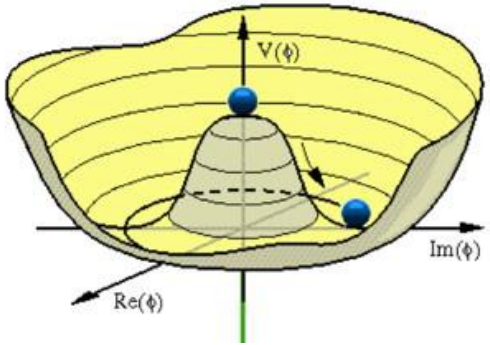
Search for HH→ 4b at CMS:
Present status and future perspectives

F.Siviero, PhD Course “The hunt for physics Beyond the Standard Model”

10/25/2019

The Higgs self-coupling

- The Higgs potential: $V(\varphi) = -\mu^2\varphi^2 + \lambda\varphi^4$
  - Expansion around the minimum: $V(\varphi) \rightarrow V(v+h)$
  - $V = V_0 + \frac{1}{2} m_h^2 h^2 + \lambda_{hhh} h^3 + \frac{1}{4} \lambda_{4h} h^4$



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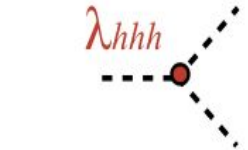

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- **λ_{hhh} is the last parameter of the Higgs potential still not measured**
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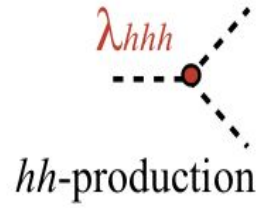
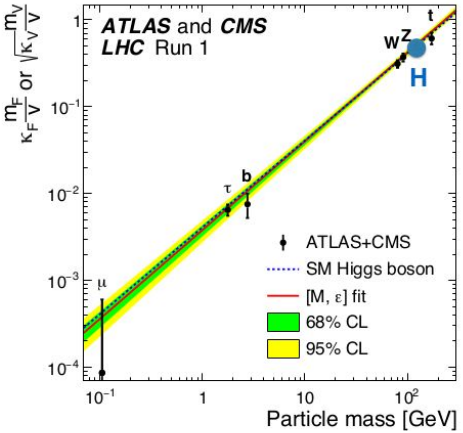
  - There could be large departure, due to physics Beyond the SM (BSM)



will the self-coupling scale linearly with the mass like other couplings?



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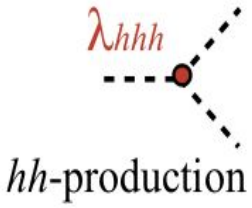

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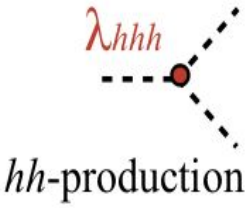

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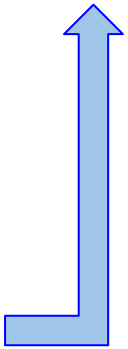
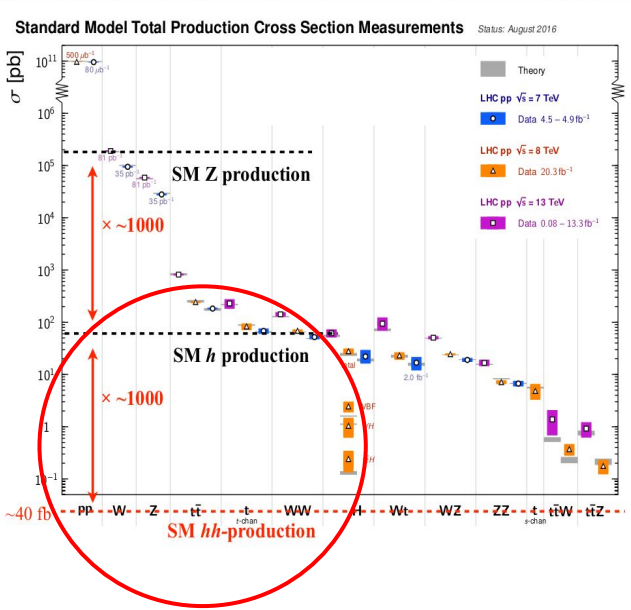


- ➔ **di-Higgs production allows measuring λ_{hhh}**
- ➔ di-Higgs measurement at the LHC of paramount importance

HH cross section

di-Higgs measurement experimentally challenging
→ very low σ



$\sigma_{HH} \sim 1/100\ \sigma_{H}$

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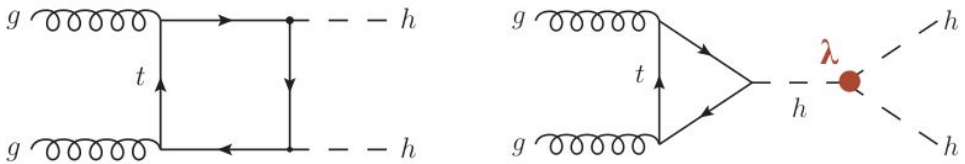

