Study of double Higgs production at 100 TeV

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on behalf of

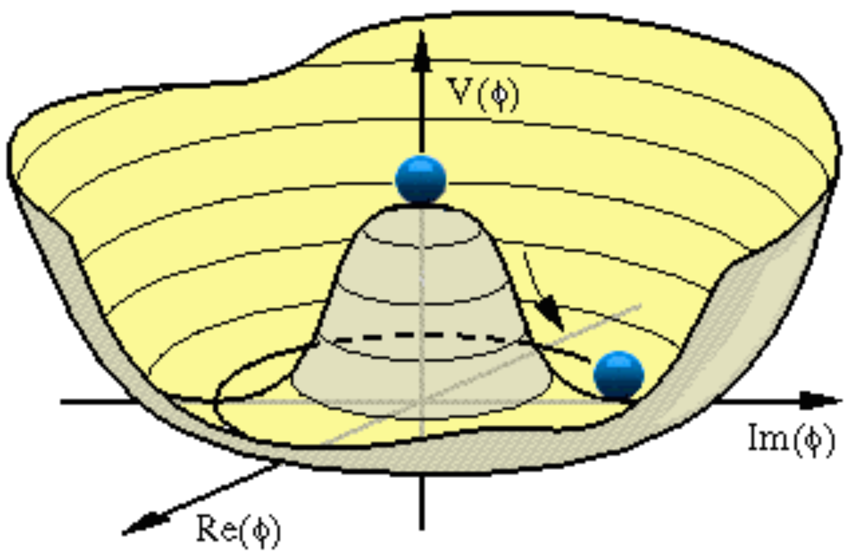
B. Di Micco, S. Braibant, M. Testa, M. Verducci et al.

Simulation and Physics Group Meeting,

August 28

The Higgs potential

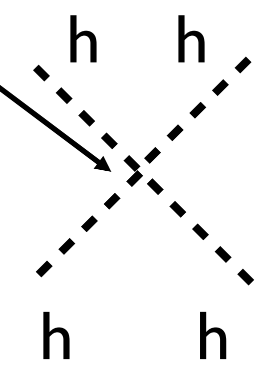
$$V(h) = \mu^2 \frac{h^2}{2} + \lambda \frac{h^4}{4}$$

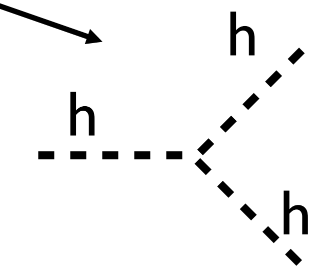


After spontaneous symmetry breaking:

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

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





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

Why is it relevant?

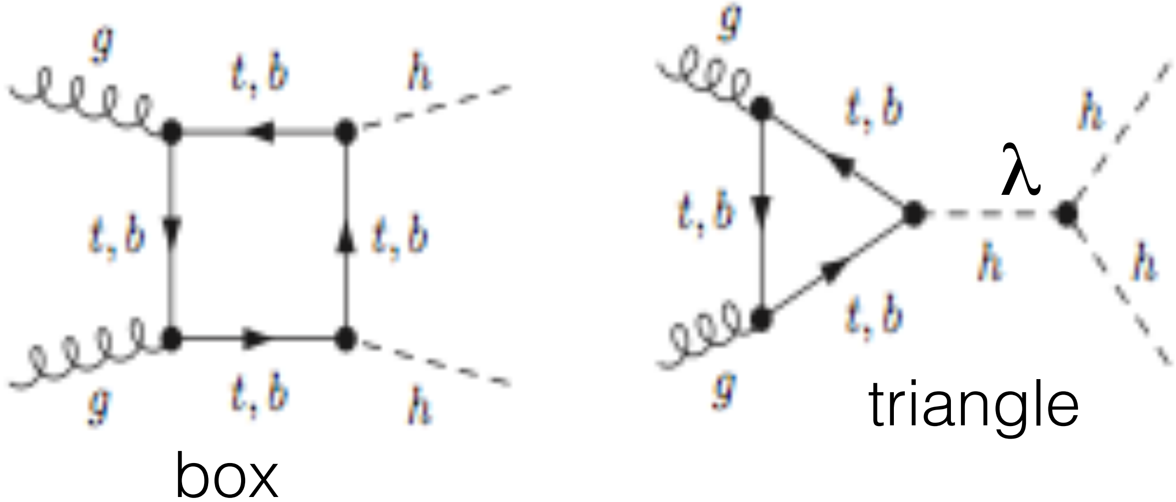
1) it is the last missing ingredient of the SM, like the Higgs boson was the last missing particle, we need to prove that things really behave like we expect;

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

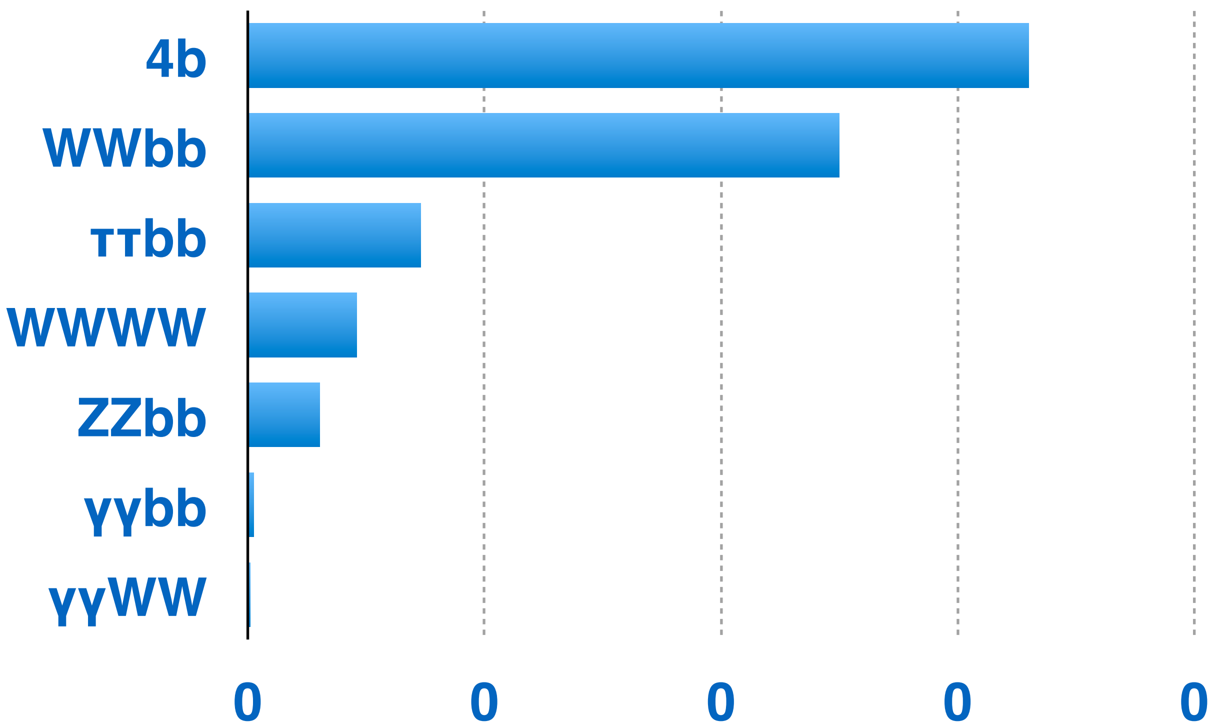
3) It could make the Higgs boson a good inflation field (see backup)

