Is the Higgs boson what we expect it to be?

ATLAS and CMS Higgs coupling combination

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Outline

Introduction

Higgs phenomenology

Inputs to the combination

Statistical framework

Combined Signal strength

Combined Higgs coupling

Towards Model independent measurements

Conclusion and outlook

Higgs boson: preparing the discovery!

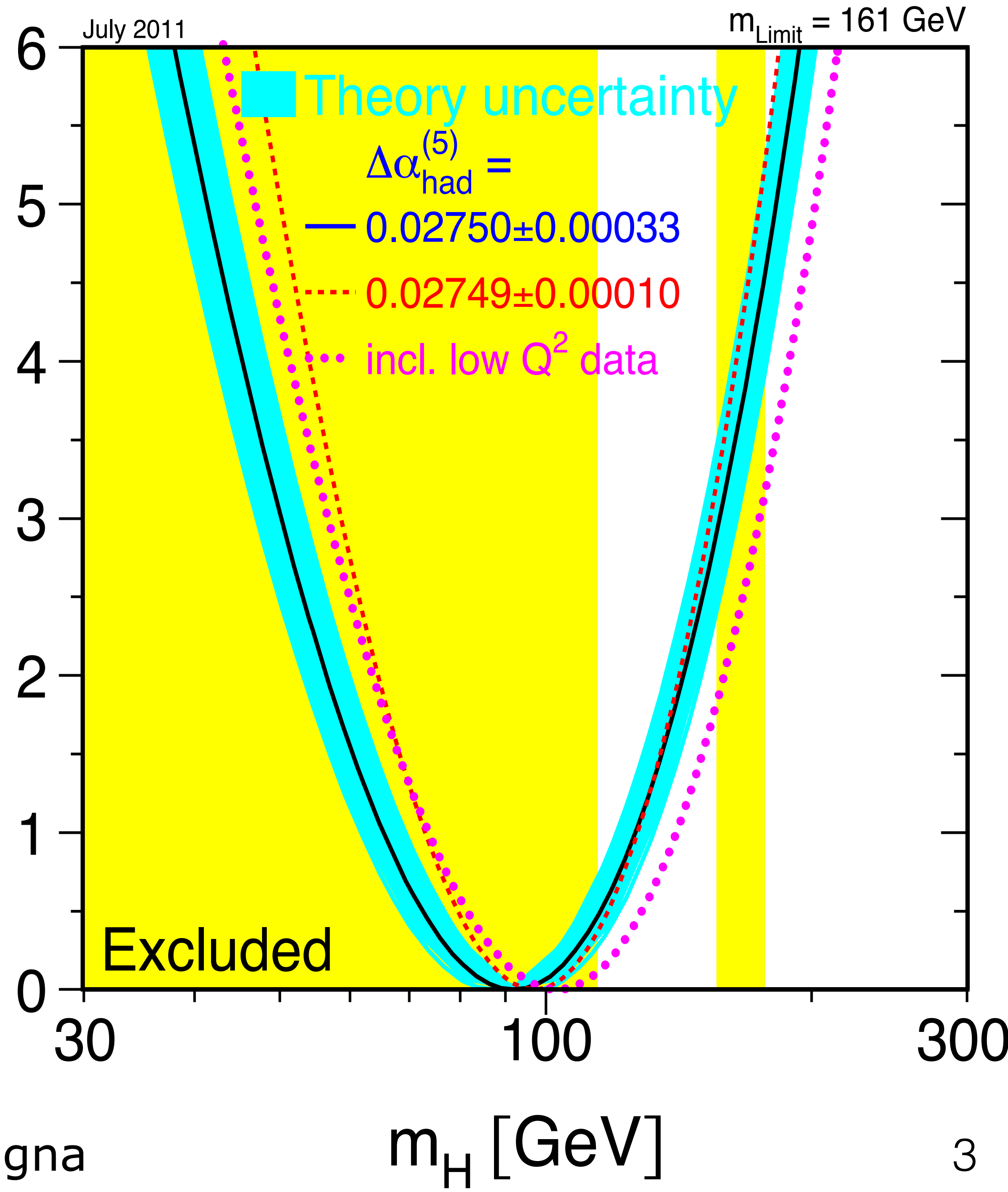
Brout–Englert–Higgs mechanism developed in the 60s
- new field at the origin of the EWK symmetry breaking

Very predictive theory:
- existence of a new scalar boson (the Higgs), whose coupling with SM particles are completely specified by the theory (for given value of m_H)
- only un-known is the Higgs boson mass itself

Higgs mass between 114 and 200 GeV from LEP, Tevatron and EW global fit

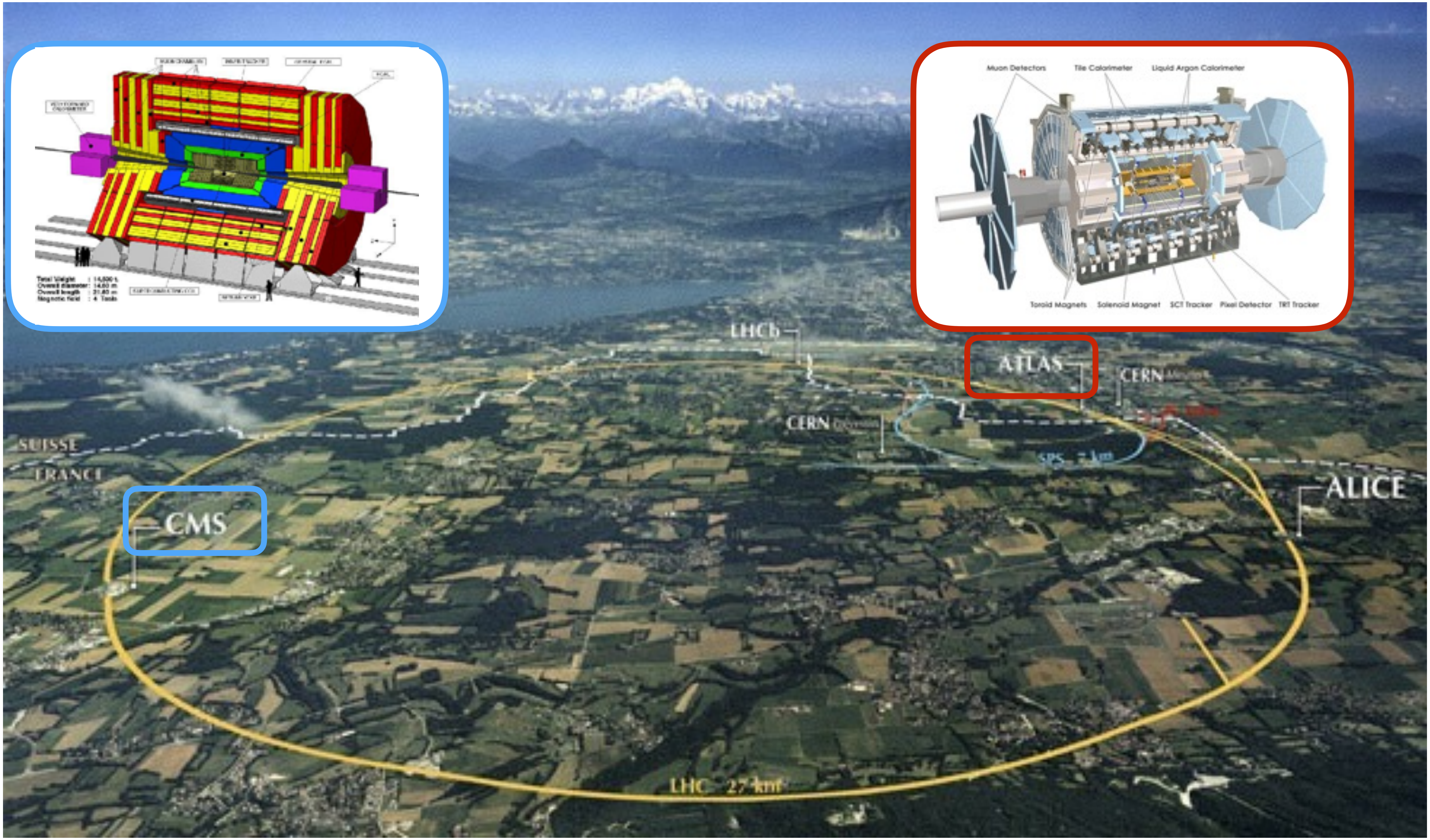
—> when LHC started, window to explore at the LHC was relatively small

Still not obvious that the simplest model was the correct theory! (and it still isn’t!)



The Large Hadron Collider (LHC)

Just re-started data taking this month!

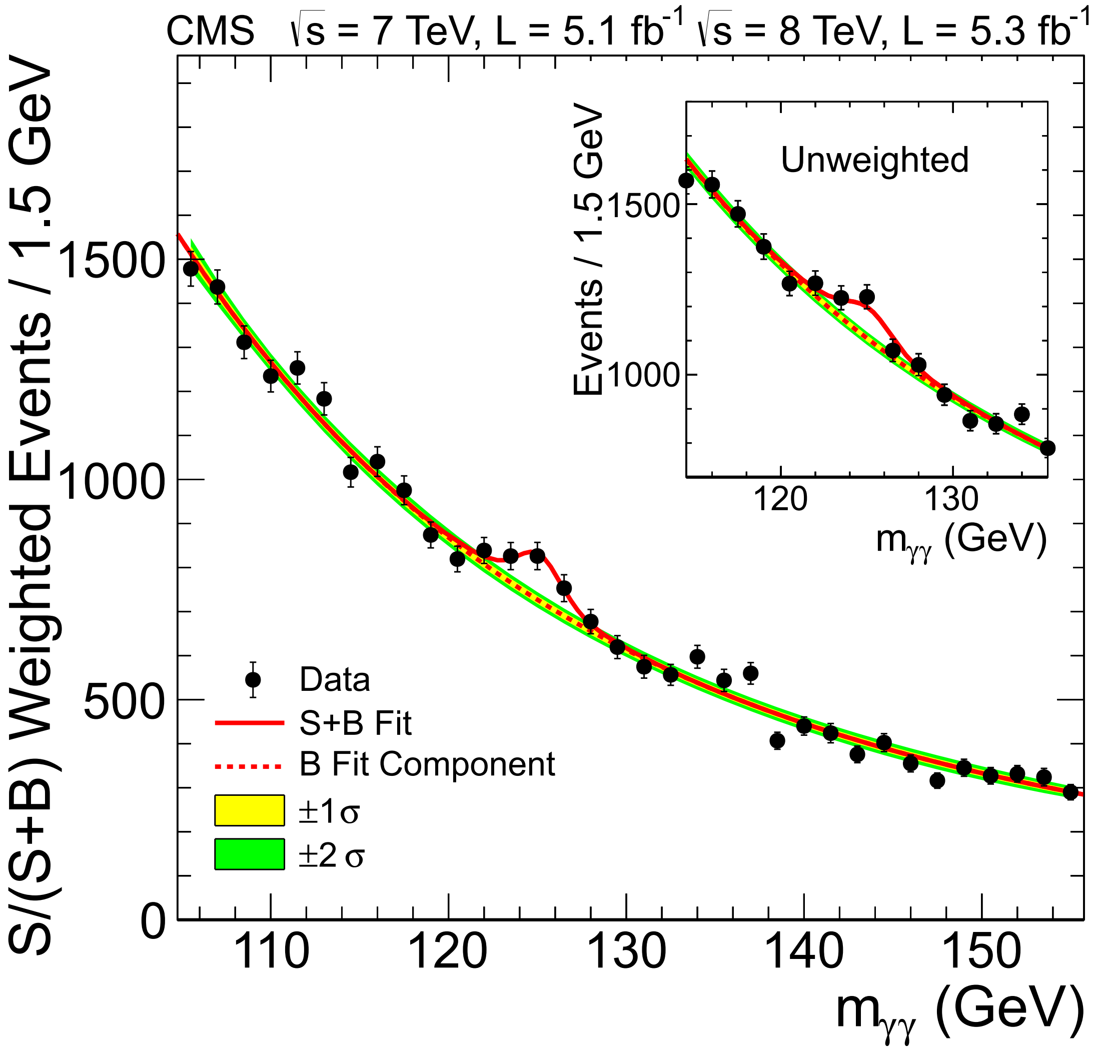


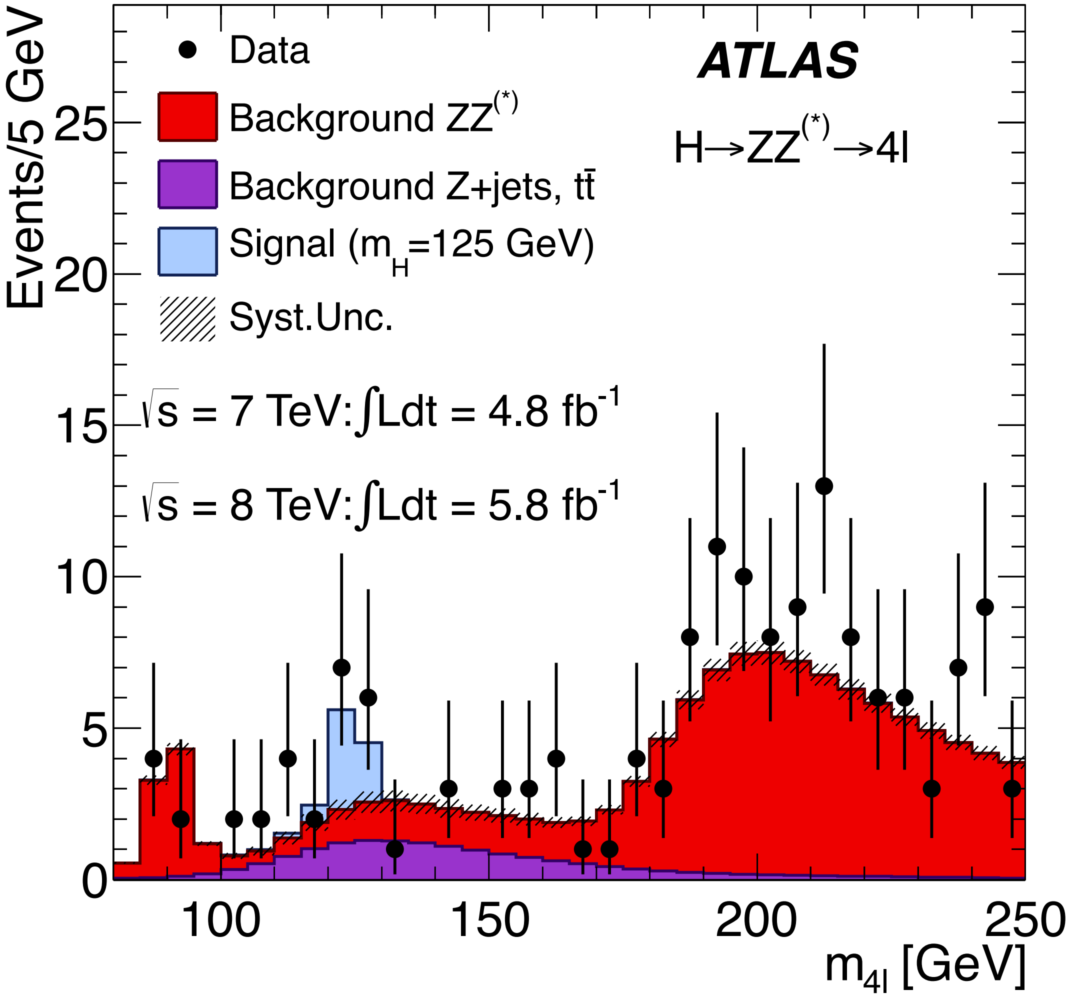
Higgs discovery- 4th of July 2012

- ~5/fb of 7TeV + ~5/fb of 8TeV data

- ≥ 5σ excess from both ATLAS and CMS
  - CMS: ɣɣ, WW, $\tau\tau$, bb, ZZ—>4leptons
  - ATLAS: ɣɣ and ZZ—>4leptons

- Englert and Higgs won the 2013 Nobel prize!





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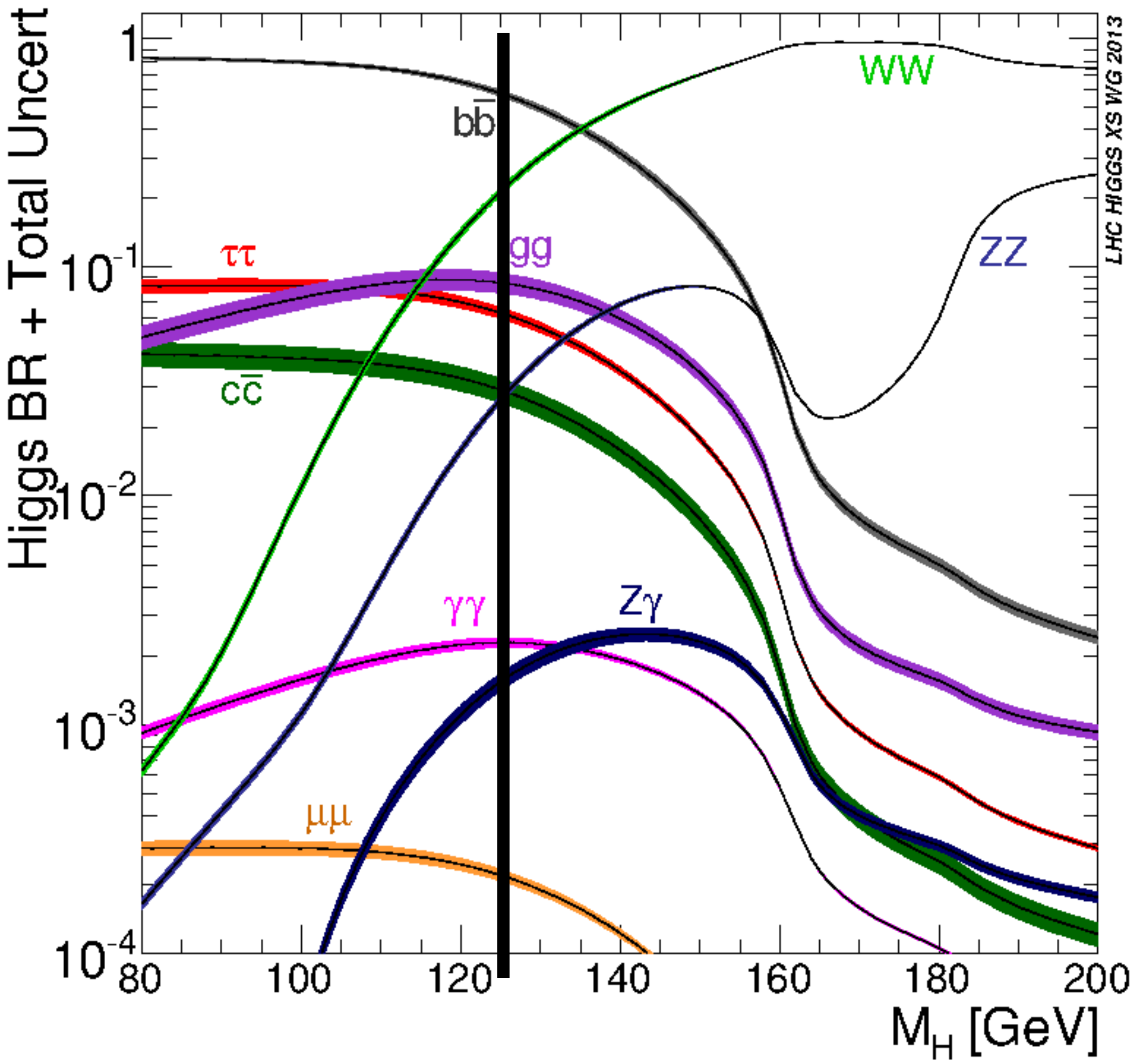
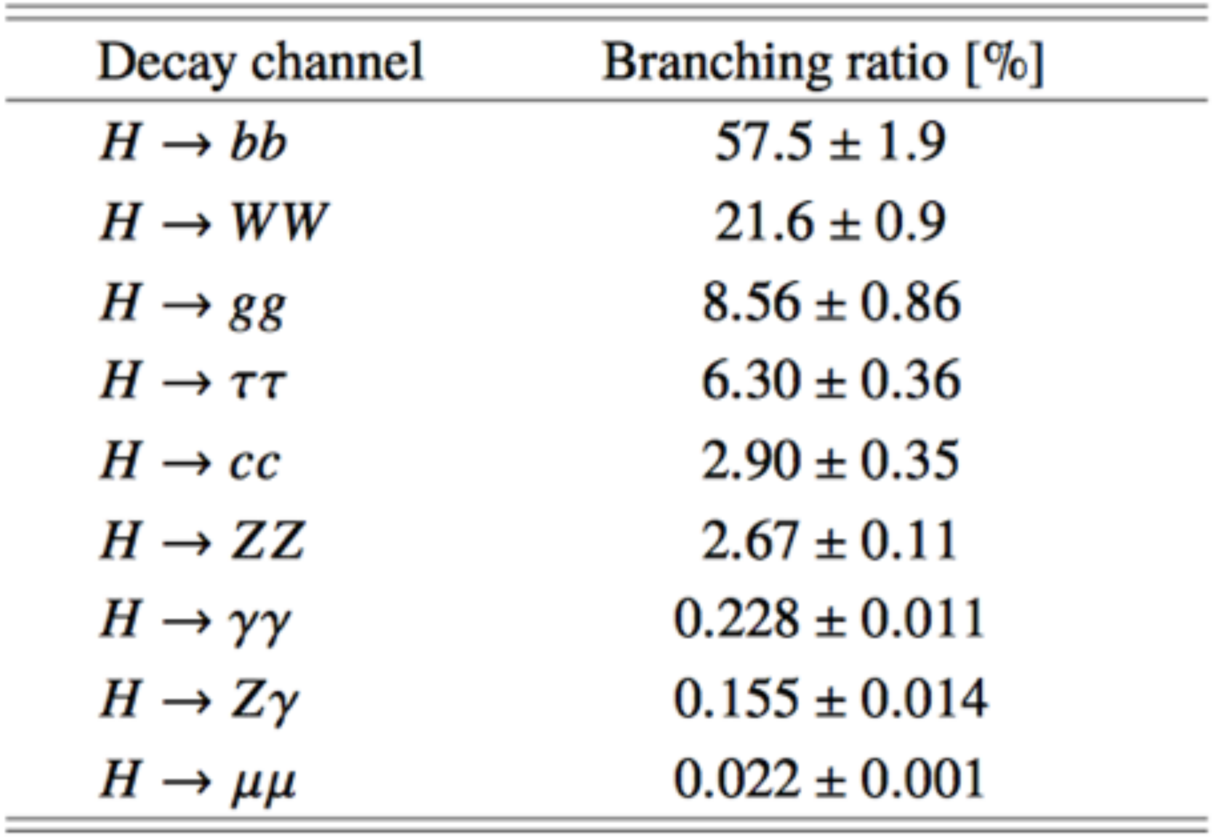
Higgs decay modes

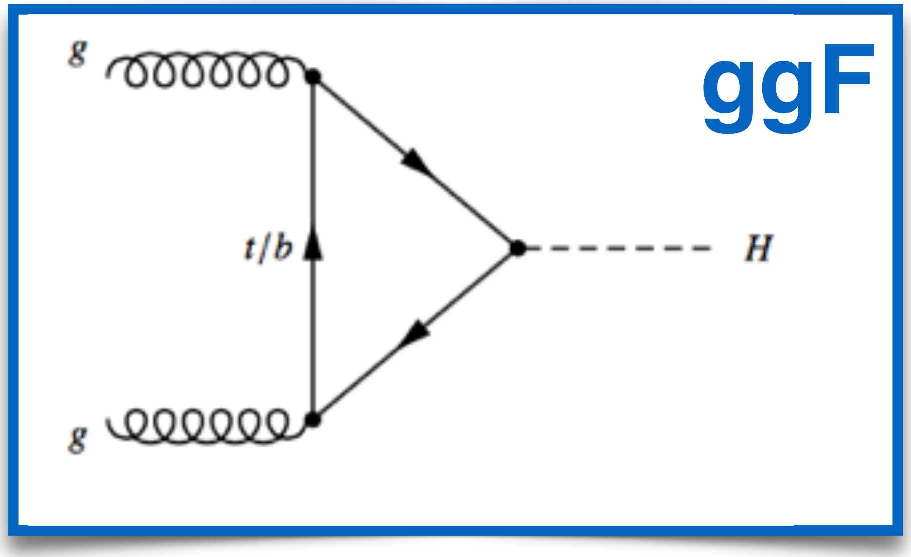




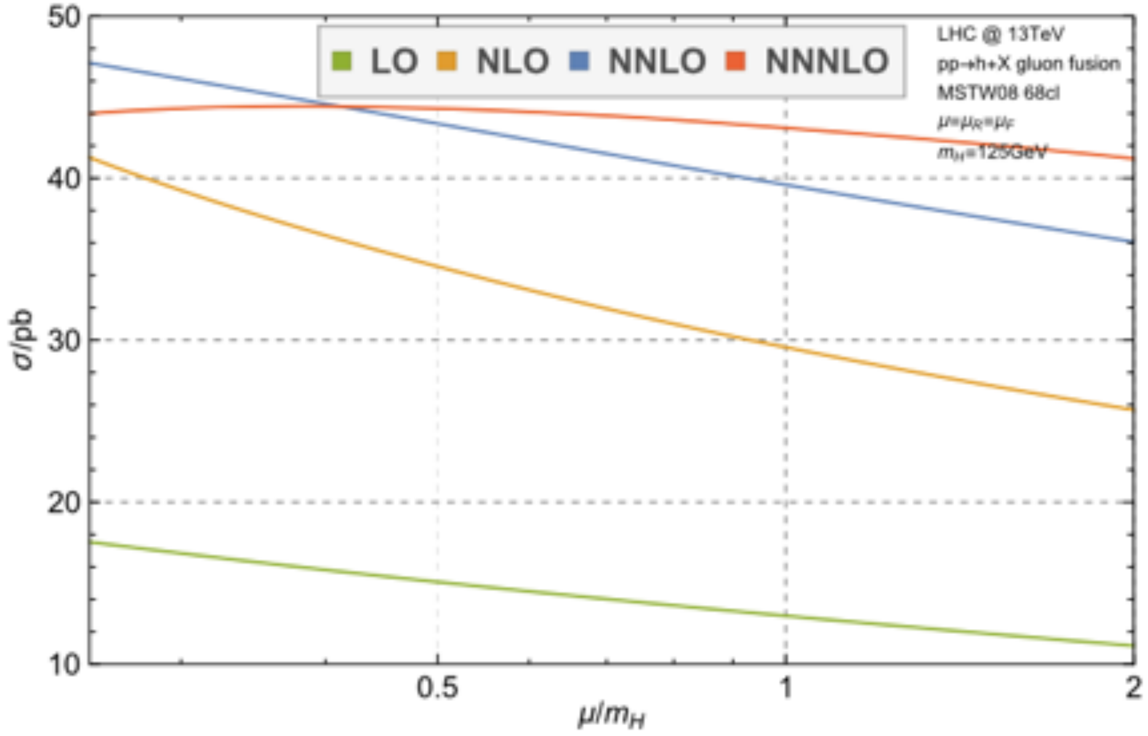
Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

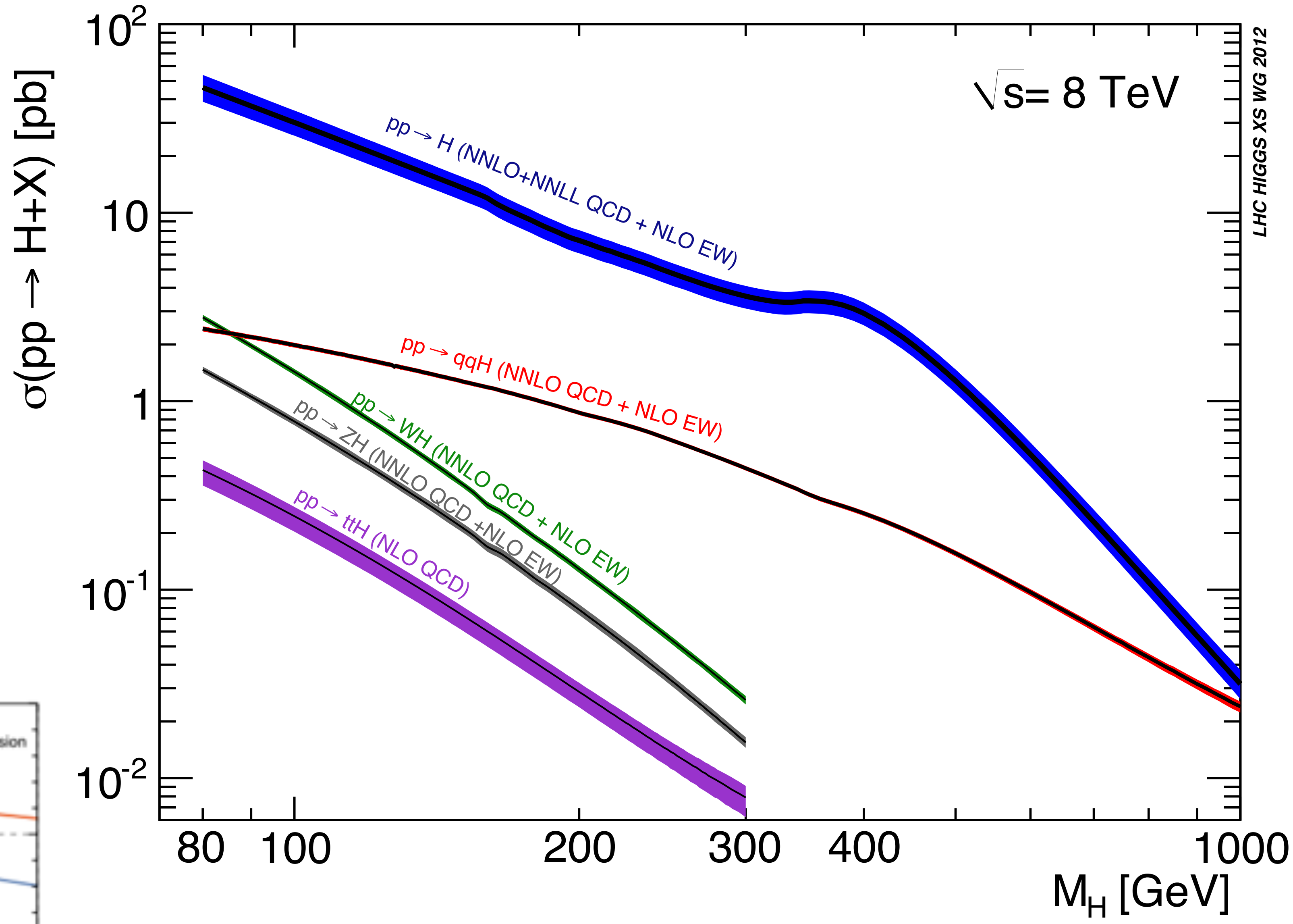
Total width Γ_{TOT} not experimentally accessible: ~4 MeV in S.M.!

