To be or not to be toponium

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Previously on
top LHC wg...

Previously on top LHC wg…

To spin, or not to spin,
that is the question

J.A. Aguilar-Saavedra
University of Granada

TOP LHC WG, CERN, November 21st 2018

Based on 1806.07438 and further work with Michelangelo

To spin, or not to spin,
that still is the question

J.A. Aguilar-Saavedra
IFT, UAM/CSIC

TOP LHC WG, CERN, November 14th 2019

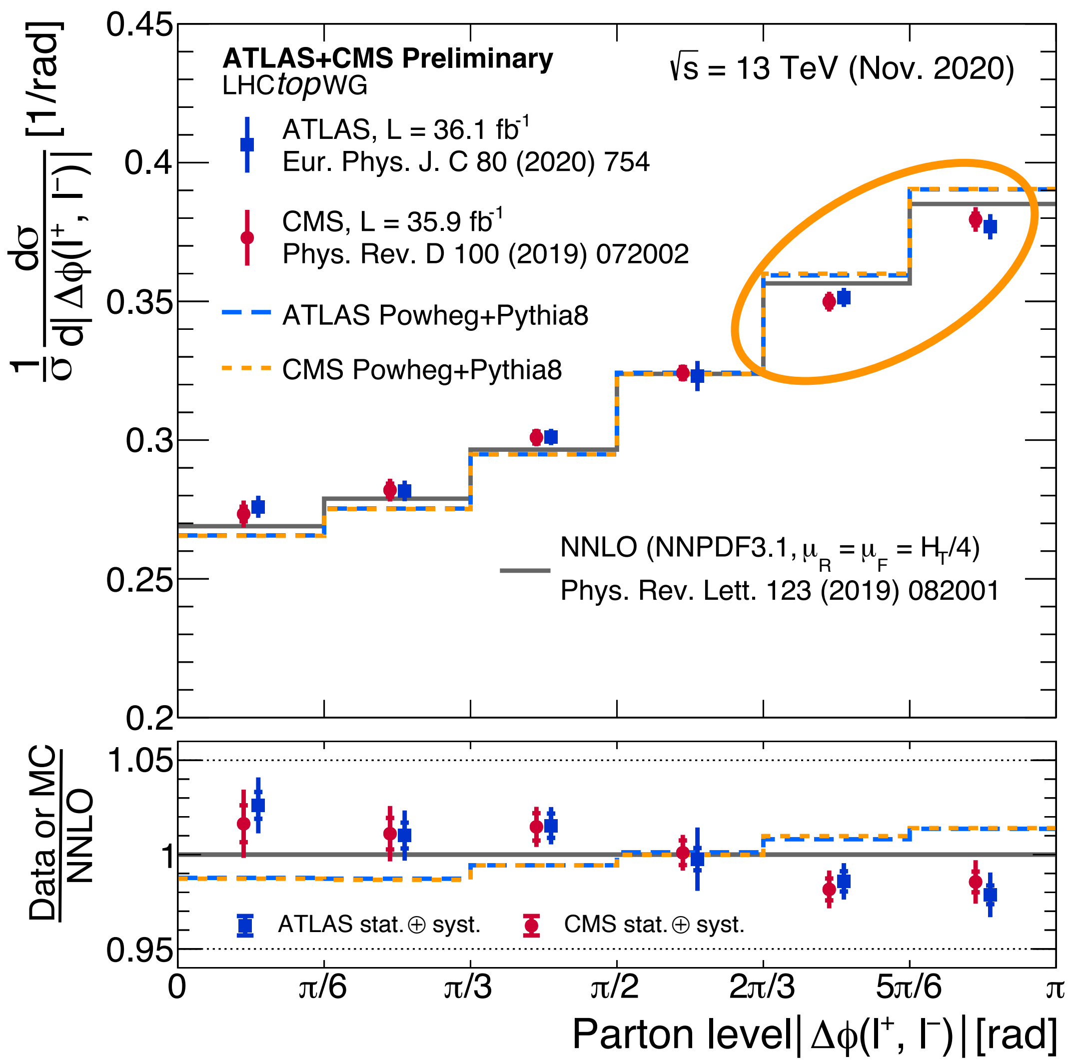
Based on 1806.07438 and further work with Michelangelo

Previously on top LHC wg…

ΔΦ anomaly in top pair production

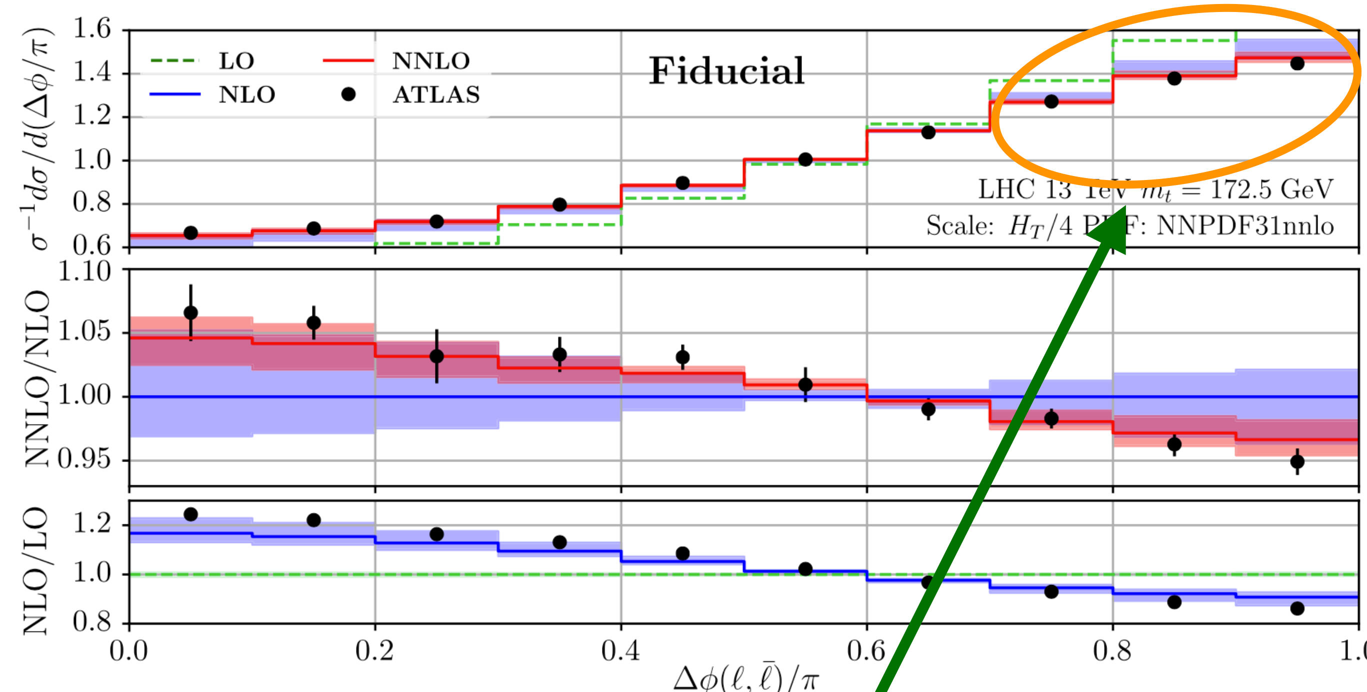
lab-frame azimuthal angle between leptons

