Higgs HL-LHC perspectives from ATLAS and CMS

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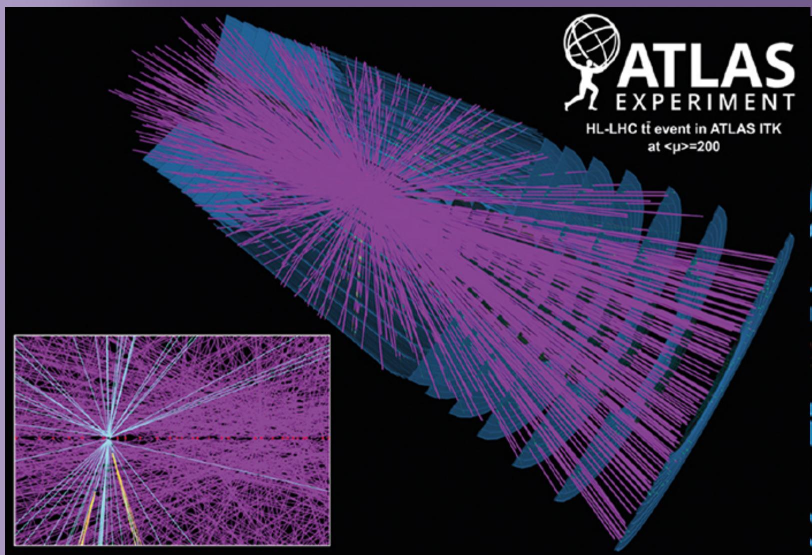
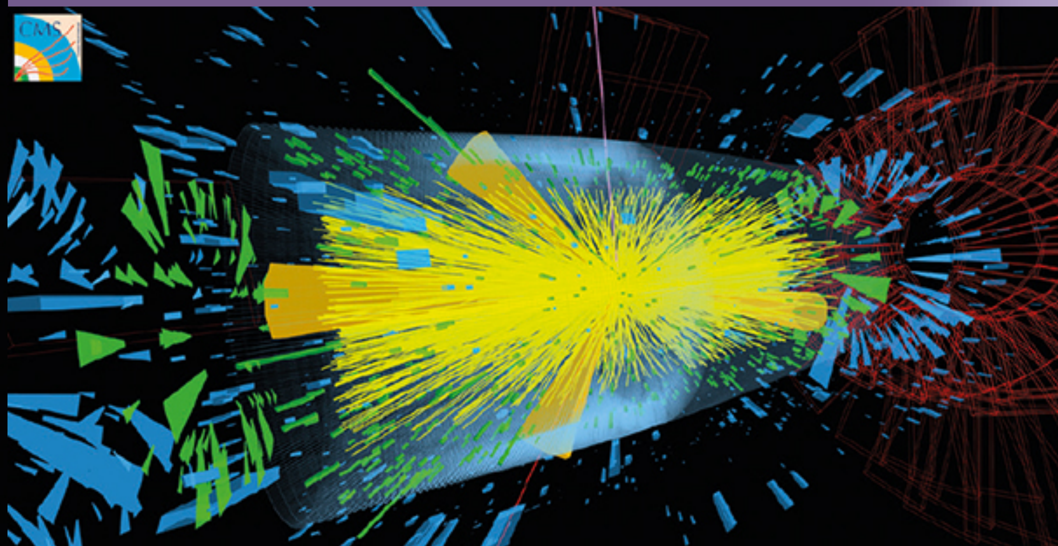




GDR Terascale - 23-25 November 2016, Paris

Outline

- HL-LHC: Accelerator & Detector Upgrade
- Analysis methods & assumptions
- Higgs signal strenght & couplings
- A rare decay: $H \rightarrow J/\psi\ \gamma$
- Higgs self-coupling
- BSM Higgs
- Conclusion and Outlook

More results in ECFA WKS October 2016, Aix-les-Bains (https://indico.cern.ch/event/524795/overview)

HL-LHC: Accelerator & Detector Upgrade

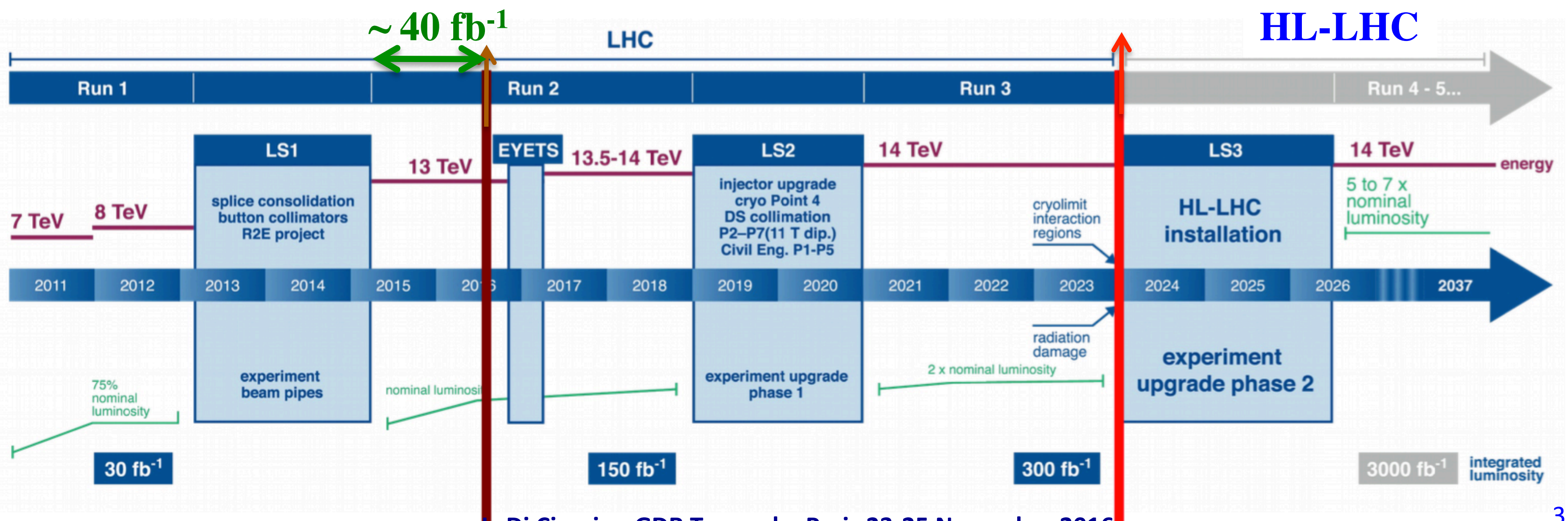
- **HL-LHC design:**
  - **Total integrated luminosity: 3000 fb^{-1} in ~ 10 years**

~ Ten times the luminosity reach of first 10 years of LHC operation

  - **Mean number of collisions per bunch crossing <PU> = 140 (200)**

- **A big challenge for the experiments => Upgrade of Detectors**
  - Very high pile up <**PU**> **= 140 (200)** → upgrade for PU mitigation
  - Intense radiation doses → upgrade to improve radiation hardness

Goal is to maintain or improve over current performance



Prospects: Analysis methods & assumptions

- **HL-LHC Higgs prospects done in two ways:**
  - **Parameterized performance of the upgraded detectors**
    - Event-generator level particles smeared with detector performance parameterized from full simulation, PU effects included.
  - **Extrapolation of Run 1 or Run 2 results**
    - Scale signal and background to higher luminosities and energy (14 TeV)
    - Unchanged analysis and ~ same detector performance as in Run 1, 2

Assumptions on the systematic uncertainties:

- **ATLAS approach**:
  - Experimental systematics scaled to best guess for HL-LHC
  - Results provided with & without (current) theory systematics
- **CMS approach, 2 main scenarios:**
  - $S1^{(+)}$: current experimental and theory systematics (+ PU & upgrade)
  - $S2^{(+)}$: experimental scaled with luminosity ($1/\sqrt{L}$) until a certain best achievable uncertainty level. The current theory systematics is halved. (+ PU & upgrade)

Relative uncertainty on the signal strenght : $\mu = \sigma_{obs}/\sigma_{SM}$

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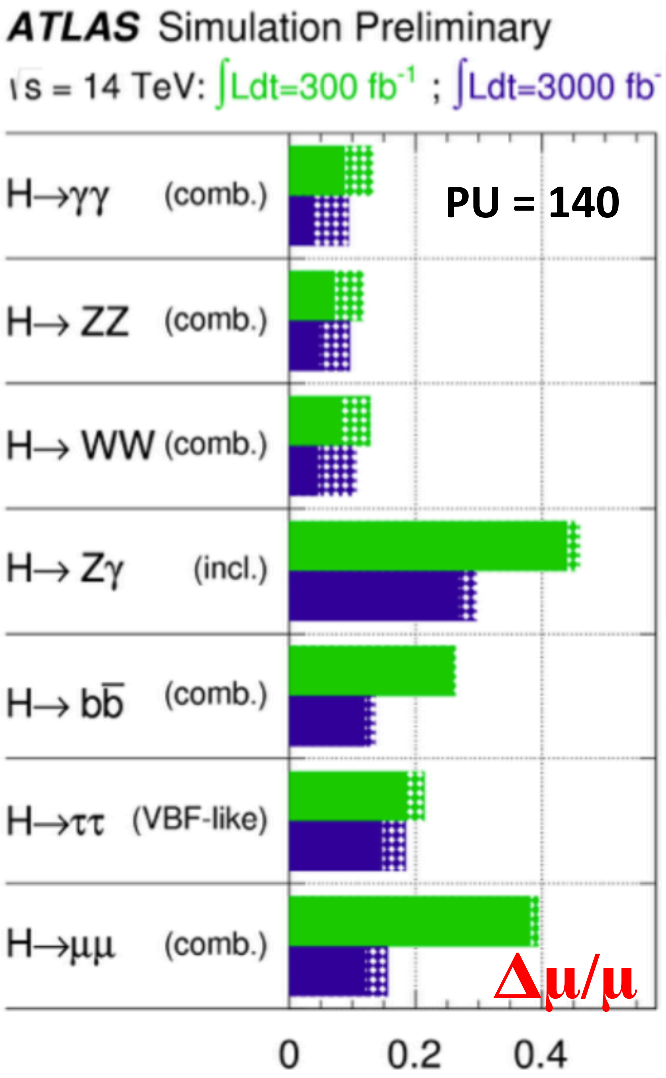

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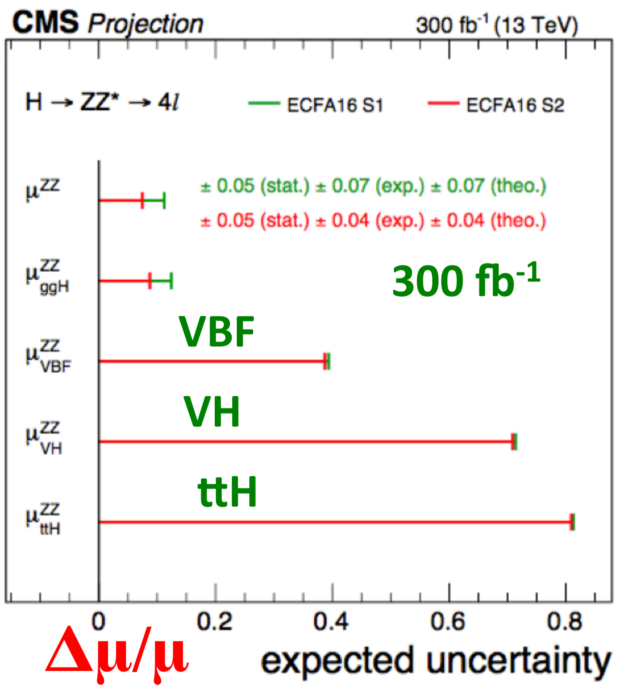