Higgs production modes directly searched for

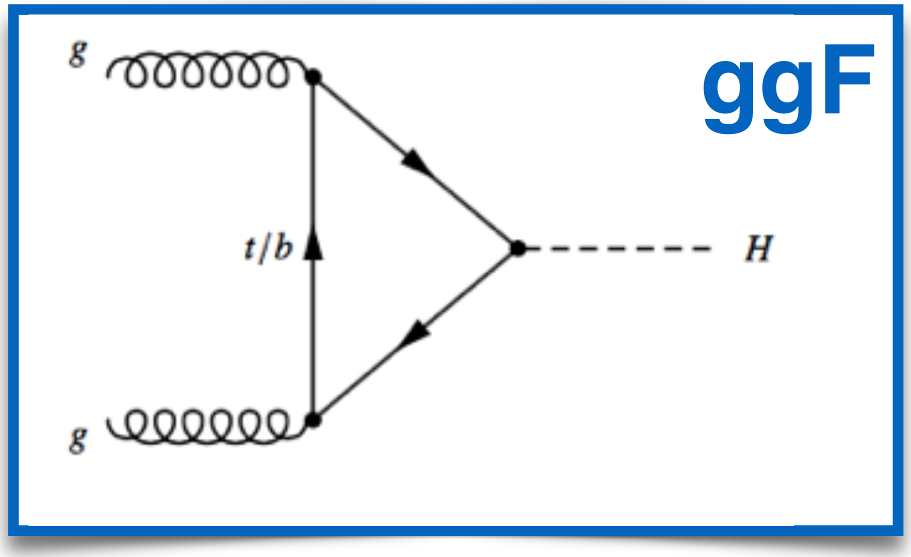


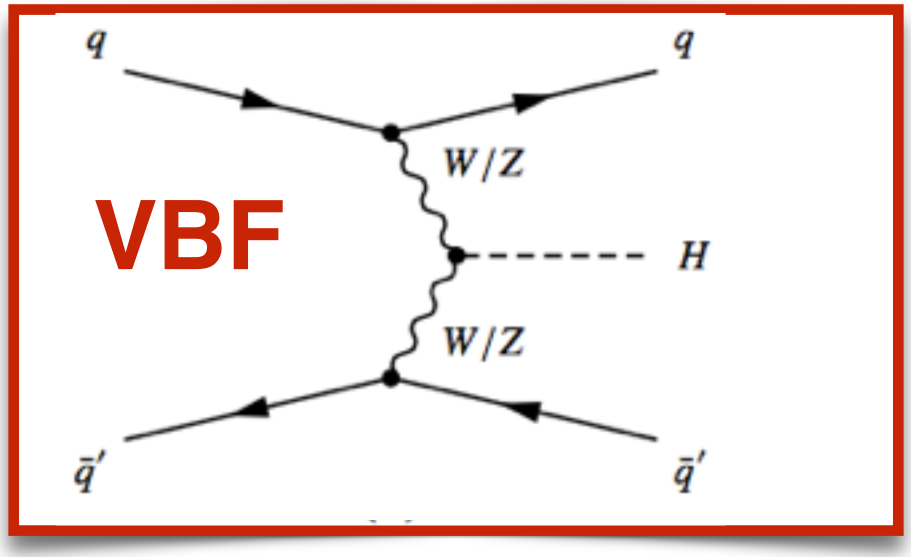
Main production mechanism
large higher order corrections (x2 NLO)

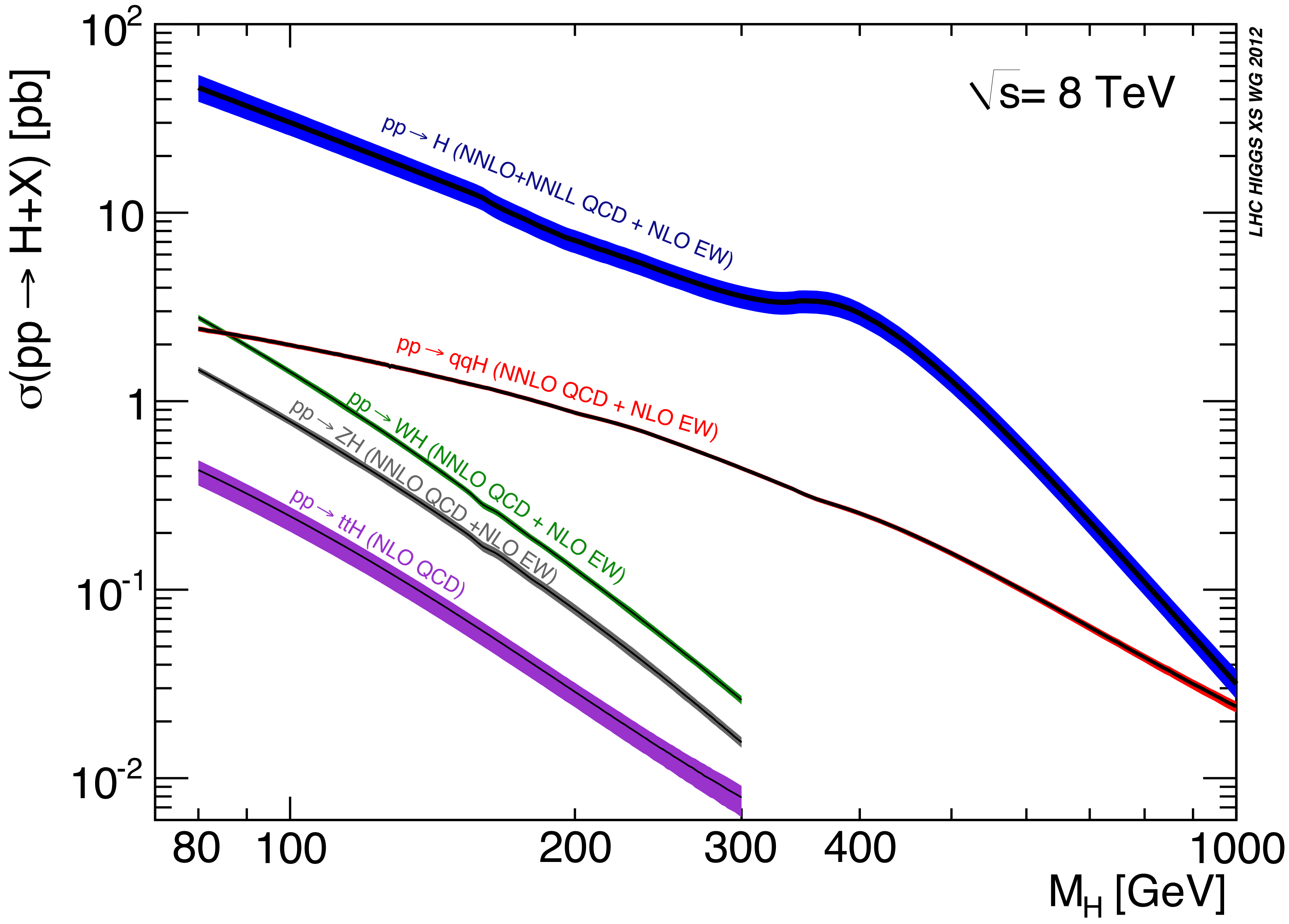




Higgs production modes directly searched for

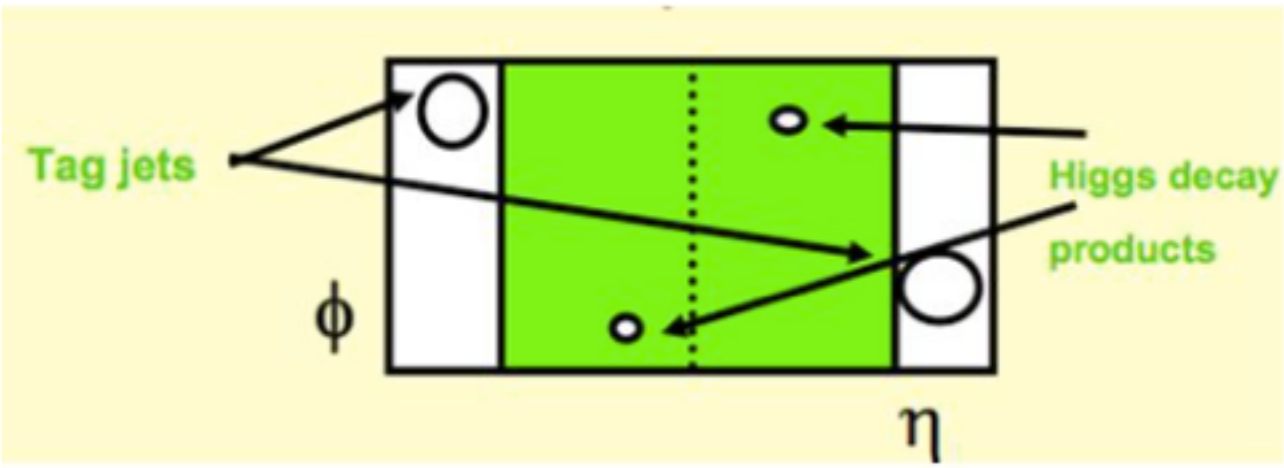




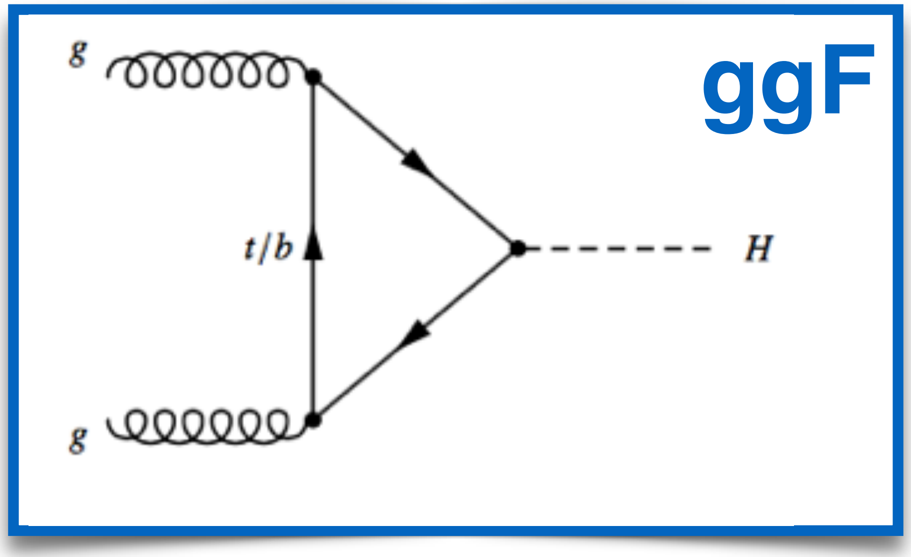


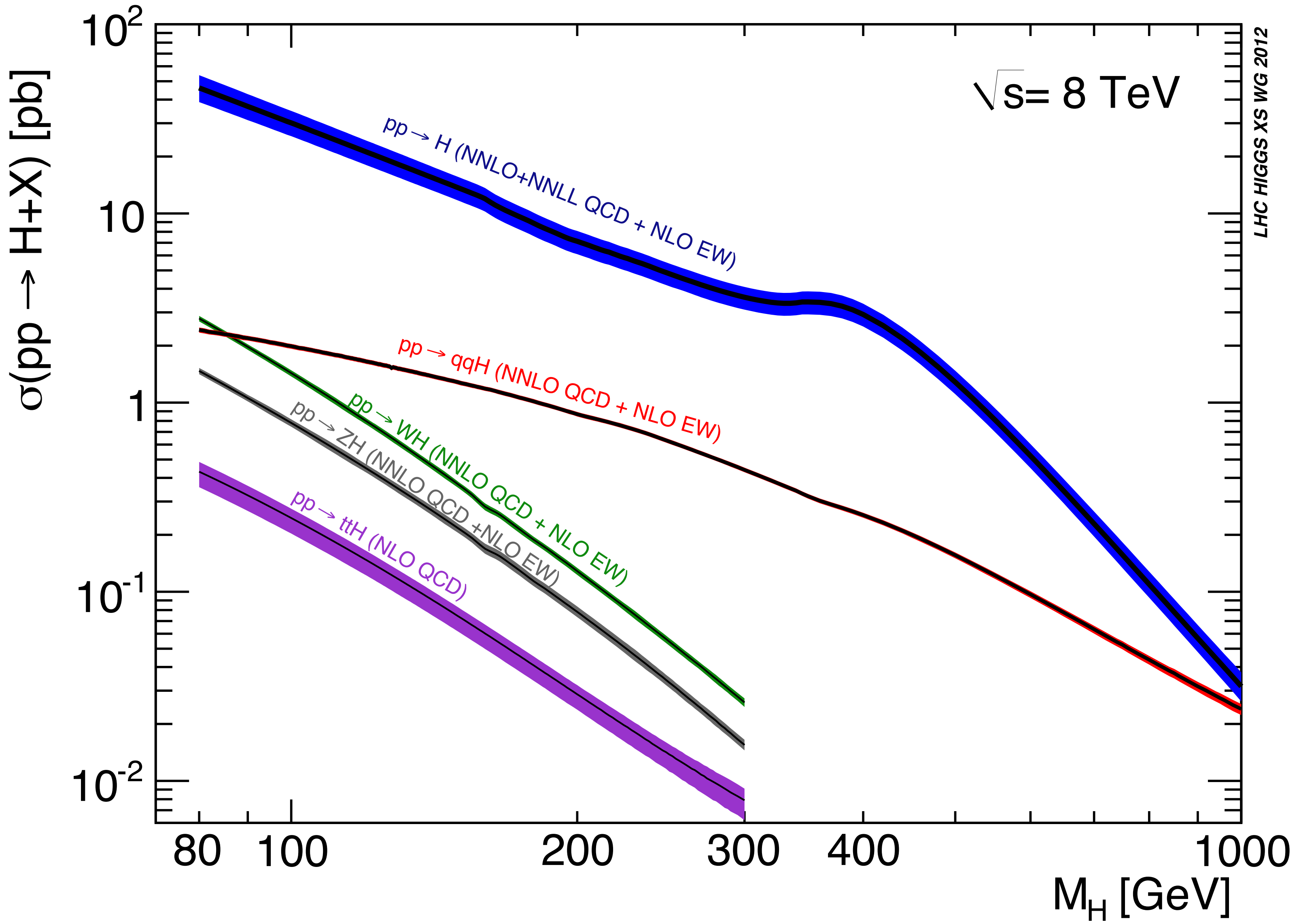
Distinct kinematics that help separating it from background:

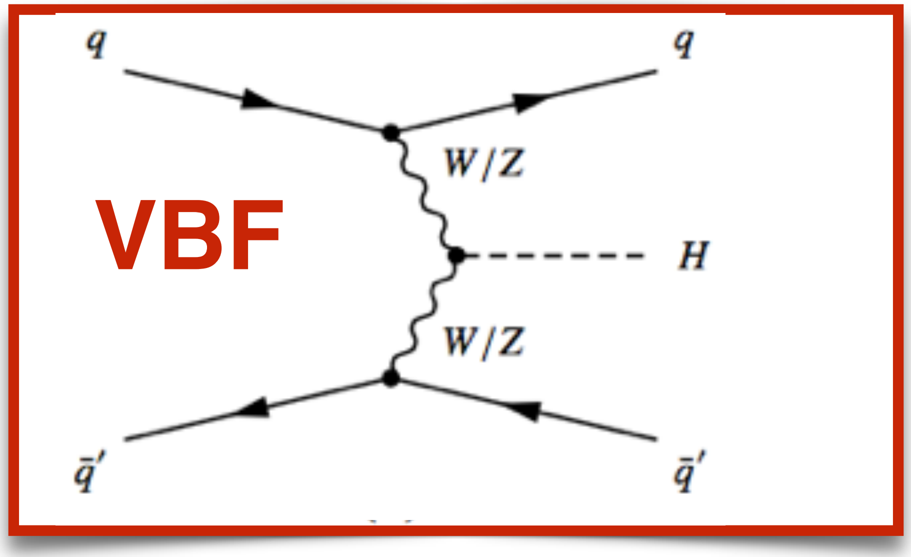
- two high pT jets with large rapidity gap
- no color flow between them
  —> suppressed hadronic activity in central region

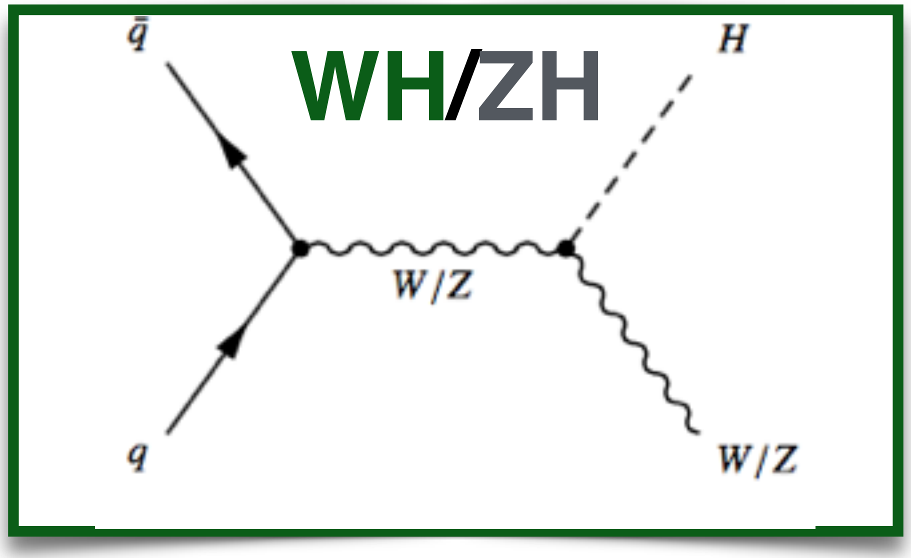


Higgs production modes directly searched for



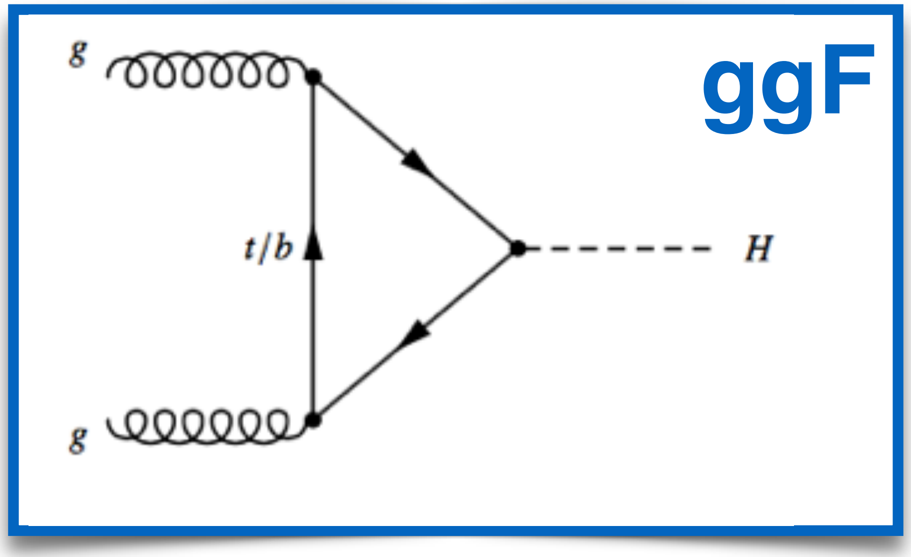


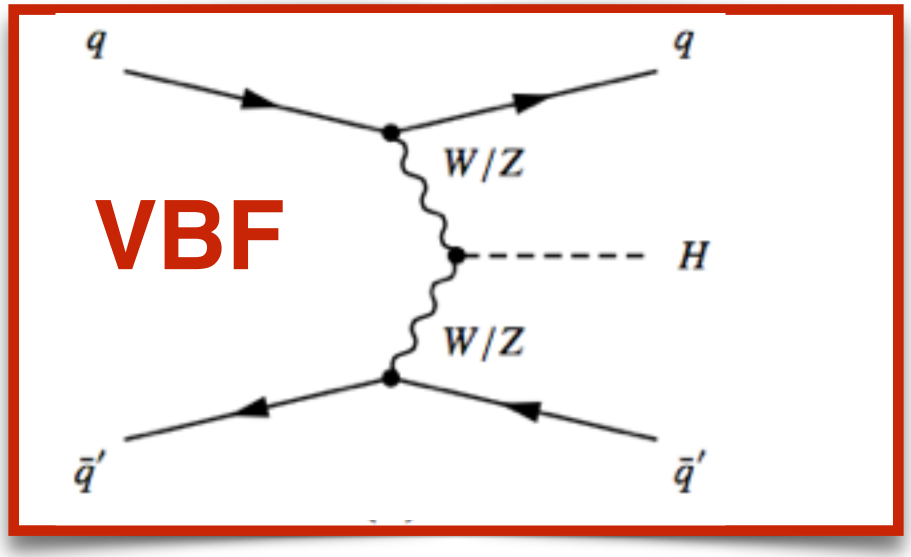


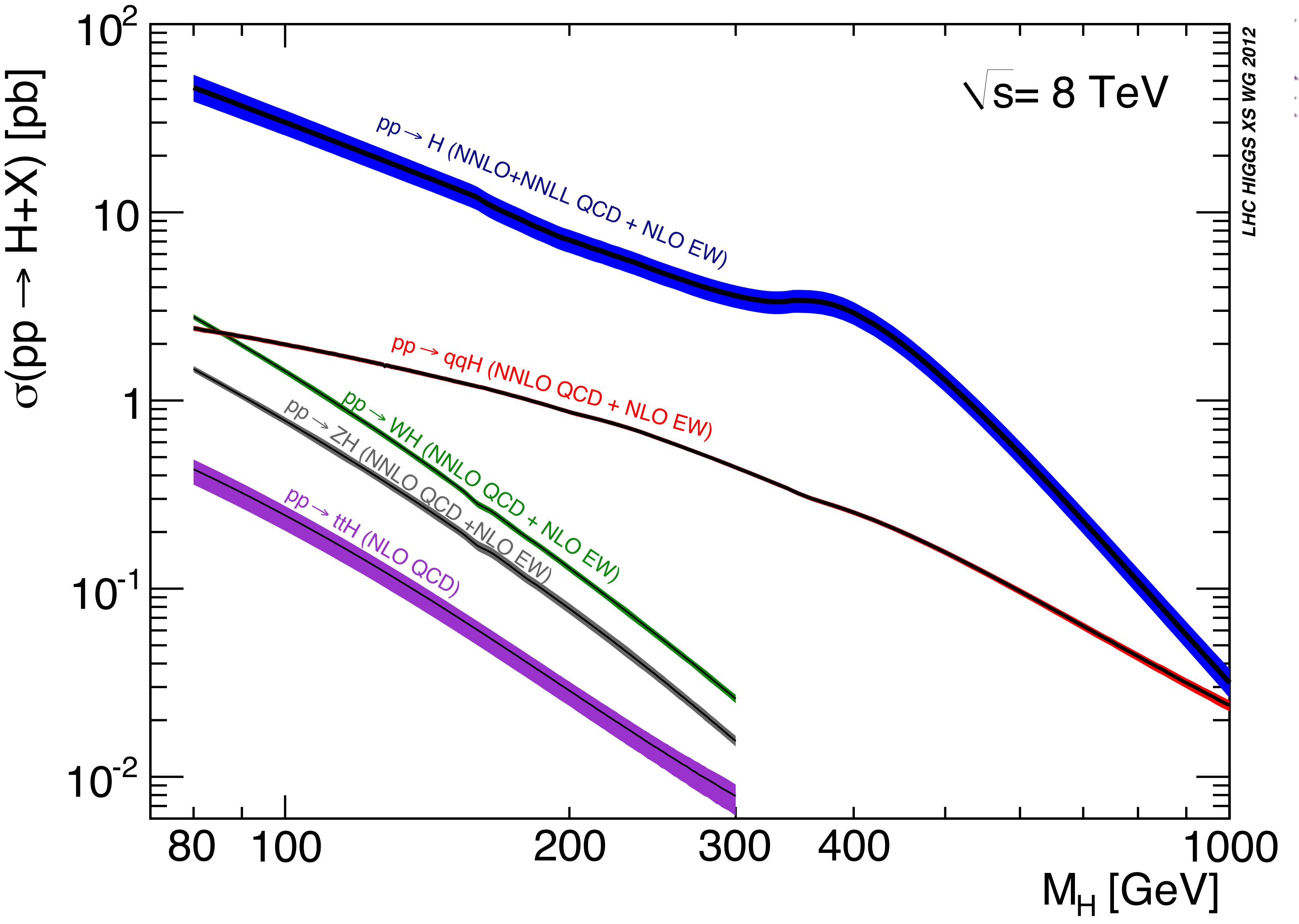


Best production mode for H—> bb decay
Leptons from W/Z decays are powerful handles against background

Higgs production modes directly searched for



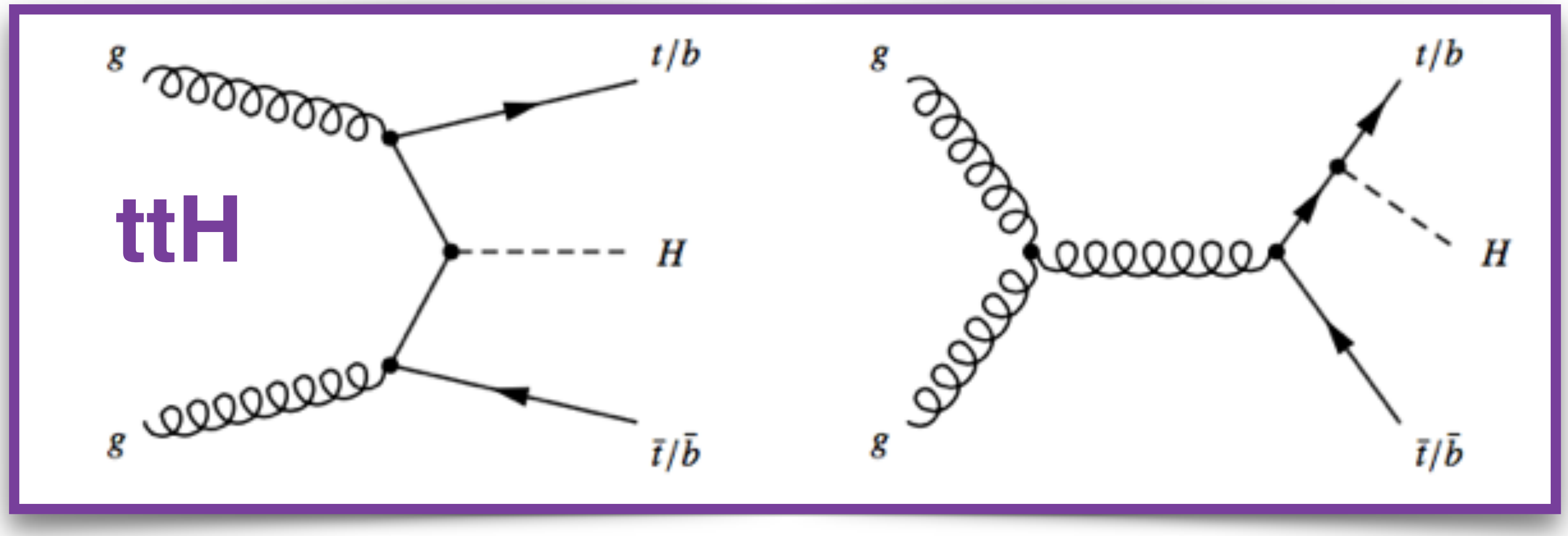




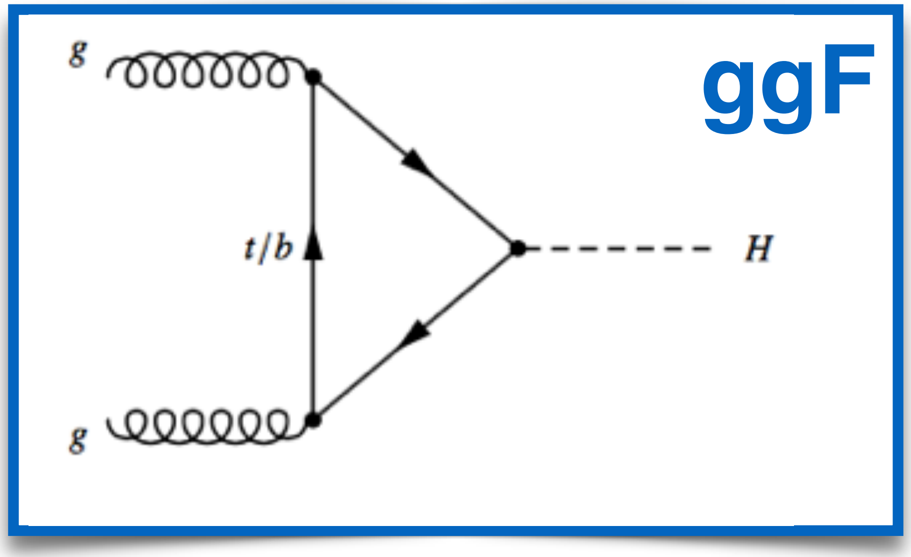
t—> Wb 100% of the time
Final states with at least two jets originating from b-quark

