Higgs Boson Physics @ CMS: Run 1 Legacy and Run 2 Outlook

Si Xie

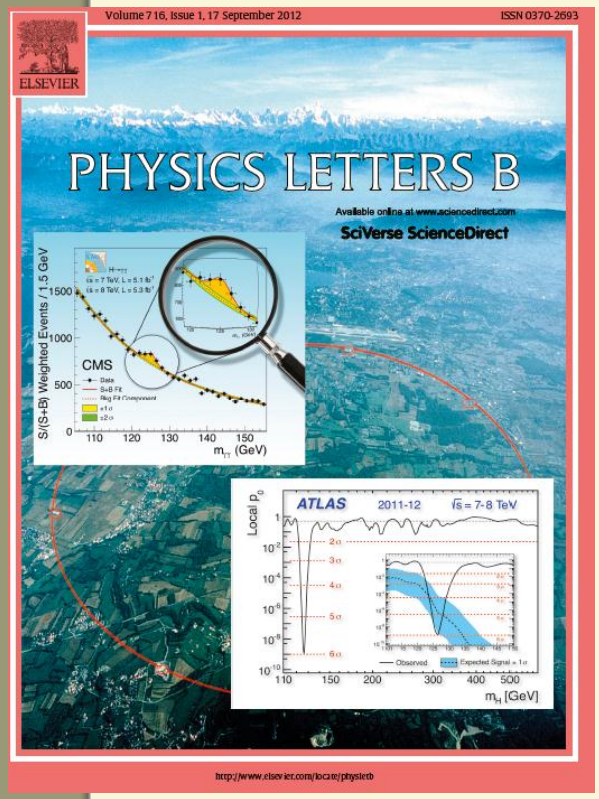
California Institute of Technology

Fermilab Joint Experimental-Theoretical Seminar

05/15/2015

Caltech

A New Elementary Particle Observed



The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

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It was a team effort !

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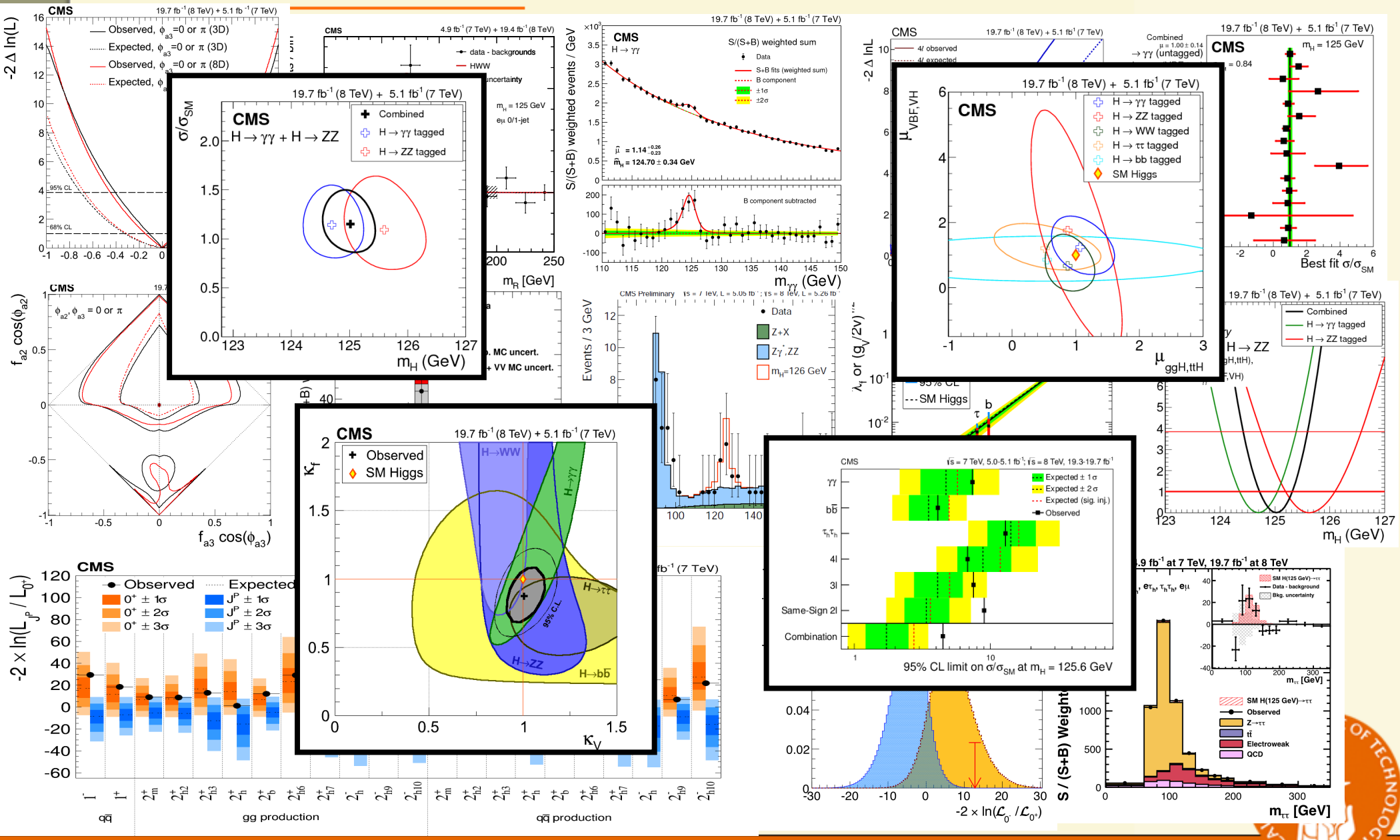
CMS Run1 Higgs Scoreboard



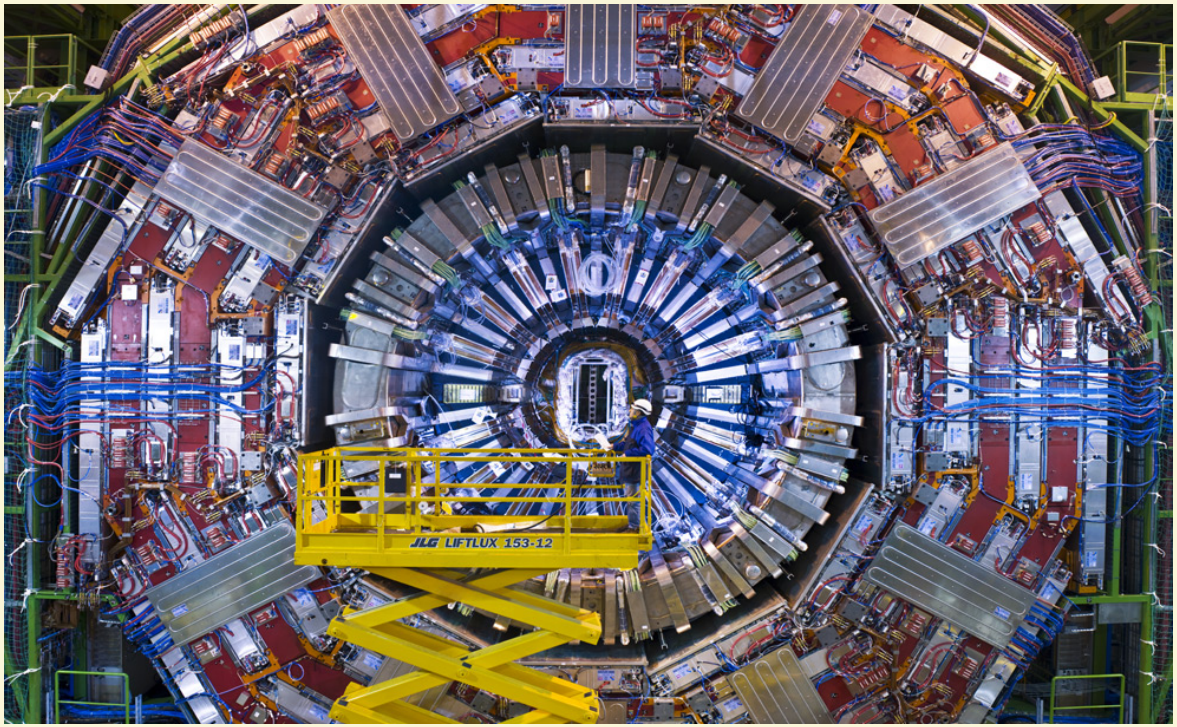
CMS Run1 Higgs Scoreboard

Many many results…

Publications (by submission date)

Date	Lumi [/fb] (7 + 8 TeV)	Analysis	Documentation
Apr-2015	19.7	Search for pseudoscalar A -> Zh -> llbb	TWiki, arXiv:1504.04710
Apr-2015	4.9 + 19.7	Search for a Higgs boson in the mass range from 145 to 1000 GeV decaying to a pair of W or Z bosons	TWiki, arXiv:1504.00936
Mar-2015	4.9 + 19.7	Combined Measurement of the Higgs Boson Mass with the ATLAS and CMS Experiments	TWiki, arXiv:1503.07589
Mar-2015	17.9	Search for X -> HH -> 4 b	TWiki, arXiv:1503.04114
Feb-2015	19.7	Search for H -> tau mu decays	TWiki, arXiv:1502.07400
Feb-2015	19.7	Search for ttH(bb) with the matrix element technique	TWiki, arXiv:1502.02485
Dec-2014	4.9 + 19.7	Higgs combination and properties (Legacy)	TWiki, arXiv:1412.8662
Nov-2014	4.9 + 19.7	Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV	TWiki, arXiv:1411.3441
Oct-2014	19.7	Search for Higgs to mumu/ee	TWiki, arXiv:1410.6679
Oct-2014	19.5	Searches for heavy Higgs bosons in two-Higgs-doublet models and for t to ch decay using multilepton and diphoton final states in pp collisions at 8 TeV	TWiki, arXiv:1410.2751
Aug-2014	4.9 + 19.7	Seach for MSSM Higgs to tautau	TWiki, arXiv:1408.3316
Aug-2014	19.7	ttH combination	TWiki, arXiv:1408.1682
Jul-2014	4.9 + 19.7	Observation of Higgs to gamma gamma decays	TWiki, arXiv:1407.0558
May-2014	5.1 + 19.7	Higgs boson width from on- vs. off-shell production and decay to Z-boson pairs	TWiki, arXiv:1405.3455
Apr-2014	4.9 + 19.7	H -> invisible Combination	TWiki, arXiv:1404.1344
Jan-2014	4.9 + 19.7	Fermion Combination	TWiki, arXiv:1401.6527
Jan-2014	4.9 + 19.7	SM H -> tautau	TWiki, arXiv:1401.5041
Dec-2013	5.1 + 19.7	H -> ZZ -> 4l	TWiki, arXiv:1312.5353
Dec-	4.9 + 19.4	H -> WW	TWiki, arXiv:1312.1129

CMS Run 1 Legacy



Run 2 Prospects

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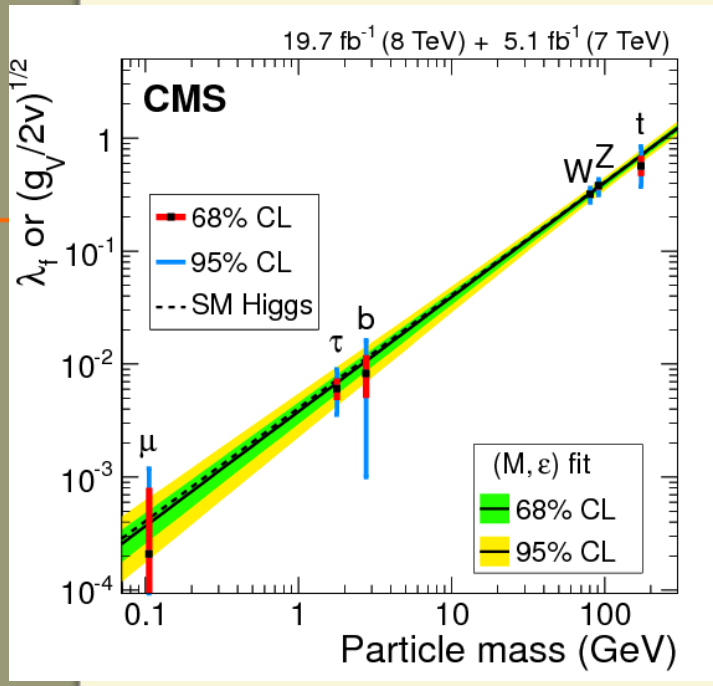

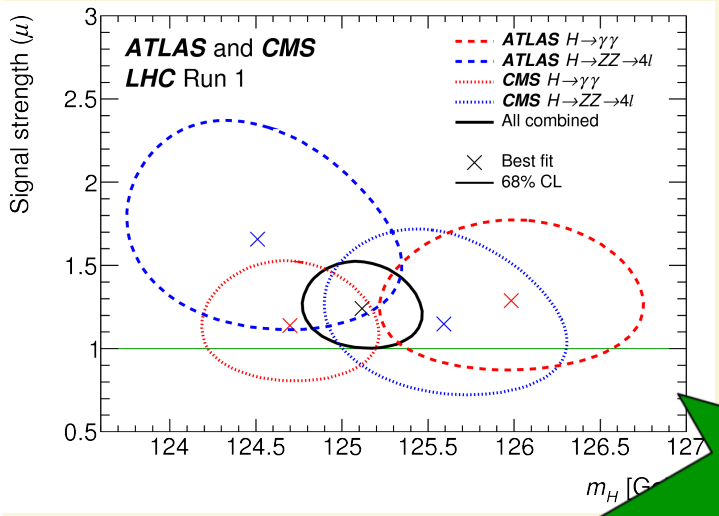

Physics Legacy

Technological Legacy

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Physics Legacy

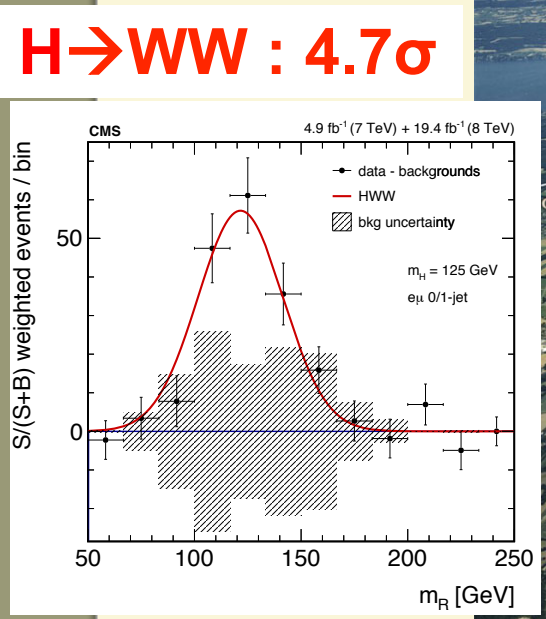
- CMS Fundamentals:
  - Magnet & Silicon Tracker
  - Muon Chambers
  - Crystal EM Calorimeter
- Particle Flow
- Big Data & Multivariate Methods
- Higher Order MC Tools

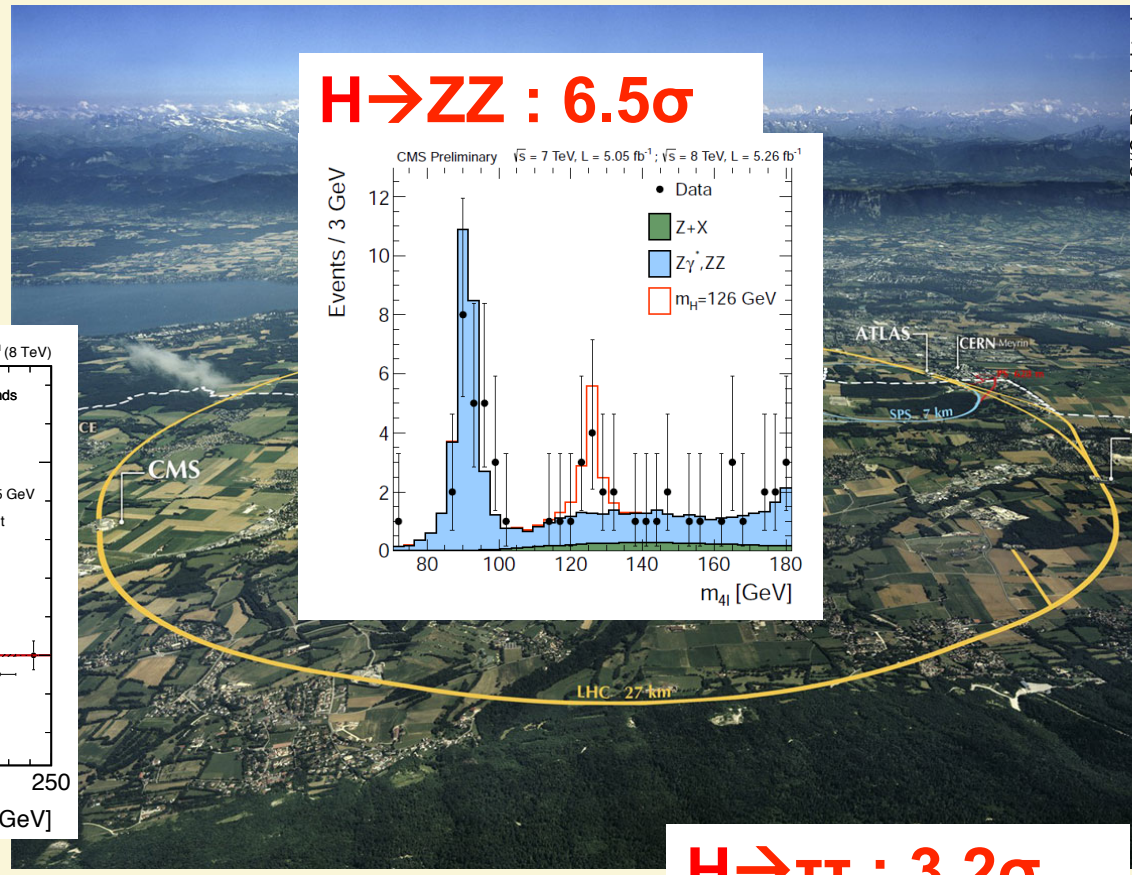
Technological Legacy

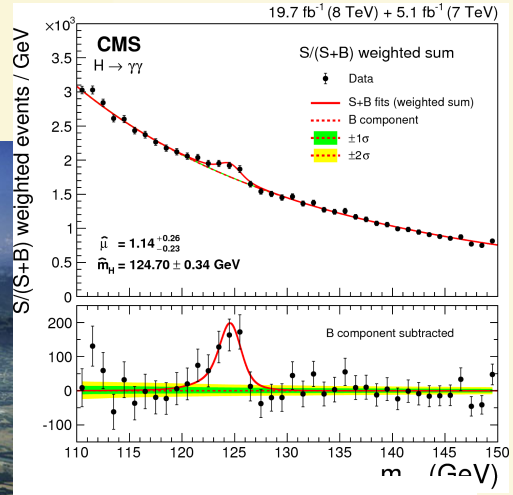
- EWK Symmetry Breaking
- Higgs Mass Parameter
- Spin & Parity
- Origin of Fermion Mass
- Fine Tuning & Hierarchy Problem

Higgs Boson : Physics Legacy

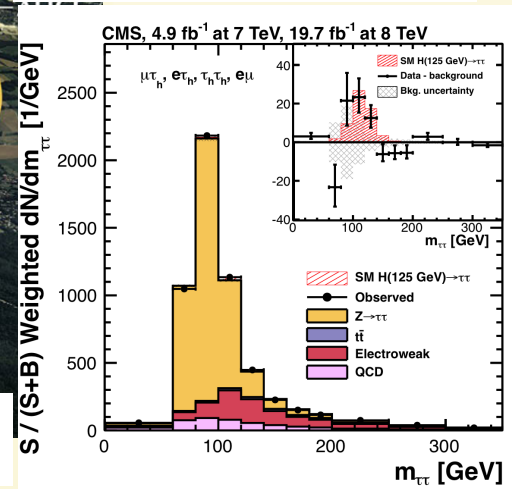
A clear unambiguous new particle observed in multiple decay channels !







H→γγ : 5.6σ



H→ττ : 3.2σ

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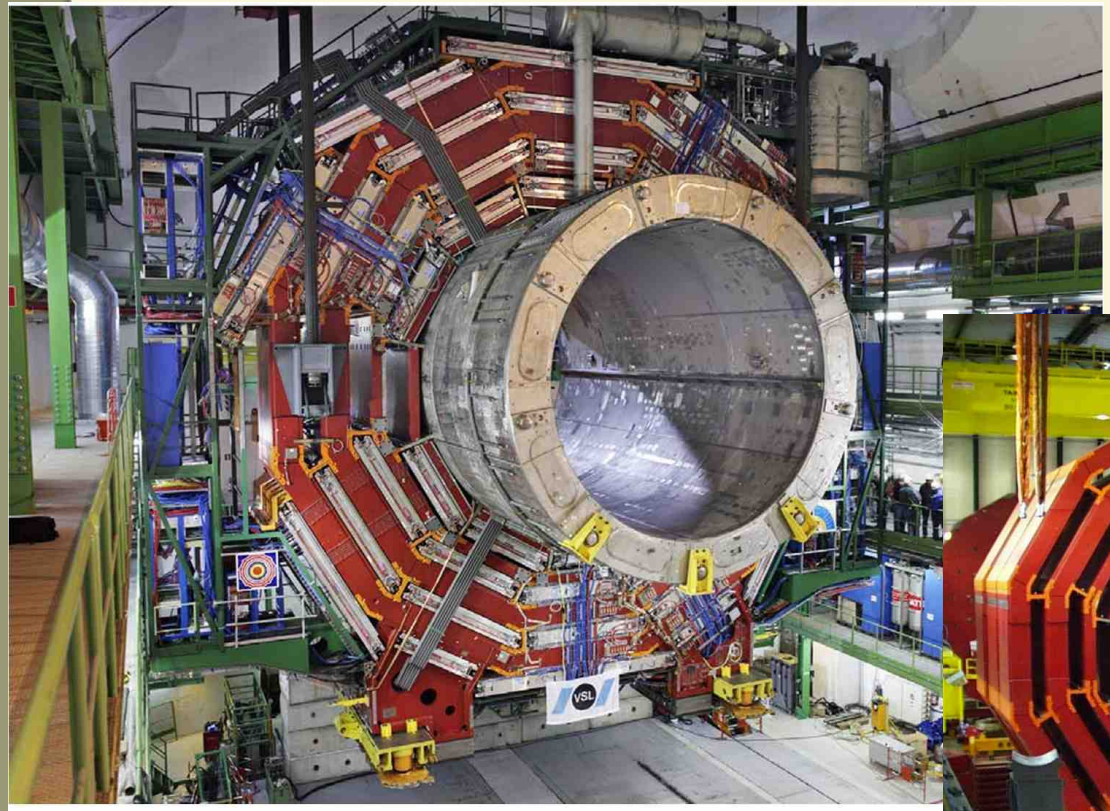
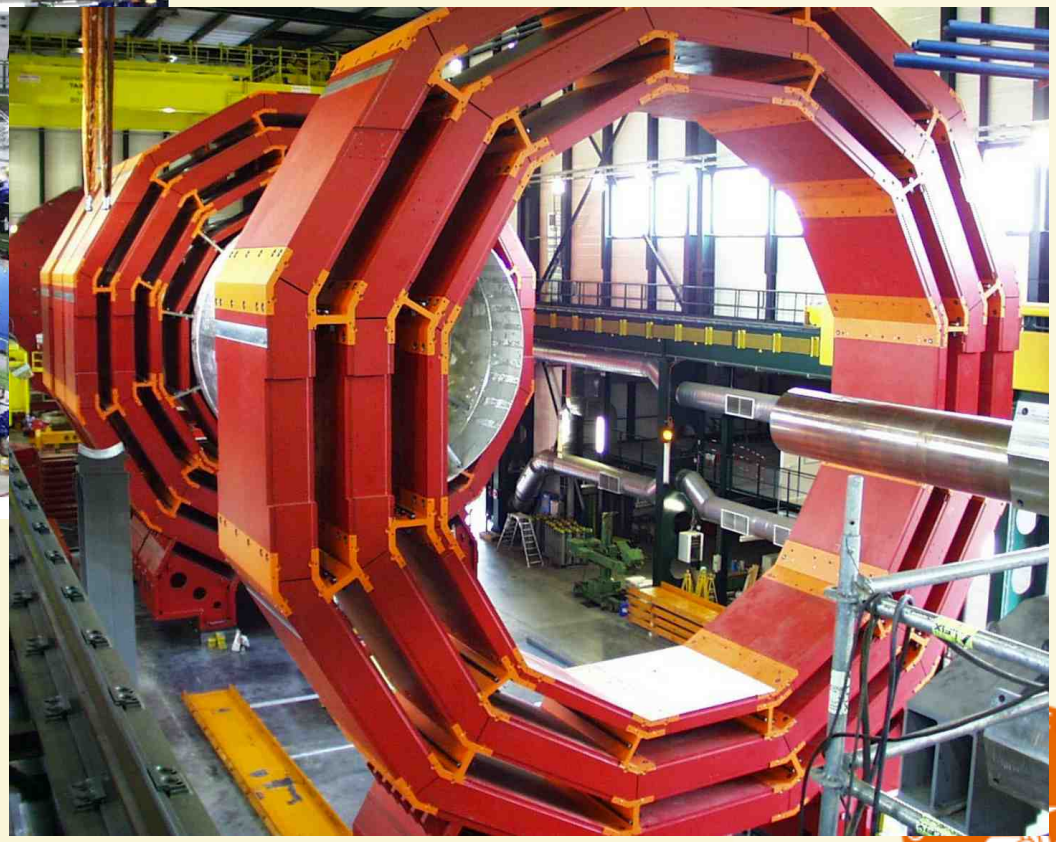
Technological Legacy: Compact Muon Solenoid





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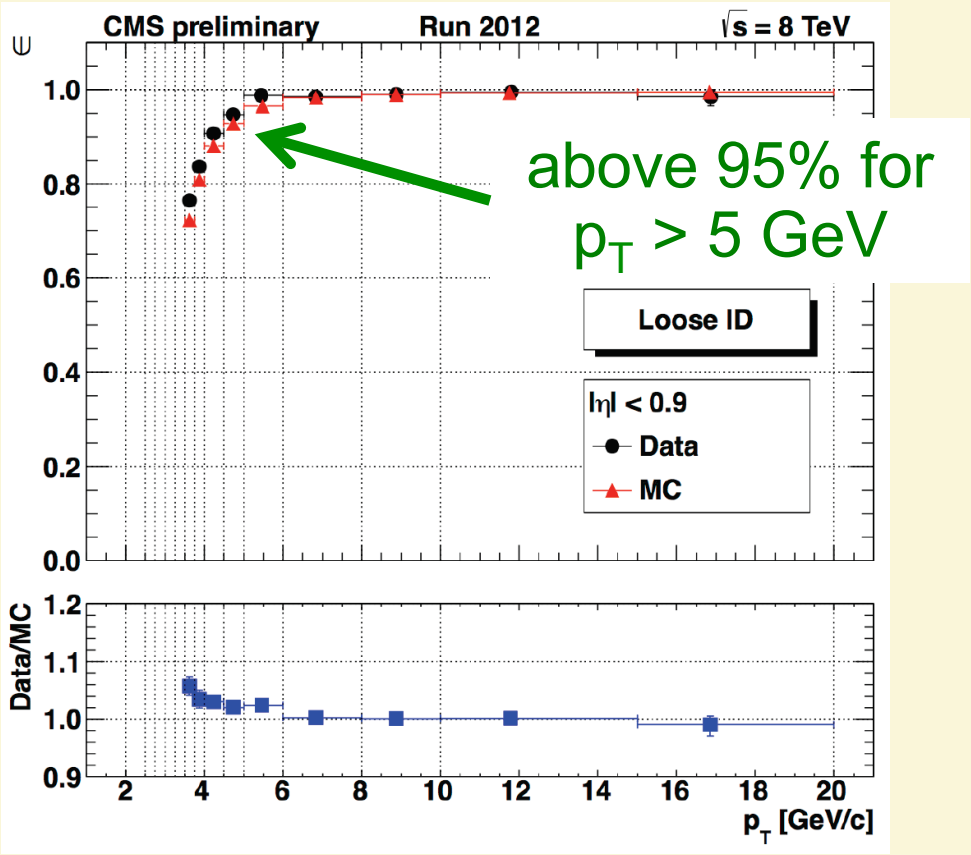
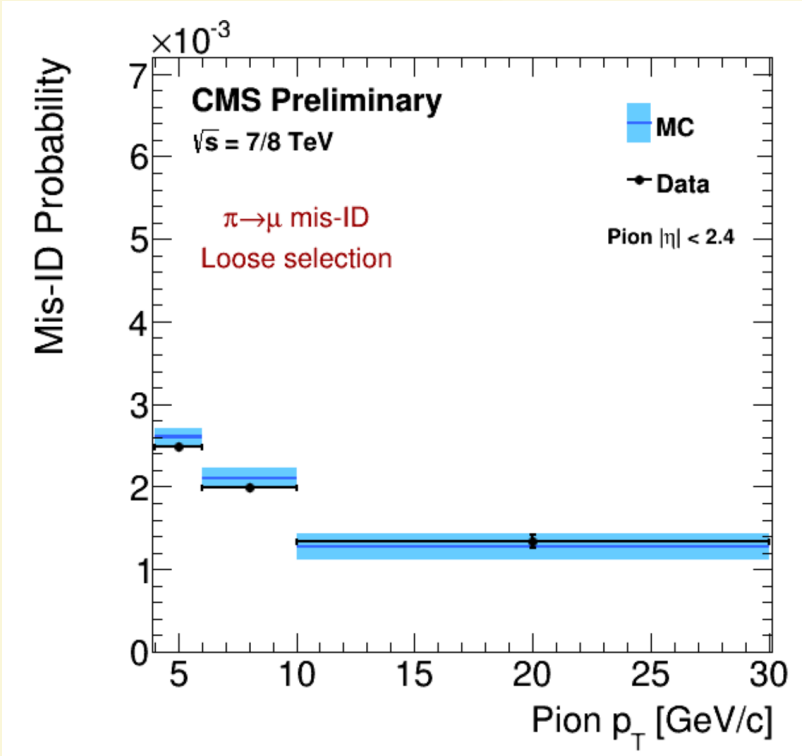
CMS: Compact Muon Solenoid





Identify Muons @ > 95% Efficiency
With Pion Mis-ID @ a few x 10^{-3}

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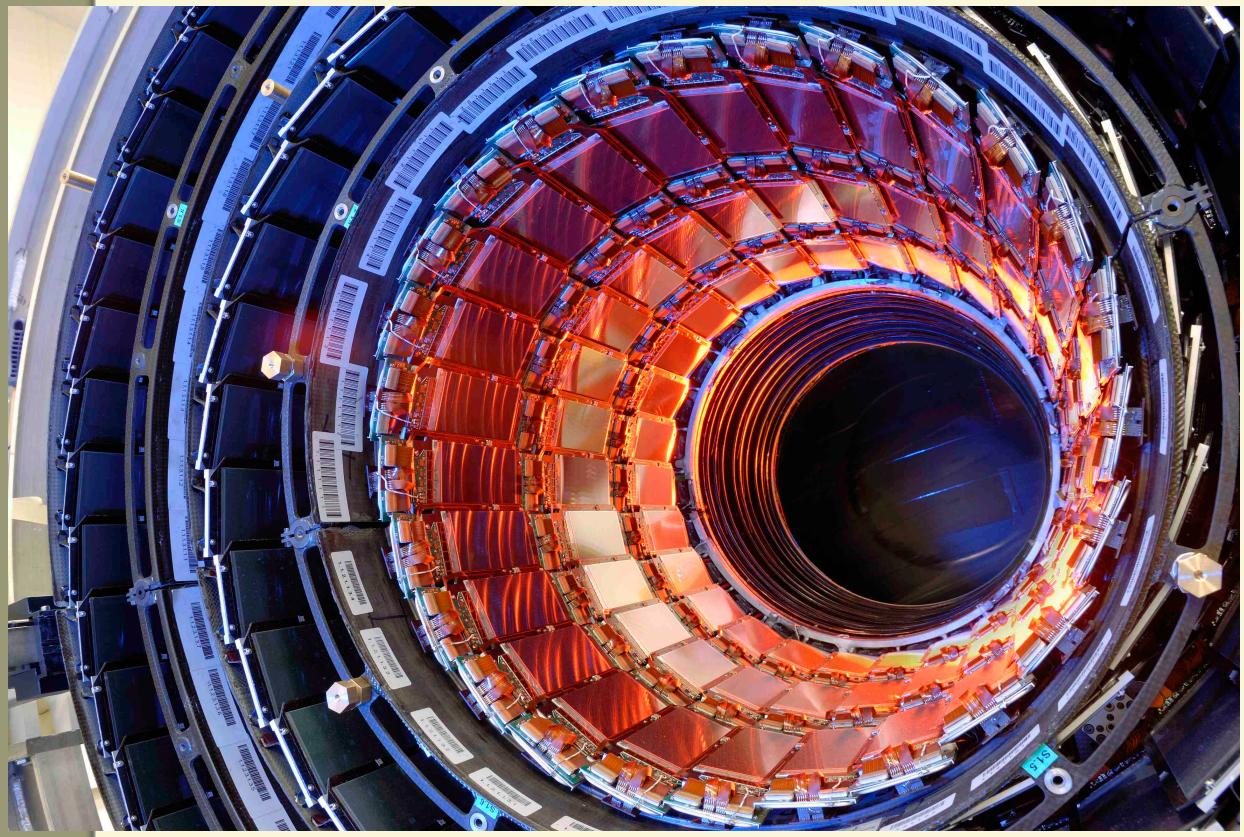
Technological Legacy: Compact Muon Solenoid