HH production and decay

Standard Model

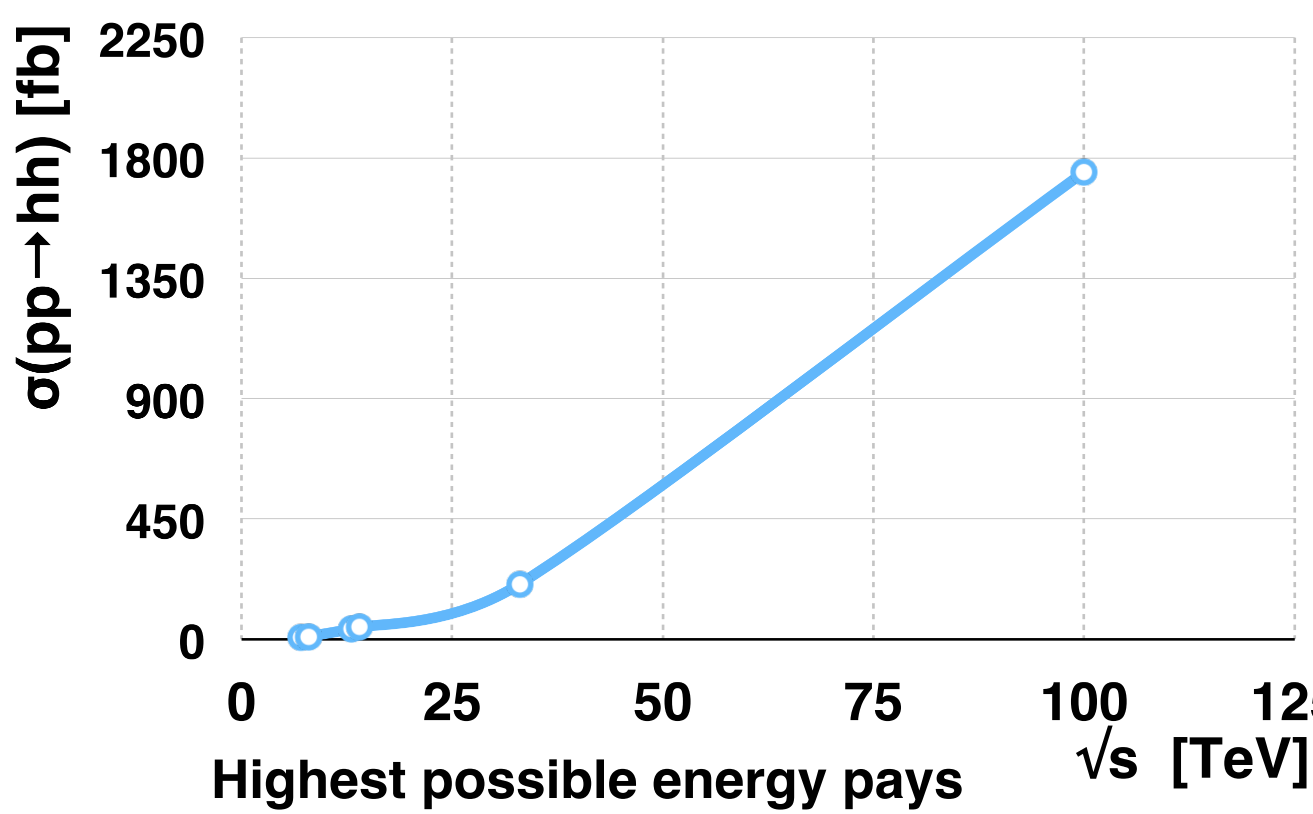


Higgs decay branching fraction



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

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



Current status @LHC

	$\sqrt{s}$ [TeV]	L (fb^{-1})	σ(fb) 95% C.L.	σ/σ_{SM} 95%C.L.
ATLAS: 4b, bb$\tau\tau$, bb$\gamma\gamma$, WW$\gamma\gamma$ WWWW	8	20,3	< 470	< 48
ATLAS: 4b	13	13,3	< 1000	< 29
CMS: 4b	13	2,32	< 11760	< 310
ATLAS: WW$\gamma\gamma$	13	13,3	< 12900	< 340
ATLAS: bb$\gamma\gamma$	13	3,2	< 5400	< 142
CMS: bb$\tau\tau$	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: bb$\gamma\gamma$	1.05 σ	[-0.8, 7.7]	< 1.7 [recalc.]
CMS: bb$\gamma\gamma$	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: bb$\tau\tau$	0.6 σ	[-4, 12]	< 4.3
CMS: bb$\tau\tau$	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.

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
  - FCC week 2017 @ Berlin
  - studies performed with different level of details, in particular trigger, eff. simulation and 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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FCC studies: $HH \to bb\gamma\gamma$

Selection:

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

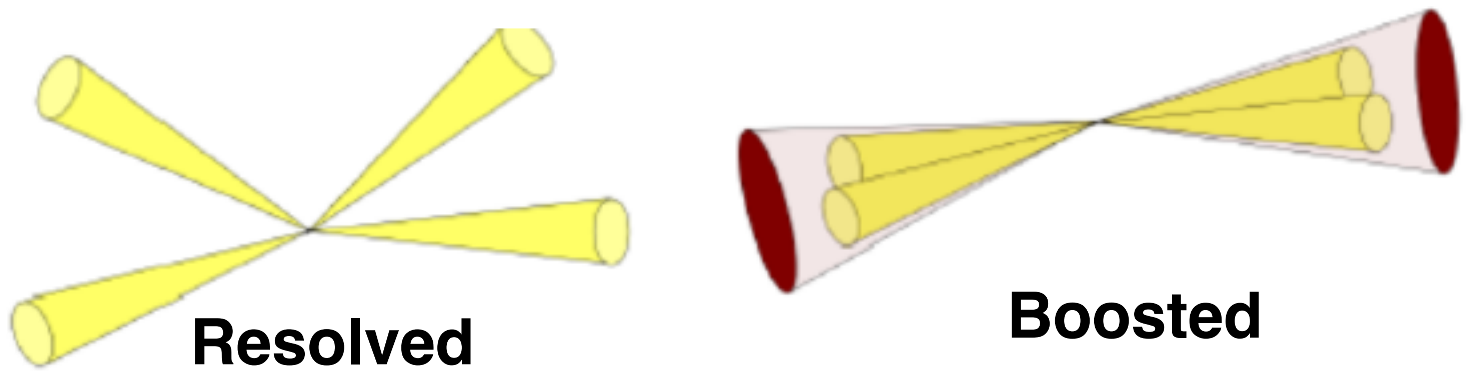
Process	Acceptance cuts [fb]	Final selection [fb]	Events ($L = 30$ ab^{-1})
$h(b\bar{b})h(\gamma\gamma)$ (SM)	0.73	0.40	12061
$bbj\gamma$	132	0.467	13996
$jj\gamma\gamma$	30.1	0.164	4909
$t\bar{t}h(\gamma\gamma)$	1.85	0.163	4883
$b\bar{b}\gamma\gamma$	47.6	0.098	2947
$b\bar{b}h(\gamma\gamma)$	0.098	7.6×10^{-3}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

FCC studies: HH→bbbb

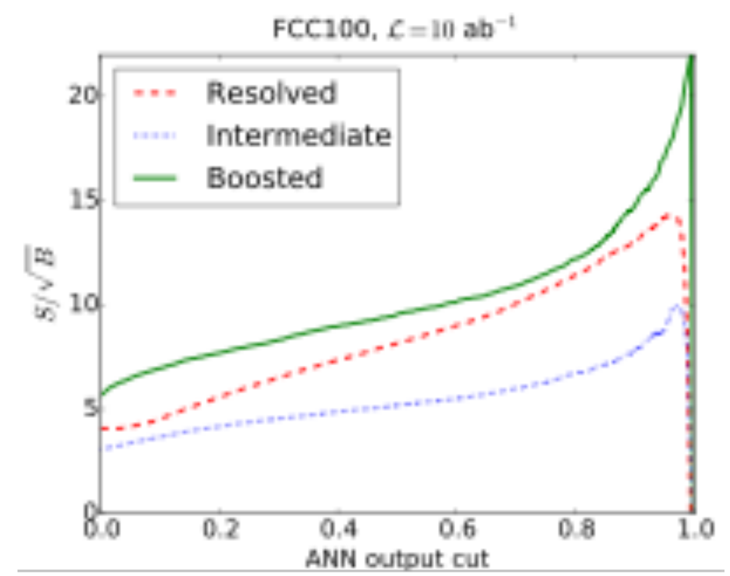
Main background: multi-jet 4b
Strategy: truth level study,
resolved + boosted analysis
(Neural Network used as signal discriminator)



