High energy probes and EFT at HE/HL LHC

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On behalf of the ATLAS and CMS collaborations
Introduction

- **Precision era**: Looking for modifications of the standard model
  - Which manifest not per se in **total yields**, but rather in distortions of **(differential) spectra**, or in **tails**
- **EFT**: Adding operators to the SM Lagrangian
  - Dim 6 example: affects **differential Higgs cross sections**
  - Dim 8 example: affects **anomalous quartic gauge coupling** \((aQGC)\) in **VBS**
Outline

- Differential cross sections
  - Attainable uncertainties on spectra at HL-LHC
  - Interpretations in terms of Higgs coupling modifiers
- VBF/VBS
  - EFT for VBS
  - Summary of results & projections
Introduction: Differential cross sections

• What is so interesting about the **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

\[ y_f = \kappa_f \cdot y_f^{SM} \]
Introduction: Differential cross sections

- Transverse momentum $p_T^H$
  - Sensitivity to modifications of effective Higgs Yukawa couplings at low $p_T$
  - Sensitivity to finite top mass effects at high $p_T$

$$y_f = \kappa_f \cdot y_f^{SM}$$
Introduction: Differential cross sections

- **Jet multiplicity** $N_{\text{jets}}$ & $p_T$ of the first jet $p_{T,\text{jet}1}$
  - New physics in the loop, sensitivity at high $p_T$

- **Rapidity** $|y^{\text{H}}|$
  - Theory distribution mostly determined by the gluon PDF; possible test

Banfi, Martin, Sanz (2014) [1308.4771]
The current state

- Primary measurements of differential cross sections from **H to 2 photons** and **H to 4 leptons**

- Current state for **13 TeV**:

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
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</thead>
<tbody>
<tr>
<td><strong>H→γγ</strong></td>
<td>$p_T^H$, $N_{jets}$, $p_T^{jet1}$, $</td>
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<td><strong>H→ZZ</strong></td>
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<td></td>
<td>[1712.02304]</td>
<td>[JHEP 1711 (2017) 047]</td>
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<tr>
<td><strong>Combination</strong></td>
<td>[ATLAS-CONF-2018-002]</td>
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$p_T^H$ : ATLAS

- Fleshed out combination from ATLAS
- Particular improvement in the low $p_T$ region
- 20%-40% uncertainties, mostly statistically dominated
\( p_T^H \): Projections from ATLAS

- \( \sim 5\% \) uncertainties for \( H \to \gamma\gamma \), between 5-10\% for \( H \to ZZ \)

- For \( H \to \gamma\gamma \), Improvement by a factor of \( \sim 8-9 \), really close to \( \sqrt{3000/36} \approx 9 \) (scaling only stat., assuming same syst.)

- \(<5\%\) uncertainty achievable with a combination
Proper combination ongoing, but we can make an attempt:

- Assume no correlations, and no bin-to-bin migrations
$p_T^H$: CMS

**DISCLAIMER: NOT A PROPER COMBINATION; BALLPARK ESTIMATE**

- Doing a very basic combination
- No bin-to-bin correlations/migrations
- Simple $\chi^2$ fit (entries weighted by uncertainty)
- This is **not** a proper combination and **not** a CMS result
- This study indicates a similar pattern to ATLAS: 20-30% statistically dominated uncertainties

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

Private study; not a CMS/ATLAS result
$p_T^H$: Projections from CMS

- Projection available for $H \rightarrow ZZ$
- 5-10% uncertainties, comparable to ATLAS $H \rightarrow ZZ$
$p_T^H$: Projections from CMS

- No proper projection for the **combination** yet, but simply scaling observed uncertainties by $\sqrt{35.9/3000}$

- Moved central values to SM expectation

- Yields $\sim 3\%$ uncertainties (a bit by construction of course), comparable to the ATLAS projections

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Private study; not a CMS/ATLAS result
Remarks on $p_{T}^{H}$

- Uncertainties of the **order of a few percent** seem achievable for HL-LHC, with $\mathcal{O}(10)$ bins up to $p_T$ 350 GeV

- Currently, uncertainties are very **statistically dominated**
  - Differentials are not hit as hard by the ‘systematics wall’
  - Good motivation to combine results from both experiments

- Possibility to improve further by including more decay channels in the combination: $H \rightarrow WW$, $VH \rightarrow bb$ (planned by ATLAS), (boosted) $H \rightarrow bb$, etc.
**Couplings: $k_t$ vs. $c_g$**

