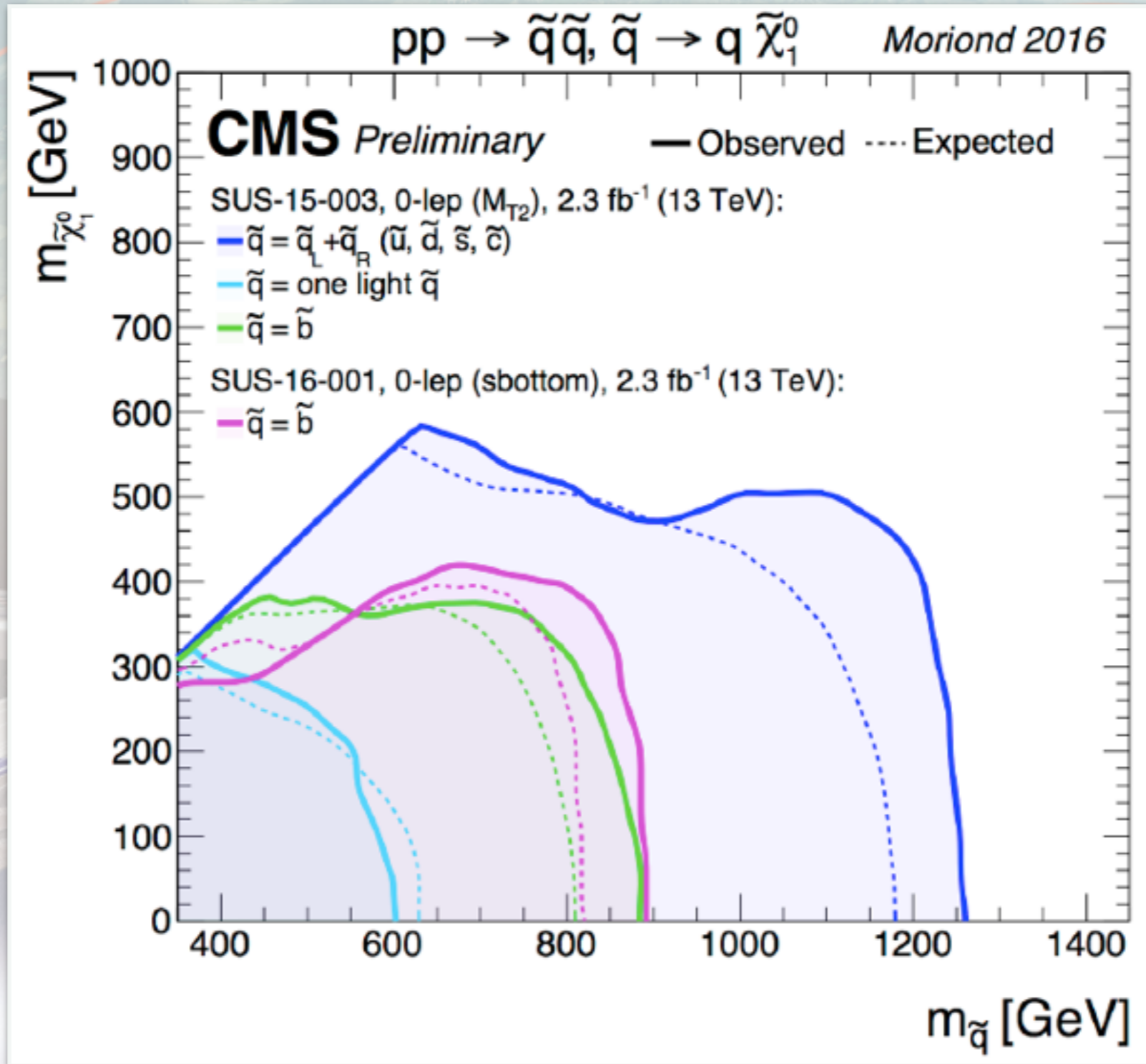


Supersymmetry

Recent results from ATLAS are found here [arXiv:1605.09318](https://arxiv.org/abs/1605.09318)



Supersymmetry



Diboson 8TeV and 13TeV combination

Table 5: Statistical significance of excesses observed at 1.8 TeV in the various searches, expressed in standard deviations.

Combination	W'	Z'	HVT ($W' + Z'$)	G_{bulk}
VV 13 TeV	0.00	0.10	0.00	0.00
VV+VH 13 TeV	0.00	0.00	0.00	-
VV 8 TeV	1.22	0.56	1.03	1.61
VV 8+13 TeV	0.20	0.46	0.33	0.35
VH 8 TeV	2.05	0.56	1.79	-
VV+VH 8 TeV	2.22	0.77	1.95	-
VV+VH 8+13 TeV	0.86	0.00	0.83	-