Differential cross sections at 3000 fb^{-1}

22 October 2018

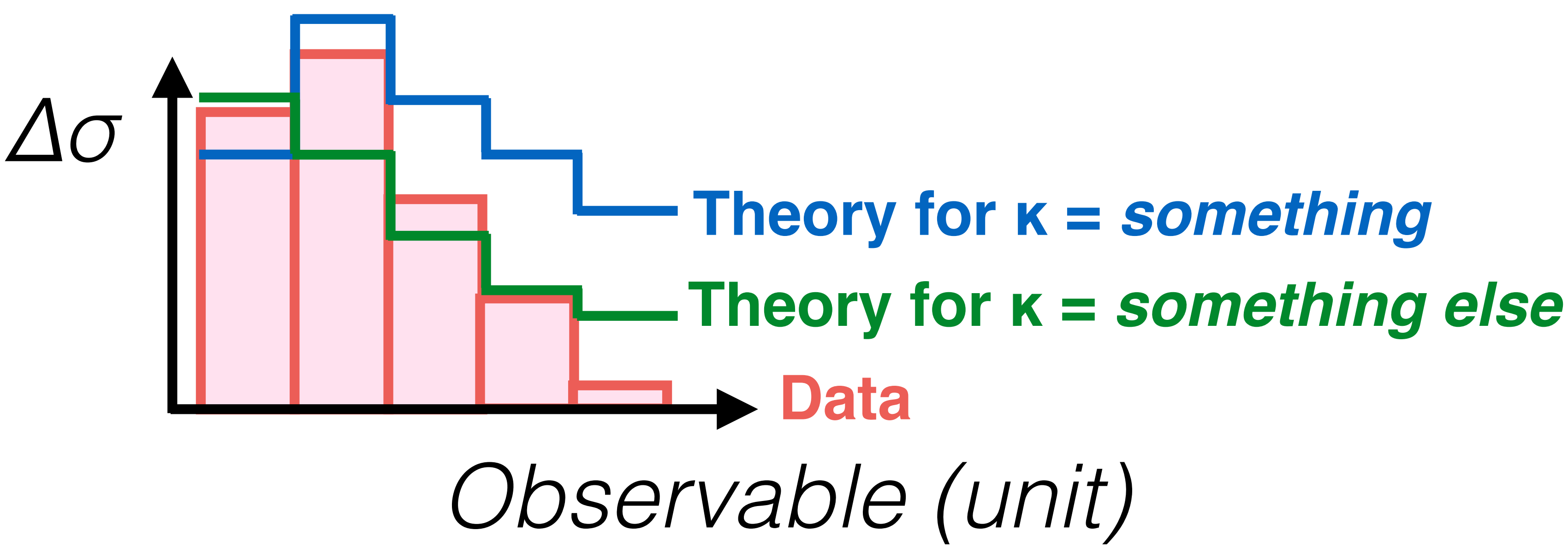
Higgs @ HL/HE-LHC - Autumn WG2 Meeting

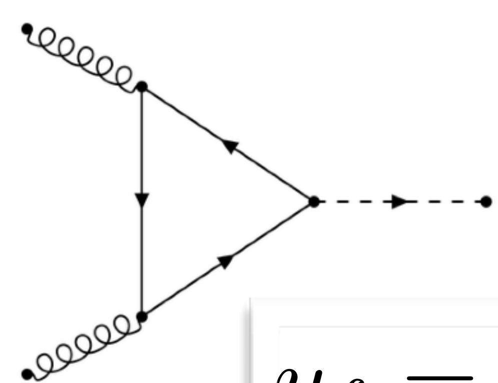
Mauro Donega[1], Javier M. G. Duarte[2], Andrew Gilbert[3], Thomas Klijnsma[1], Michael David Krohn[4], Pasquale Musella[1], David Sperka[5], Vittorio Raoul Tavolaro[1], Caterina Vernieri[6]

1: ETH Zurich
2: Fermilab
3: CERN
4: University of Colorado Boulder
5: University of Florida
6: SLAC

Differential cross sections

- Measures not only the **inclusive cross section**, but also the **shape** of the distribution
  - The **shape** may be tested versus its Standard Model expectation
- Relatively small **coupling variations** lead to significant shape distortions

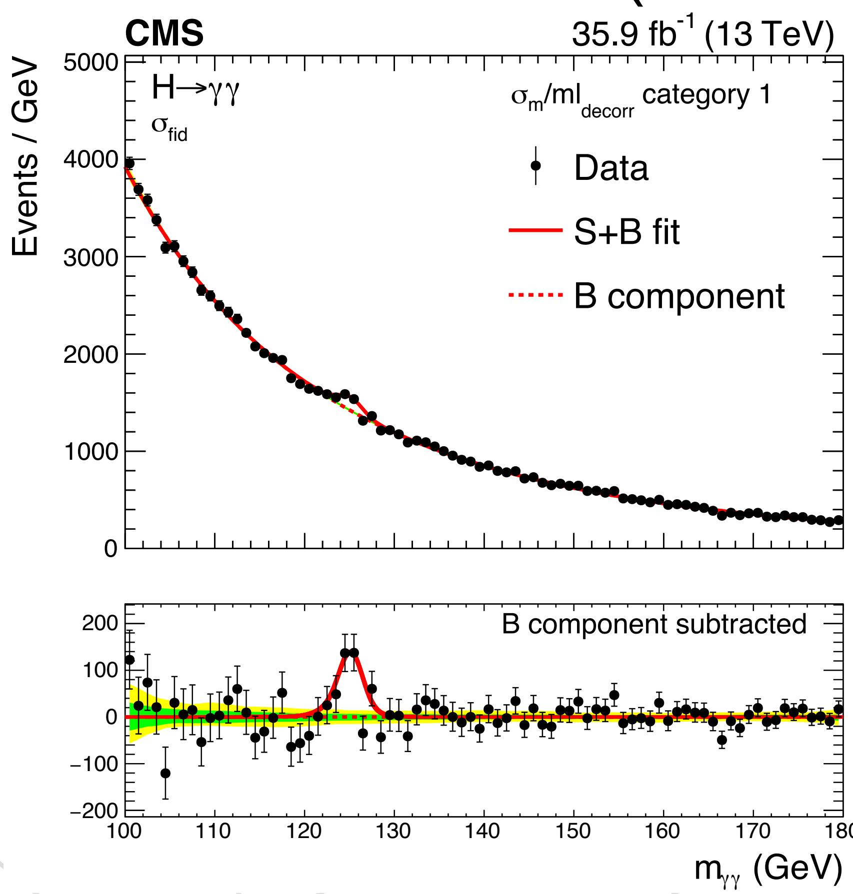




$$y_f = \kappa_f \cdot y_f^{SM}$$

Inputs to differential combination

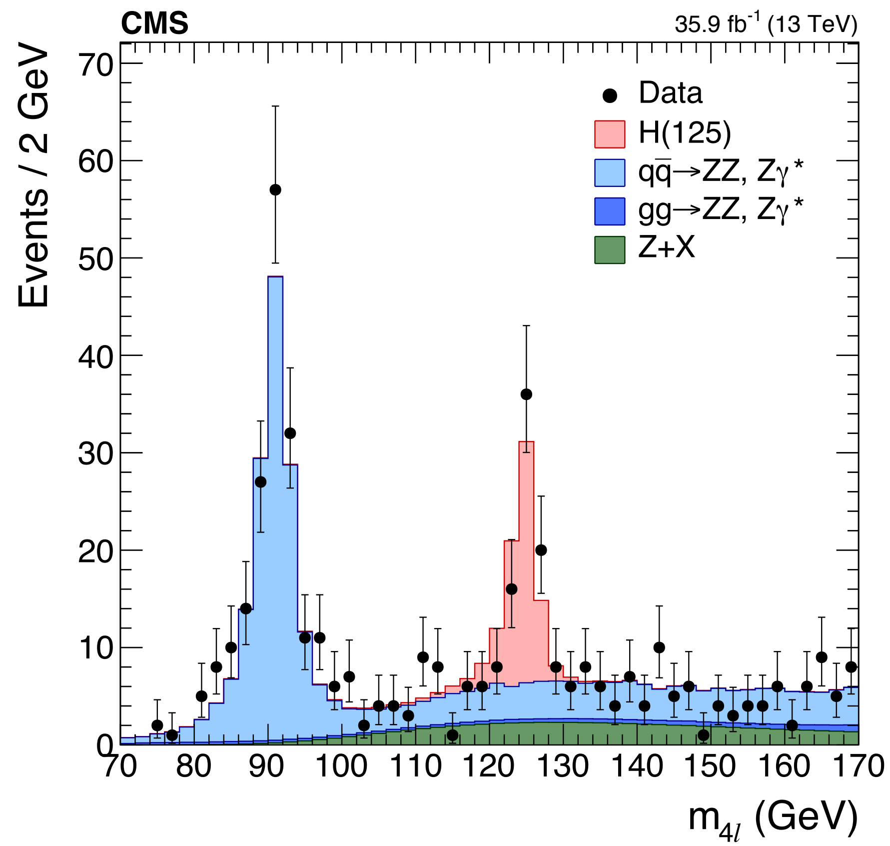
- Differential combination at 13 TeV with 35.9 fb^{-1}: cadi HIG-17-028 (CWR ended)



H → γγ

[CMS-PAS-HIG-17-025; Submitted to JHEP]

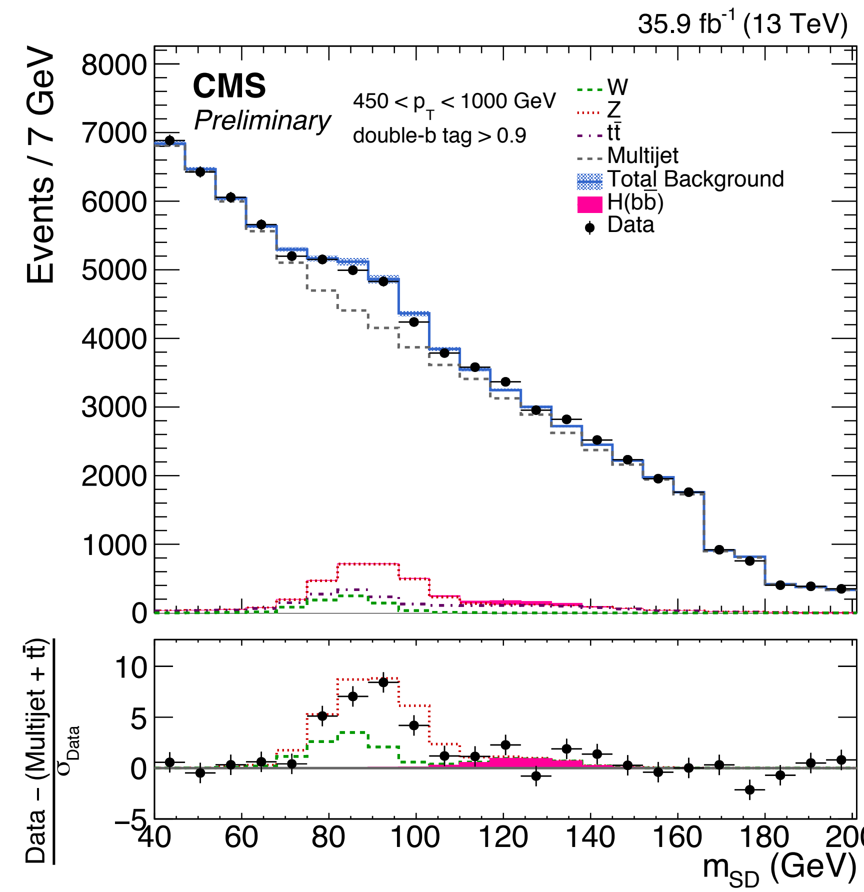
- Fit diphoton invariant mass
- Largest number signal events; diff. xs. measured for >25 observables



H → ZZ

[JHEP 1711 (2017) 047]

