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

Zurich PhD Seminar 2018

Thomas Klijnsma

8th of March 2018
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**
Introduction: Differential cross sections

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

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A Higgs coupling modifier is simply the factor with which one multiplies the SM to get the measured coupling:

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

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

**Higgs Transverse Momentum (GeV)**
Outline

Part 1: Combination of differential spectra

Part 2: Constraints on Higgs coupling modifiers

• Higgs-bottom coupling $K_b$ vs. Higgs-charm coupling $K_c$

• Top coupling modifier $K_t$ vs. gluon anomalous coupling $K_g$
Outline

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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, \( H \rightarrow WW, H \rightarrow bb, \ldots \)
  - 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:

\[
\frac{d\sigma}{dp_T^H} = \int_{p_T^H=0}^{p_T^H=125.09 \text{ GeV}} \frac{d\sigma}{dp_T^H} \, dp_T^H
\]

\[
\begin{align*}
H \rightarrow \gamma\gamma & \quad (\text{GeV}) \\
0 & \quad 50 & \quad 100 & \quad 150 & \quad 200 & \quad 250 & \quad 300 & \quad 350 & \quad 400 \\
\text{Ratio to } \text{POWHEG} & \quad 0 & \quad 0.2 & \quad 0.4 & \quad 0.6 & \quad 0.8 & \quad 1 & \quad 1.2 & \quad 1.4 & \quad 1.6 & \quad 2
\end{align*}
\]

\[
\begin{align*}
H \rightarrow ZZ & \quad (\text{GeV}) \\
0 & \quad 50 & \quad 100 & \quad 150 & \quad 200 & \quad 250 & \quad 300 & \quad 350 & \quad 400 \\
\text{Ratio to } \text{POWHEG+JHUGen} & \quad 0 & \quad 0.2 & \quad 0.4 & \quad 0.6 & \quad 0.8 & \quad 1 & \quad 1.2 & \quad 1.4 & \quad 1.6 & \quad 2
\end{align*}
\]
Combination of differential spectra

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  \( H \rightarrow WW, H \rightarrow bb, \ldots \)

• 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:

  ... and a third one for only the Higgs transverse momentum:
# Observables and their binning

- Performing combinations for **four** observables:

## $p_T^H$ (GeV)

<table>
<thead>
<tr>
<th></th>
<th>0-15</th>
<th>15-30</th>
<th>30-45</th>
<th>45-80</th>
<th>80-120</th>
<th>120-200</th>
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<tbody>
<tr>
<td>hgg</td>
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<td>hbb</td>
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## nJets

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
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<tr>
<td>hgg</td>
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## abs($y$)

<table>
<thead>
<tr>
<th></th>
<th>0.0 - 0.15</th>
<th>0.15 - 0.30</th>
<th>0.30 - 0.60</th>
<th>0.60 - 0.90</th>
<th>0.90 - 1.20</th>
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<tbody>
<tr>
<td>hgg</td>
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## $p_T^{jet}$ (GeV)

<table>
<thead>
<tr>
<th></th>
<th>&lt;30</th>
<th>30-55</th>
<th>55-95</th>
<th>95-120</th>
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# Observables and their binning

- Performing combinations for **four** observables:

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### abs(y)

- Agreement between Hgg and HZZ; To be confirmed with ATLAS

<table>
<thead>
<tr>
<th></th>
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<tbody>
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Observables and their binning

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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 \( \mu \):** \( \sigma_{\text{measured}} = \mu \cdot \sigma_{\text{SM}} \)
Fitting multiple signal strengths

- **Principle of fit**: Vary $\mu$’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.

\[ \chi^2 \text{ distributed likelihood} \]
Fitting procedure

- **combine**: Use μ’s simultaneously for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, and $H \rightarrow bb$

  \[ \chi^2 \]

  distributed likelihood

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

**CMS Preliminary**

35.9 fb\(^{-1}\) (13 TeV)

- $r_{ggH}_{PTH\_0\_15}$
- $r_{ggH}_{PTH\_15\_30}$
- $r_{ggH}_{PTH\_30\_45}$
- $r_{ggH}_{PTH\_45\_80}$
- $r_{ggH}_{PTH\_80\_120}$
- $r_{ggH}_{PTH\_120\_200}$
- $r_{ggH}_{PTH\_200\_350}$
- $r_{ggH}_{PTH\_350\_600}$
- $r_{ggH\_PTH\_GT600}$

