Di-Higgs studies

FCC Week Berlin
29-05 01-06 2017

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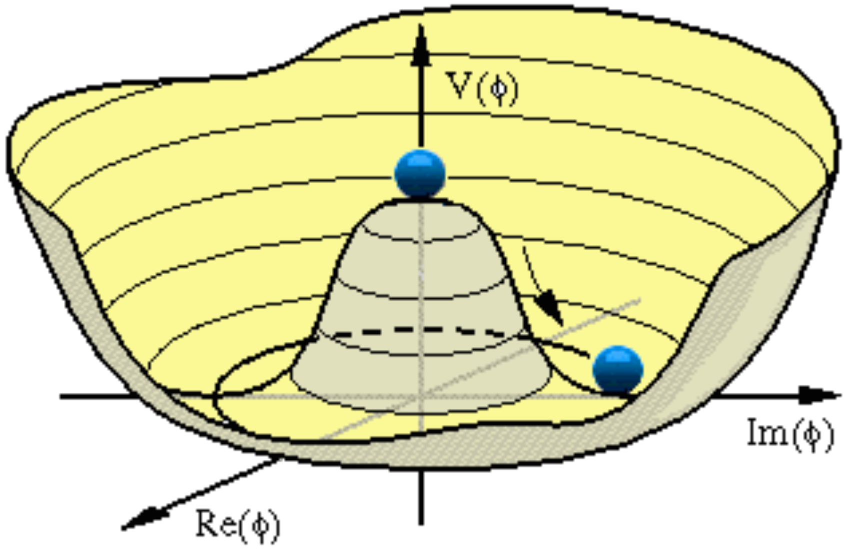
The Higgs potential

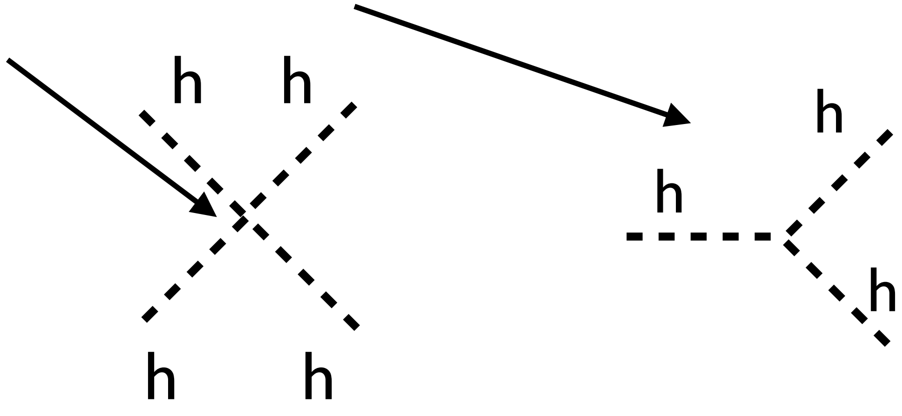
$$V(h) = \mu^2\frac{h^2}{2} + \lambda\frac{h^4}{4}$$



After spontaneous symmetry breaking:

$$\lambda h_0^2\eta^2 + \frac{\lambda}{4}\eta^4 + \lambda h_0\eta^3$$

$$m_h^2 = 2\lambda h_0^2$$



The strength of the triple and quartic couplings is fully fixed by the potential shape.

Why is it relevant?

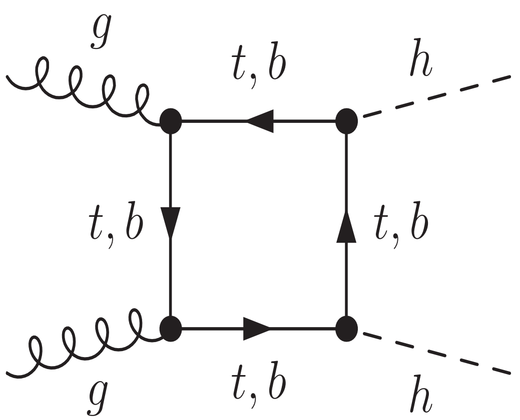
1) it is the last missing ingredient of the SM, like the Higgs boson was the last missing particle, we need to prove that things really behave like we expect;

2) It has implications on the stability of the Vacuum;

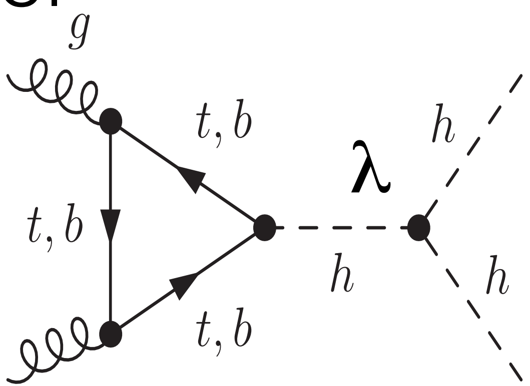
3) It could make the Higgs boson a good inflation field (see backup)

hh production and decay

Standard Model



box

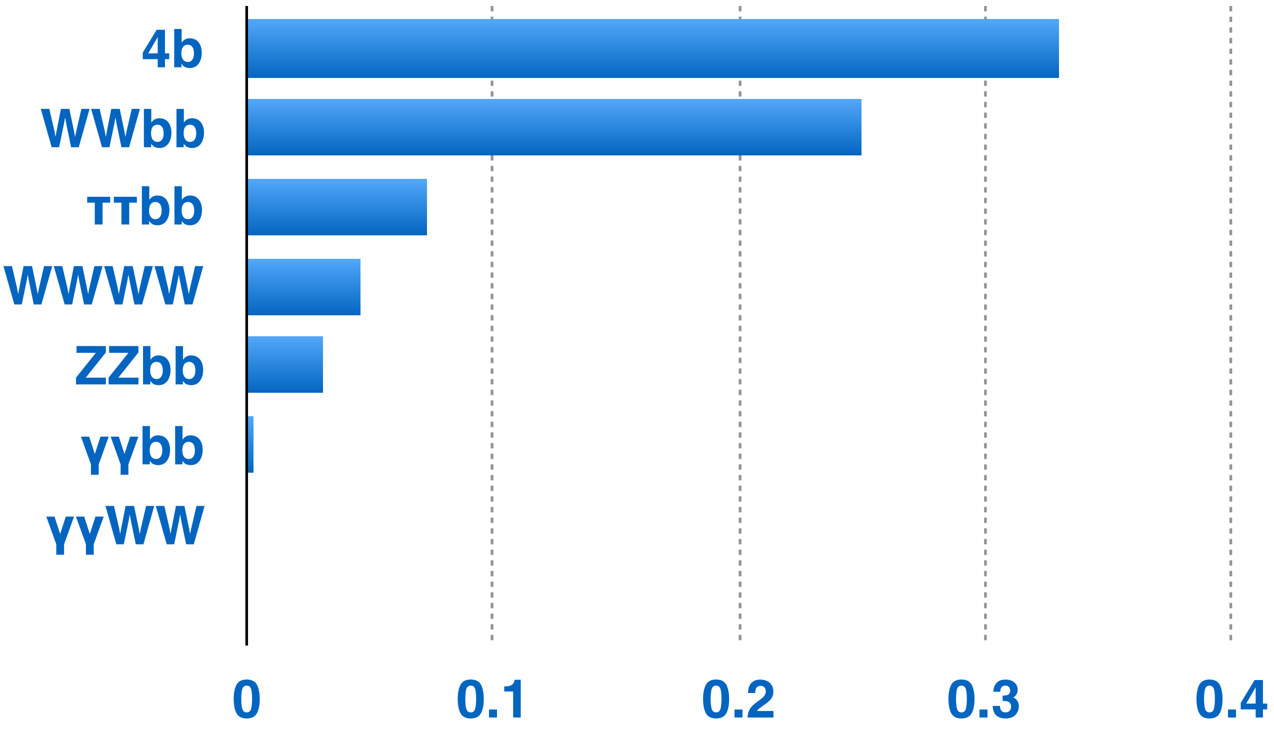


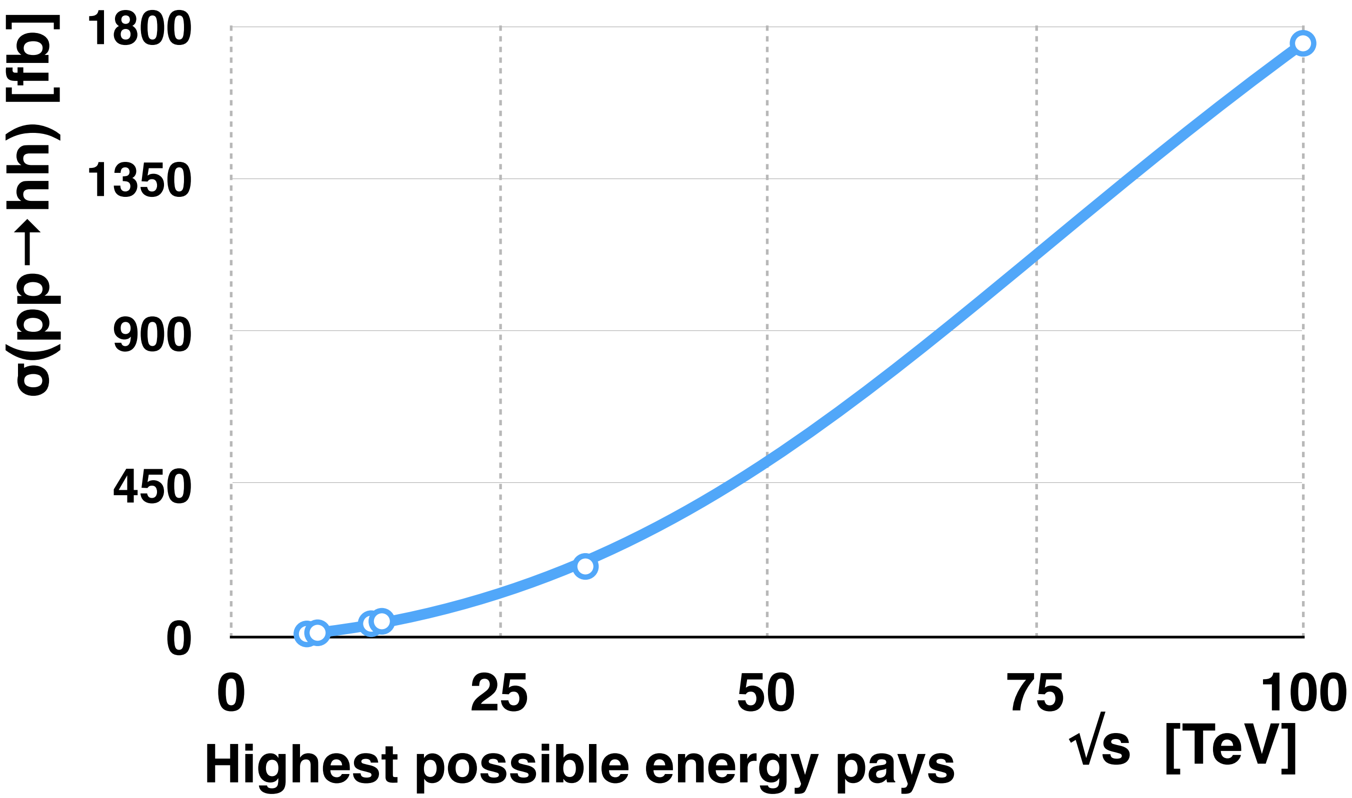
triangle

NNLO with full top mass *NLO $m_t \rightarrow \infty$

m_h = 125.09 GeV	σ(fb)	scale unc. (%)	PDF unc. (%)	α_s unc.
√s = 7 TeV	7.71	+4.0/-5.7	± 3.4	± 2.8
√s = 8 TeV	11.17	+4.1/- 5.7	± 3.1	± 2.6
√s = 13 TeV	37.91	+4.3/-6.0	± 2.1	± 2.3
√s = 14 TeV	45.00	+4.4-6.0	± 2.1	± 2.2
√s = 33 TeV*	206.6	+15.1 - 12.5	+5.8/-5.0	
√s = 100 TeV	1748	+5.1/-6.5	± 1.7	± 2.0

Higgs decay branching fraction





Highest possible energy pays

Current status @LHC

	$\sqrt{s}$ [TeV]	L (fb^{-1})	σ(fb)	σ/σ_{SM}
ATLAS: 4b, bbττ, bbγγ, WWγγ WWWW	8	20.3	< 470	< 48
ATLAS: 4b	13	13.3	< 1000	< 29
CMS: 4b	13	2.32	< 11760	< 310
ATLAS: WWγγ	13	13.3	< 12900	< 340
ATLAS: bbγγ	13	3.2	< 5400	< 142
CMS: bbττ	13	39.5	< 950	< 25
CMS: WWbb	13	36	< 3270	< 86