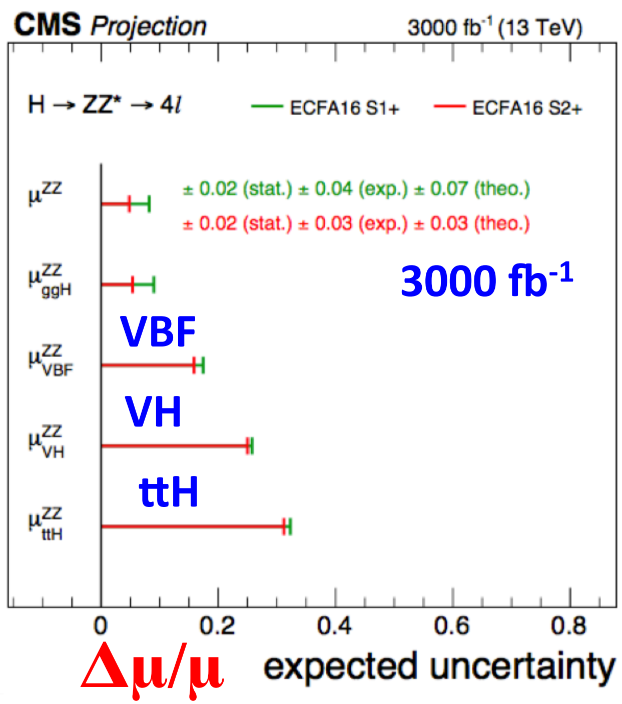

- **With 3000 fb^{-1}, rare production and decay modes will be much better measured** :
  - **VBF**, **VH** & **ttH** with **H→ ZZ→4l** $\Delta\mu/\mu \sim$ 20-30%
  - **H→ $\mu^+\mu^-$** $\Delta\mu/\mu \sim$ 15%

Higgs couplings: deviations w.r.t the SM

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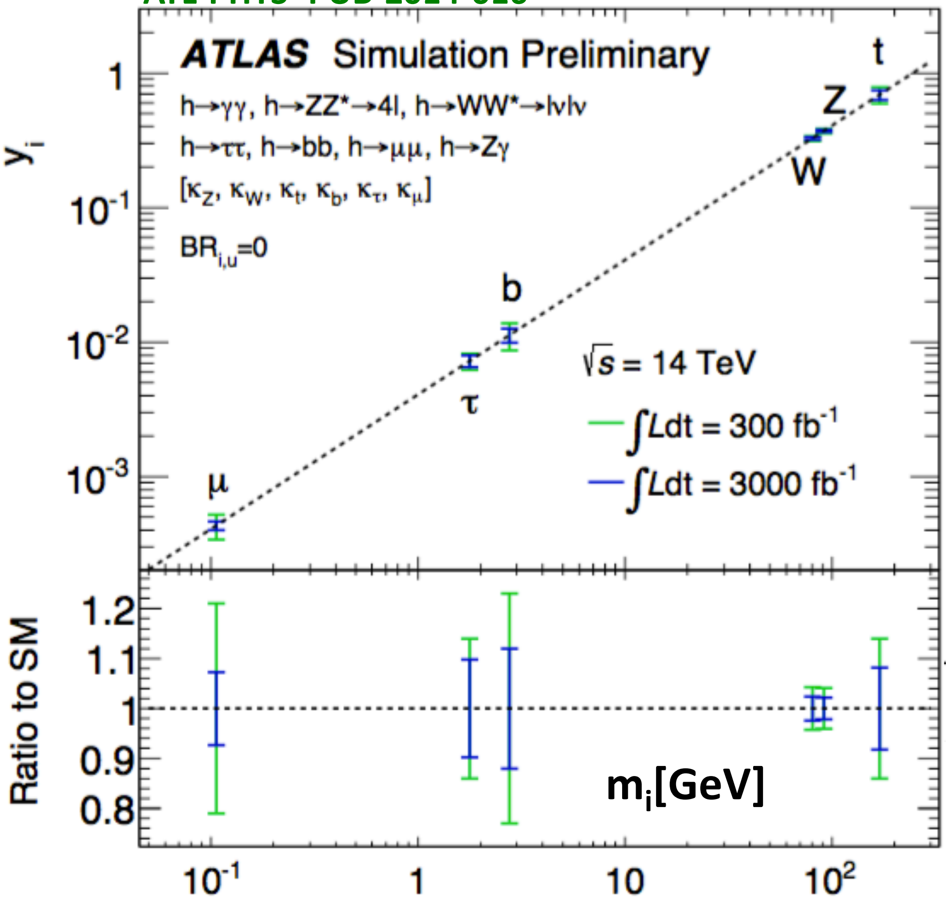

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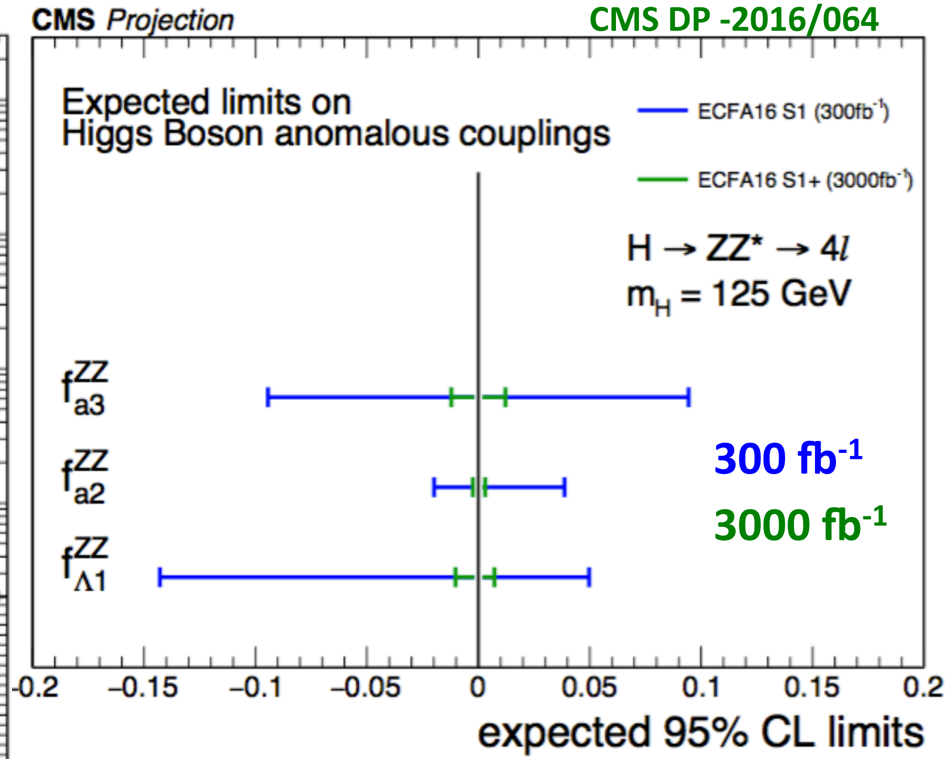

- Anomalous Couplings HZZ: $\mathbf{a_2, a_3, \Lambda_1}$
- f_{ai}= effective fractional ZZ cross sections

$$f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_j |a_j|^2\sigma_j},$$

- **With 3000 fb^{-1}:**
  - W, Z couplings **to 3%**
  - μ coupling **to 7%**
  - t,b,τ couplings **to 8%**
  - Anomalous Couplings much better constrained

Higgs couplings to charm quark: H→ J/ψ γ

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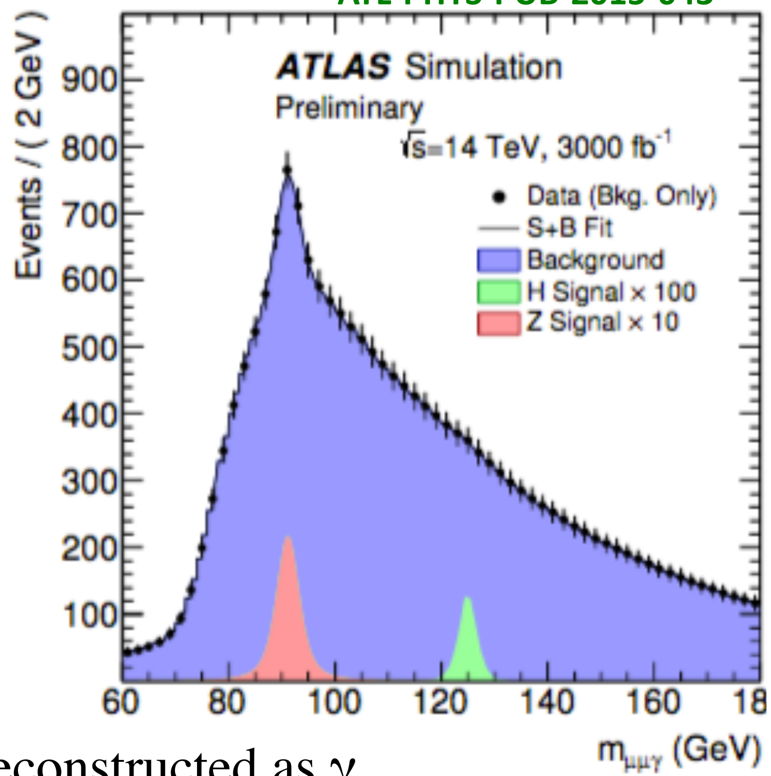


- **Very rare decay:**

  in SM: Br(H→J/ψ γ) = (2.9 ± 0.2) × 10^{-6}

  Run 1 limit: Br(H→J/ψ γ) ~ 10^{-3}

- **Magnitude and sign of the coupling to charm**
- **Sensitive to BSM physics**
- **Bkg for H→ μμγ**

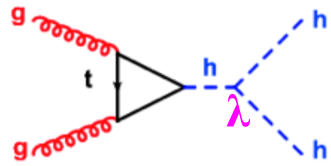
- **Use J/ψ→$\mu^+\mu^-$ decay mode**
  (Z→J/ψ γ for cross check)
- **Main bkg:**
  inclusive quarkonium production where a jet is reconstructed as γ

- **Baseline result with simple multivariate analysis (several improvements possible)**

95% CL upper limits on Br(H → J/ψγ) ~ 15 times the SM value

(no bkg systematic considered)

