Combination of Higgs differential observables and limits on Higgs couplings at CMS

Zurich PhD Seminar 2018

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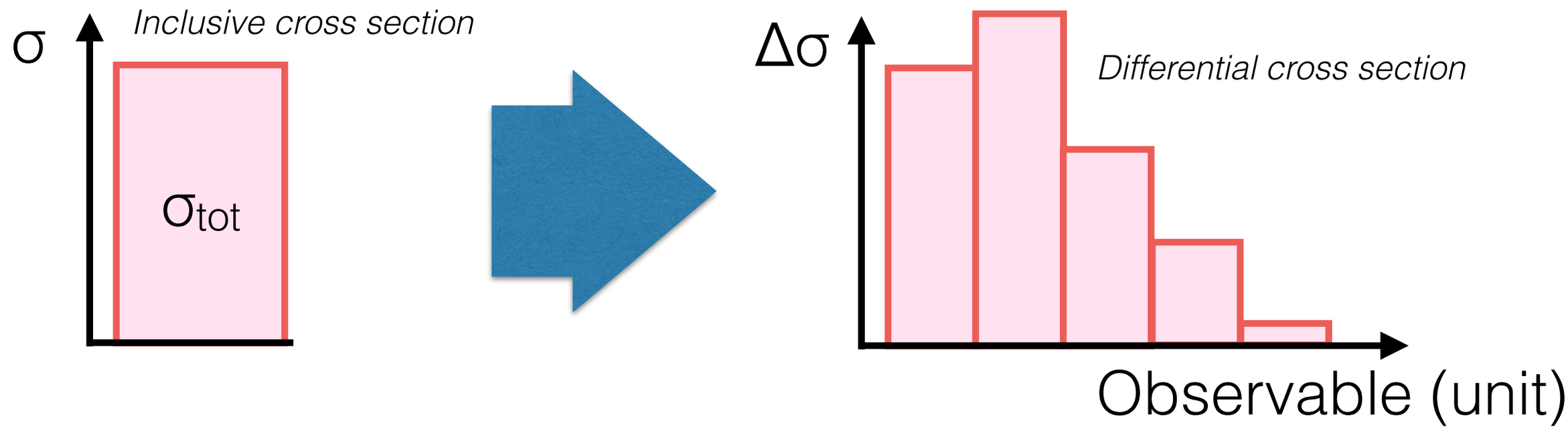
8th of March 2018

ETH zürich

Introduction: Differential cross sections



- What is so interesting about **differential cross sections**?
    - The measured **inclusive cross section** (i.e. integral of the shape) may agree perfectly well with the SM, but the measured **shape** can still deviate
    - Using the **shape** of the differential cross sections, one can measure **properties of the Higgs**

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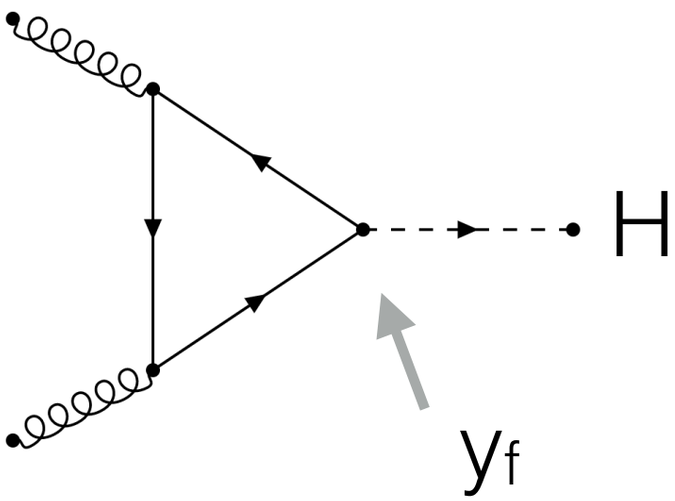

- In the SM, the Higgs couples to fermions with the corresponding **Yukawa coupling y_f^{SM}**
- A Higgs coupling modifier is simply the factor with which one multiplies the SM to get the measured coupling

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

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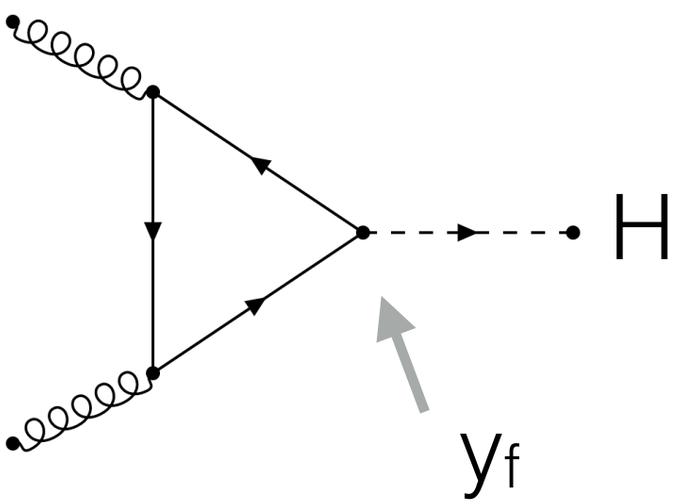

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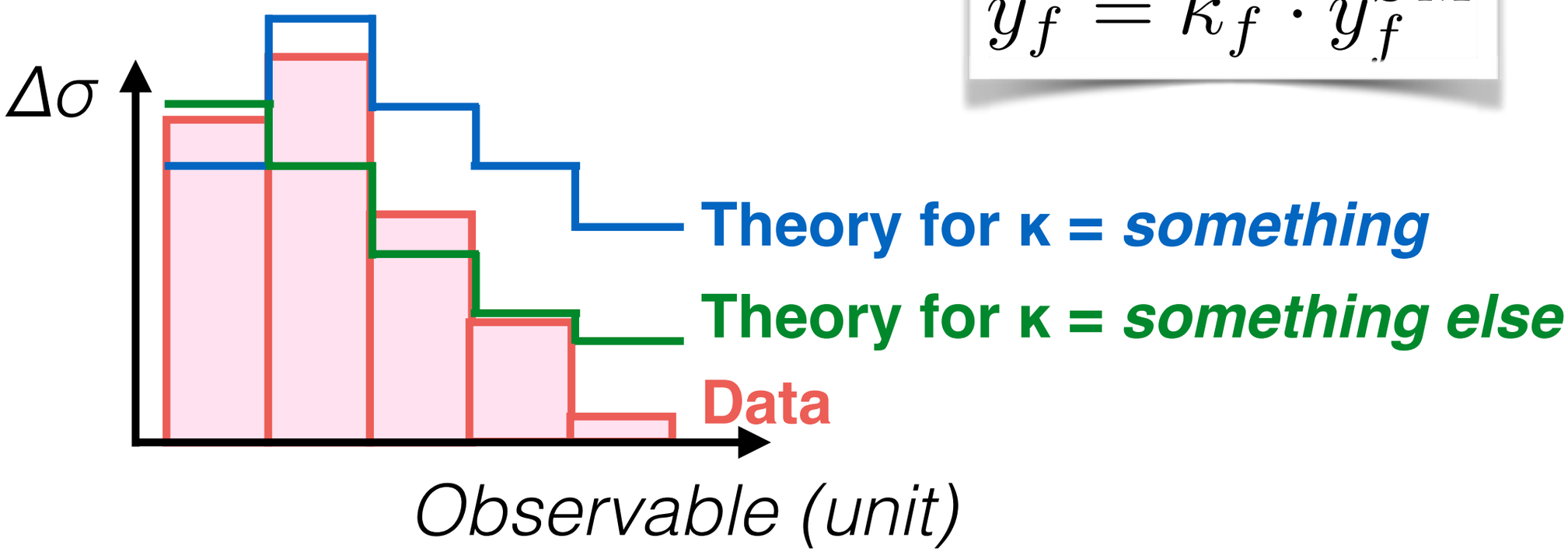
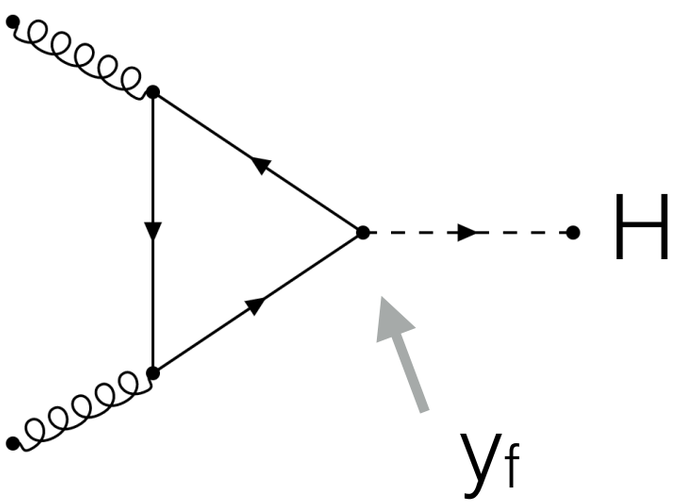


- The theory predictions for differential cross sections depend strongly on (some) **coupling variations**

Introduction: Differential cross sections



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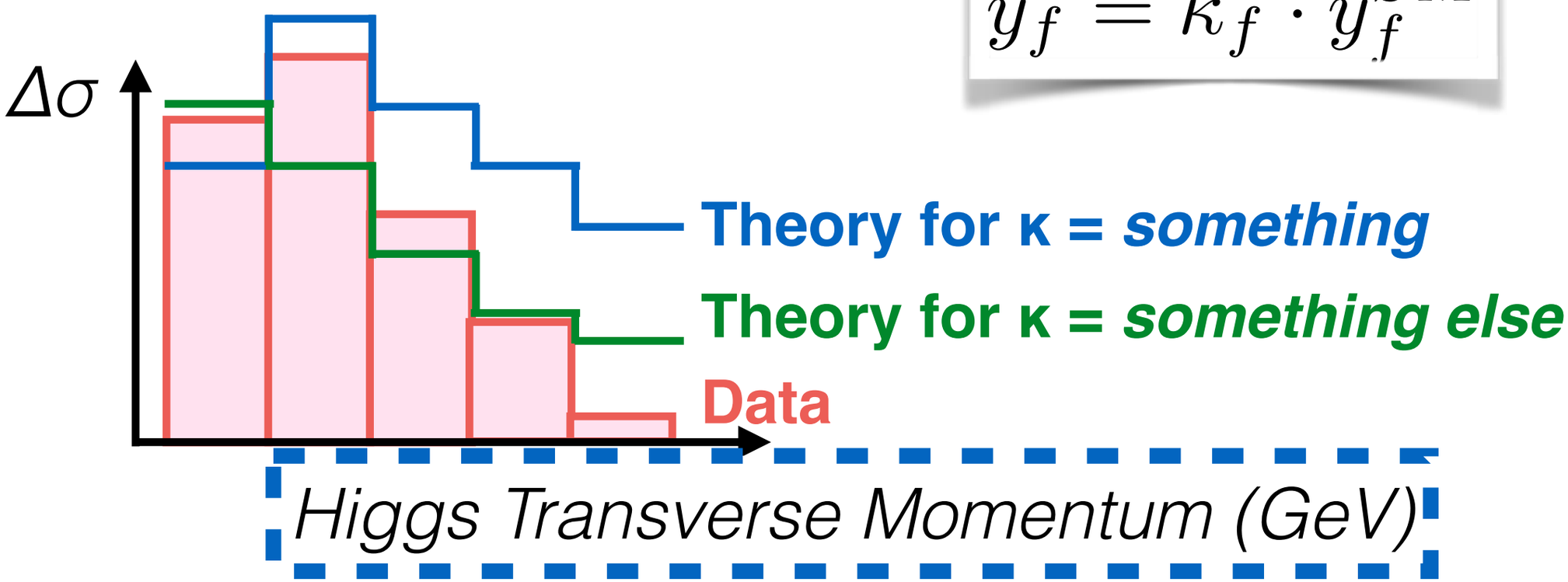

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Outline

Part 1: Combination of differential spectra

Part 2: Constraints on Higgs coupling modifiers

- Higgs-bottom coupling κ_b vs. Higgs-charm coupling κ_c
- Top coupling modifier κ_t vs. gluon anomalous coupling κ_g

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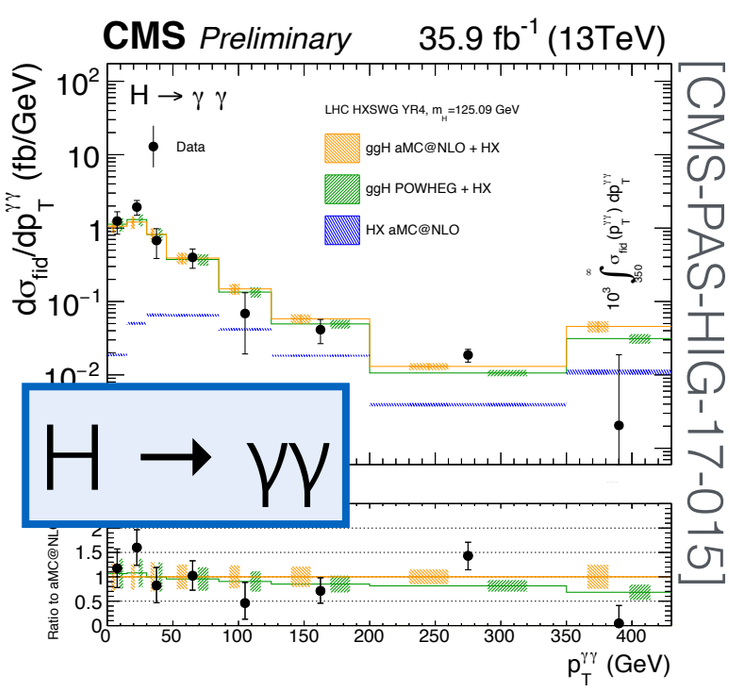
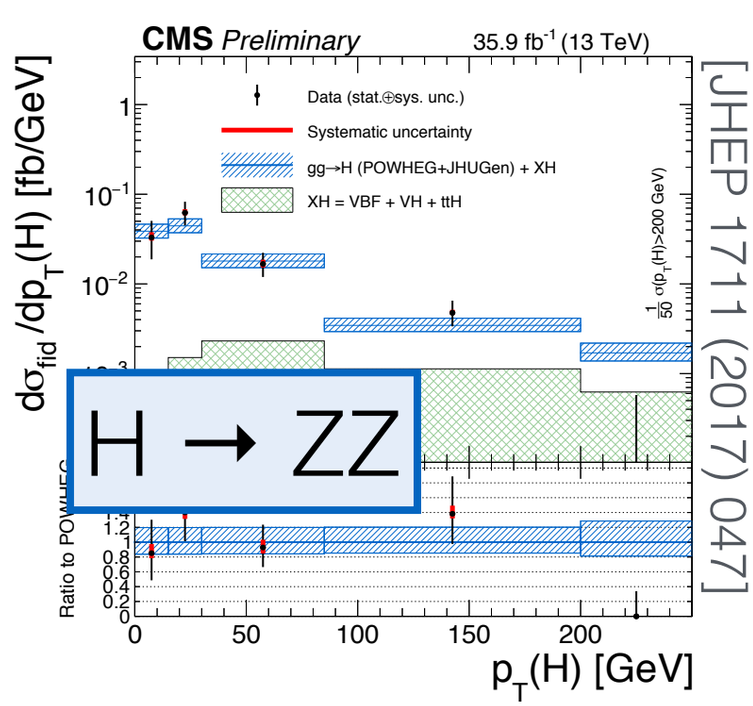
Combination of differential spectra

- Measurements of differential cross sections are made per **decay channel** of the Higgs
  - $H \rightarrow \gamma\gamma$ (2 photons), $H \rightarrow ZZ \rightarrow 4$ leptons, $H \rightarrow WW$, $H \rightarrow bb$, …
- In order to obtain a best estimate of some differential cross section, we make a **combination** (which is my addition to this game)
  - Currently including **two** measurements in the combination:





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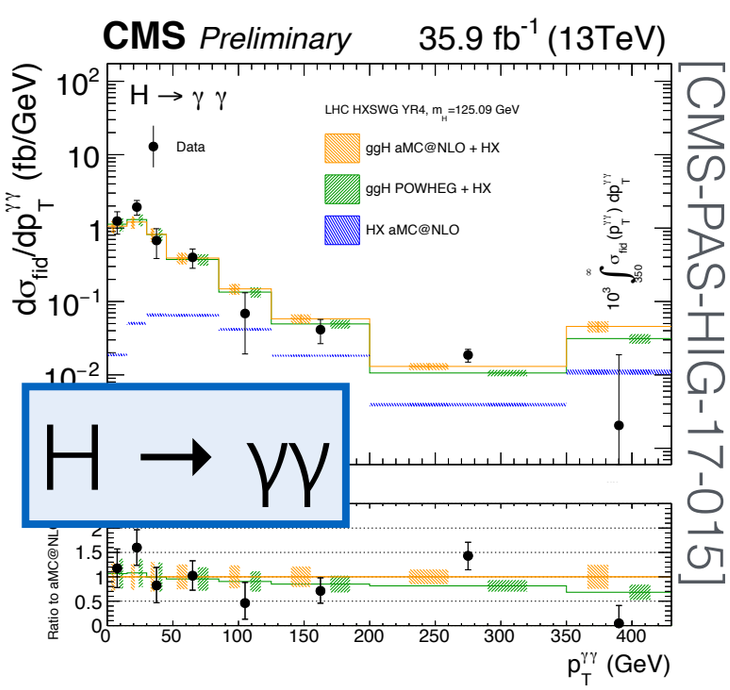
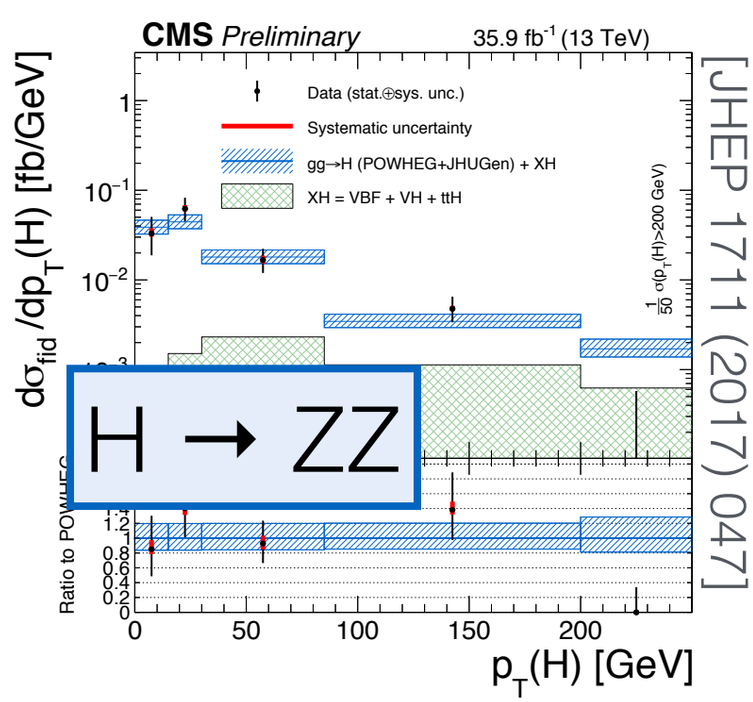


$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ$

… and a **third** one for only the <u>Higgs transverse momentum</u>:

$H \rightarrow bb$

Observables and their binning

- Performing combinations for **four** observables:

pT_H (GeV)

hgg	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	>600
hzz	0-15	15-30	30-80		80-200		>200		
hbb	*none*							350-600	>600

nJets

hgg	0	1	2	3	4+
hzz	0	1	2	3+	

abs(y)

hgg	0.0 - 0.15	0.15 - 0.30	0.30 - 0.60	0.60 - 0.90	0.90 - 1.20	1.20 - 2.50
hzz	0.0 - 0.15	0.15 - 0.30	0.30 - 0.60	0.60 - 0.90	0.90 - 1.20	1.20 - 2.50

pT_{jet} (GeV)

hgg	<30	30-55	55-95	95-120	120-200	>200
hzz	<30	30-55	55-95	>95		

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nJets

hgg	0	1	2	3	4+
hzz	0	1	2	3+	

Agreement between Hgg and HZZ; To be confirmed with ATLAS

abs(y)

hgg	0.0 - 0.15	0.15 - 0.30	0.30 - 0.60	0.60 - 0.90	0.90 - 1.20	1.20 - 2.50
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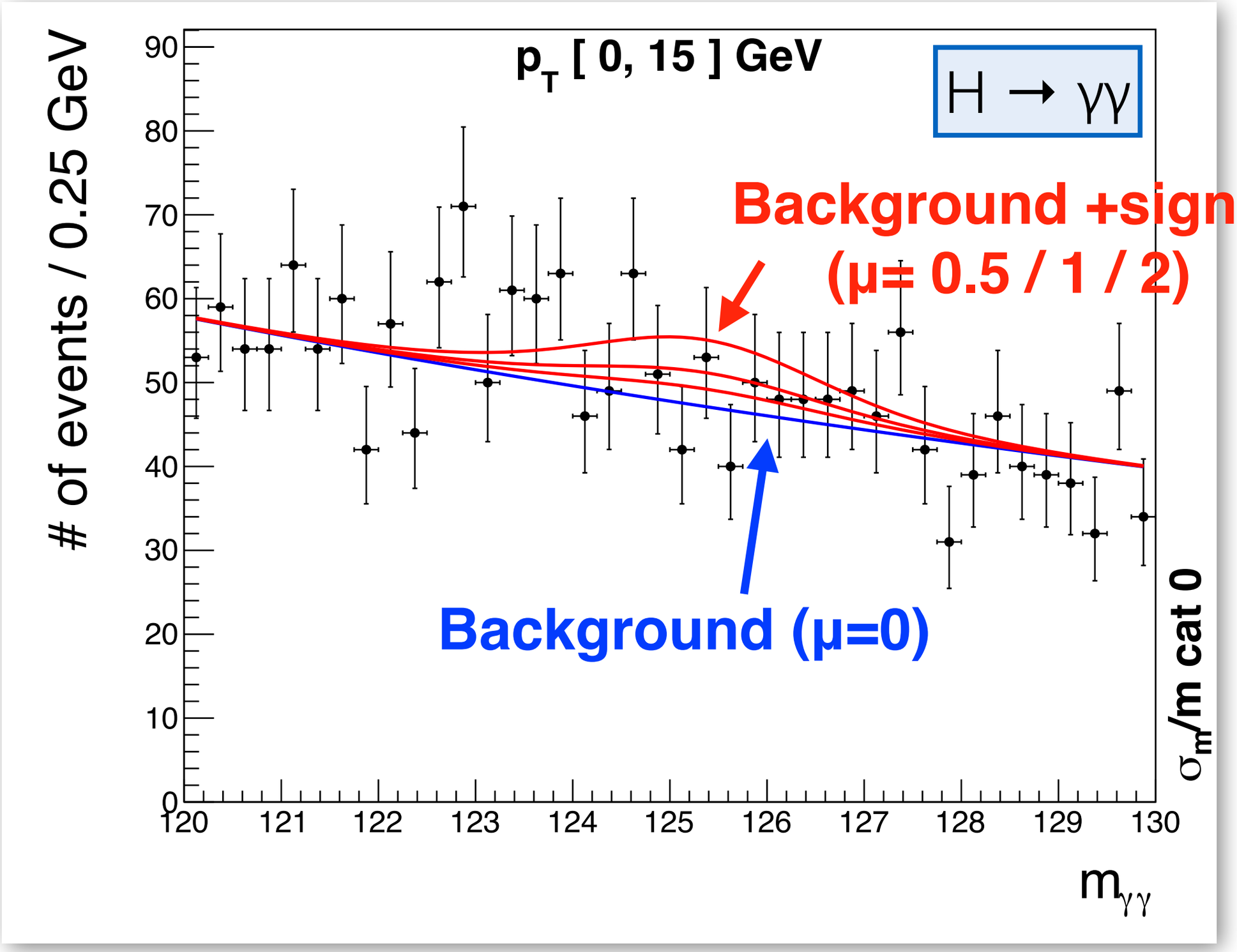
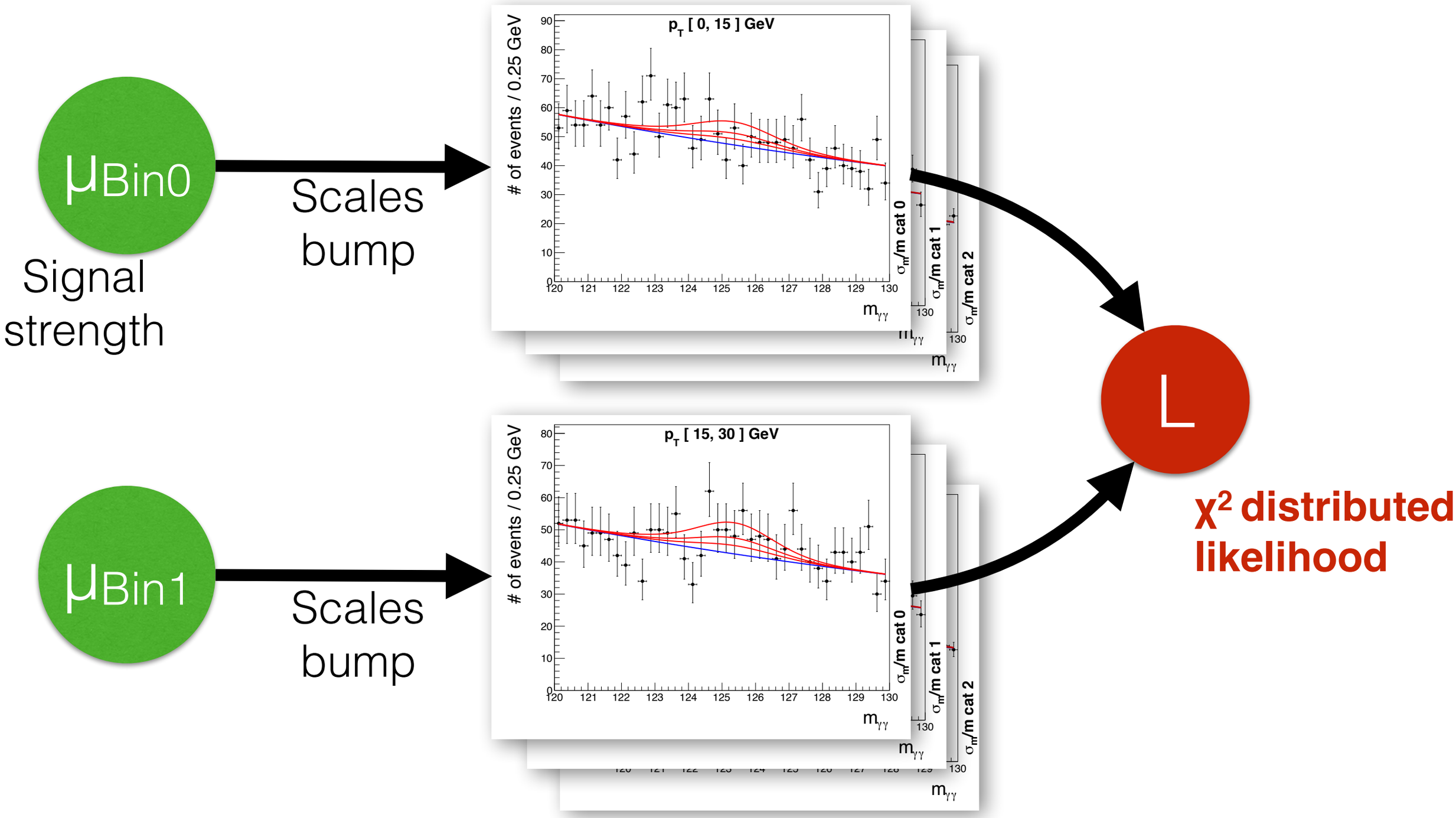
- All decay channels need to have their signal modeled for the **finest binning** (e.g. for pT, H->ZZ needs signal shapes for 30-45 and 45-80 as well)
- Changing bin boundaries is not painless
  - How many bins? Set boundaries where? How to keep statistics reasonable? Which boundaries are important for theory?
  - What was done in the past? What does ATLAS do? (Important for future combinations)
  - Waiting for 3 analyses groups to re-do their measurements for a new binning scheme takes time!

