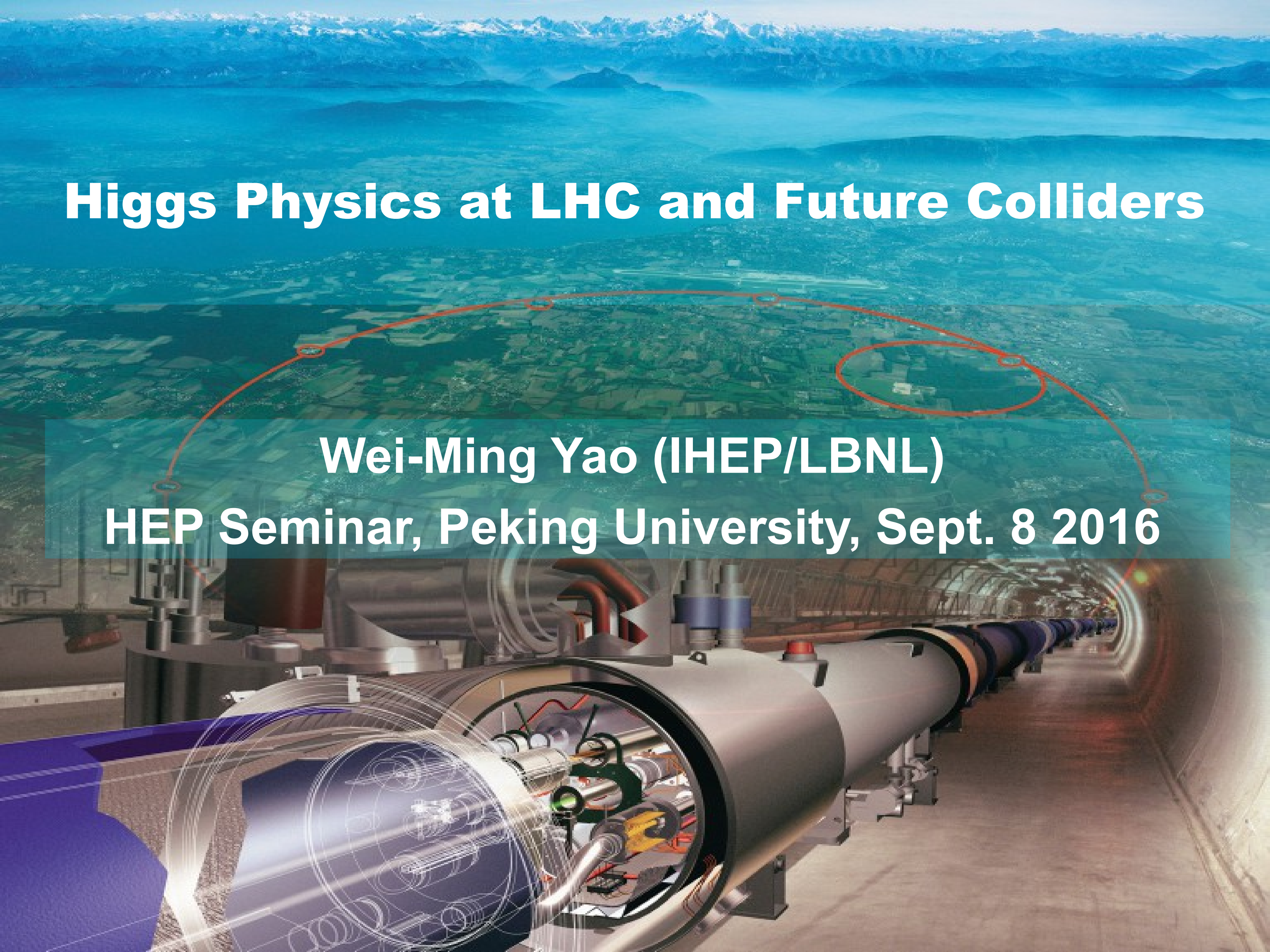


Higgs Physics at LHC and Future Colliders

Wei-Ming Yao (IHEP/LBNL)

HEP Seminar, Peking University, Sept. 8 2016

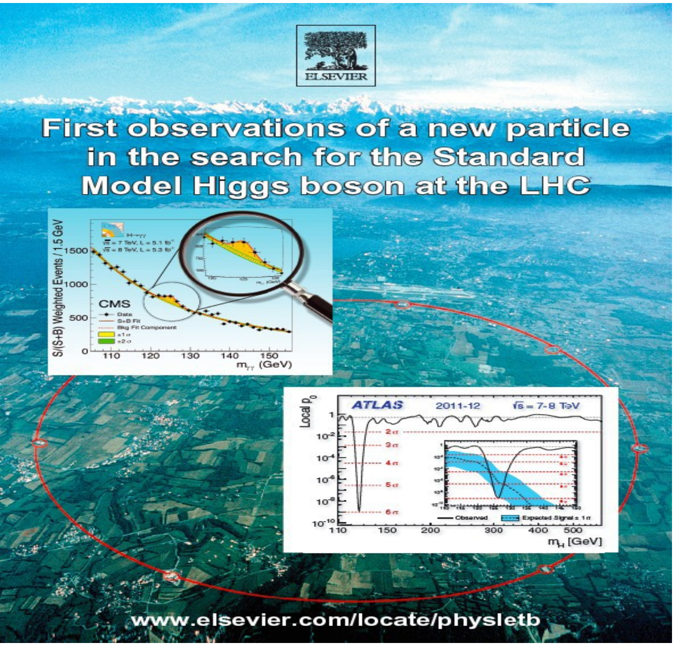
Outline

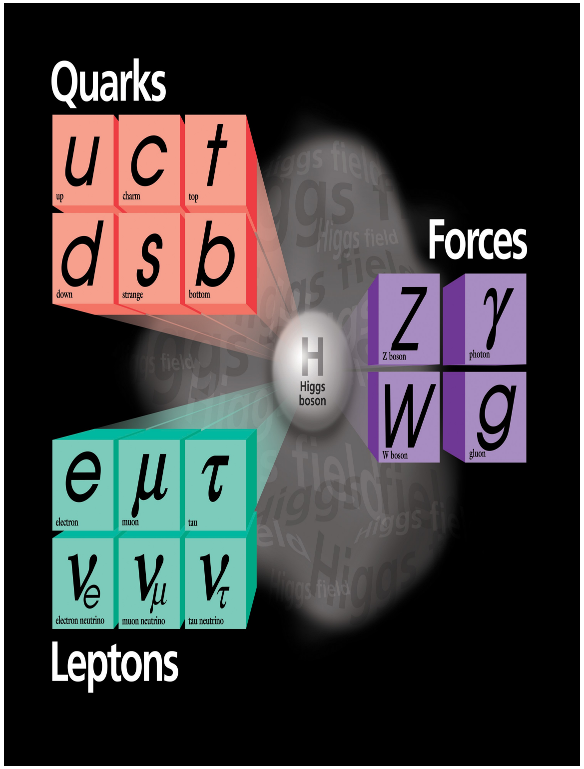
- Introduction
- The LHC program
- Highlights of Higgs results at Run2
- Higgs prospects at future colliders
- Conclusion

Introduction

•In extended run of LHC at 7 and 8 TeV, ATLAS and CMS made the anticipated discovery of Higgs boson, the culmination of a decades-long effort.

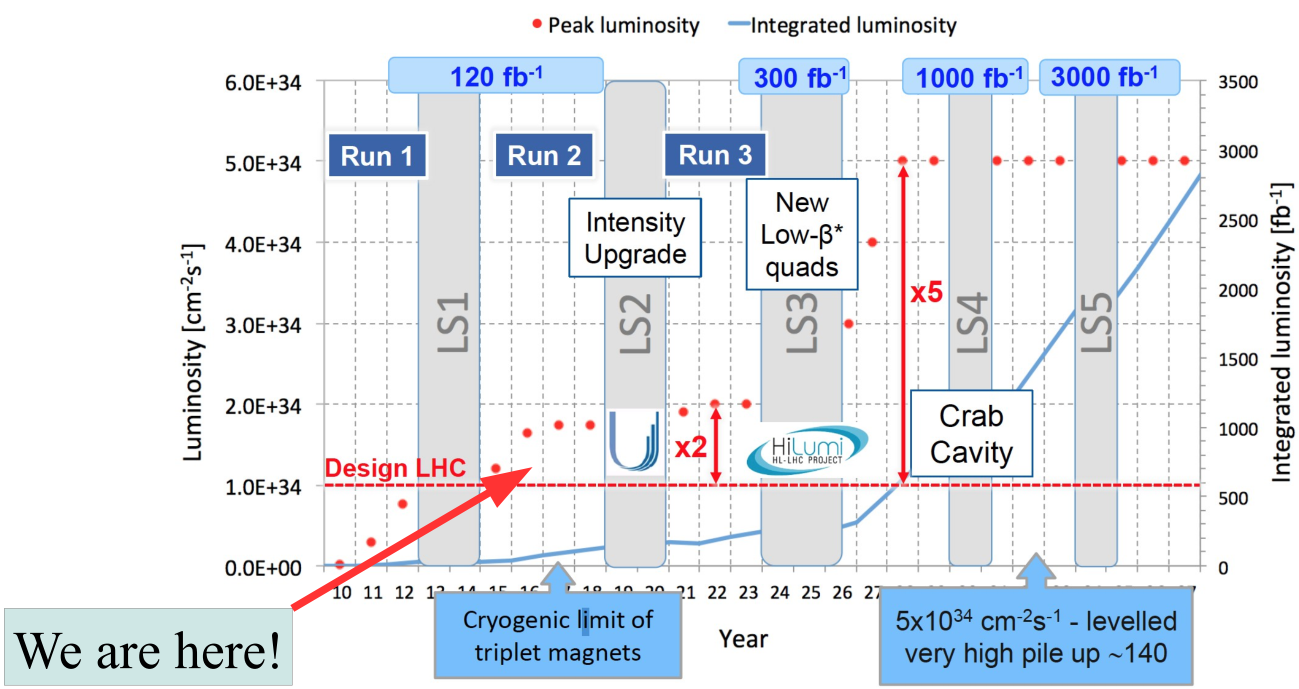
•The data so far are consistent with the Higgs boson predicted by Brout-Englert-Higgs, a cornerstone of EWSB in the standard model (SM).





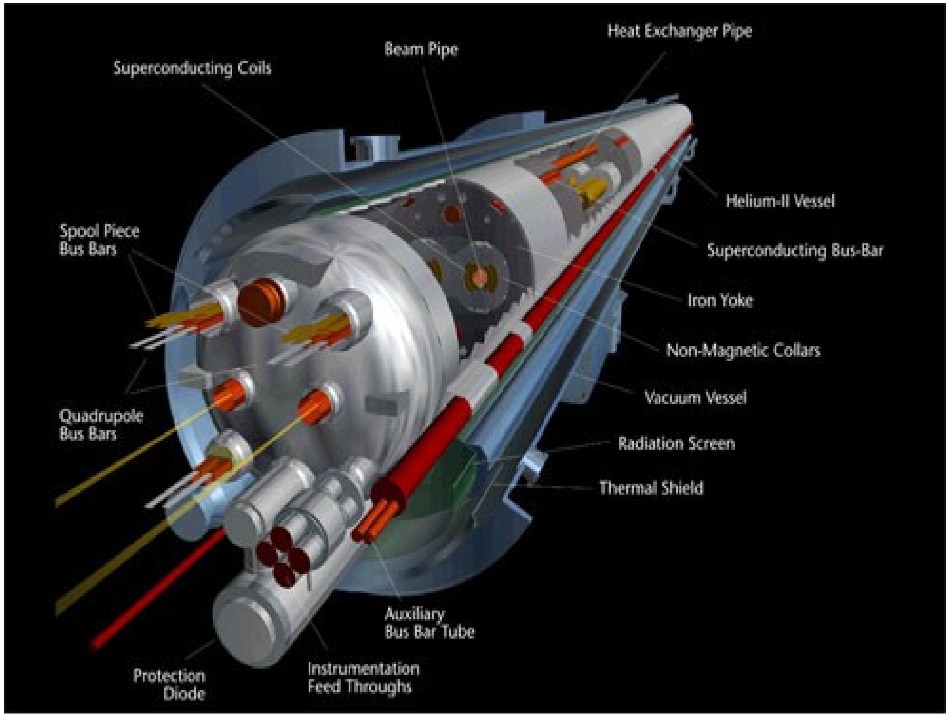
The LHC Program

- The discovery of a Higgs boson has opened the door on the scalar sector for testing validity of SM and search for BSM physics.
- With data sample up to 3000 fb^{-1} at 14 TeV LHC will provide unprecedented and unparalleled physics opportunities such as
  - Measuring the Higgs in many production and decay modes.
  - Extending the new particle searches with mass up to multi-TeV level.



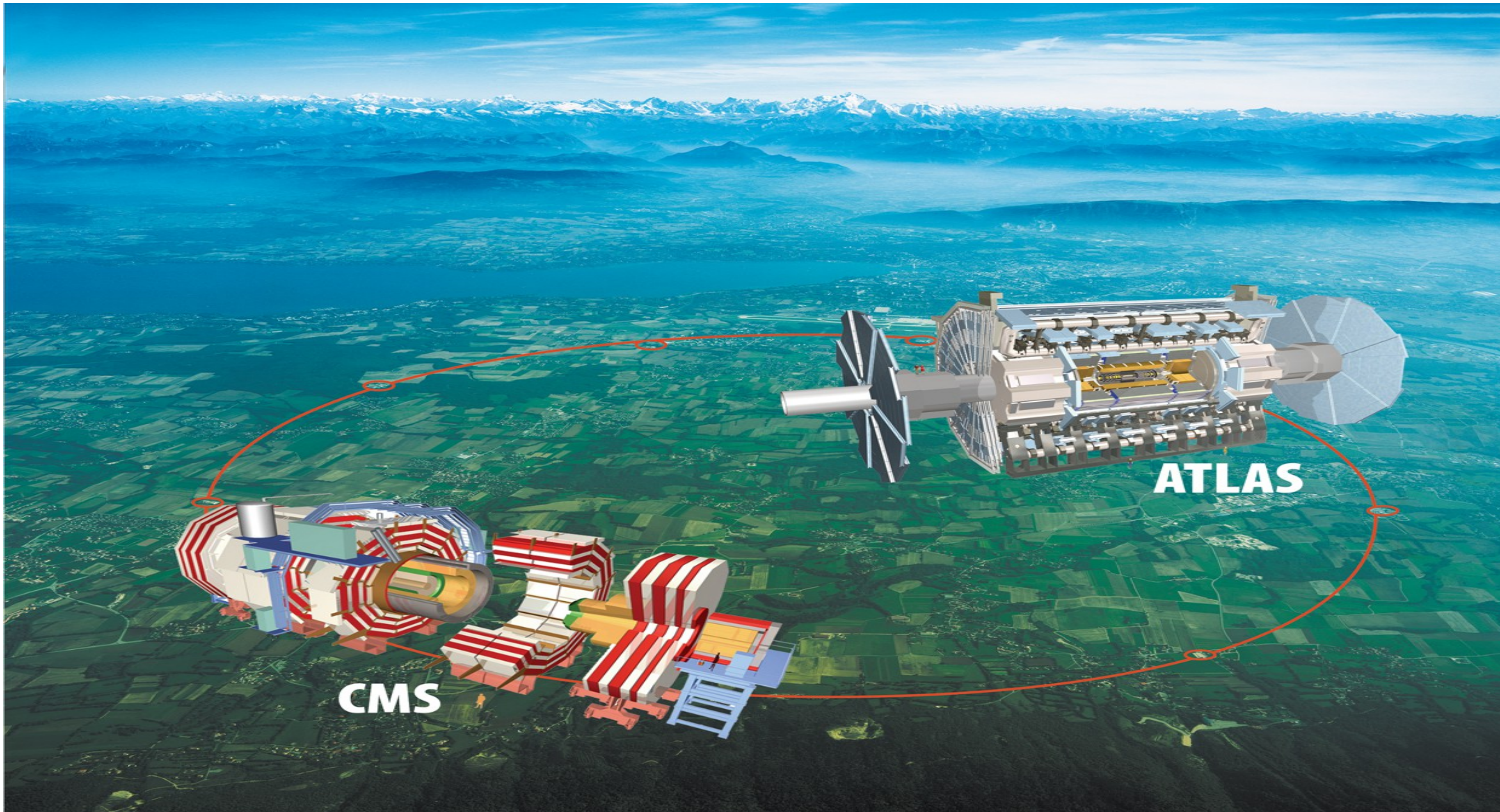
The Large Hadron Collider (LHC)

- The most powerful accelerator ever built in particle physics.
- It consists of 27km accelerator ring under 100m below ground.
- Two proton beams accelerated in opposite directions up to 7TeV.
- Most challenging component of the accelerator: 1232 high-field superconducting dipole magnets ~8.3T, operating at 1.9k.



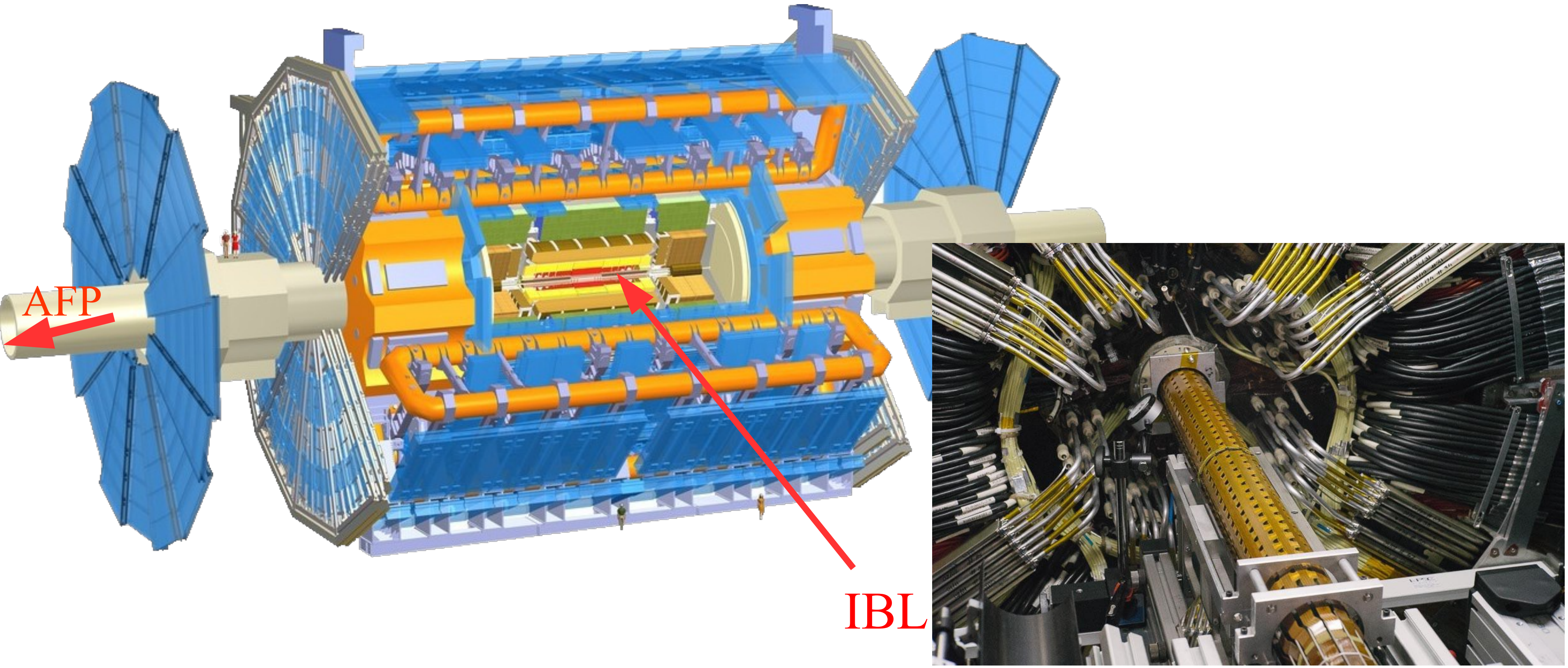
The LHC experiments

- Two multi-purpose detectors ATLAS and CMS: largest, most complex detectors ever built.