- Fit 4 lepton invariant mass
- Good s/b, close to H → γγ inclusively



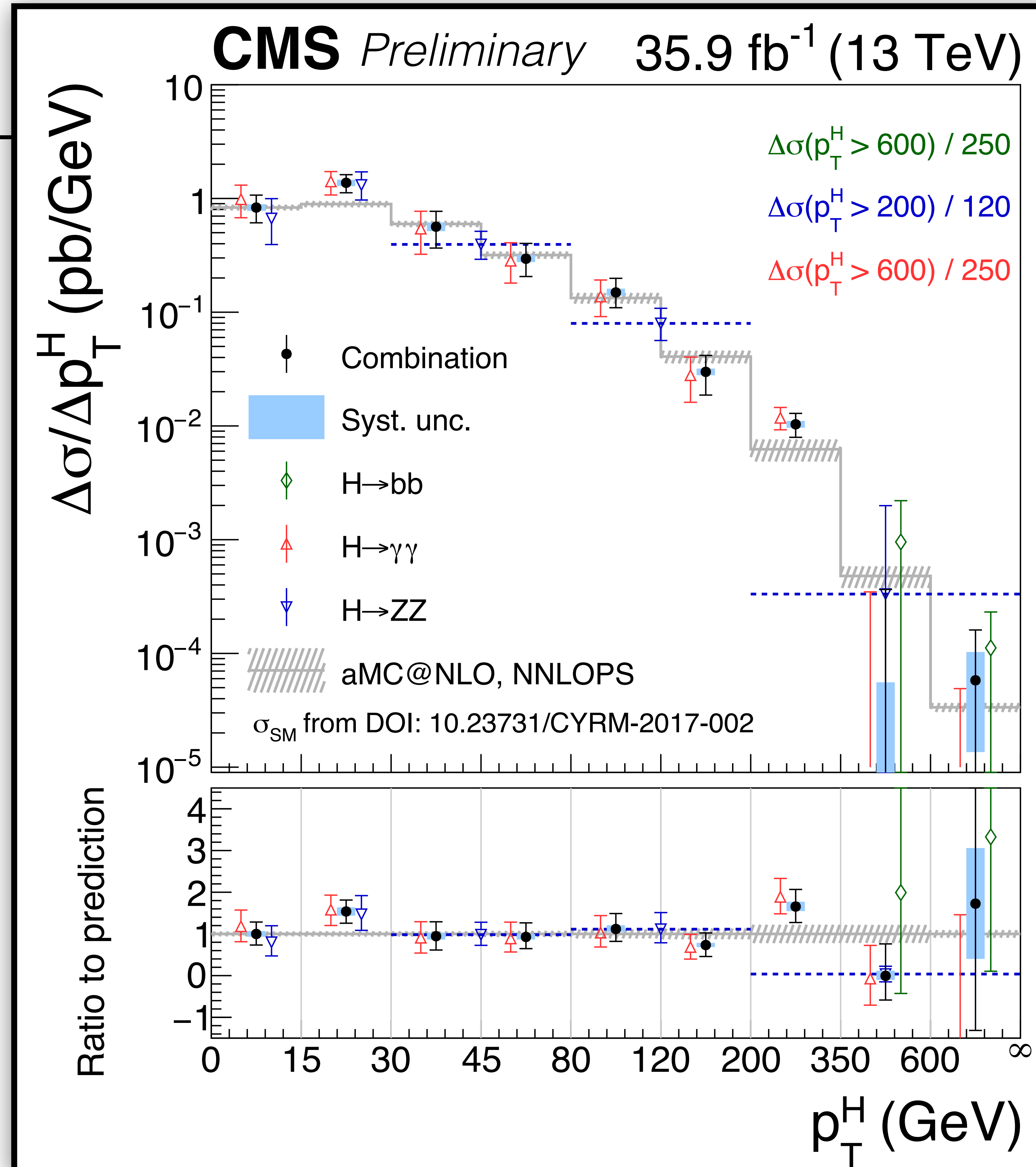
boosted H → bb

[Phys. Rev. Lett. 120 (2018), no. 7]

- Search for boosted ggH → bb
- **Only in pT comb. > 350 GeV**

pT @ 35.9 fb^{-1}

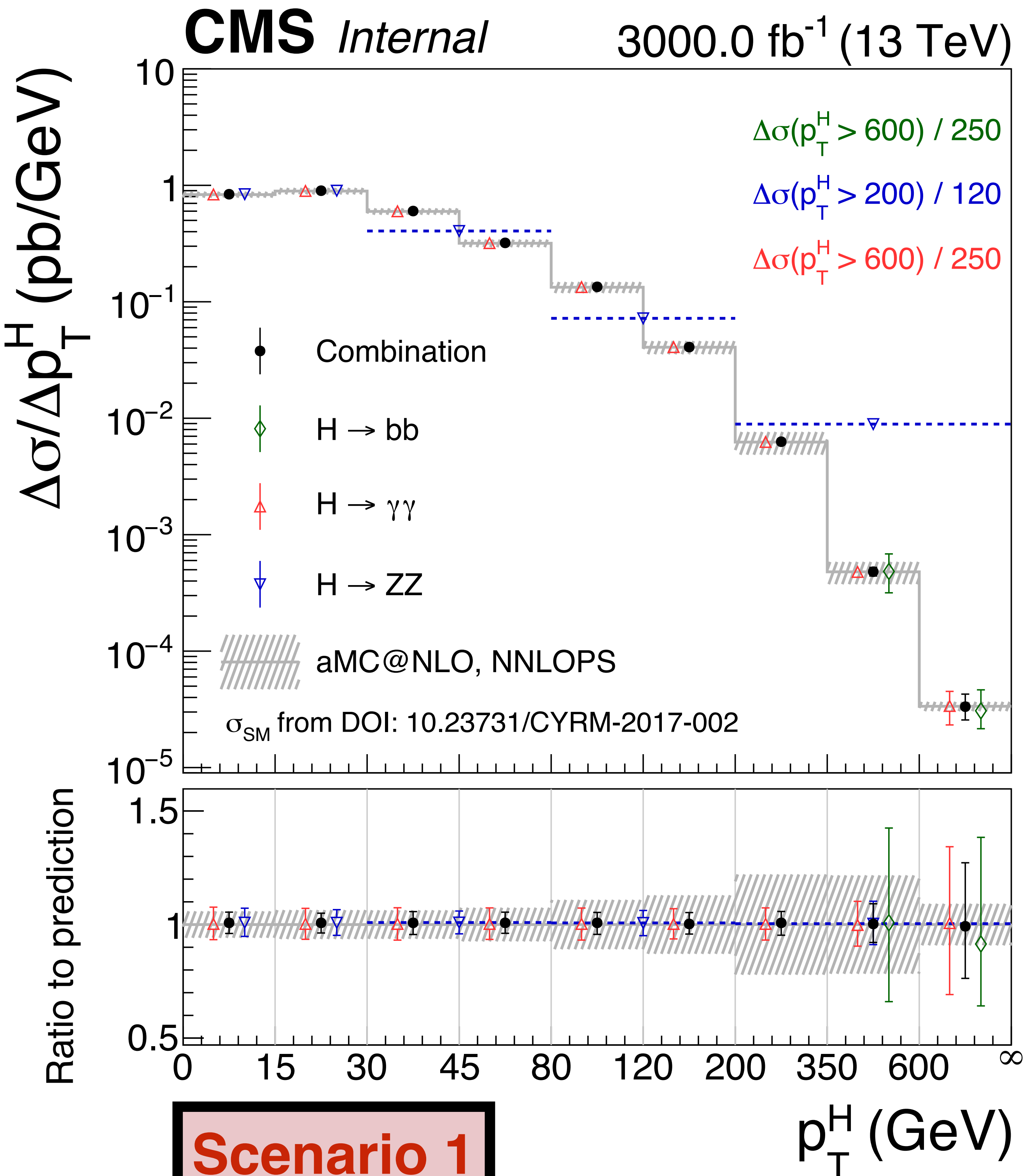
- Combined uncertainty ≤30% up to 200 GeV
- ~300% uncertainty in last bin; still usable for interpretation
- ~15% improvement of combination w.r.t.



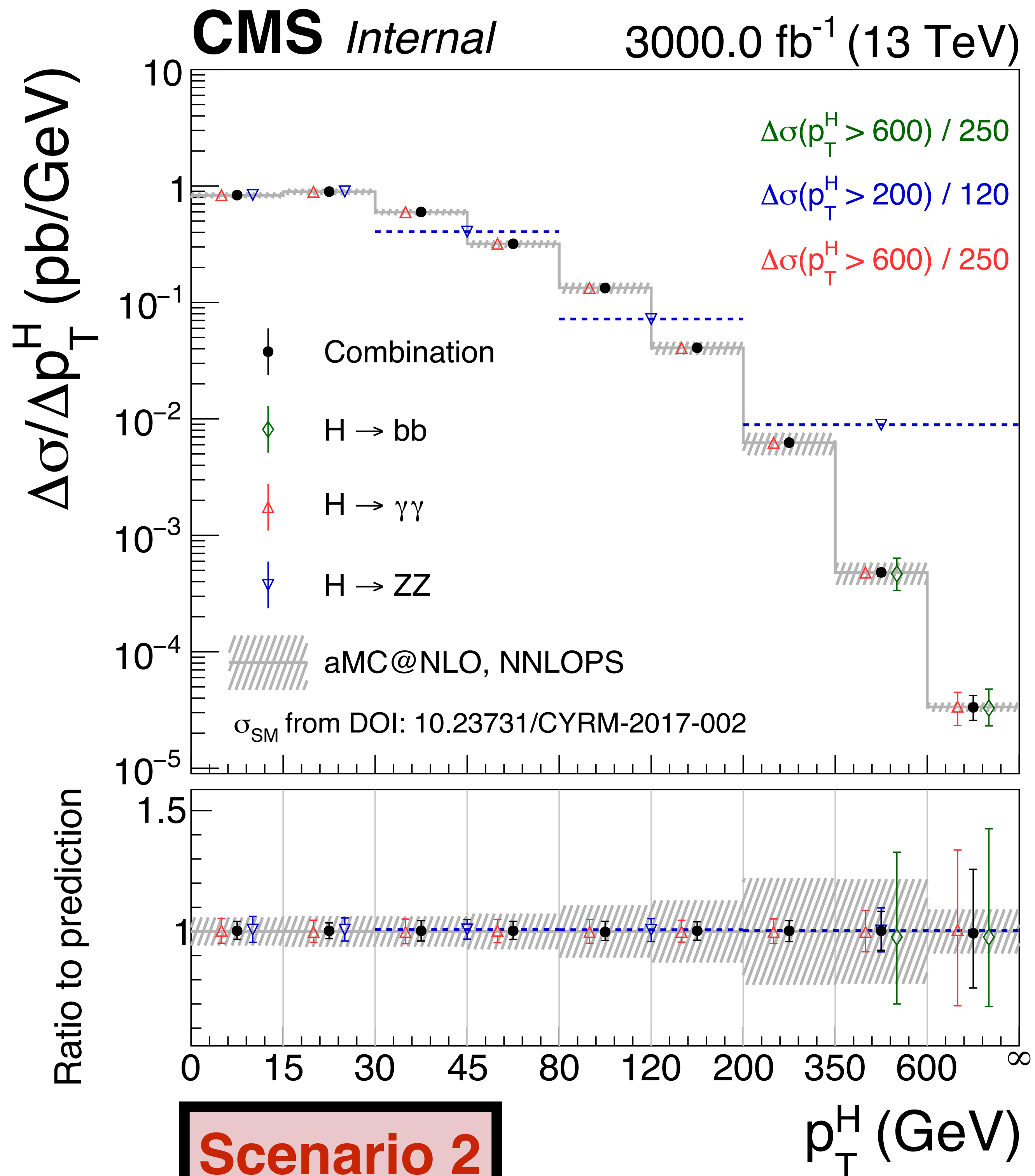
Binning p_T^H (GeV)

H → γγ	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	>600
H → ZZ	0-15	15-30	30-80		80-200		>200		
H → bb	*none*							350-600	>600

Spectra



Scenario 1



Scenario 2

Spectra: numbers

Scenario 1

	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	>600
H → γγ	7.16%	6.82%	7.13%	6.94%	7.05%	6.65%	7.09%	9.87%	32.55%
H → ZZ	6.21%	5.66%	5.02%		5.55%		9.56%		
H → bb	-	-	-	-	-	-	-	38.22%	37.11%
Comb.	4.70%	4.36%	5.04%	4.66%	4.84%	4.73%	5.23%	8.53%	25.45%
Improv.	34.40%	36.10%	29.20%	32.90%	31.40%	28.90%	26.10%	13.60%	21.80%

CMS internal

Scenario 2

	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	>600
H → γγ	5.12%	4.55%	5.10%	4.78%	4.94%	4.52%	5.10%	8.57%	32.24%
H → ZZ	5.36%	4.80%	4.06%		4.71%		9.10%		
H → bb	-	-	-	-	-	-	-	31.41%	36.81%
Comb.	3.72%	3.26%	4.22%	3.75%	3.97%	3.83%	4.37%	8.04%	24.54%
Improv.	27.30%	28.30%	17.30%	21.60%	19.60%	15.20%	14.30%	6.10%	23.90%

CMS internal

Stat. only

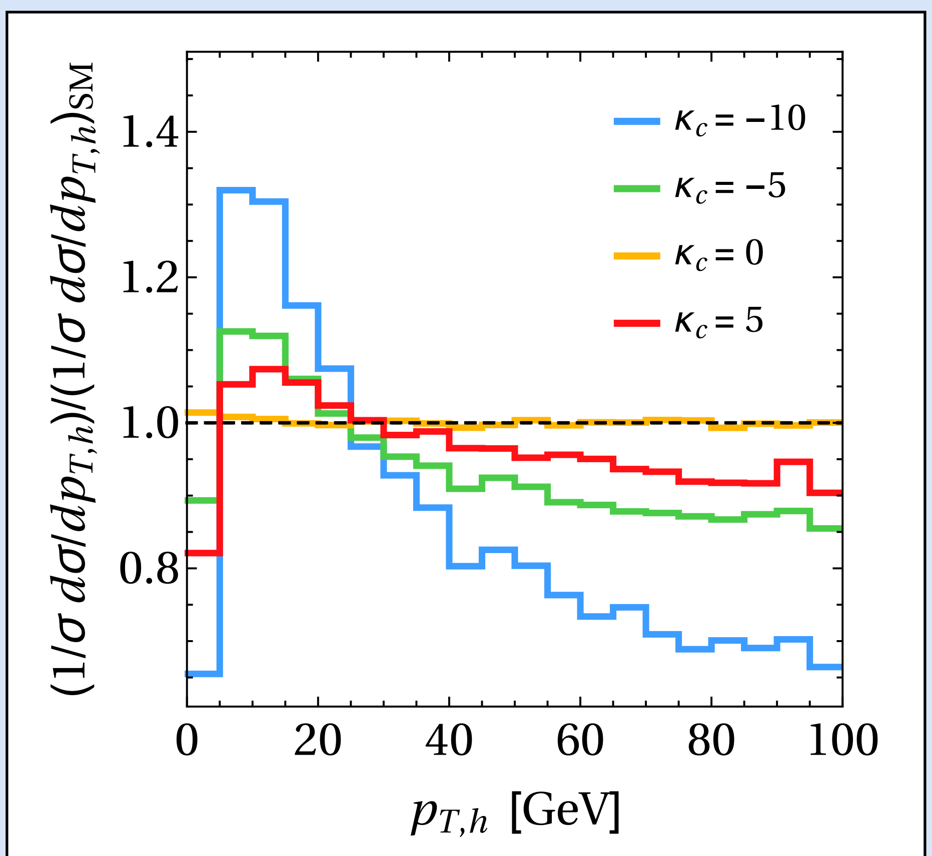
	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	>600
H → γγ	4.06%	3.24%	4.02%	3.55%	3.77%	3.33%	4.07%	7.99%	32.09%
H → ZZ	4.19%	3.91%	3.01%		3.88%		8.79%		
H → bb	-	-	-	-	-	-	-	25.63%	30.59%
Comb.	2.92%	2.50%	3.67%	3.11%	3.36%	3.20%	3.79%	7.61%	22.25%
Improv.	28.00%	22.70%	8.70%	12.50%	10.80%	4.10%	6.70%	4.80%	30.70%

