Higgs measurements @FCC-hh

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FCC-hh Physics Meeting - 28/04/2017 - CERN

Outline

- Context
- Higgs p_T
- Decay Channels:
  - $H \rightarrow ZZ \rightarrow 4l$
  - $H \rightarrow WW \rightarrow 2l2\nu$
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow \mu\mu$

Context

MLM

Goals

g_{HXY}	FCC-ee	FCC-hh
ZZ	0.16%	
WW	0.85%	
γ γ	1.7%	<1% ?
Zγ	?	1% ?
tt		1% ?
bb	0.42%	
τ τ	0.94%	
cc	1.0%	
ss	H→Vγ, in progr.	
μμ	6.4%	2% ?
uu,dd	H→Vγ, in progr.	
ee	e^+e^-→H, in progr.	
HH		5% ?
BR_{exo}	0.48%	$< 10^{-6}$?

- Setup a "task force", to work coherently on defining target precision benchmarks
- Define meas'nt strategies based on
  - precise info from FCC-ee
  - selfcontained FCC-hh inputs
- Define precision for both
  - absolute BR or BR ratio meas's
  - $d\sigma/dp_T$, (both absolute and shape) to probe BSM sensitivity
- Start by identifying ideal regions of $S/\sqrt{B}$ (B=irreducible bgs), and allow for optimal det performance
- Identify regions of optimal separation between production channels
- Identify leading exptl syst, to be tested via concrete Delphes sim's, setting performance targets

Higgs total rates

	σ(13 TeV)	σ(100 TeV)	σ(100 TeV)/σ(13 TeV)
ggH	49 pb	803 pb	16
VBF	3.8 pb	69 pb	18
ttH	0.5 pb	34 pb	68
vH	2.3 pb	27 pb	12

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$

$N_8 = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

Higgs Samples

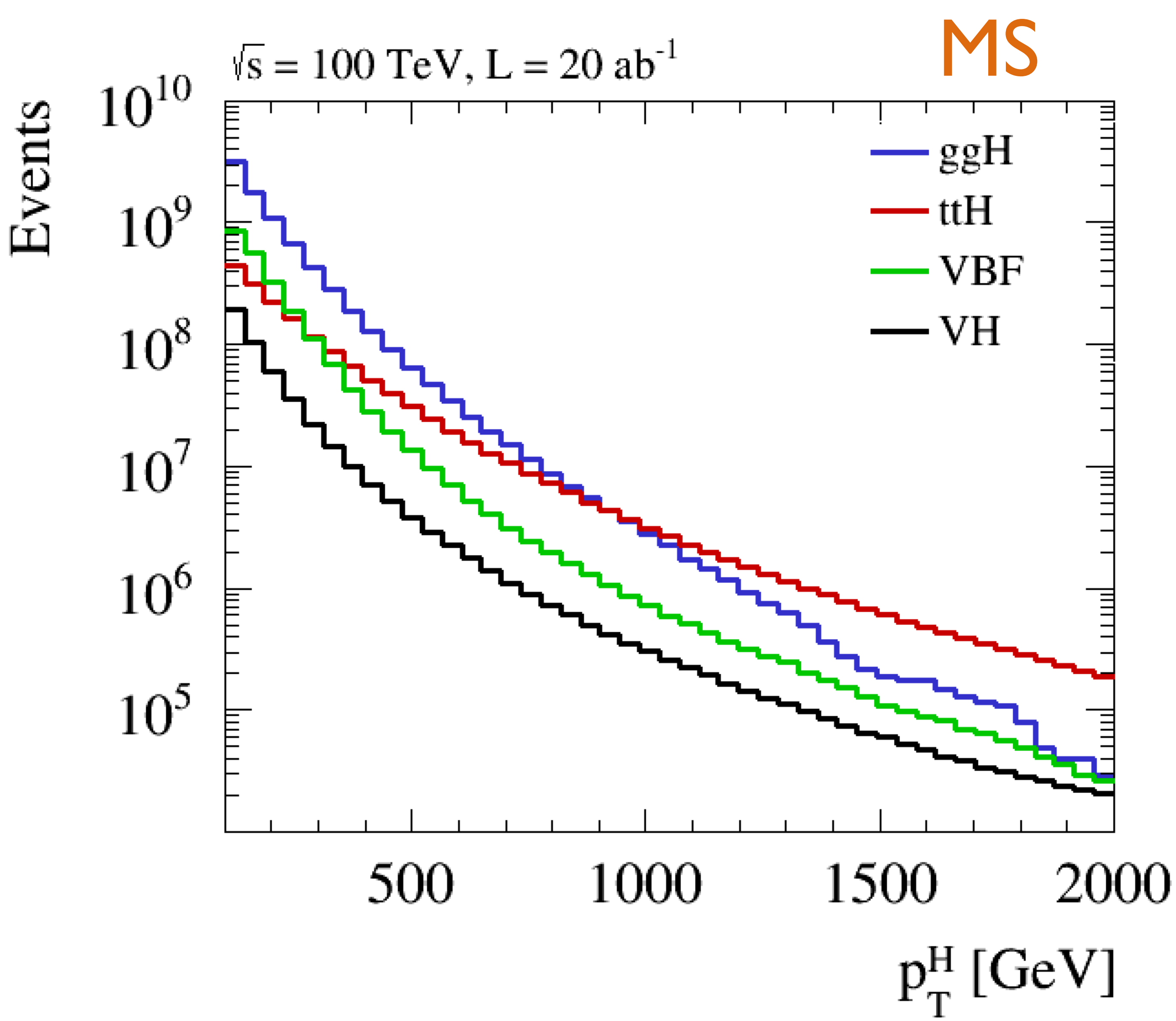
- All parton level samples produced with **MG5_aMC@NLO v. 2.5.4**
- Jet merging with **Pythia8** using **MLM matching** scheme
- ggH:
  - finite top mass, loop induced
  - 0/1/2 jets merged , xqcut = 30 GeV, Q_{cut} = 45 GeV
  - σ = 213 pb → K_{factor} = 3.7
- VBF:
  - 0/1 jets merged, xqcut = 40 GeV, Q_{cut} = 60 GeV
  - σ = 16 pb → K_{factor} = 4.3 (matching efficiency very low !!)
- VH:
  - 0/1/2 jets merged, xqcut = 40 GeV, Q_{cut} = 60 GeV
  - σ = 20 pb → K_{factor} = 1.3
- ttH:
  - 0/1 jets merged, xqcut = 80 GeV, Q_{cut} = 120 GeV
  - σ = 27 pb → K_{factor} = 1.3

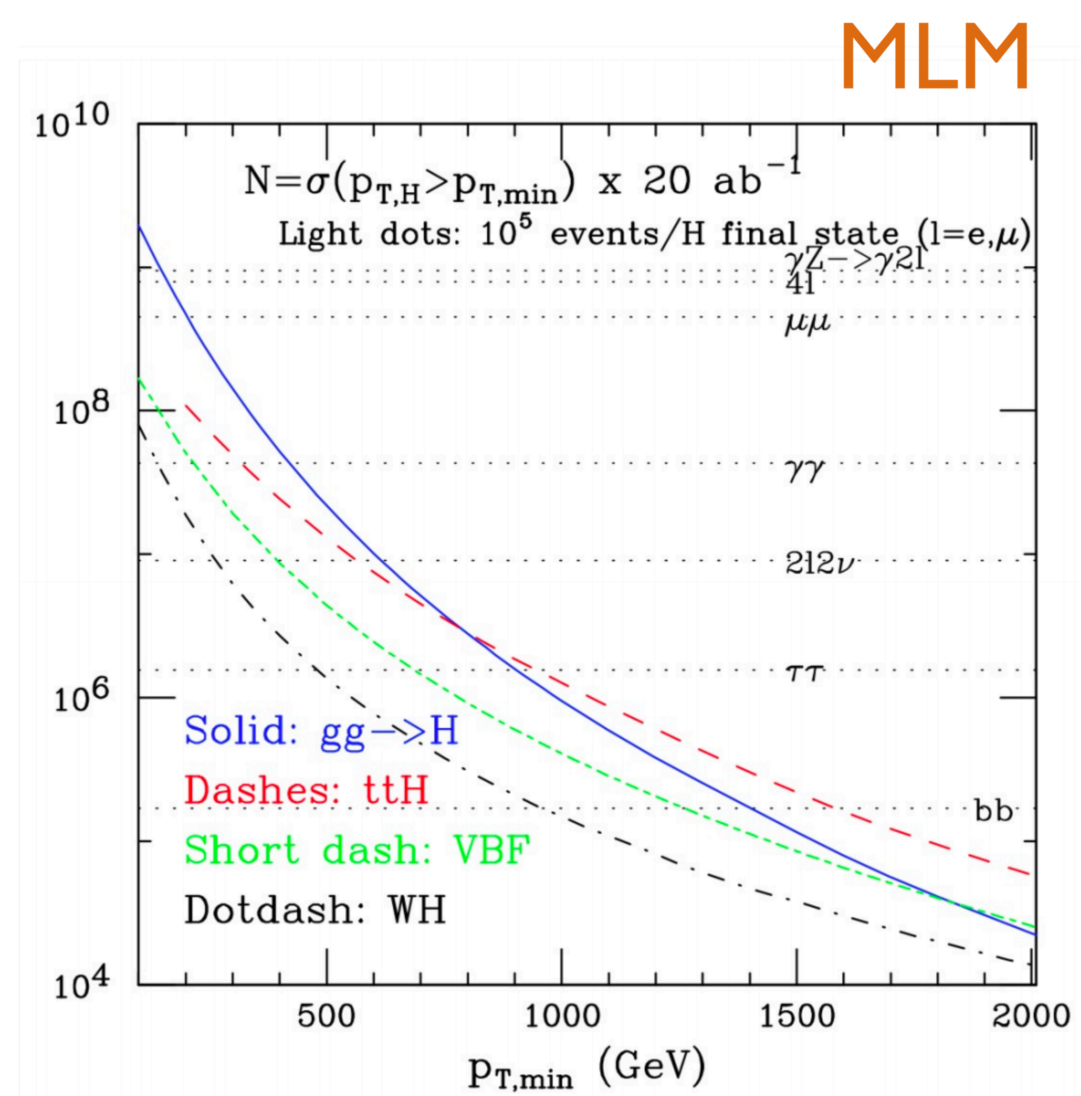
Background Samples

- ttbar:
  - 0/1/2 jets merged
  - σ = 20 nb → K_{factor} = 1.7
- Single Top (tV):
  - 0/1/2 jets merged
  - σ = 2.6 nb →
  - K_{factor} = 1.34 (careful: b-jet veto applied at NLO to remove overlap with ttbar)
- DY+jets:
  - V = W/Z+0/1/2/3 jets merged
  - non-resonant LL+0/1/2 jets
  - K_{factor} = 1.14 (computed on resonant, applied to all)
- Di-boson:
  - VV (ZZ / WW / WZ / Zγ / Wγ / γγ)+ 0/1/2 jets merged
  - LLV non-resonant (should include Zγ*/ Wγ*)
  - K_{factor} = 1.14 (same as DY, for simplicity)
- Tri-boson:
  - VVV (WWW / WWZ / WZZ / ZZZ / γZZ / γZW …)+ 0/1 jets merged
  - K_{factor} = 1.14 (same as DY, for simplicity)
- Di-photon:
  - g g → γγ + 0/1 jets merged
  - p p → γγ + 0/1/2 jets merged
  - K_{factor} = 2 (correct ?)

Higgs p_T

Higgs N($p_T > p_{T,min}$) (I)

