Higgs & EWSB @FCC-hh

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and

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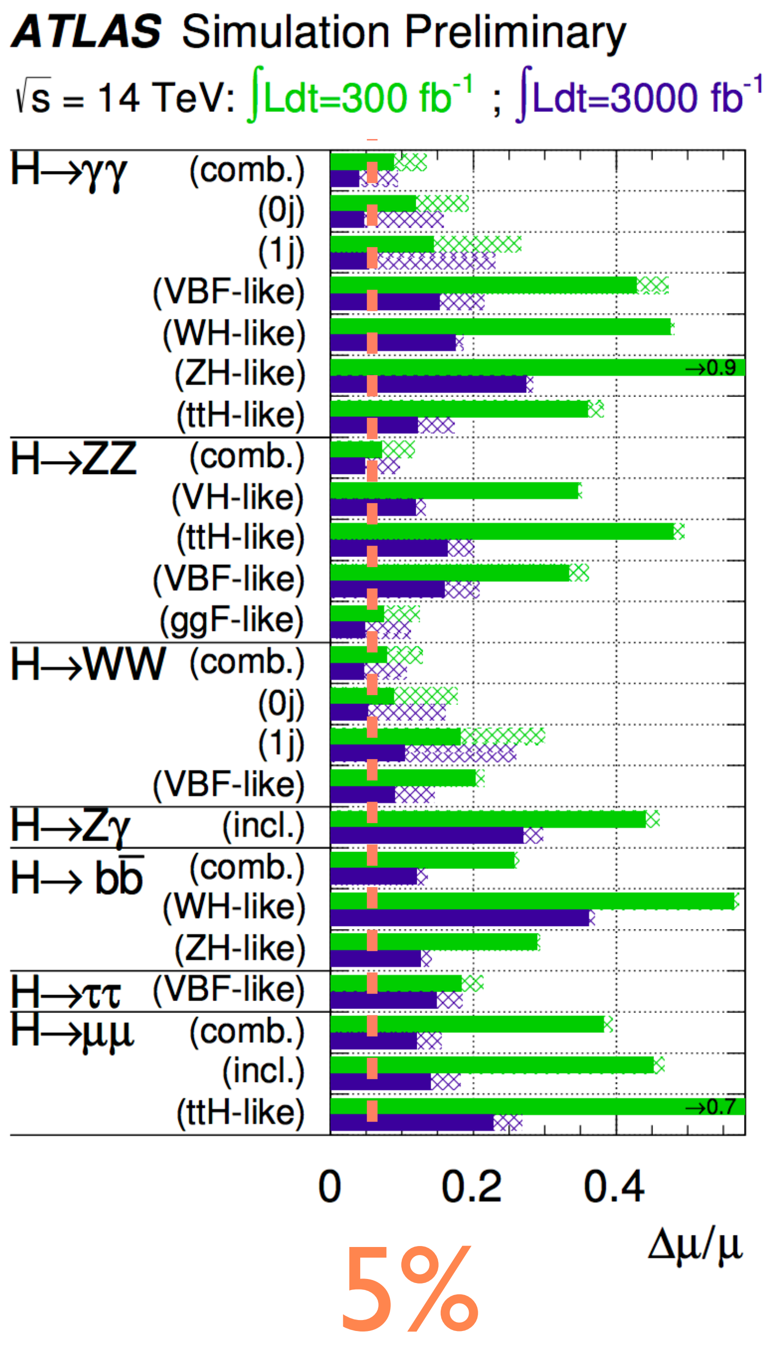
Why measuring Higgs @FCC-hh?

LHC

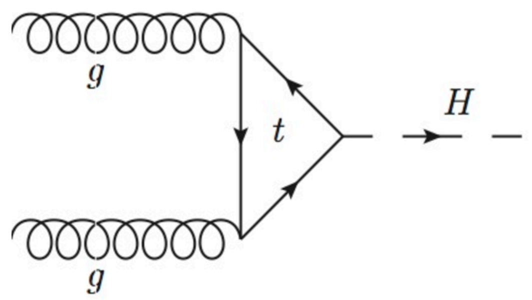


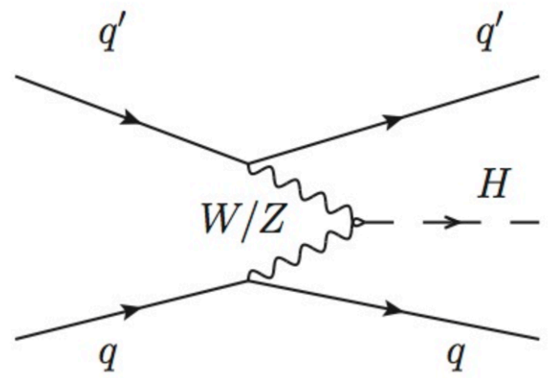
- Higgs precision measurements are **guaranteed deliverables**, because we know the Higgs exists…
- Potential **deviations** on Higgs couplings might **indicate presence of new physics**
- FCC-hh provides complementary measurements to FCC-ee:
  - **rare decays** (BR(μμ), BR(Zγ), ratios, ..) measurements will be statistically limited at FCC-ee
  - **top Yukawa and** Higgs **self-coupling**
- Directly test **unitarisation of VBS** by measuring $W_L W_L$ and $Z_L Z_L$ (not accessible at HL-LHC)

FCC-ee

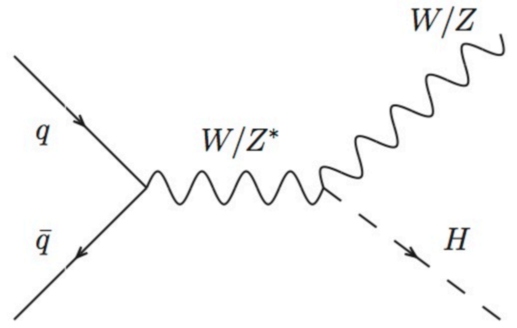
in %	FCC-ee 240 GeV	+FCC-ee 350 GeV
g_{HZ}	0.21	0.21
g_{HW}	1.25	0.43
g_{Hb}	1.25	0.64
g_{Hc}	1.49	1.04
g_{Hg}	1.59	1.18
$g_{H\tau}$	1.34	0.81
$g_{H\mu}$	8.85	8.79
$g_{H\gamma}$	2.37	2.12
Γ_H	2.61	1.55

Higgs production at FCC-hh

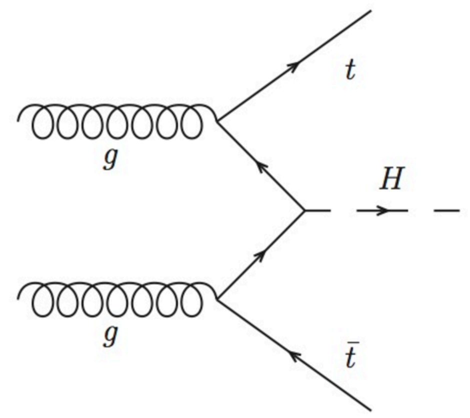




	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N^3LO)	49 pb	803 pb	16
VBF (N^2LO)	3.8 pb	69 pb	16
VH (N^2LO)	2.3 pb	27 pb	11
ttH (N^2LO)	0.5 pb	34 pb	55



	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



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

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

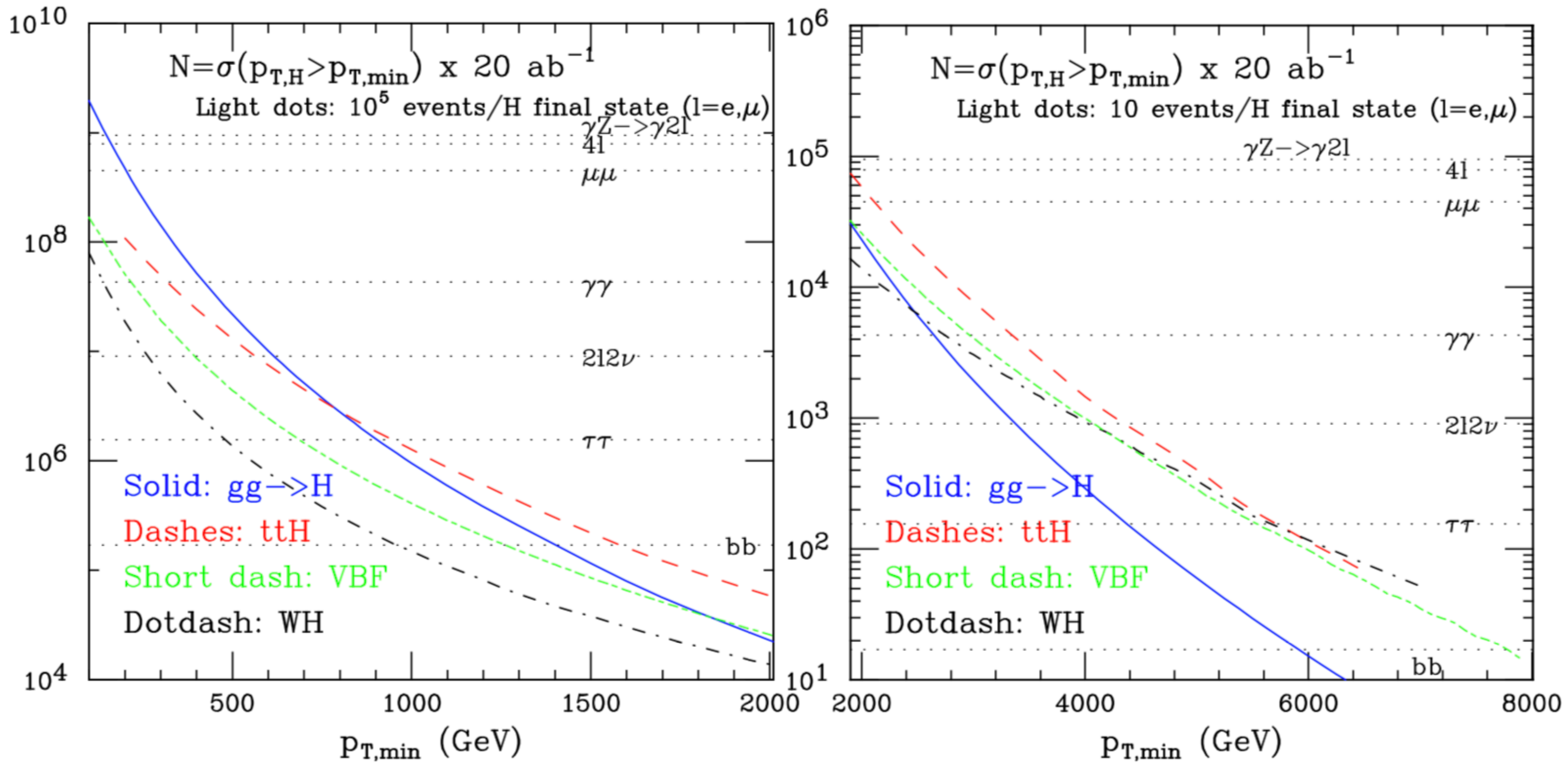
$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

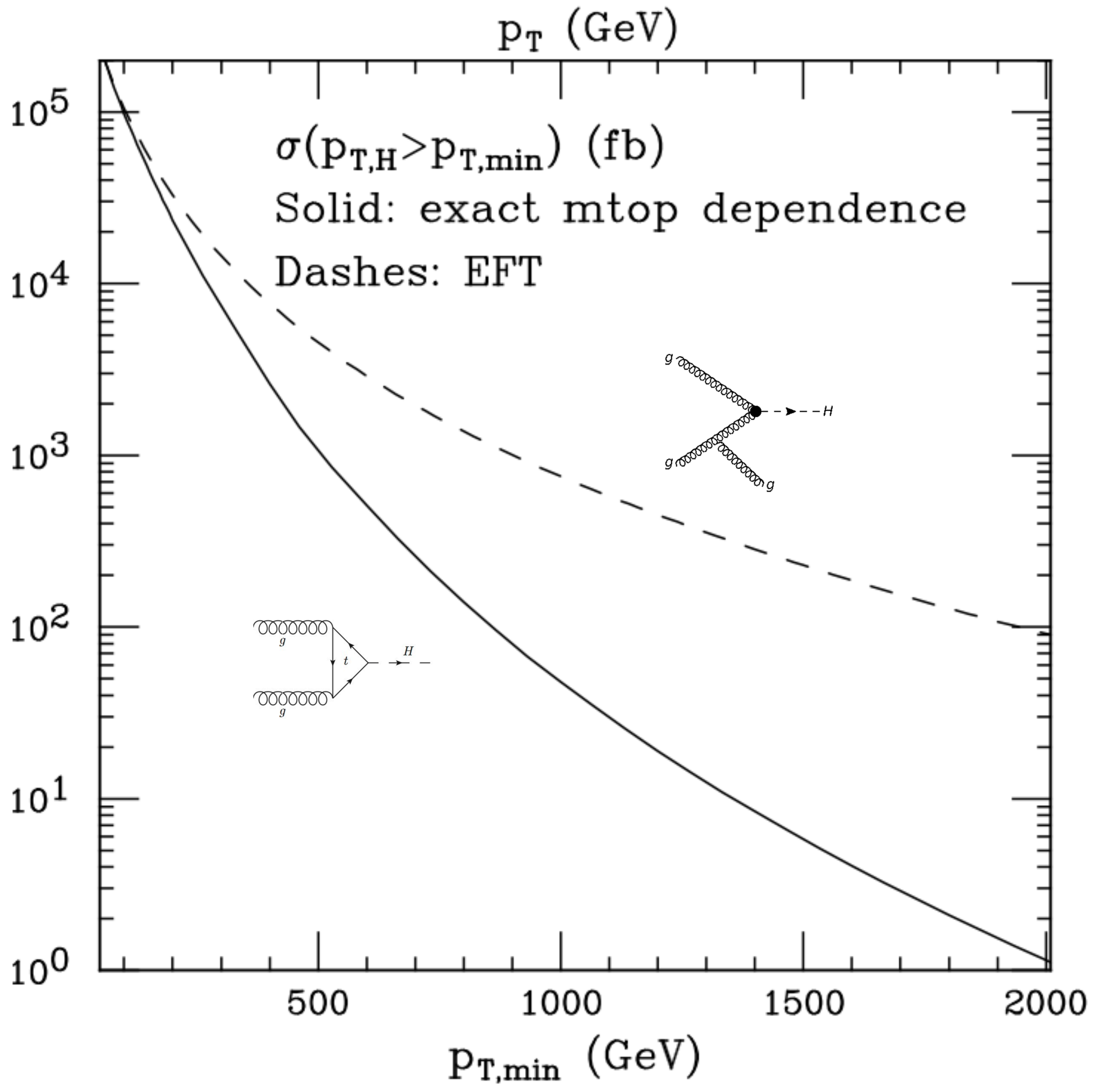
Factor: 1/100 1/10 reduction in stat. unc.

- **Large statistics** will allow to isolate **cleaner samples** in regions with:
  - higher S/B
  - smaller impact of systematics

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

from 100 TeV Higgs report





- will have at disposal, o(10^6) Higgs bosons at pT(H) > 1 TeV
- **ttH (VBF) overcomes ggH at p_T > 800 (2000) GeV,** distinctive signatures can be used
- Higgs pT spectrum is an indirect probe for new physics modifying, e.g. ggH coupling
  - heavy states running in the loop
  - complementary to Hgg measurement in e+ e-

Outline

- Will discuss **prospects for Higgs coupling measurements** at FCC-hh, by looking at following **processes (all decays with exception on ttH):**

  - ttH → bb boosted
  - H→γγ,
  - H→ZZ→4l
  - H→μμ
  - H→Zγ

- All **signal and background samples** have been generated via the following chain (using the FCCSW):

  - **MG5aMC@NLO + Pythia8**
    - LO (MLM) matched samples (up to 1/2/3 jets) and global K-factor applied to account for $N^{2/3}LO$ corrections
    - full list of signal prod. modes simulated (ggH with finite m_{top})
  - **Delphes-3.4.2** with baseline FCC-hh detector

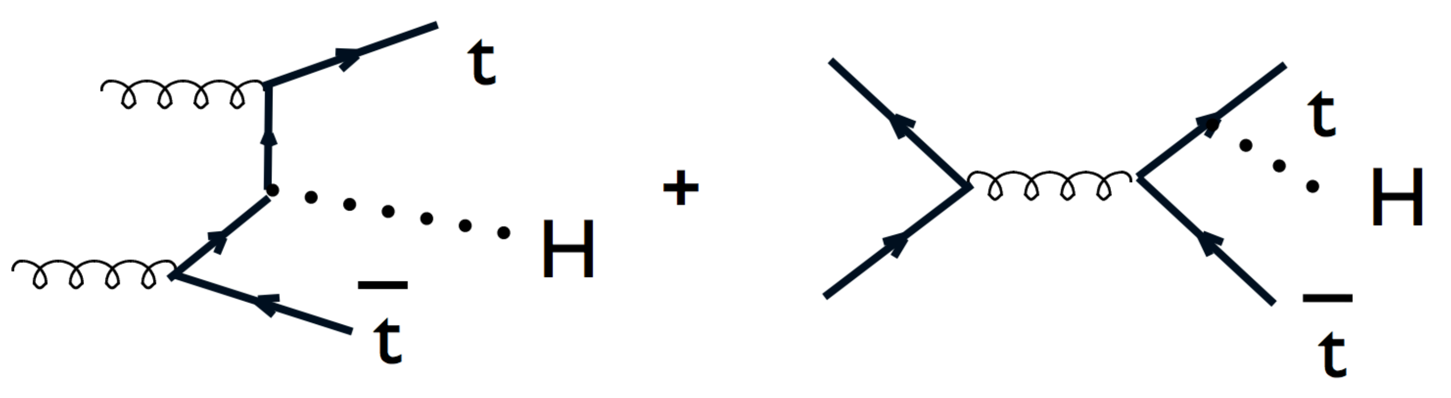
  - Full list of samples can be found here:

http://fcc-physics-events.web.cern.ch/fcc-physics-events/LHEevents.php

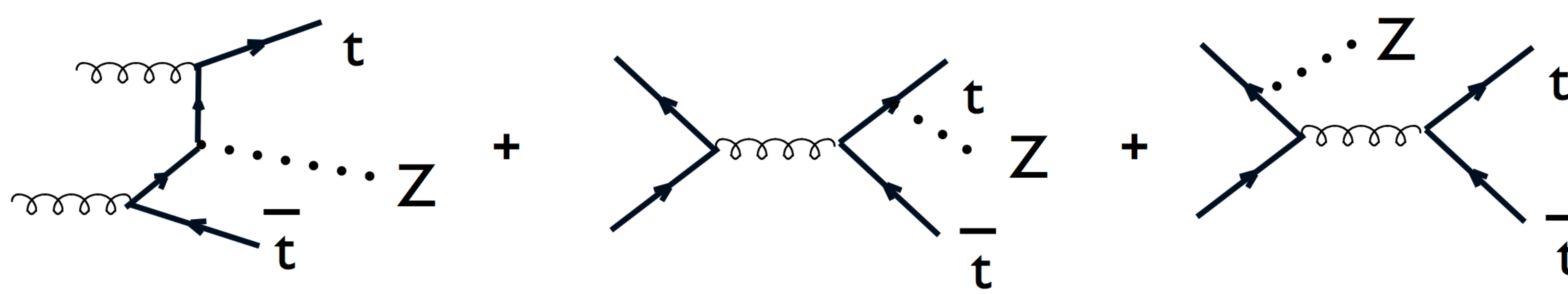
Top Yukawa

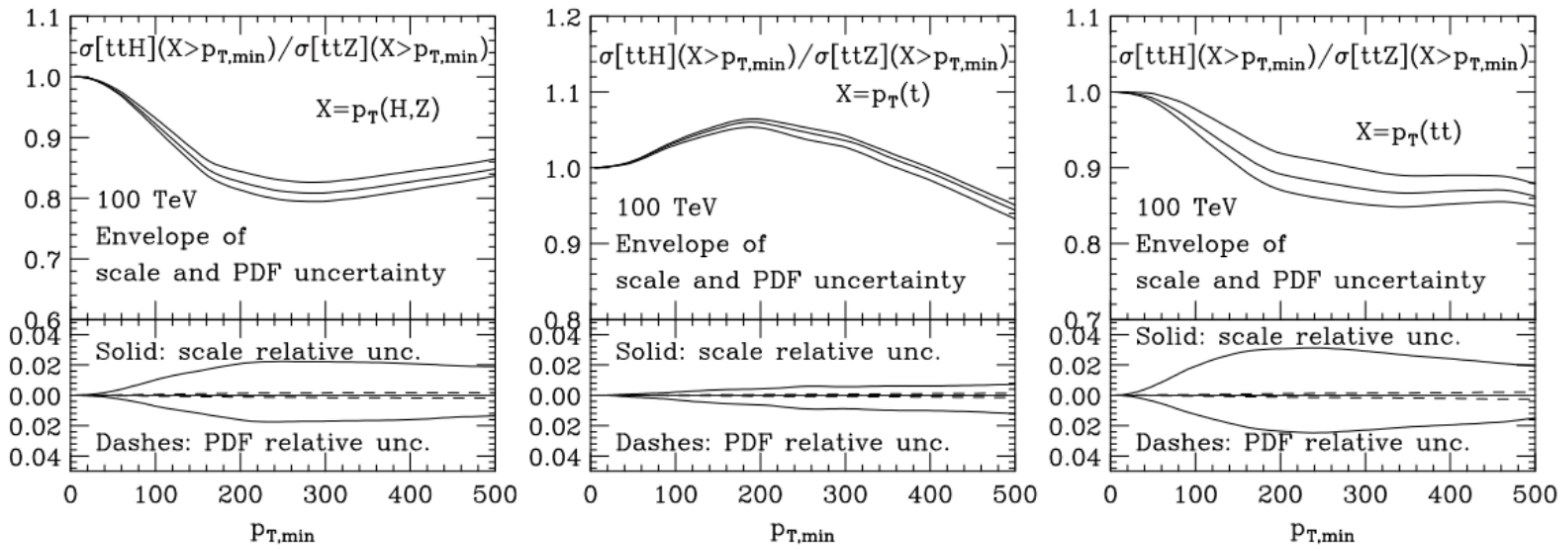
- Several possibile channels to measure top yukawa:
  - **ttH → bb, boosted [arXiv:1507.08169]**
  - ttH → WW, ZZ →multileptons (in progress)
  - ttH → γγ (in progress)
- ttH and ttZ have very similar **production dynamics**, with **highly correlated** systematics:
- **σ(ttH)/σ(ttZ)** can be predicted **with < 1% precision** across a large kinematic range

ttH



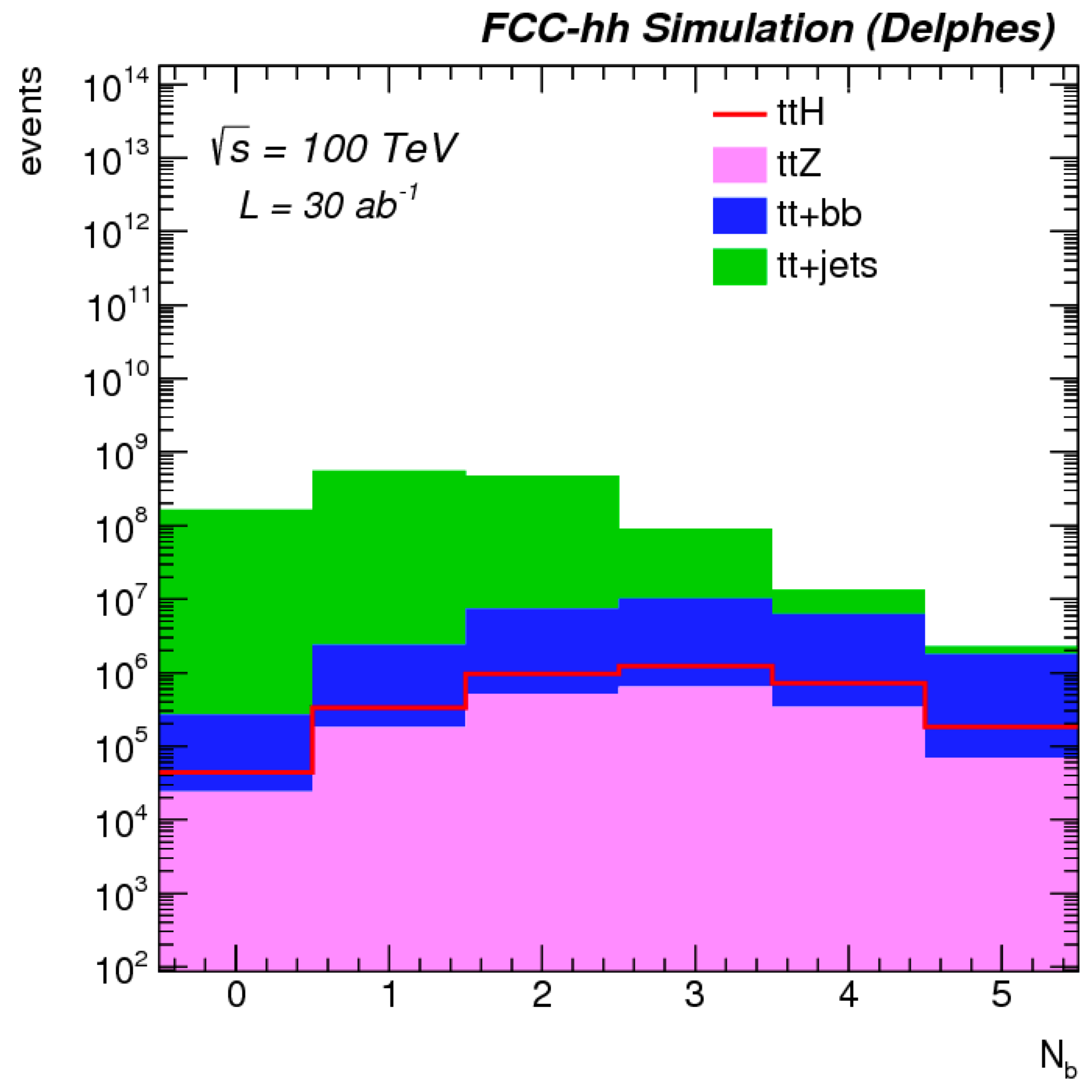
ttZ

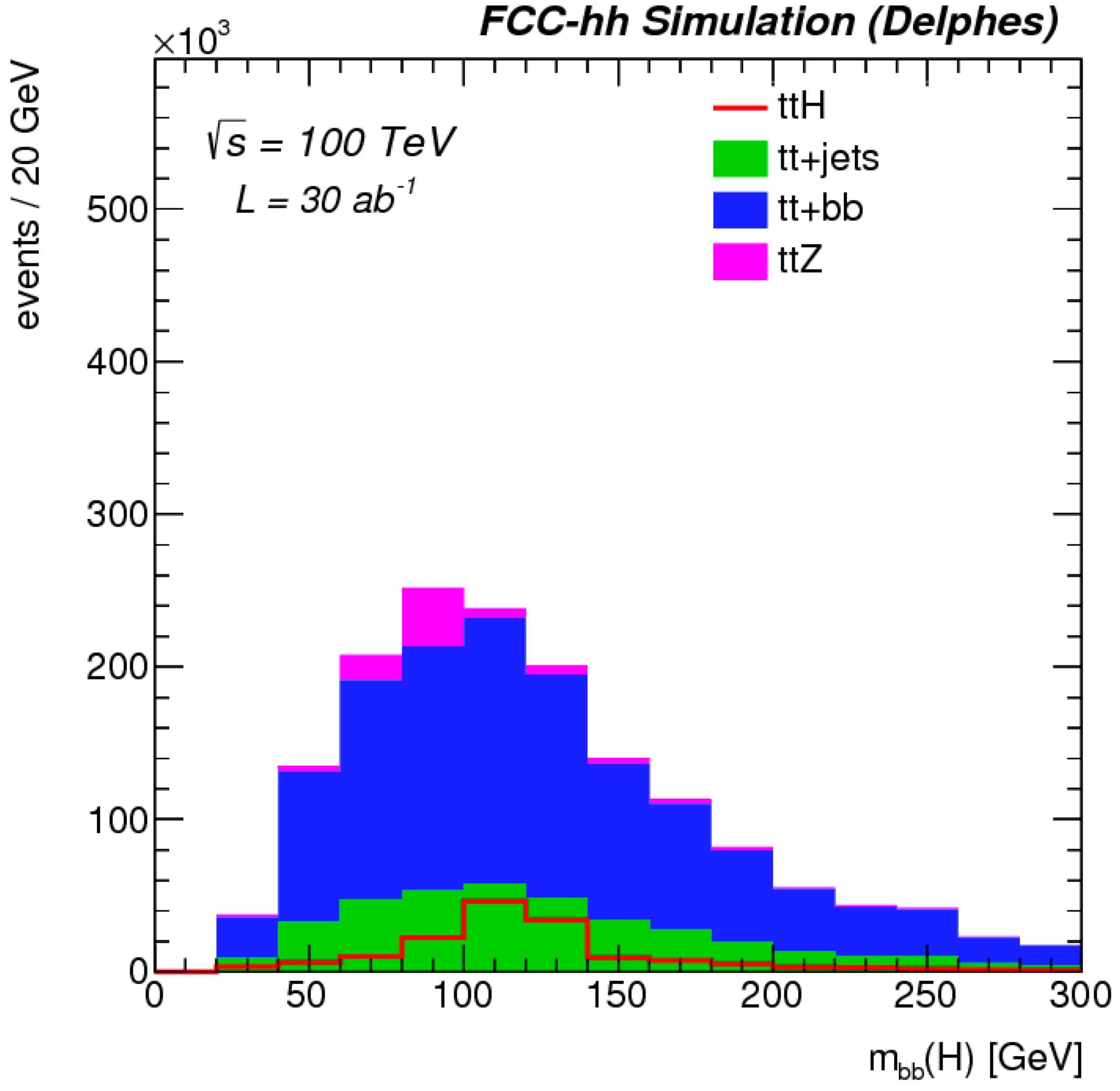




Measurement

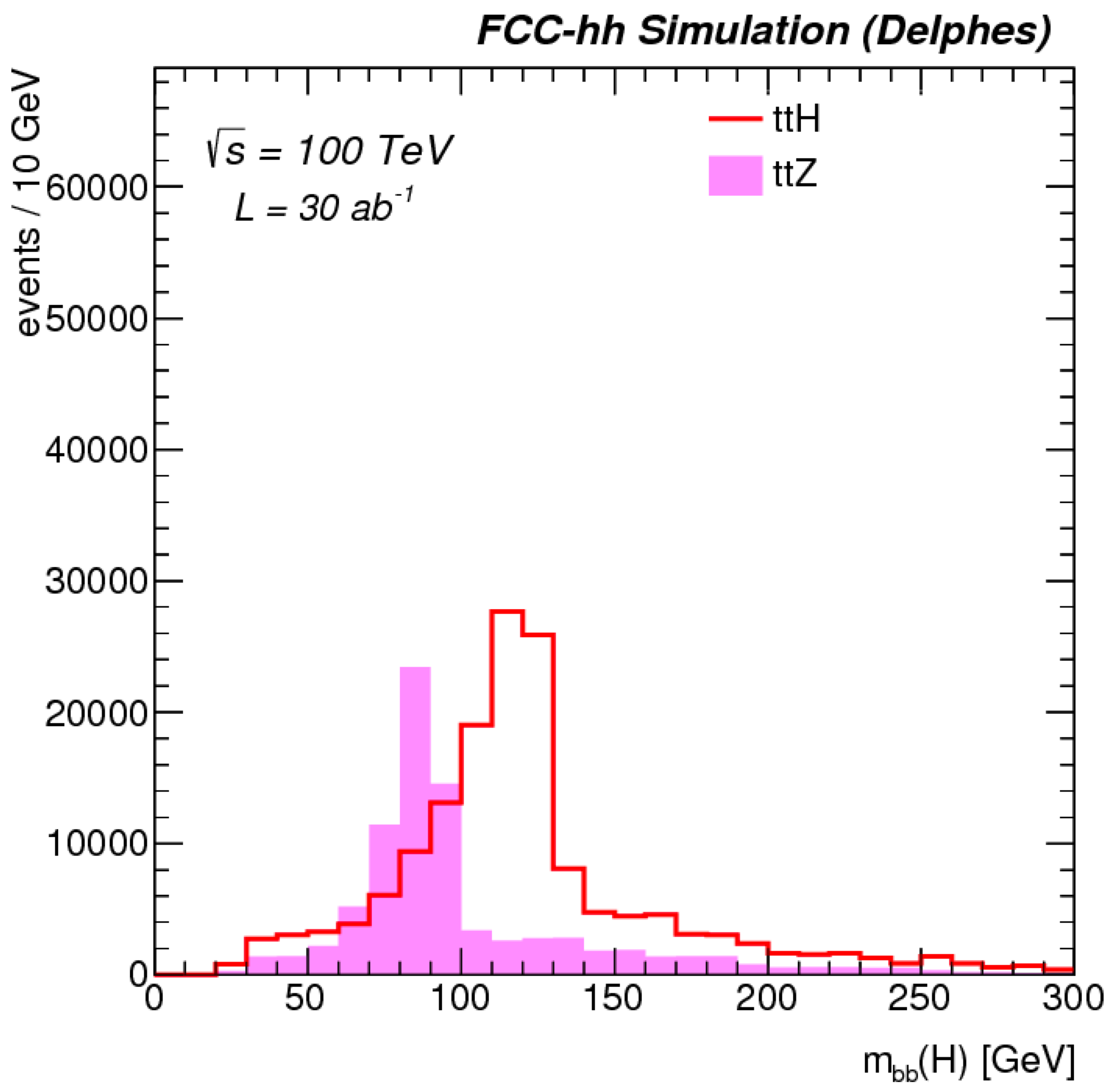
- Measure ttH/ttZ ratio in the H→bb, Z→bb channel
- Final state:
  - boosted Higgs, H→ bb
  - boosted top hadronic
  - other top leptonic decay
- Signature:
  - 2 fat-jets,
  - 1 lepton,
  - MET, (+ 1 bjet)
- Backgrounds:
  - ttZ,
  - tt+jets,
  - tt+bb
  - W/Z+jets ignored for now





Top Yukawa

Measure top Yukawa by measuring **σ(ttH)/σ(ttZ)**



- N_{ttZ} / N_{ttH} = 0.533 +/- 0.004 (stat)

  → $\delta_{stat}(N_{ttZ}/N_{ttH}) \approx 0.7$ %
  → assumes background yield under control ≲ 1% (enough statistics in the side bands)

- To be studied:

  → impact of background shape

- tt+jets rate from side band CR (m_j > 160 GeV)
- assuming shape of tt+jets under control.. (to be studied)

$\delta y_t / y_t \lesssim 1$ %

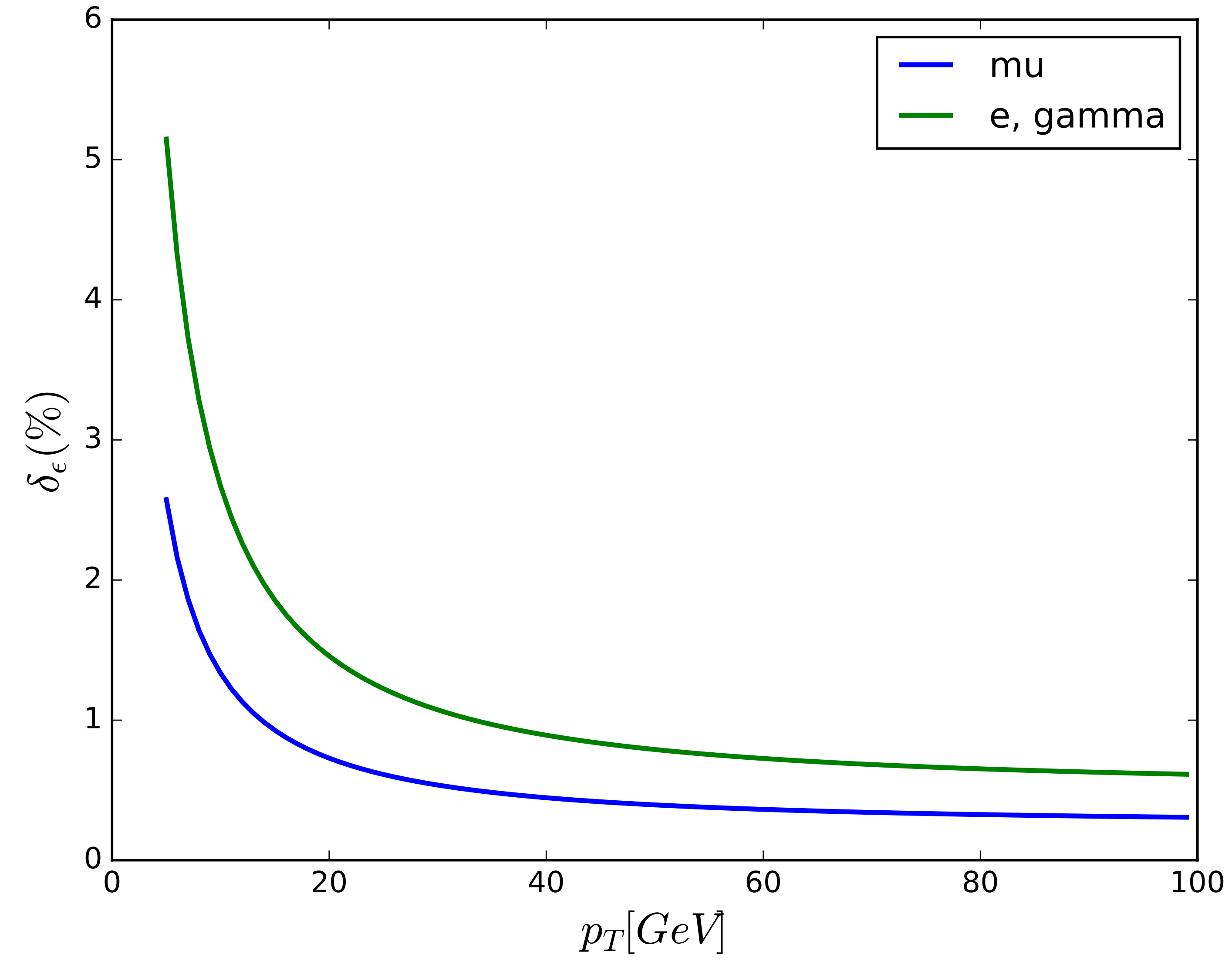
Higgs decay studies

- Will show prospects for S/B and precision on the signal strength **$\delta\mu/\mu$** in the following channels (**$H\rightarrow\gamma\gamma$, $H\rightarrow 4l$, $H\rightarrow\mu\mu$, $H\rightarrow Z\gamma$**) for various scenarios.