Higgs self-coupling



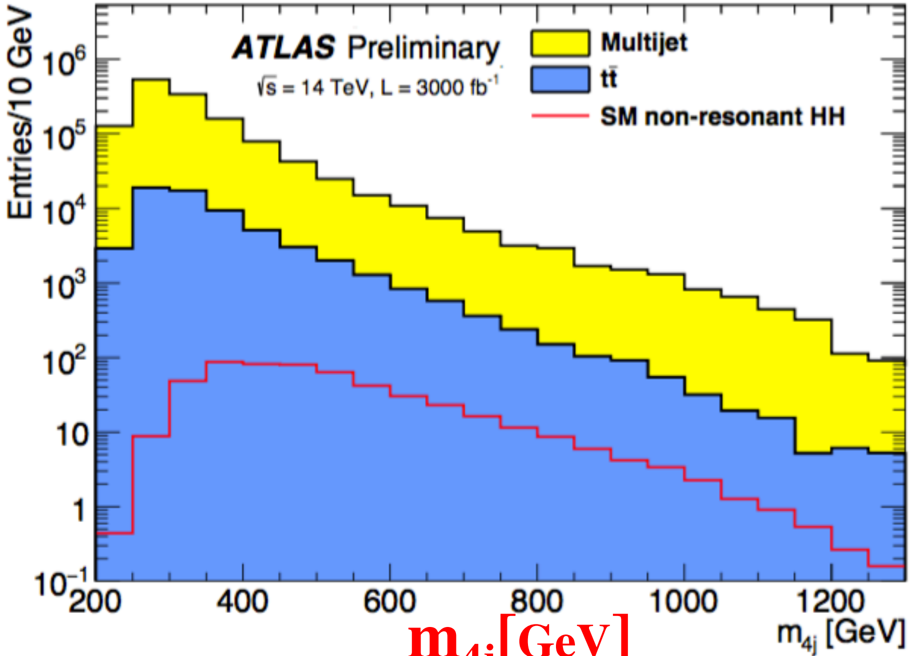
- **Very challenging:**
  - Low production cross section : **σ (pp → HH)^{SM} $_{NNLO+NNLL}$ = 33.45 fb (@ 13TeV)**

    → Use Higgs decay channels with high branching ratios (al least for one of the two H) : **HH→ bb XX** where **X = b, W, τ, γ**
  - Huge background

- **Example: HH→ $b\bar{b}$ $b\bar{b}$ (ATLAS)**
  Projection from extrapolation of Run 2 results (resolved analysis)

ATL-PHYS-PUB-2016-024

- Trigger thresholds: **p_T(jet) > 30 GeV** and **p_T(jet) > 75 GeV**
- Same: jet reconstruction, b-quark jet identification performance, selection & statistical analysis technique
- Main background (**95%**) multijet is extrapolated from Run 2



m_{4j}[GeV]

HH→ bbbb (ATLAS) & HH→ bb WW (CMS)

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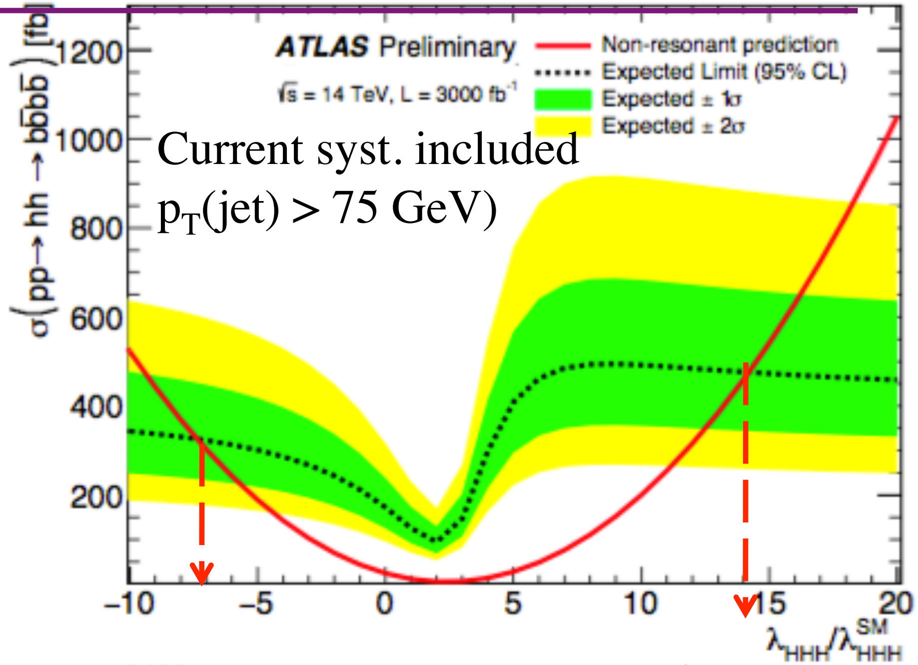
▪ HH→ $b\bar{b}b\bar{b}$

- Main impact of the uncertainties on the 95% C.L. exclusion limit (σ/σ_{SM}) is from **the background modelling**
- m_{4j} as function of λ/λ_{SM} generated with morphing technique used to set 95% C.L. upper limit on the cross-sections

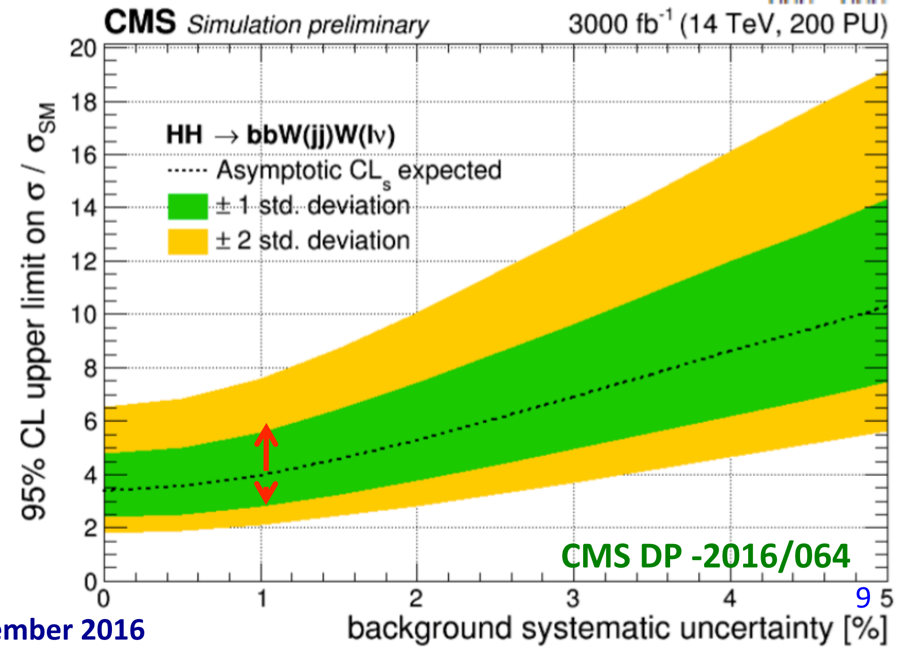
$-7.4 < \lambda/\lambda_{SM} < 14$



▪HH→ $b\bar{b}W(\ell\nu)W(jj)$

- Only background considered: **$t\bar{t}$**
- Signal optimisation via BDT
- Data driven techniques will constraint uncertainties to the per cent level

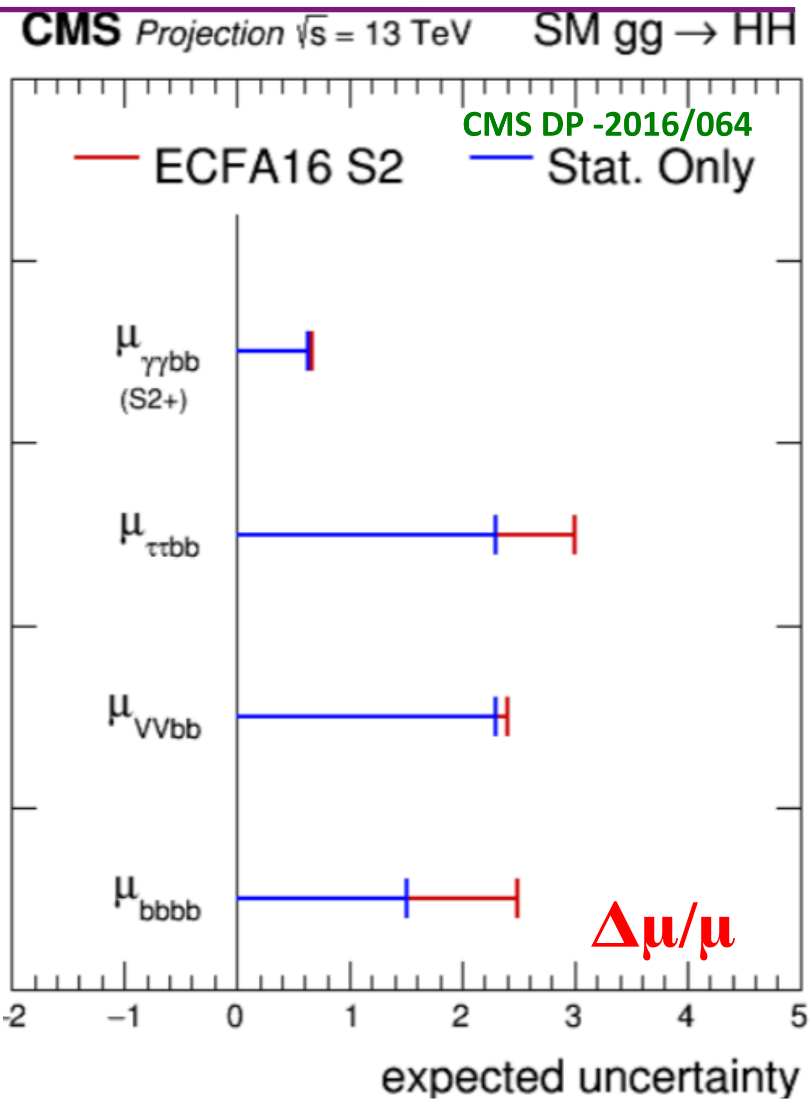
$\sigma/\sigma_{SM} \sim 3\text{-}5$



Summary of HH Projections

HH Channel	Result
HH→bbττ (FULL uncertainties)	Significance: 0.6 σ $-4 < \lambda_{HHH} / \lambda_{SM} < 12$
HH→bbbb (p_T(jet)> 75 GeV, FULL uncertainties)	$-7.4 < \lambda_{HHH} / \lambda_{SM} < 14$
HH→bbγγ (stat. uncertainties only)	Significance: 1.3 σ $-1.3 < \lambda_{HHH} / \lambda_{SM} < 8.7$
ttHH, HH→bbbb (stat. uncertainties only)	Significance: 0.35 σ