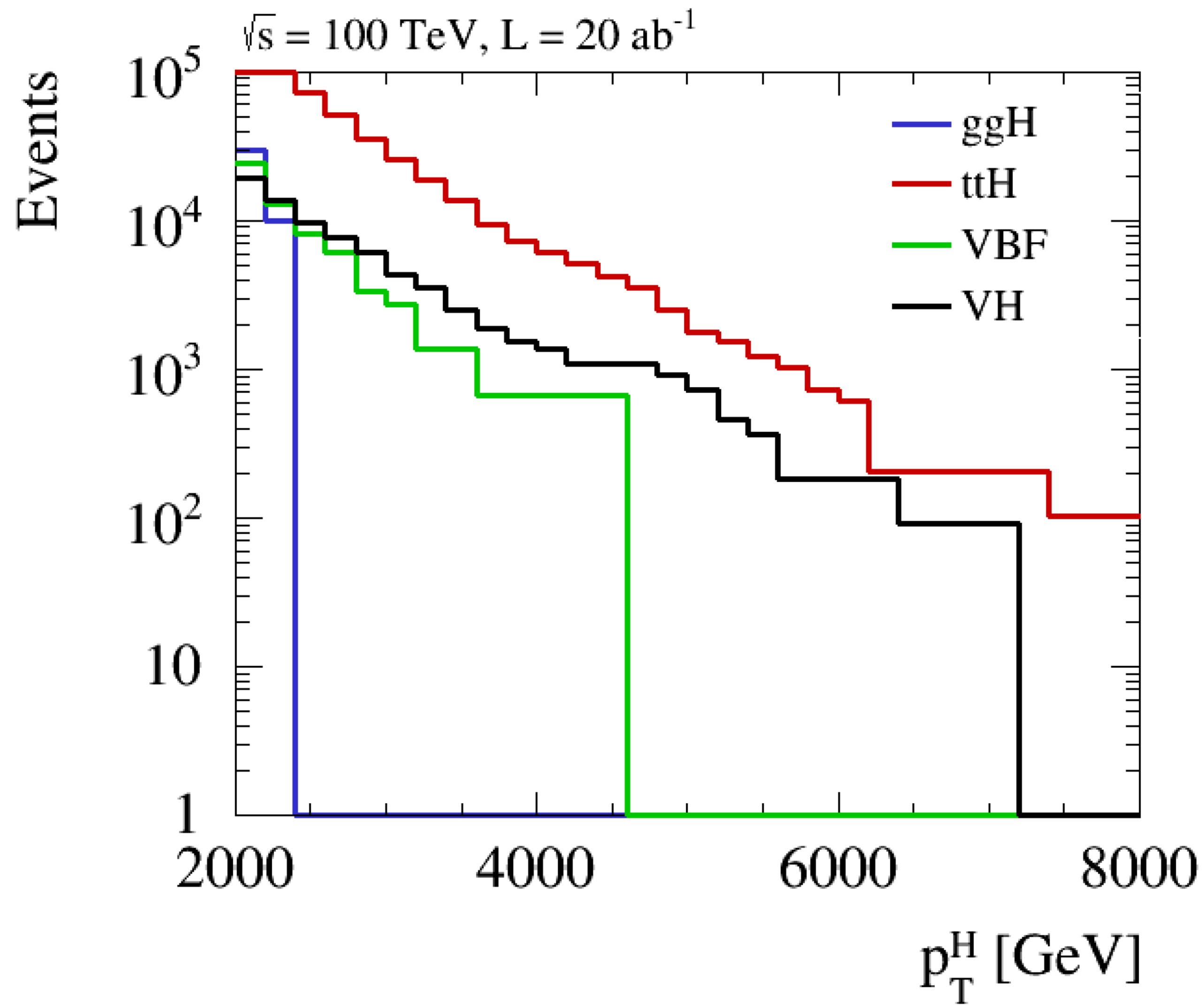




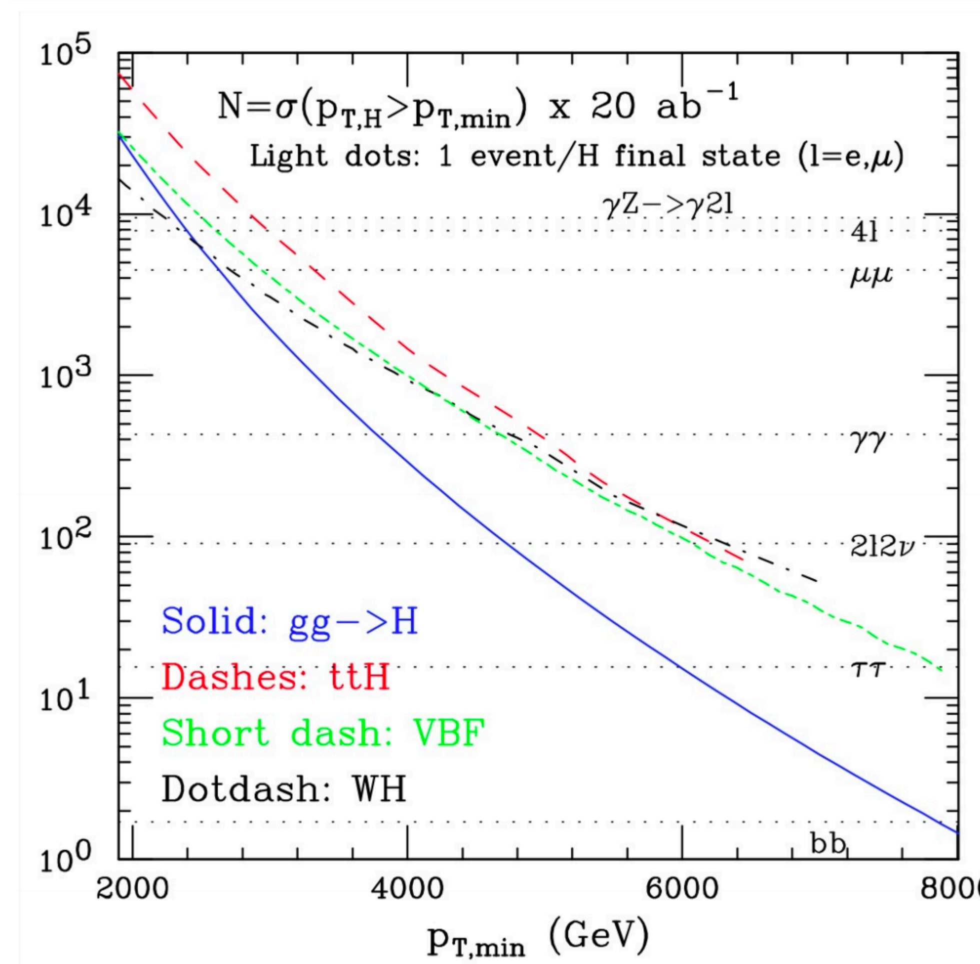
- ggH comparable
- **ttH becomes dominant at p_T > 800-900 GeV**, has slightly harder spectrum (matching?)
- similar spectra for VH (note VH vs WH)
- VBF seems off (wrong matching ?)

Higgs N(p_T > $p_{T,\,min}$) (II)

MS



MLM



- again, ttH has slightly harder spectrum (matching?)
- need more stats at high p_T to conclude anything ..

$H \to \mu\mu$

$H \rightarrow \mu\mu$ - Selection

- Very small $BR(H \rightarrow \mu\mu) \sim 2.18e\text{-}04$,

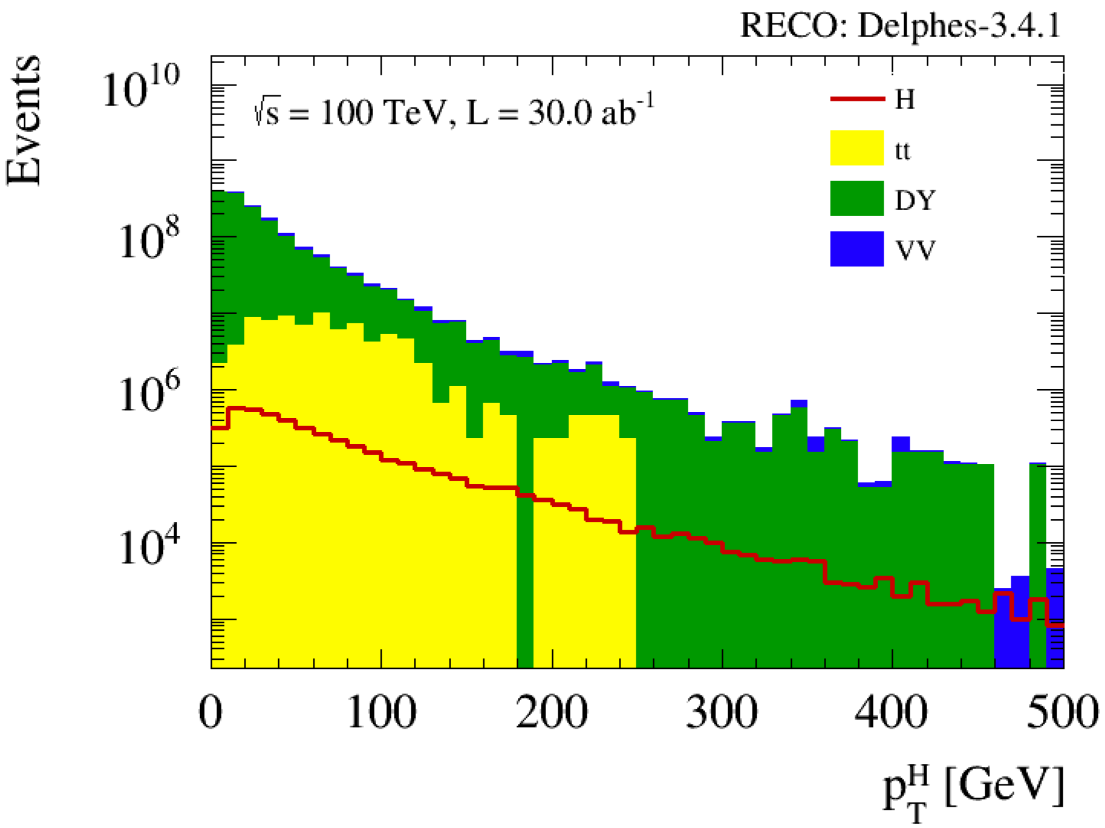
  → out of reach for HL-LHC

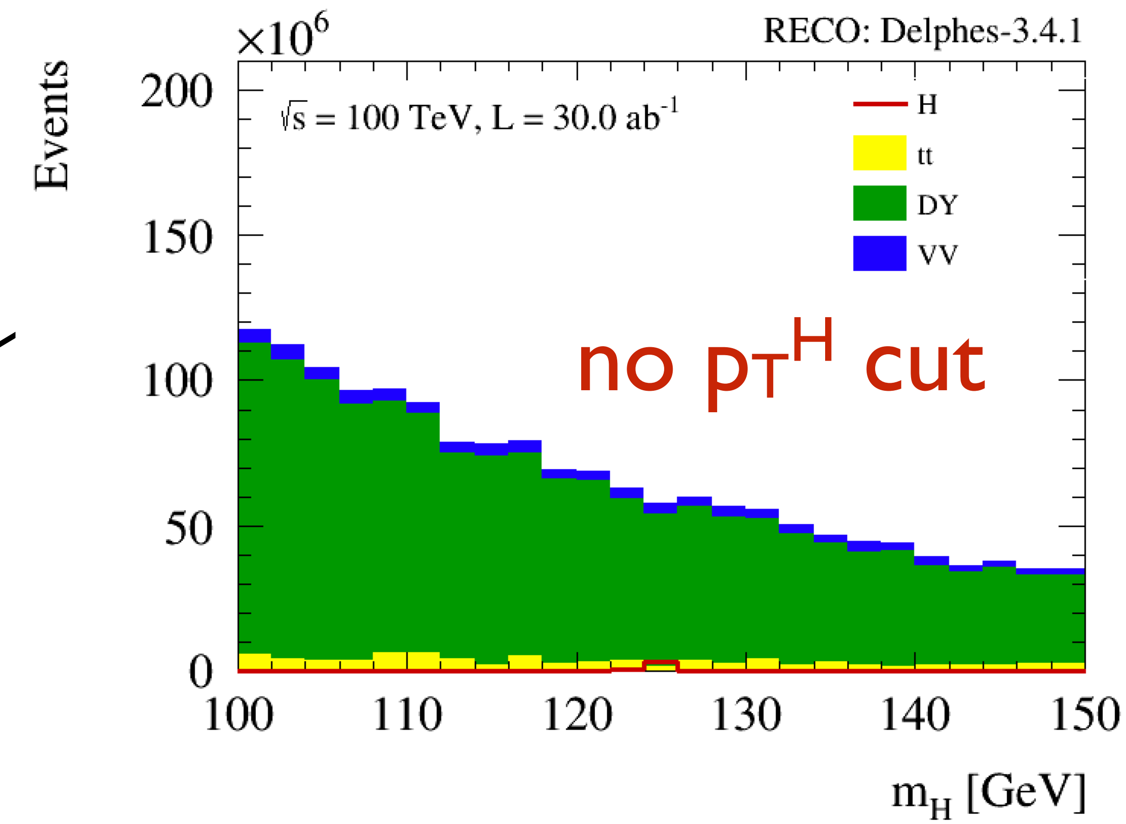
- **irreducible:** DY
- **reducible.** : ttbar, $(H \rightarrow)ZZ \rightarrow 2\mu 2\nu$

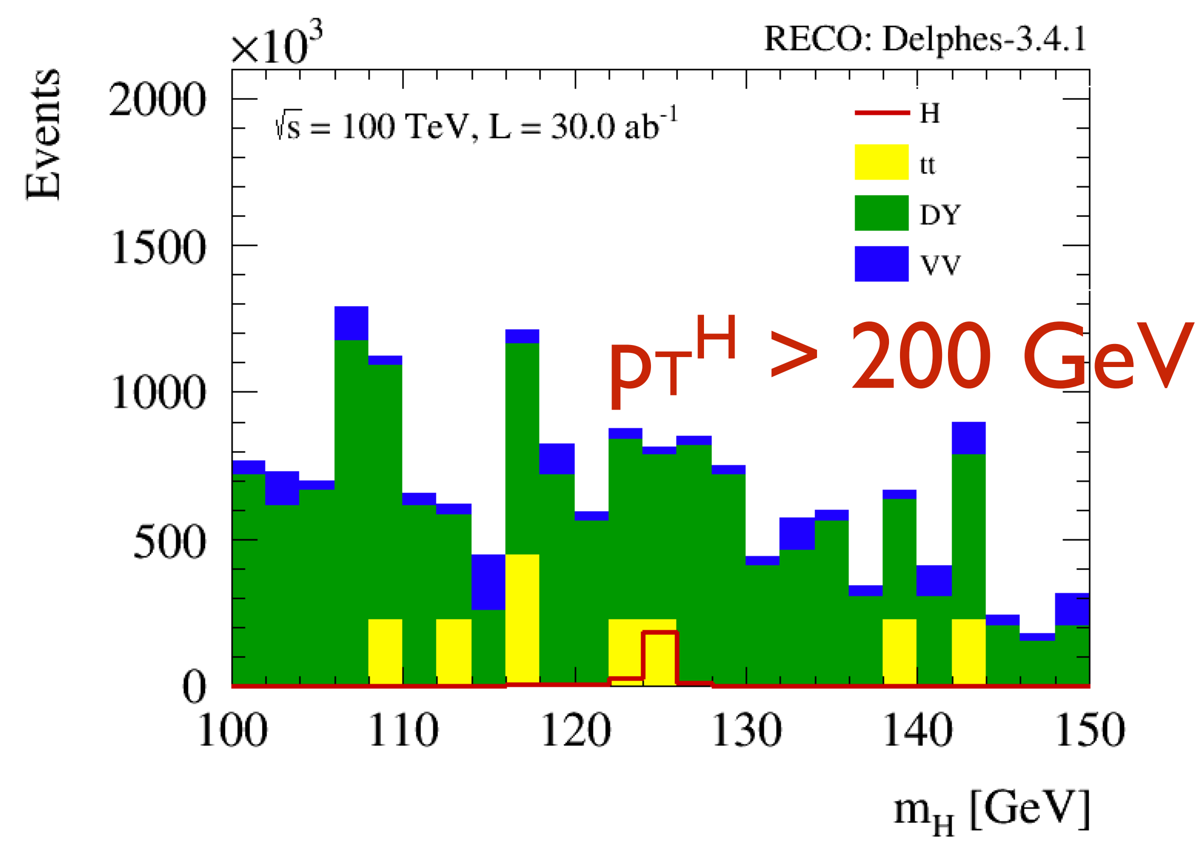
Simple cut and count strategy:

- $p_T(\mu) > 20$ GeV, $|\eta(\mu)| < 4.0$
- $E_T^{miss} < 50$ GeV (against ttbar)
- $|m_{\mu\mu} - m_H| < 2.5$ GeV
- exploit the fact that $p_{T,\mu\mu}$ is harder for signal

