$H \to \gamma\gamma$ measurements at ATLAS and CMS

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on behalf of ATLAS and CMS collaborations

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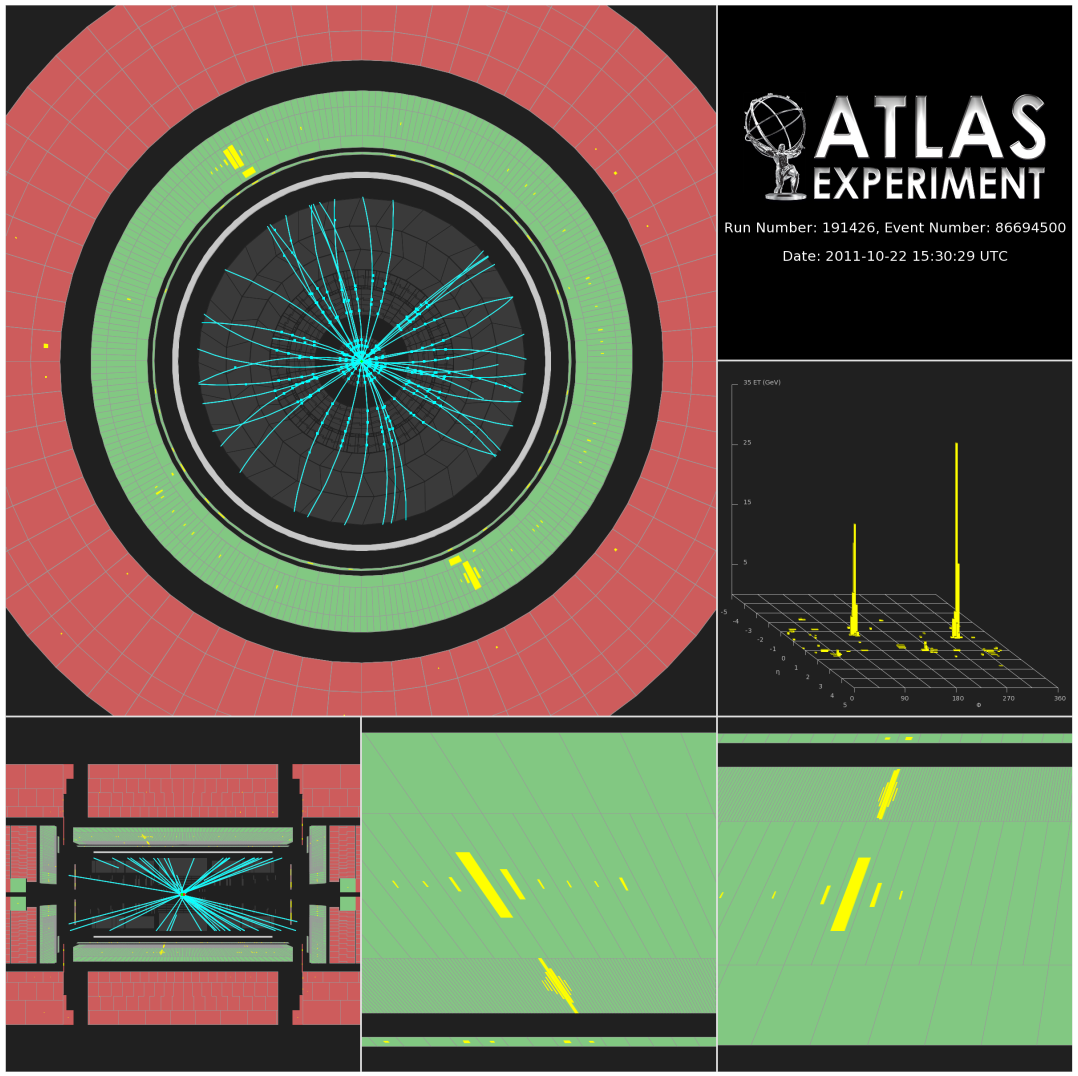
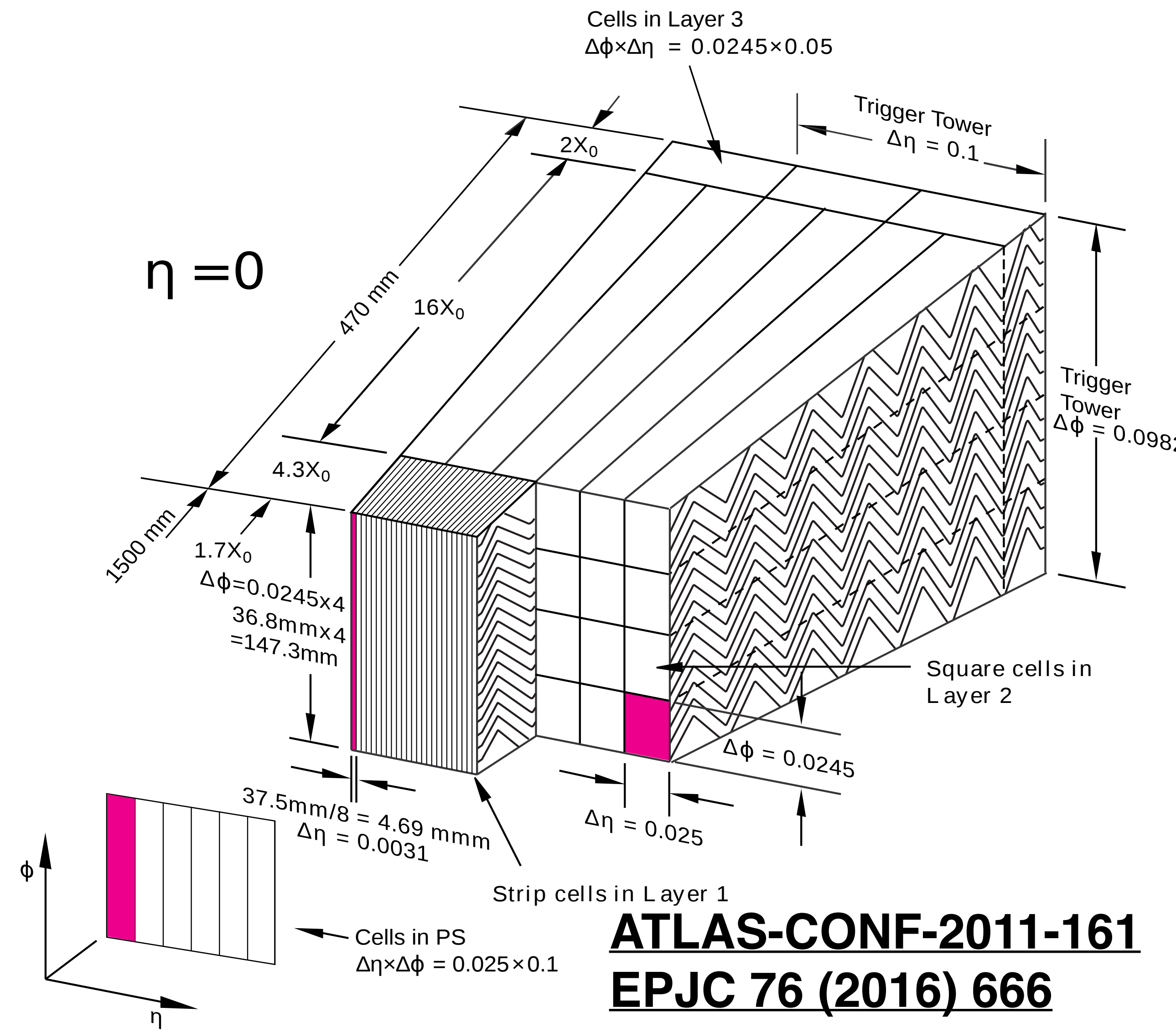
Introduction

- At the LHC, the ***$H \to \gamma\gamma$*** channel plays a key role first in the discovery of the Higgs boson, and then in the measurements of Higgs boson properties and also in searches for new physics
    - Good sensitivity: excellent mass resolution, clean signature
    - Sensitive to new physics: loop-induced process
- This talk: recent **Run 2 @13 TeV** ATLAS and CMS results from $H \to \gamma\gamma$ channel
    - Coupling and mass measurements
    - Fiducial/differential XS measurements
    - Searches: flavor changing neutral current, mono-Higgs + MET
        - Di-Higgs searches will be covered by Magda Slawinska

✳ *Not intend to summarize all the important results due to time constraints. Apologies if your favorite topic is missing!*

ATLAS EM calorimeter & photon reconstruction

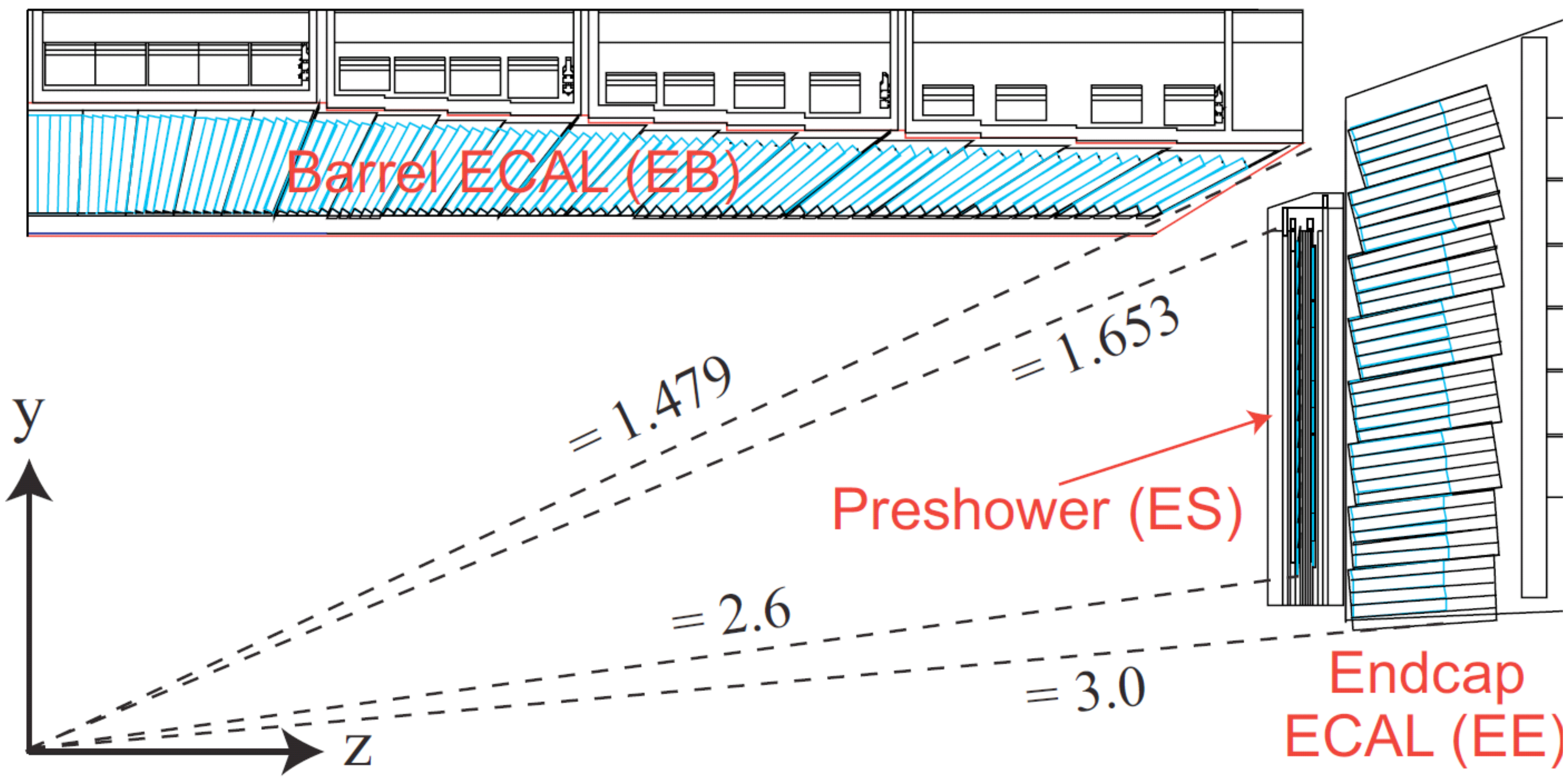




ATLAS-CONF-2011-161
EPJC 76 (2016) 666

- **Liquid Argon** sampling calorimeter with layer structure
  - First finely-segmented layer provides discrimination against neutral hadrons
  - Longitudinal shower information used in diphoton vertex finding
- Sliding window algorithm for photon reconstruction. Converted photon reconstructed by matching tracks consistent with conversion
- MC-based calibration using MVA regression technique, with additional corrections from $Z\to ee$ MC/data comparison

CMS EM calorimeter & photon reconstruction



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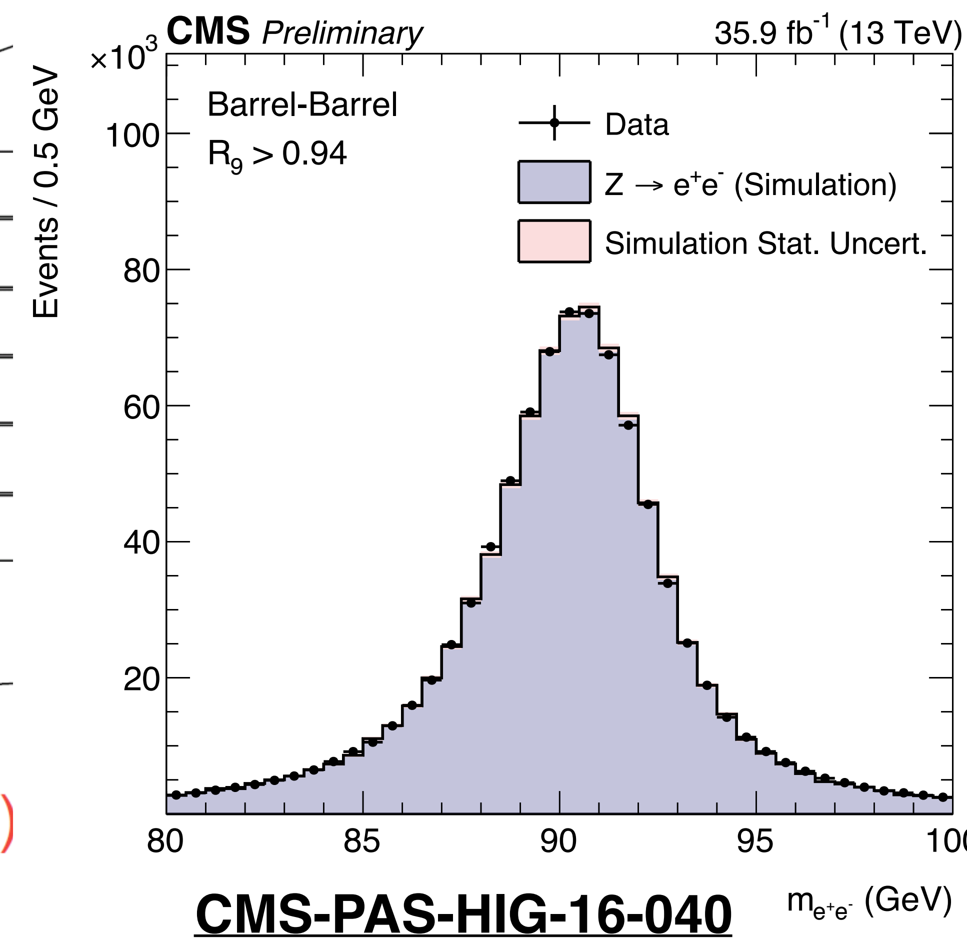
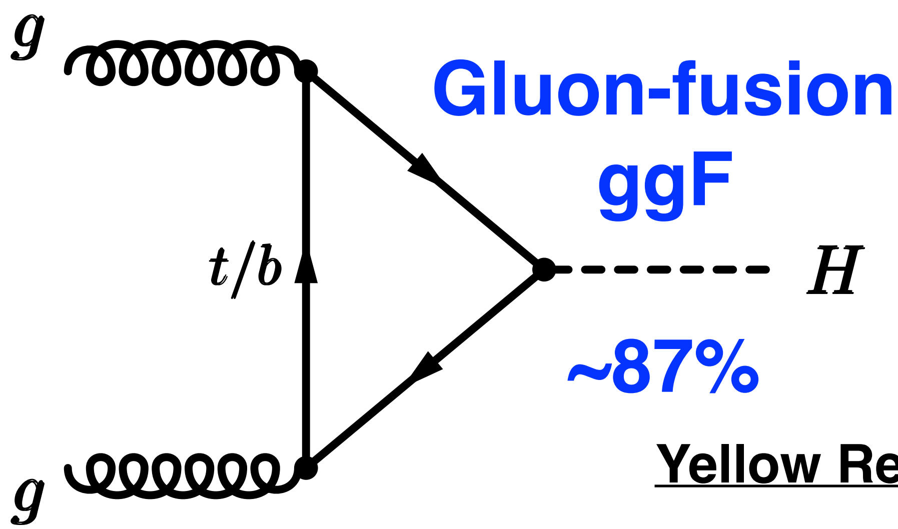


CMS-PAS-HIG-16-040

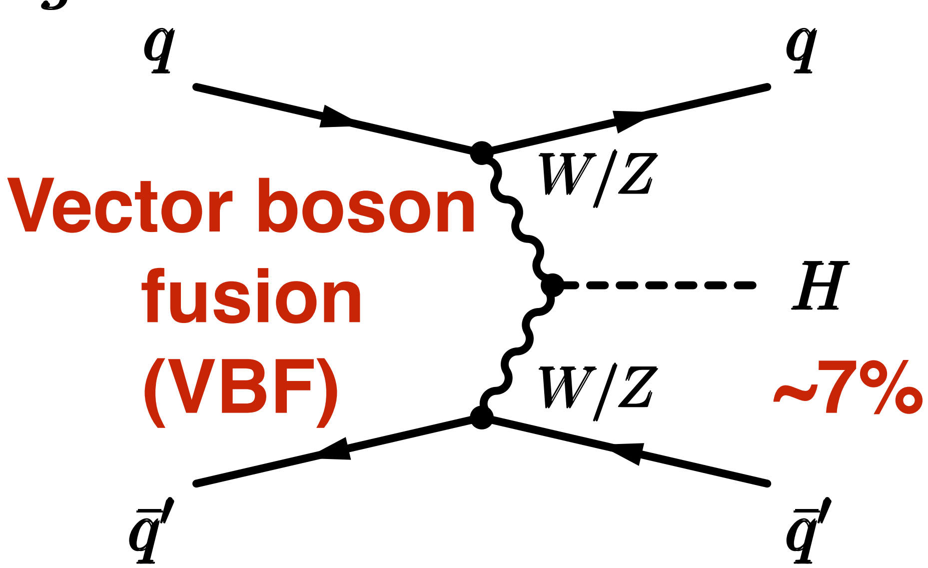
- High granularity **PbWO4 crystal** layout
- “Particle-flow” algorithm (arXiv:1706.04965) reconstruct all particles combining information from all relevant sub-detectors. Photons are identified as ECAL energy clusters not linked to the extrapolation of any charged-particle trajectory to the ECAL
- “Supercluster” for good energy containment and robustness against pileup
- Mainly use track recoiling to assign diphoton vertex
- MC-based MVA regression for calibration. Using $Z \rightarrow ee$ events where electron is reconstructed as photon for correcting energy scale in data

SM Higgs boson productions at LHC

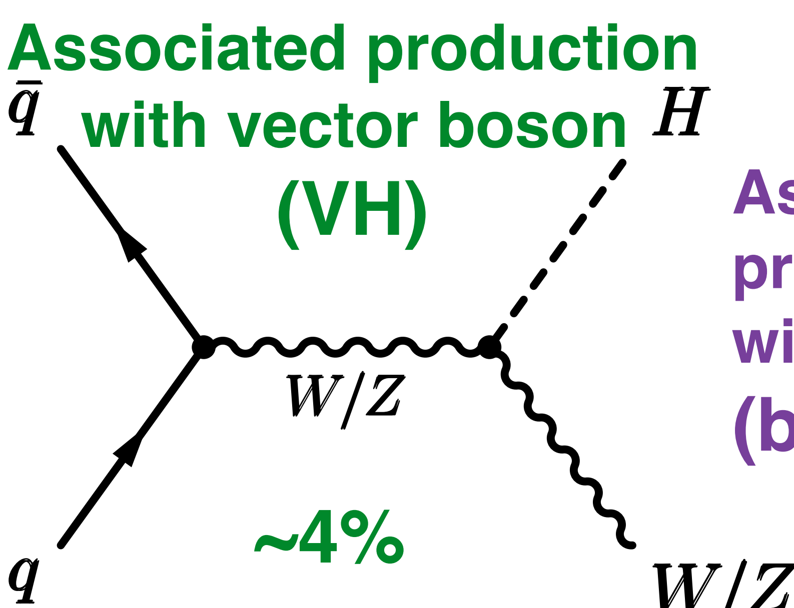


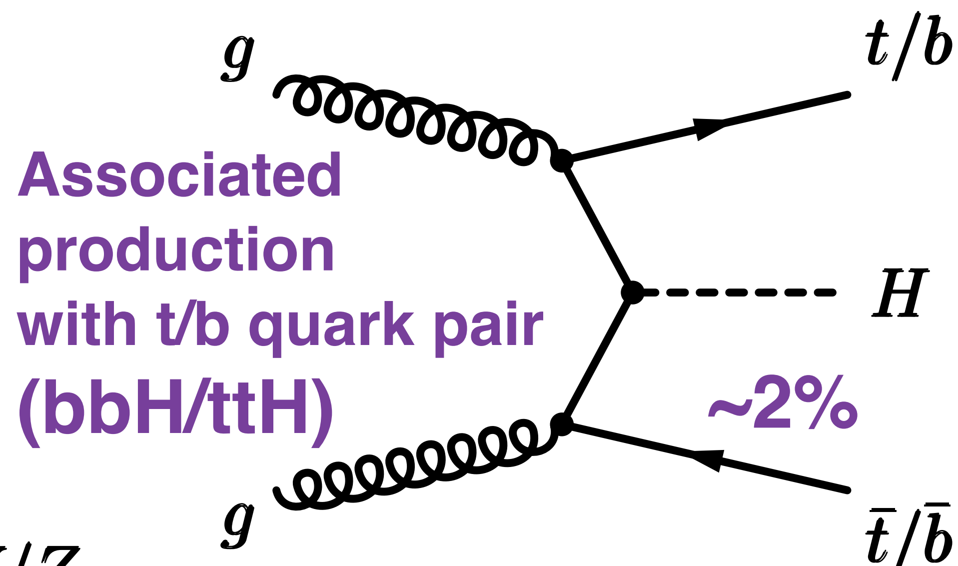
Yellow Report 4

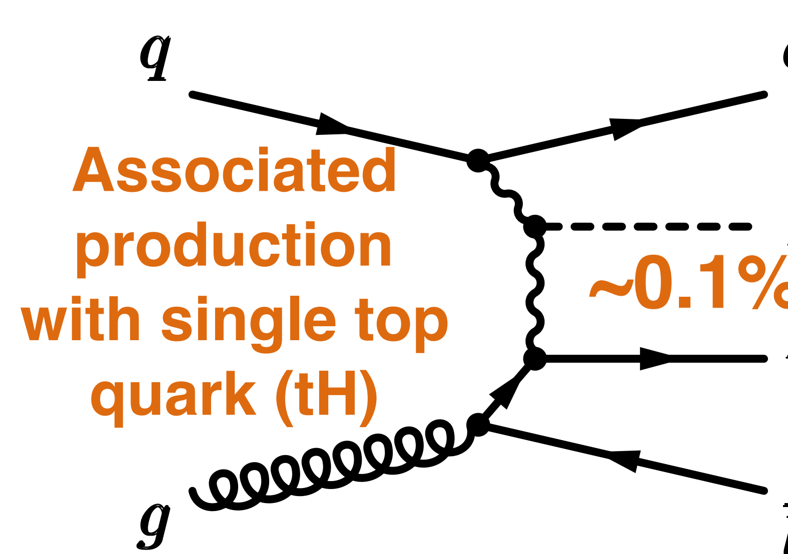
XS in pb	13 TeV	8 TeV	$\sigma_{13\ TeV}/\sigma_{8\ TeV}$
ggF	48.52	21.39	2.3
VBF	3.78	1.60	2.4
WH	1.37	0.70	2.0
ZH	0.88	0.42	2.1
bbH	0.49	0.20	2.4
ttH	0.51	0.13	3.8
tH	0.092	0.023	3.9