- $p_T$ spectrum can be used to fit $k_t$ **VS.** $c_g$

- Modify Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\alpha_S}{\pi v} c_g h G_{\mu\nu}^a G^{a,\mu\nu} \quad (\text{dim}-6)$$

$(k_t = 1, c_g = 0) \sim \text{SM}$,

$(k_t = 0, c_g = \sim 1/12) \sim \text{point-like coupling of the Higgs to gluons}$
Couplings: $k_t$ vs. $c_g$

- $p_T$ spectrum can be used to fit $k_t$ vs. $c_g$

- Modify Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\alpha_s}{\pi v} c_g h G^{\alpha}_{\mu\nu} G^{\alpha,\mu\nu}$$

$(k_t = 1, c_g = 0) \sim SM$,

$(k_t = 0, c_g = 0.007) \sim$ point-like coupling of the Higgs to gluons

---

**Figure 1**: Higgs transverse-momentum spectrum in the SM (black, solid) compared to (a) separate variations and (b) mixed contribution of the dimension-six operator for 0 GeV. The spectra presented in Figure 1 (b) correspond to switching on all three SMEFT operators. We choose $c_t = 0$, $c_b = 1$, $c_g = 0$ for SM and $c_t = 1.2$, $c_b = -2.98$, $c_g = -0.04$ to $c_t = 1.5$, $c_b = -1.8$, $c_g = 0$ to fit the Higgs to gluons due to scale variations in NLL+NLO and NNLL+NNLO case respectively. See text for more details.
Couplings: $k_t$ vs. $c_g$

- $p_T$ spectrum can be used to fit $k_t$ **VS.** $c_g$

- Modify Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\alpha_S}{\pi \nu} c_g h G_{\mu\nu}^a G^{a,\mu\nu}$$

($k_t = 1$, $c_g = 0$) $\sim$ SM,

($k_t = 0$, $c_g = 0.007$) $\sim$ point-like coupling of the Higgs to gluons
**Couplings: \( k_T \) vs. \( c_g \)**

- \( p_T \) spectrum can be used to fit \( k_T \) VS. \( c_g \)
  - Modify Lagrangian:
    \[
    \mathcal{L} = \mathcal{L}_{SM} + \frac{\alpha_S}{\pi \nu} c_g h G^{a}_{\mu\nu} G^{a,\mu\nu}
    \]

---

**Graphs:**

- **Top Panel:**
  - Comparison of Higgs transverse-momentum spectrum in the SM (black, solid) compared to (a) separate variations and (b) mixed contribution of the dimension-six operator for 0 GeV.
  - The spectra presented in Figure 1 (b) correspond to switching on all three SMEFT operators. We choose different SMEFT operators to study possible (small) deviations from the SM predictions.

- **Bottom Panel:**
  - CMS 35.9 fb\(^{-1}\) and CMS 3000 fb\(^{-1}\) data points compared to ATLAS 36.1 fb\(^{-1}\) and ATLAS 3000 fb\(^{-1}\) data points.
  - The shaded lighter and darker grey bands in the ratio indicate the uncertainty in the NNLL+NNLO case, which allows for a better discrimination between different regions of the Higgs transverse momentum distribution.

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**Additional Notes:**

- If New Physics will not be accessible at the LHC through direct searches, e.g., with the discovery of new resonances, it will be crucial to fully exploit the data to study possible (small) deviations from the SM predictions.
- The formalism for fitting the data will involve studying possible deviations from the SM predictions through appropriate higher-order corrections.
- For more discussion on the SMEFT operators impact on the spectra, refer to [1].
**Couplings: $\kappa_t$ vs. $c_g$**

- $p_T$ spectrum can be used to fit $\kappa_t$ VS. $c_g$
- Modify Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\alpha_S}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu}$$

**Figure 1:** Higgs transverse-momentum spectrum in the SM (black, solid) compared to (a) separate variations and (b) mixed contribution of the dimension-six operator for 0 GeV. The shaded lighter and darker grey bands in the ratio indicates the uncertainty with respect to the SM prediction. The limit, with just approximate inclusion of top mass, is shown.

Finally we mention the limitation of our study. The NNLL+NNLO SM predictions are known only in the heavy top limit, with just approximate inclusion of top mass. It will be crucial to fully exploit the data to study possible (small) deviations from the SM predictions. The formalism allows for a better discrimination between different scenarios with increased top-quark Yukawa coupling (up to $\kappa_t^5$), as hinted by the excess on the ATLAS limit, with just approximate inclusion of top mass. For more discussion on the SMEFT operators impact on the spectra refer to [1].