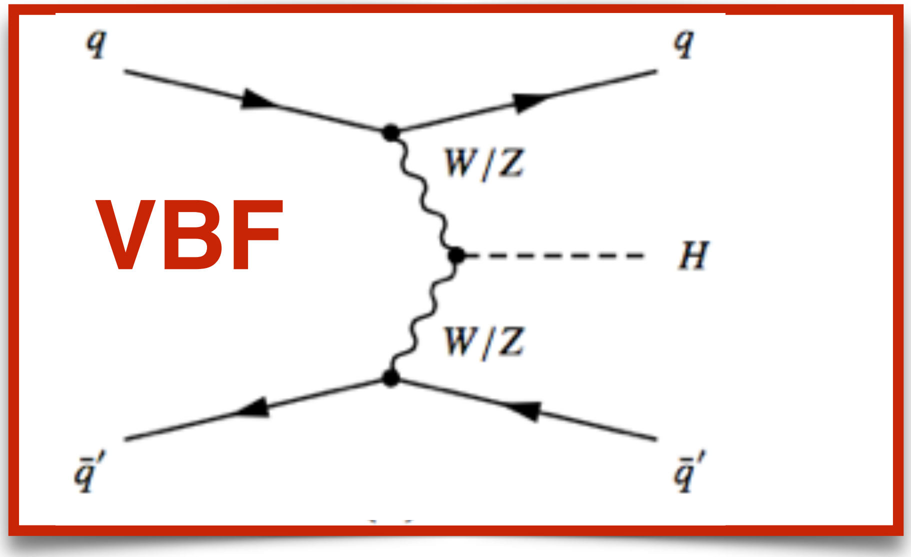
Depending on W and H decay mode, variable number of jets and leptons

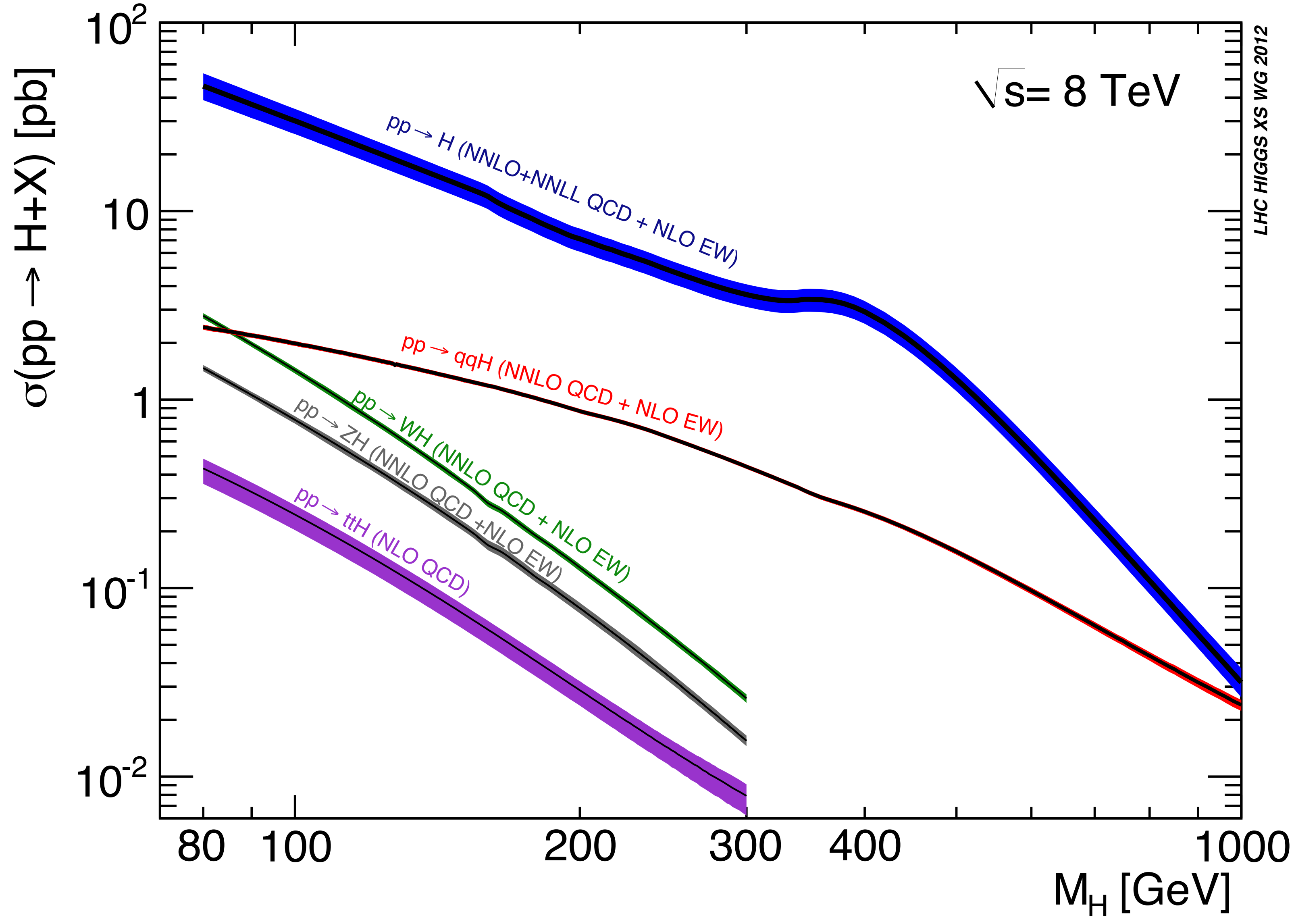
Include ~ all Higgs decay modes

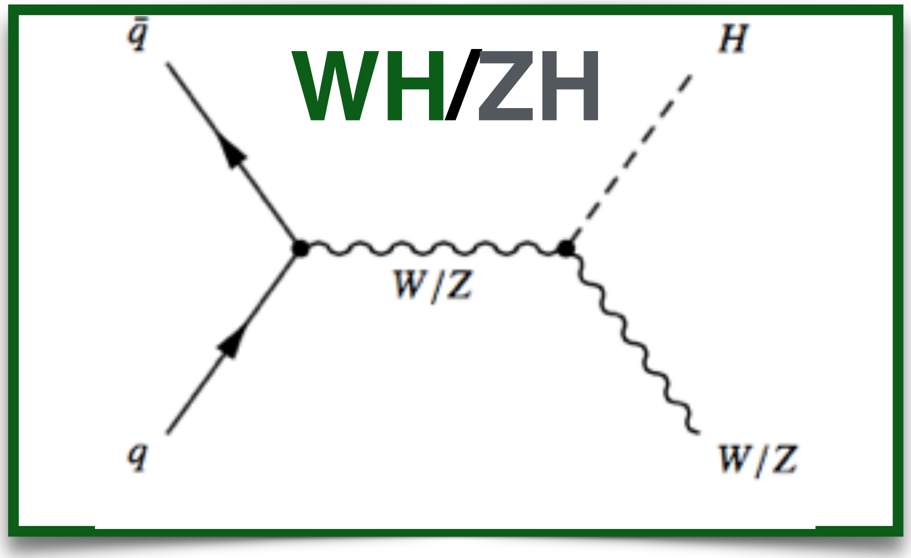


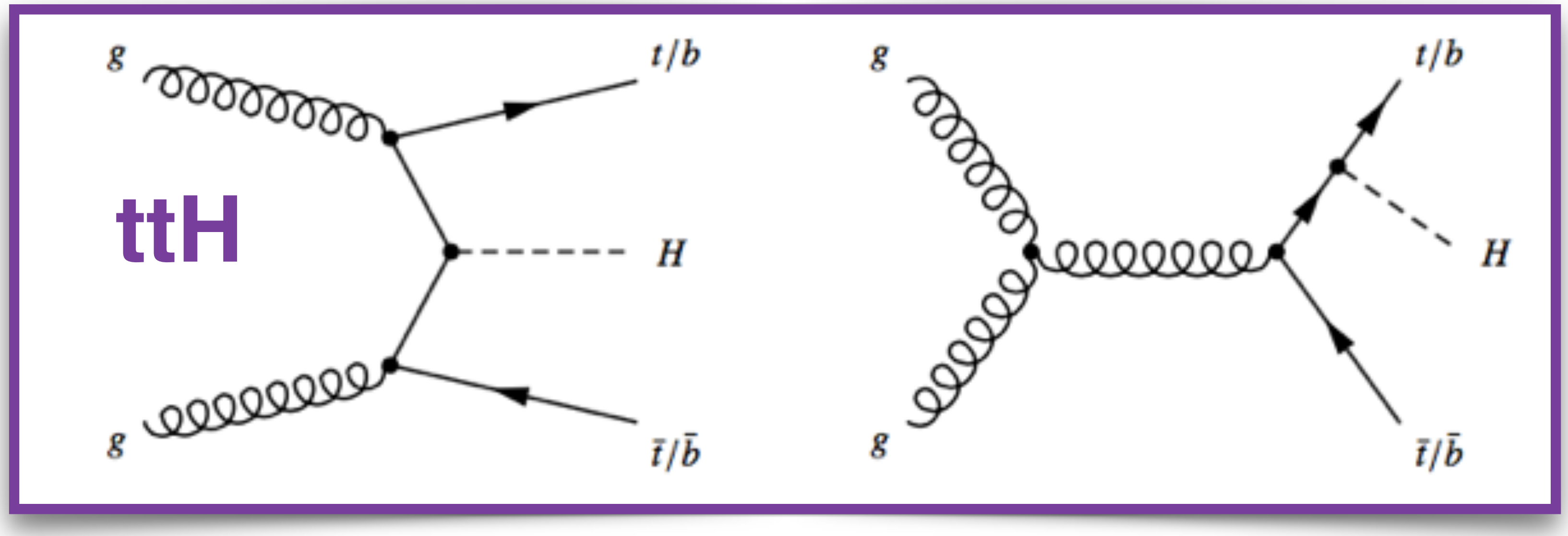
Higgs production modes directly searched for


ggF

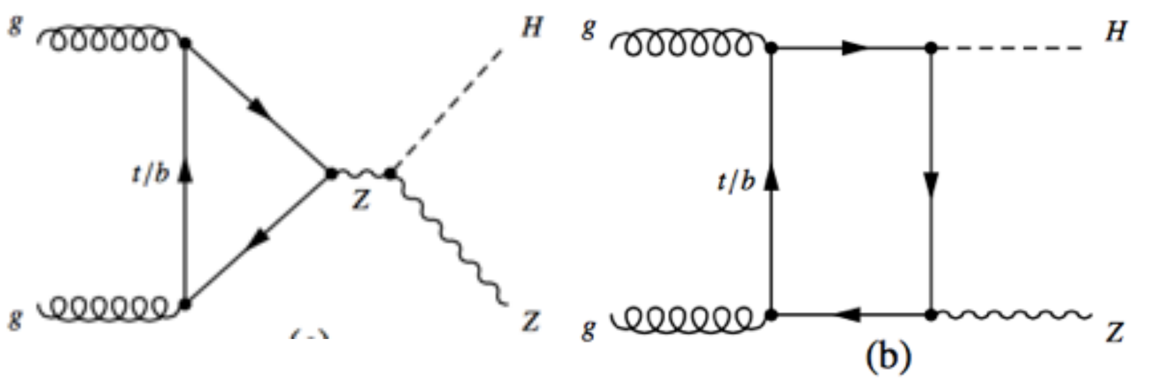

VBF



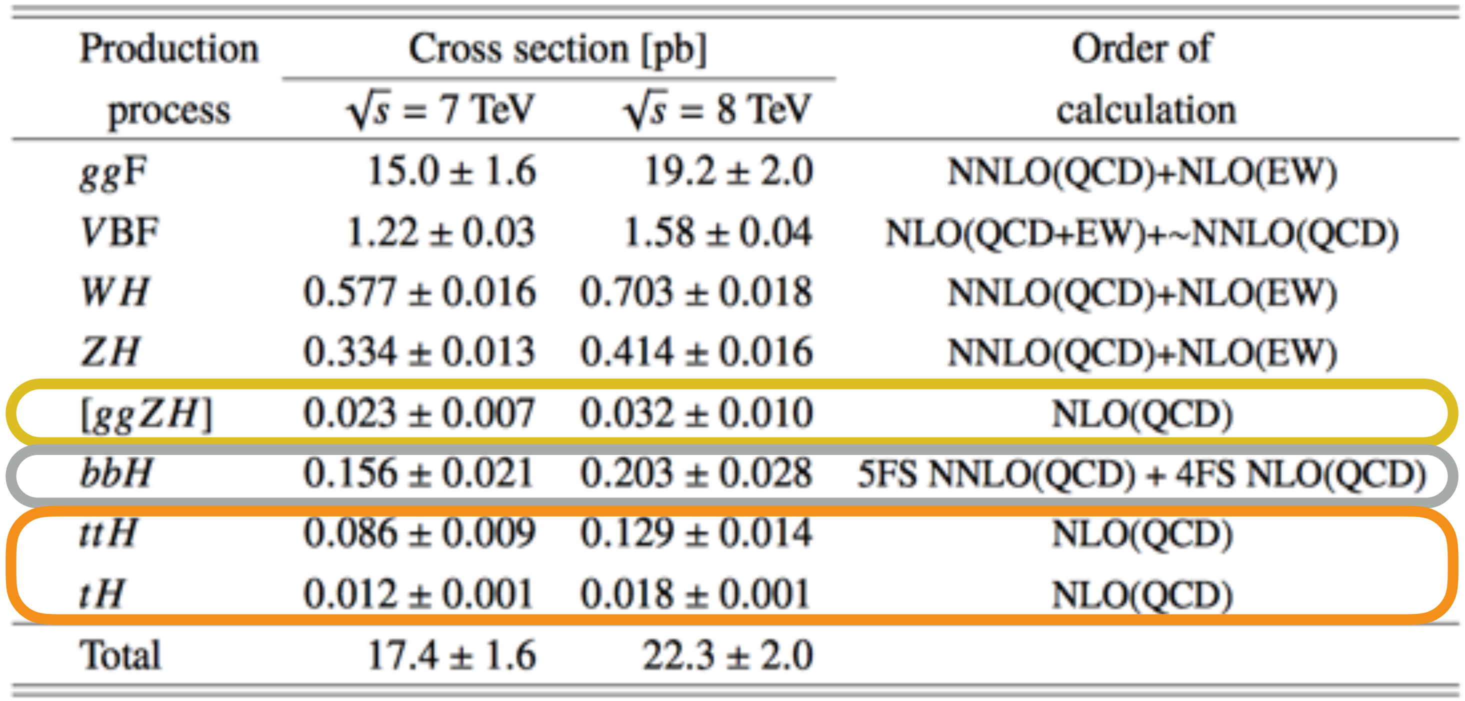

WH/ZH


ttH

Other production modes



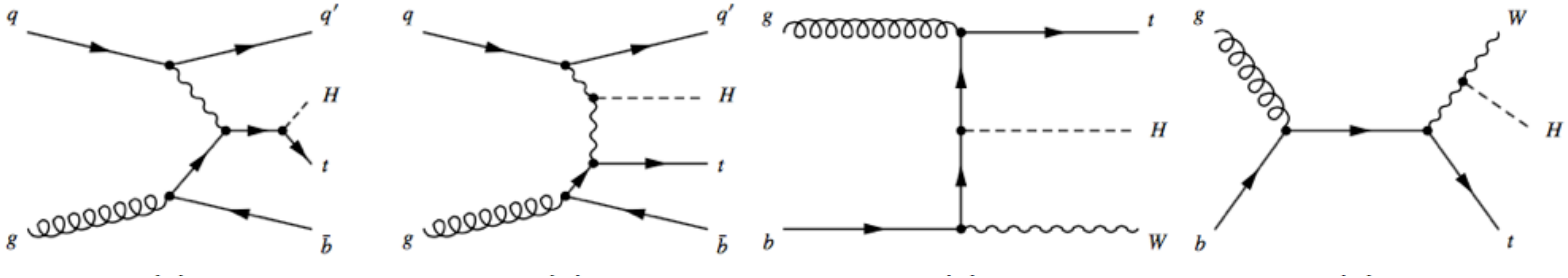
ggZH:
8% NNLO corrections for σ(ZH)
harder pT(H) spectrum
—> enhanced in the most sensitive region of H—>bb search



Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

bbH: 1% of σ(ggF) experimentally indistinguishable from ggF

tH:
very small cross section, mostly due to destructive interference
For opposite sign W/t Higgs couplings, σ(tHqb) increases by factor 13 and σ(WtH) by factor 6



Since 2012..

Final Run 1 dataset x2.5 what used for Higgs discovery

- ATLAS: 4.5/fb@7TeV and 20.3/fb@8TeV
- CMS: 5.1/fb@7TeV and 19.8/fb@TeV

—> x 2.7 Higgs bosons available with full dataset!

Various measurements to explore its properties, all consistent with S.M.

1)Higgs mass measured with < 0.2% precision arXiv: 1503.07589

- combination of ATLAS and CMS high mass resolution ɣɣ and ZZ*—>4leptons channels

$$\mathbf{M_H = 125.09 \pm 0.24\ GeV\ [\ \pm 0.21\ (stat.)\ \pm 0.11 (syst.)\ ]}$$

2)Test for Spin/Parity quantum numbers all consistent with spin-0, CP-even

- spin-2 models tested are all ruled out at 99.9% C.L.

3)Higgs discovered in boson final state, confirm couplings to fermions

- indirect evidences from ggH production mode, direct evidence from H—>tau tau decay

4) Measure Higgs yields for all accessible Production x Decay modes

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Inputs: ATLAS/CMS channels

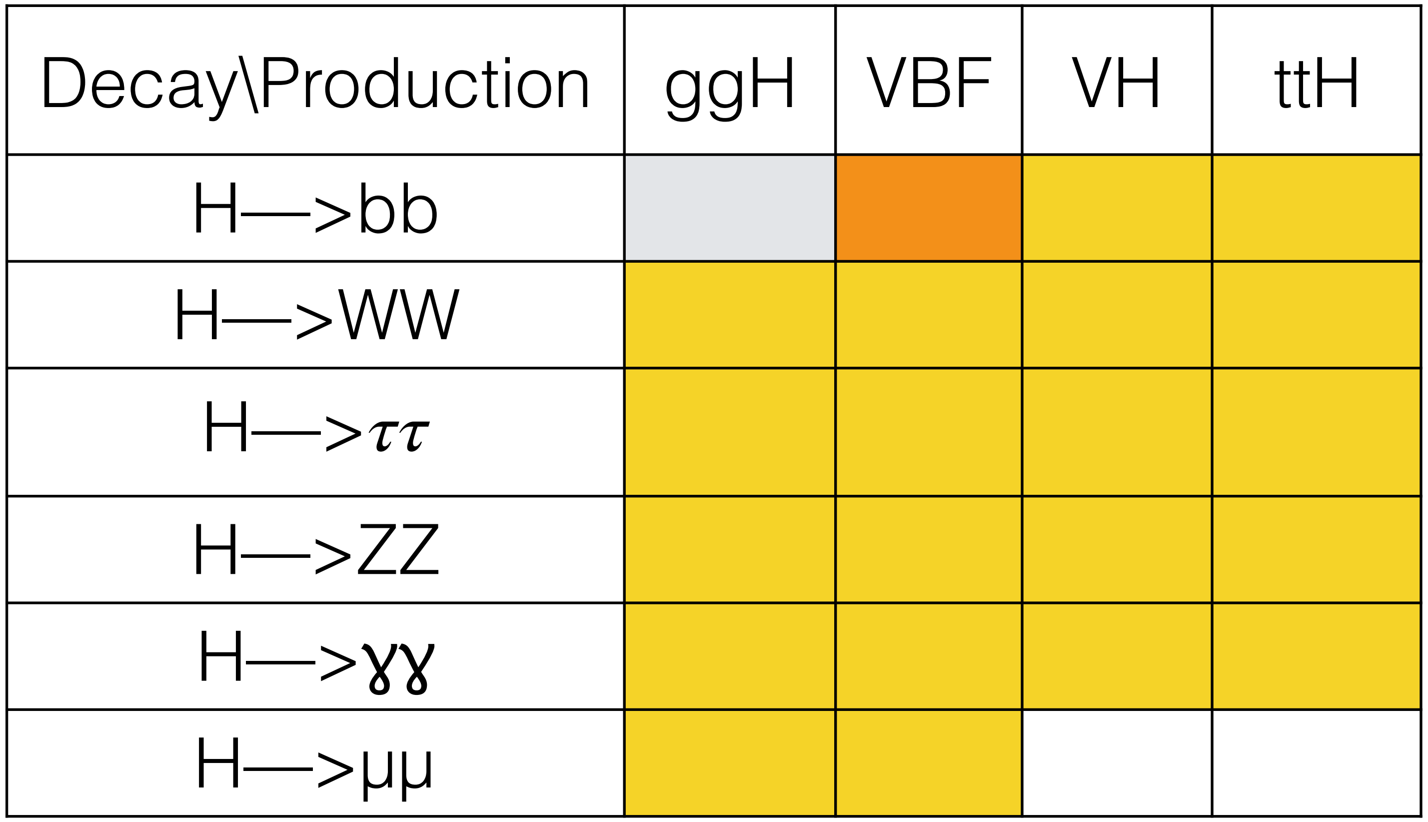
CMS-PAS-HIG-15-002
ATLAS-CONF-2015-044

Searched performed in final state associated with one decay mode
- consider (~) all production mechanisms

Channel	Signal significance [σ] (expected significance) ATLAS	CMS
$H \to \gamma\gamma$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ \to 4\ell$	6.6 (5.5)	7.0 (6.8)
$H \to WW$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	sensitivity too low	
ttH production	2.7 (1.6)	3.6 (1.3)

gg —> H —> bb:
not experimentally accessible
due to overwhelming background

qq —> Hqq —> bbqq
being searched for, not included
in the combination



Decay\Production	ggH	VBF	VH	ttH
H—>bb	▨	🟧	🟨	🟨
H—>WW	🟨	🟨	🟨	🟨
H—>$\tau\tau$	🟨	🟨	🟨	🟨
H—>ZZ	🟨	🟨	🟨	🟨
H—>$\gamma\gamma$	🟨	🟨	🟨	🟨
H—>μμ	🟨	🟨		

too small cross sections

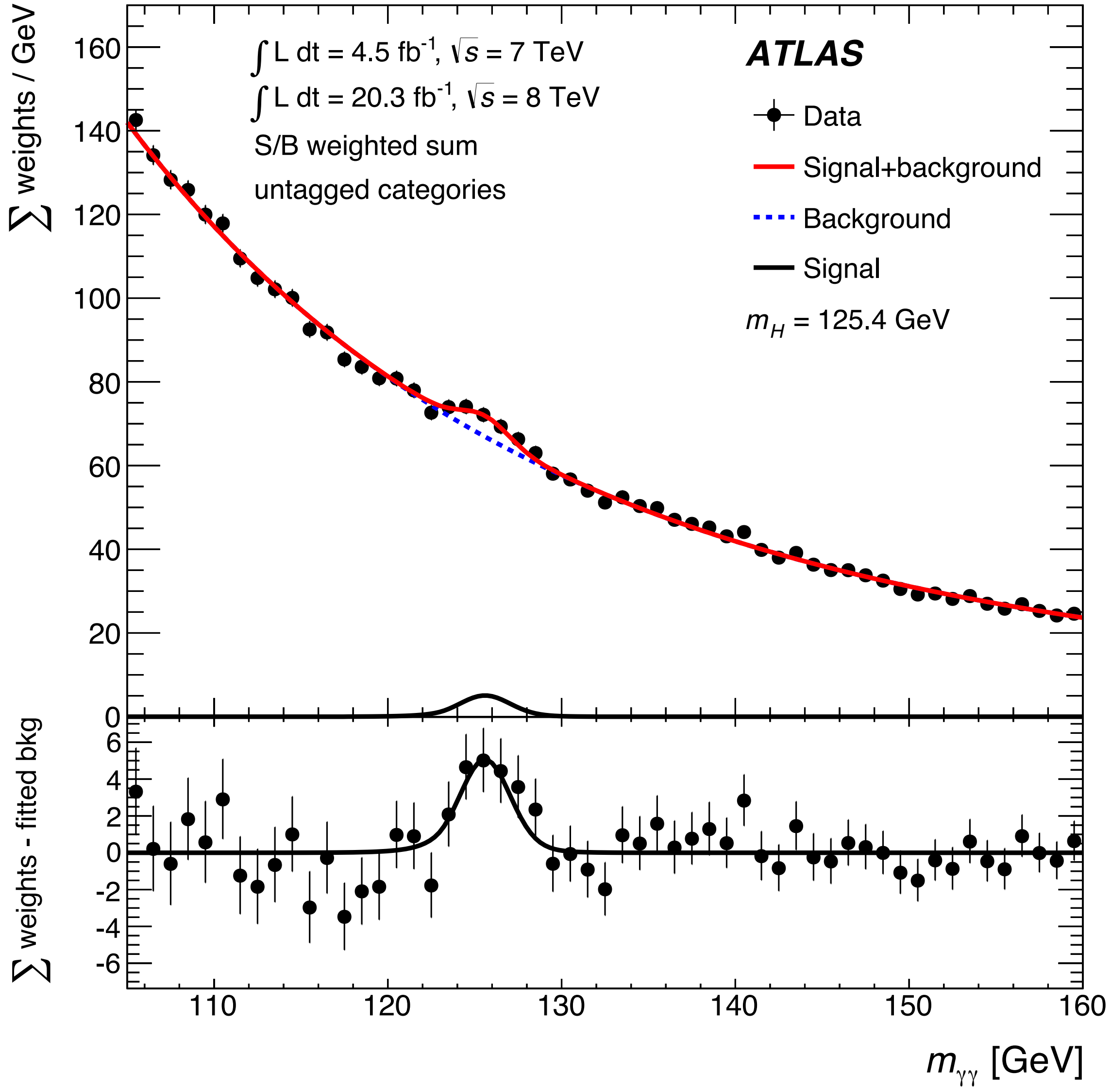
Event Categorisation

For each decay mode, events classified based on kinematic characteristics and detailed properties

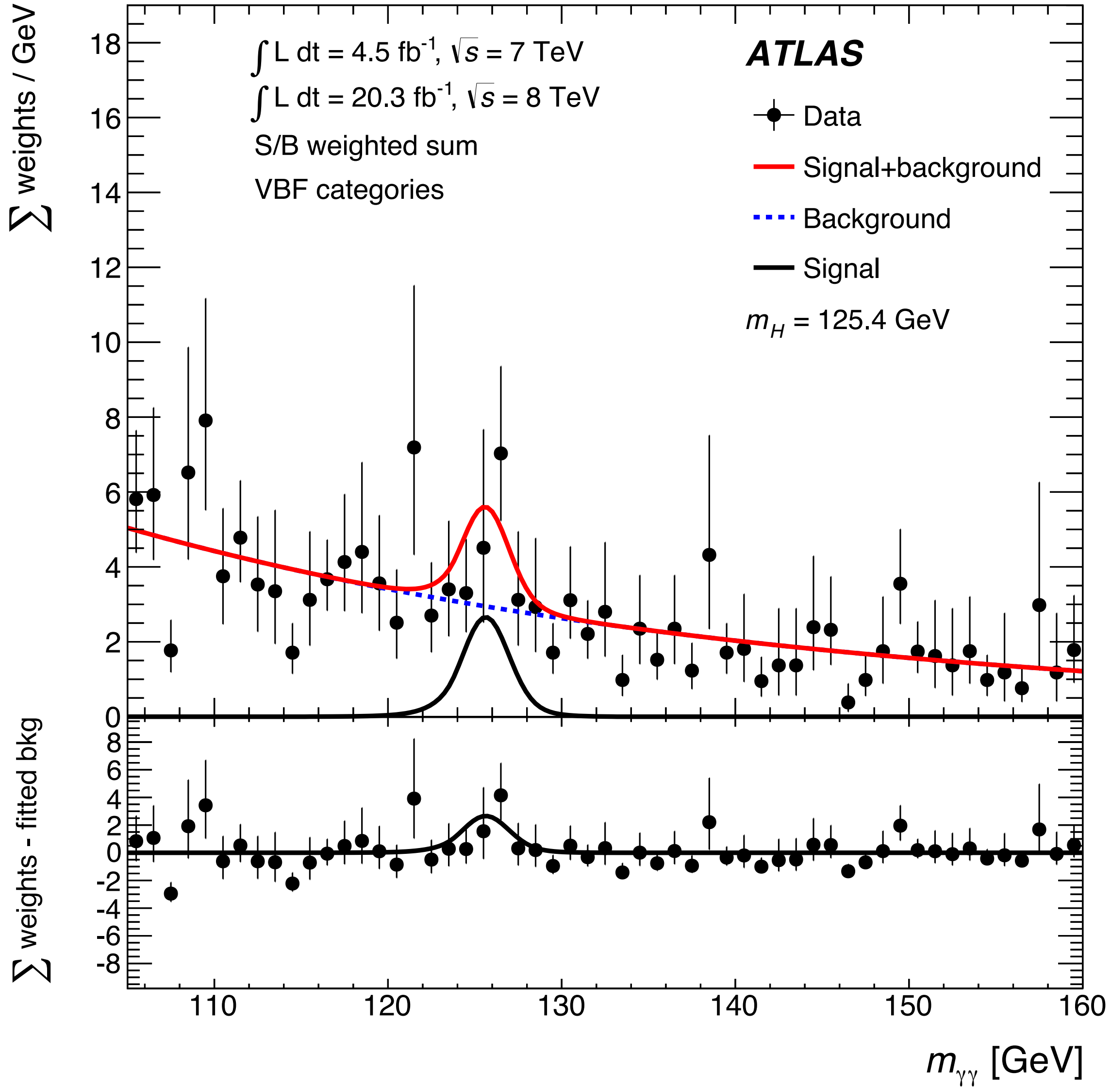
- improve overall sensitivity, thanks to better bkg rejection
- allow separation of different production modes

ATLAS+CMS combination includes ~ 600 exclusive categories

H—>ɣɣ, untagged (mostly ggF)



H—>ɣɣ, VBF



Signal Strength

- historically, first property to be measured
- characterise the Higgs boson yields

For specific production and decay mode **i —> H —> f**
ratio between the measured Higgs boson yield and the SM expectation

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

assume narrow
width approximation

Can’t access separately σ and Branching Ratio without assumptions

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \quad \text{and} \quad \mu^f = \frac{\mathrm{BR}^f}{(\mathrm{BR}^f)_{\mathrm{SM}}}.$$

signal strength for production μ_i
assume SM BR

signal strength for decay μ_f
assume SM production

Signal models

Signal yields in category k:

production and decay signal strength

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \boxed{\mu_i \mu^f} \left\{ \sigma_i^{\text{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}_{\text{SM}}^f \right\}$$