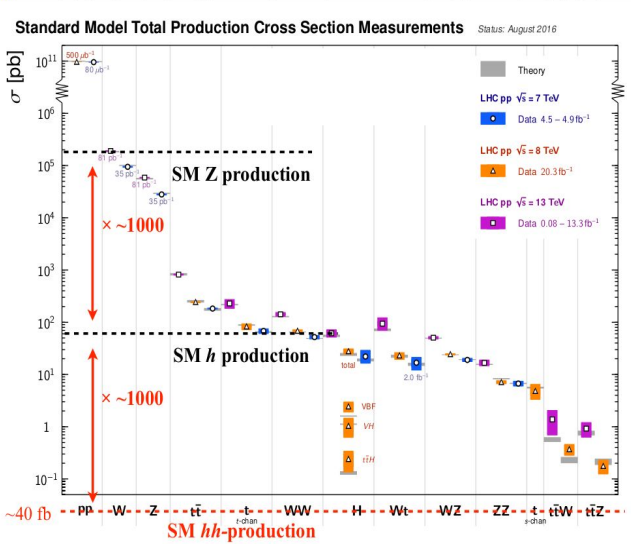

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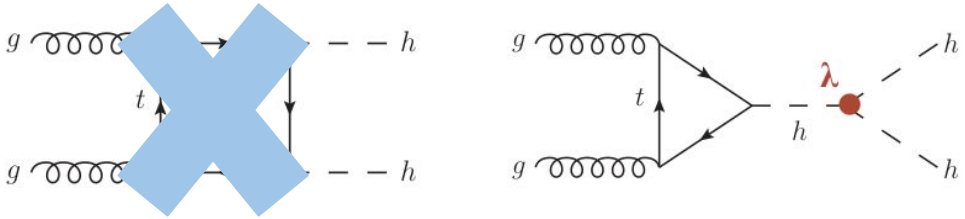
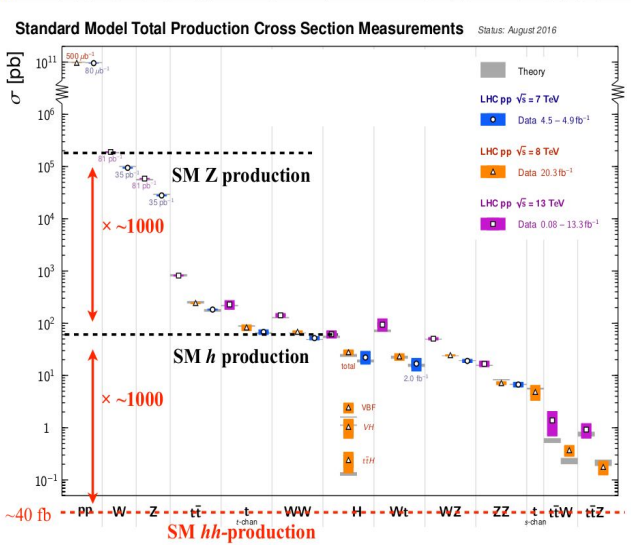


box diagram does not provide a measurement of λ_{hhh} !!!



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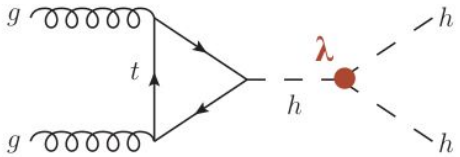
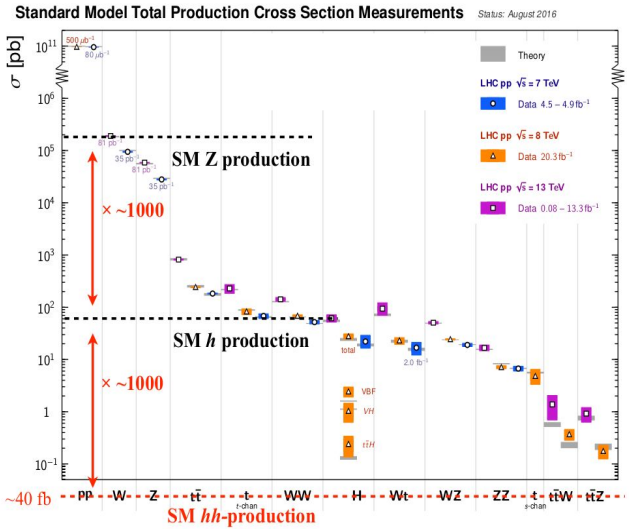




- **gg-fusion is the main production mode: σ ~ 40 fb**
  - other channels like VBF-hh: σ ~ 1 fb
- 2 different production modes:
  - Resonant
  - Non-Resonant

The coupling strength modifier

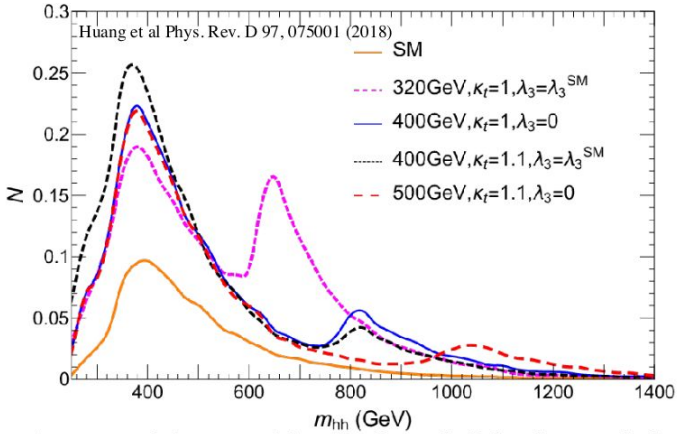
- We can quantify the variations of the self-coupling wrt SM predictions introducing the coupling strength modifier: $k = \lambda_{BSM} / \lambda_{SM}$
  - k=0 means no self coupling
  - k =1 is the SM

