Higgs Properties

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UK ESU meeting Durham, April 2018

Peter Reid, University of Edinburgh

- ***Notes for reviewers***
- The workshop is a UK national workshop to discuss UK input to the European Strategy Update.
- I will be presenting “Higgs Properties”
    - there is another presentation on “Higgs Couplings” that will cover couplings to leptons, bosons and triple-Higgs-couplings
    - I will cover measurements of mass, width, spin, CP and rare decays
- Measurements at HL-LHC, HE-LHC and future ee, pp & ep machines
- Previous presentations have already presented the future collider options and discussed some aspects of Higgs boson theory

Disclaimers

- (Proto-)experiments have not investigated every their potential to measure every Higgs property. Many studies are still underway.
- **LHC**:
  - ➡ Generally results include an estimate of systematic effects
  - ➡ Most HL-LHC results presented are for one-experiment, expect $\sqrt{2}$ improvements for ATLAS+CMS.
  - ➡ ATLAS+CMS will extrapolate current Run 2 results for a Yellow Report at the end of this year
  - ➡ I didn't find any projections for HE-LHC
- Future experiments: I**LC, CLIC, FCCxy**
  - ➡ Most important is the projectiles, energy & luminosity
  - ➡ some are generator-level studies
  - ➡ systematic effects generally not estimated: statistical errors only
  - ➡ I've not looked for CEPC projections

What we want to know!

Is our 125 GeV Higgs boson the Standard Model Higgs boson?

If not, what is it?