$\mathcal{L}(k)$: integrated luminosity

$\sum_i$: sum over production process i with inclusive cross section σ_i^{SM}

$\sum_f$: sum over decay modes f with branching fraction BR_{SM}^f

Signal models

Signal yields in category k:

production and decay signal strength

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \boxed{\mu_i \mu^f} \left\{ \sigma_i^{\text{SM}} \times \boxed{A_i^f(k) \times \varepsilon_i^f(k)} \times \text{BR}_{\text{SM}}^f \right\}$$

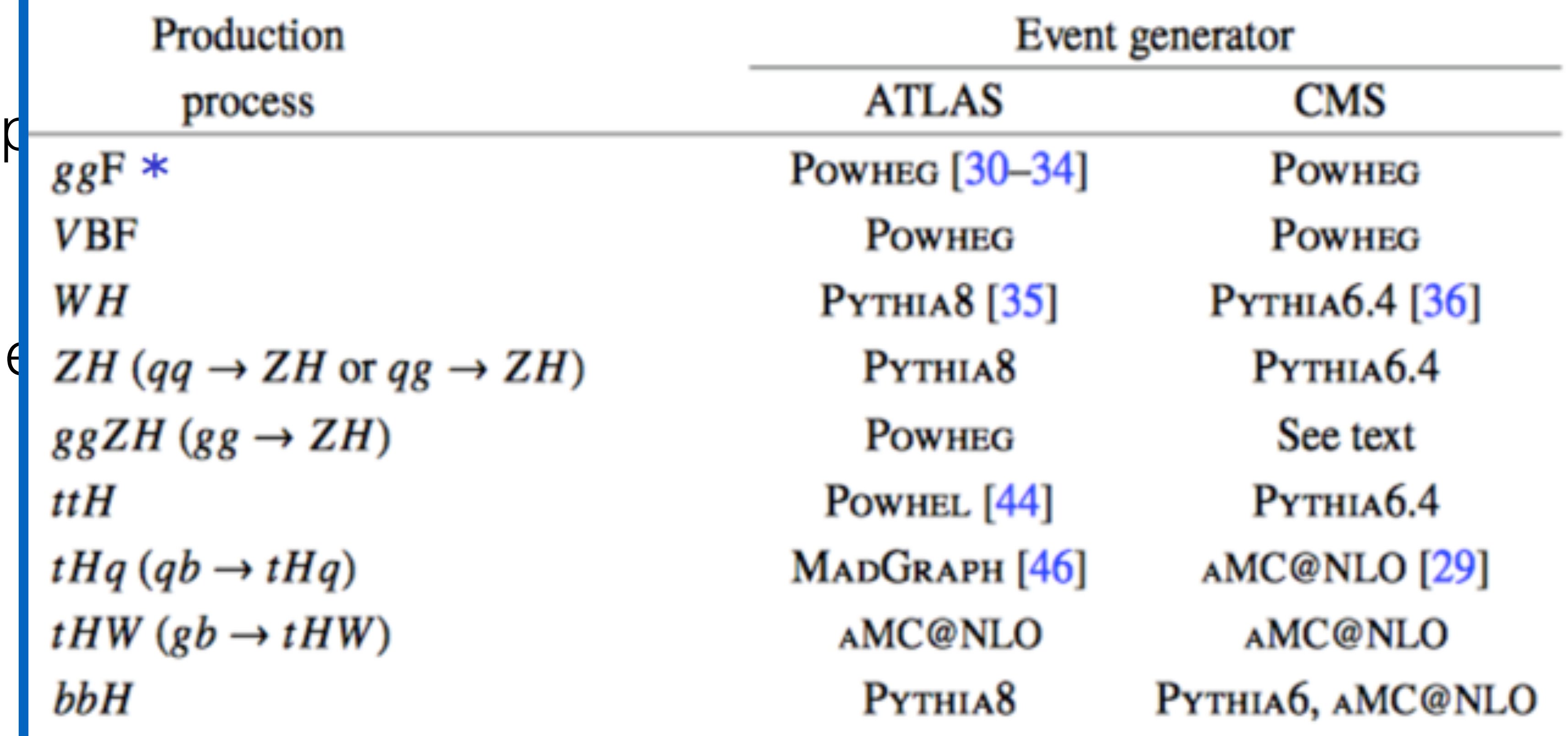
Acceptance and efficiency for process
i —> H —> f from MC simulation

$\mathcal{L}(k)$: integrated luminosity

$\sum_i$: sum over production p

$\sum_f$: sum over decay mode

Assume SM Higgs boson for acceptance & efficiency

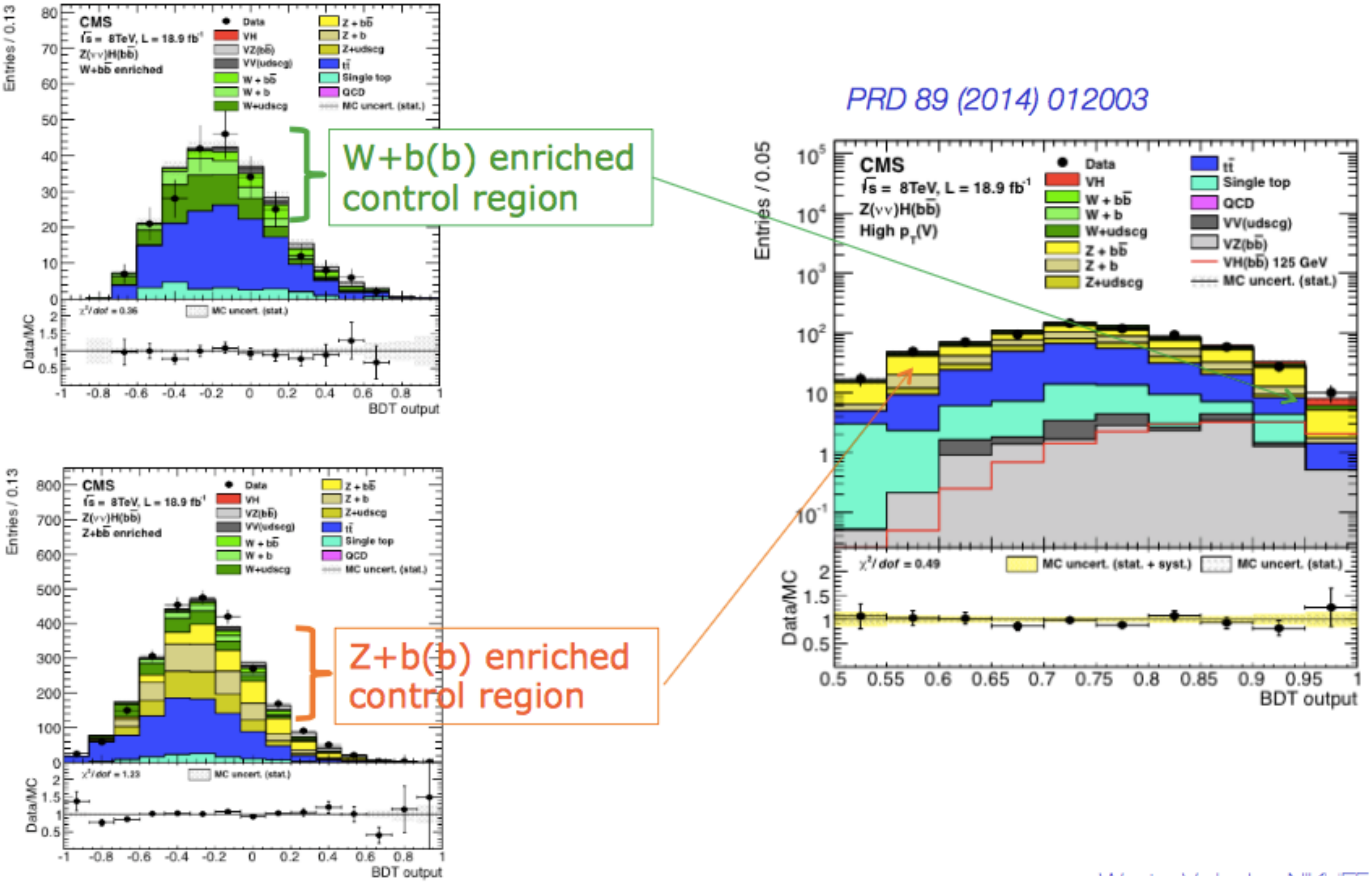


Production process	Event generator	
	ATLAS	CMS
ggF *	Powheg [30–34]	Powheg
VBF	Powheg	Powheg
WH	Pythia8 [35]	Pythia6.4 [36]
ZH ($qq \to ZH$ or $qg \to ZH$)	Pythia8	Pythia6.4
$ggZH$ ($gg \to ZH$)	Powheg	See text
ttH	Powhel [44]	Pythia6.4
tHq ($qb \to tHq$)	MadGraph [46]	aMC@NLO [29]
tHW ($gb \to tHW$)	aMC@NLO	aMC@NLO
bbH	Pythia8	Pythia6, aMC@NLO

(*) Higgs p_T distribution of ggF production reweighted to match HiRes 2.1calculation (includes NNLO and NNLL QCD corrections)

Background measurements from control regions

Background processes described by MC simulation or with data-driven model
- either constrained in control region or predicted relying on σ(theory)



W+b(b) enriched control region

Z+b(b) enriched control region

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Profile likelihood formalism for (systematic) uncertainties

- Build likelihood function for *each* signal, control region of the data

$$L(\vec{N}\,|\,\vec{\mu}_i,\vec{\mu}_f,\vec{\theta}) = \prod_{k=0,nbins} Poisson\left(N_k \,\middle|\, \sum_{i,f} \mu_i\cdot\mu^f\cdot \overset{i\to H\to f}{S^f_{i,k}(\vec{\theta})} + \overset{\text{Background}}{\sum_m B_m(\vec{\theta})}\right)$$

Inclusive SM cross-section

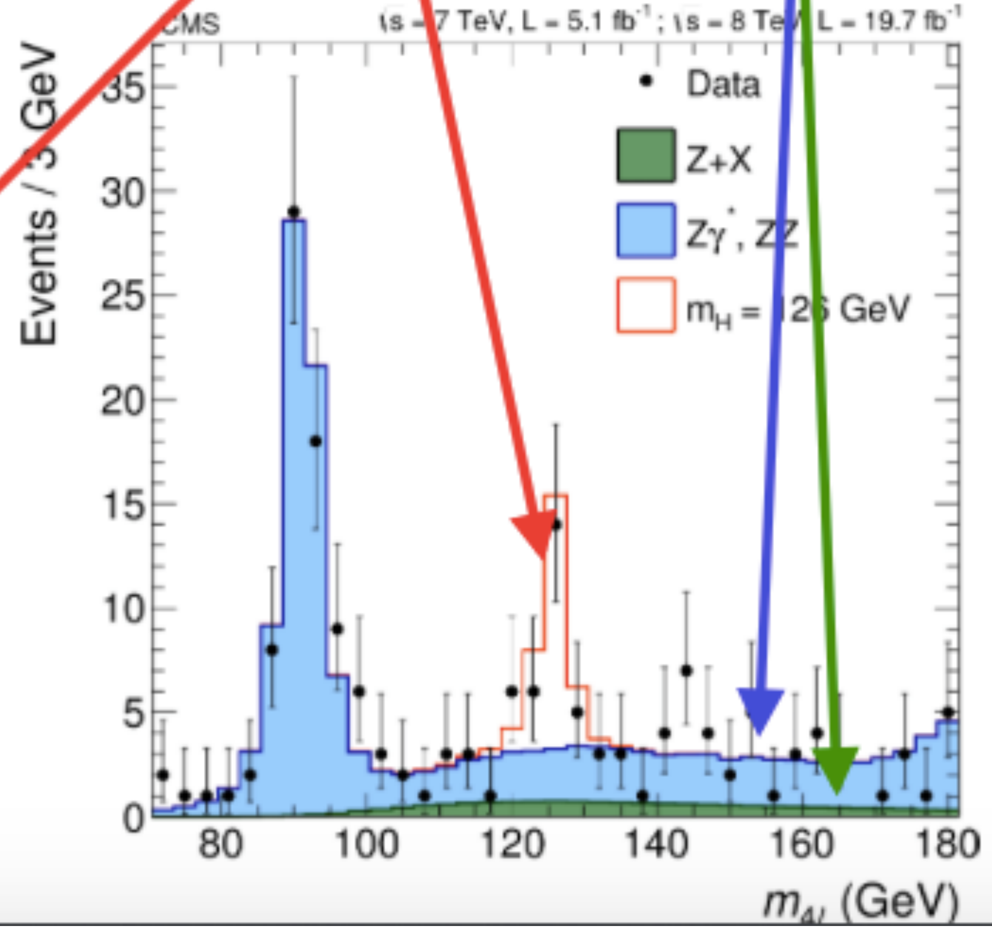
Acceptance (from MC)

Efficiency (from MC)

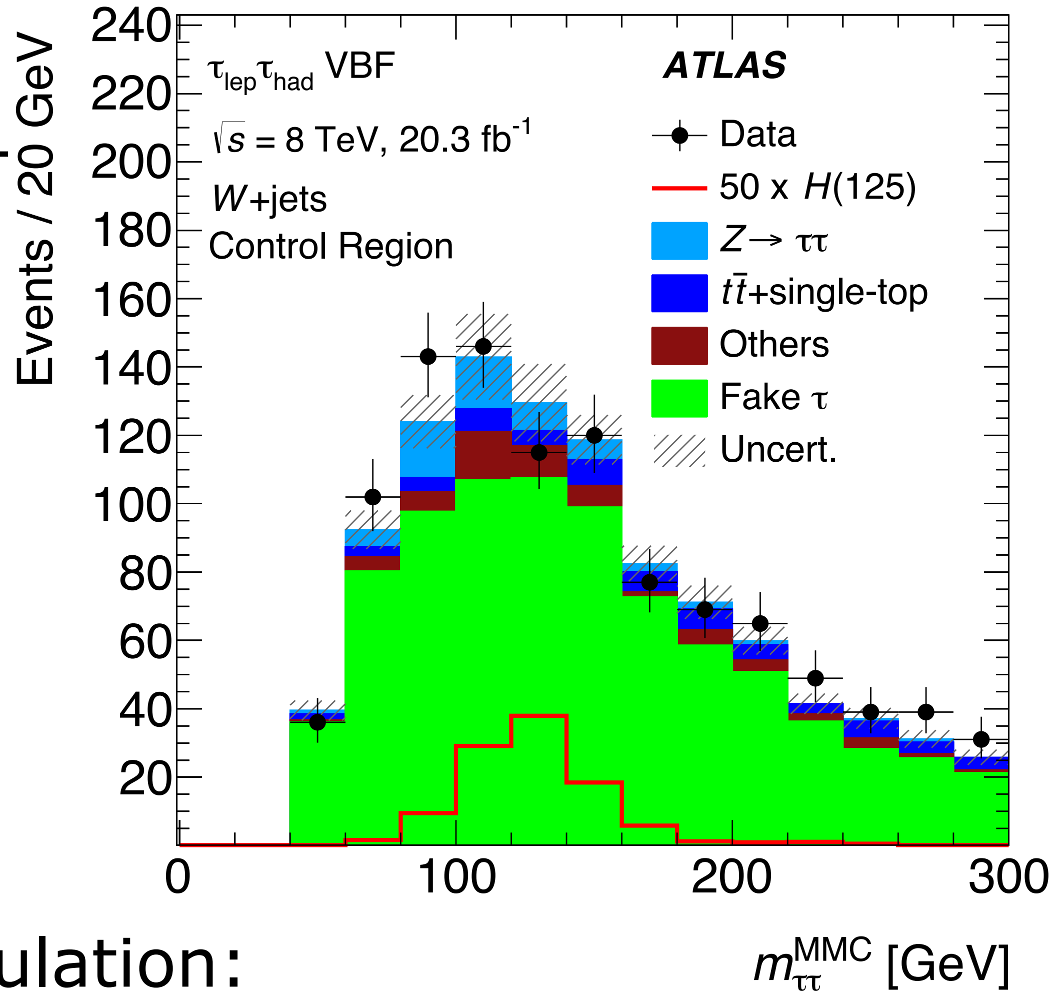
Higgs BR

Luminosity

$$\mathcal{L}(k)\times\left\{\sigma_i^{\text{SM}}\times A_i^f(k)\times\varepsilon_i^f(k)\times \text{BR}^f_{\text{SM}}\right\}$$



Systematic uncertainties



Signal and background predictions are affected by systematic uncertainties

Most expected distributions described by MC simulation:

- simulation of high energy process: uncertainty due to order in perturbation theory and choice of Parton Distribution Function
- simulation of soft physics: underlying event, parton shower model
- detector simulation: energy scale, selection efficiencies

Also, predict number of background events relying on control region

- extrapolation from control-region to signal region

control region: region of phase space with similar kinematics w.r.t signal region, but orthogonal to it

Systematic uncertainties

Likelihood can describe discriminating distribution under a wide range of parameters for which the true values are unknown (energy scales, QCD scale etc..)

$$L(\vec{N} \mid \vec{\mu}_i, \vec{\mu}_f, \vec{\theta}) = \prod_{k=0,nbins} Poisson\left(N_k \mid \sum_{i,f} \mu_i \cdot \mu^f \cdot S^f_{i,k}\boxed{(\vec{\theta})} + \sum_m B_m \boxed{(\vec{\theta})} \right)$$

θ: nuisance parameter

Correlated parameters as needed between channels and experiments

- only full correlation or no correlation considered in current combination

Uncertainties are included in the likelihood in two parts:

- auxiliary constraint on the nuisance parameter that represents the uncertainty
- parametrisation of how the signal/background predictions respond to changes in the nuisance parameter

Nuisance parameters in combined fit

Likelihood fit includes 4200 nuisance parameters

- **Detector systematic uncertainties**: generally correlated within experiment, not between experiments

- **Signal theory uncertainties** (QCD scale, PDF, UEPS) on inclusive cross sections: correlated between experiments, uncorrelated between processes

- **Signal theory uncertainties on acceptance and selection efficiency**: uncorrelated between experiments (usually small, and different method to estimate them)

- **PDF uncertainties on signal cross sections**: correlated for a given process across experiments, but uncorrelated between different processes (except WH/ZH/VBF)

- **No correlation assumed between Higgs BRs** (except WW/ZZ)
  Effect of ignoring correlation shown to be generally small, expect for few specific measurements

- **Background theory uncertainties**: usually not correlated, treated differently by the two experiments. When modelled completely by MC, fully correlate production cross sections (f.e. ZZ continuum)

Statistical treatment

From likelihood L(ATLAS+CMS) construct the profile likelihood test statistic

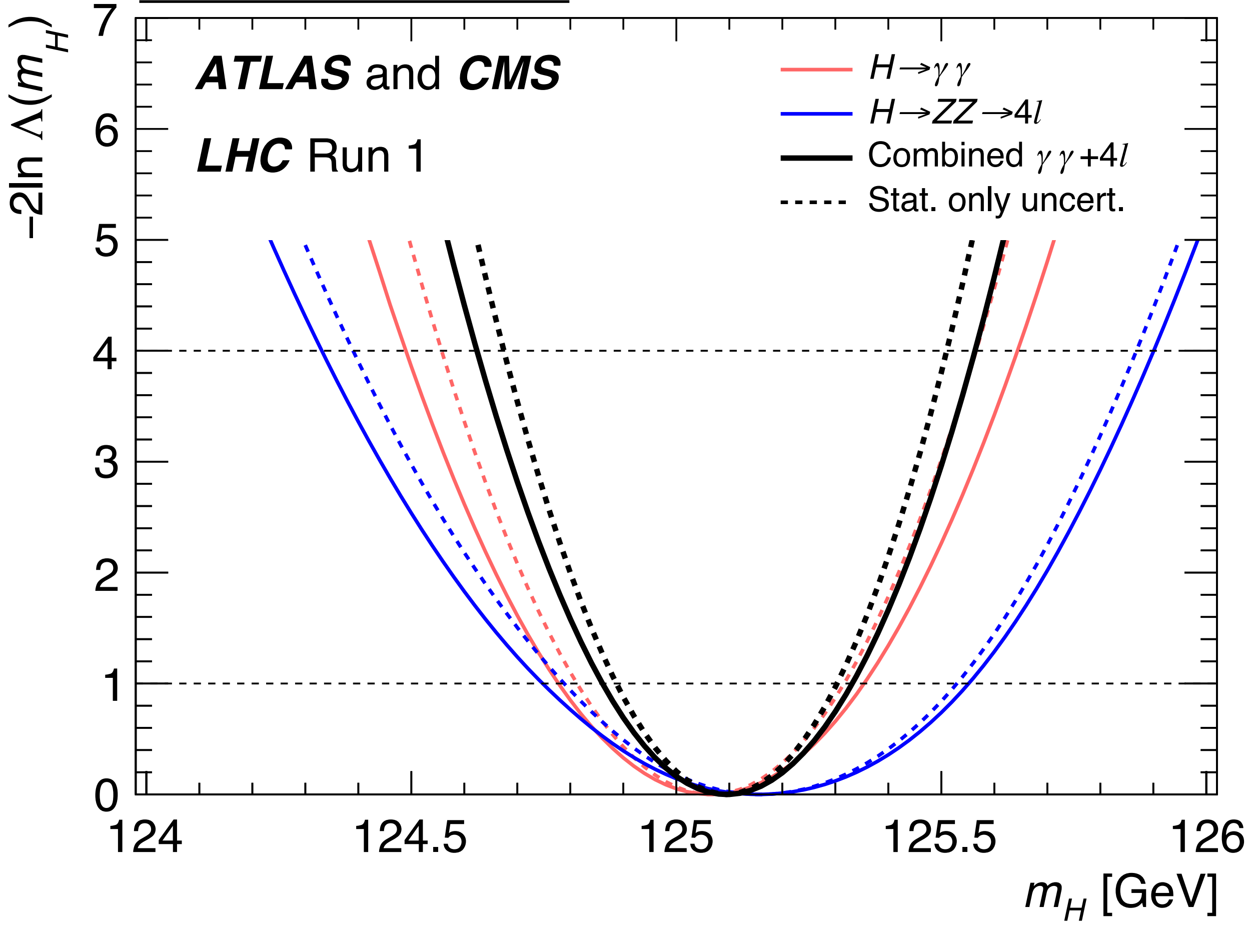
maximised likelihood for a given value of the POI

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

POI and nuisance parameters that maximise likelihood

α= parameter(s) of interest (POI) (such as μ, σ*Br etc..)

arXiv: 1503.07589



Negative log-likelihood estimator -2ln(Λ) assumed to follow a chi-squared distribution

95% Confidence Limit

68% Confidence Limit

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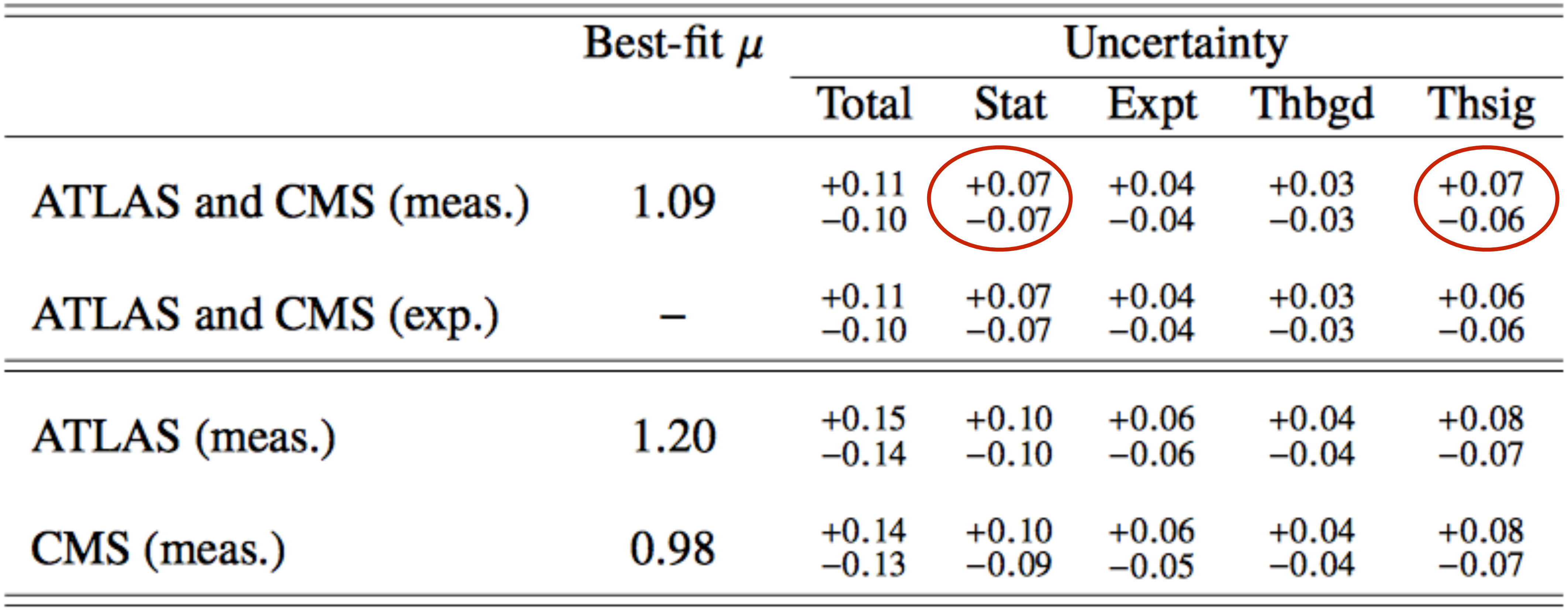
Conclusion and outlook

ATLAS + CMS combination: signal strength



	Best-fit μ	Uncertainty				
		Total	Stat	Expt	Thbgd	Thsig
ATLAS and CMS (meas.)	1.09	$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.07}_{-0.06}$
ATLAS and CMS (exp.)	–	$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.06}_{-0.06}$
ATLAS (meas.)	1.20	$^{+0.15}_{-0.14}$	$^{+0.10}_{-0.10}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$	$^{+0.08}_{-0.07}$
CMS (meas.)	0.98	$^{+0.14}_{-0.13}$	$^{+0.10}_{-0.09}$	$^{+0.06}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.08}_{-0.07}$

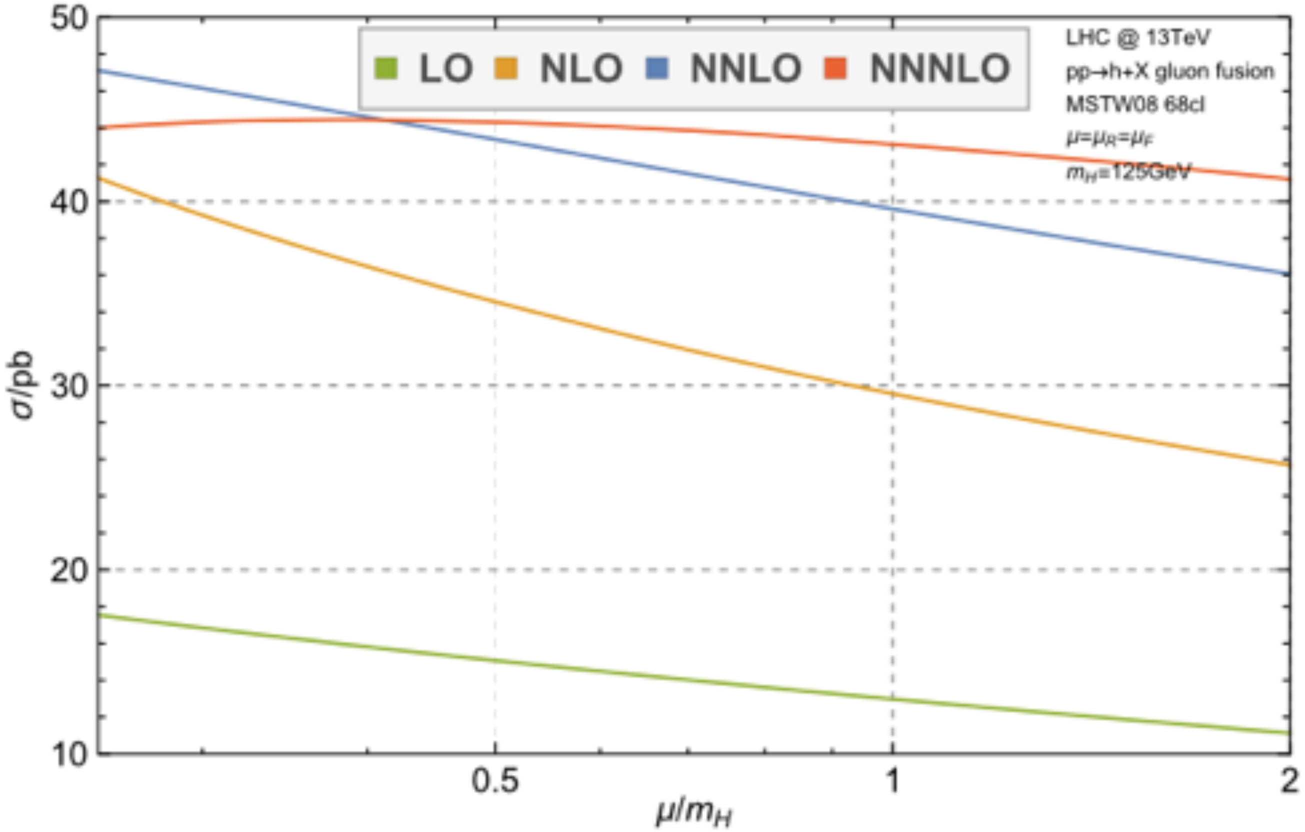
test global compatibility with the SM

Most precise result at the expense of the largest assumptions

Signal theoretical uncertainties same size as statistical uncertainty
- dominated by uncertainty on the ggF cross sections

