



# Overview of Physics Results from the CMS Experiment



**Somnath Choudhury**  
(for the CMS collaboration)



**4<sup>th</sup> International Workshop on Hadron Nuclear Physics 2015**  
7 – 11 July 2015, Krabi (Thailand)

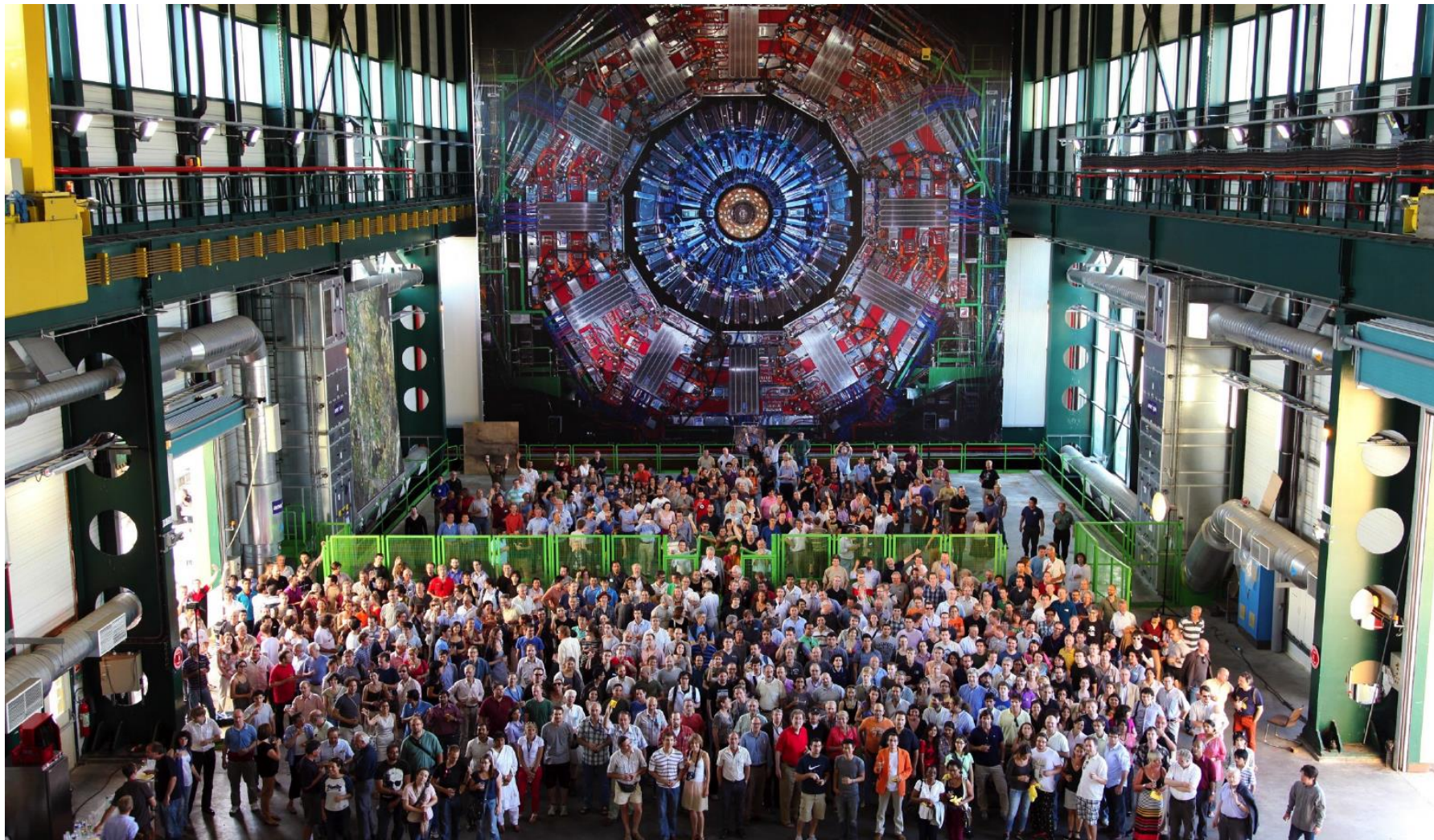
# Outline

- Higgs Physics
- EW Measurements
- QCD Physics
- B - physics
- Top physics
- Forward Physics
- BSM Searches
- Heavy Ion Physics





# The CMS Collaboration



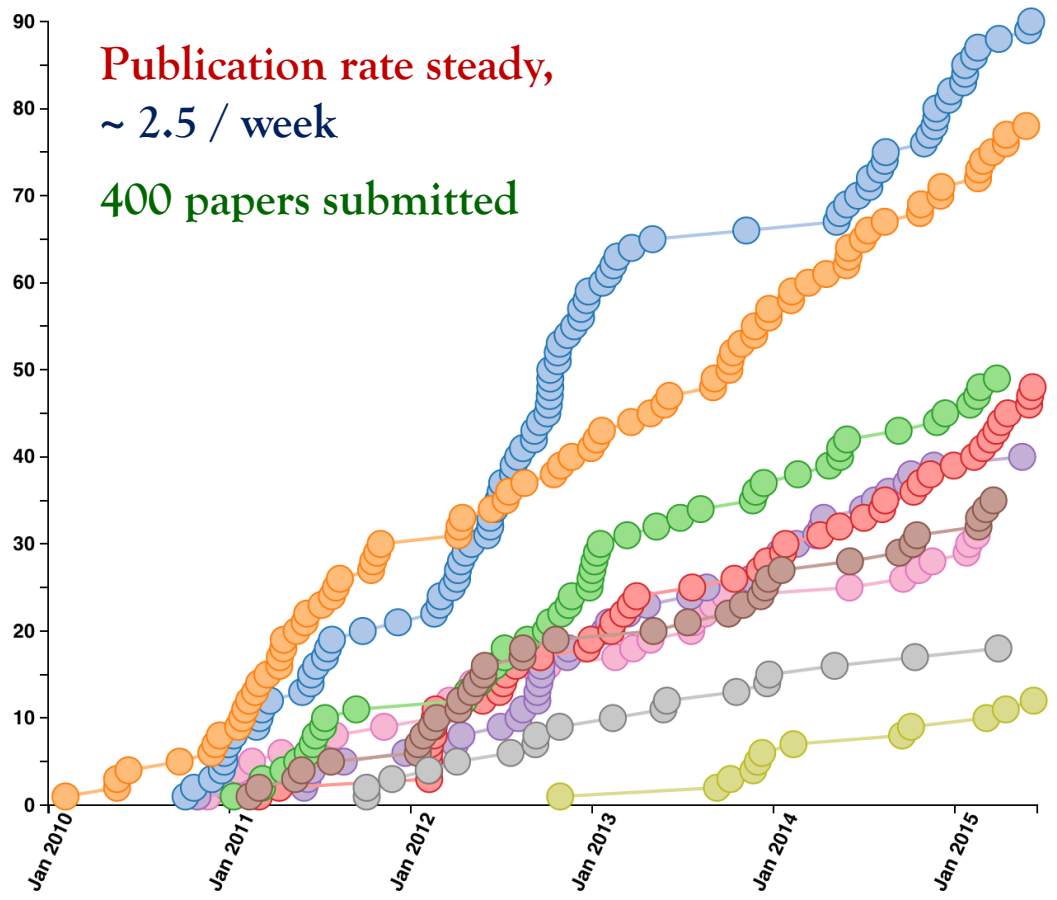


# Publications

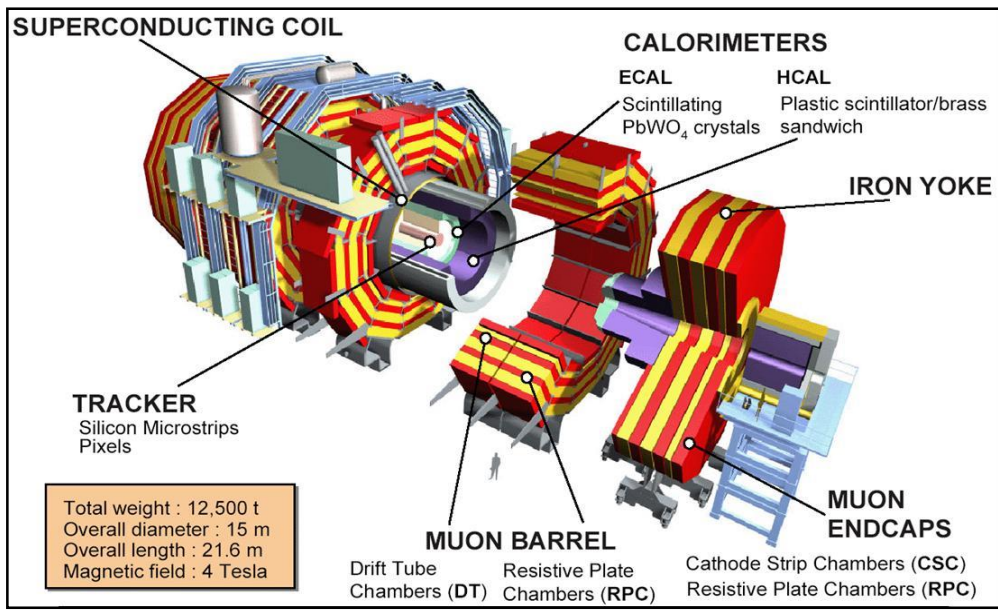


- Show all
- Total
- Exotica
- Standard Model
- Supersymmetry
- Higgs
- Top Physics
- Heavy Ion
- B Physics
- Forward Physics
- Beyond 2 Generations

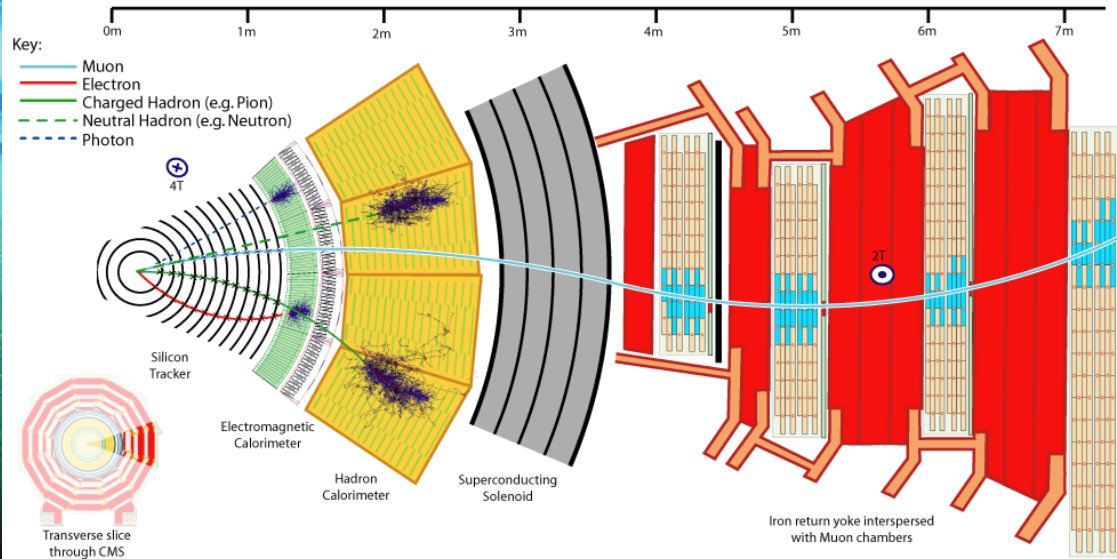
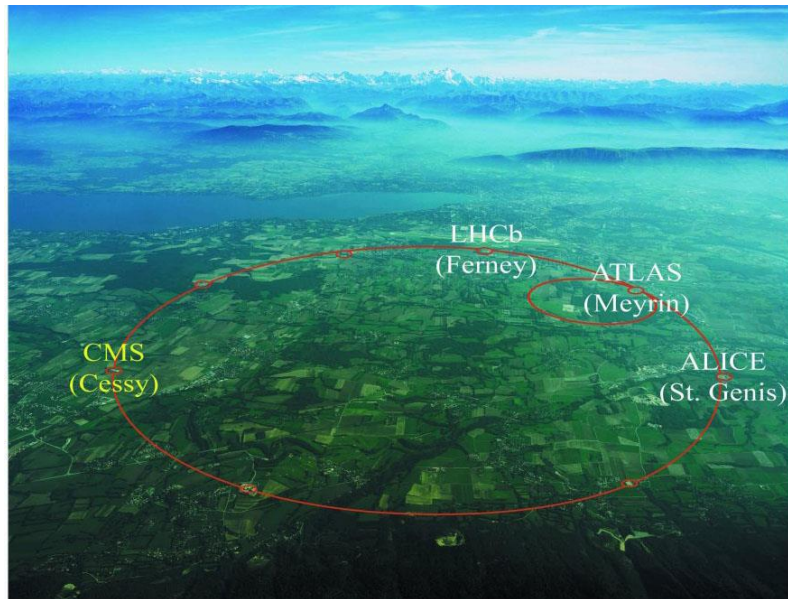
400 papers submitted as of 2015-06-09



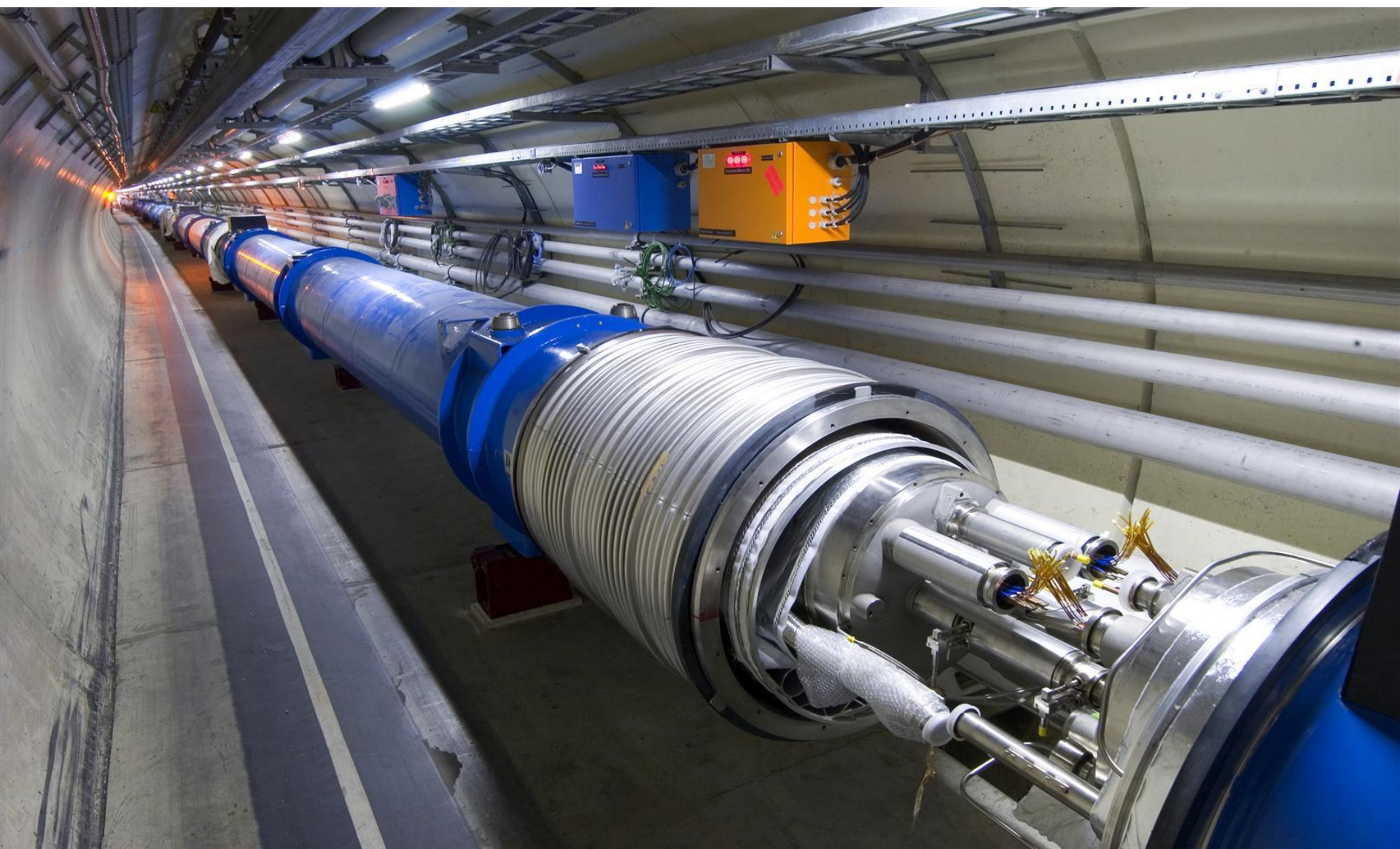
<http://cms-results.web.cern.ch/cms-results/public-results/publications/>