World's largest all-silicon tracker



Near 100% efficiency

Impact parameter resolution: ~ few 10μm

Momentum resolution: ~1-3% for 1-100 GeV

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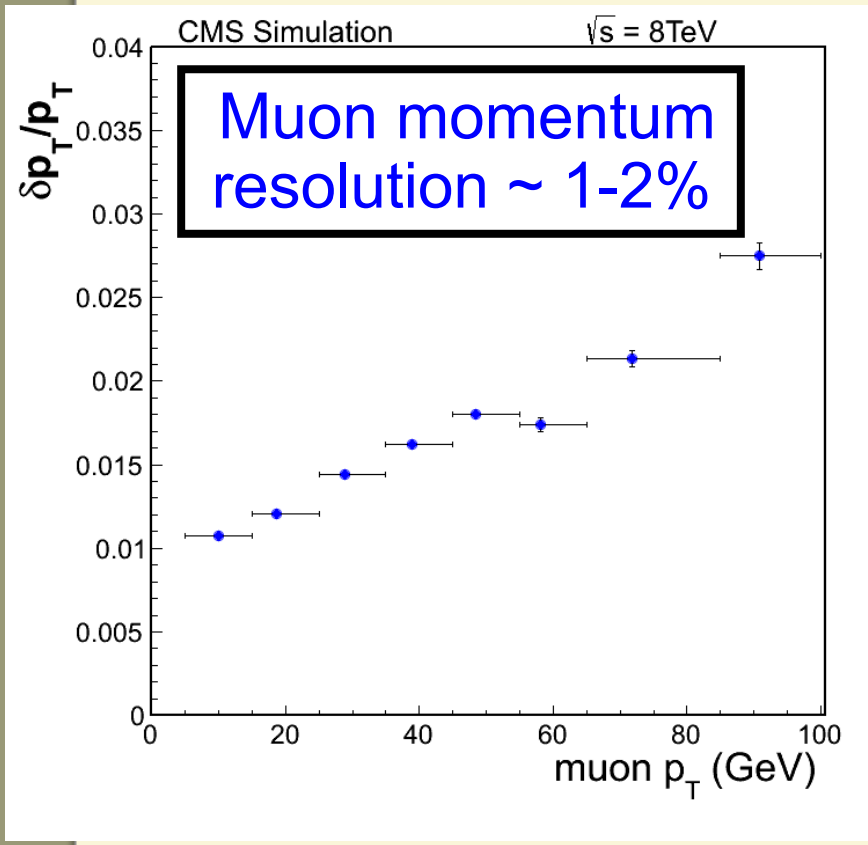
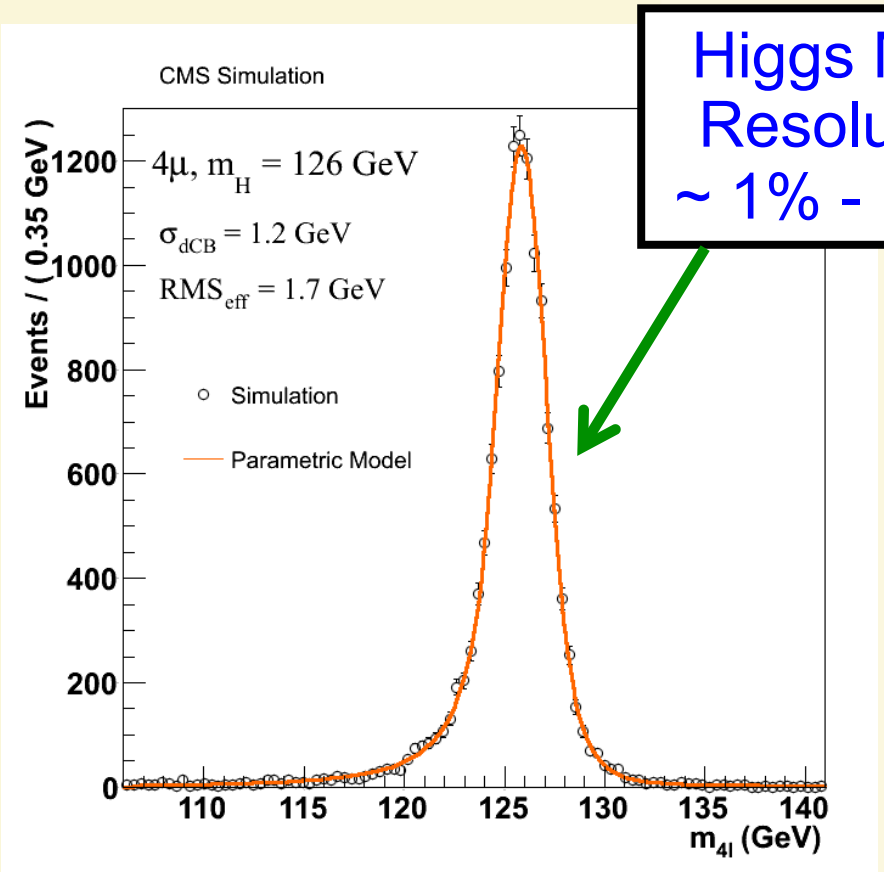
CMS: Compact Muon Solenoid





Allows to reconstruct muon momentum and Higgs mass to ~1% level

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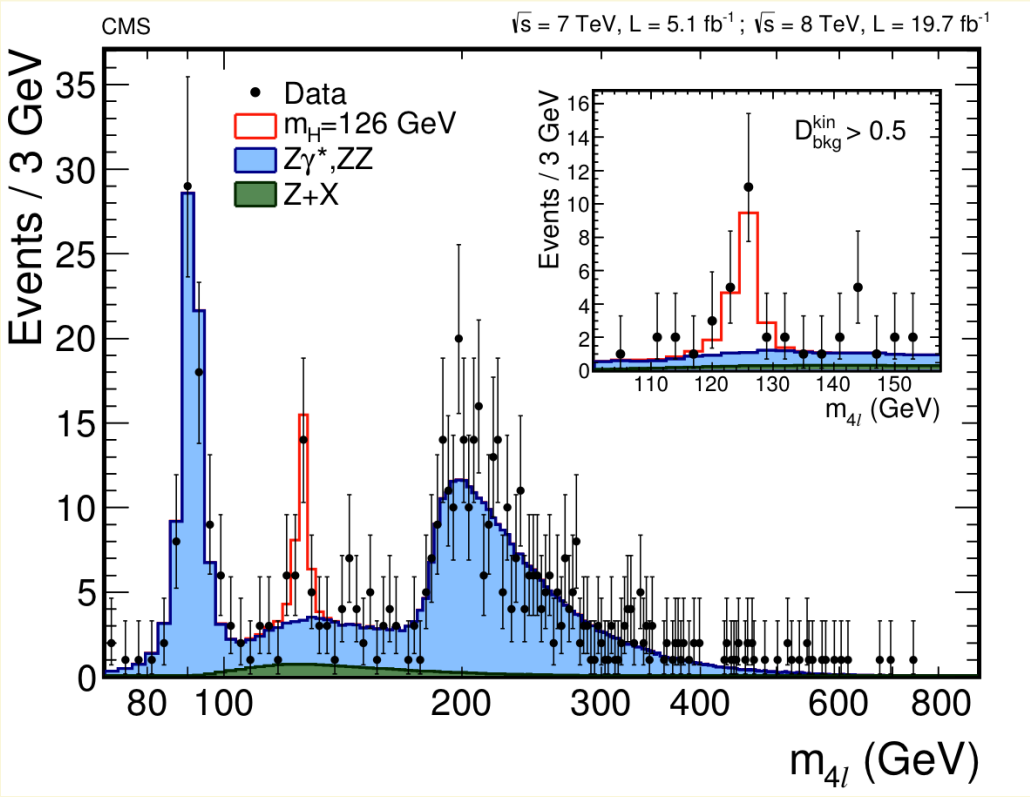
CMS: Compact Muon Solenoid

…then after a lot more hard work :



H→ZZ→4l observed @
6.5σ significance

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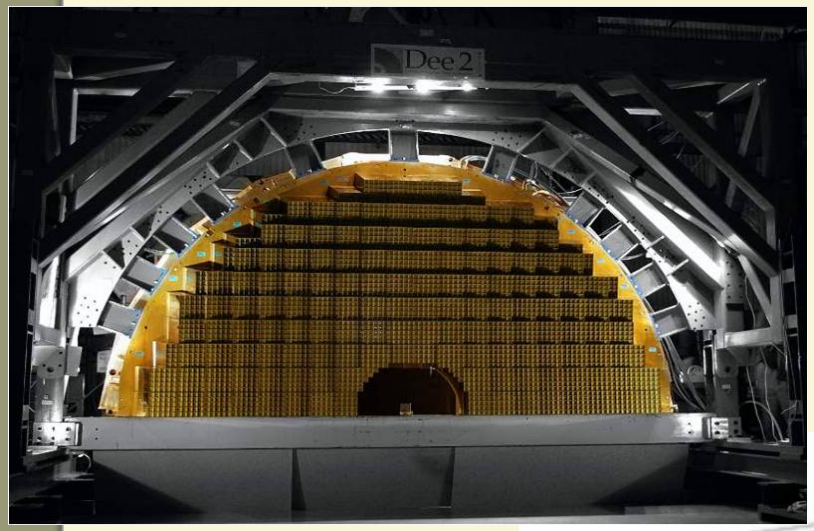
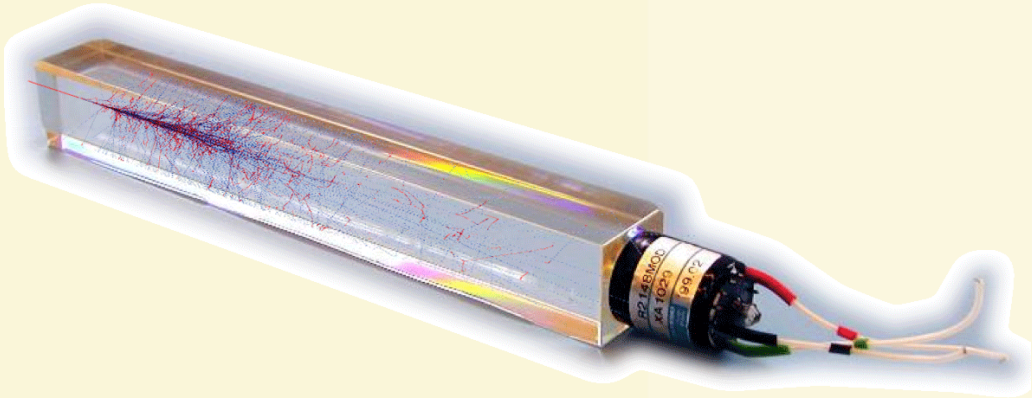
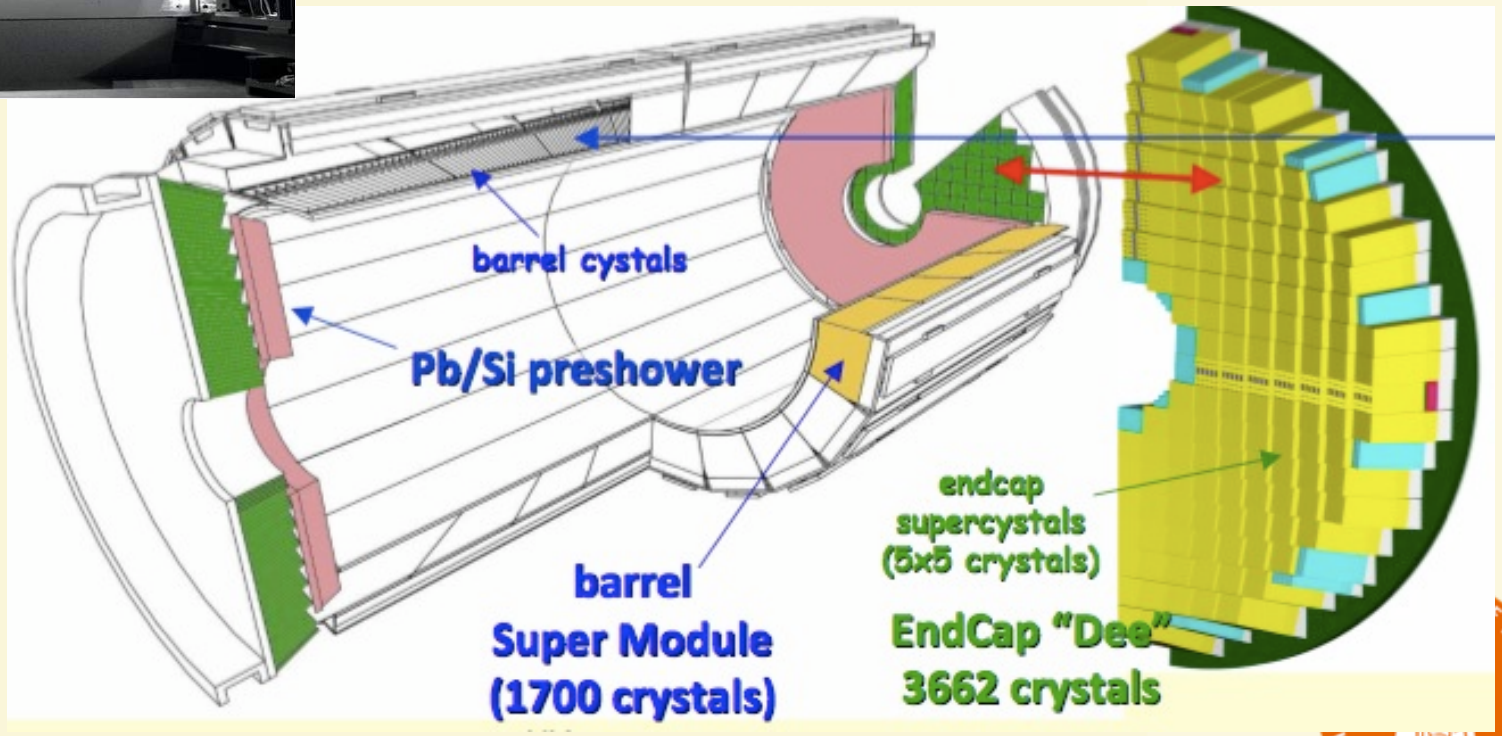
Technological Legacy:
Crystal EM Calorimeter







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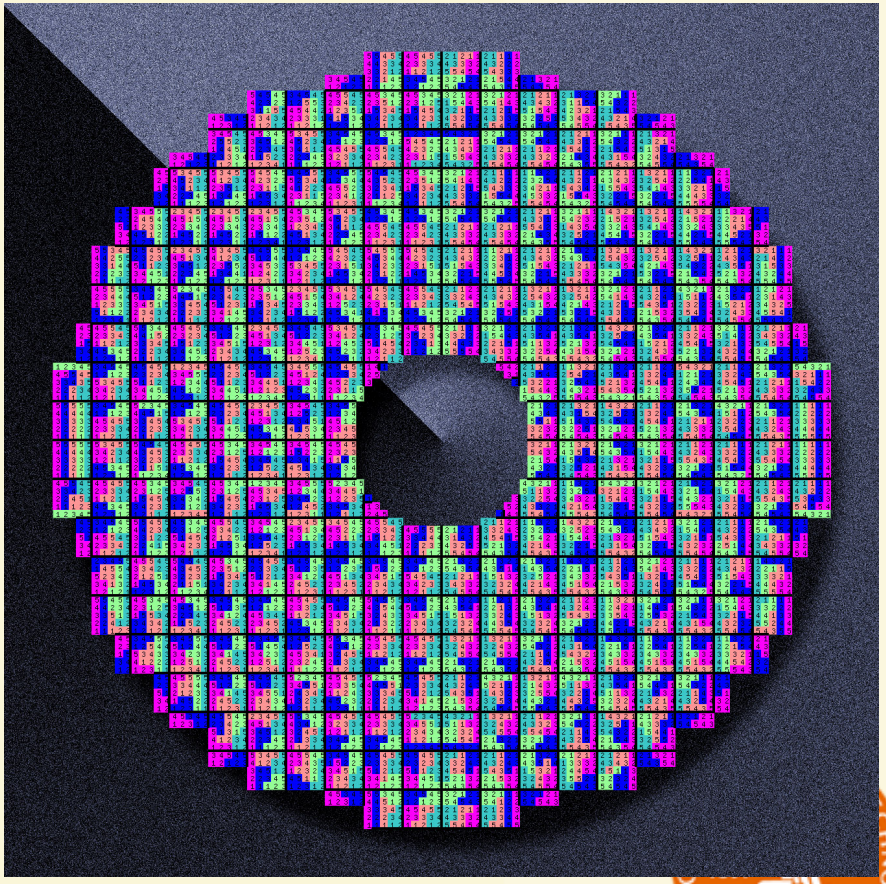
Technological Legacy:
Crystal EM Calorimeter

- Lessons in operating a calorimeter composed of ~75000 crystals

- Operational Stability
- Temperature Control (±0.05°C)
- Variations in light yield
- Monitoring over time
- Radiation Damage

→ Calibrations !



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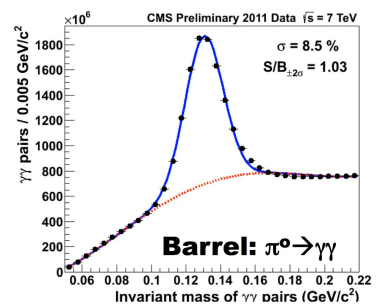
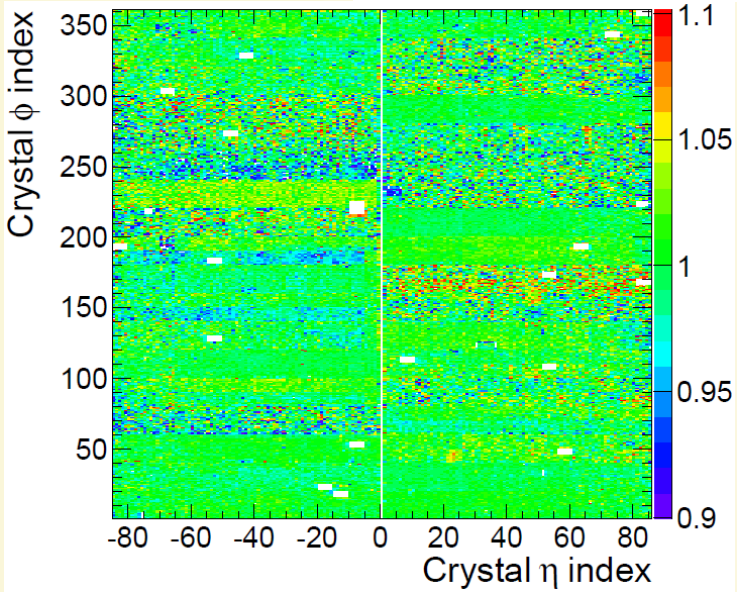
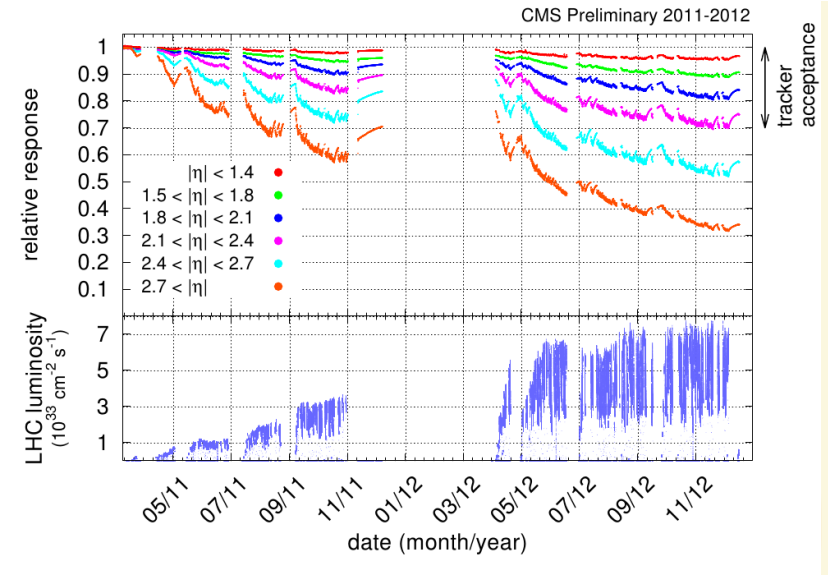
Technological Legacy: ECAL Calibration



- In-situ inter-calibrations using resonances, geometric symmetries, electron E/p
  → **for each of 75000 crystals to precision of 0.5%**
- Live monitoring of crystal transparency with laser light : **once every 40 min for each crystal**
- Corrections for local containment, module boundaries, shower-shape, pileup, etc.





Each is a monumental task

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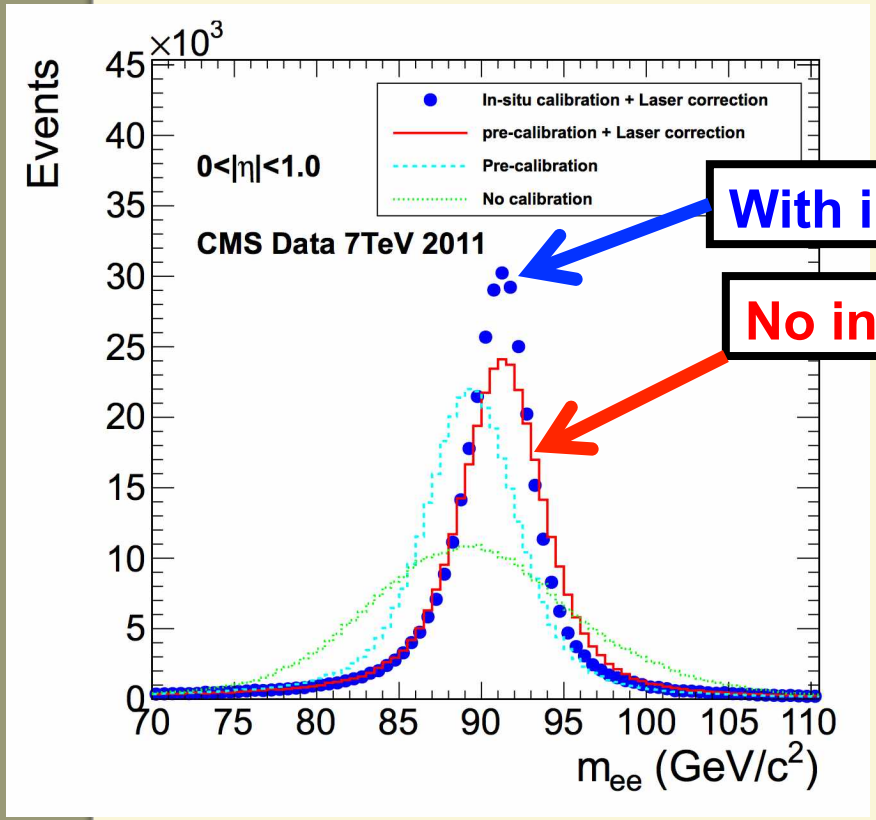
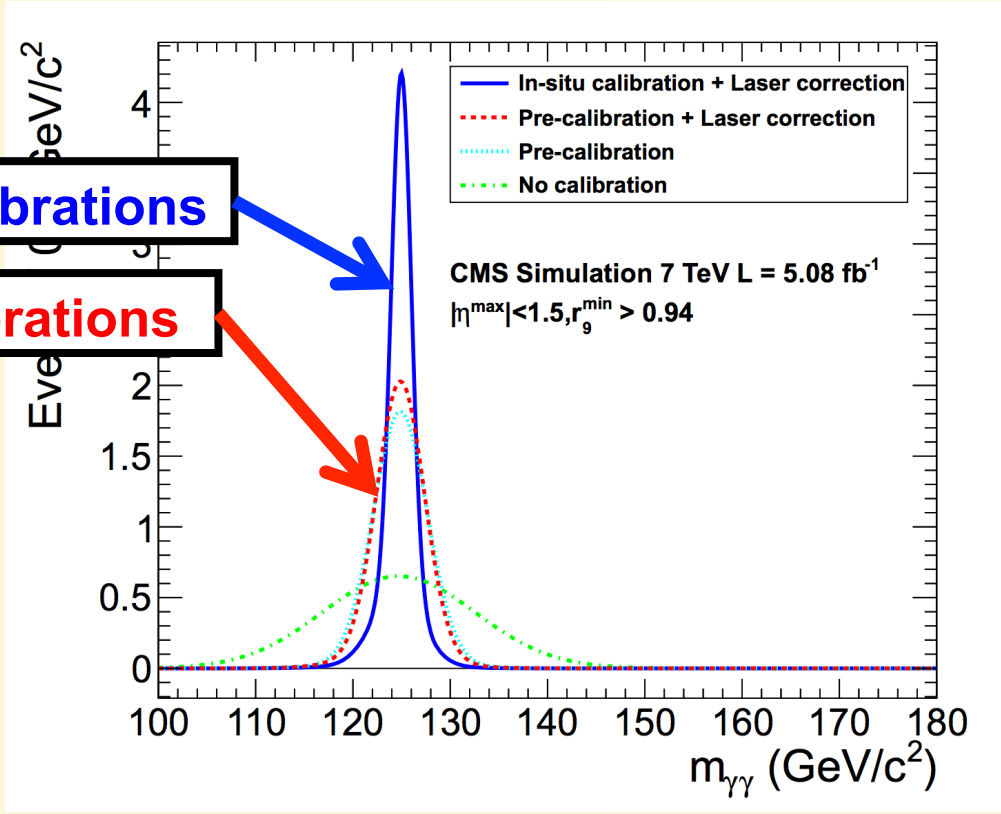
Technological Legacy:
ECAL Calibration

From: Y.Yang Caltech PhD Thesis



With inter-calibrations

No inter-calibrations



Example Trivia: CMS ECAL in-situ inter-calibration has a ~40% impact on H→γγ sensitivity

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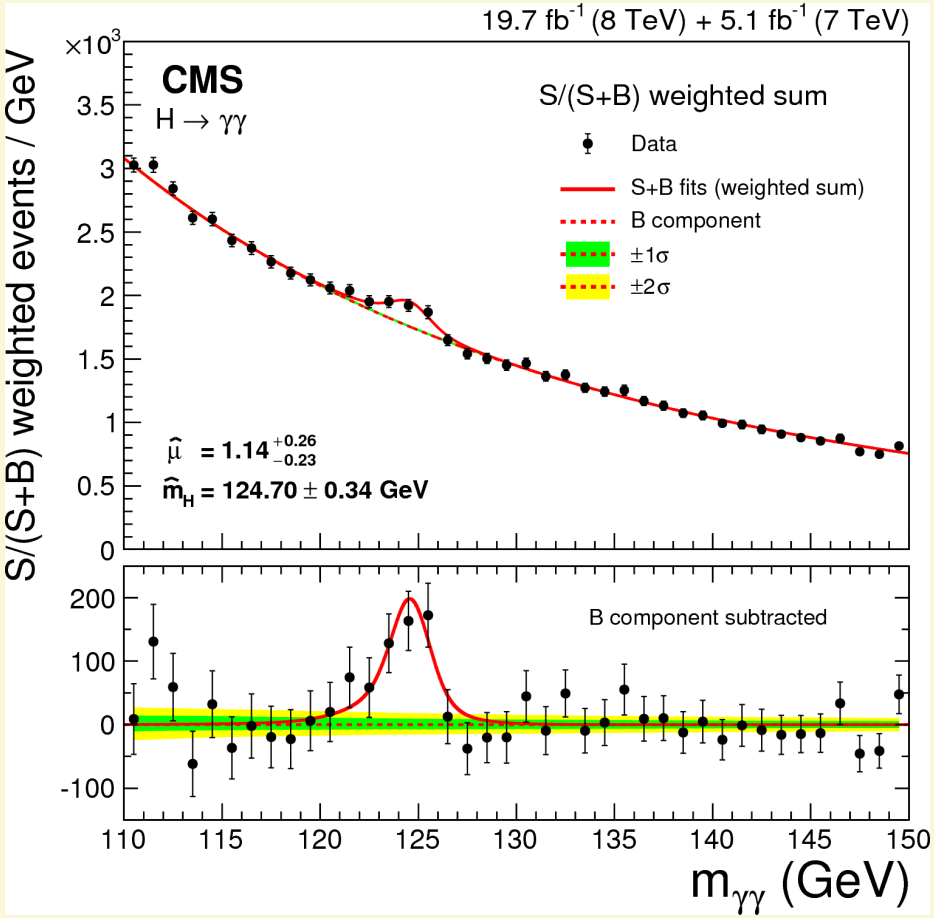
Physics Legacy: H→γγ



H→γγ observed @
5.6σ significance

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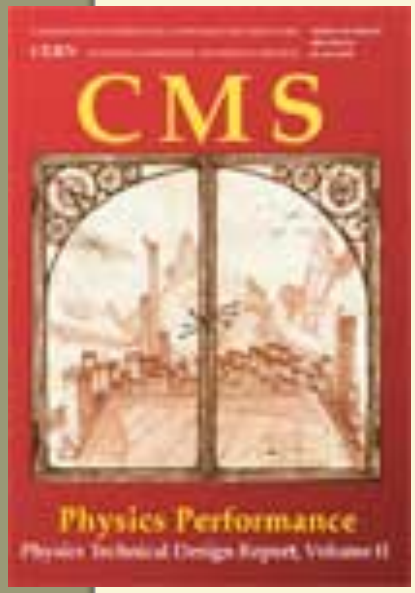
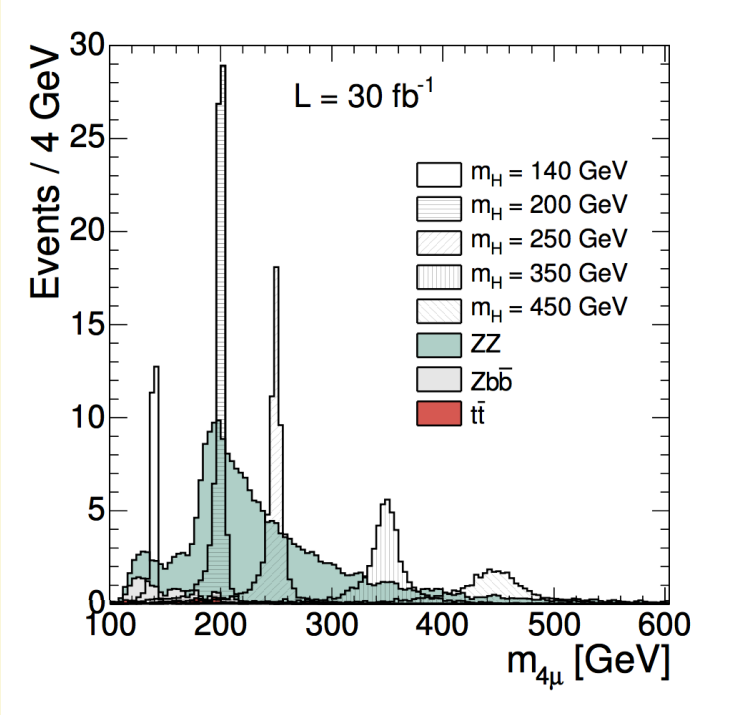
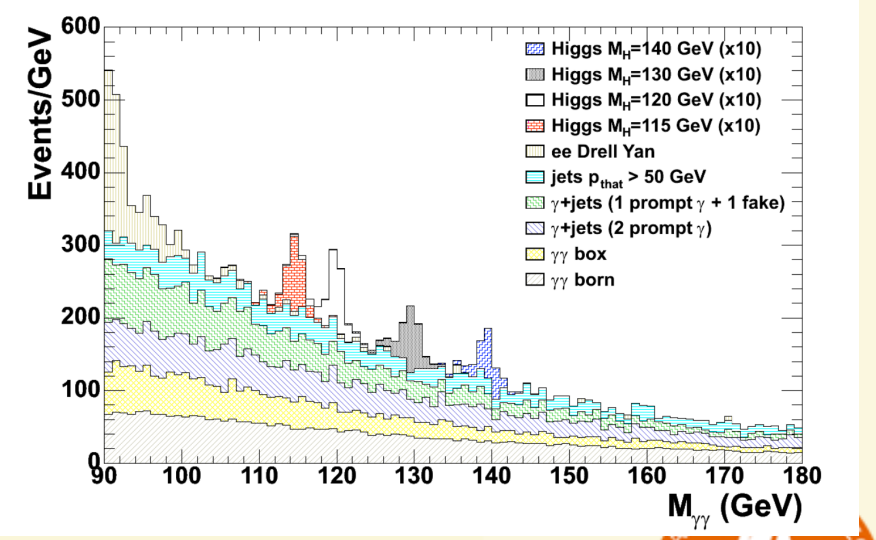
CMS Core Design

- Core design principles of CMS were indeed the key factors for the Higgs discovery
  - Strong spectrometer & all-silicon tracker
  - Clean muons
  - Precision ECAL