Parton level full phase space



Parton level fiducial

Behring et al. 1901.05407



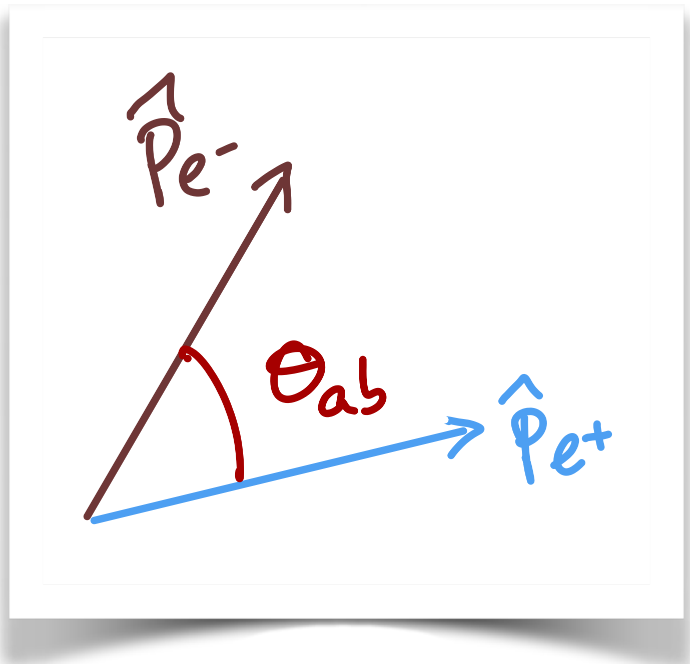
better agreement

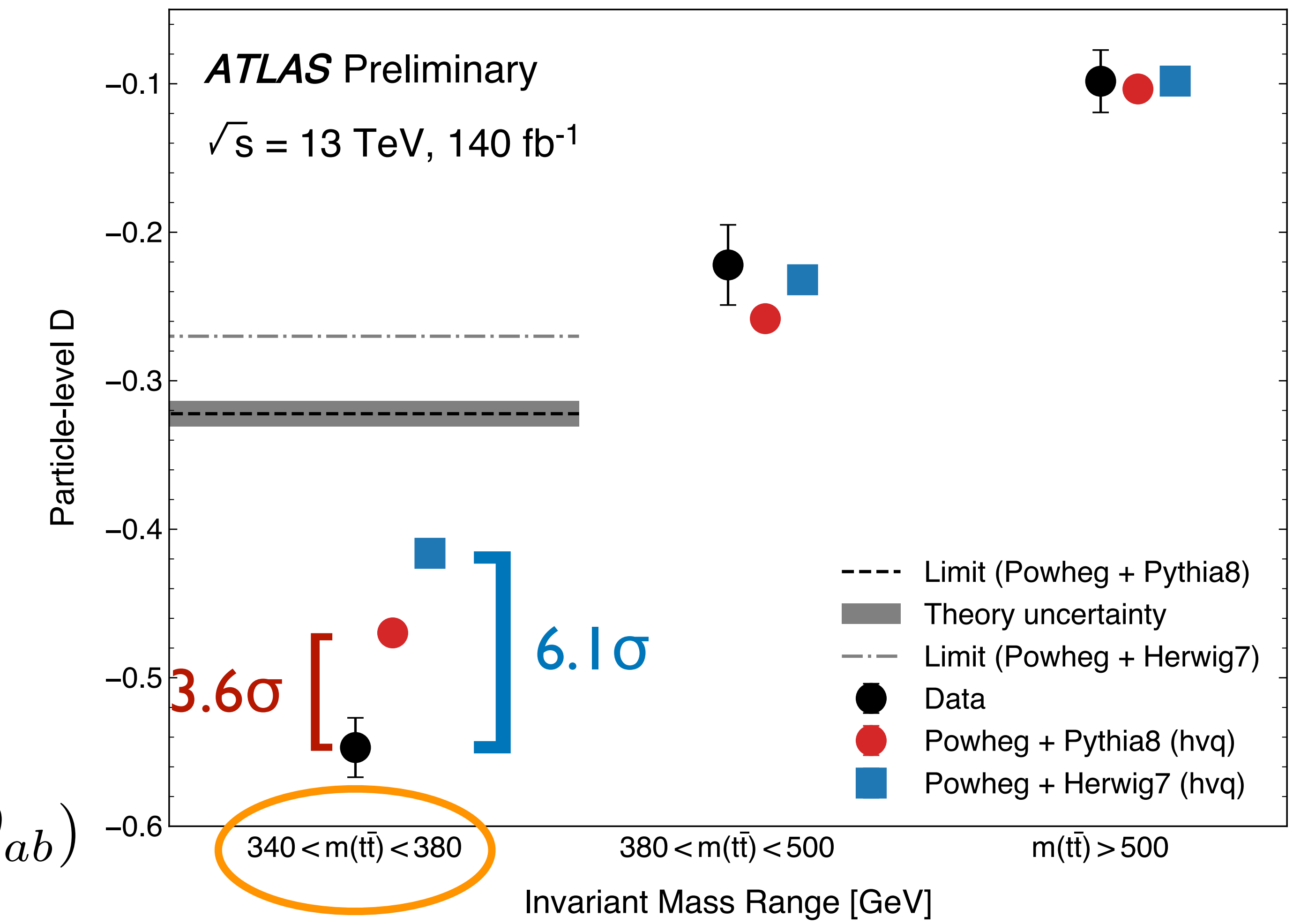
New physics explanations break Δη and σ, see here and here

Toponium and entanglement

Toponium and entanglement

ATLAS entanglement measurement near threshold exhibited a large discrepancy w.r.t. Monte Carlo [perturbative] predictions.





$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{ab}} = \frac{1}{2}\left(1 + \alpha_a\alpha_b D\cos\theta_{ab}\right)$$

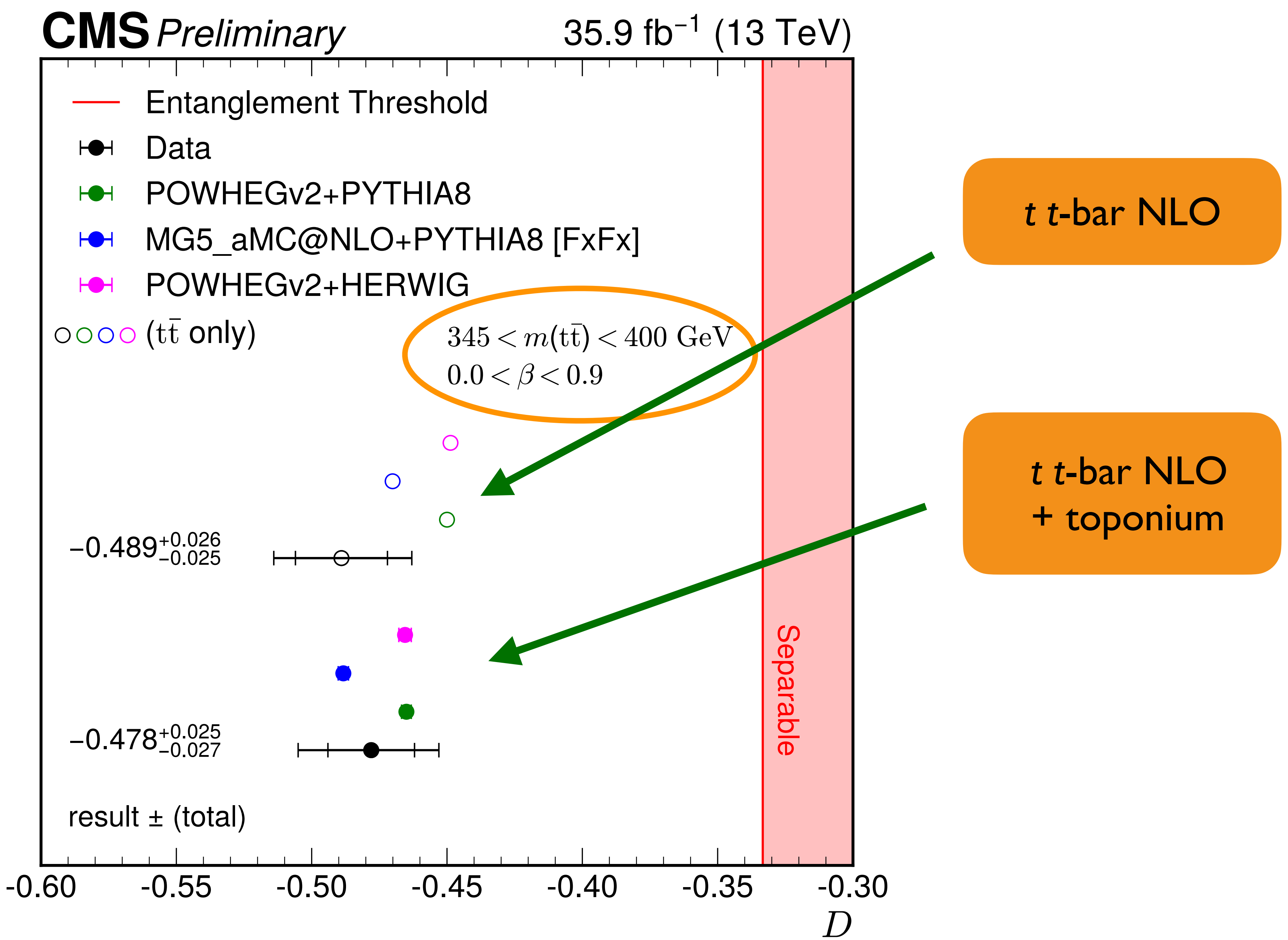
$$D = \frac{1}{3}(C_{11} + C_{22} + C_{33})$$

Entanglement test near threshold: $-3D - 1 > 0$

Toponium and entanglement

CMS found better agreement with Monte Carlo, even without toponium

[likely because looser m_{tt} cut].



Toponium hints from spin

Toponium hints from spin

Top pair: two spin-1/2 particles, simplest example of quantum correlation

$$\rho = \frac{1}{4}\left(1 \otimes 1 + \sum_i B_i^+ \sigma_i \otimes 1 + \sum_i B_i^- 1 \otimes \sigma_i + \sum_{ij} C_{ik} \sigma_i \otimes \sigma_j\right)$$

normalisation

$$\hat{n}_a = (\sin\theta_a \cos\varphi_a, \sin\theta_a \sin\varphi_a, \cos\theta_a)$$
$$\hat{n}_b = (\sin\theta_b \cos\varphi_b, \sin\theta_b \sin\varphi_b, \cos\theta_b)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_a d\Omega_b} = \frac{1}{(4\pi)^2}\left[1 + \alpha_a \vec{B}^+ \cdot \hat{n}_a + \alpha_b \vec{B}^- \cdot \hat{n}_b + \alpha_a \alpha_b \hat{n}_a^T C \hat{n}_b\right]$$

3 coefficients corresponding to top polarisation

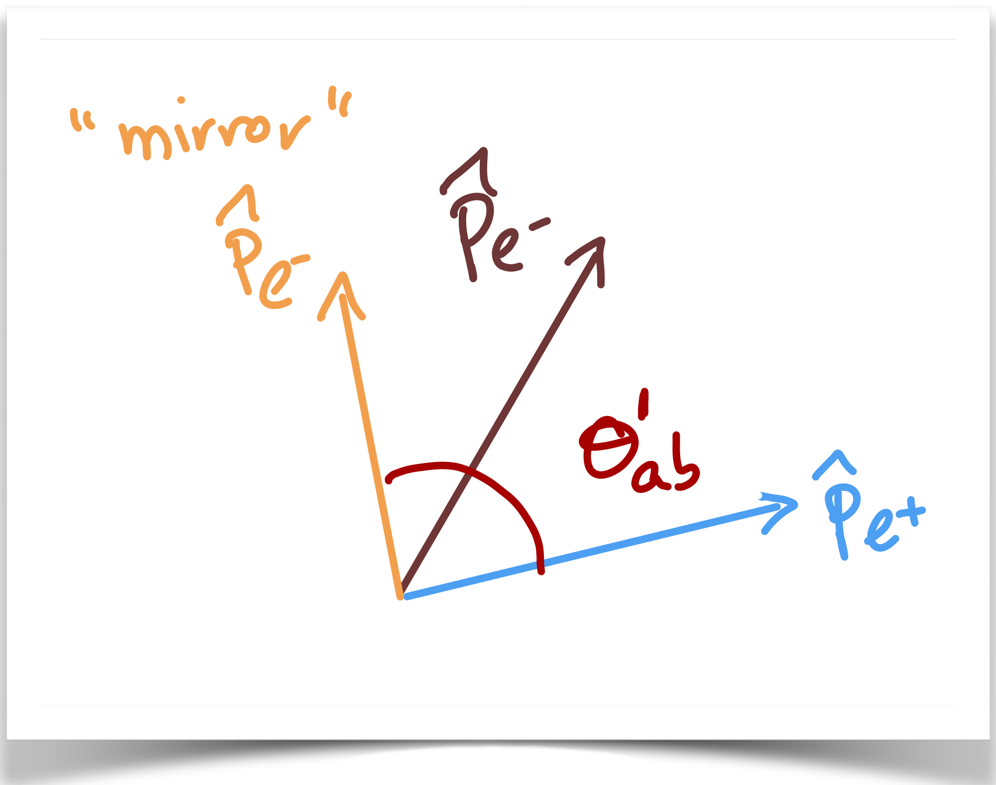
3 coefficients corresponding to anti-top polarisation

