



Standard Model results from ATLAS

"Standard Model and Beyond"
5th Symposium of the Division for Physics of Fundamental Interactions
of the Polish Physical Society
Katowice 21-23.10.2022

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(Institute of Nuclear Physics P.A.N., Cracow PL)

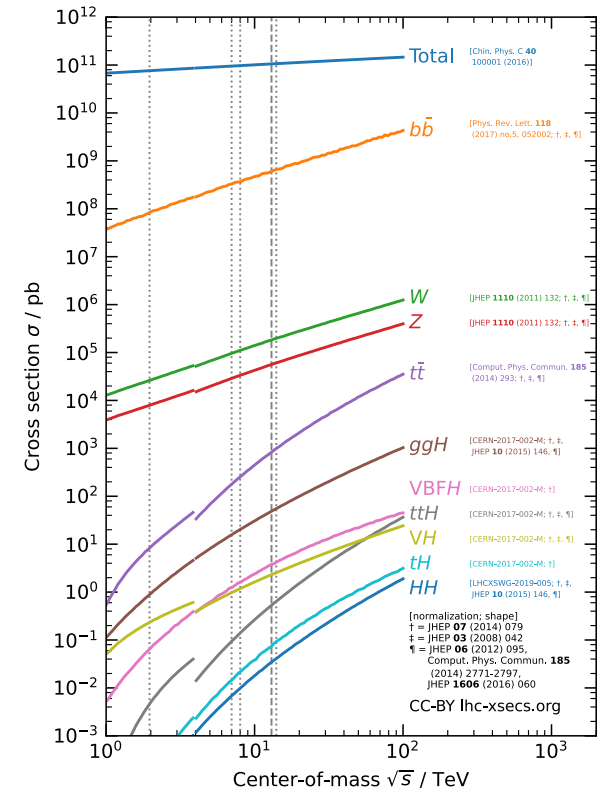
LHC @ Run 2 – a giant leap!

Energy increase:

- p - p : 8 TeV $\rightarrow$ 13 TeV (CME)
- HI energy/ $N=13$ TeV $\cdot Z/A$
(Pb-Pb: 13 TeV $\cdot 82/207=5.15$ TeV)

Cross-section increase:

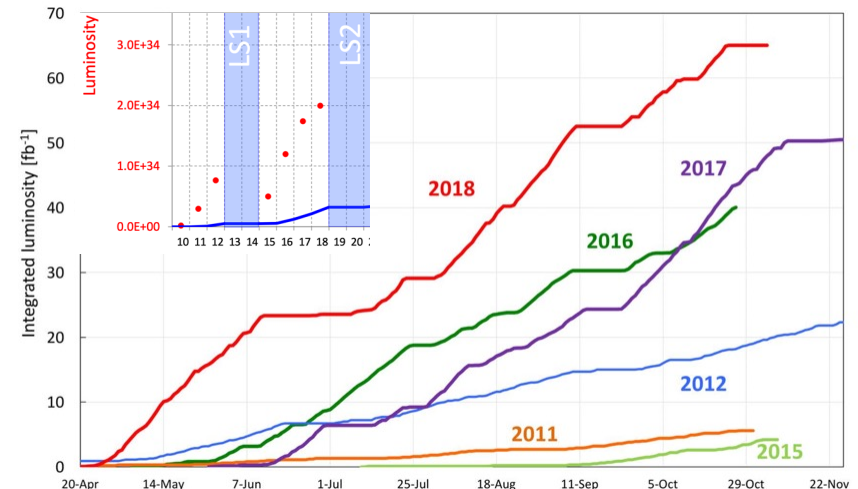
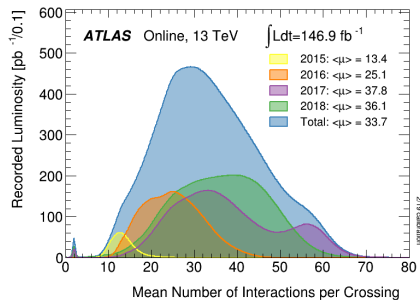
- $\sim x2$ for dominant Higgs production
- $\sim x4$ for $t\bar{t}H$, HH , $t\bar{t}$



Luminosity increase:

peak lumi 2×10^{34} (pileup!)

$L_{\text{int}} \sim 140 \text{ fb}^{-1}$ / expt.



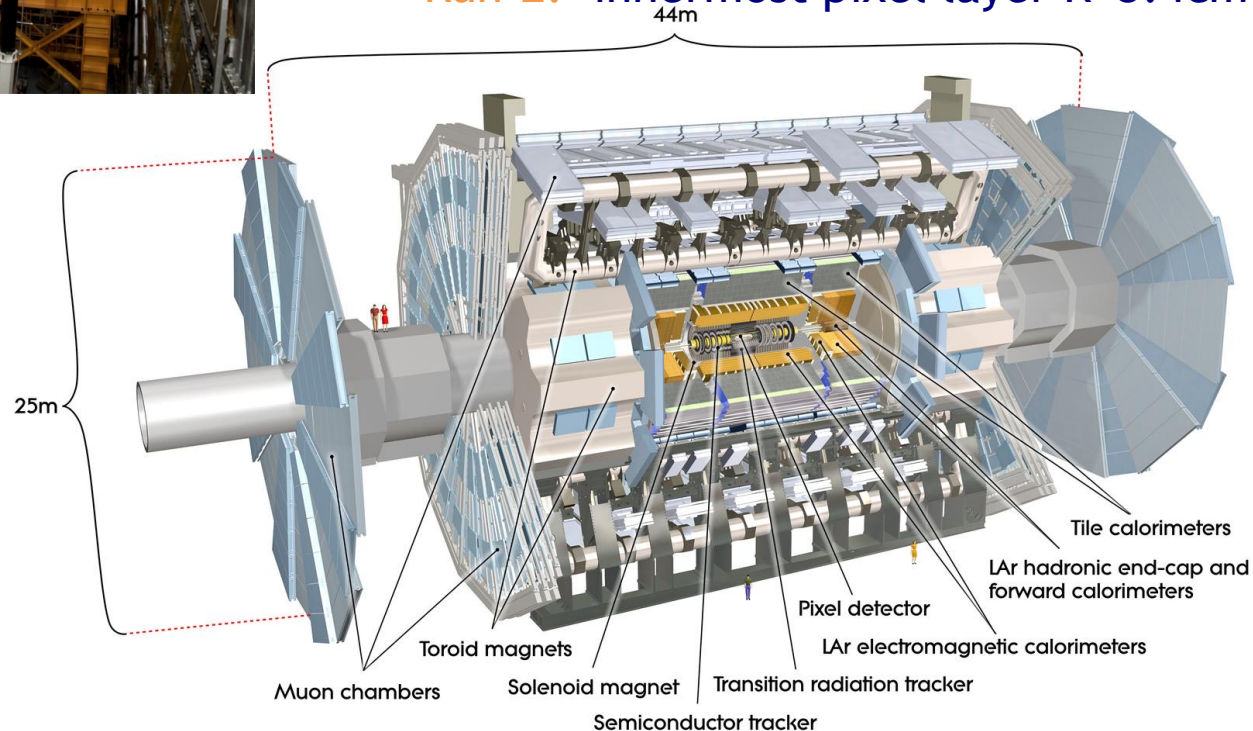
ATLAS detector



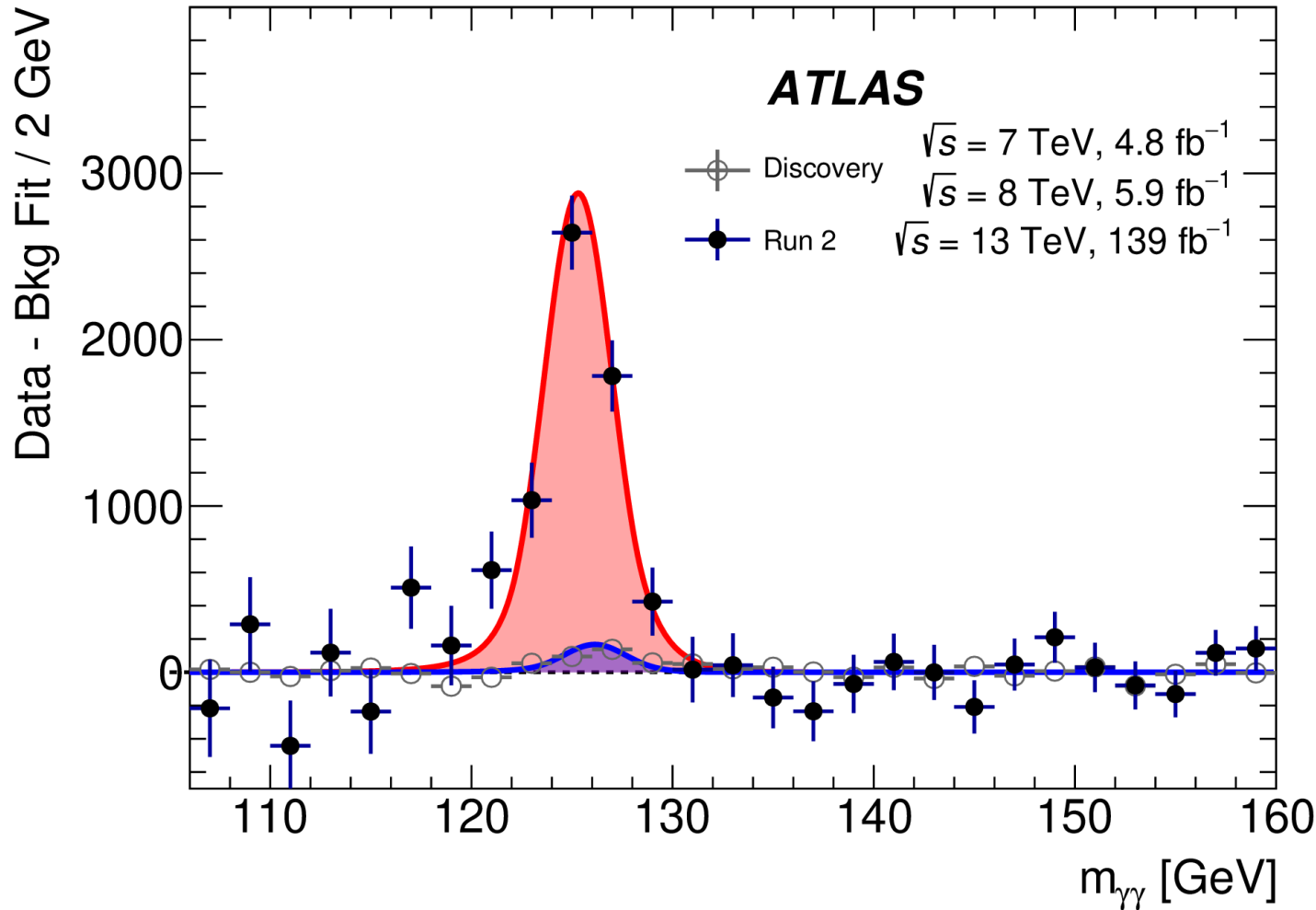
	ATLAS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10 λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03 \text{ GeV}$
Muon	$\sigma/p_T \approx 2\% \text{ @ } 50\text{GeV to } 10\% \text{ @ } 1\text{TeV}$ (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)

Run-2: innermost pixel layer $R=3.4\text{cm}$

ATLAS Collaboration
38 Countries
175 Institutions
3000 Scientific Authors total



Getting to know the 125 GeV scalar



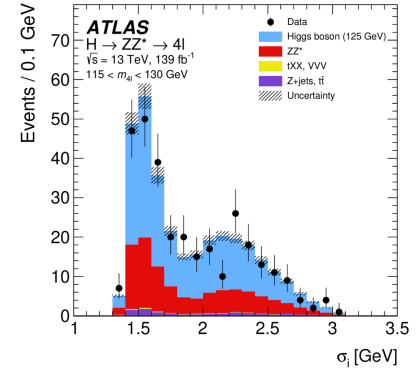
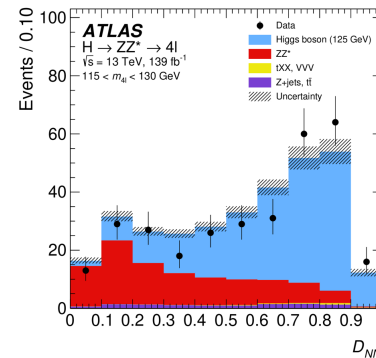
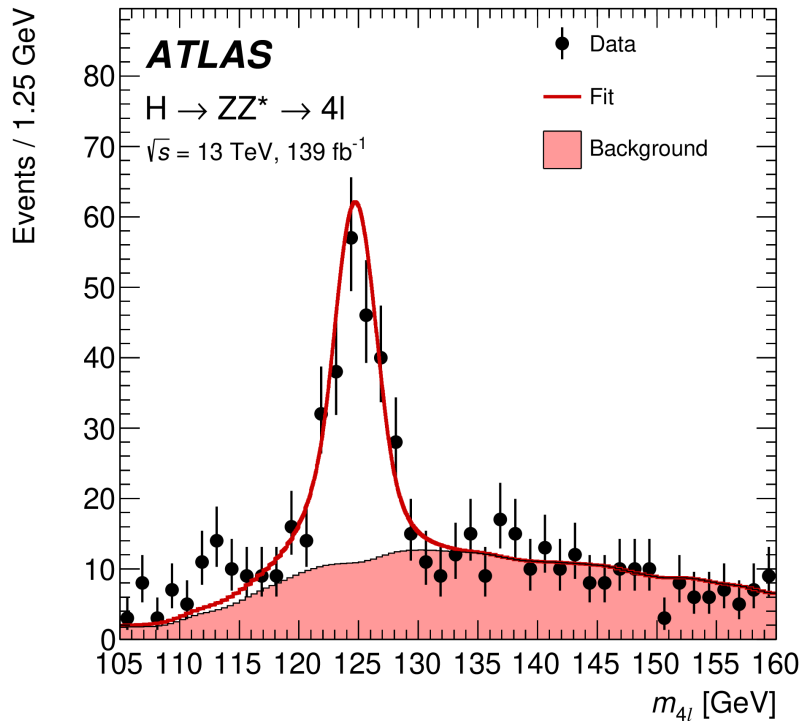
Run 2

x30

Discovery

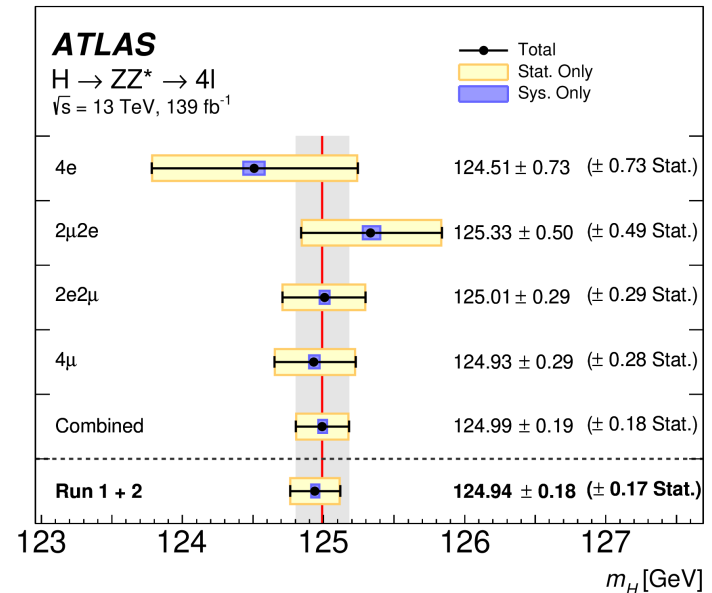
Higgs mass measurement

HIGG-2020-07



NN output to parameterise per-event resolution and composition

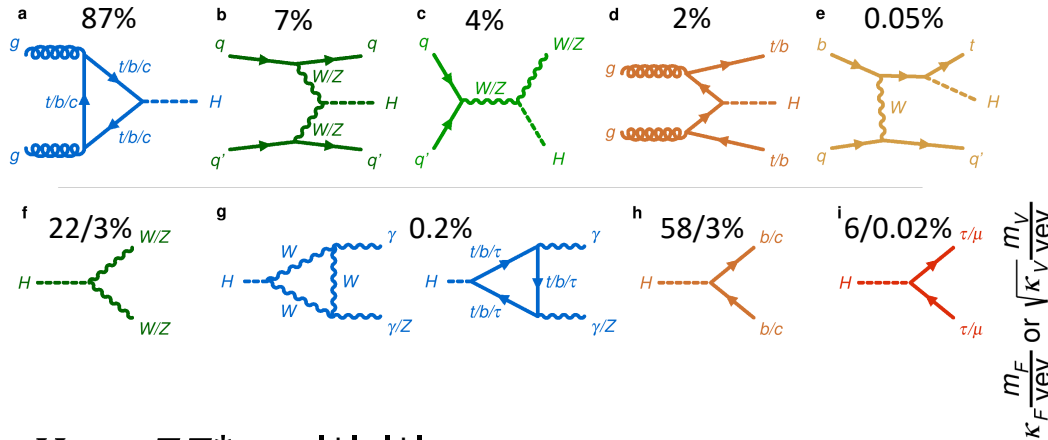
- ❖ Combined unbinned maximum-likelihood fit
- ❖ The result is **statistically** dominated!
- ❖ Largest **systematics** come from muon momentum scale and electron energy scale