Recent progress on theory: highlights

C. Anastasiou et al., PRL 114 (2015) 212001



ggH N3LO calculation

$$\sigma(gg \longrightarrow H)^{N3LO} = 19.47^{+0.32\%}_{-2.99\%}$$

$[\mu = m_H/2]$

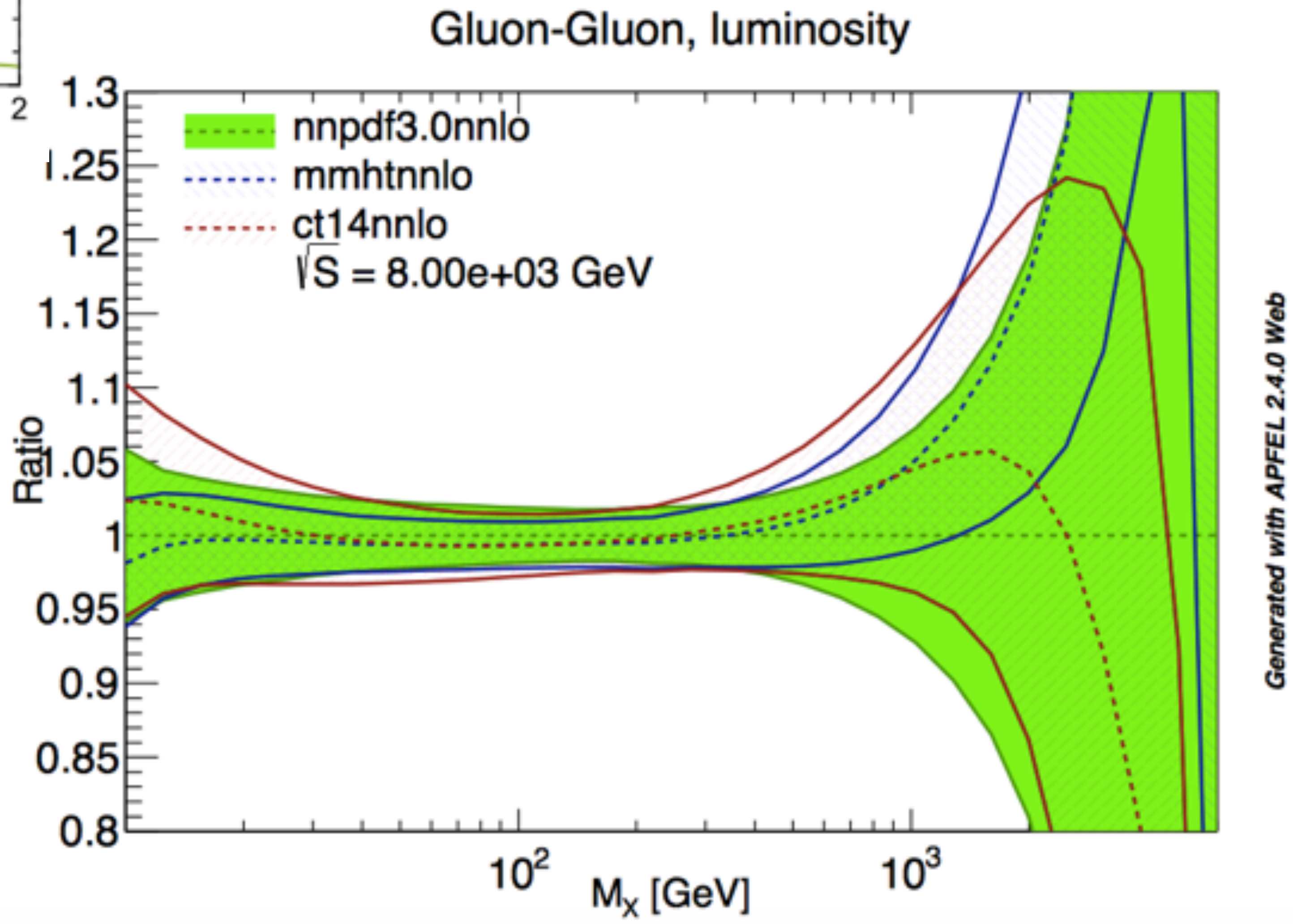
- **QCD scale uncertainty reduced from 8% to 2%**

PDF4LHCII: http://arxiv.org/abs/1510.03865

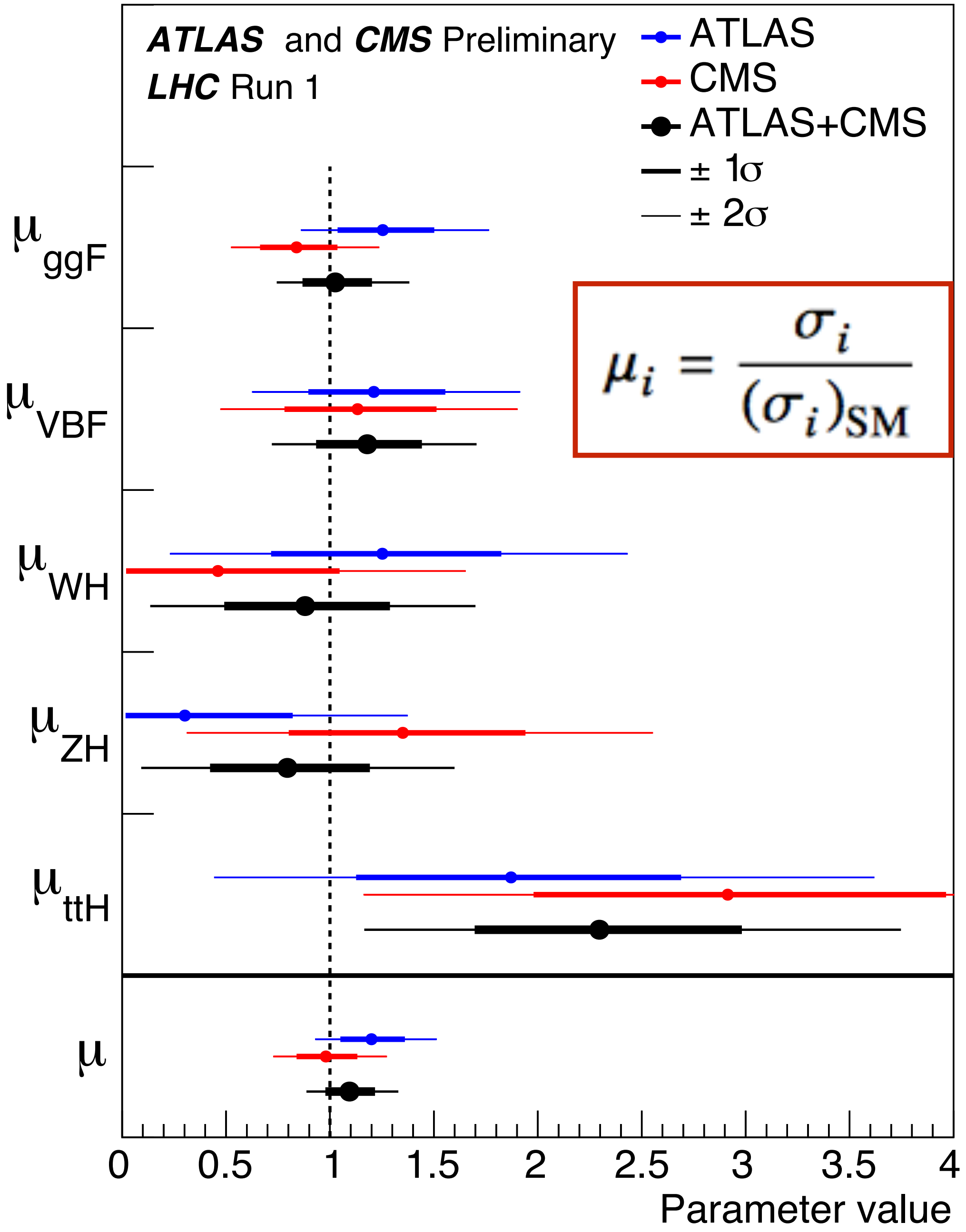
Major updates for all PDFs fits

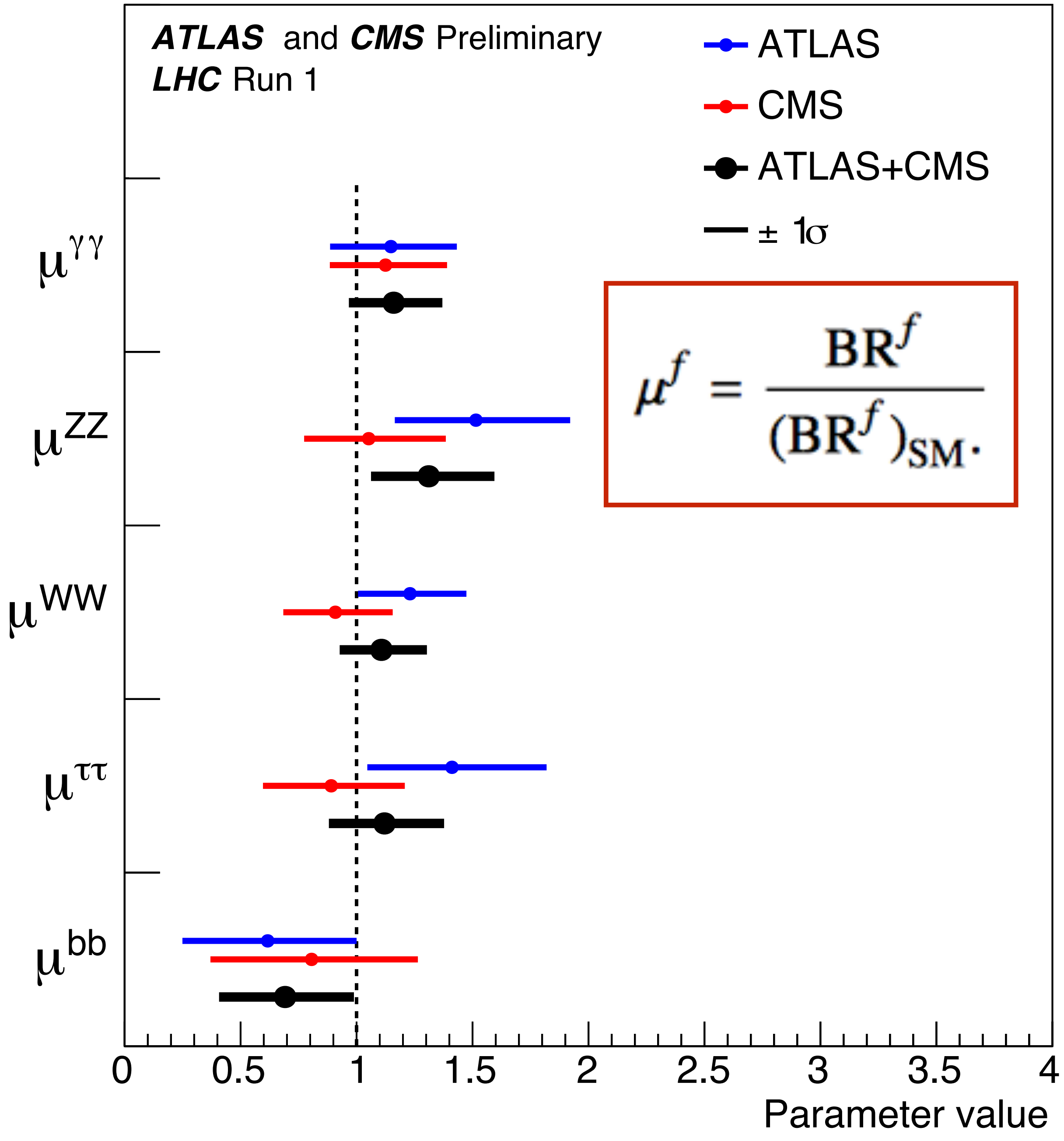
improved agreement for gluon luminosity

PDF uncertainty on gg—>H from 7% to 2%



Signal strength for production and decay





Assumptions:

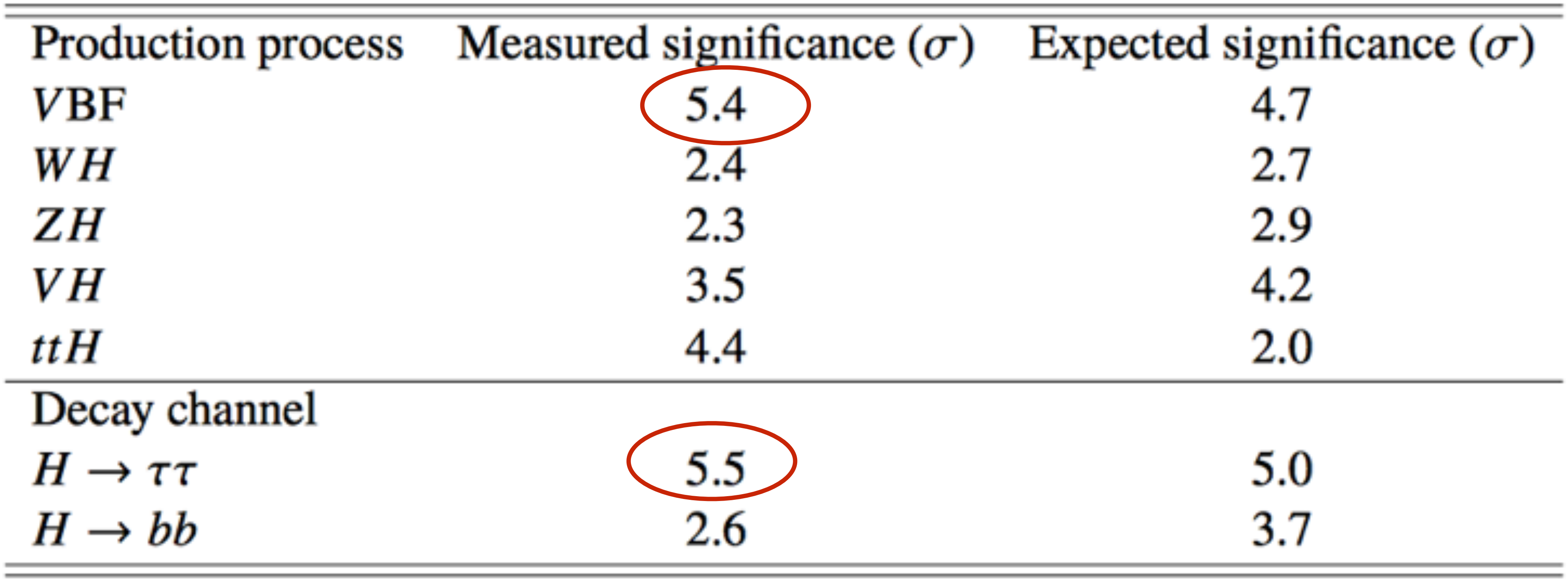
SM Branching ratios
Same signal strength modifier at 7 and 8 TeV
bbH scales as ggF, tH as ttH,
ggZH as quark-initiated ZH

Assumptions:

SM production cross sections
BRs do no depend on center of mass energy

Why combining CMS and ATLAS

Combination correspond ~ to summing ATLAS and CMS integrated luminosity
—> improve sensitivity by ~ √2

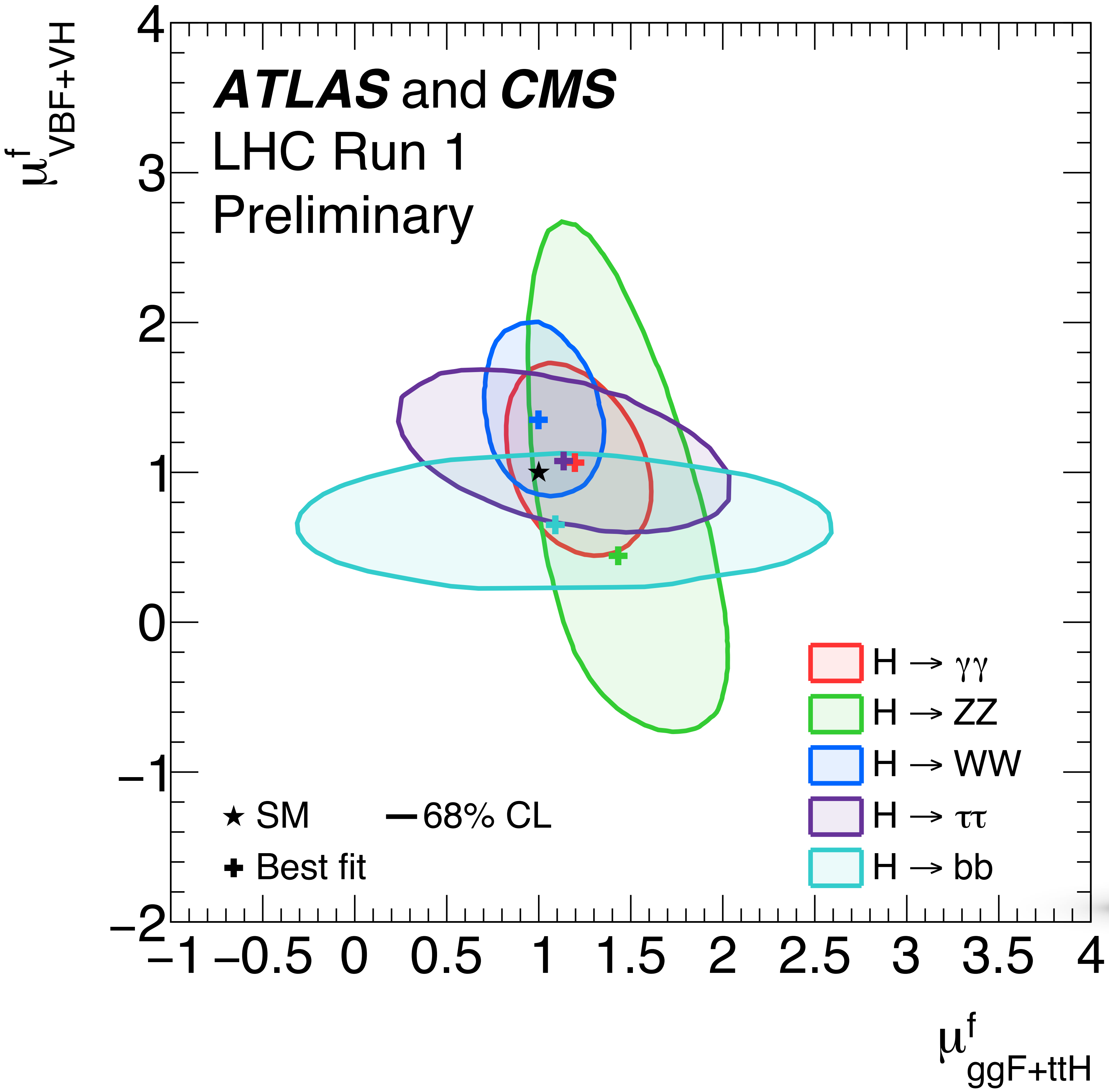


Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Evidence for VH production

Observation of VBF production and H—>tau tau decay!
—> direct observation of Higgs coupling to fermions!

Boson versus Fermion-mediated production



ggF and ttH: fermion mediated

VBF/VH: vector-boson mediated

because BRs cancel in the ratio:

$$\mu^f_V/\mu^f_F$$

combine decay modes w/o additional assumption:

$$\boxed{\mu_V/\mu_F = 1.06^{+0.35}_{-0.27}}$$

assume $\mu^f{}_V$ *and* $\mu^f{}_F$ are the same @7 TeV and @8 TeV

k-framework: beyond signal strength

Introduce a set of κ to parametrise potential deviation from the SM couplings

Assume:
- one single resonance at mass 125.09 GeV
- narrow width approximation
- tensor structure of a CP even scalar (only modifications to coupling strength)

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\boxed{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}}{\boxed{\Gamma_\mathrm{H}}}$$

SM modifiers

production **decay**

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$

Total width

$$\kappa_H^2 = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

Total width not accessible experimentally

Need assumptions on Γ_H

Assume only SM decay, adjust for re-scaling of κ

κ correspond to LO degree of freedom

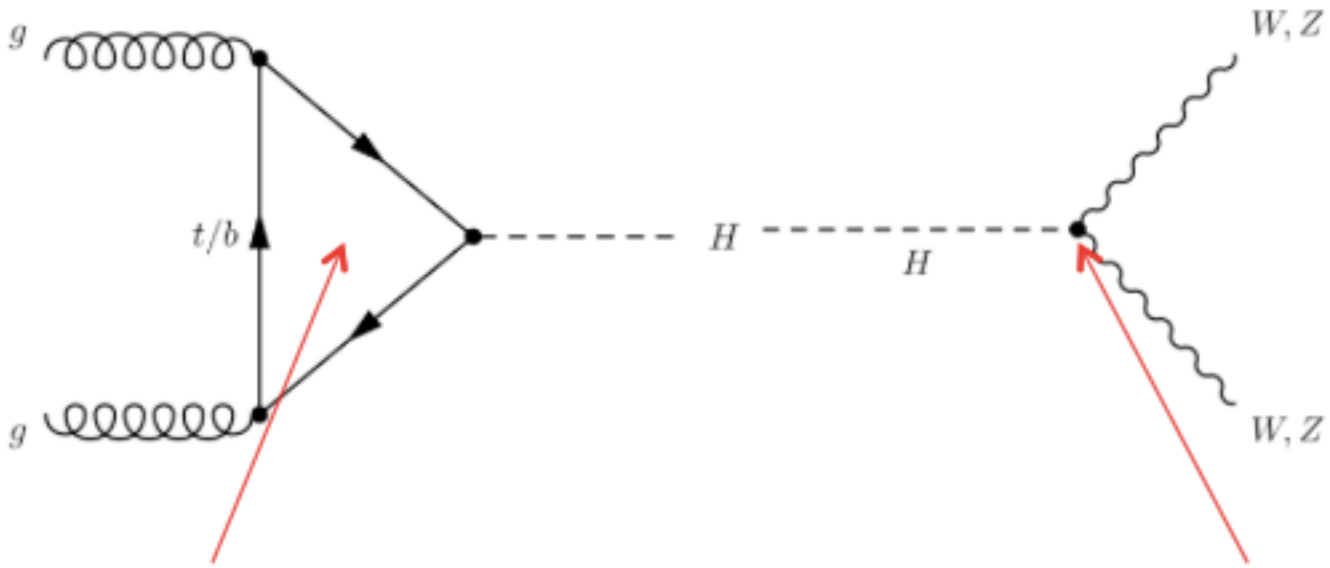
higher-order accuracy in calculation of σ and BR in SM is not necessarily preserved if $\kappa_j \neq 1$

assume that higher-order QCD corrections factorise from any rescaling of κ

—> remain valid over the whole range of κ_j values considered

k-framework: beyond signal strength

Consider σ(ggF —> H —> WW/ZZ): σ(ggF) * Γ_{WW}/Γ_{TOT}



$\sigma_{ggF} = (1.06\,\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t)\,\sigma_{ggF}(SM)$ $\Gamma_{W,Z} = \kappa^2_{W,Z}\Gamma_{W,Z}(SM)$

in case new physics in the loop, that does not couple with SM particle, use κ_g as effective coupling modifier (same thing is possible for κ_γ)

k-framework - SM modifiers

Factors depend on:
Assumed value mH,
Calculations of σ,Γ
Kinematic selections

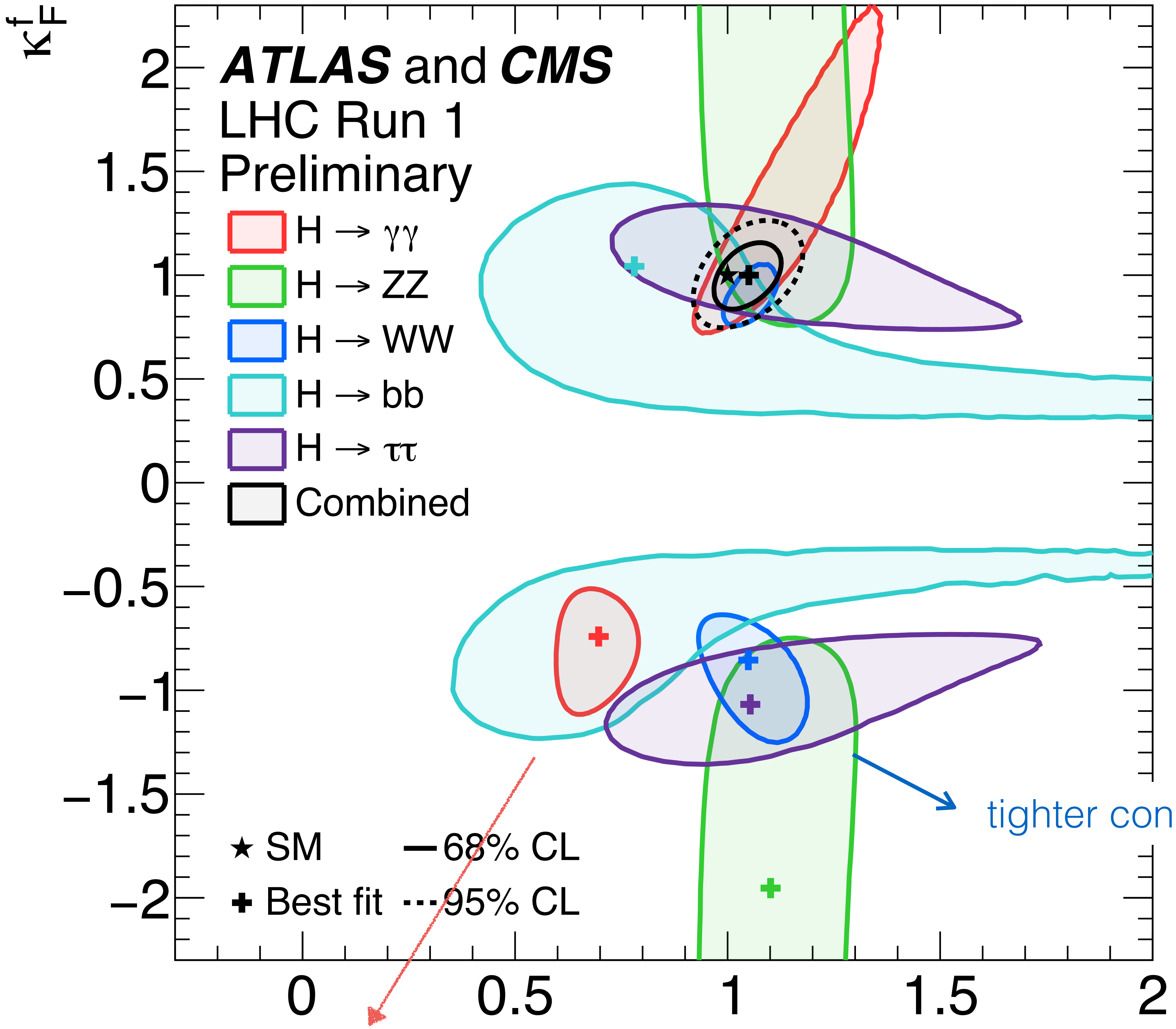
Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $\mathrm{BR}_{\mathrm{BSM}} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa^2 + 0.0016 \cdot \kappa_Z^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa^2$

process with interference allow to measure relative sign of couplings!