Mass

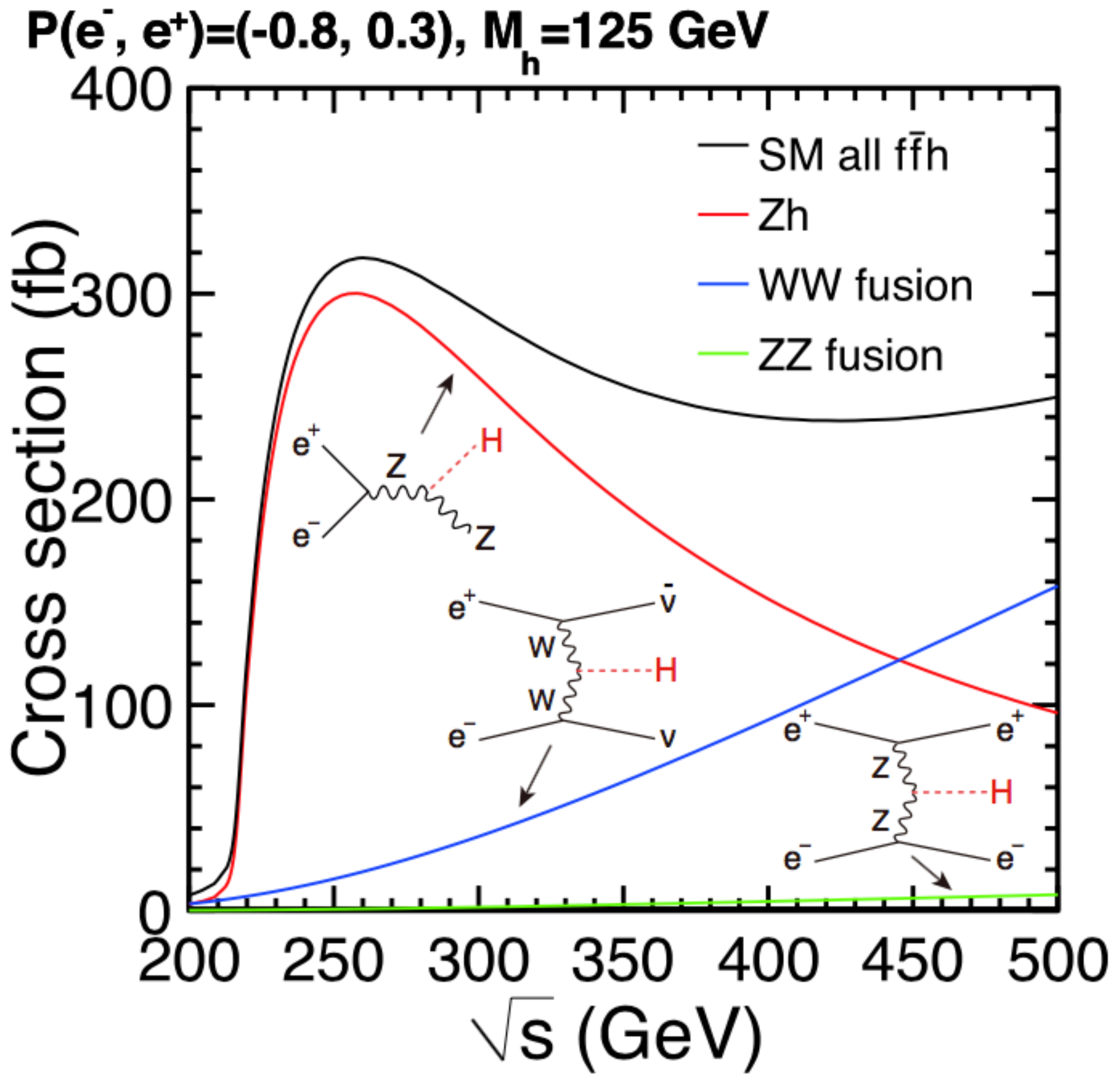
Width

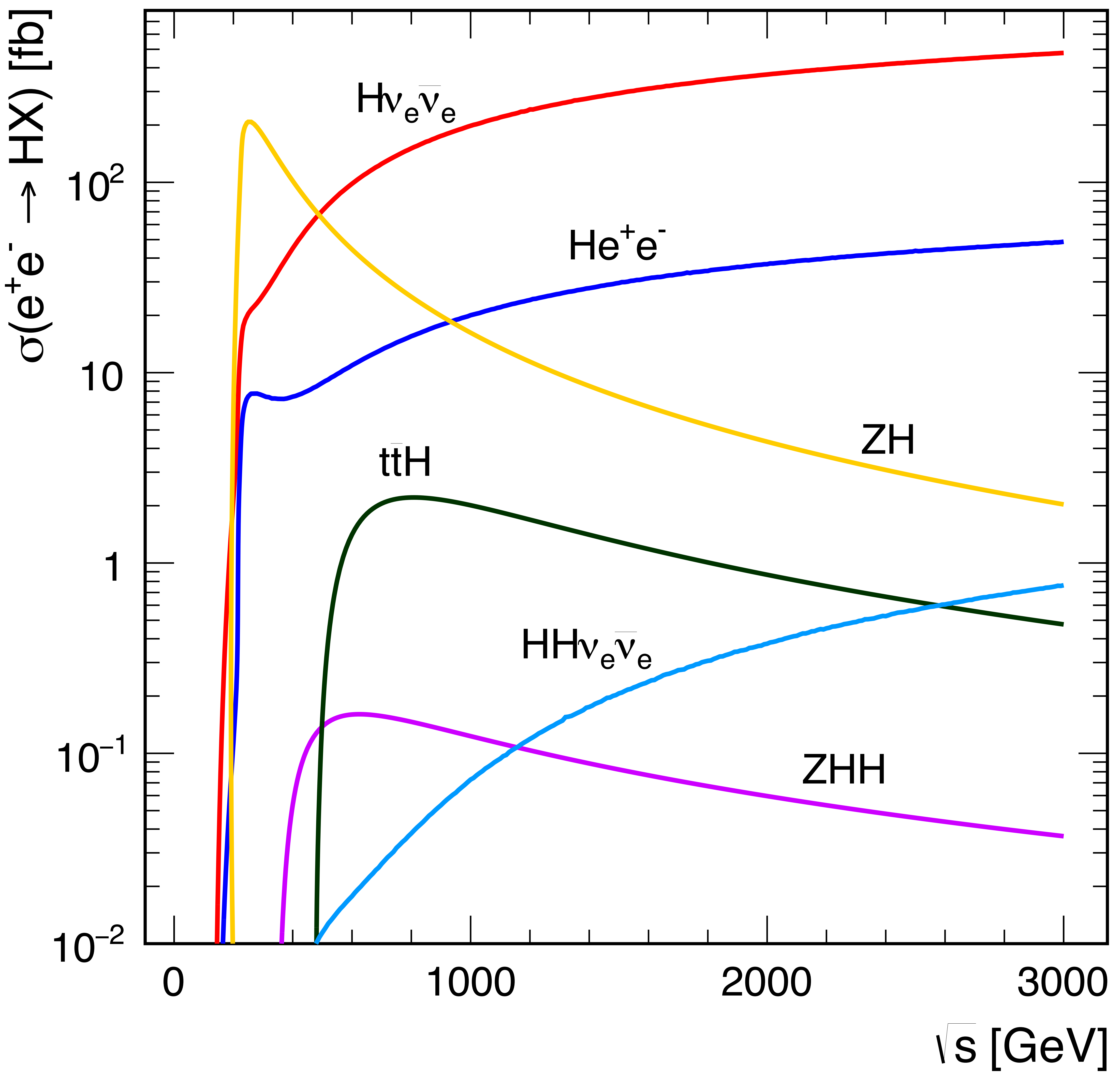
Spin / CP

Rares decay

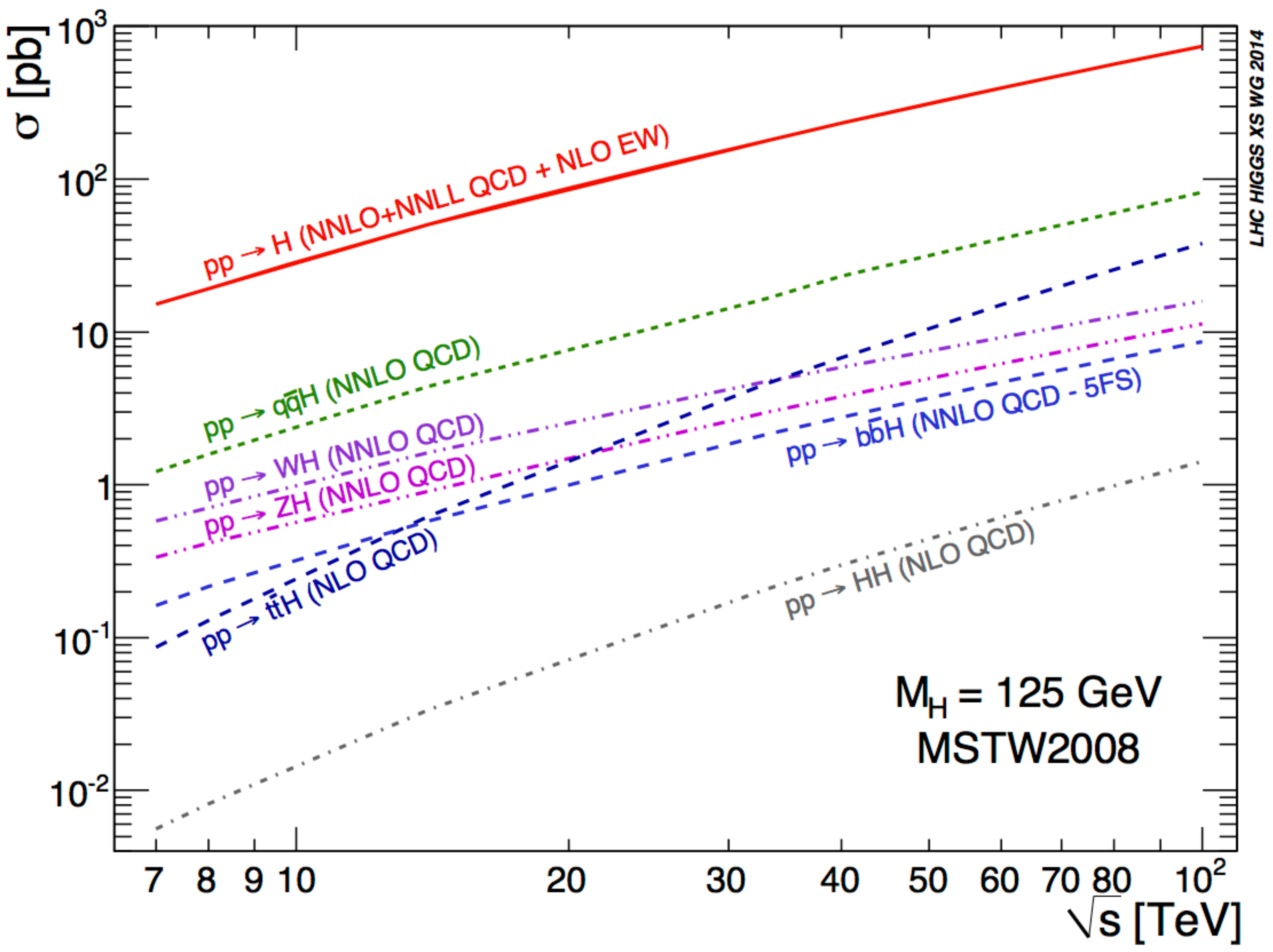
Differential Cross Sections

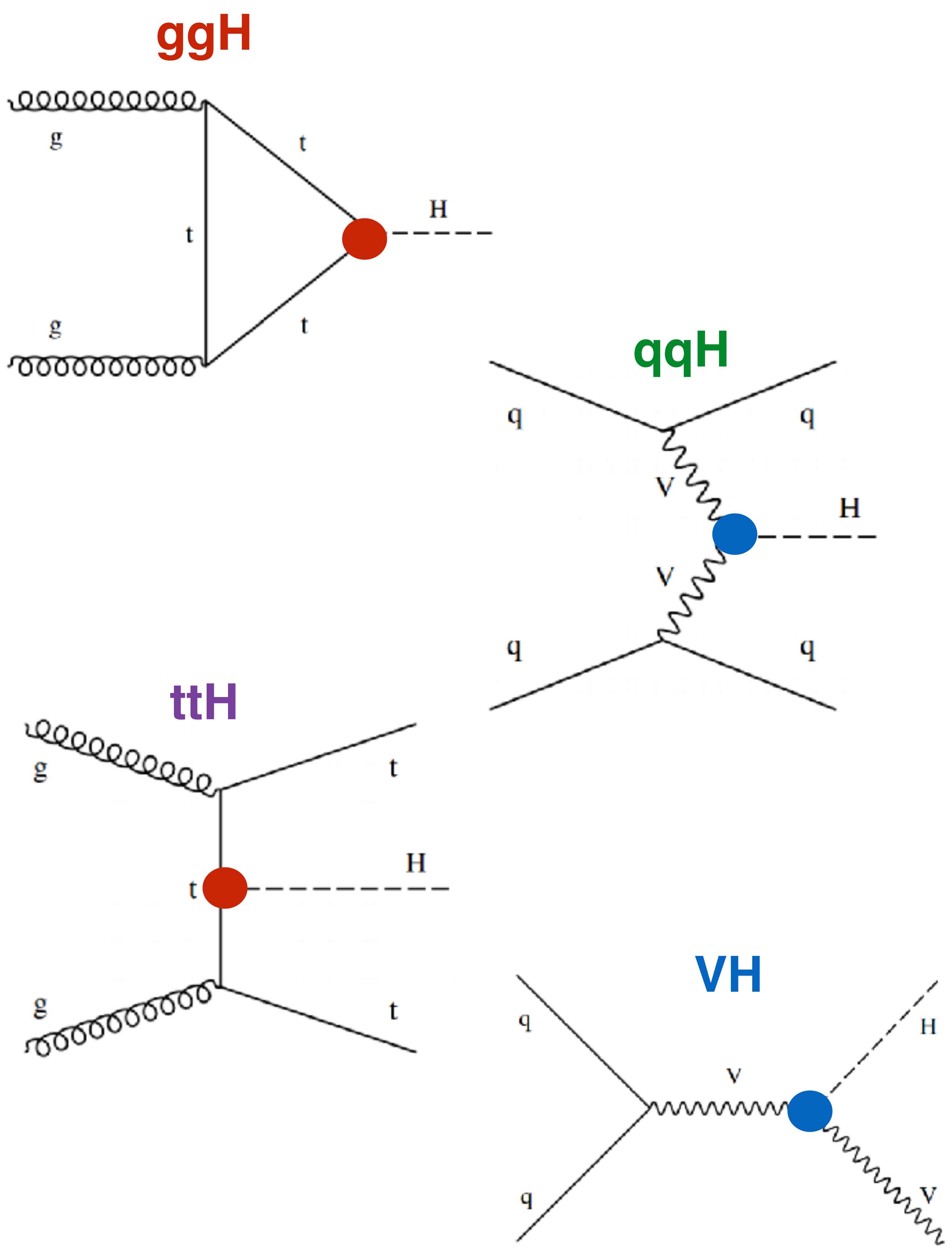
Higgs boson cross sections: e^+e^-

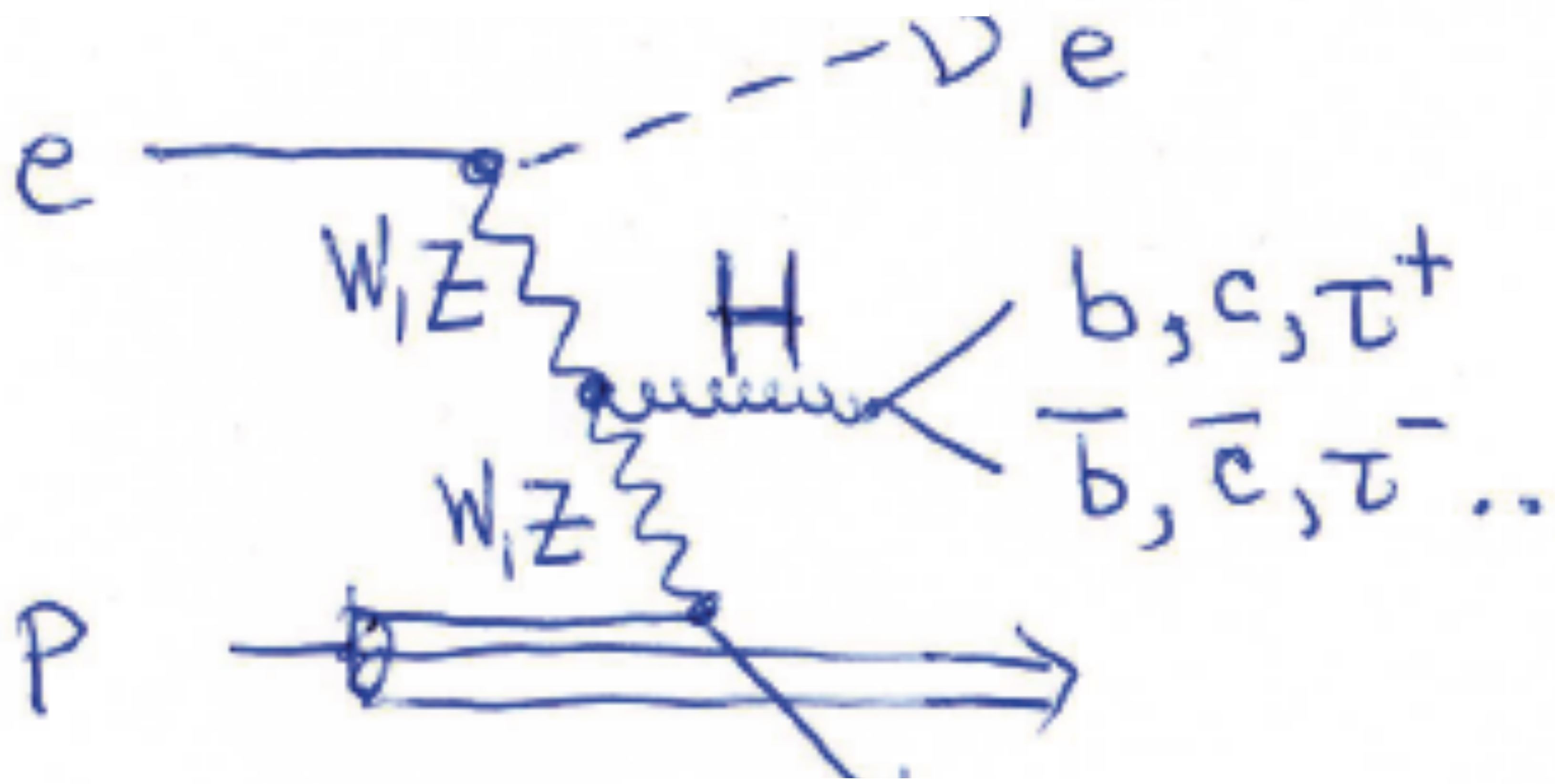




Higgs boson cross sections: *pp*







ep→HXν, HXe

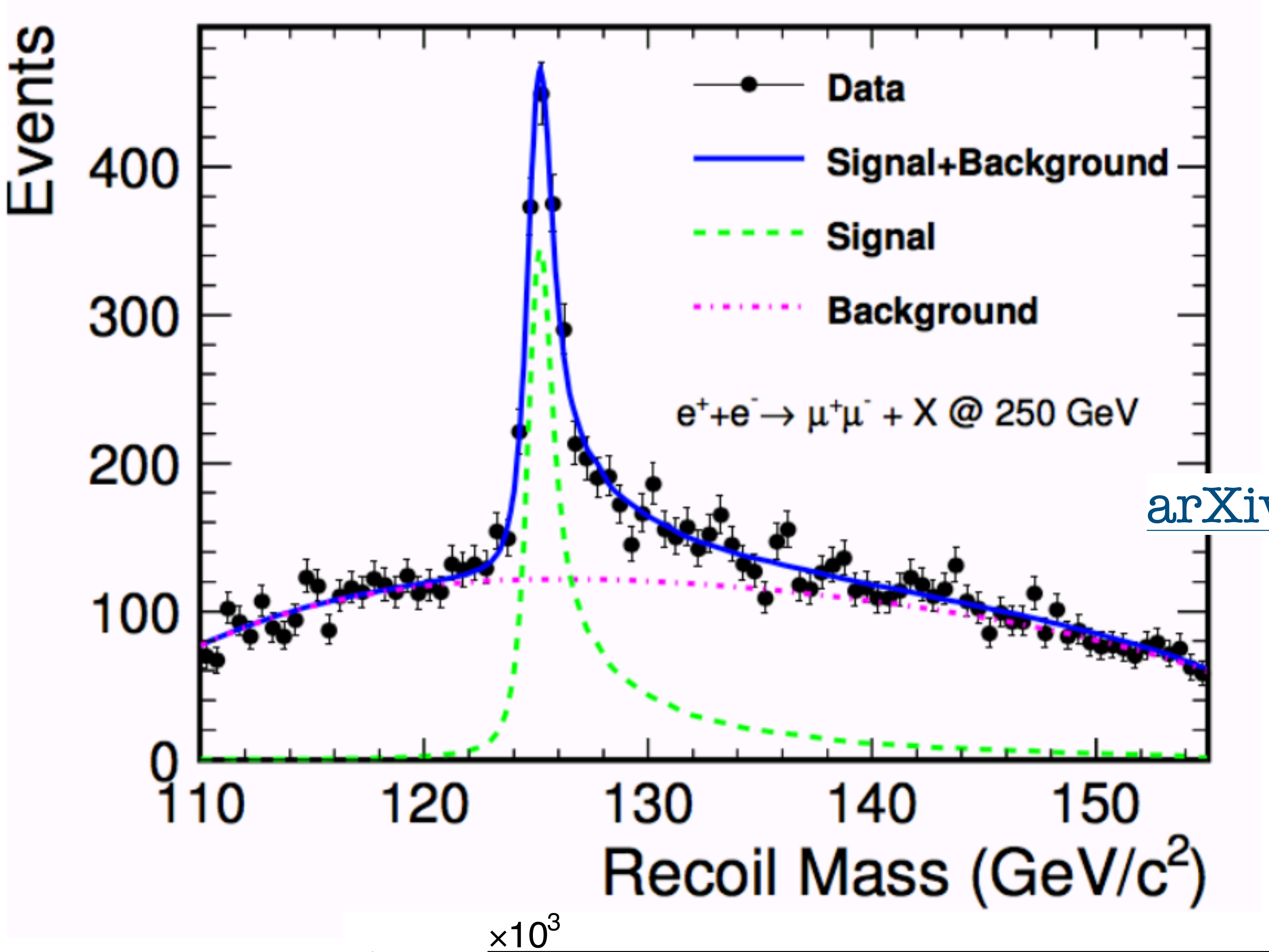
Higgs boson mass

Compare Higgs boson mass to the couplings to W and Z: check for consistency in the Standard Model

$$\delta(g_{HWW}) = 6.9\delta m_H \ ; \quad \delta(g_{HZZ}) = 7.7\delta m_H$$

arXiv:1311.6721

Higgs boson mass @ lepton collider



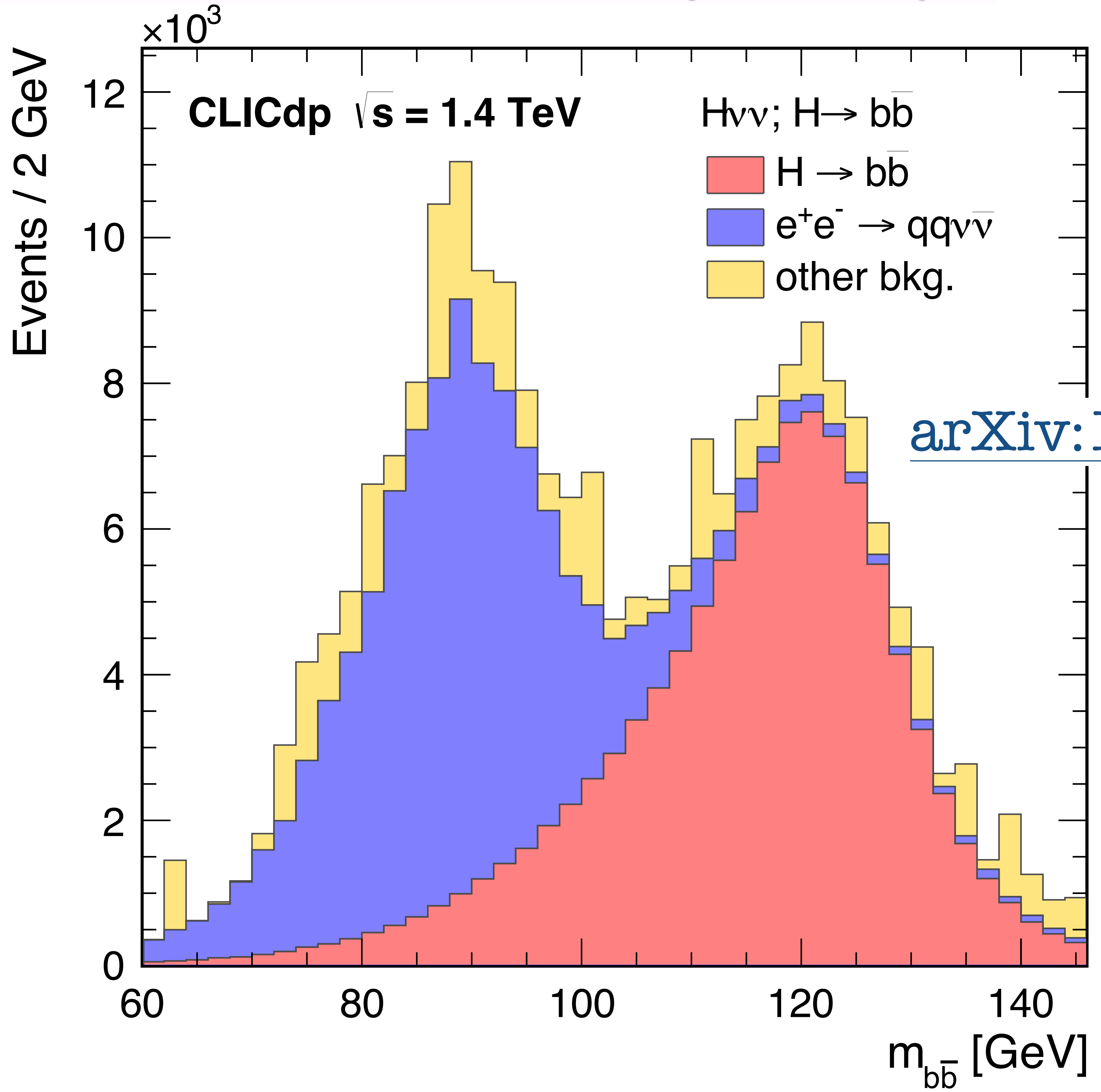
arXiv:1710.07621

ILC250: Reconstruct recoil mass from ***ZH***

$$M_X^2 = (p_{CM} - (p_{\ell^+} + p_{\ell^-}))^2 \,,$$

with **2 ab⁻¹:** m_H **= ±14 MeV**

CLIC: Measure Higgs mass directly from $H \to b\bar{b}$:



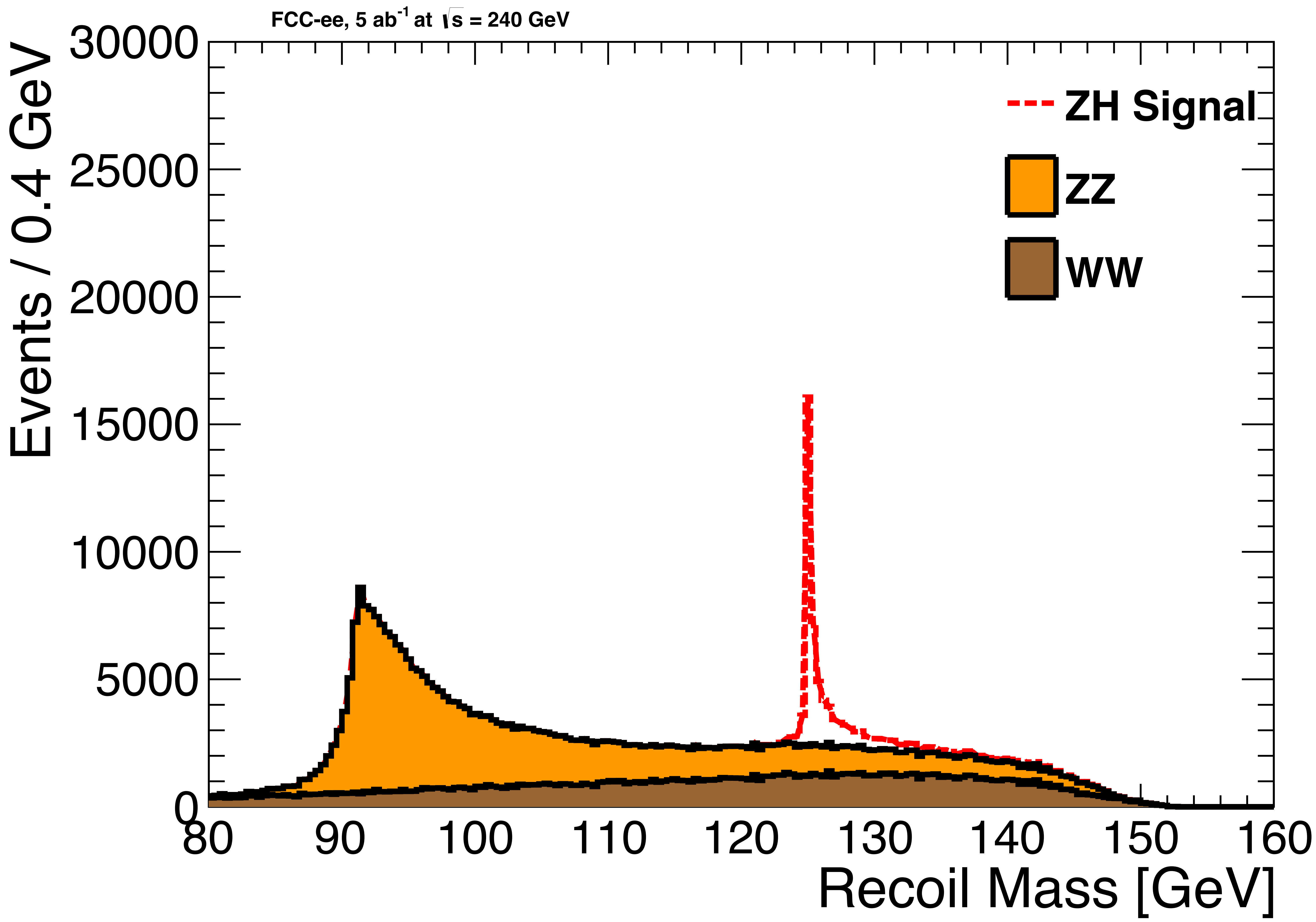
arXiv:1608.07538

$$\Delta(m_H) = 47\,\text{MeV at } 1.4\,\text{TeV}\,,$$

$$\Delta(m_H) = 44\,\text{MeV at } 3\,\text{TeV}\,.$$

A combination of both energy stages would lead to a precision of 32 MeV.

FCCee Recoil Mass



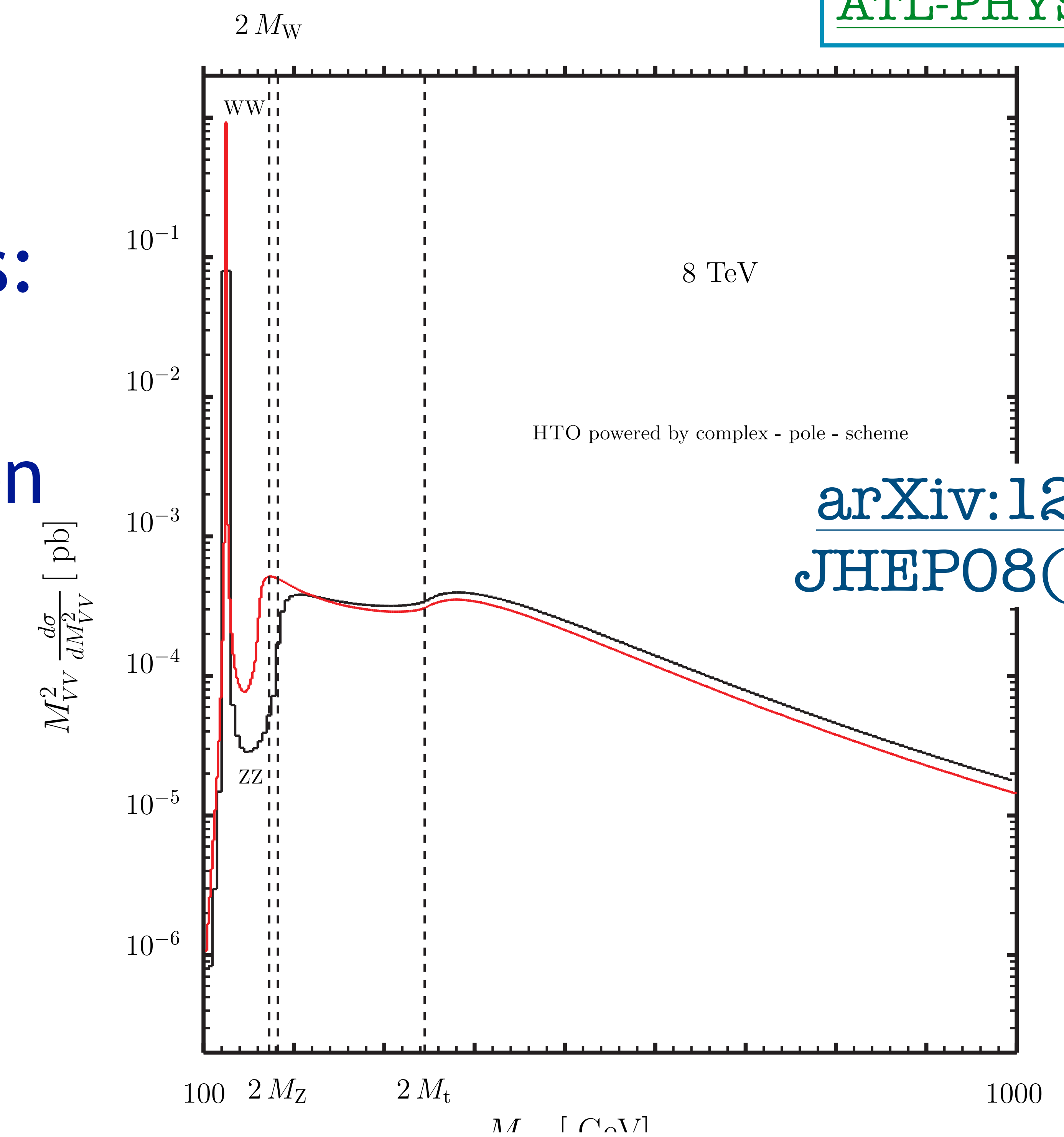
Higgs boson width

Does the Higgs boson decay as predicted?

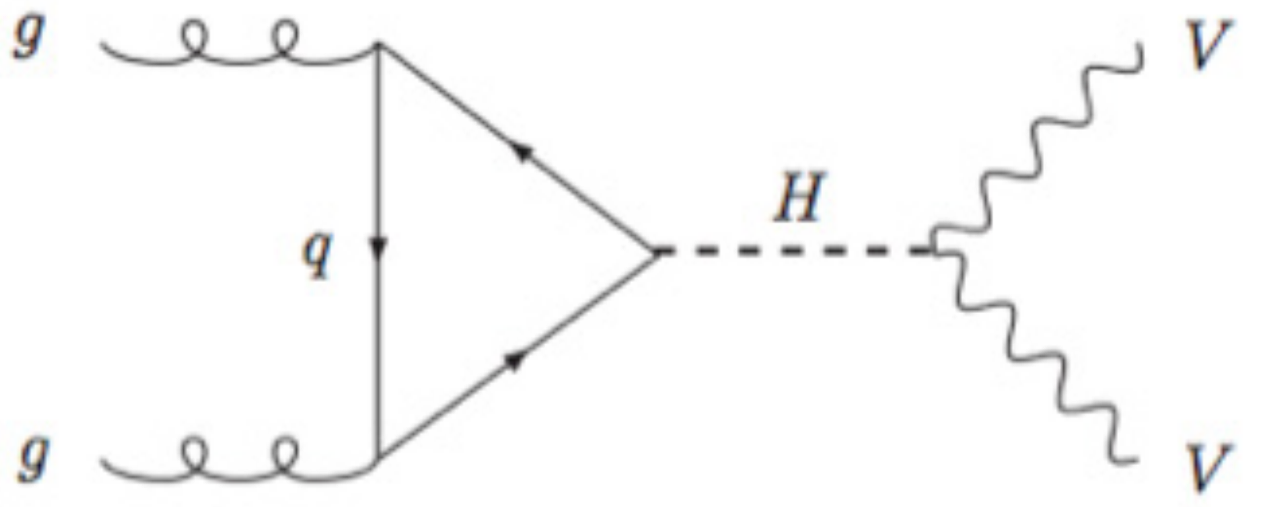
Γ_H at LHC

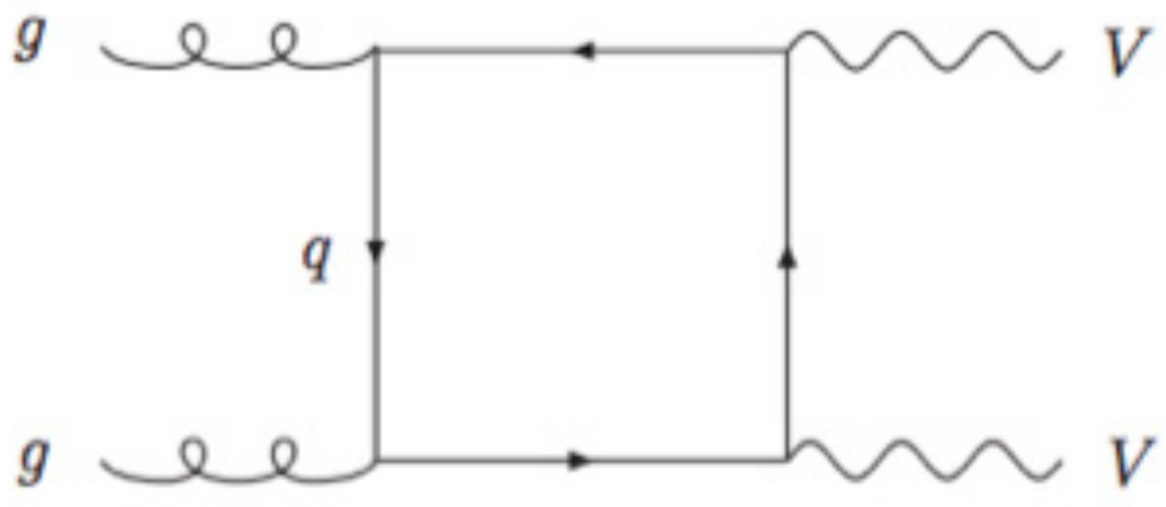
- **Direct constraints** from $m_{4\ell}$, $m_{\gamma\gamma}$ mass shape & $c\tau$ measurements: challenging even at HL-LHC
- **Indirect constraint** from interference between Higgs production and backgrounds:
  - ➡between $gg \rightarrow H \rightarrow \gamma\gamma^*$ and $gg \rightarrow \gamma\gamma^*$ (statistics dominated)
  - ➡high-mass $gg \rightarrow H \rightarrow VV$ and $gg \rightarrow VV$

