Search Higgs pair signatures at hadronic colliders

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arxiv:1604.04329

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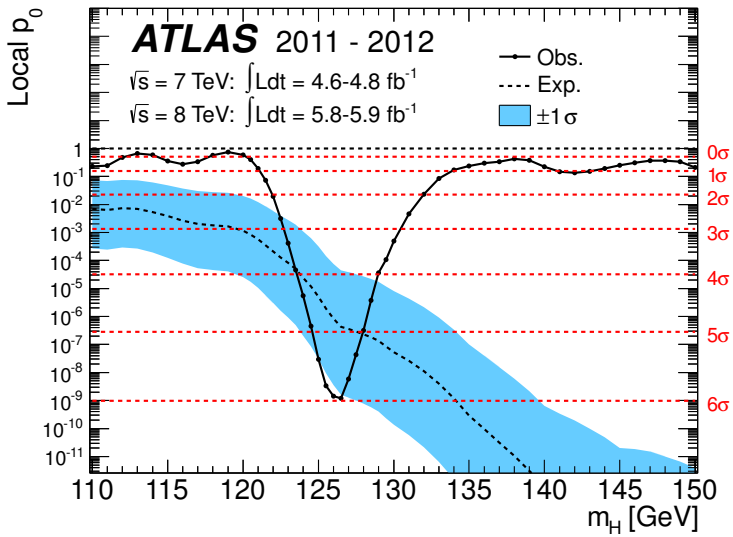
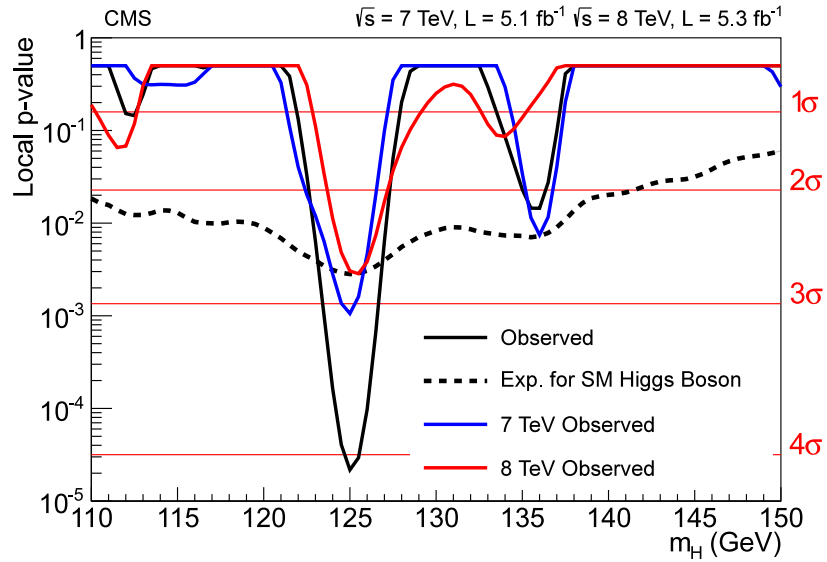
6/17/2016

