Higgs properties

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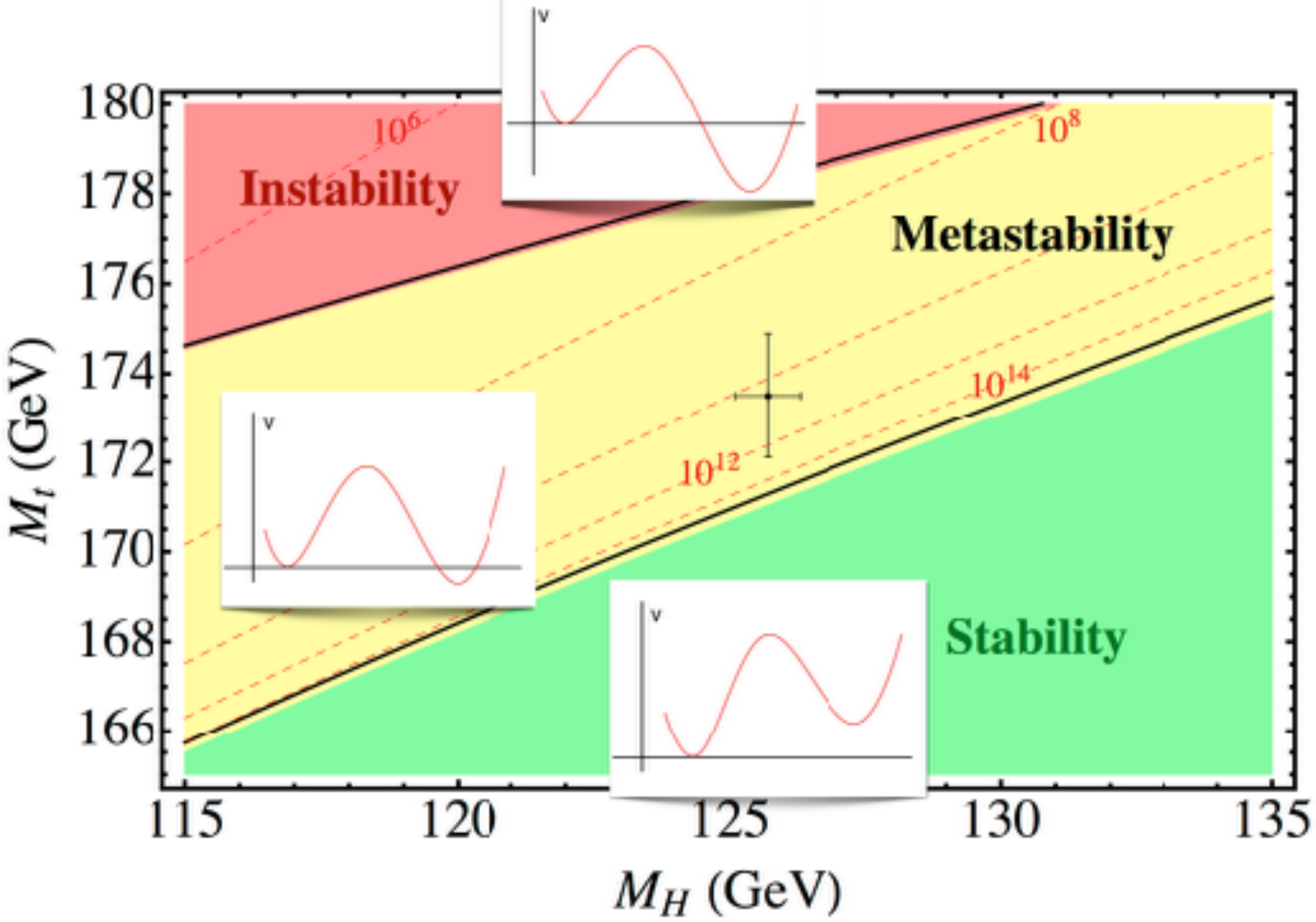
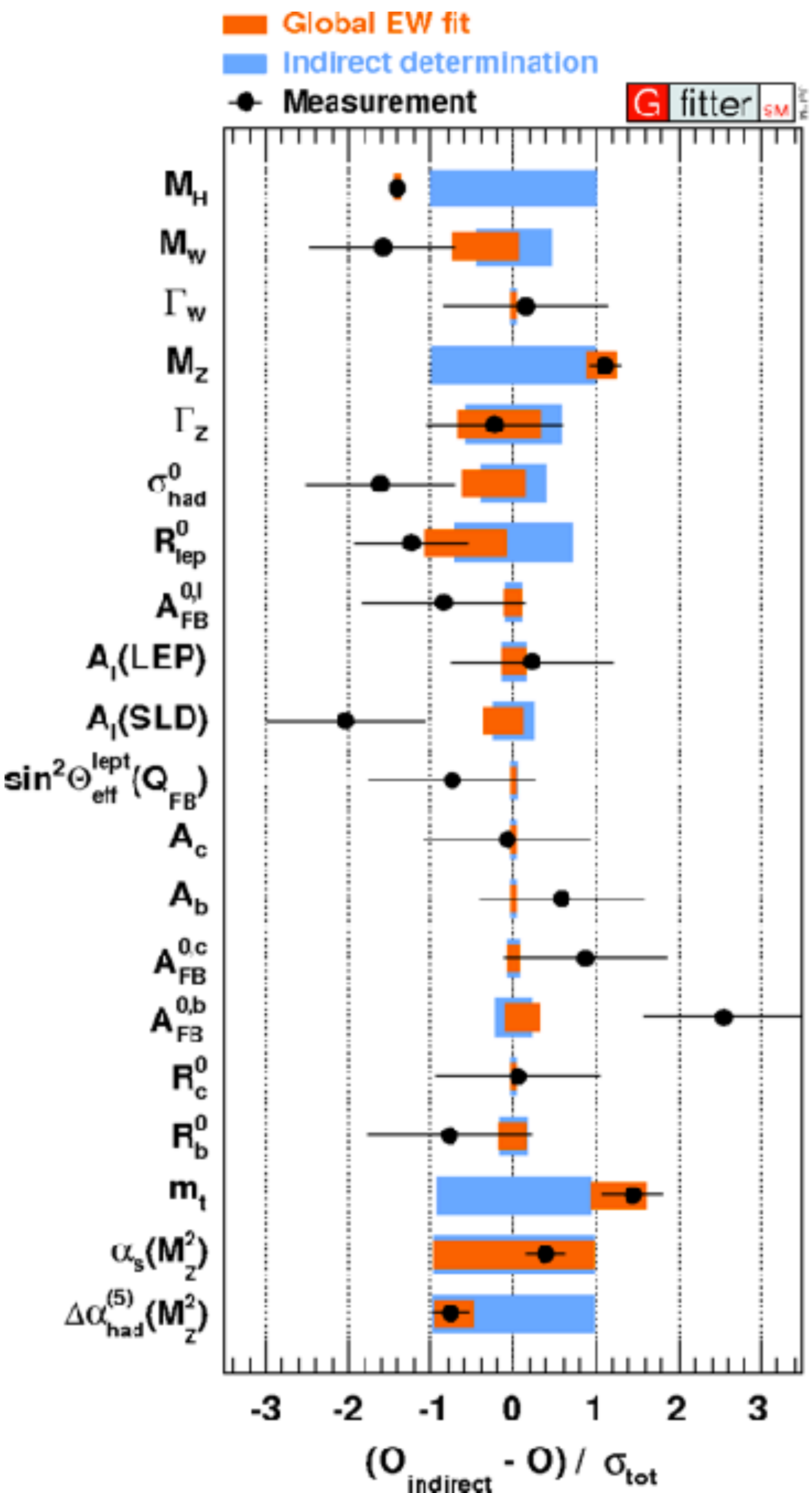
Why are we so obsessed with the Higgs?

- **Is the standard model (SM) really consistent?**
  - p-value is currently estimated to be ~0.22 (see GFitter)
    - if the Higgs would have been found @ 300 GeV p-value for the SM would be ~$3 \bullet 10^{-5}$
  - how fined-tuned are the corrections to the mass?
  - how stable is the vacuum generated by the Higgs field?





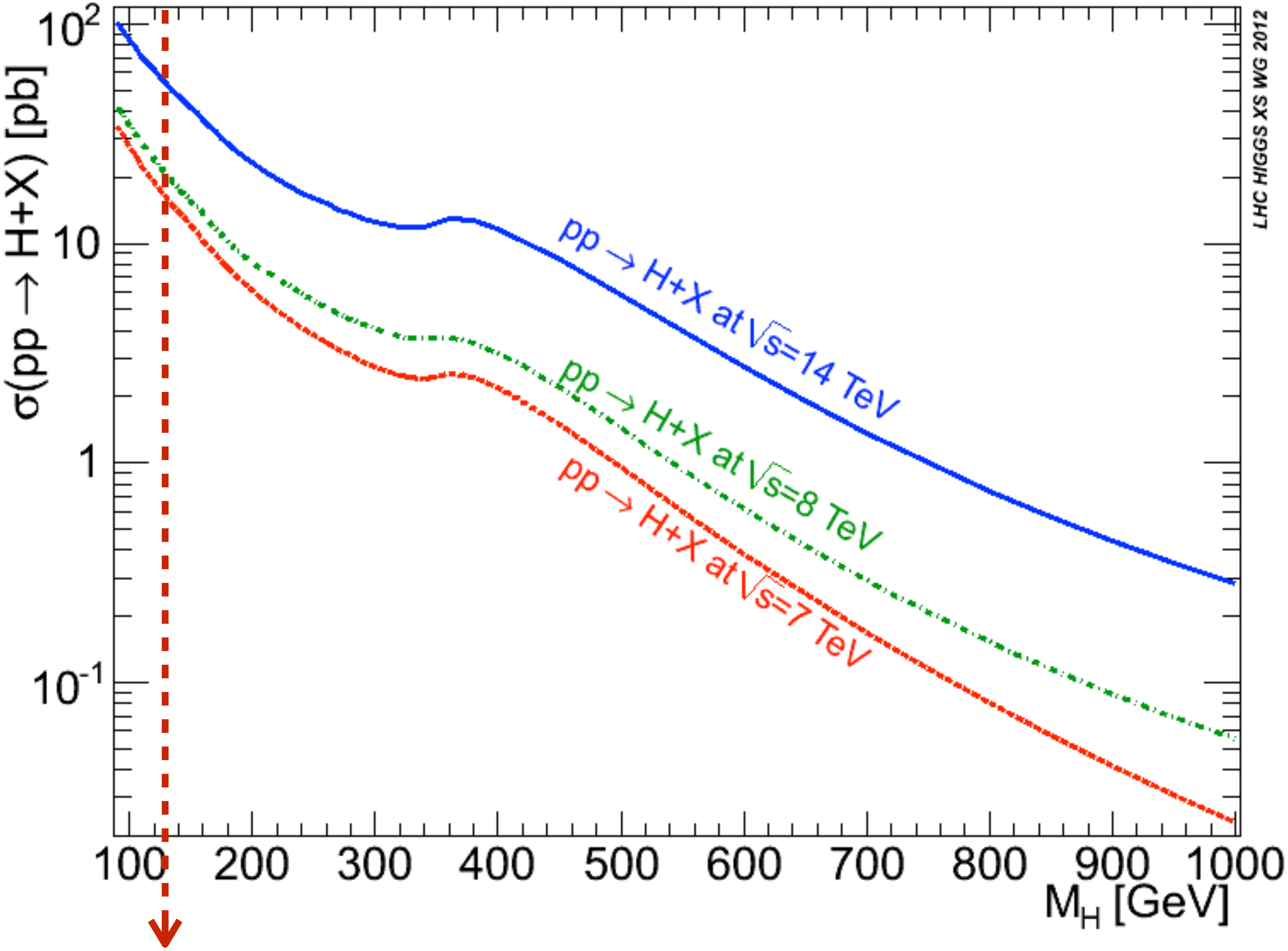
see more details in R. Gonçalo - Higgs lecture #1 - link

Outline

- 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

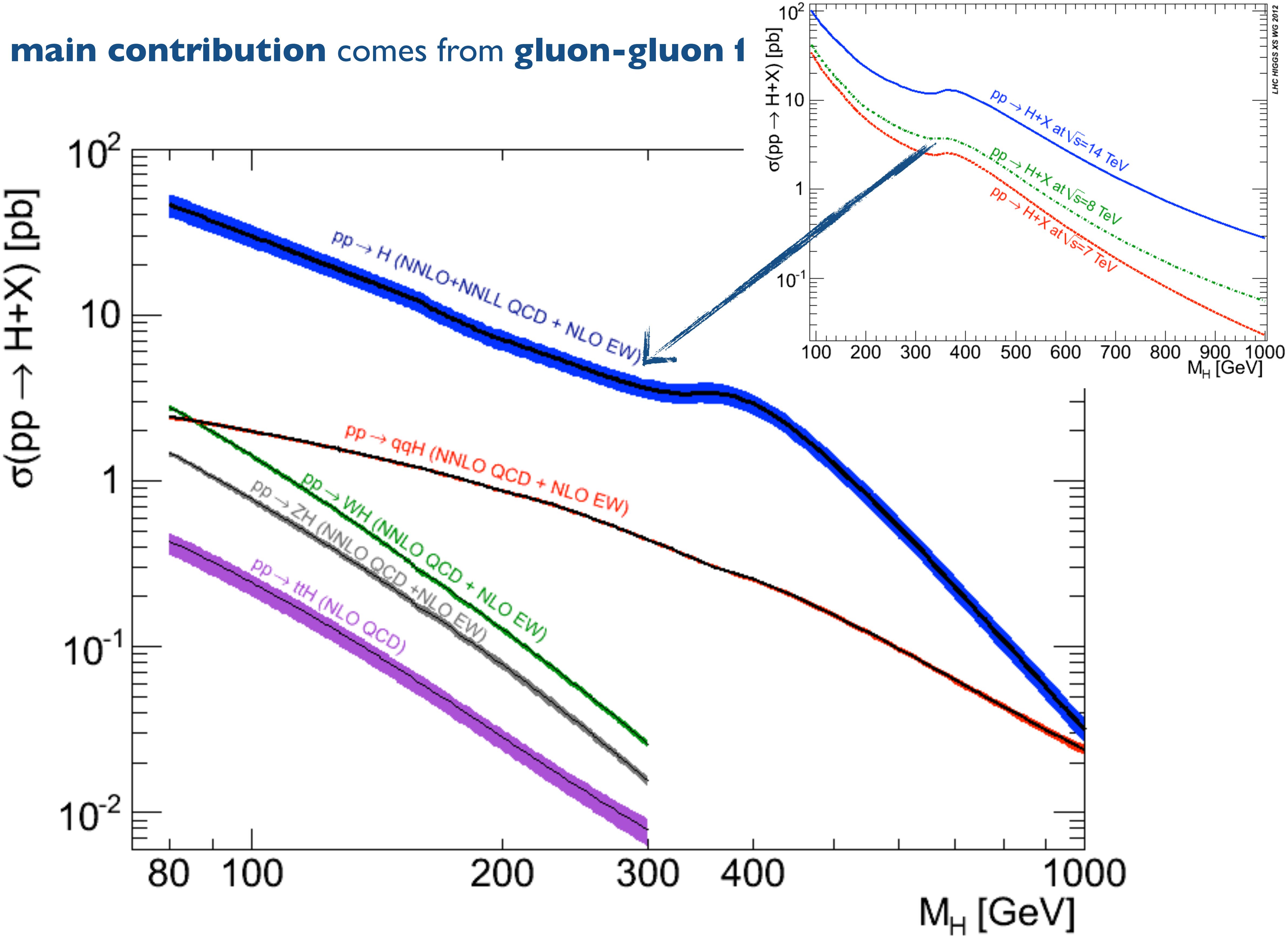
Higgs production at hadron colliders I



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

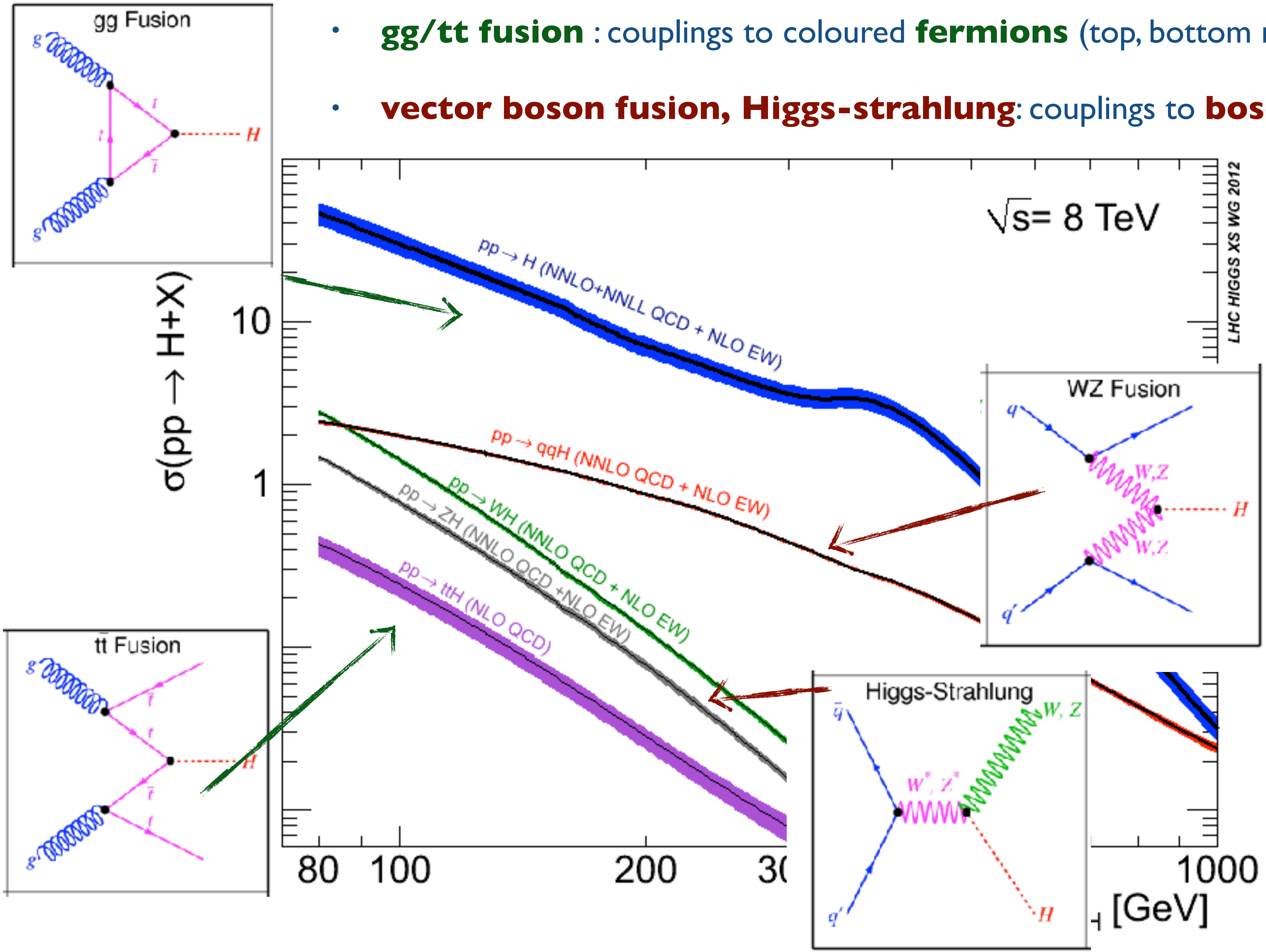
Higgs production at hadron colliders II

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



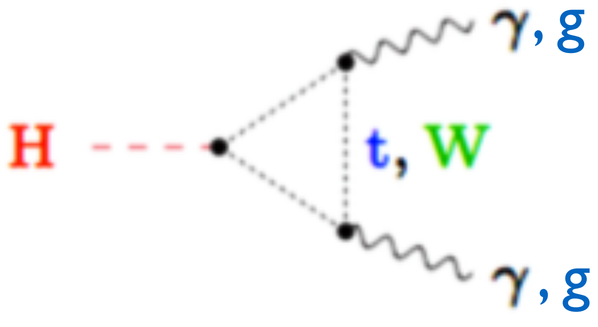
Higgs production at hadron colliders III

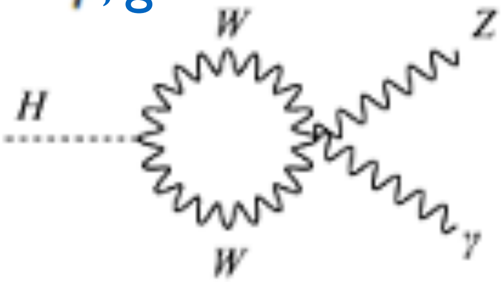
- **gg/tt fusion** : couplings to coloured **fermions** (top, bottom mostly)
- **vector boson fusion, Higgs-strahlung**: couplings to **bosons** (W, Z)



Higgs decays

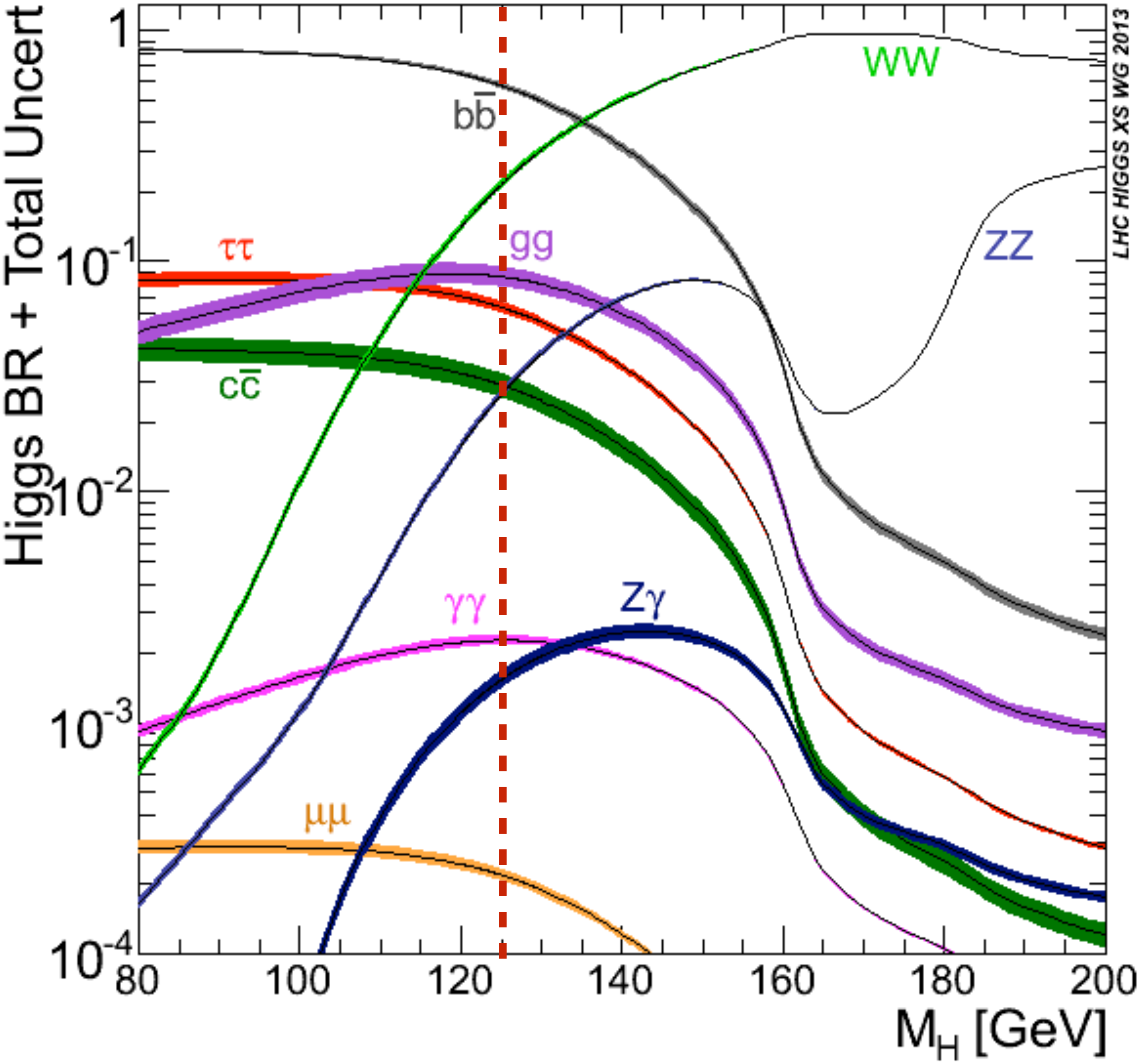
- Couplings and kinematics determine the branching ratios
- **Prefer bb, ττ, WW final states** (most massive particles)
- **Decays to gluons and photons**
  - possible through loops





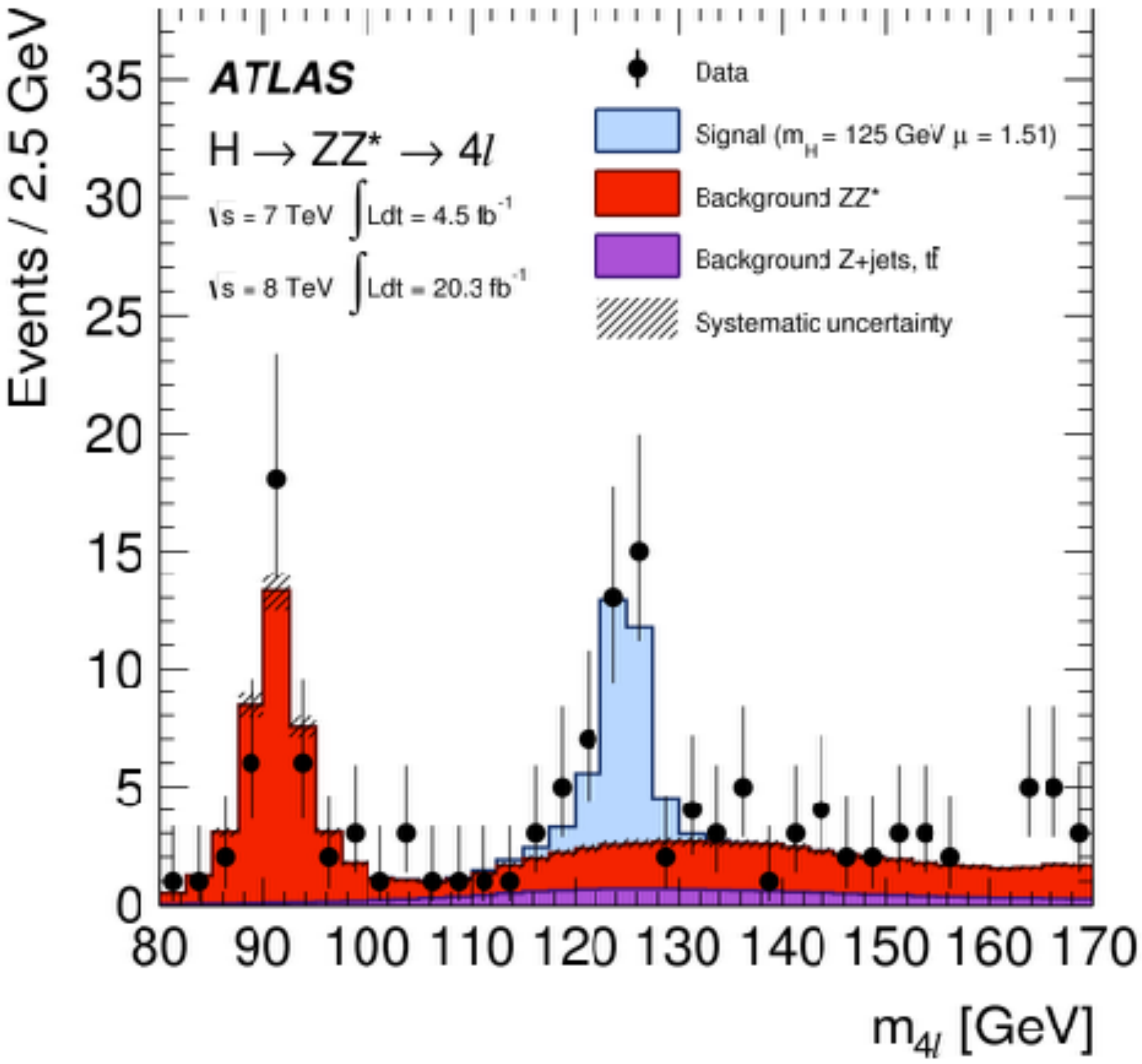
  - dominated by tops and/or W's

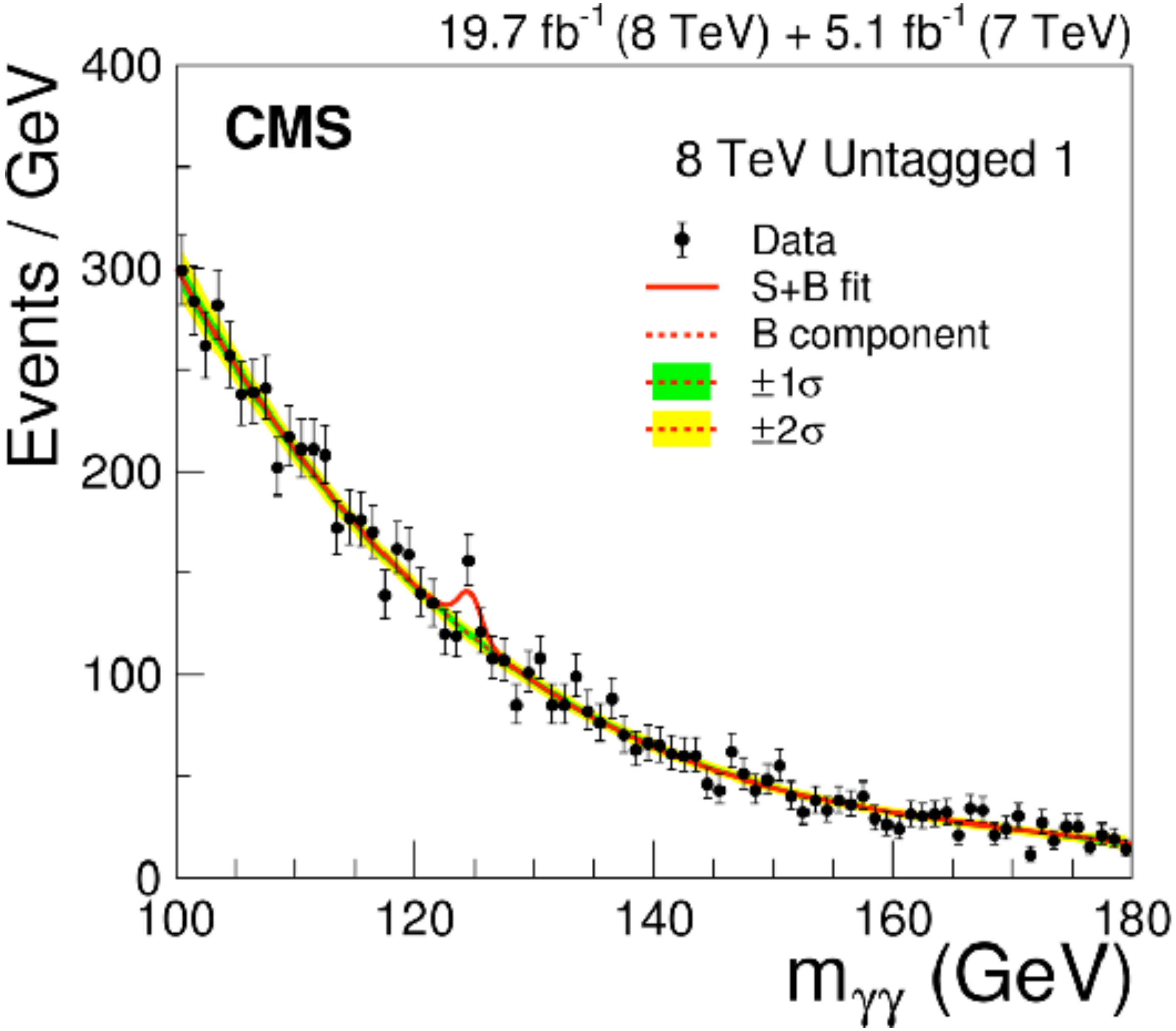
…and possibly new physics?



