European Strategy for Particle Physics

PARALLEL 1 / **Electroweak Physics**

Higgs and Top Inputs

Christian Grefe (University of Bonn)

23-27 JUNE 2025 Lido di Venezia

History of the Higgs Boson

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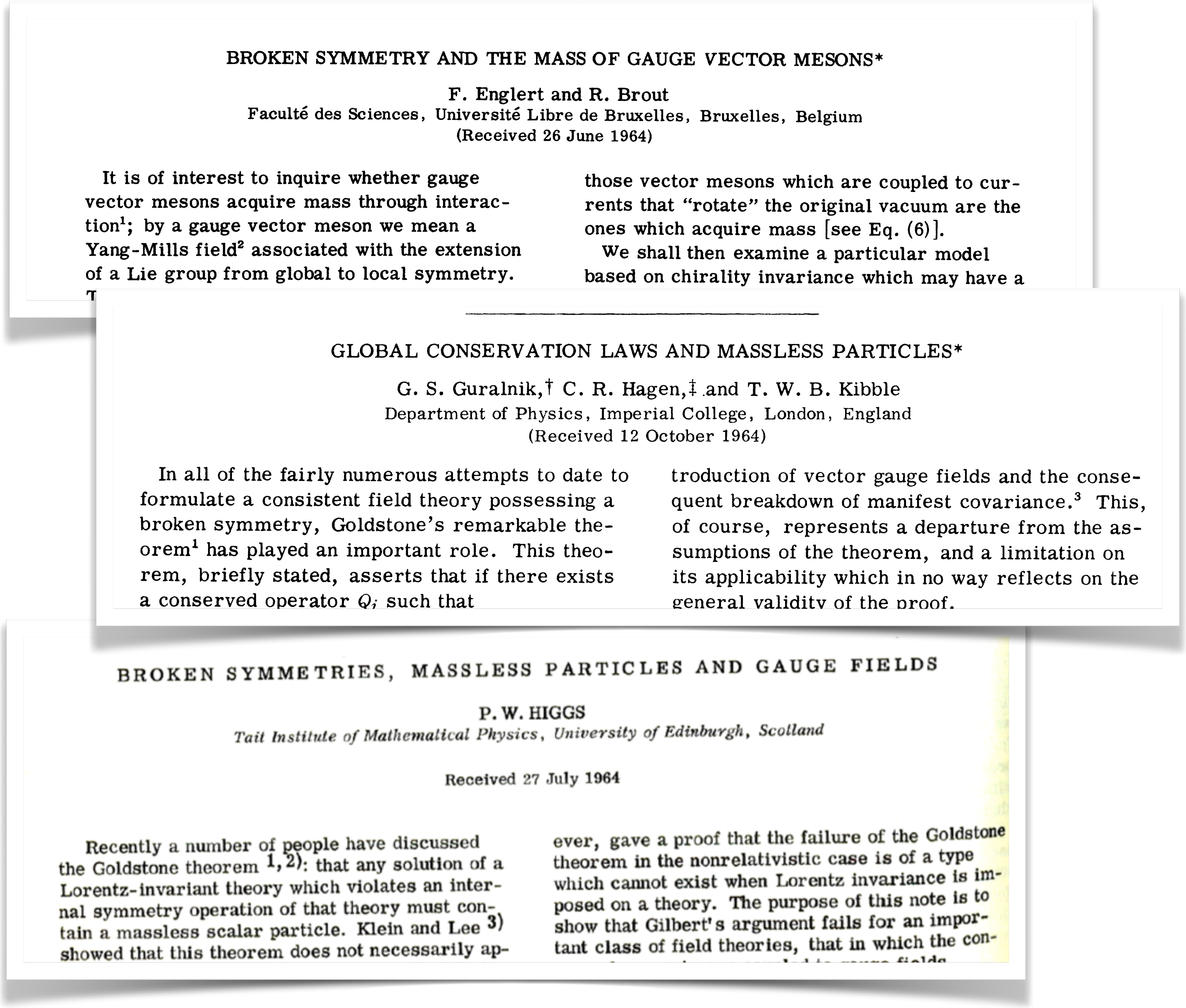
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble

Department of Physics, Imperial College, London, England

(Received 12 October 1964)

In all of the fairly numerous attempts to date to formulate a consistent field theory possessing a broken symmetry, Goldstone's remarkable theorem[1] has played an important role. This theorem, briefly stated, asserts that if there exists a conserved operator Q_i such that troduction of vector gauge fields and the consequent breakdown of manifest covariance.[3] This, of course, represents a departure from the assumptions of the theorem, and a limitation on its applicability which in no way reflects on the general validity of the proof.

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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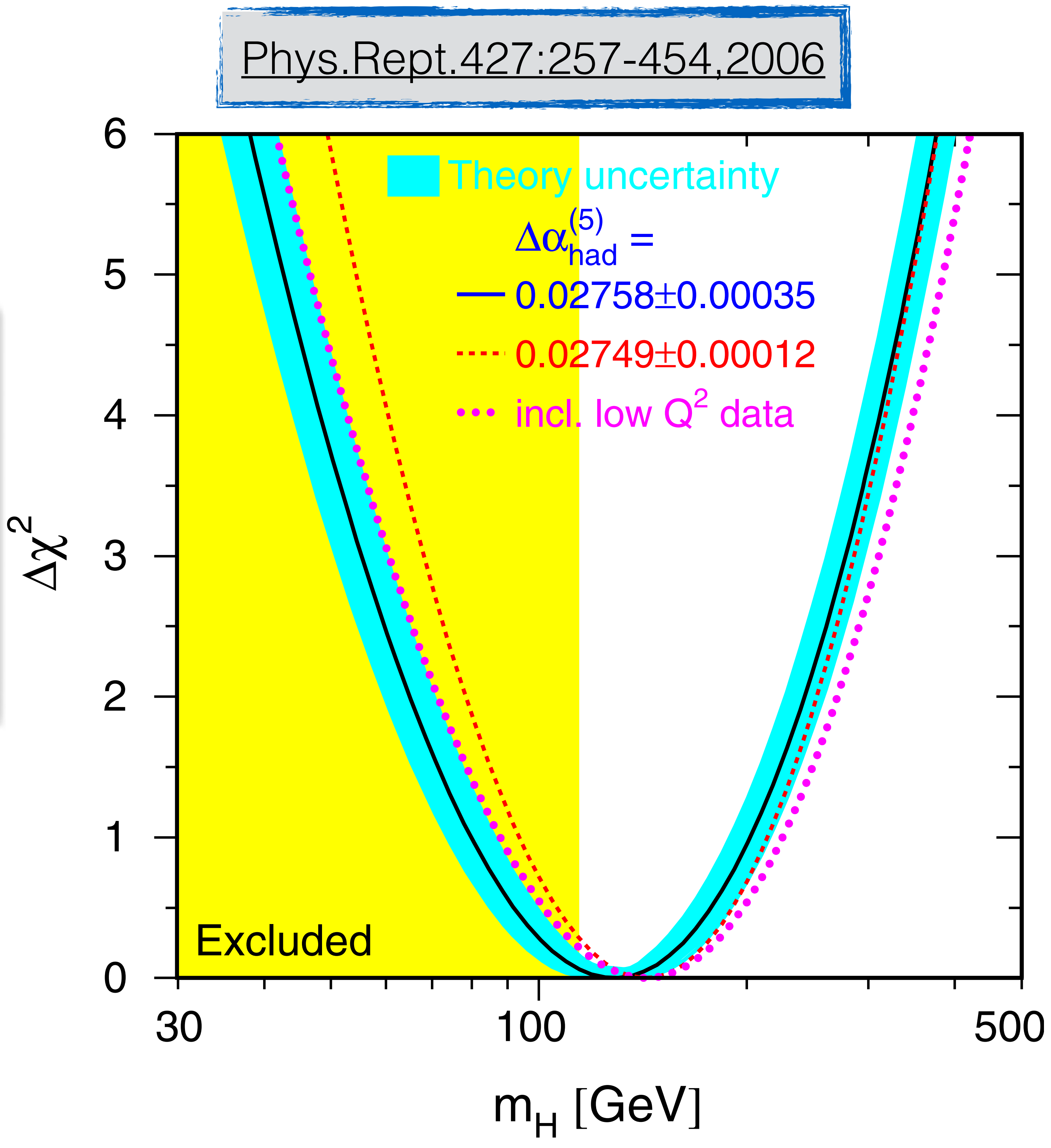
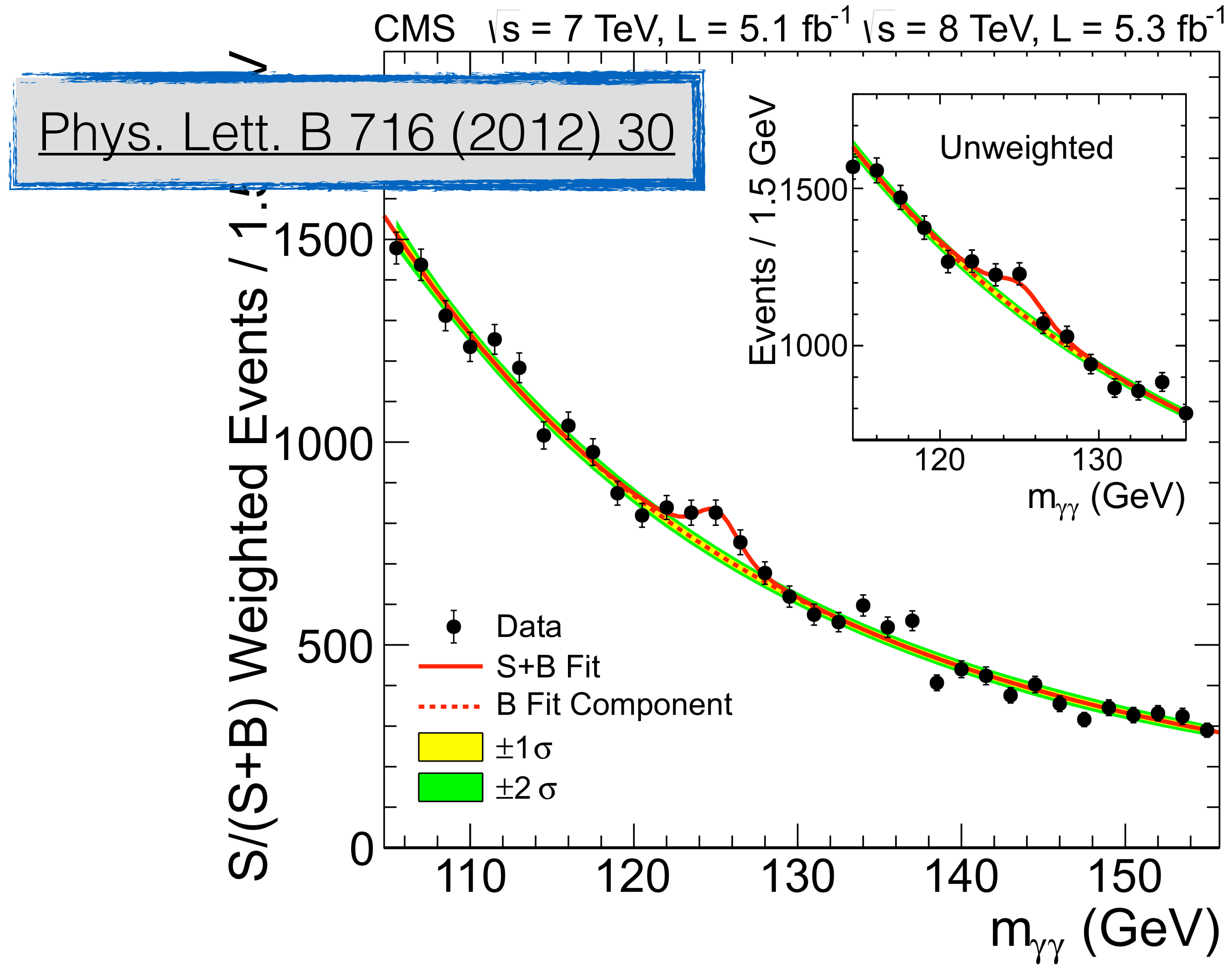
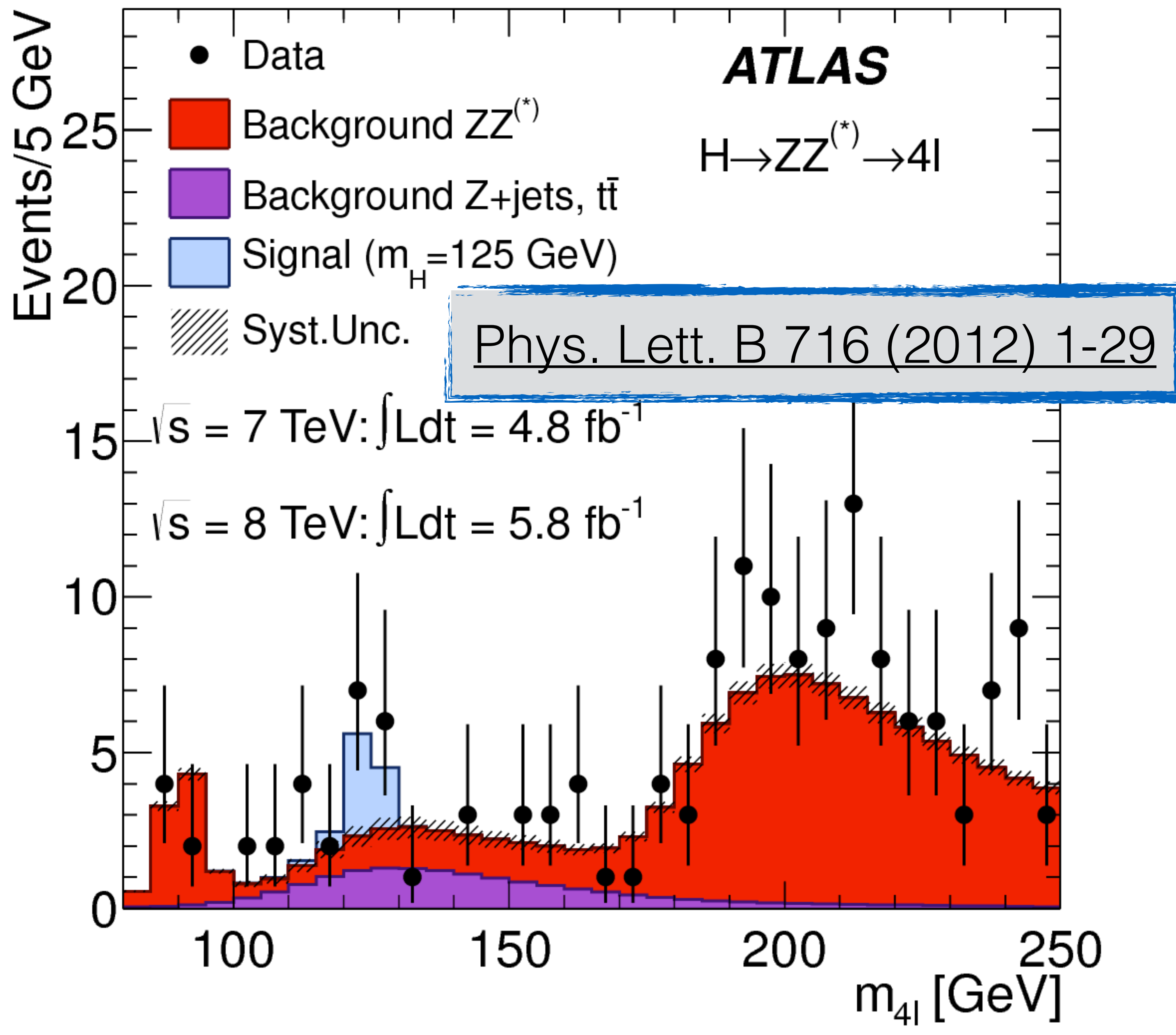
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

Recently a number of people have discussed the Goldstone theorem 1, 2): that any solution of a Lorentz-invariant theory which violates an internal symmetry operation of that theory must contain a massless scalar particle. Klein and Lee 3) showed that this theorem does not necessarily ap- ever, gave a proof that the failure of the Goldstone theorem in the nonrelativistic case is of a type which cannot exist when Lorentz invariance is imposed on a theory. The purpose of this note is to show that Gilbert's argument fails for an important class of field theories, that in which the con-

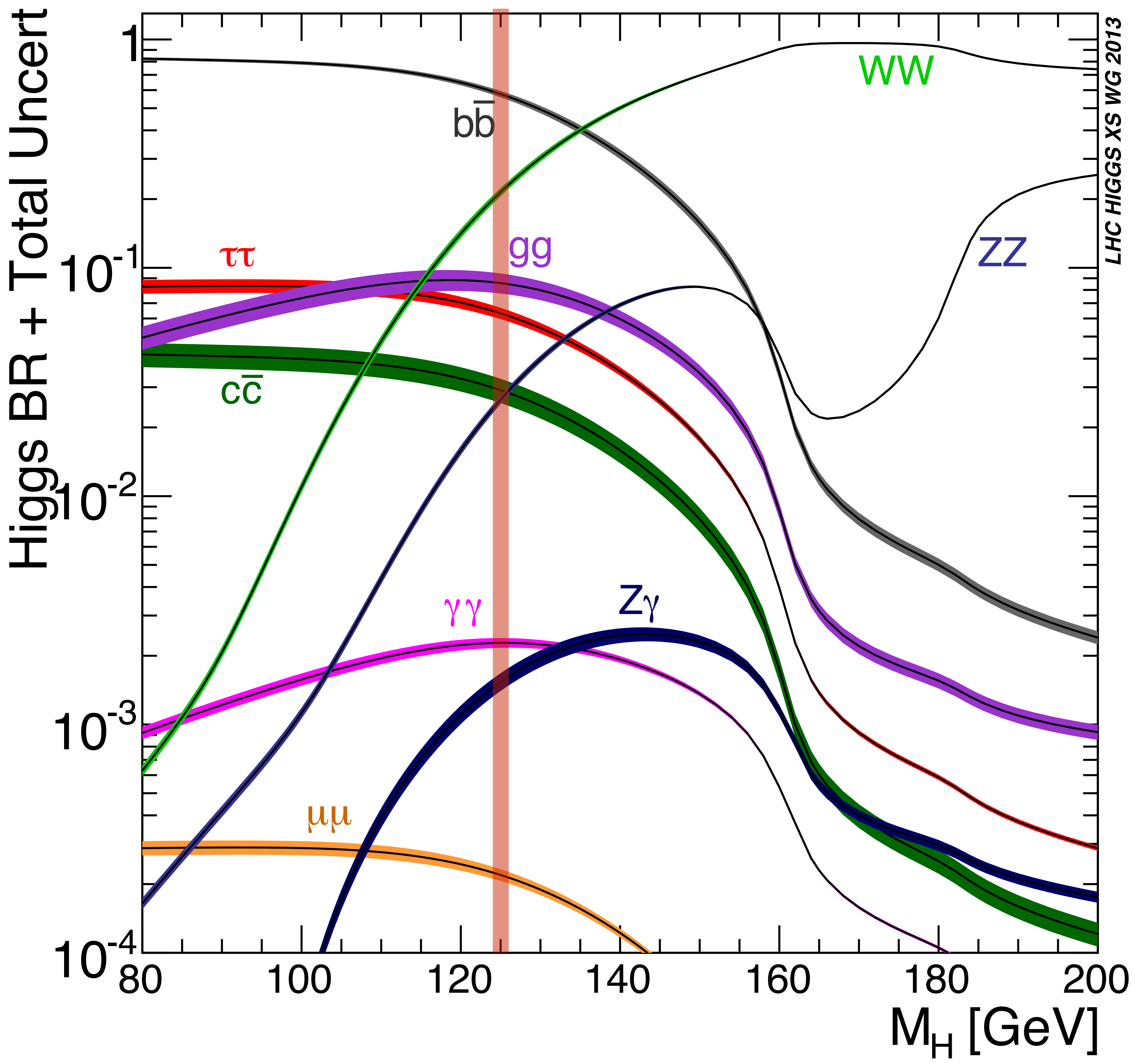




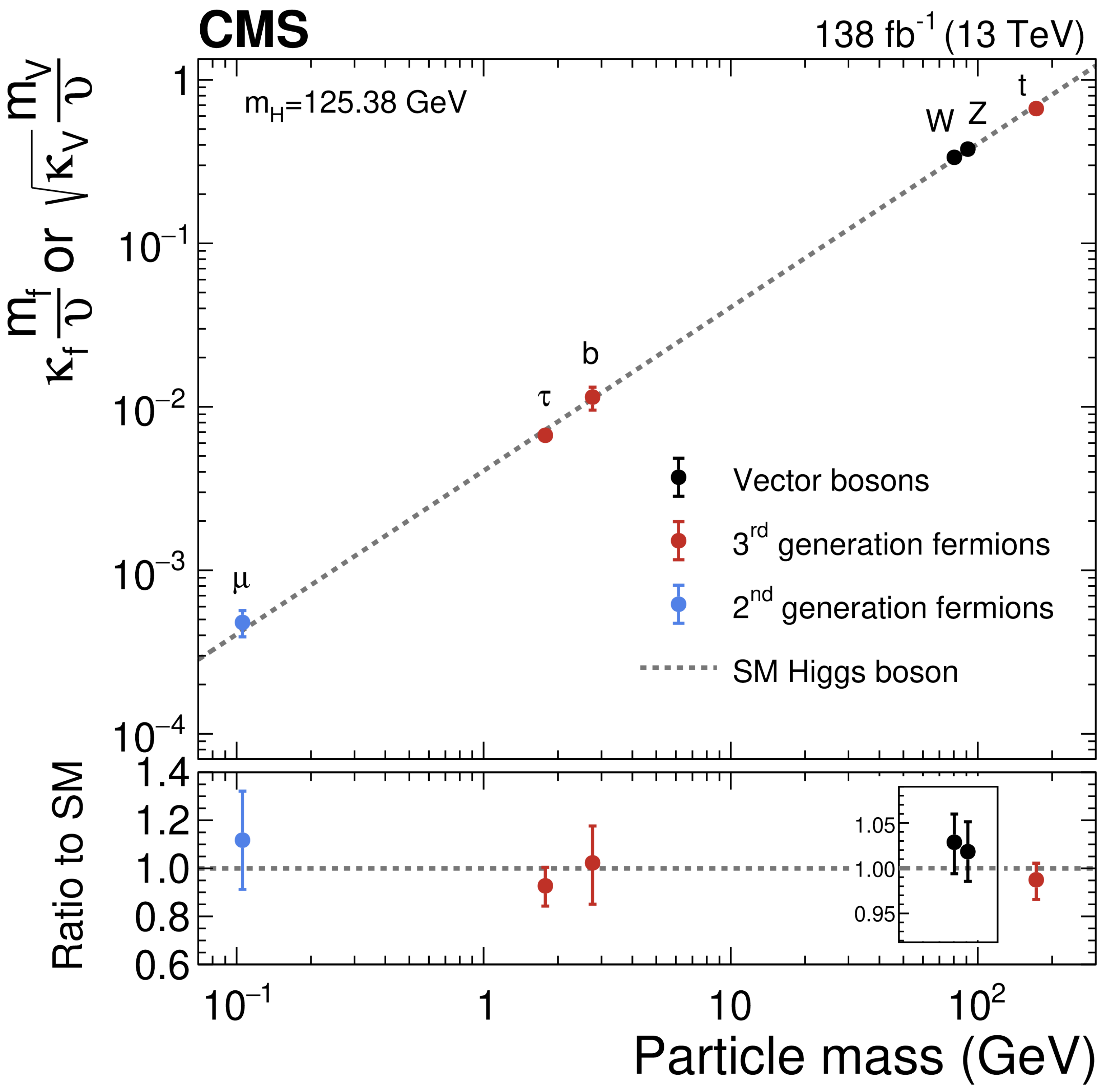


- Stringent constraints on Higgs sector from electroweak precision fits at LEP
- 50 years between theoretical prediction and experimental discovery

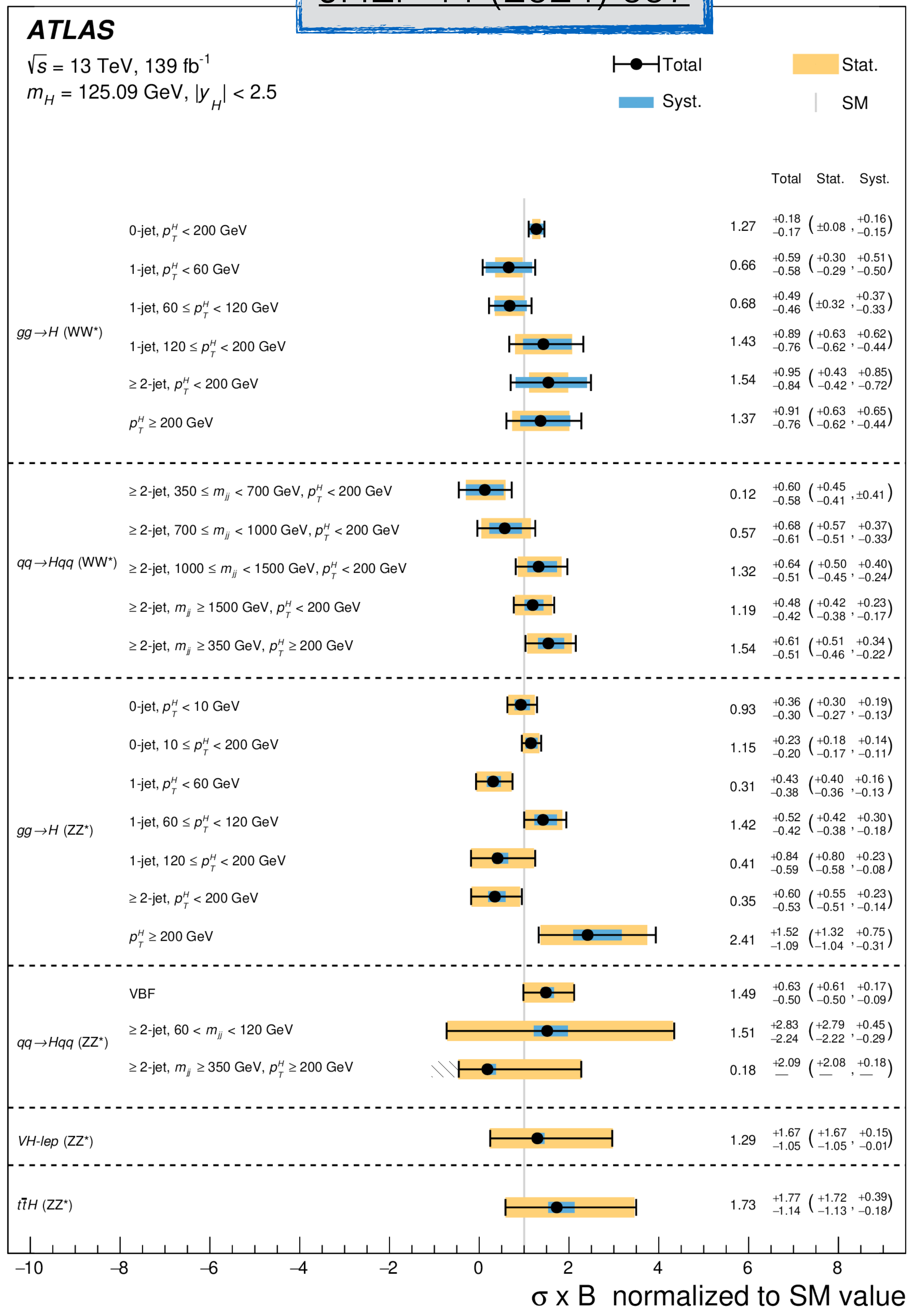
The Higgs Boson Today



Nature 607 (2022) 60-68



JHEP 11 (2024) 097



- Couplings to gauge bosons and 3rd generation fermions close to SM expectations (~10% precision), evidence for 2nd generation fermion coupling ($H \rightarrow \mu\mu$), all measurements consistent with CP-even scalar
- LHC experiments entered era of differential cross section measurements (EFT fits, etc.)