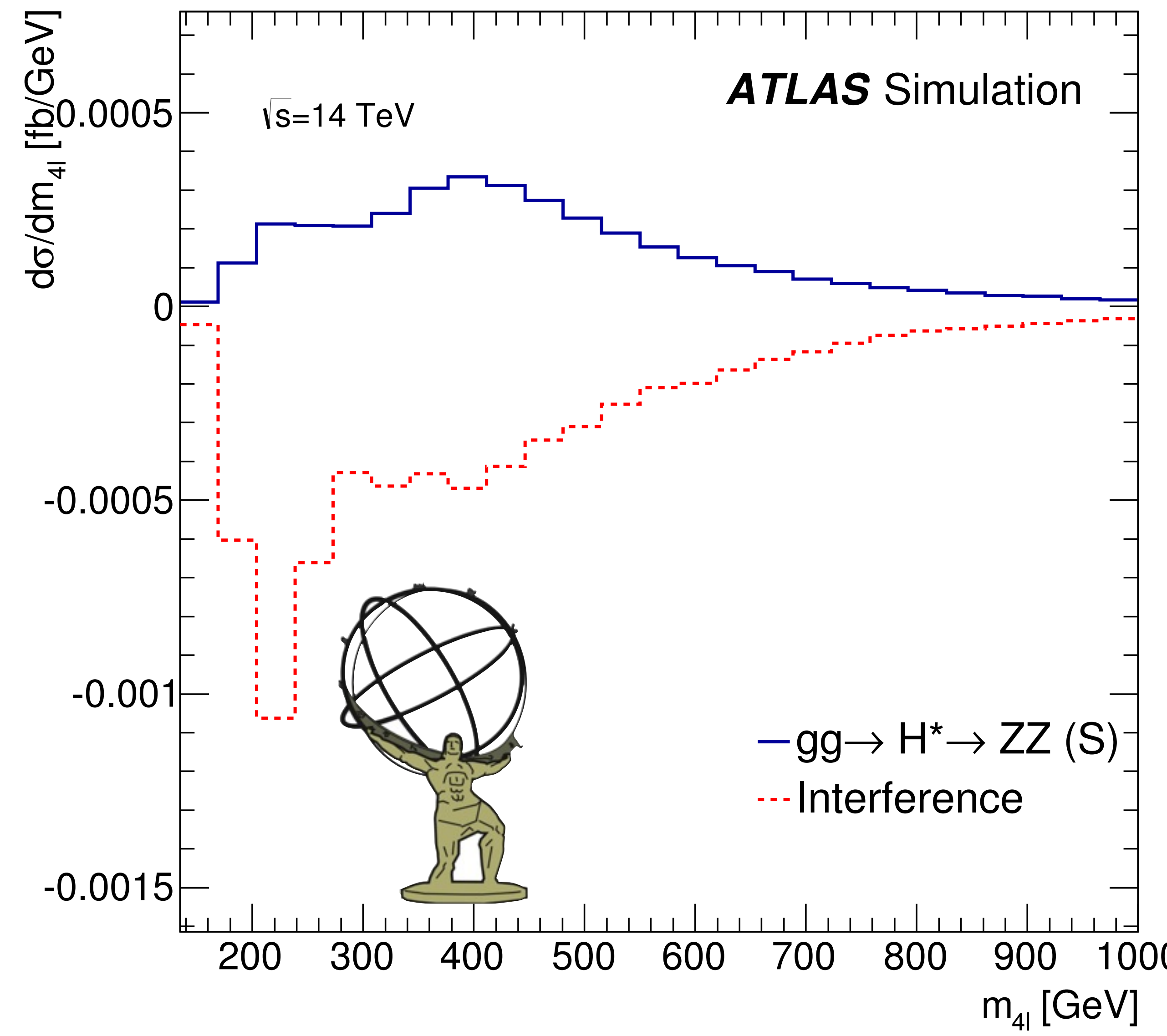
ATL-PHYS-PUB-2015-024



arXiv:1206.4803
JHEP08(2012)116







At high-mass, off-shell Higgs production and non-resonant $gg \rightarrow VV$ background (box diagram) sizeable and negative interference

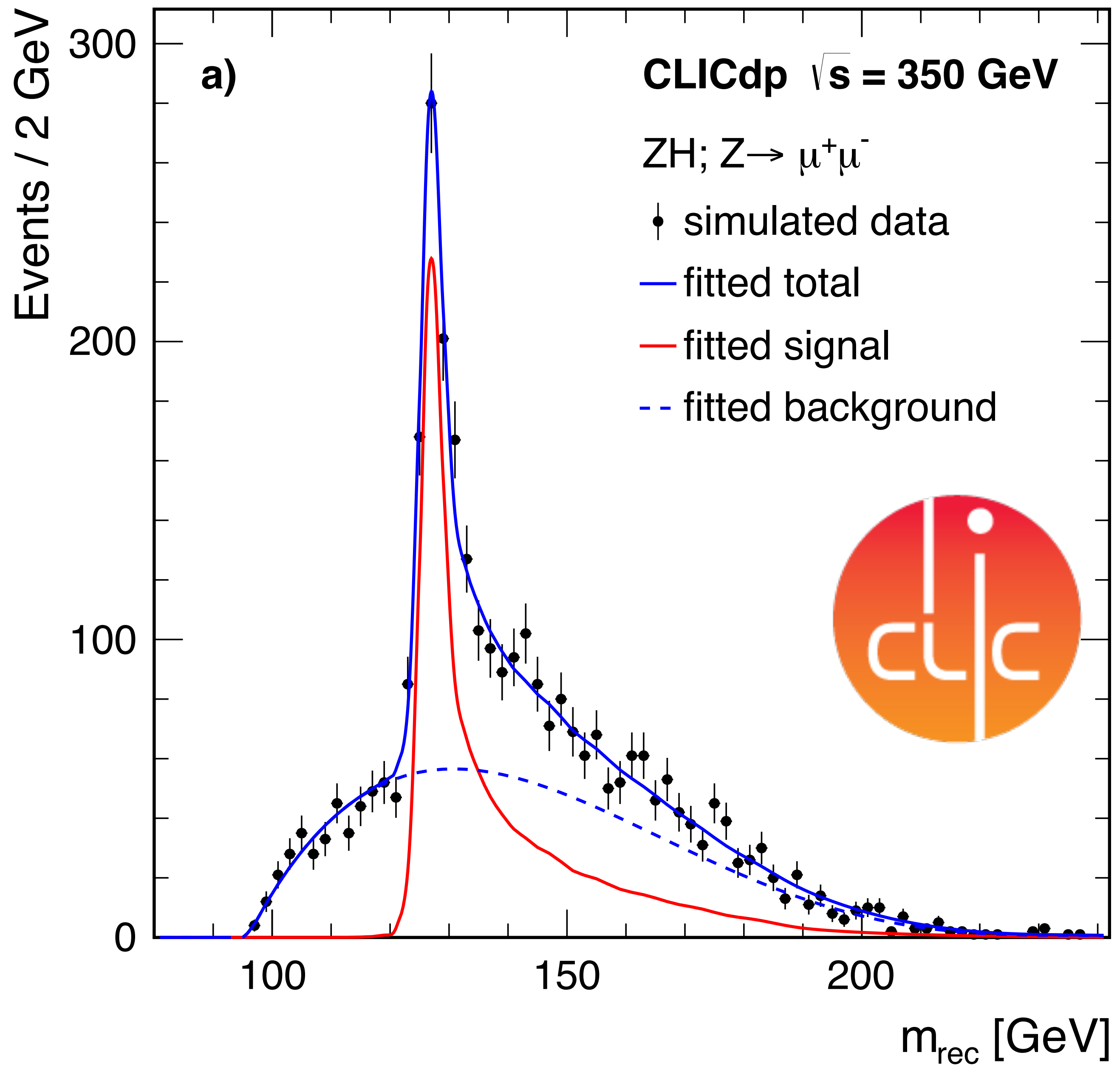
ATLAS projection for **3000 fb^{-1}** at HL-LHC **$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV (stat+sys)**

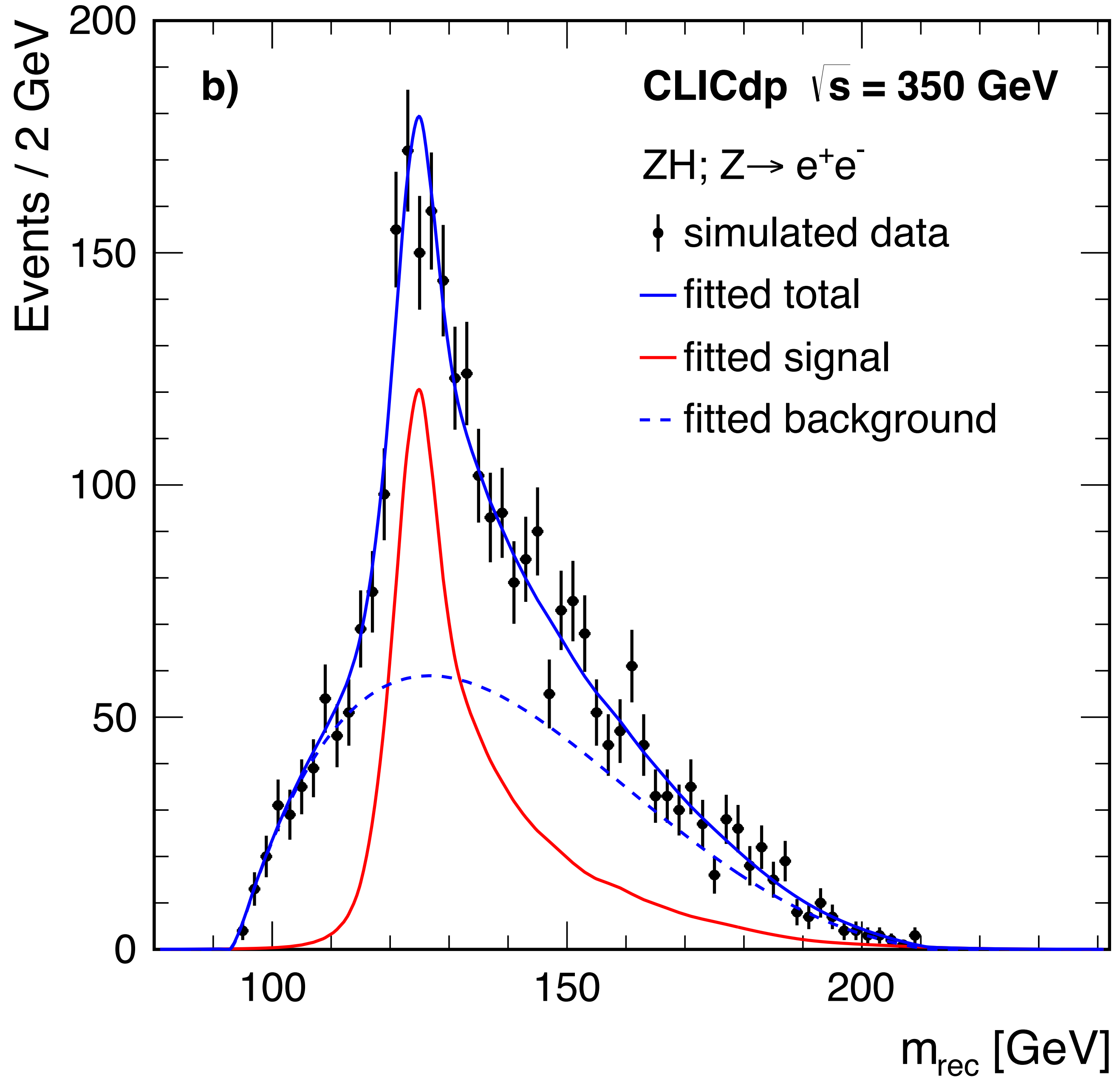
Γ_H at Lepton Collider

arXiv:1608.07538

arXiv:1710.07621

Use $e^+e^- \to ZH$, reconstruct $Z \to \mu^+\mu^-$, e^+e^-:
reconstruct recoil mass(independent of Higgs final state)



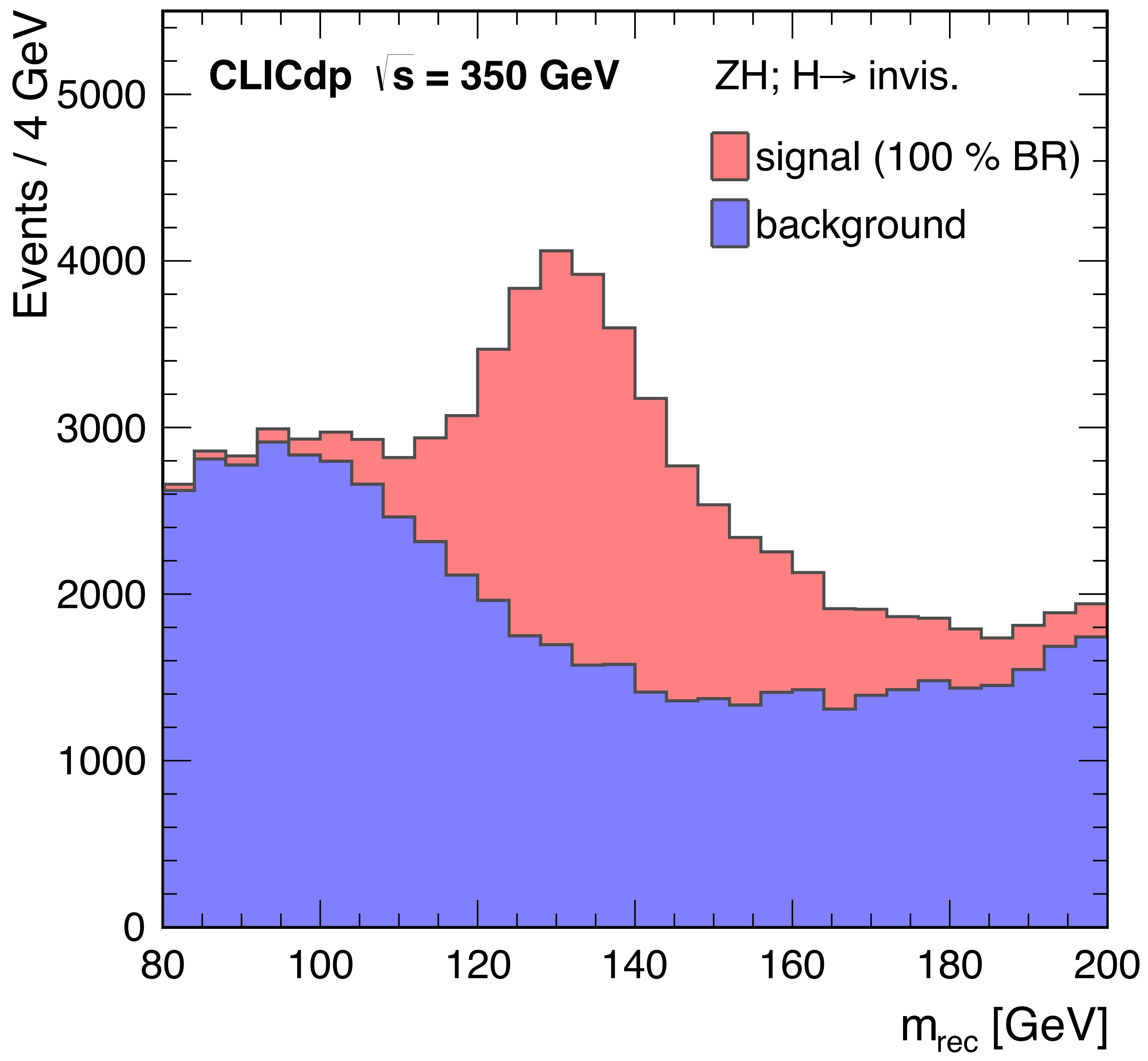


CLIC350: $\Delta(\Gamma_H) = 6.7\%$

ILC250: $\Delta(\Gamma_H) = 3.9 - 2.5\%$ (depending on fit model)

ILC500: $\Delta(\Gamma_H) = 1.7 - 2.6\%$ (depending on fit model)

$e^+e^- \to ZH$, $Z \to q\bar{q}$, $H \to$ invisible



CLIC350: $\Gamma_{invis}/\Gamma_H < 0.01$ at 90% C.L.

ILC500: $\Gamma_{invis}/\Gamma_H < 0.003$ at 95% C.L.

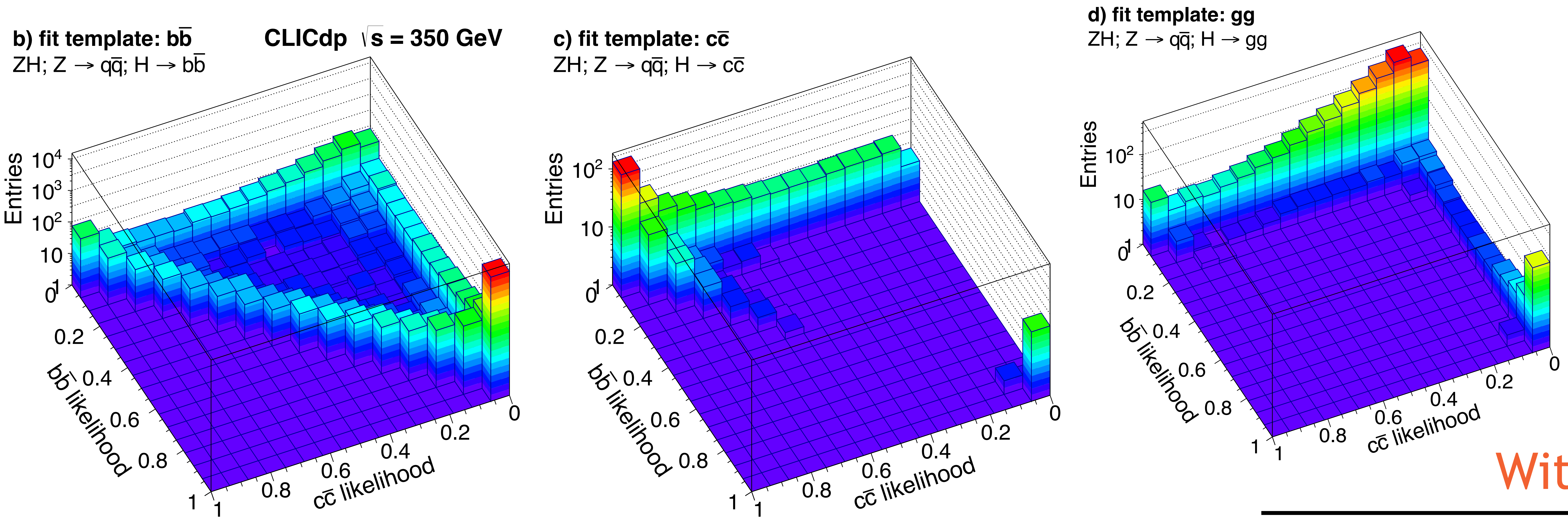
Rare Higgs Branching Ratios

Does the Higgs boson decay to second generation fermions?