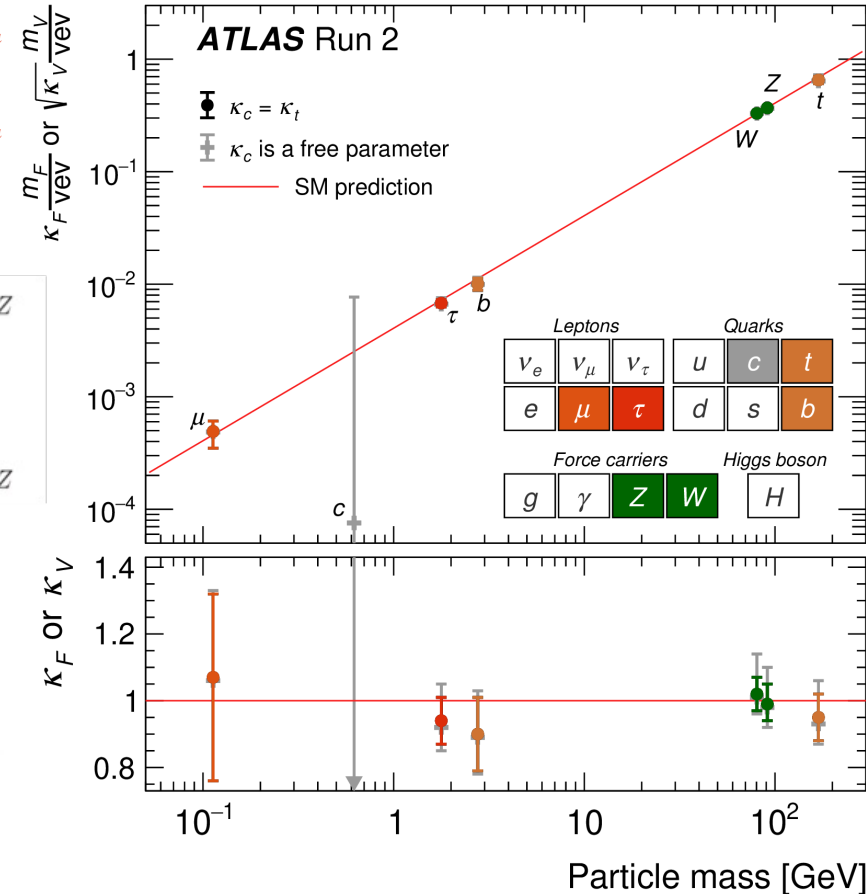
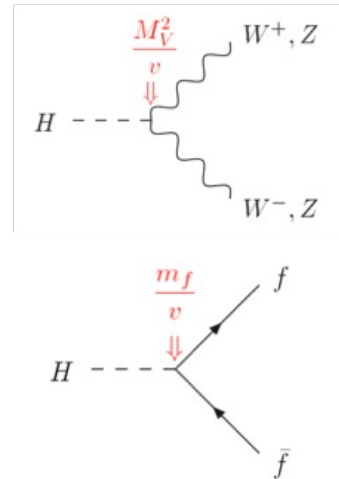
Legacy Run2 Higgs mass (4l+ $\gamma\gamma$ combined - both $\sim 0.2\text{GeV}$) **expected @ 0.14GeV** (approaching 10^{-3} precision!). We know top mass to 2×10^{-3} , W mass to 2×10^{-4}

Higgs couplings combination

[Nature 607, pages 52-59 \(2022\)](#)



$H \rightarrow ZZ^* \rightarrow |^+|^+|^+|^+$
 $H \rightarrow W^\pm W^\mp \rightarrow |^\pm \nu_l|^{\mp} \nu_l$
 $H \rightarrow \gamma\gamma$
 $H \rightarrow Z\gamma$ (limit, incl.)
 $H \rightarrow b\bar{b}$ (all but ggF)
 $H \rightarrow \tau^+\tau^-$
 $H \rightarrow \mu^+\mu^-$
 $H \rightarrow c\bar{c}$ (VBF, ZH)
 $H \rightarrow \text{invisible}$ (VBF, ZH)

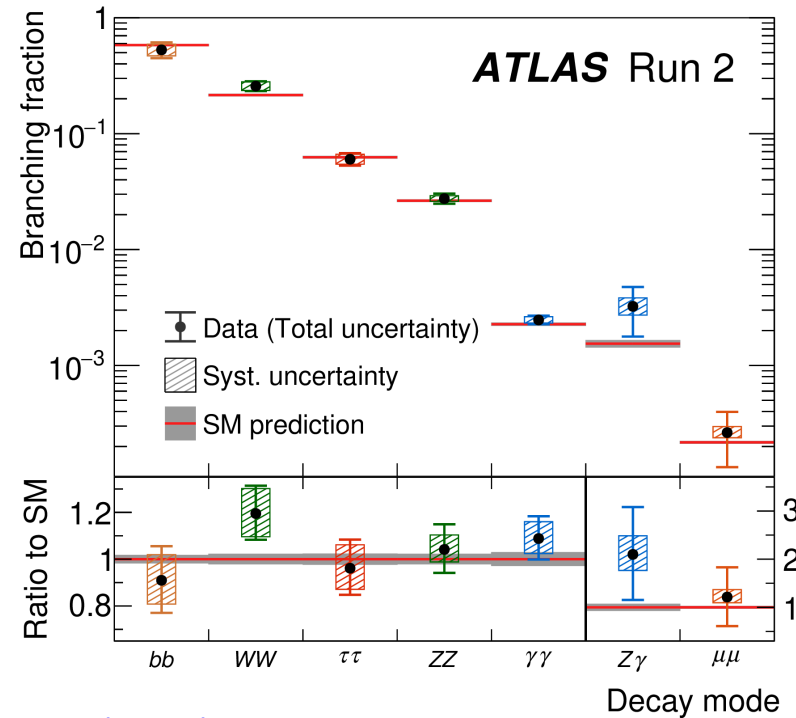
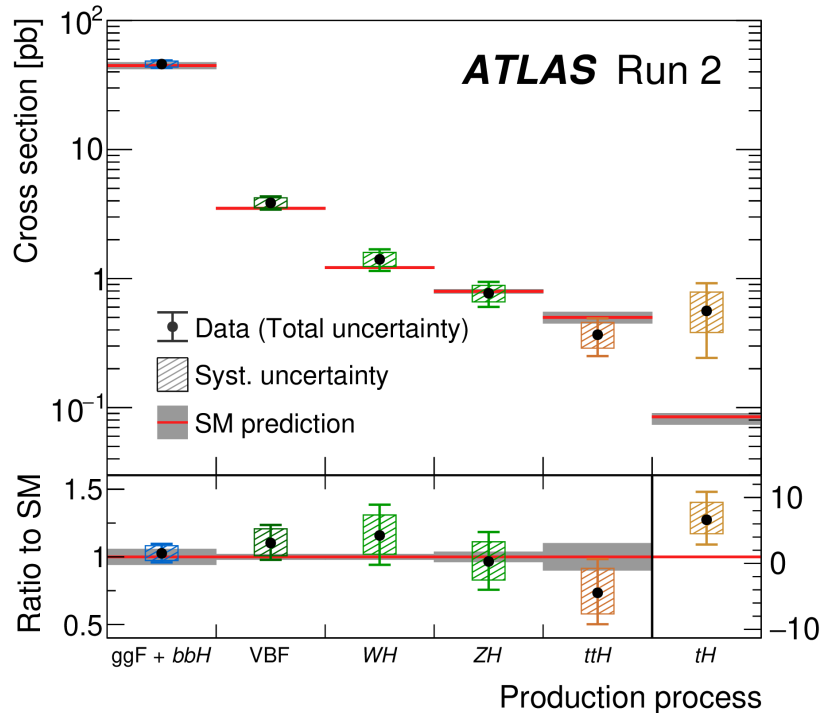
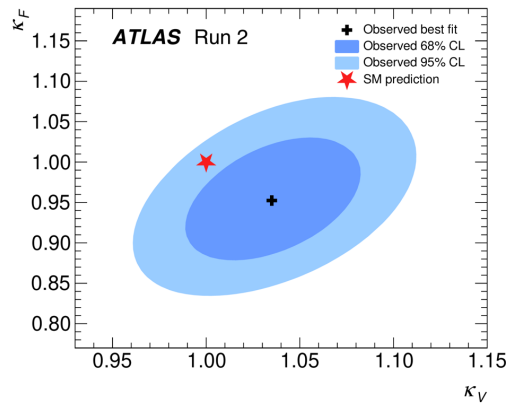
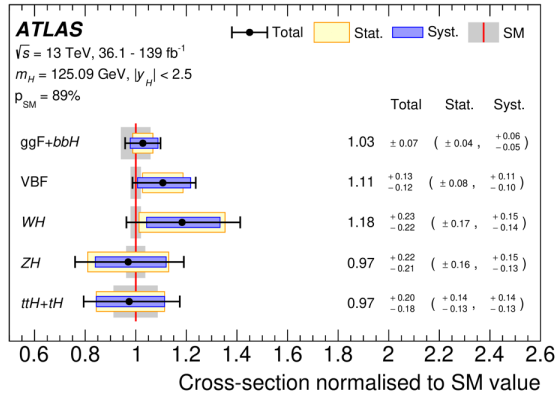


Excellent agreement of couplings across three orders of magnitude of particle mass!

Assuming $m(H) = 125.09$ GeV
[PRL 114 \(2015\) 191803](#)

Higgs couplings combination

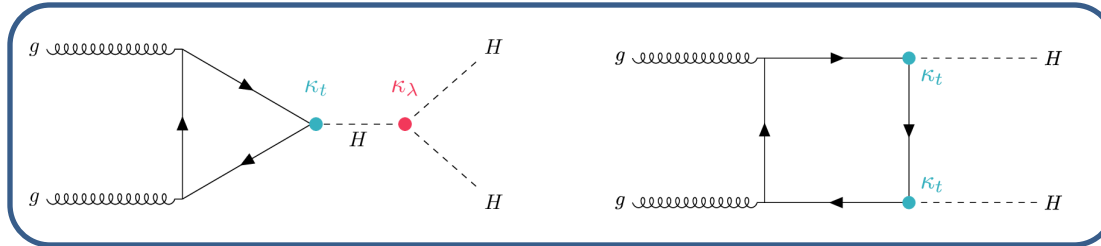
[Nature 607, pages 52-59 \(2022\)](#)



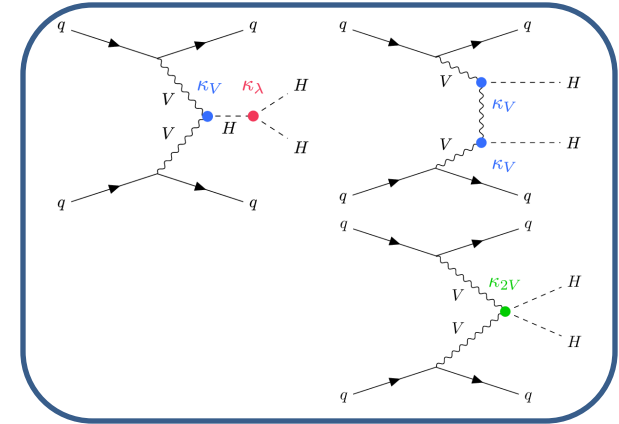
Assuming $m(H) = 125.09 \text{ GeV}$ [PRL 114 \(2015\) 191803](#)

Understanding the Higgs potential...

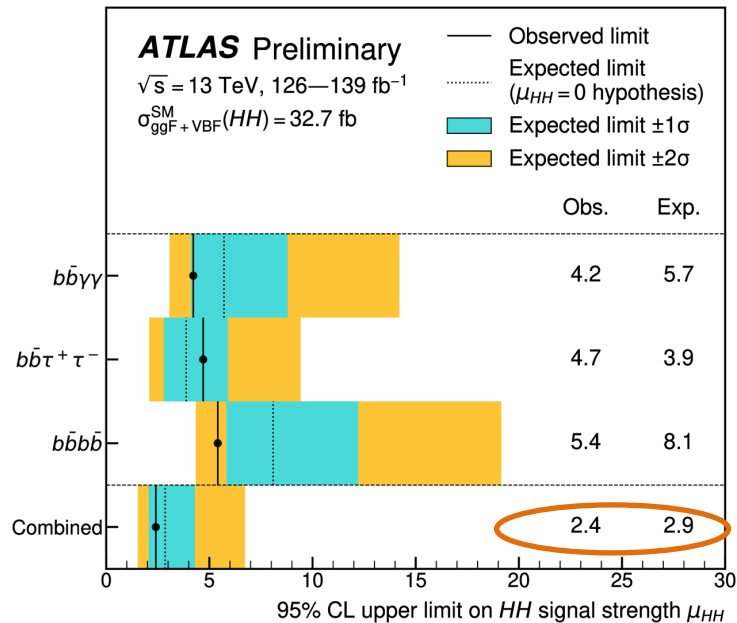
ggF: 90% of SM x-section (interfere destructively)