# Accelerator, Detector and Physics Objects



# The LHC

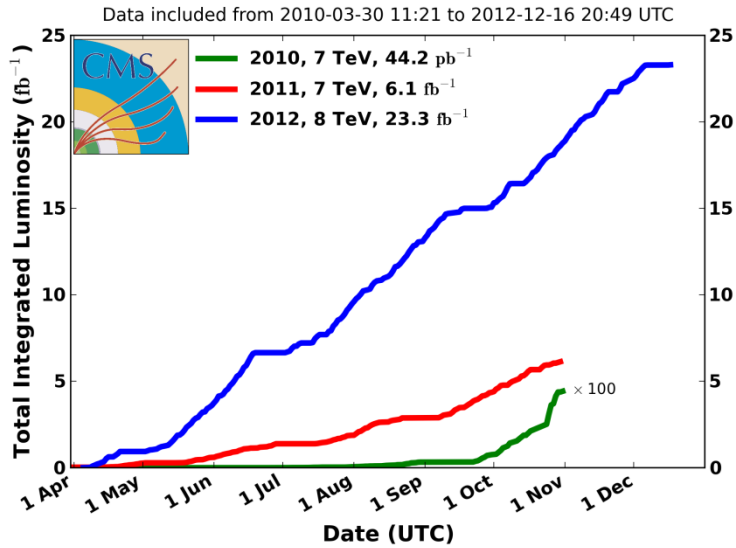




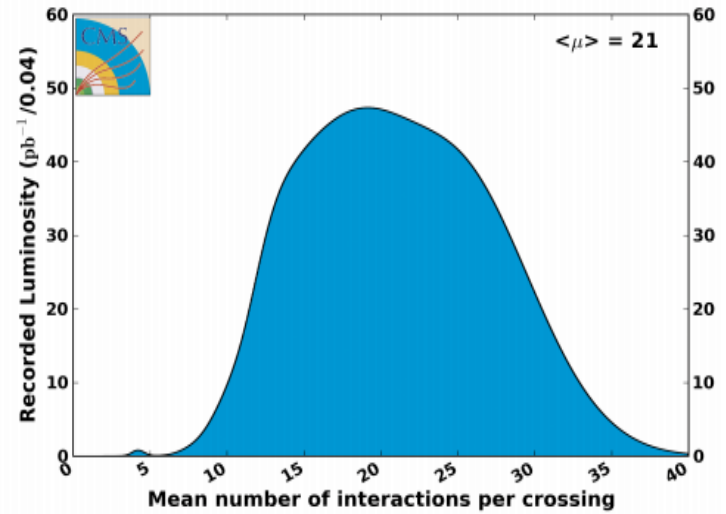
# The LHC



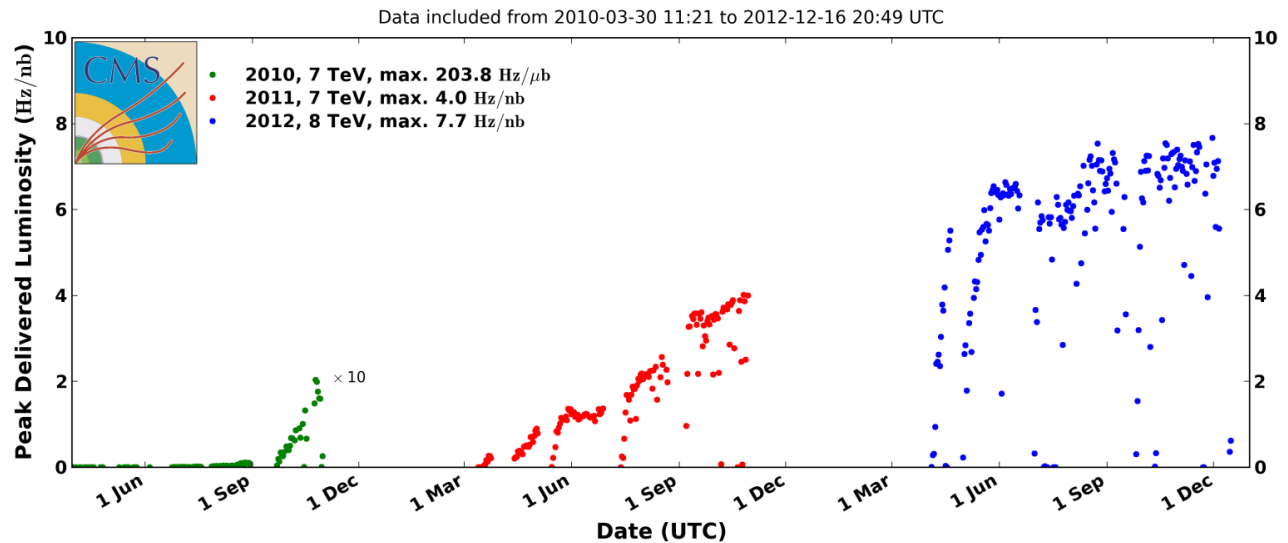
### CMS Integrated Luminosity, pp



### CMS Average Pileup, pp, 2012, $\sqrt{s} = 8$ TeV



### CMS Peak Luminosity Per Day, pp



Overall data taking  
efficiency  $\sim 91\%$

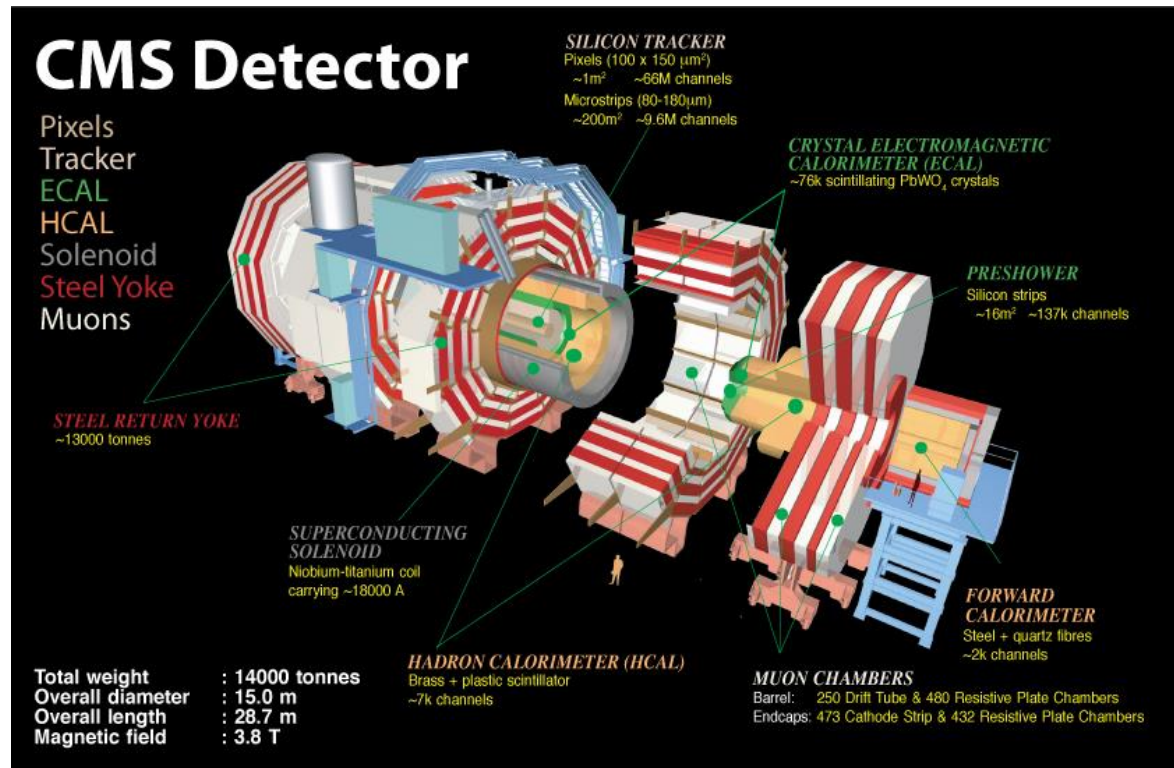
## 3.8 T superconducting solenoid envelop:

- Tracker (silicon pixel and strip detectors)  $|\eta| < 2.5$
- ECAL (PbWO<sub>4</sub> crystals)
- HCAL (brass/scintillator samplers)

Barrel  $|\eta| < 1.48$

Endcap  $1.48 < |\eta| < 3.0$

- Muon Chambers – gas ionization detectors embedded in steel return yoke outside the solenoid,  $|\eta| < 2.4$   
Drift Tubes, Cathode Strips and Resistive Plate Chambers



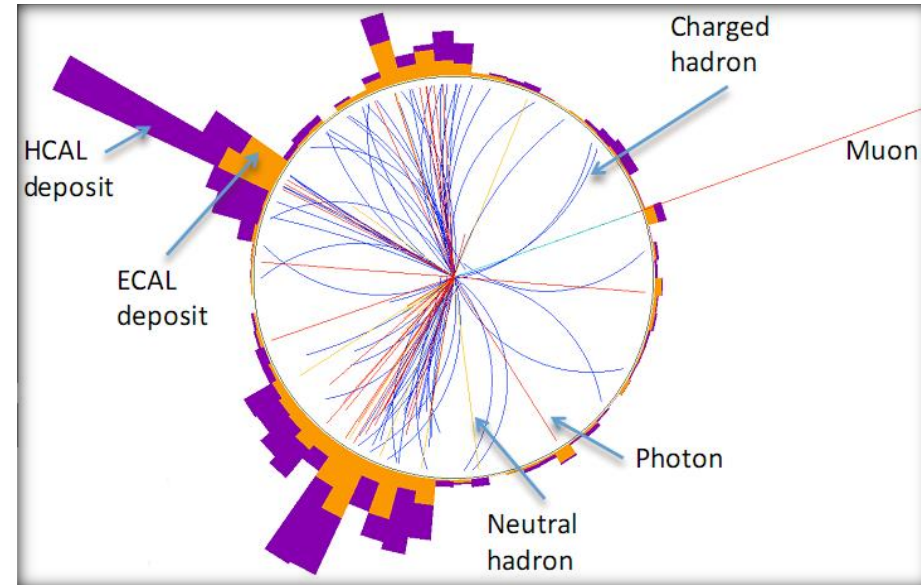


⇒ Event description in form of mutually exclusive particles

⇒ identification of all stable particles produced in the event

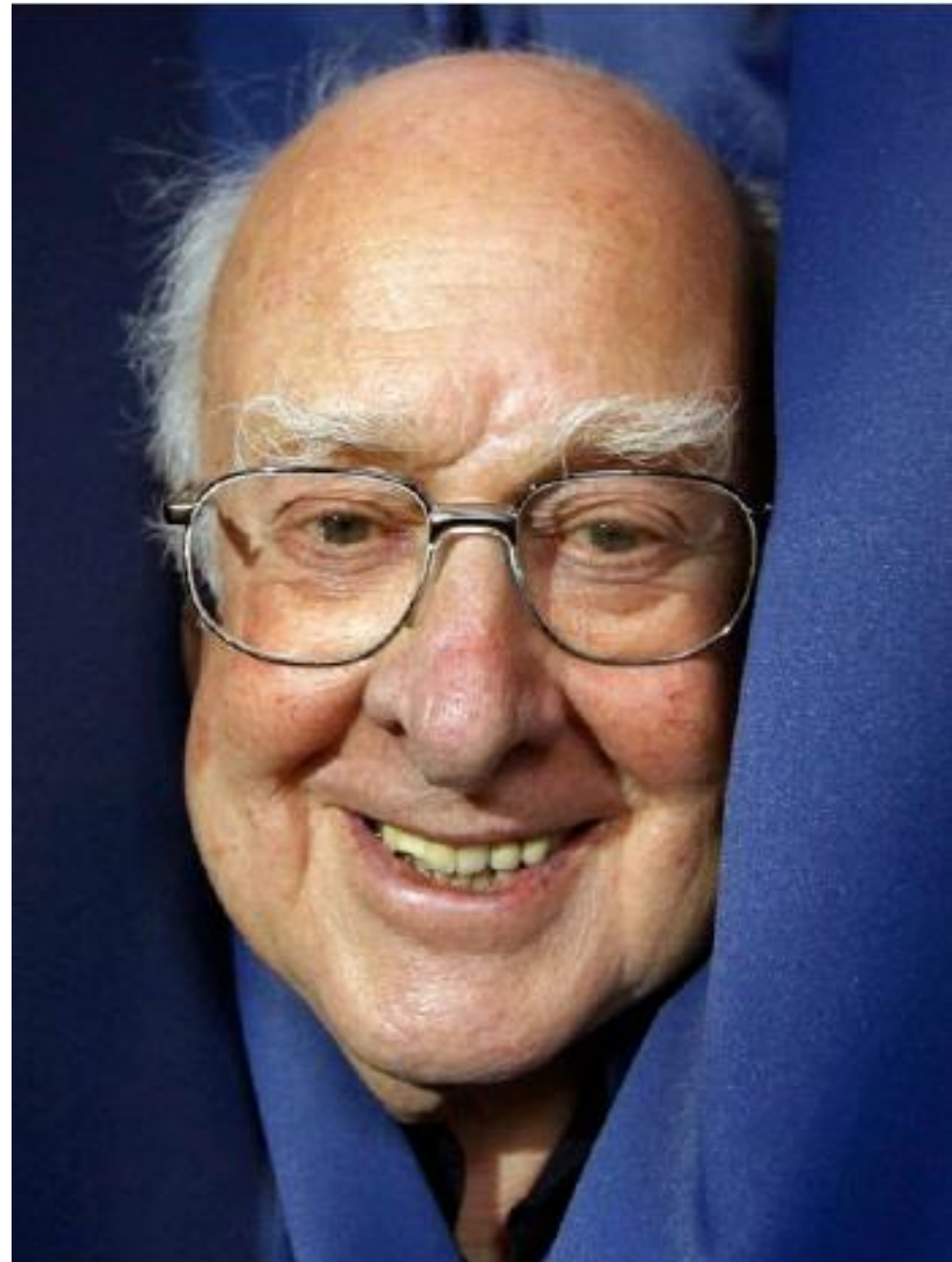
⇒ combining capabilities of each sub-detector most precise measurement of the energy and direction for each particle

⇒ individual measurements combined by a geometrical linking algorithm, e.g. extrapolating a charged-particle track into ECAL and HCAL particle ID on blocks of linked elements



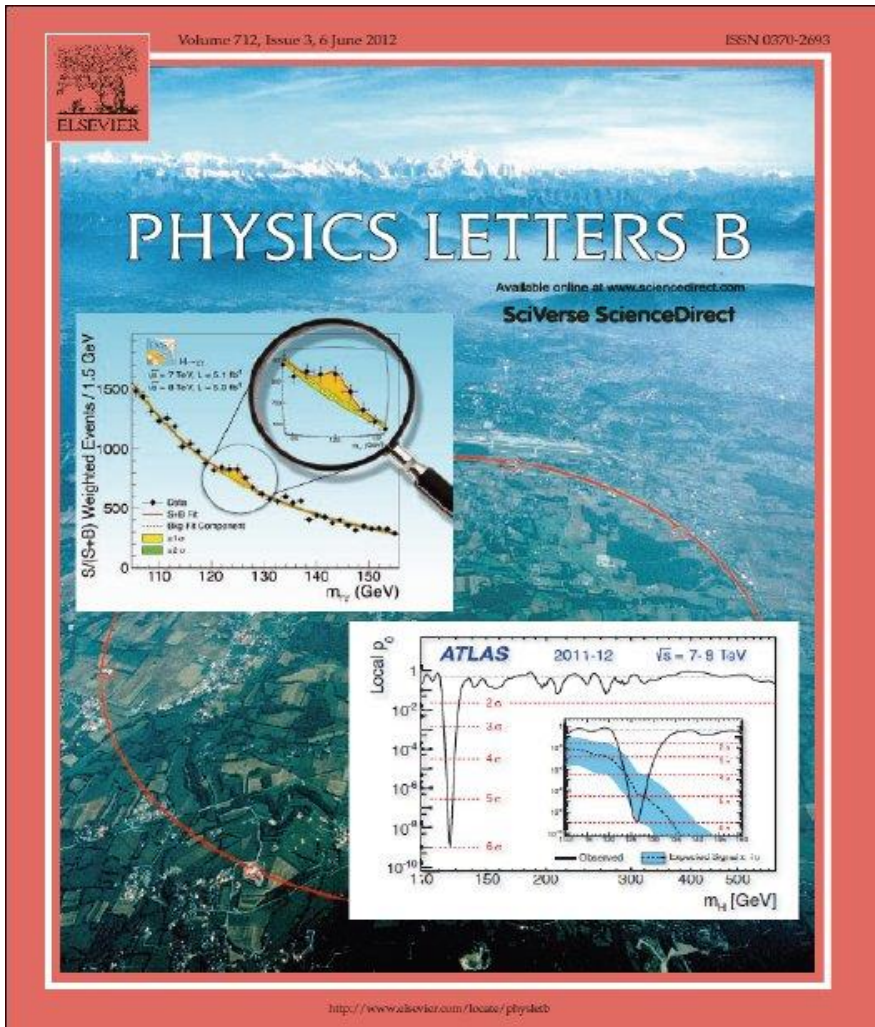
Physics object reconstruction utilises this technique, excellent performing even at high pileup

# Higgs Physics



Higgs is a journey,  
not a destination

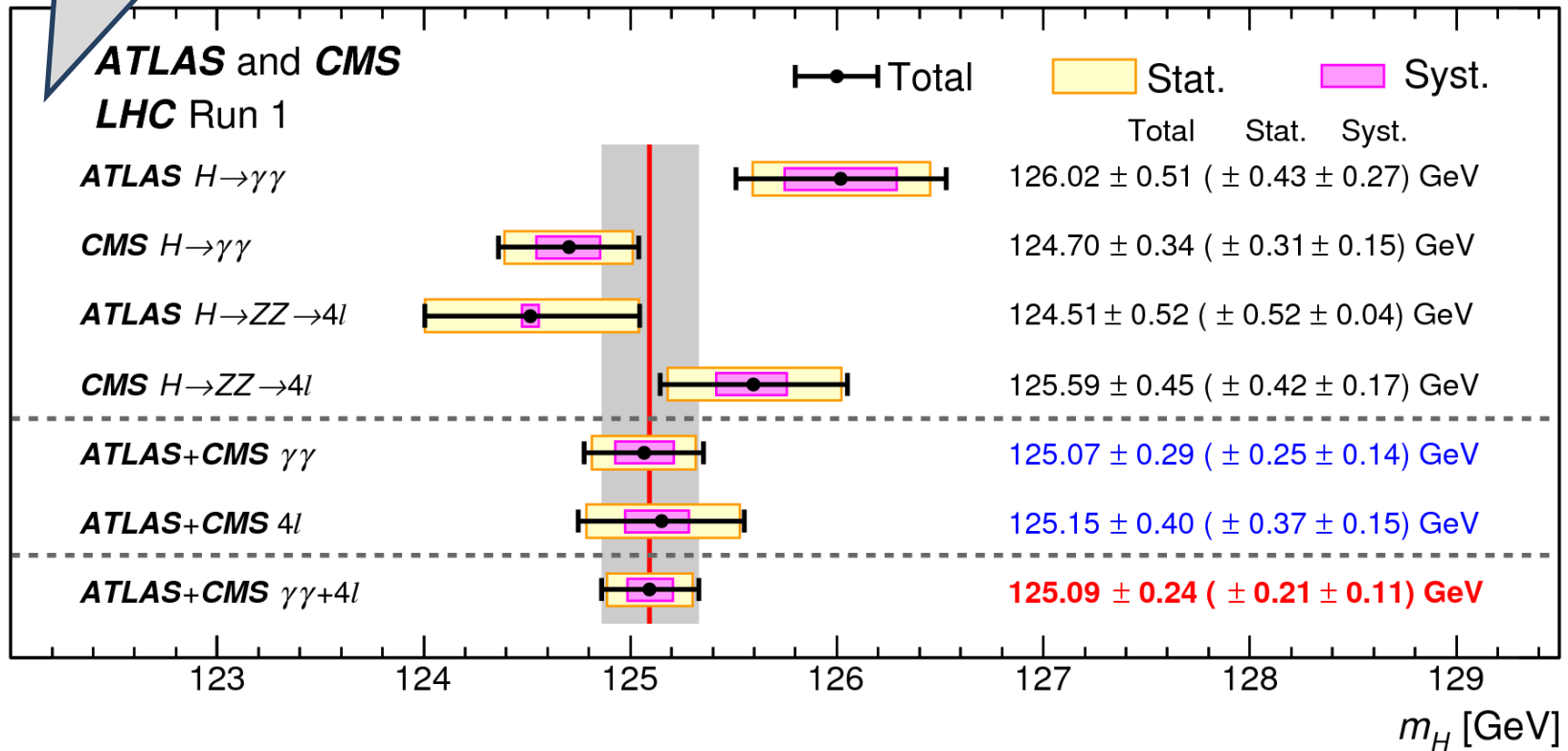
Great achievement to a four decade long quest  
 A Higgs-like state pinned down at 125 GeV mass