HL-LHC $\sqrt{s}$ = 14 TeV, L = 3000 fb^{-1}	Exp. sign	λ/λ_{SM} 95% C.L.	exp σ/σ_{SM}
ATLAS: bbγγ	1.05 σ	[-0.8, 7.7]	< 1.7 [recalc.]
CMS: bbγγ	1.6 σ		< 1.3
ATLAS: 4b	?	[0.2, 7.0]$_{stat.}$, [-3.5, 11]	< 1.5$_{stat.}$, 5.2
CMS: 4b	0.67		< 2.9$_{stat.}$, 7
ATLAS: bbττ	0.6 σ	[-4, 12]	< 4.3
CMS: bbττ	0.39		<3.9$_{stat.}$, 5.2
CMS: VVbb	0.45		< 4.6$_{stat.}$, 4.9

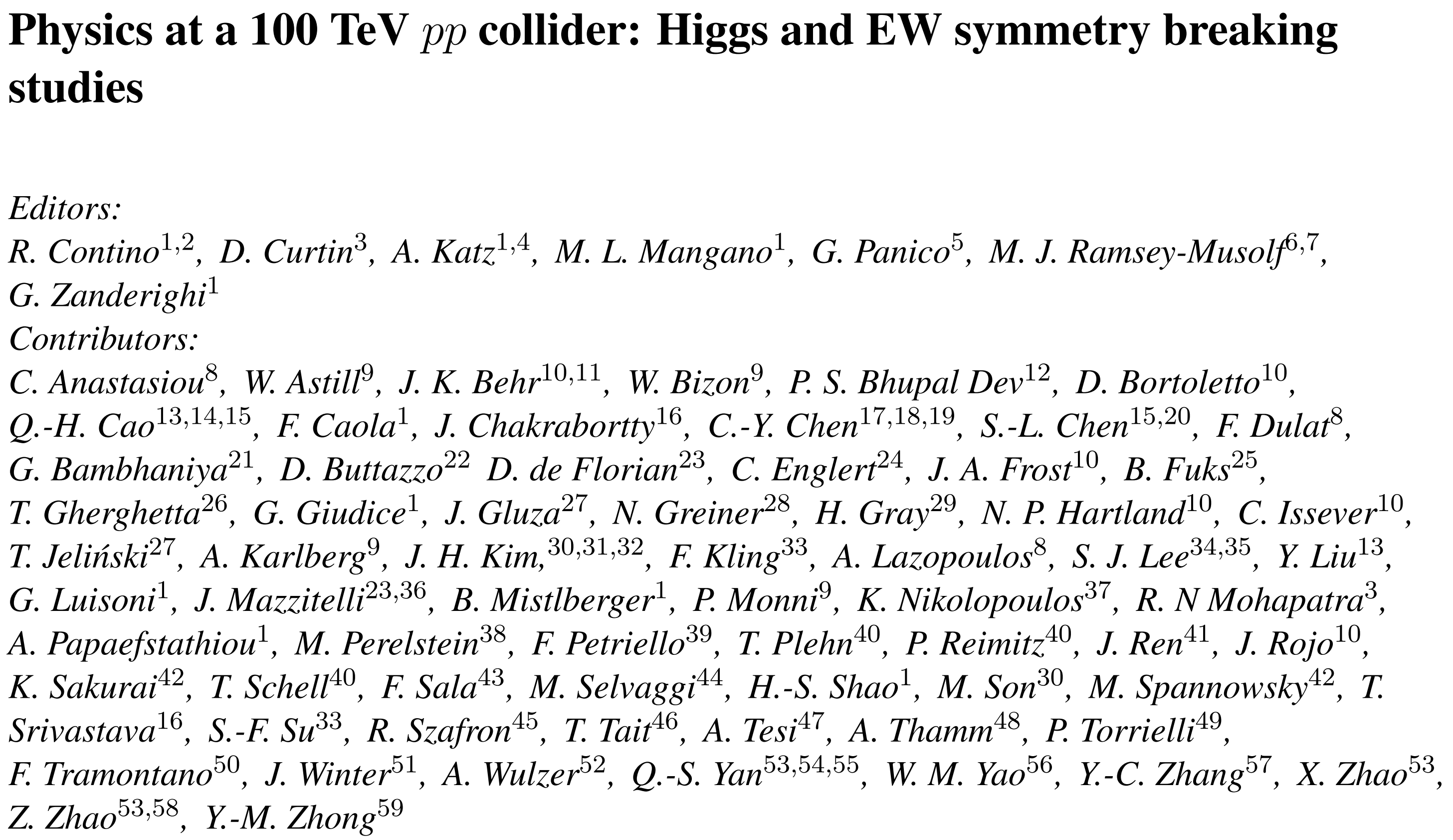
Present best channel 4b, situation will change with higher statistics when syst. dominated channels will saturate their sensitivity.

HL-LHC doesn't seem able to provide a useful constraint on λ, it could probably provide an observation of the whole process.

But advanced analysis techniques are on going… (more this summer)

FCC studies

- Main references
  - Physics at a 100 TeV pp collider [arXiv:1606.09408]
  - 1st FCC-hh Physics Workshop - 16-20 January 2017 CERN
  - FCC-hh physics analysis meetings
  - studies performed with different level of details, in particular trigger eff. simulatio pile-up studies need to be implemented in many of them, but first bulk of phys. potentiality ready.



Physics at a 100 TeV *pp* collider: Higgs and EW symmetry breaking studies

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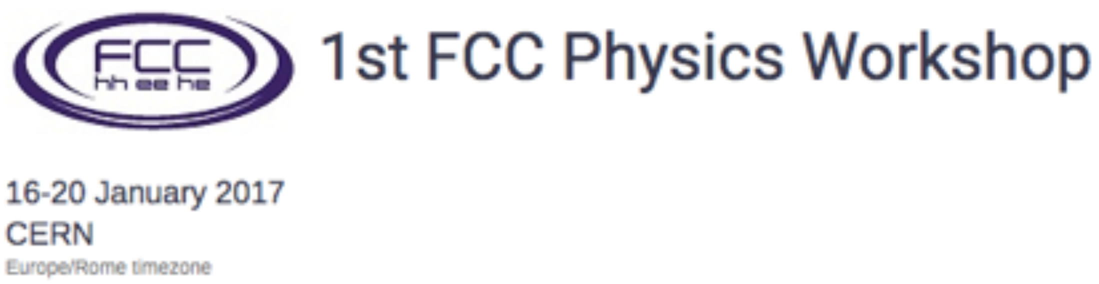


1st FCC Physics Workshop

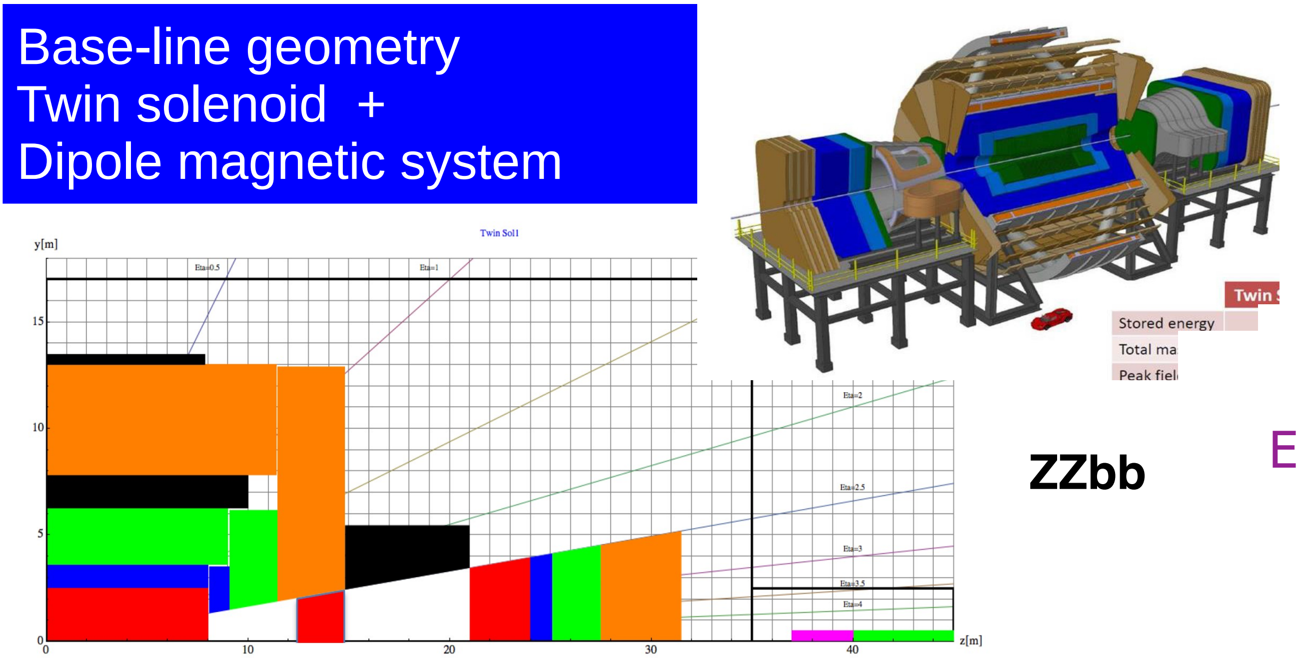
16-20 January 2017
CERN
Europe/Rome timezone

Pile-up and det. simulation

pile-up configuration used in this presentation (when used), simulated with Delphes using CMS HL-LHC cards
Jet pile-up subtraction through Jet Area correction

- WWbb 50, 200, 900 vertices

Base-line geometry
Twin solenoid +
Dipole magnetic system



ZZbb

Tracker
EMCAL
HCAL
Coil+Cryostat
Muon system

Fwd Tracker
Dipole

Detector simulation with Delphes or simple smearing of truth level objects

7

Simulation of the 5 ns low and high luminosity phase and of the 25 ns high luminosity phase

Calorimetry

ECAL granularity:
0.0125 x 0.0125 $|\eta| < 2.5$
0.025 x 0.025 $2.5 < |\eta| < 4.0$
0.05 x 0.05 $4.0 < |\eta| < 6.0$

ECAL Energy Resolution:
$\sigma(E)/E = 10\% / \sqrt{E} \oplus 1\%$
$|\eta| < 6.0$

HCAL granularity:
0.05 x 0.05 $|\eta| < 2.5$
0.1 x 0.1 $2.5 < |\eta| < 4.0$
0.2 x 0.2 $4.0 < |\eta| < 6.0$

HCAL Energy Resolution:
$\sigma(E)/E = 50\%/\sqrt{E} \oplus 3\%$ $|\eta| < 4.0$
$\sigma(E)/E = 100\%/\sqrt{E} \oplus 5\%$ $|\eta| < 6.0$

Tracking

Efficiency c-quark jets:
4 % $|\eta| < 2.5$
3 % $2.5 < |\eta| < 4.0$

Efficiency light-quark jets:
0.1 % $|\eta| < 2.5$
0.075 % $2.5 < |\eta| < 4.0$

Efficiency b-quark jets:
75% WWbb 85 % ZZbb $|\eta| < 2.5$
64% $2.5 < |\eta| < 4.0$

z_0 resolution (*)
- ***in $|\eta|<2.5$***
  - **$\sigma(z_0)$= 0.01 mm , p_T<5 GeV**
  - **$\sigma(z_0)$= 0.005 mm , p_T>5 GeV**
- **In $2.5<|\eta|<4$**
  - **$\sigma(z_0)$= 0.1 mm , p_T<5 GeV**
  - **$\sigma(z_0)$= 0.05 mm , p_T>5 GeV**
- **In $4.0<|\eta|<6.0$**
  - **$\sigma(z_0)$= 1.0 mm , p_T<5 GeV**
  - **$\sigma(z_0)$= 0.5 mm , p_T>5 GeV**

hh→bbγγ

Selection

1. 2γ, 2 b-jet $|\eta| < 4.5$, $p_T^{sub} > 35$, $p_T^{lead} > 60$ GeV
2. $|m_{\gamma\gamma} - m_h| < 2.0$, $100 < m_{bb} < 150$ GeV
3. p_T^{bb}, $p_T^{\gamma\gamma} > 100$ GeV, ΔR_{bb}, $\Delta R_{\gamma\gamma} < 3.5$

Simulation 6T magnetic field

Signal LO samples, Pythia6 showering, no pile-up simulation

Process	Acceptance cuts [fb]	Final selection [fb]	Events ($L = 30$ ab^{-1})
$h(b\bar{b})h(\gamma\gamma)$ (SM)	0.73	0.40	12061
$bbj\gamma$	132	0.467	13996
$jj\gamma\gamma$	30.1	0.164	4909
$t\bar{t}h(\gamma\gamma)$	1.85	0.163	4883
$b\bar{b}\gamma\gamma$	47.6	0.098	2947
$b\bar{b}h(\gamma\gamma)$	0.098	7.6×10^{-3}	227
$bj\gamma\gamma$	3.14	5.2×10^{-3}	155
Total background	212	1.30	27118

$S/\sqrt{B}$ 23 [3 ab^{-1}] 73 [30 ab^{-1}]

$\Delta\sigma/\sigma$ = 1.6% [30 ab^{-1}] $\Delta\lambda/\lambda$ = 6% [2.5% sig. syst.]

