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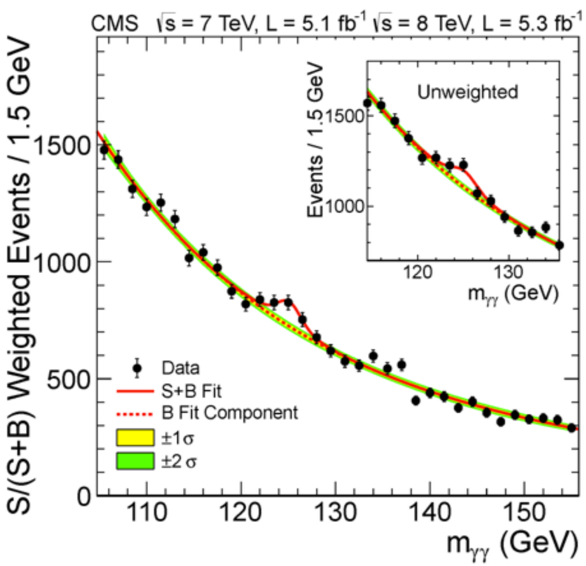
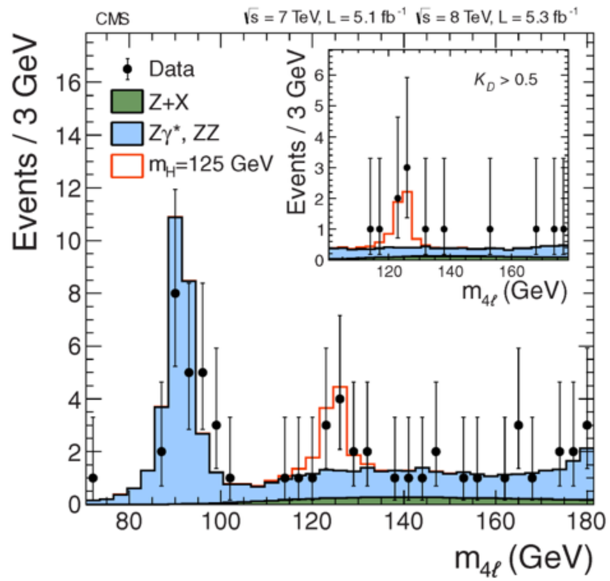
Understanding the Higgs Boson: Where We Are, Where We're Going, and How To Get There

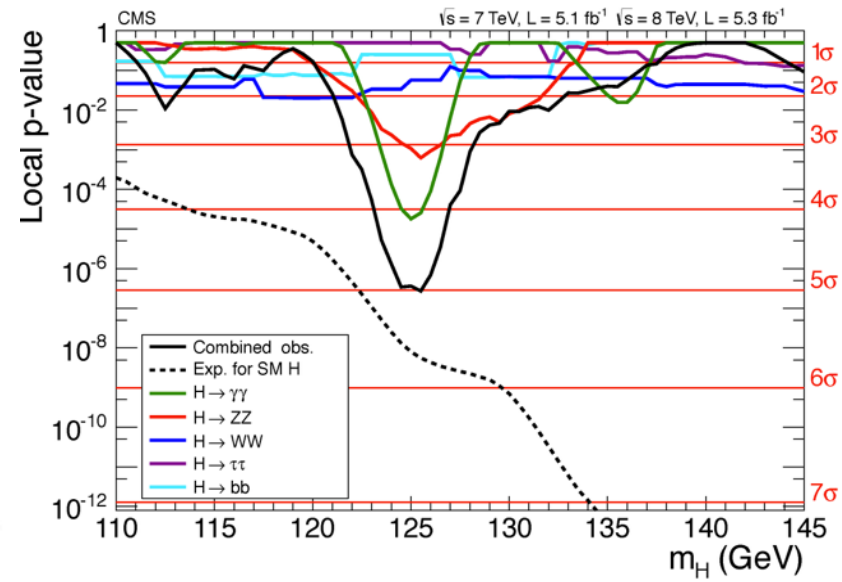
Seth Zenz, Imperial College London

University College London High Energy Physics Seminar
16 March 2018

Foreword: Higgs Discovery







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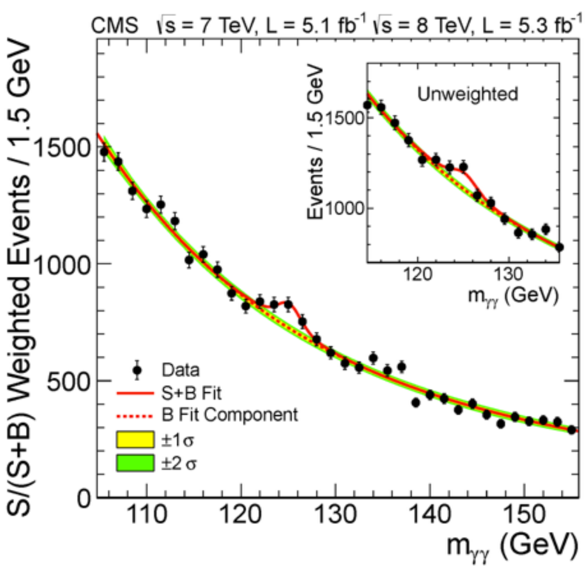

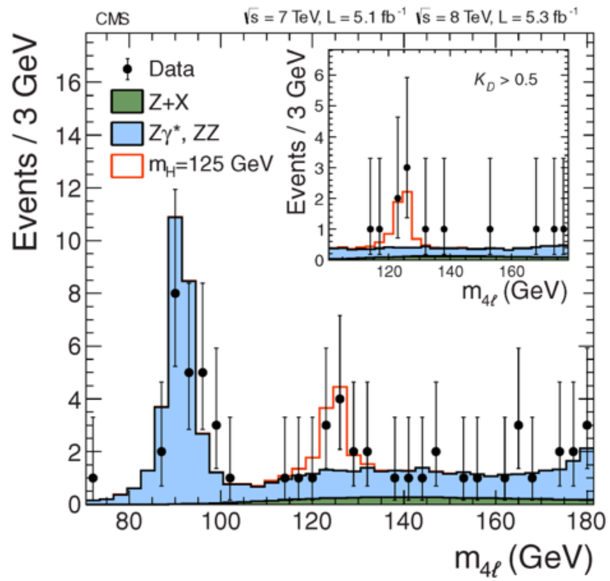

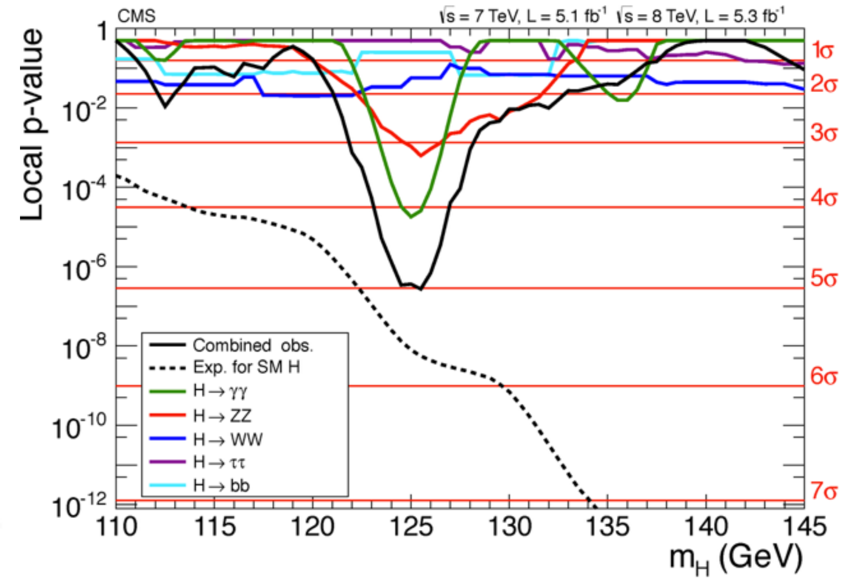

Preface: Climbing the Peaks

- How do we get from discovery to measurement?
- How do we get from ideas to finished analyses?

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Jet substructure as a new Higgs search channel at the LHC

Jonathan M. Butterworth, Adam R. Davison
Department of Physics & Astronomy, University College London.

Mathieu Rubin, Gavin P. Salam
LPTHE; UPMC Univ. Paris 6; Univ. Denis Diderot; CNRS UMR 7589; Paris, France.

It is widely considered that, for Higgs boson searches at the Large Hadron Collider, WH and ZH production where the Higgs boson decays to $b\bar{b}$ are poor search channels due to large backgrounds. We show that at high transverse momenta, employing state-of-the-art jet reconstruction and decomposition techniques, these processes can be recovered as promising search channels for the standard model Higgs boson around 120 GeV in mass.

2008

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"At high transverse momenta . . . these processes can be recovered as promising search channels for the standard model Higgs boson around 120 GeV in mass."

"employing state-of-the-art jet reconstruction and decomposition techniques"

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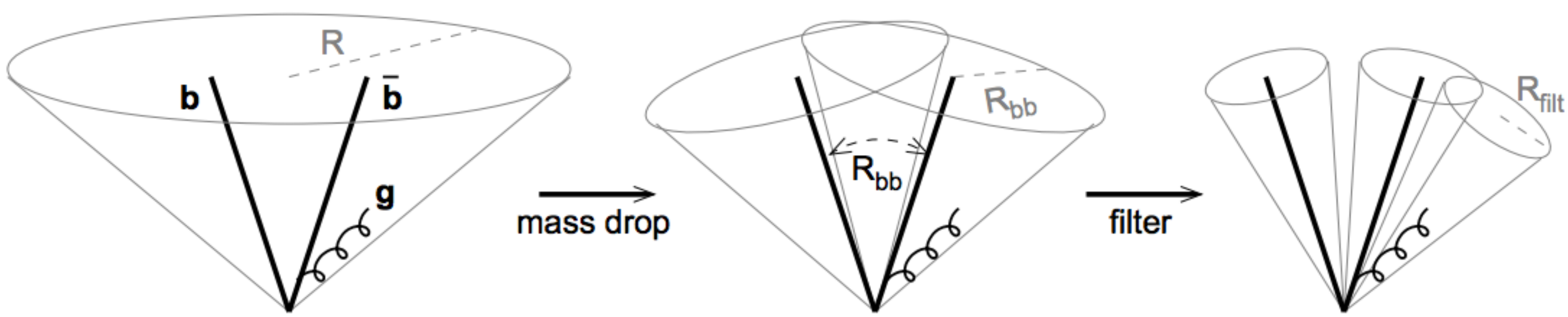

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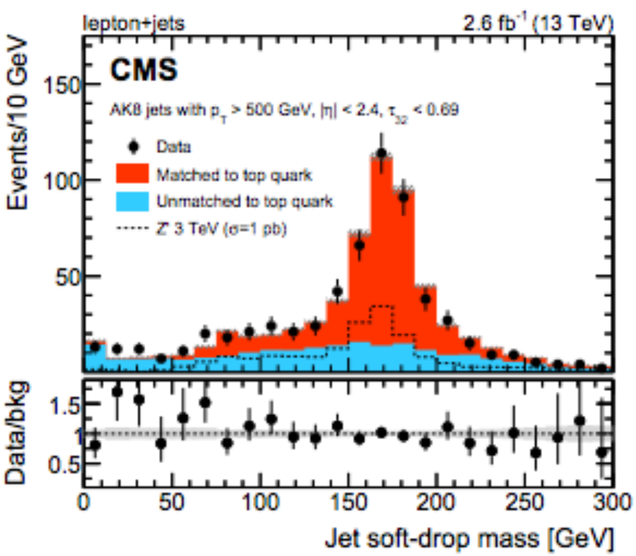
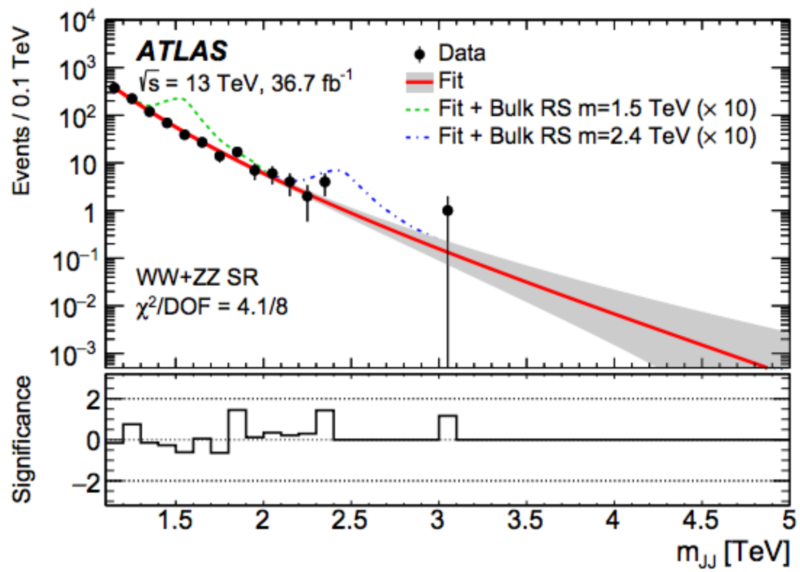
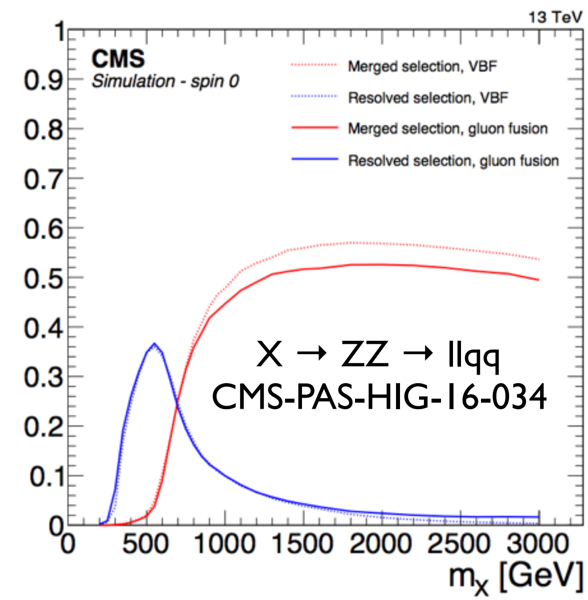


JHEP 07 (2017) 001
X → tt → lepton+jets or fully hadronic



Phys. Lett. B 777 (2017) 91
X → VV → qqqq



X → ZZ → llqq
CMS-PAS-HIG-16-034

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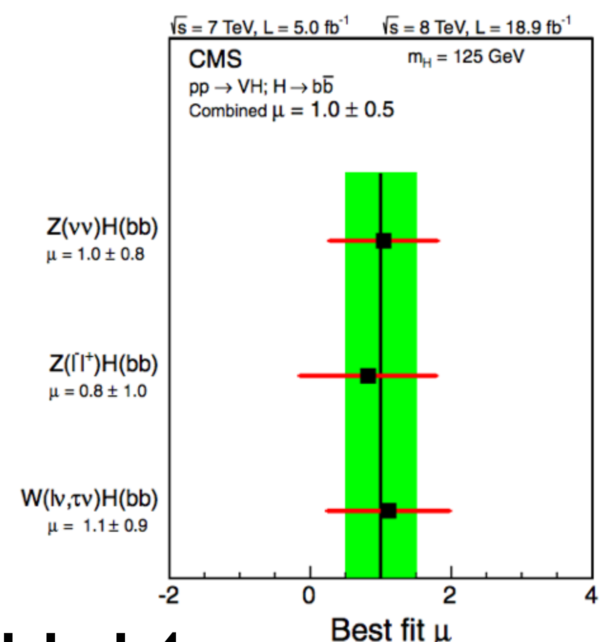
PHYSICAL REVIEW D **89,** 012003 (2014)

Search for the standard model Higgs boson produced in association with a *W* or a *Z* boson and decaying to bottom quarks

S. Chatrchyan *et al.**
(CMS Collaboration)

(Received 14 October 2013; published 21 January 2014)

A search for the standard model Higgs boson (H) decaying to $b\bar{b}$ when produced in association with a weak vector boson (V) is reported for the following channels: $W(\mu\nu)H$, $W(e\nu)H$, $W(\tau\nu)H$, $Z(\mu\mu)H$, $Z(ee)H$, and $Z(\nu\nu)H$. The search is performed in data samples corresponding to integrated luminosities of up to 5.1 inverse femtobarns at $\sqrt{s} = 7$ TeV and up to 18.9 fb^{-1} at $\sqrt{s} = 8$ TeV, recorded by the CMS experiment at the LHC. An excess of events is observed above the expected background with a local significance of 2.1 standard deviations for a Higgs boson mass of 125 GeV, consistent with the expectation from the production of the standard model Higgs boson. The signal strength corresponding to this excess, relative to that of the standard model Higgs boson, is 1.0 ± 0.5.



2011-14

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	$W(\ell\nu)H$			$W(\tau\nu)H$	$Z(\ell\ell)H$		$Z(\nu\nu)H$		
Process	Low $p_T(V)$	Int. $p_T(V)$	High $p_T(V)$		Low $p_T(V)$	High $p_T(V)$	Low $p_T(V)$	Int. $p_T(V)$	High $p_T(V)$
$V + b\bar{b}$	25.2	22.4	15.9	4.3	158.6	36.2	177.3	98.3	68.2
$V + b$	3.1	2.9	9.6	1.2	95.8	14.6	84.7	58.3	27.6
$V + udscg$	4.5	8.5	10.0	2.5	62.3	8.7	57.6	31.0	21.6
$t\bar{t}$	113.2	106.5	50.3	22.6	107.0	6.9	153.8	87.4	39.2
Single-top quark	24.1	20.3	14.7	7.4	2.9	0.4	54.5	20.1	11.7
$VV(udscg)$	0.3	1.3	1.2	0.2	2.4	0.4	2.3	1.5	1.4
$VZ(b\bar{b})$	1.1	1.4	2.3	1.1	11.0	2.7	9.5	6.9	7.7
Total backgrounds	171.7	163.4	104.1	39.4	439.8	69.8	539.7	303.5	177.4
VH	3.0	6.0	8.3	1.4	5.5	6.3	8.5	8.5	11.5
Data	185	182	128	35	425	77	529	322	188
S/B (%)	1.7	3.7	8.0	3.4	1.3	9.0	1.6	2.8	6.5

… uses well-separated standard jets only

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- Even if we know exactly where we're going…
  - How will we get there?
  - And what will we learn along the way?