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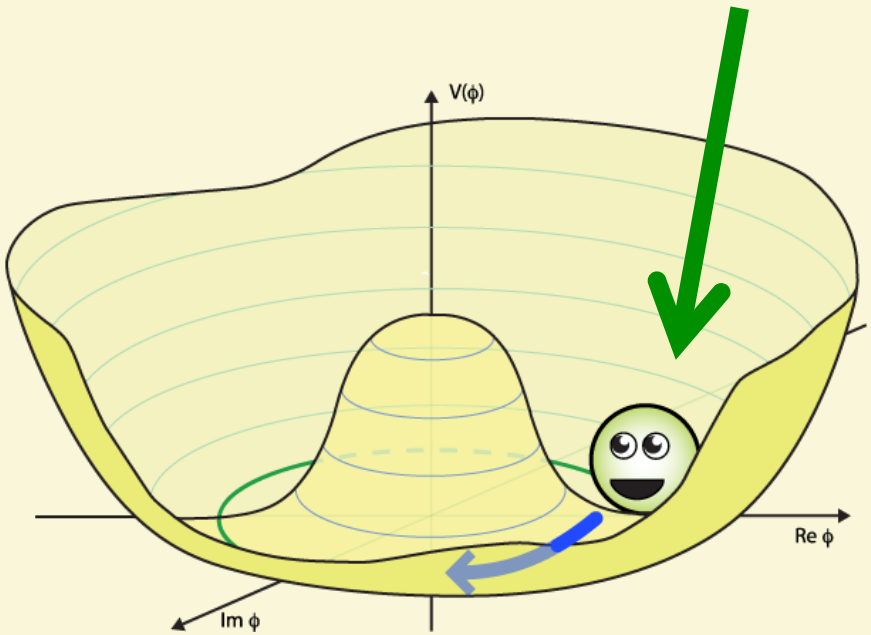
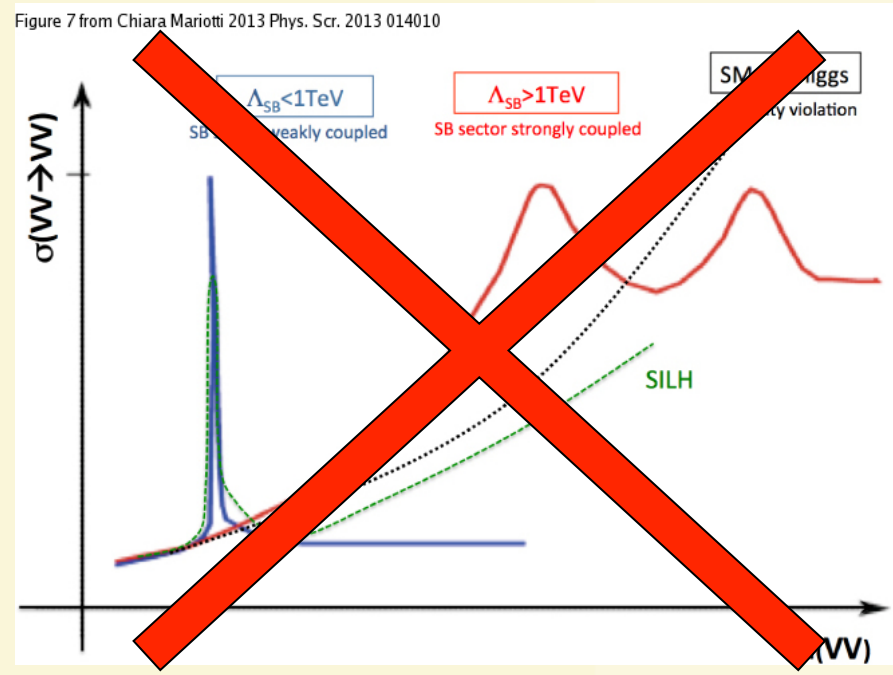
Physics Legacy: EWK Symmetry Breaking

W and Z Bosons get their masses from here





…and we avoid unitarity violation in VV scattering

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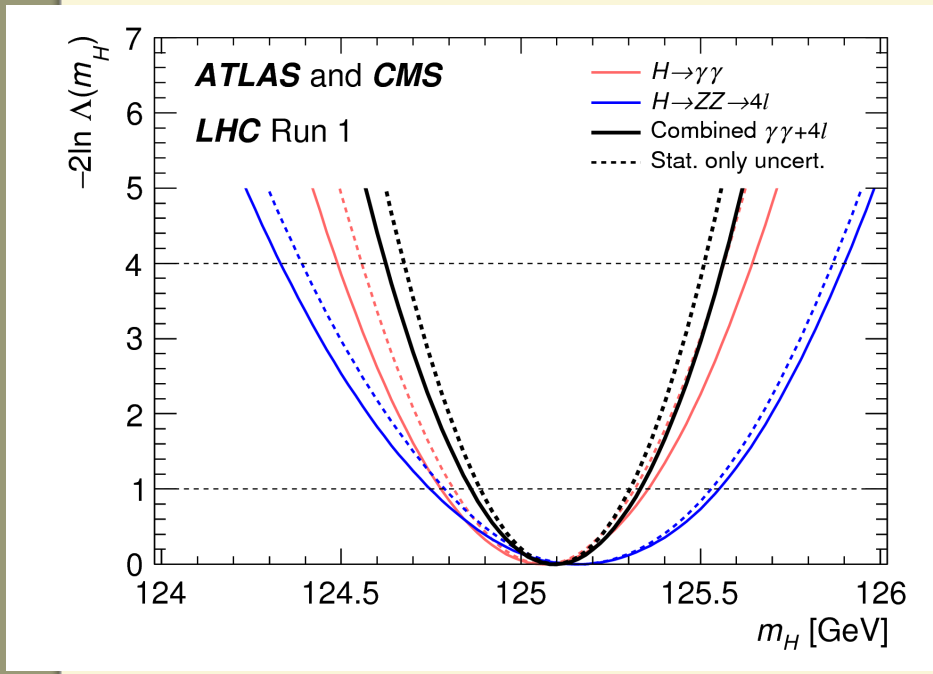
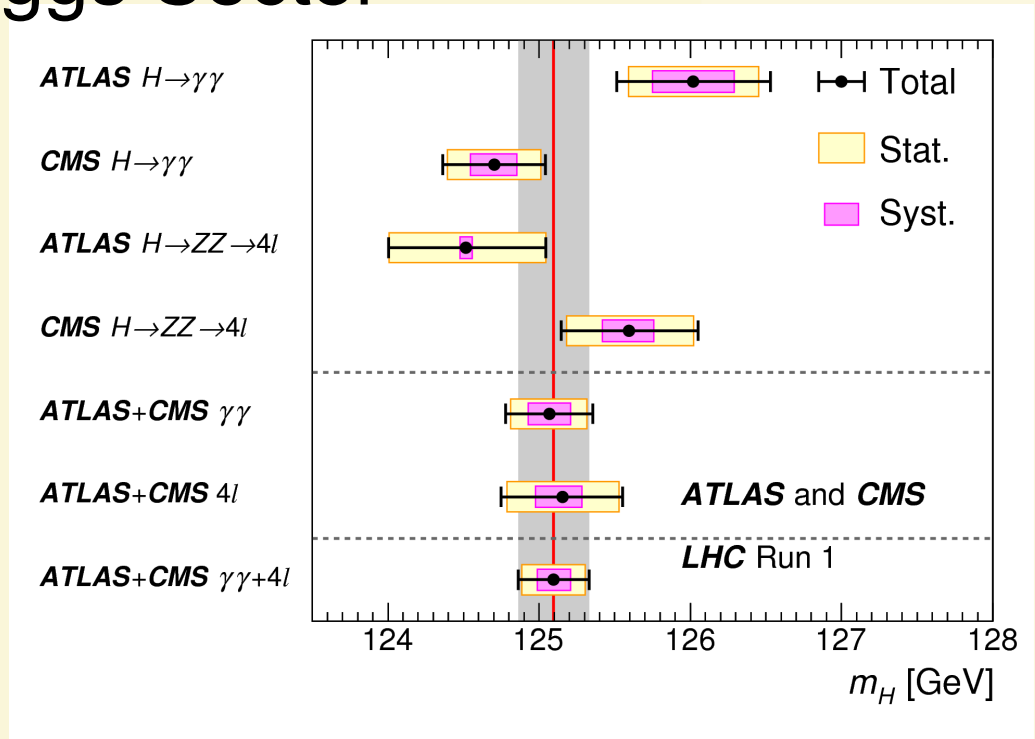
Physics Legacy: Higgs Mass at Incredible Precision

Higgs Mass : the only free parameter of the SM Higgs Sector





$$m_H = 125.09 \pm 0.21\ (\text{stat}) \pm 0.11\ (\text{sys})$$

Precision better than 0.2%

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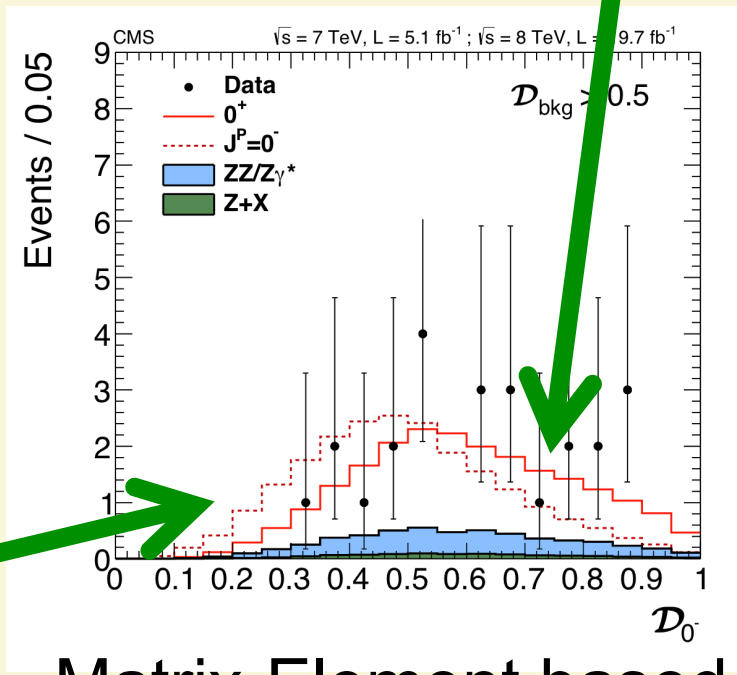
Is it a Scalar?

- A lot of clever techniques were developed to squeeze out as much information as possible from the limited data sample

Scalar

Only ~25 Higgs events here



Pseudo-scalar

Matrix-Element based Likelihood Ratio

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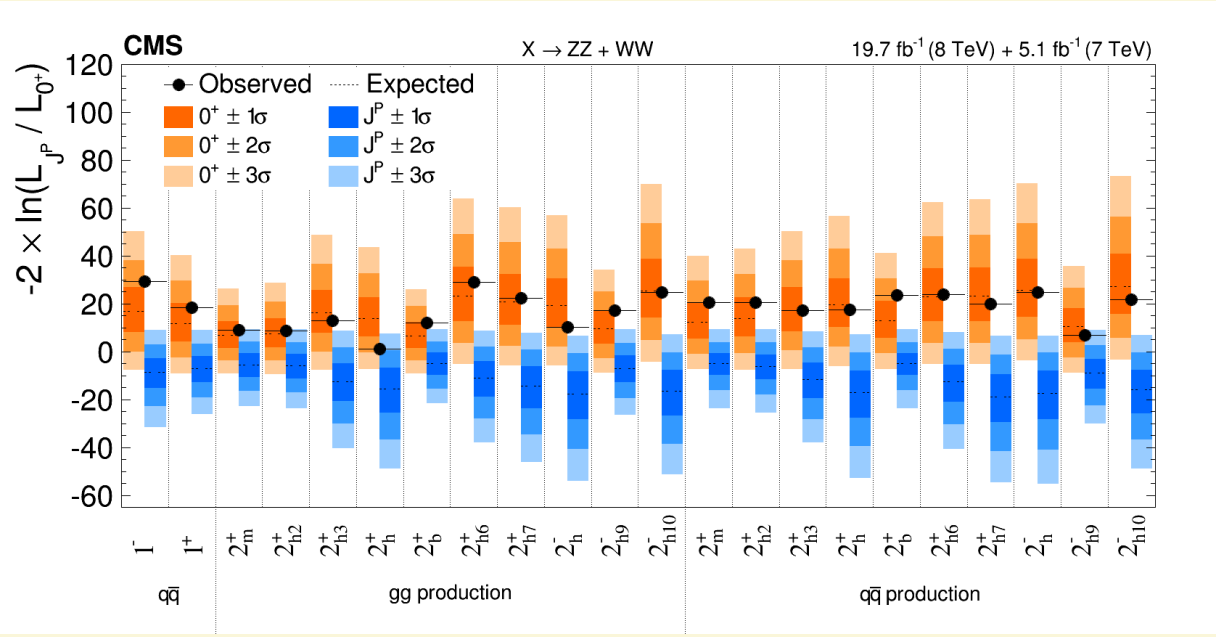
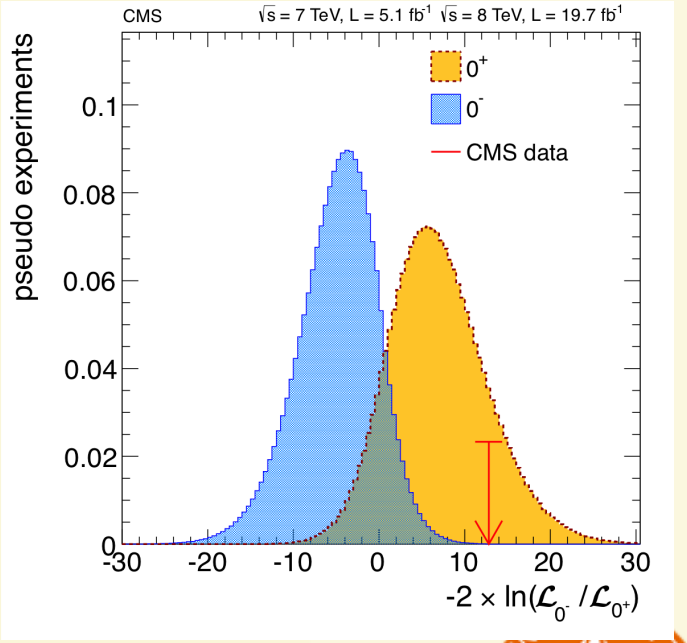
Is it a Scalar?

- Pure pseudo-scalar ruled out at 99%
- Spin-1 and Spin-2 ruled out at 4σ or more
- …pretty sure the Higgs (mostly) is a scalar





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Is it a PURE scalar?

Difficult to establish a definitive answer…

…but we can try to quantify

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Is it a PURE scalar?

(1) Parameterize a hypothetical mixed state

Starting with Spin-0 :

SM HZZ decay (a1)

Leading momentum dependent correction

$$A(X_{J=0} \to V_1 V_2) = v^{-1} \Bigg(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^*$$

$$+ a_2 f_{\mu\nu}^{*(Z)} f^{*(Z),\mu\nu} + a_3 f_{\mu\nu}^{*(Z)} \tilde{f}^{*(Z),\mu\nu}$$

$$+ a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu}$$

$$+ a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma)} f^{*(\gamma),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma)} \tilde{f}^{*(\gamma),\mu\nu} \Bigg) ,$$

non-SM scalar (a2)

SM $Z\gamma$

SM $\gamma\gamma$

Pseudo-scalars (a3)

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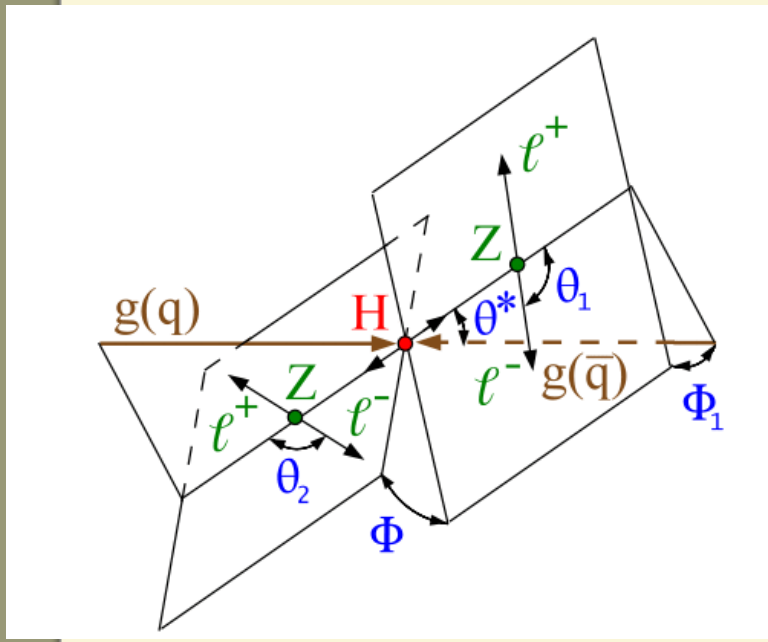
Is it a PURE scalar?

(2) Calculate probability density for observables as a function of parameters



Observables Parameters

$$P(\mathbf{\Omega} \mid \zeta),$$

$$\zeta = (a_2^{ZZ}, a_3^{ZZ}, a_2^{Z\gamma}, \ldots)$$

Observables: m_{4l}, m_{Z1}, m_{Z2}, 5 angles

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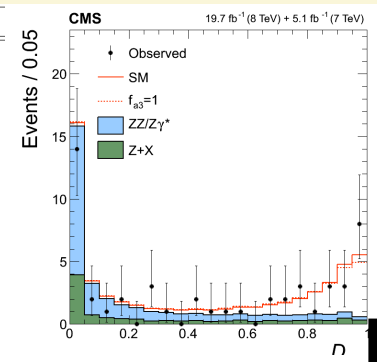
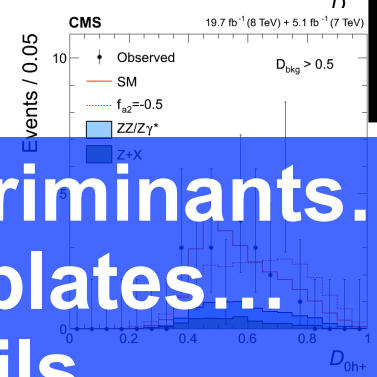
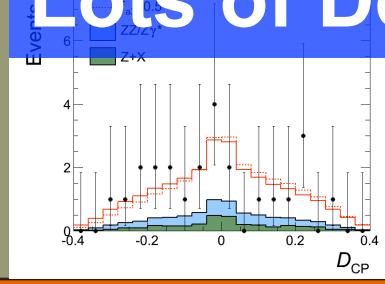
Is it a PURE scalar?

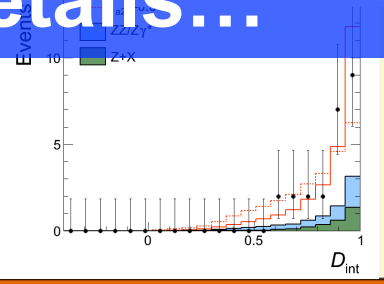
(2) Calculate probability density for observables as a function of parameters

Measurement	Observables $\vec{x}$		
$f_{\Lambda 1}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{\Lambda 1}$	
f_{a2}	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{0h+}$	$\mathcal{D}_{\rm int}$
f_{a3}	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{0-}$	$\mathcal{D}_{\rm CP}$
$f_{\Lambda 1}^{\rm WW}$	$m_{\rm T}$	$m_{\ell\ell}$	
$f_{a2}^{\rm WW}$	$m_{\rm T}$	$m_{\ell\ell}$	
$f_{a3}^{\rm WW}$	$m_{\rm T}$	$m_{\ell\ell}$	
$f_{\Lambda 1}^{Z\gamma}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{\Lambda 1}^{Z\gamma}$	$\mathcal{D}_{\rm int}^{Z\gamma,\Lambda 1}$
$f_{a2}^{Z\gamma}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{a2}^{Z\gamma}$	$\mathcal{D}_{\rm int}^{Z\gamma}$
$f_{a3}^{Z\gamma}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{a3}^{Z\gamma}$	$\mathcal{D}_{\rm CP}^{Z\gamma}$
$f_{a2}^{\gamma\gamma}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{a2}^{\gamma\gamma}$	$\mathcal{D}_{\rm int}^{\gamma\gamma}$
$f_{a3}^{\gamma\gamma}$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{a3}^{\gamma\gamma}$	$\mathcal{D}_{\rm CP}^{\gamma\gamma}$
spin-one $q\bar{q} \to X(f_{b2}) \to ZZ$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{1-}$	$\mathcal{D}_{1+}$
spin-one decay $X(f_{b2}) \to ZZ$	$\mathcal{D}_{\rm bkg}^{\rm dec}$	$\mathcal{D}_{1-}^{\rm dec}$	$\mathcal{D}_{1+}^{\rm dec}$
spin-two $q\bar{q} \to X(J^P) \to ZZ$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{J^P}^{q\bar{q}}$	
spin-two $gg \to X(J^P) \to ZZ$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{J^P}^{gg}$	
spin-two decay $X(J^P) \to ZZ$	$\mathcal{D}_{\rm bkg}^{\rm dec}$	$\mathcal{D}_{J^P}^{\rm dec}$	
spin-one $q\bar{q} \to X(f_{b2}) \to WW$	$\mathcal{D}_{\rm bkg}$	$\mathcal{D}_{1-}$	$\mathcal{D}_{1+}$
spin-two gg or $q\bar{q} \to X(J^P) \to WW$	$m_{\rm T}$	$m_{\ell\ell}$	
spin-two gg or $q\bar{q} \to X(2^+_m) \to$		$\cos\theta^*$	









Matrix Element Calculation

$$P(\vec{p}_T, Y, \phi, m_{4\ell}, m_1, m_2, \vec{\Omega}|\vec{\zeta}) = W_{\rm prod}(\vec{p}_T, Y, \phi, \hat{s}) \times \frac{d\sigma_{4\ell}(m_{4\ell}, m_1, m_2, \vec{\Omega}|\vec{\zeta})}{dm_1^2 dm_2^2 d\vec{\Omega}}$$

Production Spectrum

$$P(\vec{x}^{\rm R}|\vec{\zeta}) = \int P(\vec{x}^{\rm G}|\vec{\zeta}) T(\vec{x}^{\rm R}|\vec{x}^{\rm G}) d\vec{x}^{\rm G}$$

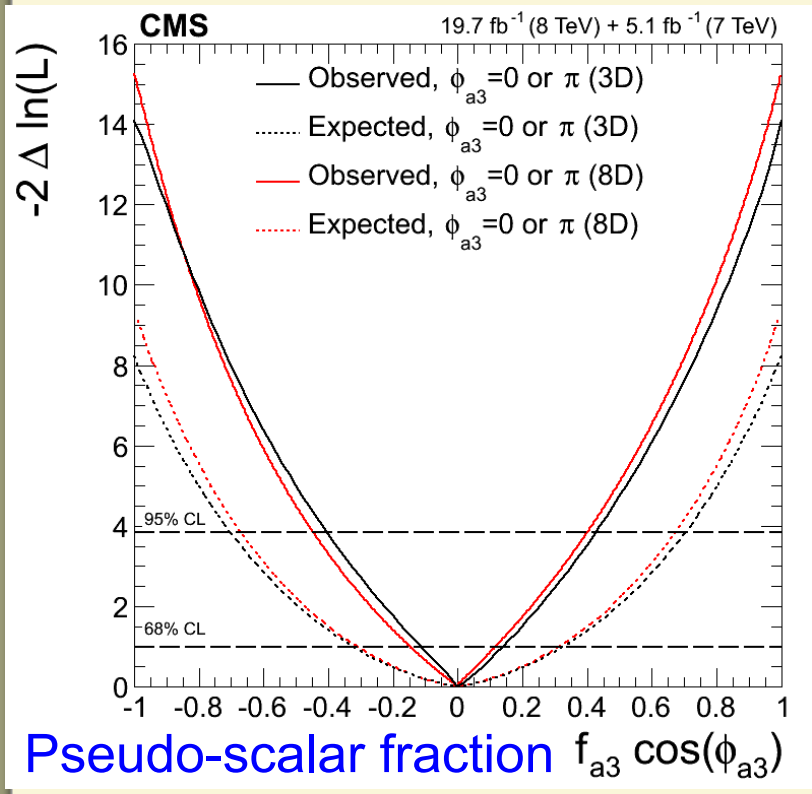
Convolution with transfer functions

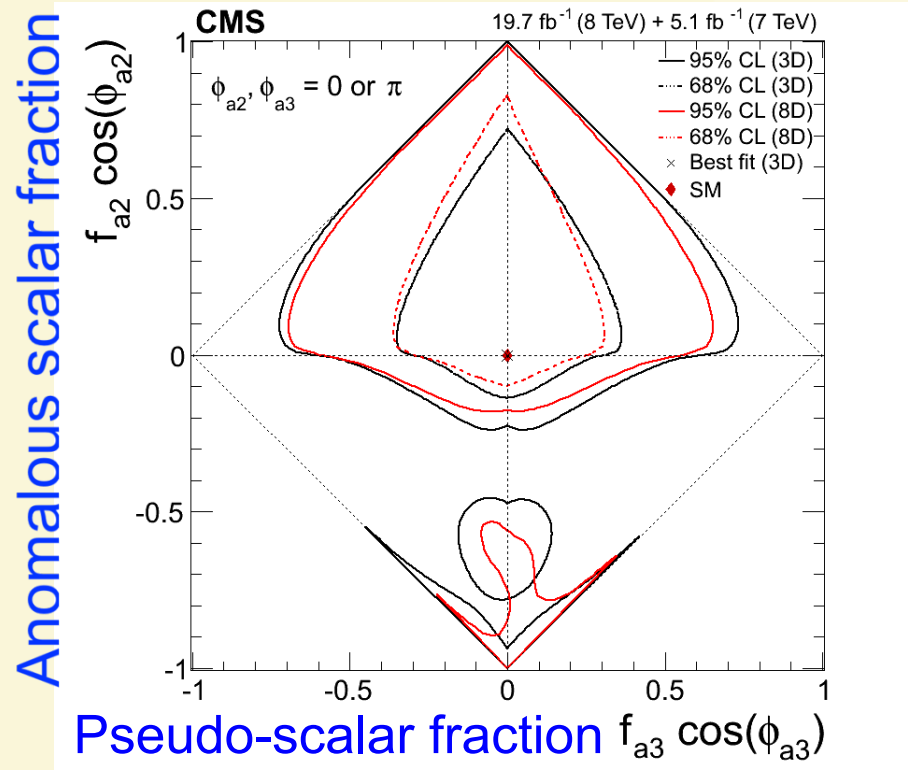
Lots of Discriminants…
Lots of Templates…
Lots of Details…

Lots of integrals…
Lots of computation…
Lots of ingenuity…

Is it a PURE scalar?

(3) Fit data to extract and constrain parameters





Pseudo-scalar mixture above ~2 x SM Higgs ruled out
(equivalent to ~40% by cross section)

Si Xie

Origin of Fermion Mass

Is Higgs responsible for generating fermion masses?

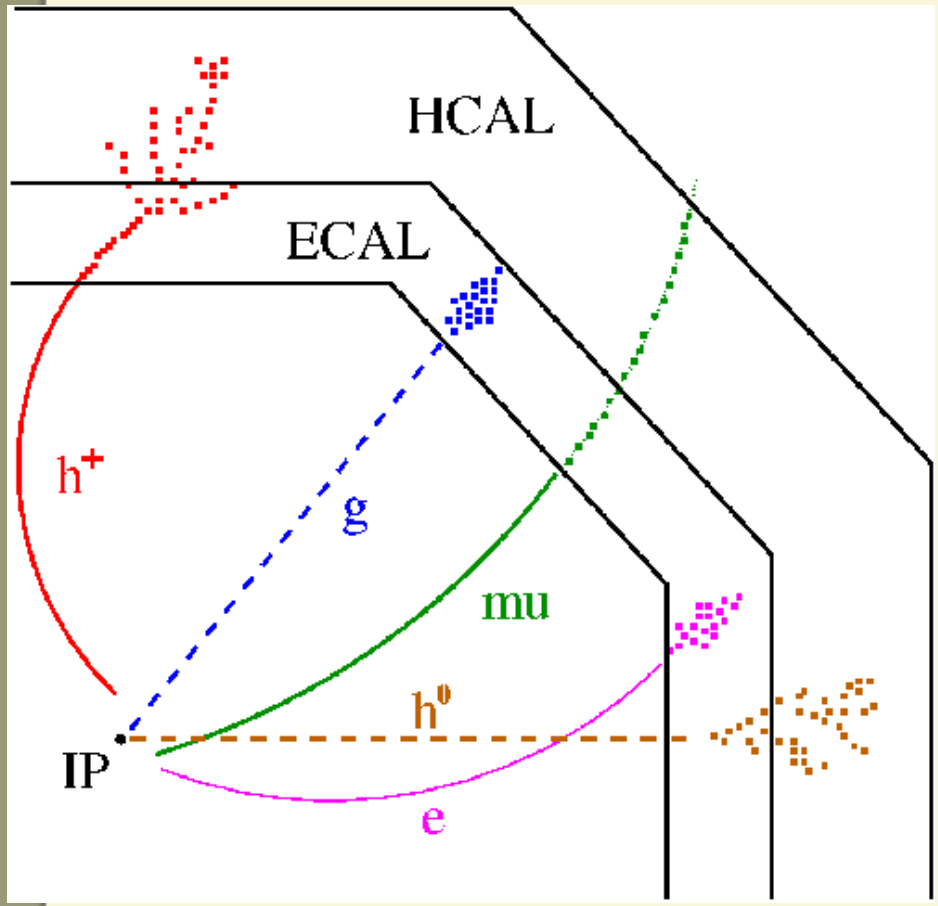
$$-\lambda_d \overline{Q}_L \Phi d_R + h.c.$$

$$-\lambda_u \overline{Q}_L \Phi^c u_R + h.c.$$

Higgs decays to $\tau\tau$?
Higgs decays to bb ?

Si Xie

Technological Legacy:
Particle Flow & Tau Reconstruction



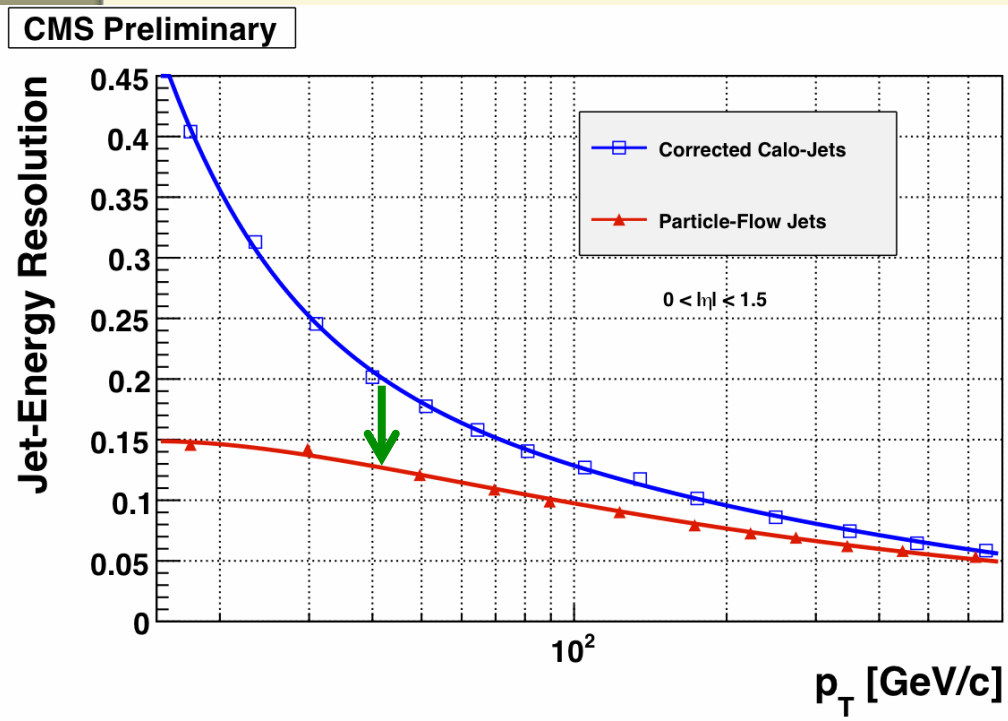
- Link tracks to EM & Hadronic clusters
- Identify e,μ,γ,h^+,h^0
- Find overlapping particles

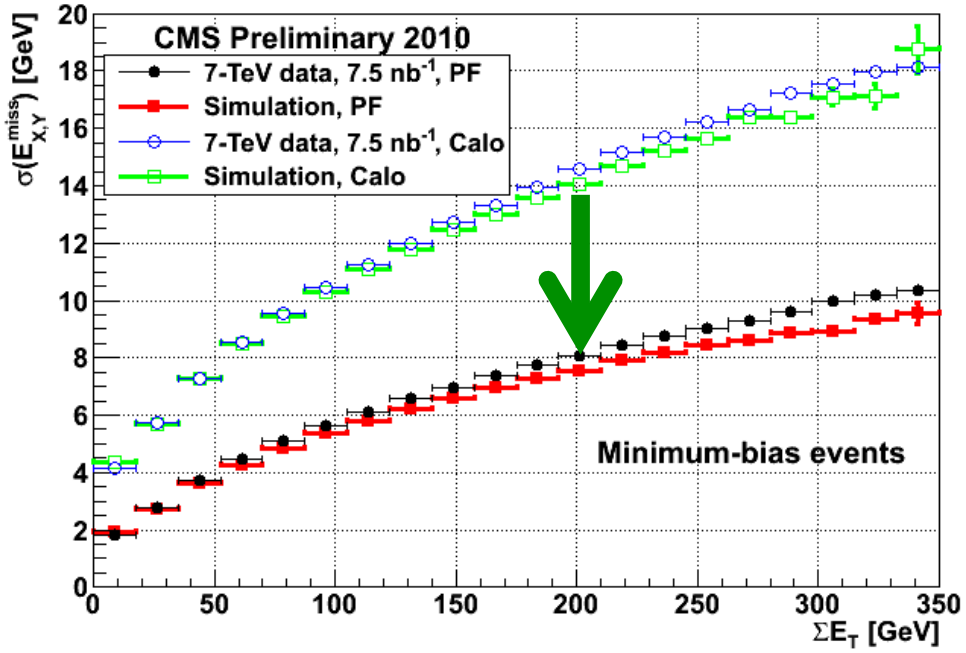
- Calibrate particles according to their average response

Si Xie

Technological Legacy:
Particle Flow & Tau Reconstruction

Improvement over pure calorimetric reconstruction
~30% Better Jet Resolution
~40% Better MET Resolution