Phys. Rev. Lett. 114 (2015) 191803

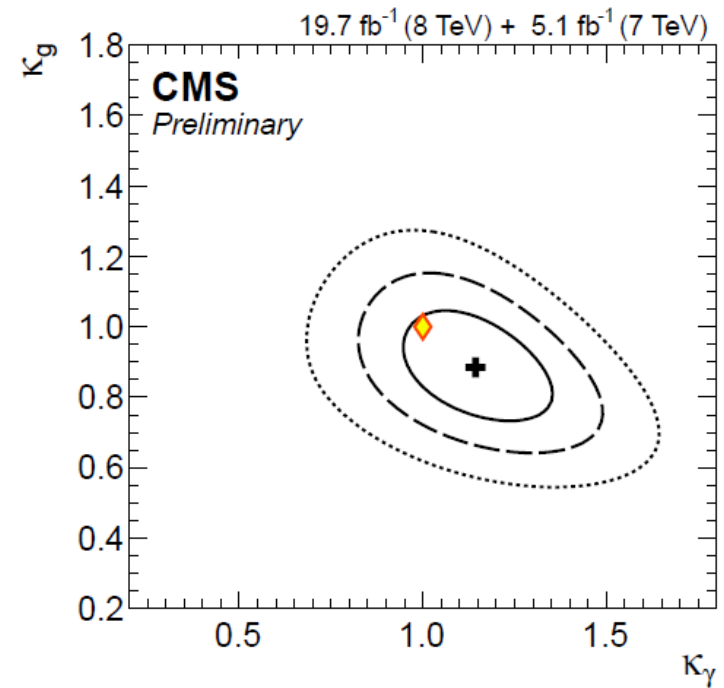
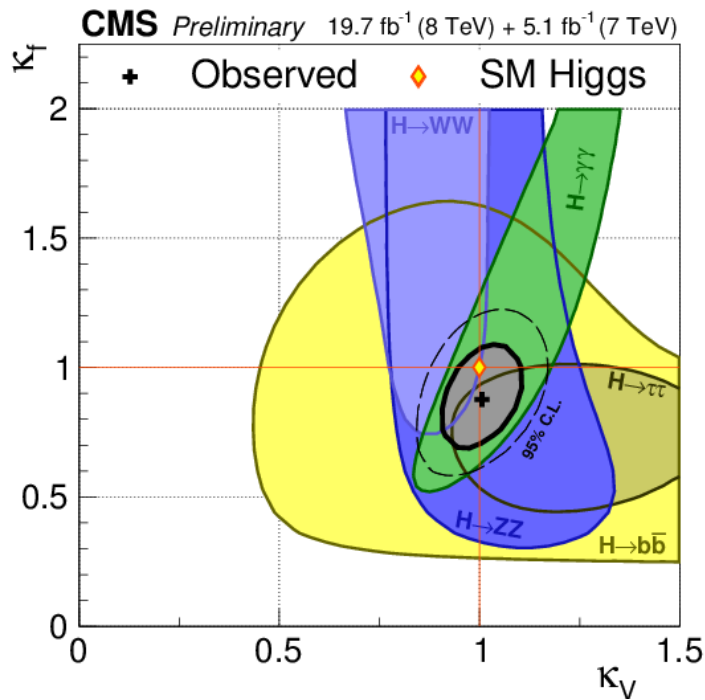
Over 5000  
authors in  
a paper

Results from simultaneous fit to the reconstructed invariant mass peaks in  $\gamma\gamma$  and  $ZZ^* \rightarrow 4l$  channels for ATLAS and CMS



CMS-PAS-HIG-14-009

2D likelihood scan for  $\kappa_g$  and  $\kappa_\gamma$  parameters assuming that  $\Gamma_{\text{BSM}}=0$

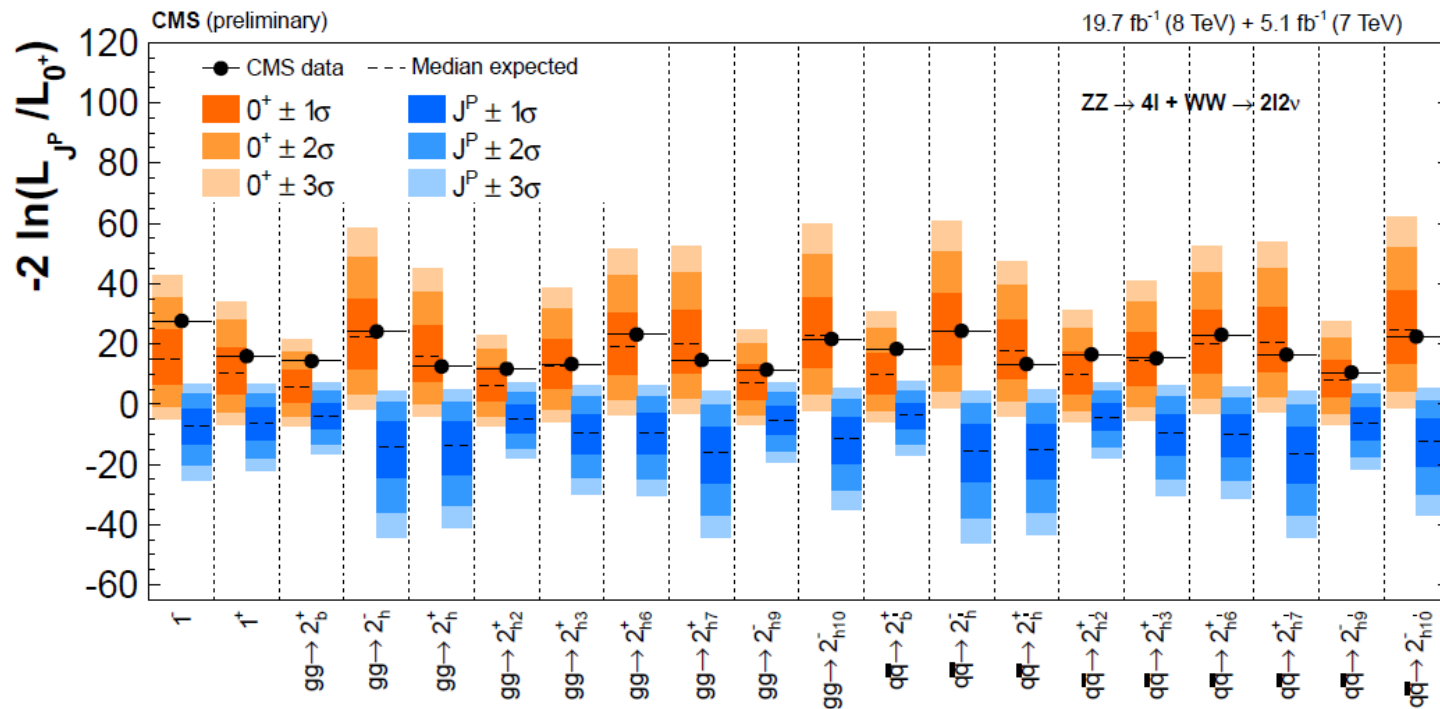


Results within  $1\sigma$  of Standard Model prediction

# Higgs Spin & Parity

CMS-PAS-HIG-14-014

- Using full angular information defining 4 lepton system
- For each hypothesis create kinematic discriminant for SM vs alternative hypothesis
- Perform 2D fit of hypothesis discriminant versus background discriminant and perform hypothesis test



Several J<sup>P</sup> hypotheses have been tested  
 Consistency with the SM scalar boson

Proposed by  
 F. Caola, K. Melnikov, PRD 88 (2013) 054024  
 N. Kauer, G. Passarino, JHEP 08 (2012) 116  
 J. Campbell et al. (arXiv:1311.3589)

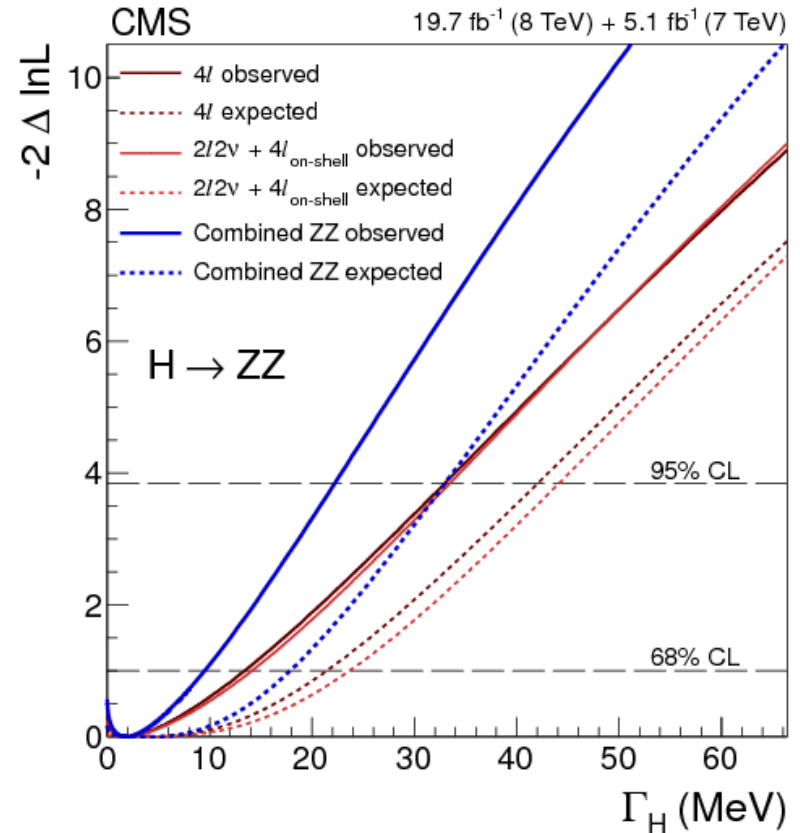
Physics Letters B 736, 64 (2014)

On shell and off shell production in ZZ:

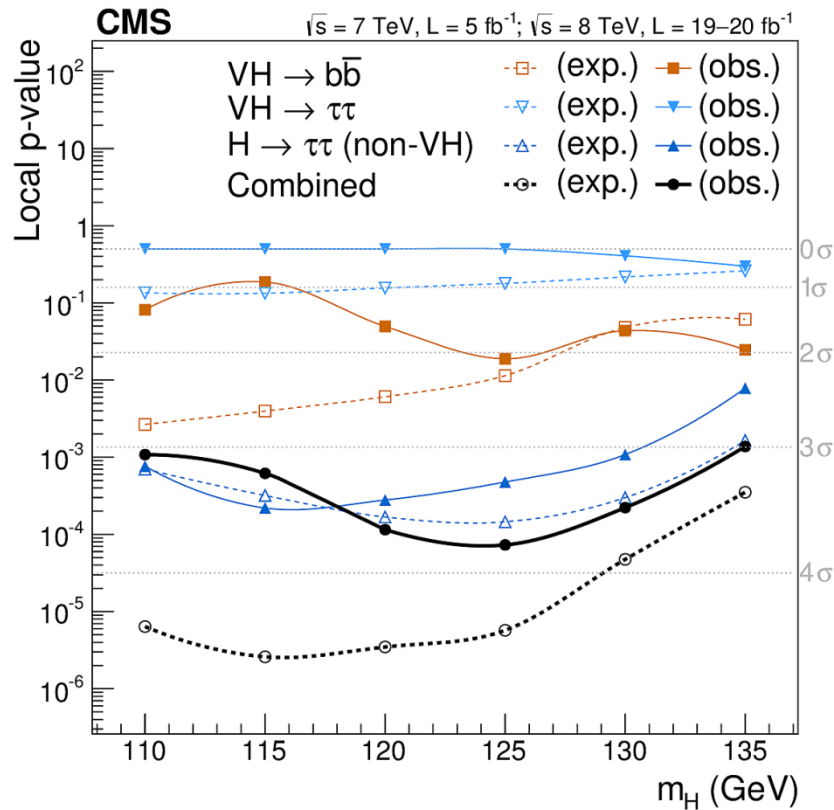
$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H}$$

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{off-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2}$$

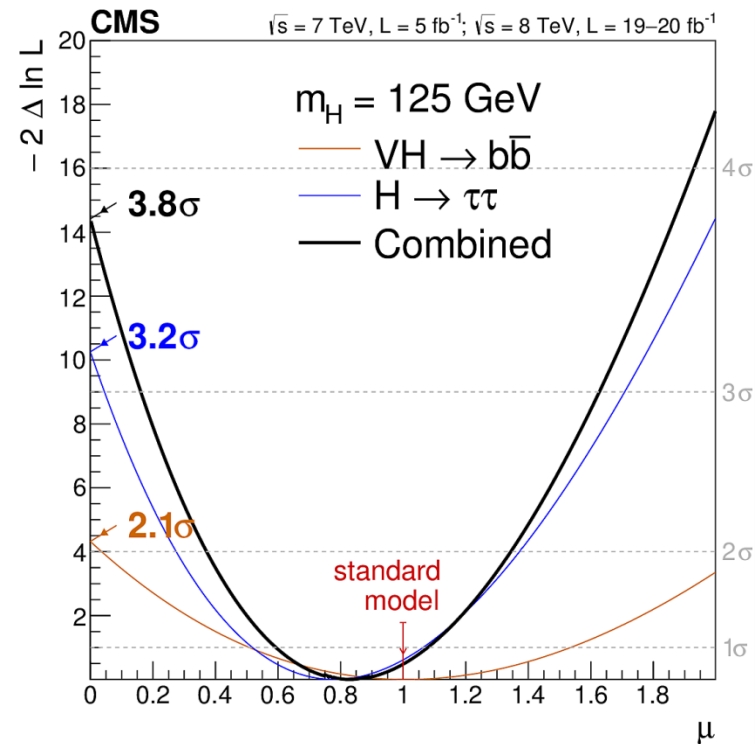
- Observed limit of 5.4 x SM corresponding to ~ 22 MeV @ 95% CL



Nature Physics 10, 557 (2014)



Channel ( $m_H = 125 \text{ GeV}$ )	Significance ( $\sigma$ )		Best-fit $\mu$
	Expected	Observed	
$VH \rightarrow b\bar{b}$	2.3	2.1	$1.0 \pm 0.5$
$H \rightarrow \tau\tau$	3.7	3.2	$0.78 \pm 0.27$
Combined	4.4	3.8	$0.83 \pm 0.24$



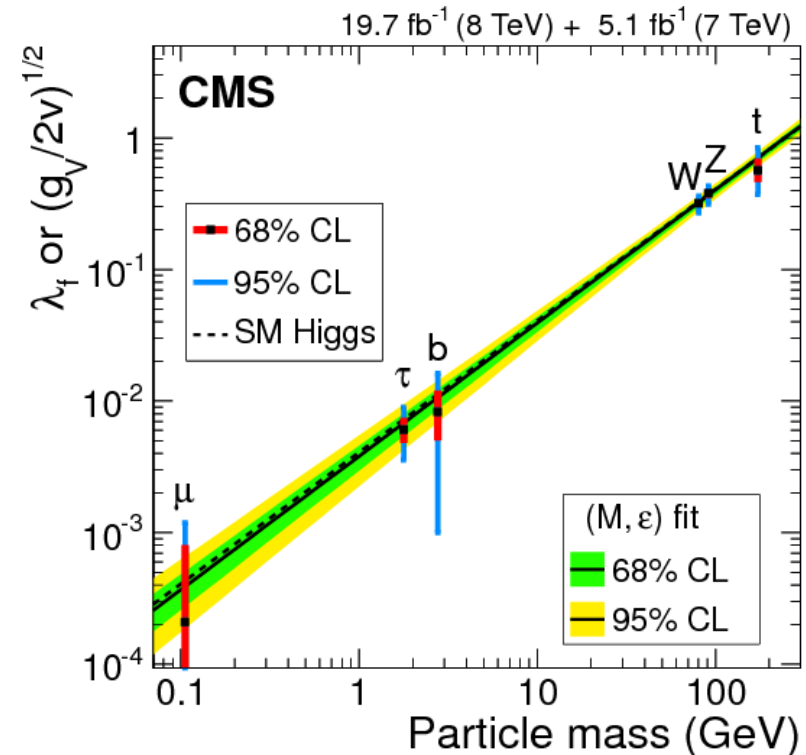
Strong evidence for the **direct coupling** of the **125 GeV Higgs boson** to **fermions**, with an **observed (expected) significance of  $3.8\sigma$  ( $4.4\sigma$ )**



- We know it exists! **Phys. Lett. B 716 (2012) 30**
- We know its a **boson**.
- We know its **mass** : **CMS PAS HIG-14-009**

$$m_H(\text{CMS}) = 125.03^{+0.26}_{-0.27} (\text{stat})^{+0.13}_{-0.15} (\text{syst})$$

- We have strong evidence that it **couple to fermions** **Nat. Phys. 10 (2014) 557**  
Couplings are determined within 15 to 20% accuracy, leaving room for **BSM physics**
- We have reasons to believe that it is a **spin 0 CP even** object  
**Phys. Rev. D 89 (2014) 092007**
- We know it's a **Higgs boson!**



Is this **THE Higgs** boson (of the SM) or is it just **A Higgs** boson?