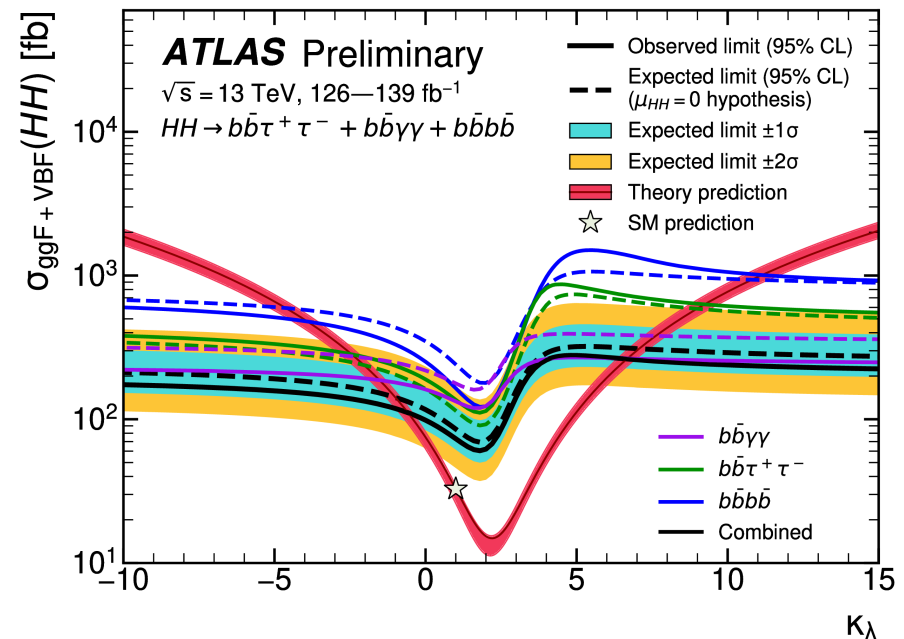
VBF: will help in the future



$b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}b\bar{b}$



Non-resonant HH search

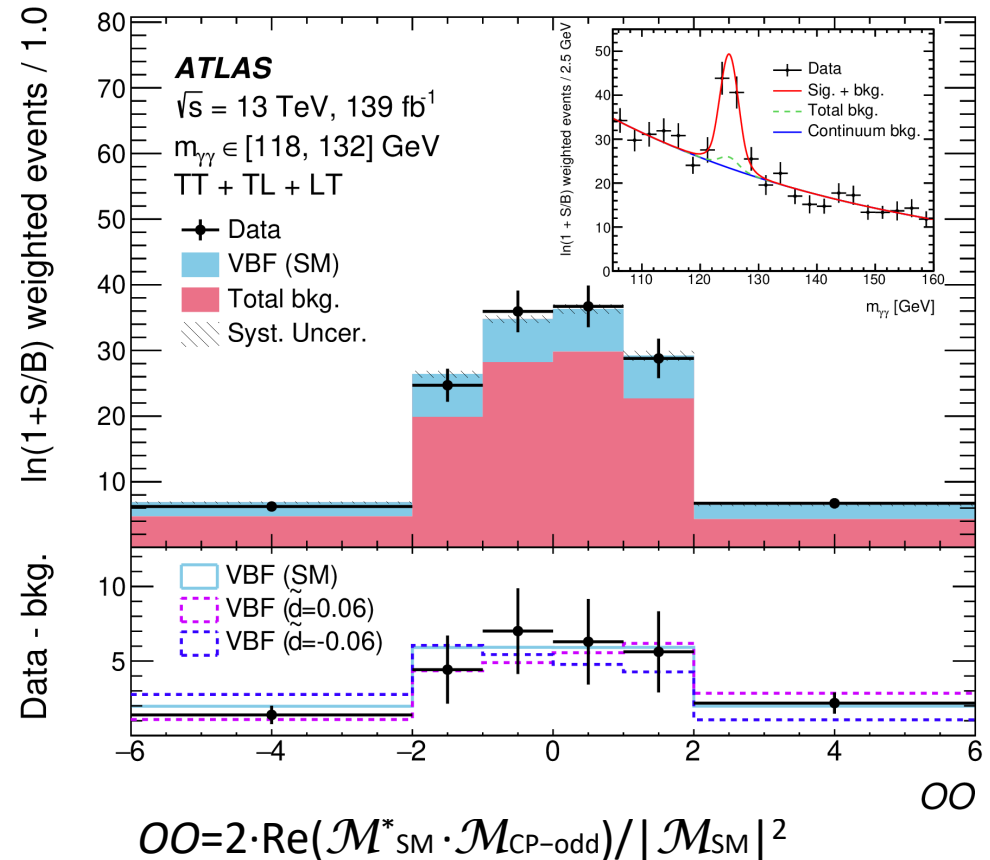


Does Higgs sector contribute to CP violation?

HIGG-2020-08

VBF $H \rightarrow \gamma\gamma$

In lack of CP-odd contribution the distribution of OO is symmetric



Obtained:

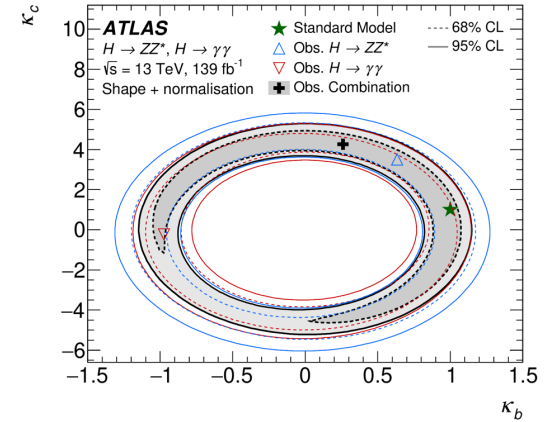
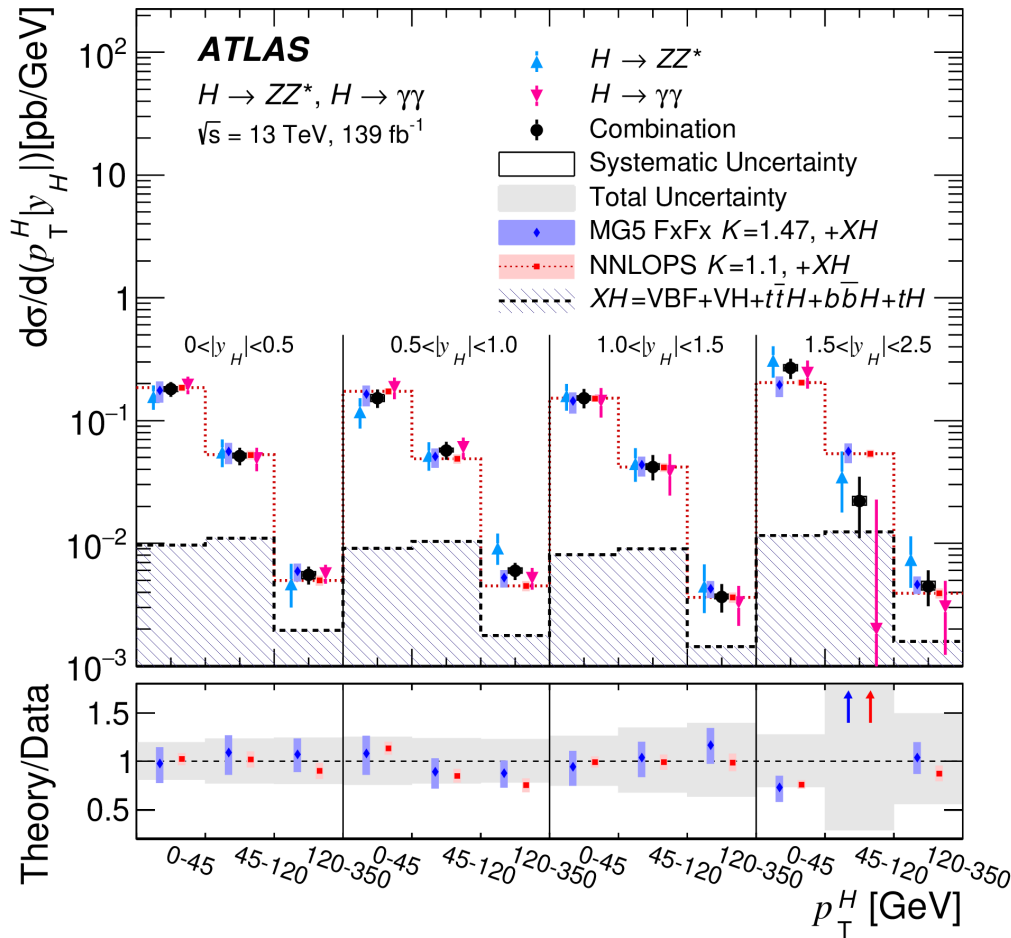
the most stringent constraint on the dimension-six CP-odd contribution to the H-V interaction EFT Lagrangian.

Be more ambitious – go differential

HIGG-2022-04

$$H \rightarrow \gamma\gamma$$

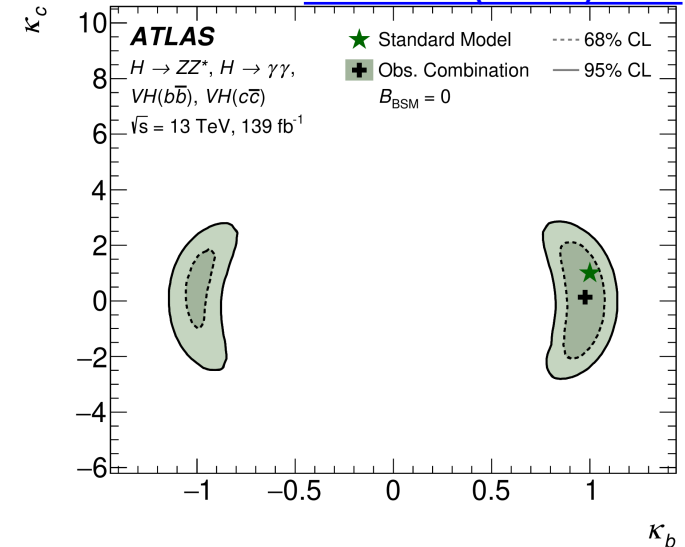
$$H \rightarrow ZZ^*$$



+

$H \rightarrow bb$: [EPJ C 81 \(2021\) 178](#)

$H \rightarrow cc$: [EPJ C 82 \(2022\) 717](#)

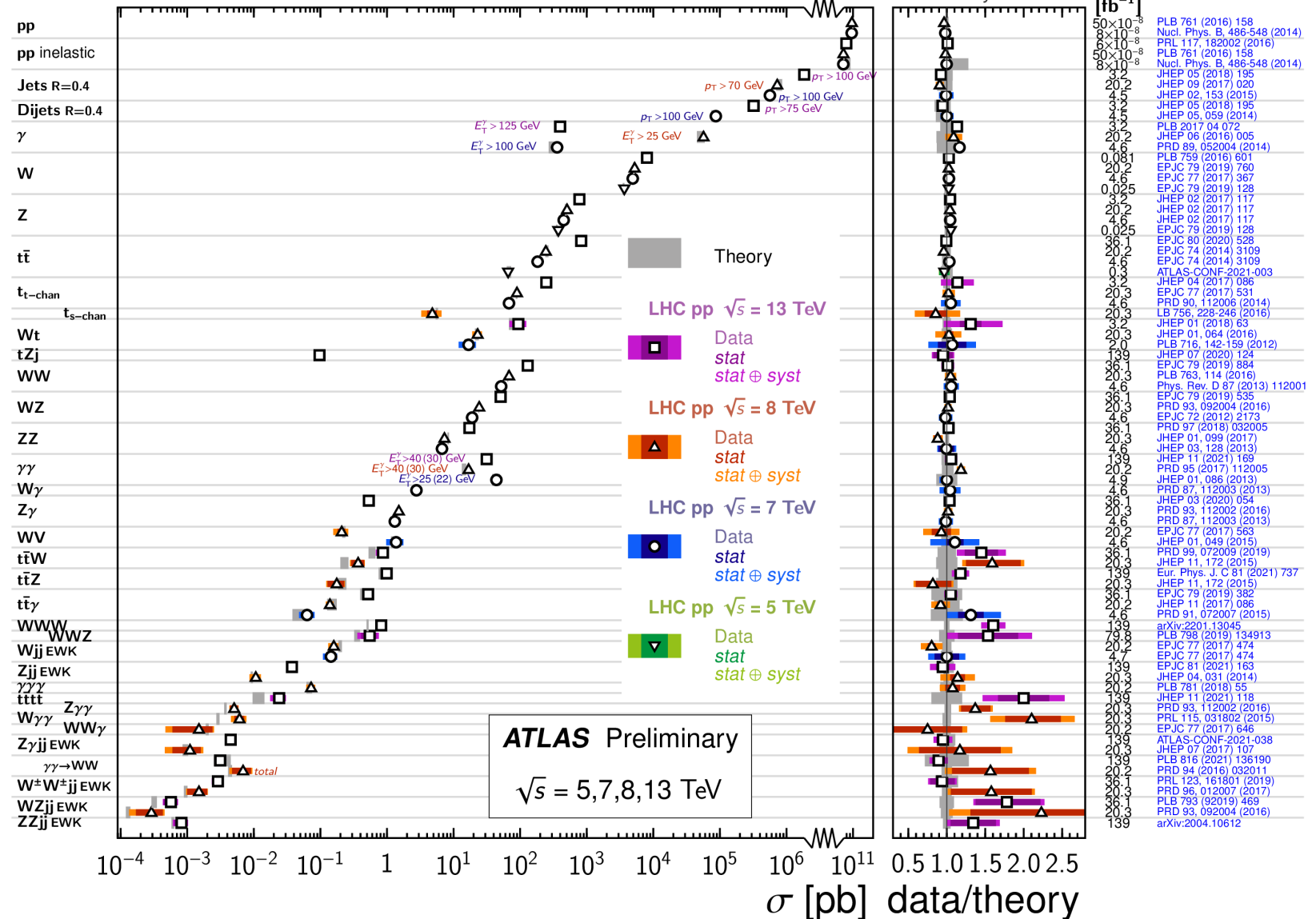


Plethora of Standard Model physics measurements

ATLAS Standard Model summary plots

Standard Model Production Cross Section Measurements

Status:
February 2022



SMEFT fit to ATLAS Higgs & EW and EWPO

Warsaw basis vectors [[JHEP 10 \(2010\) 085](#)]
or their eigen-combinations

Wilson coefficients for 28 dimension-six operators are considered ($\Lambda=1$ TeV).

Input:

STXS Higgs [[ATLAS-CONF-2021-053](#)]

SM precision [[ATL-PHYS-PUB-2021-022](#)]

LEP+SLD [[Phys. Rept. 427 \(2006\) 257](#)]

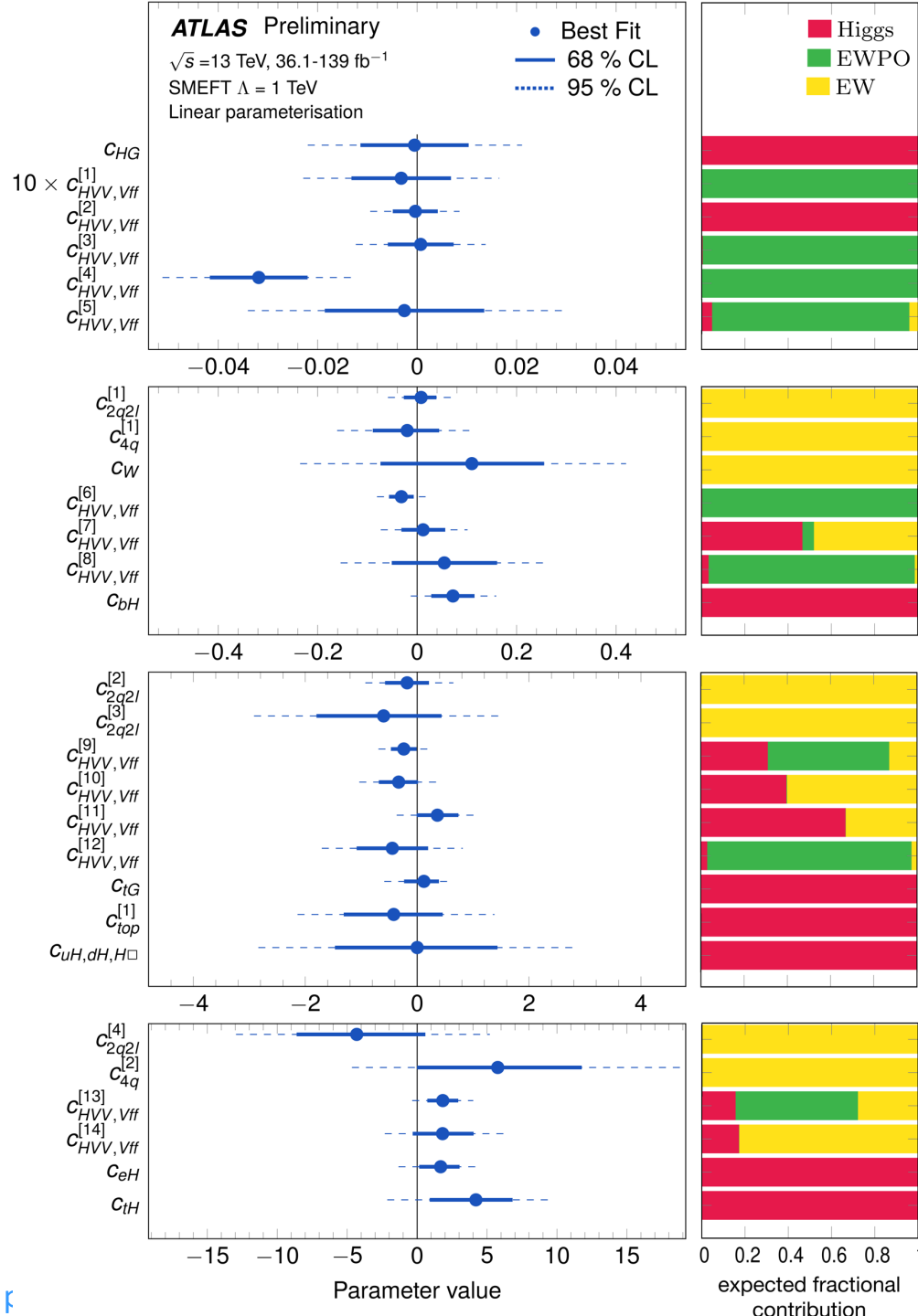
Decay channel	Target Production Modes	$\mathcal{L}$ [fb $^{-1}$]
$H \rightarrow \gamma\gamma$	ggF, VBF, WH , ZH , $t\bar{t}H$, tH	139
$H \rightarrow ZZ^*$	ggF, VBF, WH , ZH , $t\bar{t}H(4\ell)$	139
$H \rightarrow WW^*$	ggF, VBF	139
$H \rightarrow \tau\tau$	ggF, VBF, WH , ZH , $t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139
$H \rightarrow b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H$	139

Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb $^{-1}$]
$pp \rightarrow e^\pm \nu \mu^\mp \nu$	$m_{\ell\ell} > 55 \text{ GeV}$, $p_T^{\text{jet}} < 35 \text{ GeV}$	$p_T^{\text{lead. lep.}}$	36
$pp \rightarrow \ell^\pm \nu \ell^+ \ell^-$	$m_{\ell\ell} \in (81, 101) \text{ GeV}$	m_T^{WZ}	36
$pp \rightarrow \ell^+ \ell^- \ell^+ \ell^-$	$m_{4\ell} > 180 \text{ GeV}$	m_{Z2}	139
$pp \rightarrow \ell^+ \ell^- jj$	$m_{jj} > 1000 \text{ GeV}$, $m_{\ell\ell} \in (81, 101) \text{ GeV}$	$\Delta\phi_{jj}$	139

The big picture:

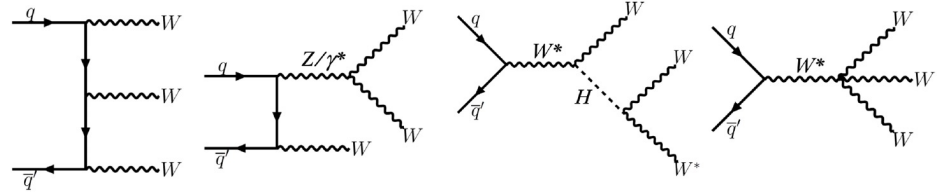
SM holds strong

LHC becomes highly competitive!



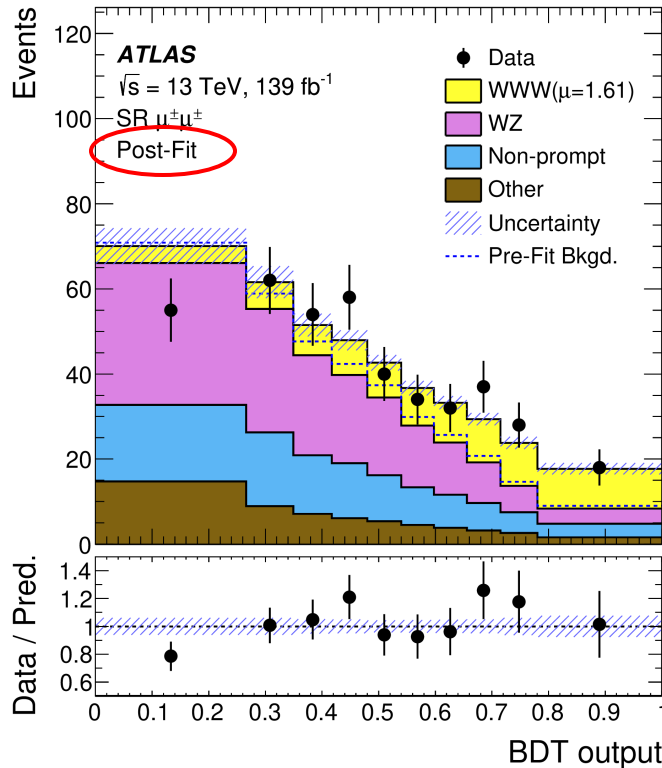
WWW observation- gauge couplings in action

[Phys. Rev. Lett. 129 \(2022\) 061803](#)



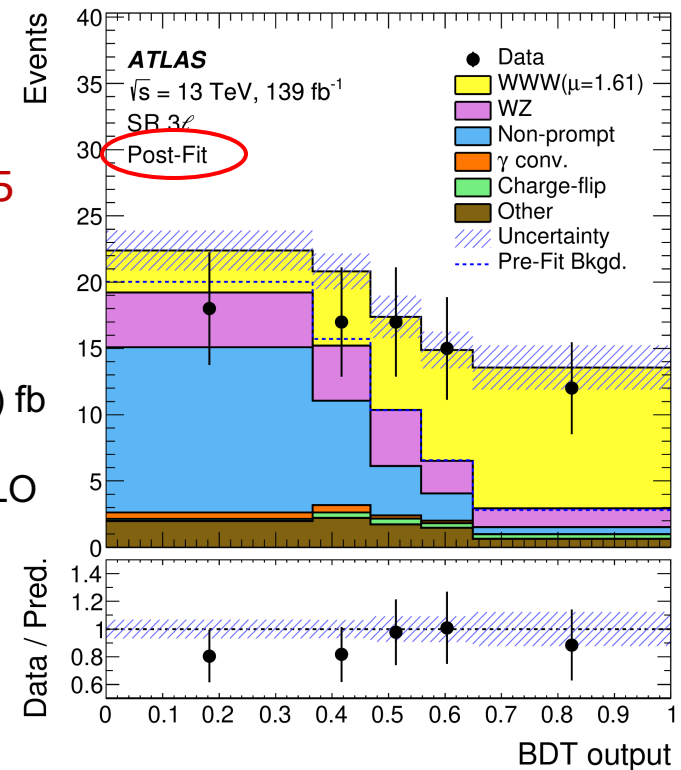
$WWW \rightarrow l^\pm \nu^\pm \nu q q$ $2 / (SS) + 2j + E_t^{\text{miss}}, b$
 $WWW \rightarrow l^\pm \nu^\pm \nu \bar{\nu}$ $3 / + E_T^{\text{miss}}, b$ ~~SFOS~~
 all combinations of $e \mu$ considered (4 channels).

Main background from WZ+jets
 estimated from MC normalized to data



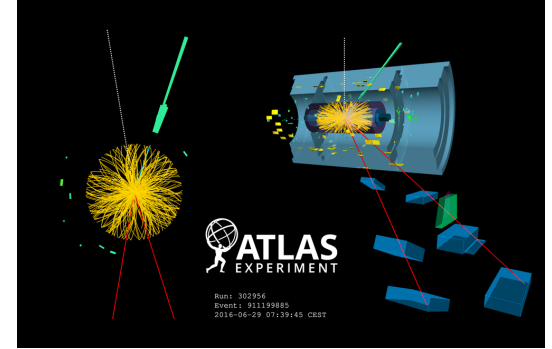
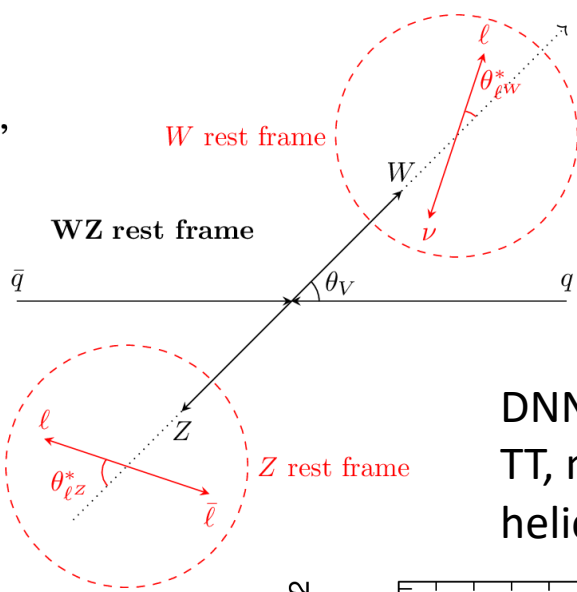
$$\mu(WWW) = 1.61 \pm 0.25$$

$\sigma_{\text{incl}} pp \rightarrow WWW$:
 $820 \pm 100 \text{ (stat)} \pm 80 \text{ (syst) fb}$
 2.6 standard deviations
 above the NLO QCD and LO
 electroweak calculation
 ($511 \pm 18 \text{ fb}$)



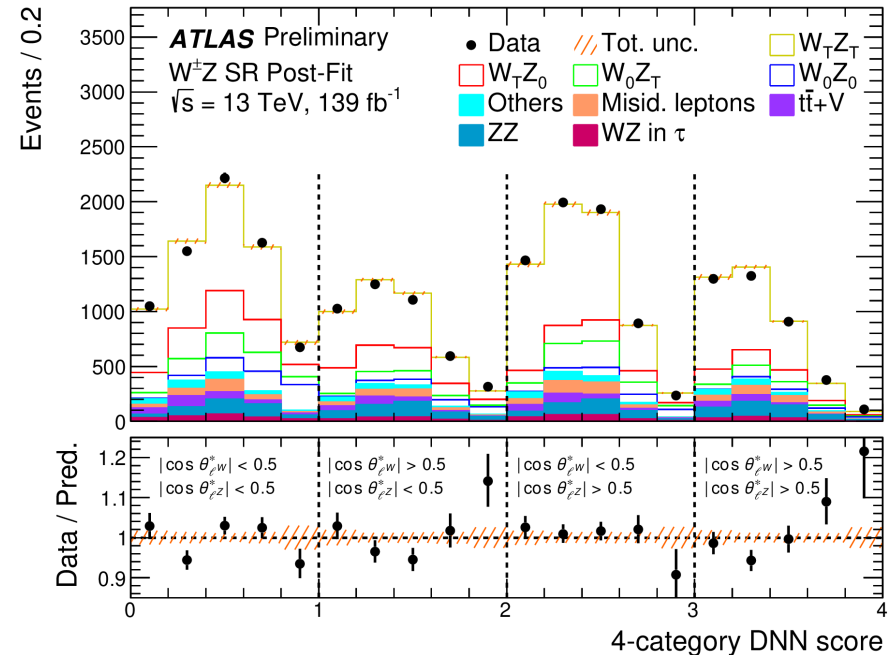
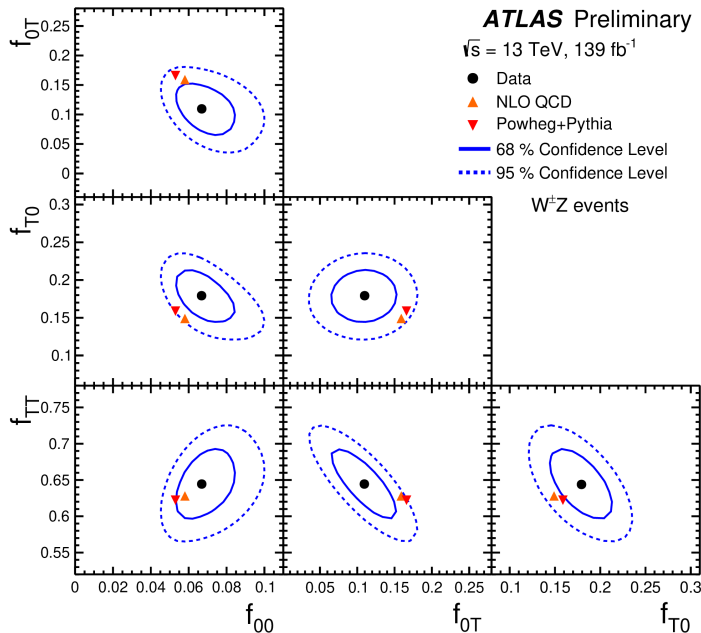
WZ – joint helicity states & longitudinal polarization

$$\begin{aligned}
 f_{00} &= \rho_{0000}, \\
 f_{TT} &= \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++}, \\
 f_{0T} &= \rho_{00--} + \rho_{00++}, \\
 f_{T0} &= \rho_{--00} + \rho_{++00}.
 \end{aligned}$$



[ATLAS-CONF-2022-053](#)

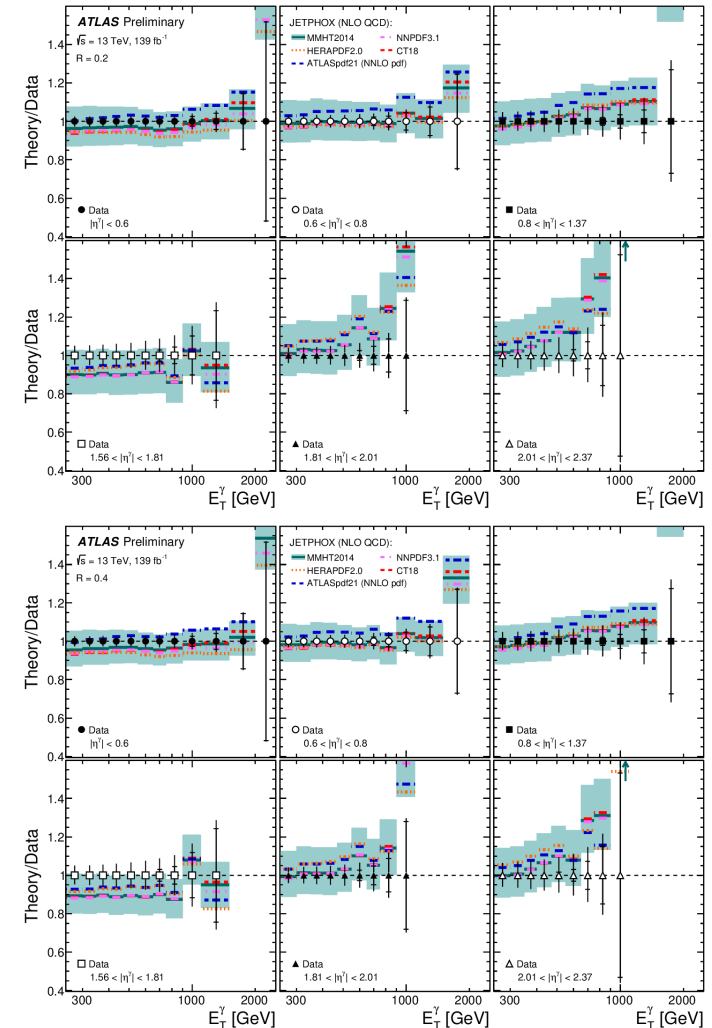
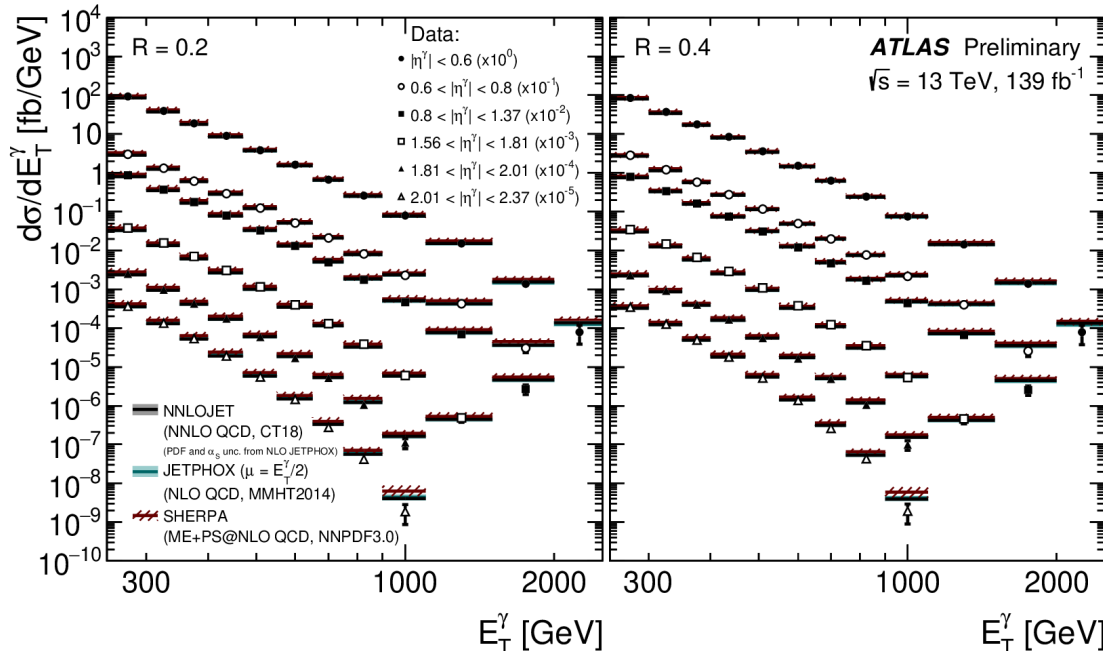
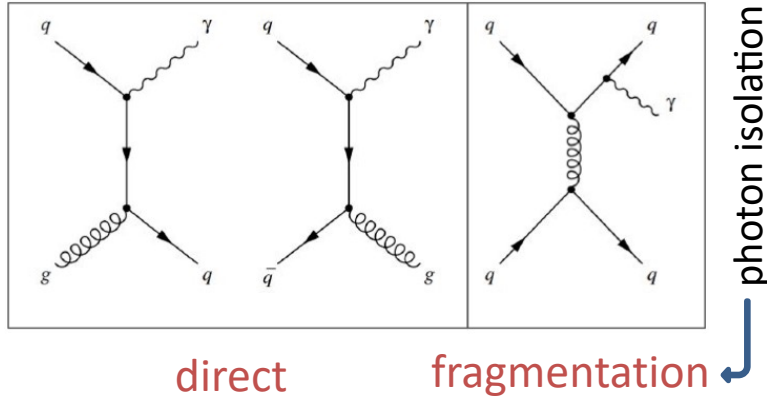
DNN trained to distinguish TT, mixed 0T and T0, and 00 helicity states