Björn "Dr. Bear" Penning

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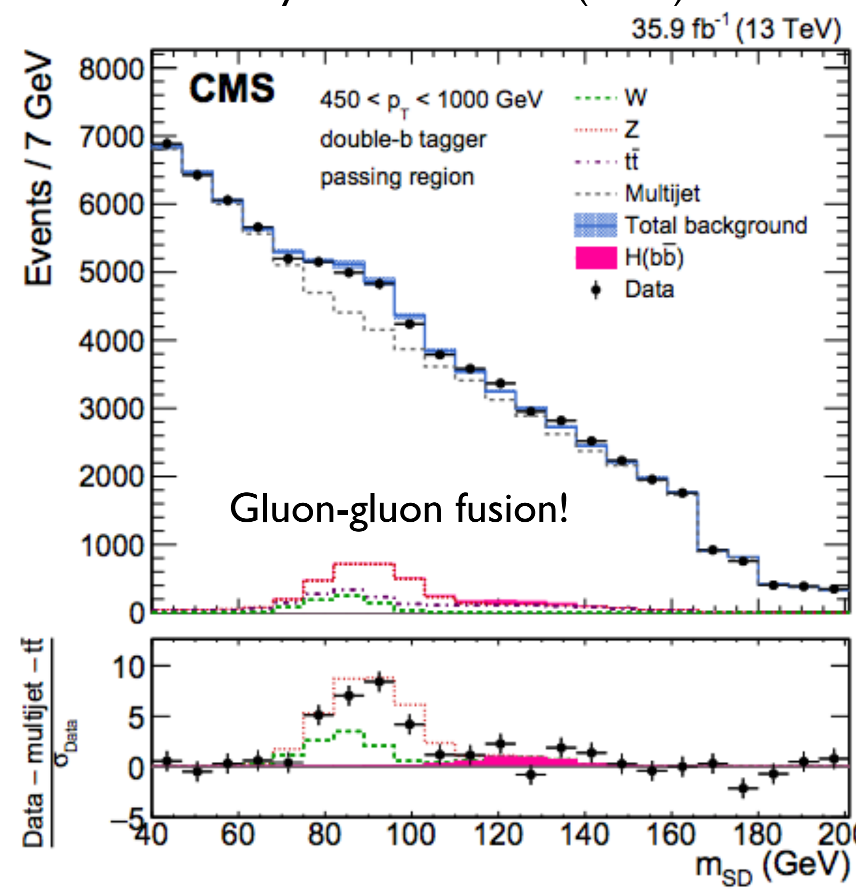
Phys. Rev. Lett. 120 (2018) 071802



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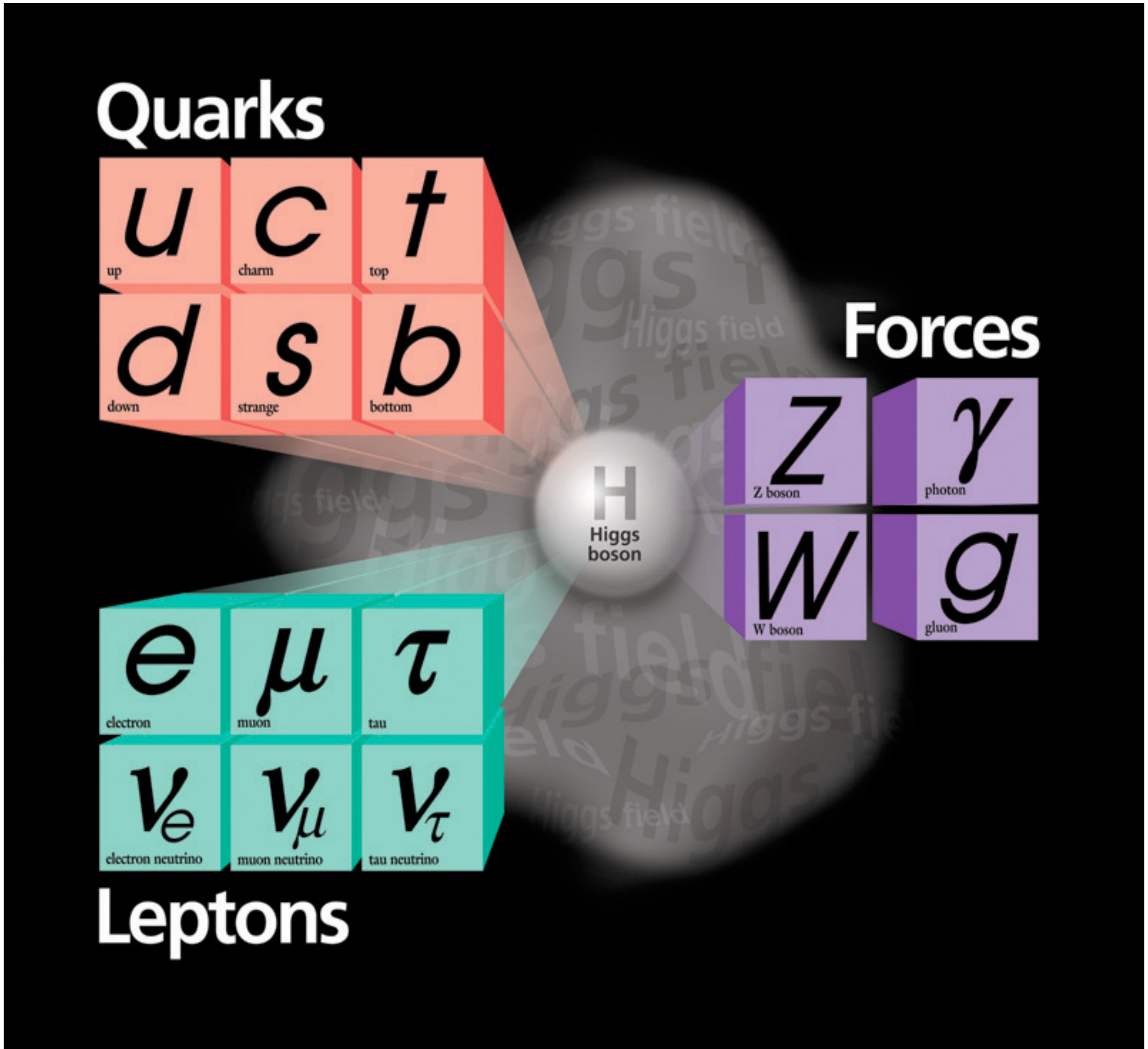
Higgs in the Standard Model



- Previously known: all Standard Model (SM) quarks, leptons, and vector bosons
- SM BEH Mechanism solves two possibly-separate problems
  - Electroweak symmetry breaking
  - Fermion masses
- With Higgs mass known, SM predicts everything else!

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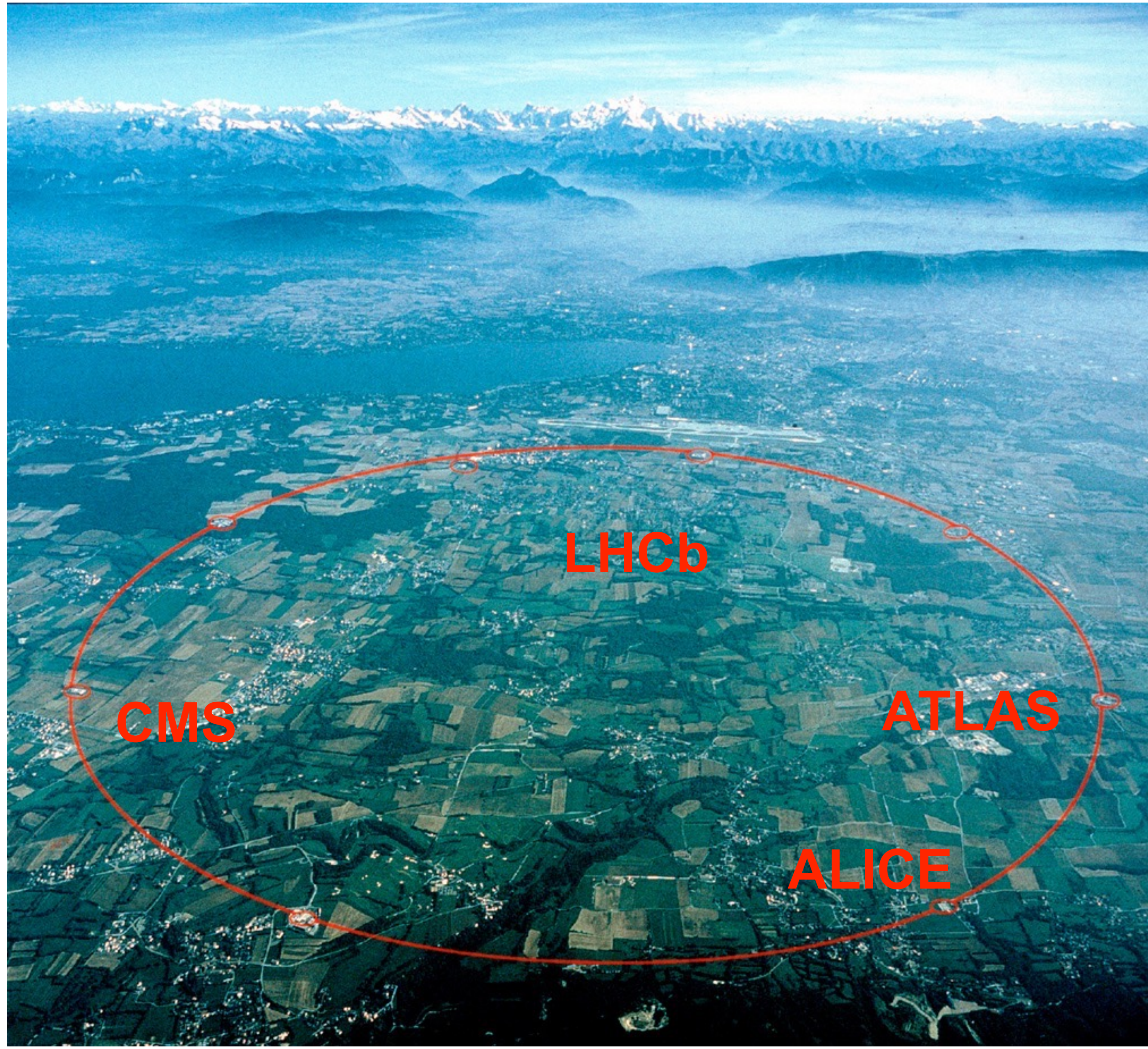
Large Hadron Collider

- p-p, Pb-Pb, p-Pb
- p-p: $\sqrt{s}$ = 7-8 TeV, now 13 TeV, ultimately ~14 TeV
- Design luminosity: $\sim 10^{34}$ cm^{-2} s^{-1}
  - Run 1: 7.7×10^{33}
  - Run 2: 2.06×10^{34}



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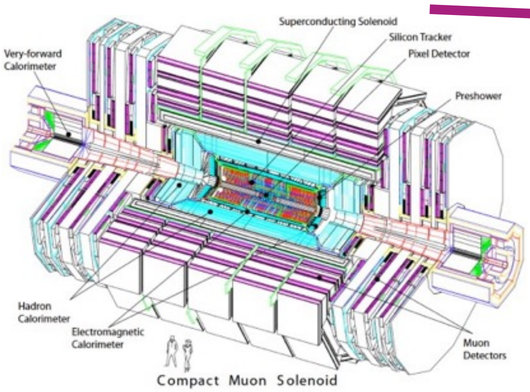
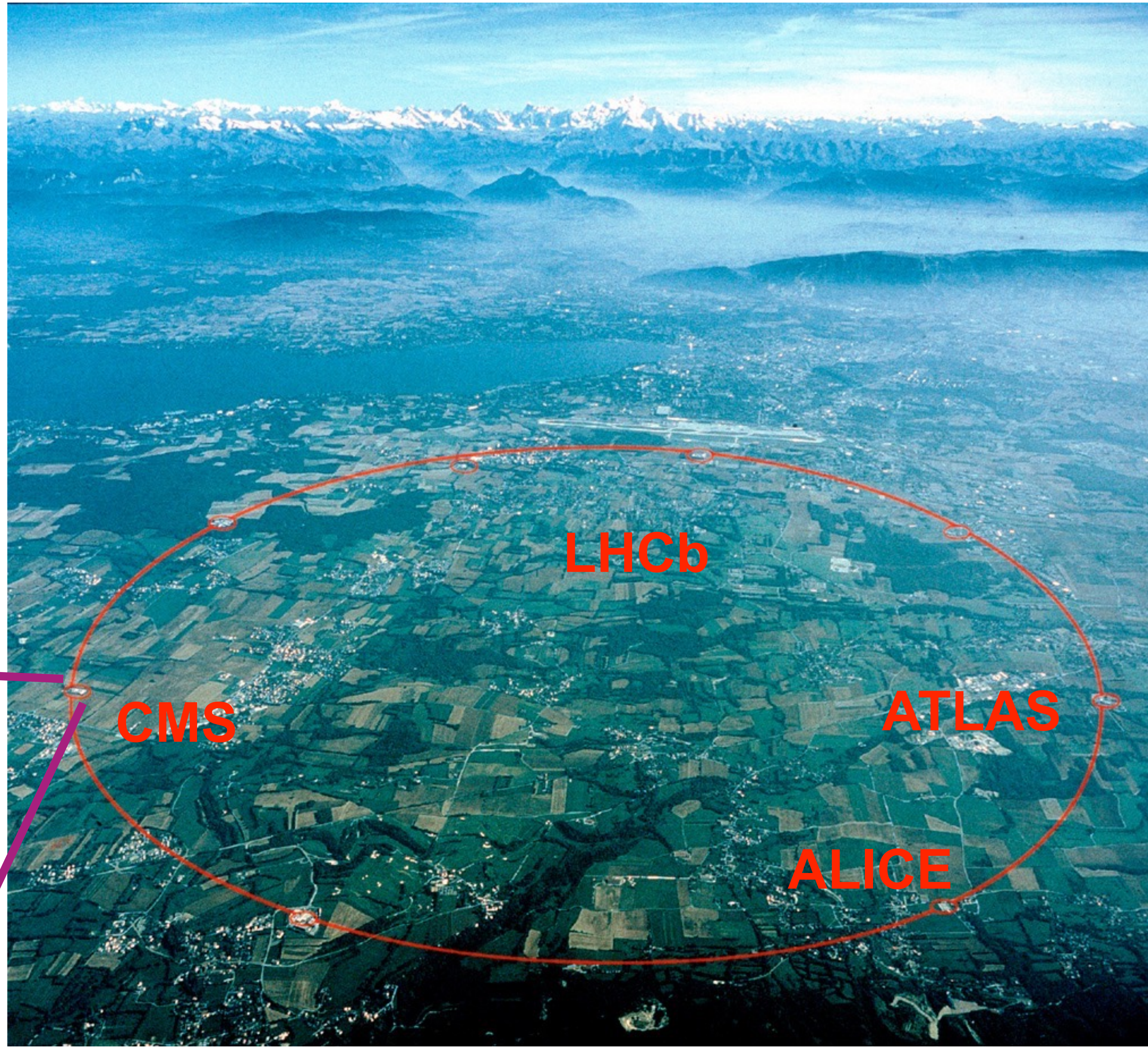
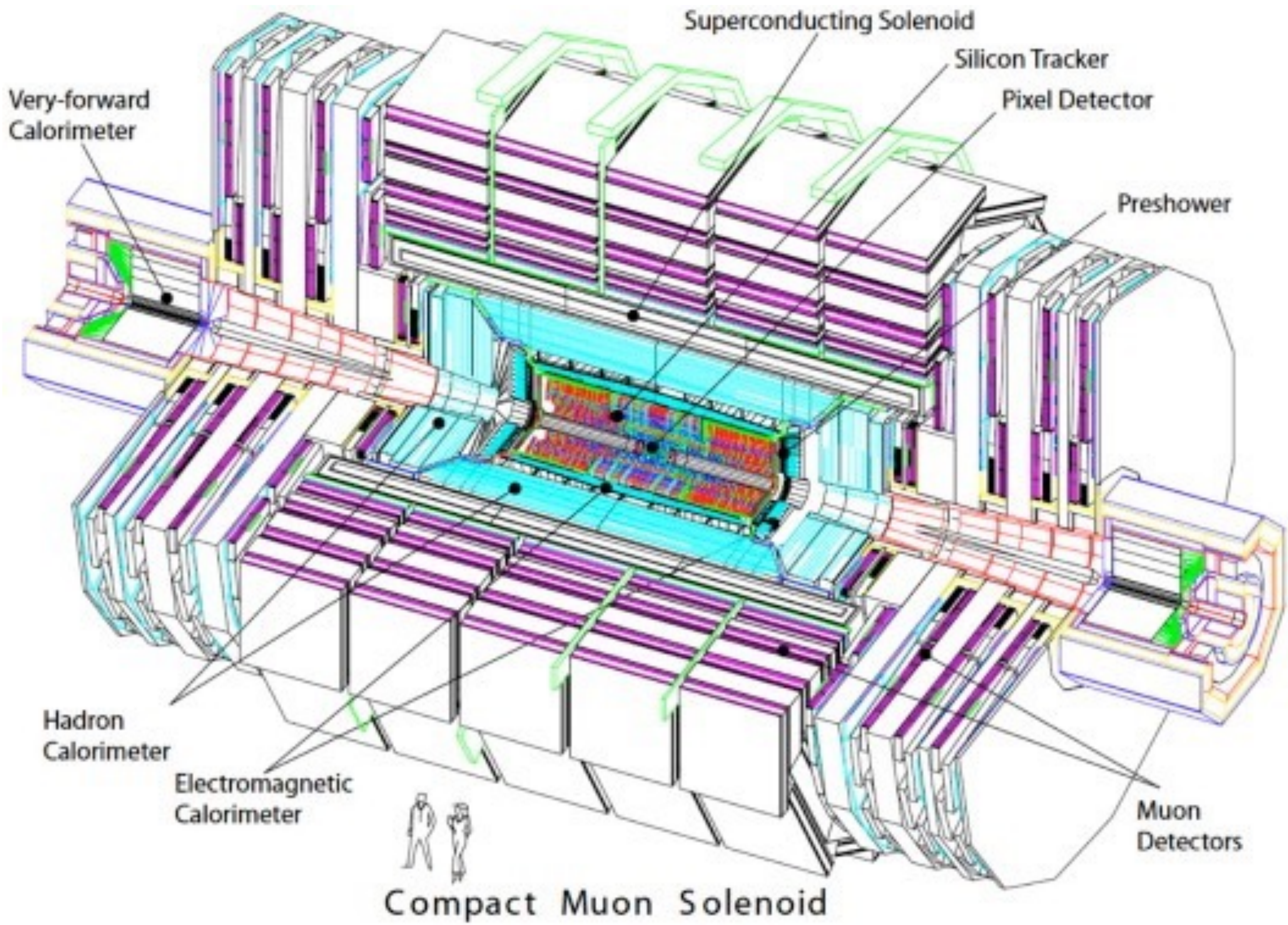
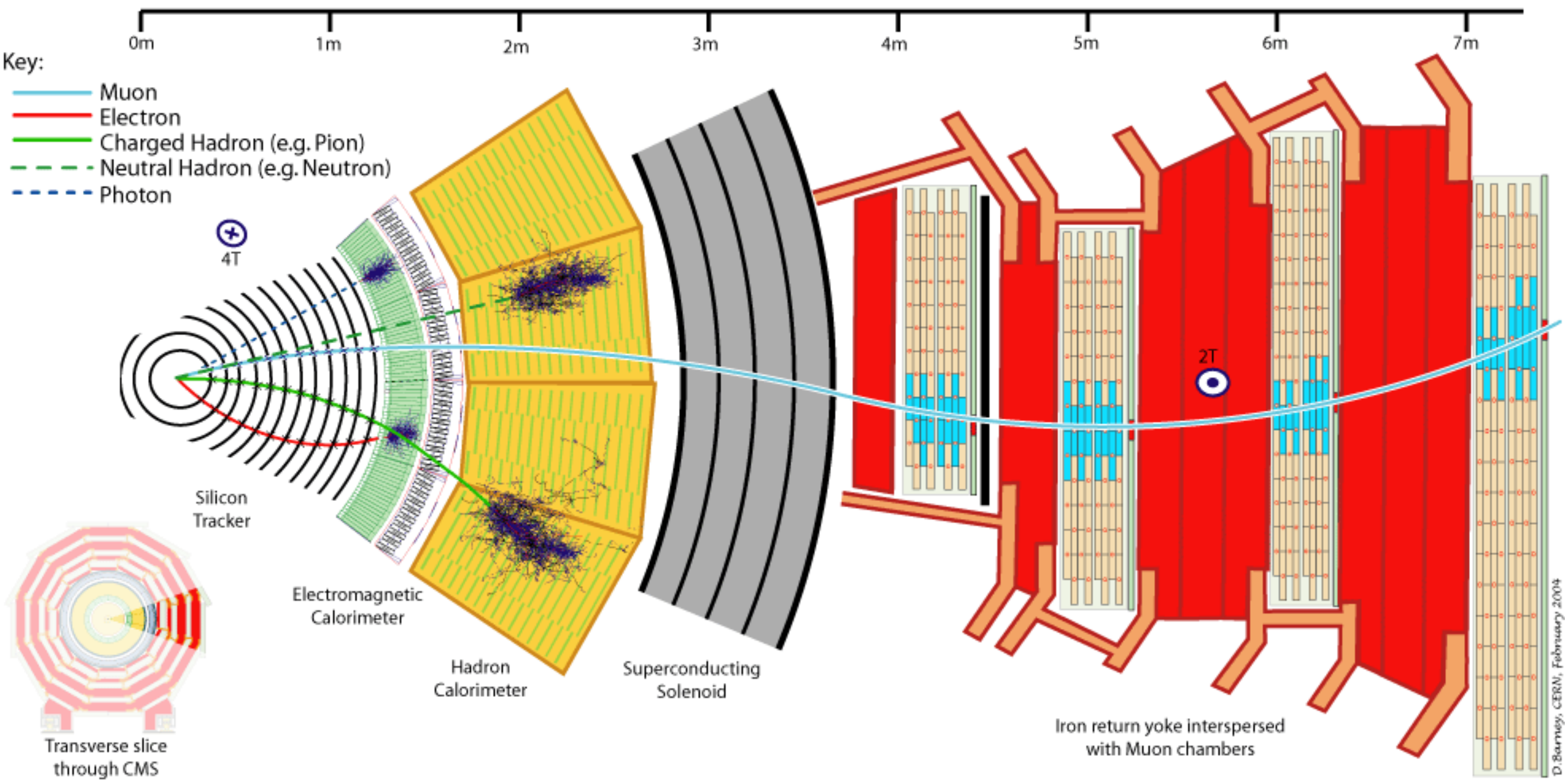