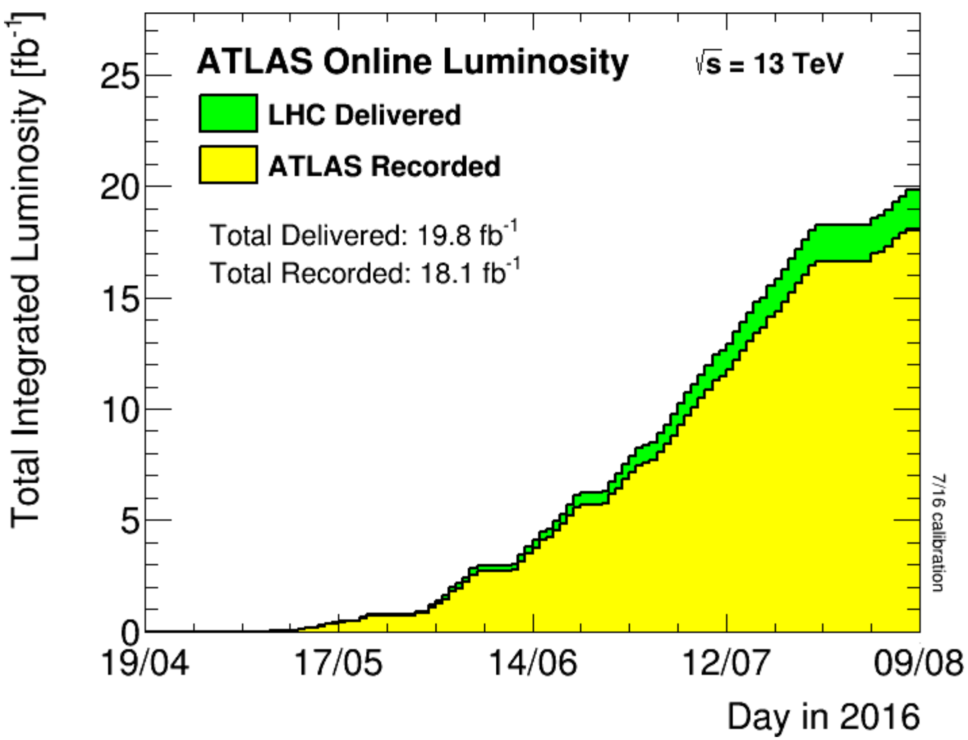
ATLAS in Run-2

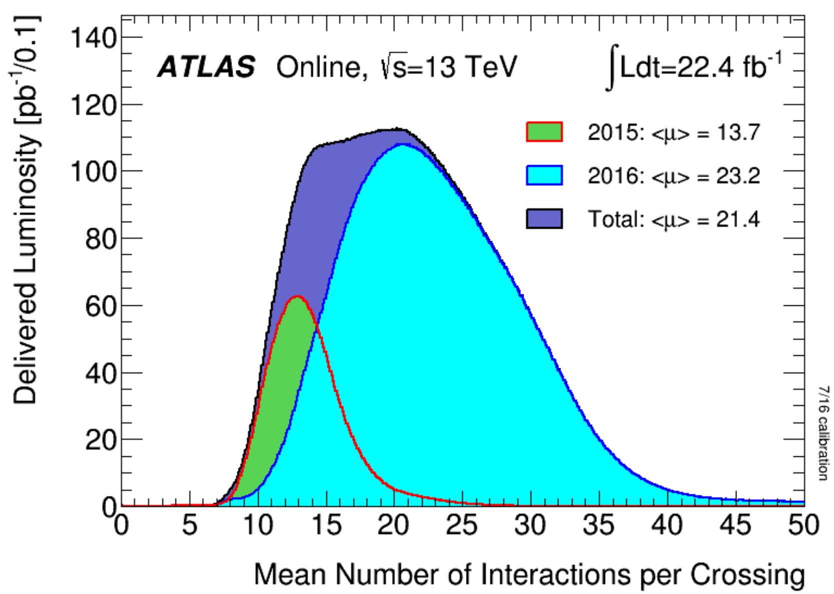
- Added new detectors in Run-2:
  - Innermost pixel layer IBL at 3.4 cm from interaction point.
  - Forward proton detector(one arm in 2016, 210m from IP).
- In addition, various consolidations provide improved running at HL and rates.



Run2 at 13 TeV

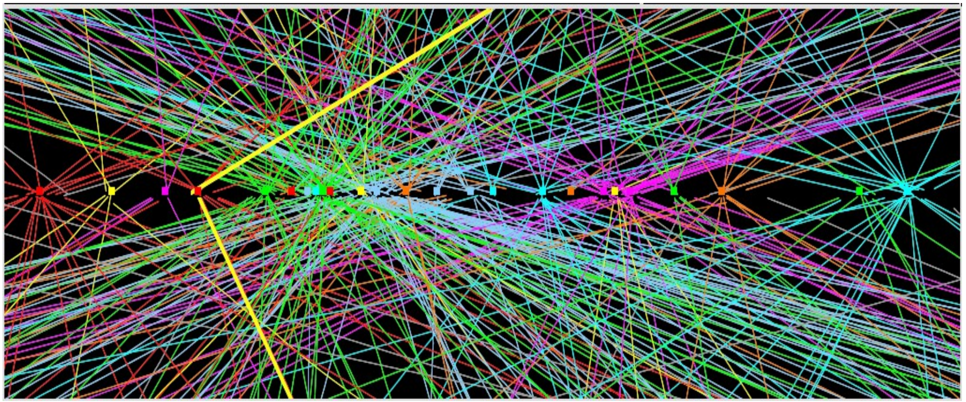
- Exceptional LHC performance in 2016 following 13TeV commissioning in 2015
- Both ATLAS and CMS have data taking efficiency > 90%.
- Results reported at ICHEP 2016 with 3-15 fb^{-1}, opened up major new-physics sensitivity at 13 TeV.

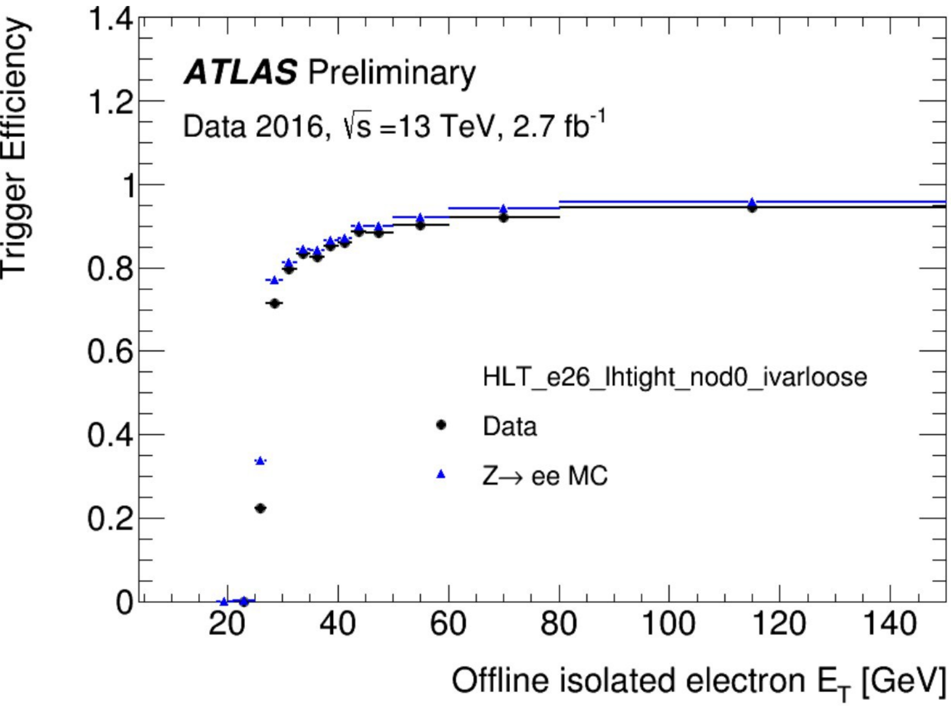


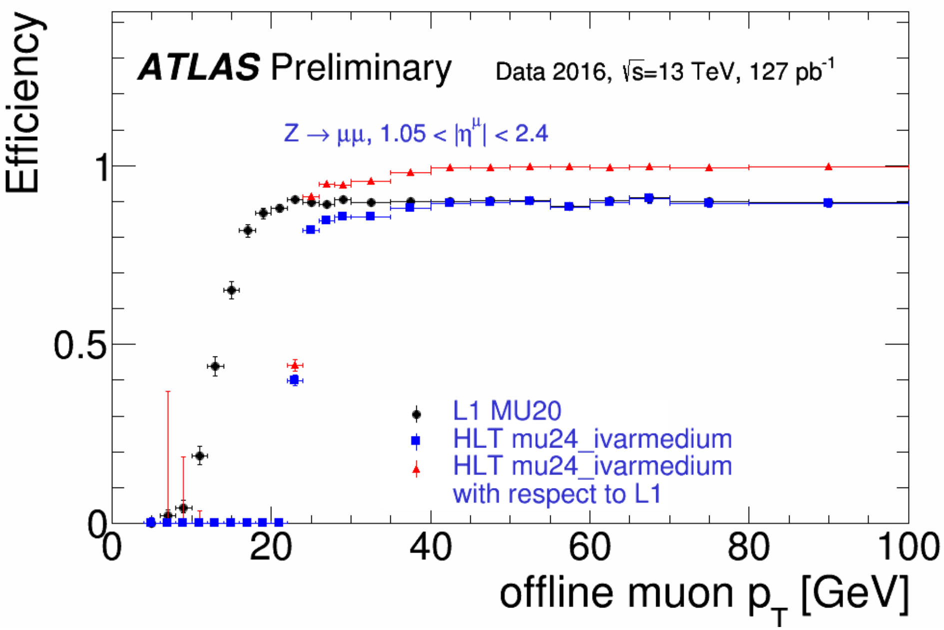


Experimental Challenges

- Difficult to reconstruct physics objects in high pile-ups at high luminosity.
- Complex trigger menu designed to meet varied physics, monitoring and performance requirements.

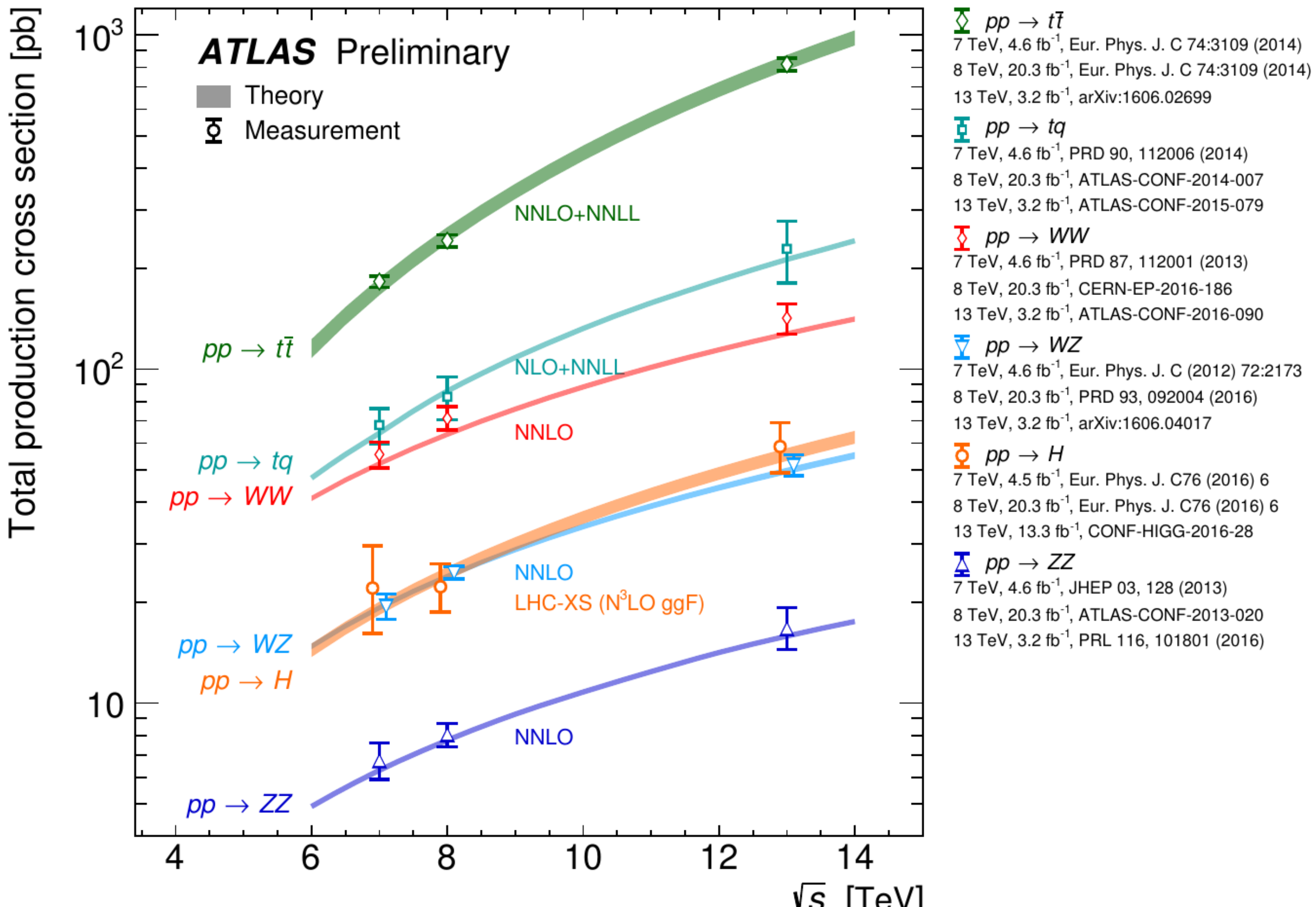






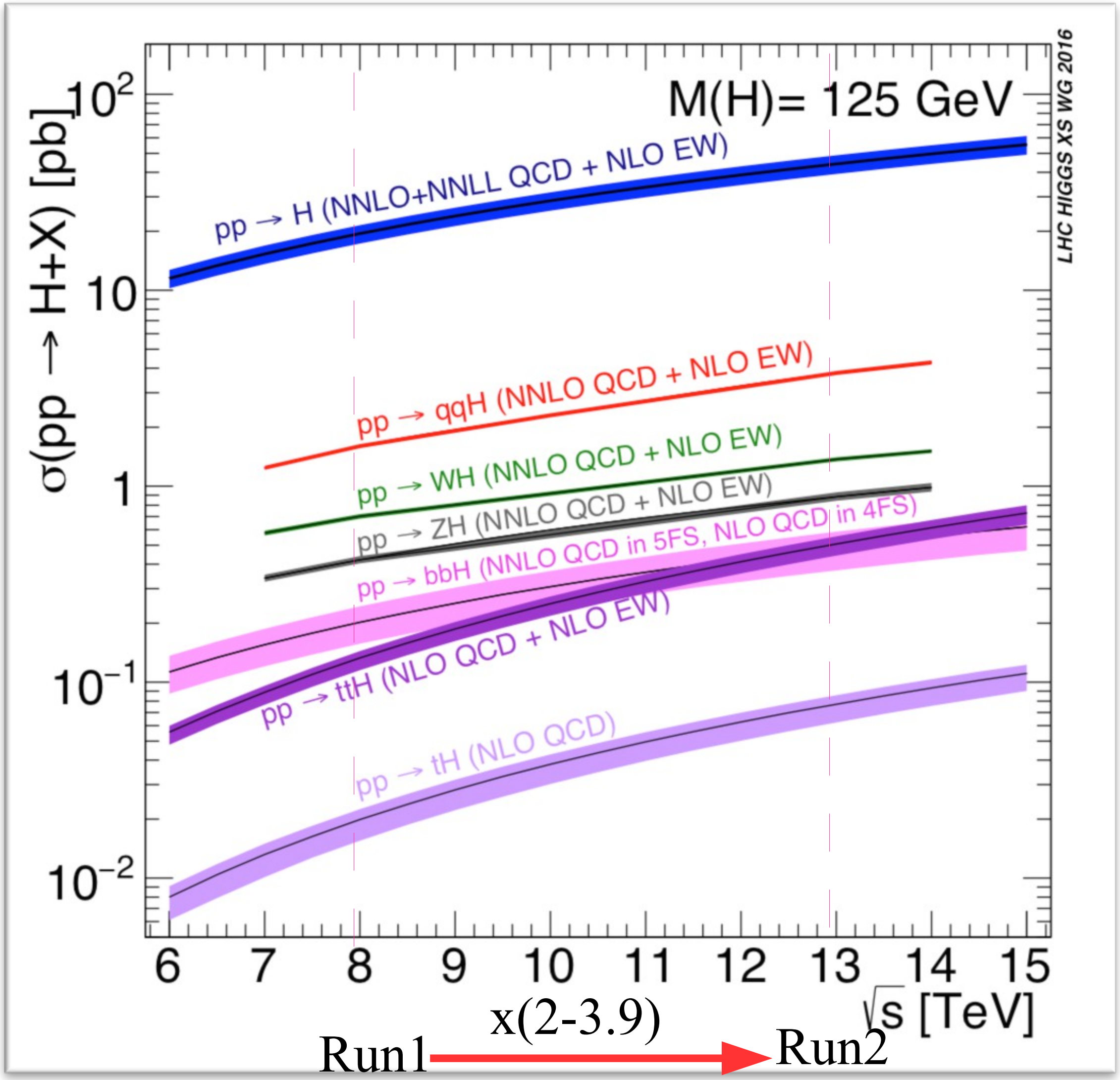
Re-discovery of SM and Calibration

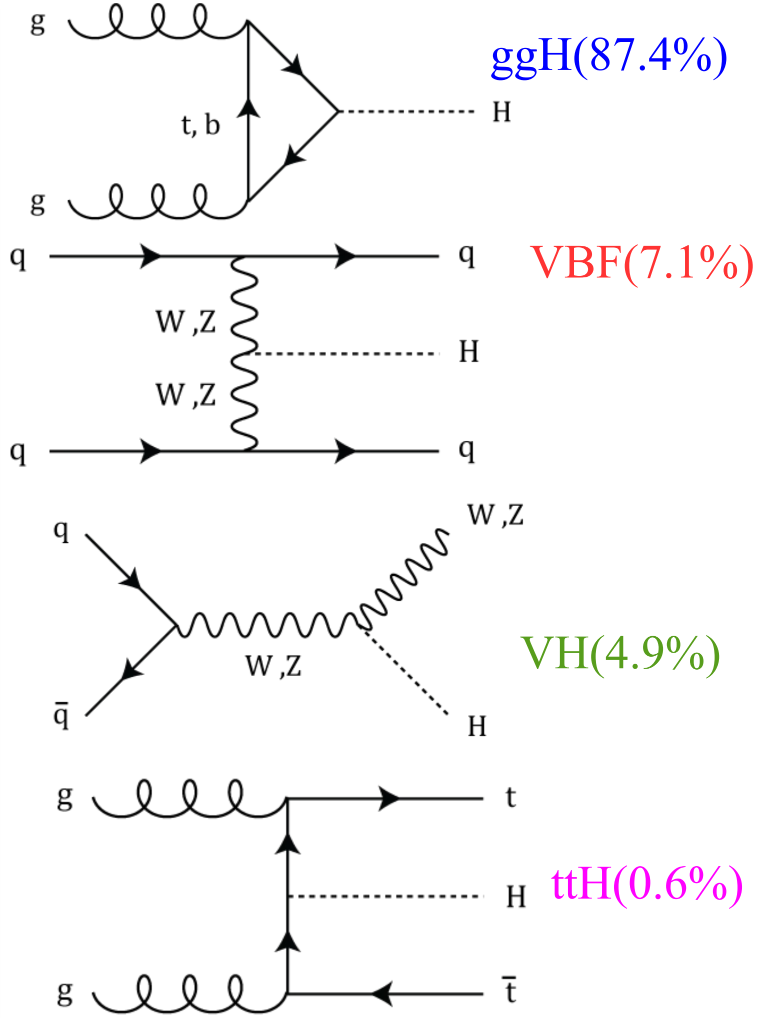
- ATLAS and CMS have measured most of SM processes with great precision that give solid base for understanding detector performance & backgrounds.