Project Overview

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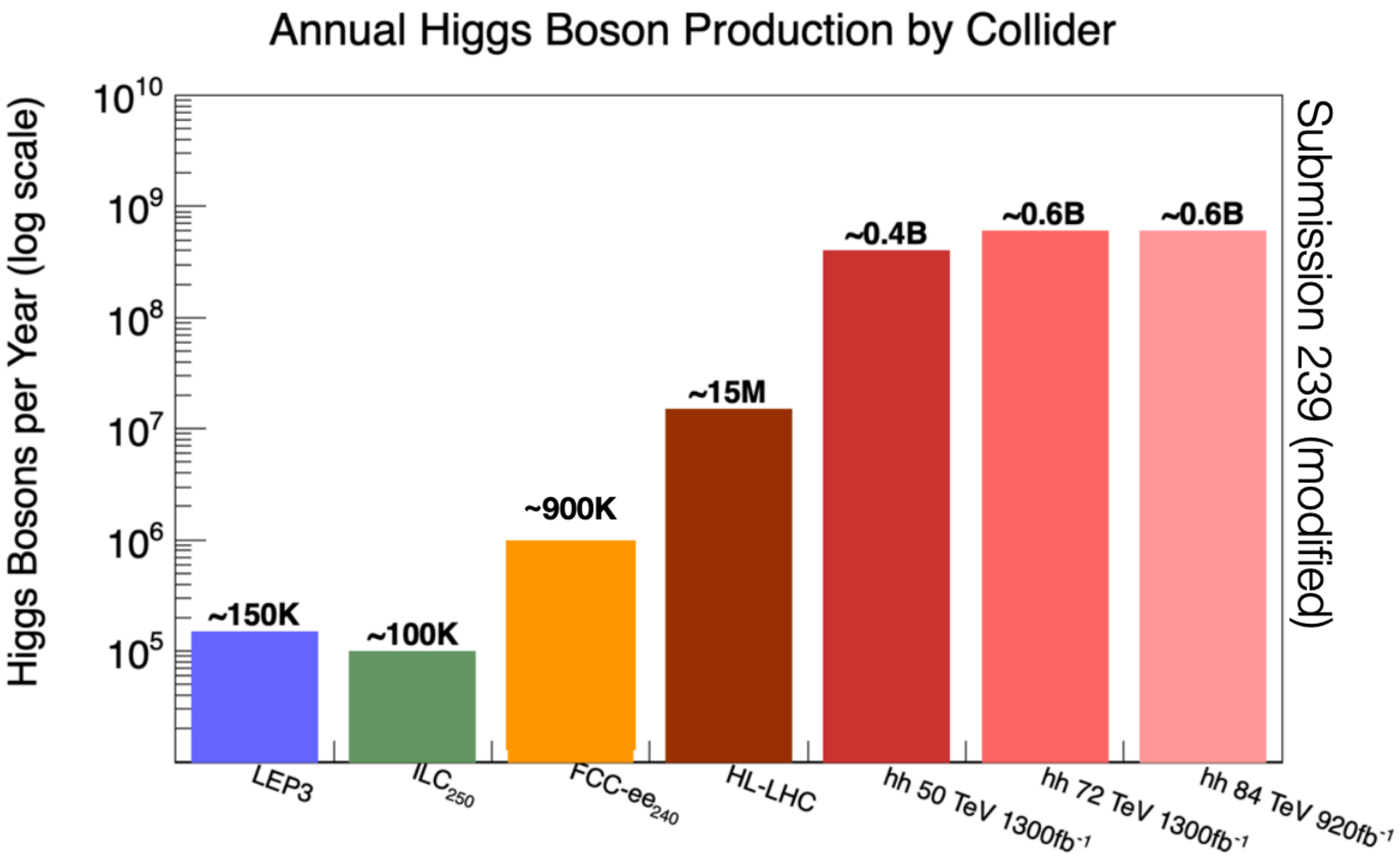
Focus of this talk

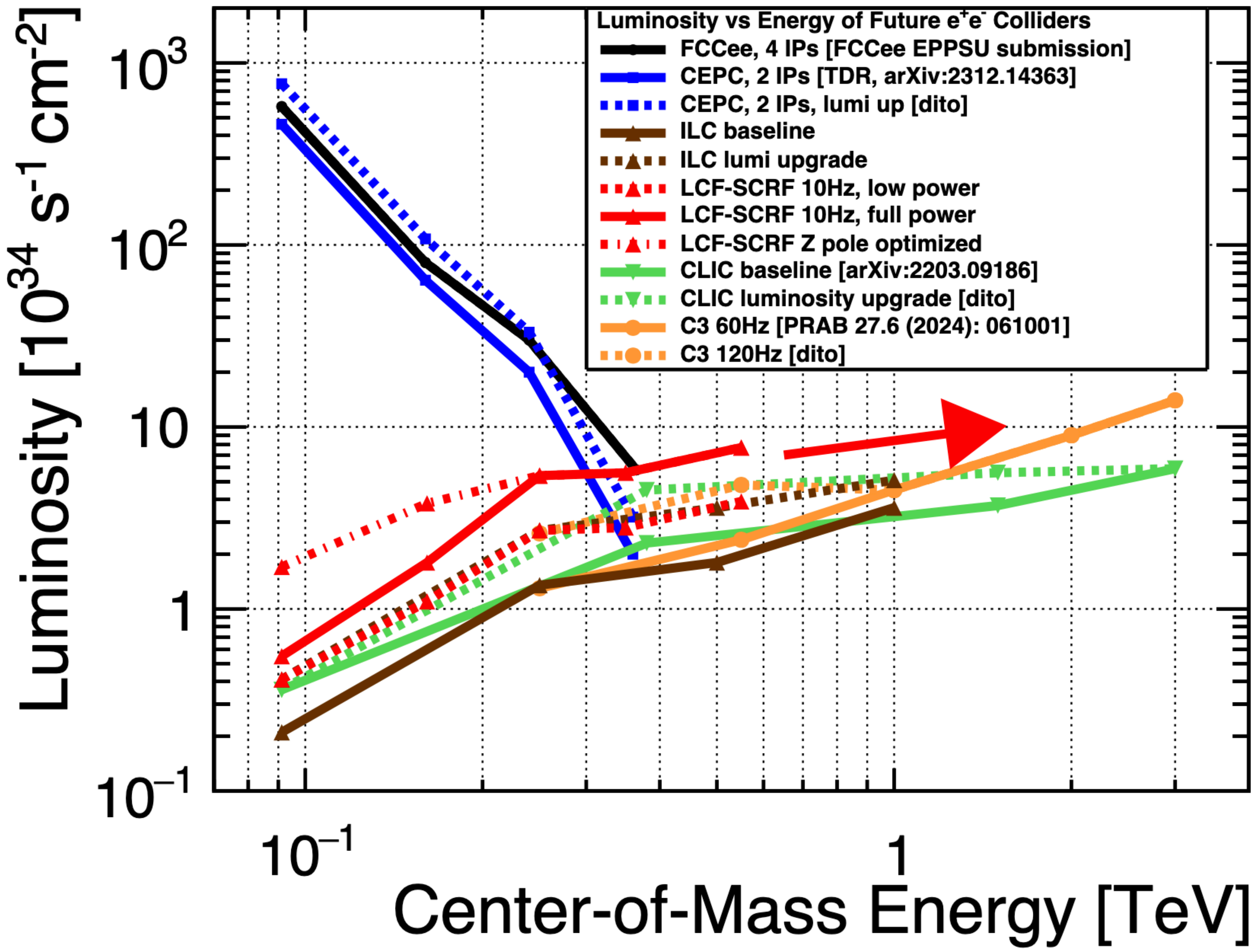
Project	IP	Z-pole (91.2 GeV)	WW (160 GeV)	Higgs (230-250 GeV)	Top (365 GeV)	Higher Energy
FCC-ee	4	205 ab^{-1} 4 year	19 ab^{-1} 2 year	11 ab^{-1} 3 year	3 ab^{-1} 5 year	—
FCC-hh	4	—	—	—	—	84.6 TeV: 0.6 ab^{-1} / year /IP
LEP3	2	53 ab^{-1} 5 years	5 ab^{-1} 4 years	2.5 ab^{-1} 6 years	—	—
Linear colliders	1	0.07 ab^{-1} 1 year	—	3 ab^{-1} 5+3 years	CLIC: 4.4 ab^{-1} 10 years	550 GeV: 8 ab^{-1} 1.5 TeV: 4 ab^{-1} 10 years
LHeC *	1	—	—	—	—	1 TeV for 6 years
Muon Collider	2	—	—	—	—	10 TeV: 10 ab^{-1} 8 years

* LHeC is not covered but has good sensitivity for $H \to WW$ and $H \to c\bar{c}$

- See Angela's slides for more details

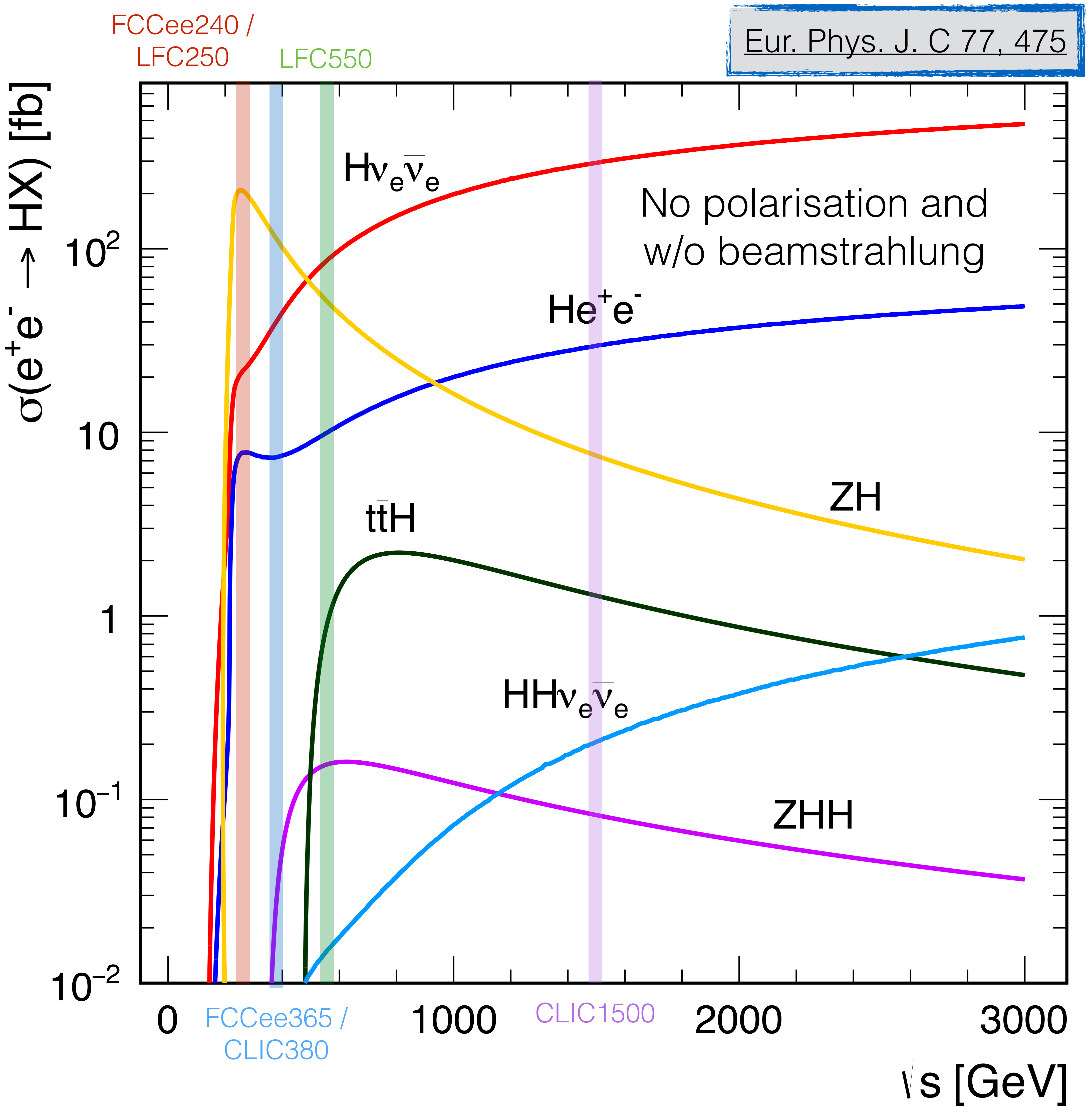
How many Higgs Bosons do we get?

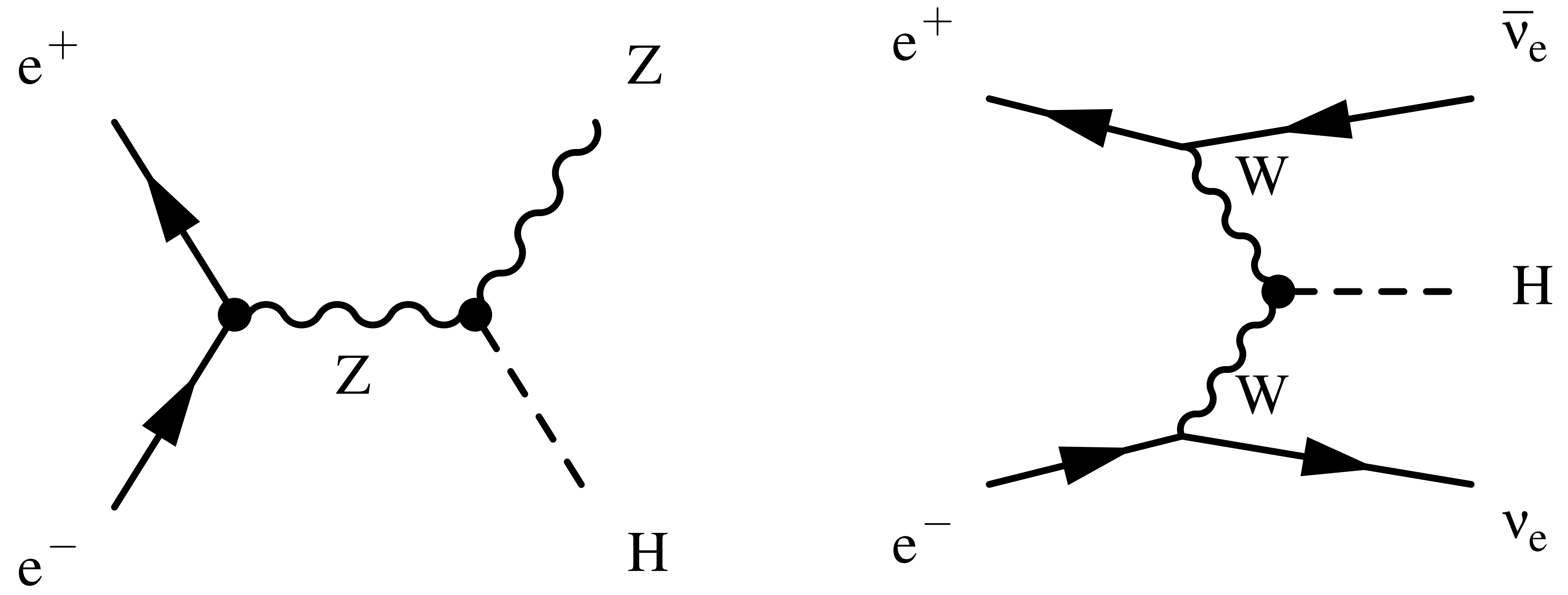




- e^+e^- colliders produce less Higgs bosons than the LHC, but they benefit from precise knowledge of initial stage and a "clean" experimental environment. pp colliders allow measurements of rare decays
  - e^+e^- **and** pp **colliders are complementary** to fully explore the Higgs sector
- Second stages of linear colliders (LCF550, CLIC1500) give access to to ttH, ZHH and $\nu_e\bar{\nu}_eHH$ production modes and higher luminosities

Higgs Production at e^+e^- colliders





- ZH associated production accessible above the kinematic threshold
- Vector boson fusion (VBF) cross section rises with higher $\sqrt{s}$
- Similarly, multi TeV muon collider has access to VBF production $\mu^+\mu^- \rightarrow \nu_\mu \bar{\nu}_\mu H$

Longitudinal e^-/e^+ Beam Polarisation

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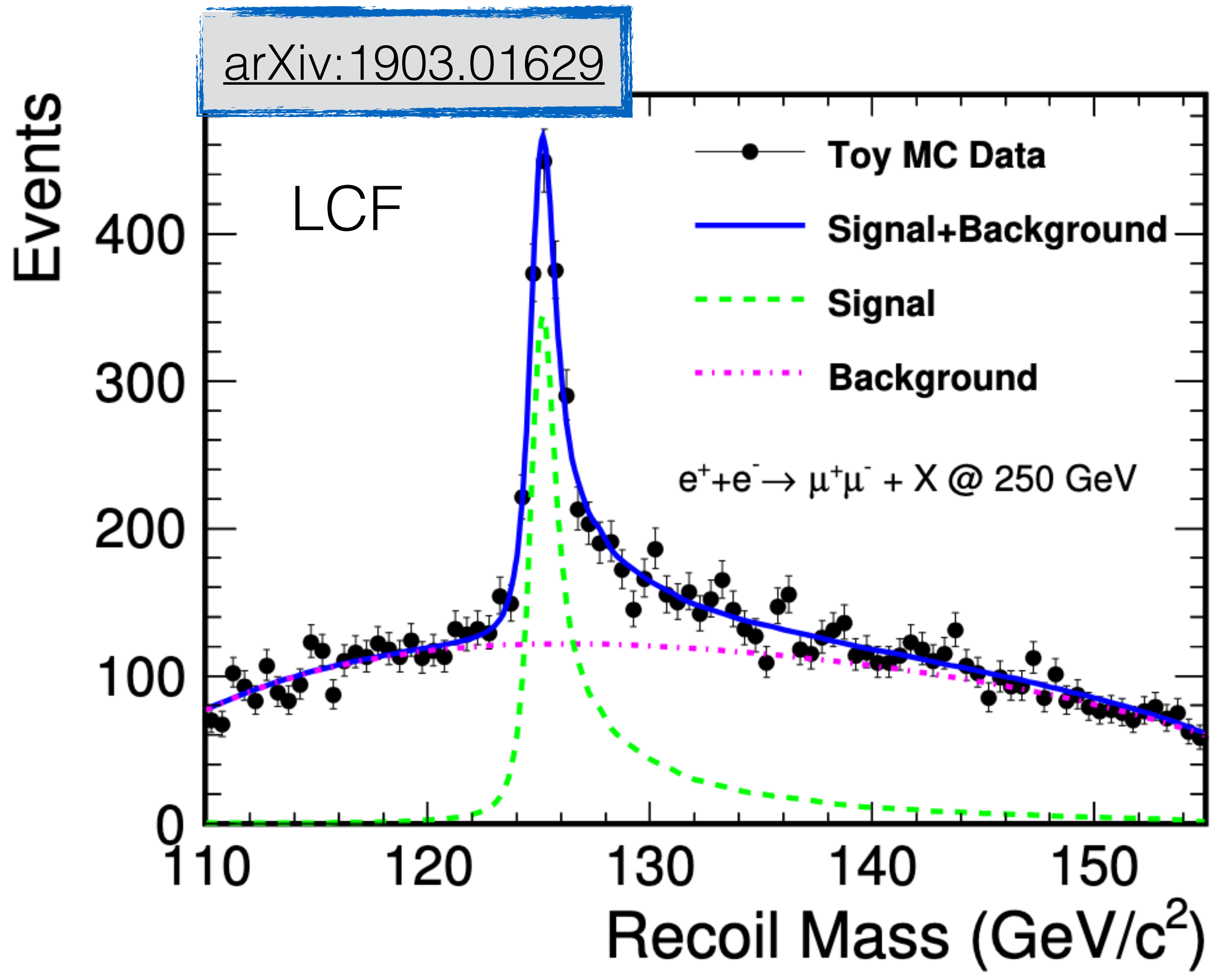
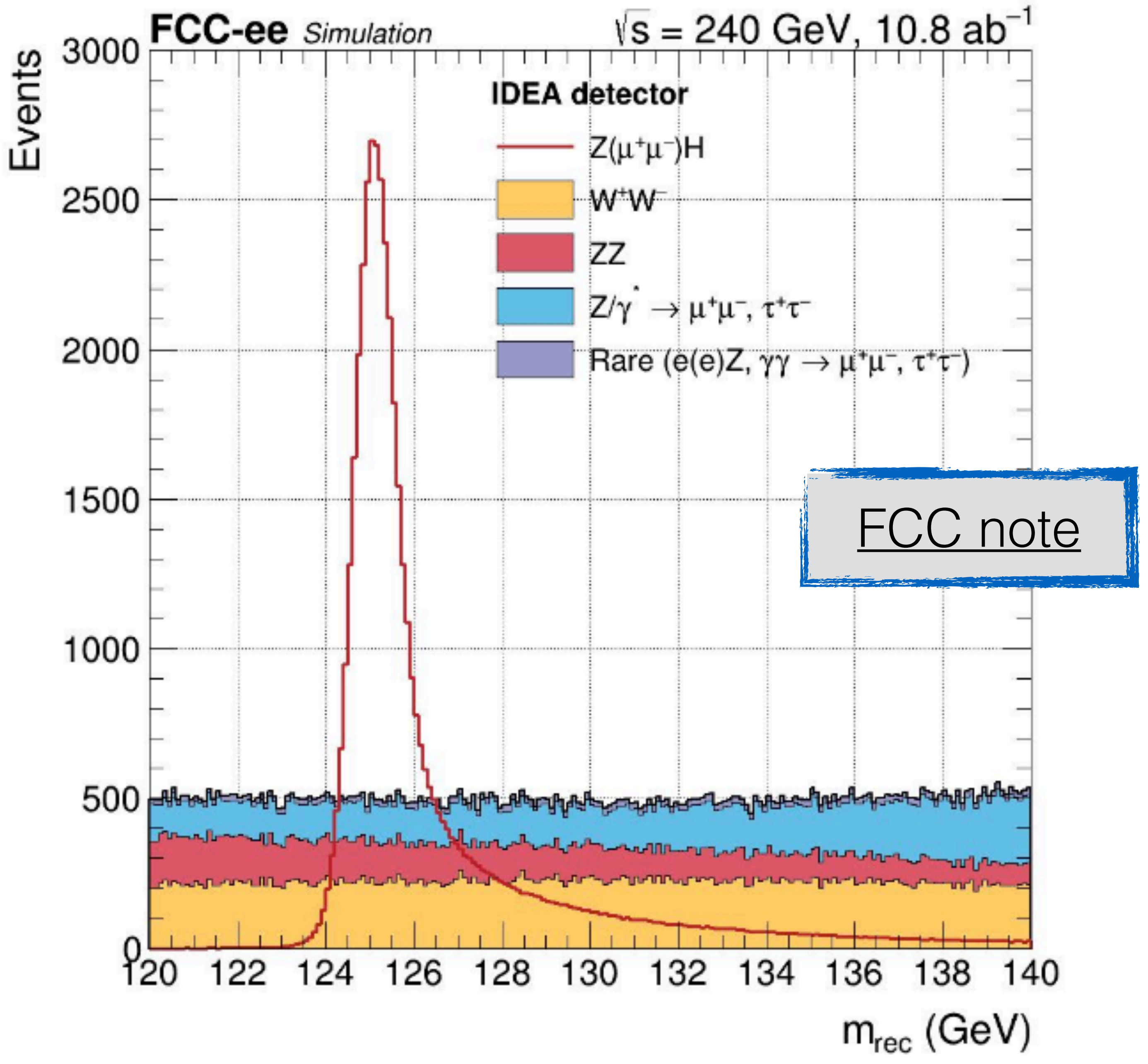
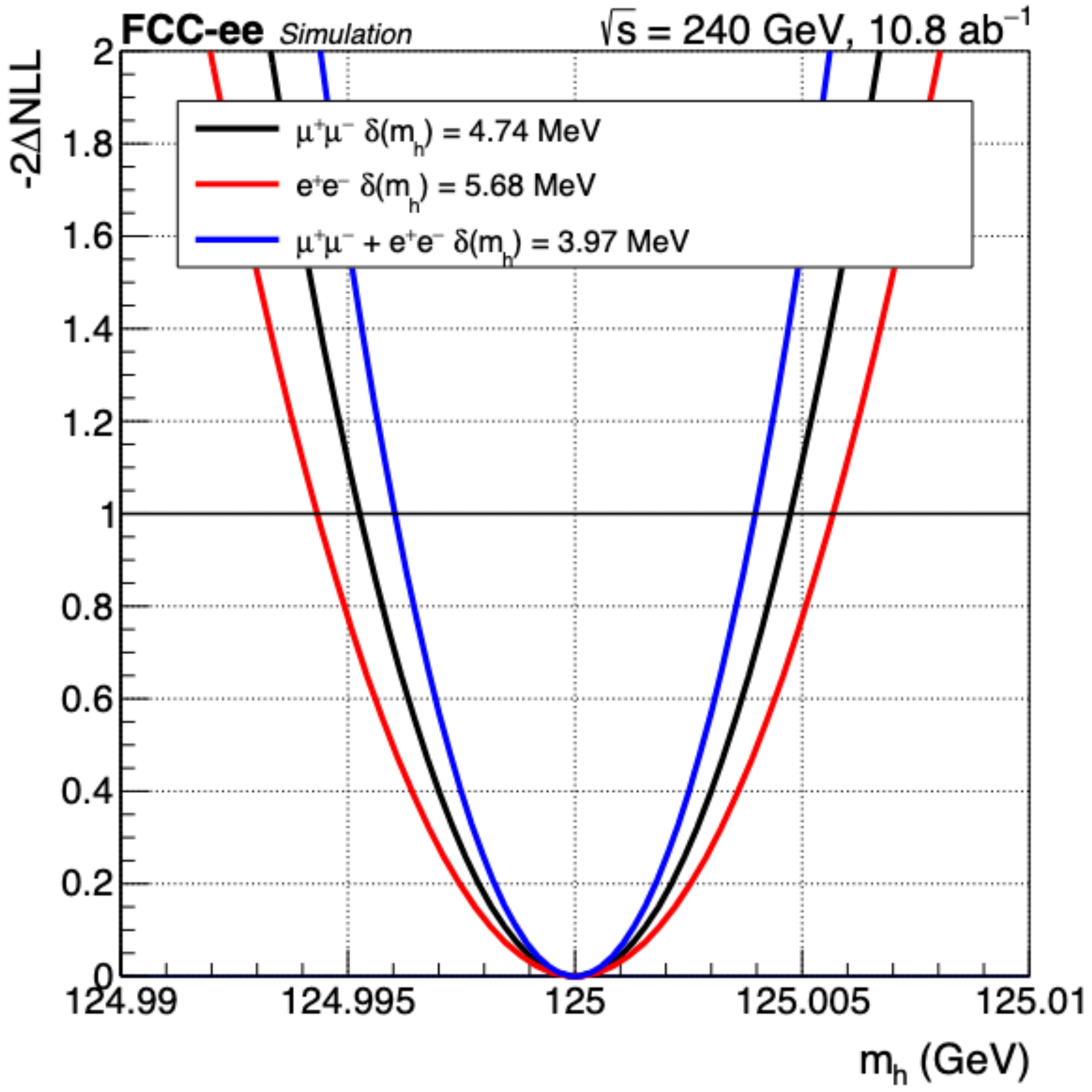
- S-channel Z/γ **exchanges are non-zero only for LR and RL** polarisation (processes like ZH production)
- WW**-fusion Higgs production is strongly enhanced for LR** and suppressed for RL polarisation
- Allows to enhance signal cross section, while suppressing backgrounds
- Direct access to chiral operators (for example in top-quark couplings) - polarised measurements **significantly reduce ambiguities and correlations in EFT fits**
- LCF250 (LFC550) assumes 80%/30% (80%/60%) e^-/e^+ polarisation, CLIC assumes 80%/0% polarisation for all stages.
- Polarisation can be determined to ~0.25% using polarimeters
- With 10-20% of the data taken with inefficient polarisation combinations (LL, RR) luminosity weighted polarisation can be calibrated to 0.1% using measurements of A_{LR} in Z decays