Signals

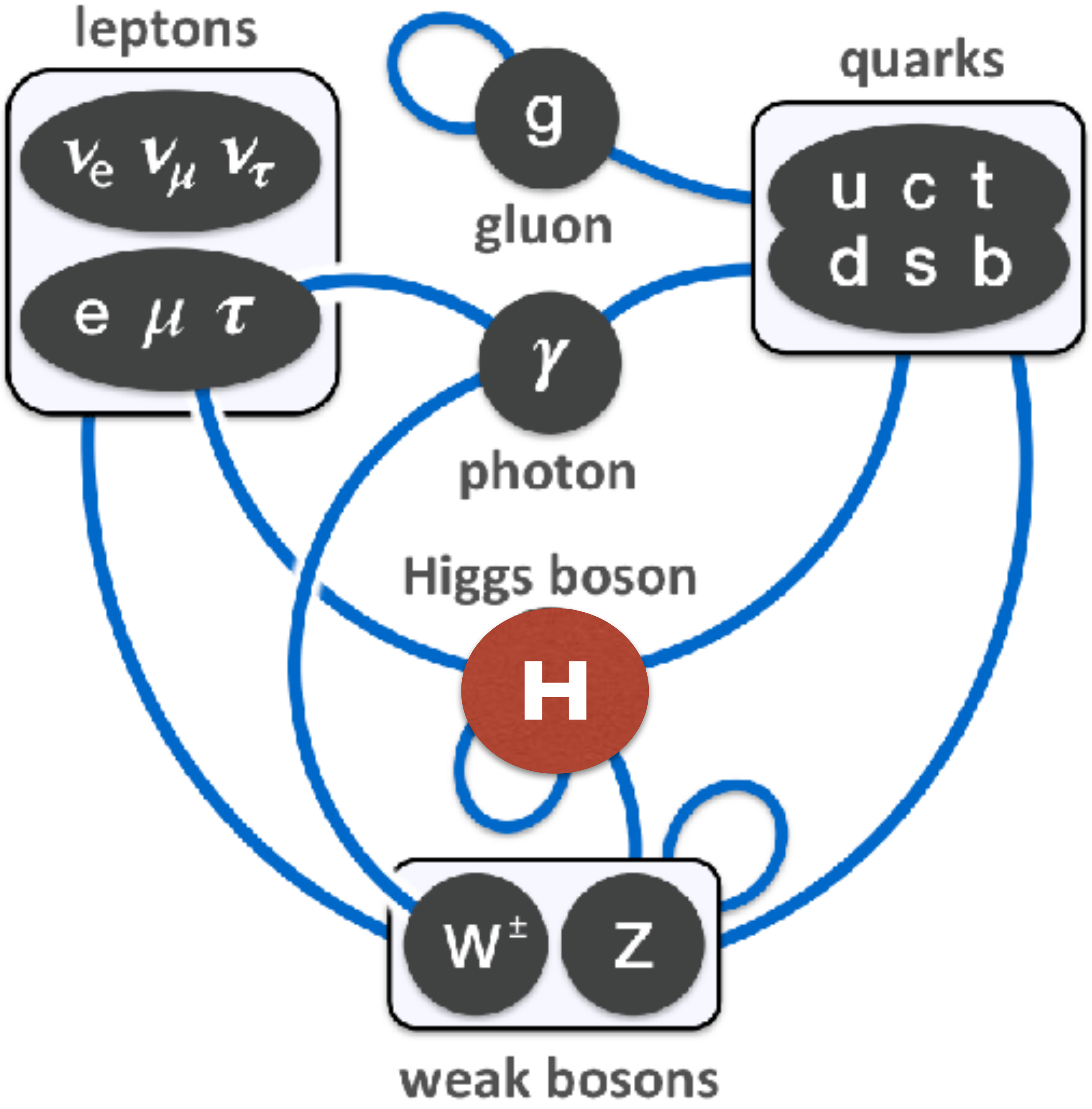
- Our experiments **count events.**
- **Backgrounds are estimated from data or simulation.**
- The **remainder is the signal** ⇒ can be compared to theory.





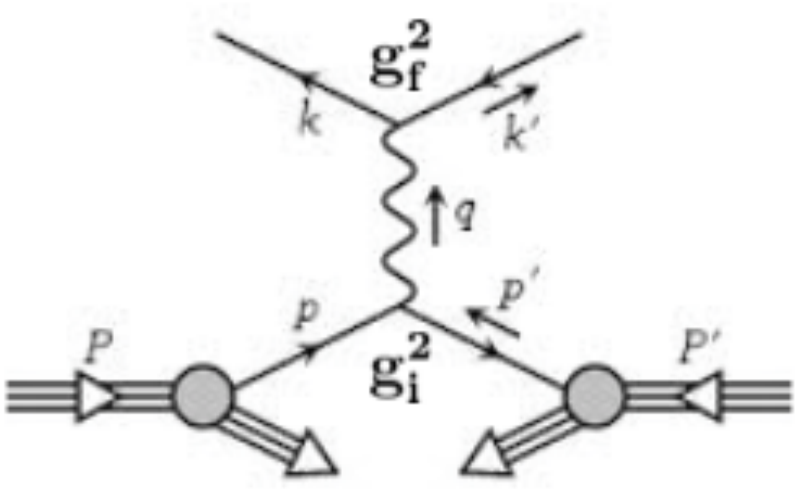
Signals, couplings

- 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



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

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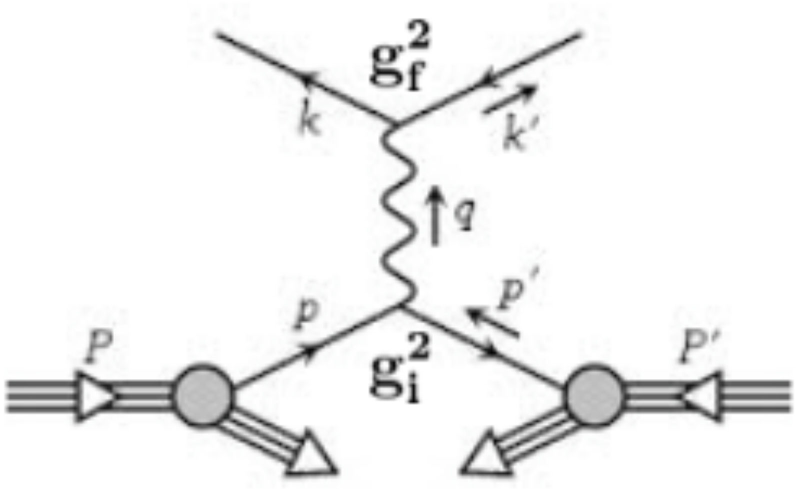
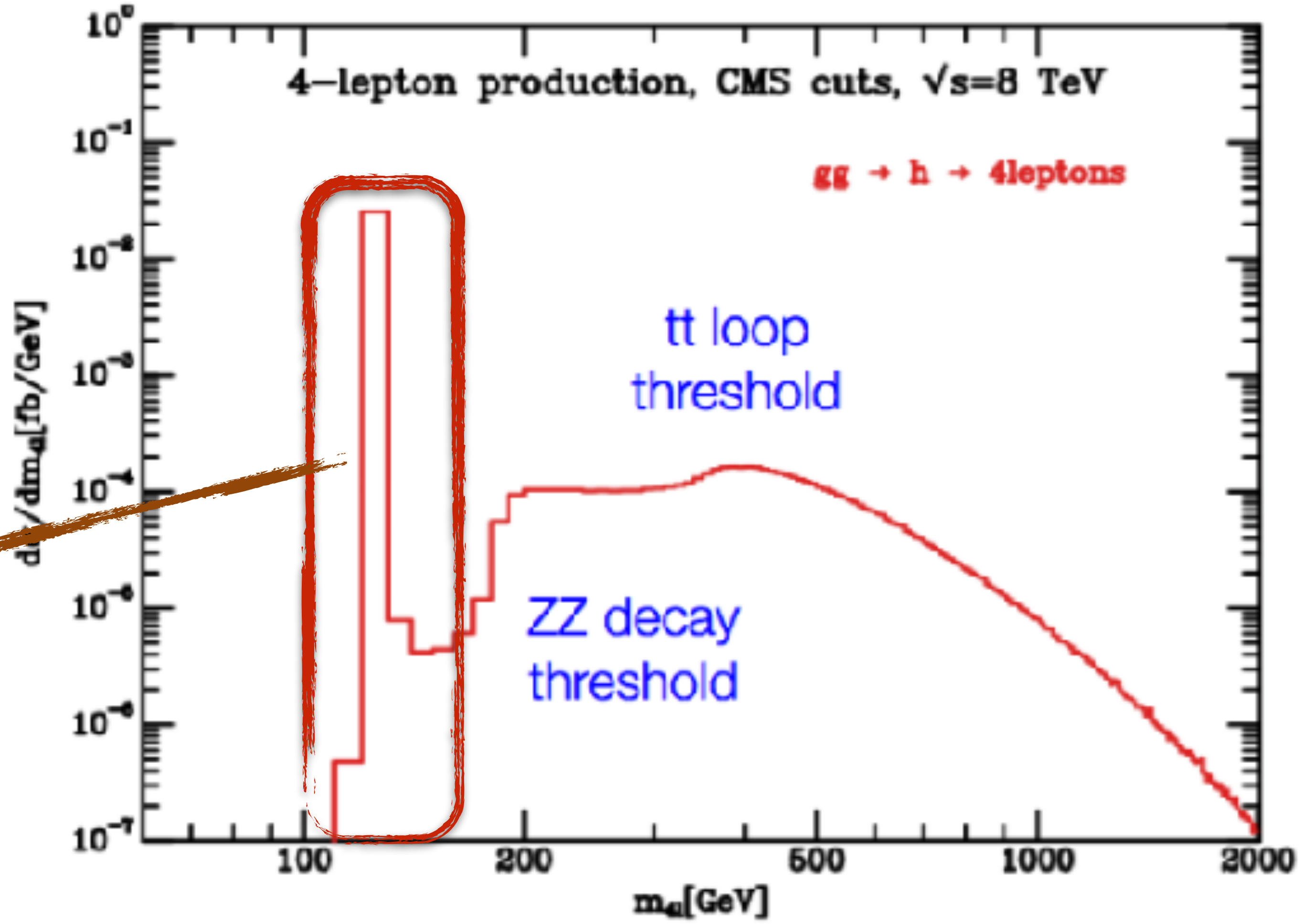


$$\sigma_{\text{on-shell}} \propto \frac{g_i^2 \cdot g_f^2}{\Gamma}$$



- **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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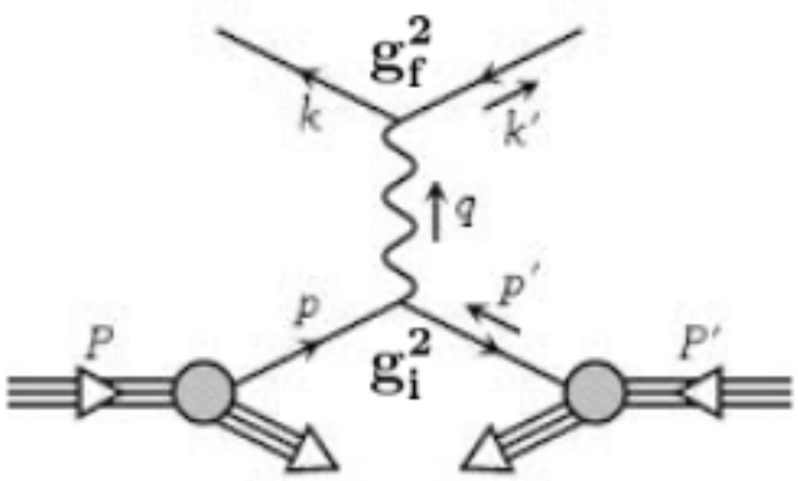
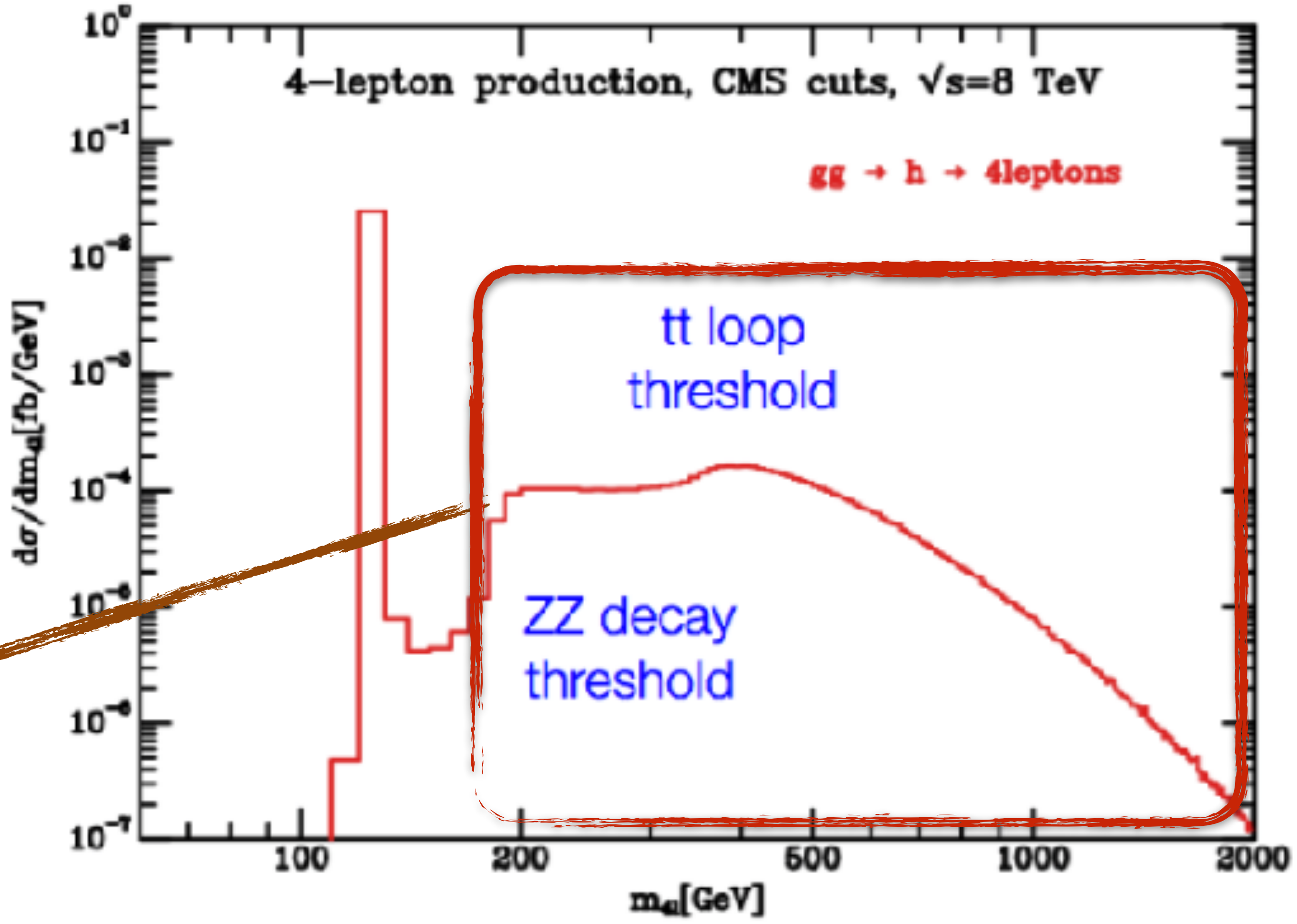


$$\sigma_{\text{on-shell}} \propto \frac{g_i^2 \cdot g_f^2}{\Gamma}$$

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



- **Off-shell production**
  - depends only on couplings
  - take the ratio of the two cross sections to measure Γ

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

Models, properties, and interpretation

First things first : how do we convert a signal rate to couplings?

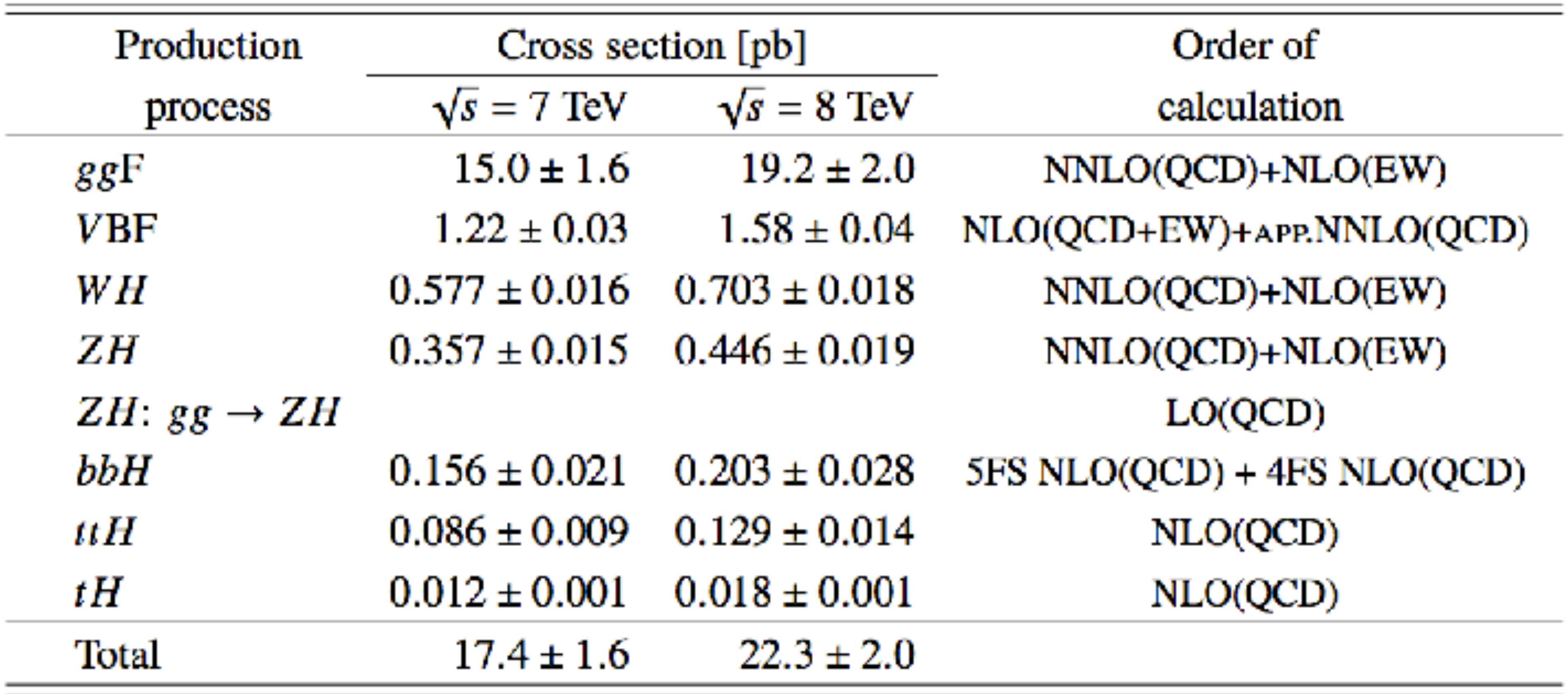
$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{ \sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f \right\}$$

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

New physics can affect production

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

- **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] $\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ 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)+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: $gg \to ZH$			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	

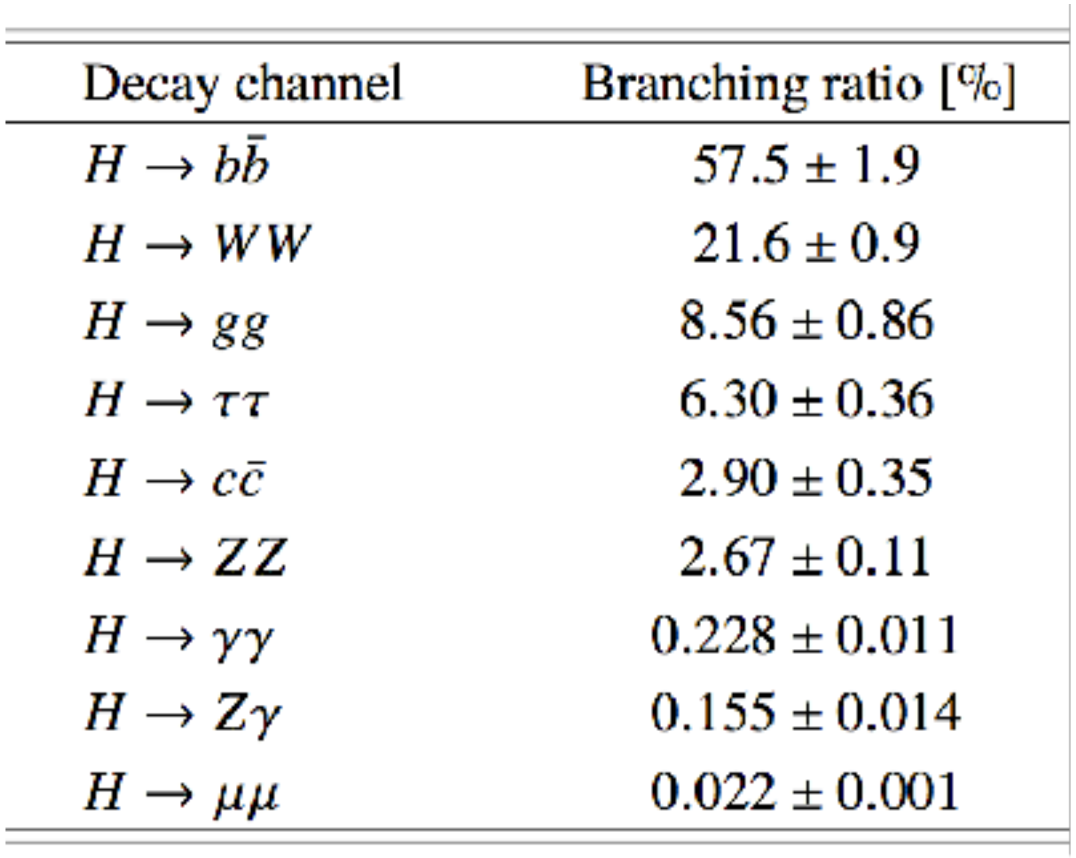
- **New physics can alter the SM expectation : model with scale parameter**

$$\sigma_i = \mu_{\mathrm{i}} \cdot \sigma_{\mathrm{SM}}$$

New physics can affect the decay

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

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



Decay channel	Branching ratio [%]
$H \to b\bar{b}$	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
$H \to c\bar{c}$	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

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

$$BR^{\mathrm{f}} = \mu^{\mathrm{f}} \cdot BR_{\mathrm{SM}}$$

  - notice that new decay channels may appear e.g. BR(H → dark matter)

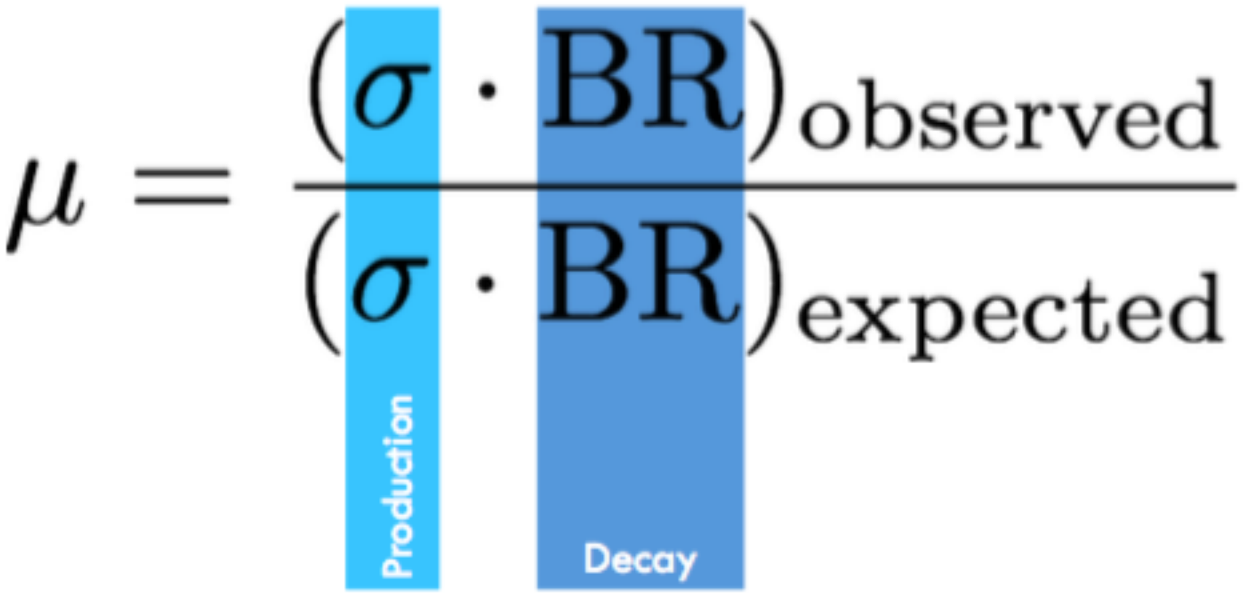
Couplings are measured from rates using signal strengths

Deviations are searched relative to the SM expectation.

Conclusions are only as good

as the accuracy and precision

of the numerator and denominator.



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

μ is the so-called signal strength

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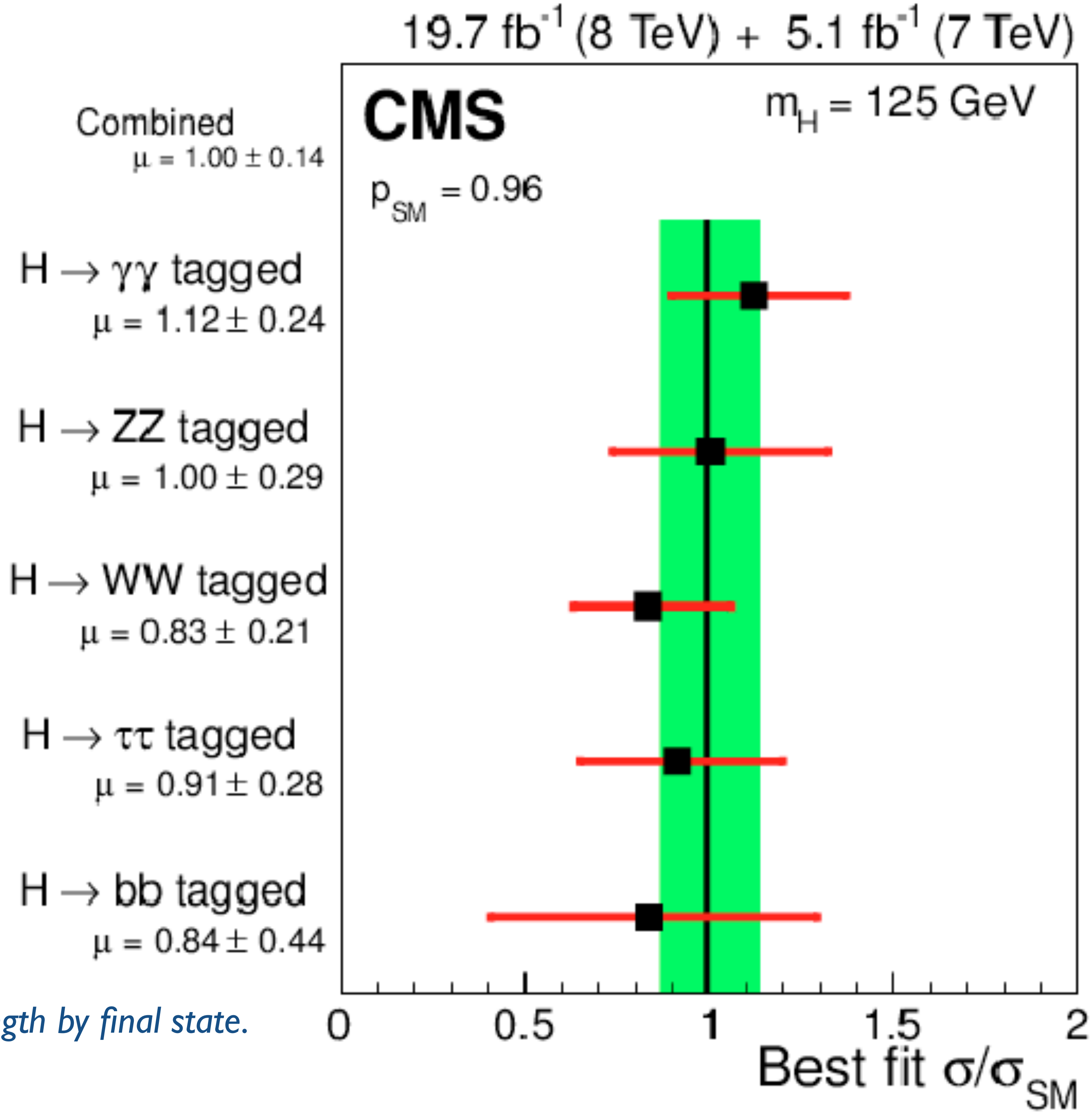
$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Data

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



Signal strength by final state.

- If the signal strength close to 1, observations are close to the SM predictions
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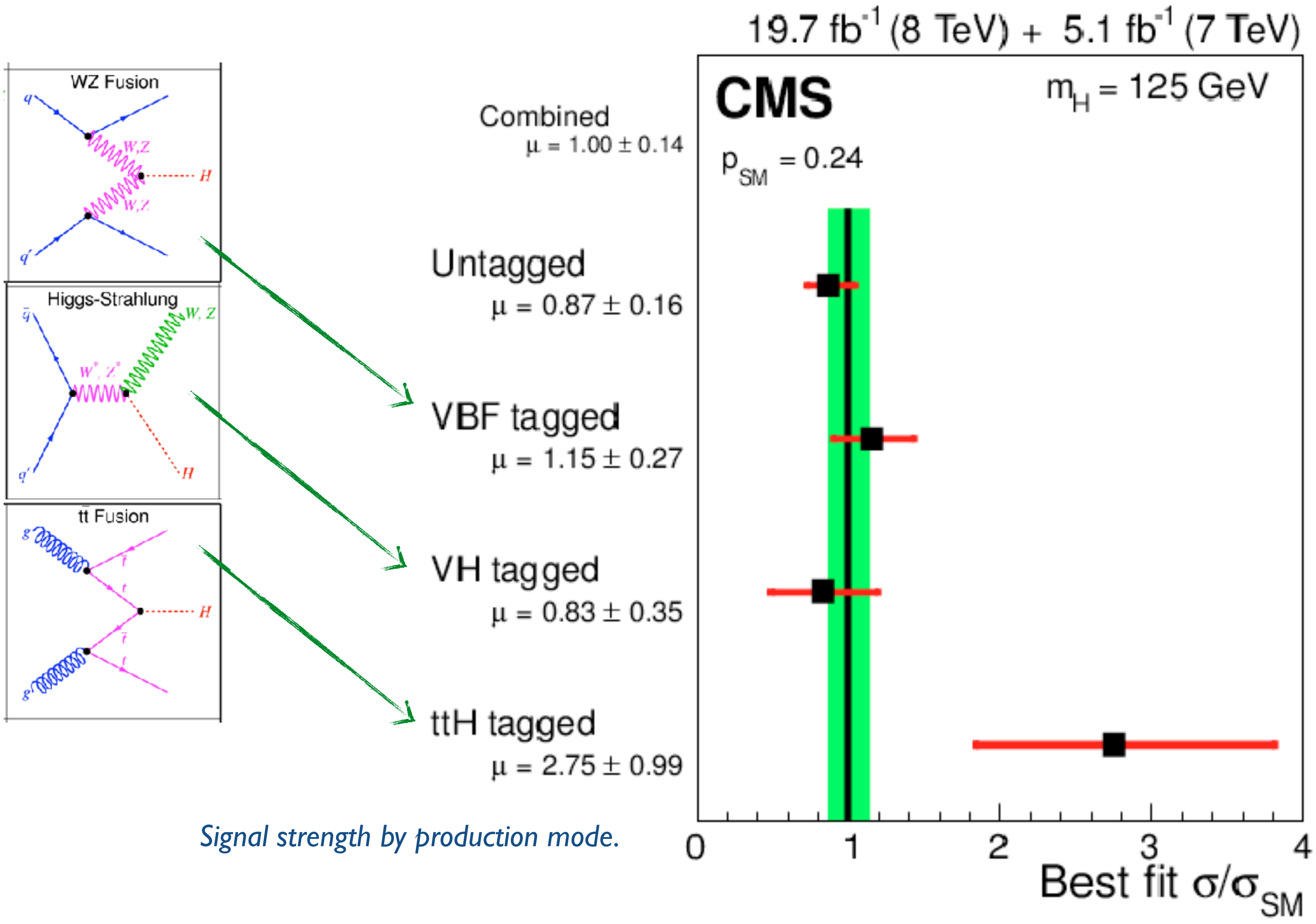


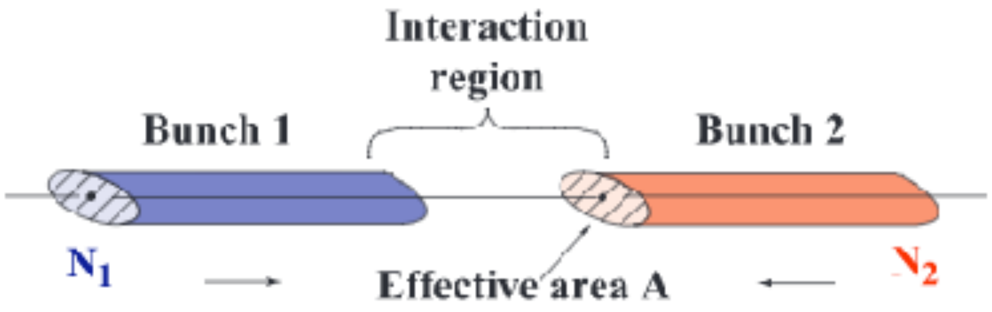
Signal strength by production mode.