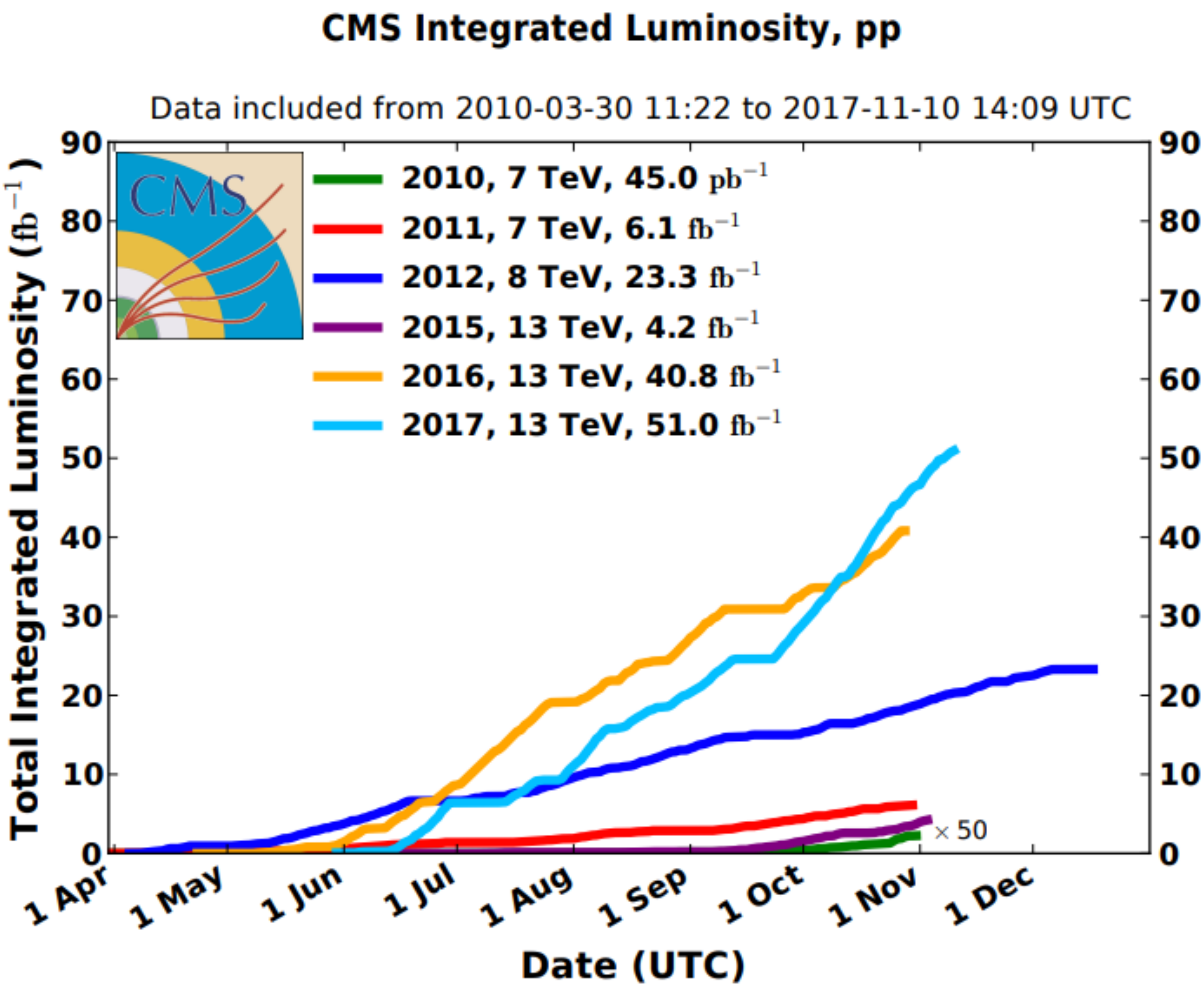
Compact Muon Solenoid



Object Reconstruction in CMS

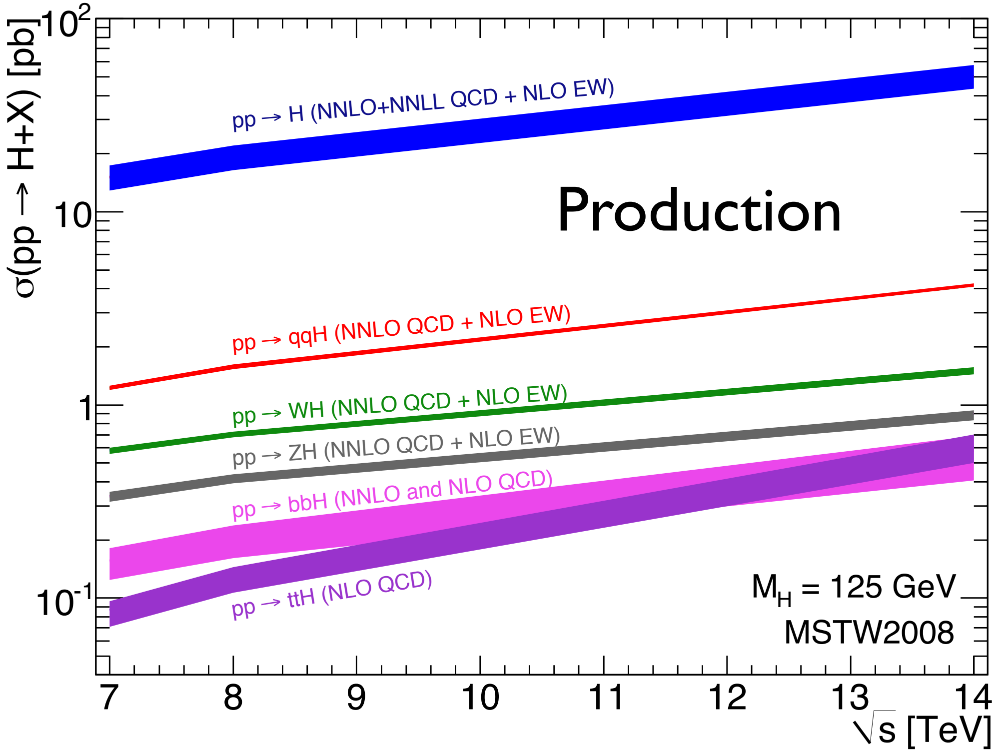


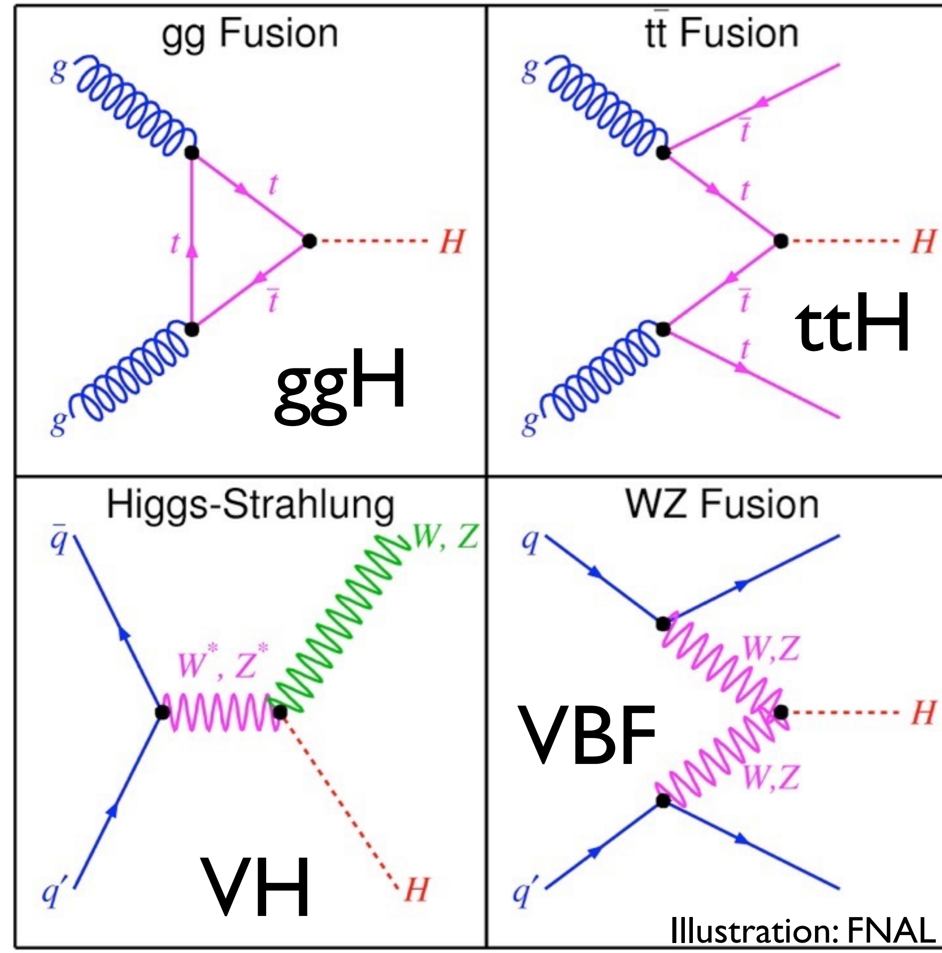
Luminosity



$$N = \mathcal{L}\sigma$$

SM Higgs Boson Production





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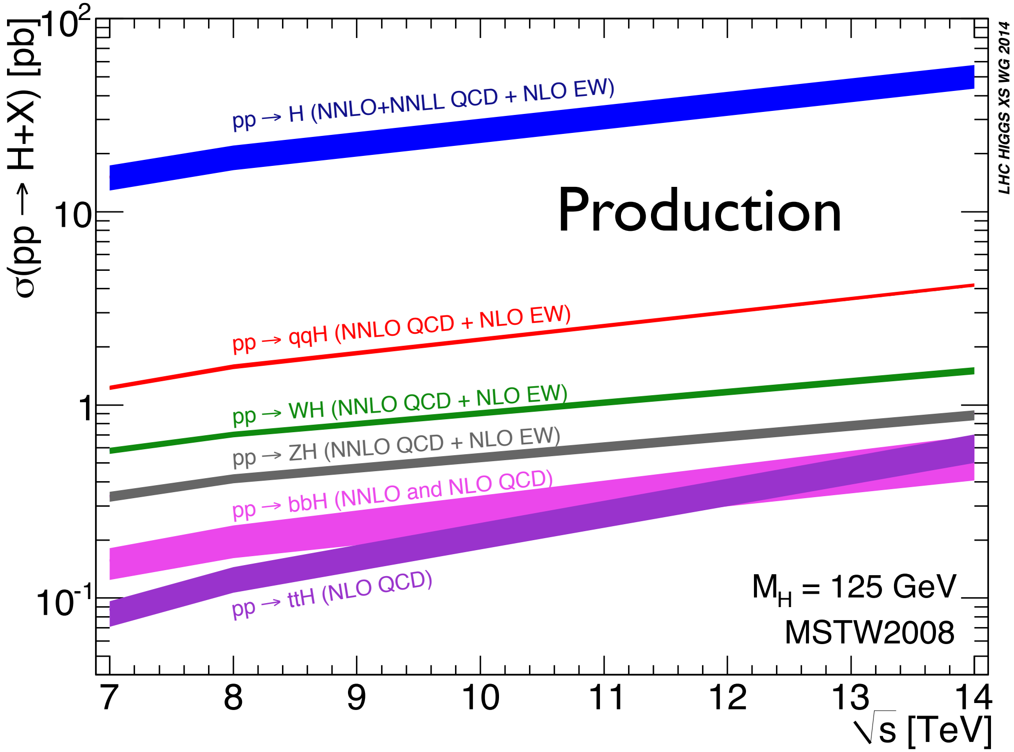
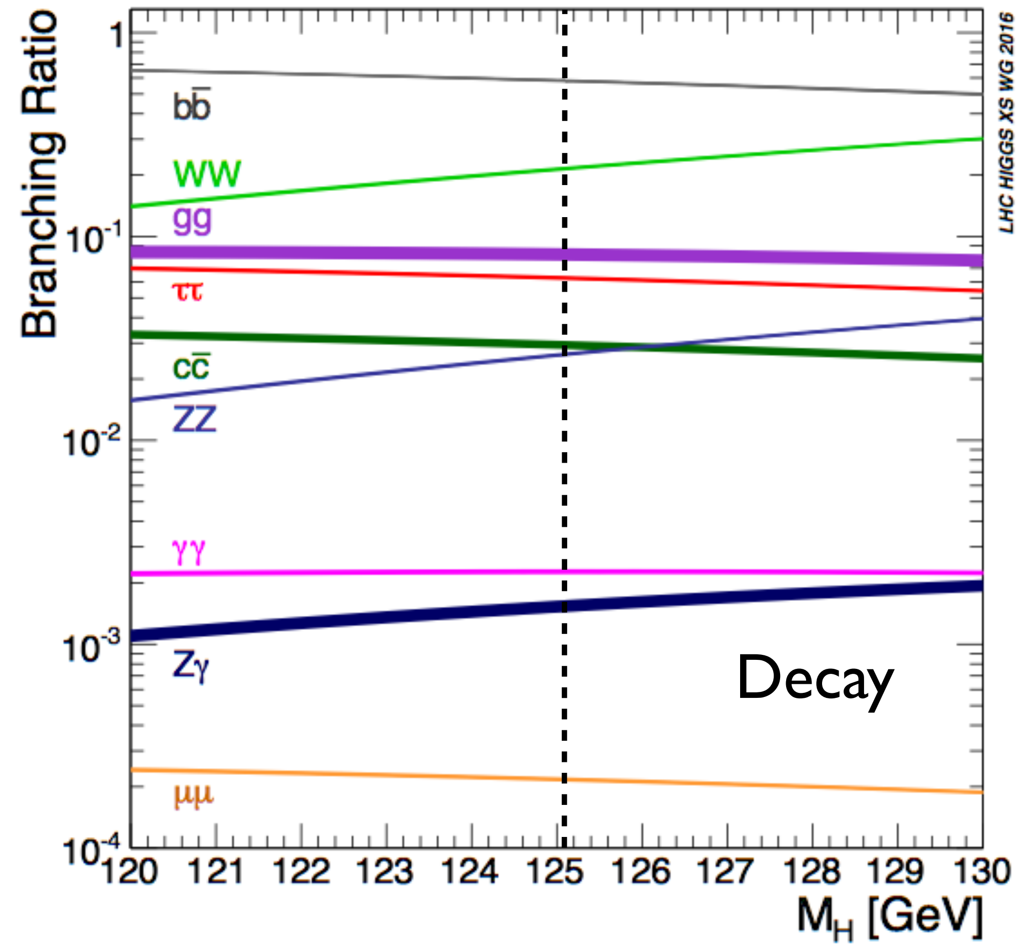
Higgs Decay Modes





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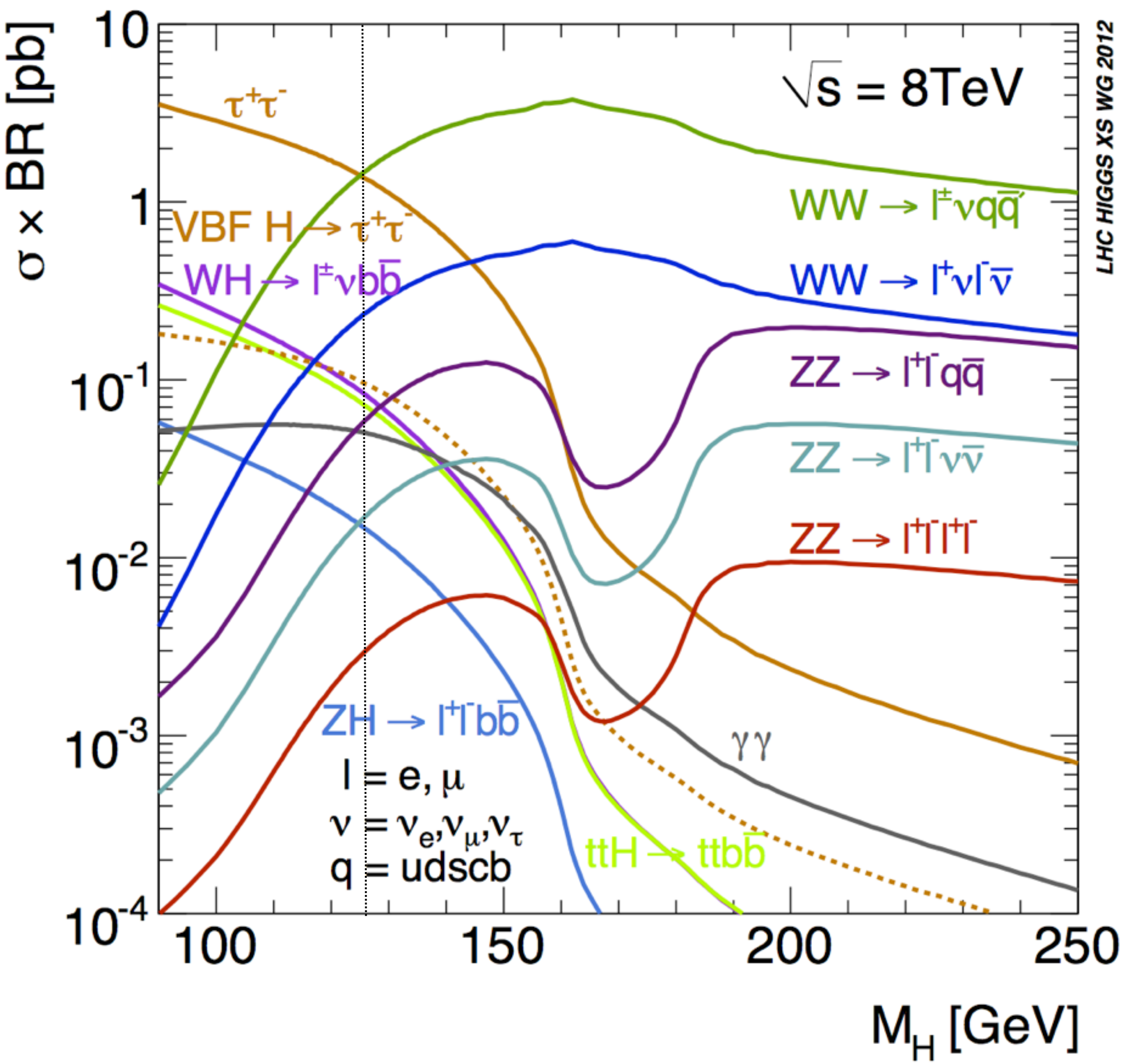
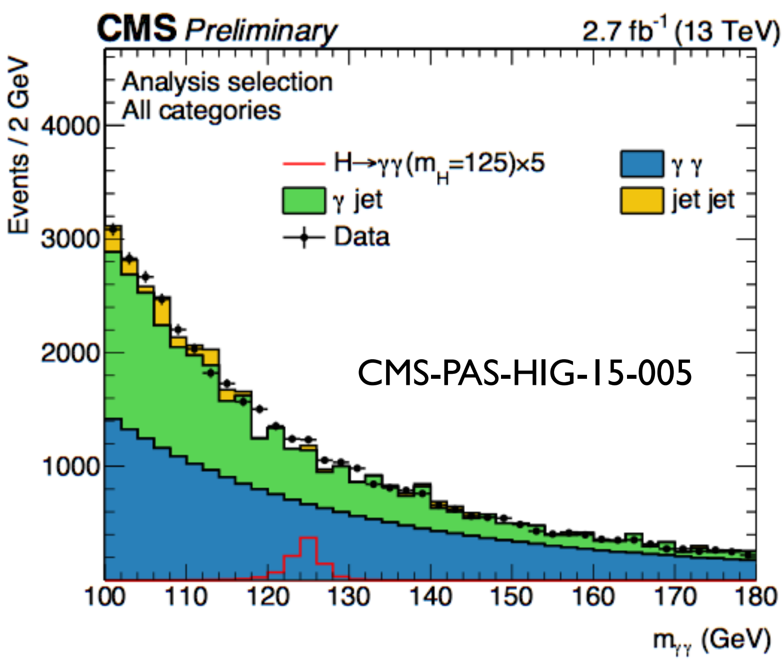
Higgs Channels: Analysis