I will use the k-factor (instead of λ) in the following slides

$\lambda_{BSM}/\lambda_{SM}$	σ_{NLO}@14TeV [fb]	σ_{NLO}@27TeV [fb]
1	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$
2	14.91	59.10
2.4	13.81	53.67
3	19.82	69.84
5	98.42	330.61
0	73.84	275.29
-1	137.69	504.9

Resonant HH production

- We can think of a **particle X with $M_x > 2M_{Higgs}$ that couples mainly with the Higgs**
- Such particle **will be visible through HH decay, as a resonance** in the invariant mass spectrum



m_{HH} distribution in presence of light stops (different values of λ and H-top coupling)

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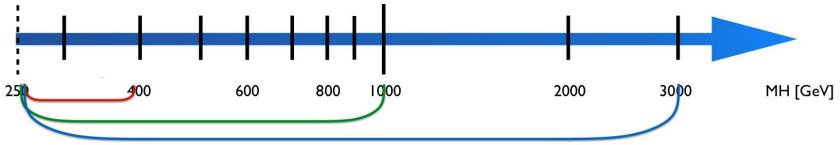
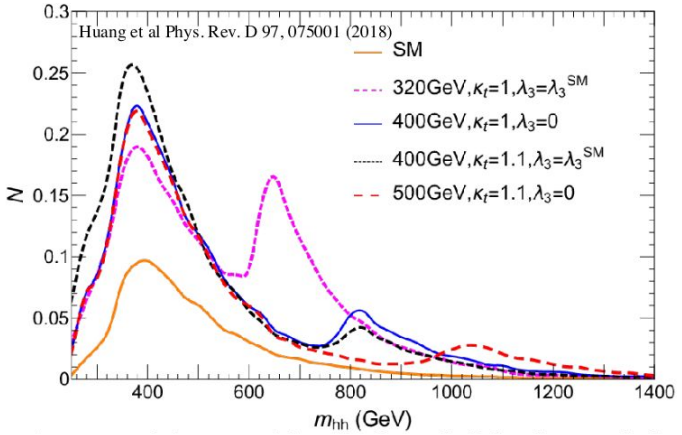
- Hypothetical resonance strongly tied to the BSM model:



★ **2HDM**: additional Higgs doublet
★ **Singlet model**: additional Higgs singlet
★ **Warped extra dimensions**: Graviton / Radion resonances



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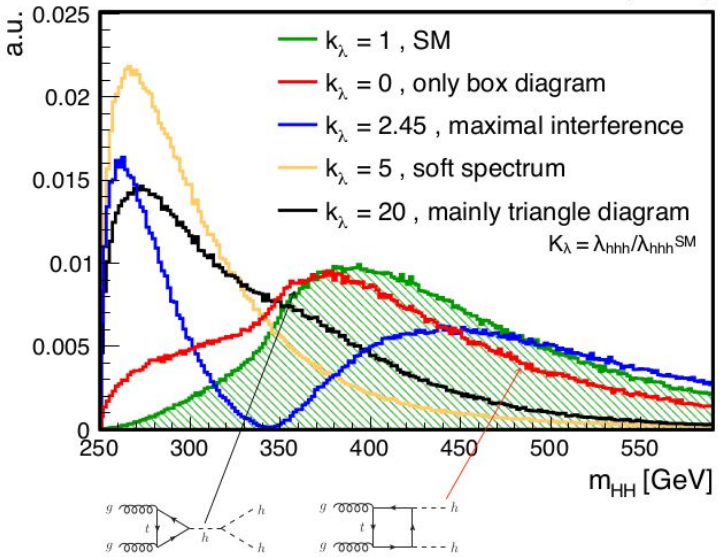
Non-Resonant HH production

- BSM physics can modify the cross section and the kinematic properties of non-resonant HH production



HH distribution for selected benchmark points plus the SM and k = λ_{BSM}/ λ_{SM}=0 scenarios

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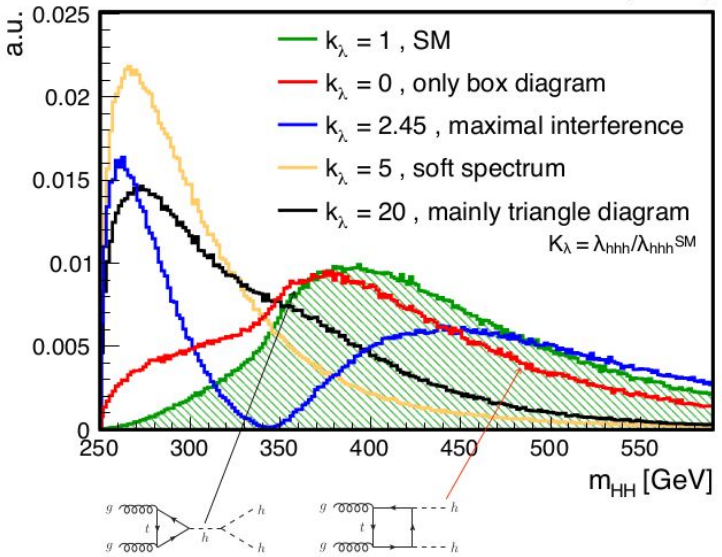