- Consider the following categories of **uncertainties**:

  - δ_{stat} = **statistical**
  - δ_{prod} = **production** + **luminosity** systematics (1-2%)
  - $\delta_{eff}^{(i)}(p_T)$ = object **reconstruction** (trigger+isolation+identification) systematics
  - δ_B = 0, **background** (assume to have ∞ statistics from control regions)

    - Assume the following baseline for **reconstruction efficiency** uncertainties $\delta_{eff}^{(i)}(p_T)$ →



Higgs decay studies

- Given how **uncertainties scale with p_T**, makes sense to **explore sensitivity at large $p_T(H)$** (also qq produced backgrounds falls more steeply)

- **Propagate systematics** based on **average p_T** of Higgs **decay product**

  - ex: $H \to \mu\mu$, with $p_T(H) > 50$ GeV:

    - $p_T(\mu_1) \sim 100$ GeV $\to$ $\delta_{eff}^{(\mu)} \approx 0.30\%$
    - $p_T(\mu_2) \sim 50$ GeV $\to$ $\delta_{eff}^{(\mu)} \approx 0.50\%$

- Assume **(un-)correlated uncertainties** for **(different) same** final state objects

- Following **scenarios** are considered:

  - δ_{stat} $\to$ stat. only (I)
  - δ_{stat} , δ_{eff} $\to$ stat. + eff. unc. (II)
  - δ_{stat} , δ_{eff} , $\delta_{prod} = 1\%$ $\to$ stat. + eff. unc. + prod (III)

H → γγ

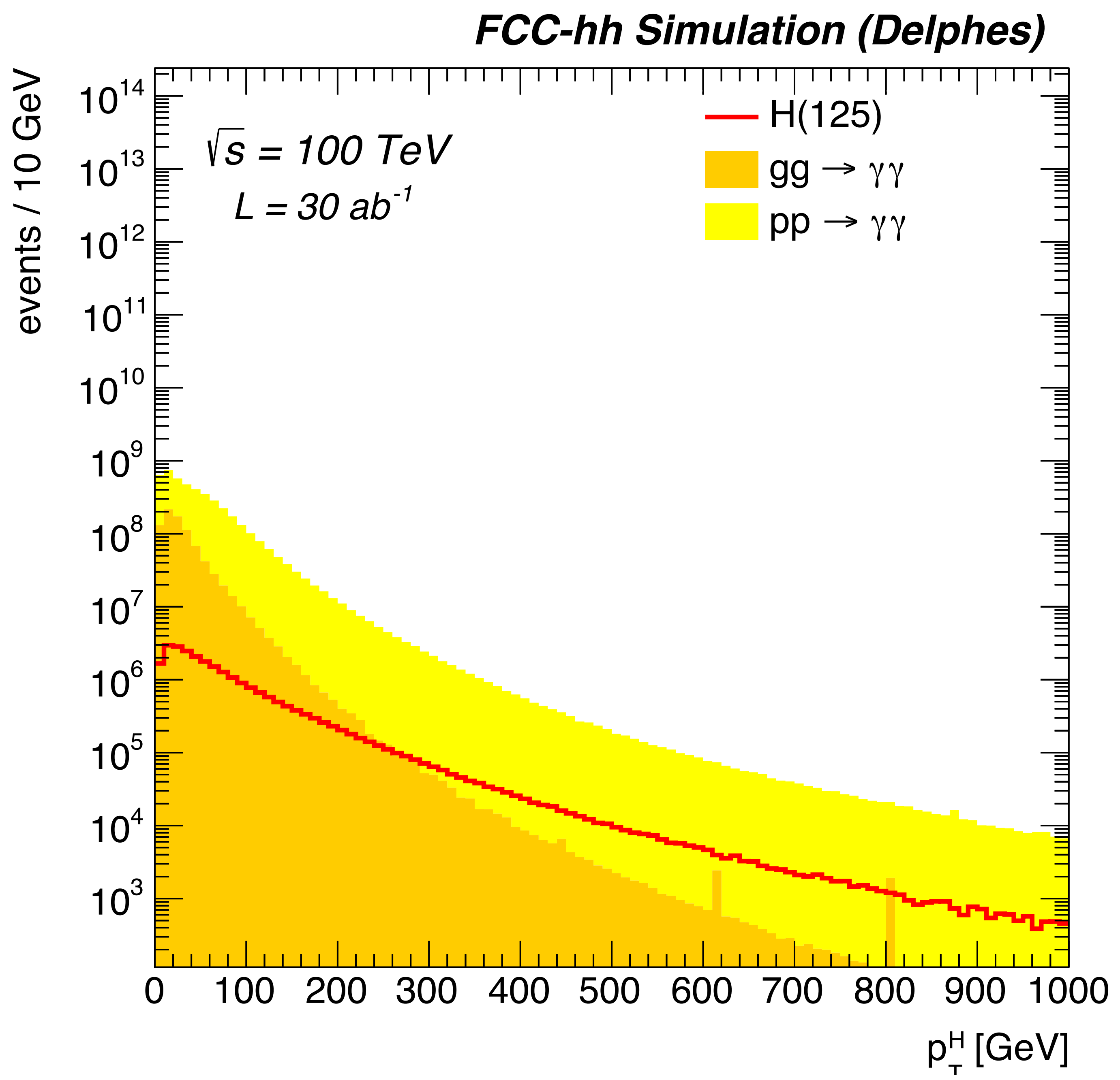
Backgrounds:

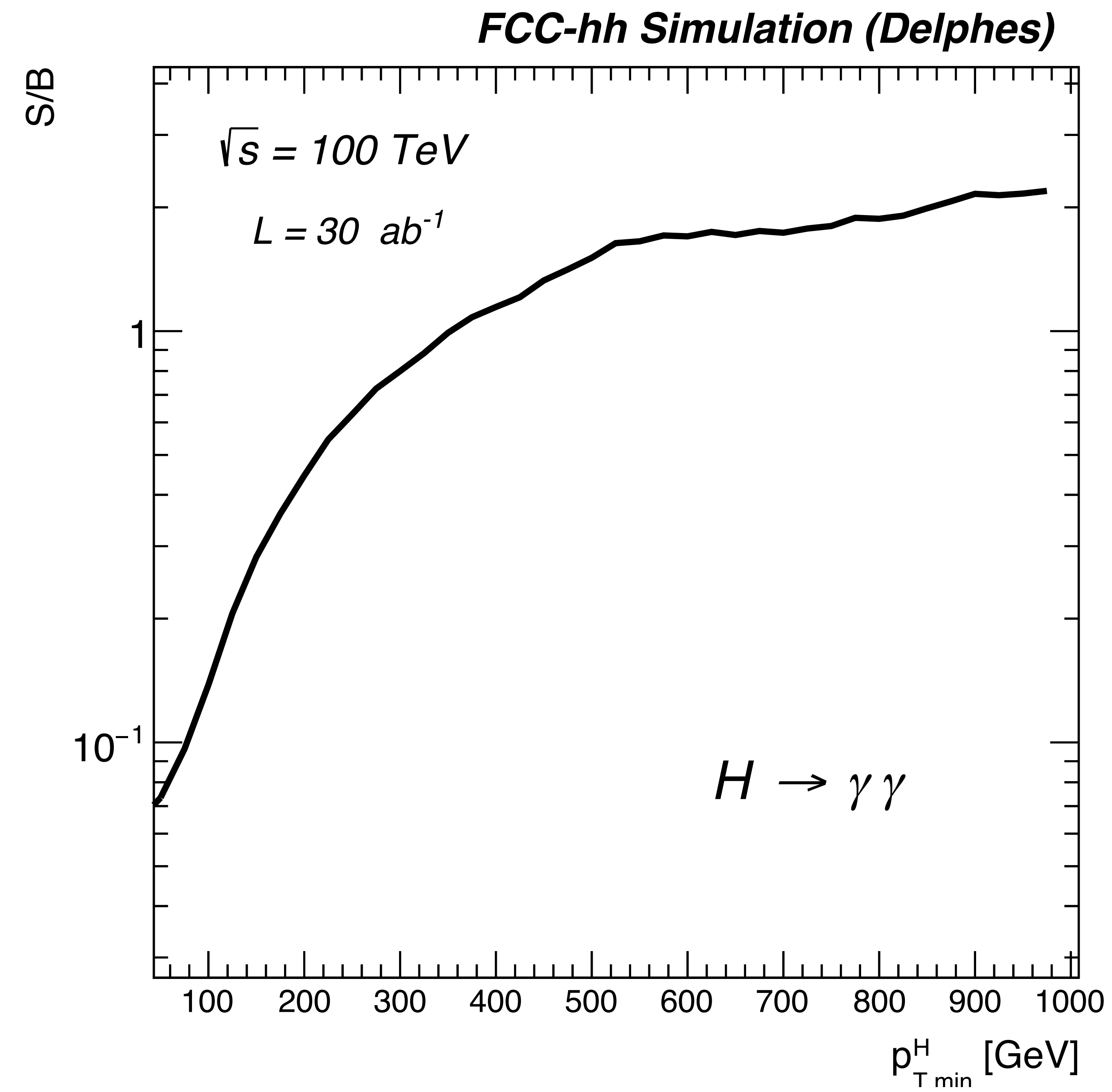
- **irreducible**: QCD γγ production
- **reducible.** : γ + jets (ignored for now)

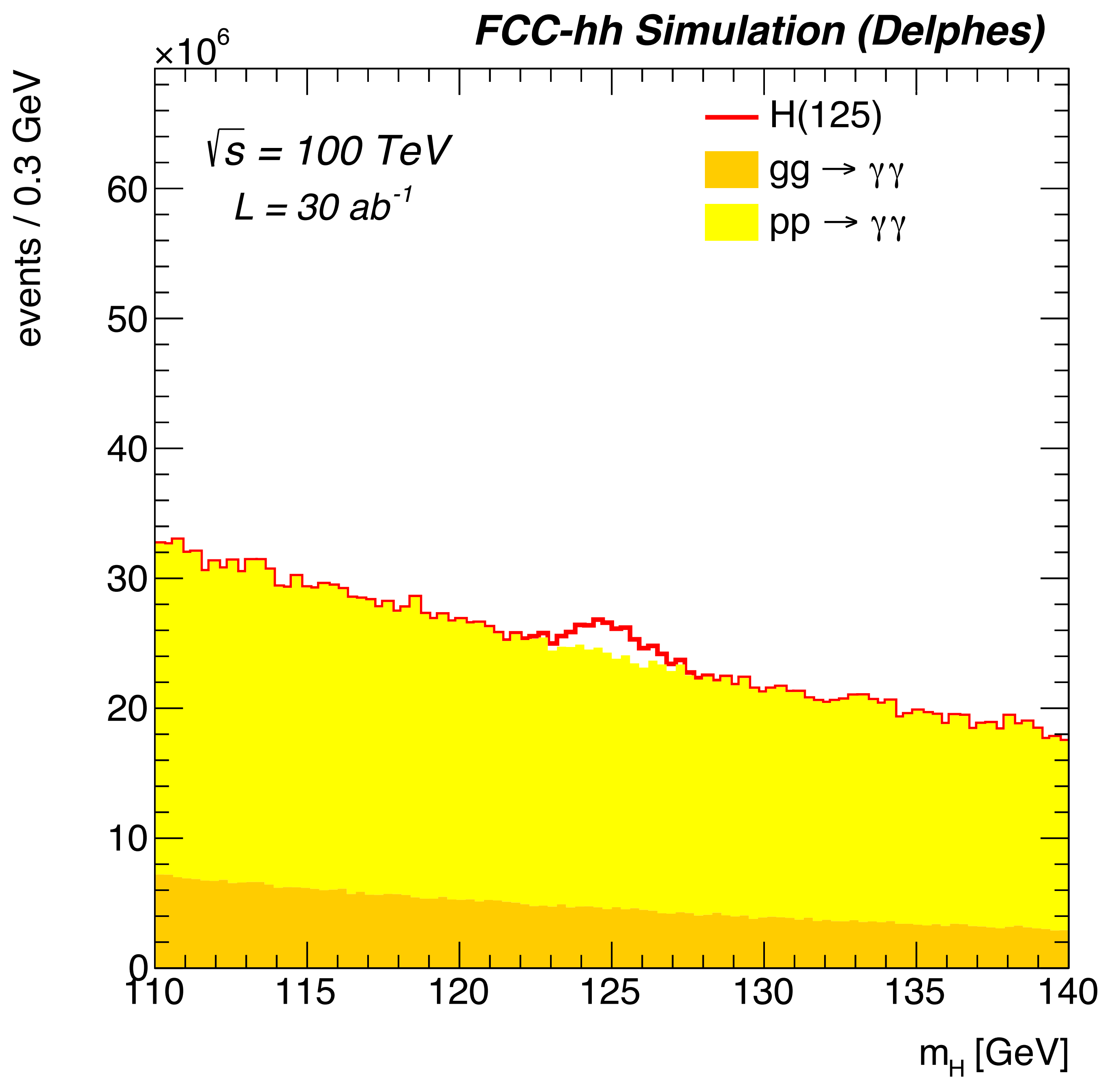
Analysis cuts

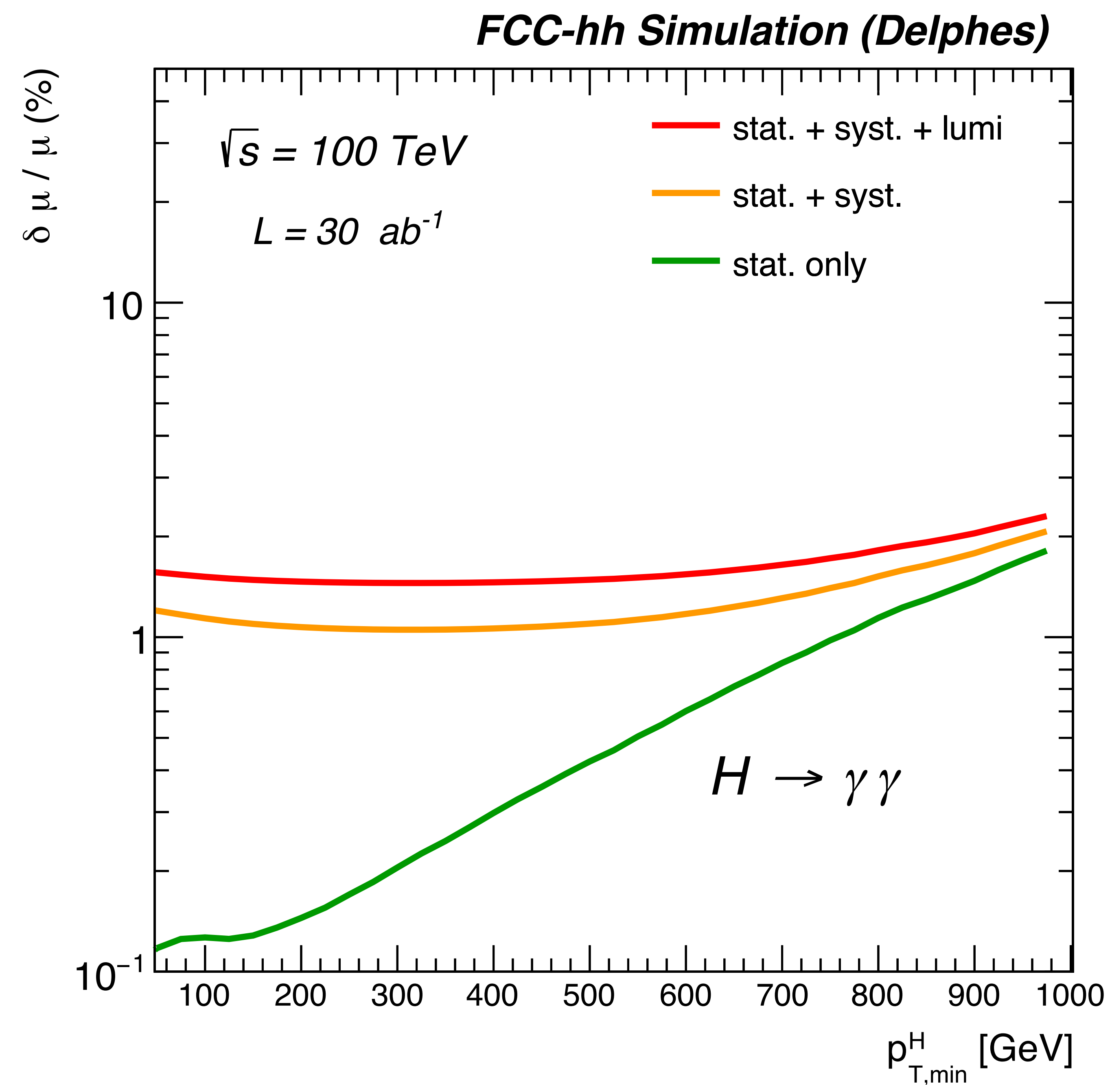
- $p_T(\gamma) > 30$ GeV, $|\eta(\gamma)| < 4.0$
- variable $p_T(H)_{min}$
- $|m_{\gamma\gamma} - m_H| < 2.5$ GeV

- **δμ/μ ≈ O(1) % precision** can be achieved up to $p_T(H)$ = 1 TeV









H → ZZ* → 4l

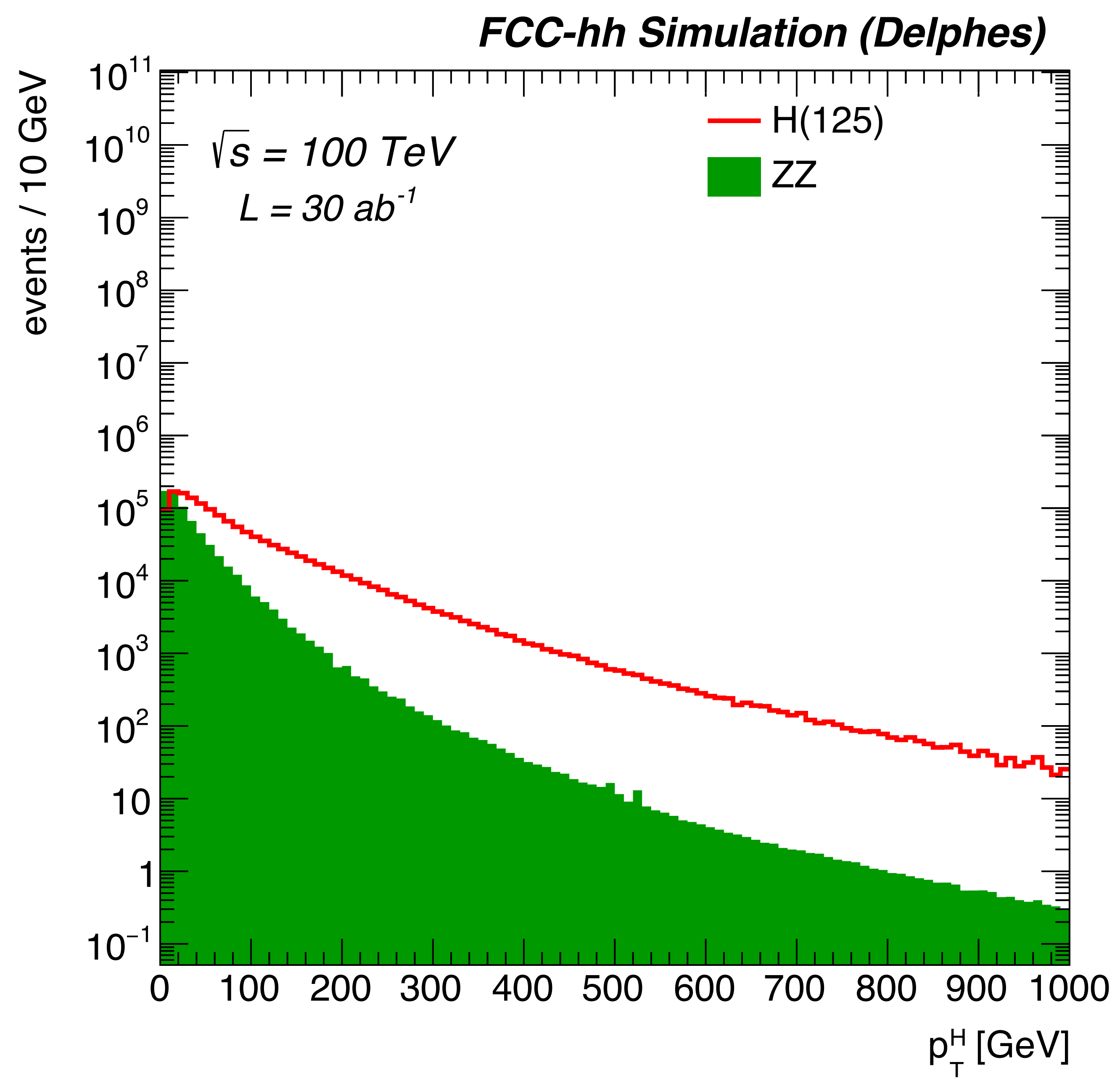
Analysis cuts:

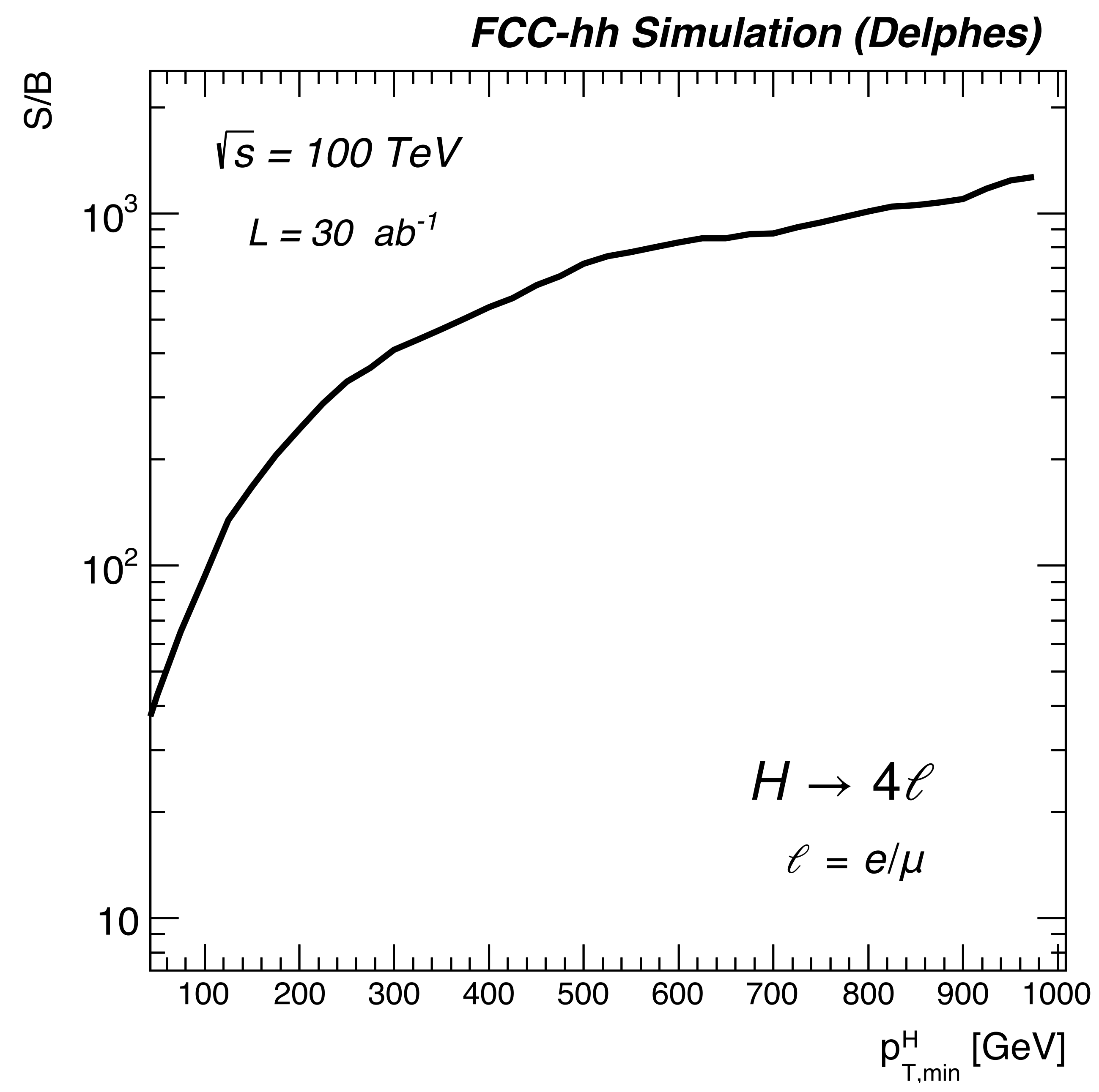
- $40. < m_{Z1} < 120.$
- $12. < m_{Z2} < 120.$
- $p_T(l) > 10$ GeV, $|\eta(\gamma)| < 4.0$
- $122.5 < m_{4l} < 127.5$ GeV

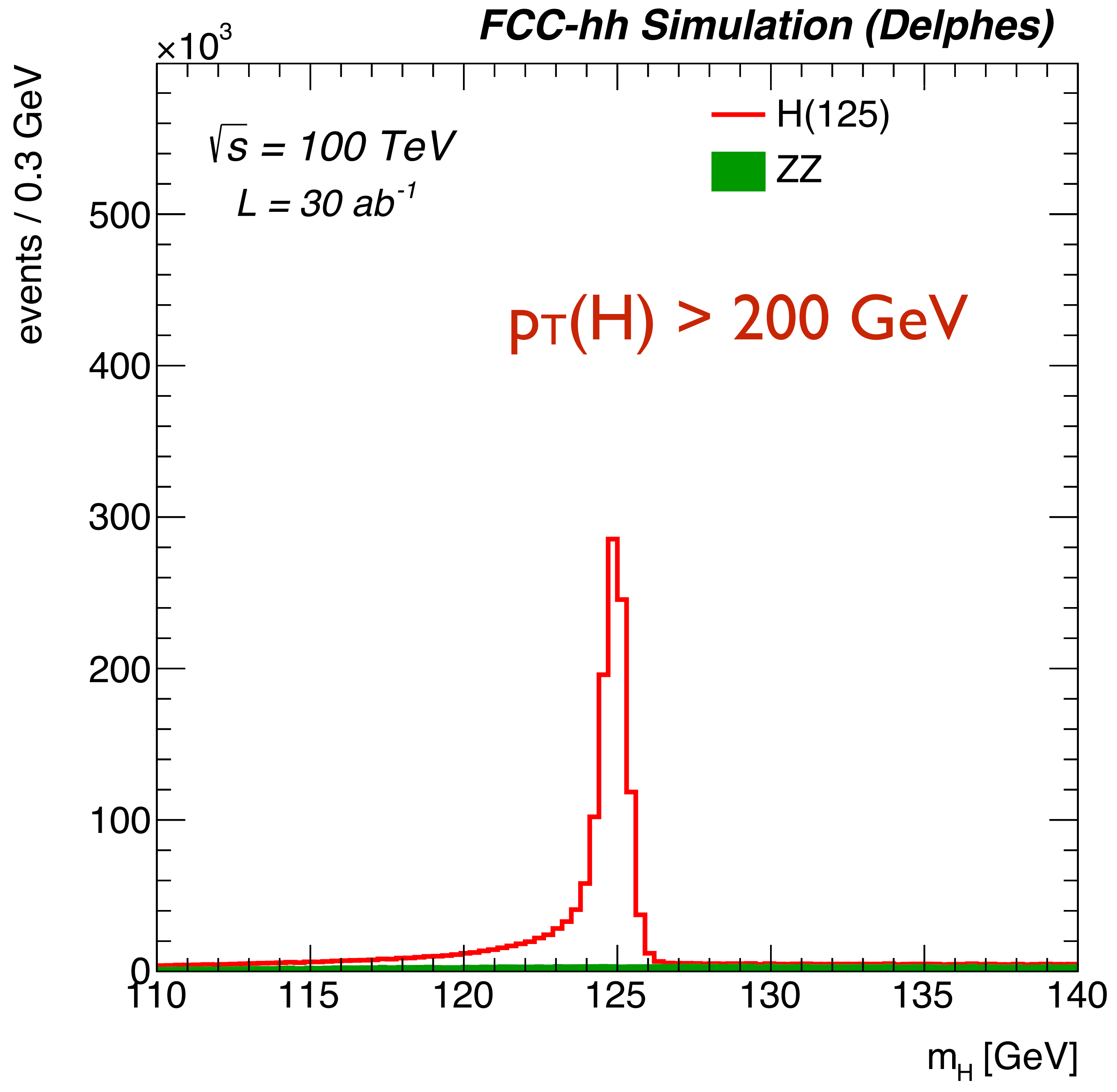
→ asymmetric cut due to FSR tail

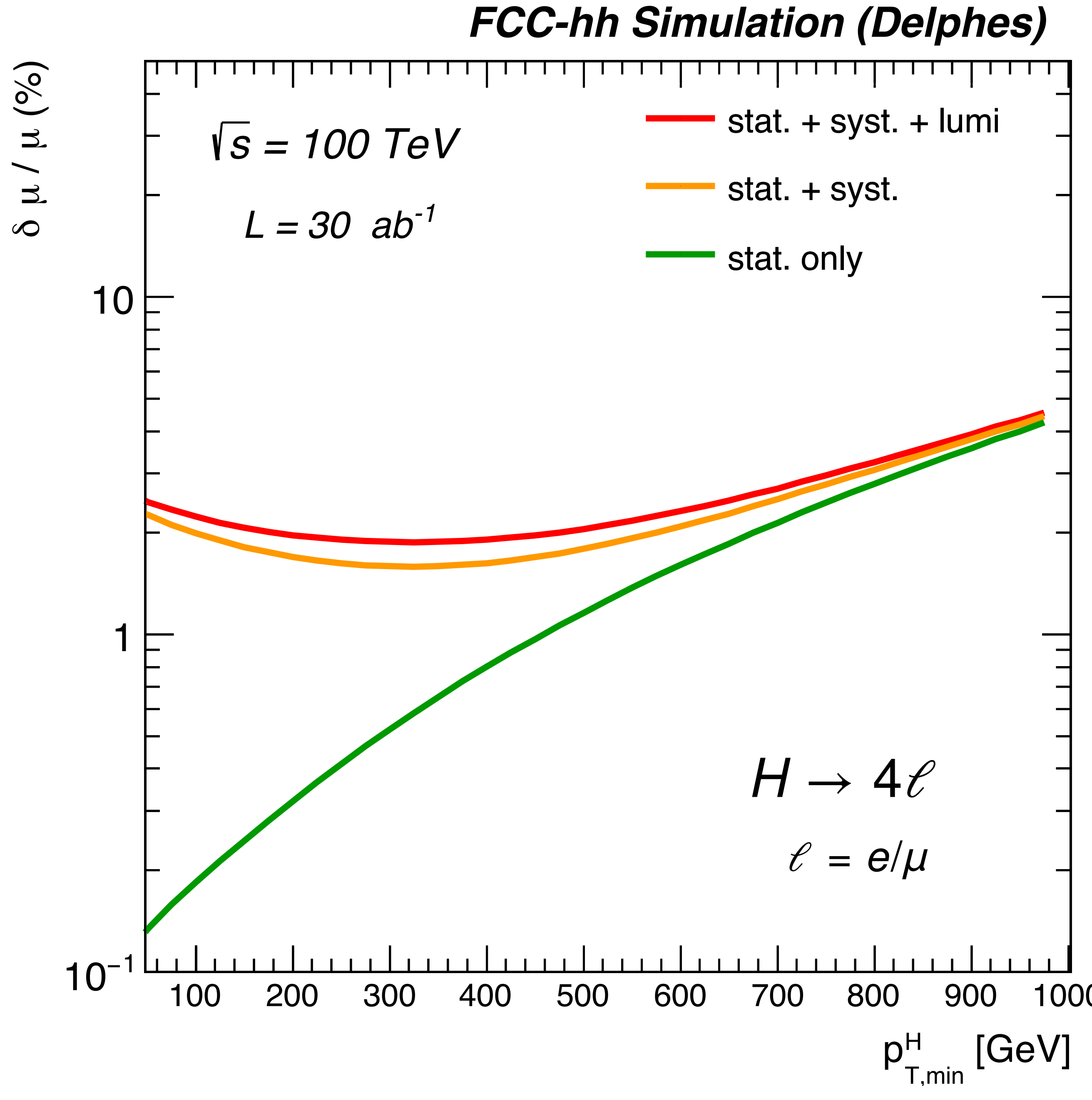
background free analysis at high pT !

- **$\delta\mu/\mu \approx 1$ % precision** can be achieved up to $p_T(H) = 500$
- At low p_T systematics will limit the measurement









