Luminosity measurements and heavy Higgs searches in decays of ZH and HH with the ATLAS detector

EPC seminar, CAS/IHEP

Xiaohu SUN（孙小虎）

2018-04-12

Contents

1. The introduction to the collider and the detector
2. The luminosity measurement
3. The BSM heavy Higgs searches with ZH and HH

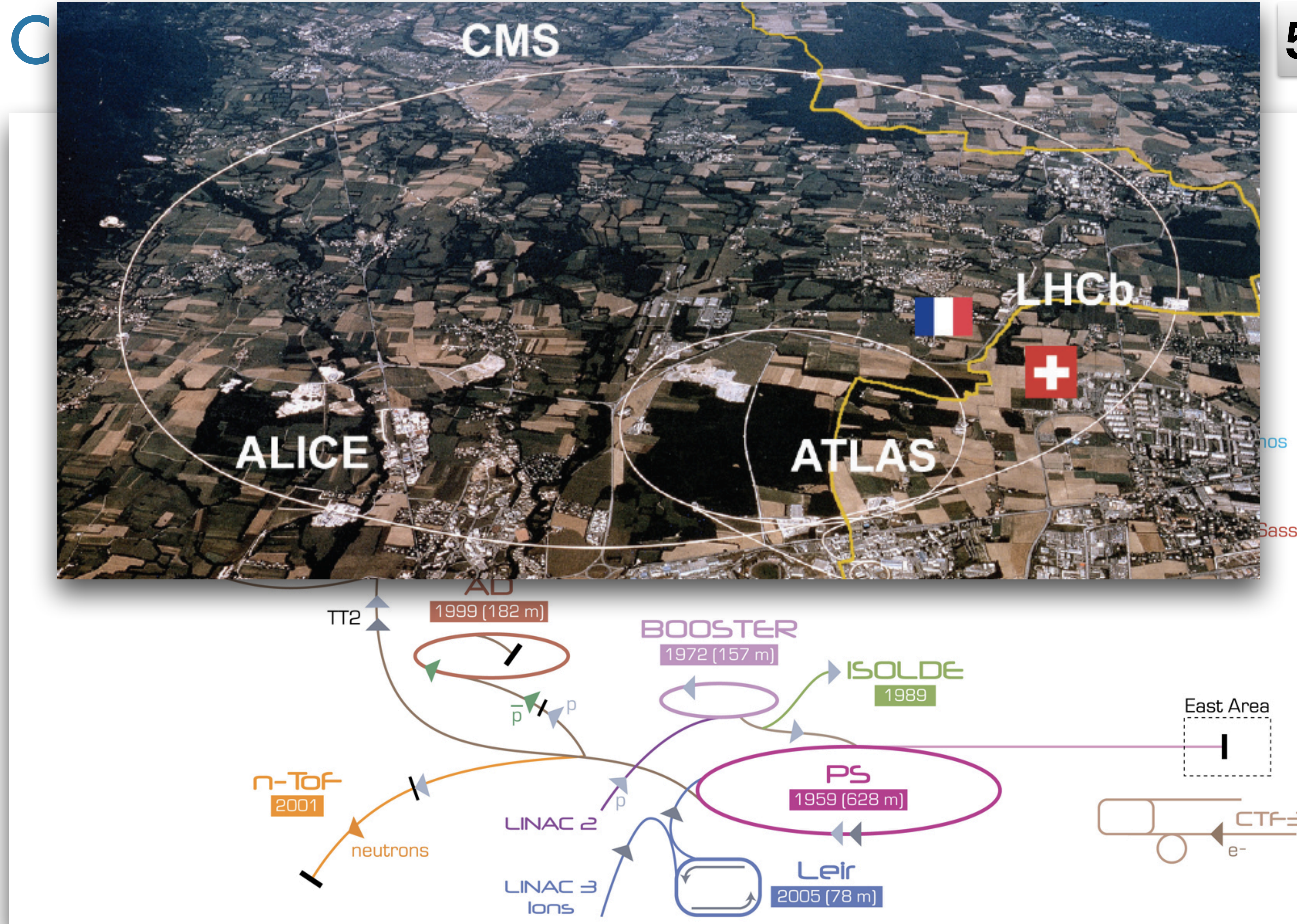
The topics in this talk contain my major activities in the last few years working with the talented ATLAS folks on the fantastic detector

1. Introduction

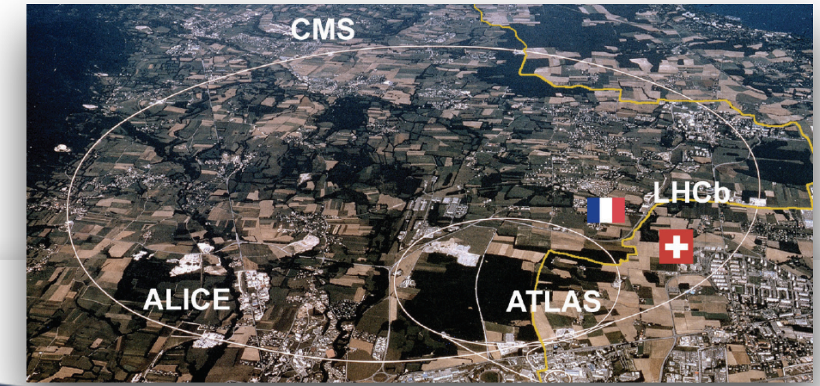
Introduction

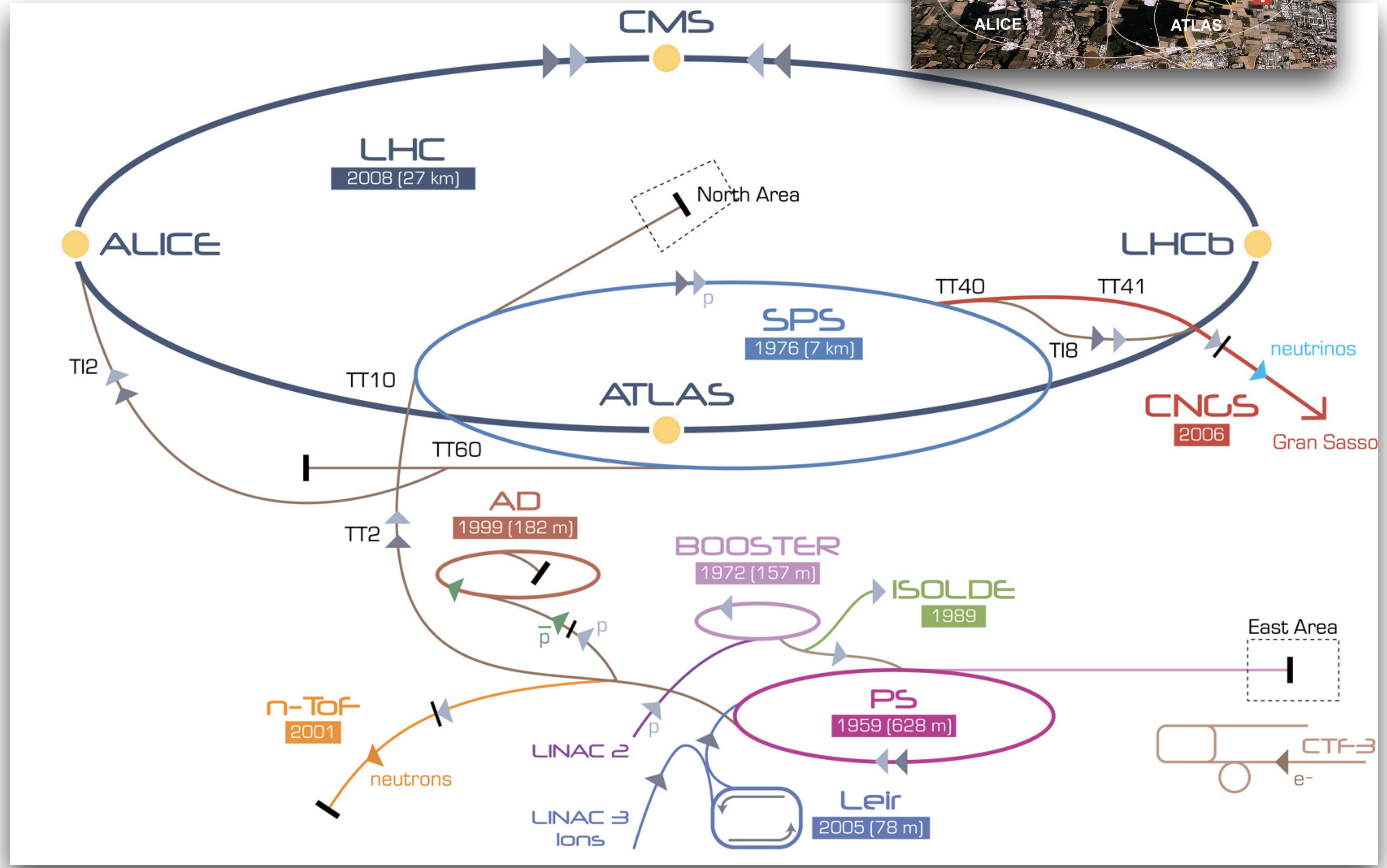
- The goals of the Large Hadron Collider (LHC):
  - Rediscover the Standard Model (SM)
  - Search for the missing SM element, the Higgs bosons
  - Search beyond the SM (BSM) for new fundamental interactions, new generations of quarks or leptons, new heavy or light bosons etc.
  - Discover direct evidence for the particle responsible for the dark matter in the Universe (SUSY?)
- We discovered one Higgs boson that looks like the SM one, but is that all?
  - Any additional BSM Higgs boson in an extended sector?

C


CMS
LHCb
ALICE
ATLAS
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
p̄
p
n-ToF
2001
neutrons
LINAC 2
p
PS
1959 (628 m)
CTF-3
e−
LINAC 3
Ions
Leir
2005 (78 m)

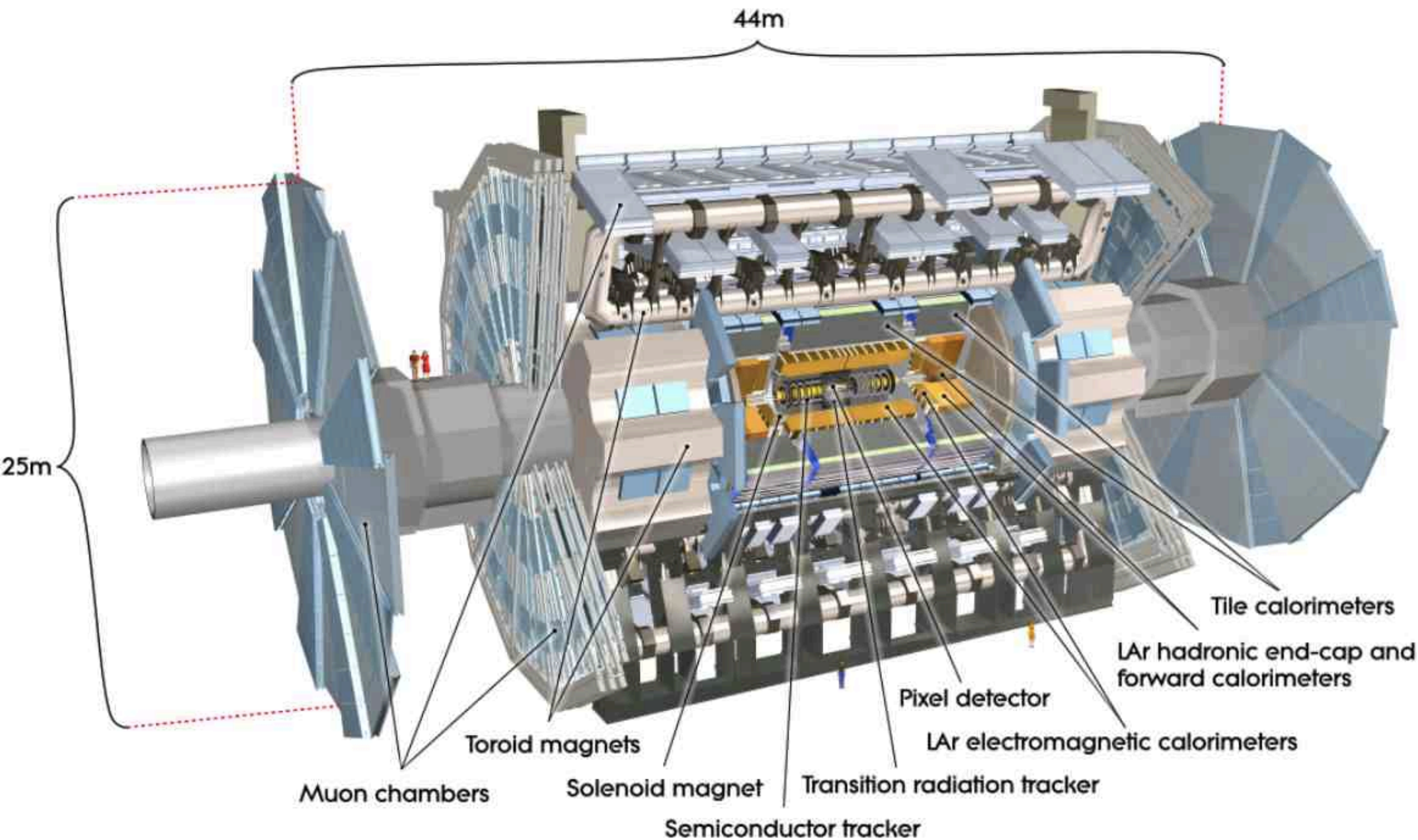
CERN accelerator complex



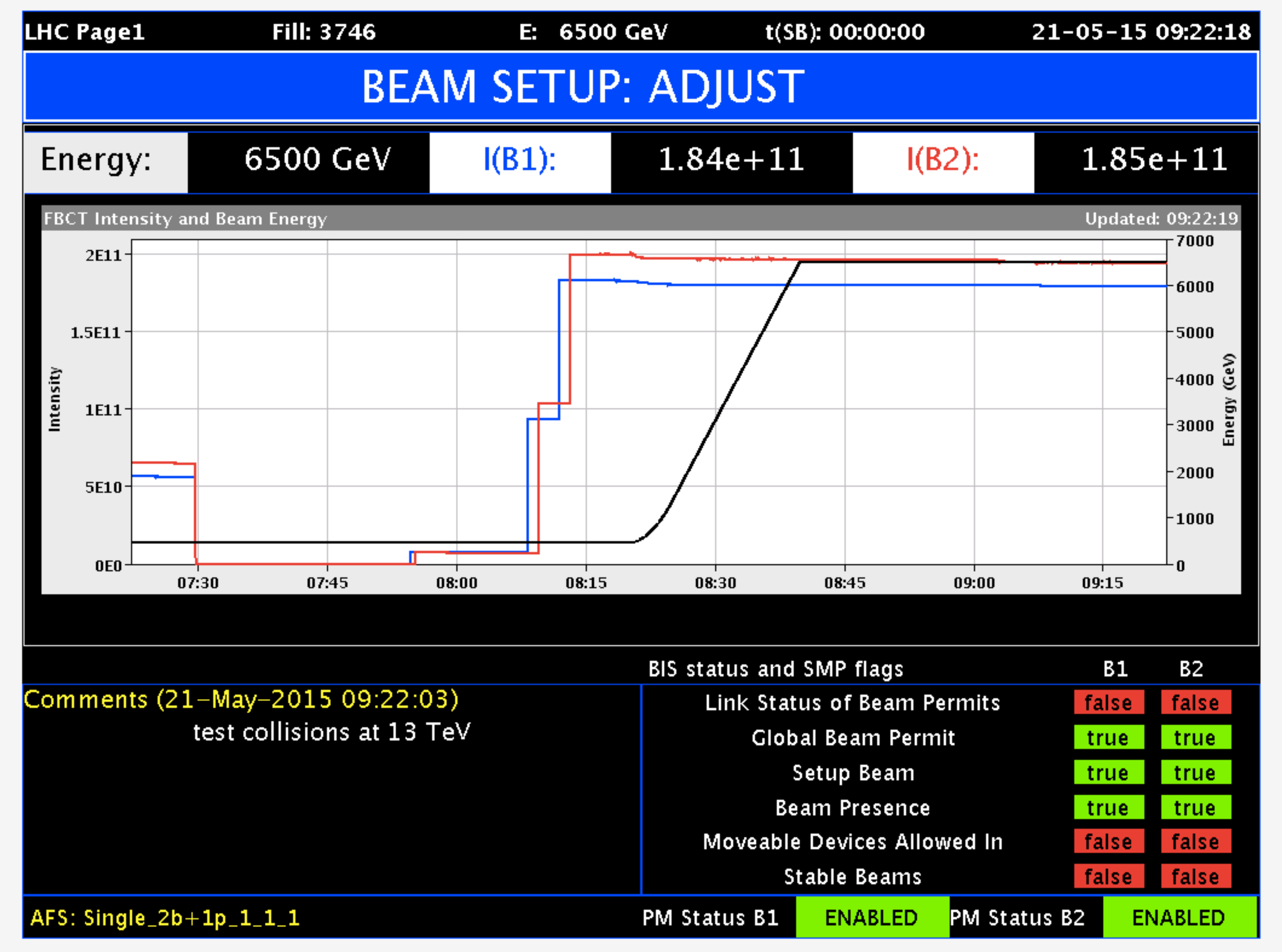


http://atominfo.cz/2014/06/cern-uz-ma-podrobny-plan-znovuspusteni-lhc/

The ATLAS detector



The first image of collisions at 13 TeV



2. The luminosity measurement

Introduction to luminosity measurements

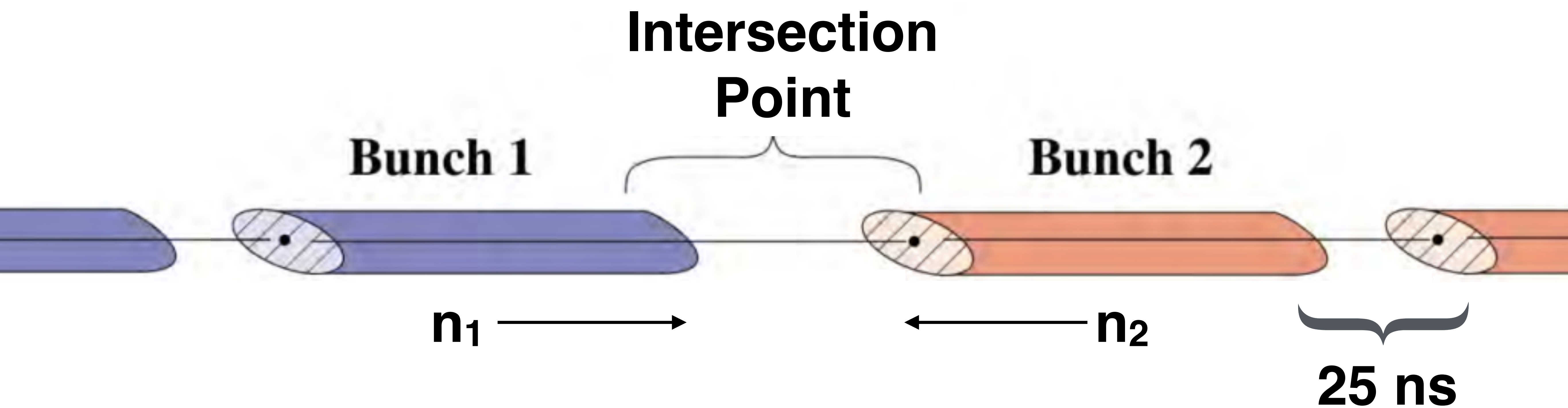
- Any search on any collider cannot be possible if the number of events ($L \times \sigma$) is not statistically sufficient
  - Centre-of-mass energy decides σ
  - Luminosity decides *L*
- An accurate measurement of the delivered luminosity is crucial to physics programs
- When doing physics analyses
  - need *L* to calculate *N* .... $$N = L \times \sigma$$
- When doing luminosity measurement
  - need *N* to calculate *L* .... $$L = \frac{N}{\sigma}$$

arXiv:1802.04146

The combined signal strength in Hγγ

Uncertainty Group	$\sigma_{\mu}^{\text{syst.}}$
Theory (QCD)	0.041
Theory ($B(H \to \gamma\gamma)$)	0.028
Theory (PDF+α_S)	0.021
Theory (UE/PS)	0.026
Luminosity	0.031
Experimental (yield)	0.017
Experimental (migrations)	0.015
Mass resolution	0.029
Mass scale	0.006
Background shape	0.027

pp collisions at the LHC



- Collide proton-proton, NOT fundamental particles
  - Not possible to calculate luminosity only from machine parameters, essentially different than ee colliders
- Collide bunch (**b**) of protons with a population n_1 and n_2 (**bunch crossing**)
- Collide trains of bunches every 25 ns
- Other features not shown: crossing angle, squeeze of bunches etc.

The methodology

$$L = \frac{N}{\sigma} \quad \rightarrow \quad \mathcal{L}_{\mathrm{b}} = \frac{\mu_{\mathrm{vis}} f_{\mathrm{r}}}{\sigma_{\mathrm{vis}}}$$

L_b, luminosity per **bunch crossing**

μ_{vis}, average # of visible inelastic interactions per **bunch crossing**

f_r, LHC revolution frequency

σ_{vis}, visible cross section

The methodology

1. μ_{vis}, obtained from **relative** luminosity measurements during physics runs during the data taking year

$$\mathcal{L}_{\mathrm{b}} = \frac{\mu_{\mathrm{vis}} f_{\mathrm{r}}}{\sigma_{\mathrm{vis}}}$$

2. σ_{vis}, obtained from **absolute** luminosity measurements during special runs with vdM scans 2-3 times per year

μ_{vis} at the peak in vdM scan, μ_{vis}^{MAX}
convolved beam size, $\Sigma_{x,y}$
bunch-population product, $n_1 n_2$

$$\sigma_{\mathrm{vis}} = \mu_{\mathrm{vis}}^{\mathrm{MAX}} \frac{2\pi \, \Sigma_x \Sigma_y}{n_1 n_2}$$

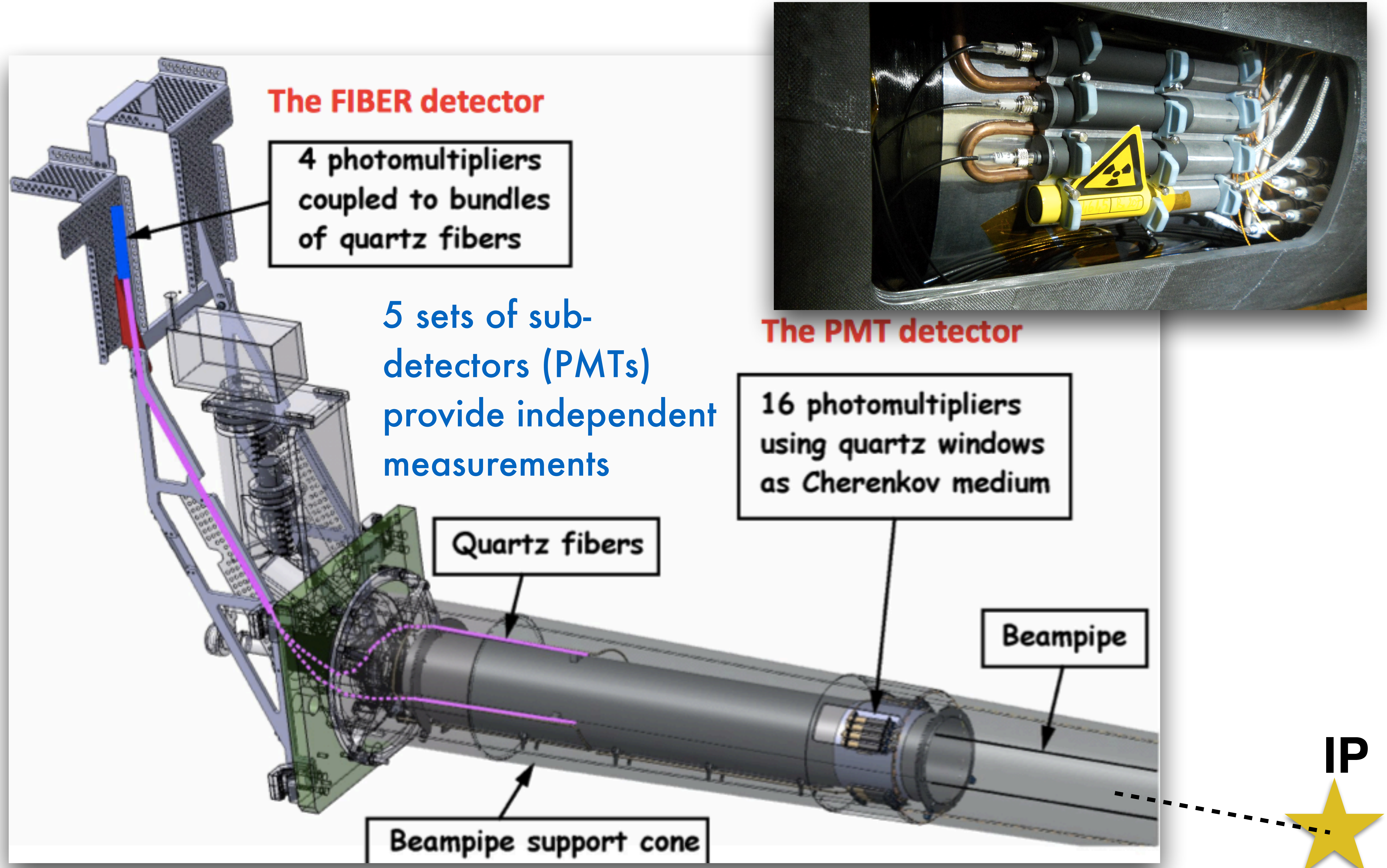
1 The relative measurements (μ_{vis})

- Measure μ_{vis} with a system that counts events/hits/charge proportional to the luminosity (LUCID, BCM, EMEC, TILE etc.)
- Provide relative instantaneous luminosity changes for a long term
- Various algorithms to convert the counting to μ_{vis} measurements (OR AND etc.), using OR as an example here:
  - N_{OR} is the number of at least one count happening; N_{BC} is the number of bunch crossing; $N_{OR} \leq N_{BC}$
  - Assume the number of inelastic interaction follow Poisson distribution

$$P_{\text{EventOR}}(\mu_{\text{vis}}^{\text{OR}}) = N_{\text{OR}}/N_{\text{BC}} = 1 - e^{-\mu_{\text{vis}}^{\text{OR}}}$$

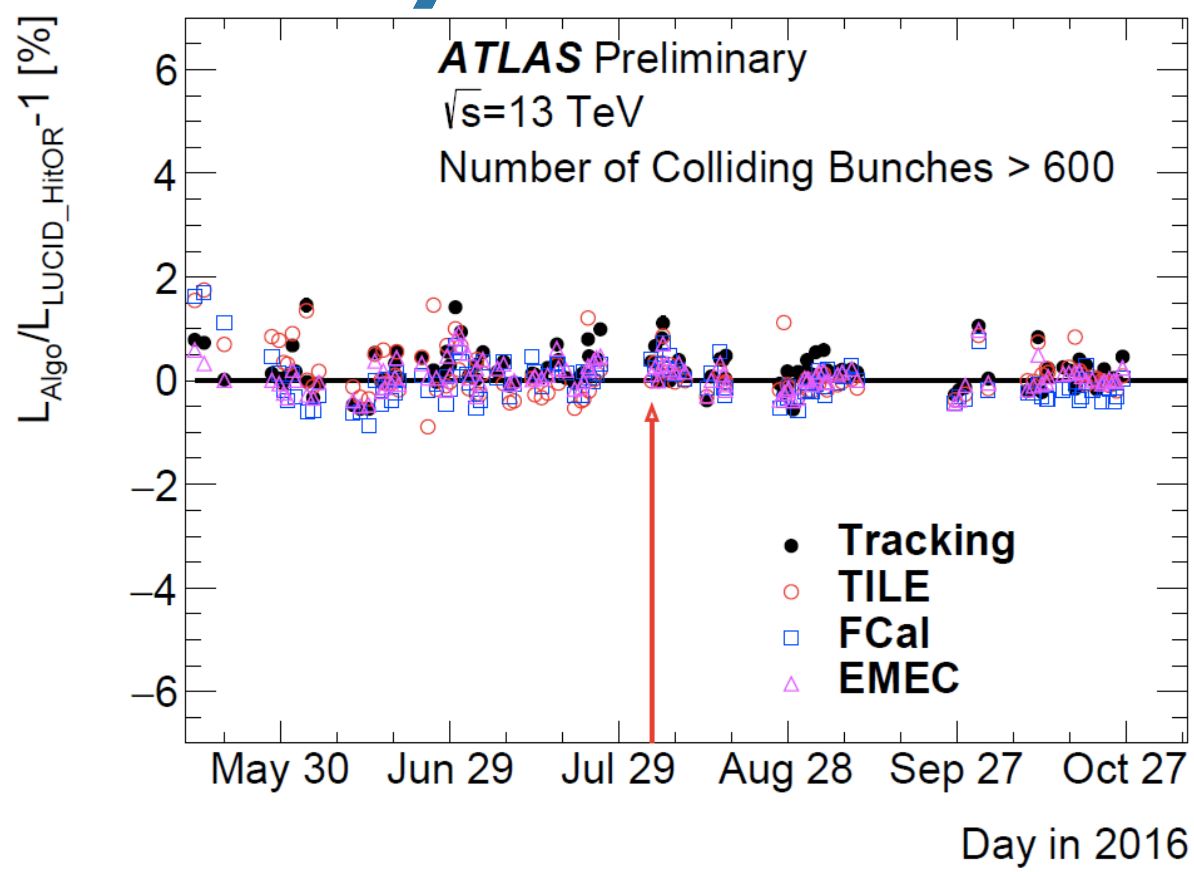
$$\mu_{\text{vis}}^{\text{OR}} = -\ln\left(1 - \frac{N_{\text{OR}}}{N_{\text{BC}}}\right)$$

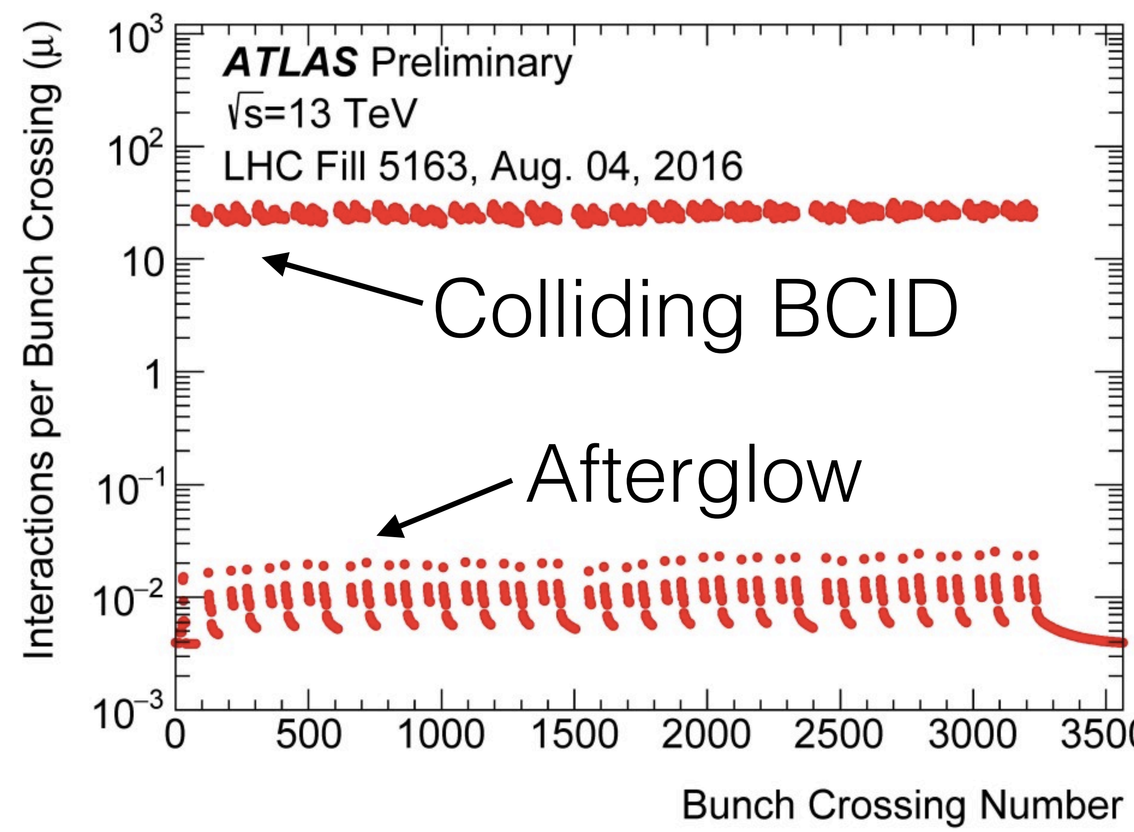
LUminosity measurement using a **C**herenkov **I**ntegrating **D**etector
LUCID measurement is preferred with 13TeV by ATLAS



Long-term stability

- LUCID and other detectors monitor relative variations in instantaneous luminosity over the time of data taking
- Fractional difference of luminosity measurements between the LUCID (HitOR) and other detectors
  - A long-term stability with a spread about 1% in 2016
- The afterglow effect (photons emitted by nuclear de-excitation from the last BCID contributing to the next one) has been tested in the non-colliding BCIDs
  - Around 3 orders of magnitude compared to the colliding BCIDs