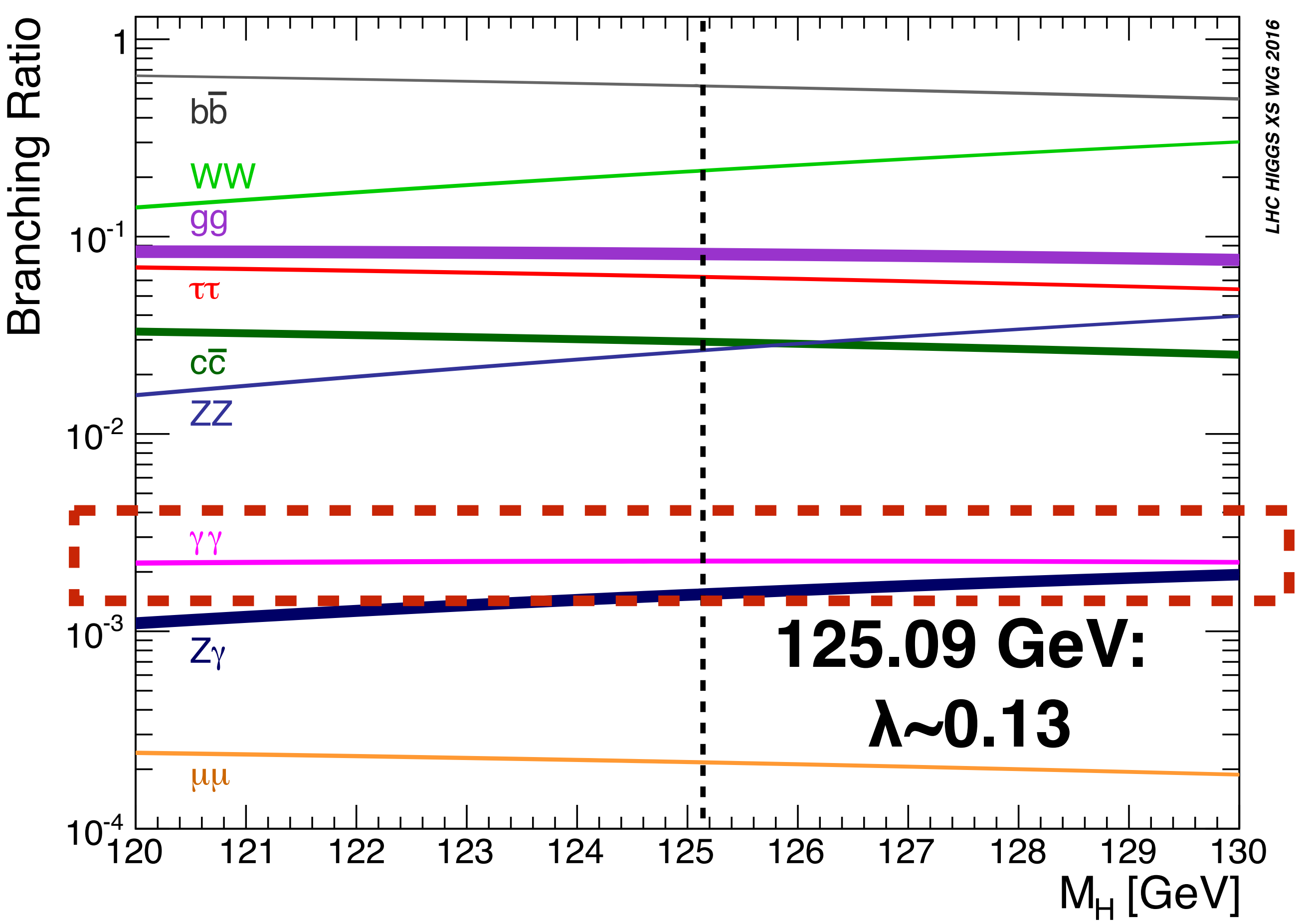
Significant boost in production XS from increased √s.
Bkg. expected to increase by factor of ~2

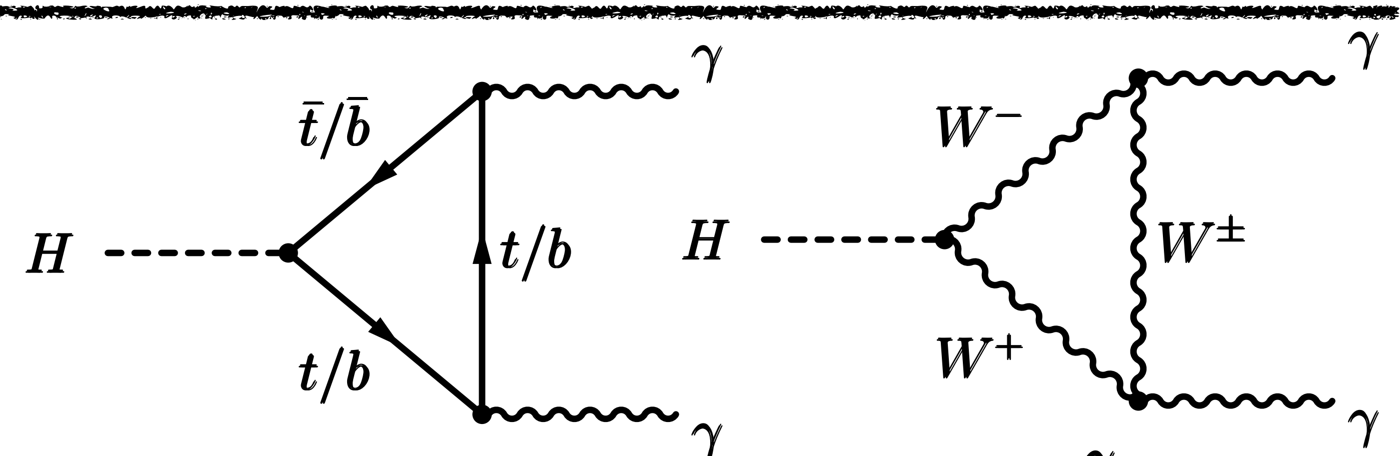
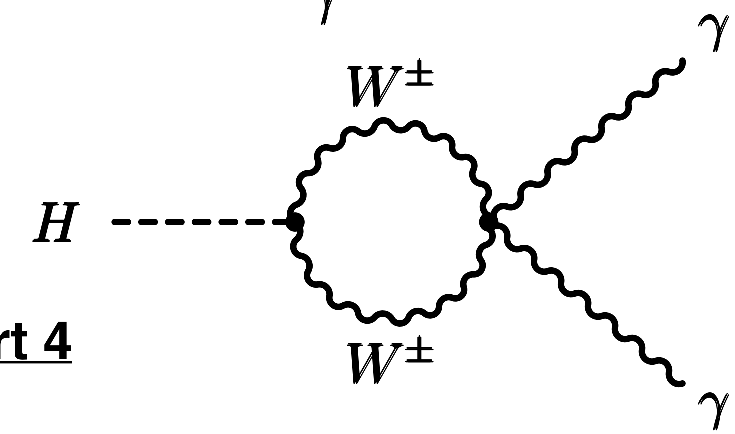






$H\to\gamma\gamma$



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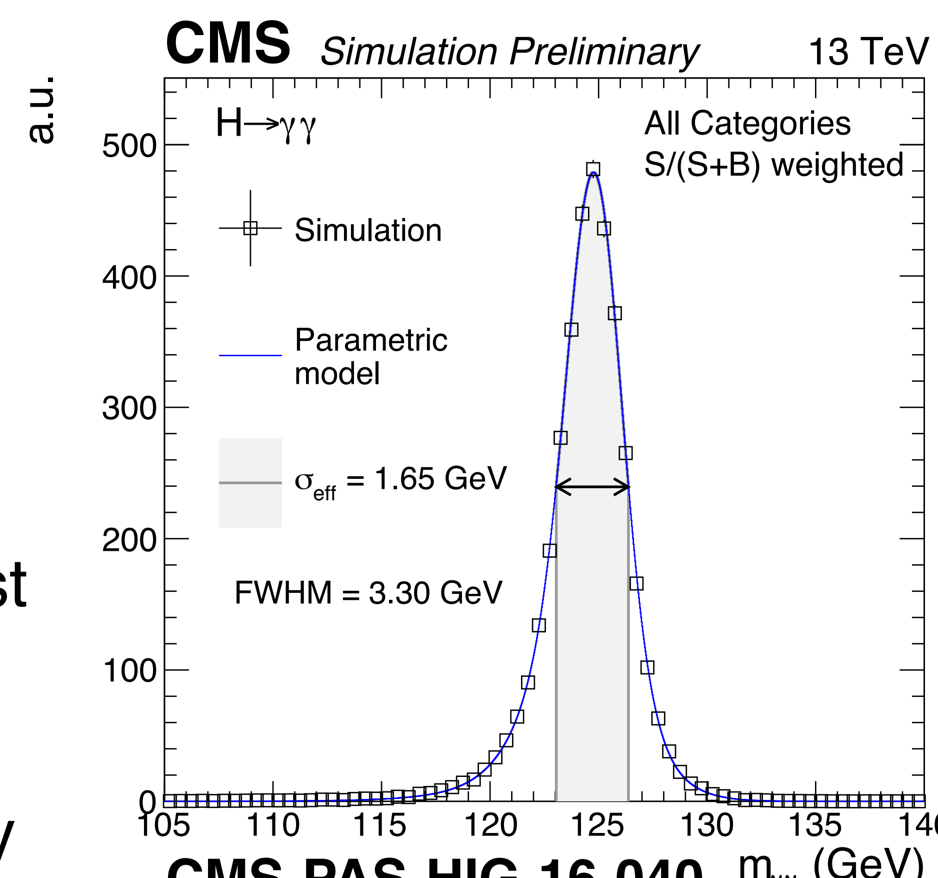
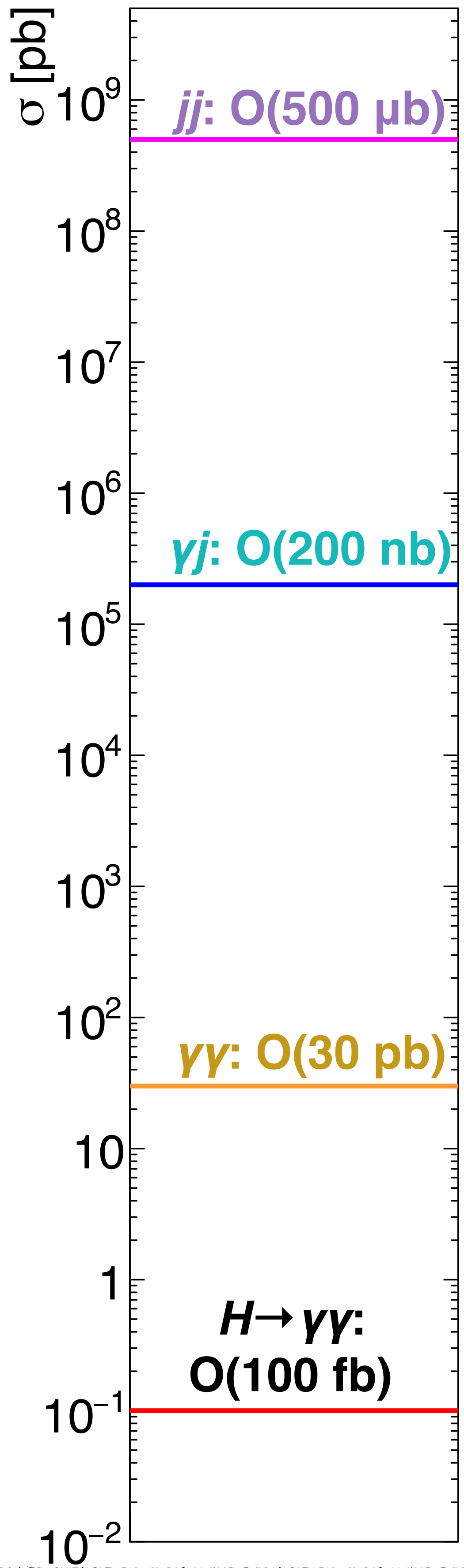
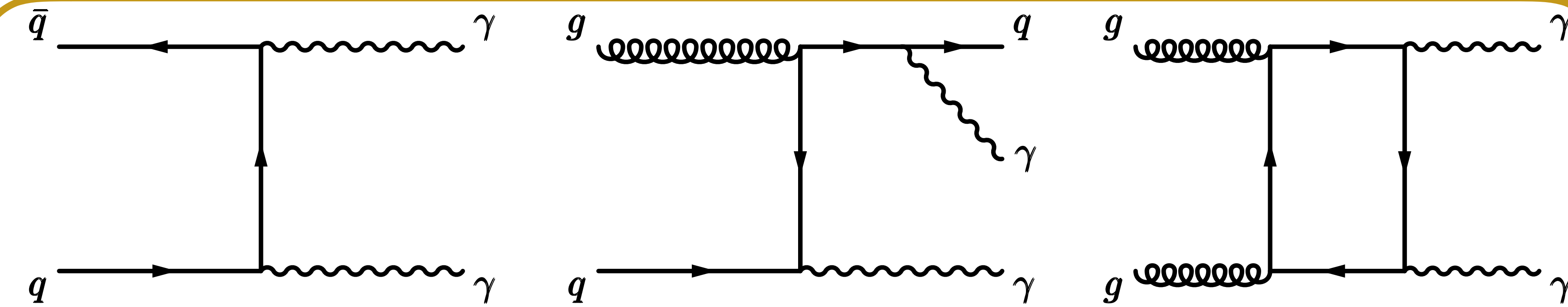


CMS-PAS-HIG-16-040

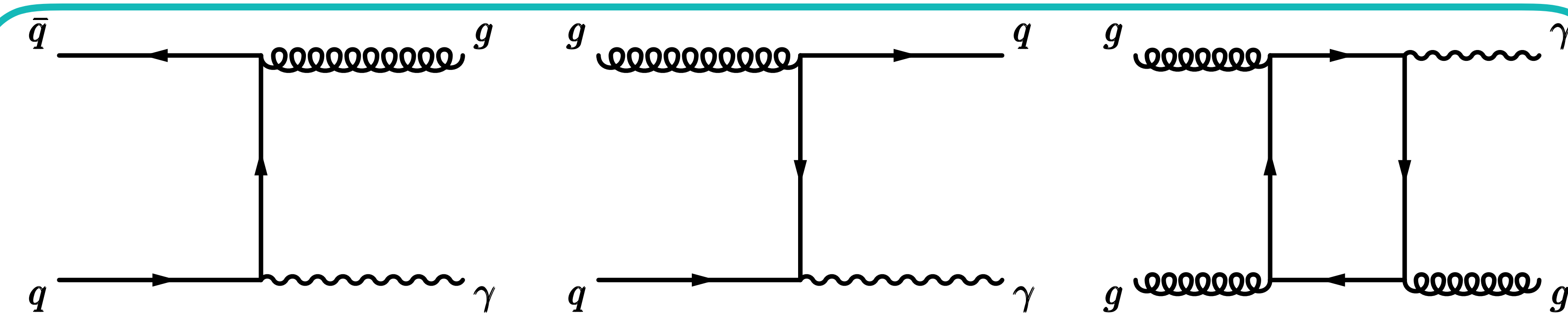
- Loop-induced process
  - Interference helps probe sign of couplings to SM particles
  - New physics could enter the loop
- Signal $m_{\gamma\gamma}$ distribution expected to be dominated by **detector resolution** (SM Γ_H is negligible)
- Variation of signal $m_{\gamma\gamma}$ resolution (quantified as smallest window containing 68% of signal) among categories in coupling analyses:
  - ATLAS: 1.42 GeV ~ 2.14 GeV, CMS: 1.32 GeV ~ 2.62 GeV

Background



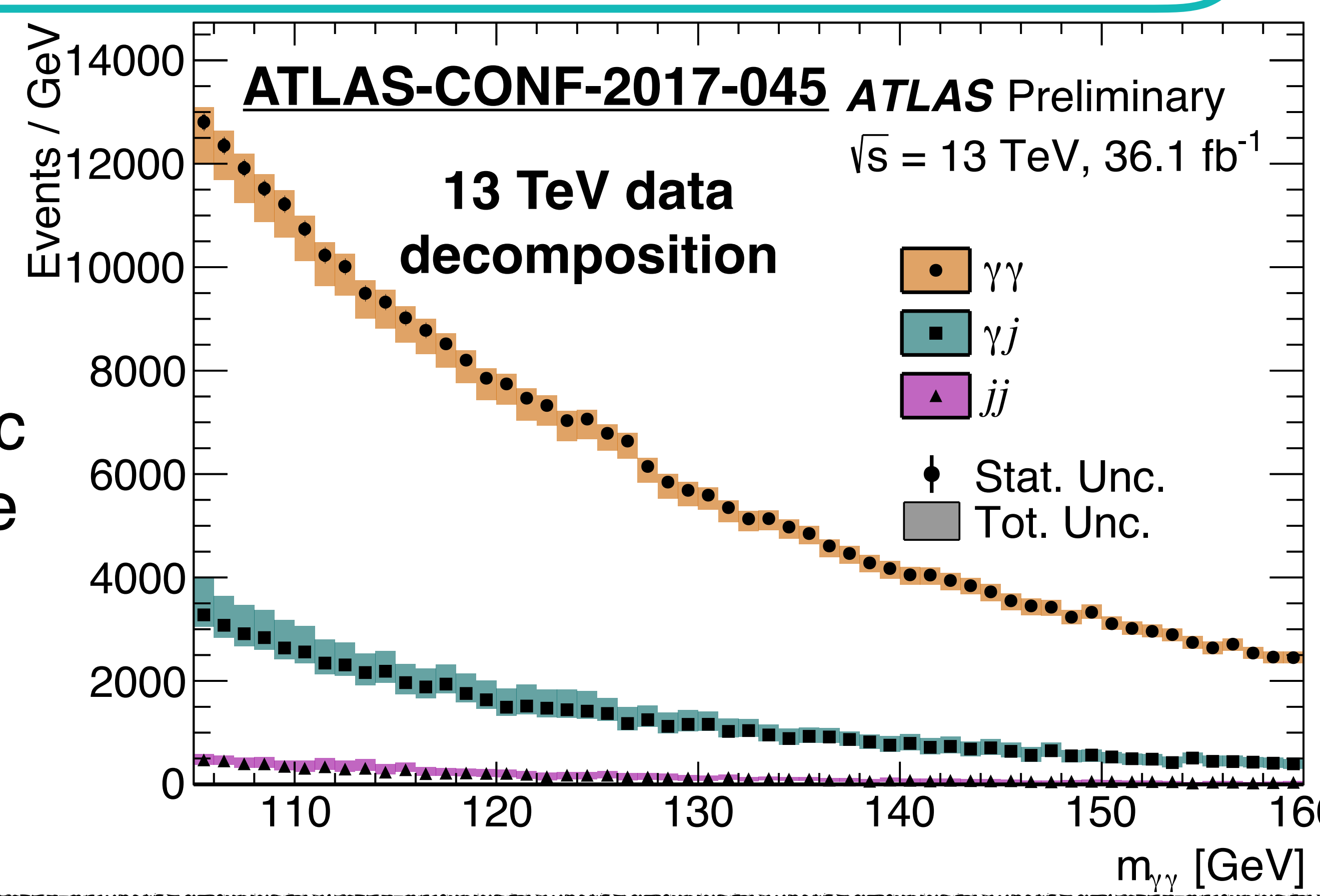


Irreducible background: SM diphoton process



Reducible background: SM photon+jet process

- Small peak sitting on large falling bkg.
- **Data-driven bkg. estimation**: use analytic function to parameterize data sideband, and interpolate under the signal peak

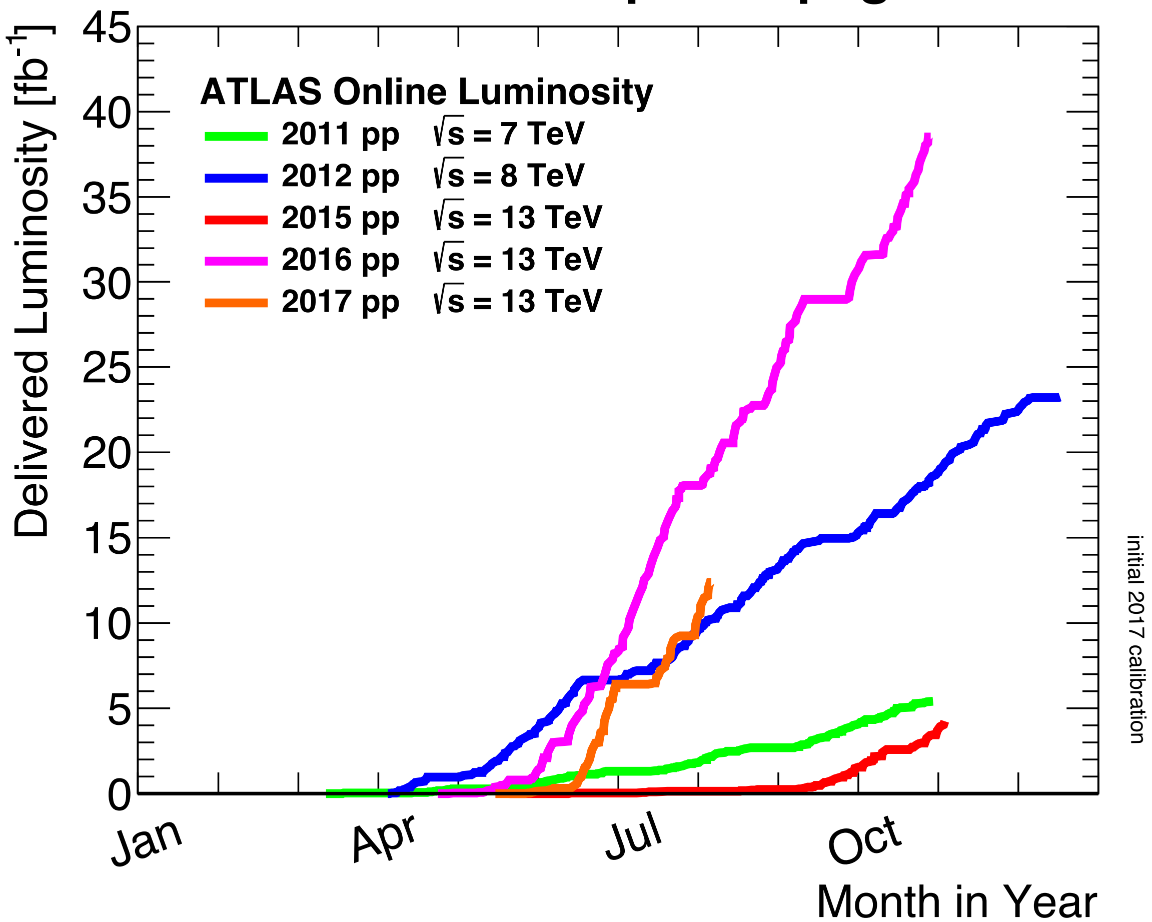


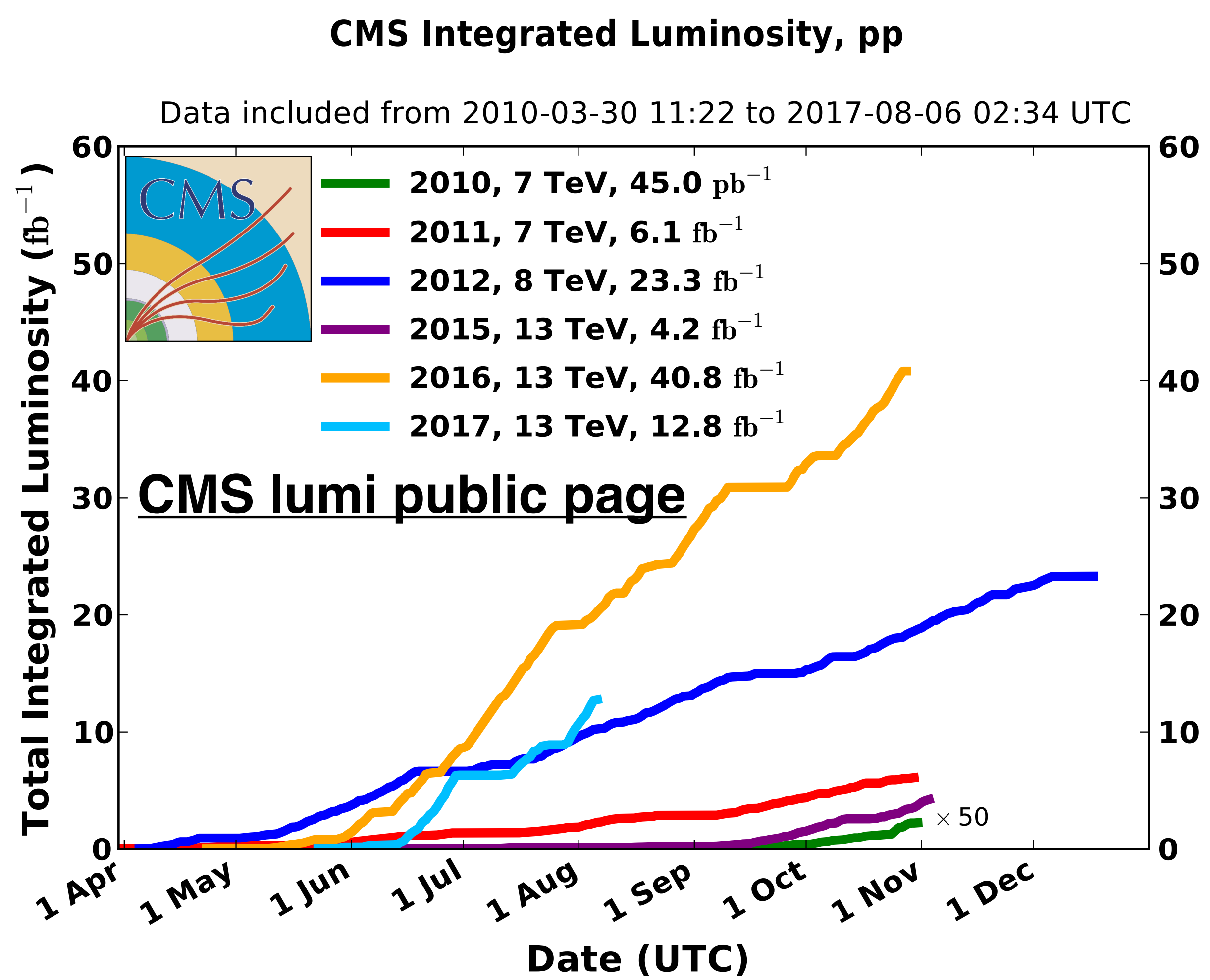
Dataset used for analysis

√s	Approx. int. lumi. (fb^{-1})	Number of H produced	Decayed to diphoton	Selected
7 TeV	5	~100,000	~200	~90
8 TeV	20	~500,000	~1,000	~400
13 TeV	36	~2,000,000	~4,500	~1,800