Higgs discovery

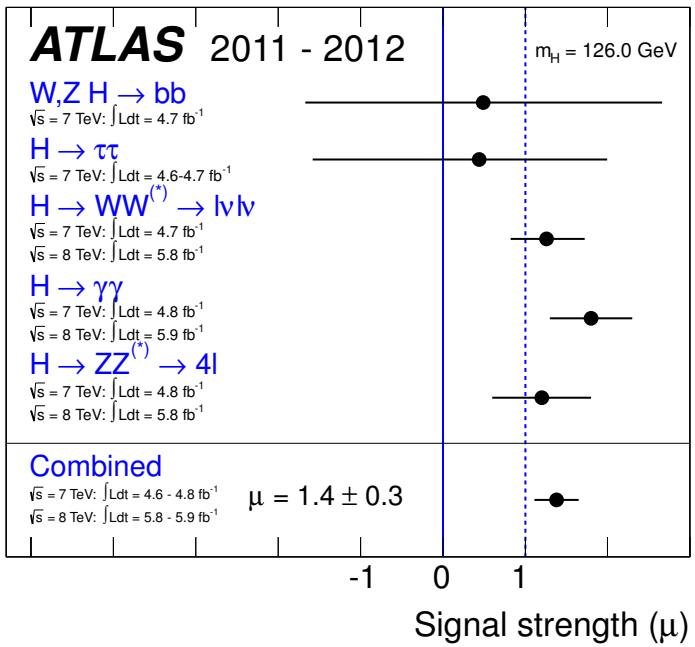


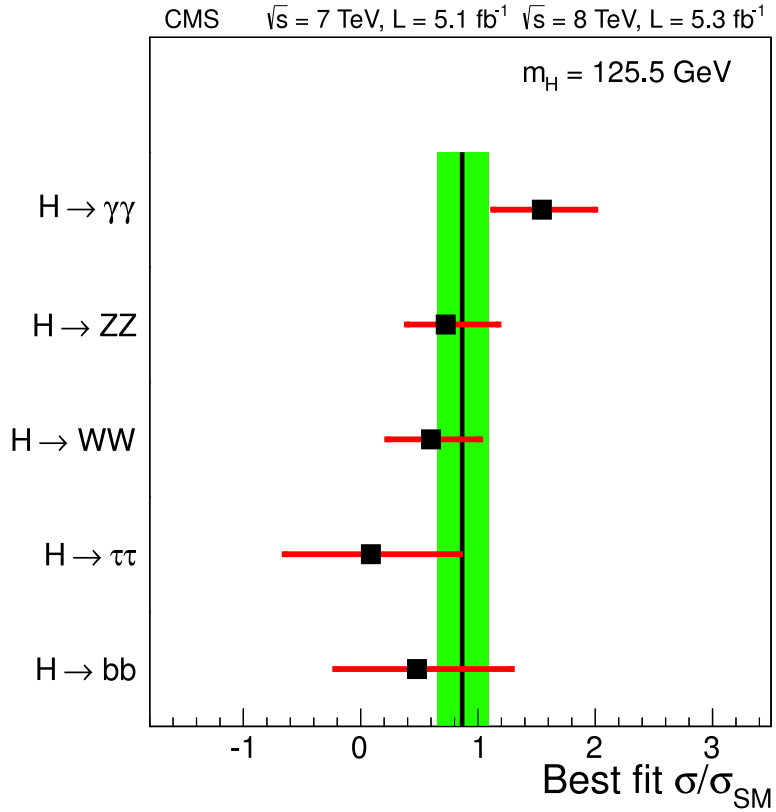


4th July, 2012, observation of a Higgs-like boson by ATLAS and CMS.

[0] 1207.7214,1207.7235

Higgs coupling





Consistent with SM predictions.

Higgs self coupling and pair production

After EWSB:

$$V = \frac{1}{2} m_h^2 h^2 + \lambda_3 \lambda_{\mathrm{SM}} v h^3 + \lambda_4 \frac{1}{4} \lambda_{\mathrm{SM}} h^4$$

$$\lambda_{\mathrm{SM}} = \frac{m_h^2}{2v^2}$$

In SM, $\lambda_3 = \lambda_4 = 1$
No CP violation in SM.

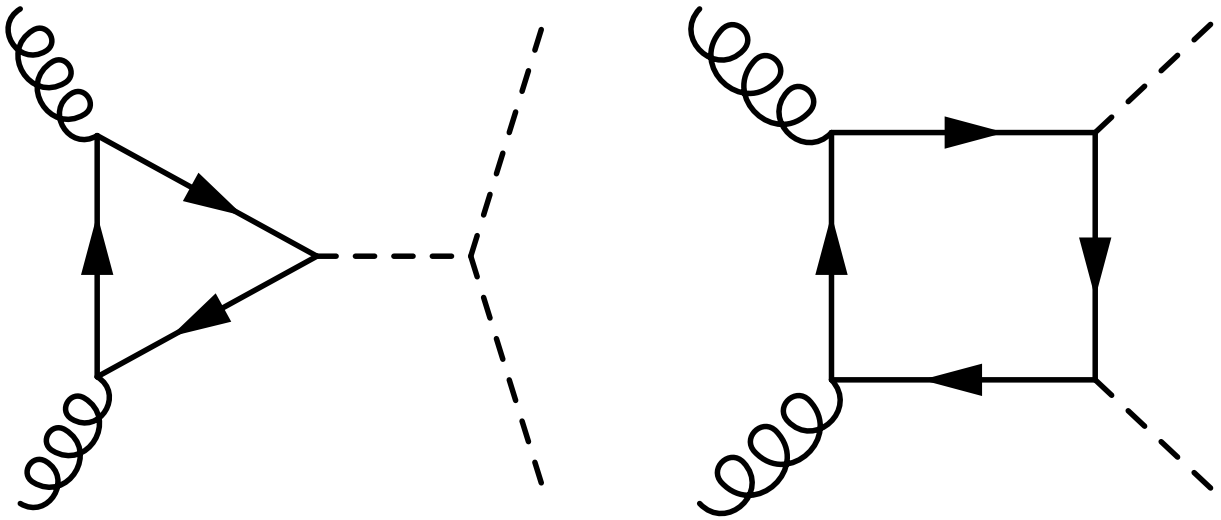
spontaneously CP violation

But in BSM, such as the following model:

$$\begin{aligned} V =& m_H^2 H^\dagger H + \frac{\lambda_H}{4}(H^\dagger H)^2 + m_S^2 S^\dagger S + \frac{\lambda_S}{4}(S^\dagger S)^2 \\ &+ \lambda_X S^\dagger S H^\dagger H \\ &+ 2\left(\mu^2 + \lambda_1 S^\dagger S + \lambda_2 H^\dagger H\right) Re(S^2) + 2\lambda_3 Re(S^4)\,. \end{aligned}$$

Z2 symmetry $S \to -S$, will be broken if S develops a complex vacum expectation value.
Higgs boson self-coupling will CP violation

gluon fusion into Higgs boson pair



Loop diagrams at LO!