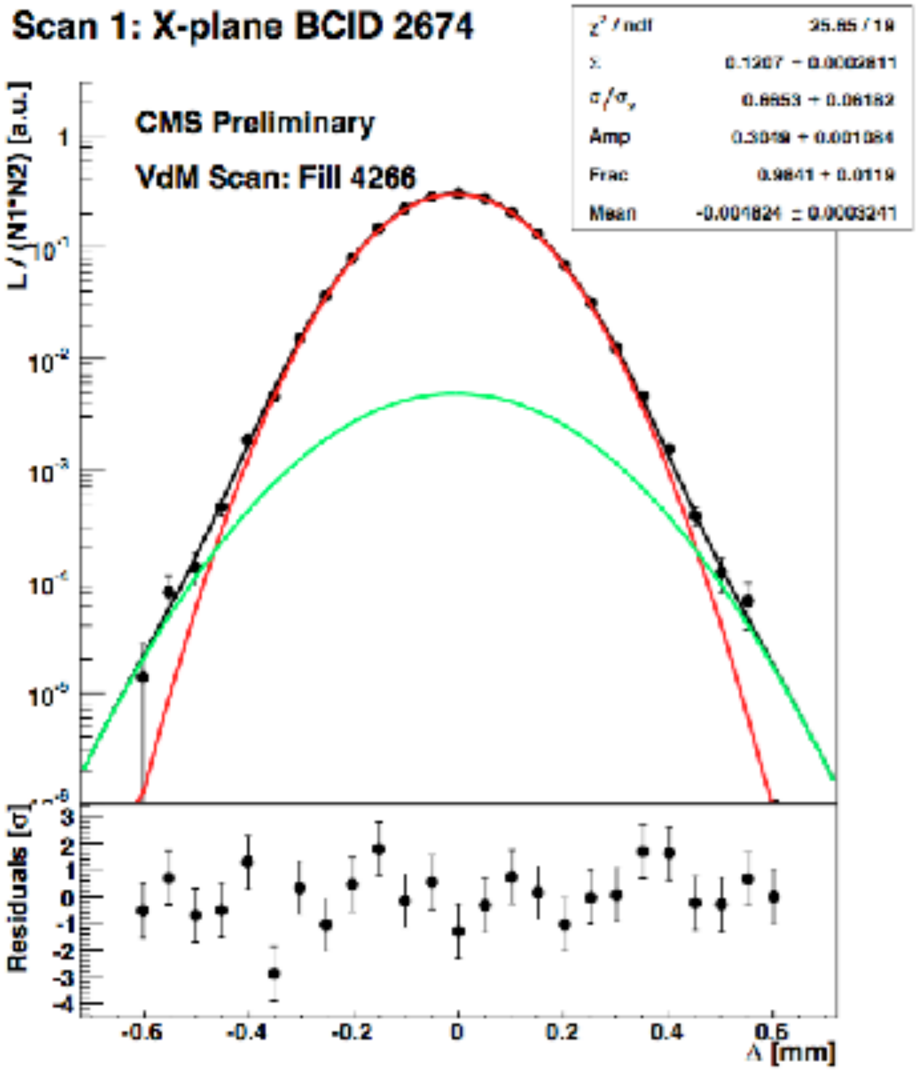
What about the other factors?

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

- Either they are fully determined in data
  - *Integrated luminosity ($\mathscr{L}$)* from Van-der-Meer scans

    see e.g. J.Varela - lecture #3 on standard model - link





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- **Either they are fully determined in data**
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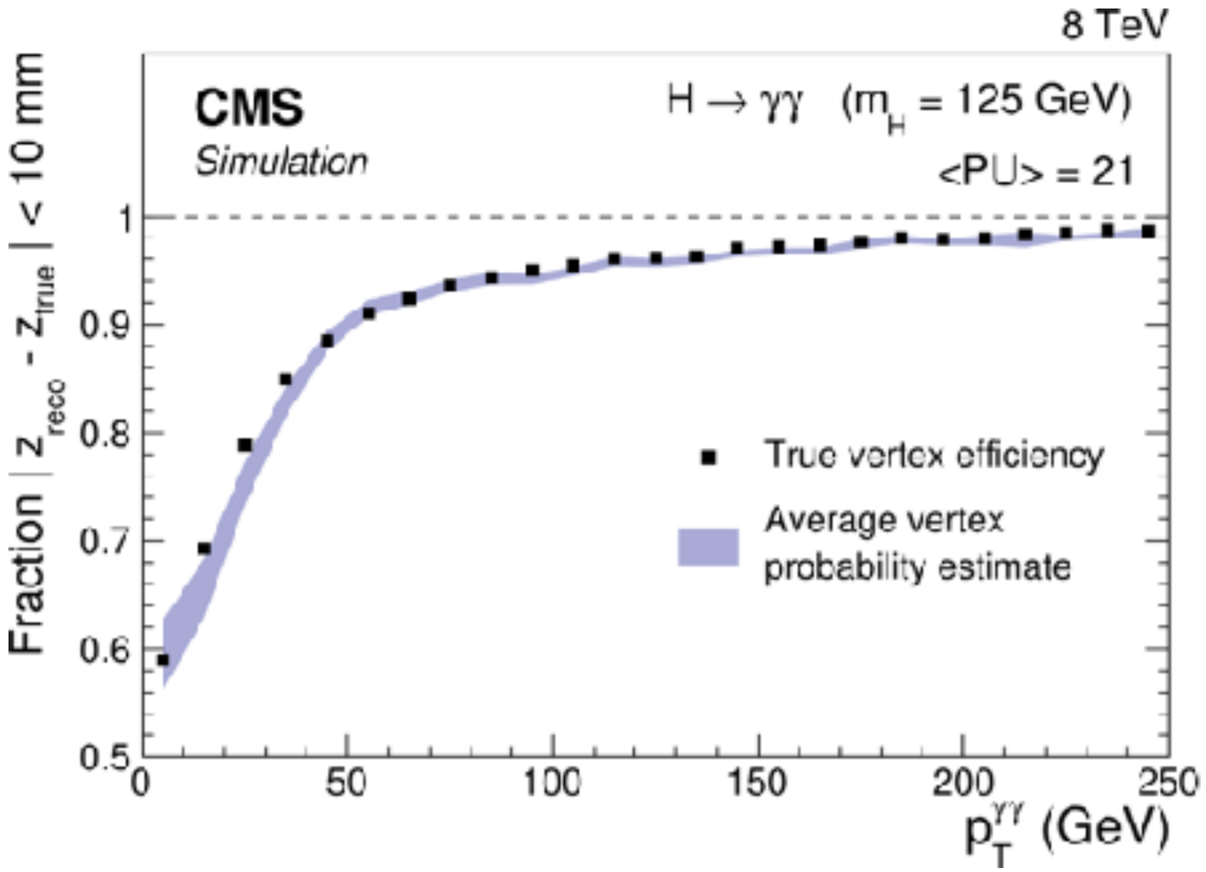
  - *efficiencies* (ε) measured from control regions
    - test dedicated selections in the analysis



Efficiency for the primary vertex selection in H→γγ

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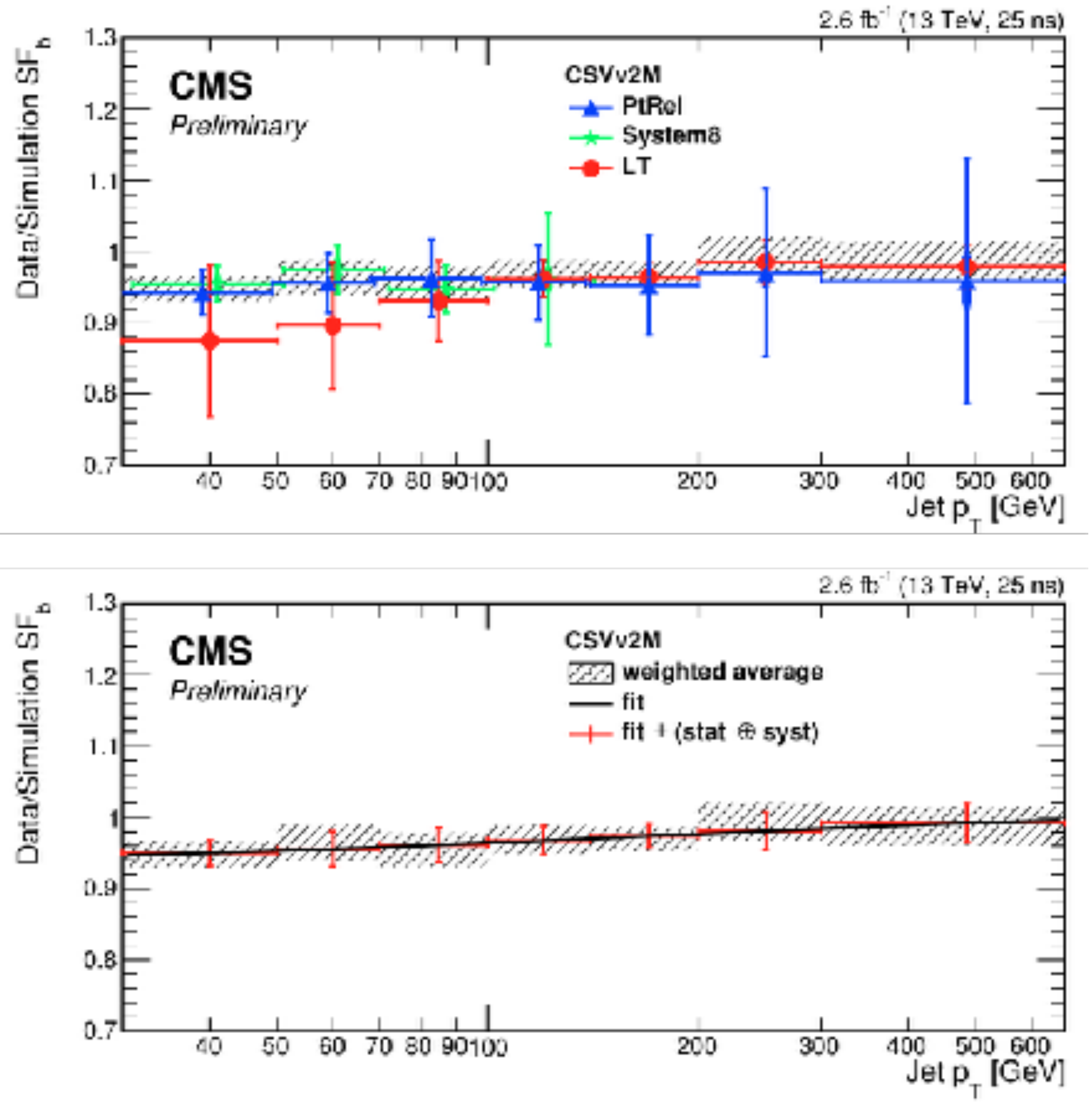
  - *efficiencies (ε)* measured from control regions
    - test dedicated selections in the analysis
    - e.g. Z→ℓℓ used for lepton efficiencies
    - e.g. dijets/top events for b-tagging efficiencies

    see e.g. M. Gallinaro - lecture #1 on top physics - link



b-tagging efficiency as function of the transverse momentum

What about the other factors?

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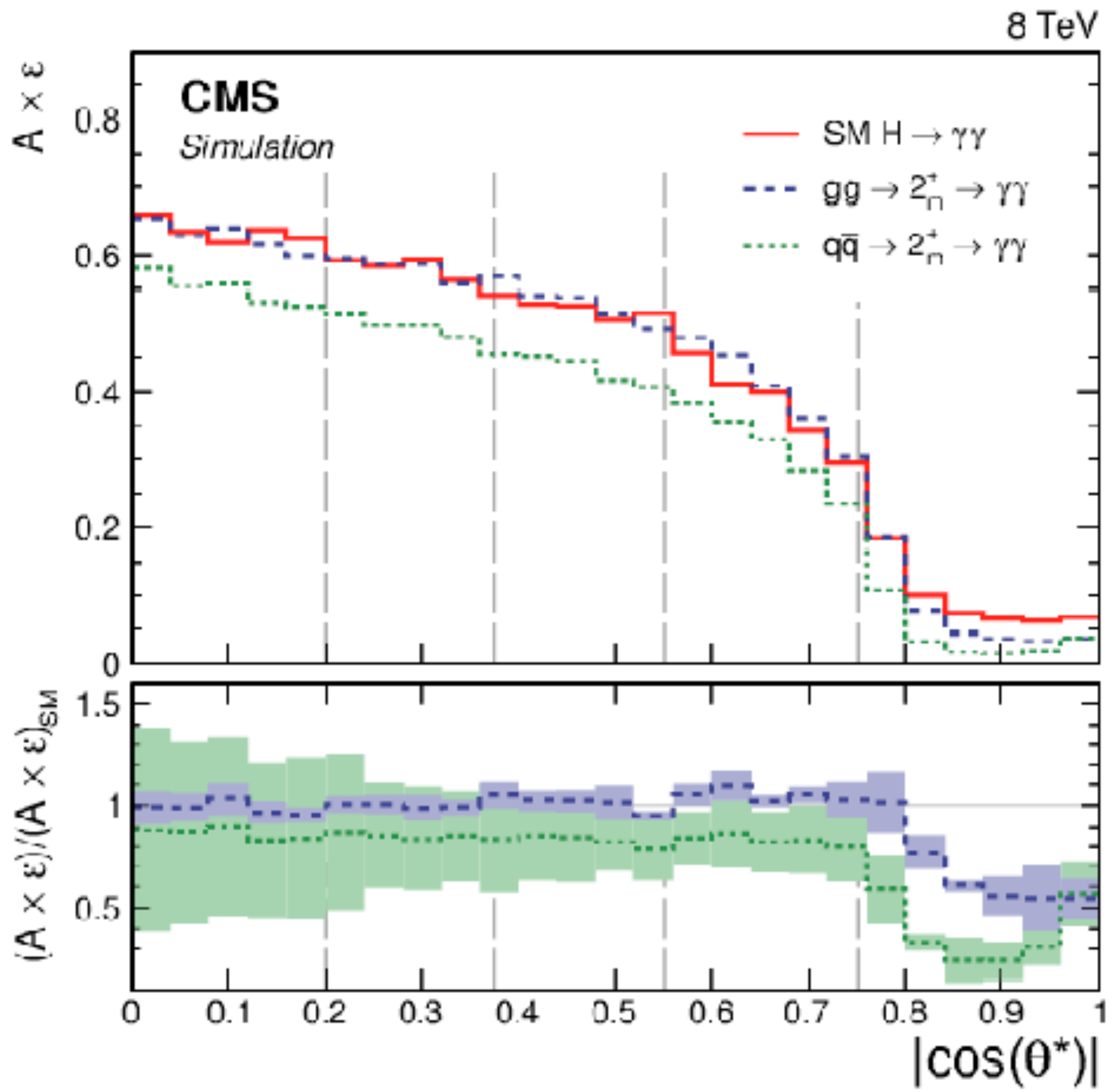
- Either they are estimated using simulation
  - acceptance depends mostly on the thresholds
  - dictated by geometry and trigger requirements
  - need to take into account physics
  - vertices at production and decay
  - but also radiation, fragmentation, hadronization, multiple parton interactions,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



Acceptance for different signal H→γγ hypothesis

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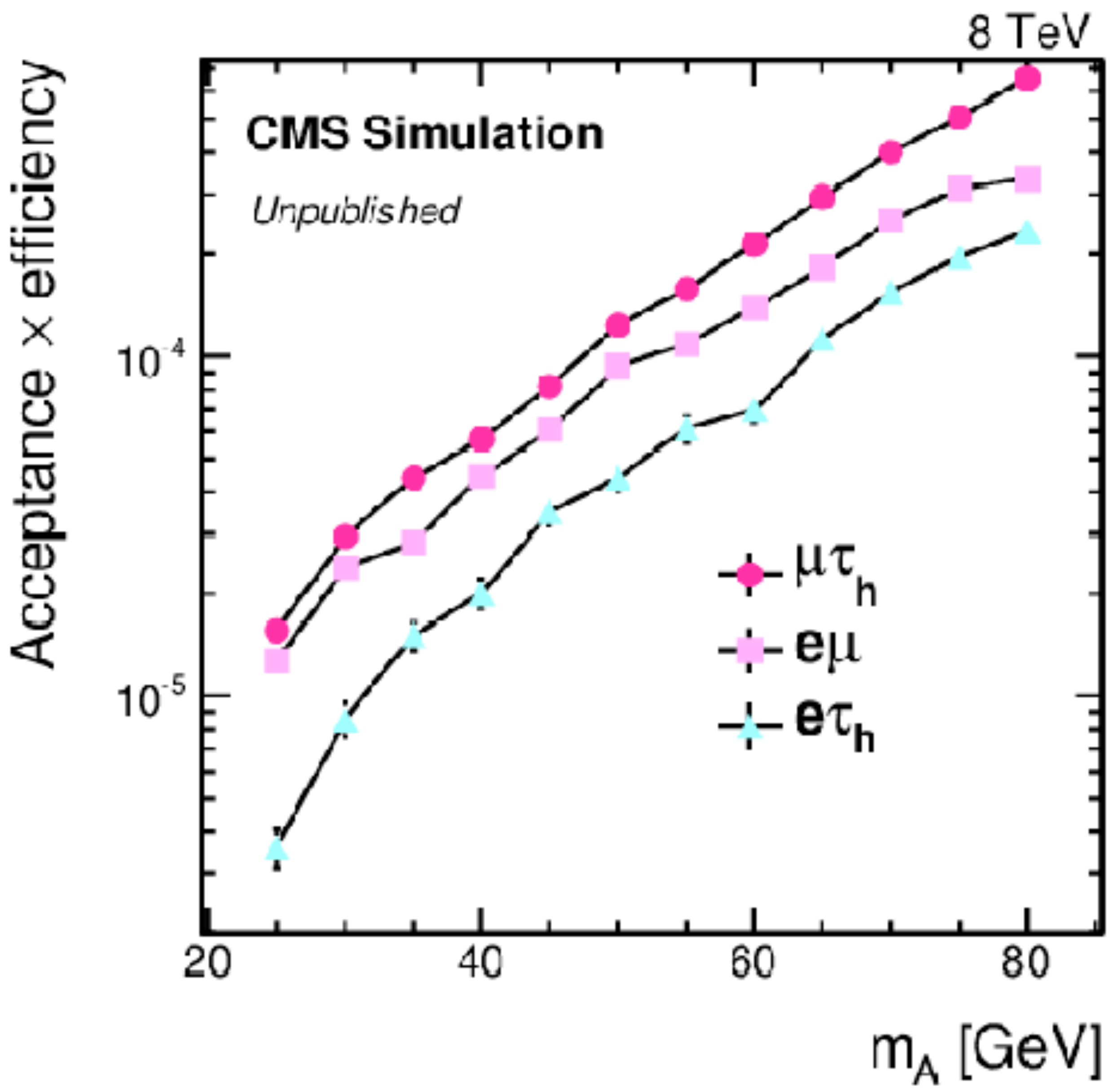

Acceptance for different signal A→ττ hypothesis

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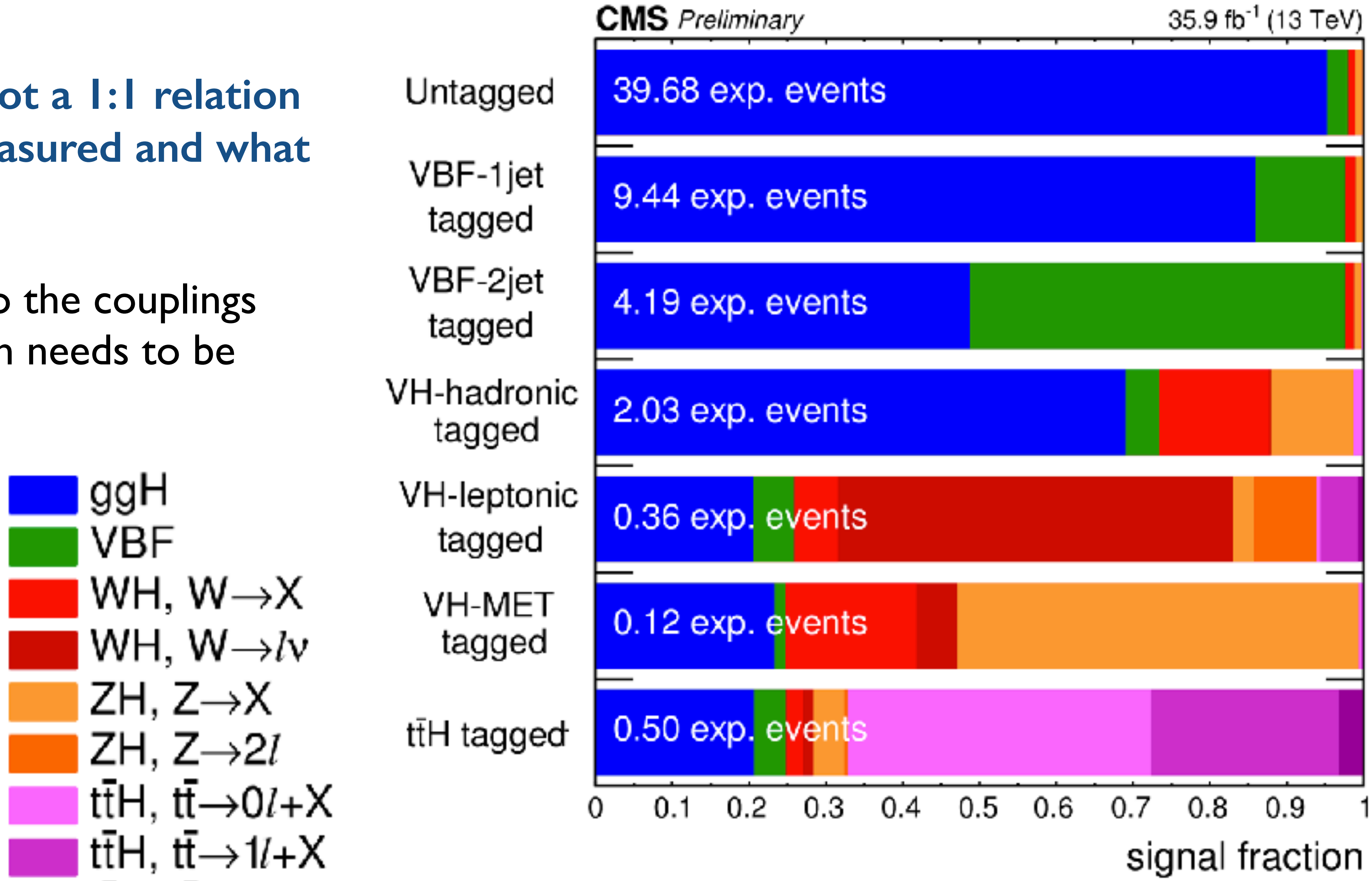
- **In the end there is not a 1:1 relation between what is measured and what can be produced**
  - to gain insight into the couplings every contribution needs to be accounted for



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

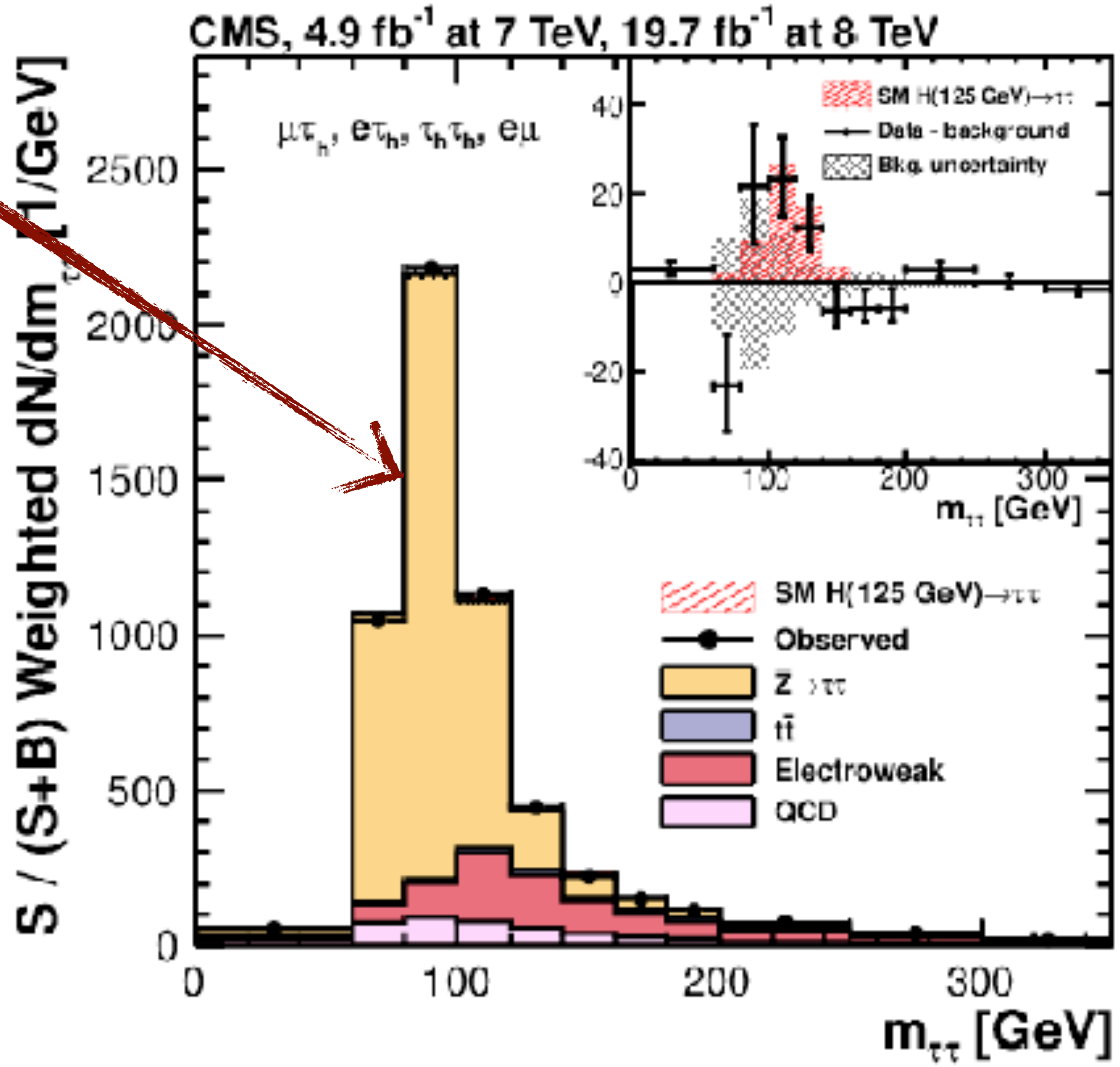
Using all the ingredients to fit the parameters of a model

- 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

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



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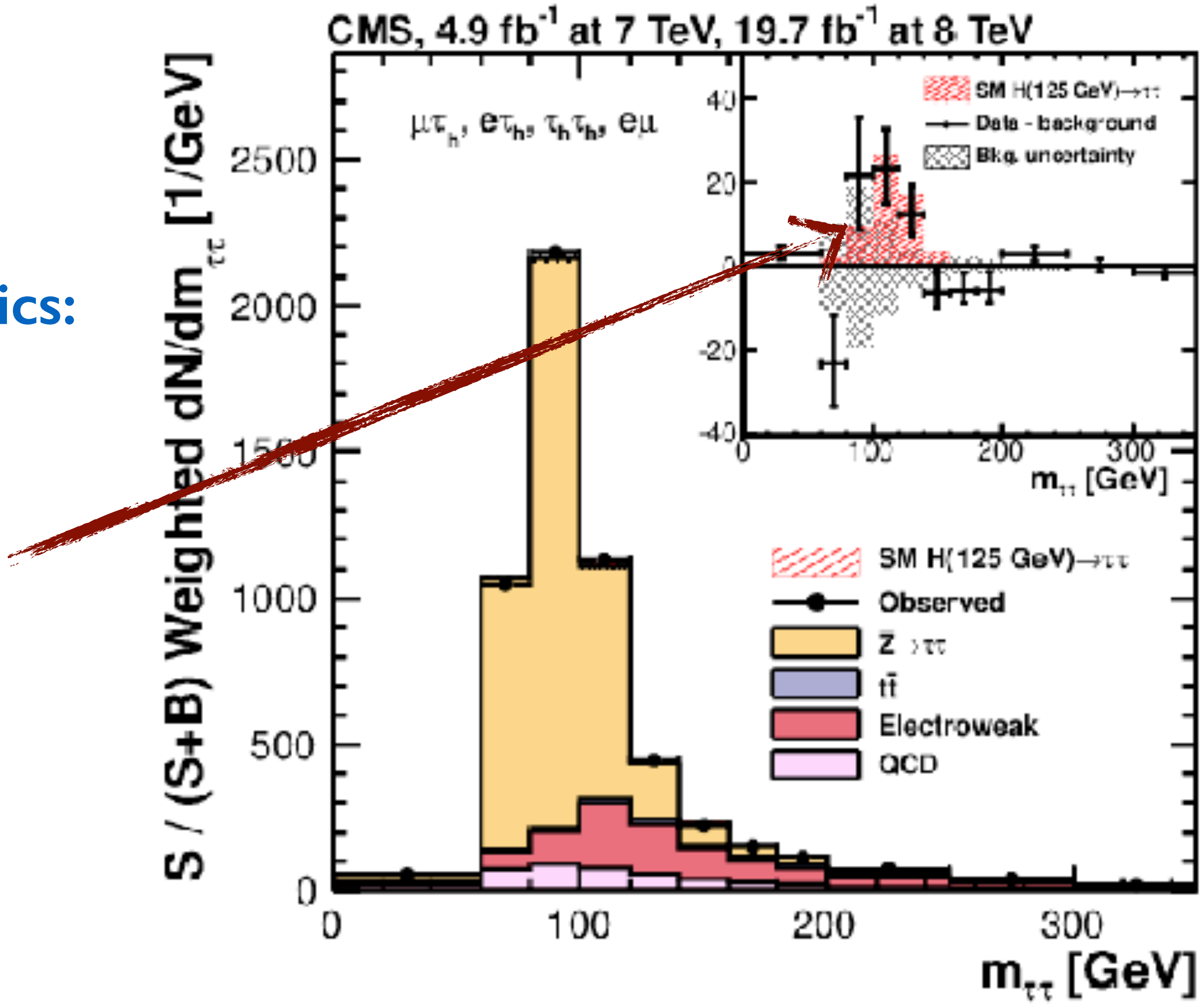
- **Counting experiments follow Poisson statistics:**