Higgs Production

- Higgs predominately produced via ggF at LHC.





Standard Model Higgs Decays

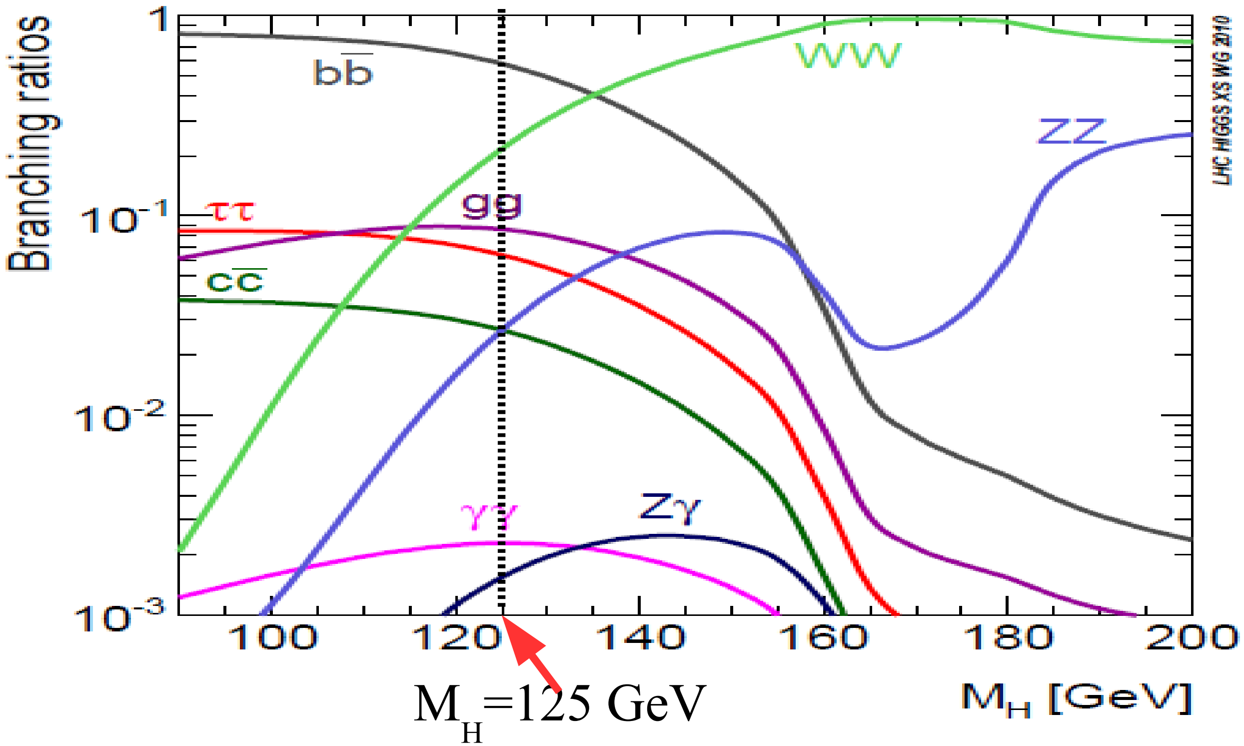
- Decay modes change as a function of M_H.
- Observed decay models so far: $H \rightarrow \gamma\gamma$, ZZ, WW, $\tau\tau$.
- Not observed yet: $H \rightarrow$ bb, cc, $\mu\mu$, $z\gamma$, gg.
- Once m_H is known, everything is determined and testable including the H self-coupling.

Higgs Coupling:

fermion $\frac{m_f}{v}\bar{f}fh$

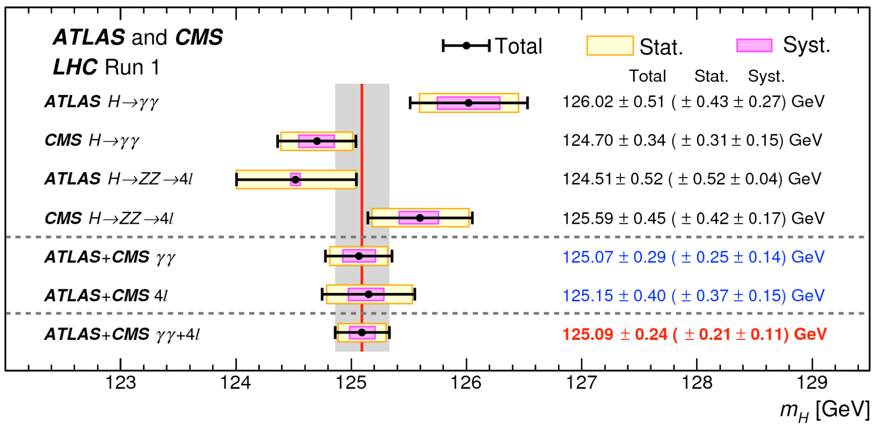
gauge $\frac{m_W^2}{v^2}W_\mu^+W_-^\mu(v+h)^2 + \frac{m_Z^2}{2v^2}Z_\mu Z^\mu(v+h)^2$

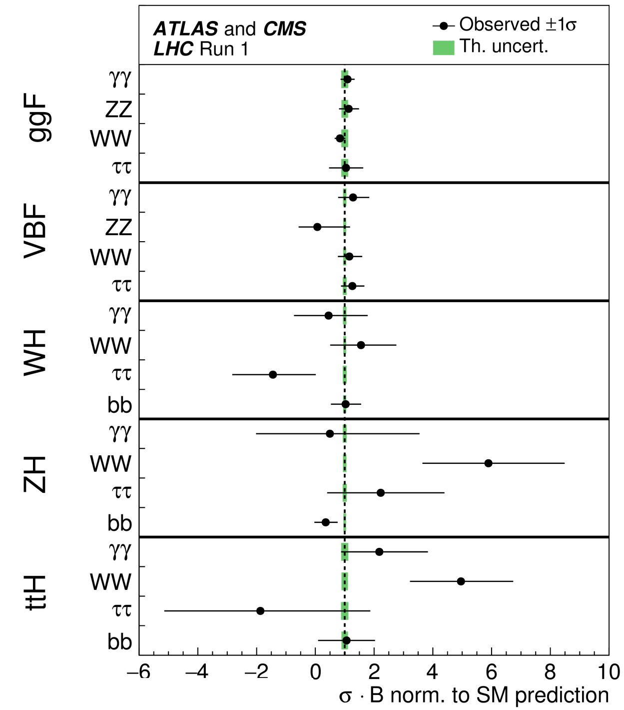
potential $\frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{2m_h^2}{v^2}h^4$

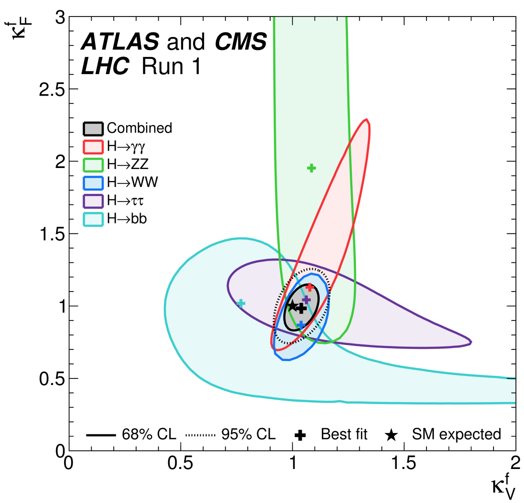


Combined Higgs Run1 Results

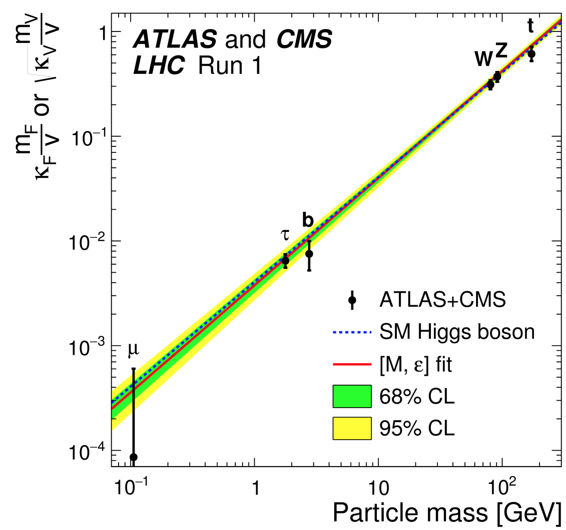
- ATLAS and CMS combined 7 and 8 TeV results:
  - M_H=125.09+-0.24 GeV (PRL 114, 191803)
  - Couplings strength:$\mu=\sigma/\sigma_{sm}$ (JHEP 08(2016) 045)







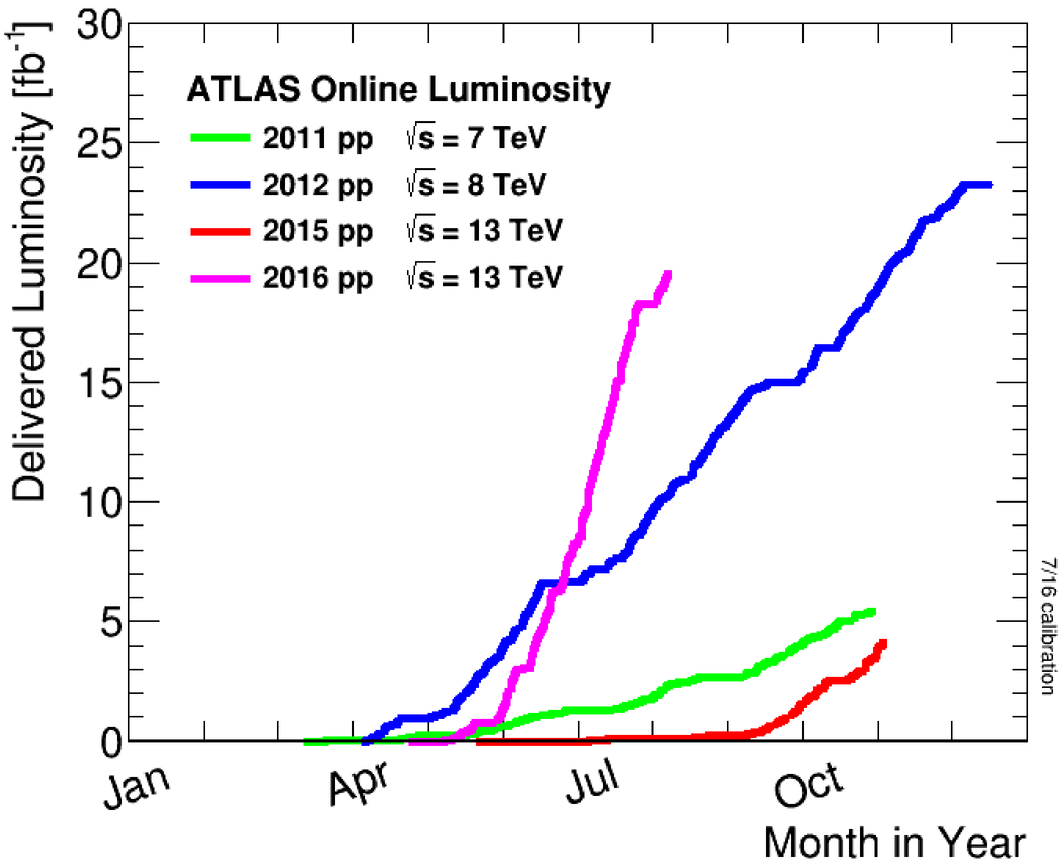
H coupling: K_V vs K_F



H coupling vs particle mass

Highlights of Higgs Results at ICHEP 2016

- Dataset per experiment for ICHEP 2016:
  - 2015: 3 fb^{-1}
  - 2016: 13 fb^{-1}
- Most Run2 analyses follow closely methods & strategies developed in Run-1.
- In this talk, I will review highlights of Higgs results reported at ICHEP 2016.

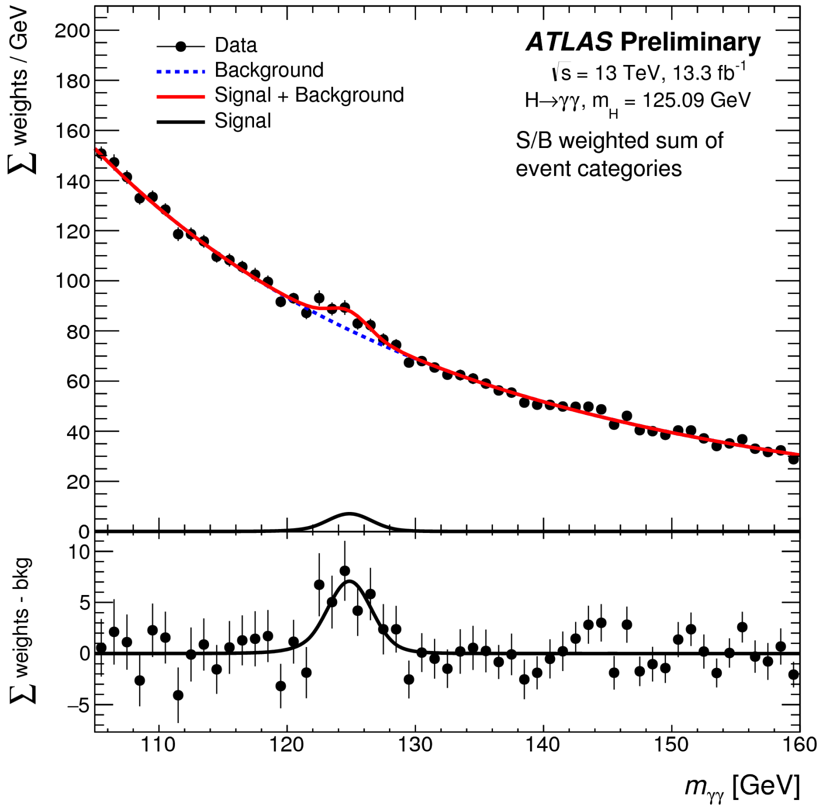


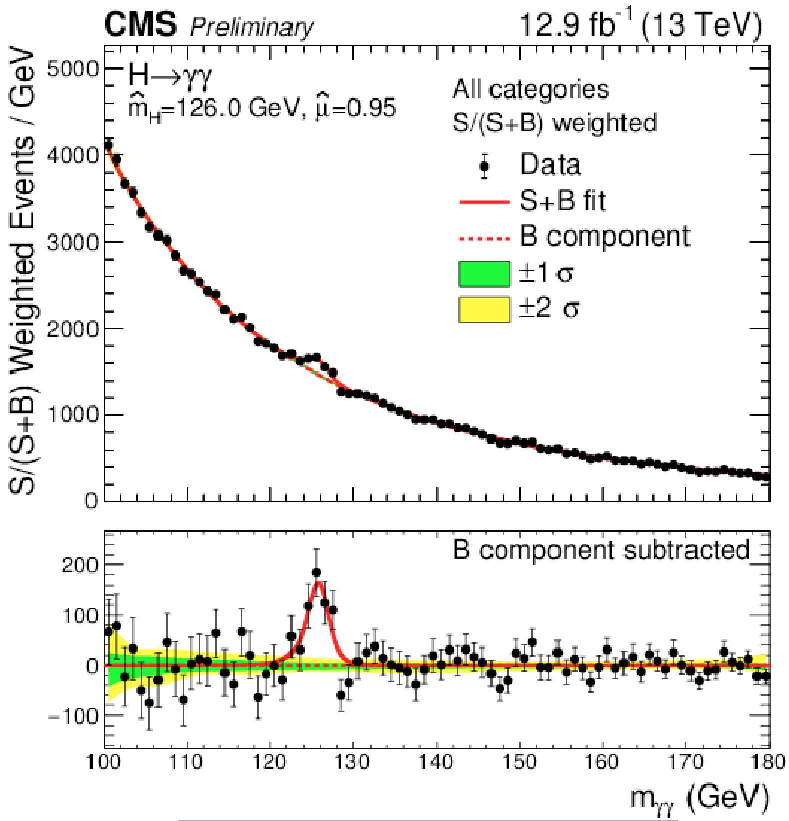
Higgs H→γγ at Run2

- Signature: consists of 2 isolated photons, a narrow peak over falling backgrnd.
- Main backgrounds: γγ irreducible, γ-jet.

ATLAS-CONF-2016-067
CMS-PAS-HIG-16-020

- Signal extracted through fit of mγγ in different event categories.





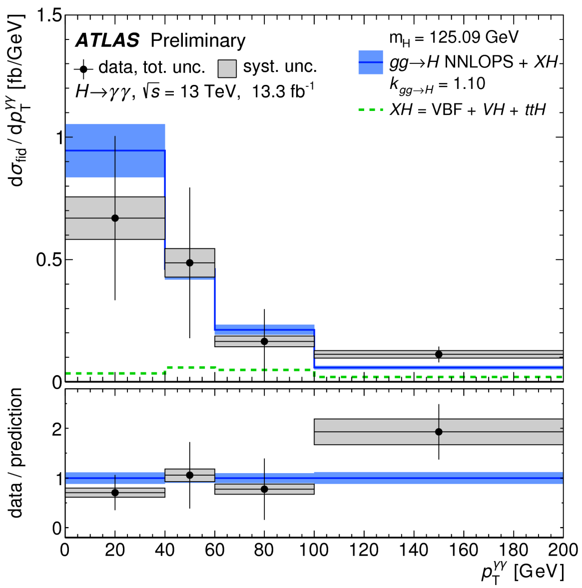
$\mu=0.85^{+0.22}_{-0.20}$

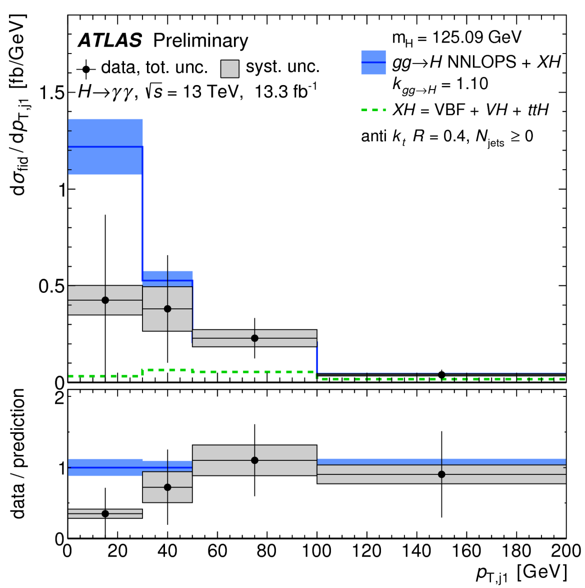
$\mu=0.95^{+0.21}_{-0.18}$

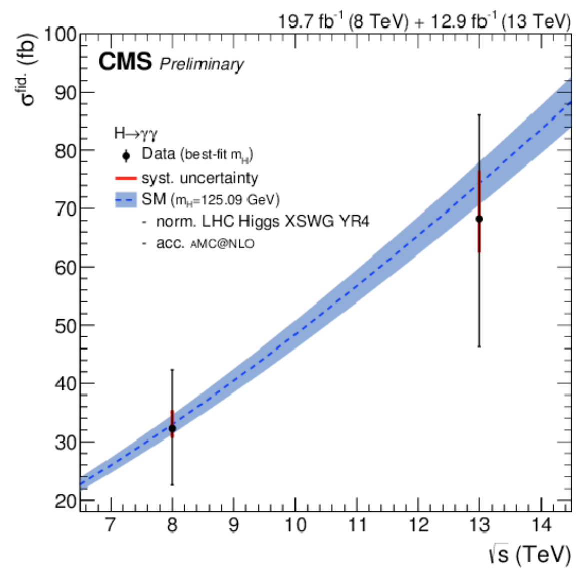
H→γγ fiducial and differential cross sections

- Fiducial xsec: corrected for detector ineff. and reso. for minimizing modeling.
- Important to improve MC generators, calculations for reducing systematics.