- R 0.4 jets p_T > 40 GeV, |η| < 2.5
- R 1.0 jets p_T > 200 GeV, |η| < 2.0
- R 0.3 jets ghost ass. to R 1.0 p_T > 50 |η| < 2.5

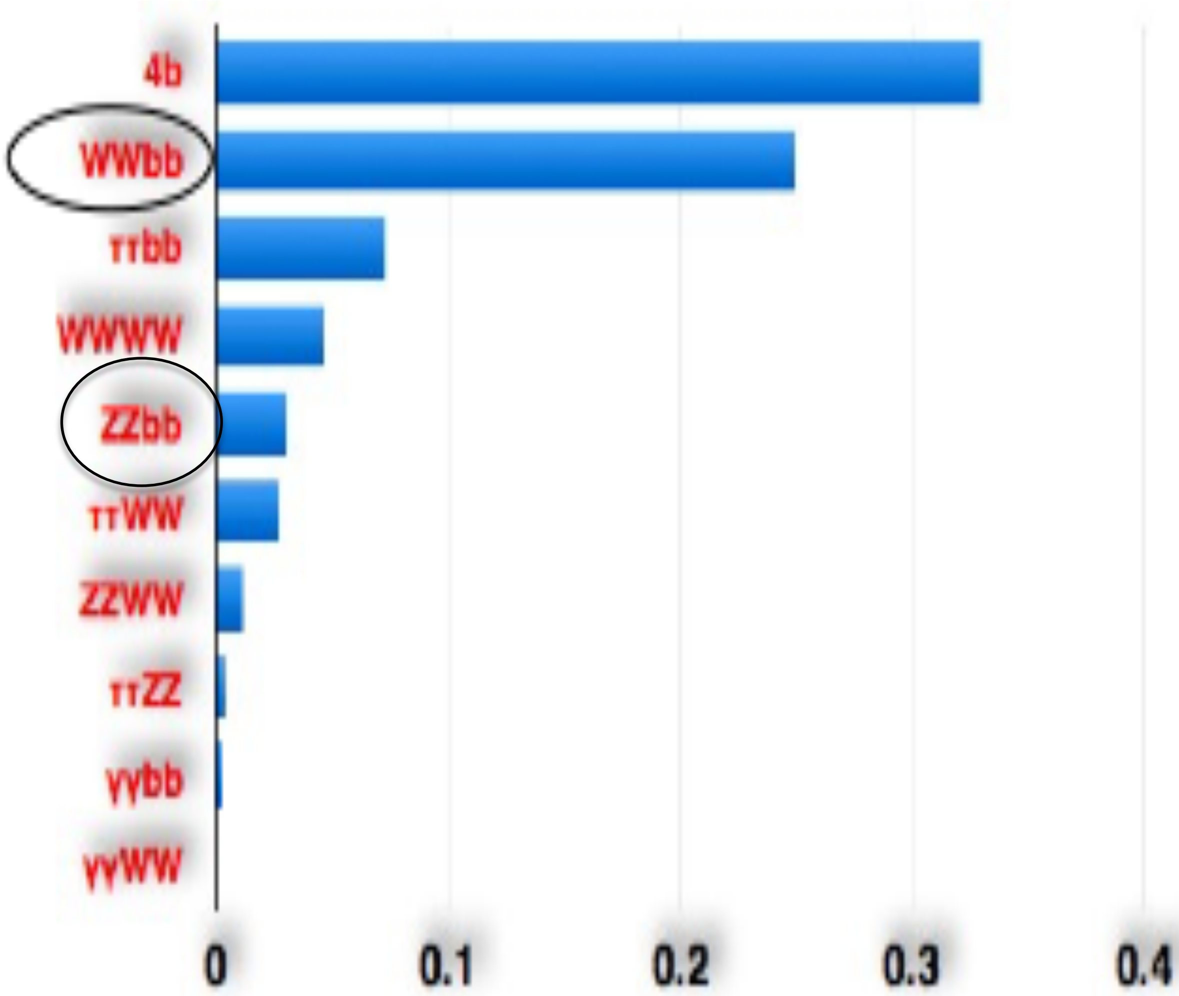
L = 10 ab^{-1}

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	$4 \cdot 10^{-3}$



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

Current studies: Italian contribution



Between the final state from the HH decay:

- 4b, WWbb are dominant
- γγbb, ZZbb are the cleanest

The **Italian community** started to work in 2016 on:

- WWbb, lnuqqbb
- ZZbb, 4lbb

Typically low yield and low background thanks to the multi-lepton final state

- We used a fast simulation tool (Delphes)
- Pileup simulation with 50, 200, 900 events

L=30 ab^{-1}	$\Delta\sigma/\sigma$	$\Delta\lambda/\lambda$
γγbb	1.3%	2.5%
4b	25% (S/B ~2%)	200%
ZZbb, 4l	~30%	~40%

Last contributions to conferences:

- B. Di Micco, IFAE – Trieste – April 19-21 2017
- B. Di Micco, FCC Week – Berlin – May 29 – June 1 2017

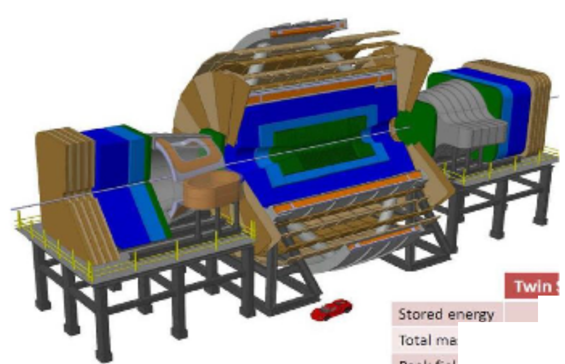
Pile-up and det. simulation with Delphes

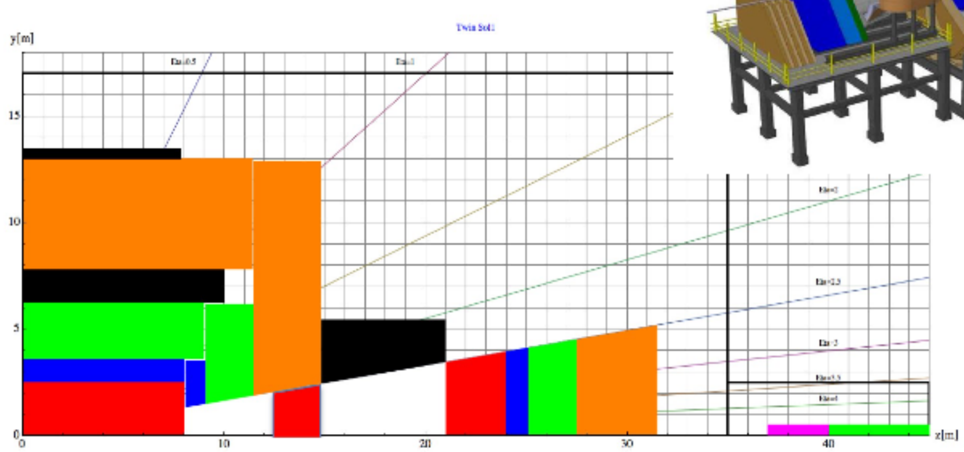
S. Braibant (Bologna), B. Di Micco, M. Testa, M. Verducci (Roma 3)