Updates:

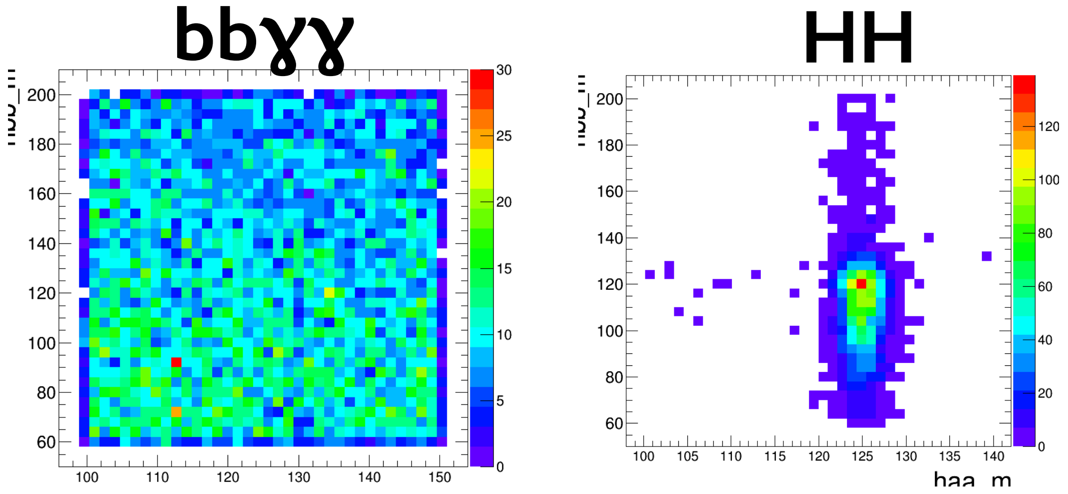
4T magnetic field
Pythia8 showering

Process	Events
hh→bbγγ	12300
bbjγ	16700
jjγγ	14272
tth(γγ)	14213
bbγγ	7078
bjγγ	1873
Total bkg.	66436

2x Total background

$\Delta\sigma/\sigma$ = 2.1% [30 ab^{-1}]
$\Delta\lambda/\lambda$ = 7% [2.5% sig. syst.]

Shape analysis m_{jj}, $m_{\gamma\gamma}$

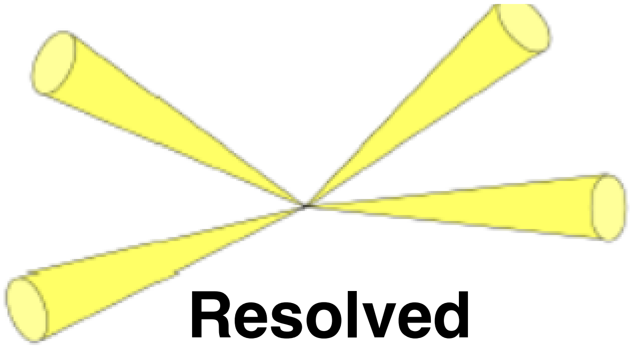


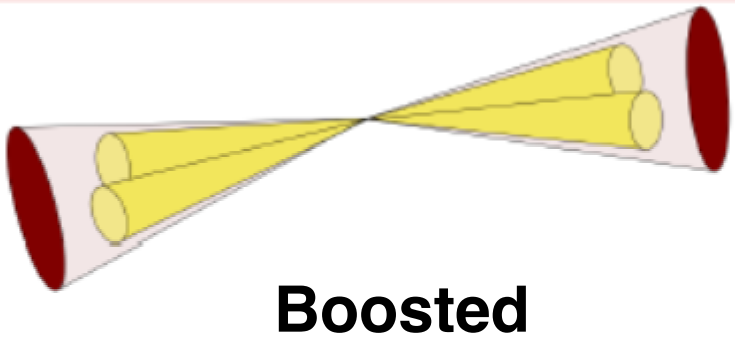
$\Delta\sigma/\sigma$ = 1.6%
$\Delta\lambda/\lambda$ = 4.2% [0% sig. syst.]

$hh \rightarrow bbbb$

Main background: multi-jet 4b
Strategy: truth level study, resolved + boosted analysis (Neural Network used as signal discriminator)

1. R 0.4 jets p_T > 40 GeV, $|\eta|$ < 2.5
2. R 1.0 jets p_T > 200 GeV, $|\eta|$ < 2.0
3. R 0.3 jets ghost ass. to R 1.0 p_T > 50 $|\eta|$ < 2.5

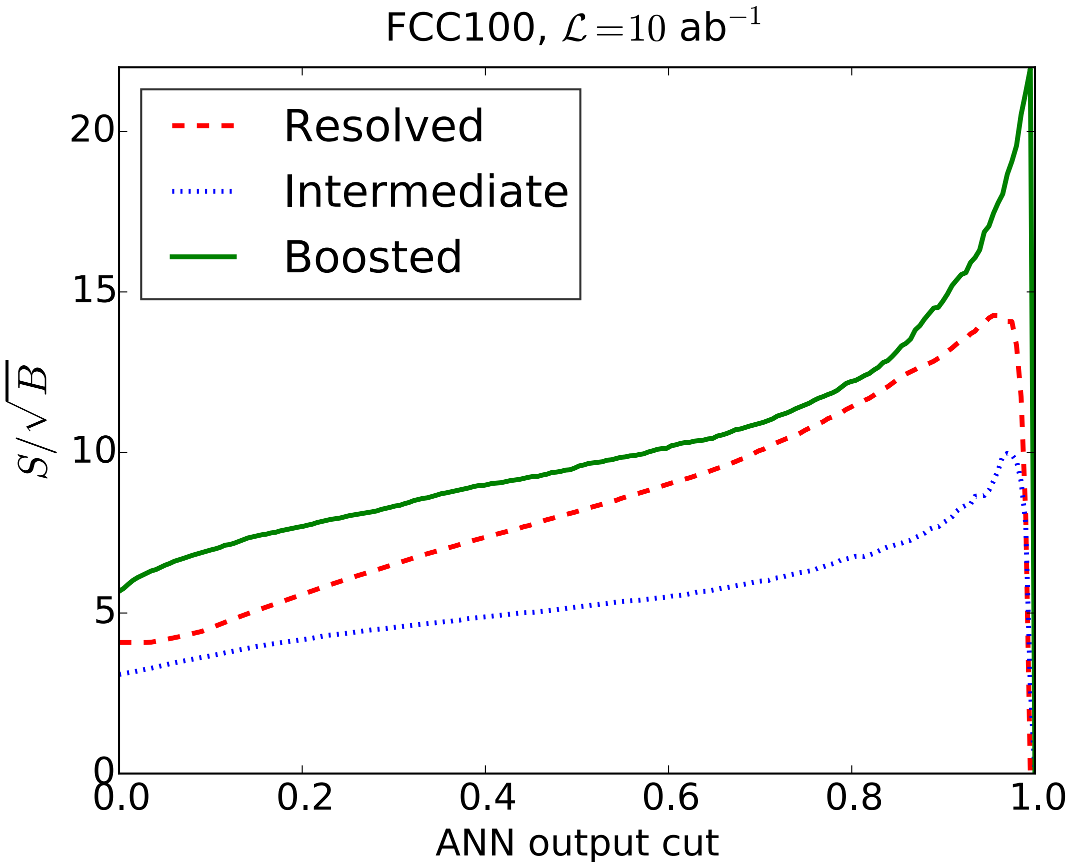




$10\ ab^{-1}$

Category		N_{ev} signal	N_{ev} back	$S/\sqrt{B}$	S/B
Boosted	$y_{cut} = 0$	$5 \cdot 10^4$	$8 \cdot 10^7$	6	$6 \cdot 10^{-4}$
	$y_{cut} = 0.99$	$2 \cdot 10^4$	$1 \cdot 10^6$	22	$2 \cdot 10^{-2}$
Intermediate	$y_{cut} = 0$	$3 \cdot 10^4$	$1 \cdot 10^8$	3	$3 \cdot 10^{-4}$
	$y_{cut} = 0.98$	$2 \cdot 10^4$	$2 \cdot 10^6$	10	$7 \cdot 10^{-3}$
Resolved	$y_{cut} = 0$	$1 \cdot 10^5$	$8 \cdot 10^8$	4	$1 \cdot 10^{-4}$
	$y_{cut} = 0.95$	$6 \cdot 10^4$	$2 \cdot 10^7$	15	$4 \cdot 10^{-3}$

	$\delta_{sys}\sigma = 25\%$	$\delta_{sys}\sigma = 100\%$
Boosted	$\lambda_3 \in [-0.1, 2.2]$	$\lambda_3 \in [-1.5, > 9]$
Intermediate	$\lambda_3 \in [0.7, 1.6]$	$\lambda_3 \in [-0.4, > 9]$
Resolved	$\lambda_3 \in [0.9, 1.5]$	$\lambda_3 \in [-0.1, 7]$



Sensitivity to λ from unboosted objects, λ diagram contributes mainly at low m_{hh}

25% on σ with S/B ~$4 \cdot 10^{-3}$, ΔB/B ~ 10^{-3} (very challenging)

Multi-lepton modes

$hh \to (b\bar{b})(ZZ^*) \to (b\bar{b})(4\ell)$, $hh \to (b\bar{b})(WW^*)/(\tau^+\tau^-) \to (b\bar{b})(\ell^+\ell^-)$, $hh \to (b\bar{b})(\mu^+\mu^-)$ and $hh \to (b\bar{b})(Z\gamma) \to (b\bar{b})(\ell^+\ell^-\gamma)$

- Typically low yield and low background thanks to the multi-lepton final state;
- Exception for WWbb → llbb (high top background)

channel	σ(100 TeV) (fb)	$N_{30\ \mathrm{ab}^{-1}}$(ideal)	$N_{30\ \mathrm{ab}^{-1}}$(LHC)
$\mathbf{hh} \to (b\bar{b})(\ell^+\ell^-\ell'^+\ell'^-)$	0.26	130	41
$\mathbf{t\bar{t}h} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})(2\ell)$	193.6	304	109
$\mathbf{t\bar{t}Z} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})(2\ell)$	256.7	66	25
$\mathbf{Zh} \to (b\bar{b})(4\ell)$	2.29	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\mathbf{ZZZ} \to (4\ell)(b\bar{b})$	0.53	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\mathbf{b\bar{b}h} \to b\bar{b}(4\ell)$ $(p_{T,b} > 15$ GeV)	0.26	$\mathcal{O}(10)$	$\mathcal{O}(1)$
$\mathbf{ZZh} \to (4\ell)(b\bar{b})$	0.12	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$

channel	σ(100 TeV) (fb)	$N_{30\ \mathrm{ab}^{-1}}$(ideal)	$N_{30\ \mathrm{ab}^{-1}}$(LHC)
$\mathbf{hh} \to (b\bar{b})(W^+W^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\ell^-\bar{\nu}_\ell)$	27.16	209	199
$\mathbf{hh} \to (b\bar{b})(\tau^+\tau^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\bar{\nu}_\tau\ell^-\bar{\nu}_\ell\nu_\tau)$	14.63	385	243
$\mathbf{t\bar{t}} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})$ (cuts as in Eq. 49)	25.08×10^3	343^{+232}_{-94}	158^{+153}_{-48}
$\mathbf{b\bar{b}Z} \to b\bar{b}(\ell^+\ell^-)$ $(p_{T,b} > 30$ GeV)	107.36×10^3	2580^{+2040}_{-750}	4940^{+2250}_{-1130}
$\mathbf{ZZ} \to b\bar{b}(\ell^+\ell^-)$	356.0	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\mathbf{hZ} \to b\bar{b}(\ell^+\ell^-)$	99.79	498	404
$\mathbf{b\bar{b}h} \to b\bar{b}(\ell^+\ell^-)$ $(p_{T,b} > 30$ GeV)	26.81	$\mathcal{O}(10)$	$\mathcal{O}(10)$