Higgs decay and previous study about Higgs pair

Branching Ratios for 125GeV SM Higgs:

Mode	Branching Ratio
$b\bar{b}$	57.8%
$\tau^+\tau^-$	6.37%
$\ell\nu jj$	6.34%
$\ell\ell\nu\nu$	1.07%
$\gamma\gamma$	0.230%
$Z\gamma$	0.155%
$\mu^+\mu^-$	0.0221%
$\ell\ell\ell\ell$	0.0126%

Studied Mode for Higgs pair production:
$b\bar{b}\gamma\gamma$,$b\bar{b}b\bar{b}$,$b\bar{b}\tau^+\tau^-$,$b\bar{b}\ell\nu jj$,$b\bar{b}\ell\ell\nu\nu$,etc.

$HH \to WWWW$ mode

BR($H \to WW^*$)$\approx$ 21.6%
Only same signed di-lepton mode $\ell^{\pm}\ell^{\pm}jjjj\nu\nu$ and three leptons mode $\ell\ell\ell jj\nu\nu\nu$ are reachable at 14TeV LHC.
They have been considered by Baur,Plehn,Rainwater(02,03)[1][2], but for $m_H > 140\,\text{GeV}$. For 125GeV Higgs boson, the branching ratio of Higgs decaying to WW^* is much smaller, and one of the two W bosons is off-shell.
Solution: Partial reconstruction for $3\ell 2j + \not{E}_T$ final-state, m_{T2}, and multivariate analysis.

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[1] U. Baur, T. Plehn and D. L. Rainwater, Phys. Rev. Lett. 89, 151801 (2002)

[2] U. Baur, T. Plehn and D. L. Rainwater, Phys. Rev. D 67, 033003 (2003)

$4\ell + \not{E}_T$ finalstate

- Tiny branching ratio: only reachable at 100TeV
- Clean background
- easy to be reconstructed.

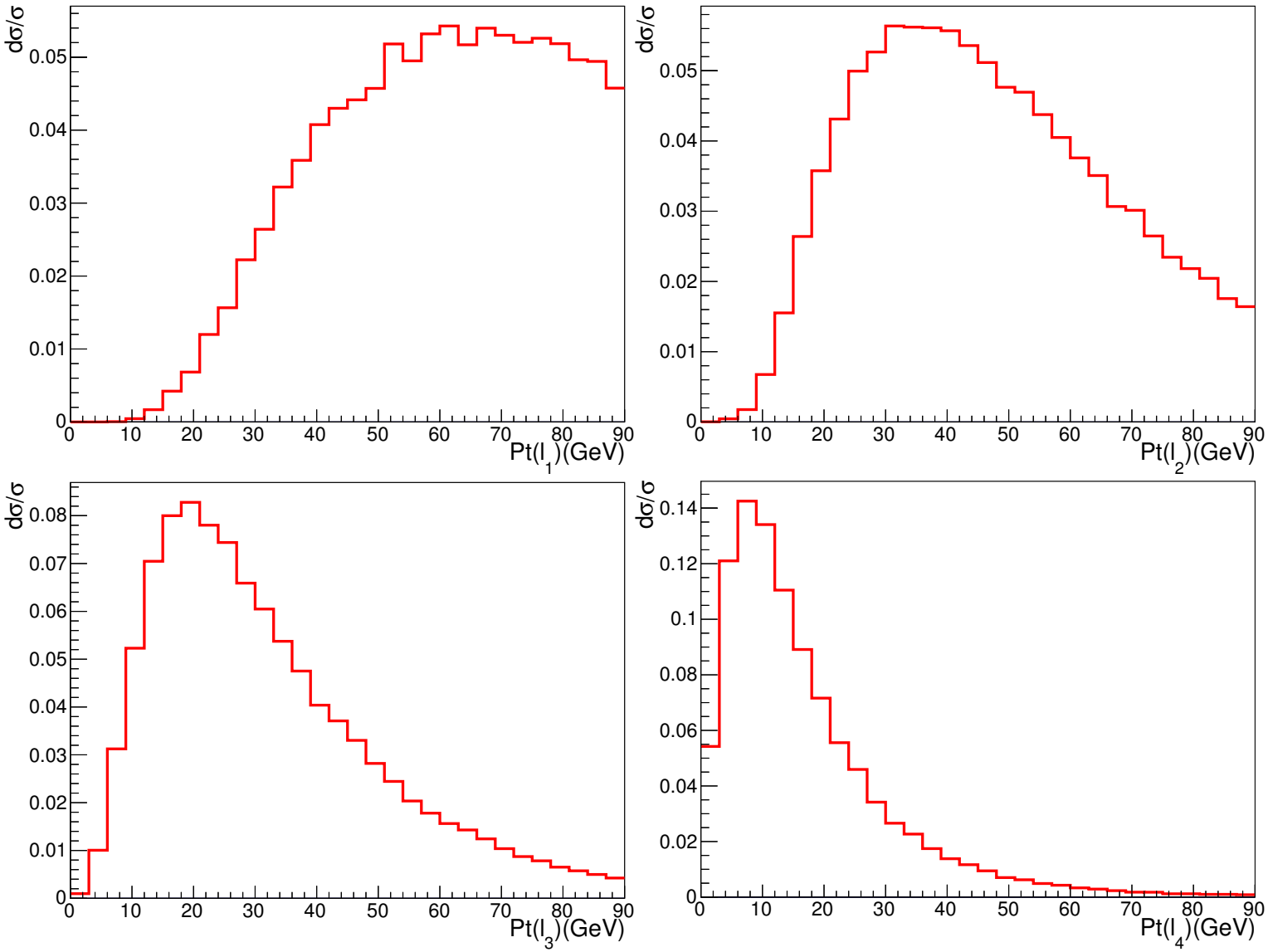
Background:

- ZZ
- Z+: $ZH, ZW^+W^-, Zt\bar{t}$
- $t\bar{t}$+:$t\bar{t}H, t\bar{t}t\bar{t}, t\bar{t}W^+W^-$
- EW:$HWW, WWWW$

	signal	$Z+$	$t\bar{t}+$	EW	ZZ
cross section(fb)	0.29	5.40,17.8,217	16.9,7.12,2.3	0.084,0.077	485
M1 $\ell^+\ell^-\ell^+\ell^-$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{2}$
M2 $e^+e^-\mu^+\mu^-$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{2}$
M3 $\ell^+\ell^-\ell^\pm\ell'^\mp$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0
M4 $\ell^+\ell^+\ell'^-\ell'^-$	$\frac{1}{8}$	0	$\frac{1}{8}$	$\frac{1}{8}$	0

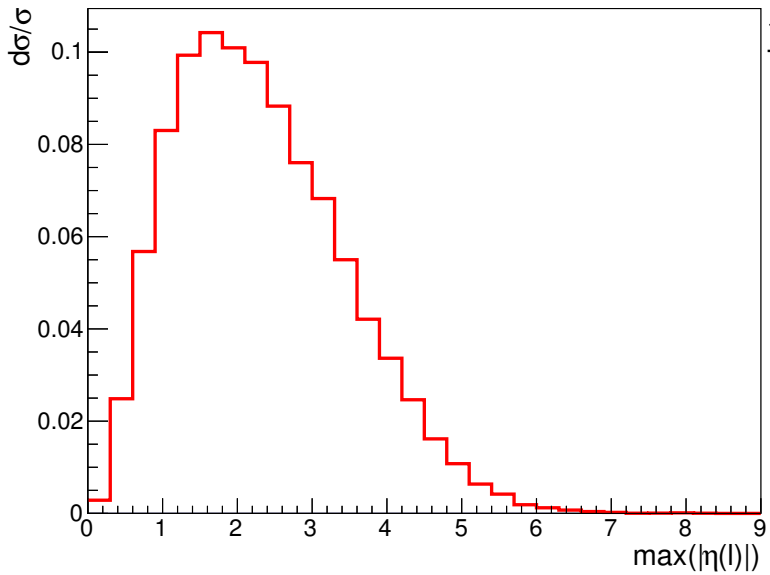
Preselection

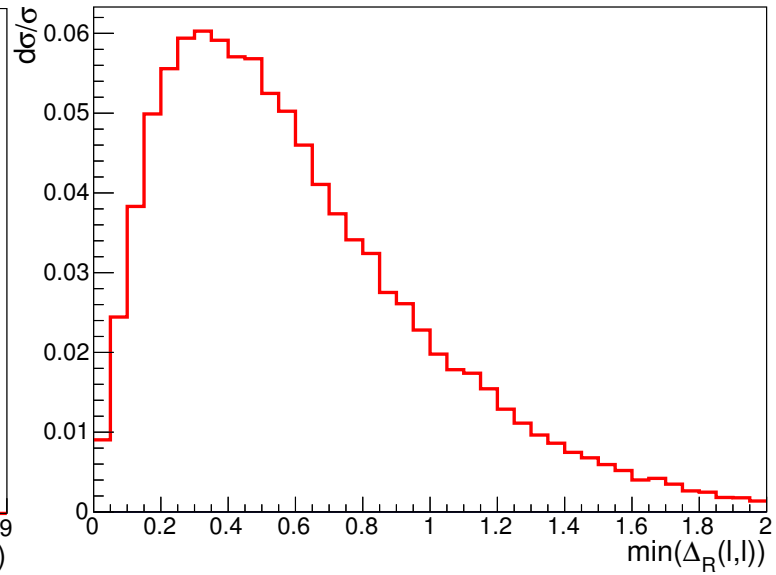
- $Pt(\ell_{1,2,3,4}) > 30, 20, 15, 8\text{GeV}$



Preselection

- $|\eta(\ell)| < 4$, $\Delta_R(\ell, \ell) > 0.15$





- b veto
- For M3, 15GeV $< m(\ell^+, \ell^-) <$ 80GeV or $m(\ell^+, \ell^-) >$ 100GeV