13 TeV	Fid σ(fb)	SM σ(fb)
ATLAS(13.3fb-1)	43.2+-14.9+-4.9	62.8+3.4-4.4
CMS(12.9 fb-1)	69+16-22+8-6	73.8+-3.8



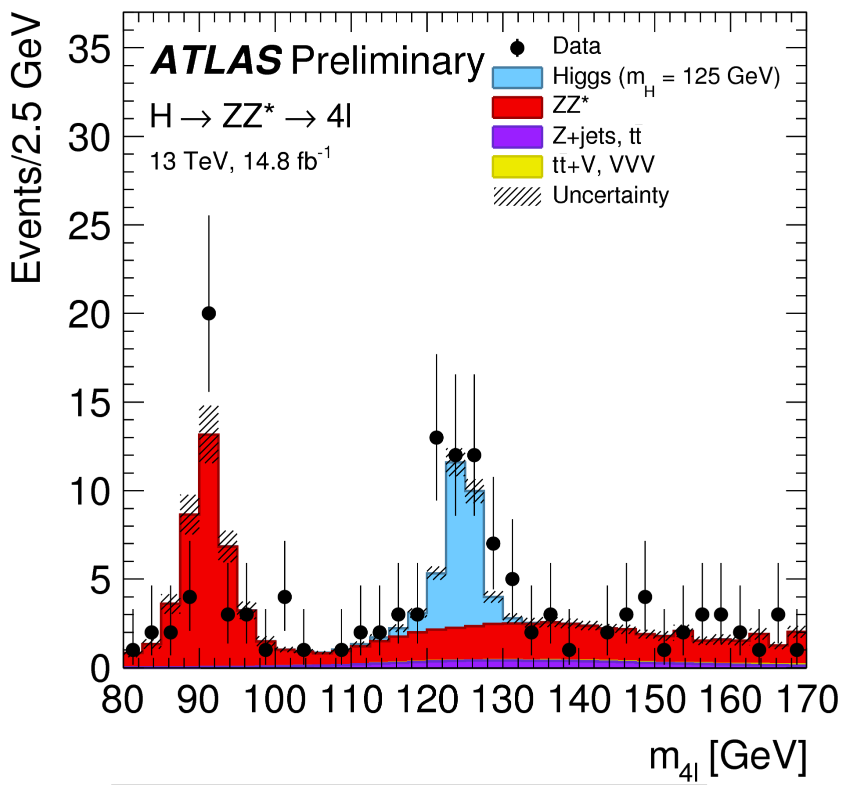




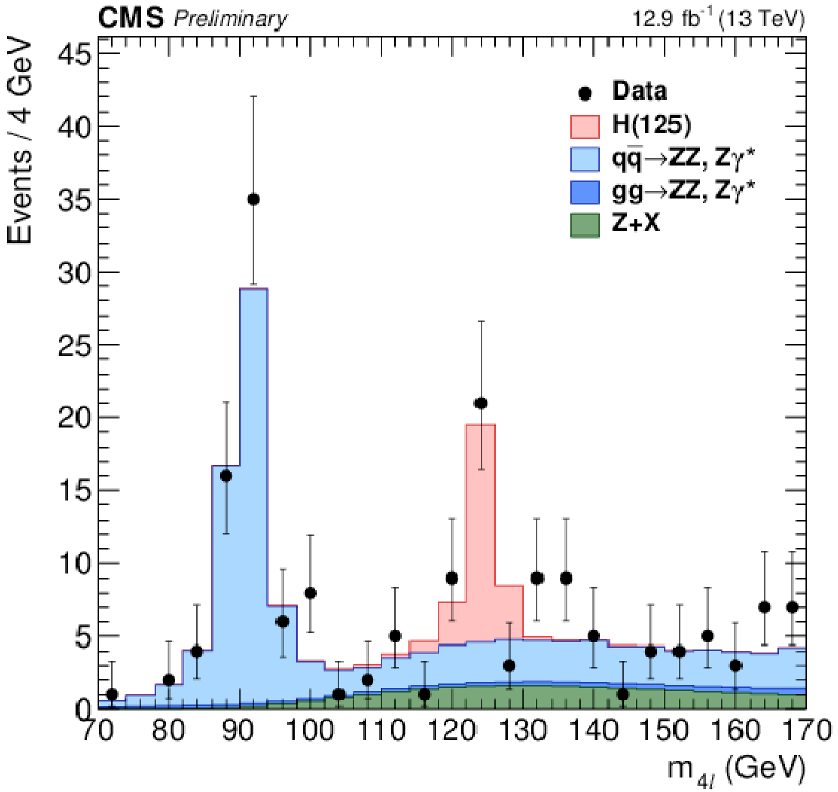
Higgs H→zz* → 4lep

- Signature: two pairs of same flavor, opposite-sign, isolated leptons with m4l
- Main backgrounds: zz, z+jets.
- Signal extracted from fit of m4l in different kinematics discriminant.

ATLAS-CONF-2016-079
CMS-PAS-HIG-16-033



M=1.13+0.18-0.17

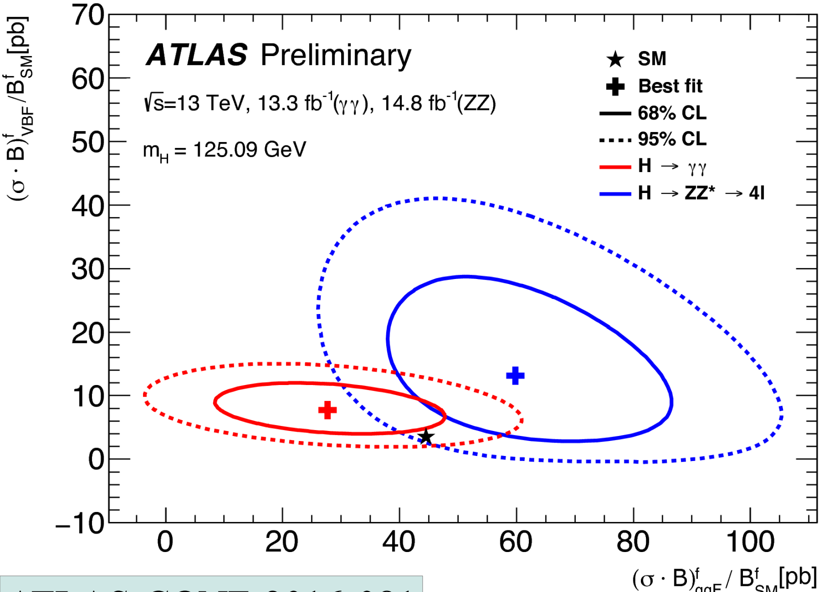


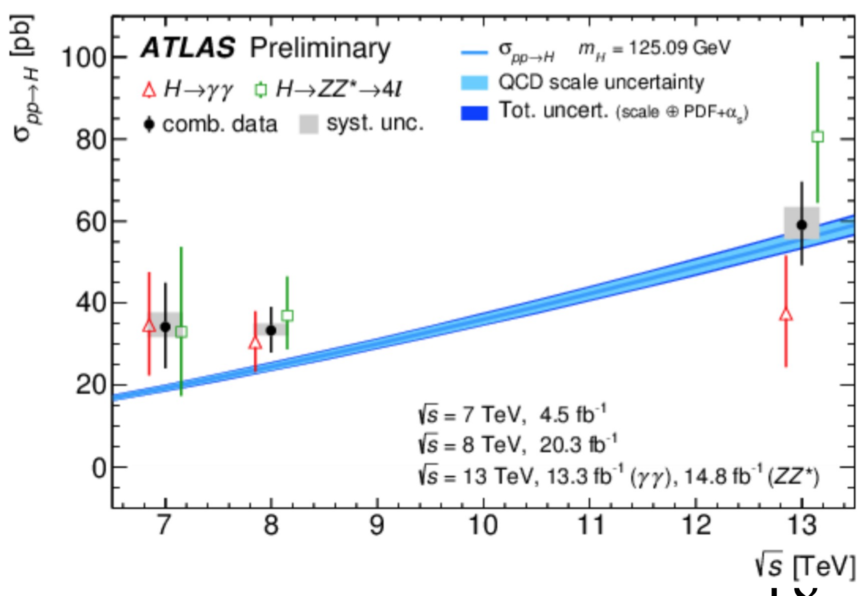
μ=0.99+0.33-0.26

Combination of H→γγ and H → zz*

- Combine H → γγ and H → zz* inclusive samples without categorization
- Higgs is observed with 10σ significance (8.6σ exp.) at 13 TeV, consistent SM.

	Measured:	SM
σ at 13 TeV (pb)	$59.0^{+9.7}_{-9.2}{}^{+4.4}_{-3.5}$	55.5+2.4-3.4
μ	1.13+0.18-0.17	1

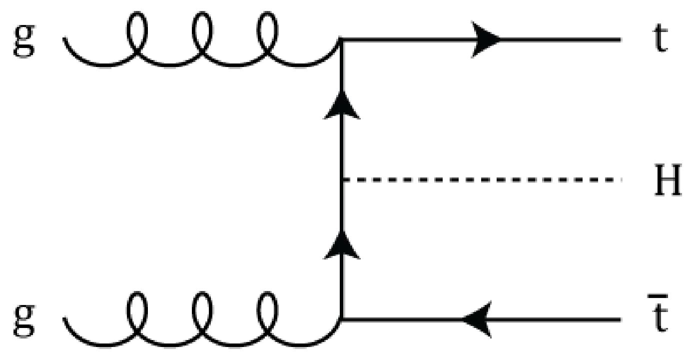




ATLAS-CONF-2016-081

Search for ttH at Run-2

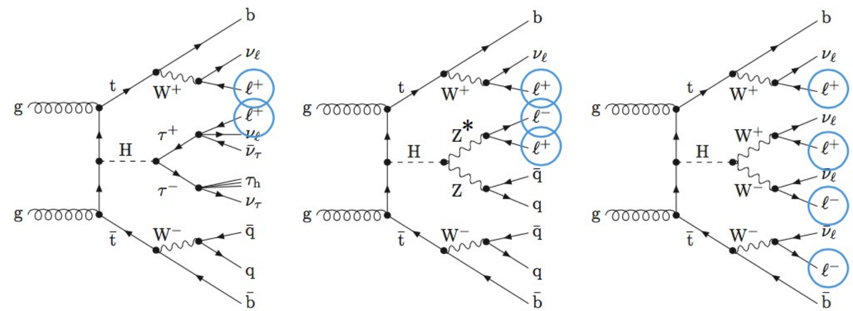
- Higher collision energy from 8 to 13 TeV has increased σ_{ttH} by a factor ot 4.
- Probe Yukawa coupling (yt) by searching for ttH production directly at LHC.
- Based on Higgs decay model, the search divided into three different channels:
  - ttH(bb): H → bb, tt → WWbb.
  - ttH(multilep): H → WW, ZZ, tautau, and additional leptons from ttbar.
  - ttH(γγ): included in H → γγ analysis
- The dominate backgrounds: tt+bb, tt+cc, tt+W, tt+Z, and QCD fakes.

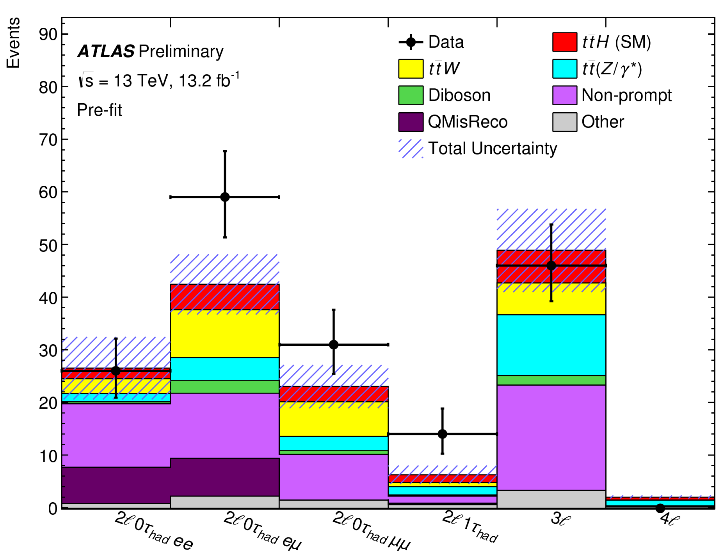


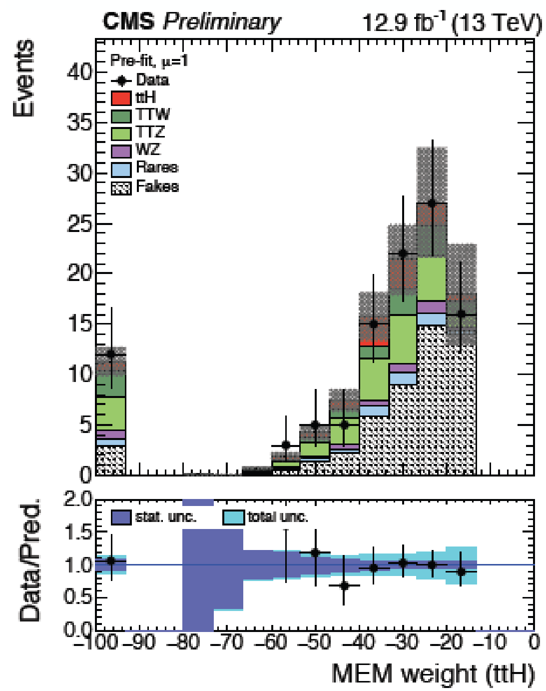
Higgs decay mode	BR (%)
H → bb	58.1
H → WW	21.5
H → ττ	6.3
H → ZZ	2.6
H → γγ	0.23

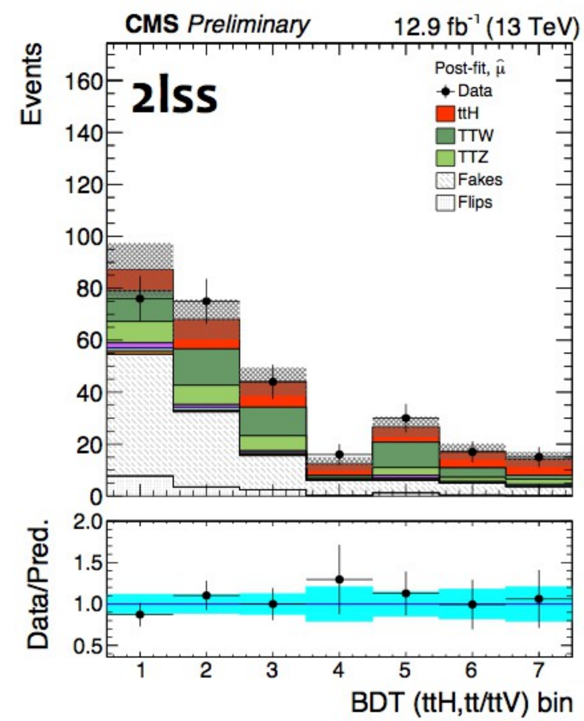
ttH(multileptons)

- Targets H decays and focus on final states with clean S/B.
- Signature: 2 SS, tri-leptons, or 4-lep +njets with b-tags.
  - ATLAS cut based in different categories.
  - CMS BDT based including ME weights.





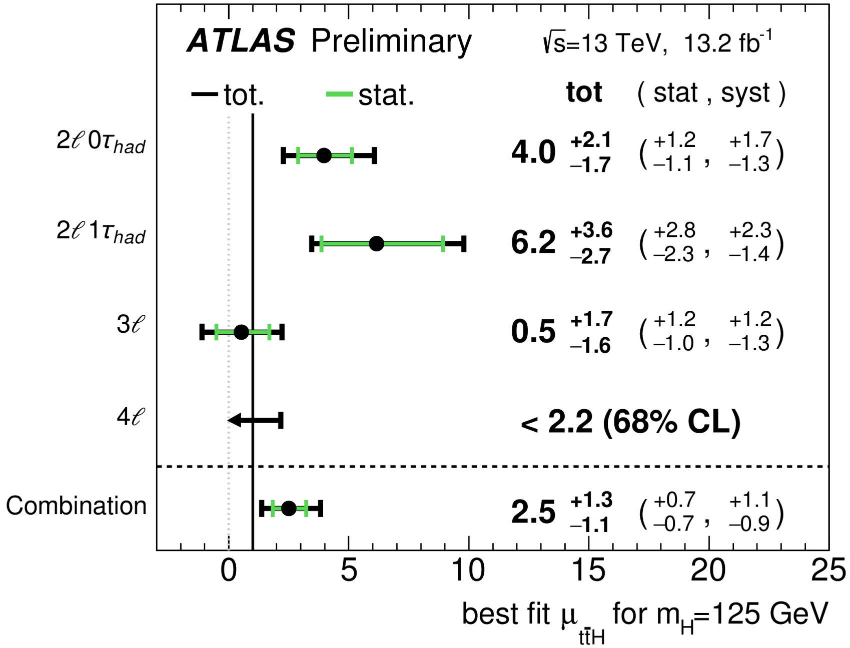


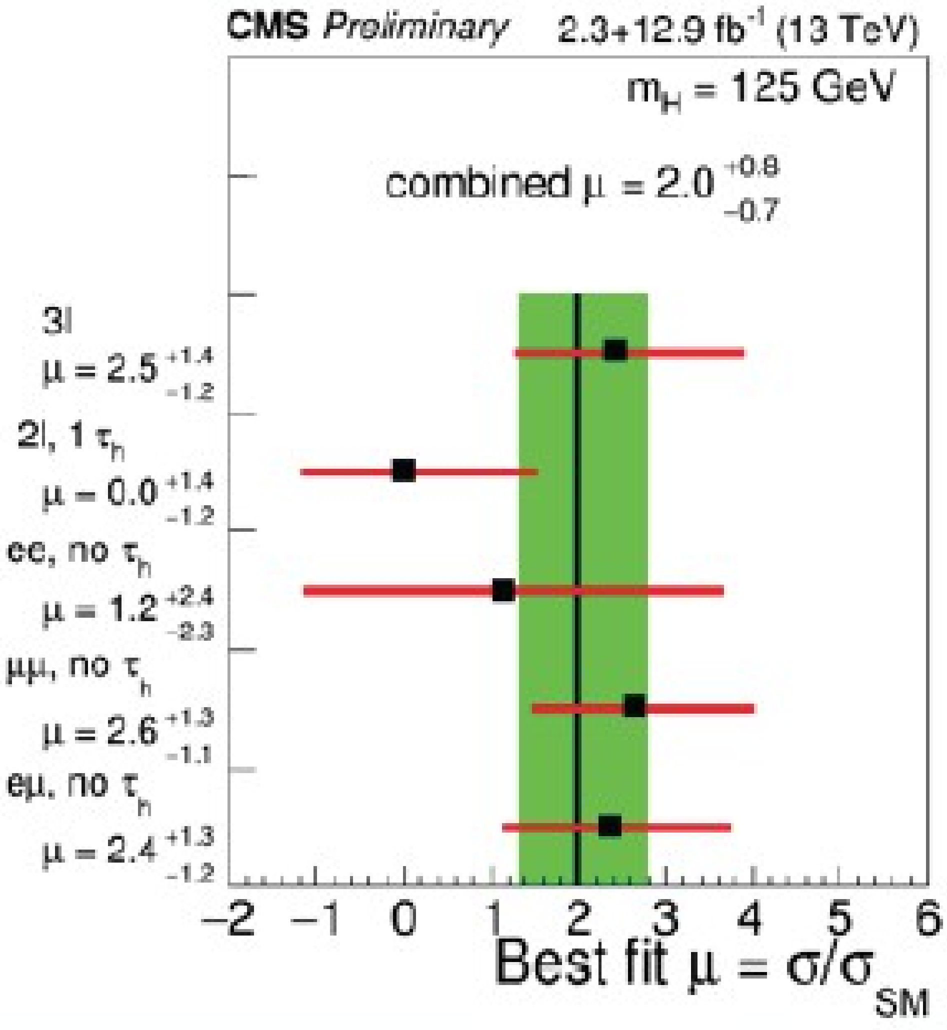


ttH(Multileptons) Results

- Dominant systematic: fake-rate and non-prompt background estimates.