30 ab^{-1}

Channel	S/√(S+B)	S/B
4l	5.8	0.35
2l	9.4	0.17

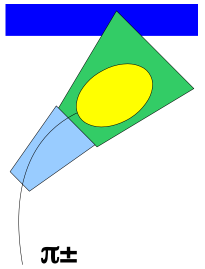
bbμμ, bbllγ have a negligible contrinution

Object in pile-up environment [WWbb analysis]

✦ *Particle Flow Reconstruction*

- Using charged hadrons, muons, electrons and calorimeter towers to build particle-flow objects
- Tracks from pile-up are rejected if $|Z_0 - Z_{\rm PV}| > \sqrt{\sigma^2(Z_0) + \sigma^2(Z_{\rm PV})}$

✦ *Jets*

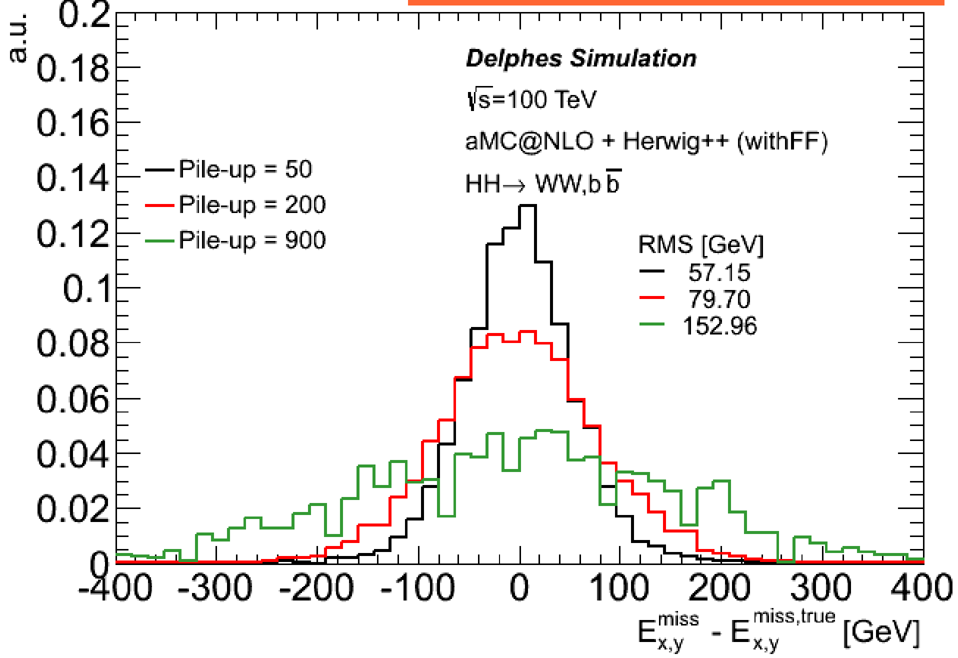


- Anti-Kt (Fast Jet) algorithm
- particle-flow objects as inputs
- R = 0.4
- Jet Area pile-up correction:
- private calibration to particle level $p_T^{\text{corrected}} = p_T^{\text{raw}} - \rho \cdot \text{JetArea}$
- $p_T^{\text{jet}} > 20$ GeV

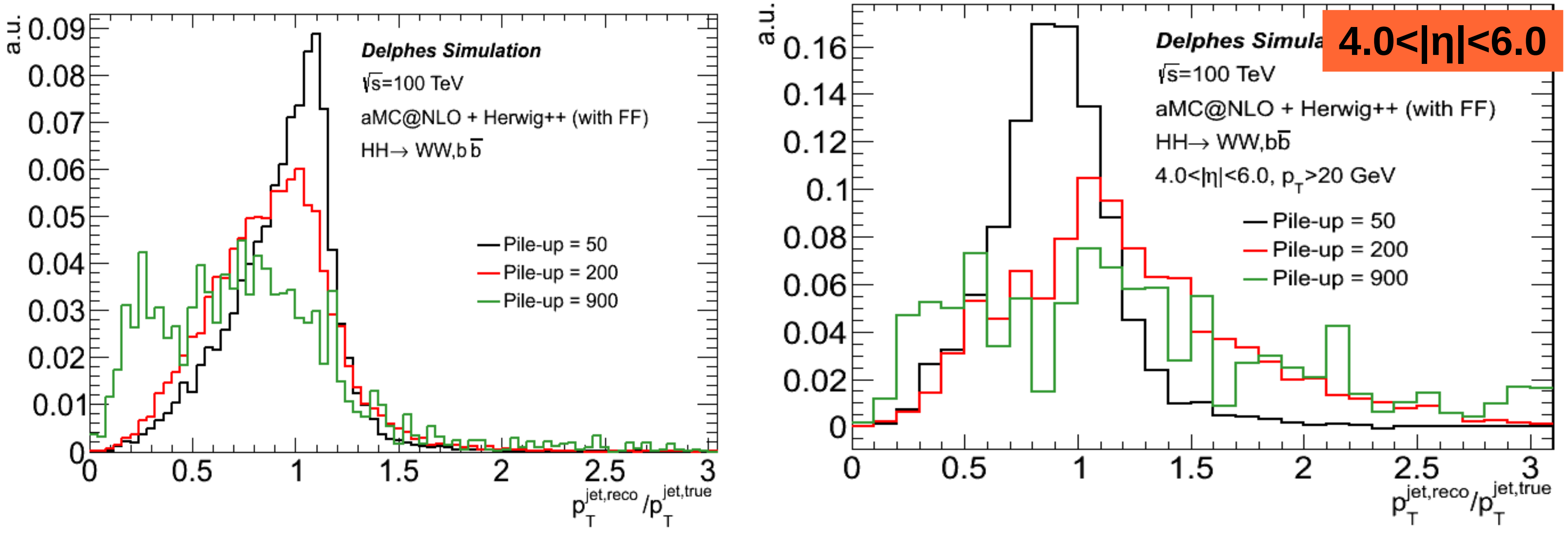
✦ *Missing Transverse Energy*

- Anti-Kt (Fast Jet) algorithm
- negative vector sum of Jets, after pile-up correction and calibration

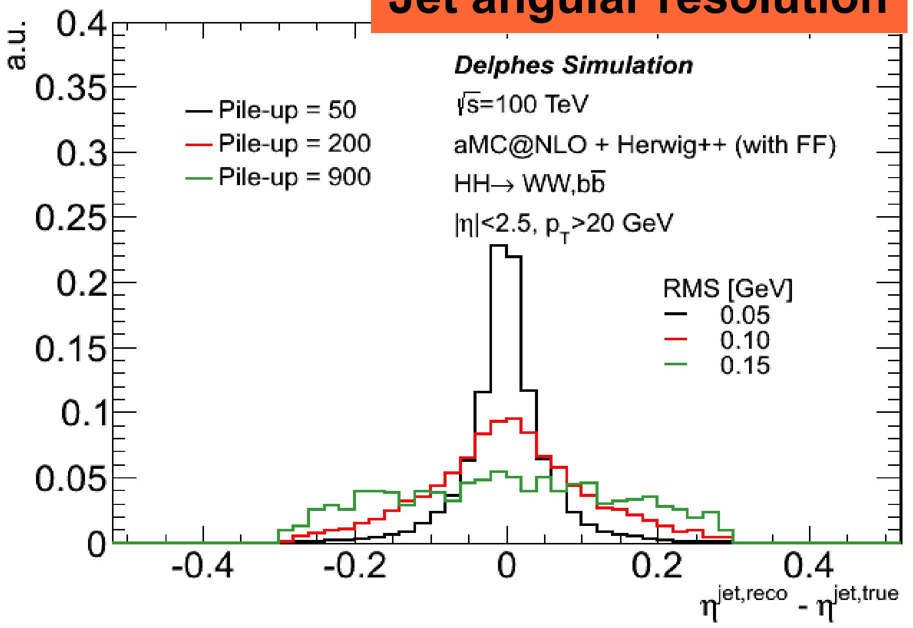
Missing ET resolution



Jet pT response



Jet angular resolution



WWbb→lνqqbb MVA analysis

Input variables

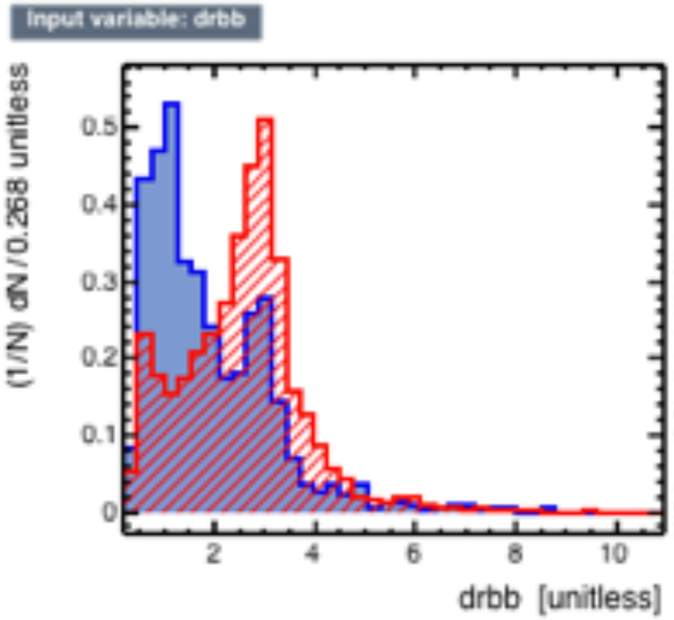
$$\Delta R_{\rm jj},\ \Delta R_{\rm bb},\ \Delta R_{\rm WW},\ m_T^{\rm WW},\ m_{\rm bb}$$

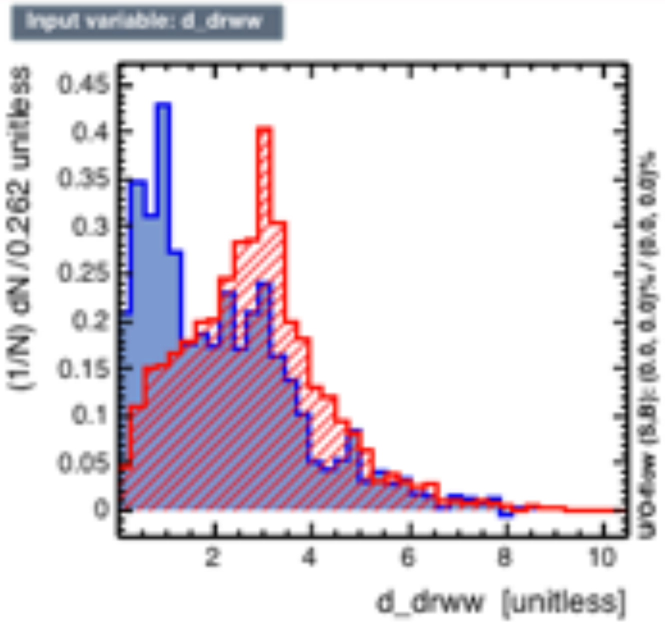
$$m_{\rm jj},\ p_T^{\rm bb},\ p_T^{\rm WW},\ E_T^{\rm miss},\ m_T^{\rm W},\ m_{\rm WW}$$