Higgs Hadronic BRs at CLIC

arXiv:1608.07538

- Aim: resolve $H\to 2$ jets signal into $H\to b\bar{b}$, $H\to c\bar{c}$ and $H\to gg$
- Fit to multivariate-derived templates using flavour tagging info *e.g.* at 350 GeV, $HZ\to 4$ jets



Also with:

- ➡ $HZ\to 2$ jets + 2 ℓ,
- ➡ $\nu\nu H\to \not{E}$ + 2 jets

With 500/fb at 350 GeV

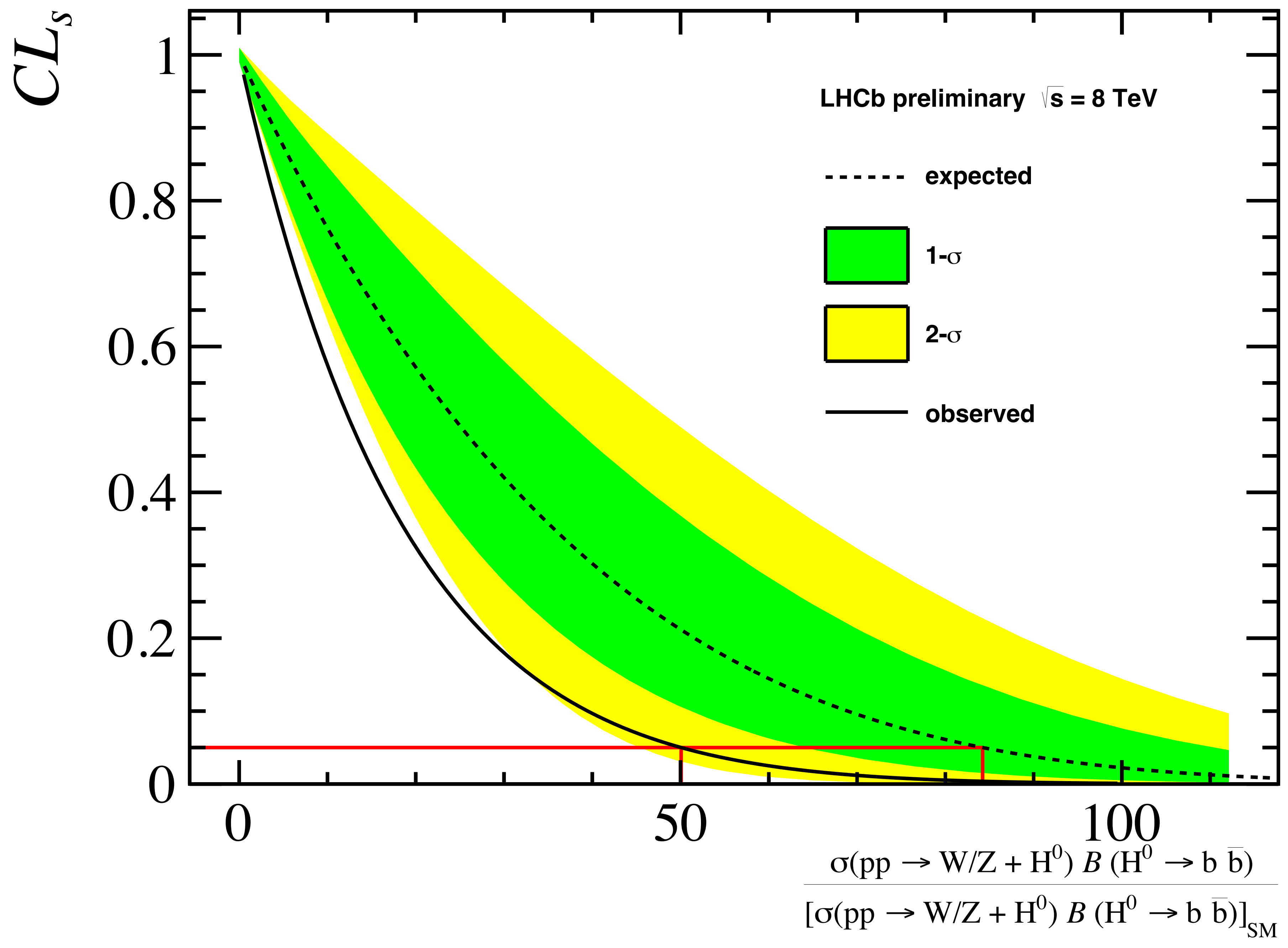
Decay	Statistical uncertainty	
	Higgsstrahlung	WW-fusion
$H\to b\bar{b}$	0.86 %	1.9 %
$H\to c\bar{c}$	14 %	26 %
$H\to gg$	6.1 %	10 %

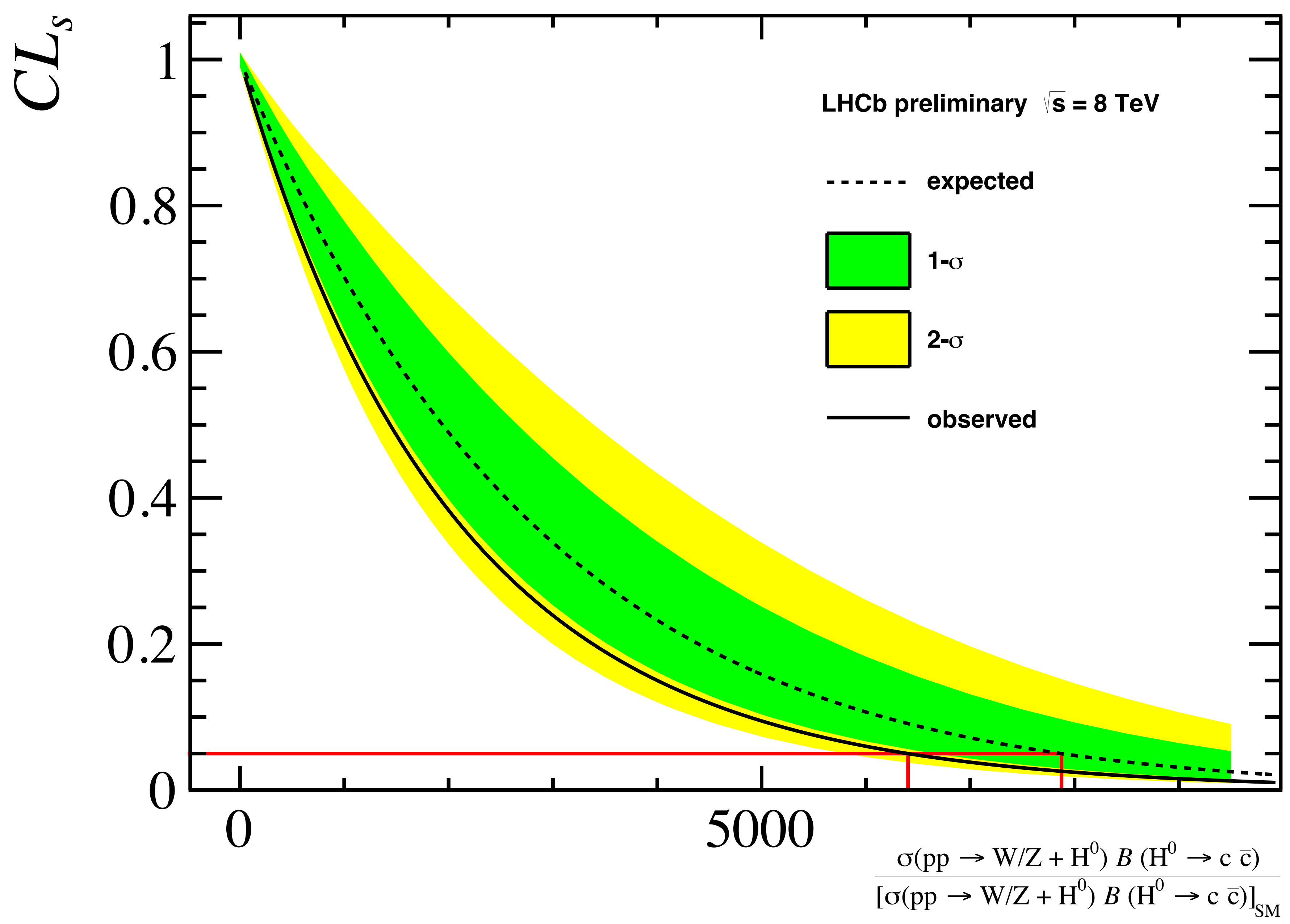
$H \to c\bar{c}$ Search at LHCb

LHCb-CONF-2016-006

Search for VH, $V \to \ell$, $H \to b\bar{b}, c\bar{c}$ in forward production $(2 < \eta < 5)$

With $1.92\ \text{fb}^{-1}$, $H \to b\bar{b} < 50 \times \text{SM}$; $H \to c\bar{c} < 7900 \times \text{SM}$, (95% CL)





Very rough information projection: LHCb could reach $5 \times \text{SM}$ with $300\ \text{fb}^{-1}$

https://indico.fnal.gov/event/16151/session/0/contribution/4/material/slides/0.pdf

$H \to J/\psi\ \gamma$ at ATLAS

- Sensitive to Higgs coupling to charm quark
  - ➡ SM expectation: $\mathrm{BR}(H \to J/\psi\ \gamma) = (2.9 \pm 0.2) \times 10^{-6}$
  - ➡ use $J/\psi \to \mu^+\mu^-$ decay mode
  - ➡ $Z \to J/\psi\ \gamma$ as a cross check
- Using multivariate analysis, events in $m(\mu^+\mu^-\gamma) \in 115\text{-}135$ GeV: ~3 signal, 1700 background

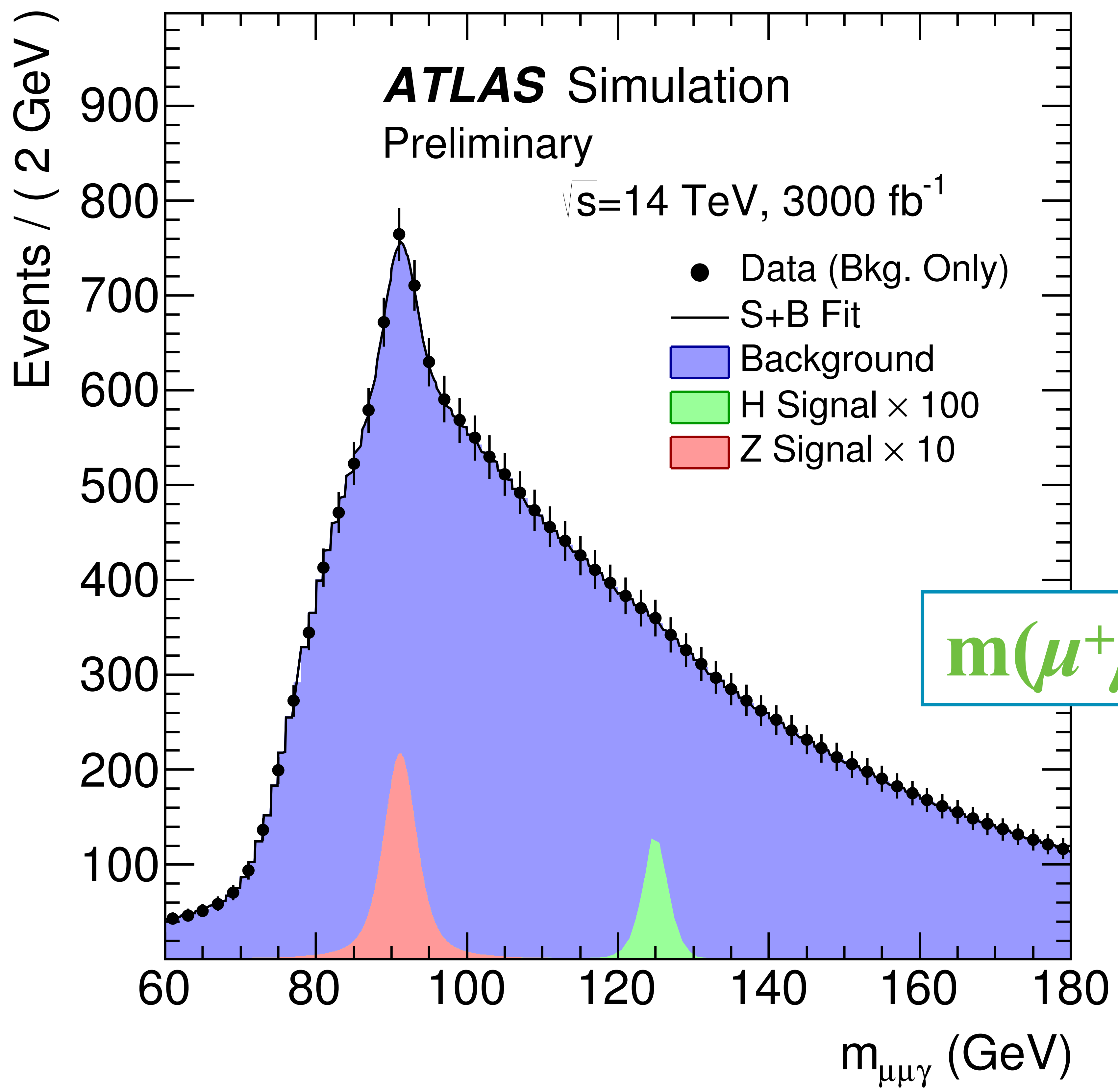
Expected limits at 95% CL (using multivariate analysis):

➡ $\mathrm{BR}(H \to J/\psi\ \gamma)$: $(44^{+19}_{-12}) \times 10^{-6}$

➡ $\sigma(gg \to H) \times \mathrm{BR}(H \to J/\psi\ \gamma)$: $(3.1^{+0.9}_{-1.3})$ fb

(no background systematics considered)

ATL-PHYS-PUB-2015-043



$m(\mu^+\mu^-\gamma)$

Also possible for lighter vectors:

Channel	Final state	Exp. SM × 10^{-6}	Run2 limit
$H \to \rho\gamma$	$\pi^+\pi^-\ \gamma$	16.8 ± 0.8	880
$H \to \phi\gamma$	$K^+K^-\ \gamma$	2.31 ± 0.11	480

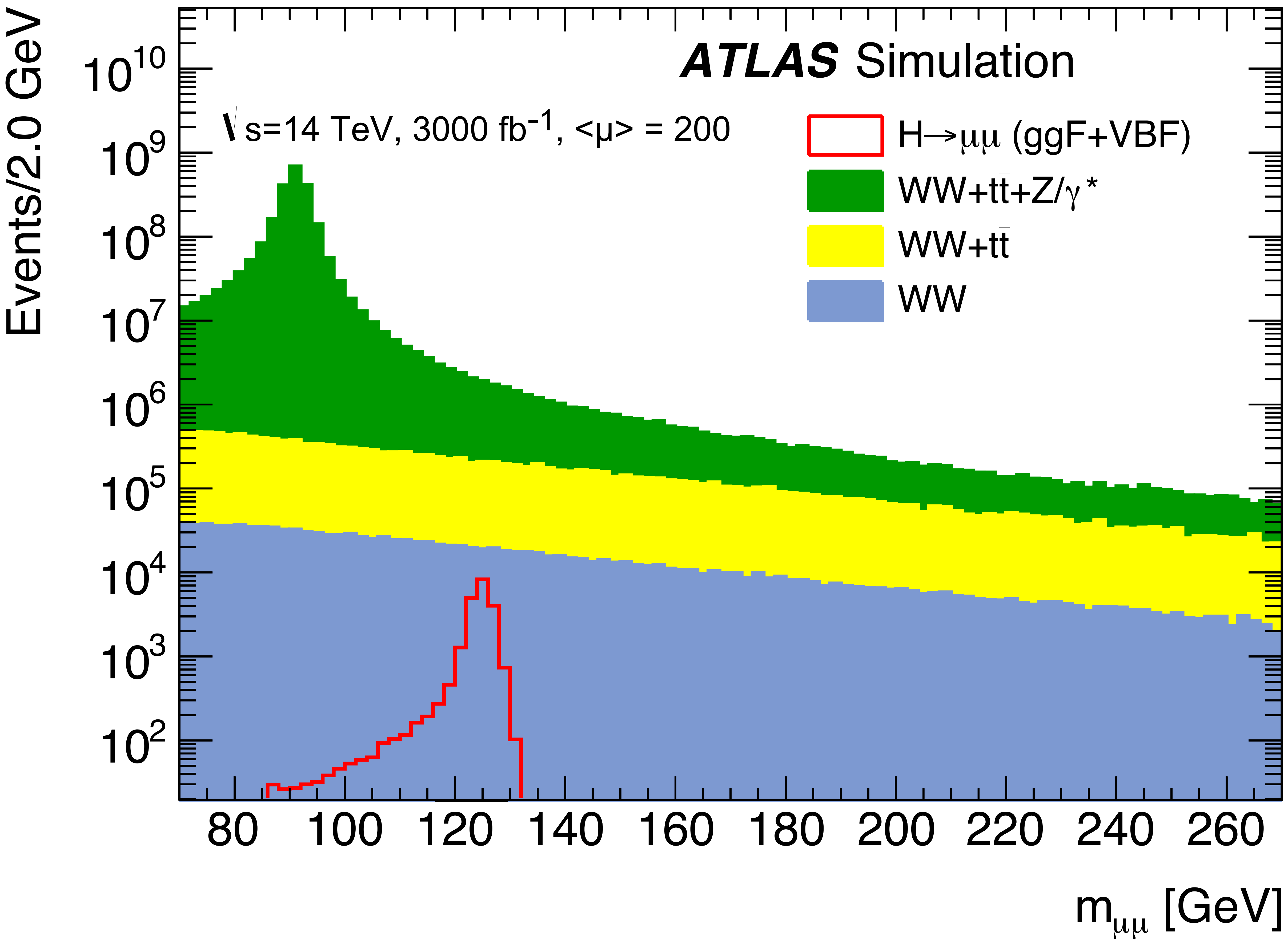
arXiv:1712.02758

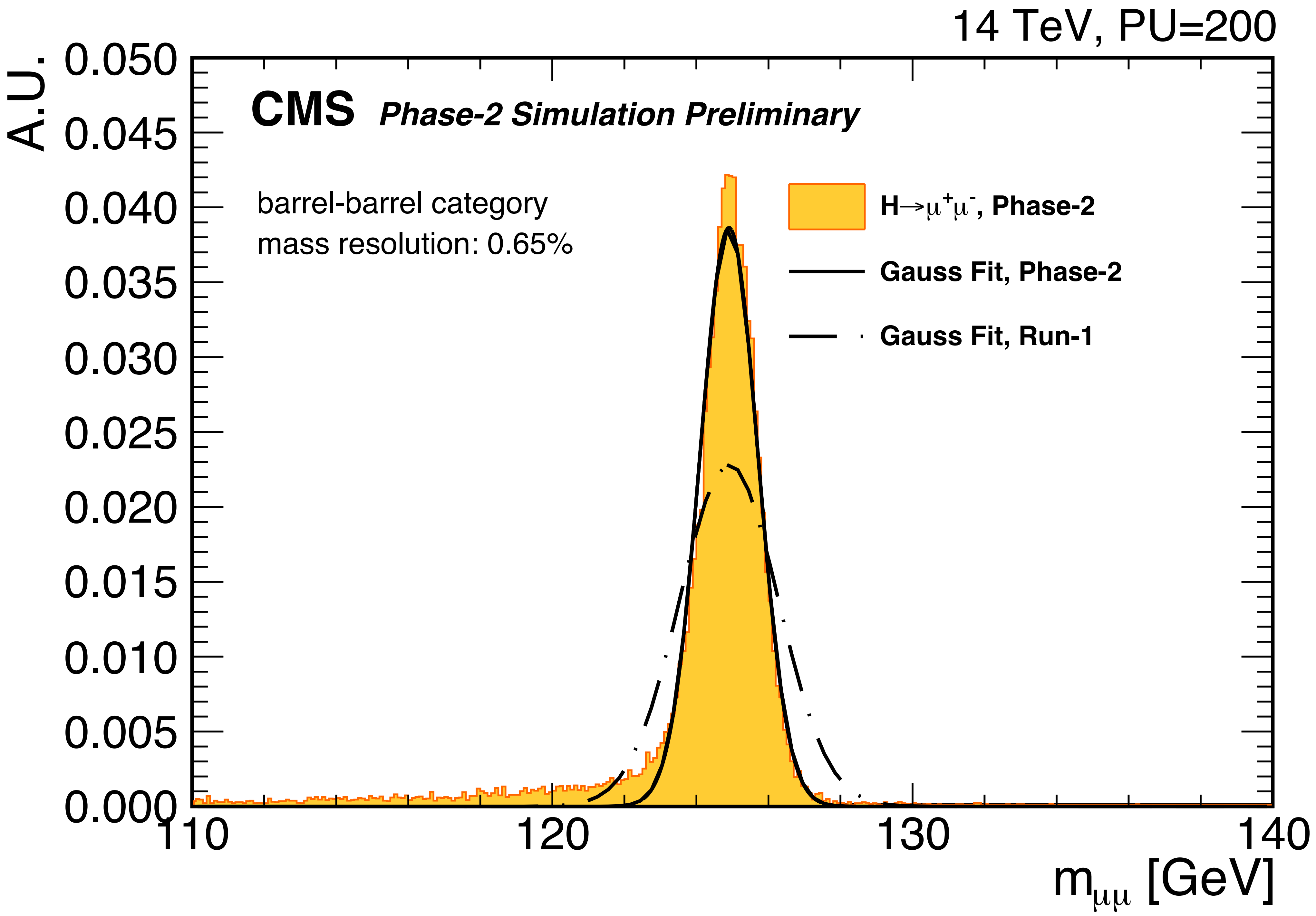
$H \to \mu^+\mu^-$ at HL-LHC

CMS-TDR-17-001

ATLAS-TDR-026

PhysRevLett.119.051802





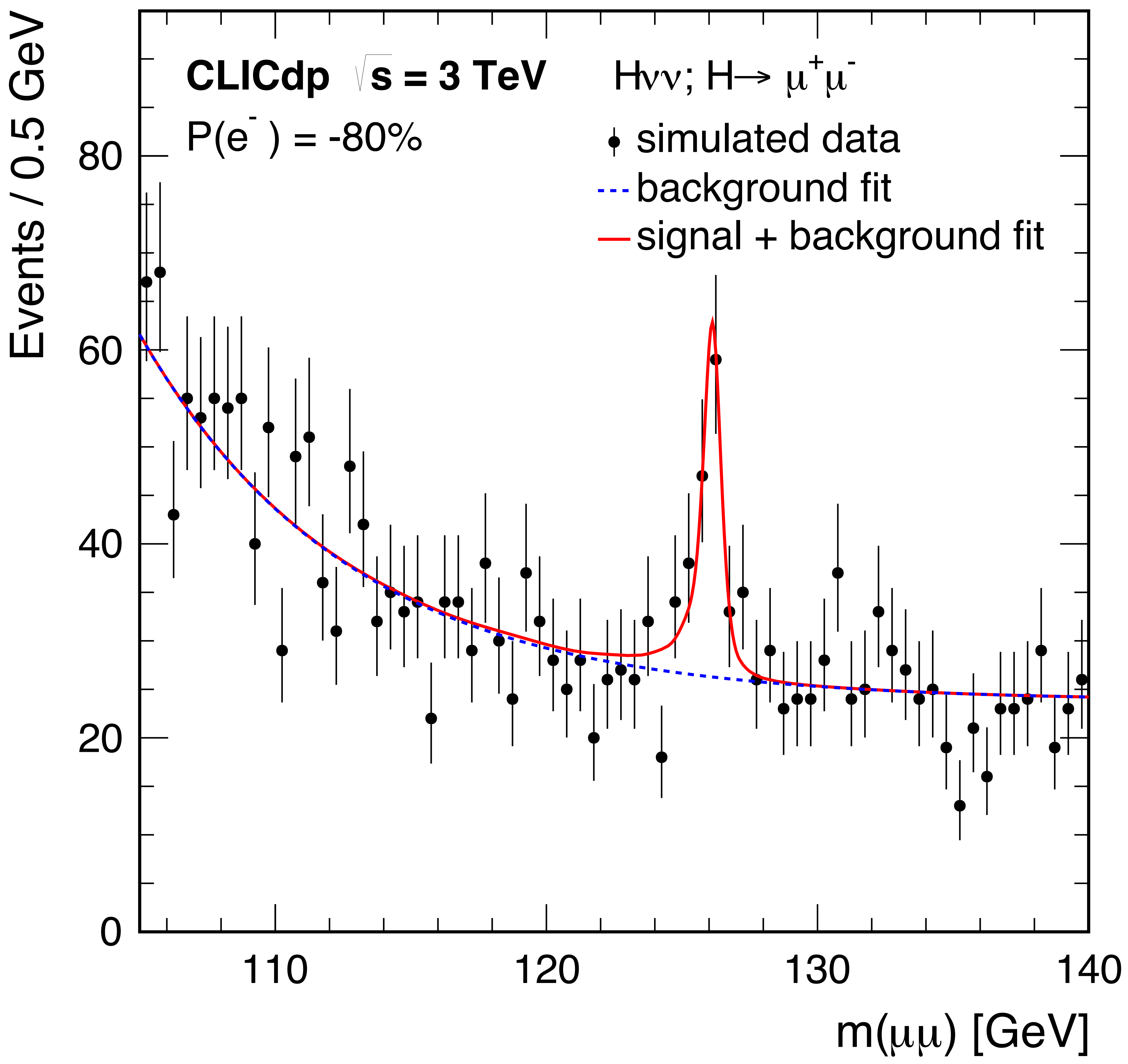
- SM prediction is **$BR(H\to\mu\mu) = 2.19 \times 10^{-4}$**
- Run 1 limit is $2.8 \times$ SM
- ATLAS production with **$3000\ fb^{-1}$**:
  - Observation at ~**7σ**
  - uncertainty of 20-25 % on signal strength