combination and Δm for M3 and M4

$\ell_1^+ \ell_2^+ \ell_3^- \ell_4^-$,

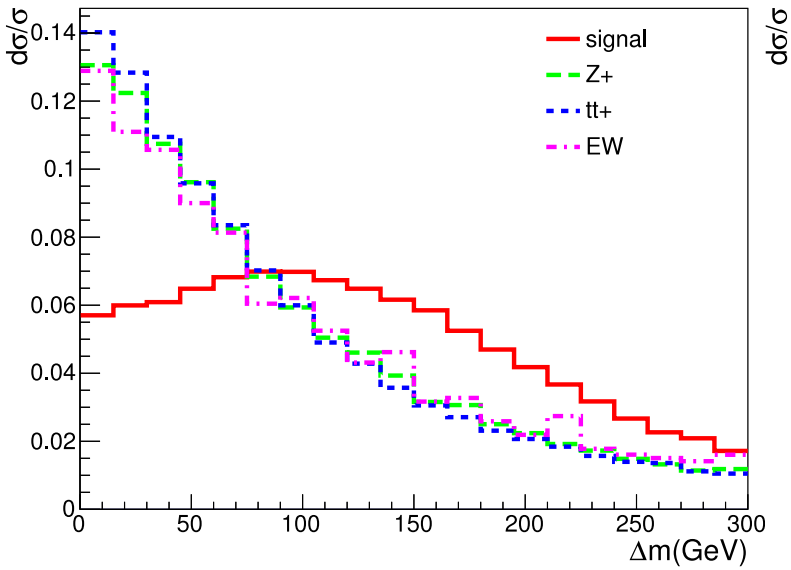
- $H_1 \to \ell_1^+ + \ell_3^- + \not{E}, H_2 \to \ell_2^+ + \ell_4^- + \not{E}$,
- $H_1 \to \ell_1^+ + \ell_4^- + \not{E}, H_2 \to \ell_2^+ + \ell_3^- + \not{E}$,

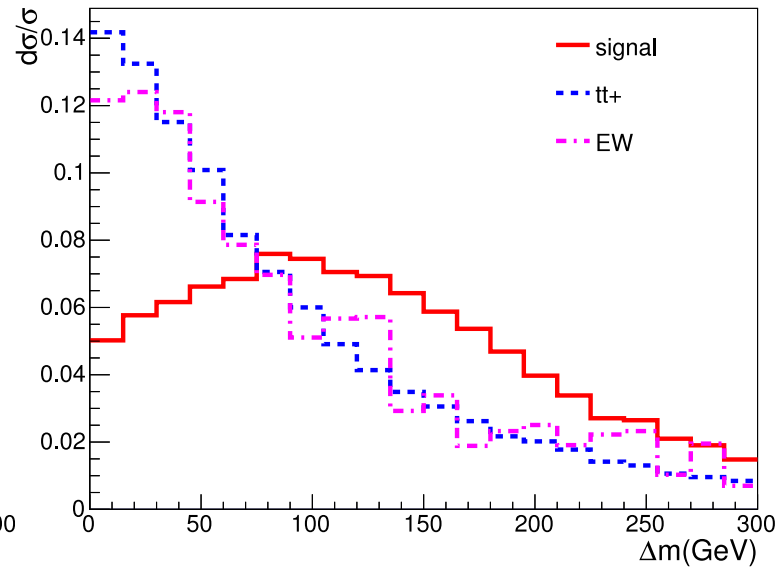
Which one?

If $m(\ell_1, \ell_3) + m(\ell_2, \ell_4) < m(\ell_1, \ell_4) + m(\ell_2, \ell_3)$ then choose the first, otherwise the second.

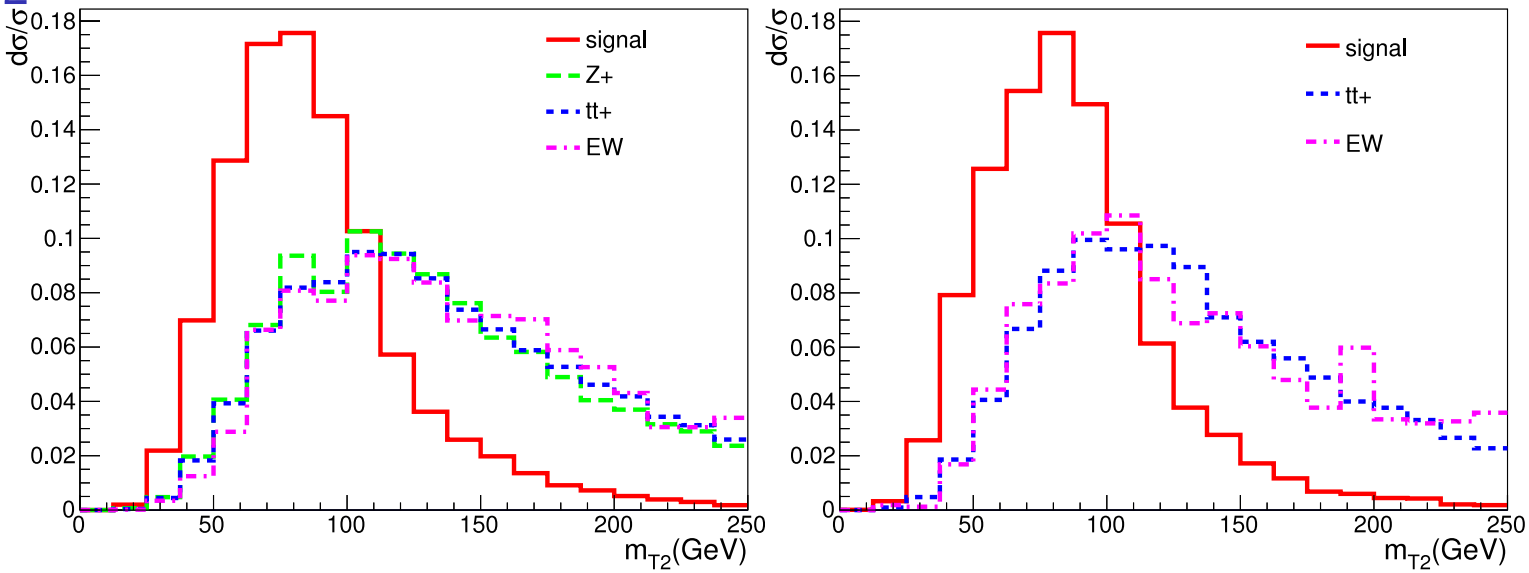
94% correctness.