Data – theory comparison of inclusive hard γ

[ATLAS-CONF-2022-065](#)

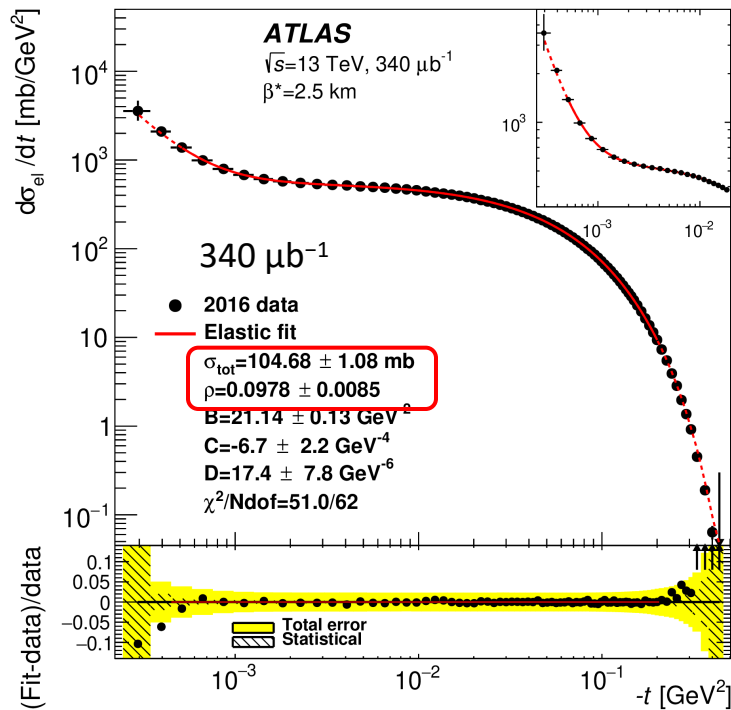
Data compared to: NLO QCD **JETPHOX** and **SHERPA** and NNLO QCD predictions from **NNLOJET** and various PDF sets



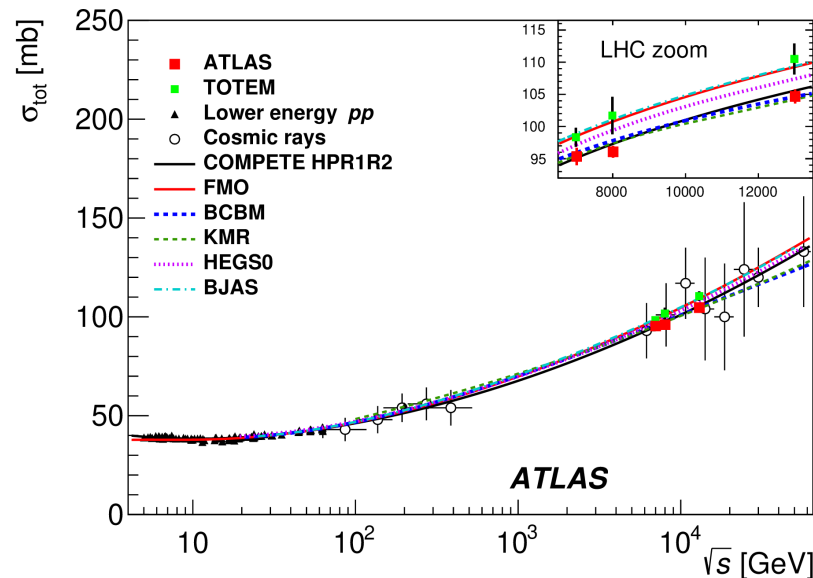
Elastic p-p scattering and total cross section

Fundamental physics using Absolute Luminosity For ATLAS :

- Thanks to the acceptance of ALFA and $\beta^*=2.5$ km, the kinematical reach goes down as low as $-t = 2.5 \times 10^{-4} \text{ GeV}^2$ allowing for extraction of $f_{\text{el}}(t)$ & $\rho = \text{Re}(f_{\text{el}}(t))/\text{Im}(f_{\text{el}}(t))$ thanks to CNI.
- The total cross section is then obtained owing to the optical theorem ($\sim \text{Im}(f_{\text{el}}(0))$)



[arXiv:2207.12246](https://arxiv.org/abs/2207.12246)



Please, see (tomorrow afternoon) the poster by **dr Rafał Staszewski** for further details on this interesting new measurement!

Pb-Pb: The photon collider $\gamma\gamma \rightarrow \tau\tau$ candidate

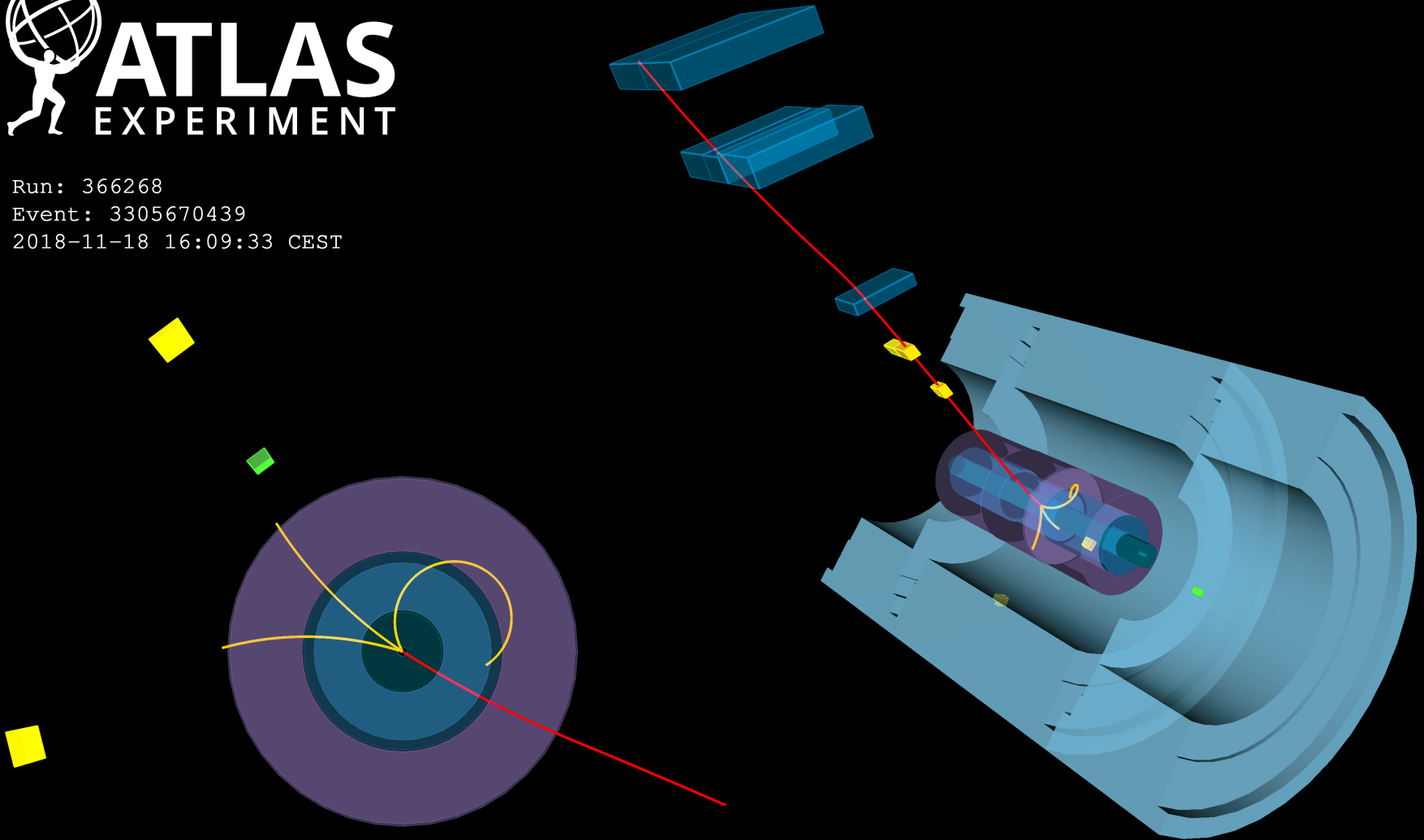


ATLAS
EXPERIMENT

Run: 366268

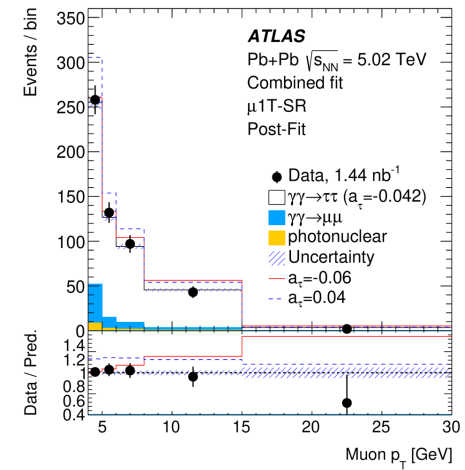
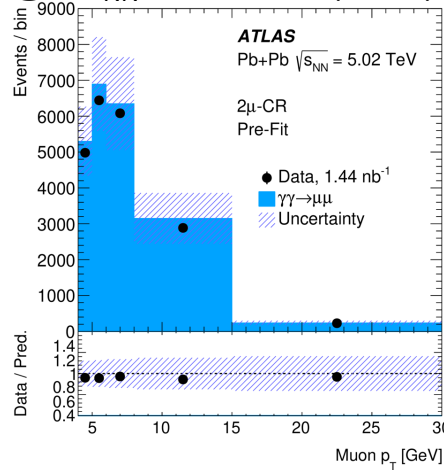
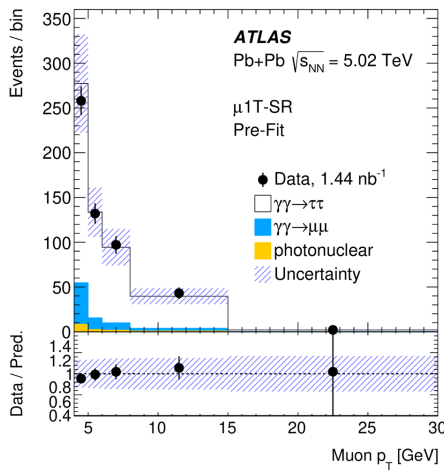
Event: 3305670439

2018-11-18 16:09:33 CEST



Pb-Pb: $\gamma\gamma \rightarrow \tau\tau$ and τ -lepton magnetic moment

1.44 nb⁻¹ Pb+Pb collisions @ $\sqrt{s_{NN}}=5.02$ TeV (2018)



$a_l = 1/2 (g_l - 2)$ of charged leptons (electrons, muons, and τ -leptons) - cornerstone tests of the SM:

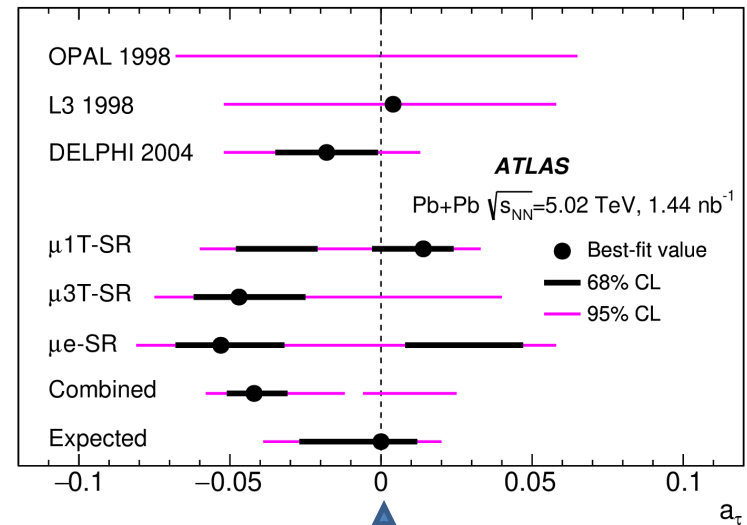
$$a_{SM} = 0.001\,177\,21\,(5)$$

Dedicated reconstruction of low p_T hadronic τ 's
PL fit to three SR's and $\mu\mu$ CR => reduction of main systematics (photon flux, lumi, etc.)

$$\mu_{\tau\tau} = 1.04 \pm 0.05 \text{ (stat)} \pm 0.03 \text{ (syst)}$$

Constraints on the anomalous a_τ

STDM-2019-19



~~SUMMARY~~

THANK YOU

J^{CP} of the 125 GeV Higgs

ATLAS J^{CP}:

Eur. Phys. J. C75 (2015) 476

CMS J^{CP}:

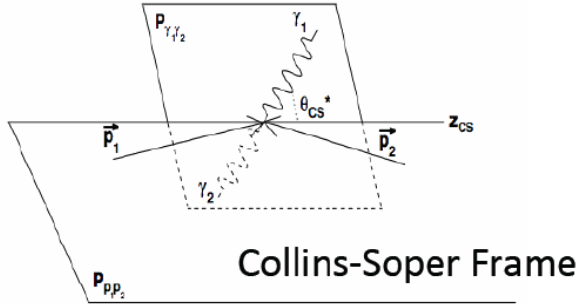
Phys. Rev. D 92, 012004

Testing for alternative J^{CP} scenarios using decay kinematics.