CERN-ISR-PO-68-31 (1968) for the vdM scan

2 The absolute measurements (σ_{vis})

- Measure σ_{vis} of various detectors 2-3 times a year with van de Meer scans

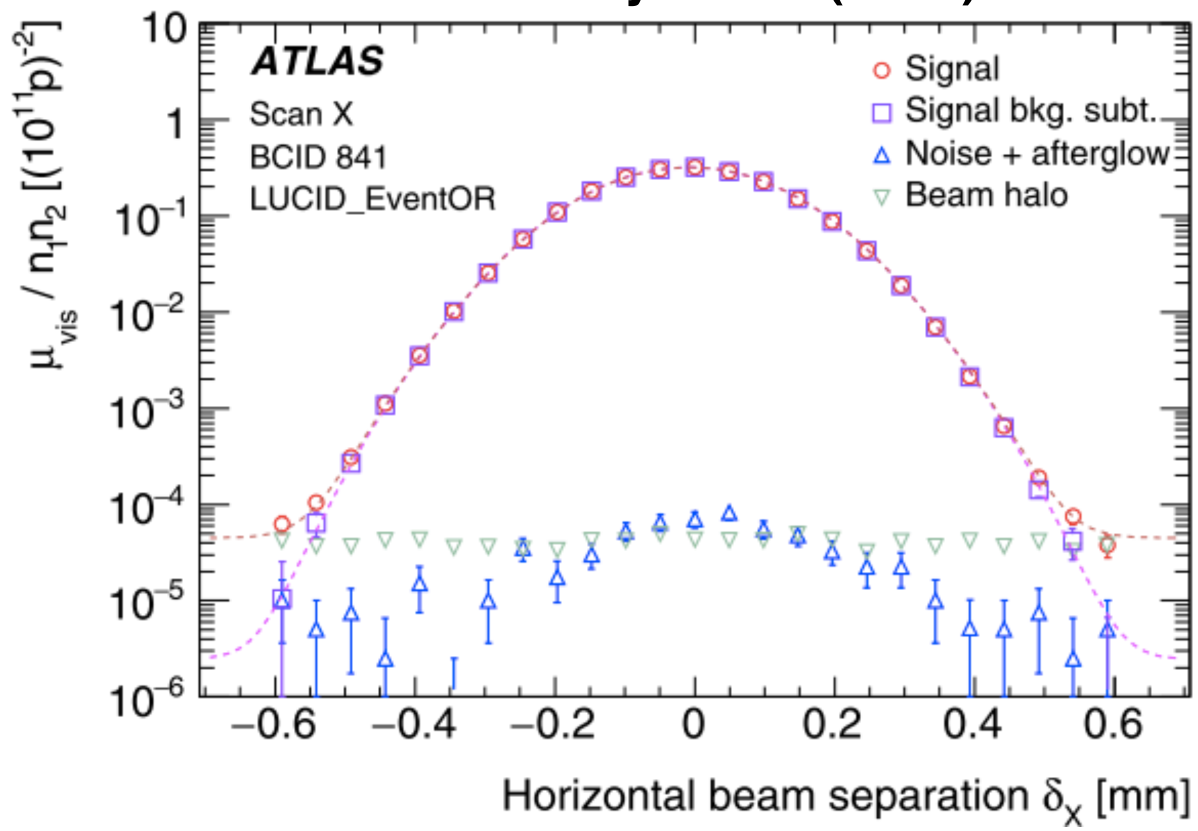
$$\sigma_{\text{vis}} = \mu_{\text{vis}}^{\text{MAX}} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2}$$

- Define the convolved beam size Σ_x , using $R_x(\delta)$ any quantity proportional to the luminosity measured during a horizontal scan when the two beams are separated horizontally by a distance δ

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R_x(\delta)\, \mathrm{d}\delta}{R_x(0)}$$

- Σ_x is directly measurable by any counting system which does not need to be mounted in the vacuum chamber

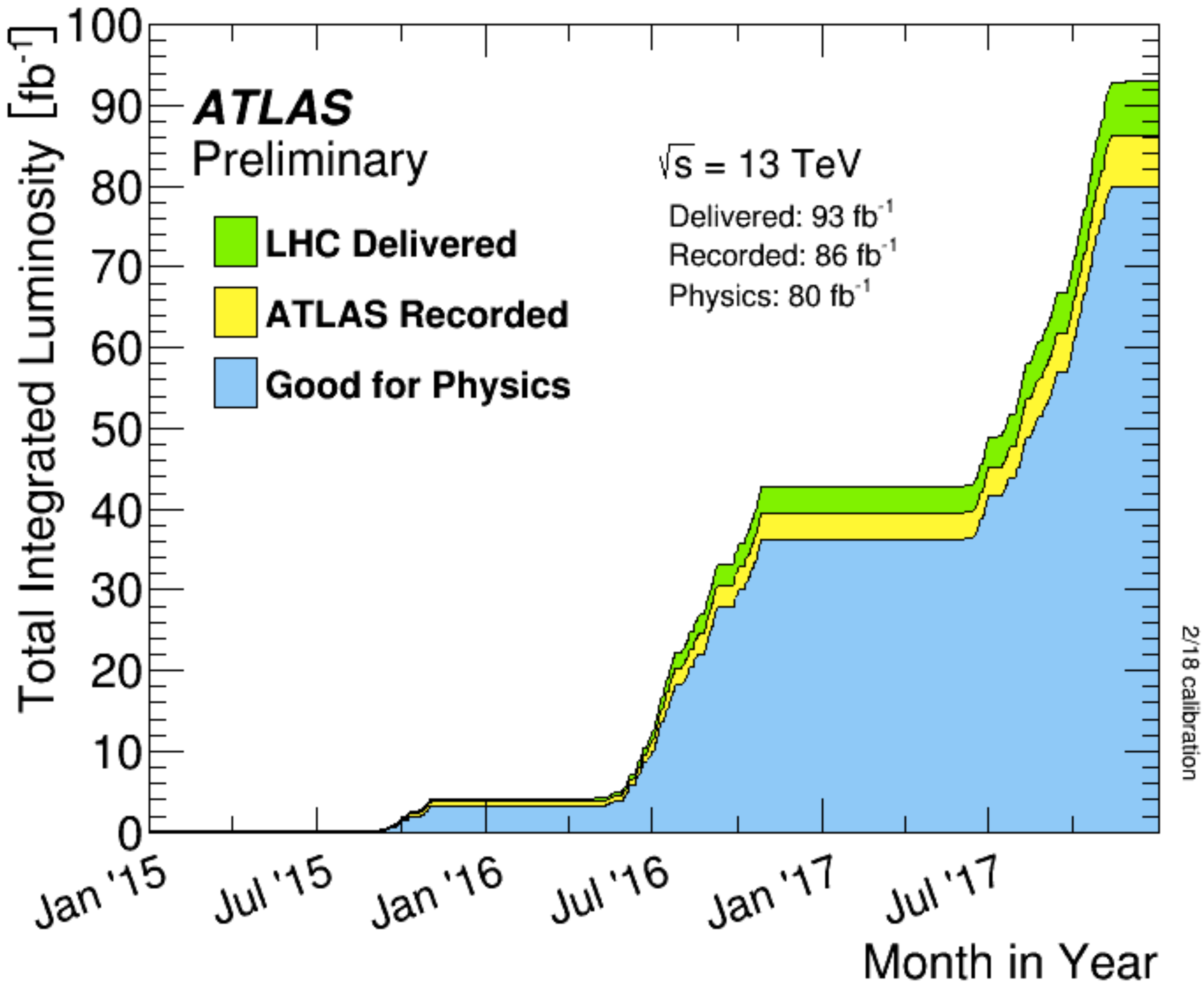
Eur. Phys. J. C (2016) 76:653



Background comes from
- Electronic noise
- Afterglow
- Beam halo (single-beam background)

All of them are negligible in small beam separation but sizeable in large beam separation

The accumulated luminosity



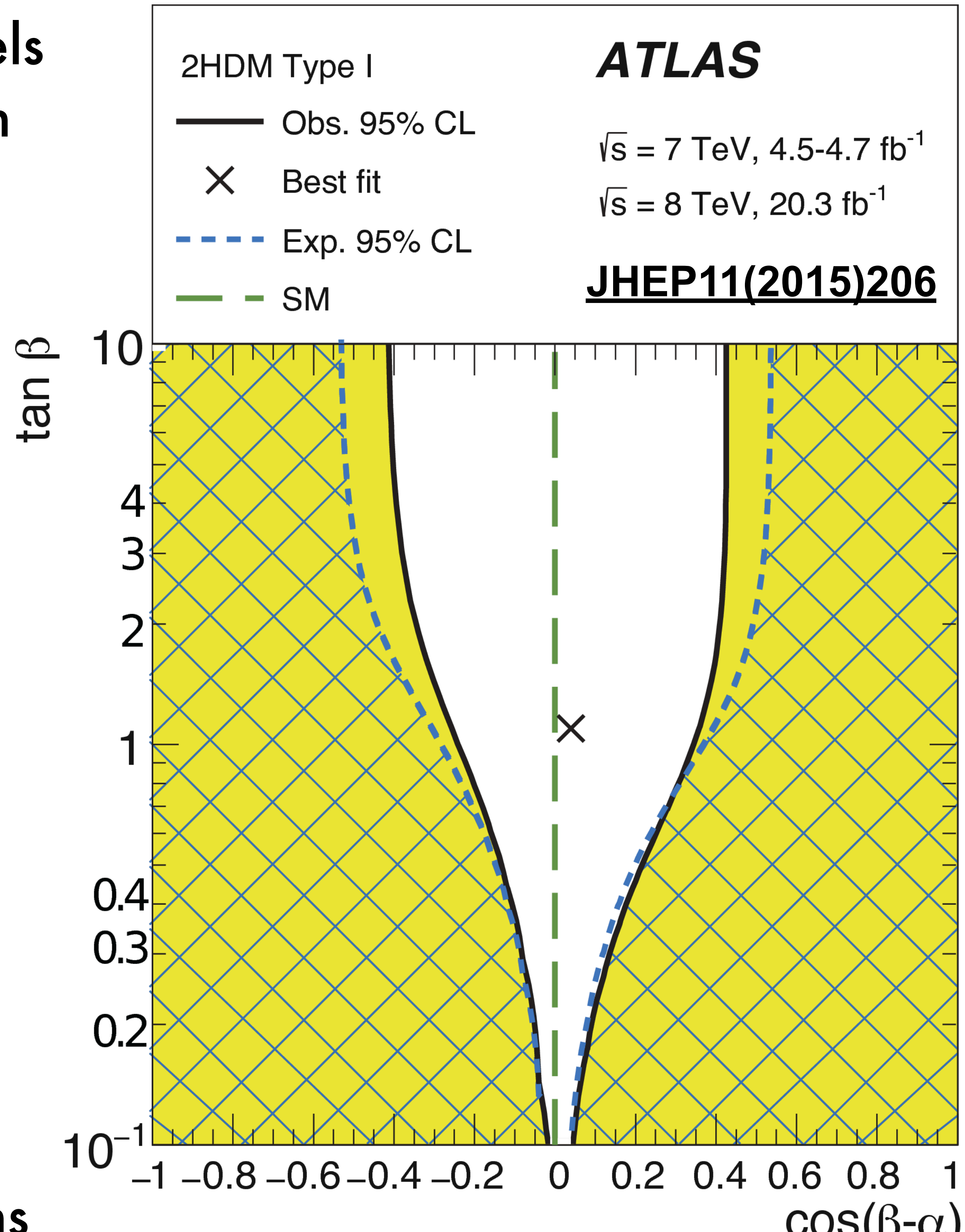
3. The BSM Higgs searches

Overview

- Heavy neutral Higgs searches via bosons are of great interests
  - A→ZH (H is **NOT** the SM Higgs): mass splitting 2HDM
  - X→VH (H is the SM Higgs): 2HDM, HVT
  - X→HH or pp→HH (SM Higgs): 2HDM, hMSSM, EWK singlet, SM Higgs trilinear self-coupling (non-resonant)
- There are other interesting searches for heavy Higgs with VV/ττ, Light Higgs, charged Higgs etc. in BSM Higgs sector extensions (not in this talk)

2HDM: a brief introduction

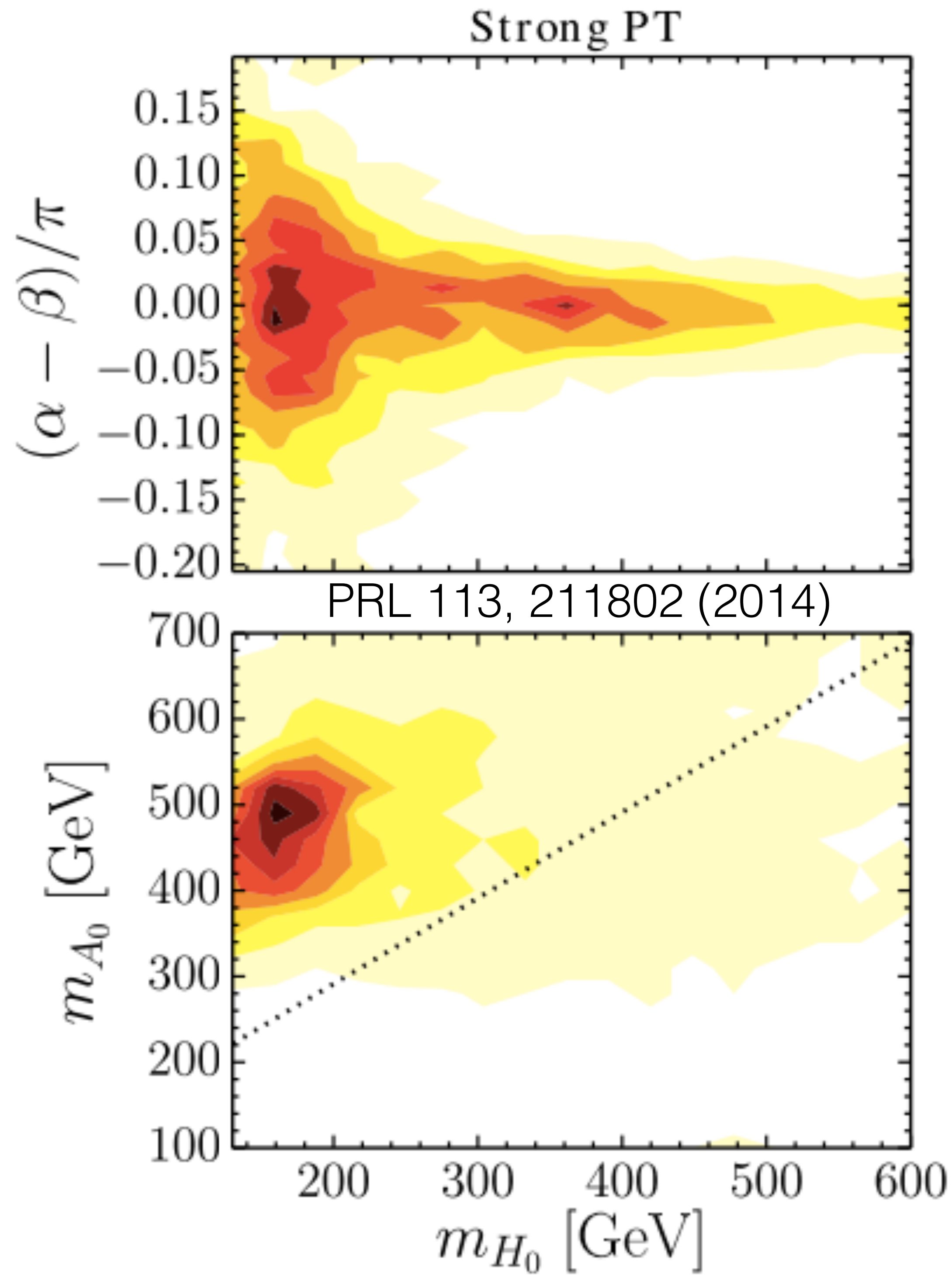
- 2-Higgs-doublet models: a collection of models that simply extends the SM by introducing an additional doublet
- Predict A, H, h (125 GeV) and $H^{\pm}$
- Parameters:
  - Masses of the predicted Higgs bosons
  - tanβ: ratio of vacuum expectation values (VEVs) of the two doublets $v_{1,2}$ (with $v_1^2+v_2^2=v^2$)
  - α: mixing between CP-even states
- The **SM alignment limit** at **cos(β-α)=0** where the h couplings to fermions and bosons come back to the SM values



SM Higgs couplings constraints in 2HDM

AZH: motivation

- The generation of the cosmic matter-antimatter asymmetry, via electroweak baryogenesis, requires a strongly 1st-order electroweak phase transition (EWPT)
    - The strongly 1st-order EWPT favours a large **mass splitting** of the two heavy Higgs bosons, for example, in the 2HDM implementation
- A→ZH is a "smoking gun" signature of 2HDM with a strong EWPT and **llbb** is the golden channel (see backup slides)
- The current LHC results are mainly motivated by MSSM-like scenarios where heavy Higgs mass splitting is small, i.e. A→ZH is kinematically forbidden



PRL 113, 211802 (2014)

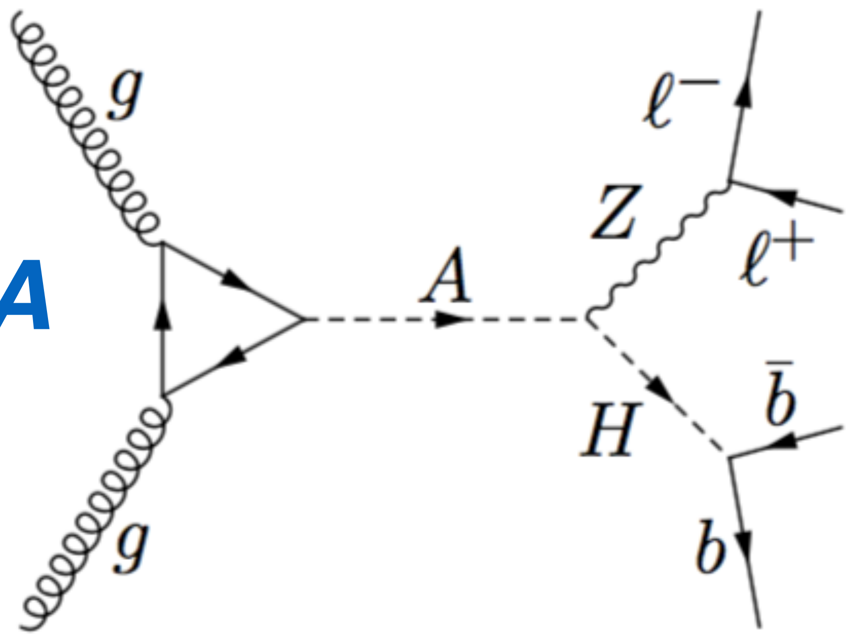
"AZH: the first mass splitting analysis on ATLAS"

Just came out last Thursday! (link and arXiv:1804.01126)

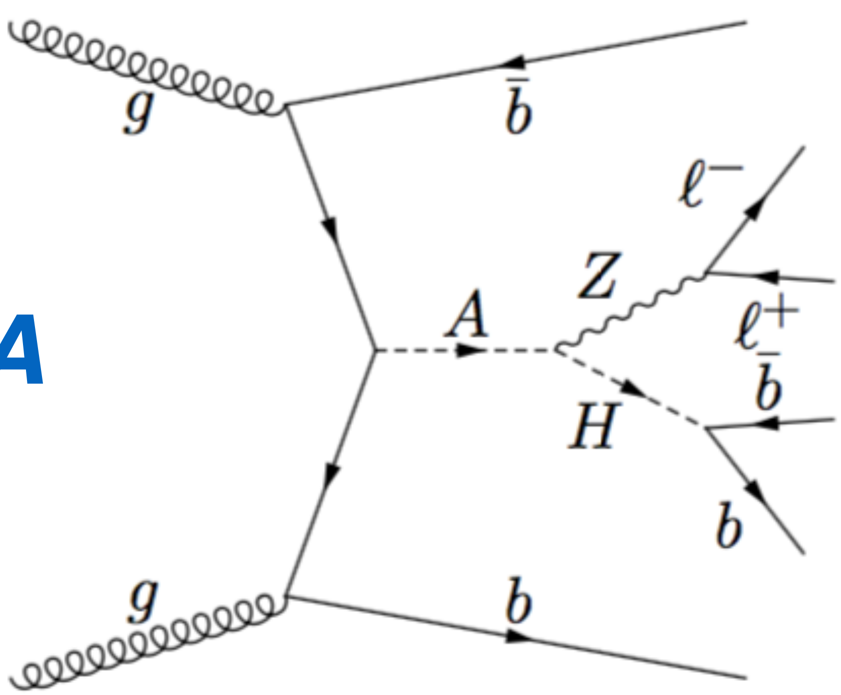
arXiv:1804.01126

AZH event selection

ggA

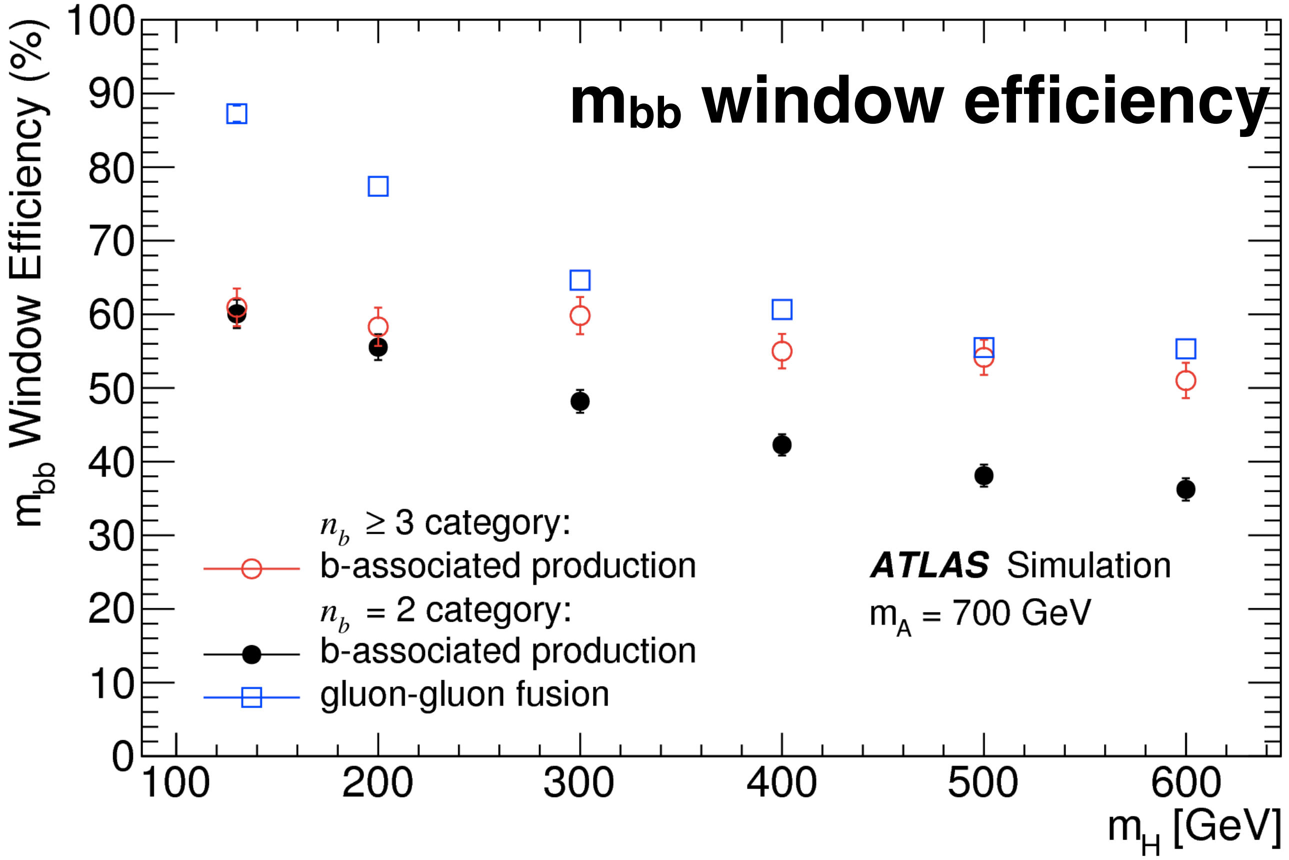


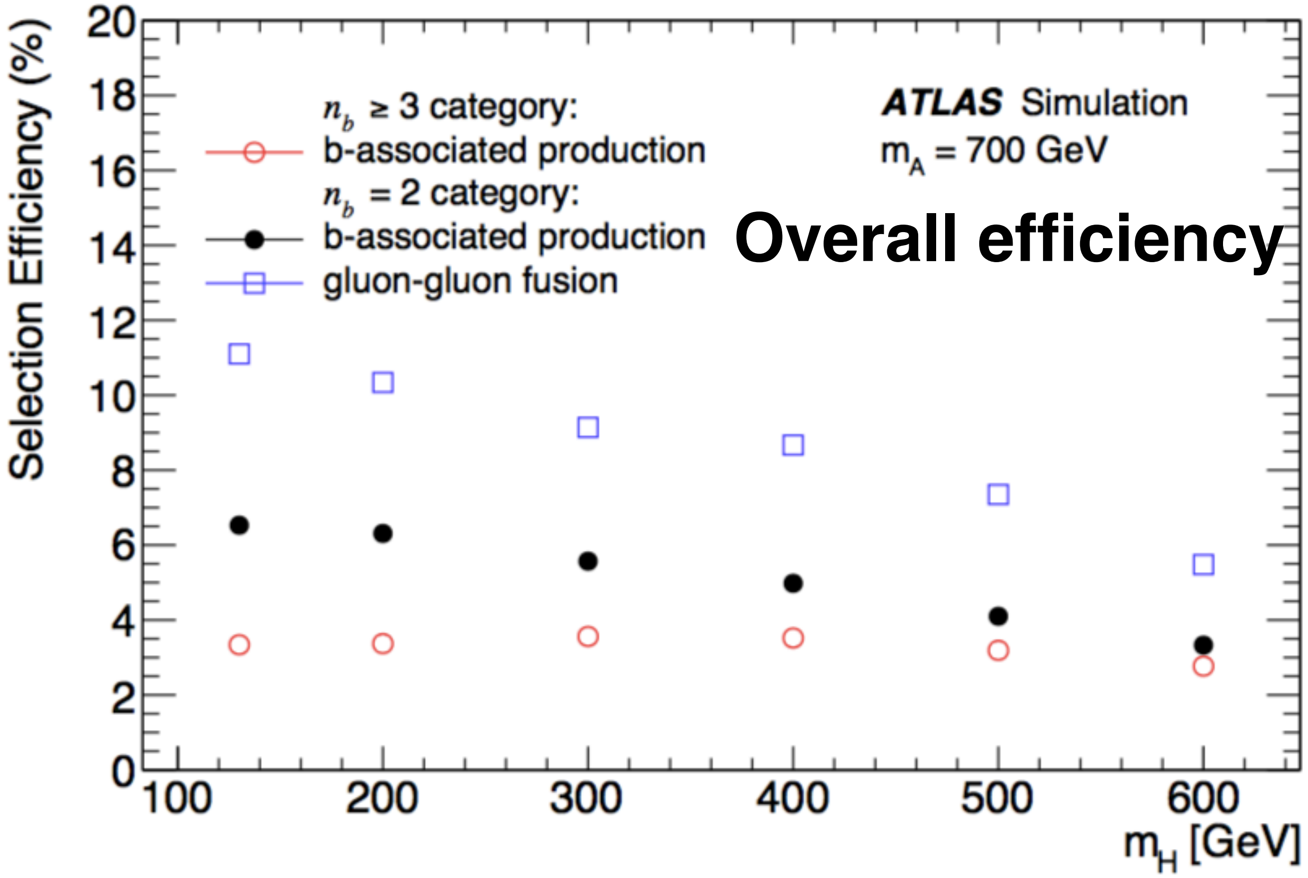
bbA



- Searching 2 unknown particles, both heavier than 125 GeV: A and H with **$m_A > m_H + m_Z$**
- Define **SR** according to:
  - ll: exactly 2 same-flavour leptons, m_{ll} sits in 80-100 GeV
  - bb: at least 2 bjets with one of them having $p_T >$ 45 GeV, m_{bb} sits in a running window as a function of m_H
  - $E^{miss}_T / \sqrt{H_T} < 3.5\ GeV^{1/2}$, $\sqrt{\Sigma p_T^2} / m_{llbb} > 0.4$
  - Number of bjets = 2 or 3+, for ggA and bbA productions
- Define **CR** by opposite-flavour for top, by inverting m_{bb} for Vjets

AZH signal efficiency

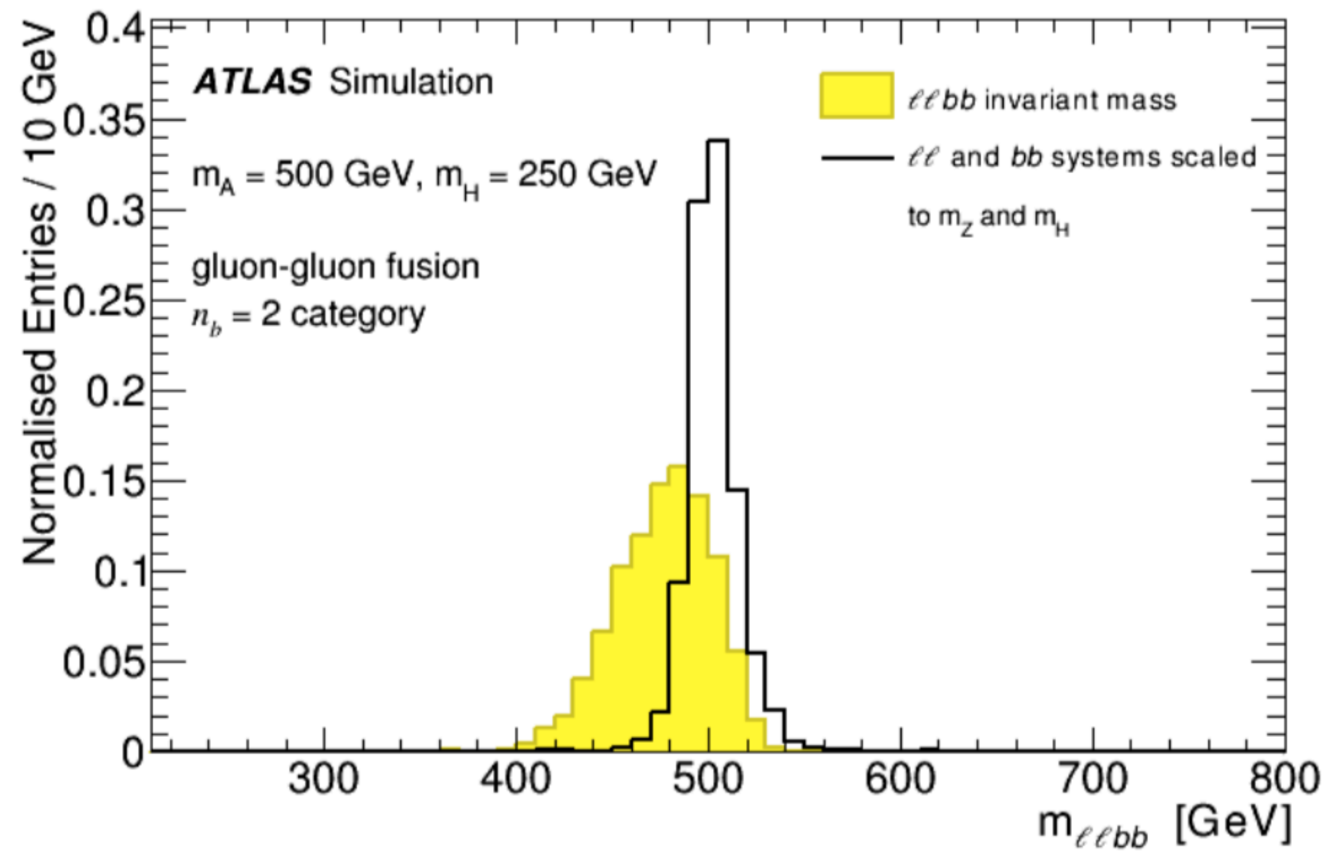


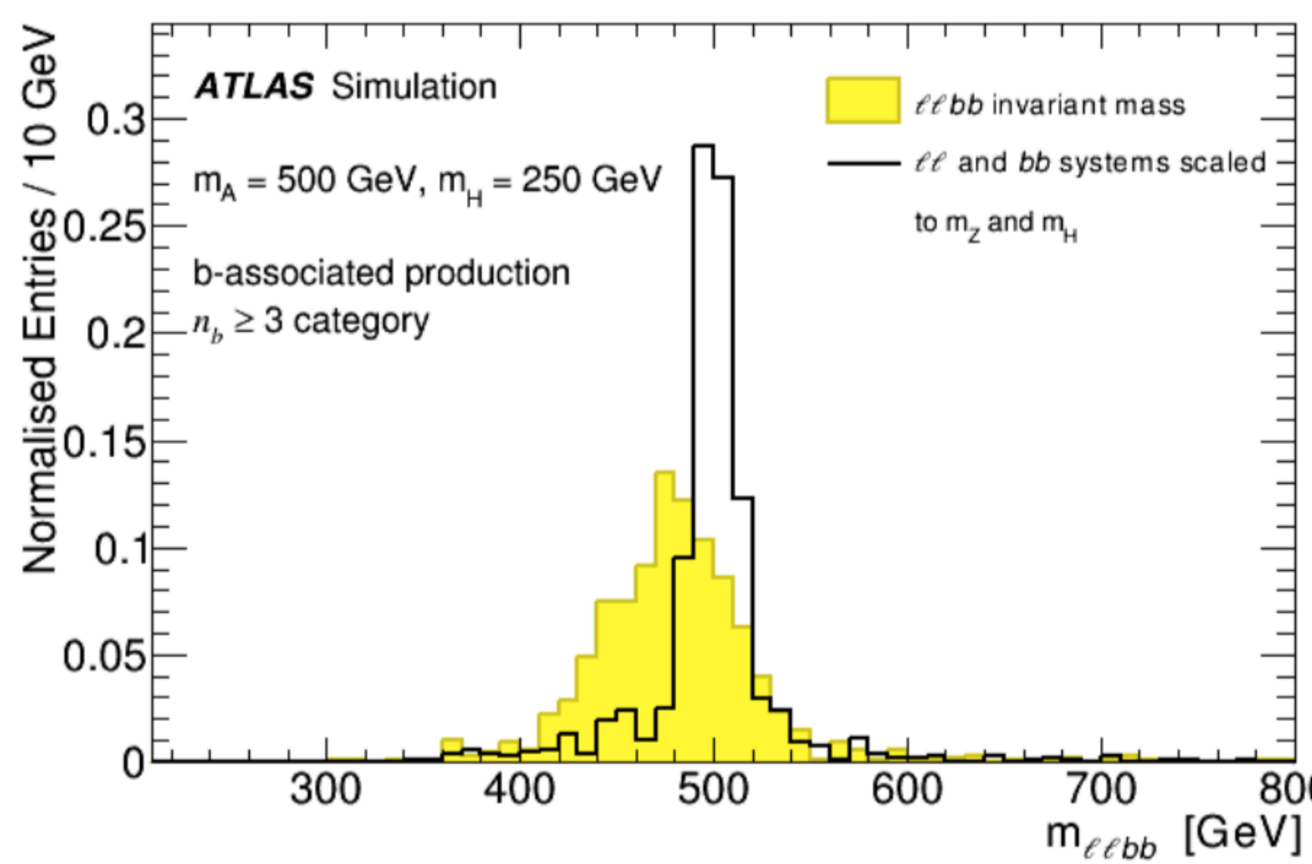


arXiv:1804.01126

AZH mass resolution improvement

- The m_{llbb} resolution is improved by **a factor two** without significantly distorting backgrounds
  - Scale ll 4-momentum to match Z boson mass
  - Scale bb 4-momentum to match assumed m_H
- m_{llbb} resolution is 0.3%-4%