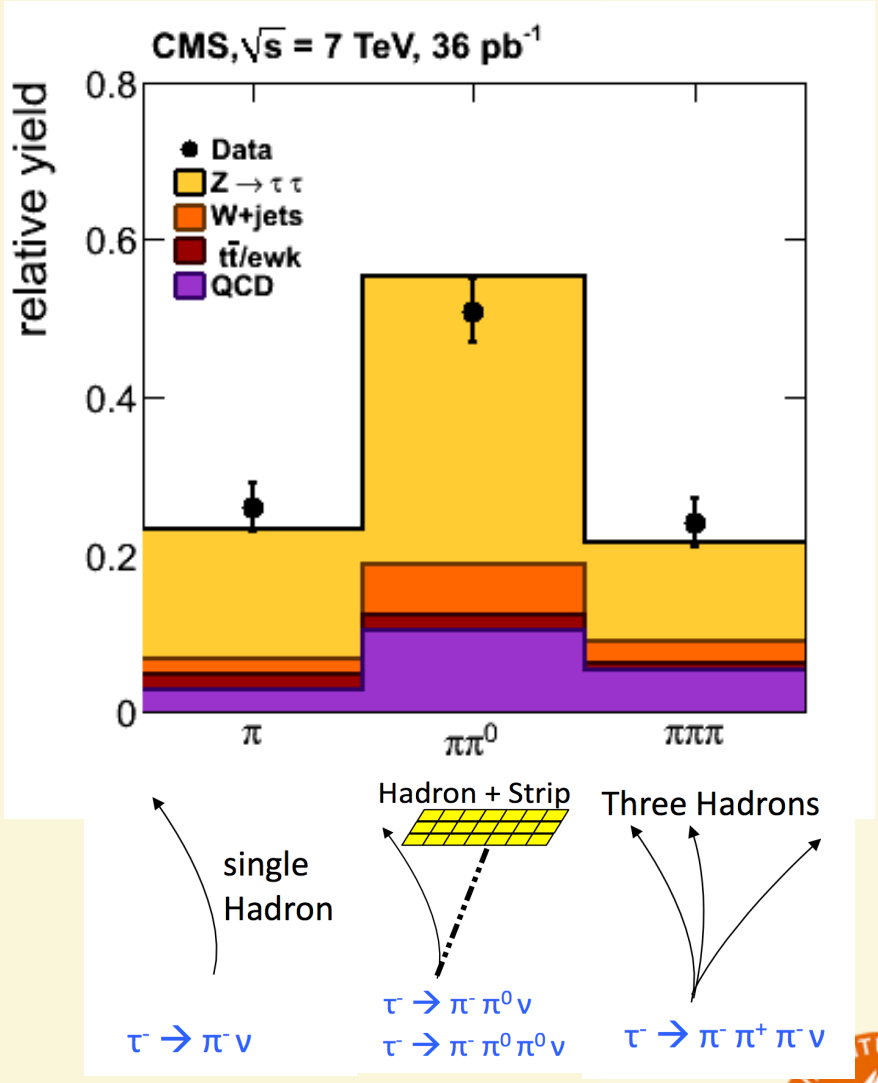


Si Xie

Technological Legacy:
Particle Flow & Tau Reconstruction

Well Performing Tau Reconstruction

Decay Channel	Branching Ratio
$\tau^- \rightarrow h^- \nu_\tau$	11.6%
$\tau^- \rightarrow h^- \pi^0 \nu_\tau$	26.0%
$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$	9.5%
$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$	9.8%



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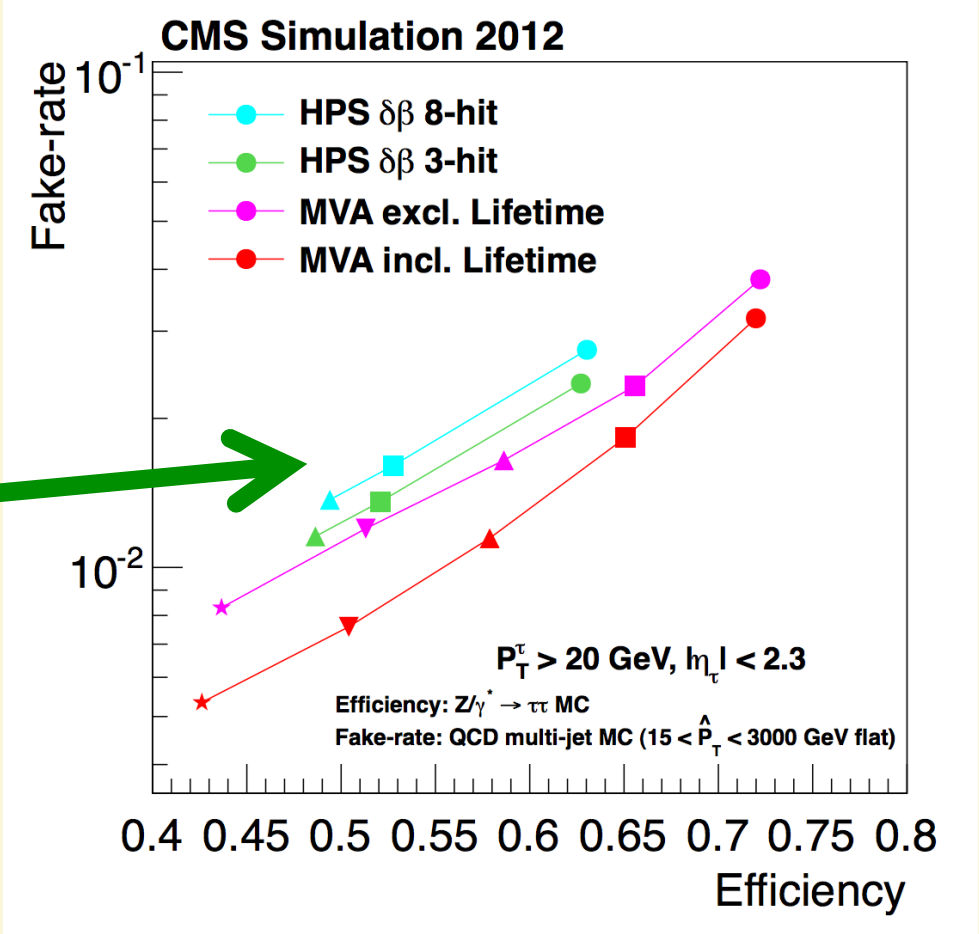
Technological Legacy:
Particle Flow & Tau Reconstruction

Well Performing Tau Reconstruction

~ 60% Efficiency
@ 1-2% Mis-ID



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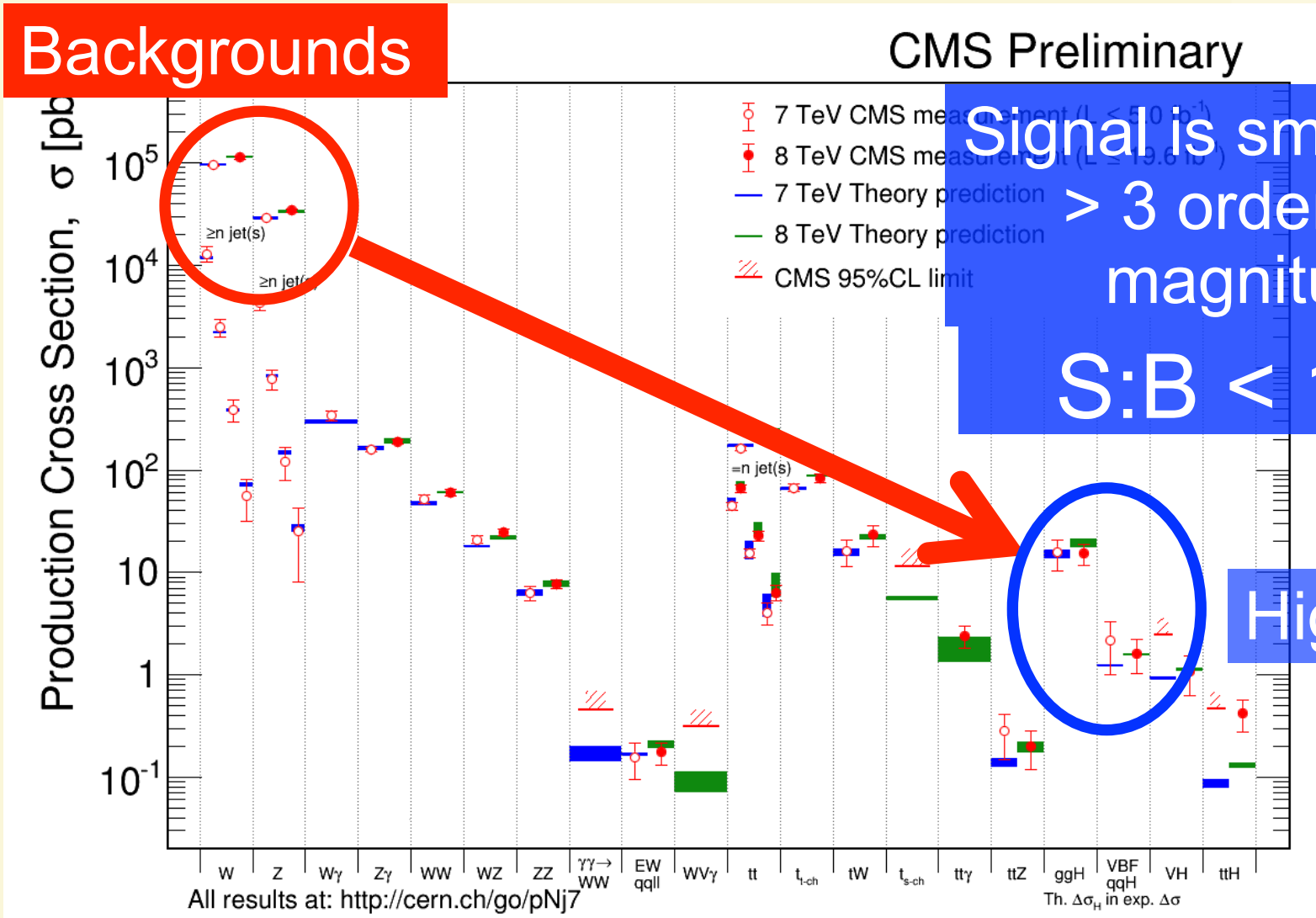
Technological Legacy:
Era of Big Data & MVA Techniques



Signal is smaller by > 3 orders of magnitude

$S:B < 10^{-3}$

Higgs

Si Xie

Technological Legacy:
Era of Big Data & MVA Techniques

Higgs : serious needle in a needle stack problem

Si Xie

Technological Legacy:
Era of Big Data & MVA Techniques

- MVA's used on an unprecedented large scale and all were necessary to discover the Higgs:

  - Vertexing
  - Electron ID & Iso
  - Muon ID & Iso
  - Photon ID
  - Tau ID & Iso
  - Tau Vs Electron Discriminator
  - Tau Vs Muon Discriminator
  - B-tagging
  - Quarks Vs Gluons

  - Photon energy regression
  - Electron momentum regression
  - B-Jet energy regression
  - MET Recoil regression
  - Pileup Jet ID
  - H→WW S/B discriminator
  - H→γγ S/B categorizer
  - H→bb S/B discriminator
  - …
  - …

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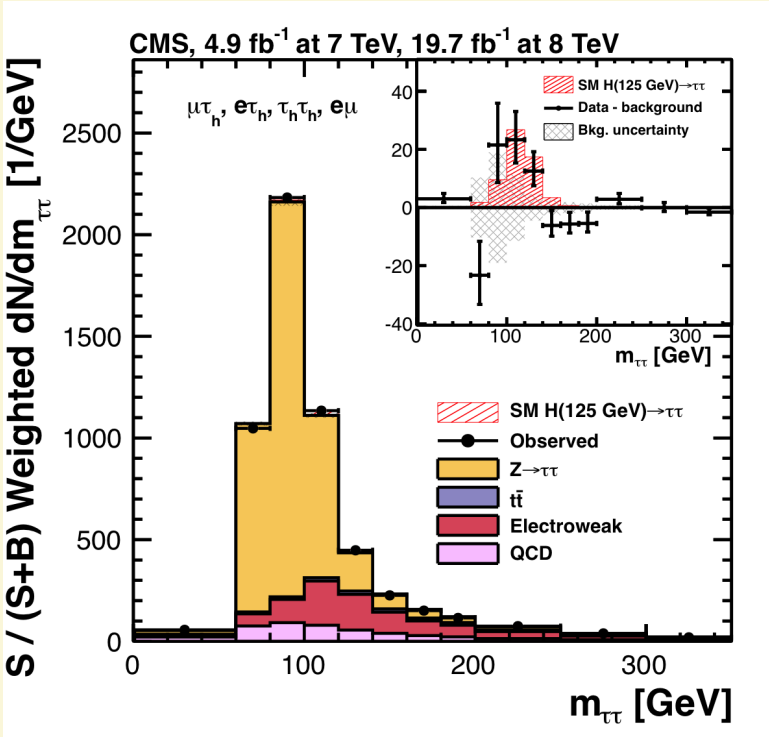
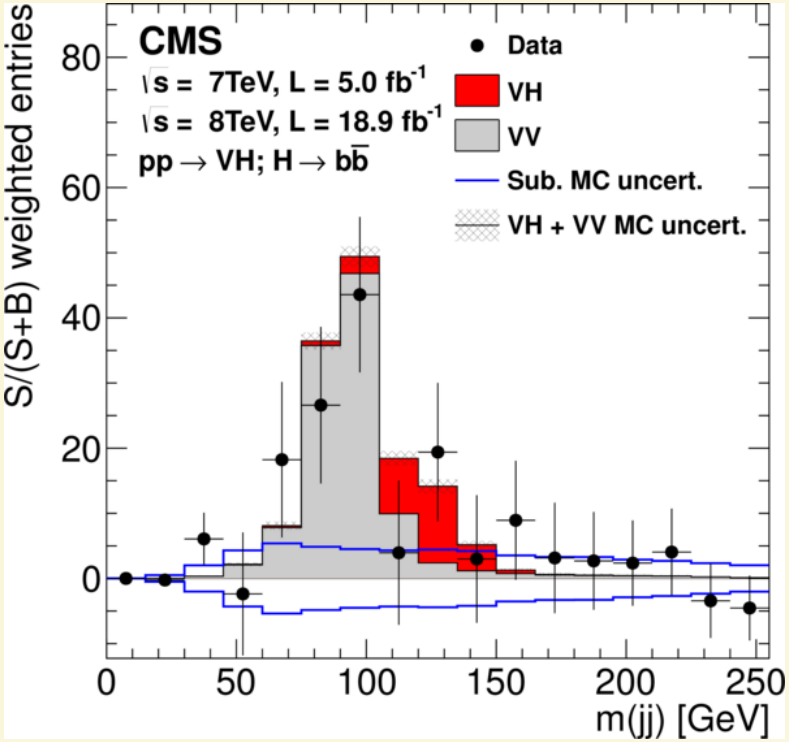
Physics Legacy: Fermion Mass





H→ττ : 3.2 σ

H→bb : 2.1 σ

Combined Significance : 3.8 σ

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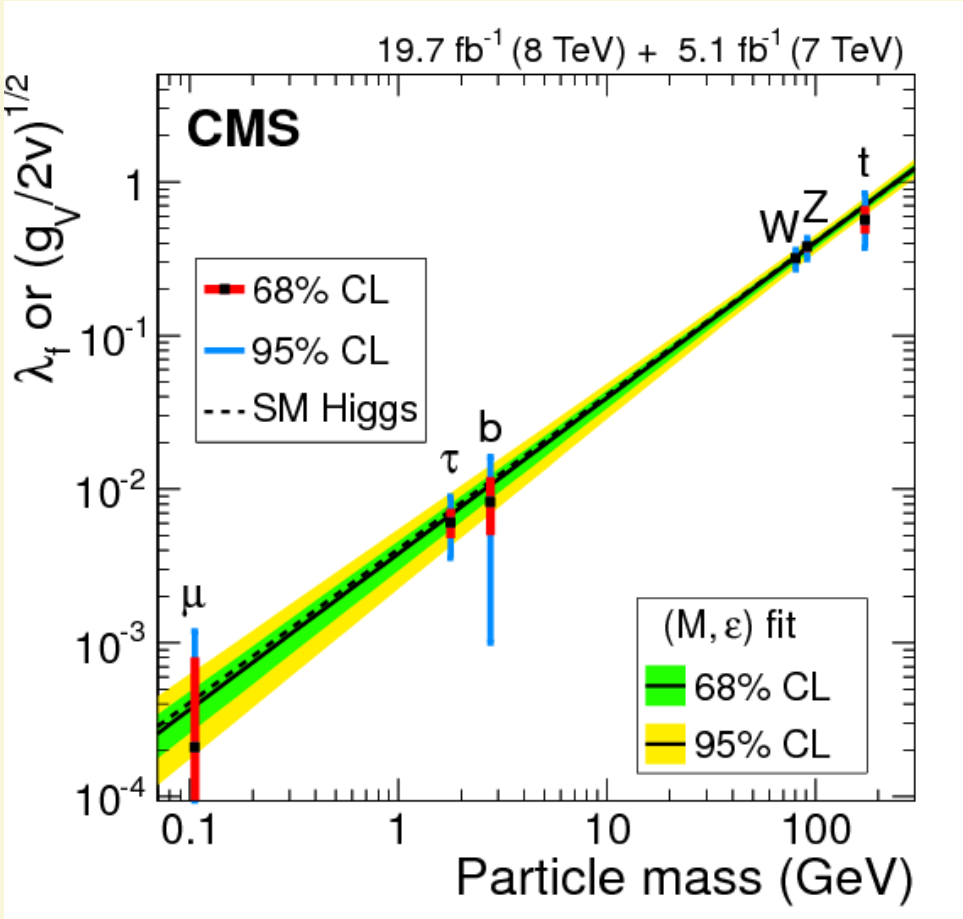
Physics Legacy: Fermion Mass

- Pretty consistent picture of Higgs couplings
- Very strong evidence that fermion masses are indeed generated by Higgs Yukawa couplings



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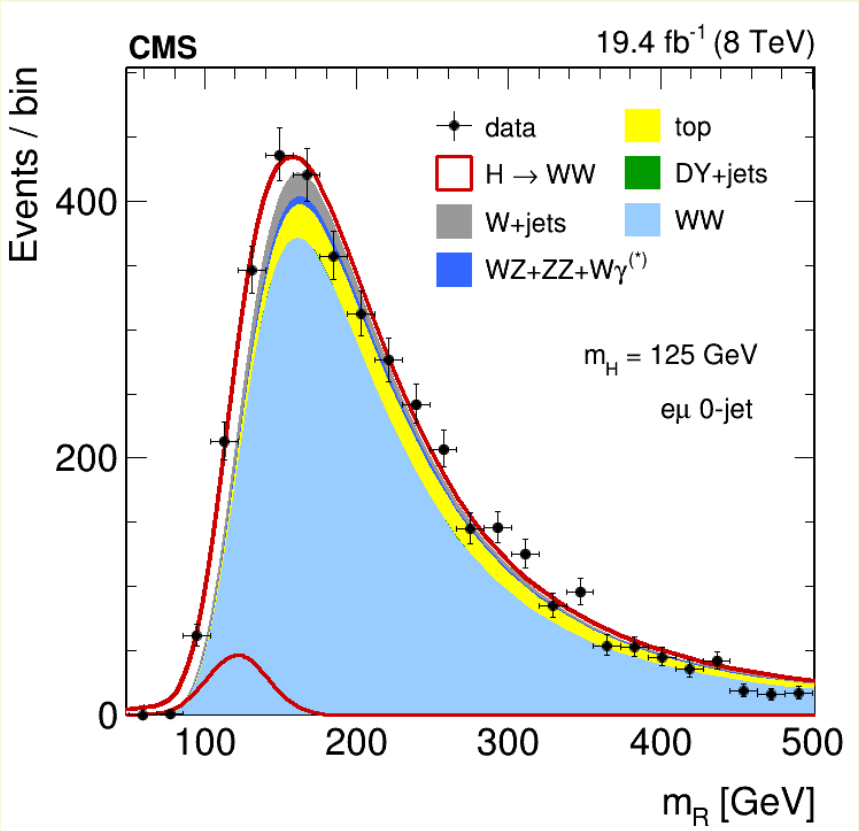
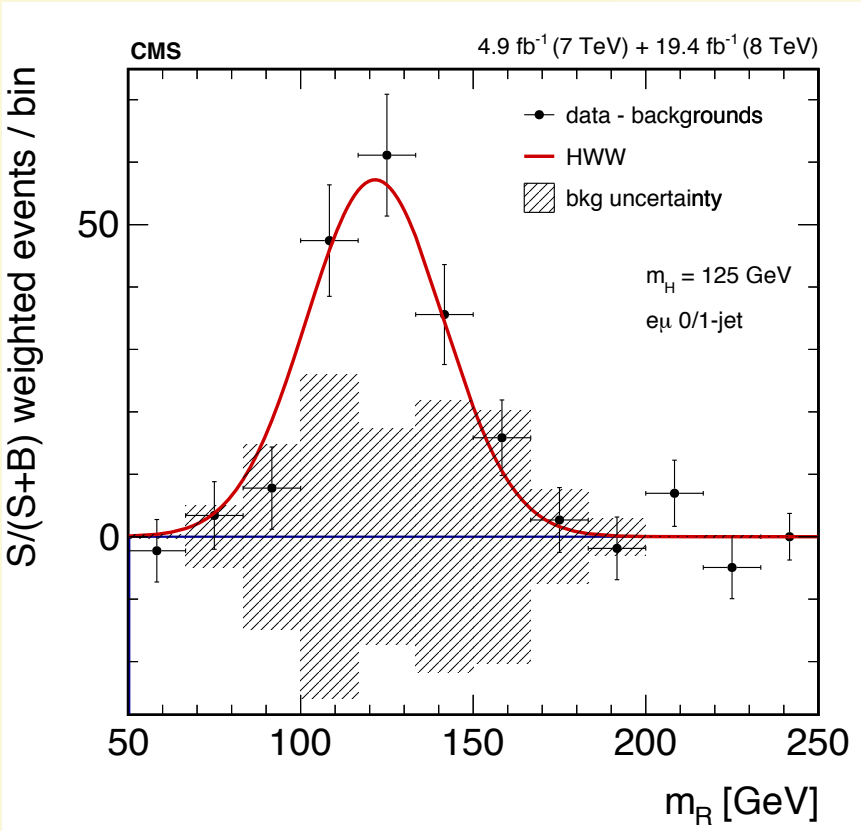
Technological Legacy:
Era of Big Data & MVA Techniques

- Besides MVA methods, other novel techniques were also developed:
  - Kinematic fits
  - Matrix element discriminants
  - Special mass variables
    (SVFit $H \rightarrow \tau\tau$ mass, Razor)

Technological Legacy:
Era of Big Data & MVA Techniques

- Razor variable m_R developed in context for pair produced SUSY particles decaying to visible & invisible particles
- Applies well to H→WW , and was used to measure m_H





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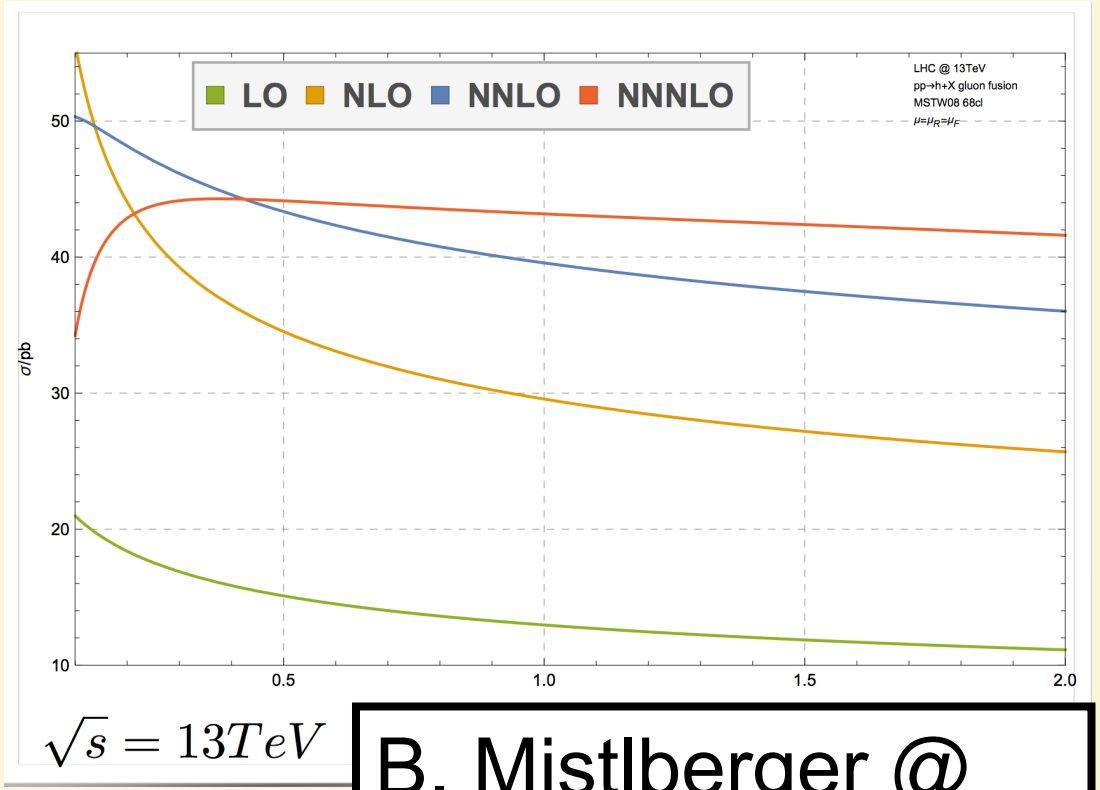
Legacy: Experiment – Theory Feedback

- Many many new MC Tools and calculations motivated by LHC Higgs experimental results:
  - Higgs production has largest LO→NLO→NNLO corrections of all LHC processes
  - Use of NLO MC popularized with Higgs @ LHC (eg. POWHEG, MC@NLO)
  - Fully NLO + extra parton now being commissioned for CMS : aMC@NLO

Legacy: Experiment – Theory Feedback

- Impressive achievements still in the pipeline: NNNLO Higgs Cross section



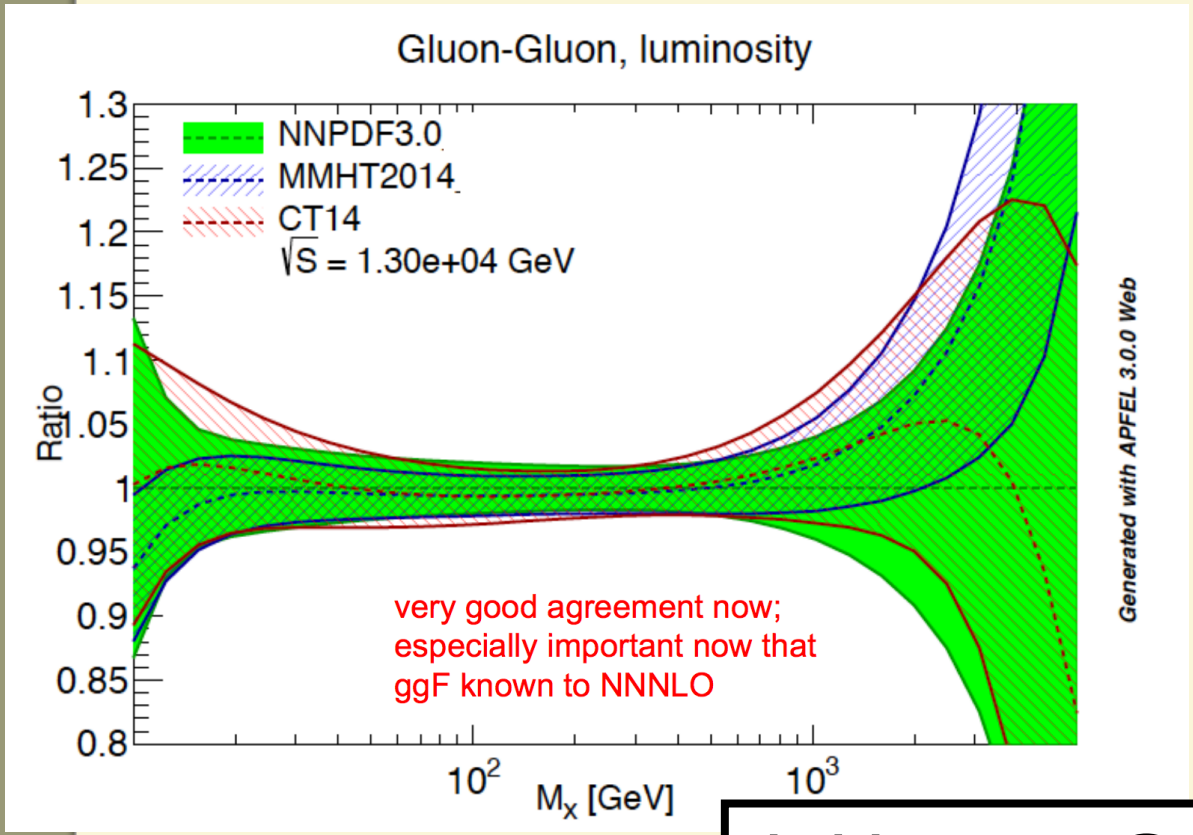
B. Mistlberger @ Moriond QCD 2015

- Scale variation uncertainty improves from 8% to ~3%

Si Xie

Legacy: Experiment – Theory Feedback

- New PDF uncertainties are also improved



- CT14, NMHT2014, NNPDF3.0 are in much better agreement now
- Uncertainty for ggH cross section decreases from 7% → ~2.5%

J. Huston @ LPC Topic of the week on Wednesday

Si Xie

Physics Legacy: Higgs Boson and What Else?