Δm





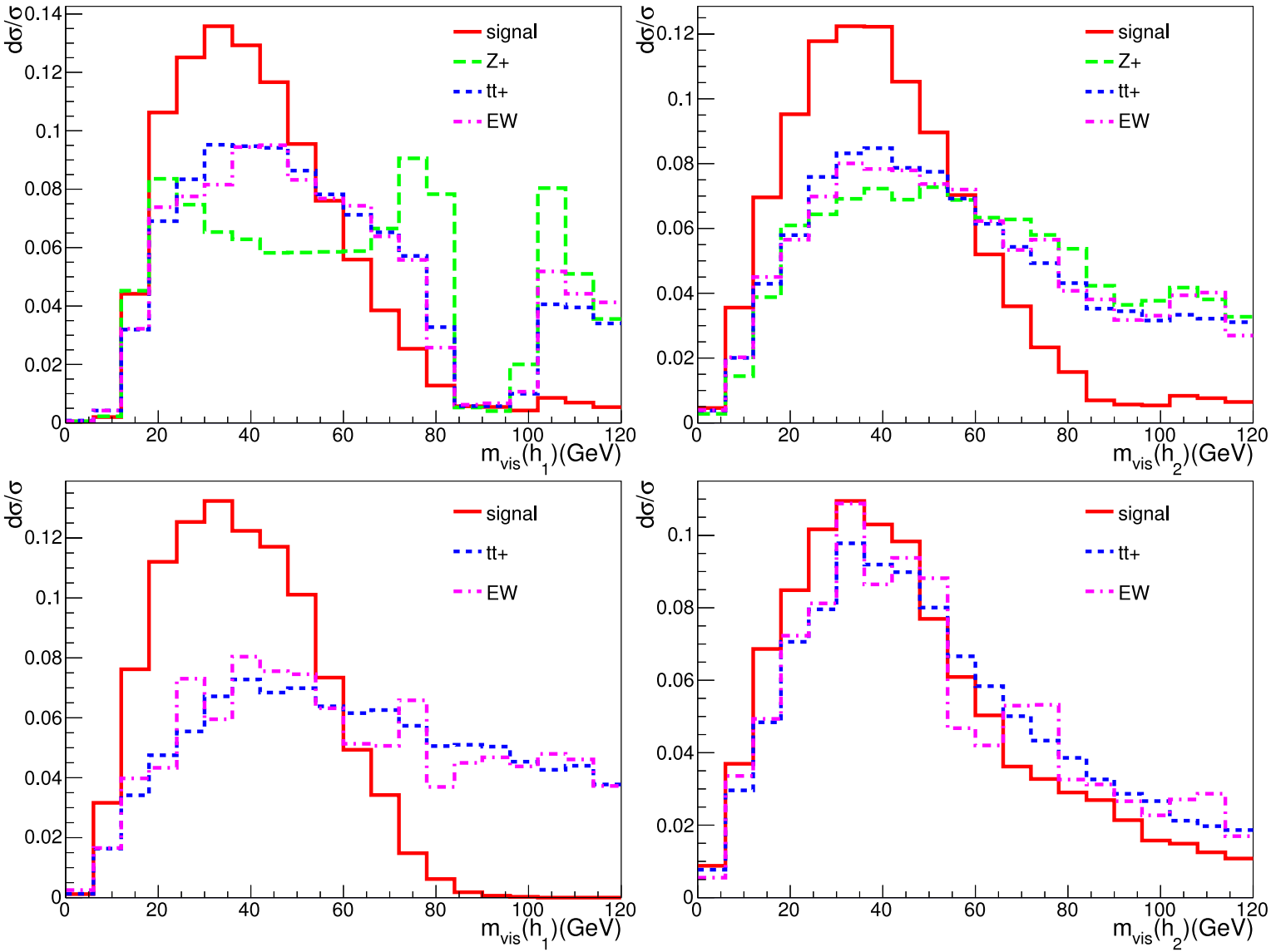
m_{T2} for M3 and M4



$$H_1 \to (\ell_1^+ + \ell_3^-) + \not{E}_1$$
$$H_2 \to (\ell_2^+ + \ell_4^-) + \not{E}_2$$

$$m_{T2} = \min_{\vec{P}_T(\not{E}_1)+\vec{P}_T(\not{E}_2)=\vec{\not{E}}_T} \left\{ \max \left[m_T(\vec{P}_T(\ell_1\ell_3), \vec{P}_T(\not{E}_1)), \right.\right.$$
$$\left.\left. m_T(\vec{P}_T(\ell_2\ell_4), \vec{P}_T(\not{E}_2)) \right] \right\}$$

visible mass for M3 and M4



significane for M3 and M4

	$M3$			$M4$		
processes	preselection	cut-based	BDT	preselection	cut-based	BDT
signal	172	68.8	99.8	55.2	28.8	43.9
background	5340	273	274	302.6	18.0	23.8
S/B	0.032	0.25	0.38	0.18	1.6	1.9
$S/\sqrt{B}$	2.35	4.2	6.1	3.17	6.8	9.2