Fitting signal strengths

- **Signal strength μ:** $\sigma_{\text{measured}} = \mu \cdot \sigma_{\text{SM}}$

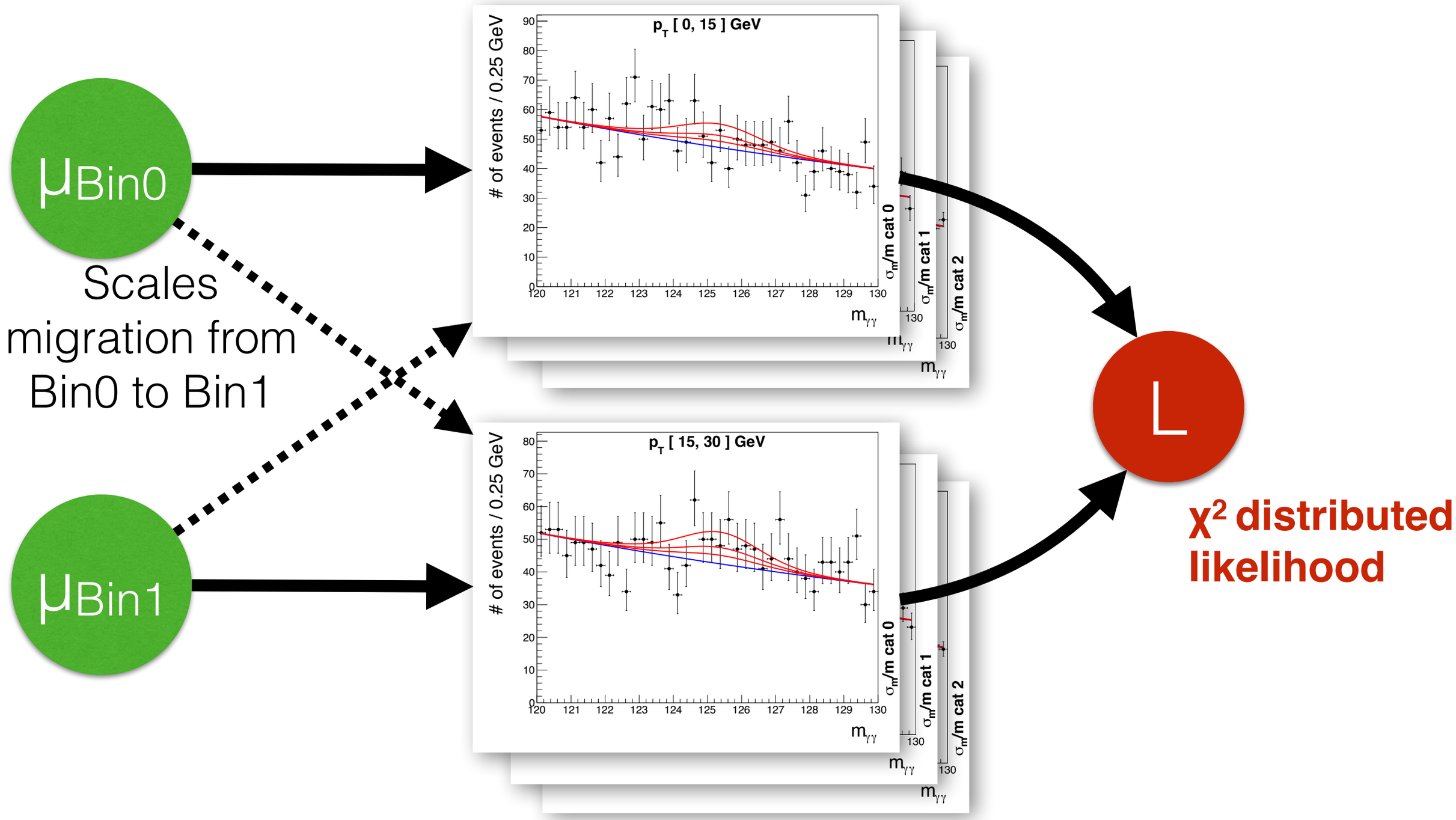


Fitting multiple signal strengths



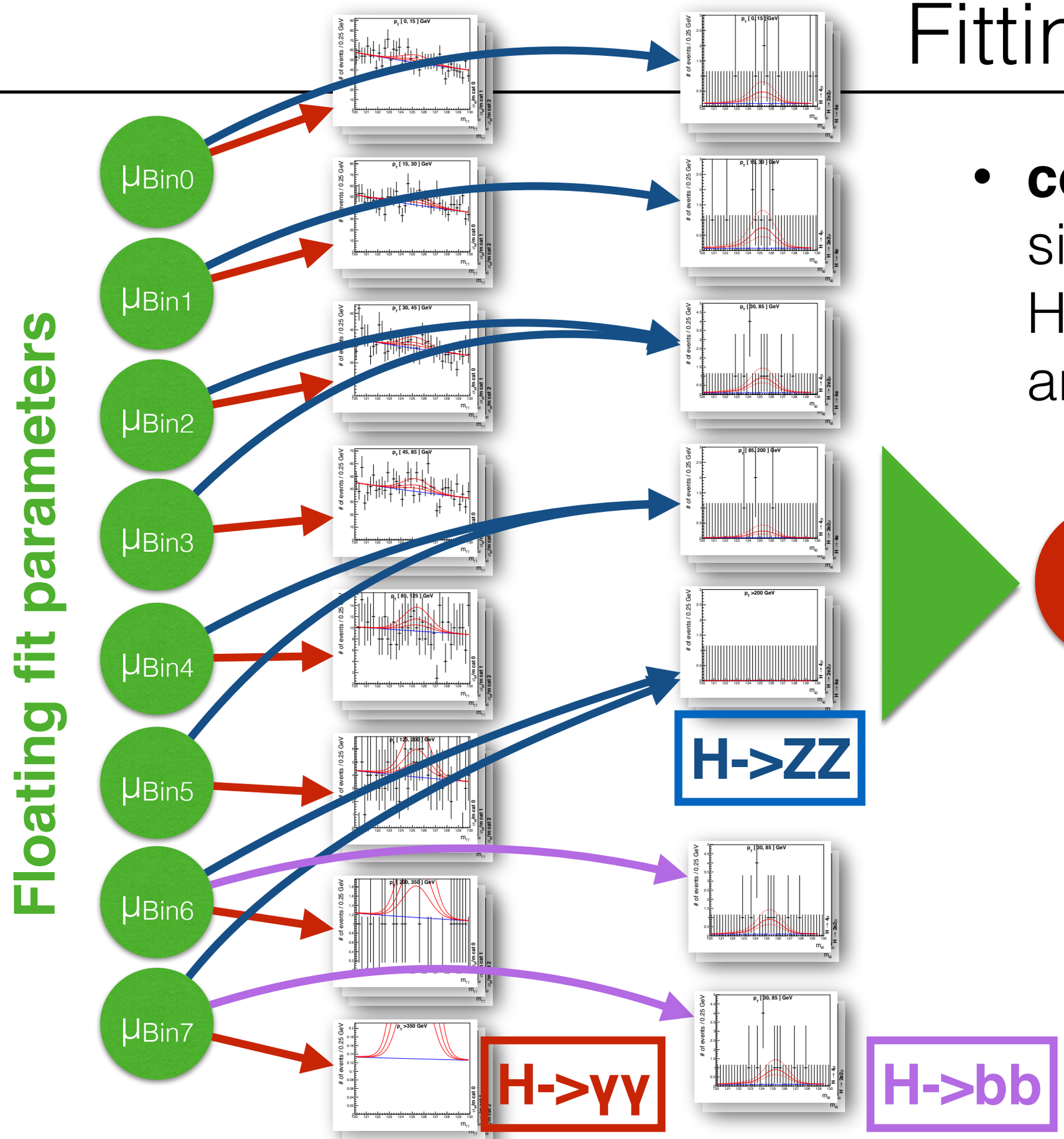
- **Principle of fit**: Vary μ's until the bump fits best to data (i.e. L is maximised)

Fitting multiple signal strengths



- **Bin-to-bin migrations** are taken into account and scaled accordingly

Fitting procedure

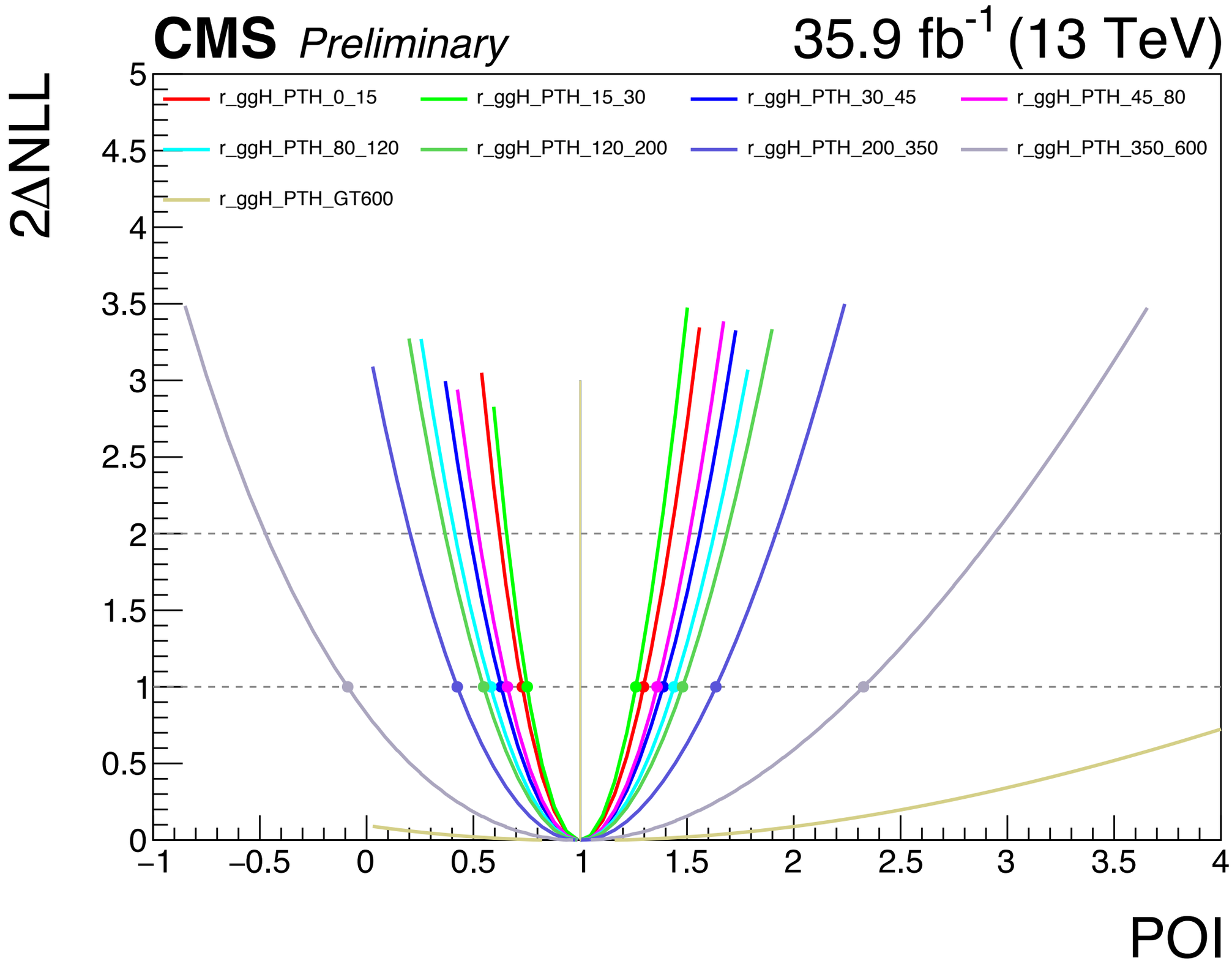


- **combine**: Use μ's simultaneously for H → γγ, H → ZZ, and H → bb

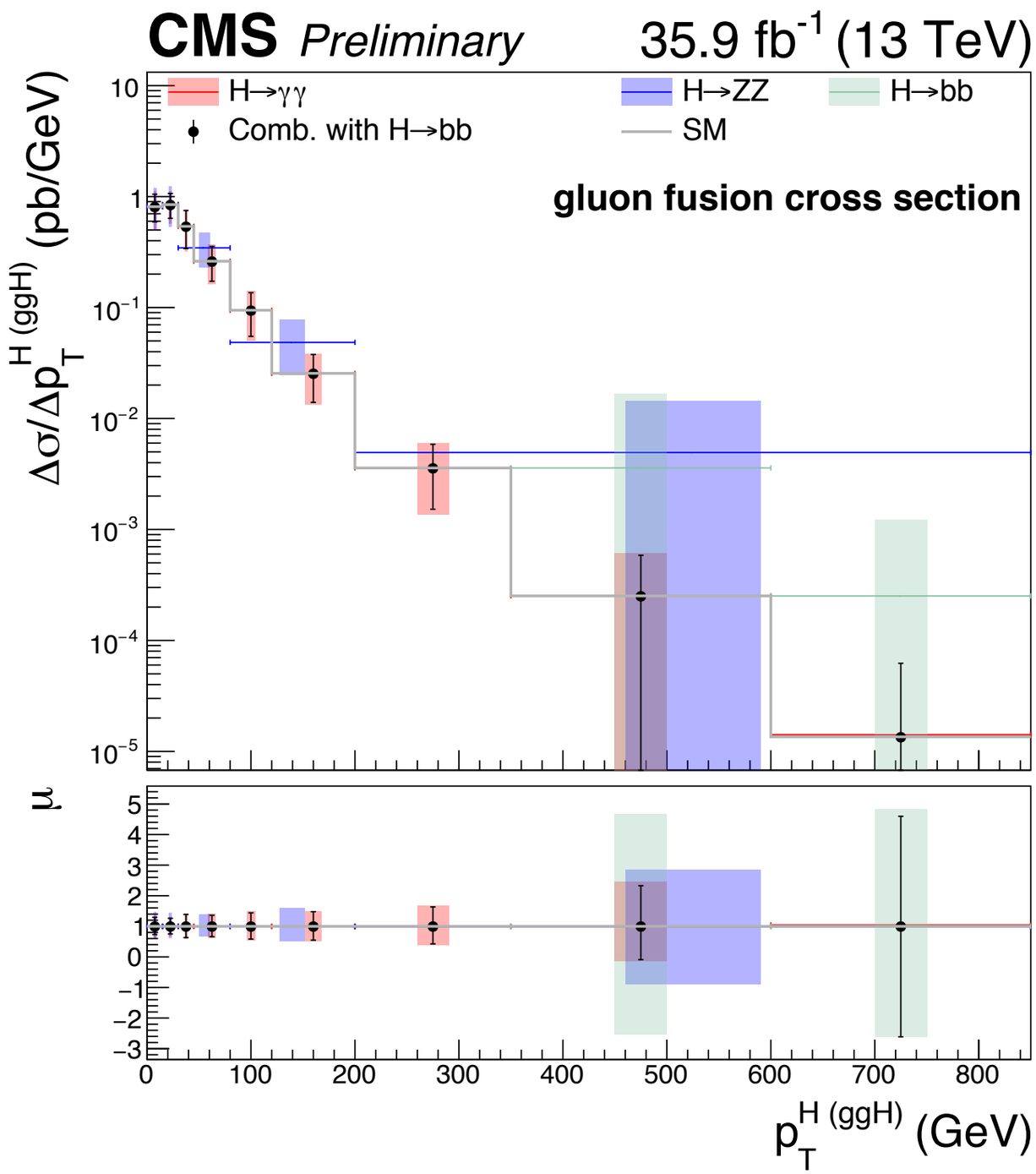
χ^2 distributed likelihood

- Two arrows to one shape means the sum of two underlying signal shapes is fitted

Scans over signals strengths



$p_{T\,Higgs}$ (ggF cross sections)

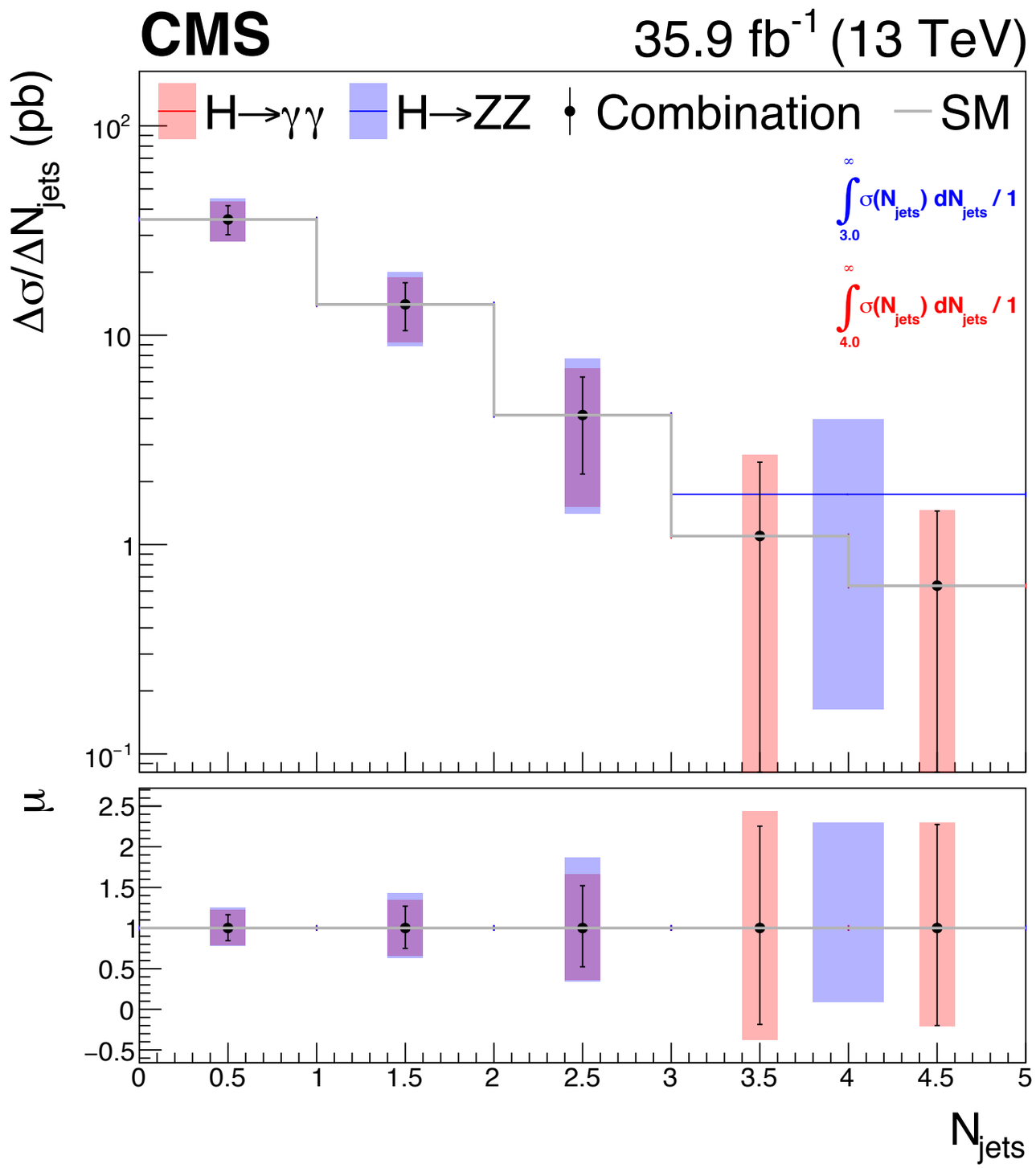


- Up to 25% reduction of uncertainty on spectrum
- General pattern of smaller uncertainty, with the combination result in between the individual spectra

Uncertainty reduction w.r.t. H -> γγ only

0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600
25.6%	**21.0%**	**8.4%**	**10.8%**	**10.8%**	**5.0%**	**6.6%**	**7.1%**

Njets



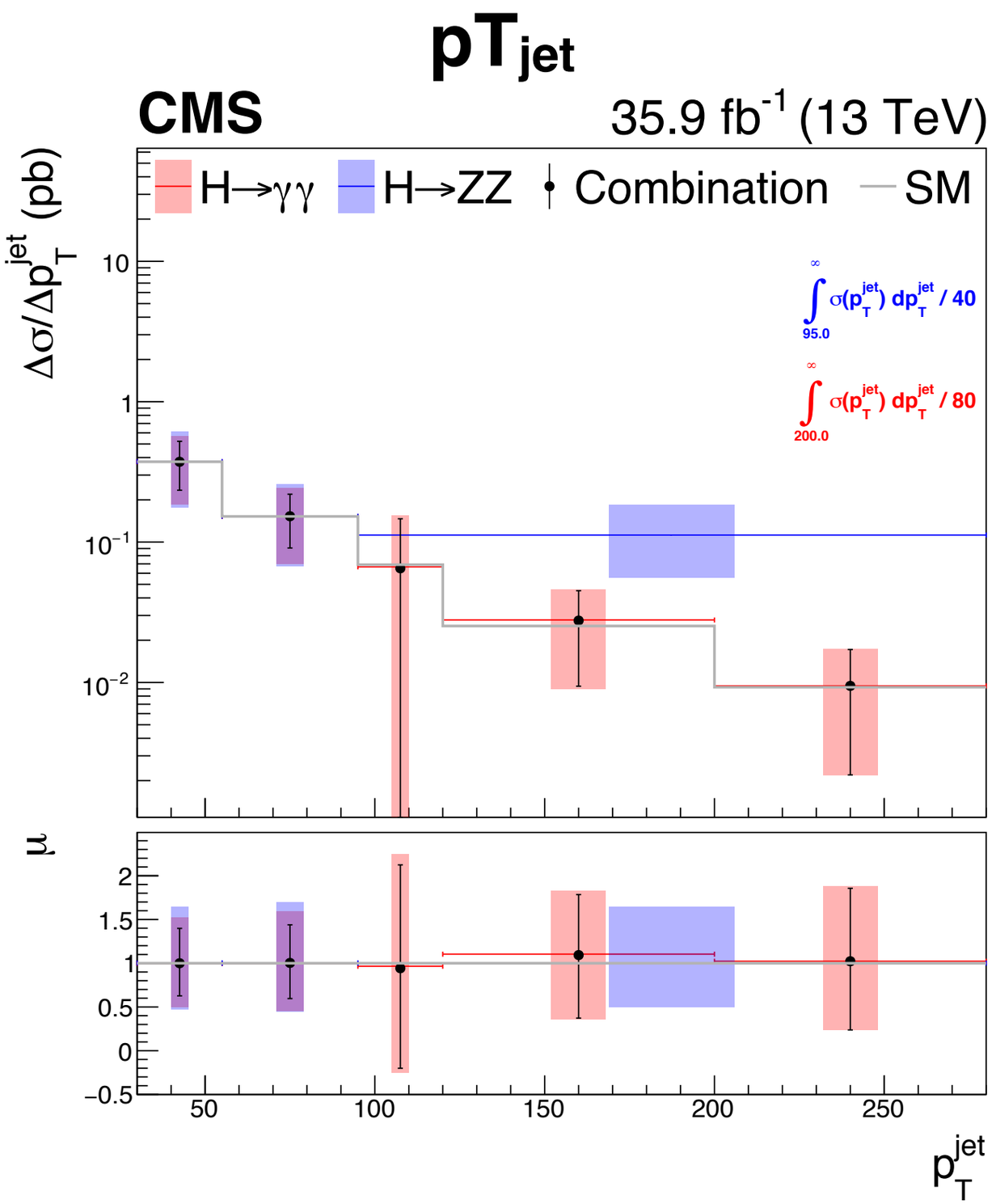
Jet:

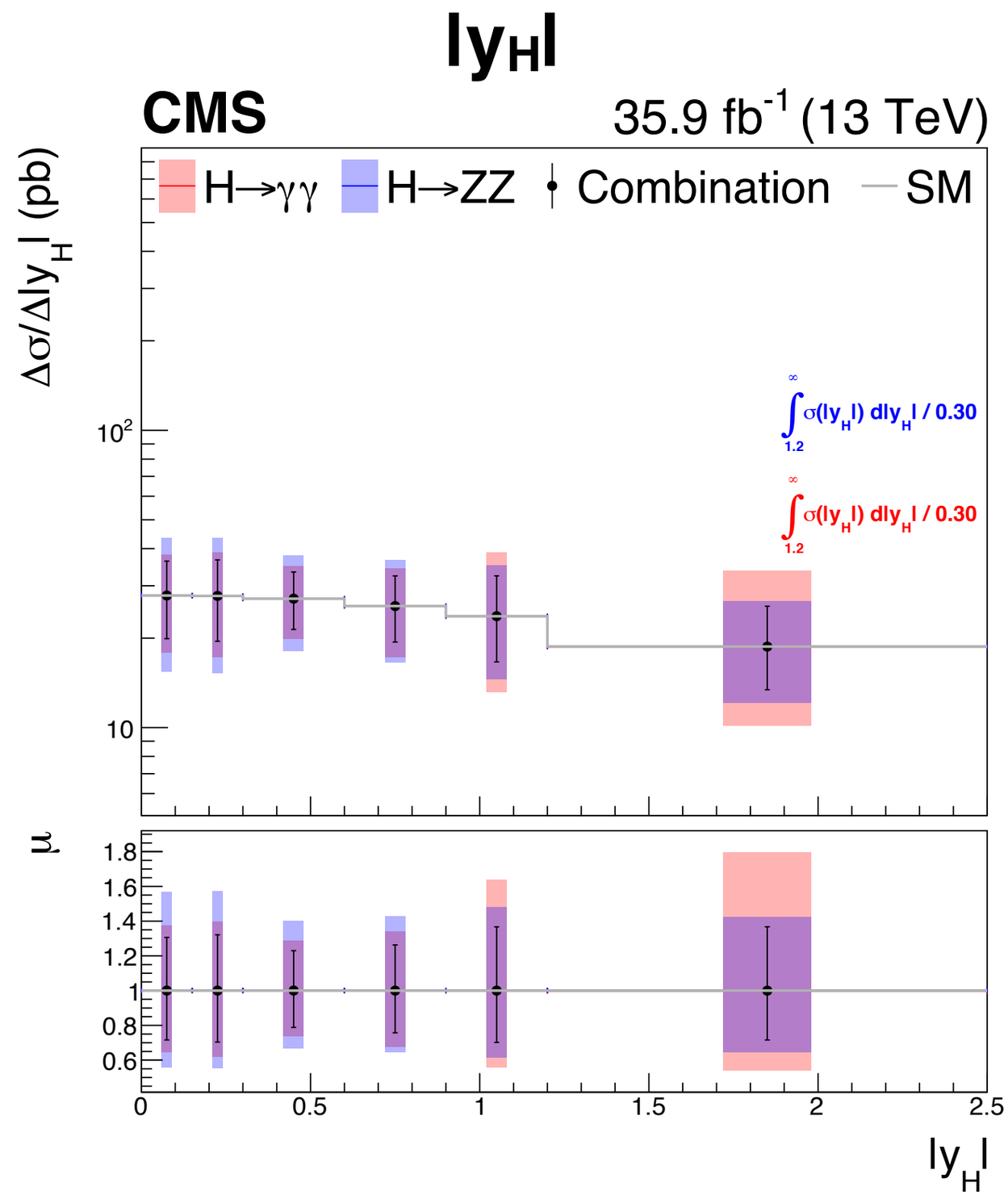
- $|\eta| < 2.5$
- pT > 30 GeV

Uncertainty reduction w.r.t. H -> γγ only

26.9%	24.4%	23.3%	13.3%	1.2%

$|y_H|$, pT_{jet}

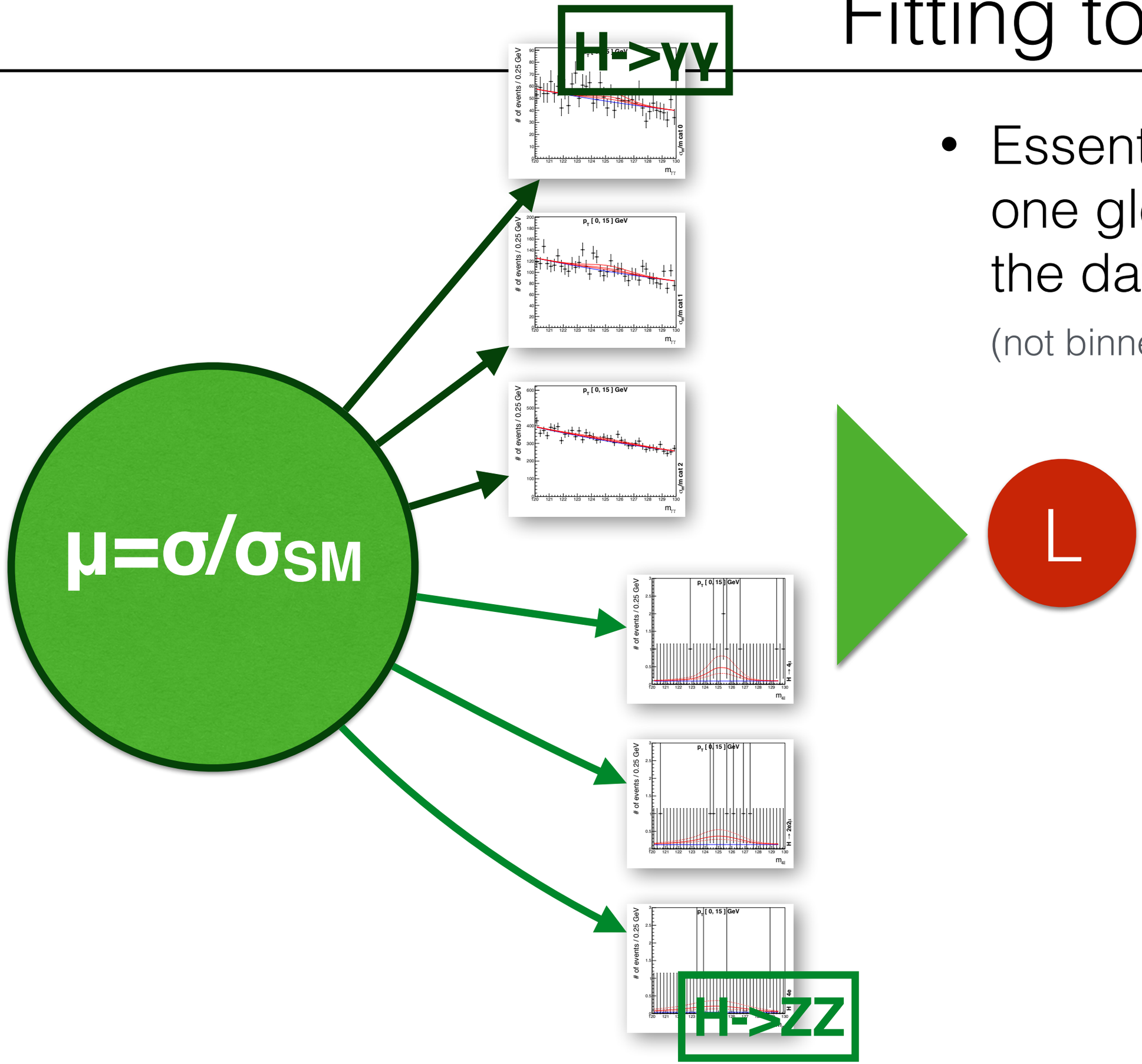

pTjet
CMS
35.9 fb-1 (13 TeV)
H→γγ
H→ZZ
Combination
SM
Δσ/Δp_T^jet (pb)
∫ σ(p_T^jet) dp_T^jet / 40
95.0
∫ σ(p_T^jet) dp_T^jet / 80
200.0
μ
p_T^jet


|yH|
CMS
35.9 fb-1 (13 TeV)
H→γγ
H→ZZ
Combination
SM
Δσ/Δ|y_H| (pb)
∫ σ(|y_H|) d|y_H| / 0.30
1.2
μ
|y_H|

Fitting total XS

- Essentially a fit with one global scale to the data categories

  (not binned in any observable)



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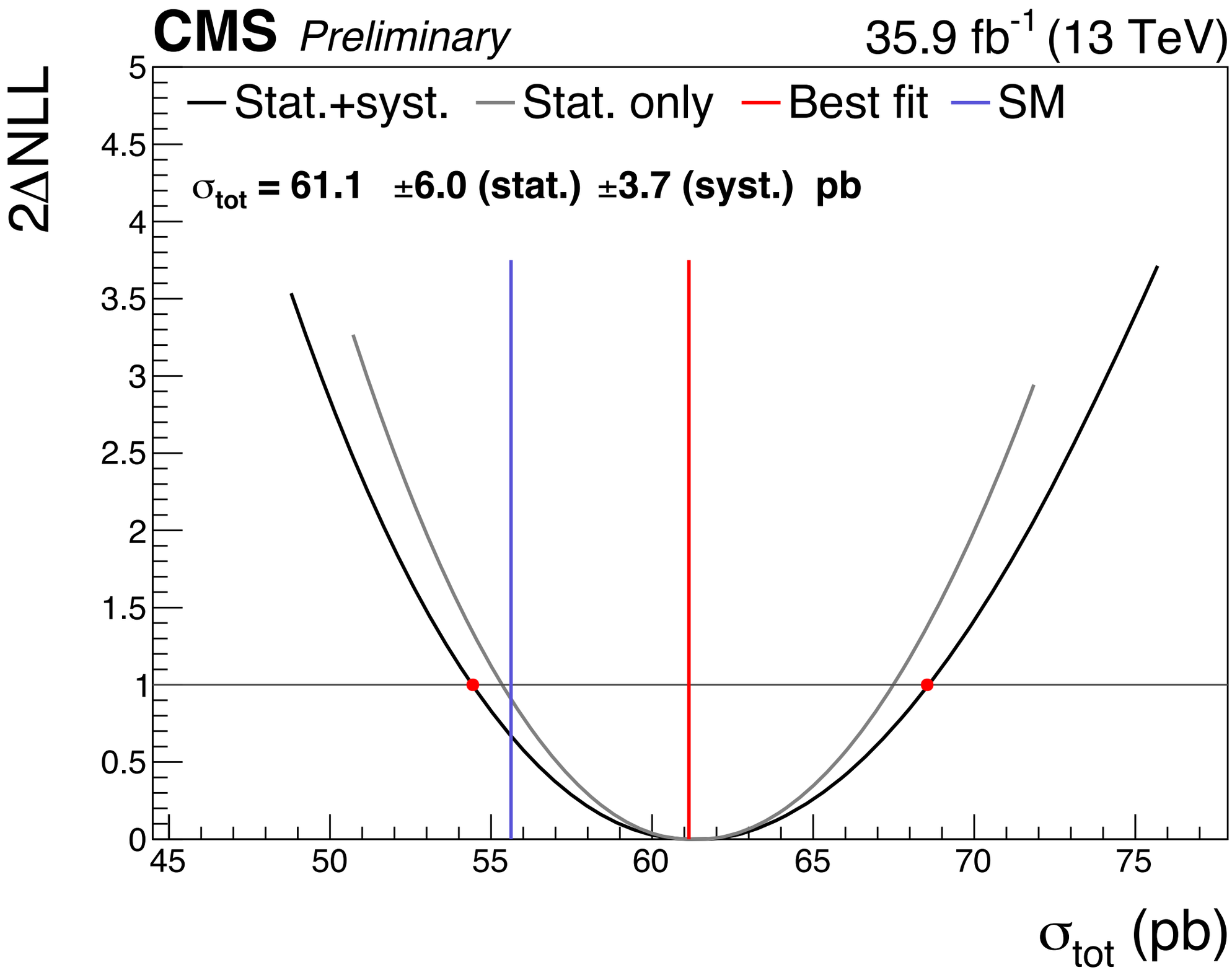

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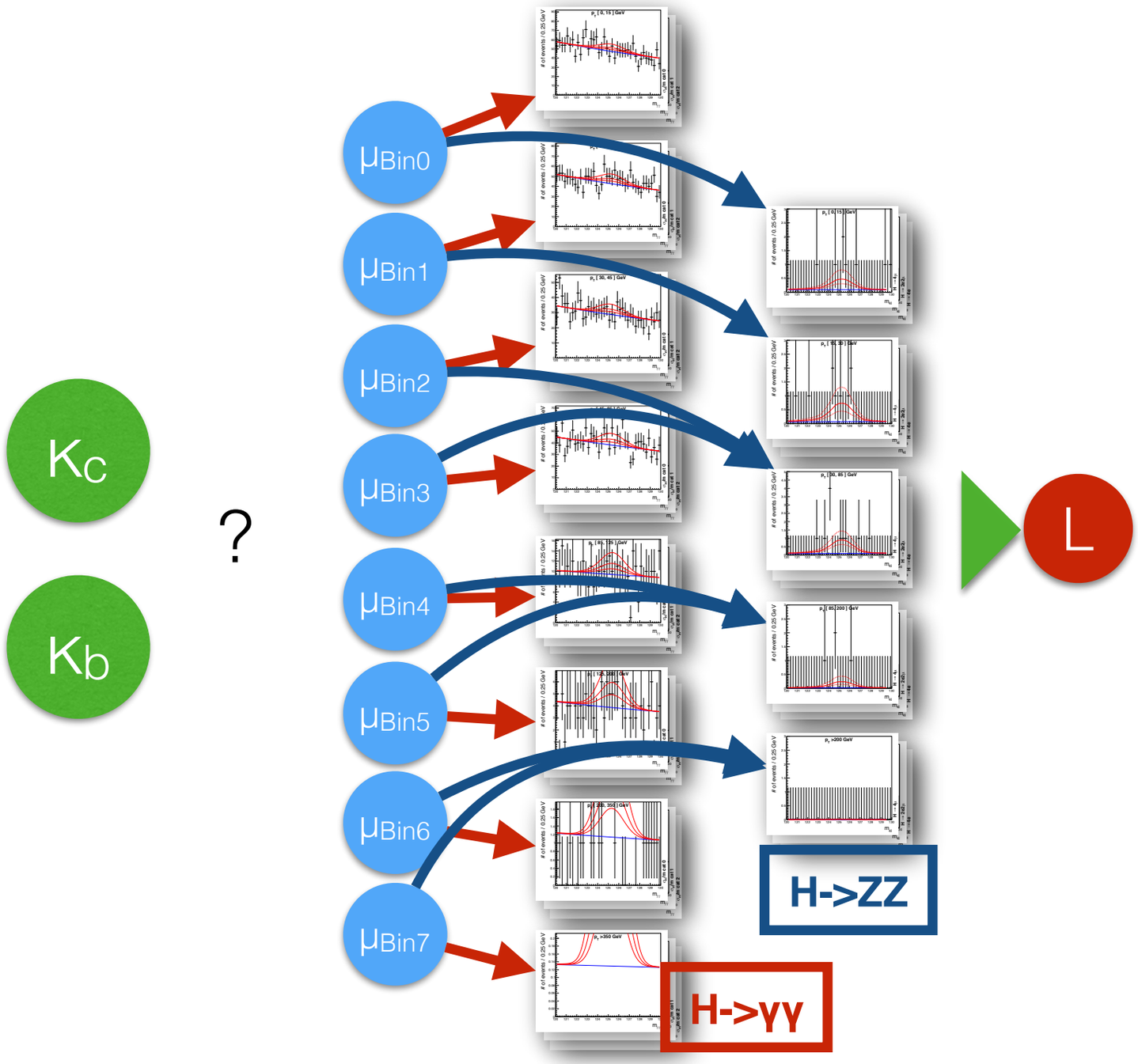
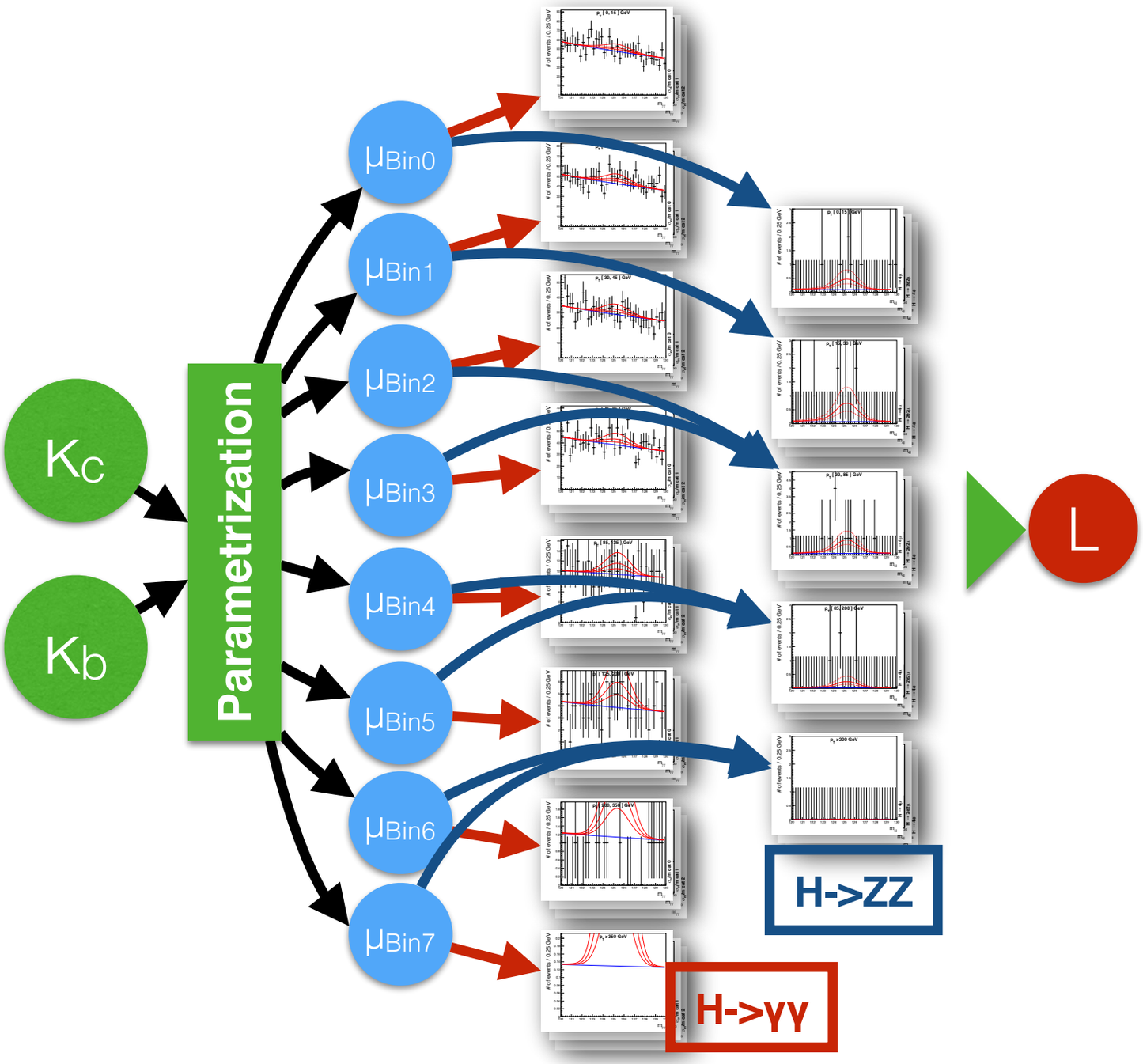
Fitting couplings



- Obtain 2D likelihood by varying κ_c and κ_b
- The contributions from **xH** (i.e. *not ggH*) are set to SM

Fitting couplings



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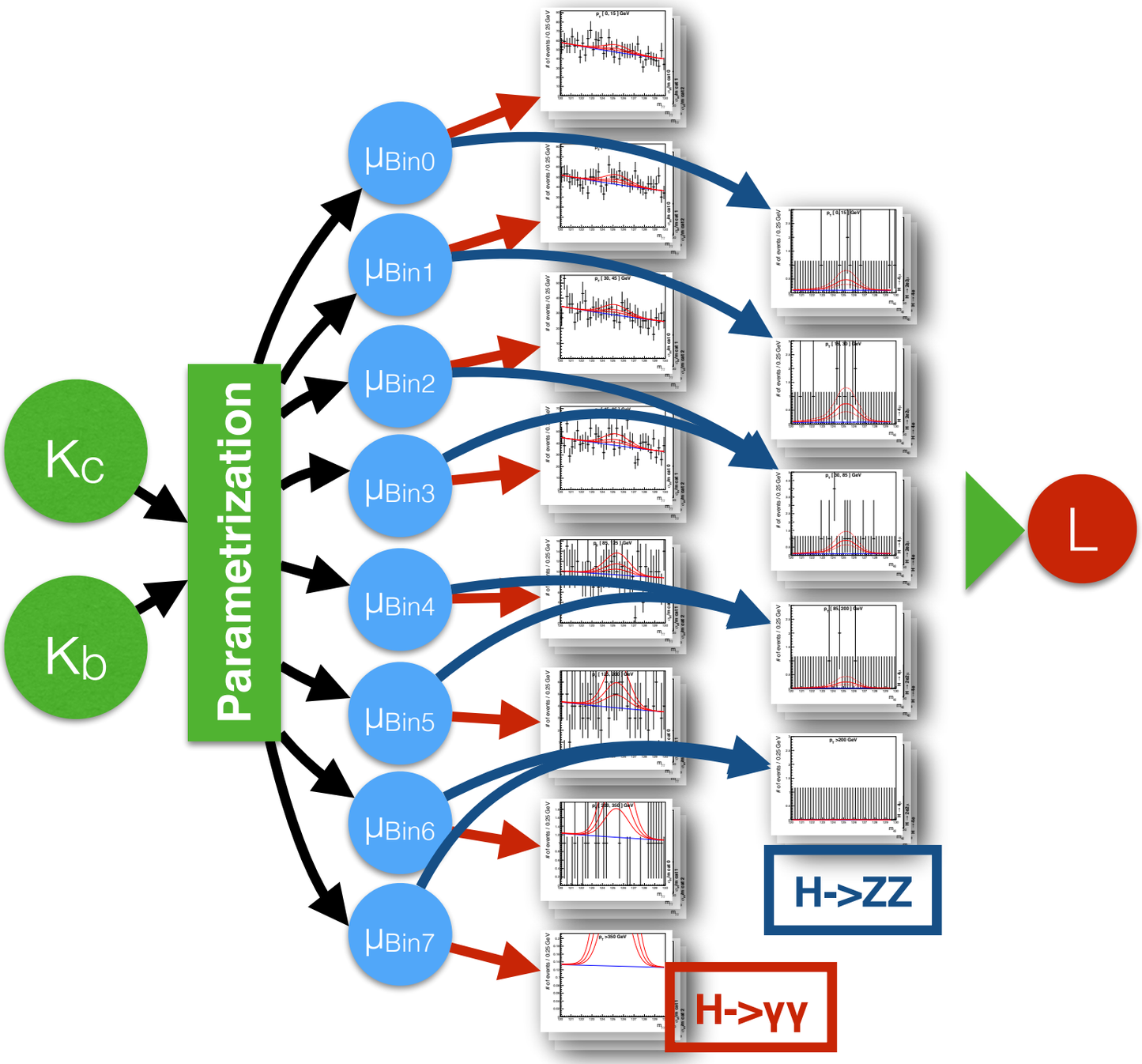
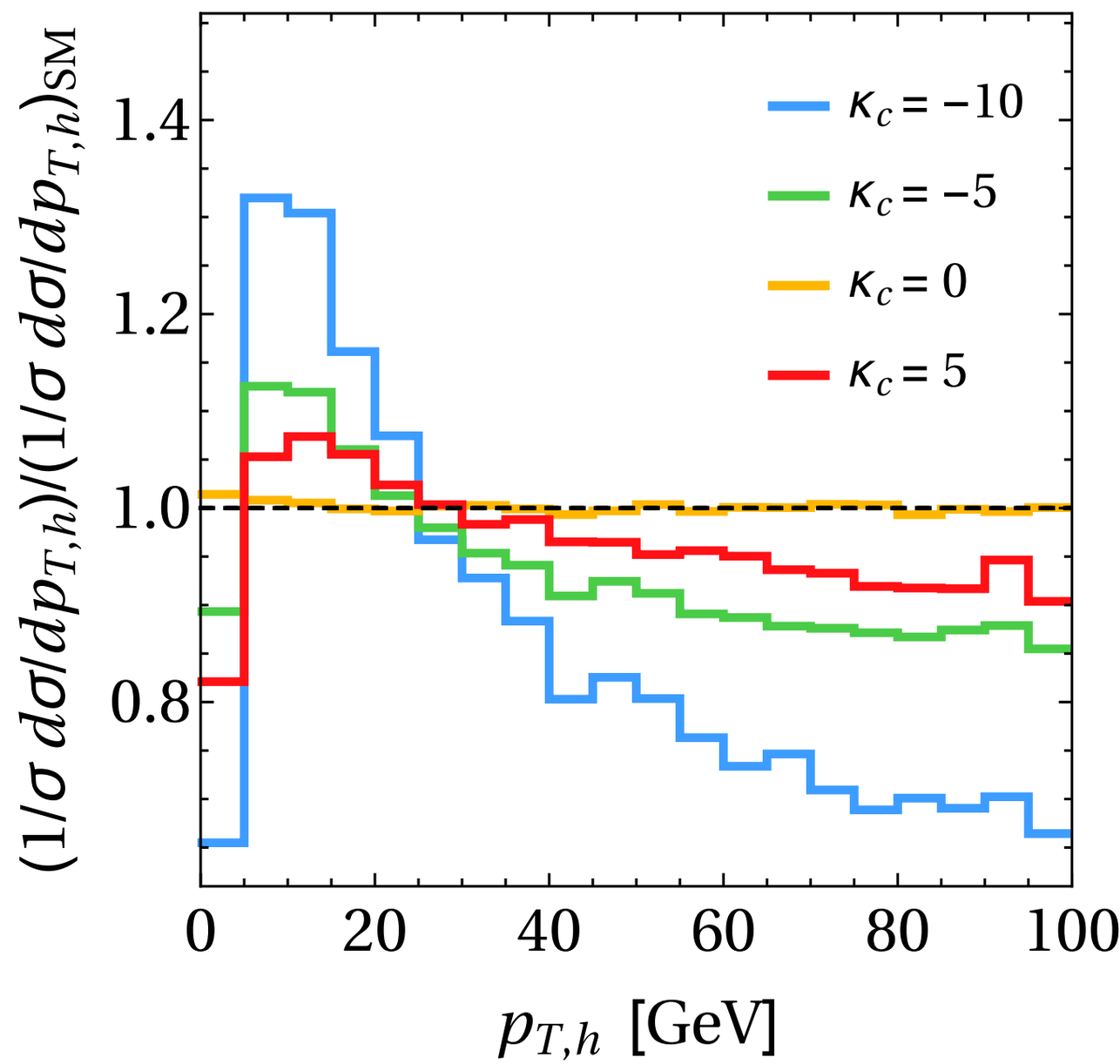


- Obtain 2D likelihood by varying κ_c and κ_b
- The contributions from **xH** (i.e. *not ggH*) are set to SM
- Two details need special attention:
  - **#1** Implementation of the parametrization
  - **#2** Implementation of the theory uncertainties