- Higgs Boson confirmed, with mass ~ 125 GeV
- Radiative Corrections to Higgs Mass:

$$\delta m_h^2 = \frac{3}{16\pi^2 v^2}(m_h^2 + 2m_W^2 + m_Z^2 + 4m_t^2)\Lambda^2 \sim \left(\frac{\Lambda}{500GeV}\right)^2$$

tends to push m_H to high energy scales (GUT, Planck) unless there is **extreme fine tuning**

- So…we expected new physics @ ~ TeV scale

But…nothing so far…

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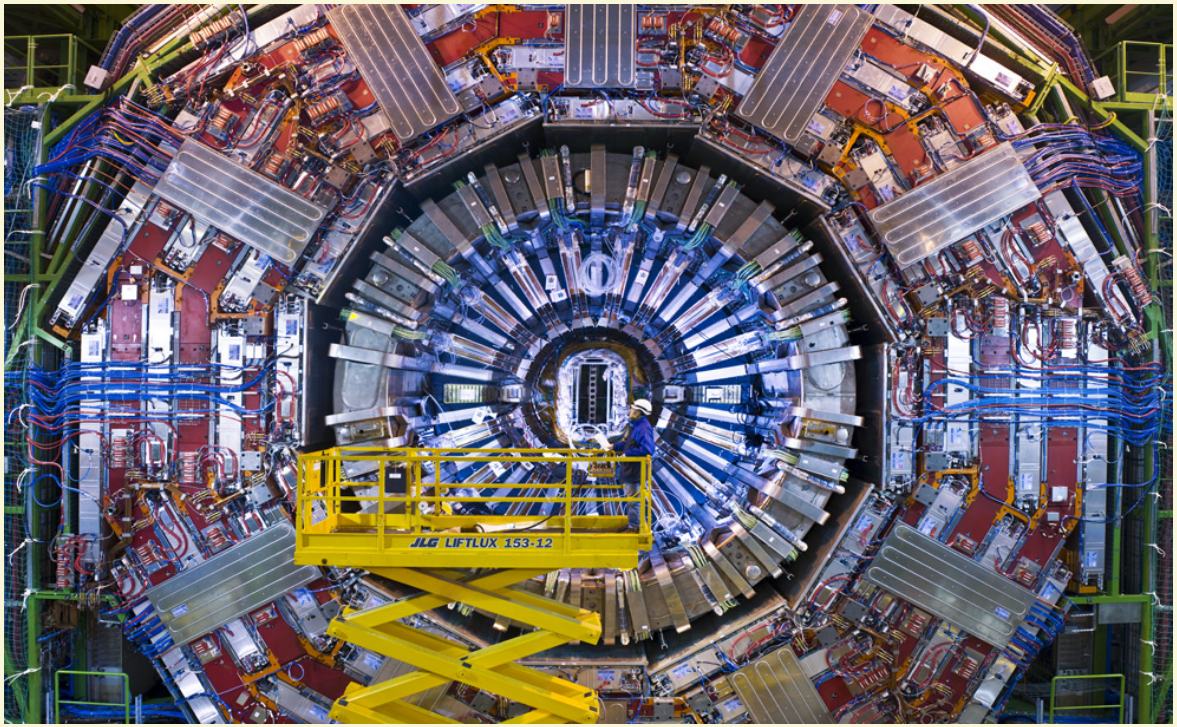
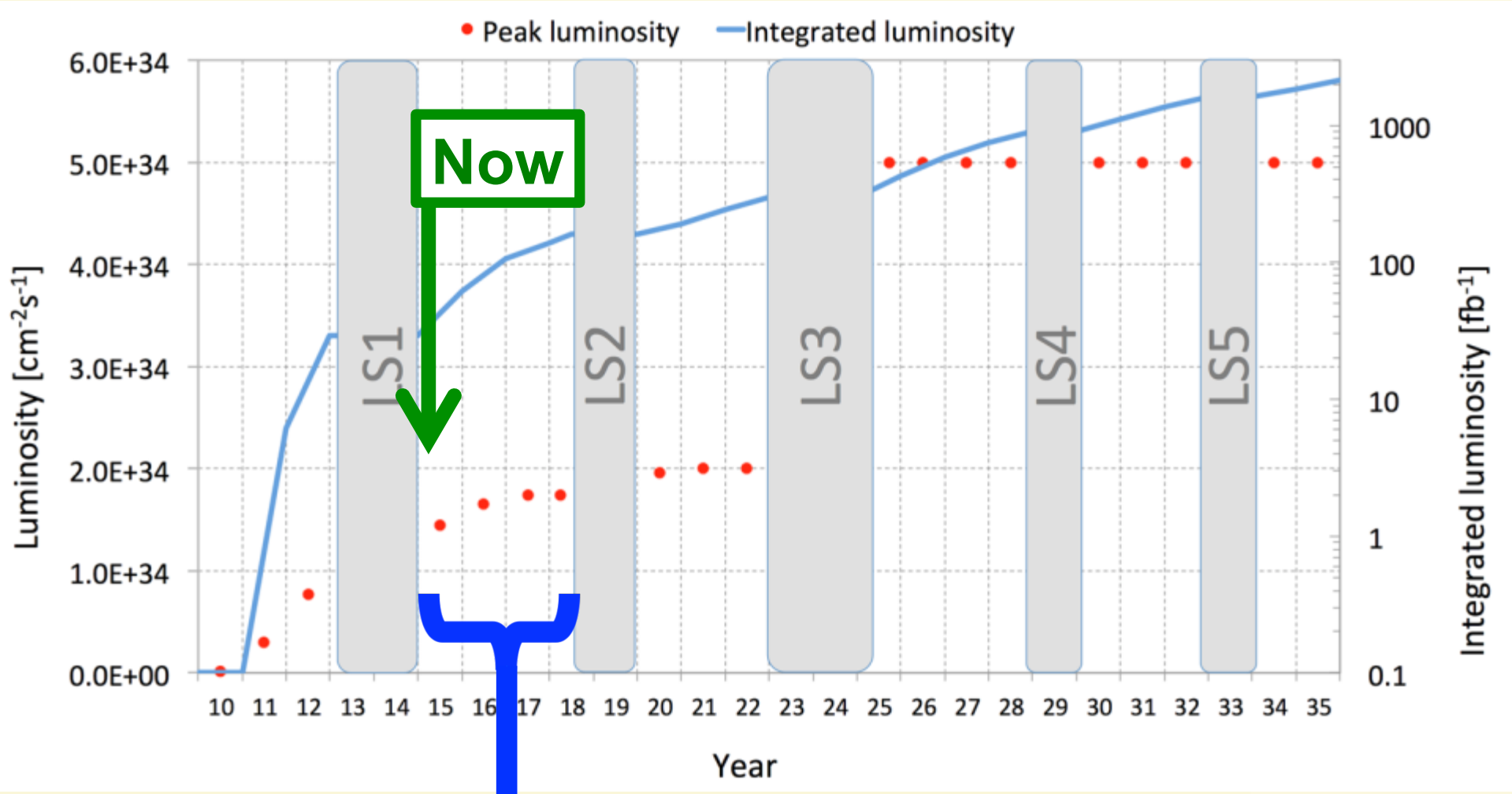
CMS Run 1 Legacy



Run 2 Prospects

Si Xie

LHC Run 2



Run 2 : up to ~150 fb^{-1}

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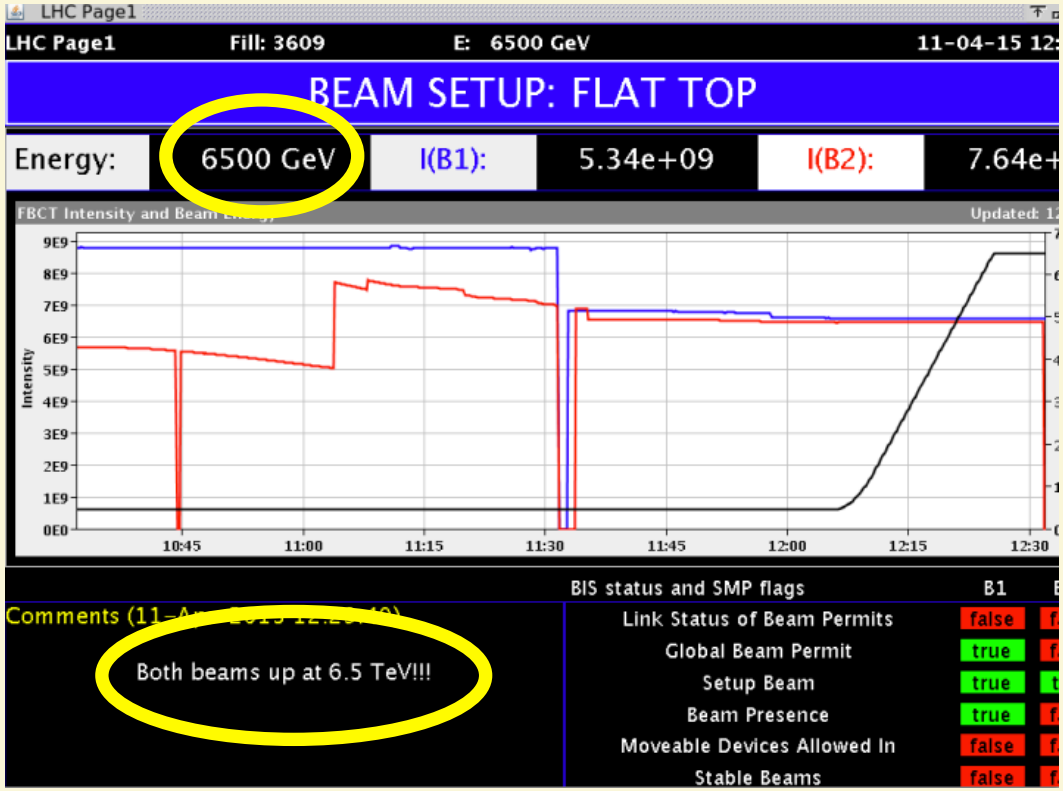
LHC Run 2

- Run 2 Commissioning well under way
- 6.5 TeV Beam Energy already achieved
- If things go according to schedule, **expect collisions in mid-June**



6.5 TeV

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LHC Run 2

What to expect on Higgs ?

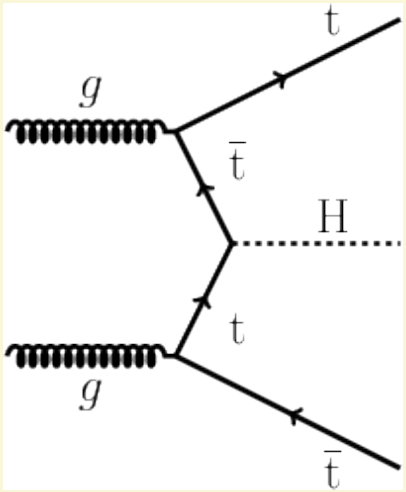
- Establish H→bb decay
- Establish VBF production mode
- Establish ttH production mode
- More precise measurements
- More searches involving Higgs

I will give a sneak preview of 3 chosen examples

Si Xie

ttH Production

- Top Yukawa already probed through gluon fusion production and H→γγ decay
- But direct observation can yield more information



ttH cross section
8 TeV : 0.13 pb
13 TeV : 0.51 pb (4 x bigger)

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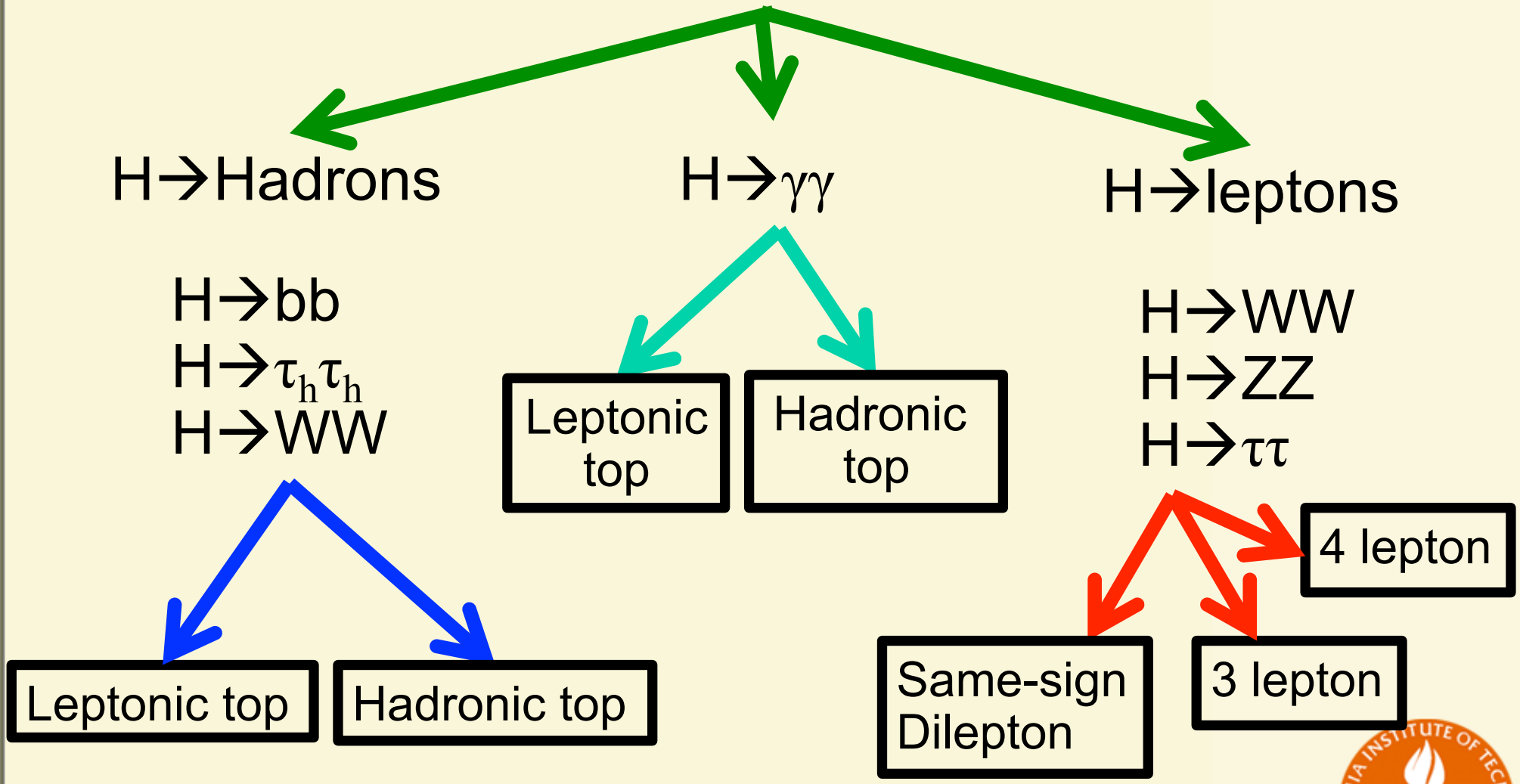
ttH Production

3 Categories of Higgs Decays



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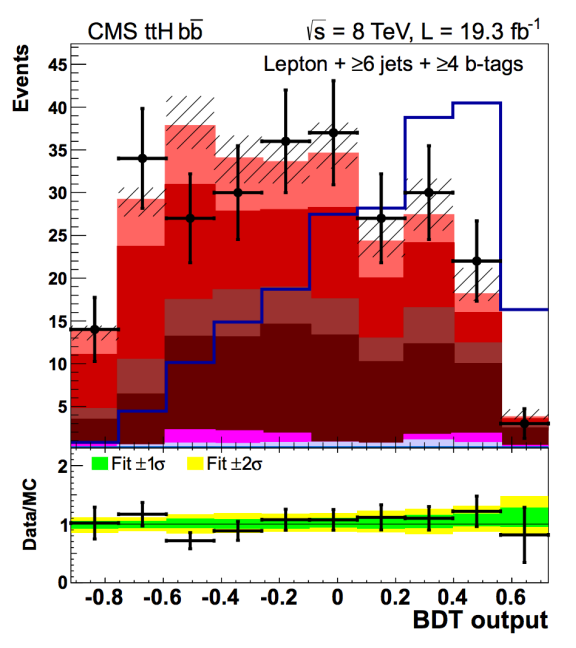
ttH Production

3 Categories of Decays

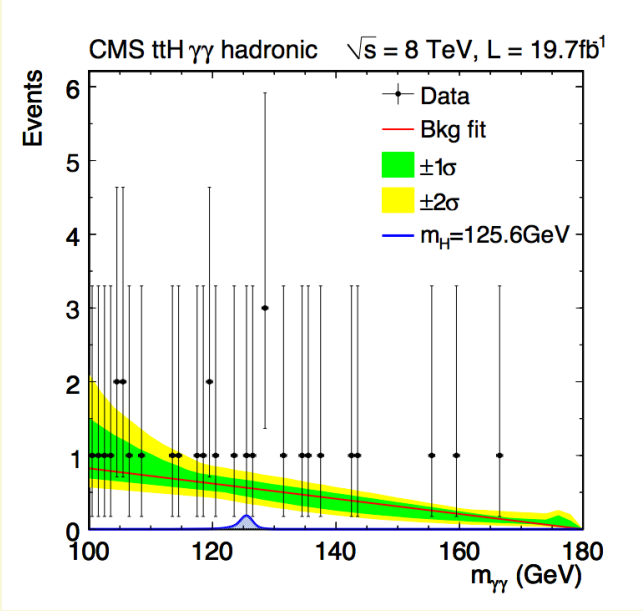
H→Hadrons

MVA discriminant



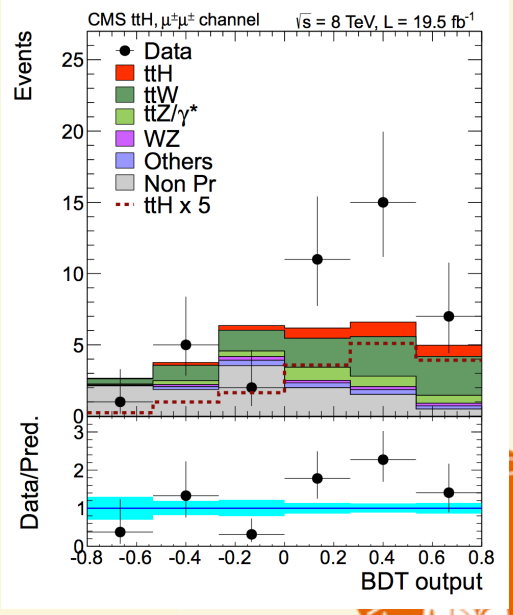
H→γγ

$m_{\gamma\gamma}$

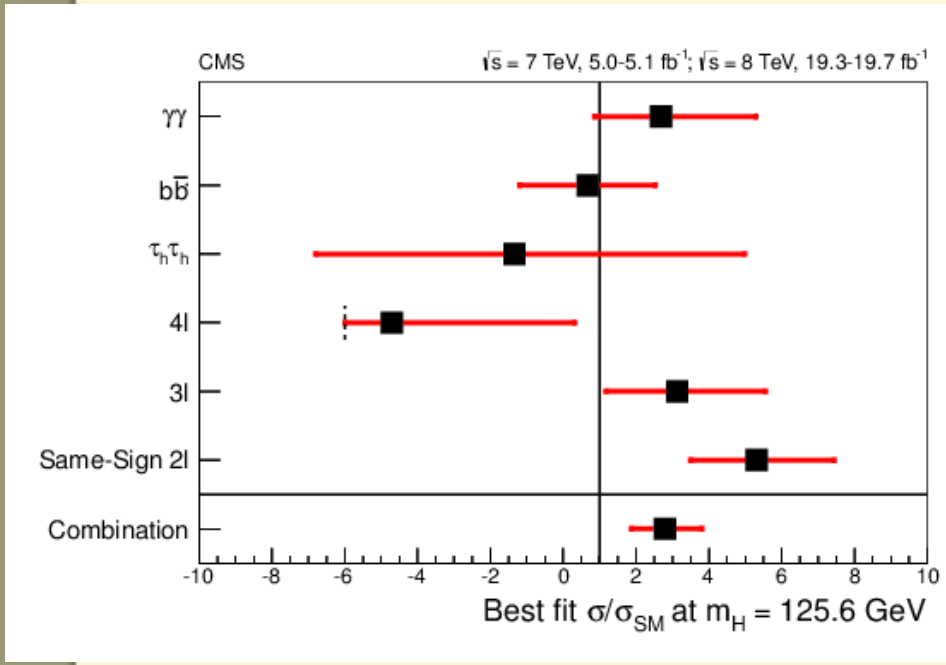


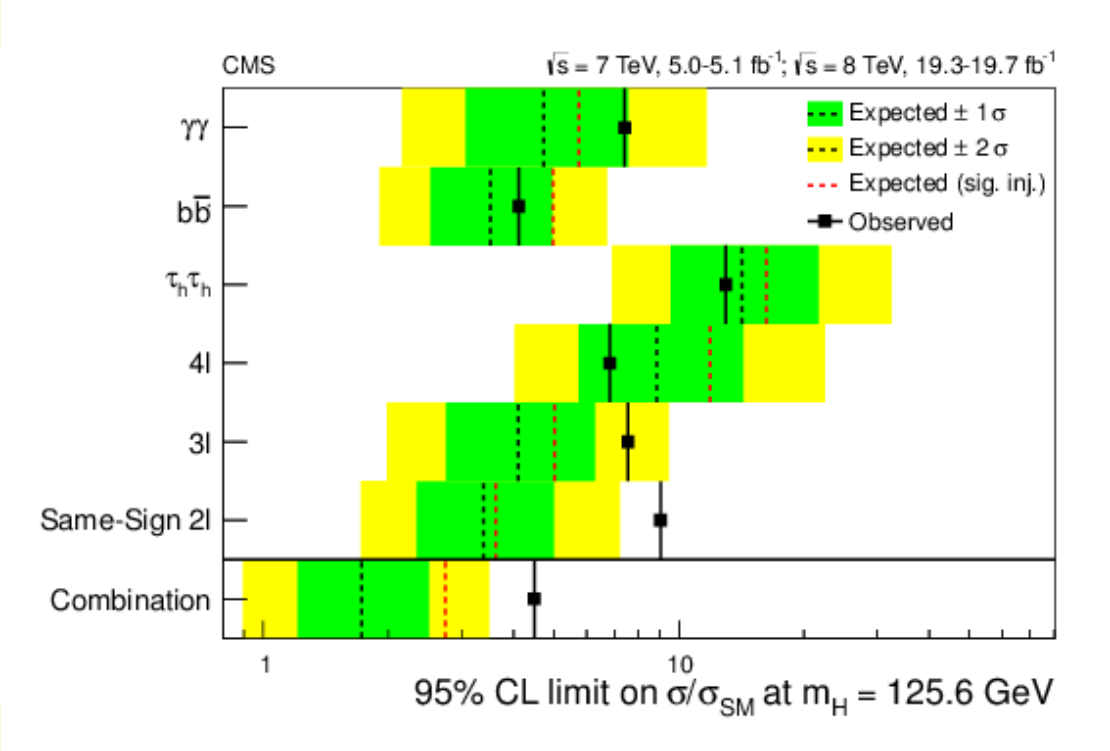
H→leptons

MVA discriminant



ttH Combined Result





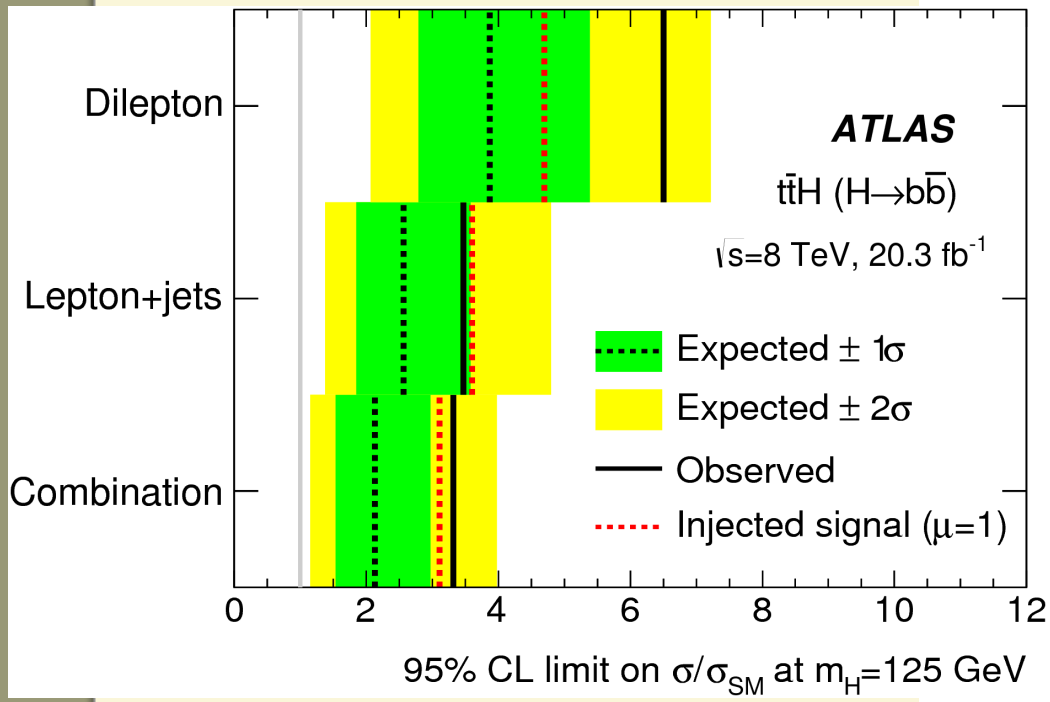
Best Fit $\mu = 2.8 \pm 1.0$ Significance : 3.4σ

Excess above SM expectation ~ **2σ**

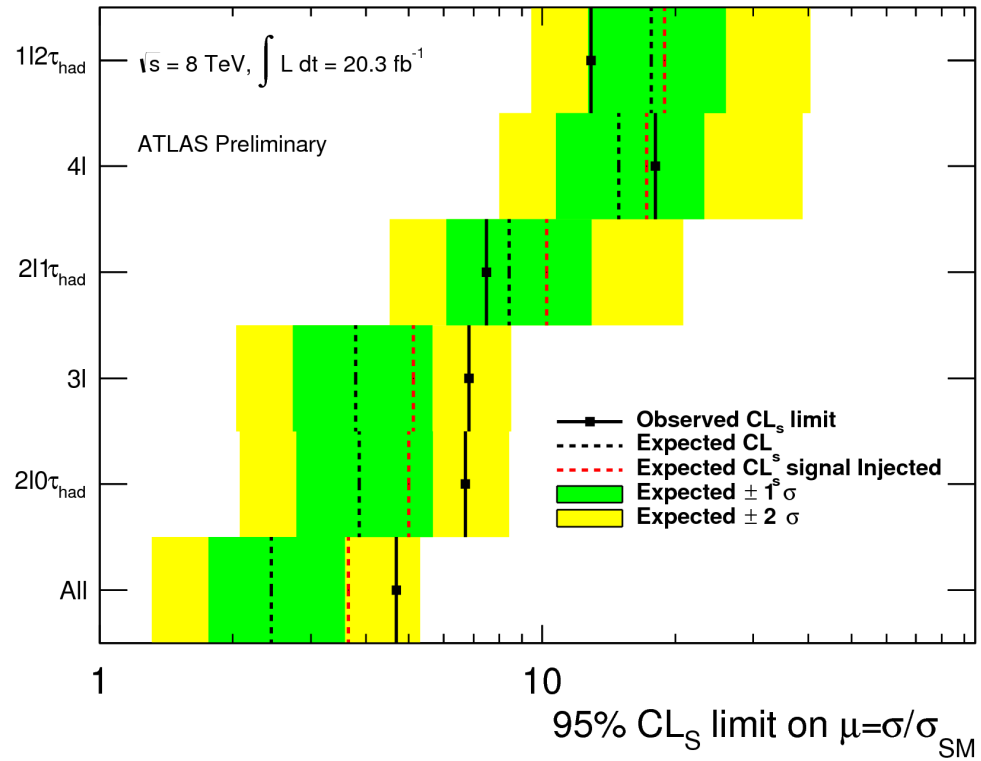
Si Xie

ATLAS Hints?

H→bb



H→lepton decays



Best Fit μ = 1.5 ± 1.1

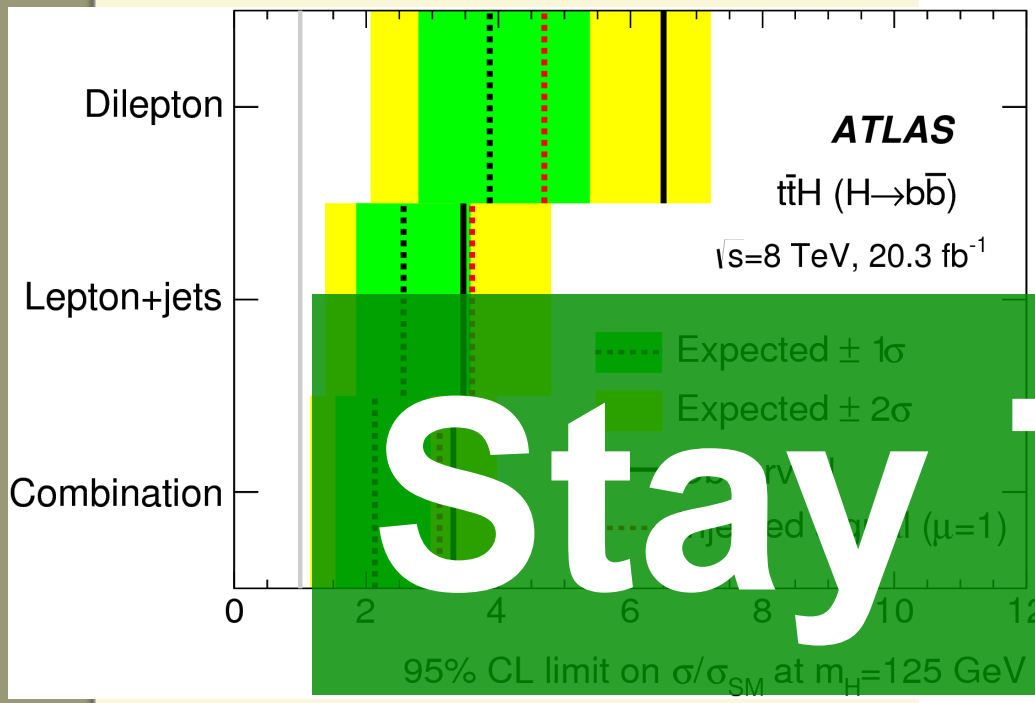
Best Fit μ = 2.1 ± 1.3

Excess above SM expectation ~ **1σ**

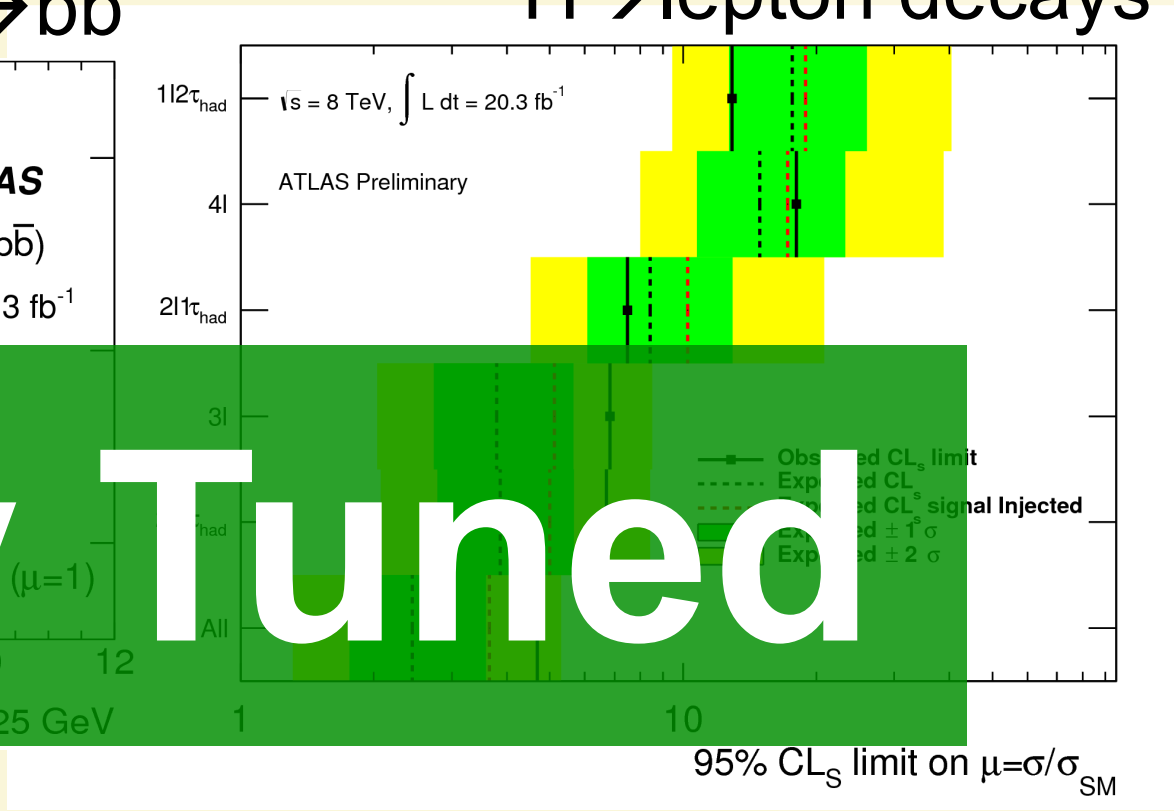
Si Xie

ATLAS Hints?

H→bb



H→lepton decays



Stay Tuned

Best Fit μ = 1.5 ± 1.1

Best Fit μ = 2.1 ± 1.3

Excess above SM expectation ~ **1σ**

Si Xie

Higgs $\rightarrow \mu\tau$

- Off-diagonal Yukawa's generally allowed
  - Theories with more than 1 Higgs doublet (eg. SUSY) , Composite Higgs, etc.
- Indirect limits on $H \rightarrow \mu\tau$ or $H \rightarrow e\tau$ only at ~10% level

Higgs $\rightarrow \mu\tau$

- Search in $H \rightarrow \mu\tau_e$ and $H \rightarrow \mu\tau_h$ channels
- Signature is very similar to SM $H \rightarrow \tau\tau$ except:

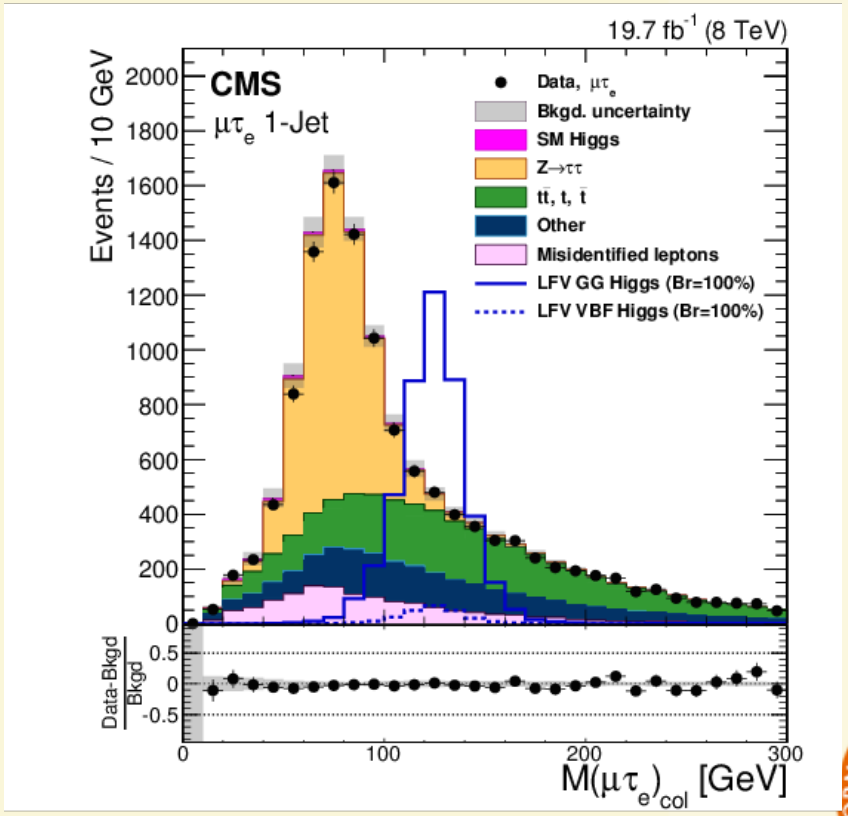
  (1) Muon is from prompt decay and carries larger momentum

  (2) Only one neutrino, so MET tends to be collinear to visible tau decay products

Si Xie

Higgs →μτ

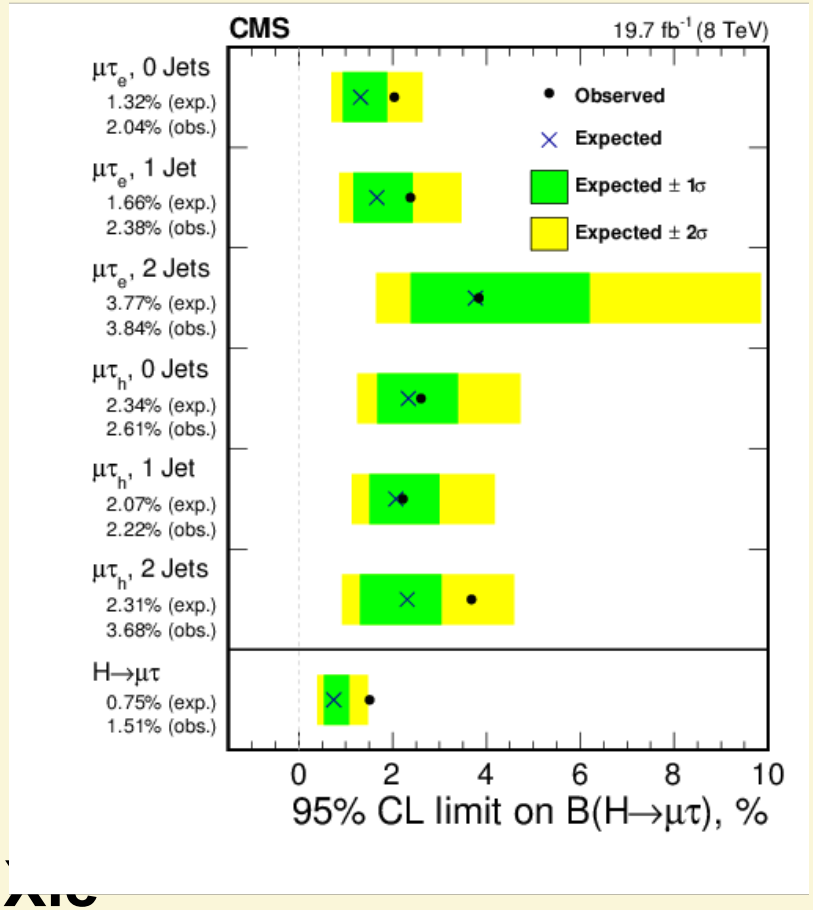
- Categorize by N_{Jet} bins
- Kinematic selection on lepton p_T, m_T, $\Delta\Phi_{\mu,\tau,MET}$
- Final discriminant is Higgs mass from collinear approximation