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

- 50, 200, 900 vertices

Base-line geometry
Twin solenoid +
Dipole magnetic system





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 % $2.5 < |\eta| < 4.0$

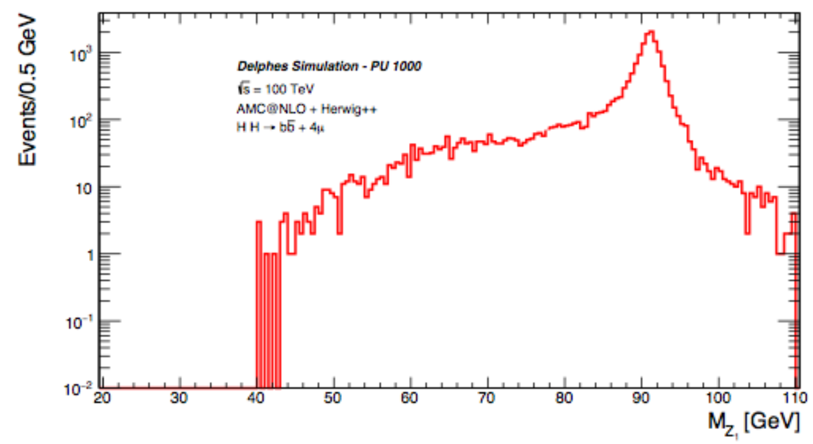
Efficiency b-quark jets:
75% WWbb 85 % ZZbb $|\eta| < 2.5$
64% $2.5 < |\eta| < 4.0$

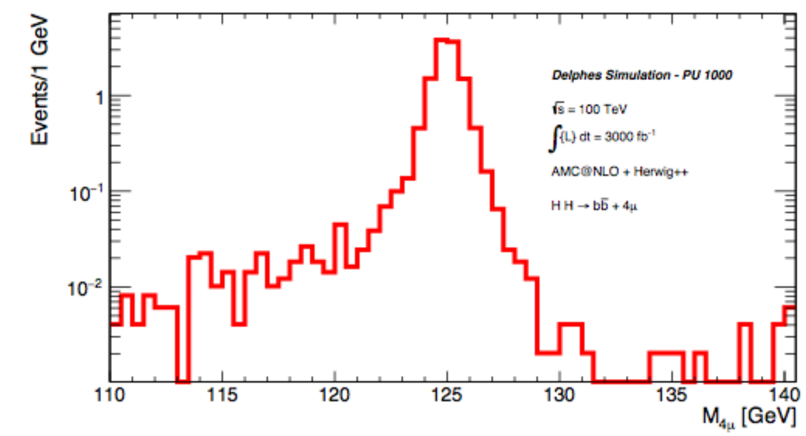
z_0 resolution (*)
- ***in $|\eta|<2.5$***
  - $\sigma(z_0)$= 0.01 mm , p_T<5 GeV
  - $\sigma(z_0)$= 0.005 mm , p_T>5 GeV
- **In $2.5<|\eta|<4$**
  - $\sigma(z_0)$= 0.1 mm , p_T<5 GeV
  - $\sigma(z_0)$= 0.05 mm , p_T>5 GeV
- **In $4.0<|\eta|<6.0$**
  - $\sigma(z_0)$= 1.0 mm , p_T<5 GeV
  - $\sigma(z_0)$=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

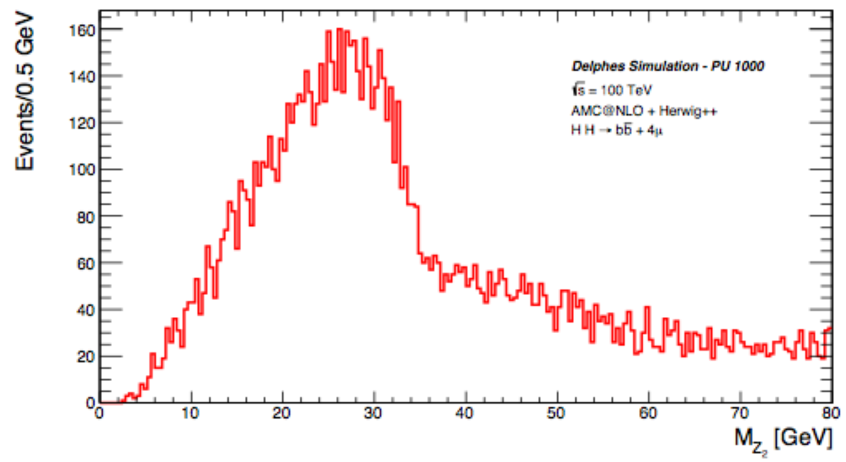
HH→ZZbb→4lbb, l=e,μ

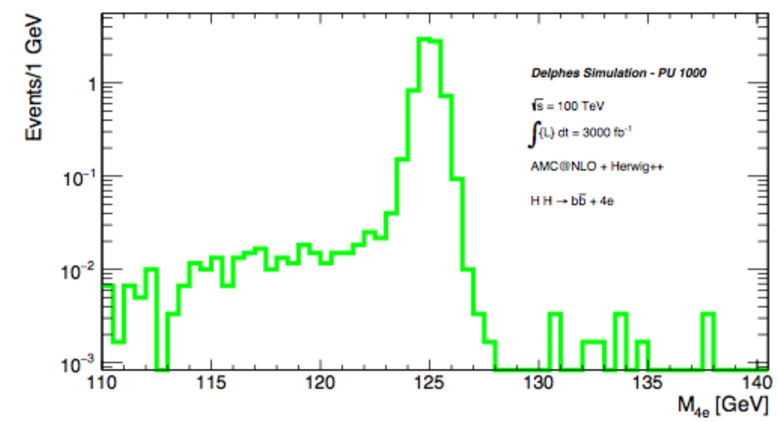
N. De Filippis (Bari), S. Braibant (Bologna)

- ≥ 4 muons with p_T > 5 GeV, |η| < 4.0
- ≥ 4 electrons with p_T > 7 GeV, |η| < 4.0
- Z_1 selection: $\ell^+\ell^-$ pair with mass close 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>1 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









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

	σ·L·Br(hh→ZZbb→4lbb)	no b-jet req.	with b-jet	ε (no b-jet)	ε (b-jet)
4e					
4μ	161	61	12,1	38%	7,4%
4e	161	40	7,7	25%	4,8%
Tot	322	101	20	31%	6,2%

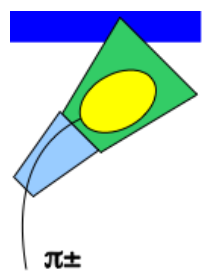
- forward b-tagging can be an important ingredient of the analysis, need to test configuration with fwd dipole
- big impact from lepton isolation cut (not presented here) → bug found in Delphes

Object in PU environment [WWbb analysis]