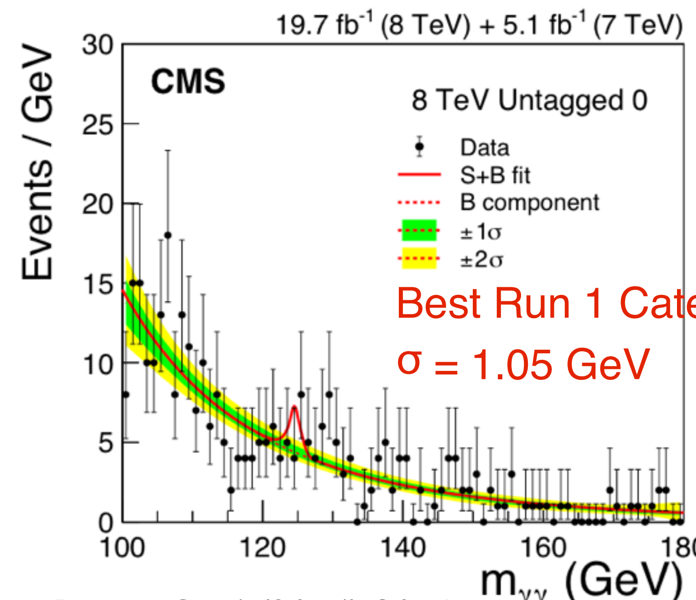


- Complete detector signature created by the Higgs decay *and* the decay products of particles from the production process
- Which analyses are possible?
  - Rate of detector signature
  - Rate of backgrounds
  - Tools for background rejection

H → γγ Overview

- Maximize Signal-to-Background using mass: $m_{\gamma\gamma}^2 = 2E_1E_2(1 - \cos\Delta\alpha)$
- Some photons have better energy resolutions than others
  - Barrel
  - Well-contained
  - Avoid "cracks" in detector
- Categorize events by resolution to maximize Signal-to-Background



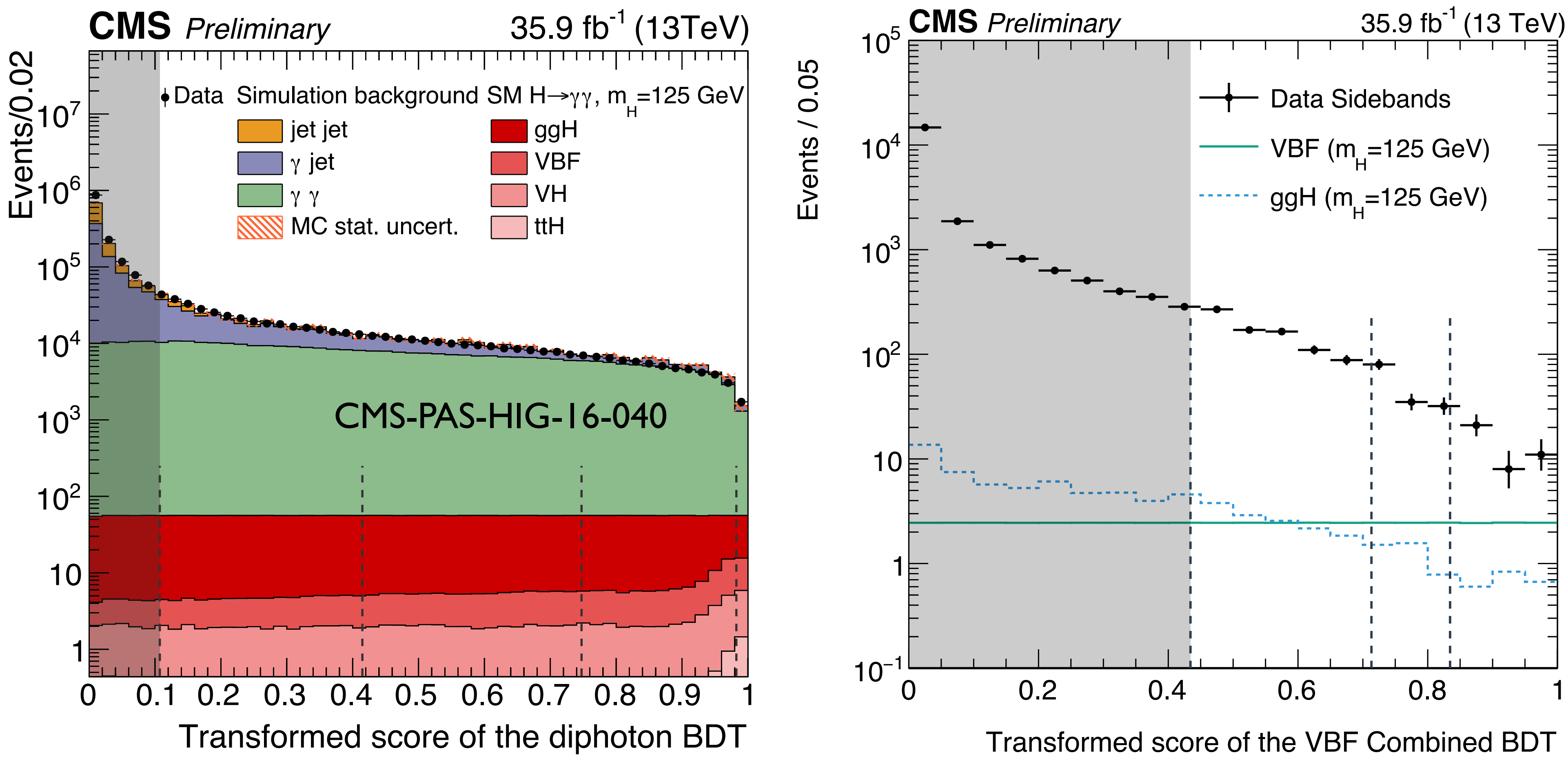


Best Run 1 Category
σ = 1.05 GeV

Worst Category
σ = 2.62 GeV

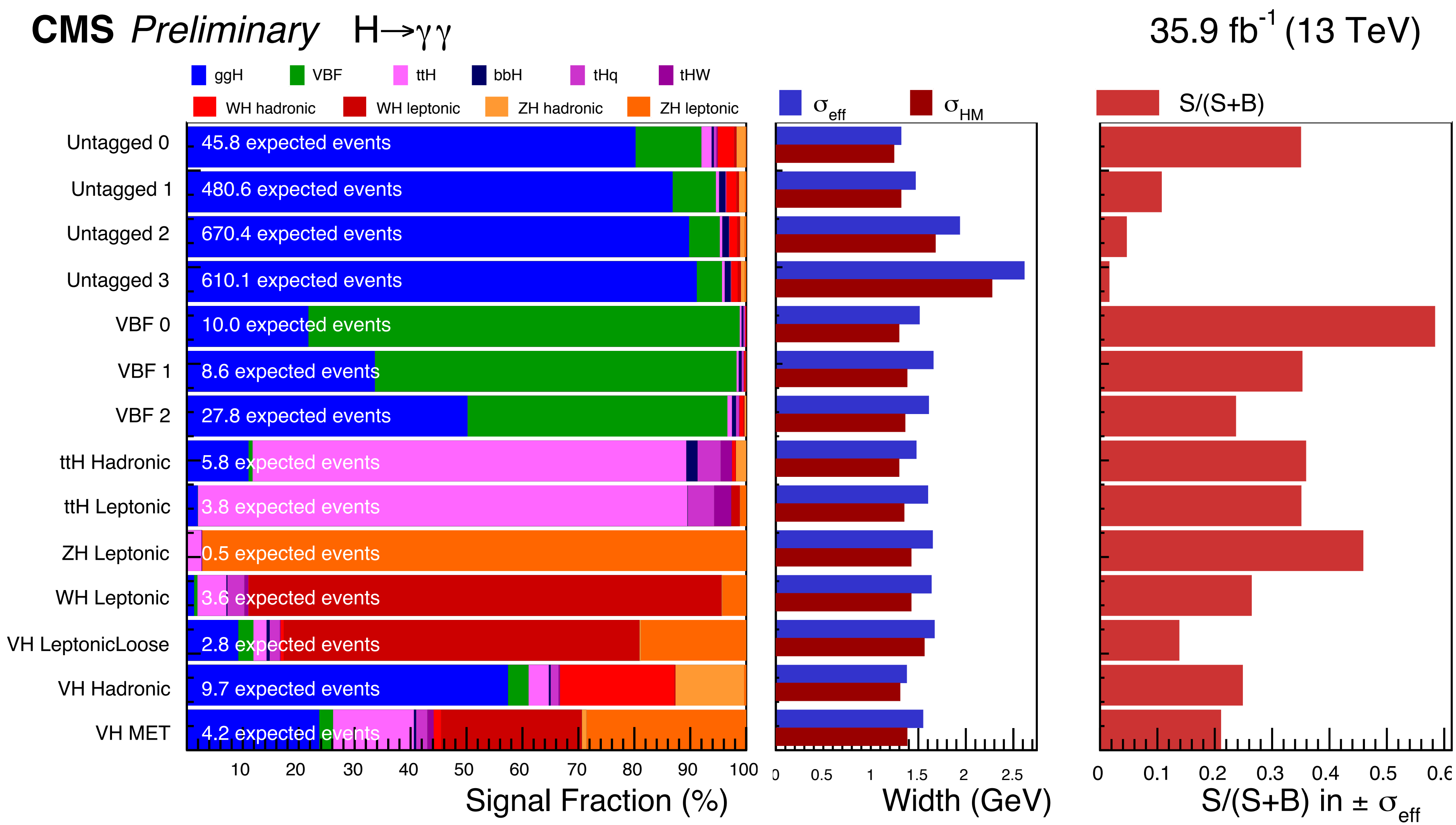
Eur. Phys. J. C 74 (2014) 3076

H → γγ Categorization



- Classifier BDT's independent of $m_{\gamma\gamma}$ – fit in next step

H → γγ Categorization



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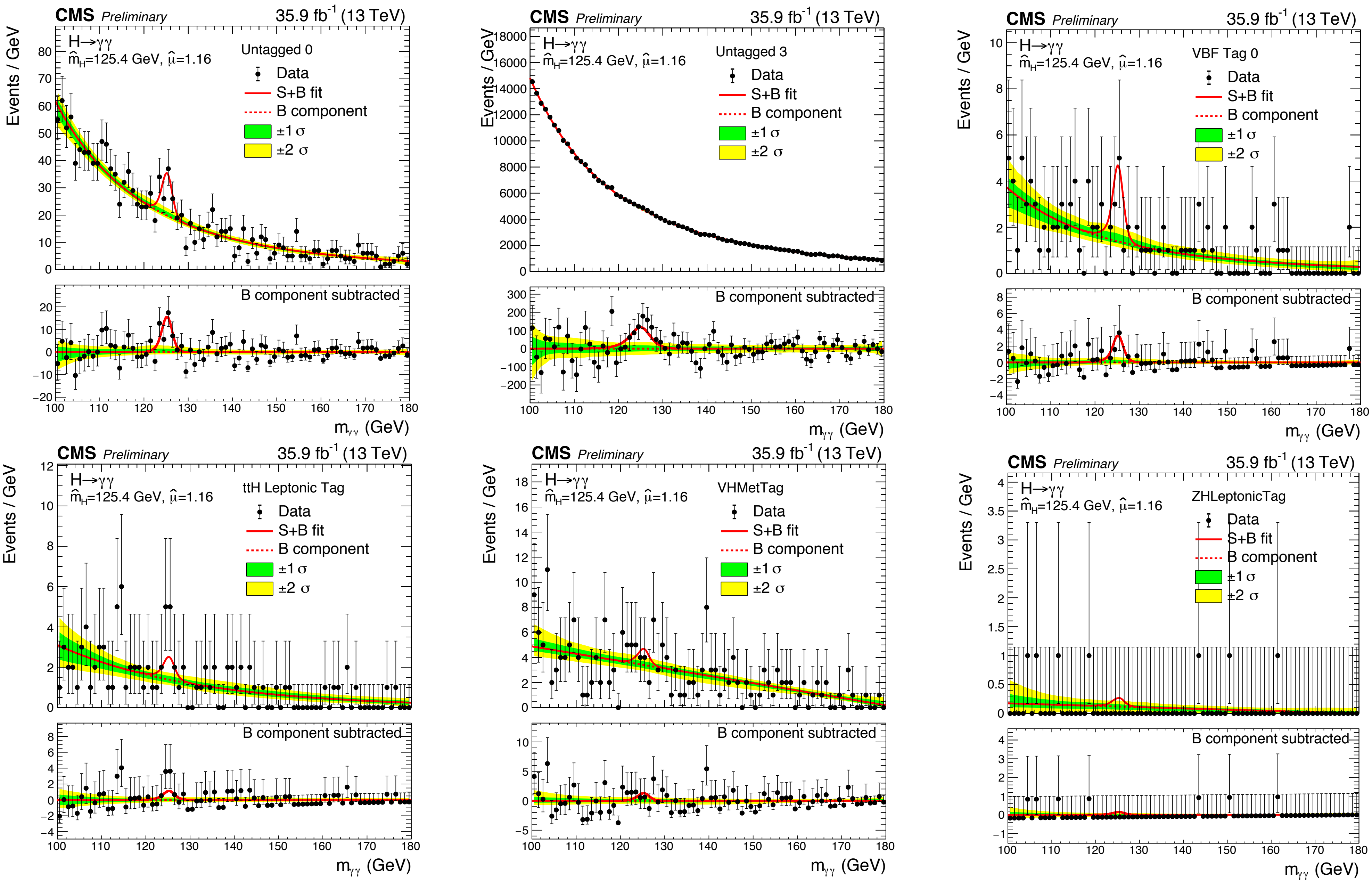
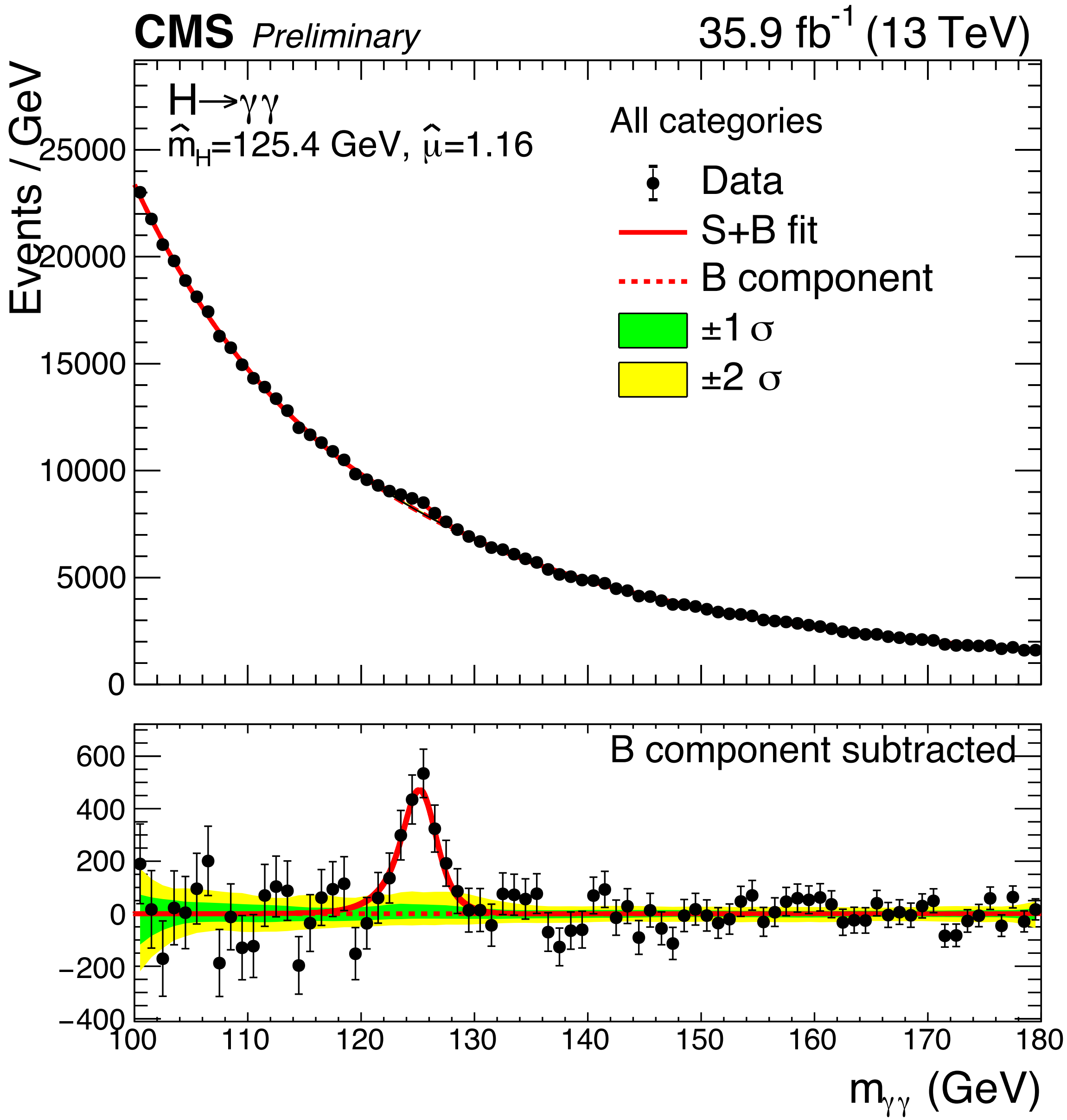
Signal extraction



Beyond Discovery



- In 2012, discovering the Higgs required a sophisticated simultaneous fit of all decay and production modes across entire experiments
- Now we *can* just add up one decay mode naively and see a clear peak
- Or we can apply our sophisticated fits to measure the properties of the Higgs boson…

