



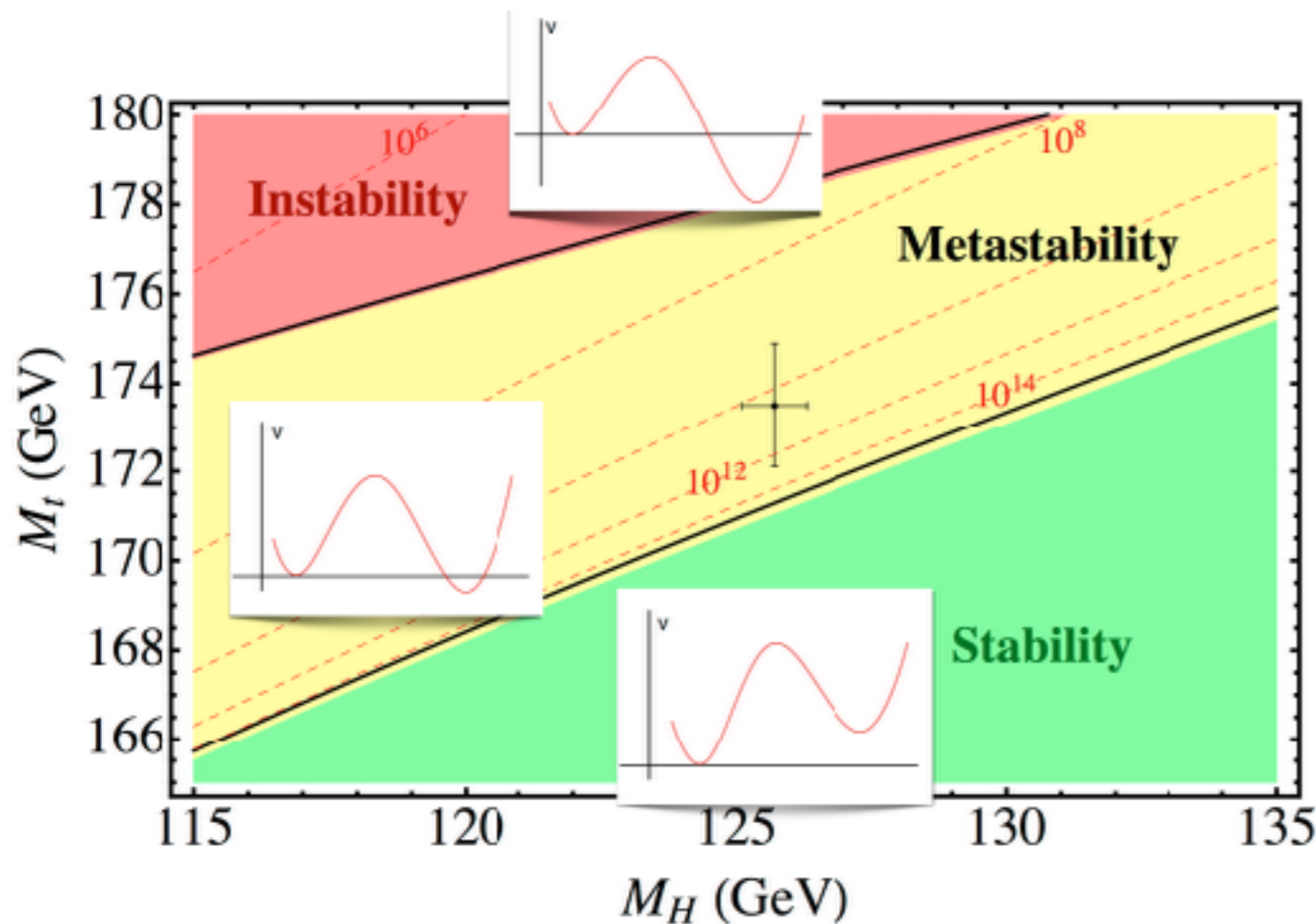
Higgs properties

Pedro Ferreira da Silva (CERN) - psilva@cern.ch

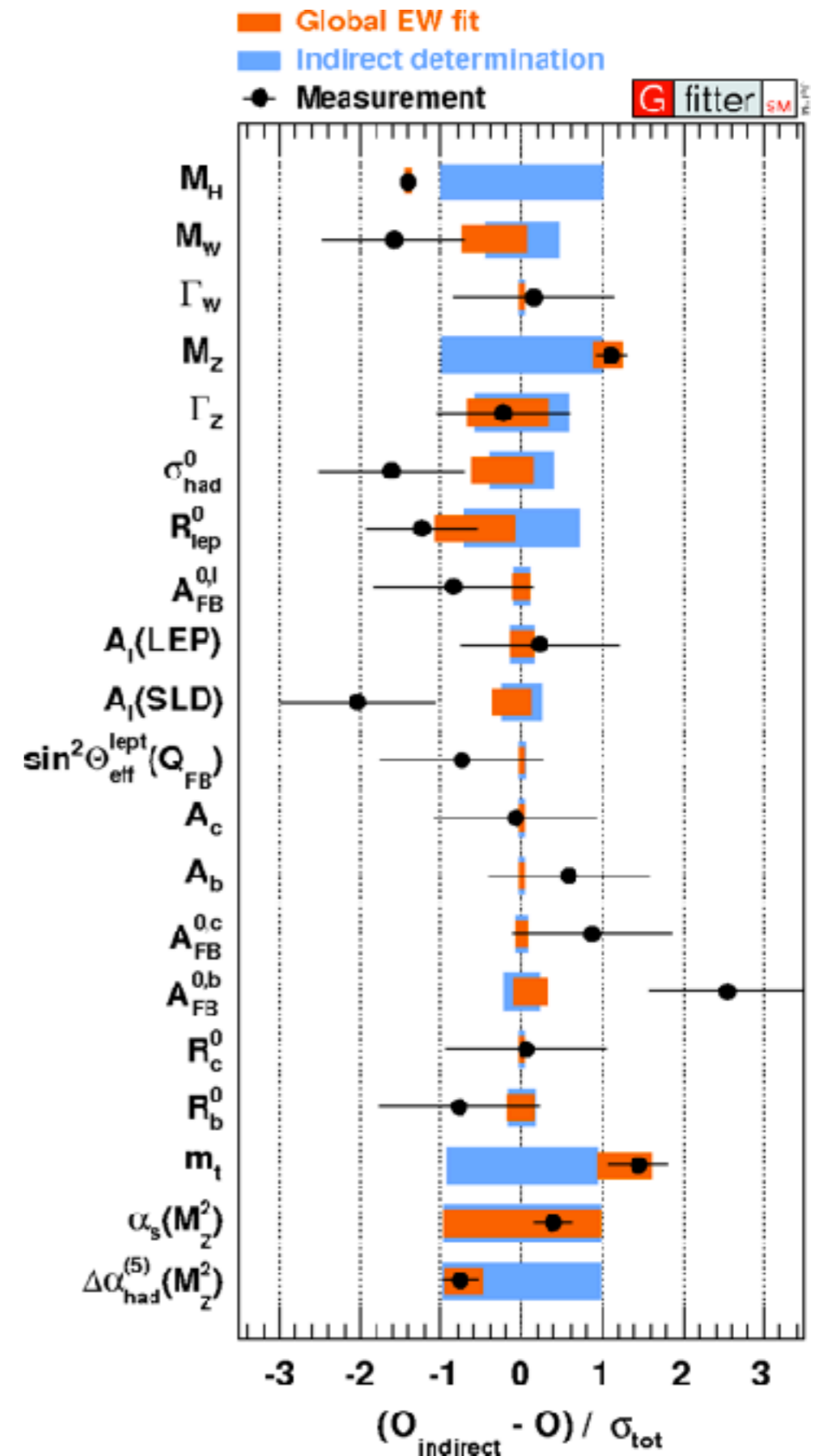
Why are we so obsessed with the Higgs?

- **Is the standard model (SM) really consistent?**

- p-value is currently estimated to be ~ 0.22 (see [GFitte](#))
 - if the Higgs would have been found @ 300 GeV p-value for the SM would be $\sim 3 \cdot 10^{-5}$
- how fined-tuned are the corrections to the mass?
- how stable is the vacuum generated by the Higgs field?



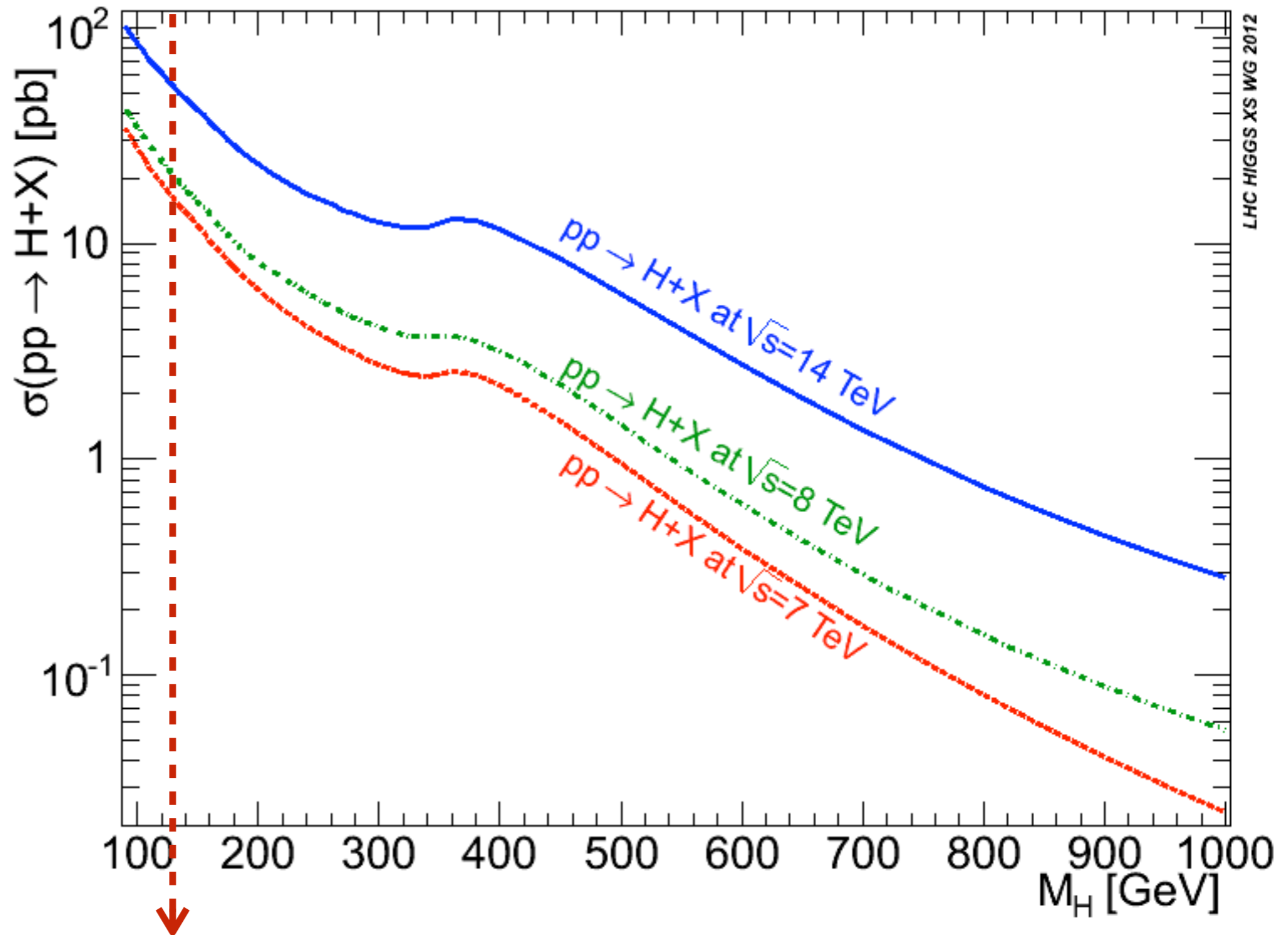
see more details in R. Gonçalo - Higgs lecture #1 - [link](#)



- **From rates to couplings**
- **Models, properties, and interpretation**
- **Results: mass, charge, spin and parity, couplings**
- **Case study: bounding the Higgs width**
- **Conclusions**

From rates to couplings

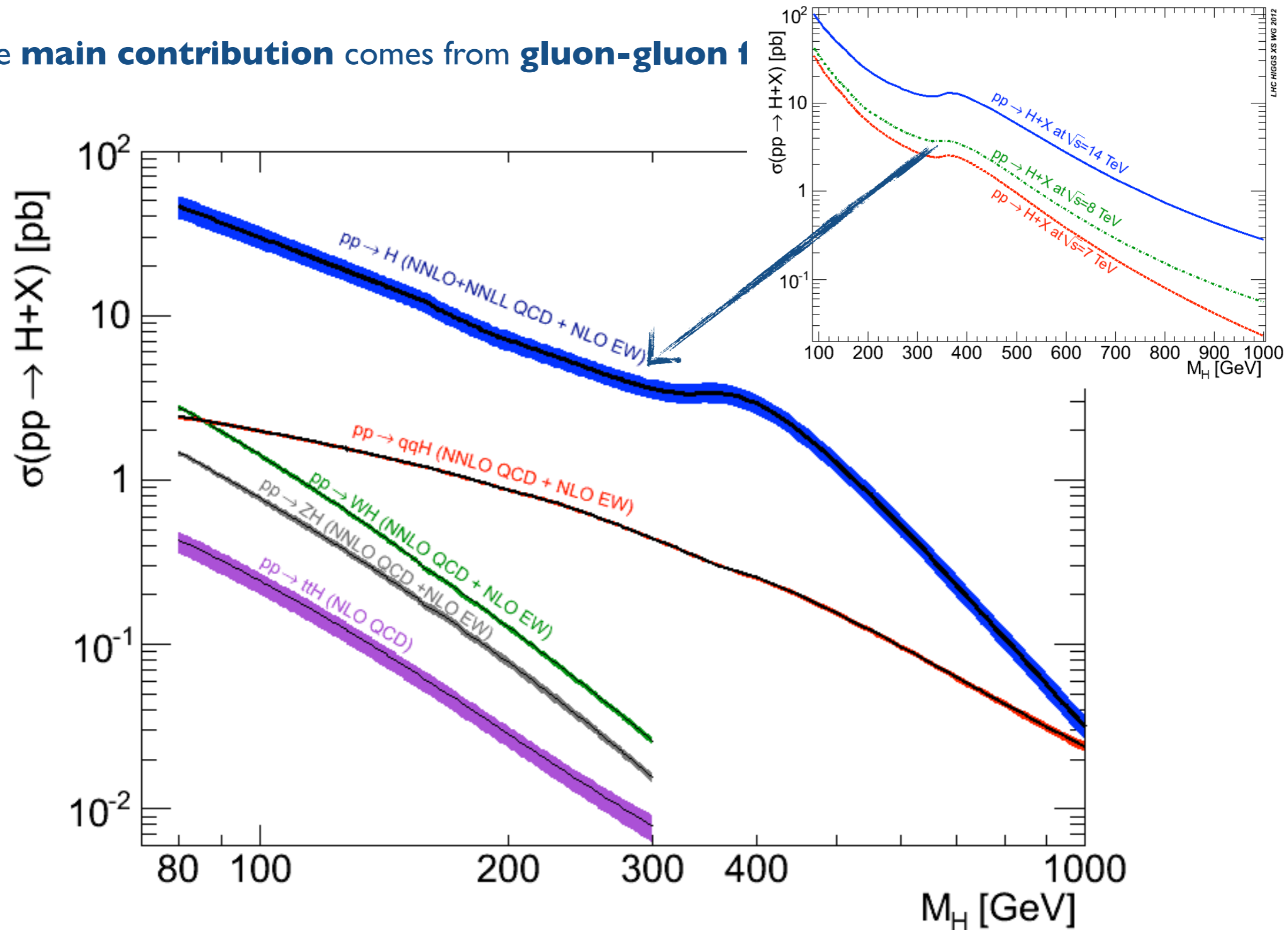
Higgs production at hadron colliders I



- The **inclusive Higgs production** is at the level of **20 pb** (60 pb) at **8 TeV** (14 TeV)

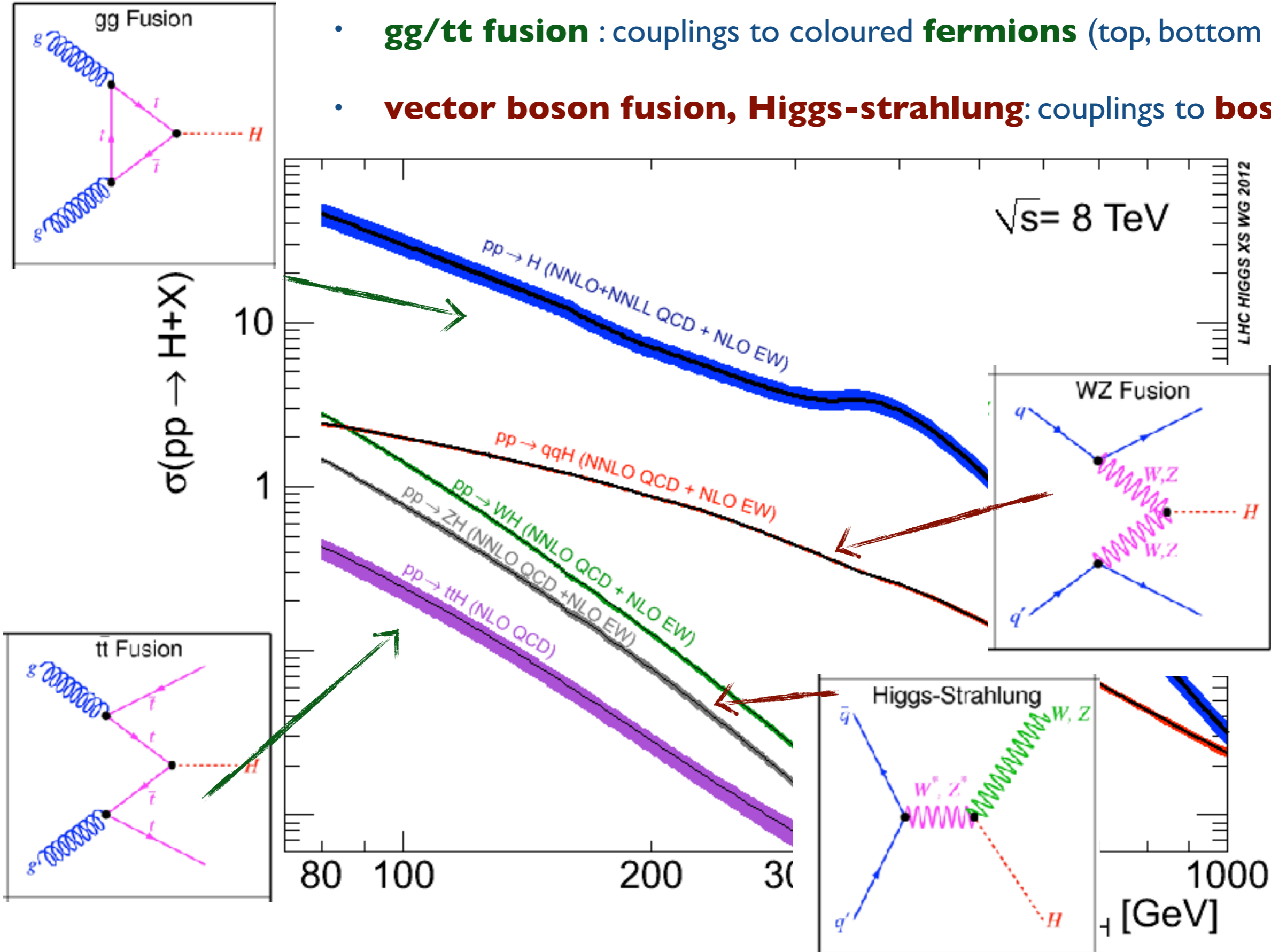
Higgs production at hadron colliders II

- The **main contribution** comes from **gluon-gluon fusion**



Higgs production at hadron colliders III

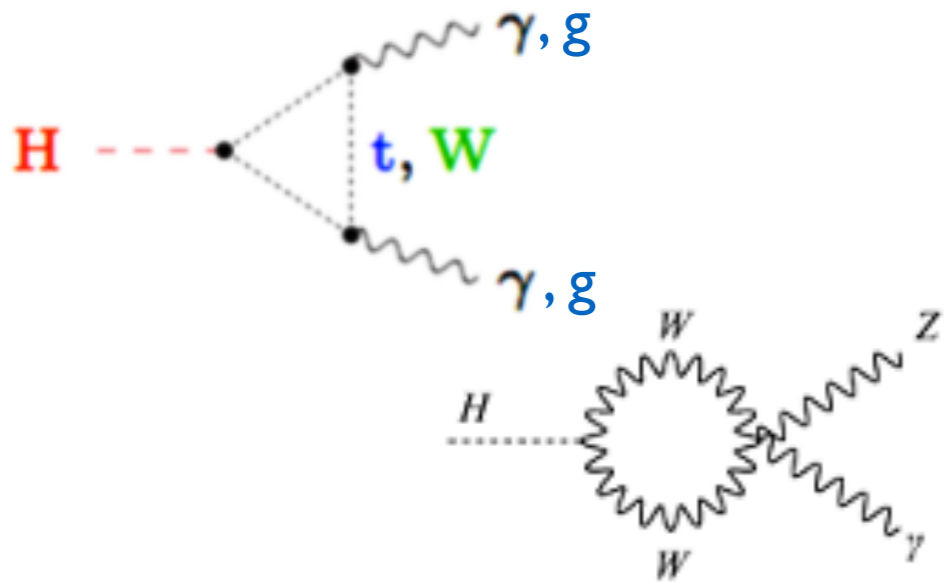
- **gg/tt fusion** : couplings to coloured **fermions** (top, bottom mostly)
- **vector boson fusion, Higgs-strahlung**: couplings to **bosons** (W, Z)



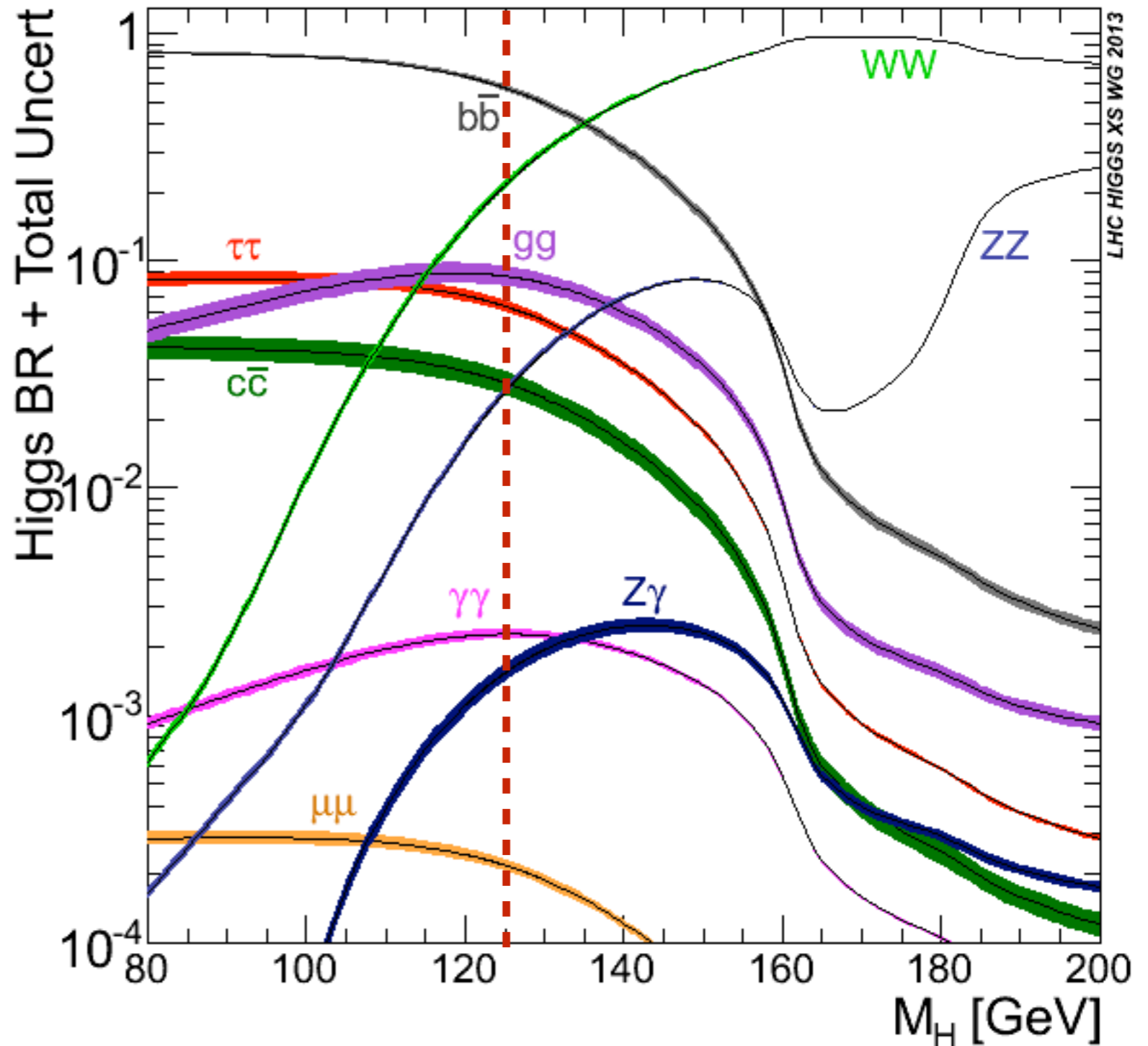
Higgs decays

- Couplings and kinematics determine the branching ratios
- **Prefer bb , $\tau\tau$, WW final states** (most massive particles)
- **Decays to gluons and photons**

- possible through loops

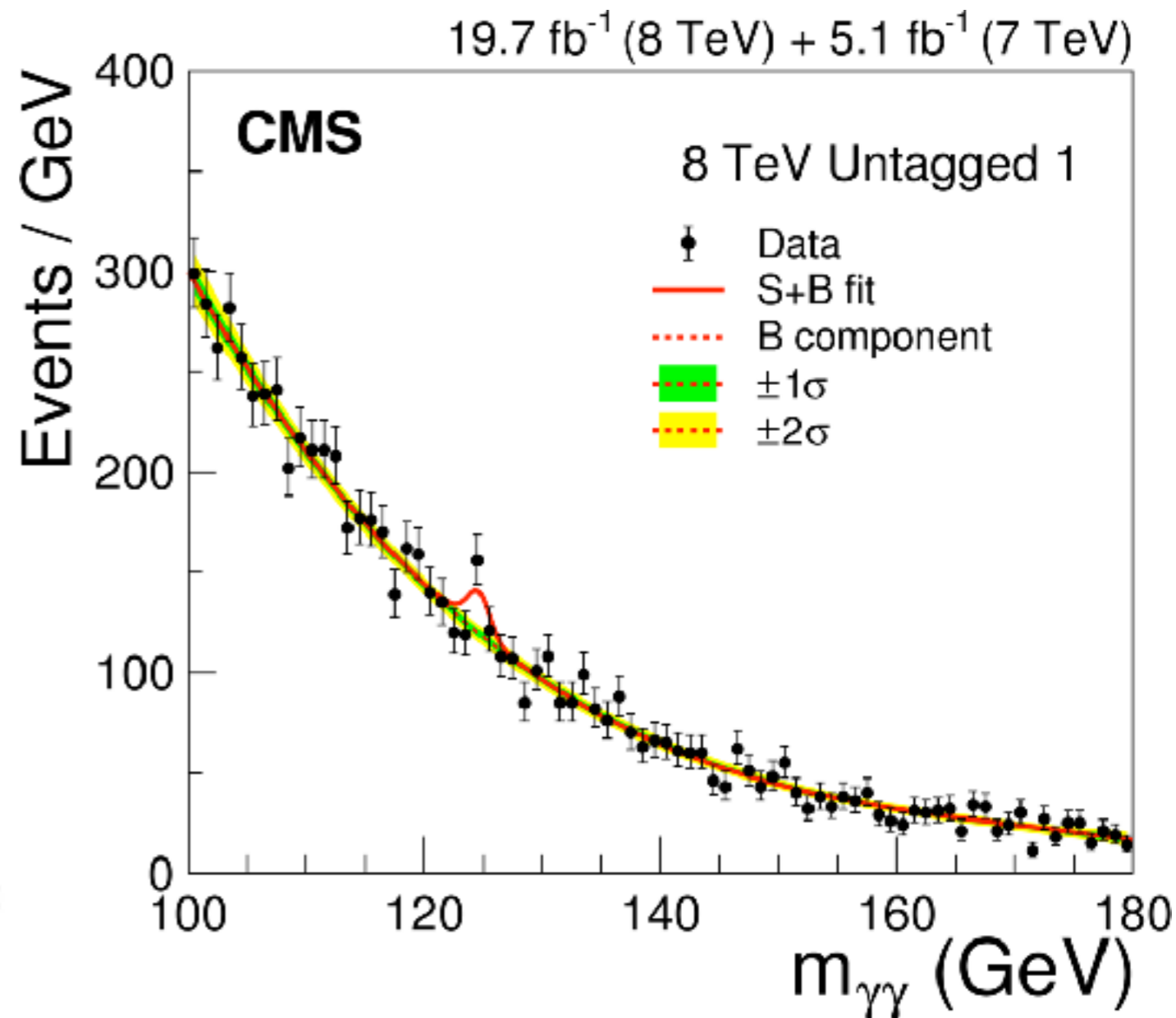
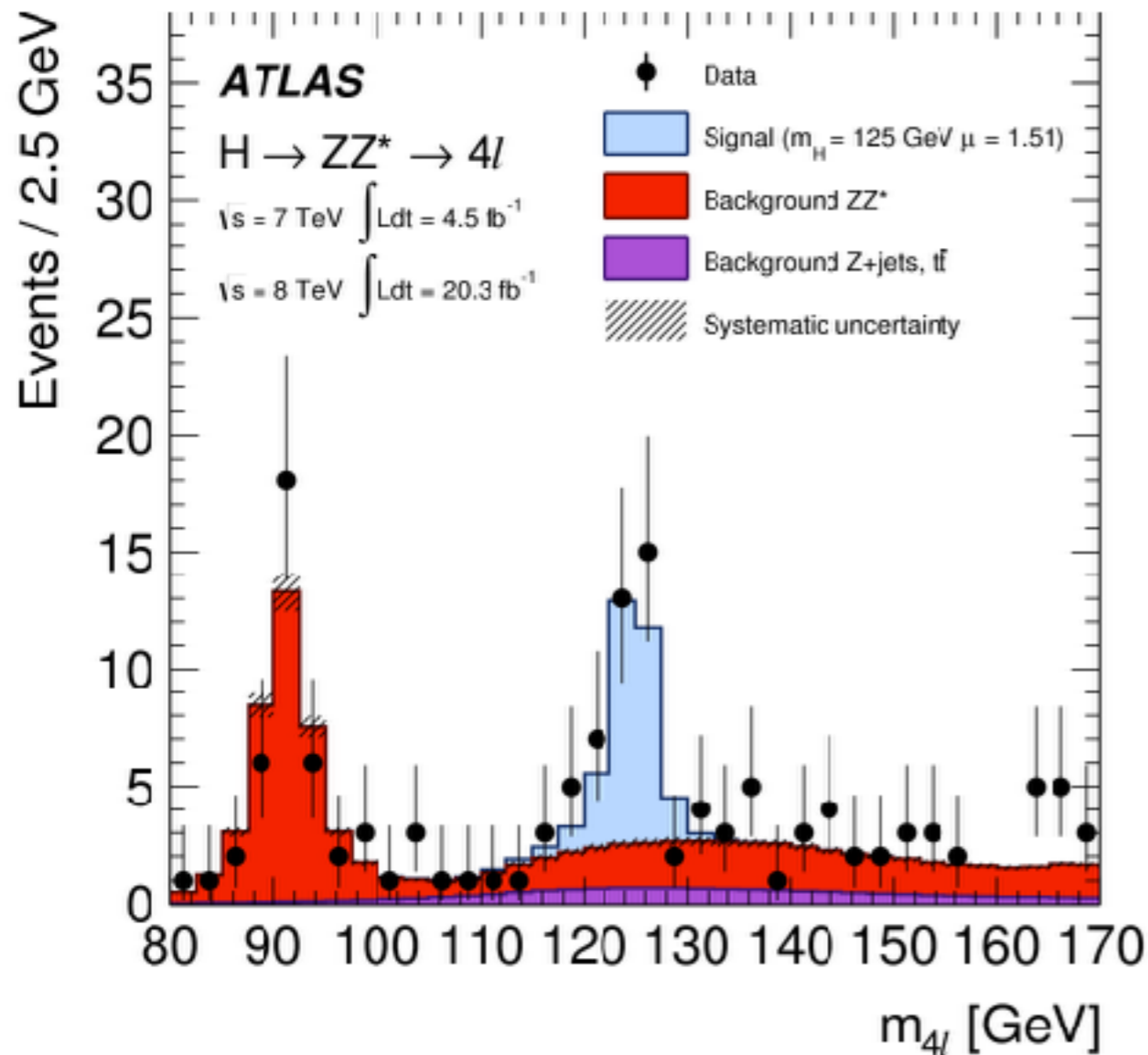


- dominated by tops and/or W's
...and possibly new physics?