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



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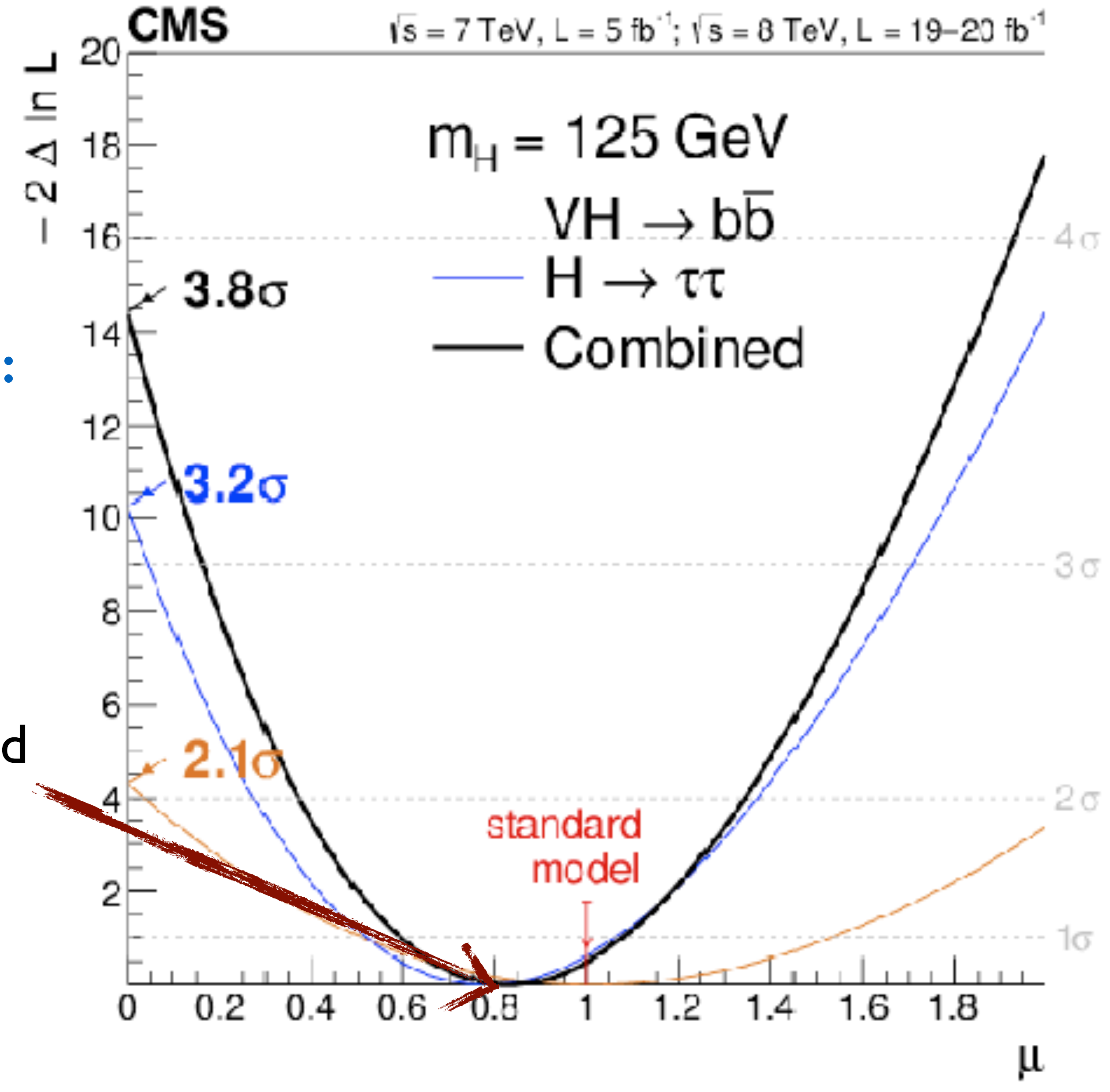
  - most probable value for μ maximises likelihood



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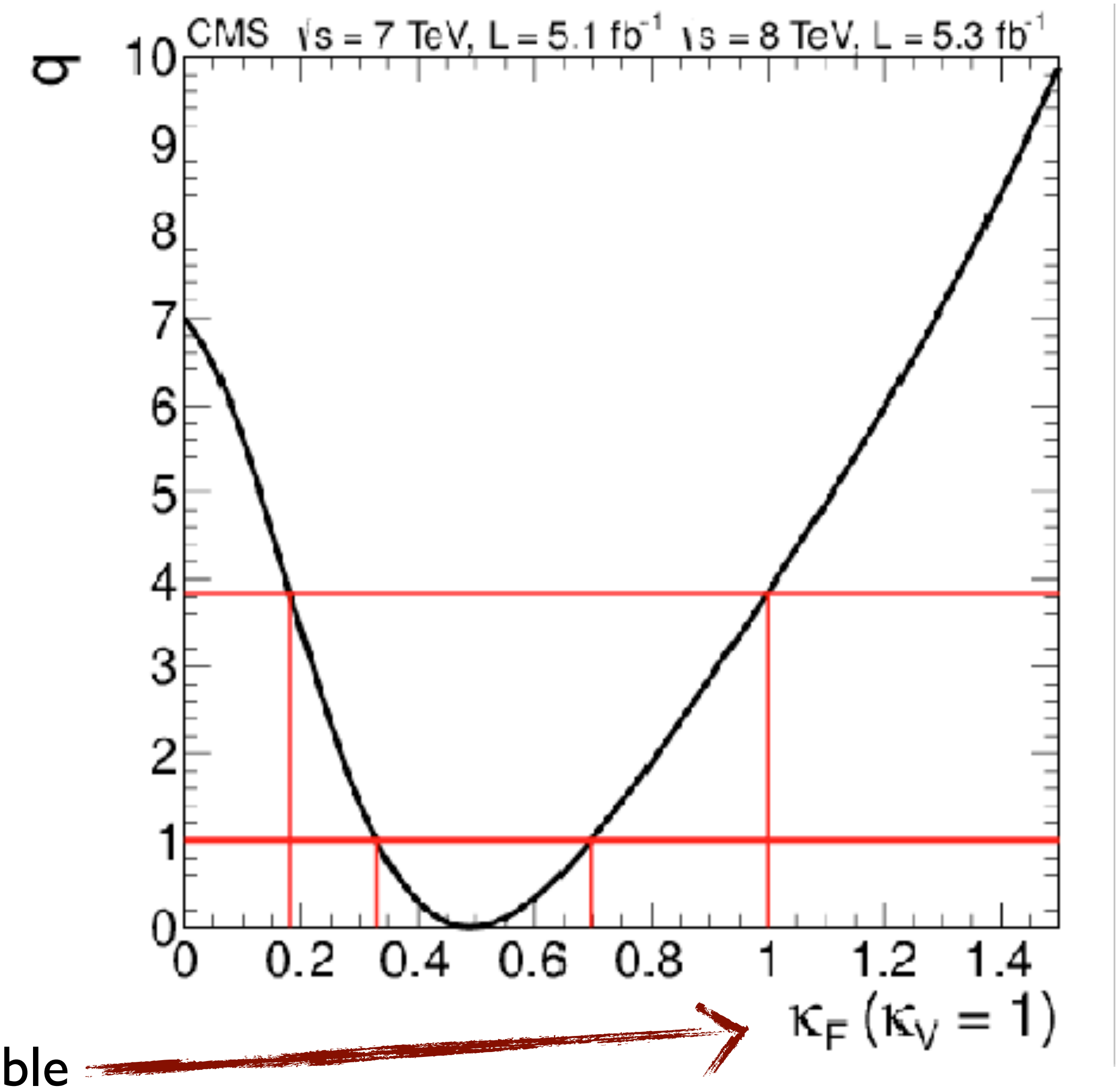
- **Easy to change parameters/theory framework**
  - probabilities are invariant under change of variable

see statistics lecture by P. Vischia - link

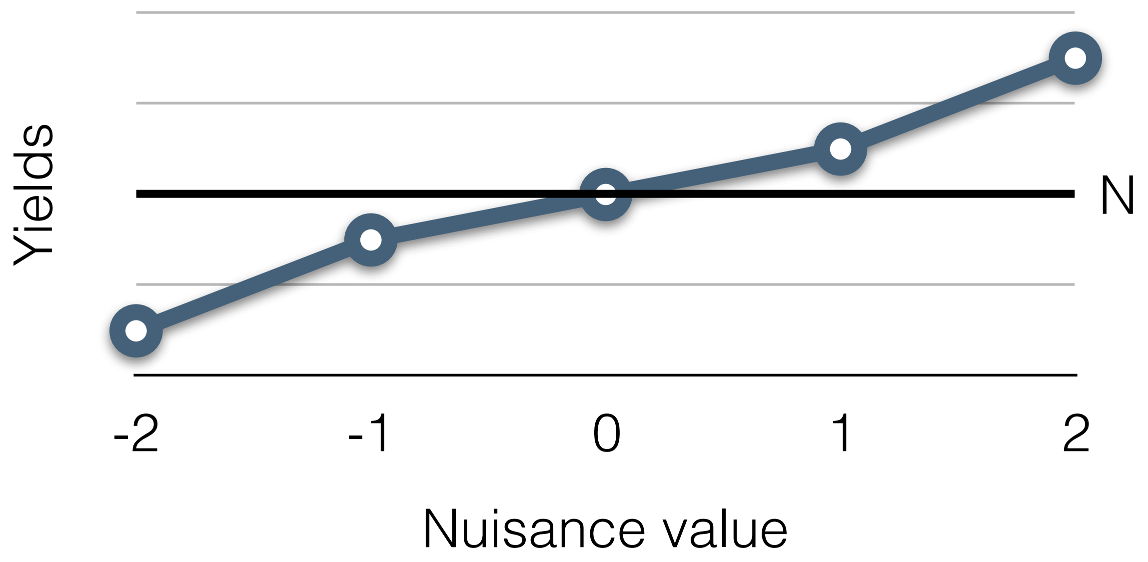


$$\mu \to \mu(\kappa_F, \kappa_V)$$
$$\lambda(\mu) \to \lambda(\kappa_F, \kappa_V)$$

Incorporating uncertainties in the fit I

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

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



- **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

$$\mathcal{L}[\lambda(\mu, \vec{\theta})] = \mathcal{P}_{\text{oisson}}[n_{\text{obs}}|\lambda(\mu, \vec{\theta})] \cdot \prod_i \mathcal{P}_{\text{DF}}(0|\theta_i)$$

Incorporating uncertainties in the fit II

- **Profile likelihood ratio test statistics:**

maximizes L for specified μ

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

maximize L

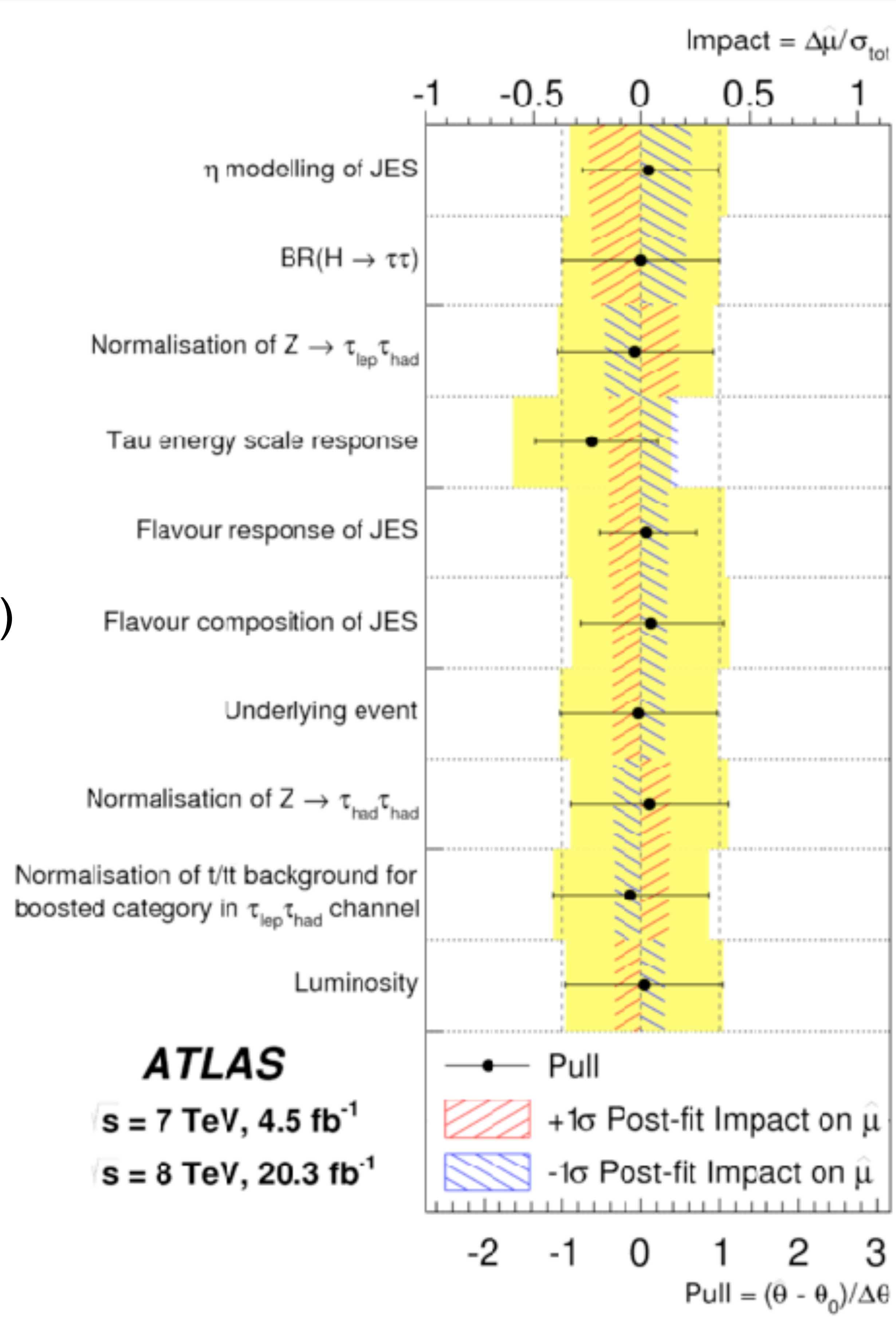
  - for each likelihood evaluation all systematic uncertainties (nuisances) are varied
  - normalise to the likelihood at best fit value
  - maximum determines best set of parameters (nuisances are profiled)
- **Combined fit for Higgs properties at the LHC**
  - >200 channels and >4000 nuisances in the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

Incorporating uncertainties in the fit III

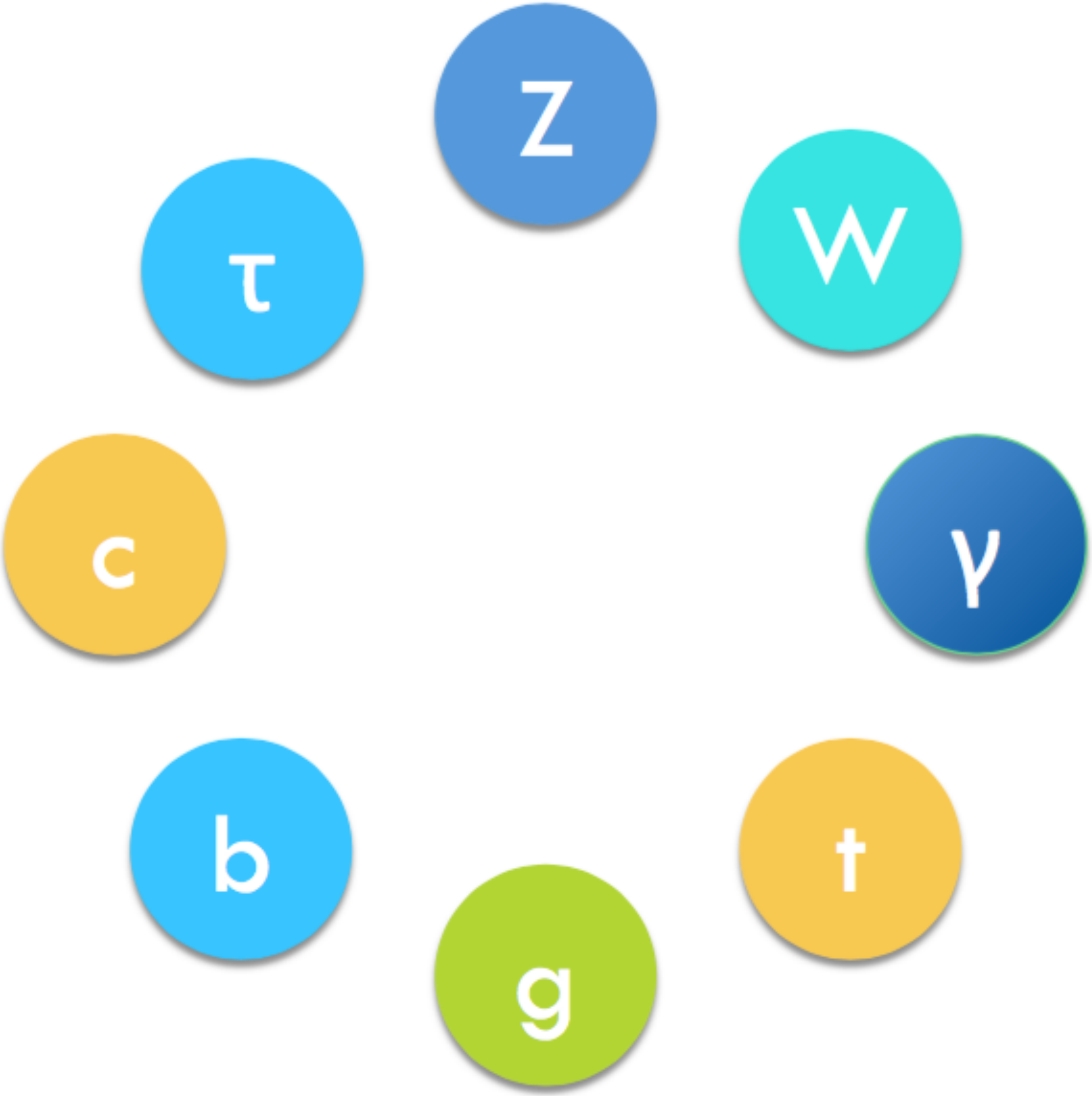
- *Here is an example from a H→ττ search*

- **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 ±1σ and check variation in μ



The model: scalar coupling structure



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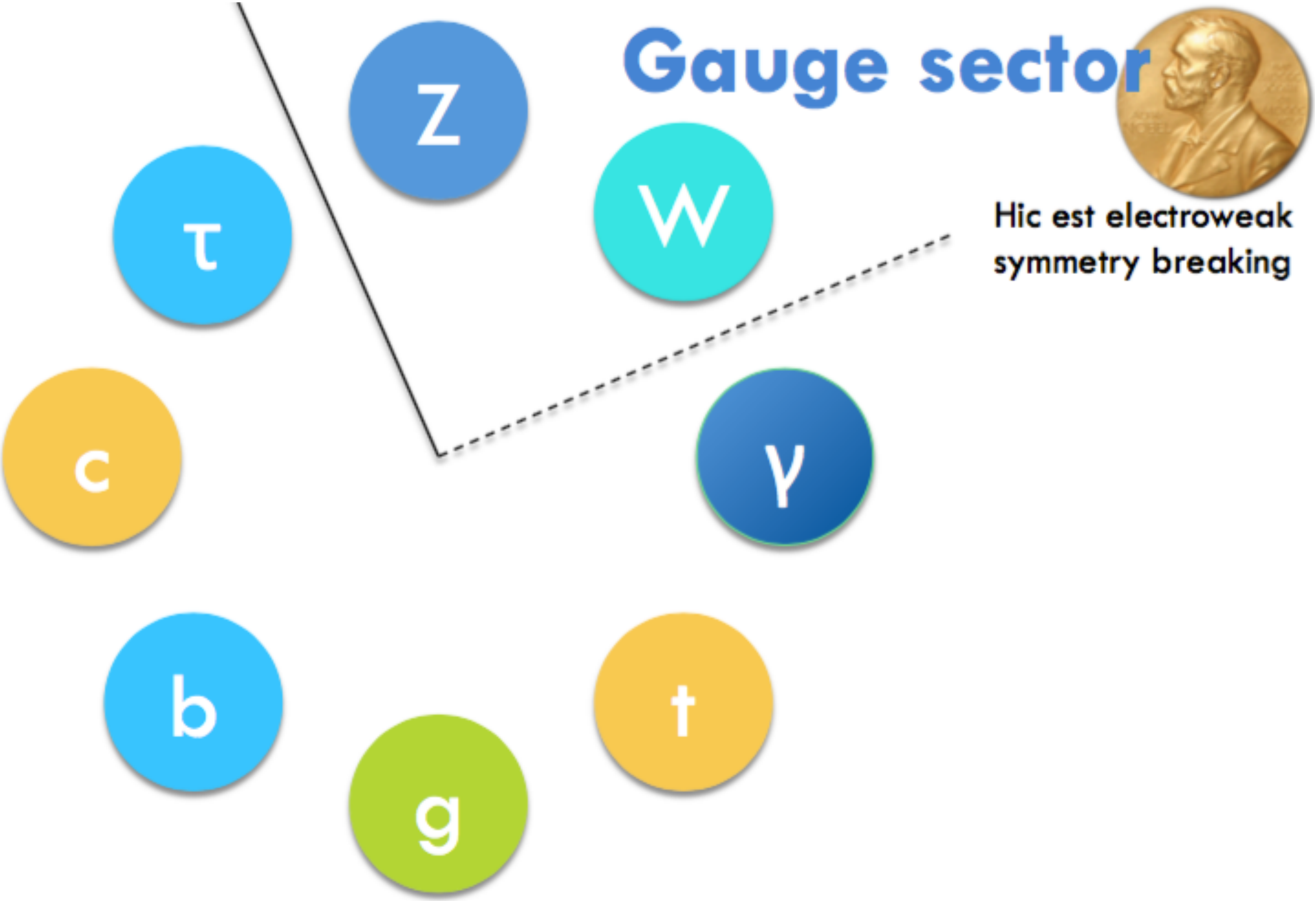
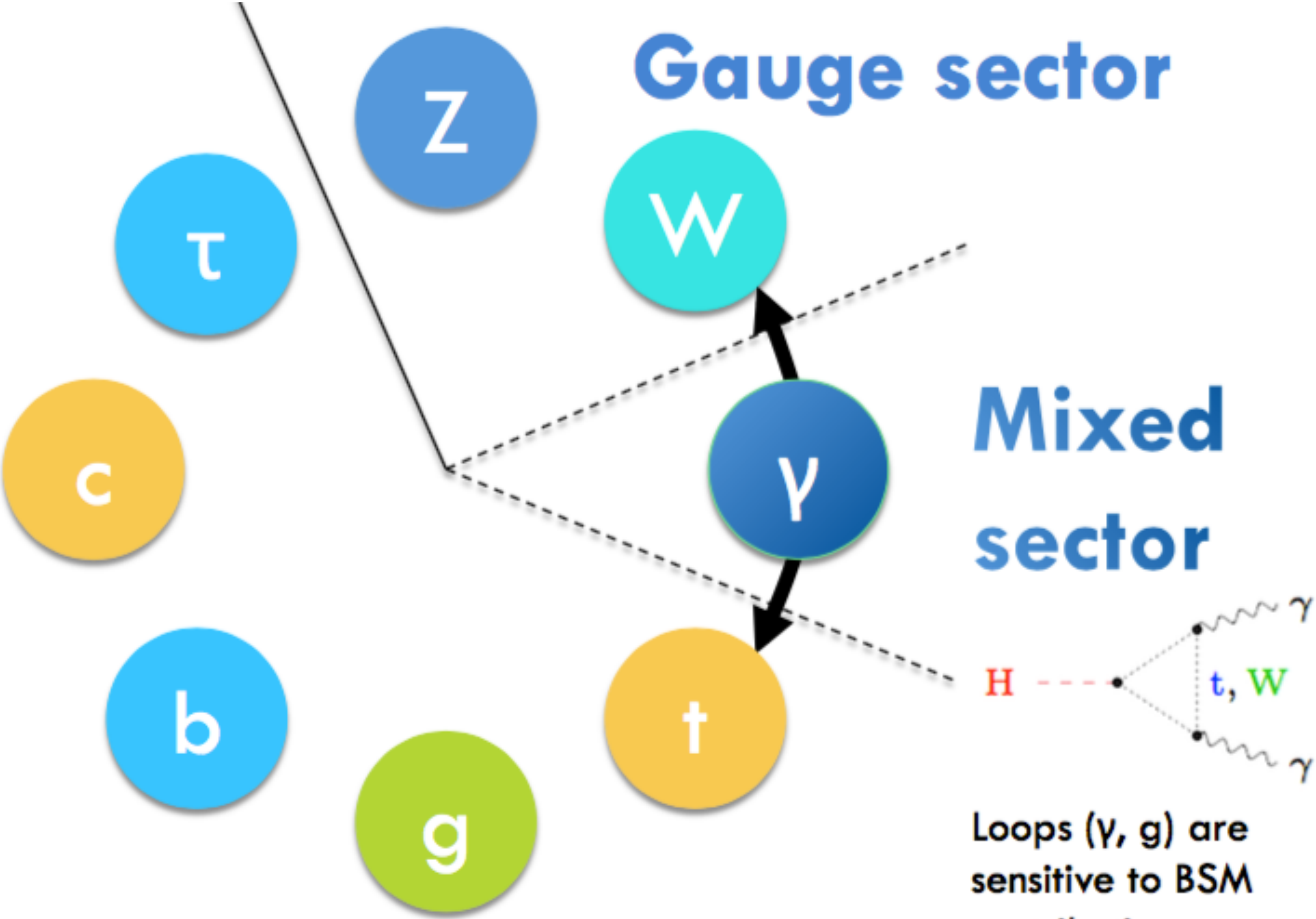


Gauge sector

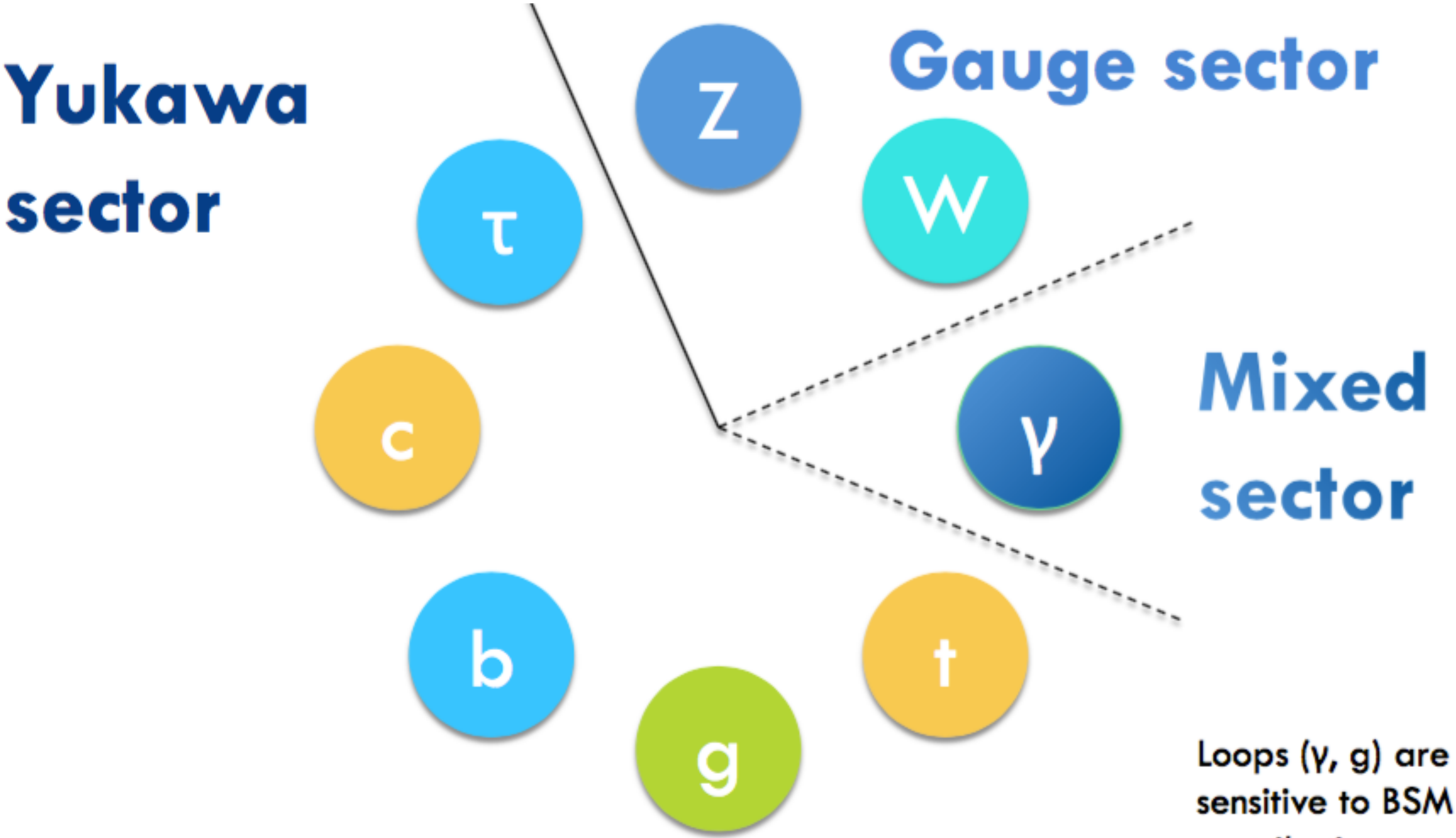
Hic est electroweak symmetry breaking

The model: scalar coupling structure



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

The model: scalar coupling structure



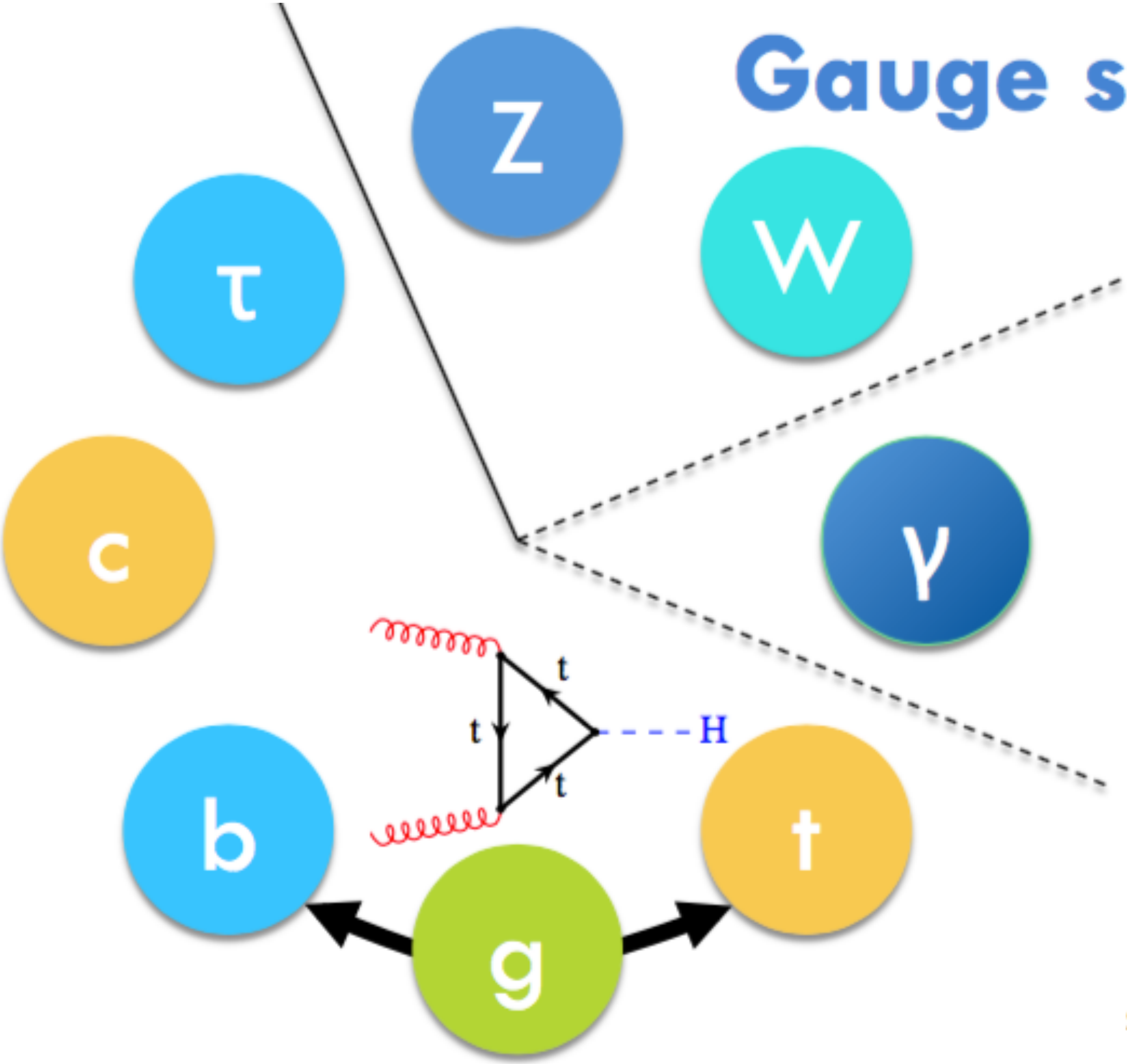
Loops (γ, g) are sensitive to BSM contributions.