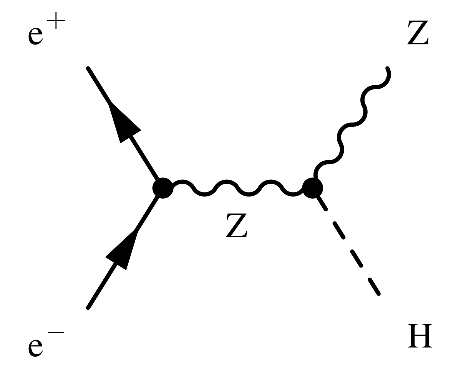
Higgs mass measurement using Z-Recoil



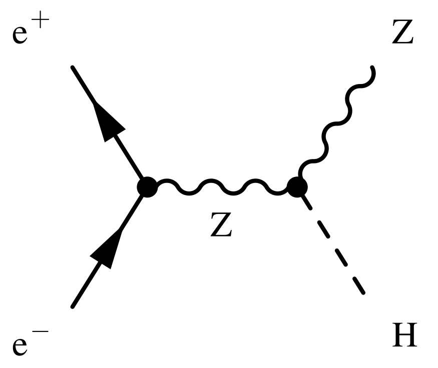




- Well defined initial state allows to determine Higgs mass from the recoil $m_H = s - 2\sqrt{s}E_Z + m_Z^2$ using $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$. Requires **excellent track momentum resolution**.
- Largest uncertainty from knowledge of $\sqrt{s}$: beam energy calibration; smearing of initial electron energy spectrum ISR effects and for linear colliders Beamstrahlung
- Projected precision **4 / 12 / 38 MeV** (FCCee / LCF250 / CLIC380)



Measuring Invisible Higgs Decays



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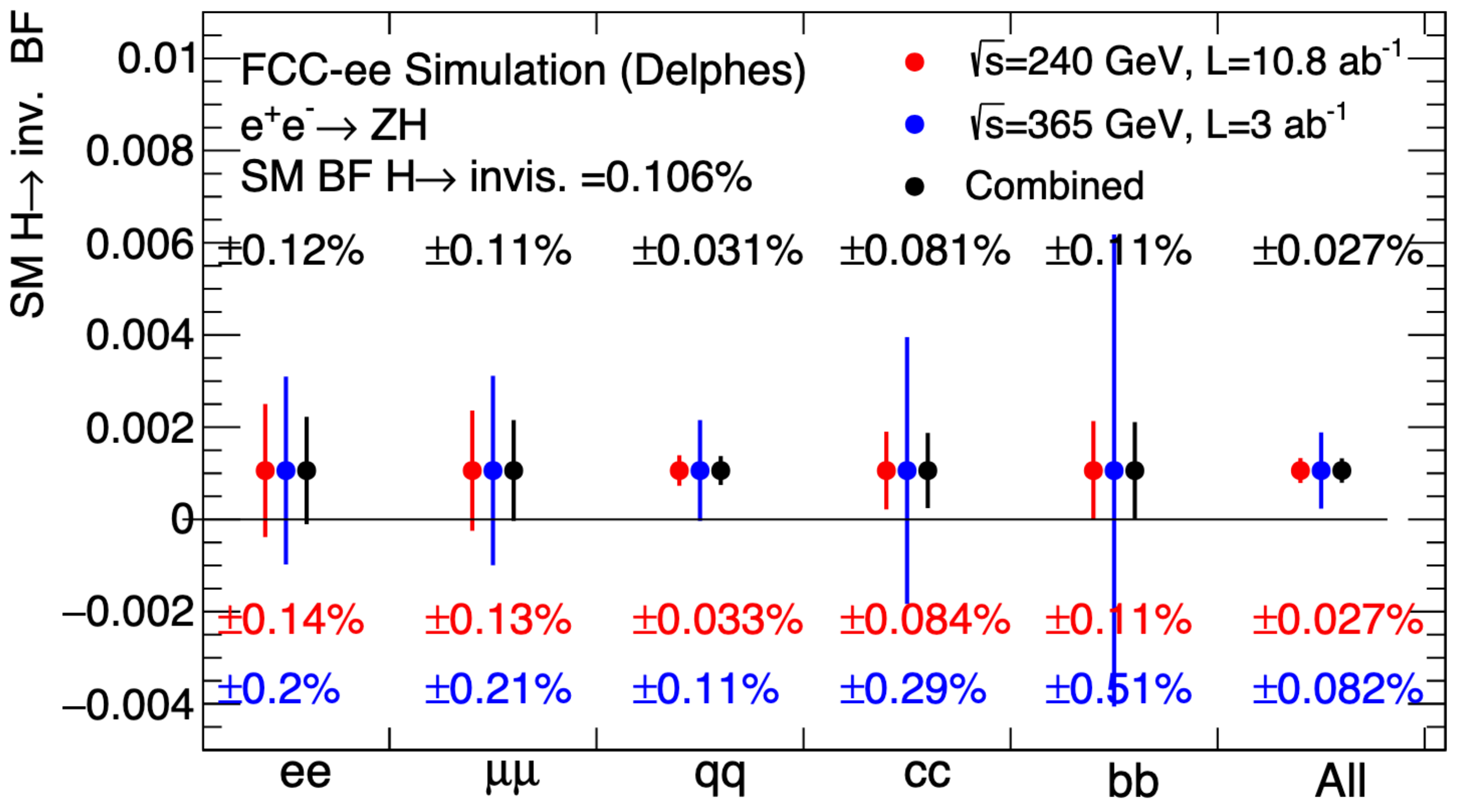
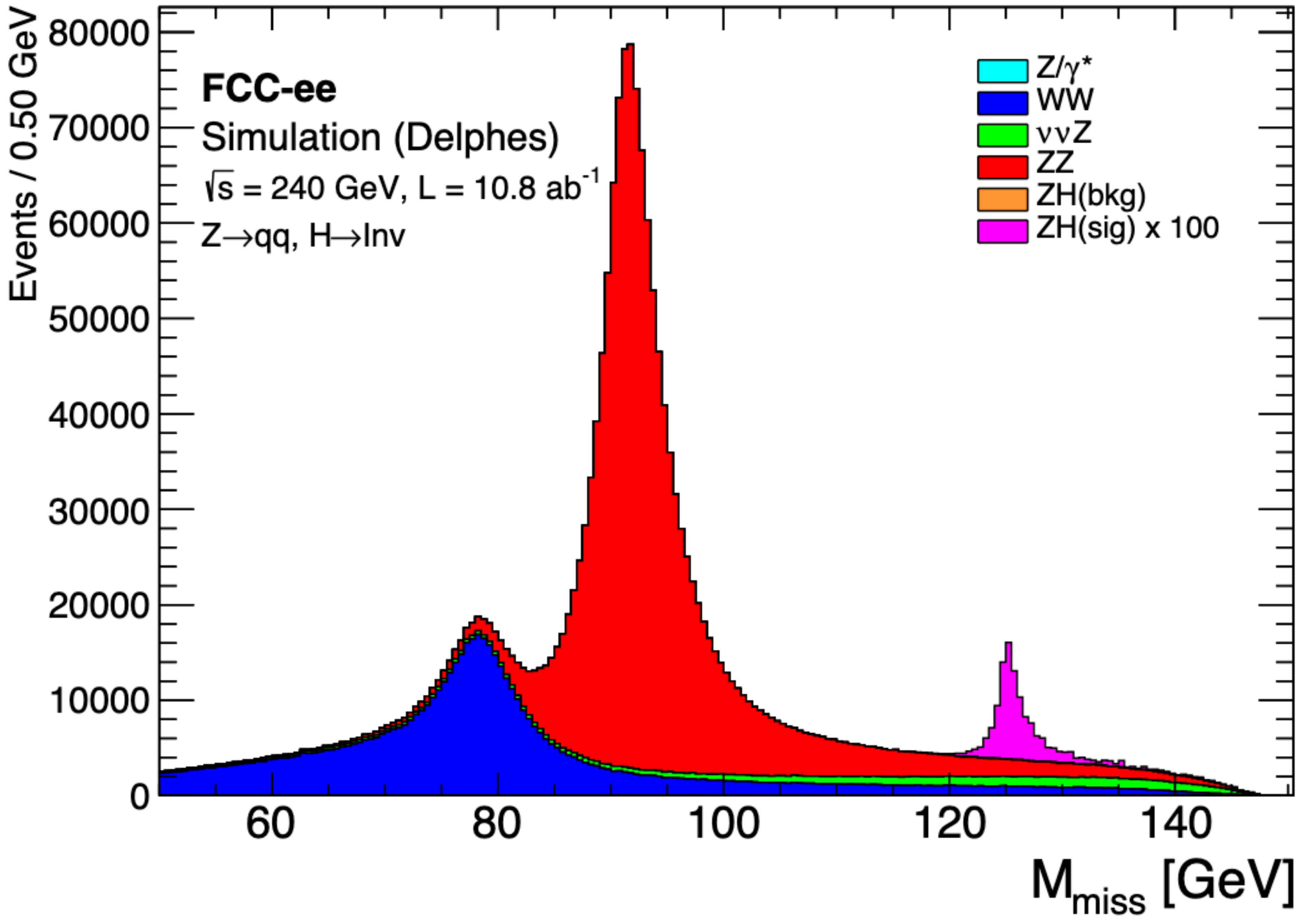
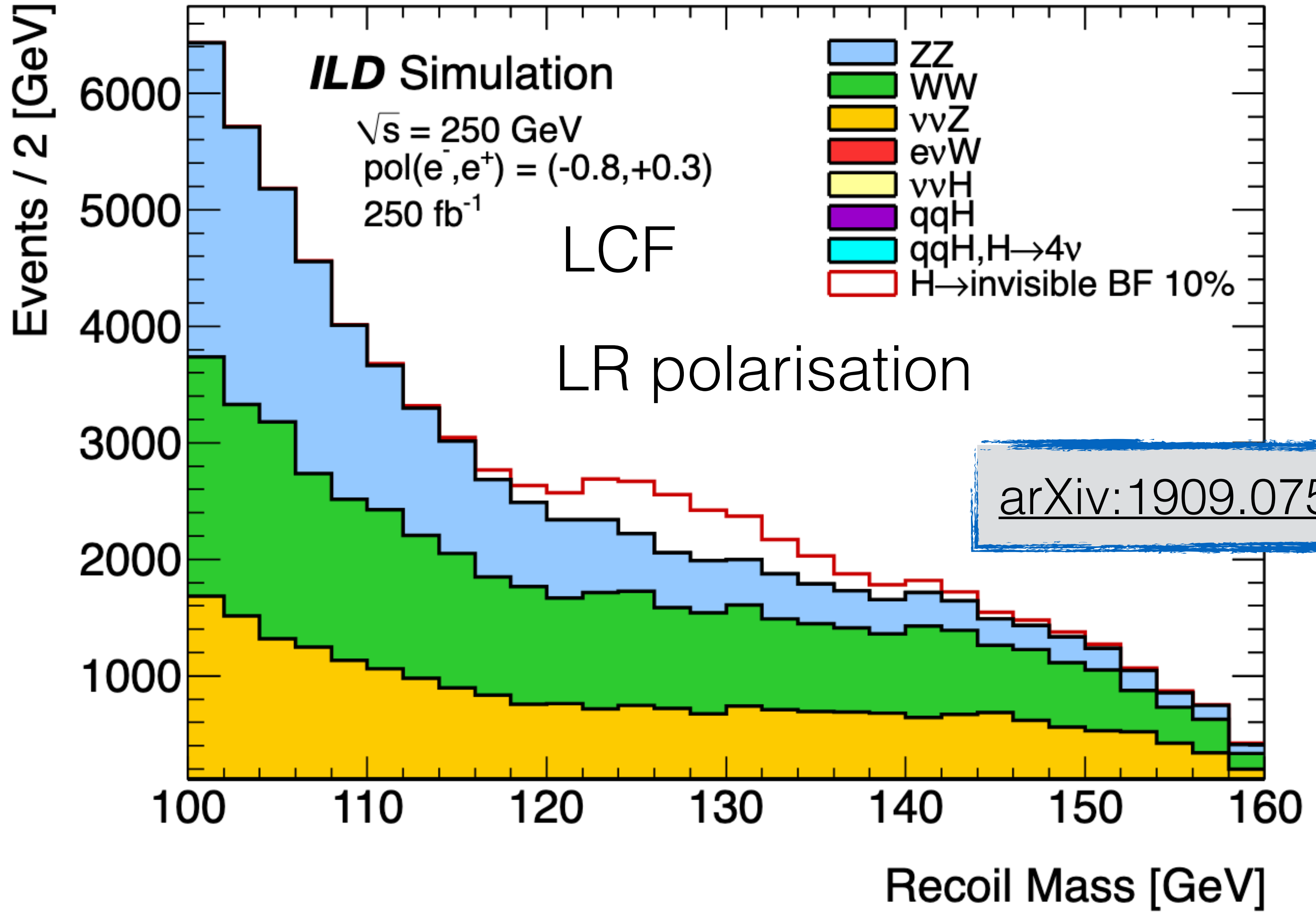
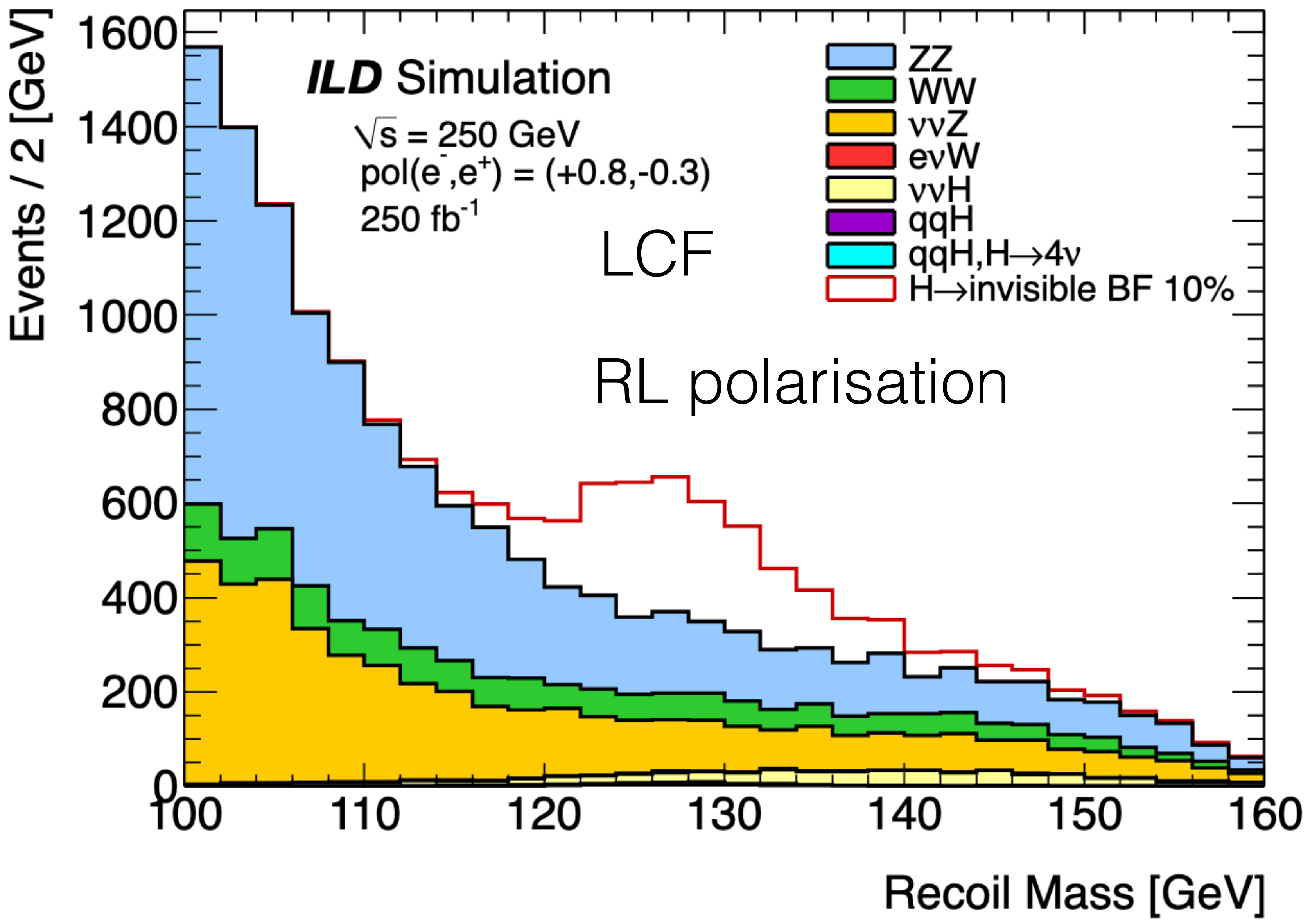


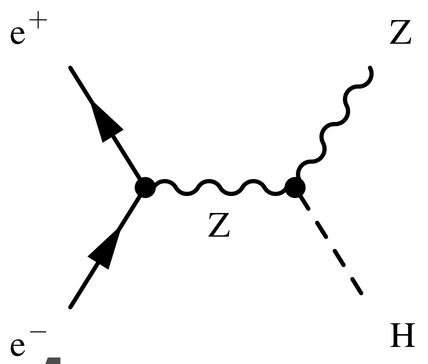




arXiv:1909.07537



- Only invisible decay in the SM: $H \to ZZ \to \nu\nu\nu\nu$ (BR = 0.106%)
- Best individual measurements from $ZH \to q\bar{q} +$ missing energy using recoil mass or missing mass at the ZH peak - requires **excellent hadronic energy resolution**
- Beam polarisation helps in suppressing backgrounds and modifies signal cross section
- 95% CL **upper limit on $\mathbf{BR_{inv}}$ 0.055-0.12%** (after subtracting $H \to ZZ \to 4\nu$)