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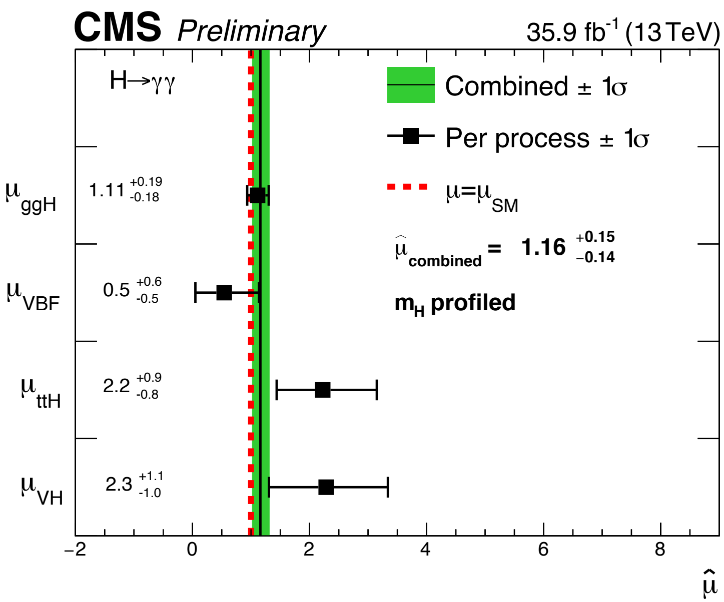
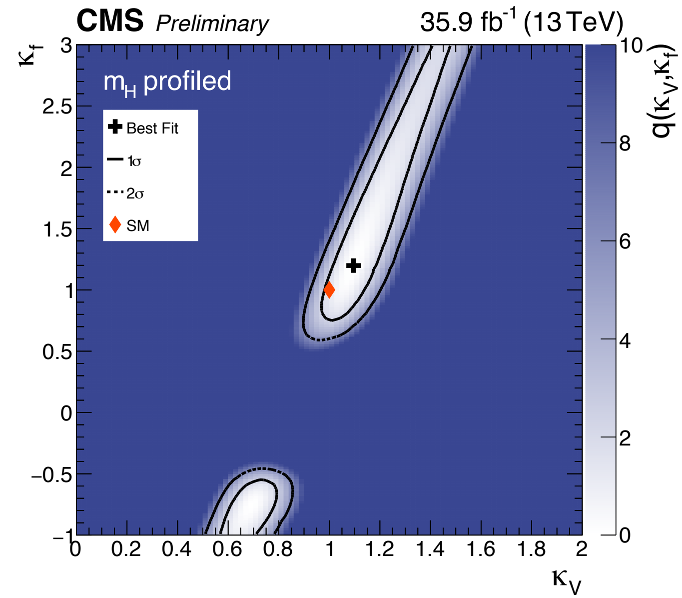
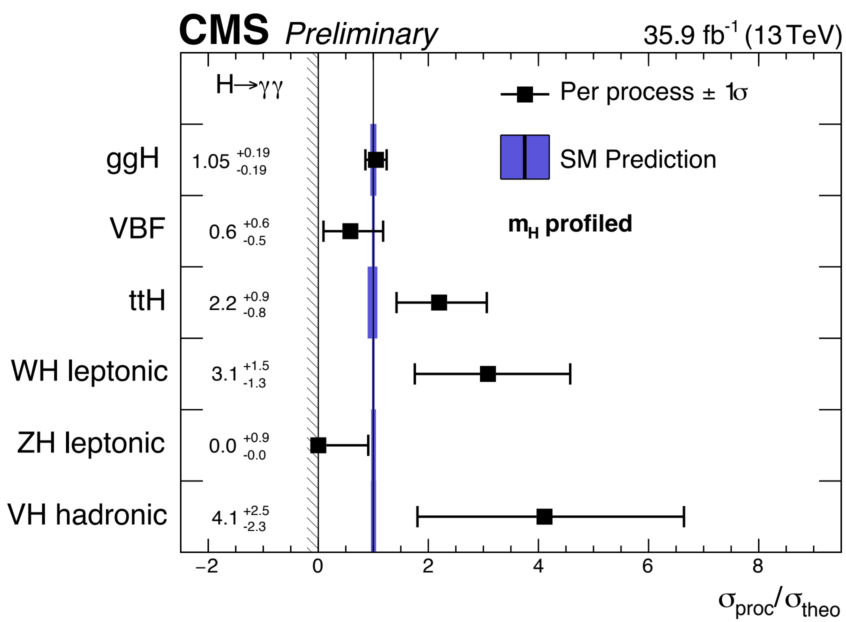
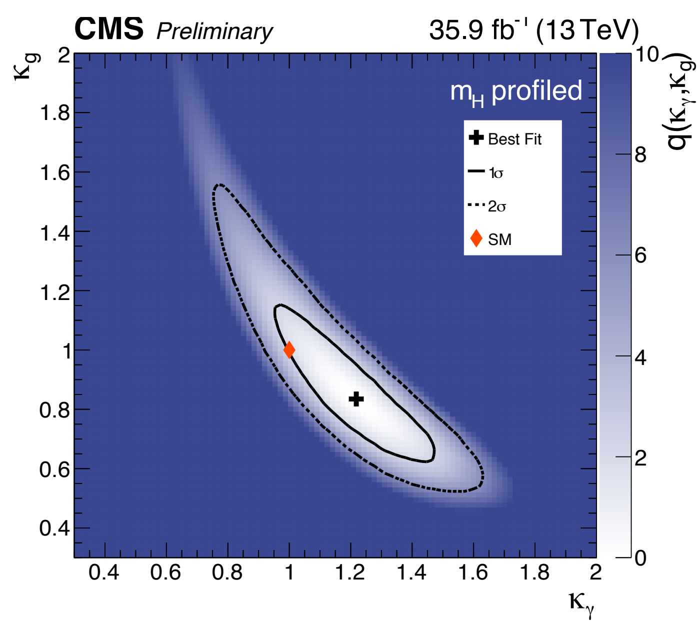
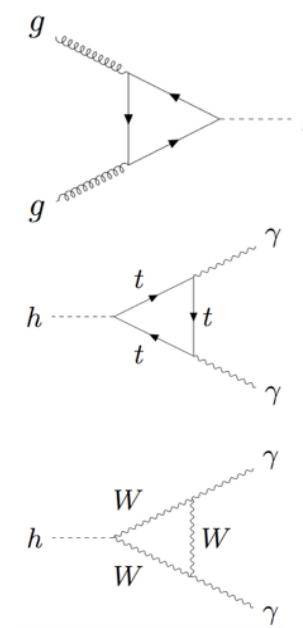
H → γγ Run 2 Results (so far)





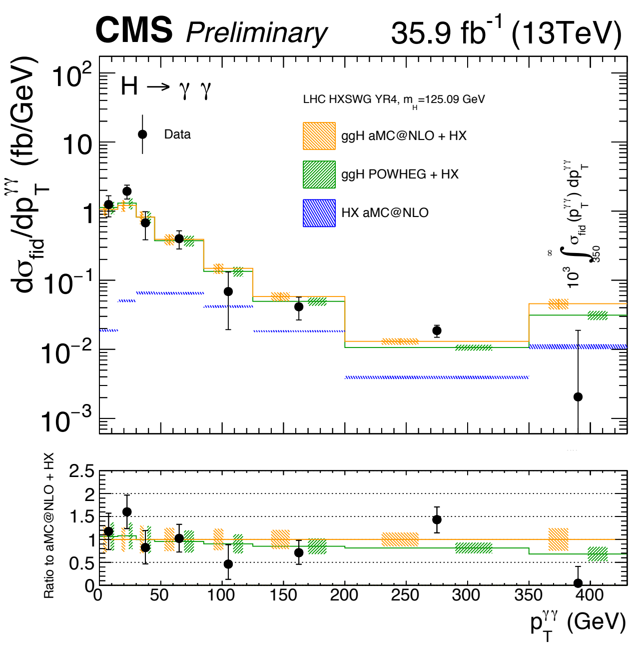


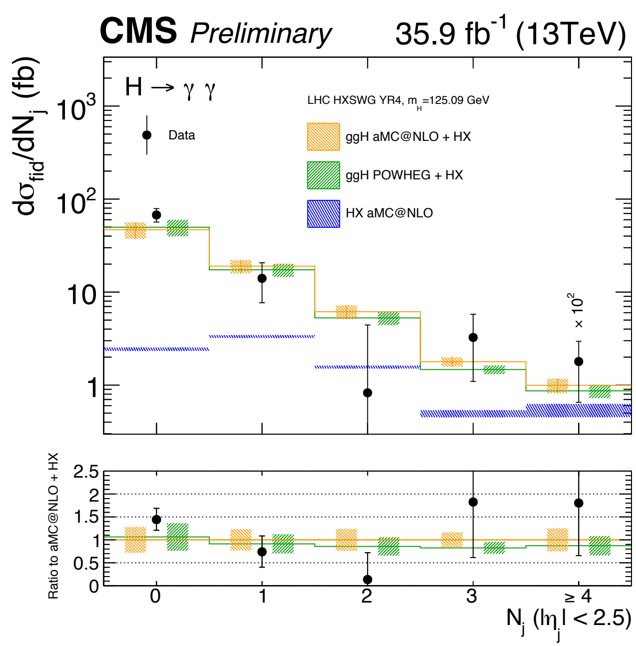




Fiducial and differential

- With simplified resolution classification, we can also bin H →γγ events in event shape variables
- Further test of SM predictions





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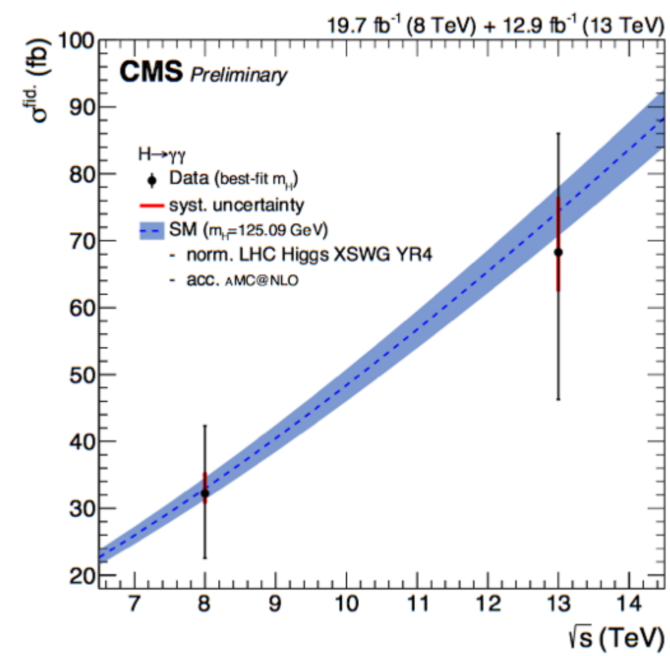

CMS-PAS-HIG-16-020

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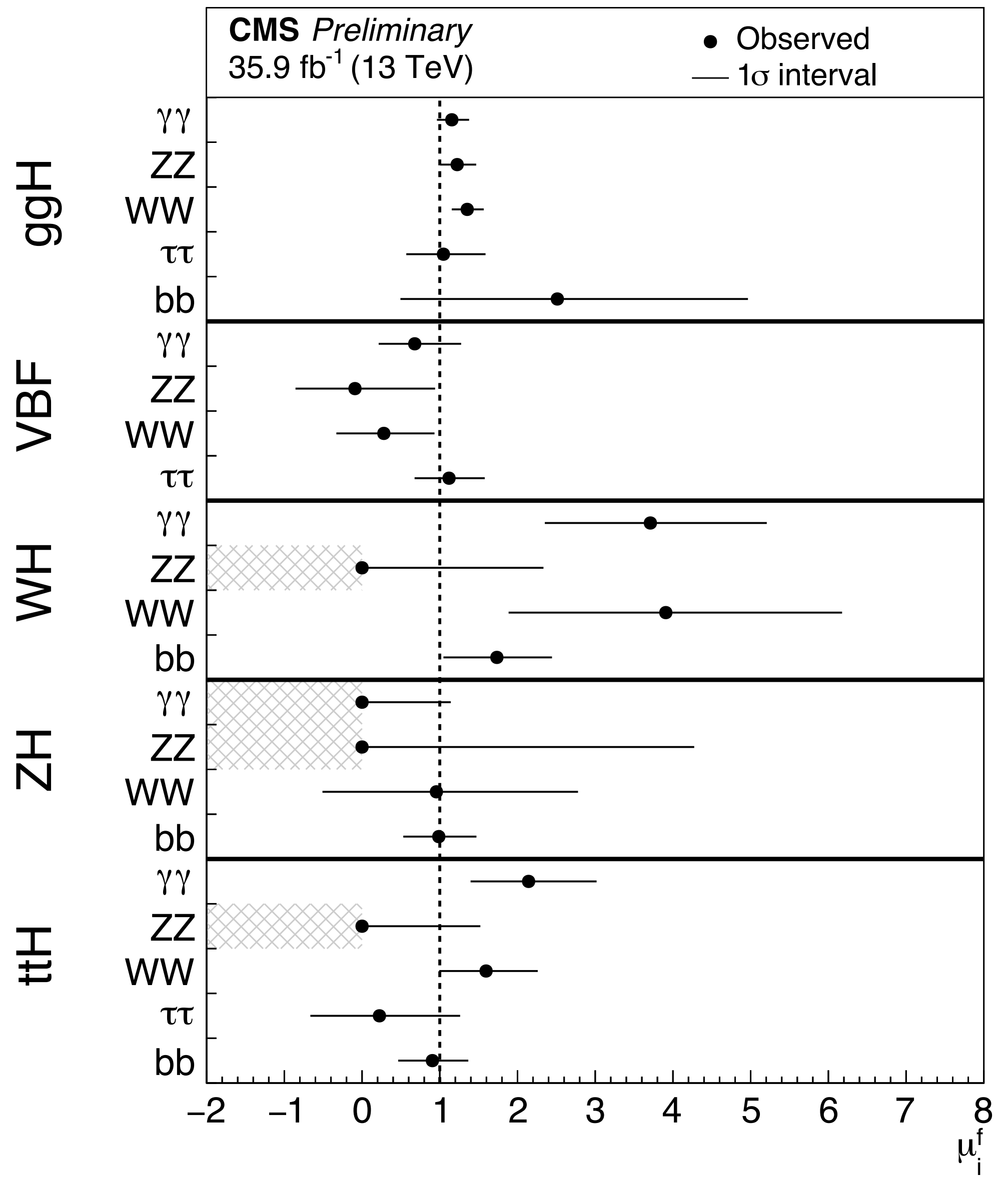
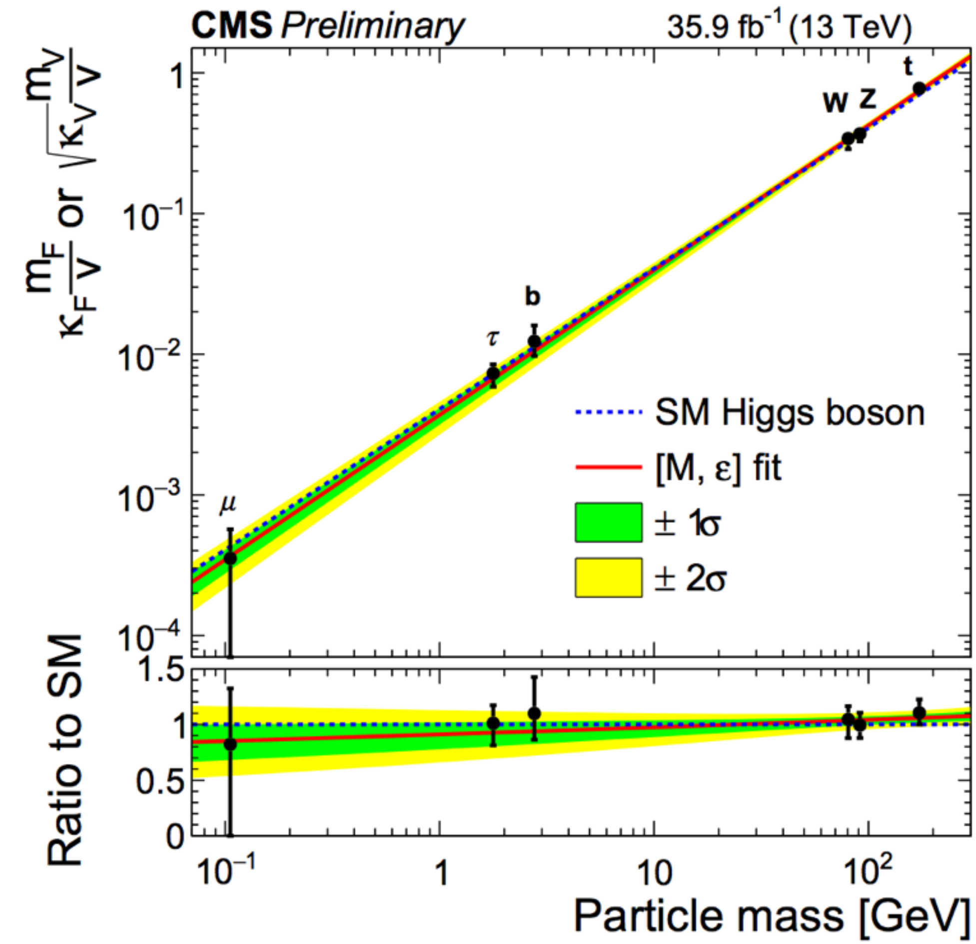
SM: The Whole Picture