The model: scalar coupling structure

Yukawa sector

Gauge sector

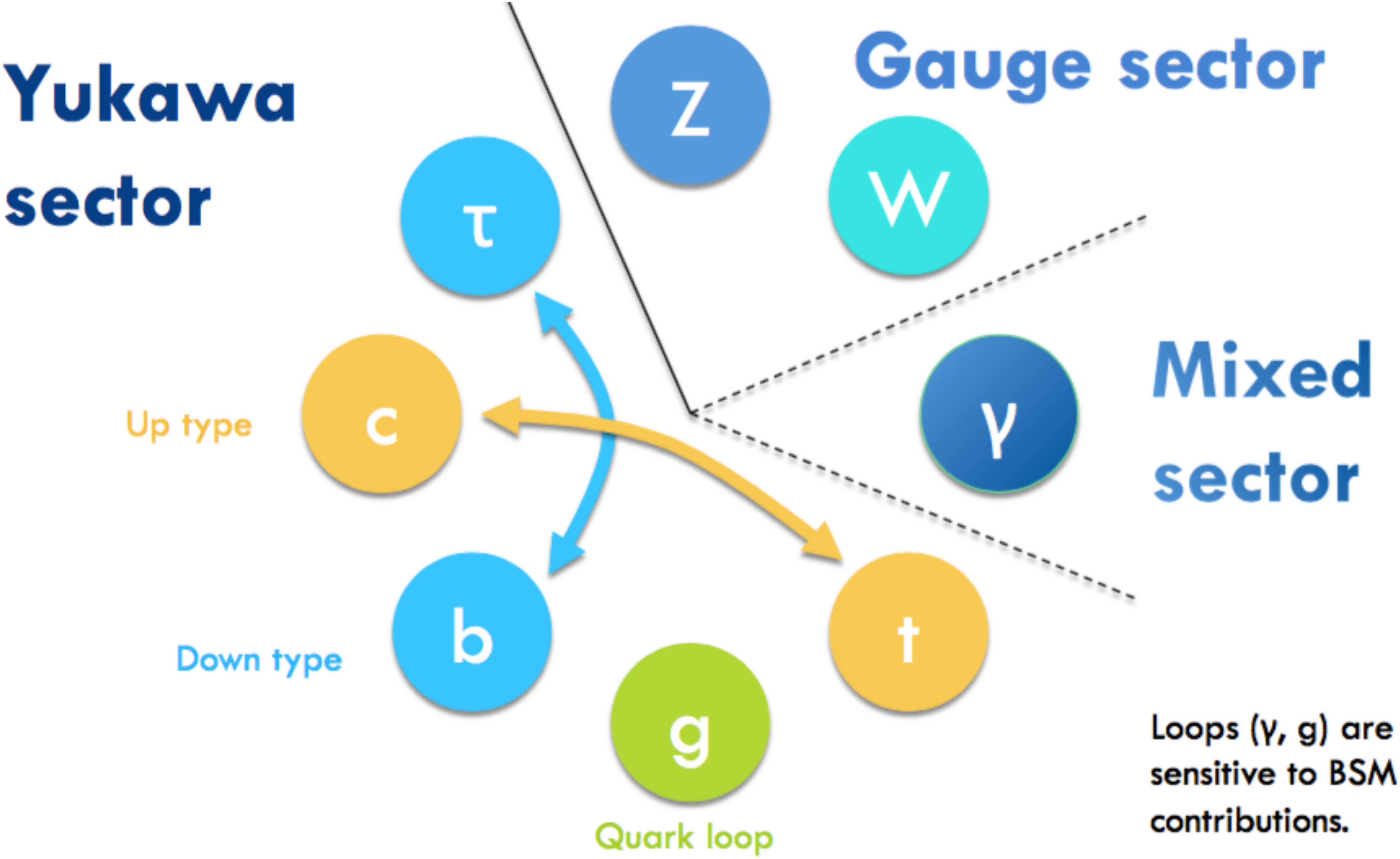
Mixed sector



Quark loop

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

The model: scalar coupling structure



Yukawa sector

Gauge sector

Mixed sector

Up type

Down type

Quark loop

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

Parameterizing deviations from SM couplings

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

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

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

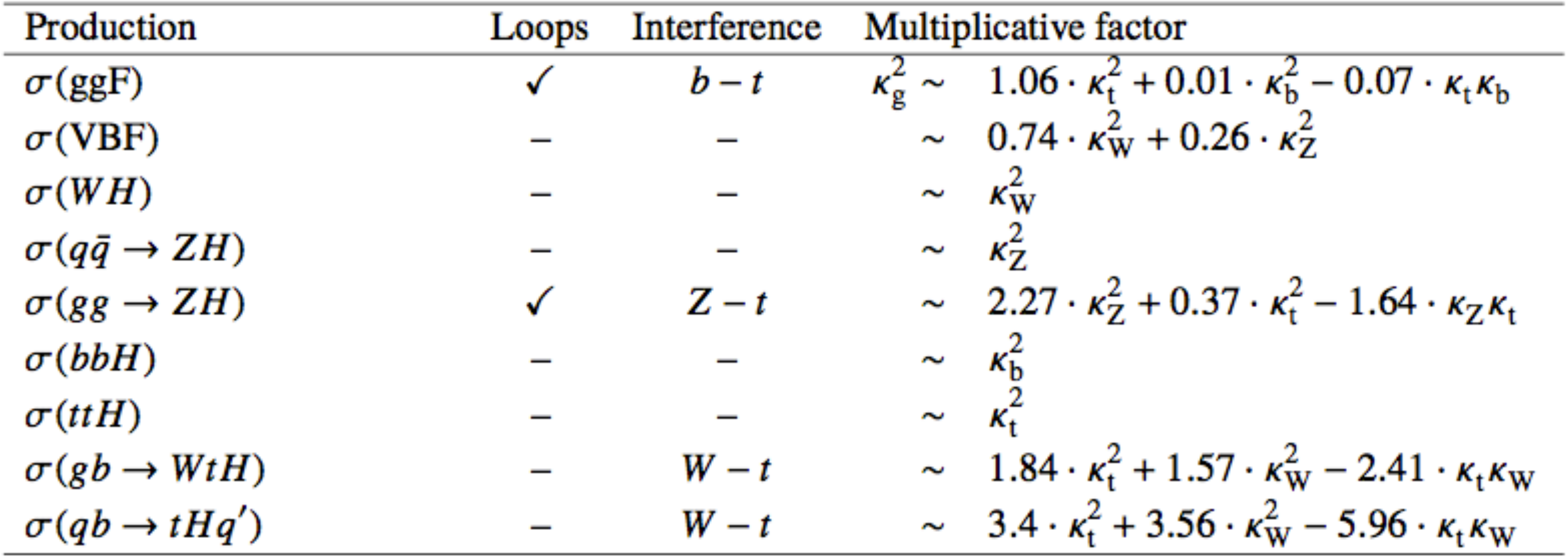
$$\kappa_H^2 = \textstyle\sum_j \mathrm{BR}^j_{\mathrm{SM}} \kappa_j^2$$

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

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

Deviations in production

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

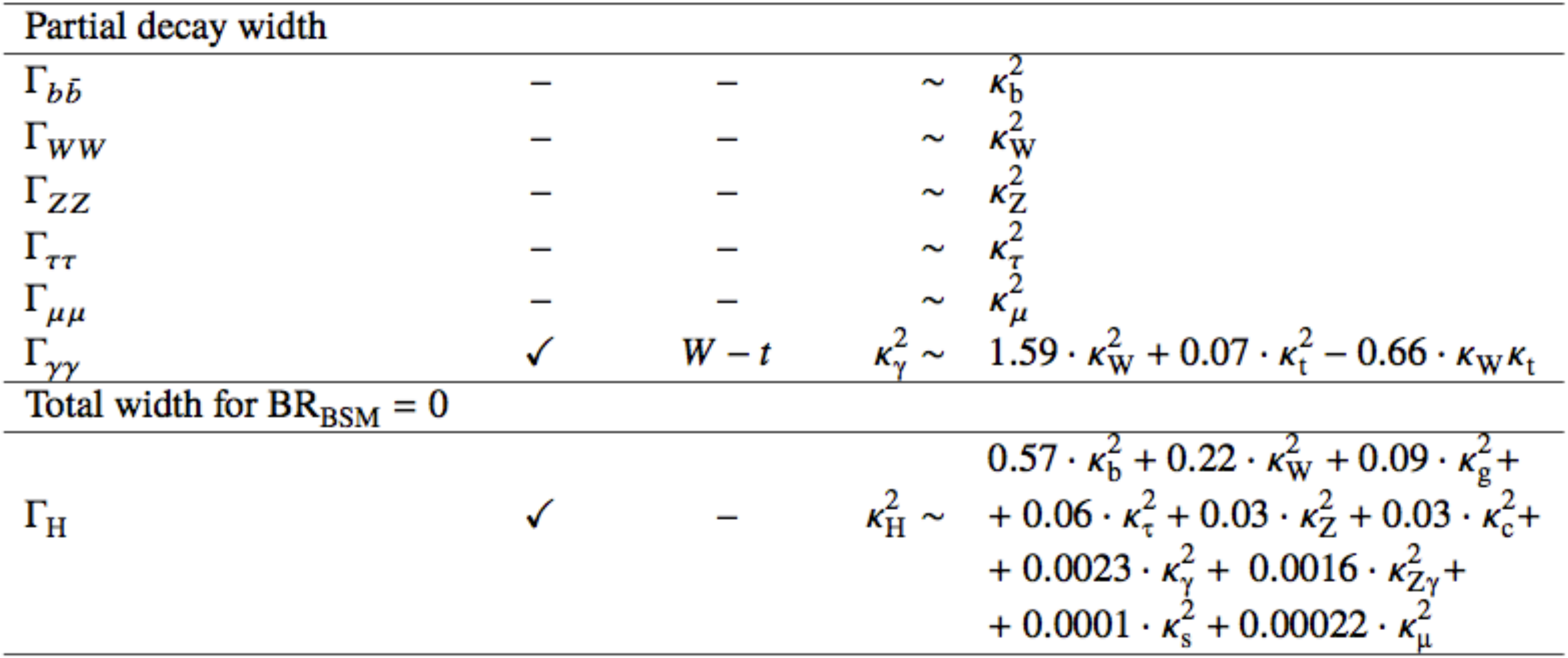


Production	Loops	Interference	Multiplicative factor
$\sigma(\mathrm{ggF})$	✓	$b-t$	$\kappa_{\mathrm{g}}^2 \sim 1.06 \cdot \kappa_{\mathrm{t}}^2 + 0.01 \cdot \kappa_{\mathrm{b}}^2 - 0.07 \cdot \kappa_{\mathrm{t}}\kappa_{\mathrm{b}}$
$\sigma(\mathrm{VBF})$	–	–	$\sim 0.74 \cdot \kappa_{\mathrm{W}}^2 + 0.26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

see details in arXiv:1307.1347

Deviations in decays

- Direct decays (WW, ZZ, etc.) are assigned with a single parameter
- Decays via loops (ɣɣ, Zɣ) depend on the particles running in the loop

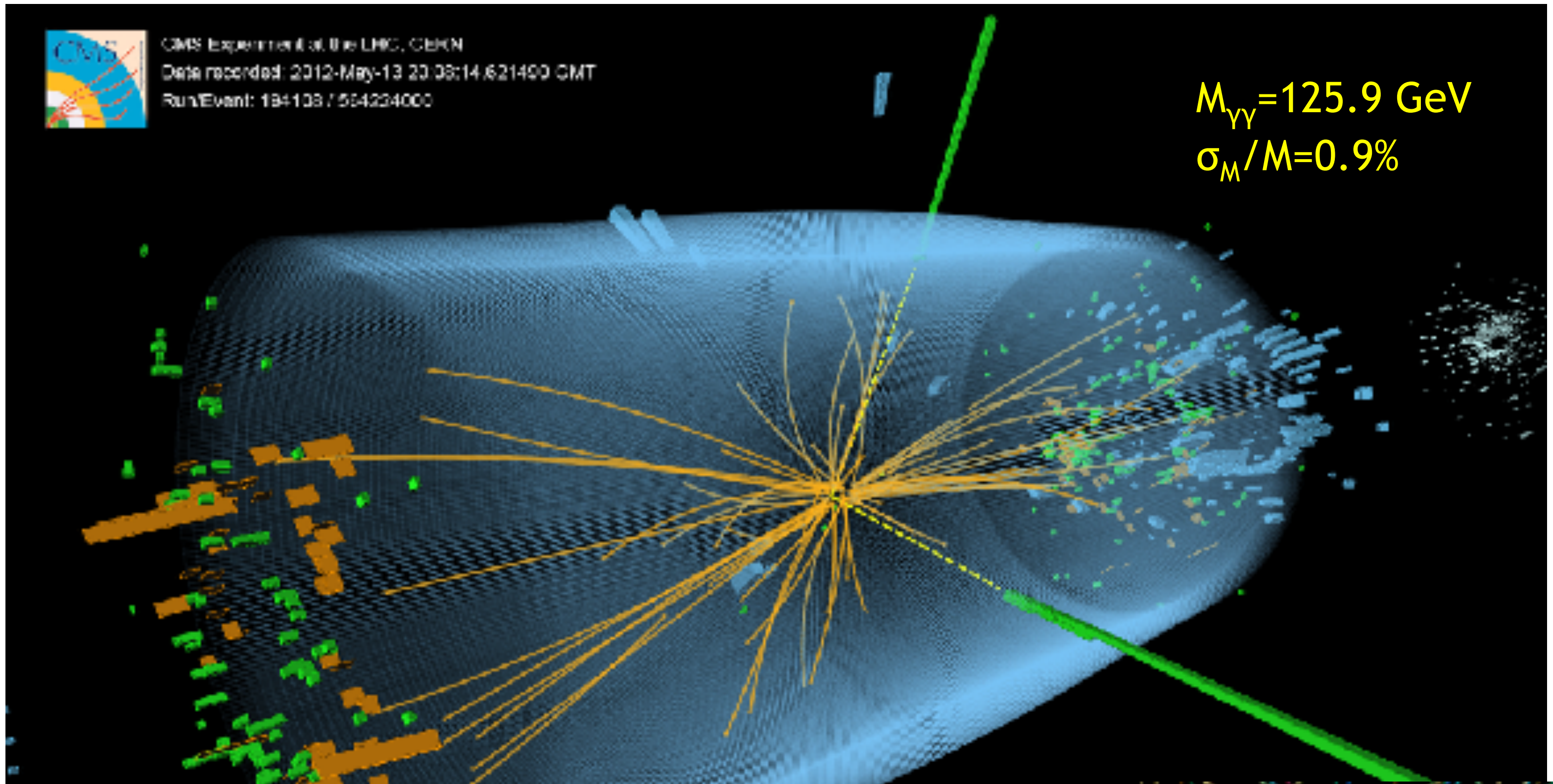


Partial decay width				
$\Gamma_{b\bar{b}}$	–	–	$\sim$	κ_{b}^2
Γ_{WW}	–	–	$\sim$	κ_{W}^2
Γ_{ZZ}	–	–	$\sim$	κ_{Z}^2
$\Gamma_{\tau\tau}$	–	–	$\sim$	κ_{τ}^2
$\Gamma_{\mu\mu}$	–	–	$\sim$	κ_{μ}^2
$\Gamma_{\gamma\gamma}$	✓	$W-t$	$\kappa_{\gamma}^2 \sim$	$1.59 \cdot \kappa_{\mathrm{W}}^2 + 0.07 \cdot \kappa_{\mathrm{t}}^2 - 0.66 \cdot \kappa_{\mathrm{W}}\kappa_{\mathrm{t}}$
Total width for $\mathrm{BR}_{\mathrm{BSM}} = 0$				
Γ_{H}	✓	–	$\kappa_{\mathrm{H}}^2 \sim$	$0.57 \cdot \kappa_{\mathrm{b}}^2 + 0.22 \cdot \kappa_{\mathrm{W}}^2 + 0.09 \cdot \kappa_{\mathrm{g}}^2 +$ $+ 0.06 \cdot \kappa_{\tau}^2 + 0.03 \cdot \kappa_{\mathrm{Z}}^2 + 0.03 \cdot \kappa_{\mathrm{c}}^2 +$ $+ 0.0023 \cdot \kappa_{\gamma}^2 + 0.0016 \cdot \kappa_{\mathrm{Z}\gamma}^2 +$ $+ 0.0001 \cdot \kappa_{\mathrm{s}}^2 + 0.00022 \cdot \kappa_{\mu}^2$

see details in arXiv:1307.1347

Results: mass, charge, spin and parity, couplings

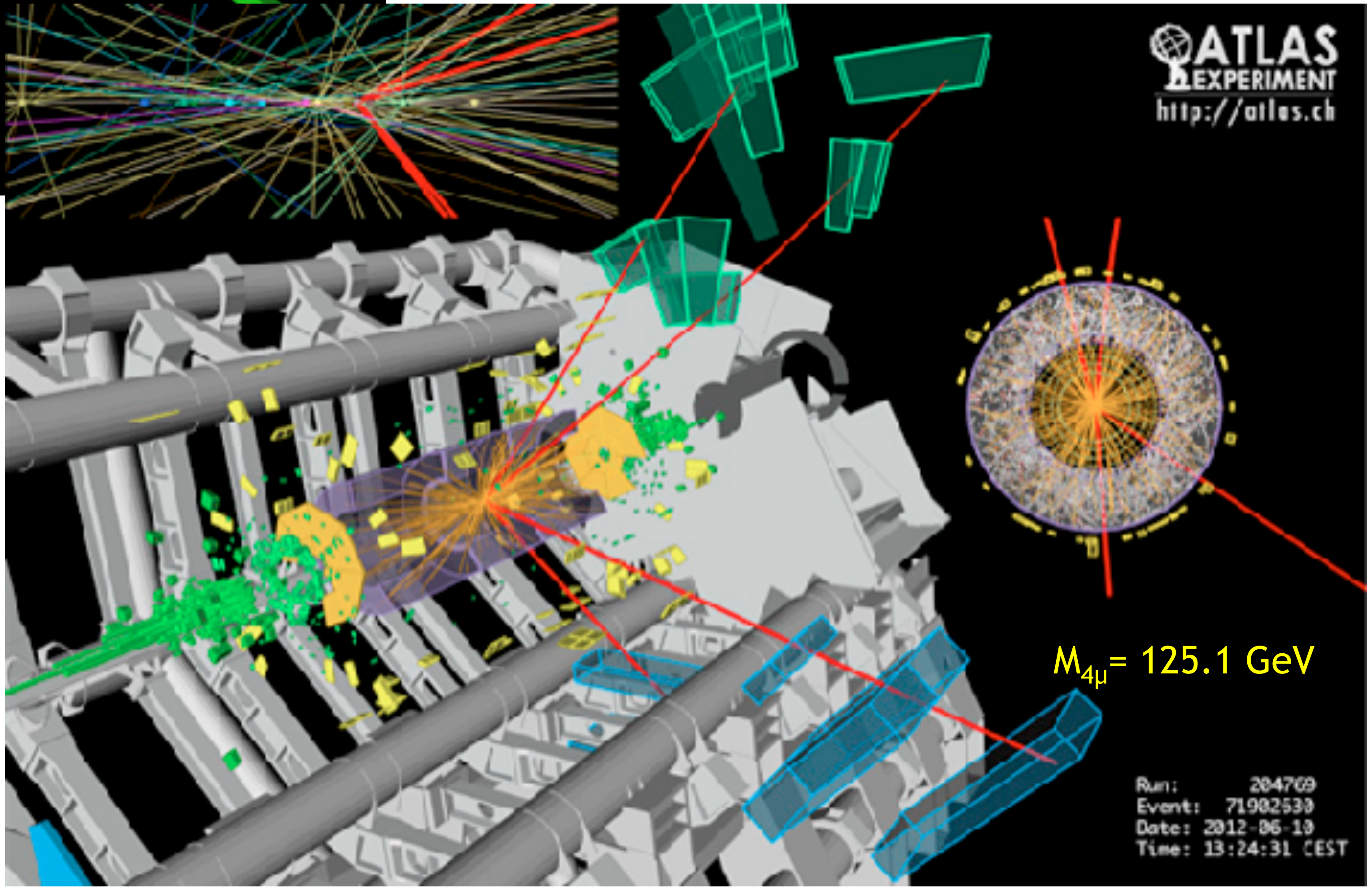
Mass



$M_{\gamma\gamma}$=125.9 GeV
σ_M/M=0.9%

- The two channels with highest resolution are used to measure the mass: γγ and 4l

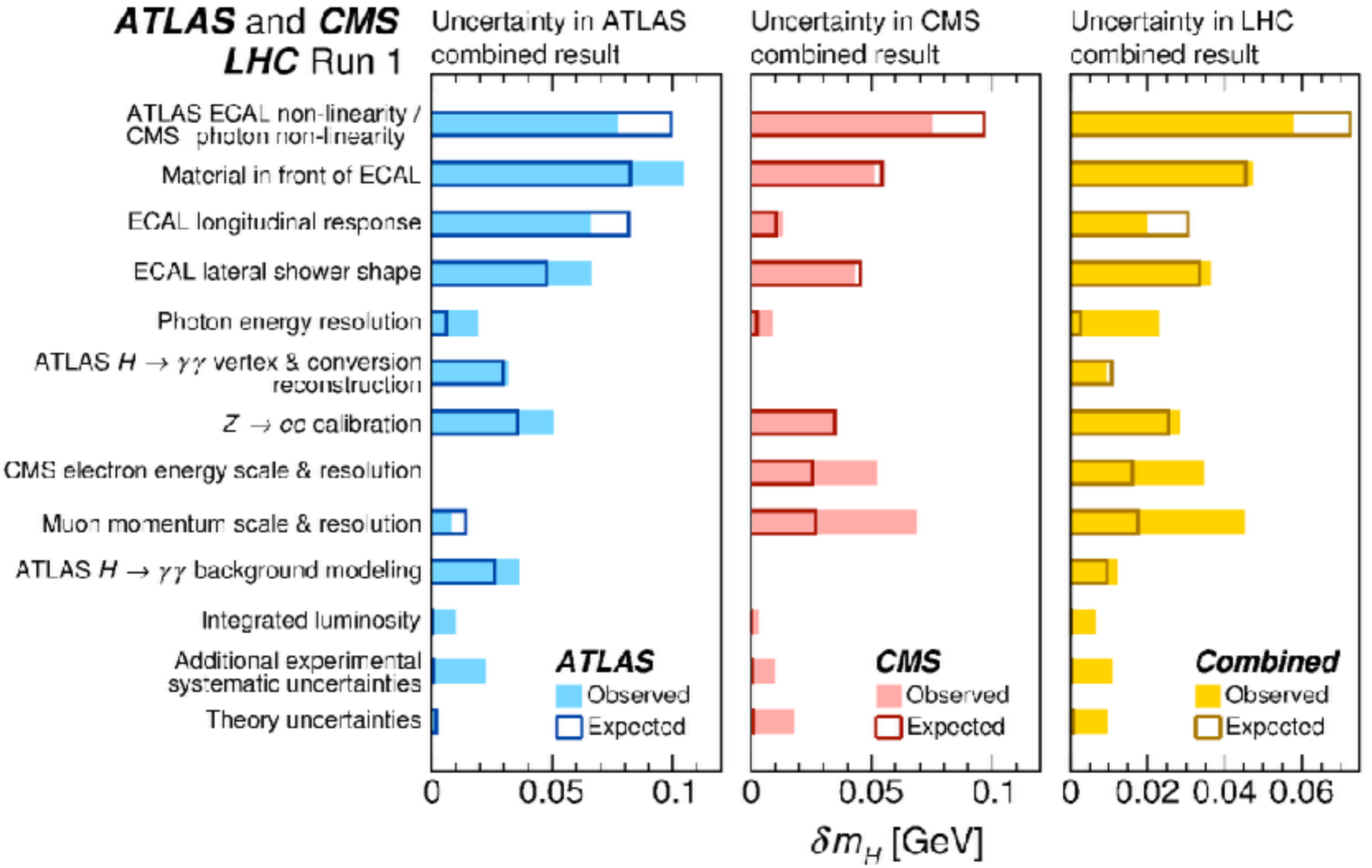
- Energy scale and resolution are the most important systematic effects to understand