9 spin correlations

Measured by ATLAS and CMS since some time

Toponium hints from spin

Diagonal spin correlations are fully determined by measuring <u>only</u> relative angles between leptons.



Use the mirror image of ℓ^- momentum, reflected in the K-R plane

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta'_{ab}} = \frac{1}{2}\left(1+\alpha_a\alpha_b D_3\cos\theta'_{ab}\right)$$

$$D_3 = \frac{1}{3}(C_{11}+C_{22}-C_{33})$$

$$\{D,\, D_i,\, D_j\} \quad \longrightarrow \quad \{C_{11},\, C_{22},\, C_{33}\}$$

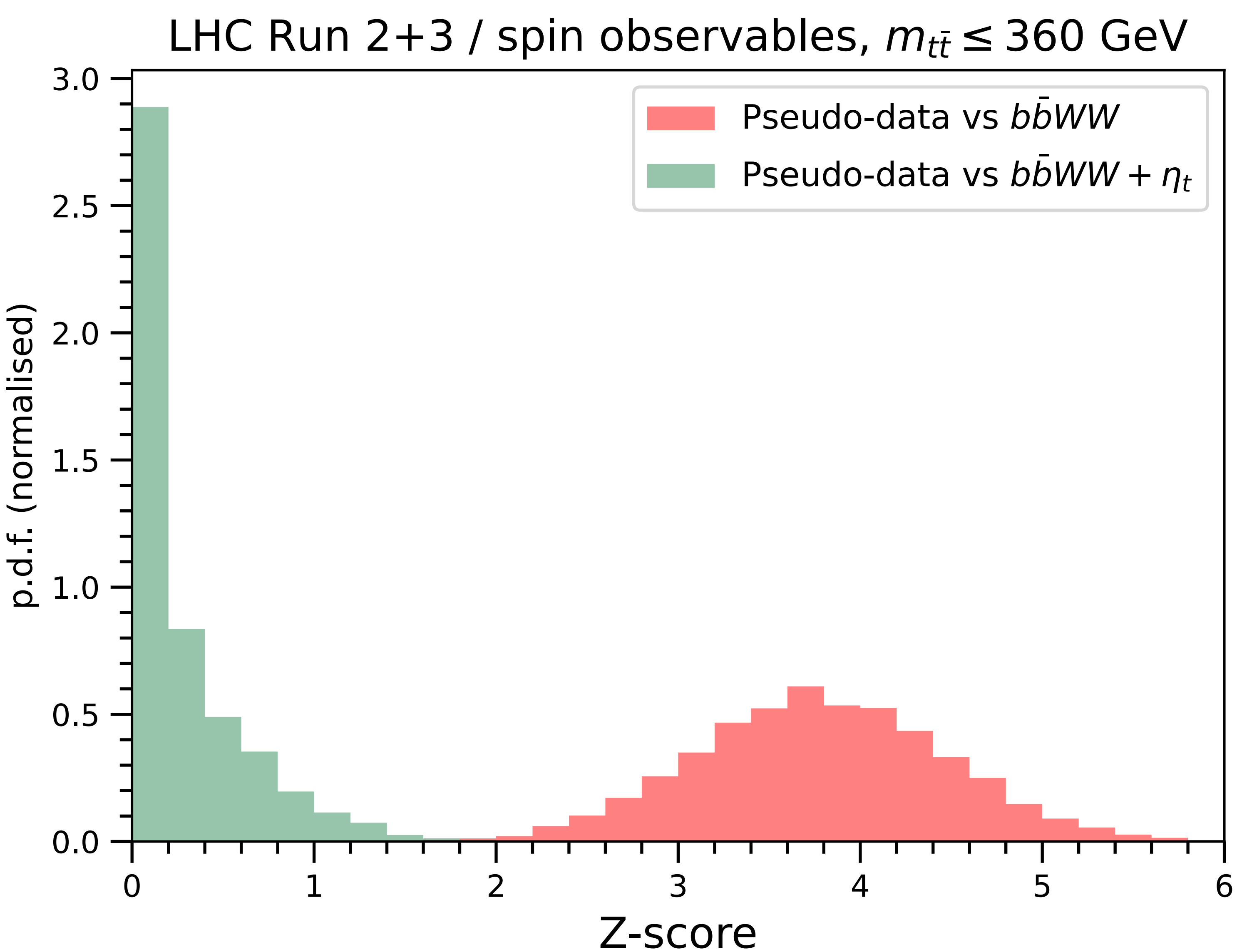
No need to stress that there is more to spin than just diagonal C_{ii}

Toponium hints from spin

The full characterisation of spin in the *t t*-bar pair is achieved with the four angles θ_a, ϕ_a, θ_b, ϕ_b of the two leptons / spin analysers.

→ Include also θ_{ab} for better discrimination

K, R, N axes are not well determined for slow tops



The agreement with toponium / disagreement w.r.t. SM can be assessed by using a multi-variate method.

Toponium hints from colour

Toponium hints from colour

The jet pull and pull angle have been used to test colour connection of *W* hadronic decay products. Gallichio, Schwartz 1001.5027

For the colour connection between *b* and *b*-bar from top pair decays, the differences are washed out by bin migrations.

Instead, a set of global event shape variables

$$\tau_n^{(\beta)} = \frac{1}{\sum_i E_i} \sum_i p_{Ti} \min \left\{ \Delta R_{1i}^{\beta}, \Delta R_{2i}^{\beta}, \ldots \Delta R_{ni}^{\beta} \right\}$$

analogous to subjettiness [Thaler, van Tilburg 1011.2268] proves to be useful.

➡ Include also *b* and *b*-bar subjettiness + jet multiplicity + particle multiplicity for better discrimination