arXiv:1608.07538

$H \to \mu^+\mu^-$ at CLIC

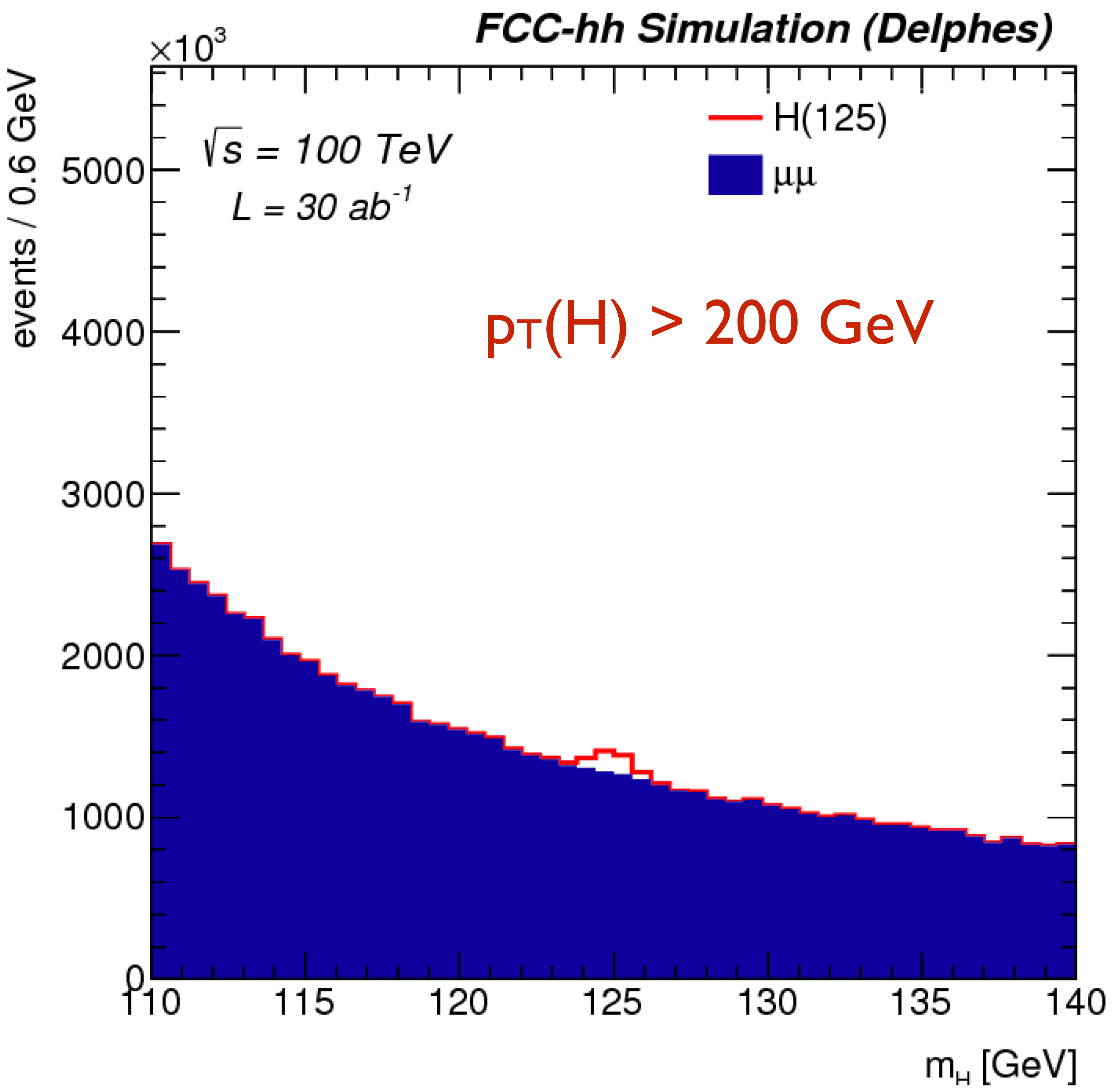
$$\frac{\Delta[\sigma(H\nu_e\bar{\nu}_e)\times BR(H\to\mu^+\mu^-)]}{\sigma(H\nu_e\bar{\nu}_e)\times BR(H\to\mu^+\mu^-)} = 38\,\% \text{ at } 1.4\,\text{TeV},$$

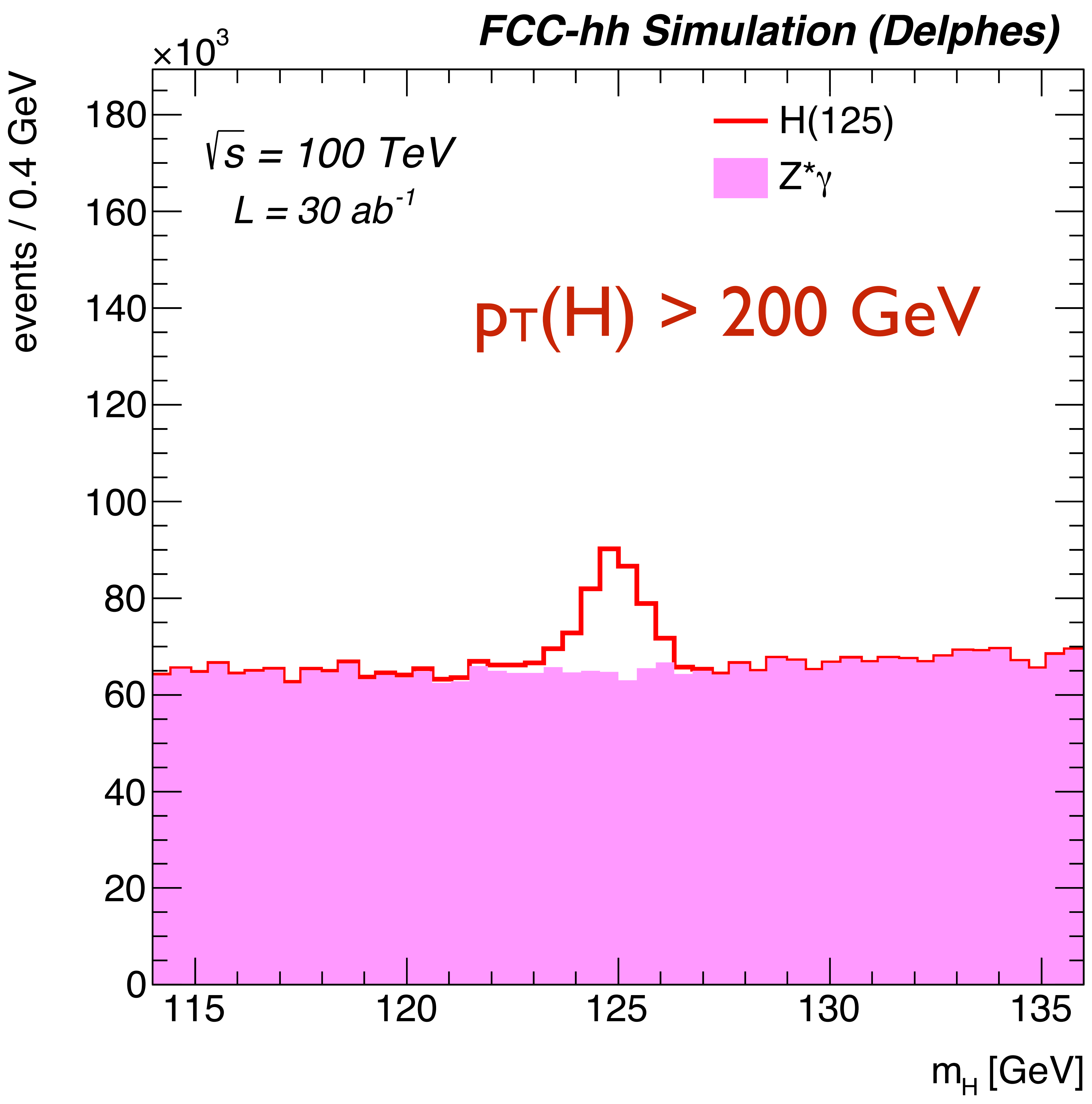
$$\frac{\Delta[\sigma(H\nu_e\bar{\nu}_e)\times BR(H\to\mu^+\mu^-)]}{\sigma(H\nu_e\bar{\nu}_e)\times BR(H\to\mu^+\mu^-)} = 25\,\% \text{ at } 3\,\text{TeV}.$$



Very clean, narrow signal!

$H \to \mu^+\mu^-$ & $H \to Z\gamma$ at FCCpp





Spin & CP

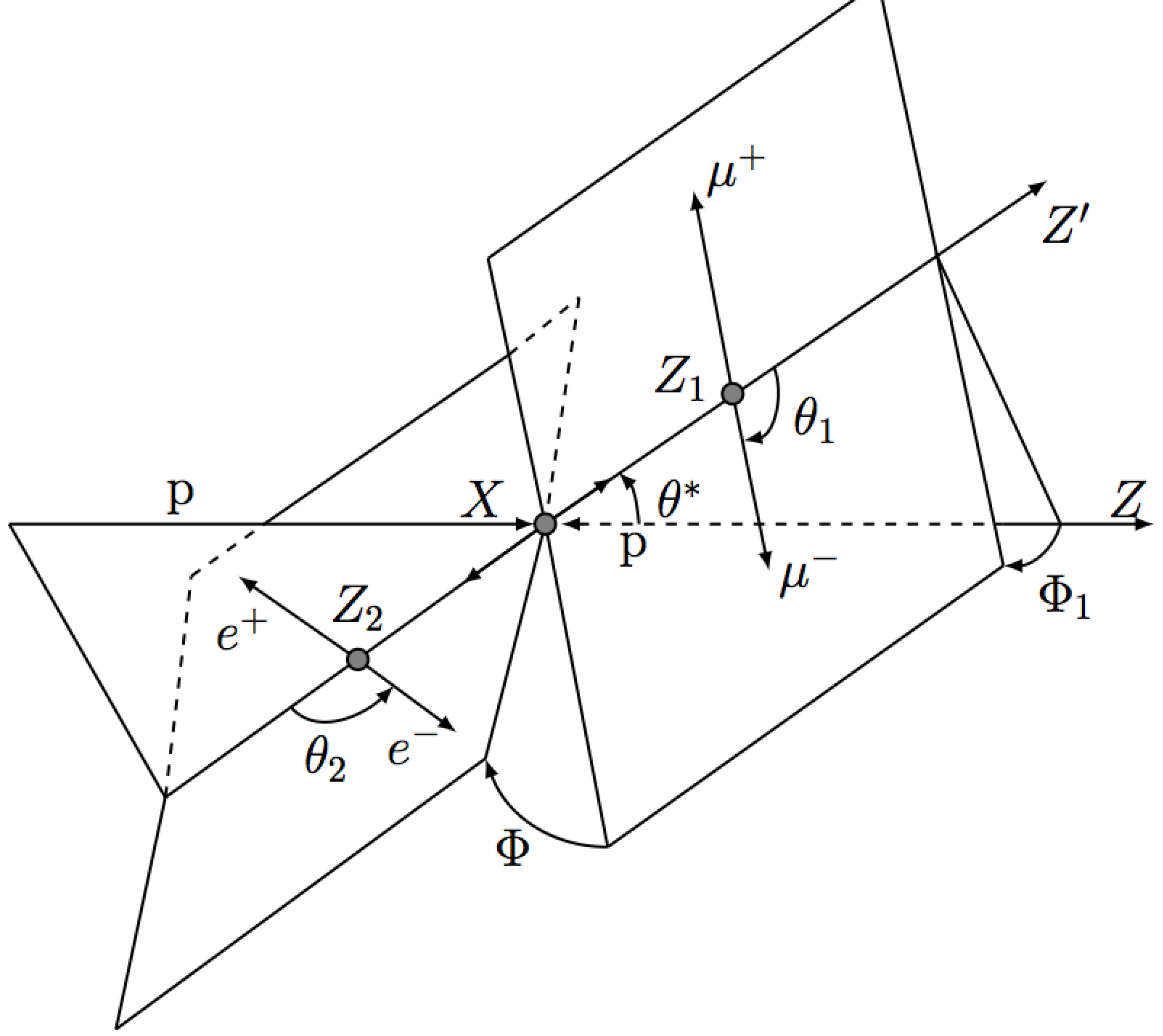
Only pseudoscalar in there?

Many places to look … several different parameterisations of CP used

CP Studies at HL-LHC

- $H \to ZZ \to 4\ell$ used to reconstruct the full angular decay structure.

- Sensitive to non-SM ($\mathbf{CP} = \mathbf{0}^+$) contributions.



$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^\star \epsilon_2^\star + a_2 f_{\mu\nu}^{\star(1)} f^{\star(2),\mu\nu} + a_3 f_{\mu\nu}^{\star(1)} \tilde{f}^{\star(2),\mu\nu}\right)$$

SM tree processes

loop **CP**-even contributions

CP-odd contributions (BSM)

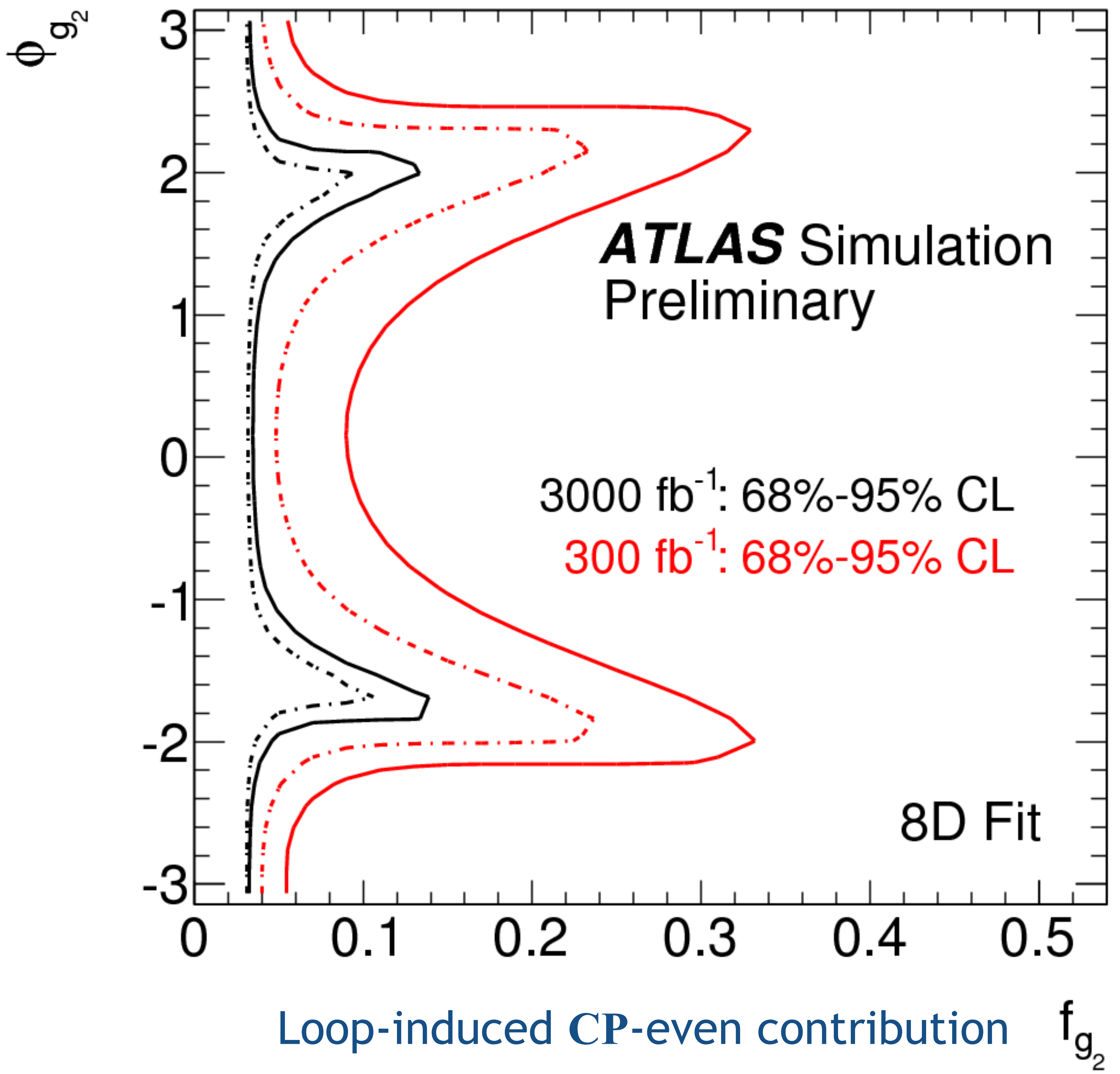
- Fit fraction of event (f_{ai}) and phases (ϕ_i) to observed decay:

$$\phi_{a_i} = \arg\left(\frac{a_i}{a_1}\right) \qquad f_{a_i} = \frac{|a_i|^2 \sigma_i}{|a_1|^2 \sigma_1 + |a_i|^2 \sigma_i}$$