B. Di Micco, M. Testa, M. Verducci (Roma 3)

✦ *Particle Flow Reconstruction*

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



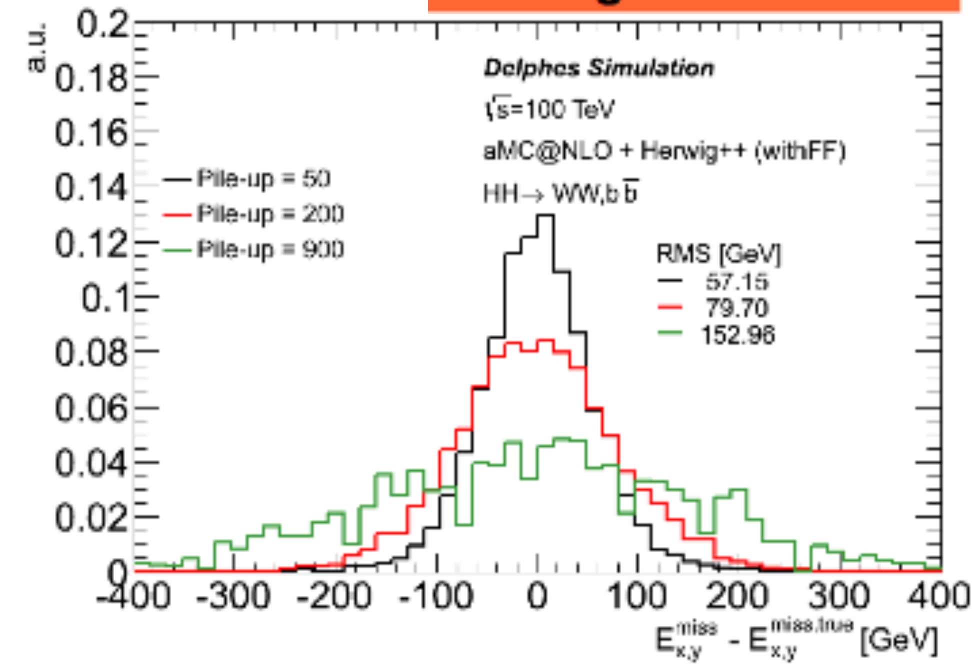
✦ *Jets*

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

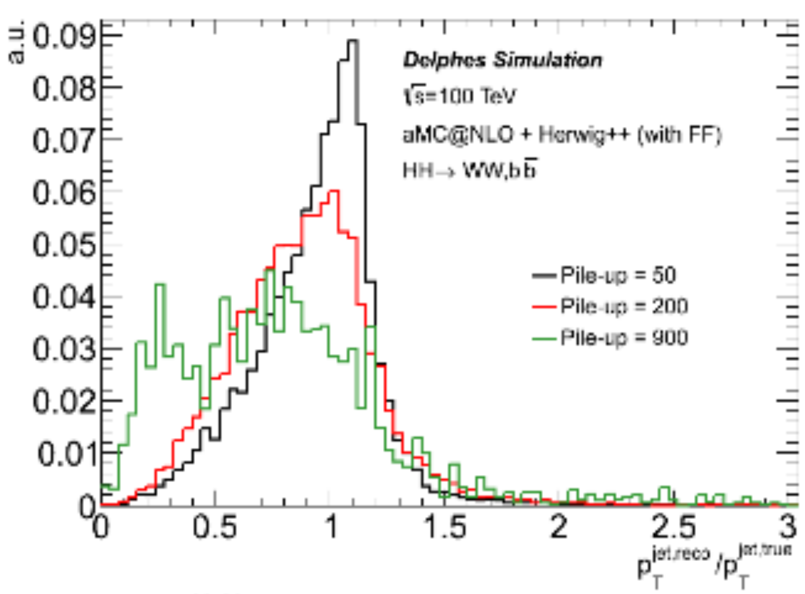
✦ *Missing Transverse Energy*

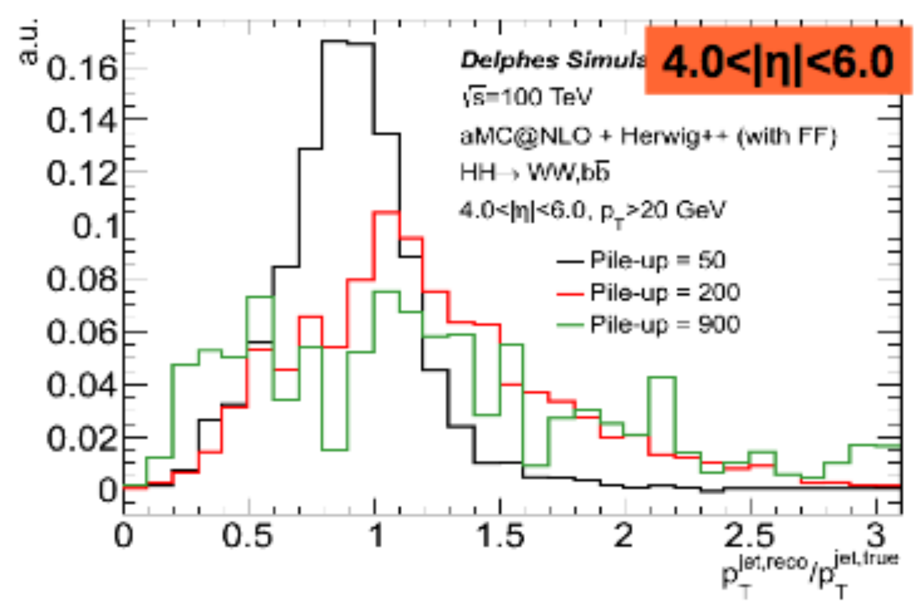
- Anti-Kt (Fast Jet) algorithm
- negative vector sum of Jets, after pile-up correction and calibration

Missing ET resolution

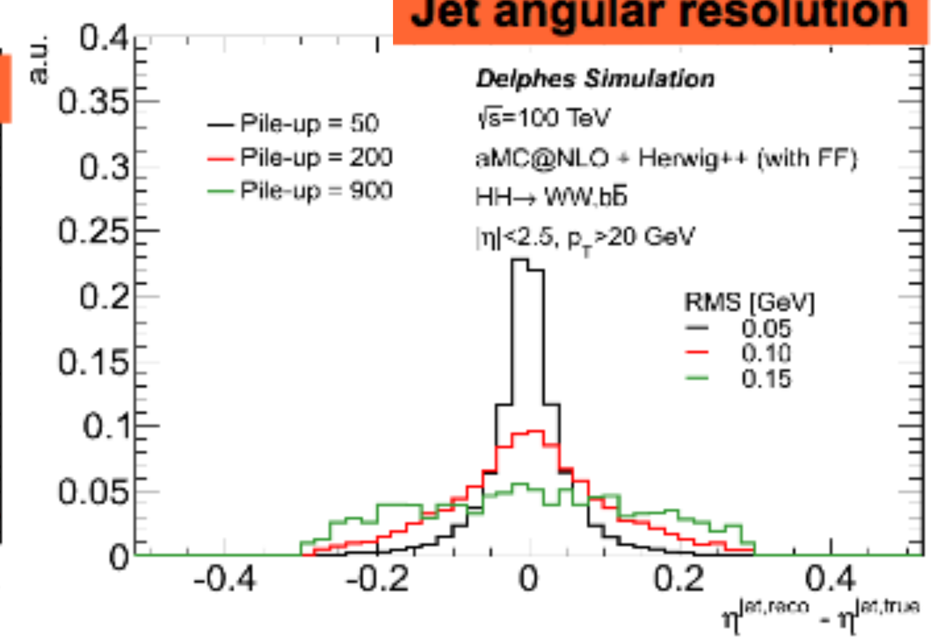


Jet pT response





Jet angular resolution



HH→WWbb→lνqqbb: MVA analysis

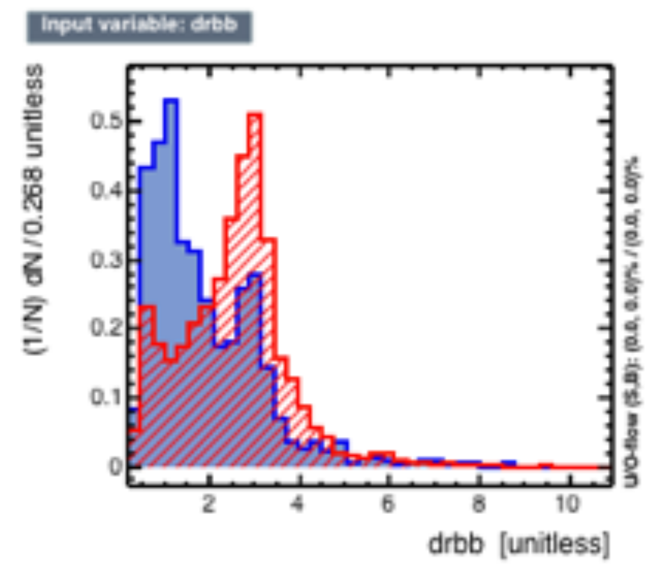
B. Di Micco, M. Testa, M. Verducci (Roma 3)