$H \rightarrow \mu\mu$ - Plots

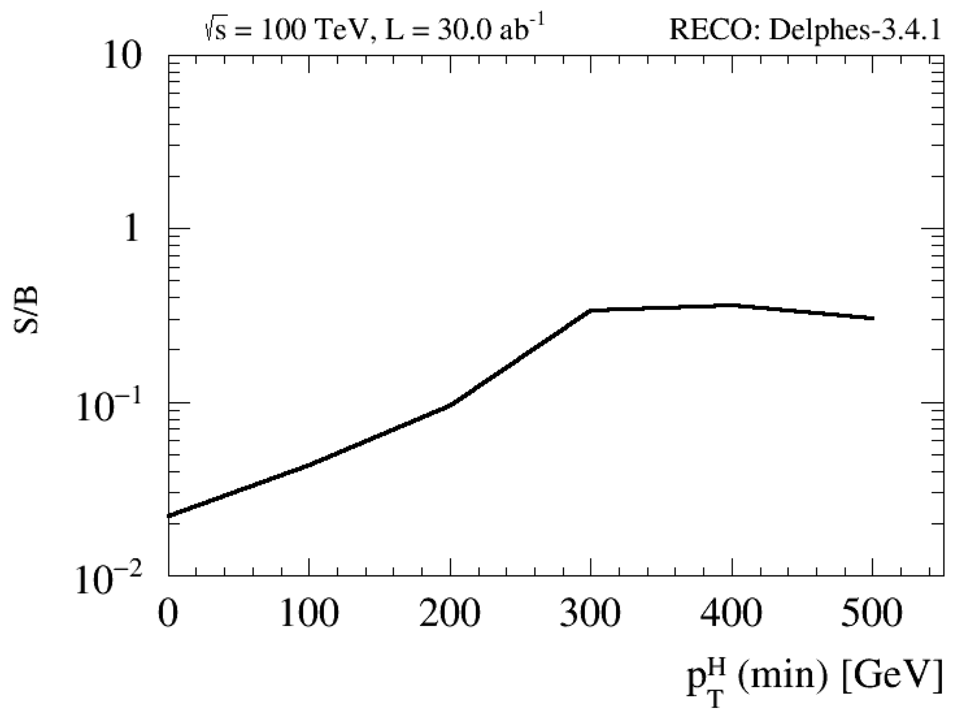


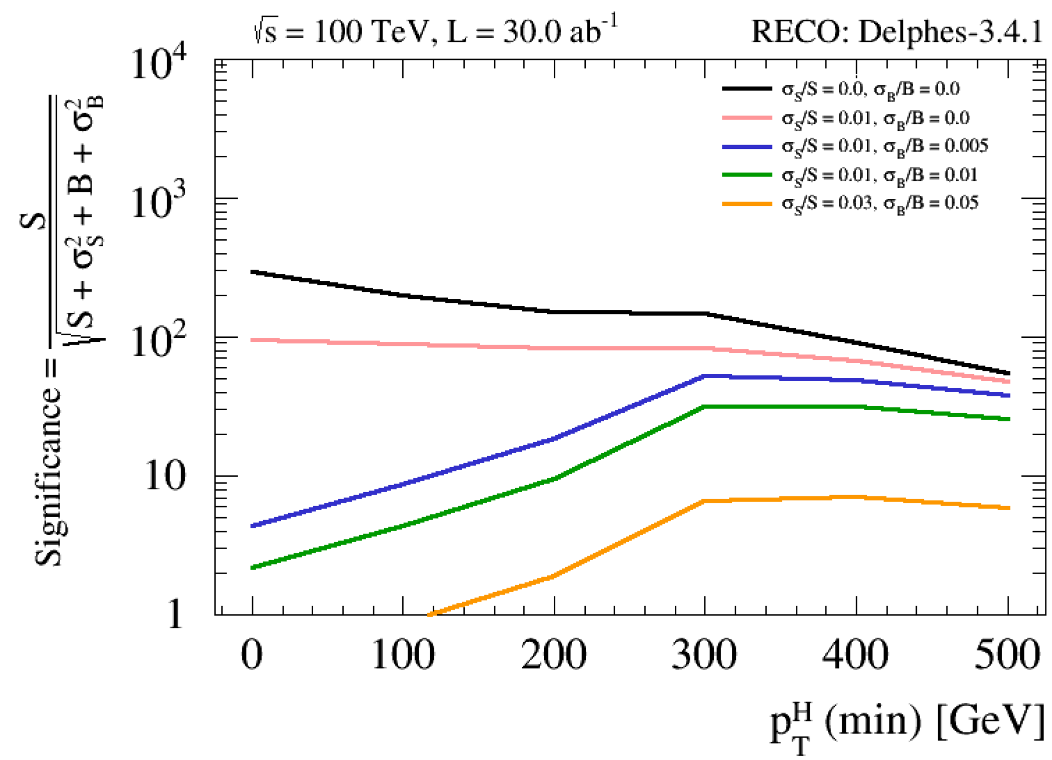




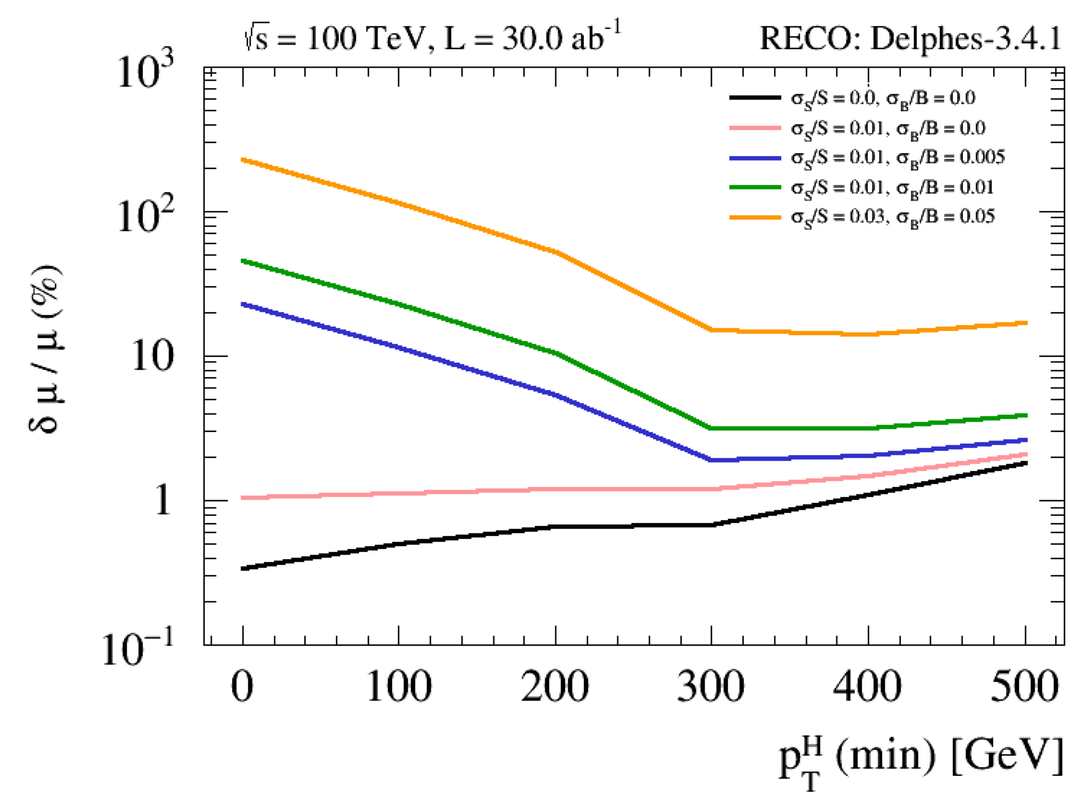
- previous selection applied except window cut around Higgs mass
- **can gain in background rejection at high $p_T(H)$**

H → μμ - Expected sensitivity





- **O(1) % precision** on signal strength can be achieved
- more **background MC stats** needed to conclude at **high p_T**
- this study far from being optimised:
  - fit on m(μμ)
  - including photon FSR to improve mass reso.
  - apply b-jet veto (tricky, suppresses ttH)?
  - …



$H \rightarrow \gamma\gamma$

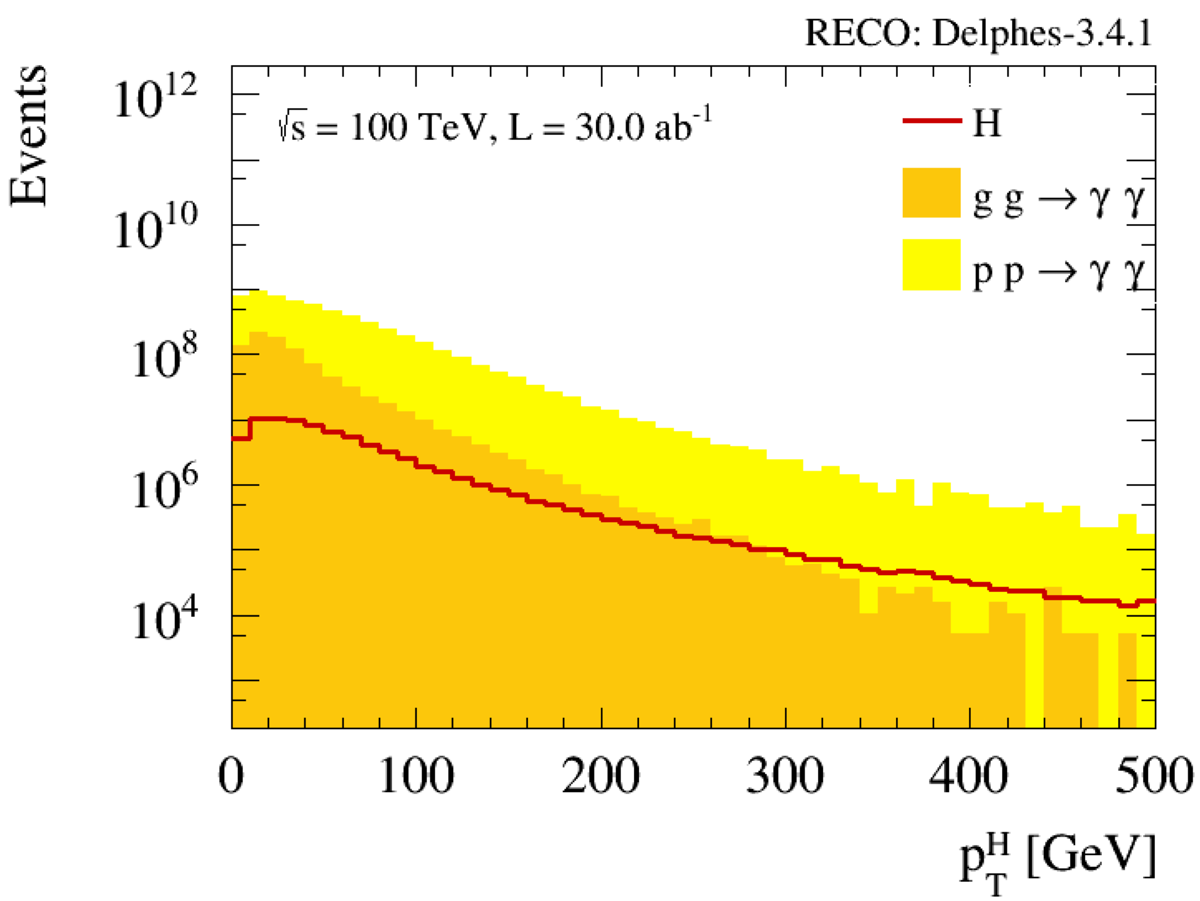
$H \rightarrow \gamma\gamma$ - Selection

- BR($H \rightarrow \gamma\gamma$) ~ 2.27e-03,
- **irreducible**: QCD $\gamma\gamma$ production
- **reducible.** : γ + jets (ignored for now)

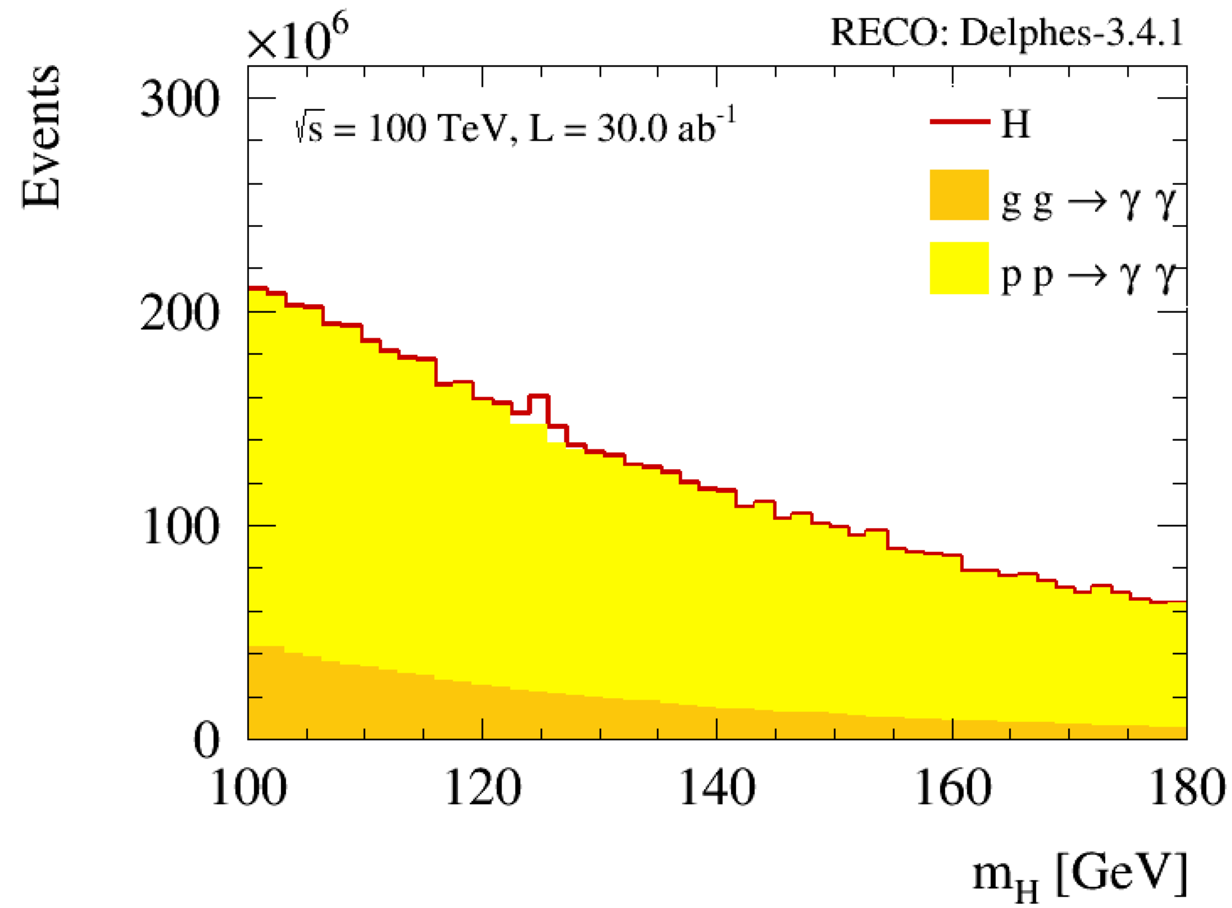
<u>Simple cut and count strategy</u>:

- $p_T(\gamma) > 30$ GeV, $|\eta(\gamma)| < 4.0$
- $|m_{\gamma\gamma} - m_H| < 5.0$ GeV
- exploit the fact that $p_{T,\gamma\gamma}$ is harder for signal

H → γγ - Plots

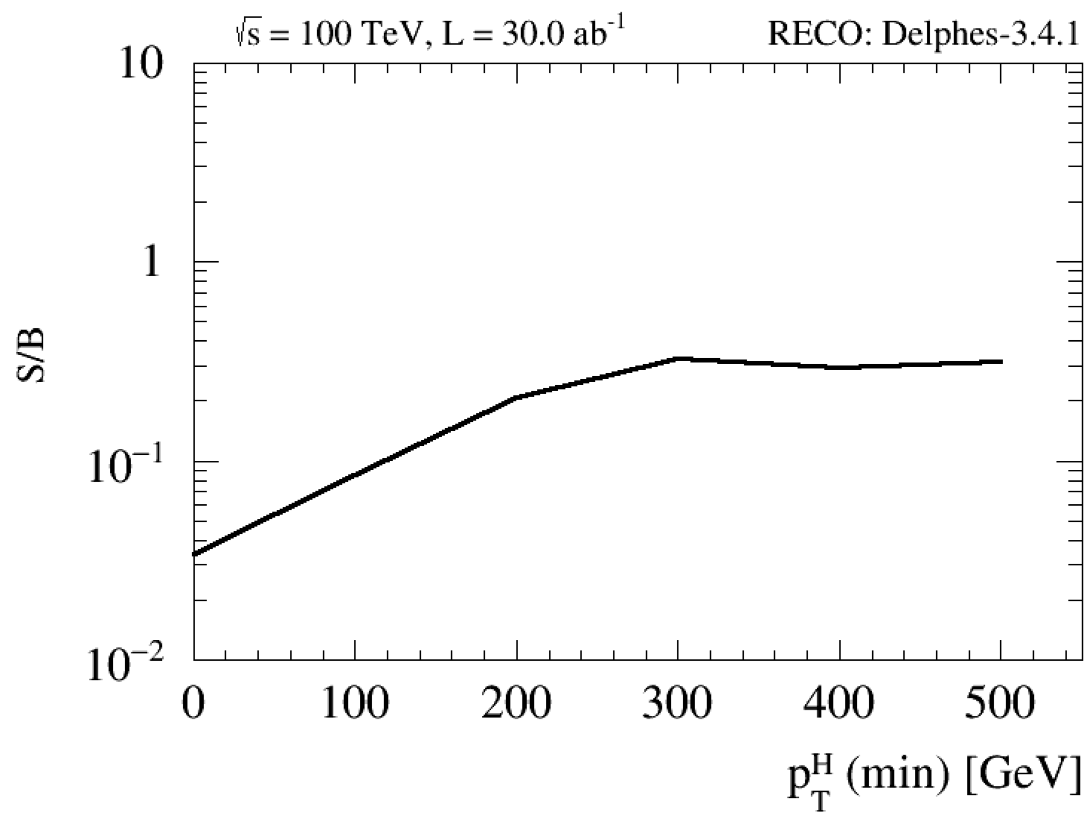


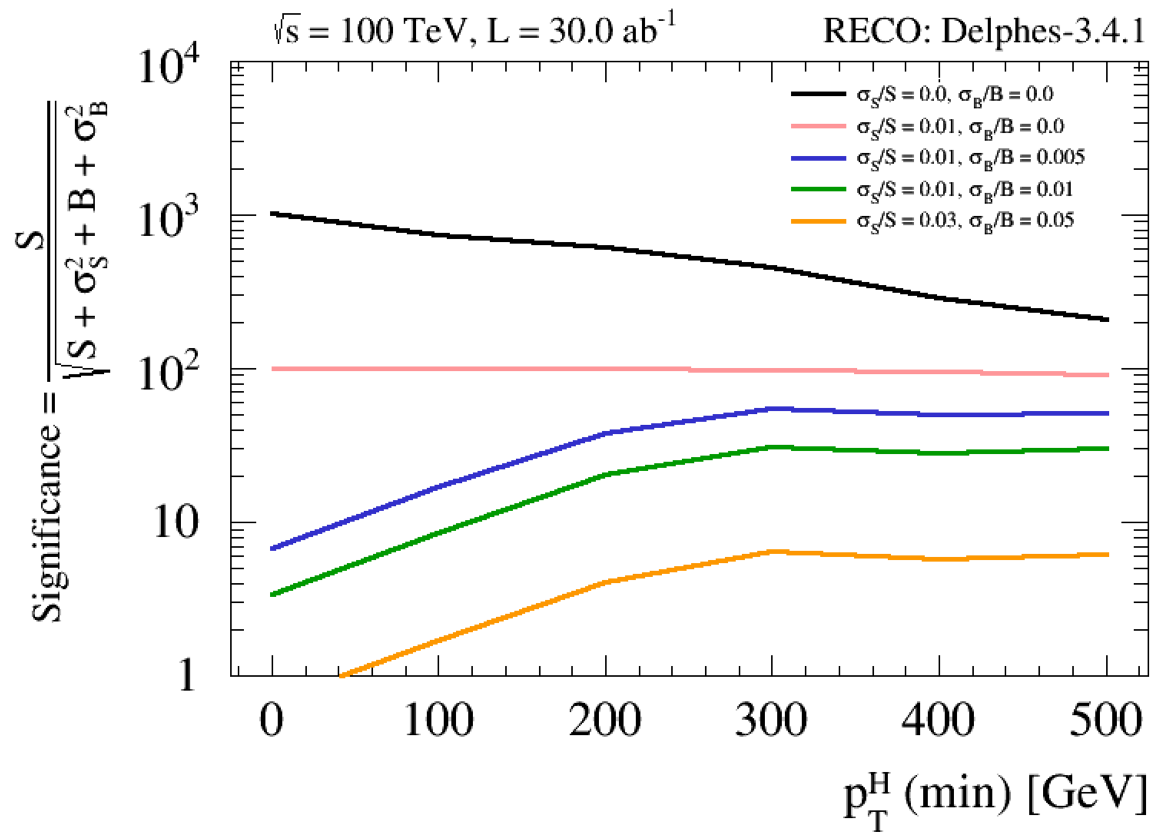
RECO: Delphes-3.4.1
Events
√s = 100 TeV, L = 30.0 ab-1
H
g g → γ γ
p p → γ γ
10^12
10^10
10^8
10^6
10^4
0
100
200
300
400
500
p_T^H [GeV]

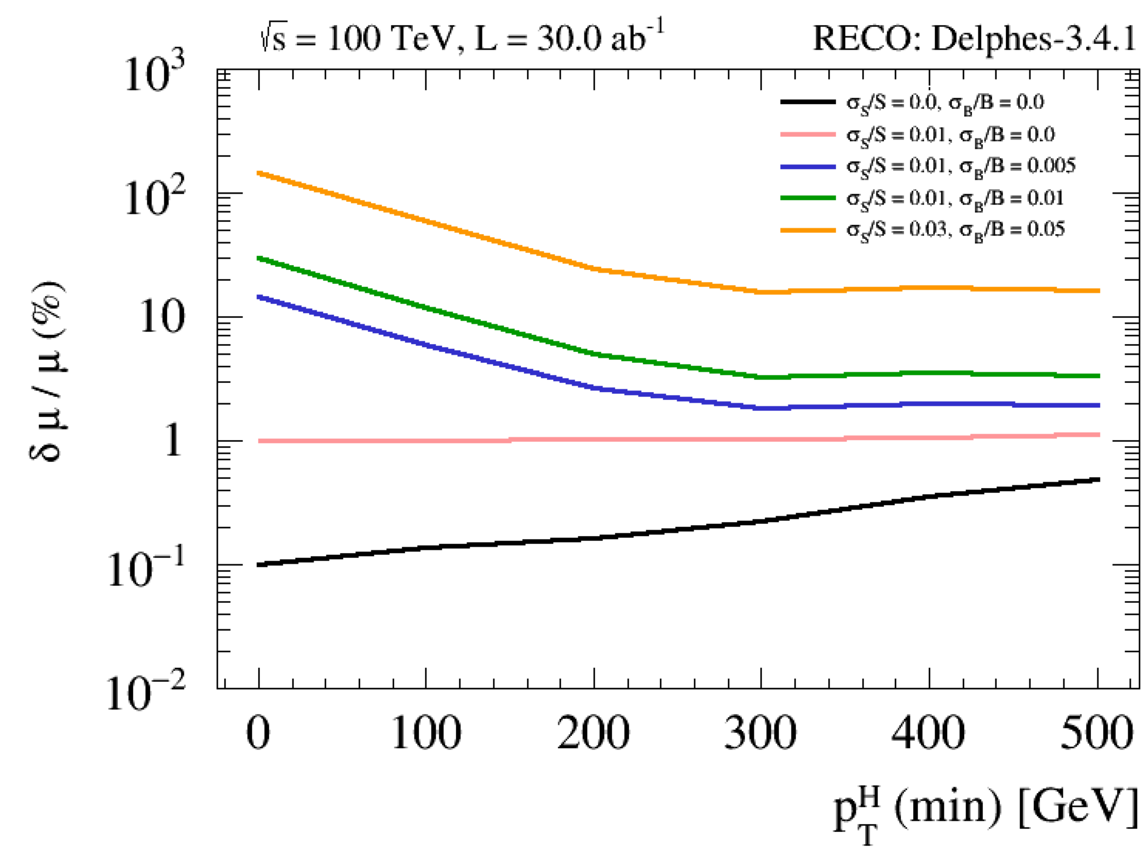


×10^6
RECO: Delphes-3.4.1
Events
√s = 100 TeV, L = 30.0 ab-1
H
g g → γ γ
p p → γ γ
300
200
100
0
100
120
140
160
180
m_H [GeV]

H → γγ - Expected sensitivity







- **O(1) % precision** on signal strength can be achieved
- increase in sensitivity seems to reach plateau at $p_{T,H}$ ~ 300 GeV
- Possible improvements:
  - background K-factors
  - include photon fake rate
  - …

$H \rightarrow ZZ^* \rightarrow 4l$

$H \rightarrow ZZ^* \rightarrow 4l$ - Selection

- BR($H \rightarrow ZZ^* \rightarrow 4l$) ~ 1.24e-04,
- **irreducible:** ZZ/Zɣ*
- **reducible.** : VVV - ttbar (not included here due MC stats)

Simple cut and count strategy:

- $40. < m_{Z1} < 120.$
- $12. < m_{Z2} < 120.$
- $p_T(l) > 10$ GeV, $|\eta(\gamma)| < 4.0$

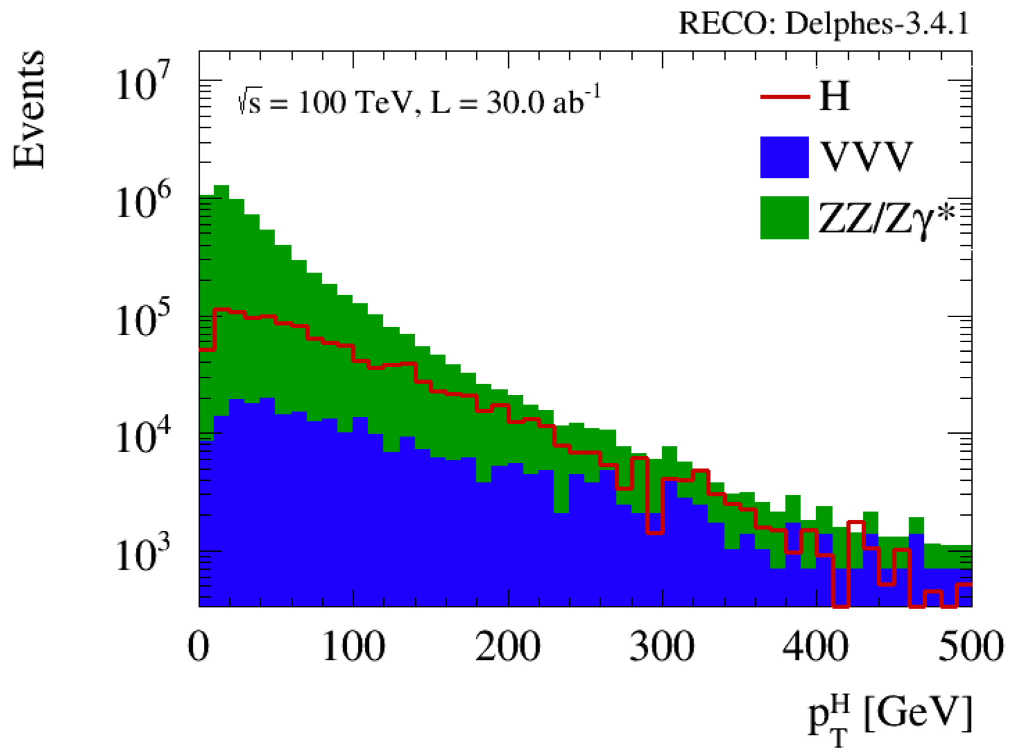
→ higher threshold compared to 13 TeV, due to larger ttbar contribution (soft leptons from semi-leptonic b becays)