assume $\kappa_t > 0$ without loss of generality

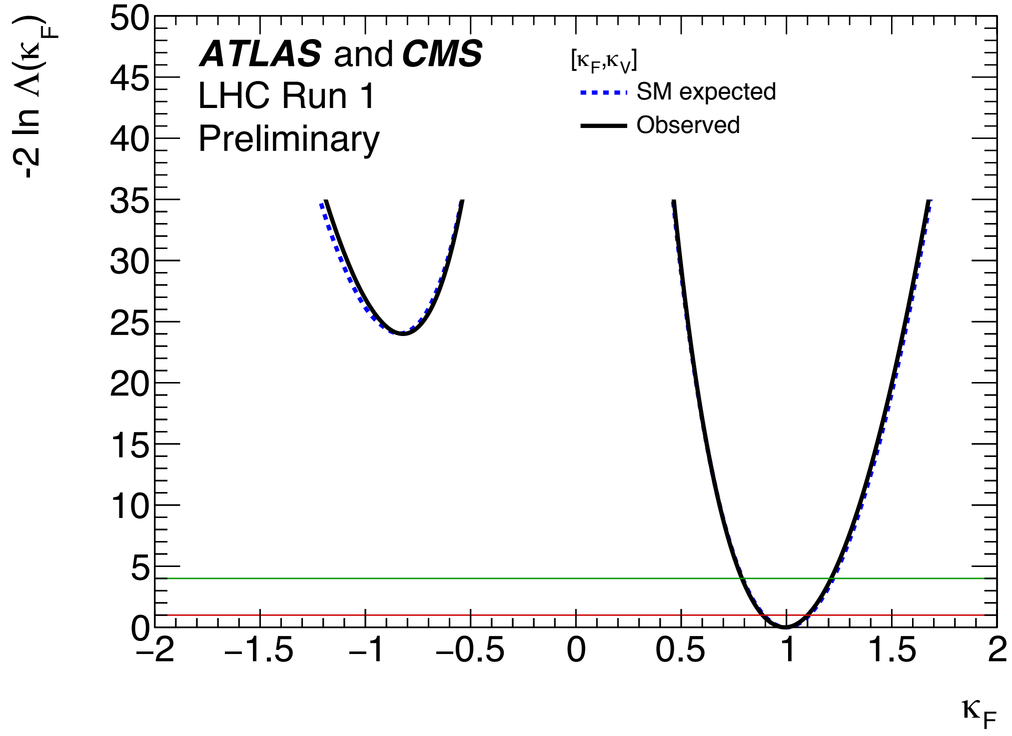
Boson and Fermion couplings

test difference between boson couplings (related to EWK symmetry breaking) and Yukawa couplings to fermions $\kappa_Z = \kappa_W = \kappa_V$ and $\kappa_t = \kappa_\tau = \kappa_b = \kappa_F$



tighter constraint on kF and kV from HWW

Likelihood contour for negative kF solution different for channels with interference contributions



opposite signed for kv and kF strongly disfavoured

Assumptions:
no new particles in loop
no invisible (BMS) decay

Constraint on tree level couplings

assume no new particles in loops
no invisible (BSM) decay

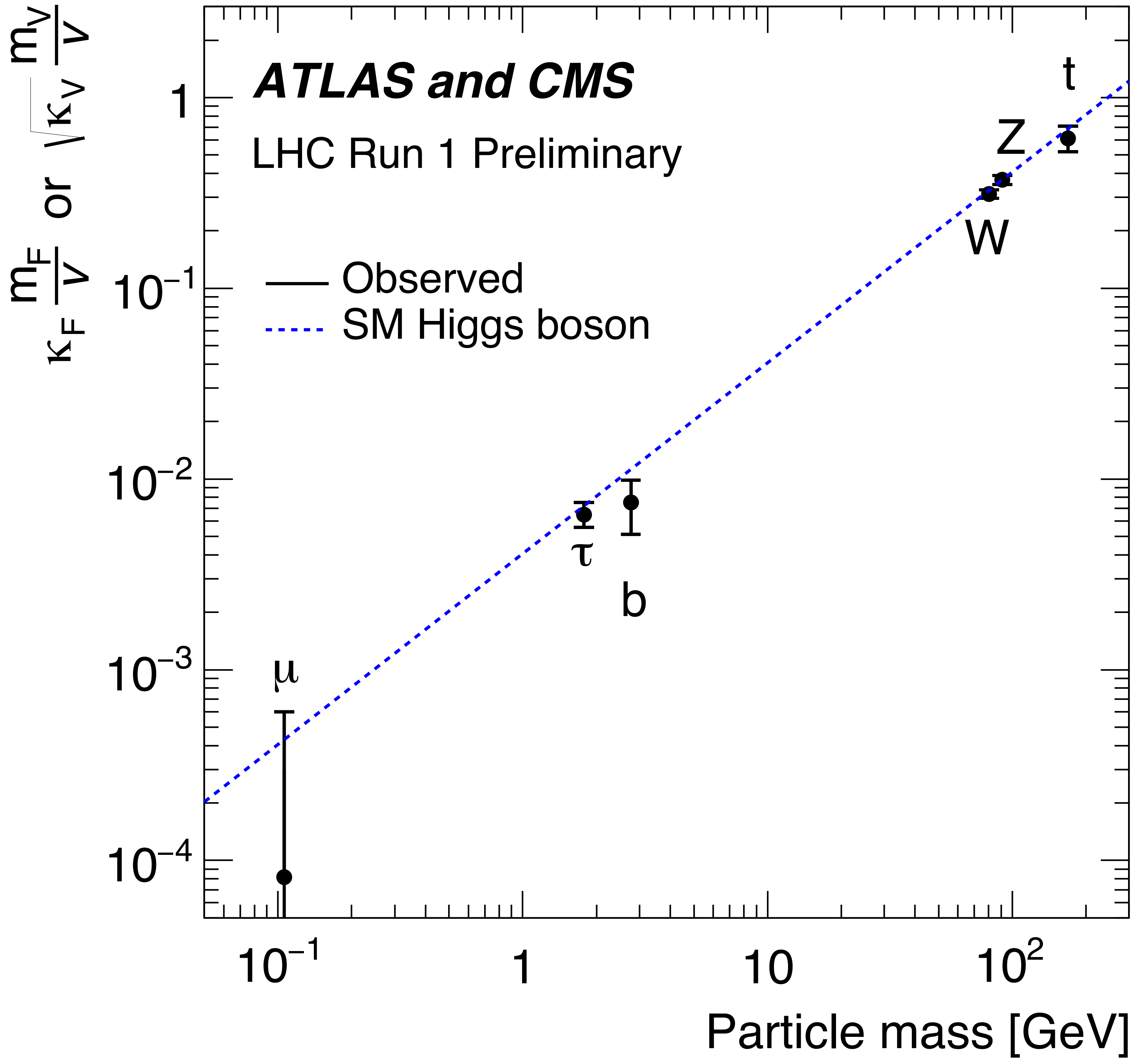
fit for tree-level couplings

κZ, **κ**W, **κ**t, **κ**tau, **κ**b, **κ**mu

express these parameters as reduced coupling modifiers

—> qualitative consistency of the measurements with the SM

$g_{W, Z, H}\ \alpha\ M^2_{W, Z, H}$ and $g_F\ \alpha\ m_F$



Limits on BMS contributions

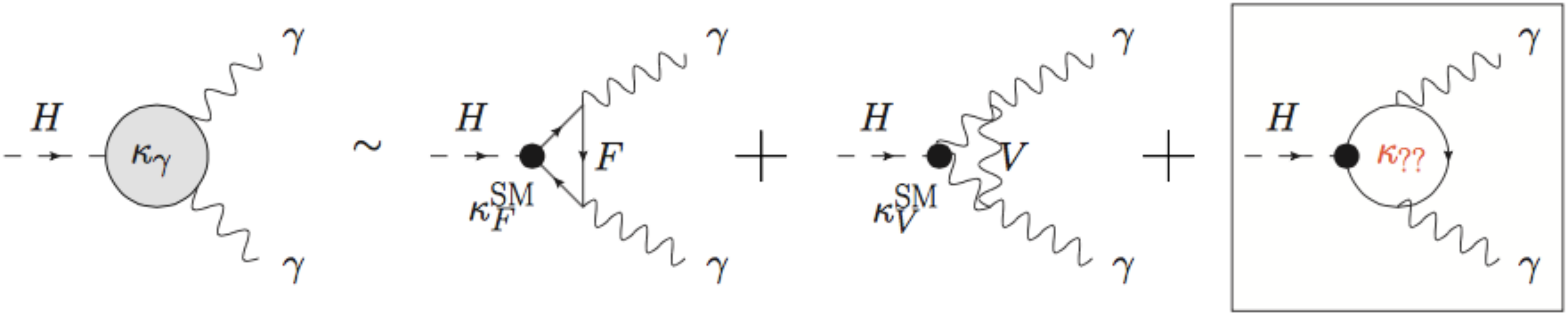
New particles in the loops

BSM scenarios with new heavy particles that contributes only to loop processes

Fix all non-loop κ_i to SM value

new particles do not contribute to $\Gamma(H)$

—> only κ_g and κ_γ may be affected by new particles



(a)

represent loop process with effective parameters instead of SM content

—> κ_g and κ_γ only free parameters in the fit

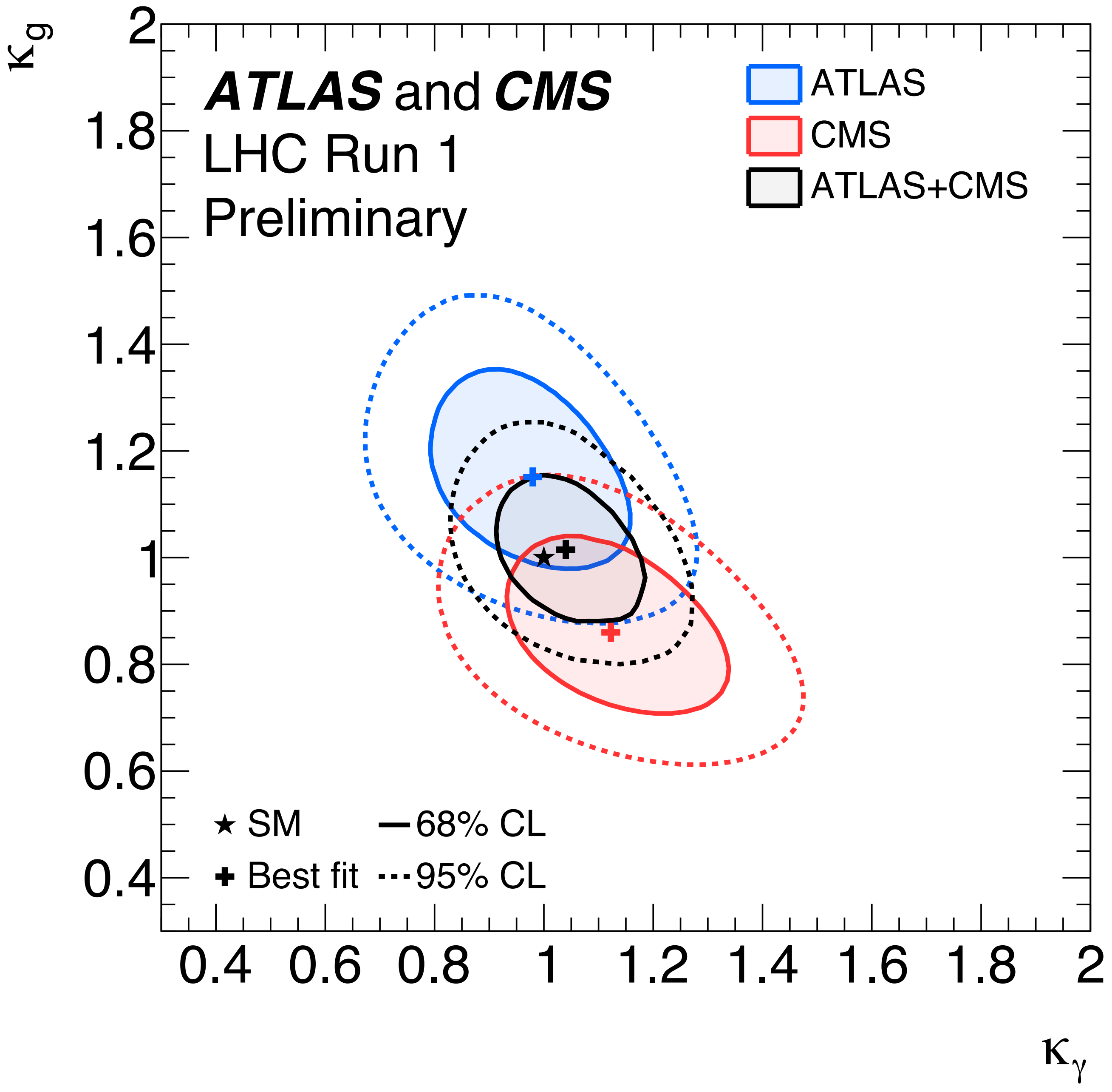
New particles in the loops

BSM scenarios with new heavy particles that contributes only to loop processes

Fix all non-loop κ_i to SM value

new particles do not contribute to Γ(H)

—> only κ_g and κ_γ may be affected by new particles



κ_g=1 and κ_γk1

lies within the 68% C.L. region

p-value of compatibility
with the S.M.: 82%

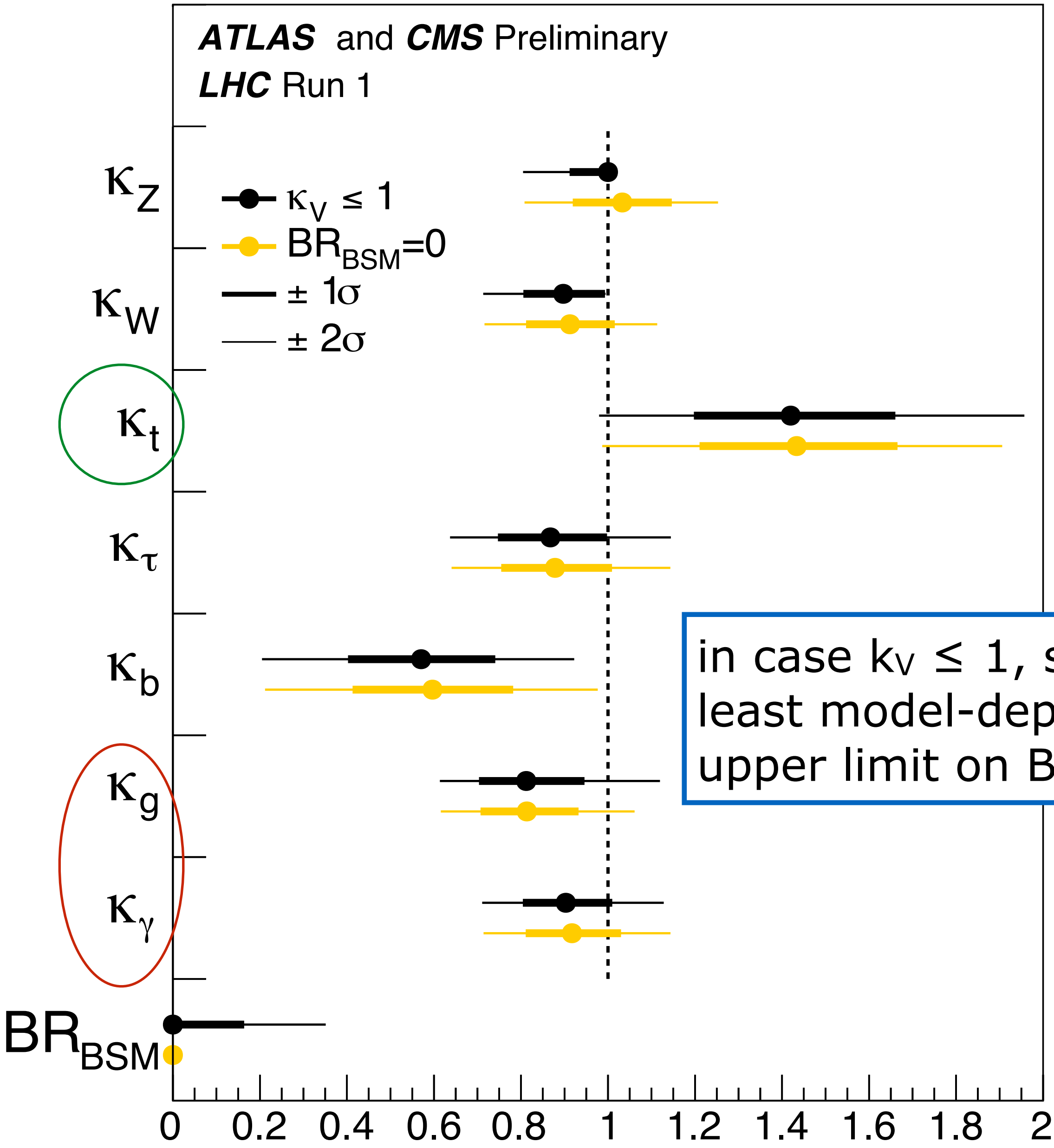
Contribution to the Total width from BSM

Set limits on BR to invisible and undetectable Higgs decay modes, BR_{BSM}
- if such decay exists, total width larger than in the SM

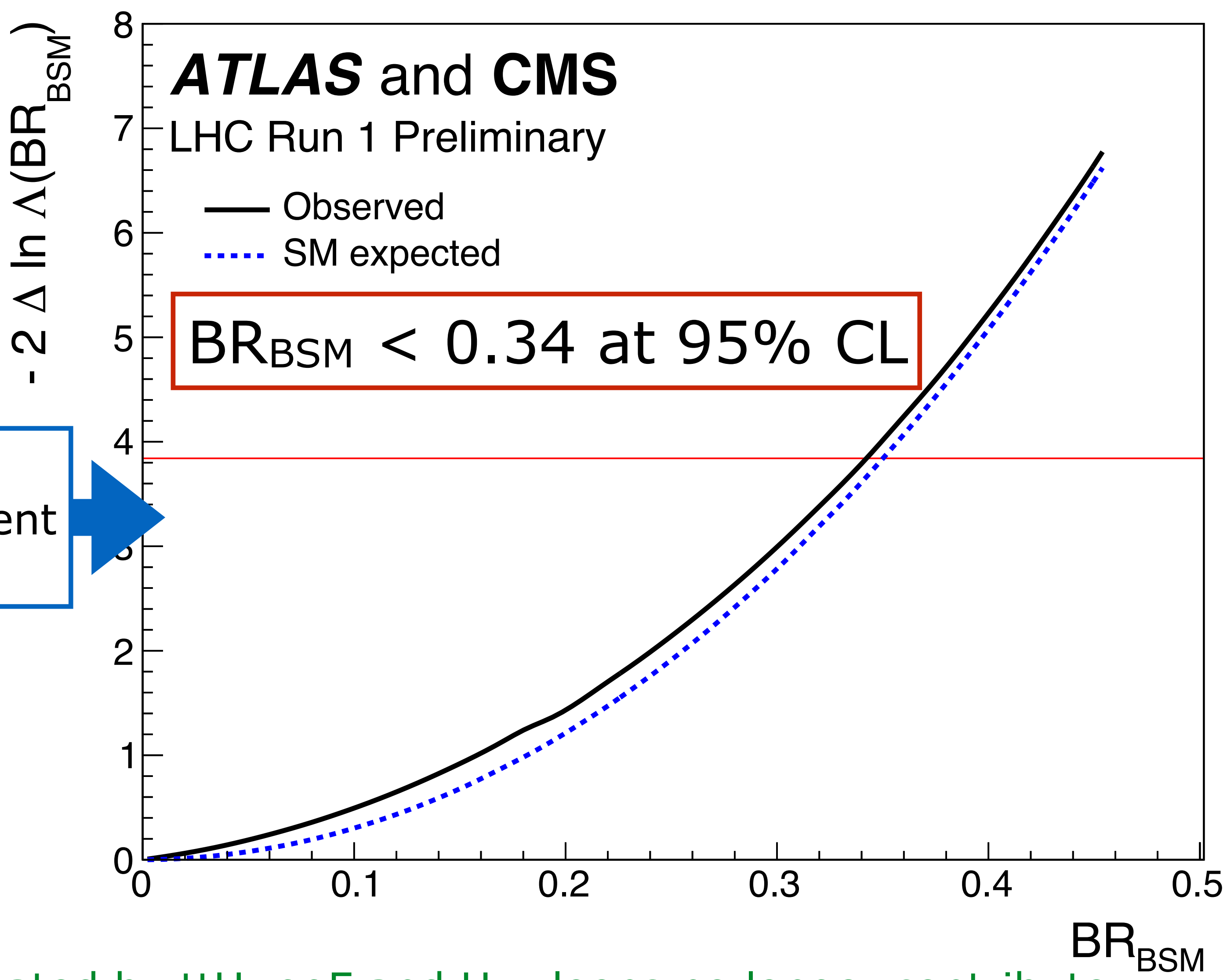
$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

if $BR_{BSM} > 0$ then all observed cross sections are lowered by common factor

$$\sigma_i \cdot BR^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\boxed{\Gamma_H}}$$



in case $k_V \leq 1$, set least model-dependent upper limit on BR_{BSM}



$BR_{BSM} < 0.34$ at 95% CL

κ_g and κ_γ effective coupling modifiers

κ_t: dominated by ttH, ggF and Hγγ loops no longer contribute

Direct search for invisible decay

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H—>invisible is associated with high Missing Transverse Energy

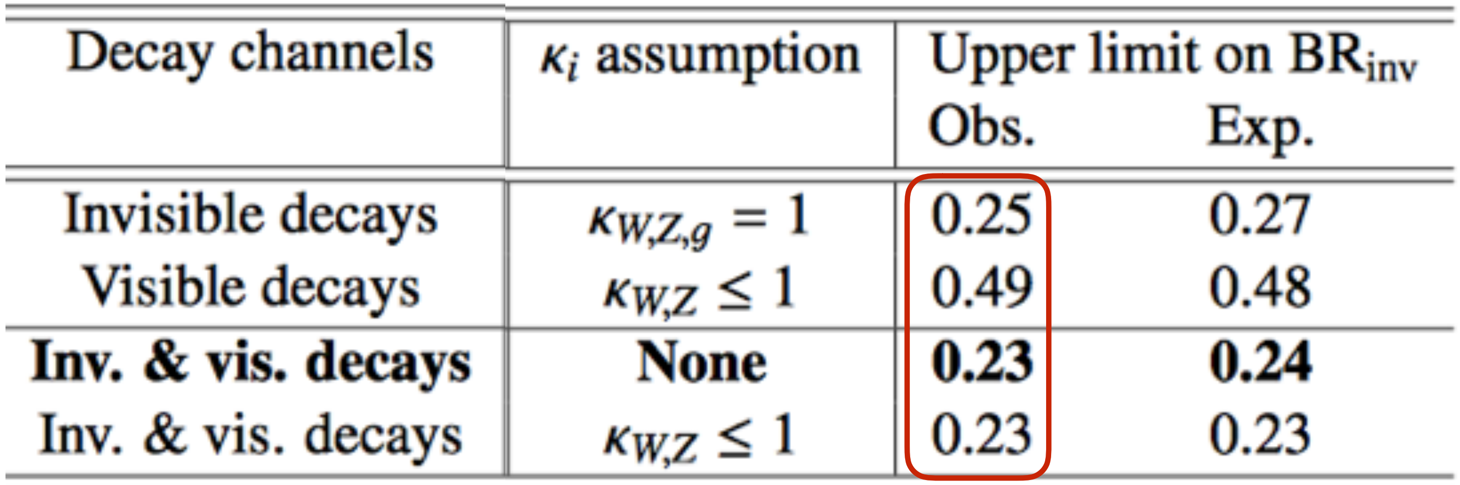
Use topology of the production mode to tag Higgs events

- search in VBF production set most stringent limit
- also Z(—>ll)H and V(—>jj)H explored

—> Upper limit on BR(H—>inv): 0.25 at 95% C.L.

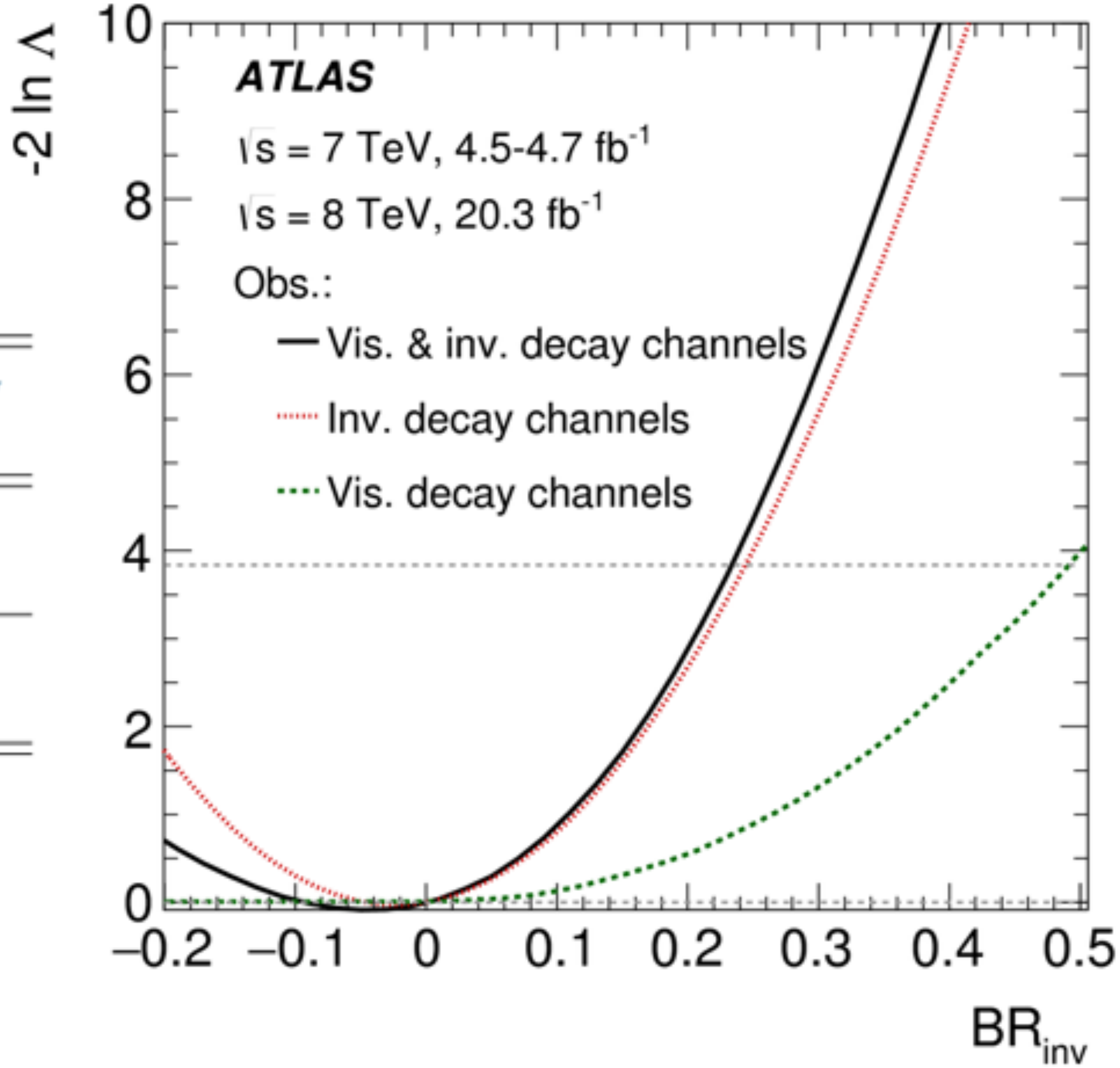
BR(H—>ZZ—>4ν): 0.1%
well below sensitivity

Can include direct searches in global coupling fit



Decay channels	κ_i assumption	Upper limit on BR_{inv} Obs.	Upper limit on BR_{inv} Exp.
Invisible decays	$\kappa_{W,Z,g} = 1$	0.25	0.27
Visible decays	$\kappa_{W,Z} \leq 1$	0.49	0.48
Inv. & vis. decays	**None**	**0.23**	**0.24**
Inv. & vis. decays	$\kappa_{W,Z} \leq 1$	0.23	0.23

11% tighter limit in combination



ATLAS only fit. CMS has similar results

Generic parametrisation

All previous results rely on a number of assumptions

Present final Run1 results with minimal assumptions and minimal dependencies from theoretical uncertainties

Most generic model based on ratio of cross sections and BR

$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right),$$

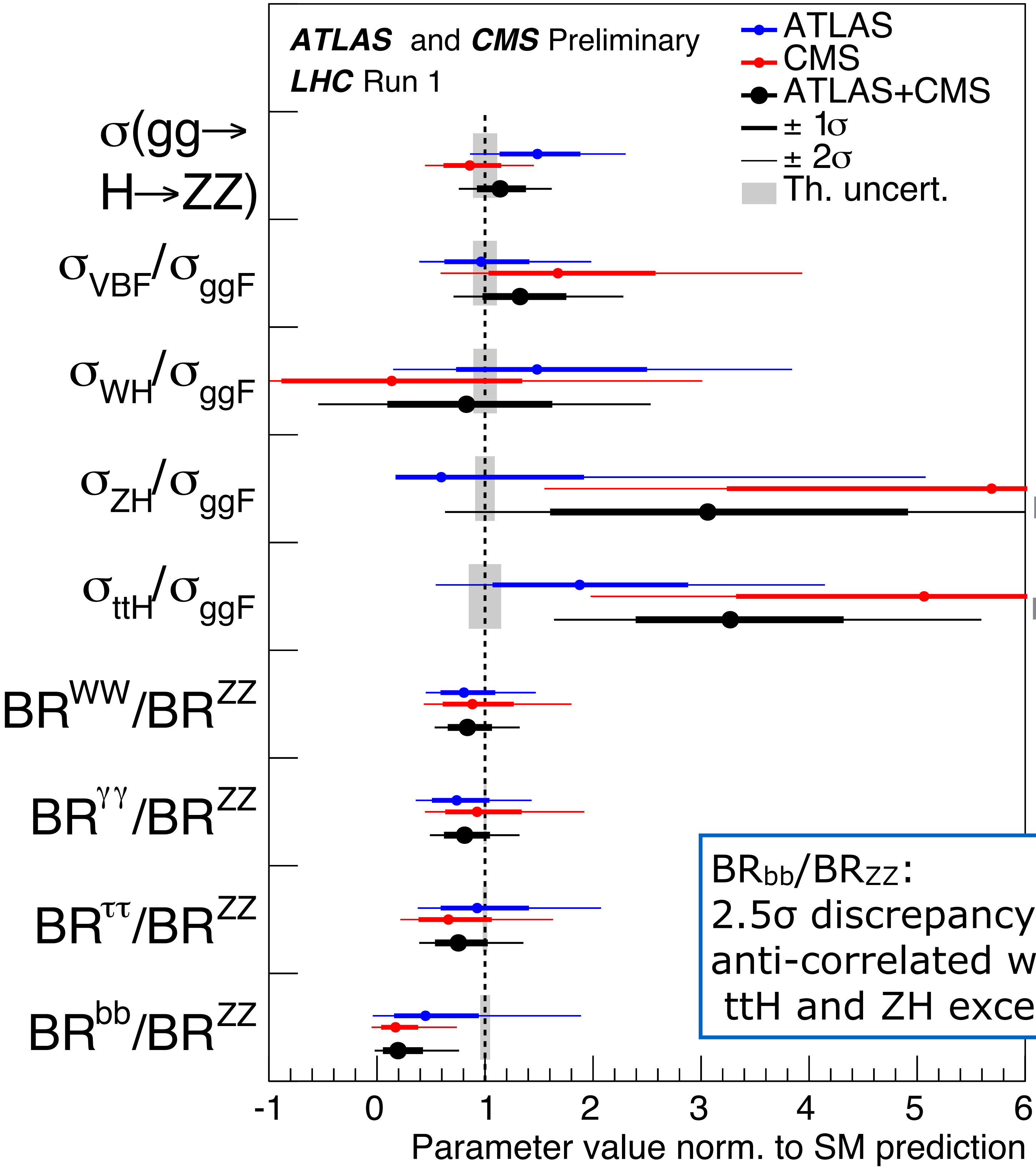
no total width assumption, only narrow width approximation

large theory uncertainties on signal production sec and BRs can be ignored
—> results will stay valid also when newer calculations will be available

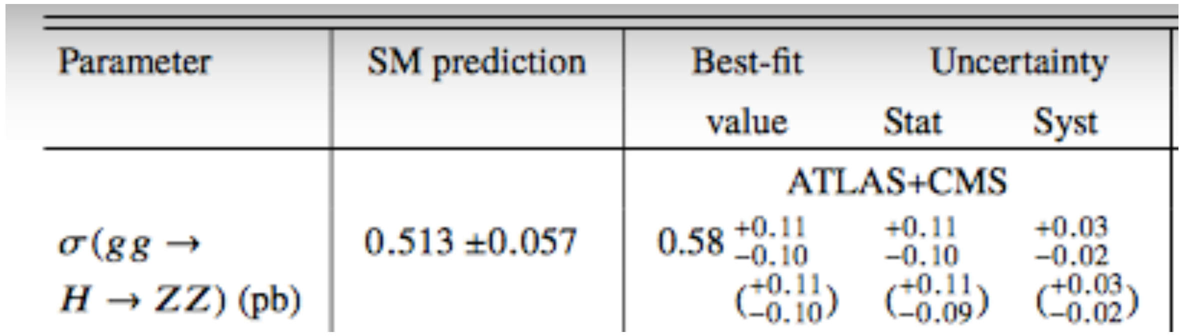
SM assumption enters only in acceptances and selection efficiencies:

- kinematics described via SM Higgs simulations

Generic parametrisation



σ(gg—>H —>ZZ) chosen because of small uncertainties, mostly stats (sys: 4%)

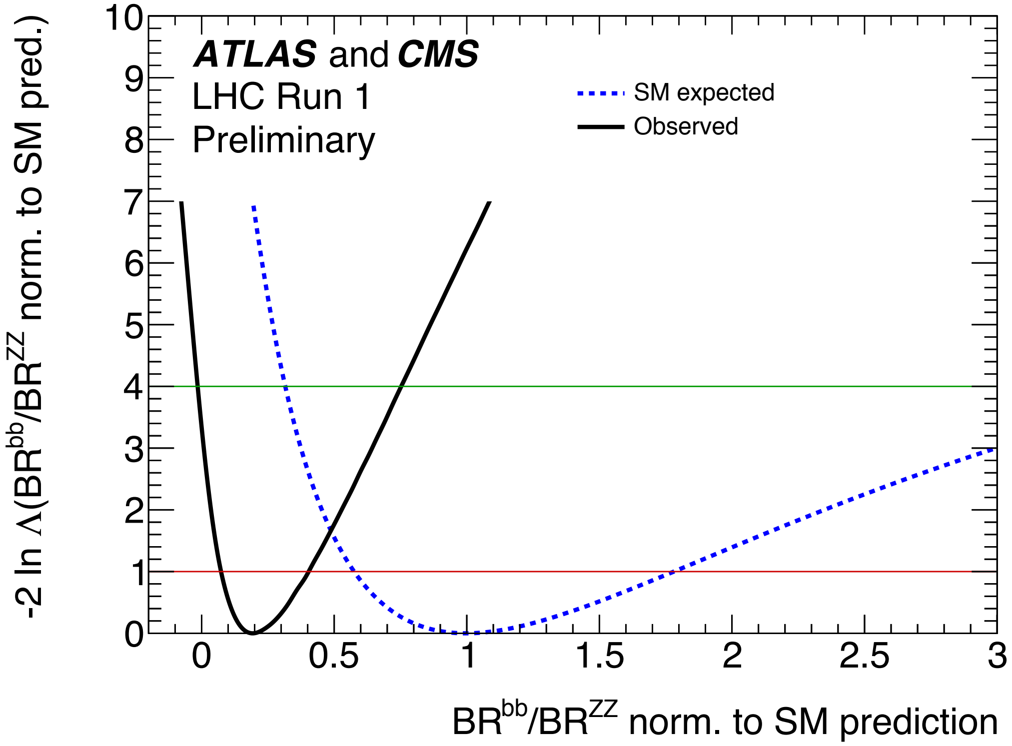


Parameter	SM prediction	Best-fit value	Uncertainty Stat	Syst
		ATLAS+CMS		
$\sigma(gg \to H \to ZZ)$ (pb)	0.513 ±0.057	0.58 $^{+0.11}_{-0.10}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.11}_{-0.10}$ $\left(^{+0.11}_{-0.09}\right)$	$^{+0.03}_{-0.02}$ $\left(^{+0.03}_{-0.02}\right)$

excess due to CMS H—>ZZ 2 jet cat.