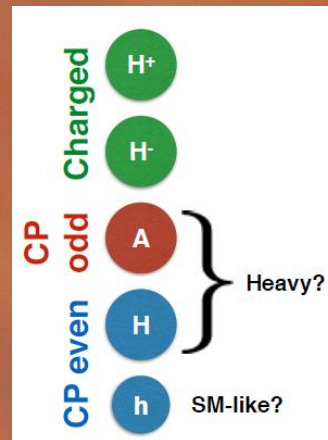
- Run I searches covered a large range of BSM Higgs boson signatures
- **LHC is the discovery machine**
  - the adventure in the TeV energy regime has just begun



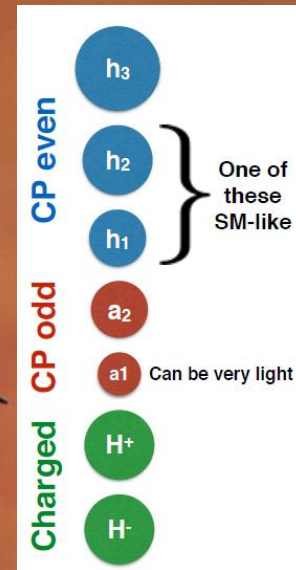
Lepton Flavour Violating  
Higgs Decays

Invisible Higgs Decays

MSSM / 2 HDM

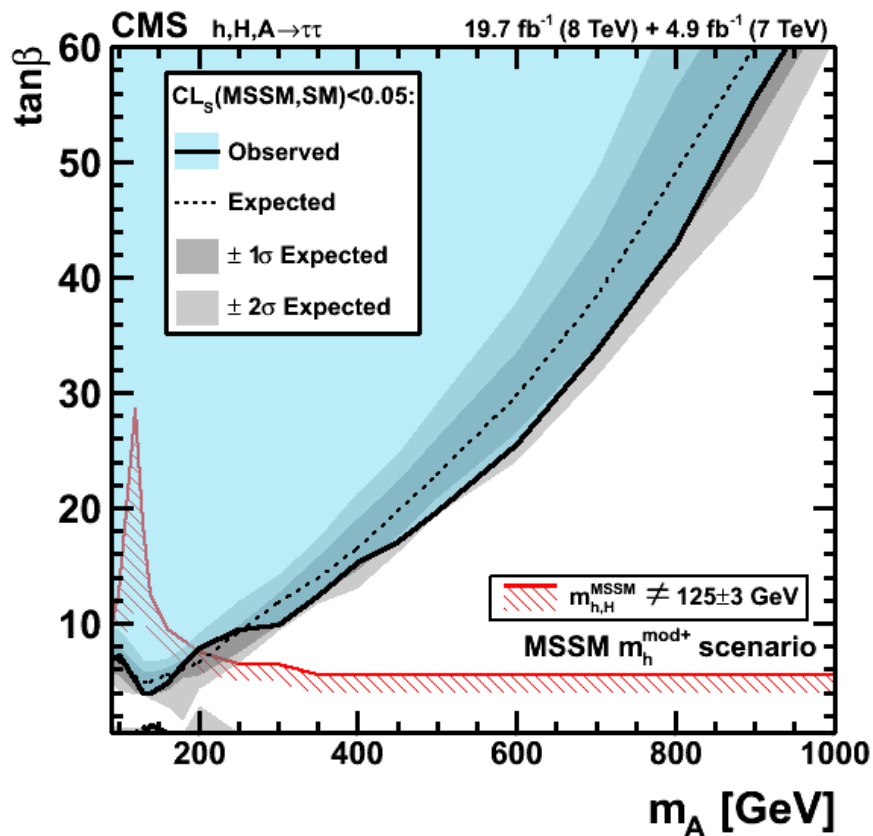


Next-to-MSSM  
(NMSSM)



# Neutral MSSM Higgs

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13021PaperTwiki>



95% CL upper bound on cross-section x  $\mathcal{B}r(\Phi \rightarrow \tau\tau)$  – based on the mass shape of  $m_{\tau\tau}$  distribution mapped to  $m_A - \tan\beta$  plane (4FS + 5FS)

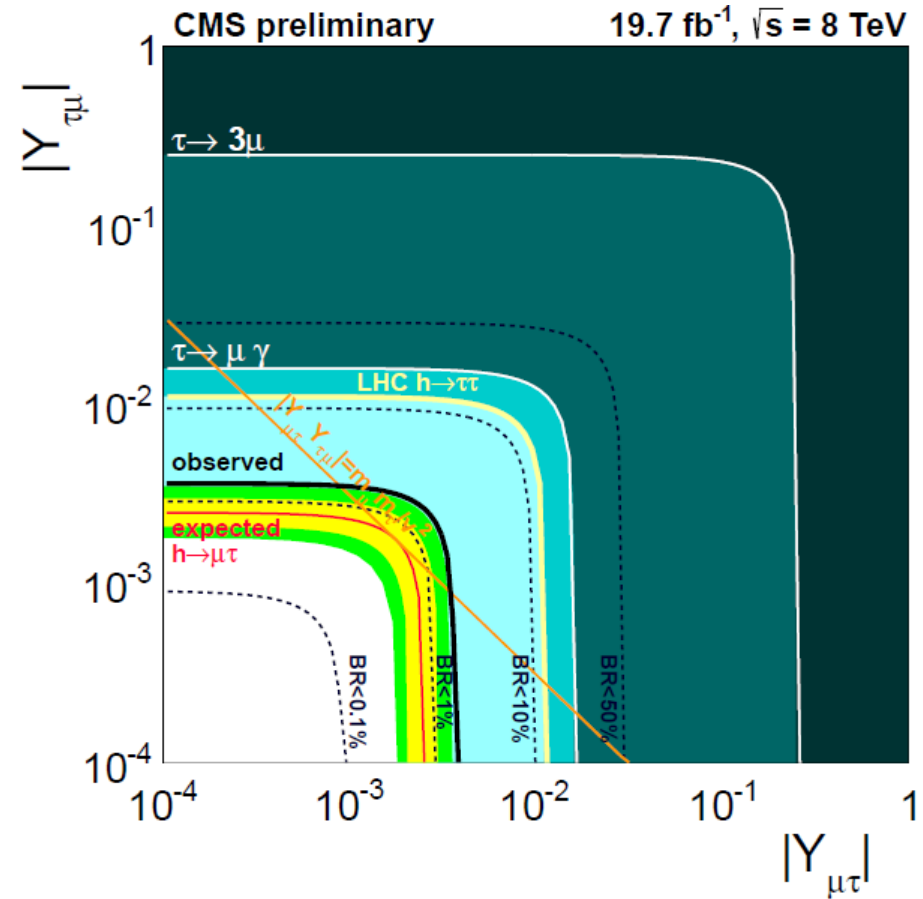
Excludes previously unexplored region: reaching  $\tan\beta \sim 3.9$  at  $m_A = 140 \text{ GeV}$

CMS PAS HIG-14-005

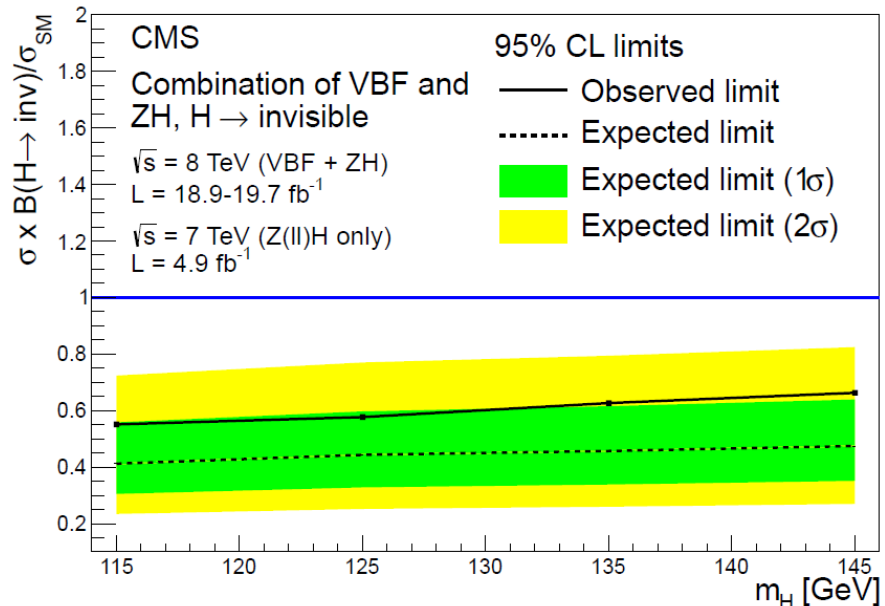
$$B(H \rightarrow l^\alpha l^\beta) = \frac{\Gamma(H \rightarrow l^\alpha l^\beta)}{\Gamma(H \rightarrow l^\alpha l^\beta) + \Gamma_{SM}}$$

$$\Gamma(H \rightarrow l^\alpha l^\beta) = \frac{m_h}{8\pi} (|Y_{l^\beta l^\alpha}|^2 + |Y_{l^\alpha l^\beta}|^2)$$

- Constraint placed on  $B(H \rightarrow \mu\tau) < 1.57\%$  at 95% CL
- The best fit branching fraction is  $B(H \rightarrow \mu\tau) = (0.89^{+0.40}_{-0.37})\%$
- The limit is subsequently used to constrain the  $Y_{\mu\tau}$  Yukawa coupling

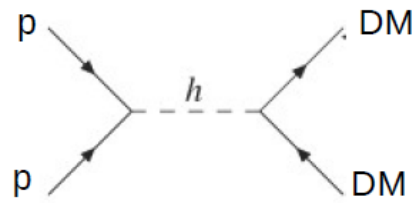


Eur. Phys. J. C 74 (2014) 2980

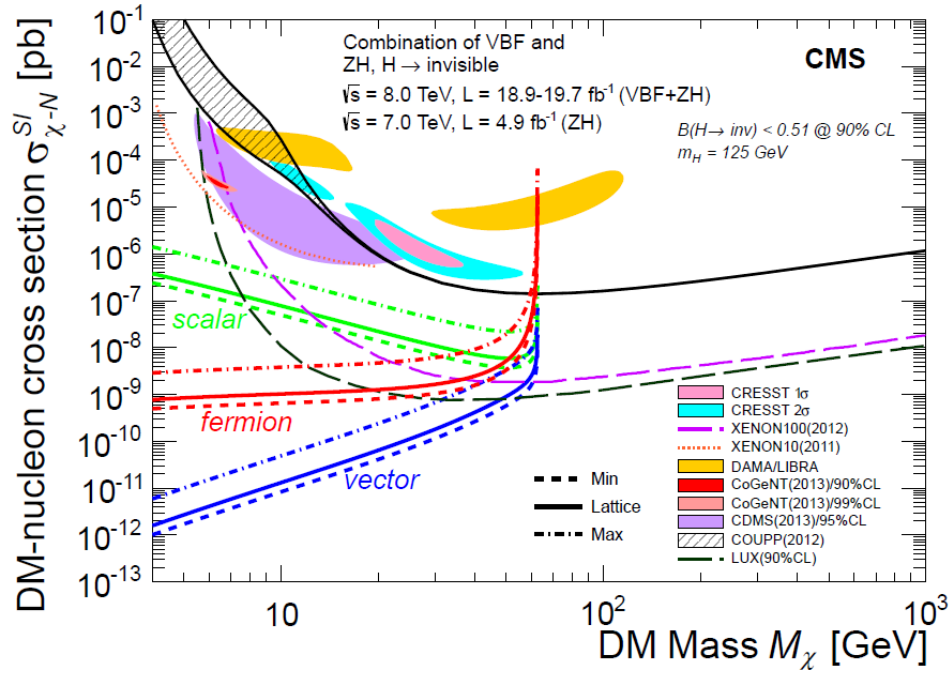
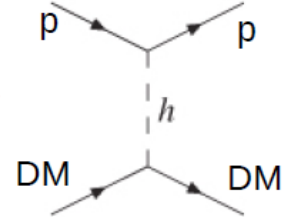


Excluded on 95% CL:  
 **$BR(H \rightarrow \text{inv.}) < 0.58$  at 125 GeV**  
 (expected  $< 0.44$ )

Measured:



Translate into:

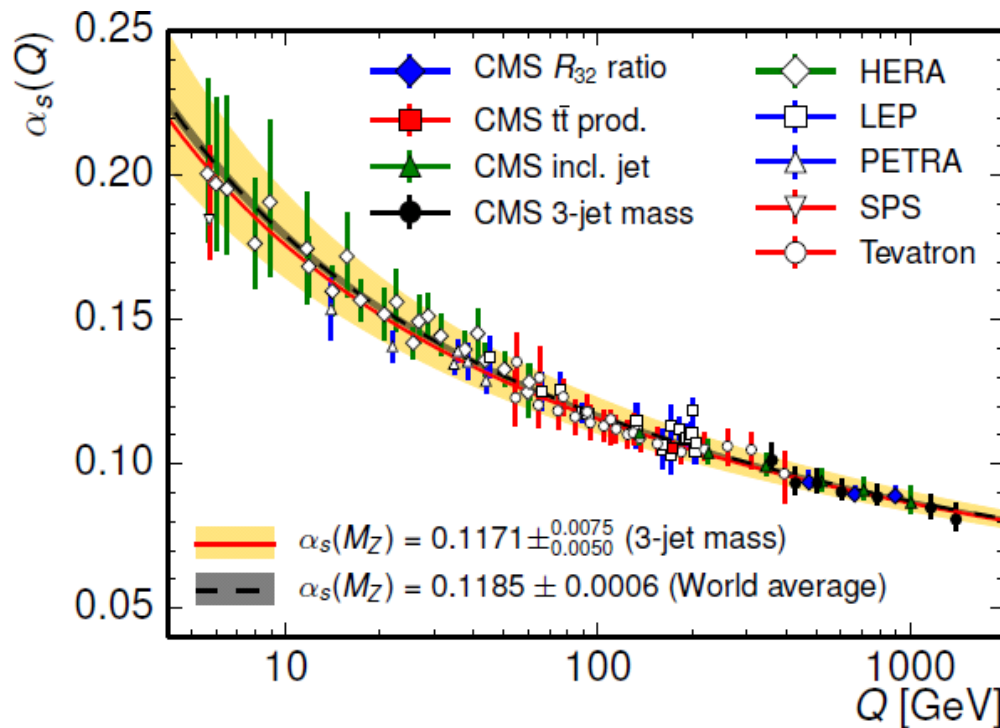




# QCD Physics

# $\alpha_s$ measurement

Ratio of 3-jets to 2-jets, 3-jet mass, and incl. jet x-sections constrain  $\alpha_s$  up to so far unprobed scales  $Q \sim 1.4$  TeV



arXiv:1410.6765, arXiv:1412.1633

Measurements dominated by theoretical uncertainty.  
PDF & scale uncertainty, e.g. incl. jets:

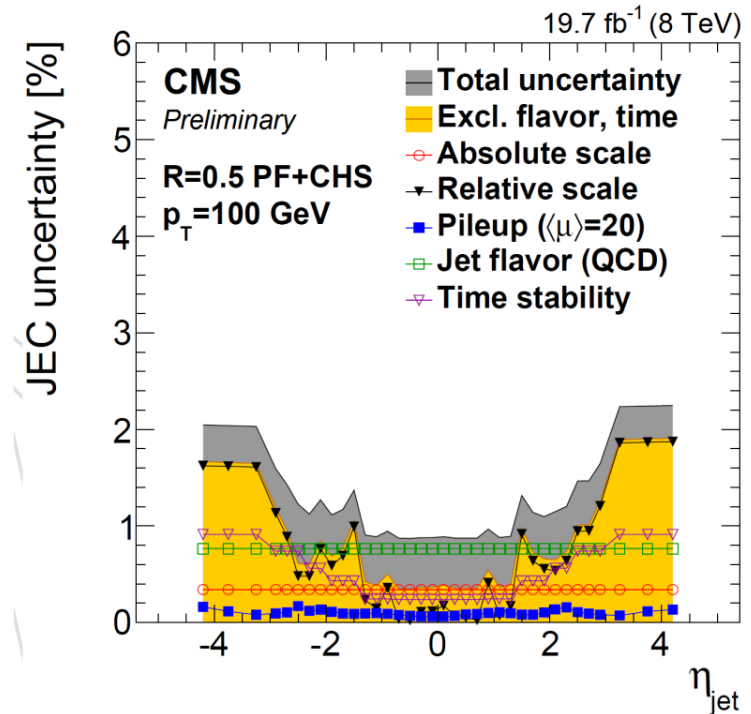
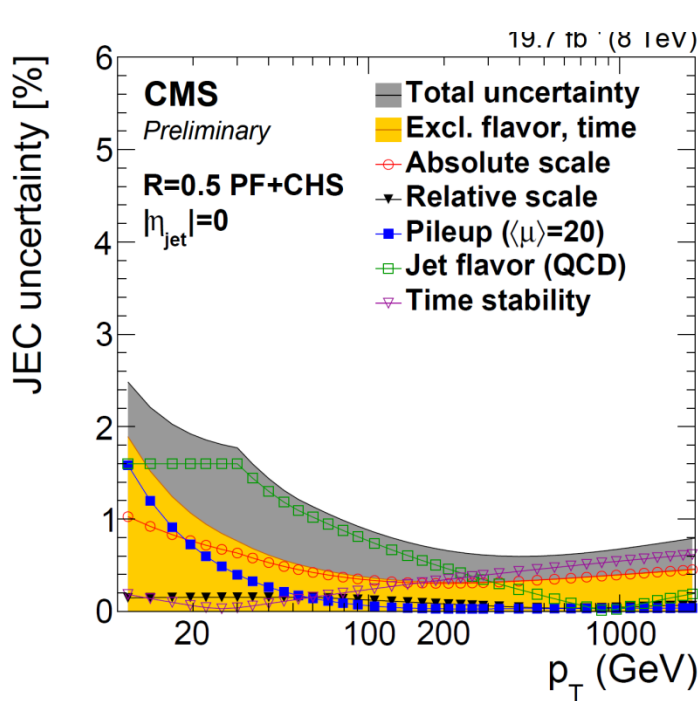
$$\alpha_s(M_Z) = 0.1185 \pm 0.0019 \text{ (exp)} \begin{matrix} +0.0060 \\ -0.0037 \end{matrix} \text{ (theo)}$$



**CMS-JME-13-004**

## Legacy performance for jet energy scale and resolution for 8 TeV data

- Corrections derived accounting for pile-up, detector response, residual  $\eta$  and  $p_T$  dependence, and (optionally) flavour
- Corrections derived using a mix of dijet,  $Z$ +jet, and  $\gamma$ +jet data
- Uncertainties  $< 3\%$  across the phase space considered by most analyses