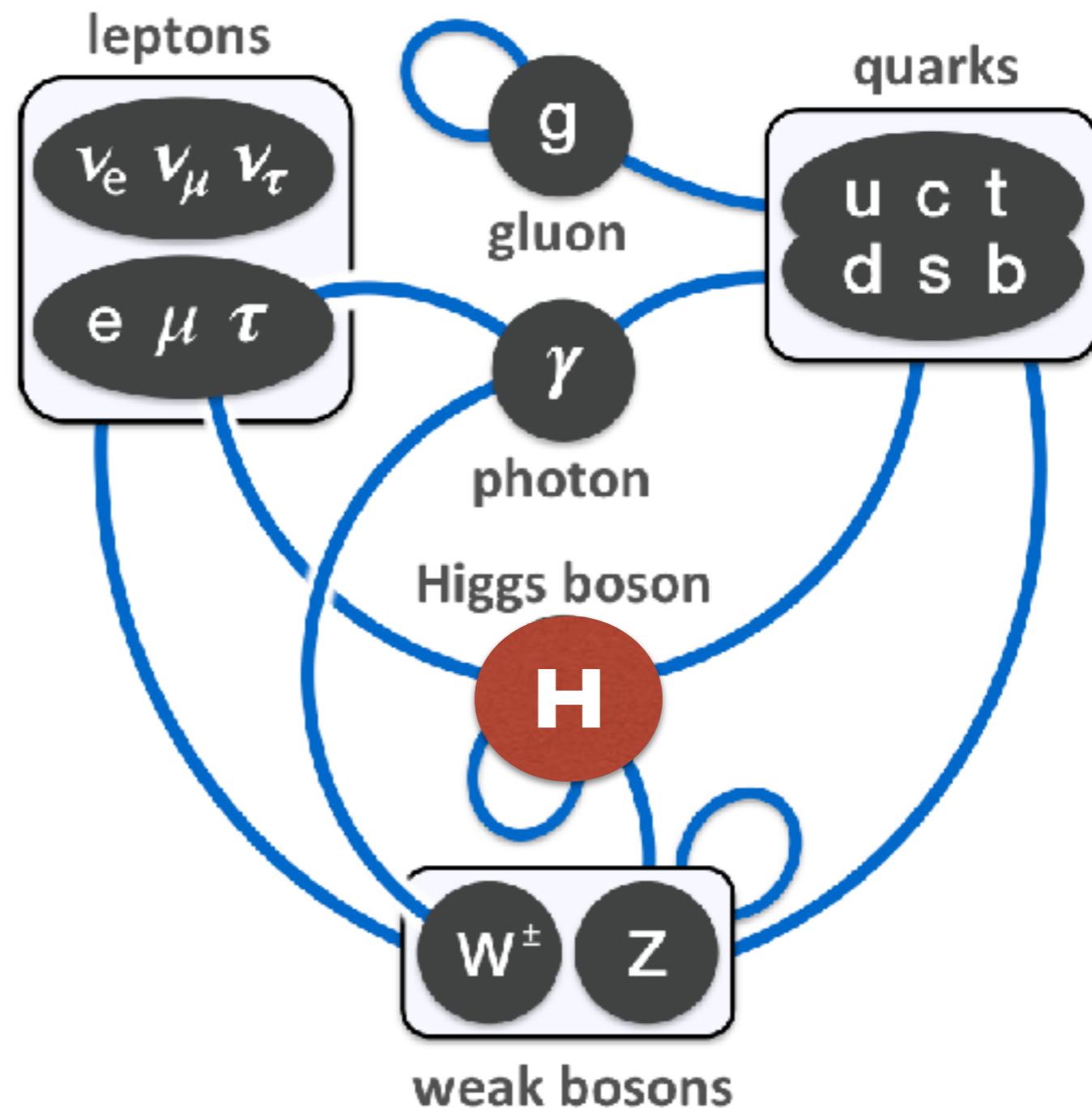
Signals

- Our experiments **count events**.
- **Backgrounds are estimated from data or simulation.**
- The **remainder is the signal** \Rightarrow can be compared to theory.



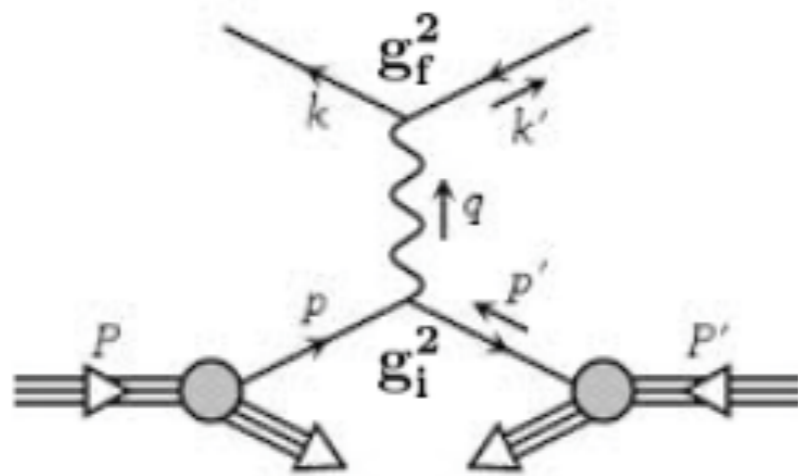
Signals, couplings

- The Higgs gives mass to fermions and vector bosons
- Different couplings at production and decay
- Can we disentangle them?



Signals, couplings and width

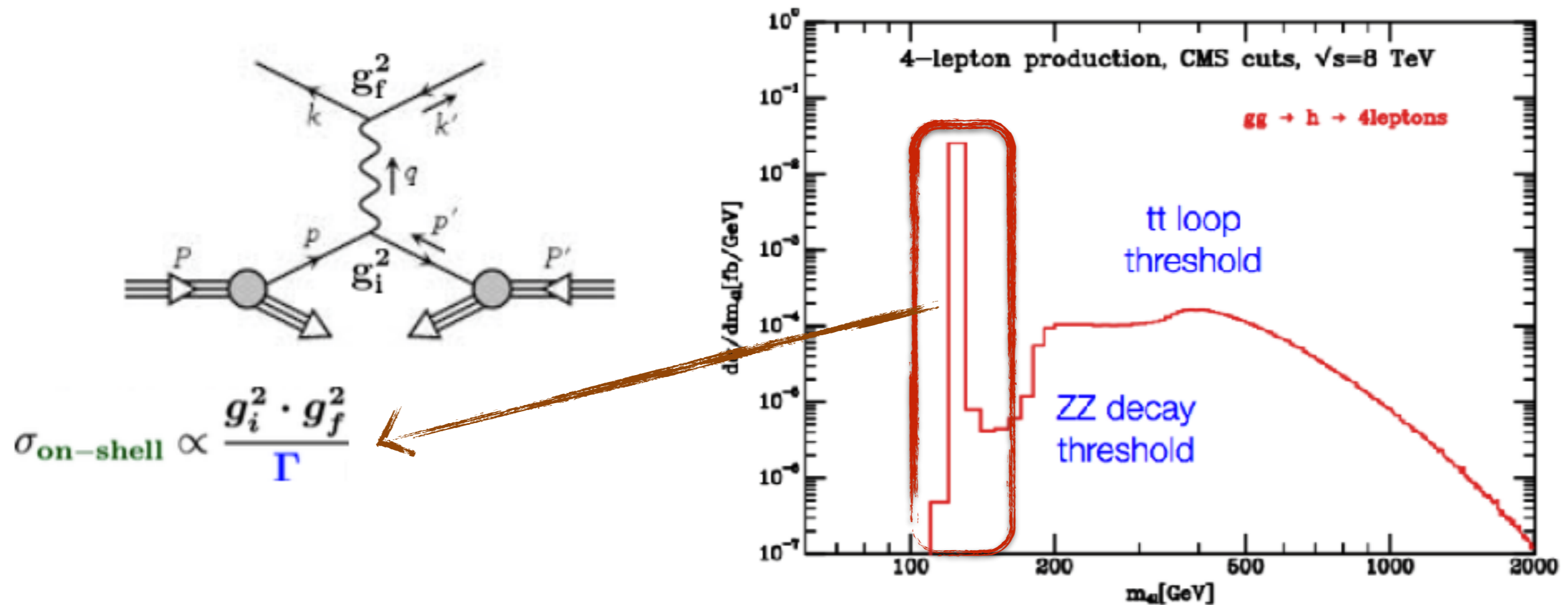
- The observed production rate holds, as well, information on the total width Γ
 - depends on the propagator and the couplings of a particle



$$\sigma \propto \int \frac{g_i^2 \cdot g_f^2}{(s - m_0^2)^2 + \Gamma^2 m^2} ds$$

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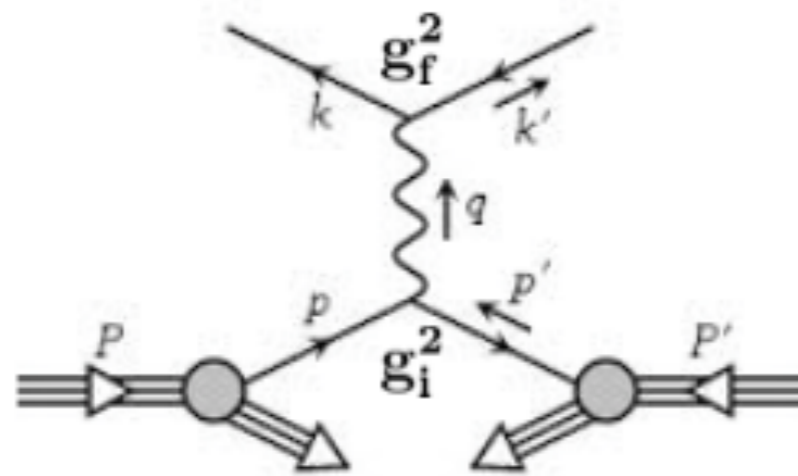


- **On-shell production**

- lineshape often limited by detector resolution
- knowing the branching ratios and the cross section determines Γ

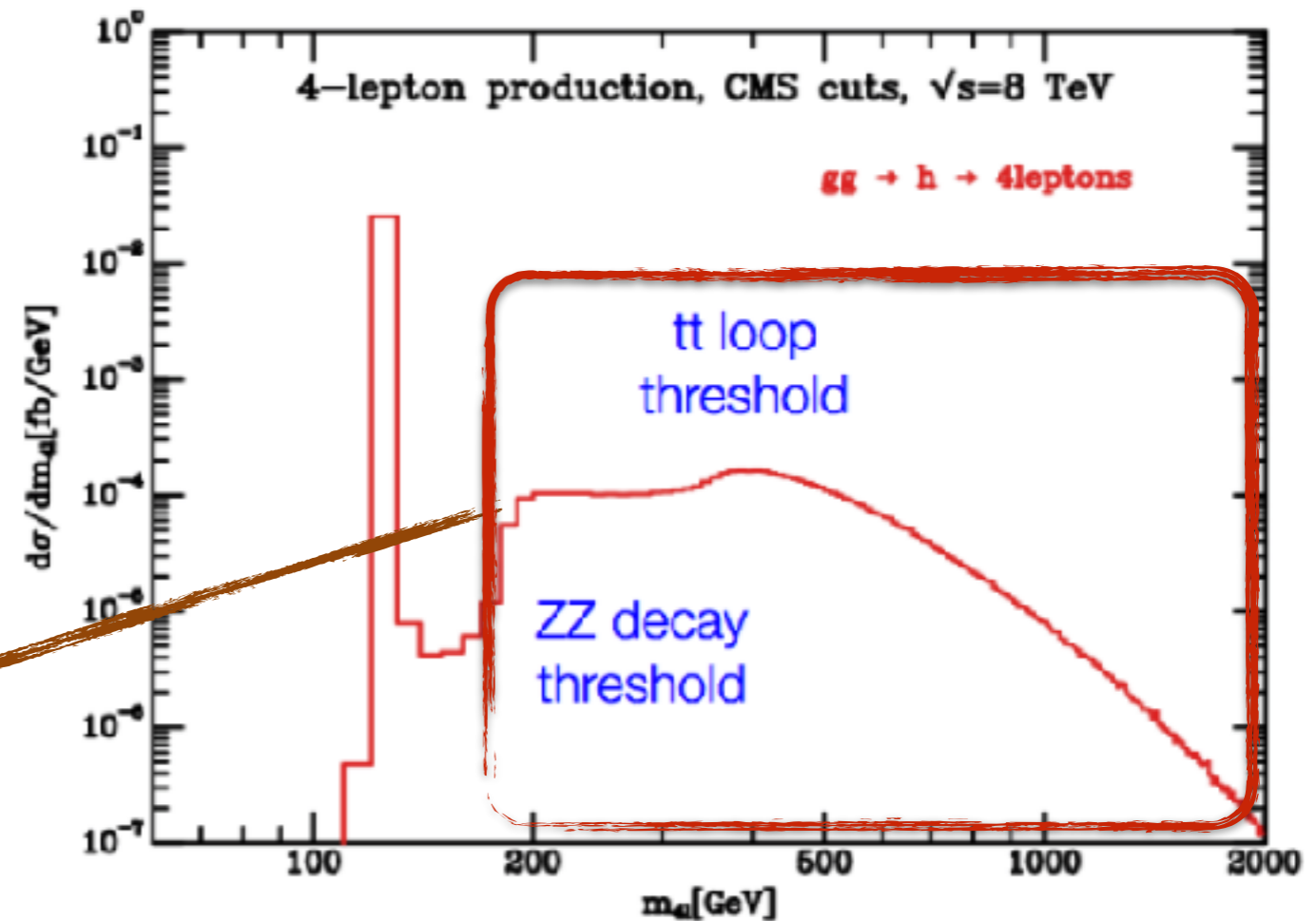
Signals, couplings and width

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$$\sigma_{\text{on-shell}} \propto \frac{g_i^2 \cdot g_f^2}{\Gamma}$$

$$\sigma_{\text{off-shell}} \propto g_i^2 \cdot g_f^2$$



• Off-shell production

- depends only on couplings
- take the ratio of the two cross sections to measure Γ

$$\frac{\sigma_{\text{off-shell}}}{\sigma_{\text{on-shell}}} \propto \Gamma$$

Models, properties, and interpretation

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

- **The expected signal rates in a given channel (k) depend on the**
 - integrated luminosity used for the analysis - \mathcal{L}
 - cross section - σ
 - branching ratio to the final state used in the analysis - BR
 - an overall selection efficiency factor $A \times \varepsilon$ which depends on the initial and final state

New physics can affect production

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

- Most Higgs production modes are precisely predicted by the standard model
 - uncertainties range from 2-3% (EW productions like VH) to 10% (strong productions like ggH)

Production process	Cross section [pb]		Order of calculation
	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$	
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)+APP.NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.357 ± 0.015	0.446 ± 0.019	NNLO(QCD)+NLO(EW)
ZH: $gg \rightarrow ZH$			LO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NLO(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	

- New physics can alter the SM expectation : model with scale parameter

$$\sigma_i = \mu_i \cdot \sigma_{\text{SM}}$$

New physics can affect the decay

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

- The SM Higgs branching ratios are determined to 1-3% precision

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

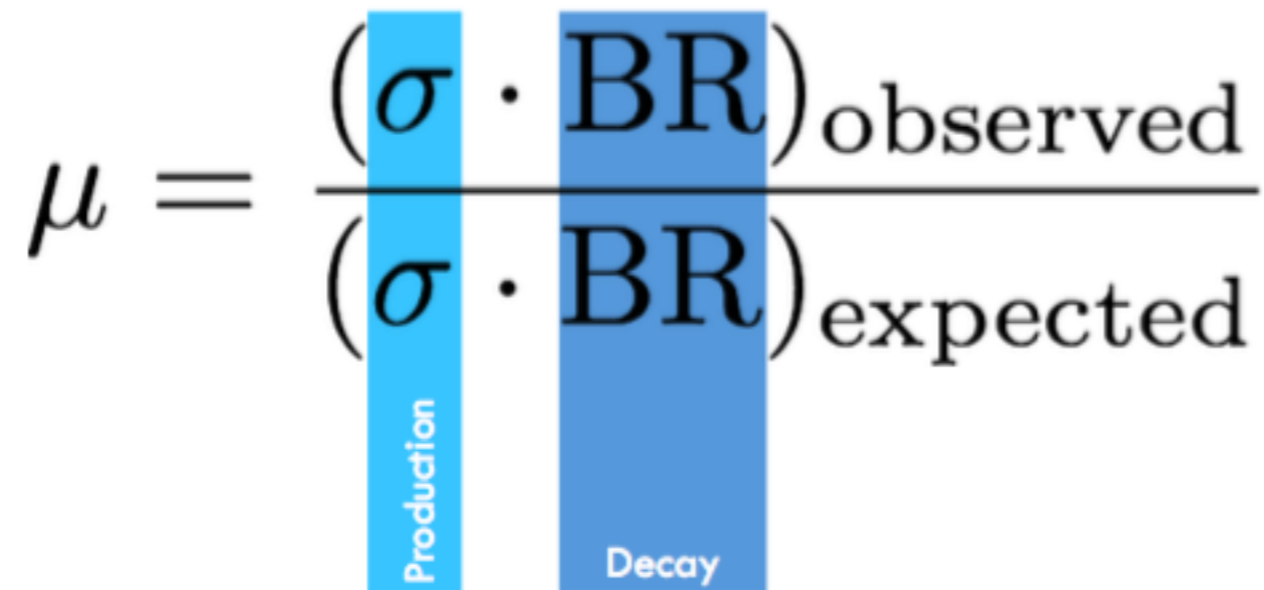
- Again new physics can modify these branching ratios: model with scale parameter

$$\text{BR}^f = \mu^f \cdot \text{BR}_{\text{SM}}$$

- notice that new decay channels may appear e.g. $\text{BR}(H \rightarrow \text{dark matter})$

Deviations are searched relative to the SM expectation.

Conclusions are only as good as the accuracy and precision of the numerator and denominator.

$$\mu = \frac{(\sigma \cdot \text{BR})_{\text{observed}}}{(\sigma \cdot \text{BR})_{\text{expected}}}$$


μ is the so-called signal strength

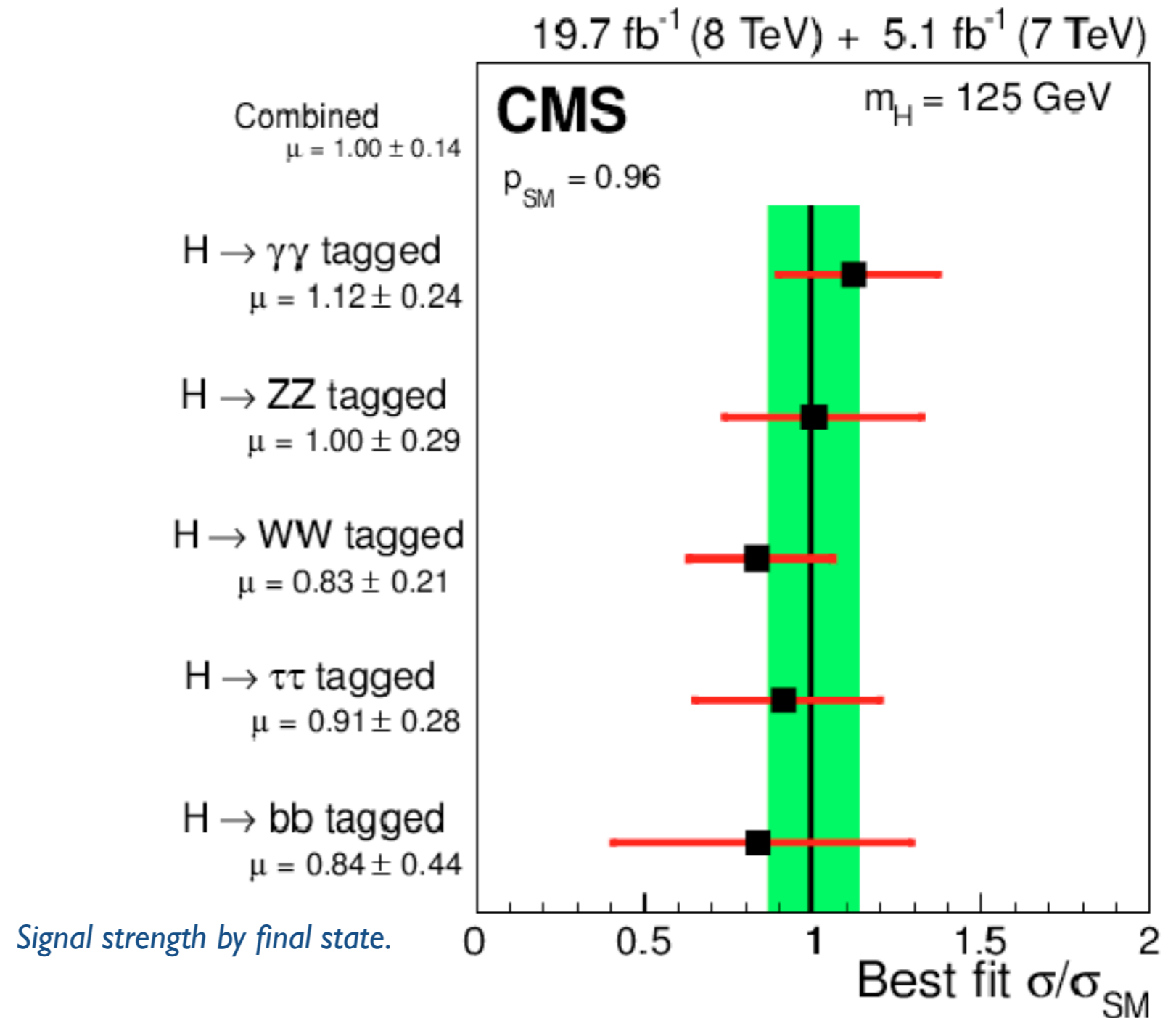
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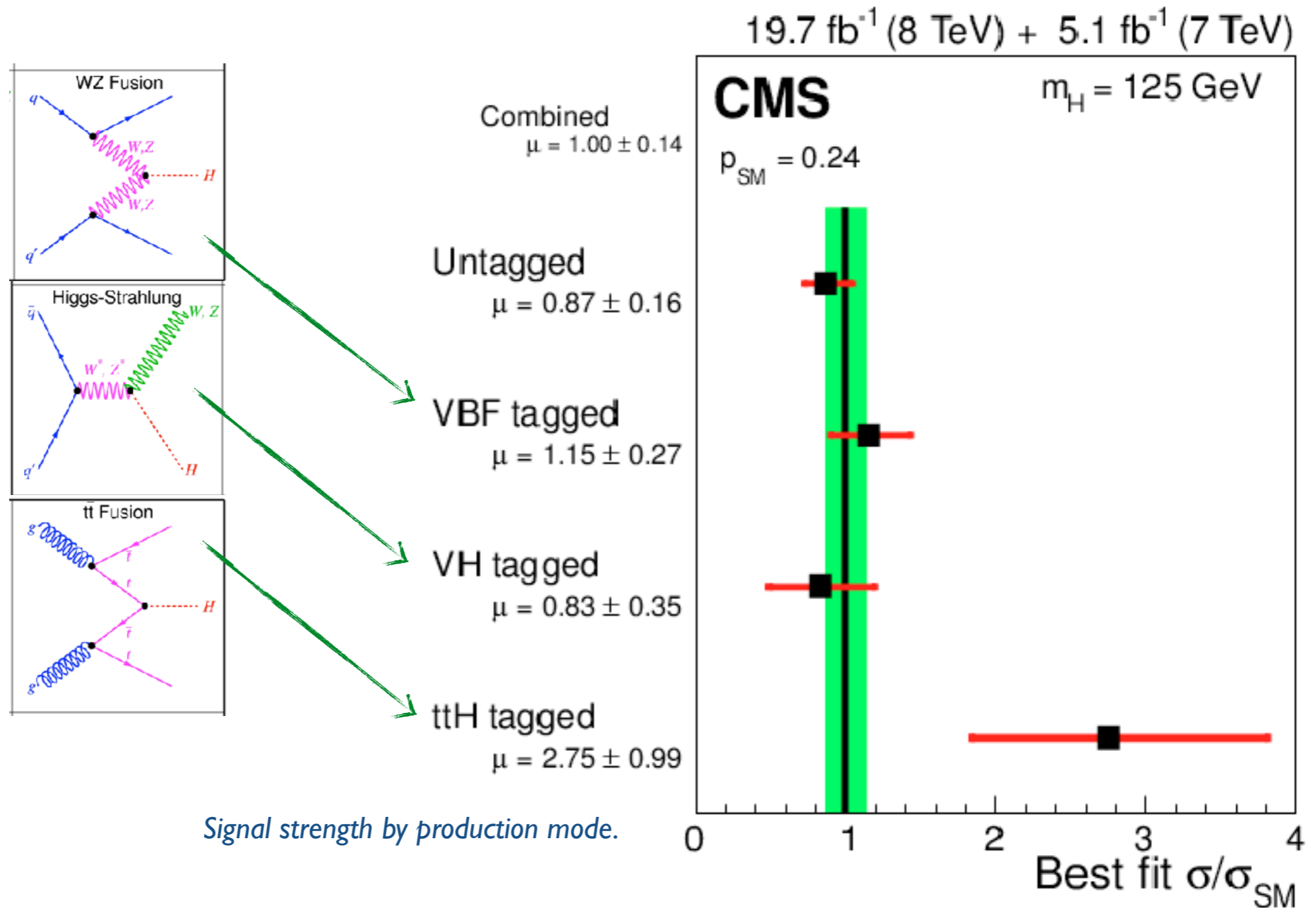
$$\mu = \frac{(\sigma \cdot \text{BR})_{\text{observed}} \text{ Data}}{(\sigma \cdot \text{BR})_{\text{expected}} \text{ Standard Model}}$$

μ is the so-called signal strength

- If the signal strength close to 1, observations are close to the SM predictions
- Compatibility with theory depends on the uncertainty
- Conclusion depends on both experimental and theoretical accuracies



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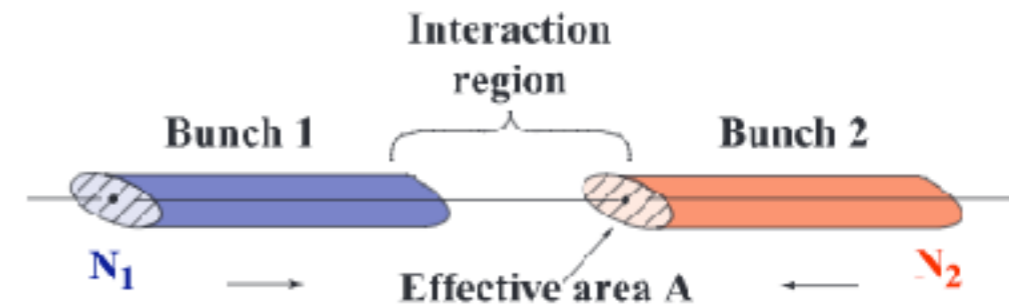
What about the other factors?