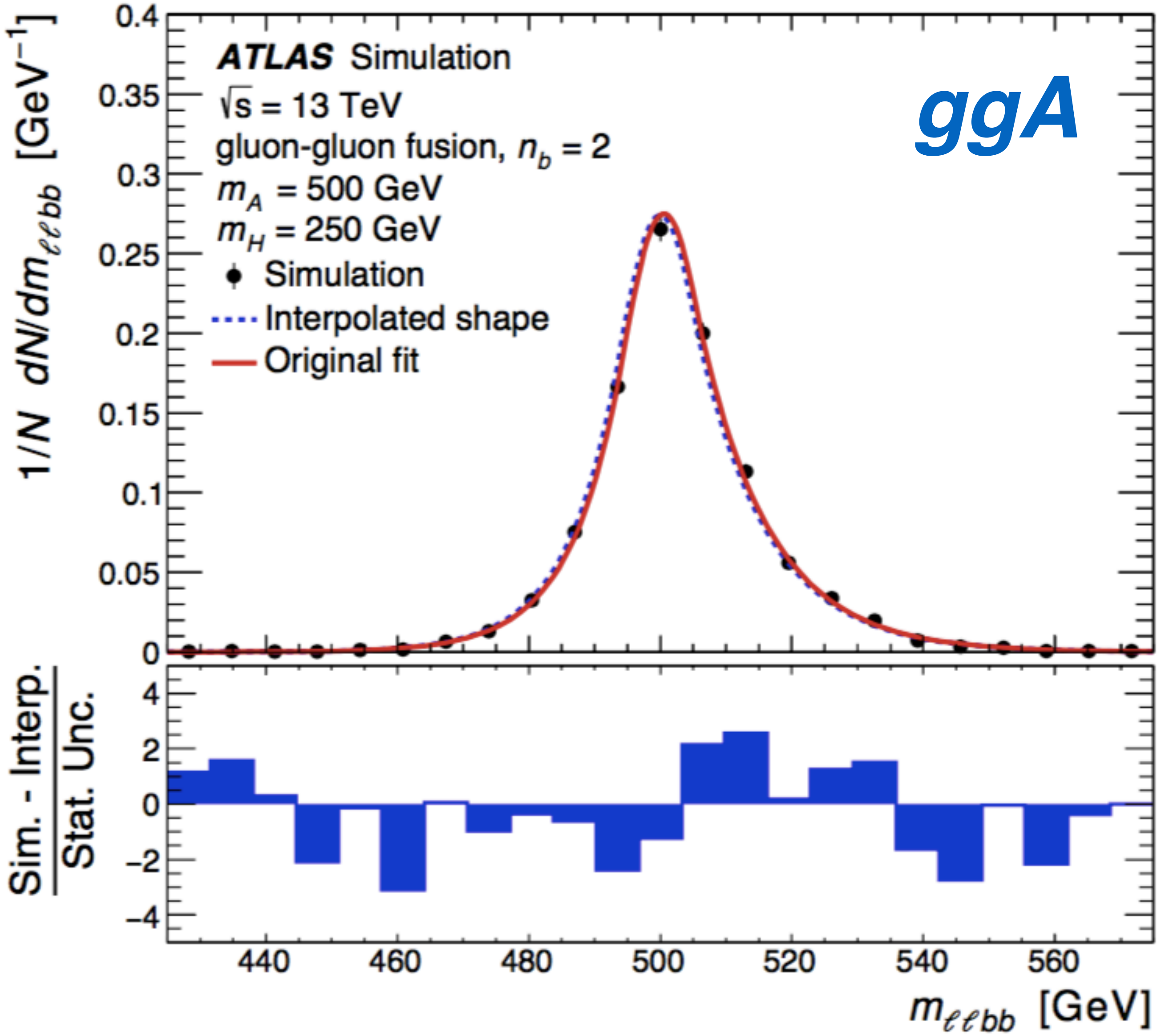


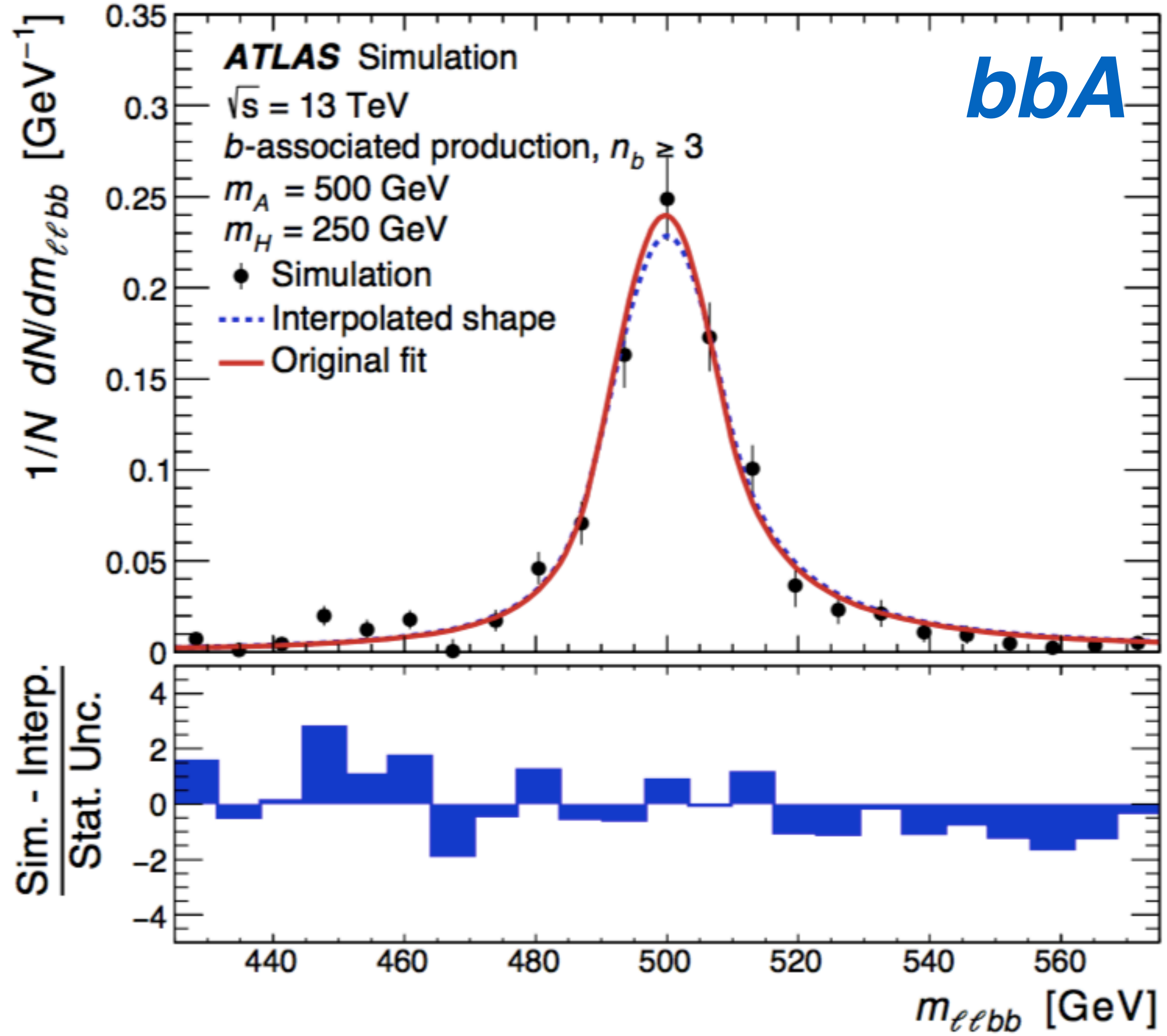
arXiv:1804.01126

Signal modelling (narrow width)

ggA signal is modelled with EGE function

$$f_{\mathrm{EGE}}(m;a,\sigma,k_L,k_H) = \begin{cases} e^{\frac{1}{2}k_L^2 + k_L\left(\frac{m-a}{\sigma}\right)} & \frac{m-a}{\sigma} \leq -k_L \\ e^{-\frac{1}{2}\left(\frac{m-a}{\sigma}\right)^2} & \text{for } -k_L < \frac{m-a}{\sigma} \leq k_H \\ e^{\frac{1}{2}k_H^2 - k_H\left(\frac{m-a}{\sigma}\right)} & \frac{m-a}{\sigma} > k_H \end{cases}$$





$$f_{\mathrm{DSCB}}(m;a,\sigma,k_L,k_H,n_1,n_2) = \begin{cases} g(m;a,-\sigma,k_L,n_1)\cdot e^{-\frac{1}{2}k_L^2} & \frac{m-a}{\sigma} \leq -k_L \\ e^{-\frac{1}{2}\left(\frac{m-a}{\sigma}\right)^2} & \text{for } -k_L < \frac{m-a}{\sigma} \leq k_H \\ g(m;a,\sigma,k_H,n_2)\cdot e^{\frac{1}{2}k_H^2} & \frac{m-a}{\sigma} > k_H \end{cases}$$

bbA signal is modelled with DSCB function given its fatter distributions

Signal modelling (large width)

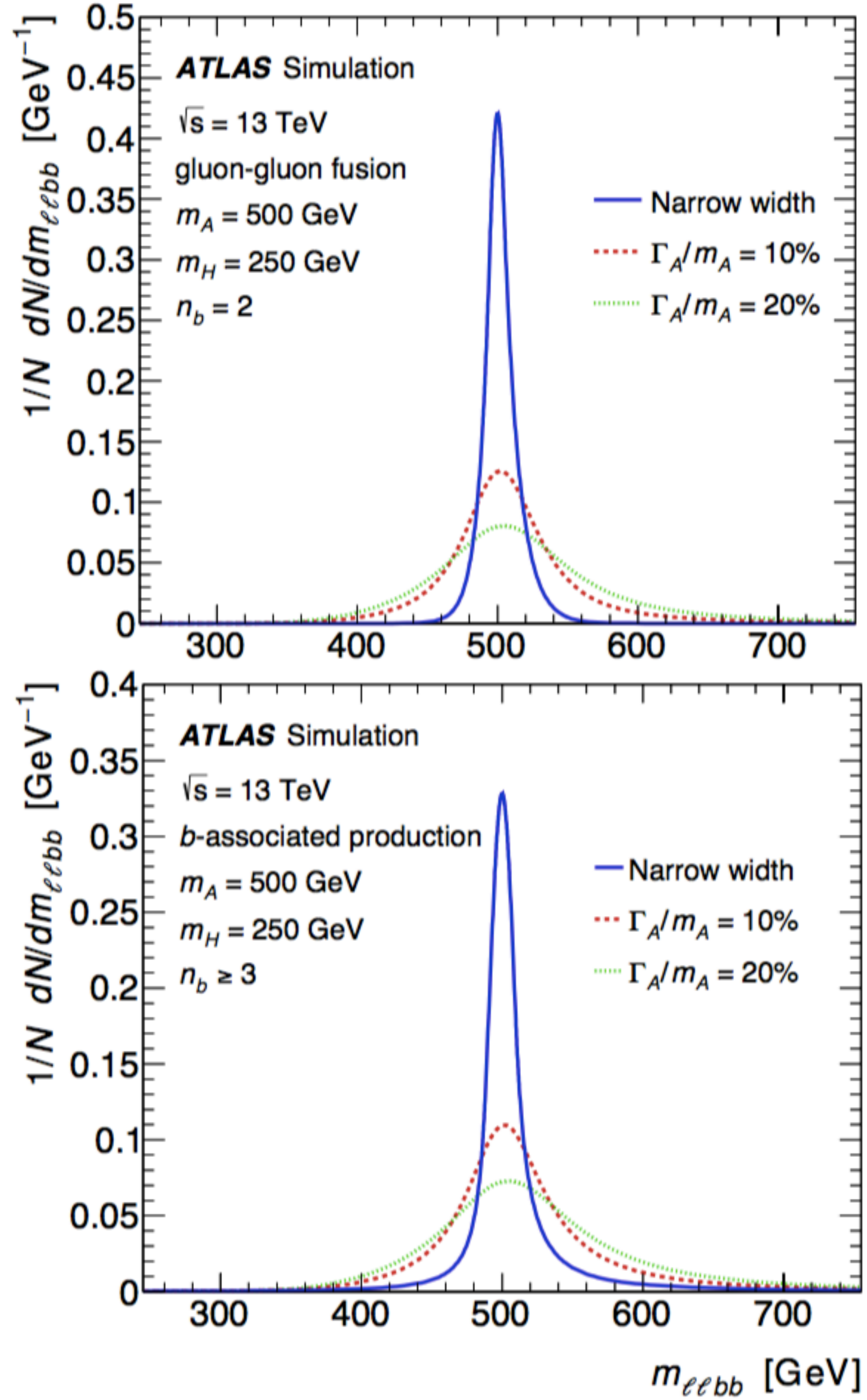
- Larget width is considered as it can grow as high as 20% in the 2HDM phase space of interests
- Use truth line shape as core and weight narrow-width signals to get large-width shapes

$$f_{\mathrm{NW}}(x)\Big|_{m_{\mathrm{H}}} \cong \int_0^{\infty} \delta(m - m_{\mathrm{A}}) \cdot f_{\mathrm{EGE}}\Big(x\big|\mu(m), \sigma(m), k_{\mathrm{L}}(m), k_{\mathrm{H}}(m)\Big)\Big|_{m_{\mathrm{H}}} dm$$

$$f_{\mathrm{LW}}(x)\Big|_{m_{\mathrm{H}}} = \int_0^{\infty} g_{\mathrm{LW}}(m) \cdot f_{\mathrm{EGE}}\big(x|\mu(m), \sigma(m), k_{\mathrm{L}}(m), k_{\mathrm{H}}(m)\big)\Big|_{m_{\mathrm{H}}} dm$$

truth line shape at parton level (NW or LW)

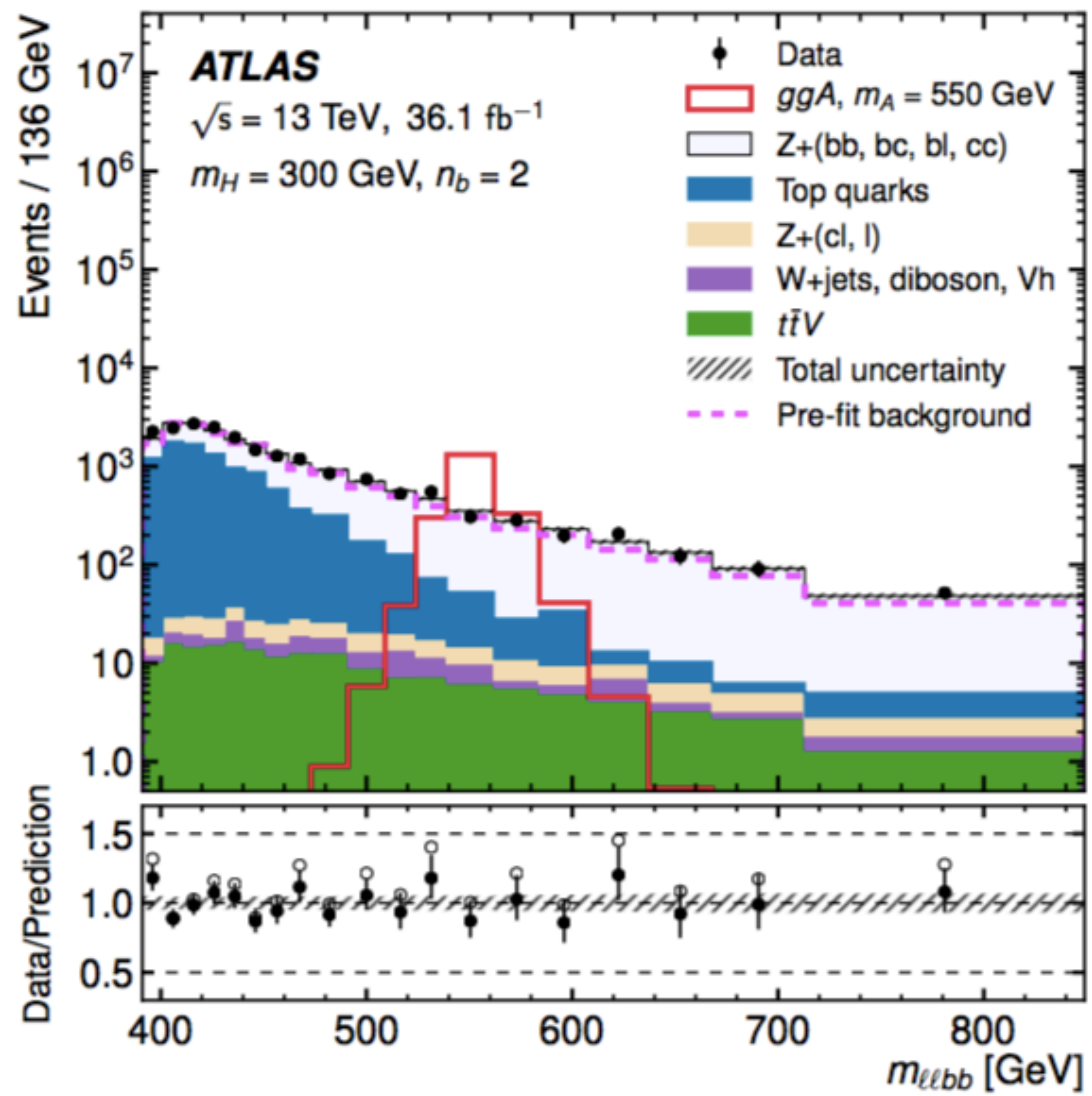
reconstructed line shape with detector effects



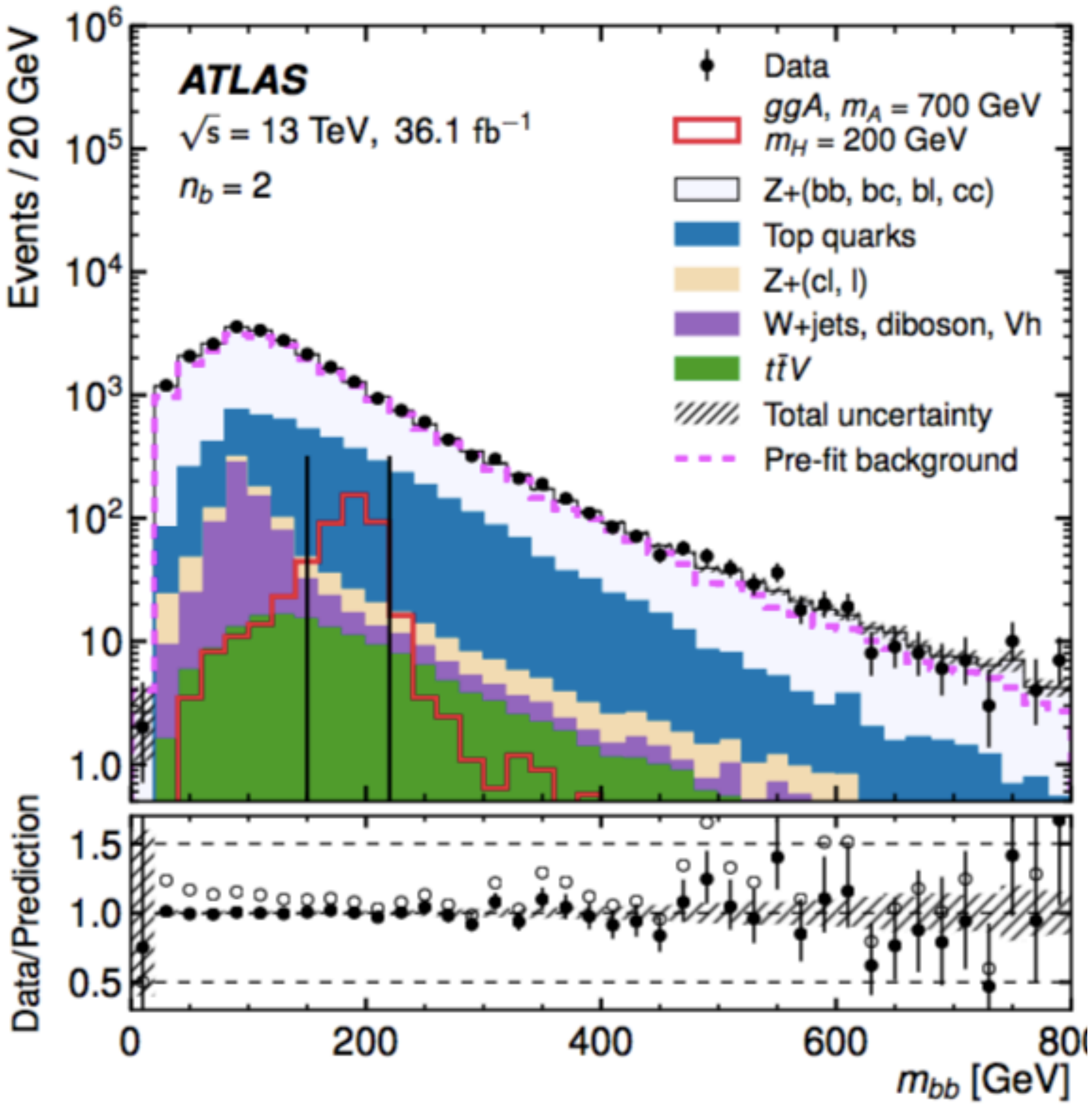
arXiv:1804.01126

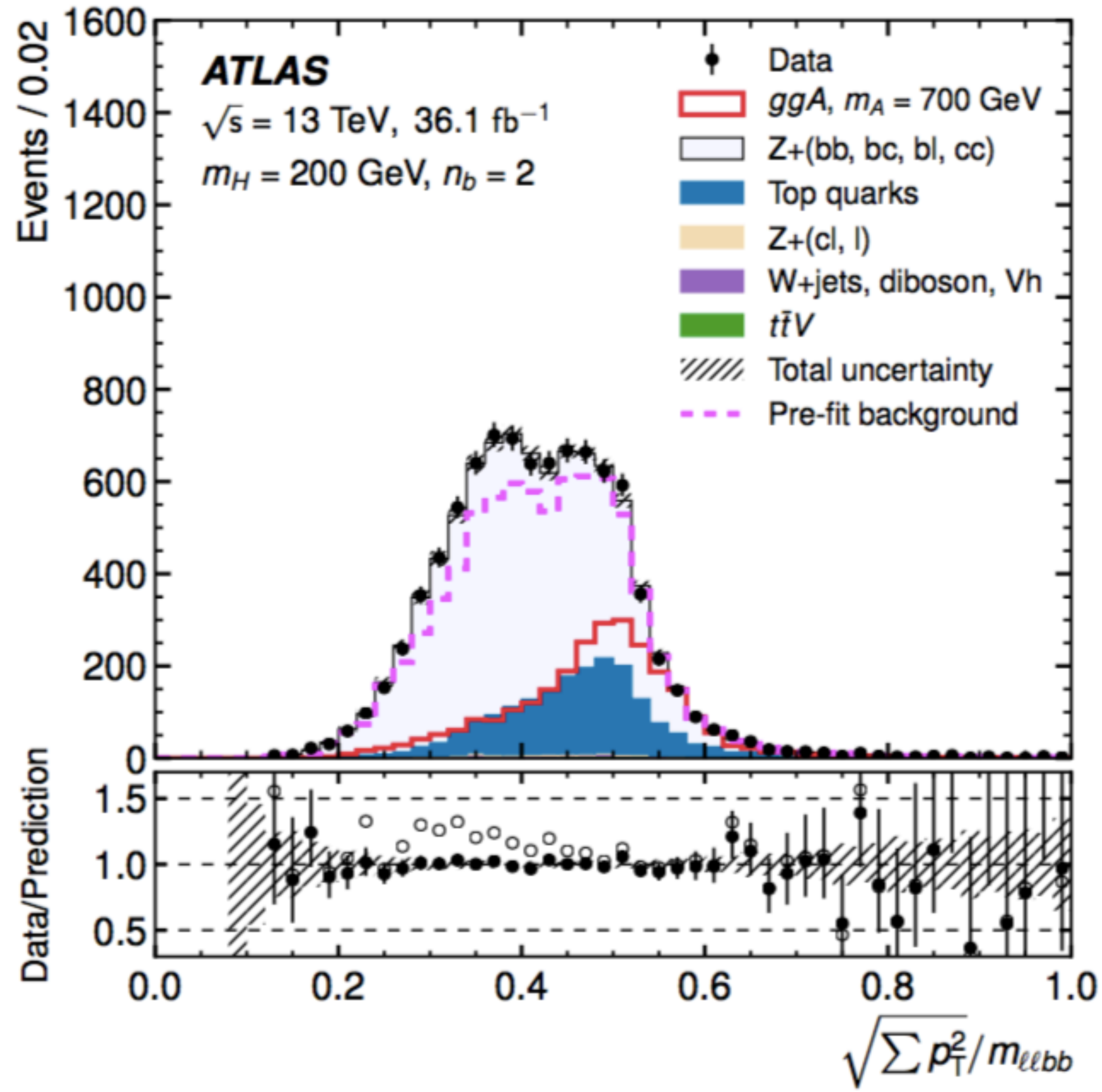
Signal and background

- For more than 1700 assumptions on (m_A,m_H) in our scan, the signal
  - Shape is made by linearly interpolating the shape parameters between the mass points that have MC
  - Normalisation is made by 2D interpolation using thin plate splines
- The backgrounds mainly come from Vjets and ttbar modelled with MC, while their normalisation is controlled from simultaneous fits to relevant CRs



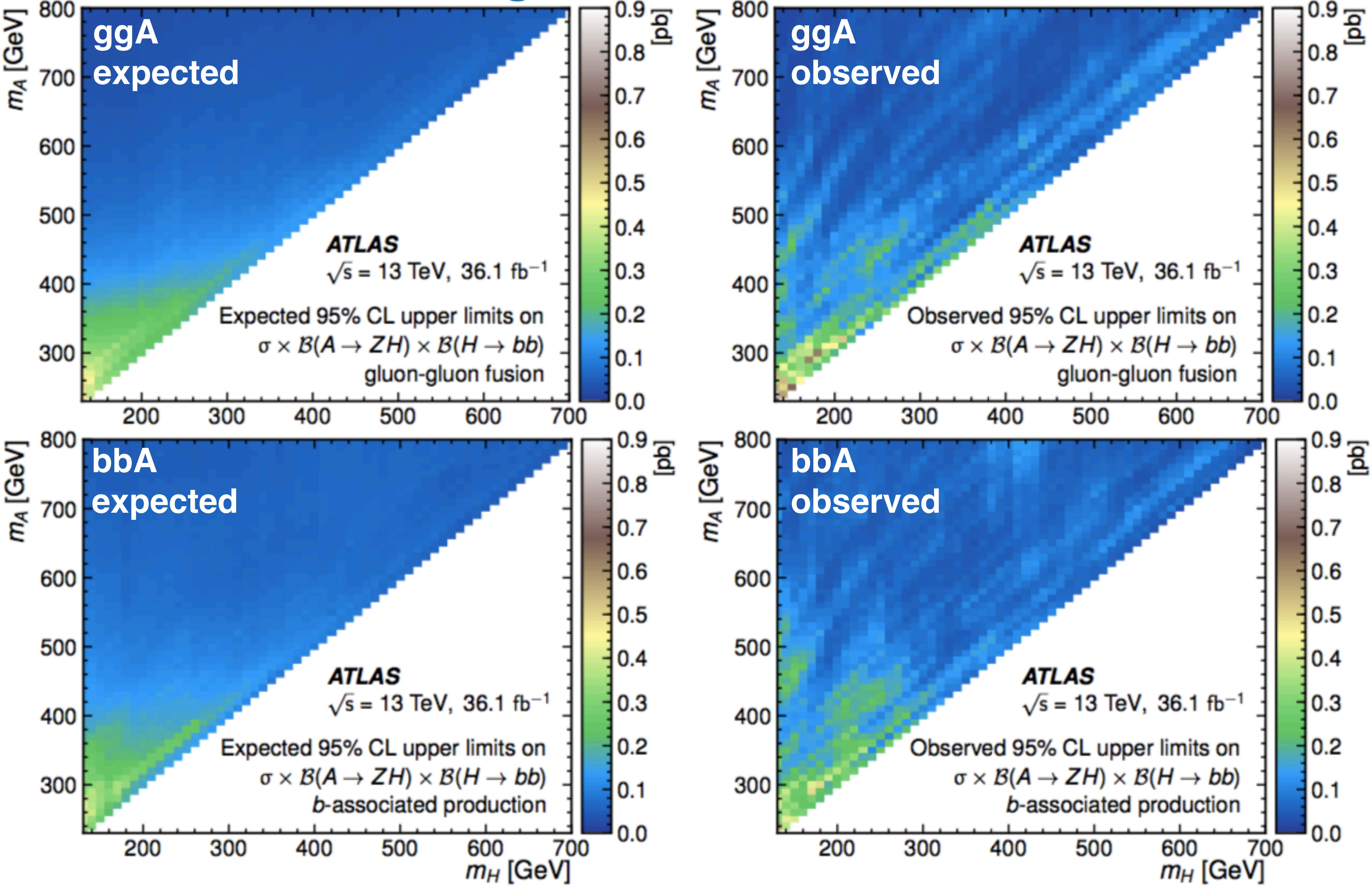
More kinematics





arXiv:1804.01126

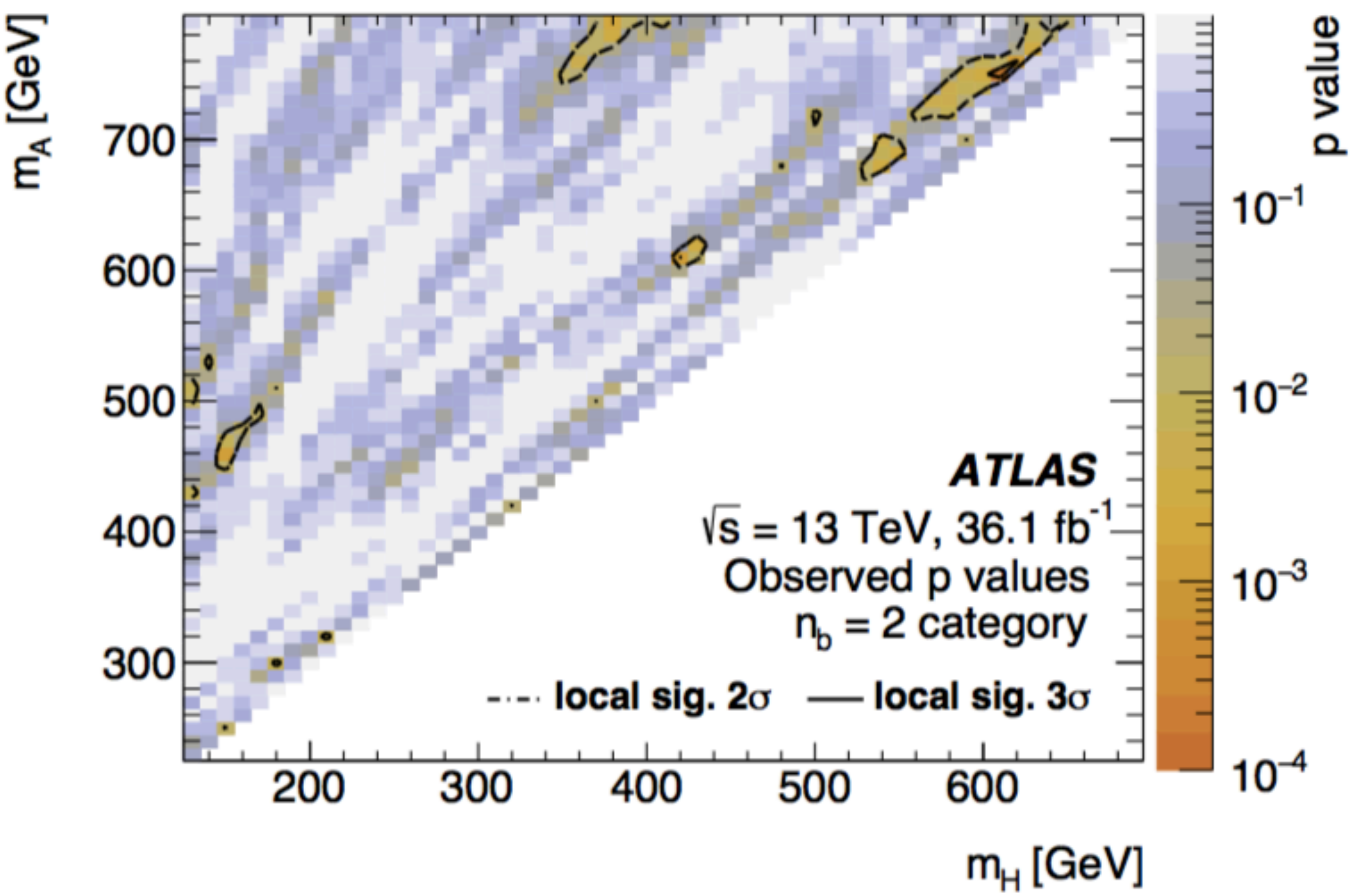
AZH general xs limits

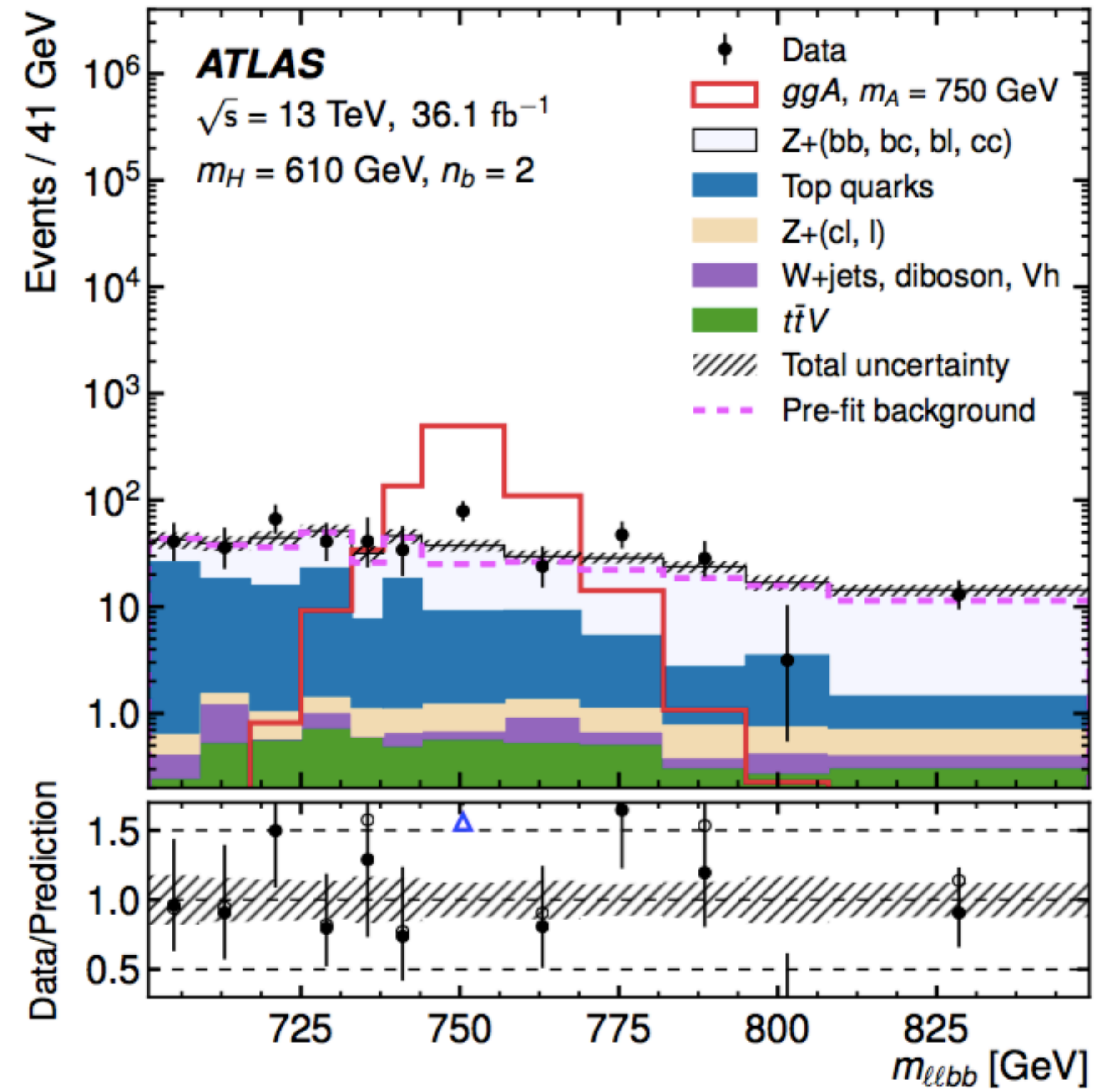


arXiv:1804.01126

AZH p-value

- A local significance 3.5 σ is observed at (mA, mH) = (750, 610) GeV with ggA
- The corresponding global significance is 2.0 σ