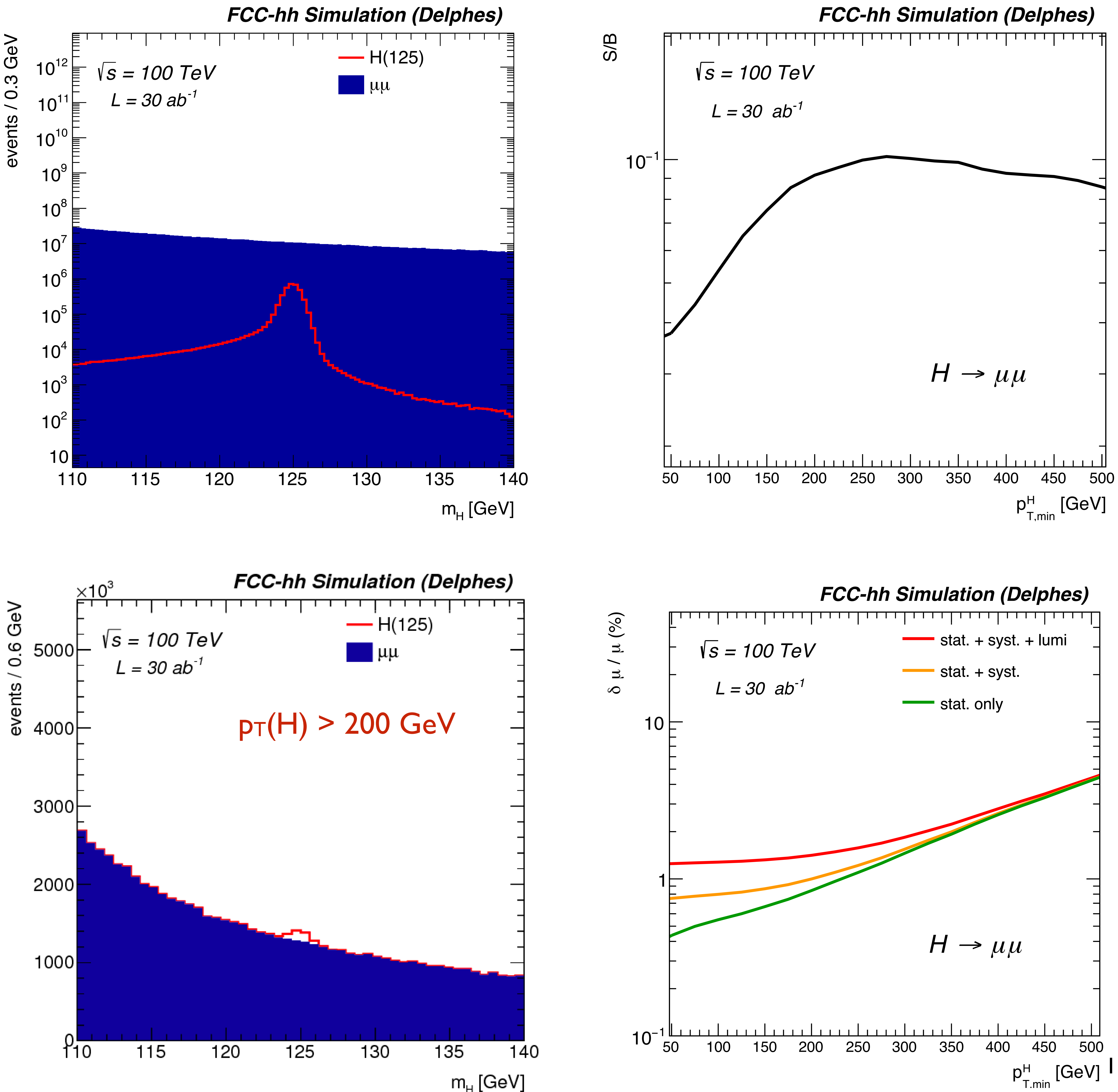
H → μμ

- Very small BR(H → μμ) ~ 2.18e-04,
  → %-level precision out of reach at FCC-ee

Analysis cuts

- $p_T(\mu) > 20$ GeV, $|\eta(\mu)| < 4.0$
- $|m_{\mu\mu} - m_H| < 1$ GeV

δμ/μ ≈ 1 % stat. precision
can be achieved up to $p_T(H) = 300$ GeV



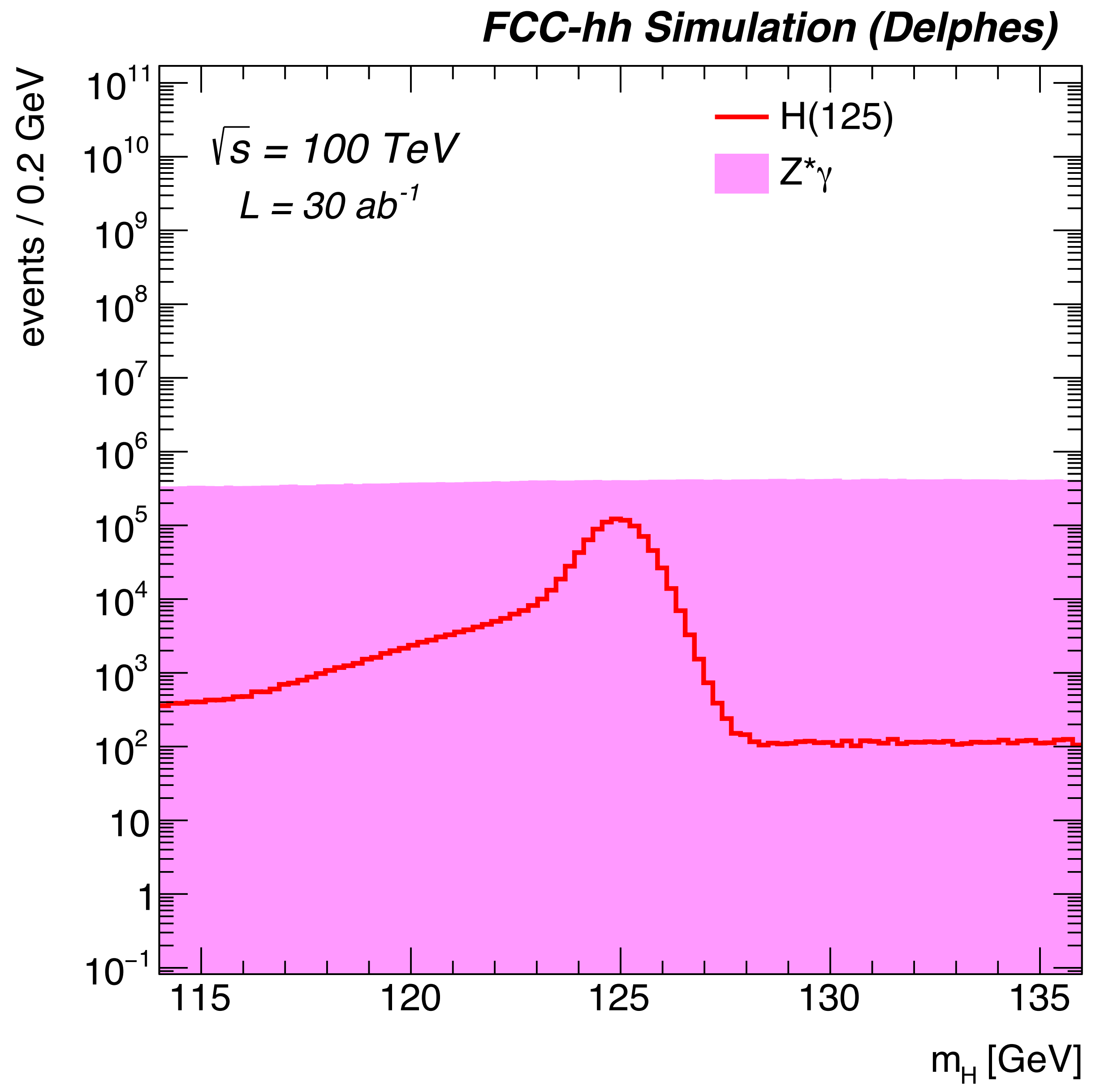
H → Zɣ → llɣ

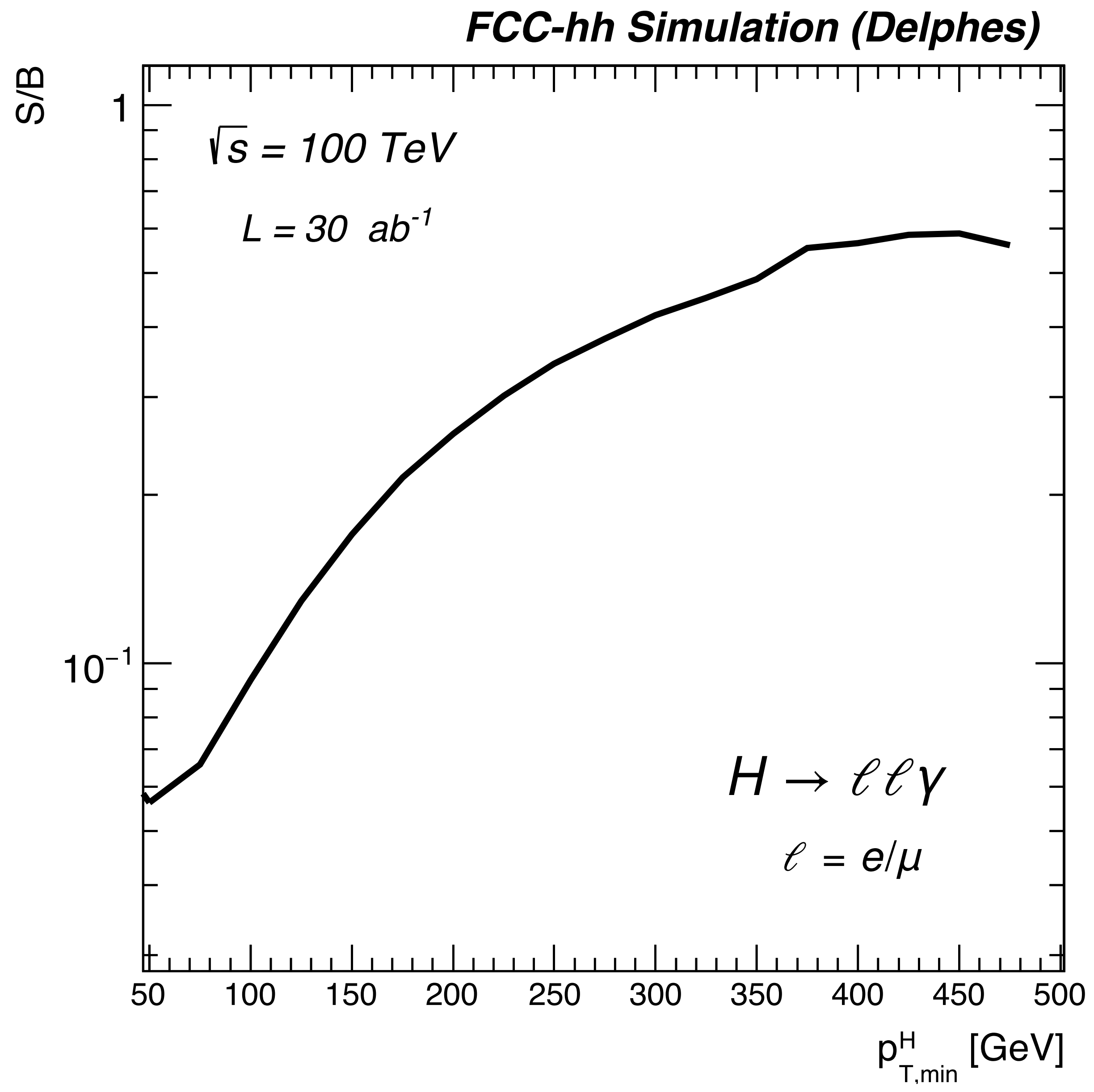
- BR(H → Zɣ*) ~ 1.5e-03,
- **irreducible**: Zɣ

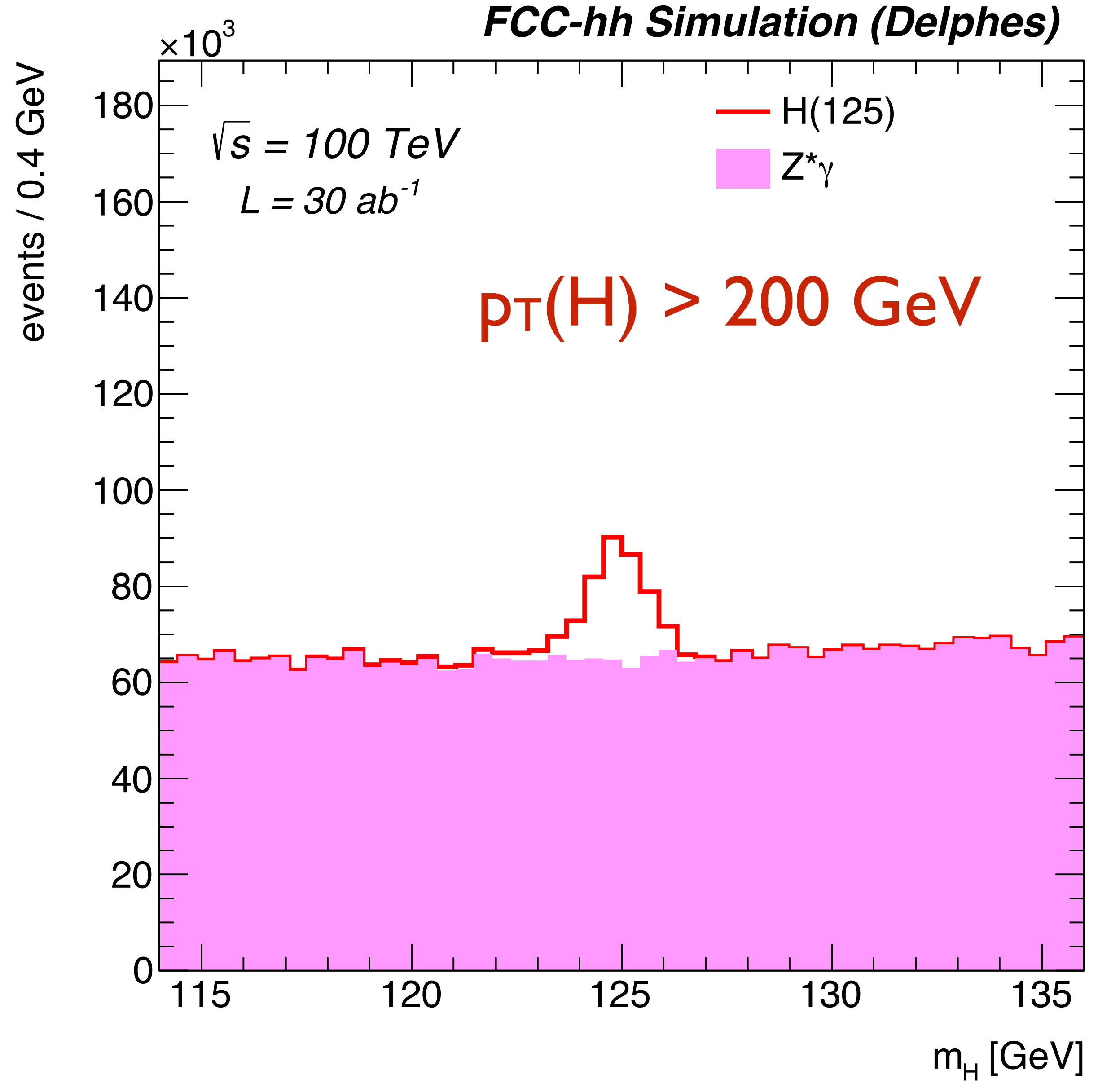
Simple cut and count strategy:

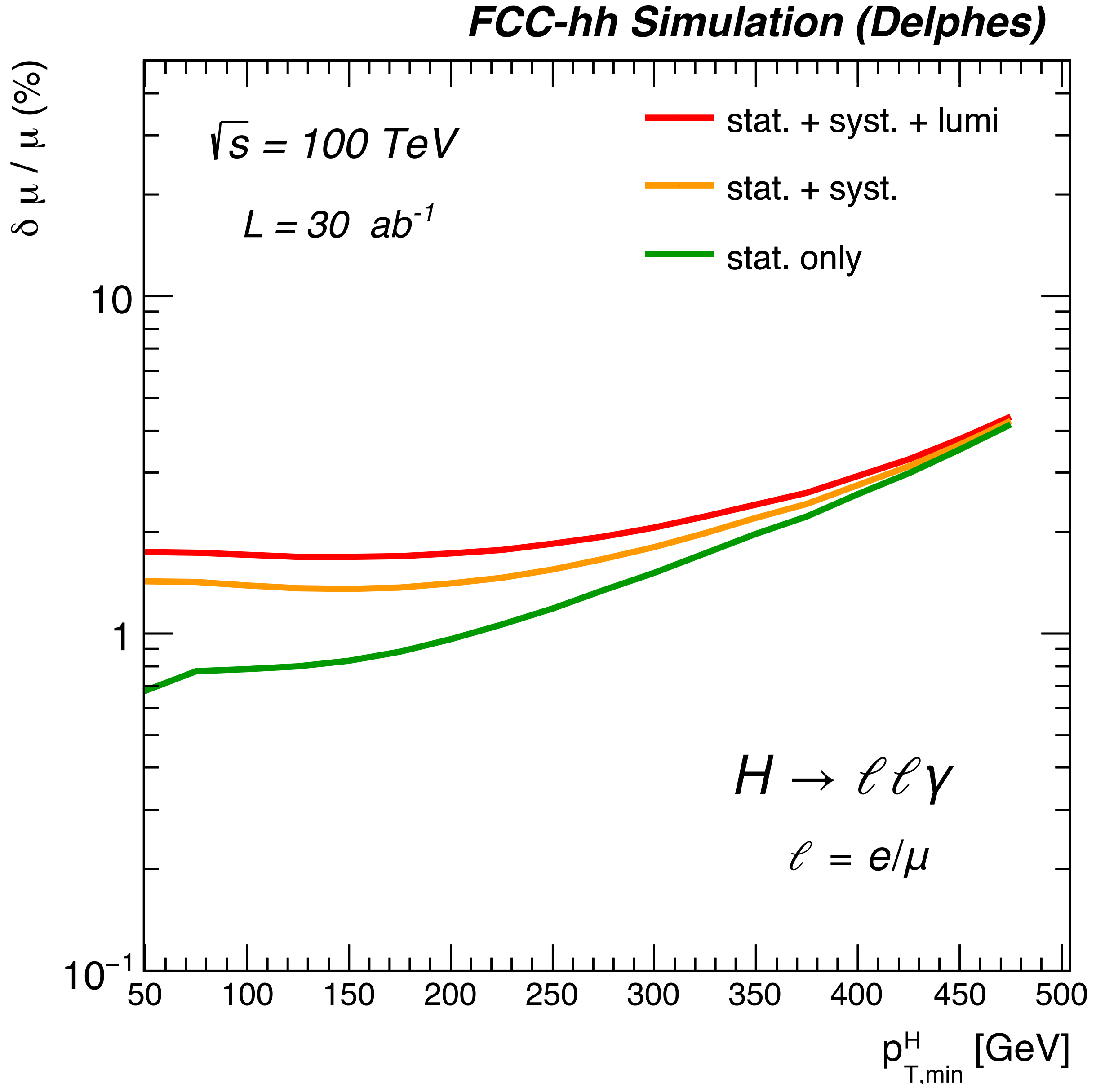
- $75 < m_{Zl} < 105.$
- $p_T(l) > 20$ GeV, $|\eta(l)| < 4.0$
- $p_T(\gamma) > 15$ GeV, $|\eta(\gamma)| < 4.0$
- $122.5 < m_{ll\gamma} < 127.5$ GeV

δμ/μ ≈ 1 % stat. precision
can be achieved up to $p_T(H) = 200$ GeV









Comments

- Statistics are so **large** (even for the rare decays) is most cases that the systematics (or lumi) wall (2-3% ?) for absolute measurement will be hit well before the full 20-30 ab^{-1} @100 TeV

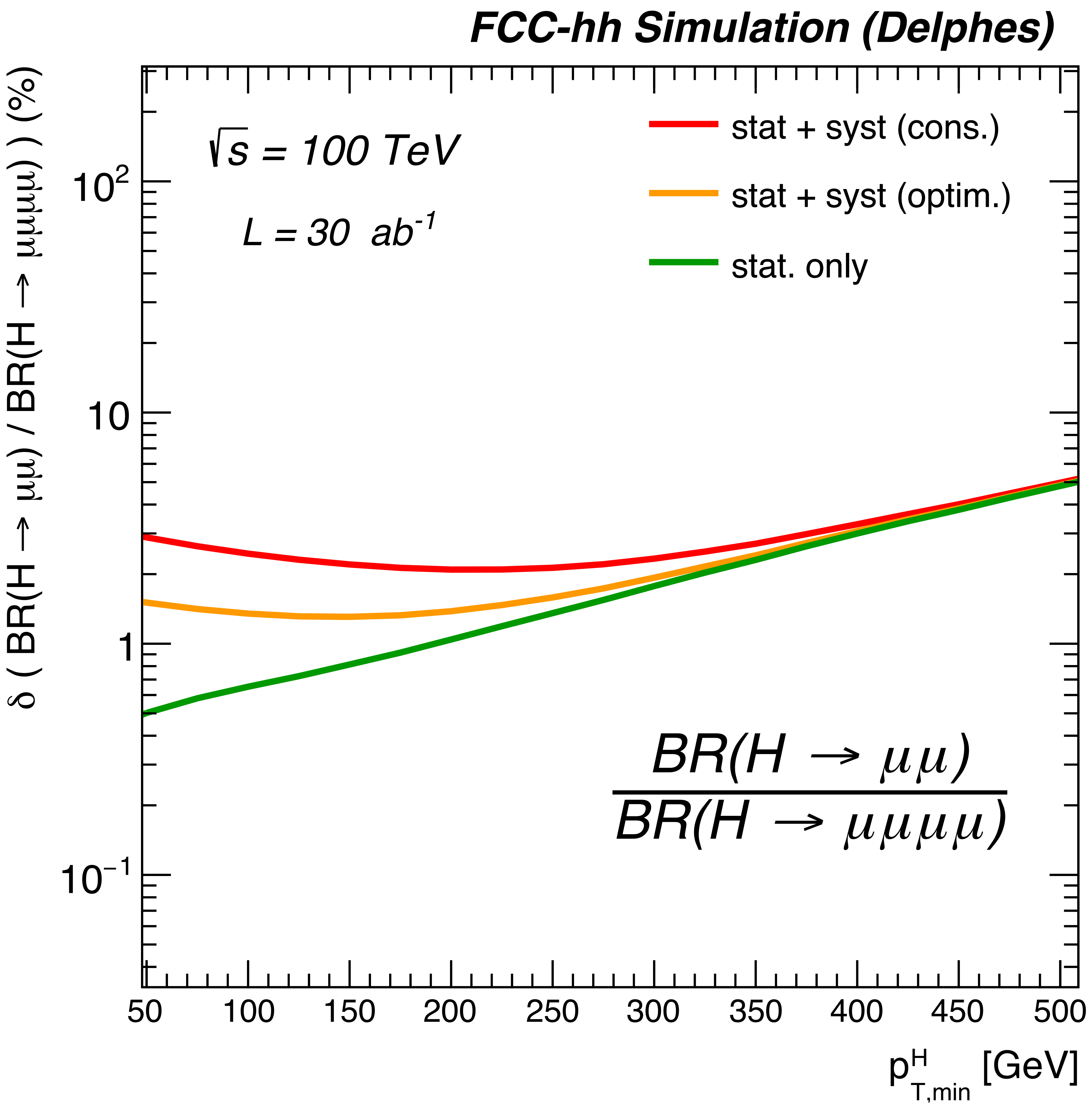
- In order to **cancel systematics** (from production, luminosity, etc..) a possibility is to **measure ratios of BRs**:

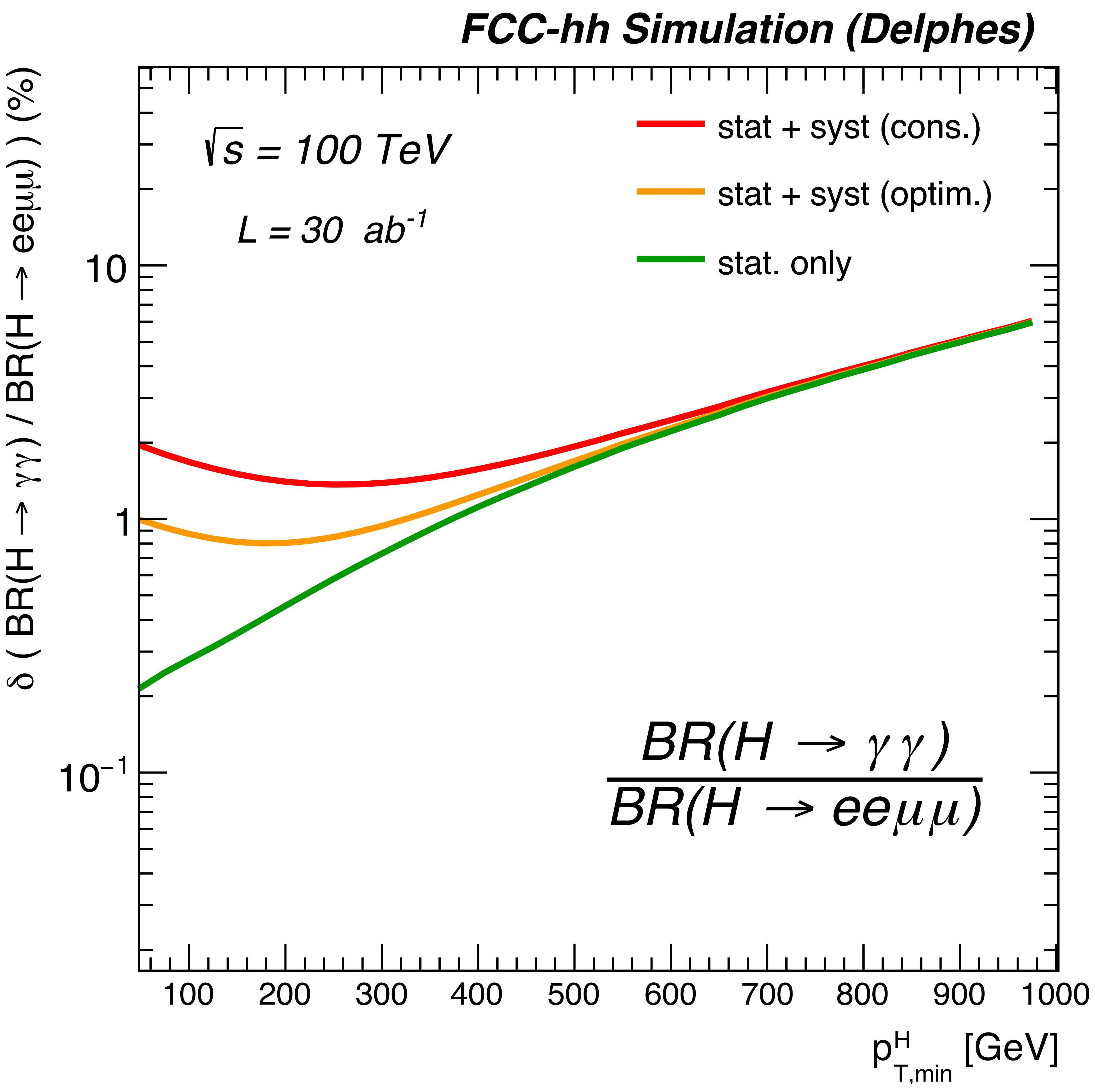
  - BR(μμ)/BR(4l) or BR(μμ)/BR(γγ)
  - BR(Zγ)/BR(4l) or BR(Zγ)/BR(γγ)

  → stat only **(sub)-percent precision can be reached** (provided absolute measurement given by Higgs factories)

  → assume we have good control of relative fraction of various production modes.

Ratios of BRs

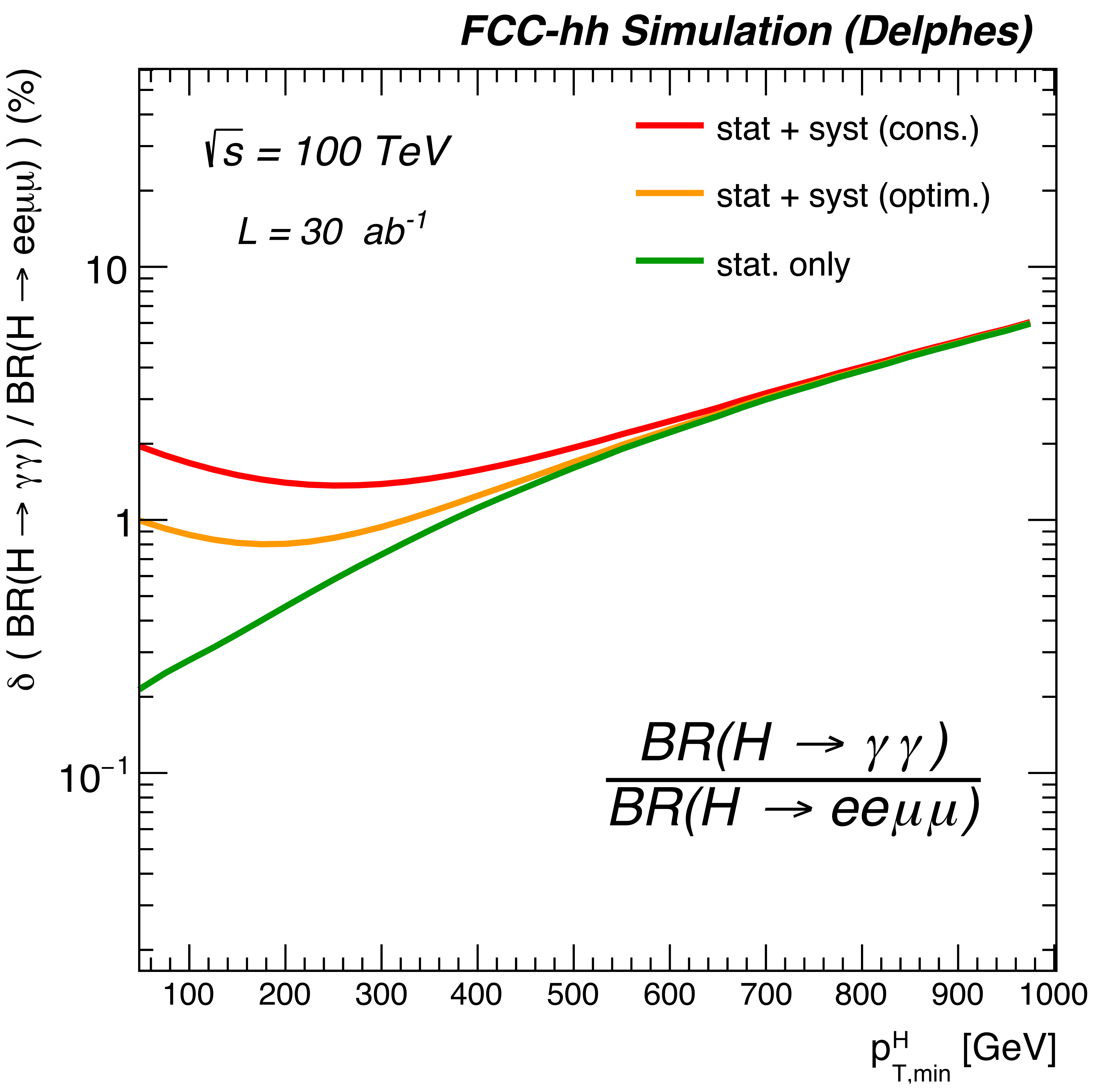


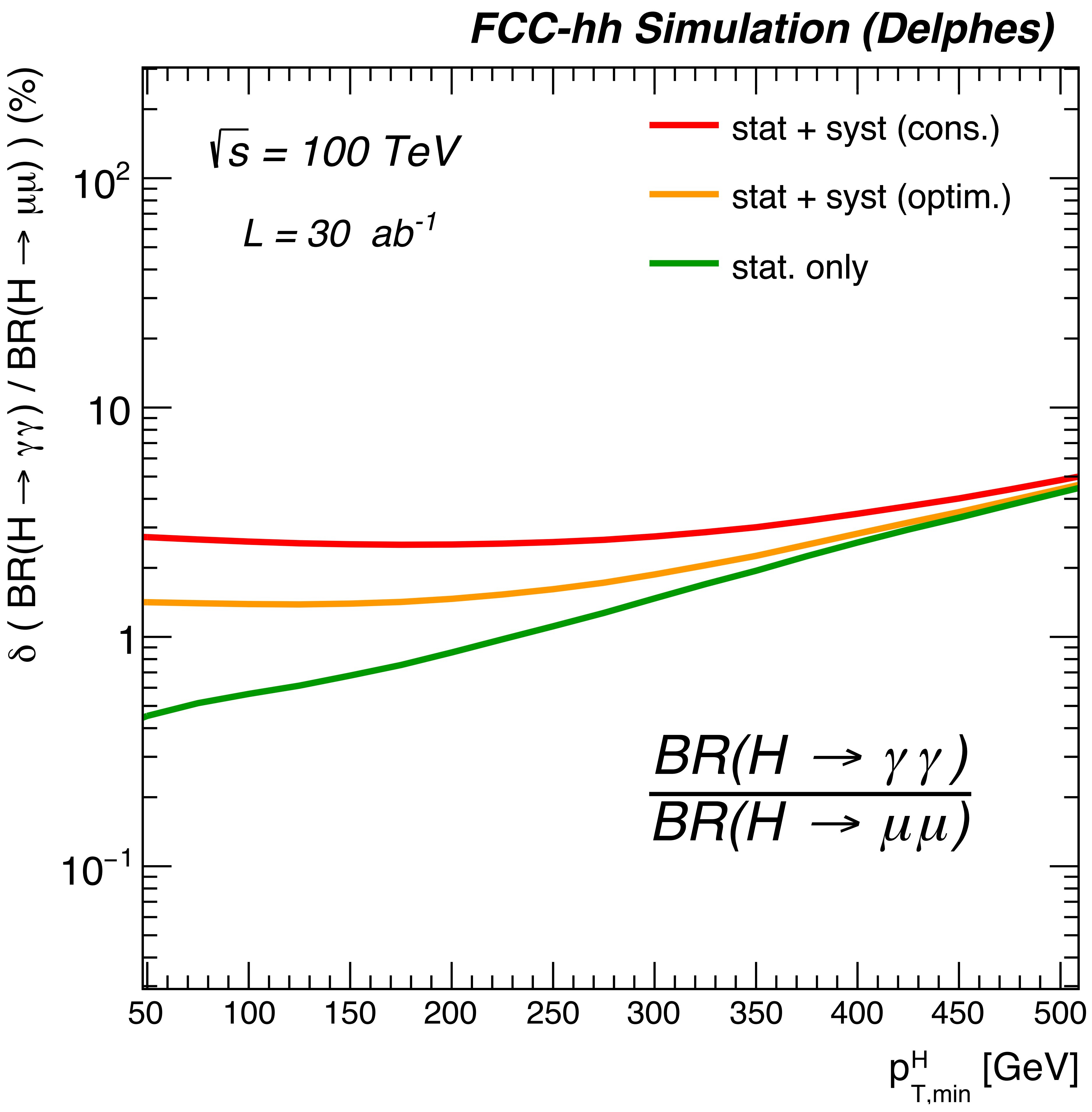


1 % **precision** (including systematics) within reach

- assumes 100% between e,ɣ systematics
- 1 % **precision** (including systematics) within reach

Ratios of BRs





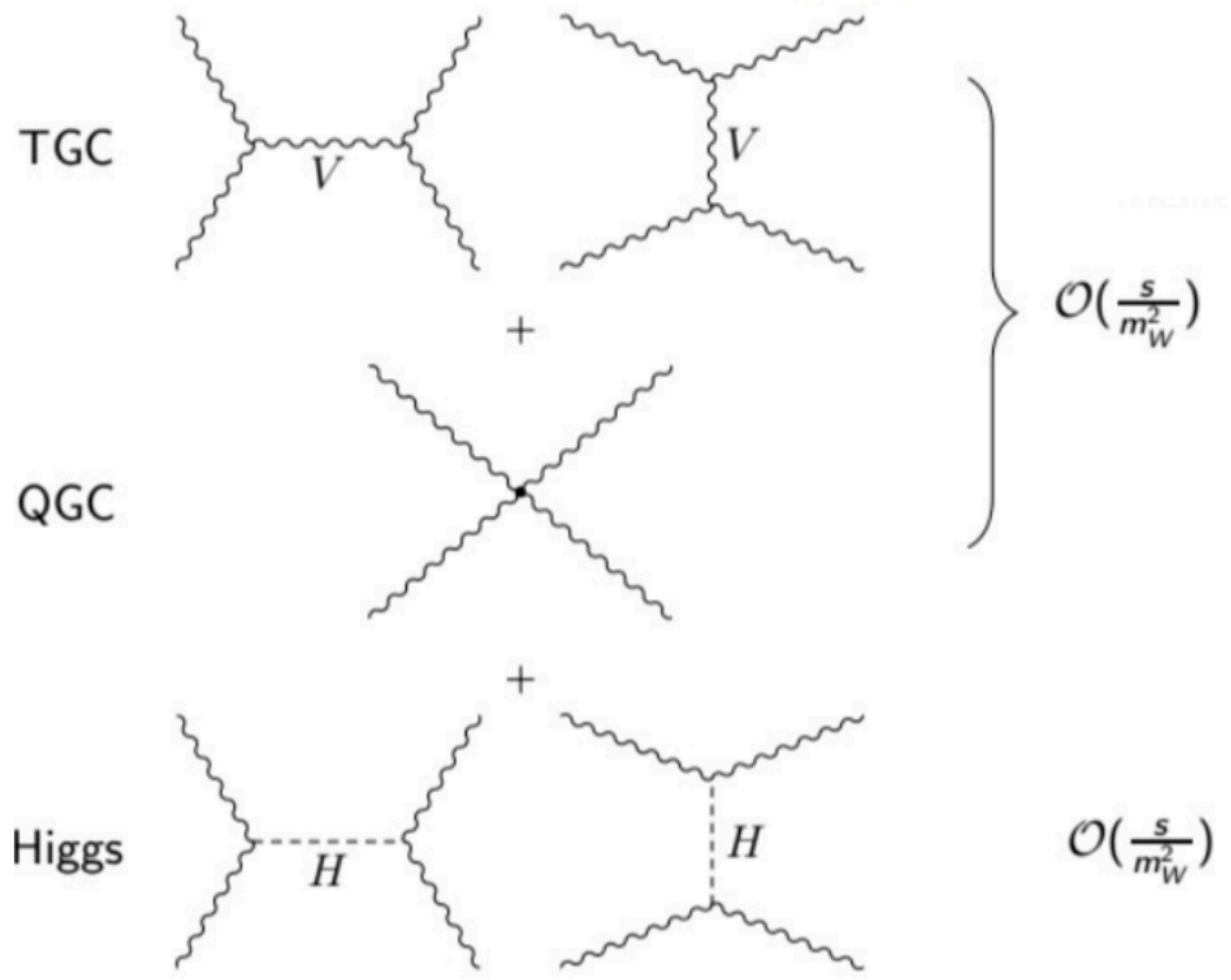
1 % precision (including systematics) within reach

VBS

- A Higgs of 125 GeV has been observed at LHC but new physics may still be hidden in EWSB

- Energy growth of (TGC+QGC) is tamed by HIGGS exchange !

- New physics could disturb this delicate unitarity balance involving longitudinally polarized VBS → rate increase



VBS

- VVjj cross sections , EWK contribution only (mJJ > 500 GeV)

  - $W^\pm W^\pm jj \rightarrow 2l2\nu jj \approx$ 146 fb (small "QCD" contribution)
  - $ZZjj \rightarrow 4ljj \approx$ 27 fb (large "QCD" contribution x4 here)

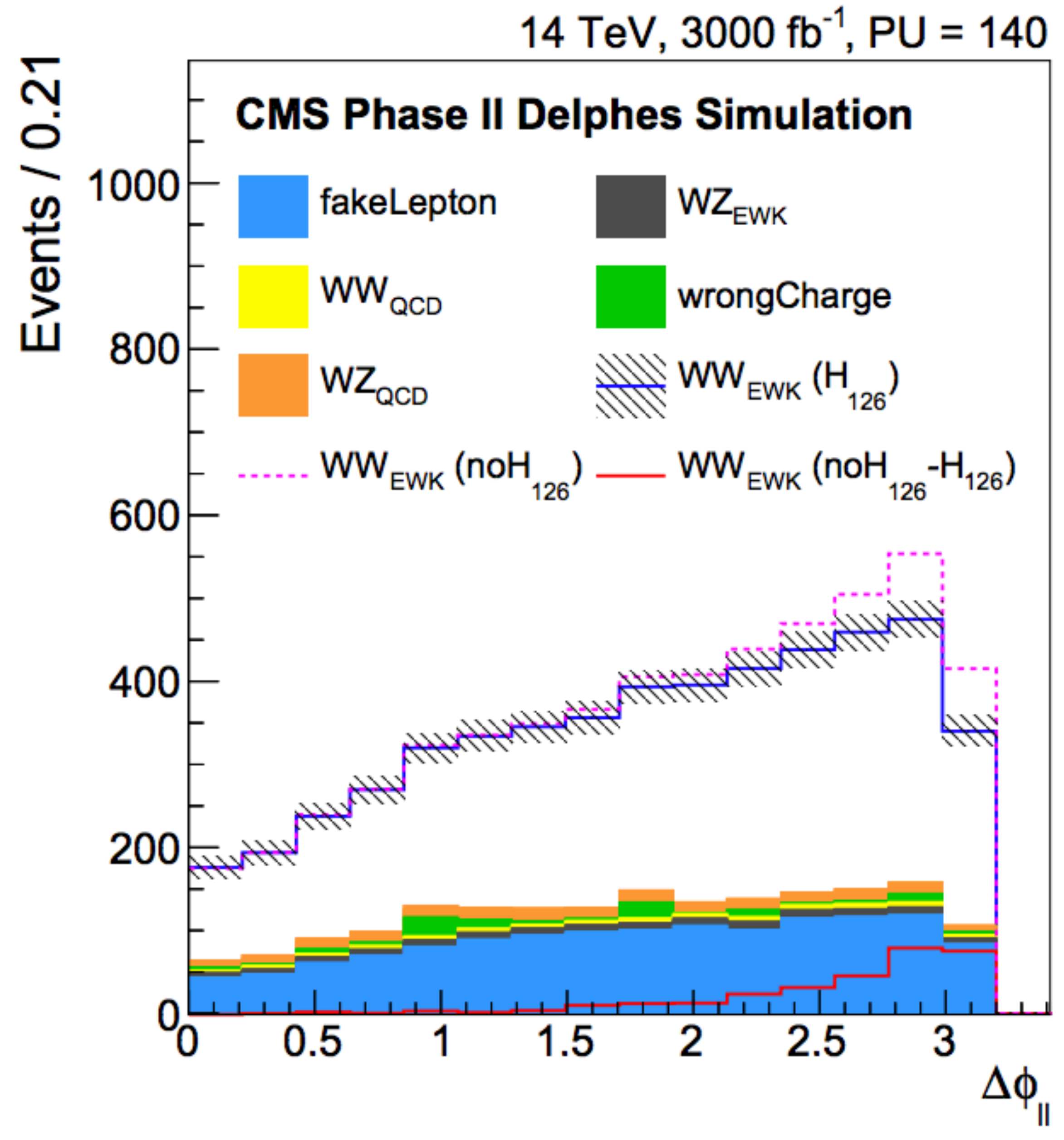
Assessments on the expected precision for:

- VBS cross section in **$W_LW_L \rightarrow 2l2\nu$** (same sign) and **$Z_LZ_L \rightarrow 4l$**