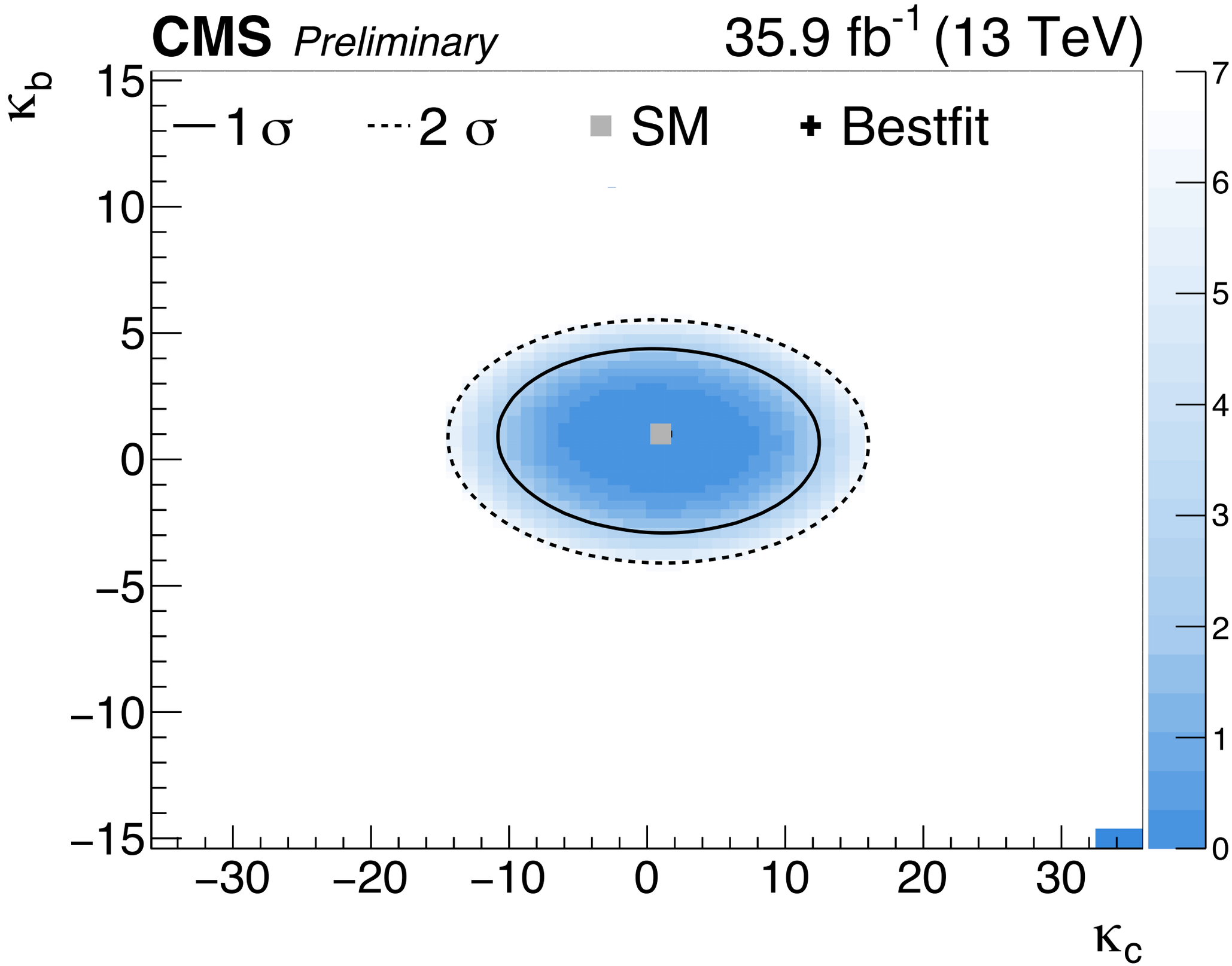
κ_c VS. κ_b

- pT spectrum **for ggH only** shows **shape distortion** when modifying κ_c and κ_b
- **Spectra given by the theorists**
- Instead of fitting freely floating μ's (as in the pT combination), now fitting **$\mu(\kappa_c, \kappa_b)$**

Bishara, Haisch, Monni, Re (2016) [1606.09253]



κ_c vs. κ_b: Nominal fit result (combination only)



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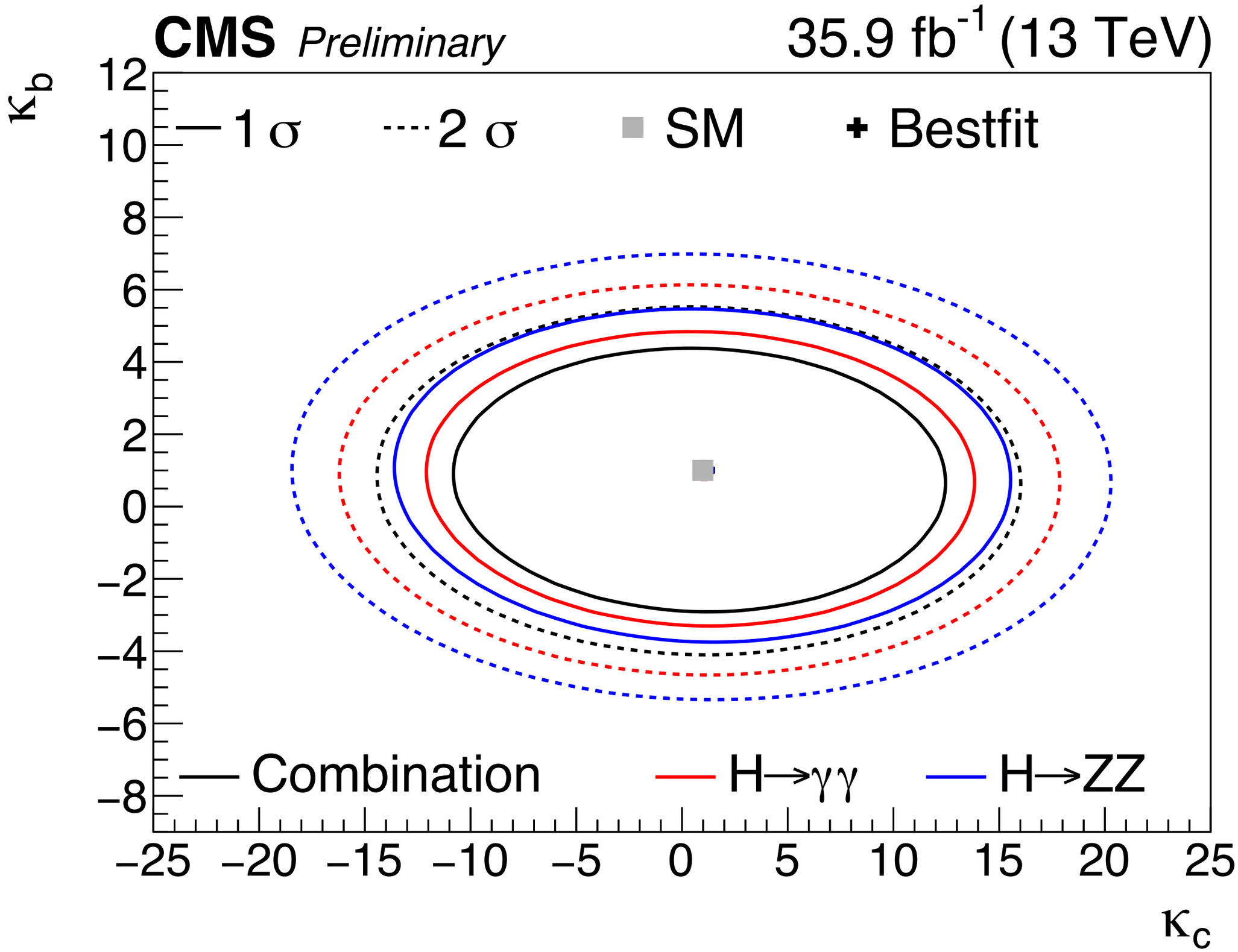
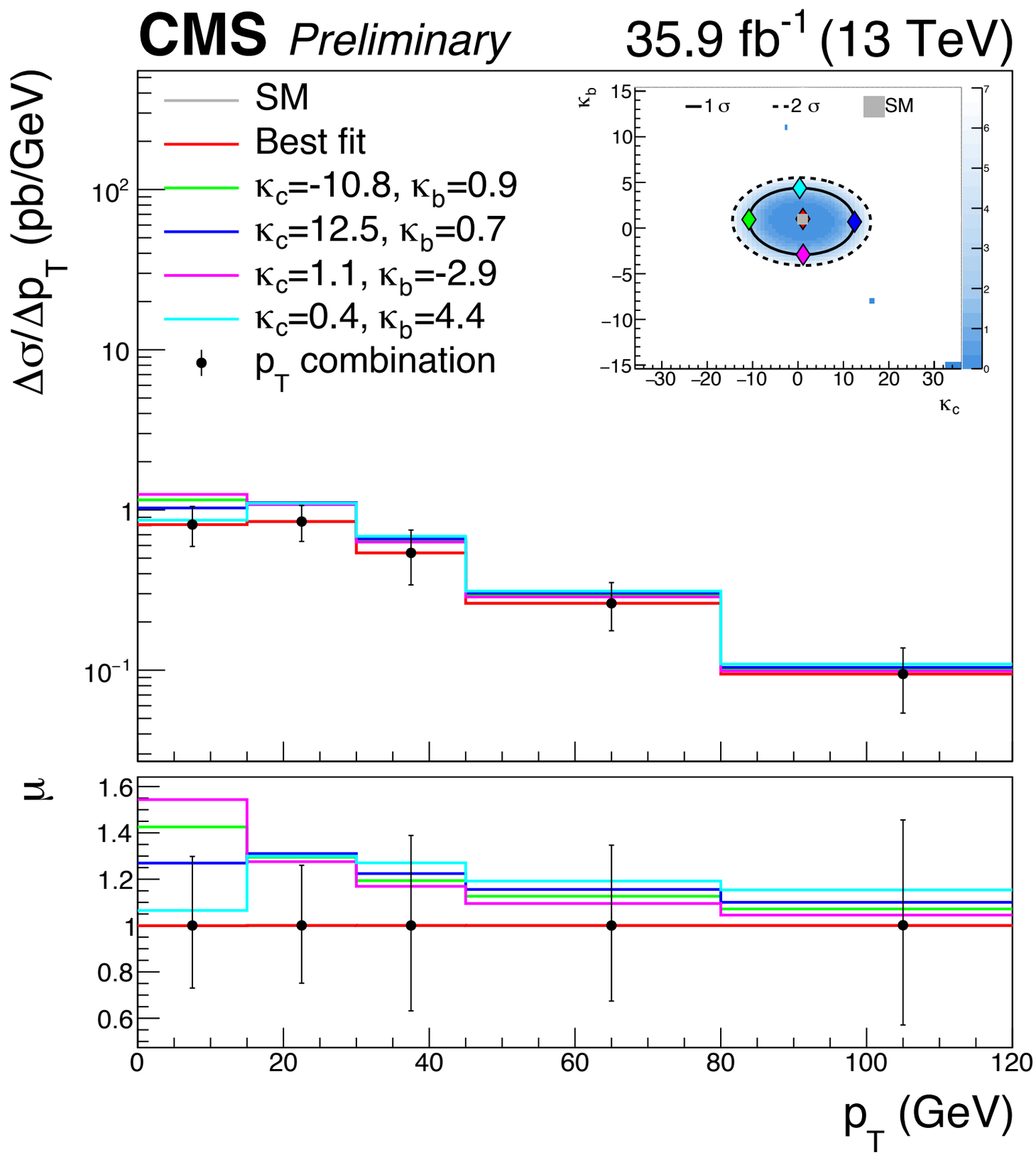
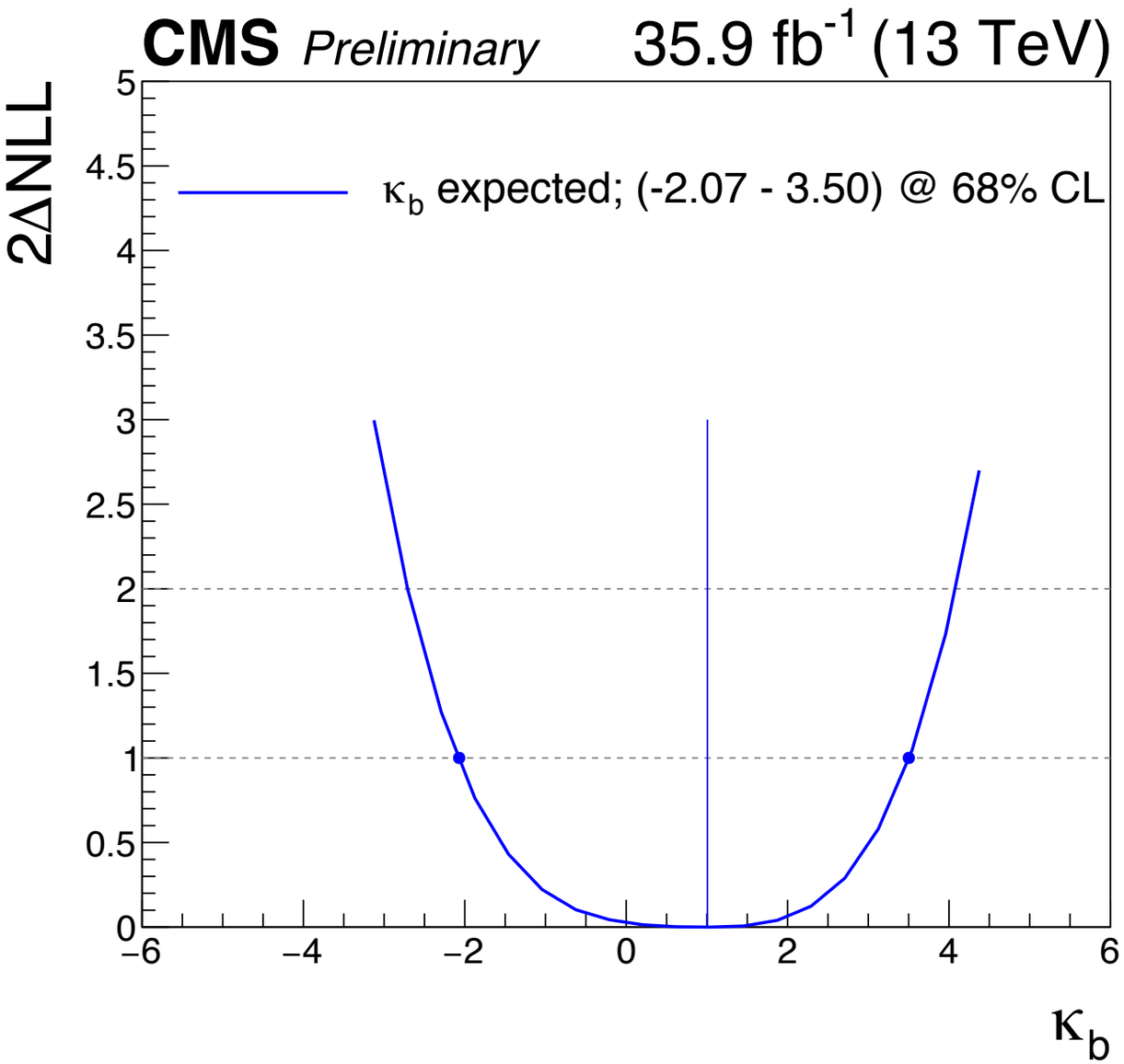


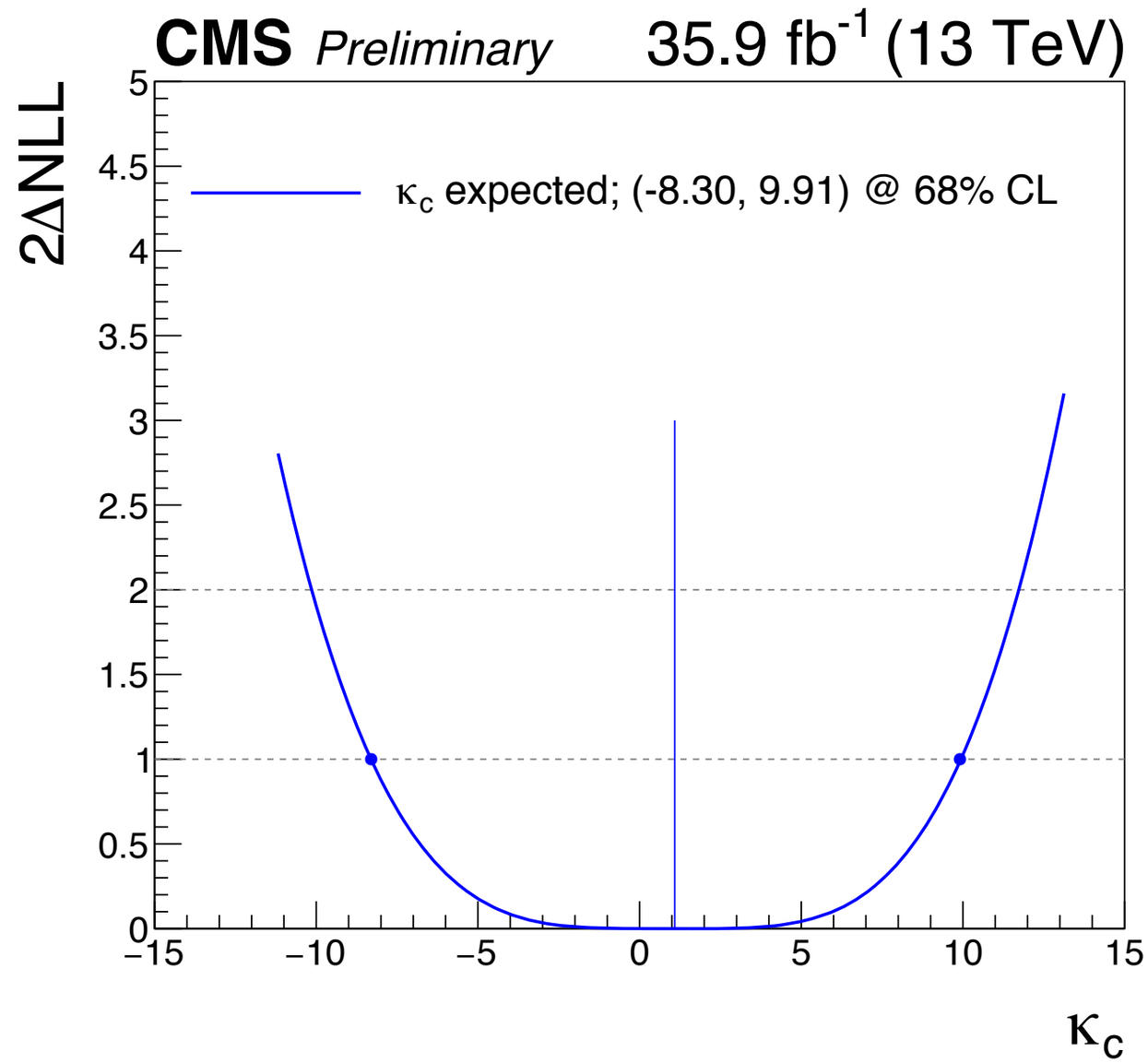
κ_c vs. κ_b: Visualisation of fits



(The colors of the lines match with the colors of the diamonds)

κ_c vs. κ_b: 1D scans





- Scan over 1 coupling, while profiling the other

K_t VS. K_g

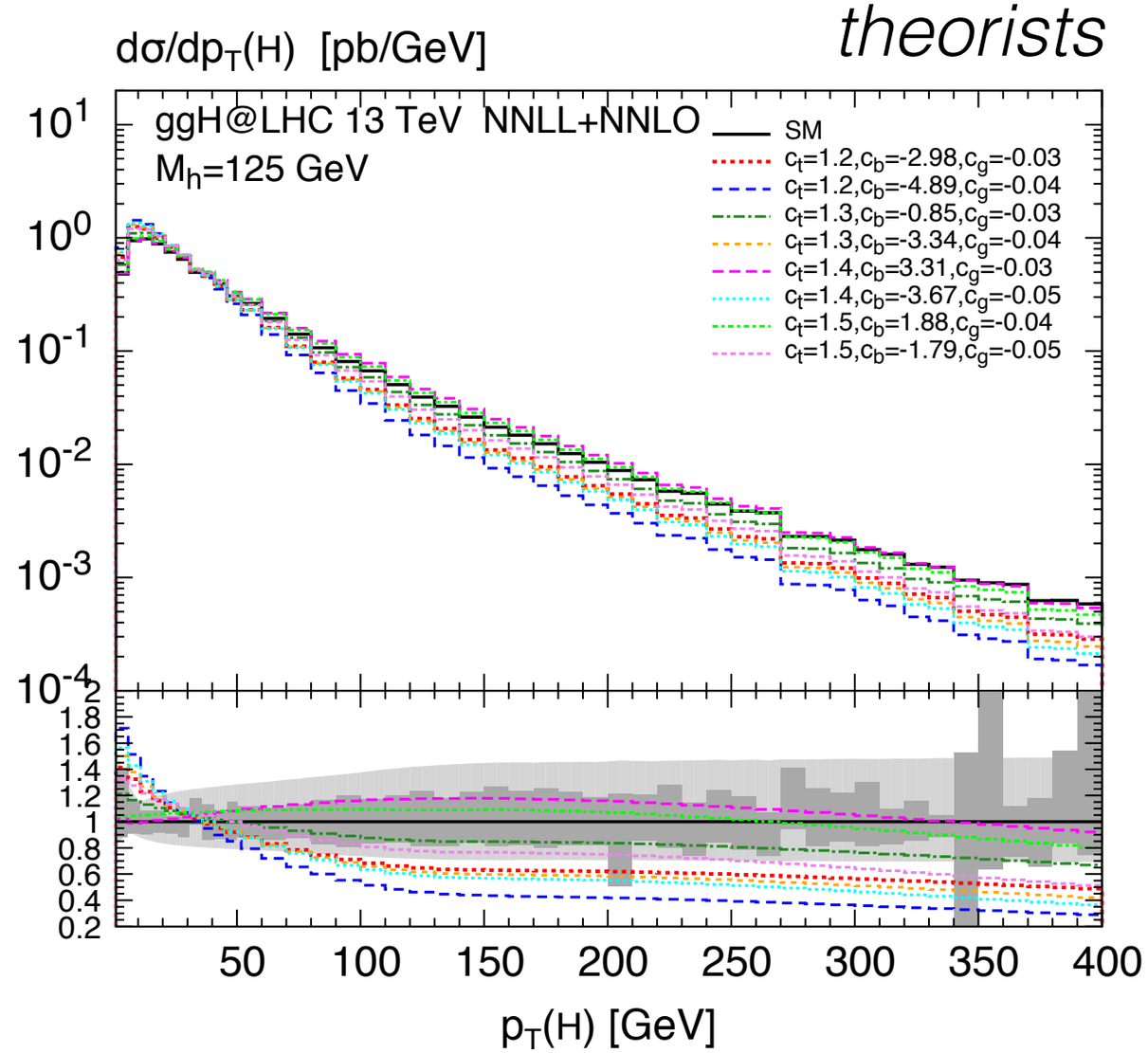
- Consider the following modifications to the SM Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

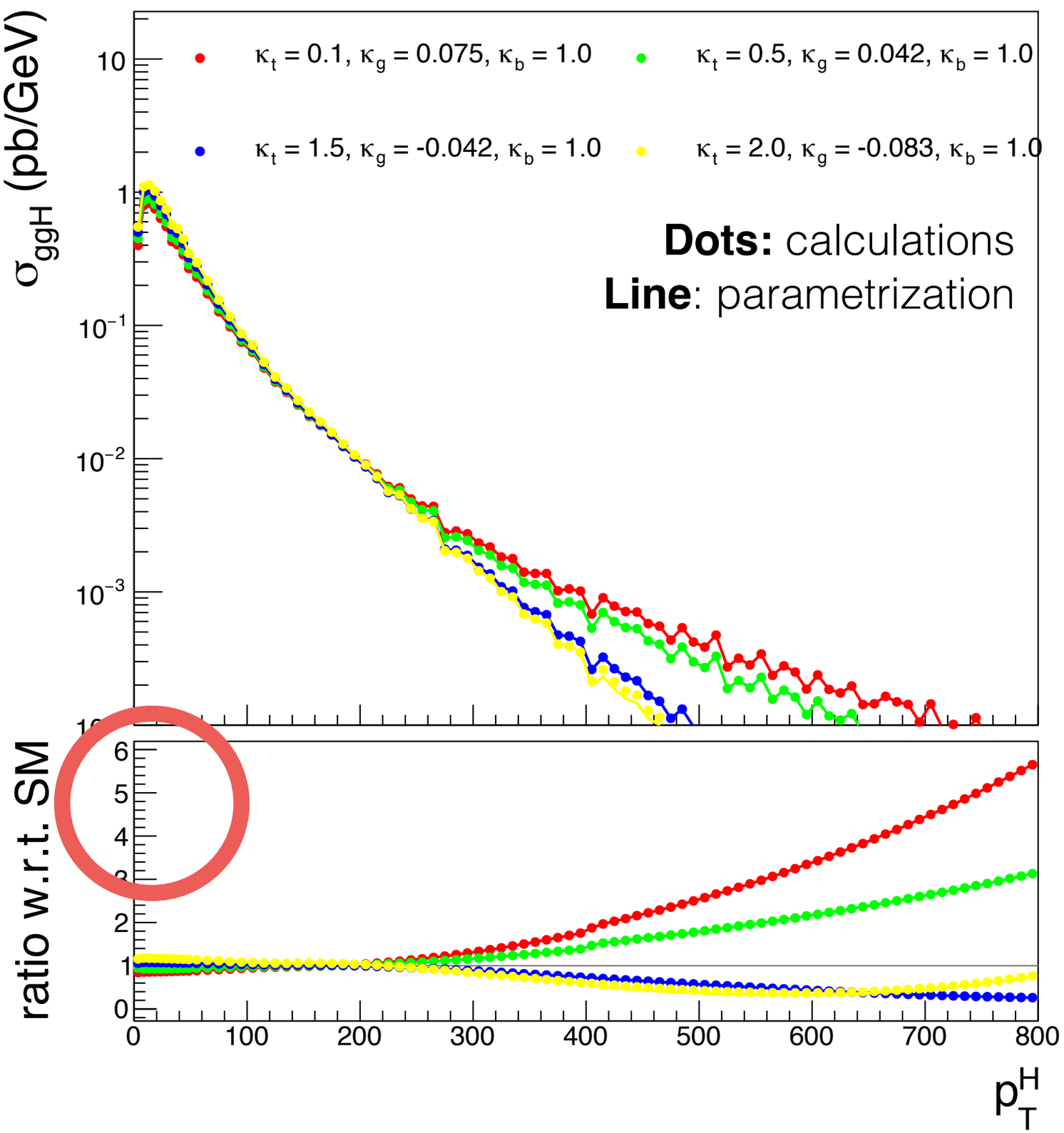
*Theory calculations **given** by theorists*