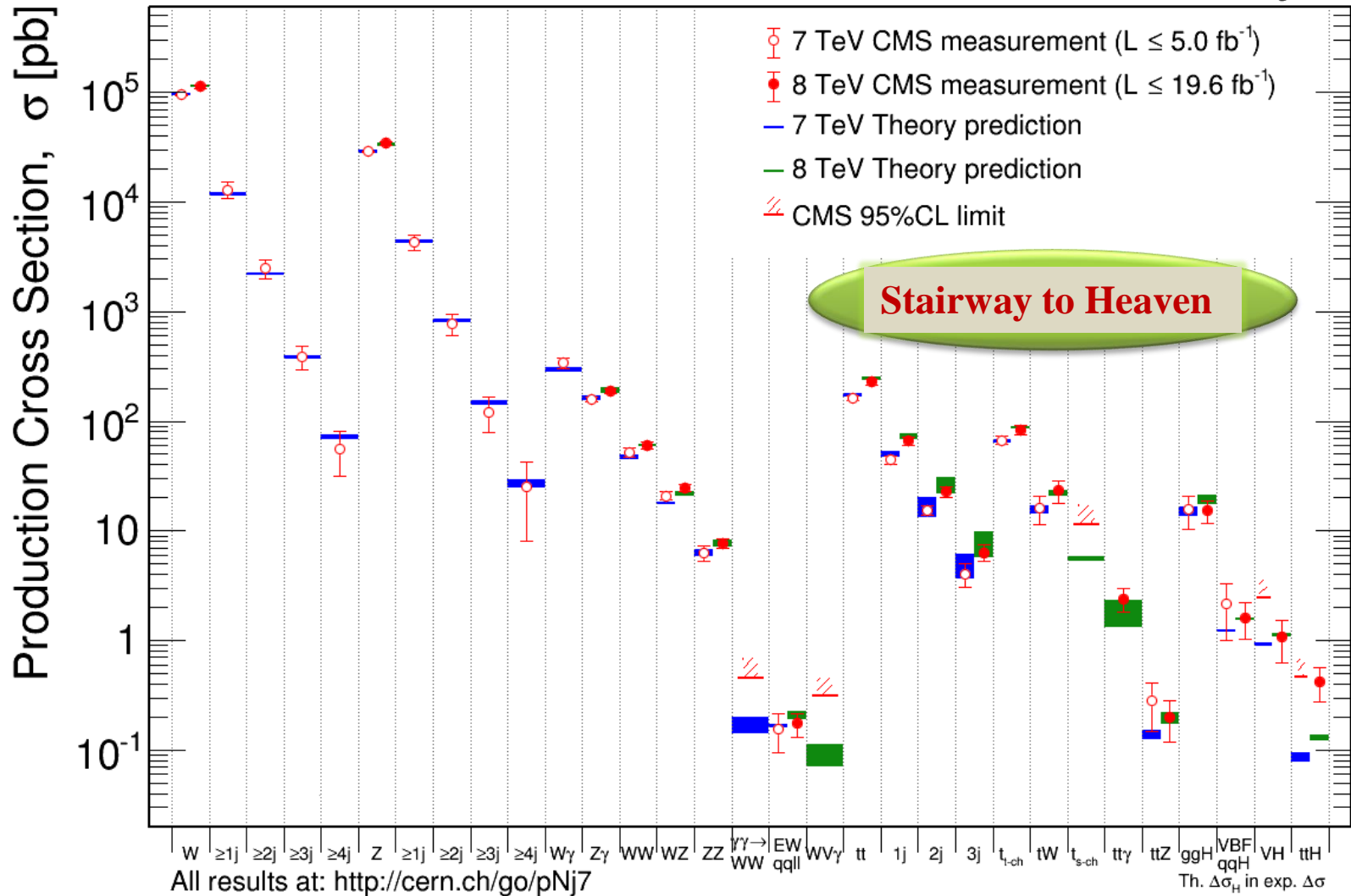


# Electroweak Physics



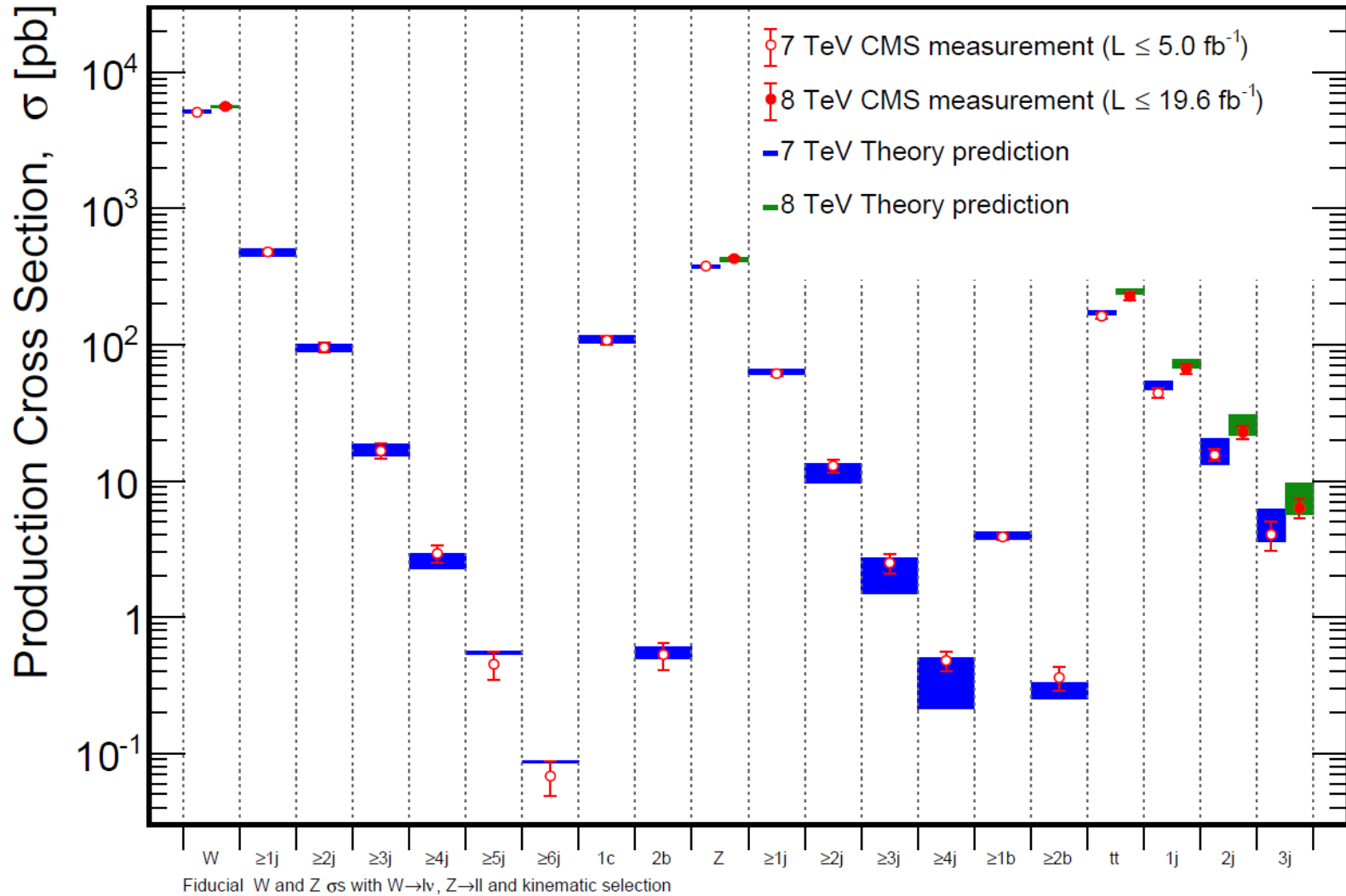
Mar 2015

CMS Preliminary



Mar 2014

CMS Preliminary



# Top Physics

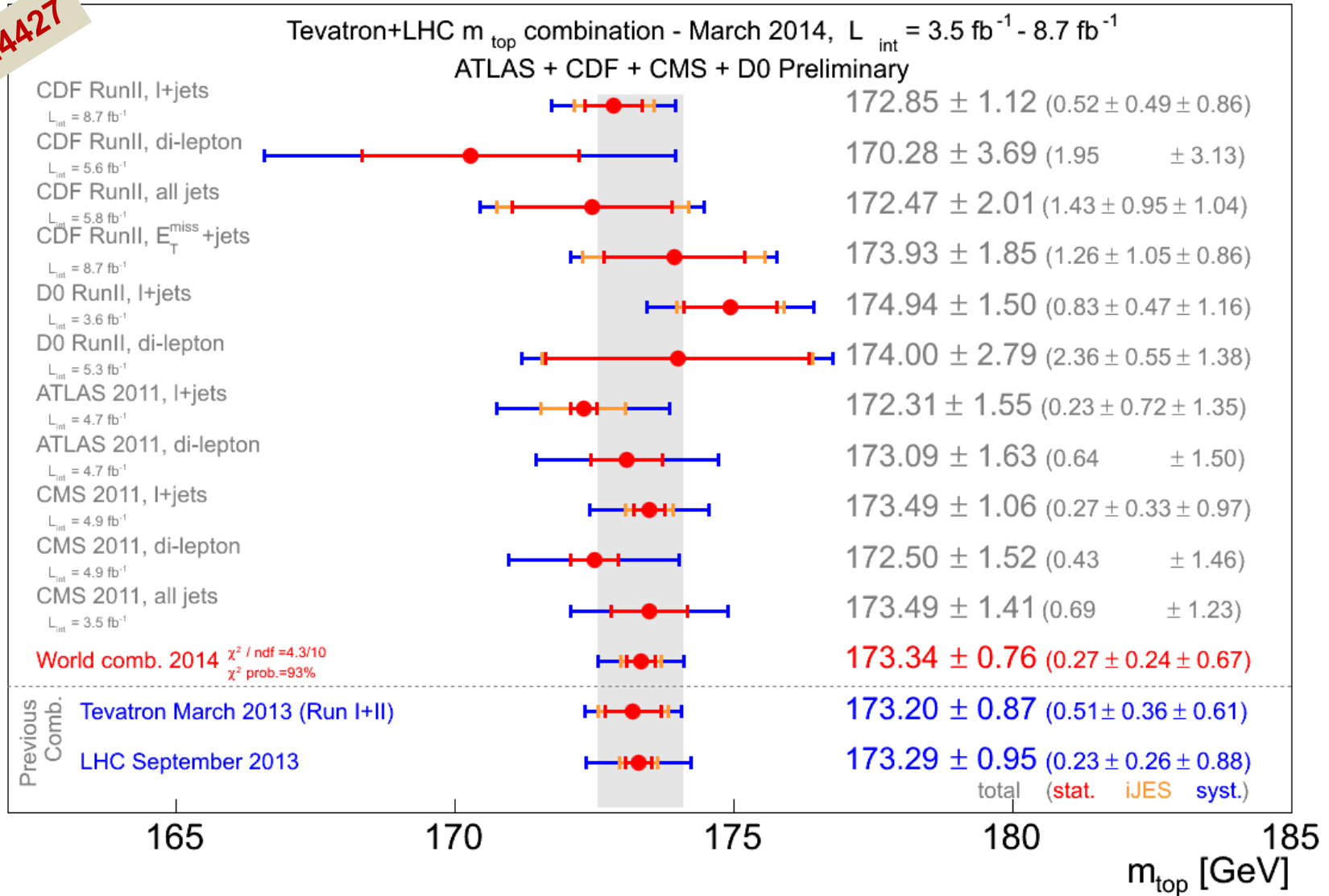


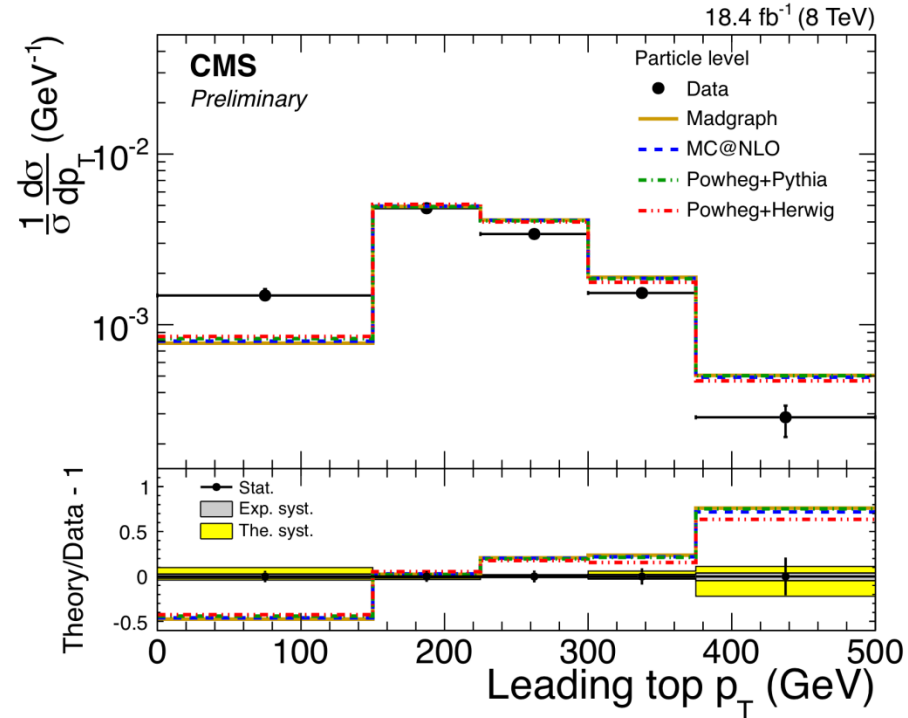
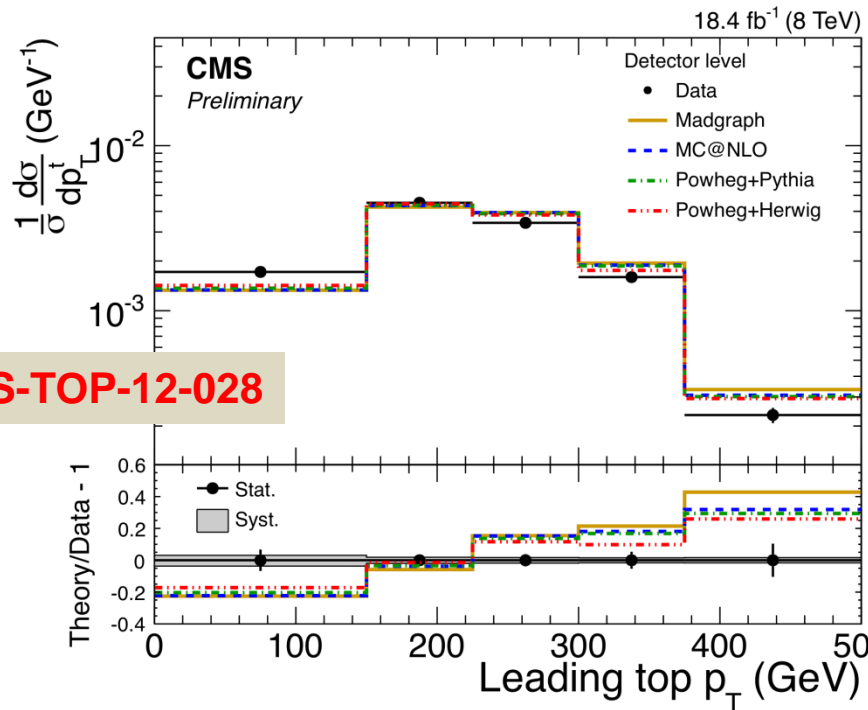


# Combined LHC + Tevatron Top Mass



arXiv: 1403.4427





Inclusive cross sections

$275.6 \pm 39.0$  pb (14% precision)

dominated by **JES** and **BTag** uncertainties  
performed differential measurements as a  
function of **top  $p_T$**

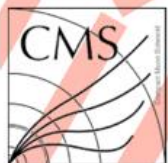
- results presented at **detector**, **parton**, and **particle** level
- theory predicts **systematically harder spectrum**
- in agreement with measurements in **lepton+jets** and **dilepton channels** at parton level

# Forward & Small-x QCD Physics

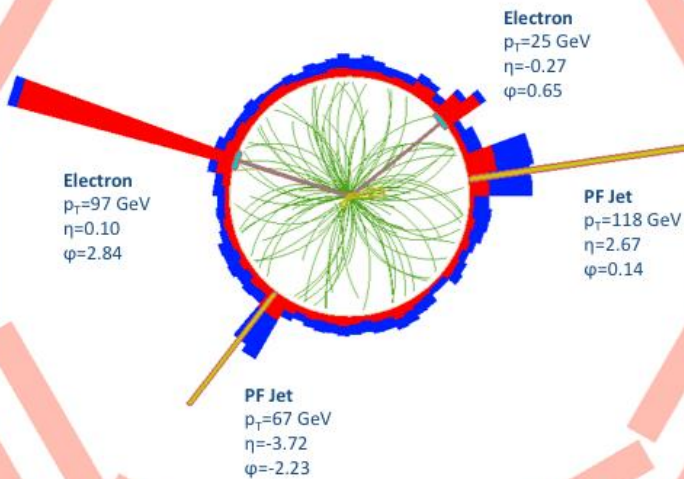




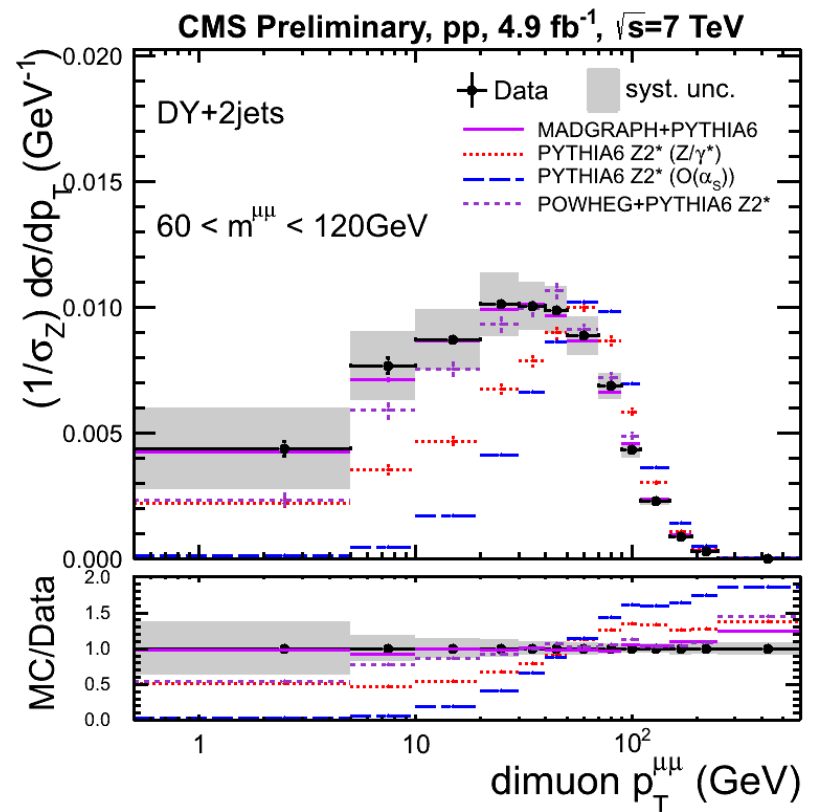
## CMS-PAS-FSQ-12-035



CMS Experiment at LHC, CERN  
 Data recorded: Tue May 22 14:53:14 2012 CEST  
 Run/Event: 194702 / 156701816  
 Lumi section: 151