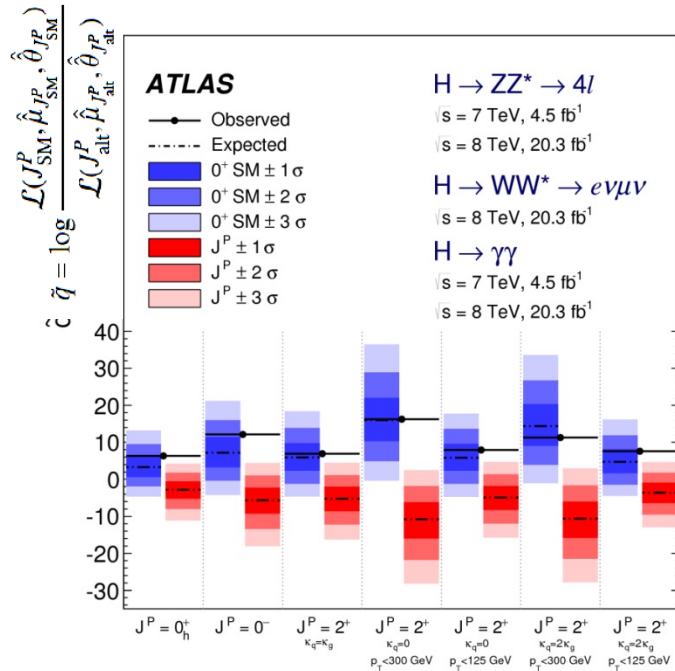
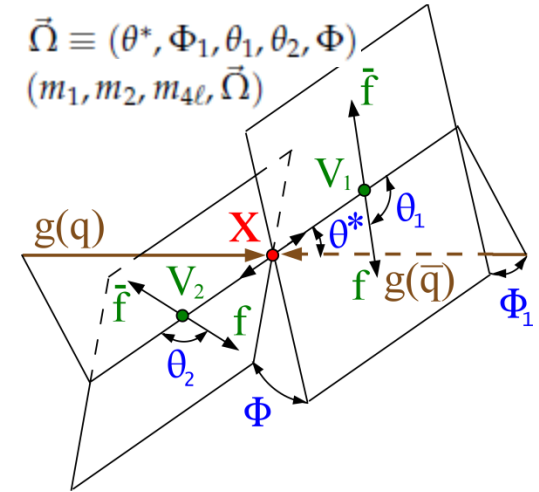
ZZ: full kinematics available

WW: $m^{\ell\ell}$, $p_T^{\ell\ell}$, $\Delta\phi^{\ell\ell}$ and m_T

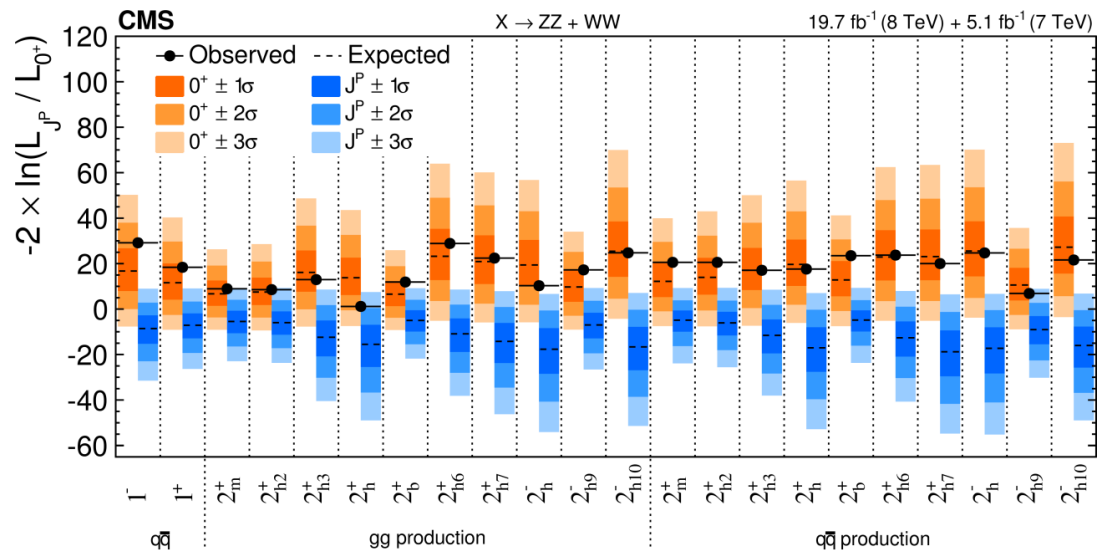
$\gamma\gamma$: $\cos(\Theta_{CS}^*)$, $p_T^{\gamma\gamma}$



Note: Landau-Yang theorem precludes J=1 hypothesis in the presence of H→γγ



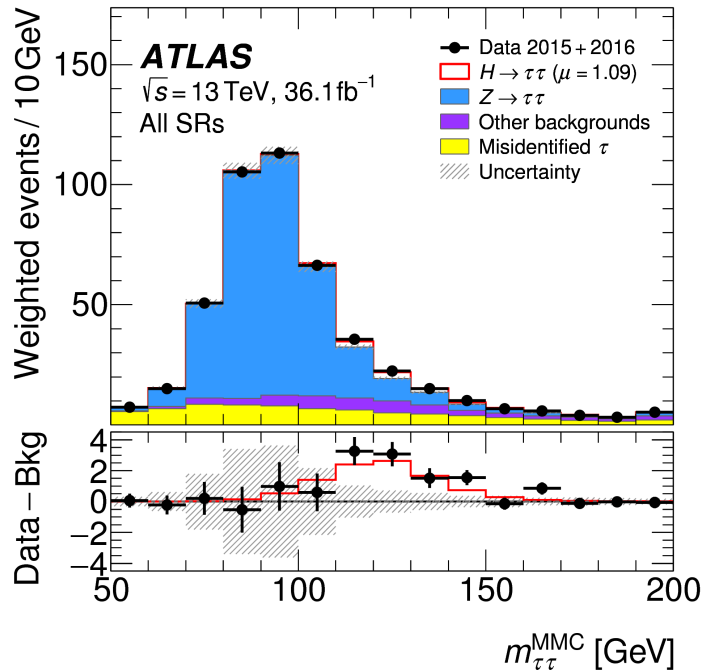
Exclusions @ 99% CL or better



2018

Run 2 (36 fb⁻¹) H → ττ

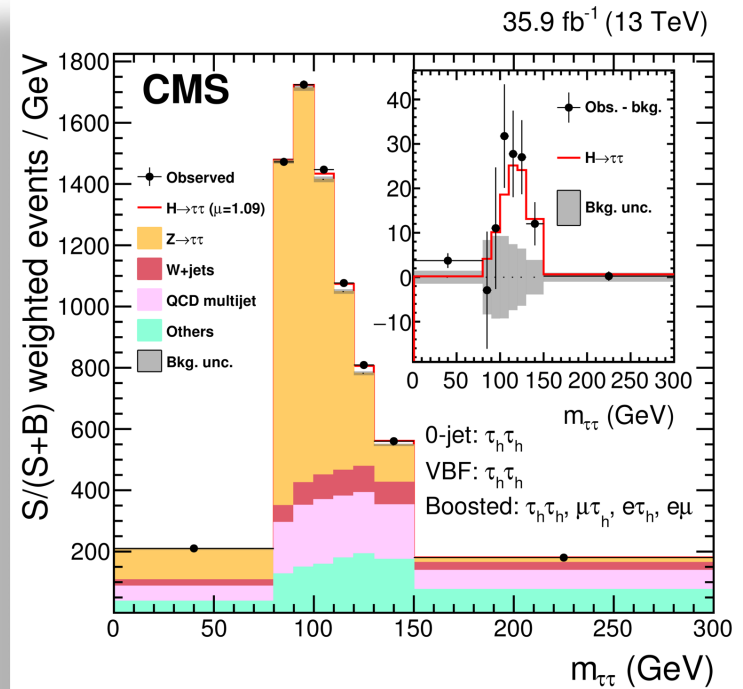
ATLAS Phys. Rev. D 99 (2019) 072001



MMC: Nucl. Instrum. Meth. A 654 (2011) 481

Signal strength: $\mu = 1.09 + 0.35 - 0.30$
 Significance: $S = 4.4 (4.1 \text{ exp.}) \sigma$
 ⊕ Run 1:
 Significance: $S = 6.4 (5.4 \text{ exp.}) \sigma$

CMS Phys. Lett. B 779 (2018) 283



SVFIT: J. Phys.: Conf. Ser. 513 022035

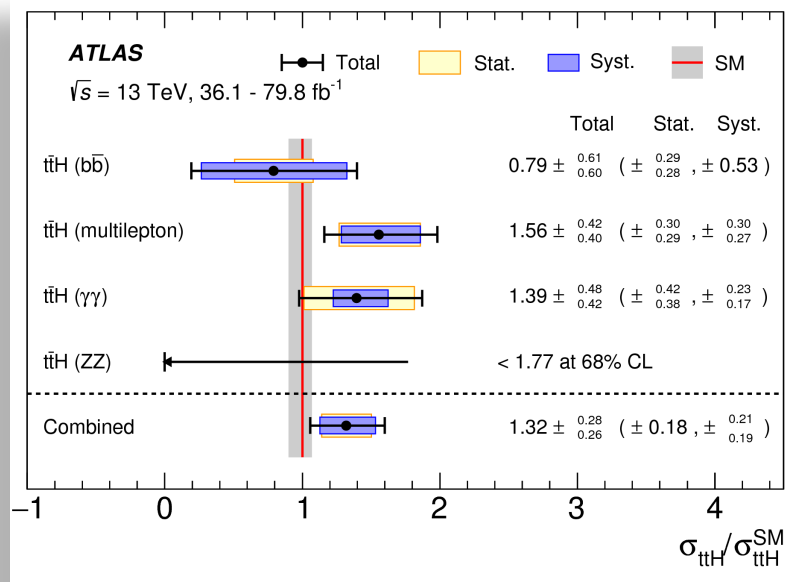
Signal strength: $\mu = 1.09 + 0.27 - 0.26$
 Significance: $S = 4.9 (4.7 \text{ exp.}) \sigma$
 ⊕ Run 1:
 Significance: $S = 5.9 (5.9 \text{ exp.}) \sigma$

Clear observation!

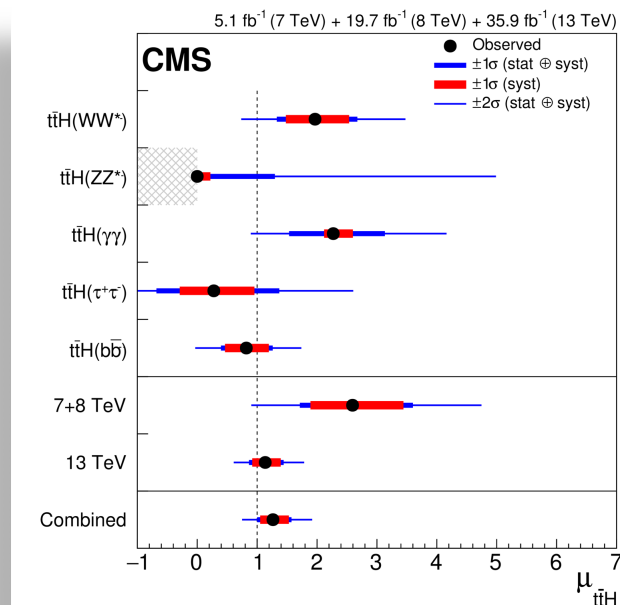
2018

Run 2 $t\bar{t}H$

ATLAS Phys. Lett. B 784 (2018) 173



CMS PRL 120 (2018) 231801

Higgs decays to WW^* , ZZ^* , $\gamma\gamma$, $\tau\tau$, $b\bar{b}$ consideredMultiple categories. Final ML fit to bins in $\log_{10}(S/B)$ Signal strength: $\mu = 1.32 + 0.28 - 0.26$ Significance: $S = 5.8(4.9 \text{ exp.})\sigma$ $\oplus$ Run 1:Significance: $S = 6.3(5.1 \text{ exp.})\sigma$ Signal strength: $\mu = 1.23 + 0.45 - 0.43$ Significance: $S = 3.2(2.8 \text{ exp.})\sigma$ $\oplus$ Run 1:Significance: $S = 5.2(4.2 \text{ exp.})\sigma$

Observation! At last 😊

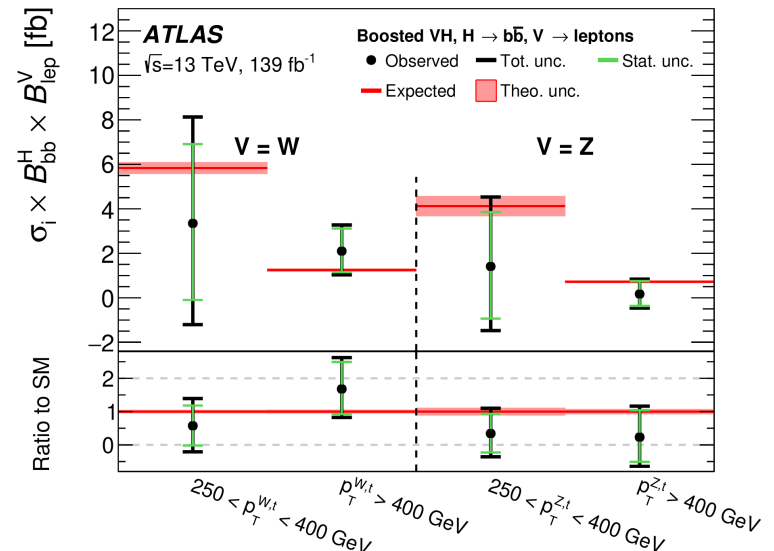
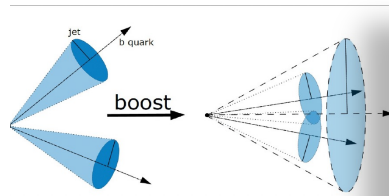
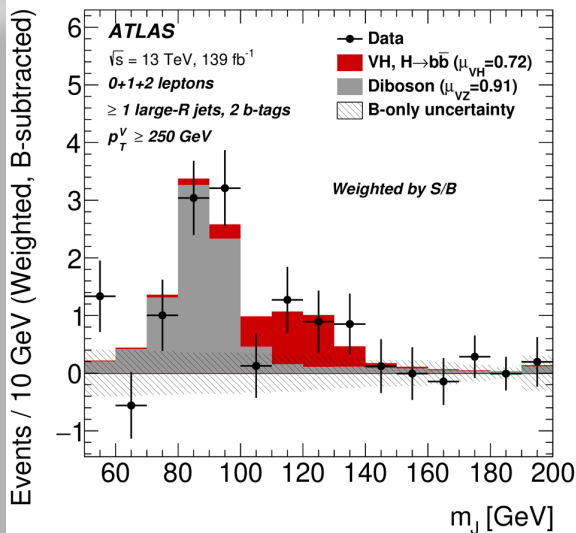
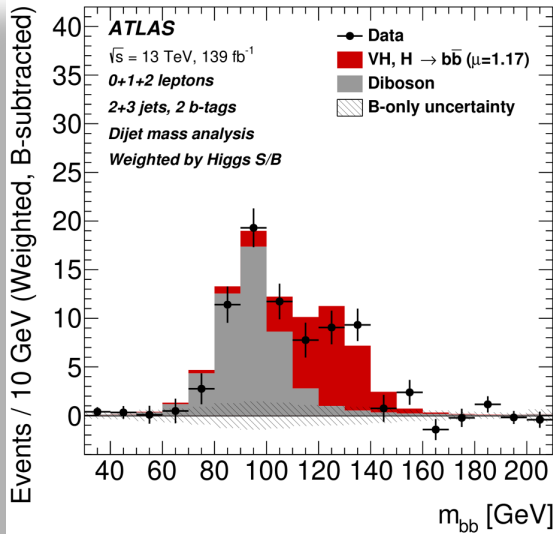
2020

Run 2 (139 fb⁻¹) VH, H→bb

ATLAS Resolved VH→bb arXiv:2007.02873 (2020)
 Boosted VH→bb arXiv:2008.02508 (2020)

Signal strength: $\mu = 1.02 \pm 0.12 \pm 0.14$
 Significance: $S = 6.7(6.7 \text{ exp.})\sigma$
 Significance (ZH): $S = 5.3(5.1 \text{ exp.})\sigma$