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

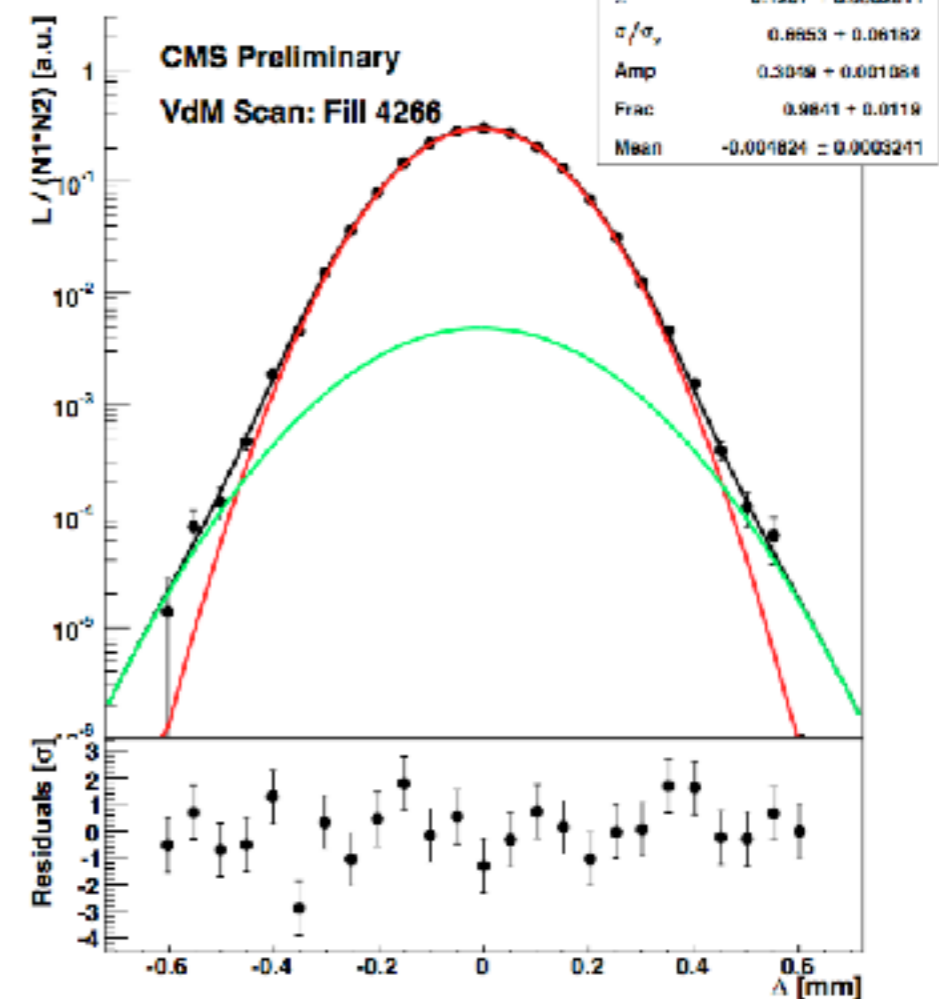
- Either they are fully determined in data

- *Integrated luminosity* (\mathcal{L}) from Van-der-Meer scans

see e.g. J.Varela - lecture #3 on standard model - [link](#)



Scan 1: X-plane BCID 2674

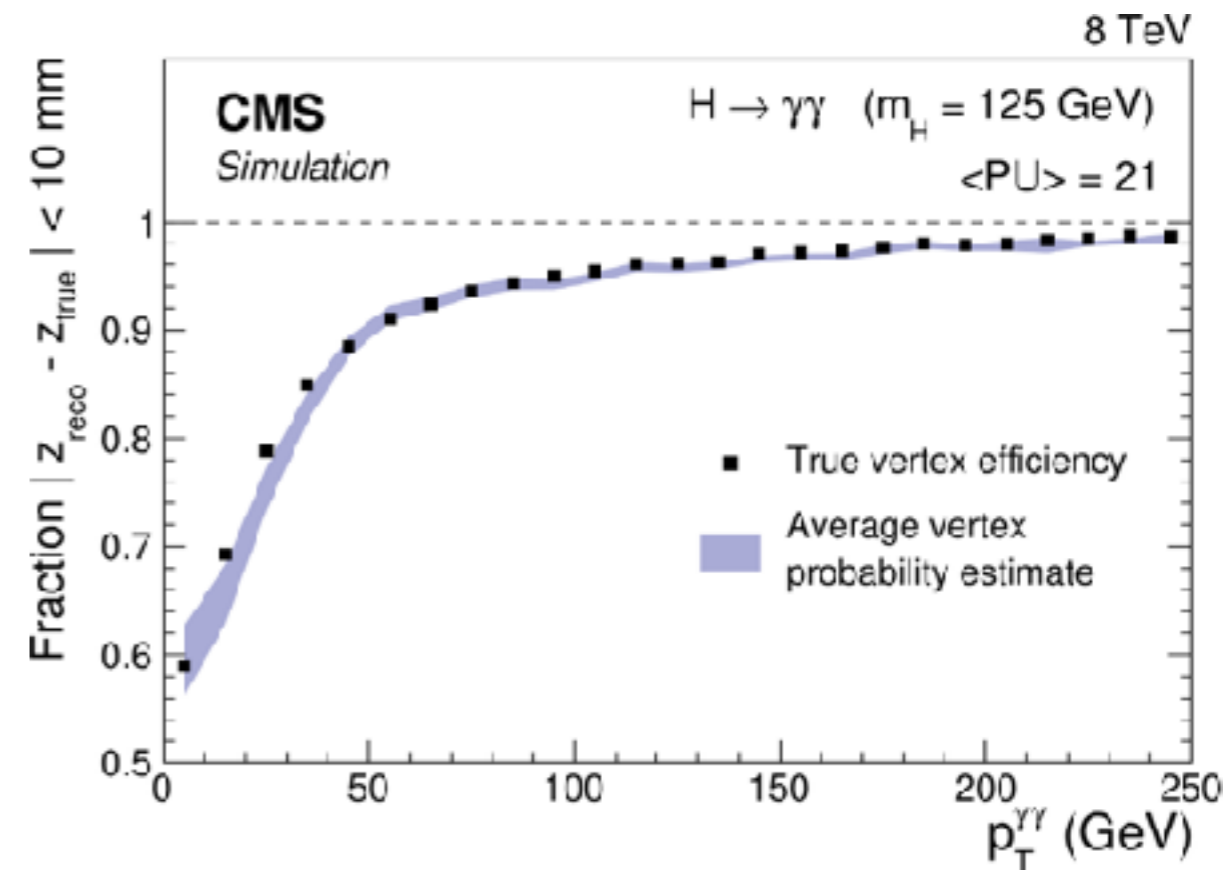


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- *efficiencies* (ε) measured from control regions
 - test dedicated selections in the analysis



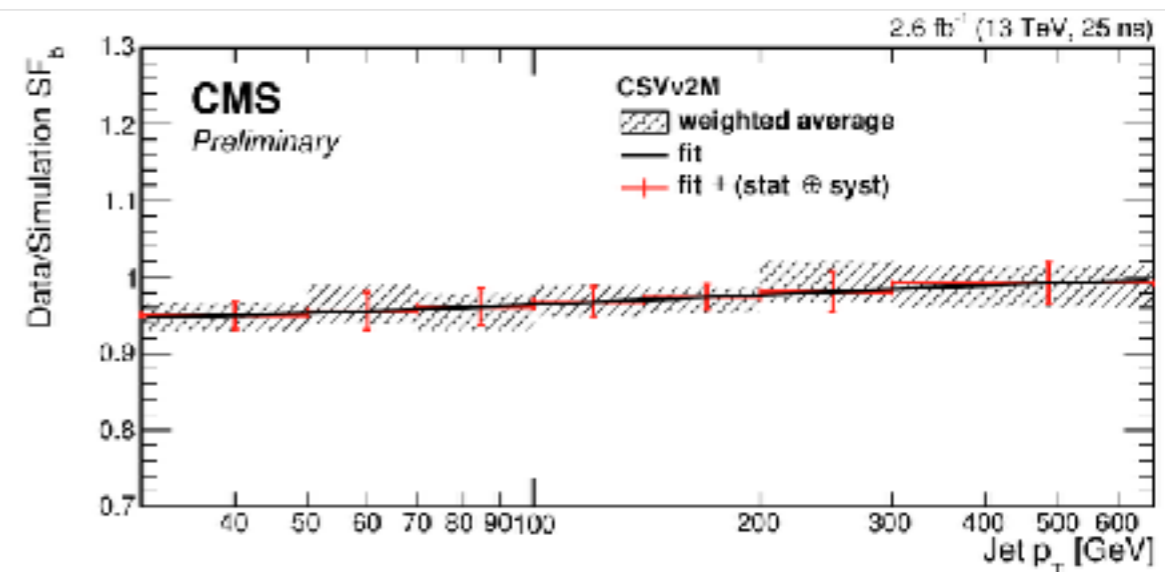
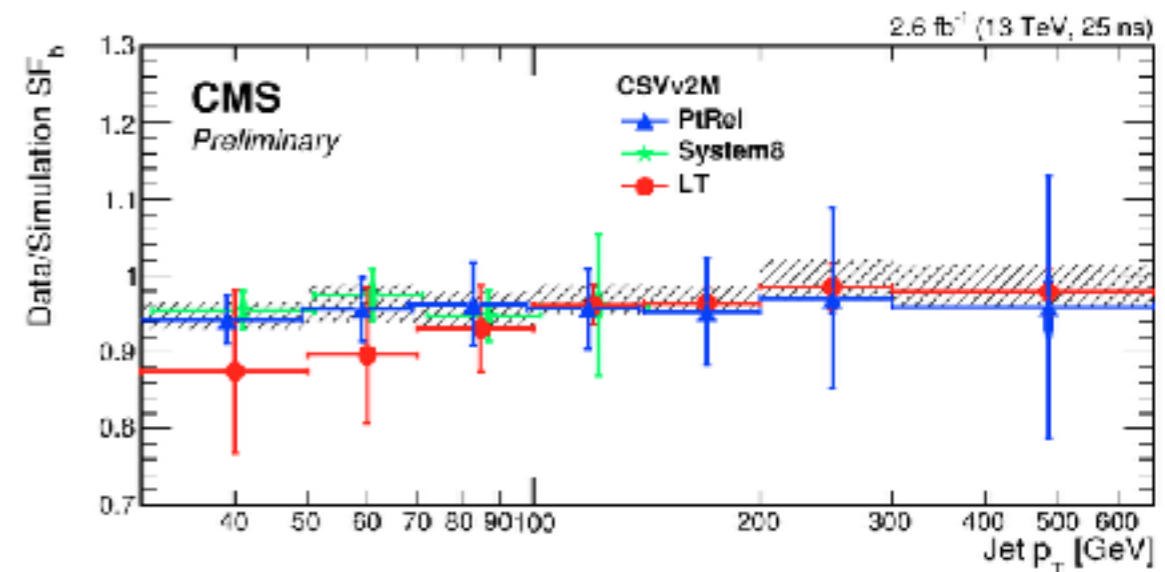
Efficiency for the primary vertex selection in $H \rightarrow \gamma\gamma$

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 - e.g. $Z \rightarrow \ell\ell$ used for lepton efficiencies
 - e.g. dijets/top events for b-tagging efficiencies
- see e.g. M. Gallinaro - lecture #1 on top physics - [link](#)



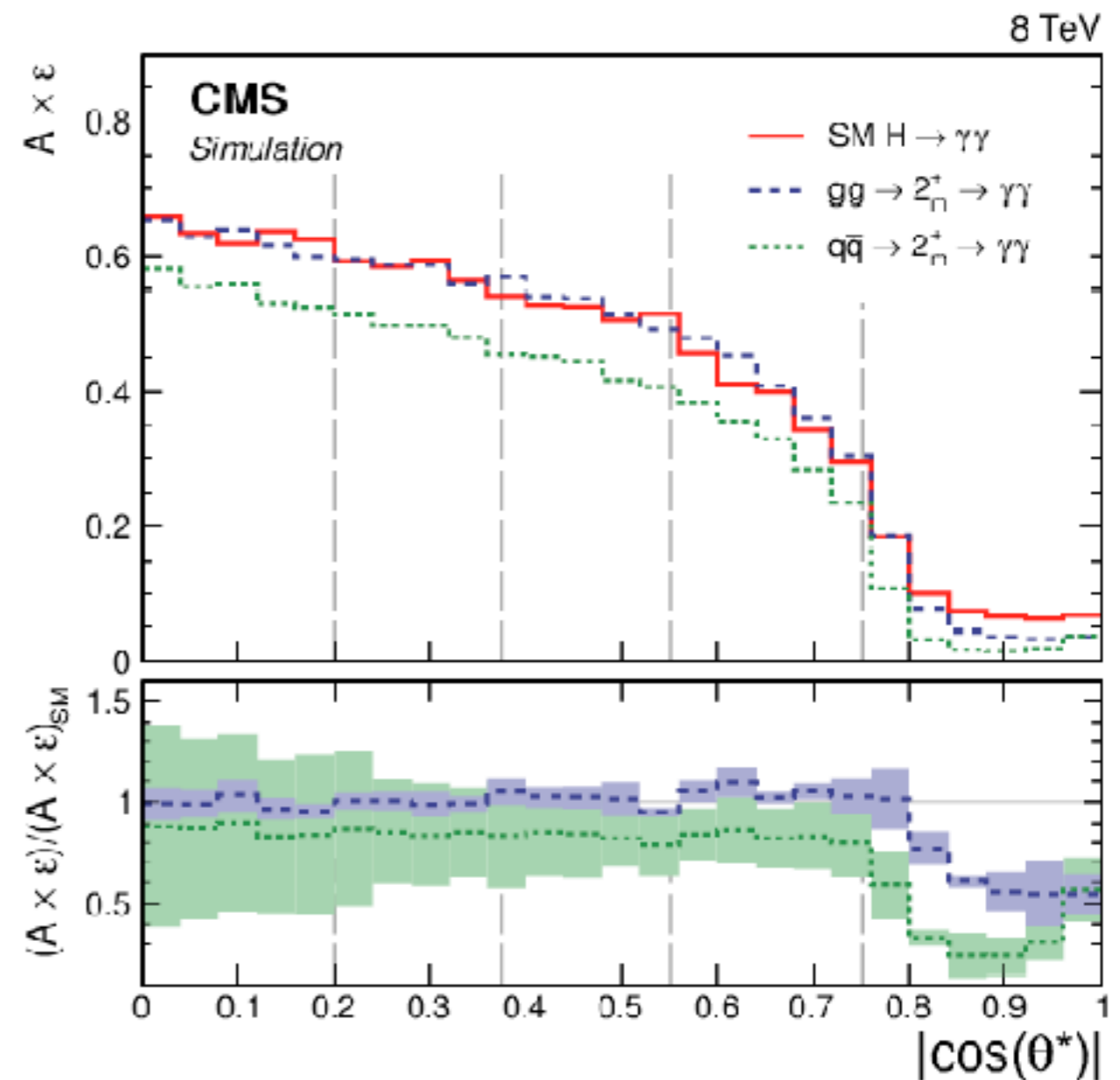
b-tagging efficiency as function of the transverse momentum

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- Either they are estimated using simulation

- acceptance depends mostly on the thresholds
- dictated by geometry and trigger requirements
- need to take into account physics
- vertices at production and decay
- but also radiation, fragmentation, hadronization, multiple parton interactions, beam remnants (aka the underlying event)
- and PDFs, QCD scale choices...



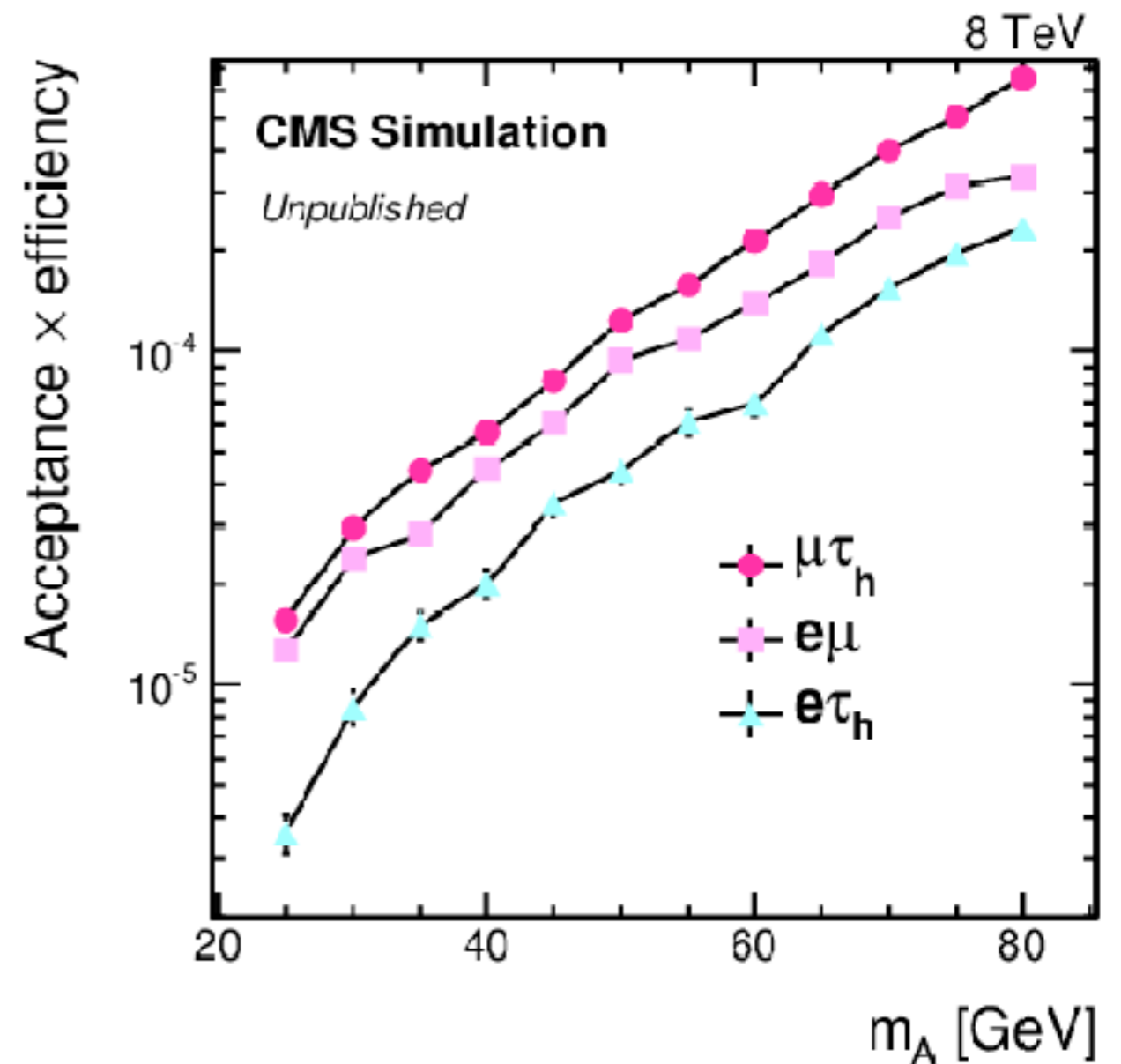
Acceptance for different signal $H \rightarrow \gamma\gamma$ hypothesis

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Acceptance for different signal $A \rightarrow \tau\tau$ hypothesis

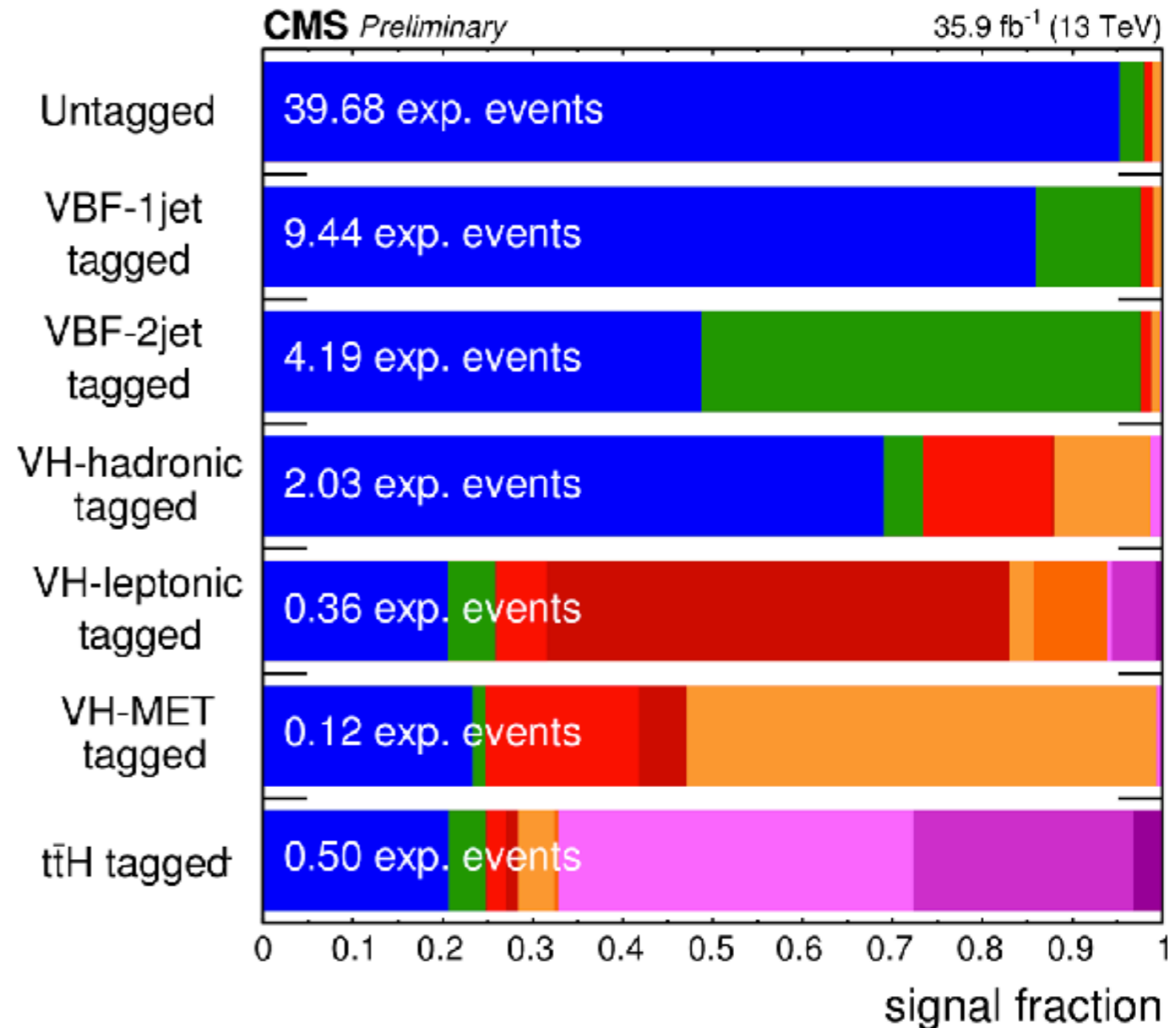
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In the end there is not a 1:1 relation between what is measured and what can be produced

to gain insight into the couplings every contribution needs to be accounted for

- ggH
- VBF
- WH, W→X
- WH, W→lv
- ZH, Z→X
- ZH, Z→2l
- ttH, tt→0l+X
- ttH, tt→1l+X
- ttH, tt→2l+X



Acceptance for different categories in the H→ZZ→4l analysis

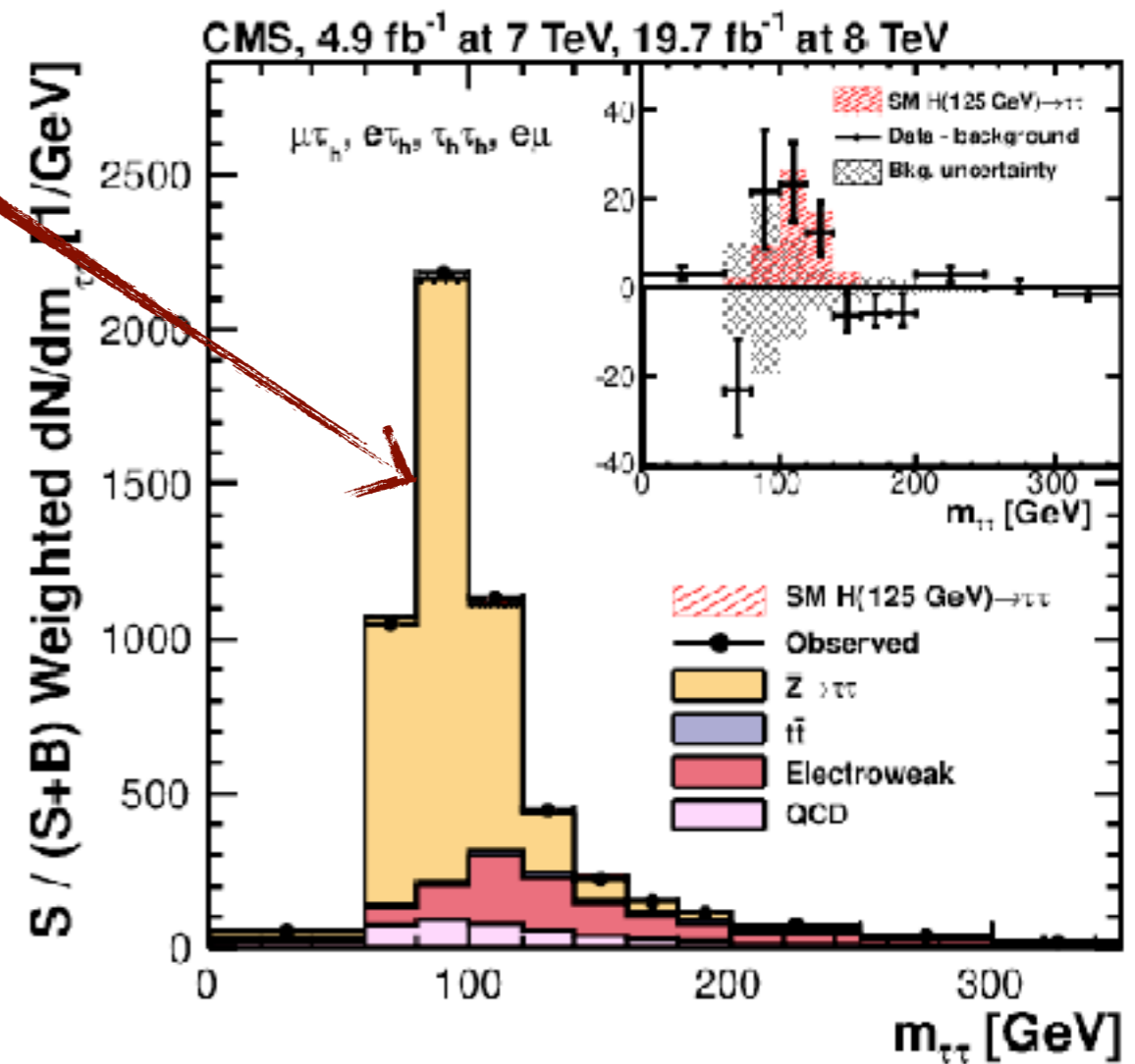
Using all the ingredients to fit the parameters of a model

- At the end of the analysis we have a prediction for signal and background

$$\lambda = n_{\text{signal}} + n_{\text{background}}$$

- λ is a function of the signal strength

$$\lambda = \lambda(\mu)$$



Using all the ingredients to fit the parameters of a model

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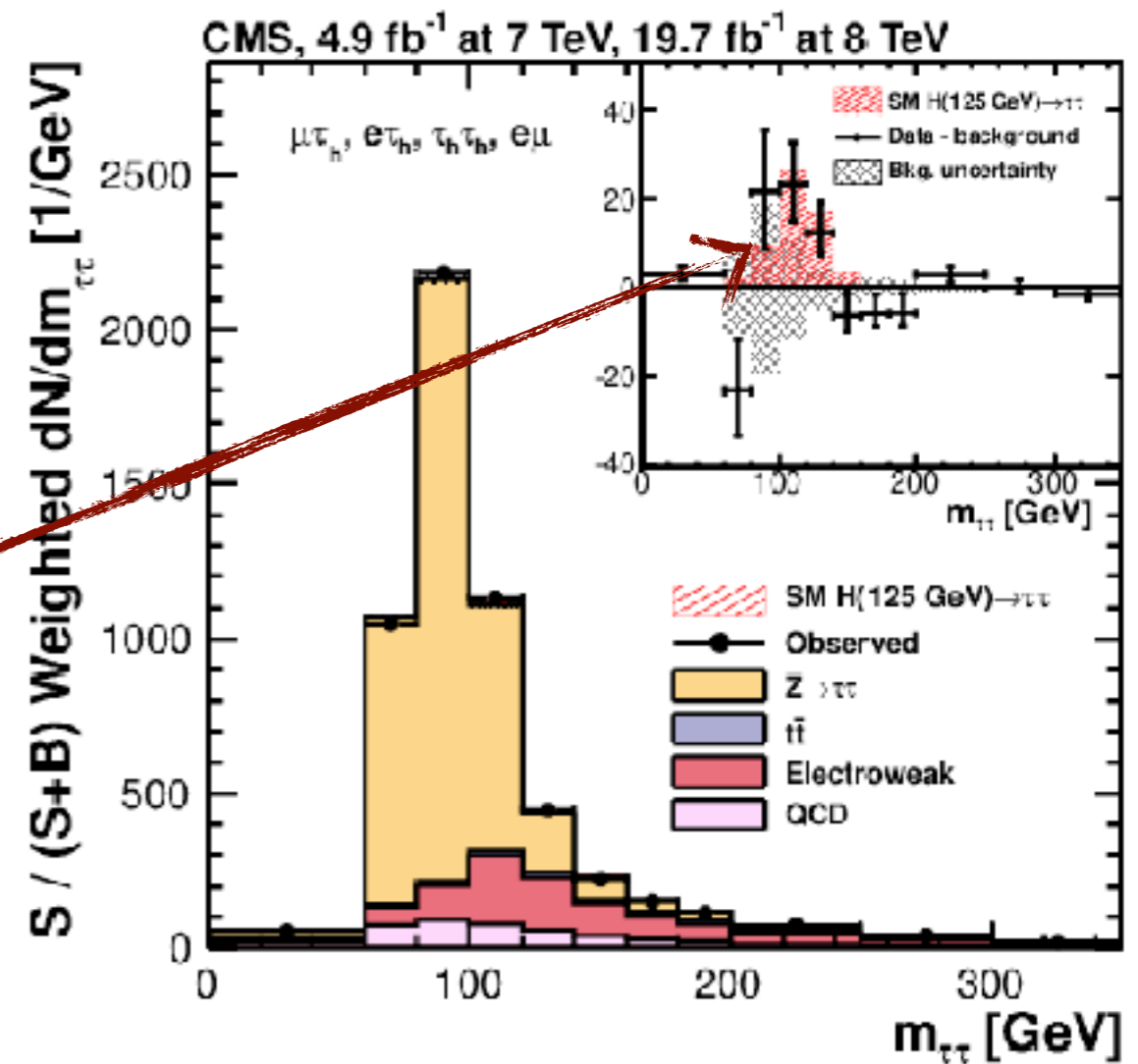
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- Counting experiments follow Poisson statistics:

$$\mathcal{L}(\lambda) = \mathcal{P}_{\text{oisson}}(n_{\text{obs}}|\lambda) = \frac{\lambda^{n_{\text{obs}}} \cdot e^{-\lambda}}{n_{\text{obs}}!}$$



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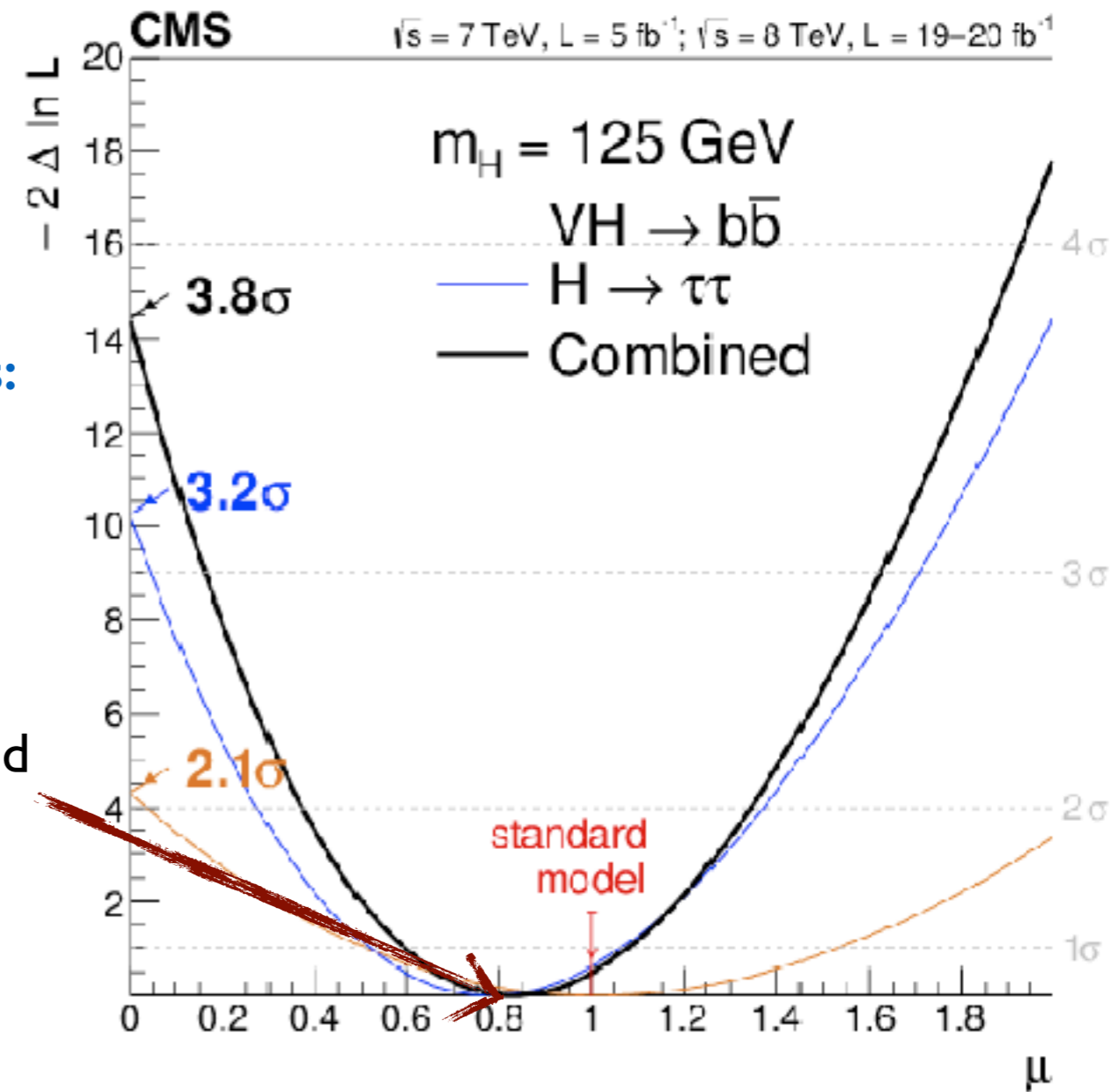
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- most probable value for μ maximises likelihood