Detector

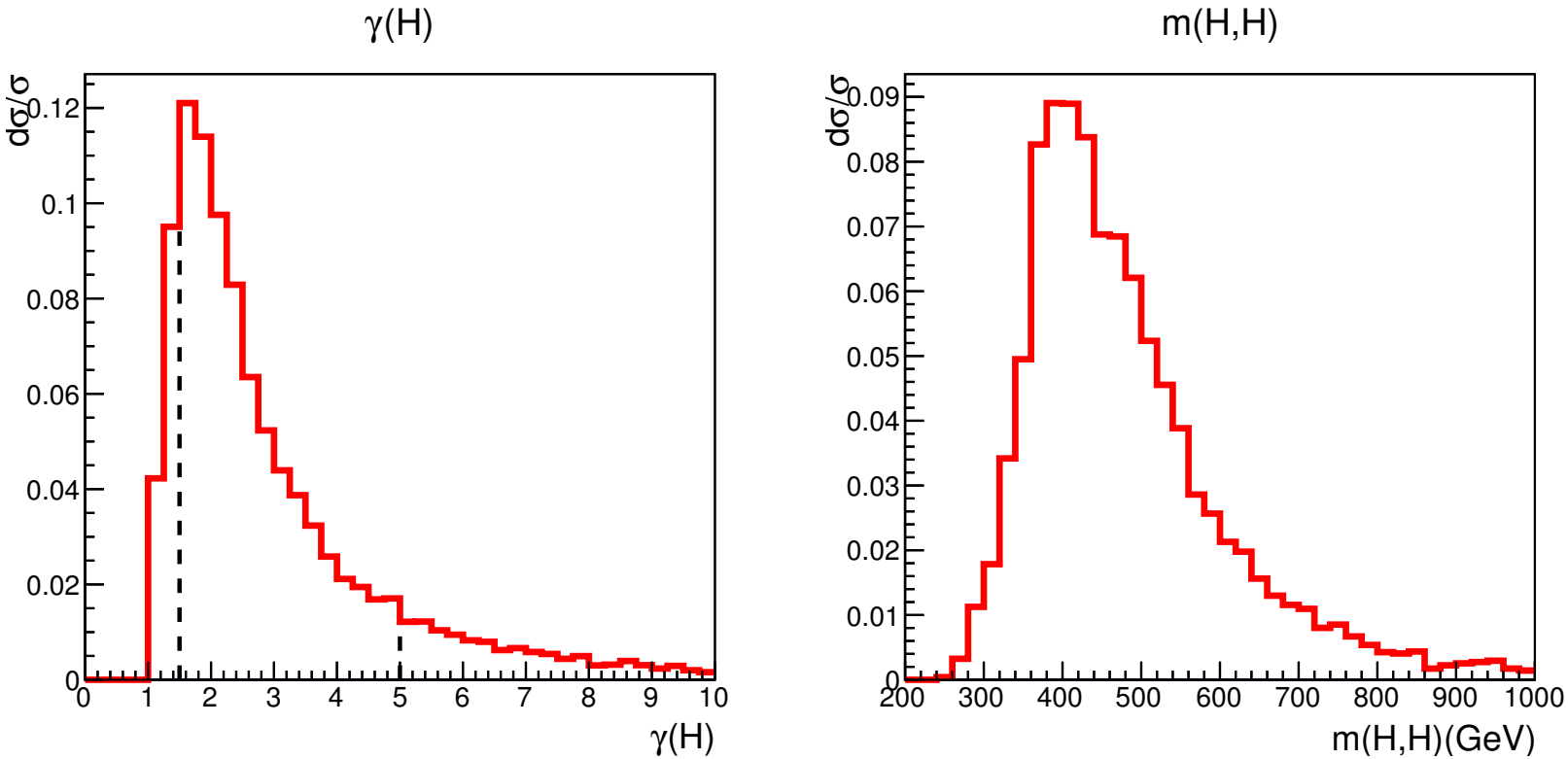
	$\eta(\ell)$	$\eta(b)$	$\Delta R(\ell)$	$Pt(j)$(GeV)	$Pt(\ell)$(GeV)
ATLAS-like	2.5	2.5	0.5	20	10
A1	4.0	2.5	0.5	20	10
A2	4.0	4.0	0.5	20	10
A3	4.0	4.0	0.3	20	10
FCC	6.0	6.0	0.3	40	20
F1	6.0	6.0	0.3	20	20
F2	6.0	6.0	0.3	20	10

results

	M3			M4		
	S	B	$S/\sqrt{B}$	S	B	$S/\sqrt{B}$
Hadron	99.8	274.3	6.1	43.9	23.8	9.2
ATLAS-like	13.2	62.4	1.7	6.3	8.5	2.2
A1	18.6	108.3	1.8	8.7	13.4	2.4
A2	18.3	93.3	1.9	8.7	11.6	2.6
A3	35.8	156.2	2.9	16.7	18.9	3.8
FCC	18.6	82.6	2.0	8.0	13.6	2.2
F1	18.3	57.5	2.4	8.1	8.0	2.9
F2	38.2	177.5	2.9	17.5	19.1	4.0

Thank you!