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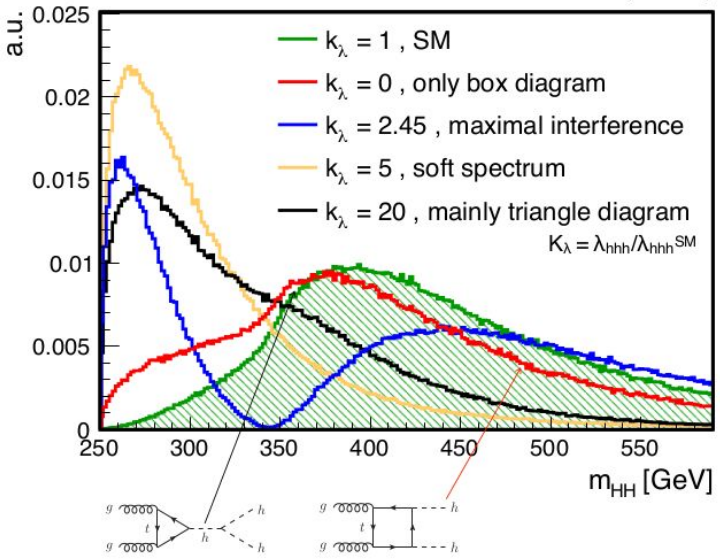
- **"Benchmark" points** with different anomalous couplings* → different k values in each point → different **HH distribution**

**anomalous means not SM*



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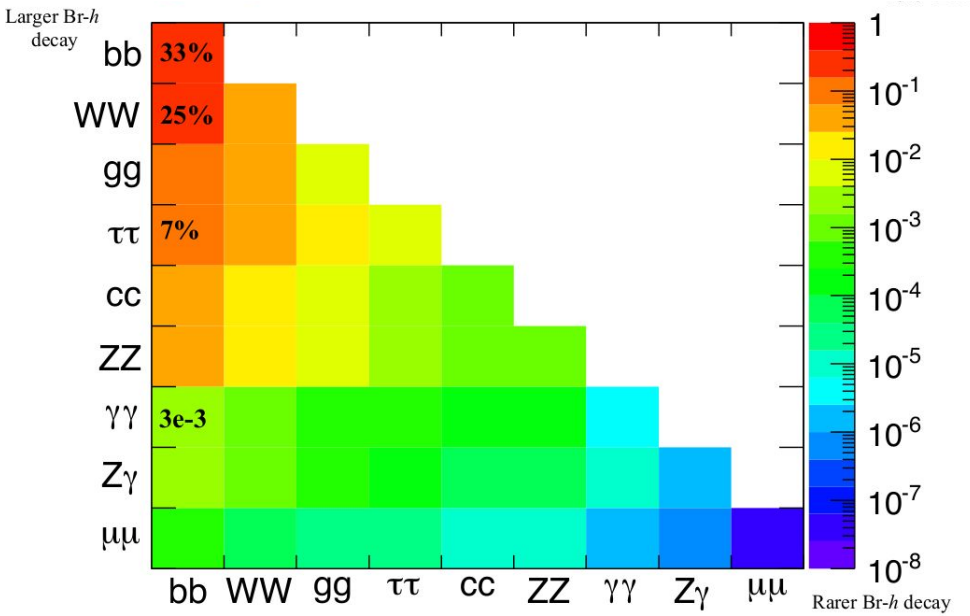
HH → 4b

- The observation of HH is made through the final states resulting from the di-Higgs decays
- Many different final states



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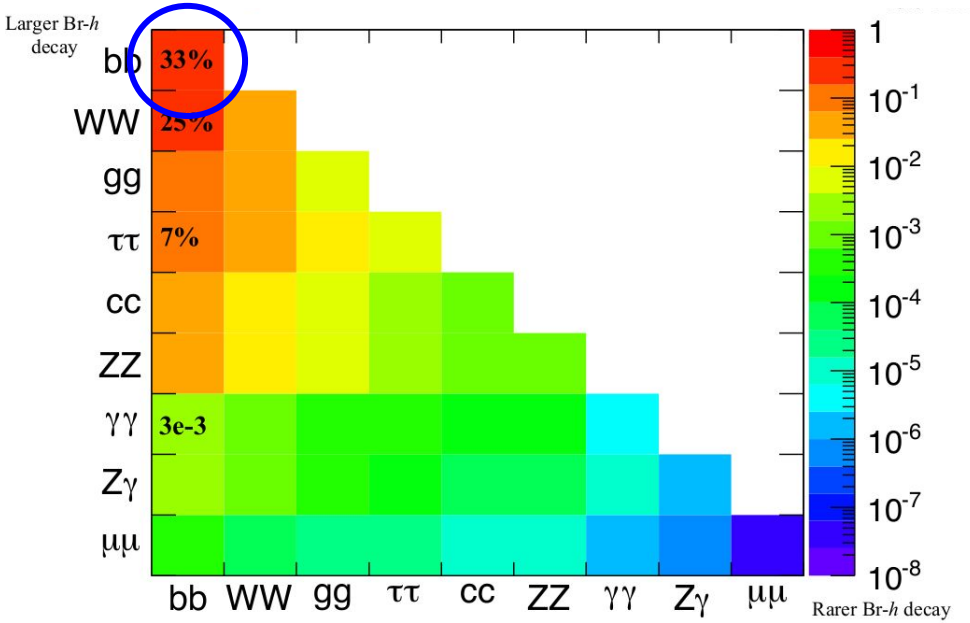
- **HH → 4b** will be considered in this talk
- **Largest Branching Ratio (BR)**
- **but very large contamination from multi-jet background**