## CMS-PAS-FSQ-13-003

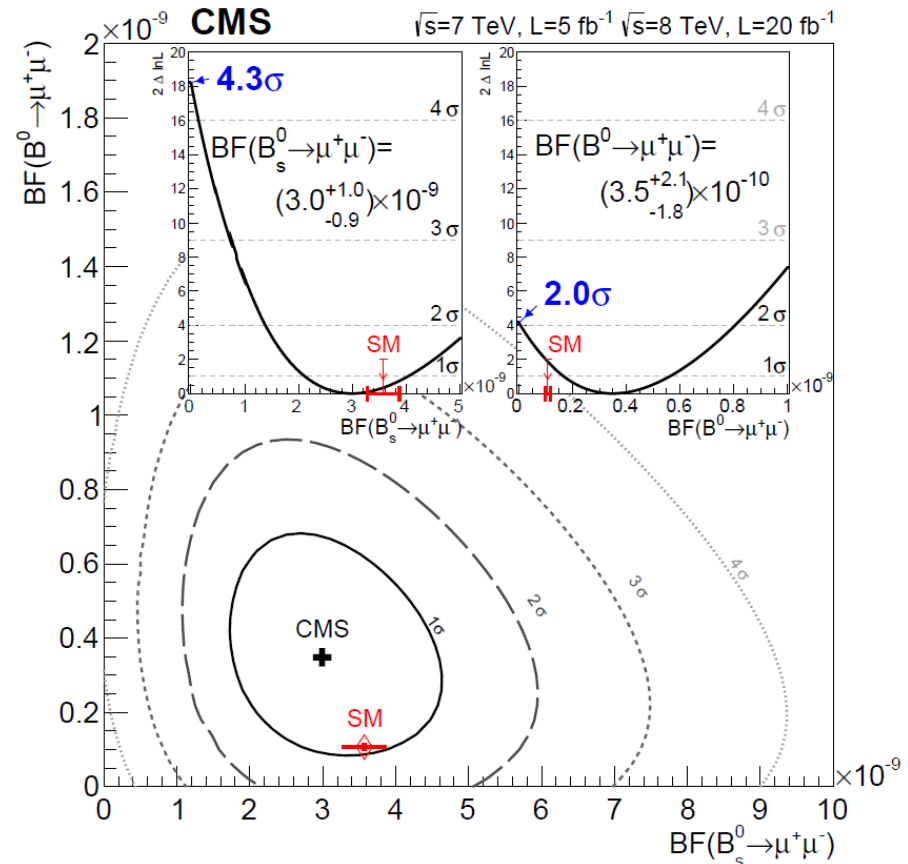
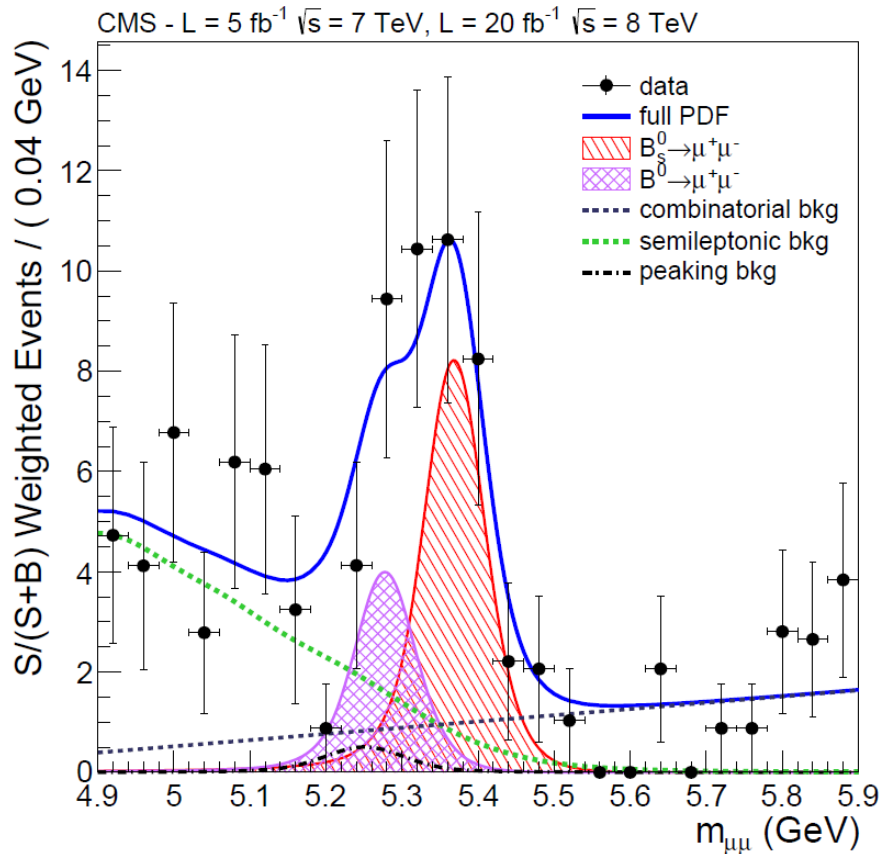


## B - physics



Phys. Rev. Lett. 111 (2013) 101804

maximum-likelihood fit to dimuon invariant mass distribution for BF ( $B_s \rightarrow \mu^+\mu^-$ ), significance 4.3 $\sigma$





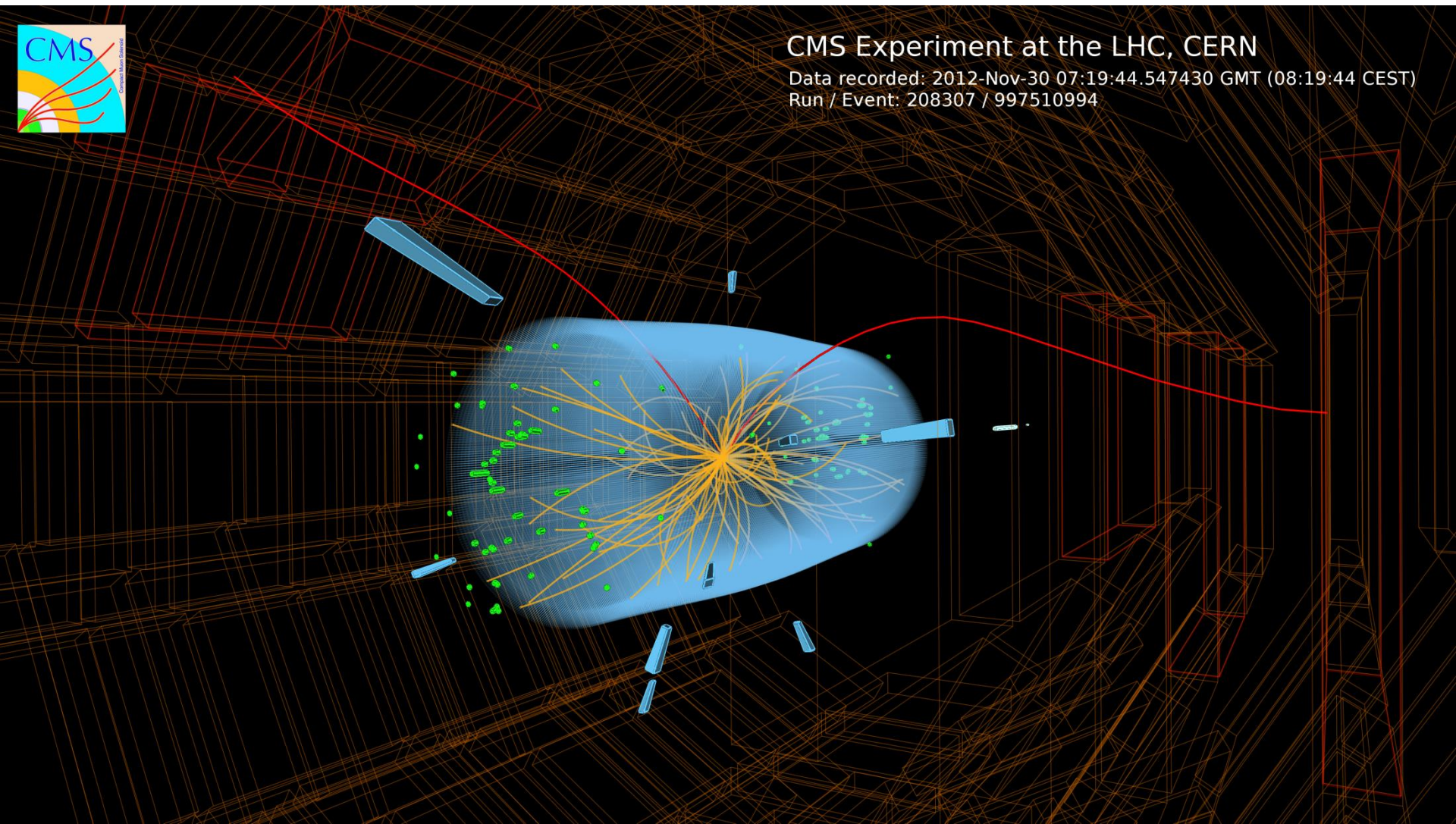
# Event Display $B_s \rightarrow \mu\mu$



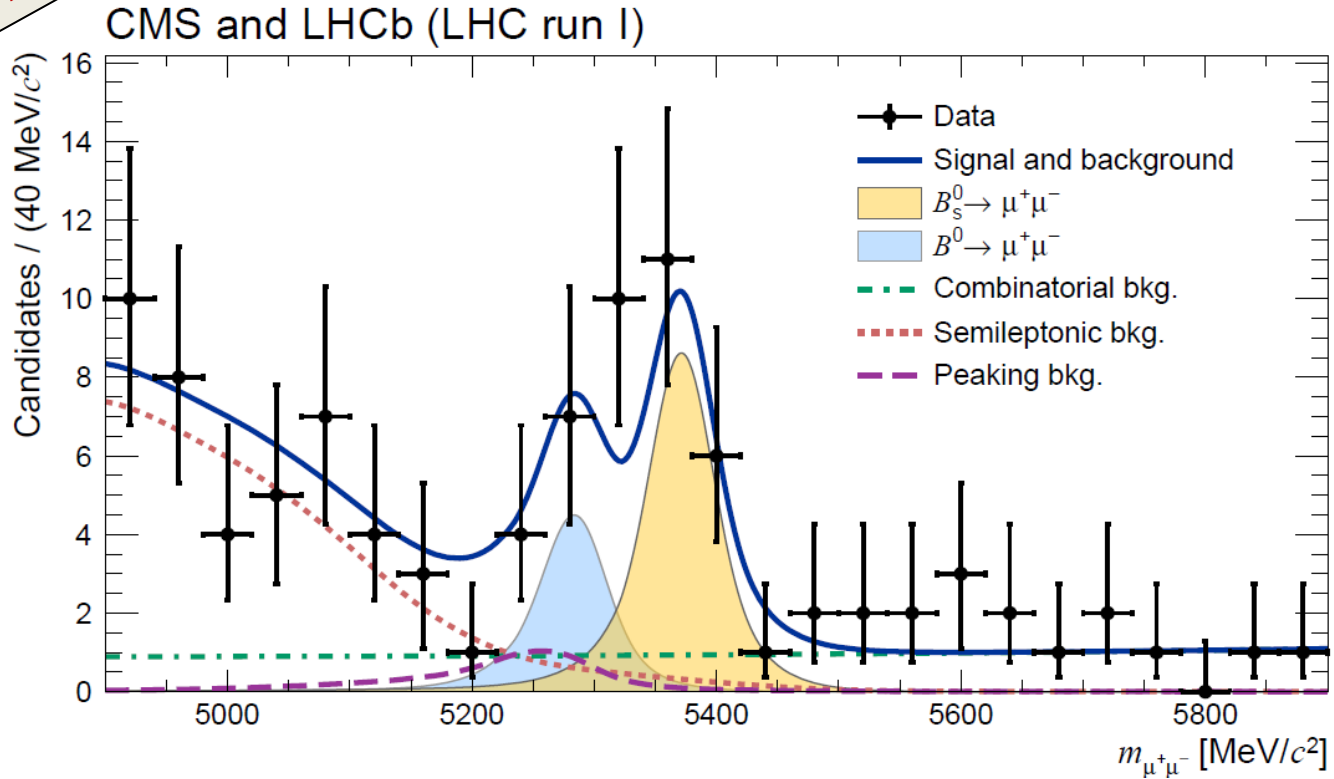
CMS Experiment at the LHC, CERN

Data recorded: 2012-Nov-30 07:19:44.547430 GMT (08:19:44 CEST)

Run / Event: 208307 / 997510994



**Nature 522 (2015) 68**

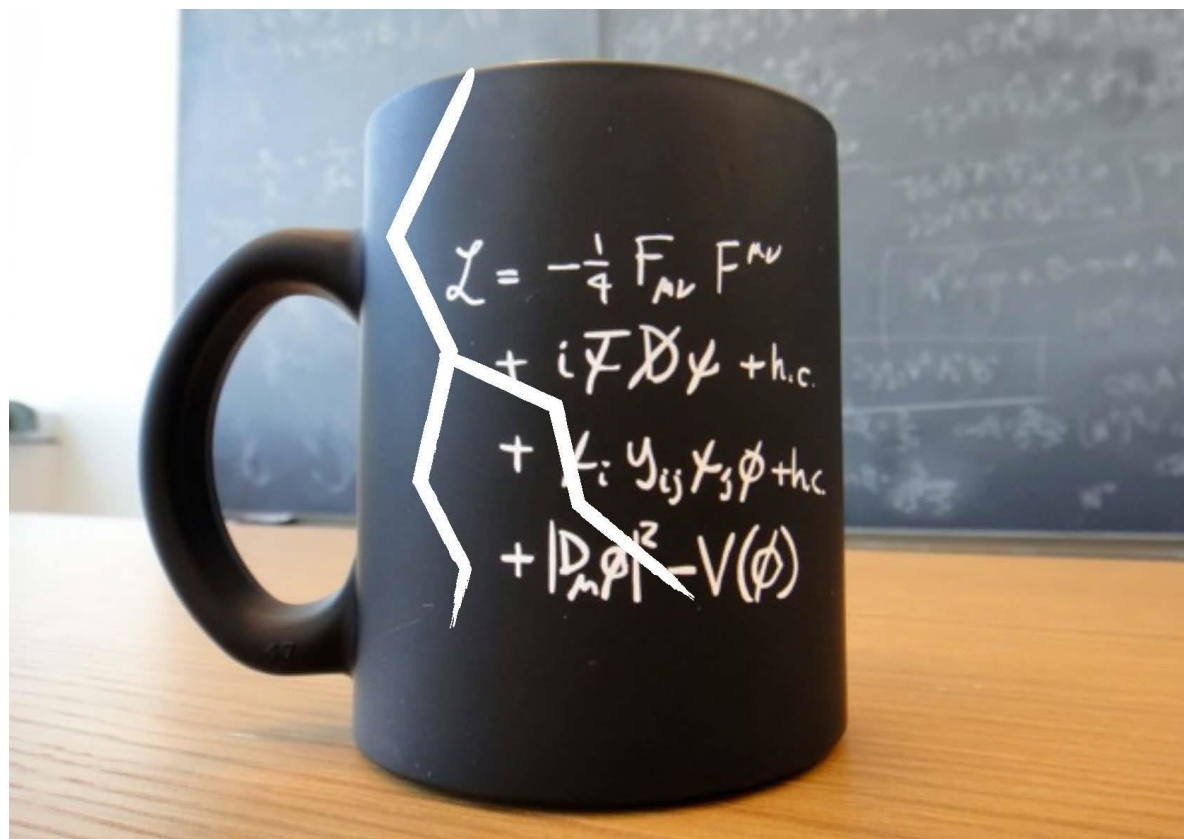


First observation of the  $B_s^0 \rightarrow \mu^+\mu^-$  decay, with  $6\sigma$  significance, and the best measurement of its branching fraction so far, and  $3\sigma$  evidence for the  $B^0 \rightarrow \mu^+\mu^-$  decay

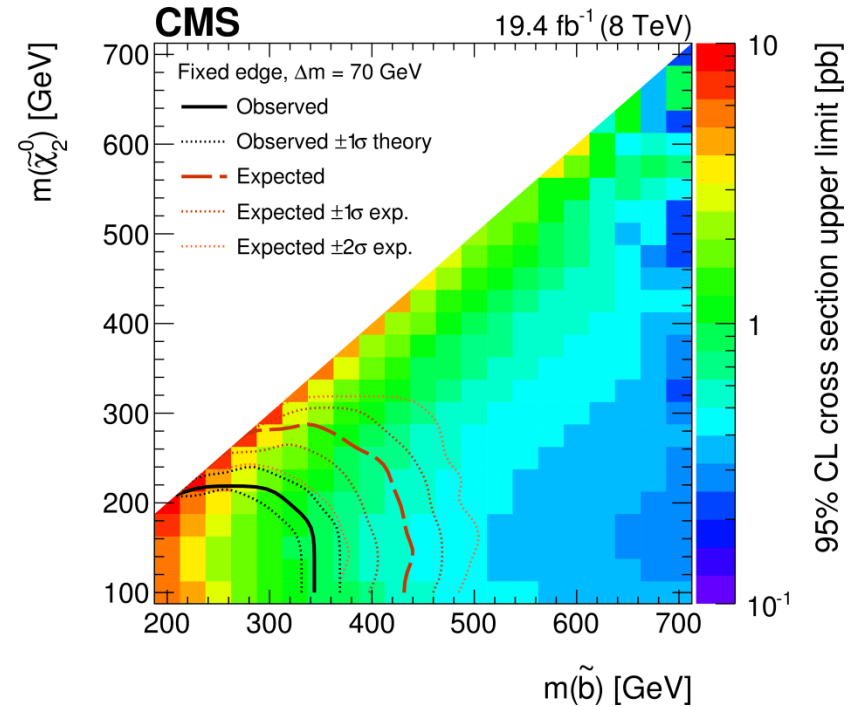
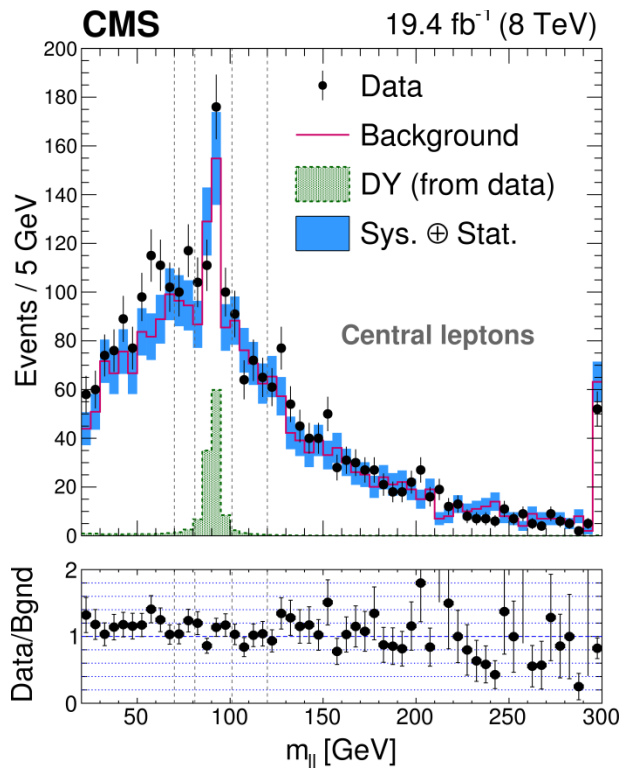
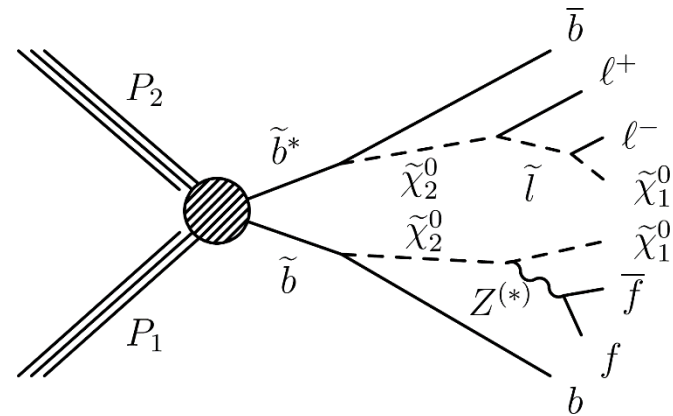
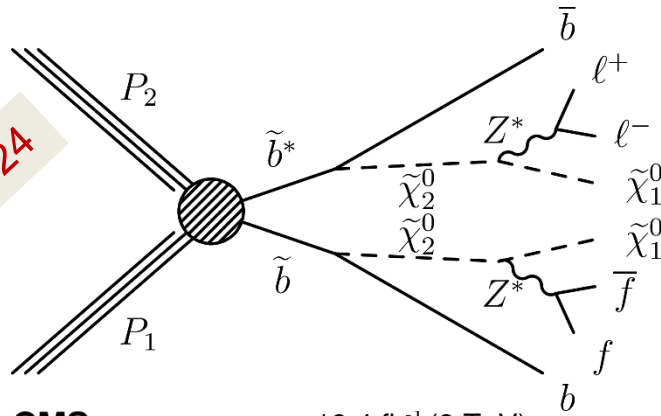
"They have been stuck in that model, like birds in a gilded cage, ever since."