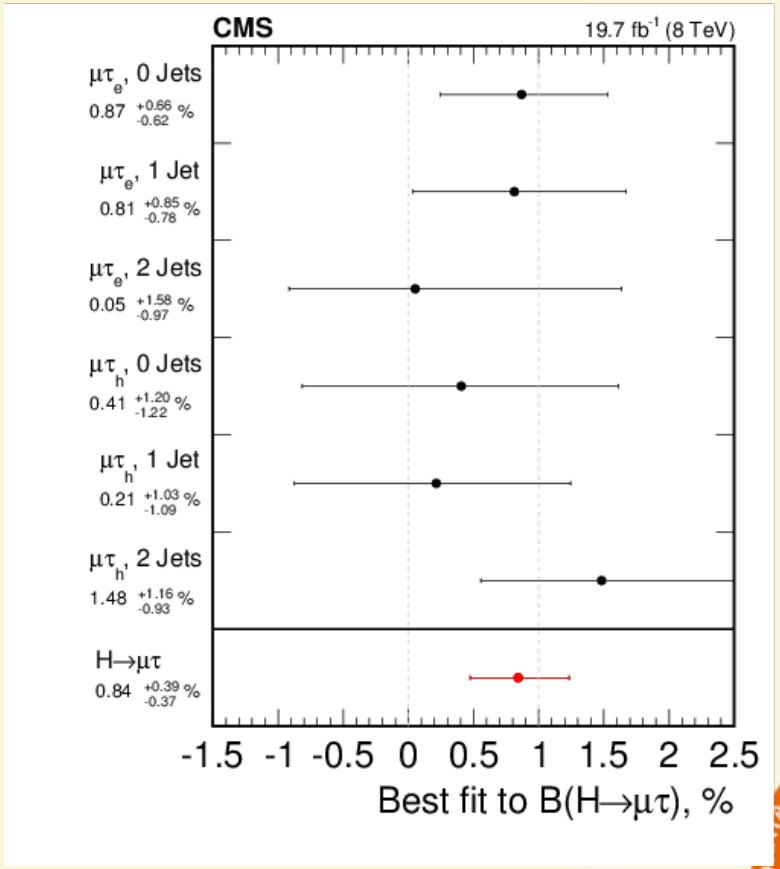


Si Xie

Higgs →μτ

- Observe small excesses in a few categories
- Best fit BR at 0.84% ± 0.4%
- Significance is 2.4 σ





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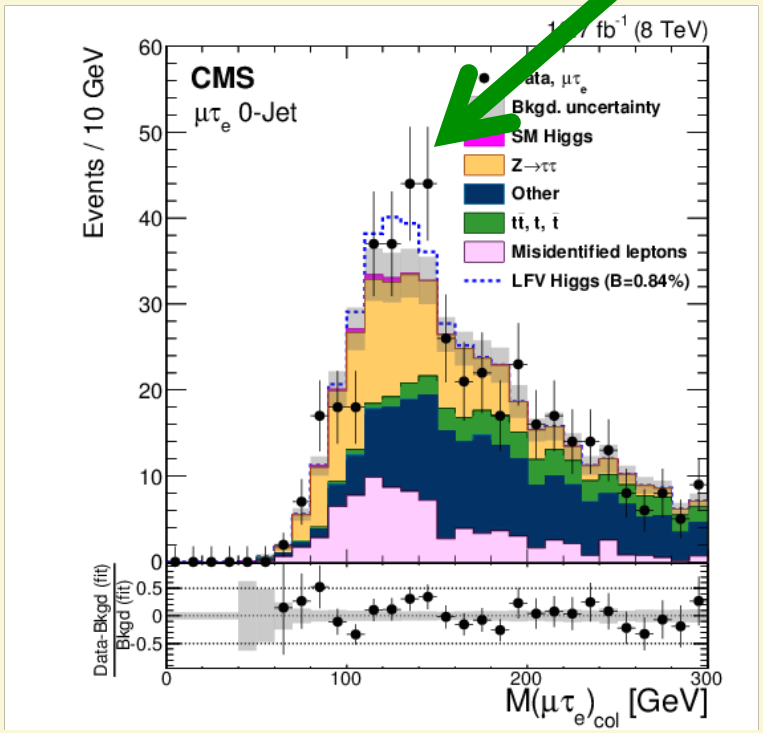
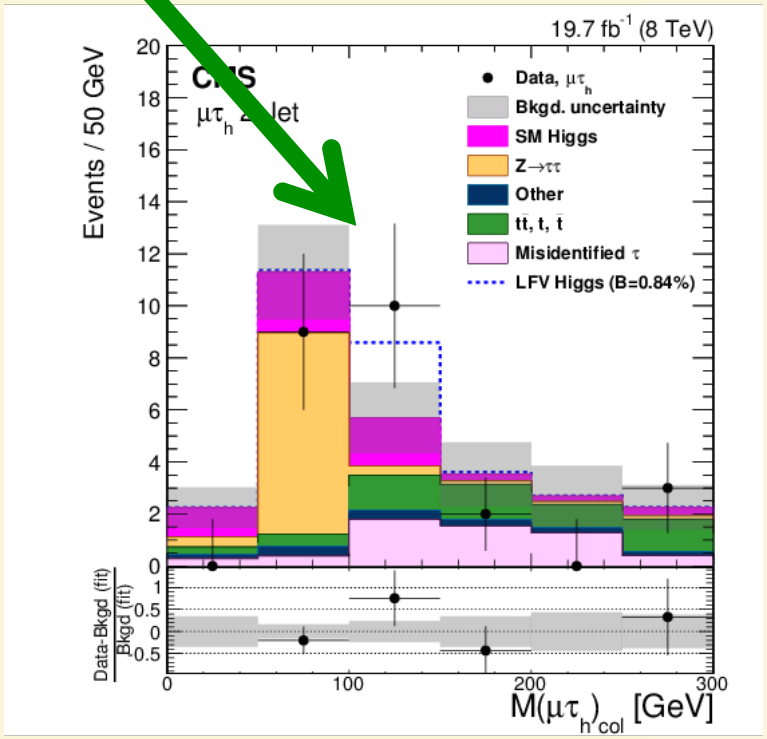
Higgs →μτ

- Couple of examples of the excesses

$\mu\tau_e$ 0-Jet



$\mu\tau_h$ 2-Jet



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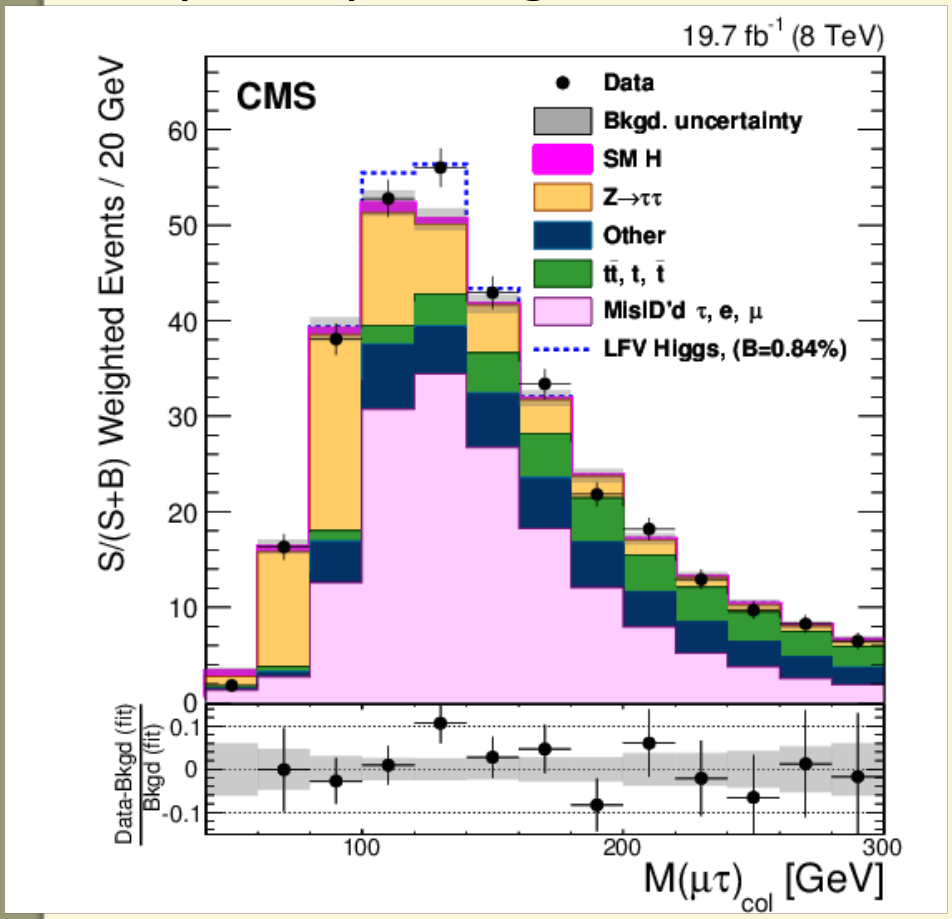
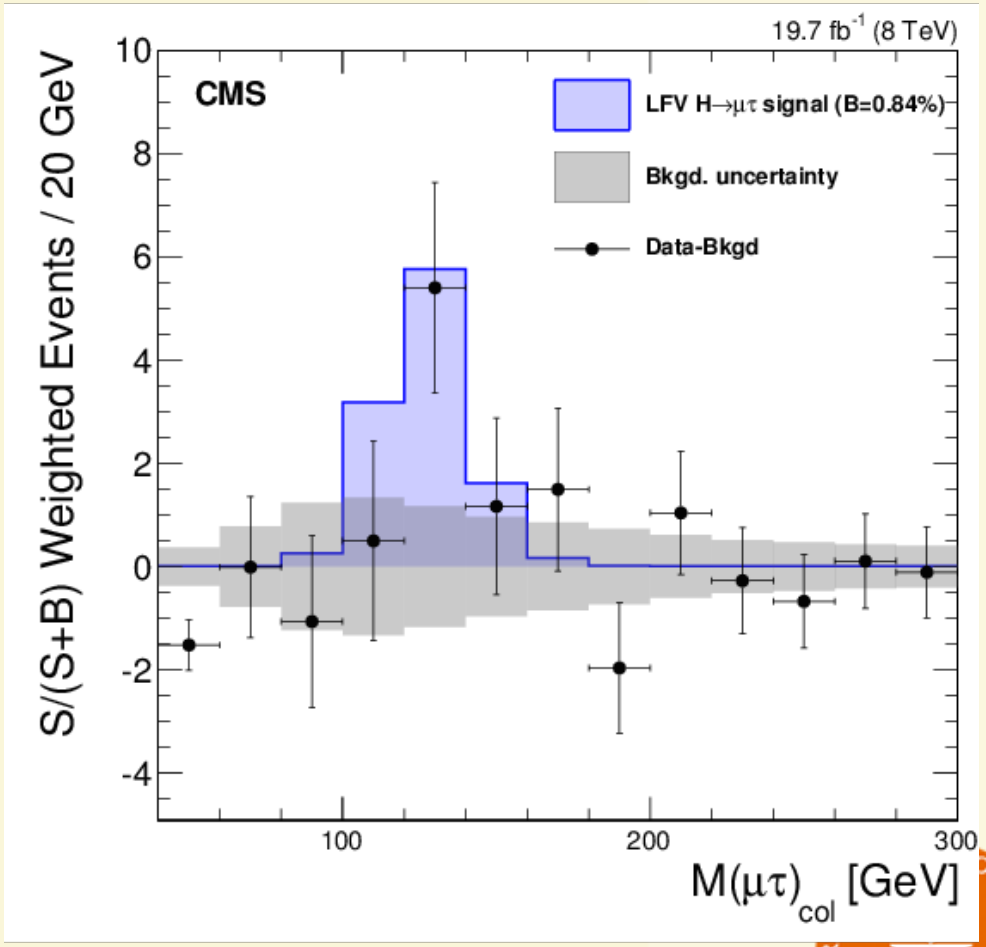
Higgs →μτ

All Channels Combined
S/(S+B) weighted



Background subtracted



Si Xie

The other Higgs's : A→ZH

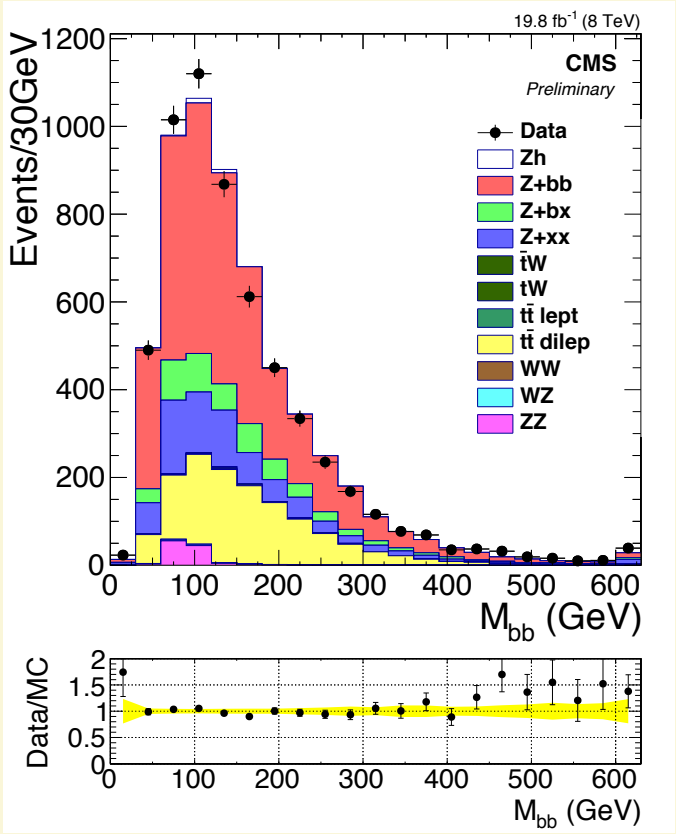
- Any model with two Higgs doublets (eg. SUSY) predicts additional Higgs particles:
  - Another CP-even scalar : H
  - A CP-odd pseudoscalar : A
  - Two charged scalars (H^+,H^-)

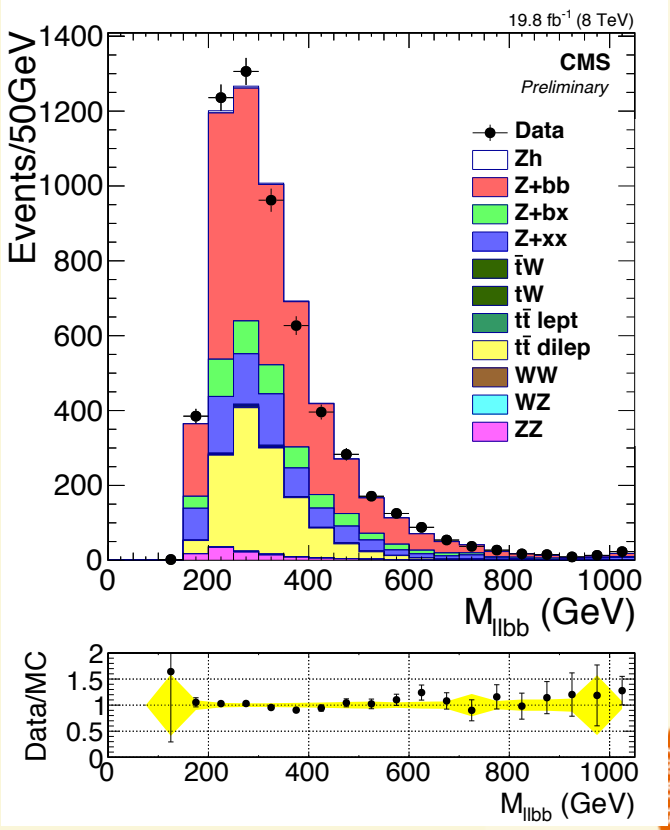
- Recently suggestions that large (A,H) mass splitting may yield favorable baryo-genesis
- Then A→ZH is the most frequent decay mode
- So…let's search for it…

A→ZH→llbb

- Select Z→ee & Z→μμ decays + 2 b-tagged jets
- Suppress ttbar by requiring low MET significance
- Search for excesses in bins of m_{bb} and m_{llbb}

New





Si Xie

A→ZH→llbb

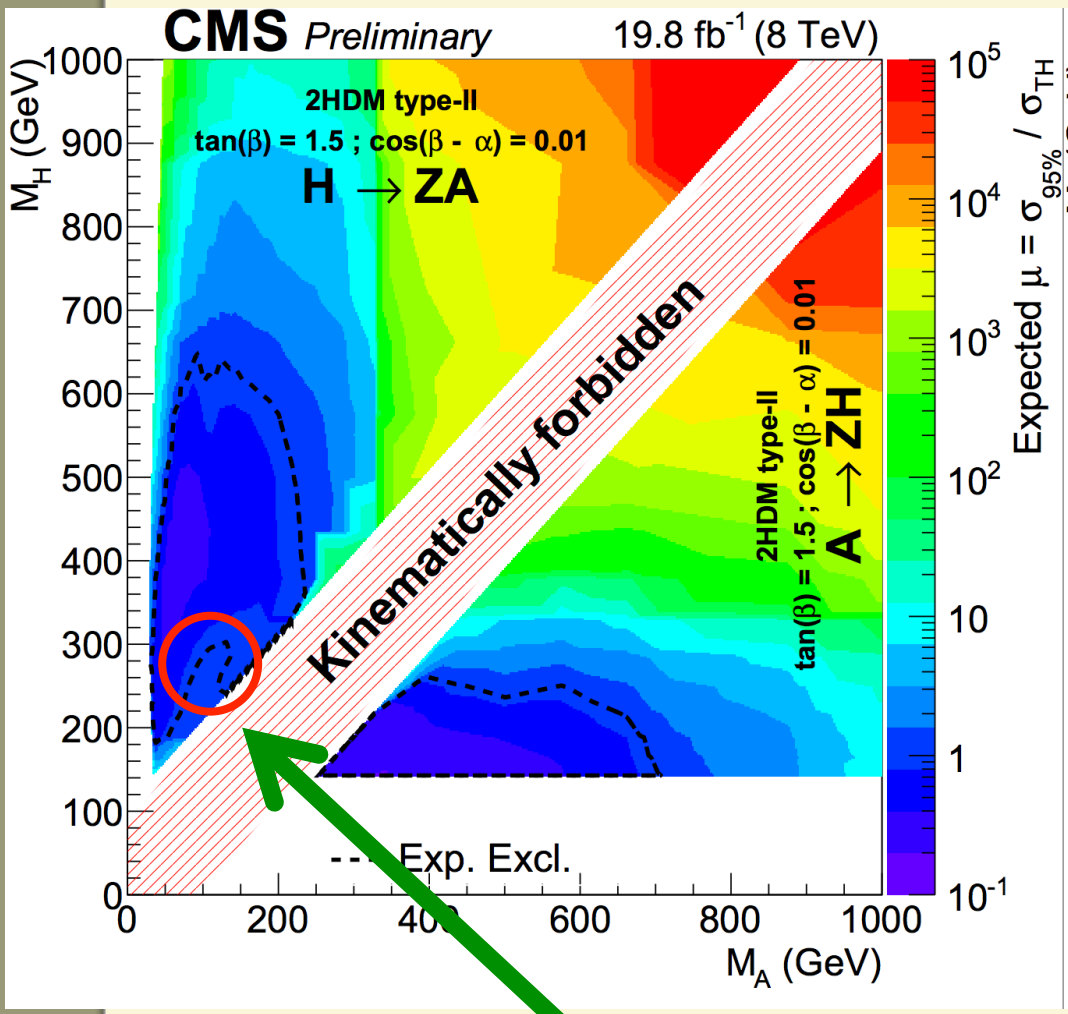
- Two most significant excesses found are in regions centered at:
  (1) M_{bb} ~93 GeV, m_{llbb} ~ 286 GeV
    - **Local significance: 2.6 σ**
    - **With LEE: 1.6 σ**
  (2) M_{bb} ~575 GeV, m_{llbb} ~ 662 GeV
    - Local significance: 2.85 σ
    - With LEE: 1.9 σ

- Excess (1) is in a region where one expects sensitivity to the signal.
  - ie. it's consistent with SUSY

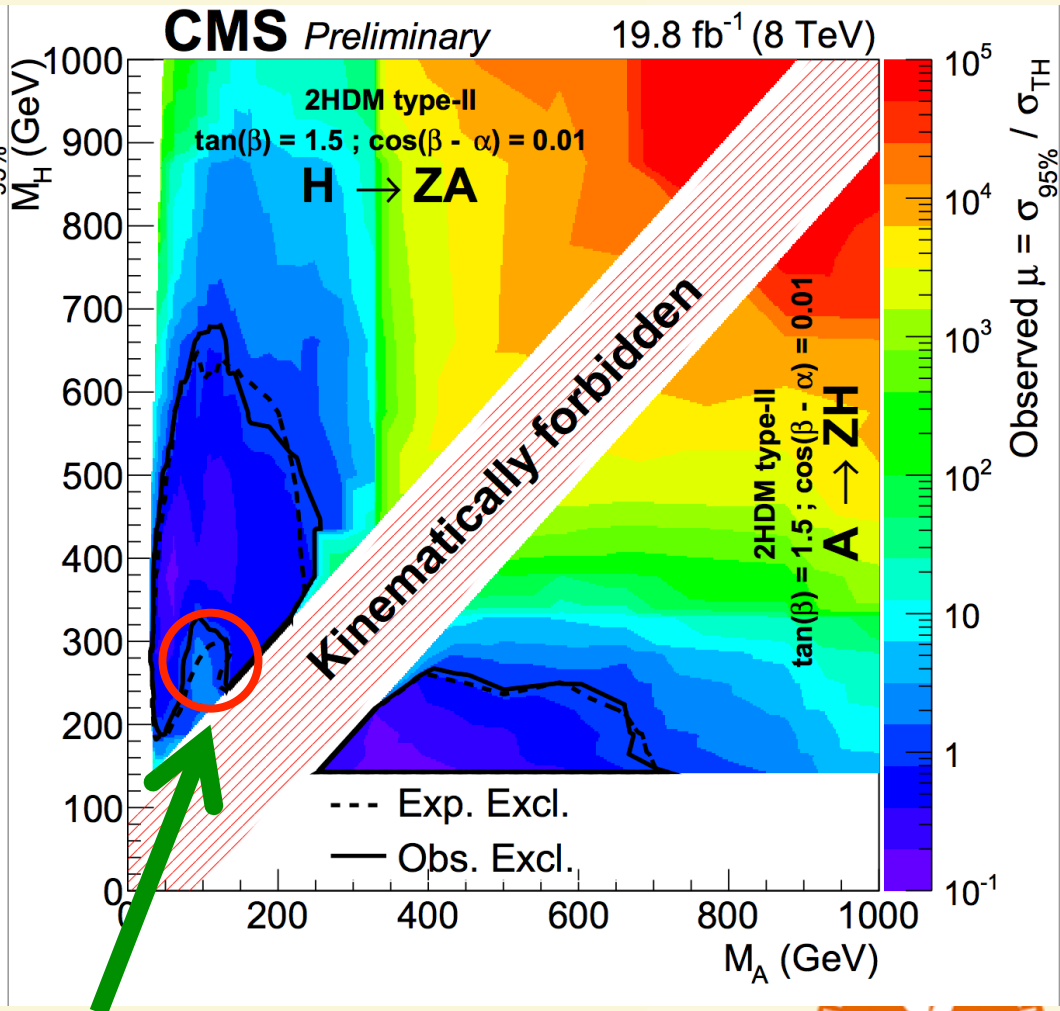
Si Xie

A→ZH→llbb

Expected



Observed



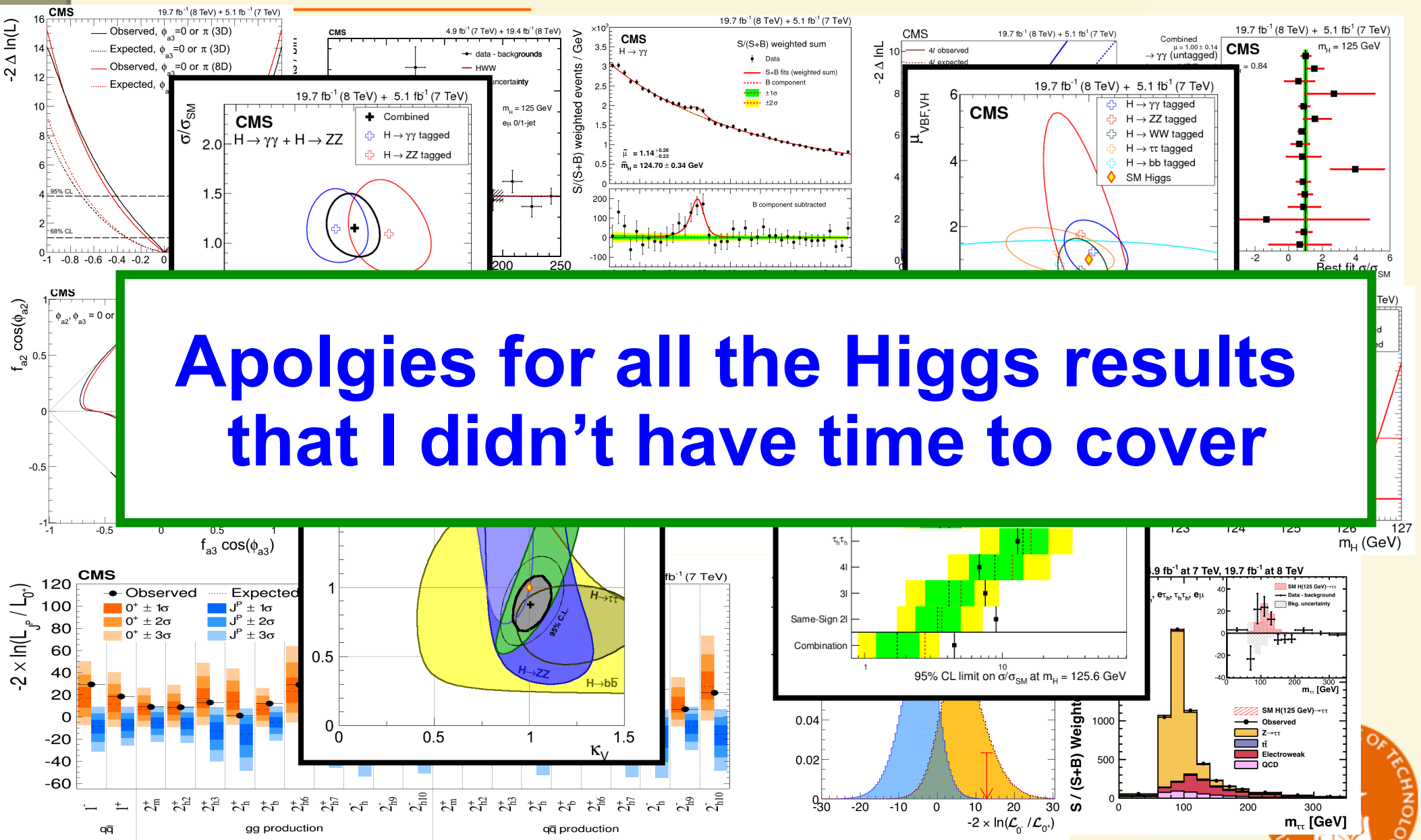
Excess (1) is here

Si Xie

Summary

Si Xie

CMS Run1 Higgs Scoreboard

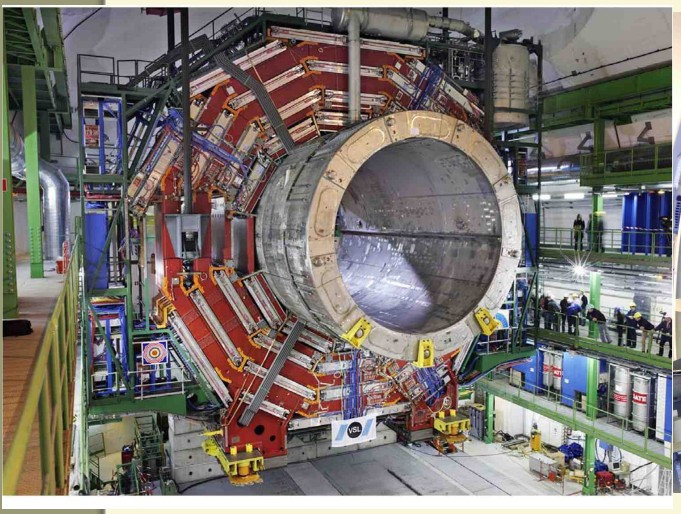


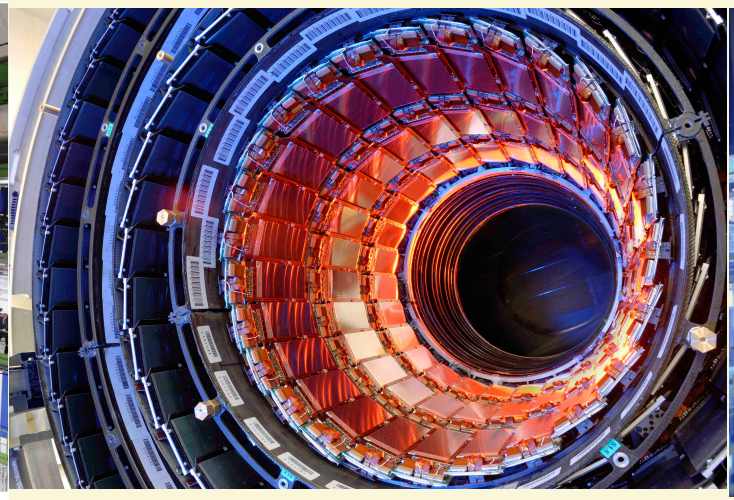
Apolgies for all the Higgs results that I didn't have time to cover

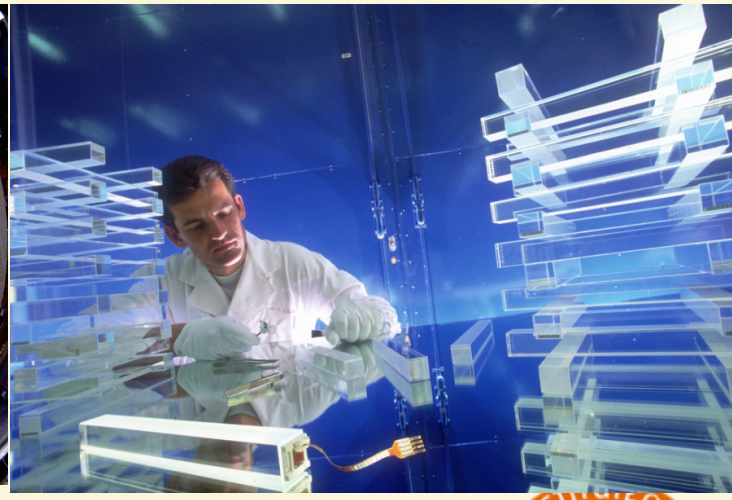
Summary : The Run1 Legacy

(1) Success in the core design of the CMS experiment made the Higgs discovery possible

- Strong solenoid spectrometer & silicon tracking
- Clean muons
- Precision ECAL



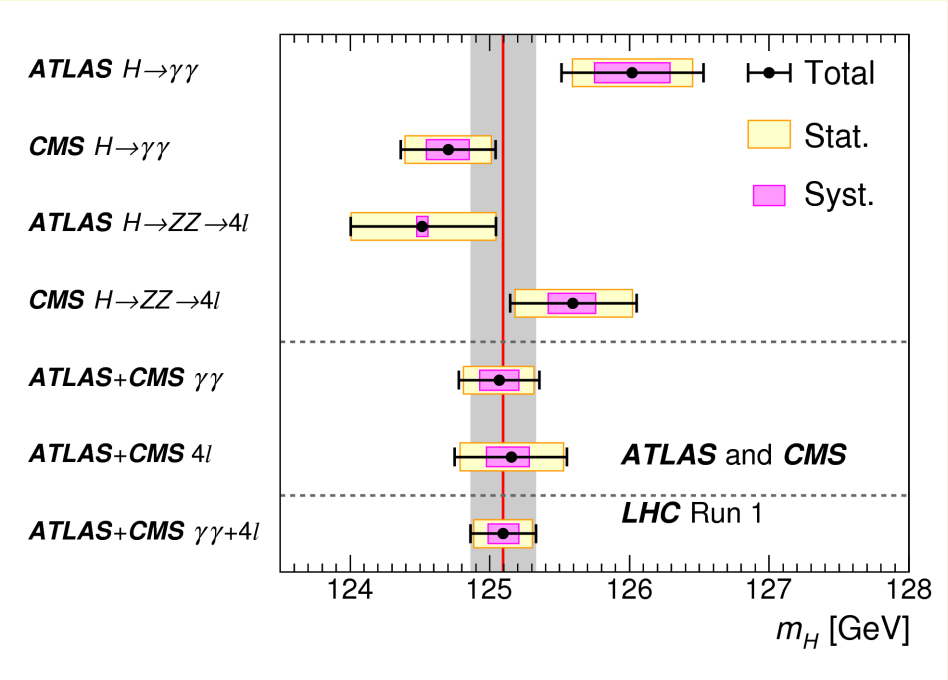


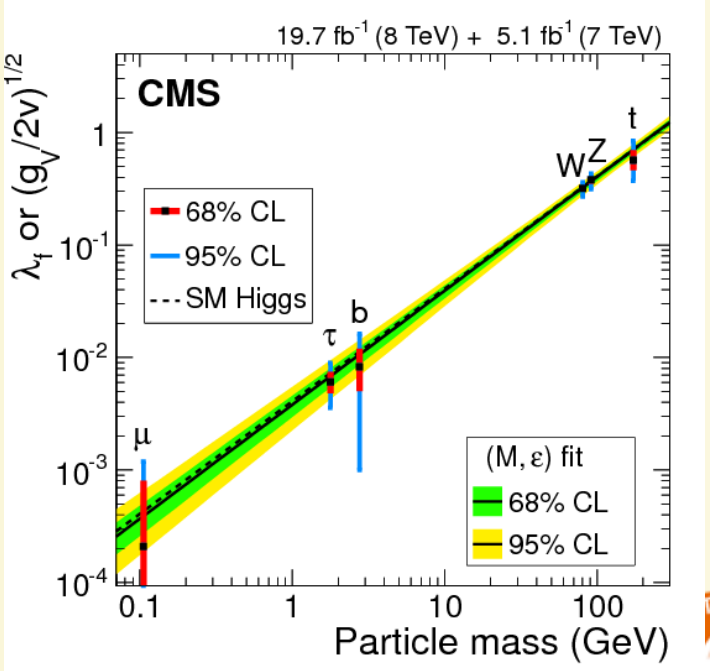


Summary : The Run1 Legacy

(2) The Higgs Boson is very Standard Model

- A spin-0 scalar as far as we can tell
- Mass = 125 GeV with 0.2% precision
- No significant deviations from the SM predictions