CMS-PAS-HIG-17-031

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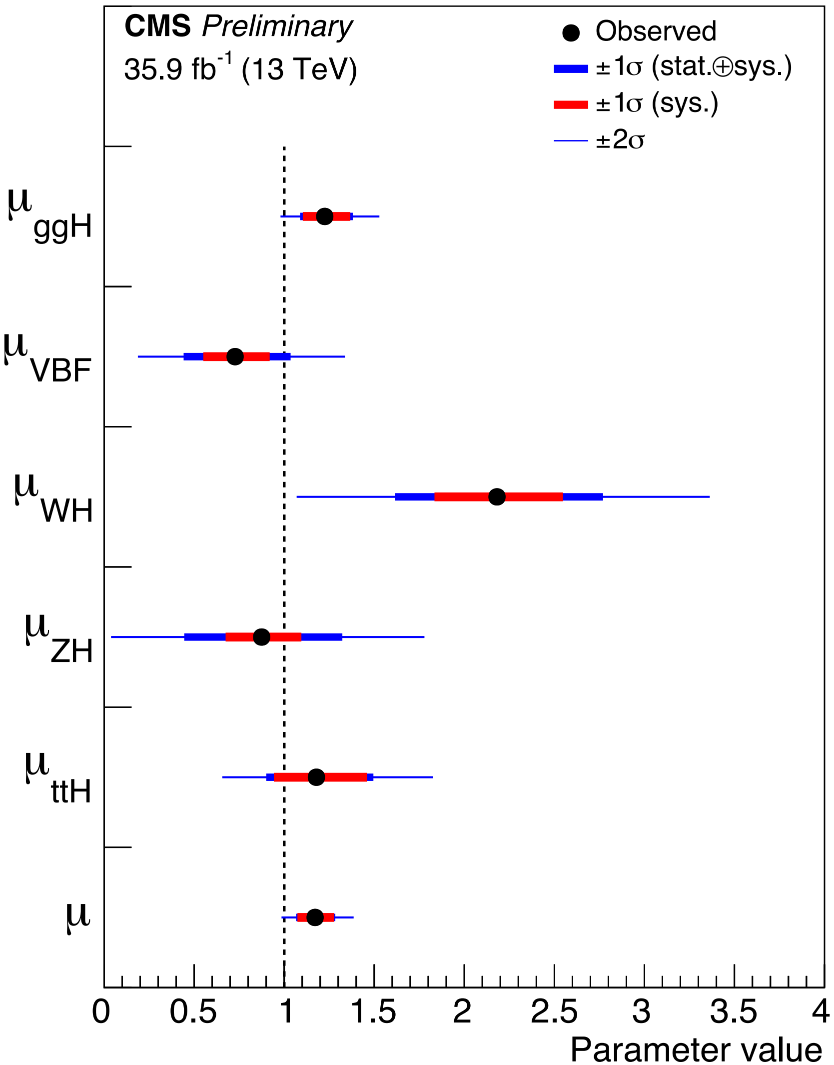
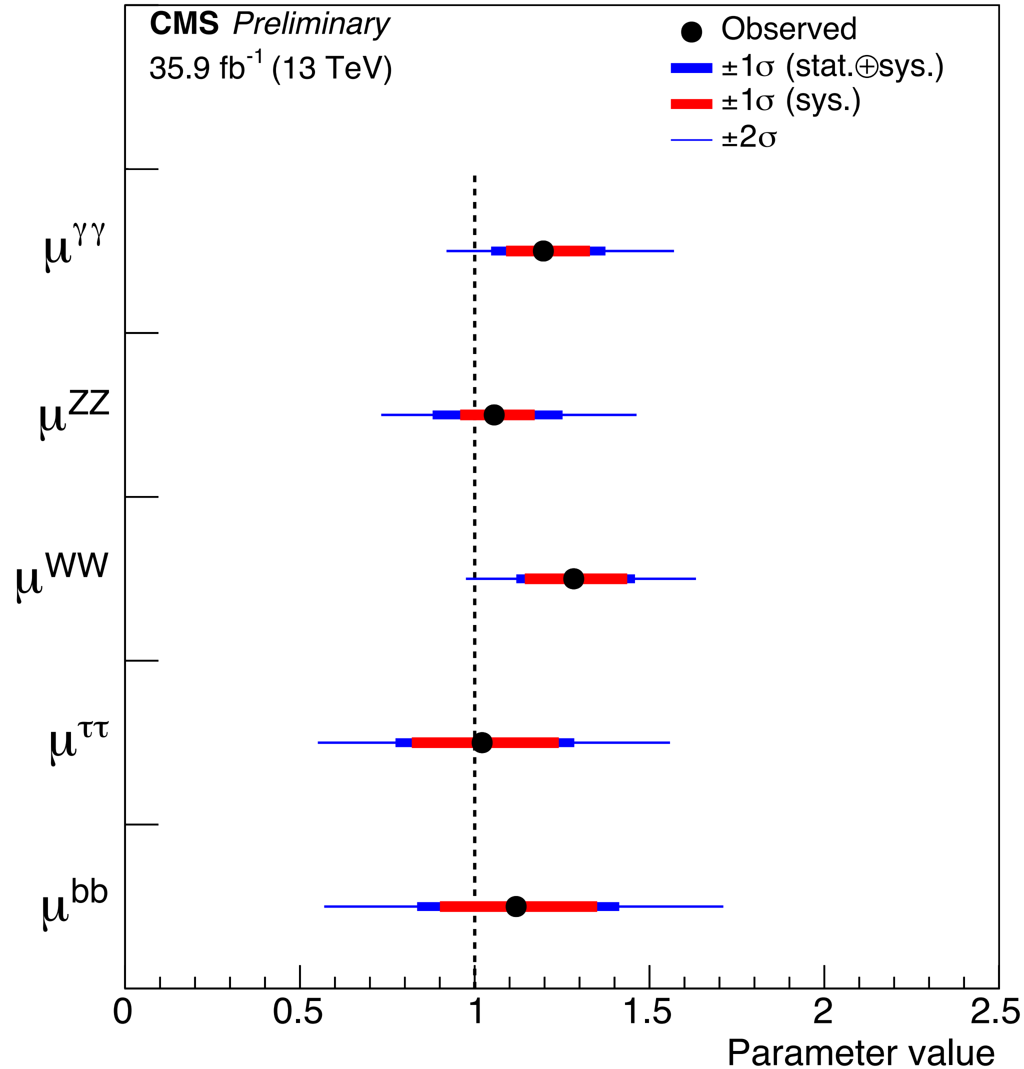
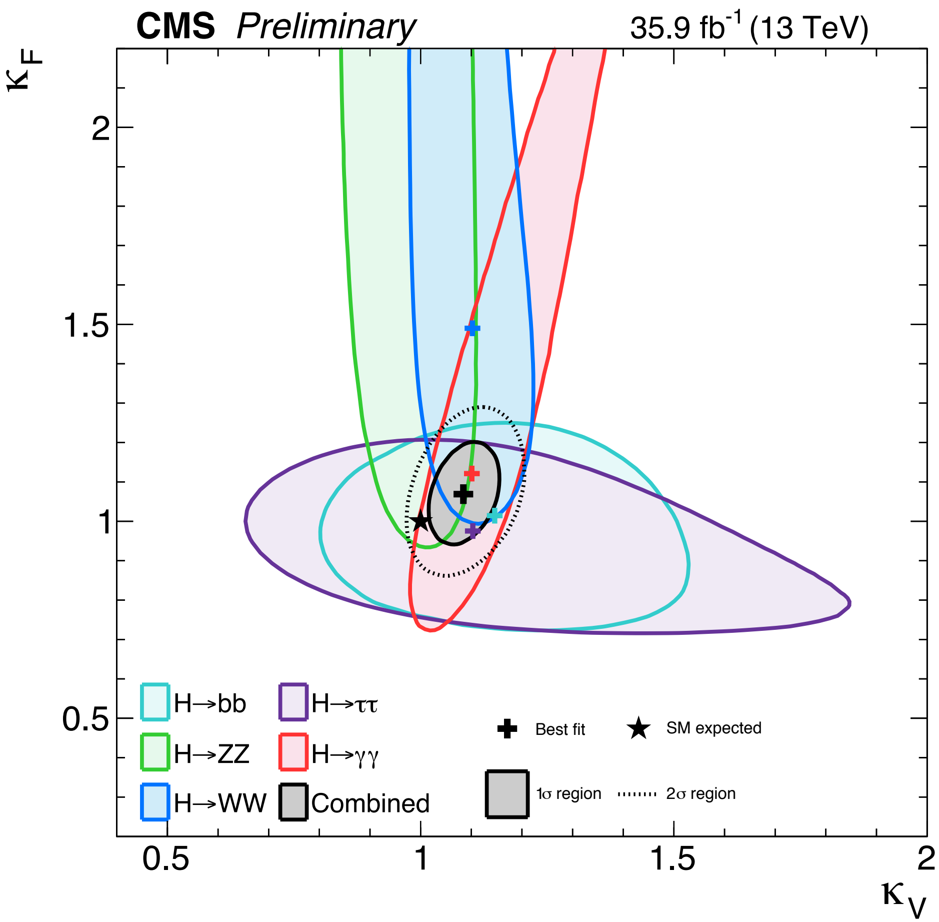
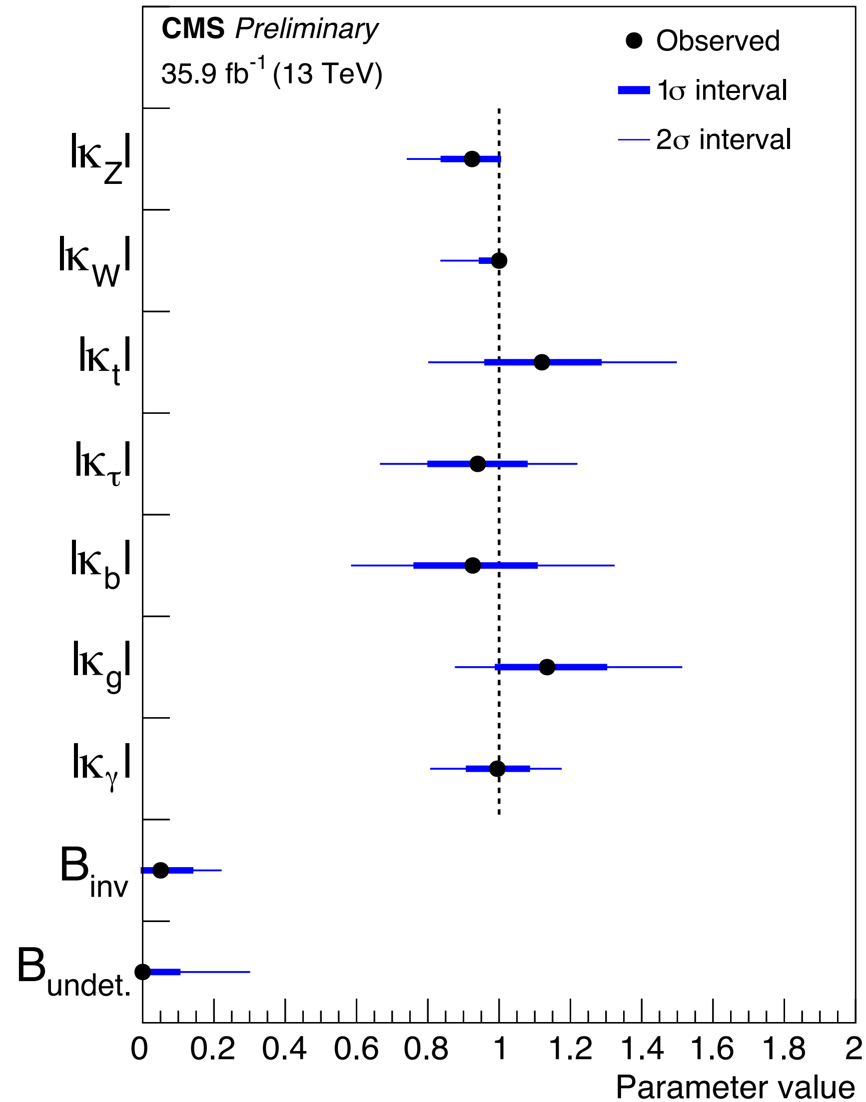
By Production and Decay





Benchmark Model Fits





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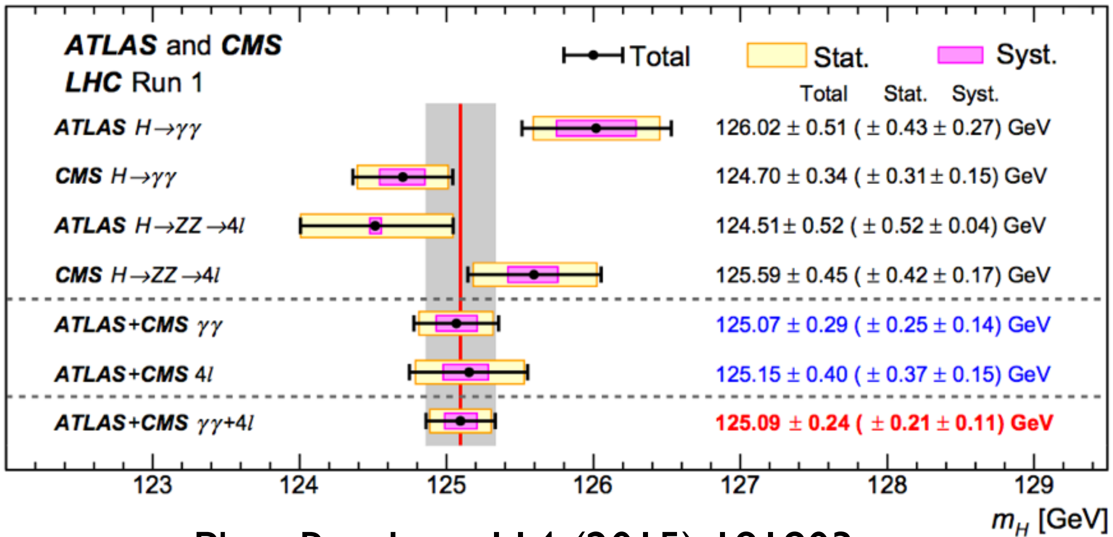
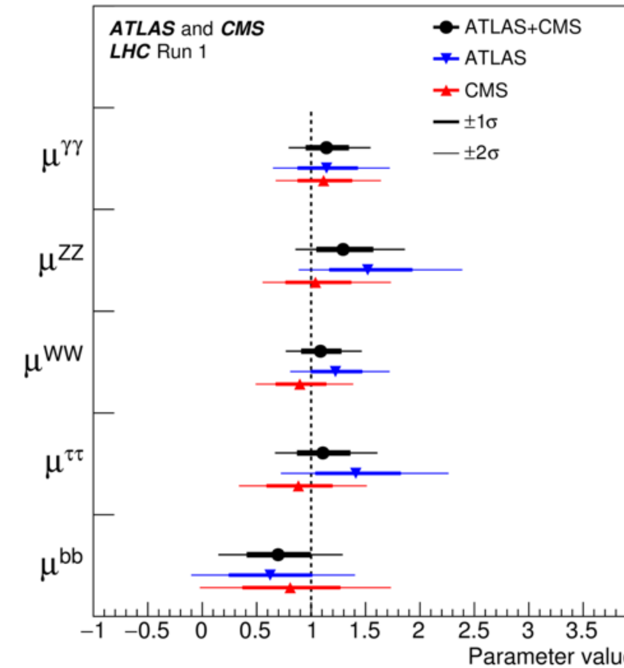
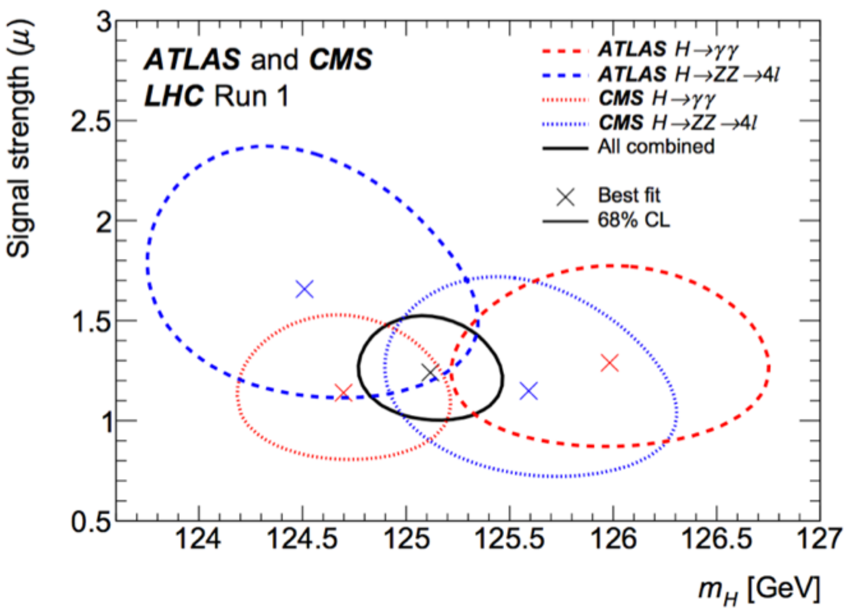
ATLAS-CMS Run 1 Combination



Phys. Rev. Lett. 114 (2015) 191803



J. High Energy Phys. 08 (2016) 045



- For the word's best Higgs measurements, use all available data from the LHC!
- Which mass uncertainty is not like the others?

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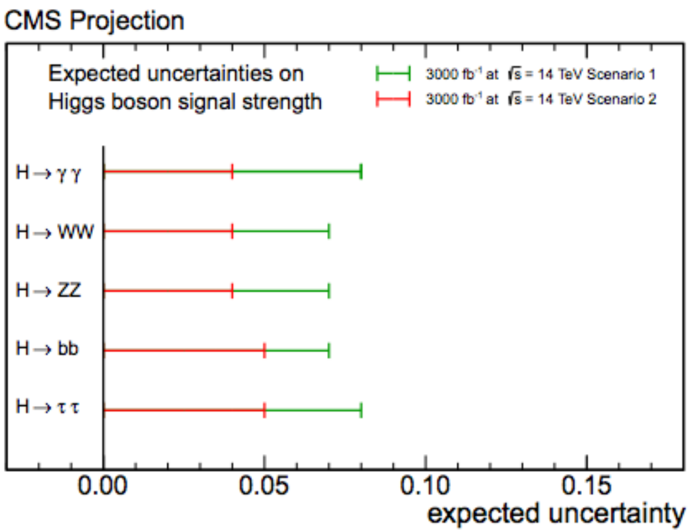
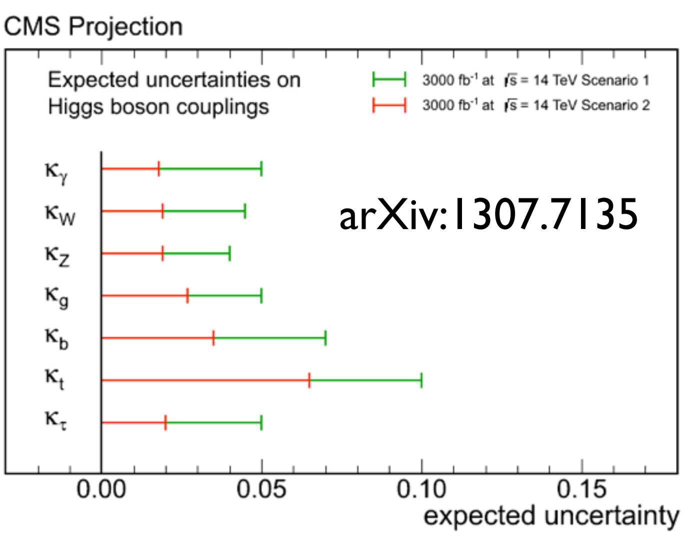
The HL-LHC

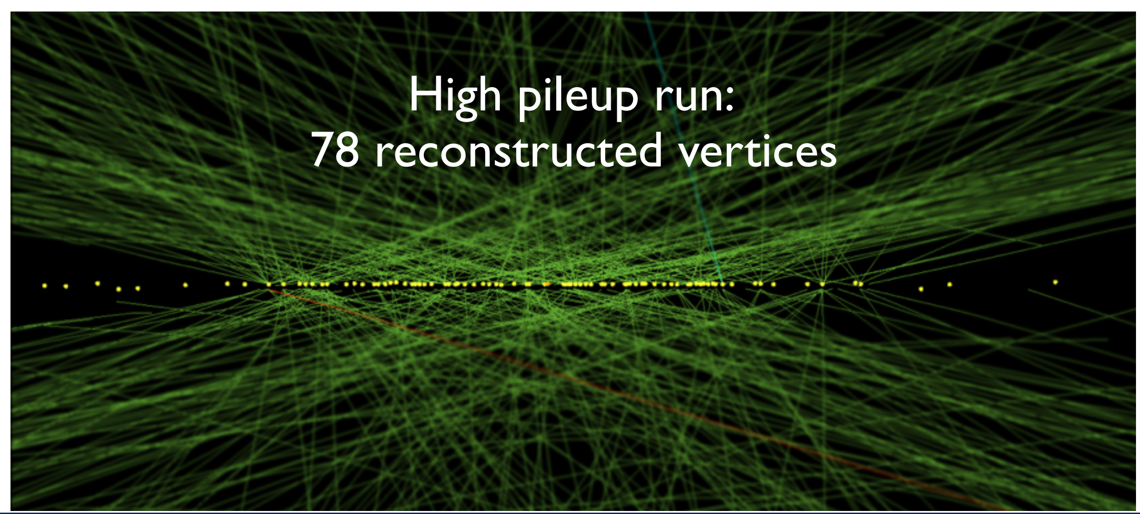
- High luminosity LHC will collect up to 3000 fb^{-1} starting in 2025
- Critical challenge: maintaining performance with 140 pileup