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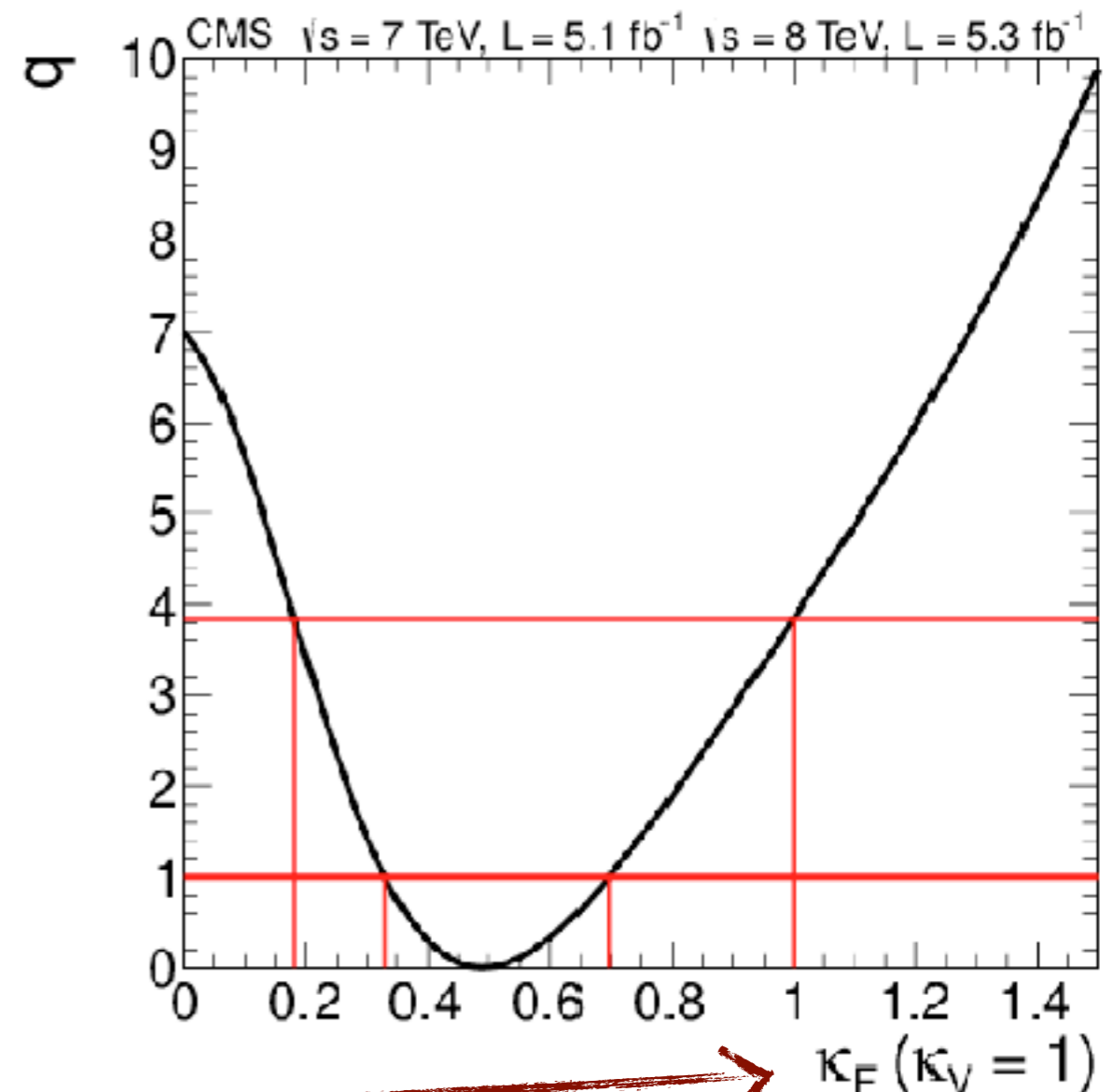
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- most probable value for μ maximises likelihood

- Easy to change parameters/theory framework**

- probabilities are invariant under change of variable

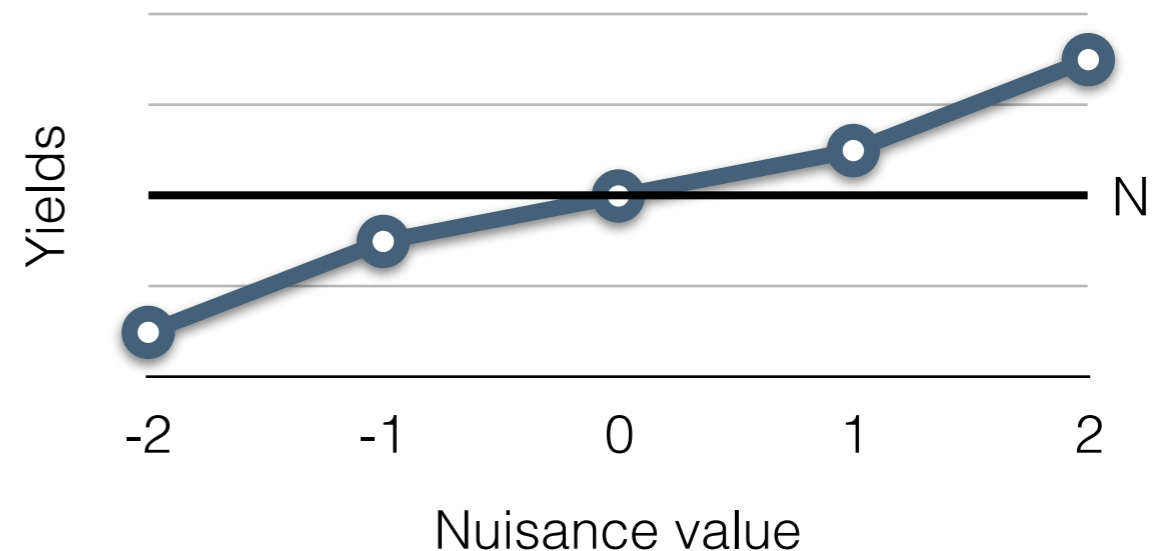
see statistics lecture by P. Vischia - [link](#)



$$\begin{aligned} \mu &\rightarrow \mu(\kappa_F, \kappa_V) \\ \lambda(\mu) &\rightarrow \lambda(\kappa_F, \kappa_V) \end{aligned}$$

- **Systematic uncertainties affect the baseline prediction**
 - can incorporate in the model as scaling factors
 - θ = nuisance parameters = random variables

$$n_{\text{signal}} = n_{\text{signal}}^0 \cdot (1 + \theta_{\text{pileup}}) \cdot \dots$$



- **Include probability distributions (PDFs) for θ in the likelihood**
 - nuisance parameters are allowed to float penalized by a PDF
 - PDFs are educated guesses most of the time

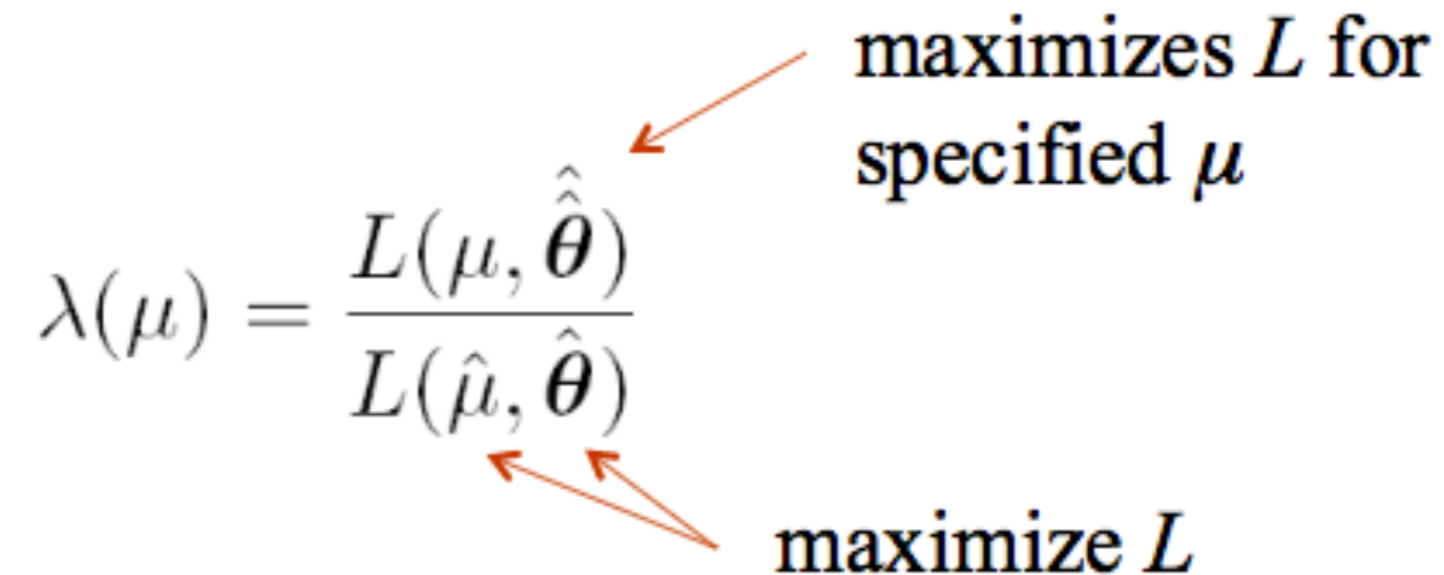
$$\mathcal{L}[\lambda(\mu, \vec{\theta})] = \mathcal{P}_{\text{oisson}}[n_{\text{obs}} | \lambda(\mu, \vec{\theta})] \cdot \prod_i \mathcal{P}_{\text{DF}}(\theta_i)$$

- Profile likelihood ratio test statistics:

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}})}{L(\hat{\mu}, \hat{\theta})}$$

maximizes L for specified μ

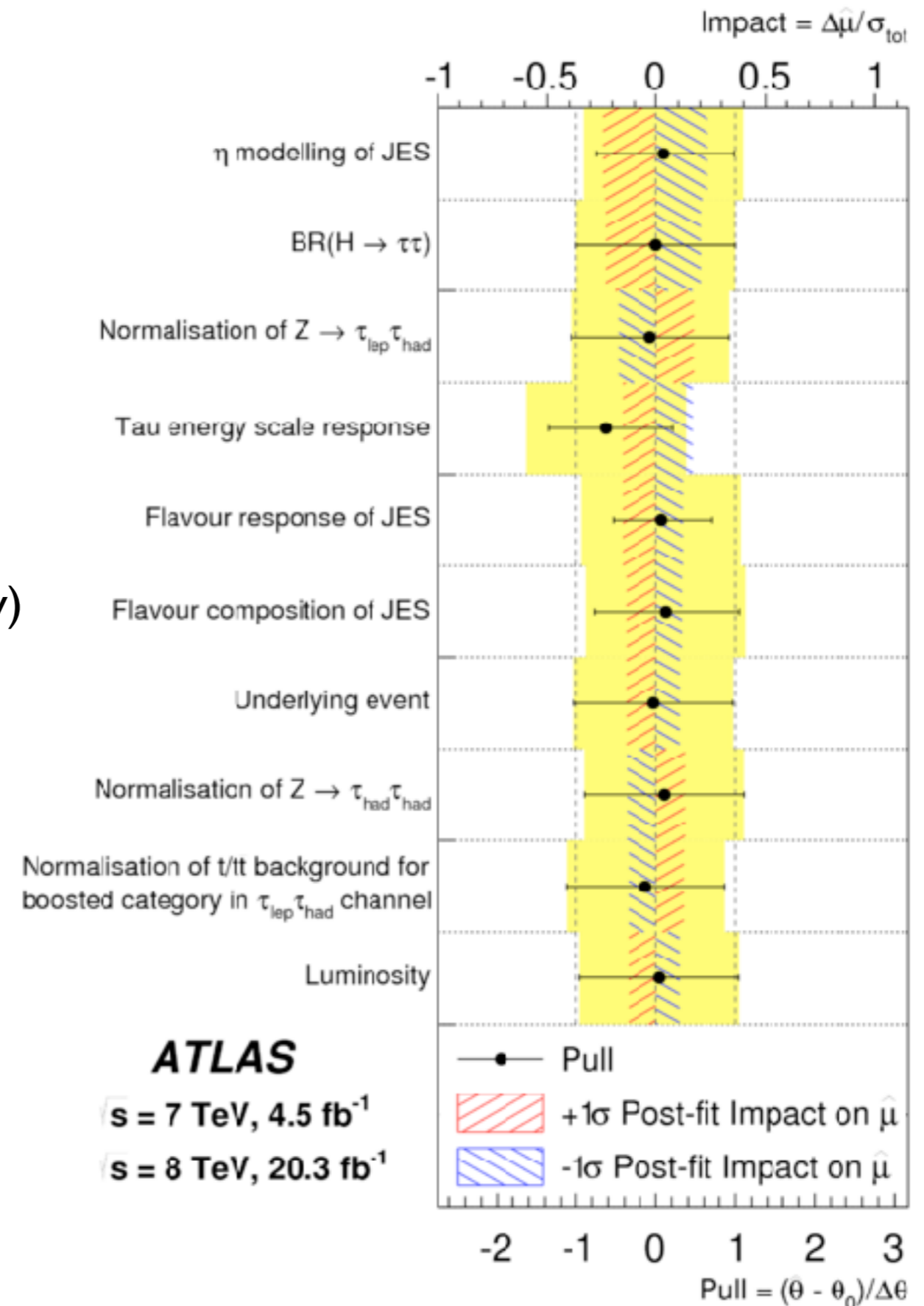
maximize L

The diagram shows the profile likelihood ratio test statistic formula. The numerator is $L(\mu, \hat{\hat{\theta}})$ and the denominator is $L(\hat{\mu}, \hat{\theta})$. An arrow points from the text "maximizes L for specified mu" to the $\hat{\hat{\theta}}$ term in the numerator. Two arrows point from the text "maximize L" to the $\hat{\mu}$ and $\hat{\theta}$ terms in the denominator.

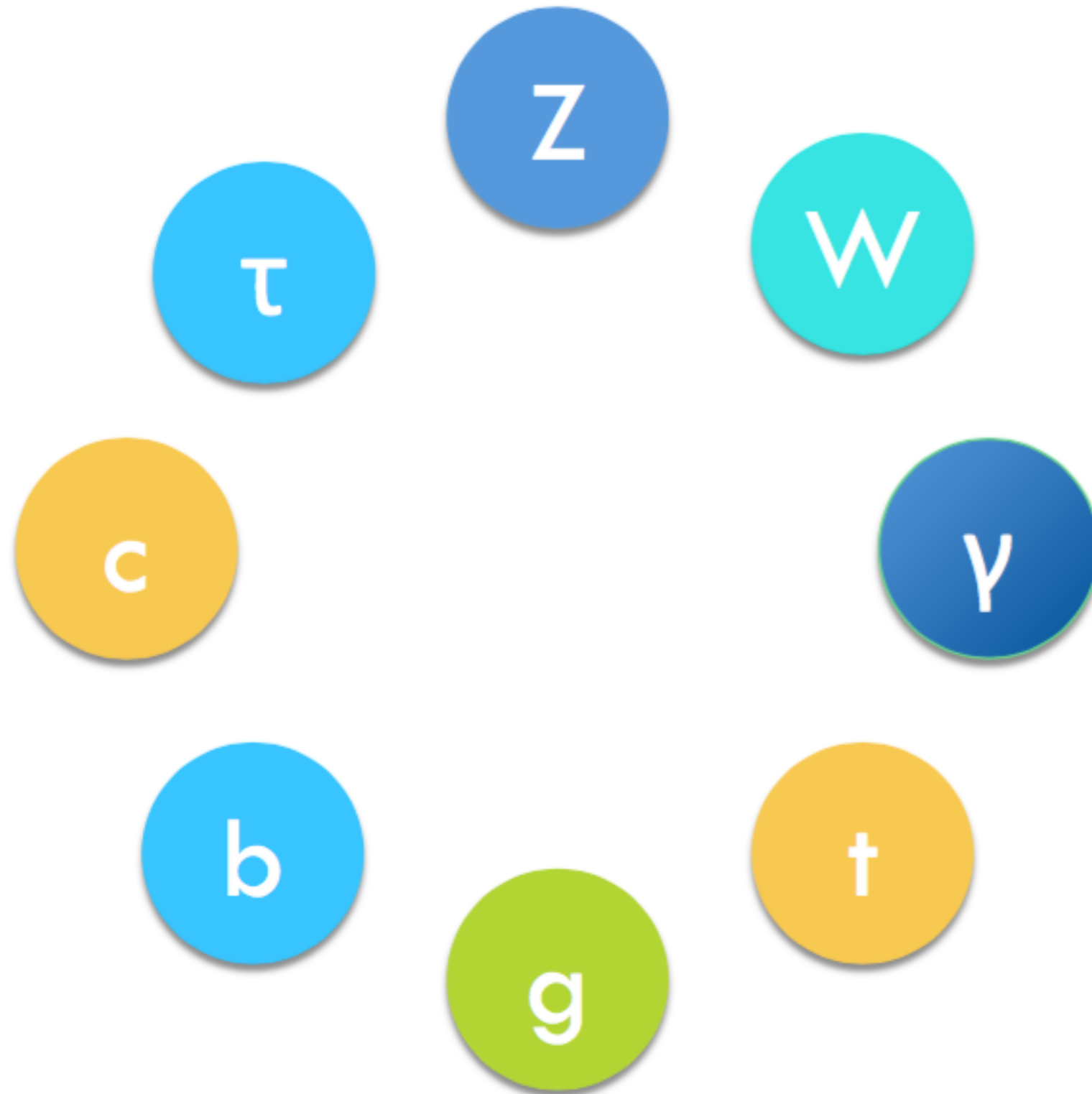
- for each likelihood evaluation all systematic uncertainties (nuisances) are varied
 - normalise to the likelihood at best fit value
 - maximum determines best set of parameters (nuisances are profiled)
- **Combined fit for Higgs properties at the LHC**
 - >200 channels and >4000 nuisances in the fit

Incorporating uncertainties in the fit III

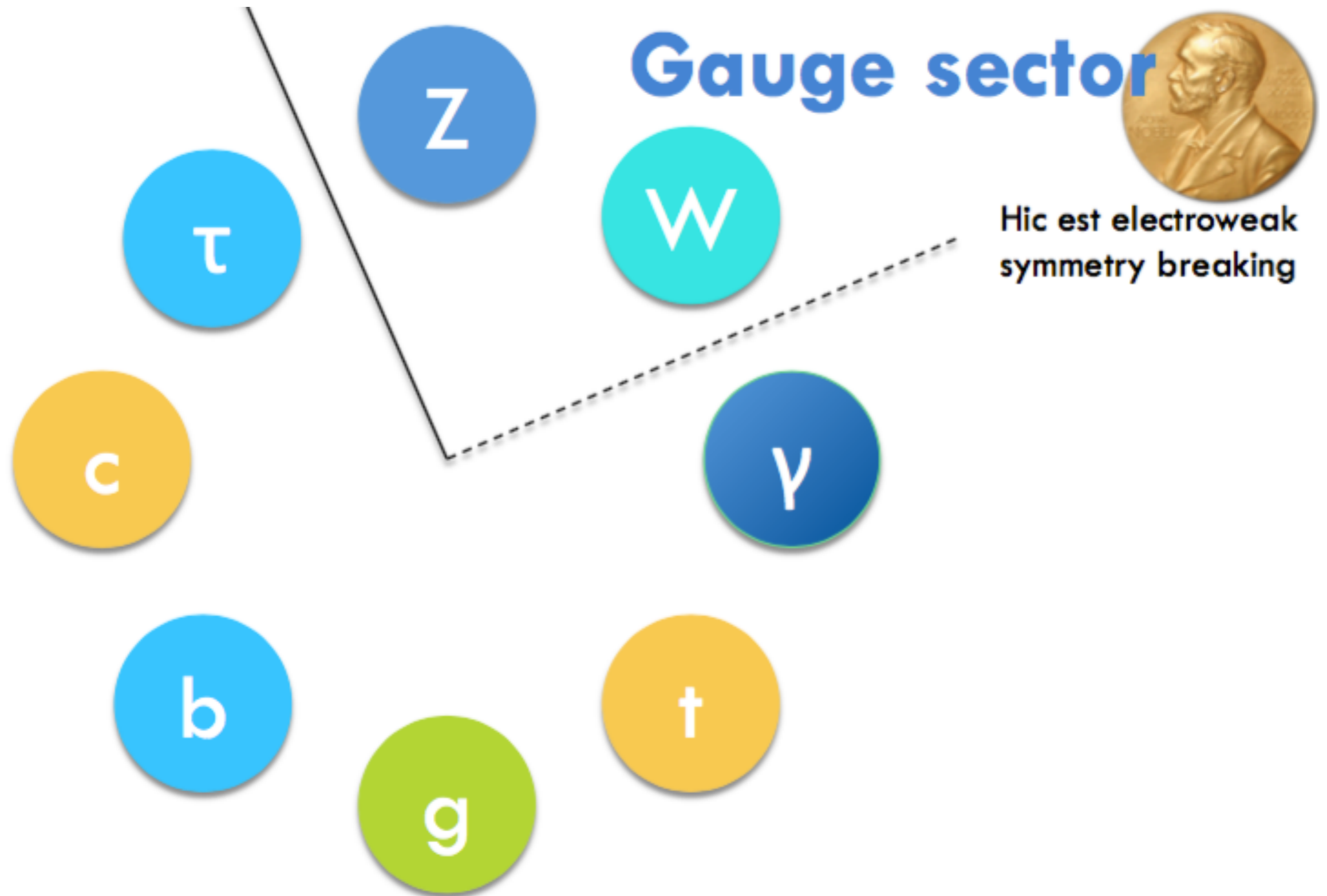
- Here is an example from a $H \rightarrow \tau\tau$ search
- If the fit uses several categories
 - nuisances are fit
 - can be constrained (smaller uncertainty)
- Impact on the measurement
 - fix all values to postfit results
 - shift by $\pm 1\sigma$ and check variation in μ



The model: scalar coupling structure

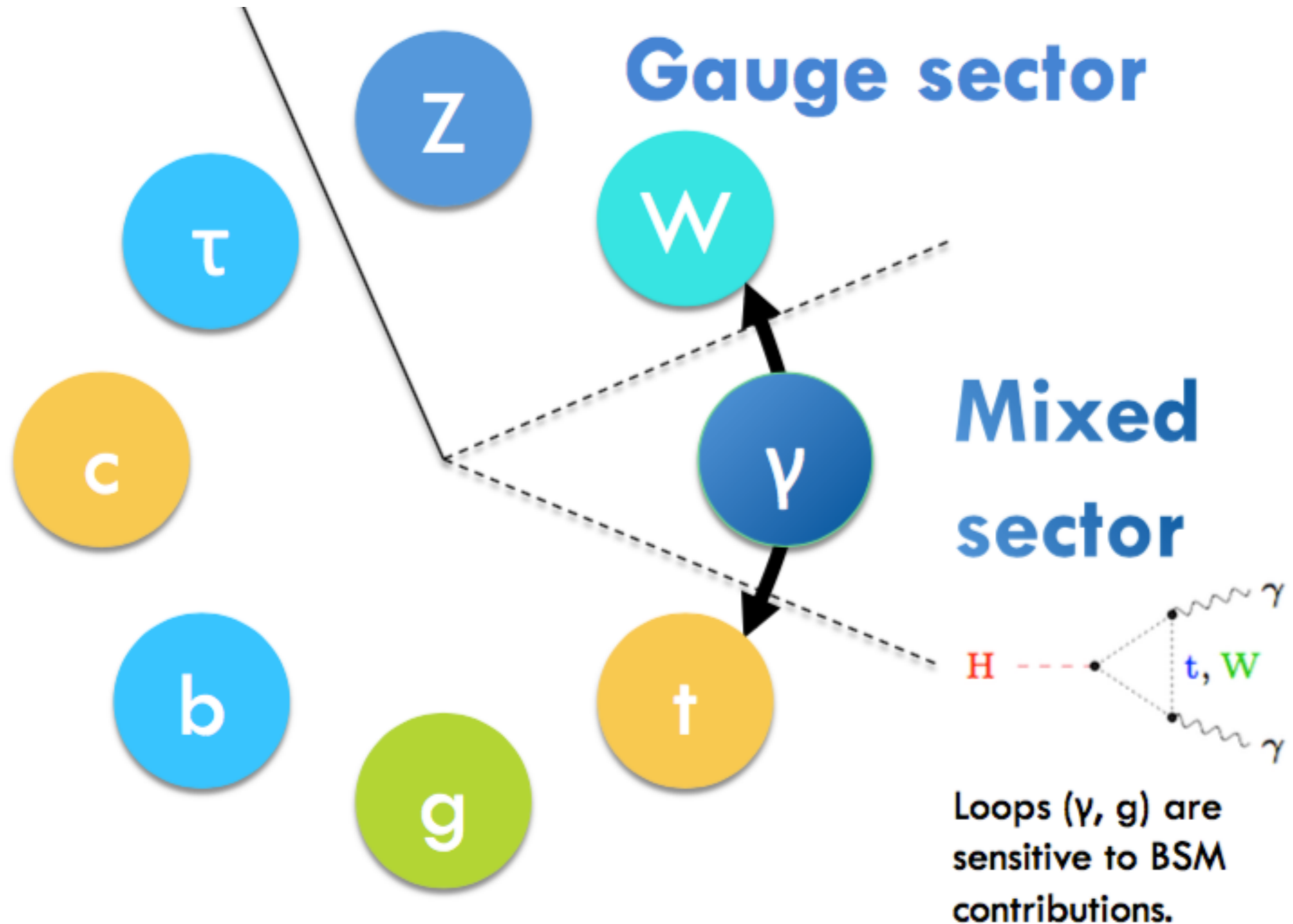


The model: scalar coupling structure



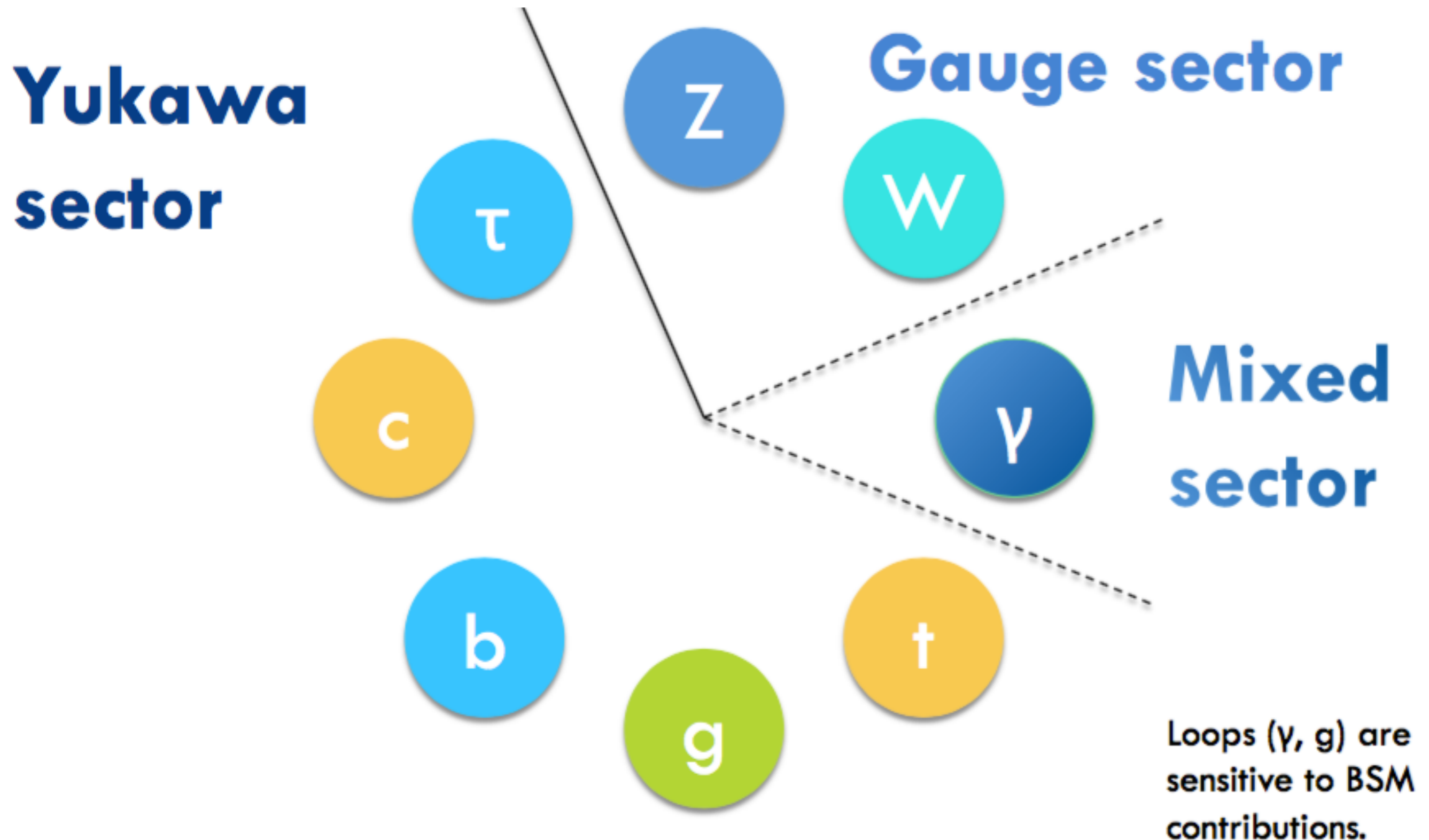
The model: scalar coupling structure

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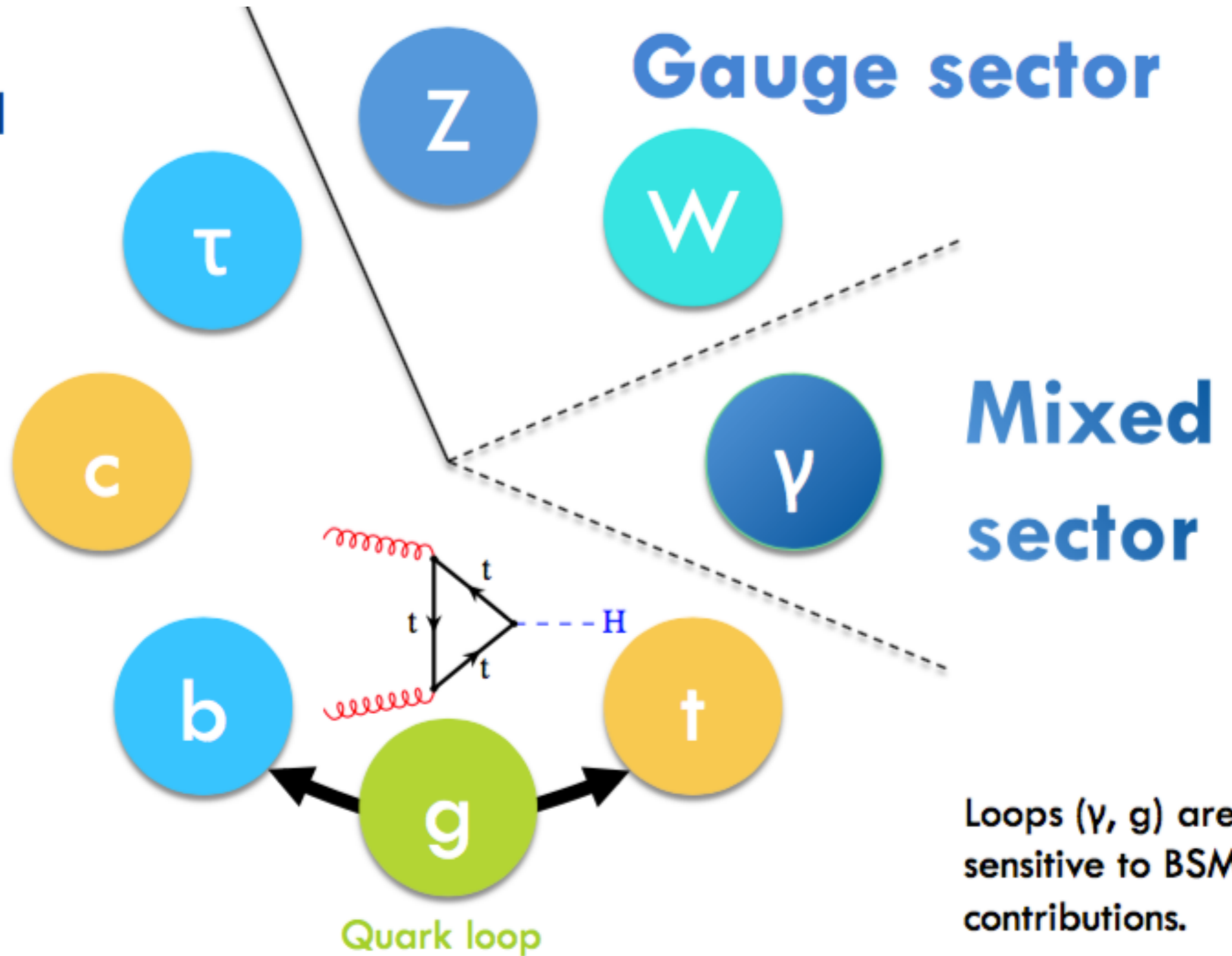
The model: scalar coupling structure

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The model: scalar coupling structure

Yukawa sector



Loops (γ , g) are sensitive to BSM contributions.