Toponium characterisation

Toponium characterisation

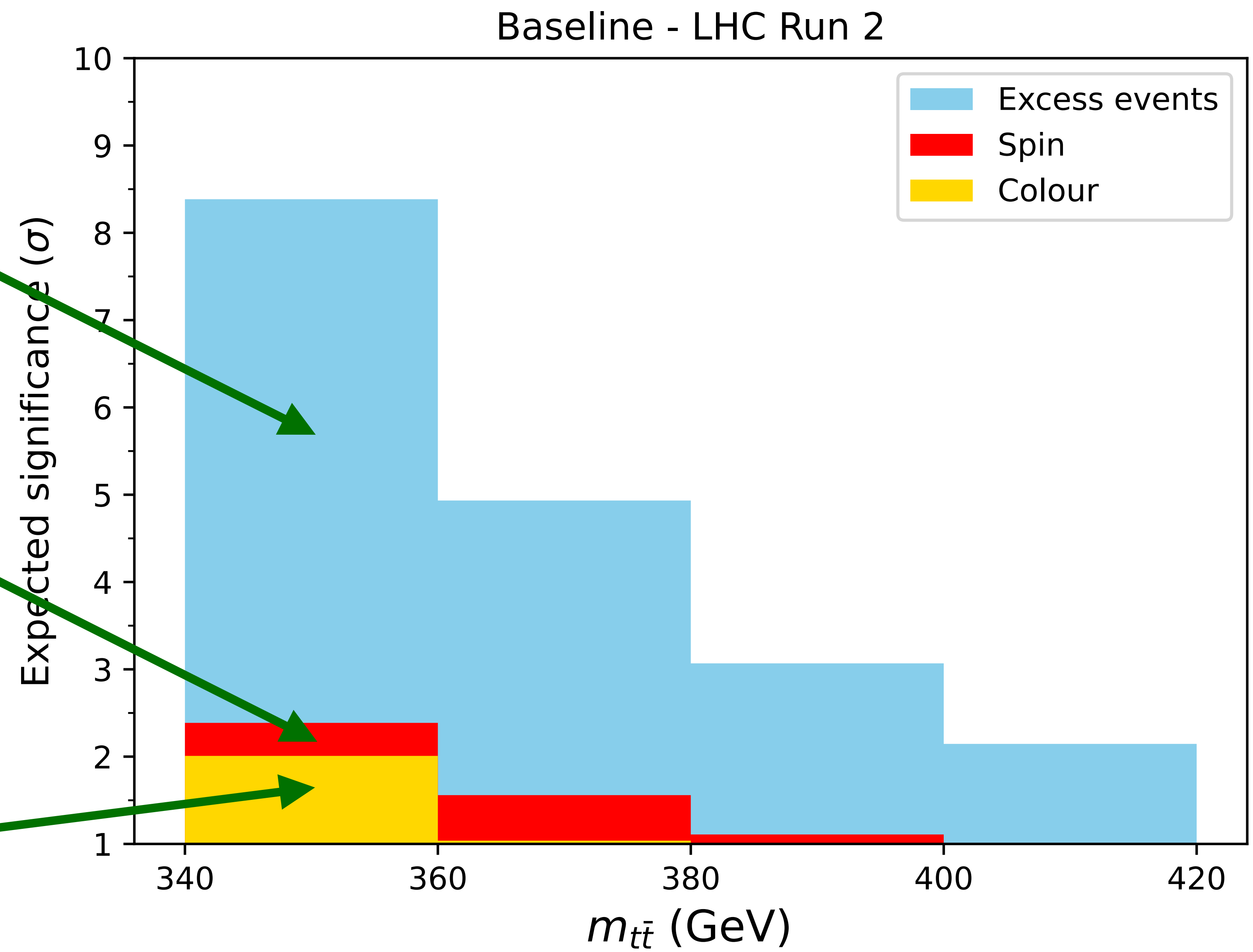
The presence of toponium leads to

JAAS 2407.20330

an event excess near threshold

that modifies spin observables like a 0^-

and looks like a colour singlet

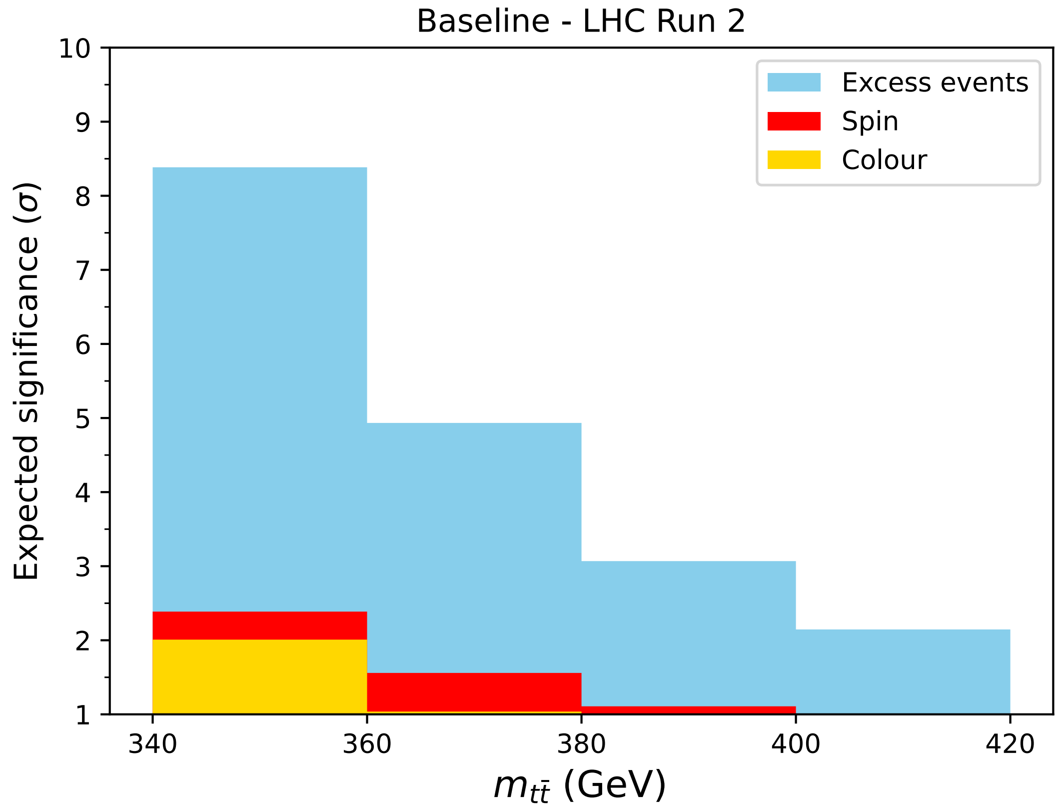


- The expected significance for spin characterisation is smaller than for excess events
- And even smaller for colour characterisation

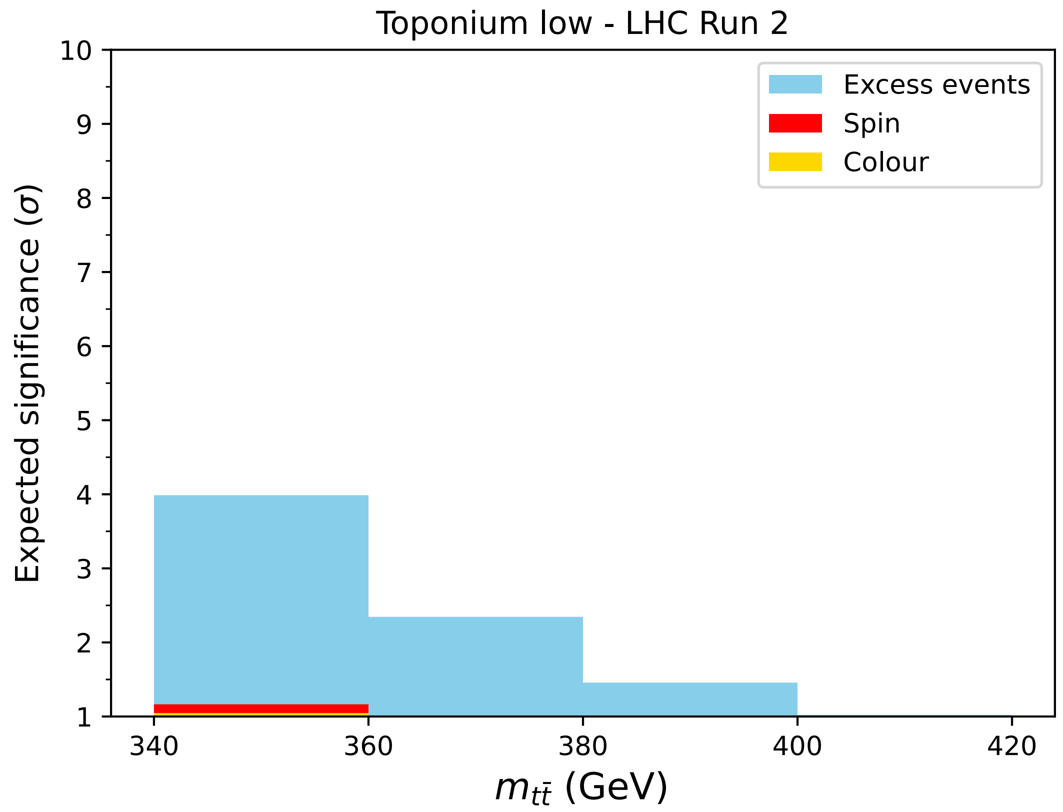
Toponium characterisation

Significance decreases if toponium cross section is smaller

x-sec: Sumino, Yokoya 1007.0075



x-sec: Kiyo et al. 0812.0919

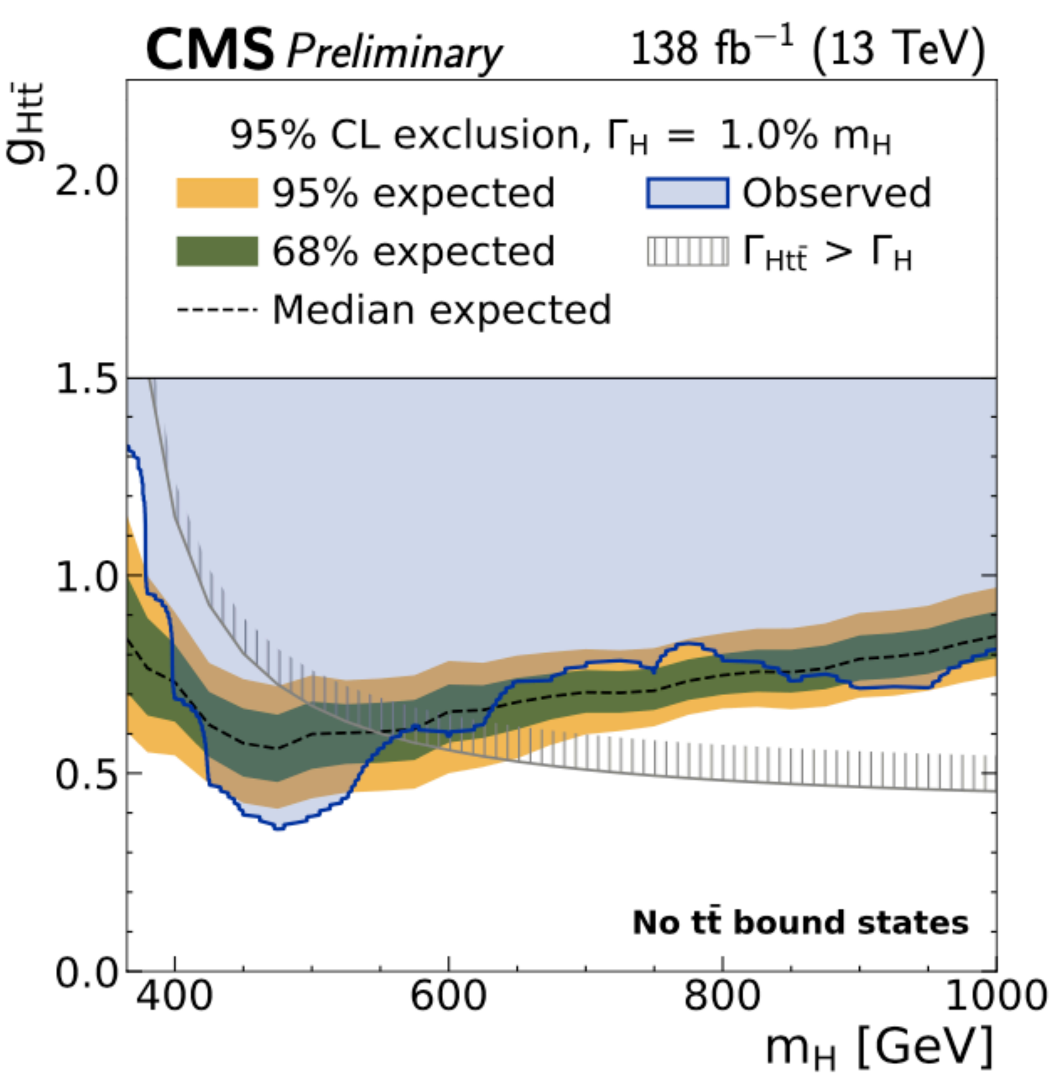


CMS entanglement measurement points to the larger cross section - provided toponium is the only missing effect in Monte Carlo.