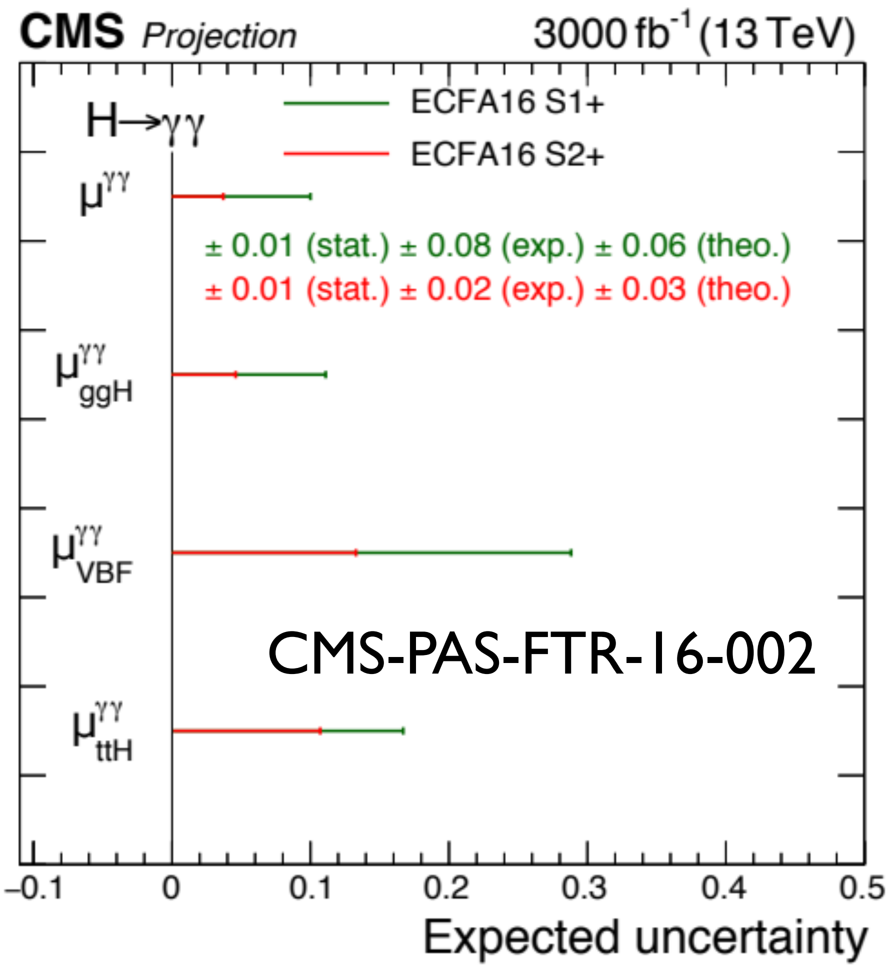


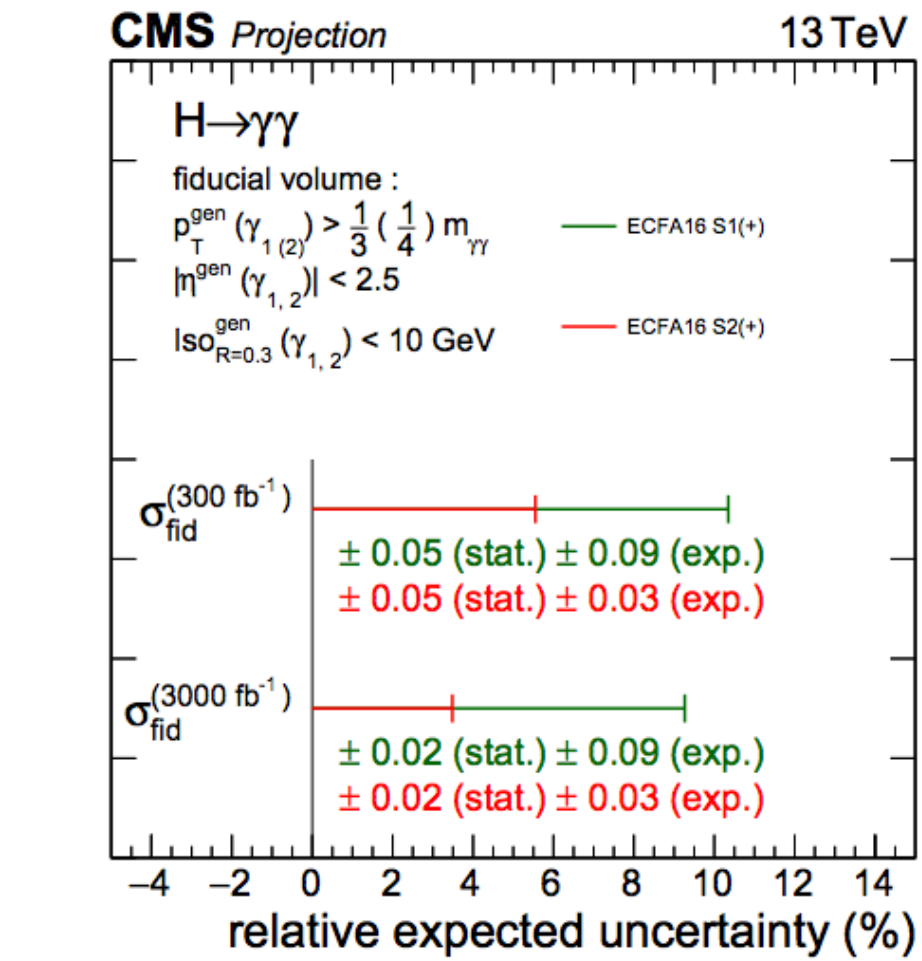
arXiv:1307.7135

SM Higgs Process	Number of events
All, LHC Run 1	660k
All, HL-LHC, 3000 fb^{-1}	170M
VBF Production (all decays)	13M
ttH Production (all decays)	1.8M
$H \to \gamma\gamma$	390k
$H \to Z\gamma$	260k
$H \to \mu\mu$	37k
HH (all decays)	121k
HH → WWWW	5580
$HH \to bb\gamma\gamma$	320
$HH \to \gamma\gamma\gamma\gamma$	0.6



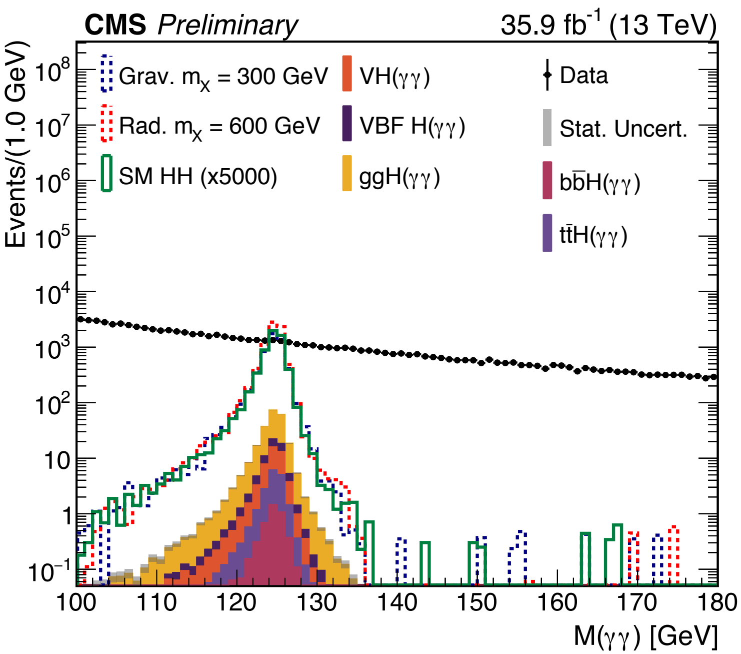
H → γγ at HL-LHC

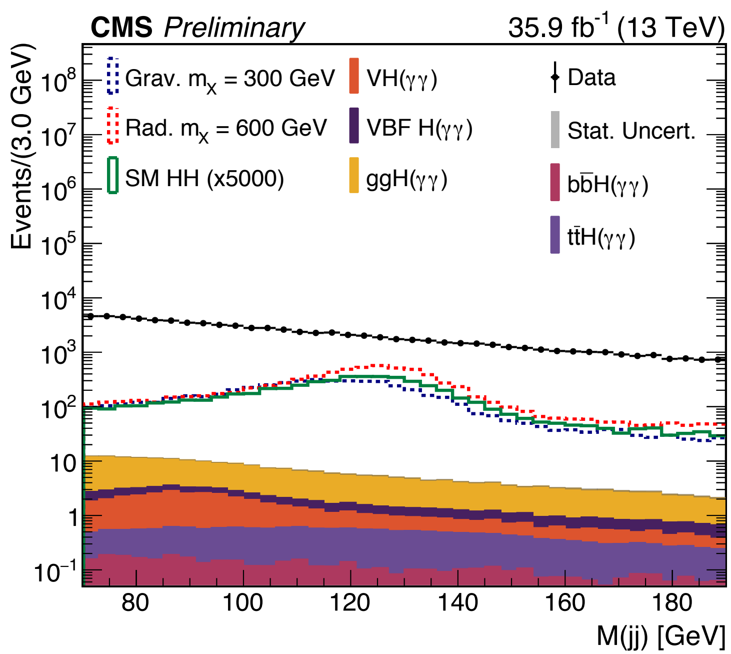


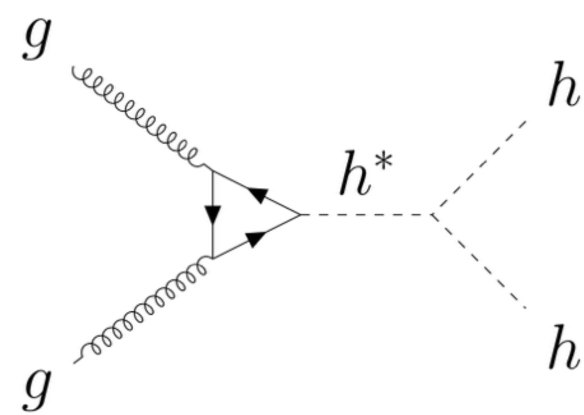


- Extremely precise H →γγ HL-LHC fiducial cross section projection
- ⇒ we can do very finely binned differential measurements

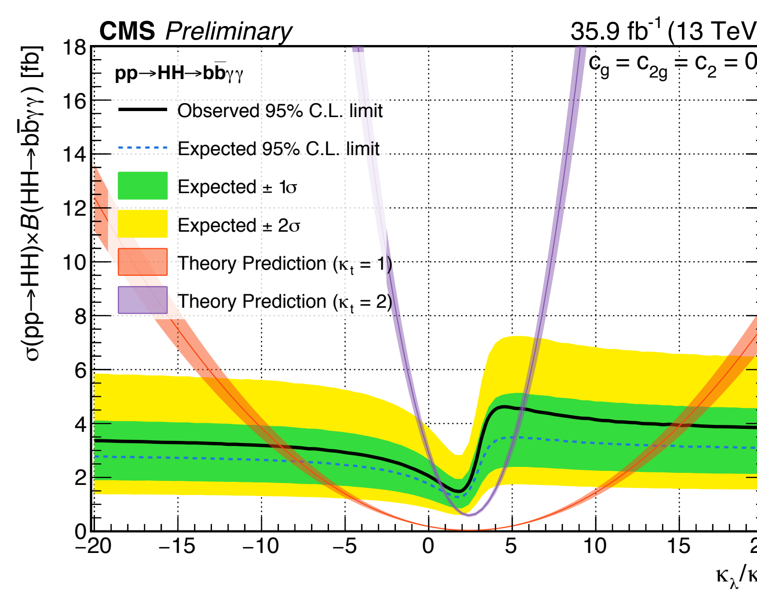
Di-Higgs







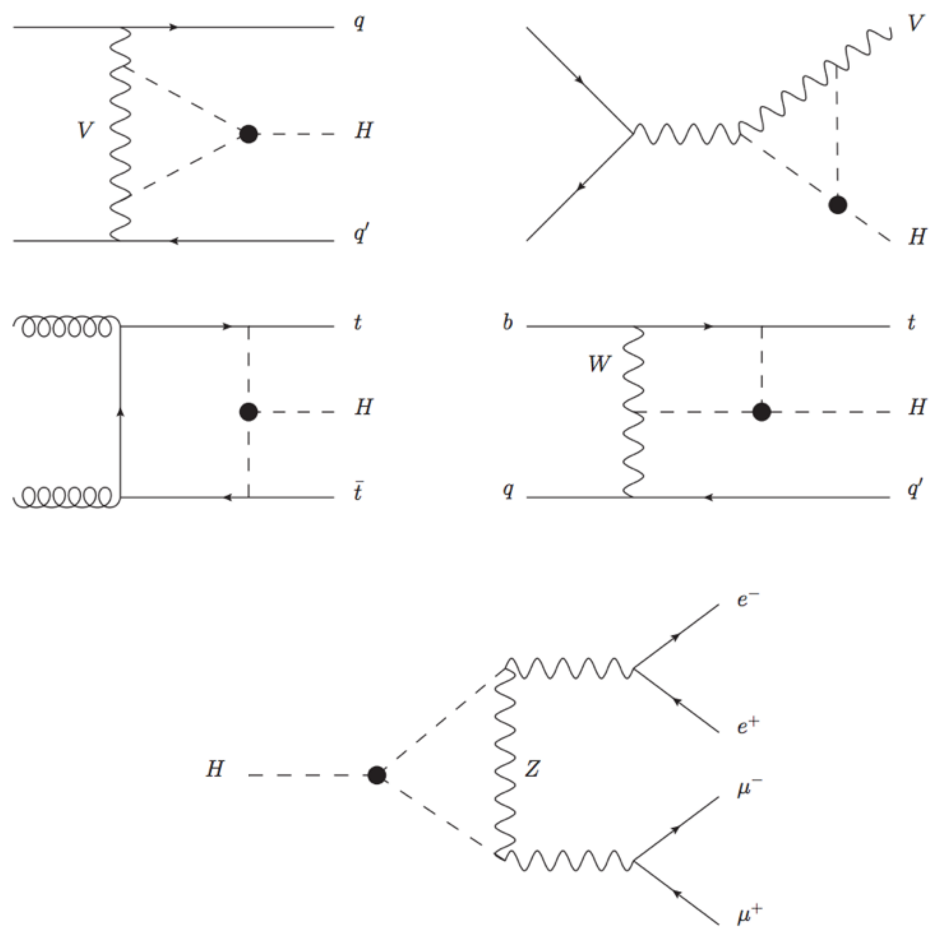
CMS-PAS-HIG-17-008

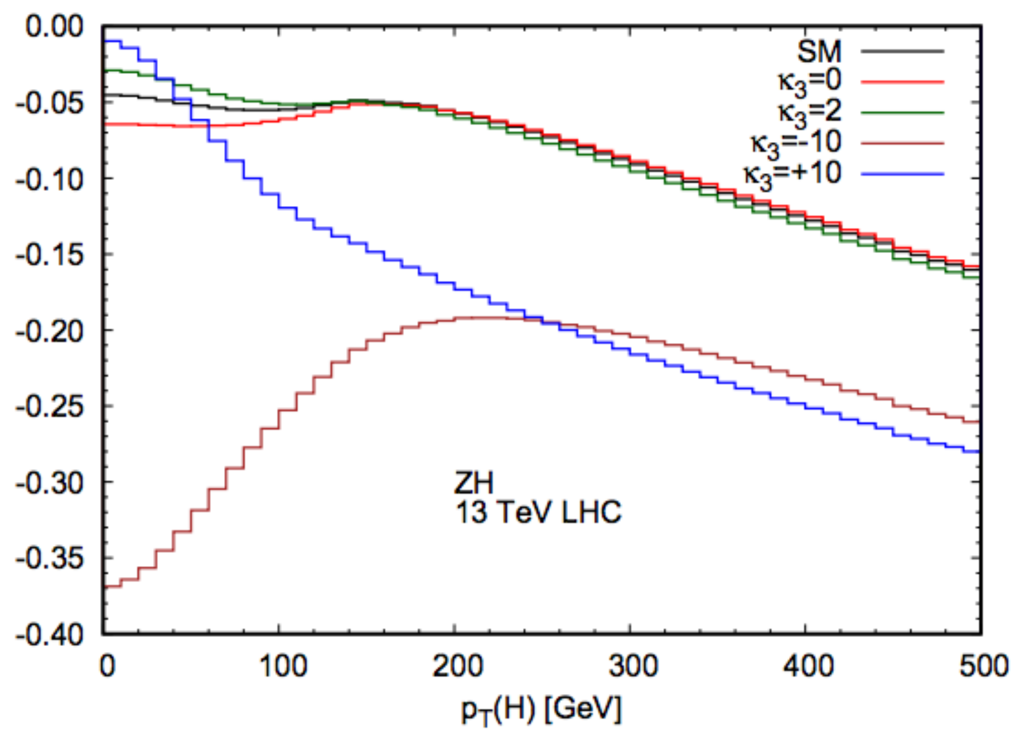


- With 2016 data, HH → bbγγ cross section limit (95% CL) less than 19.2 times the SM
- 3000 fb^{-1} is about the right amount of data to measure the SM prediction!

Higgs Trilinear coupling

- Non-SM trilinear coupling also changes single Higgs cross sections, including changing differential distributions





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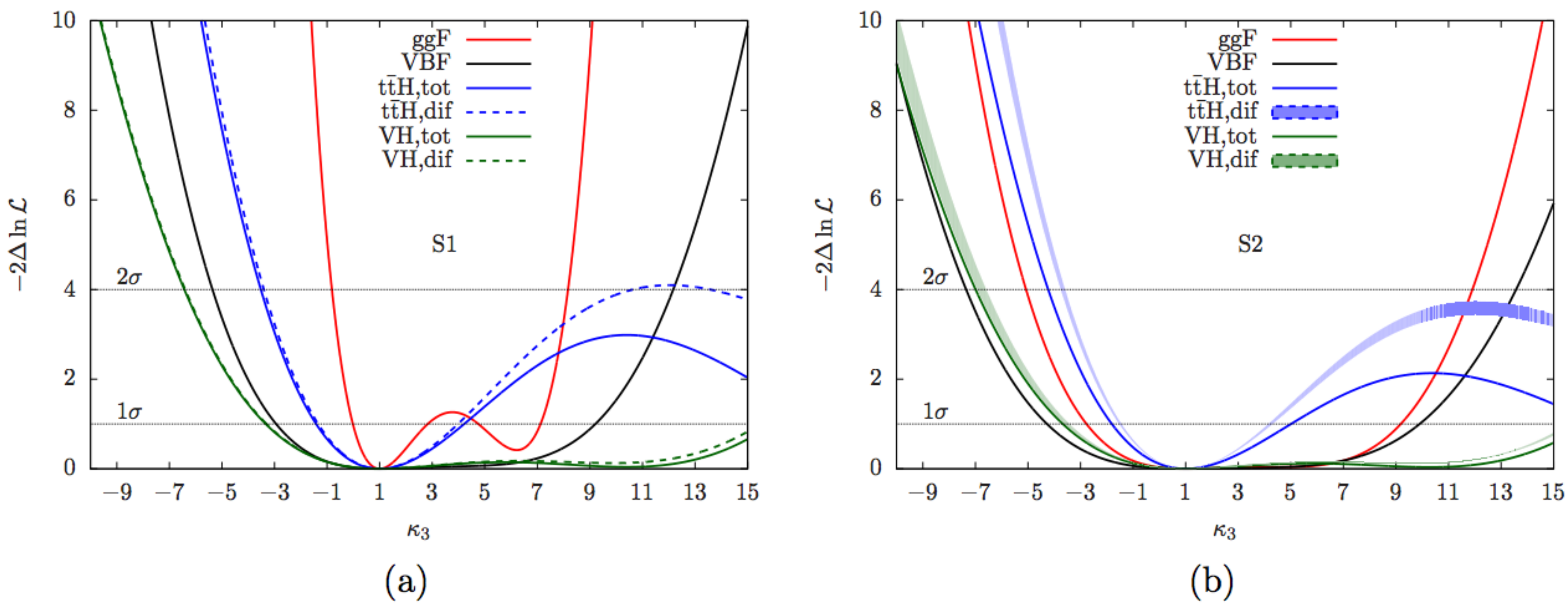

Figure 12: 1σ and 2σ bounds on κ_3 from single production processes, based on future projections for ATLAS-HL at 14 TeV. Left: only statistical uncertainty (S1). Right: experimental systematic uncertainty and theory uncertainty included (S2).