CMS internal

Theory predictions under coupling modifications

Variations of κ_b and κ_c:

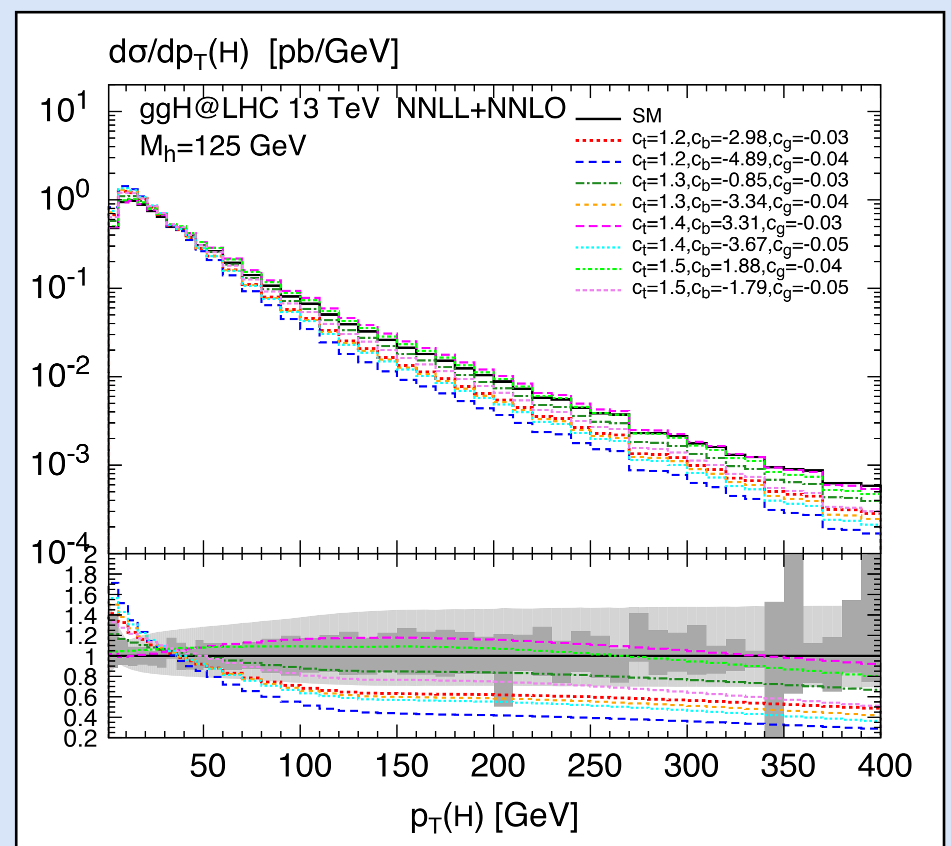
- p_T-spectrum including light quark effects (using recent developments in p_T-resummation techniques)
- no ggHbb, up to 120 GeV



Variations of κ_t and c_g:

- Adding dimension-6 operators to the Standard Model Lagrangian
- Operator $\mathbf{c_g}$ yields direct Higgs-gluon coupling
- Tensor structure: Heavy top-mass lim.

$$\sigma \simeq \left|\kappa_t + 12 c_g\right|^2 \cdot \sigma_{\rm SM}$$



Inclusive vs. differential

- What is the additional information obtained from using the **shape information**?

Branching fractions freely floating

- **Shows the constraint purely from the theory, using only the 'shape' (overall normalization is profiled out)**

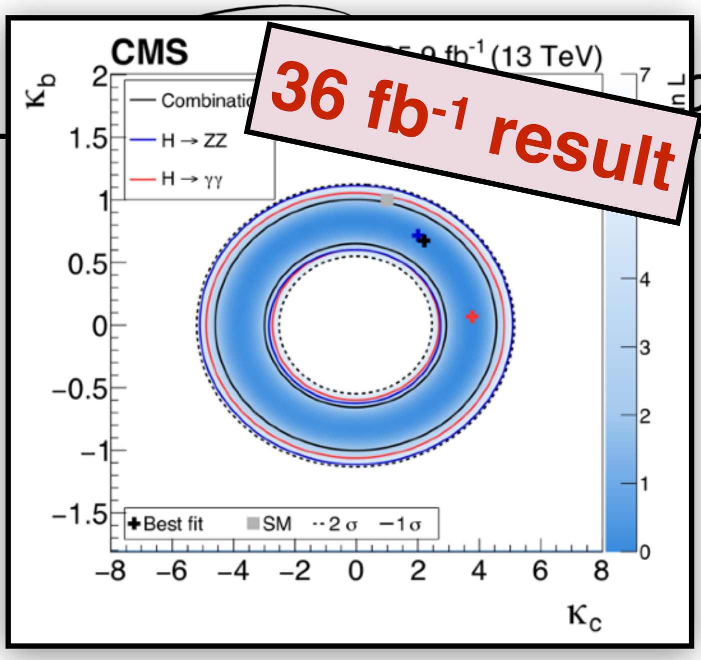
  - Effectively profiles the overall normalization
  - Only the distortions of the differential spectra are used to constrain the Higgs couplings

- What is the best we can do, including **inclusive and shape information**?

Coupling-dependent branching fractions

- **Assumes full knowledge of how the Higgs decays; no BR_{BSM}, full understanding of resolved loop**

Interpretation



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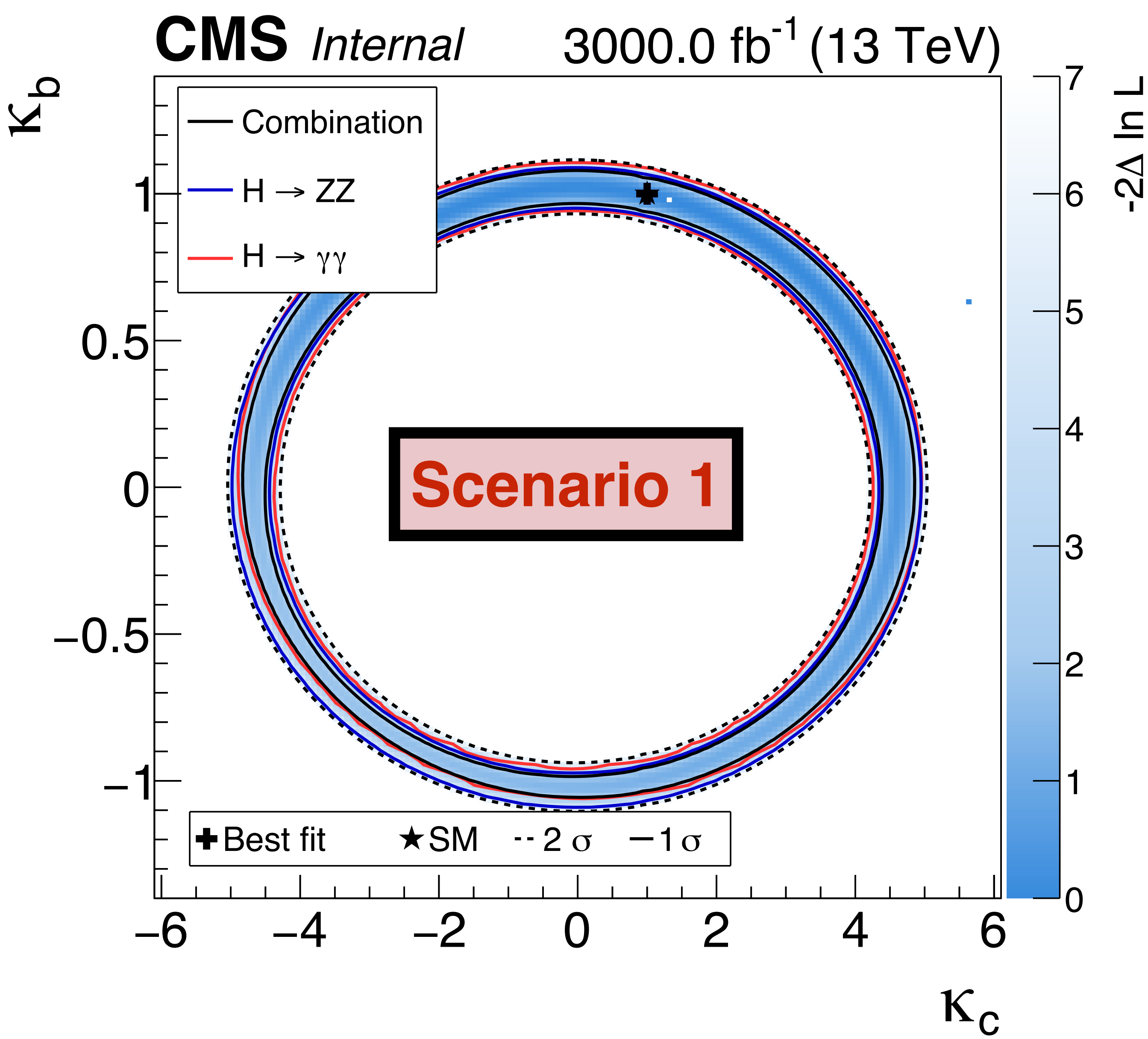
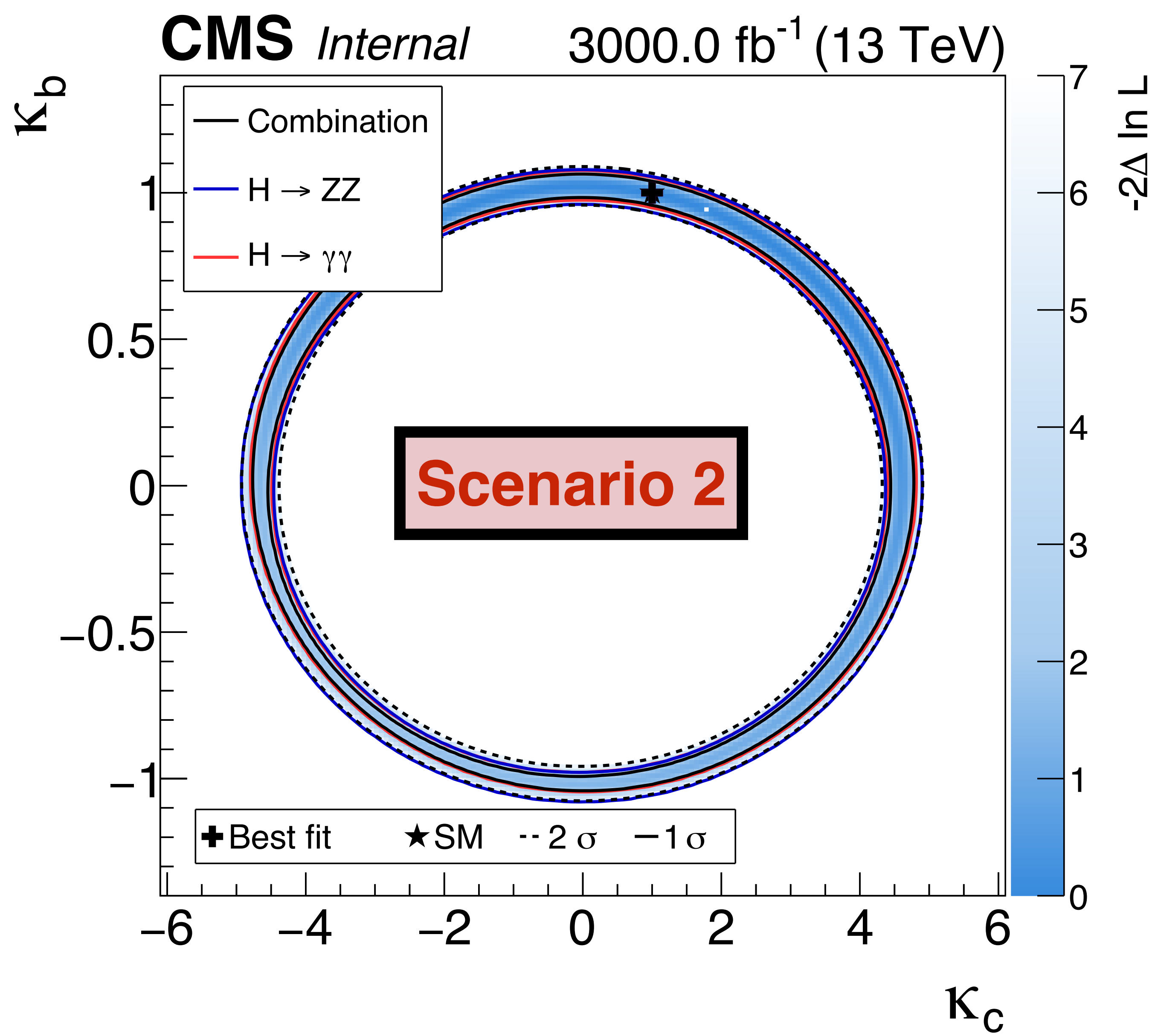
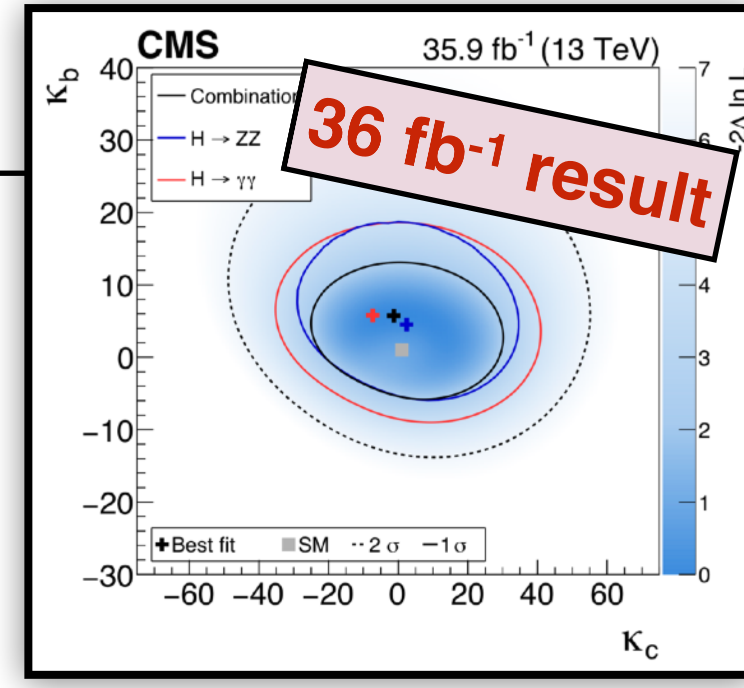