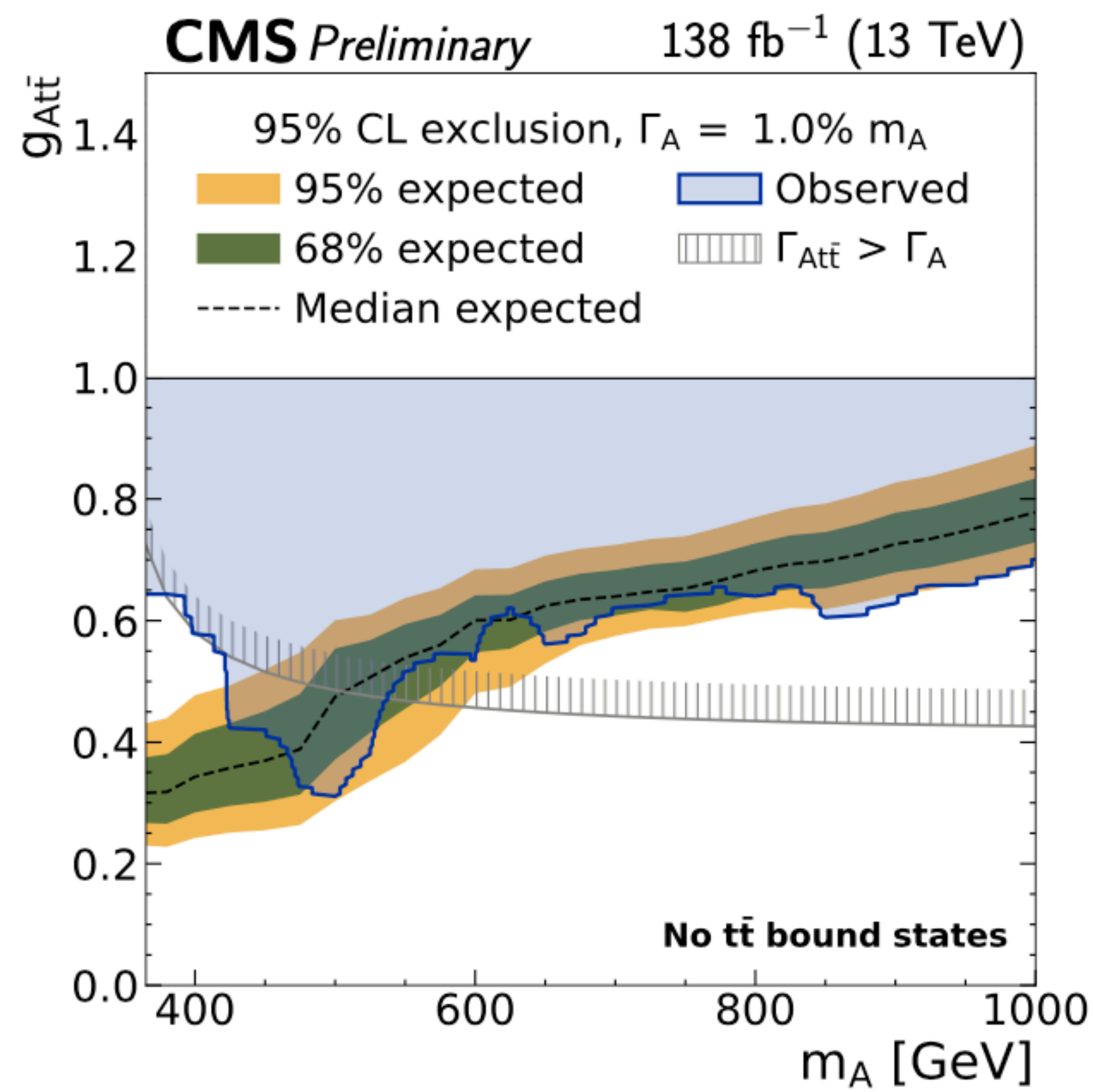
Toponium characterisation

Of course, regular searches for new scalars in *t t*-bar final states are also sensitive to toponium / …