2.4σ excess over SM ttH prediction due to multi-lepton categories

BR_{bb}/BR_{ZZ}:
2.5σ discrepancy anti-correlated with ttH and ZH excess



27.05.2016

E. Pianori, Universitá di Bolo

Summary of Run1 experience

Discovery of a new scalar massive boson on July 2012 was a major discovery

- prompted a lot of measurements to test its compatibility with the Higgs boson of the S.M

Combining ATLAS and CMS Higgs boson improves precision

- sensitivity on signal strength improved by almost √2
- observation of H —> tautau decay and VBF production
- signal strength measured with O(10)% precision
- Many parameterisations have been studied
  All results are consistent with the S.M. predictions within uncertainties
  p-value compatibility with the S.M. in range 10%-88%

With increasing size of data sample, move towards more model independent measurements

- reduce the number of assumptions
- reduce dependence on theory uncertainties

—> measure as many fiducial and differential cross sections as possible

Introduction

Higgs phenomenology

Inputs to the combination

Statistical framework

Combined Signal strength

Combined Higgs coupling

Towards Model independent measurements

Conclusion and outlook

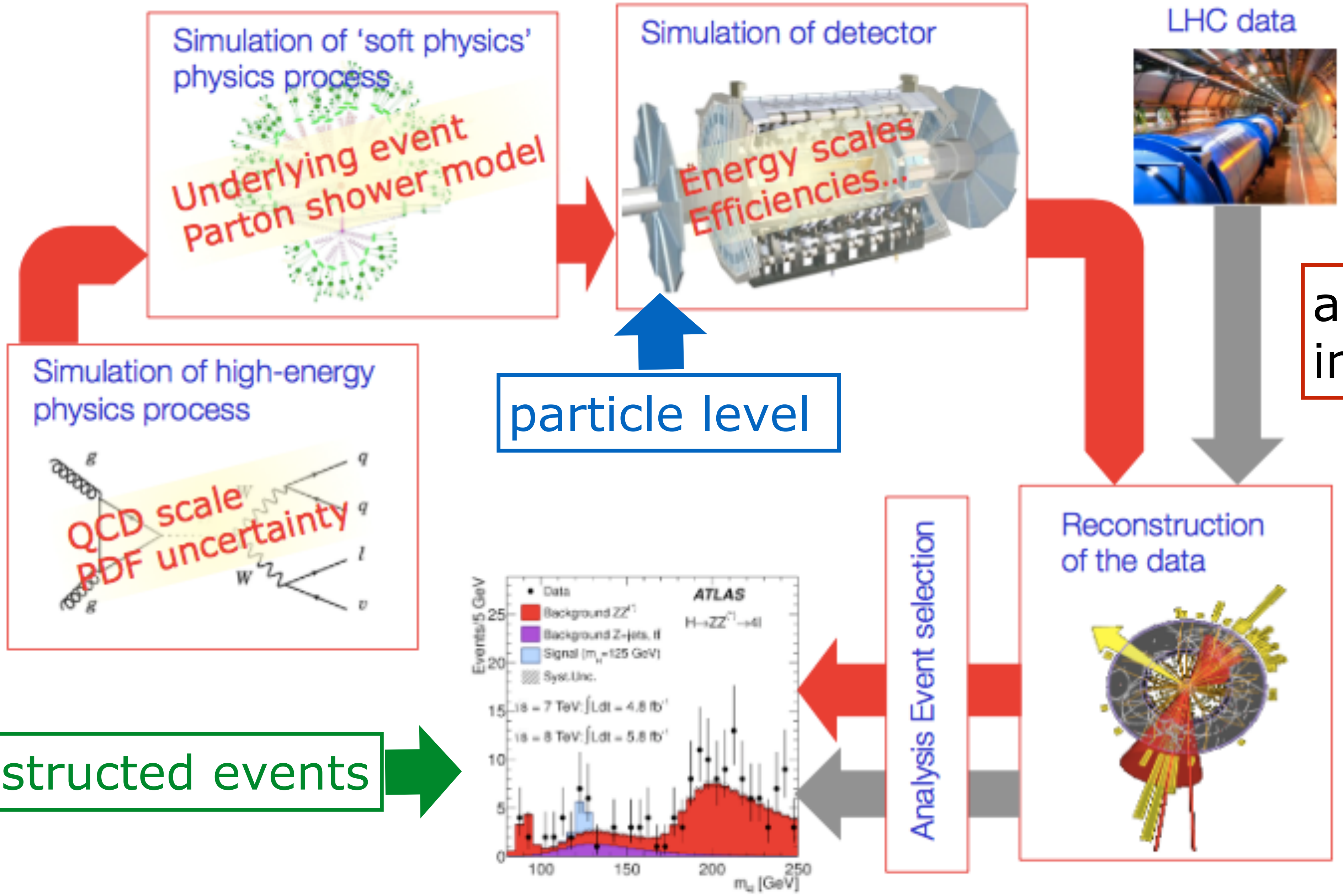
Fiducial and differential cross sections

The cross section, σi, in a given fiducial region is given by:

$$\sigma_i = \frac{N_i^{data} - N_i^{bkg}}{\boxed{c_i} \int L dt} \qquad c_i = \frac{N_i^{\mathrm{reco}}}{N_i^{\mathrm{fid}}}$$

reconstructed event yield

event yield at particle level



particle level

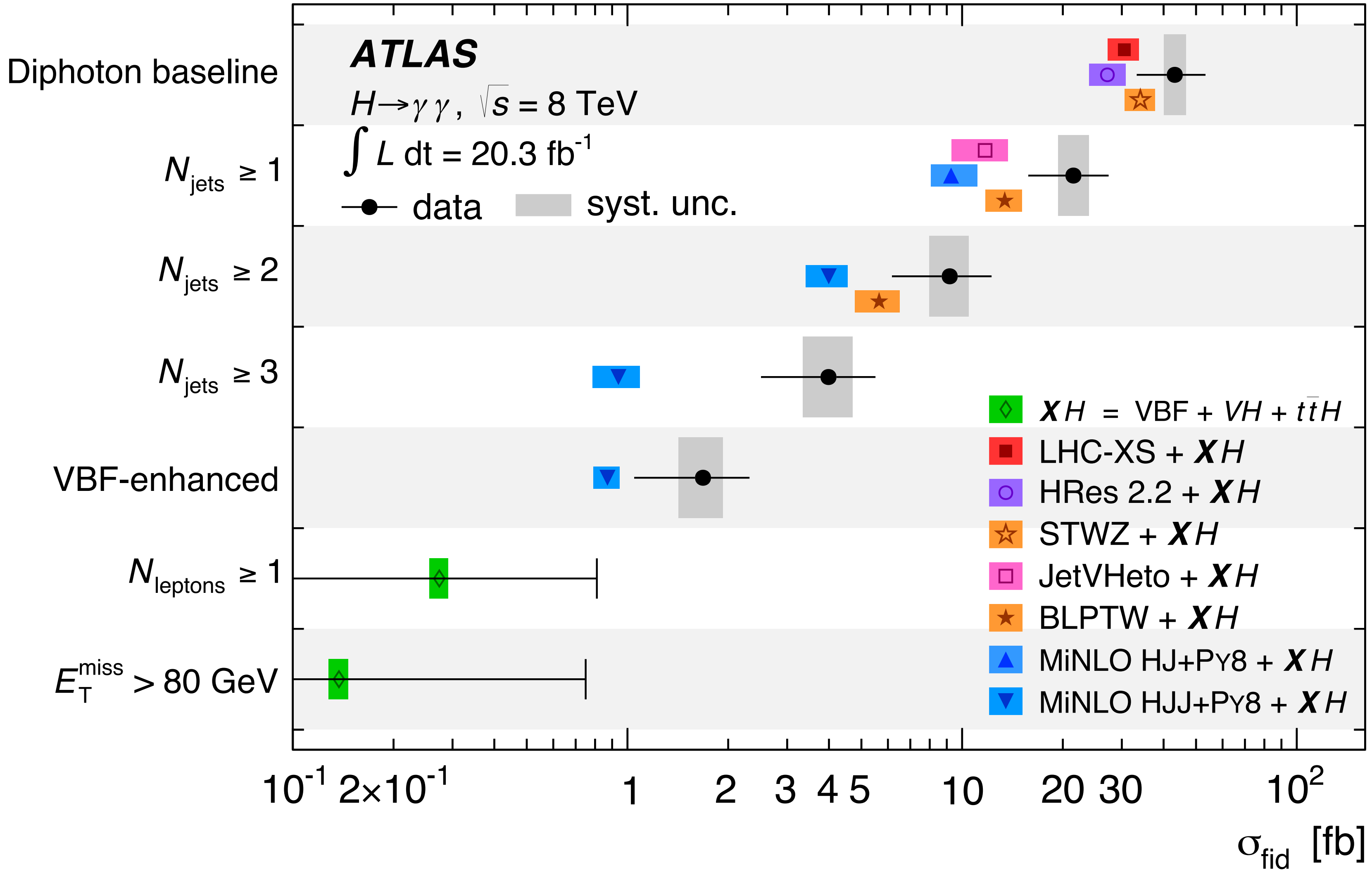
already performed in Run 1 for ZZ/γγ

reconstructed events

Fiducial and differential cross sections

Allows for direct comparison with theoretical predictions:

JHEP09(2014)112



<u>Fiducial Volume (baseline):</u>

2 isolated photons, $|\eta| < 2.37$

$p_T/m_{\gamma\gamma} > 0.35$ (0.25)

≥1 jet: $p_T > 30$ GeV, $|y| < 4.4$.

Theoretical uncertainties have limited impact on differential cross section:

uncertainty on σ fiducial [%]	**Baseline**	**Njets >=3**	**VBF-enhanced**
Signal extraction (stat)	±22	±33	±34
Jet energy scale/resolution		+15, -13	+12, -11
Theoretical modelling	+3.3, -1.0	+6.3, -4.9	+2.2,-3.2

Fiducial and **differential** cross sections

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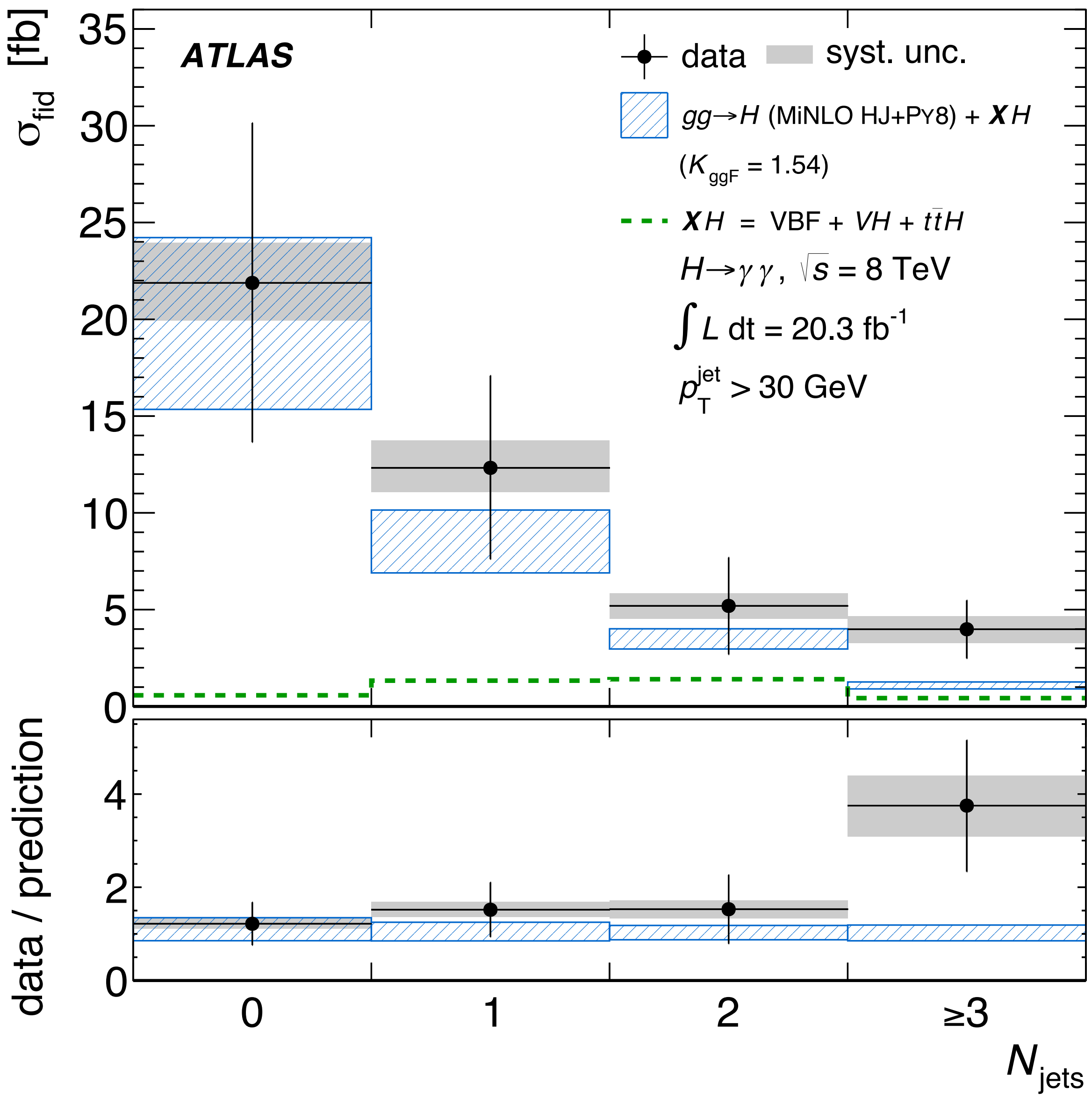
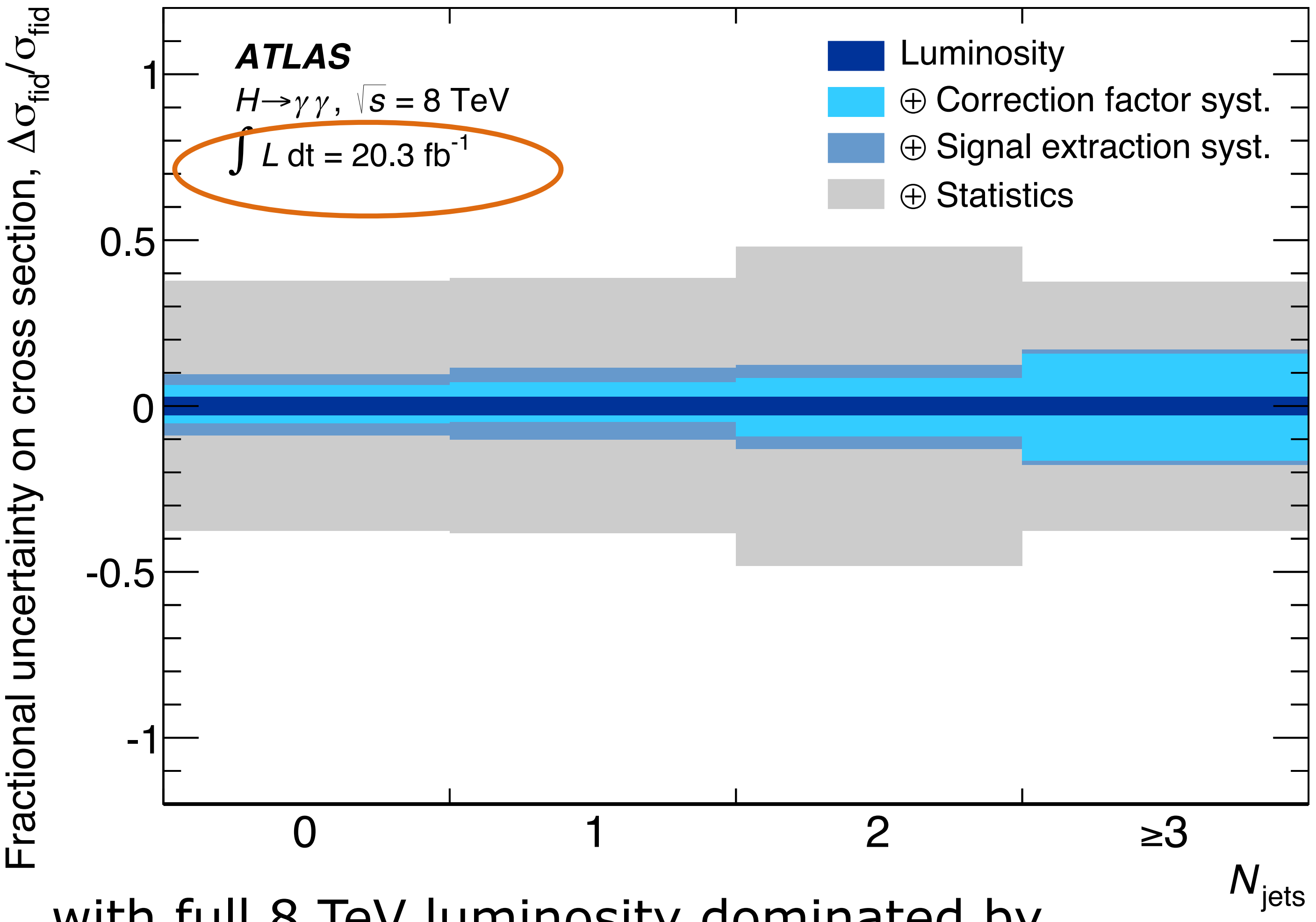
Measure the cross section in bin of a differential distribution:

- number of jets associated with Higgs productions



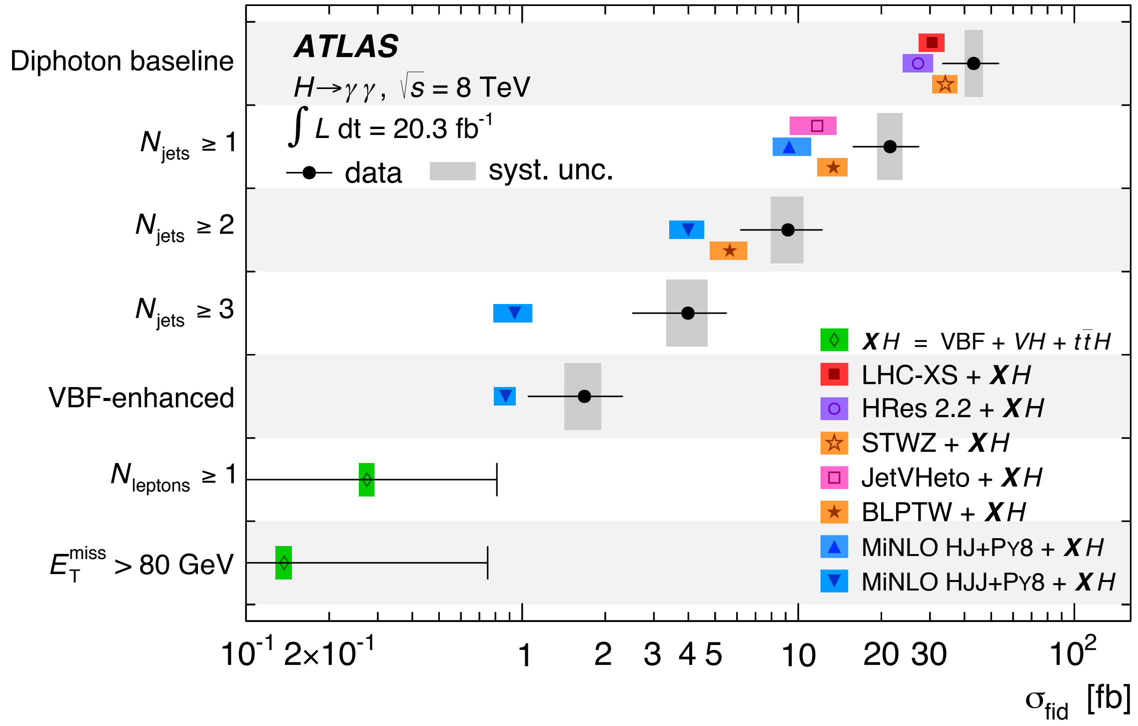


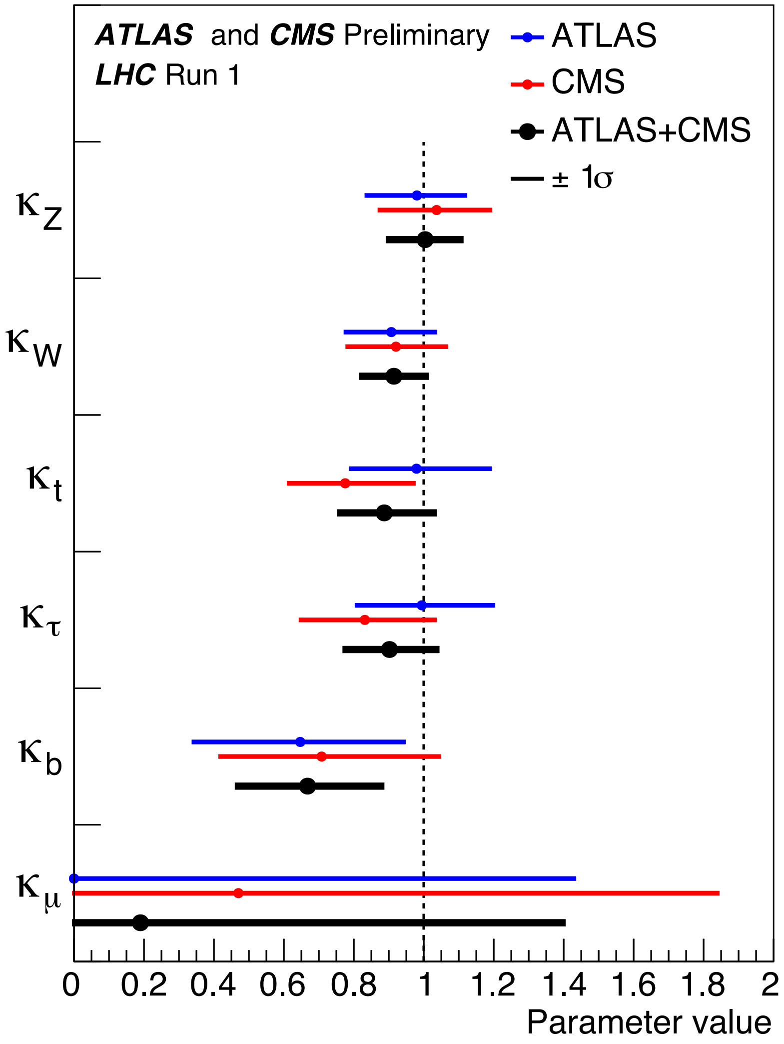
with full 8 TeV luminosity dominated by statistical uncertainties!

with fiducial cross sections (total or differential) can test BSM scenarios

- signal kinematics distribution for BSM model are different w.r.t. SM, hence also signal selection efficiencies

Run2 measurements





Measurement ⟷ Interpretation

minimal theory-dependence

theory-dependent

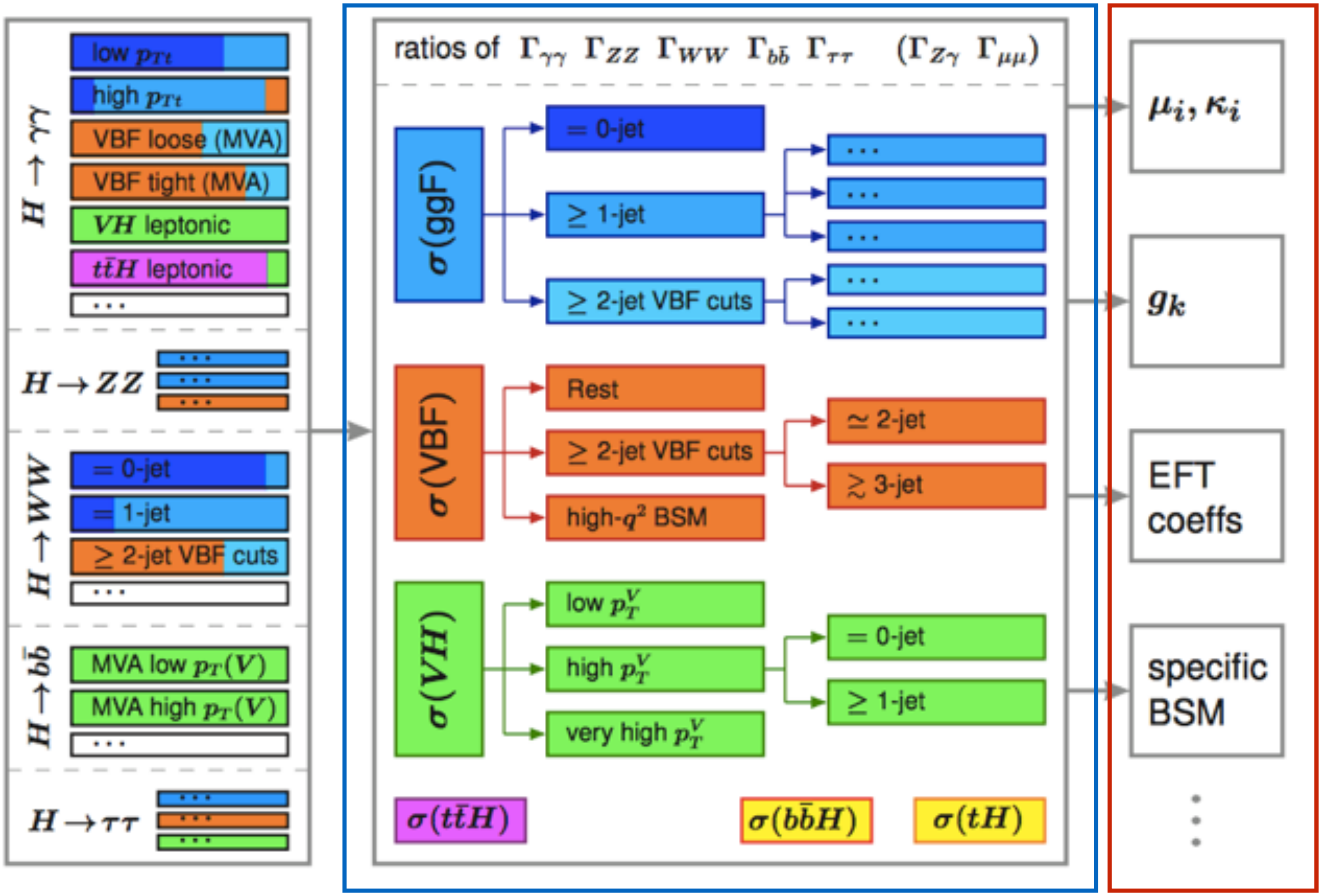
Fiducial Cross Sections

Couplings Fit

Need well established signal to perform measurement

—> will take a lot of integrated luminosity to measure fiducial cross sections for all productions/decay modes. Global analyses desirable in the meantime.