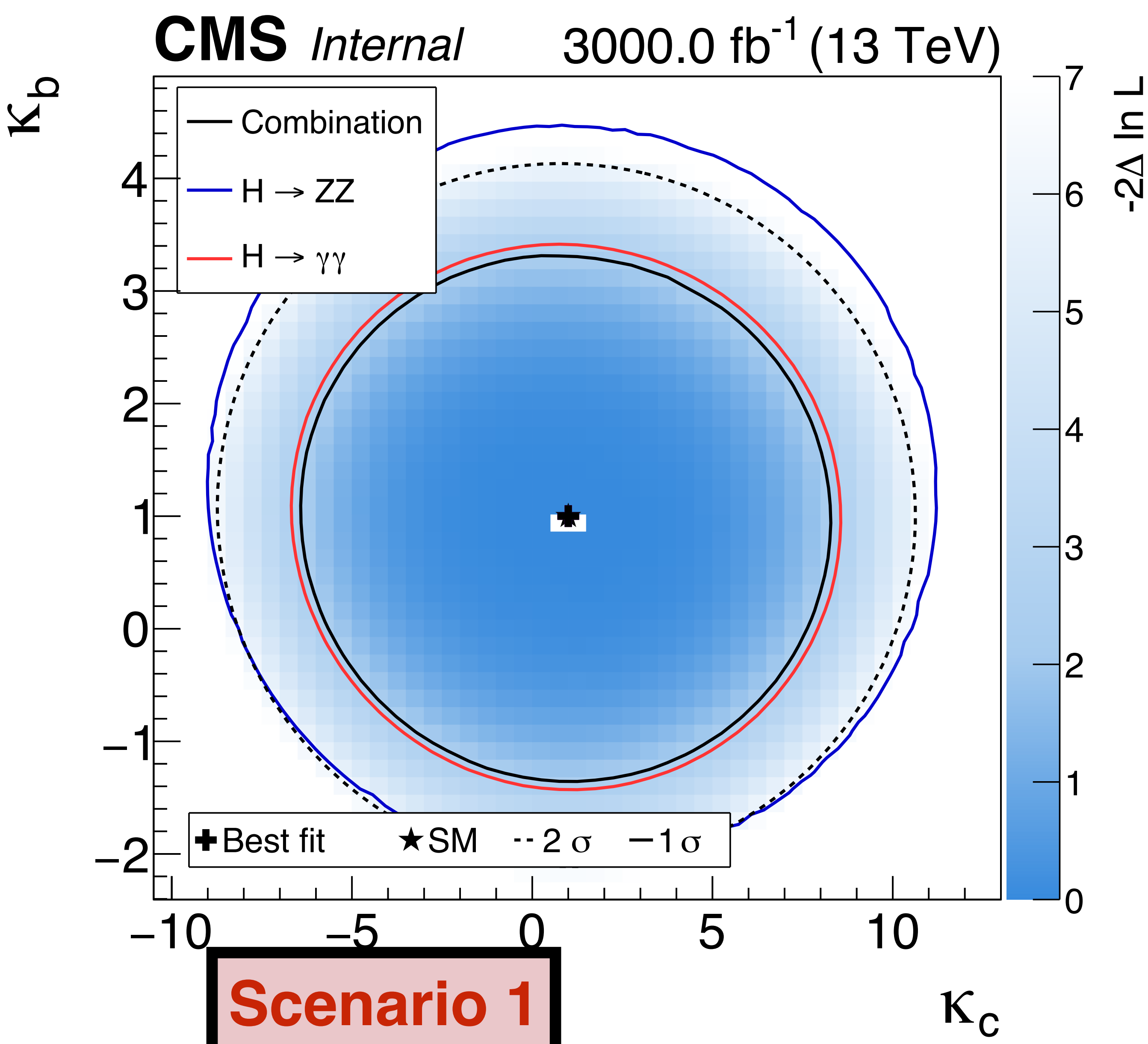
Interpretation

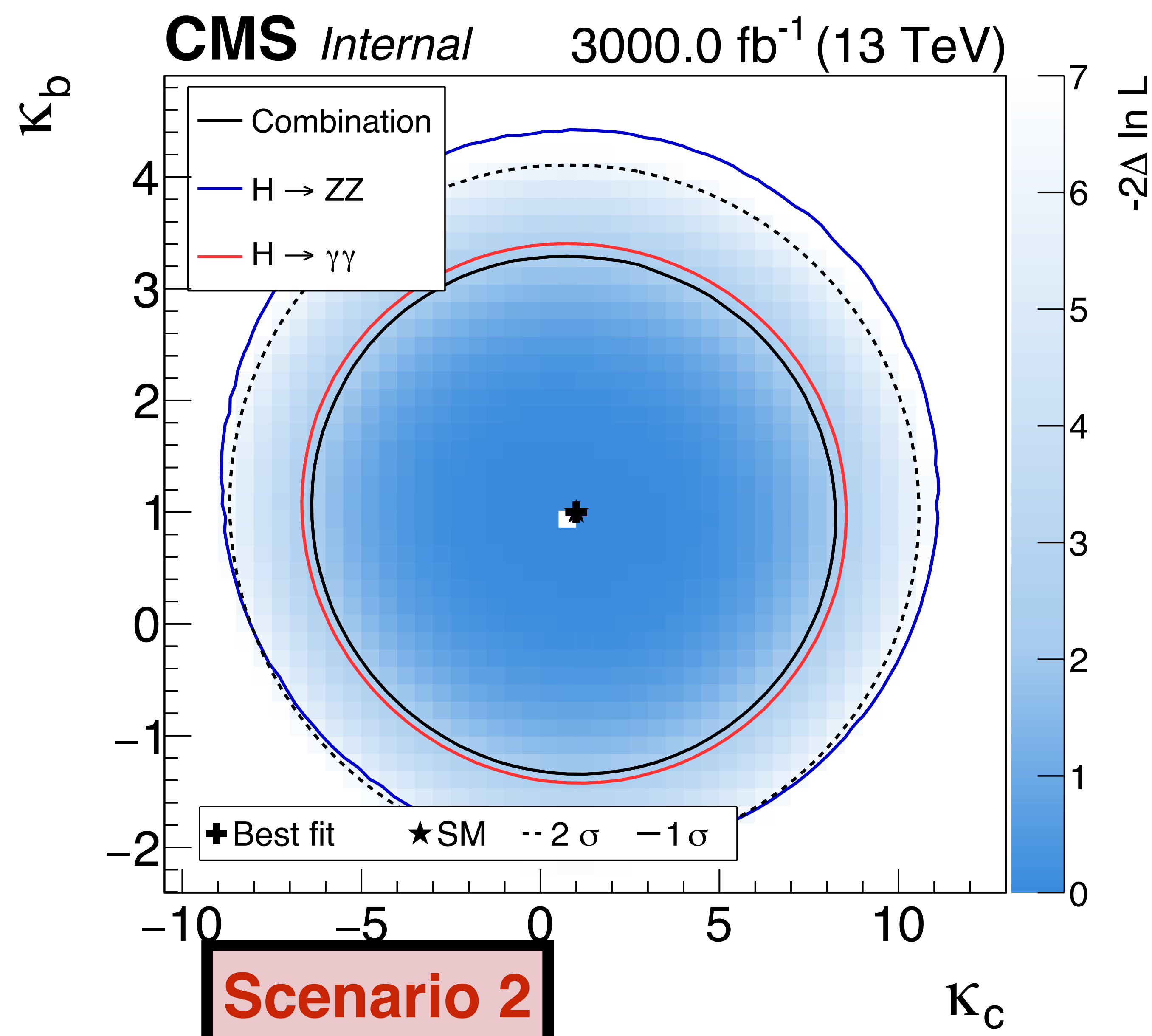


Branching fractions freely floating

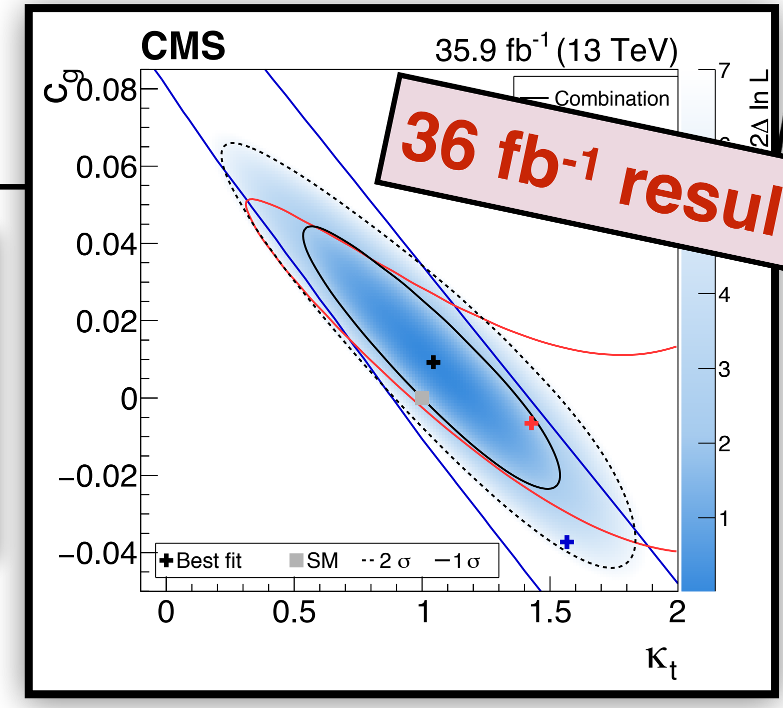
- **Shows the constraint using only the 'shape'**