scalar 0^+



pseudo-scalar 0^-

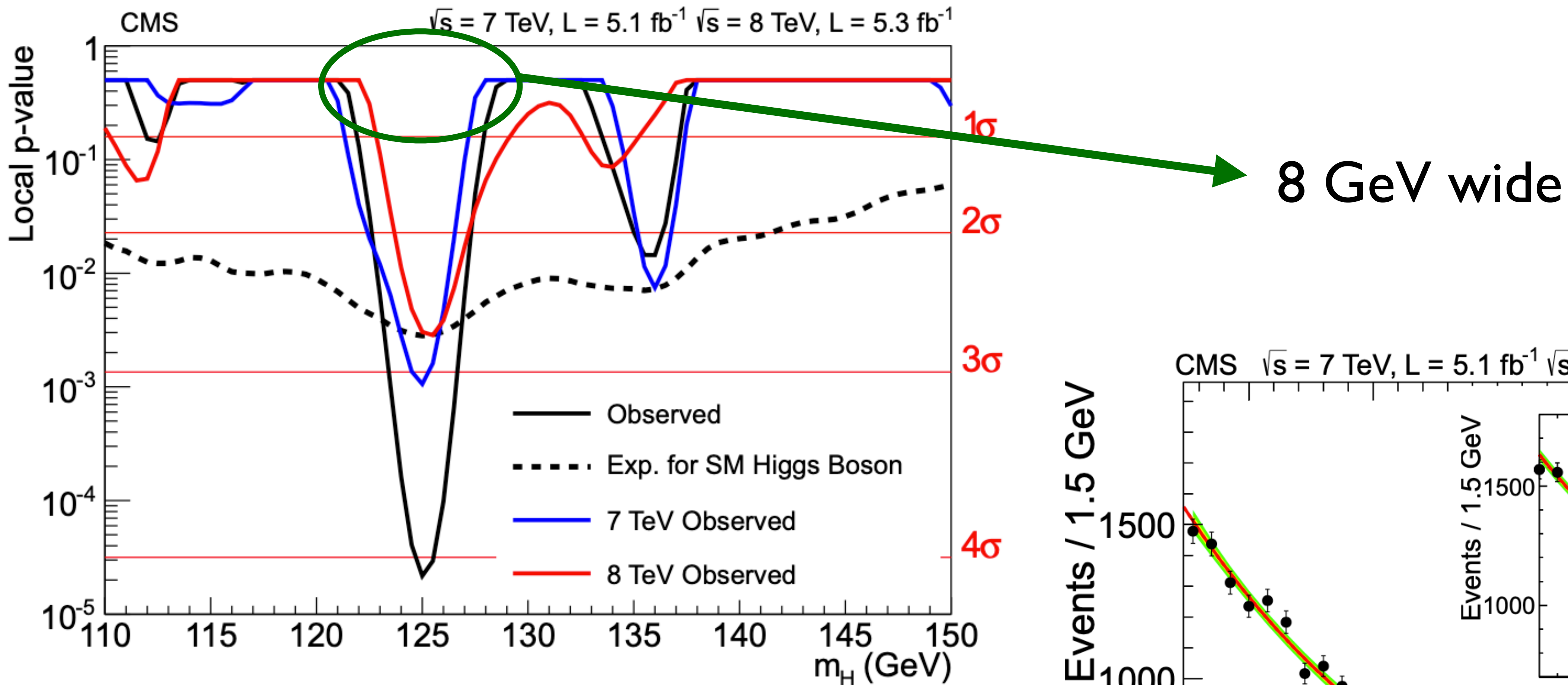


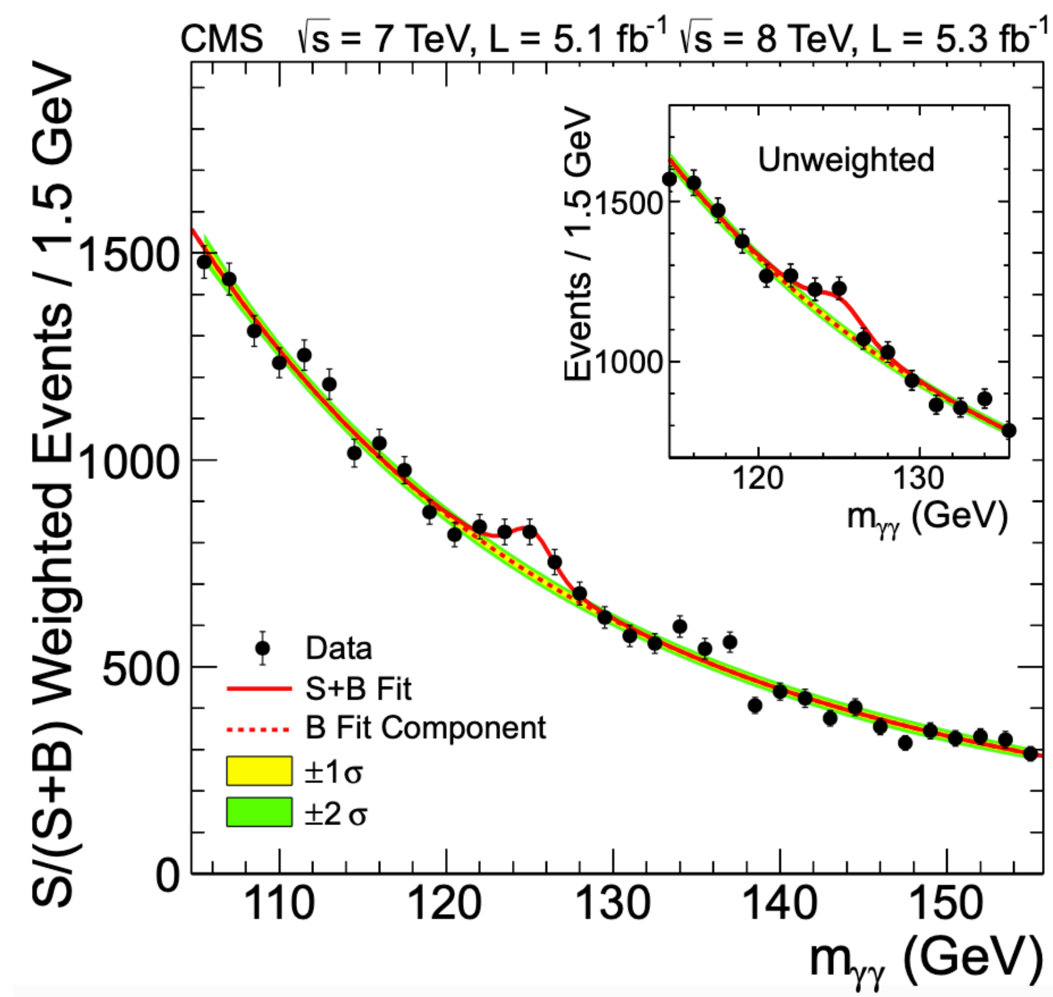
… could we already claim discovery? Depending on your standards.

CMS `Toponium'
vs Higgs

CMS `Toponium´ vs Higgs

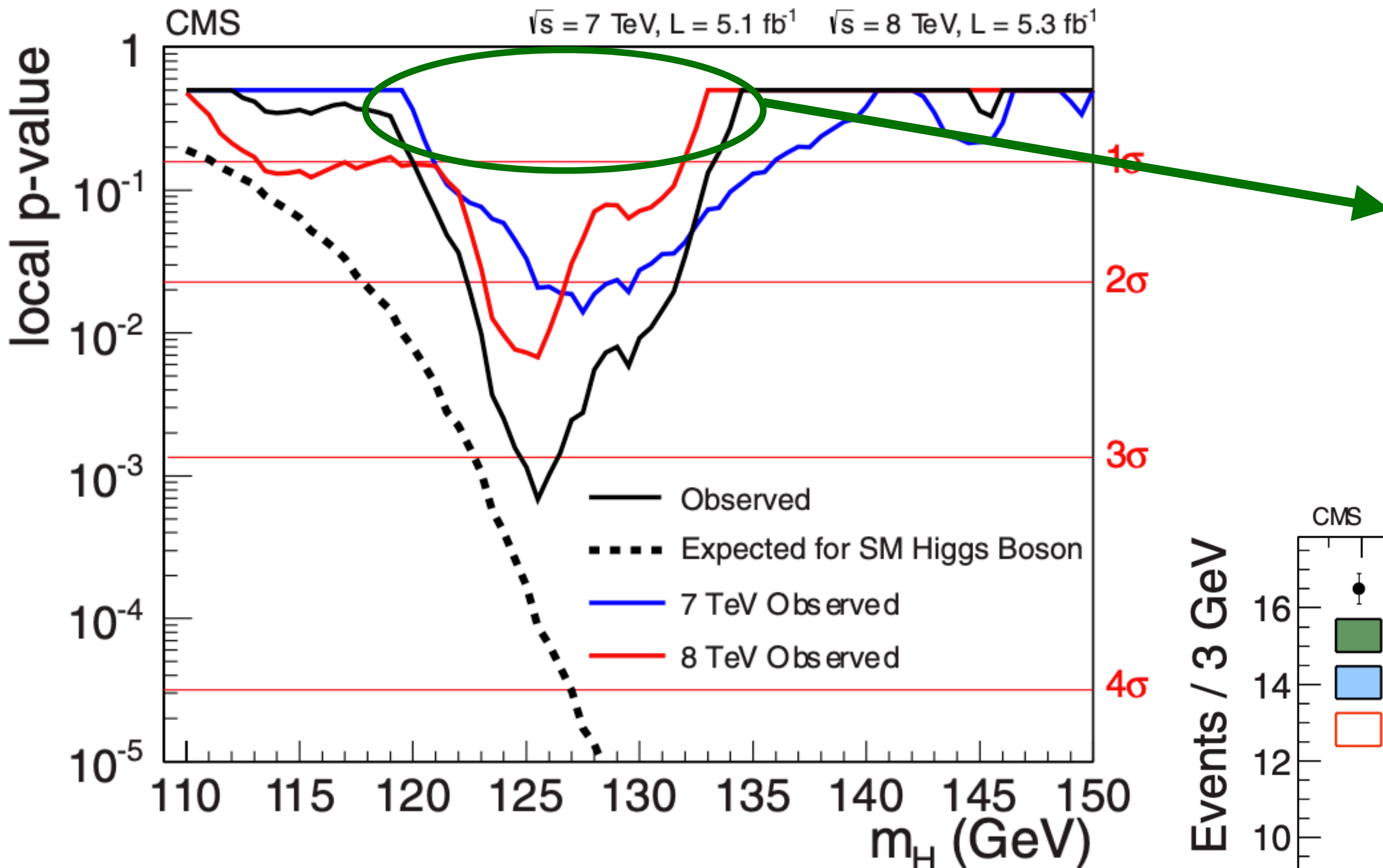
CMS saw a significant, narrow excess in γγ …