The model: scalar coupling structure

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Yukawa sector

Up type



Down type



Gauge sector

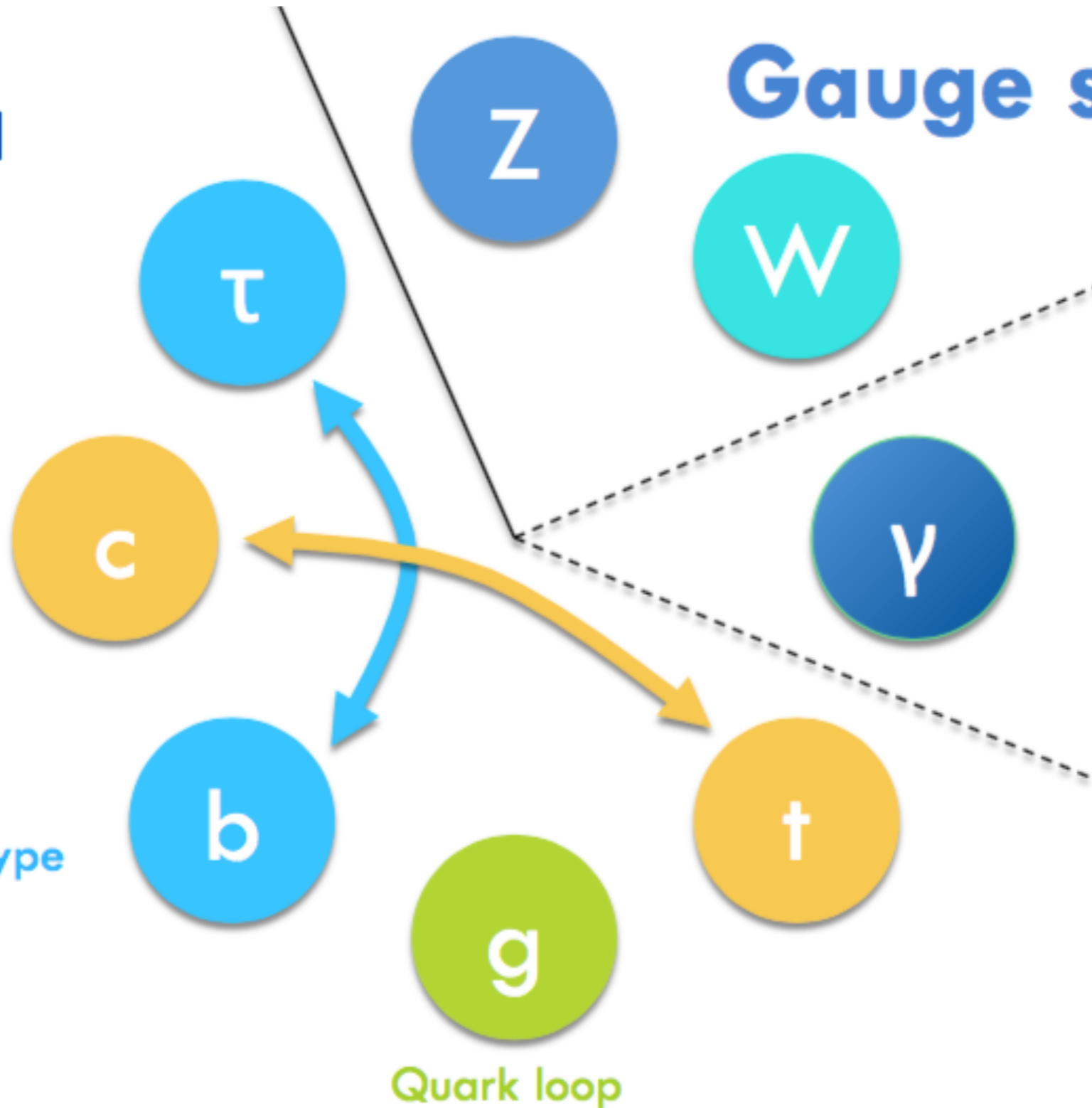


Mixed sector



Quark loop

Loops (γ , g) are sensitive to BSM contributions.



- Use a strength modified (kappa) of the cross section or the branching ratio

$$\kappa_j^2 = \sigma_j / \sigma_j^{\text{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma_{\text{SM}}^j$$

- When affecting the branching ratios, the width is naturally modified by

$$\kappa_H^2 = \sum_j \text{BR}_{\text{SM}}^j \kappa_j^2$$

- If the Higgs is also allowed to decay to new invisible particles (dark matter?) then the total width is

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{\text{SM}}}{1 - \text{BR}_{\text{BSM}}}$$

Deviations in production

- associated productions (VH, ttH) involve direct couplings \Rightarrow single parameter
- loops, internal propagators (ggH, VBF) parameterised as function of particles involved

Production	Loops	Interference	Multiplicative factor
$\sigma(\text{ggF})$	✓	$b - t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(\text{WH})$	–	–	$\sim \kappa_W^2$
$\sigma(q\bar{q} \rightarrow \text{ZH})$	–	–	$\sim \kappa_Z^2$
$\sigma(\text{gg} \rightarrow \text{ZH})$	✓	$Z - t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(\text{bbH})$	–	–	$\sim \kappa_b^2$
$\sigma(\text{ttH})$	–	–	$\sim \kappa_t^2$
$\sigma(\text{gb} \rightarrow \text{WtH})$	–	$W - t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(\text{qb} \rightarrow \text{tHq}')$	–	$W - t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$

see details in [arXiv:1307.1347](https://arxiv.org/abs/1307.1347)

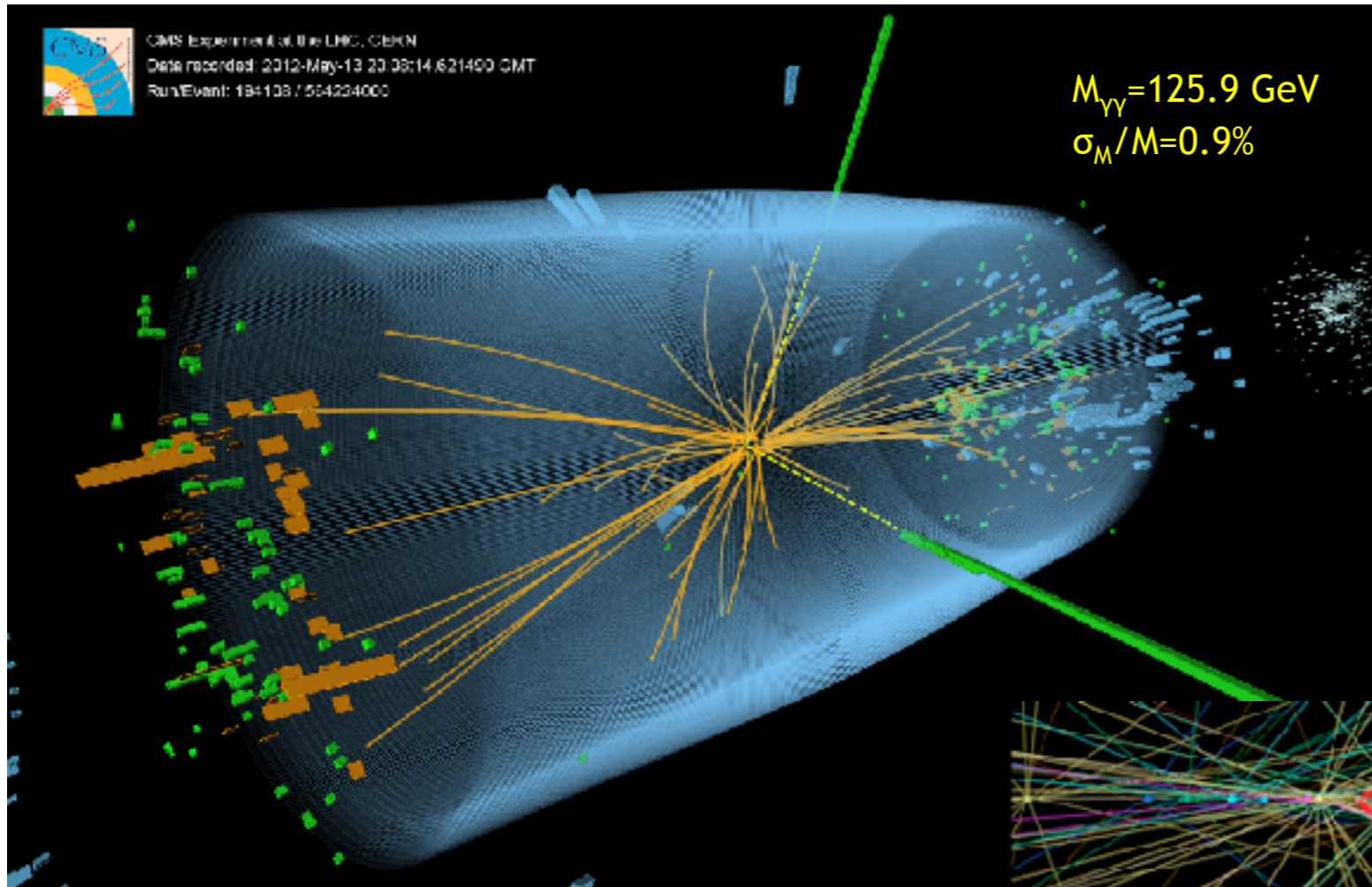
Deviations in decays

- Direct decays (WW, ZZ, etc.) are assigned with a single parameter
- Decays via loops ($\gamma\gamma$, Z γ) depend on the particles running in the loop

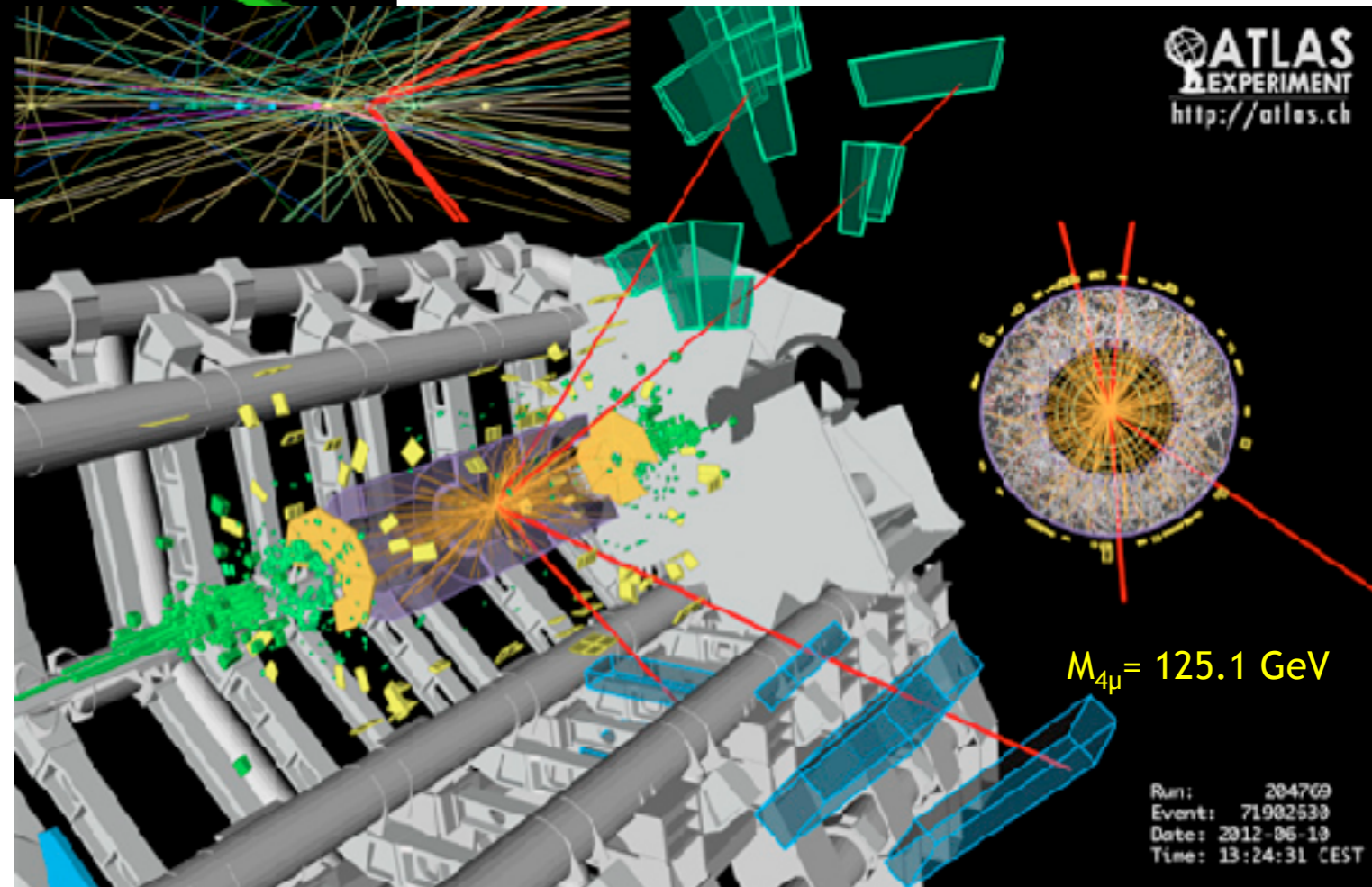
Partial decay width				
$\Gamma_{b\bar{b}}$	–	–	\sim	κ_b^2
Γ_{WW}	–	–	\sim	κ_W^2
Γ_{ZZ}	–	–	\sim	κ_Z^2
$\Gamma_{\tau\tau}$	–	–	\sim	κ_τ^2
$\Gamma_{\mu\mu}$	–	–	\sim	κ_μ^2
$\Gamma_{\gamma\gamma}$	✓	W – t	$\kappa_\gamma^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
Total width for $\text{BR}_{\text{BSM}} = 0$				
Γ_H	✓	–	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

see details in [arXiv:1307.1347](https://arxiv.org/abs/1307.1347)

Results: mass, charge, spin and parity, couplings

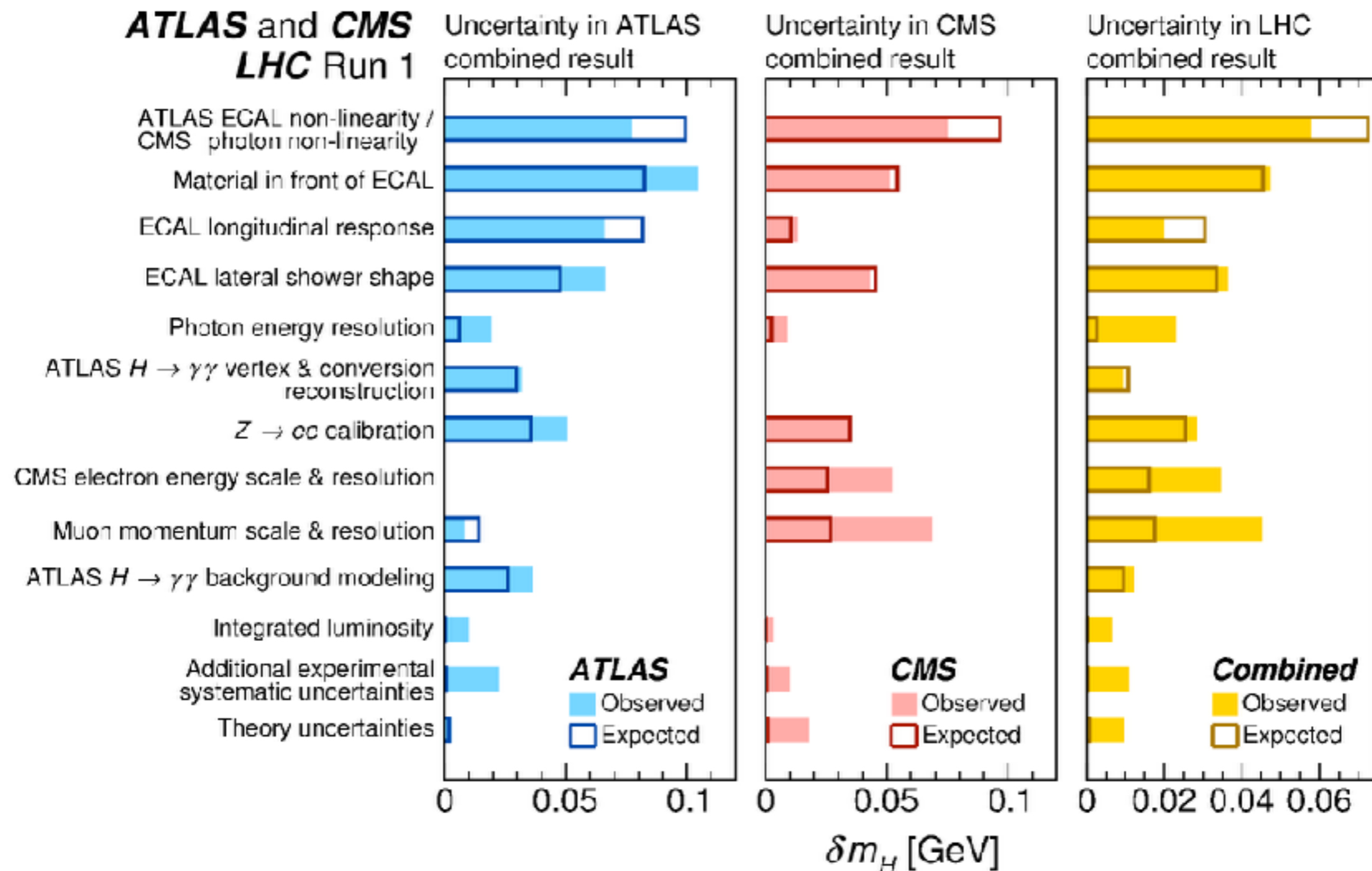


- The two channels with highest resolution are used to measure the mass: $\gamma\gamma$ and $4l$
- Energy scale and resolution are the most important systematic effects to understand

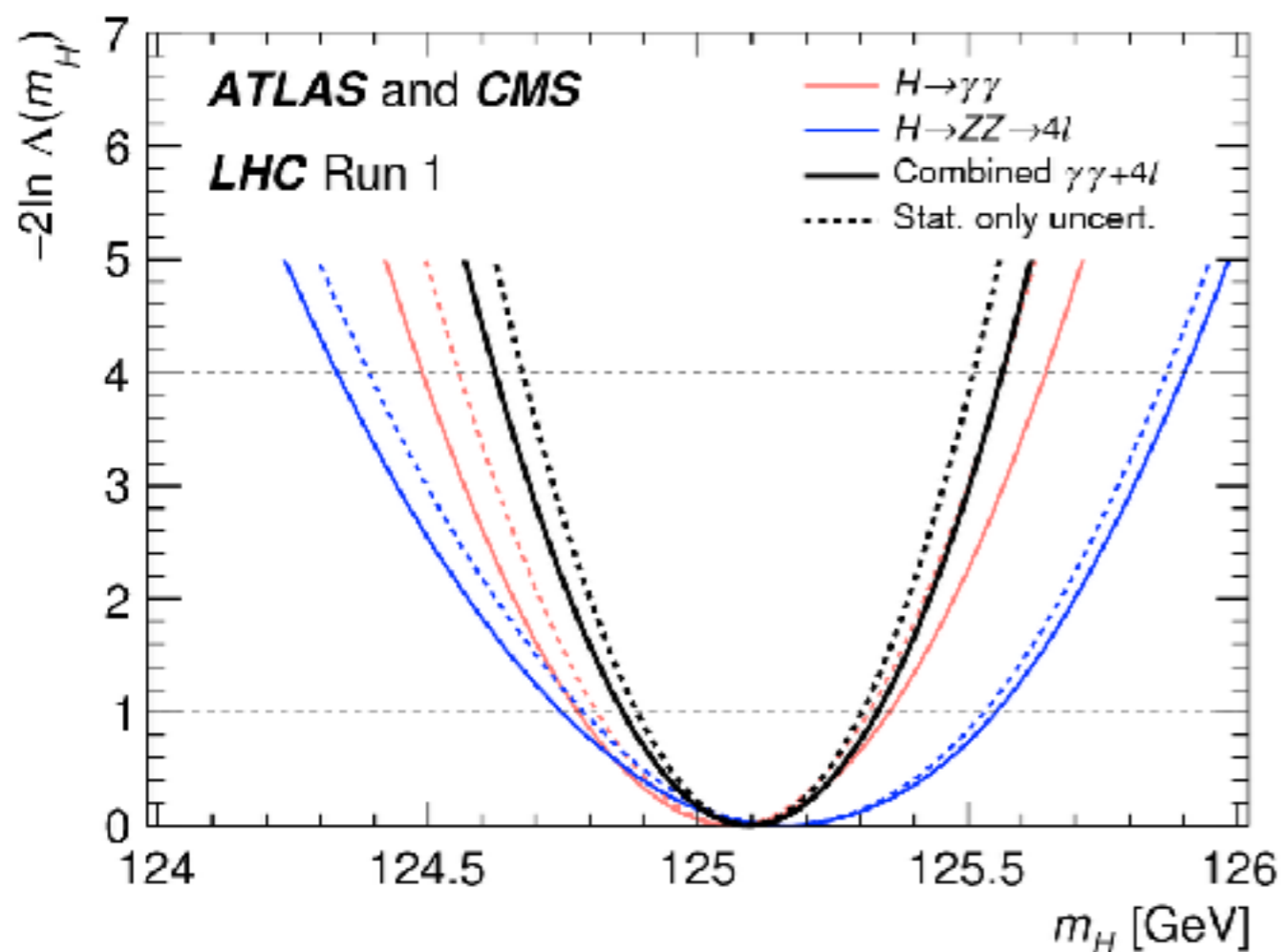


Impact of the systematic effects on the mass

- Gain from combining experiments: statistics and partially uncorrelated systematics
- Largest impact from energy scales, as expected