In this plot, missing strong discrimination power from $>400$ GeV.
VBS / VBF
The necessity to include all vector-boson scattering diagrams for $V_1 V_2 \to V_3 V_4$ in order to obtain EVBA predictions for the production of a vector-boson pair $V_3 V_4$, not necessarily near a Higgs boson resonance, was first mentioned in @9# and @11#. The possible diagrams for these processes, $q_1 q_2 \to q_1 q_8 V_3 V_4$, where $q_i, q_i^8$ are quarks, are shown in Fig. 2.

It was further pointed out that the yield of $V_3 V_4$ pairs from $q_1 q_2 \to q_1 q_8 V_3 V_4$ must be discussed together with the yield from the direct reaction $q_1 q_2 \to V_3 V_4$ unless a suitable analysis of the different proton remnants from the two production mechanisms allows one to separate the different production mechanisms.

In first applications to vector-boson scattering, again only the contribution from the longitudinal intermediate states was considered while the contribution from transverse states was neglected. This contribution was taken to be small against the $q_1 q_2 \to V_3 V_4$ contribution while the contribution from $V_1, L V_2, L \to V_3 V_4$ could be large if the longitudinal vector bosons interact strongly. The interest in the strongly interacting scenario @12# was the original motivation to use the EVBA.

The EVBA has been used for vector-boson scattering in @2#, @13–17#. In @14#, the EVBA was used only for the longitudinal intermediate states. The transverse states were taken into account by a complete perturbative calculation to lowest order in the coupling of the process $q_1 q_2 \to q_1 q_8 V_3 V_4$. This calculation requires the evaluation of more diagrams than only the vector-boson scattering diagrams, as indicated in Fig. 3. To be precise, in @14# the EVBA was used only to calculate the difference between the cross sections in a strongly interacting model and in the standard model with a light Higgs boson. This difference shows an interesting behavior in a strongly interacting scenario and was therefore considered as a potential signal for strongly interacting vector bosons. The difference receives a contribution virtually only from the longitudinal states. It was found @14# that this calculation agrees with a complete perturbative calculation to about 10% evidenced for $W_6 Z$ and $W_6 W_6$ production if the standard model with a heavy Higgs boson is taken as the strongly interacting model. I note that for strong scattering a method has been recently described which does not make use of the EVBA @18#.

In @13,16,17# the application of the EVBA was extended to the contributions from all intermediate polarization states. It was known, however, that the EVBA can overestimate results of complete perturbative calculations by a factor of 3 if the transverse helicities are important @19,20#. Other comparisons of results of complete calculations for $pp \to V_3 V_4 X$ with EVBA results @21,22# showed that the EVBA is always a good approximation on the Higgs boson.

FIG. 2. The diagram for $q_1 q_2 \to q_1 q_8 V_3 V_4$ in the effective vector-boson approximation and the diagrams for vector-boson scattering.
Without the Higgs (or some other NP), cross sections diverge

- Not sure if Higgs is solely responsible
- Explore high energy, see if Higgs preserves unitarity at all energies
Without the Higgs (or some other NP), cross sections diverge

- Not sure if Higgs is solely responsible
- Explore high energy, see if Higgs preserves unitarity at all energies

**Quartic Gauge Coupling**, only few diagrams allowed in the SM:

Any other couplings would be NP

Parametrizable via EFT
EFT approach

- Add higher dimension operators to the SM Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{c^{(6)}}{\Lambda^2} \mathcal{O}^{(6)}_i + \sum_{j} \frac{c^{(8)}}{\Lambda^2} \mathcal{O}^{(8)}_j + \ldots$$

- Compare measurements under $\mathcal{L}$ vs. $\mathcal{L}_{\text{SM}}$, look for NP!
EFT approach

- Add higher dimension operators to the SM Lagrangian:

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c^{(6)}_i}{\Lambda^2} \mathcal{O}^{(6)}_i + \sum_j \frac{c^{(8)}_j}{\Lambda^2} \mathcal{O}^{(8)}_j + \ldots \]

- Compare measurements under \( \mathcal{L} \) vs. \( \mathcal{L}_{\text{SM}} \), look for NP!