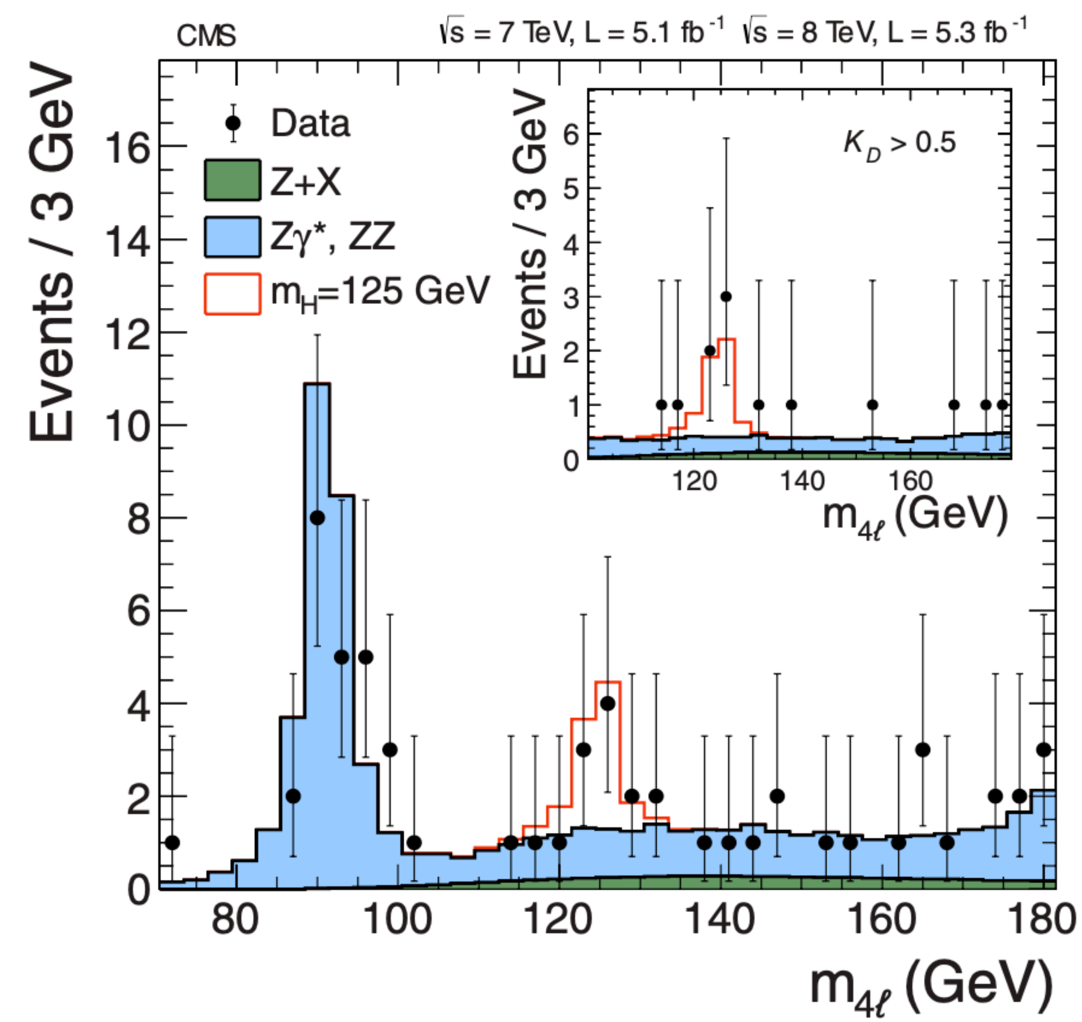


CMS `Toponium´ vs Higgs

… plus another excess in *ZZ* at about the same place …

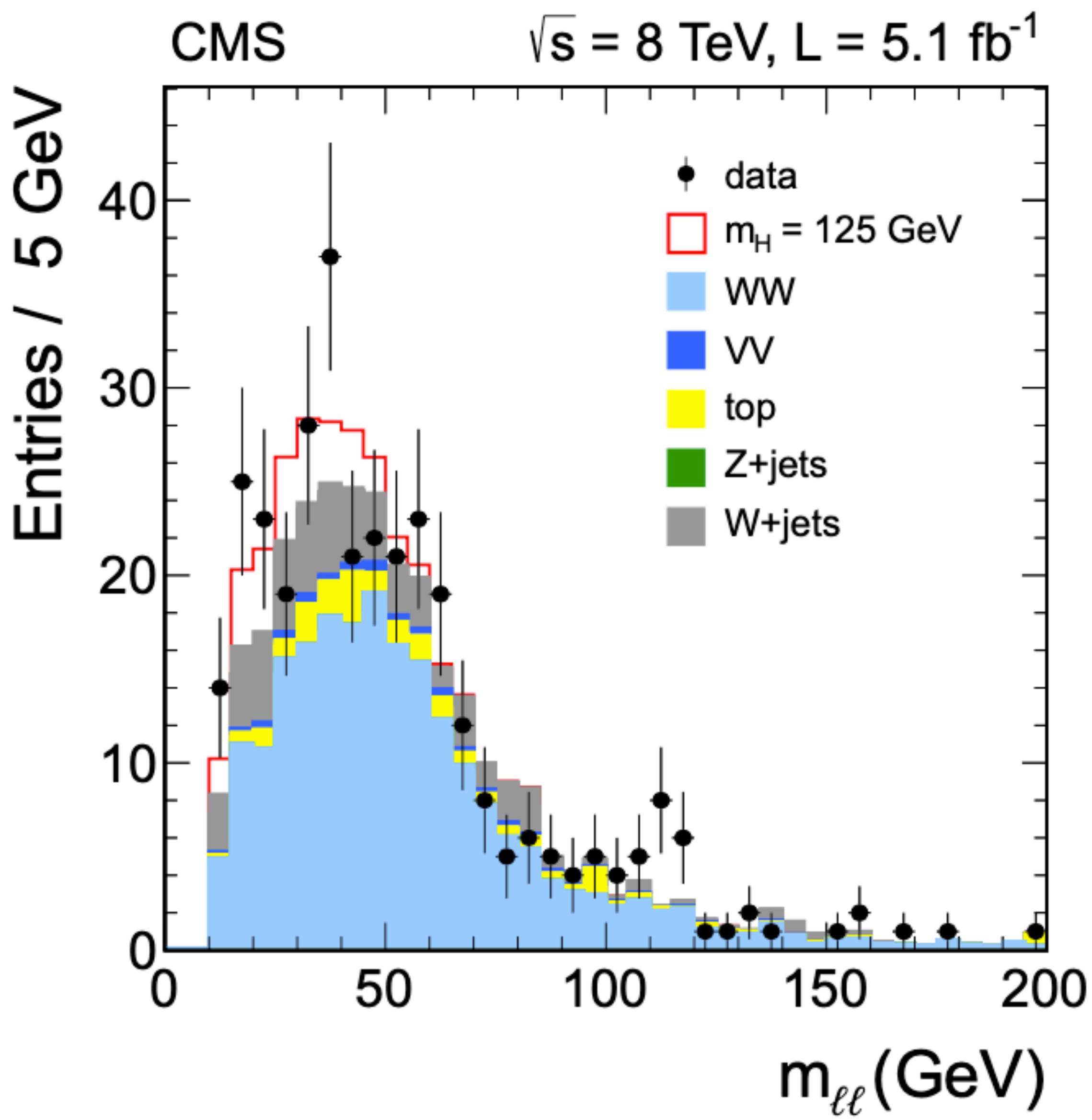


15 GeV wide



CMS `Toponium´ vs Higgs

… plus another excess in *WW* that was compatible …



and ATLAS saw the same excesses too!

CMS `Toponium´ vs Higgs

	CMS `Toponium´	Higgs	Superluminal ν
Narrow excess?	✘	✔	✘
Bump seen on smooth distribution?	✘	✔	✘
In different channels*?	✘	✔	✘
Seen by more than one experiment?	✘	✔	✘
At least 5σ?	✔	✔	✔

* I do not consider *t t*-bar dilepton and semileptonic as different channels, in which respects to possible mismodeling effects.

Personal thoughts

- The very nature of deviations due to toponium [wide & at the lower m_{tt} side] complicate `observation´ claims.*
- One must not forget other mismodeling issues in *t t*-bar!
- ... nor that there is a 50% theoretical uncertainty on its cross section: toponium effects could well be much smaller.
- The `dilemma´ of whether the CMS excess is 0^- toponium or a new pseudoscalar relies on the implicit assumption that the excess is due to a particle.
- One's own belief `*this must be toponium*´ does not qualify as a discovery.
- More work on this would be welcome.

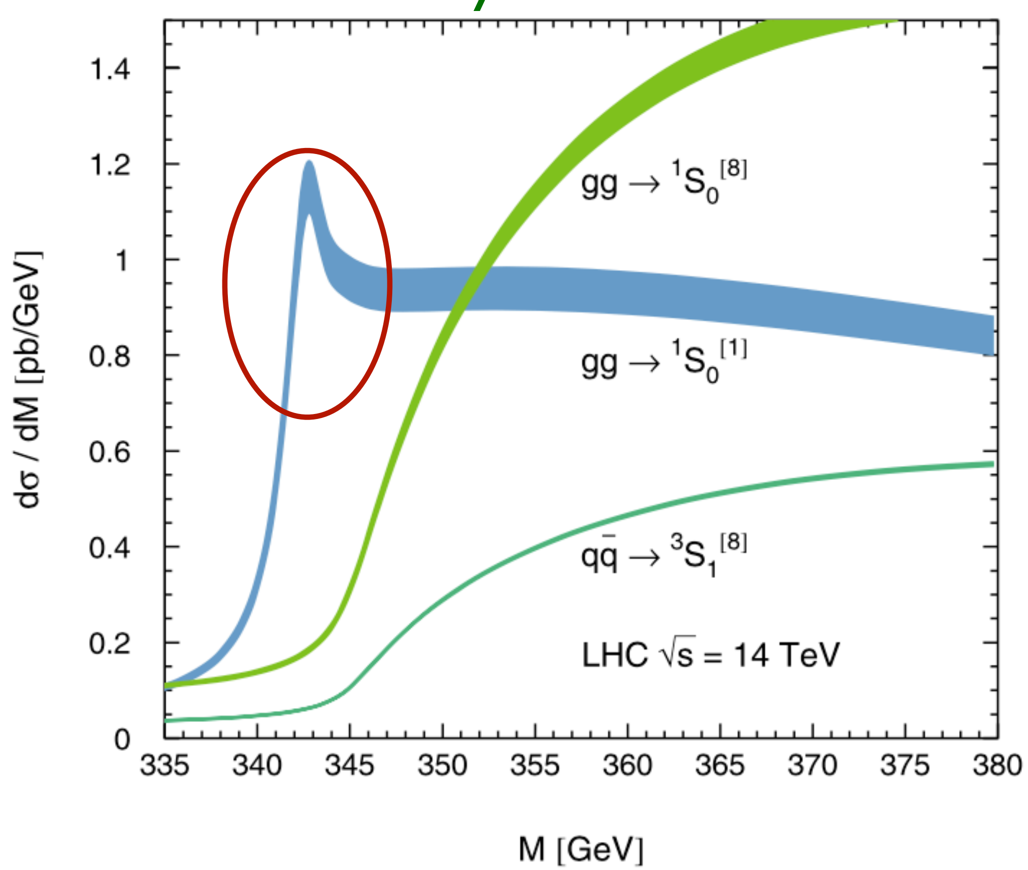
* I know CMS does not *officially* make any claim.

End

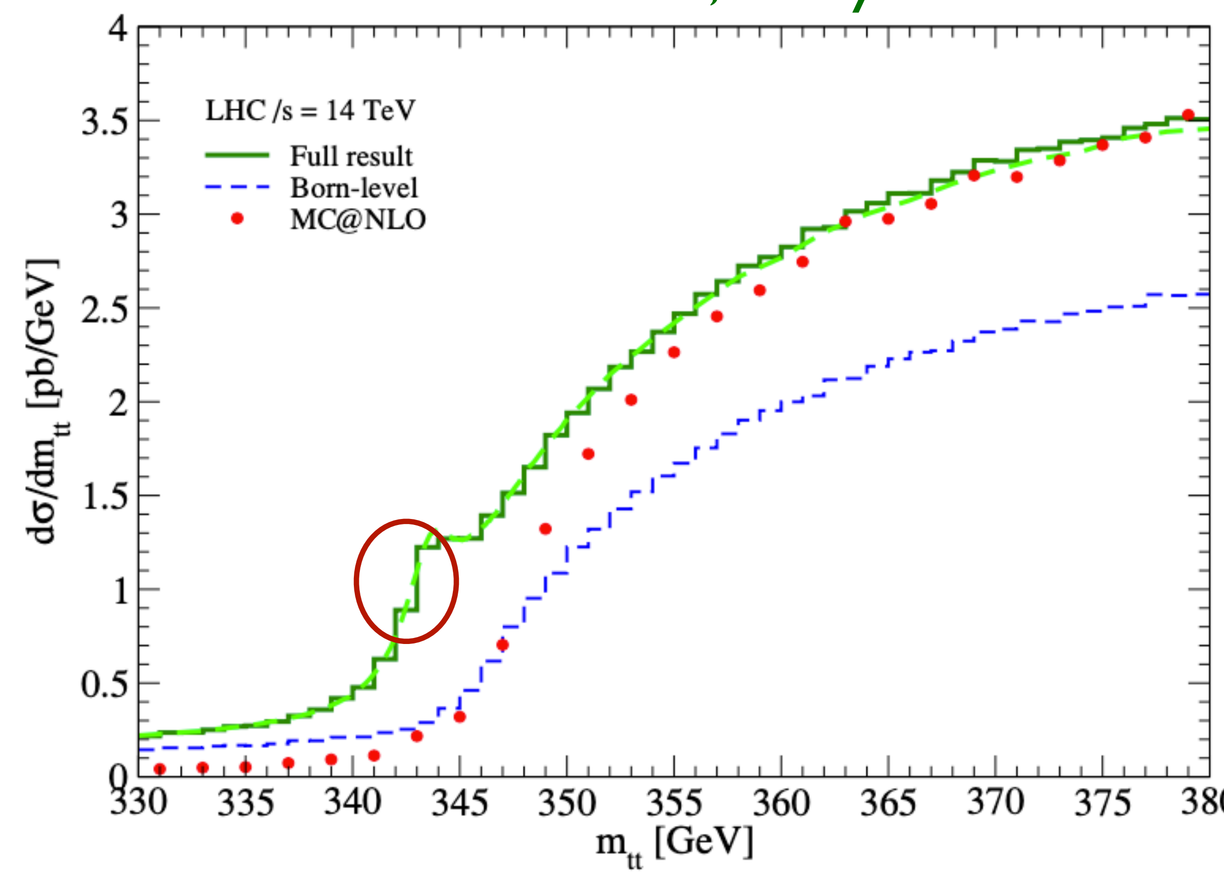
Toponium!