8 March 2018 - Thomas Klijnsma - Zurich PhD Seminar 2018
**Uncertainty reduction w.r.t. $H \rightarrow \gamma\gamma$ only**

<table>
<thead>
<tr>
<th>$p_T^{H_{ggF}}$ (GeV)</th>
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<th>15-30</th>
<th>30-45</th>
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<th>80-120</th>
<th>120-200</th>
<th>200-350</th>
<th>350-600</th>
</tr>
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<tbody>
<tr>
<td>25.6%</td>
<td>21.0%</td>
<td>8.4%</td>
<td>10.8%</td>
<td>10.8%</td>
<td>5.0%</td>
<td>6.6%</td>
<td>7.1%</td>
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</tbody>
</table>

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

Jet:
• $|\eta| < 2.5$
• $p_T > 30$ GeV

Uncertainty reduction w.r.t. $H \rightarrow \gamma\gamma$ only

26.9%  24.4%  23.3%  13.3%  1.2%
$|y_H|$, $p_T^{\text{jet}}$

**CMS**

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

<table>
<thead>
<tr>
<th>$H \rightarrow \gamma \gamma$</th>
<th>$H \rightarrow ZZ$</th>
<th>Combination</th>
<th>SM</th>
</tr>
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$\Delta \sigma / \Delta p_T^{\text{jet}}$ (pb)

$\int \sigma(p_T^{\text{jet}}) \, dp_T^{\text{jet}} / 40$

$\int \sigma(p_T^{\text{jet}}) \, dp_T^{\text{jet}} / 80$

$\mu$

$p_T^{\text{jet}}$

$|y_H|$

$\int \sigma(|y_H|) \, dy_H / 0.30$

$\int \sigma(|y_H|) \, dy_H / 0.30$

$\mu$

$|y_H|$
Fitting total XS

- Essentially a fit with one global scale to the data categories (not binned in any observable)

\[ \mu = \frac{\sigma}{\sigma_{SM}} \]
**Fitting total XS**

**CMS Preliminary**

35.9 fb\(^{-1}\) (13 TeV)

\[ \sigma_{\text{tot}} = 61.1 \pm 6.0 \text{ (stat.)} \pm 3.7 \text{ (syst.)} \text{ pb} \]
Outline

Part 1: Combination of differential spectra

Part 2: Constraints on Higgs coupling modifiers

- Higgs-bottom coupling $K_b$ vs. Higgs-charm coupling $K_c$
- Top coupling modifier $K_t$ vs. gluon anomalous coupling $K_g$
Fitting couplings

- Obtain 2D likelihood by varying $k_c$ and $k_b$

- The contributions from $xH$ (i.e. not $ggH$) are set to SM
Fitting couplings

- Obtain 2D likelihood by varying $\kappa_c$ and $\kappa_b$

- The contributions from $xH$ (i.e. not $ggH$) are set to SM
Fitting couplings

- Obtain 2D likelihood by varying $\kappa_c$ and $\kappa_b$
- 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
pT spectrum for ggH only shows shape distortion when modifying $k_c$ and $k_b$

- Spectra given by the theorists
- Instead of fitting freely floating $\mu$'s (as in the pT combination), now fitting $\mu(k_c, k_b)$
κ_c vs. κ_b: Nominal fit result (combination only)

CMS Preliminary

35.9 fb^{-1} (13 TeV)

σ

SM

Bestfit

Preliminary CMS (13 TeV) -1

σ

2

0

35.9 fb^{-1} (13 TeV)

0

1

2

3

4

5

6

7

κ_c

κ_b
$\kappa_C$ vs. $\kappa_b$: Nominal fit result

CMS Preliminary

35.9 fb$^{-1}$ (13 TeV)

Combination $\gamma\gamma \rightarrow H$ $\rightarrow ZZ$

$H\rightarrow\gamma\gamma$  $H\rightarrow ZZ$

-1 $\sigma$  -2 $\sigma$ SM  Bestfit
κ_C vs. κ_b: Visualisation of fits

CMS Preliminary

35.9 fb^{-1} (13 TeV)