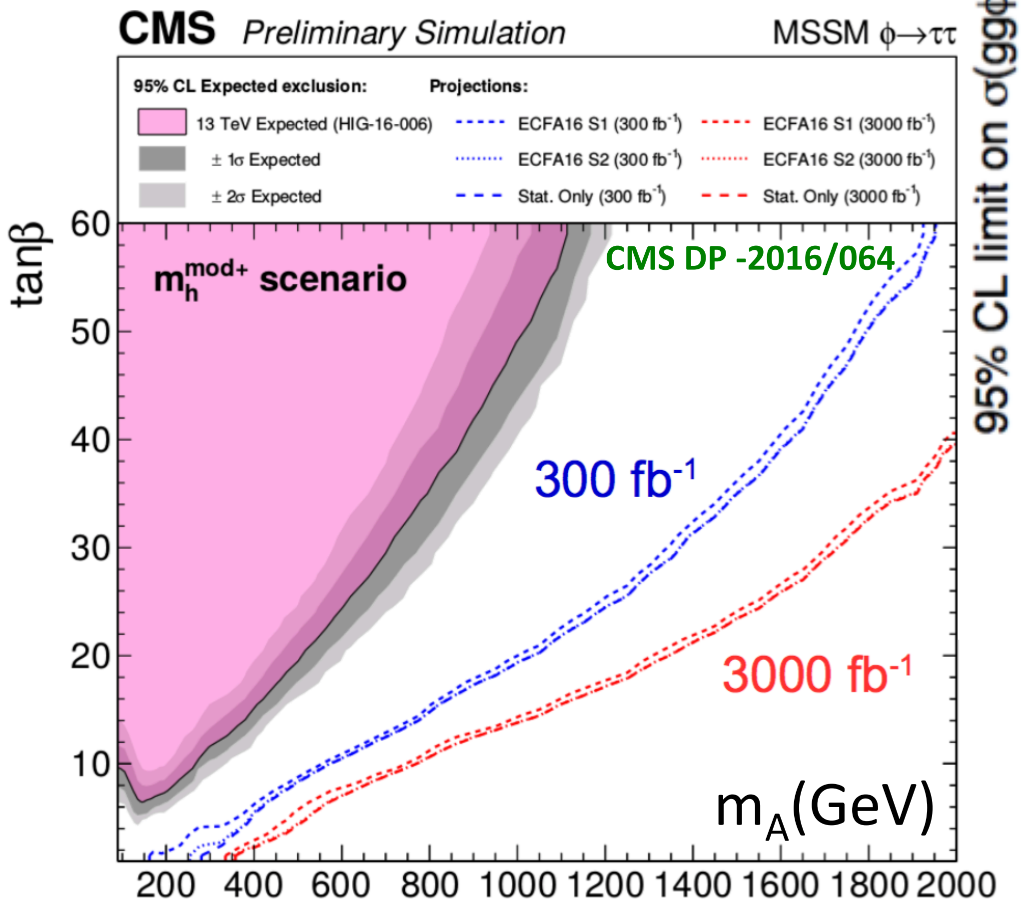
V. Martin – ECFA 2016, Aix-les-Bains

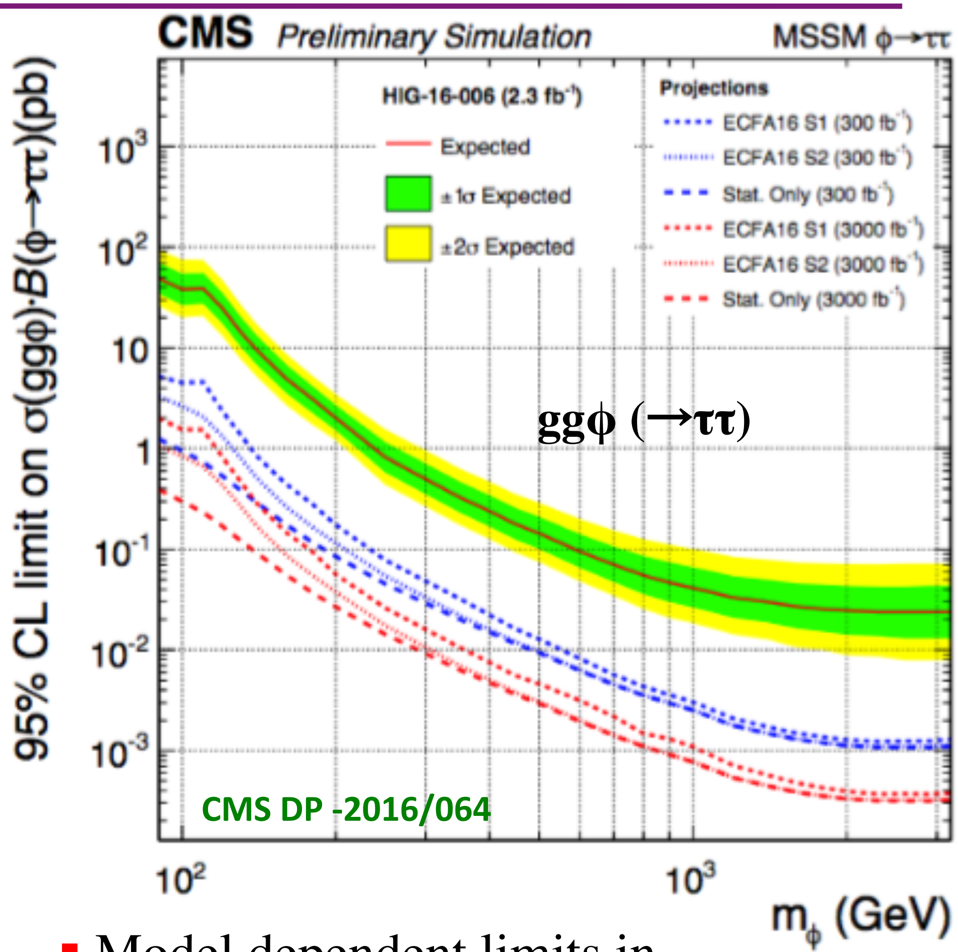


- Measuring HH production is challenging
- Need to use as many production mechanisms and final states as possible

BSM Higgs: heavy Higgs $\phi \rightarrow \tau^+\tau^-$

- One of the most sensitive channels for constraining extended Higgs models
- Cross section limits on:
  - $gg\,\phi\ (\rightarrow \tau^+\tau^-)$
  - $bb\,\phi\ (\rightarrow \tau^+\tau^-)$





- Model dependent limits in a benchmark scenario : $\mathbf{m^{mod+}}$
- Sensitivity at high m_A is still dominated by statistics

Conclusion & Outlook

- **High-Luminosity LHC very challenging environment**
- Expect that upgraded detector ~ same current performance at highest pile-up levels than now and even better in some areas

HL-LHC brings us:

- differential distributions & couplings measurements to W/Z/3rd gen. with **precision** and across **broad kinematics,** which could reveal signs of:
  - new particles in loops (too heavy to be produced, or hard to observe)
  - non-fundamental nature of Higgs
  - or simply confirm, in detail, a highly non-trivial part of the SM
- proof of expected coupling to 2nd generation (ex: $H \rightarrow \mu\mu$, $H \rightarrow J/\psi\, \gamma$)
- much higher sensitivity for rare decays involving new physics
- first exploration of Higgs potential (HH)

Prospect studies very likely conservatives since analyses often not optimised

Room for improvements

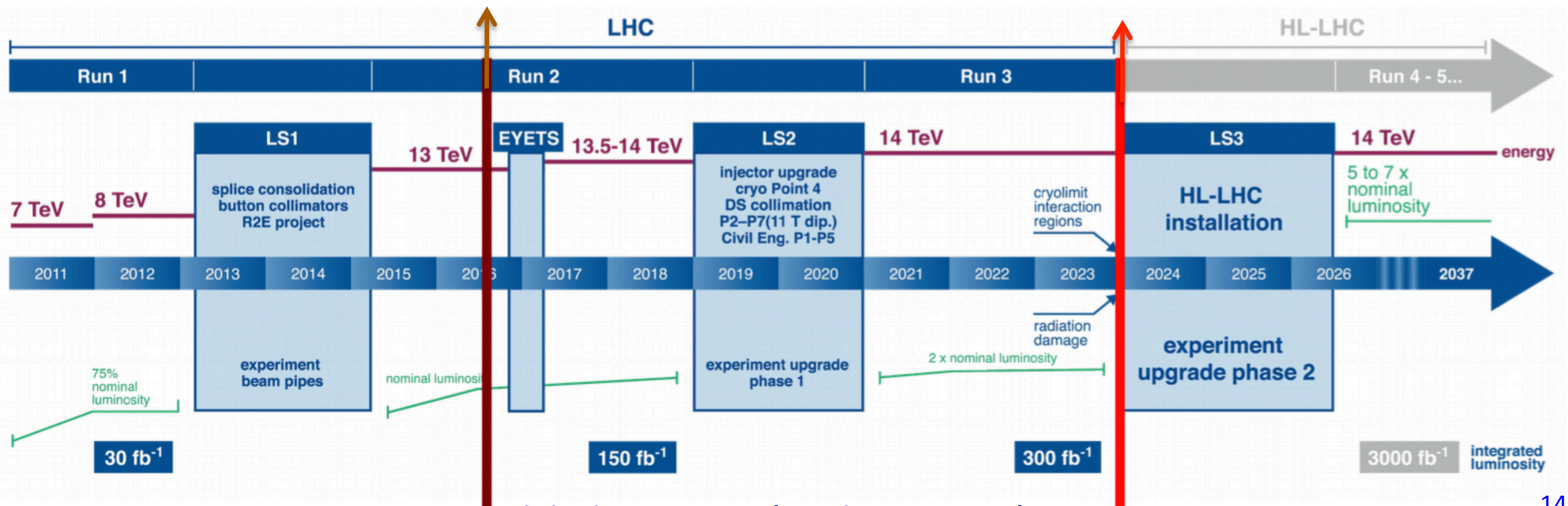
The direct BSM search program, will approach its asymptotic limits before the 3 ab^{-1} are collected, while the study of Higgs properties (together with high Q^2 gauge boson behavior) may well dominate the endgame

Backup

HL-LHC Plan

- **LHC Run 2 very successful:**
  integrated luminosity **delivered/per exp ~ 40 fb^{-1}**,
  Peak luminosity ~ 1.4 x 10^{34}cm^{-1}s^{-1})
- **HL-LHC goal:**
  - Total integrated luminosity of **3000 fb^{-1} in ~ 10 years**
    - * implies integrated luminosity of **250-300 fb^{-1}** per year
    - * requires **peak luminosity 5 (7) x 10^{34} cm^{-1}s^{-1}.** With levelling
    - * **mean number of collision per bunch crossing <PU> = 140 (200)**
  - Ultimate performance: peak luminosity **7.5** x **10^{34}** cm^{-1}s^{-1} and **4000 fb^{-1}**