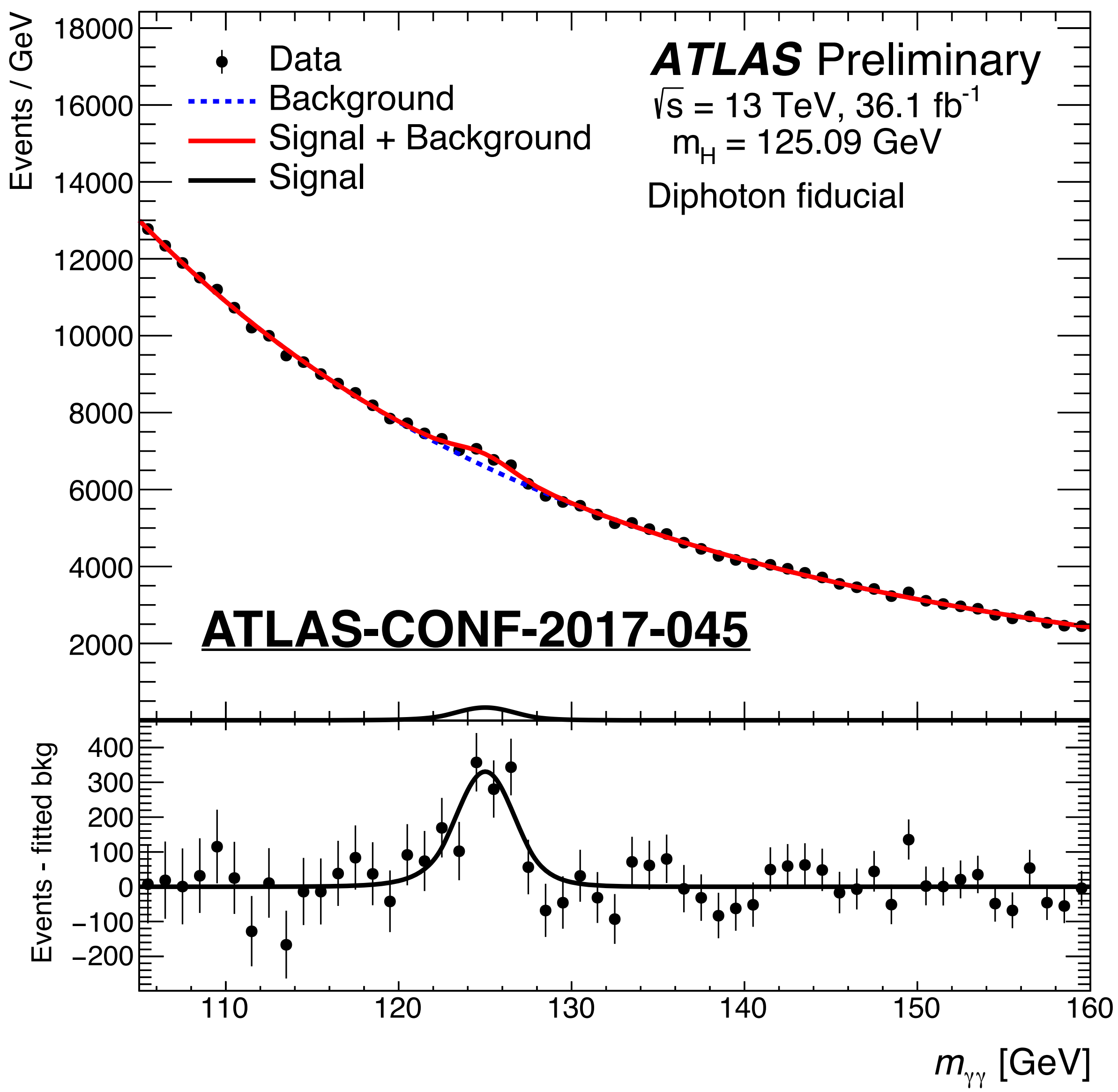
Assuming SM prediction @ m_H = 125.09 GeV. Using 40% as selection efficiency

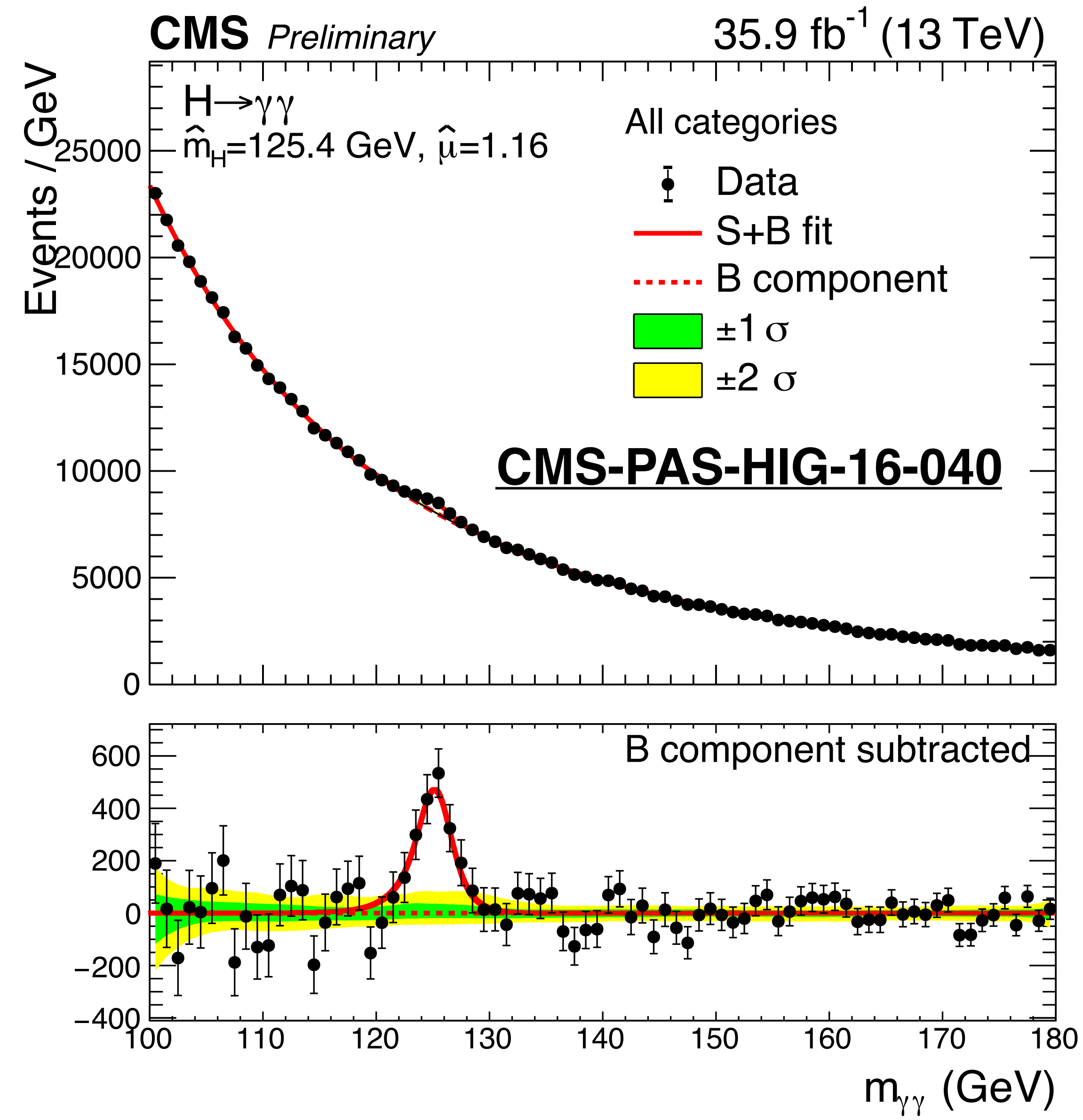
ATLAS lumi public page





Typical diphoton event selections

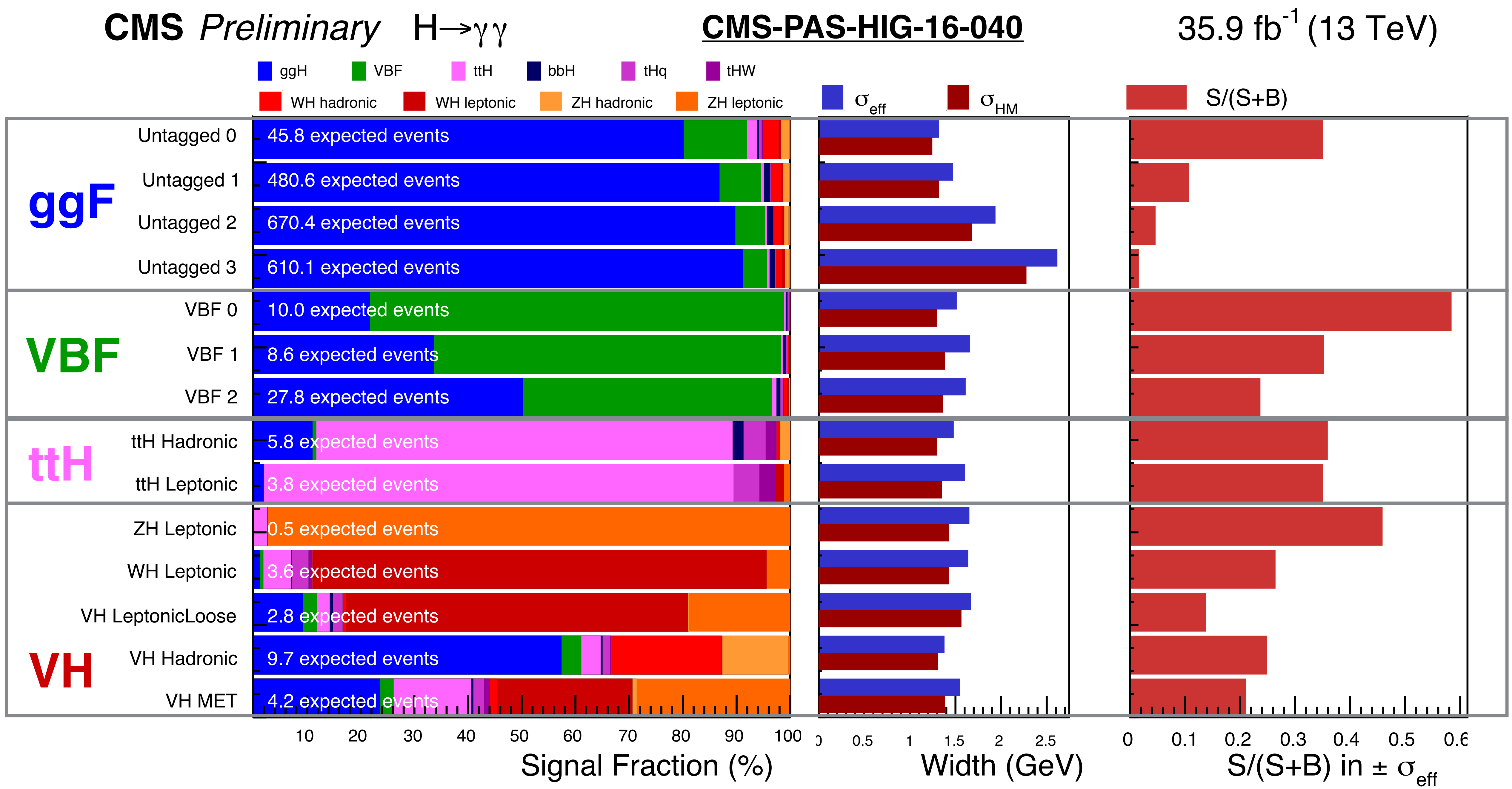




- Skim data sample with diphoton trigger
- "Relative" E_T selection (E_T>f·$m_{\gamma\gamma}$) to make bkg. shape easy to model
- Apply fiducial η cut according to calorimeter geometry
- Photon identification based on shower shapes
- Isolation selections to further suppress hadronic activities

Measurements

Coupling analysis: general idea

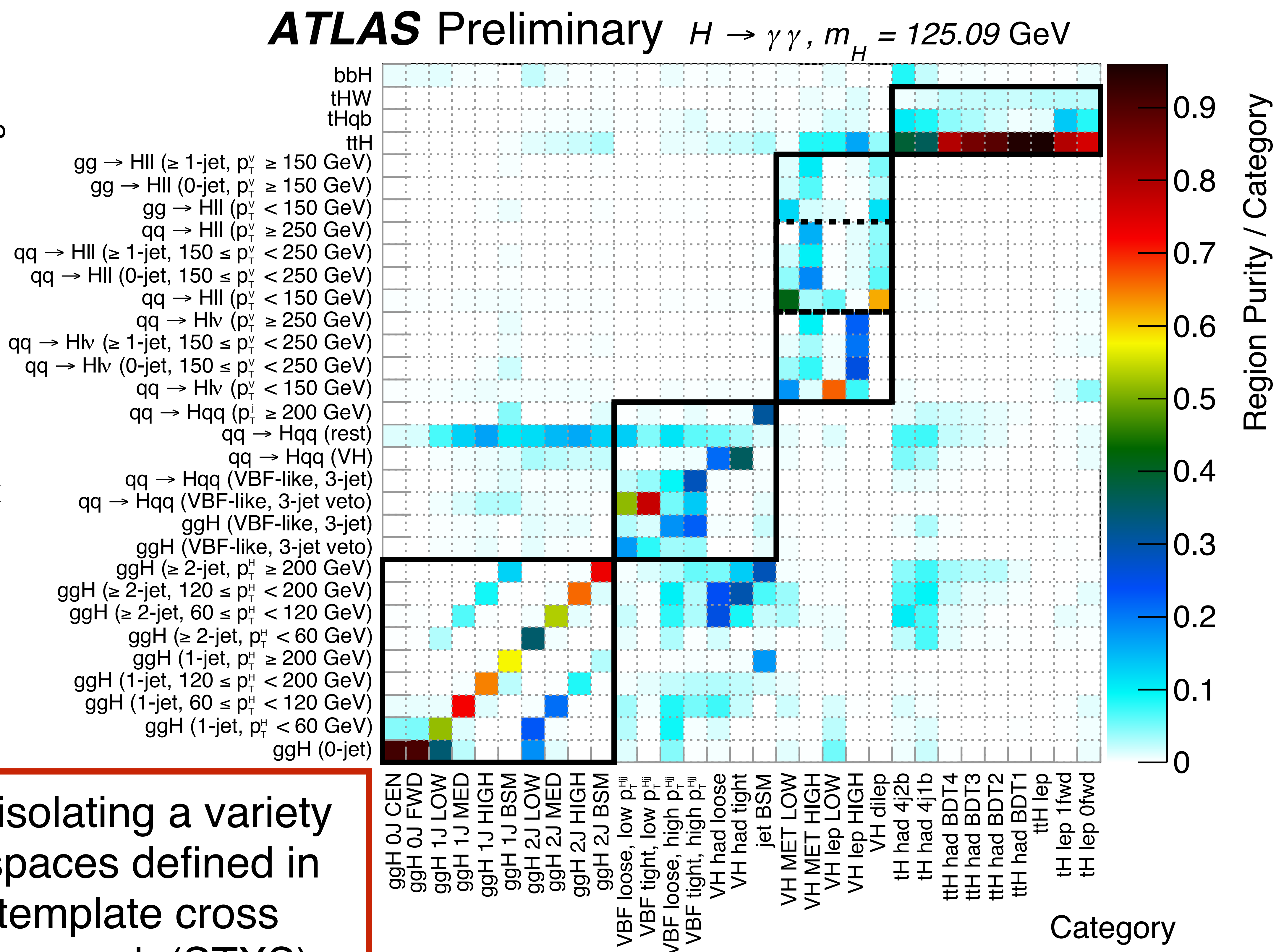


- Divide inclusive data sample into categories
  - Isolate different production modes
  - Improve sensitivity by introducing variety in S/B and resolution

✳ *There is good agreement between SM prediction (white text in plot) and observation in each category*

Coupling analysis: general idea (cont'd)

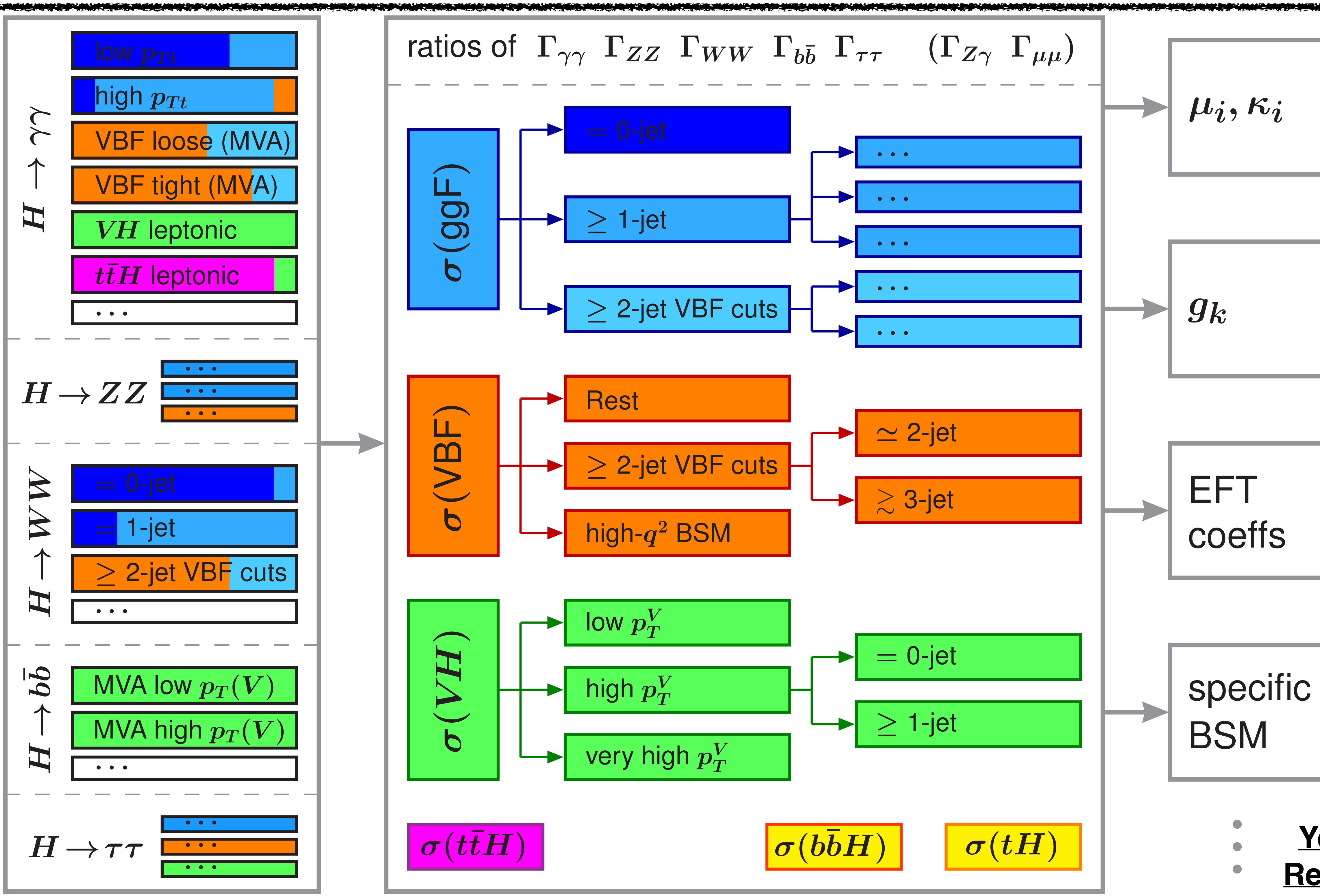
More details on STXS bin definitions can be found in back up slides or <u>Yellow Report 4</u>



<u>**ATLAS-CONF-2017-045**</u>

- Also start isolating a variety of phase spaces defined in simplified template cross section framework (STXS)

STXS framework



Yellow Report 4

- Designed to evolve Run 1 style signal strength measurement in a systematic way that reduces dependence on theory predictions

Inclusive signal strength

- Signal strength: N(obs. signal)/N(exp. signal)
- ATLAS: $\mu = 0.99 \pm 0.14 = 0.99^{+0.12}_{-0.11}(\text{stat.})^{+0.06}_{-0.05}(\text{exp.})^{+0.06}_{-0.05}(\text{th.})$
- CMS: $\mu = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10}(\text{stat.})^{+0.09}_{-0.08}(\text{exp.})^{+0.06}_{-0.05}(\text{th.})$
- Main experimental syst. uncertainties: photon energy scale and resolution, photon ID, luminosity etc.

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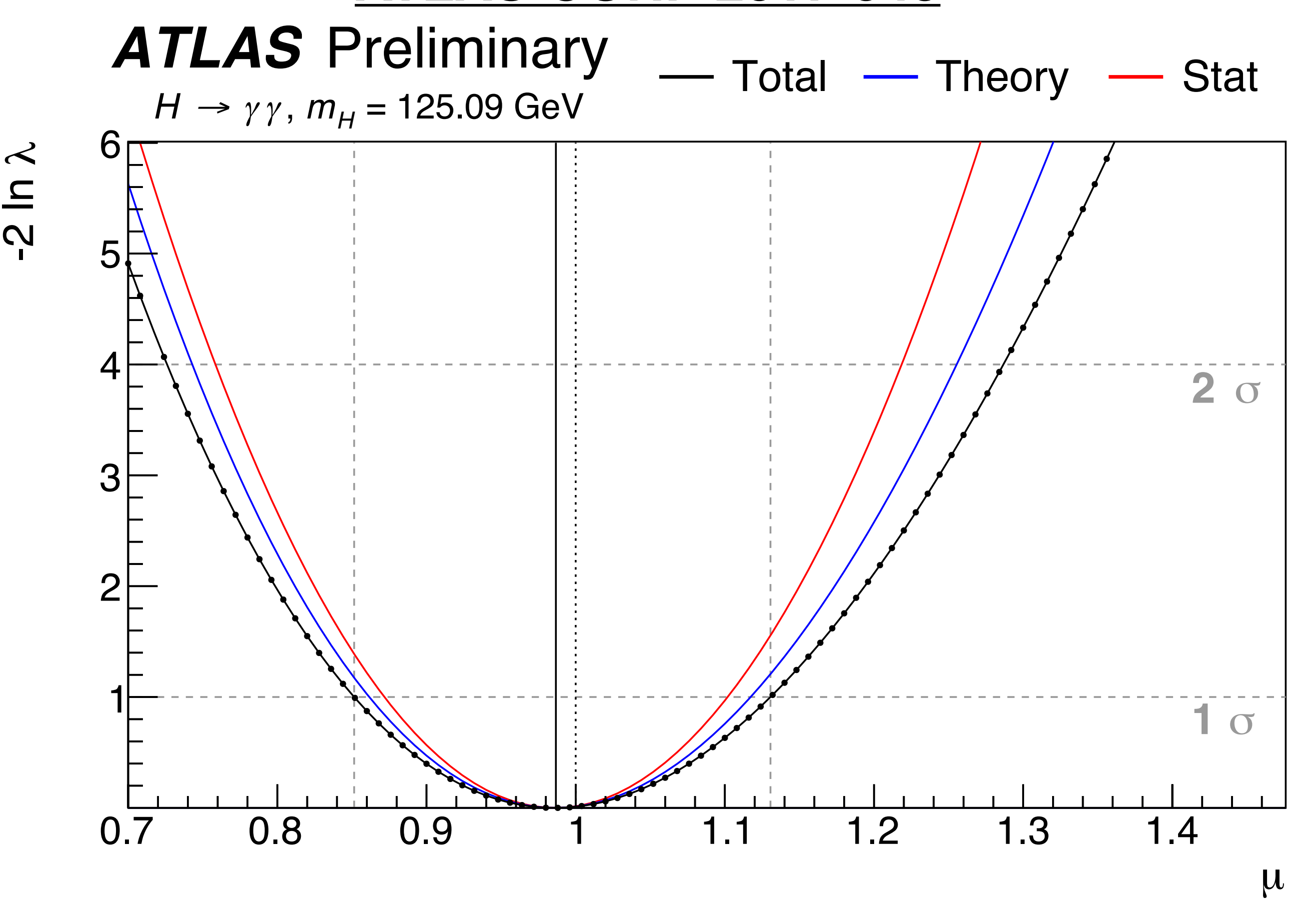