(The colors of the lines match with the colors of the diamonds)
\( \kappa_c \) vs. \( \kappa_b \): 1D scans

- Scan over 1 coupling, while profiling the other

---

**CMS Preliminary**

\( 35.9 \text{ fb}^{-1} \) (13 TeV)

\( \kappa_b \) expected; (-2.07 - 3.50) @ 68\% CL

\( \kappa_c \) expected; (-8.30, 9.91) @ 68\% CL

---

8 March 2018 - Thomas Klijnsma - Zurich PhD Seminar 2018
• Consider the following modifications to the SM Lagrangian:

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

• 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:

![Diagram showing Higgs transverse-momentum spectrum in the SM compared to variations with different SMEFT operators.](image)
$\kappa_t$ vs. $\kappa_g$: Parametrization

- Note **strong distortions** in the tail
- Coupling sensitivity very strong at high $p_T$
- Here $H \rightarrow b\bar{b}$ helps a lot
$\kappa_t$ vs. $\kappa_g$: Nominal fit result (combination only)

CMS Preliminary

35.9 fb$^{-1}$ (13 TeV)

Preliminary CMS (13 TeV)

$\sigma_1$ $\sigma_2$ SM Bestfit

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$\kappa_t$ vs. $\kappa_g$: Nominal fit result (combination only)

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

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

is symmetric under

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

Exactly mirrored
$\kappa_t$ vs. $\kappa_g$: Nominal fit result (combination only)

CMS $\sqrt{s}$

35.9 fb$^{-1}$ (13 TeV)

From shape

From normalization

From normalization

0.3

0.2

0.1

0.1

0

-0.1

-0.2

-0.3

-5

-4

-3

-2

-1

0

1

2

3

4

5

$\kappa_t$

$\kappa_g$

$\sigma$
$\kappa_t$ vs. $\kappa_g$: Only normalization (combination only)

- Fits only the **integral** of the spectrum ($\kappa_t, \kappa_g$) to the total observed cross section
$\kappa_t$ vs. $\kappa_g$: Visualisation of fits

CMS Preliminary

35.9 fb$^{-1}$ (13 TeV)

- Strong sensitivity is offset by huge statistical uncertainties
- This becomes more promising at higher luminosity
$k_t$ vs. $k_g$: Nominal fit result

CMS Preliminary

35.9 fb$^{-1}$ (13 TeV)

$C_g$ vs. $k_t$

$1\sigma$, $2\sigma$, SM, Bestfit

H$\rightarrow\gamma\gamma$, Combination, Comb. with H$\rightarrow$bb
$\kappa_b$ vs. $\kappa_t$: Fit results

- Parametrization

- Nominal fit result
$\kappa_b$ vs. $\kappa_t$: Visualisation of fits

CMS

<table>
<thead>
<tr>
<th>$\kappa_t$</th>
<th>$\kappa_b$</th>
<th>0.4</th>
<th>10.5</th>
<th>2.1</th>
<th>-4.0</th>
<th>11.2</th>
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<tr>
<td>1.0</td>
<td>0.8</td>
<td>0.85</td>
<td>1.0</td>
<td>1.1</td>
<td>0.9</td>
<td>0.8</td>
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35.9 fb$^{-1}$ (13 TeV)

$\mu$
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 $\kappa_b$ vs. $\kappa_c$, $\kappa_t$ vs. $\kappa_g$ and $\kappa_b$ vs. $\kappa_t$

• Obtained constraints on couplings indicate competitiveness with direct probes of Higgs couplings, in particular $\kappa_c$
Back up
Parametrization

- Described for $\kappa_b/\kappa_c$ variations, but same method used for other coupling variations
Parametrization

• Described for $\kappa_b/\kappa_c$ variations, but same method used for other coupling variations

• Assume cross section is parabolic function of couplings:

$$\sigma_{ggH} = \left| \sum_i A_i \cdot \kappa_i \right|^2 = A\kappa_b^2 + B\kappa_c^2 + C\kappa_t^2 + D\kappa_b\kappa_c + E\kappa_b\kappa_t + F\kappa_c\kappa_t$$
Parametrization

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- Can find the cross section for any set of $\kappa$’s if we know the coefficients $A$, …, $F$
Parametrization