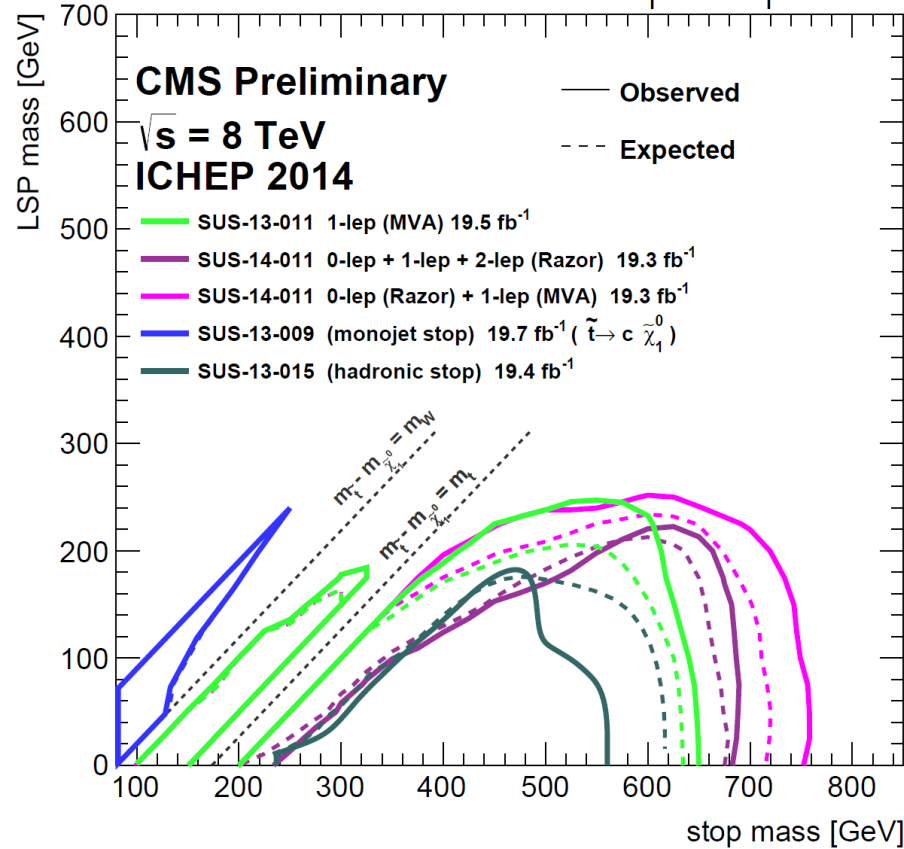
## BSM Physics



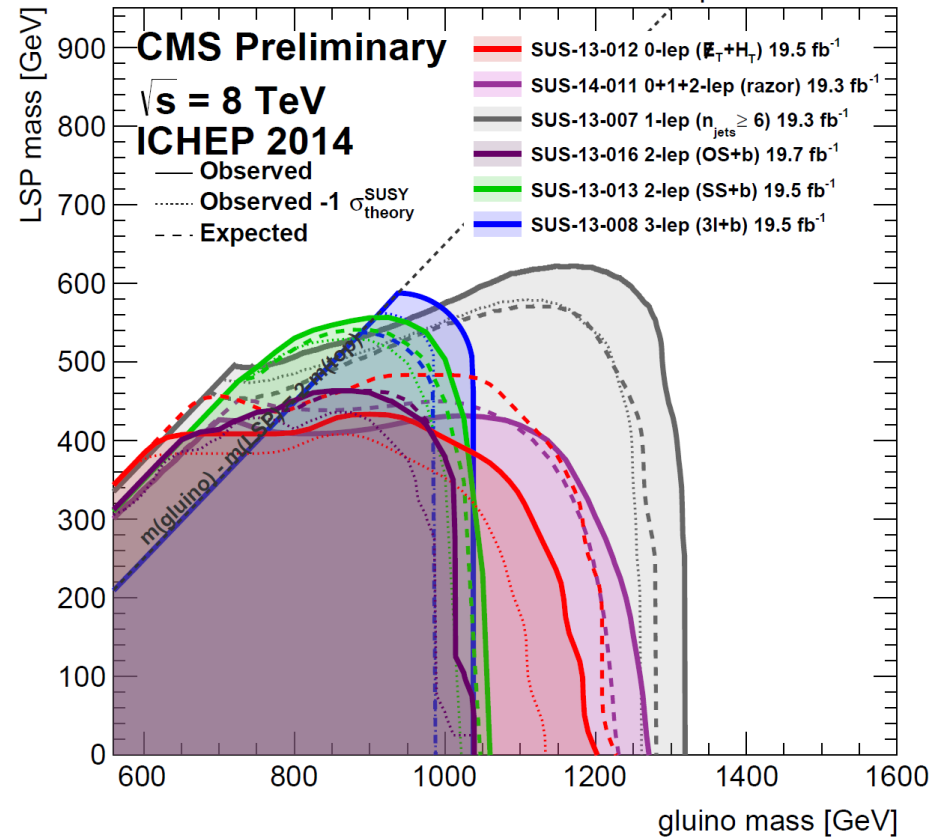
JHEP 04 (2015) 124



$\tilde{t}\text{-}\tilde{t}$  production,  $\tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0$



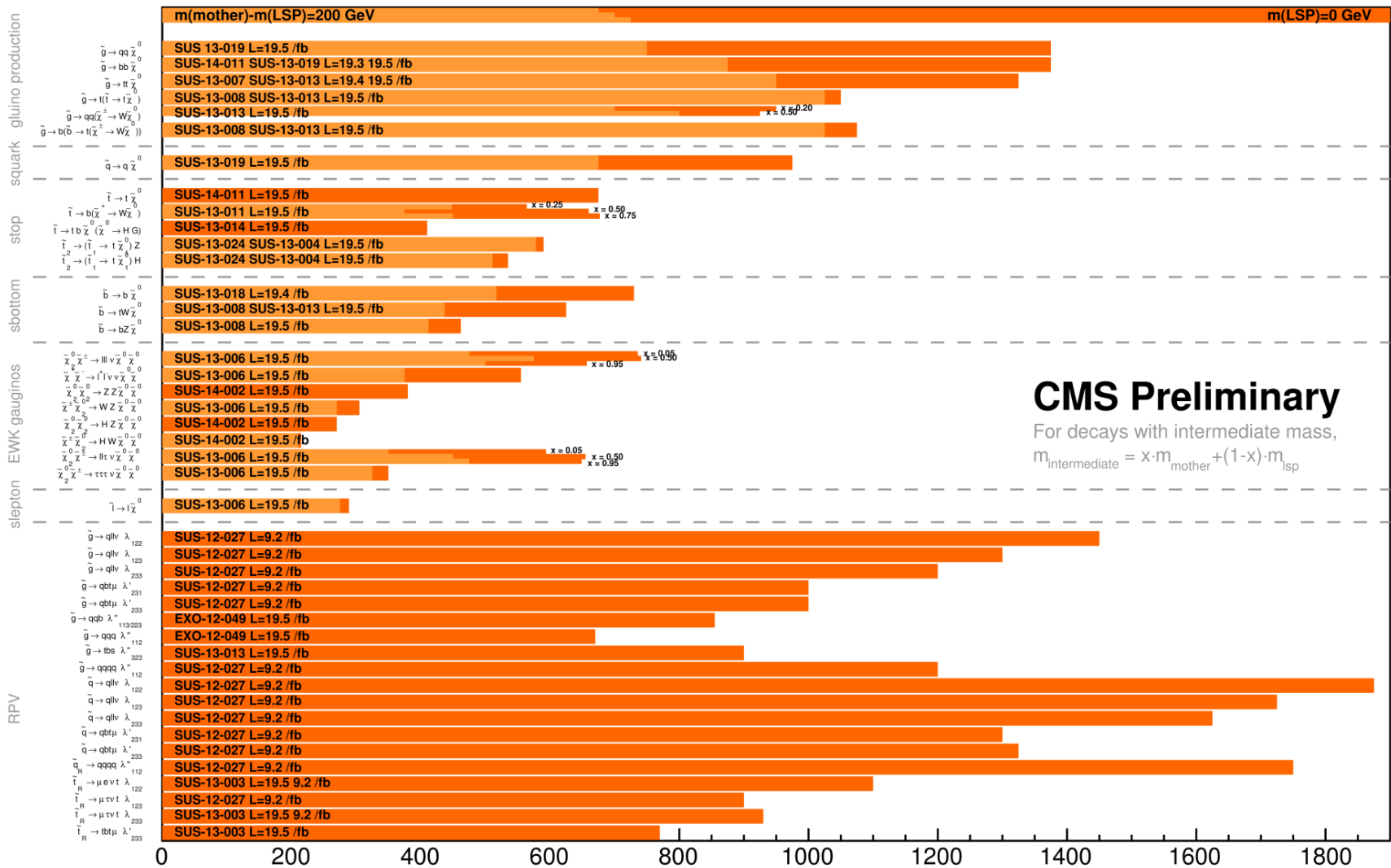
$\tilde{g}\text{-}\tilde{g}$  production,  $\tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0$



<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>

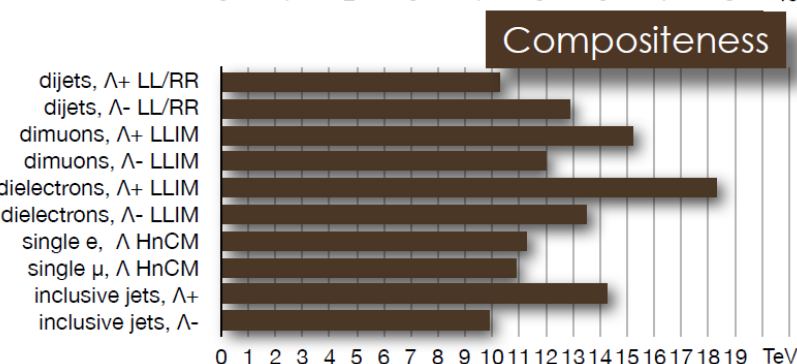
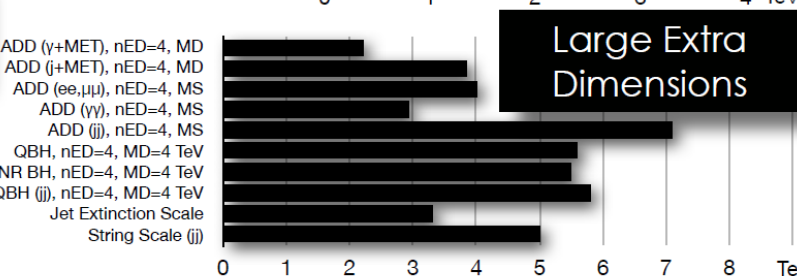
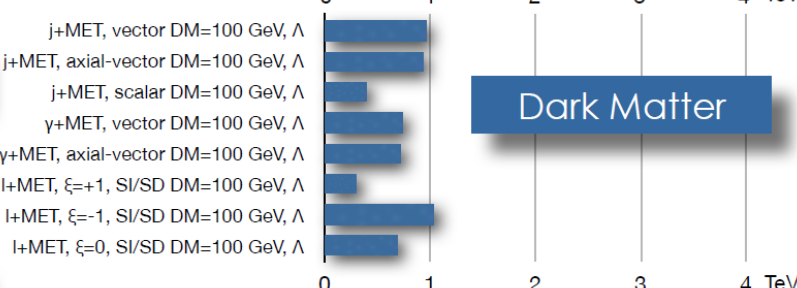
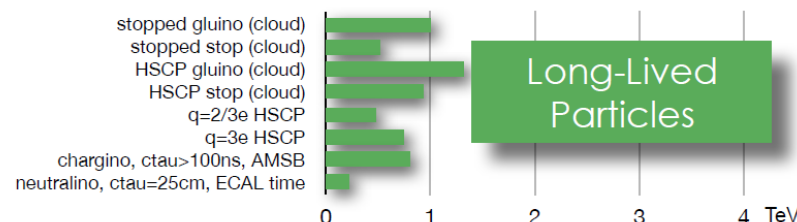
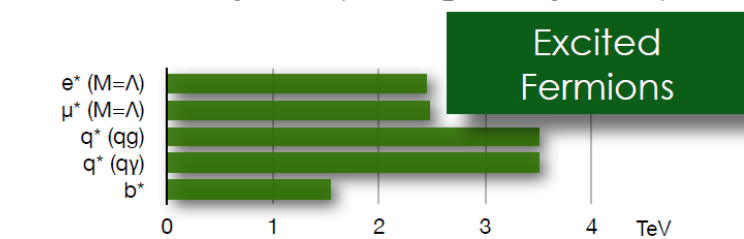
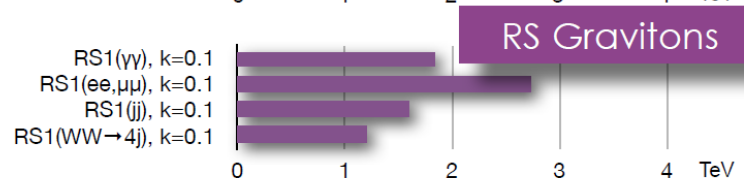
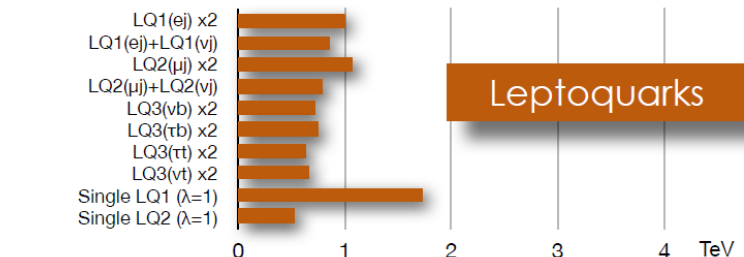


# SUSY searches summary



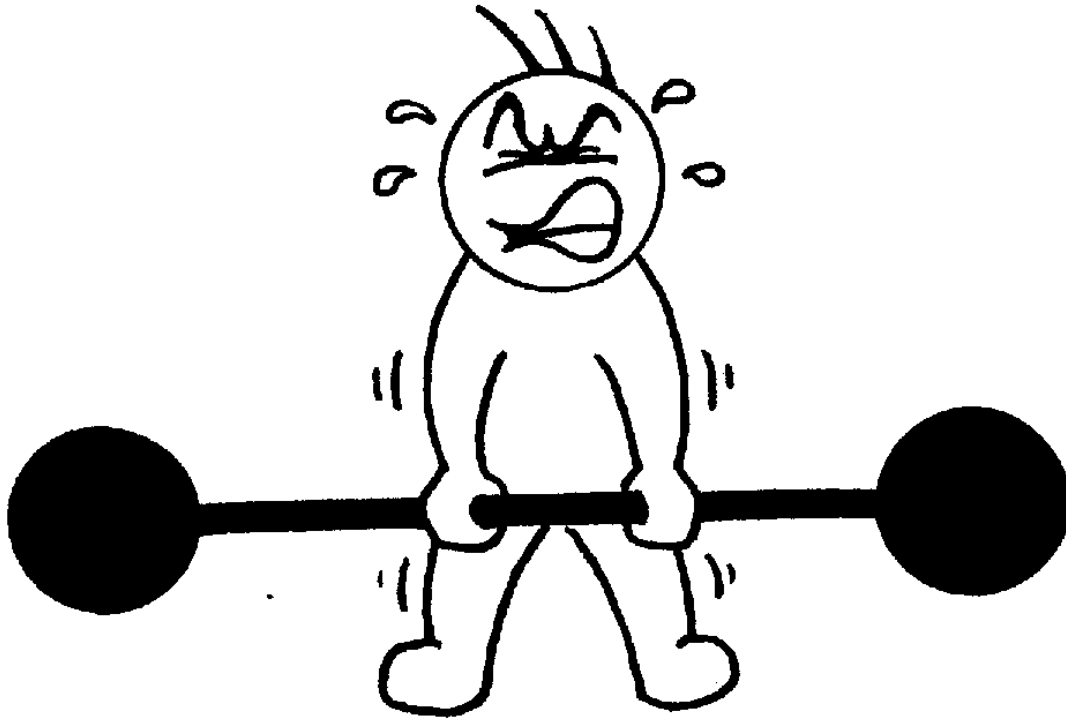
**CMS Preliminary**  
 For decays with intermediate mass,  
 $m_{\text{intermediate}} = x \cdot m_{\text{mother}} + (1-x) \cdot m_{\text{LSP}}$

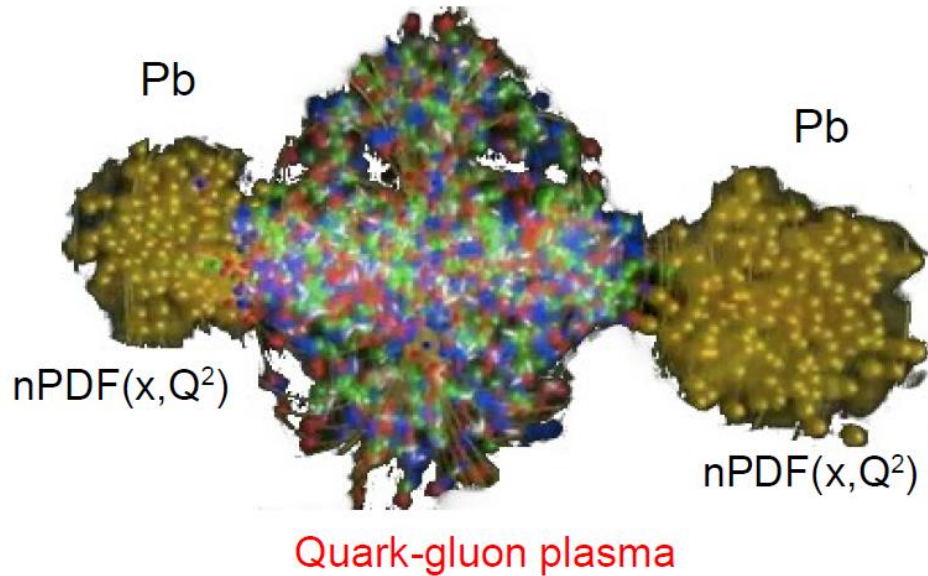
\*Observed limits, theory uncertainties not included  
 Only a selection of available mass limits  
 Probe \*up to\* the quoted mass limit  
 Mass scales [GeV]