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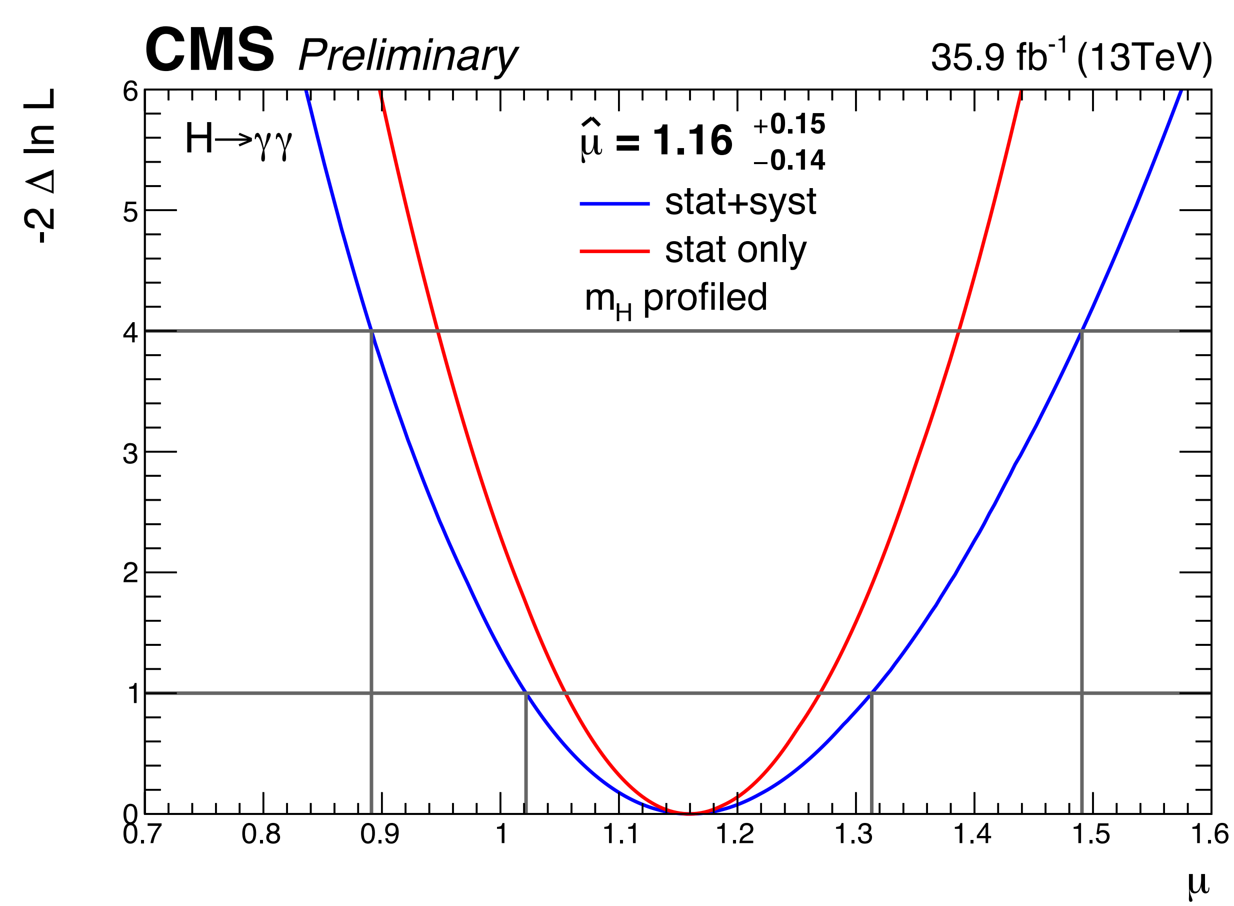
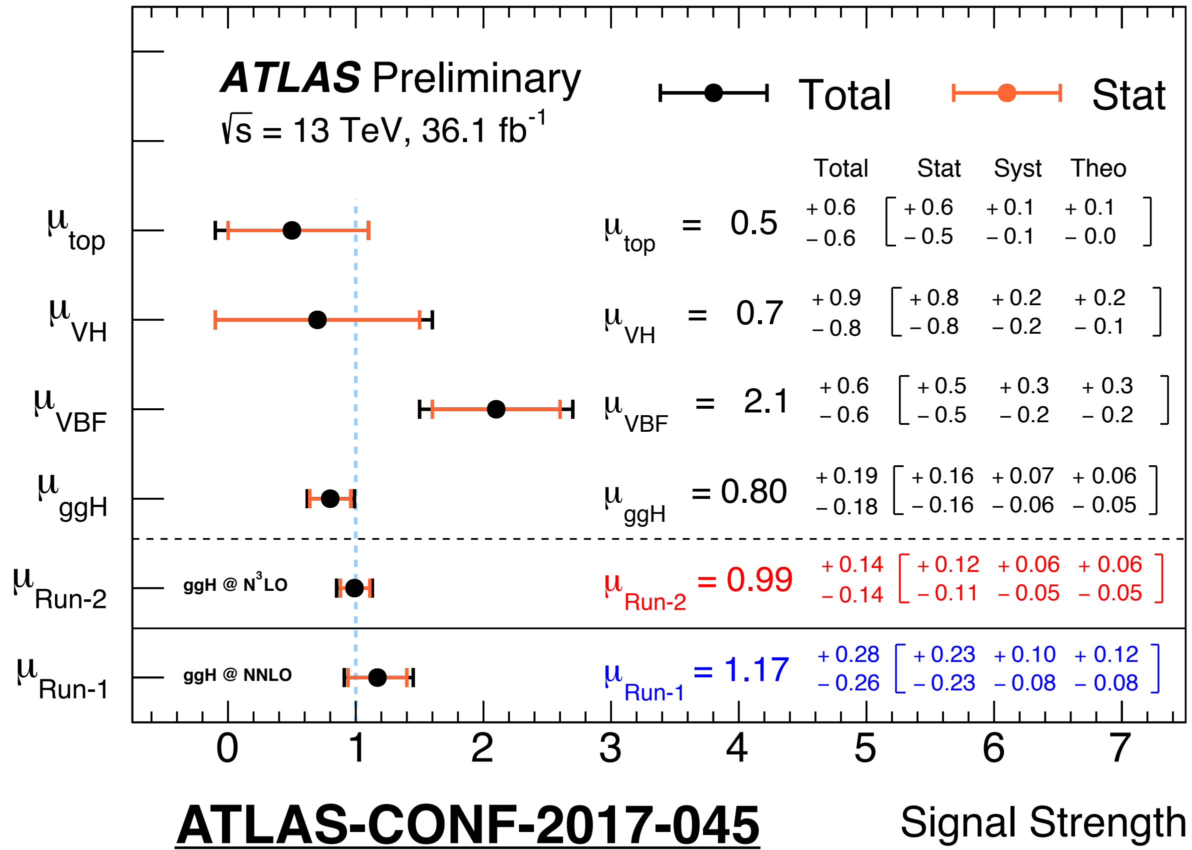


Signal strength for each production mode



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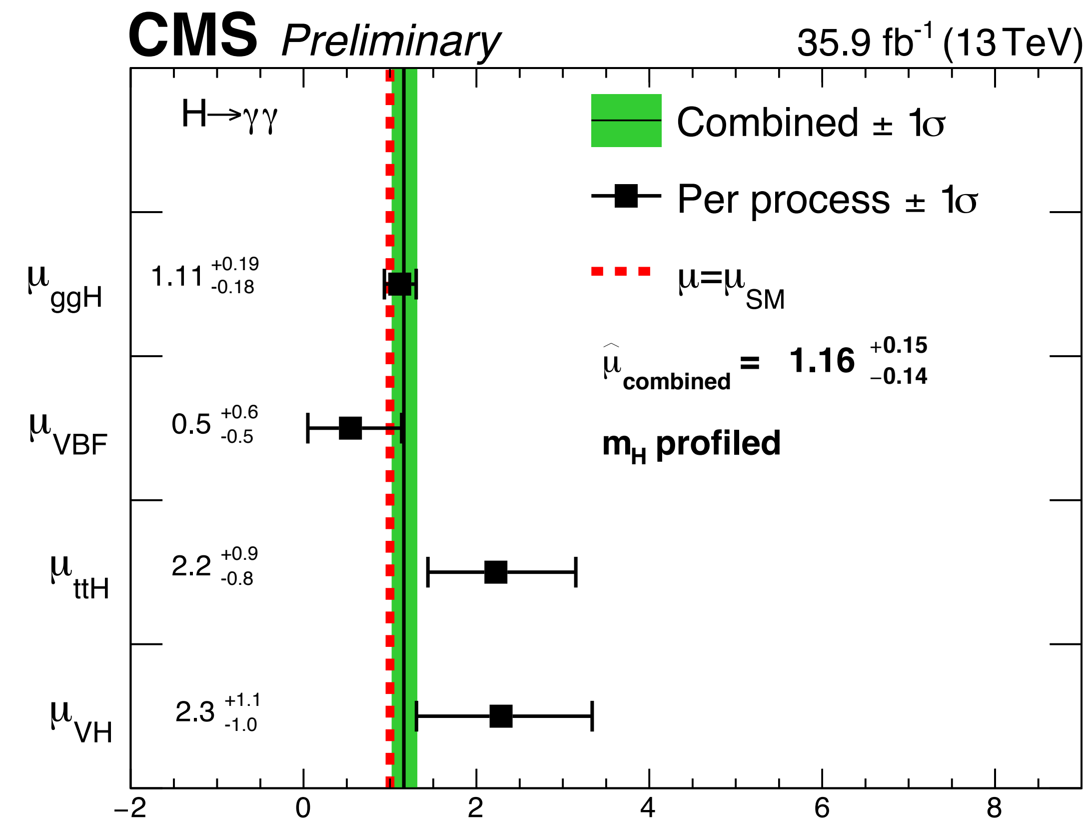

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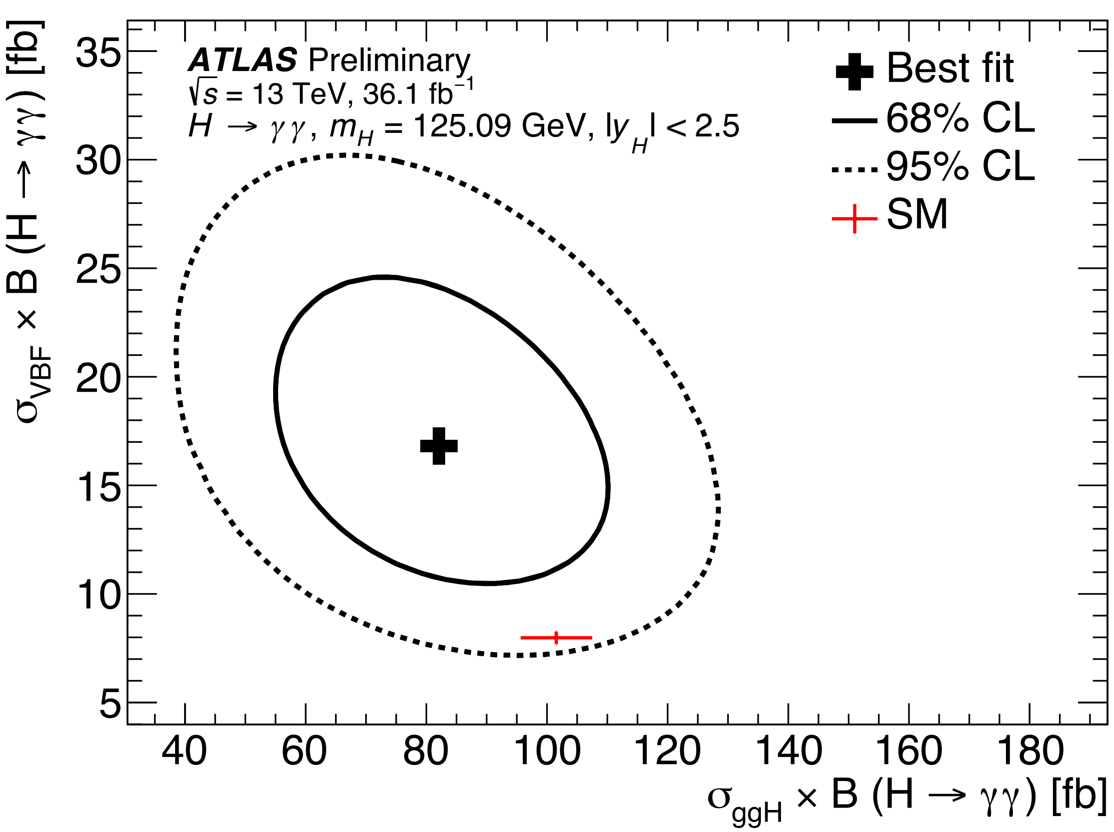
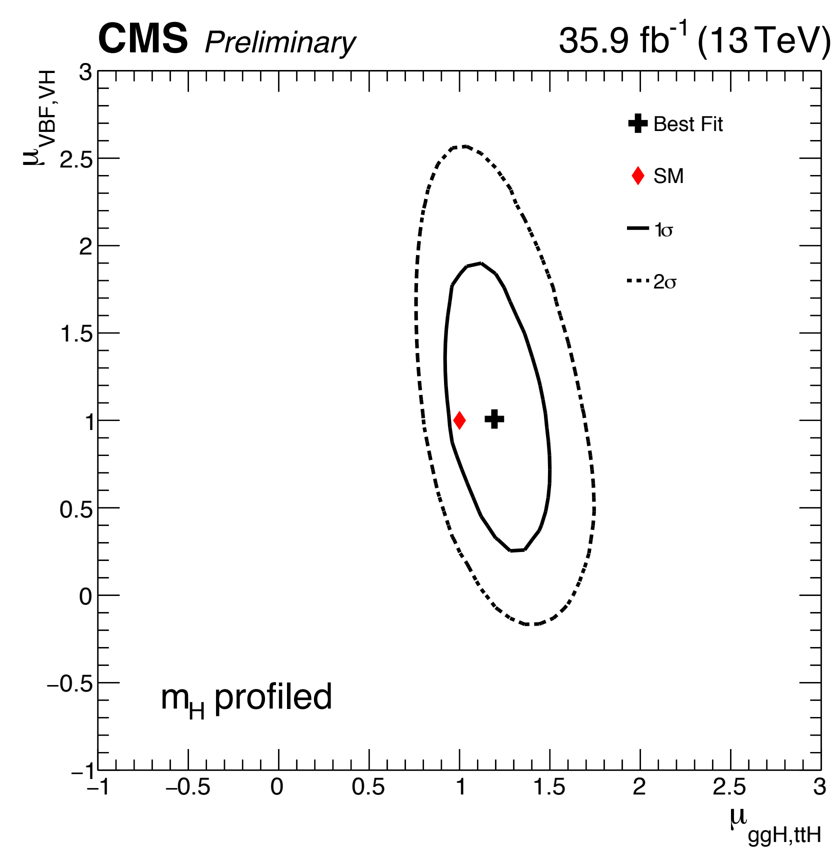
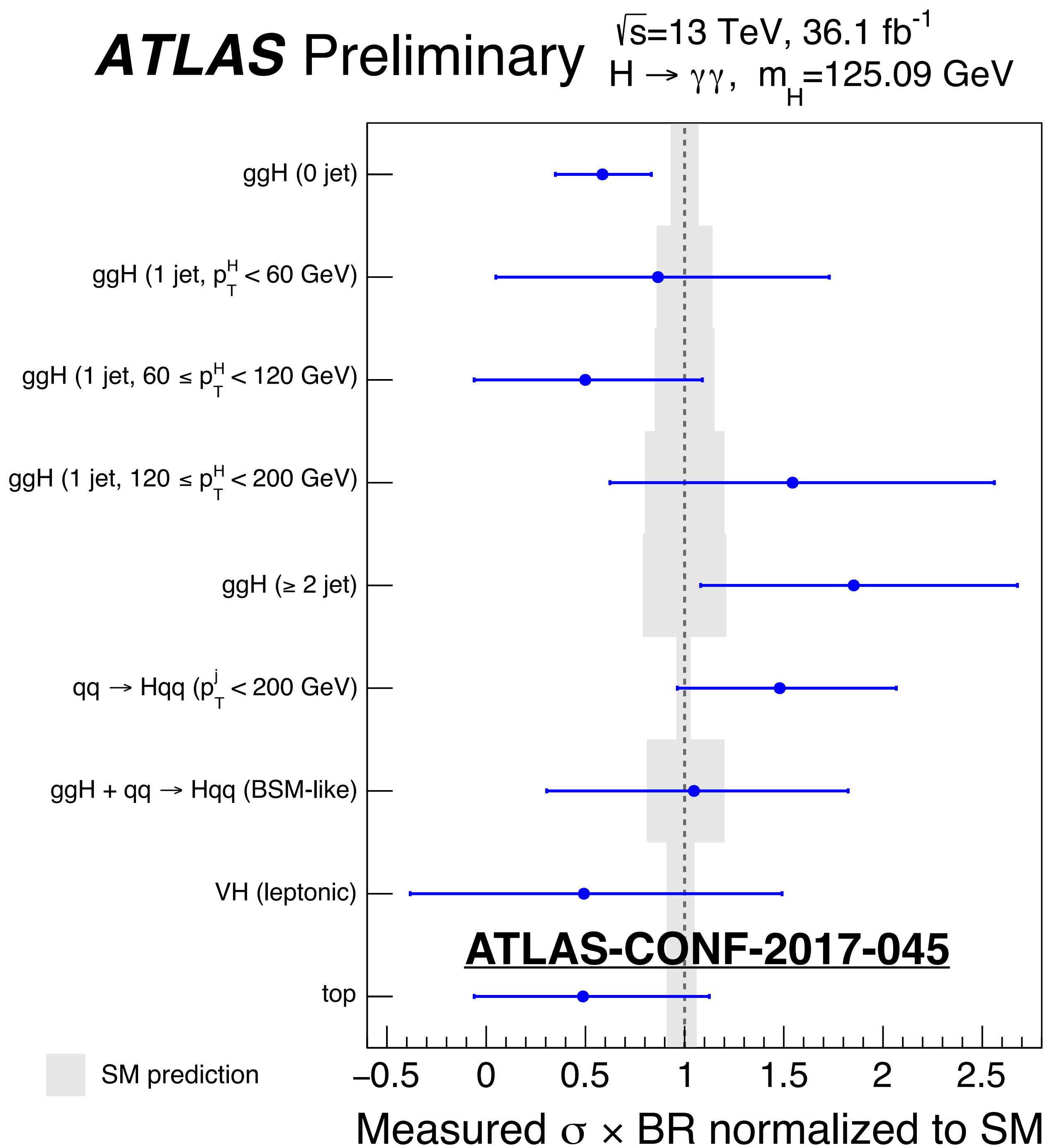


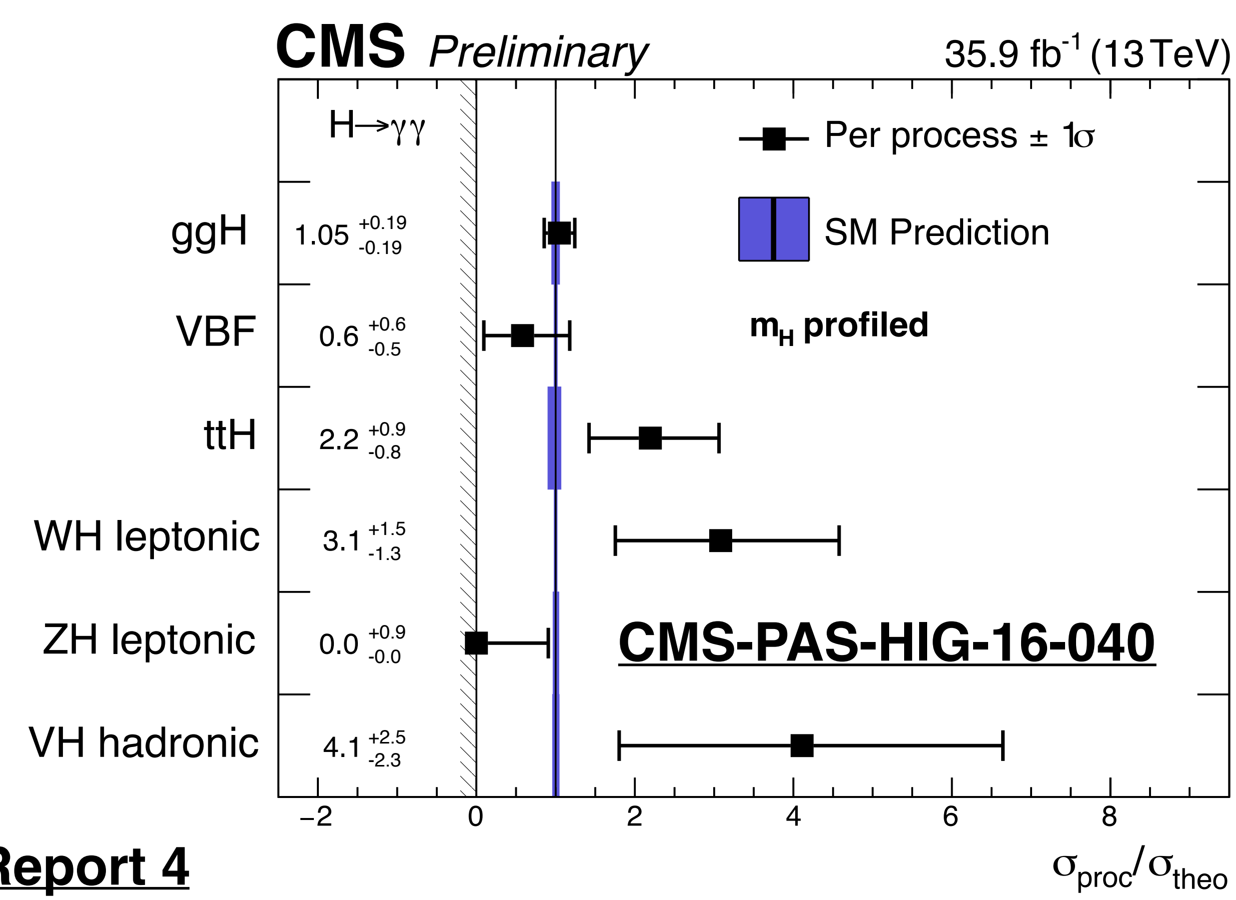


Simplified template cross section results



- ATLAS: use merged "**Stage 1**" STXS framework. Merging bins to improve sensitivity and reduce correlations between bins
- Explore different kinematic regions
  - Jet and pT bins of *gg→H*
  - High p_T bin of *gg→H* and High jet p_T bin of *qq→Hqq* (sensitive to BSM)

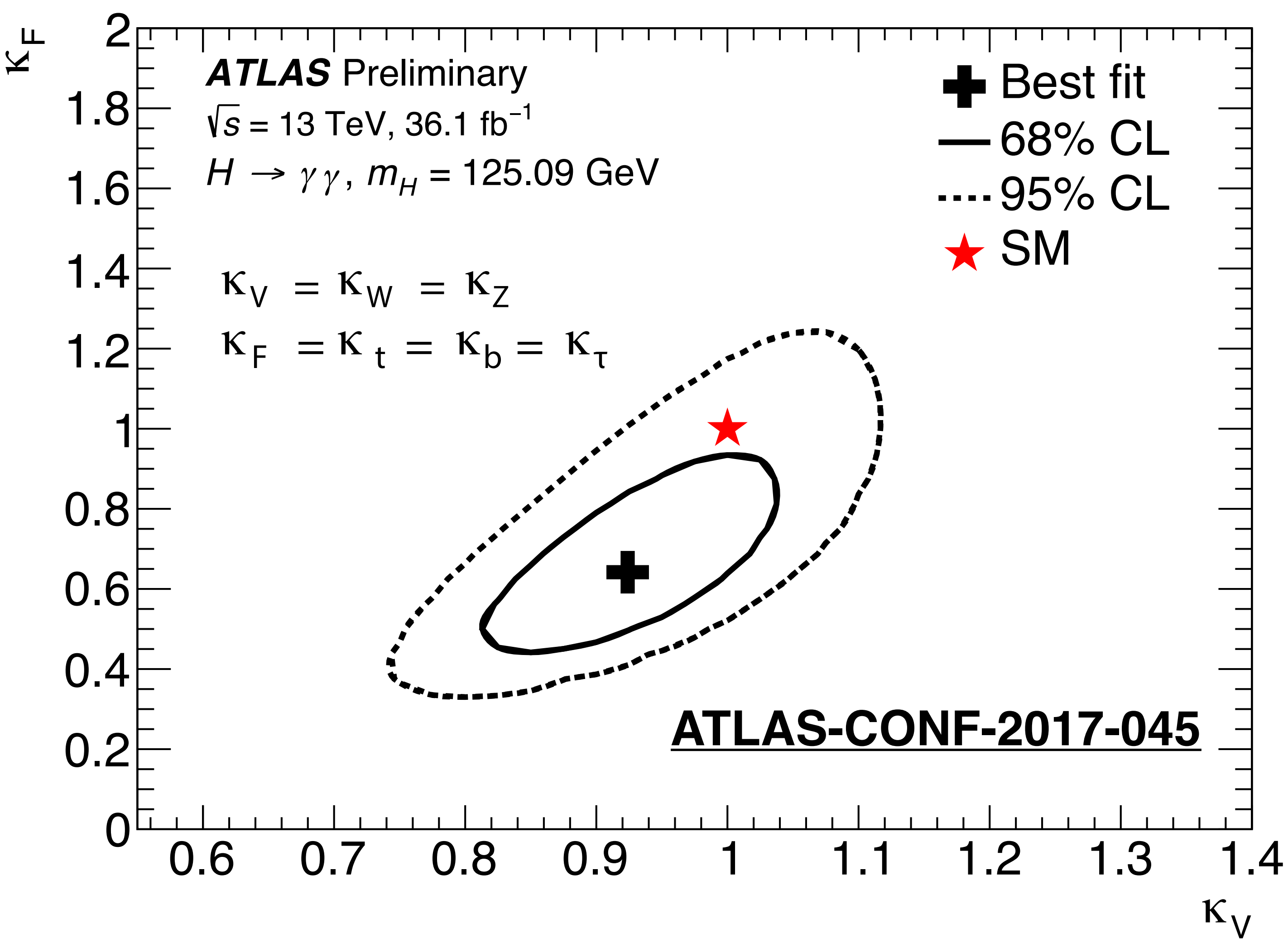
✳ *Both ATLAS and CMS present XS measurements normalized to SM, not signal strengths!*