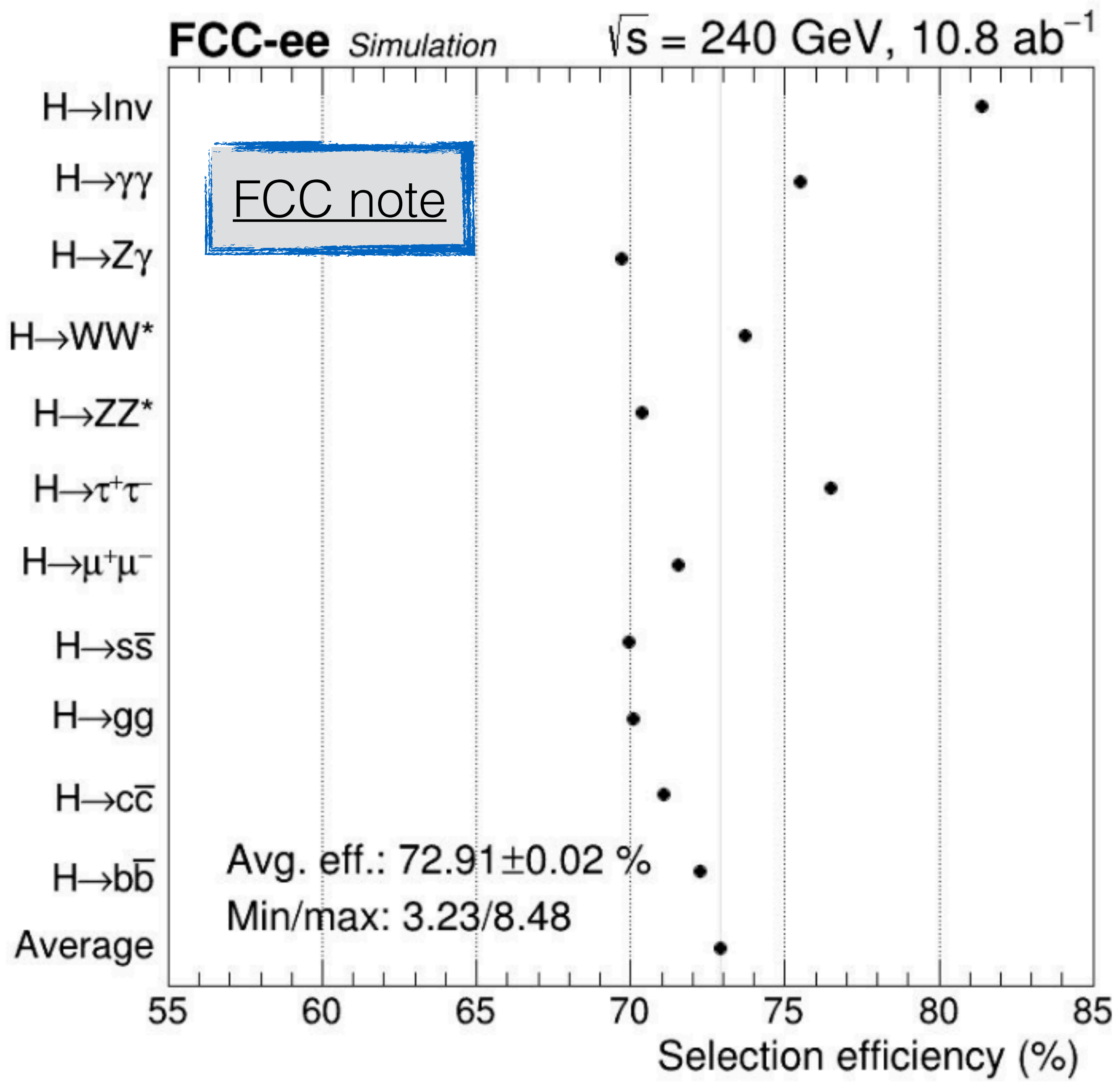


Total ZH Cross Section

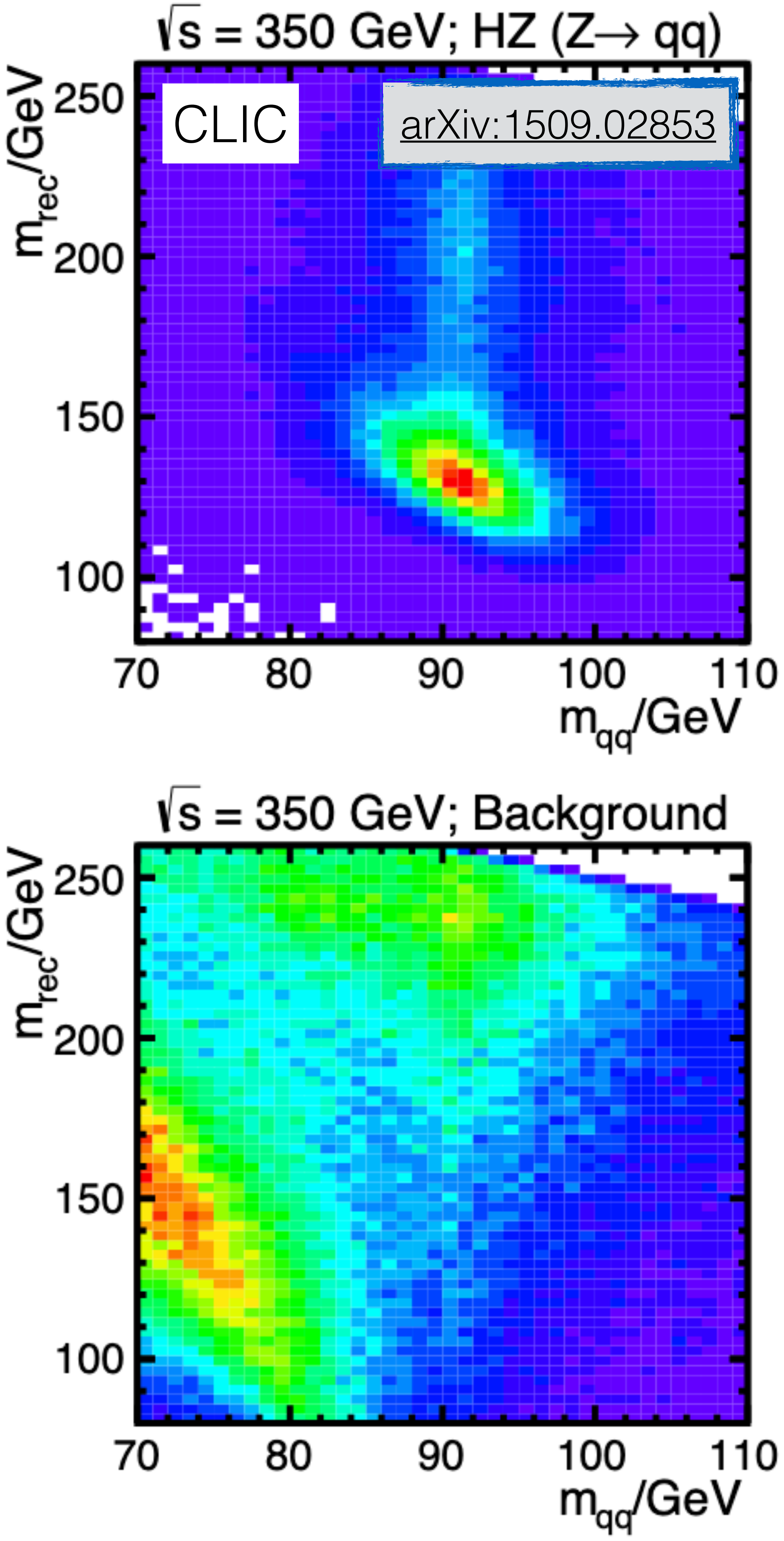
- Measure the total rate by tagging only Z boson decays independent of H decay mode

- Combination of all **hadronic Z decays has higher sensitivity** but is slightly less model-independent than just using $Z \to ee$ and $Z \to \mu\mu$.

- All-hadronic channels requires to perform **jet-association** using Z mass and **careful validation of selection efficiency** for different H decays to stay model-independent due to more complicated final state and possible confusion



Combined uncertainty:
0.4-0.6%



Total Width of the Higgs Boson

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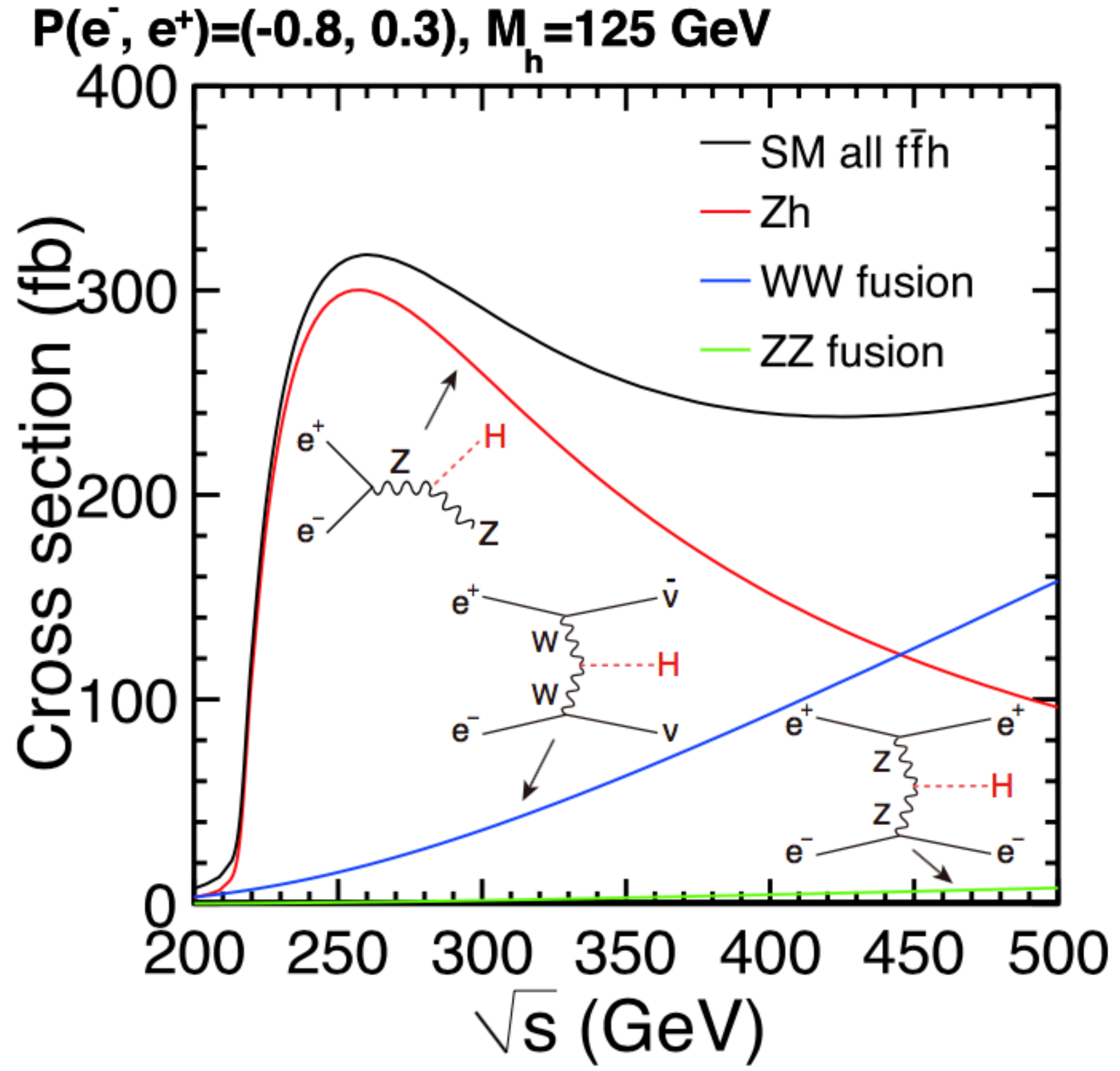
- Measurement at pp colliders compares on-shell and off-shell cross sections for $H \to ZZ^*$ - needs to make assumptions

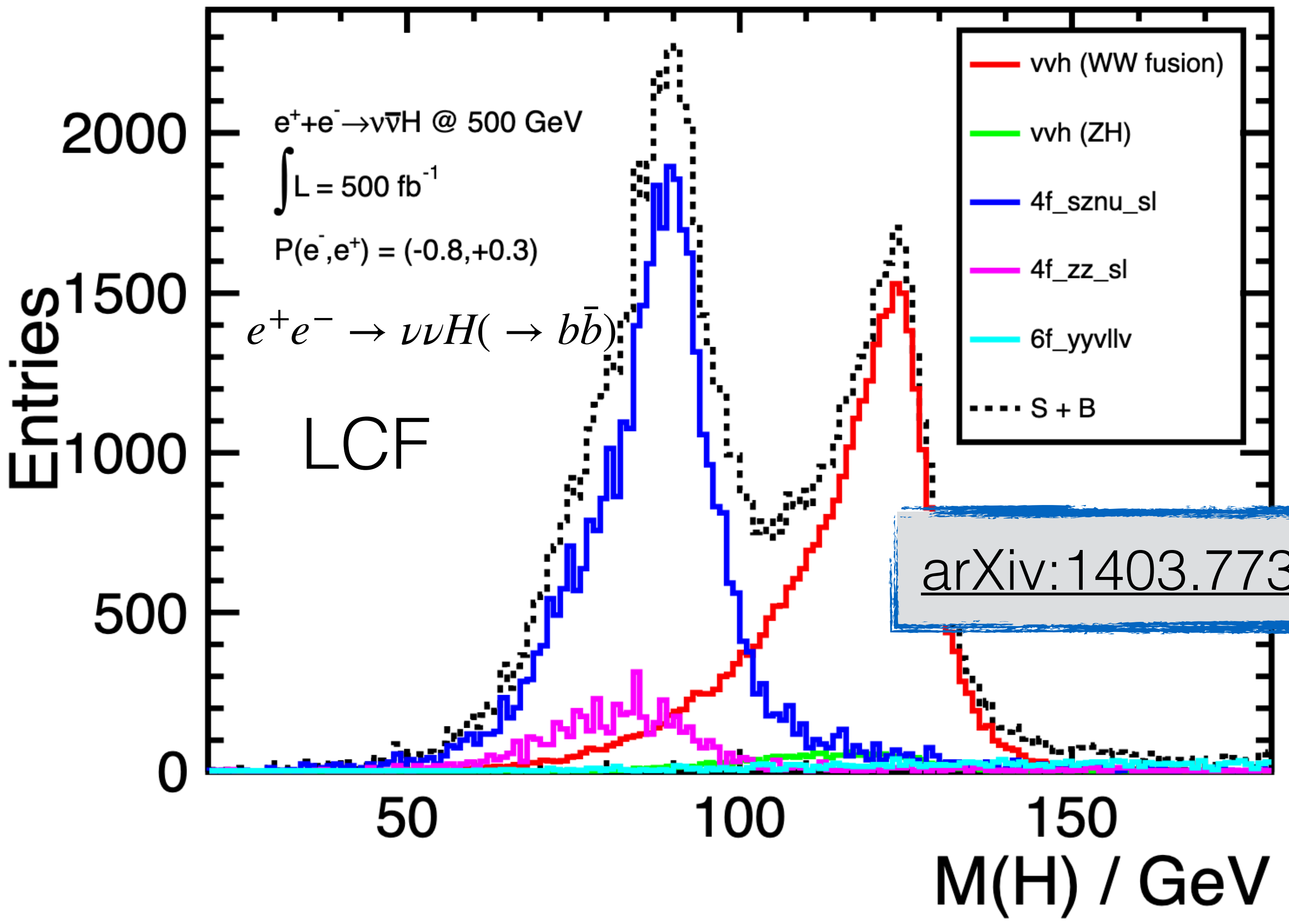
- Model independent extraction via

$$\Gamma_H \propto \frac{(\sigma_{e^+e^- \to ZH} \times BR_{H \to ZZ^*})^2}{\sigma_{e^+e^- \to ZH}}$$

- Measurement of $BR_{H \to ZZ^*}$ statistically limited for linear colliders - better result when including other Higgs decays in combined fit using $\Gamma_H \propto \frac{g_{HZZ}^2 g_{HXX}^2}{\sigma_{e^+e^- \to ZH} \times BR_{H \to XX}}$ and

$$\Gamma_H \propto \frac{g_{HWW}^2 g_{HXX}^2}{\sigma_{e^+e^- \to \nu\nu H} \times BR_{H \to XX}}$$ at higher $\sqrt{s}$

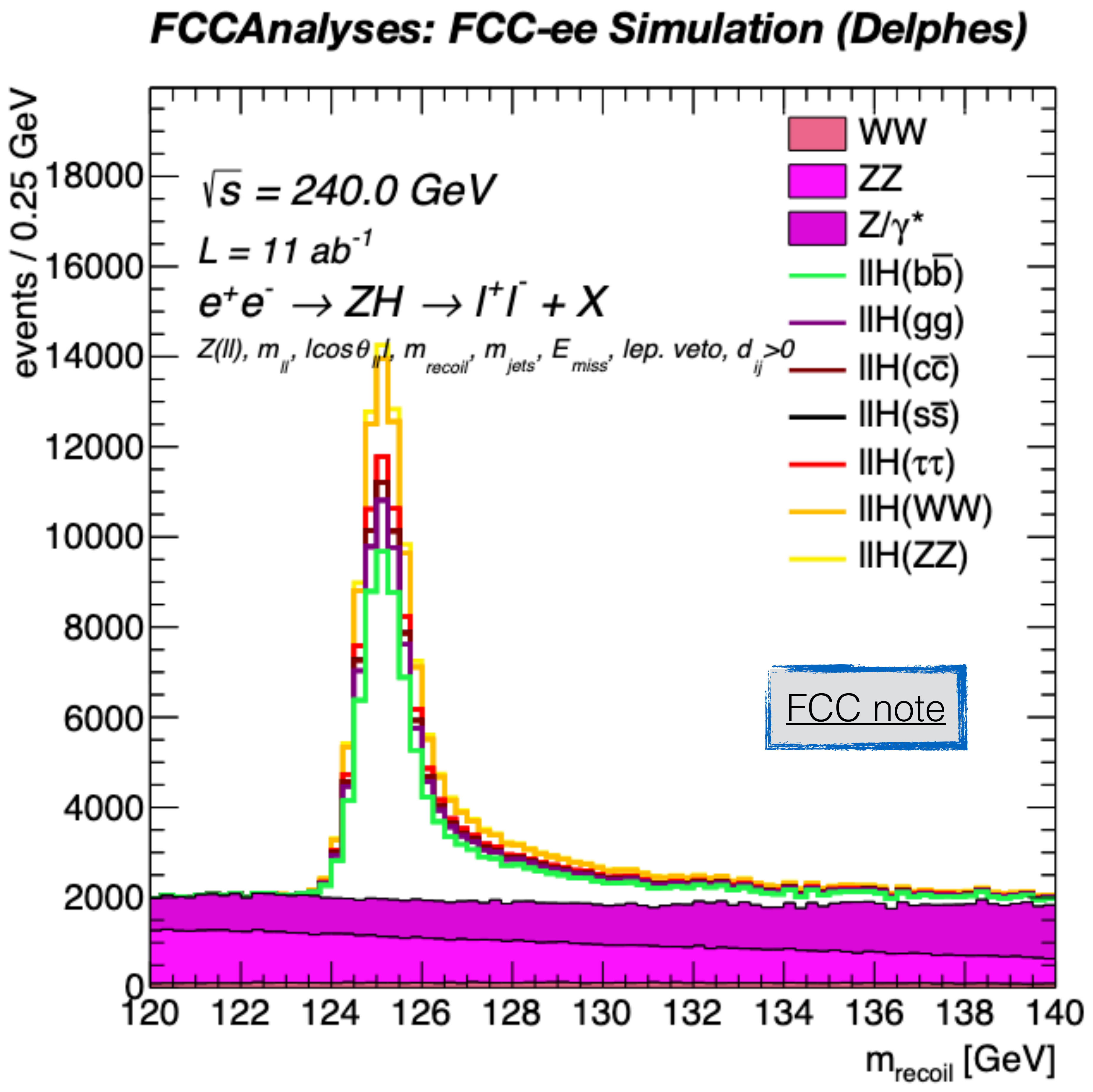




arXiv:1403.7734

Hadronic Higgs Decays

- Exploit ZH production with $Z \to \ell\ell$, $Z \to q\bar{q}$, and $Z \to \nu\bar{\nu}$ decays (not all channels used for all projections)
- Clustering events exclusively into 4 jets or 2 jets + di-leptons or missing energy
- Allows simultaneous extraction of branching ratios for $H \to b\bar{b}$, $H \to c\bar{c}$, $H \to gg$ and upper limits on light quark couplings
- Important contributions from hadronic W, Z and τ -lepton decays
- Significant **improvement from recent developments in flavour tagging** - linear collider numbers derived using "old" algorithms



$$\delta(\sigma \times BR_{H\to b\bar{b}}) \approx 0.2\text{-}0.4\,\%$$
$$\delta(\sigma \times BR_{H\to c\bar{c}}) \approx 1.6\text{-}5\,\%$$
$$\delta(\sigma \times BR_{H\to gg}) \approx 0.8\text{-}2.1\,\%$$

Higgs Factory Projections

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$\sqrt{s}$ FCCee	240 GeV $\mathscr{L} = 10.8\,\text{ab}^{-1}$		365 GeV $\mathscr{L} = 3.12\,\text{ab}^{-1}$	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
H → $\tau\tau$	±0.58		±1.2	±5.6 (*)
H → $\mu\mu$	±11		±25	
H → WW*	±0.80		±1.8 (*)	±2.1 (*)
H → ZZ*	±2.5		±8.3 (*)	±4.6 (*)
H → $\gamma\gamma$	±3.6		±13	±15
H → Zγ	±11.8		±22	±23
H → $\nu\nu\nu\nu$	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

Input 217

Collider $\sqrt{s}$ $\mathscr{L}$	LCF 250 GeV 2.7ab^{-1} [%]	LCF 350 GeV 0.135ab^{-1} [%]	CLIC 350 GeV 2.2ab^{-1} [%]	CLIC 350 GeV 4.3ab^{-1} [%]	LCF 500 6.4ab^{-1} [%]	LCF 1 TeV 6.4ab^{-1} [%]	CLIC 1.4 TeV 4ab^{-1} [%]	CLIC 3 TeV 5ab^{-1}
σ_{HZ}	0.62	2.5	0.79	0.56	0.8		2.0	4.3
$\sigma_{HZ} \cdot BR_{b\bar{b}}$	0.41	2.1	0.41	0.29	0.5			
$\sigma_{HZ} \cdot BR_{c\bar{c}}$	2.5	15	7	5	3.6			
$\sigma_{HZ} \cdot BR_{gg}$	2.1	11.4	2.9	2.1	3.0			
$\sigma_{HZ} \cdot BR_{\tau\tau}$	0.98	5.5	3.0	2.1	1.2			
$\sigma_{HZ} \cdot BR_{ZZ}$	5.5	34			6.9			
$\sigma_{HZ} \cdot BR_{WW}$	1.4	7.6	2.4	1.7	1.6			
$\sigma_{HZ} \cdot BR_{\gamma\gamma}$	10				10			
$\sigma_{HZ} \cdot BR_{inv}$	0.19	1.2	0.3	0.2	0.42			
$\sigma_{\nu_e\bar{\nu}_e H} \cdot BR_{b\bar{b}}$	2.5	2.5	0.9	0.6	0.30	0.30	0.2	0.2
$\sigma_{\nu_e\bar{\nu}_e H} \cdot BR_{c\bar{c}}$		26	12	9	2.5	1.6	3.7	4.4
$\sigma_{\nu_e\bar{\nu}_e H} \cdot BR_{gg}$		11	4.8	3.4	1.6	1.3	3.6	2.7
$\sigma_{\nu_e\bar{\nu}_e H} \cdot BR_{\tau\tau}$		22			2.8	1.5	2.6	2.8
$\sigma_{\nu_e\bar{\nu}_e H} \cdot BR_{\mu\mu}$					28	16	23	16
$\sigma_{\nu_e\bar{\nu}_e H} \cdot BR_{ZZ}$		27			3.4	2.2	3.4	2.5
$\sigma_{\nu_e\bar{\nu}_e H} \cdot BR_{WW}$		7.8			0.96	0.88	0.6	0.4
$\sigma_{\nu_e\bar{\nu}_e H} \cdot BR_{\gamma\gamma}$					7.6	4.6	9	6
$\sigma_{e^+e^-H} \cdot BR_{b\bar{b}}$							1.1	1.5

Input 140

LEP3 Single Higgs Measurements

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	HL-LHC*	LEP3 **	Comment and leading err	FCCee
C.o.M. energy		230		240
No. of Experiments	2	2		4
Prog Integ. Lumi (ab-1)	3	2.5		10.8
Years of Running	10	6		3
Observable (σ, %) or as indicated		σ.Br		σ.Br
δm(H) (MeV)	100	9.2	Sys: knowledge of Eb(ee)	4
δΓ(H)/ΓH (%)	50			
δσ(HZZ)/g(HZZ)	1.6	0.3		0.13
δσ(HWW)/g(HWW)	1.6	1.8		0.8
δσ(Hττ)/g(Hττ)	1.9	1.3		0.58
δσ(Hγγ)/g(Hγγ)	1.8	8.2		3.6
δσ(Hμμ)/g(Hμμ)	3	25.2		11
δσ(Hcc)/g(Hcc)	100	3.7	LHC from ~CMS/√2	1.6
δσ(Hbb)/g(Hbb)	3.6	0.5		0.21
δσ(Hgg)/g(Hgg)	2.4	1.8		0.8
δσ(Htt)/g(Htt)	3.4			
δσ(HZγ)/g(HZγ)	6.8	27.0		11.8
BR (H>inv) (%) 95%CL	<2.5		LHC from CMS/√2	
BR (H>EXO) (%) 95%CL	<4			<1.1
δ(H self-cplg) (%) 95%CL	30 (SM)	91.5	HH from LHC, ZH from ee	40