- dimension-six operators related to the modification of the Yukawa couplings of the top and bottom to the Higgs [1505.03706]

- Examples of the p_T-distribution for coupling variations:

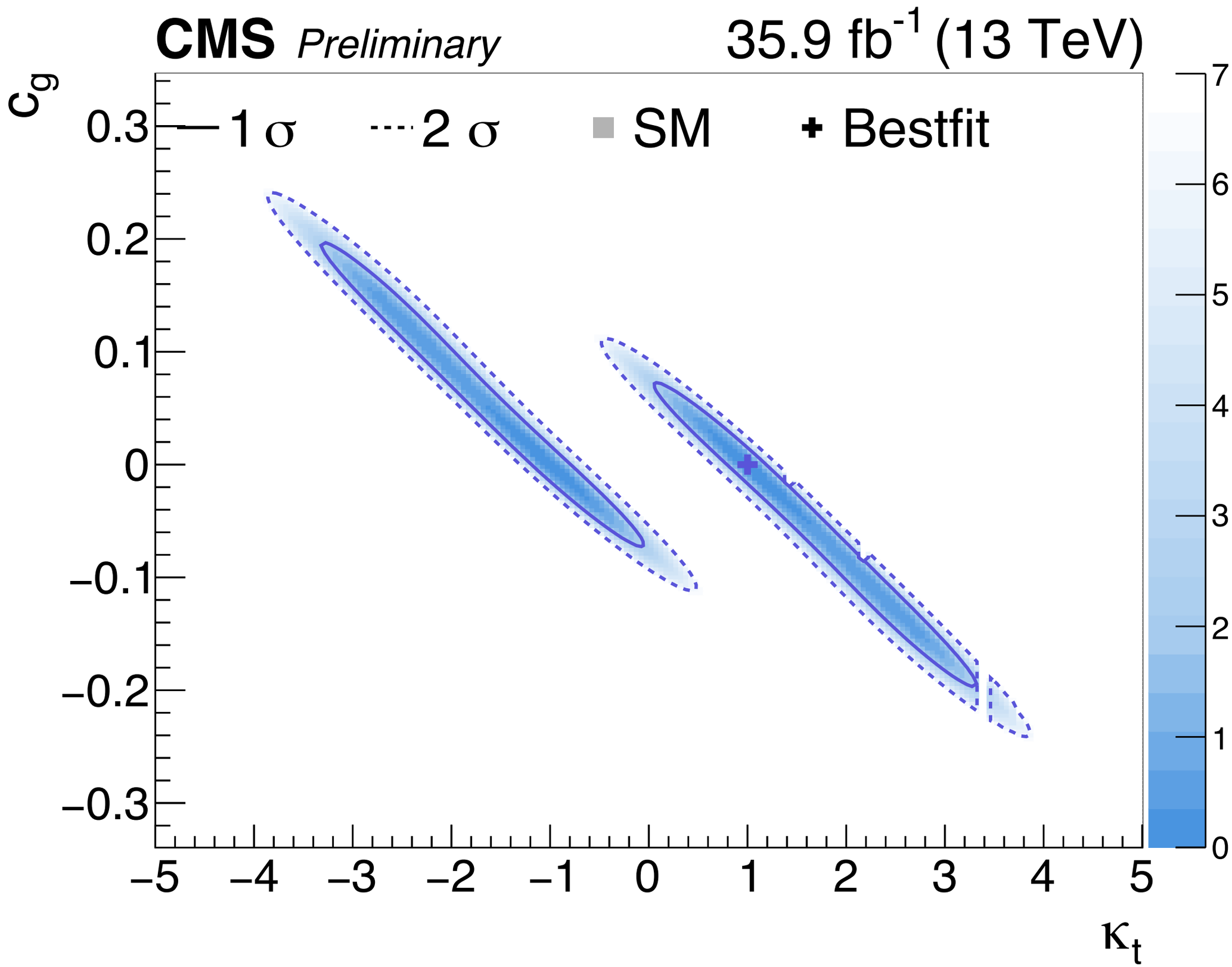


κ_t vs. κ_g: Parametrization



- Note **strong distortions** in the **tail**
- Coupling sensitivity very strong at high p_T
- Here H → bb helps a lot

κ_t vs. κ_g: Nominal fit result (combination only)



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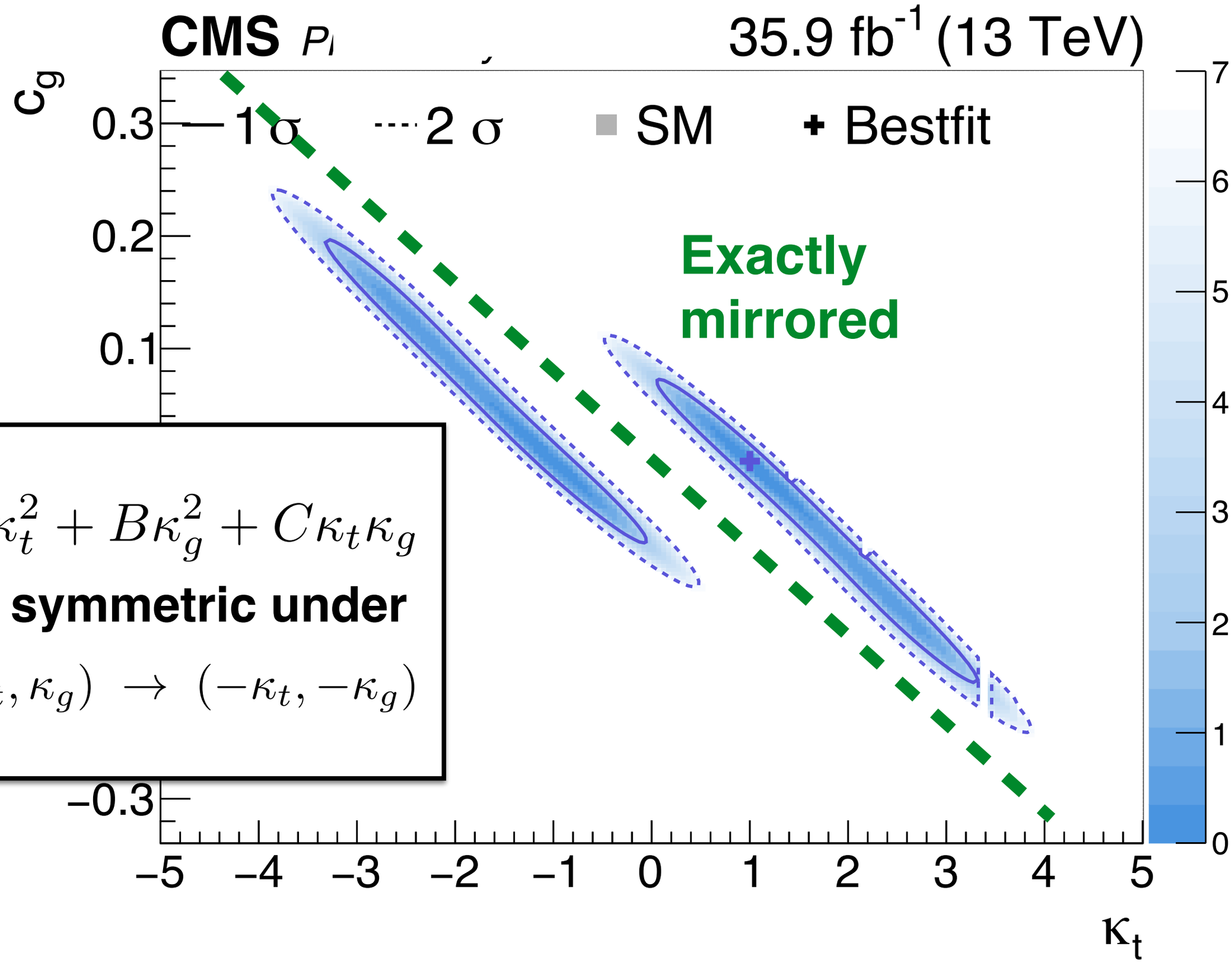
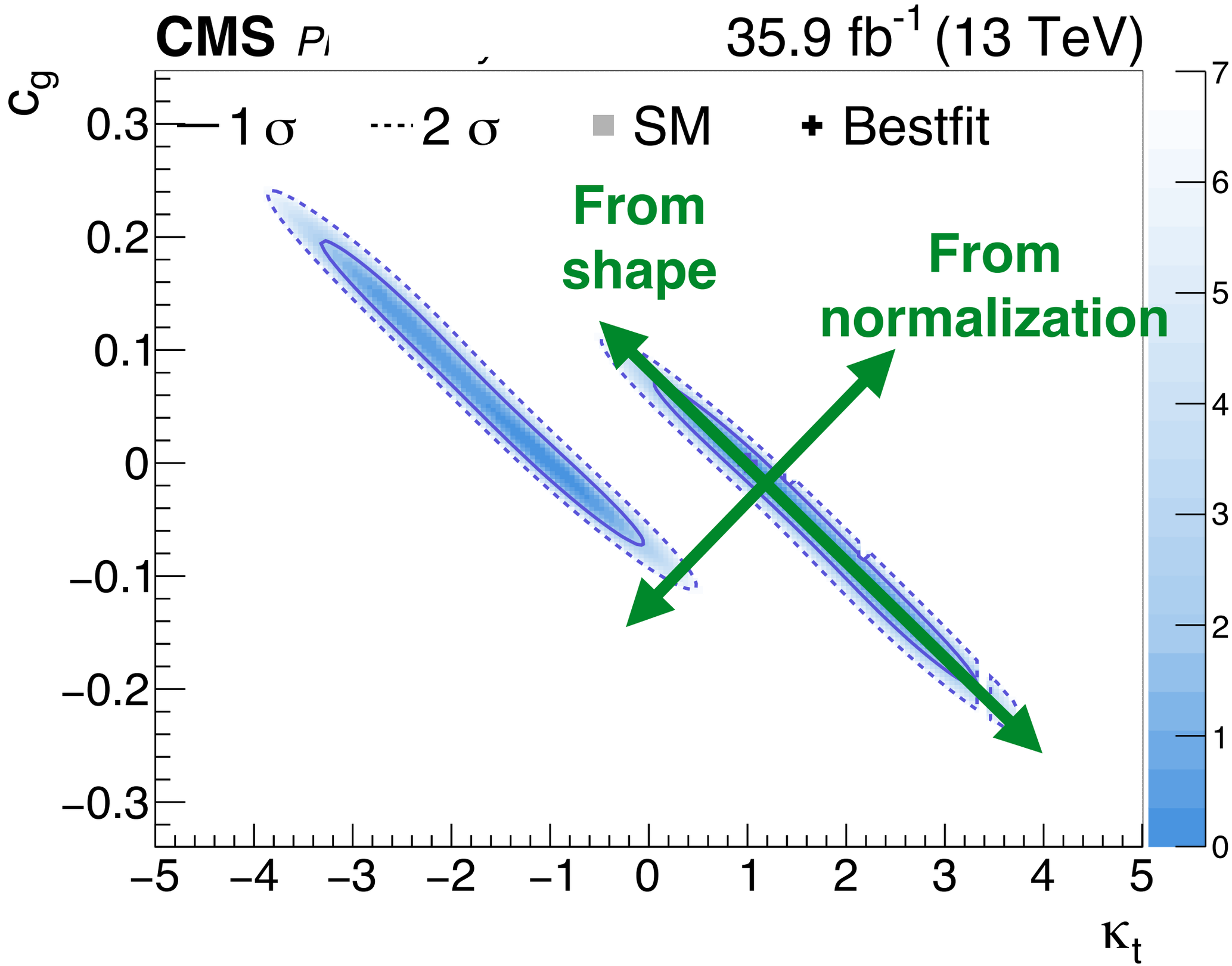


$$A\kappa_t^2 + B\kappa_g^2 + C\kappa_t\kappa_g$$

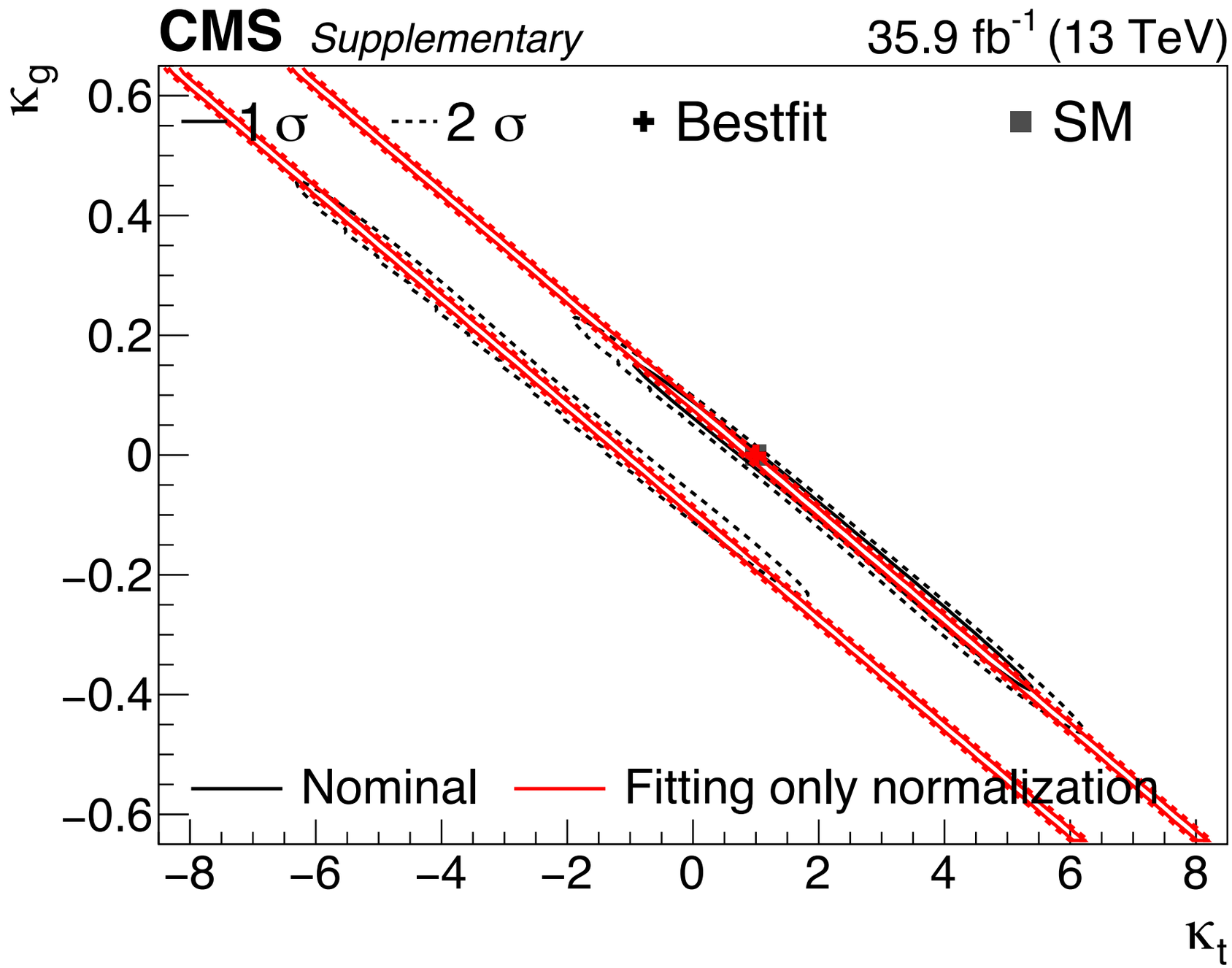
is symmetric under

$$(\kappa_t, \kappa_g) \rightarrow (-\kappa_t, -\kappa_g)$$

κ_t vs. κ_g: Nominal fit result (combination only)

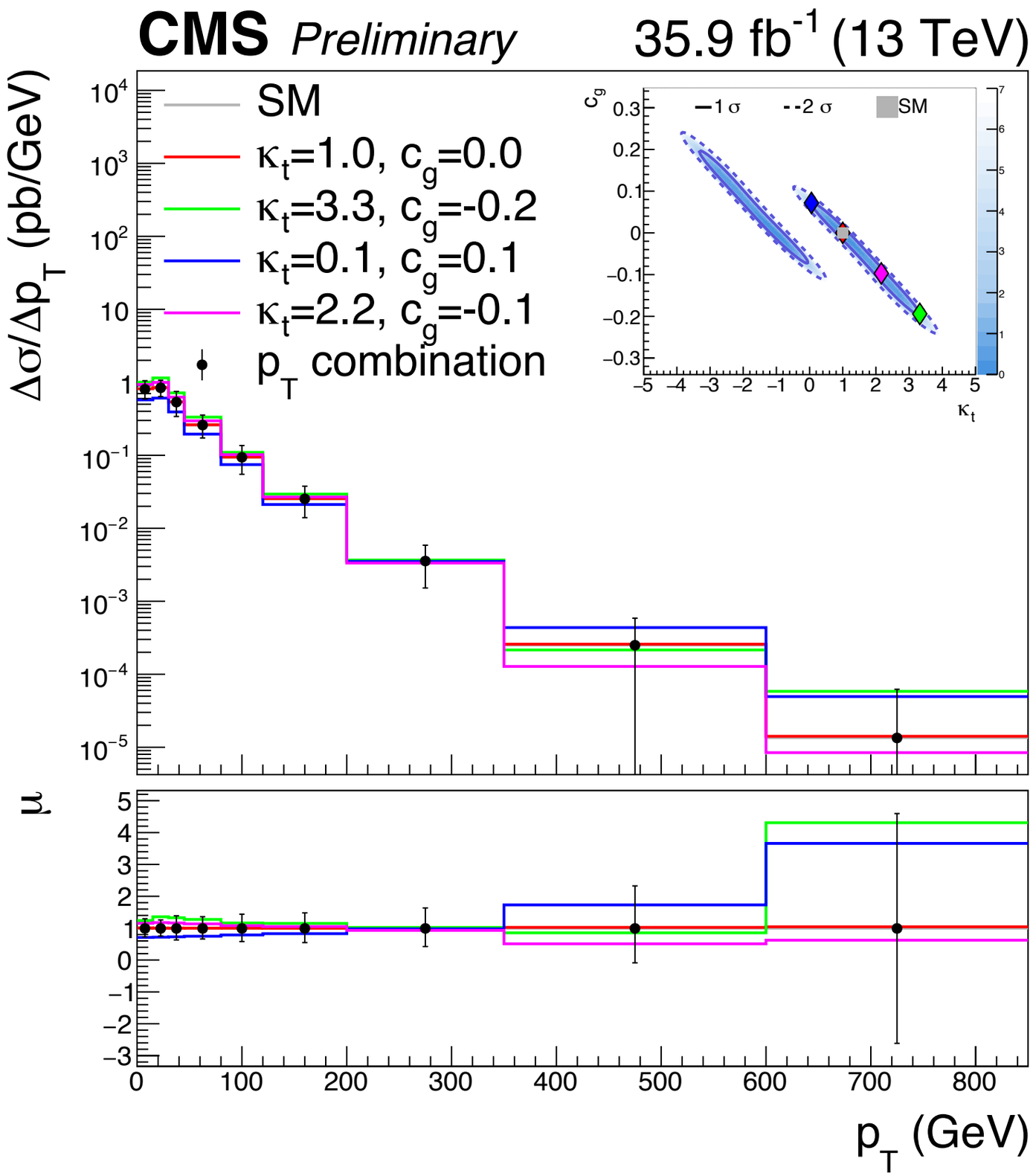


κ_t vs. κ_g: Only normalization (combination only)



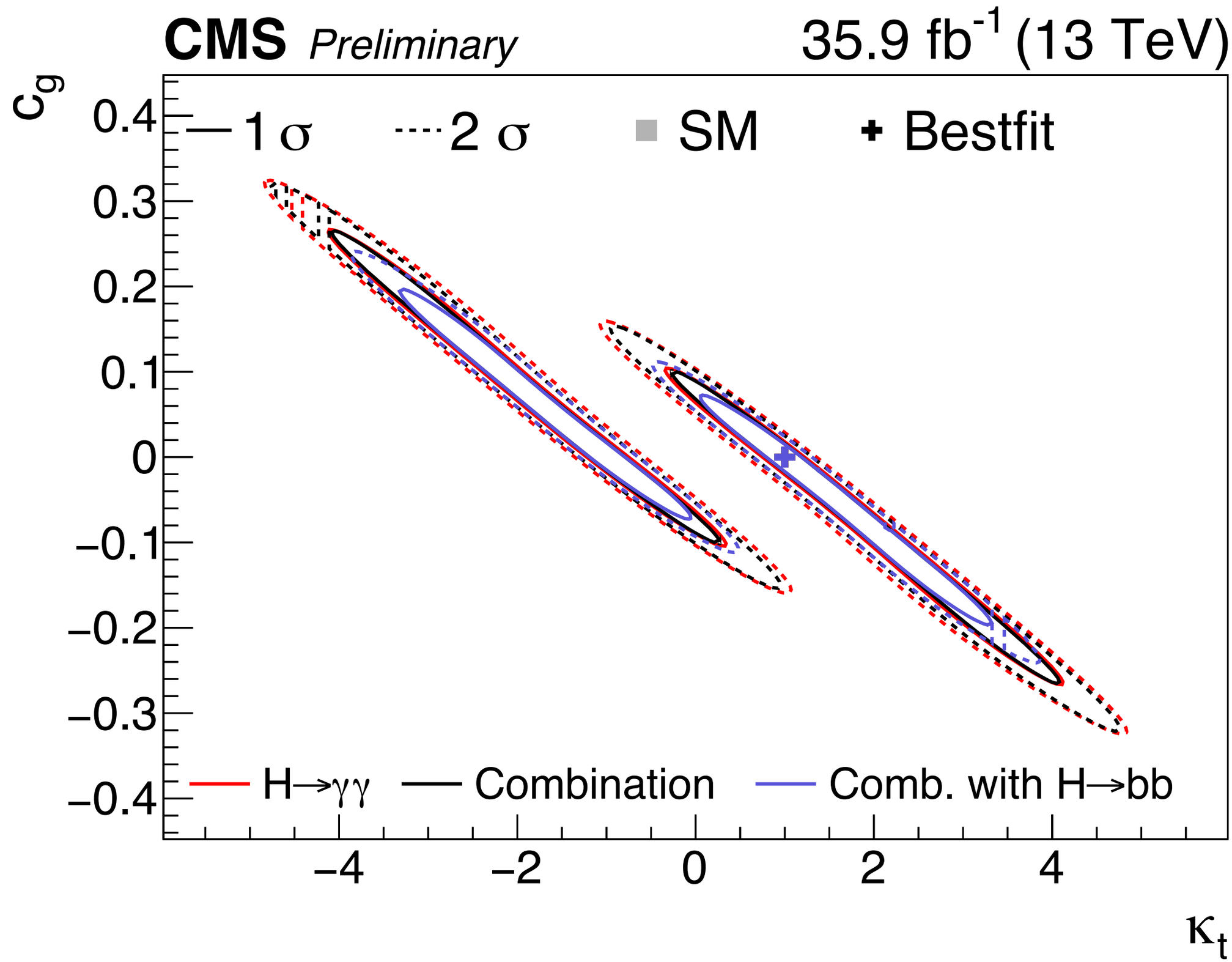
- Fits only the **integral** of the spectrum(κ_t, κ_g) to the total observed cross section