Higgs boost

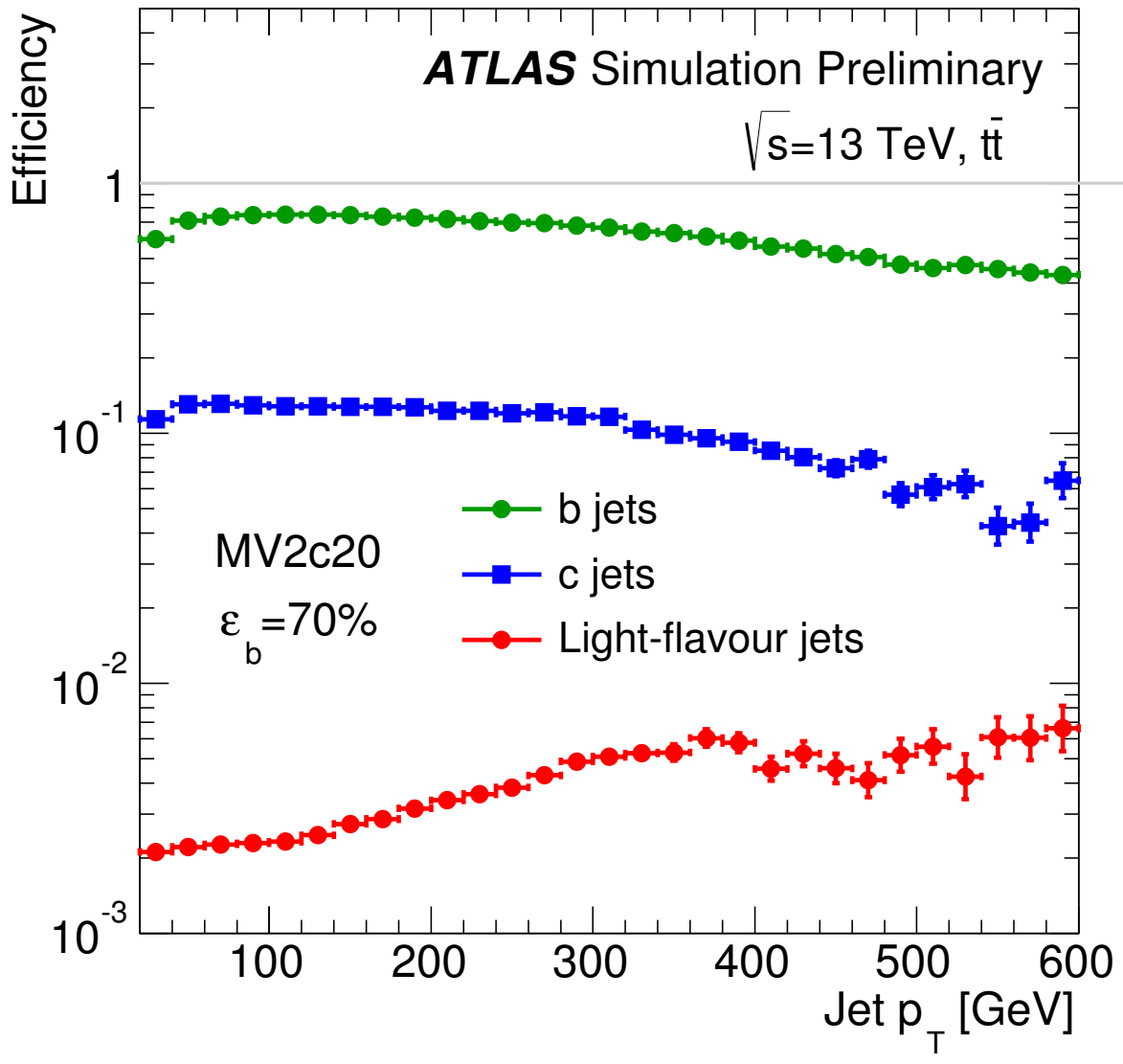


γ factor ($\gamma = E(H)/m_H$) and the invariant mass of Higgs pair. Higgs boson is moderately boosted due to top quark loop.

partial reconstruction methods

	Methods	The percentage of correctness (%)
1	$\lvert m_{H(ll)} - m_{H(ljj)} \rvert$	68.9
2	$\Delta_R(l^{\pm}, l^{\mp})$	85.0
3	$\Delta_R(l^{\pm}, W_{jj})$	89.9
4	$P_t[H(ll)] + P_t[H(ljj)]$	90.3
5	$\Delta_R(H(ll), H(ljj))$	92.0
6	$m_{H(ll)} + m_{H(ljj)}$	95.4

The percentage of correctness at the parton level.



ATL-PHYS-PUB-2015-022