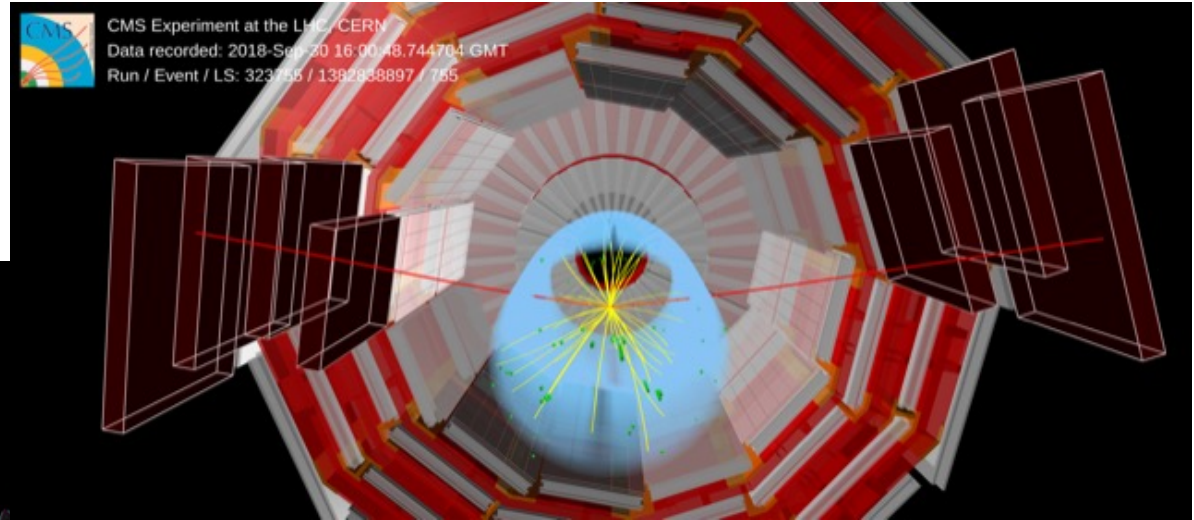
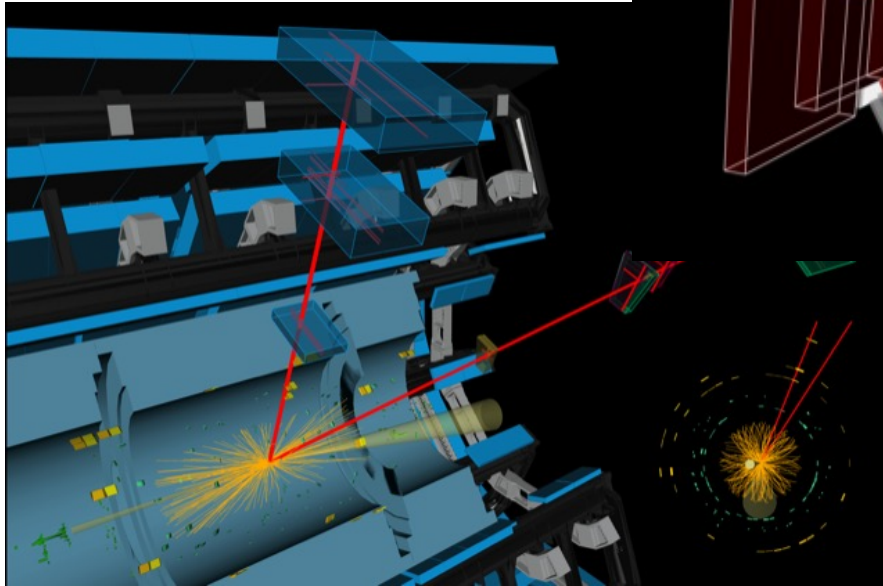
All backgrounds except VZ subtracted



Boosted analysis: measurement at high p_T - increased sensitivity to BSM physics

2020 Observation of $H \rightarrow \mu^+ \mu^-$ (ICHEP2020)

ATLAS: VBF candidate



CMS: ggH 0-jets candidate

Run 2 (139 fb⁻¹)

ATLAS: [Phys. Lett. B 812 \(2021\) 135980](#)

CMS: [JHEP 01 \(2021\) 148](#)

2020

SM Yields & Signal Resolution

ATLAS

$m_{\mu\mu} \in 120\text{--}130\text{ GeV}$:

- VBF: 18.6 / 369
- ggF: 843.0 / 441185
- VH: 4.7 / 412
- ttH: 1.2 / 15

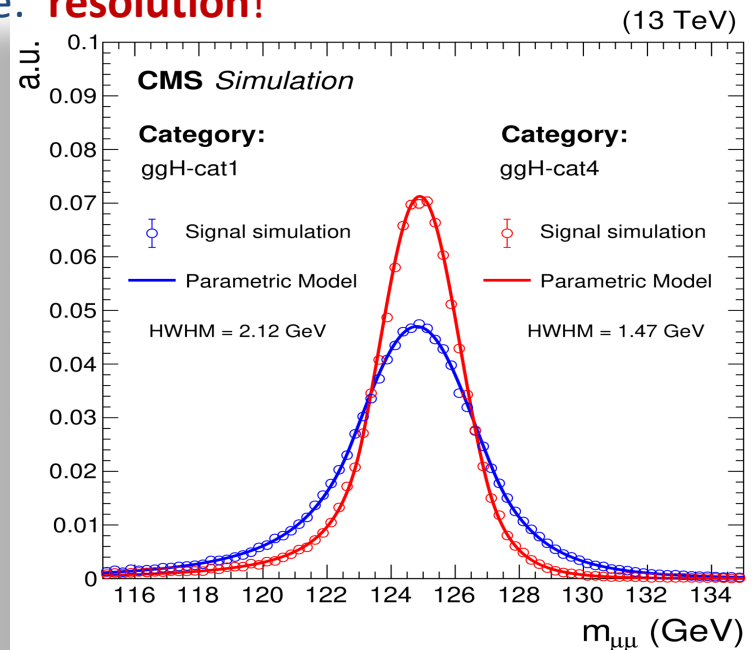
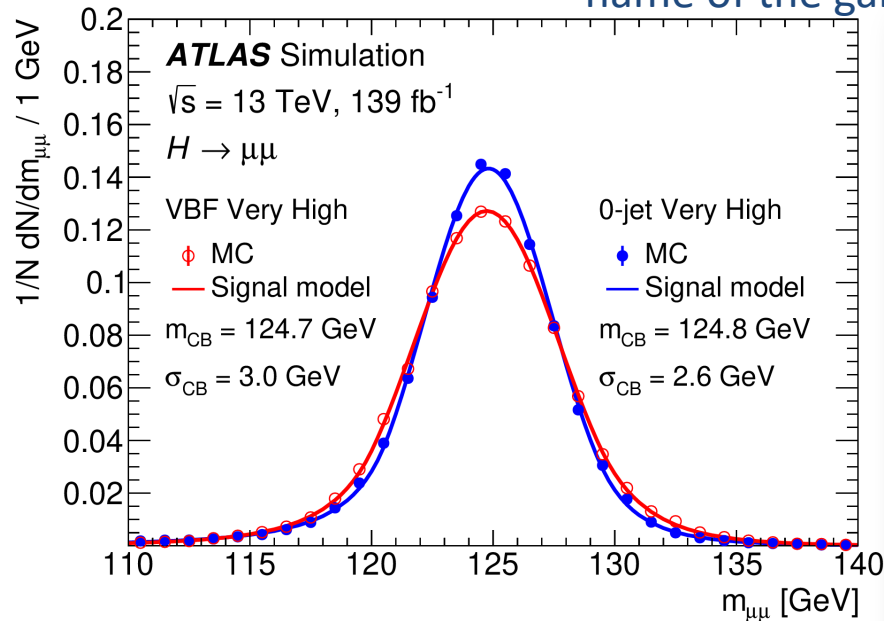
(~52% overall efficiency)

CMS

$m_{\mu\mu} \in 115\text{--}135\text{ GeV}$:

- VBF: 48.0 / 9420 (28.5/530)
- $m_{\mu\mu} \in 125.38\text{ GeV} \pm \text{HWHM}$:
- ggF: 890.8 / 155310
 - VH: 4.1 / 65
 - ttH: 11.9 / 4403 (2.0/11)
- (~58% overall efficiency)

name of the game: **resolution!**



2020

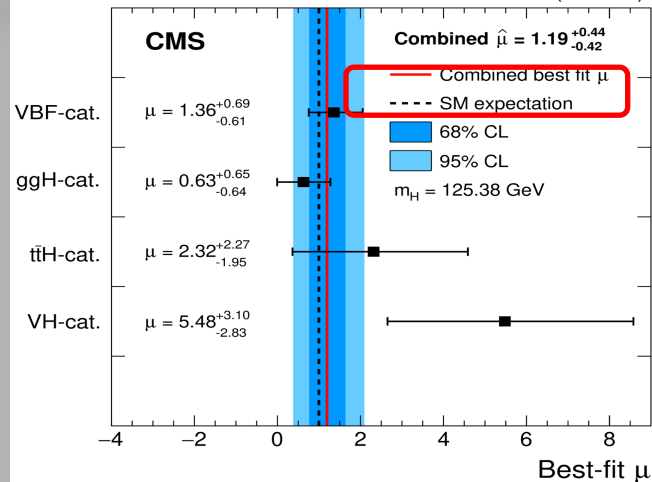
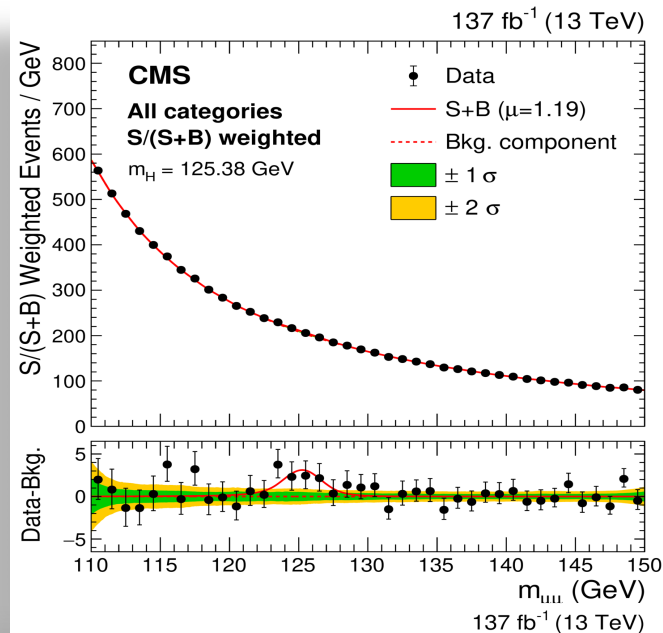
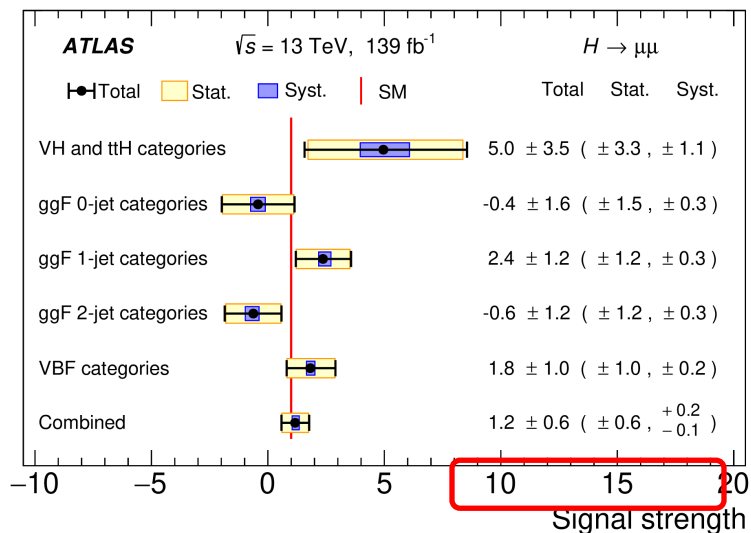
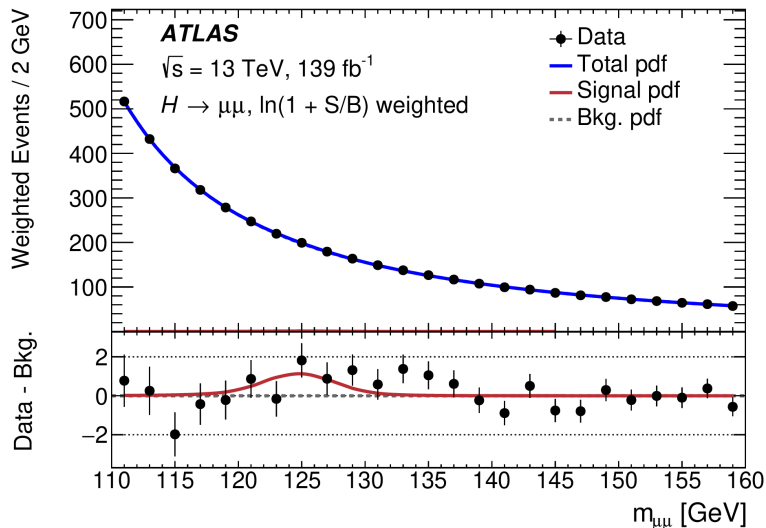
ATLAS

Results

CMS

Obs. (exp.) significance: $S=2.0\sigma$ (1.7σ)

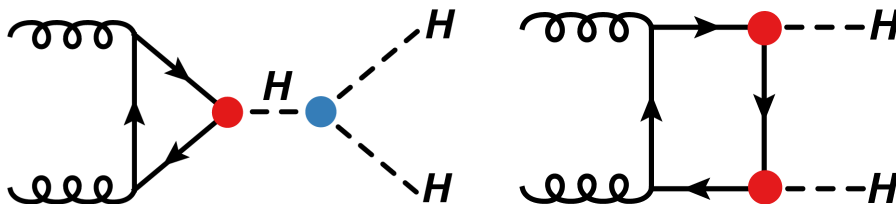
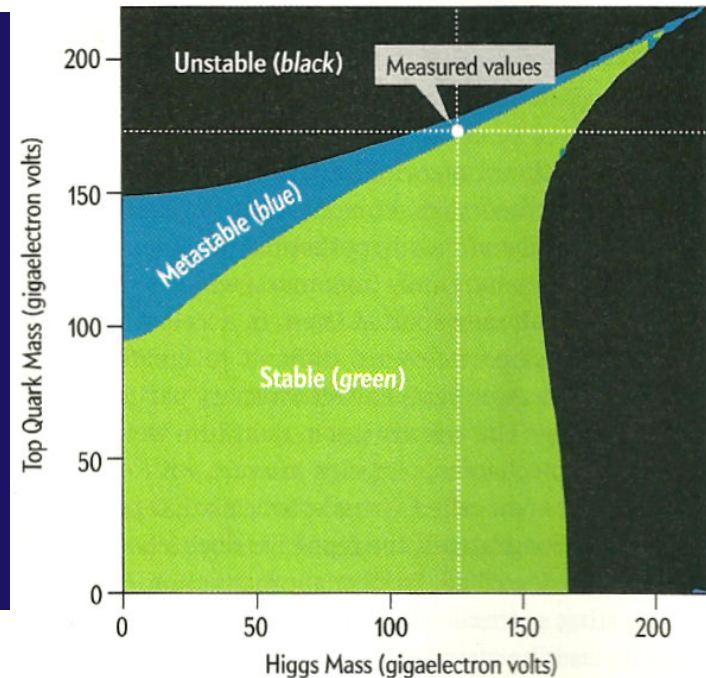
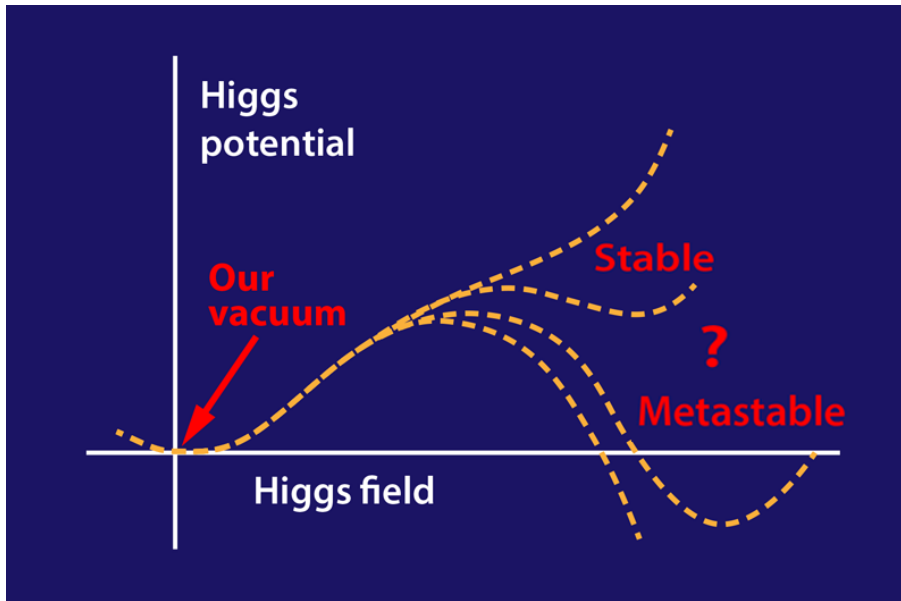
Obs. (exp.) significance: $S=2.95\sigma$ (2.46σ)



What is out fate?