κ_t vs. κ_g: Visualisation of fits

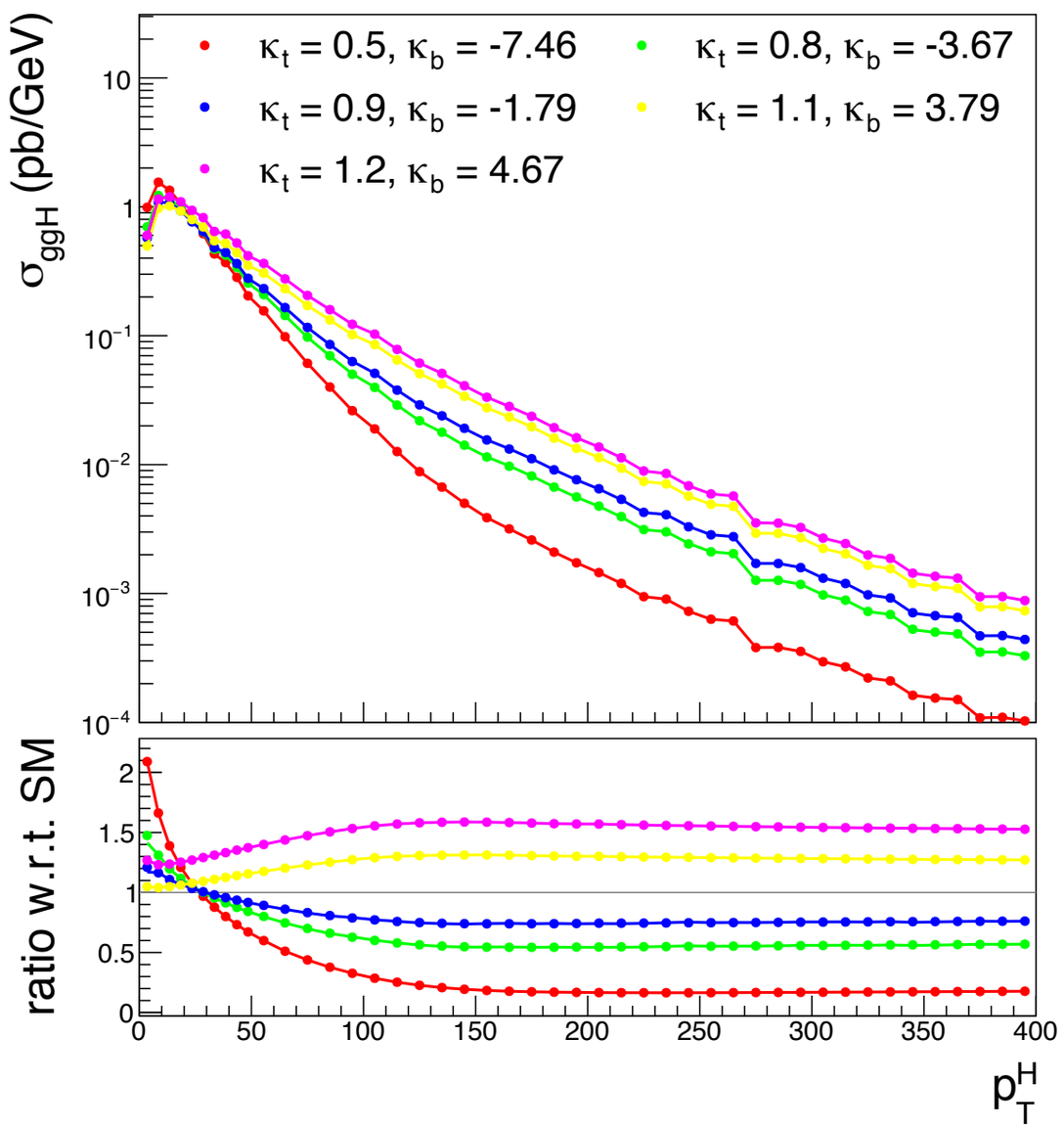


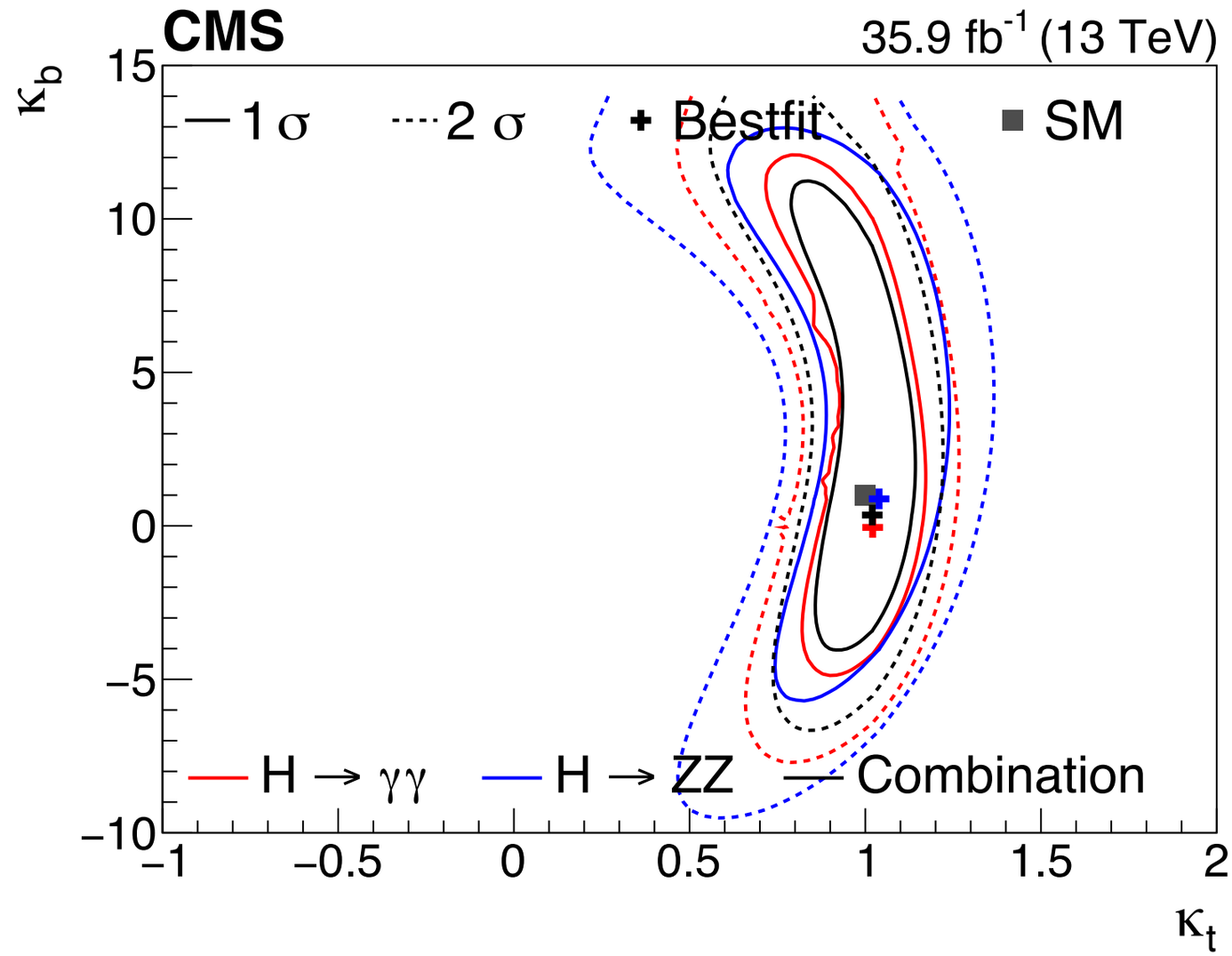
- Strong sensitivity is offset by huge statistical uncertainties
- This becomes more promising at **higher luminosity**

κ_t vs. κ_g: Nominal fit result



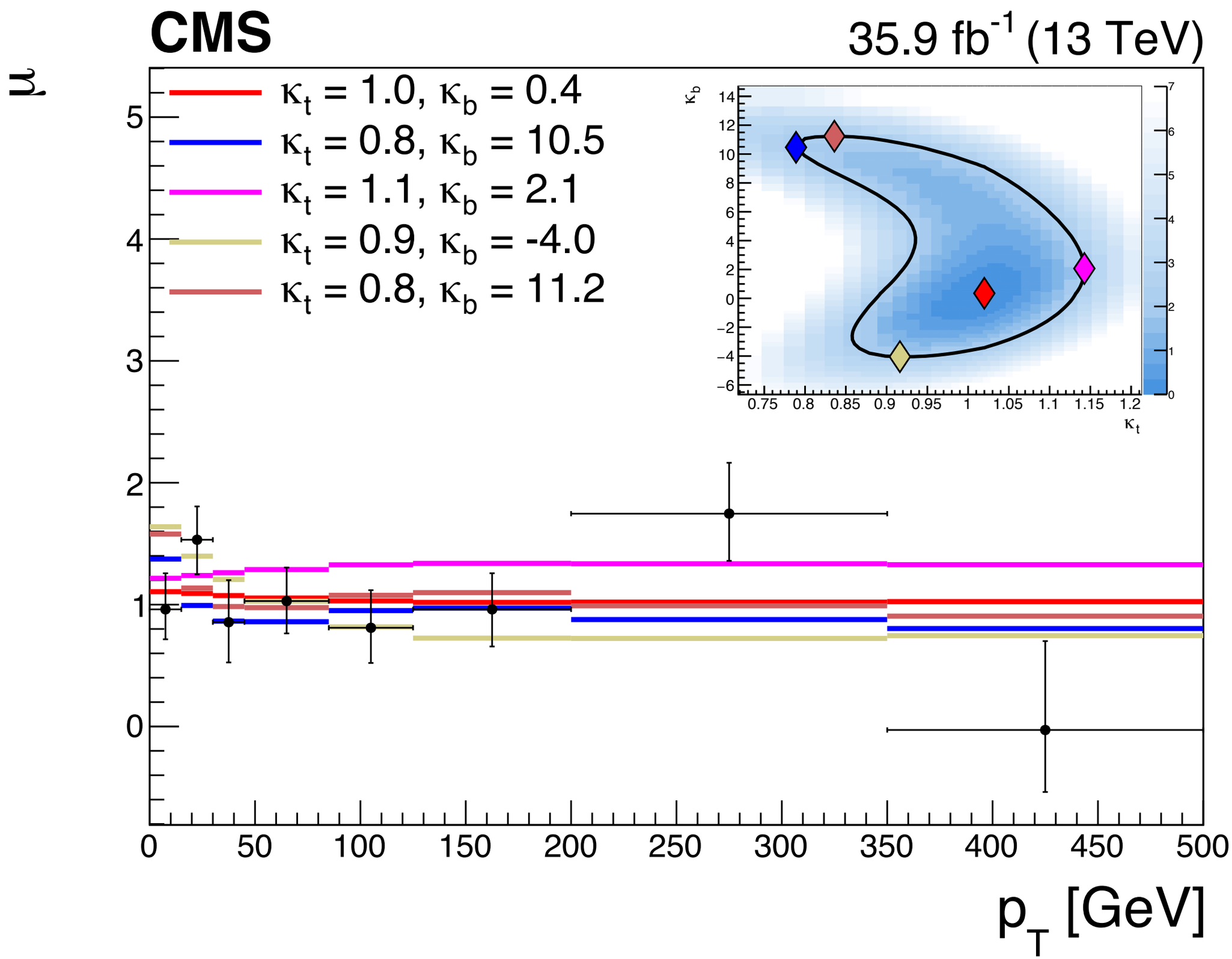
κ_b vs. κ_t: Fit results





- Parametrization
- Nominal fit result

κ_b vs. κ_t: Visualisation of fits



Conclusion

- Differential cross sections promise an interesting way to probe the properties of the Higgs
- Presented the *expected* differential cross sections for observables **p_T^H, N_{jets}, rapidity and p_T^{jet}**
- Presented some *expected* limits on **κ_b** vs. **κ_c**, **κ_t** vs. **κ_g** and **κ_b** vs. **κ_t**
- Obtained constraints on couplings indicate competitiveness with direct probes of Higgs couplings, in particular κ_c

Back up

ETH zürich

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$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} \kappa_{b,1}^2 & \kappa_{c,1}^2 & \kappa_{t,1}^2 & \kappa_{b,1}\kappa_{c,1} & \kappa_{b,1}\kappa_{t,1} & \kappa_{c,1}\kappa_{t,1} \\ \kappa_{b,2}^2 & \kappa_{c,2}^2 & \kappa_{t,2}^2 & \kappa_{b,2}\kappa_{c,2} & \kappa_{b,2}\kappa_{t,2} & \kappa_{c,2}\kappa_{t,2} \\ \kappa_{b,3}^2 & \kappa_{c,3}^2 & \kappa_{t,3}^2 & \kappa_{b,3}\kappa_{c,3} & \kappa_{b,3}\kappa_{t,3} & \kappa_{c,3}\kappa_{t,3} \\ \kappa_{b,4}^2 & \kappa_{c,4}^2 & \kappa_{t,4}^2 & \kappa_{b,4}\kappa_{c,4} & \kappa_{b,4}\kappa_{t,4} & \kappa_{c,4}\kappa_{t,4} \\ \kappa_{b,5}^2 & \kappa_{c,5}^2 & \kappa_{t,5}^2 & \kappa_{b,5}\kappa_{c,5} & \kappa_{b,5}\kappa_{t,5} & \kappa_{c,5}\kappa_{t,5} \\ \kappa_{b,6}^2 & \kappa_{c,6}^2 & \kappa_{t,6}^2 & \kappa_{b,6}\kappa_{c,6} & \kappa_{b,6}\kappa_{t,6} & \kappa_{c,6}\kappa_{t,6} \end{bmatrix} \begin{bmatrix} A \\ B \\ C \\ D \\ E \\ F \end{bmatrix}$$

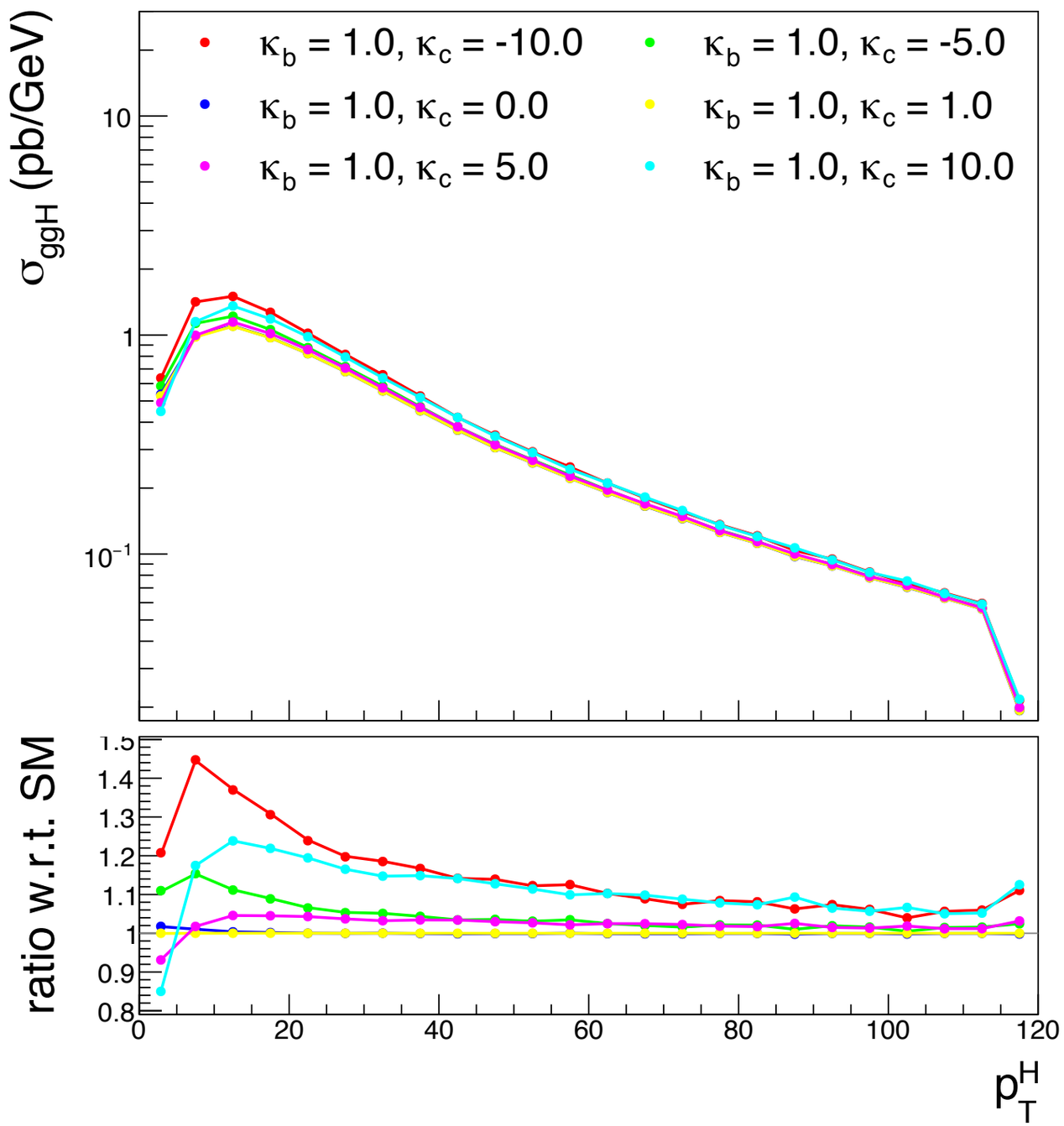
Parametrization

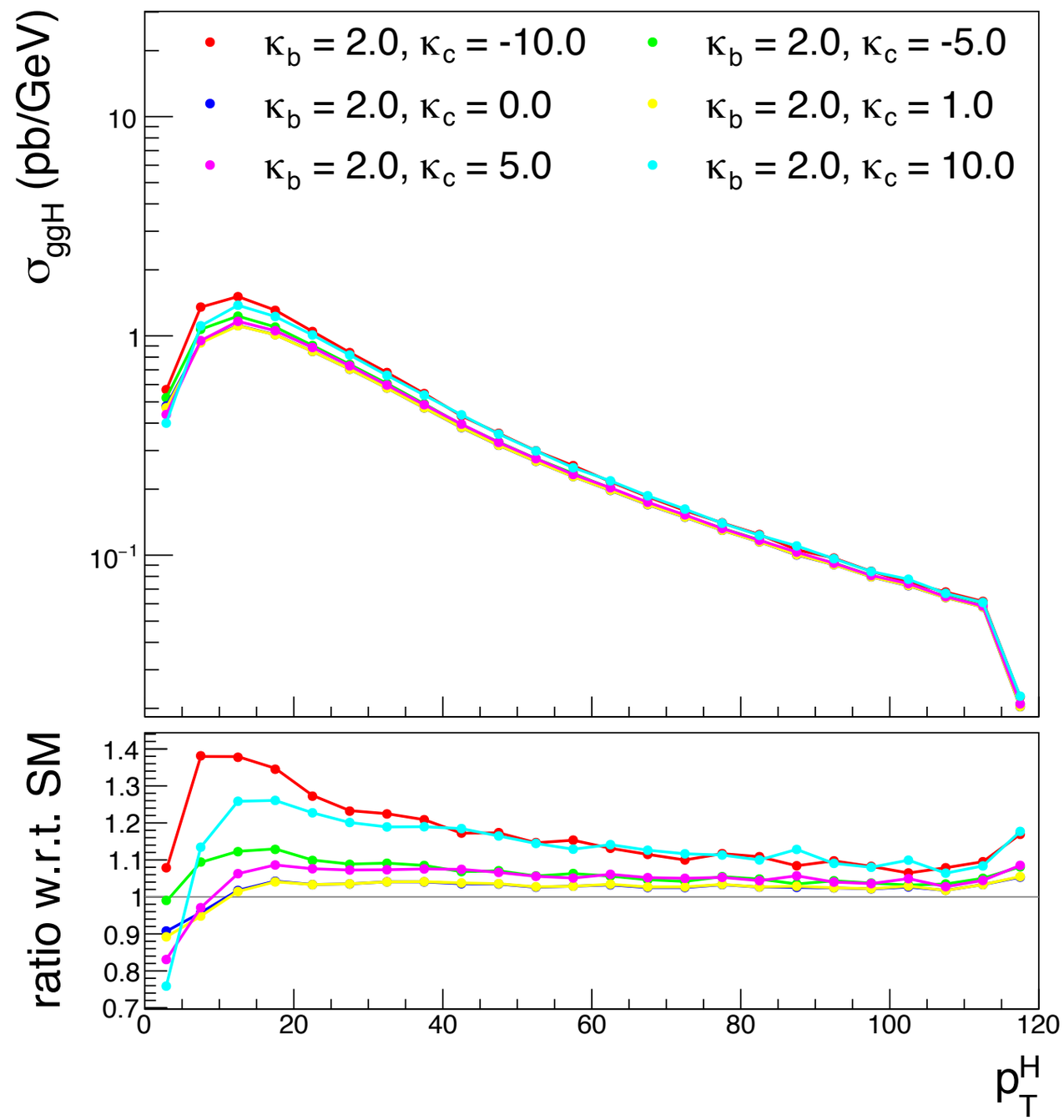
- Find values of coefficients by simple matrix inversion:

$$\begin{bmatrix} A \\ B \\ C \\ D \\ E \\ F \end{bmatrix} = \begin{bmatrix} \kappa_{b,1}^2 & \kappa_{c,1}^2 & \kappa_{t,1}^2 & \kappa_{b,1}\kappa_{c,1} & \kappa_{b,1}\kappa_{t,1} & \kappa_{c,1}\kappa_{t,1} \\ \kappa_{b,2}^2 & \kappa_{c,2}^2 & \kappa_{t,2}^2 & \kappa_{b,2}\kappa_{c,2} & \kappa_{b,2}\kappa_{t,2} & \kappa_{c,2}\kappa_{t,2} \\ \kappa_{b,3}^2 & \kappa_{c,3}^2 & \kappa_{t,3}^2 & \kappa_{b,3}\kappa_{c,3} & \kappa_{b,3}\kappa_{t,3} & \kappa_{c,3}\kappa_{t,3} \\ \kappa_{b,4}^2 & \kappa_{c,4}^2 & \kappa_{t,4}^2 & \kappa_{b,4}\kappa_{c,4} & \kappa_{b,4}\kappa_{t,4} & \kappa_{c,4}\kappa_{t,4} \\ \kappa_{b,5}^2 & \kappa_{c,5}^2 & \kappa_{t,5}^2 & \kappa_{b,5}\kappa_{c,5} & \kappa_{b,5}\kappa_{t,5} & \kappa_{c,5}\kappa_{t,5} \\ \kappa_{b,6}^2 & \kappa_{c,6}^2 & \kappa_{t,6}^2 & \kappa_{b,6}\kappa_{c,6} & \kappa_{b,6}\kappa_{t,6} & \kappa_{c,6}\kappa_{t,6} \end{bmatrix}^{-1} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix}$$

- Accurate for spectra with low statistical noise
- κ_t set to 1.0 (SM) for the κ_c vs. κ_b analysis

κ_c vs. κ_b: Parametrization

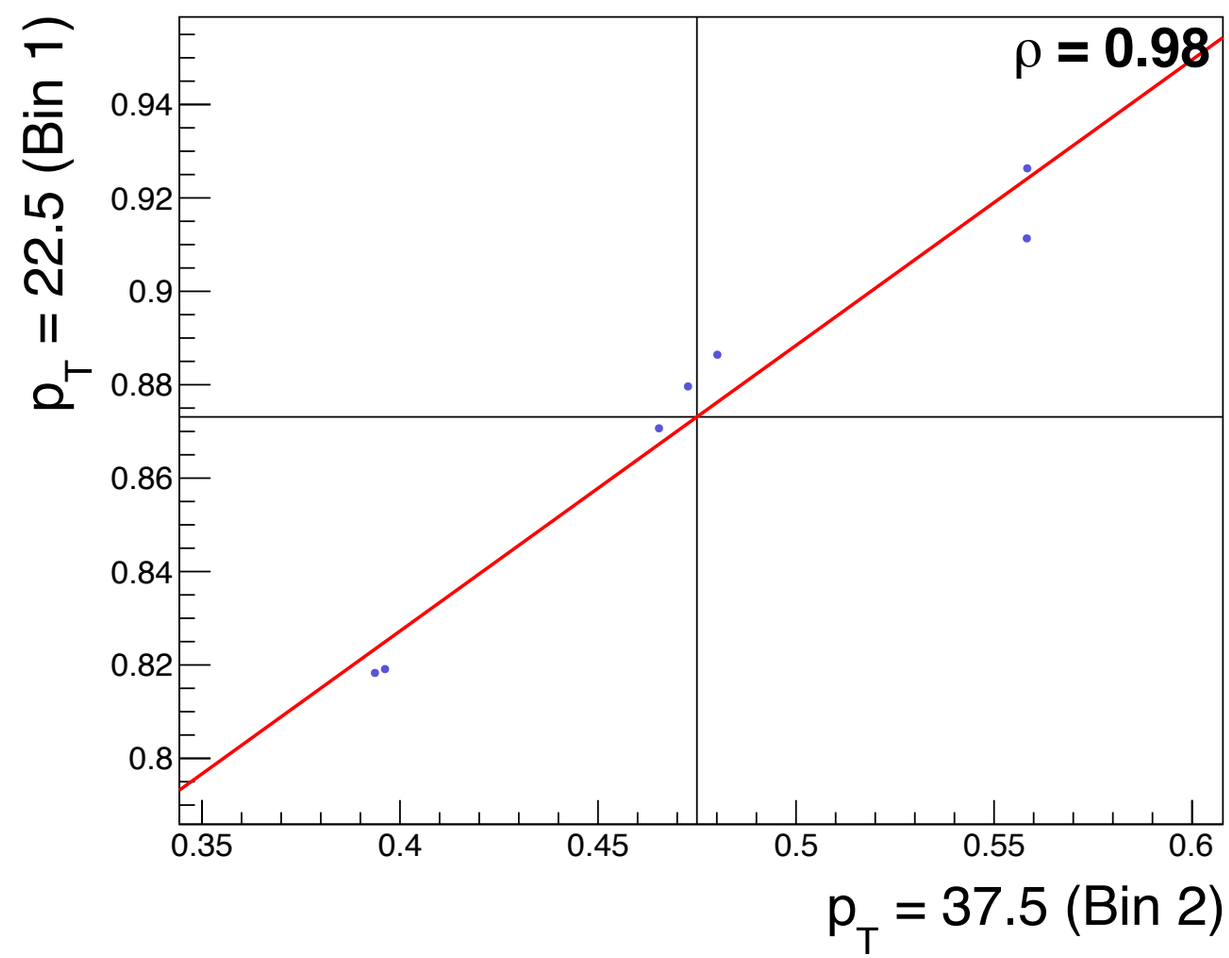




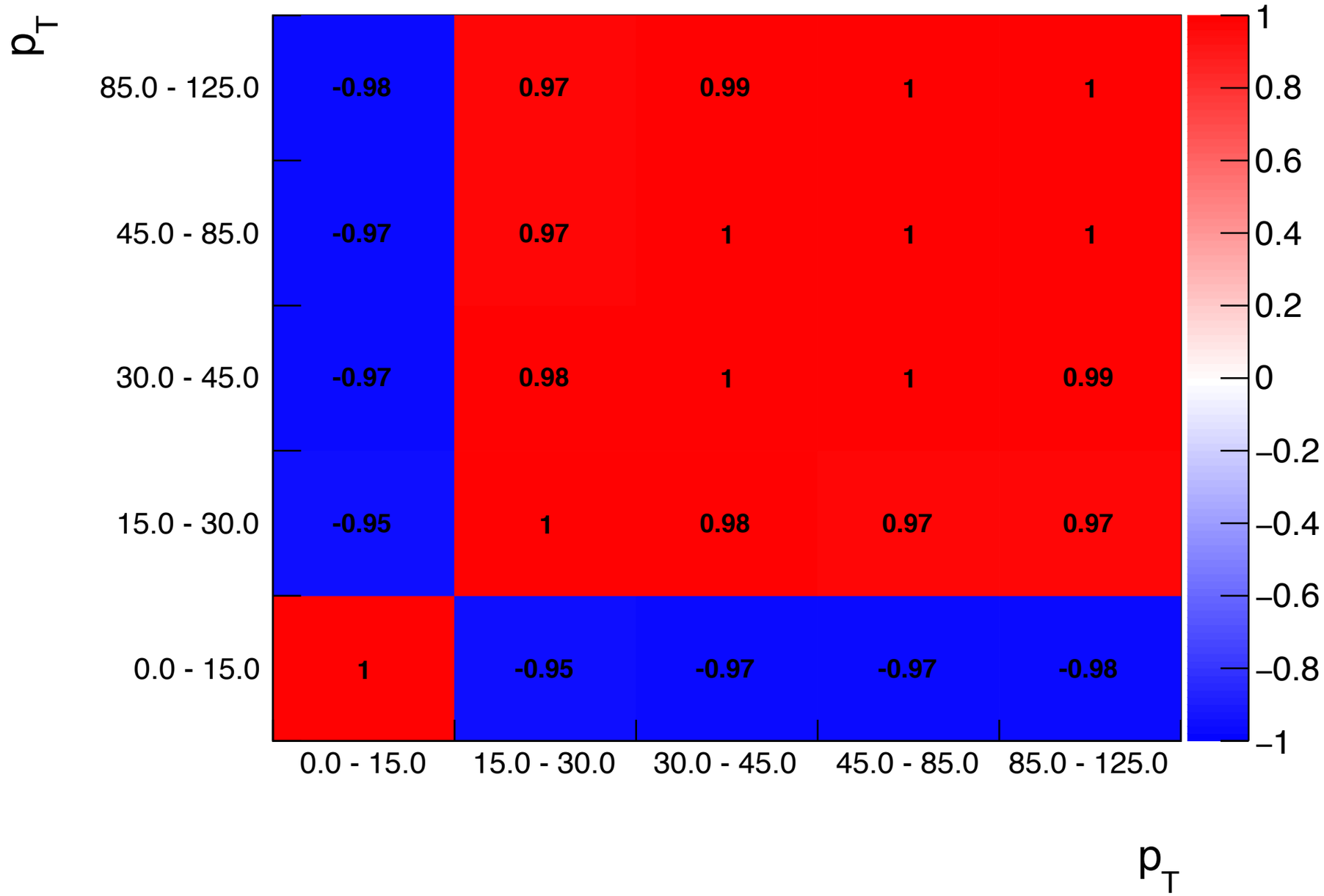
- Plots only split to avoid overcrowdedness
- **Dots:** calculations; **Line**: parametrization
- Correlation structure taken directly from scale variations
  - Fit result very robust under different correlation structures (x-checked)