ATLAS:μ=2.5+1.3-1.1





CMS:μ=2.0+0.8-0.7

Search for H → bb at Run2

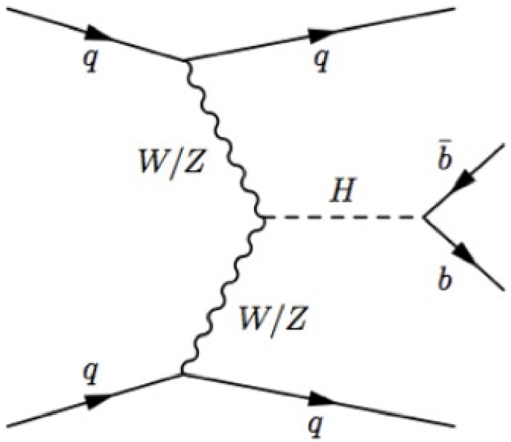
•Important to establish largest coupling of Higgs to b quarks

•Inclusive H → bb search extremely challenging:

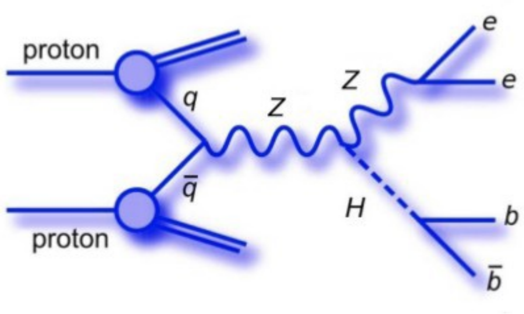
- •Overwhelming background from QCD multi-jet production

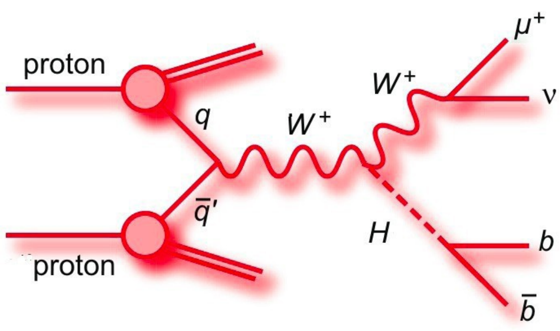
•Exploit associated production modes:

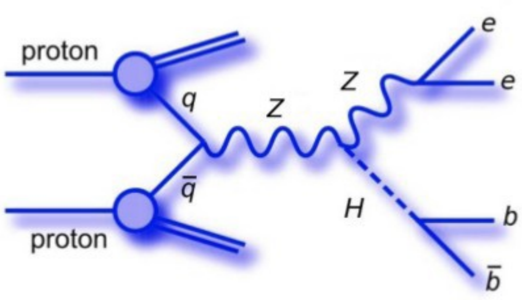
- •ttH
- •VH with lepton/MET provides clean signature
- •VBF with tagging of forward jets



•Focus on associated VH(→ bb) three major channels:







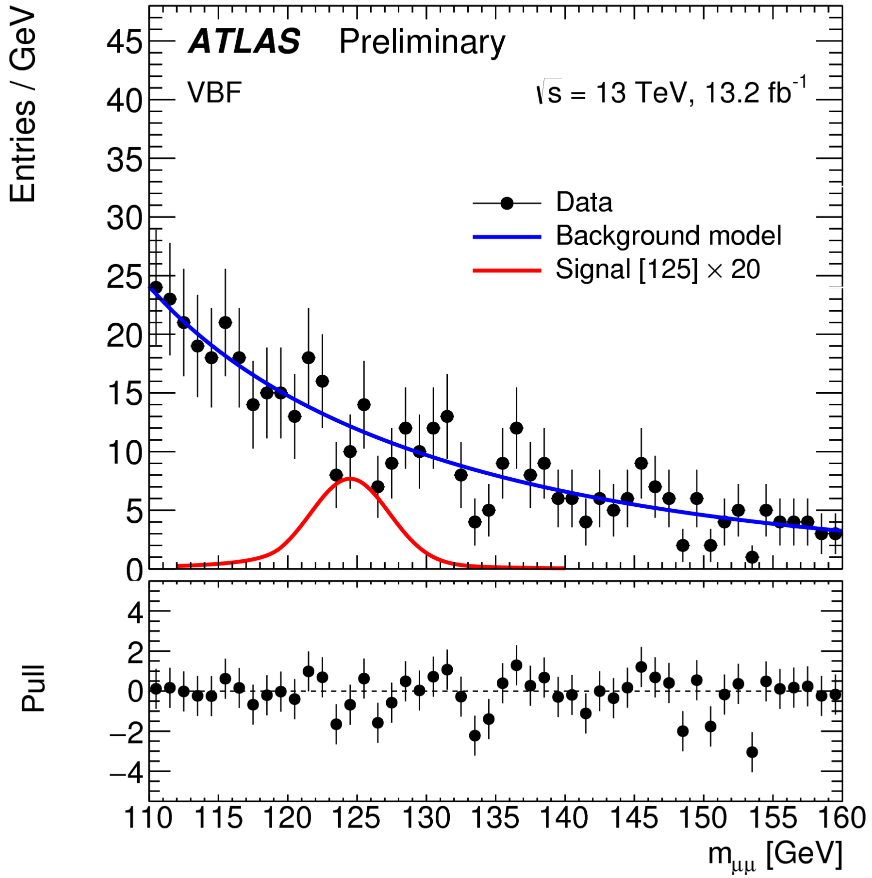
Summary of VH(→ bb) Results

•Status of VH(→ bb) measurements:

VH(→ bb)	Sig (expectation)
ATLAS(13TeV)	0.4σ (1.94σ)
ATLAS+CMS (8TeV)	2.6σ (3.7σ)
Tevatron (CDF+D0)	2.8σ
W(Z)Z(-->bb)	
ATLAS(13 TeV) Observed μ	0.91+-0.17+0.32-0.27
Significance	3.0σ (3.2σ)

H → μμ

- A very rate decay in the SM
  - Probe Yukawa-coupling to 2nd generation.
  - Test of the Higgs coupling to lep.
- Signature: very clean signature from dimuon final state but dominated by DY.
- Analysis strategy:
  - search for peak in $m_{\mu\mu}$ over smoothly falling background.
  - Categorize events according to VBF and ggF signature enriched.



ATLAS	Upper limit x SM(expected)
Run 1	7.1 (7.2)
Run 2	4.4 (5.5)
Combined Run1, Run2	3.5 (4.5)

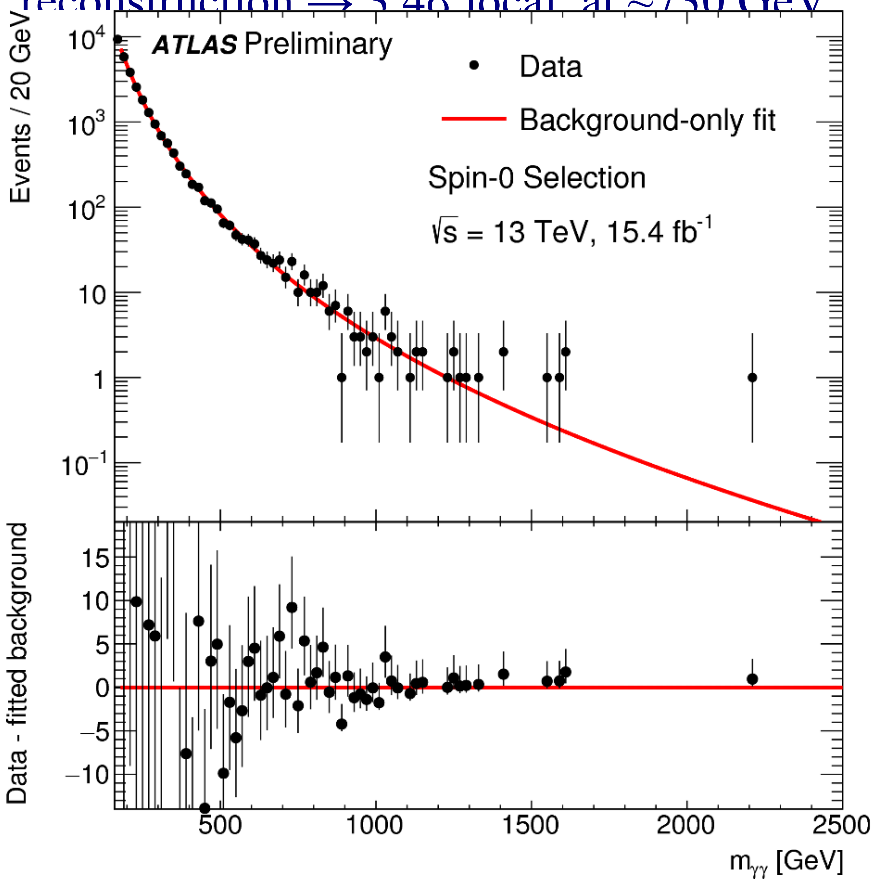
Beyond the SM

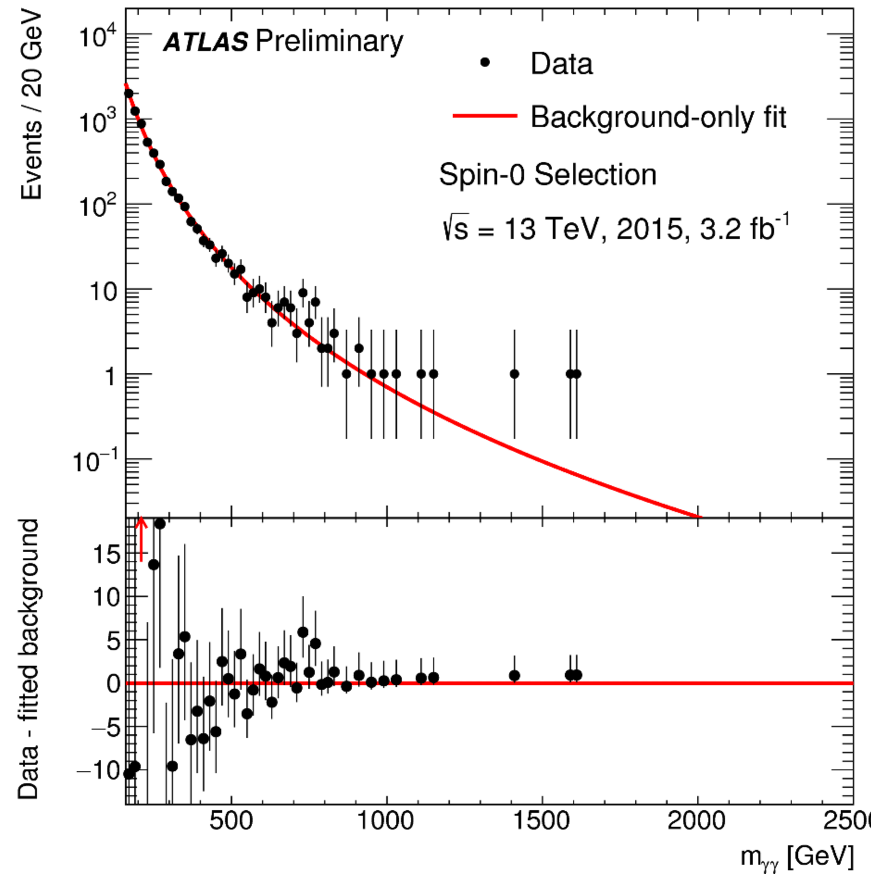
- The 125 GeV Higgs is so far consistent with the SM prediction
- Extensions of the standard model often include two or more Higgs doublets.
  - Heavy Higgs(H)
  - Charged Higgs(H+-)
  - Pseudo-scalar Higgs (A)
- Current limits still allow for Higgs to couple to new particles or new couplings
  - Higgs to invisible
  - Lepton flavor violation decays
- With increased collision energy to 13 TeV, the LHC has opened a new window for discovery of new BSM physics.

Heavy H → γγ Searches

Localized excess seen in 2015 ATLAS data

- 2.1σ global (3.9σ local) significance at 750 GeV (spin-0 search), width ~50 GeV
- After reprocessing, new 2016 reconstruction → 3.4σ local, at ~730 GeV





With 2015+2016 data:

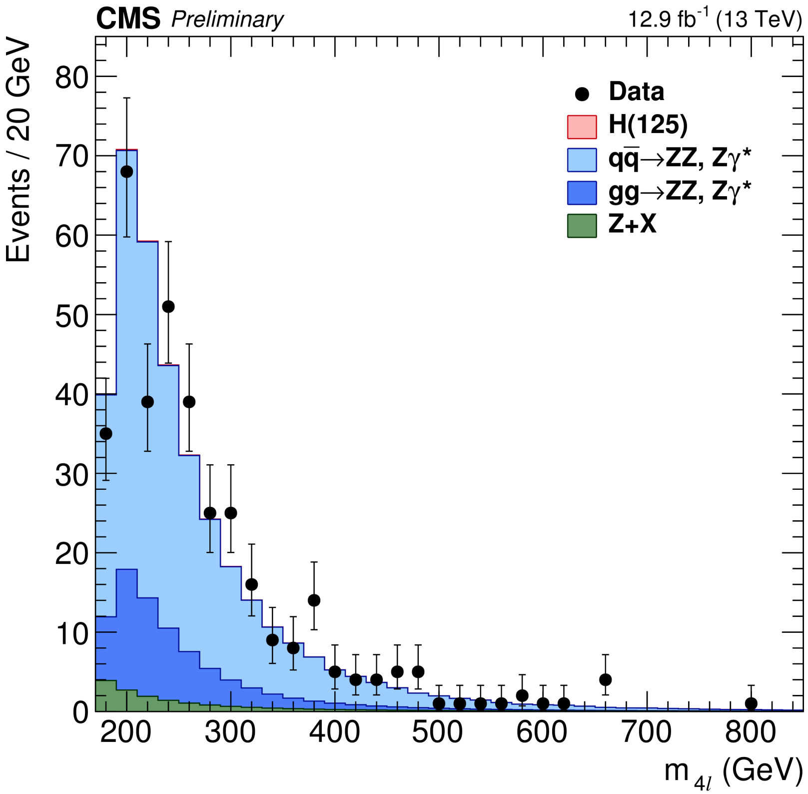
- Small excess at 710 GeV (Γ/m~10%)
- Local significance 1.4σ, global <1σ

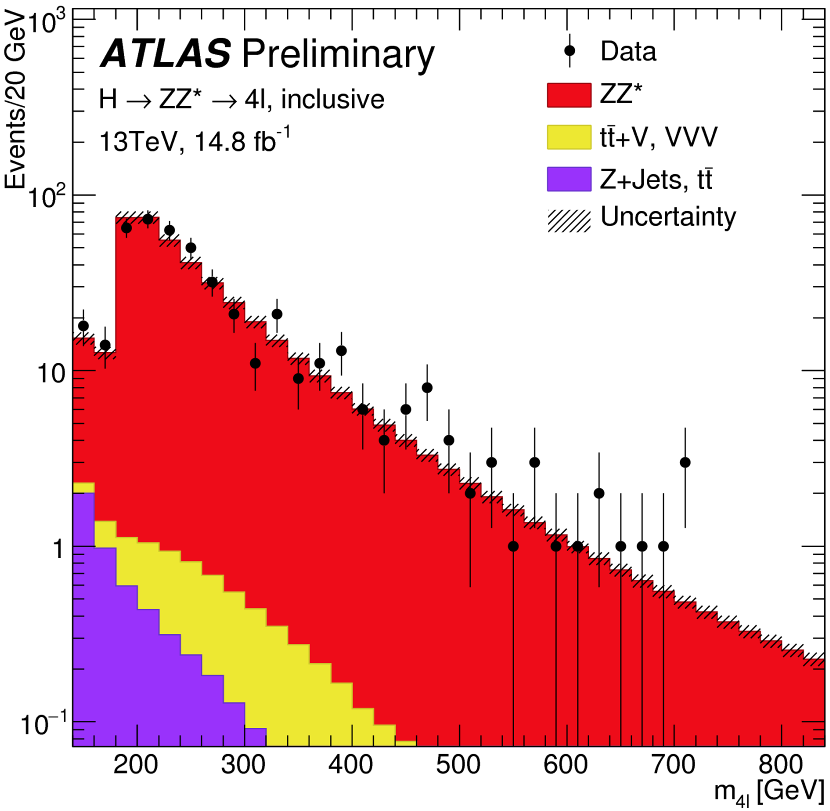
ATLAS-CONF-2016-059

Heavy H → ZZ → 4l

CMS-PAS-HIG-16-033
ATLAS-CONF-2016-079

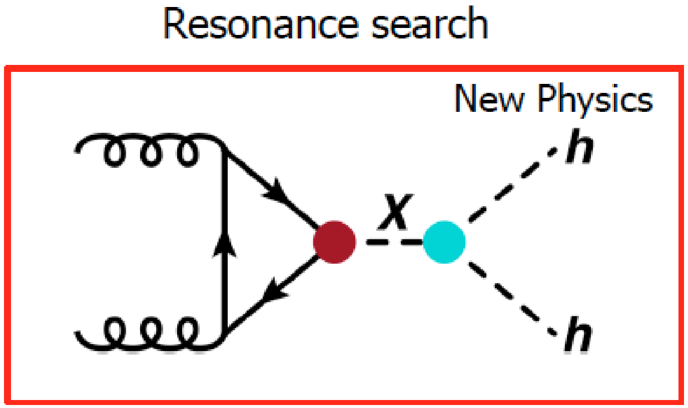
- Search for an additional heavy scalar
  - Assumed to be produced via the ggF and VBF processes
- Extension of the H → zz measurement and fits the m4l distribution
- No signal found and we set limits for cross section limits with assumptions.