CP Studies at HL-LHC

ATL-PHYS-PUB-2013-013

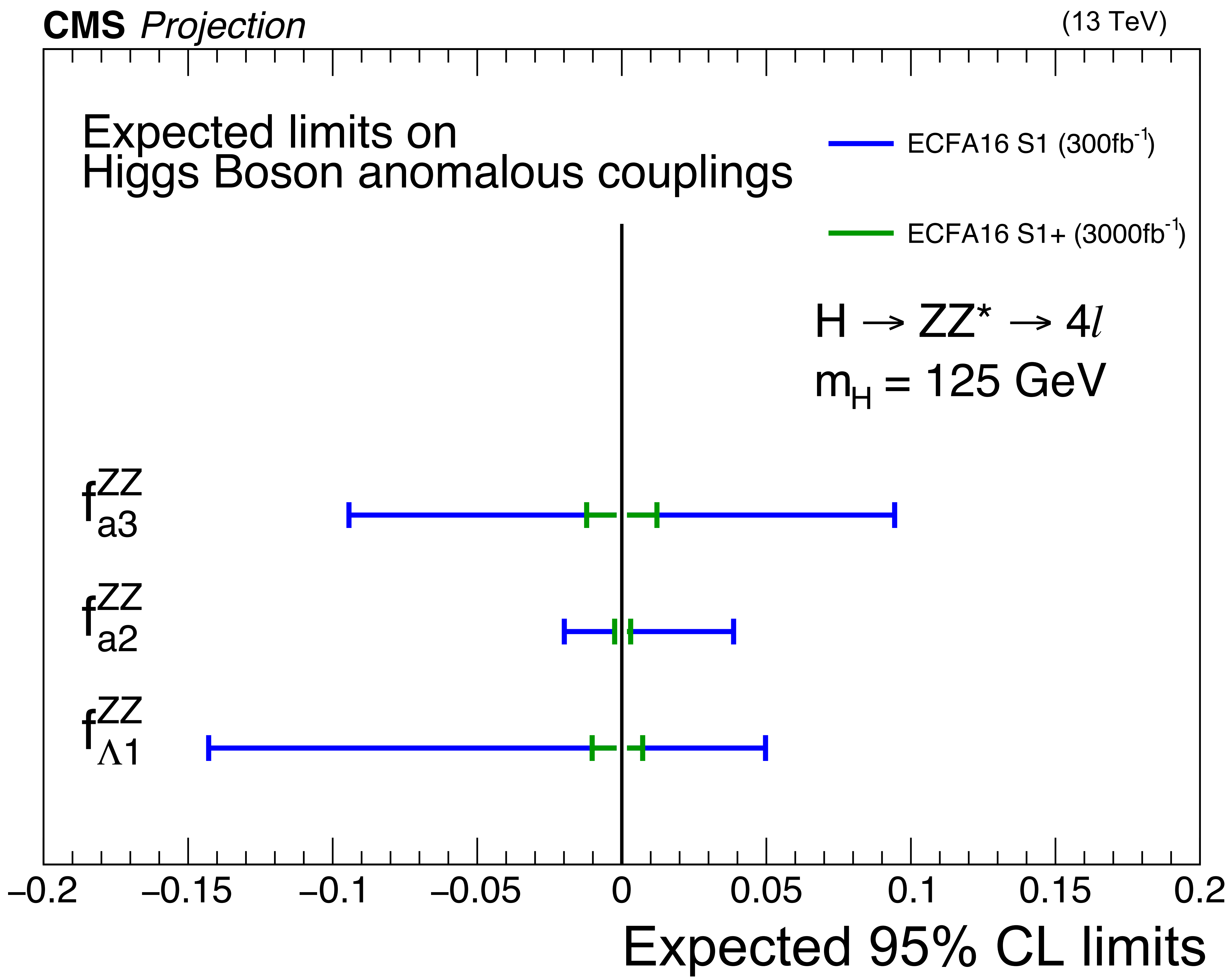
CMS-PAS-FTR-16-002



Loop-induced CP-even contribution

$$a_1 = g_1 \frac{m_V^2}{m_H^2} + \frac{s}{m_H^2}\left(2g_2 + g_3 \frac{s}{\Lambda^2}\right); \quad a_2 = -\left(2g_2 + g_3 \frac{s}{\Lambda^2}\right); \quad a_3 = -2g_4,$$

$$f_{g_i} = \frac{|g_i|^2 \sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}; \quad \phi_{g_i} = \arg\left(\frac{g_i}{g_1}\right).$$



Percent-level sensitivity, but still statistics limited

CP Studies at ILC250

arXiv:1710.07621

$$\Delta\mathcal{L}_{hZZ} = \frac{1}{2}\frac{\tilde{b}}{v} h Z_{\mu\nu} \tilde{Z}^{\mu\nu}.$$

$\tilde{b} \equiv a_3$ can be measured to 0.5% at ILC250

$H \to \tau^+\tau^-$ decay probed

$$\Delta\mathcal{L}_{h\tau\tau} = -\frac{\kappa_\tau y_\tau}{\sqrt{2}} h\tau^+(\cos\phi + i\sin\phi\gamma_5)\tau^-$$

CP phase: $\phi = 0$ in the SM

ϕ measured to 3.8° at ILC250

CP Studies at FCCee

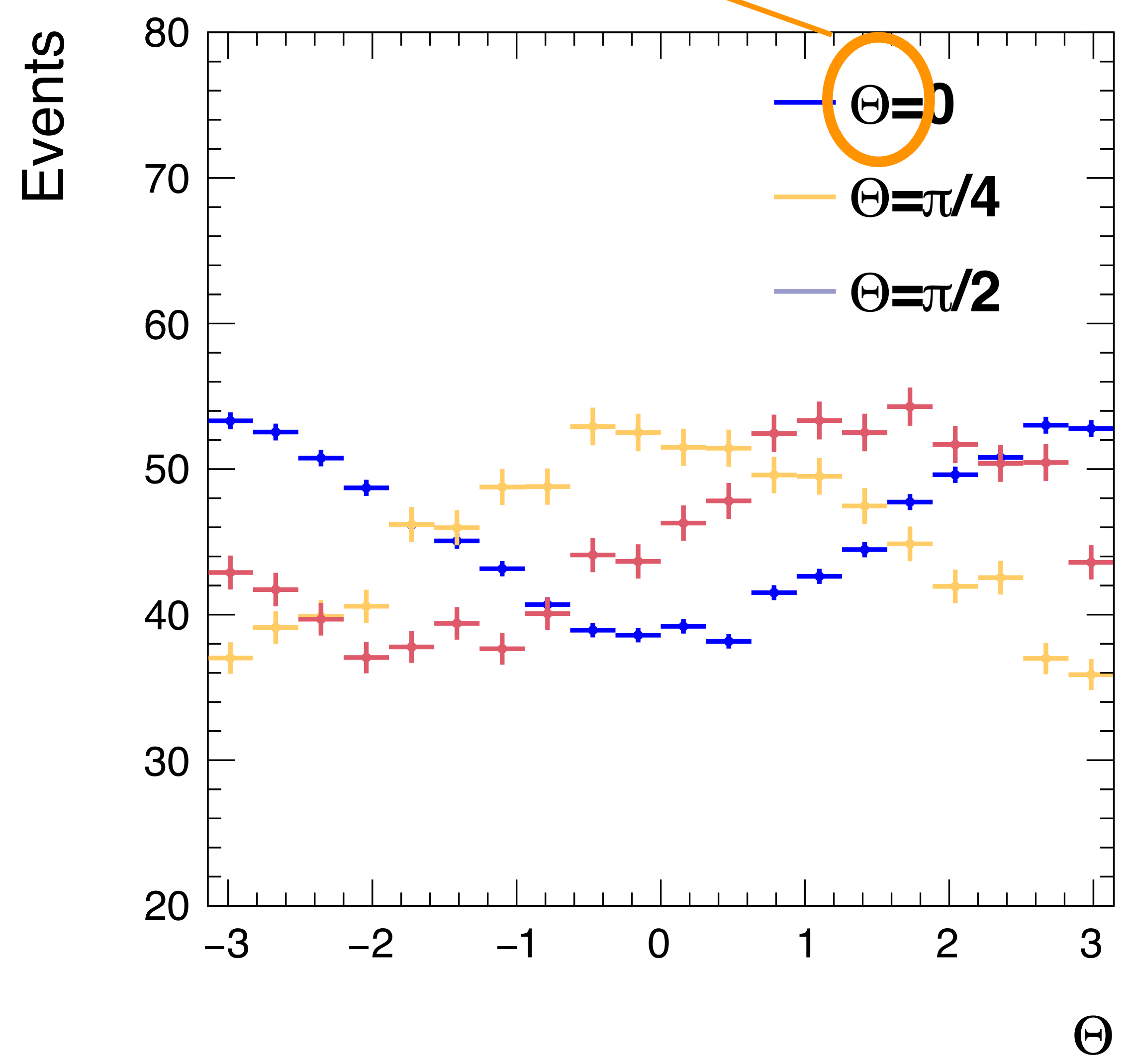
M. Klute at FCC week 2018

$$\Delta\mathcal{L}_{h\tau\tau} = -\frac{\kappa_\tau y_\tau}{\sqrt{2}} h\tau^+(\cos\phi + i\sin\phi\gamma_5)\tau^-$$

- ➡ **$H\rightarrow\tau\tau$ decay is promising channel to study CP violation**
  - Tree level couplings to quarks and leptons
  - CP-even and CP-odd couplings induced at the same order
- ➡ **CP violation can be probed through τ polarization**
  - τ decays clean enough that the spin information is not washed out by hadronization effects
  - pion emission preferred in the direction of the τ spin in rest frame $\tau^\pm \rightarrow \rho^\pm \nu_\tau \rightarrow \pi^\pm \pi^0 \nu_\tau$
  - exploring $\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta)f$
  - model using effective lagrangian

Andres Rios (MIT), Aram Apyan (FNAL)

following arXiv:1308.1094



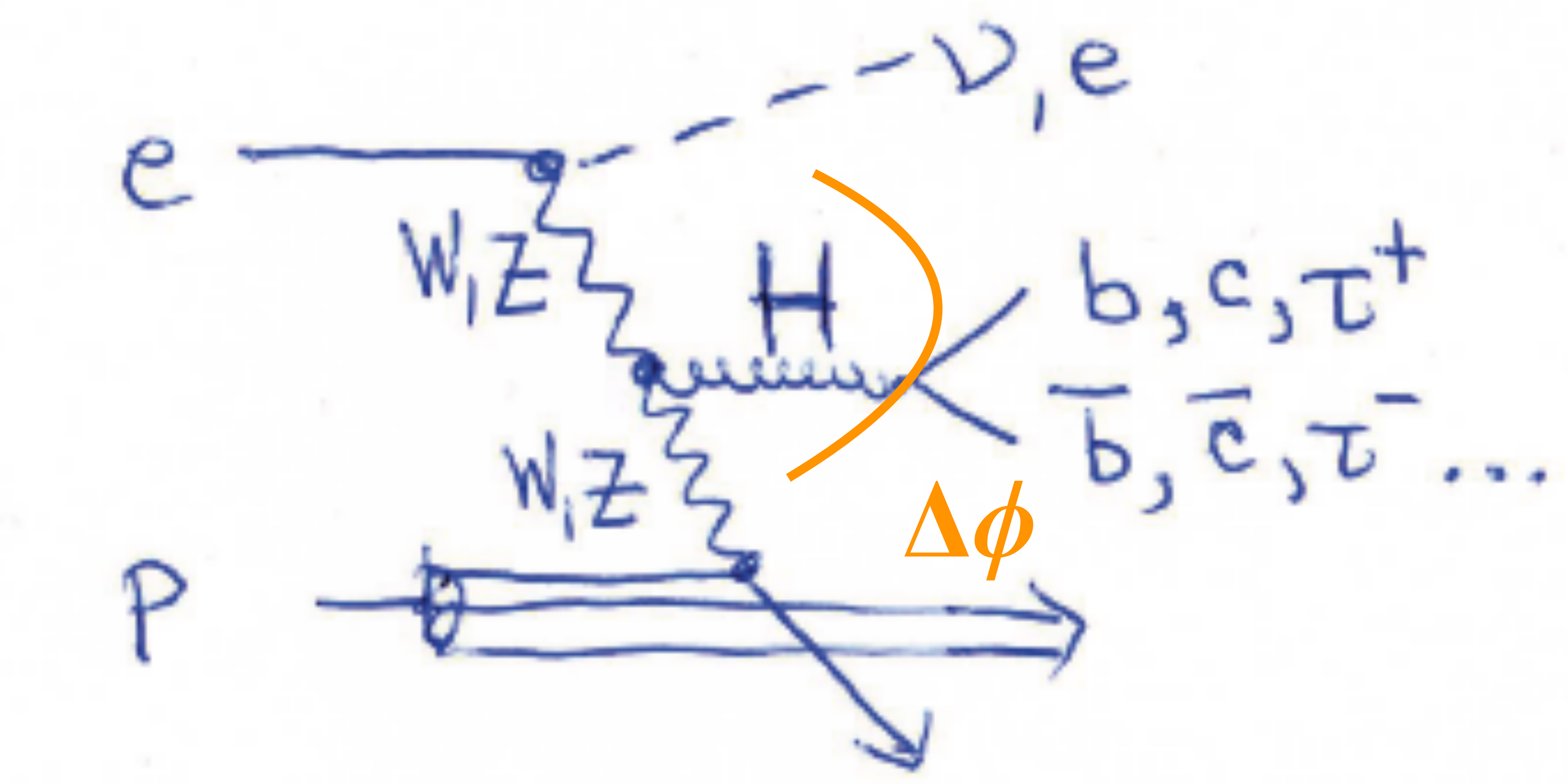
- 920 signal event in 5ab-1
- expected 68% CL
  - 0.17 radian (0.05 in GEN level study)
  - 9.7 degree (2.9 in GEN level study)

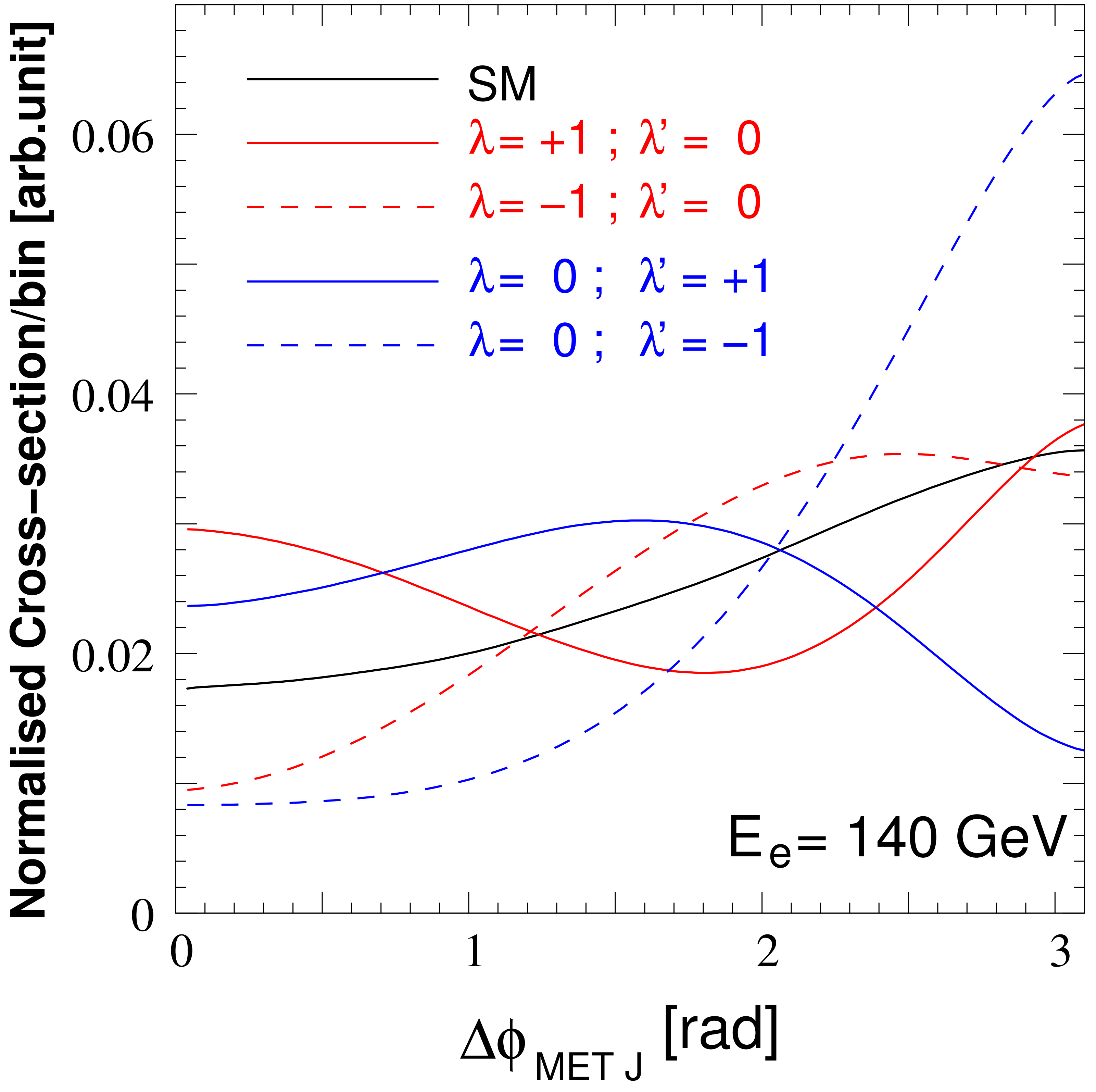
CP Studies at LHeC

U. Klein at HL/HE LHC meeting April 2018

LHeC CDR

LHeC provides access to **CP** structure of ***WWH*** and ***ttH*** coupling





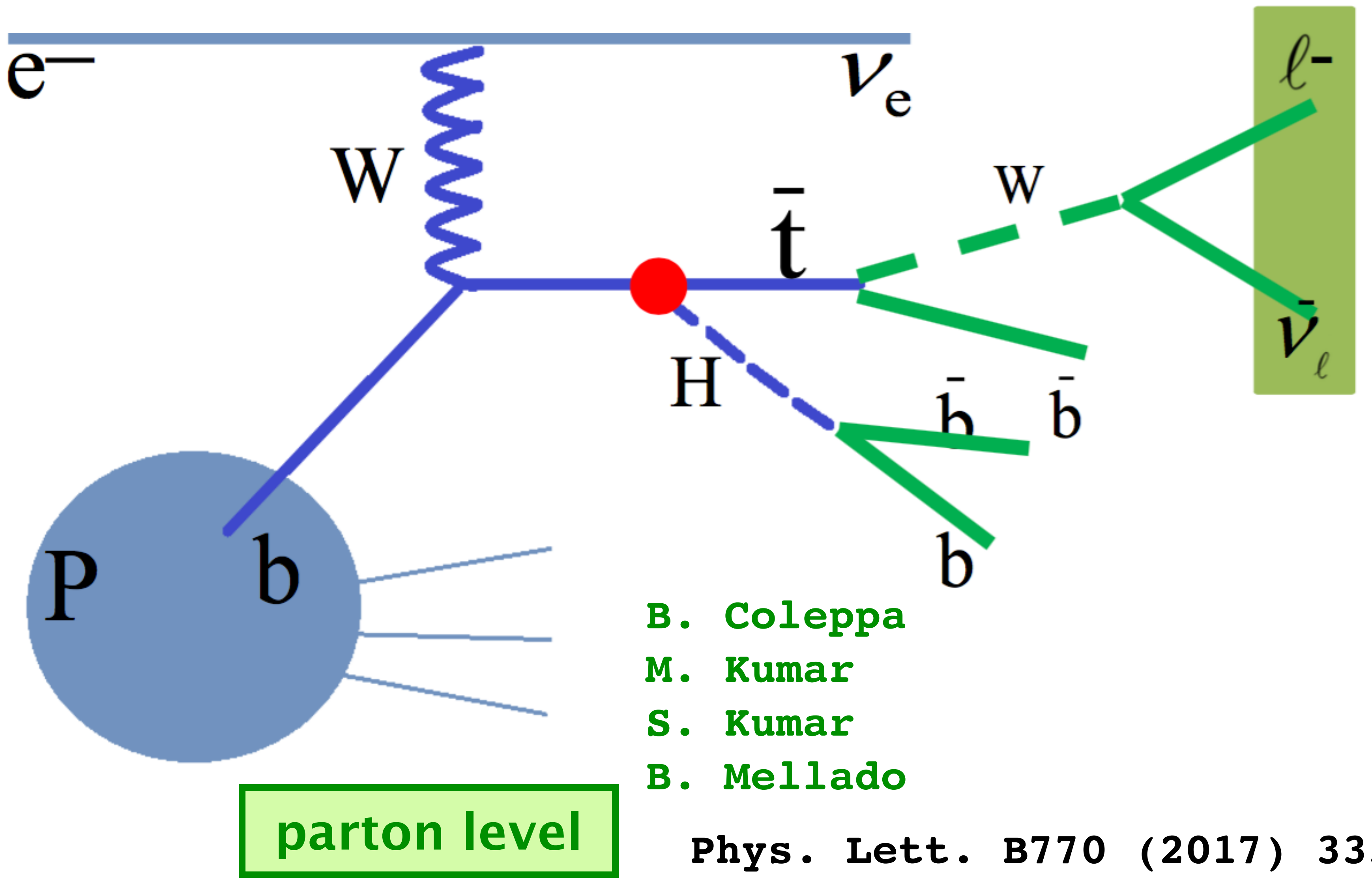
$$\Gamma^{(\mathrm{BSM})}_{\mu\nu}(p,q) = \frac{-g}{M_W}\left[\lambda\left(p.q\, g_{\mu\nu} - p_\nu q_\mu\right) + i\lambda'\, \epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