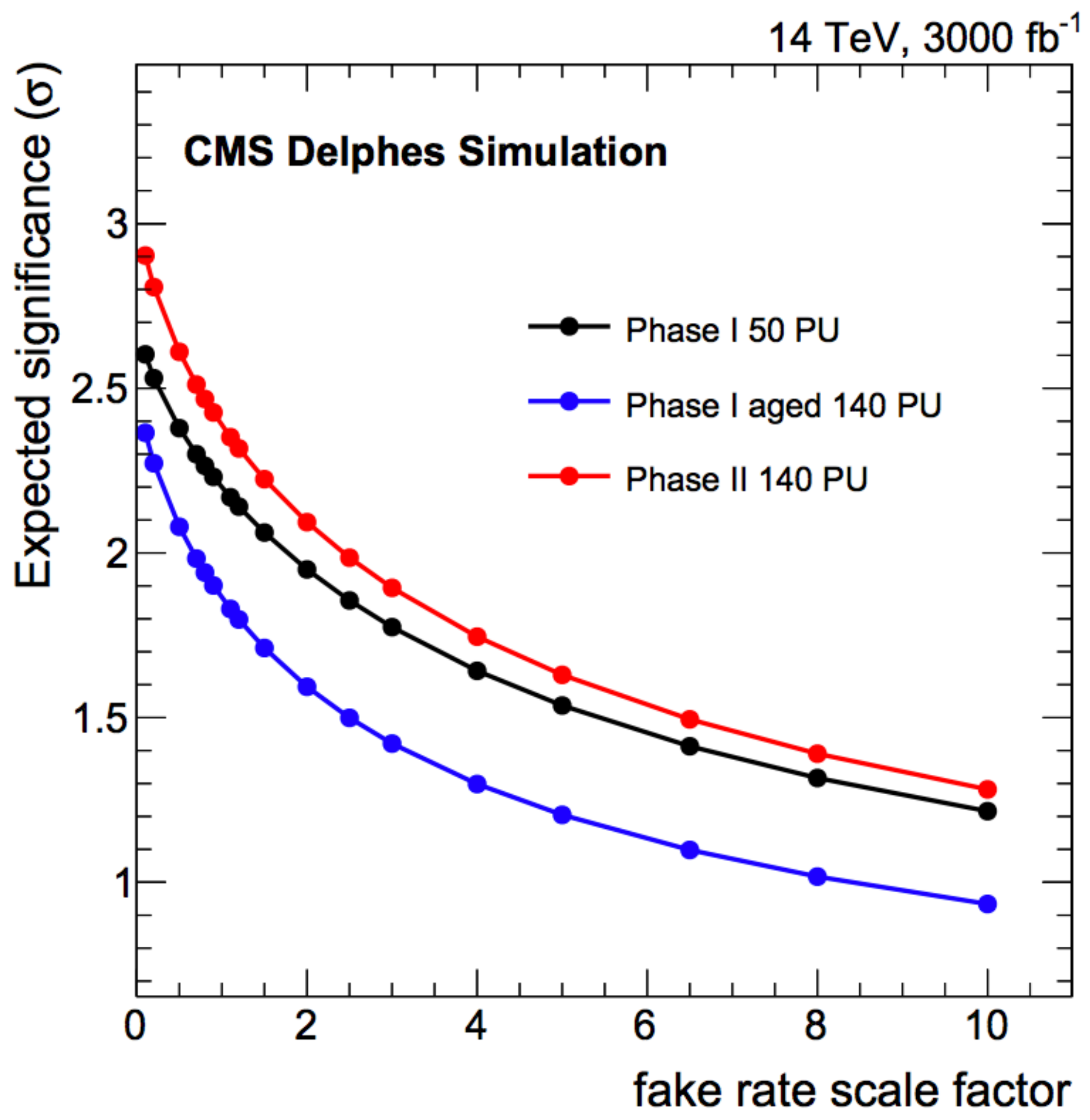
- **Discovery potential** for longitudinal scattering

- Very crude (PRELIMINARY) statistical estimate of the sensitivity:

  - assume V_TV_T and V_TV_L are known and are background, together with QCD VVjj
  - compute **stat. significance of V_LV_L signal**



CMS CR -2015/219

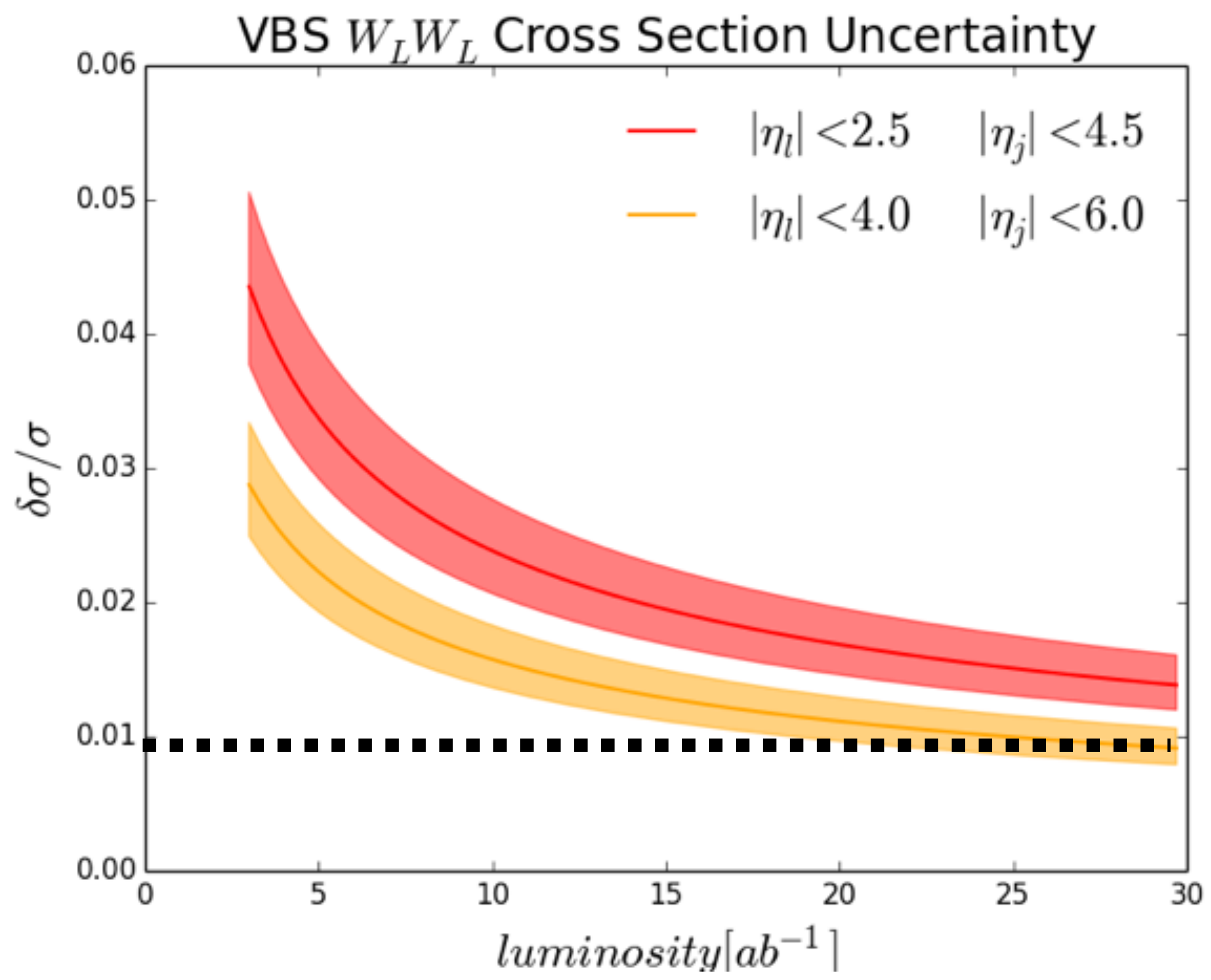


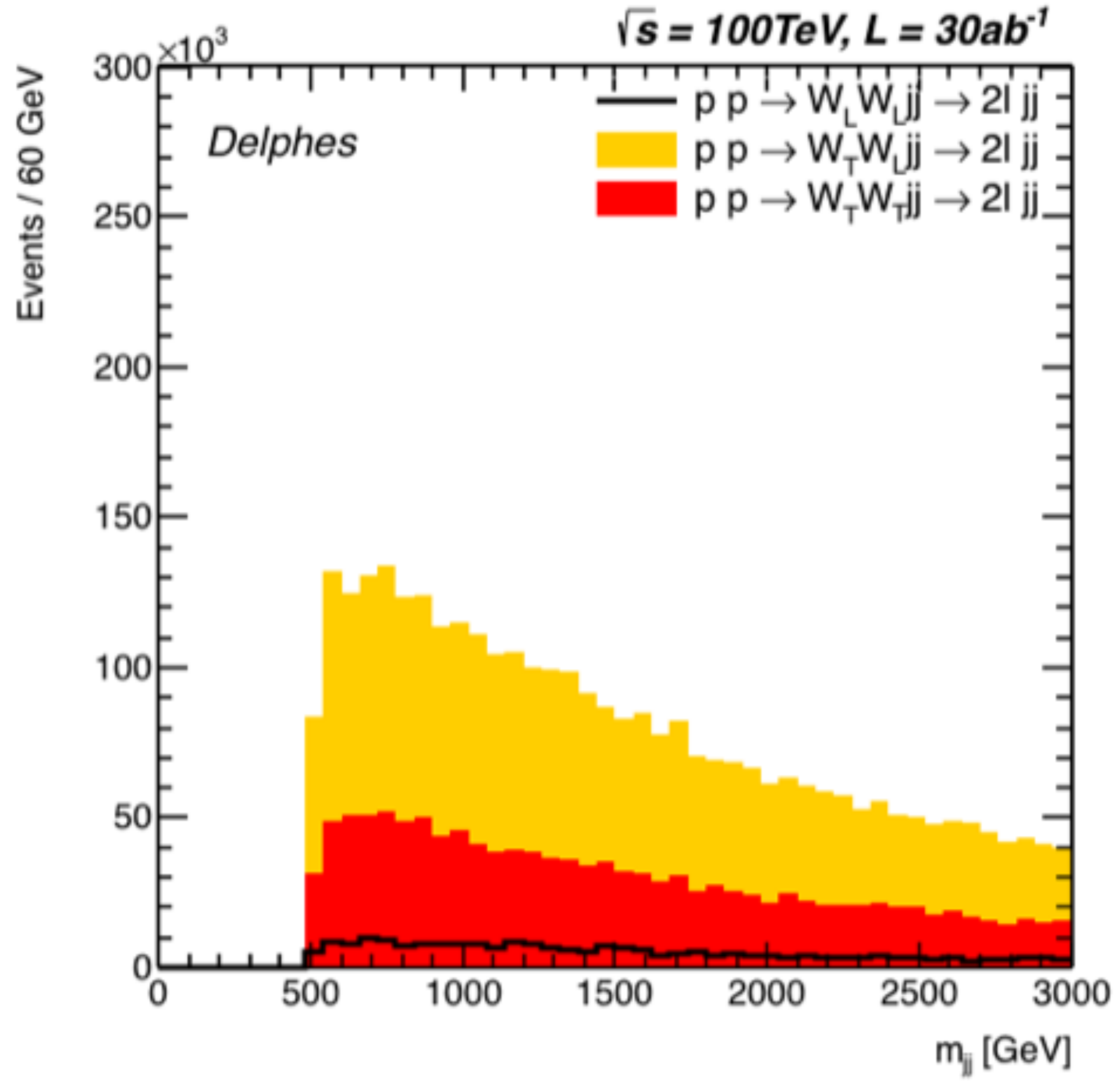
VBS (WW same sign)

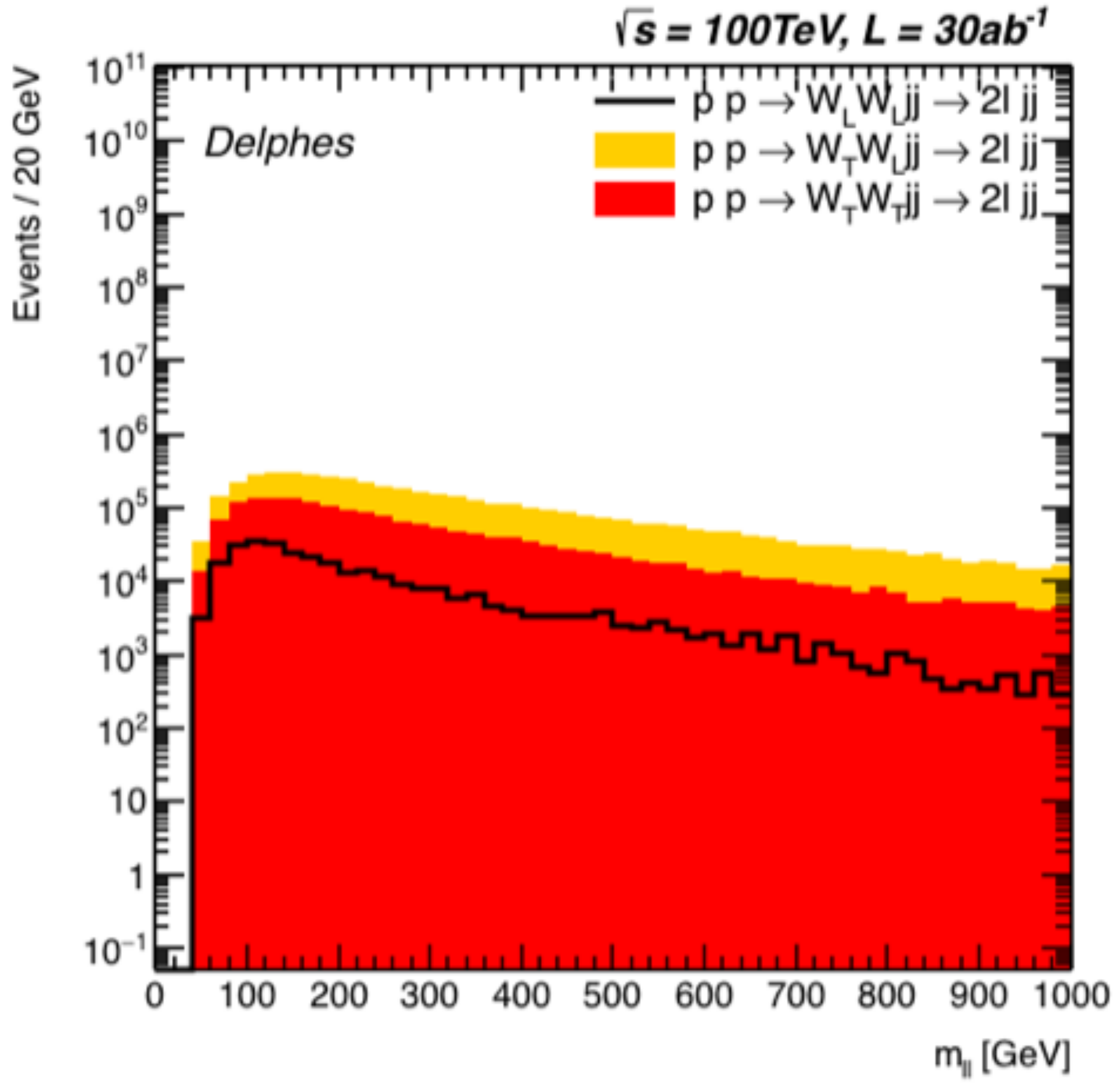
Simple cut and count strategy:

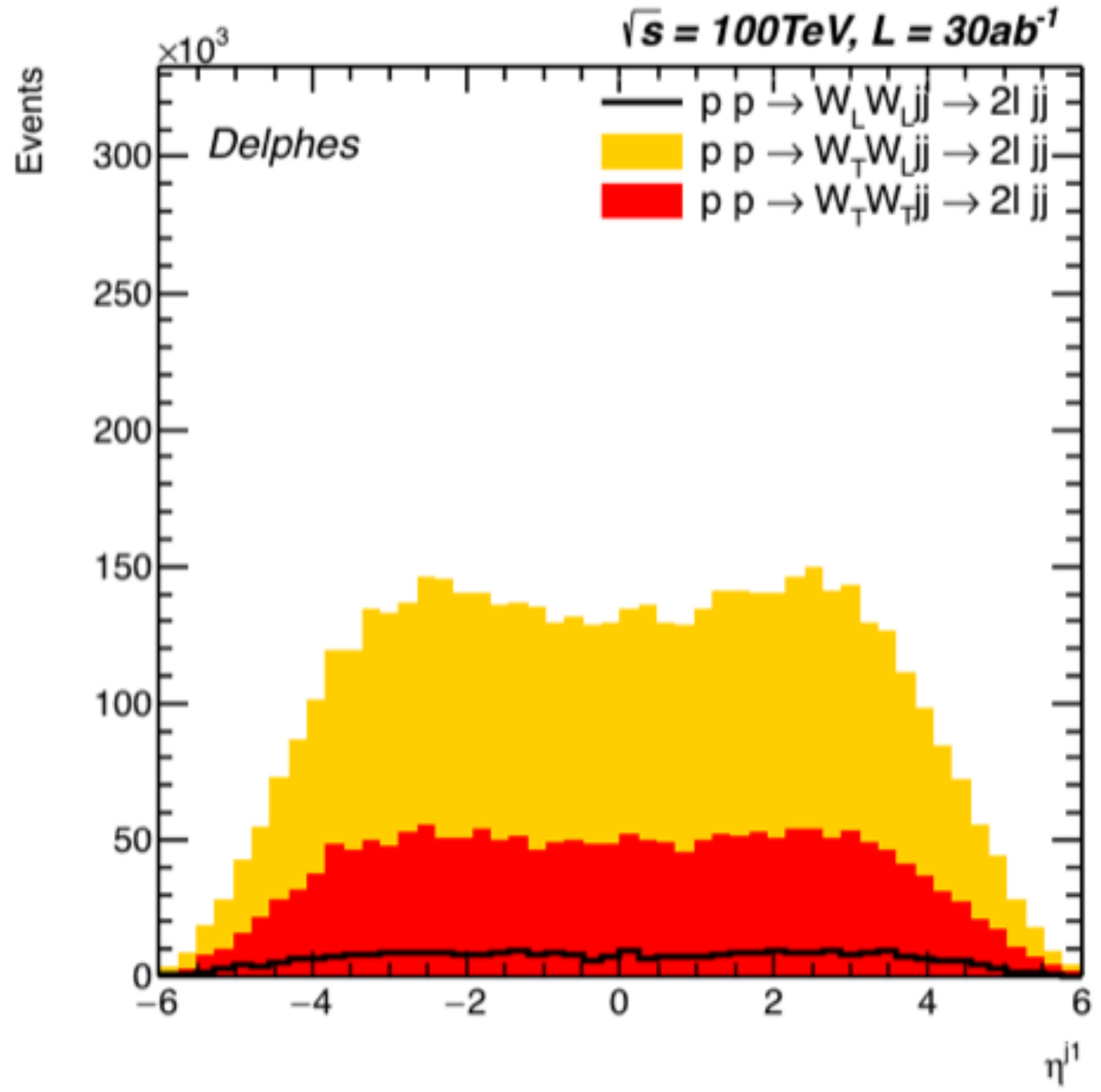
- $p_T(l) > 20$ GeV, $|\eta(l)| < 4.0$
- $p_T(j) > 30$ GeV, $|\eta(j)| < 6.0$
- $\Delta\eta(j,j) > 2{,}5$
- $m(j,j) > 500$ GeV