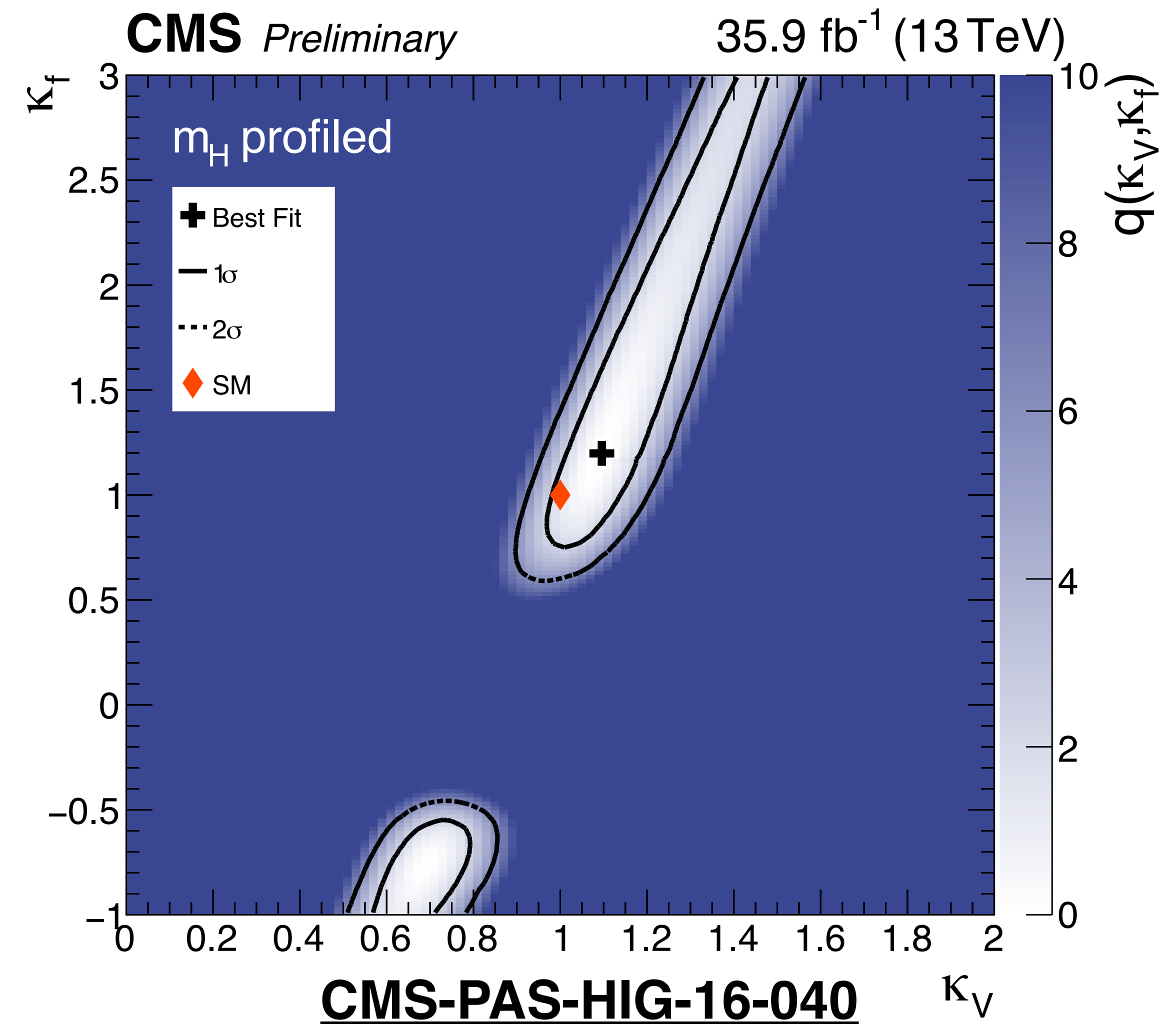


- CMS: use "Stage 0"-like version of STXS (e.g. explore production modes inclusively)

Yellow Report 4

Fitting data with coupling modifiers (kappa framework)

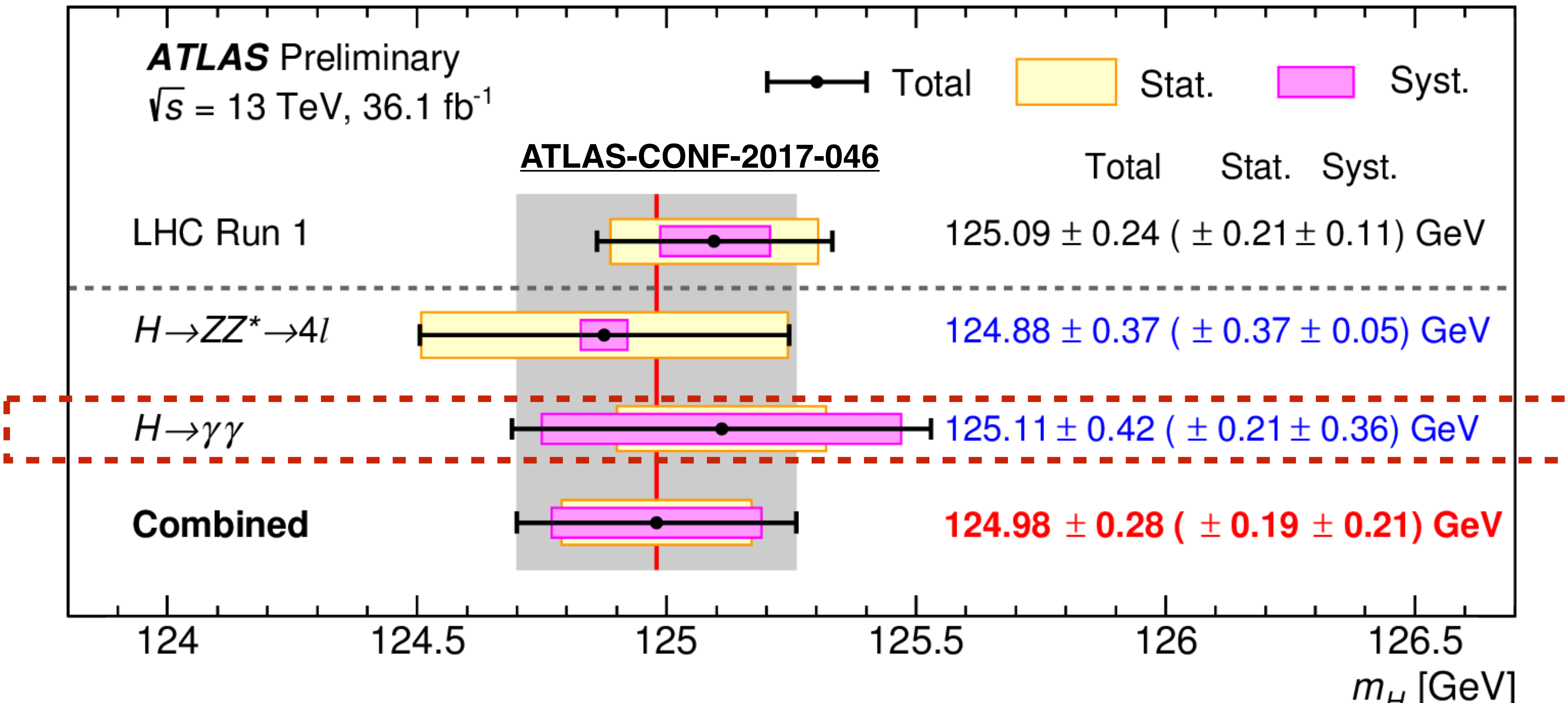




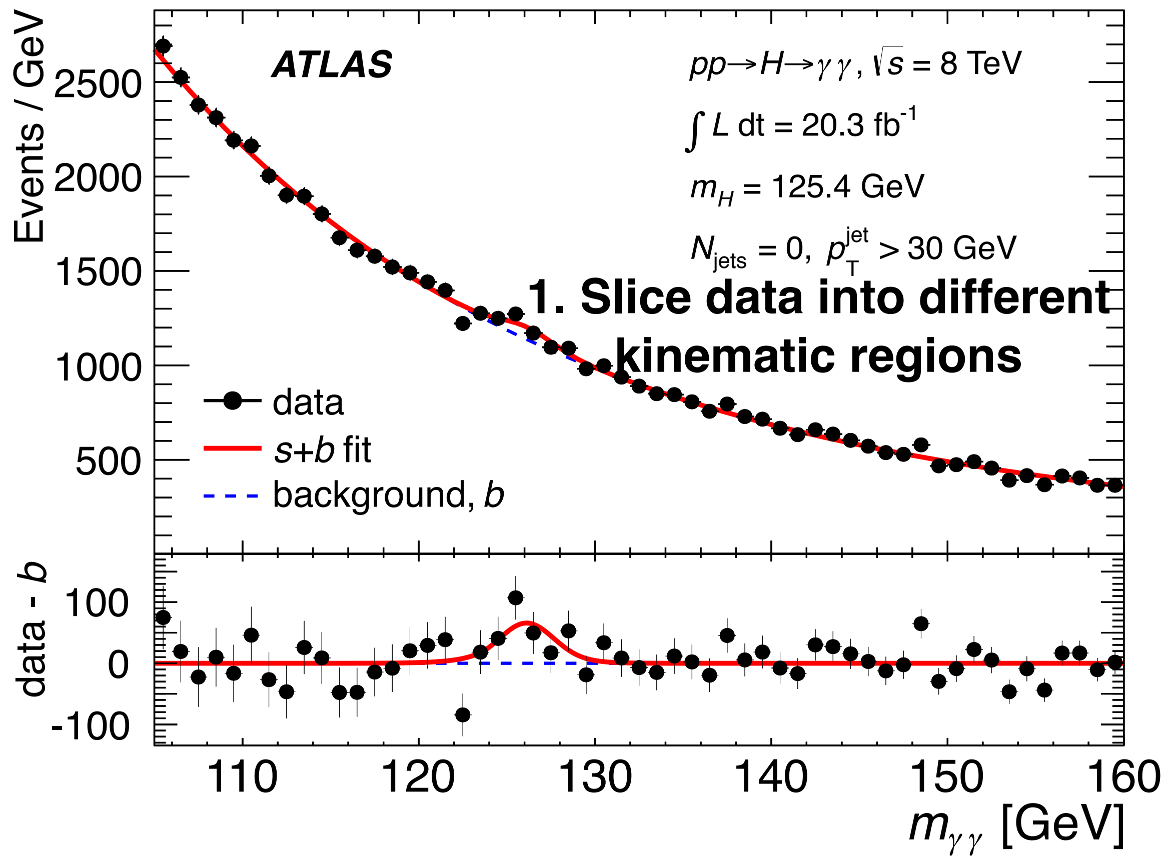
- Assign uniform coupling modifiers to all fermions (κ_F) and to all vector bosons (κ_V)
  - Resolve loop vertices and total width with SM particles
  - Assume no additional BSM contribution to total width
- $H\rightarrow\gamma\gamma$ channel provides crucial sensitivity for determining the relative sign of κ_F w.r.t. κ_V

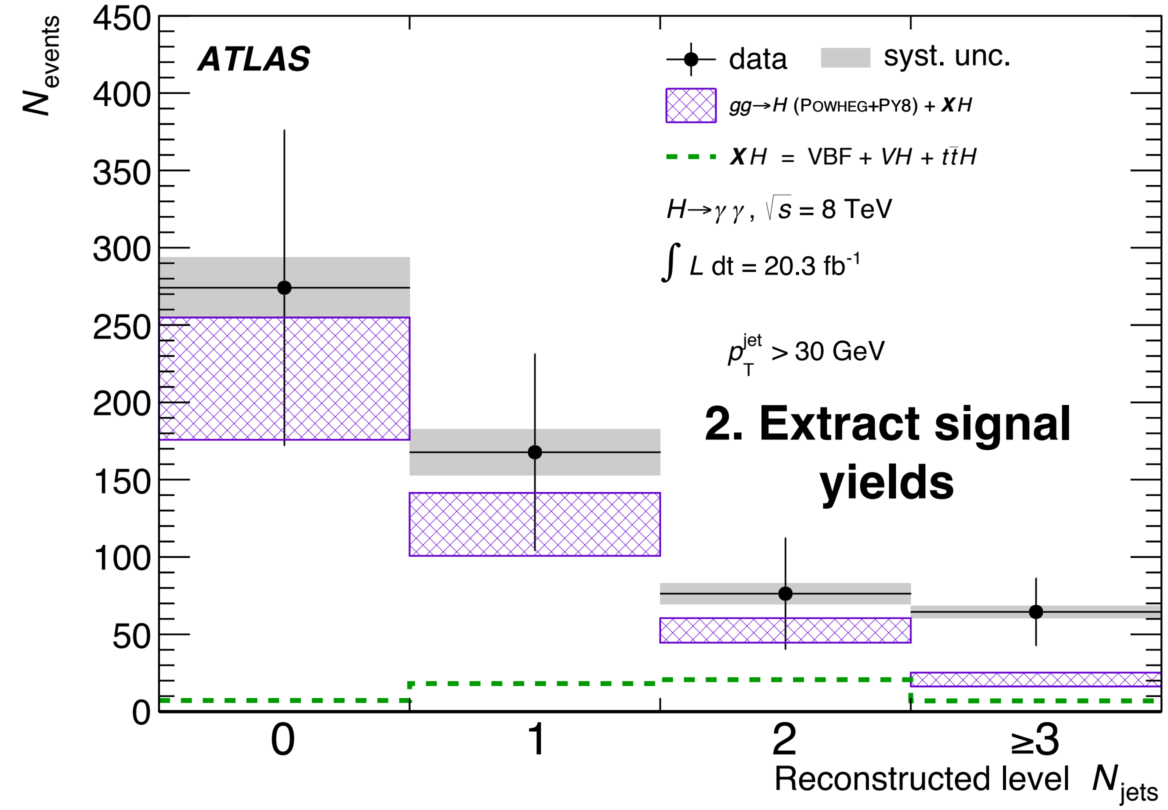
Mass results

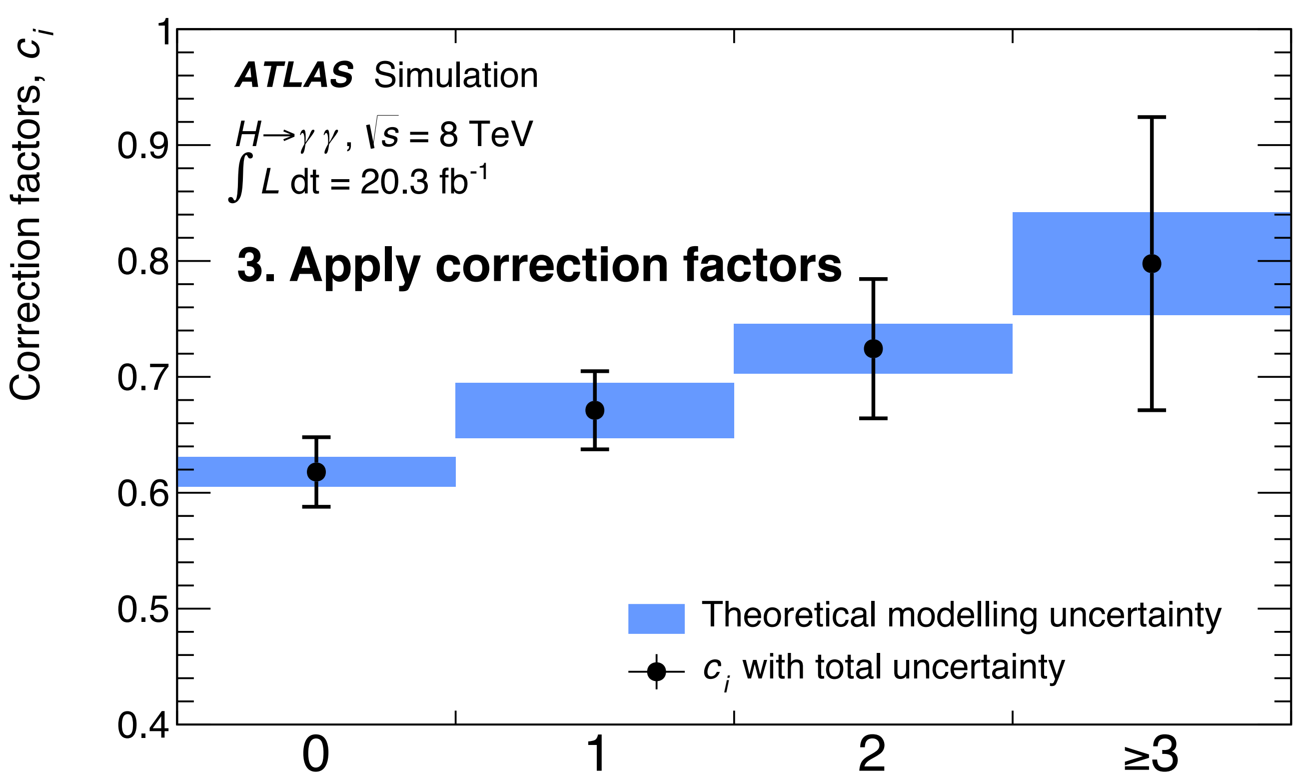
- In Run 2, both ATLAS and CMS reuse **coupling categories** to measure m_H
  - ATLAS: **m_H = 125.11 ± 0.21 (stat.) ± 0.36 (syst.) GeV** from preliminary calibration, with leading syst. uncertainty from non-linearity and layer calibrations
  - CMS: best fit mass at **125.4 GeV**, with **~150 MeV** stat. uncertainty, and syst. uncertainty preliminarily estimated to be **200~300 MeV** (under study)
- Both experiments start to be limited by **syst. uncertainty** in $H\rightarrow\gamma\gamma$

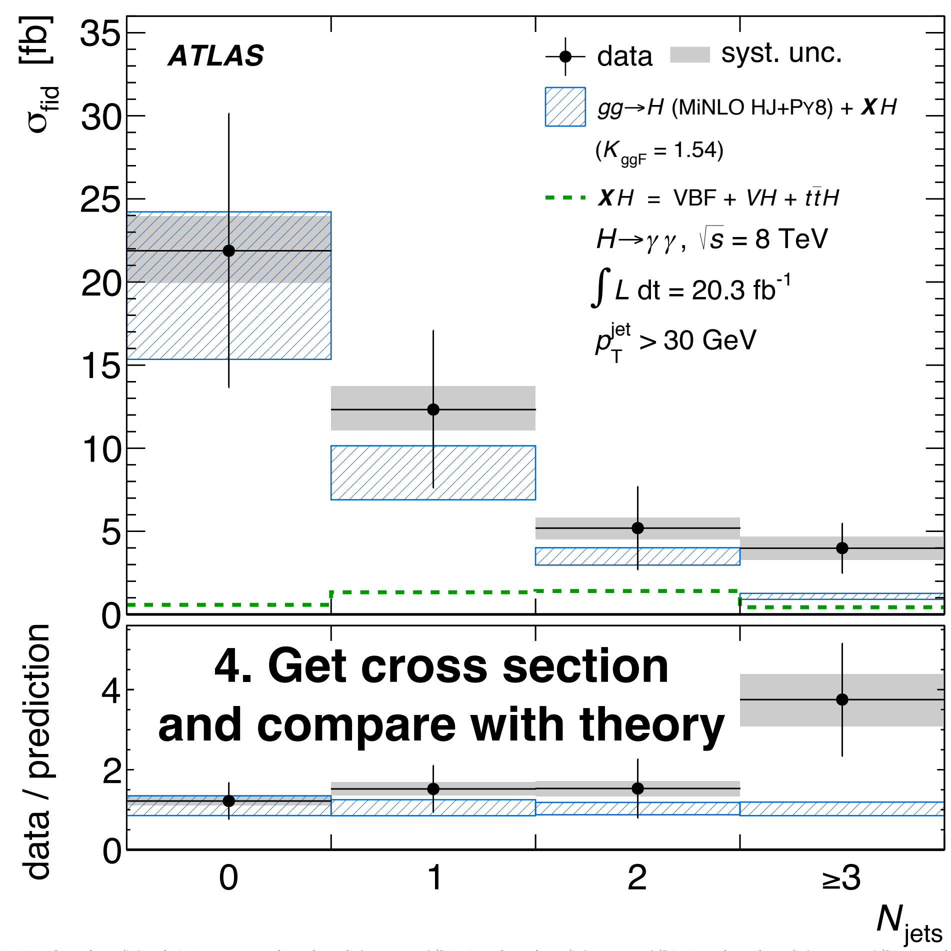


Fiducial/diff. XS measurements: general idea









JHEP 09 (2014) 112

Fiducial cross sections

- Inclusive fiducial cross section in good agreement with SM
- Fiducial cross sections in regions sensitive to either different production modes or BSM physics are also provided
    - No obvious tension with several theory calculations

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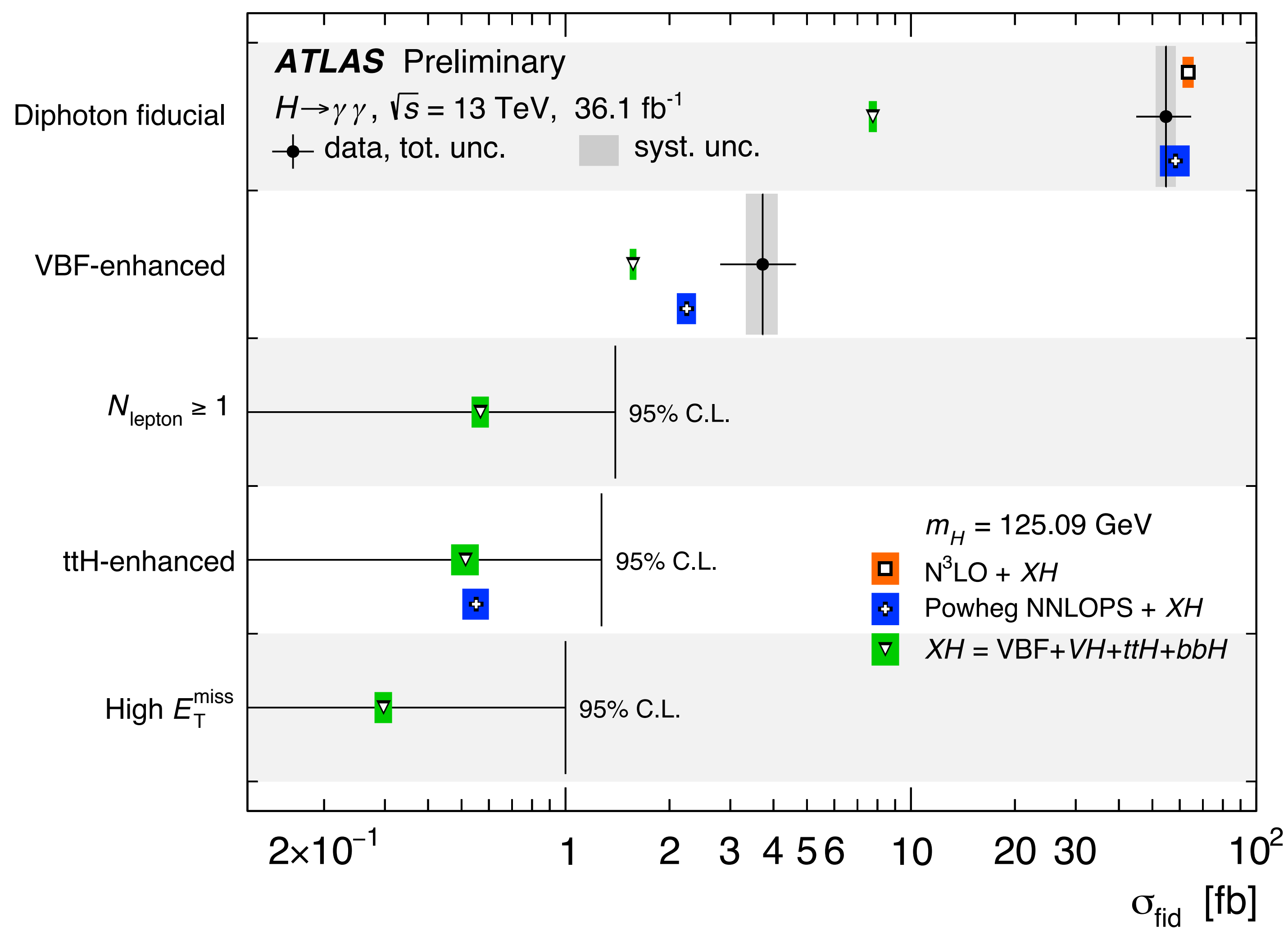