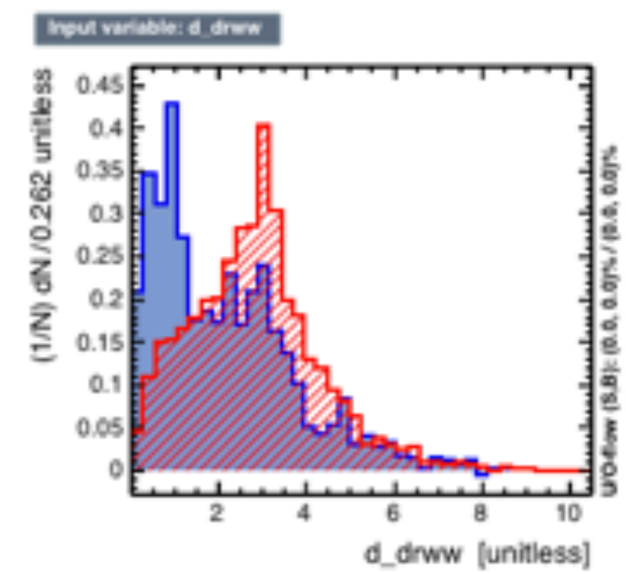
Input variables:

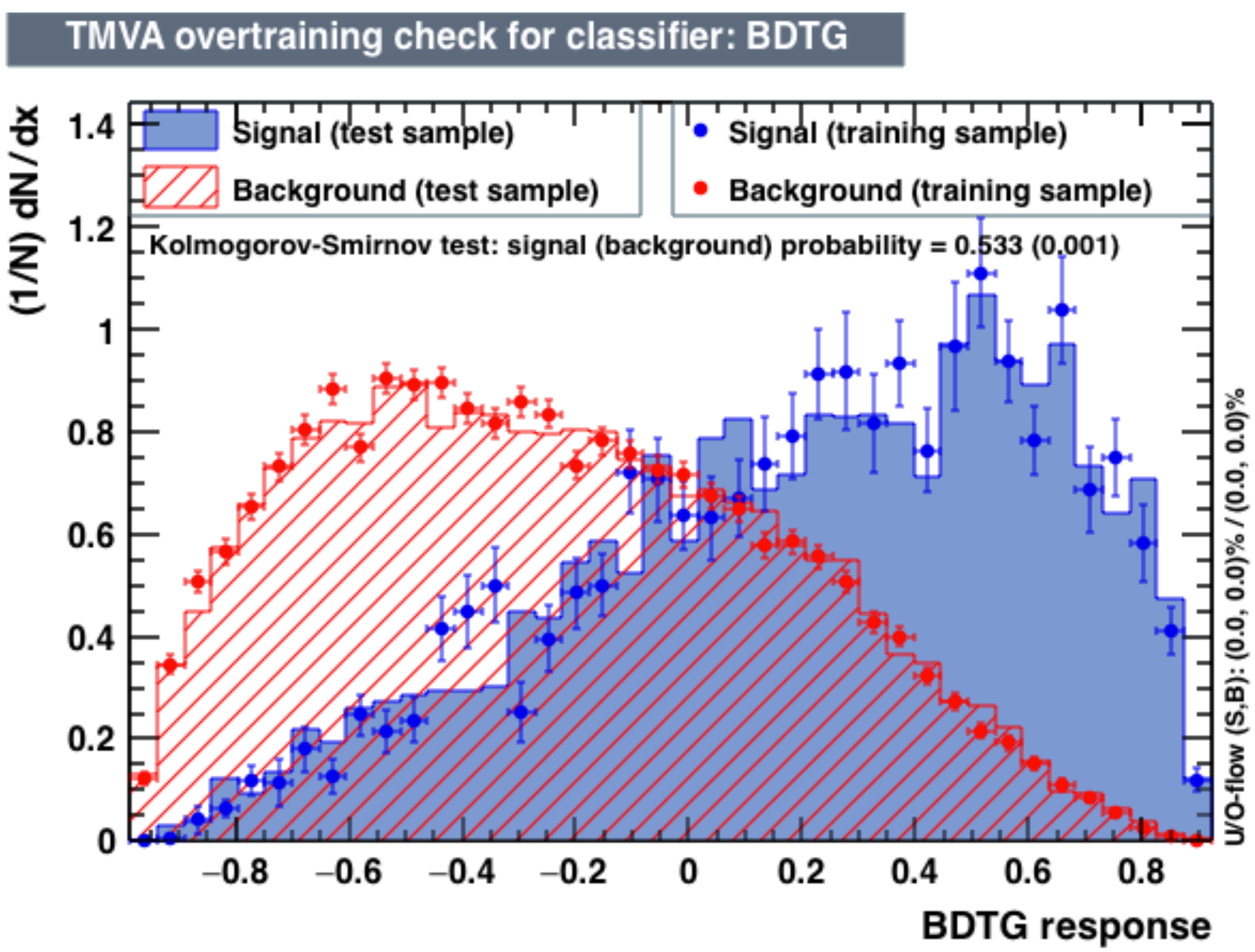
$$\Delta R_{\mathrm{jj}},\ \Delta R_{\mathrm{bb}},\ \Delta R_{\mathrm{WW}},\ m_T^{\mathrm{WW}},\ m_{\mathrm{bb}}$$
$$m_{\mathrm{jj}},\ p_T^{\mathrm{bb}},\ p_T^{\mathrm{WW}},\ E_T^{\mathrm{miss}},\ m_T^{\mathrm{W}},\ m_{\mathrm{WW}}$$

Pre-training cuts:

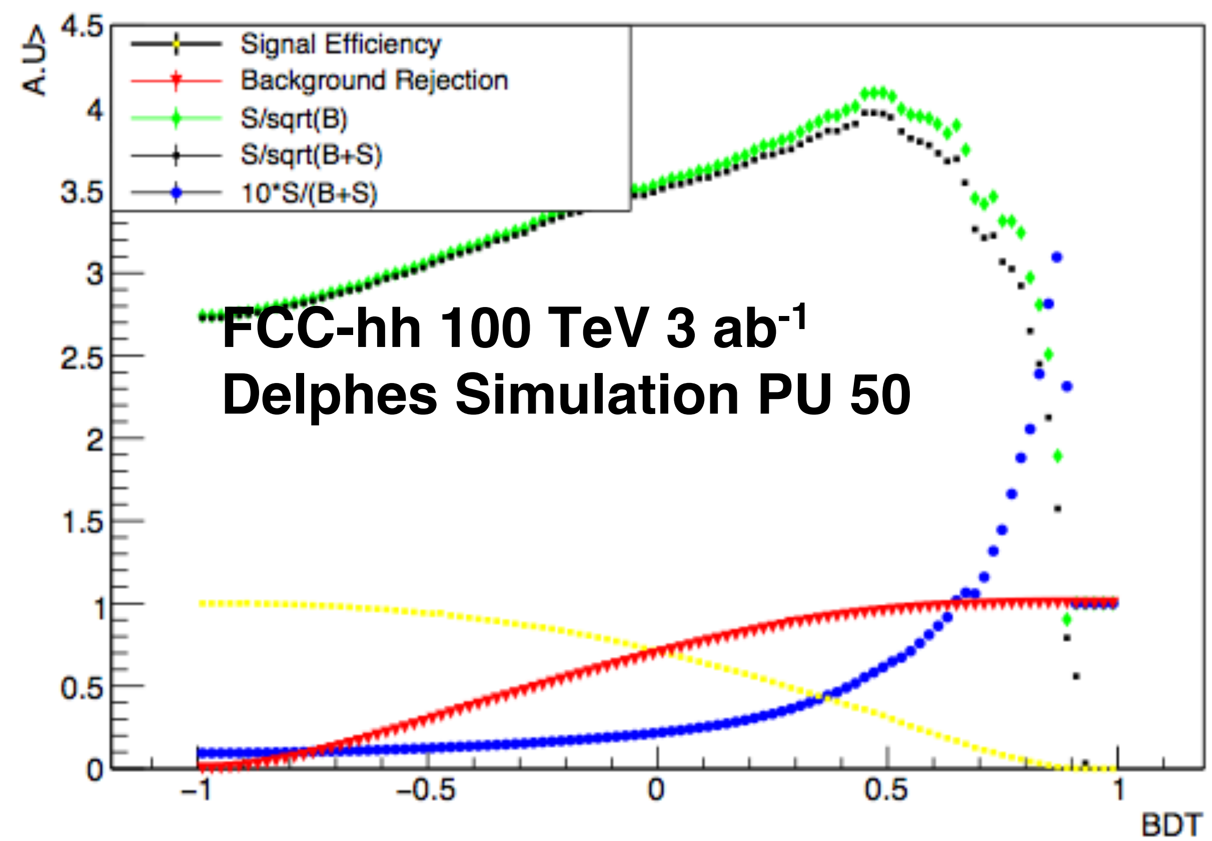
$$p_T^{\mathrm{WW}},\ p_T^{\mathrm{bb}} > 150,\ 80 < m_{bb} < 180\,\mathrm{GeV}$$
$$\Delta R_{bb} < 2.0$$