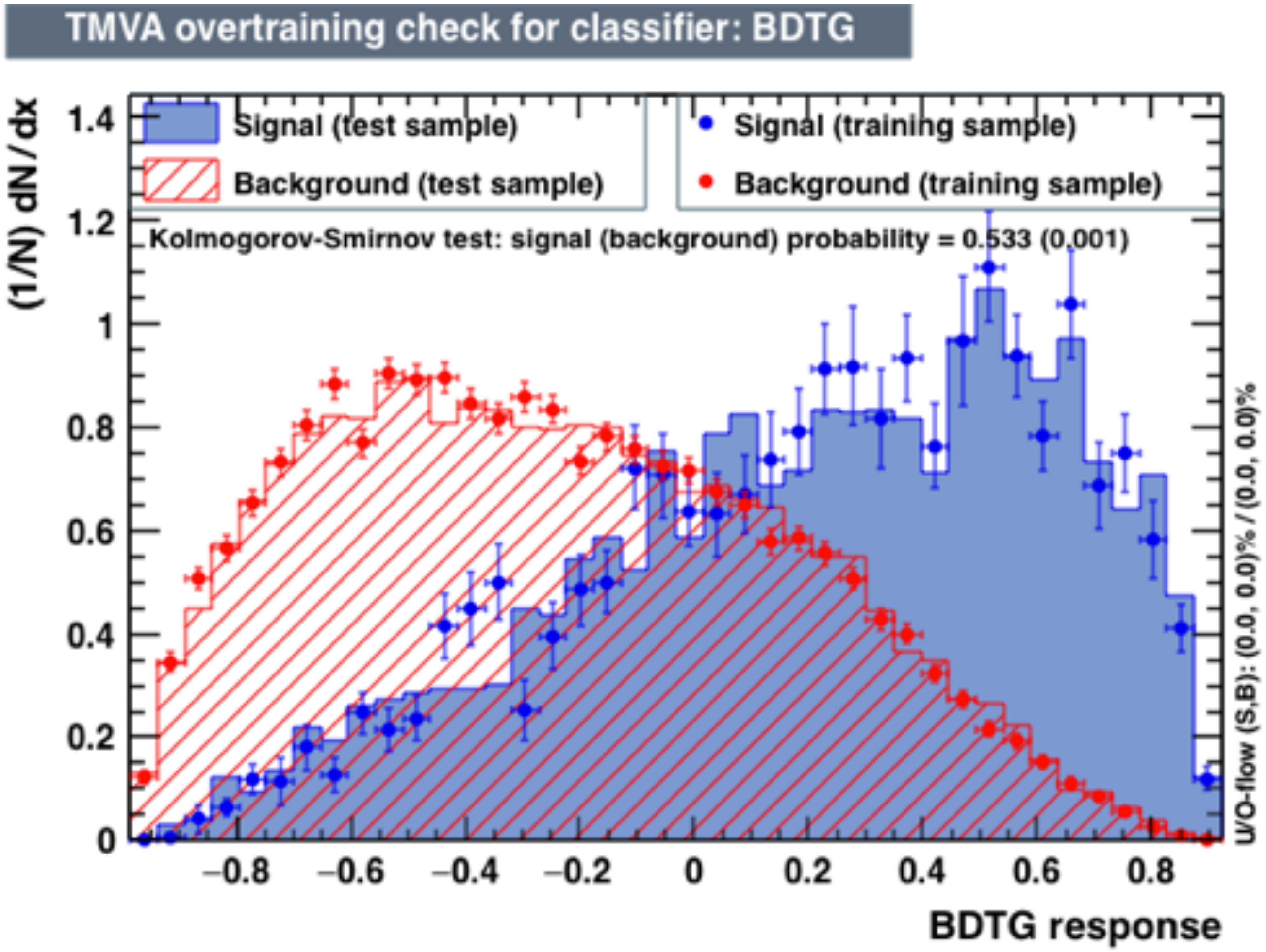
Pre-training cuts:

$$p_T^{\rm WW},\ p_T^{\rm bb} > 150,\ 80 < m_{bb} < 180\,{\rm GeV}$$

$$\Delta R_{bb} < 2.0$$

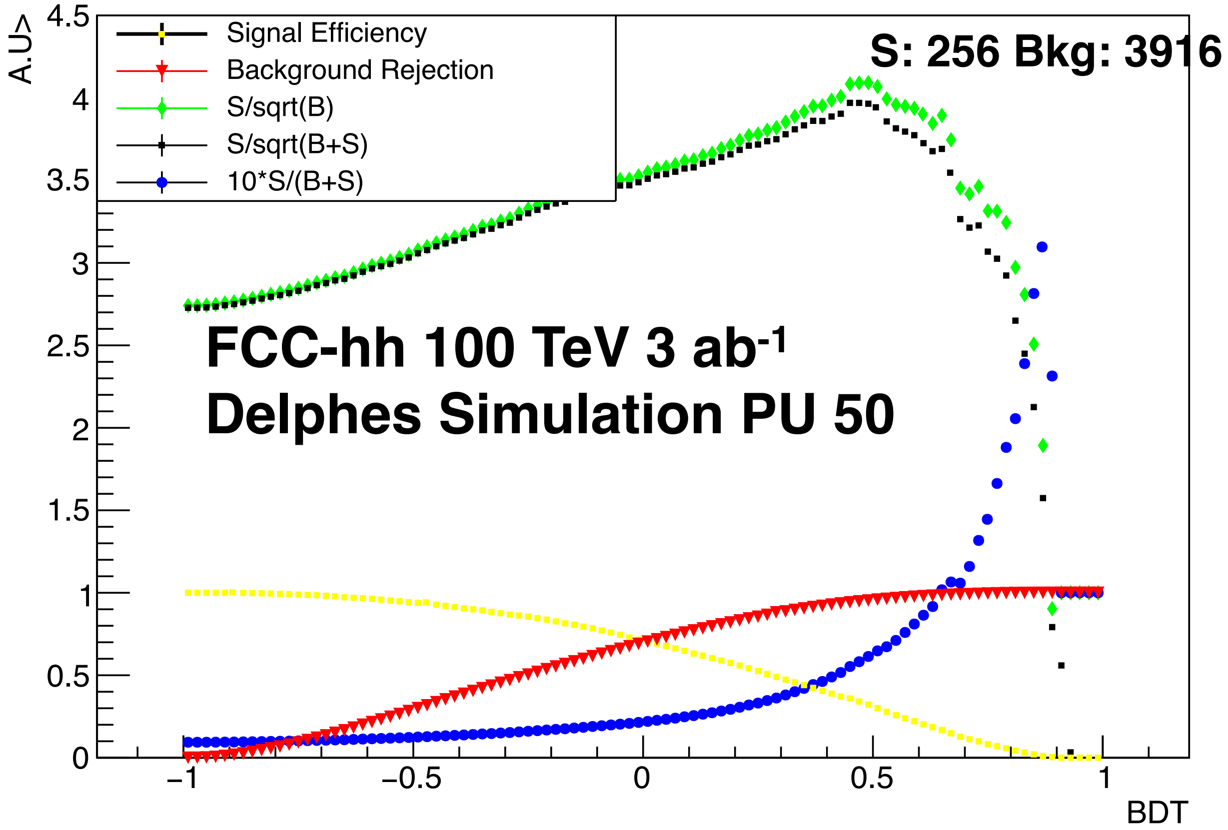




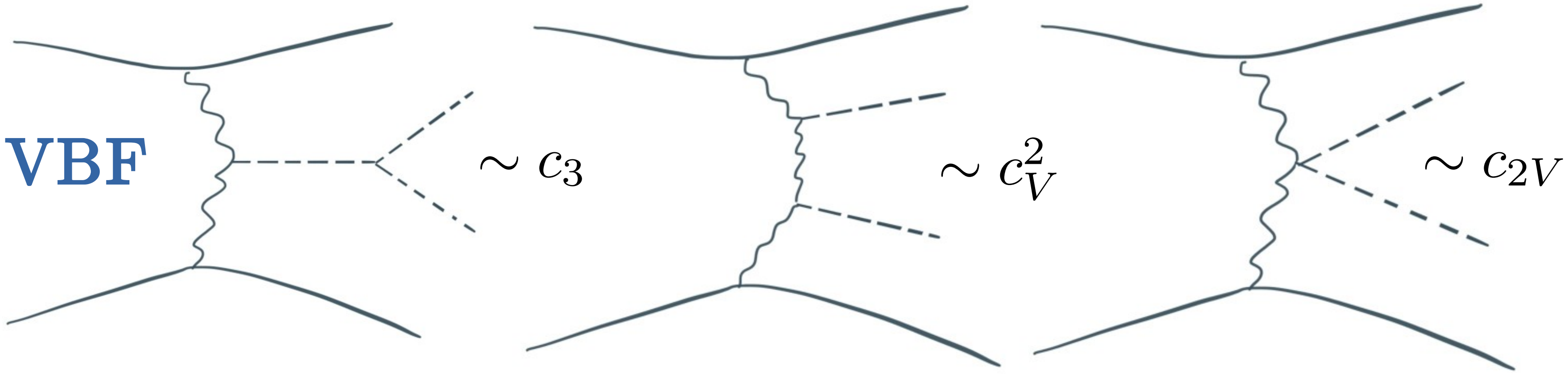


stat. sign. 4.1σ with S/B 0.06, 13σ @30 ab^{-1}

very preliminary



VBF hh production



SM

$$\mathrm{c_V = c_{2V} = c_3 = 1}$$

$$\boxed{\sigma/\sigma_{\mathrm{SM}} = 1 + a\,\delta + b\,\delta^2}$$

$$\boxed{\delta_i \equiv c_i - 1}$$

dashed : before cuts
solid : after cuts

		14 TeV	100 TeV
Acceptance cuts	p_{T_j} (GeV) $\geq$	25	40
	p_{T_b} (GeV) $\geq$	25	35
	$\lvert\eta_j\rvert \leq$	4.5	6.5
	$\lvert\eta_b\rvert \leq$	2.5	3.0
VBF cuts	$\lvert\Delta y_{jj}\rvert \geq$	5.0	5.0
	m_{jj} (GeV) $\geq$	700	1000
	Central jet veto: $p_{T_{j_3}}$ (GeV) $\leq$	45	65
	m_{hh} (GeV) $\geq$	500	1000

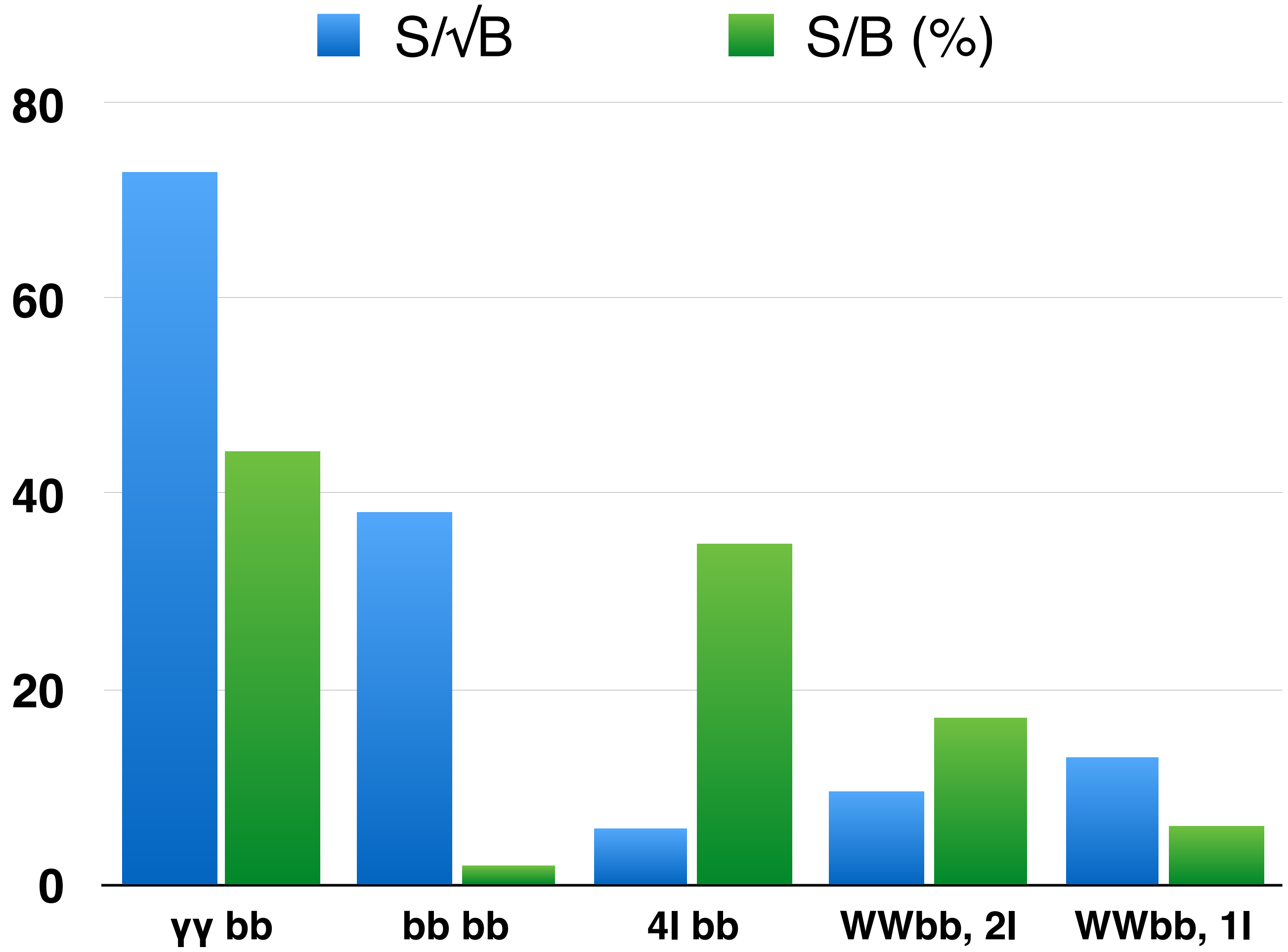
VBF jets at high η go in the very forward region, 50% event loss with η acceptance of 4 instead of 5