Ten times the luminosity reach of first ~ 10 years of LHC operation



Upgrade of ATLAS & CMS

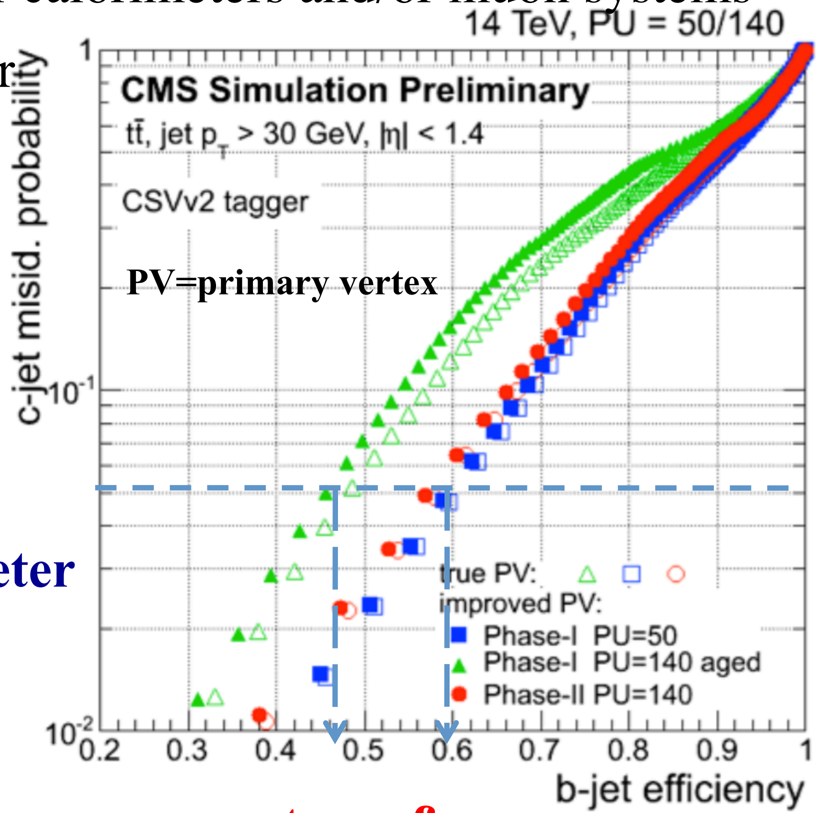
HL-LHC provides an extreme challenge to the experiments

- Very high pile up <**PU**> **= 140 (200)** → upgrade for PU mitigation
- Intense radiation doses → upgrade to improve radiation hardness

- **New triggering and data-acquisition** capabilities to cope with **higher data rates**
  - tracking information at the hardware level of the trigger
  - replacement front- and back-end electronics for calorimeters and/or muon systems

- **New tracking systems** with new silicon-sensor technology :
  - increase granularity & tracker coverage
  - lighter mechanical structures and material

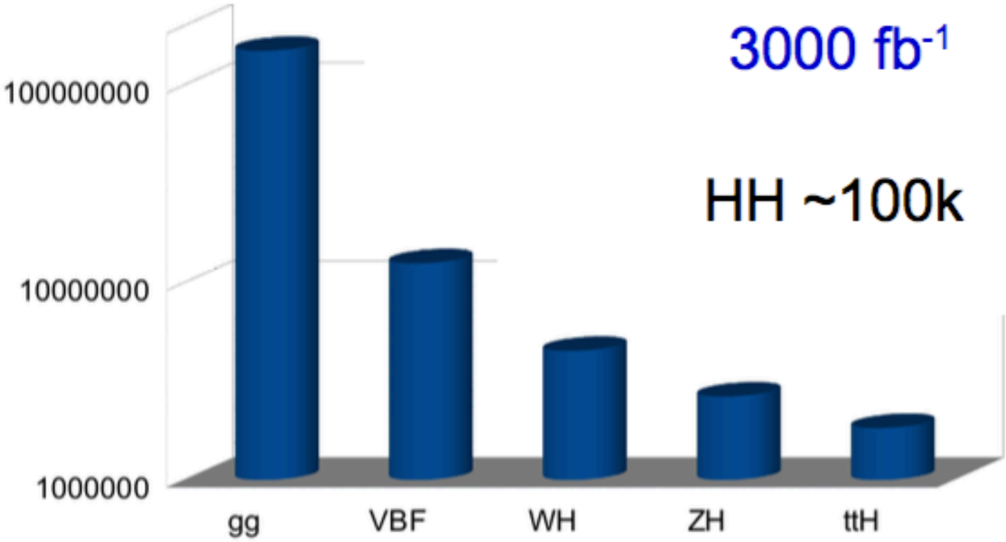
Improved b-tagging capabilities →



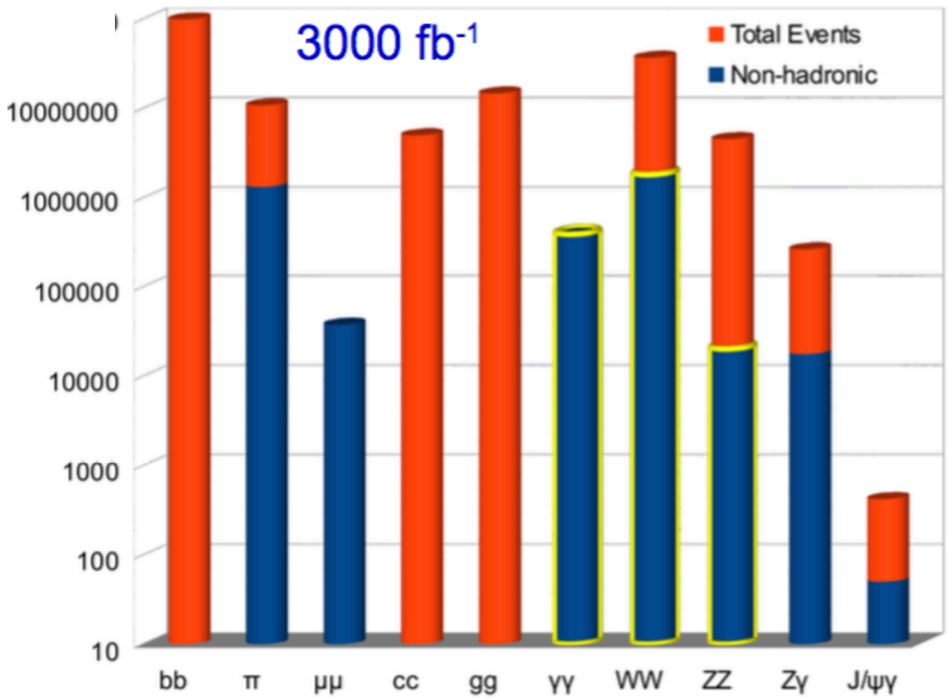
- ATLAS**: high-granularity timing detector** (~ps) in front of the endcap LAr calorimeters
- CMS: new **high-granularity endcap calorimeter**
- Muons **: add new chambers (or replace)** and read-out electronics

Goal is to maintain or improve over current performance

Higgs Production Channels



Higgs Decay Channels



Higgs width Γ_H from m_{4l} (off/on-shell)

- Constrain the Higgs boson width Γ_H from ratios:

$$\frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

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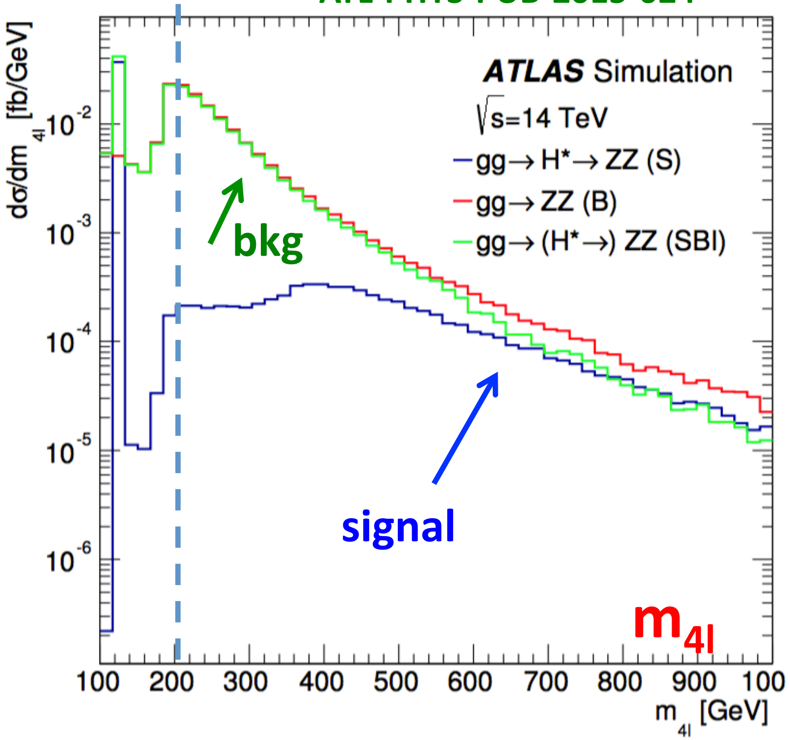
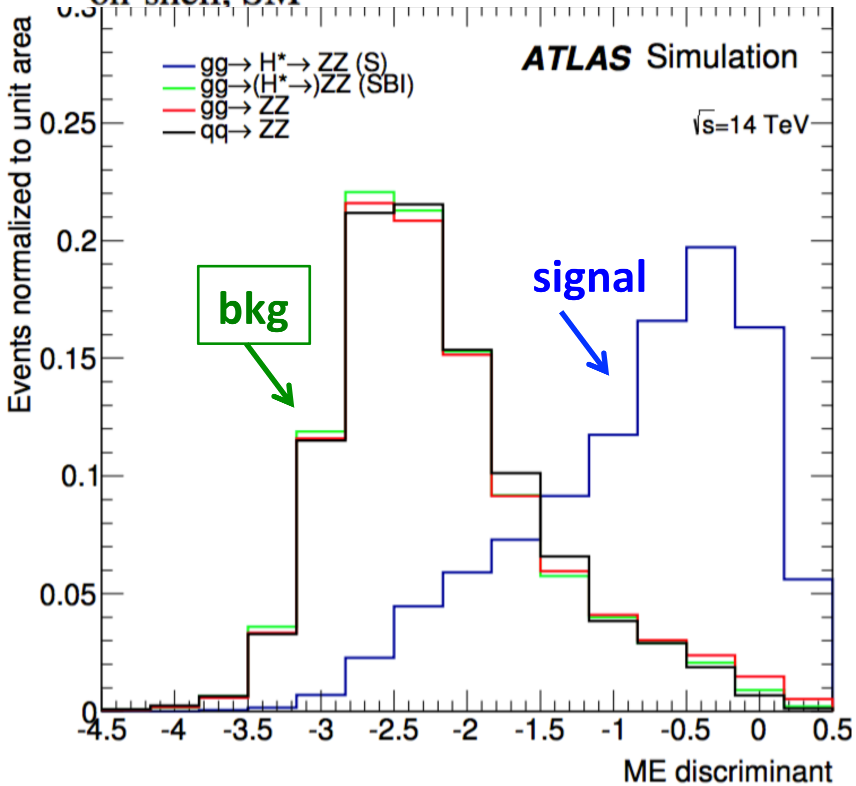