Higgs potential and self-couplings

The confirmed BEH mechanism depends barely on the local expansion of the Higgs potential



Higgs self-interaction probed e.g. via the di-Higgs production (0.1% of $pp \rightarrow H$ x-section).

Currently not observable, unless New Physics contributes!

LHC: the top factory

275 million top quarks produced in 140 fb^{-1}



Nature Phys. 17 (2021) 813-818

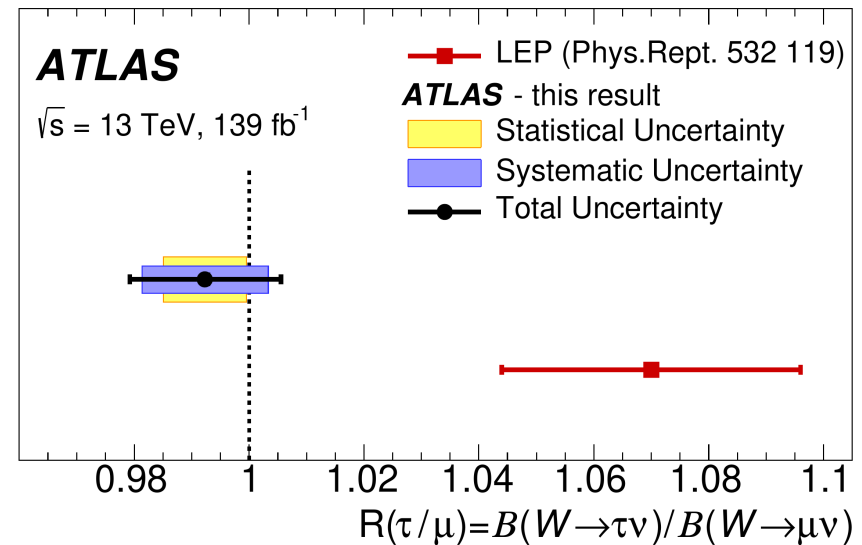
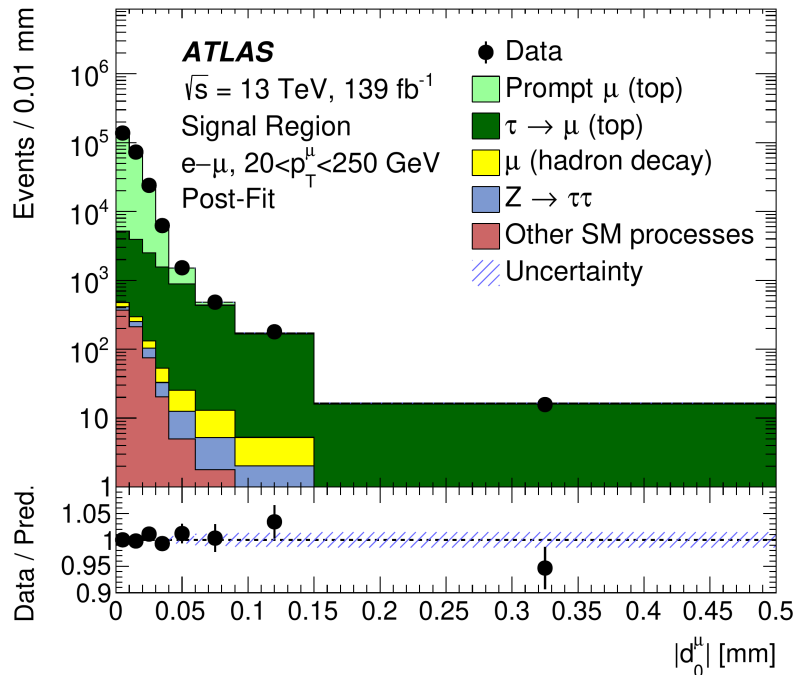
tt candidate event with one electron, one muon and two b-jets

LFU: any sign of “new physics”?

τ/μ

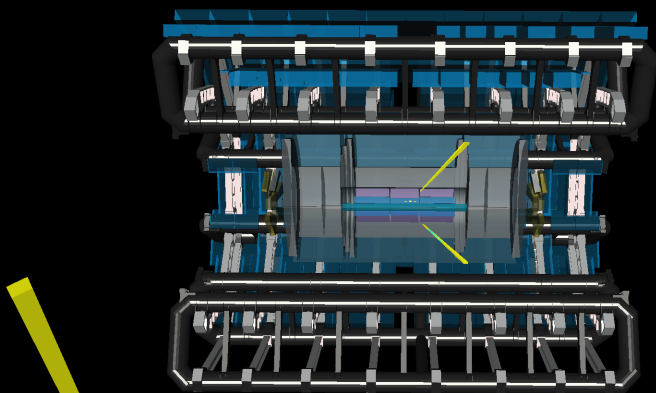
ATLAS NATURE Phys. 17 (2021) 813-818

- Use large $t\bar{t}$ sample as clean probe of W bosons (**di-leptonic decays, $\text{tag}(e,\mu)$ –*and-probe* (μ)**)
- Measure ratio of prompt ($W \rightarrow \mu\nu$) to softer, delayed muons from tau decays ($W \rightarrow \tau\nu \rightarrow \mu\nu\nu$)
- Also motivated by long-standing 2.7σ LEP deviation *Phys. Rep.* **532**, 119–244 (2013):
 $R = \text{BR}(W \rightarrow \tau\nu) / \text{BR}(W \rightarrow \mu\nu) = 1.070 \pm 0.026$



$$R = \text{BR}(W \rightarrow \tau\nu) / \text{BR}(W \rightarrow \mu\nu) = \mathbf{0.992 \pm 0.013}$$

The photon collider $\gamma\gamma \rightarrow \gamma\gamma$ candidate



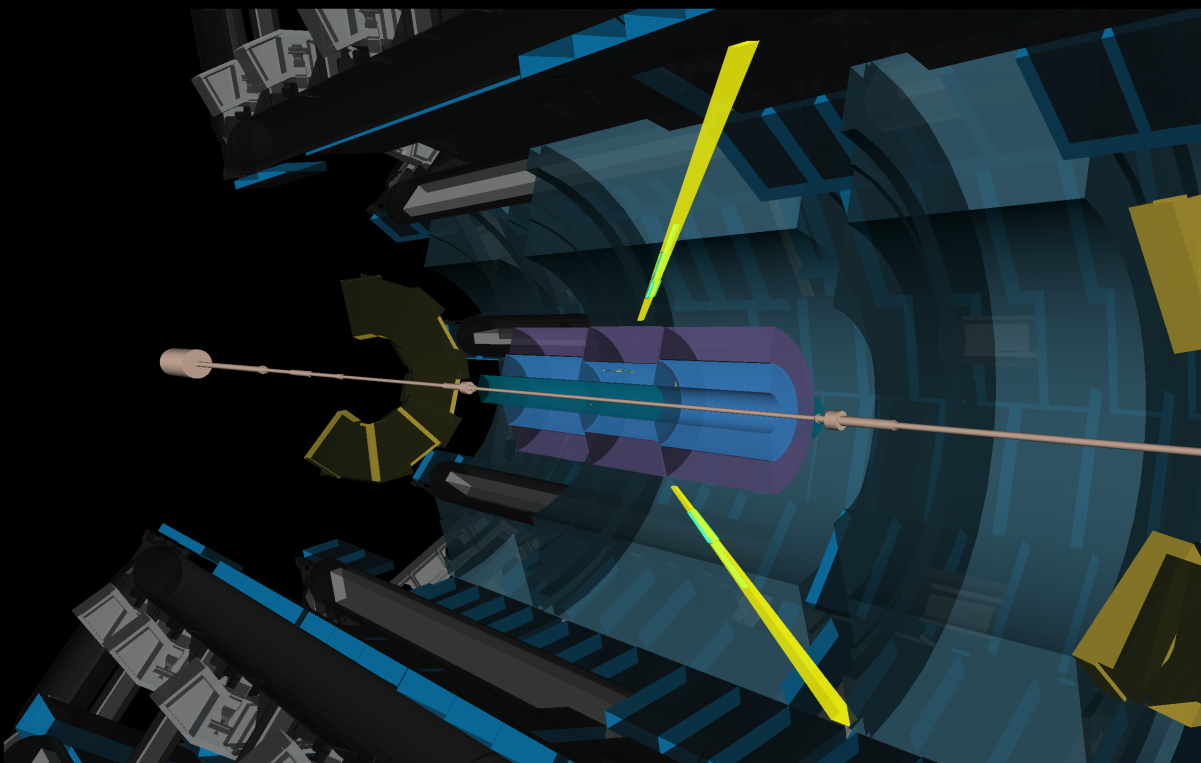
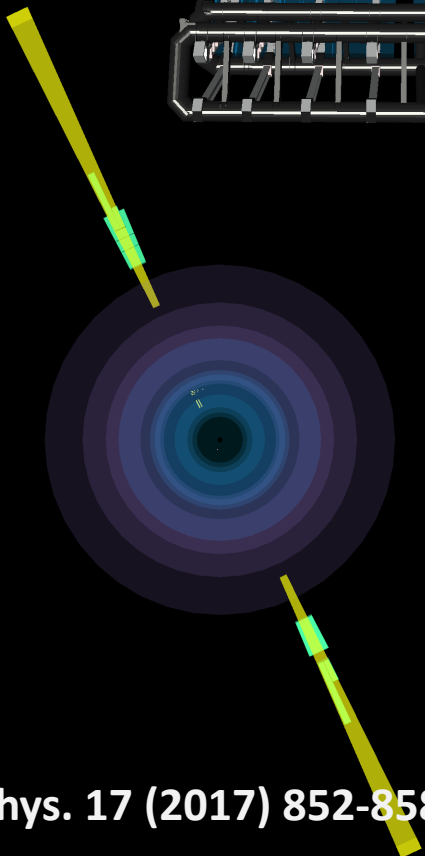
ATLAS
EXPERIMENT

Pb+Pb

Run: 287931

Event: 461251458

2015-12-13 09:51:07 CEST

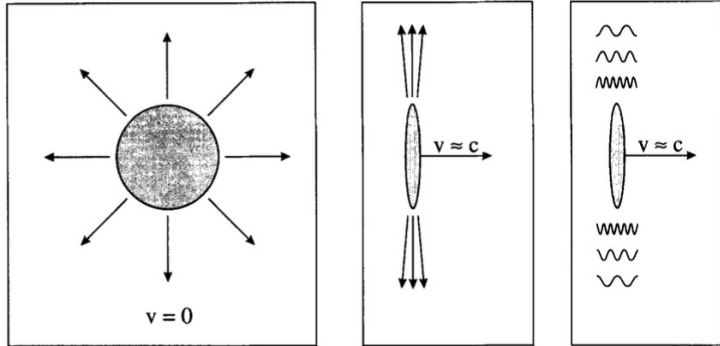


Nature Phys. 17 (2017) 852-858

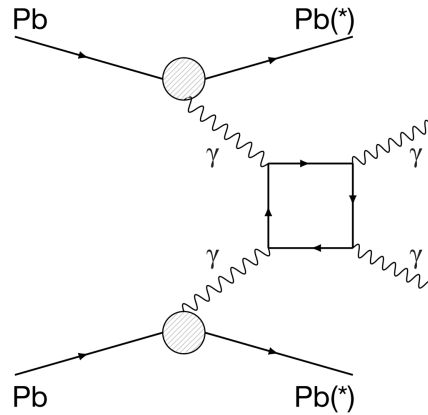
The photon collider

ATLAS JHEP 03 (2021) 243

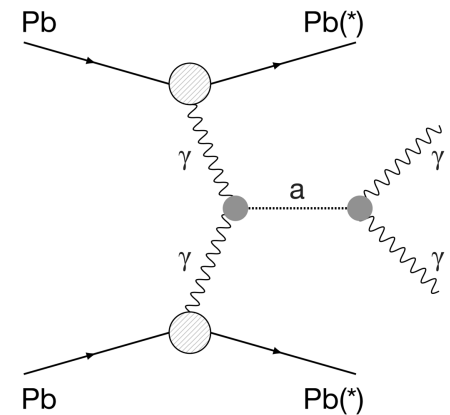
Quasi-real photon flux



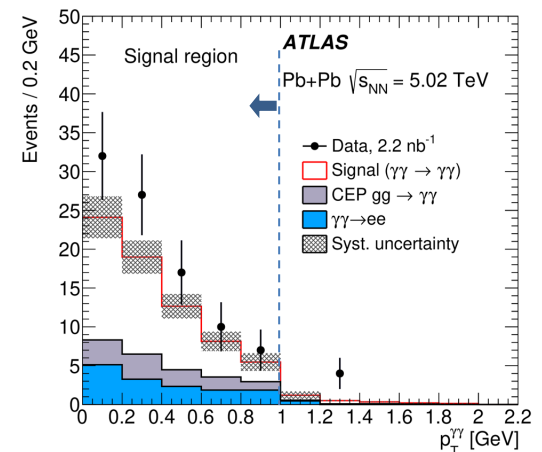
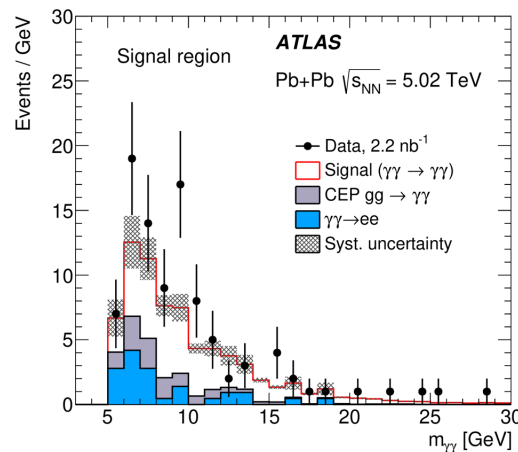
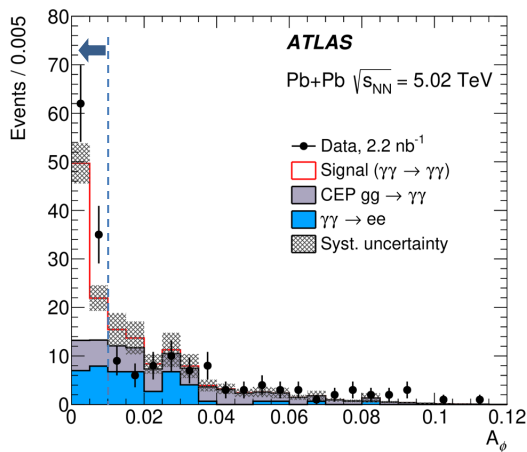
Quantum nature of EM



Probe BSM effects



$m_{\gamma\gamma} > 5 \text{ GeV}$, $p_T^{\gamma\gamma} < 1(2) \text{ GeV}$, no tracking activity, no activity in the forward region



$$\sigma_{\text{fid}} = 120 \pm 17 \text{ (stat.)} \pm 13 \text{ (syst.)} \pm 4 \text{ (lumi.) nb} \Rightarrow \text{(within } 2\sigma \text{ from SM predictions)}$$