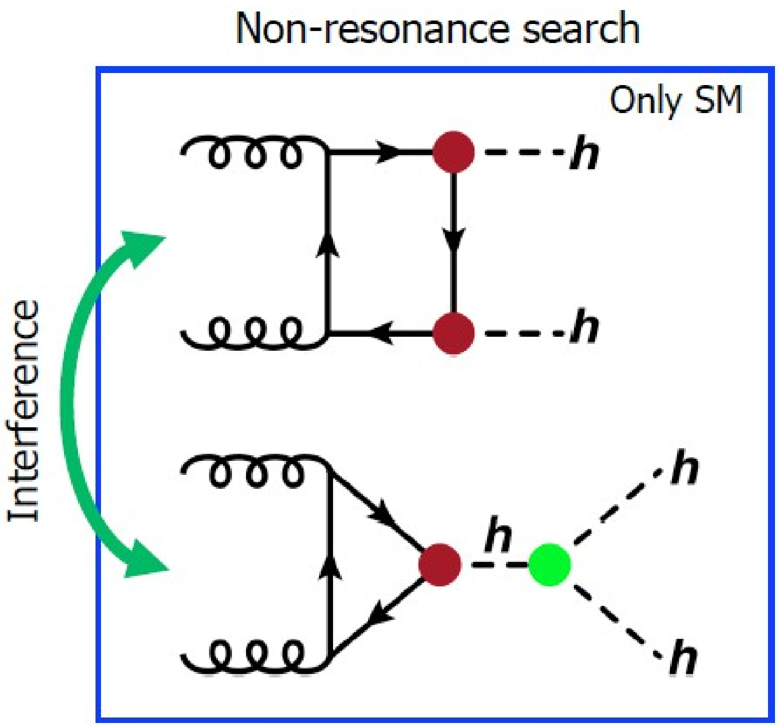




Heavy Higgs H→ hh

- Resonance searches
  - Resonance searches benchmark models: spin-0(radion) and spin-2 (G)
- Non-resonance searches
  - BSM can be enhanced by resonance or particle in the loop and can be modeled in EFT adding dim-6 operators to the SM Lagrangian
- Decay channels:
  - hh → bbbb, bbττ, bbWW, bbγγ

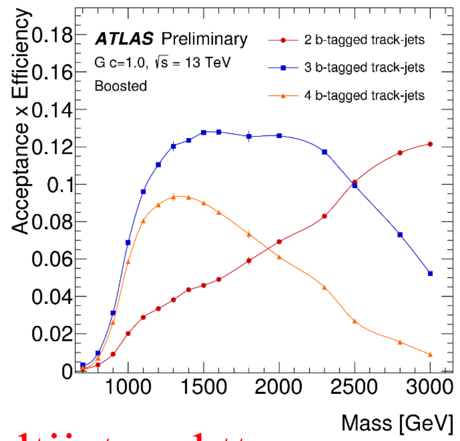


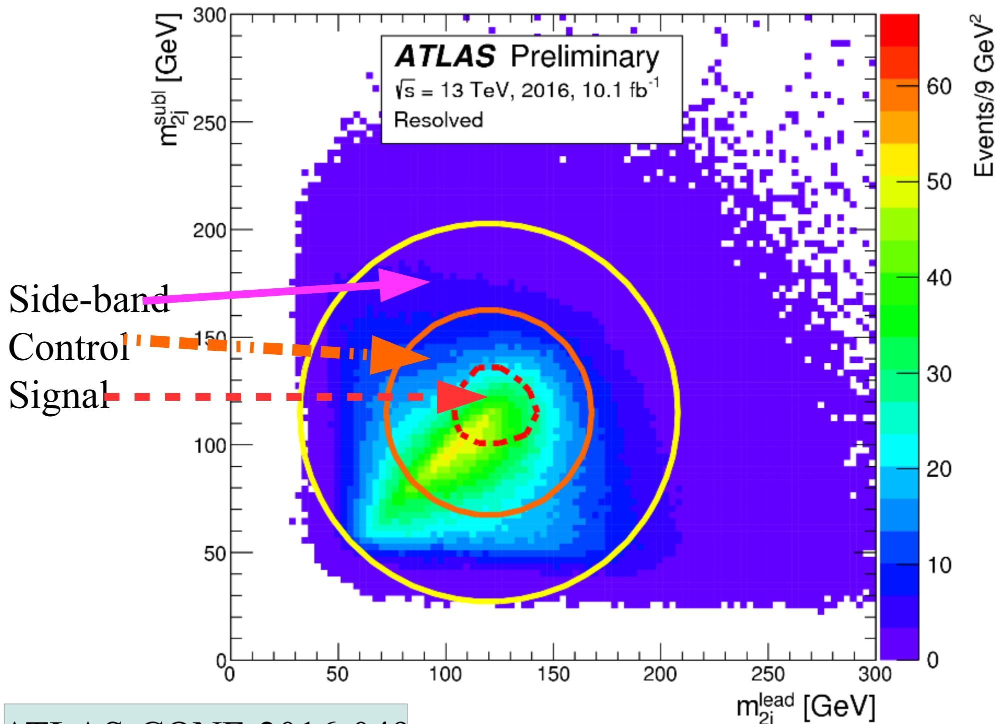


CMS-PAS-HIG-16-029
CMS-PAS-HIG-16-028

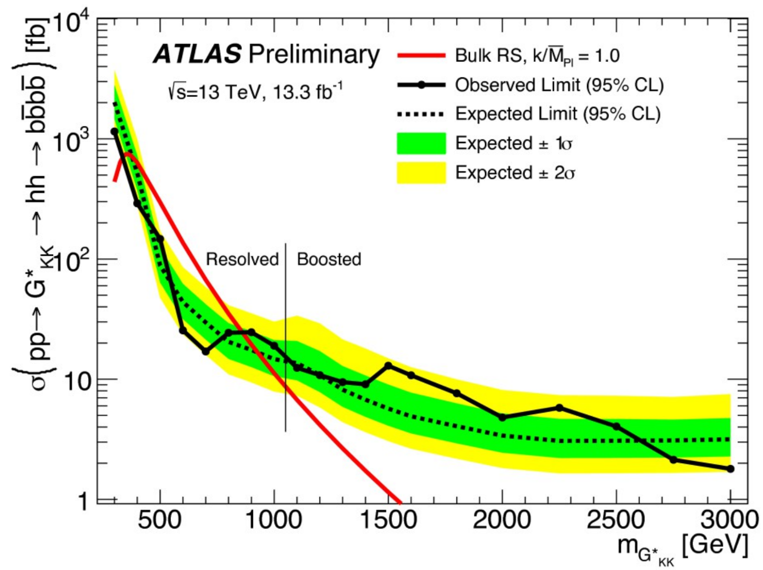
Higgs H → hh → bbbb

- Resonant search for resolved analysis:
  - Anti-kT(R=0.4) jet, pair of b-jets to form H candidate
- Boosted analysis
  - Anti-kT(R=1) jet, Pt>250, mJ>50 GeV + b-tags
  - Invariant mass of two large-R jets





- Dominant bkg: multijet and tt
- Limit on spin-2: mR>850 GeV
- Limit on non-resonate: σ<330 fb

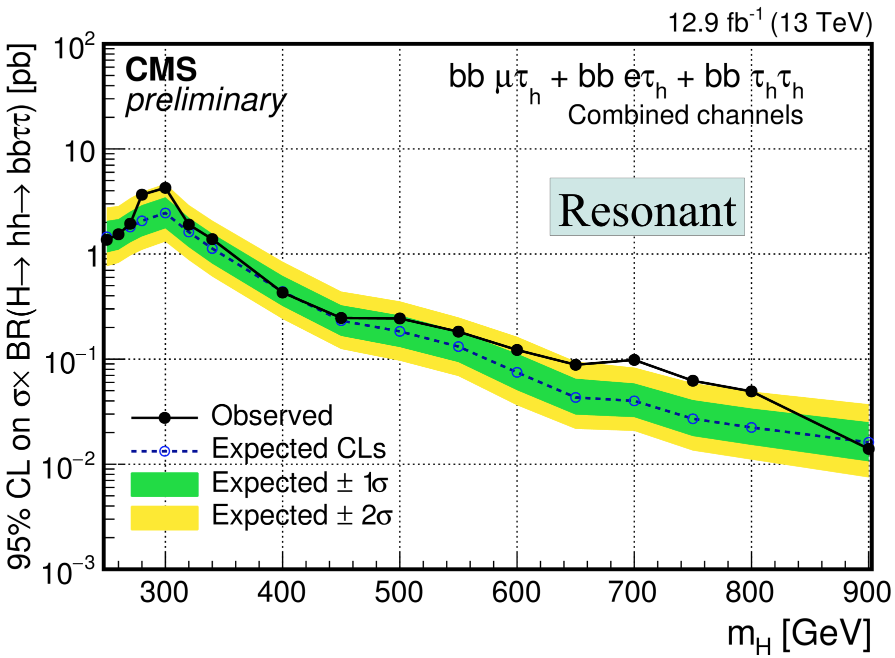


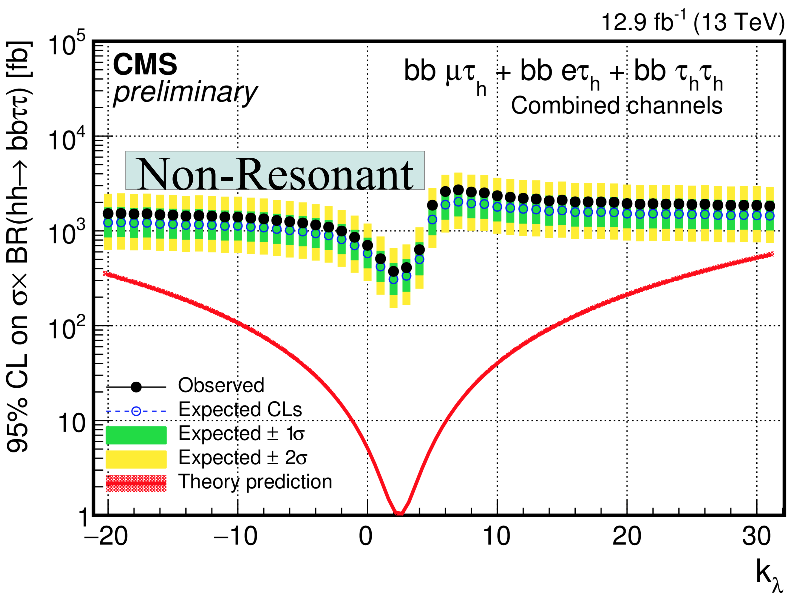
ATLAS-CONF-2016-049

Higgs H → hh → bbττ

- Resonant search
  - Fit to the invariant mass of tautau and bb
  - At high mH → boosted regime, uses substructure for jets and btag
- Non-resonant search
  - Limits as a function of the ratio of the anomalous trilinear coupling to SM
  - At SM, the cross section limit corresponds to ~200(170) x SM predictions.

CMS-PAS-HIG-16-029
CMS-PAS-HIG-16-028

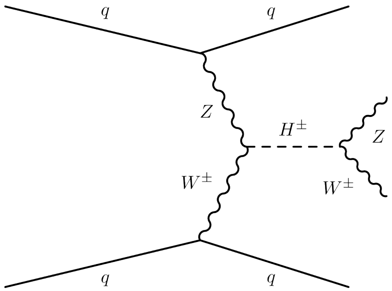


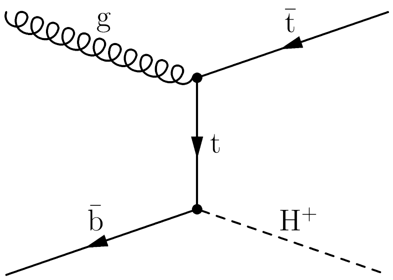


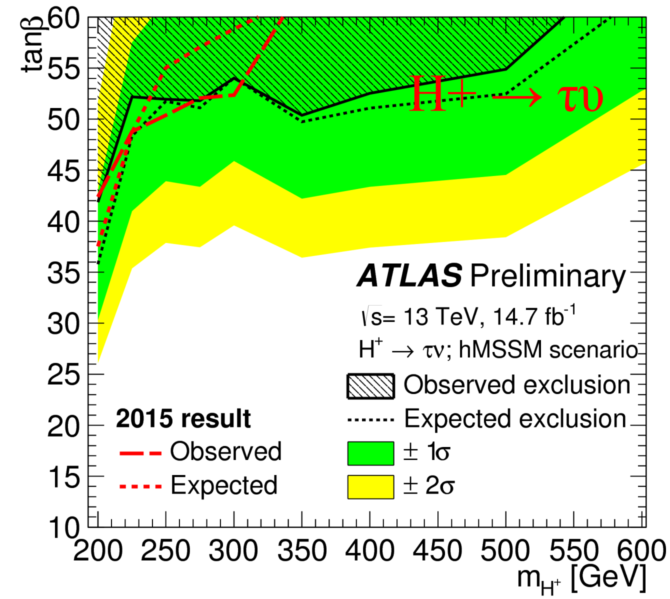
Search for Charged Higgs

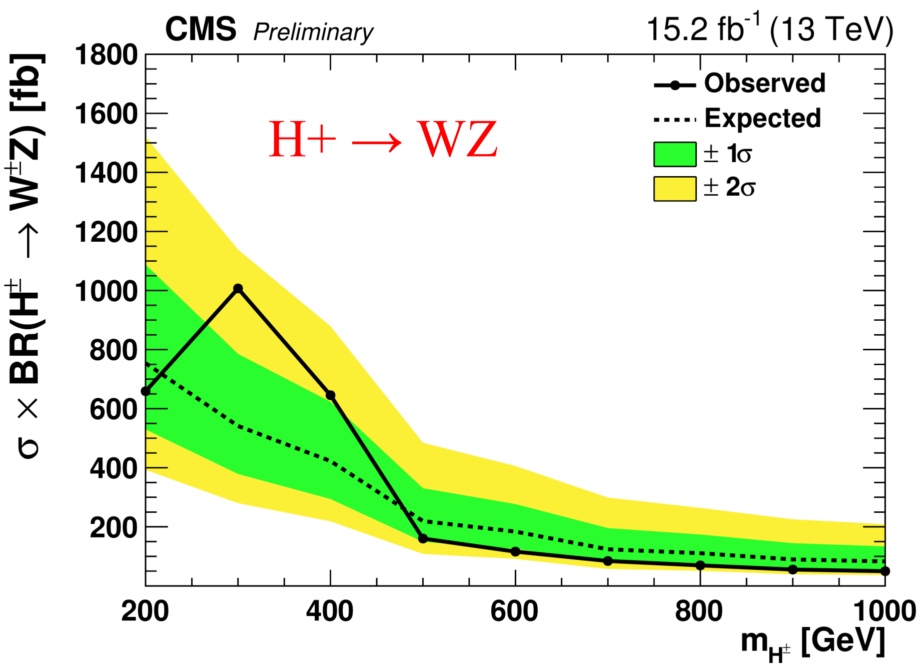
- Charged Higgs boson appear in many extensions of the SM

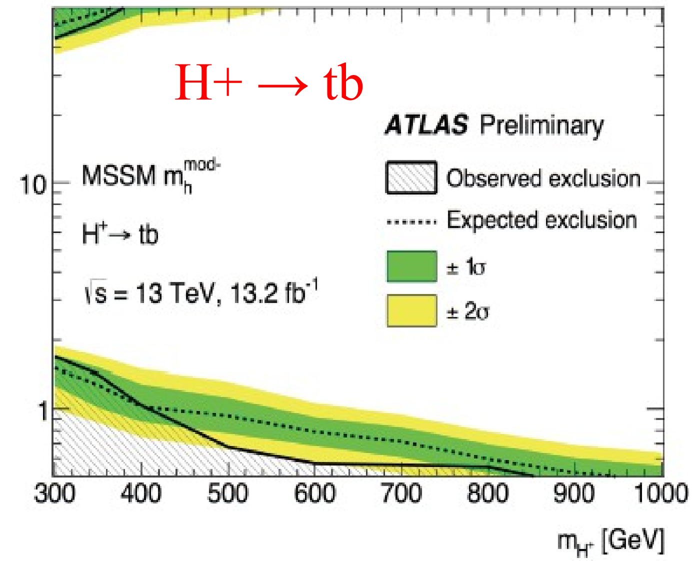
CMS-PAS-HIG-16-027
ATLAS-CONF-2016-089
ATLAS-CONF-2016-088





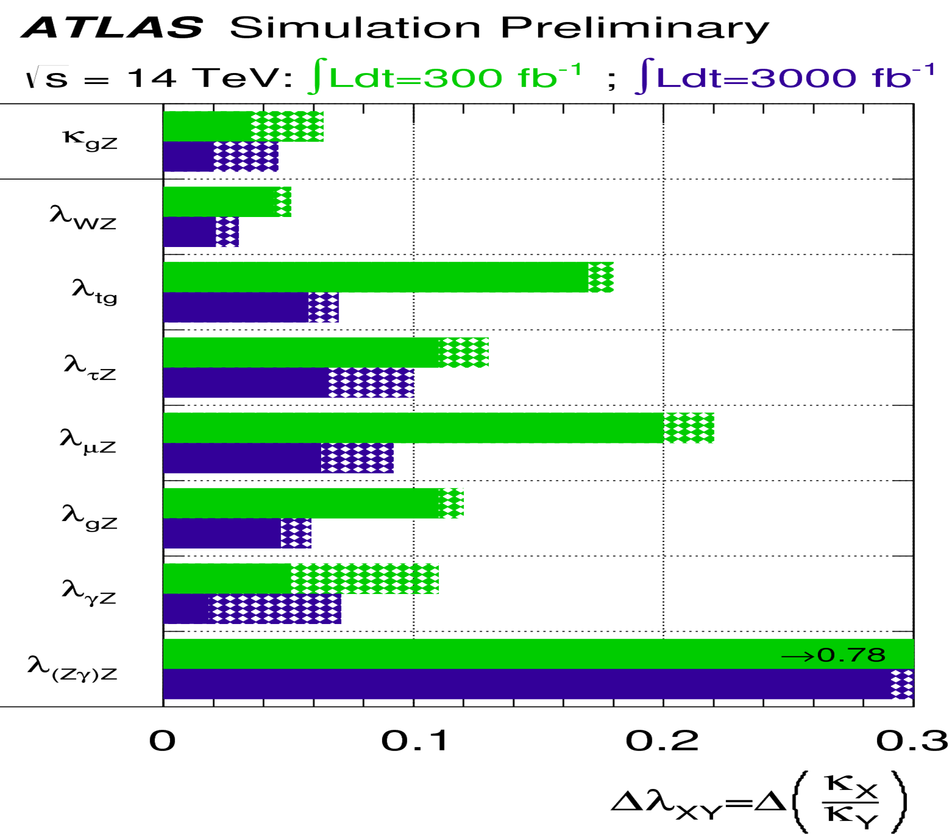


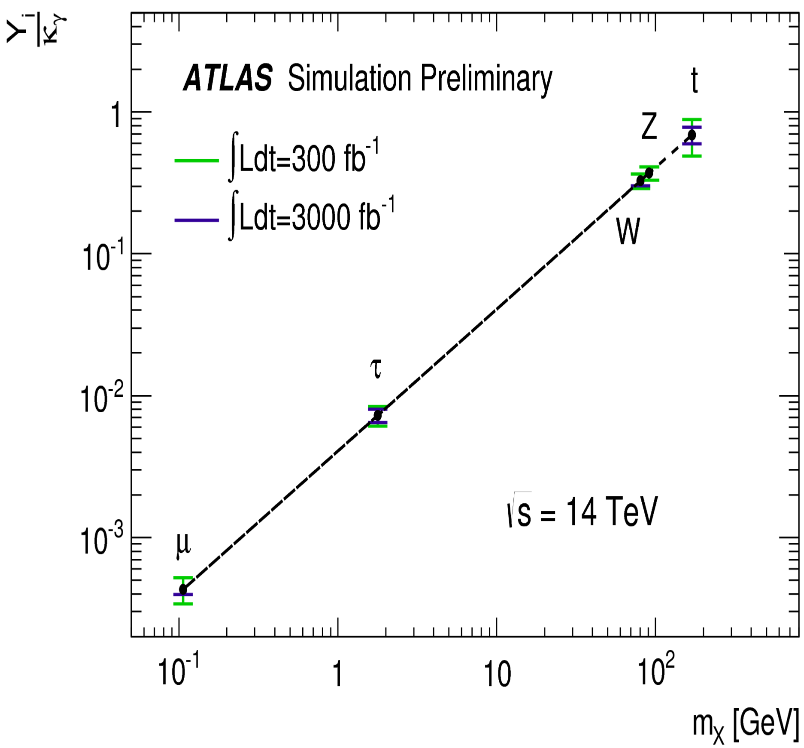




HL-LHC Prospects for Higgs boson coupling

- Some uncertainties cancel in ratio of partial widths:
  - Sensitive probe expecting new physics to affect couplings differently
- Expected precision ~3-10% for HL-LHC, a factor of 2-3 better than LHC.
- Theory uncertainty becomes more important in most cases.