→ could also apply b-jet veto

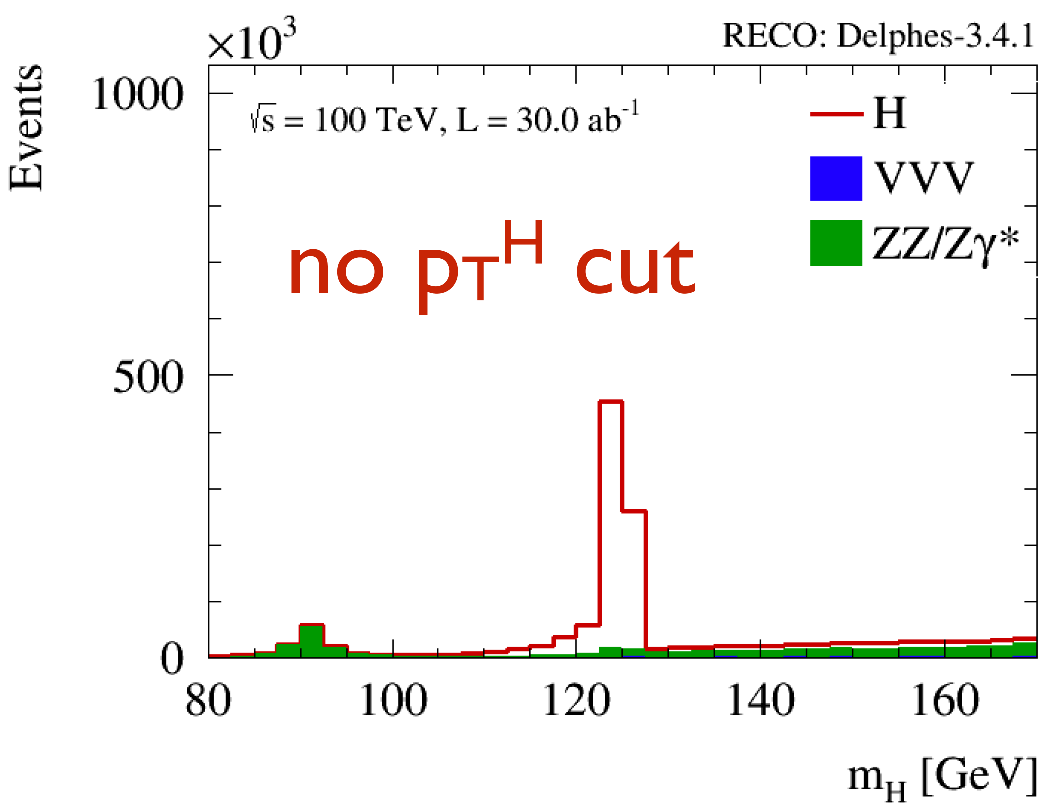
- $120 < m_{4l} < 127.5$ GeV

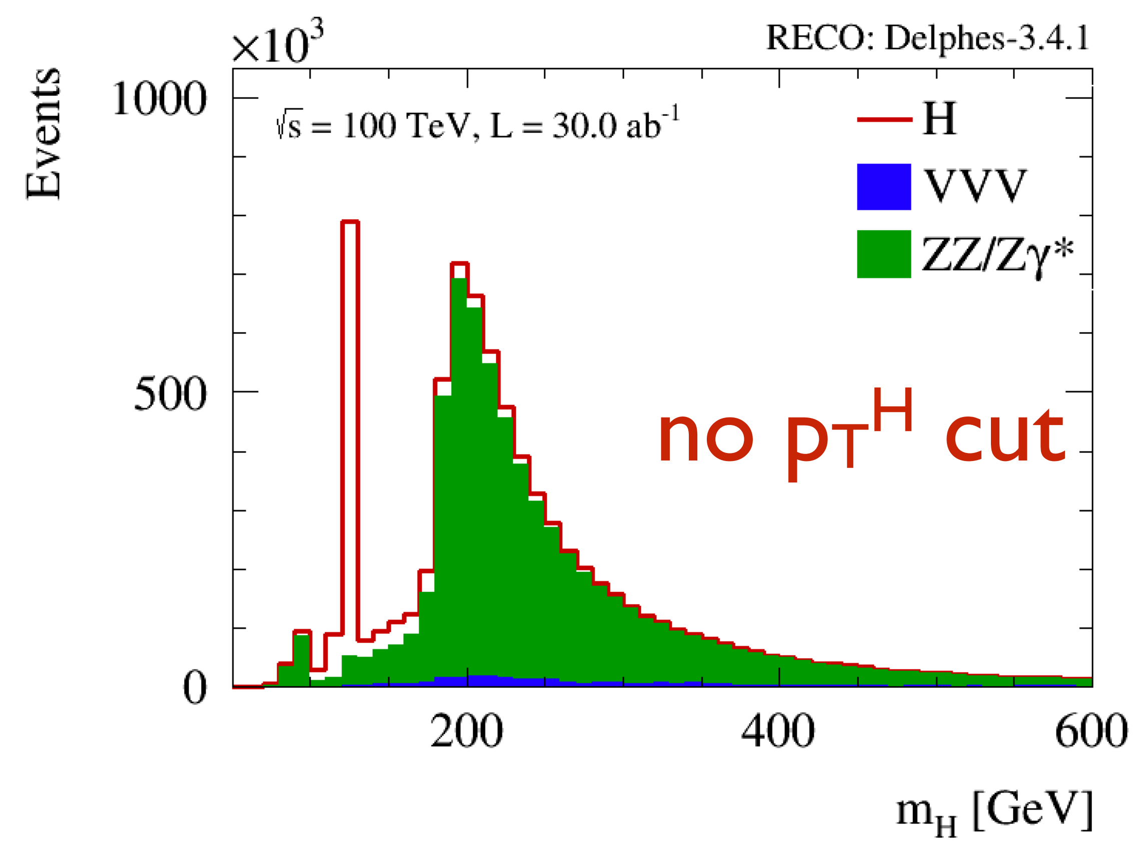
→ asymmetric cut due to FSR tail

H → ZZ* → 4l - Plots

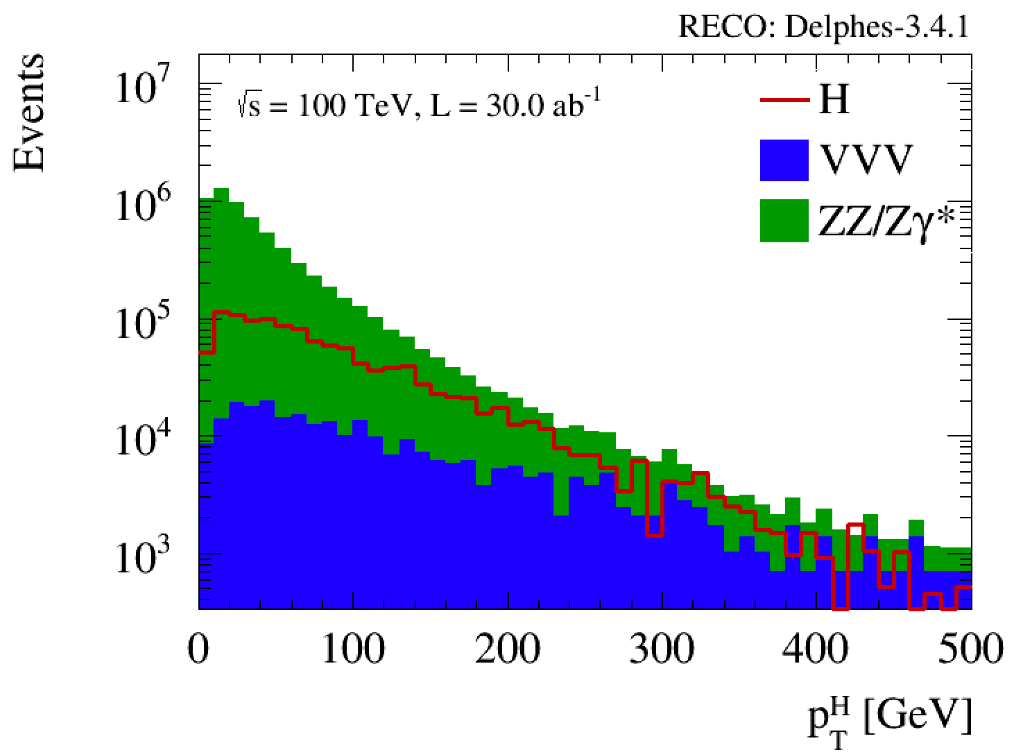


- Z/γ* peak highly suppressed
  → due to cuts?
  → or simply normalization bug

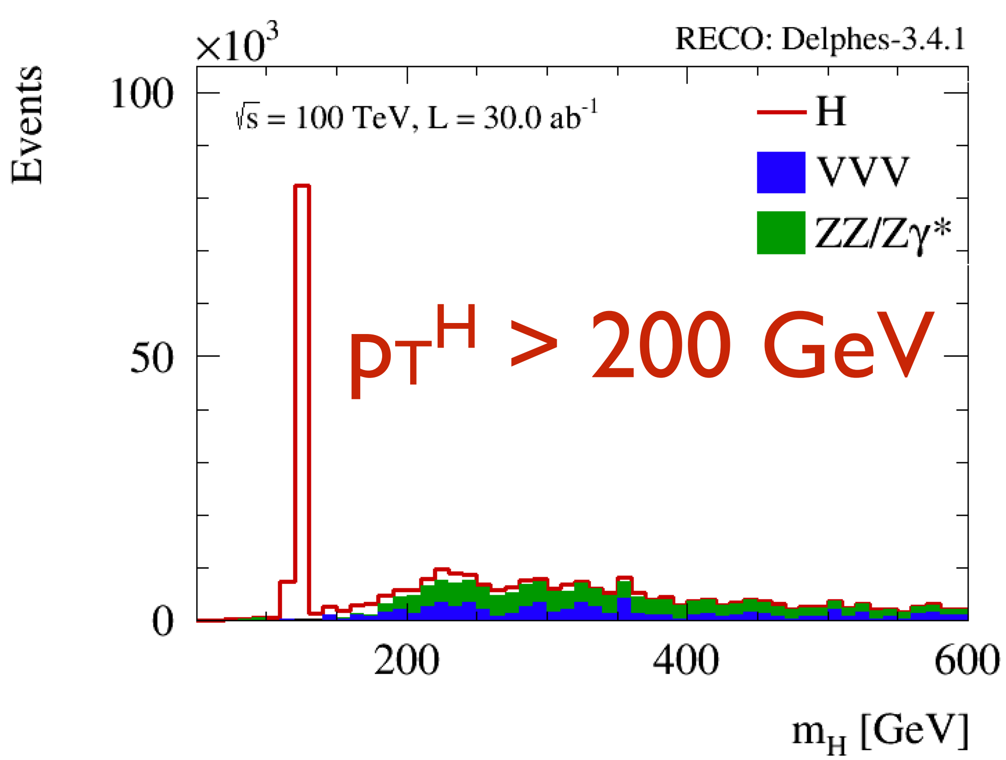




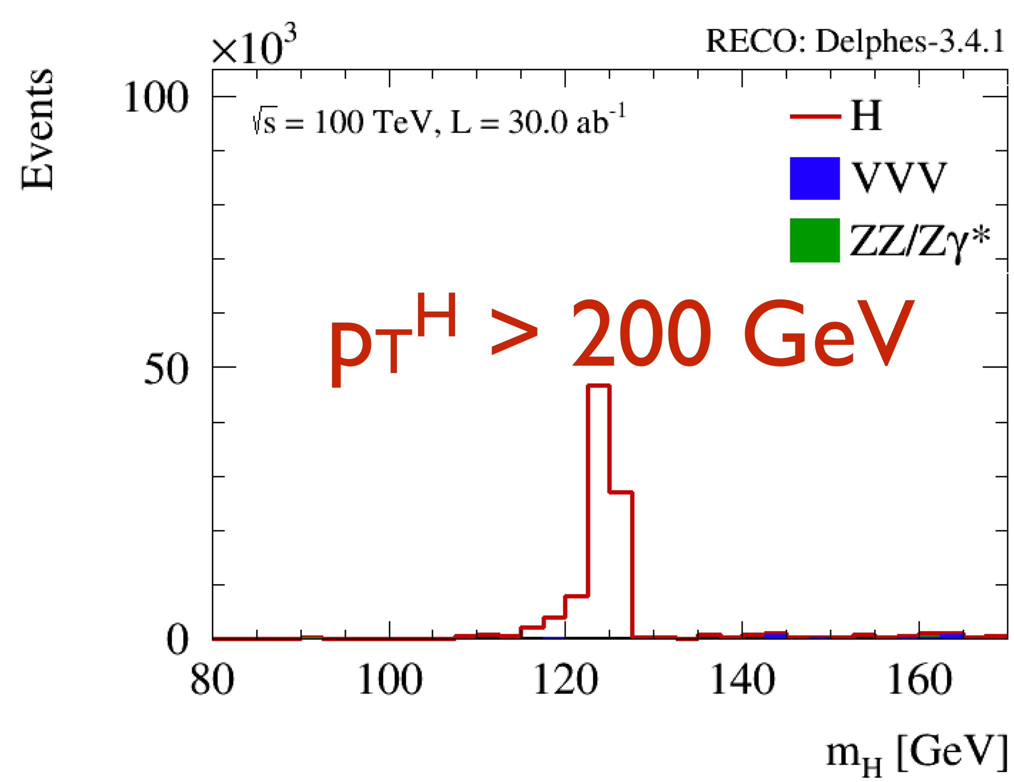
H → ZZ* → 4l - Plots



basically background free at high pT !