- Obtain about ±6 x SM from shape



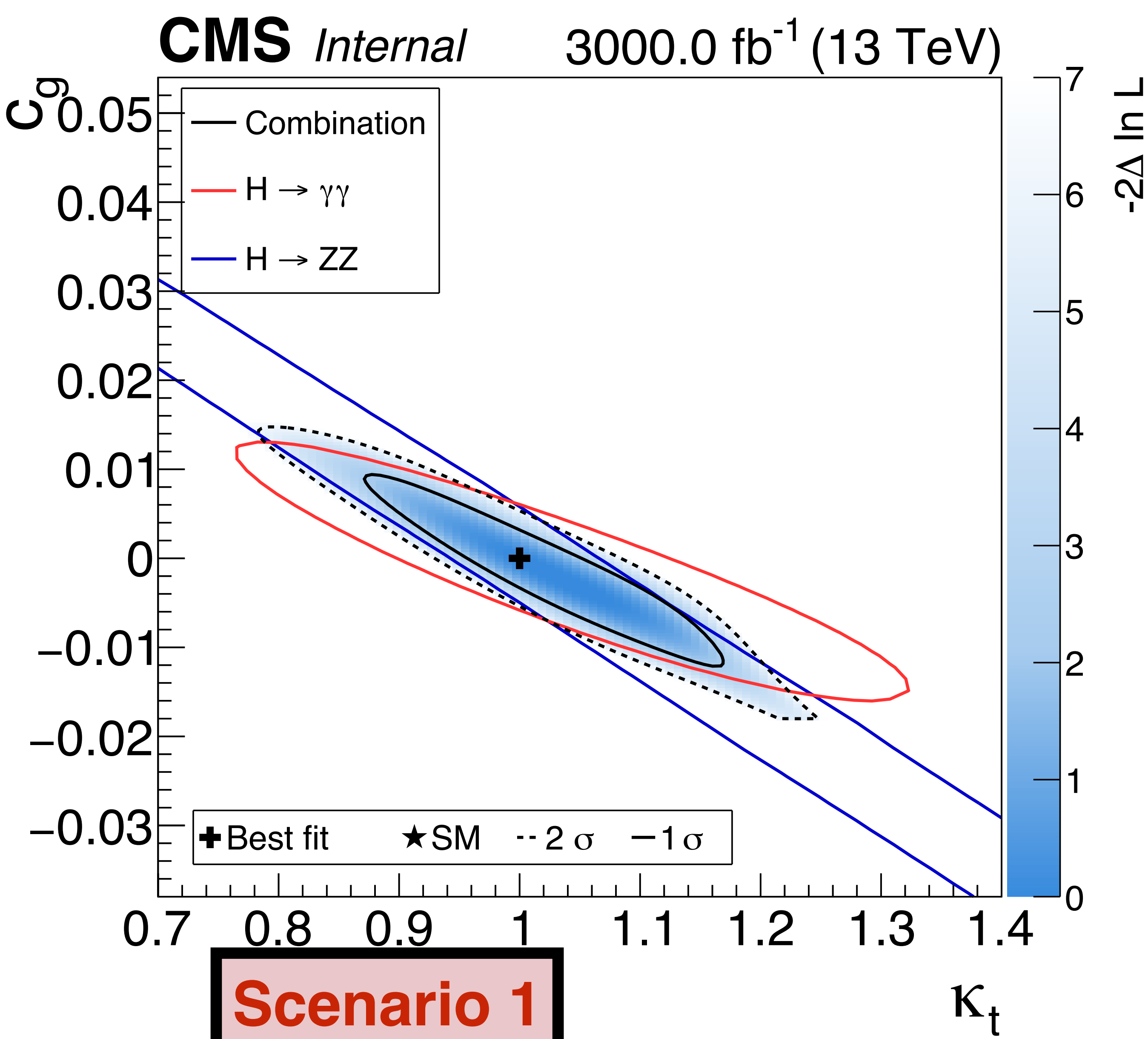


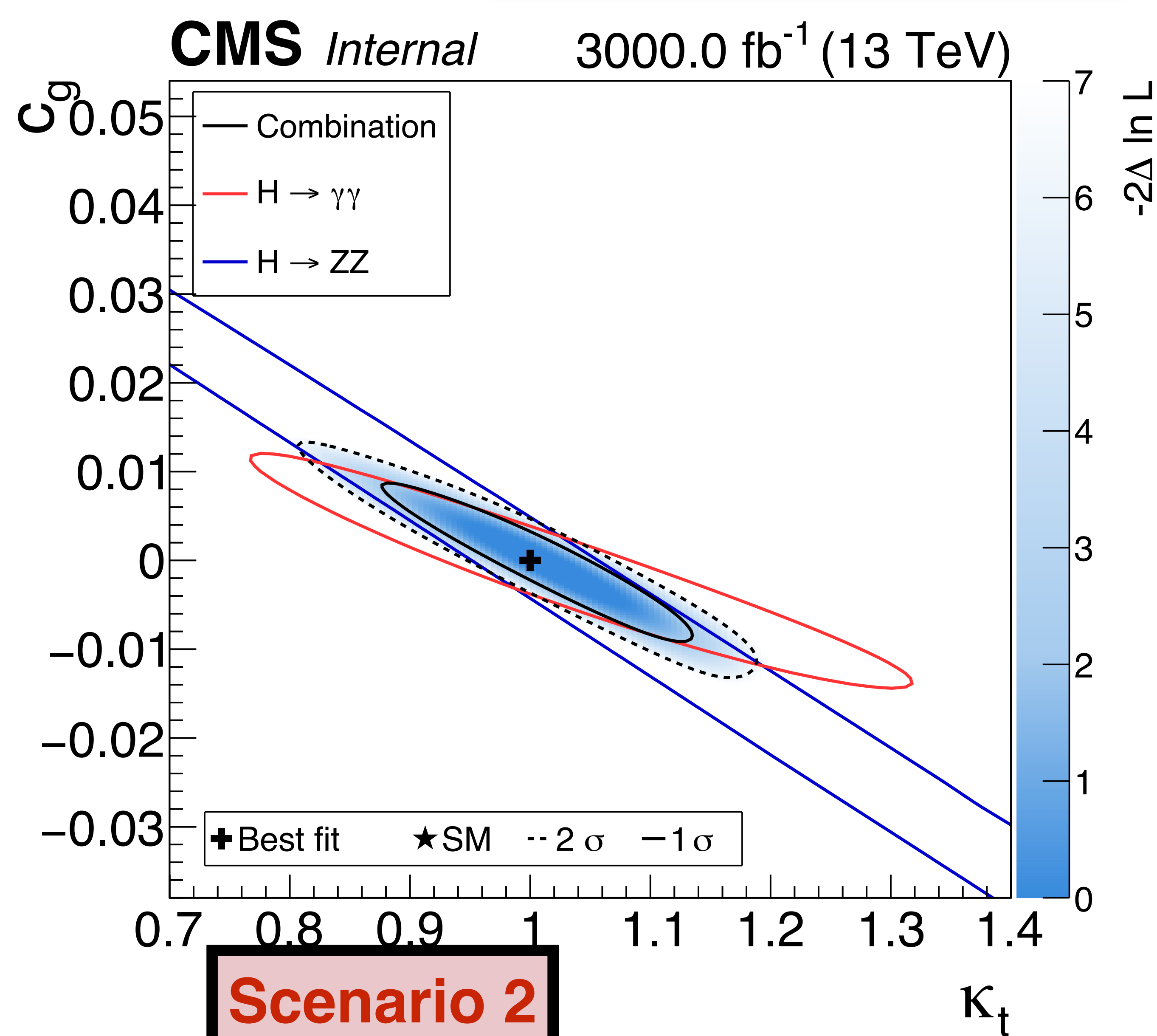
Interpretation



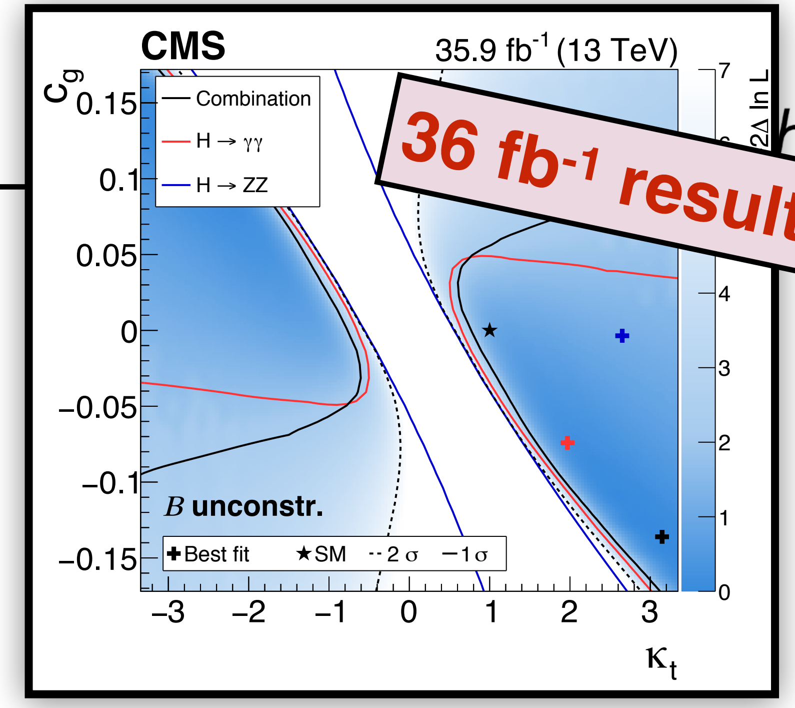
Coupling-dependent branching fractions

- Assumes full knowledge of how the Higgs decays; no BR_{BSM}, full understanding of resolved loop