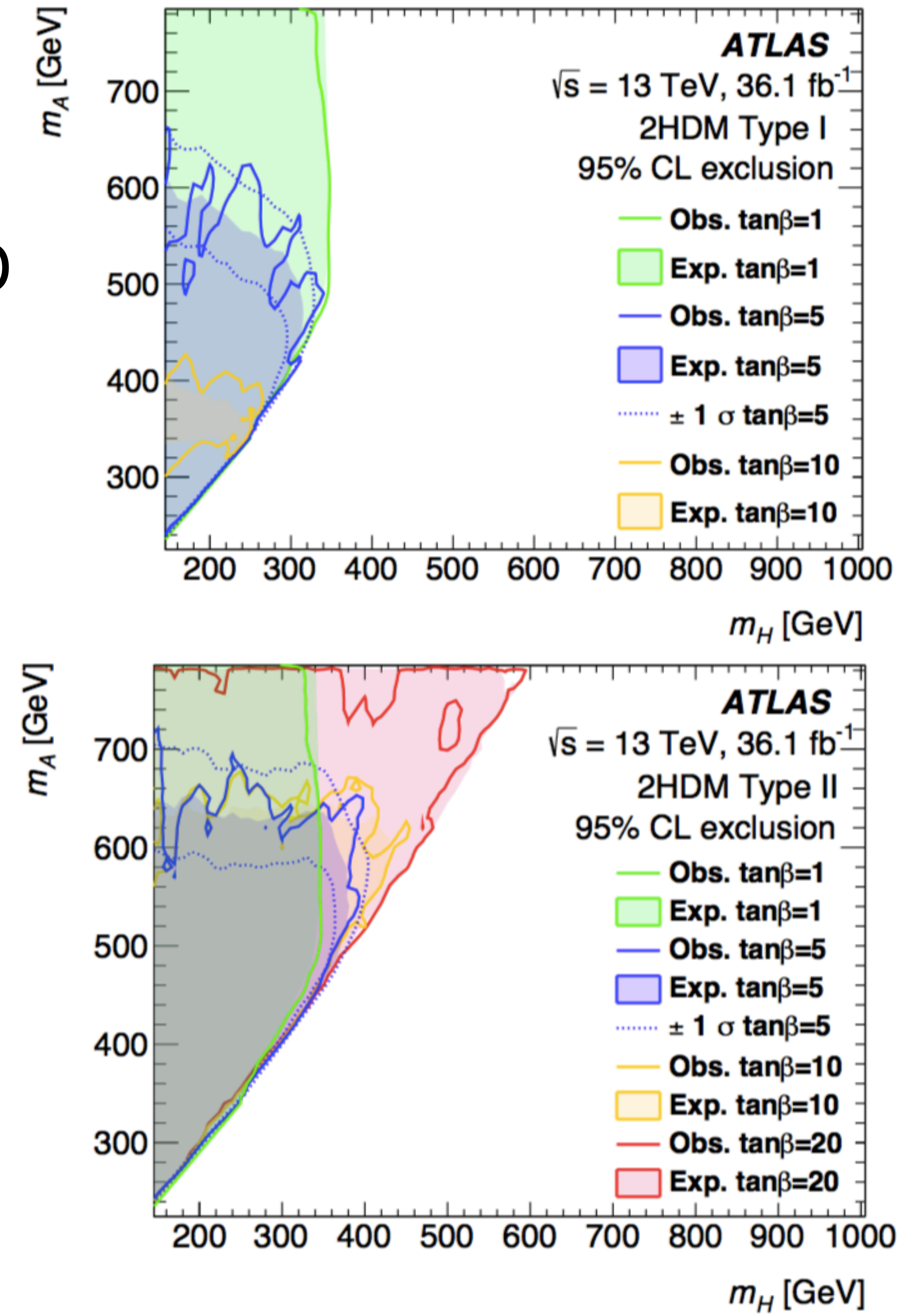


(a) m_{bb} window for m_H =610 GeV

arXiv:1804.01126

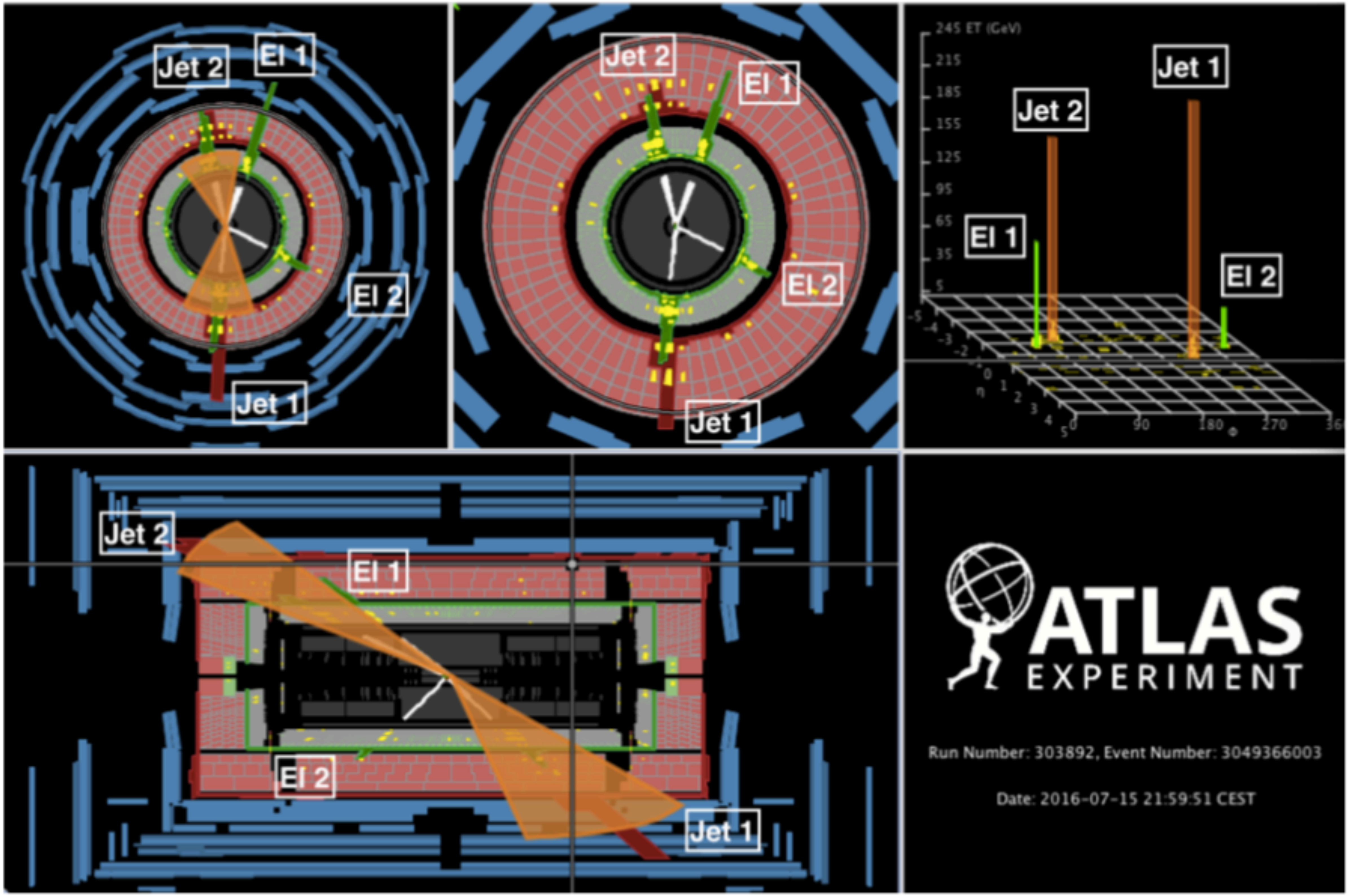
AZH interpretation in 2HDM

- The xs limits with large width consideration is used to interpret 2HDM at the SM alignment cos(β-α)=0
  - This is unique with AZH, as most of ATLAS heavy Higgs searches with VV or HH decays do not have sensitivity at the SM alignment limit given their diminishing BRs
- The exclusion is stronger than the **CMS** results (~270 GeV, us ~350 GeV) in terms of m_H at a similar phase point tanβ~1



arXiv:1804.01126

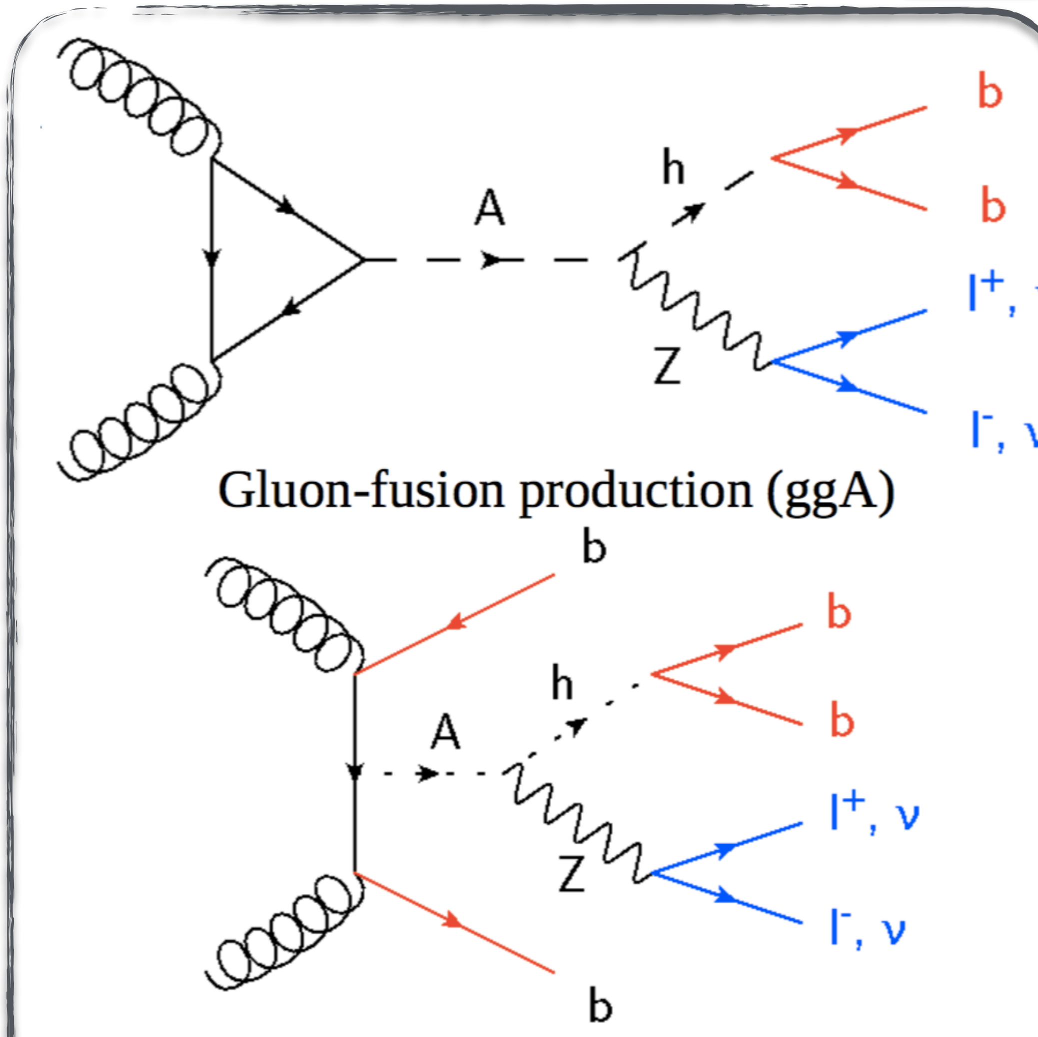
A candidate AZH event



arXiv:1712.06518

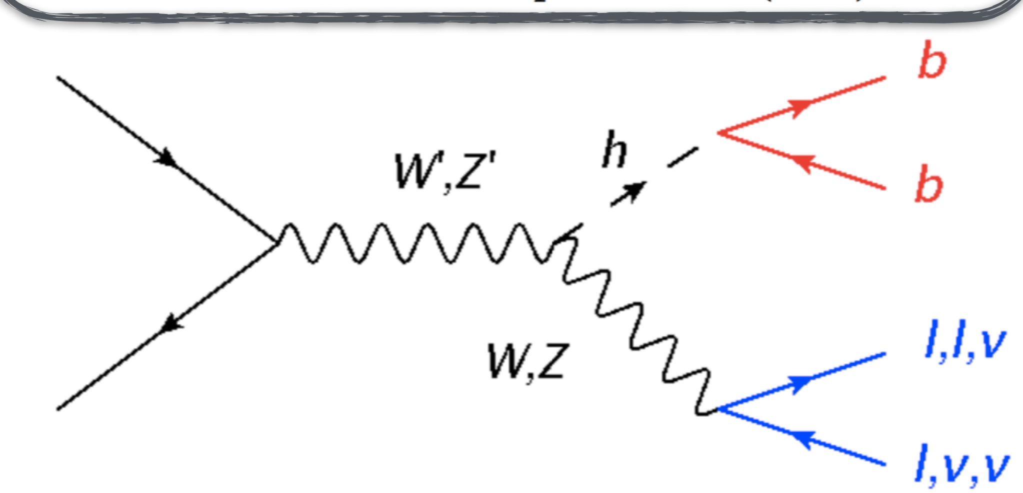
Vh resonances

- Fresh results from the end of 2017
- New heavy Higgs (A) from a second Higgs doublet (2HDM that predicts H±, h, H and A) additional to the SM one, such MSSM, Axion, Baryogenesis models
- New vector resonances (W',Z') in models that assume new strong interactions in a higher energy scale to solve the naturalness problem, such as Minimal Walking Technicolour, Little Higgs, composite Higgs models



Gluon-fusion production (ggA)

b-associated production (bbA)



$Z'/A \to Zh \to \ell^+\ell^- b\bar{b}$ $W' \to W^\pm h \to \ell^\pm \nu b\bar{b}$

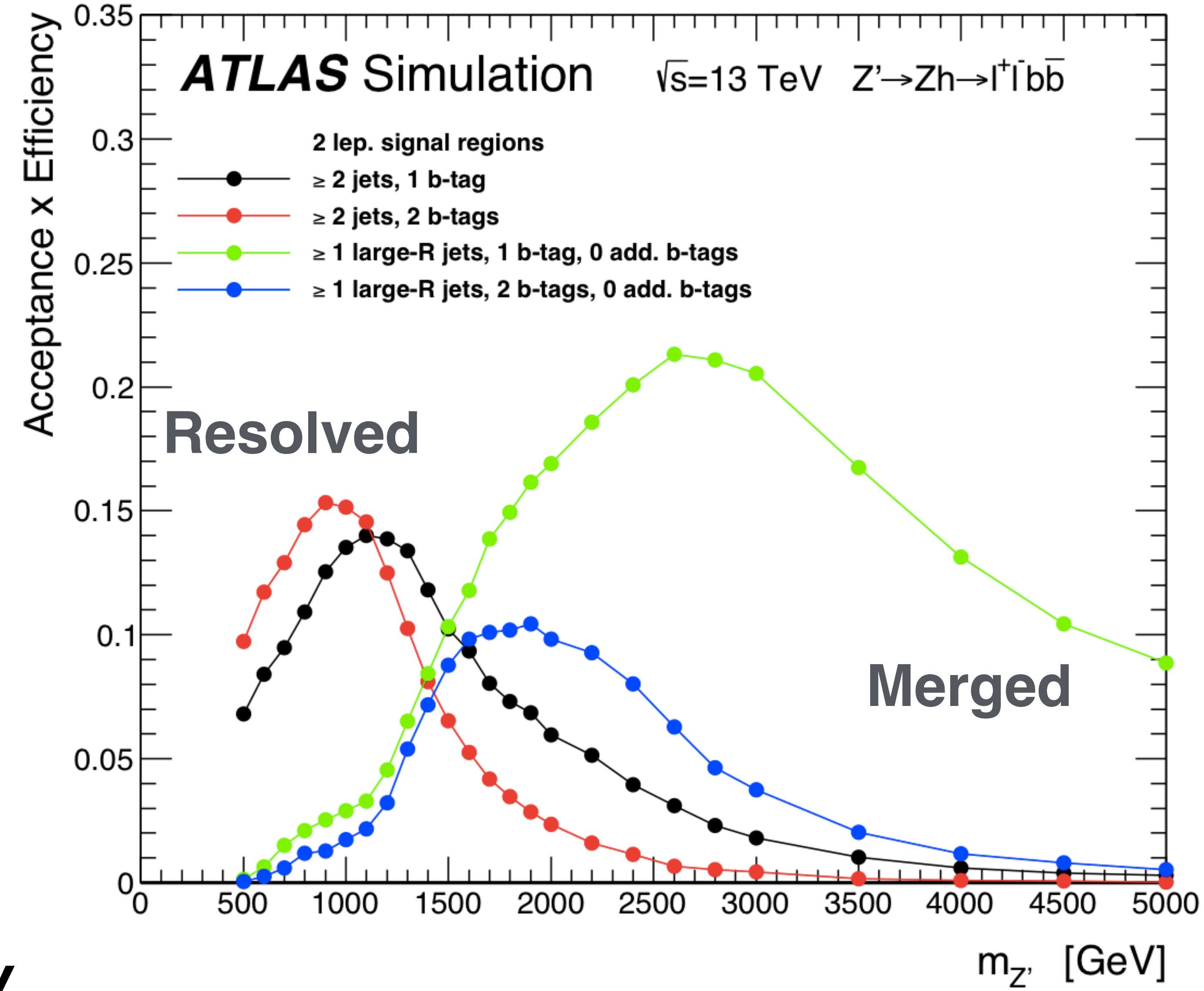
$Z'/A \to Zh \to \nu\bar{\nu} b\bar{b}$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-10/

arXiv:1712.06518

Vh event selections

- Define SR according to
  - V decays (vv, lv, ll) by asking 0/1/2 leptons
  - Open angle of h decays: resolved if two bjets are separated large enough, merged otherwise



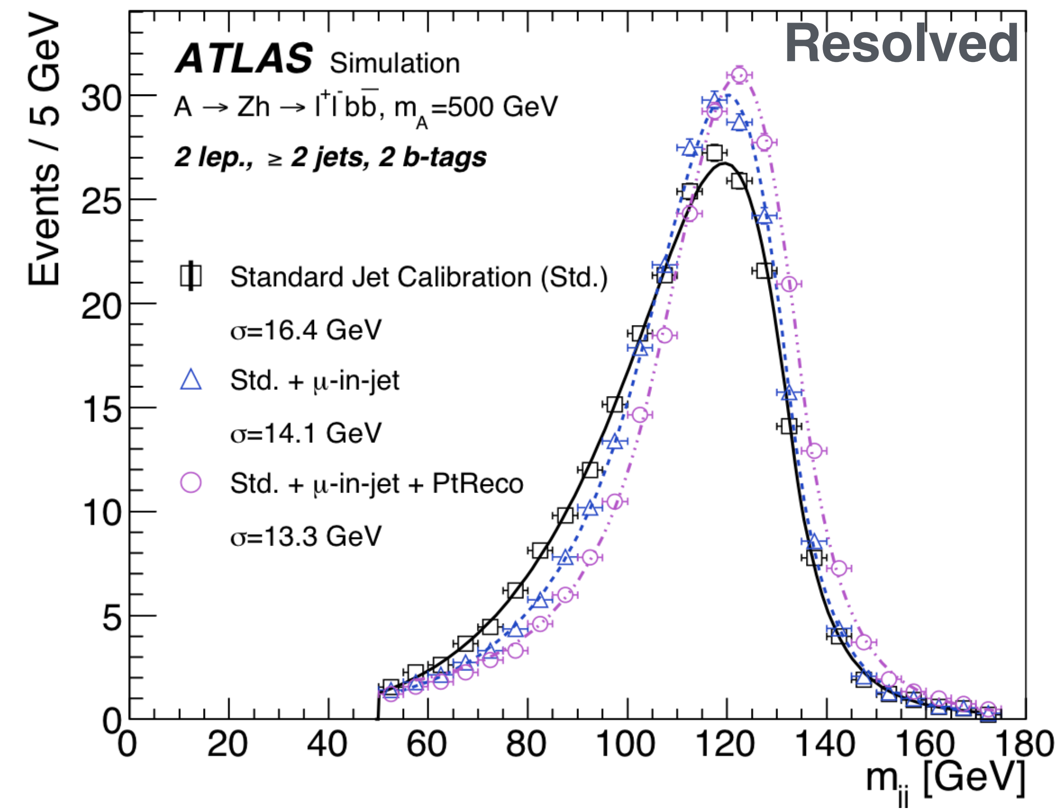
- Define CR in the table below

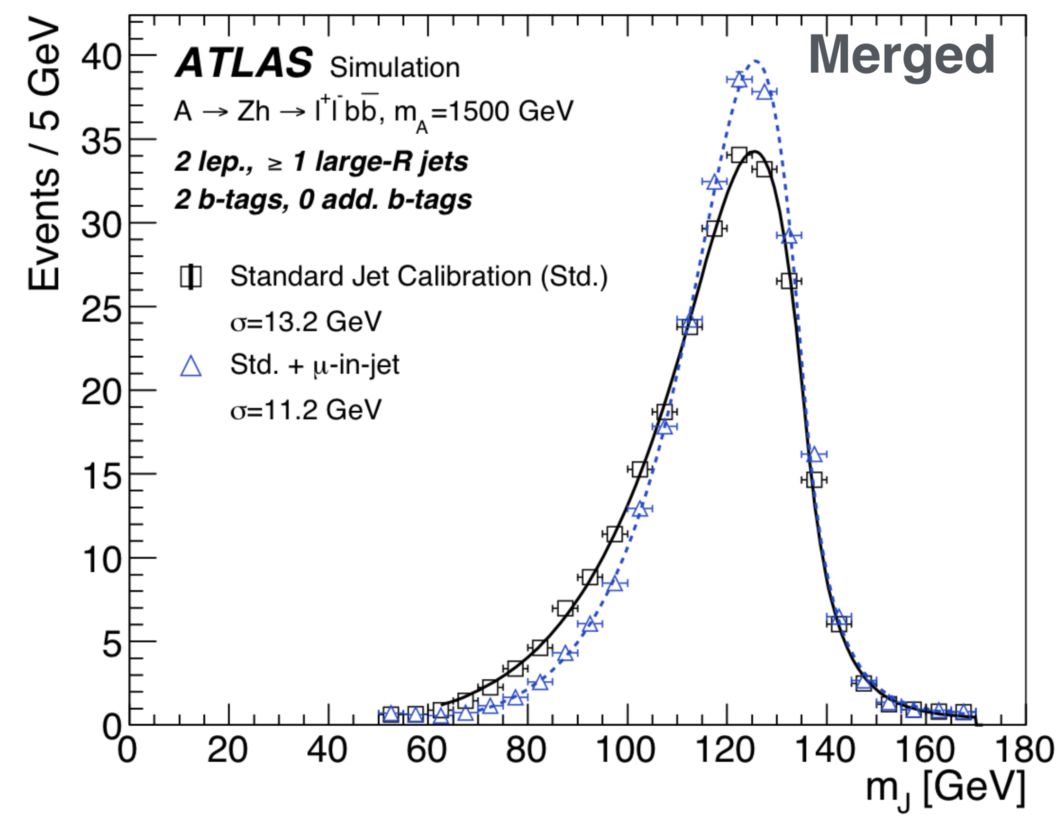
Fit		Channel	Resolved signal regions	Merged signal regions	Resolved control regions
A		0-lepton	1, 2, 3+ b-tag	1, 2 b-tag, and 1, 2 b-tag add. b-tag	–
		2-lepton	1, 2, 3+ b-tag	1, 2 b-tag, and 1+2 b-tag add. b-tag	1+2 b-tag , 3+ b-tag $e\mu$
HVT	Z', W'	0-lepton	1, 2 b-tag	1, 2 b-tag	–
	W'	1-lepton	1, 2 b-tag	1, 2 b-tag	1, 2 b-tag m_{jj} sideband
	Z'	2-lepton	1, 2 b-tag	1, 2 b-tag	1+2 b-tag $e\mu$

arXiv:1712.06518

Vh mass resolution improvement

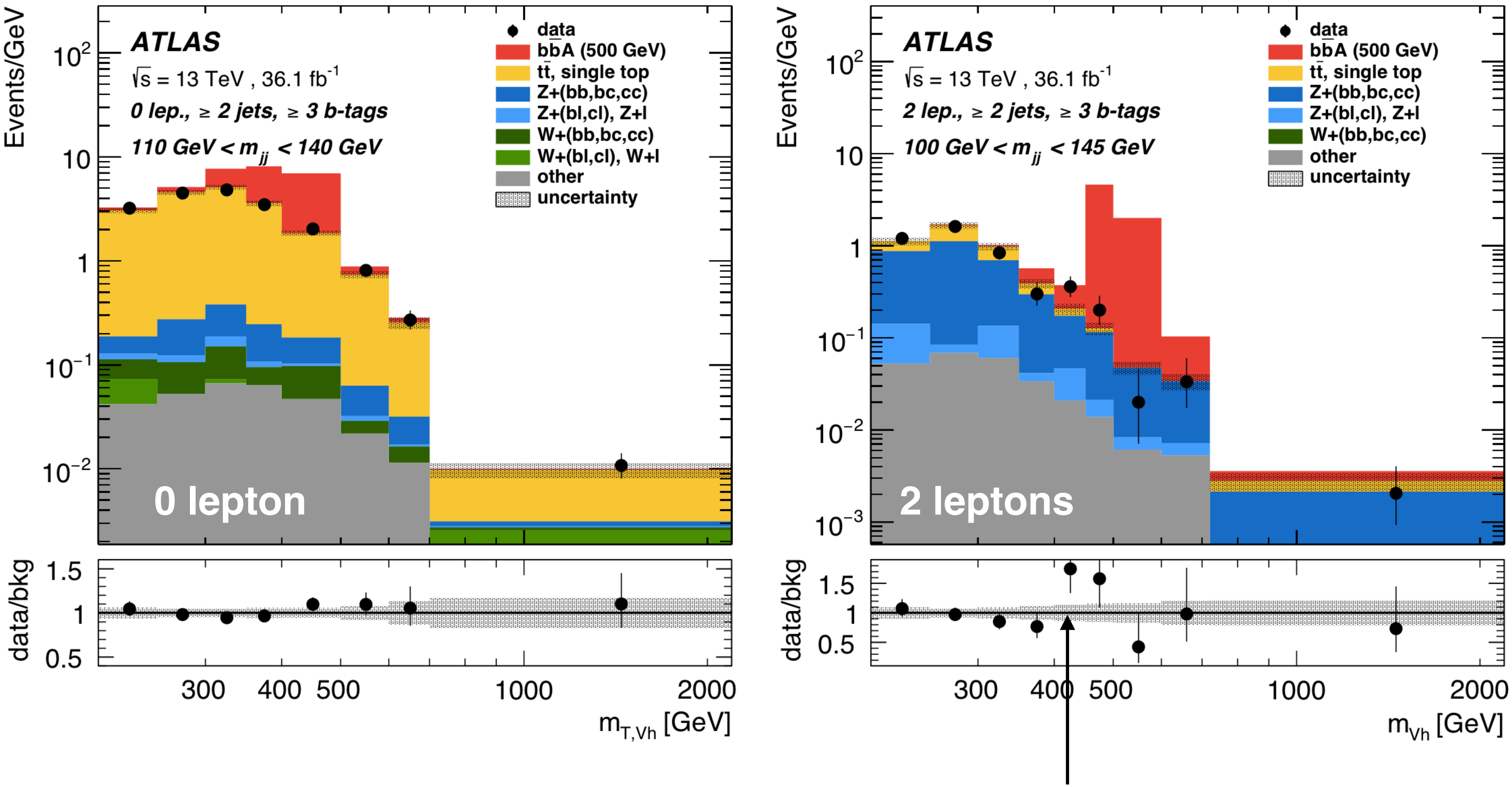
- Muon-in-jet correction
  - Add muon momentum (p_T>5 GeV, closet dR) to the jet
  - Account for the semileptonic decays of the b-hadrons
- PtReco
  - Correct jet momentum as a function a jet p_T trained with truth b-jets from the Higgs decay
  - Account for biases in the response of b-jets
- Over improvement on resolution is about 20%