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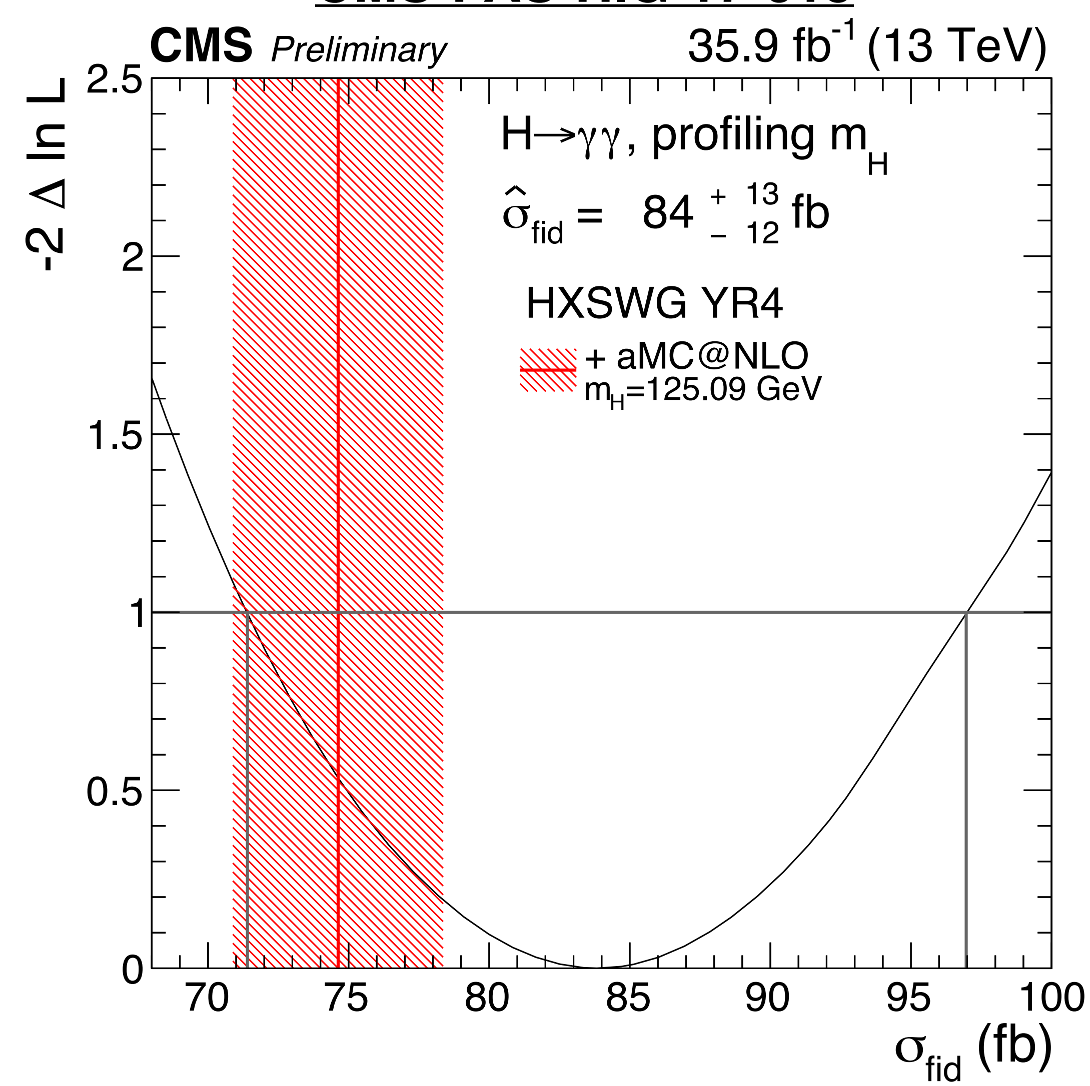
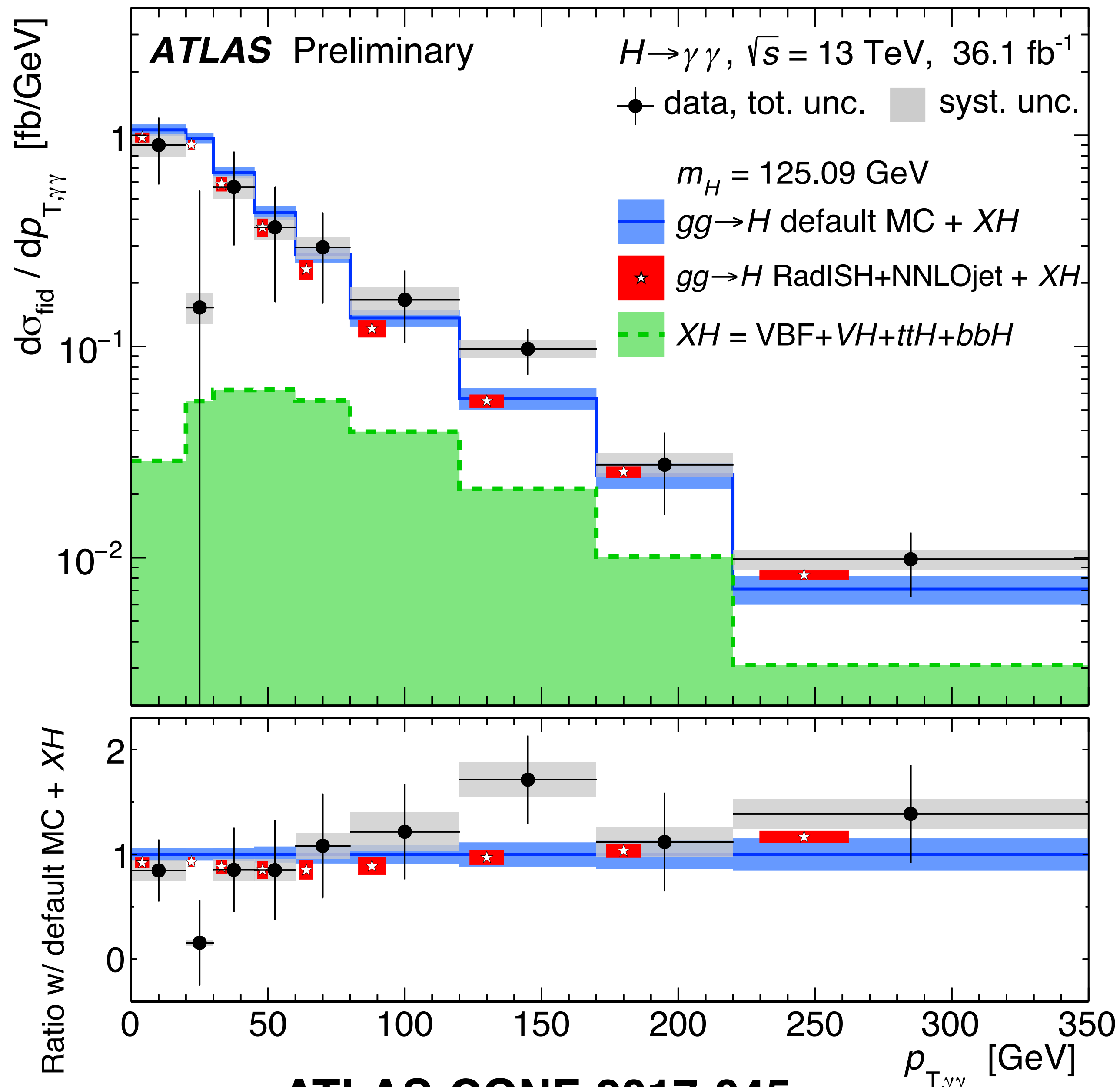
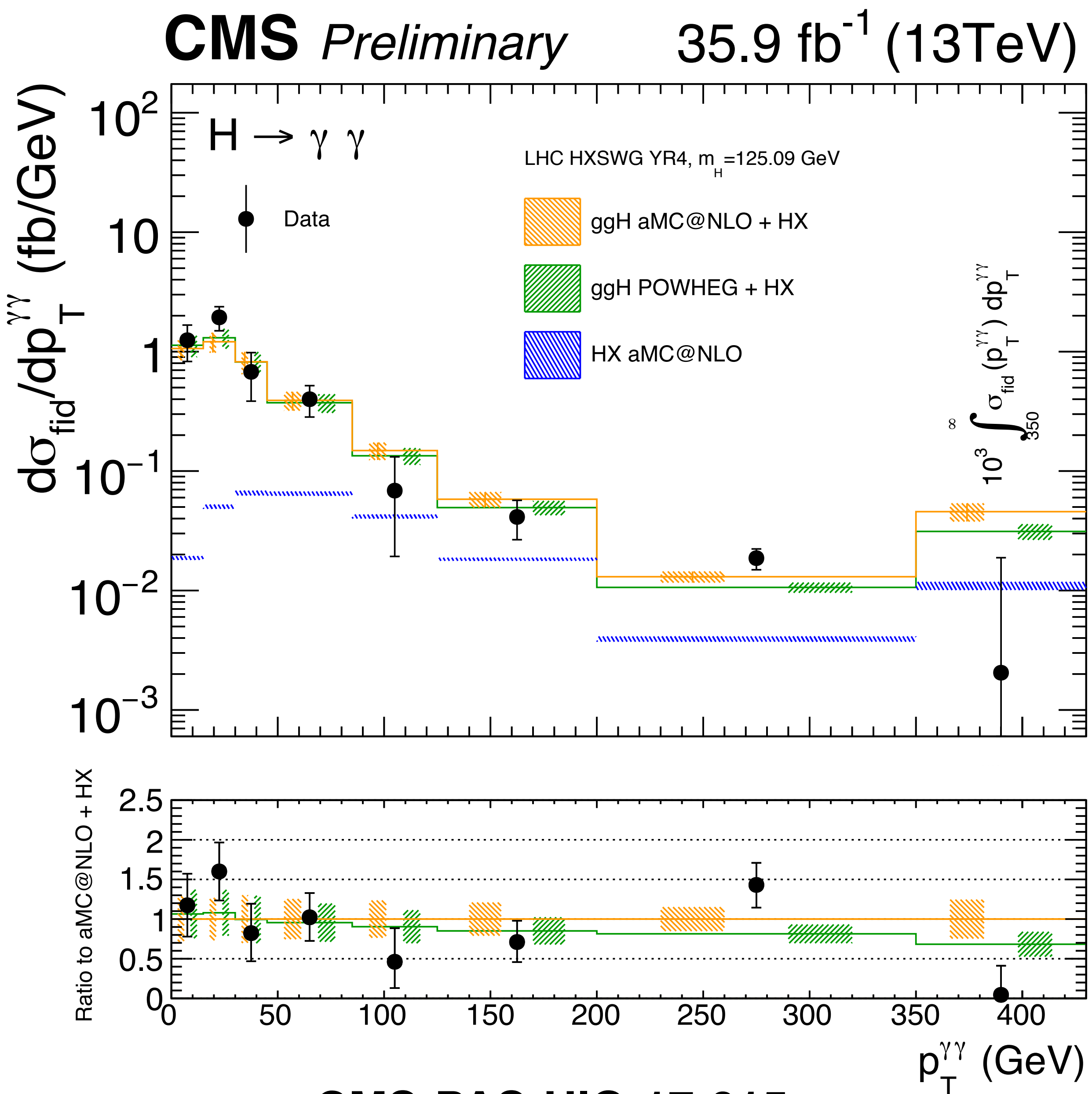


Differential distributions: $p_T^{\gamma\gamma}$





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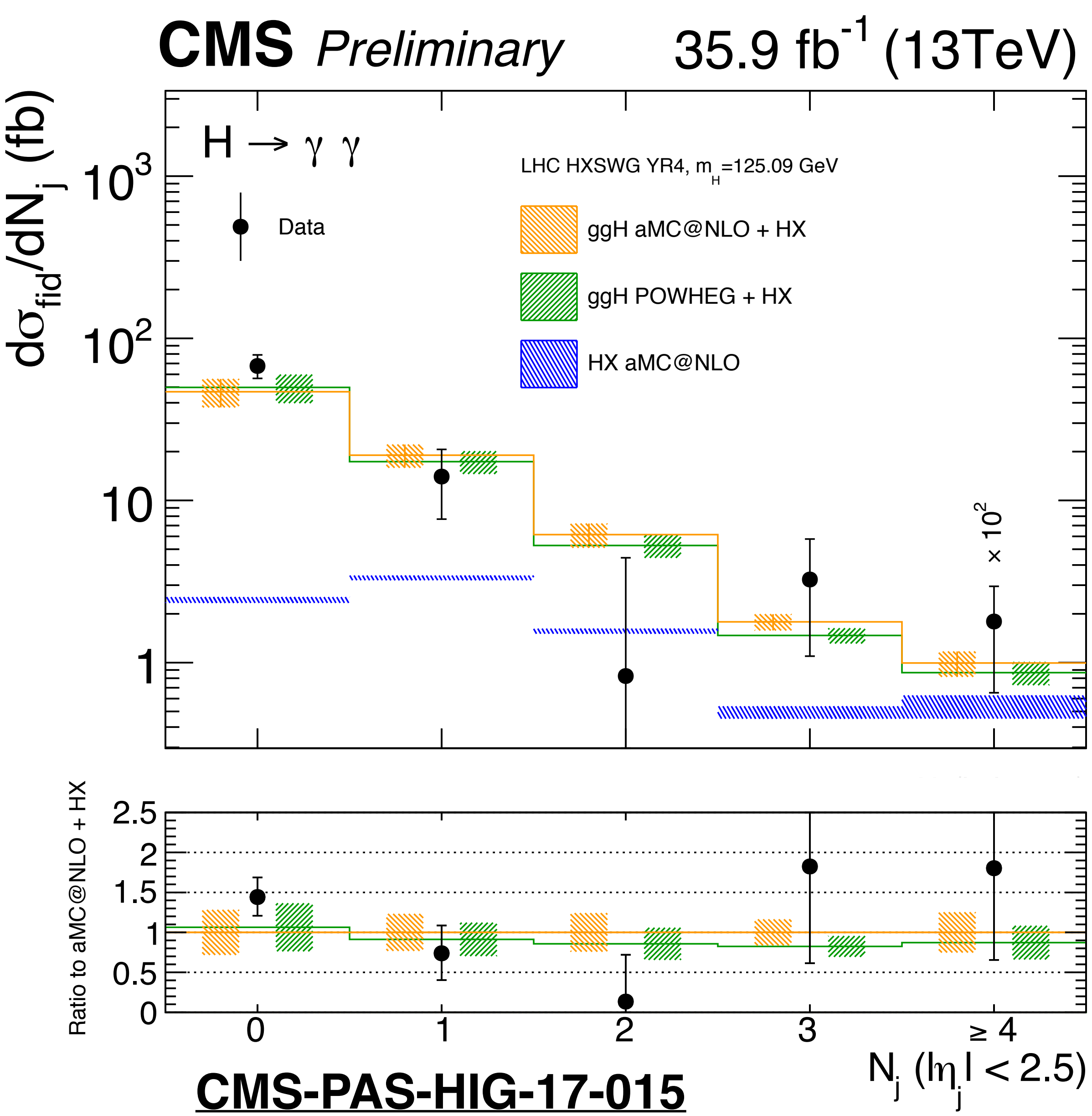
CMS-PAS-HIG-17-015

- Diphoton p_T spectrum probes perturbative QCD modeling of ggF. High p_T tail is sensitive to new physics in the ggF loop
- Good agreement with SM given current stat.

Differential distributions: N_{jet} and |cosθ*|



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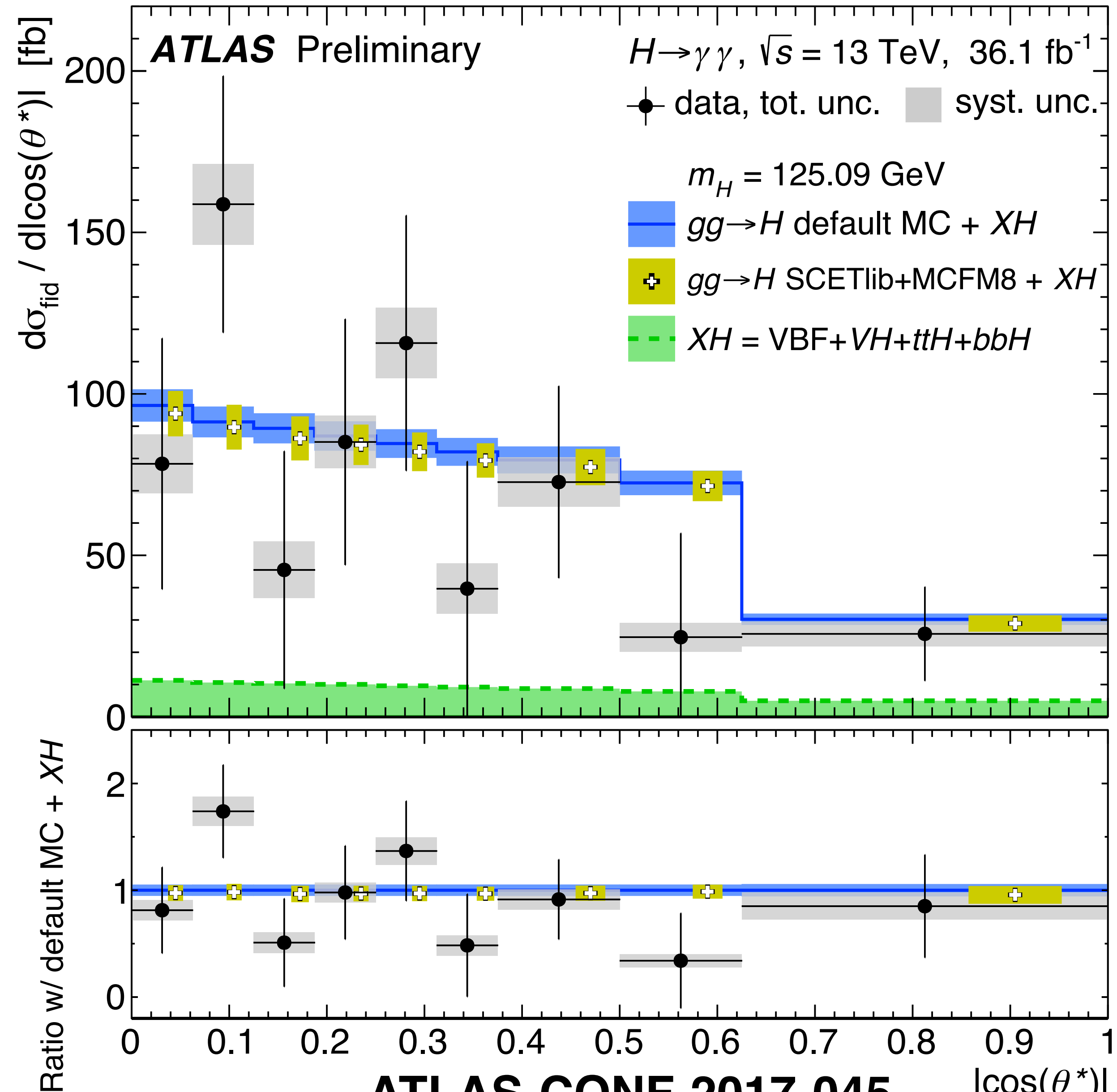


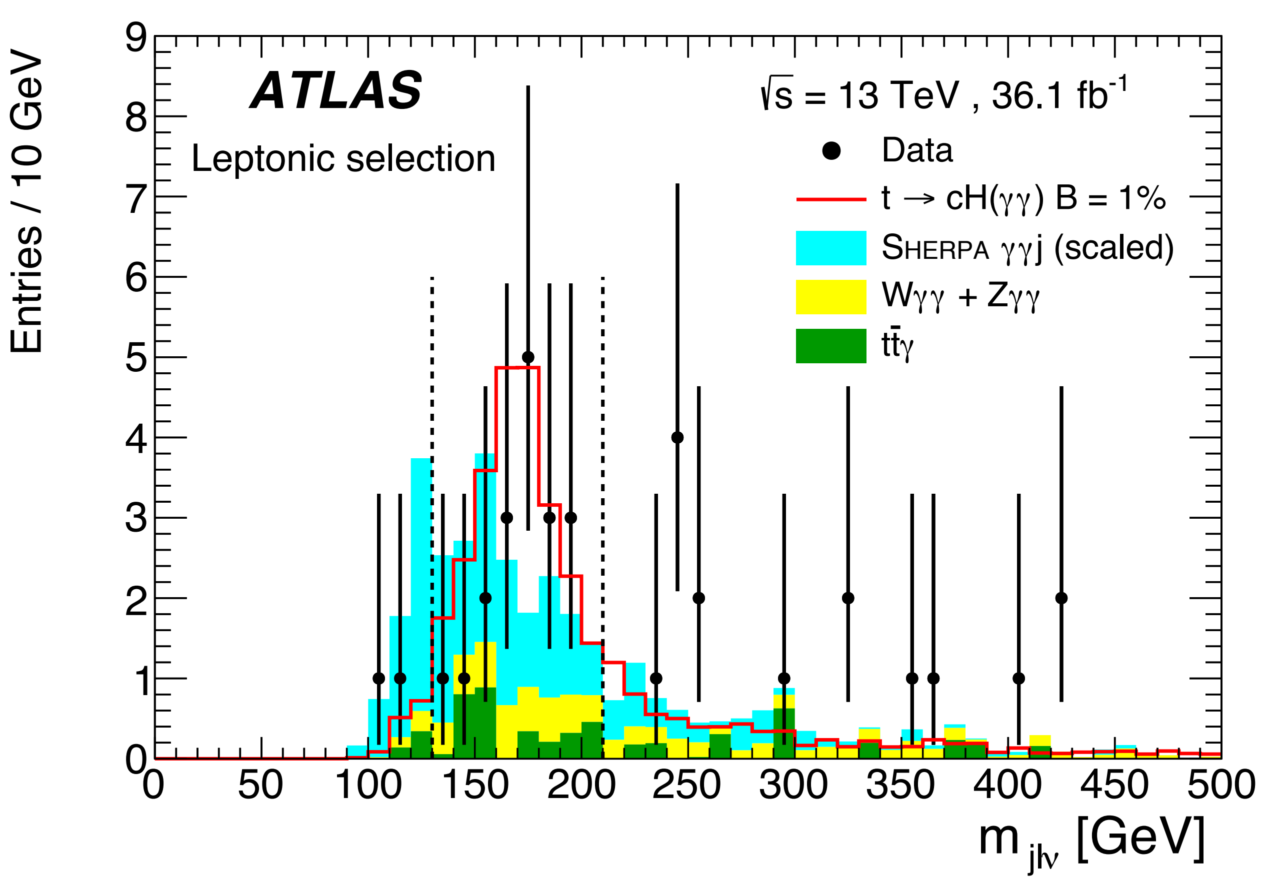
ATLAS-CONF-2017-045

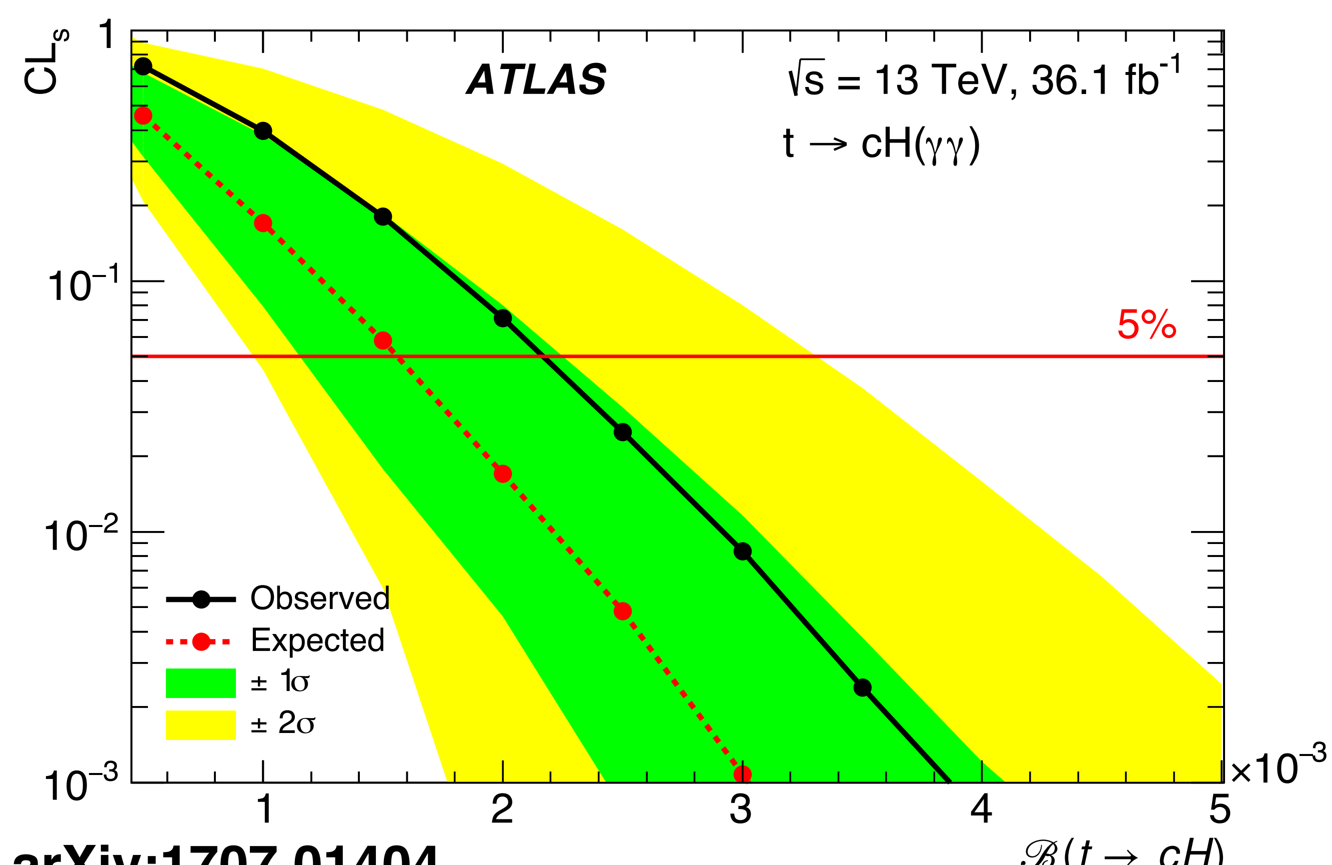
- Jet multiplicity sensitive to theoretical modeling of QCD and also composition of different production modes
- |cosθ*| probes the spin of the particle
- Good agreement with SM given current stat.