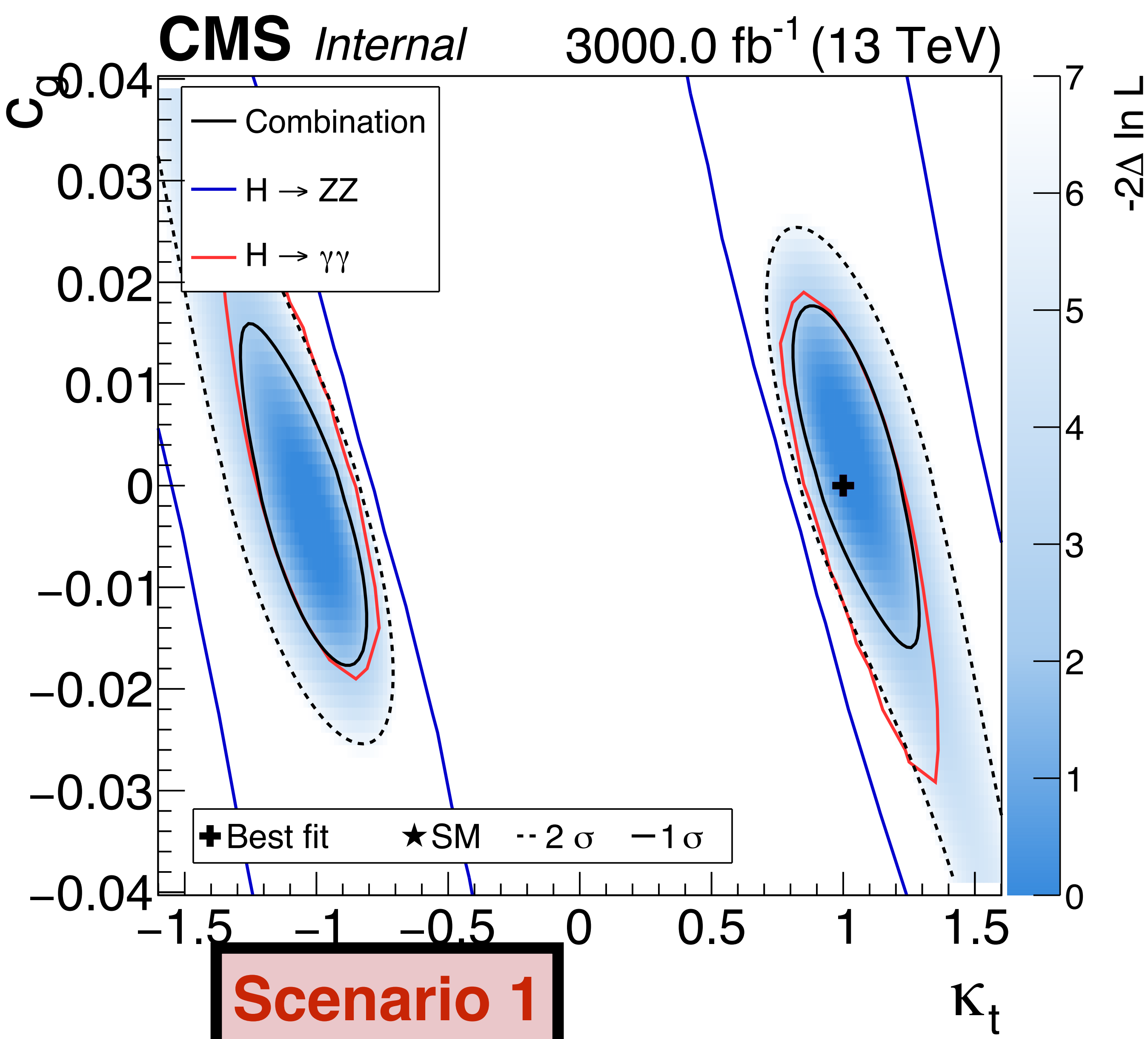
Interpretation

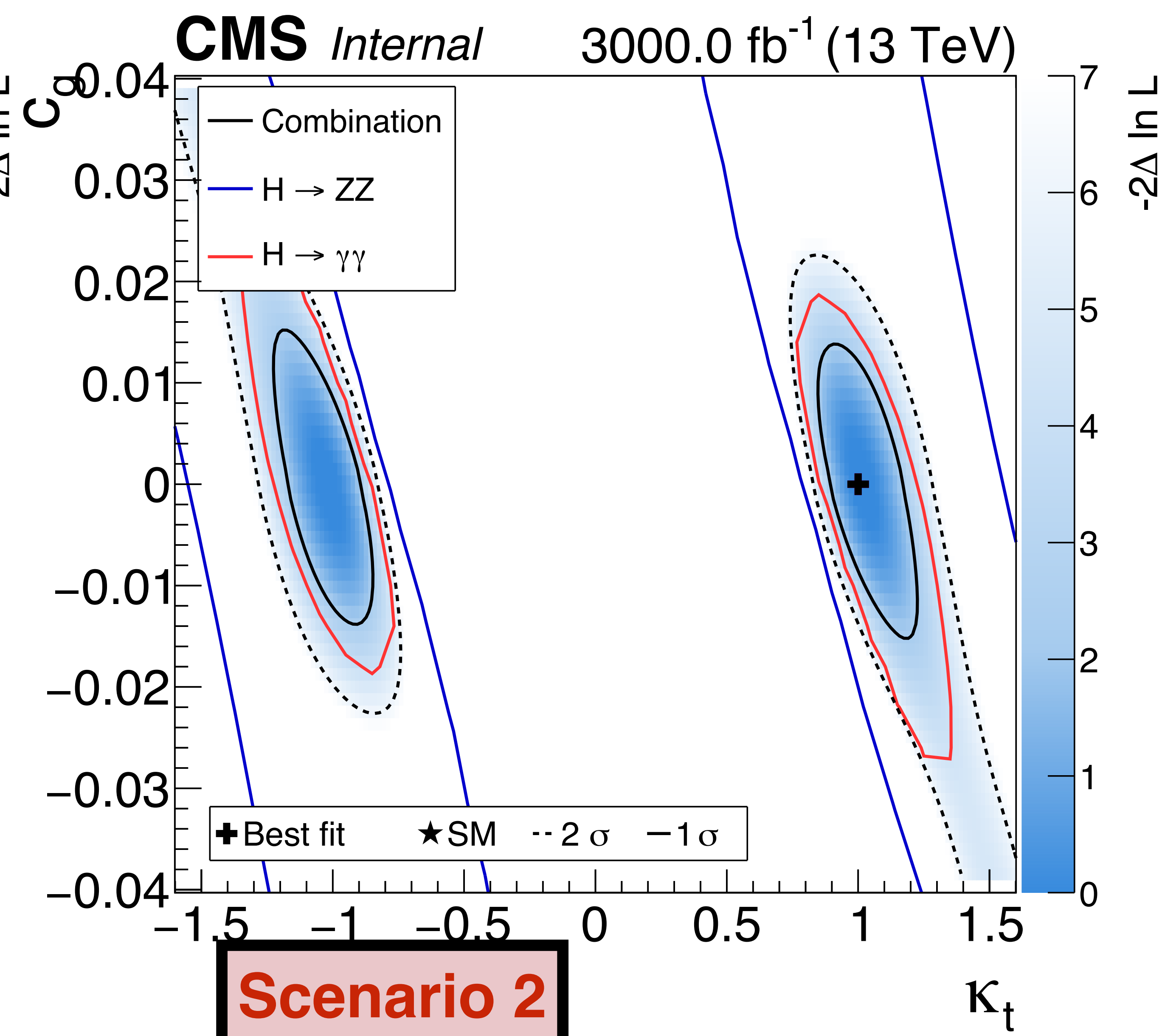


Branching fractions freely floating

- **Shows the constraint using only the 'shape'**

- Strongly improved as stat uncertainties dominate the 36 fb^{-1} result



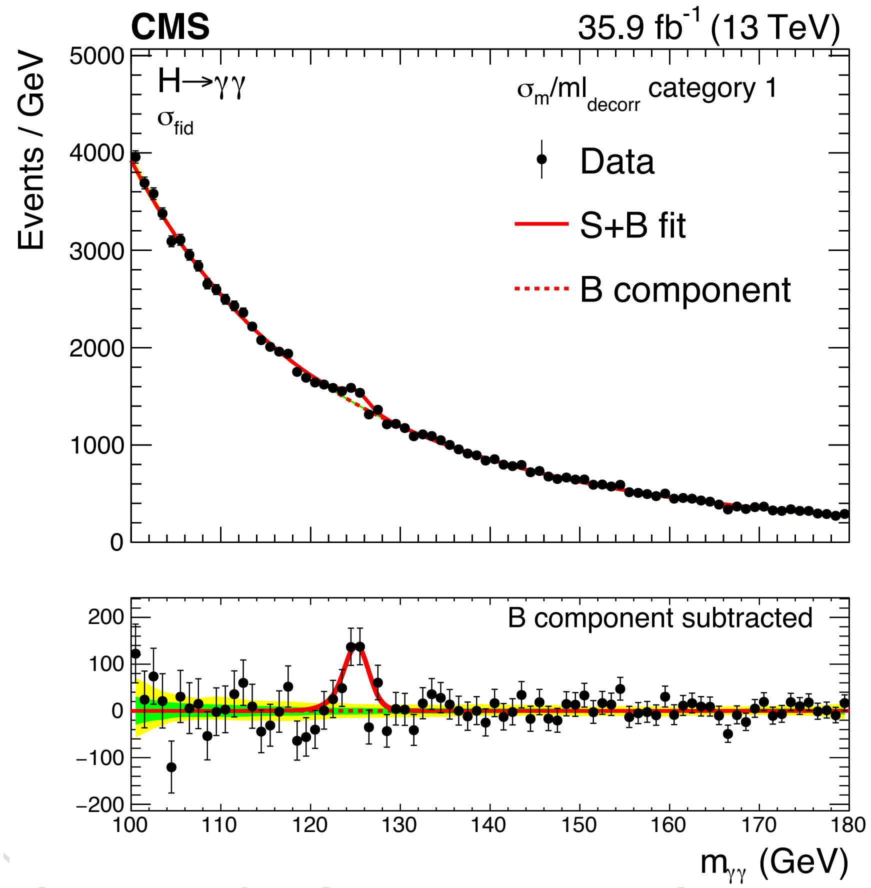


Conclusion

- Presented projections of the p_T spectrum and interpretations in terms of Higgs boson couplings at 3000 fb^{-1}
- ~5% uncertainty expected up to $p_T < 350$ GeV
- ~25% uncertainty for $p_T > 600$ GeV
- 6 x SM on κ_c using only shape

Back up

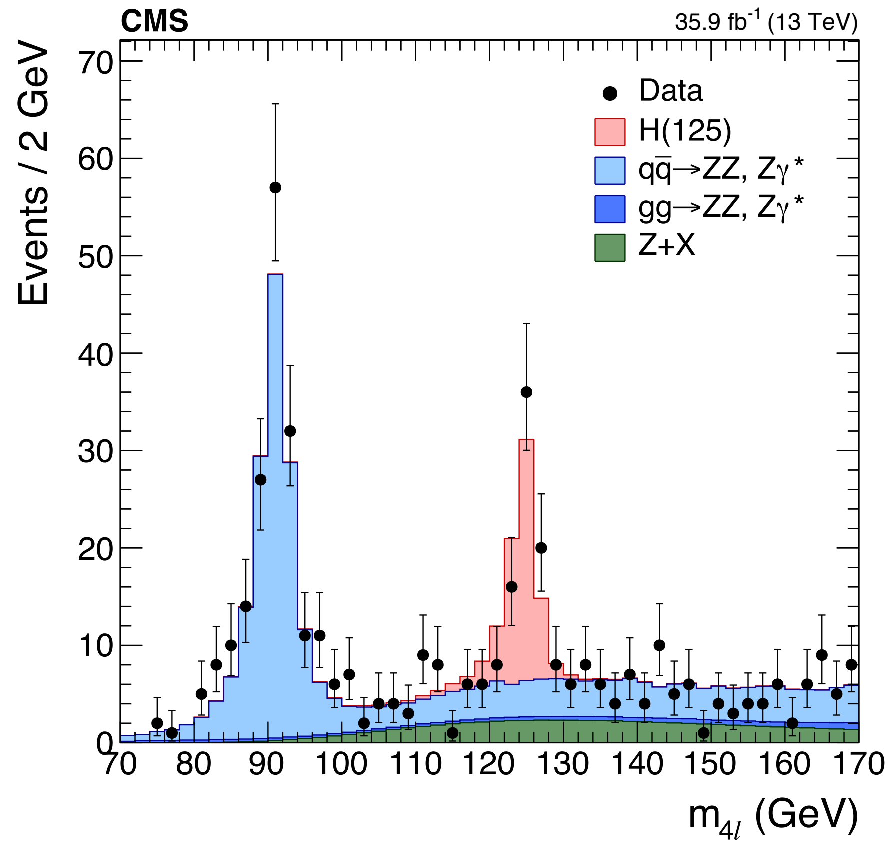
Inputs to differential combination



H → γγ

[CMS-PAS-HIG-17-025; Submitted to JHEP]

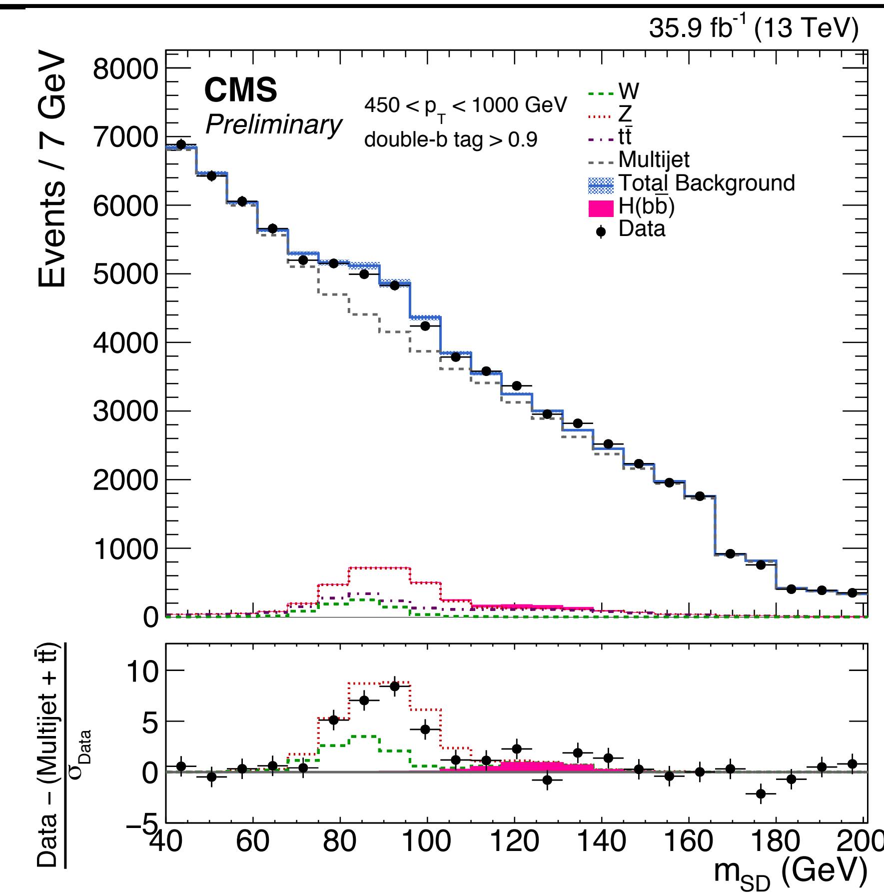
- Fit diphoton invariant mass
- Categories: Mass resolution
- Largest number signal events; diff. xs. measured for >25 observables



H → ZZ

[JHEP 1711 (2017) 047]

- Fit 4 lepton invariant mass
- Categories: ZZ decay channels
- Good s/b, close to H → γγ inclusively



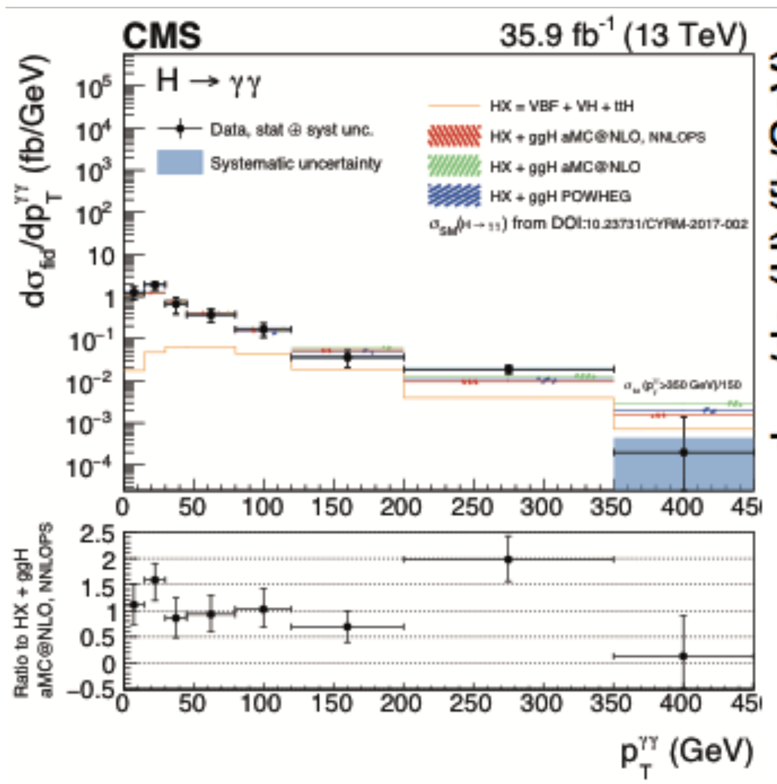
boosted H → bb

[Phys. Rev. Lett. 120 (2018), no. 7]

- Search for boosted ggH → bb
- Fit to fat jet mass spectrum
- Categories: passing/failing 2b tag
- Only in pT comb. > 350 GeV