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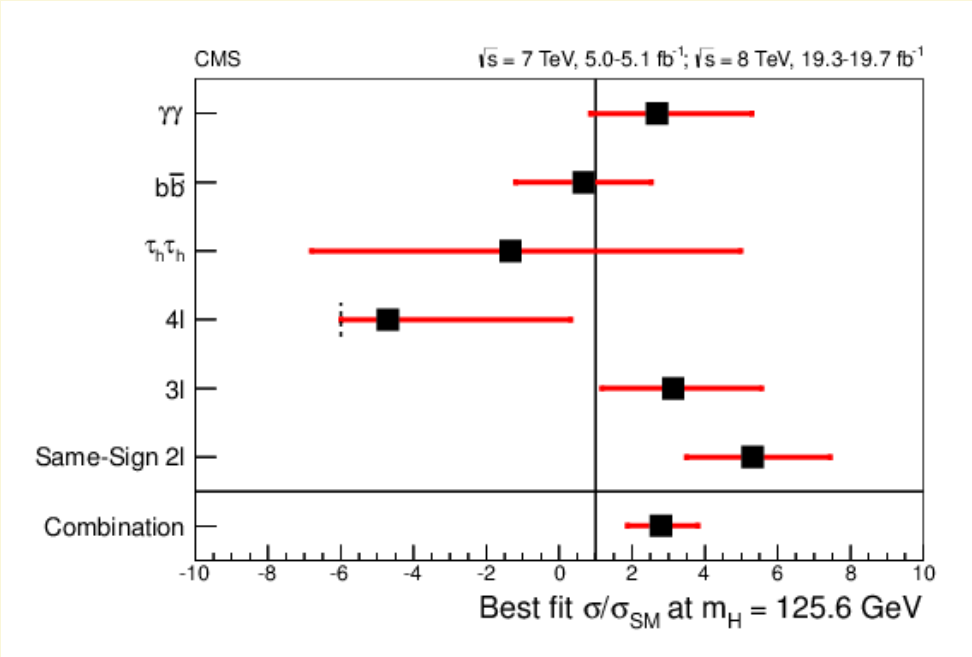
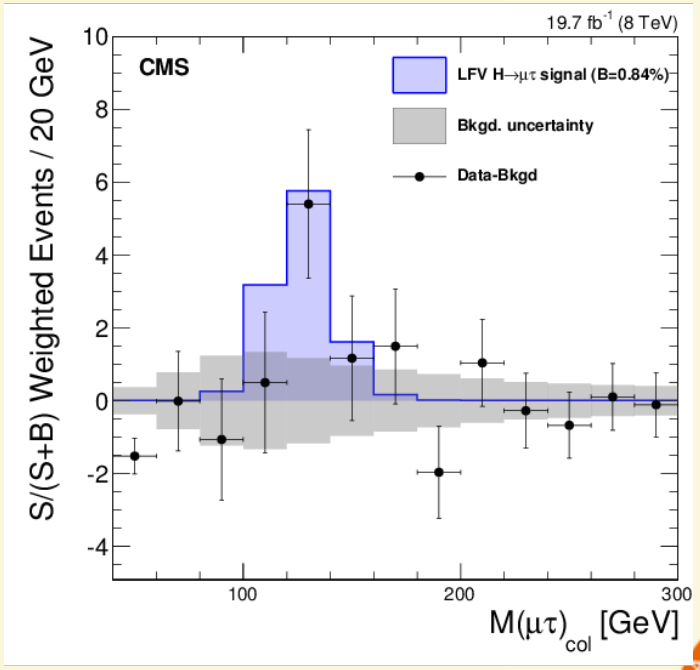
Summary : The Run1 Legacy

(3) But there are **intriguing hints** …

… or statistical fluctuations





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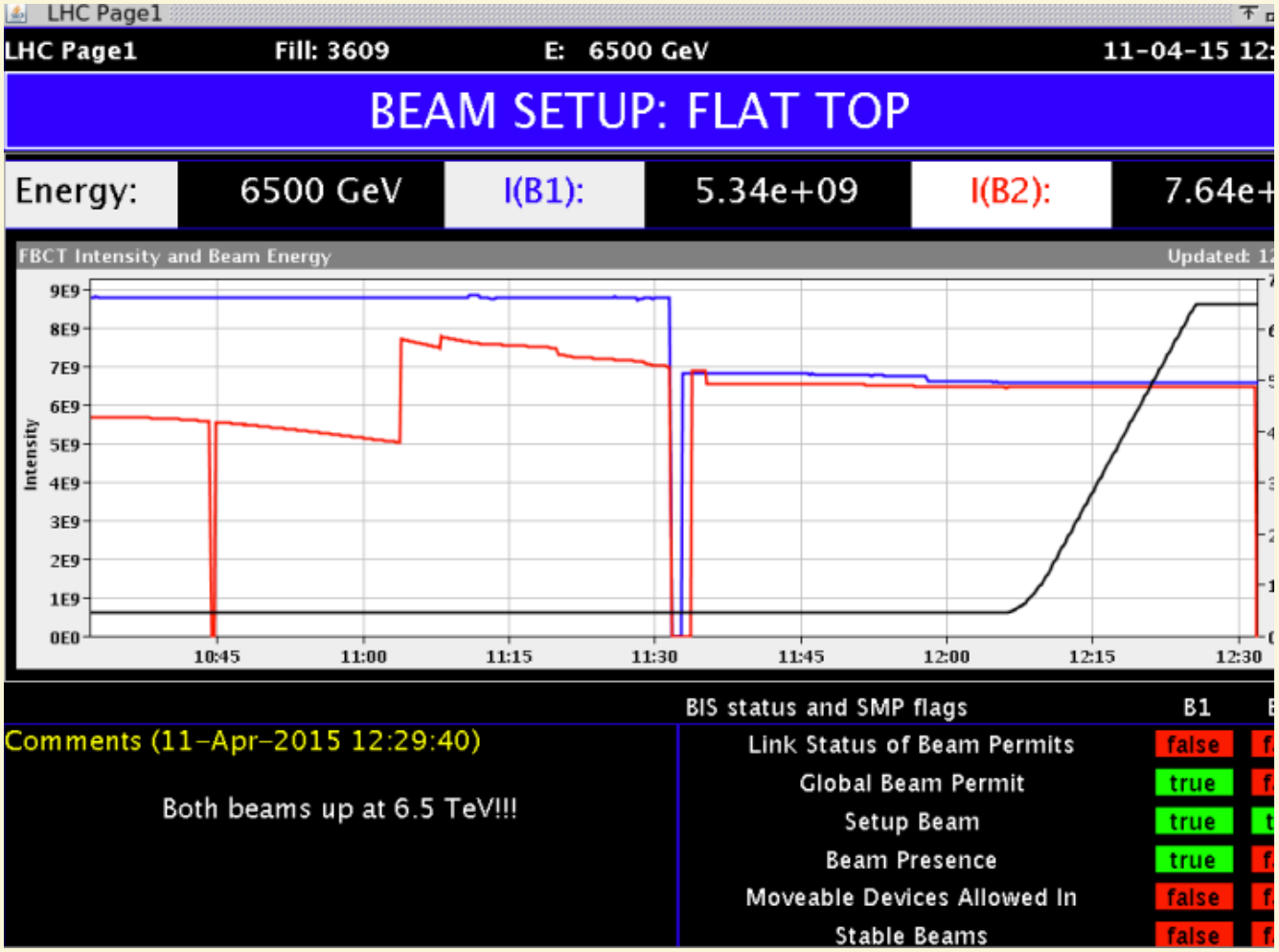
Stay Tuned For Run2



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Backup

CMS Run1 Higgs Scoreboard

	Significance	
Channel	**Expected**	**Observed**
$H \rightarrow ZZ$	6.3 σ	6.5 σ
$H \rightarrow \gamma\gamma$	5.3 σ	5.6 σ
$H \rightarrow WW$	5.4 σ	4.7 σ
$H \rightarrow \tau\tau$	3.9 σ	3.8 σ
$H \rightarrow bb$	2.6 σ	2.0 σ
$H \rightarrow \mu\mu$	< 0.1 σ	0.4 σ

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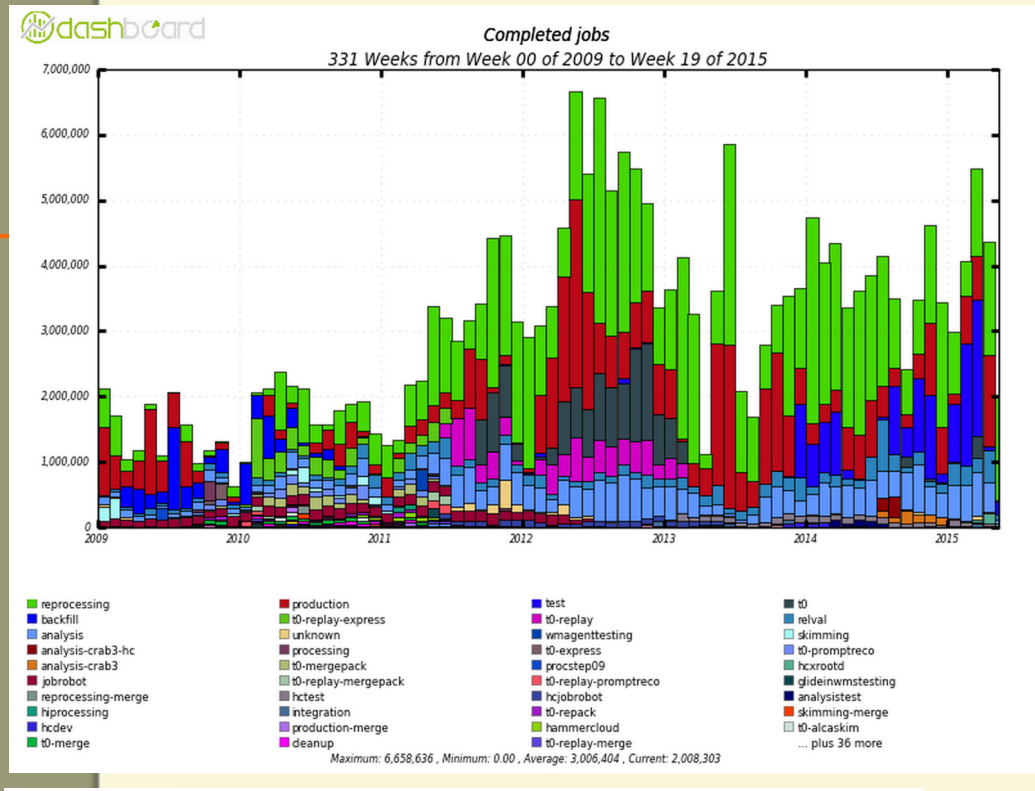
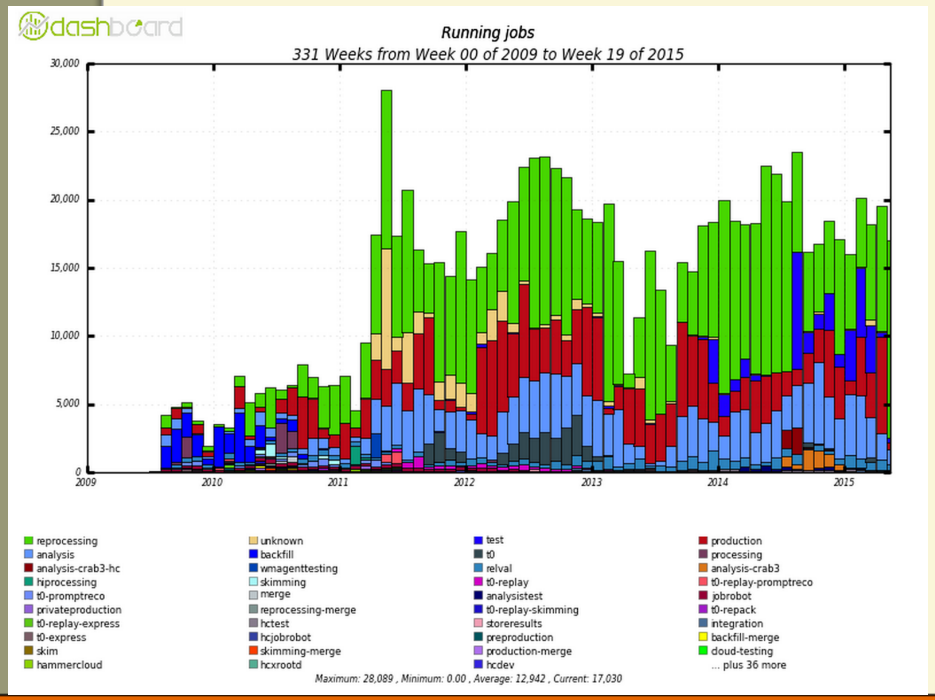
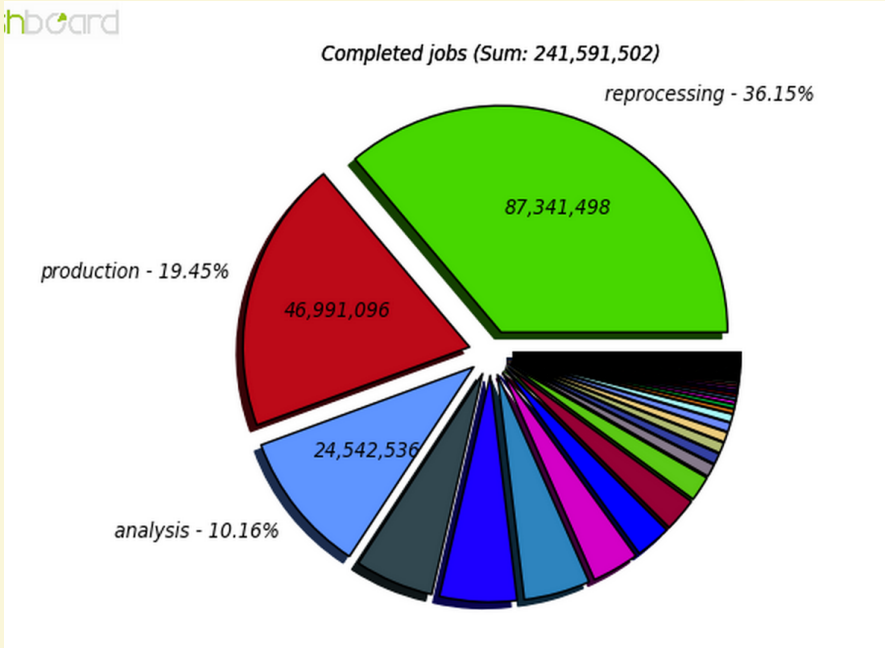
Technological Legacy: Trigger & Computing

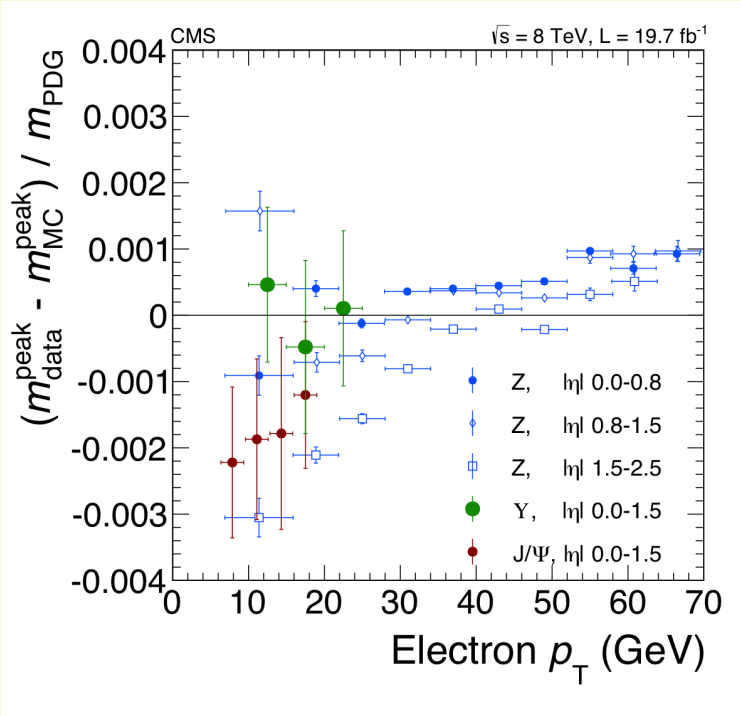


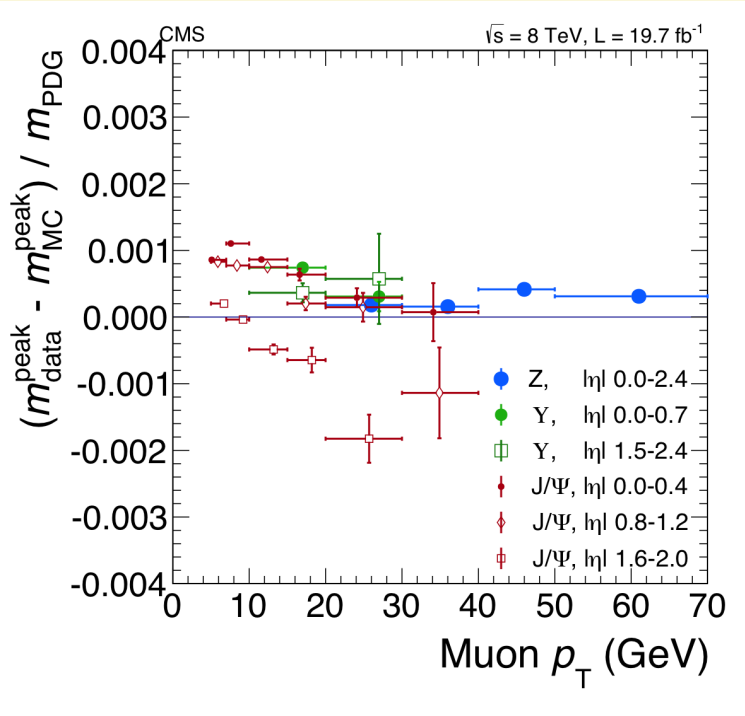
- 241M jobs completed from 2009 - 2015
- Average 3M jobs per week
- Up to 28K jobs simultaneously running





H→ZZ Calibrations





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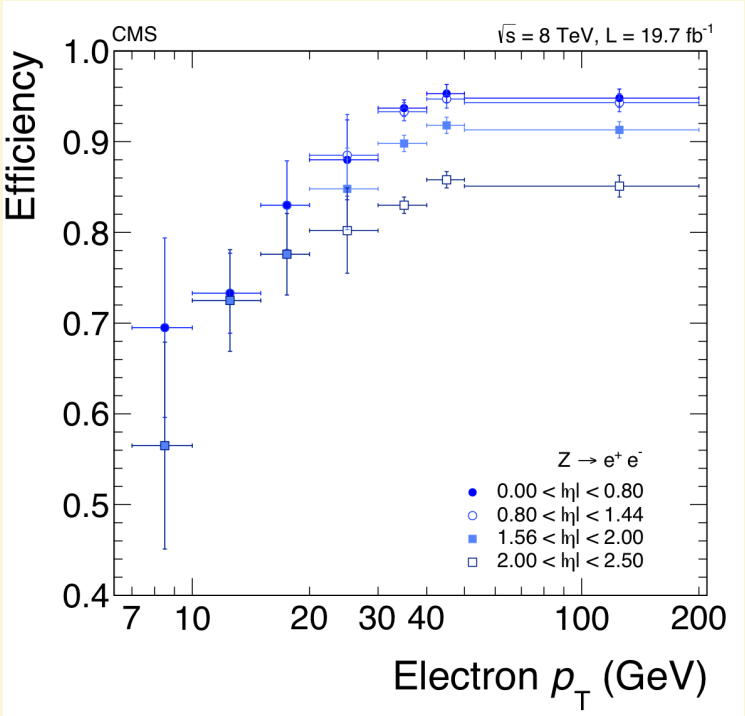
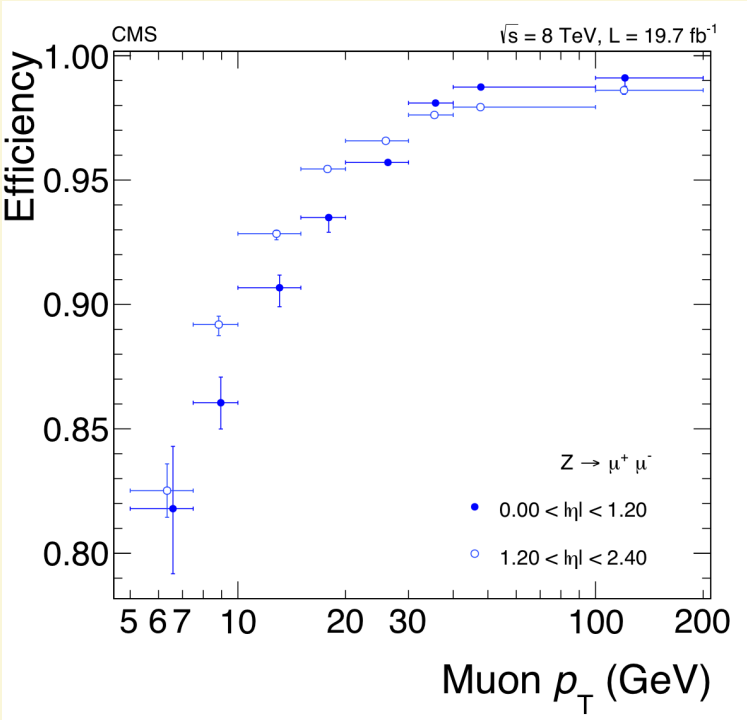
H→ZZ Lepton Efficiency





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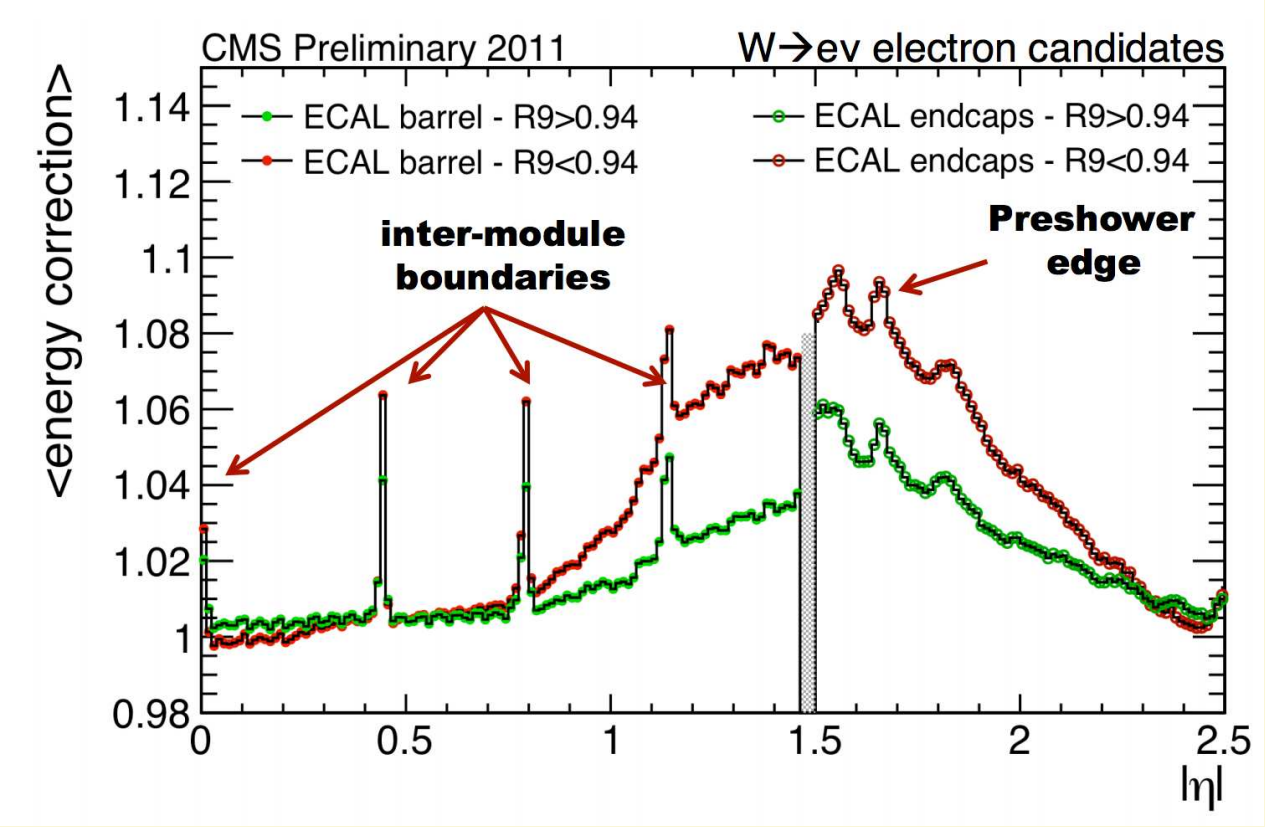
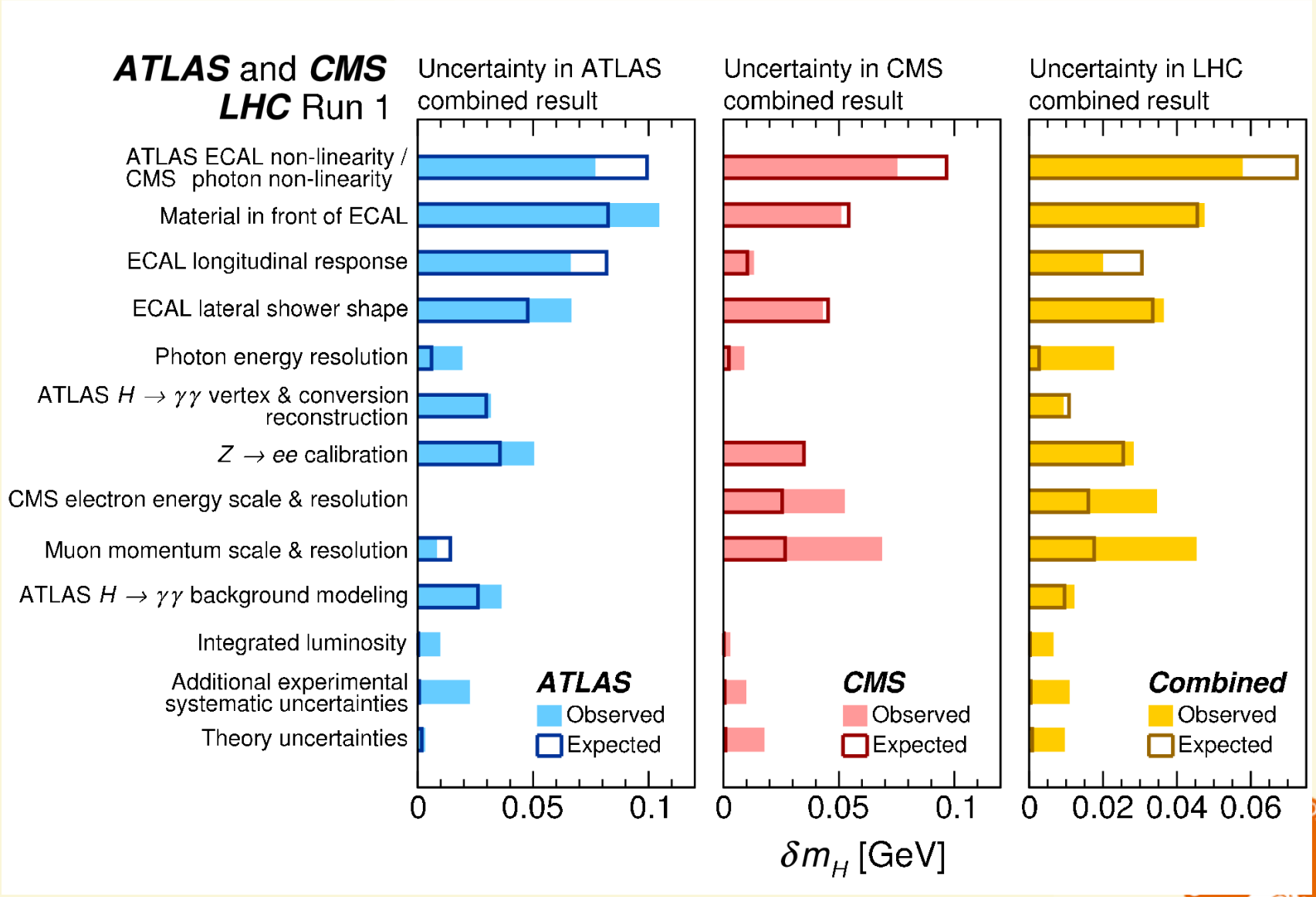
Technological Legacy: ECAL Calibration

- Cluster corrections vs pseudorapidity



Si Xie

Higgs Mass Systematics



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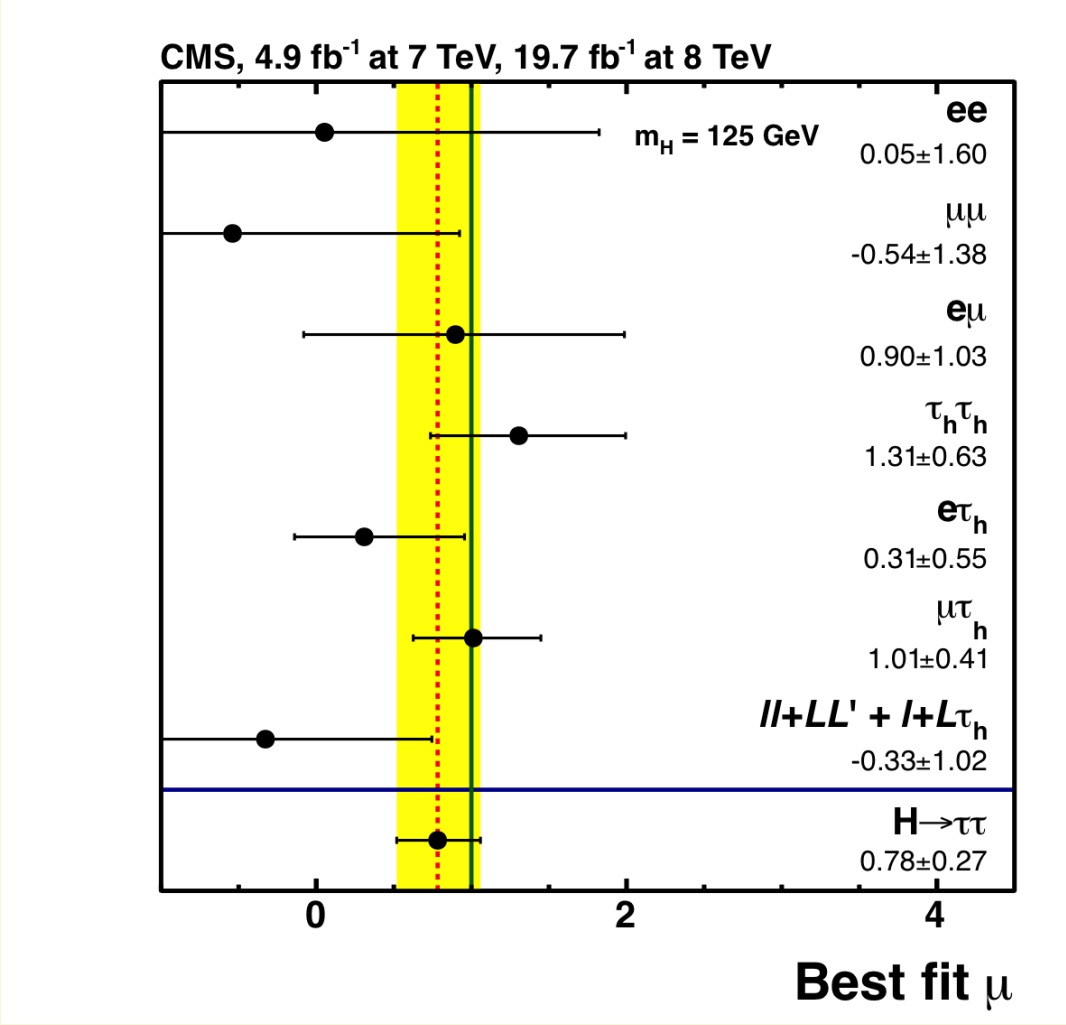
Higgs→Tautau