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- **Largest Branching Ratio (BR)**
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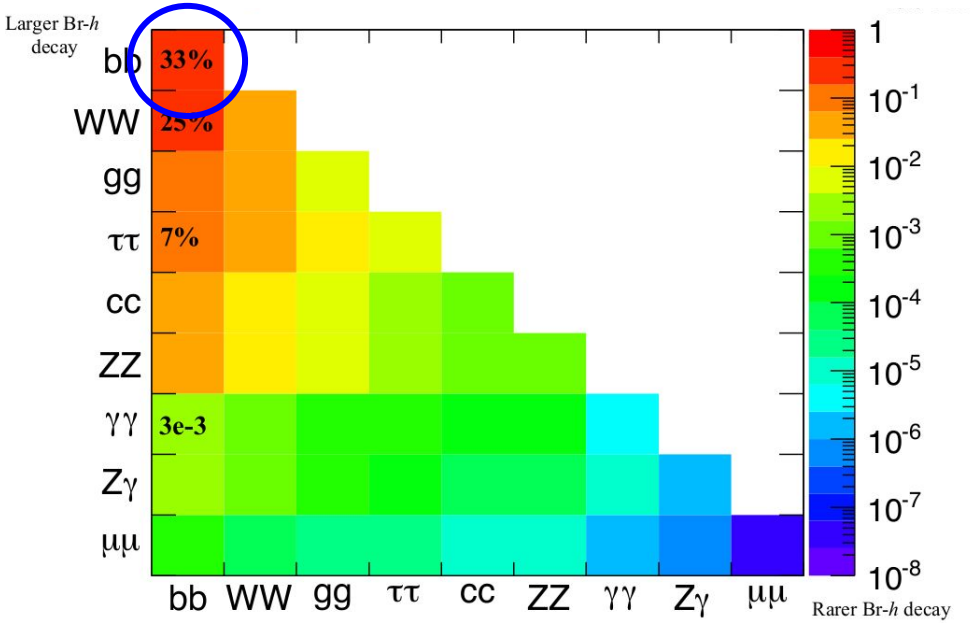
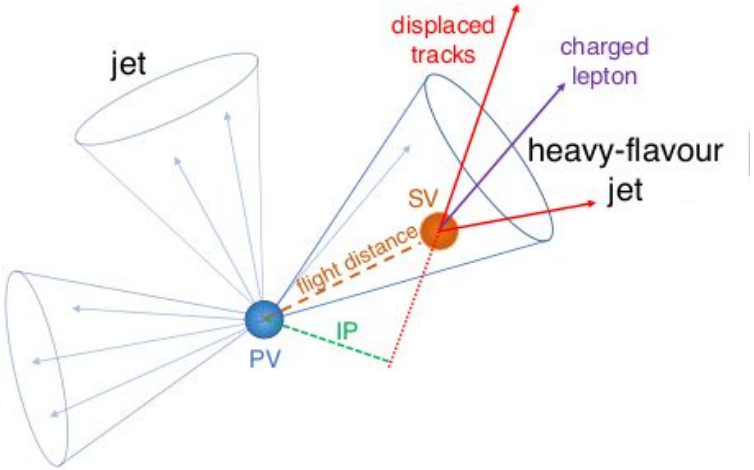
- **2 main categories for this final state:**
  - **Resolved**
  - **Boosted**



B-jet identification

- The b-jet identification is crucial in the HH → 4b final state
- It is achieved exploiting the *displaced secondary vertexes*
- **Long lifetime of b quarks** → sizeable distance between b production point and its decay point → ***displaced secondary vertex*** that can be resolved from the primary vertex



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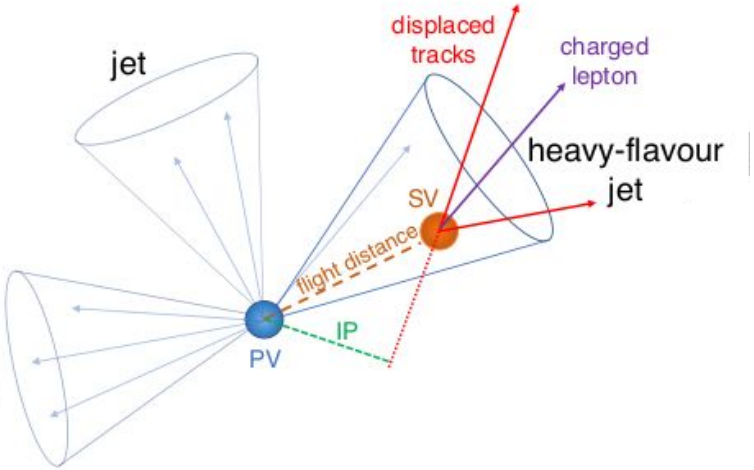
- **Secondary vertex + Multivariate background analysis → b-tagging**



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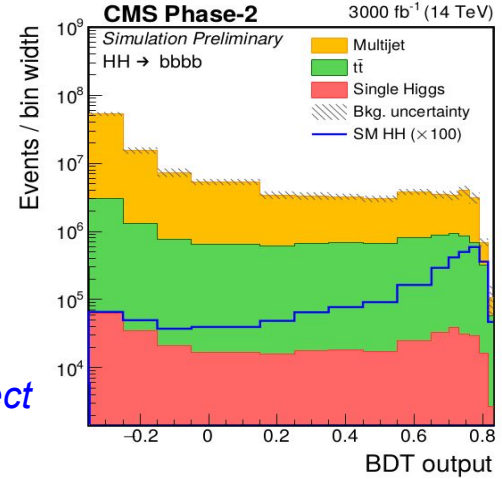

phase-2 prospect

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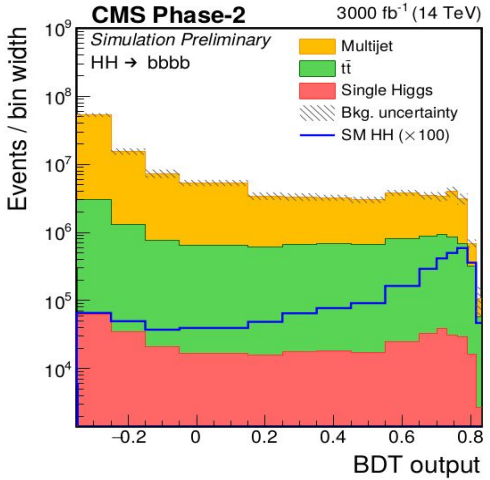
- **Mainly SM HH are expected in this topology**