Not strong sensitivity to SM hh production, but adds information on New Physics operators

	68% probability interval on $\delta_{c_{2V}}$	
	$1 \times \sigma_{\mathrm{bkg}}$	$3 \times \sigma_{\mathrm{bkg}}$
LHC_{14}	$[-0.37, 0.45]$	$[-0.43, 0.48]$
HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$
FCC_{100}	$[0, 0.01]$	$[-0.01, 0.01]$

	95% probability upper limit on μ	
	$1 \times \sigma_{\mathrm{bkg}}$	$3 \times \sigma_{\mathrm{bkg}}$
LHC_{14}	109	210
HL-LHC	49	108
FCC_{100}	12	23

Conclusion



- γγbb looks to be the golden channel;
- need to reach maximal accuracy in this channel simulation, implementing pile-up simulation and more accurate fake estimate;
- detector design should be driven by minimisation systematics on it;
- more work needed on WWbb to fully exploit its potentiality;
- highly boosted topologies are less useful for λ measurement, sensitivity to λ from low m_{hh} region

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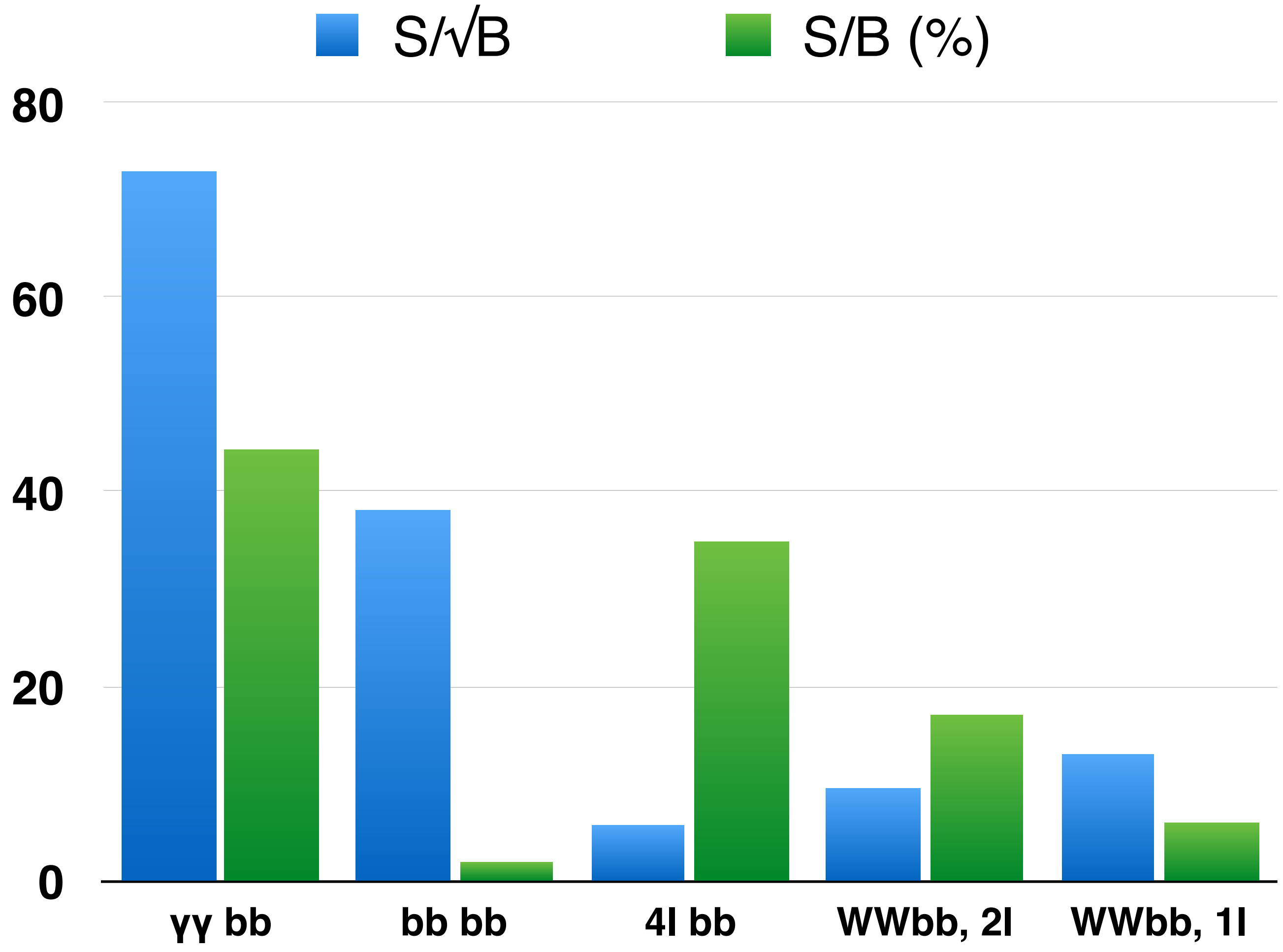

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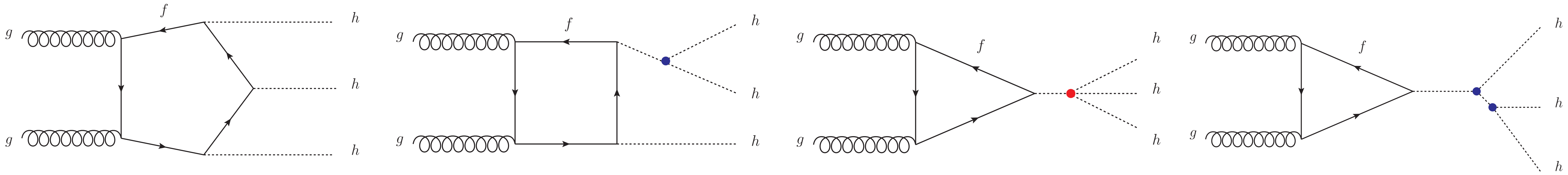
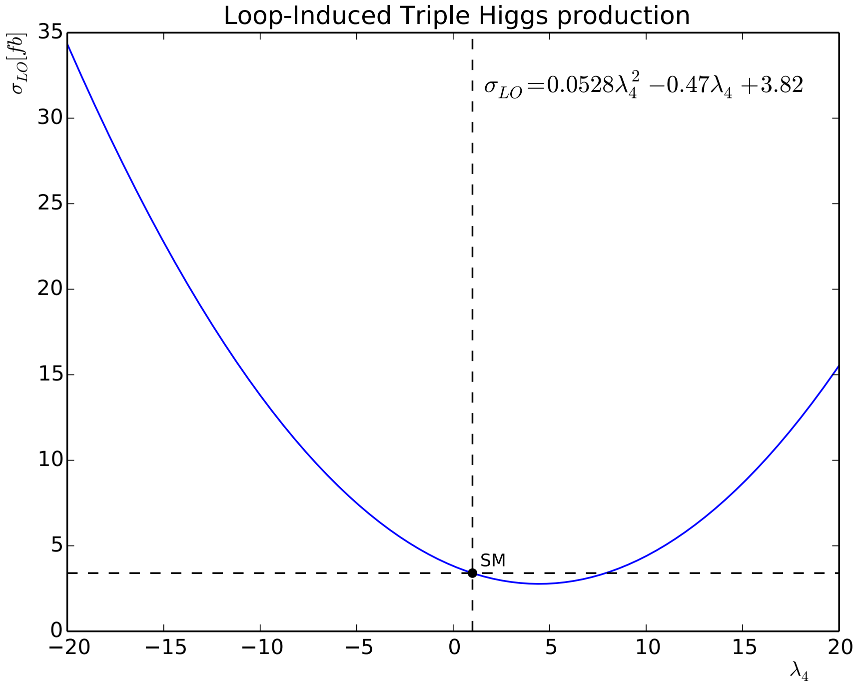
FCC-hh looks to have a strong physics case

Higgs quartic





observable	selection cut
$p_{T,b_{\{1,2,3,4\}}}$	$> \{80, 50, 40, 40\}$ GeV
$\lvert\eta_b\rvert$	< 3.0
$m_{bb}^{\text{close},1}$	$\in [100, 160]$ GeV
$m_{bb}^{\text{close},2}$	$\in [90, 170]$ GeV
$\Delta R_{bb}^{\text{close},1}$	$\in [0.2, 1.6]$
$\Delta R_{bb}^{\text{close},2}$	no cut
$p_{T,\gamma_{\{1,2\}}}$	$> \{70, 40\}$ GeV
$\lvert\eta_\gamma\rvert$	< 3.5
$\Delta R_{\gamma\gamma}$	$\in [0.2, 4.0]$
$m_{\gamma\gamma}$	$\in [124, 126]$ GeV

	Signal	$b\bar{b}jj\gamma\gamma$	$Ht\bar{t}$	S/B	$S/\sqrt{B}$
preselection	50	2.3×10^5	2.2×10^4	2.5×10^{-4}	0.14
$\chi^2_{H,min} < 6.1$	26	4.6×10^4	9.9×10^3	5.0×10^{-4}	0.14
$\lvert m_H^{rec} - 126\text{ GeV}\rvert < 5.1$ GeV	20	1.7×10^4	7.0×10^3	8.1×10^{-4}	0.15

30 ab^{-1}: $-4 < \lambda_4 < 16$

Higgs boson as inflaton

Gravitational action coupled to the SM sector

$$S = \int \left[\frac{1}{2}M_{\rm pl}^2 R + \mathcal{L}\right] d^4x\sqrt{-g} = \int \left[\frac{1}{2}M_{\rm pl}^2 R - \frac{1}{2}\partial_\mu h \partial^\mu h + V(h) + \ldots\right] d^4x\sqrt{-g}$$

Inflation model

- need a scalar field (h is a scalar field)
- need a well shaped potential, with a slow-roll condition

$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \longrightarrow H^2 = \frac{8\pi G}{3}V(\phi) \simeq const. \longrightarrow a(t) \simeq e^{Ht} \quad \left(H(t) = \frac{\dot{a}}{a}\right)$$

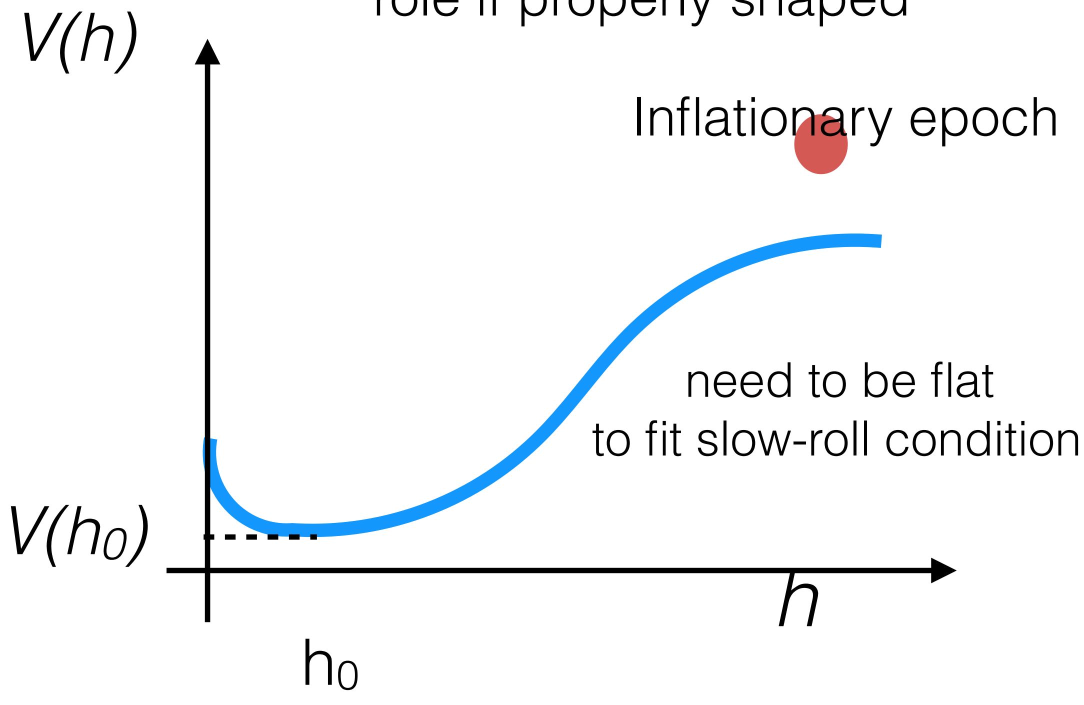
universe radius, exponentially expanding during inflation