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

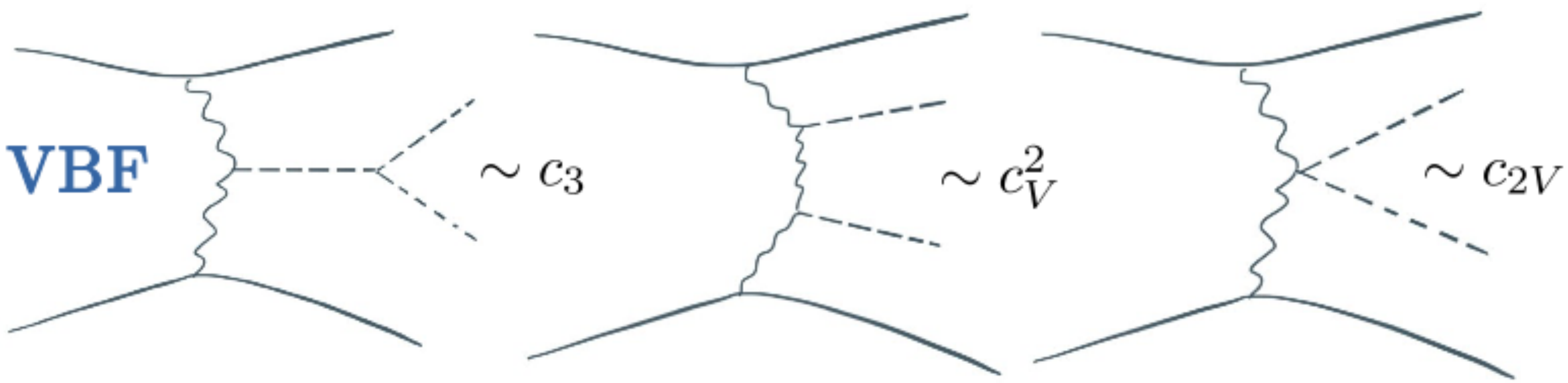


Conclusion and plans

- Fix the Delphes configuration and the handling of pileup (all+Michele Selvaggi)
- Simulation of the background for ZZbb and WWbb in various pileup scenario is our close-term priority (S. Braibant, N. De Filippis, B. Di Micco) – End September
- Optmization of the analyses with delphes (isolation, ID, pileup rejection) (all) - October
- Provide an internal document about those analyses (S. Braibant, N. De Filippis, B. Di Micco) – September – October → eventually contribute to CDR
- From now on we are going to follow and contribute regularly to CepC and FCC meetings.

Backup

VBF hh production



SM

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

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

$$\delta_i \equiv c_i - 1$$

dashed : before cuts
solid : after cuts

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

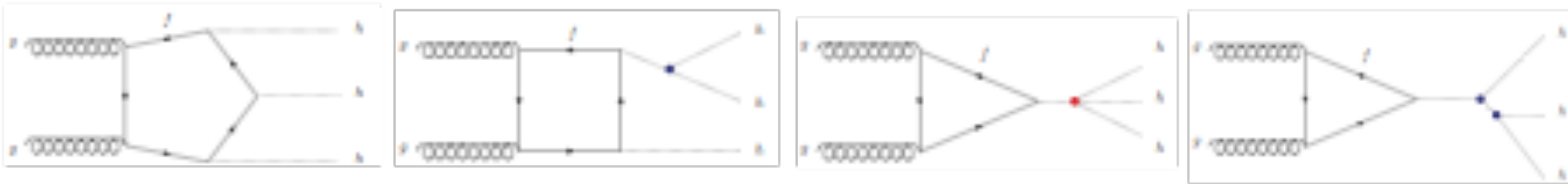
Not strong sensitivity to SM hh production, but adds information on New Physics operators

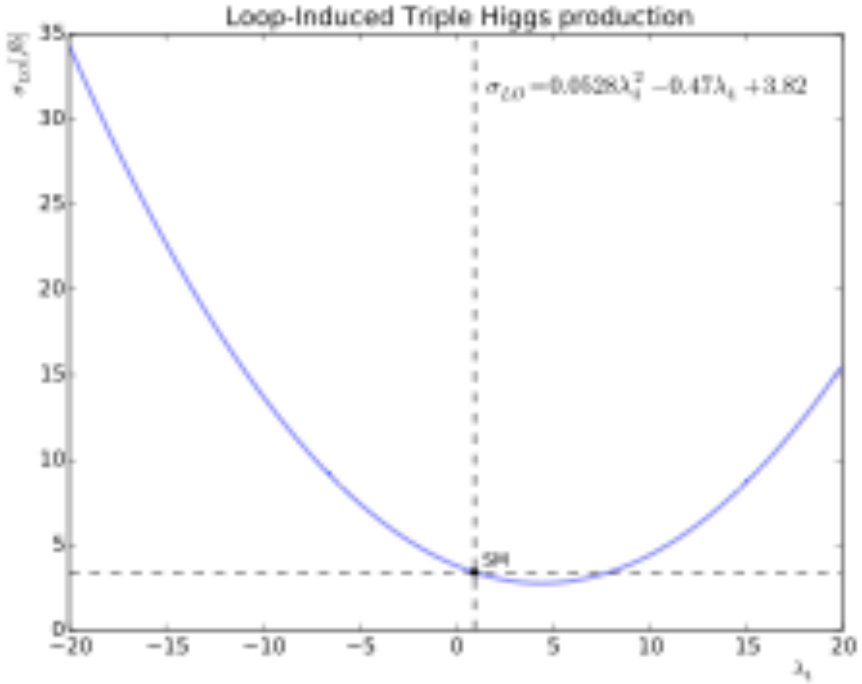
			14 TeV	100 TeV
Acceptance cuts		p_{T_j} (GeV) $\geq$	25	40
		p_{T_b} (GeV) $\geq$	25	35
		$\lvert\eta_j\rvert \leq$	4.5	6.5
		$\lvert\eta_b\rvert \leq$	2.5	3.0
VBF cuts		$\lvert\Delta y_{jj}\rvert \geq$	5.0	5.0
		m_{jj} (GeV) $\geq$	700	1000
	Central jet veto:	$p_{T_{j_3}}$ (GeV) $\leq$	45	65
		m_{hh}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

	68% probability interval on $\delta_{c_{2V}}$	
	$1 \times \sigma_{\rm bkg}$	$3 \times \sigma_{\rm bkg}$
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	
	$1 \times \sigma_{\rm bkg}$	$3 \times \sigma_{\rm bkg}$
LHC_{14}	109	210
HL-LHC	49	108
FCC_{100}	12	23