- **dim-8 operators** needed to induce (anomalous) QGC without TGC vertices

  - Modifications of existing SM vertices, and newly allowed vertices
Experimental aspects of VBS

Very forward jet, large $\Delta \eta$

Rather central w.r.t. backgrounds

Main decay channels: WW, WZ, ZZ

See NP effects in tails of distributions
Experimental aspects of VBS

- Currently statistically limited at high energy
- General prospects of HL LHC:
  - Better statistics in the tail
  - Harsh pileup conditions
  - Better forward coverage
  - Availability of differential cross sections

Very forward jet, large $\Delta\eta$

Rather central w.r.t. backgrounds

Main decay channels: WW, WZ, ZZ
VBS: Same-sign WW → lνlν

- ssWW largest σ_{EW}/σ_{QCD}

- Recent 5.5 (5.7) σ observed (expected) significance by CMS

- Increased reach projected at HL-LHC
The VBS mode at by a conservative factor of 6.3 Statistical Analysis

- Exactly two selected leptons (each with
- At least one selected lepton must fire the trigger.
- The templates for ssWW-QCD and (scaled)
  in the dilepton plus diphoton channel
  rate for the three detector scenarios. The last column is summarizing the LHC Run-I observed
  Table 2: Expected 95% CL limits on the coefficients for BSM higher order (dimension-eight)
  (right) operators.

Figure 9: Distributions of the di-lepton invariant mass (left)

- The main background contributions are from
  The invariant mass of the two highest-
  is the invariant mass of the two tag jets (left)
- from the W boson decay
  struct the Z boson within 10 GeV of its mass. When all three leptons have the same

- Projected limits on dim-8 operators show much stronger constraints
VBS: Same-sign WW → lvlv

### ATLAS @ 3000 fb⁻¹

<table>
<thead>
<tr>
<th>model</th>
<th>300 fb⁻¹</th>
<th>3 ab⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{S_0}/\Lambda^4$</td>
<td>10 TeV⁻⁴</td>
<td>4.5 TeV⁻⁴</td>
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</table>

5σ discovery values

[ATLAS-PHYSPUB-2013-006]

### 95% CLs @ 3000 fb⁻¹

<table>
<thead>
<tr>
<th></th>
<th>Phase I (TeV⁻⁴)</th>
<th>Phase II (TeV⁻⁴)</th>
<th>Phase I aged (TeV⁻⁴)</th>
<th>Run-I results (TeV⁻⁴)</th>
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<tr>
<td>S₀</td>
<td>2.47</td>
<td>2.49</td>
<td>2.85</td>
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<tr>
<td>S₁</td>
<td>8.19</td>
<td>8.25</td>
<td>9.45</td>
<td>131 [12]</td>
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<tr>
<td>M₀</td>
<td>1.88</td>
<td>1.76</td>
<td>2.03</td>
<td>4.6 [38]</td>
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<tr>
<td>M₁</td>
<td>2.54</td>
<td>2.38</td>
<td>2.72</td>
<td>1.7 [38]</td>
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<tr>
<td>M₆</td>
<td>3.78</td>
<td>3.54</td>
<td>4.05</td>
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<td>M₇</td>
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<td>3.24</td>
<td>3.75</td>
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<td>0.17</td>
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<td>T₁</td>
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<td>0.070</td>
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<td>T₂</td>
<td>0.25</td>
<td>0.23</td>
<td>0.25</td>
<td>7.1 [12]</td>
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### 95% CLs @ 35.9 fb⁻¹

<table>
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<tr>
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<th>Observed limits (TeV⁻⁴)</th>
<th>Expected limits (TeV⁻⁴)</th>
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<tbody>
<tr>
<td>$f_{S_0}/\Lambda^4$</td>
<td>[-7.7, 7.7]</td>
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<tr>
<td>$f_{T_2}/\Lambda^4$</td>
<td>[-0.89, 1.02]</td>
<td>[-0.80, 0.95]</td>
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</table>

- Projected limits on dim-8 operators show much stronger constraints

[ATL-PHYS-PUB-2017-023]
VBS: $WZ \rightarrow \ell
\nu\nu$

- Larger $\sigma$ than VBS $ZZ$, while still able to construct $m_{\nu\nu}$

- Attainable sensitivity in the tails at high lumi

- Much better precision on the cross section

- $5\sigma$ discovery values:

\[
\begin{array}{c|c|c}
\text{ATLAS-PHYS-PUB-2013-006} & 300 \text{ fb}^{-1} & 3000 \text{ fb}^{-1} \\
\frac{f_{T1}}{\Lambda^4} & 1.3 \text{ TeV}^{-4} & 0.6 \text{ TeV}^{-4}
\end{array}
\]
VBS: ZZ → llll