Searches

Search for flavor changing neutral currents

- $t \rightarrow qH$ process highly suppressed in SM: ideal channel for probing new physics
- Analysis targeting ttbar events, with one top decay to Wb and the other to $H(\gamma\gamma)q$, $q=u, c$
- No significant deviation from background hypothesis observed. Exclude B($t \rightarrow cH$) above **2.2×10^{-3}** at 95% CL. Exclude B($t \rightarrow uH$) above **2.4×10^{-3}**



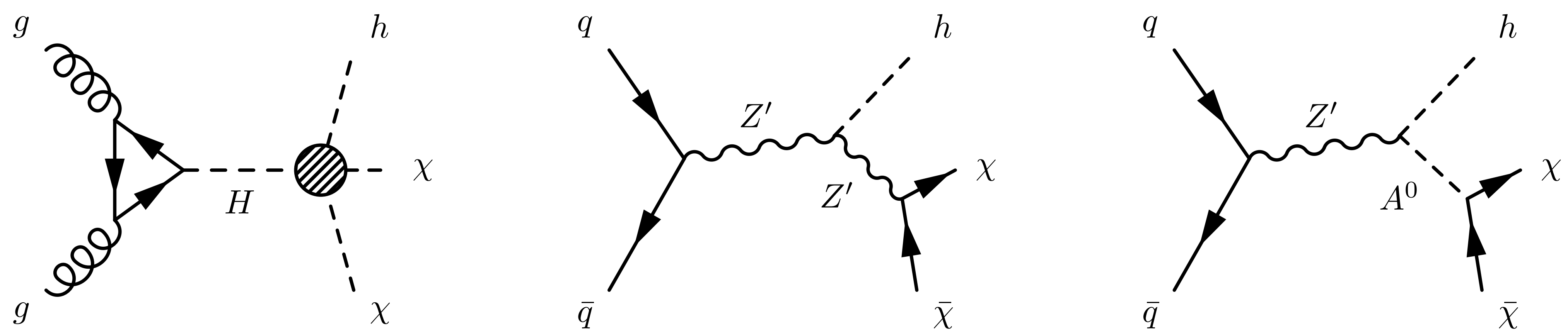


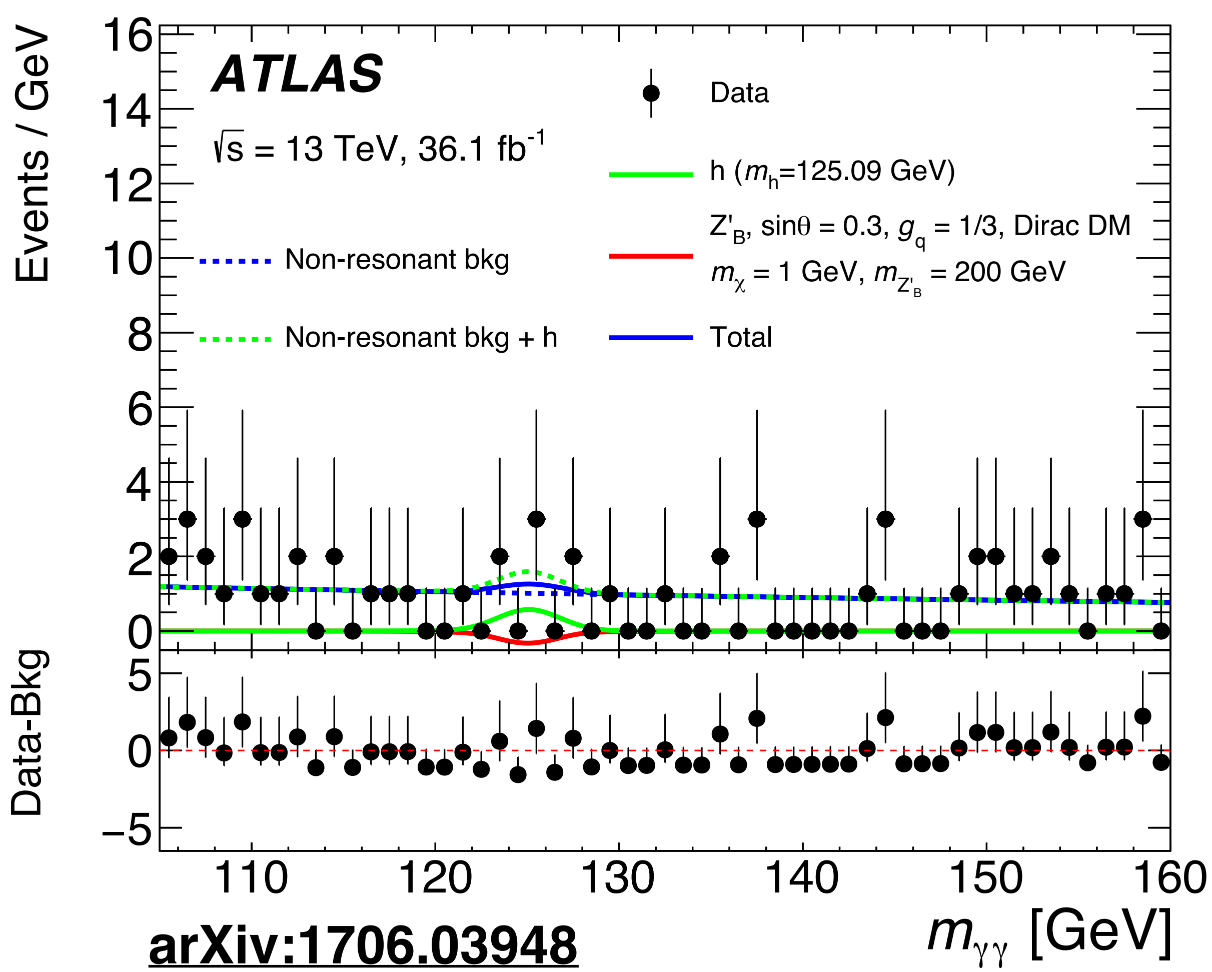
arXiv:1707.01404

Mono-Higgs + MET, $H \to \gamma\gamma$ search

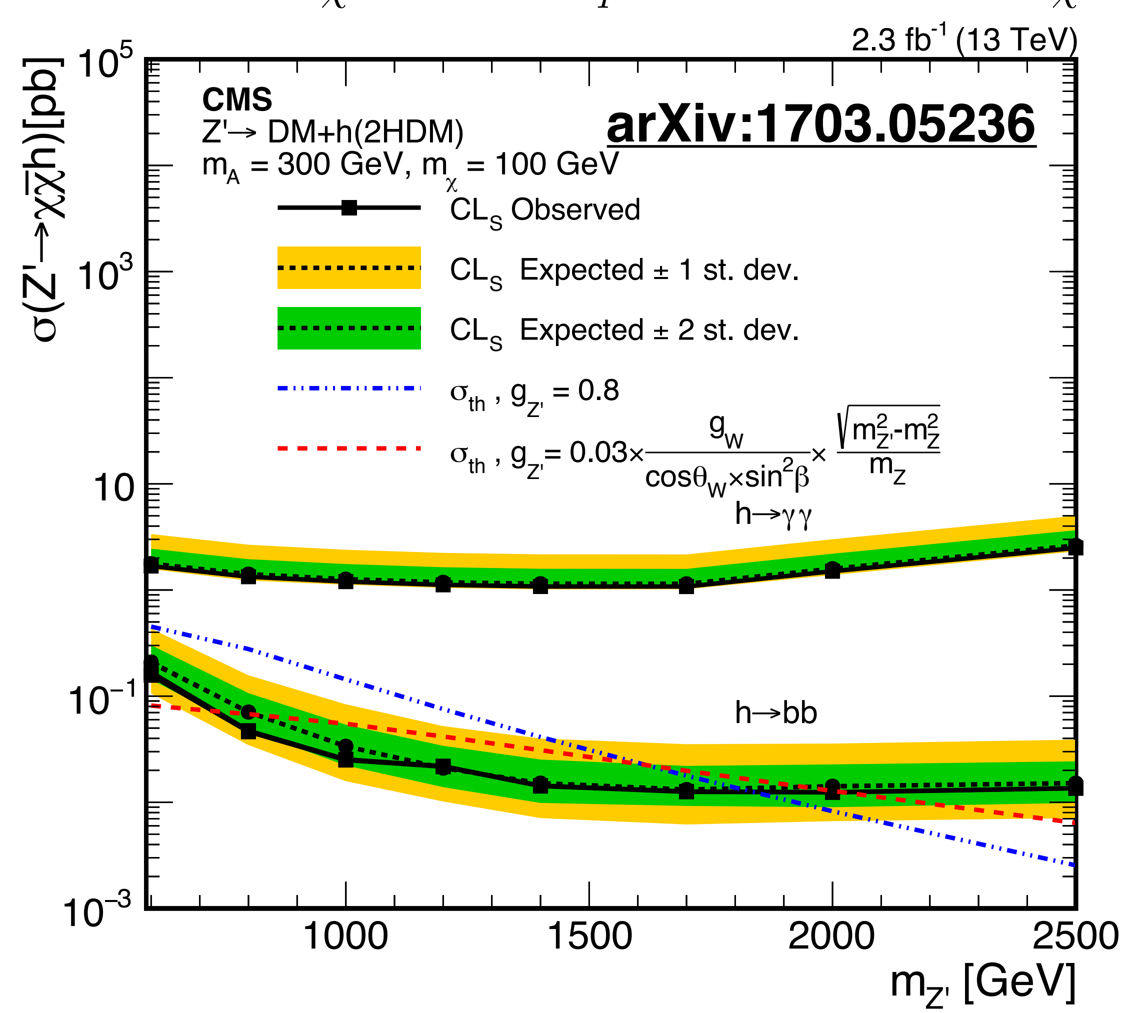
- Search for dark matter (MET) produced in association with Higgs boson

No excess over SM (yet)





arXiv:1706.03948



Conclusion

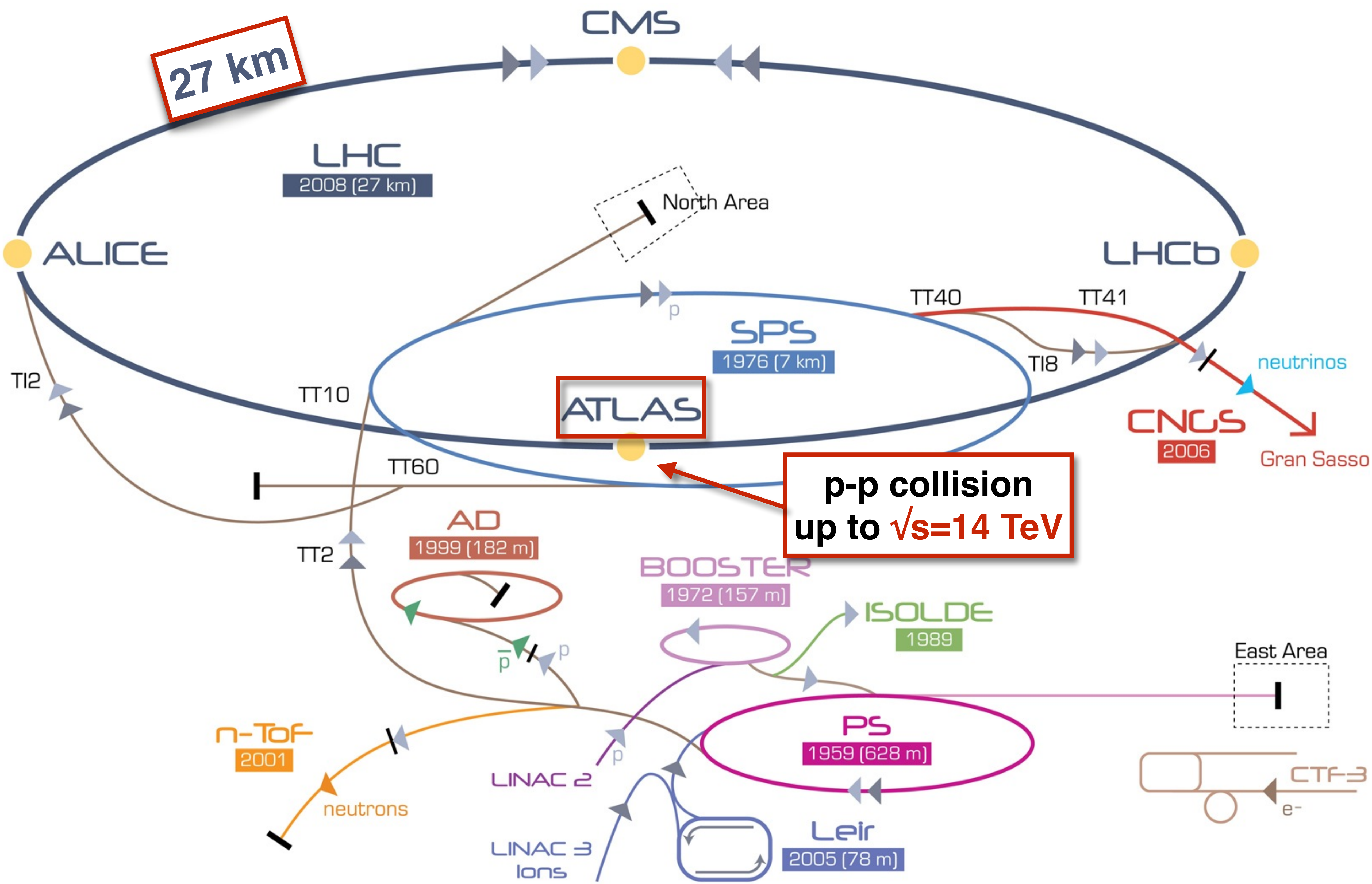
- Measurements of Higgs boson properties agree with SM / previous measurements
    - Signal strength $\mu^{ATLAS}_{\gamma\gamma}$ = 0.99±0.14, $\mu^{CMS}_{\gamma\gamma} = 1.16^{+0.15}_{-0.14}$
    - Signal strength/cross section of different production modes consistent with SM, and dominated by stat. uncertainty
    - Start exploring a variety of phase spaces using STXS framework
    - Mass measurement now dominated by syst. uncertainties. $m_H{}^{ATLAS}_{\gamma\gamma}$ = 125.11 ± 0.42 GeV, CMS best-fit at 125.4 GeV
    - Fiducial/differential cross sections agree with SM, but limited by stat. uncertainty
- Searches for new physics (FCNC, dark matter etc.) involving Higgs boson performed using diphoton decay channel. No excess found so far, but limited by stat.
- LHC Run 2 data-taking continues until the end of 2018
    - Expect ~120 fb^{-1} collected in total: stat. uncertainty should further reduce to about half of current level
    - Also more optimization of analysis as well as interpretations of data underway. Stay tuned!

References

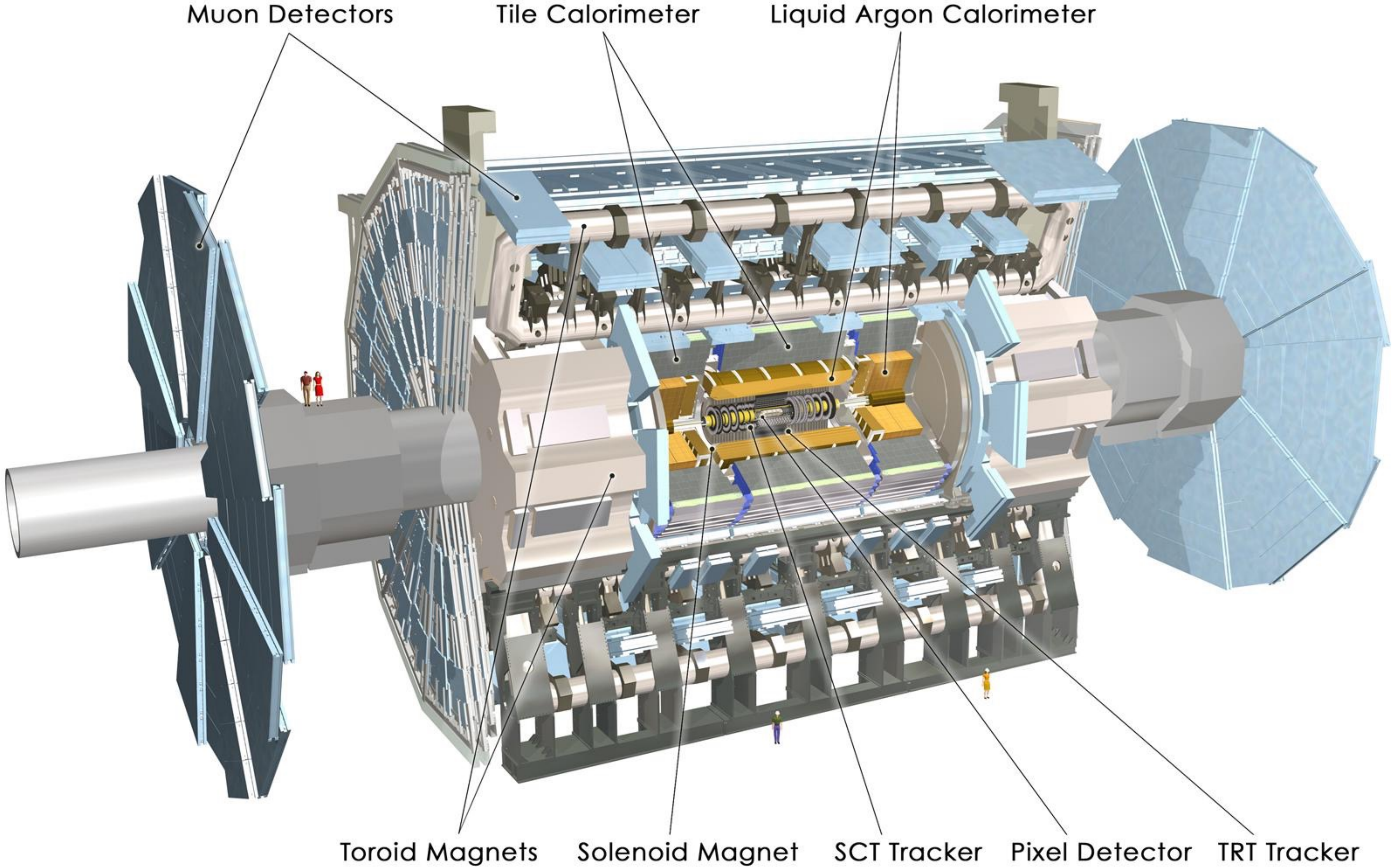
- ATLAS-CONF-2011-161: Search for the Standard Model Higgs boson in the diphoton decay channel with 4.9 fb^{-1} of ATLAS data at $\sqrt{s}$ = 7 TeV
- EPJC 76 (2016) 666: Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run-1 data
- CERN-LHCC-2006-001: CMS Physics : Technical Design Report Volume 1: Detector Performance and Software
- ATLAS luminosity public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2
- CMS luminosity public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults
- Yellow Report 4: Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector
- ATLAS-CONF-2017-045: Measurements of Higgs boson properties in the diphoton decay channel with 36.1 fb^{-1} pp collision data at the center-of-mass energy of 13 TeV with the ATLAS detector
- CMS-PAS-HIG-16-040: Measurements of properties of the Higgs boson in the diphoton decay channel with the full 2016 data set
- JHEP 09 (2014) 112: Measurements of fiducial and differential cross sections for Higgs boson production in the diphoton decay channel at $\sqrt{s}$ = 8 TeV with ATLAS
- CMS-PAS-HIG-17-015: Measurement of differential fiducial cross sections for Higgs boson production in the diphoton decay channel in pp collisions at $\sqrt{s}$ = 13 TeV
- ATLAS-CONF-2017-046: Measurement of the Higgs boson mass in the $H\to ZZ^*\to 4\ell$ and $H\to\gamma\gamma$ channels with $\sqrt{s}$ = 13 TeV pp collisions using the ATLAS detector
- arXiv:1707.01404: Search for top quark decays $t\to qH$, with $H\to\gamma\gamma$, in $\sqrt{s}$ = 13 TeV pp collisions using the ATLAS detector
- arXiv:1706.03948: Search for dark matter in association with a Higgs boson decaying to two photons at $\sqrt{s}$ = 13 TeV with the ATLAS detector
- arXiv:1703.05236: Search for associated production of dark matter with a Higgs boson decaying to bb or $\gamma\gamma$ at $\sqrt{s}$ = 13 TeV

Backup

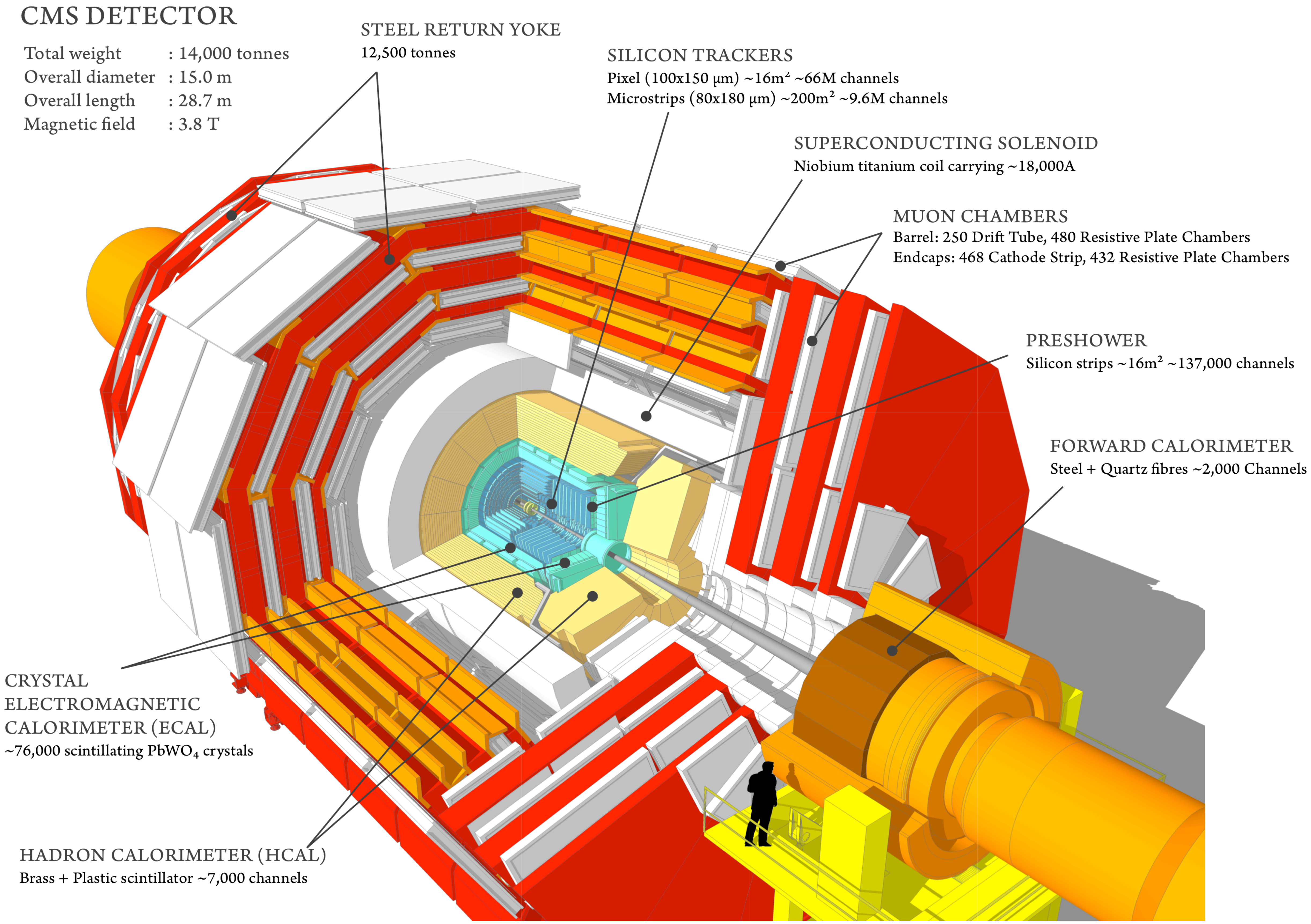
Large Hadron Collider at CERN



ATLAS detector



CMS detector



Signal MC samples

ATLAS

Process	Generator	Showering	PDF set	Order of calculation	σ[pb] $\sqrt{s} = 13$ TeV
ggH	Powheg NNLOPS	Pythia8	PDF4LHC15	N^{3}LO(QCD)+NLO(EW)	48.52
VBF	Powheg Box	Pythia8	PDF4LHC15	NNLO(QCD)+NLO(EW)	3.78
WH	Powheg Box	Pythia8	PDF4LHC15	NNLO(QCD)+NLO(EW)	1.37
$q\bar{q}' \to ZH$	Powheg Box	Pythia8	PDF4LHC15	NNLO(QCD)+NLO(EW)	0.76
$gg \to ZH$	Powheg Box	Pythia8	PDF4LHC15	NNLO(QCD)+NLO(EW)	0.12
$t\bar{t}H$	MadGraph5_aMC@NLO	Pythia8	NNPDF3.0	NLO(QCD)+NLO(EW)	0.51
$b\bar{b}H$	MadGraph5_aMC@NLO	Pythia8	CT10	5FS(NNLO)+4FS(NLO)	0.49
$tHq\bar{b}$	MadGraph5_aMC@NLO	Pythia8	CT10	4FS(LO)	0.07
tHW	MadGraph5_aMC@NLO	Herwig++	CT10	5FS(NLO)	0.02
$\gamma\gamma$	Sherpa	Sherpa	CT10		