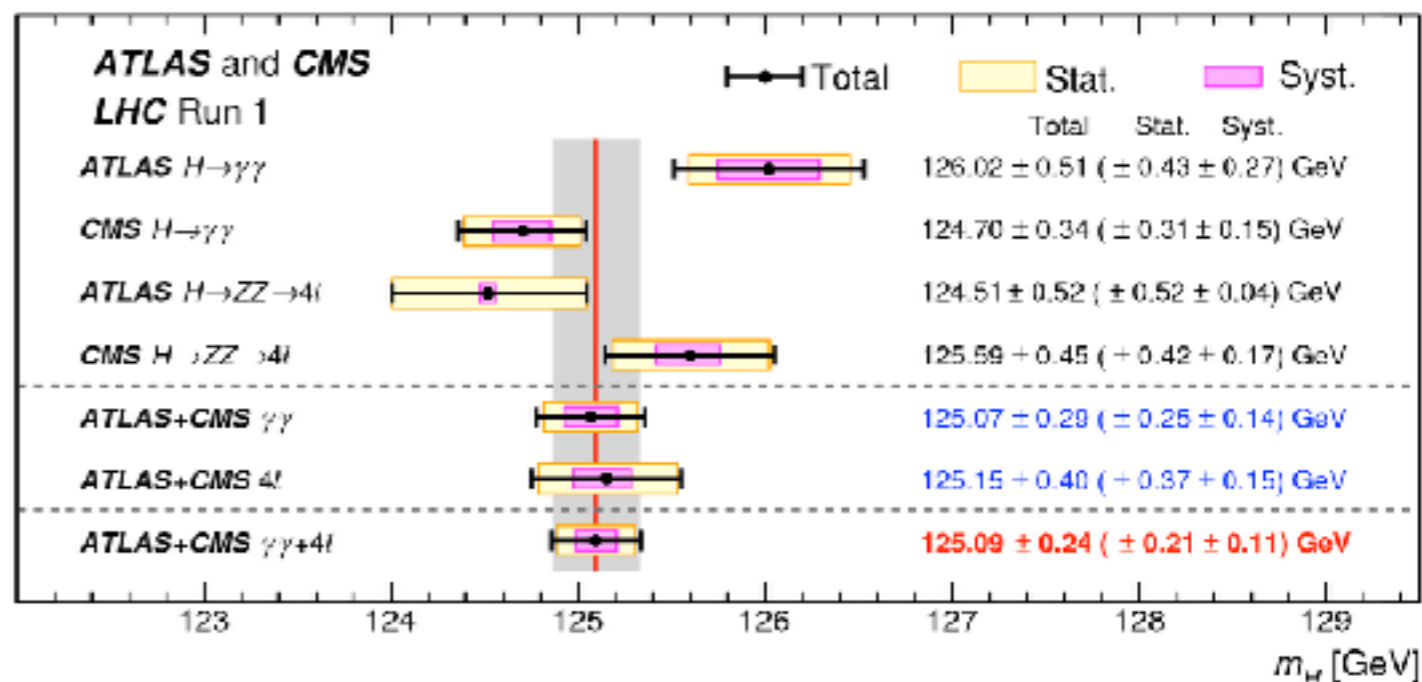


Combined LHC mass measurement

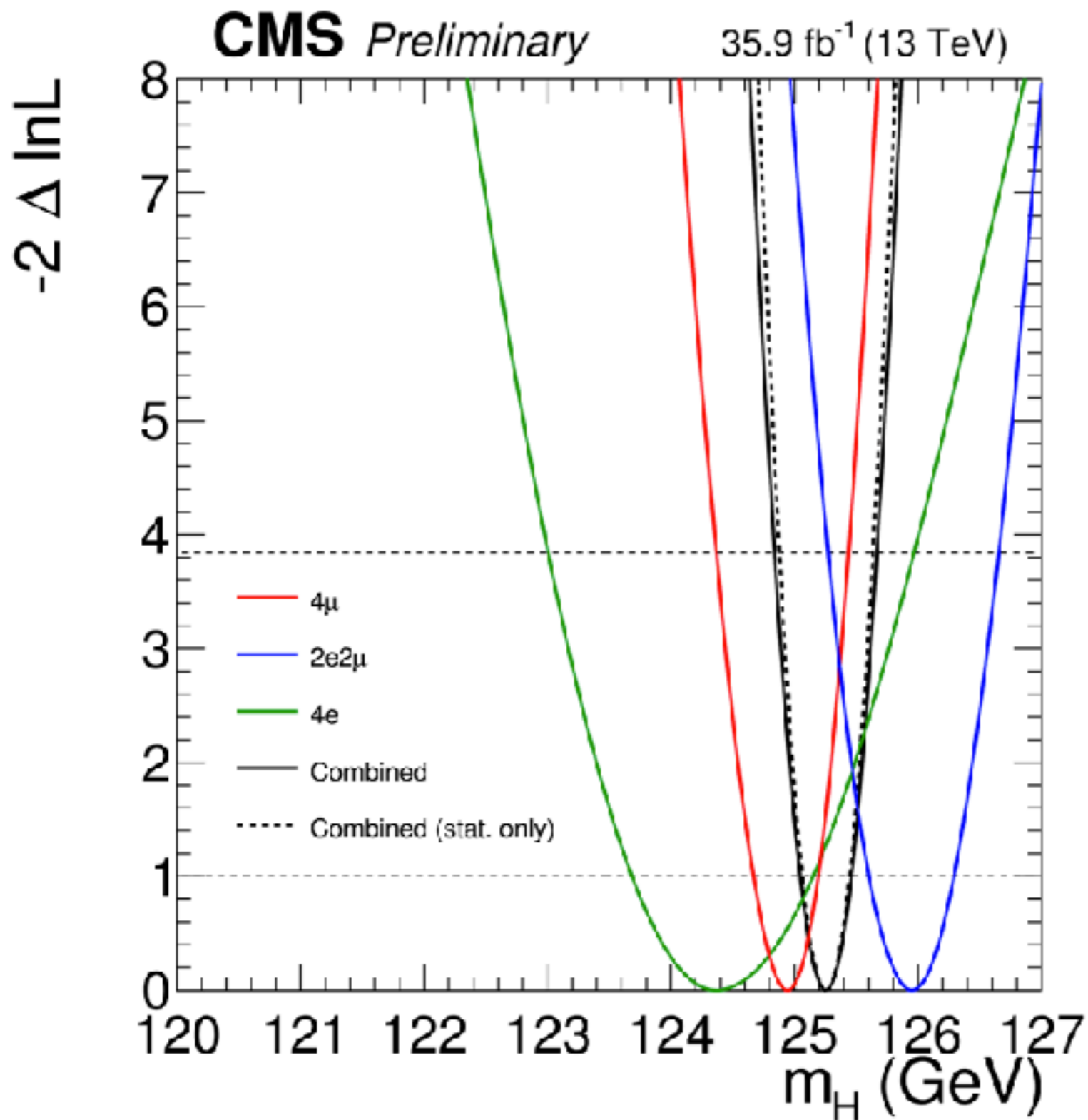


$$M_H = 125.09 \pm 0.21 \text{ (stat.)} \\ \pm 0.11 \text{ (syst.) GeV}$$

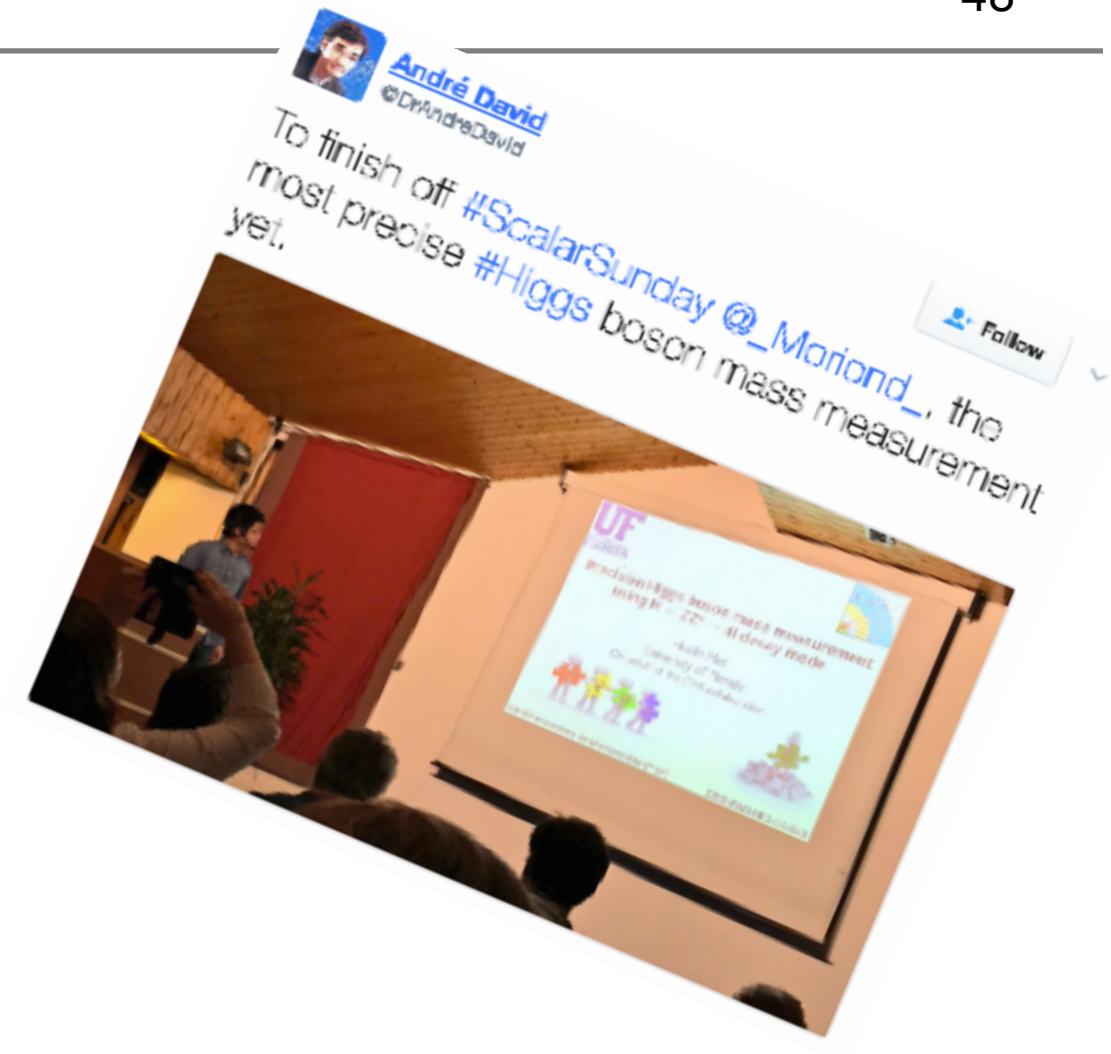
- Tensions between channels have different signs in the different experiments
- Differences are compatible with statistical fluctuations
- Final result is still statistically limited



Latest news on mass measurement



see details in [HIG-16-041](#)



- High precision measurement using 4 leptons in the final state ($H \rightarrow ZZ$)
 - statistically limited at this point

$$M_H = 125.26 \pm 0.21 \text{ (total) GeV}$$

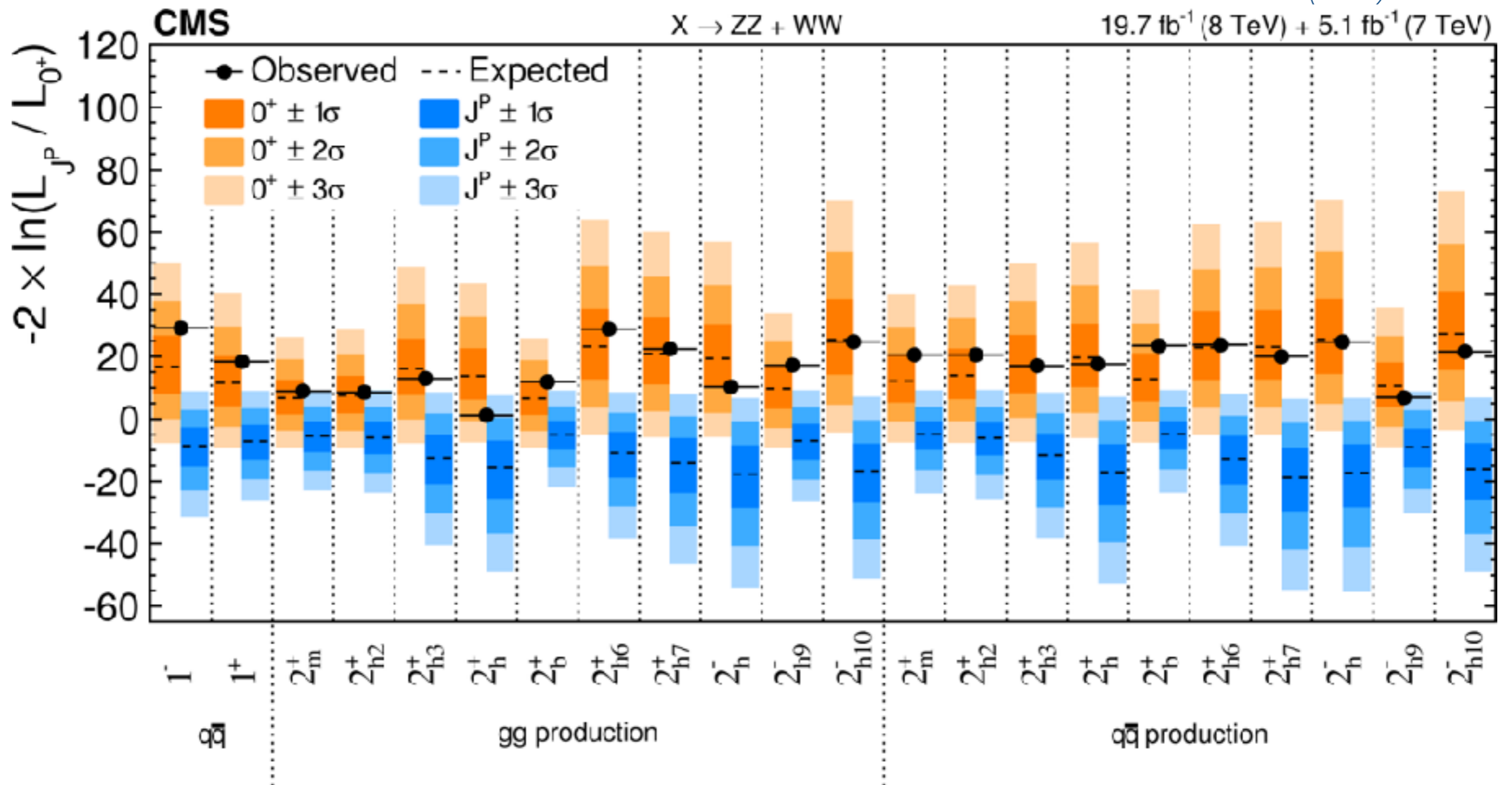
0

this one is easy

J^P (spin, parity)

- No direct measurement of J^P
- Use dedicated distributions to test different hypothesis
- No other hypothesis than the standard model is favoured $\Rightarrow J^P=0^+$

PRD 92 (2015) 012004



Signal strength per production/decay tags

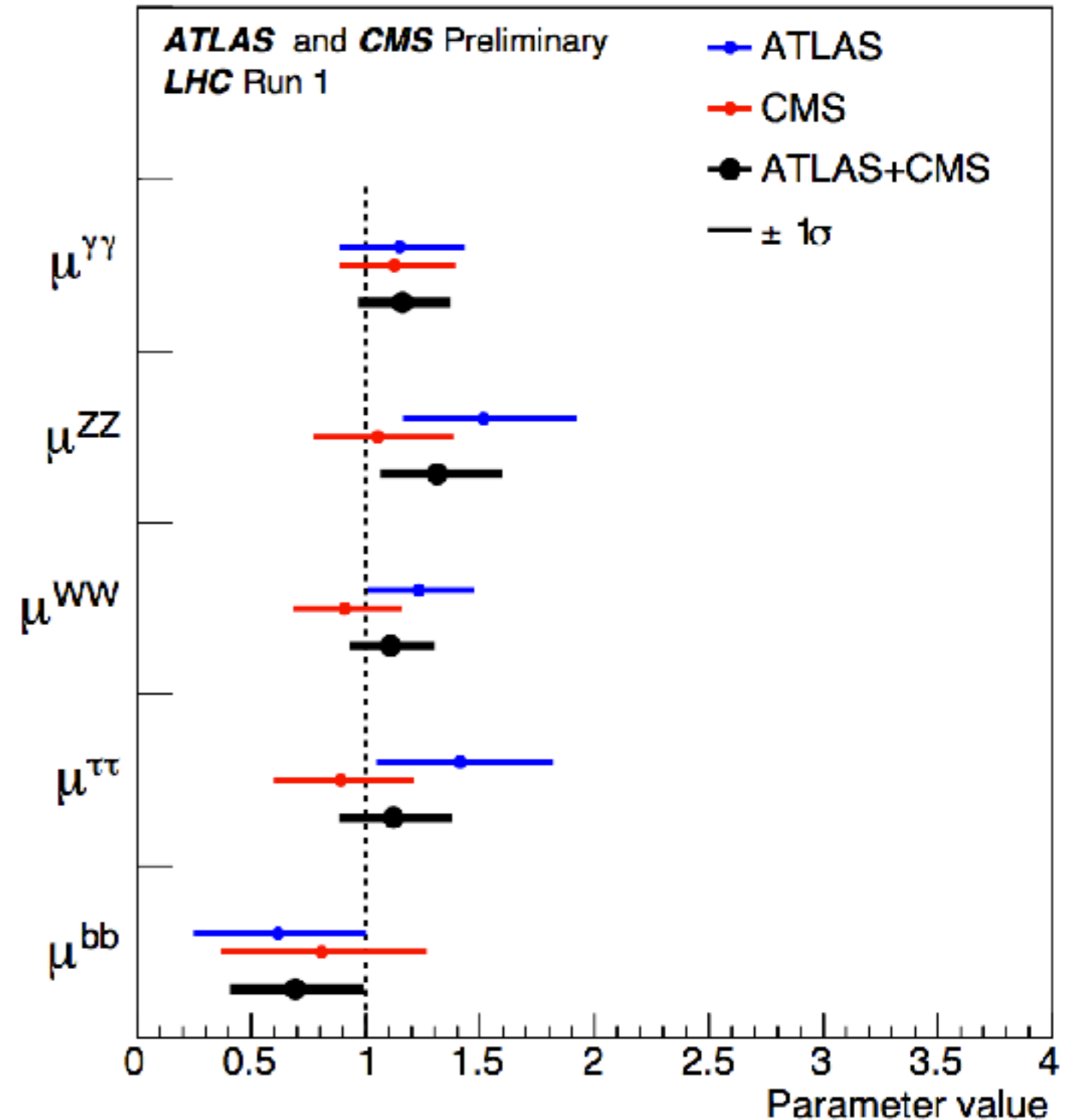
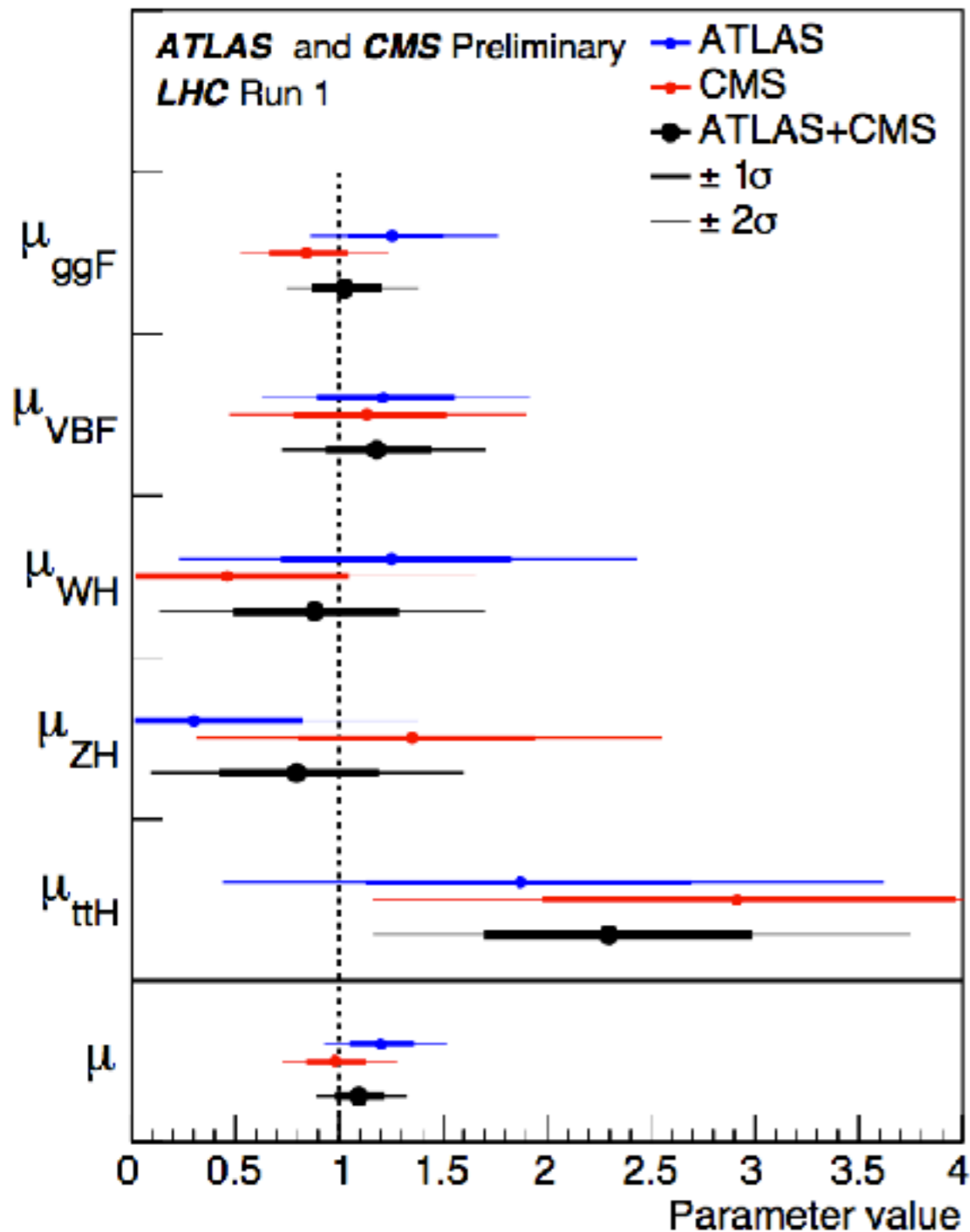
51

- **Signal strengths in different channels are consistent with 1 (SM)**

- largest difference $< 3\sigma$ from ttH analyses

ATLAS-CONF-2015-044

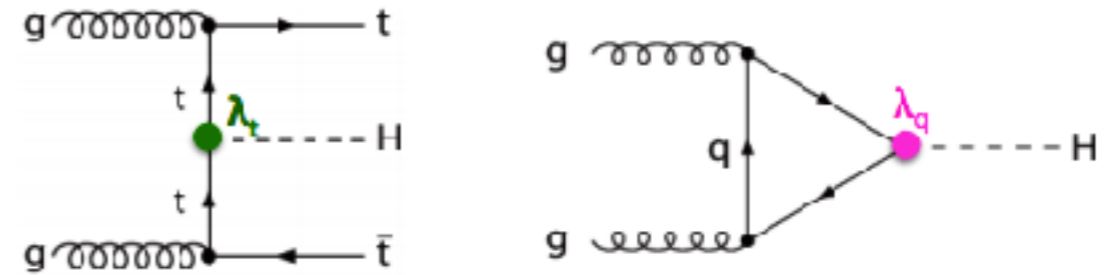
CMS-PAS-HIG-15-002



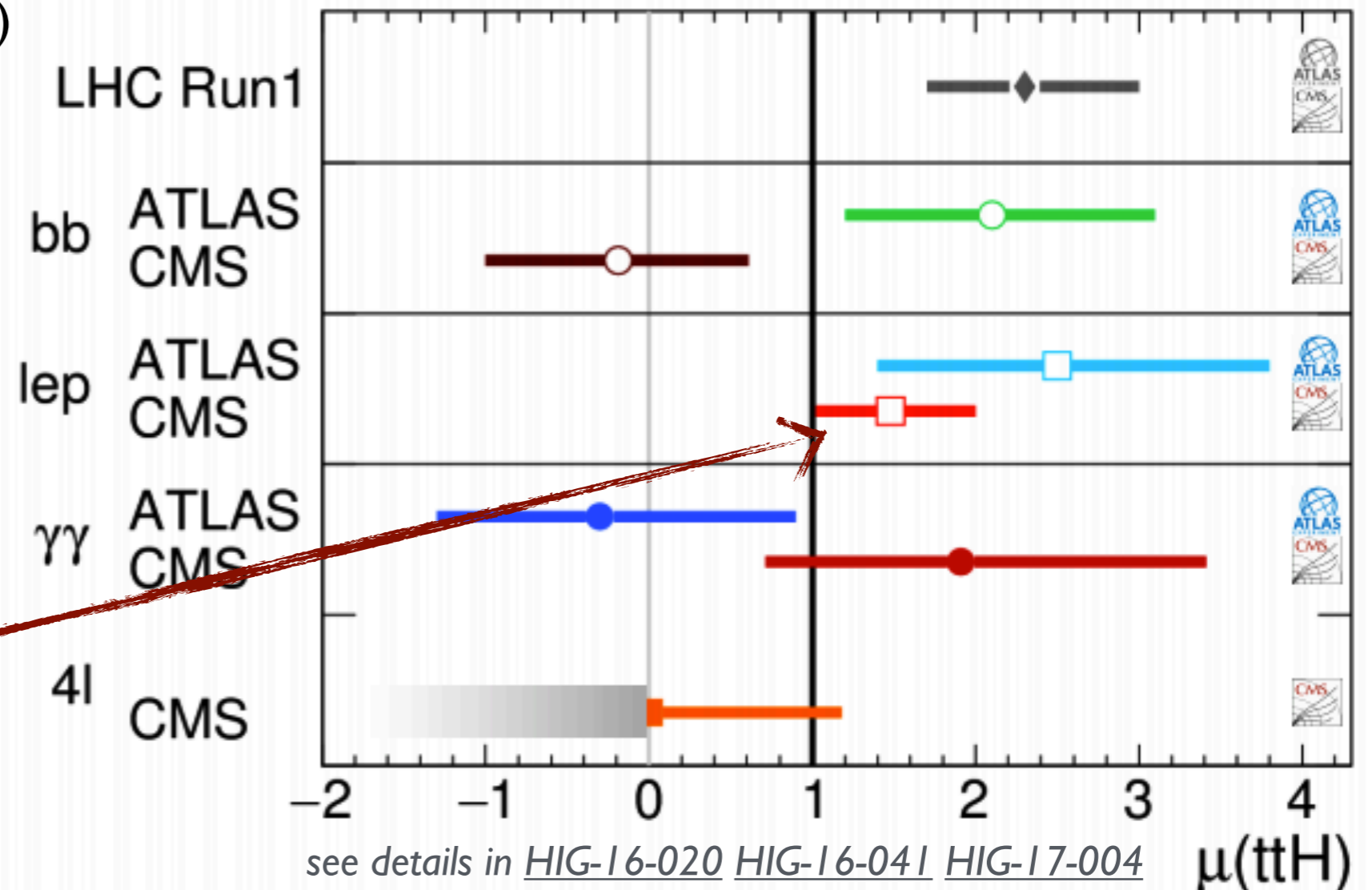
Latest news on the top Yukawa coupling

- Despite being the largest of the couplings it is challenging to measure λ_t directly
- Combine several analysis benefiting either from:

- large yields ($H \rightarrow bb/\tau\tau$)
- medium rate/purity ($H \rightarrow WW$)
- high purity ($H \rightarrow ZZ, \gamma\gamma$)



Significance
observed 3.3σ
expected 2.5σ



Testing production modes per final state

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ATLAS-CONF-2015-044

CMS-PAS-HIG-15-002

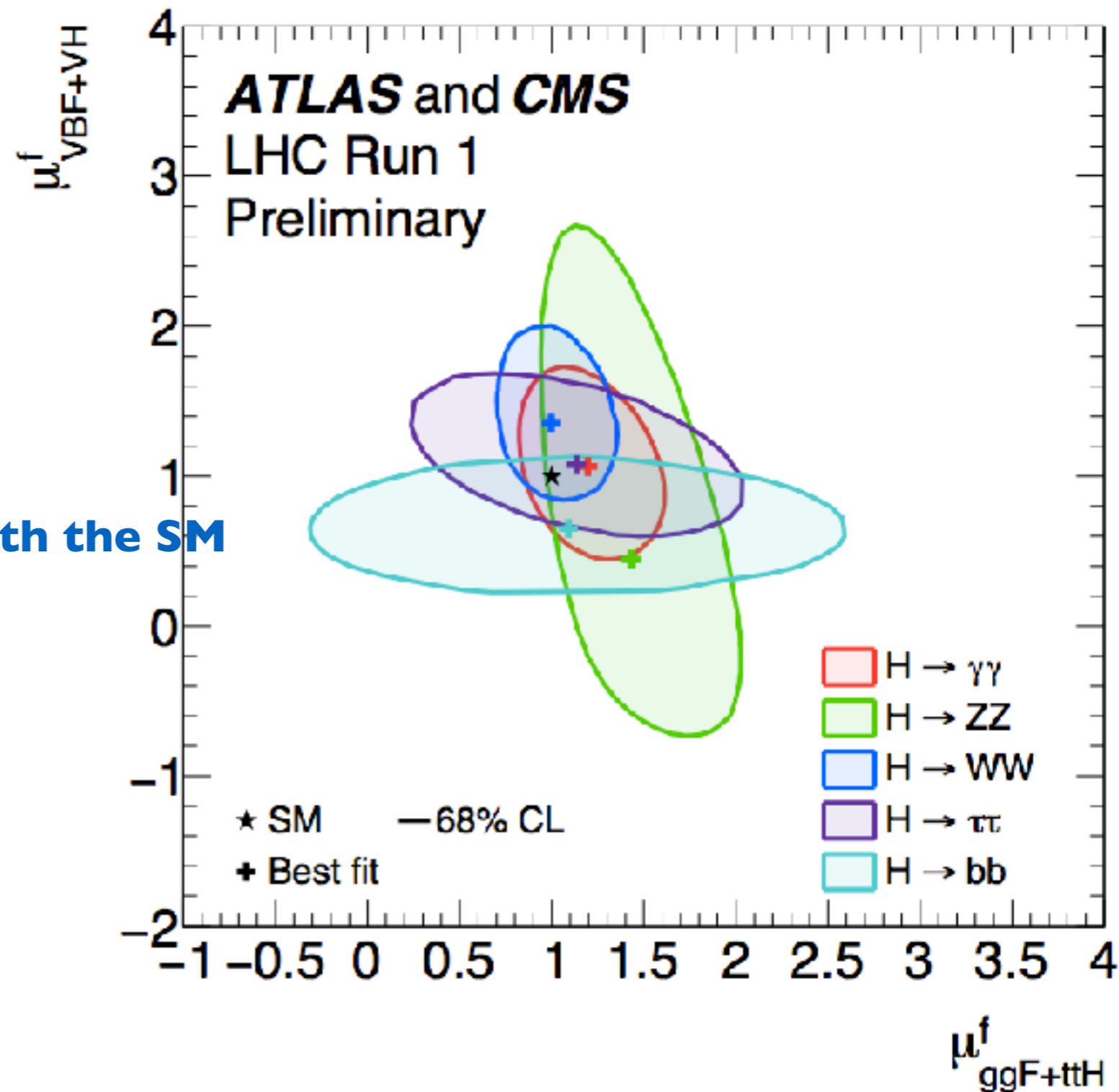
- Test strength of the production modes

- separately for each final state
- VBF+VH = bosons in production
- ggF+ttH = fermions in production

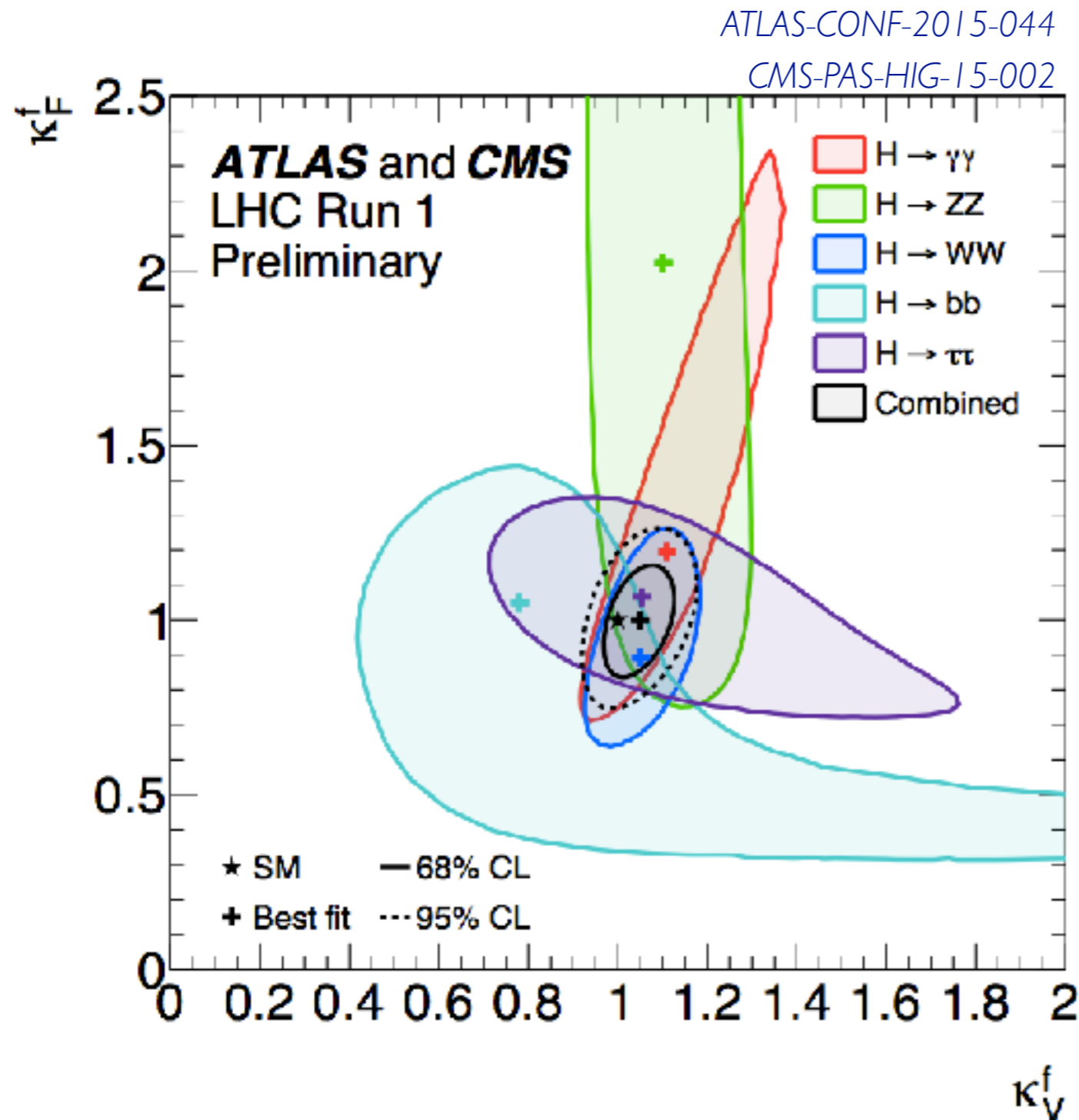
- **All results in are compatible with the SM**

- **H → bb and H → ZZ**

- provide the smaller correlations
- dominated by VH and ggF productions



Couplings to fermions and bosons I



- Use kappa modifiers to parameterise both production and decay modes
- Simplify to test separately couplings to fermions and to vector bosons
- All results in agreement with each other
 - incoherent results for negative k scenario
- **Combination of all channels fully compatible with the SM hypothesis**