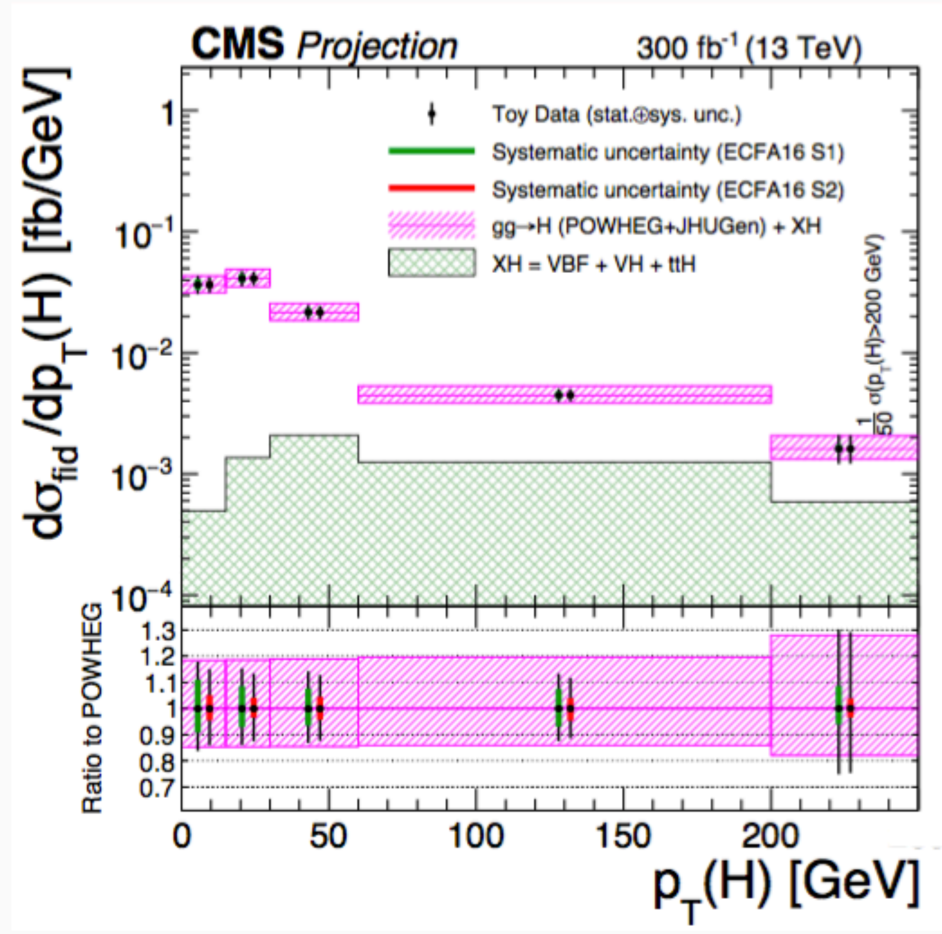


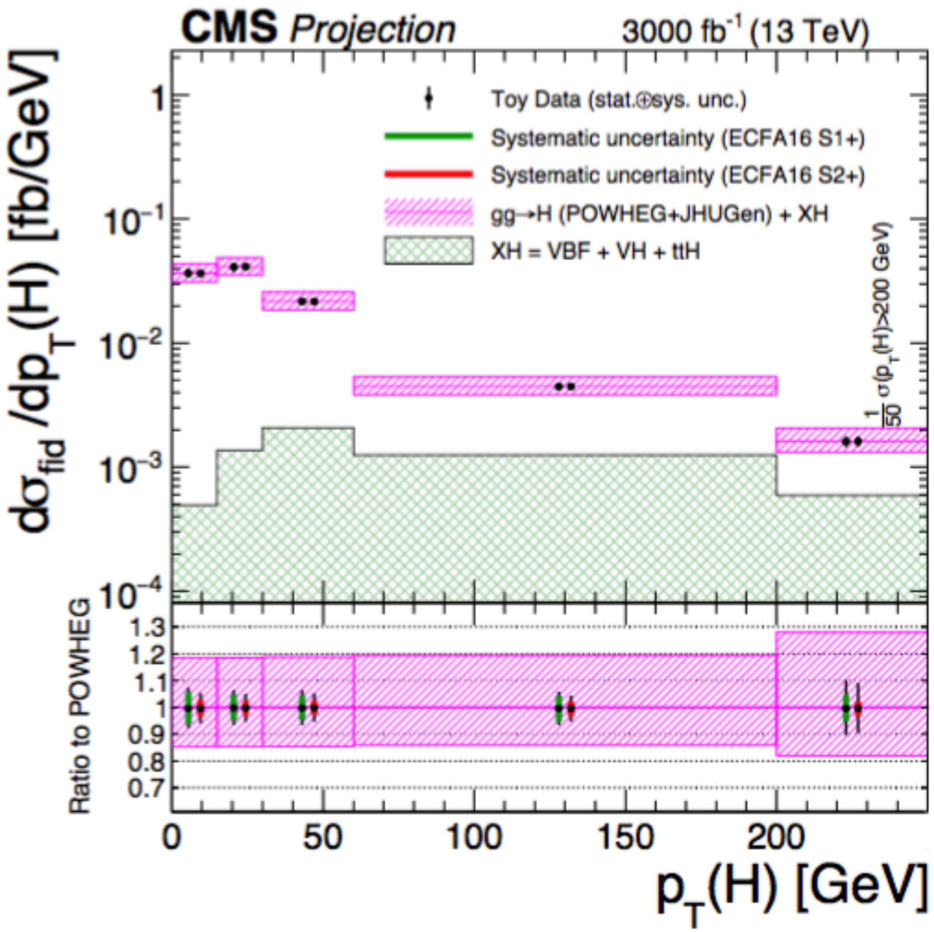
- Use m(4l) shape and matrix element to discriminate signal from background

$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV (stat+sys)

Run 1 limit:
$\Gamma_H < 22.7$ MeV at 95% CL (WW, ZZ)

Differential $p_T(H)$ Cross Section





Michelangelo L. Mangano

$$O = |\langle f|L|i\rangle|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. $\delta O = 1\%$ ⇒ Λ ~ 2.5 TeV

For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

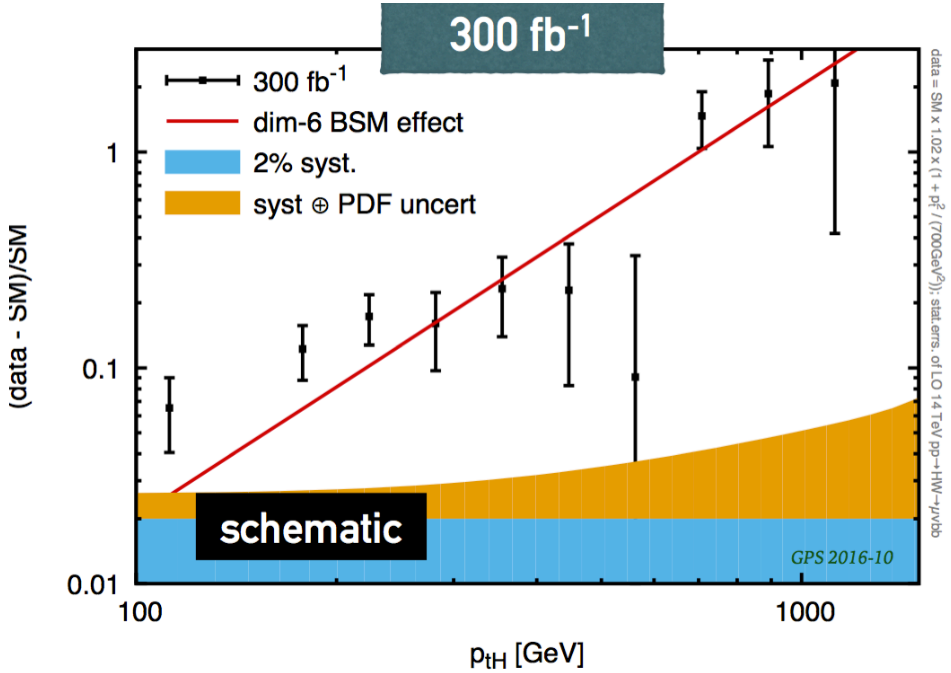
$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

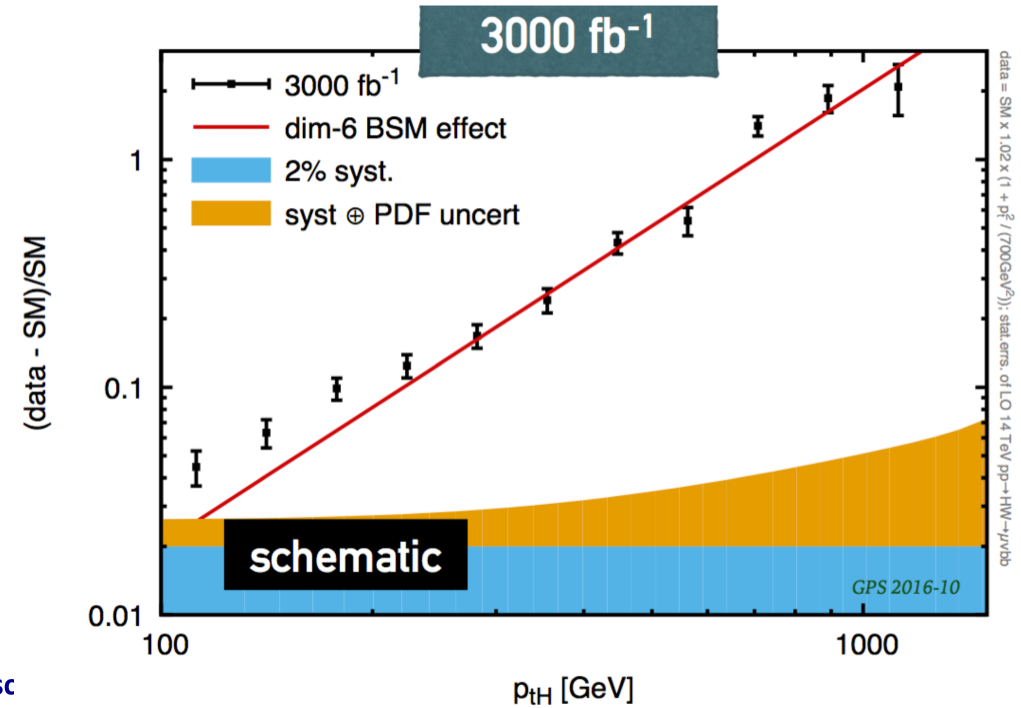
⇒ **kinematic reach** probes large Λ even if precision is low