**CMS Preliminary**

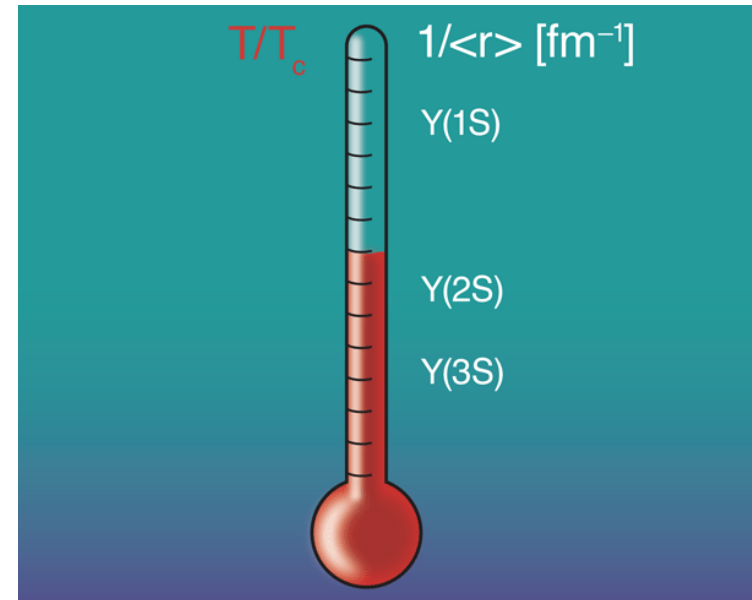
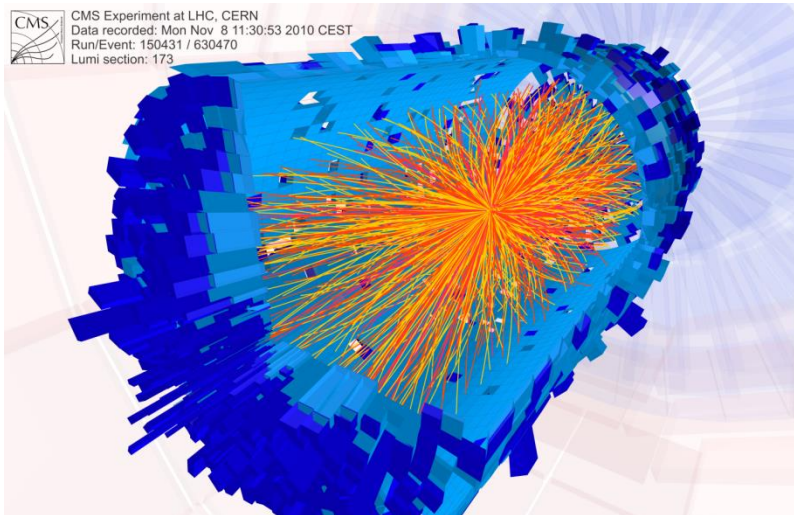
# Heavy Ion Physics





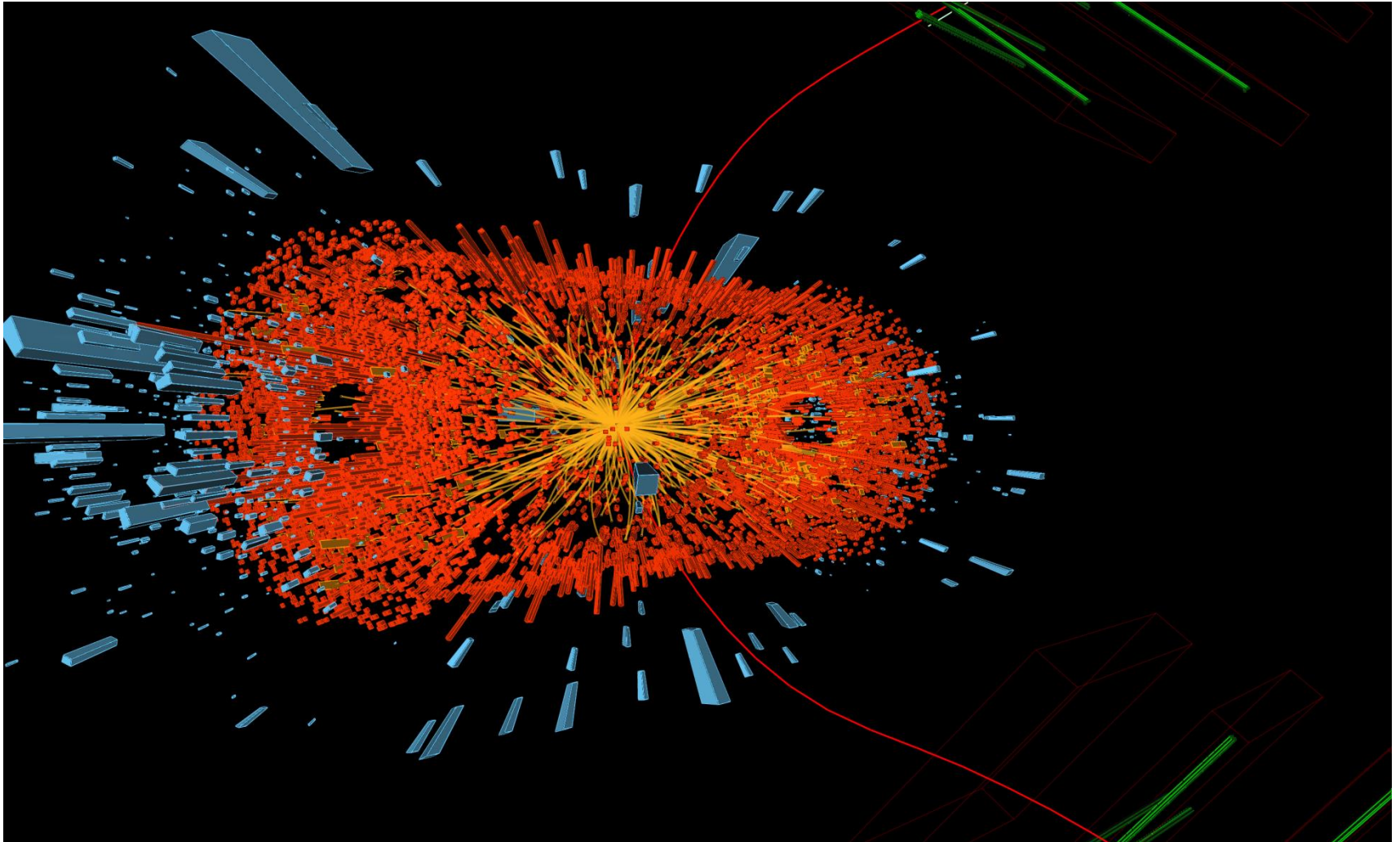
Smashing heavy nuclei inside particle colliders creates a hot nuclear matter thought similar to the primordial QGP

To explore properties of the medium, CMS compares the properties of the particles produced in heavy ion collisions (PbPb) with those produced in proton collisions



# $\Upsilon$ Production

**CMS** first experiment to successfully separate signals of the **three  $\Upsilon$  states** in heavy ion collisions



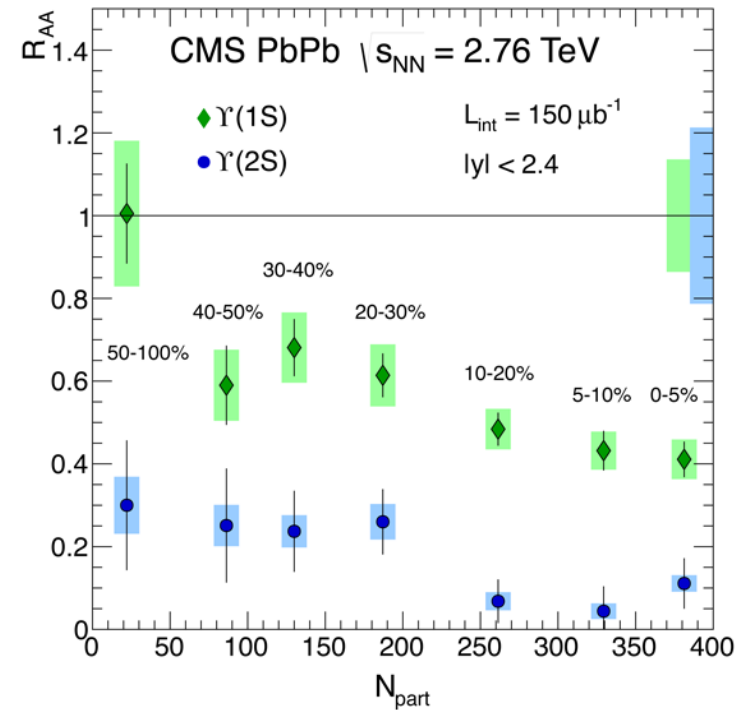
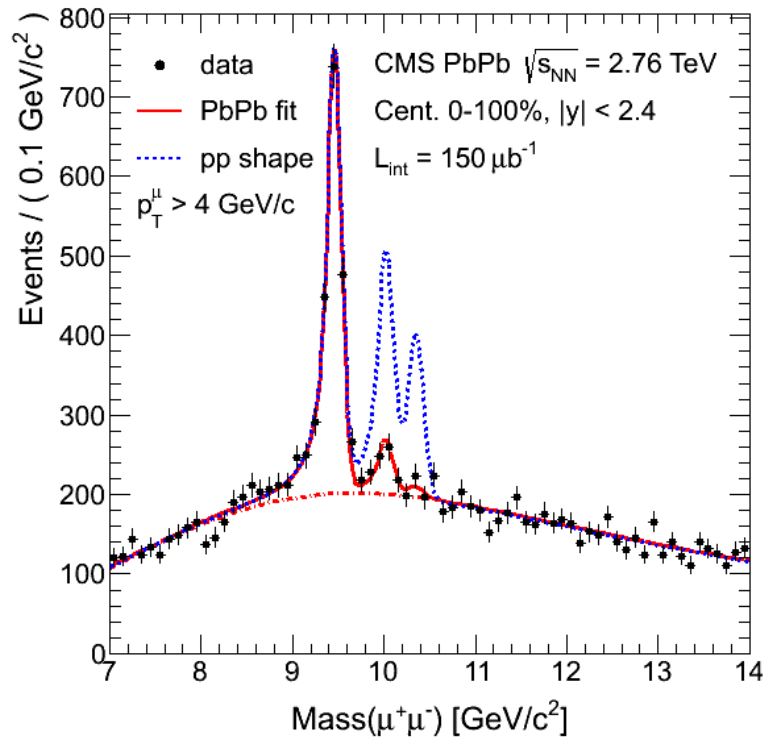
# $\Upsilon$ Suppression

Having to traverse the hot medium will cause particles such as  $\Upsilon$ , produced in these interactions, to “melt” or be suppressed in it

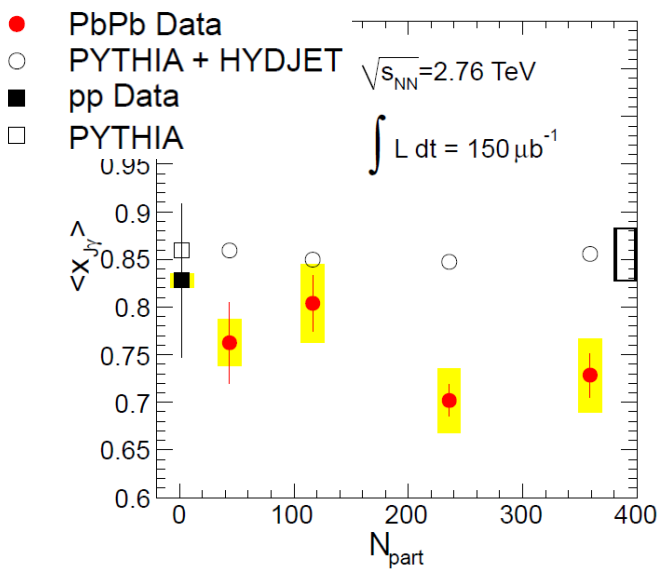
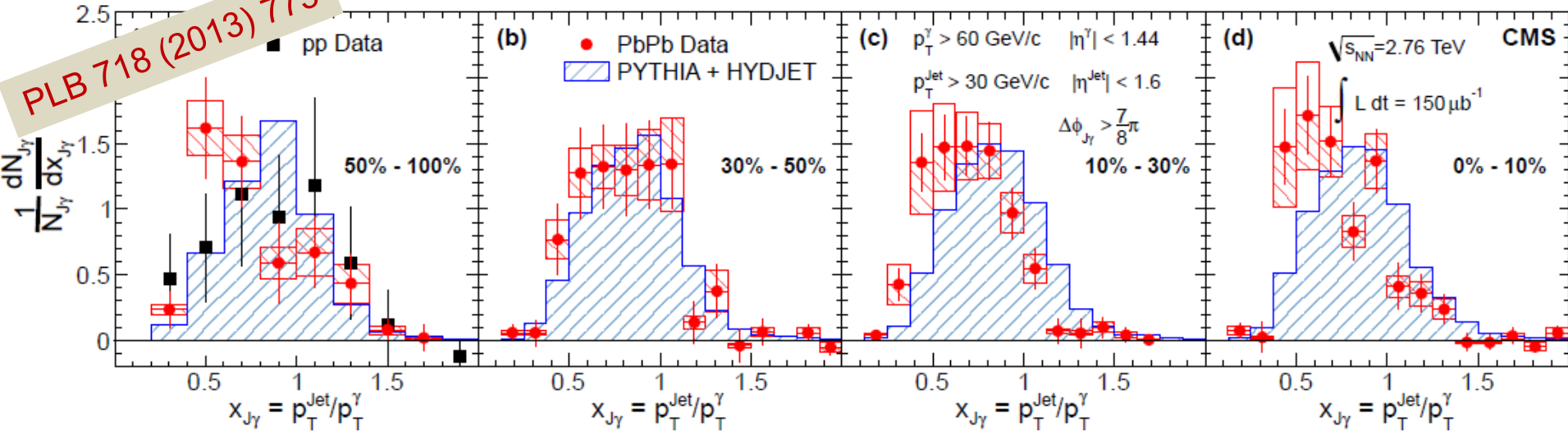
Bound states possibly destroyed as a result of interacting with the medium before they could decay into muons

Ratio of  $\Upsilon(2S)$  to  $\Upsilon(1S)$   $\sim 21\%$  and ratio of  $\Upsilon(3S)$  to  $\Upsilon(1S)$   $\sim 6\%$  in PbPb collisions relative to those with pp collisions - results with  $5\sigma$  significance

PRL 109 (2012) 222301



PLB 718 (2013) 773



$\gamma$ -jet momentum balance as function of collision centrality and compared to pp data and PYTHIA calculations

Isolated photon as an estimate of the partonic energy at production allows unbiased characterization of in-medium parton energy loss

With increasing collision centrality, a significant decrease in the ratio  $p_T^{\text{jet}}/p_T^\gamma$  relative to pp observed

# Summary & Prospects

LHC Page1

Fill: 3746

E: 6500 GeV

t(SB): 00:00:00

21-05-15 09:22:18

## BEAM SETUP: ADJUST

Energy:

6500 GeV

I(B1):

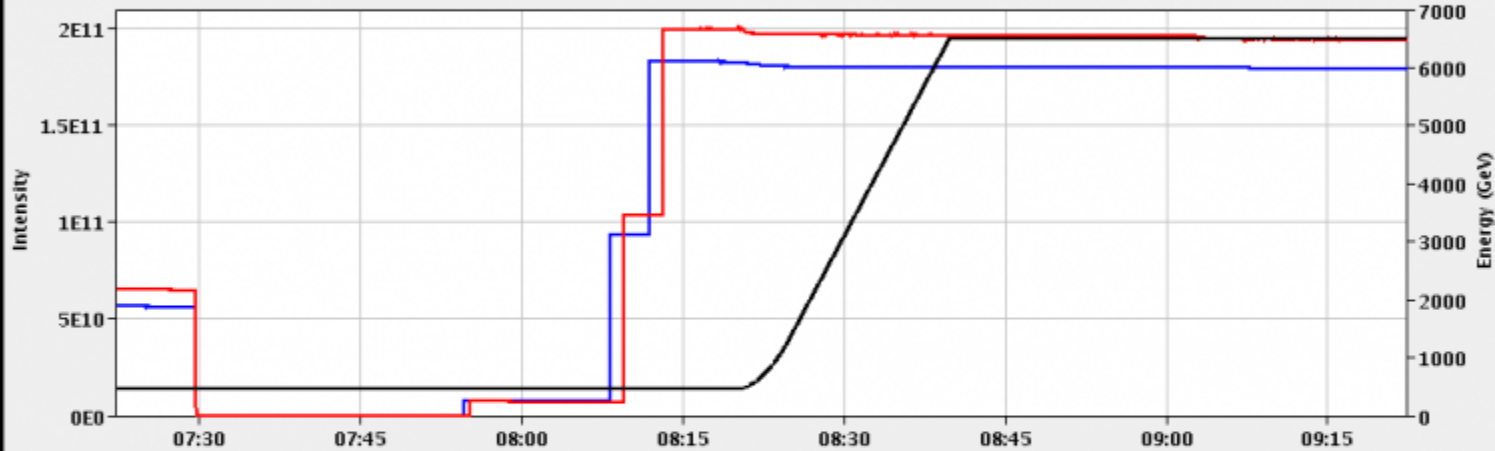
1.84e+11

I(B2):

1.85e+11

FBCT Intensity and Beam Energy

Updated: 09:22:19



### BIS status and SMP flags

B1 B2

Comments (21-May-2015 09:22:03)  
test collisions at 13 TeV

Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: Single\_2b+1p\_1\_1\_1

PM Status B1

ENABLED

PM Status B2

ENABLED



After the 125 GeV **Higgs boson discovery**, the measurement of its properties and cross-section have been performed at LHC run-1

A first Higgs combination measurement of ATLAS and CMS on **Higgs mass**

In the BSM Higgs searches, **no additional Higgs bosons** have been detected

Cross-section measurement in **electroweak, top and QCD physics** very well compared to theoretical predictions

**Top mass** measurement combining LHC and Tevatron data

**$B_s \rightarrow \mu^+ \mu^-$  observed for the first time and the results combined with LHCb**

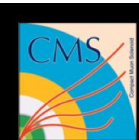
**The heavy ion physics program yielded excellent results on the state of nuclear matter characterisation**

**No new physics detected so far in Higgs or SUSY sector or other exotic scenarios / dark matter searches**

**But**

**we only collected < 1% of the LHC Luminosity @ half the centre-of-mass energy**

13 TeV run has started and the hunt for new physics has begun



CMS Experiment at the LHC, CERN

Data recorded: 2015-Jun-03 08:48:32.279552 GMT

Run / Event / LS: 246908 / 77874559 / 86