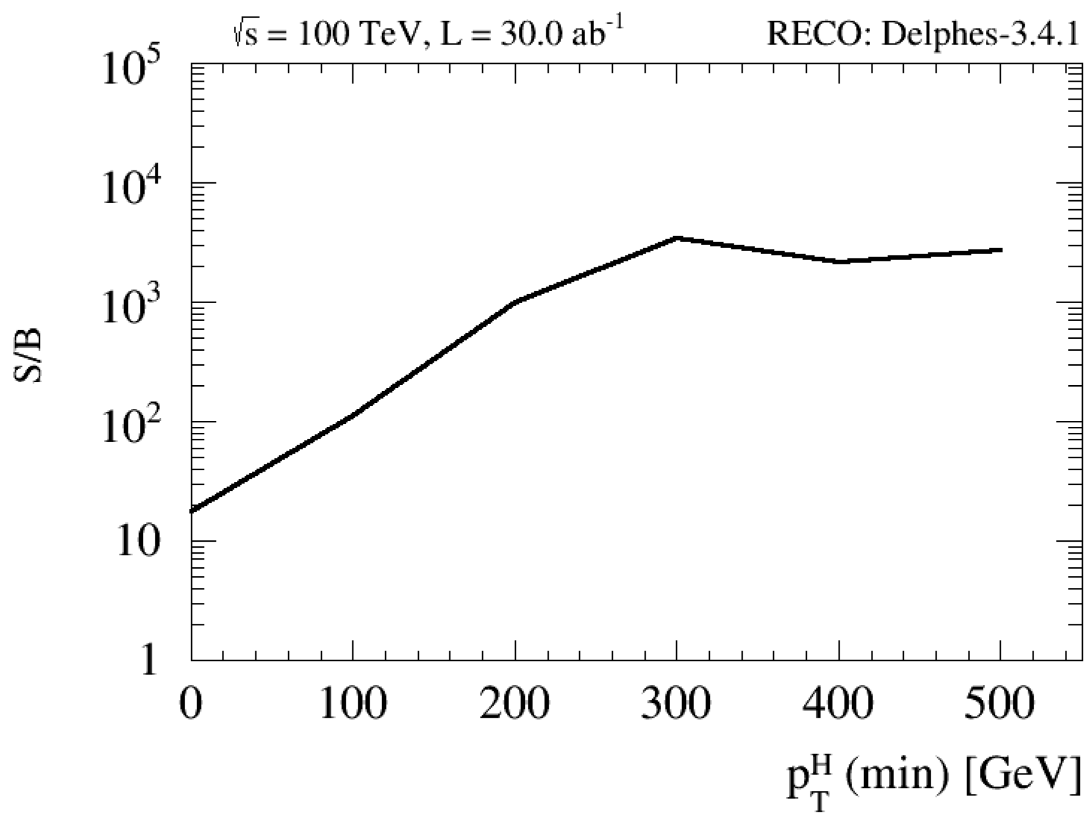


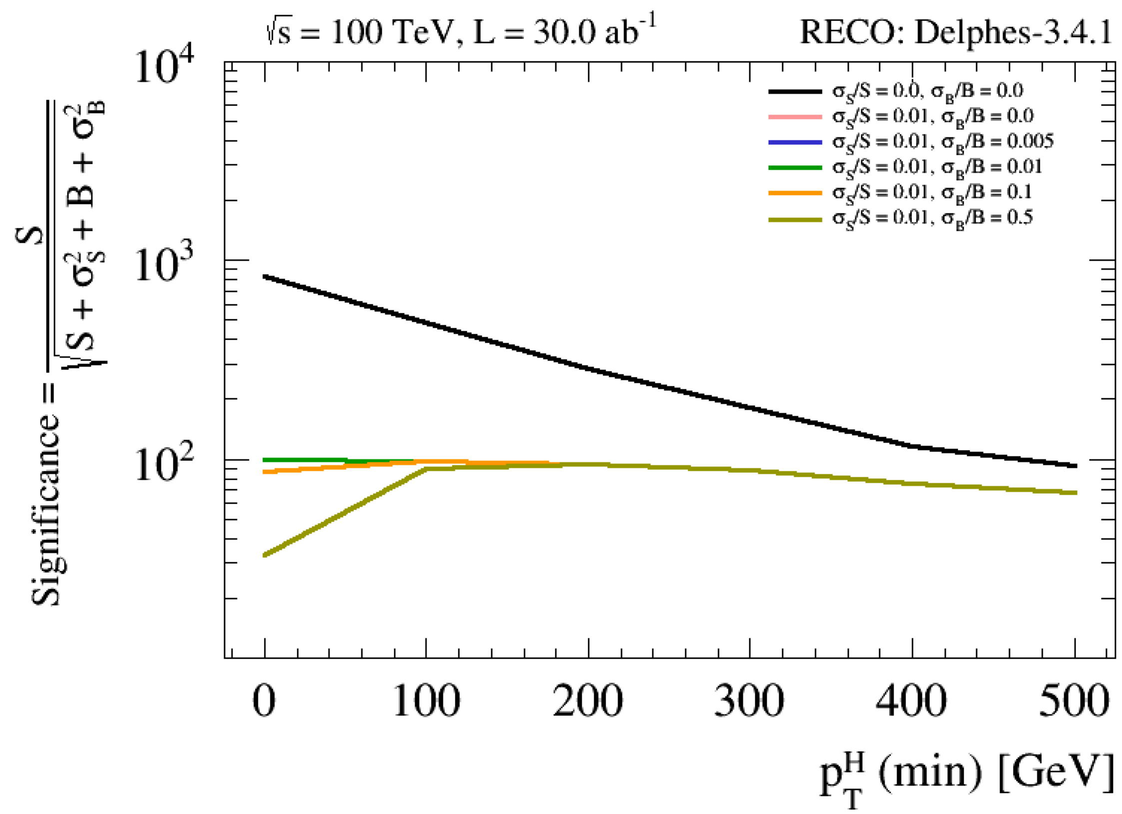
$p_T^H > 200$ GeV



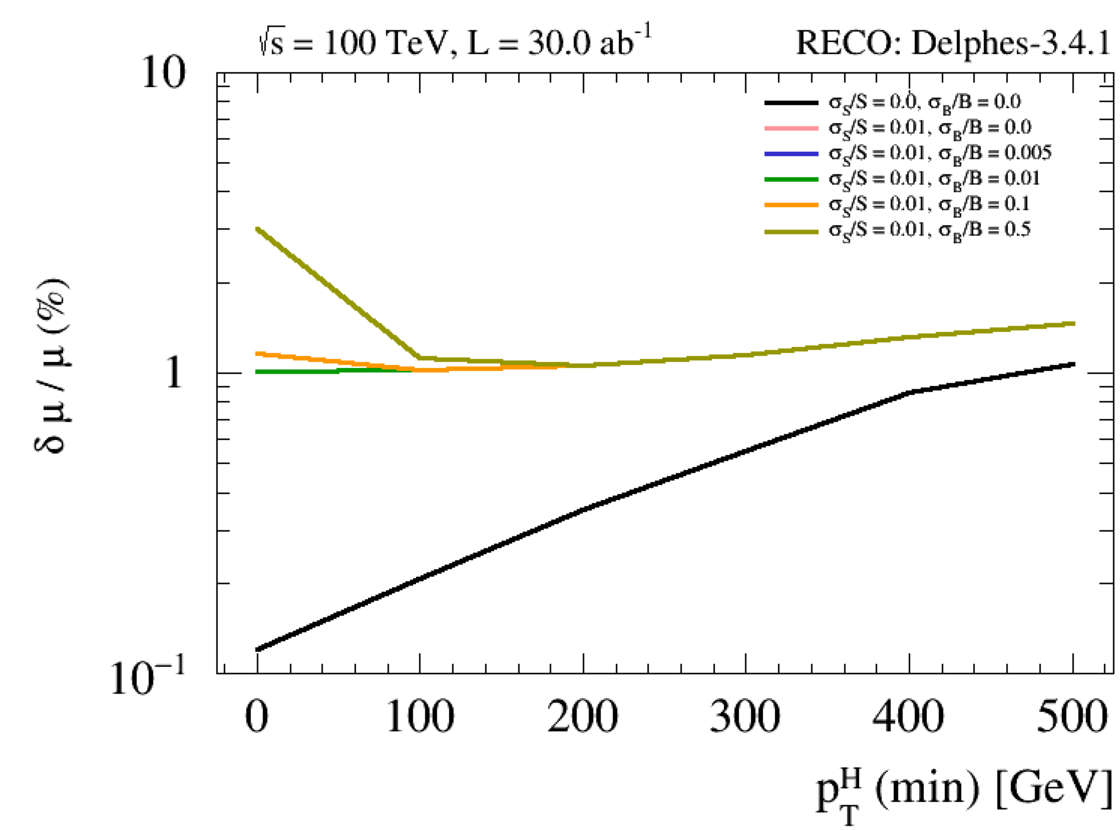
$p_T^H > 200$ GeV

$H \rightarrow ZZ^* \rightarrow 4l$ - Expected sensitivity





- **O(1) % precision** on signal strength can be achieved
- increase in sensitivity seems to reach plateau at $p_{T,H} \sim 100$ GeV
- only limited by uncertainty on signal
- this study far from being optimised:
  - fit on m(4l)
  - including photon FSR to improve mass reso.
  - apply b-jet veto (tricky, suppresses ttH)?
  - …



$H \rightarrow WW^* \rightarrow 2l2\nu$

$H \rightarrow WW^* \rightarrow 2l2\nu$ - Selection

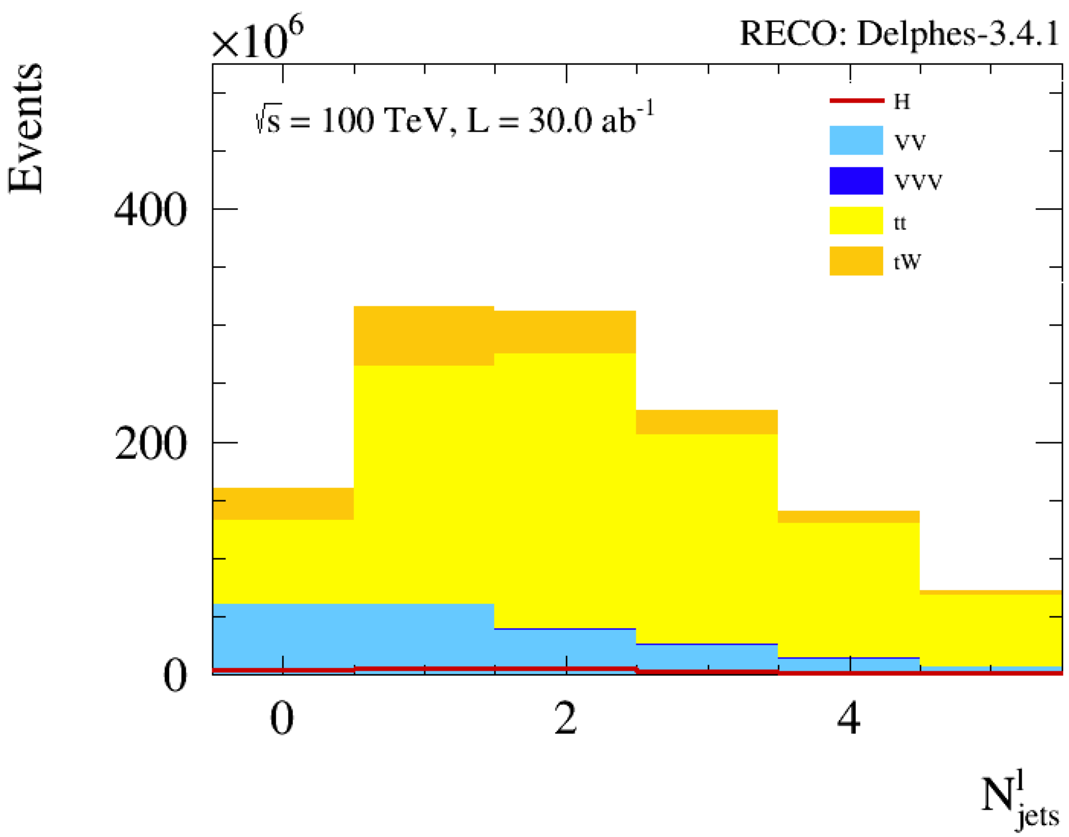
- BR($H \rightarrow WW^* \rightarrow 2l2\nu$) ~ 8.52e-3,
- **irreducible:** WW^* (only qq WW here)
- **reducible.** : ttbar, tW, VVV, DY, W+jets (fakes, not included here)

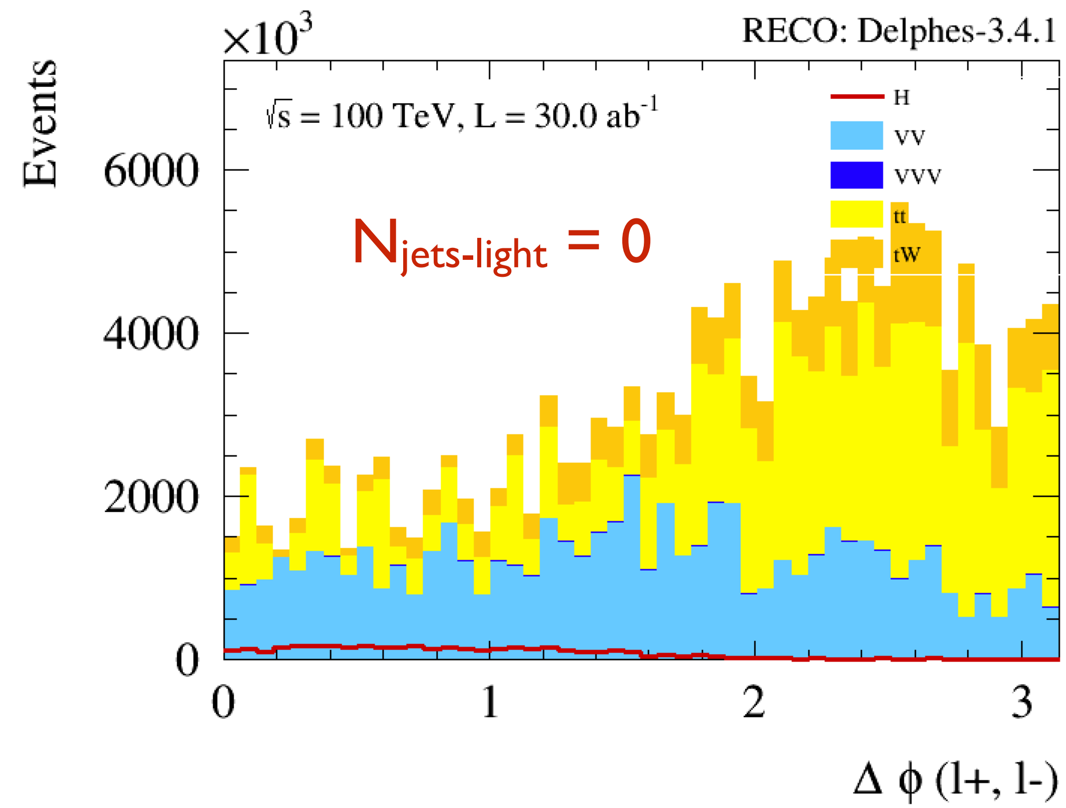
Simple cut and count strategy:

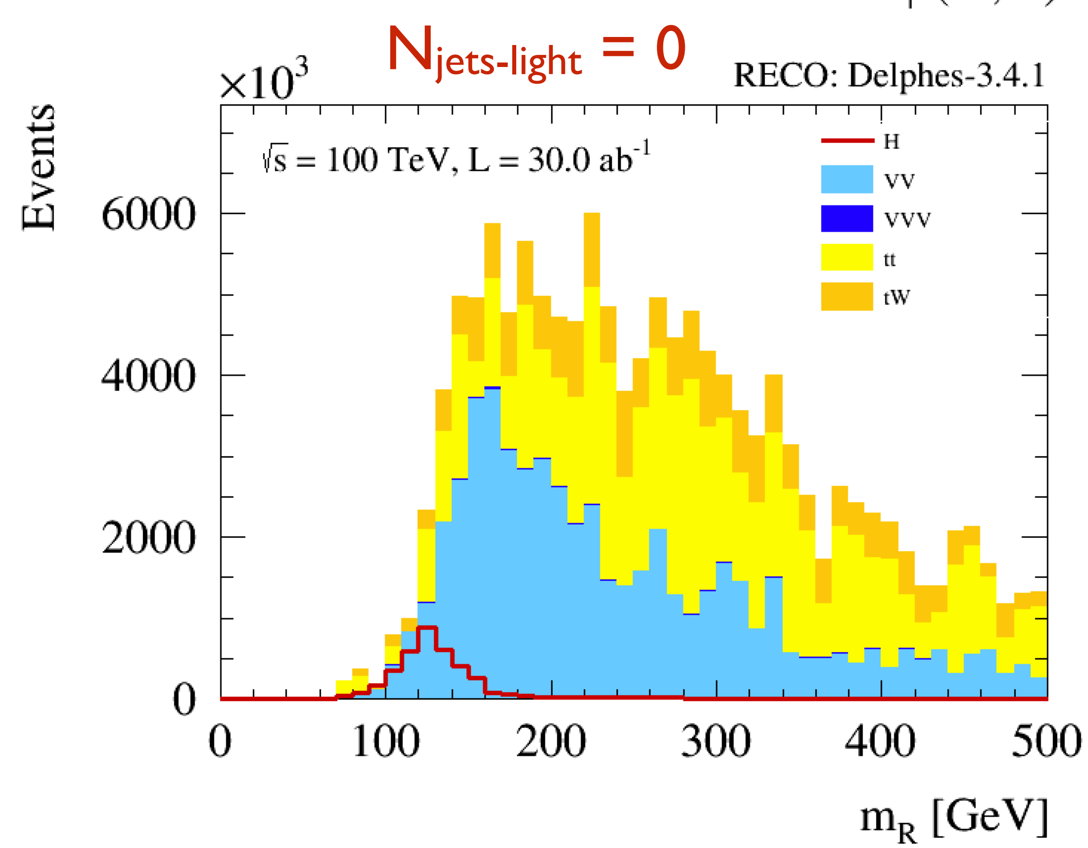
- only consider opposite flavor eμ final state (no DY)
- crucial part of this analysis is **jet veto** against ttbar:
  - relax jet veto and take advantage of H high pT spectrum?
  - or apply jet veto and study H at threshold?