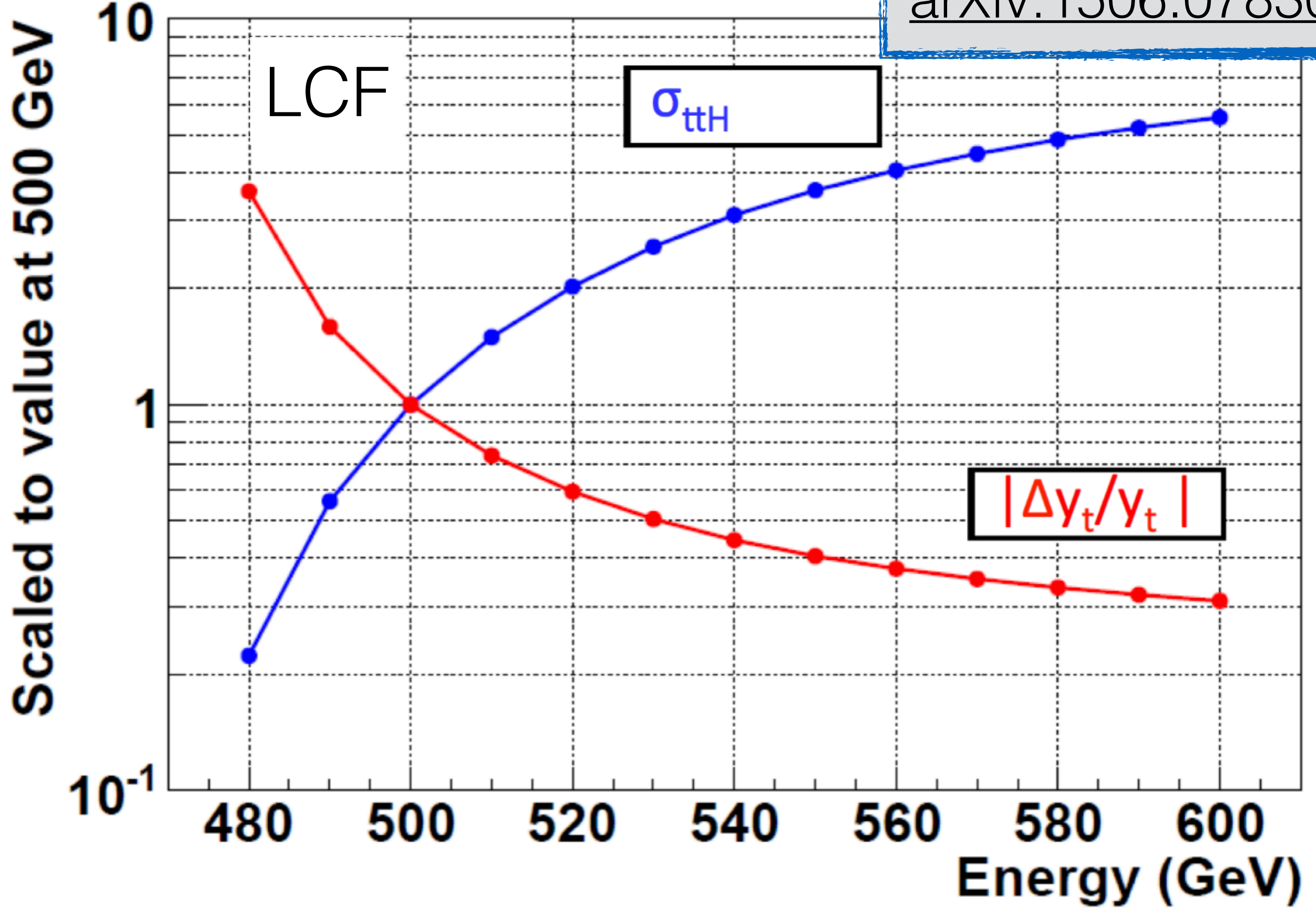
Input 188

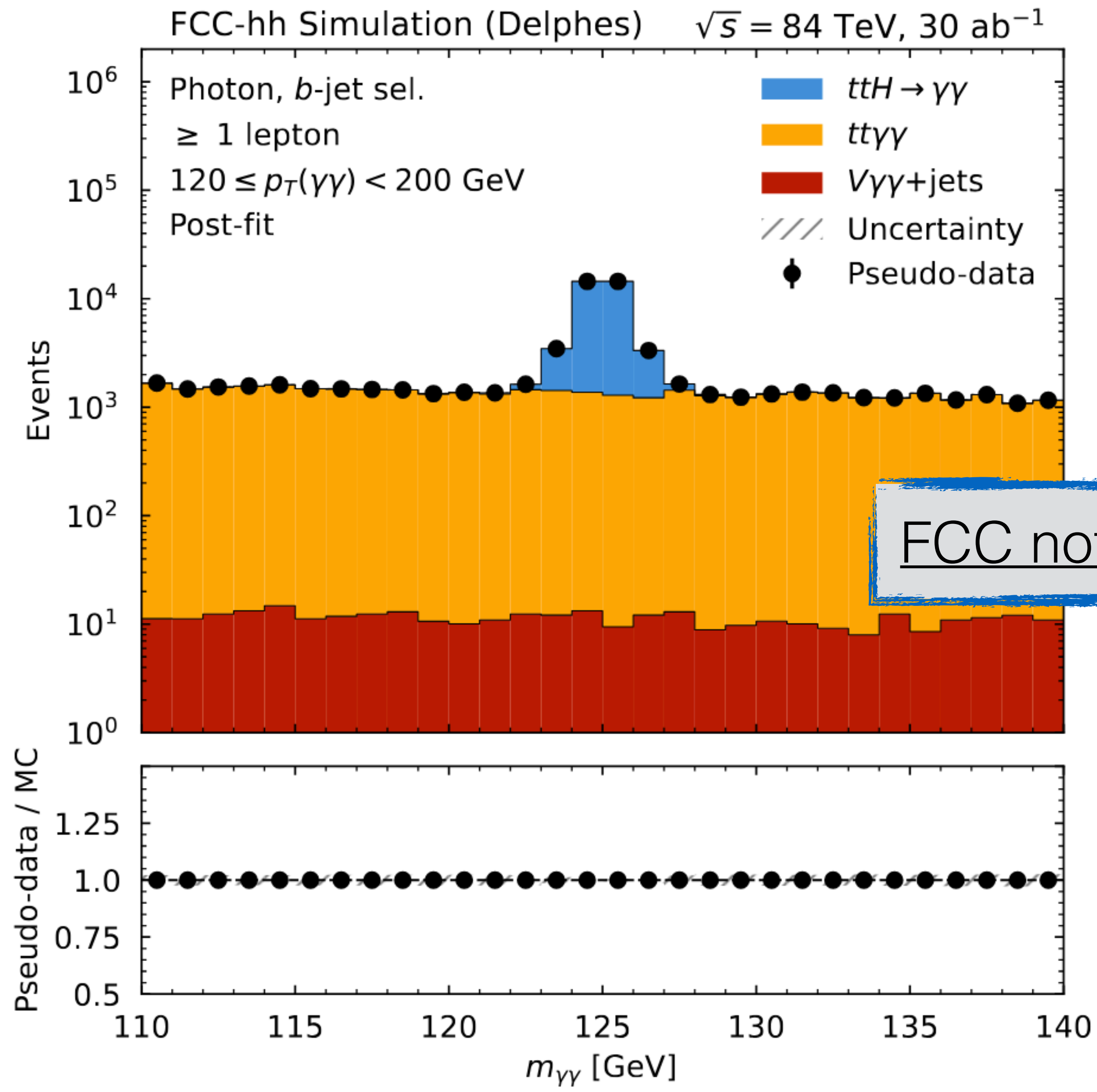
- Statistical uncertainties have been scaled from FCCee projections

Top Yukawa Couplings

- $e^+e^- \rightarrow t\bar{t}H$ production opens at $\sqrt{s} = 480$ GeV - cross section doubles from 500 to 550 GeV (motivation for LFC550) with a projected uncertainty of $y_t < 3\%$
- Similar uncertainties are projected for CLIC1500 [JHEP 11 (2019) 003] (without possible luminosity upgrade from 100 Hz operations)
- Indirect measurement using loop corrections in $e^+e^- \rightarrow t\bar{t}$ yields about 2% precision [arXiv:2503.18713]
- Measurement of $t\bar{t}H(\rightarrow \gamma\gamma)$ or $t\bar{t}H(\rightarrow b\bar{b})/t\bar{t}Z(\rightarrow b\bar{b})$ at FCChh projects uncertainty on $\kappa_t \approx 1\,\%$

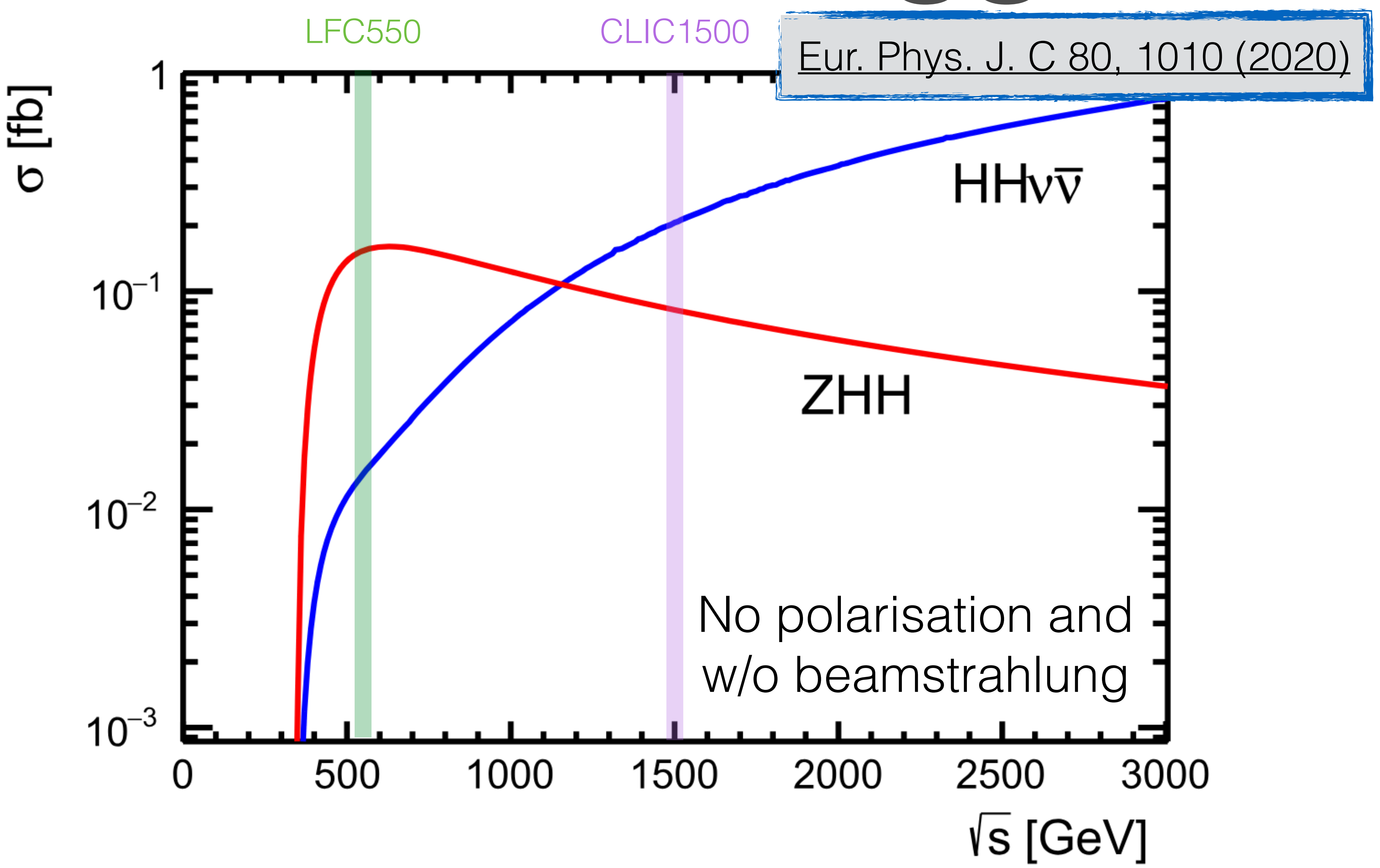
arXiv:1506.07830

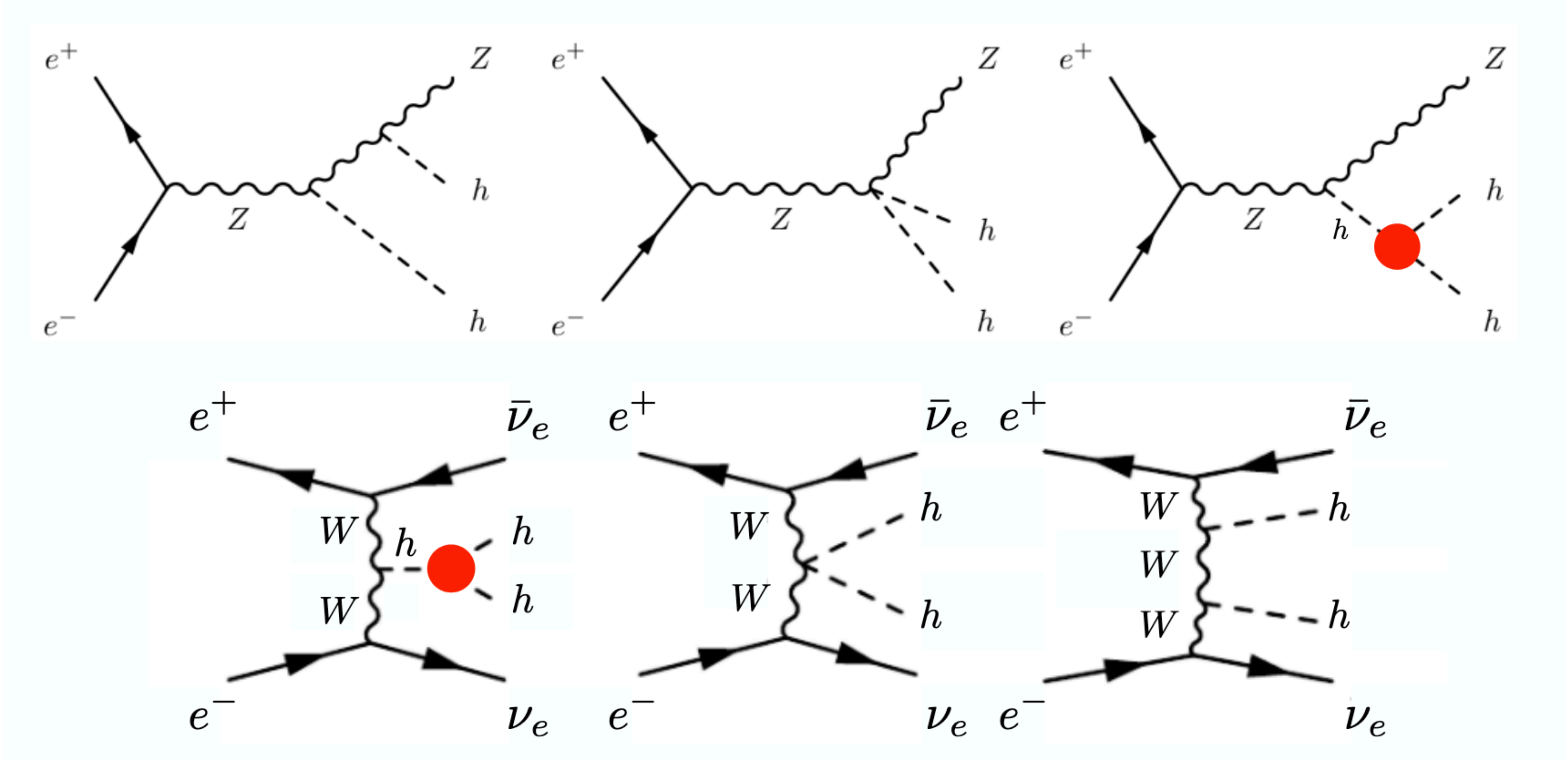




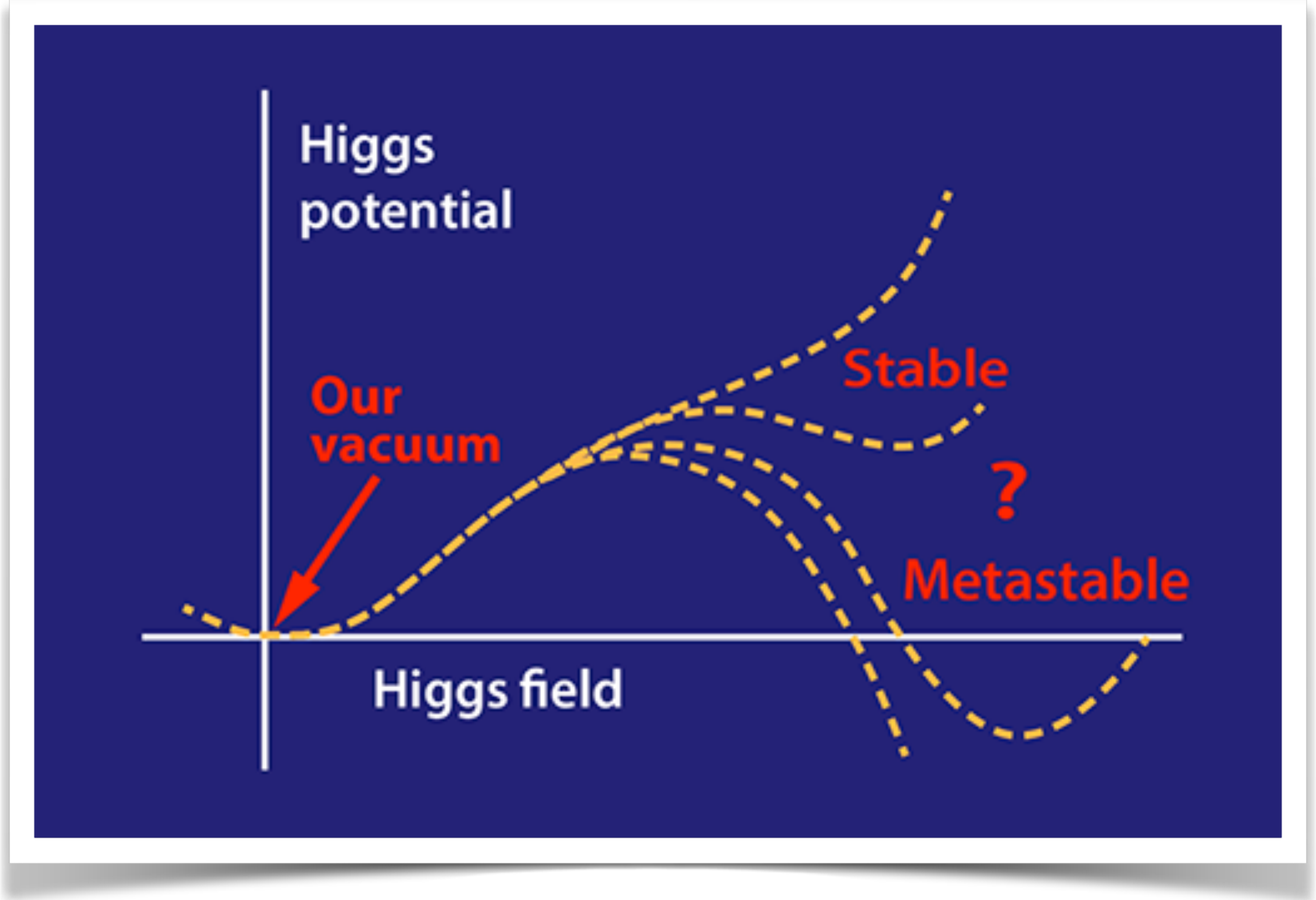
FCC note

Di-Higgs Production in e^+e^-





- Make use of ZHH and $\nu\nu HH$ final states depending on $\sqrt{s}$
- Sensitive to triple Higgs coupling vertex. Interference from quartic $ZZHH$ and $WWHH$ couplings, as well as double VHH vertices can be disentangled using kinematics and global fits of the Higgs sector



Di-Higgs Production in e^+e^- @ $\sqrt{s} = 550\,$GeV

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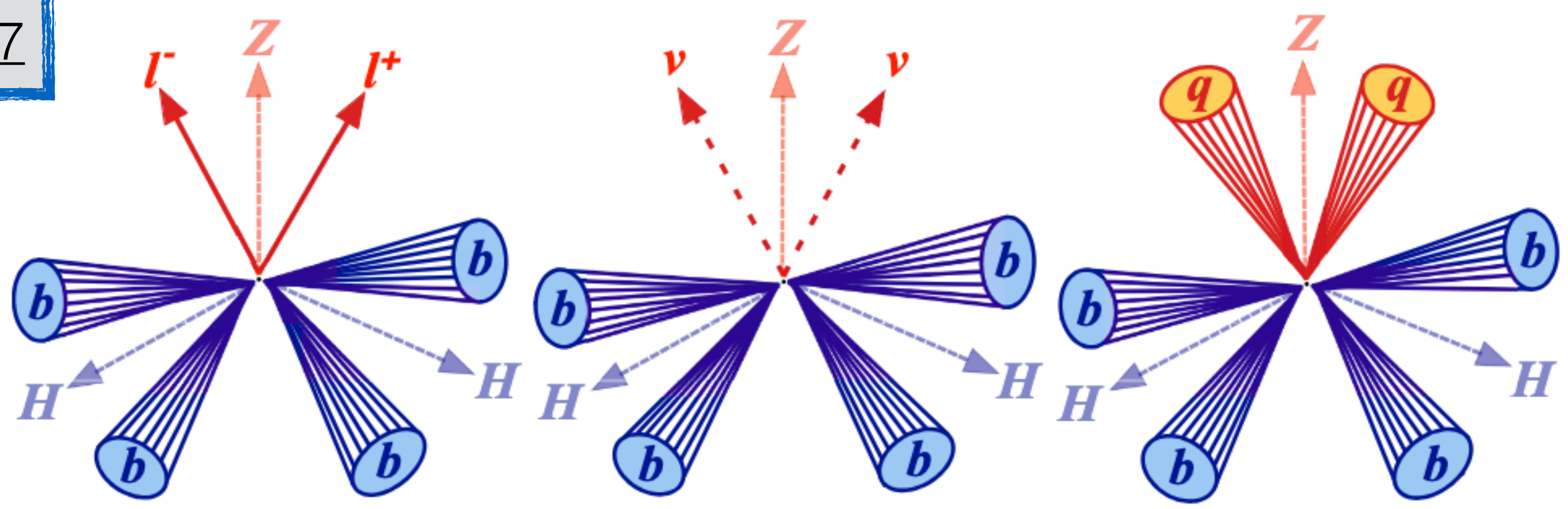
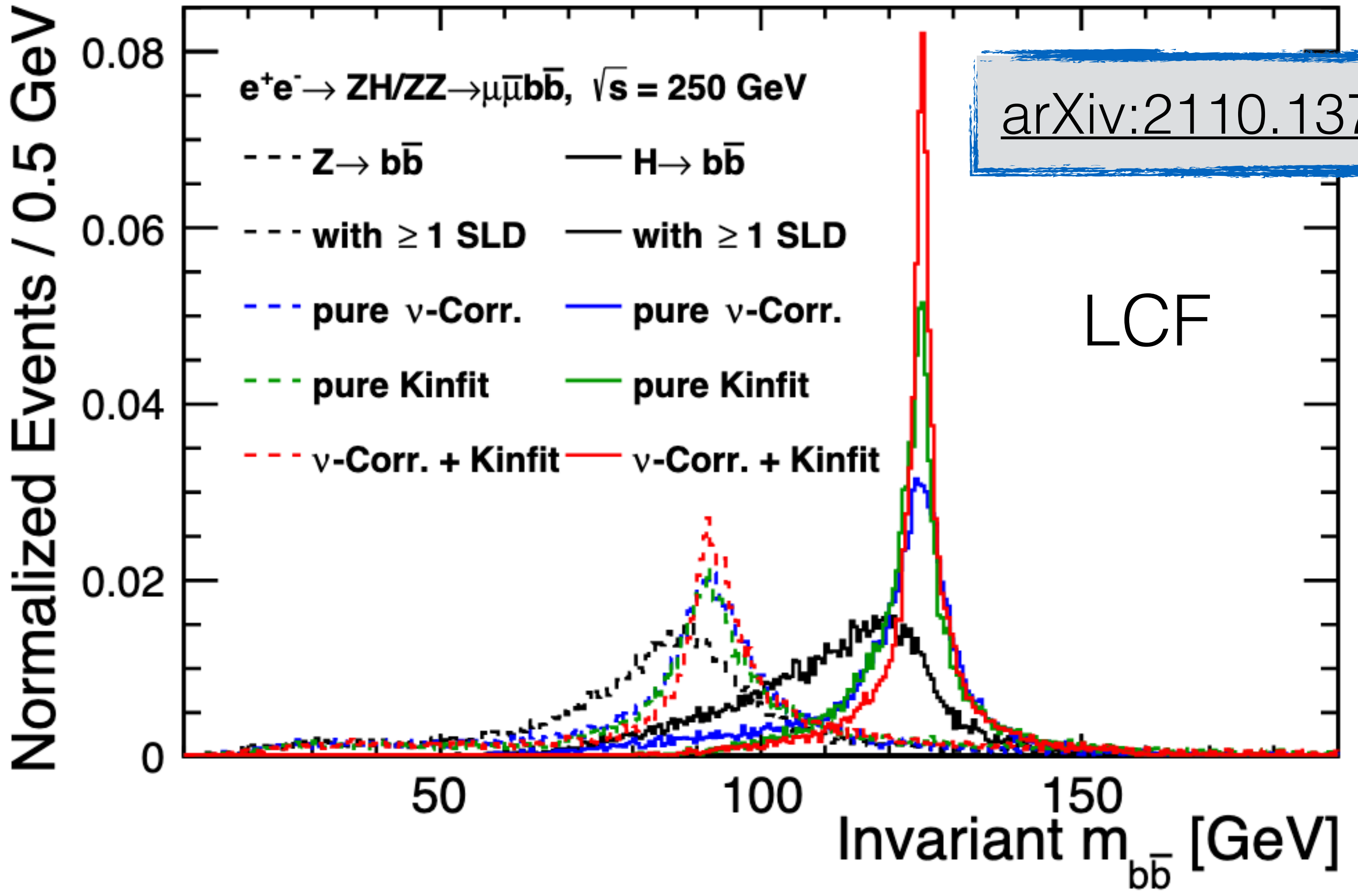
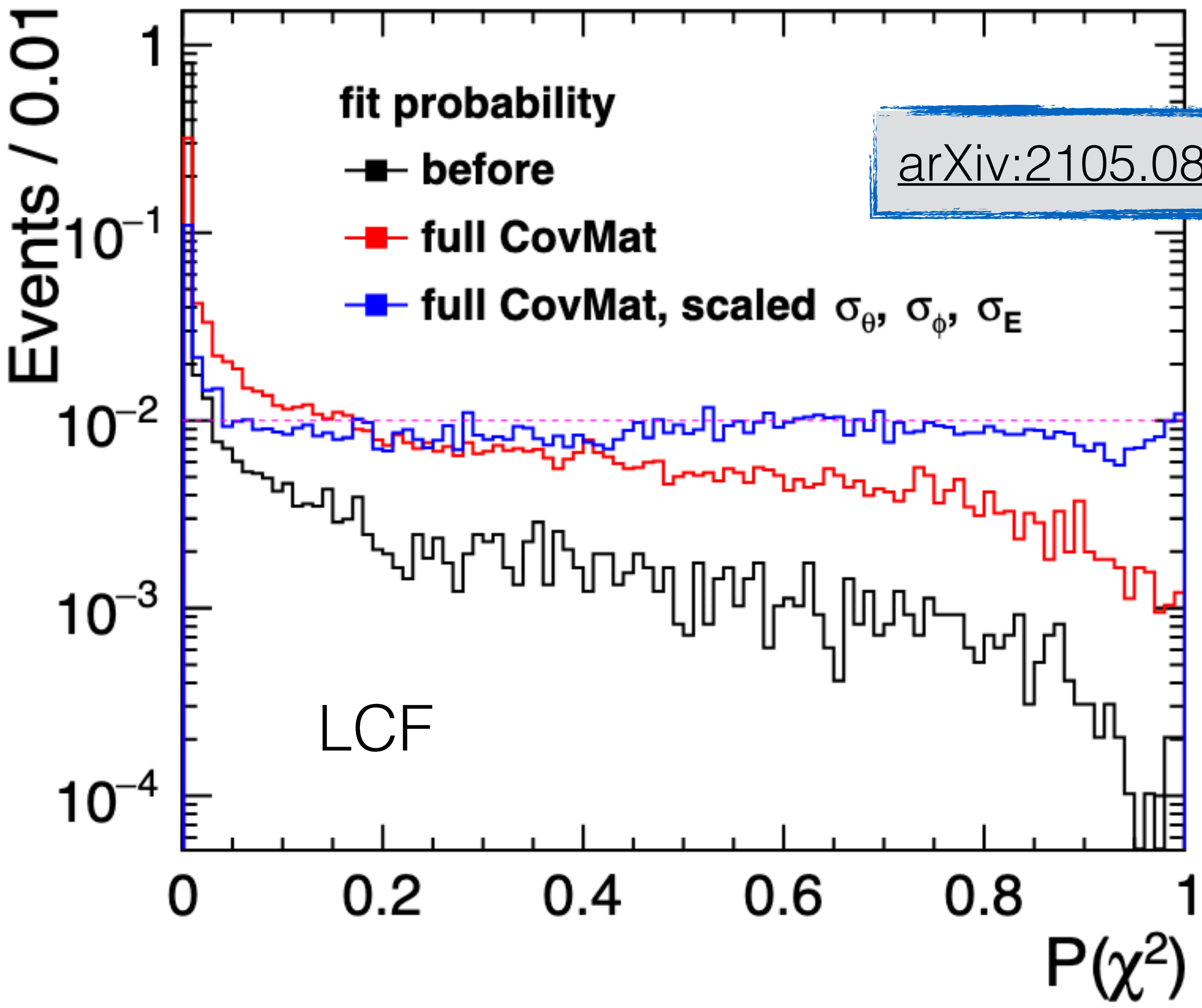