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* large: cone with radius 0.8 (anti kt algorithm)

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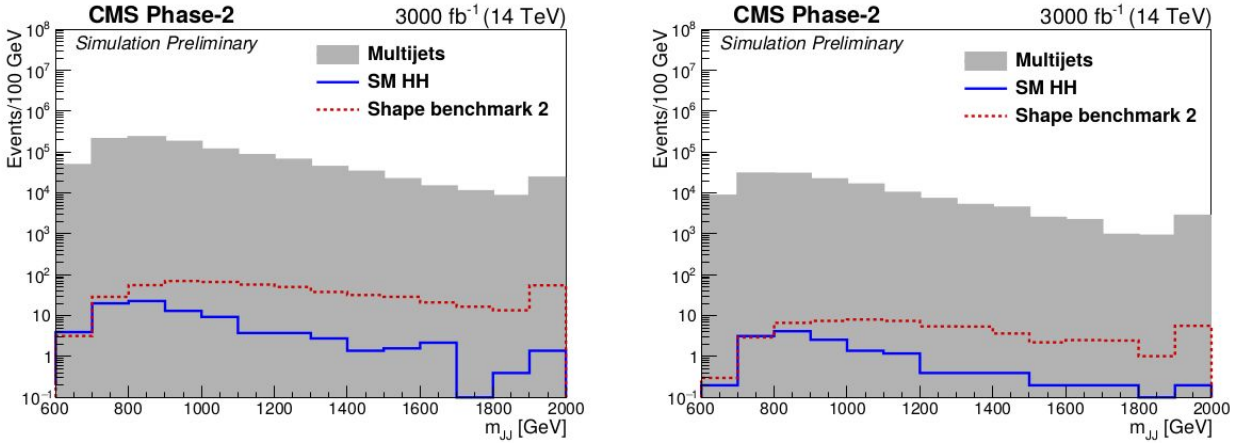
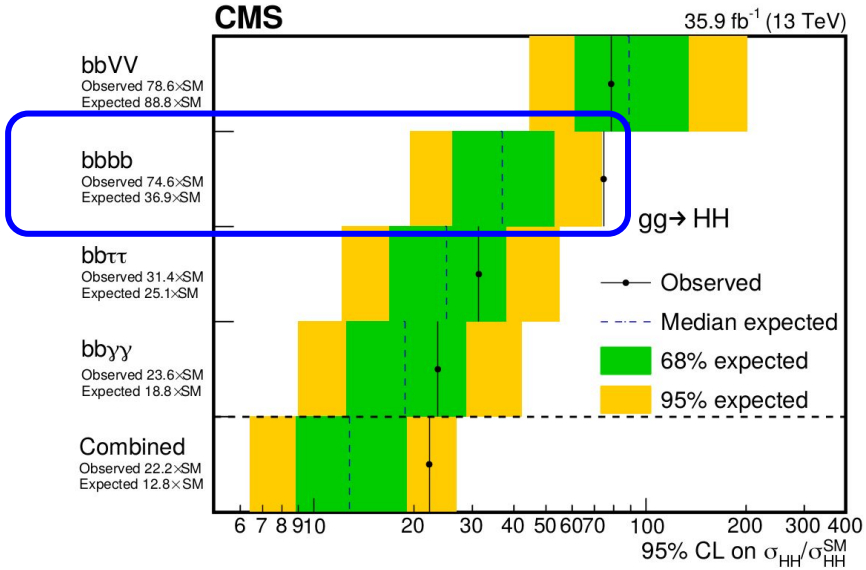
- The event is required to contain at least **2 large* jets** with $p_T > 300$ GeV and $|\eta| < 3$
- Algorithm to exclude soft and collinear components + sub b-jets identification
- **3 or 4 jets categories**



m_{jj} distribution: 3b (left) and 4b (right) categories
SM HH in red and one of the EFT benchmark points mentioned previously in blue

Present CMS results

- Current Run 2 HH measurements are performed with approximately 36 fb $^{-1}$ @13 TeV
- **Observed (expected) upper limit on σ_{HH} in the 4b final state is 74.6 (36.9) x SM predictions** (the dashed lined represents the upper limit in the background-only hypothesis)



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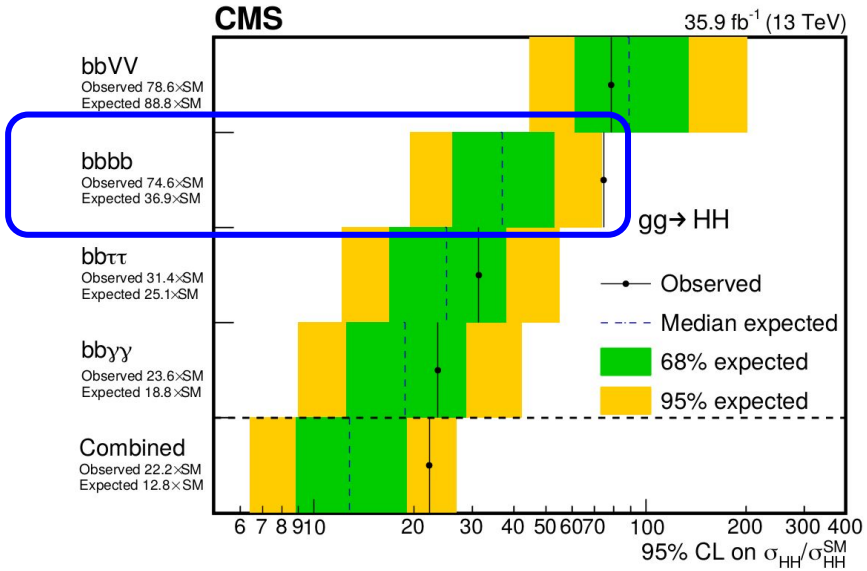