- $p_T(l_1) > 25$ GeV, $p_T(l_2) > 15$ GeV, $|\eta(l_i)| < 4.0$
- $N_{bjets} = 0$
- $pT_{ll} > 45.$
- $\Delta\phi_{ll} < 90$ deg.
- $50 < m_R < 200$

$H \rightarrow WW^* \rightarrow 2l2\nu$ - Jet Veto

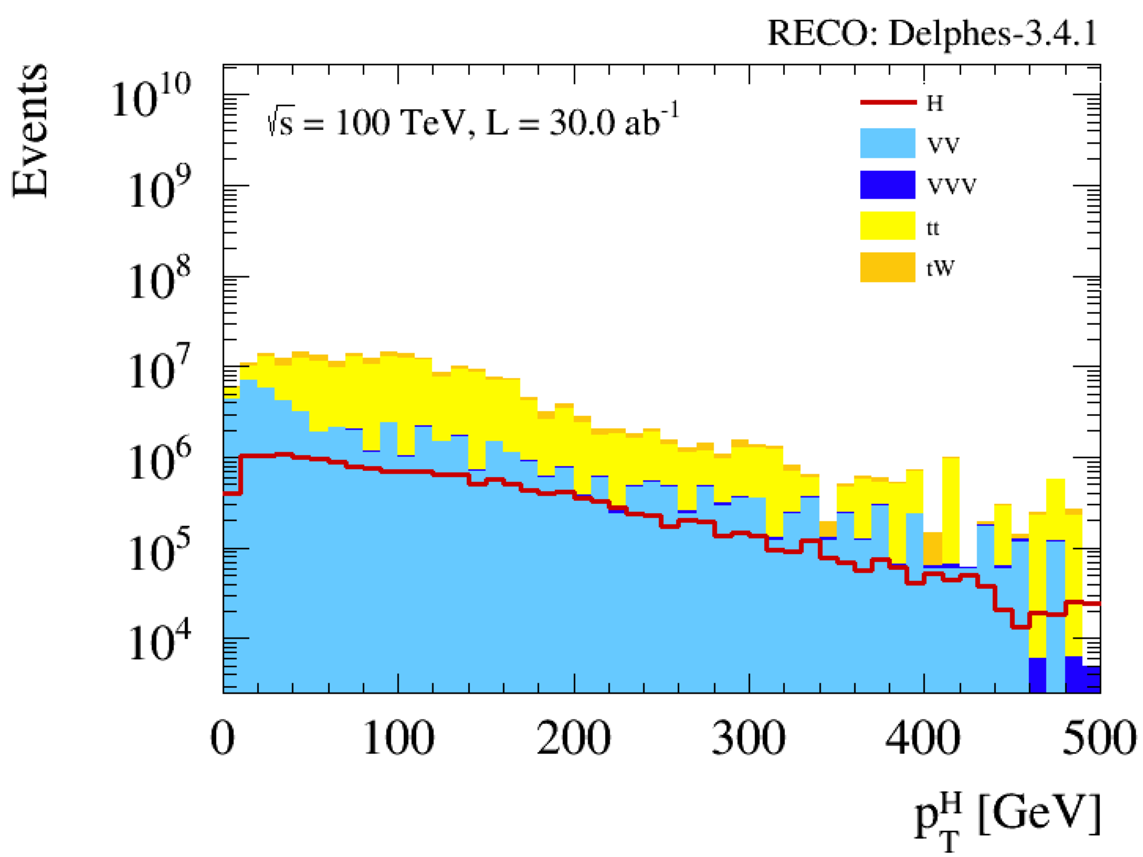


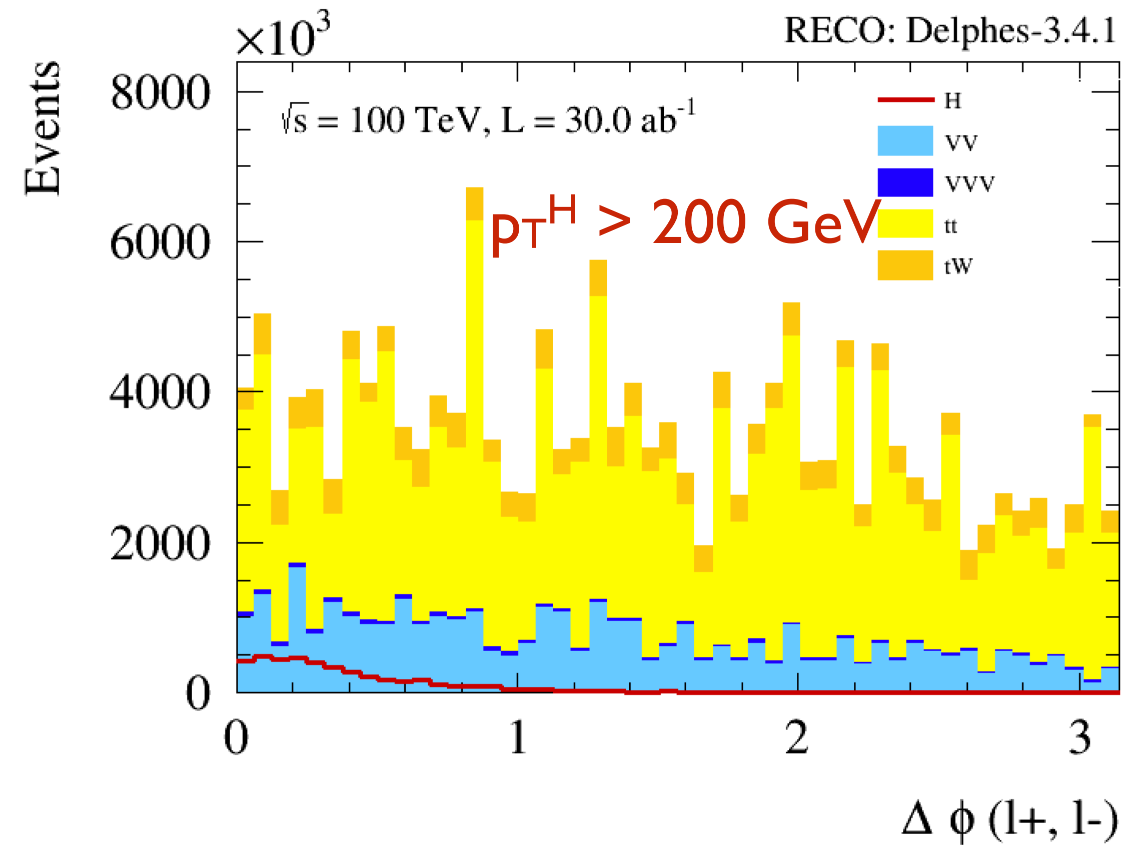


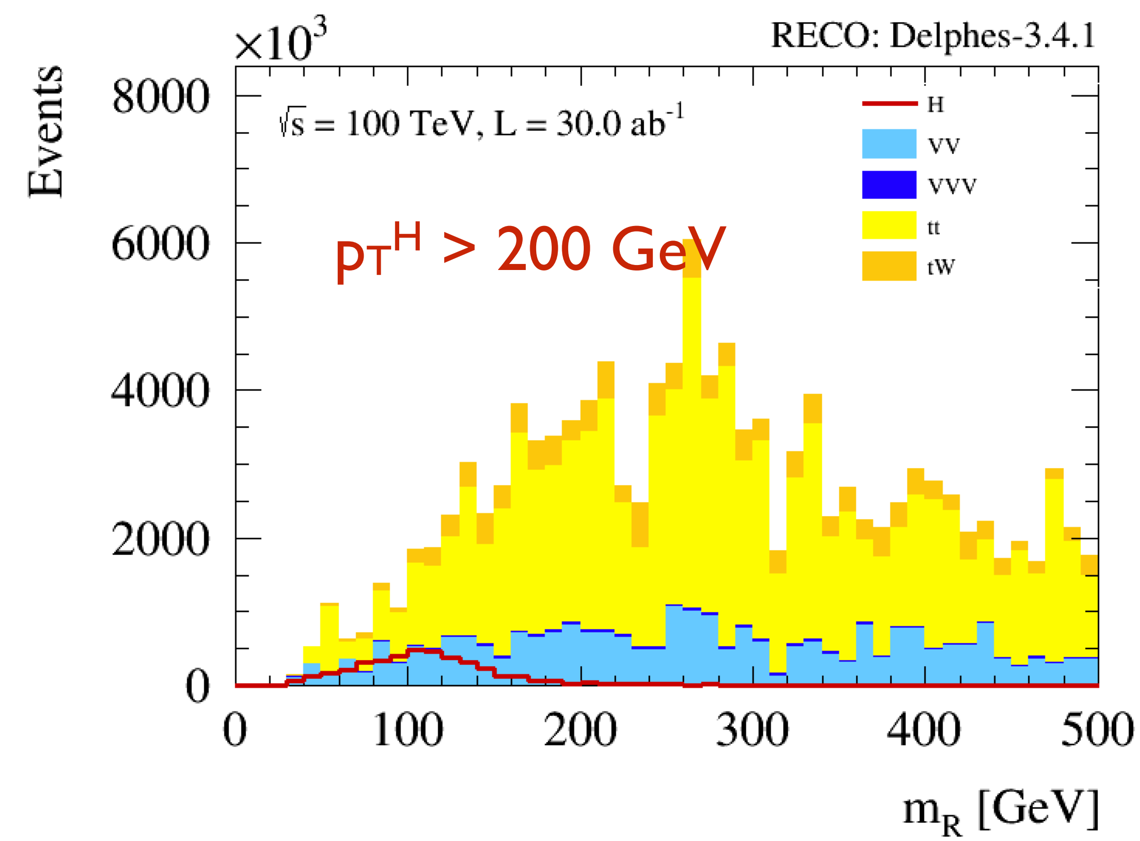


- b-jet veto applied already
- top features $N_{jets\text{-}light} > 0$

H → WW* → 2l2ν - Higgs p_T

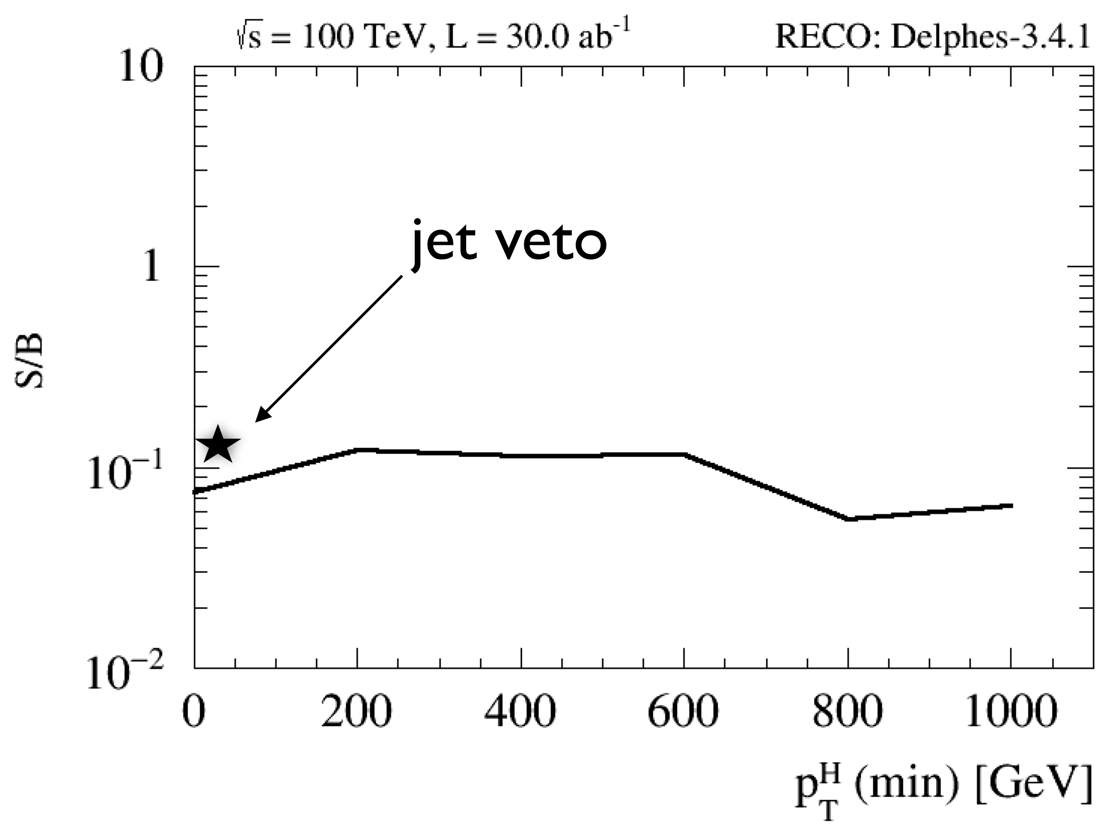


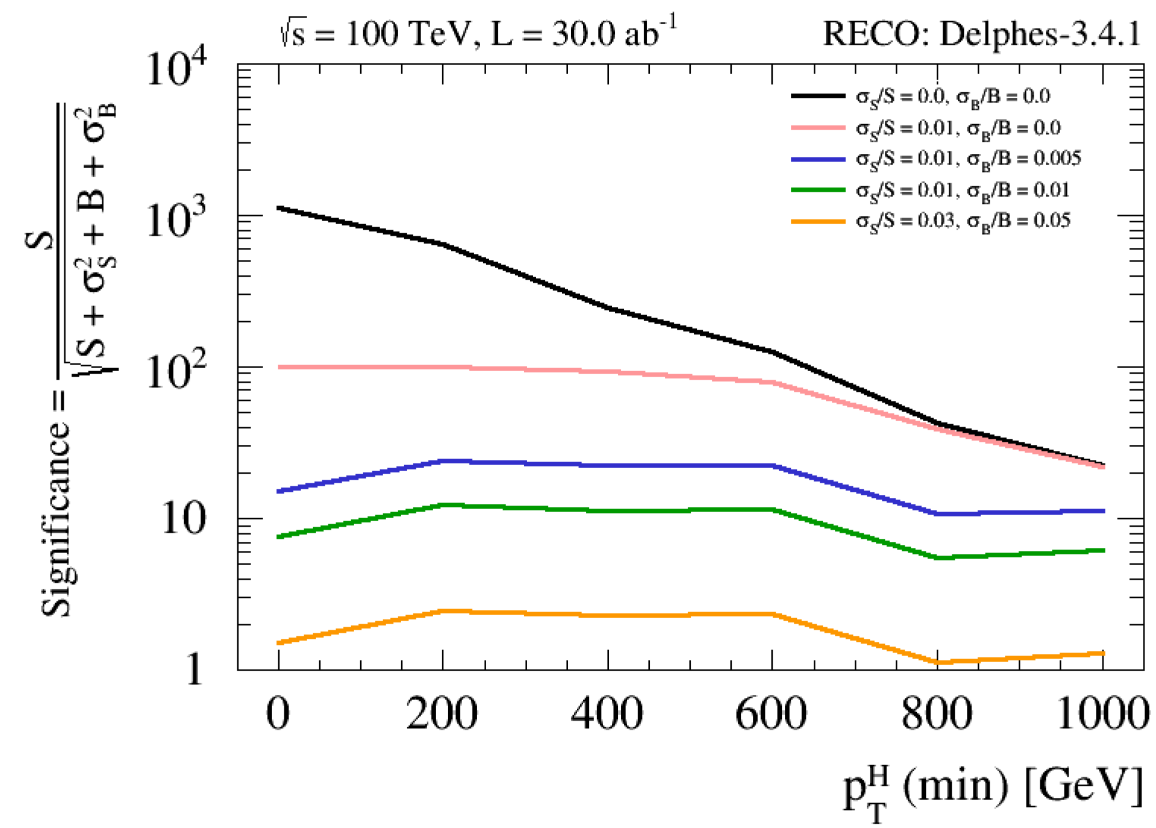




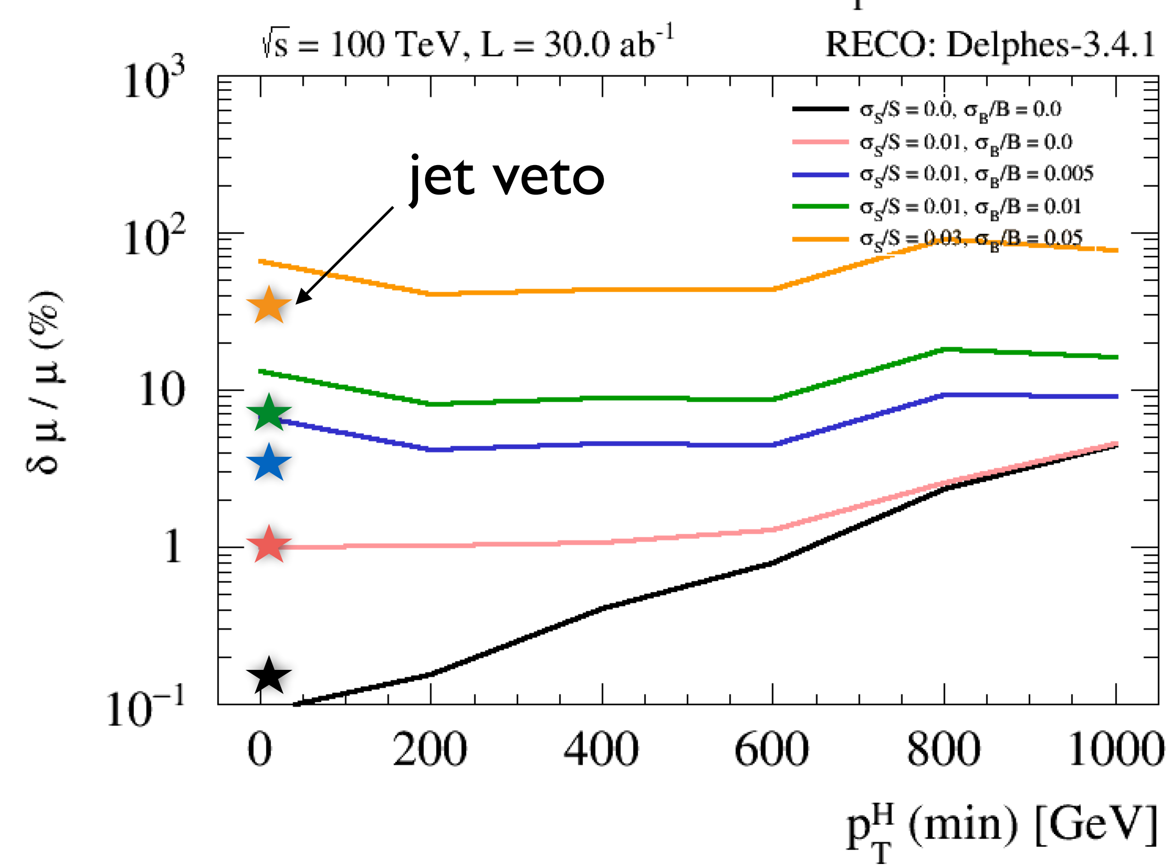
- exploit Higgs p_T
- pay price of higher top background