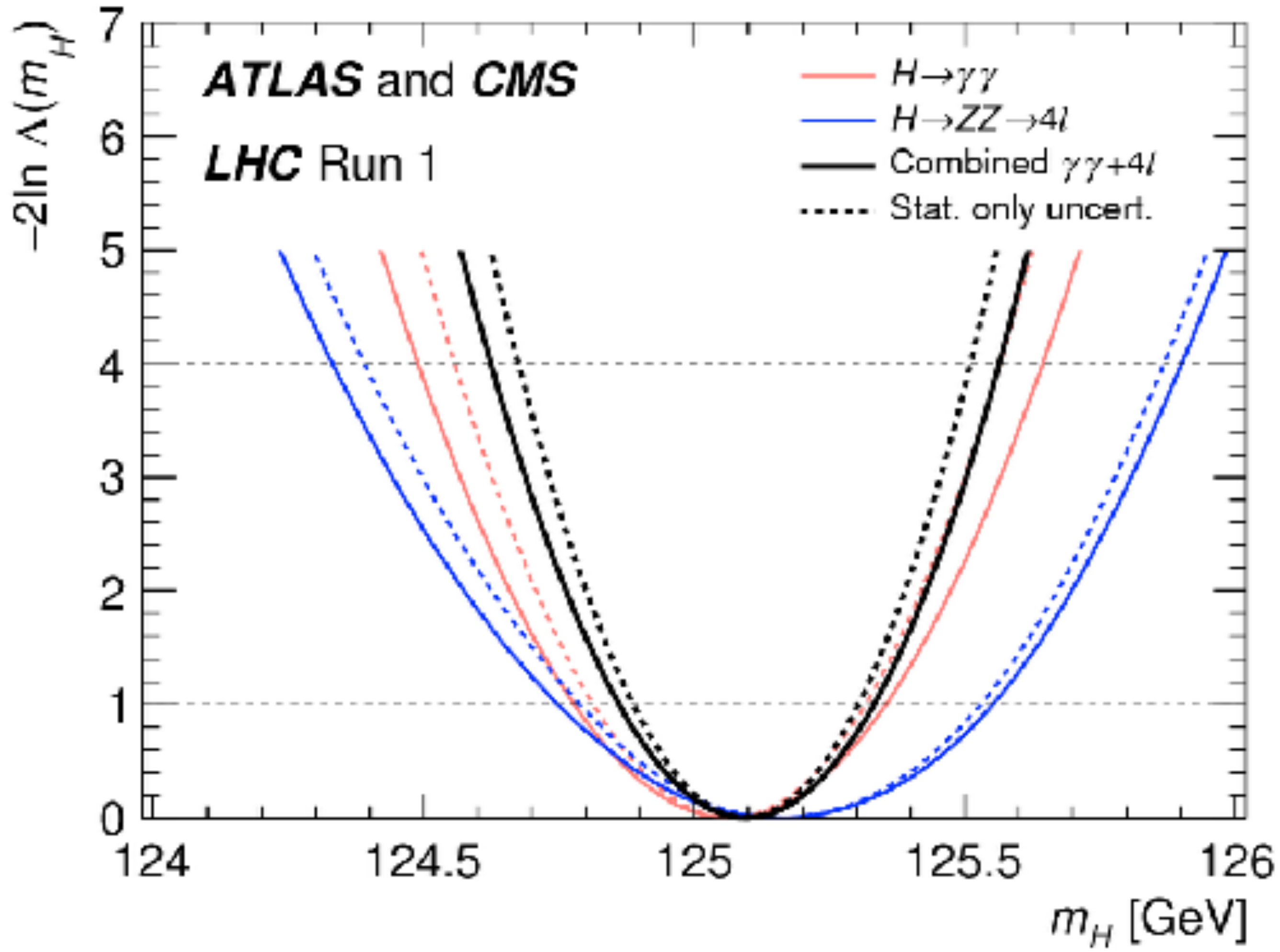
$M_{4\mu}$= 125.1 GeV

Impact of the systematic effects on the mass

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

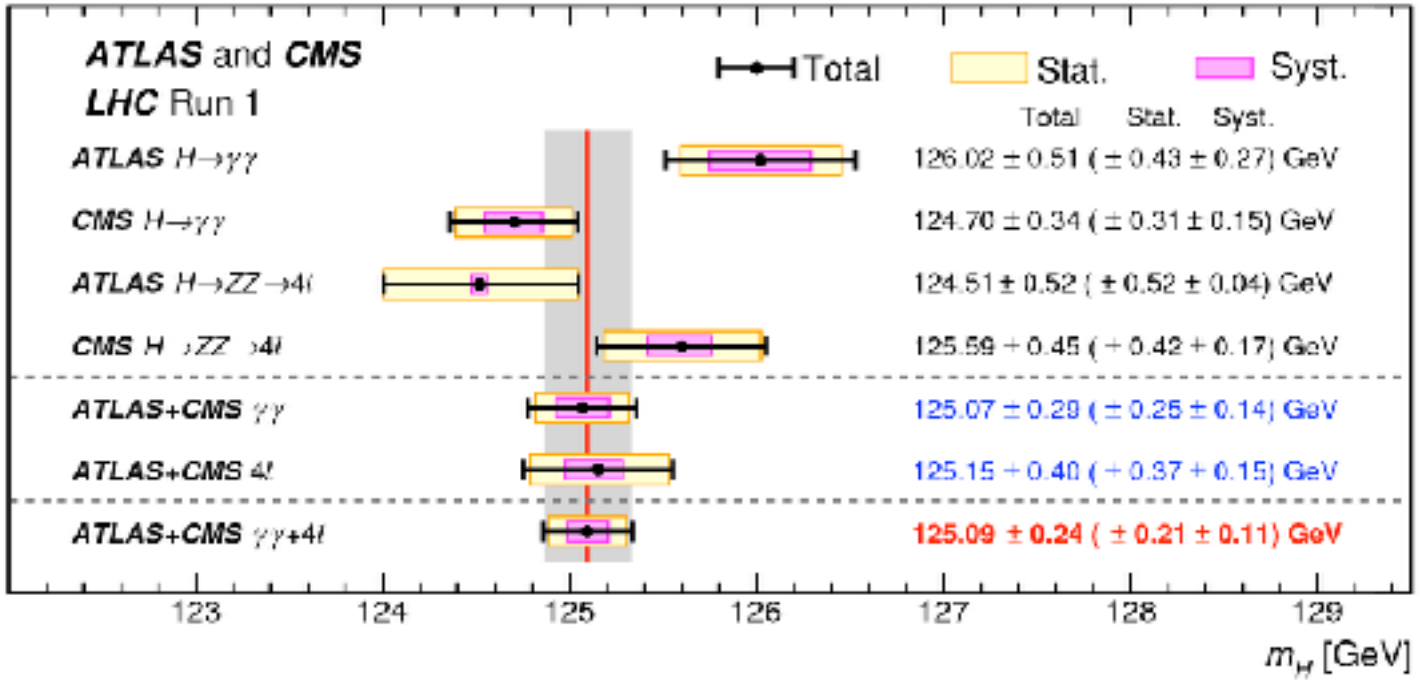


Combined LHC mass measurement

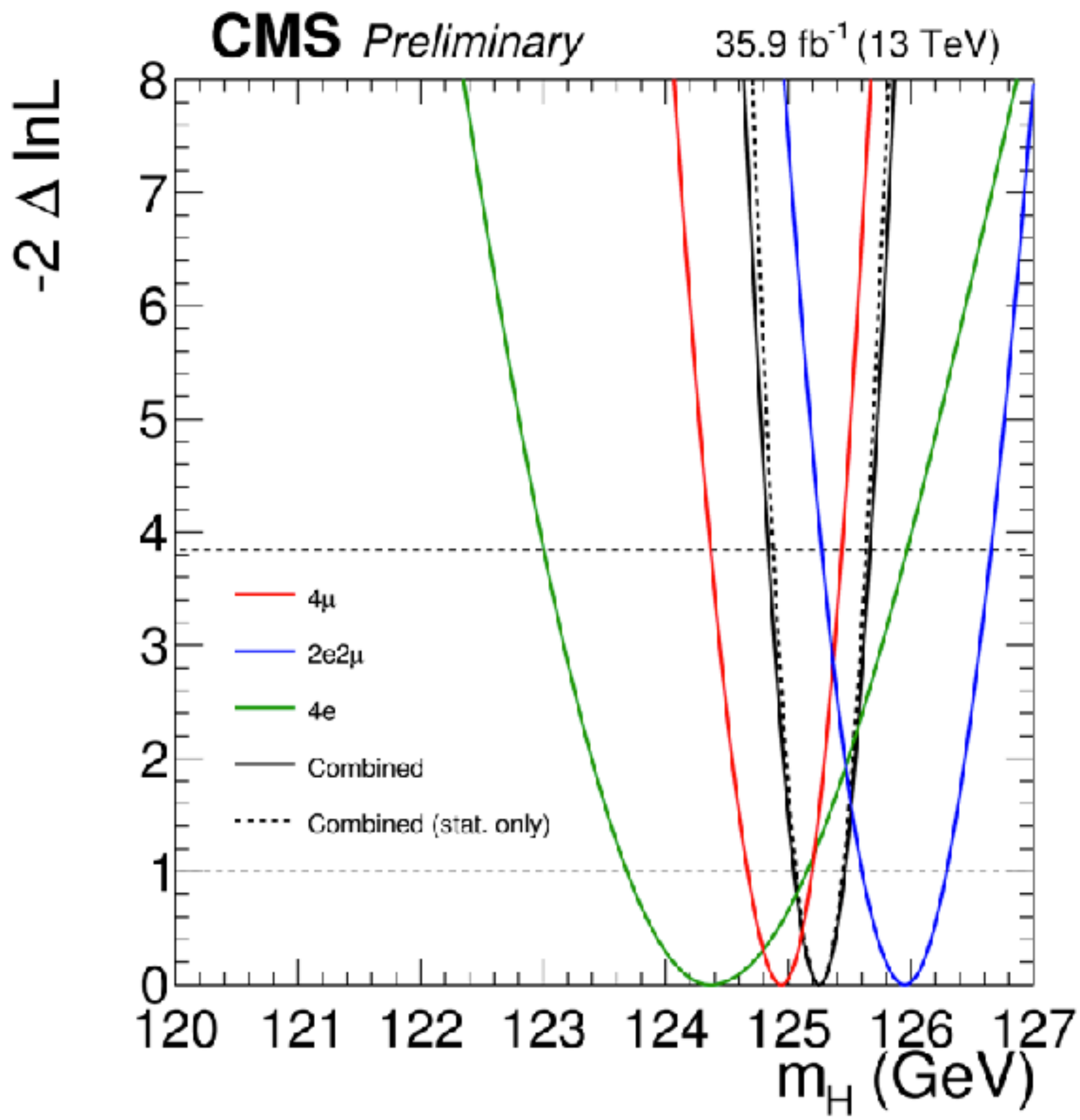


M_H =125.09 ± 0.21 (stat.)
± 0.11(syst.) GeV

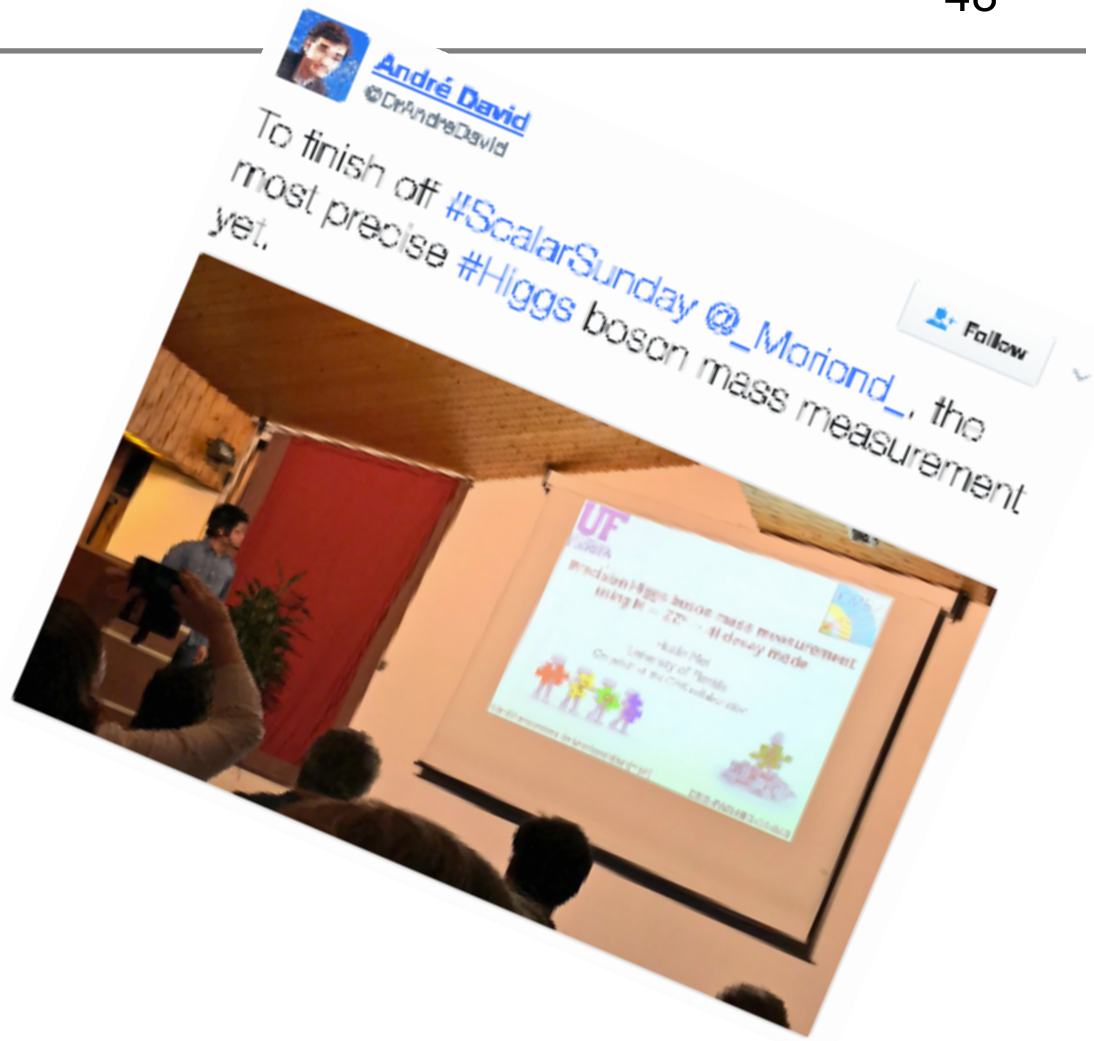
- Tensions between channels have different signs in the different experiments
- Differences are compatible with statistical fluctuations
- Final result is still statistically limited



Latest news on mass measurement



see details in HIG-16-041



André David
@DrAndreDavid

To finish off #ScalarSunday @_Moriond_, the most precise #Higgs boson mass measurement yet.

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

$M_H = 125.26 \pm 0.21$ (total) GeV

Charge

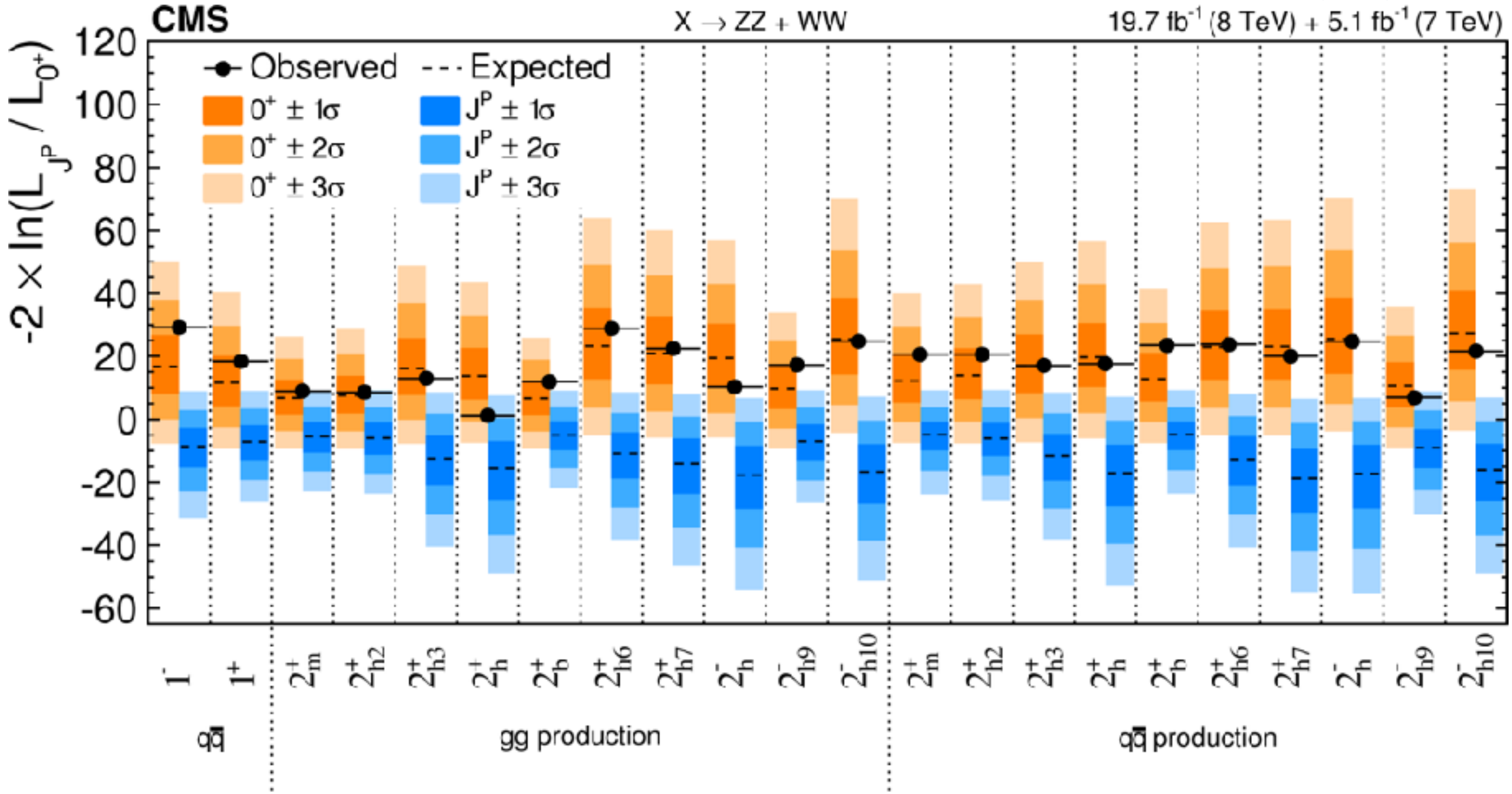
0

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 ⇒ $JP=0^+$

PRD 92 (2015) 012004



Signal strength per production/decay tags

- **Signal strengths in different channels are consistent with 1 (SM)**
  - largest difference <3σ from ttH analyses

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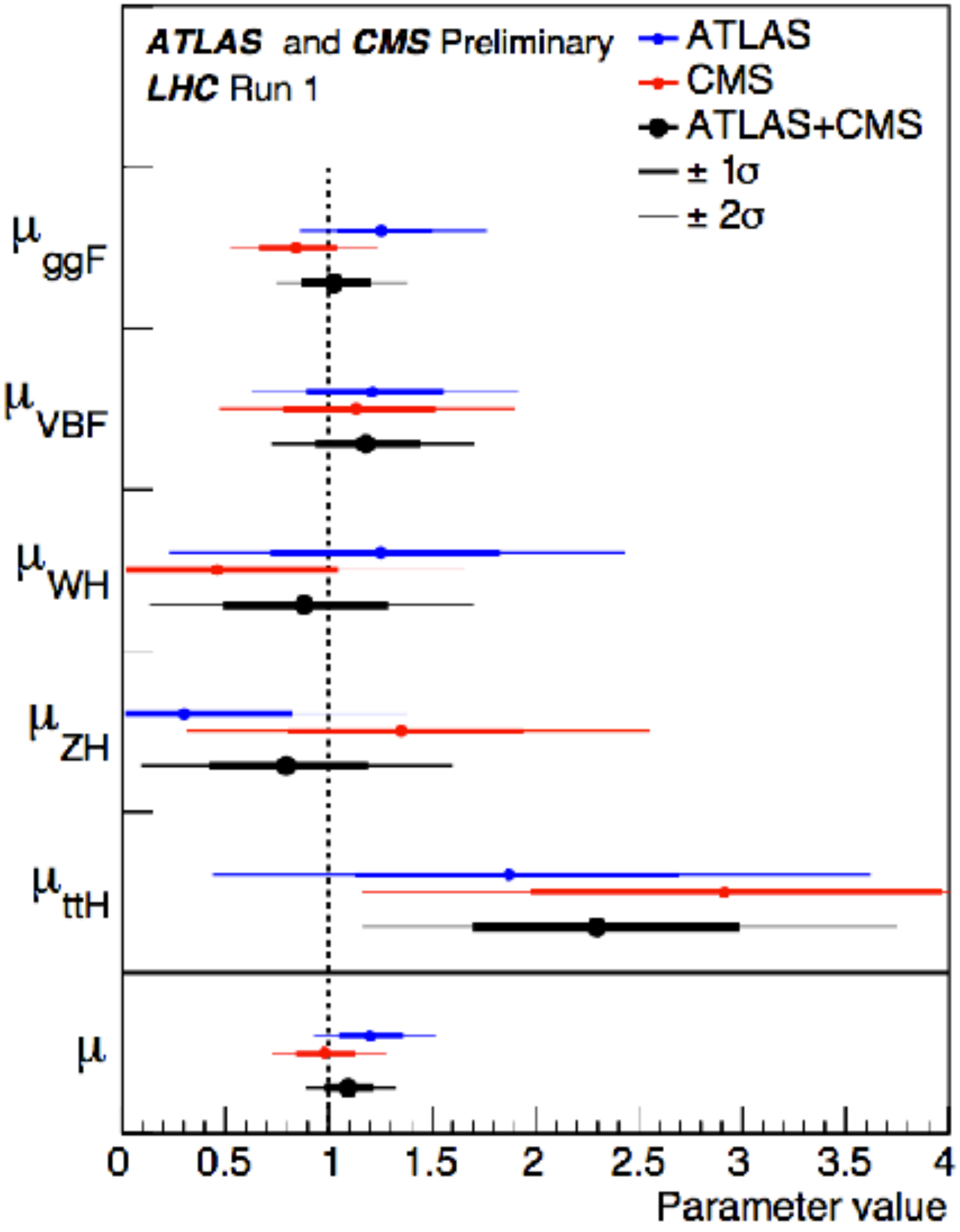
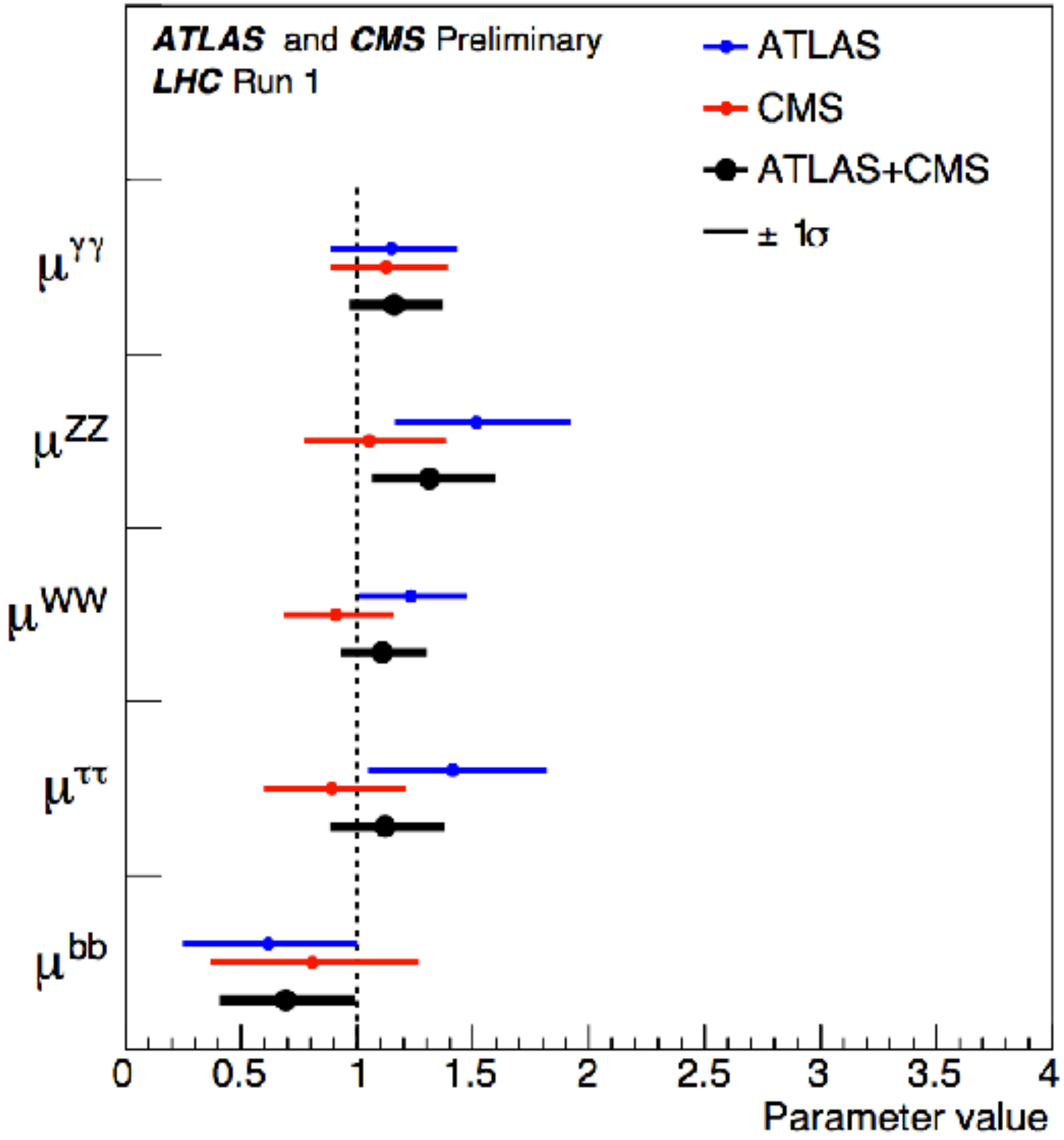
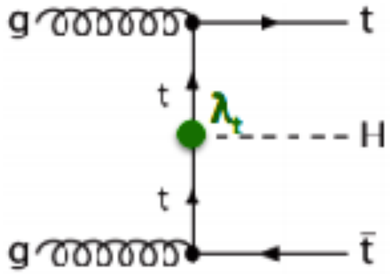
CMS-PAS-HIG-15-002

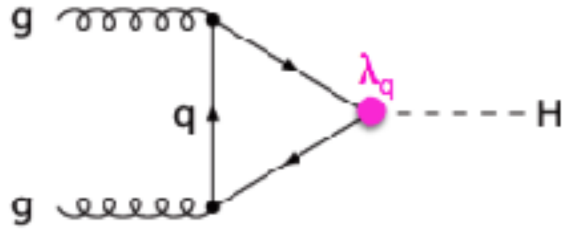


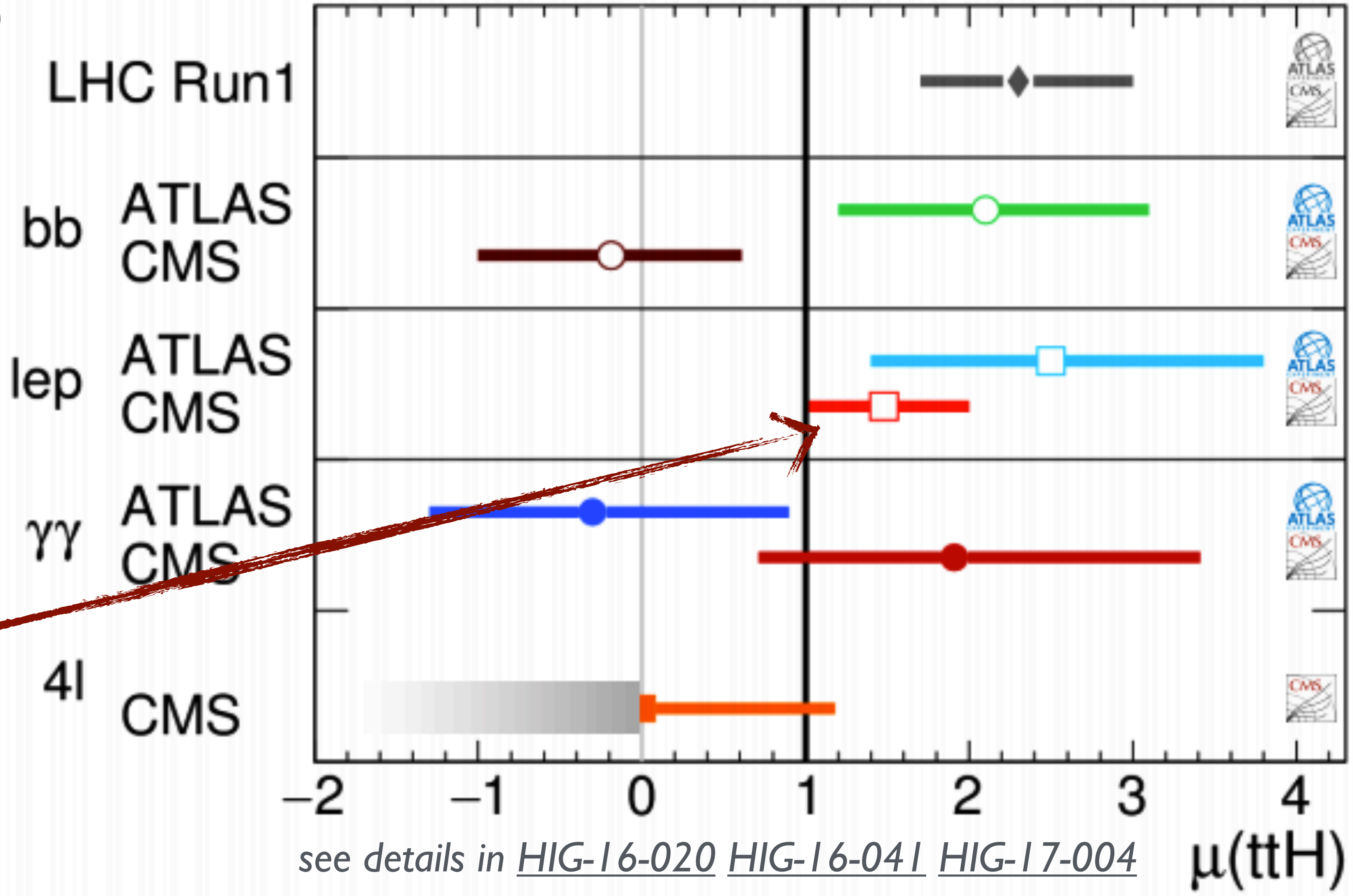


Latest news on the top Yukawa coupling

- **Despite being the largest of the couplings it is challenging to measure λ_t directly**
- Combine several analysis benefiting either from:
  - large yields ($H \to bb/\tau\tau$)
  - medium rate/purity ($H \to WW$)
  - high purity ($H \to ZZ, \gamma\gamma$)







see details in HIG-16-020 HIG-16-041 HIG-17-004

Significance

observed 3.3σ

expected 2.5σ

Testing production modes per final state

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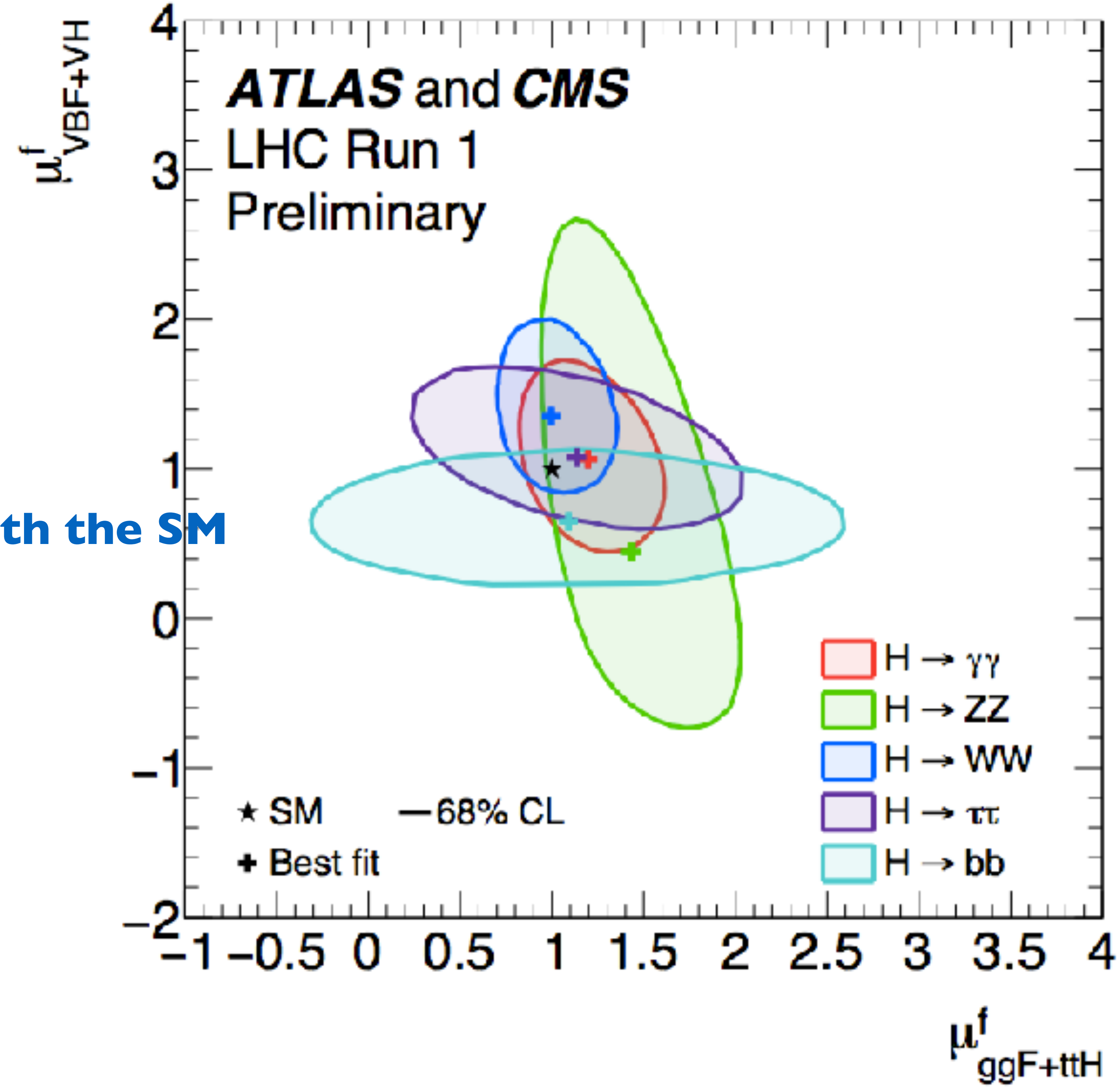
CMS-PAS-HIG-15-002

- 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

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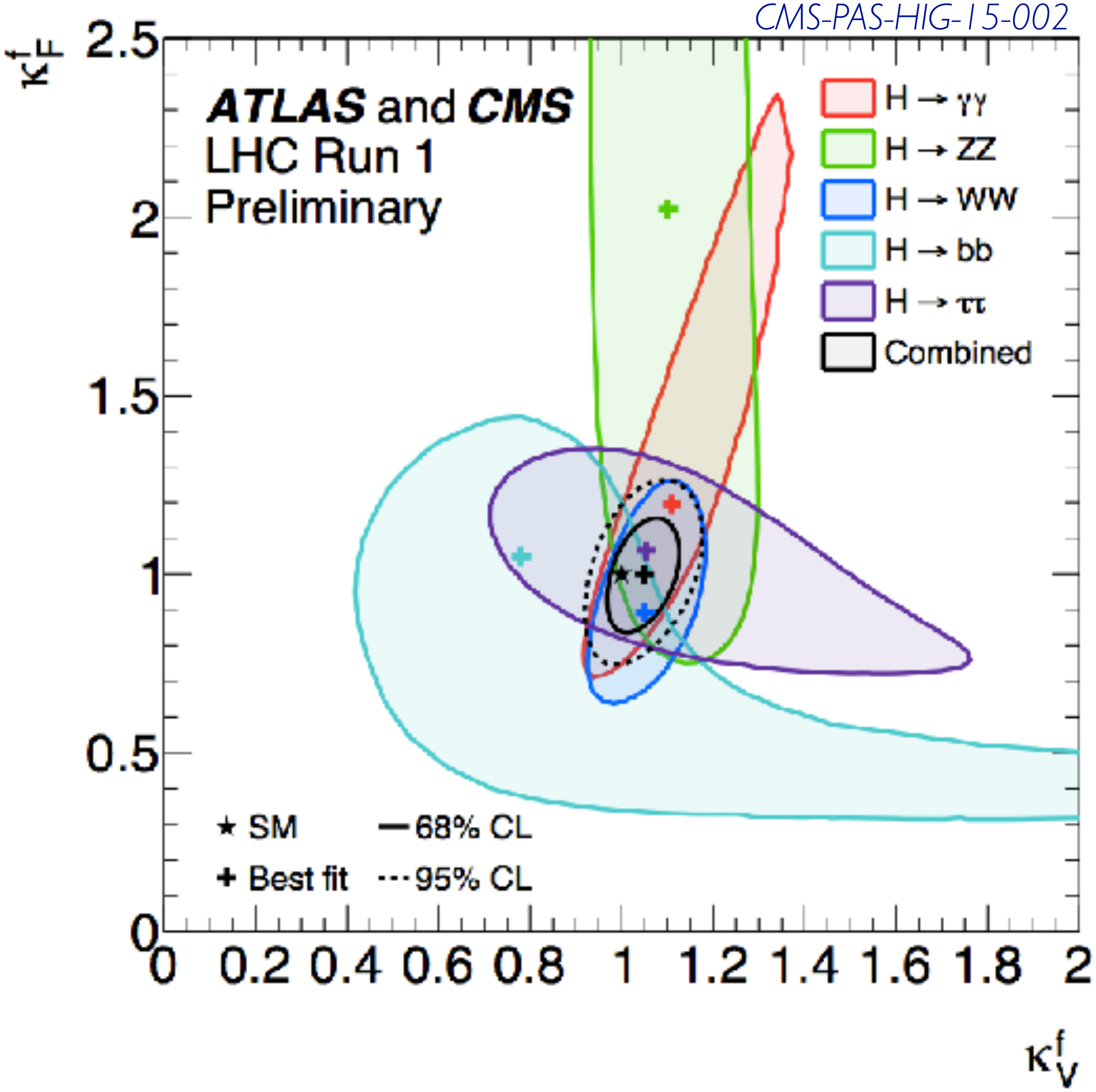

- Use kappa modifiers to parameterise both production and decay modes
- Simplify to test separately couplings to fermions and to vector bosons
- All results in agreement with each other
  - incoherent results for negative k scenario
- **Combination of all channels fully compatible with the SM hypothesis**

Couplings to fermions and bosons II

- Using separate k for the most massive particles

- **All in agreement with the SM**
  - sligthly lower coupling for b (<2σ deviation)
  - not yet sensitive to muons

- Notice that
  - for gauge bosons κ_V = vev × $m_V^{2\varepsilon}$ / $M^{1+2\varepsilon}$
  - for fermions κ_f = vev × m_f^{ε} / $M^{1+\varepsilon}$
  - in the SM ε=0 and vev=M=246 GeV

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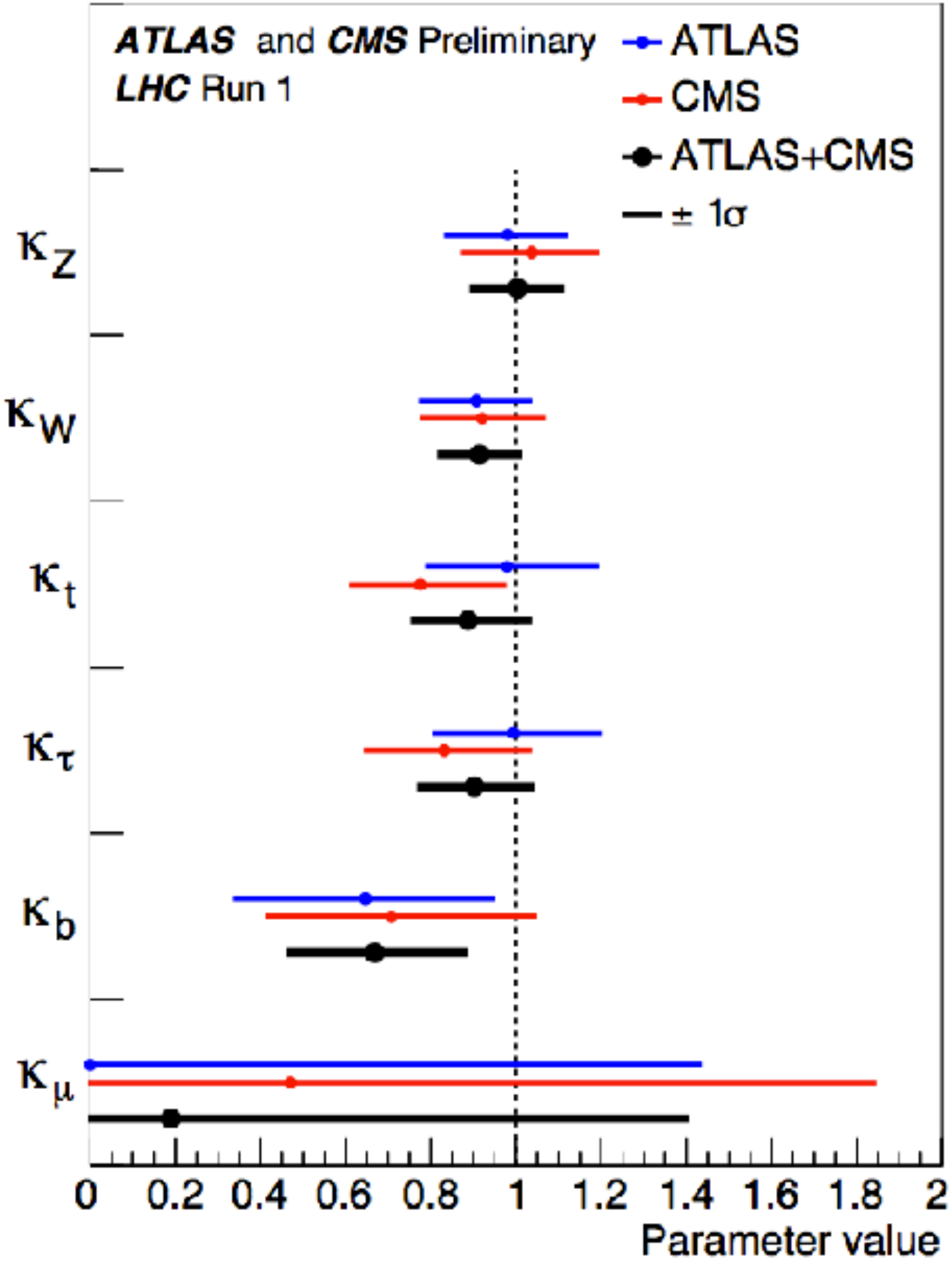