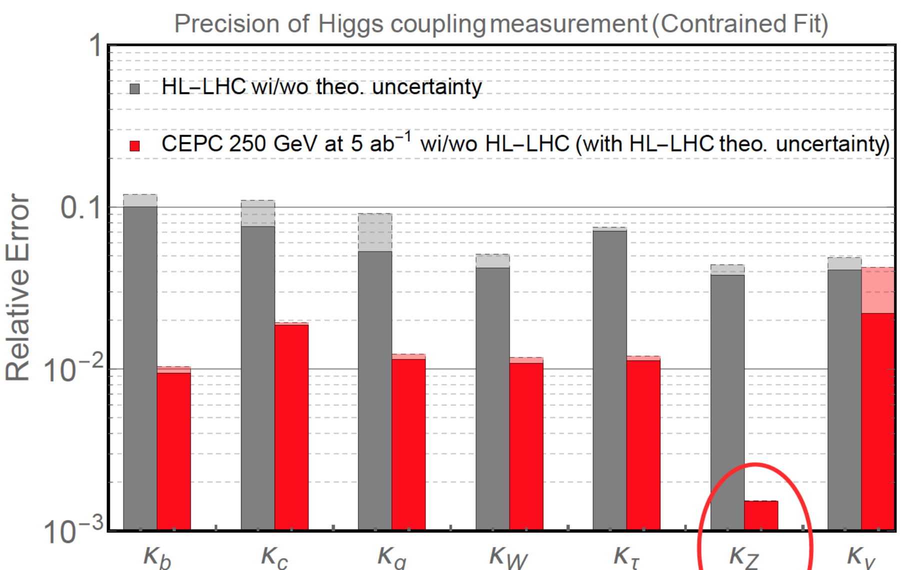


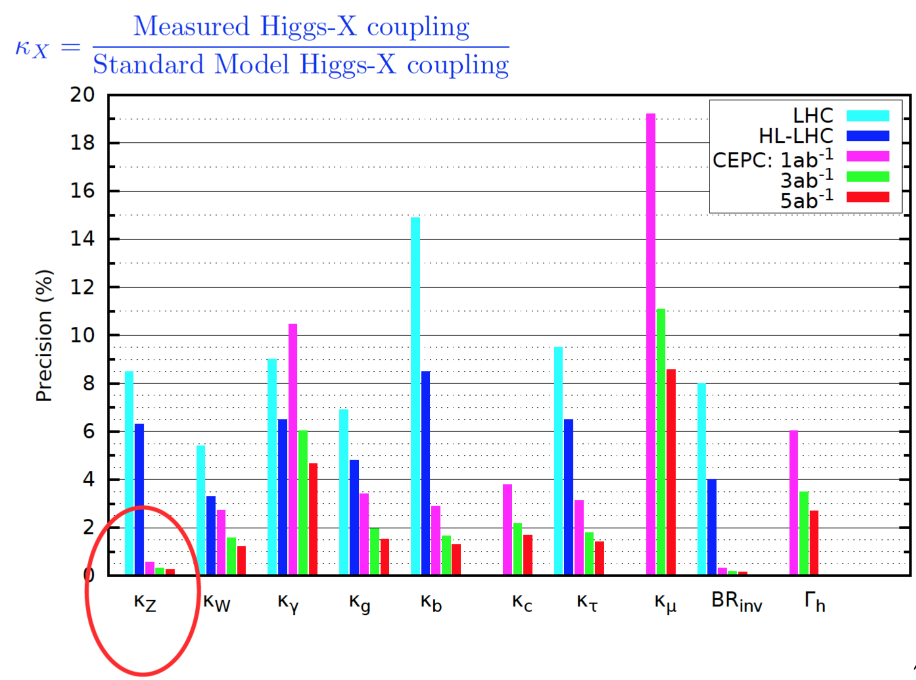


ATL-PHYS-PUB-2013-014

Physics case for CEPC

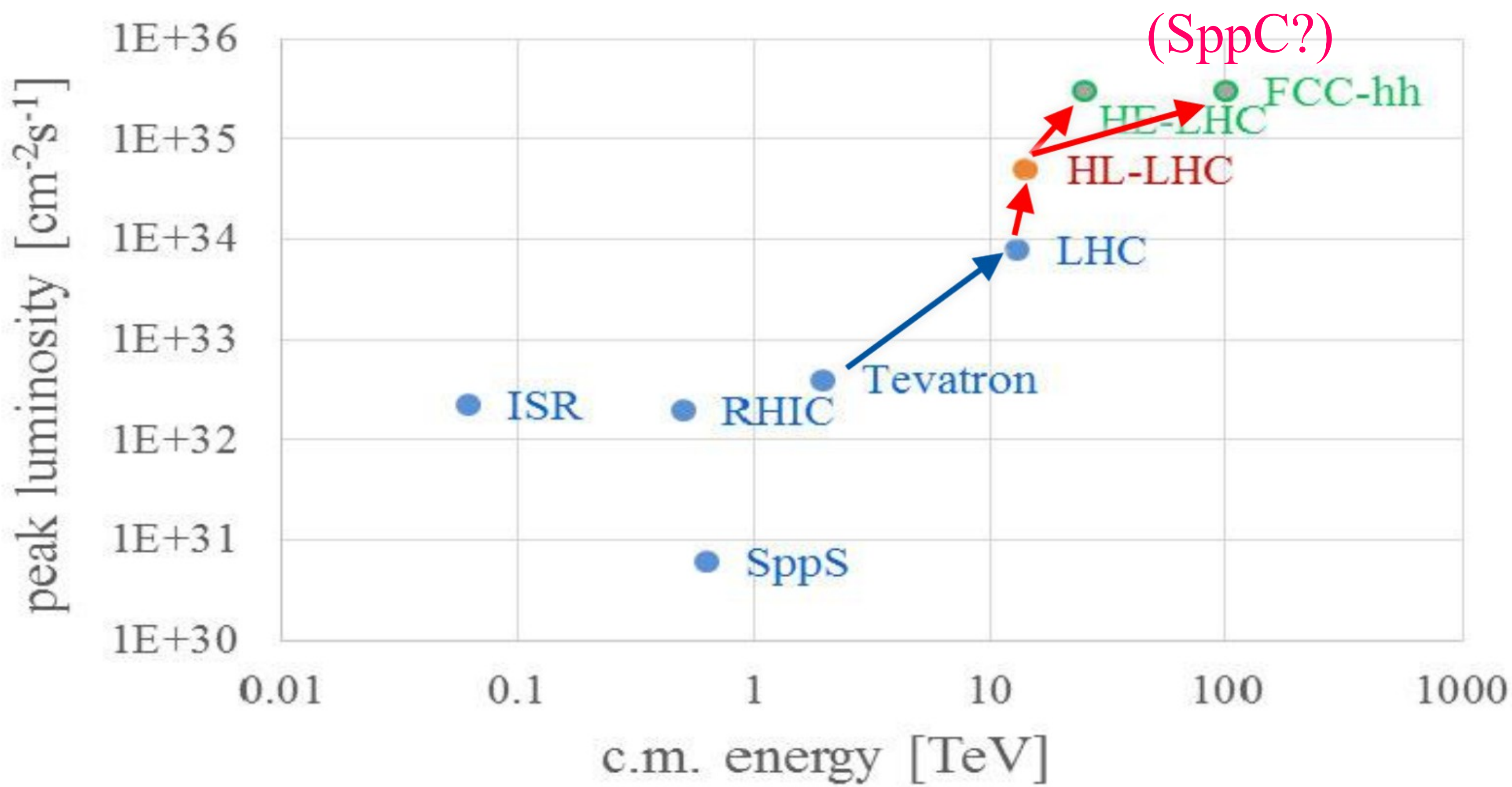
- To go beyond the LHC, we can do precision measurement ($\delta \sim (v/M_{NP})^2$) or go higher energy collisions.
- 1% or less precision measurements can be only achieved at the e+e- collider.
- Cover significant ground and answering important questions beyond the LHC
- Advantage of circular e+e- collider is able to convert to pp collider at 2nd stage.





IHEP-CEPC-DR-2015-01

Future projects

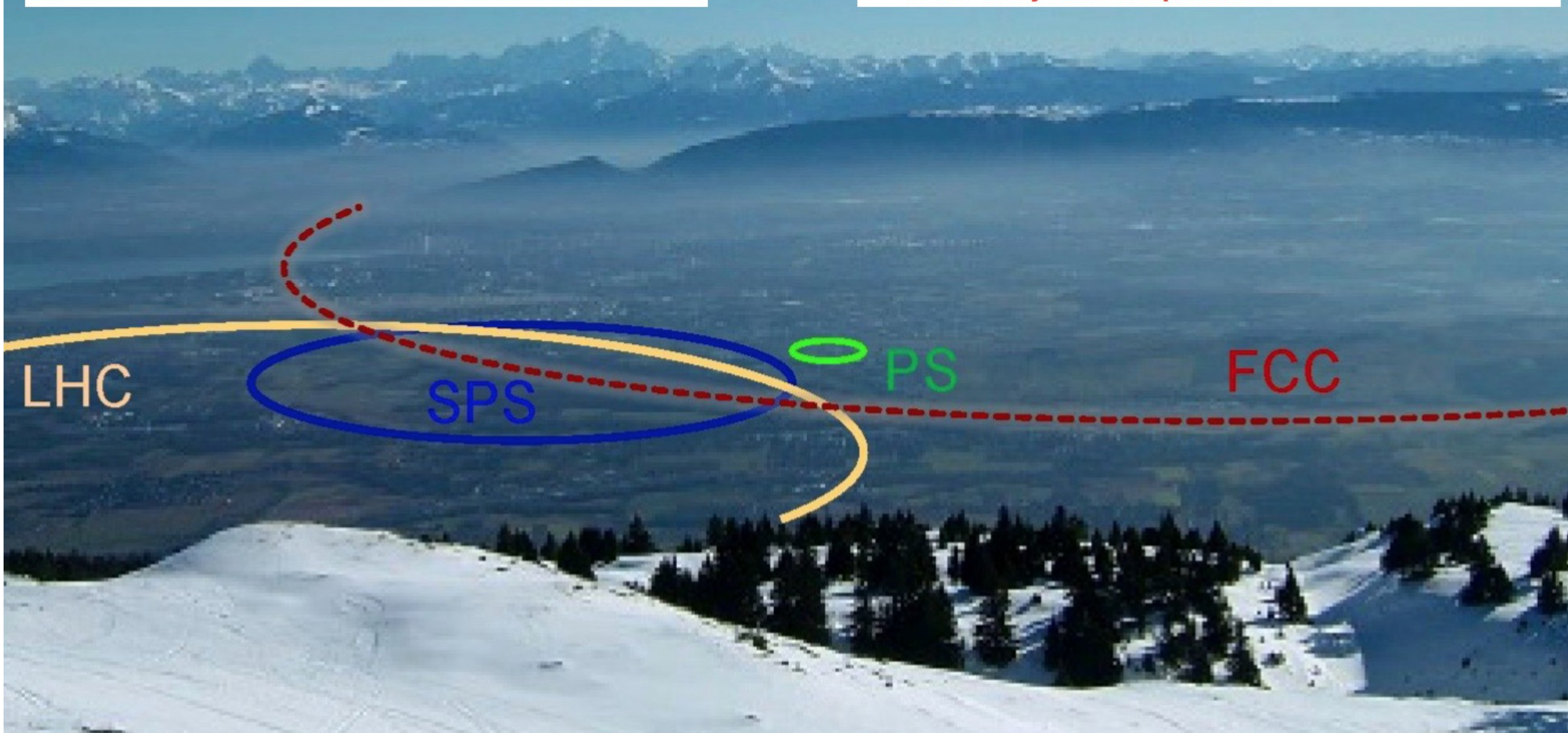


$E_{LHC} \sim \sqrt{(E_{Tevatron} * E_{FCC})}$

The FCC-hh Collider at 100 TeV

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [$cm^{-2}s^{-1}$]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

- **Phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
  250 fb^{-1}/year (averaged)
  2500 fb^{-1} within 10 years (~HL LHC total luminosity)
- **Phase 2 (ultimate): ~2.5 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
  1000 fb^{-1}/year (averaged)
  ➔ 15,000 fb^{-1} within 15 years
- **Yielding total luminosity O(20,000) fb^{-1} over ~25 years of operation**



Higgs physics at 100 TeV

- Providing an energy frontier as well as intensity frontier experiment.
- Discovery of extended Higgs sectors >1Tev(EWPT, DM, Naturalness)
- Huge number of Higgs bosons produced (10Billions), two order of magnitude increase with respect to HL-LHC.

ArXiv:1606.0940V1

- VBF, ttH and other rare processes become more important.

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

$N_{100}=\sigma_{100TeV}*20\ ab^{-1}$

$N_{14}=\sigma_{14TeV}*3ab^{-1}$

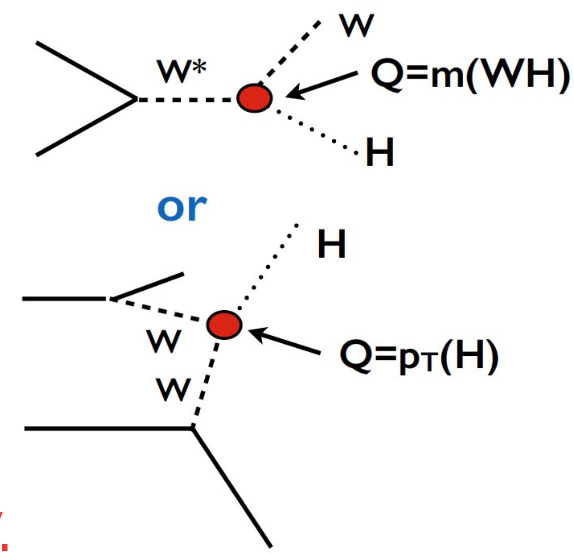
$N_8=\sigma_{8TeV}*20\ fb^{-1}$

Table 20: Indicative total event rates at 100 TeV (N_{100}), and statistical increase with respect to the statistics of the LHC run 1 (N_8) and the HL-LHC (N_{14}), for various prodution channels. We define here $N_{100} = \sigma_{100\ TeV} \times 20\ \text{ab}^{-1}$, $N_8 = \sigma_{8\ TeV} \times 20\ \text{fb}^{-1}$, $N_{14} = \sigma_{14\ TeV} \times 3\ \text{ab}^{-1}$.

Higgs as a Probe for High Mass Scale (λ)

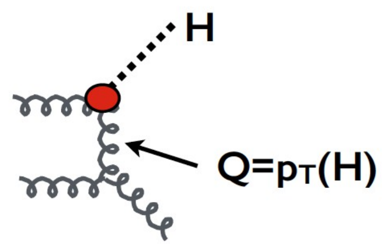
- For BSM EFT, $\mathcal{L} = \mathcal{L}_{SM} + 1/\lambda^2 * \sum O_k + \ldots$ where λ is the cut off scale
- Any observable: $O = |\langle f|\mathcal{L}|i\rangle|^2 = O_{SM}(1 + O(\mu^2/\lambda^2) + \ldots)$, $\mu = m_H, \nu, Q$
- $\delta O \sim (\nu/\lambda)^2 \sim 6\%(\mathrm{TeV}/\lambda)^2 \sim 1\% \Rightarrow \lambda > 2.5$ TeV.

$\delta BR(H \to WW^*)$



- $\delta O \sim (Q/\lambda)^2 \sim 15\%$ up to Q=1TeV $\Rightarrow \lambda > 2.5$ TeV.

$\delta BR(H \to gg)$



gg→H→γγ at large Pt

- With more statistics, we can focus in the semi-boosted region where the backgrounds are smaller, which could improve sensitivities.
- Pt(H)>300 GeV, S/B~1, very clean probe of Higgs up to large Pt.

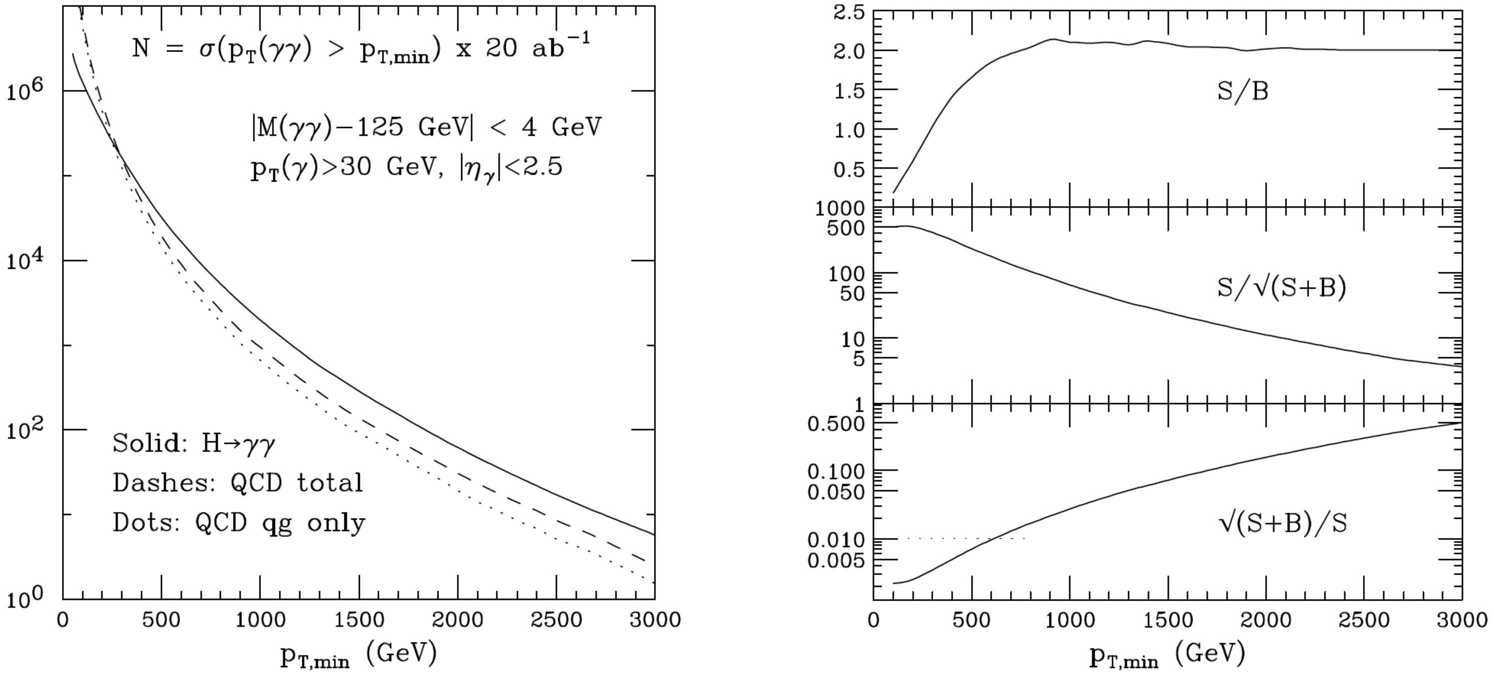
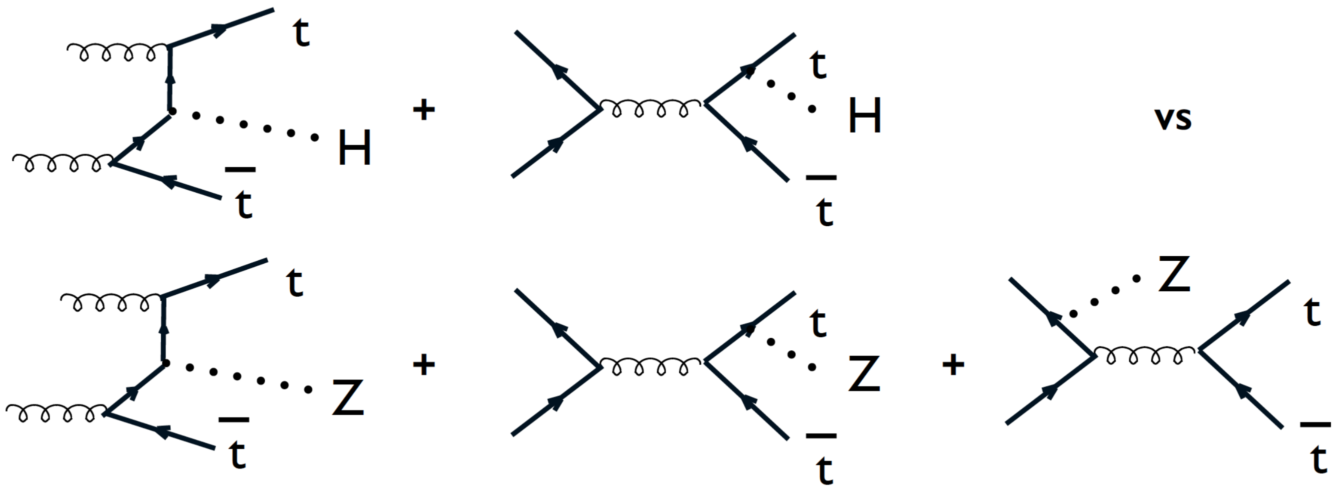


Fig. 45: Left: Integrated transverse momentum rates (20 ab^{-1}) for a photon pair with mass close to the Higgs mass: signal and QCD background. Right: S/B, significance of the signal, and potential statistical accuracy of the sample.