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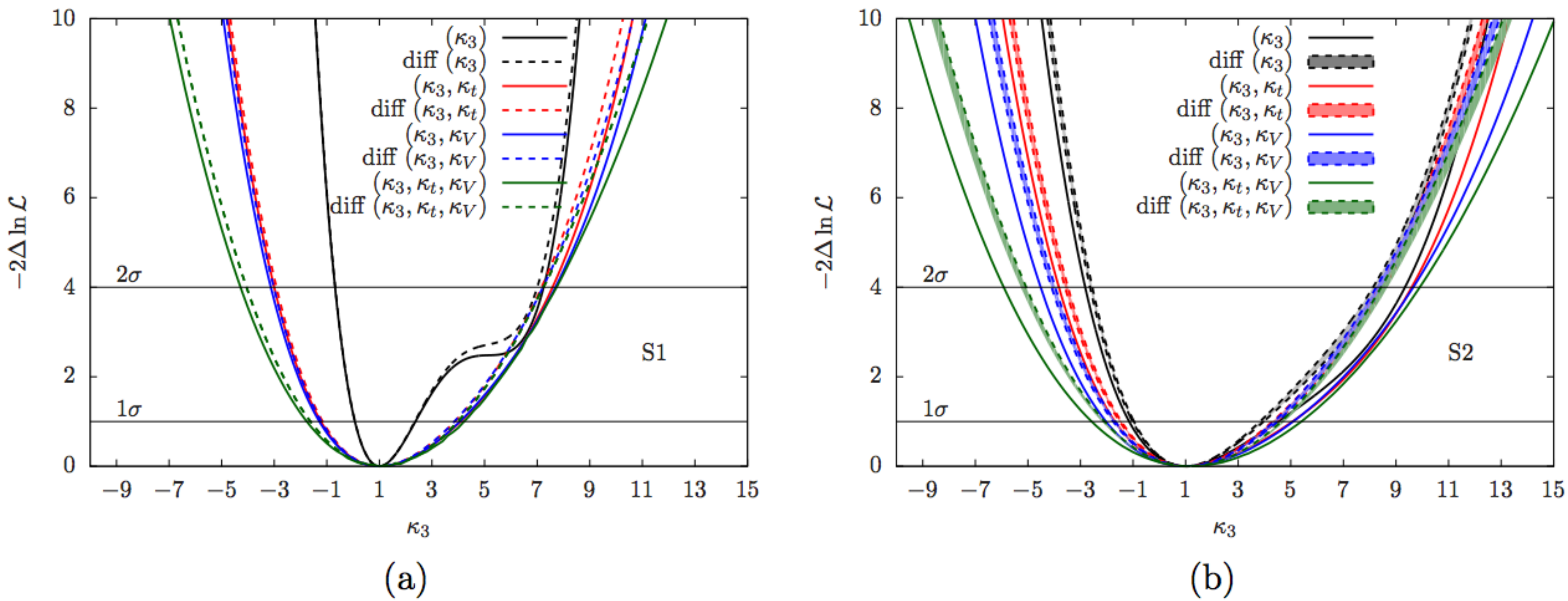

Figure 13: 1σ and 2σ bounds on κ_3 including all production processes, based on future projections for ATLAS-HL at 14 TeV. Left: only statistical uncertainty (S1). Right: experimental systematic uncertainty and theory uncertainty included (S2).

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Higgs Trilinear Coupling

- Non-SM trilinear coupling also changes single Higgs cross sections, including changing differential distributions
- What if we combine these constraints with di-Higgs searches, or even do a broader electroweak fit?
- How much data do we really need to tightly constrain the Higgs trilinear coupling?

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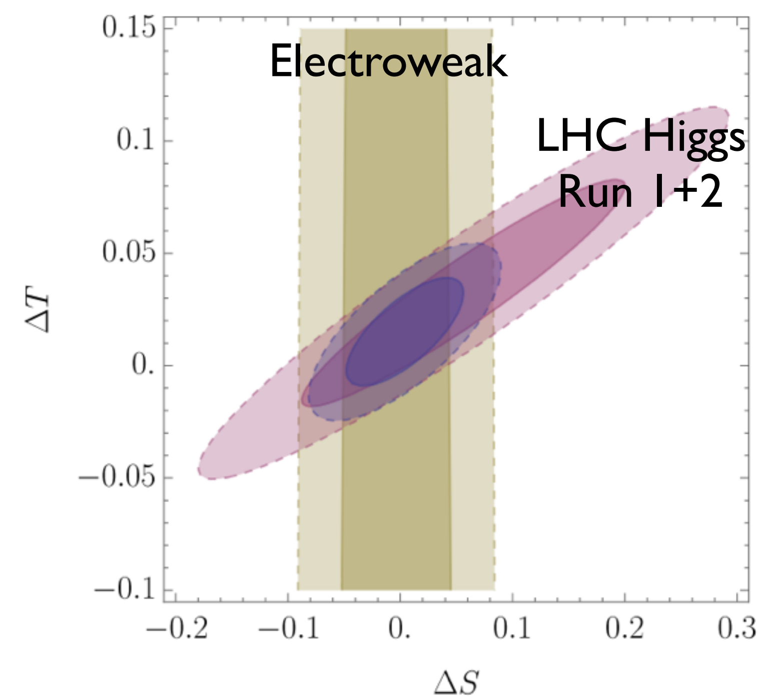
Higgs Trilinear Coupling

- Non-SM trilinear coupling also changes single Higgs cross sections, including changing differential distributions
- What if we combine these constraints with di-Higgs searches, or even do a broader electroweak fit?
- How much data do we really need to tightly constrain the Higgs trilinear coupling?
- Should we be thinking bigger and measuring a range of Effective Field Theory (EFT) parameters?



Updated Global SMEFT Fit to Higgs, Diboson and Electroweak Data

John Ellis[a,b], Christopher W. Murphy[c], Verónica Sanz[d] and Tevong You[e]

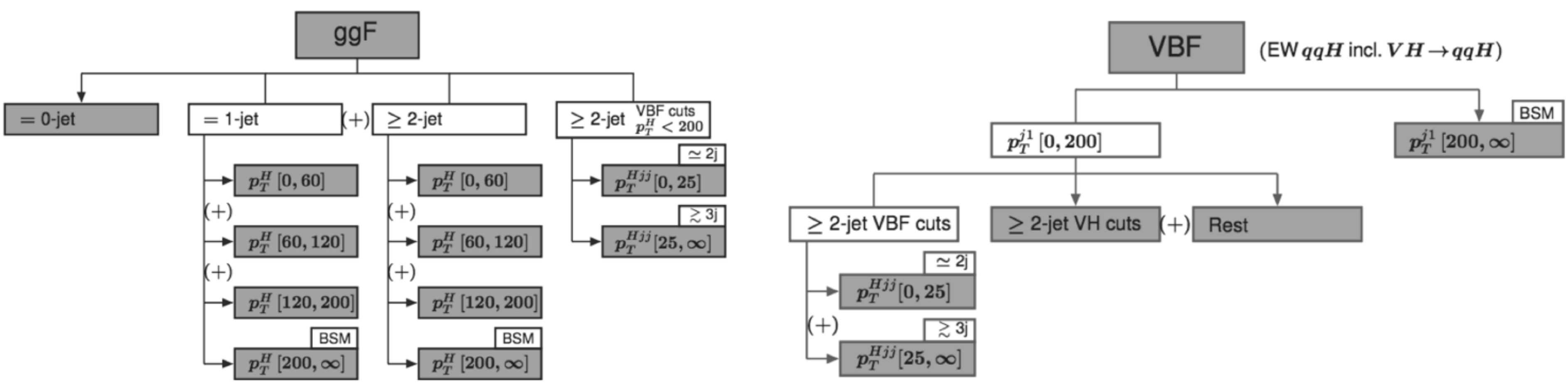
arXiv:1803.03252

Outline

- The Higgs, the Standard Model, and the Large Hadron Collider
- Compact Muon Solenoid detector (as an example)
- Higgs Properties → Analysis Strategy
  - Production and decay modes
  - Overview of $H \to \gamma\gamma$ (as an example)
- **Where we are**: what sort of Higgs Boson is it?
  - Production and decay
  - Differential measurements
- **Where we're going**: the High Luminosity LHC (2025 and beyond)
  - Analysis projections and measurements
  - Higgs trilinear couplings
- **How to get there**, and what can we learn along the way?
  - Measurements for Run 2 (2015-18) and Run 3 (2021-23)
  - Stepping stones toward the HL-LHC

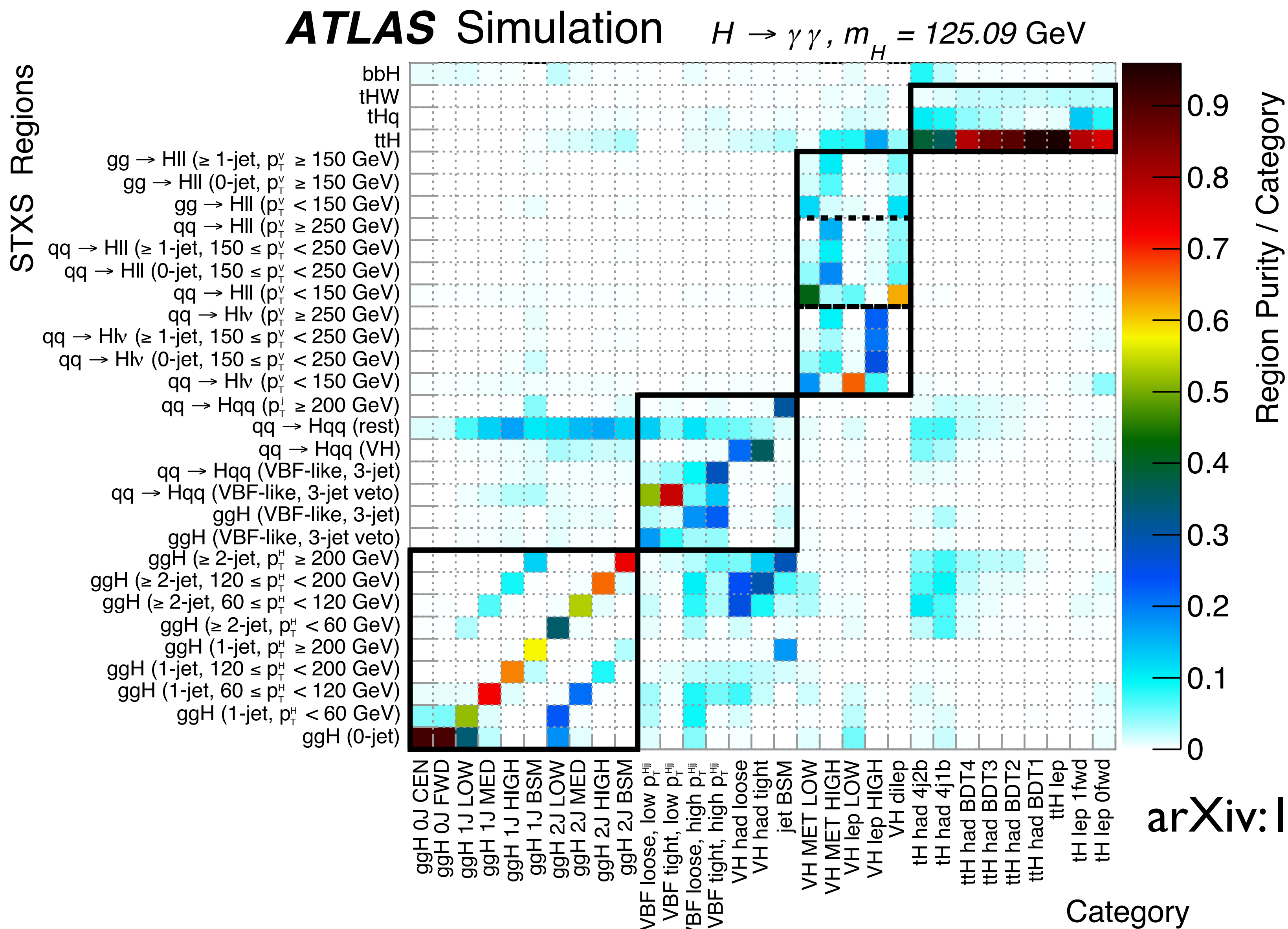
New Properties to Measure in Run 2 and 3

- Run 2 SM Higgs analyses must be adapted for improved properties measurements
- Example idea being implemented: Simplified Higgs Template Cross Sections
- Extract μ-like cross section scalings in defined phase space(s)
  - Reduce theory uncertainties
  - More precisely targeted as more data become available
- Other frameworks: expanded κ's, Effective Field Theory parameters
- What's the best approach for experiment to communicate with theory?



Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector, arXiv:1610.07922

STXS Stage 1



arXiv:1802.04146

Stepping Stones: STXS Bin Merging

Process	Measurement region	Particle-level stage-1 region
ggH + $gg \to Z(\to qq)H$	0-jet	0-jet
	1-jet, $p_T^H < 60$ GeV	1-jet, $p_T^H < 60$ GeV
	1-jet, $60 \leq p_T^H < 120$ GeV	1-jet, $60 \leq p_T^H < 120$ GeV
	1-jet, $120 \leq p_T^H < 200$ GeV	1-jet, $120 \leq p_T^H < 200$ GeV
	$\geq$ 1-jet, $p_T^H > 200$ GeV	1-jet, $p_T^H > 200$ GeV
		$\geq$ 2-jet, $p_T^H > 200$ GeV
	$\geq$ 2-jet, $p_T^H < 200$ GeV or VBF-like	$\geq$ 2-jet, $p_T^H < 60$ GeV
		$\geq$ 2-jet, $60 \leq p_T^H < 120$ GeV
		$\geq$ 2-jet, $120 \leq p_T^H < 200$ GeV
		VBF-like, $p_T^{Hjj} < 25$ GeV
		VBF-like, $p_T^{Hjj} \geq 25$ GeV
$qq' \to Hqq'$ (VBF + VH)	$p_T^j < 200$ GeV	$p_T^j < 200$ GeV, VBF-like, $p_T^{Hjj} < 25$ GeV
		$p_T^j < 200$ GeV, VBF-like, $p_T^{Hjj} \geq 25$ GeV
		$p_T^j < 200$ GeV, VH-like
		$p_T^j < 200$ GeV, Rest
	$p_T^j > 200$ GeV	$p_T^j > 200$ GeV
VH (leptonic decays)	VH leptonic	$q\bar{q} \to ZH$, $p_T^Z < 150$ GeV
		$q\bar{q} \to ZH$, $150 < p_T^Z < 250$ GeV, 0-jet
		$q\bar{q} \to ZH$, $150 < p_T^Z < 250$ GeV, $\geq$ 1-jet
		$q\bar{q} \to ZH$, $p_T^Z > 250$ GeV
		$q\bar{q} \to WH$, $p_T^W < 150$ GeV
		$q\bar{q} \to WH$, $150 < p_T^W < 250$ GeV, 0-jet
		$q\bar{q} \to WH$, $150 < p_T^W < 250$ GeV, $\geq$ 1-jet
		$q\bar{q} \to WH$, $p_T^W > 250$ GeV
		$gg \to ZH$, $p_T^Z < 150$ GeV
		$gg \to ZH$, $p_T^Z > 150$ GeV, 0-jet
		$gg \to ZH$, $p_T^Z > 150$ GeV, $\geq$ 1-jet
Top-associated production	top	$t\bar{t}H$
		W-associated tH (tHW)
		t-channel tH (tHq)
$b\bar{b}H$	merged w/ ggH	$b\bar{b}H$

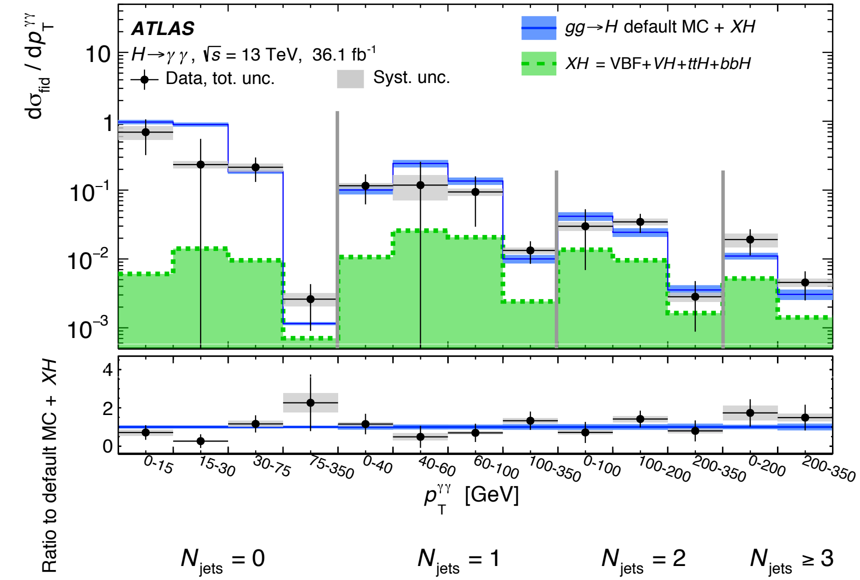
- STXS bins as initially defined are tough to measure!
- Limited statistics
- Sometimes hard to separate even in principle

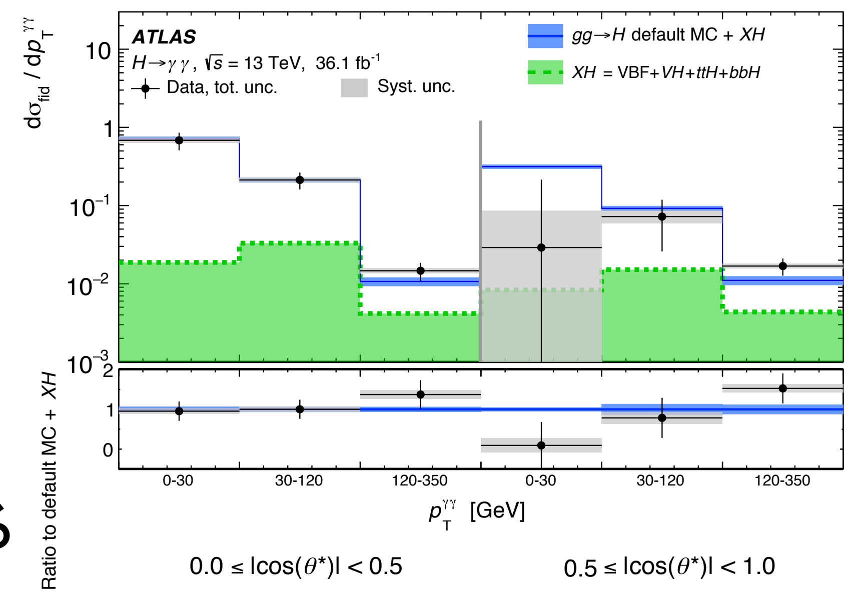
arXiv:1802.04146

Stepping Stones: Double-differential Distributions

- With HL-LHC data, we can provide decent measurements of double-differential distributions
- First examples arriving
- Future binning not mapped out (yet)… what will the impact really be?
- Goal at each step is to give the finest binning that has a meaningfully small statistical and expert

arXiv:1802.04146





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Conclusions

- Many ways to use make precision measurements of SM-like Higgs properties and potential deviations
  - Cross sections (differential, STXS, …)
  - Fits to parameters that modify the SM (κ's, EFT's)
- Related approaches would take several more seminars
  - Direct searches for BSM Higgs bosons
  - SM Higgs bosons in BSM events
  - Fits for parameters in specific BSM models (e.g. 2HDM)
- More fundamental work: detector upgrades, reconstruction, and reducing systematics
- Which ideas will bear fruit, and when?
  - All we can do is try, and find out!
  - My prediction: whatever precision we need, the right combination of state-of-the-art techniques will get us there before our current projections suggest
- Higgs looks like the Standard Model, but stay tuned…