Theory uncertainties

- Scale variations given by theorists: **Size** of theory uncertainties known
- **Correlations** between bins calculated using the correlation coefficient of the individual <u>scale variations</u>
  - (μ_R, μ_F) = (0.5, 0.5), (0.5, 1), (1, 0.5), (1, 1), (1, 2), (2, 1), (2, 2)
- Cross check with <u>uncorrelated</u> and <u>no theory uncertainties</u> is performed
- Bin-to-bin correlations are notoriously difficult to calculate theoretically
- Stewart-Tackmann is inappropriate for pT

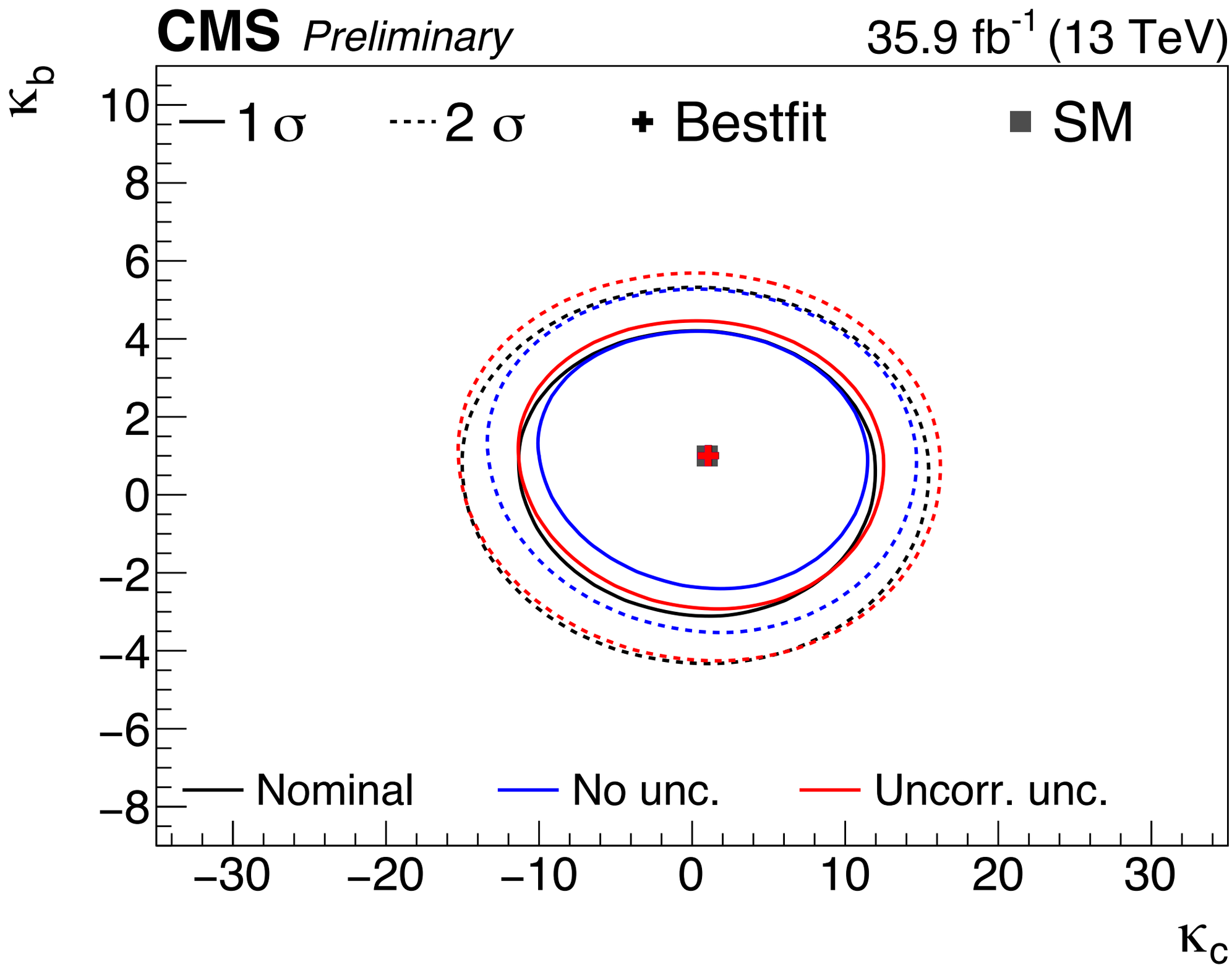


Theory uncertainties

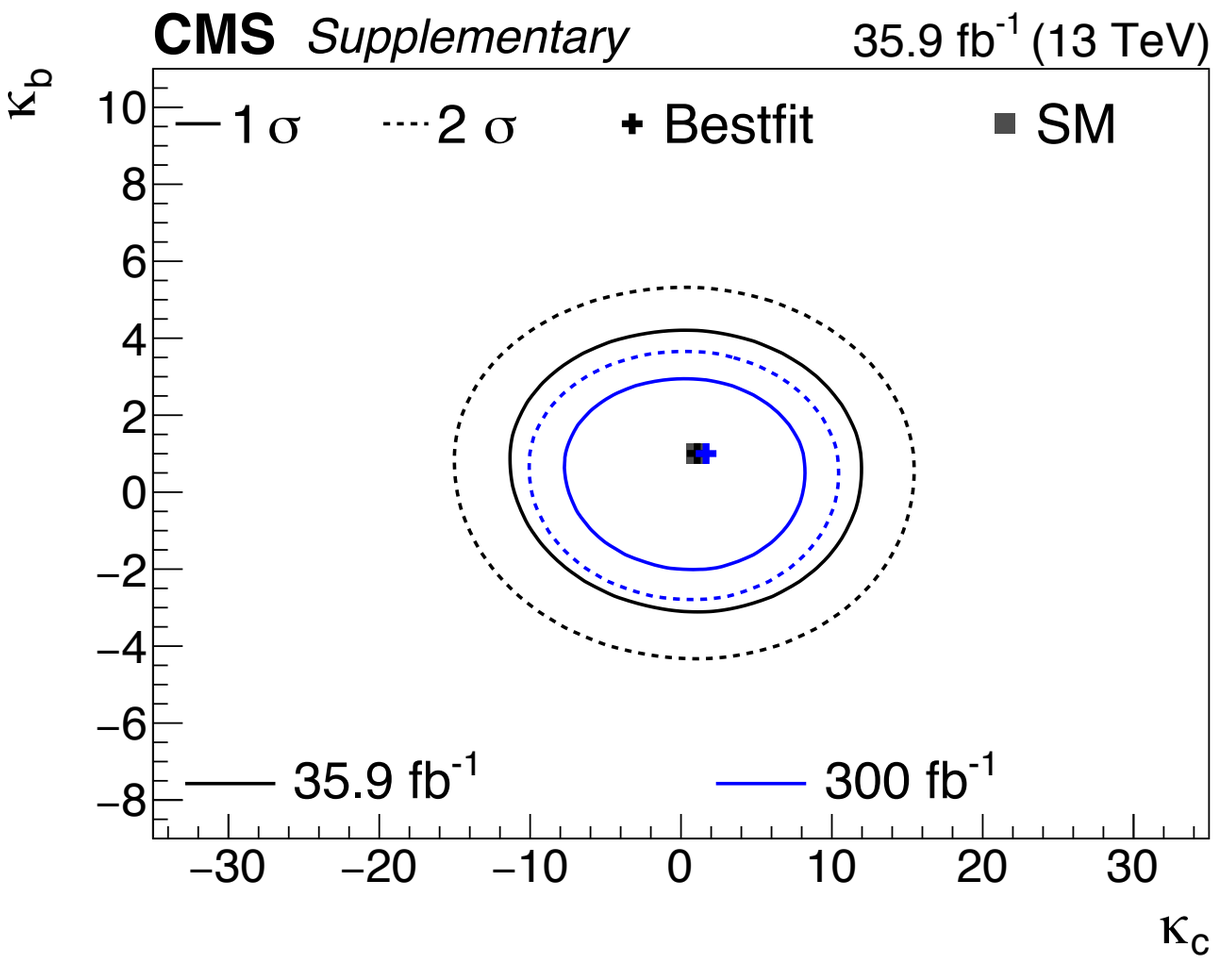


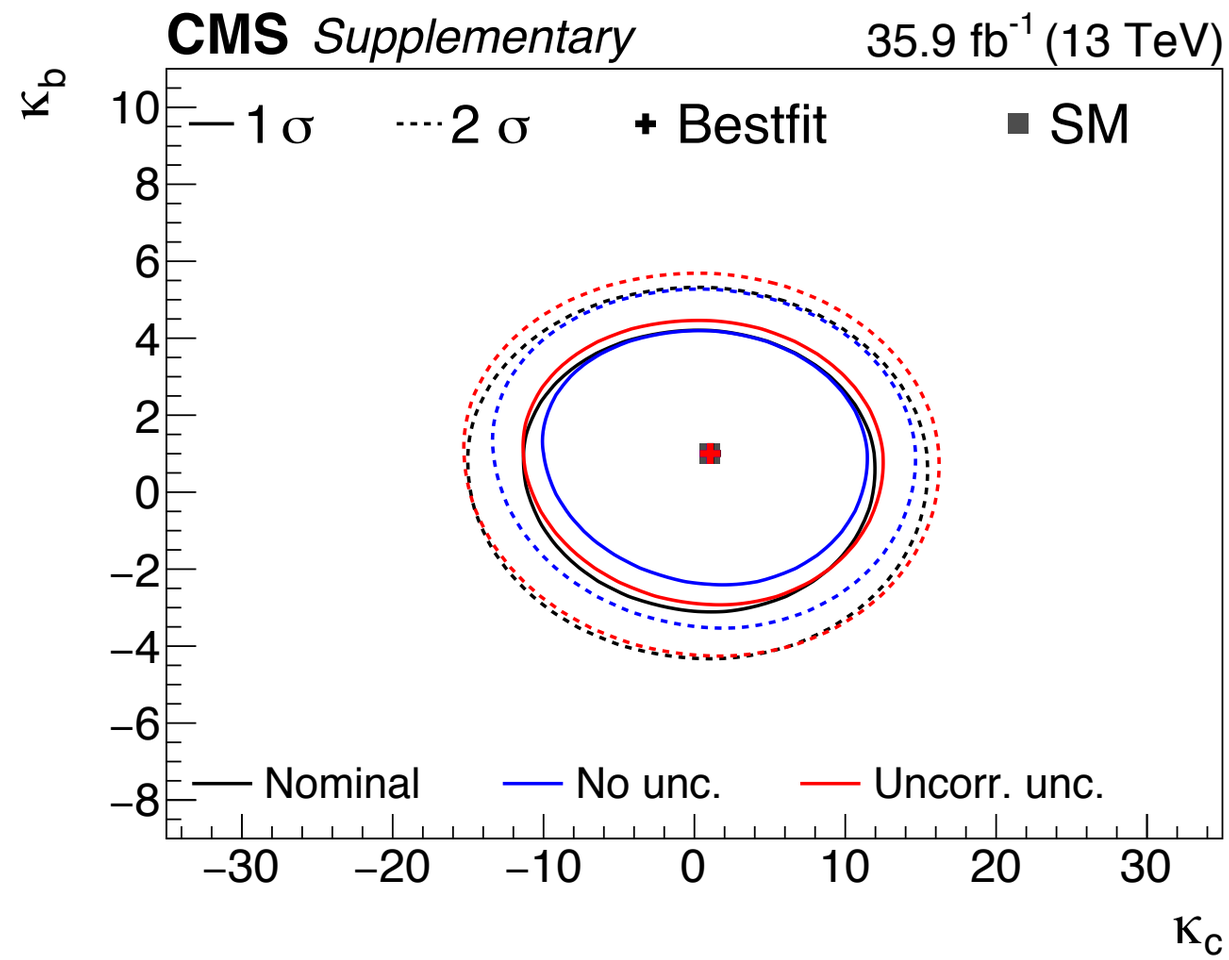
- Anti-correlated at very low pT —> Dominated by resummation
- Strongly correlated at high pT

Theory uncertainty cross check



κ_c vs. κ_b Extra studies: High lumi, theory x-check

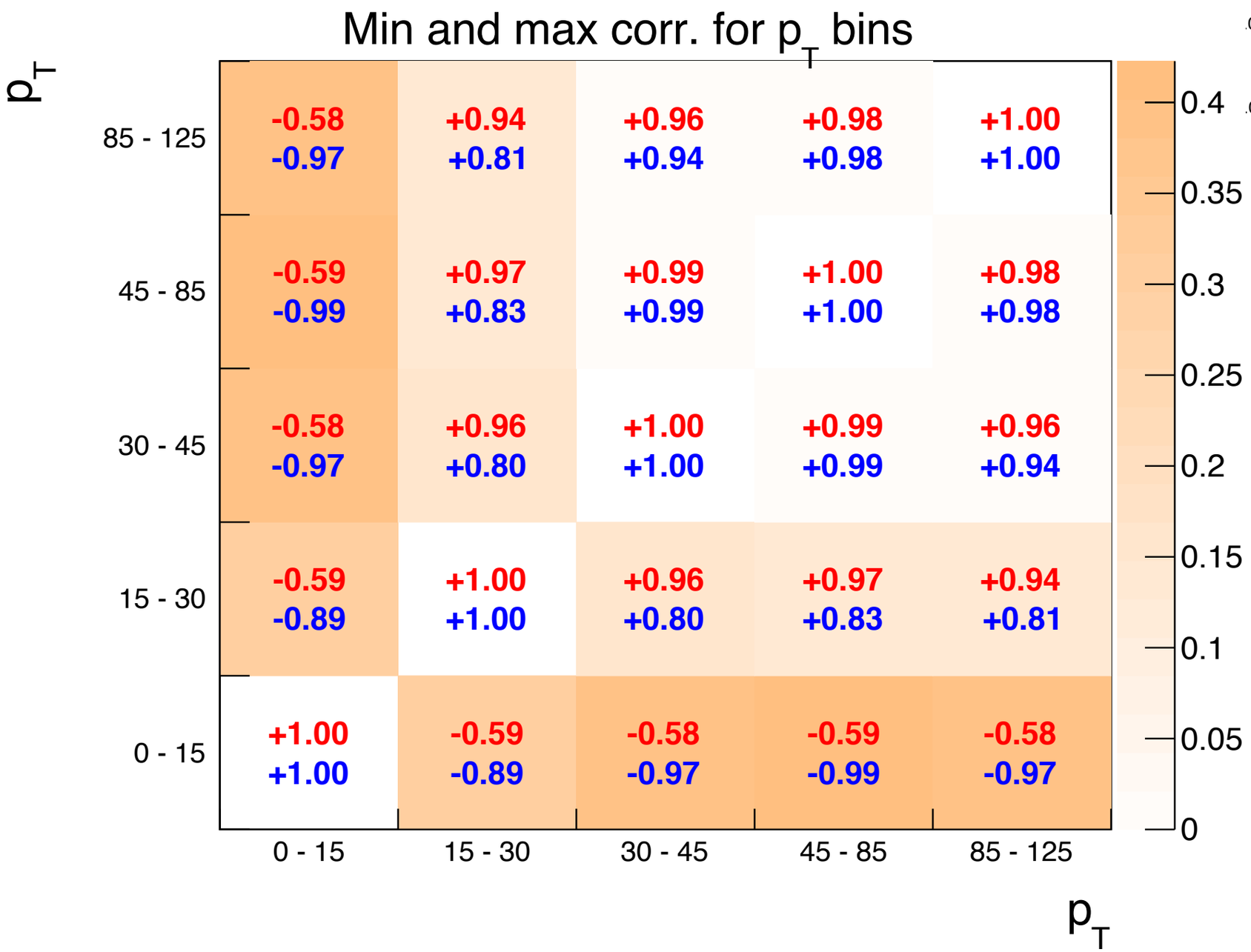


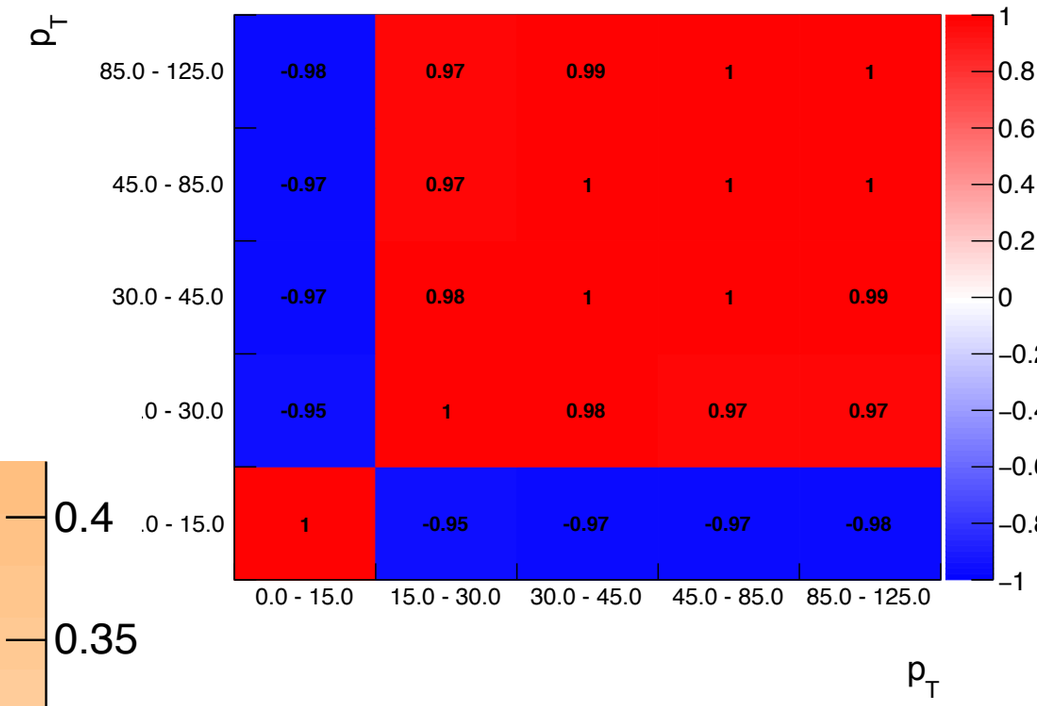


- Expected sensitivity at high luminosity
- Combination re-fitted for different correlation structures

κ_c vs. κ_b: Correlation matrix cross check

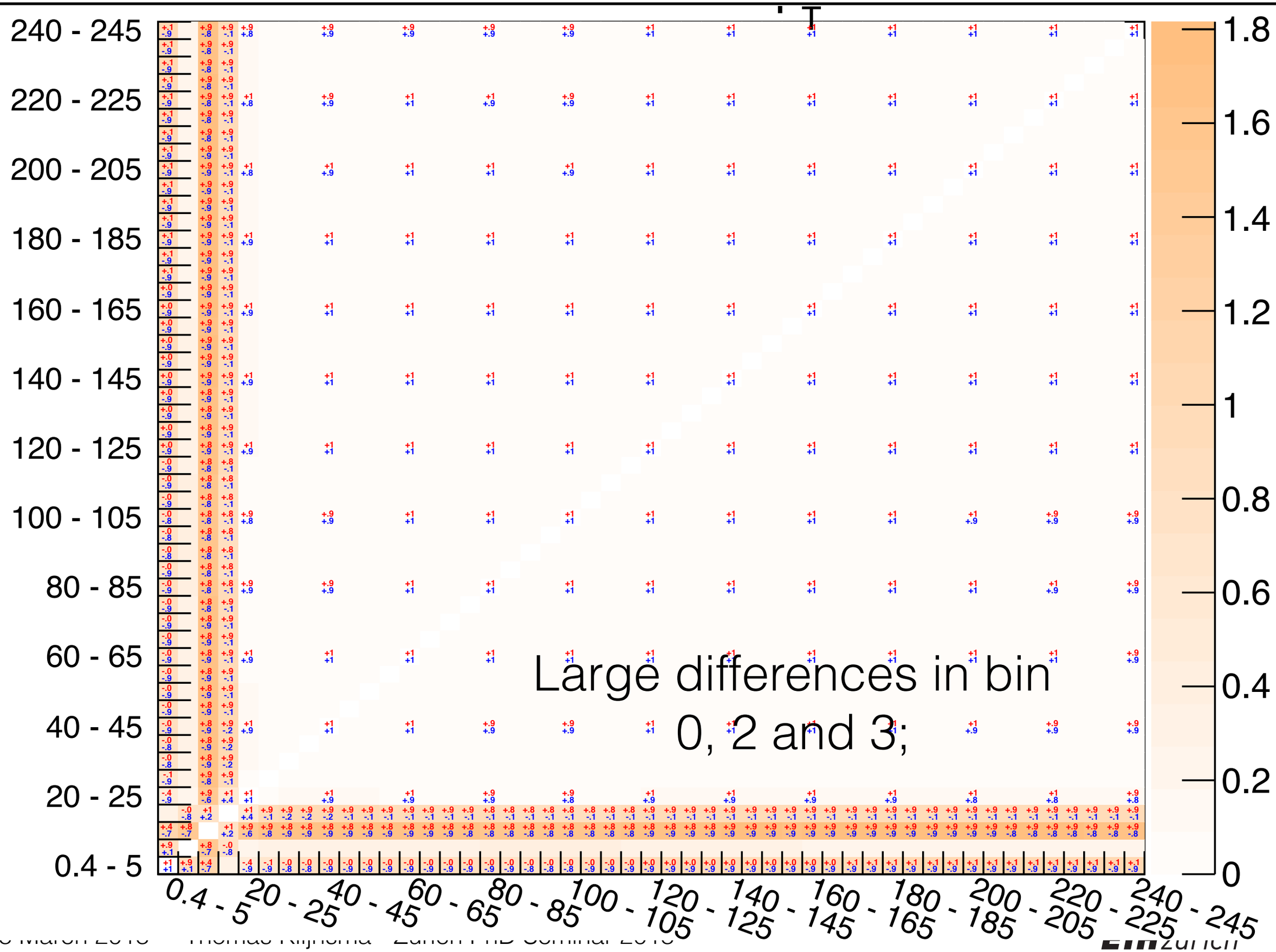
- Re-compute correlation matrix at all the available coupling variations





- Non-negligible difference in first bin
- Expected effect on the actual scan is still small