- Combine $\ell\ell b\bar{b}b\bar{b}$, $\nu\bar{\nu}b\bar{b}b\bar{b}$ and $q\bar{q}b\bar{b}b\bar{b}$ channels to measure $\sigma(ZHH)$
- Biggest challenges: **jet assignment, jet energy resolution and flavour tagging**
- Baseline projected uncertainty on $\sigma(ZHH) \approx 15.2\,\%$ @ LCF550
- Very **significant improvements expected** from better kinematic fitting, jet energy calibration for heavy flavour jets, flavour tagging and the inclusion of additional Higgs decay modes. **Extrapolation of these improvements** results in an uncertainty of $\sigma(ZHH) \approx 7.5\,\%$

arXiv:2110.13731

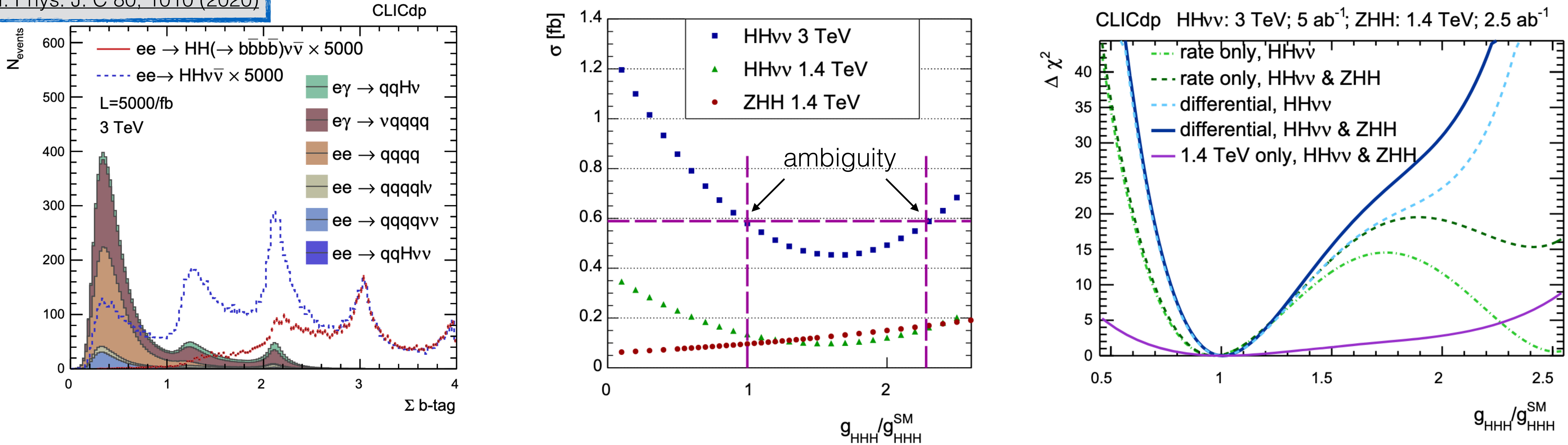


arXiv:2105.08480



Di-Higgs Production in e^+e^-, $\sqrt{s} > 1$ TeV

Eur. Phys. J. C 80, 1010 (2020)

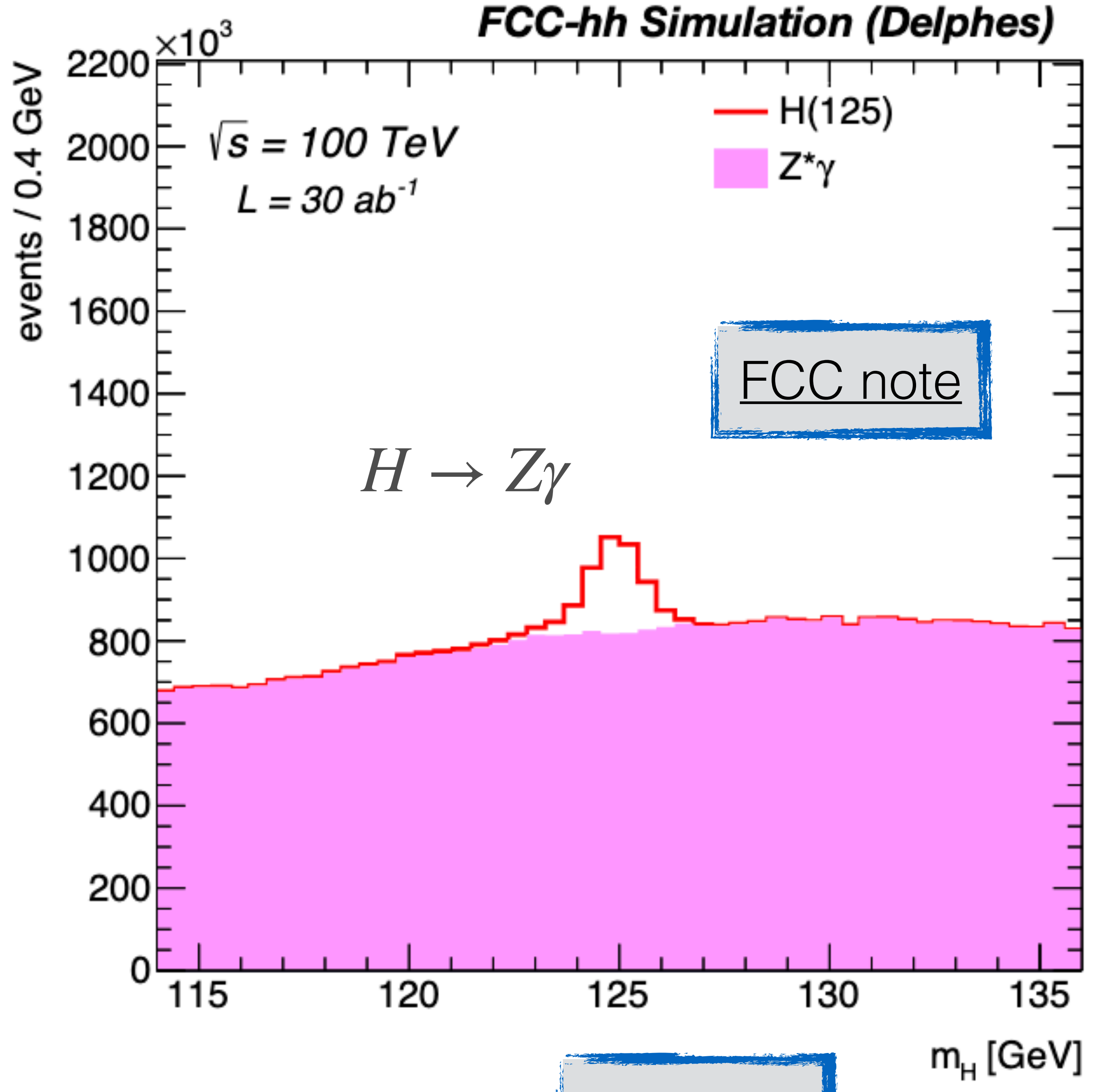


- $\nu\nu HH$ at high $\sqrt{s}$: combine $HH \to b\bar{b}b\bar{b}$ and $HH \to b\bar{b}W^+W^-$ channels
- **Flavour tagging is crucial** - results were obtained using "old" algorithms
- Expected uncertainty on $\sigma(\nu\nu HH) \approx 22\,\%$ @ CLIC1500. Make use of differential distributions to distinguish final states sensitive to the self-coupling λ
- Combination with ZHH to maximise sensitivity and to disentangle ambiguity in κ_λ extraction

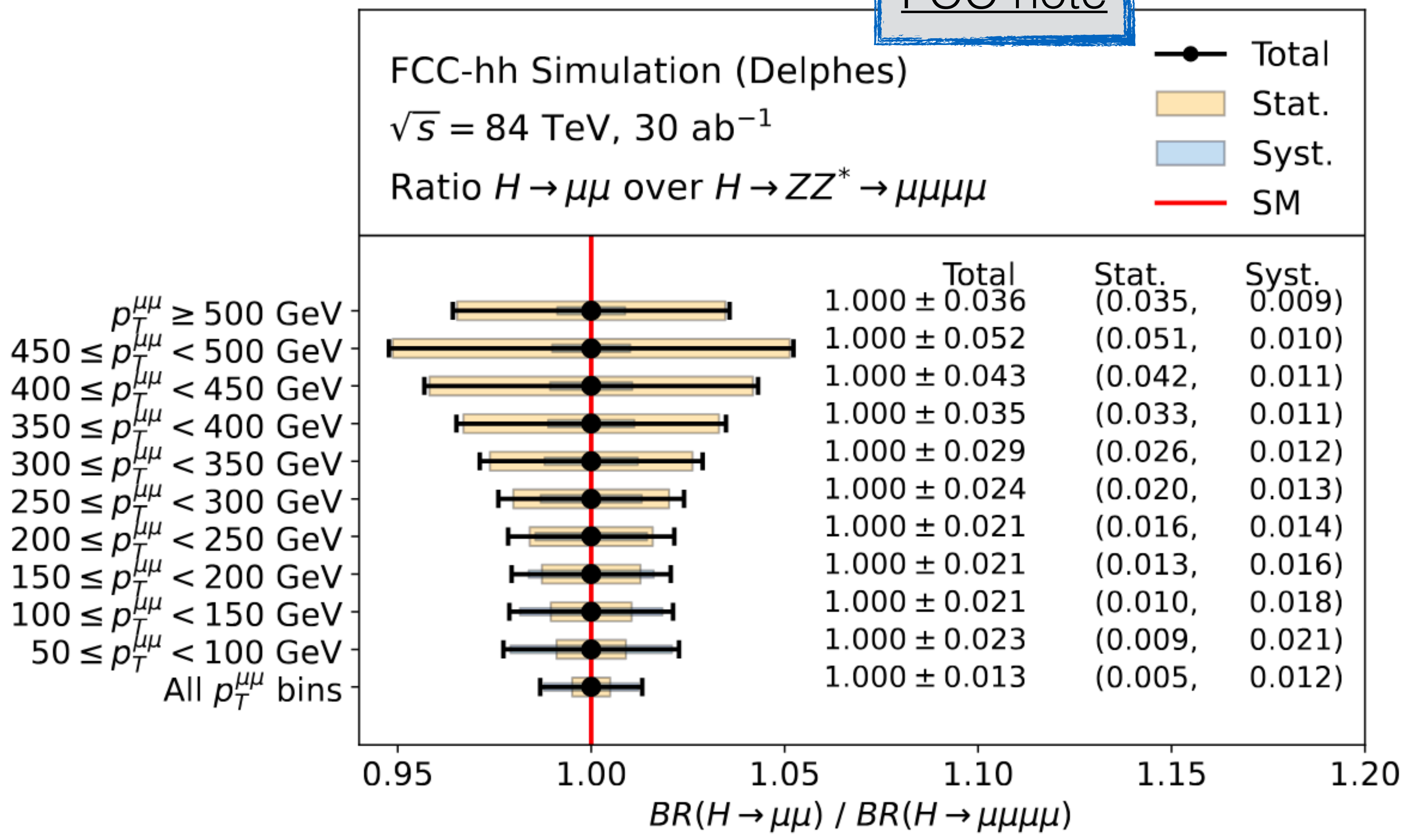
FCChh Measurements of Rare Higgs Decays

Input 217

observable	param	stat.	stat. + syst.	
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \gamma\gamma)$	$\delta\mu$	0.1%	1.4%	(*)
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \mu\mu)$	$\delta\mu$	0.4%	1.2%	
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \ell\ell\ell\ell)$	$\delta\mu$	0.2%	1.8%	(*)
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \gamma\ell\ell)$	$\delta\mu$	1.1%	1.7%	(*)
$\mu = \sigma(\mathrm{ttH})\,\mathcal{B}(\mathrm{H} \to \gamma\gamma)$	$\delta\mu$	0.4%	2.2%	
$\mathrm{R} = \mathcal{B}(\mathrm{H} \to \mu\mu)/\mathcal{B}(\mathrm{H} \to \mu\mu\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	1.3%	
$\mathrm{R} = \mathcal{B}(\mathrm{H} \to \gamma\gamma)/\mathcal{B}(\mathrm{H} \to \mathrm{ee}\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	0.8%	(*)
$\mathrm{R} = \mathcal{B}(\mathrm{H} \to \gamma\gamma)/\mathcal{B}(\mathrm{H} \to \mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	1.3%	(*)
$\mathrm{R} = \mathcal{B}(\mathrm{H} \to \mu\mu\gamma)/\mathcal{B}(\mathrm{H} \to \mu\mu\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	1.6%	2.0%	(*)
$\mathrm{R} = \sigma(\mathrm{ttH})\,\mathcal{B}(\mathrm{H} \to \mathrm{b\bar{b}})/\sigma(\mathrm{ttZ})\,\mathcal{B}(\mathrm{Z} \to \mathrm{b\bar{b}})$	$\delta\mathrm{R}/\mathrm{R}$	1.2%	2.0%	(*)
$\mathrm{R} = \sigma(\mathrm{VBF-H}))\,\mathcal{B}(\mathrm{H} \to \mathrm{e}\mu\nu\nu)/\sigma(\mathrm{VBS-WW}))\,\mathcal{B}(\mathrm{WW} \to \mathrm{e}\mu\nu\nu)$	$\delta\mathrm{R}/\mathrm{R}$	1.9%	2.0%	
$\mathcal{B}(\mathrm{H} \to \mathrm{invisible})$	$\mathcal{B}$@95%CL	1.2×10^{-4}	2.6×10^{-4}	(*)
$\sigma(\mathrm{HH})$	$\delta\kappa_\lambda$	3.5%	5.2%	



- FCChh will produce about 30 billion Higgs bosons in $30\,\mathrm{ab}^{-1}$, allowing measurements of $H \to \gamma\gamma$, $H \to \mu\mu$, $H \to Z\gamma$ with **1-2% uncertainty** (systematically limited)



- Measured ratios depend on precise measurement of $H \to ZZ^*$ at FCCee

Di-Higgs Production at FCChh

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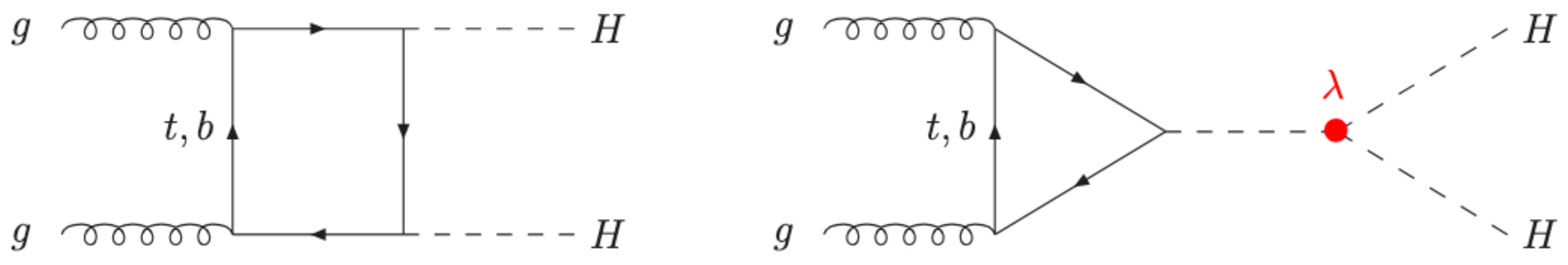
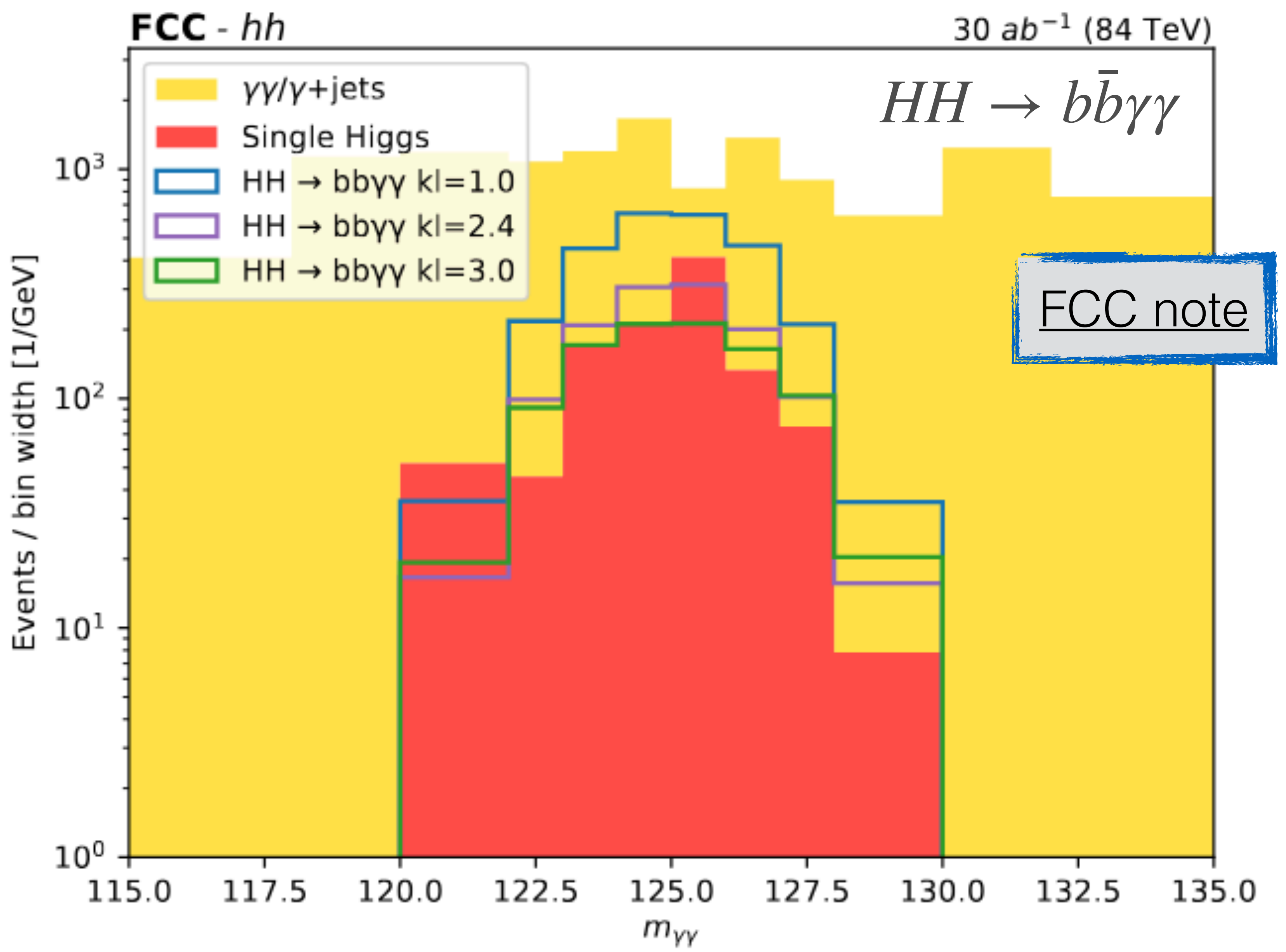
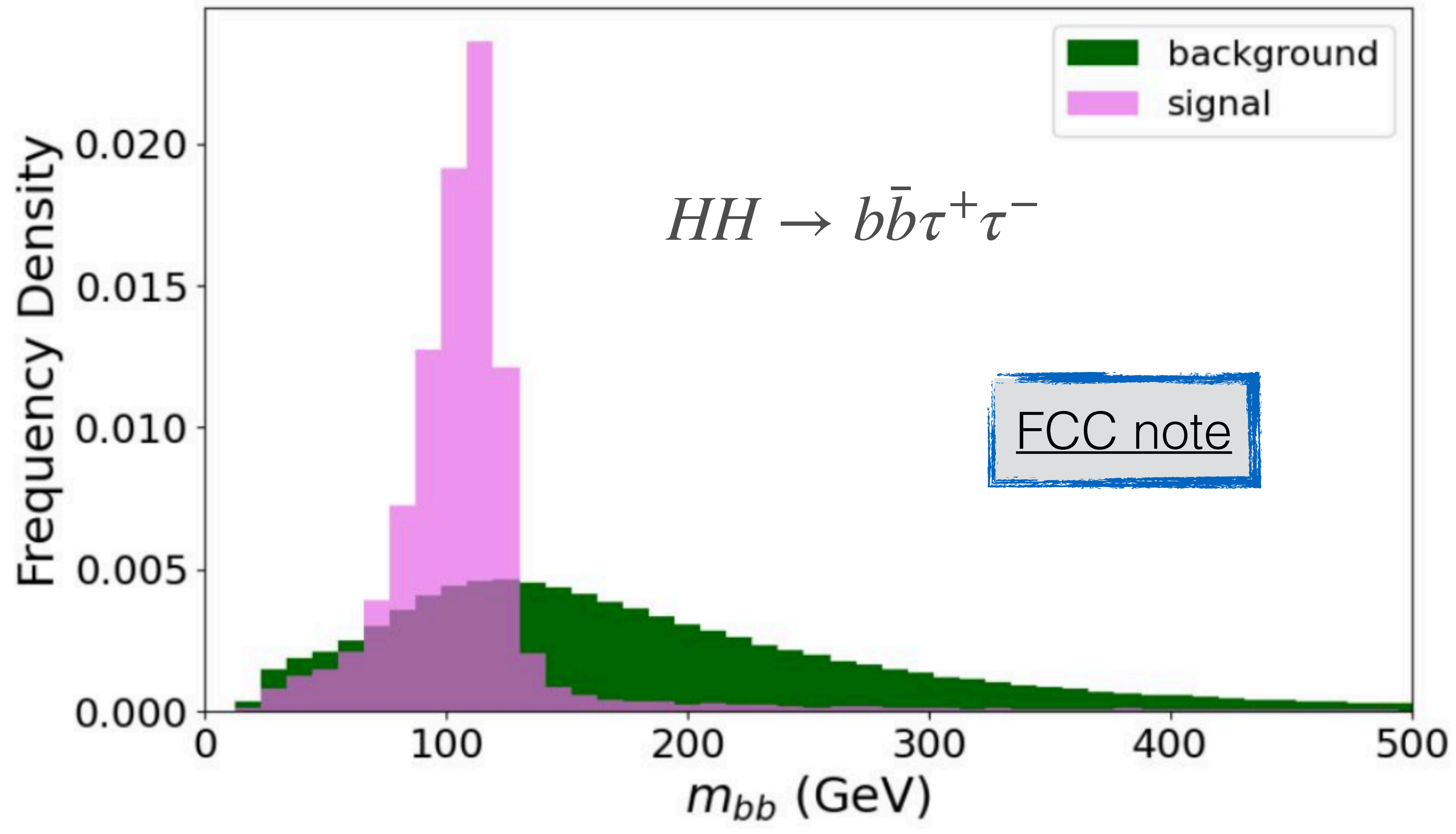