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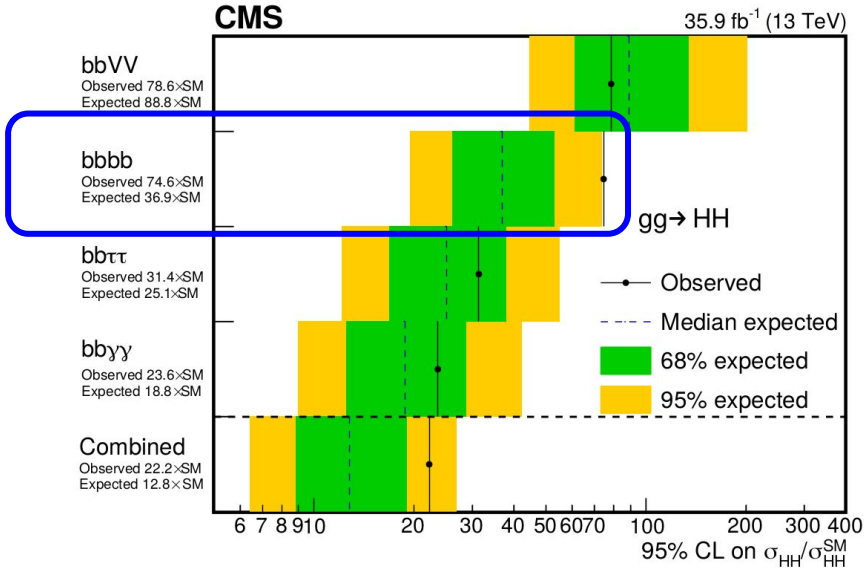
- **observed (expected) k-factor: -11.8 (-7.1)< k< 18.8 (13.6) at 95% CL**
- Due to the extremely low cross section **much more data** than the present one are **needed** to put significative constraints

→ **Future colliders!**



Prospects at HL-LHC and HE-LHC

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- High-Luminosity LHC (**HL-LHC**) will (hopefully) **observe HH** and put tighter constraints on signal strength
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So, what's next?

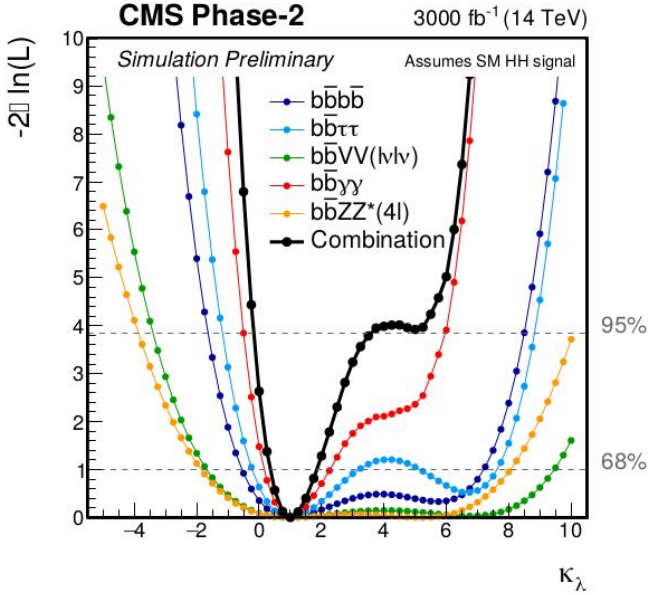
- **HE-LHC**: HL-LHC but higher energy exploiting magnet designed for the FCC
- **FCC**: ~100km tunnel, capable of reach 100 TeV

High-Energy: σ_{HH} increases by about a factor of 4 (40) at 27 (100) TeV wrt 13 TeV

Expected results at HL-LHC

- Significant improvements are expected at the HL-LHC:
  - **Expected upper limit on σ_{HH}** in the 4b final state considering statistical+systematic (stat only) uncertainties is **2.1 (1.6) x SM prediction**
  - **-0.18< k< 3.6 at 95% CL** assuming a SM HH signal