CP-conserving　　**CP**-violating

CP Studies at LHeC

C. Swanenberger at 2nd FCC physics workshop

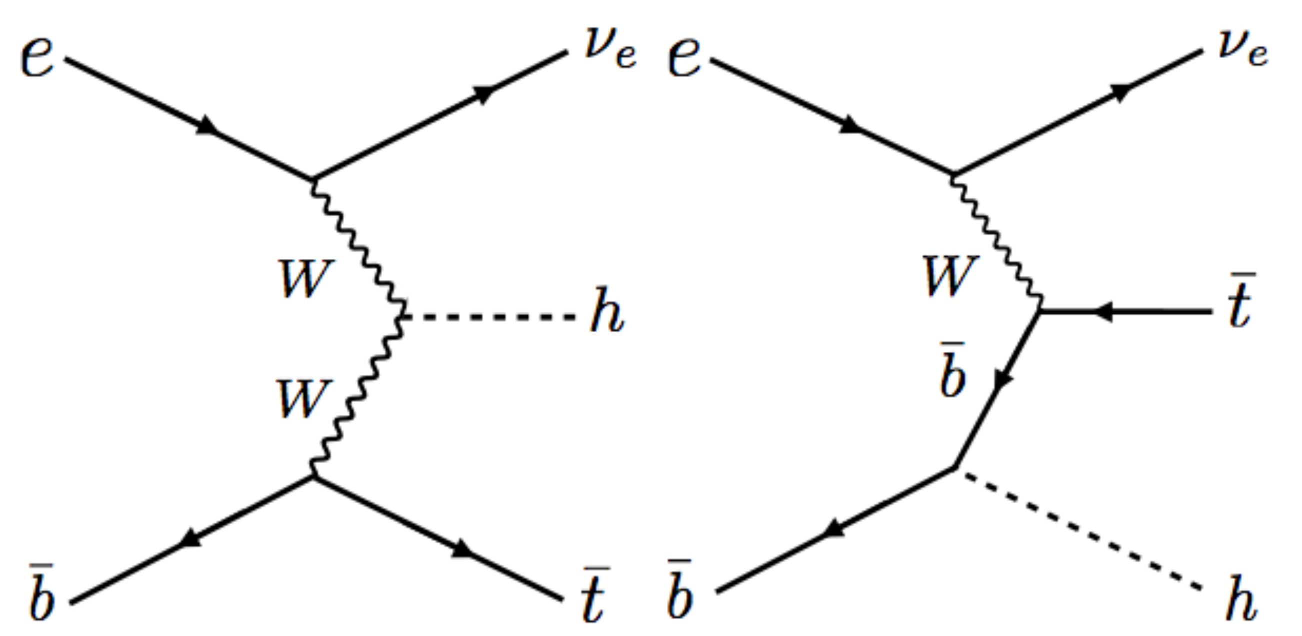
LHeC allows access to CP structure of *WWH* and *ttH* coupling



B. Coleppa
M. Kumar
S. Kumar
B. Mellado

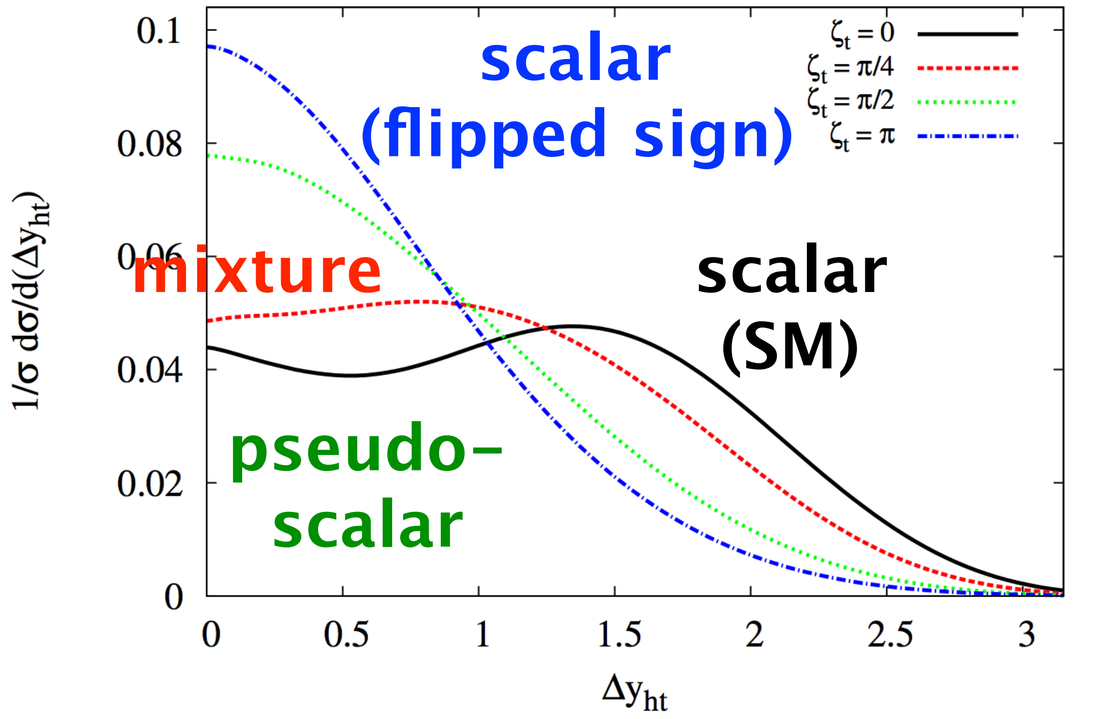
Phys. Lett. B770 (2017) 335

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]t\,h$$

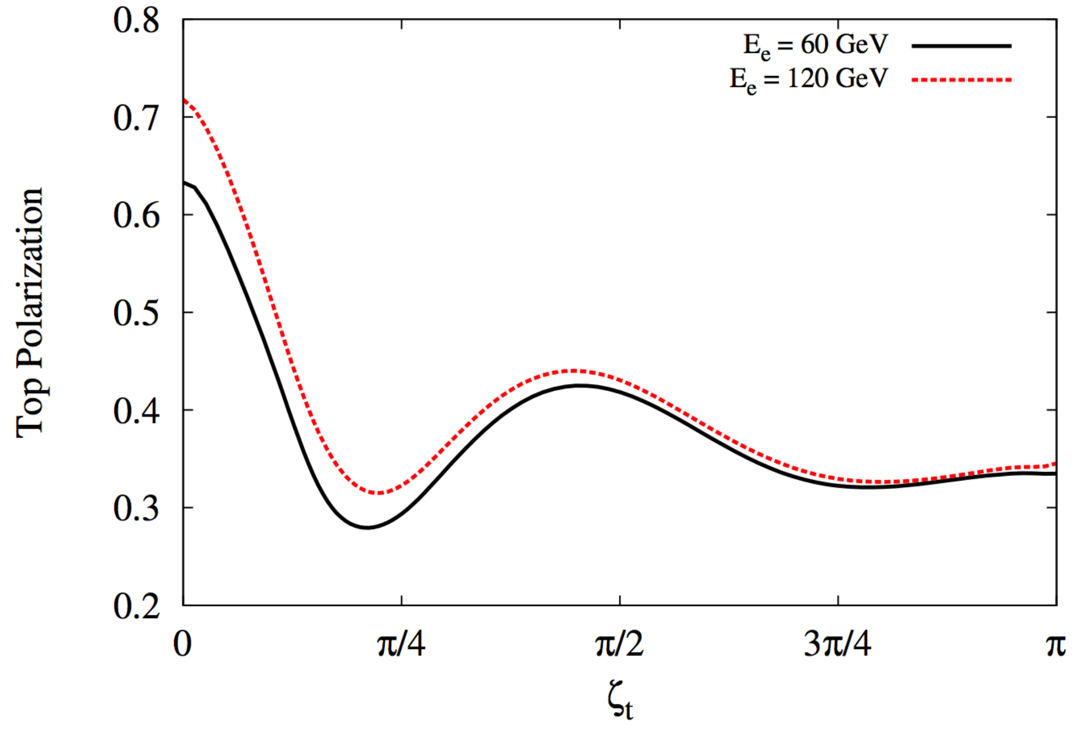


LHeC

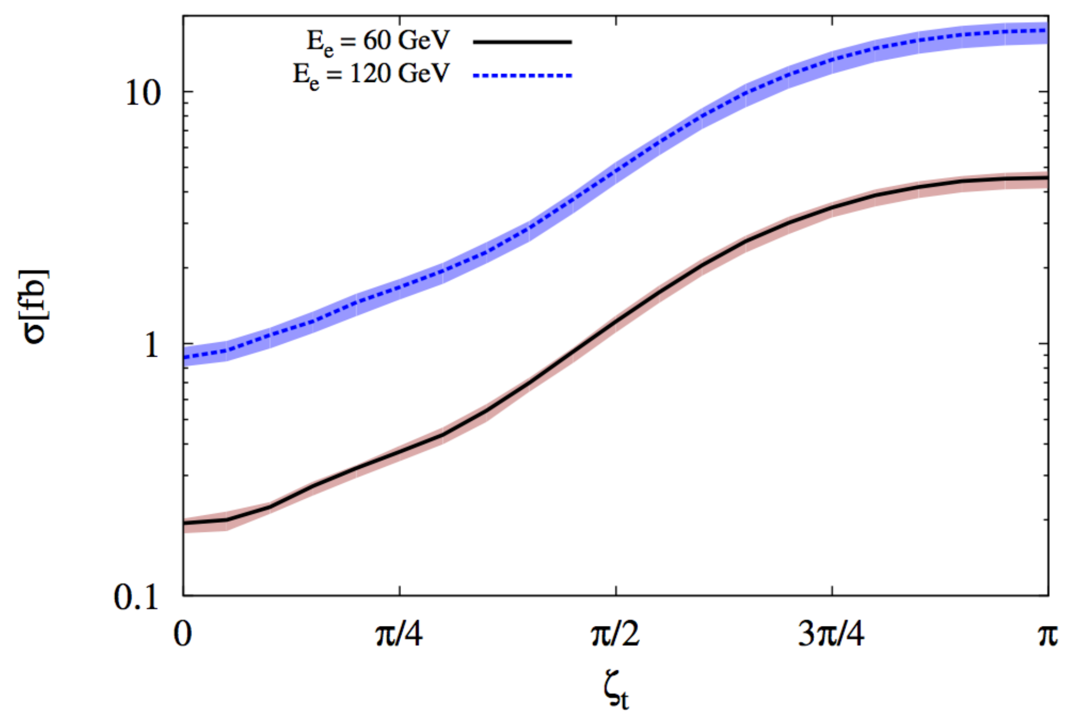
rapidity difference (H,$\bar{t}$)



top polarisation



fiducial incl. cross-section



Differential Cross Sections

Is the devil in the detail?

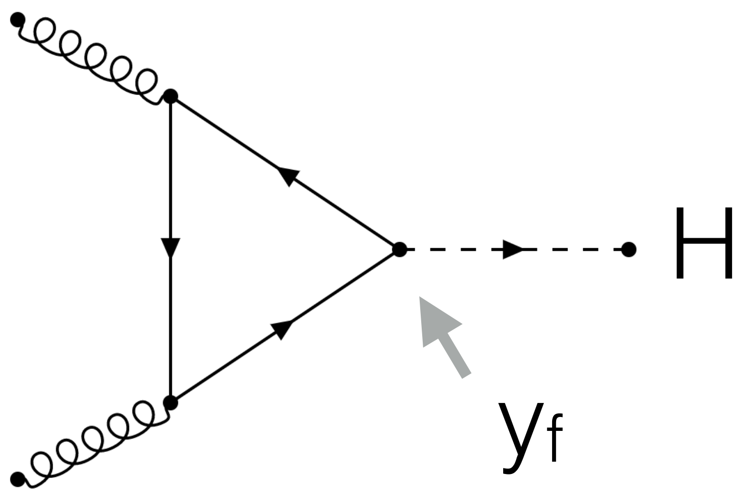
Differential Cross Sections

Thomas Klinjsma, HL/HE
LHC Meeting, 8th April 2018

Transverse momentum $p_T(H)$

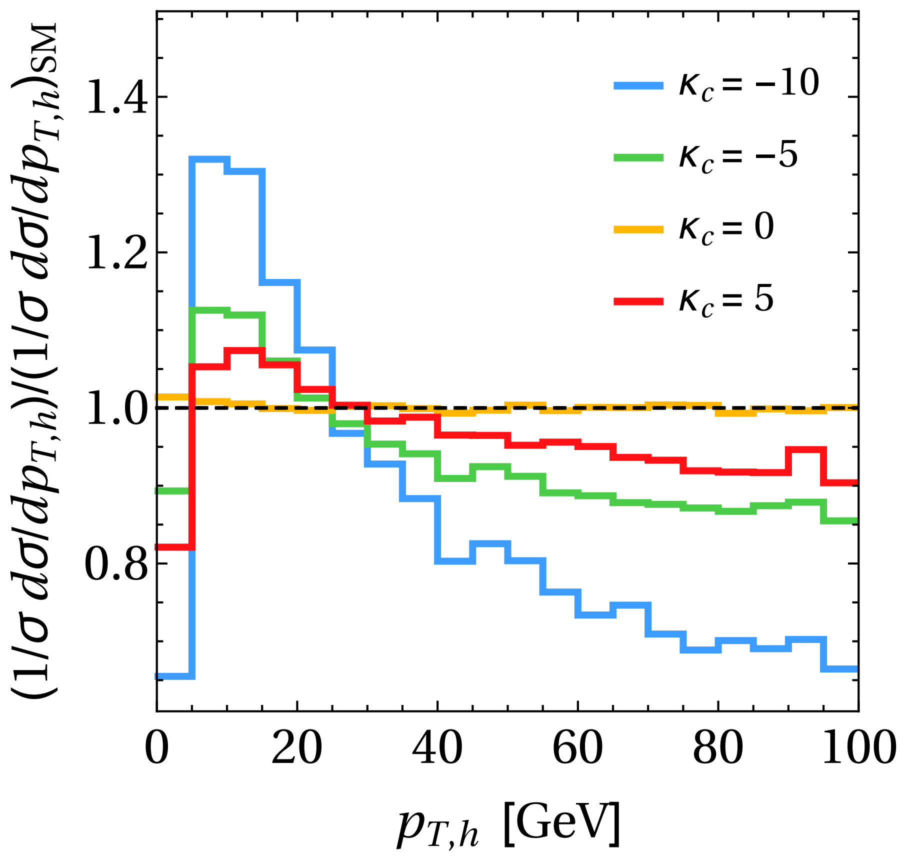
➡Sensitivity to modifications of effective Higgs Yukawa couplings

➡Sensitivity to finite top mass effects

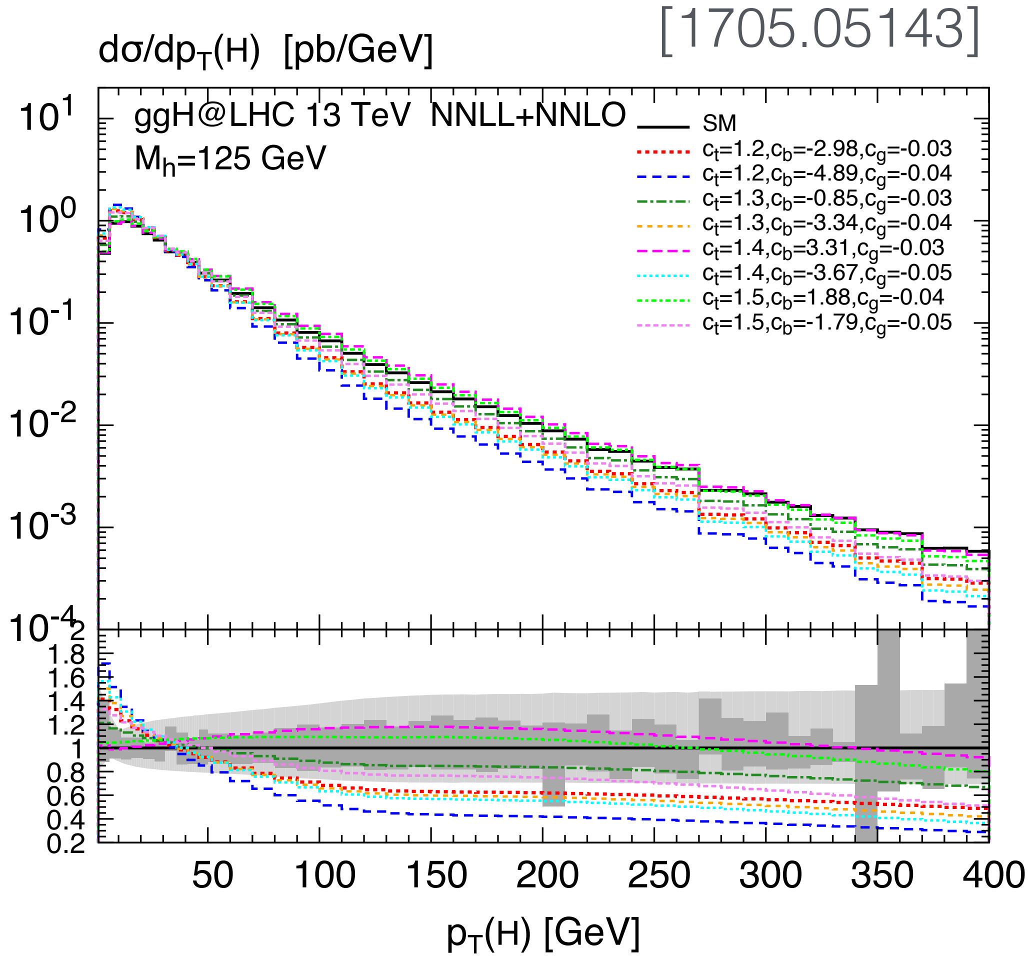


$$y_f = \kappa_f \cdot y_f^{SM}$$

Bishara, Haisch, Monni, Re (2016) [1606.09253]

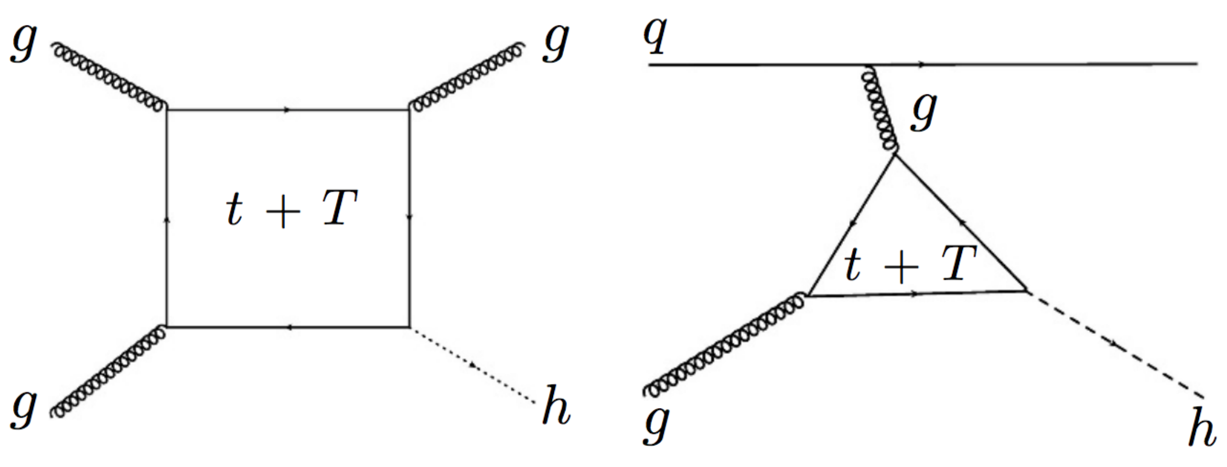


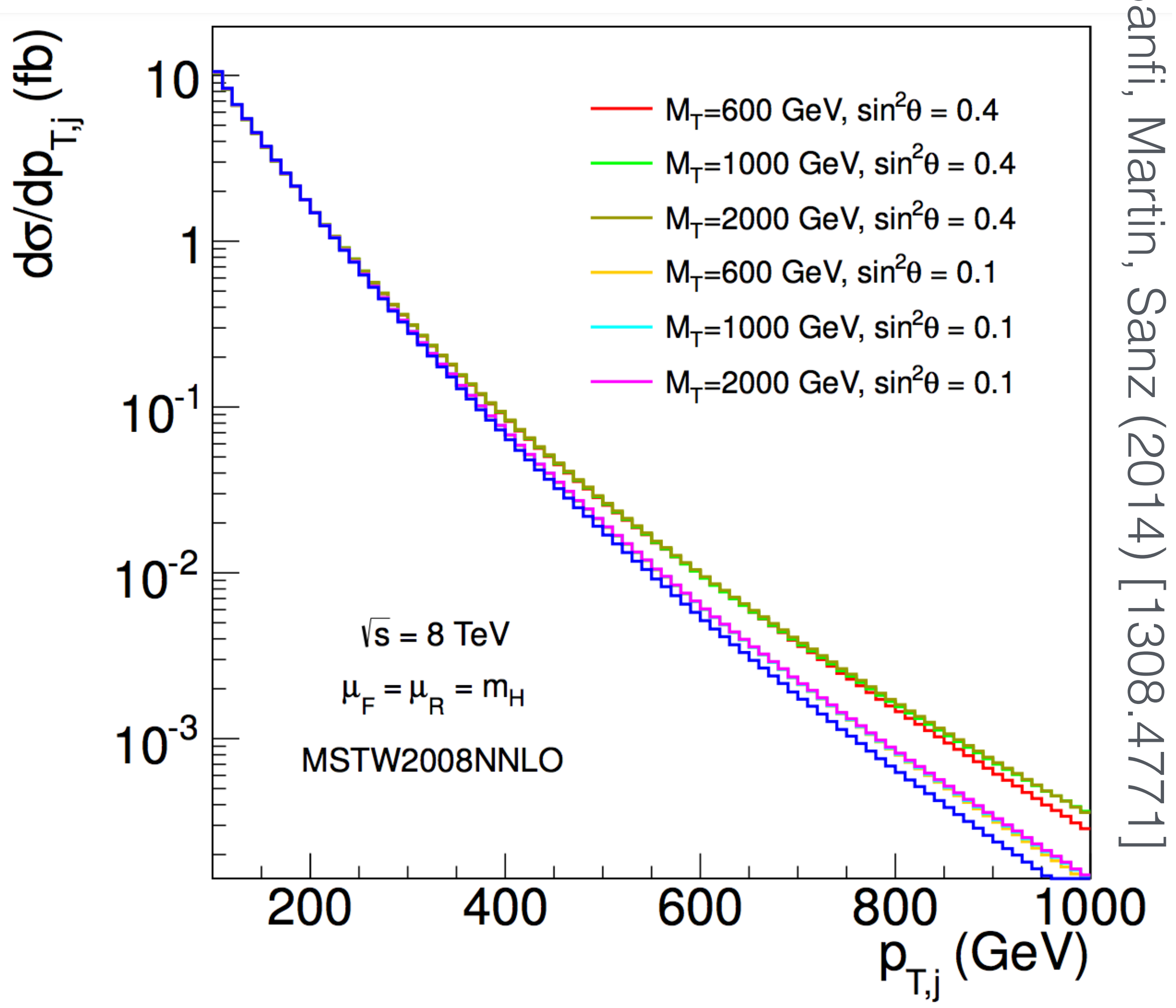
Grazzini, Ilnicka, Spira, Wiesemann (2017) [1705.05143]