Non-perturbative corrections in the colour-singlet channel produce a pseudo-bound-state near threshold.

Kiyo et al. 0812.0919



Sumino, Yokoya 1007.0075



The toponium resonance produced in pp collisions has

$J^P = 0^-$

$m \simeq 2m_t - 2$ GeV

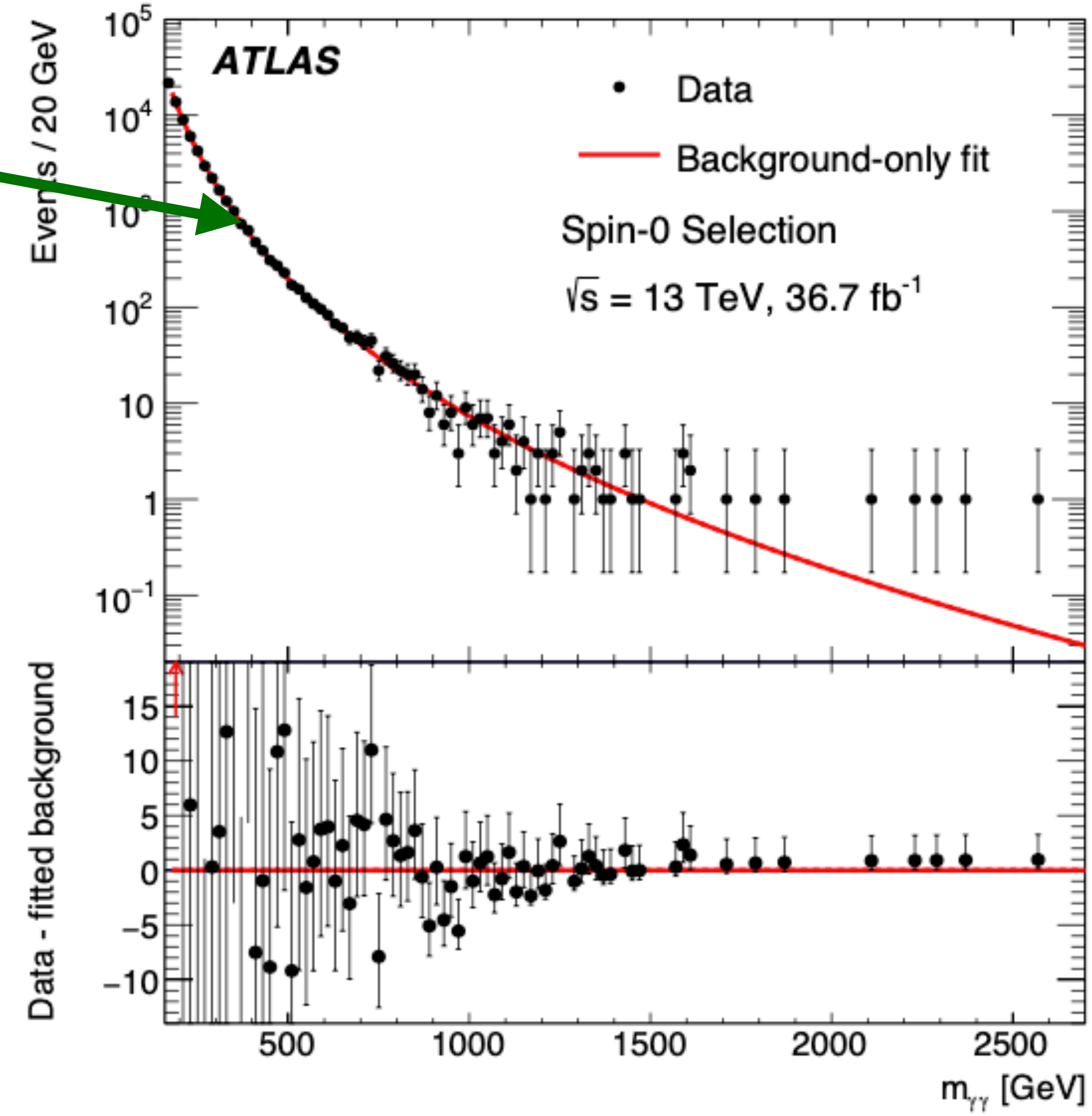
$\Gamma \simeq 2\Gamma_t$

The toponium contribution is very well approximated by a pseudo-scalar with these parameters.

CMS `Toponium´ vs Higgs

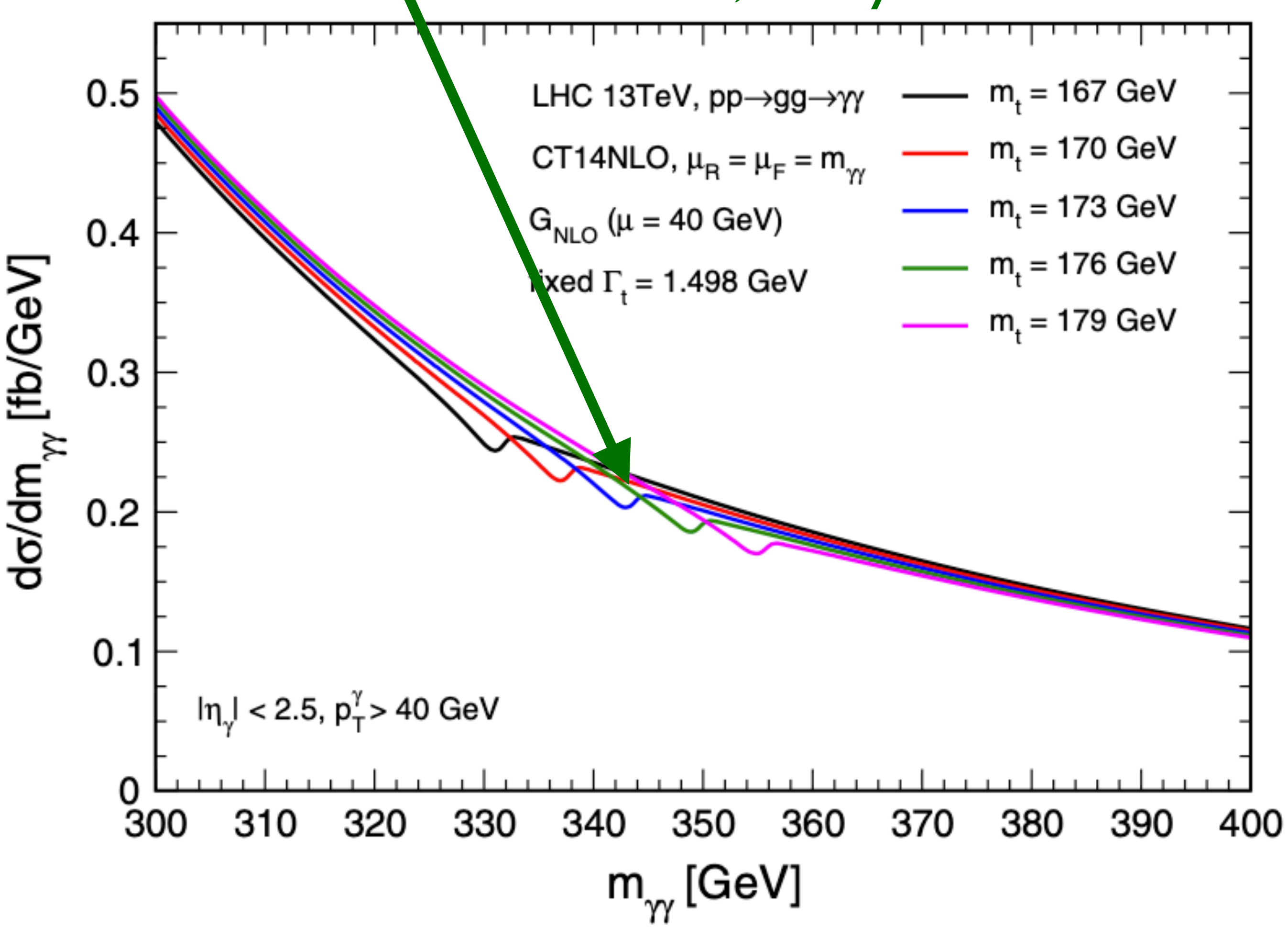
Diphoton final state

bkg ~ 1.3 fb/GeV



kink ~ 0.1 fb

Kawabata, Yokoya 1607.00990



now this is the end