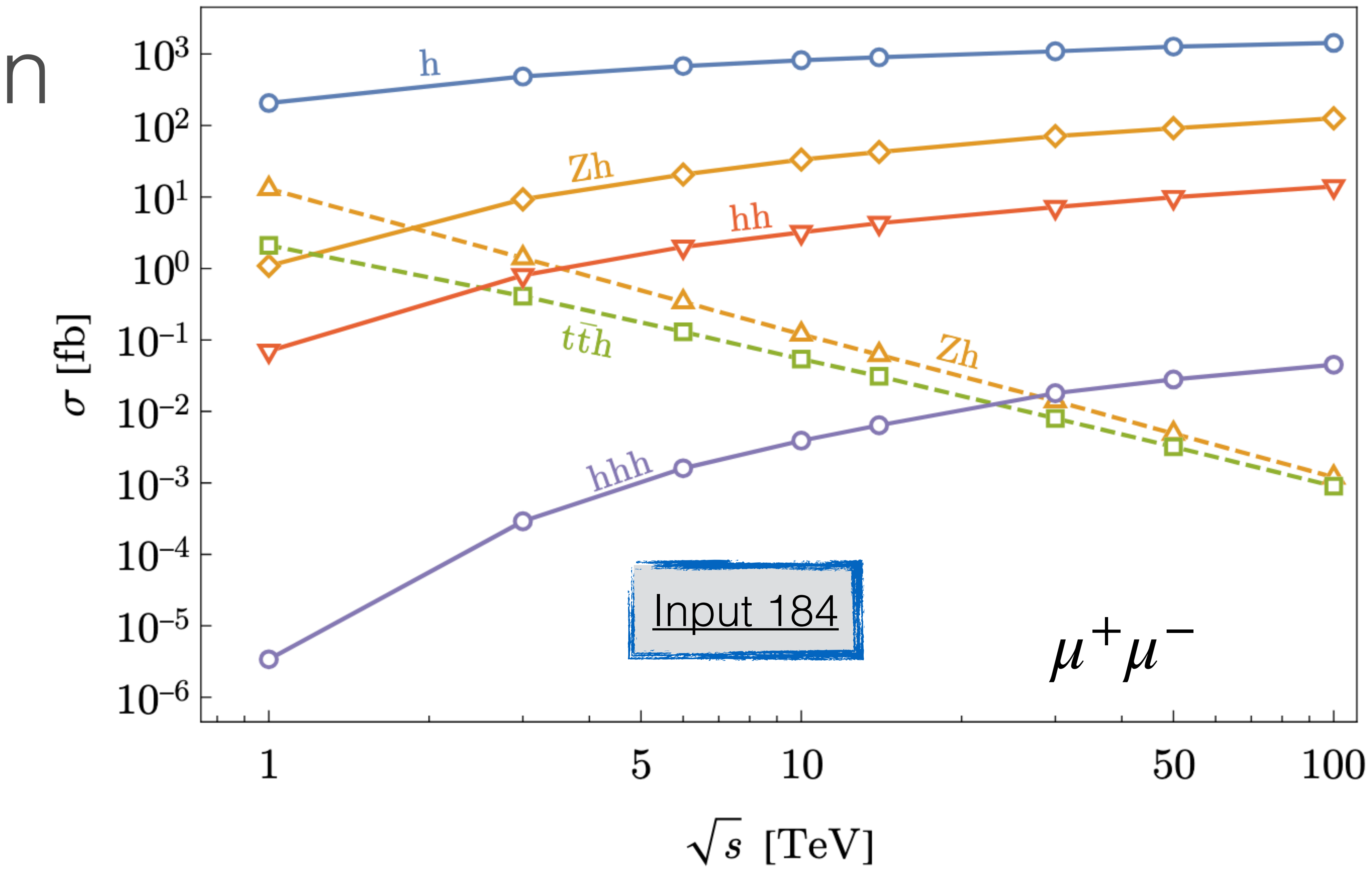
- Similar to HL-LHC most sensitivity in channels that can be cleanly tagged: $HH \to b\bar{b}\gamma\gamma$, $HH \to b\bar{b}\tau^+\tau^-$ and $HH \to b\bar{b}W^+W^- \to b\bar{b}\ell\ell + E_T^{\text{miss}}$

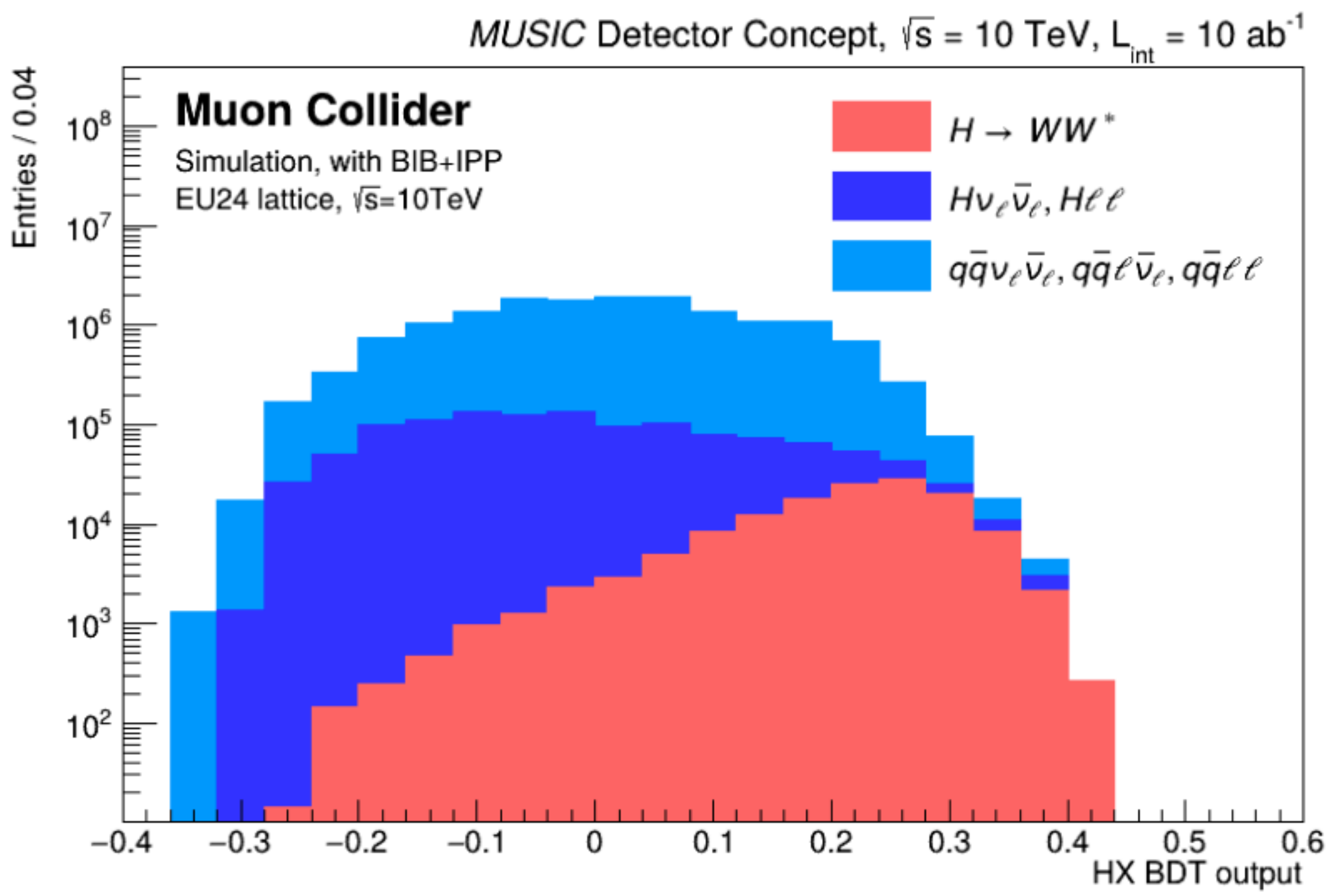
- Combination for all channels in progress, expect ~5% uncertainty on κ_λ from $HH \to b\bar{b}\gamma\gamma$ alone, expected qual precision from $HH \to b\bar{b}\tau^+\tau^-$

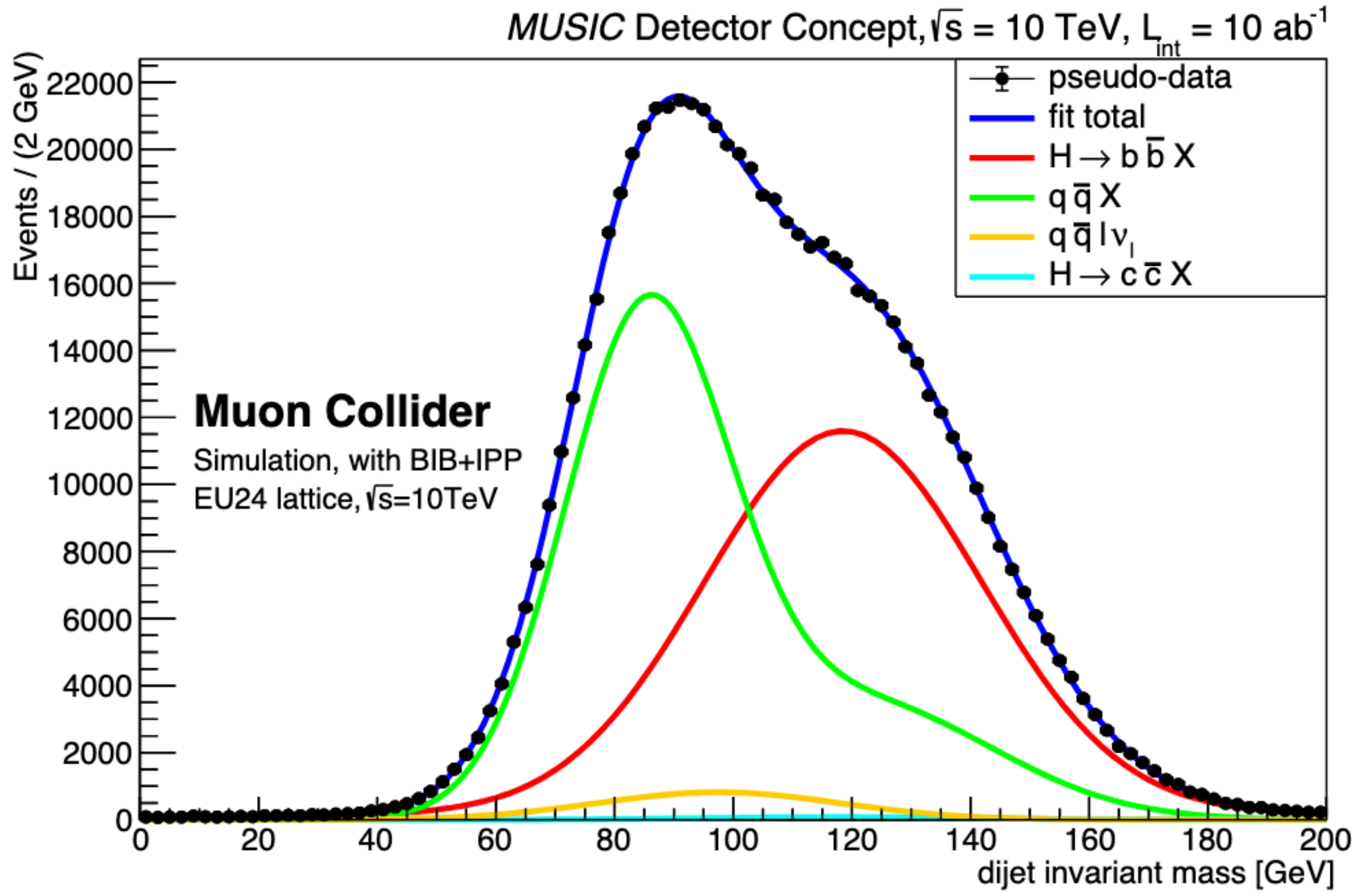


Higgs Production in $\mu^+\mu^-$ @ $\sqrt{s} = 10$ TeV

- Similar to multi-TeV e^+e^- collisions production modes with WW fusion are dominant
- Projections for uncertainty on $\sigma(H \to b\bar{b}) \approx 0.28\,\%$ (0.78% @ 3 TeV)
- Uncertainty $\sigma(H \to WW^*) \approx 0.58\,\%$







Di-Higgs Production in $\mu^+\mu^-$ @ $\sqrt{s} = 10$ TeV

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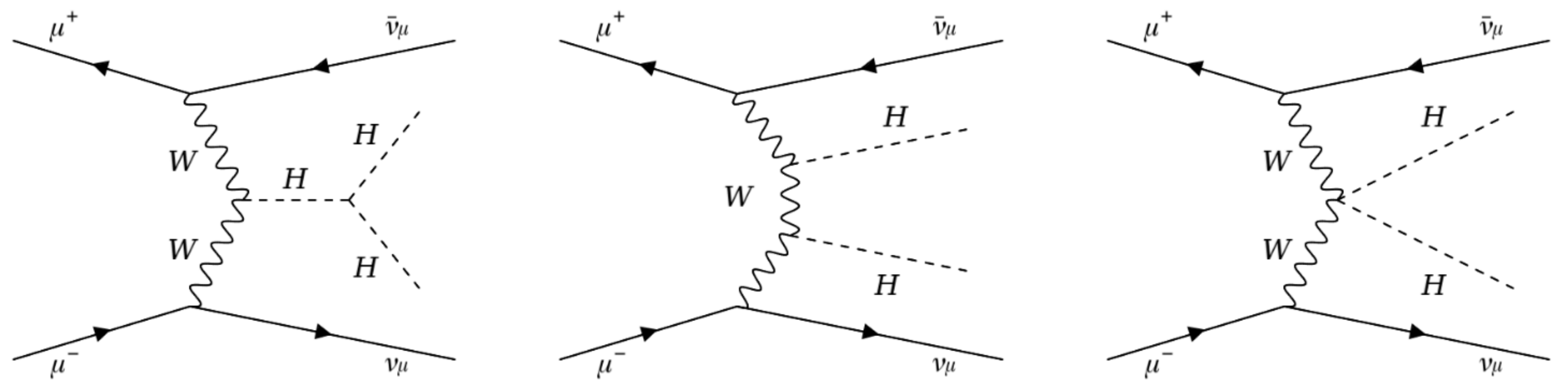
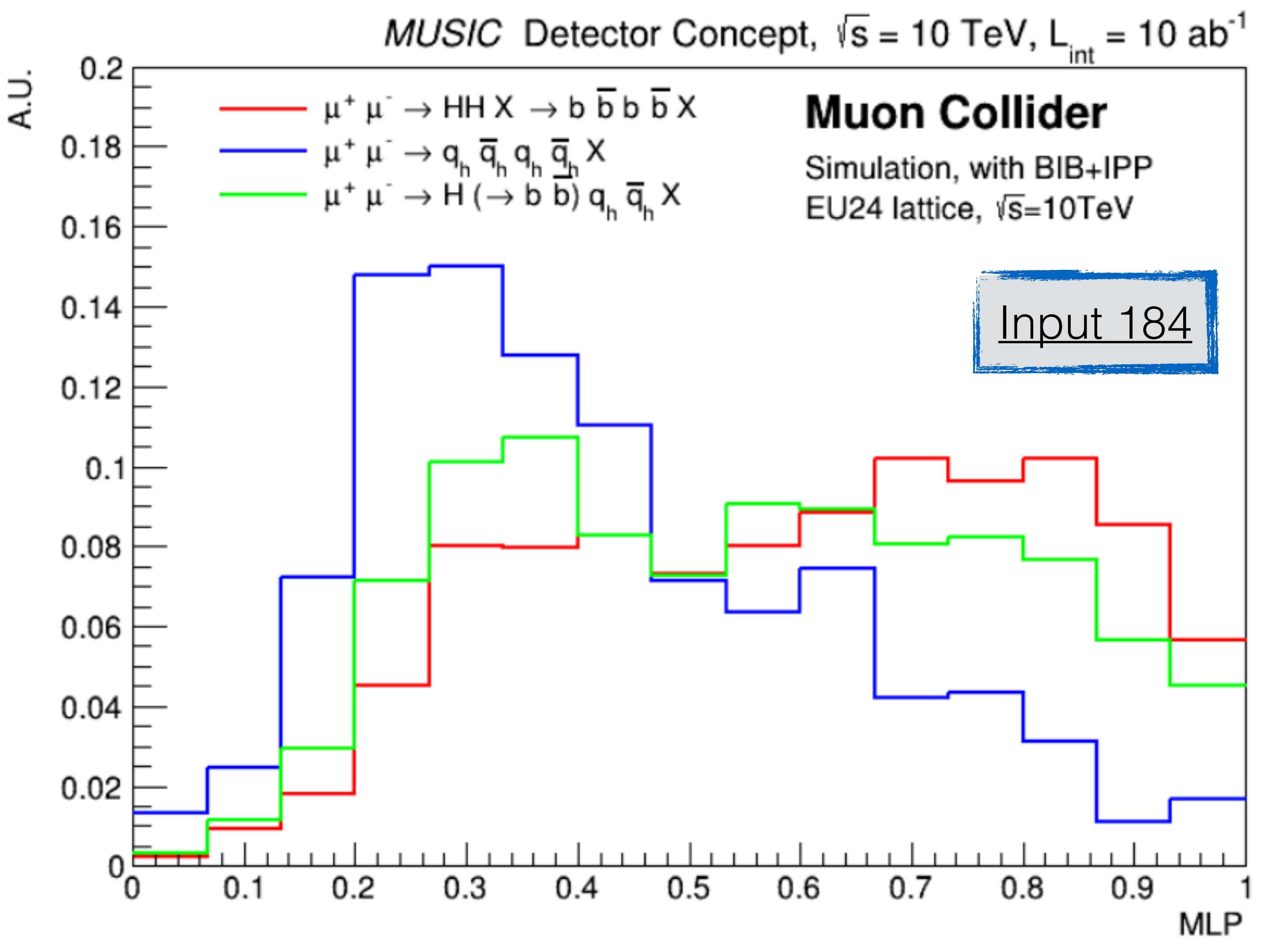
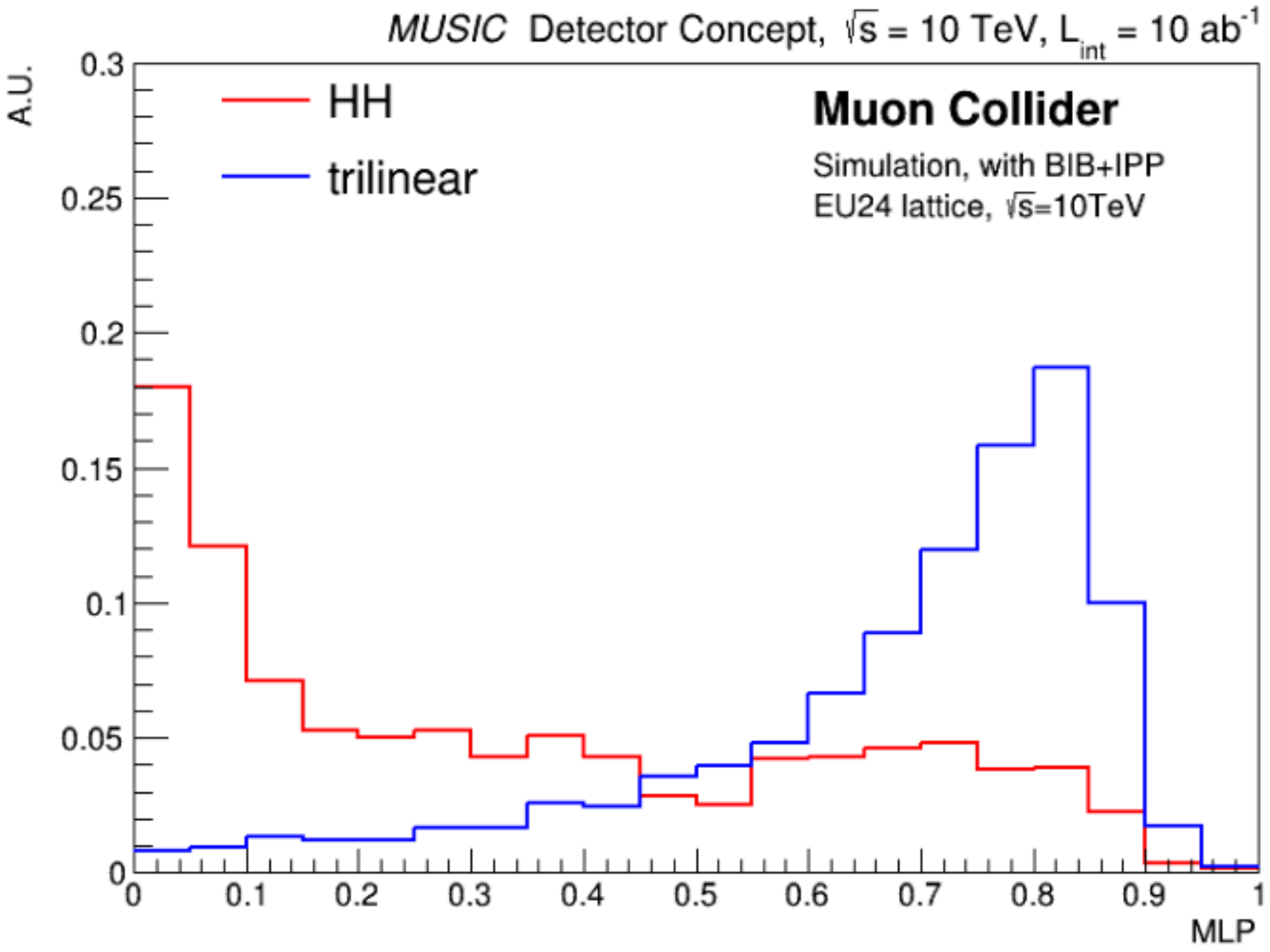
- Benefit from **clean selection of b-jets** and use channel with highest BR: precision on $\sigma(\nu\nu b\bar{b}b\bar{b}) \approx 6\,\%$, statistically limited
- Using kinematic observables of the two Higgs systems allows to **select events that are sensitive to the self-coupling λ**







The Top Quark Measurements (today)

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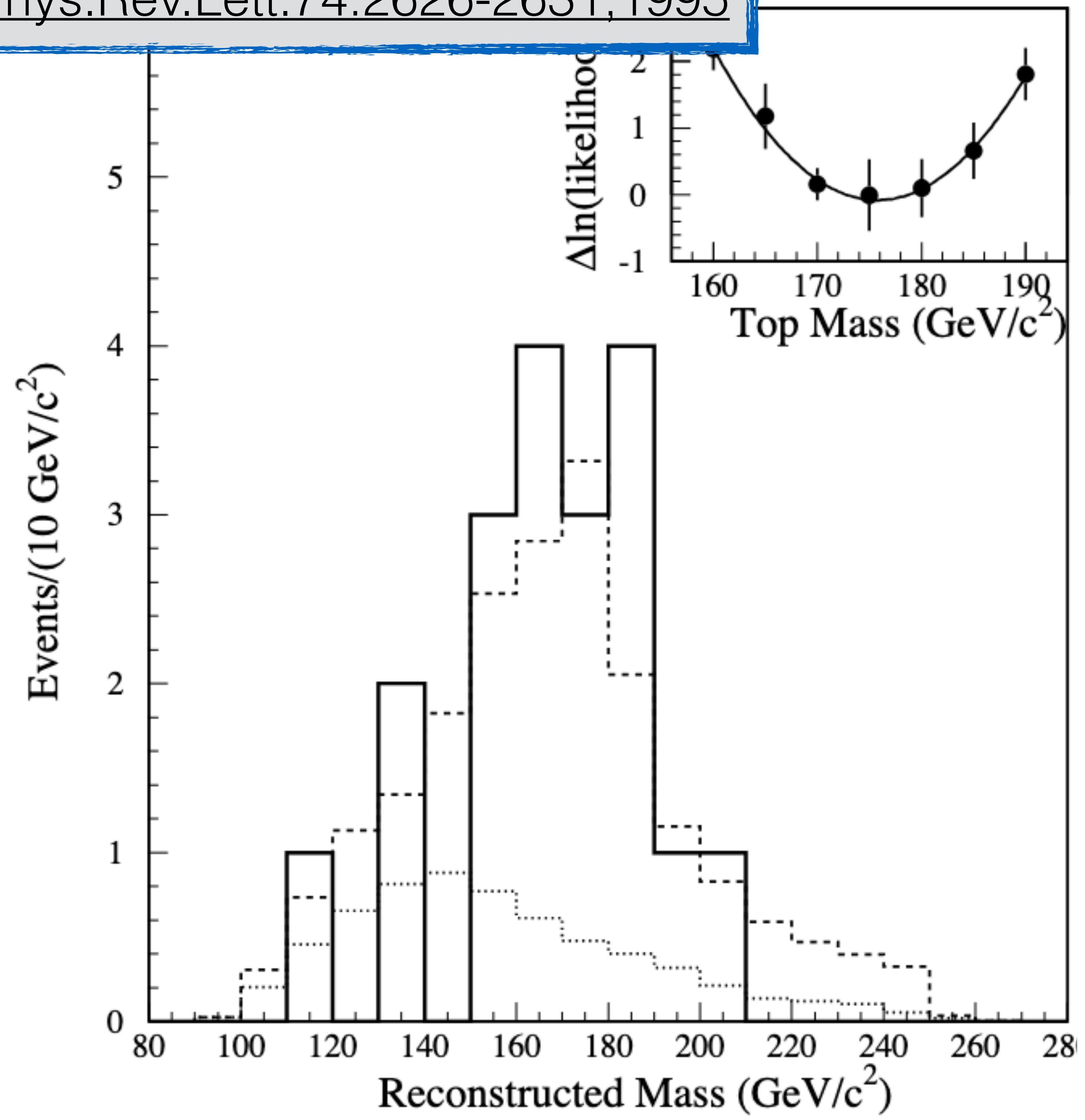
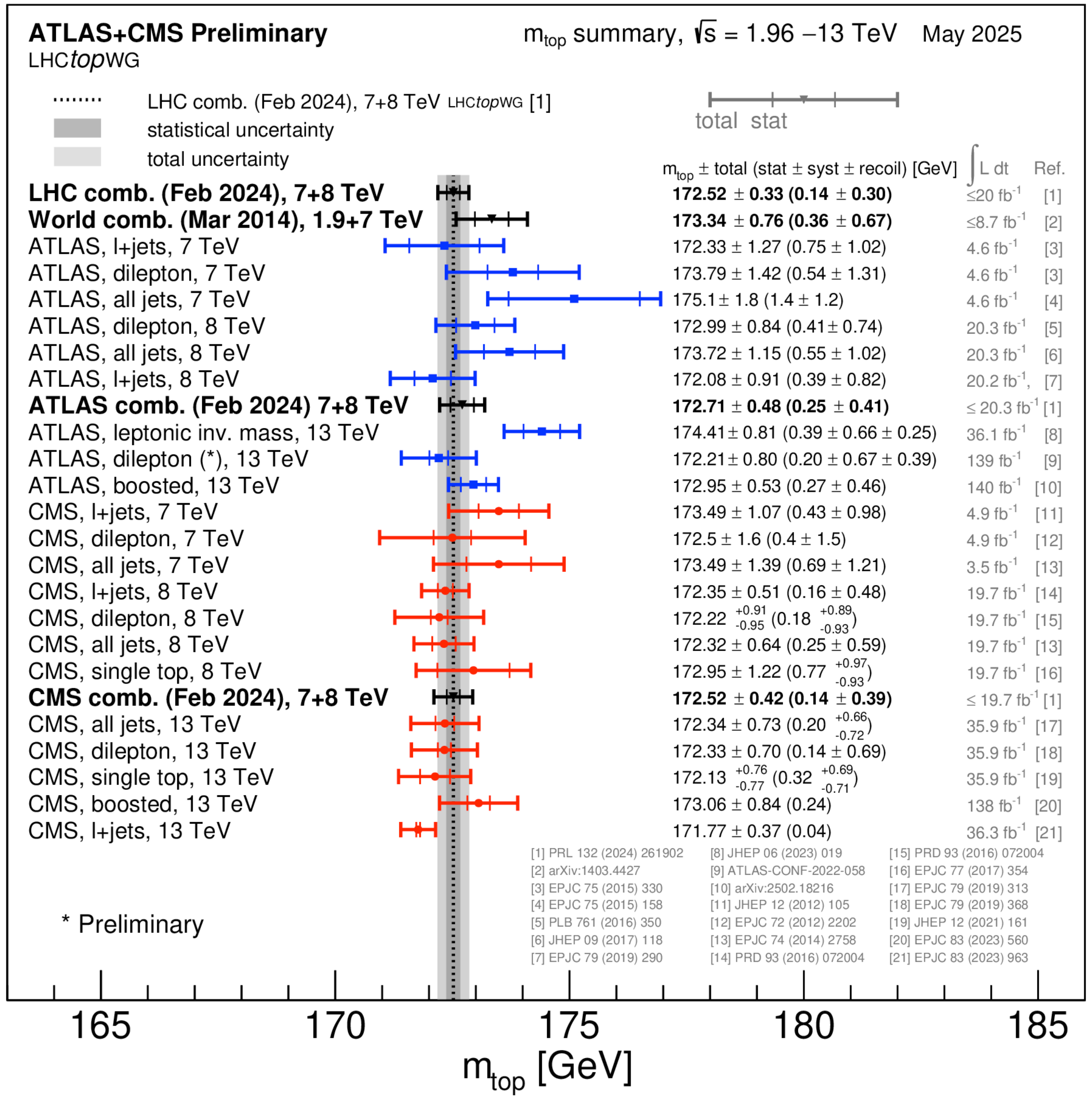
Phys.Rev.Lett.74:2626-2631,1995