arXiv:1712.06518

Vh global fits: 2-lepton bbA signal

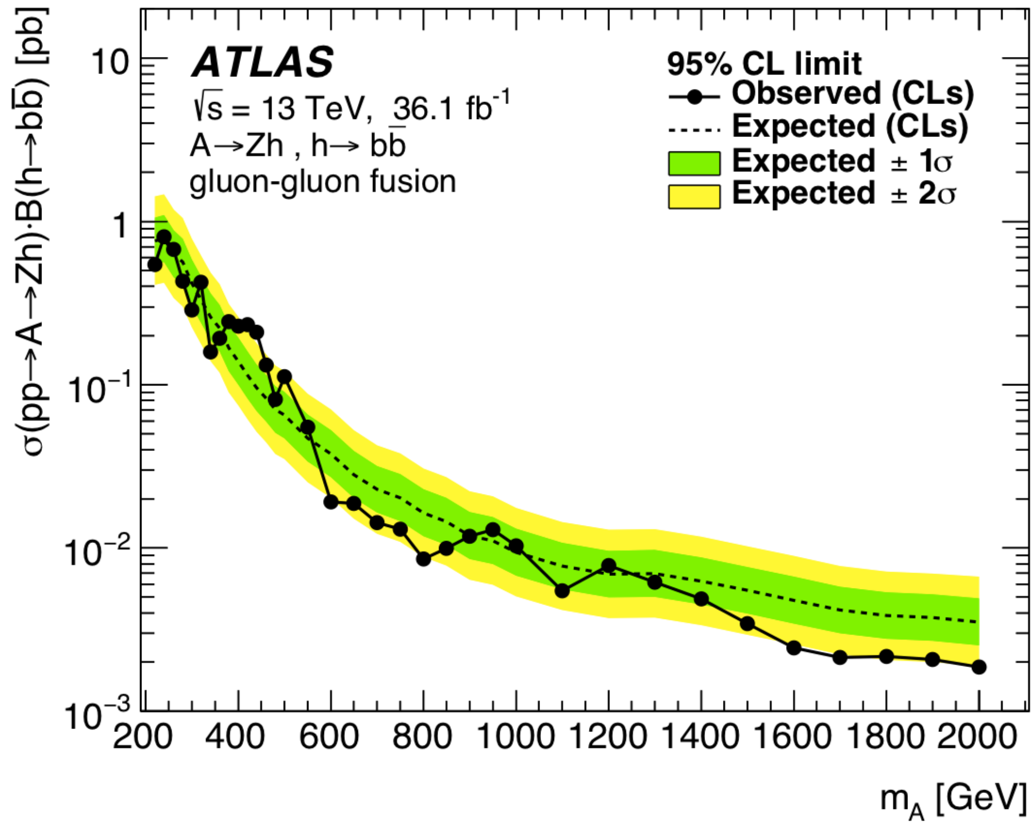


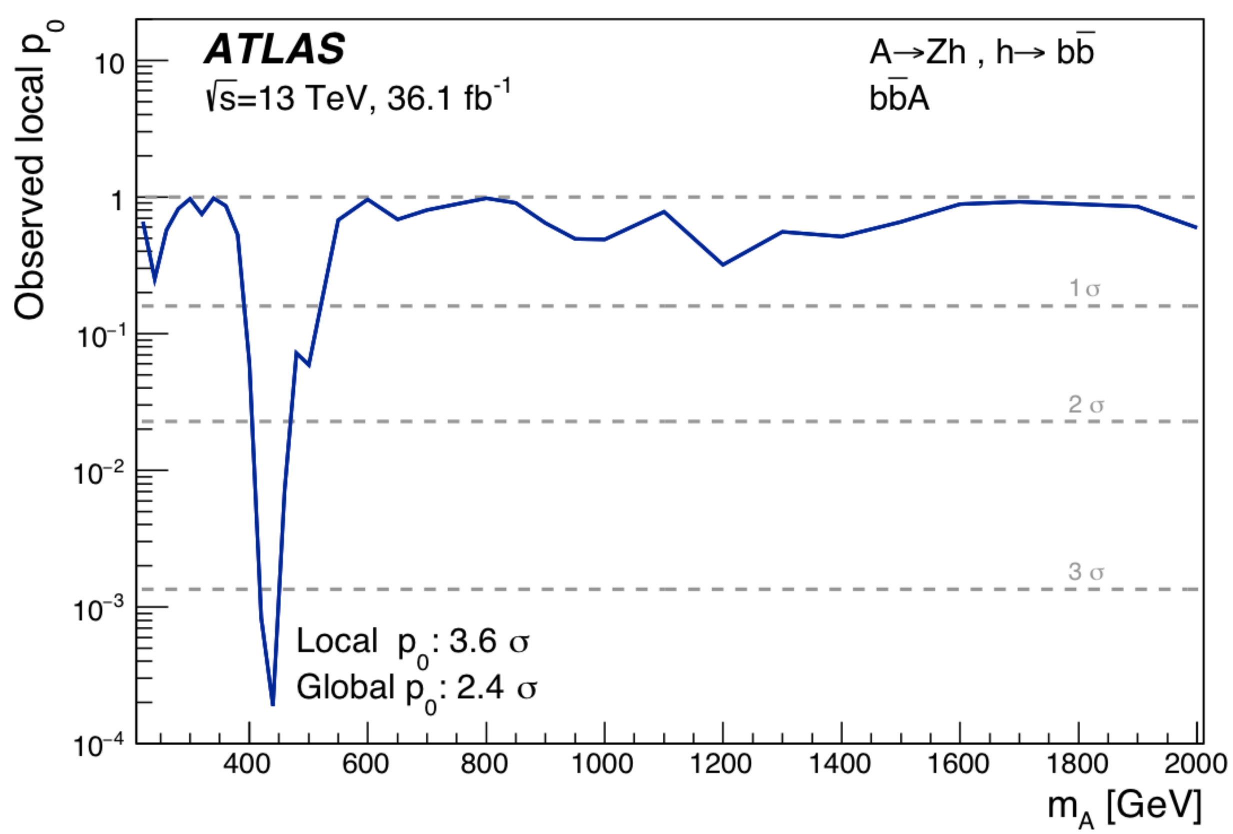
Small data excess

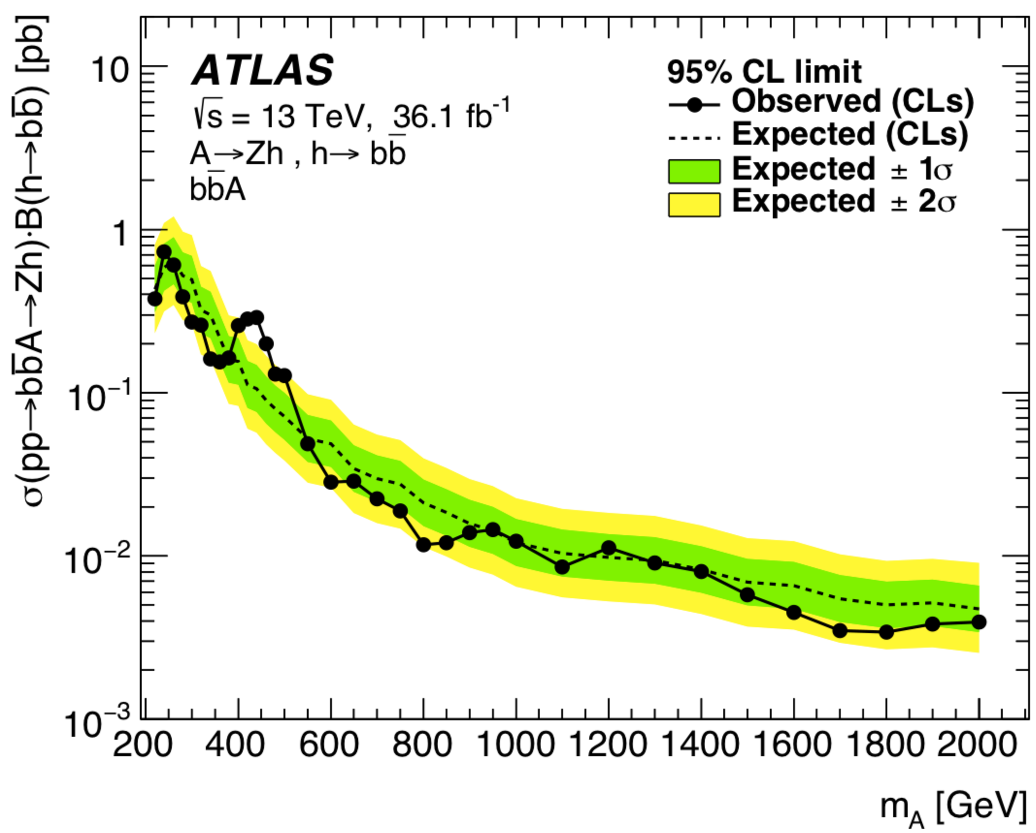
arXiv:1712.06518

Vh results on CP-odd A in 2HDM

- Local data excess at ~400GeV mainly found in bbA 3b+ events
  - Local significance 3.6 σ
  - Global significance 2.4 σ
- 2HDM interpretation on the next pave

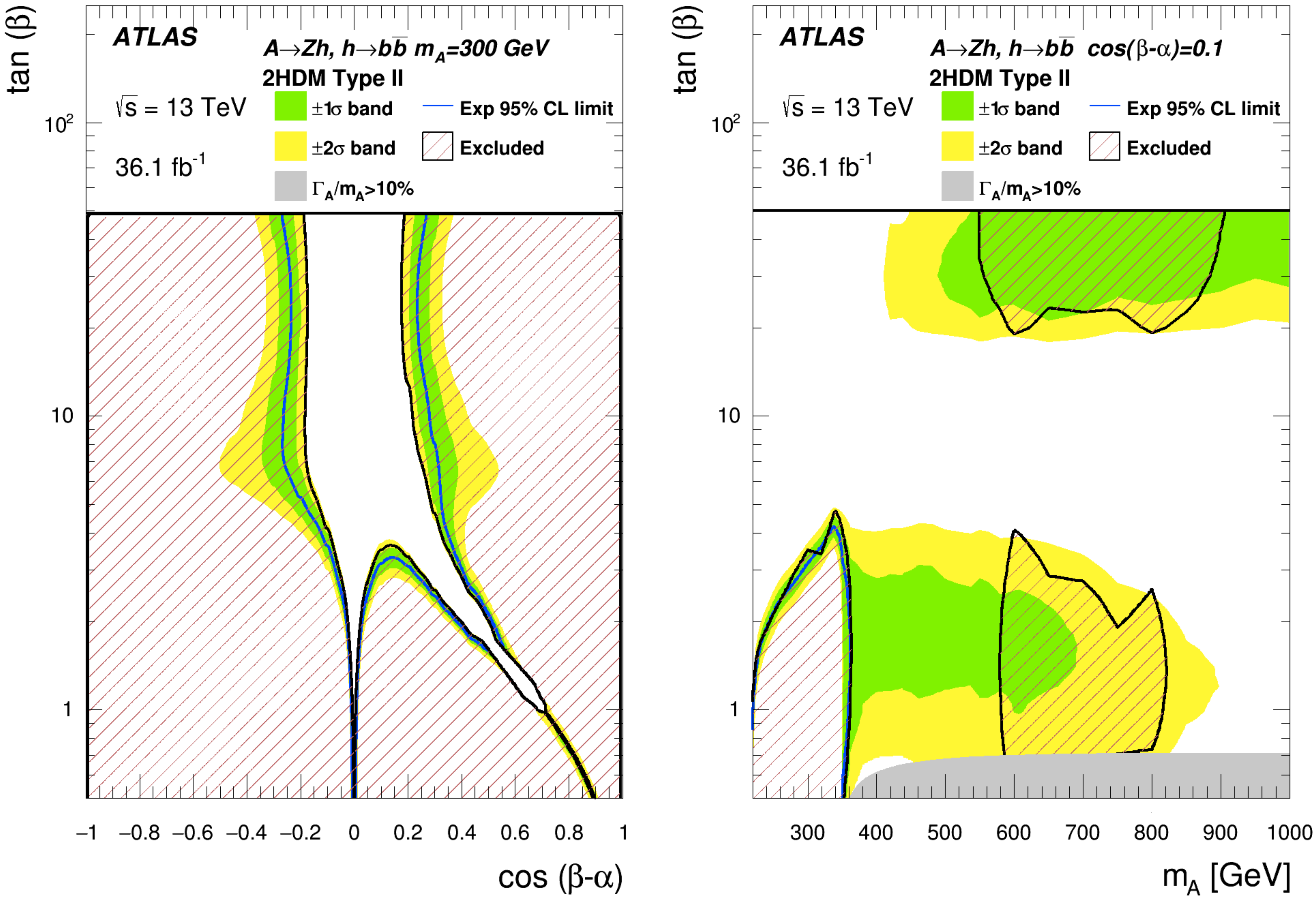






arXiv:1712.06518

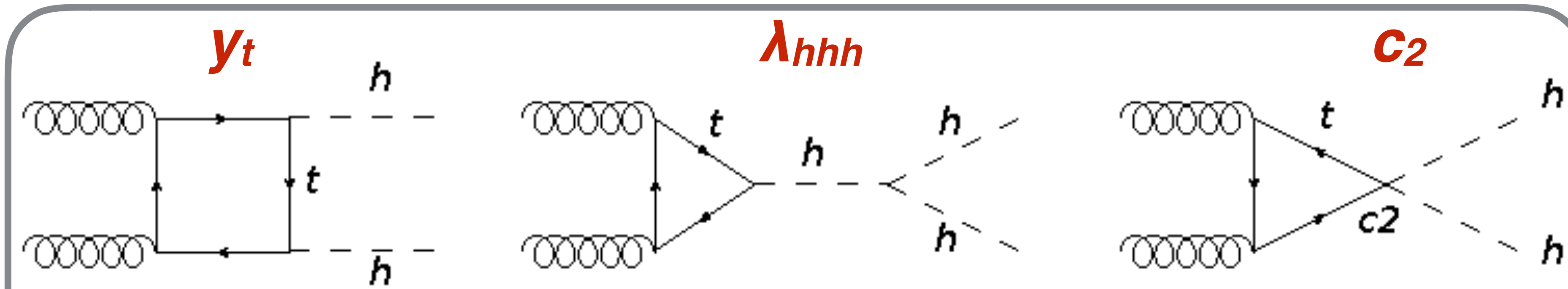
Vh 2HDM interpretation



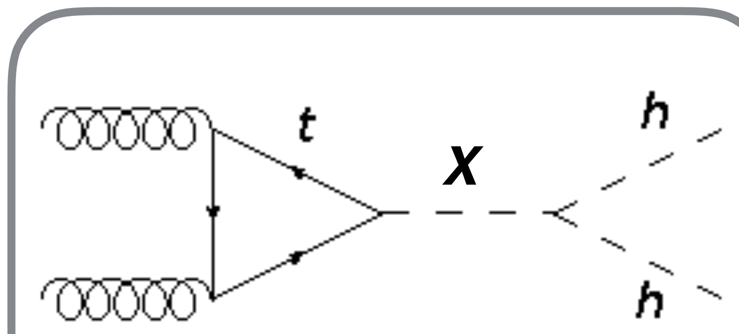
HH searches: motivation

- The SM non-resonant production has a xs **3** orders of magnitude smaller than the single Higgs due to the destructive interference
- Non-resonant searches to probe
  - **Trilinear Higgs self-coupling (a fundamental SM parameter that is directly NOT measured yet)**
  - Top Yukawa coupling, and new EFT couplings etc.

- Resonant searches to probe:
  - EWK singlet
  - 2HDM
  - MSSM
  - Graviton models
  - etc.



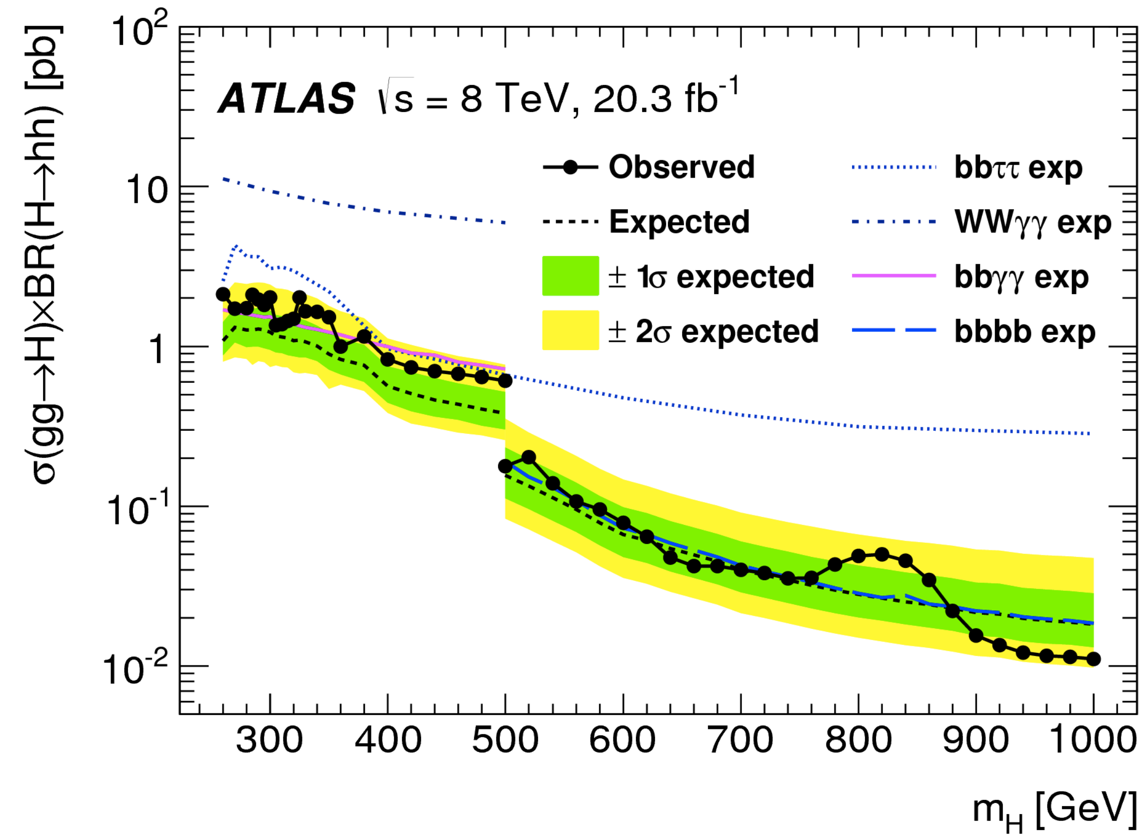
Non-resonance



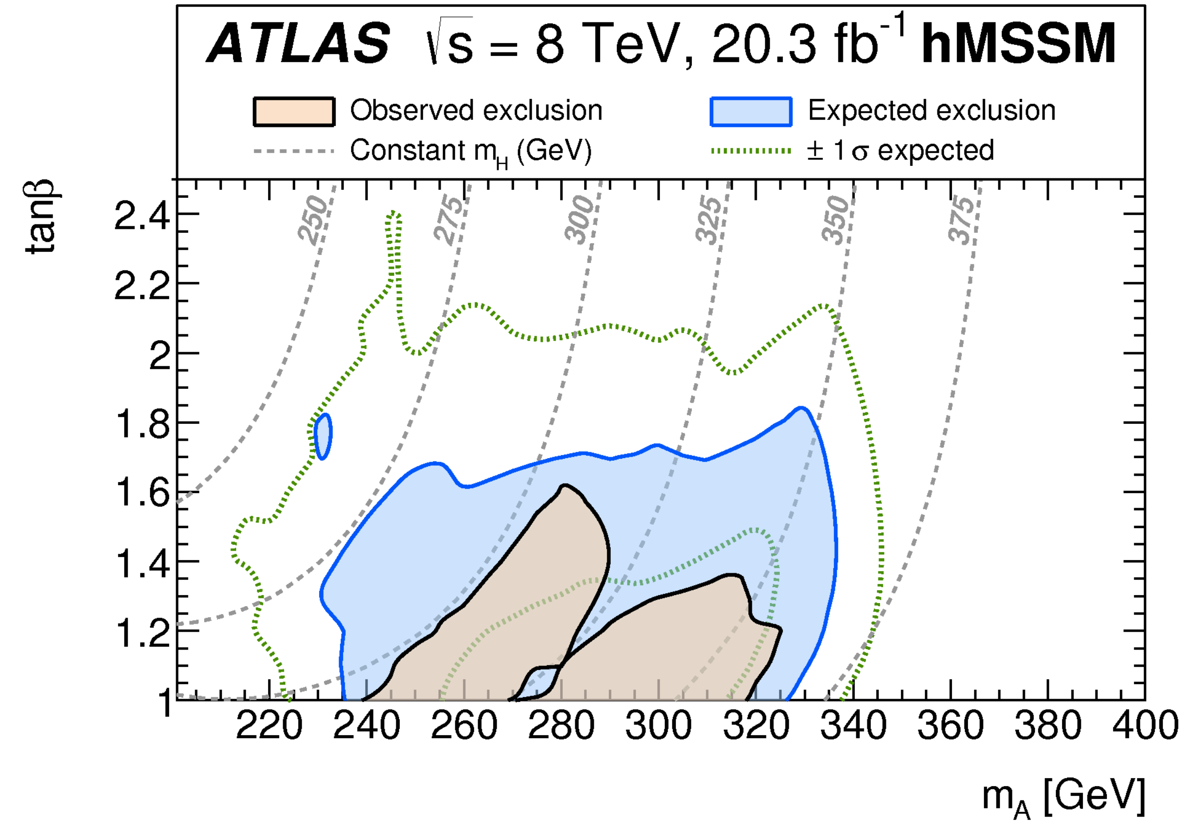
Resonance

Run I ATLAS results

- Four channels were searched for HH with ATLAS in Run 1
- Upper limits on the non-resonant production are **50** times of the SM prediction after combining all channels
- Upper limits on resonant production is set and used to interpret hMSSM

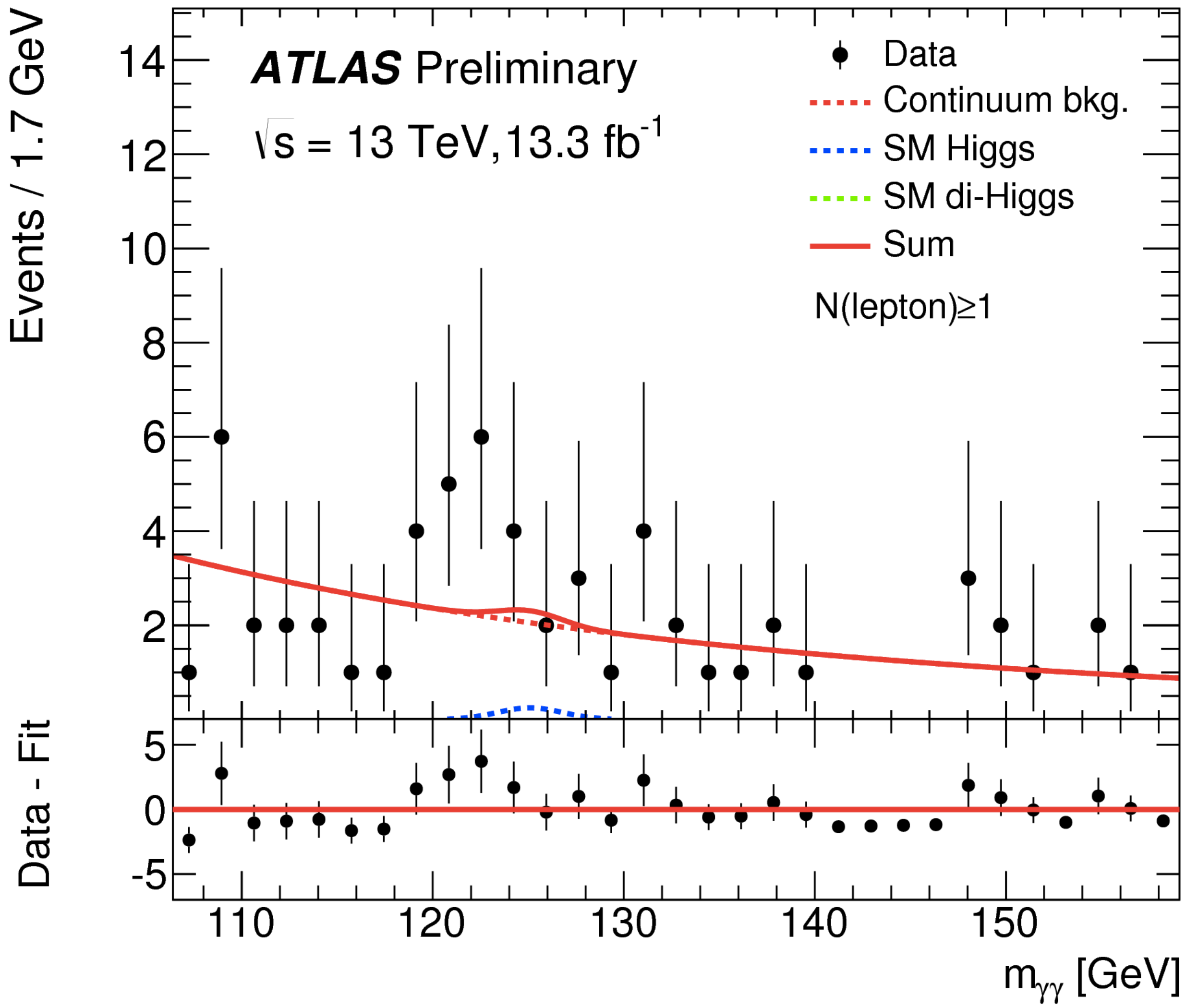


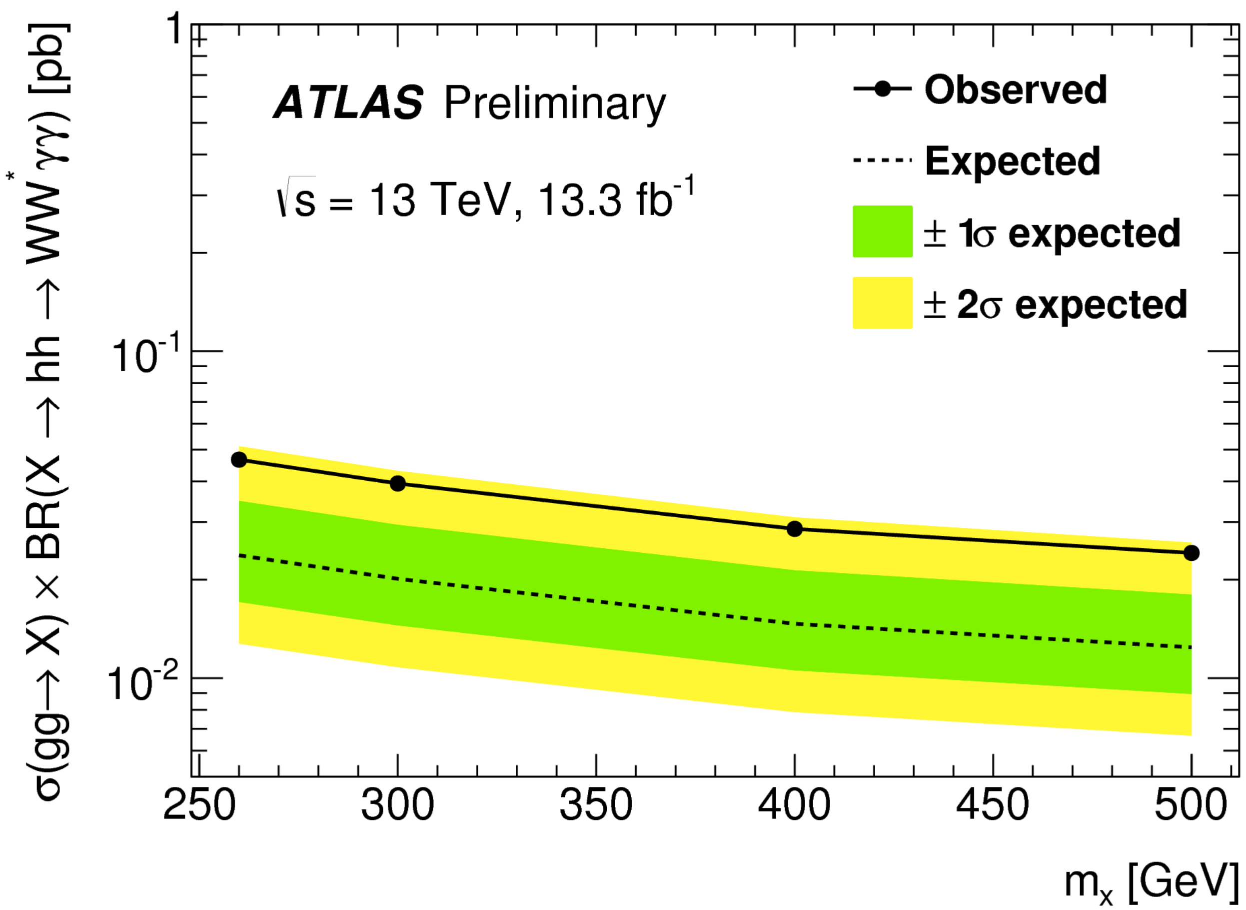
Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
Non-resonant	Upper limit on the cross section [pb]				
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70



Phys. Rev. D 92, 092004 (2015)

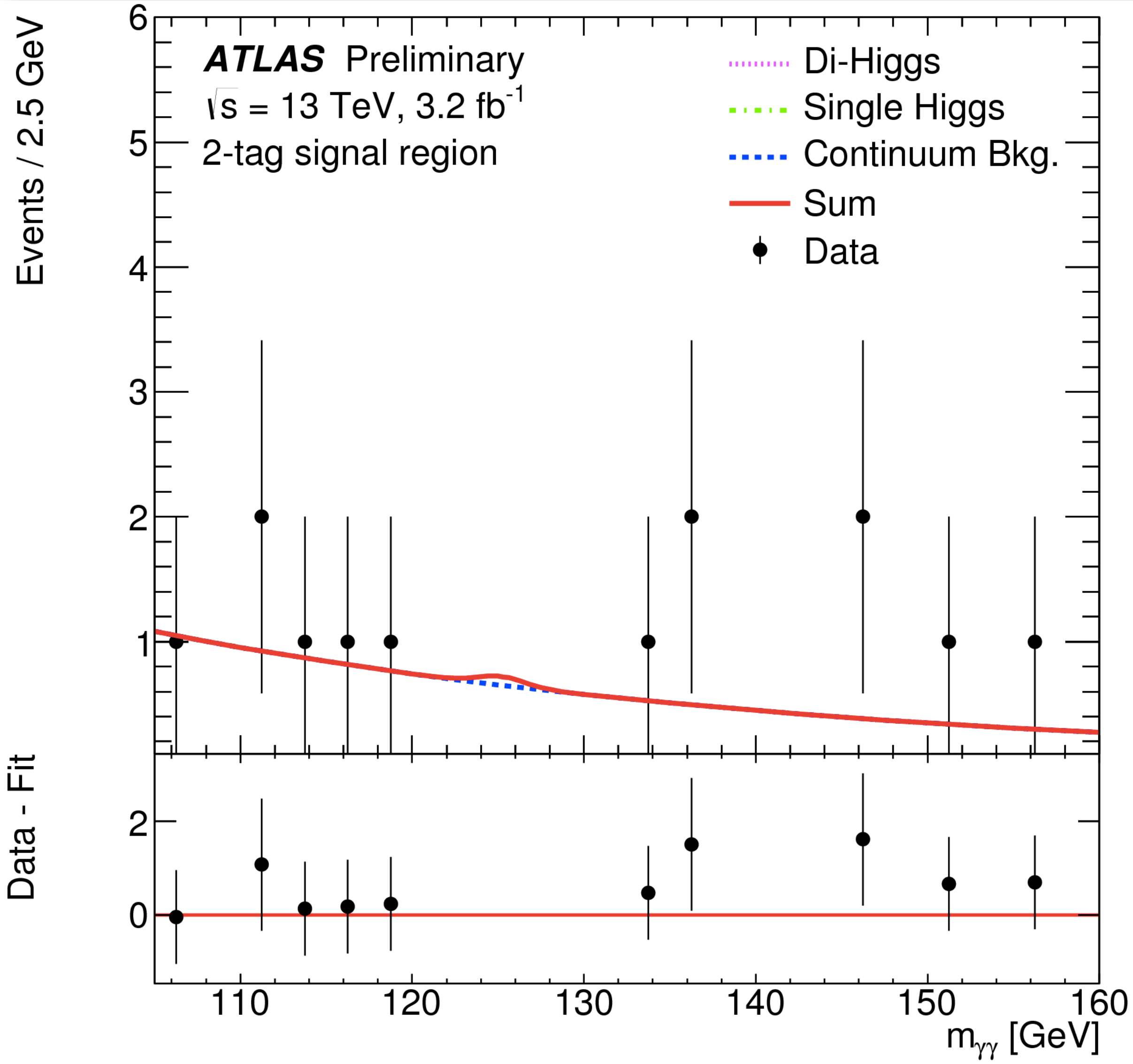
Run2 WWγγ

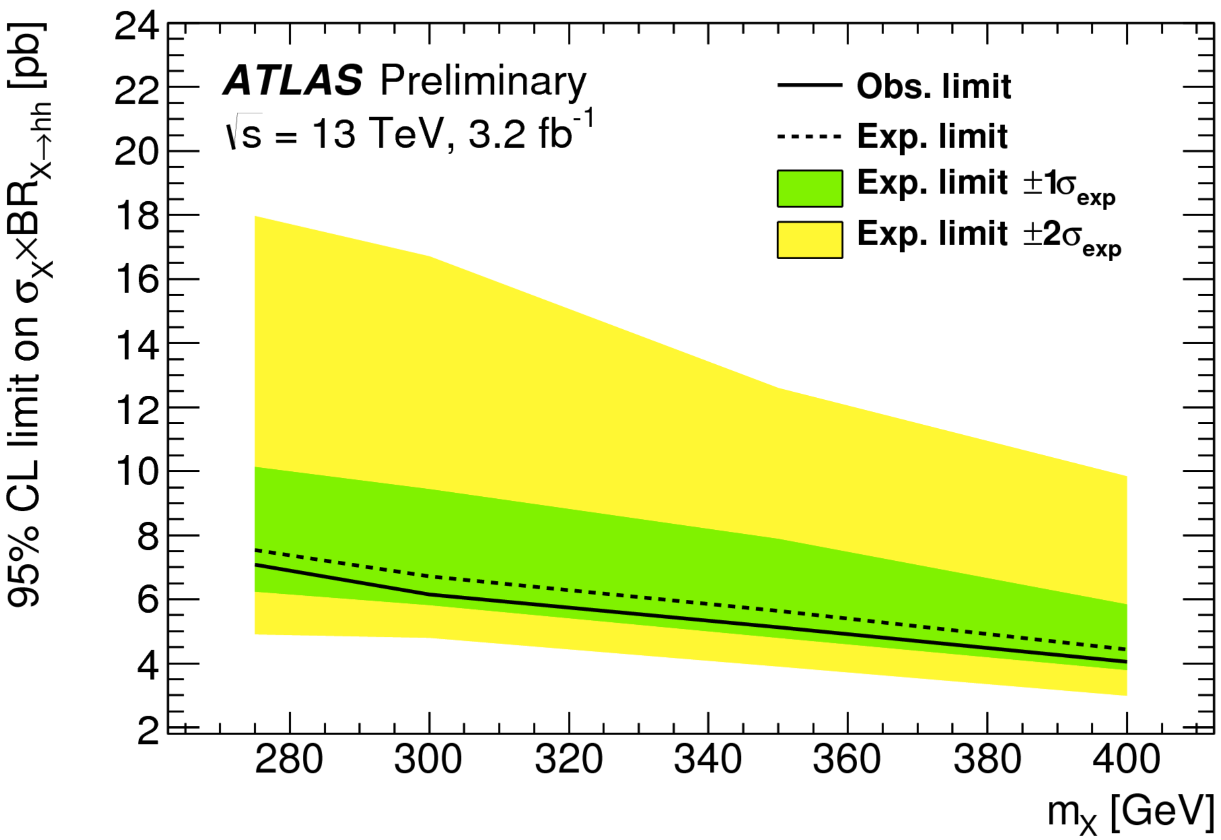




- Latest CONF results with 13.3 fb^{-1} in ICHEP 2016 (link)
- Large BR from WW and characteristic signature from γγ
- Dominant background: multiphoton+multijet backgrounds
- No significant data excess is found
- Upper limits on non-resonant SM Higgs pair production:
  - 386 times of the SM prediction