Min-max correlation matrix in theory binning

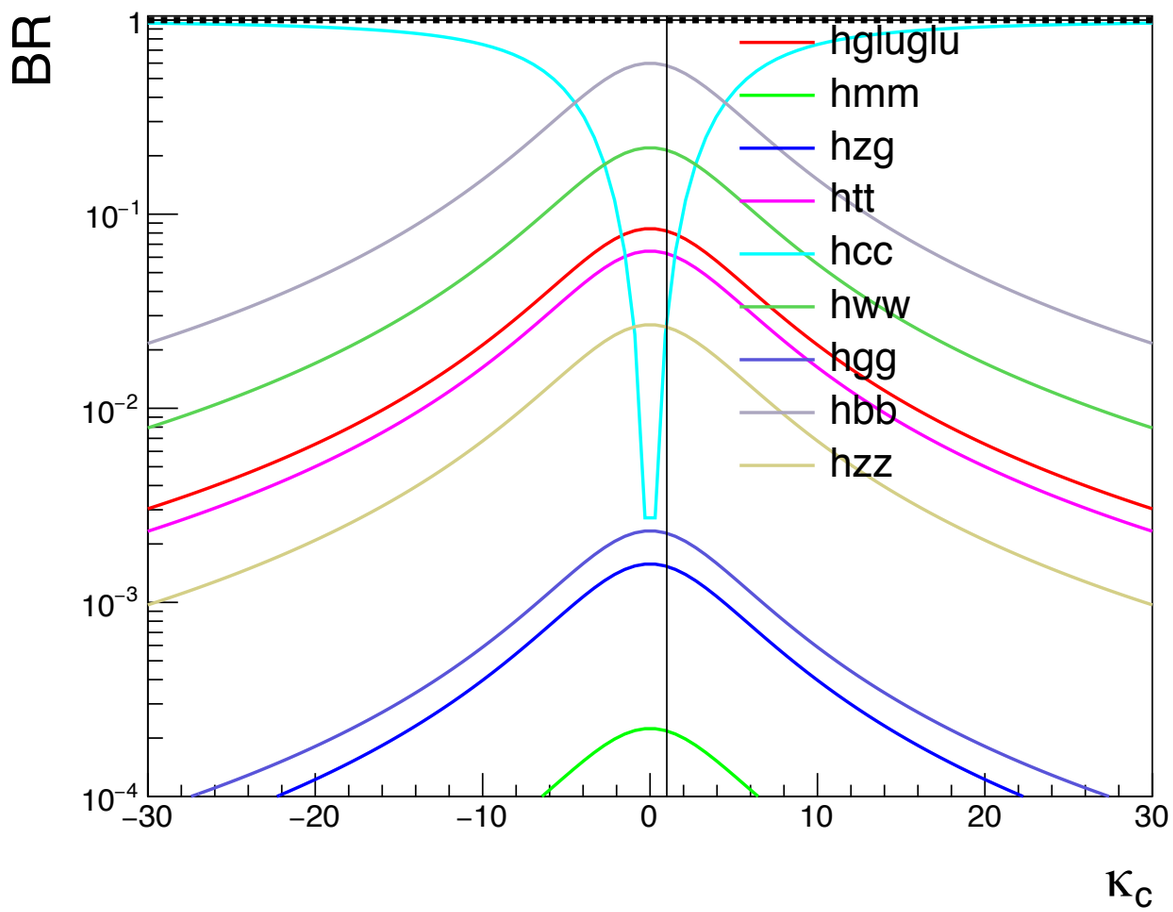


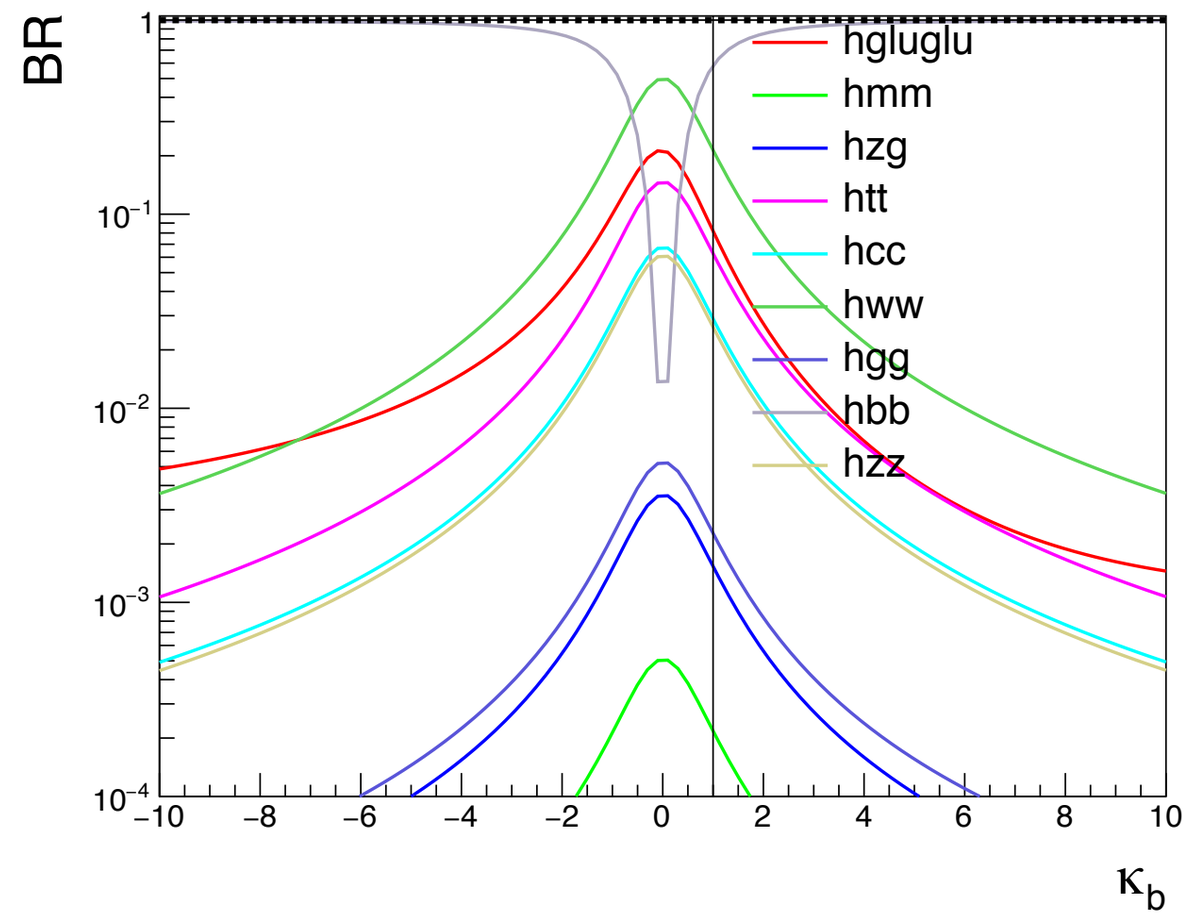
BR dependency on κ's

- Results so far assumed BRs fixed at SM

*: hww, hzz, hgg, htt, hbb, hzg, hmm, hcc, hgluglu, hss

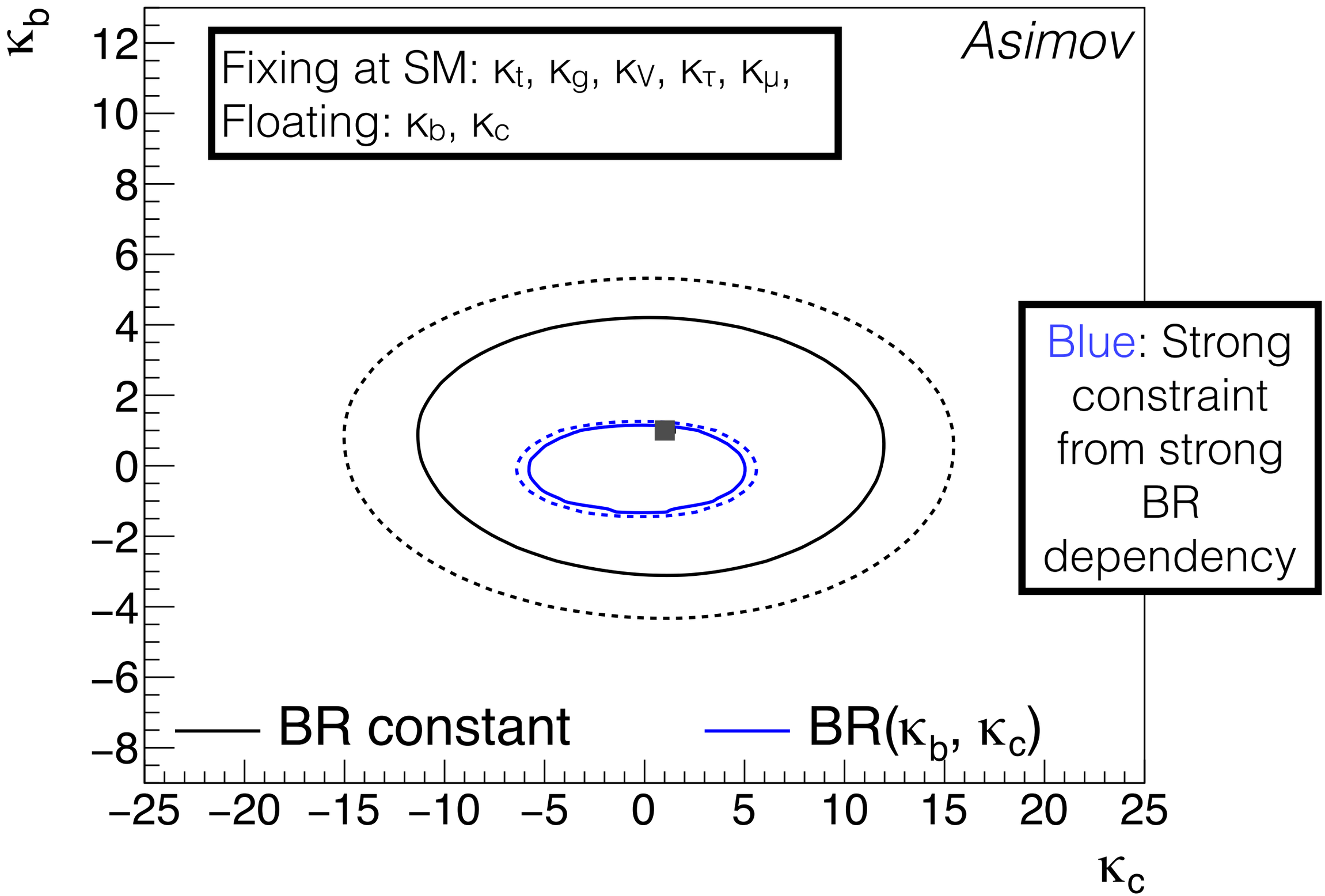
- Implemented dependency of **all Higgs decay modes*** using code from **LHCHCGModels.py**





- Relatively quickly reaching >99% H -> bb/cc

κ_c vs. κ_b: BR dependency on κ's

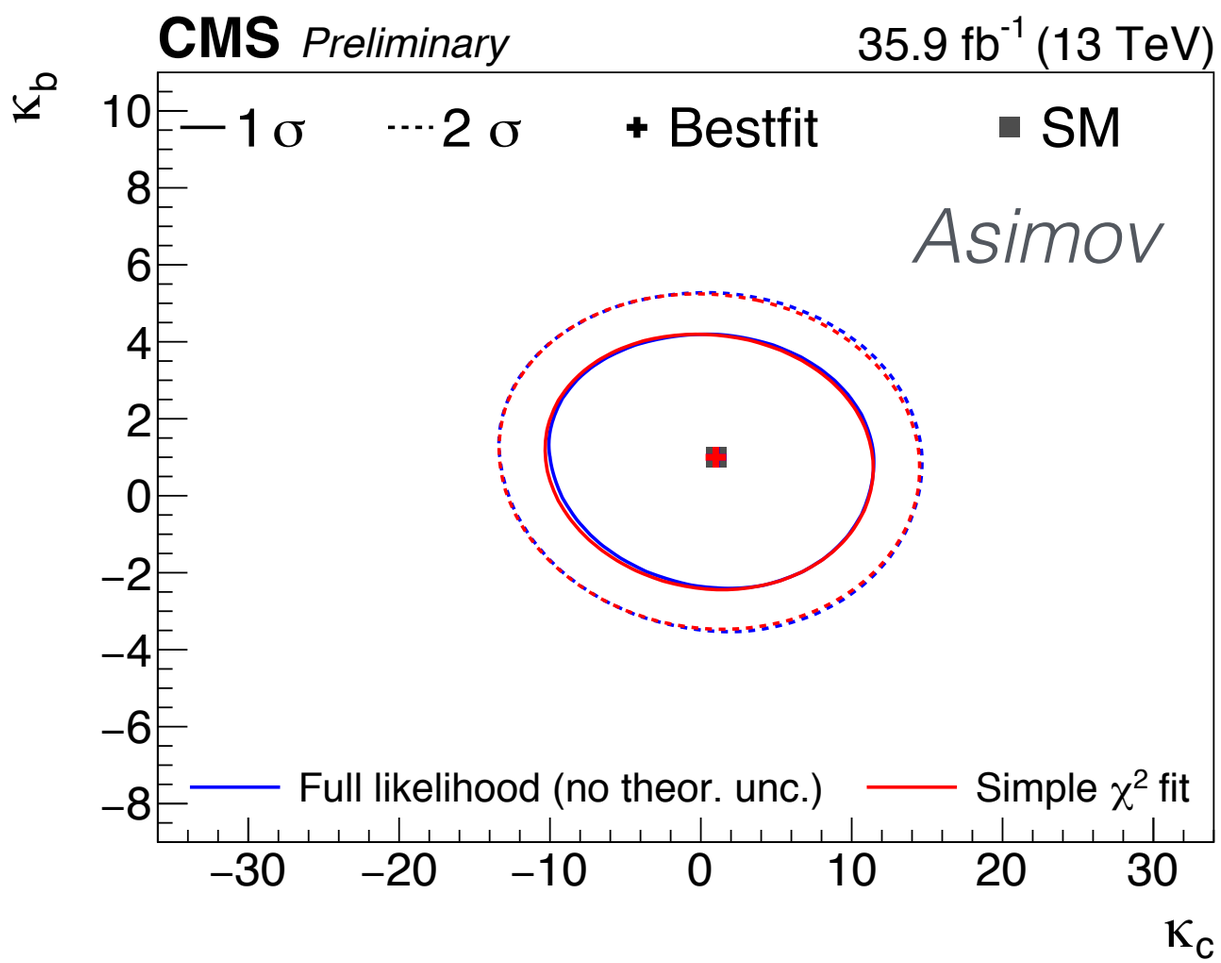


What would a theorist fit?

- Remove combine, and do a simple χ^2 fit:

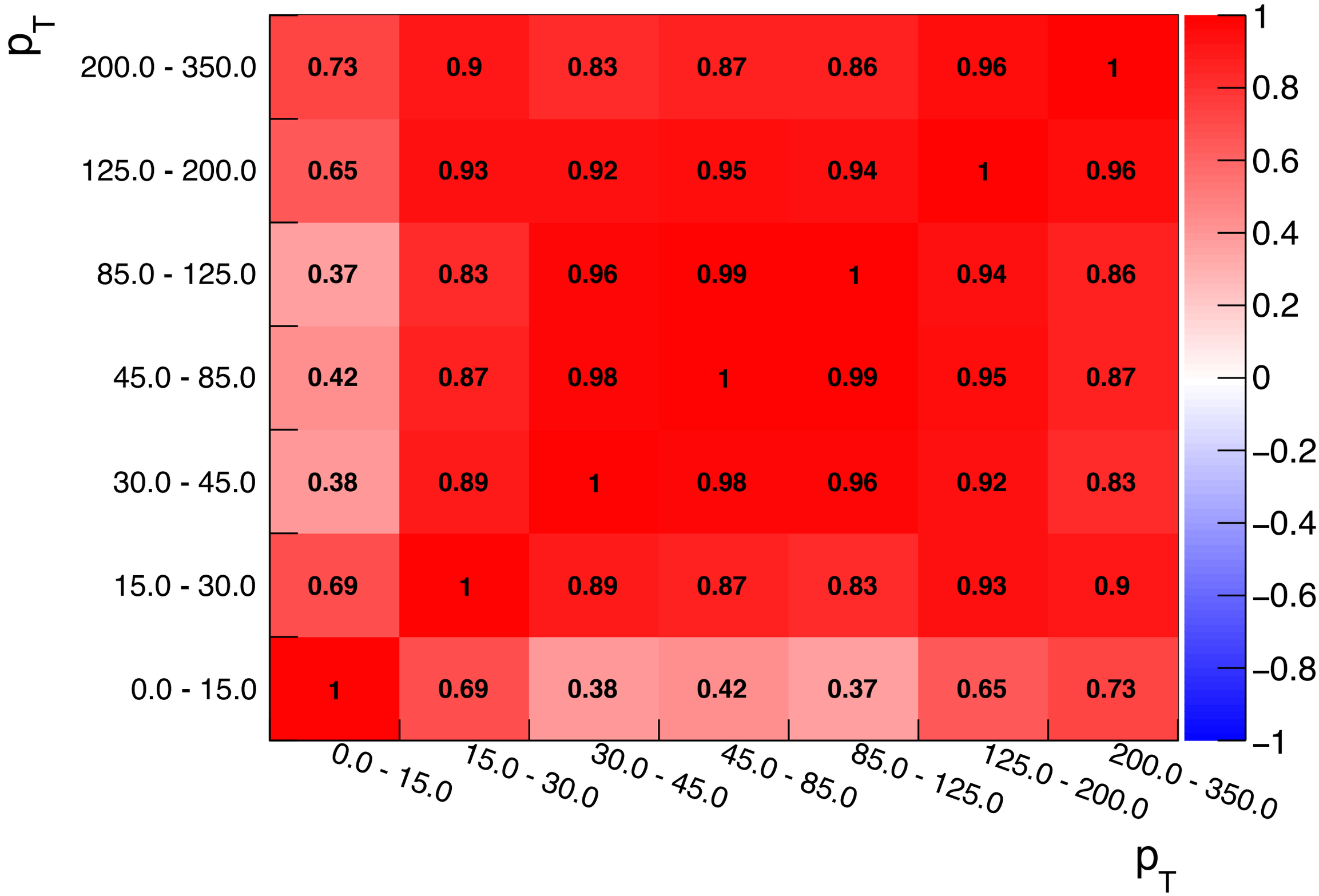
$$\chi^2 = (\vec{\mu}(\vec{\kappa}) - \vec{\mu}_{obs})^T \cdot C^{-1} \cdot (\vec{\mu}(\vec{\kappa}) - \vec{\mu}_{obs})$$

- Using the combination result *without a coupling model* (i.e. beginning of the slides) for μ_{obs} and C

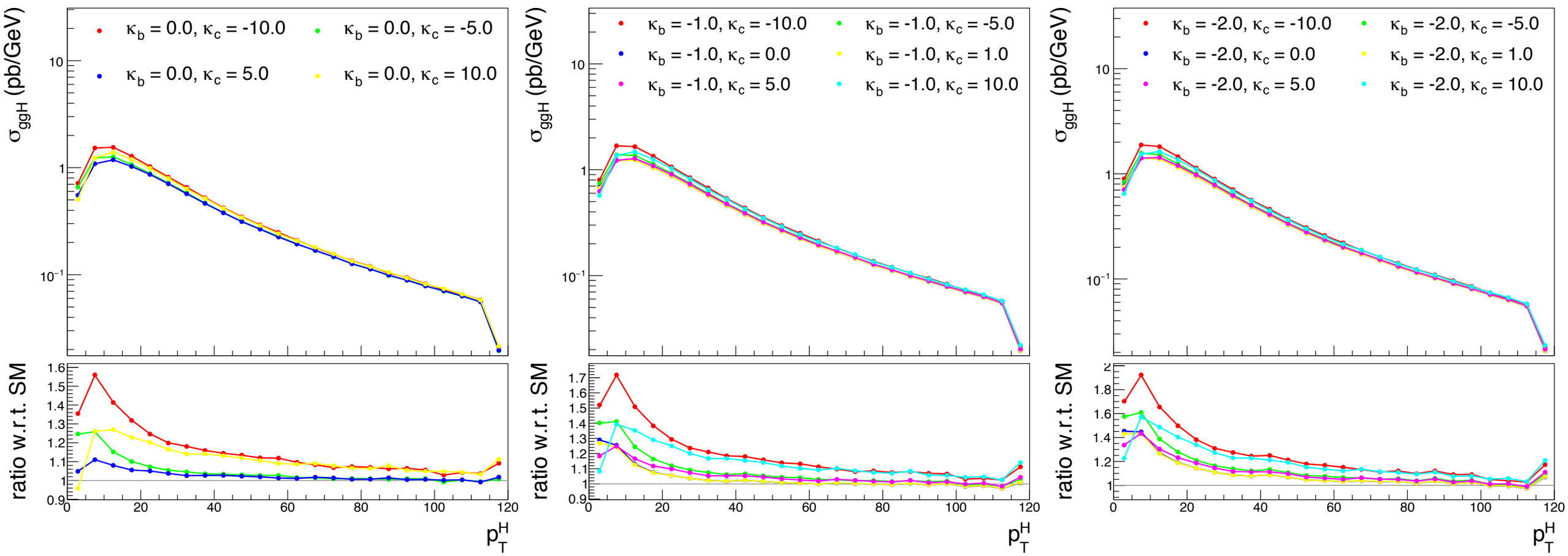


- Comparable results, slightly more constrained fit using the simple χ^2

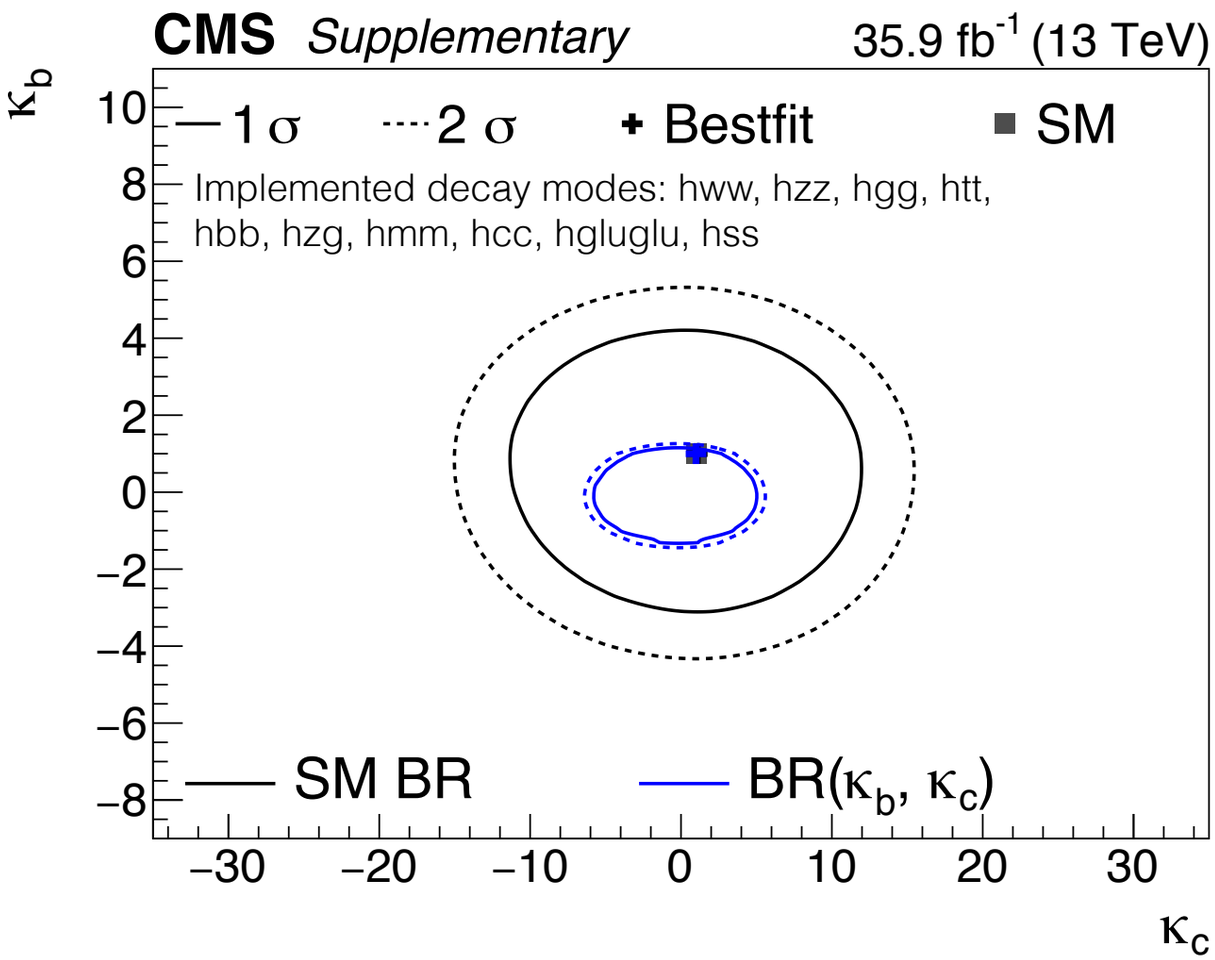
κ_t vs. κ_g: Correlation matrix

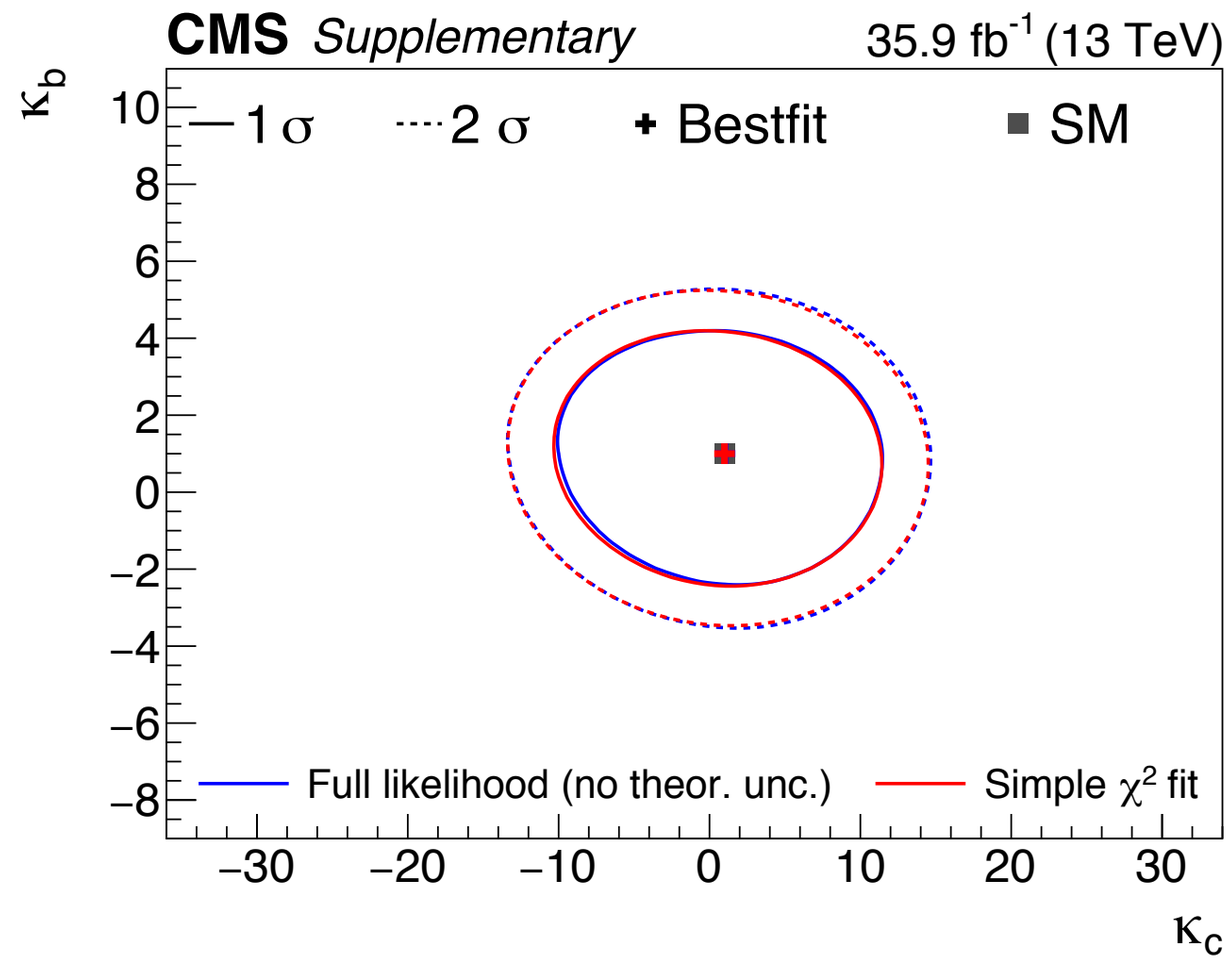


κ_c vs. κ_b: Parametrization



κ_c vs. κ_b Extra studies: scaling BRs, χ^2 fit





- Expected sensitivity when letting the BRs depend on κ_c and κ_b
  - Strong discrimination power from the full width
- Fit result when performing a χ^2 fit
  - No theory unc. implemented