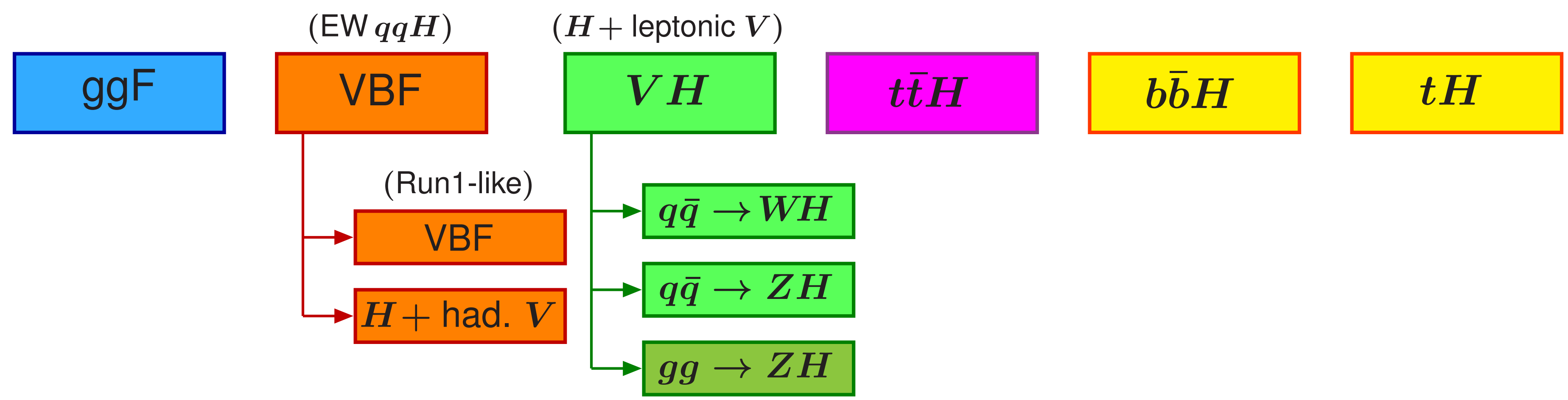
- CMS use MG5_aMC@NLO interfaced with Pythia8

Additional generators used in fiducial/differential measurements

- ATLAS
  - The Powheg NNLOPS calculation is normalized to the N3LO prediction using a K-factor of $K_{ggH} = 1.1$. This prediction is labeled as “default MC” in the plots
  - RadISH+NNLOjet provides $p_T^{\gamma\gamma}$ predictions using a p_T^H resummation to NNLL and matching to the one jet NNLO differential spectrum from NNLOjet. The shown RadISH+NNLOjet prediction does not include corrections from the finite top and bottom quark masses
  - SCETlib provides predictions for $|\cos\theta^*|$ at $NNLO+NNLL_{\phi}'$ accuracy derived by applying a resummation of the virtual corrections to the gluon form factor. The underlying NNLO predictions are obtained using MCFM8 with zero-jettiness subtractions.
- CMS: use PowHeg for ggF

STXS Stage 0 and 1 definitions

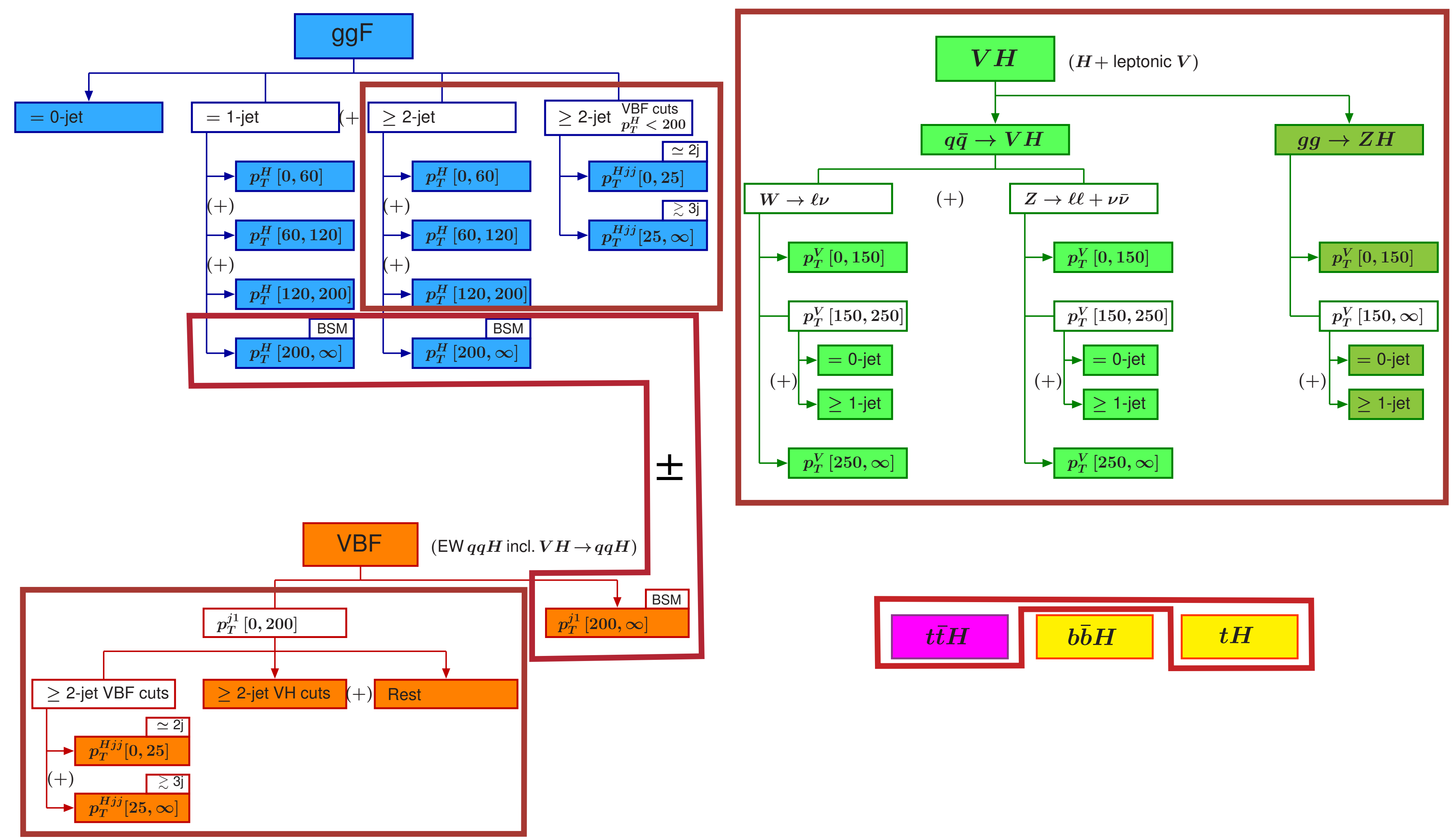
Stage 0 definition



ATLAS preliminary

Stage 1 definition

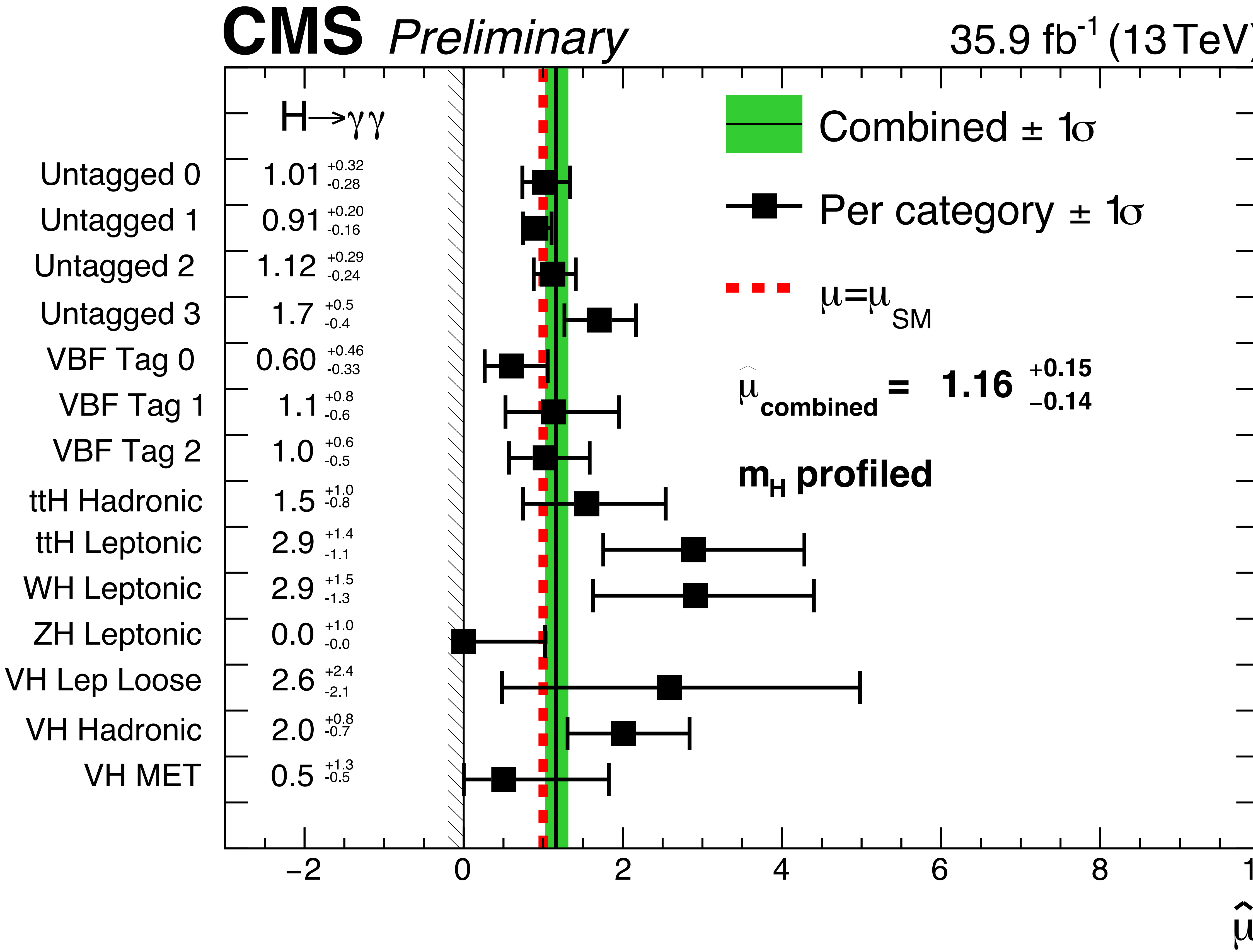
Red boxes indicate merging applied by ATLAS analysis



Signal mass resolution and S/B in ATLAS coupling analysis

category	σ_{68} [GeV]	s_{90}	b_{90}	$s_{90}/(b_{90}+s_{90})$	obs events
ggH 0J CEN	1.61	254	5338	0.05	51722
ggH 0J FWD	2.14	445	20224	0.02	140729
ggH 1J LOW	1.91	329	7934	0.04	62330
ggH 1J MED	1.82	135	2839	0.05	23355
ggH 1J HIGH	1.63	27	235	0.10	2313
ggH 1J BSM	1.44	1.9	7	0.21	88
ggH 2J LOW	1.92	121	3102	0.04	23888
ggH 2J MED	1.82	72	1725	0.04	13955
ggH 2J HIGH	1.64	27	284	0.09	2678
ggH 2J BSM	1.42	7	25	0.21	303
VBF loose, low p_T^{Hjj}	1.84	19	109	0.15	895
VBF tight, low p_T^{Hjj}	1.64	12	16	0.49	136
VBF loose, high p_T^{Hjj}	1.80	23	256	0.08	2009
VBF tight, high p_T^{Hjj}	1.66	23	111	0.16	1085
VH had loose	1.71	15	222	0.06	1893
VH had tight	1.54	11	46	0.19	473
jet BSM	1.42	25	280	0.08	2912
VH MET LOW	1.83	0.5	3.4	0.13	26
VH MET HIGH	1.56	1.2	2.3	0.34	25
VH lep LOW	1.78	6	51	0.10	414
VH lep HIGH	1.52	1.4	2.4	0.37	24
VH dilep	1.74	0.8	1.1	0.44	10
tH had 4j2b	1.70	0.6	7	0.08	59
tH had 4j1b	1.66	2.3	48	0.05	422
ttH had BDT4	1.63	2.3	14	0.14	125
ttH had BDT3	1.62	0.6	2.3	0.19	22
ttH had BDT2	1.59	1.6	3.9	0.29	37
ttH had BDT1	1.60	1.3	2.0	0.40	21
ttH lep	1.62	2.2	2.7	0.44	28
tH lep 1fwd	1.72	1.0	1.9	0.35	19
tH lep 0fwd	1.67	0.9	3.6	0.20	34

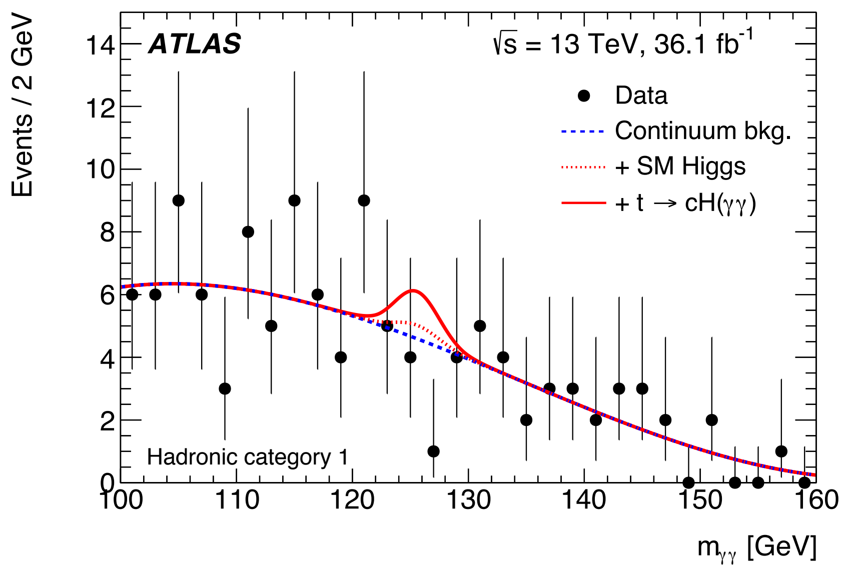
Signal strength per category in CMS coupling analysis

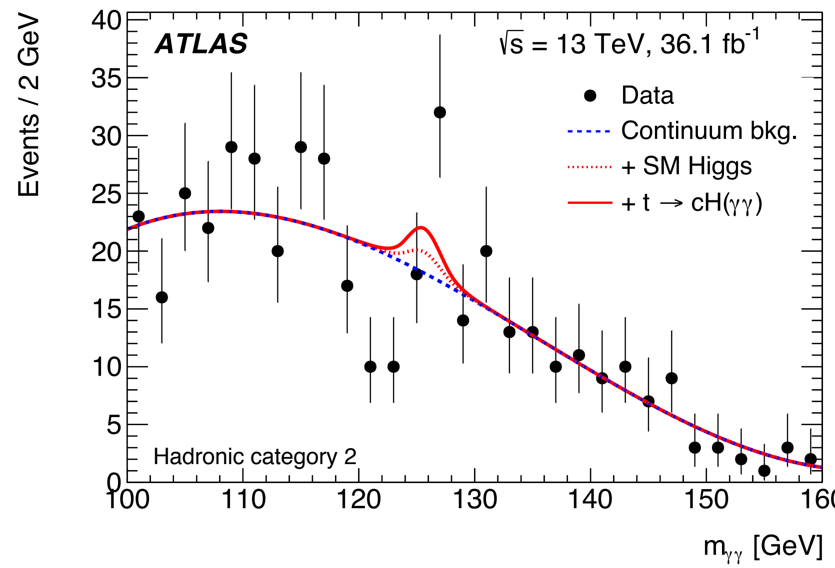


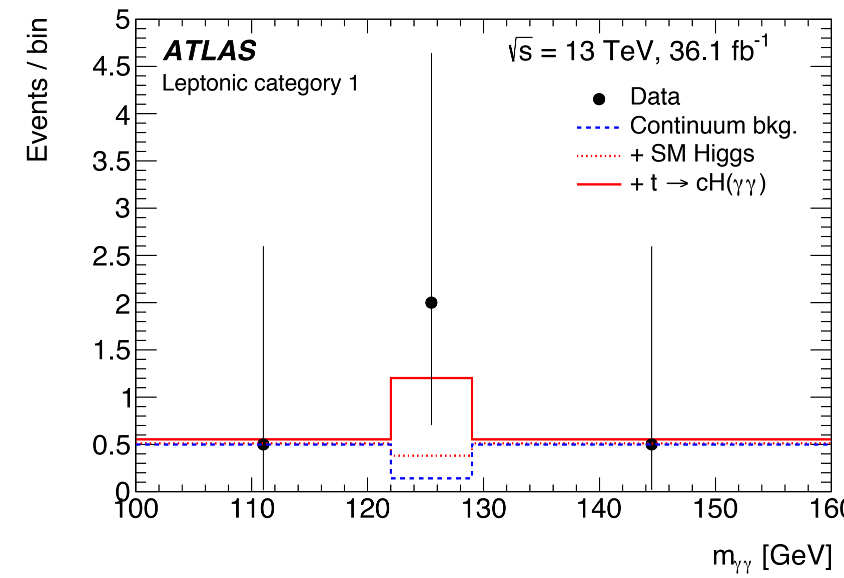
Impact of energy scale systematic uncertainties on ATLAS m_H result

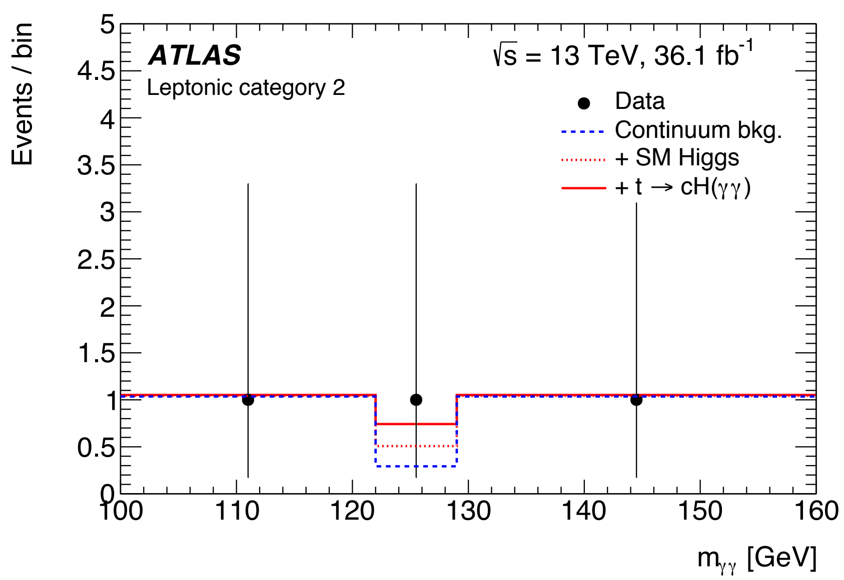
Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
LAr cell non-linearity	± 200
LAr layer calibration	± 190
Non-ID material	± 120
Lateral shower shape	± 110
ID material	± 110
Conversion reconstruction	± 50
$Z \to ee$ calibration	± 50
Background model	± 50
Primary vertex effect on mass scale	± 40
Resolution	$^{+20}_{-30}$
Signal model	± 20

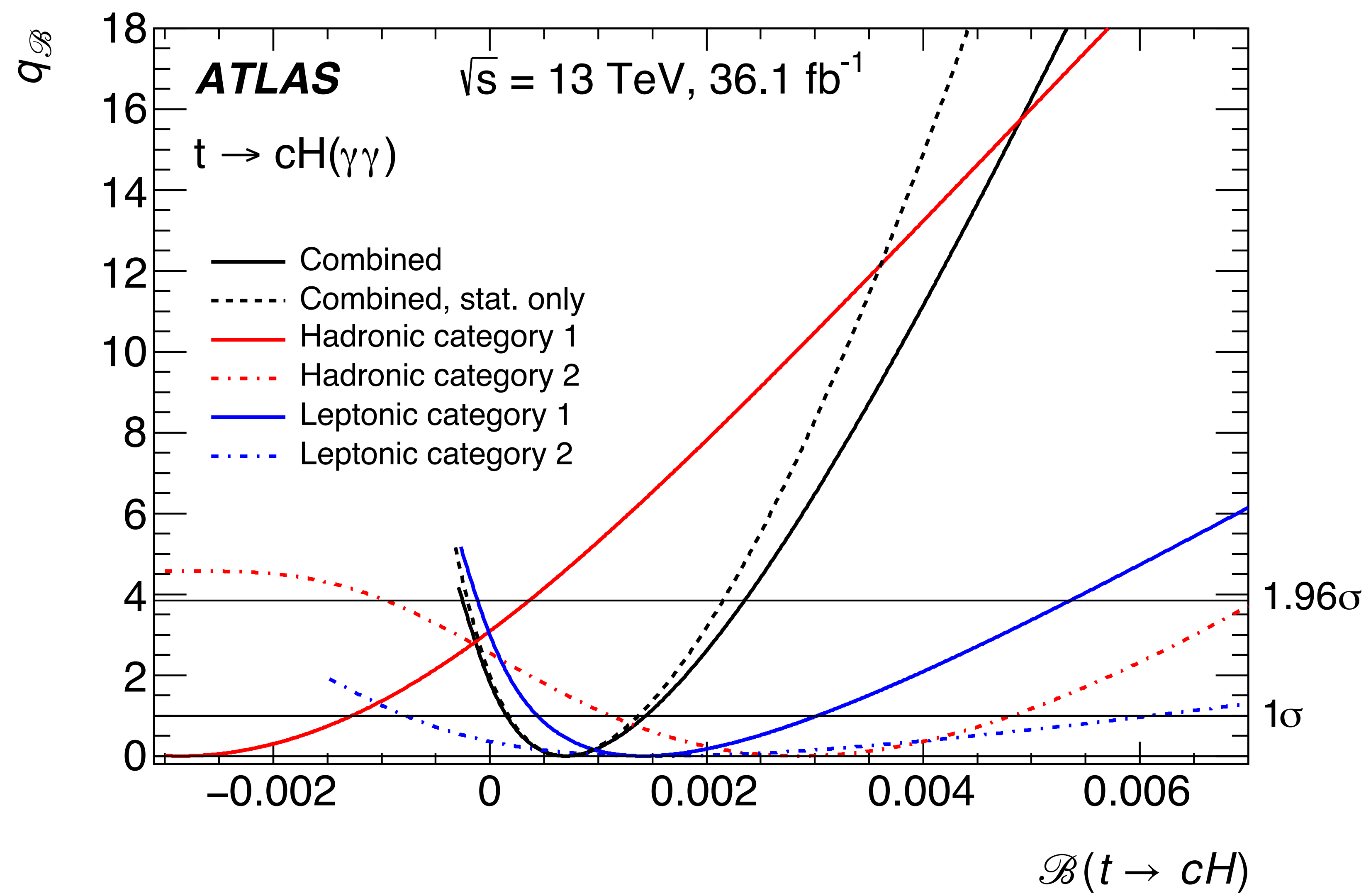
FCNC per category results











- No significant excess over SM background