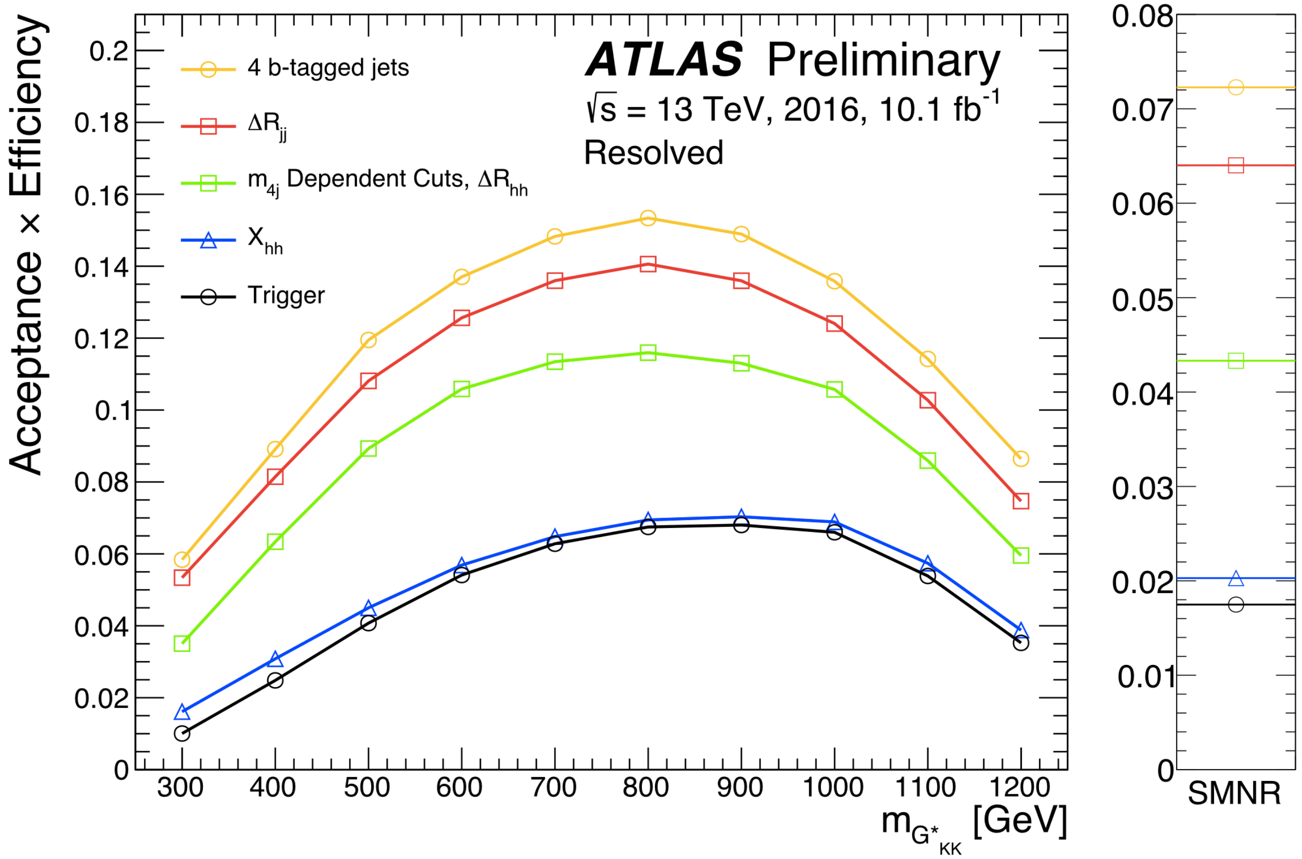
Run2 bbγγ

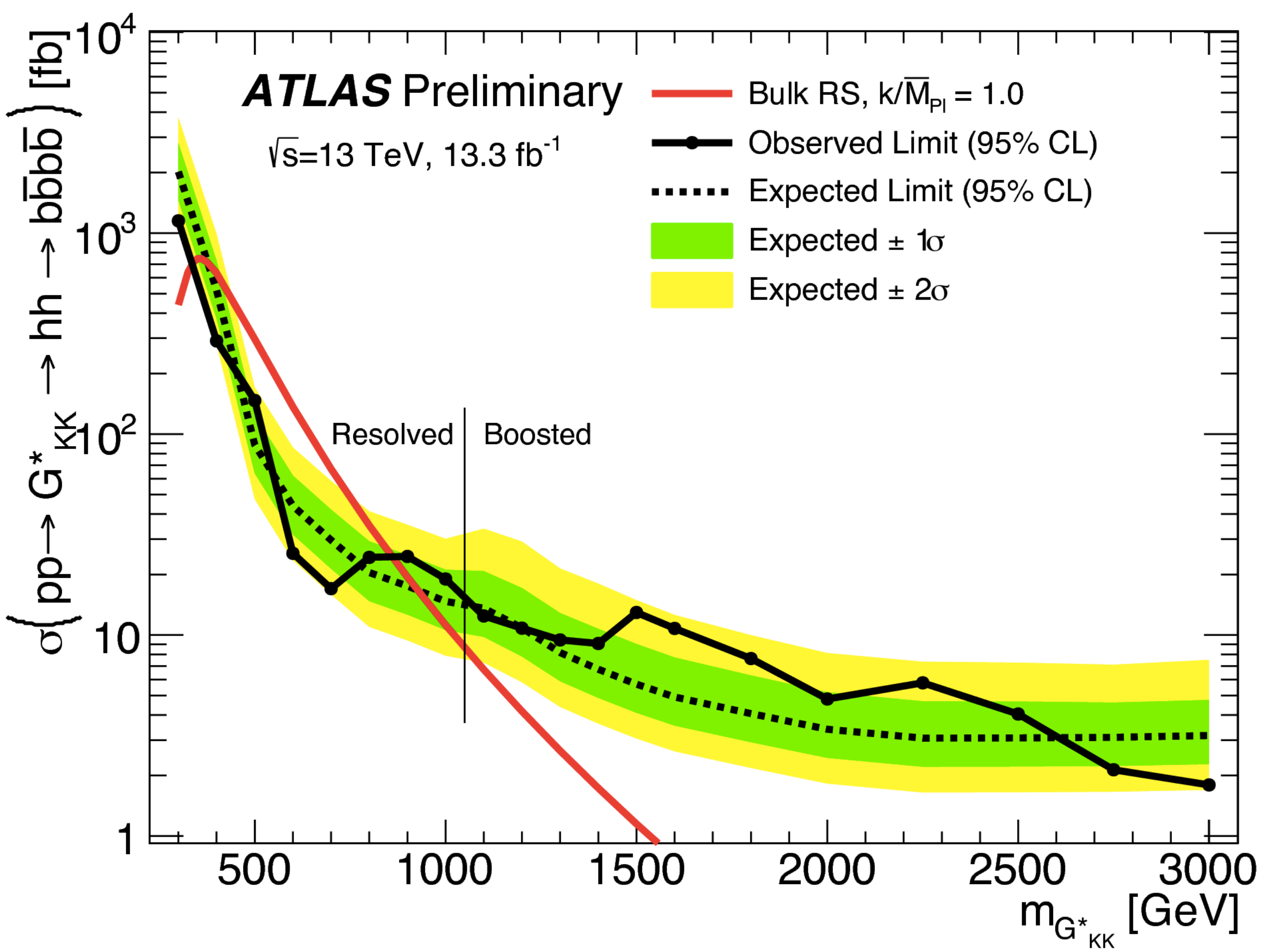




- Latest CONF results with 3.2 fb-1 13 TeV (link)
- Large BR from bb and good mass resolution from γγ
- Dominant background: multiphoton+multijet backgrounds
- No significant data excess is found
- Upper limits on non-resonant SM Higgs pair production:
  - 117 times of the SM prediction

Run2 bbbb



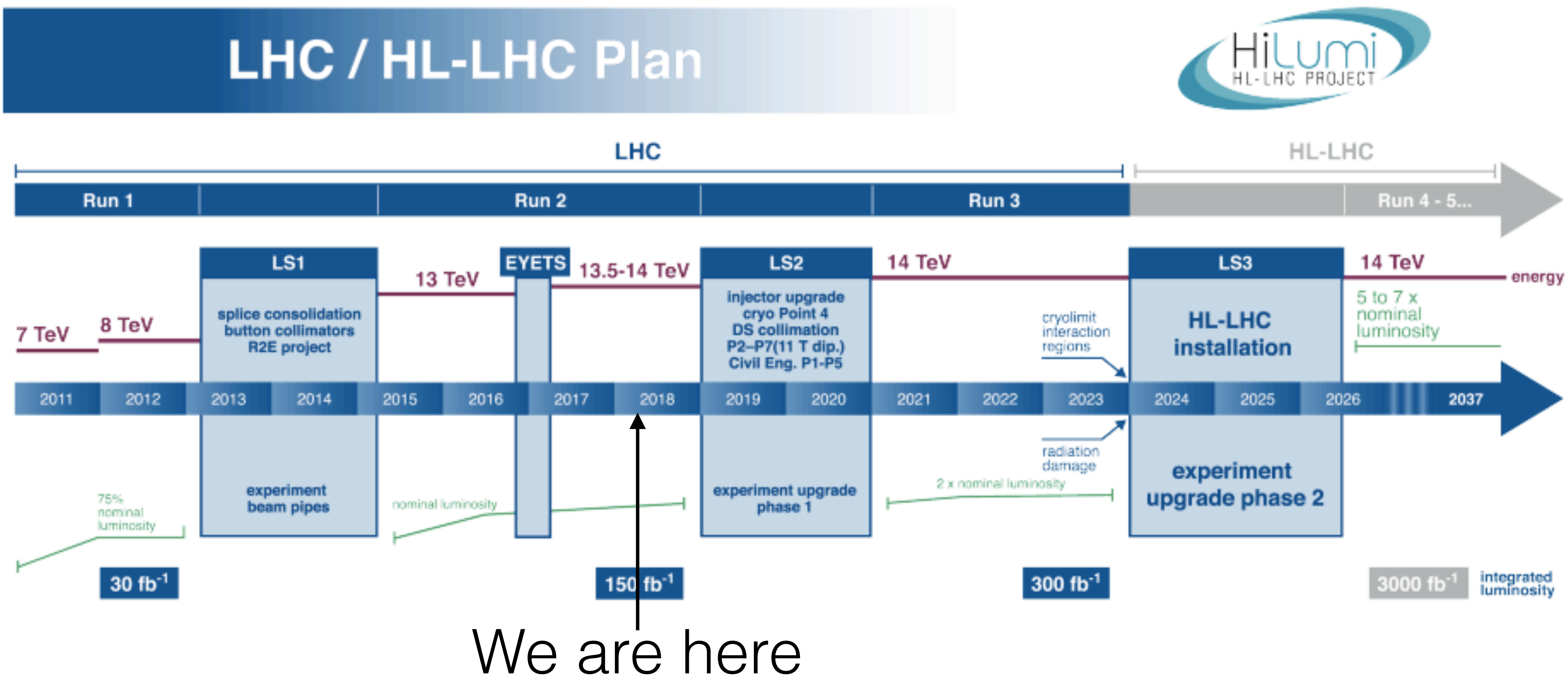


- Latest CONF results with 13.3 fb^{-1} 13TeV (link): to be superseded by EXOT-2016-31 very soon
- Largest BR in all hh channels
- Dominant backgrounds: multijet and top
- No significant data excess is found
- Upper limits on non-resonant SM Higgs pair production:
  - 29 times of the SM prediction

Summary

- The luminosity measurement with new data is undergoing
  - LUCID detector went smoothly in the last year and will continue to provide the nominal luminosity measurement
  - FIBER detector will replace all other BI PMTs in Run3 given its flexibility in terms of space
- Heavy Higgs boson searches with ZH and HH are of great interest after the discovery of the SM Higgs boson
  - There are already a lot of results with Run1 and part of Run2 data going out in searches of heavy Higgs bosons
  - There will be more coming out very soon with partial data and certainly more to the end of Run 2

LHC / HL-LHC Plan



Run 2 data taking will end in this year (2018)

There will be lots of opportunities of measurement and search paper in next two years (~2019)

There will be more intensive efforts on the upgrade projects in next four years (~2020)

Then a Run 3 will start and last another three years with many surprises ahead (~2023 and after)

I wish the LHC fruitful coming years!

Thanks for your attendance!

Backup slides

LUCID

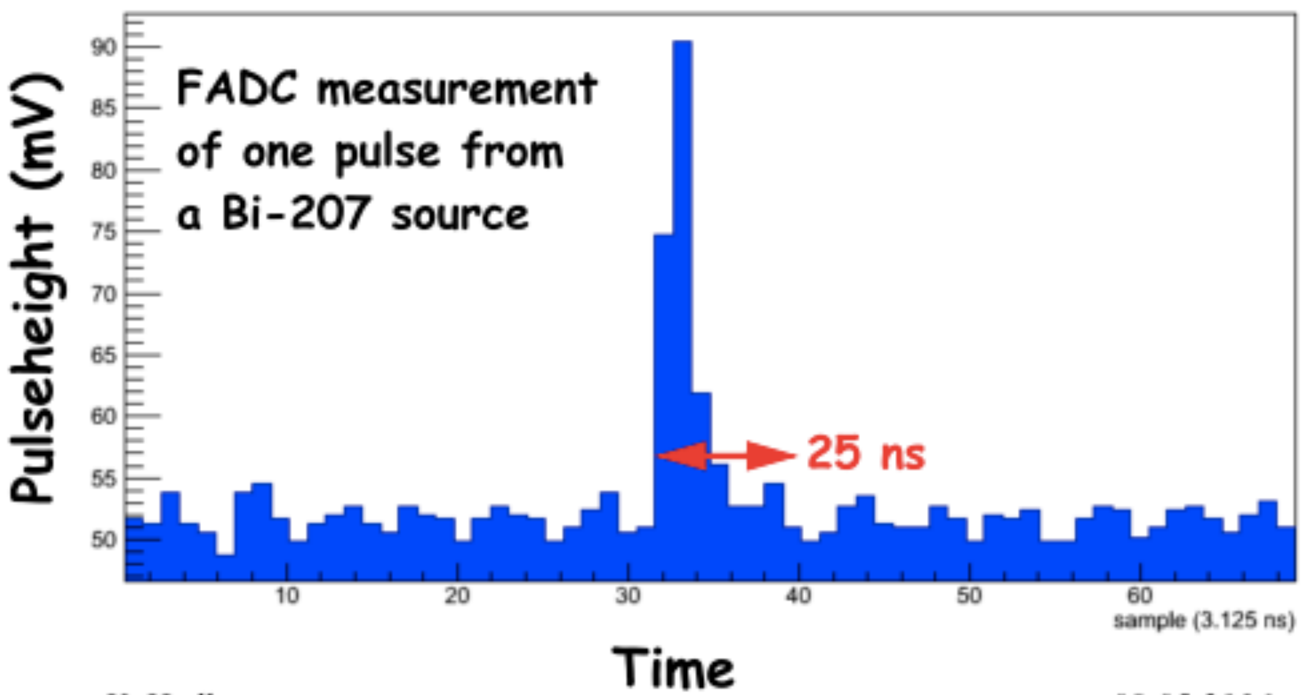
Zero-starvation:

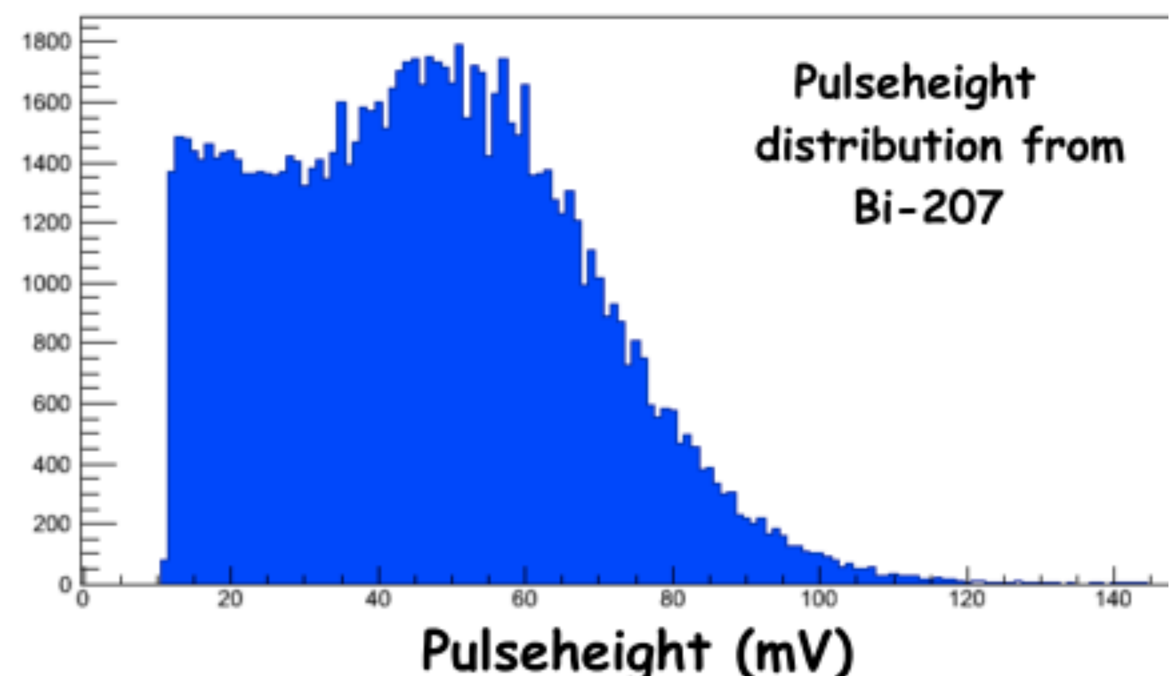
Algorithm	σ^{vis} (mb)	ε (%)	μ_{max}	
BI_OR	32.4	40.5	24	4+4 pmts
BI_OR_A	19.3	24.2	41	4 pmts
BI_AND	6.38	8.0	125	4 AND 4 pmts
BI_C9	6.44	8.0	125	1 pmt
MOD_OR	21.7	27.1	36	4+4 modified pmts

$$\mathcal{L}_{BCID} = \frac{-\ln(1 - f)}{\sigma_{vis}} f_{LHC}$$

$$\mathcal{L}_{BCID} = \frac{C}{\sigma_{vis}} f_{LHC}$$

Bi-207 give monoenergetic electrons from internal conversions with an energy above the Cherenkov threshold in quartz. The half-life is 33 years.





Eur. Phys. J. C (2016) 76:653

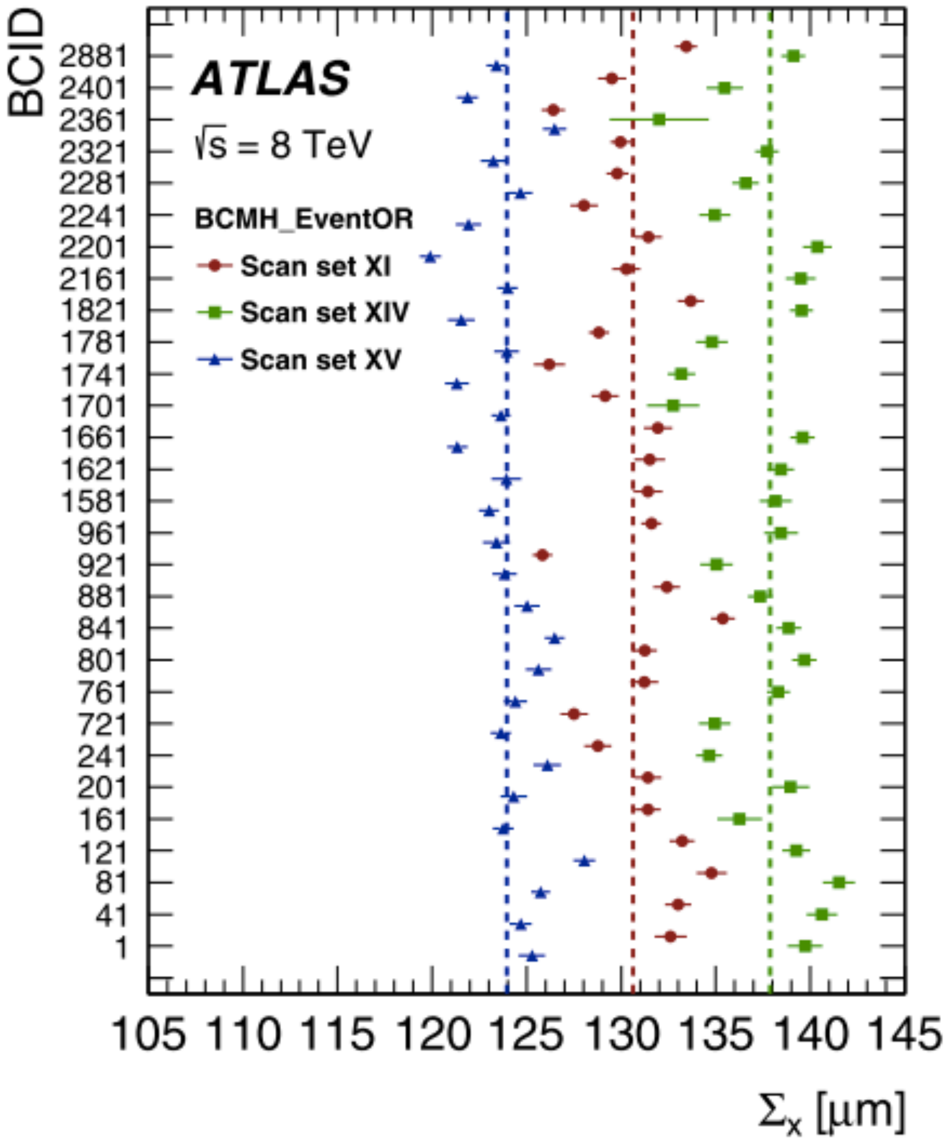
The uncertainties on σ_{vis}

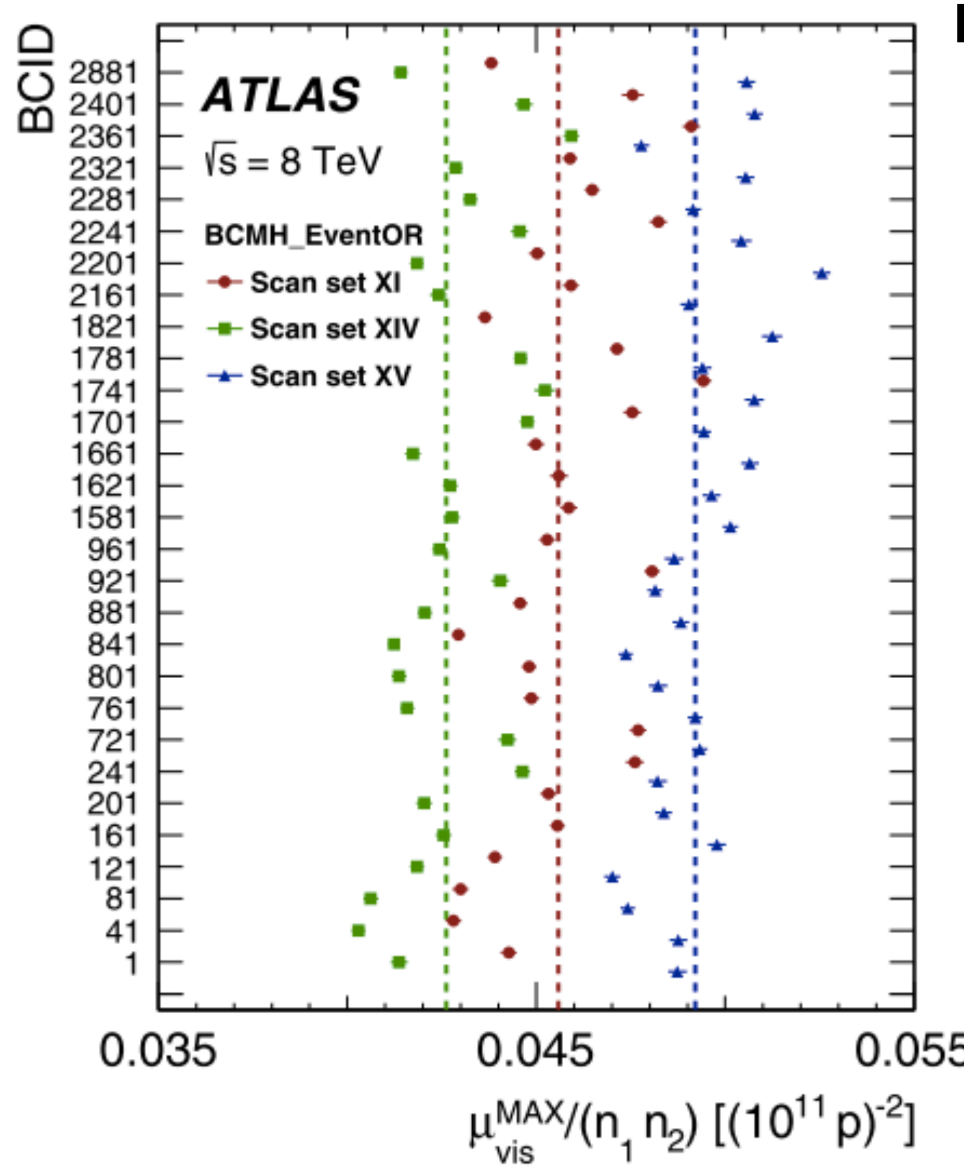
- Reference specific luminosity (the luminosity measured by different detectors should be consistent. The diff. is treated as uncertainty)
- Length-scale calibration (bunch positions in the transverse plane)
- Fit model (alternative signal modelling functional forms)
- Non-factorization correction (diff. of factorisation and non-factorisation particle density function)

Table 6 Fractional systematic uncertainties affecting the visible cross-section $\overline{\sigma}_{vis}$ averaged over *vdM* scan sets XI–XV (November 2012)

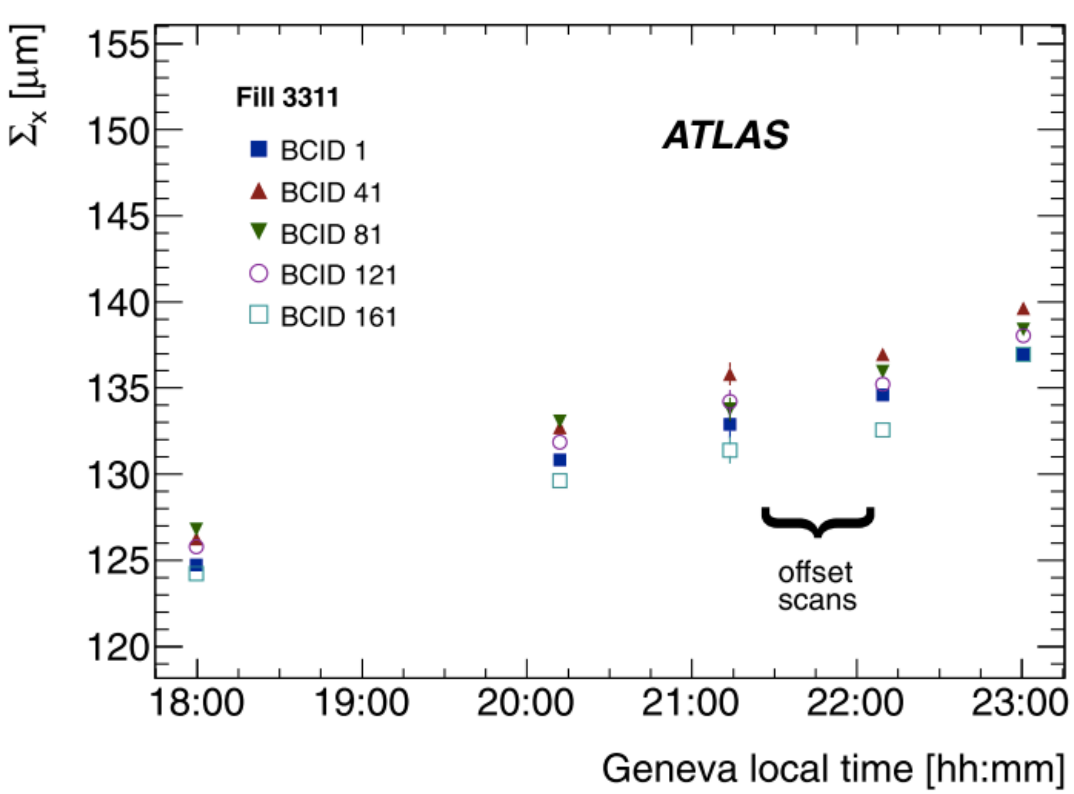
Source	Uncertainty (%)
Reference specific luminosity	0.50
Noise and background subtraction	0.30
Length-scale calibration	0.40
Absolute ID length scale	0.30
Subtotal, instrumental effects	0.77
Orbit drifts	0.10
Beam-position jitter	0.20
Beam–beam corrections	0.28
Fit model	0.50
Non-factorization correction	0.50
Emittance-growth correction	0.10
Bunch-by-bunch σ_{vis} consistency	0.23
Scan-to-scan consistency	0.31
Subtotal, beam conditions	0.89
Bunch-population product	0.24
Total	1.20

Eur. Phys. J. C (2016) 76:653





Emittance (evolvement of convolved beam size) within a vdM scan



Emittance (evolvement of convolved beam size) in several vdM scan

Eur. Phys. J. C (2016) 76:653

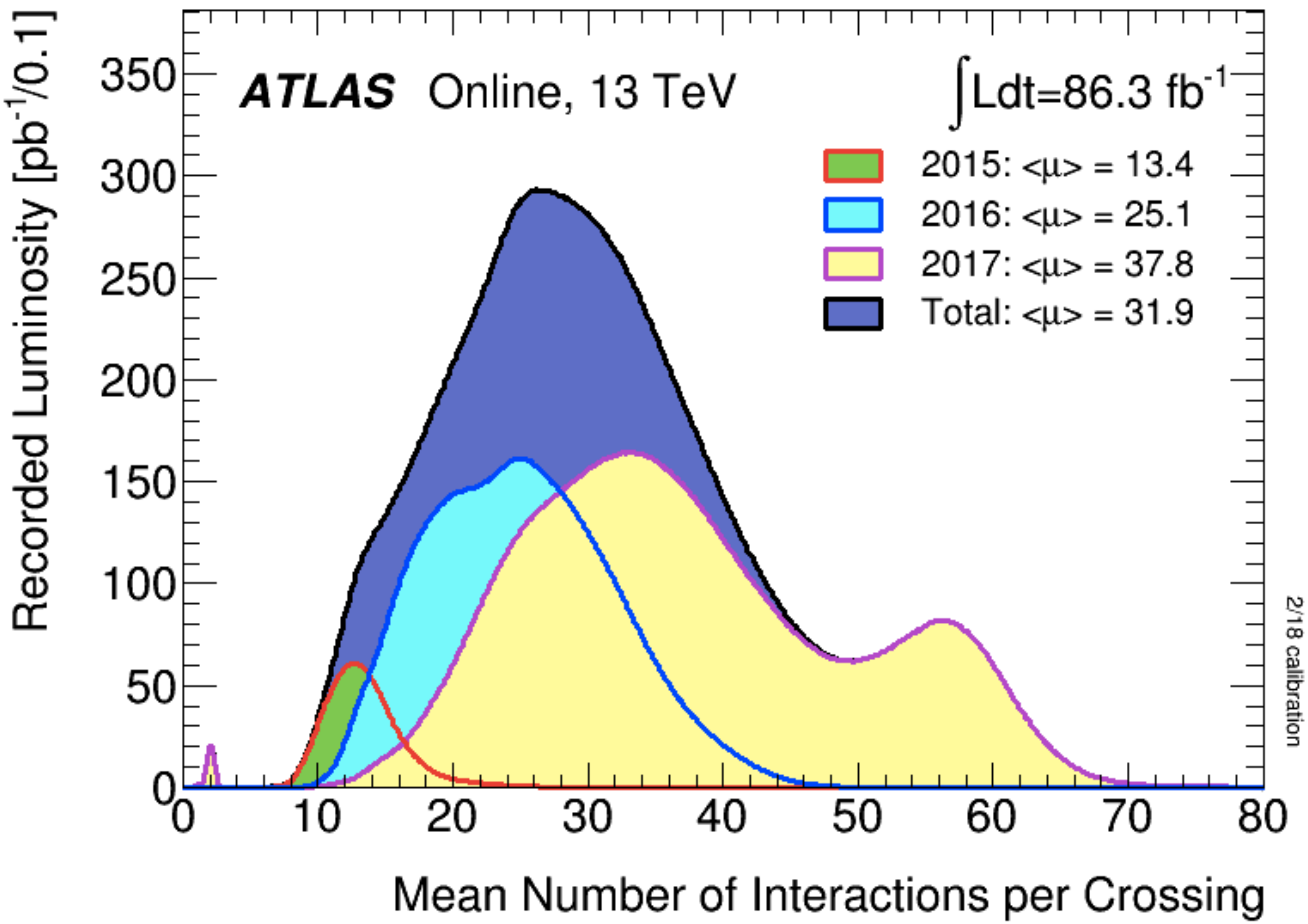
The uncertainties of luminosity measurements

Table 9 Relative uncertainty in the calibrated luminosity scale, broken down by source