In order to make this to work

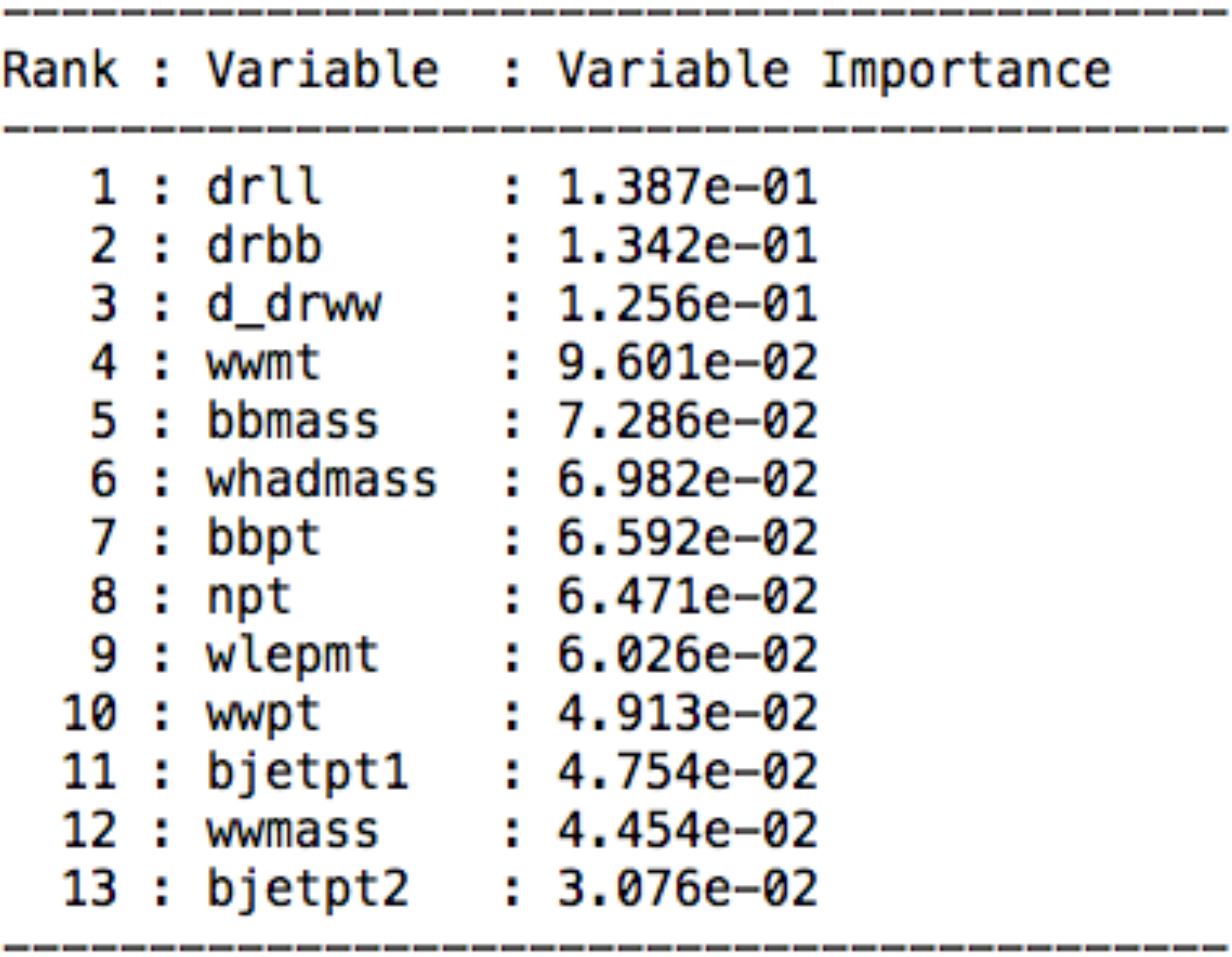
$$h >> h_0 \quad V(h) \sim \lambda h^4 \quad \lambda \sim 10^{-13}$$

Intringuing, λ nearly vanishes for high h value with the present value of top and Higgs mass.

The Higgs potential could have such role if properly shaped



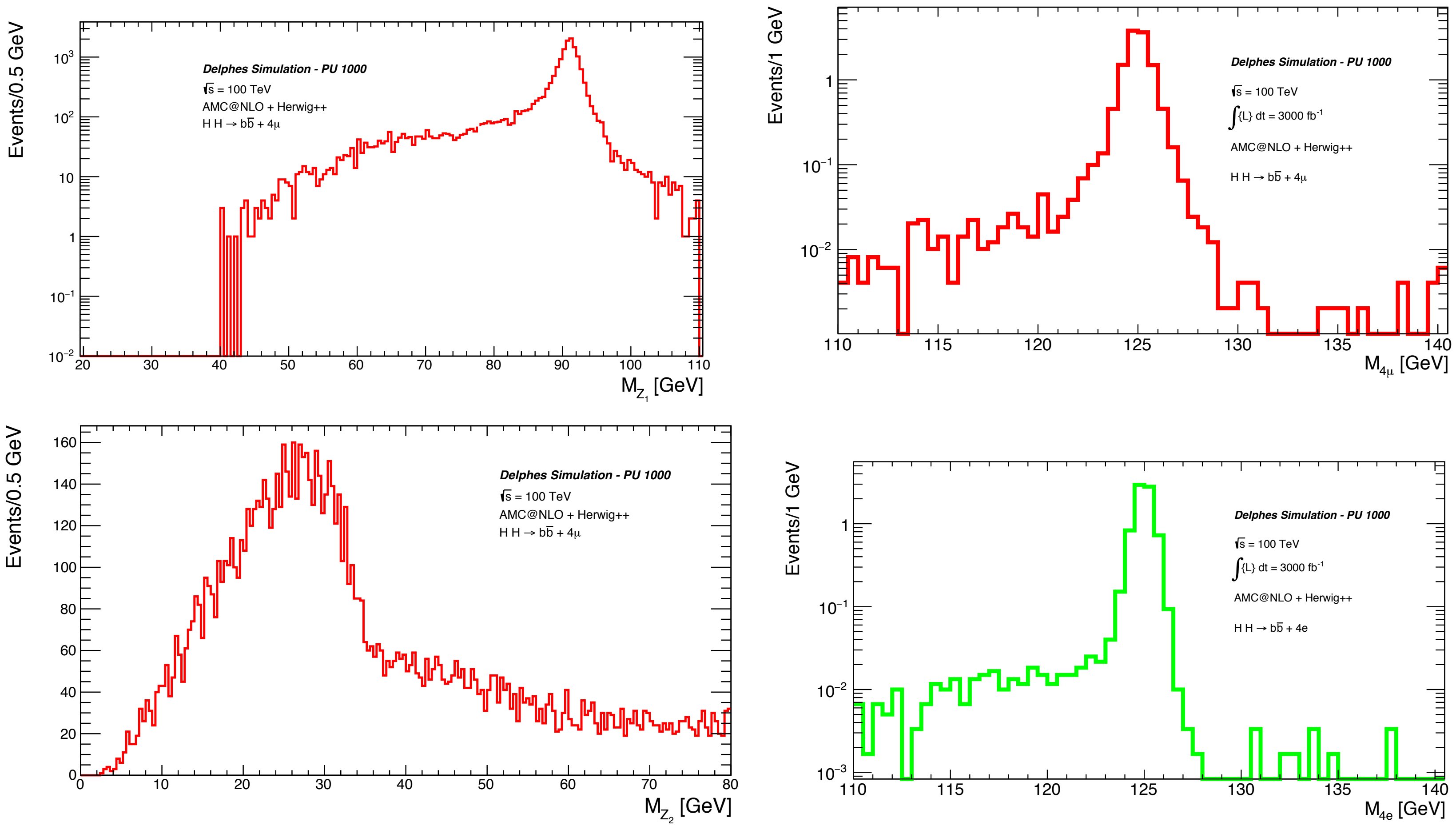
Understanding the Higgs potential is the last missing piece of the SM, and it could have fundamental cosmological implications.



```
------------------------------------------
Rank : Variable  : Variable Importance
------------------------------------------
   1 : drll      : 1.387e-01
   2 : drbb      : 1.342e-01
   3 : d_drww    : 1.256e-01
   4 : wwmt      : 9.601e-02
   5 : bbmass    : 7.286e-02
   6 : whadmass  : 6.982e-02
   7 : bbpt      : 6.592e-02
   8 : npt       : 6.471e-02
   9 : wlepmt    : 6.026e-02
  10 : wwpt      : 4.913e-02
  11 : bjetpt1   : 4.754e-02
  12 : wwmass    : 4.454e-02
  13 : bjetpt2   : 3.076e-02
------------------------------------------
```

The hh→ZZbb→4lbb channel

- ≥ 4 muons with $p_T > 5$ GeV, $|\eta| < 4.0$
- ≥ 4 electrons with $p_T > 7$ GeV, $|\eta| < 4.0$
- Z_1 selection: $\ell^+\ell^-$ pair with mass closest to the nominal Z boson mass
  40 GeV < m_{Z1} < 120 GeV
- Z_2 selection: second $\ell^+\ell^-$ pair
  12 GeV < m_{Z2} < 120 GeV
- Among the 4 selected leptons: at least one with p_T>20 GeV and one with p_T>10 GeV
- QCD suppression: $m(\ell^+\ell^-) > 4$ GeV
- Kinematic cuts: $m_{4\ell} > 120$ GeV, $m_{4\ell} < 130$ GeV
- At least 2 b-jets with $p_T > 30$ GeV