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\[
\sigma_{ggH} = \left| \sum_i A_i \cdot \kappa_i \right|^2 = A\kappa_b^2 + B\kappa_c^2 + C\kappa_t^2 + D\kappa_b\kappa_c + E\kappa_b\kappa_t + F\kappa_c\kappa_t
\]

- Can find the cross section for any set of $\kappa$'s if we know the coefficients $A$, ..., $F$

- Use 6 known points: $\sigma_1(\vec{\kappa}_1), \sigma_2(\vec{\kappa}_2), \sigma_3(\vec{\kappa}_3), \sigma_4(\vec{\kappa}_4), \sigma_5(\vec{\kappa}_5), \sigma_6(\vec{\kappa}_6)$
Parametrization

- Described for $\kappa_b/\kappa_c$ variations, but same method used for other coupling variations

- Assume cross section is parabolic function of couplings:

$$\sigma_{ggH} = \left| \sum_i A_i \cdot \kappa_i \right|^2 = A\kappa_b^2 + B\kappa_c^2 + C\kappa_t^2 + D\kappa_b\kappa_c + E\kappa_b\kappa_t + F\kappa_c\kappa_t$$

- Can find the cross section for any set of $\kappa$’s if we know the coefficients $A$, ..., $F$

- Use 6 known points: $\sigma_1(\vec{\kappa}_1)$, $\sigma_2(\vec{\kappa}_2)$, $\sigma_3(\vec{\kappa}_3)$, $\sigma_4(\vec{\kappa}_4)$, $\sigma_5(\vec{\kappa}_5)$, $\sigma_6(\vec{\kappa}_6)$
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
- \( \kappa_t \) set to 1.0 (SM) for the \( \kappa_c \) vs. \( \kappa_b \) analysis

8 March 2018 - Thomas Klijnsma - Zurich PhD Seminar 2018
\( \kappa_c \) vs. \( \kappa_b \): 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 scale variations
  
  • \(( \mu_R, \mu_F ) = ( 0.5, 0.5 ), ( 0.5, 1 ), ( 1, 0.5 ), ( 1, 1 ), ( 1, 2 ), ( 2, 1 ), (2, 2)\)

• Cross check with uncorrelated and no theory uncertainties is performed

• Bin-to-bin correlations are notoriously difficult to calculate theoretically

• Stewart-Tackmann is inappropriate for \( p_T \)
Theory uncertainties

- Anti-correlated at very low $p_T$ —> Dominated by resummation
- Strongly correlated at high $p_T$
Theoretical uncertainty cross check

CMS Preliminary

35.9 fb⁻¹ (13 TeV)

$\kappa_b$

- Nominal
- No unc.
- Uncorr. unc.

$\kappa_c$

Best fit

SM

-1σ
-2σ
\( \kappa_c \) vs. \( \kappa_b \) 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

Large differences in bin 0, 2 and 3.
BR dependency on $\kappa$’s

- Results so far assumed BRs fixed at SM

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

- Relatively quickly reaching >99% $H \rightarrow bb/cc$

*: hww, hzz, hgg, htt, hbb, hzg, hmm, hcc, hgluglu, hss
\( \kappa_c \ vs. \ \kappa_b: \) BR dependency on \( \kappa \)'s

Fixing at SM: \( \kappa_t, \kappa_g, \kappa_V, \kappa_\tau, \kappa_\mu, \)
Floating: \( \kappa_b, \kappa_c \)

Blue: Strong constraint from strong BR dependency

Asimov
What would a theorist fit?

- Remove combine, and do a simple \( \chi^2 \) fit:

\[
\chi^2 = (\bar{\mu}(\kappa) - \bar{\mu}_{obs})^T \cdot C^{-1} \cdot (\bar{\mu}(\kappa) - \bar{\mu}_{obs})
\]

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

- Comparable results, slightly more constrained fit using the simple \( \chi^2 \)
$\kappa_t$ vs. $\kappa_g$: Correlation matrix
κ_c vs. κ_b: Parametrization
$\kappa_c$ vs. $\kappa_b$ Extra studies: scaling BRs, $\chi^2$ fit

- Expected sensitivity when letting the BRs depend on $\kappa_c$ and $\kappa_b$
  - Strong discrimination power from the full width

- Fit result when performing a $\chi^2$ fit
  - No theory unc. implemented