Couplings to fermions and bosons II

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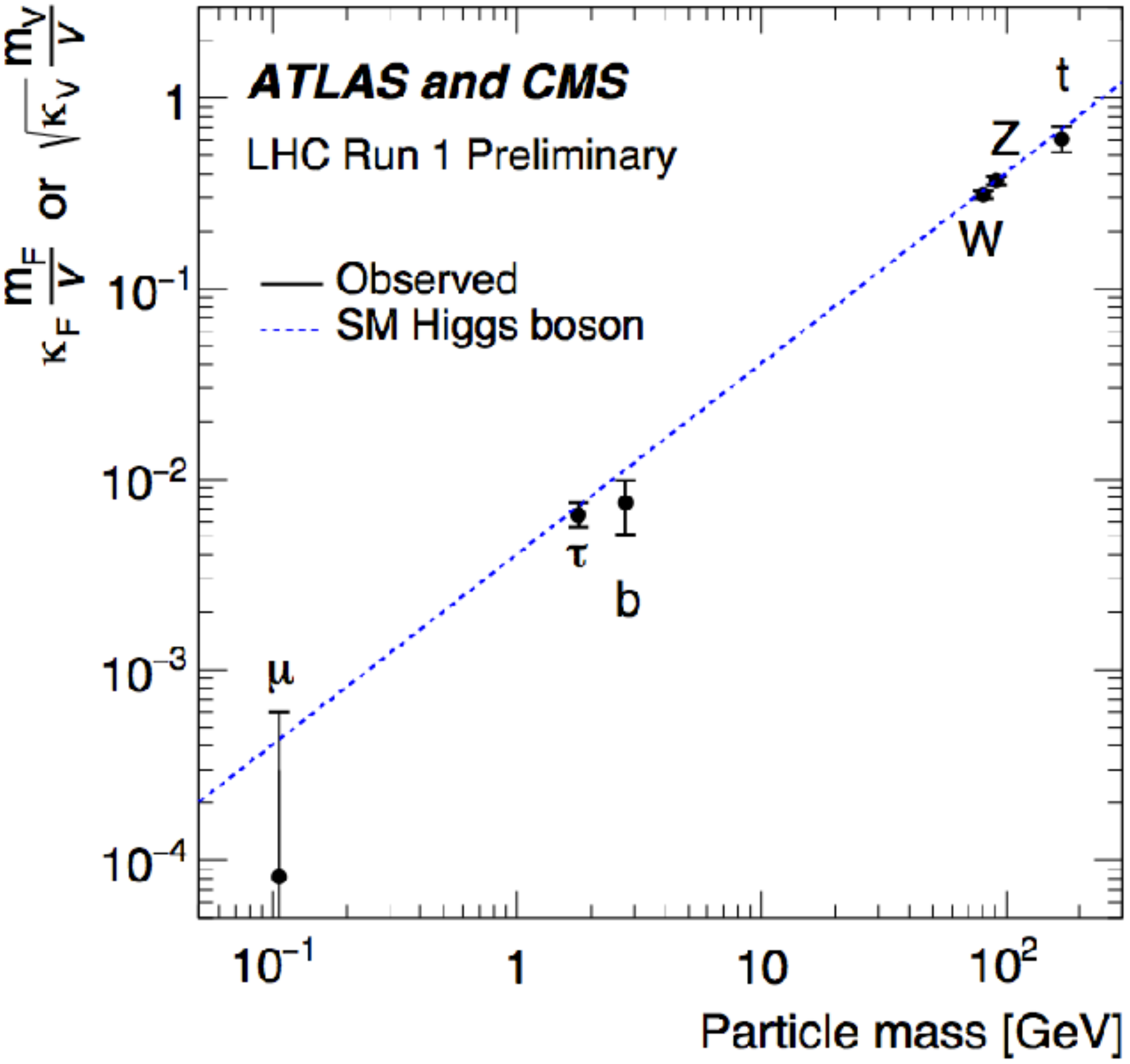
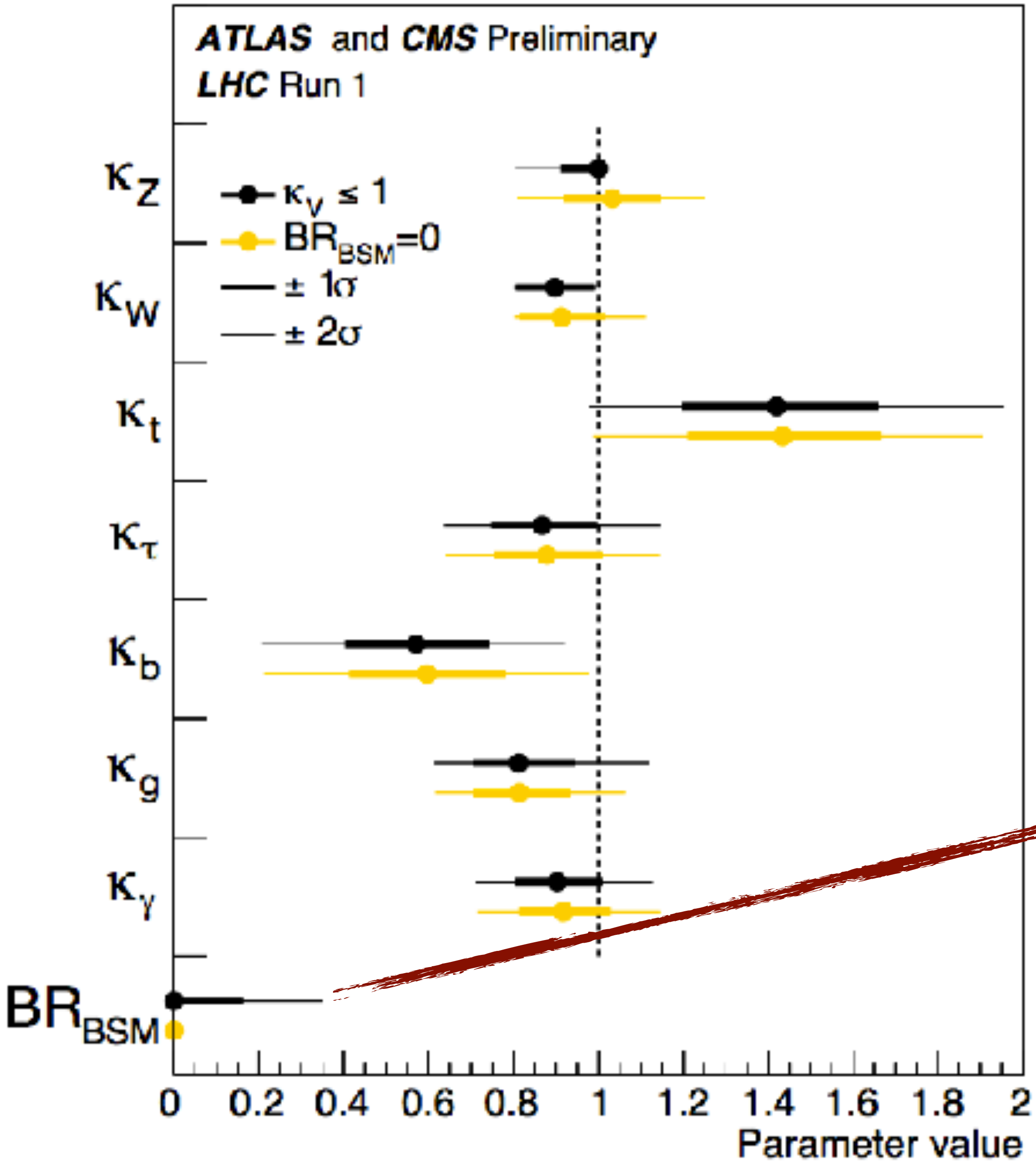
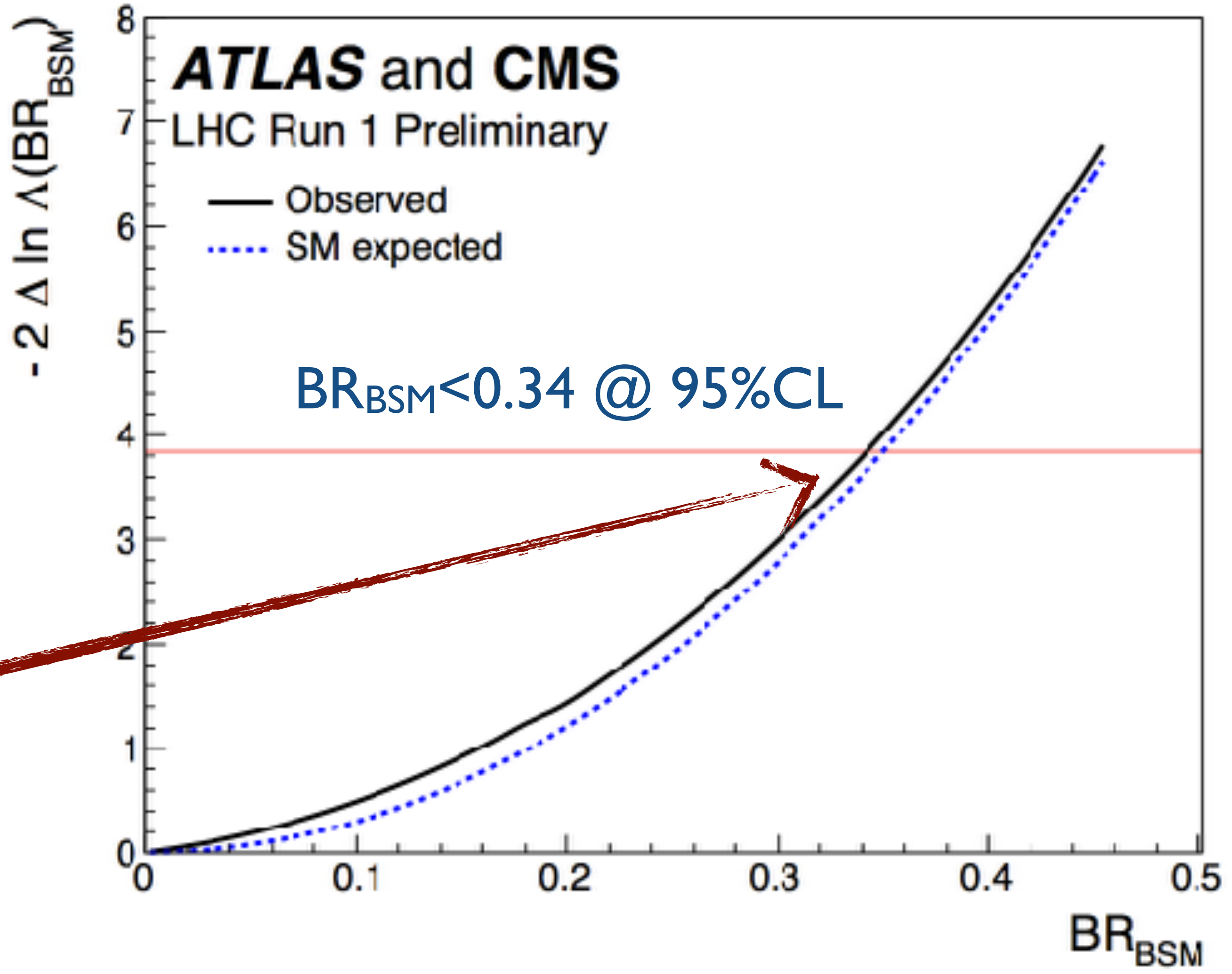


Beyond the standard model contributions I

- **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 ɣɣ)



- **Not yet any sign of new**



BR_{BSM}<0.34 @ 95%CL

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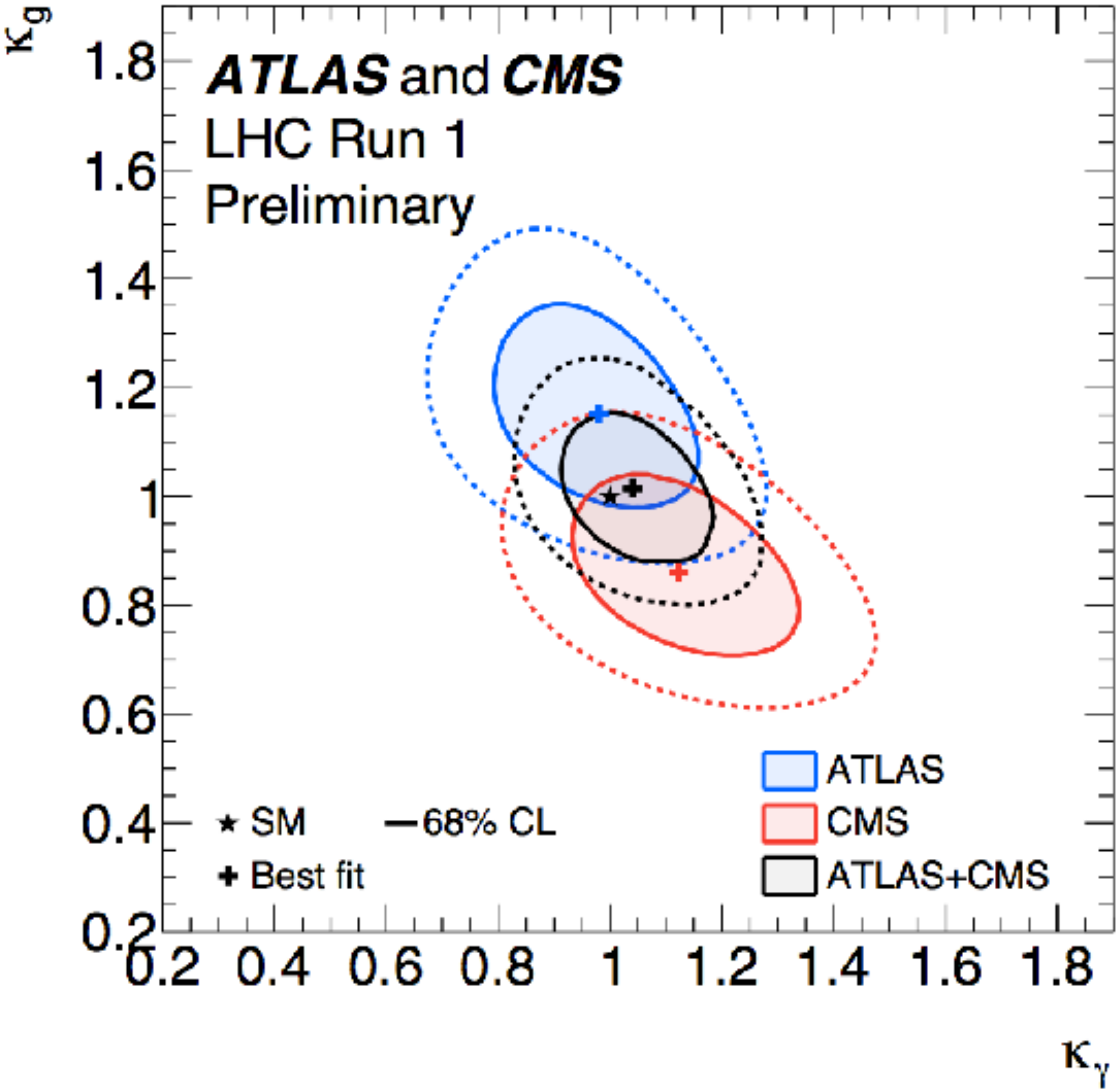
Beyond the standard model contributions II

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



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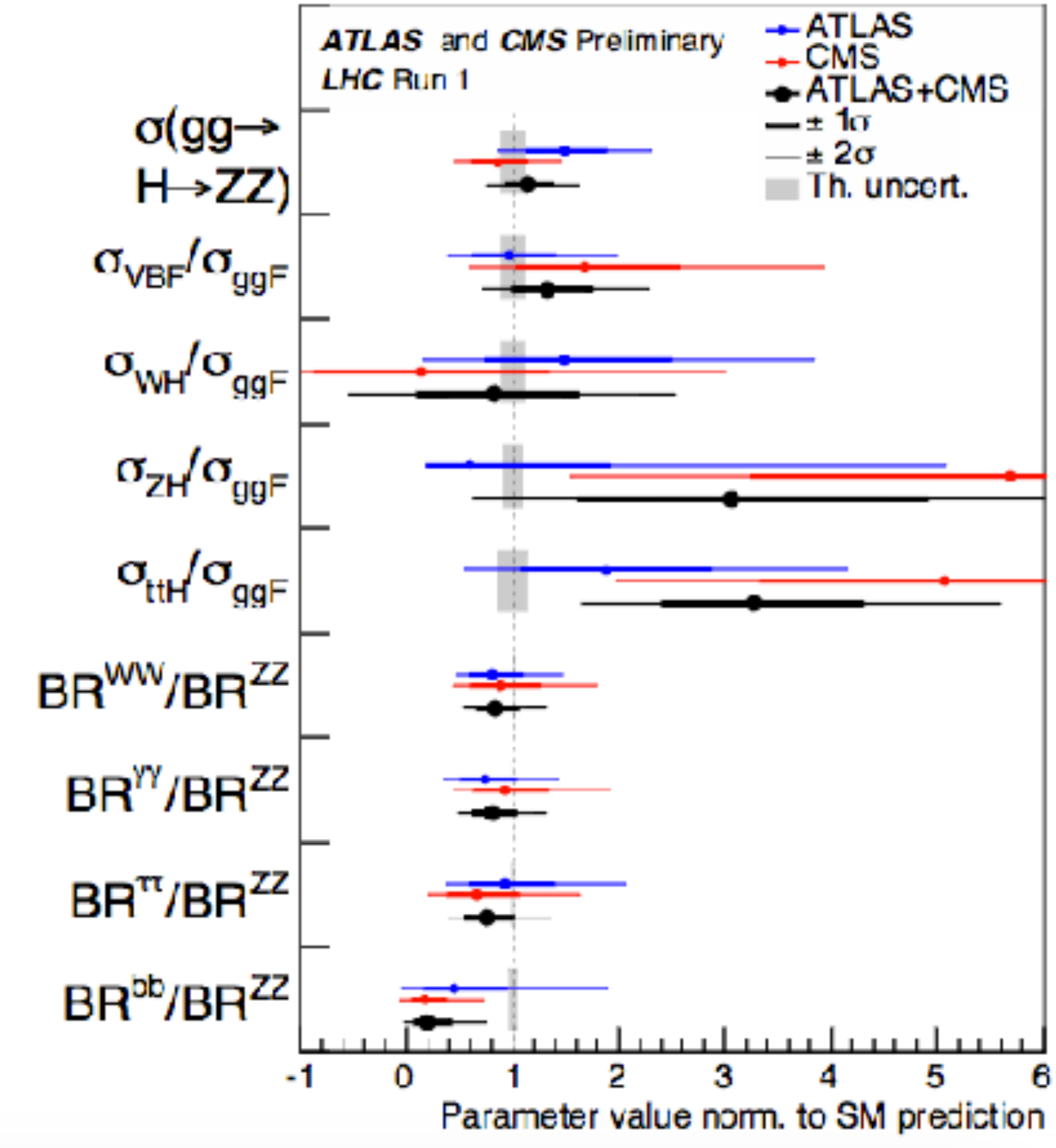
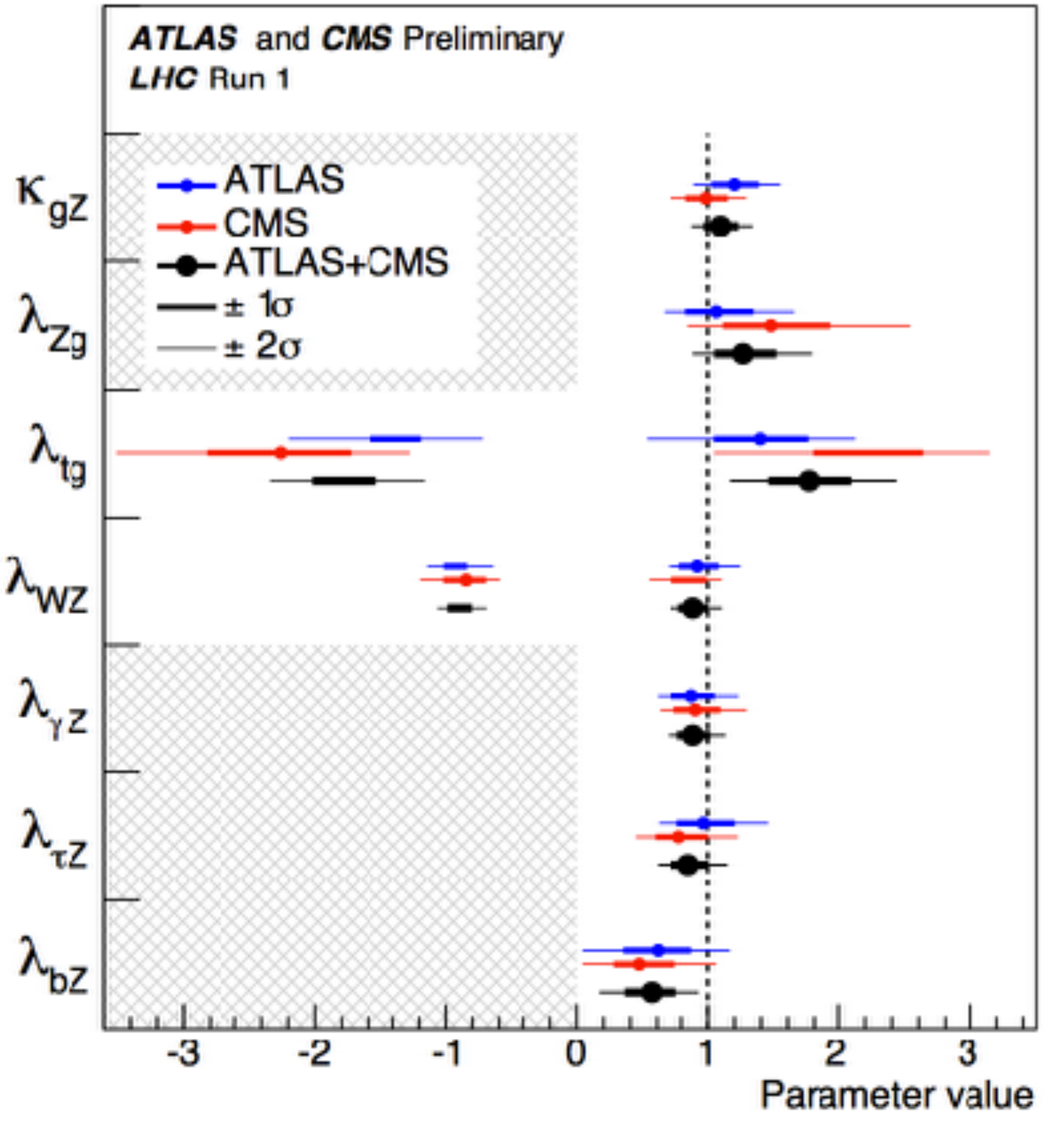
Generic parameterisations

- Ratios are useful to cancel partially the uncertainties
  - use gg→H→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)





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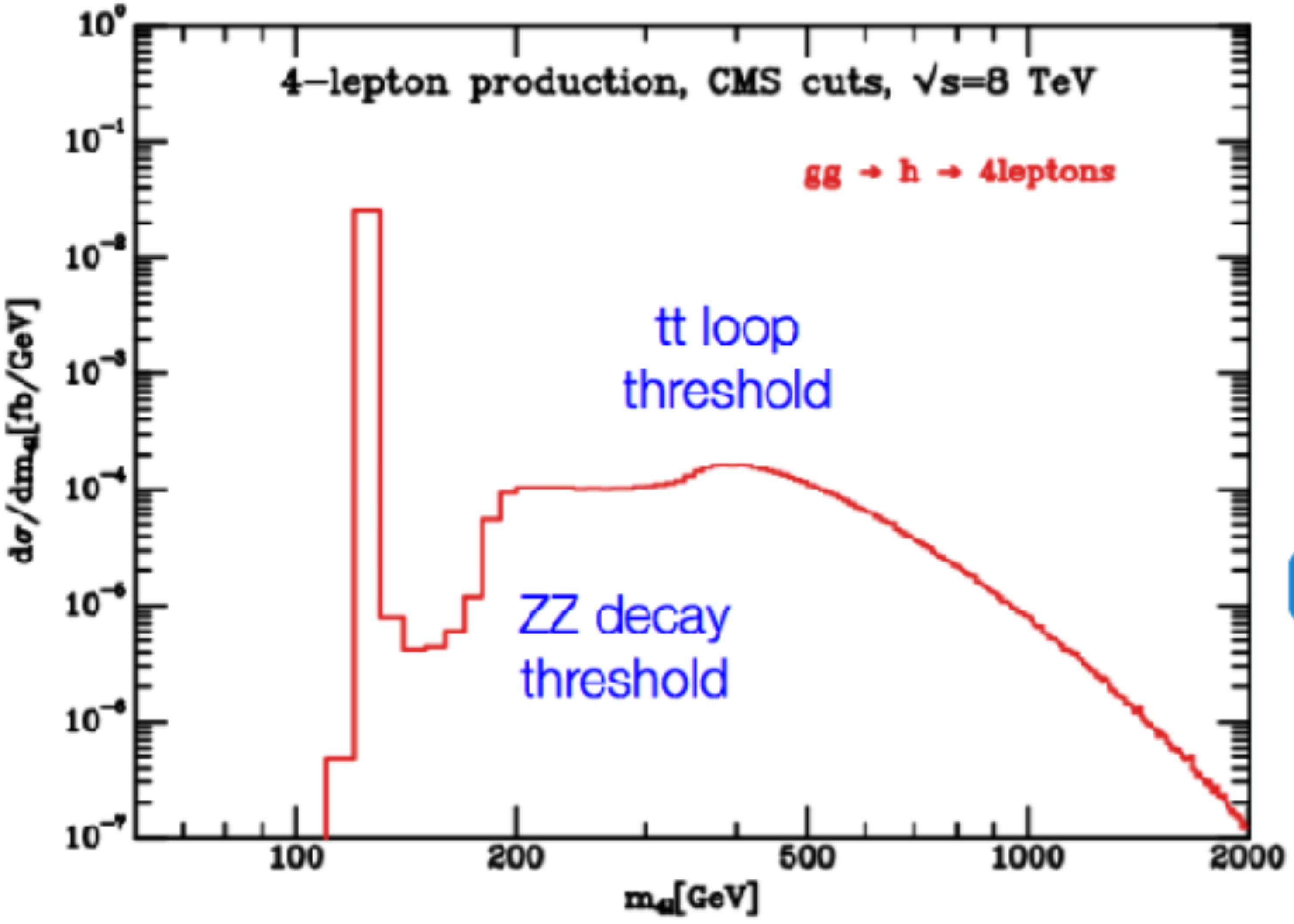
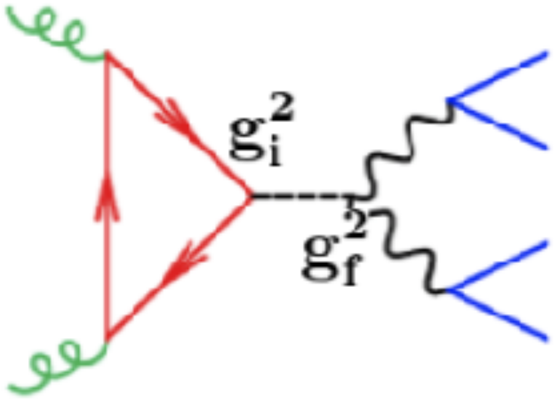
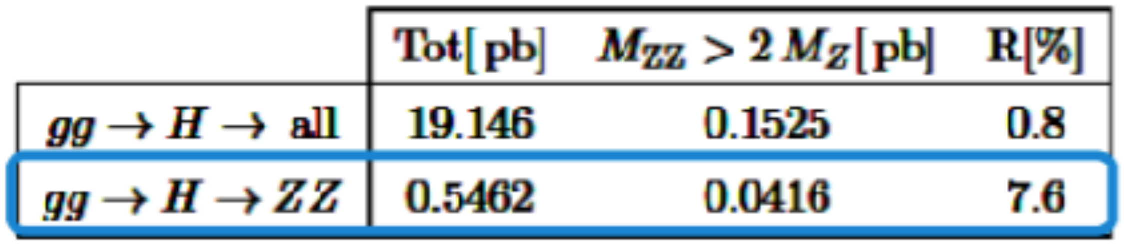
Case study: bounding the Higgs width

Higgs off-shell production and decay

- Although the SM Higgs is expected to be very narrow ~8% production is off-shell
  - mixed effect of production and decay with enhancements at $2m_V$ and $2m_t$ thresholds
  - modelling initially implementation 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[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

Higgs off-shell production and decay

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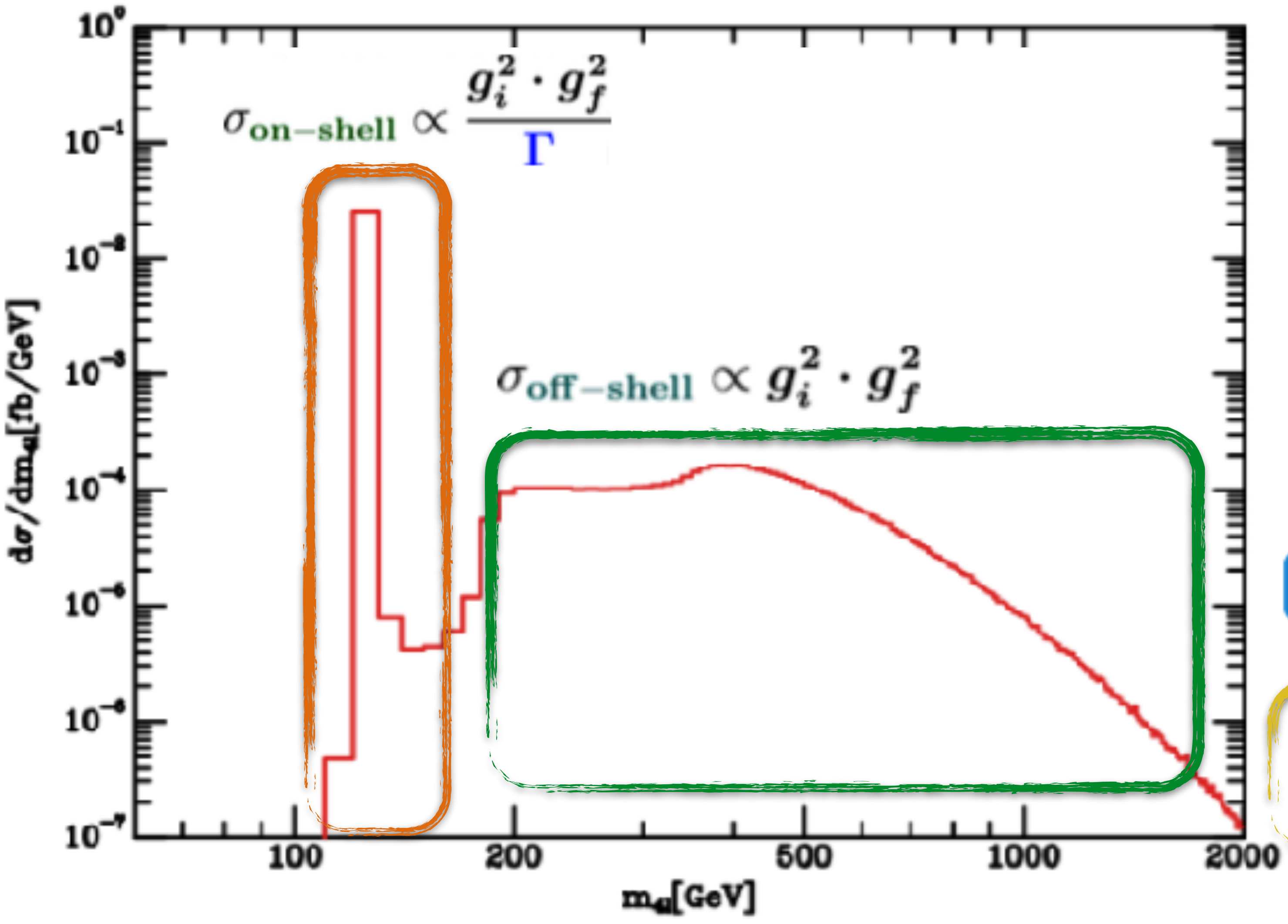