Jet multiplicity N_{jets} & p_T of the first jet

➡New physics in the loop, sensitivity at high p_T

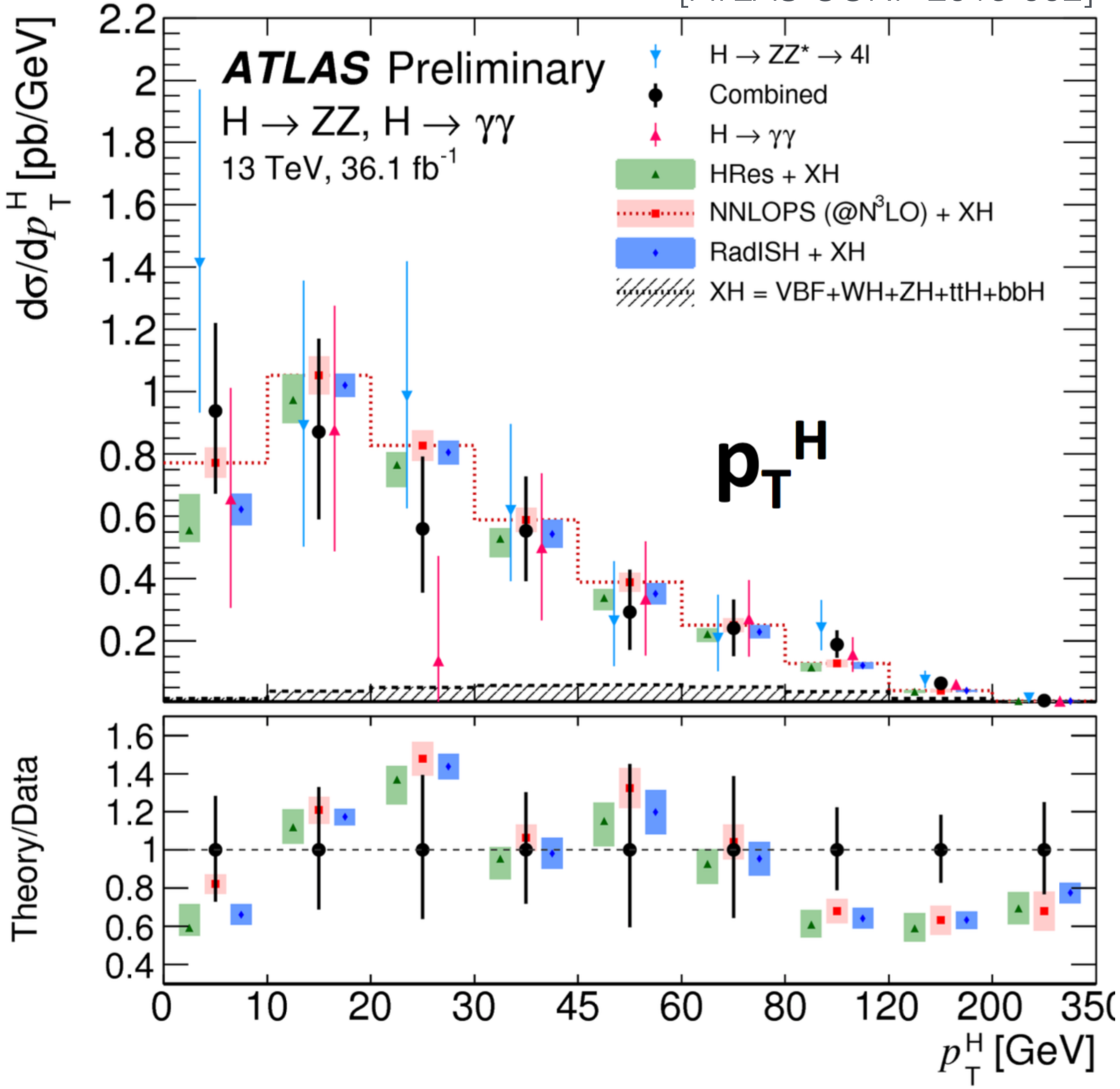


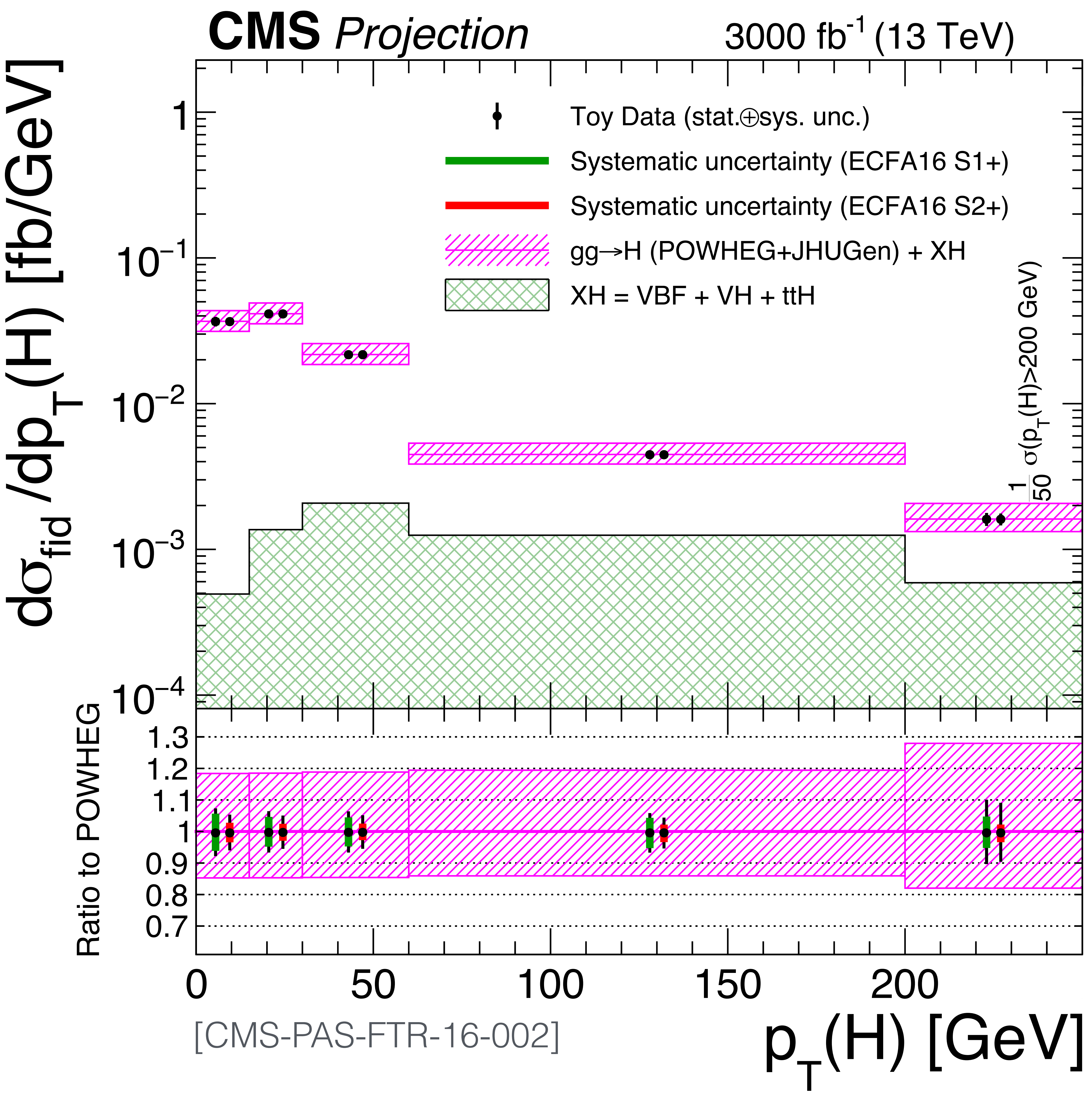


Banfi, Martin, Sanz (2014) [1308.4771]

Differential Cross Sections at HL-LHC

[ATLAS-CONF-2018-002]





[CMS-PAS-FTR-16-002]

Personal Conclusions

- Lots still to learn about the Higgs boson: All possible future colliders will tell us much more about Higgs properties!
- If you (only) want measure Higgs properties & couplings soon, an e^+e^- collider is the best option.
- $\sqrt{s} = 250$ **GeV** (ILC250, FCCee): *ZH* production ⇒ good
- $\sqrt{s} = 380$ **GeV** (CLIC380, FCCee): adds $WW \to \nu\bar{\nu}H$ production ⇒ better
- $\sqrt{s} > 550$ - **600 GeV** (ILC upgrade?, CLIC1500)

  adds $t\bar{t}H$ and *ZHH* production ⇒ best

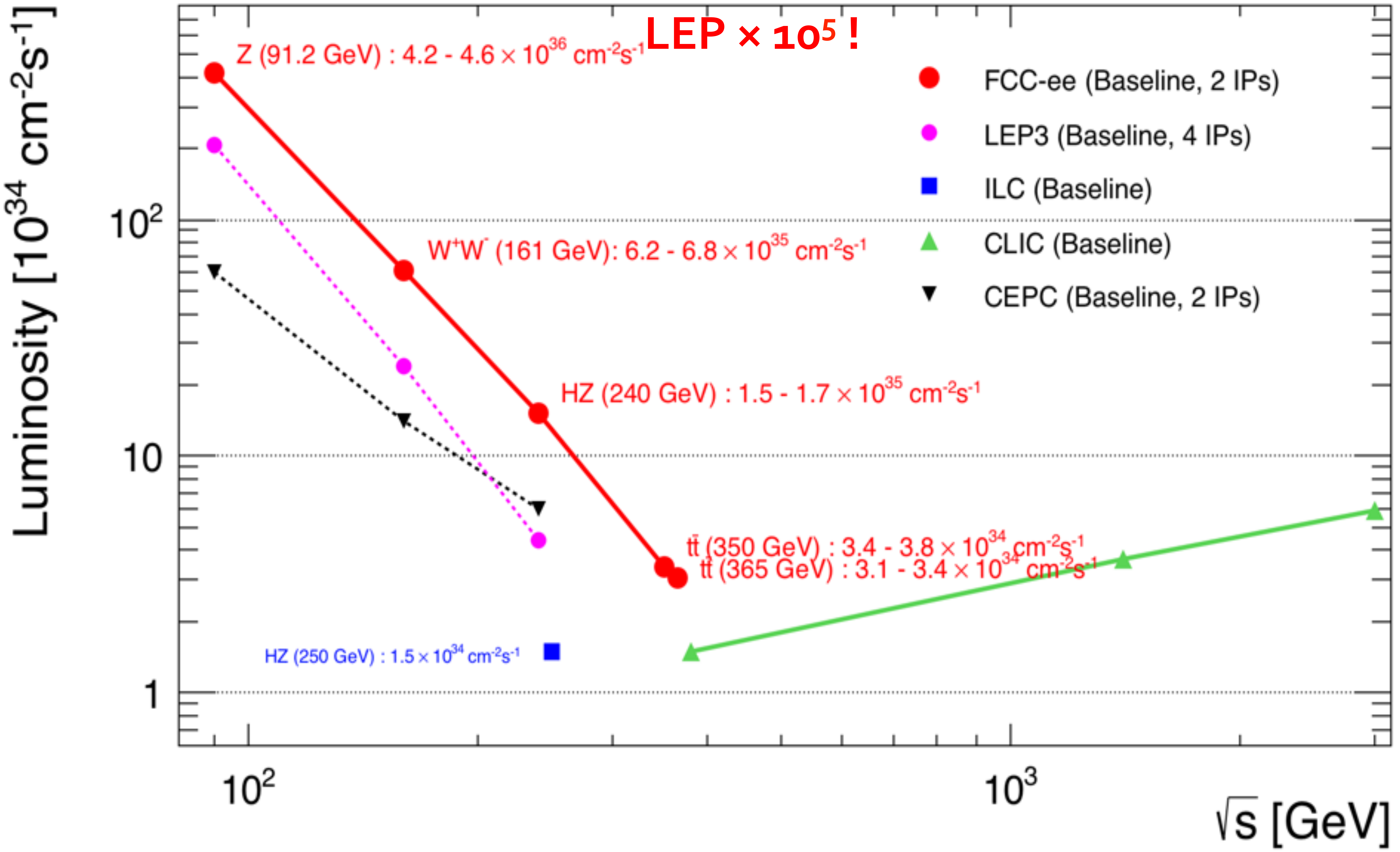
Backup

What kind of Higgs?

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [38]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [39]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [39]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [39]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [40]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [41]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [42]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [43]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [44]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Table 3: Percent deviations from SM for Higgs boson couplings to SM states in various new physics models. These model points are unlikely to be discoverable at 14 TeV LHC through new particle searches even after the high luminosity era ($3\,\mathrm{ab}^{-1}$ of integrated luminosity). From [20].

Patrizia Azzi, FCC week 2018



Indirect constraint on Γ_H from offshell production

- $\sigma_{offshell} \sim g_g^2 g_V^2$ does not depend on the total width Γ_H, $\sigma_{onshell}$ does
  - In terms of coupling modifiers

$$\frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell, SM}}} = \mu_{\text{off-shell}} = \kappa^2_{g,\text{off-shell}}\cdot\kappa^2_{V,\text{off-shell}} \qquad \frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}}\cdot\kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

- Under the assumption of equal on-peak and off-peak coupling modifiers, limit on $\mu_{offshell}$ can be reinterpreted, combined with $\mu_{onshell}$, as **limit on Γ_H**
  - Strong assumption , $k_g(s)$ sensitive to possible new physics at higher mass scales
  - New physics which modify off-shell signal strength do not change bkg predictions

$$\kappa^2_{g,\,\text{on-shell}}\,\kappa^2_{V,\,\text{on-shell}} \leq \kappa^2_{g,\,\text{off-shell}}\,\kappa^2_{V,\,\text{off-shell}}$$

- Latest experimental results (WW+ZZ in Run1 for ATLAS and CMS, 4l Run2 CMS) :

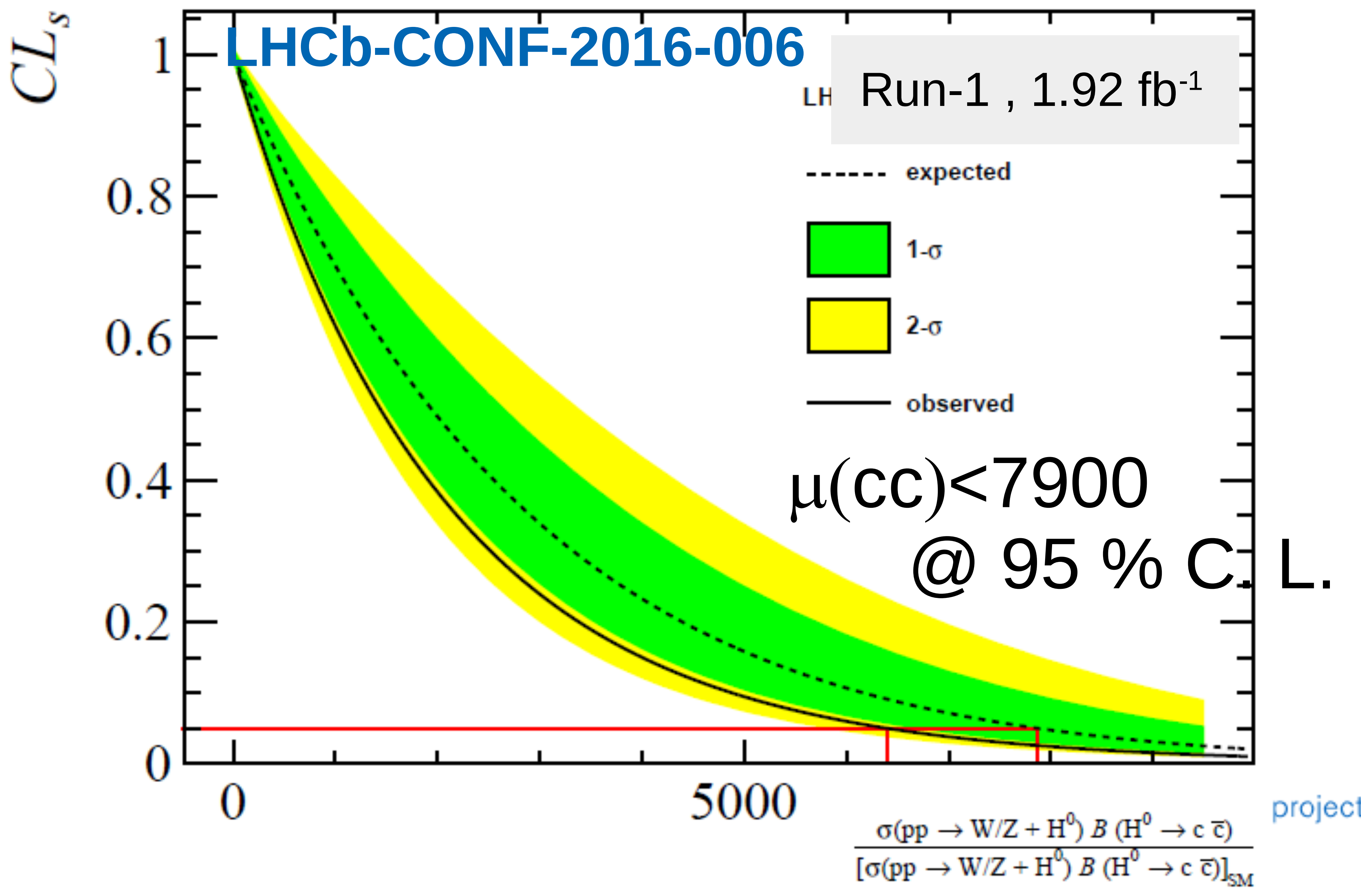
ATLAS Run1	CMS Run1	CMS Run2
Γ_H < 22.7 MeV @ 95%CL (<33 MeV exp.)	Γ_H < 13MeV @ 95%CL (<26MeV exp.)	4l: Γ_H < 41 MeV @ 95%CL (<32 MeV exp.)
ATLAS Run1 Eur.Phys.J.C (2015) 75:335	CMS Run1 JHEP 09 (2016) 051	CMS Run2 ,12.9 fb^{-1} CMS PAS HIG-16-033

- For HL-LHC most of the consideration done for $\mu_{offshell}$ valid here as well
  - In this interpretation, the uncertainty on $\mu_{off\text{-}shell}$ dominates
    - ~ 5% precision achievable for $\mu_{onshell}$ ZZ
  - Estimate using 4l alone by ATLAS (10% syst on R^B_{H*})

$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV ATL-PHYS-PUB-2015-024

LHC: $H \to c\bar{c}$

- Search for leptonic W/Z+ H→ bb/cc final states (Forward production)
- LHCb angular acceptance → Challenging for integrated cross sections and uncertainties



300 fb^{-1} at 14 TeV: $|\kappa_c| \lesssim 7$

↓

30% di-c-tagging efficiency: $|\kappa_c| \lesssim 4$

↓

better electron reconstruction: $|\kappa_c| \lesssim 3$

↓

further improvements: $|\kappa_c| \lesssim 2.2$

projections taken from talk by Mike Williams

- First publication H→cc from LHCb → Possible reach 5 xSM @ 300 fb^{-1}
- Extrapolation H → J/Ψ γ @ HL-LHC : 15 xSM @ 3000 fb^{-1} (ATLAS)
- ZH→ cc @ Run-2 (arxiv:1802.04329): μ < 110 (150^{+80}_{-40}) @ 95 % C.L. (ATLAS)