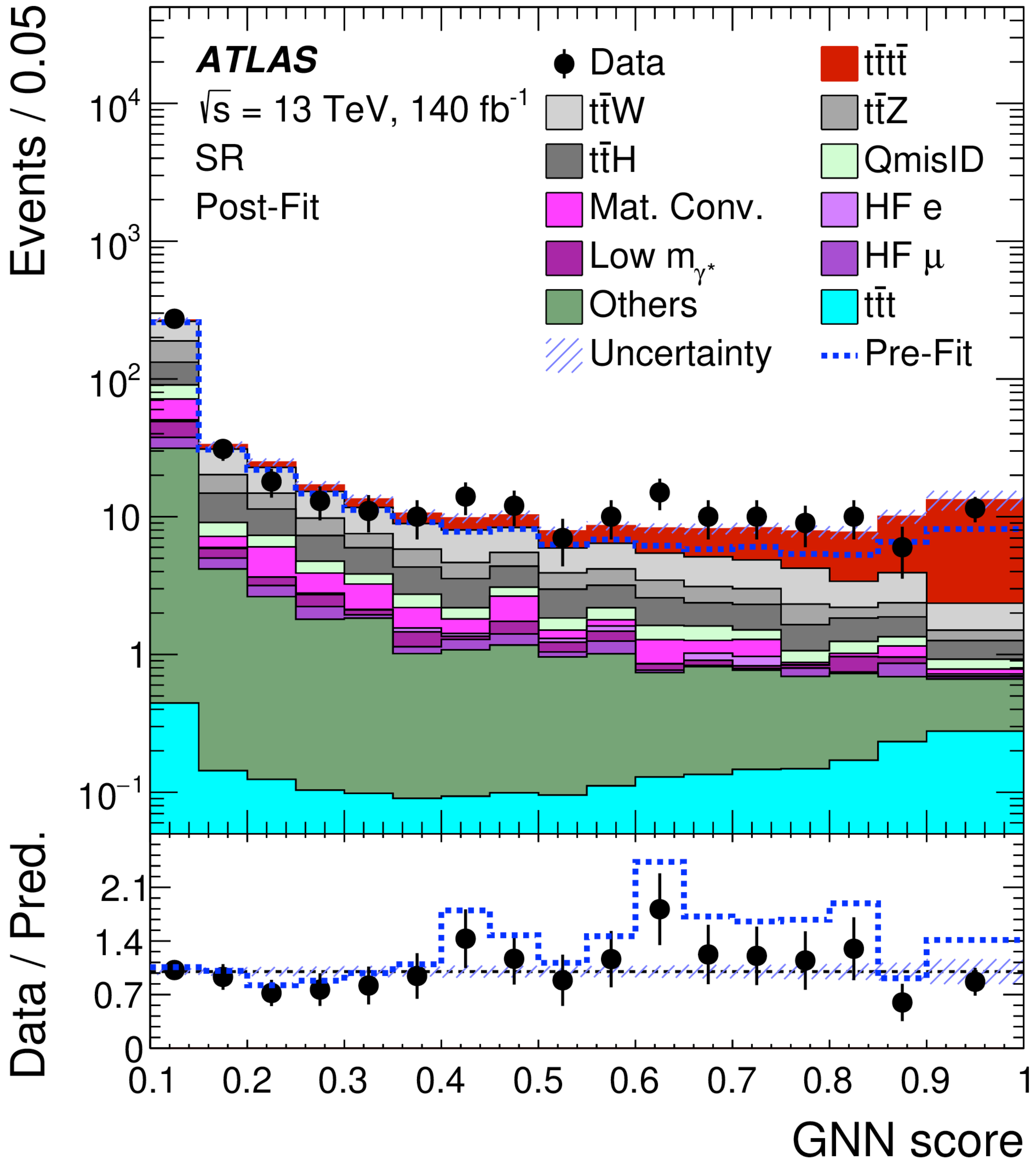
- Top quark predicted after bottom quark discovery in 1977
- Discovered by CDF and DØ in 1995 at the Tevatron



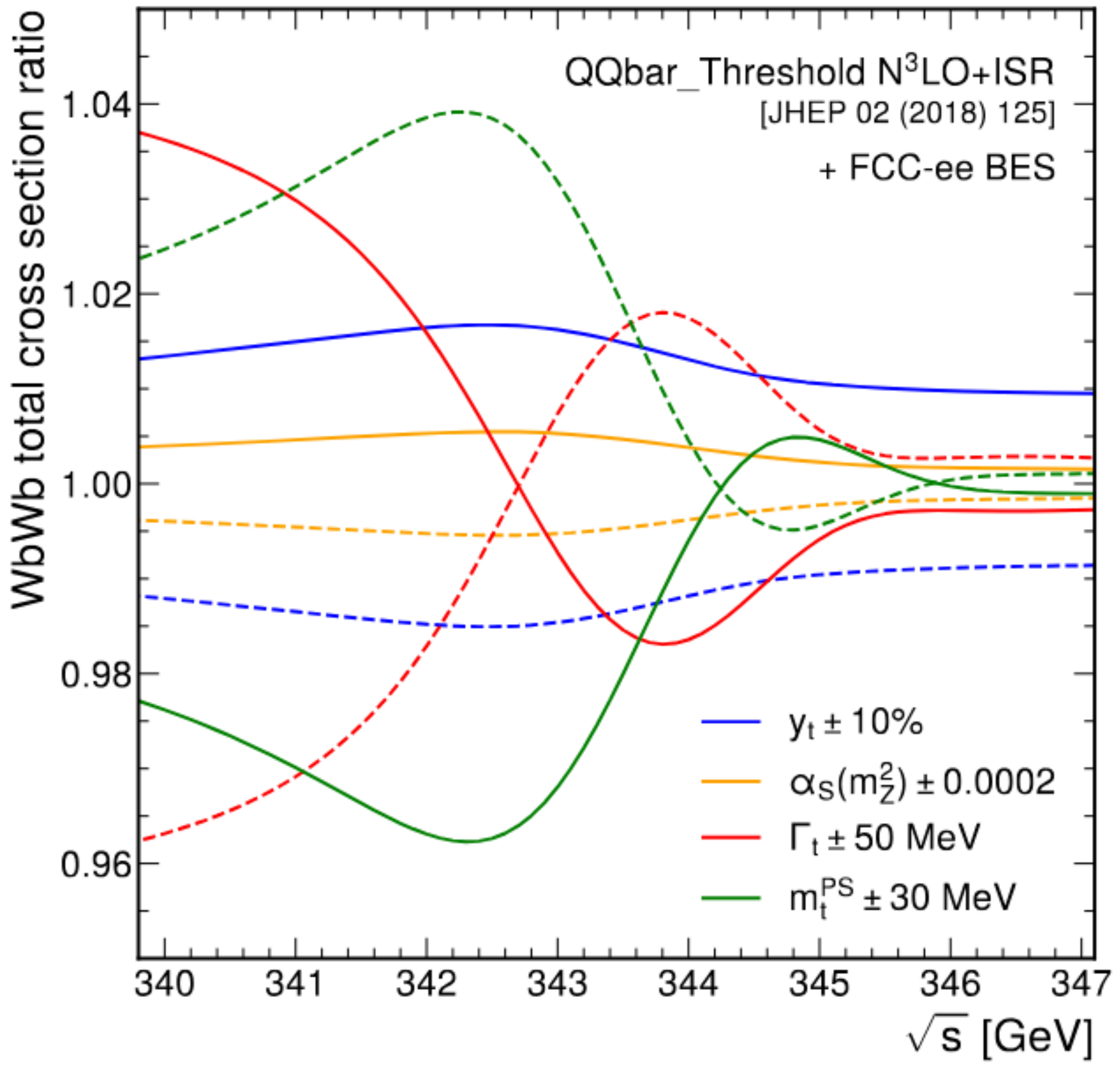
$m_t = 172.56 \pm 0.31$ GeV (latest PDG combination)

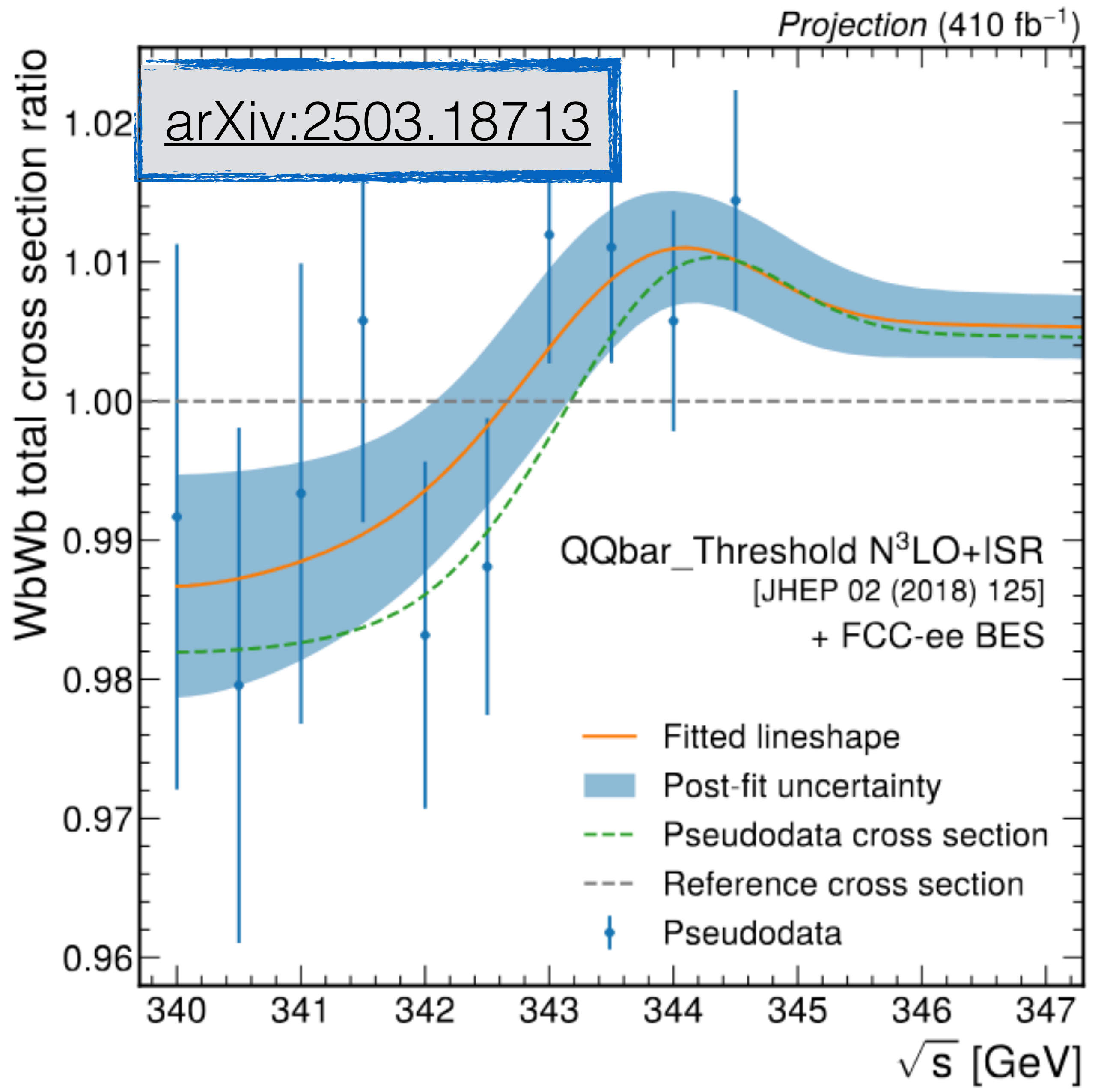
CMS and ATLAS observed $pp \rightarrow t\bar{t}t\bar{t}$

Eur. Phys. J. C 83 (2023) 496



Measuring the Top Quark Mass





arXiv:2503.18713

Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_{top} (MeV)	172 570	±	290	**4.2**	4.9*	From $t\bar{t}$ threshold scan parametric, beam calibration
Γ_{top} (MeV)	1 420	±	190	**10.0**	6.0*	From $t\bar{t}$ threshold scan parametric, beam calibration
y_{top}		±	10%	**1.5%**	1.5%*	From $\sqrt{s} = 365$ GeV run paramteric, beam calibration
g_{ttZ} (L-R)		±	10-30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run

FCC note

- The most precise measurements for the **top quark mass and total width will be performed using a scan** of ~10 mass points around the $t\bar{t}$ threshold using 100-200 fb^{-1} (LCF,CLIC) or 400 fb^{-1} (FCCee)
    - Expected precision **5 MeV for FCCee 20-40 MeV for LCF and CLIC**
    - **Simultaneous extraction of total width.** Large systematic uncertainties from α_s and y_t which can also be profiled
- Measurements from the continuum $\gamma t\bar{t}$ production at higher $\sqrt{s}$ are possible but significantly worse (~200 MeV)

More Top Quark Measurements at e^+e^-

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- Polarised beams allow to disentangle γ and Z couplings in $e^+e^- \to t\bar{t}$
- At least two additional cross section measurements at energies above the $t\bar{t}$ threshold are necessary to resolve ambiguities in dim-6 SMEFT fits
- Constraints on $eett$ operators that enter ZH coupling at NLO
- ttZ production
- Measurements of A_{FB}
- Searches for FCNC decays
- …

$\sqrt{s}$ **CLIC**	380 GeV[a]		1.4 TeV[b]		3 TeV[b]	
$P(e^-)$	-80%	+80%	-80%	+80%	-80%	+80%
$\sigma_{t\bar{t}}$[c] [fb]	161.00	75.97	18.44	9.84	3.52	1.91
stat. unc. [fb]	0.77	0.52	0.21	0.29	0.07	0.09
A_{FB}	0.1761	0.2065	0.567	0.620	0.596	0.645
stat. unc.	0.0067	0.0059	0.008	0.020	0.014	0.034

JHEP 11 (2019) 003

Top Quark Production at Highest Energies

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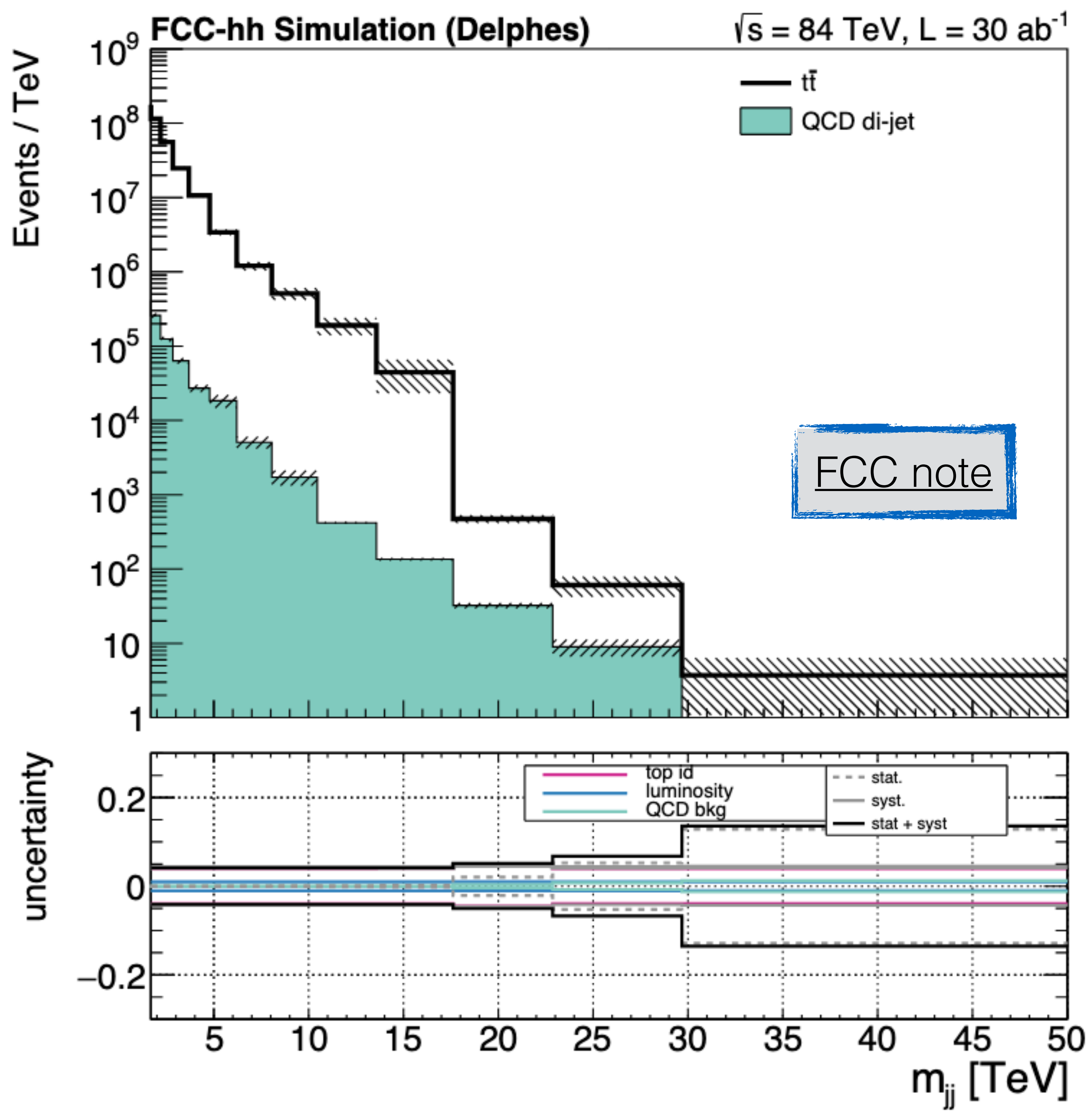
- Top quark pairs are produced abundantly at the FCChh but they are typically extremely boosted
- Needs **development of dedicated boosted top taggers** - projected uncertainties differential cross section in $m_{t\bar{t}} < 10\,\%$ up to the highest energies
- Uncertainty on $\sigma(t\bar{t}t\bar{t}) < 4\,\%$ using just one channel (opposite flavour, same sign 4ℓ). Significant improvement expected once more channels are included.



Limitations and Caveats

- All predictions come with limitations and caveats - **ideally, similar levels of sophistication** for all ingredients of the projections for a meaningful comparison
- How realistic are the proposed **detector concepts** (material budget, efficiencies, etc.)
- **Fast simulation studies** simplify reconstruction effects, in particular from beam-related backgrounds or pile-up
  - Assumed performance numbers should be substantiated with dedicated full simulation studies
- **Reconstruction algorithms** have varying level of sophistication - in particular for particle flow, particle identification and jet flavour tagging
- **Not all channels have being exploited** by all projects
- **Analysis techniques are constantly evolving**: some results still derived using cut-based selections, other use NNs, etc. - there is still room for significant improvements!

Extrapolation of Results for Briefing Book

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- To compare capabilities of the different projects on similar footing we need to make a choice
  - Assume that detector performance and beam background effects are secondary effects - **prioritise equalising included channels, reconstruction and analysis techniques**
- **Extrapolate "best" results across all Higgs factory projects** taking into account integrated luminosity, number of experiments and beam polarisation effects on the signal (conservative since it assumes similar scaling for all backgrounds)

Backup

Higgs Factories close to ZH threshold

Future Colliders Comparative Evaluation - Working Group Report

	CLIC	FCC-ee				LCF		
						LP	FP	
Circumference/length collider tunnel [km]	11.4	90.7				33.5		
Number of experiments (IPs)	2	4				2		
Synchrotron radiation power per beam [MW]	—	50				—		
c.o.m. energy [GeV]	380	91.2	160	240	365	250	91.2	250
Longitudinal polarisation (e^- / e^+) [%]	±80 / 0	0 / 0[a]				±80 / ±30		
Number of years of operation (total)	10	4	2	3	5	5	1	3
Nominal years of operation (equivalent)[b]	8	3	2	3	4.5	3	1	3
Instantaneous luminosity per IP above 0.99 $\sqrt{s}$ (total) [10^{34} cm^{-2} s^{-1}]	1.3 (2.2)	140	20	7.5	1.4	1 (1.35)	0.28 (0.28)	2 (2.7)
Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs per year of nominal operation [ab^{-1}/y]	0.32 (0.54)	69	9.6	3.6	0.67	0.24 (0.32)	0.067 (0.067)	0.48 (0.65)
Integrated luminosity above 0.99 $\sqrt{s}$ (total) over all IPs over the full programme [ab^{-1}]	2.56 (4.4)	205	19.2	10.8	3.1	0.72 (0.97)	0.067 (0.067)	1.44 (1.94)
Peak power consumption [MW]	166	251	276	297	381	143	123	182
Electricity consumption per year of nominal operation [TW h/y][c]	0.82	1.2	1.3	1.4	1.9	0.8	0.7	1.0

CLIC Single Higgs Projections

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arXiv:2503.21857

Channel	Measurement	Observable	Statistical precision 350 GeV (50 Hz) $2.2\,ab^{-1}$	350 GeV (100 Hz) $4.3\,ab^{-1}$	Reference [2]
ZH	Recoil mass distribution	m_H	52 MeV	38 MeV	[2]
ZH	$\sigma(ZH) \times BR(H \to \text{invisible})$	Γ_{inv}	0.3 %	0.2 %	[2]
ZH	$\sigma(ZH) \times BR(Z \to l^+l^-)$	g^2_{HZZ}	1.8 %	1.3 %	[2]
ZH	$\sigma(ZH) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	0.9 %	0.6 %	[2]
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	0.41 %	0.29 %	[2]
ZH	$\sigma(ZH) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	7 %	5 %	[2]
ZH	$\sigma(ZH) \times BR(H \to gg)$		2.9 %	2.1 %	[2]
ZH	$\sigma(ZH) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	3.0 %	2.1 %	[2]
ZH	$\sigma(ZH) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	2.4 %	1.7 %	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	0.9 %	0.6 %	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	12 %	9 %	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		4.8 %	3.4 %	[2]

Table 2: Summary of the precisions obtainable for the Higgs observables with the first stage of CLIC for two integrated luminosity scenarios, corresponding to 50 Hz running and 100 Hz running, respectively; and assuming unpolarised beams. For the branching ratios, the measurement precision refers to the expected statistical uncertainty on the product of the relevant cross section and branching ratio; this is equivalent to the expected statistical uncertainty of the product of couplings divided by Γ_H as indicated in the third column.

Channel	Measurement	Observable	Statistical precision 1.4 TeV $4.0\,ab^{-1}$	3 TeV $5.0\,ab^{-1}$	Reference
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	29 MeV	28 MeV	[2]
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	2.0 %†	4.3 %†‡	[10]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	0.2 %	0.2 %	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	3.7 %	4.4 %	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		3.1 %	2.7 %	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	2.6 %	2.8 %	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	23 %	16 %	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		9 %	6 %*	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		26 %	19 %*	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	0.6 %	0.4 %*	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	3.4 %	2.5 %*	[2]
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1.1 %	1.5 %*	[2]
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	4.5 %	–	[3]

Table 3: Summary of the precisions obtainable for the Higgs observables in the higher-energy CLIC stages with the updated luminosities of $4.0\,ab^{-1}$ at $\sqrt{s} = 1.4\,TeV$, and $5.0\,ab^{-1}$ at $\sqrt{s} = 3\,TeV$. In both cases unpolarised beams have been assumed. For g_{Htt}, the 3 TeV case has not yet been studied. Numbers marked with $*$ are extrapolated from $\sqrt{s} = 1.4\,TeV$ to $\sqrt{s} = 3\,TeV$ while $\dagger$ indicates projections based on fast simulations. For the branching ratios, the measurement precision refers to the expected statistical uncertainty on the product of the relevant cross section and branching ratio; this is equivalent to the expected statistical uncertainty of the product of couplings divided by Γ_H, as indicated in the third column. ‡ The value for $\sigma(ZH) \times BR(\text{all hadronic})$ at 3 TeV has been confirmed as 4% in a full-simulation study [11].