Differential cross sections

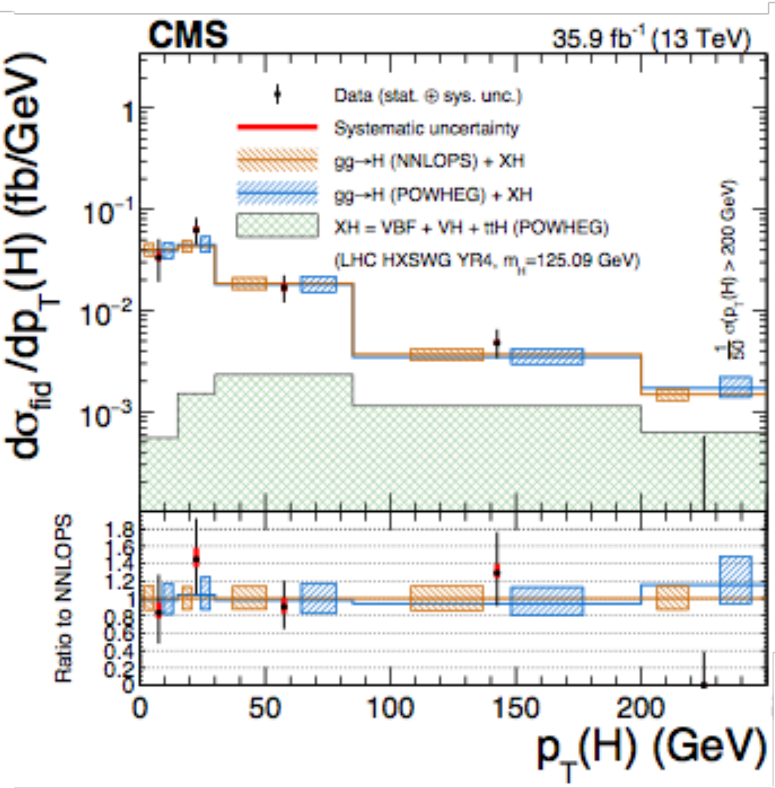
- Differential combination at 13 TeV with 35.9 fb^{-1}: cadi HIG-17-028 (CWR ended)
- Combination concerns 3 decay channels:



H —> 2 photons

(Datacard from Vittorio Tavolaro)

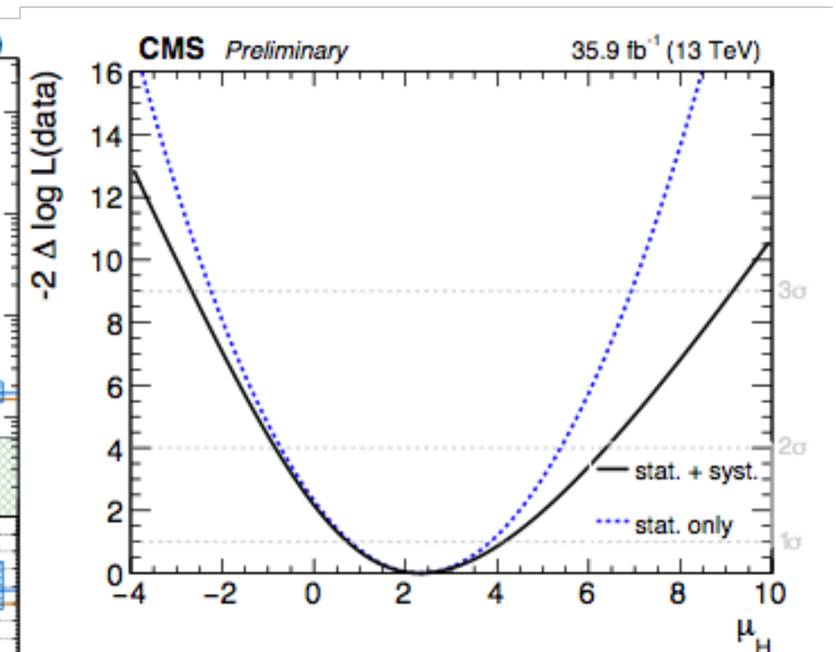
[CMS-PAS-HIG-17-025]



H —> 4 leptons

(Datacard from David Sperka)

[JHEP 1711 (2017) 047]



H —> 2 bottom

(Datacard from Javier Duarte, Michael Krohn and Caterina Vernieri)

[Phys. Rev. Lett. 120 (2018), no. 7]

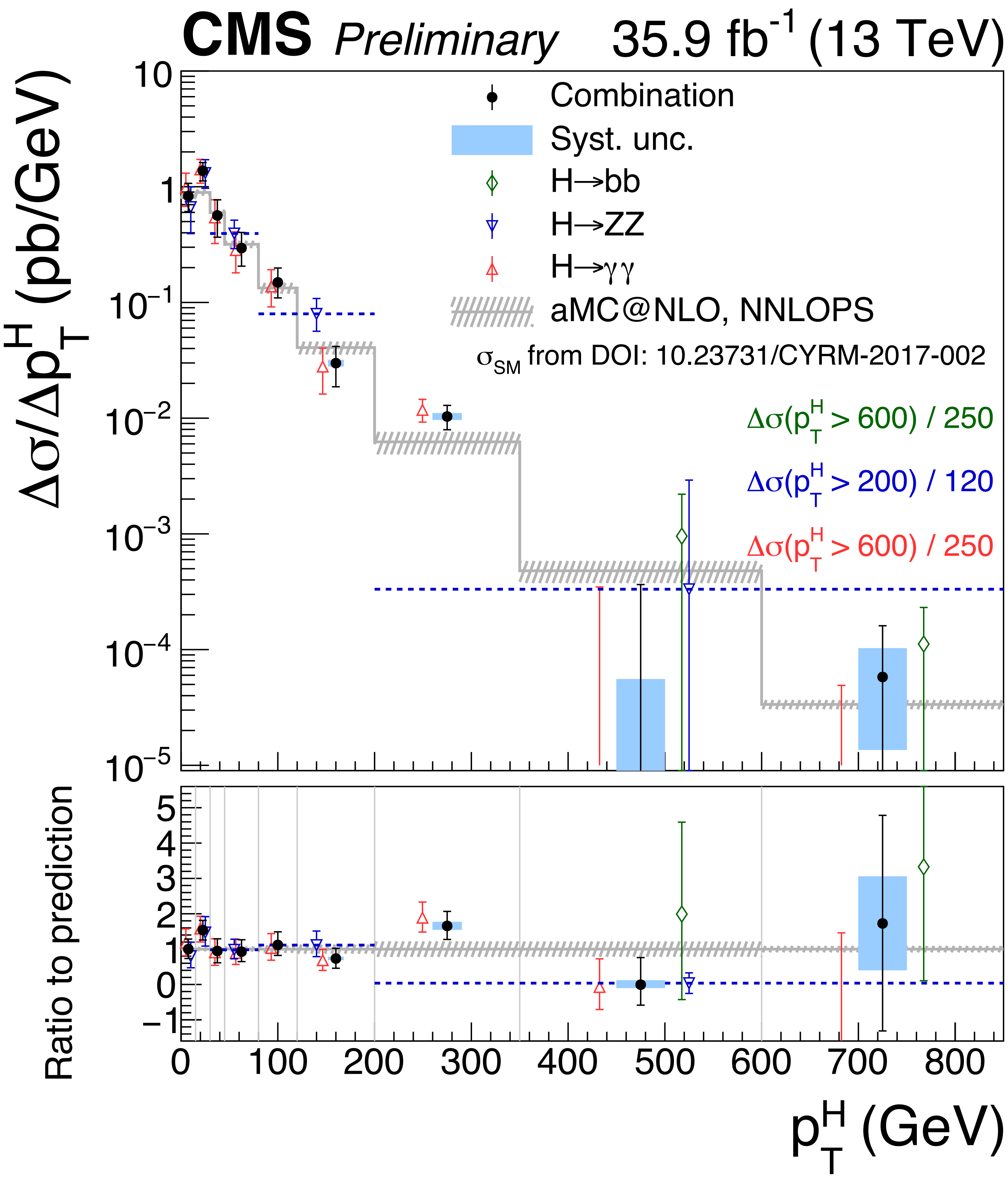
Only for (high) p_T^H

Overview of projections

- pT spectrum, $H \rightarrow \gamma\gamma$ / $H \rightarrow ZZ$ / $H \rightarrow bb$ / combination
- 2D-differential pT / N_{jets} **- TODO**
- Interpretation:
  - κ_b vs. κ_c: BRs freely floating / BRs(**κ**)
  - κ_t vs. c_g: BRs freely floating / BRs(**κ**)

- Notable omissions:
  - 1D N_{jets}, $|y_H|$, $p_{T,\, jet}$
  - κ_t vs. κ_b: BRs freely floating / BRs(**κ**)

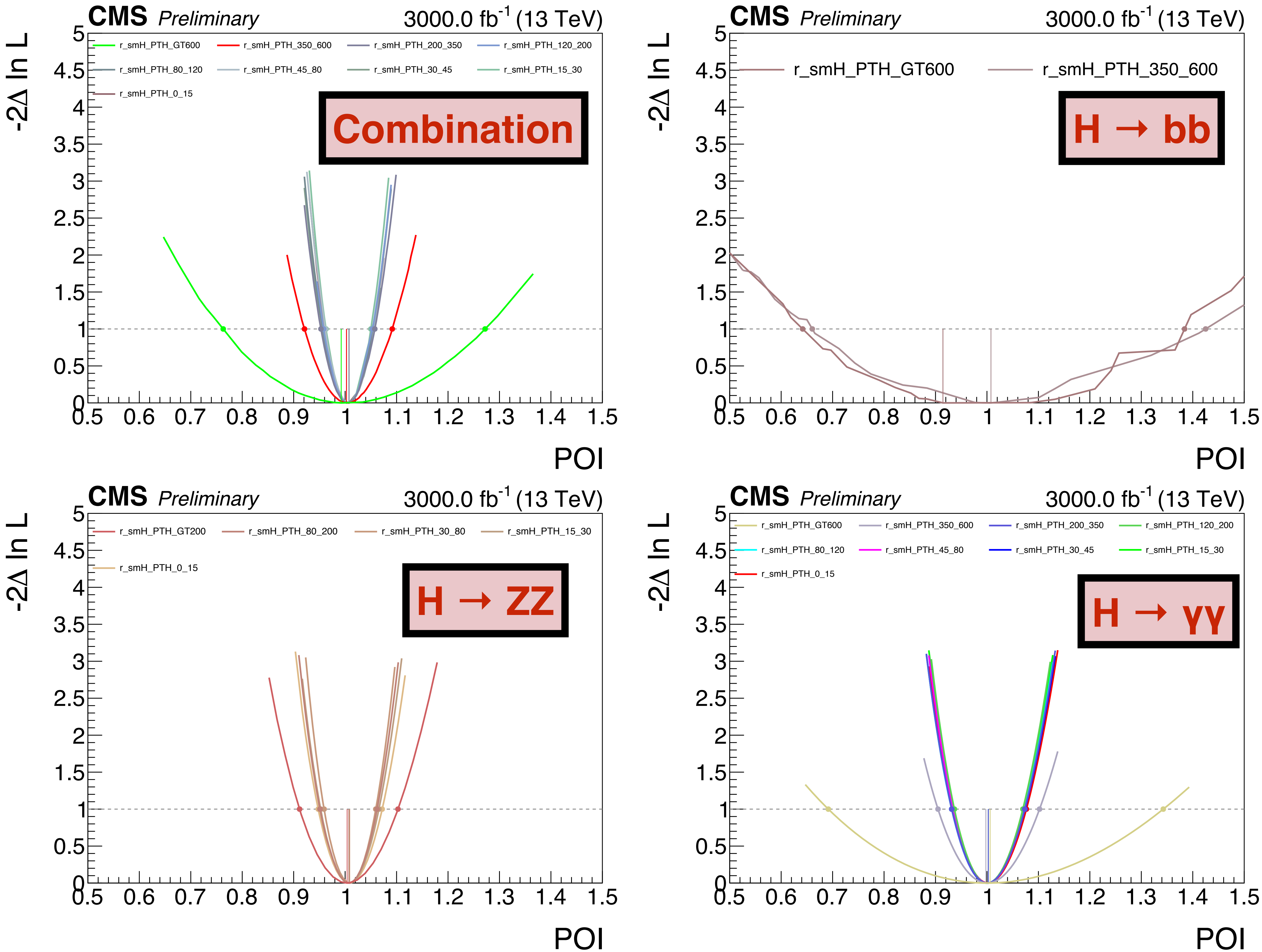
p_T at 35.9 fb^{-1}


CMS Preliminary
35.9 fb-1 (13 TeV)
Combination
Syst. unc.
H→bb
H→ZZ
H→γγ
aMC@NLO, NNLOPS
σSM from DOI: 10.23731/CYRM-2017-002
Δσ(pTH > 600) / 250
Δσ(pTH > 200) / 120
Δσ(pTH > 600) / 250
Δσ/ΔpTH (pb/GeV)
Ratio to prediction
pTH (GeV)
10
1
10−1
10−2
10−3
10−4
10−5
5
4
3
2
1
0
−1
0
100
200
300
400
500
600
700
800

p_T at 35.9 fb^{-1}

	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	>600
$H \rightarrow \gamma\gamma$	38.00%	36.43%	37.58%	35.78%	37.65%	29.68%	42.45%	71.67%	699.73%
$H \rightarrow ZZ$	36.19%	41.66%	27.68%		36.20%		29.14%		
$H \rightarrow bb$	-	-	-	-	-	-	-	250.97%	339.05%
Comb.	27.58%	27.79%	33.88%	30.91%	33.39%	28.25%	39.69%	67.31%	304.96%
Improv.	27.40%	23.70%	9.80%	13.60%	11.30%	4.80%	6.50%	6.10%	56.40%