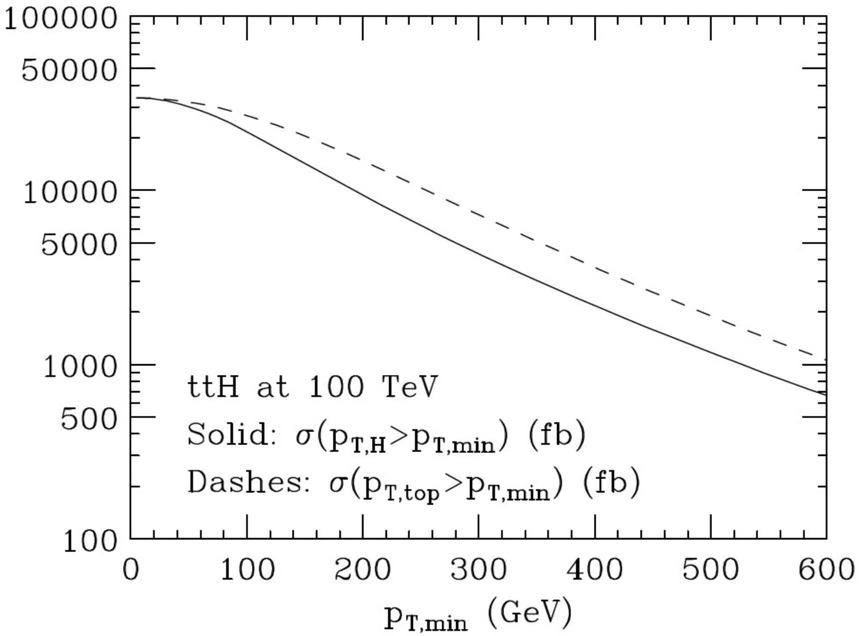
Top Yukawa y_{top} from σ(ttH)/σ(ttZ)



- Identical production dynamics
  - Correlated QCD corrections, correlated scale dependence
  - Correlated αs systematics
- mZ~mH: expect almost identical kinematic boundaries
  - Correlated PDF systematics
  - Correlated Mtop systematics
- For a given y_{top}, the ratio σ(ttH)/σ(ttZ) is well predicted.

Top Yukawa y_{top} Sensitivity

MLM, Plehn, Reimitz, Schell, Shao arXiv:1507.08169



$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$

Events/20ab^{-1} , with tt→$\ell\nu$+jets

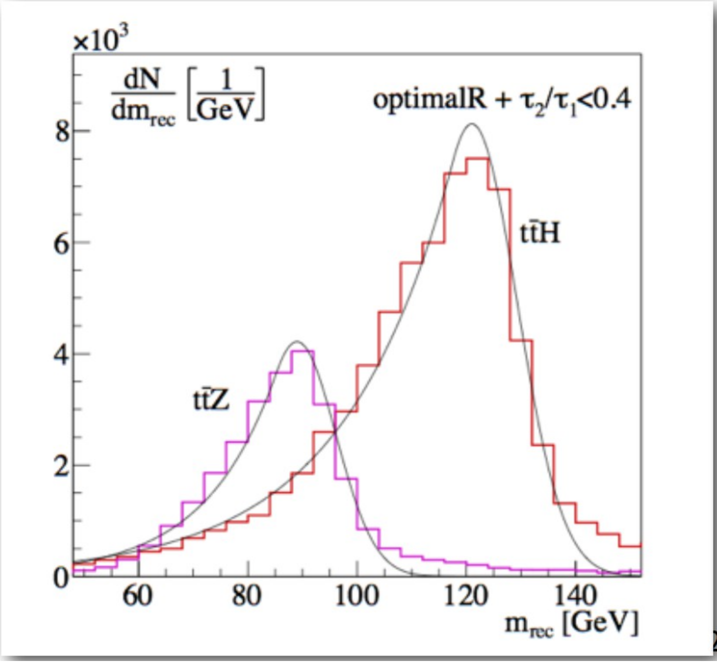
⇒ huge rates, exploit

boosted topologies

Top fat C/A jet(s) with R = 1.2, |y| < 2.5, and $p_{T,j}$ > 200 GeV

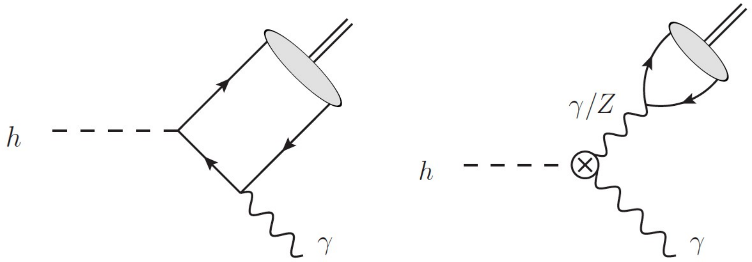
- δy_t (stat + syst $_{TH}$) ~ 1%

- great potential to reduce to similar levels $\delta_{exp\ syst}$
- consider other decay modes, e.g. 2l2nu



Rare Higgs decays

- Exclusive modes: BR(H→Vγ)~10^{-6} (V = vector meson) , allow extraction of Yukawa couplings to first 2 quark generations. (Bodwin et al PRD 88(2013) 053003, Kagan et al PRL 114(2015) 101802)
  - H → J/Ψ γ (y_c)
  - H → Φ γ (y_s)
  - H → ρ γ ($y_{u,d}$)



- Limits on H→ J/Ψ γ from LHC:
  - Current @ LHC 8 TeV 20 fb^{-1} <$1.5x10^{-3}$
  - LHC @14 TeV 300 fb^{-1} < 150 $x10^{-6}$
  - HL-LHC @14 TeV 3 ab^{-1} <$45x10^{-6}$

- FCC 100 TeV seems able to reach ~10^{-6}, close to SM value with 100 times increases in number of events with respect to the HL-LHC.

New analysis of HH production for the FCC report

R.C., C. Englert, G. Panico, A. Papaefstathiou, J. Ren, M. Selvaggi, M. Son, M. Spannowsky, W. Yao

- Goals:
  1. improve on previous studies and get a commonly-agreed estimate
  2. study dependence on efficiencies and systematics

Previous analyses:

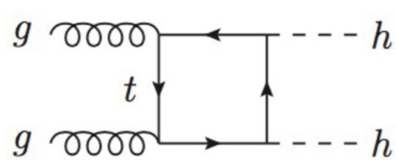
W. Yao arXiv:1308.6302 (Snowmass Summer Study 2013)

Barr, Dolan, Englert, de Lima, Spannowsky JHEP 1502 (2015) 016

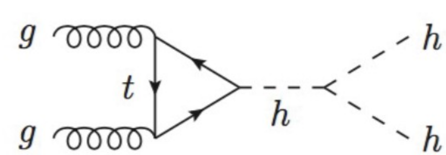
Azatov, R.C., Panico, Son PRD 92 (2015) 035001

H-J. He, J. Ren, W. Yao PRD 93 (2016) 015003

Signal: double Higgs production via gluon fusion ($gg \to hh$)



$\sim const.$



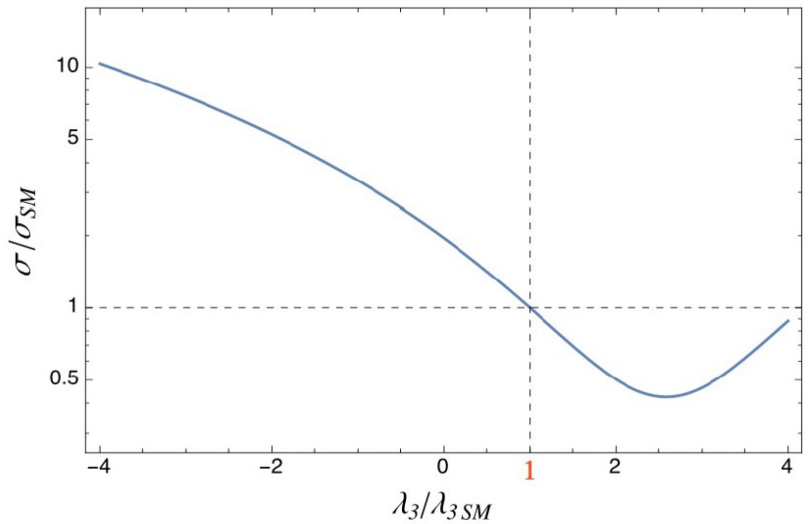
$$\sim \lambda_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$$

→ Most sensitivity on trilinear coupling comes from threshold events

	Signal cross section [fb] at NNLO+NNLL *
14 TeV	$45.05^{+4.4\%}_{-6.0\%} \pm 3.0\% \pm 10\%$
100 TeV	$1749^{+5.1\%}_{-6.6\%} \pm 2.7\% \pm 10\%$

$\sim 40\times$ increase

Theoretical uncertainties: scale; PDFs $+\alpha_s$; infinite m_t approx.



	# Higgs pairs to bbγγ
LHC: 14TeV 300fb^{-1}	36
HL-LHC: 14TeV 3ab^{-1}	360
FCC: 100TeV 20ab^{-1}	92 x 10^3

← percent precision physics

Backgrounds:

- $b\bar{b}\gamma\gamma$
- $t\bar{t}h(\gamma\gamma)$
- $b\bar{b}h(\gamma\gamma)$
- $jj\gamma\gamma$ (two fake b-jets)
- $b\bar{b}j\gamma$ (one fake photon)

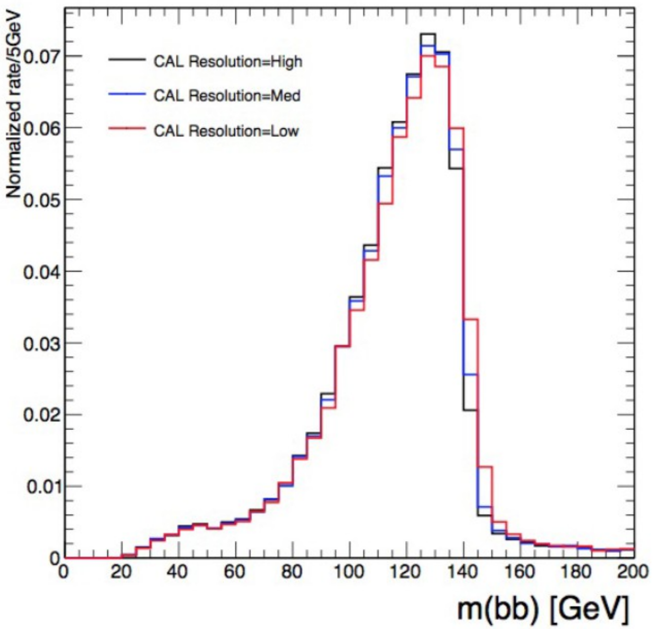
* Results of the recent full-m$_{top}$ NLO calculation (Borowka et al, arXiv: 1604.06447) not included here (as yet….)

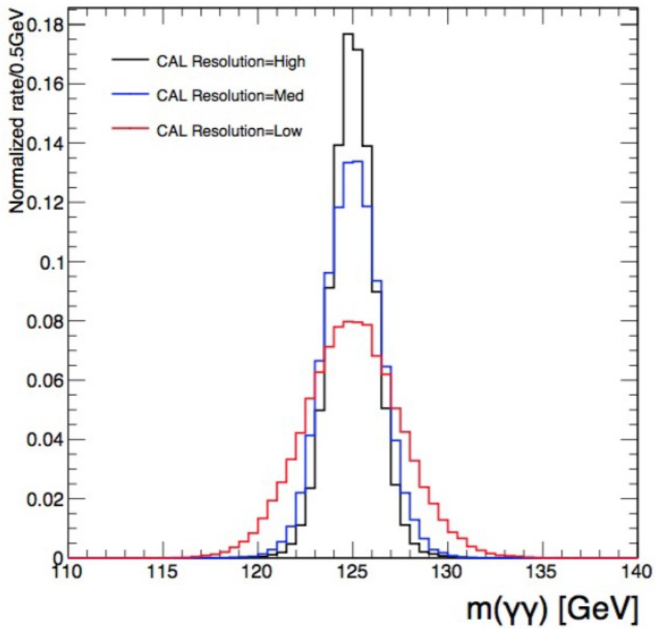
Montecarlo Simulation: MadGraph5_aMC@NLO ⟶ Pythia 6 ⟶ Delphes (FCC card)

Three benchmark scenarios for ECAL and HCAL resolution:

$$\Delta E = \sqrt{a^2 E^2 + b^2 E}$$

	ECAL				HCAL			
	$\lvert\eta\rvert \le 4$		$4 < \lvert\eta\rvert \le 6$		$\lvert\eta\rvert \le 4$		$4 < \lvert\eta\rvert \le 6$	
	a	b	a	b	a	b	a	b
low	0.02	0.2	0.01	0.1	0.05	1.0	0.05	1.0
medium	0.01	0.1	0.01	0.1	0.03	0.5	0.05	1.0
high	0.007	0.06	0.01	0.1	0.01	0.3	0.03	0.5





High
$\Delta m(\gamma\gamma) = 1.5\,\text{GeV}$

Med
$\Delta m(\gamma\gamma) = 2.0\,\text{GeV}$

Low
$\Delta m(\gamma\gamma) = 3.0\,\text{GeV}$

Analysis Strategy of HH → bbγγ

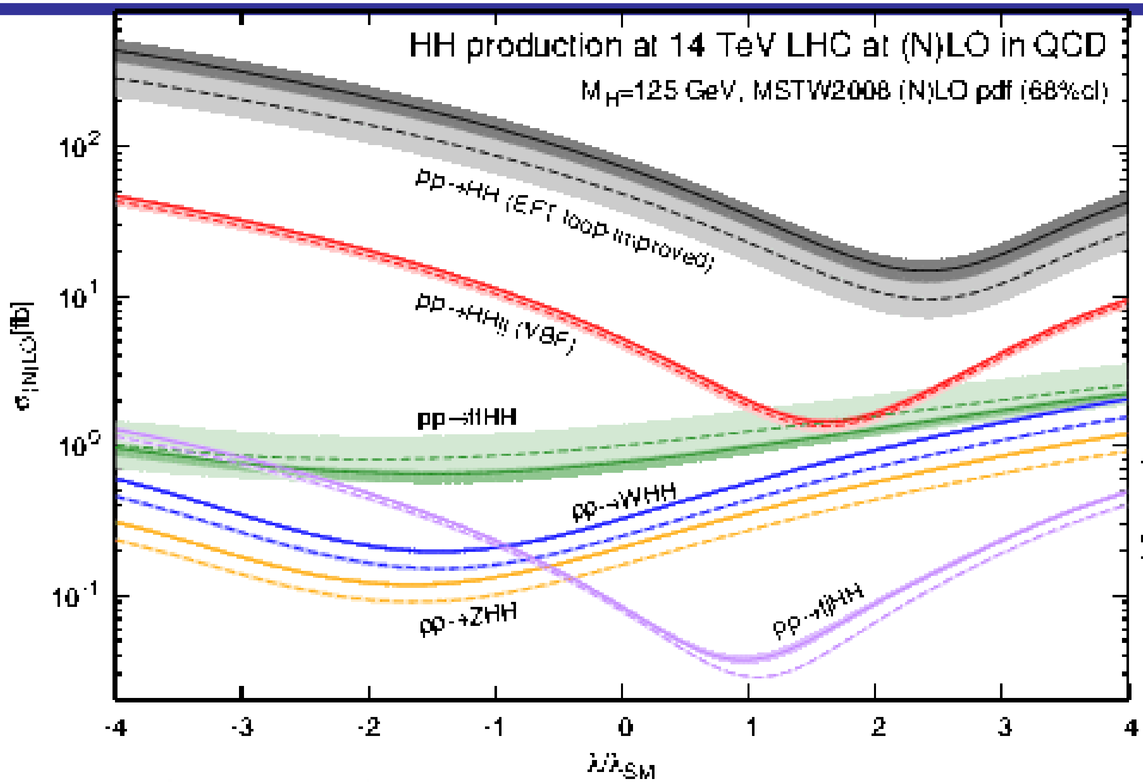
- Interested in events at threshold, no boosted techniques needed.
- Optimize cuts to maximize sensitivity on trilinear coupling not xsec.
- Event selections:
  - Two isolated photons, |eta|<4.5, Pt(1)>60 GeV, Pt(g2)>35 GeV
  - Jets anti-kt with cone 0.4, |eta|<4.5, pt(b1)>60, pt(b2)>35 GeV
  - |mgg -mh|<2.0, 3.0, 4.5 for high/med/low scenarios
  - Pt(bb), Pt(gg)>100 GeV, DeltaR*bb), DeltaR(gg)<3.5

Process	Acceptance cuts [fb]	Final selection [fb]	Events ($L = 30$ ab^{-1})
$h(b\bar{b})h(\gamma\gamma)$ (SM)	0.73	0.40	12061
$bbj\gamma$	132	0.467	13996
$jj\gamma\gamma$	30.1	0.164	4909
$t\bar{t}h(\gamma\gamma)$	1.85	0.163	4883
$b\bar{b}\gamma\gamma$	47.6	0.098	2947
$b\bar{b}h(\gamma\gamma)$	0.098	7.6×10^{-3}	227
$bj\gamma\gamma$	3.14	5.2×10^{-3}	155
Total background	212	1.30	27118

S/B=0.45
S/sqrt(S+B)=61.

Triple Higgs coupling sensitivity

- Higgs self-coupling dependence at 14 TeV and 100 TeV are similar.



process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–

Summary

- LHC Run-2 is moving at the full speed and ATLAS and CMS are doing very well in accommodating high luminosity.
- Exploration of the new energy regime of 13 TeV has started.
- The Higgs boson has been measured and are consistent with the SM.
- Searches for BSM Higgs has been performed in various channels and no significant excess is observed.
- Energy frontier of LHC remains open to discovery and exploration of unexpected physics at the highest energy scales.
- With 3000 fb^{-1} fb of HL-LHC and future colliders, we should be able to understand the Higgs sector down to unprecedented level including the Higgs self-coupling and whatever the new physics will appear.
- This is very exciting time for the particle physics!