Couplings to fermions and bosons II

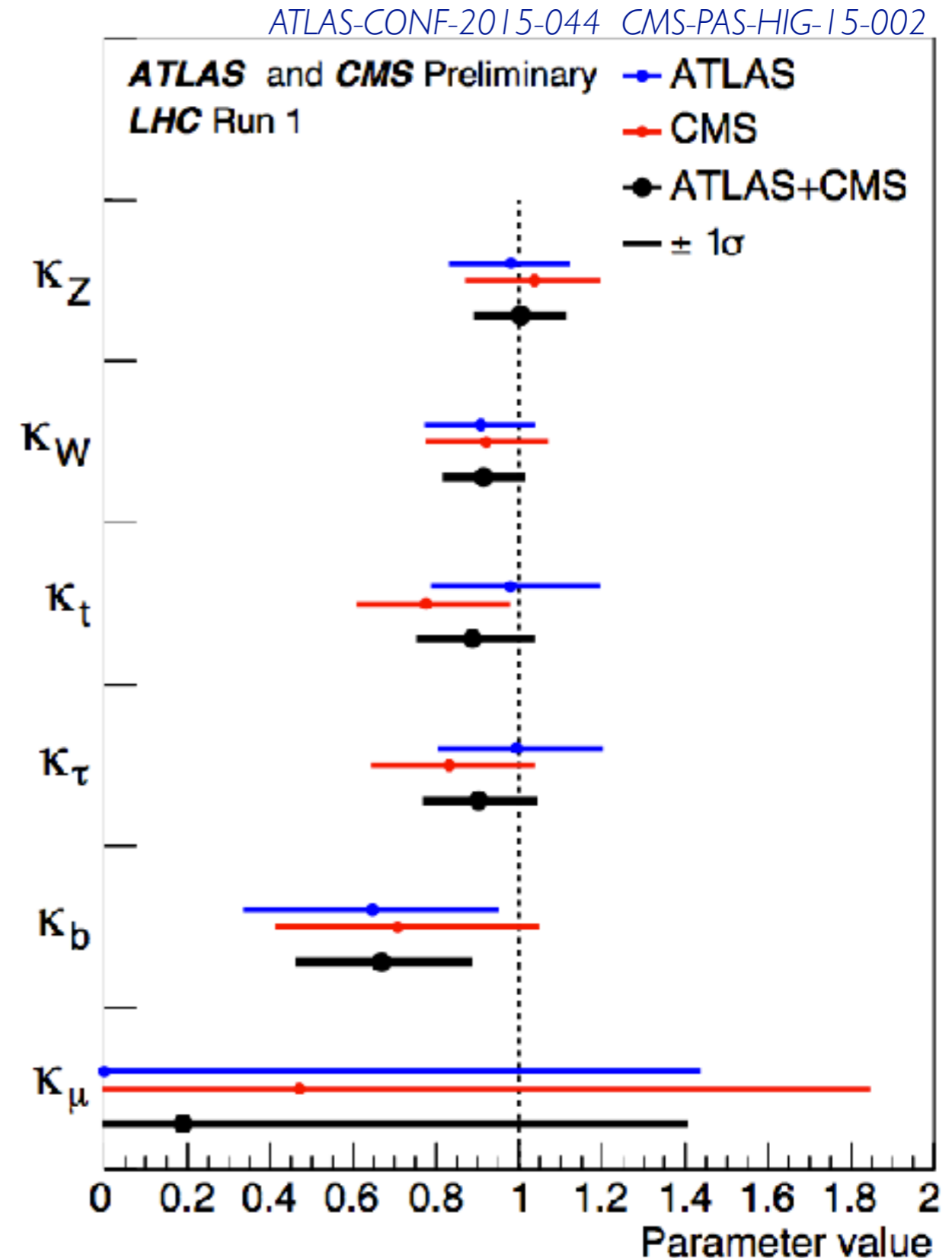
- Using separate k for the most massive particles

- All in agreement with the SM**

- slightly lower coupling for b ($<2\sigma$ deviation)
- not yet sensitive to muons

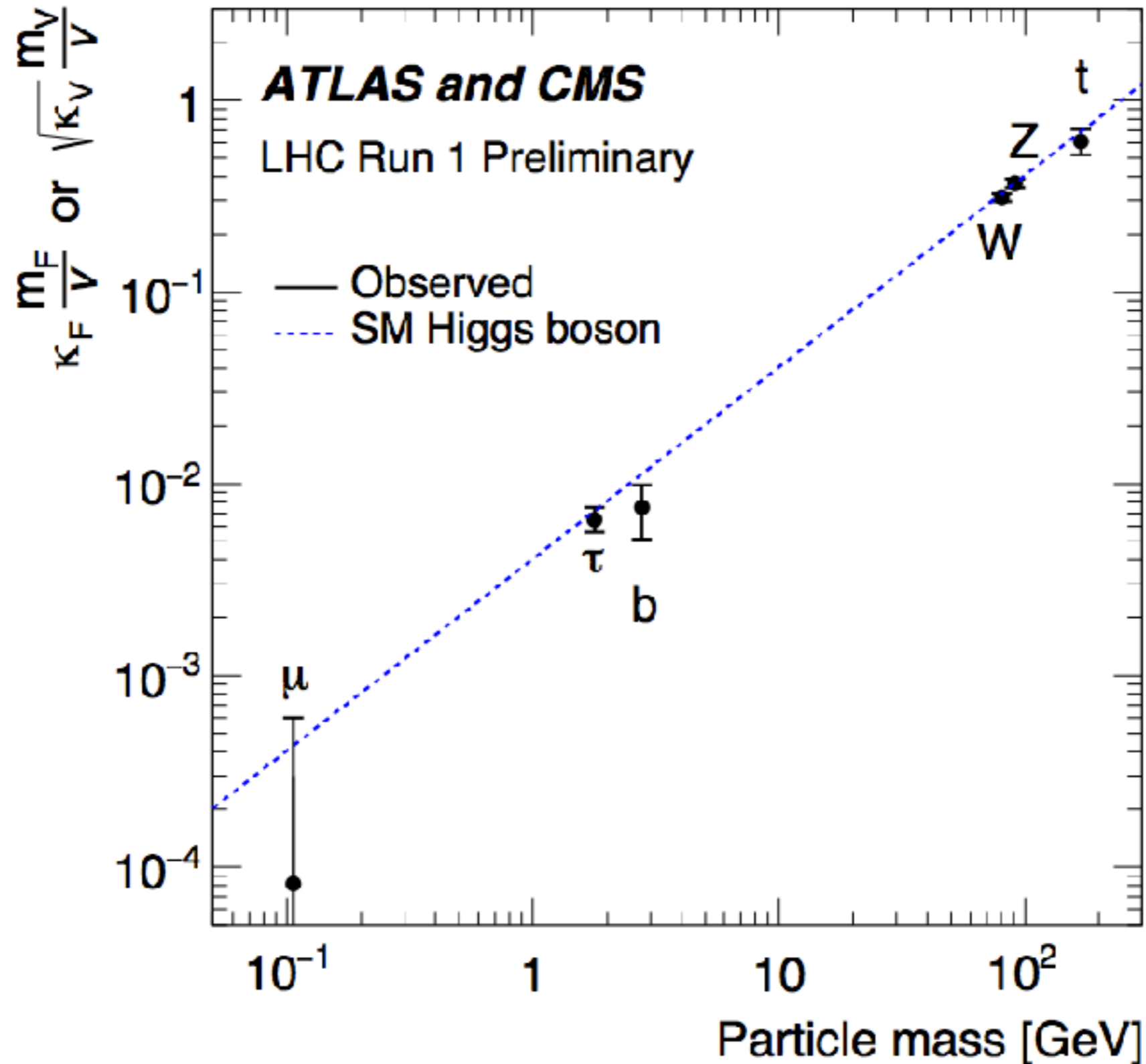
- Notice that

- for gauge bosons $K_V = v_{\text{ev}} \times m_V^{2\varepsilon} / M^{1+2\varepsilon}$
- for fermions $K_f = v_{\text{ev}} \times m_f^\varepsilon / M^{1+\varepsilon}$
- in the SM $\varepsilon=0$ and $v_{\text{ev}}=M=246$ GeV

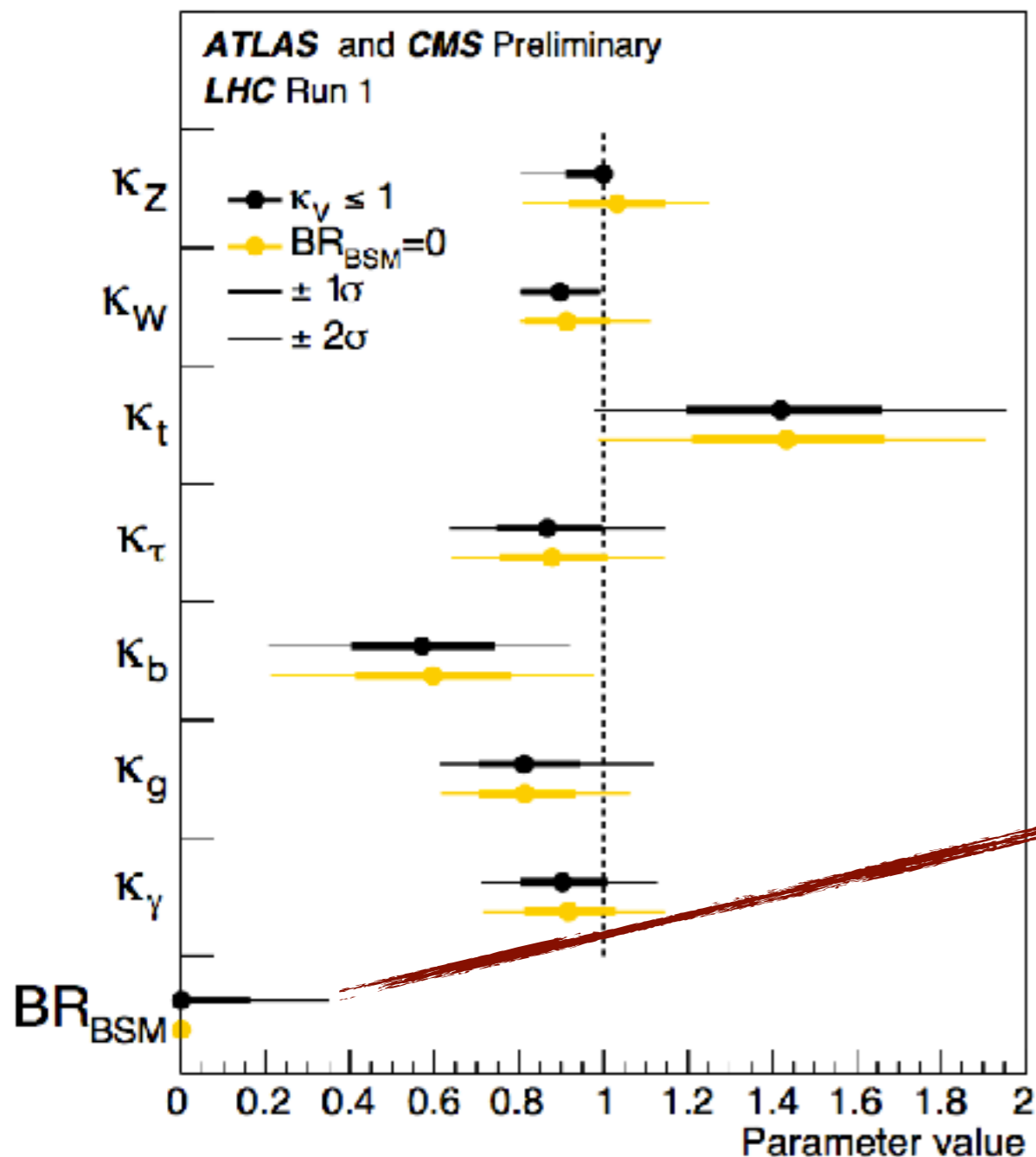


Couplings to fermions and bosons II

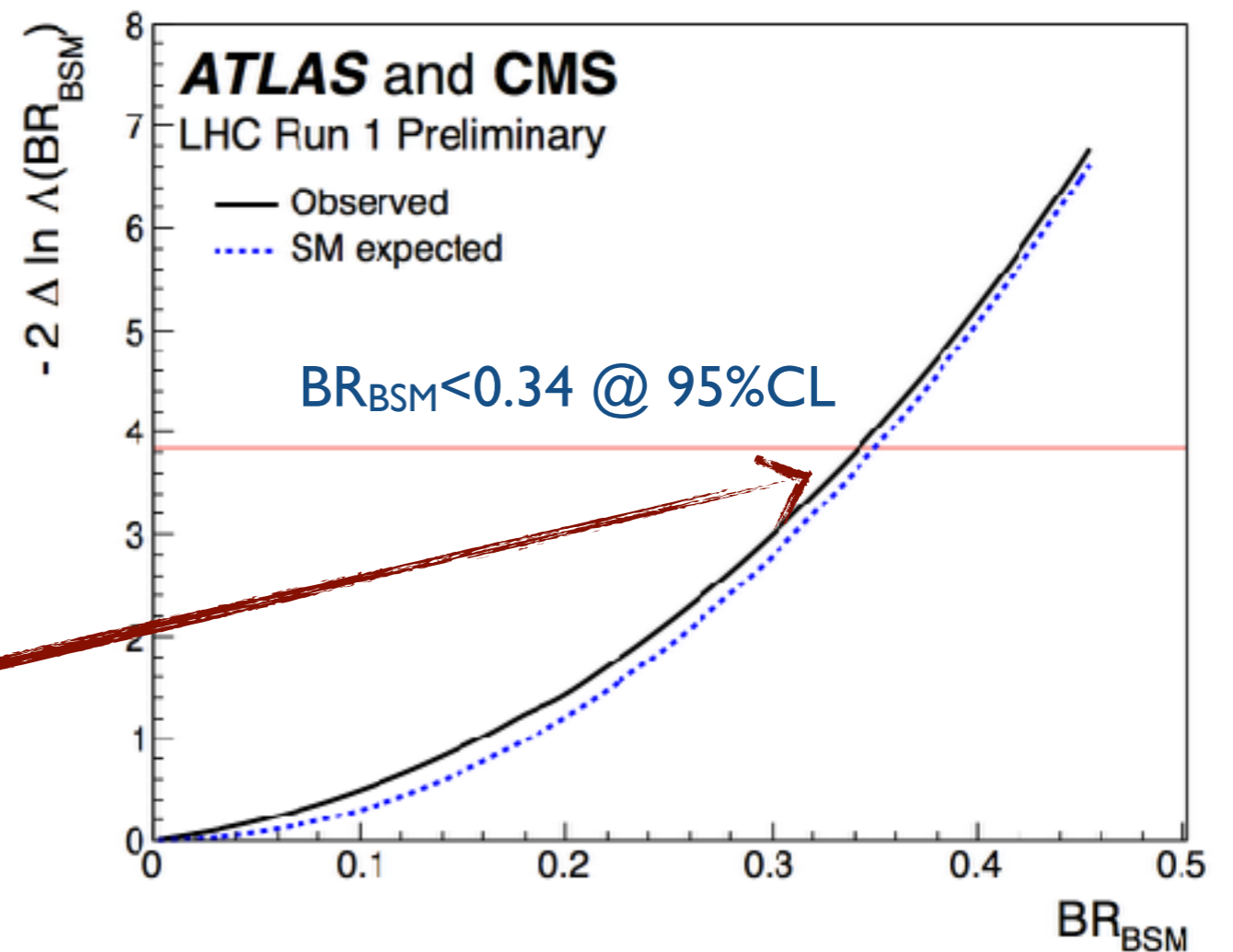
ATLAS-CONF-2015-044 CMS-PAS-HIG-15-002



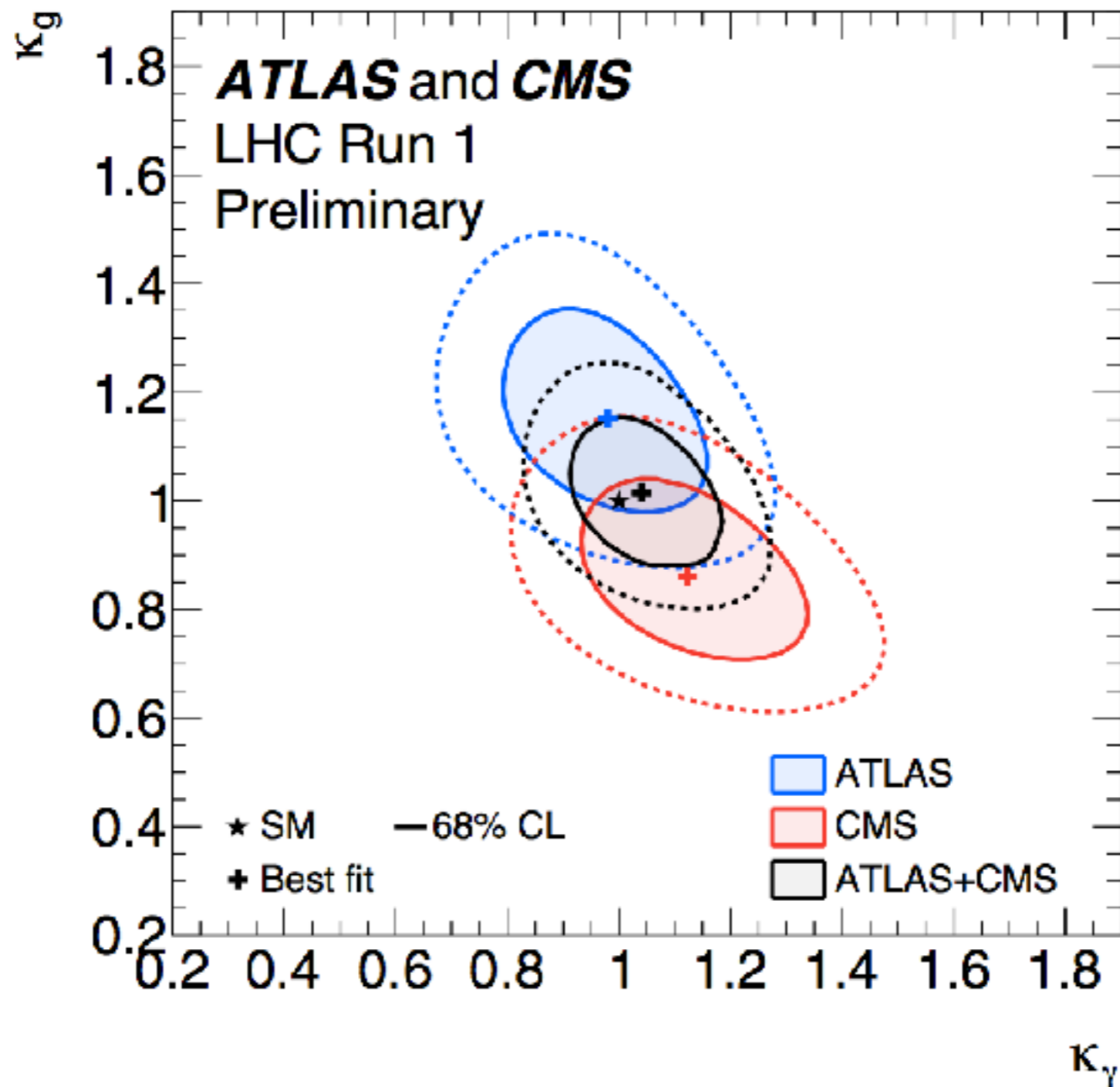
- **The total width can't be extracted from σ .BR measurements**
 - test BR_{BSM} assuming couplings to vector bosons are reduced in strength
 - alternatively assume no new decays and test heavy particles in loops (gg and $\Upsilon\Upsilon$)



- **Not yet any sign of new**



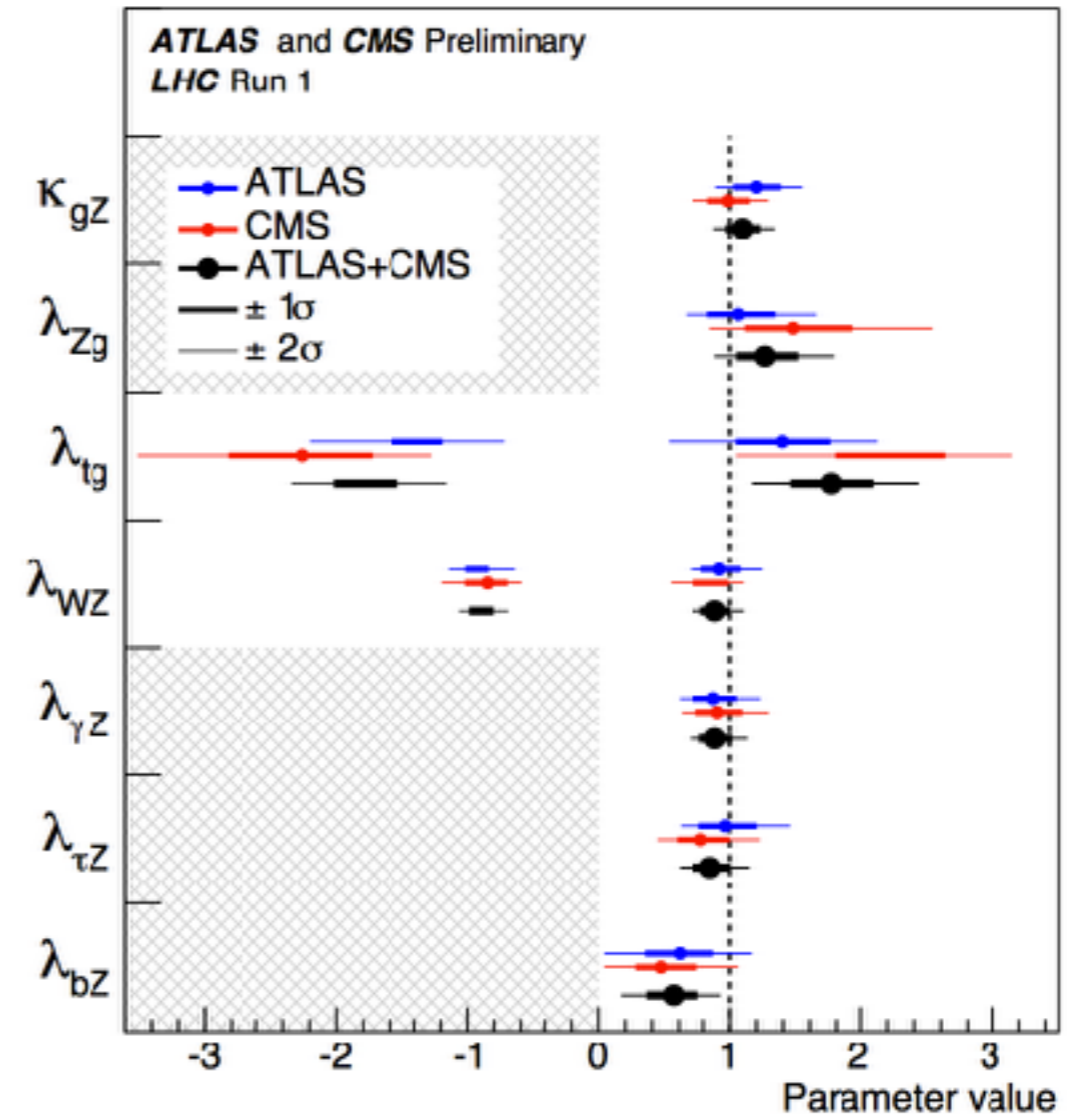
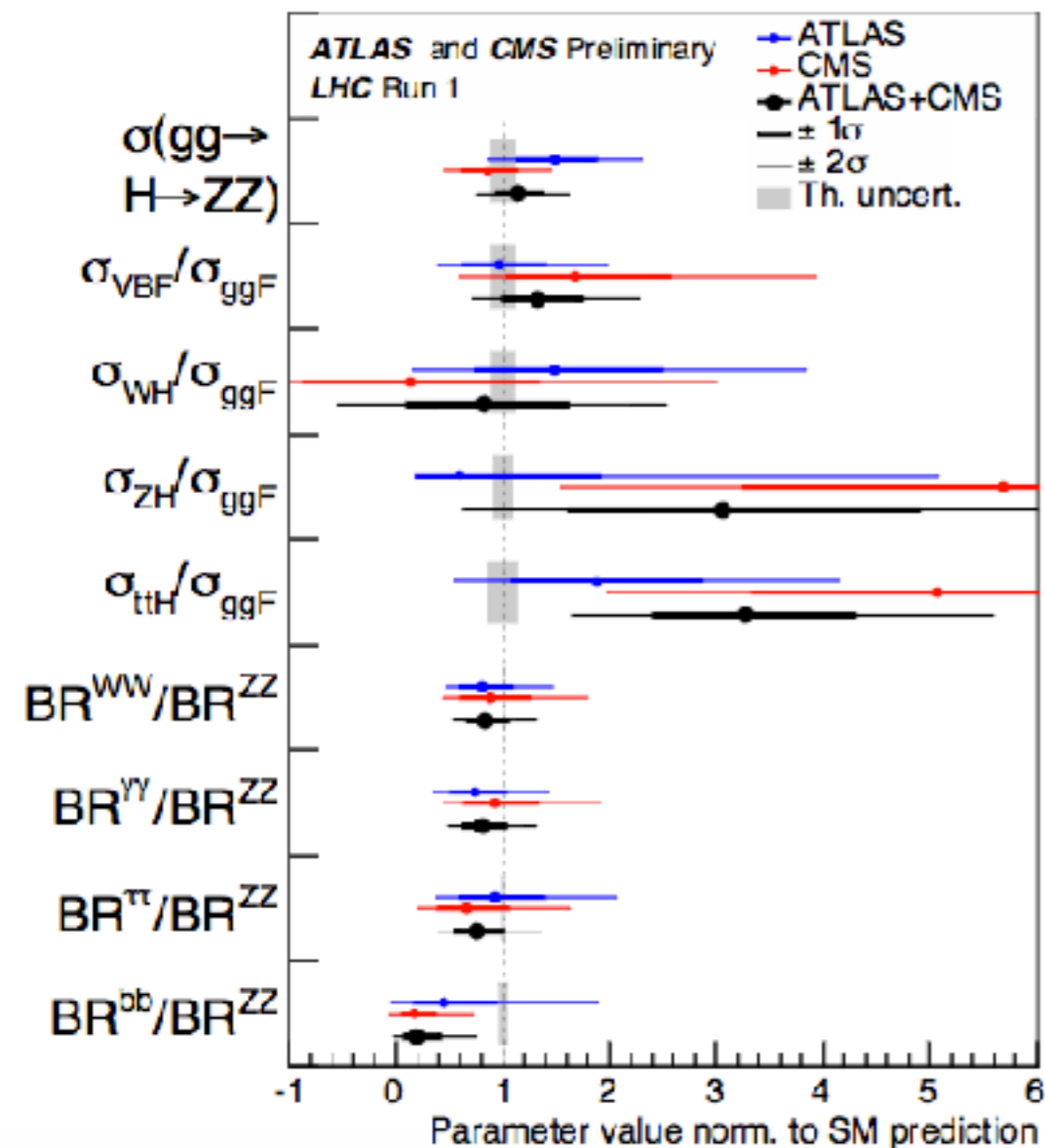
- **Test modifications in the two main loops: gluon-gluon fusion and $H \rightarrow \gamma\gamma$ decays**
 - tree level couplings are assumed to be SM-like
 - additional heavy fermions or a H^\pm would modify the effective gluon or photon coupling



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

Generic parameterisations

- Ratios are useful to cancel partially the uncertainties
 - use $gg \rightarrow H \rightarrow ZZ$ as reference (cleanest channel, lower systematics)
 - ratios of cross sections or of coupling modifiers show no significant deviations from SM
 - largest deviation in BR^{bb}/BR^{ZZ} due to large ZH and ttH observed (in particular in CMS)

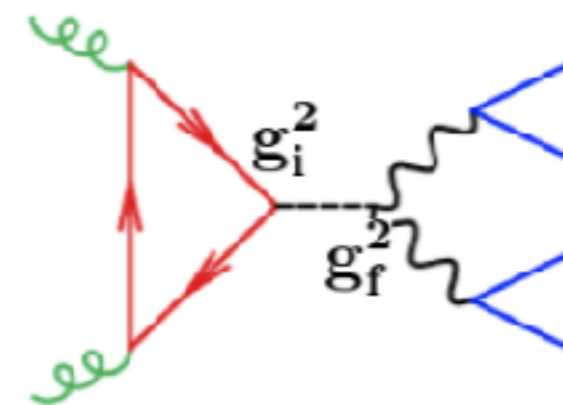
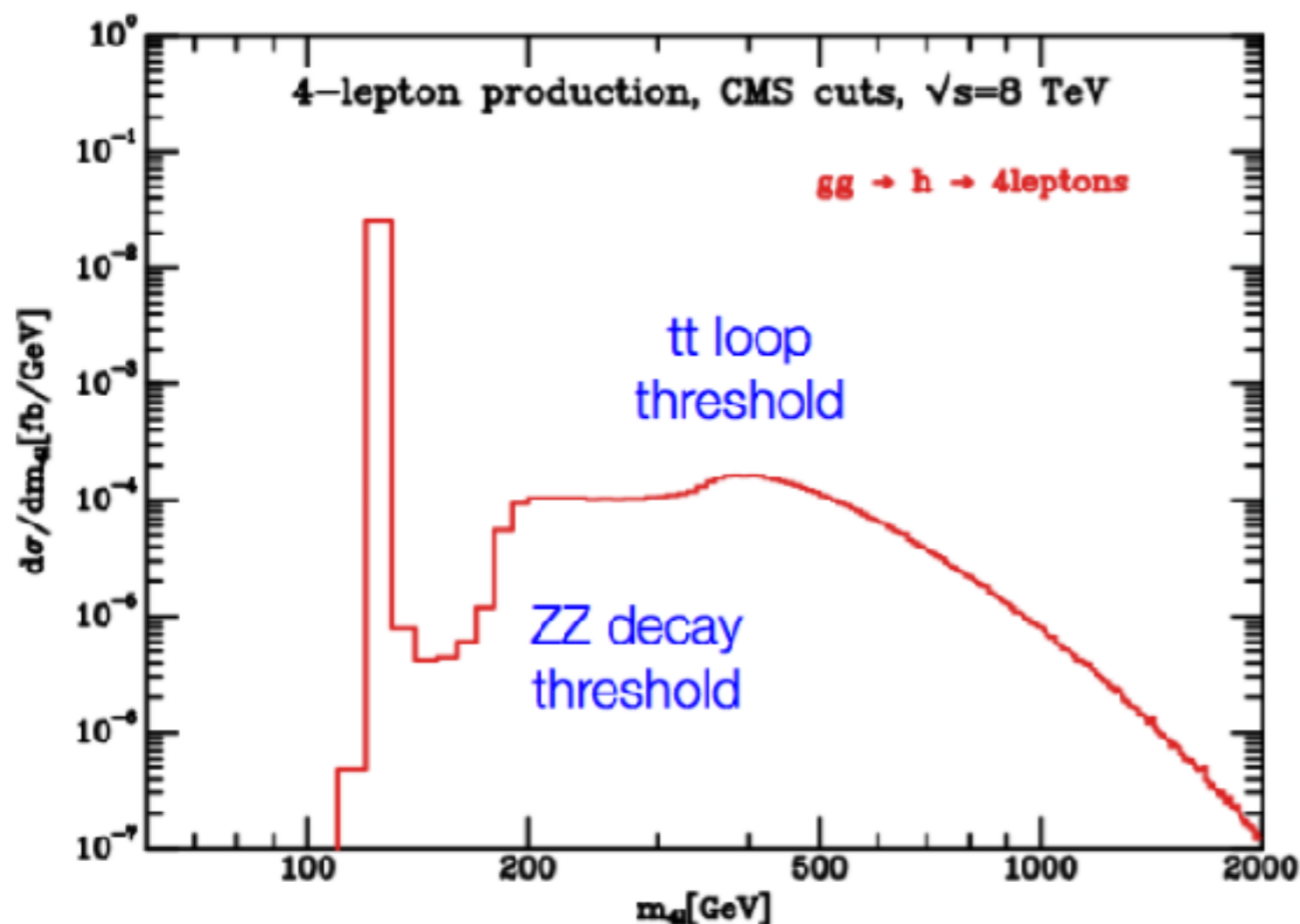