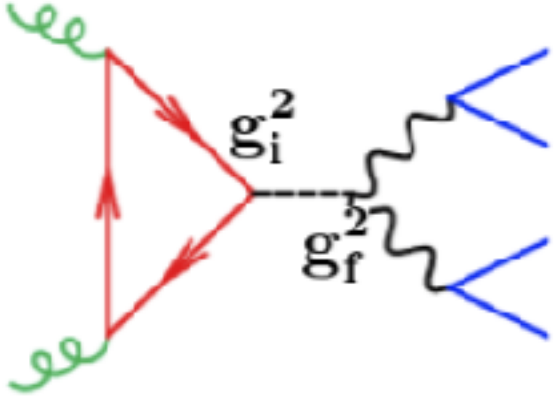

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$gg \to H \to$ all	19.146	0.1525	0.8
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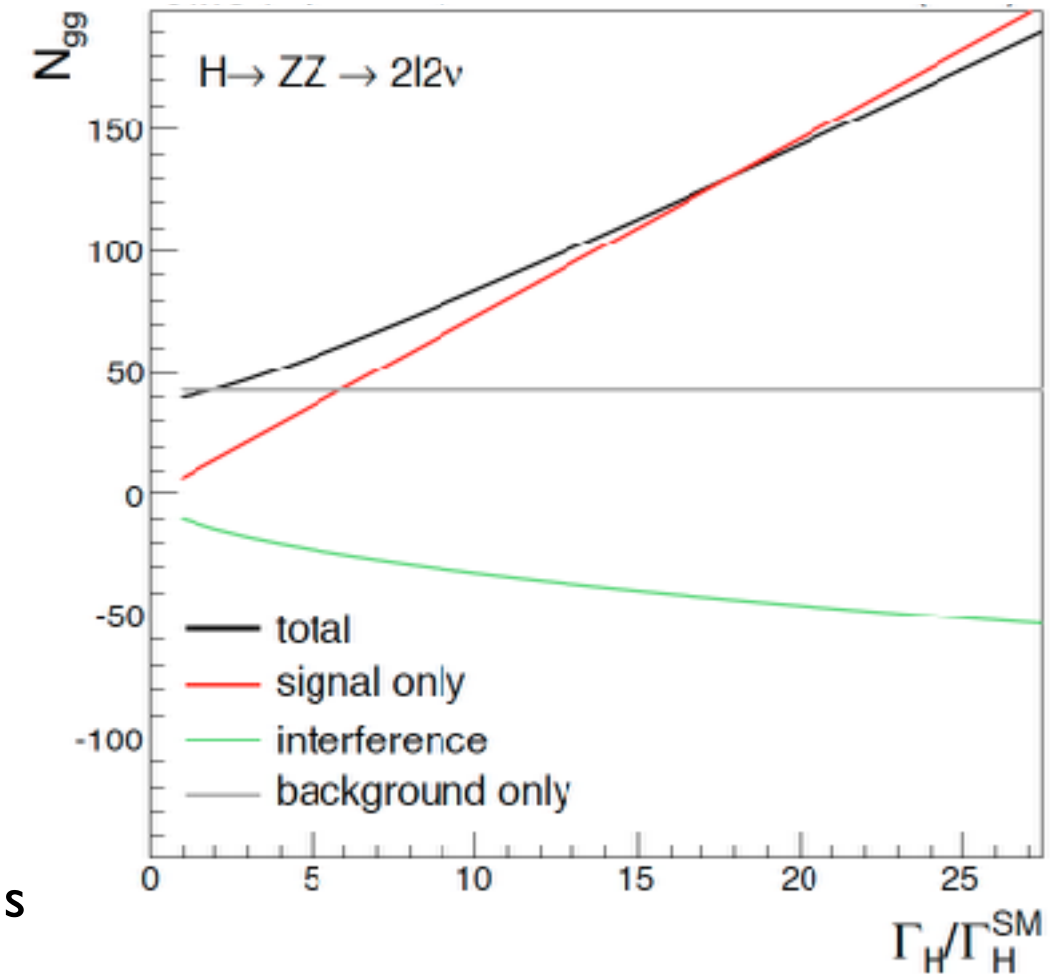
Extract Γ, from off-shell / on-shell ratio, assuming couplings independent of m_{VV}

Analysis strategy

- Search for anomalous ZZ production through gluon-gluon and vector boson fusion

- Inclusive final state observed (4ℓ or 2ℓ2ν)

- 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

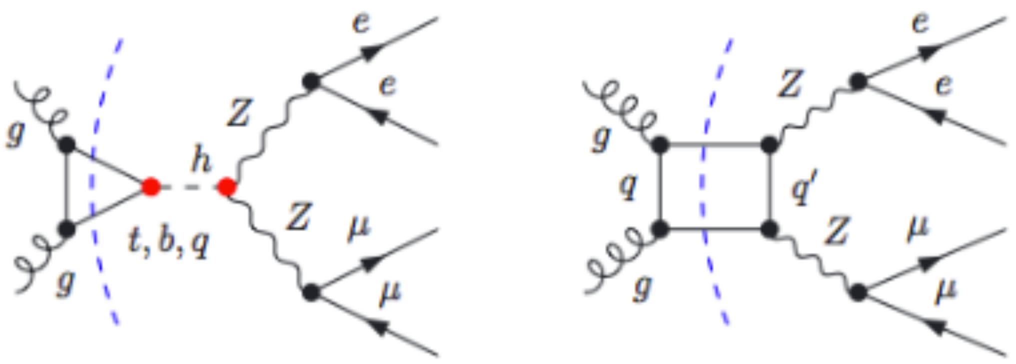


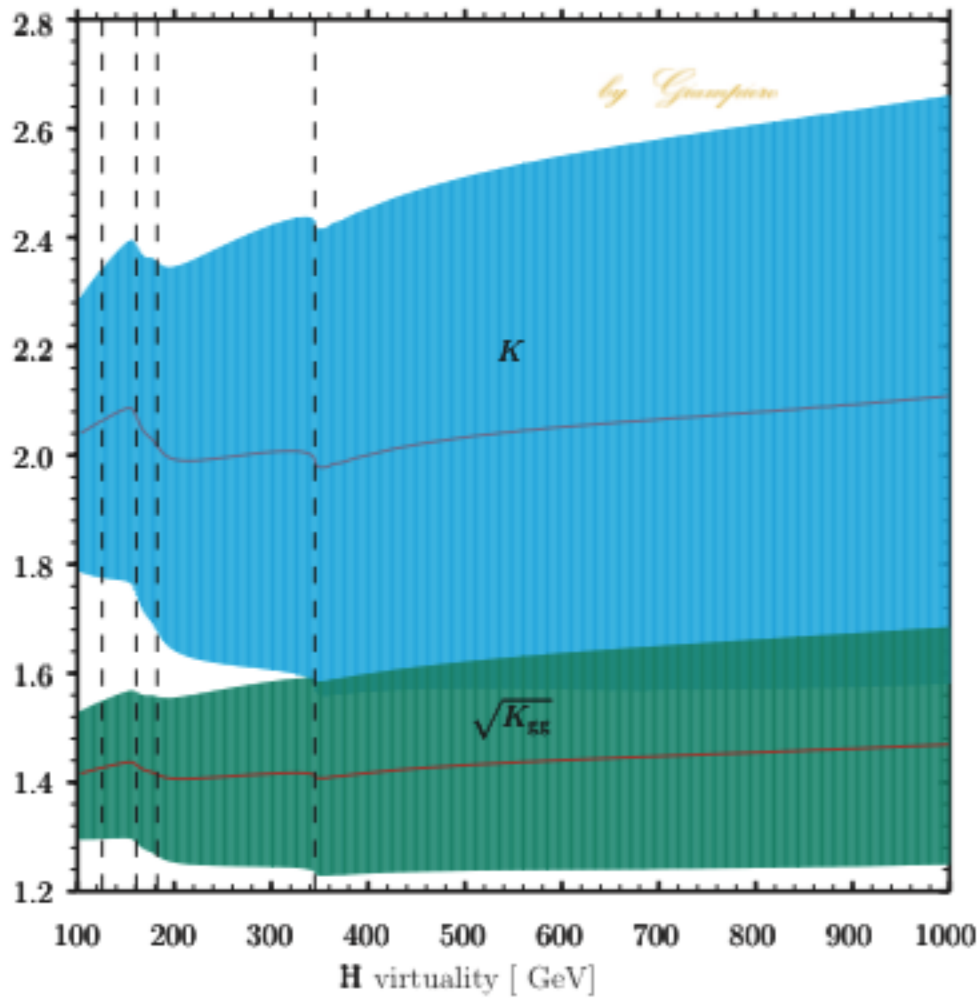
$$
\begin{aligned}
\mathcal{P}^{\text{off-shell}}_{\text{tot}}(\vec{x}) = {} & \left[\mu_{\text{ggH}} \times (\Gamma_{\text{H}}/\Gamma_0) \times \mathcal{P}^{\text{gg}}_{\text{sig}}(\vec{x}) + \sqrt{\mu_{\text{ggH}} \times (\Gamma_{\text{H}}/\Gamma_0)} \times \mathcal{P}^{\text{gg}}_{\text{int}}(\vec{x})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

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 → VV as function of m_{ZZ}

  Bonvini et al. PRD88 (2013) 034032, Passarino arXiv:1312.2397

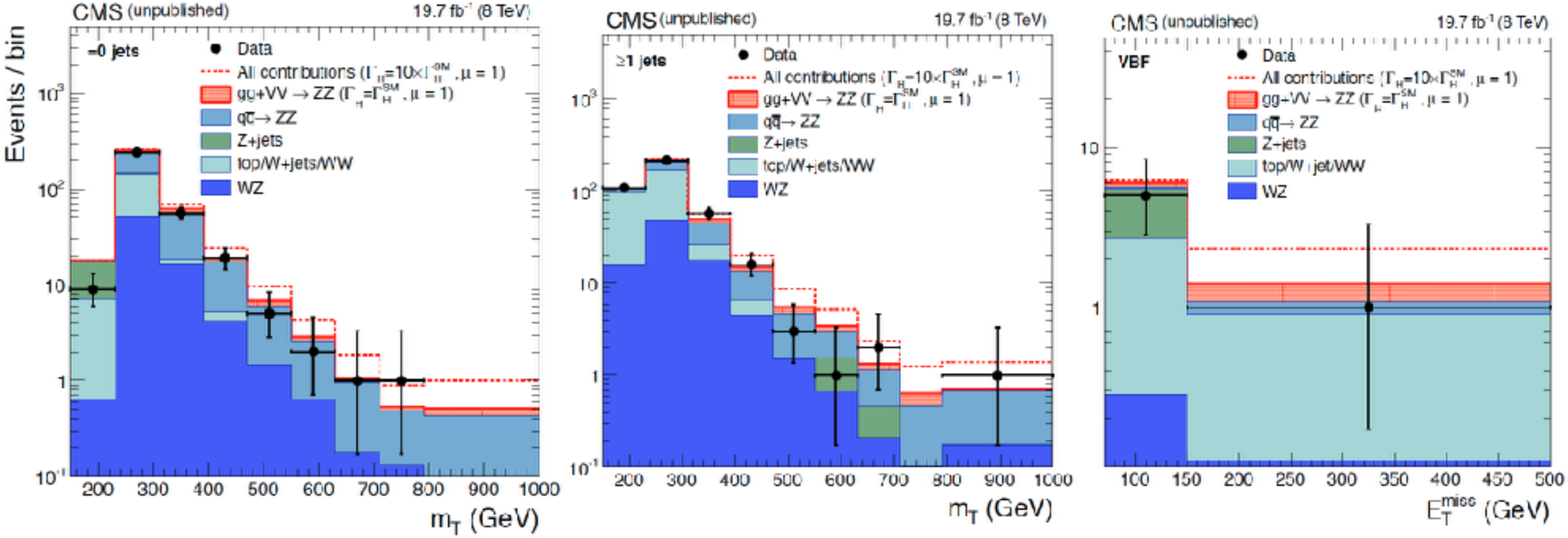




- **VBF** production is generated with Phantom or Madgraph
  - expect to yield ~10% in the high mass regime
  - inclusive generation, as in gg case
  - no dynamical scaling is applied on VBF models

Discriminators used in the 2ℓ2ν analysis

PLB 736 (2014) 64



- Analysis has been checked inclusively and binned according to the jets
  - VBF category has priority, selected with M_{jj}>500 GeV, Δη>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 → ZZ separation according to expected sensitivity for Γ

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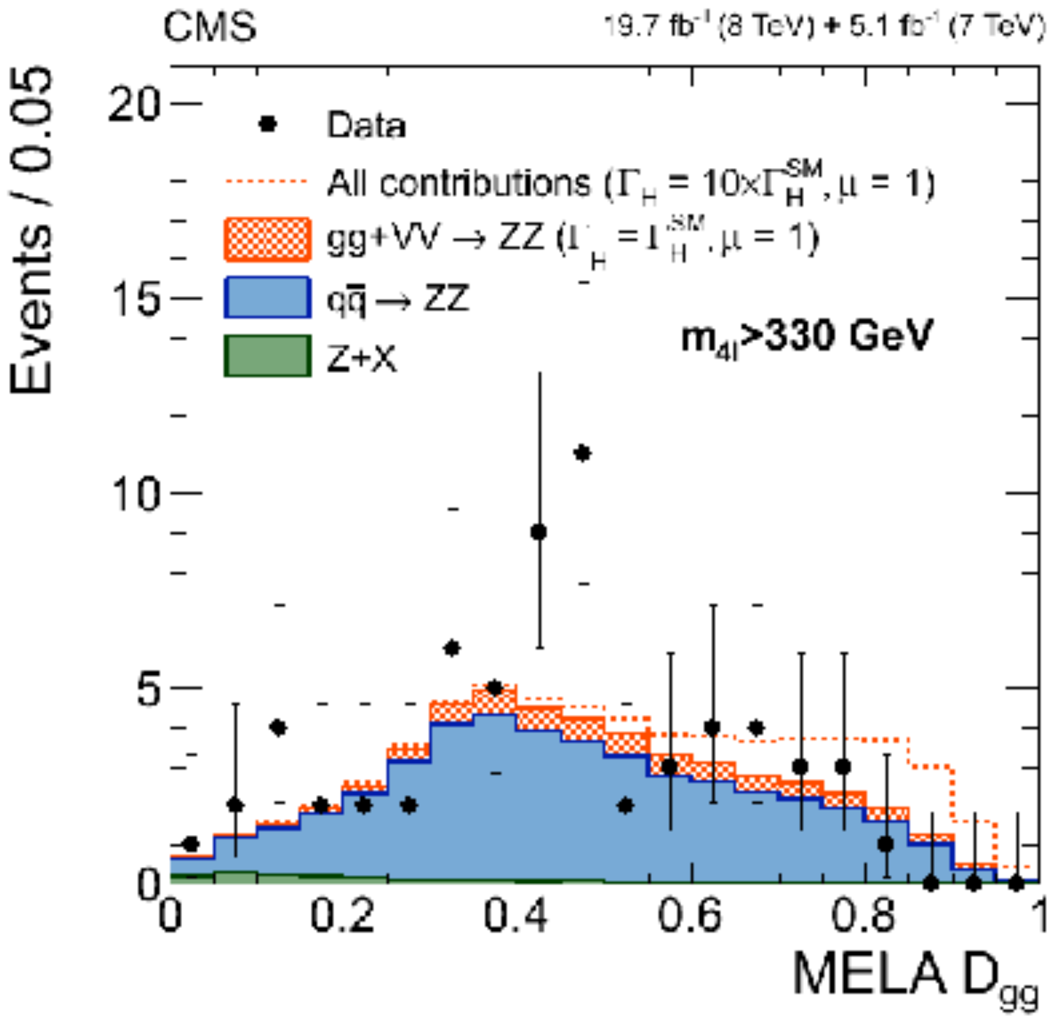
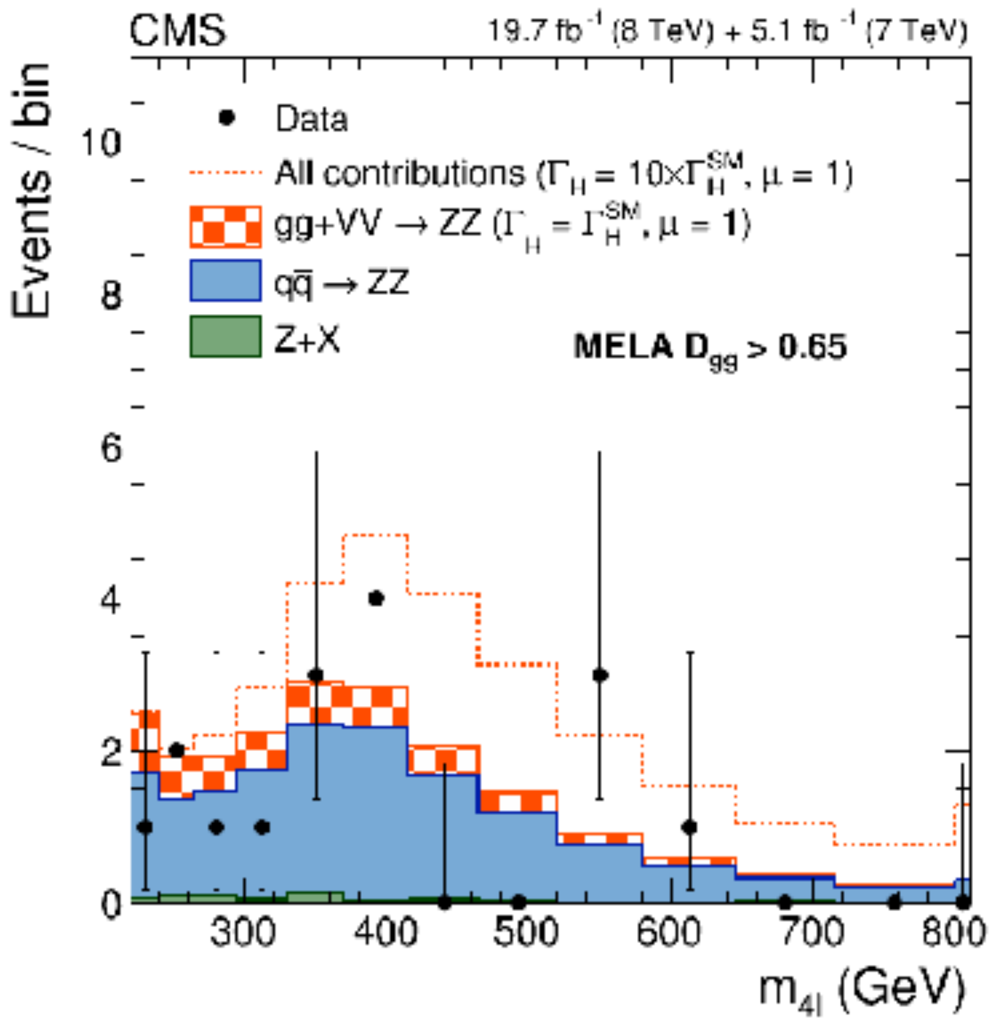




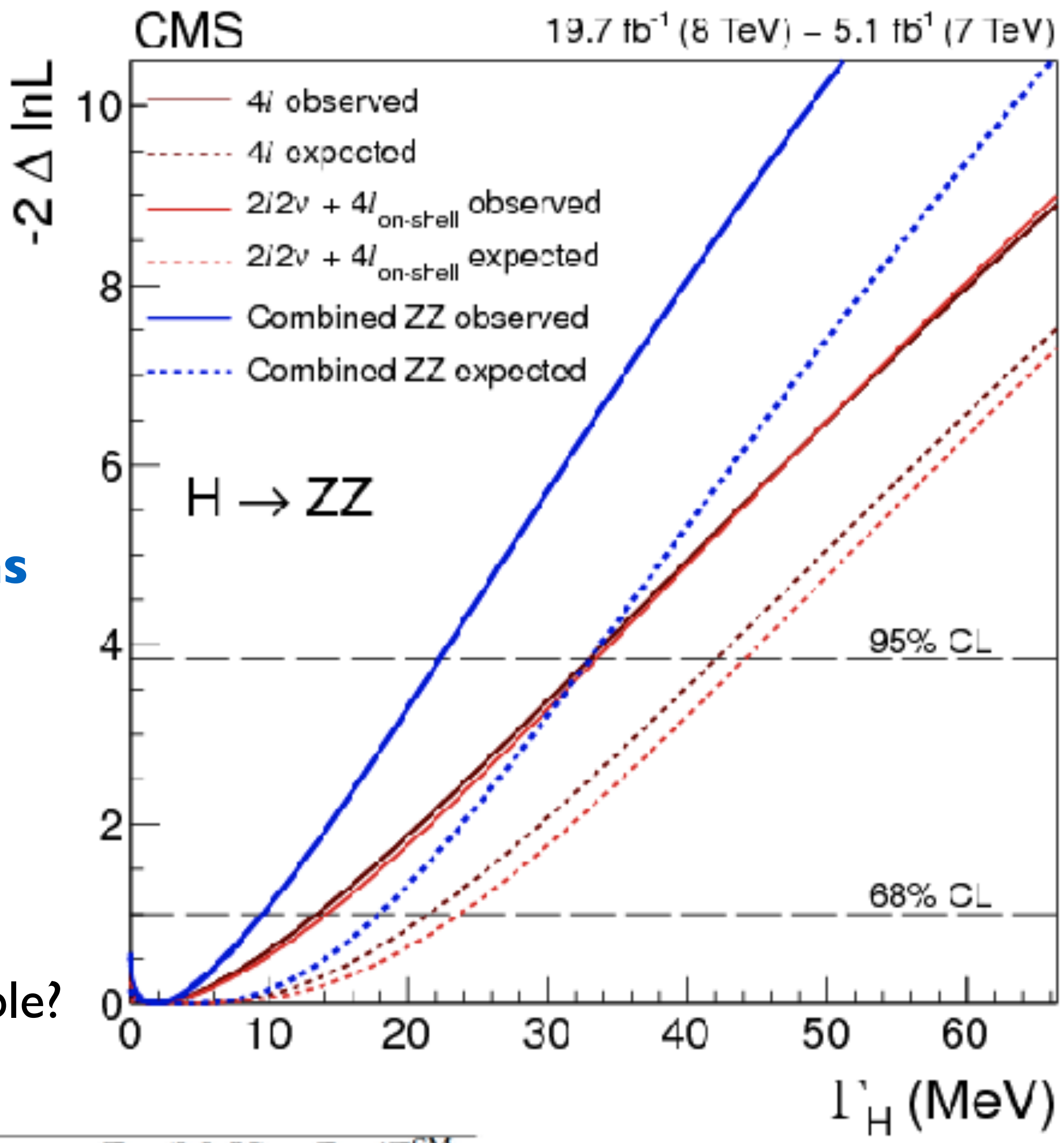
Results

- Both channels are combined to set limits

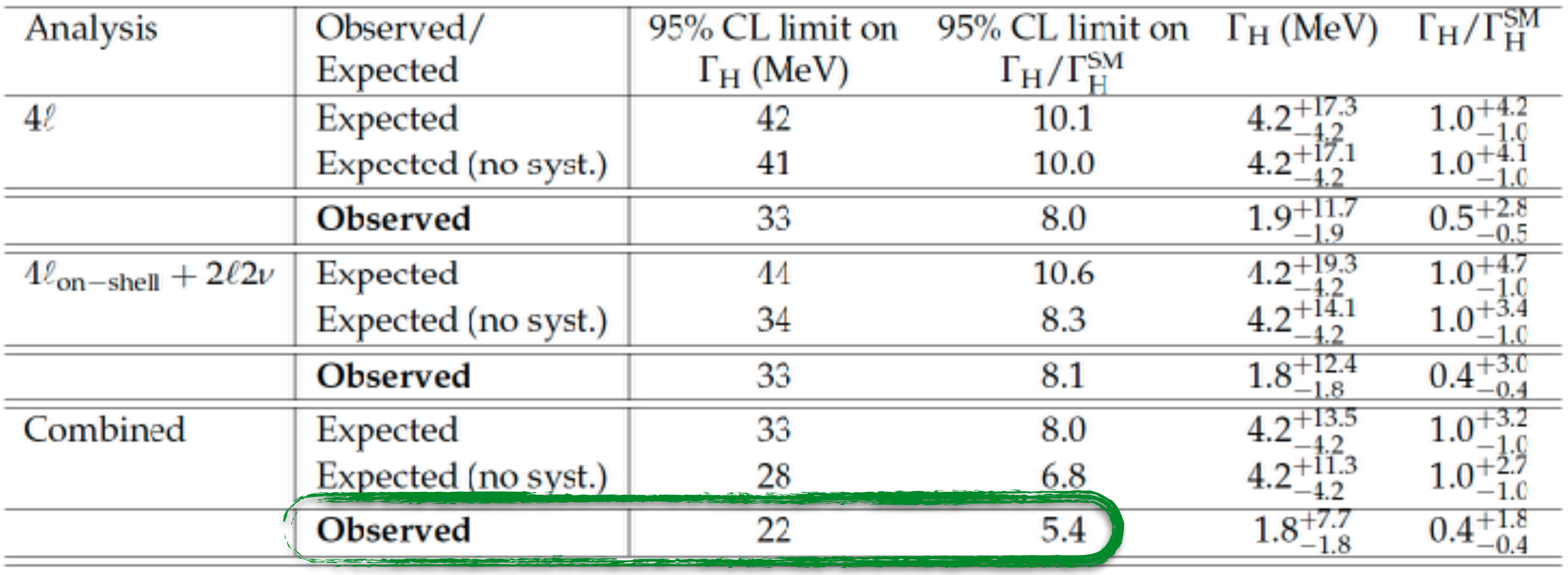
$\Gamma_H < 5.4\ \Gamma_H^{SM}$ @ 95% CL

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?



PLB 736 (2014) 64



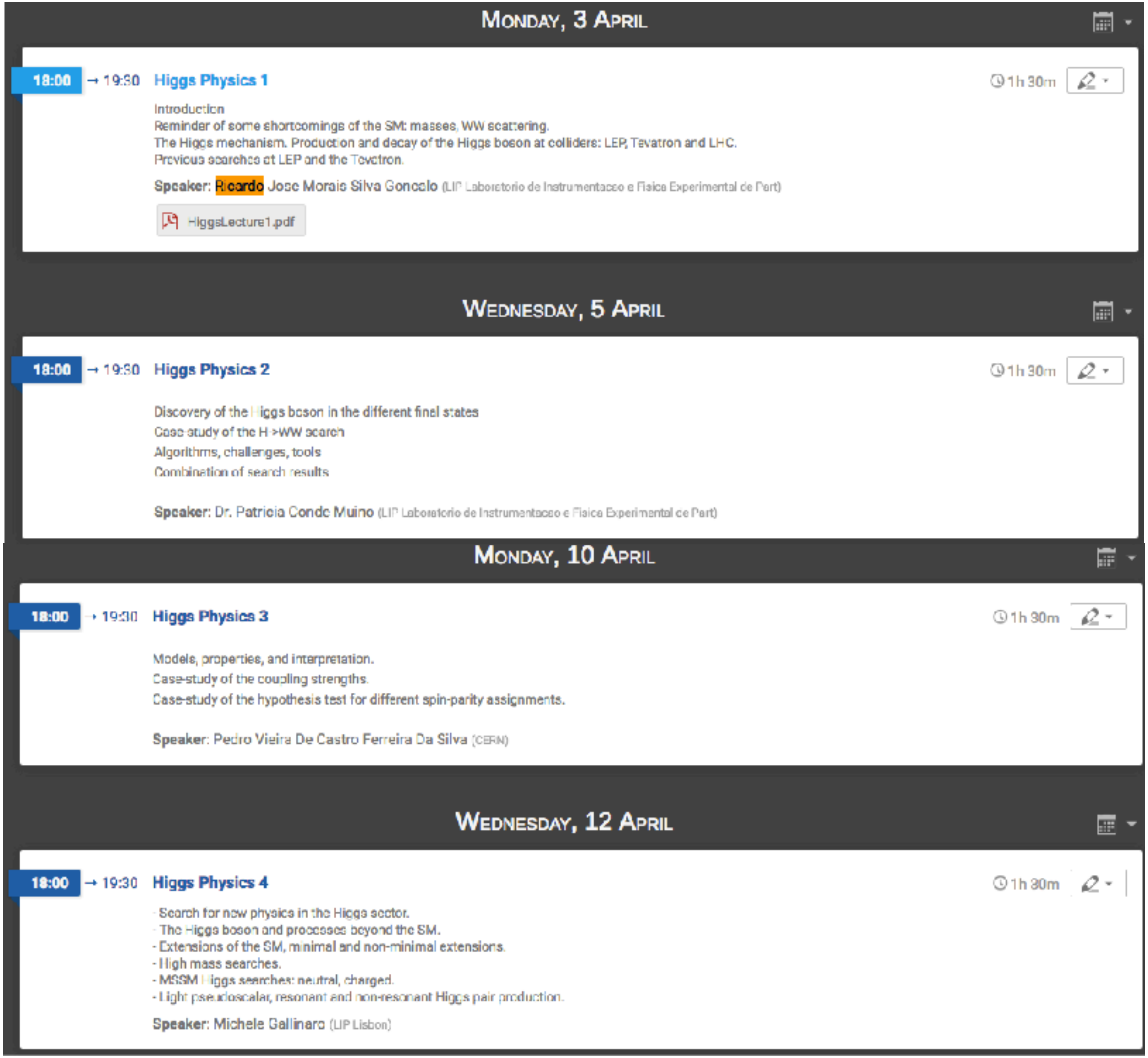
Analysis	Observed/ Expected	95% CL limit on Γ_H (MeV)	95% CL limit on Γ_H/Γ_H^{SM}	Γ_H (MeV)	Γ_H/Γ_H^{SM}
4ℓ	Expected	42	10.1	$4.2^{+17.3}_{-4.2}$	$1.0^{+4.2}_{-1.0}$
	Expected (no syst.)	41	10.0	$4.2^{+17.1}_{-4.2}$	$1.0^{+4.1}_{-1.0}$
	Observed	33	8.0	$1.9^{+11.7}_{-1.9}$	$0.5^{+2.8}_{-0.5}$
$4\ell_{on-shell} + 2\ell 2\nu$	Expected	44	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

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 ath 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



MONDAY, 3 APRIL

18:00 → 19:30 **Higgs Physics 1** 1h 30m

Introduction
Reminder of some shortcomings of the SM: masses, WW scattering.
The Higgs mechanism. Production and decay of the Higgs boson at colliders: LEP, Tevatron and LHC.
Previous searches at LEP and the Tevatron.

Speaker: Ricardo Jose Morais Silva Goncalo (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

HiggsLecture1.pdf

WEDNESDAY, 5 APRIL

18:00 → 19:30 **Higgs Physics 2** 1h 30m

Discovery of the Higgs boson in the different final states
Case study of the H->WW search
Algorithms, challenges, tools
Combination of search results

Speaker: Dr. Patricia Conde Muino (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

MONDAY, 10 APRIL

18:00 → 19:30 **Higgs Physics 3** 1h 30m

Models, properties, and interpretation.
Case-study of the coupling strengths.
Case-study of the hypothesis test for different spin-parity assignments.

Speaker: Pedro Vieira De Castro Ferreira Da Silva (CERN)

WEDNESDAY, 12 APRIL

18:00 → 19:30 **Higgs Physics 4** 1h 30m

- Search for new physics in the Higgs sector.
- The Higgs boson and processes beyond the SM.
- Extensions of the SM, minimal and non-minimal extensions.
- High mass searches.
- MSSM Higgs searches: neutral, charged.
- Light pseudoscalar, resonant and non-resonant Higgs pair production.

Speaker: Michele Gallinaro (LIP Lisbon)