Higgs quartic coupling





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}: $-4 < \lambda_4 < 16$

Multi-leptons: HH→bbZZ,bbWW,bbμμ

$hh \to (b\bar{b})(ZZ^*) \to (b\bar{b})(4\ell)$, $hh \to (b\bar{b})(WW^*)/(\tau^+\tau^-) \to (b\bar{b})(\ell^+\ell^-)$, $hh \to (b\bar{b})(\mu^+\mu^-)$ 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	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$

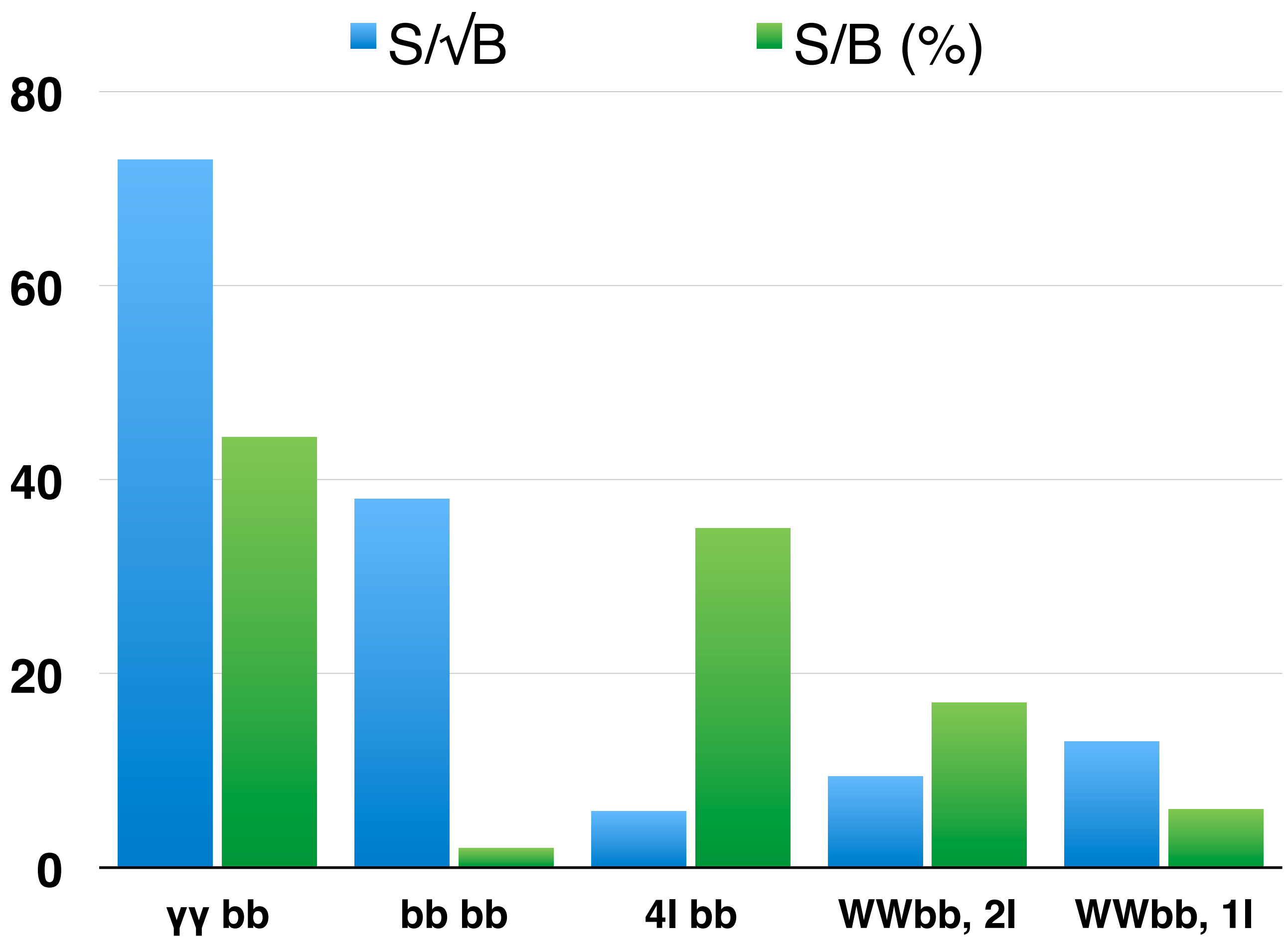
channel	σ(100 TeV) (fb)	$N_{30\ \mathrm{ab}^{-1}}$(ideal)	$N_{30\ \mathrm{ab}^{-1}}$(LHC)
$\mathbf{hh} \to (b\bar{b})(W^+W^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\ell^-\bar{\nu}_\ell)$	27.16	209	199
$\mathbf{hh} \to (b\bar{b})(\tau^+\tau^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\bar{\nu}_\tau\ell^-\bar{\nu}_\ell\nu_\tau)$	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

FCC studies: S/N ratio



- 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 of 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

FCC-hh looks to have a strong physics case

Higgs boson as inflaton

Gravitational action coupled to the SM sector

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

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

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

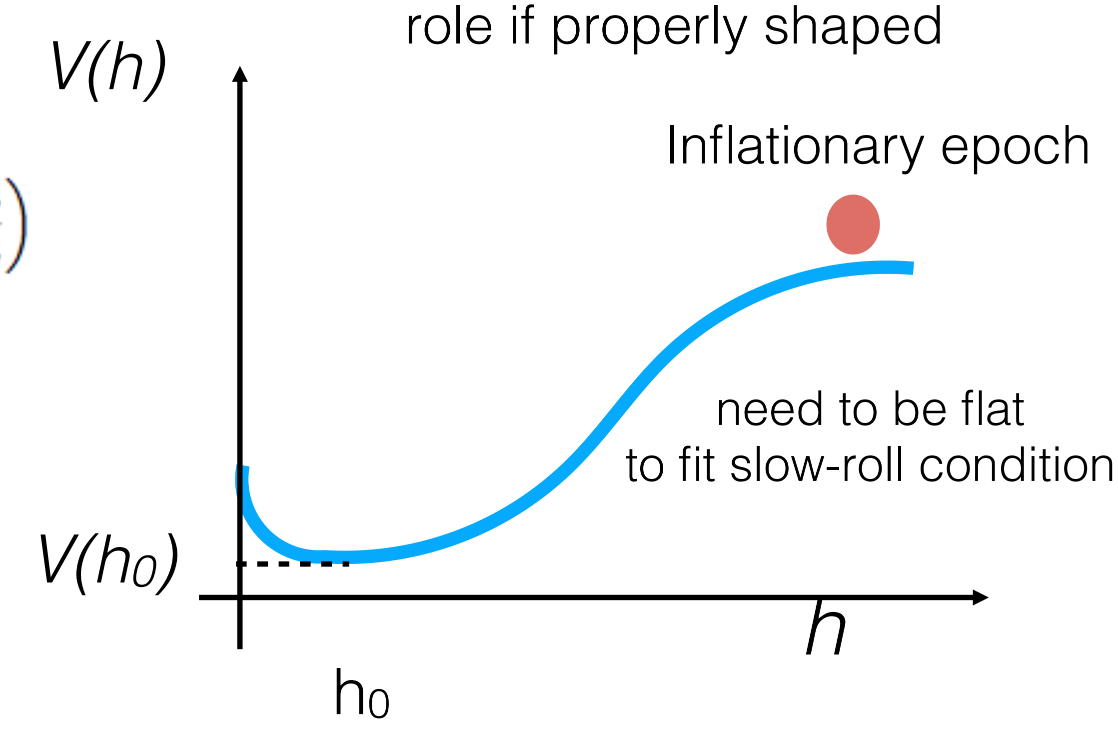
universe radius, exponentially expanding during inflation

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.