Simplified (template) Cross Section



Experimental analyses
as in Run1, for each decay channel, split events in category

Interpretation stage:
separate step

Measurement: mu per production mode, split into mutually exclusive kinematic bins for each of the main production modes

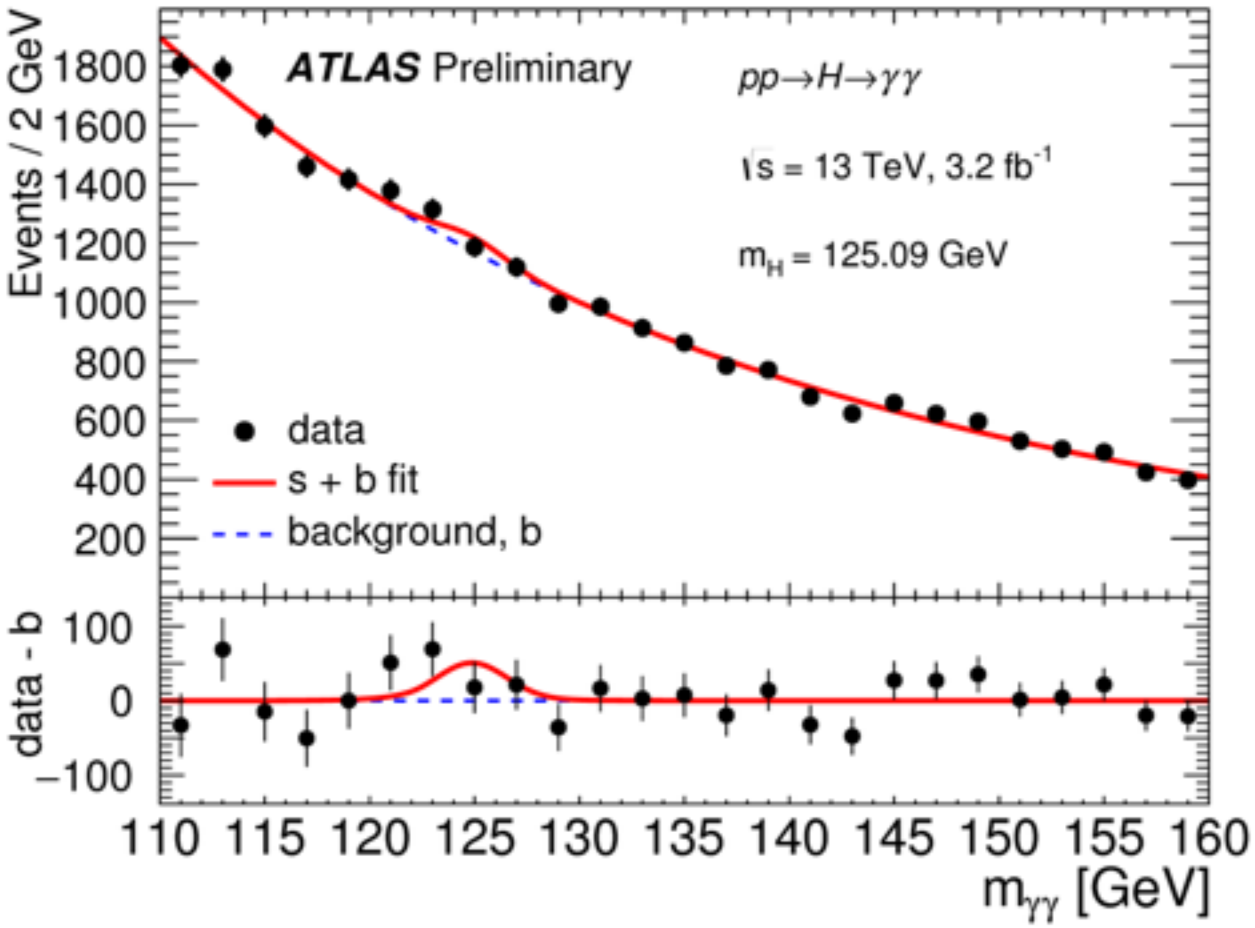
e.g. $\mu_{gg\to H}$ ***old*** → $\mu^{0-jet}_{gg\to H}$ $\mu^{\geq 1-jet}_{gg\to H}$ $\mu^{\geq 2-jet+VBF}_{gg\to H}$ ***new***

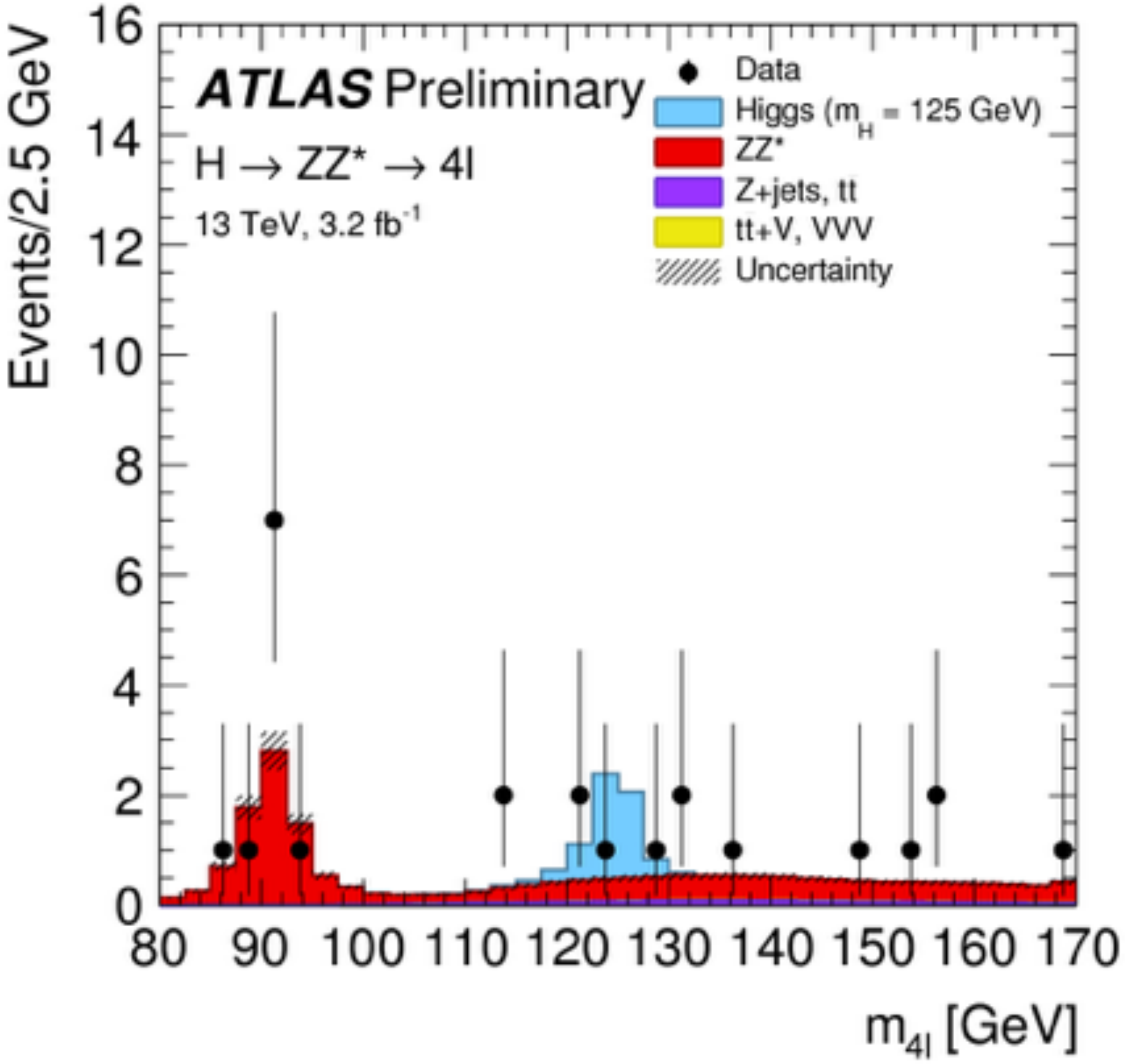
Goal: balance between optimisation for sensitivity while reducing dominant theory dependence in the measurement

Run-2 so far: 3.2/fb of 13 TeV data

H —> γγ (ATLAS-CONF-2015-060)
fitted number of candidate events:
113 ± 74 (stat) +43/-25 (syst)

Sensitivity to SM Higgs:
expected 1.9σ/ observed **1.5σ**



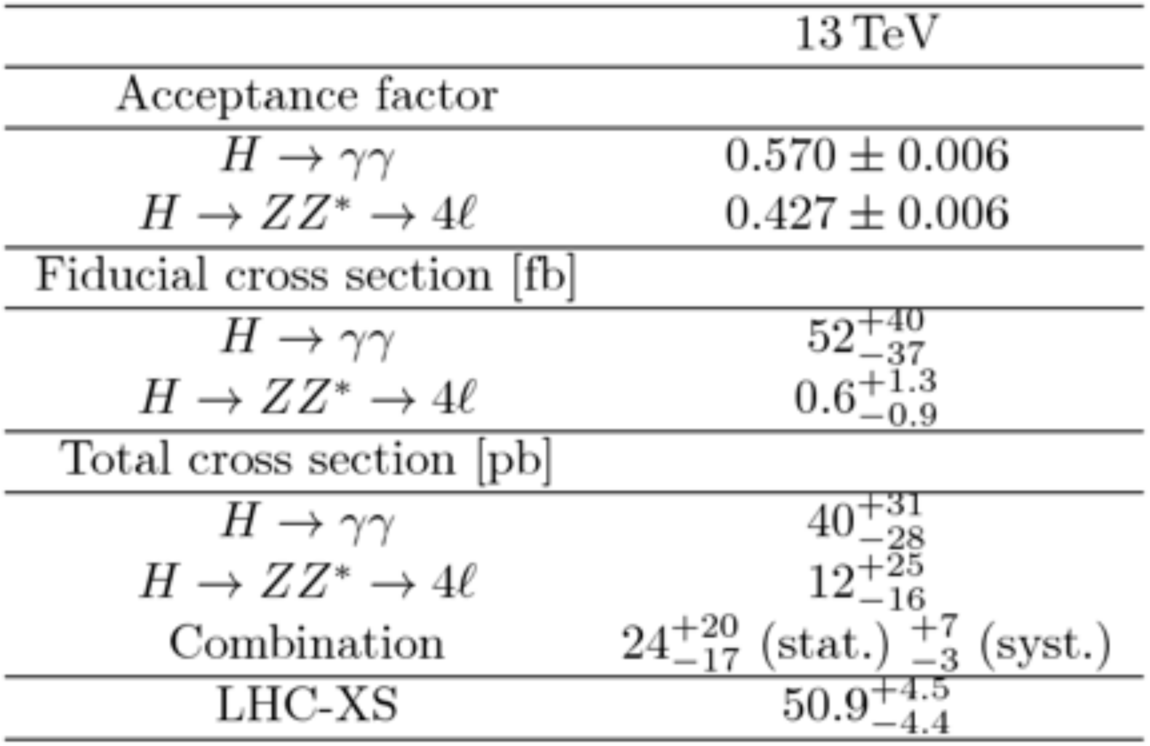


H —>ZZ (ATLAS-CONF-2015-059)
expected signal events in [120,130] GeV: 4
fitted number of candidate events:
1.0 +2.3/-1.5

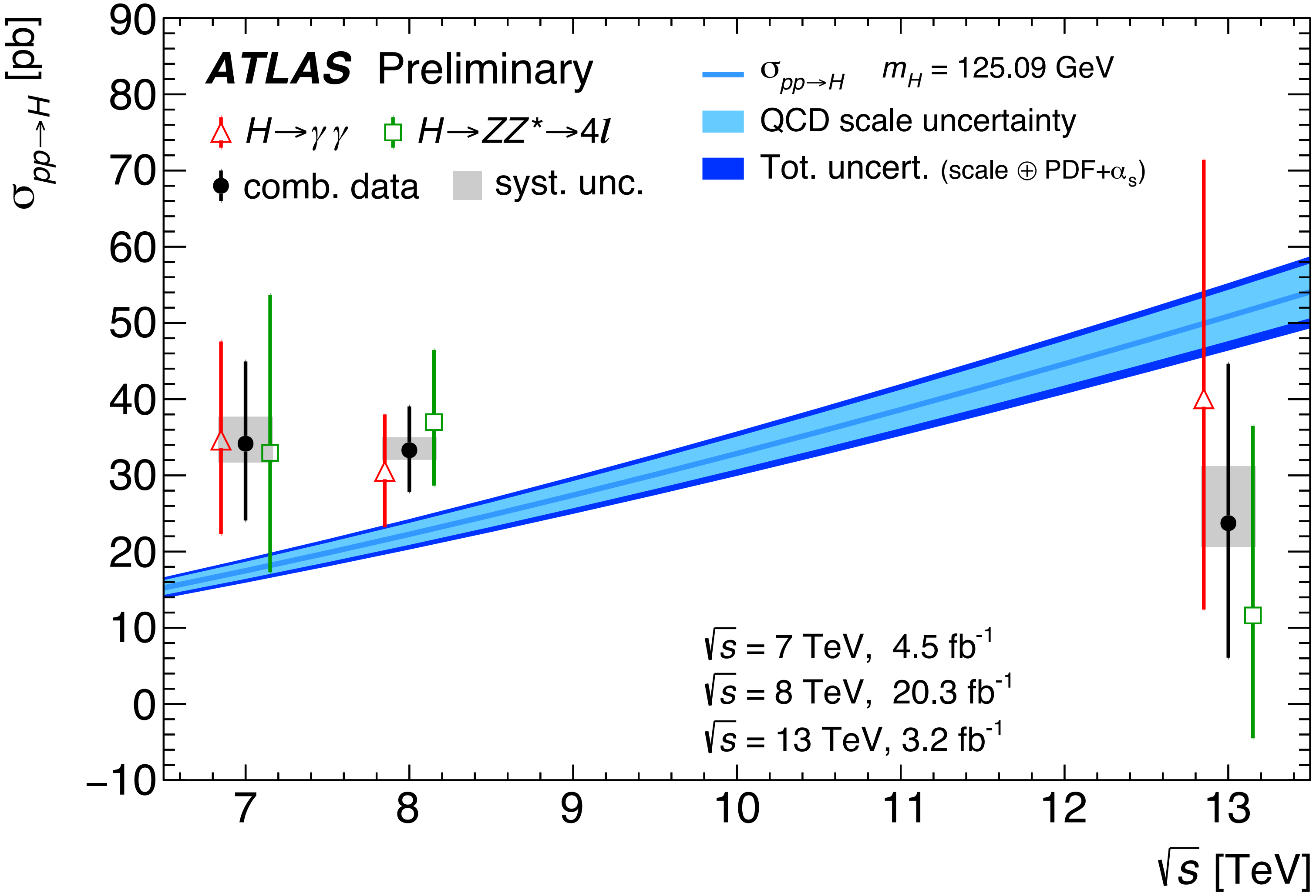
Sensitivity to SM Higgs:
expected 2.8σ / observed **0.7σ**

Measurement of the Higgs cross section

From **Fiducial** to **Total** Inclusive Higgs production cross section



	13 TeV
Acceptance factor	
$H \to \gamma\gamma$	0.570 ± 0.006
$H \to ZZ^* \to 4\ell$	0.427 ± 0.006
Fiducial cross section [fb]	
$H \to \gamma\gamma$	52^{+40}_{-37}
$H \to ZZ^* \to 4\ell$	$0.6^{+1.3}_{-0.9}$
Total cross section [pb]	
$H \to \gamma\gamma$	40^{+31}_{-28}
$H \to ZZ^* \to 4\ell$	12^{+25}_{-16}
Combination	24^{+20}_{-17} (stat.) $^{+7}_{-3}$ (syst.)
LHC-XS	$50.9^{+4.5}_{-4.4}$



Combined observed significance:
Expected: 3.4σ
Observed: 1.4σ

Compatibility with SM: 1.3σ

Outline

Introduction

Higgs phenomenology

Inputs to the combination

Statistical framework

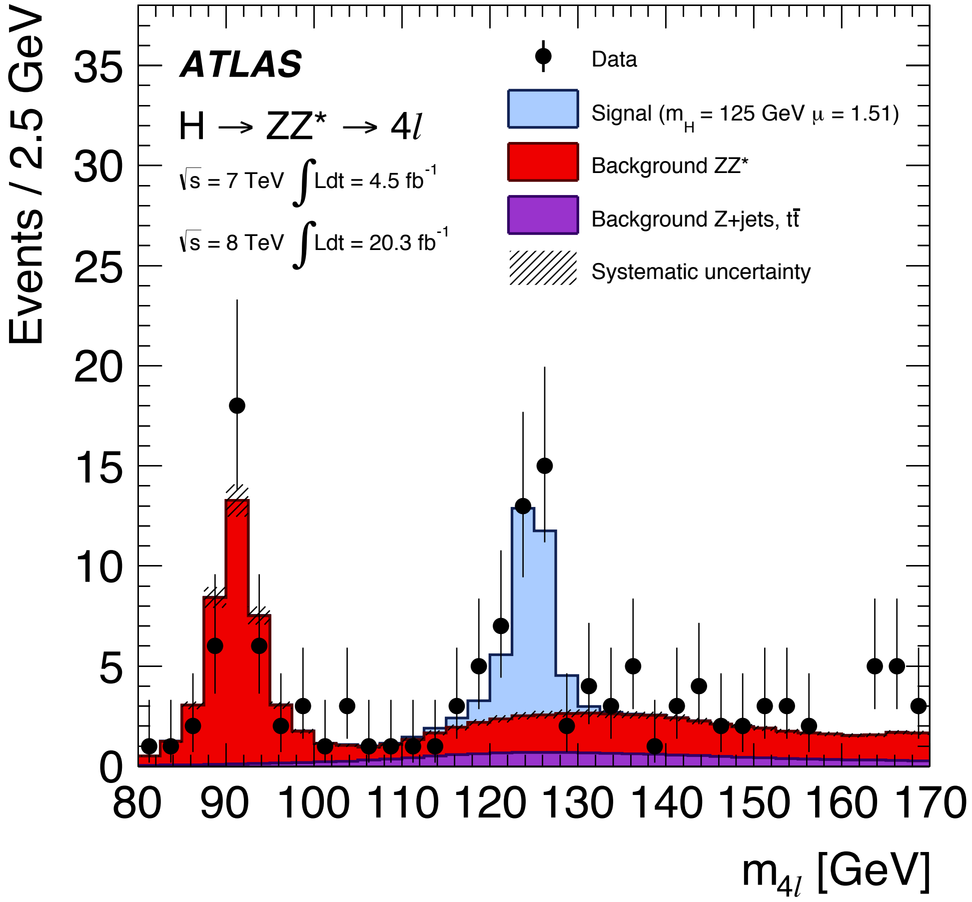
Combined Signal strength

Combined Higgs coupling

Towards Model independent measurements

Conclusion and outlook

Conclusion



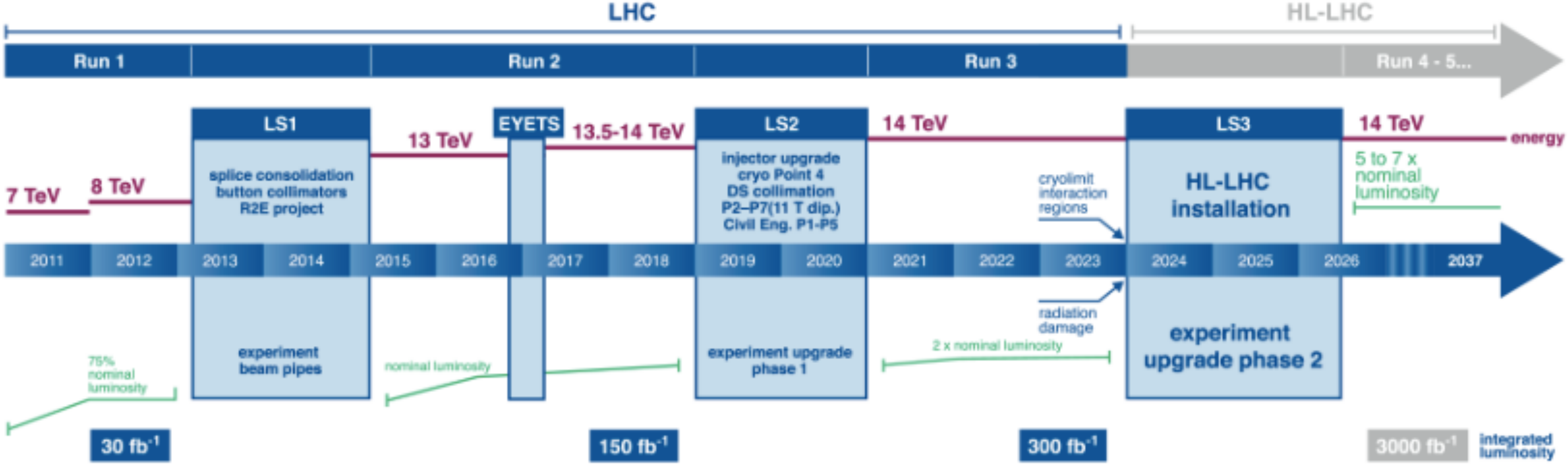
The first run of the LHC was a major success
a new particle has been discovered!

Since then, a wealth of measurements confirmed its compatibility with the predictions from the S.M.

But the devil hides in the details!
current precision in coupling measurement is far from the few % level needed to exclude and constrains new physics not already excluded by lack of direct observation!

Eagerly waiting for more data from the LHC!!

Outlook



Run2: x5 $\int\mathcal{L}$

$\sqrt{s}$ = 8 TeV —> 13 TeV
σ(ggF) x2.3
σ(VBF) x2.4
σ(ttH) x3.9

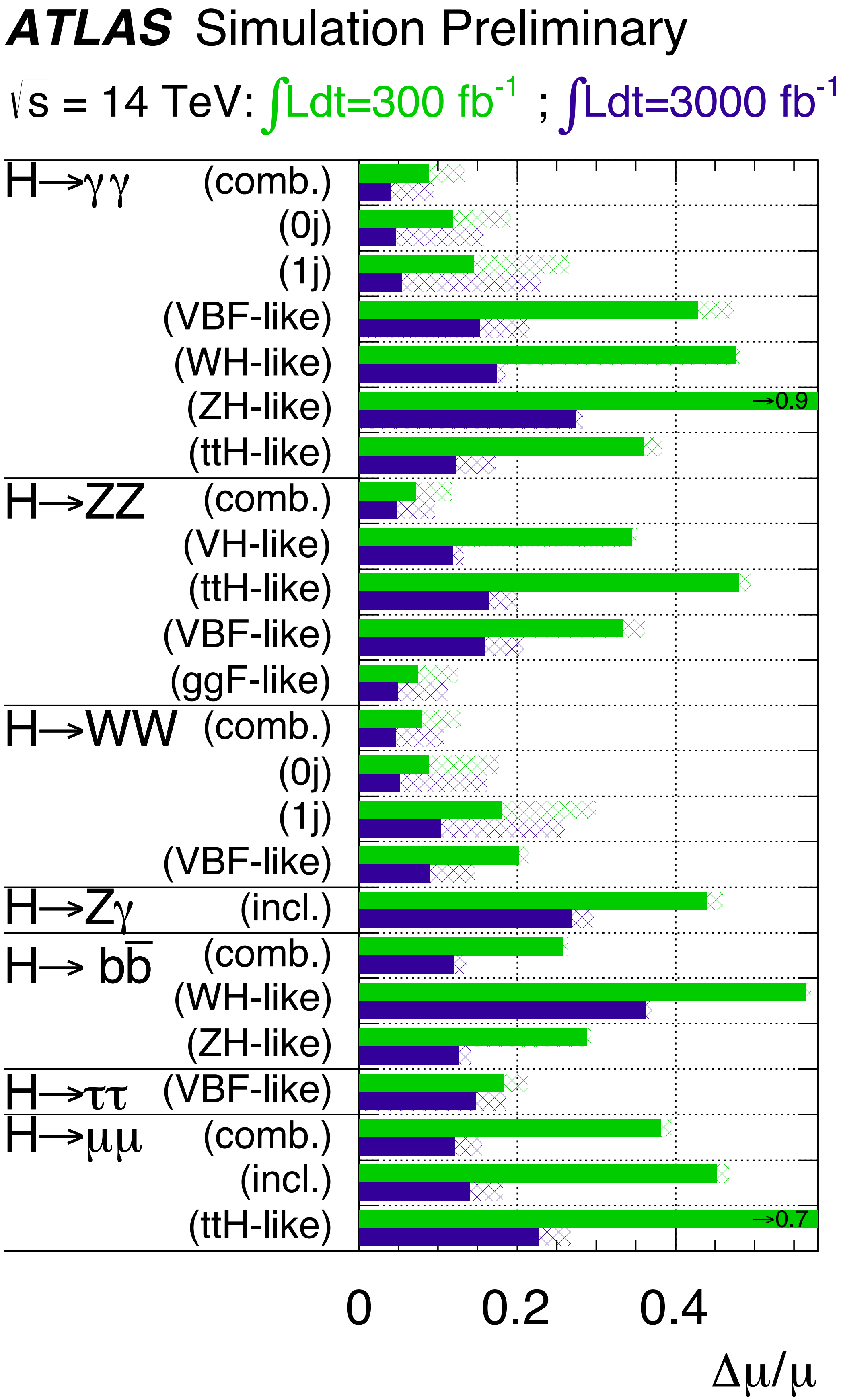
Run3: x10 $\int\mathcal{L}$

A lot more Higgs events coming! as well as:
- large increase in <number of collision/bunch crossing>
- harder to trigger and reconstruct them

It may become harder to identify Higgs events in the future, so not so fast progress on precision measurements! projections do not scale with $\sqrt{\mathcal{L}}$!

BackUp

Prospect



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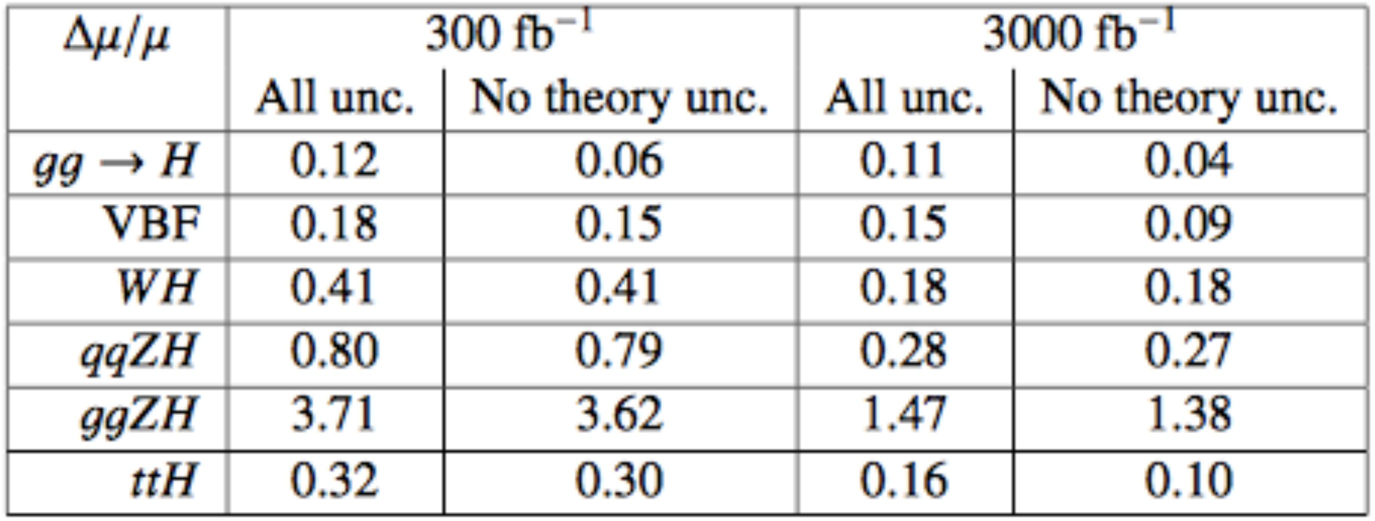
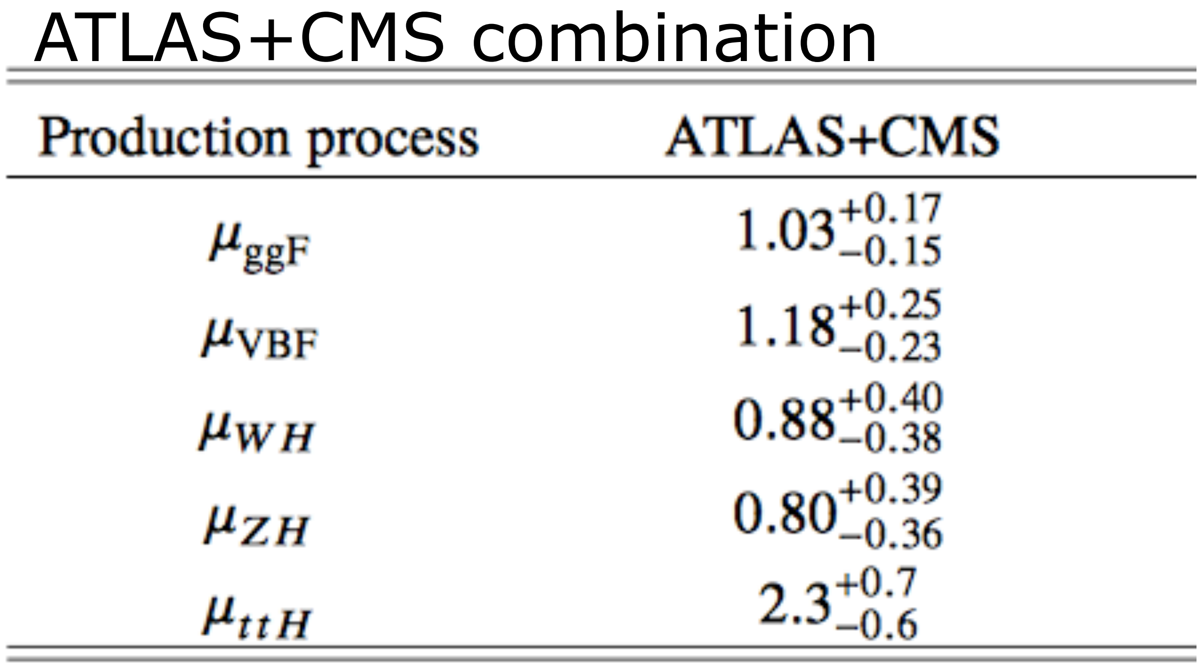


$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$gg \to H$	0.12	0.06	0.11	0.04
VBF	0.18	0.15	0.15	0.09
WH	0.41	0.41	0.18	0.18
$qqZH$	0.80	0.79	0.28	0.27
$ggZH$	3.71	3.62	1.47	1.38
ttH	0.32	0.30	0.16	0.10



ATLAS+CMS combination

Production process	ATLAS+CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$

Event Categorisation

Each category:

- dominated by one decay mode, very little contaminations from others
- not very pure in case of production modes

—> large cross-contaminations in most channels