Present result:-12< k< 19



expected likelihood scan as a function of k

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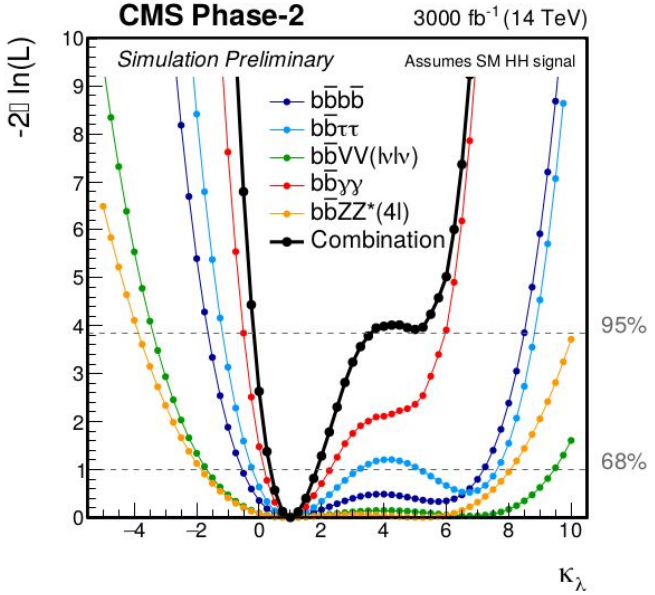
- BSM might be found only in the case of very large deviations from the SM (i.e. not requiring precision measurements)



expected likelihood scan as a function of k

Other final states

- **In the final states considered by CMS one Higgs alway decays in bb, in order to have a sufficiently high BR**

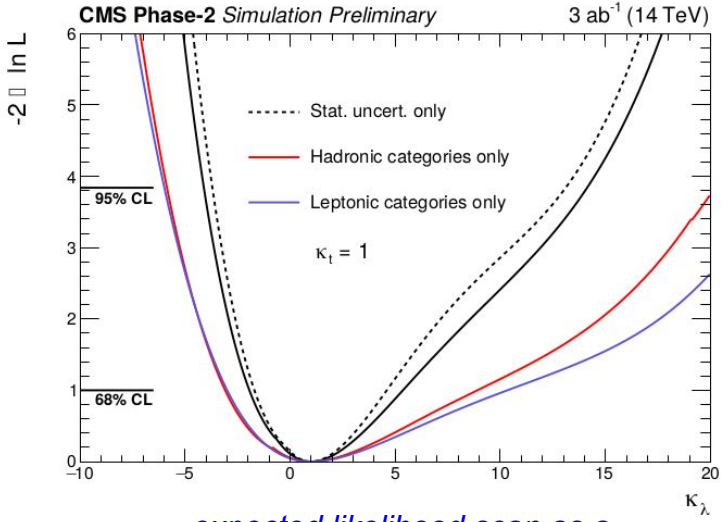
- **HH → bbττ**
  - two b-tagged jets + τ_h (tau hadronic decay) + isolated μ/e
  - main background from ttbar or ττ from Drell-Yann
  - Run2 observed 95% CL upper limit on **σ_{HH} 31.4 x SM prediction**

- **HH → bbγγ**
  - full reconstruction of the final objects
  - excellent di-photon invariant mass resolution
  - Run2 observed 95% CL upper limit on **σ_{HH} 23.6 x SM prediction**

Indirect probes

- **Study λ_{hhh}** indirectly using the **single Higgs** production
- self coupling enters in the one-loop correction of single H production:
  - Modified λ_{BSM} has much smaller effects
  - but much higher experimental precision on single Higgs

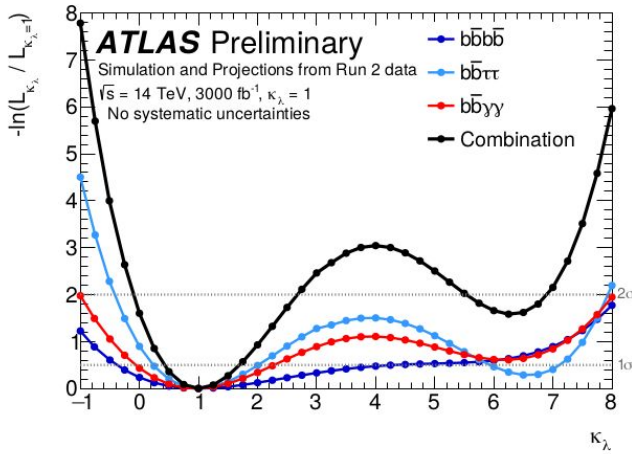
HL-LHC: -4.1< k< 14.1 at 95% CL
worse than with direct search



expected likelihood scan as a function of k

ATLAS results

- The current Run 2 measurements of the Higgs-boson-pair production are performed with approximately 36 fb^{-1} @13TeV
- **Observed (expected) limit on the σ_{HH} is 6.7 (10.4) x SM expectation**
- The ratio of the Higgs boson self-coupling to its SM expectation is observed (expected) **$-5.0 < \kappa < 12.1$ ($-5.8 < \kappa < 12.0$)**



Summary

- **di-Higgs production allows measuring the Higgs self-coupling λ_{hhh}**
- λ_{hhh} is the last unknown parameter of the Higgs potential → crucial for our understanding of the Electroweak symmetry breaking
  - **A path for BSM physics!**

Summary

- **di-Higgs production allows measuring the Higgs self-coupling λ_{hhh}**
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- HH production has a **small cross section** → experimentally challenging
  - Resonant production → look for resonances
  - Non-resonant → look to the kinematic distribution of HH

Summary

- **di-Higgs production allows measuring the Higgs self-coupling λ_{hhh}**
- λ_{hhh} is the last unknown parameter of the Higgs potential → crucial for our understanding of the Electroweak symmetry breaking
  - **A path for BSM physics!**
- HH production has a **small cross section** → experimentally challenging
  - Resonant production → look for resonances
  - Non-resonant → look to the kinematic distribution of HH
- The HH → 4b is a promising final state:
  - **LHC**: CMS with Run2 data able to put rather **loose constraints** on the σ_{HH} upper limit
  - **HL-LHC: observation of HH** and largely improved constraints
  - **HE-LHC / FCC: λ_{hhh} precision measurements**

Thank you!

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