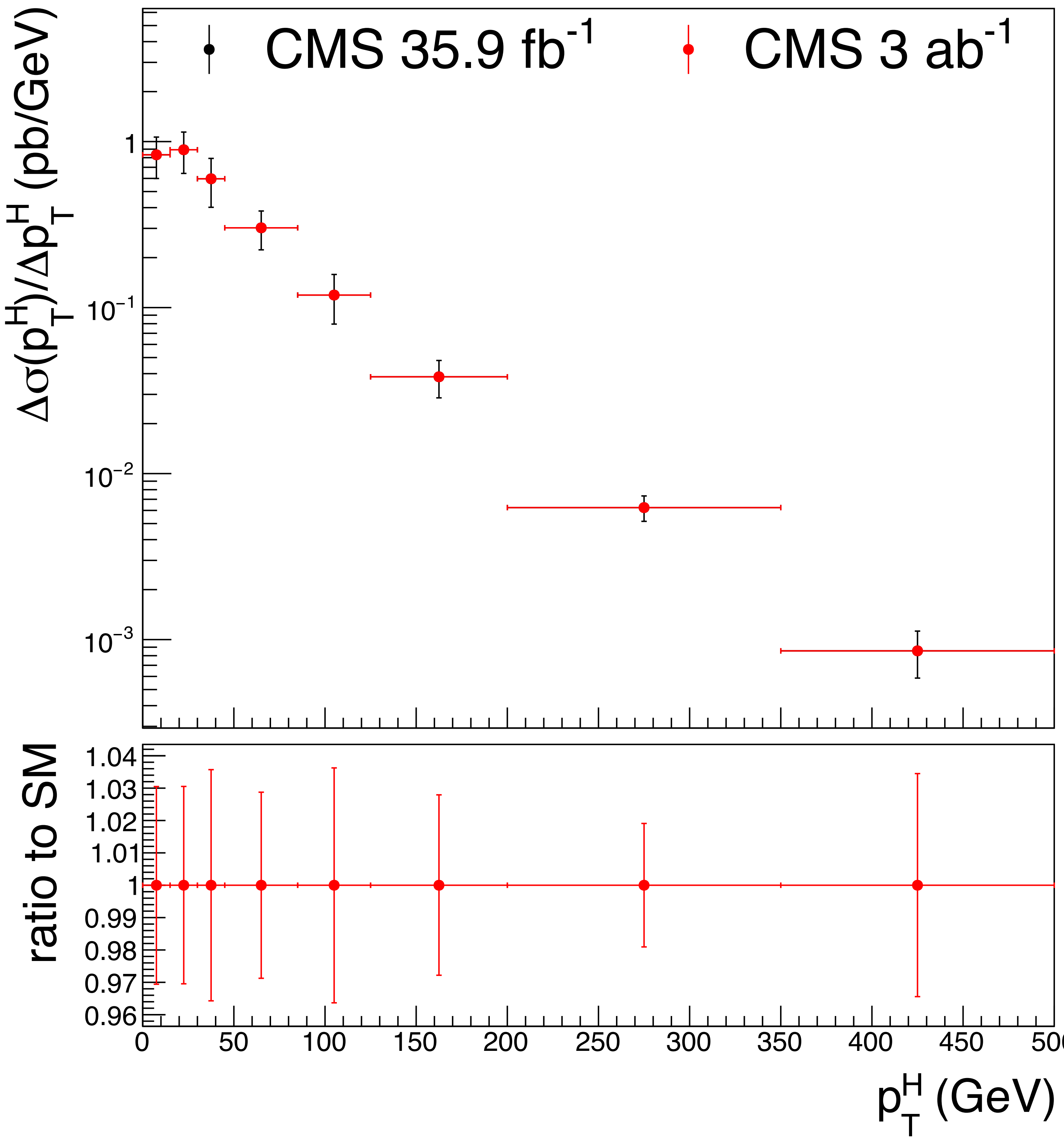
Scans


CMS Preliminary
3000.0 fb^{-1} (13 TeV)
-2Δ ln L
POI
r_smH_PTH_GT600
r_smH_PTH_350_600
r_smH_PTH_200_350
r_smH_PTH_120_200
r_smH_PTH_80_120
r_smH_PTH_45_80
r_smH_PTH_30_45
r_smH_PTH_15_30
r_smH_PTH_0_15
Combination
CMS Preliminary
3000.0 fb^{-1} (13 TeV)
-2Δ ln L
POI
r_smH_PTH_GT600
r_smH_PTH_350_600
H → bb
CMS Preliminary
3000.0 fb^{-1} (13 TeV)
-2Δ ln L
POI
r_smH_PTH_GT200
r_smH_PTH_80_200
r_smH_PTH_30_80
r_smH_PTH_15_30
r_smH_PTH_0_15
H → ZZ
CMS Preliminary
3000.0 fb^{-1} (13 TeV)
-2Δ ln L
POI
r_smH_PTH_GT600
r_smH_PTH_350_600
r_smH_PTH_200_350
r_smH_PTH_120_200
r_smH_PTH_80_120
r_smH_PTH_45_80
r_smH_PTH_30_45
r_smH_PTH_15_30
r_smH_PTH_0_15
H → γγ

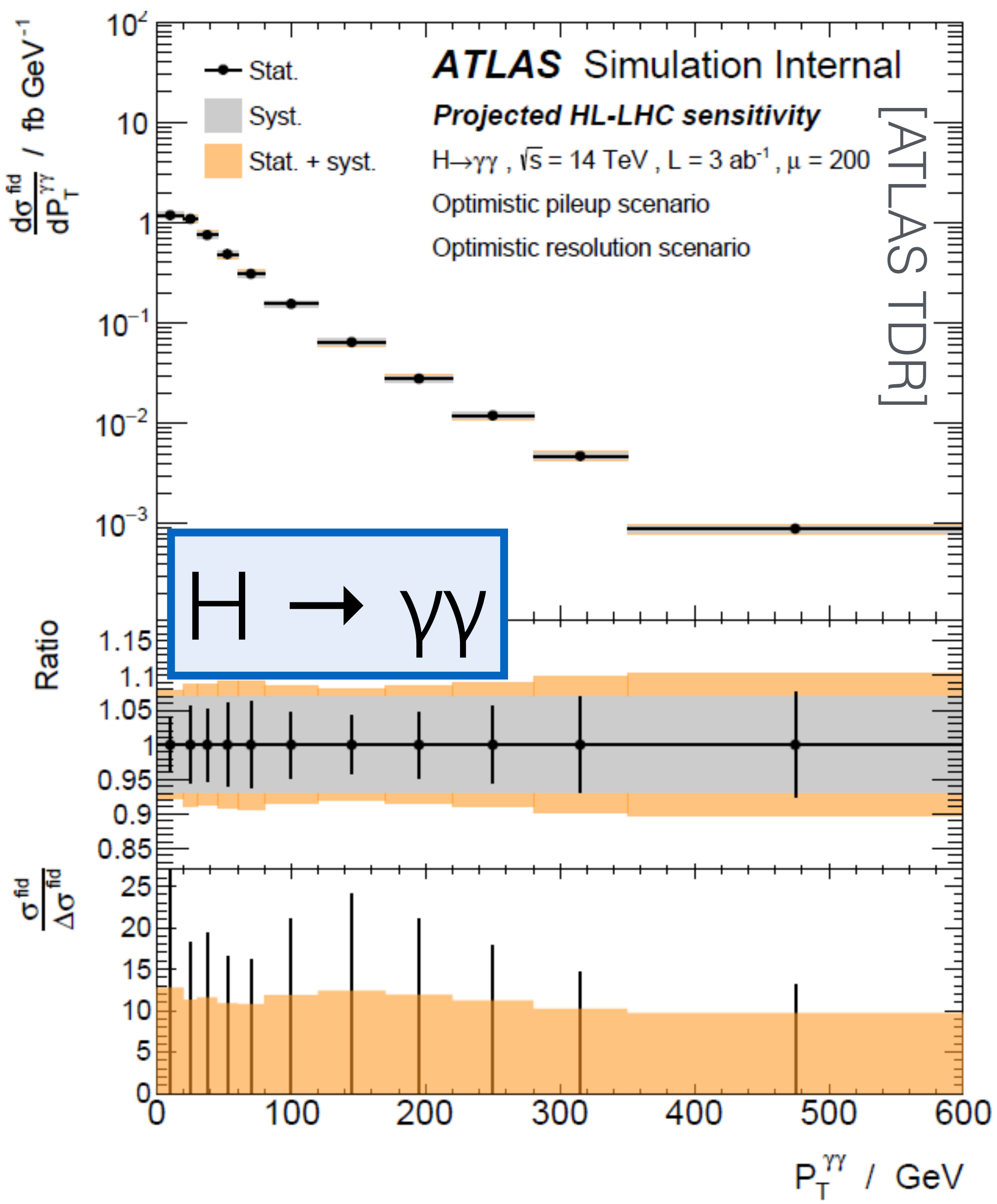
p_T^H: Projections from CMS

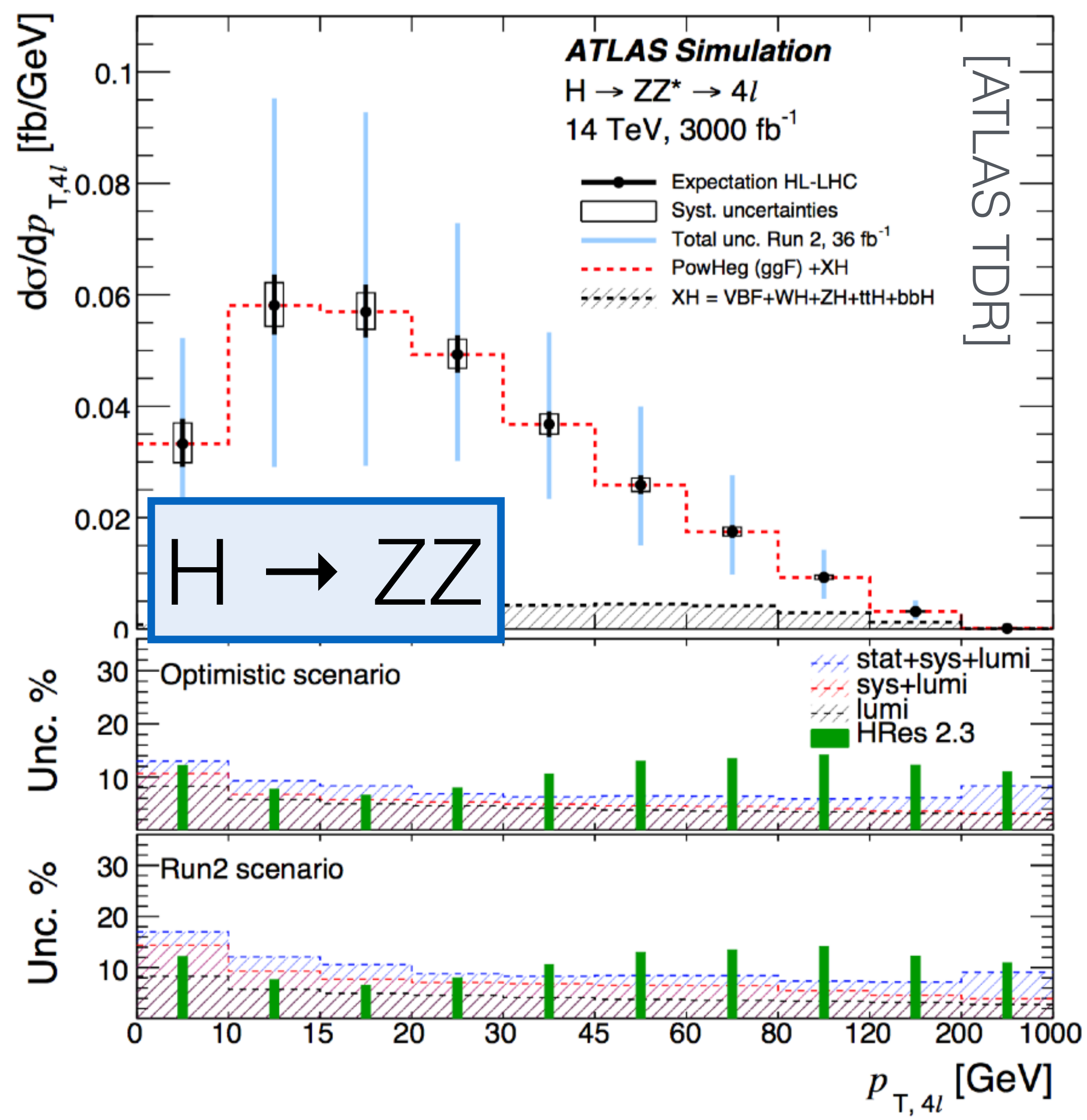
IPA ETH zürich

- Very naive result presented at **HL meeting at Fermilab**
- Simply scaling observed uncertainties by $\sqrt{35.9/3000}$
- Moved central values to SM expectation
- Yields **~3%** uncertainties (a bit by construction of course), comparable to the ATLAS projections



p_T^H: Projections from ATLAS





- ~5% uncertainties for H → γγ, between 5-10% for H → ZZ
- For H → γγ, Improvement by a factor of ~8-9, really close to $\sqrt{3000/36} \simeq 9$ (scaling only stat., assuming same syst.)
- **<5%** uncertainty achievable with a combination