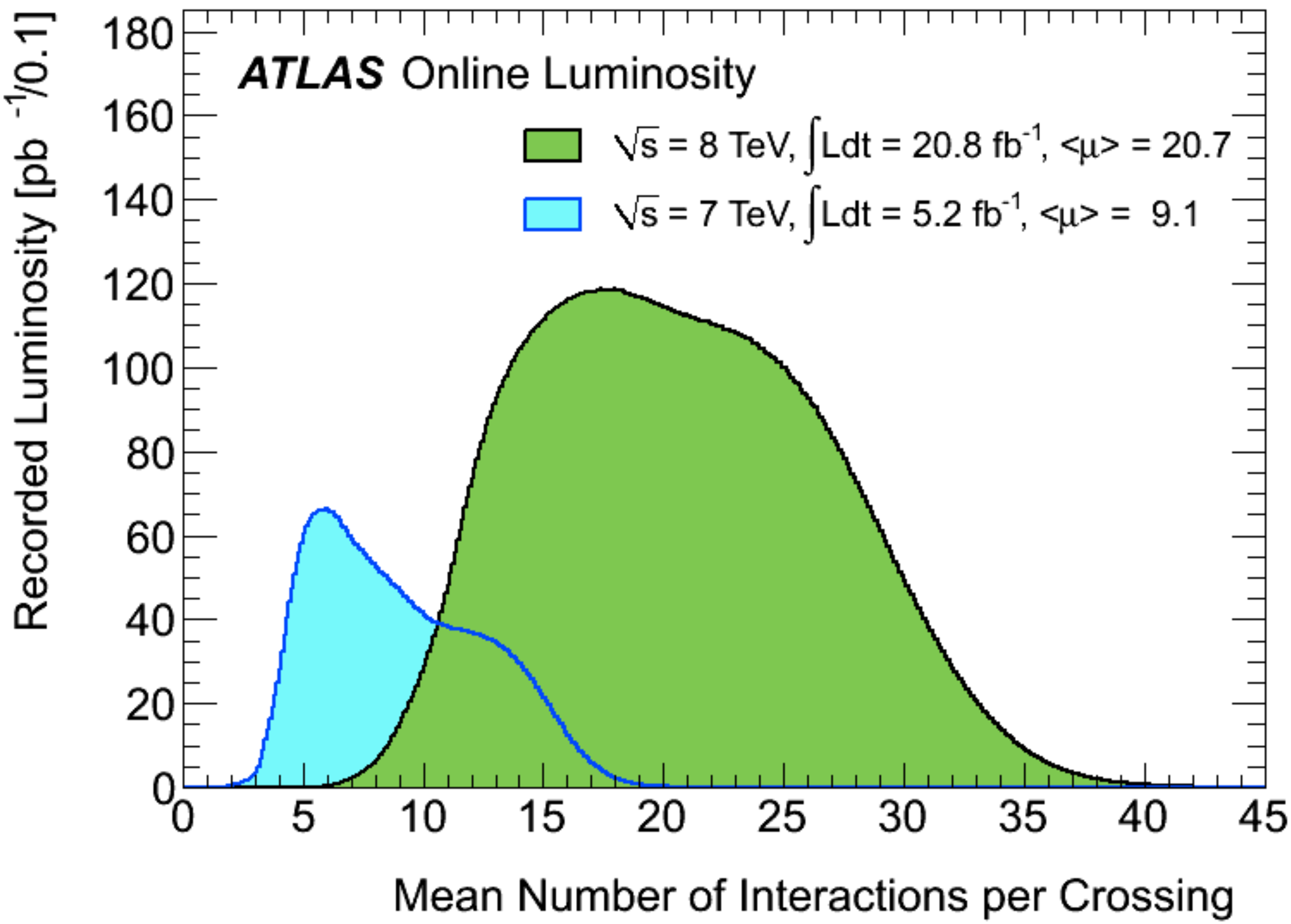
Uncertainty source	$\delta\mathcal{L}/\mathcal{L}$ [%]
van der Meer calibration	1.2
Afterglow subtraction	0.2
Calibration transfer from *vdM*-scan to high-luminosity regime	1.4
Long-term drift correction	0.3
Run-to-run consistency	0.5
Total	1.9

2012

Number of Interactions per Crossing



Number of Interactions per Crossing



Detector conditions

ATLAS pp 25ns run: June 5-November 10 2017										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.9	99.3	99.5	99.4	99.9	97.8	99.9	100	100	99.2
Good for physics: 93.6% (43.8 fb^{-1})										

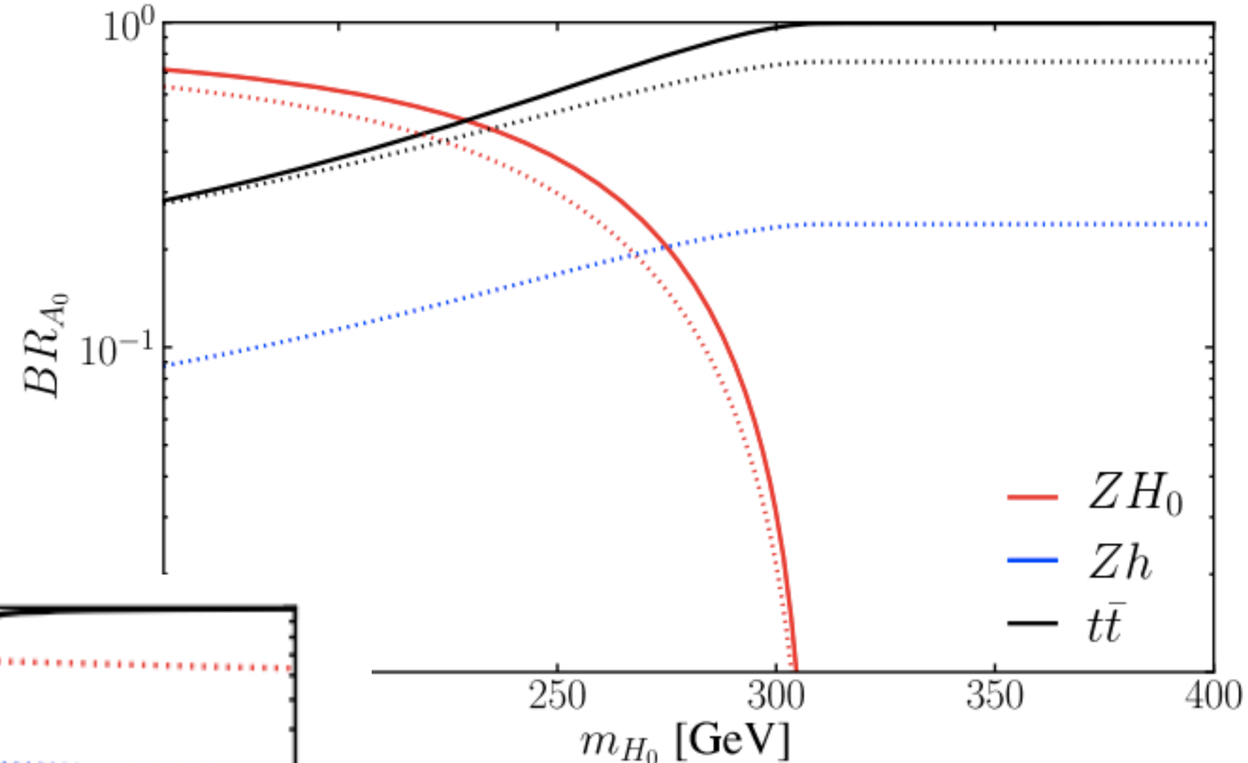
Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at $\sqrt{s}$=13 TeV between June 5 – November 10 2017, corresponding to a delivered integrated luminosity of 50.4 fb^{-1} and a recorded integrated luminosity of 46.8 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.5 fb^{-1}. Analyses that don't require the toroid magnet can use these data.

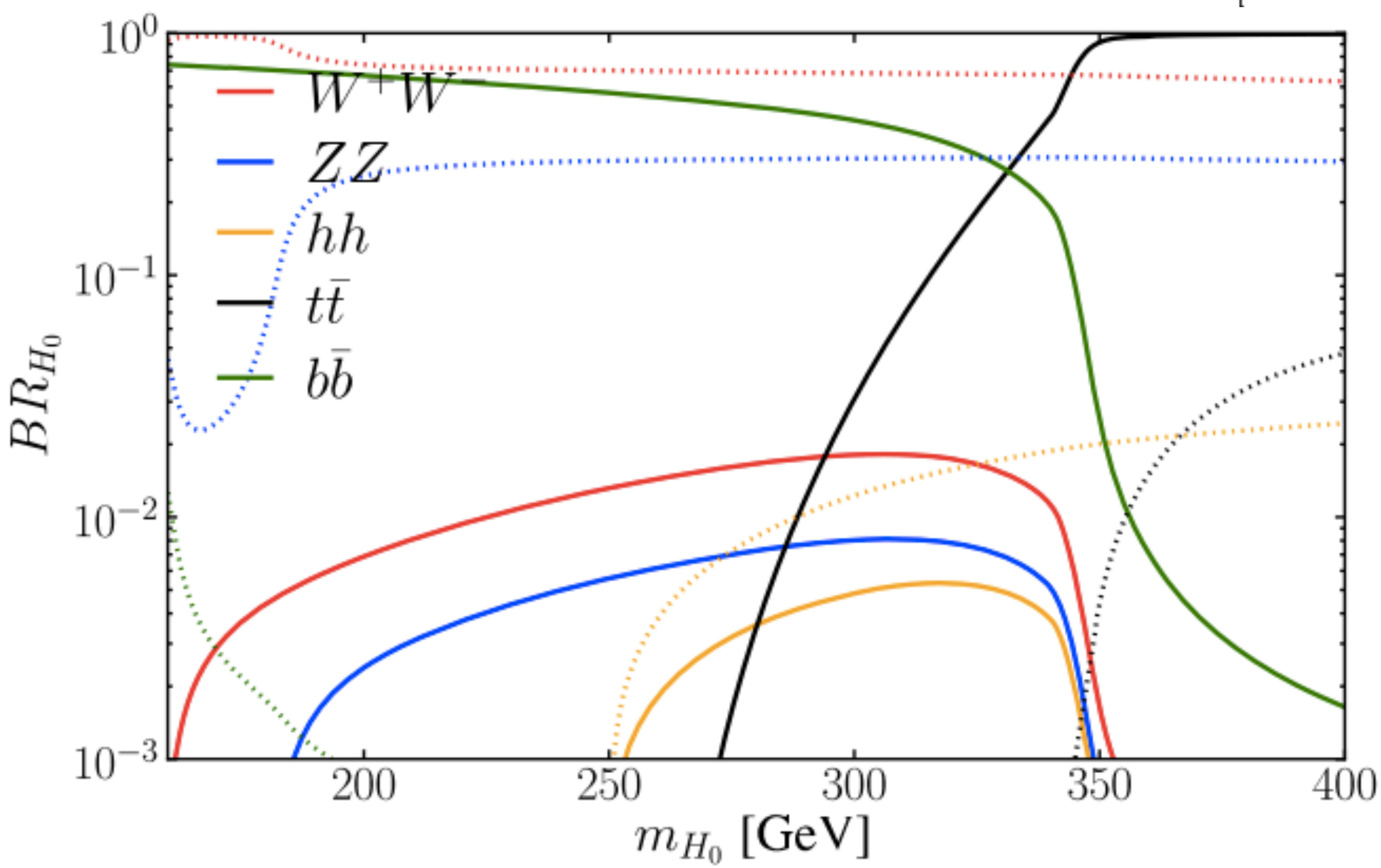
2HDM couplings

y_{2HDM}/y_{SM}	2HDM 1	2HDM 2	2HDM 3	2HDM 4
hVV	$s_{\beta-\alpha}$	$s_{\beta-\alpha}$	$s_{\beta-\alpha}$	$s_{\beta-\alpha}$
hQu	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$
hQd	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$
hLe	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$
HVV	$c_{\beta-\alpha}$	$c_{\beta-\alpha}$	$c_{\beta-\alpha}$	$c_{\beta-\alpha}$
HQu	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$
HQd	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$
HLe	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$
AVV	0	0	0	0
AQu	$1/t_\beta$	$1/t_\beta$	$1/t_\beta$	$1/t_\beta$
AQd	$-1/t_\beta$	t_β	$-1/t_\beta$	t_β
ALe	$-1/t_\beta$	t_β	t_β	$-1/t_\beta$

2HDM BRs for large mass splitting

FIG. 2 (color online). Top (bottom): Main branching ratios of the CP-odd (CP-even) scalar A_0 (H_0) as a function of m_{H_0} for $m_{A_0} = m_{H^\pm} = 400$ GeV, $\tan\beta = 2$, $\mu = 100$ GeV, $\alpha - \beta = 0.001\pi$ (solid lines), and $\alpha - \beta = 0.1\pi$ (dotted lines).





2HDM Type I

PRL 113, 211802 (2014)

AZH event selection and uncertainties

Table 1: Summary of the event selection for signal and control regions.

Single-electron or single-muon trigger

Exactly 2 leptons (e or μ) ($p_T > 7$ GeV) with the leading one having $p_T > 27$ GeV

Opposite electric charge for $\mu\mu$ or $e\mu$ pairs; 80 GeV $< m_{\ell\ell}, m_{e\mu} <$ 100 GeV, $\ell = e, \mu$

At least 2 b-jets ($p_T > 20$ GeV) with one of them having $p_T > 45$ GeV

$E_T^{miss}/\sqrt{H_T} < 3.5\ \text{GeV}^{1/2}$, $\sqrt{\Sigma p_T^2}/m_{\ell\ell bb} > 0.4$

	$n_b = 2$ category	$n_b \geq 3$ category
	Exactly 2 b-tagged jets	At least 3 b-tagged jets
Signal region	ee or $\mu\mu$ pair $0.85 \cdot m_H - 20$ GeV $< m_{bb} < m_H + 20$ GeV	$0.85 \cdot m_H - 25$ GeV $< m_{bb} < m_H + 50$ GeV
Top control region	$e\mu$ pair $0.85 \cdot m_H - 20$ GeV $< m_{bb} < m_H + 20$ GeV	$0.85 \cdot m_H - 25$ GeV $< m_{bb} < m_H + 50$ GeV
Z+jets control region	ee or $\mu\mu$ pair $m_{bb} < 0.85 \cdot m_H - 20$ GeV or $m_{bb} > m_H + 20$ GeV	$m_{bb} < 0.85 \cdot m_H - 25$ GeV or $m_{bb} > m_H + 50$ GeV

Gluon–gluon fusion production				b-associated production			
(230, 130) GeV		(700, 200) GeV		(230, 130) GeV		(700, 200) GeV	
Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]
Data stat.	32	Data stat.	49	Data stat.	35	Data stat.	46
Total syst.	36	Total syst.	22	Total syst.	38	Total syst.	26
Sim. stat.	22	Sim. stat.	10	Sim. stat.	26	Sim. stat.	12
Bkg. model.	16	Bkg. model.	10	b-tagging	14	Bkg. model.	11
JES/JER	12	Theory	9.1	JES/JER	11	b-tagging	10
b-tagging	9.9	b-tagging	8.5	Bkg. model.	9.8	Theory	6.8
Theory	7.5	Leptons	4.2	Theory	7.0	JES/JER	6.2

Vh event selections

Variable	Resolved	Merged
Common selection		
Number of jets	≥2 small-R jets (0, 2-lep.) 2 or 3 small-R jets (1-lep.)	≥1 large-R jet
Leading jet p_T [GeV]	> 45	> 250
m_{jj}, m_J [GeV]	110–140 (0,1-lep.), 100–145 (2-lep.)	75–145
0-lepton selection		
E_T^{miss} [GeV]	> 150	> 200
$\sum p_T^{jet_i}$ [GeV]	> 150 (120^*)	–
$\Delta\phi(j, j)$	$< 7\pi/9$	–
p_T^{miss} [GeV]	$> 30^\ddagger$	
$\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss})$	$< \pi/2$	
$\Delta\phi(\vec{E}_T^{miss}, h)$	$> 2\pi/3$	
$\min[\Delta\phi(\vec{E}_T^{miss}, \text{small-}R\text{ jet})]$	$> \pi/9$ (2 or 3 jets), $> \pi/6$ (≥ 4 jets)	
$N_{\tau_{had}}$	0^{**}	
1-lepton selection		
Leading lepton p_T [GeV]	> 27	> 27
E_T^{miss} [GeV]	> 40 ($80^\dagger$)	> 100
$p_{T,W}$ [GeV]	$> \max[150,\ 710 - (3.3 \times 10^5\ \text{GeV})/m_{Vh}]$	$> \max[150,\ 394 \cdot \ln(m_{Vh}/(1\ \text{GeV})) - 2350]$
$m_{T,W}$ [GeV]	< 300	
2-lepton selection		
Leading lepton p_T [GeV]	> 27	> 27
Sub-leading lepton p_T [GeV]	> 7	> 25
$E_T^{miss} / \sqrt{H_T}$ [$\sqrt{\text{GeV}}$]	$< 1.15 + 8 \times 10^{-3} \cdot m_{Vh}/(1\ \text{GeV})$	
$p_{T,\ell\ell}$ [GeV]	$> 20 + 9 \cdot \sqrt{m_{Vh}/(1\ \text{GeV}) - 320}^{\dagger\dagger}$	
$m_{\ell\ell}$ [GeV]	$[\max[40\ \text{GeV},\ 87 - 0.030 \cdot m_{Vh}/(1\ \text{GeV})],\ 97 + 0.013 \cdot m_{Vh}/(1\ \text{GeV})]$	

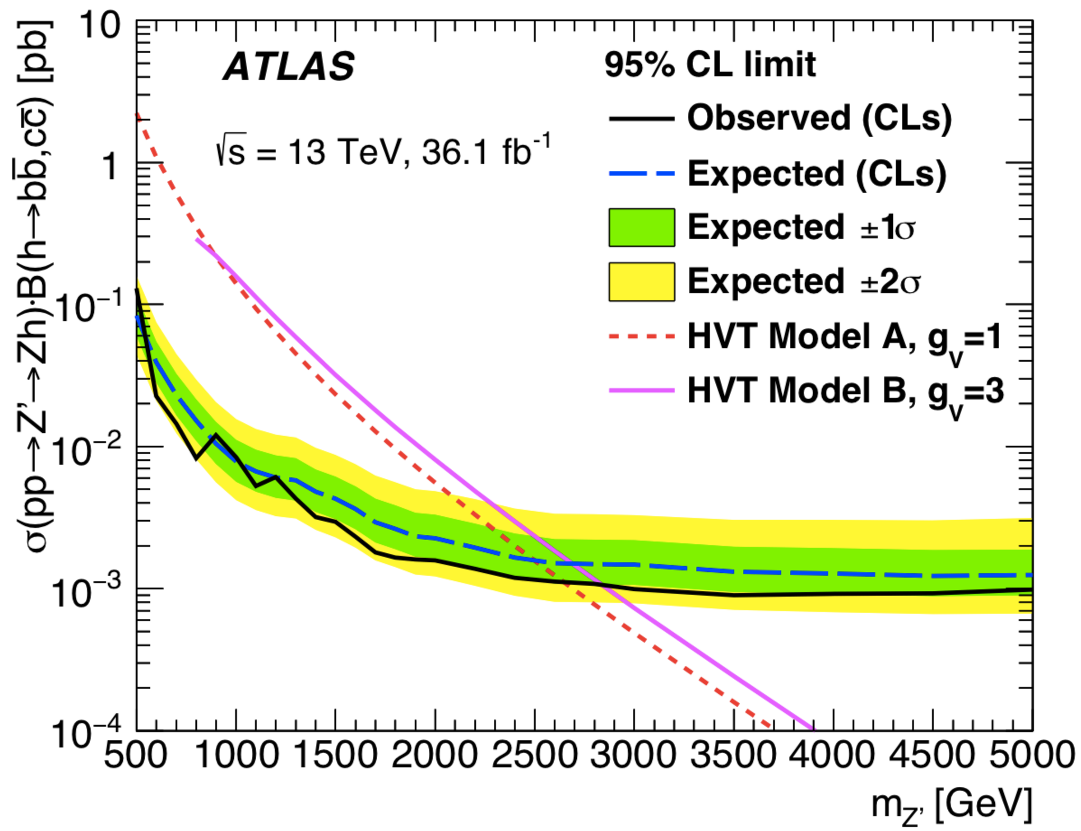
Vh: heavy vector triplet (HVT)

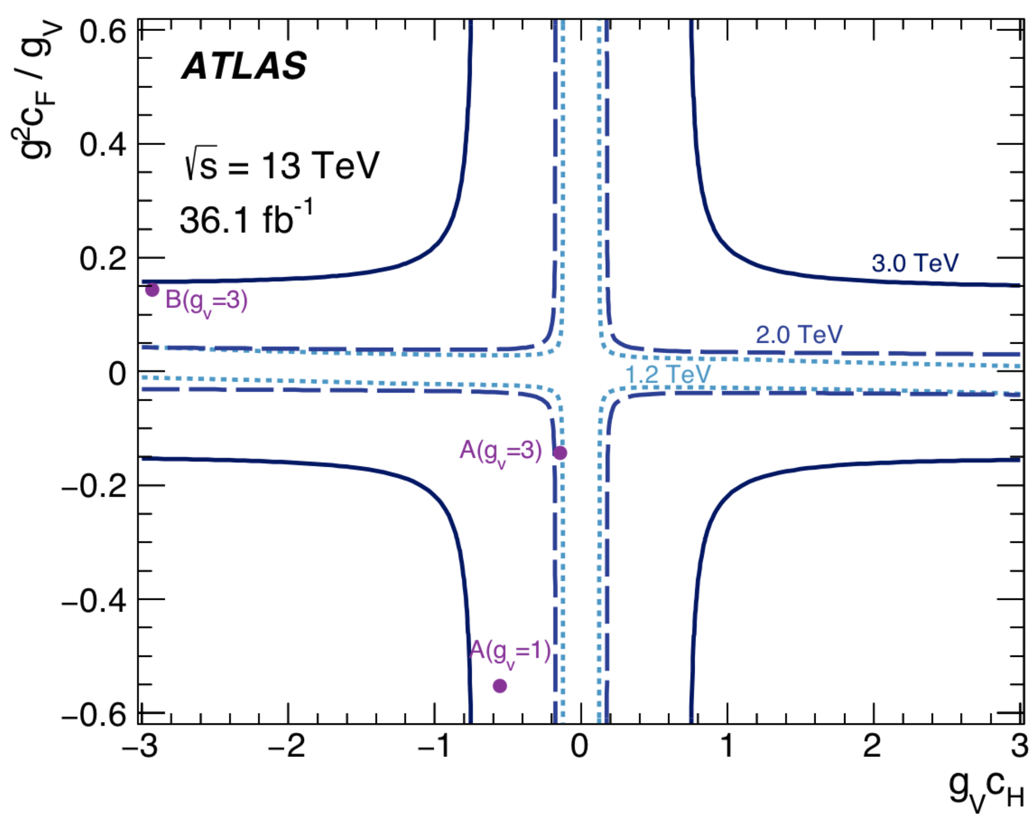
- HVT, a simplified model of strong interactions, is used as benchmarks, based on a phenomenological Lagrangian
- Model A: the BR to fermions and gauge bosons are comparable
- Model B: fermionic couplings are suppressed
- At low resonance masses and large g_V couplings, the HVT models fail to reproduce the SM parameters
  - This search focuses on high masses, from 500 GeV up to 5 TeV
- The new heavy vector bosons, W′ and Z′, collectively denoted by V′, couple to the Higgs and gauge bosons via a combination of parameters $g_V c_H$ and to the fermions via the combination $(g^2/g_V)c_F$, where g is the $SU(2)_L$ gauge coupling. The parameter g_V represents the strength of the new vector-boson interaction, and c_H and c_F represent corrections to the coupling strength specific to Higgs bosons and fermions, respectively.

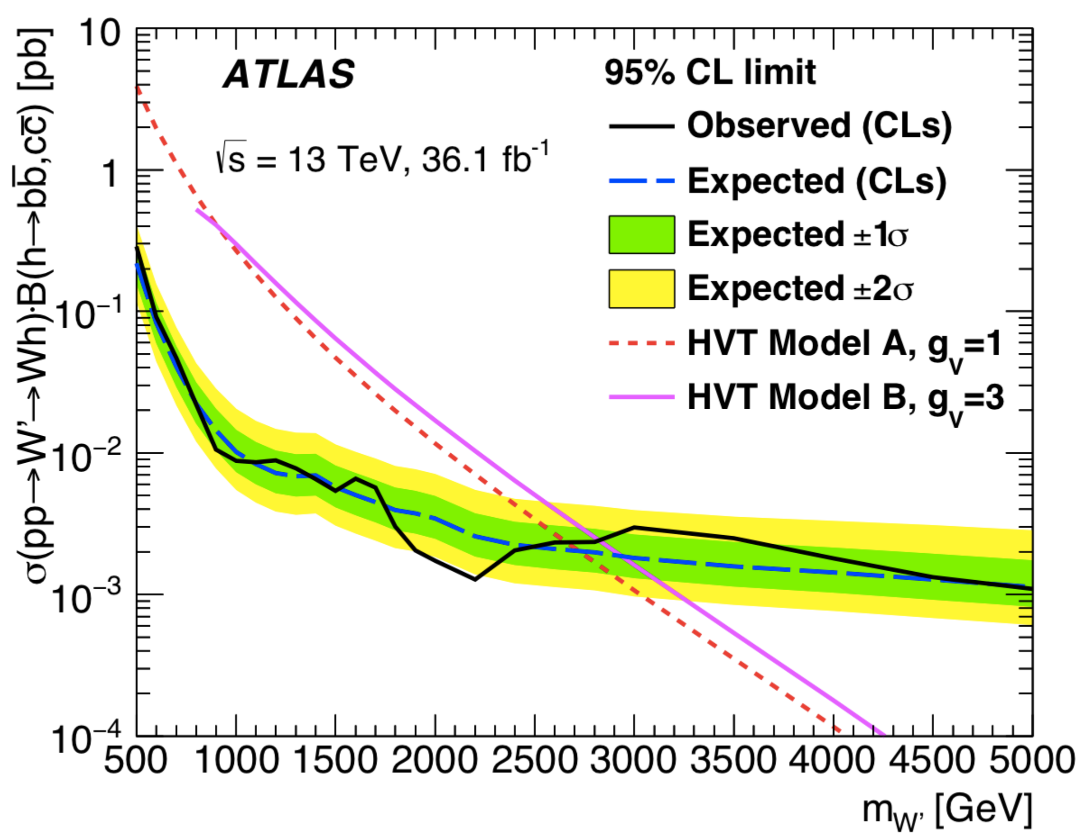
arXiv:1712.06518

Vh results on heavy vector boson

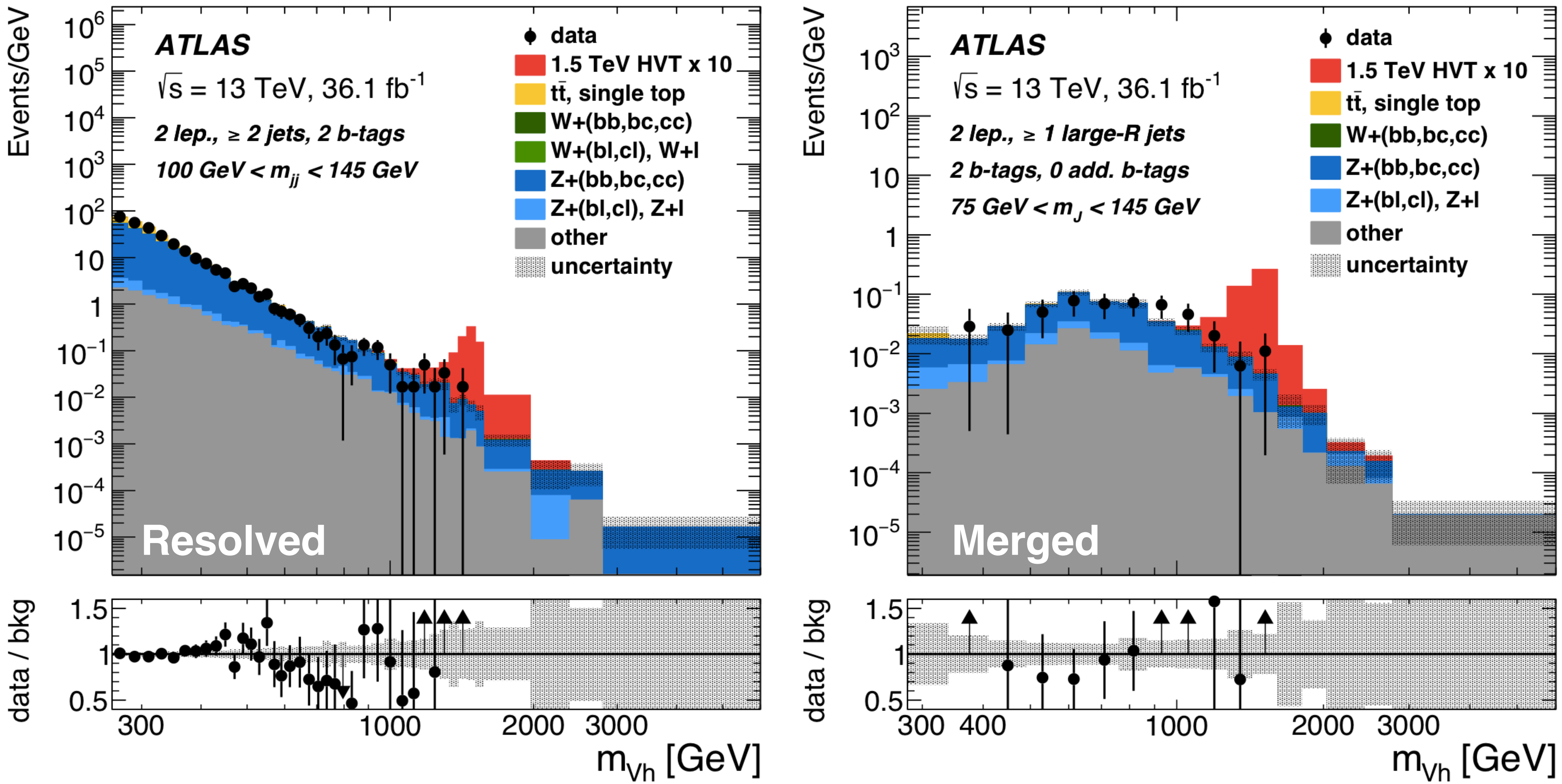
- No significant data excess is found
- 95% CL limits are made on $m_{V'}$
- Correspondingly, interpretations are made in HVT phase space