Case study: bounding the Higgs width

Higgs off-shell production and decay

61

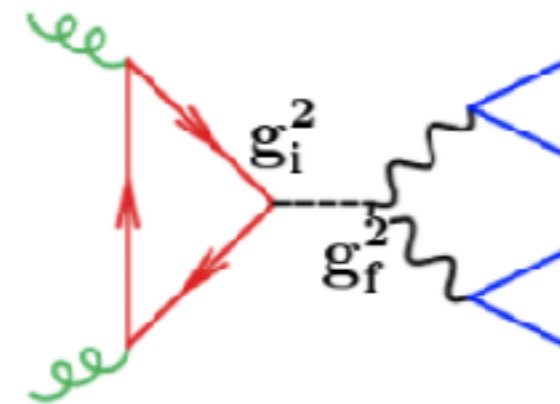
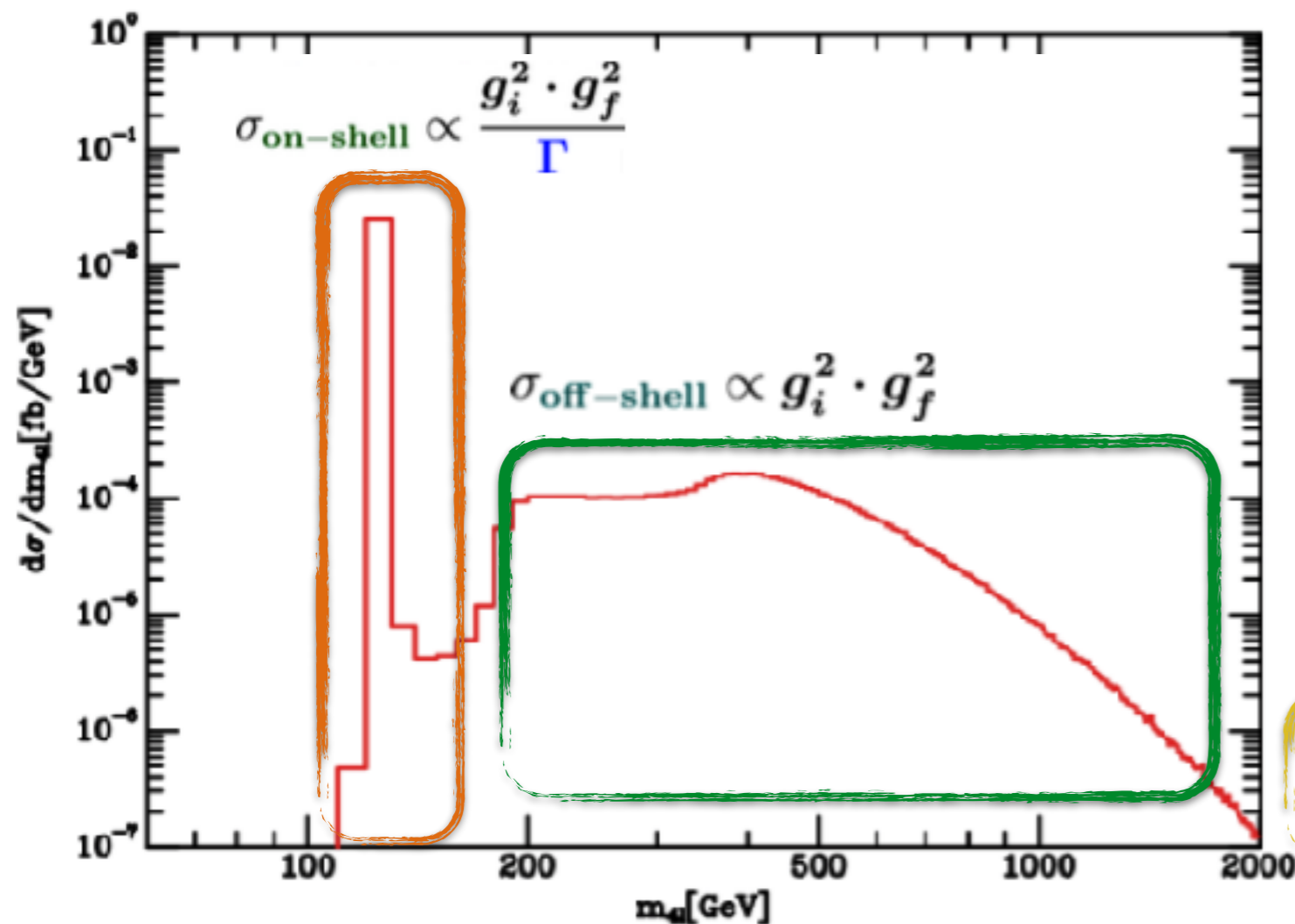
- Although the SM Higgs is expected to be very narrow $\sim 8\%$ production is off-shell
 - mixed effect of production and decay with enhancements at $2m_V$ and $2m_t$ thresholds
 - modelling initially implemented in gg2VV by Kauer and Passarino, JHEP 08 (2012) 16
 - follow-up Caola and Melnikov PRD88 (2013) 054025, Campbell et al arXiv:1311.3589



	Tot[pb]	$M_{ZZ} > 2 M_Z$ [pb]	R[%]
$gg \rightarrow H \rightarrow \text{all}$	19.146	0.1525	0.8
$gg \rightarrow H \rightarrow ZZ$	0.5462	0.0416	7.6

Higgs off-shell production and decay

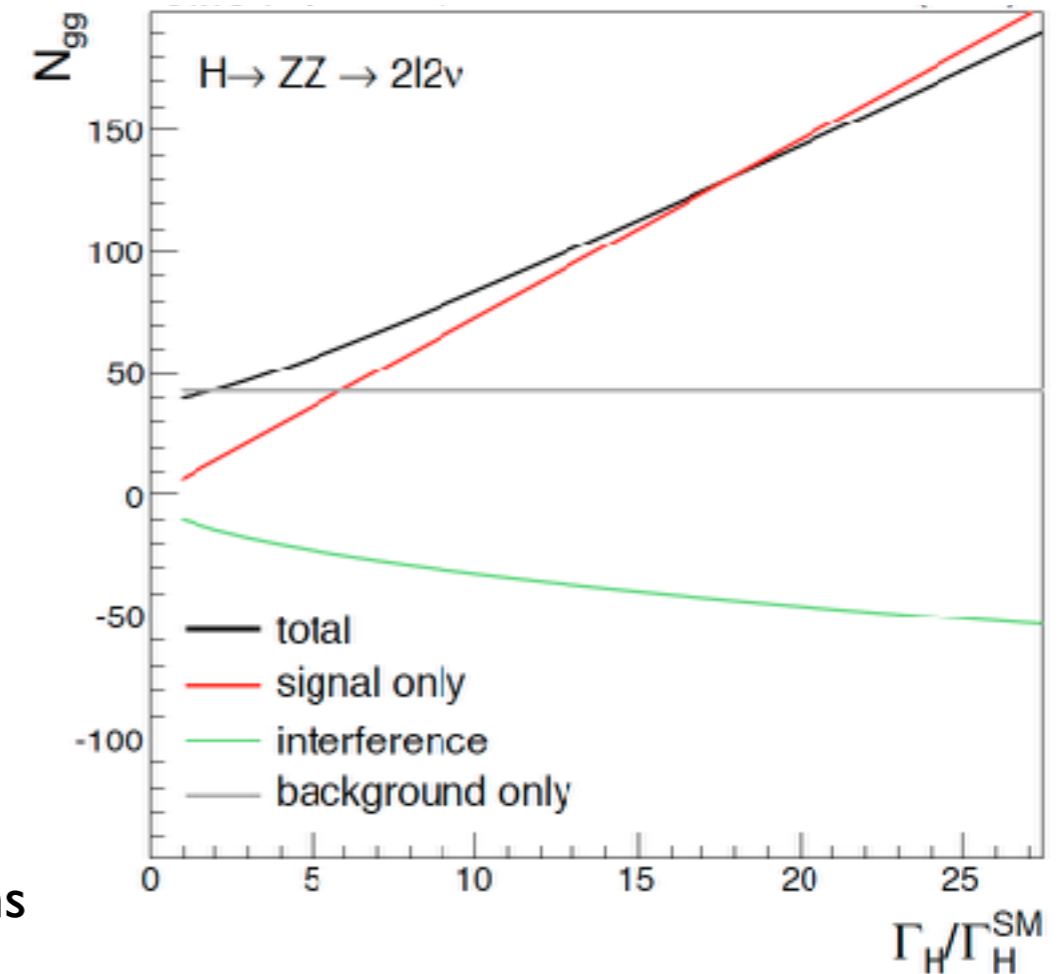
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Extract Γ , from off-shell / on-shell ratio, assuming couplings independent of m_V

- Search for anomalous ZZ production through gluon-gluon and vector boson fusion
- Inclusive final state observed (4ℓ or $2\ell 2\nu$)
- Parametrisation for expected event yields contains
 - separate terms for signal, continuum and interference
 - separate gg and VBF components
 - profile likelihood fit is performed to different distributions



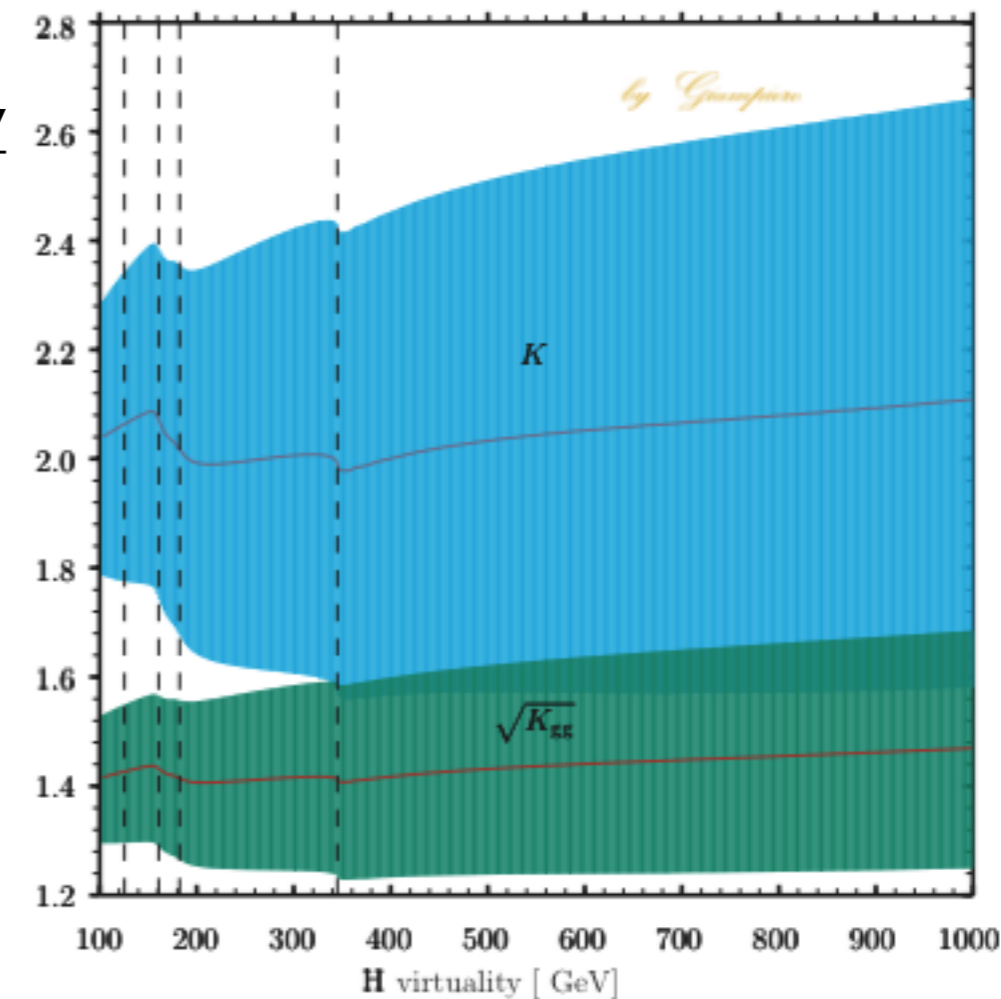
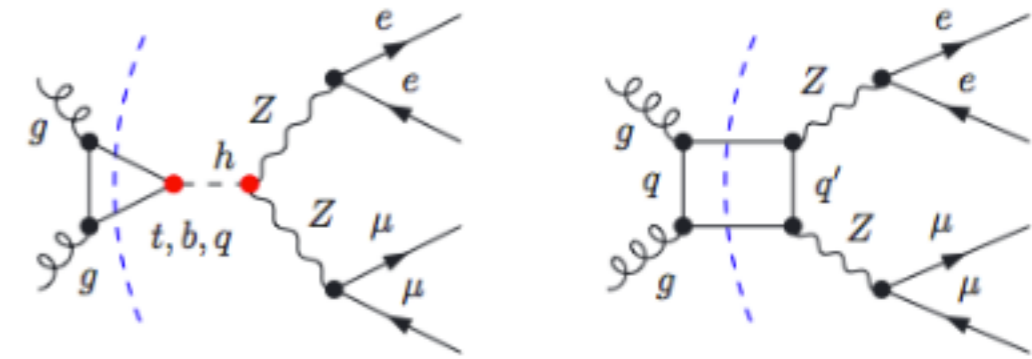
$$\begin{aligned}
 \mathcal{P}_{\text{tot}}^{\text{off-shell}}(\vec{x}) = & \left[\mu_{ggH} \times (\Gamma_H/\Gamma_0) \times \mathcal{P}_{\text{sig}}^{gg}(\vec{x}) + \sqrt{\mu_{ggH} \times (\Gamma_H/\Gamma_0)} \times \mathcal{P}_{\text{int}}^{gg}(\vec{x}) + \mathcal{P}_{\text{bkg}}^{gg}(\vec{x}) \right] \\
 & + \left[\mu_{\text{VBF}} \times (\Gamma_H/\Gamma_0) \times \mathcal{P}_{\text{sig}}^{\text{VBF}}(\vec{x}) + \sqrt{\mu_{\text{VBF}} \times (\Gamma_H/\Gamma_0)} \times \mathcal{P}_{\text{int}}^{\text{VBF}}(\vec{x}) + \mathcal{P}_{\text{bkg}}^{\text{VBF}}(\vec{x}) \right] \\
 & + \mathcal{P}_{\text{bkg}}^{q\bar{q}}(\vec{x}) + \dots
 \end{aligned}$$

Signal models

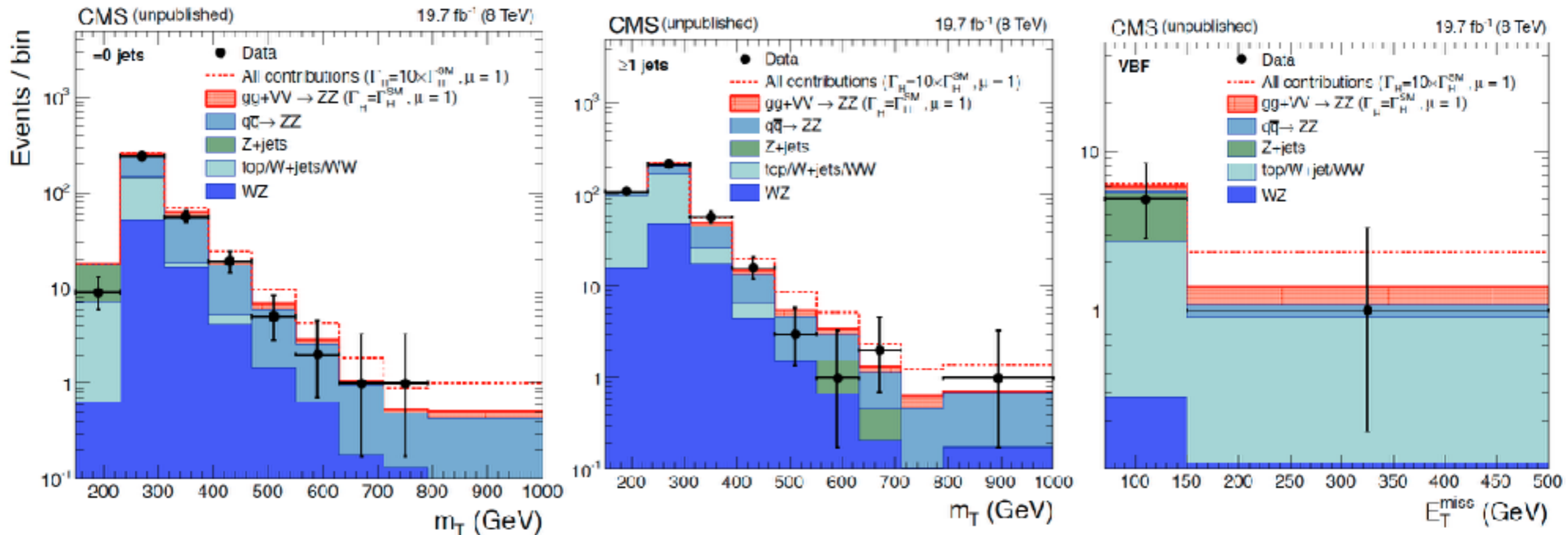
- **ggH** modelled with gg2VV or MCFM ($m_H=125.6$ GeV)
 - inclusive generation: Higgs, continuum and interference
 - dynamic renormalisation and factorisation scales $:= m_{ZZ}/2$
 - scaled with NNLO k-factors for $gg \rightarrow VV$ as function of m_{ZZ}

Bonvini et al. PRD88 (2013) 034032, Passarino [arXiv:1312.2397](https://arxiv.org/abs/1312.2397)

- **VBF** production is generated with Phantom or Madgraph
 - expect to yield $\sim 10\%$ in the high mass regime
 - inclusive generation, as in gg case
 - no dynamical scaling is applied on VBF models



Discriminators used in the $2\ell 2\nu$ analysis

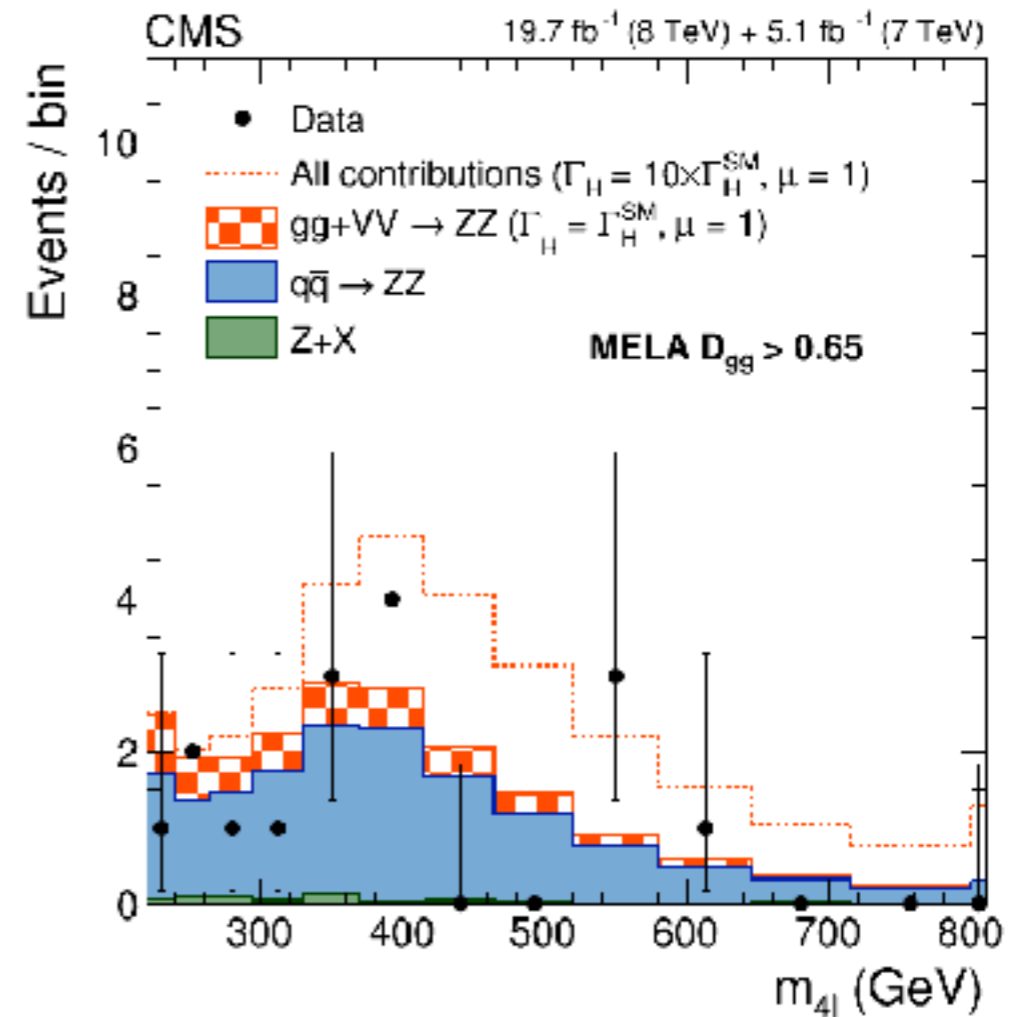
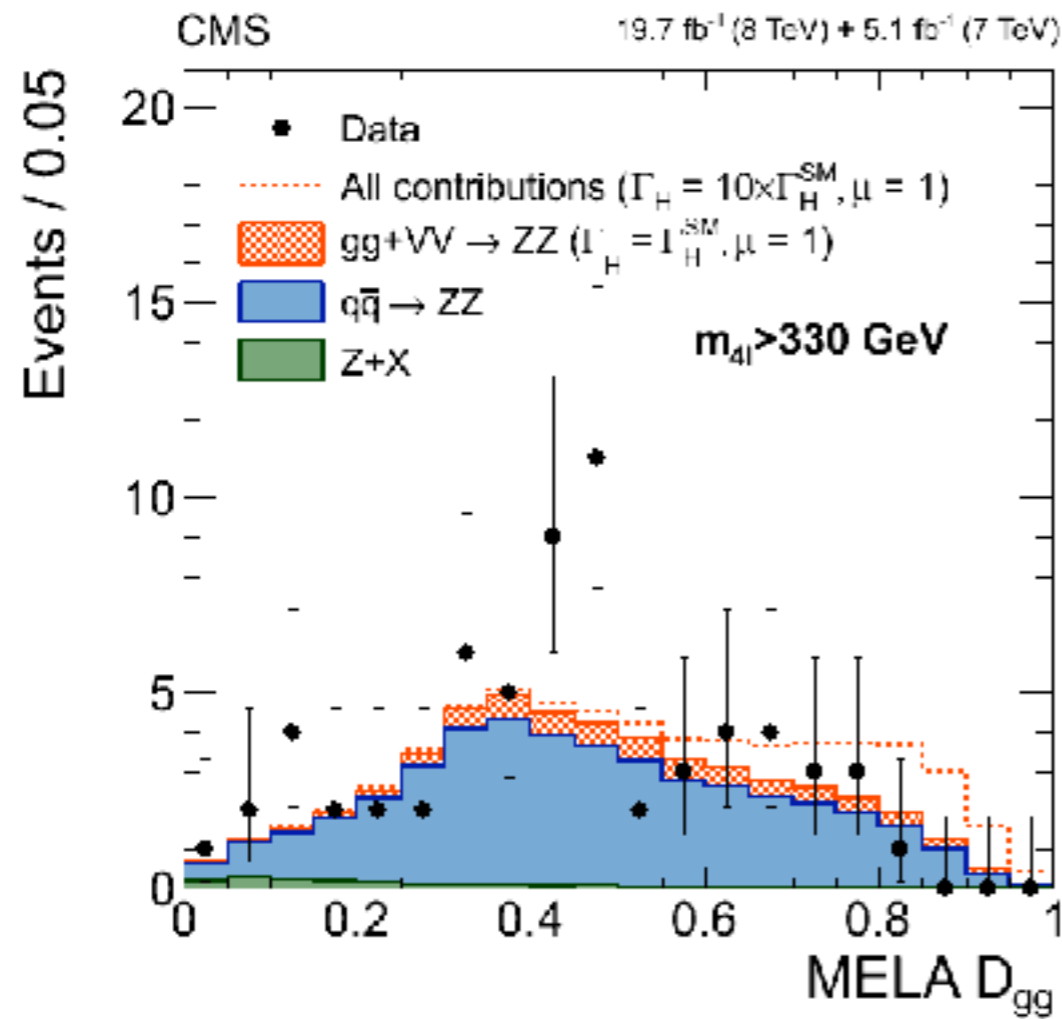


- Analysis has been checked inclusively and binned according to the jets
 - VBF category has priority, selected with $M_{jj} > 500$ GeV, $\Delta\eta > 4$ + central jet veto: use E_T^{miss}
 - if no VBF jet count jets with $p_{T} > 30$ GeV : use transverse mass
- **Data is in agreement with the expectations, in all the categories**

Discriminators used in the 4ℓ analysis

- Use a matrix-element likelihood approach (MELA)
 - use information about Z masses and angles in the CM frame
 - optimize $gg \rightarrow ZZ$ separation according to expected sensitivity for Γ

PLB 736 (2014) 64



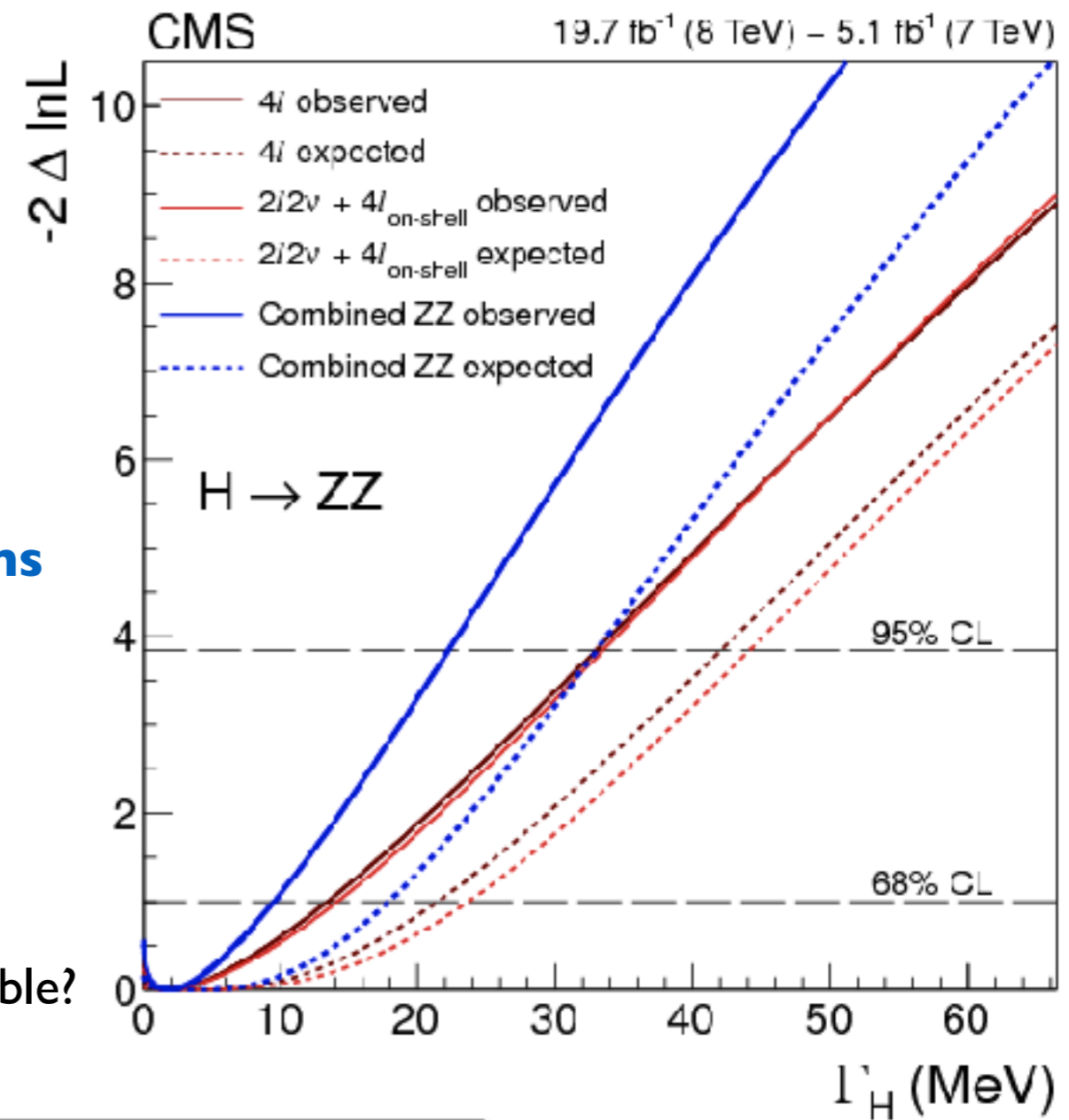
Results

- Both channels are combined to set limits

$$\Gamma_H < 5.4 \Gamma_H^{\text{SM}} @ 95\% \text{ CL}$$

still allowing large room for BSM contributions

- Observed limits are overall stringent then expected
 - improved agreement with NLO EWK corrections (WZ/ZZ production)
 - indicative that higher order corrections are non-negligible?



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Analysis	Observed/ Expected	95% CL limit on Γ_H (MeV)	95% CL limit on $\Gamma_H/\Gamma_H^{\text{SM}}$	Γ_H (MeV)	$\Gamma_H/\Gamma_H^{\text{SM}}$
4ℓ	Expected	42	10.1	$4.2^{+17.3}_{-4.2}$	$1.0^{+4.2}_{-1.0}$
	Expected (no syst.)	41	10.0	$4.2^{+17.1}_{-4.2}$	$1.0^{+4.1}_{-1.0}$
	Observed	33	8.0	$1.9^{+11.7}_{-1.9}$	$0.5^{+2.8}_{-0.5}$
$4\ell_{\text{on-shell}} + 2\ell 2\nu$	Expected	41	10.6	$4.2^{+19.3}_{-4.2}$	$1.0^{+4.7}_{-1.0}$
	Expected (no syst.)	34	8.3	$4.2^{+14.1}_{-4.2}$	$1.0^{+3.4}_{-1.0}$
	Observed	33	8.1	$1.8^{+12.4}_{-1.8}$	$0.4^{+3.0}_{-0.4}$
Combined	Expected	33	8.0	$4.2^{+13.5}_{-4.2}$	$1.0^{+3.2}_{-1.0}$
	Expected (no syst.)	28	6.8	$4.2^{+11.3}_{-4.2}$	$1.0^{+2.7}_{-1.0}$
	Observed	22	5.4	$1.8^{+7.7}_{-1.8}$	$0.4^{+1.8}_{-0.4}$

150x more stringent than from on-shell line-shape measurement

Conclusions

- **All LHC Run I results point to a SM like Higgs**
 - Run 2 results: direct evidence for ttH , precise m_H , more to come
- **For couplings we haven't yet entered precision era**
 - more data is needed as well as better theory predictions
 - couplings to tops, muons still to be established at the LHC
 - others will be impossible at the LHC (light quarks, electrons)
- **Initial interpretations based on simplified frameworks**
- **There is still a long way to go to understand the Higgs sector**
 - all that is needed is one small deviation from the SM predictions