$\delta\mu/\mu \approx 1$ % stat. precision







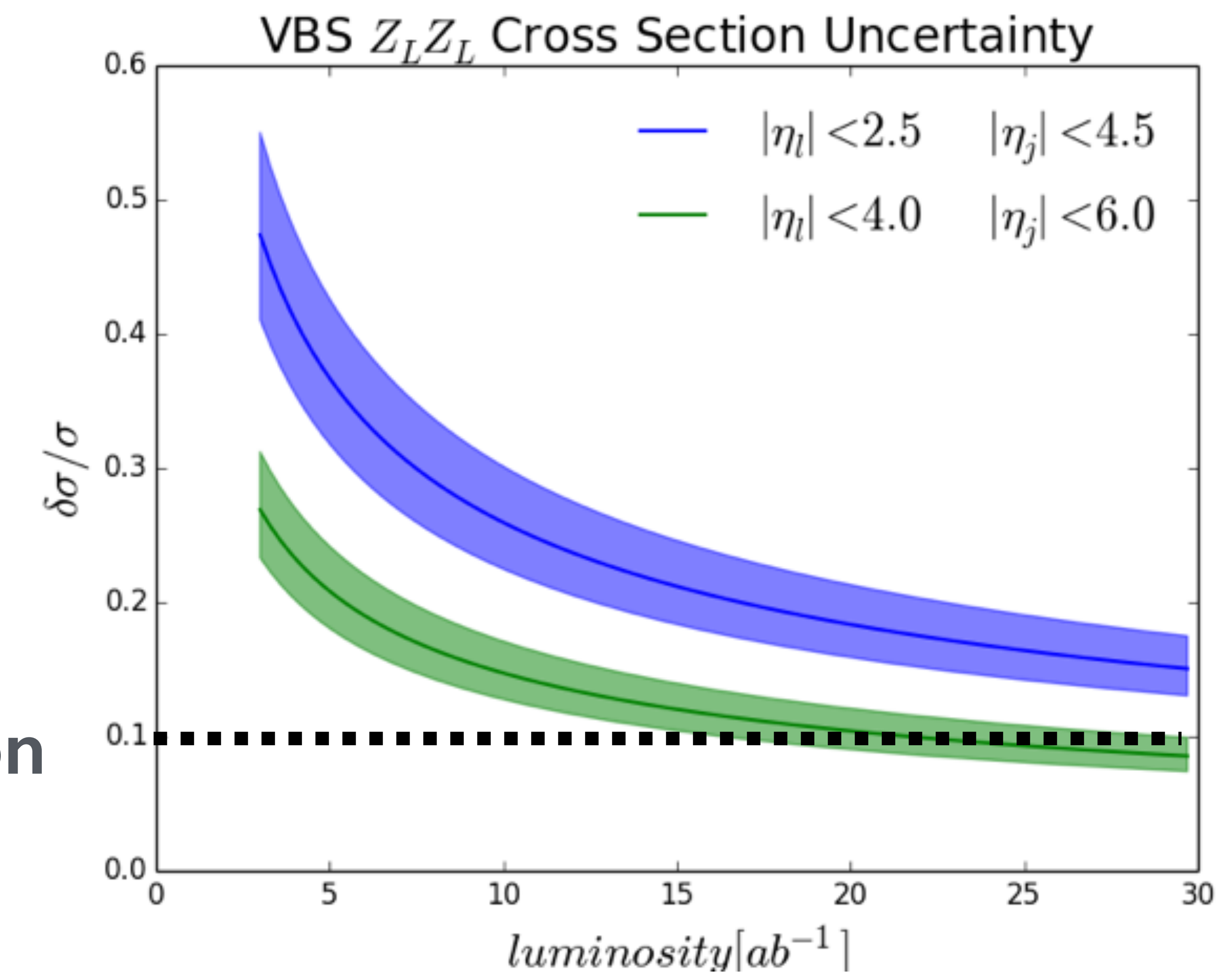


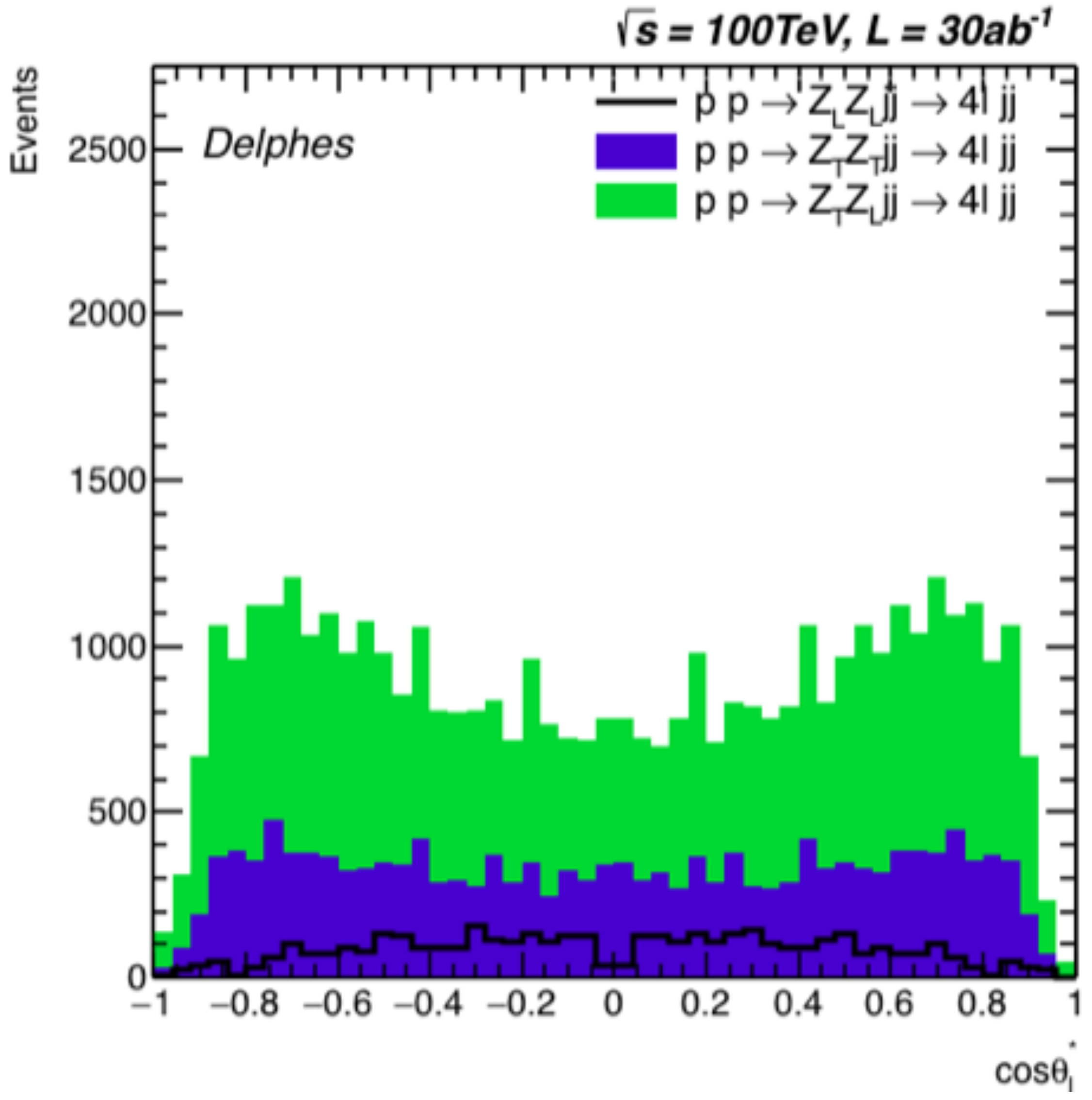
VBS (ZZ)

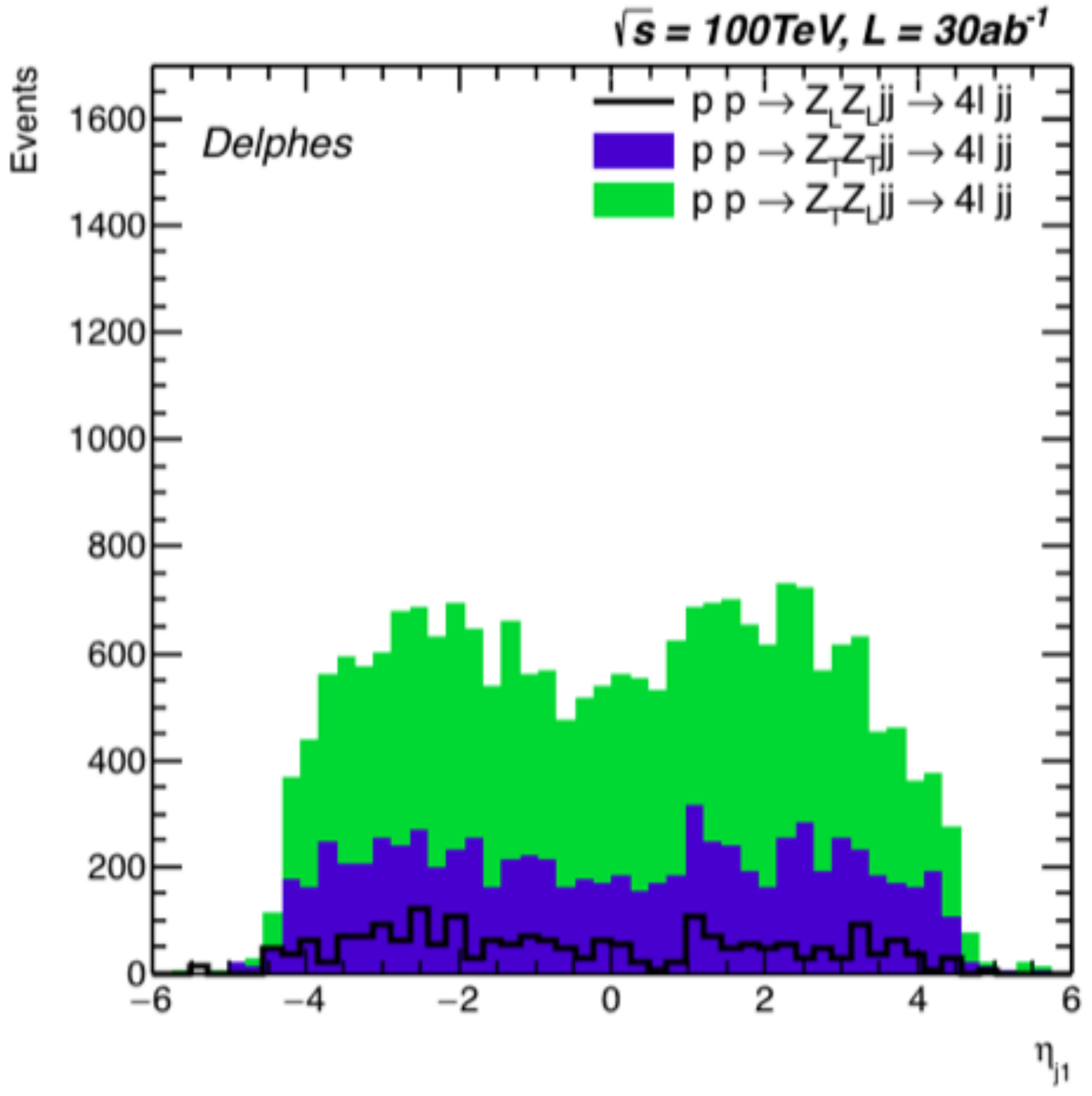
Simple cut and count strategy:

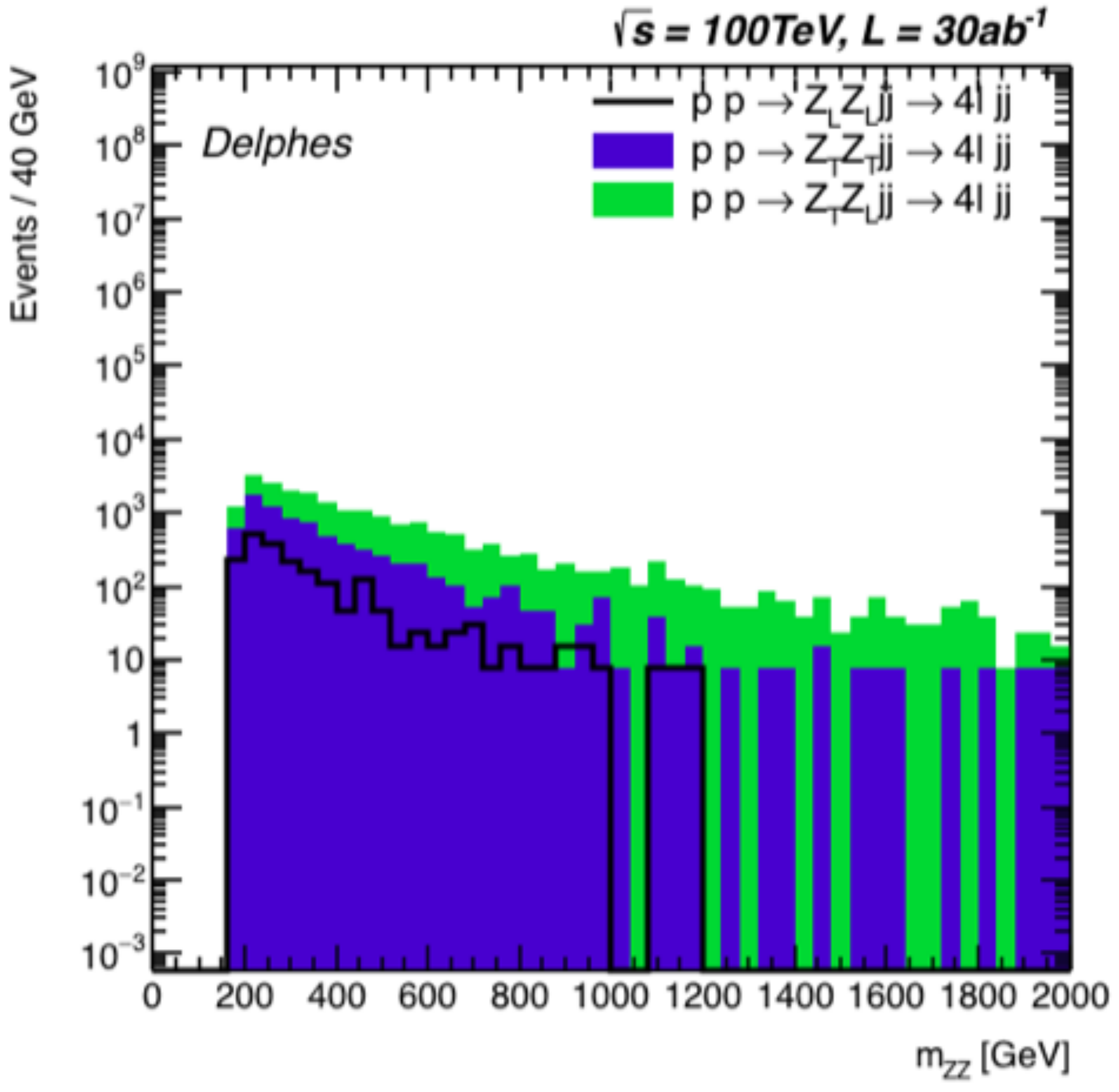
- $p_T(l) > 20$ GeV, $|\eta(l)| < 4.0$
- $p_T(j) > 30$ GeV, $|\eta(j)| < 6.0$
- $\Delta\eta(j,j) > 3.5$
- $m(j,j) > 1000$ GeV

$\delta\mu/\mu \approx 10$ % stat. precision









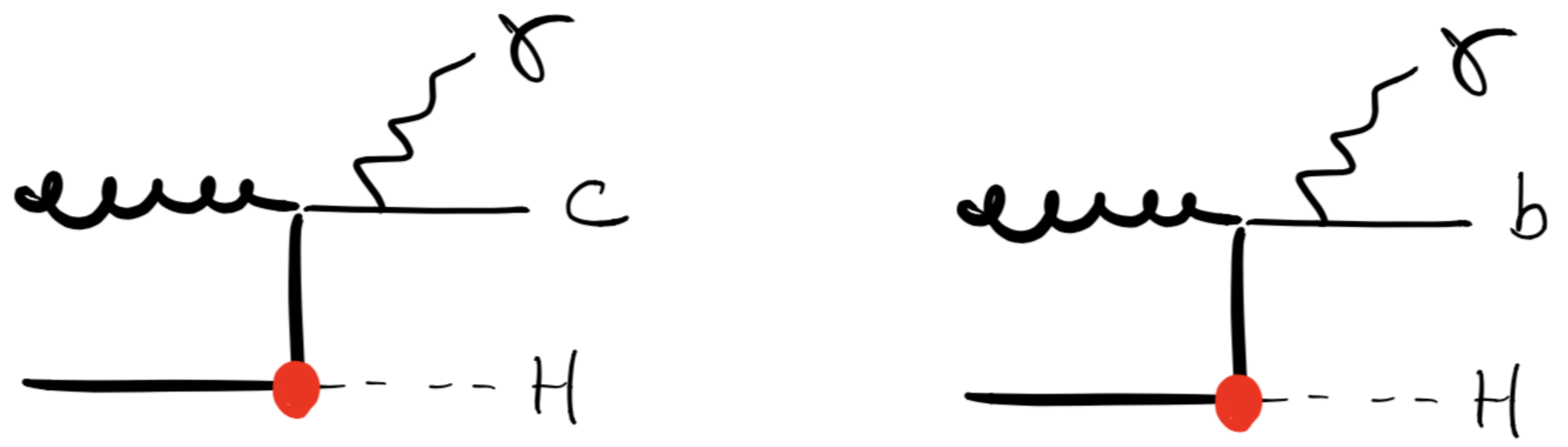
Conclusions & outlook

- The FCC-hh machine will produce > 10^{10} **Higgs bosons**
- Such **large statistics** open up a whole new range of possibilities
- First look at some Higgs **decay channels** was presented using **fast detector simulation** and simple **cut and count** analysis
- Measuring **ratios of couplings** (or equivalently BRs), allows to cancel systematics (1% precision on "rare" couplings within reach after absolute HZZ measurement in e+e-)
- VBS longitudinal polarisations $V_L V_L$ can be measured at 1% level ($W_L W_L$ same sign) and 10% ($Z_L Z_L$)
- Extremely rich Higgs program at the FCC, that goes much beyond (light yukawa, Higgs off-shell width measurement, Higgs differentials)

Backup

Charm and light yukawa

- Probe in production:
  - Charge (charm) = Charge (bottom)



- Exclusive H → J/ψ γ decay (J/ψ → μμ)

- VH → ll cc

Mode / Method	Branching Fraction $[10^{-6}]$ NRQCD [171]	LCDA LO [170]	LCDA NLO [173]
$\mathrm{Br}(H \to \rho^0 \gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(H \to \omega \gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(H \to \phi \gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\mathrm{Br}(H \to J/\psi\, \gamma)$	$2.79\,^{+0.16}_{-0.15}$	–	2.95 ± 0.17
$\mathrm{Br}(H \to \Upsilon(1S)\, \gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(H \to \Upsilon(2S)\, \gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(H \to \Upsilon(3S)\, \gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$