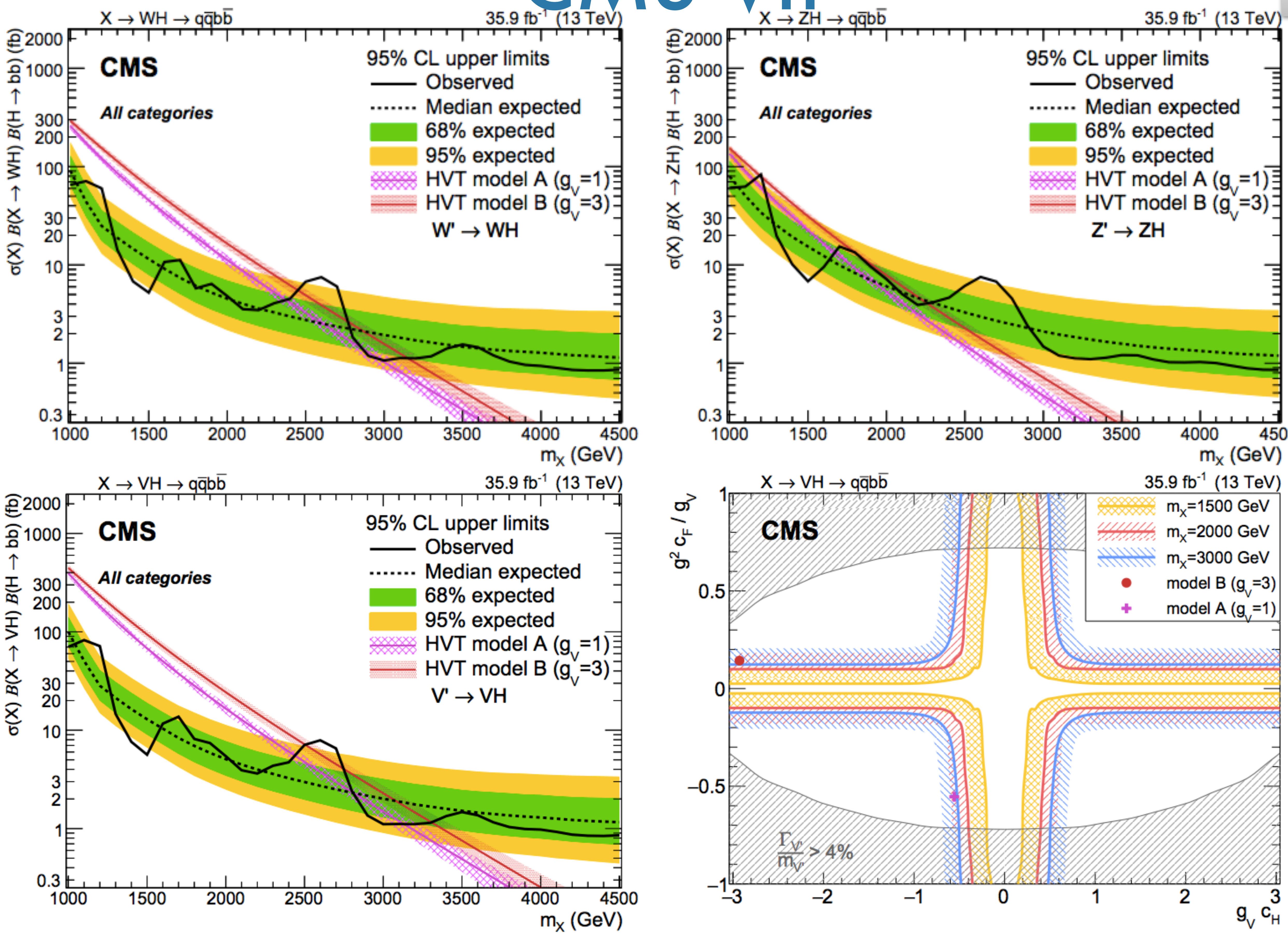


Vh global fits: 2-lepton cases

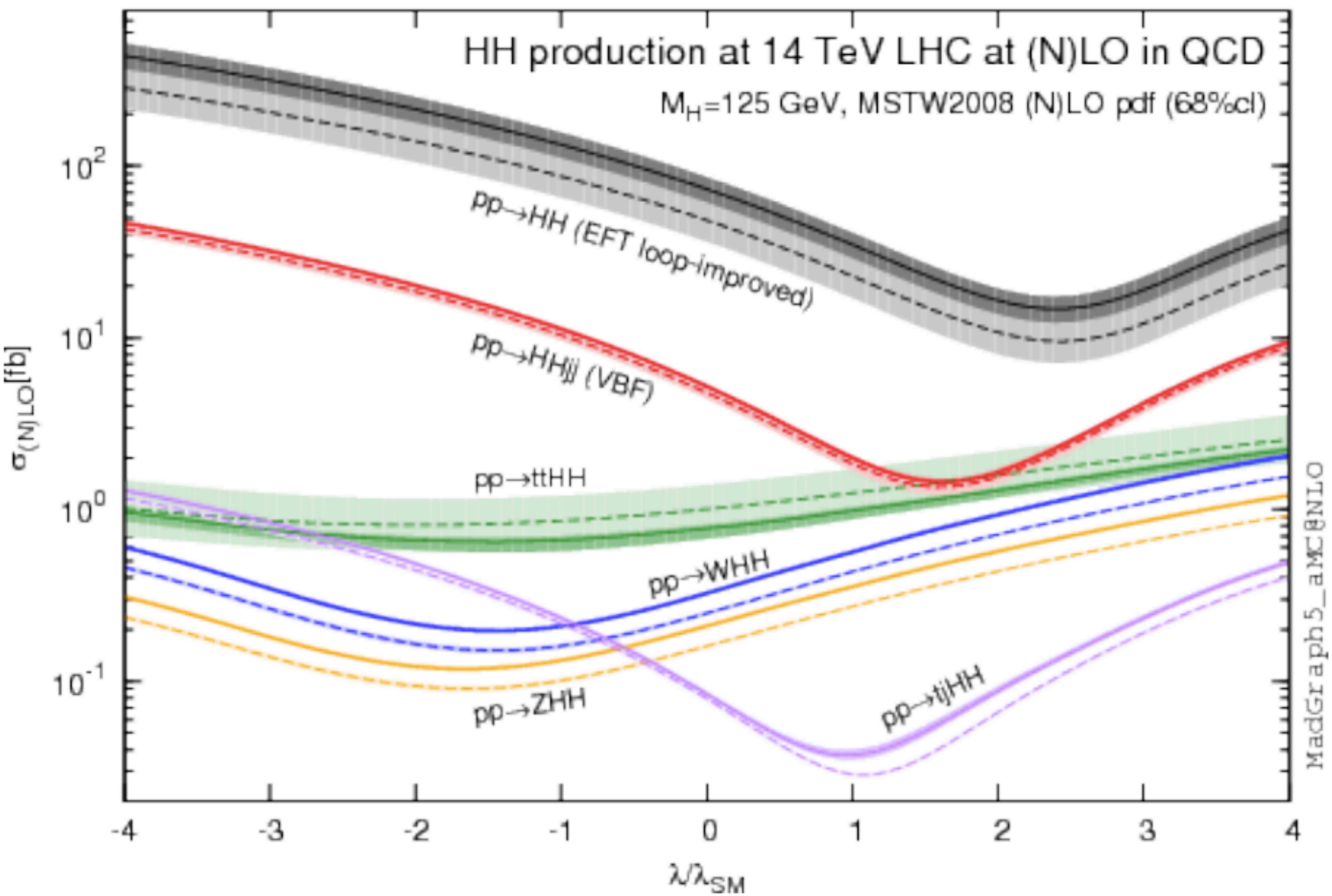


CMS Vh

arXiv:1707.01303

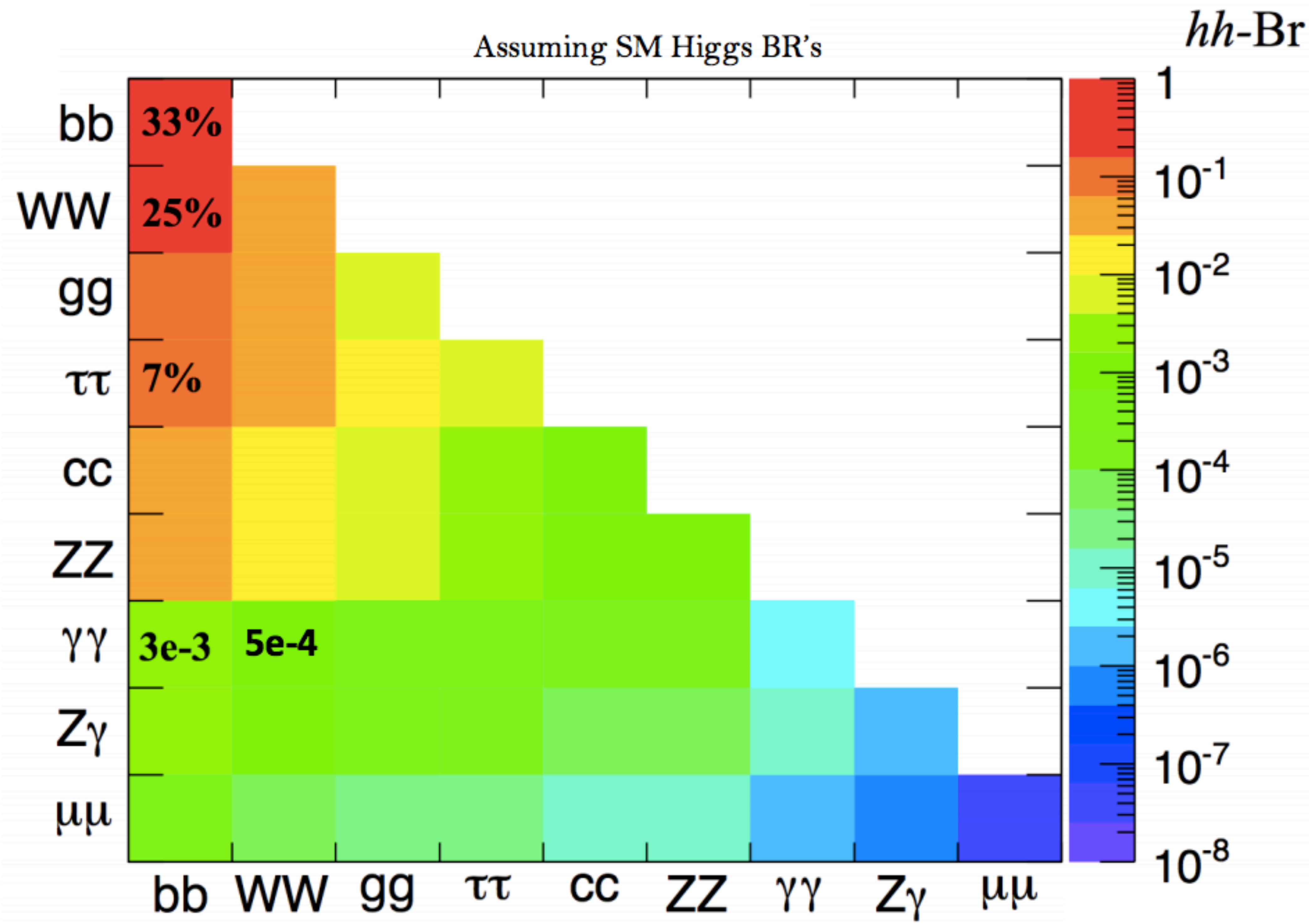


HH non-resonant production



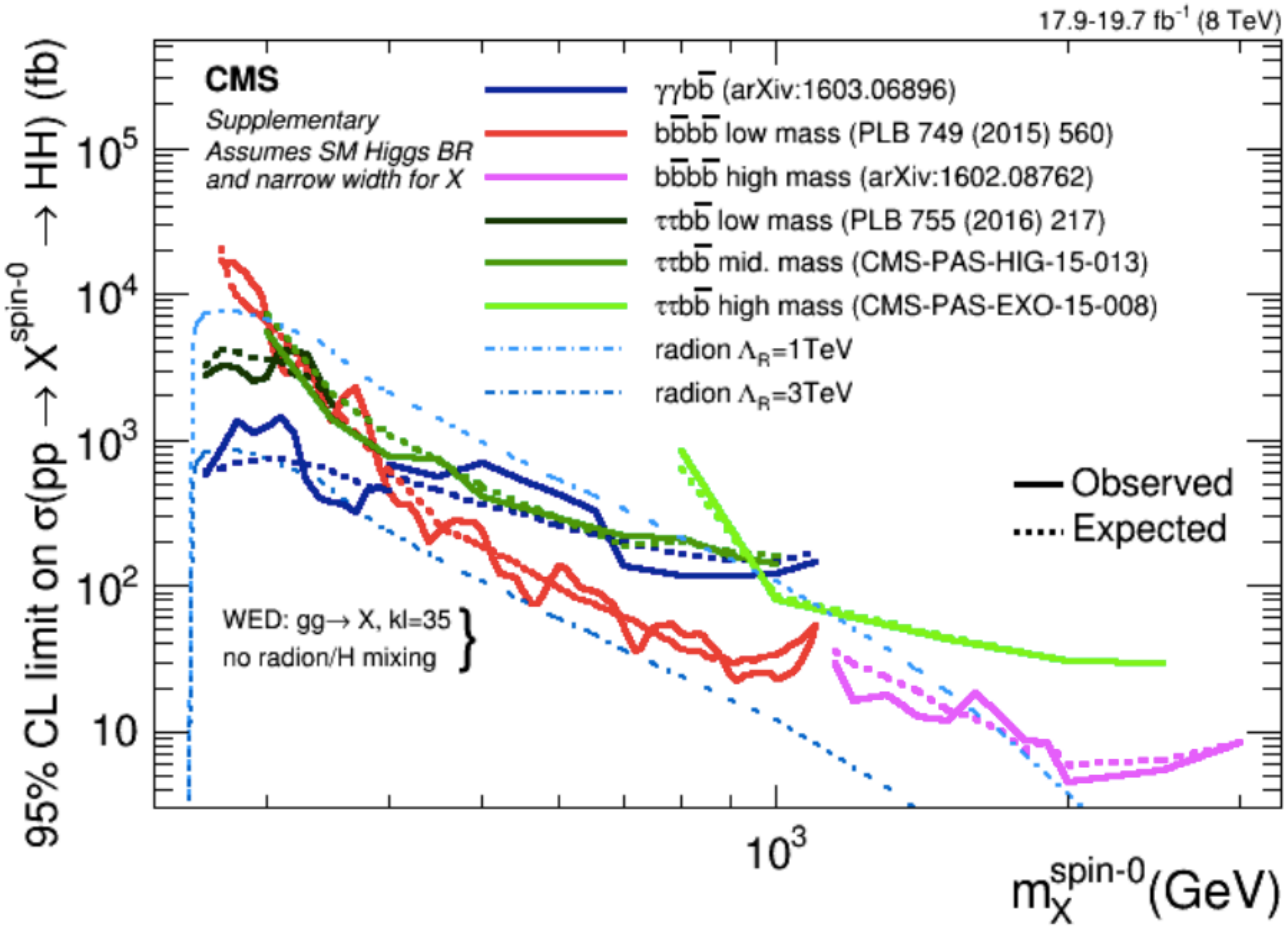
Phys.Lett. B732 (2014) 142-149 arXiv:1504.05596

HH BRs



ATL-PHYS-SLIDE-2014-694

CMS HH results Run1



Same level as
ATLAS resonant limits

- CMS limits on non-resonant production: 43 (47) x SM prediction (expected)
  - bbtautau + bbgammagamma combination, Phys. Rev. D 96, 072004 (2017)
  - Comparable with ATLAS, both at O(50x SM)

HH publication Run2

ATLAS

- bbbb (NEW!)
  - L=27.5 fb^{-1} , 36.1 fb^{-1}
  - ATLAS-EXOT-2016-31
- bbγγ
  - L=3.2 fb^{-1}
  - ATLAS-CONF-2016-004
- WWγγ
  - L=13.3 fb^{-1}
  - ATLAS-CONF-2016-071

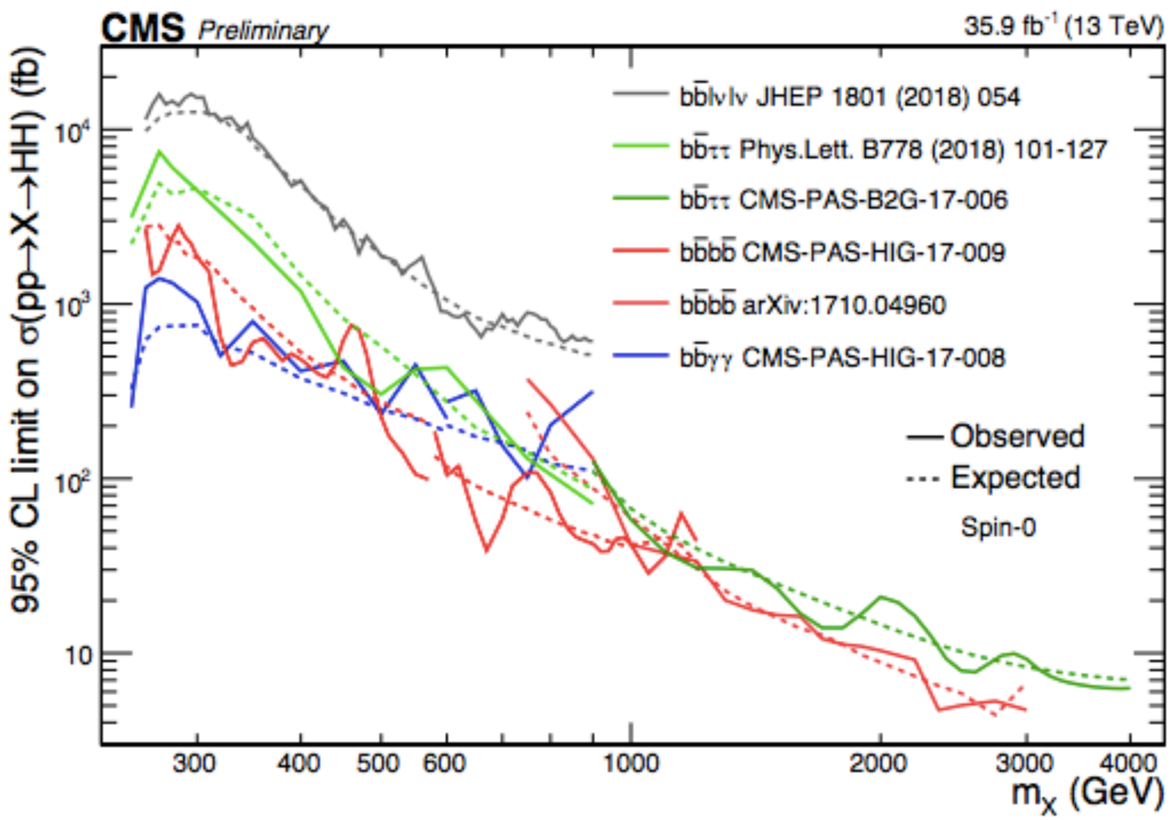
Many extremely nice results!!!!
Unfortunately will not be able to cover all the details or analyses

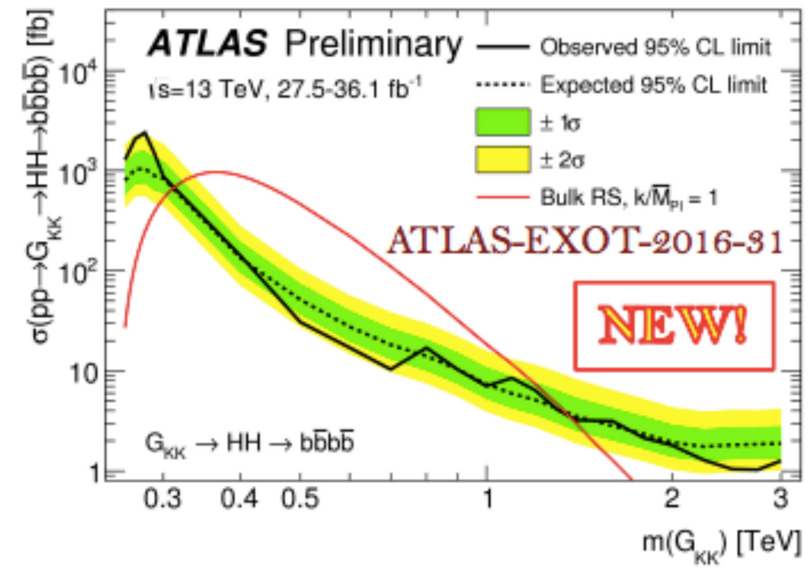
CMS

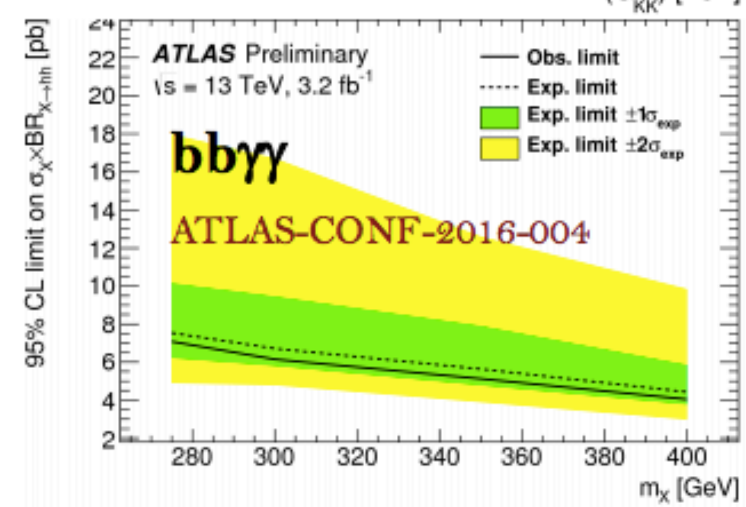
- bbbb
  - L=35.7 fb^{-1} , 2.3 fb^{-1}
  - arXiv:1710.04960
  - PAS-HIG-17-009
  - PAS-HIG-16-026
- bbγγ
  - L=35.7 fb^{-1}
  - PAS-HIG-17-008
- bbττ
  - L=35.7 fb^{-1}
  - Phys. Lett. B 778 (2018) 101
  - PAS-B2G-17-006
- bbVV(→lνlν)
  - L=35.7.3 fb^{-1}
  - JHEP 01 (2018) 054, [1708.04188]

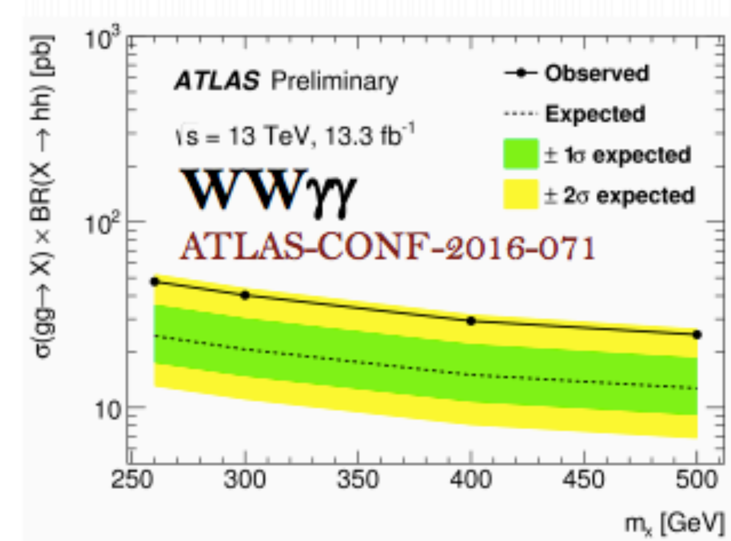
Michael Kagan Moriond 2018

HH resonant results Run2





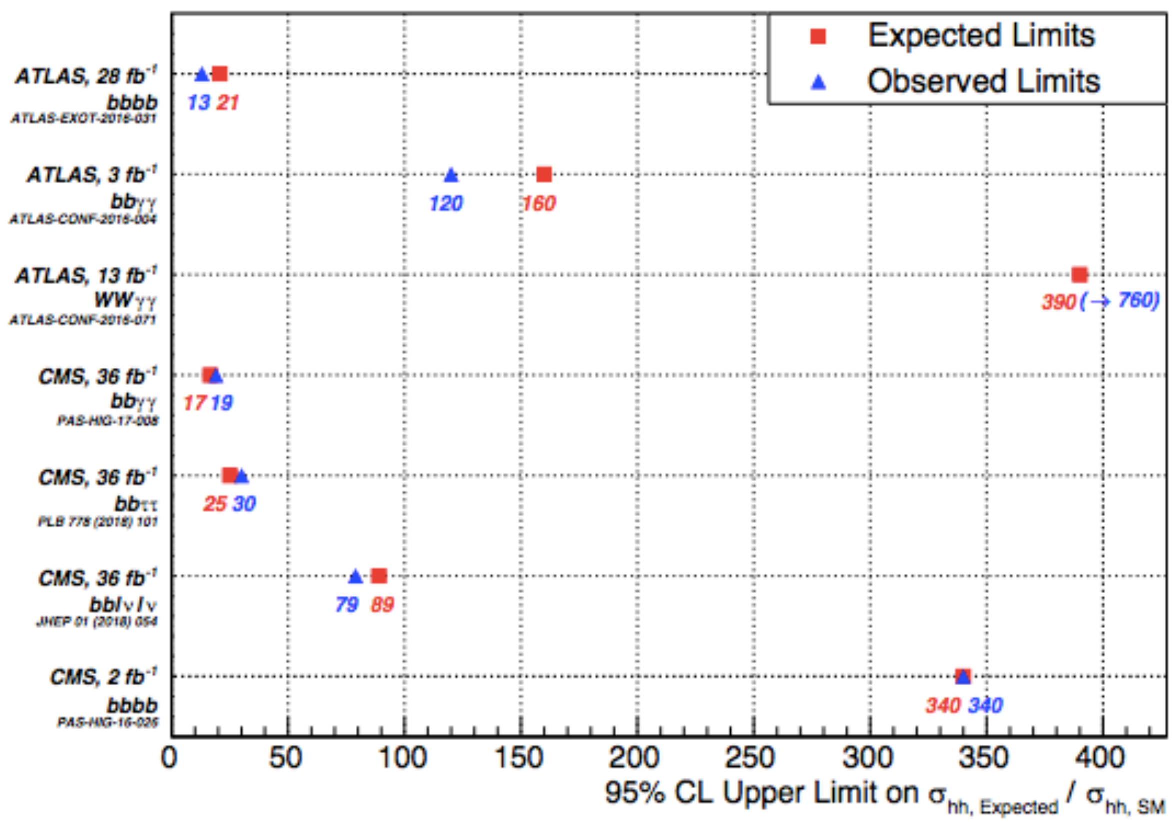




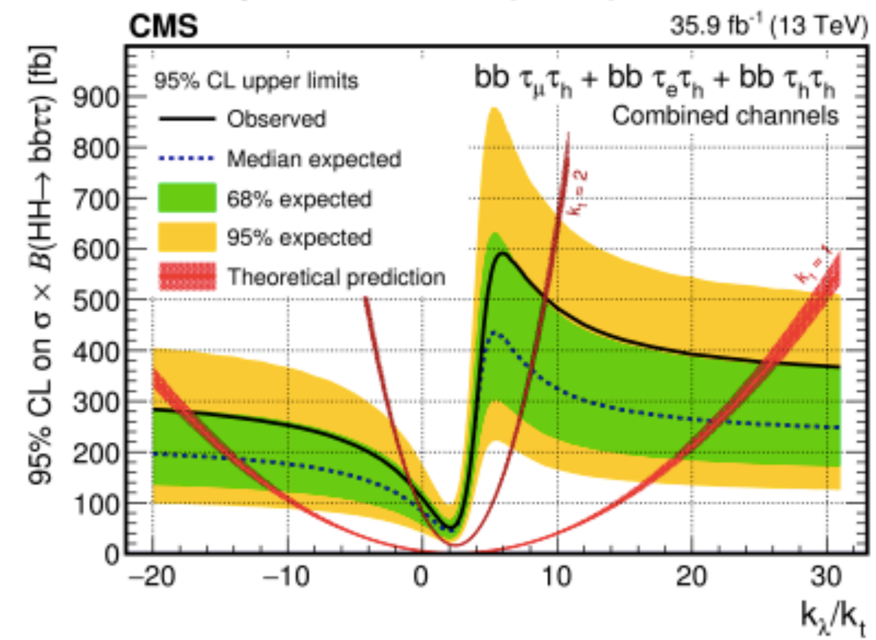
- Limits O(pb) for low mass resonances around 300 GeV
- Limits O(fb) for high mass resonances above a TeV

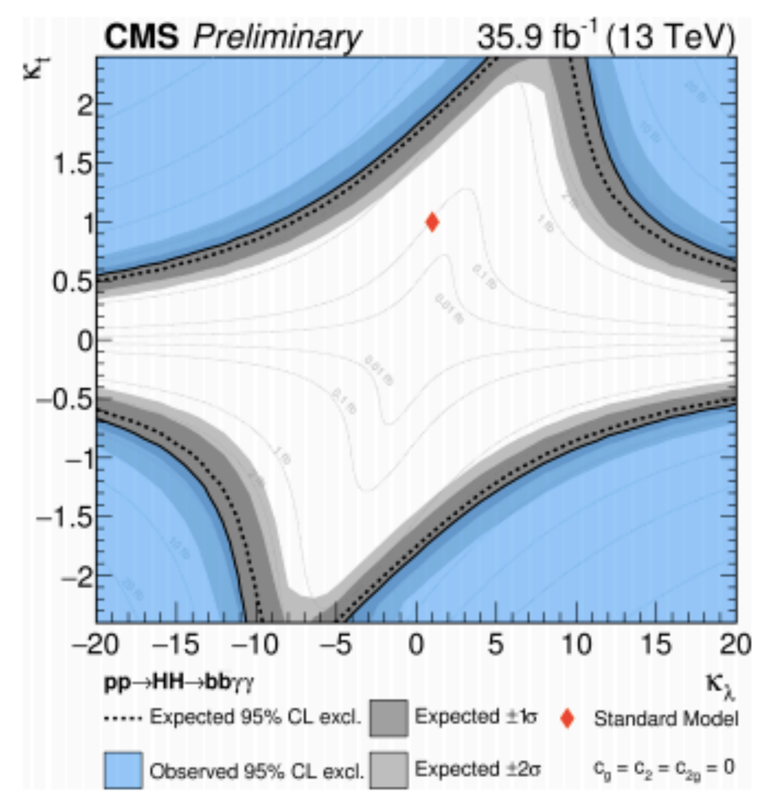
Michael Kagan Moriond 2018

HH non-resonant results Run2



Phys. Lett. B 778 (2018) 101





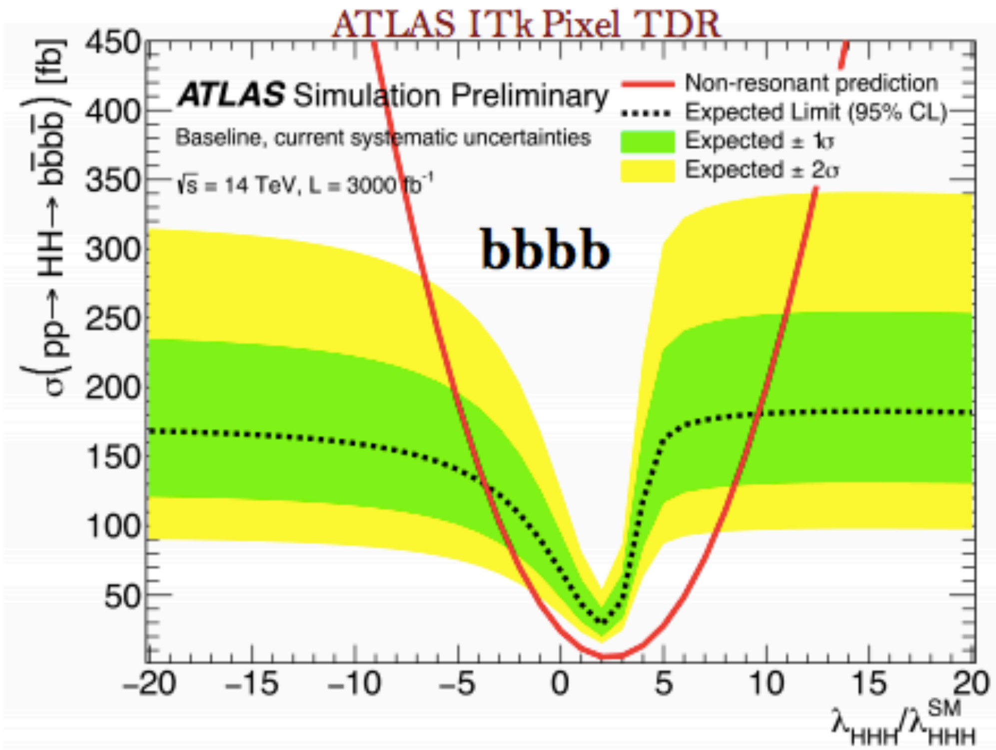
PAS-HIG-17-008

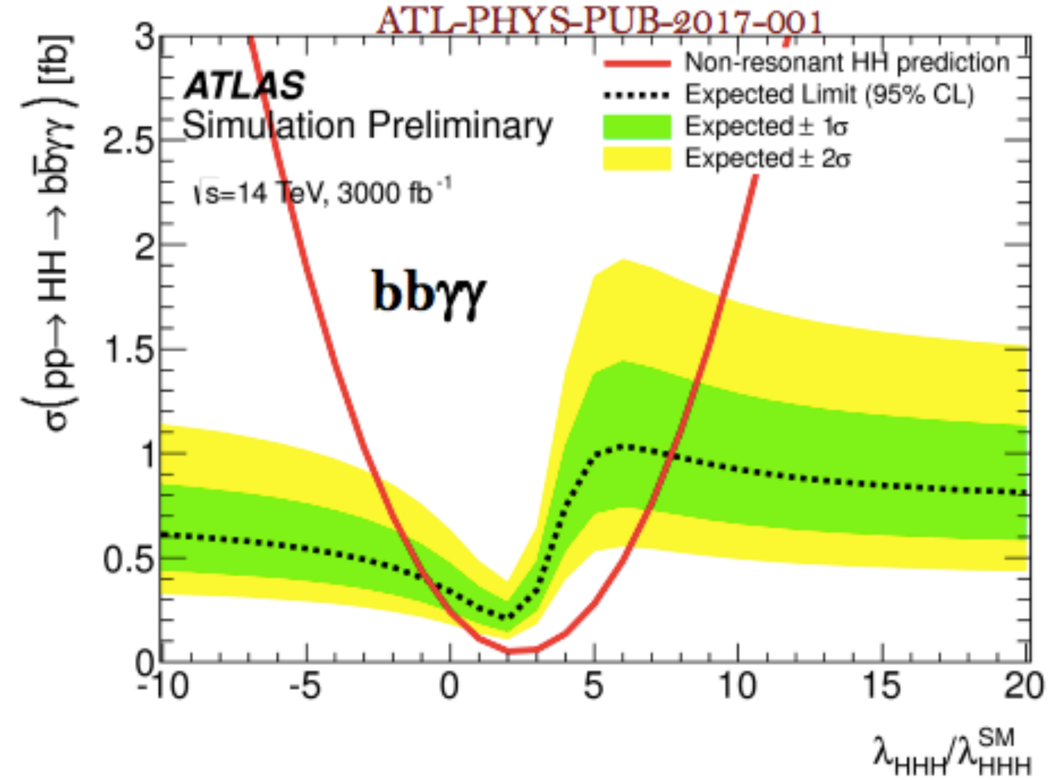
- SM production limits reach ~20xσ_{SM}
- Best channel limits on anomalous trilinear coupling: $\frac{\lambda}{\lambda_{SM}} \in [-8, 15]$
- Assuming $\sqrt{N}$ improvements L=120 fb^{-1} in Run II will bring single channel limits at or below 10xσ_{SM}!

or maybe 5

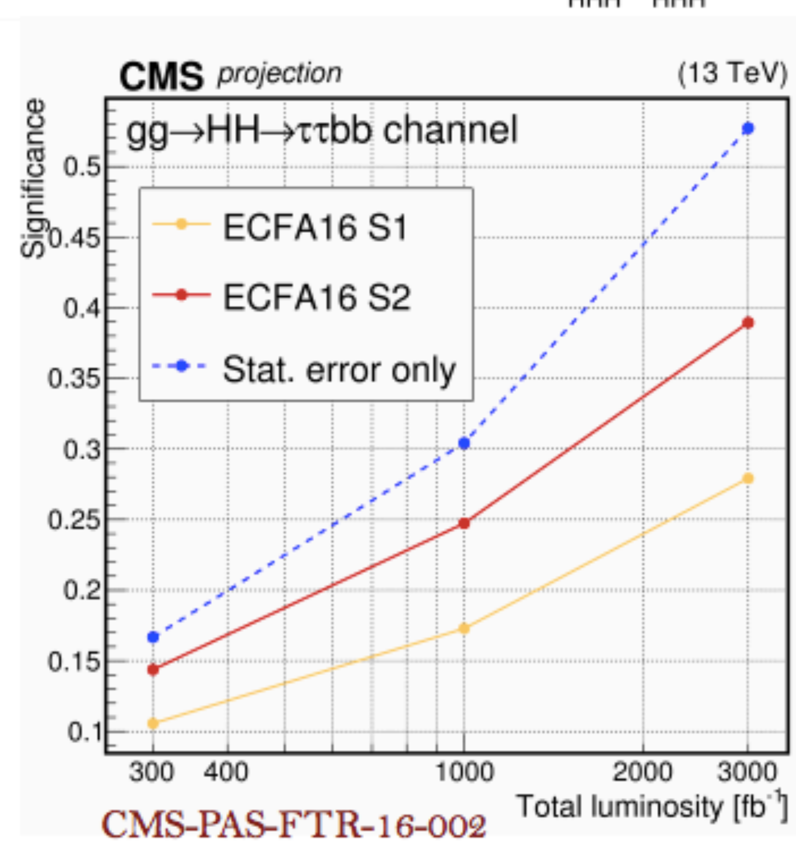
Michael Kagan Moriond 2018

HH HL-LHC





- HL-LHC projections show a challenging future
- Cross section limits ~(few)xσ_{SM} per channel
- Coupling limits $\sim\frac{\lambda}{\lambda_{SM}} \in [-1, 8]$ for single channel
- Is this the whole story?



Michael Kagan Moriond 2018