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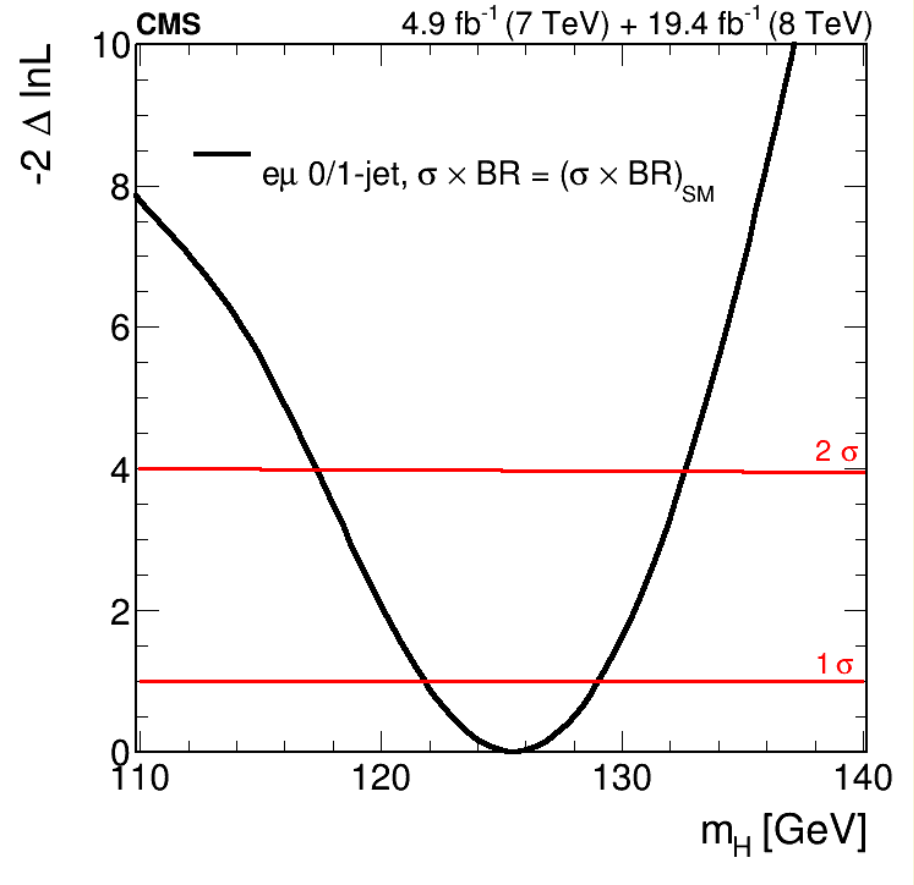
Technological Legacy:
Era of Big Data & MVA Techniques

- Can measure m_H to ~ 3 GeV : much better than the standard H→WW analysis



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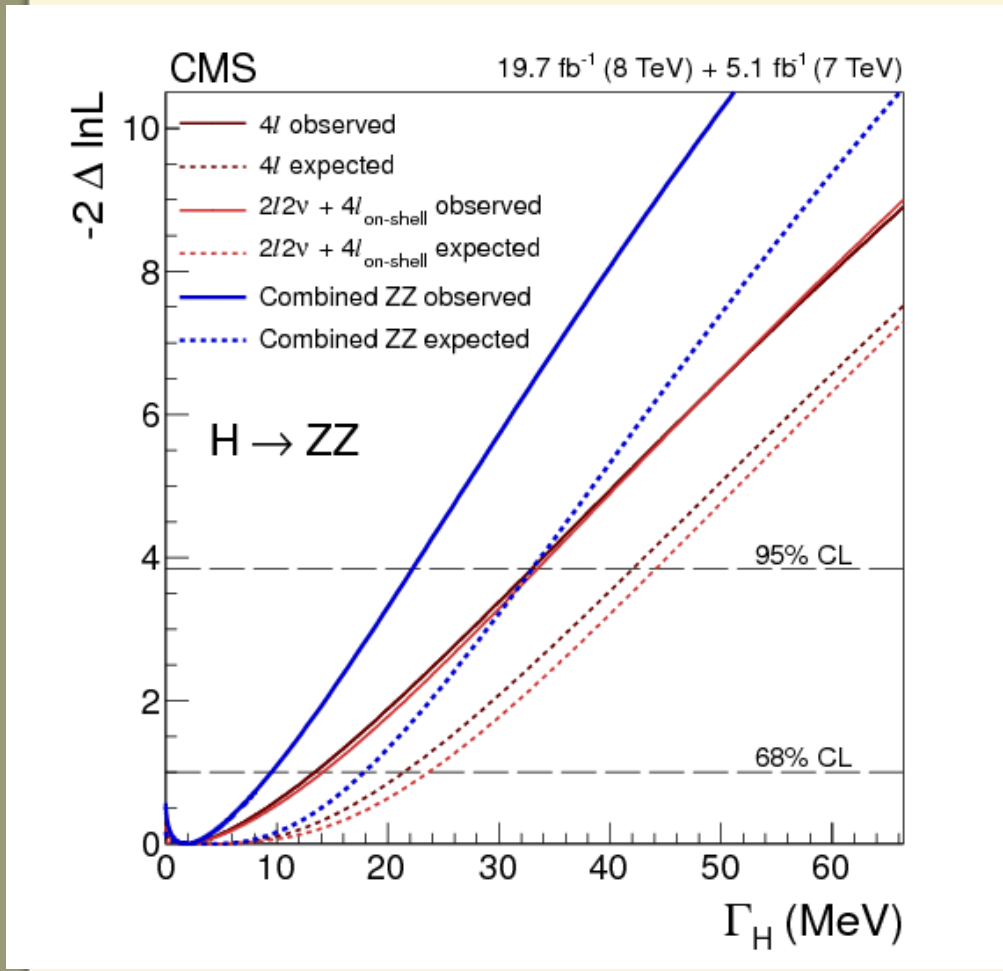
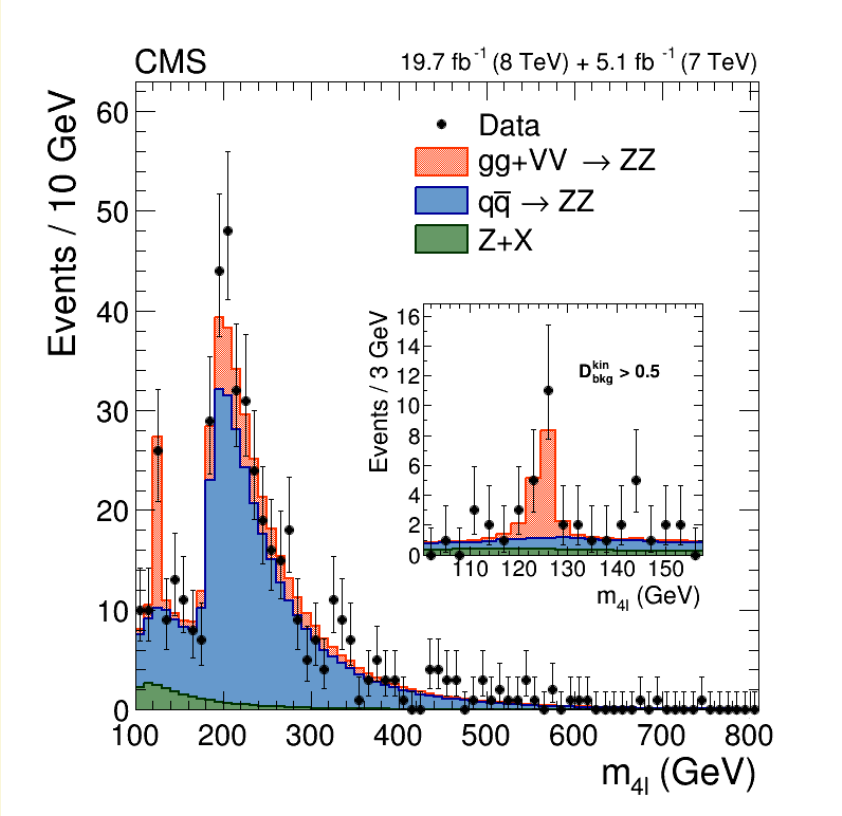
Higgs Width Measurement

- Higgs Width < 22 MeV (~5.4 times SM prediction) at 95% CL





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ttH Production : H→ Hadrons

Lepton + Jets	Signal : Bkg	Exp Signal Events
6+ jets, 2 b-tags	0.3%	28.5
4 jets, 3 b-tags	0.2%	12.4
5 jets, 3 b-tags	0.5%	18.1
6+ jets, 3 b-tags	0.8%	18.9
4 jets, 4 b-tags	1.3%	1.5
5 jets, 4 b-tags	2.3%	4.4
6 jets, 4 b-tags	2.6%	6.7

Dilepton	Signal : Bkg	Exp Signal
3 jets, 2 b-tags	0.1%	7.4
4+ jets, 2 b-tags	0.3%	14.5
3+ b-tags	1.3%	10.0

Si Xie

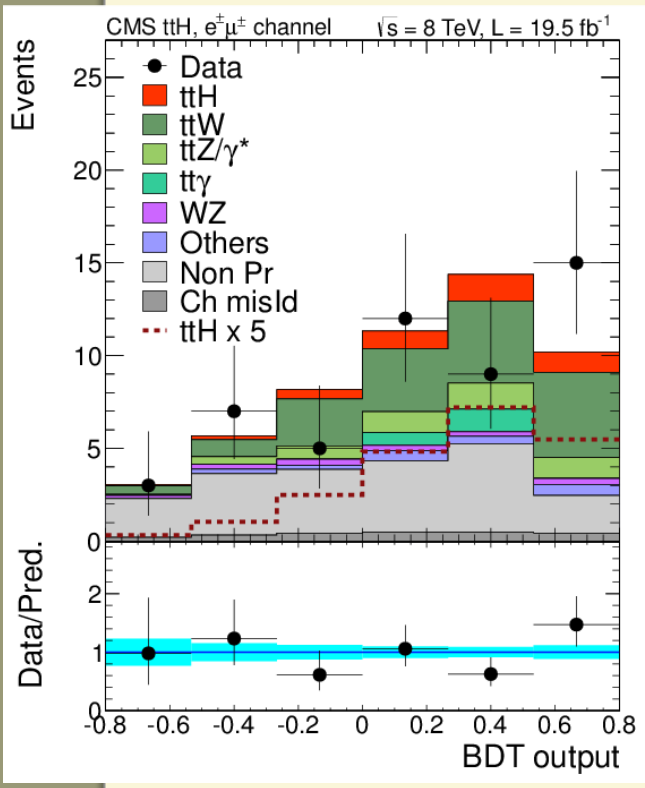
ttH Production : H→ $\gamma\gamma$

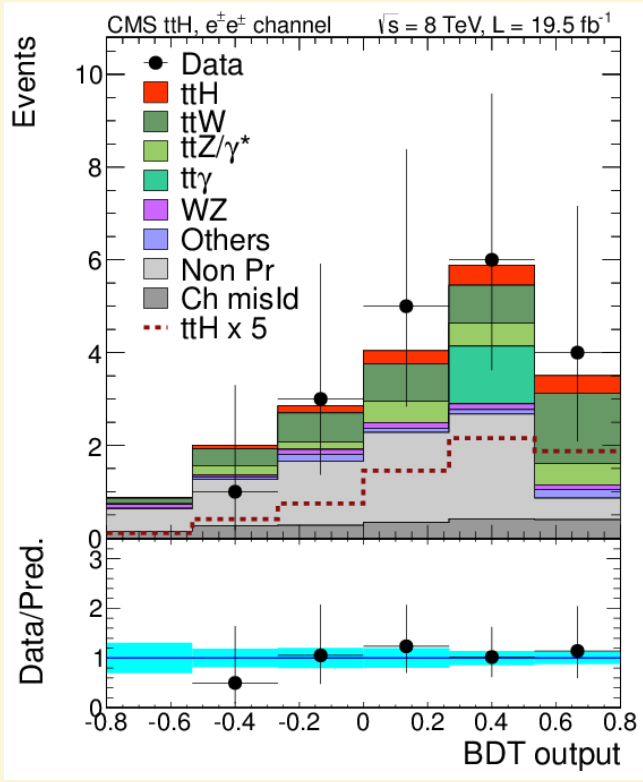
Expected yield in 2012 8TeV data

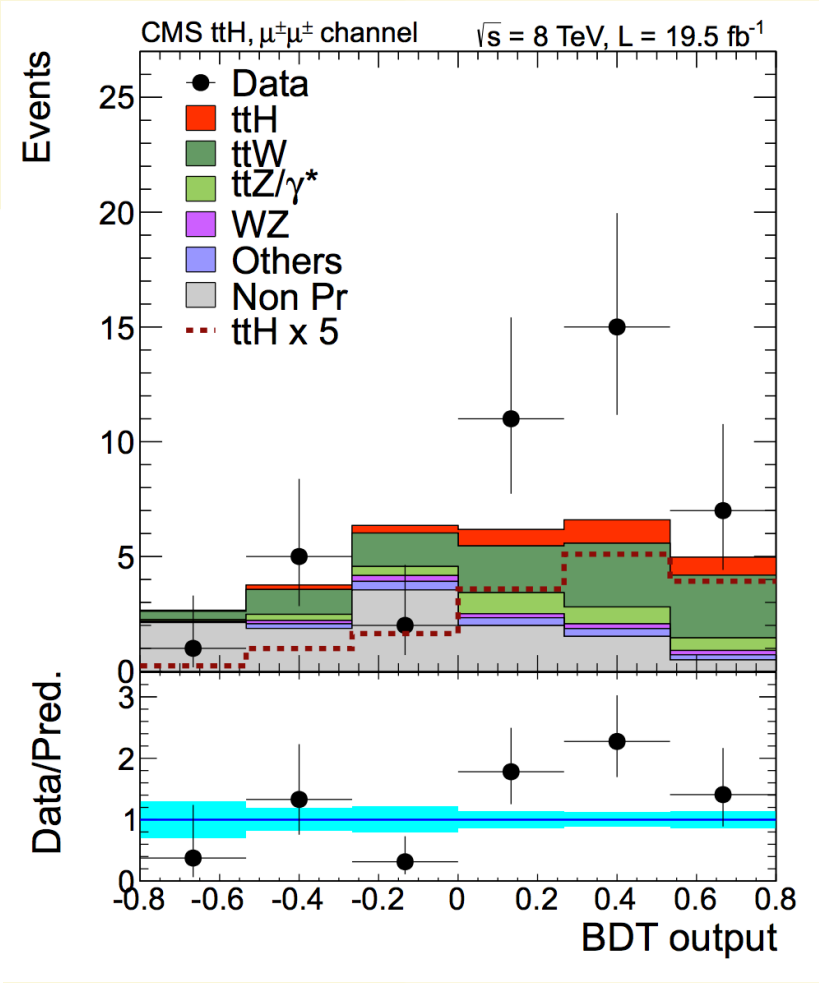
Yield	Hadronic Channel	Leptonic Channel
ttH	0.51	0.45
Total Higgs	0.03	0.01
Data	32	11

Si Xie

ttH Combined Result







Si Xie

Higgs →μτ

Sample	$H \to \mu\tau_h$			$H \to \mu\tau_e$		
	0-Jet	1-Jet	2-Jets	0-Jet	1-Jet	2-Jets
misidentified leptons	1770 ± 530	377 ± 114	1.8 ± 1.0	42 ± 17	16 ± 7	1.1 ± 0.7
$Z \to \tau\tau$	187 ± 10	59 ± 4	0.4 ± 0.2	65 ± 3	39 ± 2	1.3 ± 0.2
ZZ, WW	46 ± 8	15 ± 3	0.2 ± 0.2	41 ± 7	22 ± 4	0.7 ± 0.2
$W\gamma$	—	—	—	2 ± 2	2 ± 2	—
$Z \to ee$ or $\mu\mu$	110 ± 23	20 ± 7	0.1 ± 0.1	1.6 ± 0.7	1.8 ± 0.8	—
$t\bar{t}$	2.2 ± 0.6	24 ± 3	0.9 ± 0.5	4.8 ± 0.7	30 ± 3	1.8 ± 0.4
$t\bar{t}$	2.2 ± 1.1	13 ± 3	0.5 ± 0.5	1.9 ± 0.2	6.8 ± 0.8	0.2 ± 0.1
SM H background	7.1 ± 1.3	5.3 ± 0.8	1.6 ± 0.5	1.9 ± 0.3	1.6 ± 0.2	0.6 ± 0.1
sum of backgrounds	2125 ± 530	513 ± 114	5.4 ± 1.4	160 ± 19	118 ± 9	5.6 ± 0.9
LFV Higgs boson signal	66 ± 18	30 ± 8	2.9 ± 1.1	23 ± 6	13 ± 3	1.2 ± 0.3
data	2147	511	10	180	128	6

Si Xie

A→ZH→llbb Bkg Model

- M_{llbb} spectrum for Z+jets process is reweighted at gen-level for NLO effects, by comparing madgraph with aMC@NLO
- A fit to m_{ll} and product of b-tag discriminators is done to determine correction factors for different bkg components:
  - Z+bb , Z+b+jet, Z+light jets, ttbar

Event yields after final selection cuts

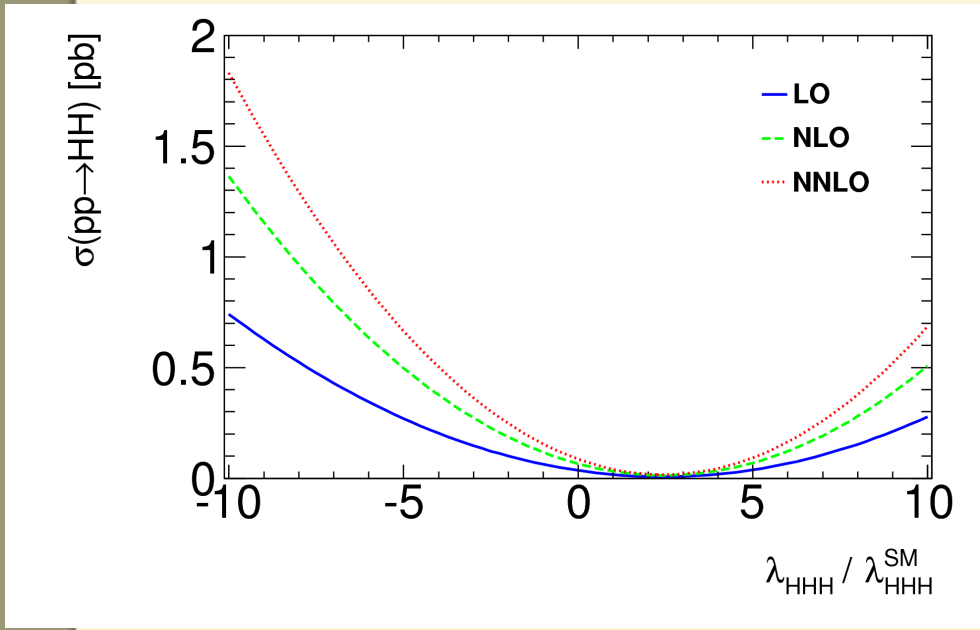
Zbb	Zbx	Zxx	tW	$t\bar{t}$	WZ	ZZ	WW	Zh	tot. MC	data
3039 ±51	494±24	780±37	29±4	1270±8	12±1	113±1	0.3±0.2	21.5±0.1	5758±68	5776

Si Xie

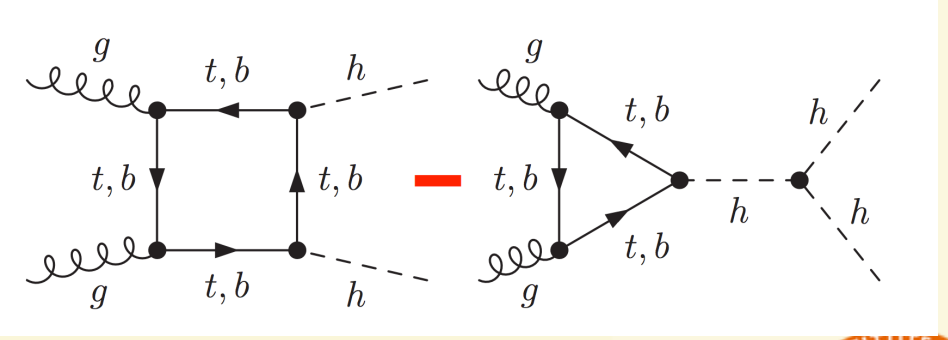
HH Production

- Primary channel to extract information on the Higgs potential → structure of the EWK Phase Transition

- Two interfering diagrams:
  (destructive)



BOX − **HHH self coupling**



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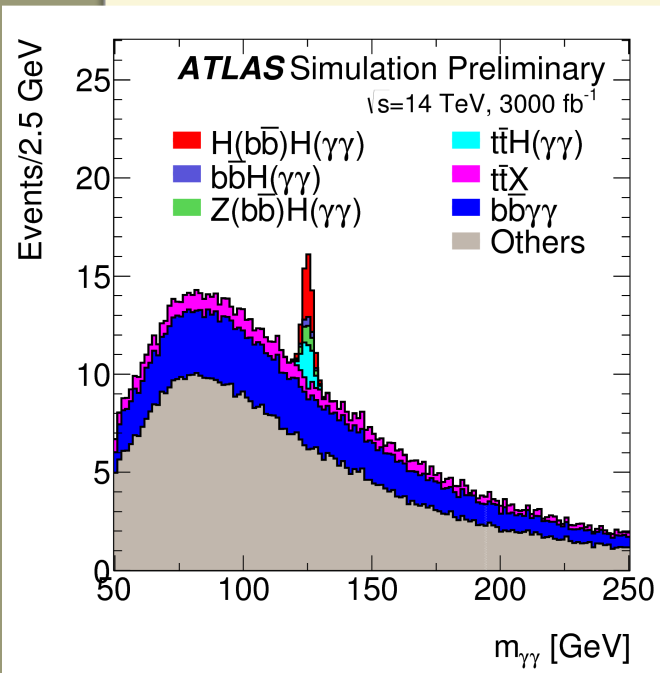
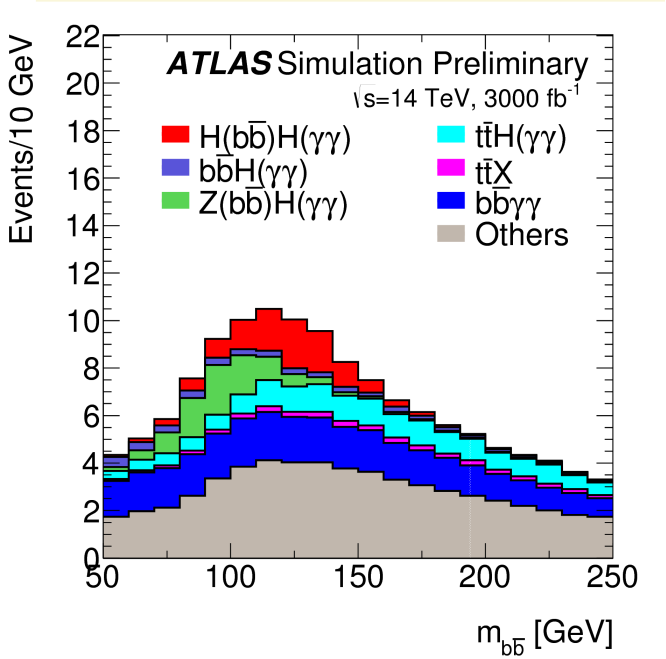
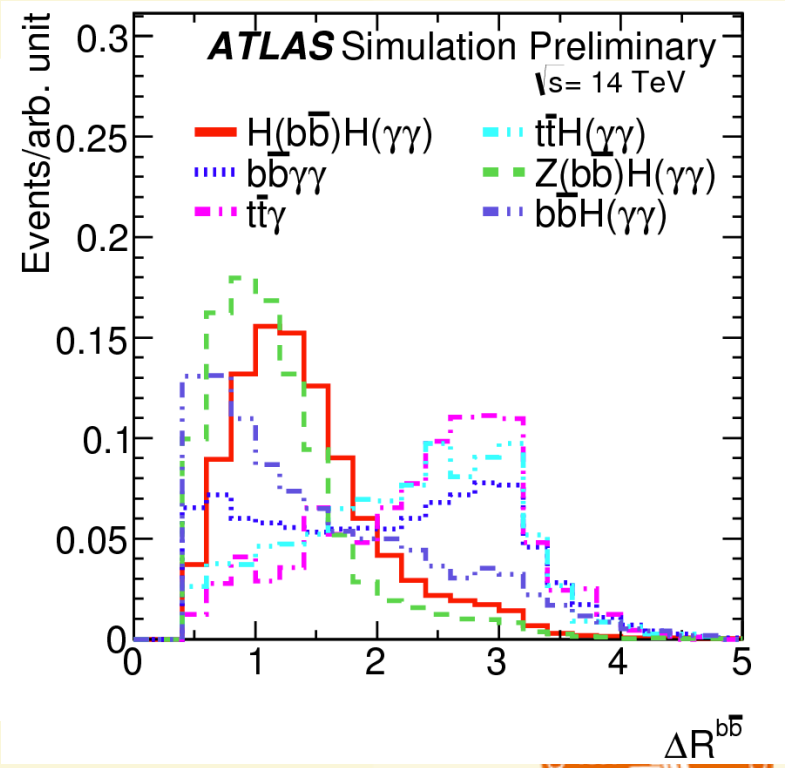
HH → bb γγ

- Bkg suppressed by resonances & decay kinematics
- Resonant bkg : ZH & ttH , H→γγ
- Non-resonant bkg: bbγγ , fake photons, mistags







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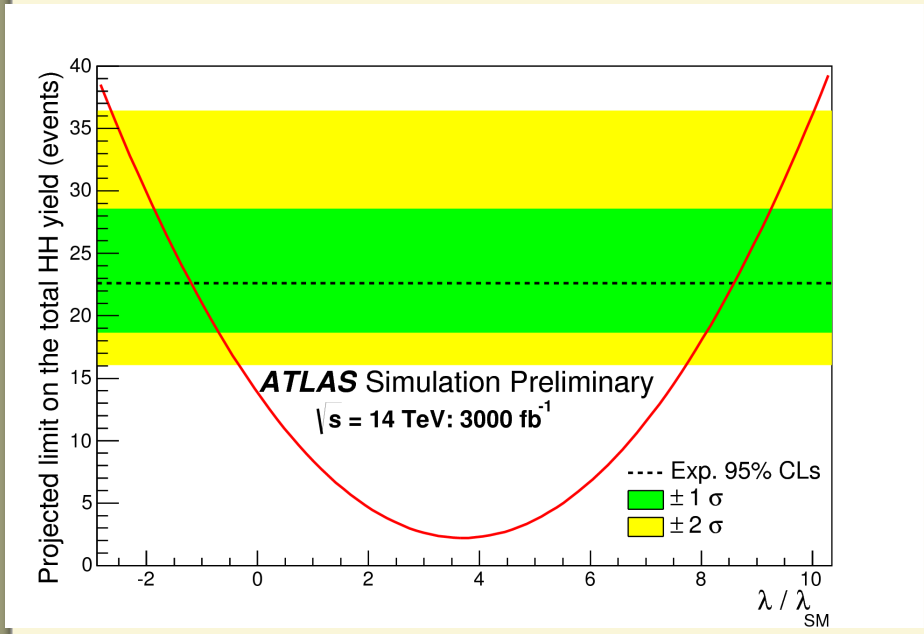
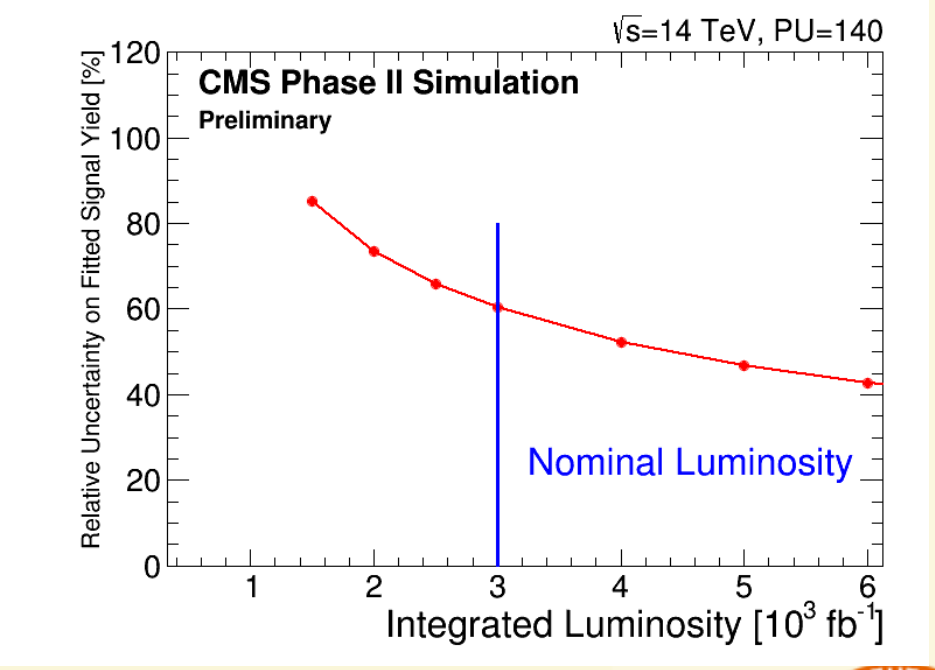
ATL-PHYS-PUB-2014-019

HH → bb γγ

- Preliminary projections show cross section measurement sensitivity at the level of ~60-80% per experiment → 50% for combination

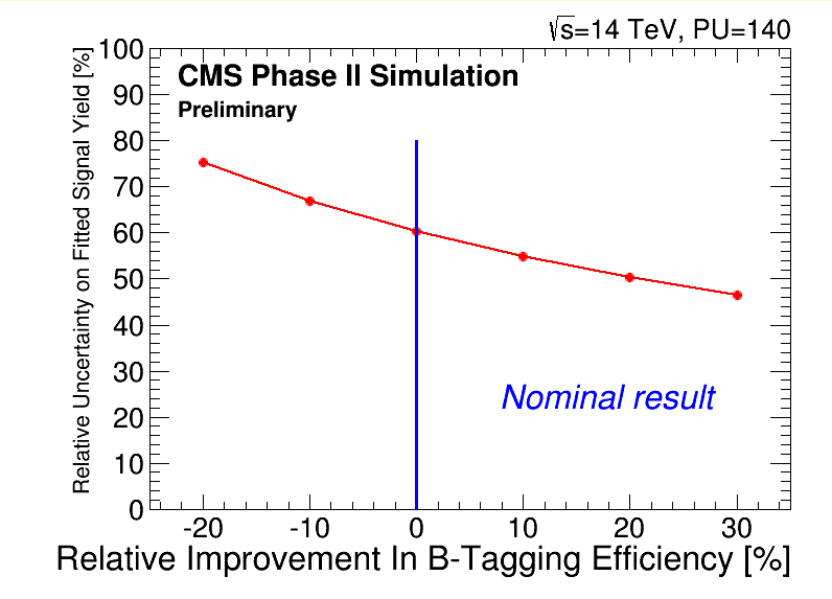


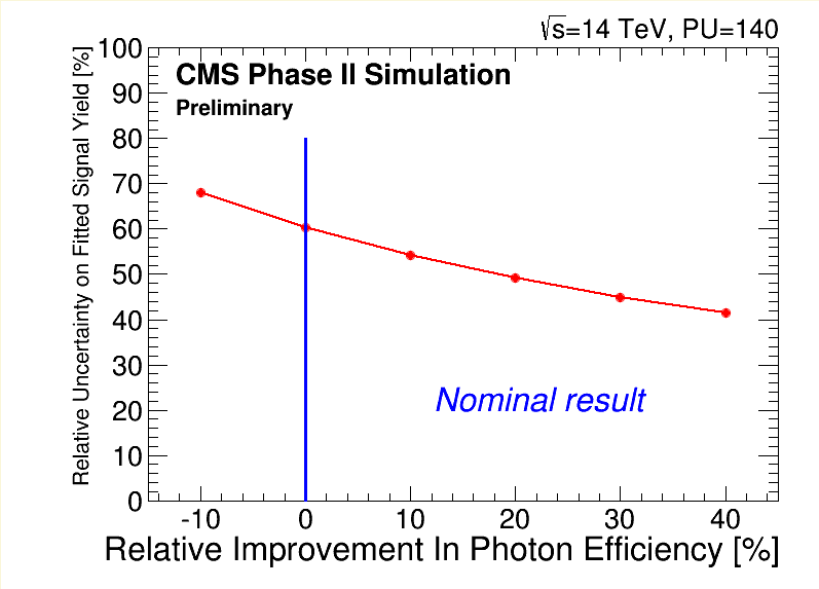


Si Xie

HH → bb γγ

- Preliminary projections show cross section measurement sensitivity at the level of ~60-80% per experiment → 50% for combination
- But very sensitive to detector performance…
  …and improvements still possible





Si Xie

Higgs Couplings

Translated to coupling measurements…
(with current systematics)

CMS

L (fb^{-1})	K_γ	K_W	K_Z	K_g	K_b	K_t	K_τ	$K_{Z\gamma}$	K_μ	BR_{invis}
300	7%	6%	6%	8%	13%	15%	8%	41%	23%	28%
3000	5%	5%	4%	5%	7%	10%	5%	12%	8%	17%

ATLAS

L (fb^{-1})	K_γ	K_W	K_Z	K_g	K_b	K_t	K_τ	$K_{Z\gamma}$	K_μ	BR_{invis}
300	9%	9%	8%	14%	23%	22%	14%	24%	21%	22%
3000	5%	5%	4%	9%	12%	11%	10%	14%	8%	14%

Si Xie

Theory Systematics : What is needed to keep it below 10% of total

Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j → 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j → 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j → VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j → VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

→ Reduce Theory Systematics by 50%

→ Also Reduce Exp Syst by Lumi

	K_γ	K_W	K_Z	K_g	K_b	K_t	K_τ	$K_{Z\gamma}$	K_μ	BR_{invis}
ATLAS	5→4	5→5	4→4	9→7	12→11	11→9	10→9	14→14	8→7	14→11
CMS	5→2	5→2	4→2	5→3	7→4	10→7	5→2	12→10	8→8	17→6