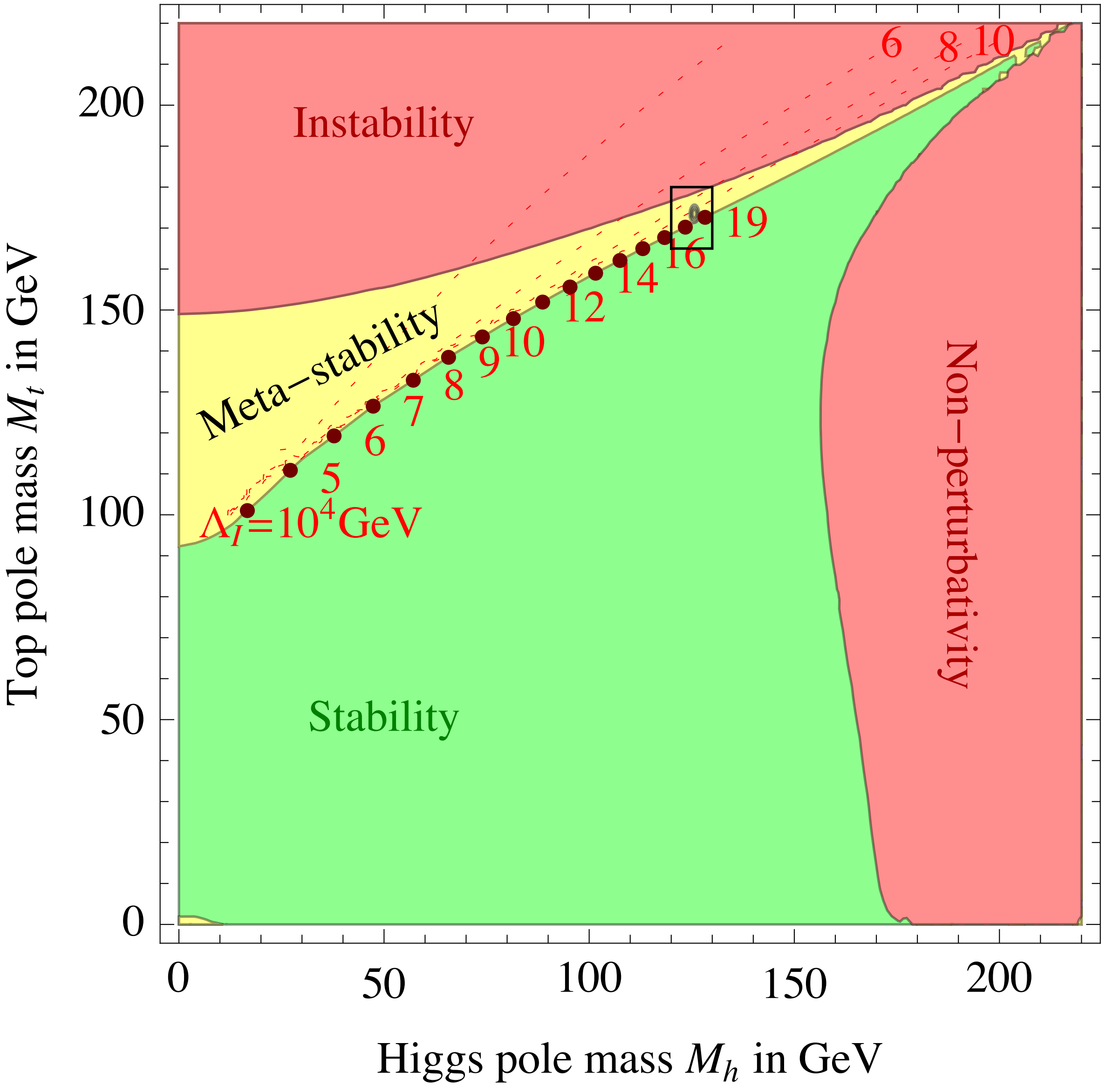
$$\mathcal{L} = 3\,\mathrm{ab}^{-1}$$

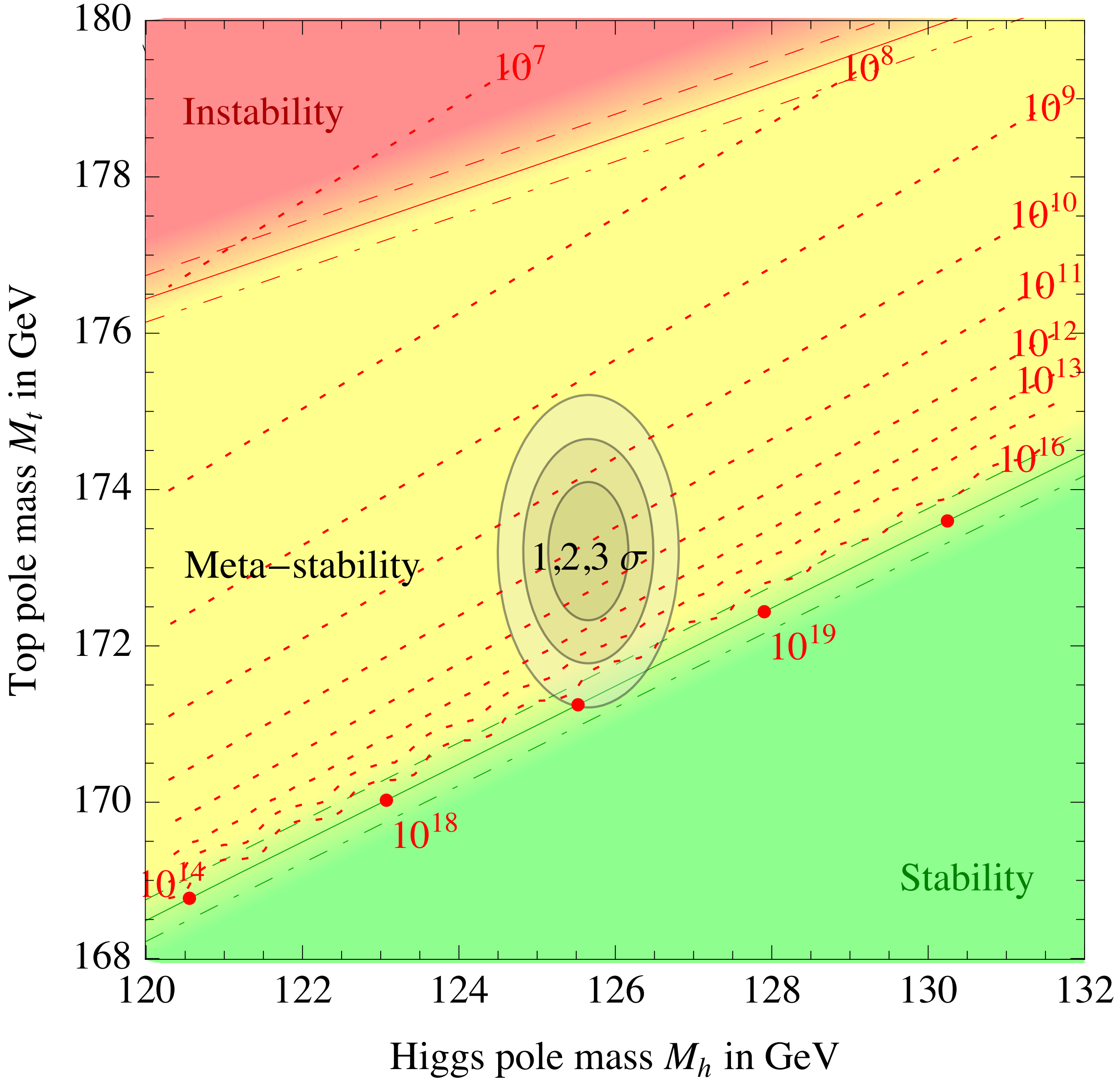
	σ·L·Br(hh→ZZbb→4lbb	no b-jet req.	with b-jet	ε (no b-jet)	ε (b-jet)
4μ	161	61	12.1	38%	7.4%
4e	161	40	7.7	25%	4.8%
Tot	322	101	20	31%	6.2%

- forward b-tagging can be an important ingredient of the analysis, need to test configuration with fwd dipole
- big impact from lepton isolation cut (not presented here), need to optimise isolation criteria

Vacuum stability regions

We are at the edge between stability and instability, in a quite narrow region of the meta-stability region (many theoretical speculations are starting, why are we there?)



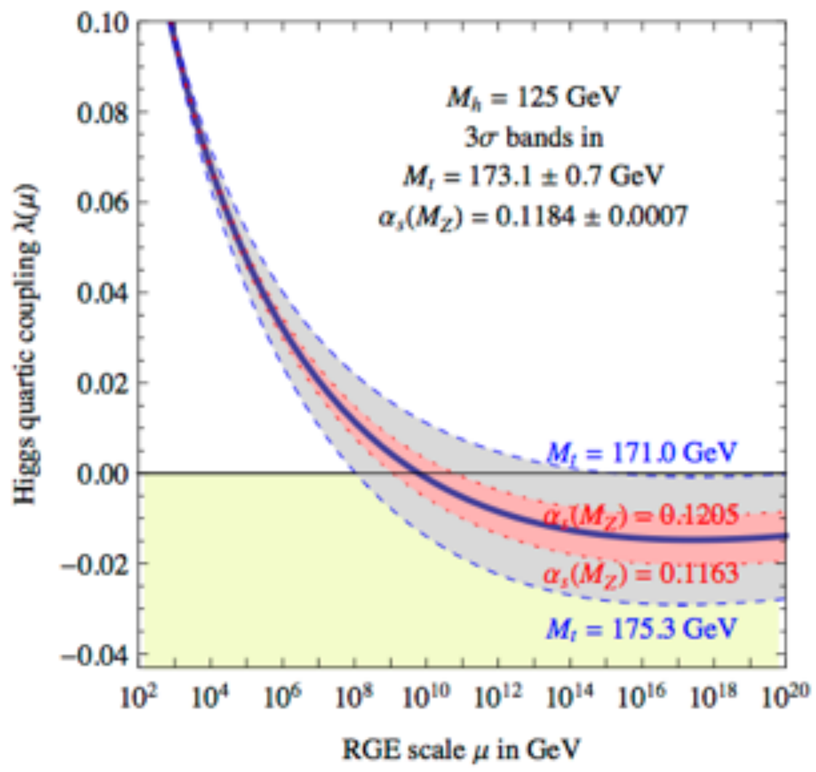


Vacuum stability

$$V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\Lambda(scale)\Phi^4$$

arXiv:1307.3536v2

Dario Buttazzo[a,b], Giuseppe Degrassi[c], Pier Paolo Giardino[a,d],
Gian F. Giudice[a], Filippo Sala[b,e], Alberto Salvio[b,f],
Alessandro Strumia[d]

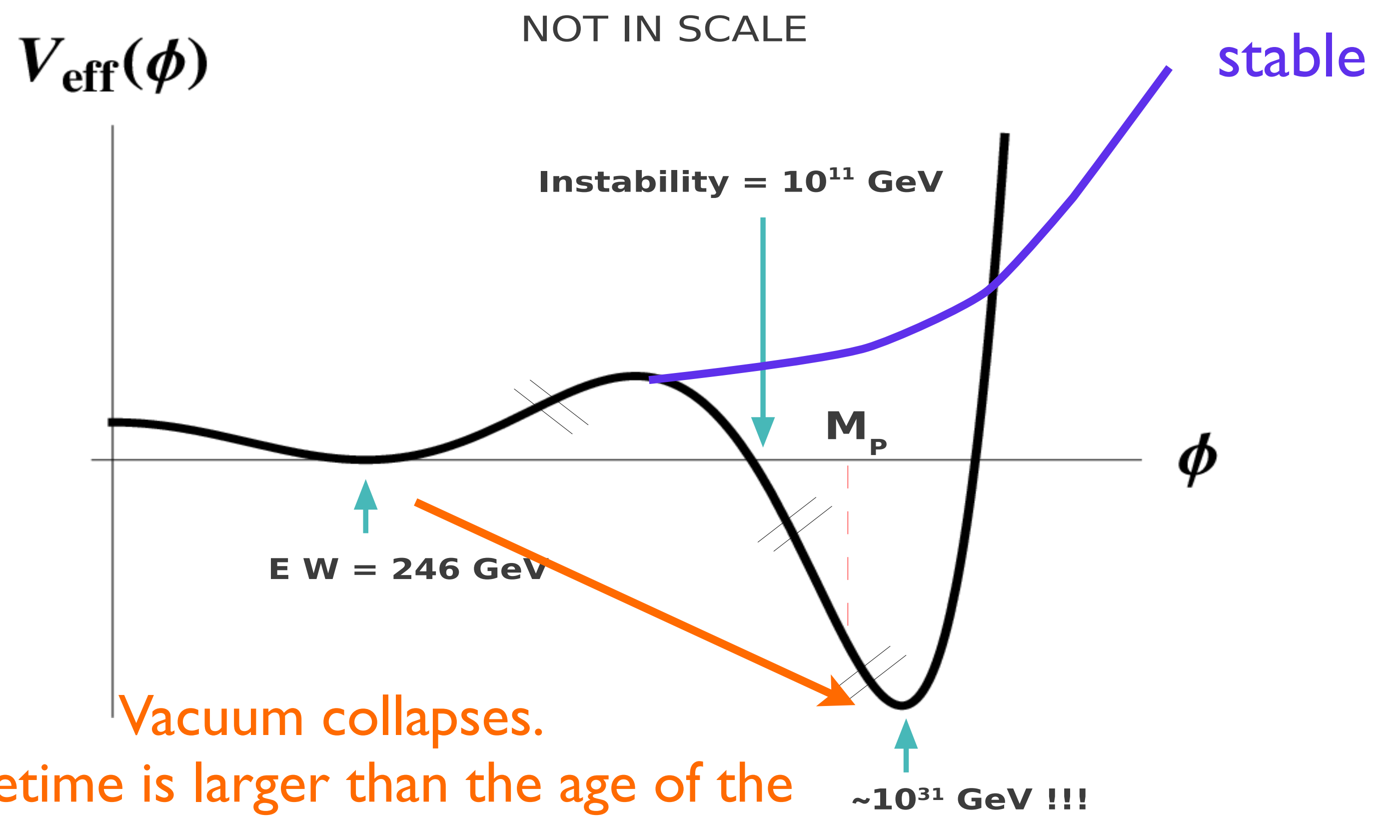


$$\lambda(\mu) \sim F(y_t, \lambda(m_H)) = F'(m_t, m_H)$$

$$\lambda(m_H) = \frac{m_H^2}{2v^2} = 0.1301 \pm 0.0007$$

See Buttazzo *et al.* and talk from V. Branchina (Moriond QCD 2014)

+ ...



Vacuum collapses.

If the lifetime is larger than the age of the universe we call it metastable otherwise it is unstable. What's the shape of the Higgs potential?

The modification of λ with the energy implies a dependence Λ(Φ). The Higgs potential has a shape that is more complex than just λΦ⁴.