e.g. $\delta O_Q = 15\%$ at Q=1 TeV ⇒ Λ~2.5 TeV

WH at large Q^2 with dim-6 BSM effect

G.Salam





Study of the Higgs potential : HH production

- **Milestone in Higgs physics:**

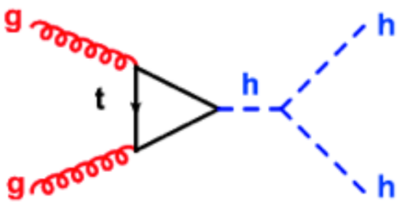
  access the Higgs self-coupling

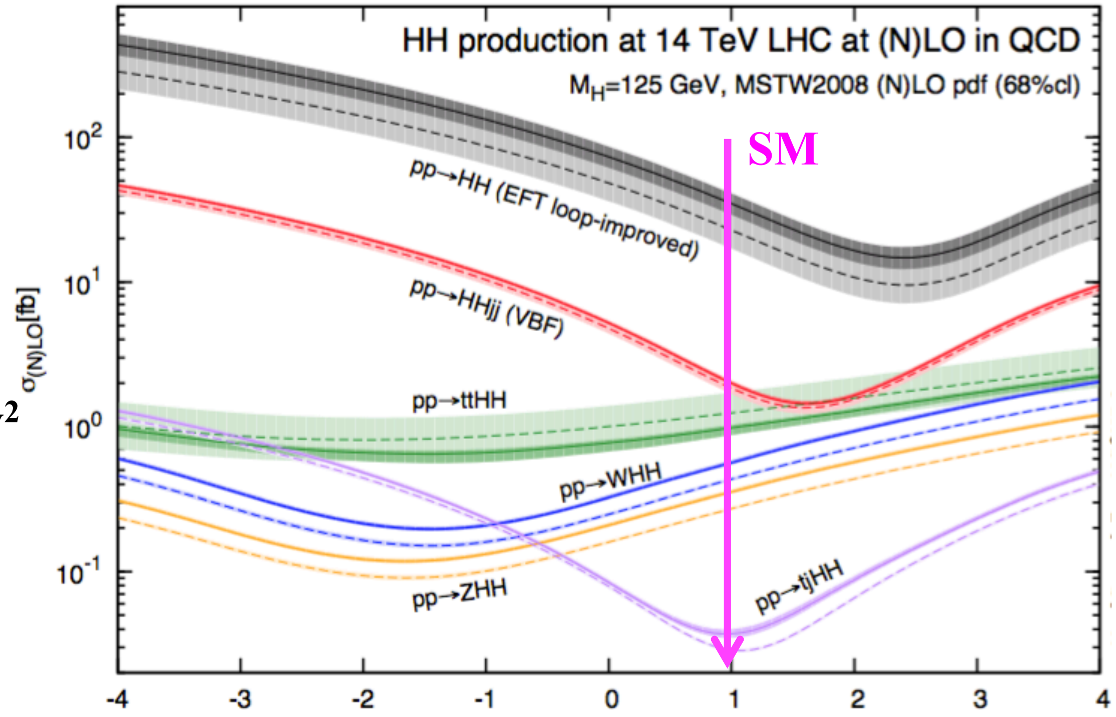
$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$\phi(x) = \phi_0 + h(x)$$

$\lambda = m_H^2/2v^2$

$$\mathcal{L} = .. - \lambda\, v\, h^3(x) + ..$$





λ/λ_{SM}

- **Very challenging:**
  - Low production cross section : $\sigma\,(pp \to HH)^{SM}_{NNLO+NNLL} = 33.45$ fb (@ 13TeV)

    → Use Higgs decay channels with high branching ratios (al least for one of the two H) : **HH→ bb XX** where **X = b, W, τ, γ**
  - Huge background

Table 1: Branching ratios for different HH final states, and their corresponding overall expected yields in 3000 fb^{-1} of data, assuming a total production cross section of 40.8 fb [7,8] and a Higgs mass of 125 GeV.

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	4.1×10^4
$b\bar{b} + W^+W^-$	25%	3.1×10^4
$b\bar{b} + \tau^+\tau^-$	7.4%	9.0×10^3
$W^+W^- + \tau^+\tau^-$	5.4%	6.6×10^3
$ZZ + b\bar{b}$	3.1%	3.8×10^3
$ZZ + W^+W^-$	1.2%	1.4×10^3
$\gamma\gamma + b\bar{b}$	0.3%	3.3×10^2
$\gamma\gamma + \gamma\gamma$	0.0010%	1

Study of the Higgs potential : HH

- **Channels investigated:**

HH→ bb ττ
HH→ bb bb
HH→ bb γγ
} ATLAS & CMS

tt HH, HH→ bb bb — ATLAS

HH→ bb WW → bb ℓν ℓν, bb jj ℓν, CMS

- **Example: HH→ bb bb (ATLAS)**
  Projection from extrapolation of Run 2 results (resolved analysis)

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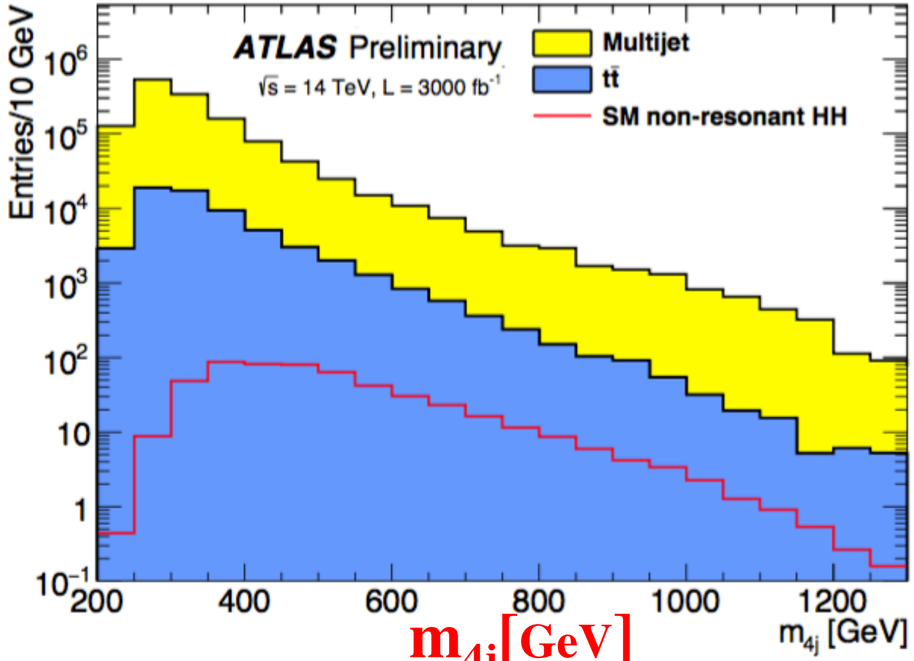
- Trigger threshold: **p_T(jet) > 30 GeV** and **p_T(jet) > 75 GeV**
- Same jet reconstruction and b-quark jet identification performance
- Same selection and statistical analysis technique
- Main background (**95%**) multijet is extrapolated from Run 2

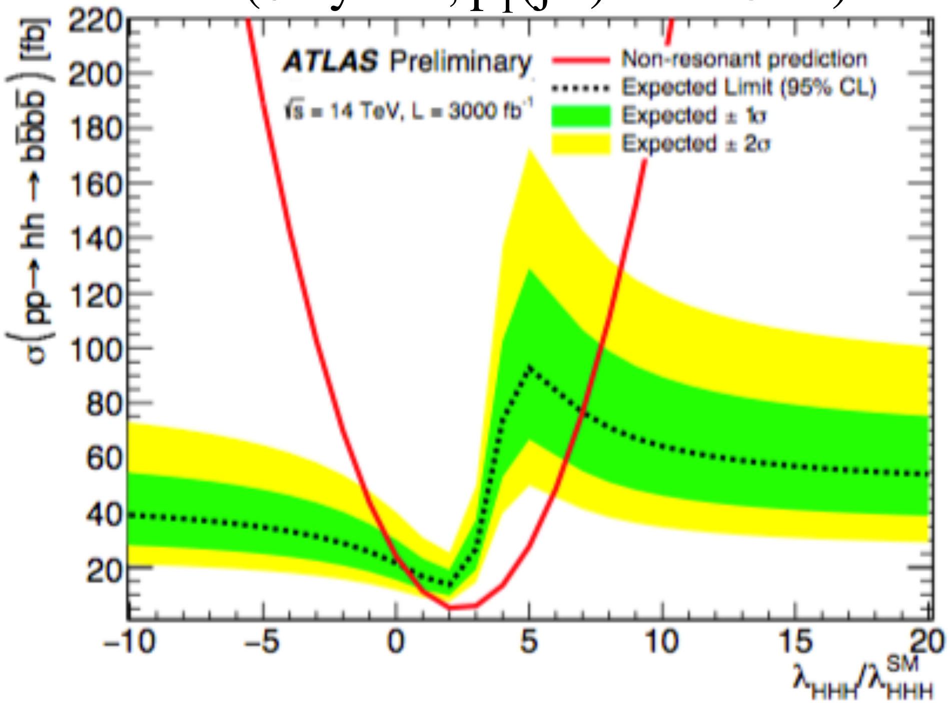


m_{4j}[GeV]

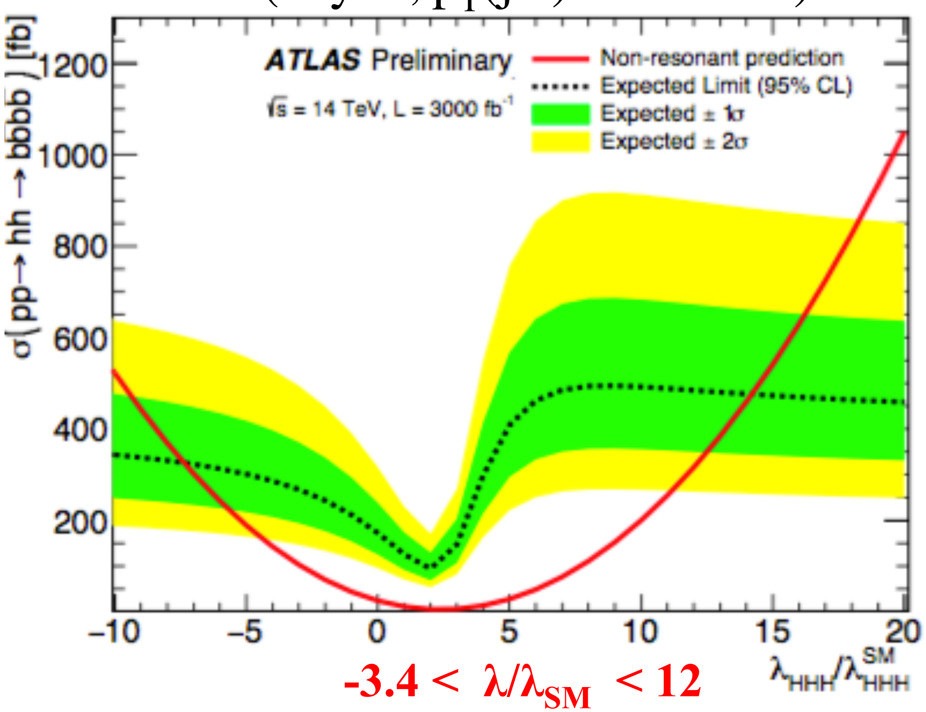
HH→ bbbb

- Main impact of the uncertainties on the 95% C.L. exclusion is from the background modelling
- **m_{4j}** as function of **λ/λ_{SM}** generated with morphing technique used to set 95% C.L. upper limit on the cross-sections

Optimistic scenario (only stat, p_T(jet) > 30 GeV)



Pessimistic scenario (+syst., p_T(jet) > 75 GeV)