- trade-off between top and WW

H → WW* → 2l2ν - Expected sensitivity





- **O(1) % precision** on signal strength can be achieved
- Suprisingly (without uncertainties), jet veto does not help much
  - because b-jet veto already applied
  - signal is very jetty
- high p_T moderately helps

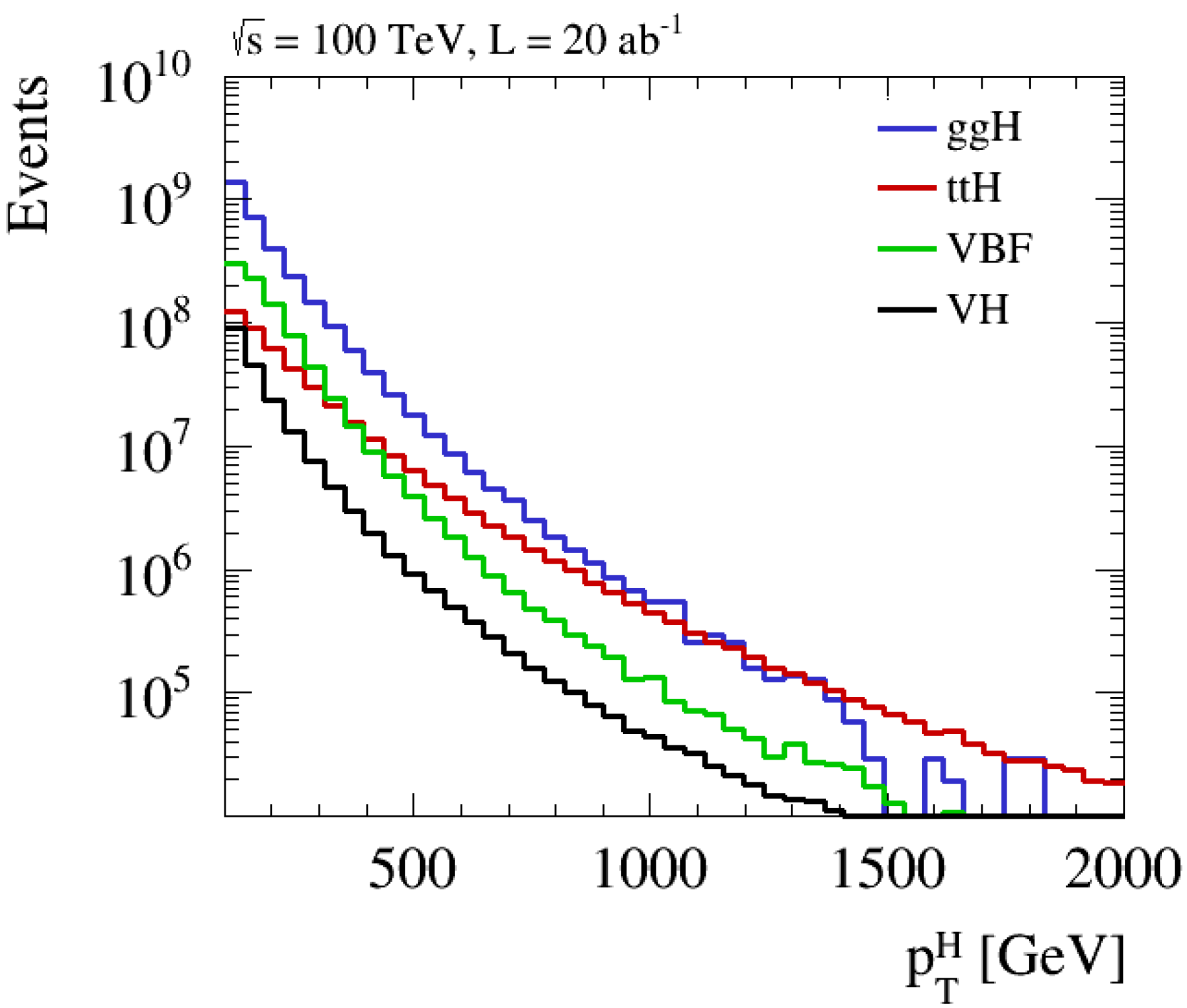


Conclusions

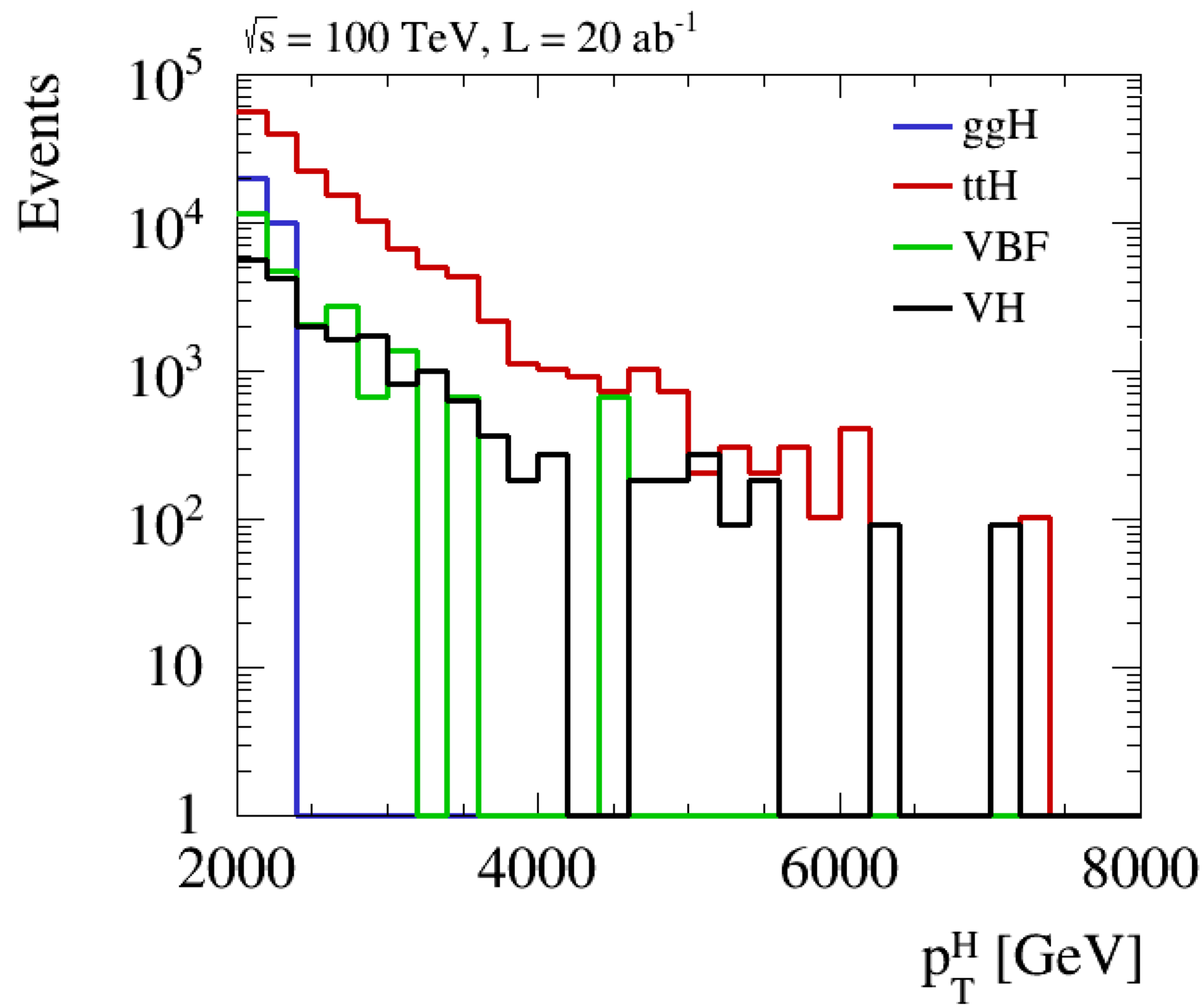
- Started to look at few channels
- More to come: ttH, VH(bb), Zγ, $\tau\tau$

Backup

Higgs pT



√s = 100 TeV, L = 20 ab-1
Events
ggH
ttH
VBF
VH
500
1000
1500
2000
pTH [GeV]



√s = 100 TeV, L = 20 ab-1
Events
ggH
ttH
VBF
VH
2000
4000
6000
8000
pTH [GeV]