- Fully reconstructable final state
- 13 TeV CMS result, reaching up to $m_{ZZ} \sim 1600$ GeV

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Exp. lower</th>
<th>Exp. upper</th>
<th>Obs. lower</th>
<th>Obs. upper</th>
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<td>$f_{T0}/\Lambda^4$</td>
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<td>$f_{T2}/\Lambda^4$</td>
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<td>$f_{T9}/\Lambda^4$</td>
<td>-2.1</td>
<td>2.1</td>
<td>-1.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

- Projection from ATLAS
  $(m_{jj} > 1$ TeV)
VBF

- Projections for VBF
- Good for precision measurements of the Higgs signal strength, and couplings to other particles
Conclusion

• HL-LHC opens up some interesting avenues for NP-searches at high energy

  • Deviations in **differential spectra** at high pT can be fitted to Higgs coupling modifiers, e.g. $\kappa_t/c_g$

  • NP-potential in the tails of **VBS**

• **EFT** in both cases a good framework for interpretation

  • Interpretation by theorists or experimentalists?

• Both cases currently **limited by statistics**

  • 3 ab$^{-1}$ of data opens up possibilities for new measurements, and would provide competitive limits on Higgs couplings
Back up
Introduction

- **Transverse momentum** $p_T^H$
  - Sensitivity to modifications of effective Higgs Yukawa couplings
  - Sensitivity to finite top mass effects

- **Jet multiplicity** $N_{jets}$ & $p_T$ of the first jet $p_{jet1}$
  - New physics in the loop, sensitivity at high $p_T$

- **Rapidity** $|y^H|$
  - Theory distribution mostly determined by the gluon PDF; possible test
The transverse states were neglected. This contribution was taken to be small was considered while the contribution from transverse states was considered while the contribution from transverse states was the original motivation to use the EVBA has been used for vector-boson scattering in first applications to vector-boson scattering, again only unless a suitable analysis of the different proton rem-

\[
\begin{align*}
W & \rightarrow W \\
W & \rightarrow W \\
W & \rightarrow Z \\
W & \rightarrow Z
\end{align*}
\]

...
Couplings: $\kappa_b$ vs. $\kappa_c$

- Can use the $p_T$ spectra to fit $\kappa_b$ vs. $\kappa_c$
- Simply vary $\kappa_b$ vs. $\kappa_c$ until the spectrum matches the observed spectrum the best
- What can we do with this at 3 ab$^{-1}$? 

![Graph showing normalized cross sections for inclusive Higgs production](image)

Bishara, Haisch, Monni, Re (2016) [1606.09253]
Couplings: $\kappa_b$ vs. $\kappa_c$

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- Simply vary $\kappa_b$ vs. $\kappa_c$ until the spectrum matches the observed spectrum the best
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**Diagram:**

- Plot of $(1/\sigma)(d\sigma/dp_T,h)/(1/\sigma)(d\sigma/dp_T,h)$ for $\kappa_c = -10, -5, 0, 5$
- CMS 35.9 fb$^{-1}$ and ATLAS 36.1 fb$^{-1}$

**Note:** Private study; not a CMS/ATLAS result.
Couplings: $\kappa_b$ vs. $\kappa_c$

- Can use the $p_T$ spectra to fit $\kappa_b$ vs. $\kappa_c$
  - Simply vary $\kappa_b$ vs. $\kappa_c$ until the spectrum matches the observed spectrum the best
  - What can we do with this at 3 ab$^{-1}$?

![Graph showing total cross sections for inclusive Higgs production with next-to-next-to-leading-logarithmic (NNLL) order algorithms and resummation of logarithms in $p_T, h$](image)
Couplings: $\kappa_b$ vs. $\kappa_c$

- Theorist fit on ATLAS combined pT-spectrum indicates $\kappa_c$ sensitivity of order $[-10, 10]$ @ 68% CL

- Projections*:
  - $\sim[-1.5, 4.0]$ @ 300 fb$^{-1}$
  - $\sim[-0.5, 3.0]$ @ 3000 fb$^{-1}$

*: Some side notes:
- Optimistic projections for theory uncertainties
- Assuming also $H \to WW$
- Correlations taken from 8 TeV case