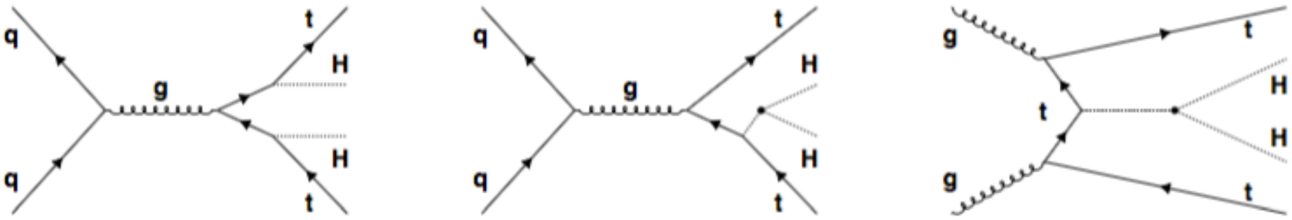


$-3.4 < \lambda/\lambda_{SM} < 12$

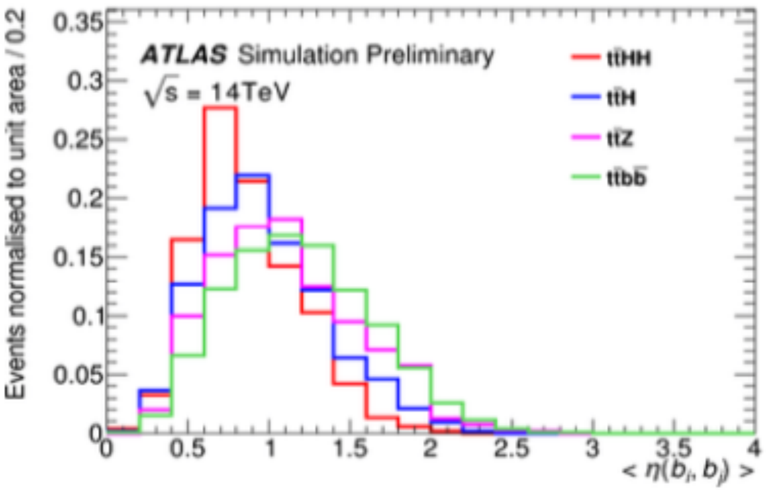
Maxim Perelstein, Cornell
Higgs Couplings Workshop, SLAC-Nov 2016

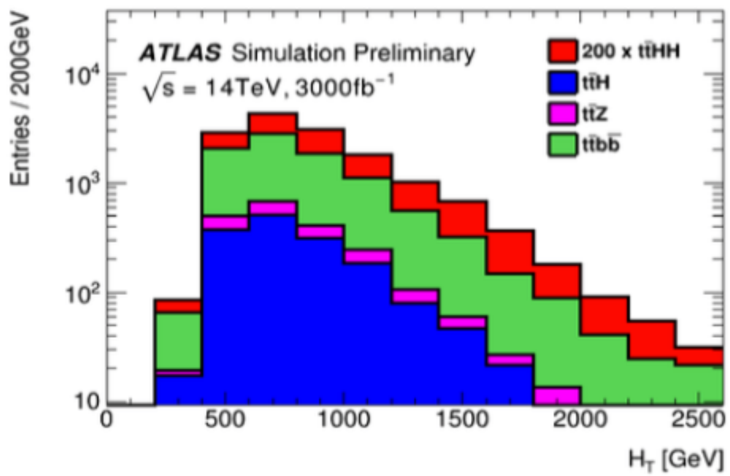
- Measuring Higgs cubic coupling gives new information about the shape of the Higgs potential
- Large (up to ~factor-of-two) deviations from the SM are possible, consistent with current Higgs data
- Models with first-order electroweak phase transition (needed for viable electroweak baryogenesis) generically predict large deviations of Higgs cubic from the SM
- A ~10%-level measurement of the Higgs cubic would provide a stringer test of such models

ttHH



- (ttHH) ~ 1 fb
- 6 b-jets, 2 light jets, e/μ and missing-ET
- Cut-based analysis; no cut on Higgs candidate mass, too many combinatorics

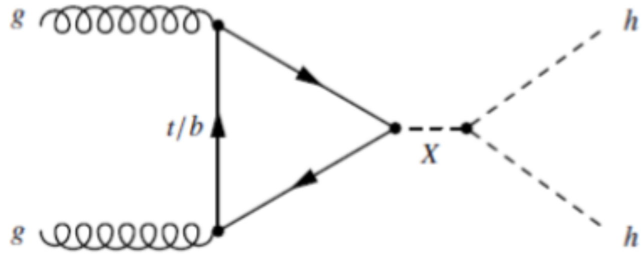




- For ≥5 b-tags: 25 signal events, 7100 background
- background dominated by c-jets mis-tagged as b-jets from W→cs
- **significance of ttHH production (no syst. error): 0.35 σ**

Sensitivity to resonant bbbb (spin 0)

- Process = gg → X → HH → bbbb

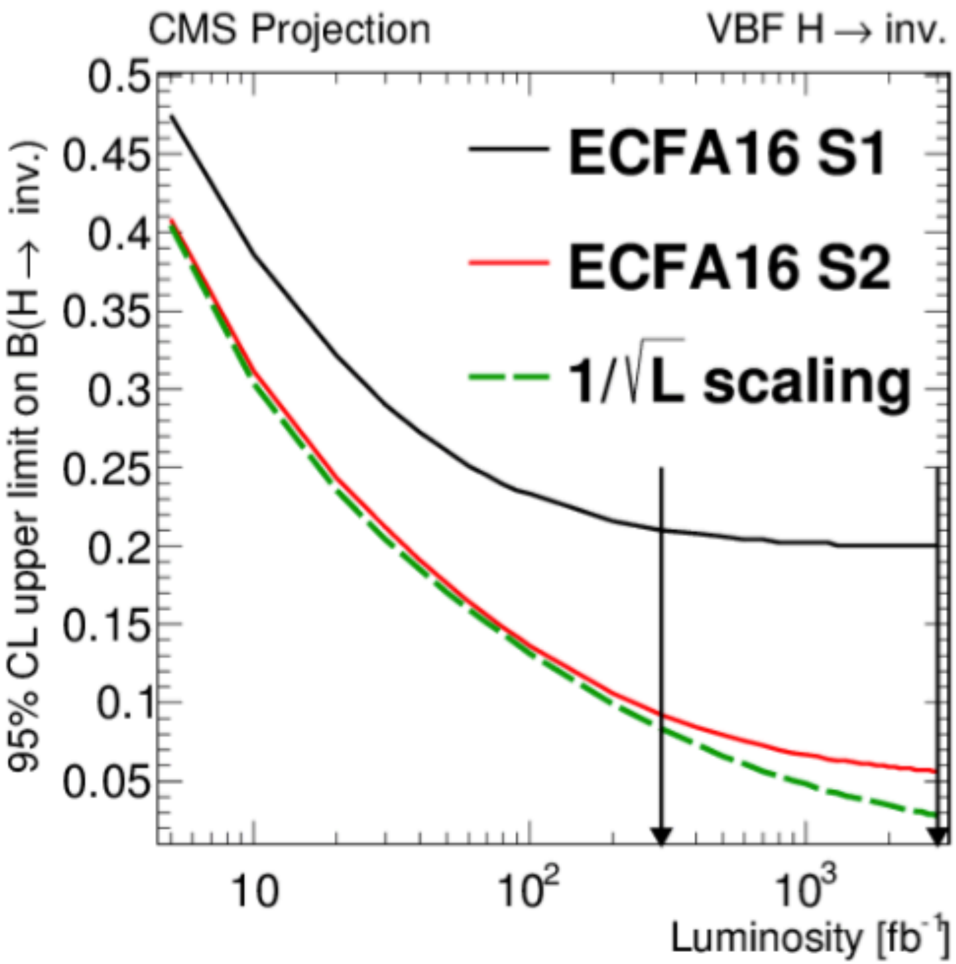


- Projection based on the 13 TeV analysis (2.3 fb^{-1}, **CMS-PAS-HIG-16-002**)
- m_X = mass of the spin 0 resonance
- Λ_R = value of the mass scale excluded at 95% CL

CMS DP -2016/064

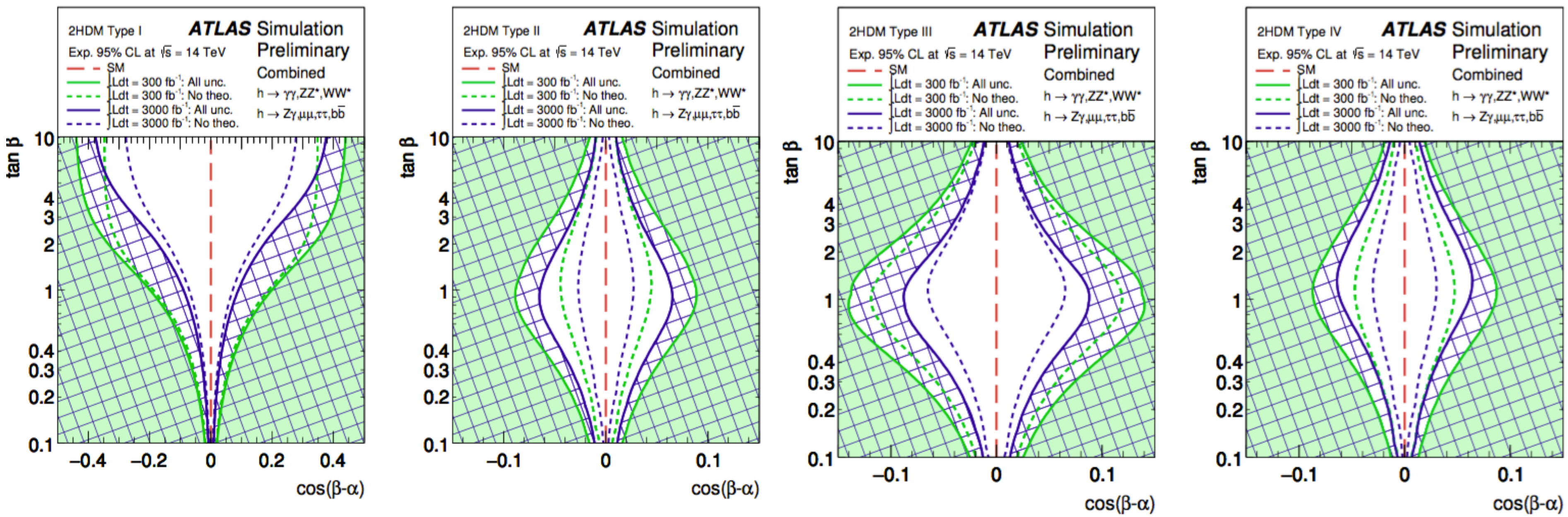
m_X (TeV)	Median expected limits on σ (fb)			$\sigma_R(\Lambda_R = 1$ TeV) (fb)	Λ_R (TeV) excluded
	2.3 fb^{-1}	ECFA16 S2+	Stat. Only		
0.3	2990	46	41	7130	13
0.7	129.4	7.3	3.4	584	8.9
1.0	81.5	4.4	2.4	190	6.6

VBF H invisible



	ECFA16 S1	ECFA16 S2	$1/\sqrt{L}$ scaling
300 fb^{-1}	0.210	0.092	0.084
3000 fb^{-1}	0.200	0.056	0.028

BSM Higgs constraints



(a) Type I

(b) Type II

(c) Type III

(d) Type IV

Higgs couplings: deviations w.r.t the SM ($y_f^{SM} \sim m_f / v \quad y_V^{SM} \sim M^2_{W,Z} / v$)

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$$y_{V,i} = \sqrt{\kappa_{V,i} \frac{g_{V,i}}{2v}}$$

$$y_{F,i} = \kappa_{F,i} \frac{g_{F,i}}{\sqrt{2}}$$