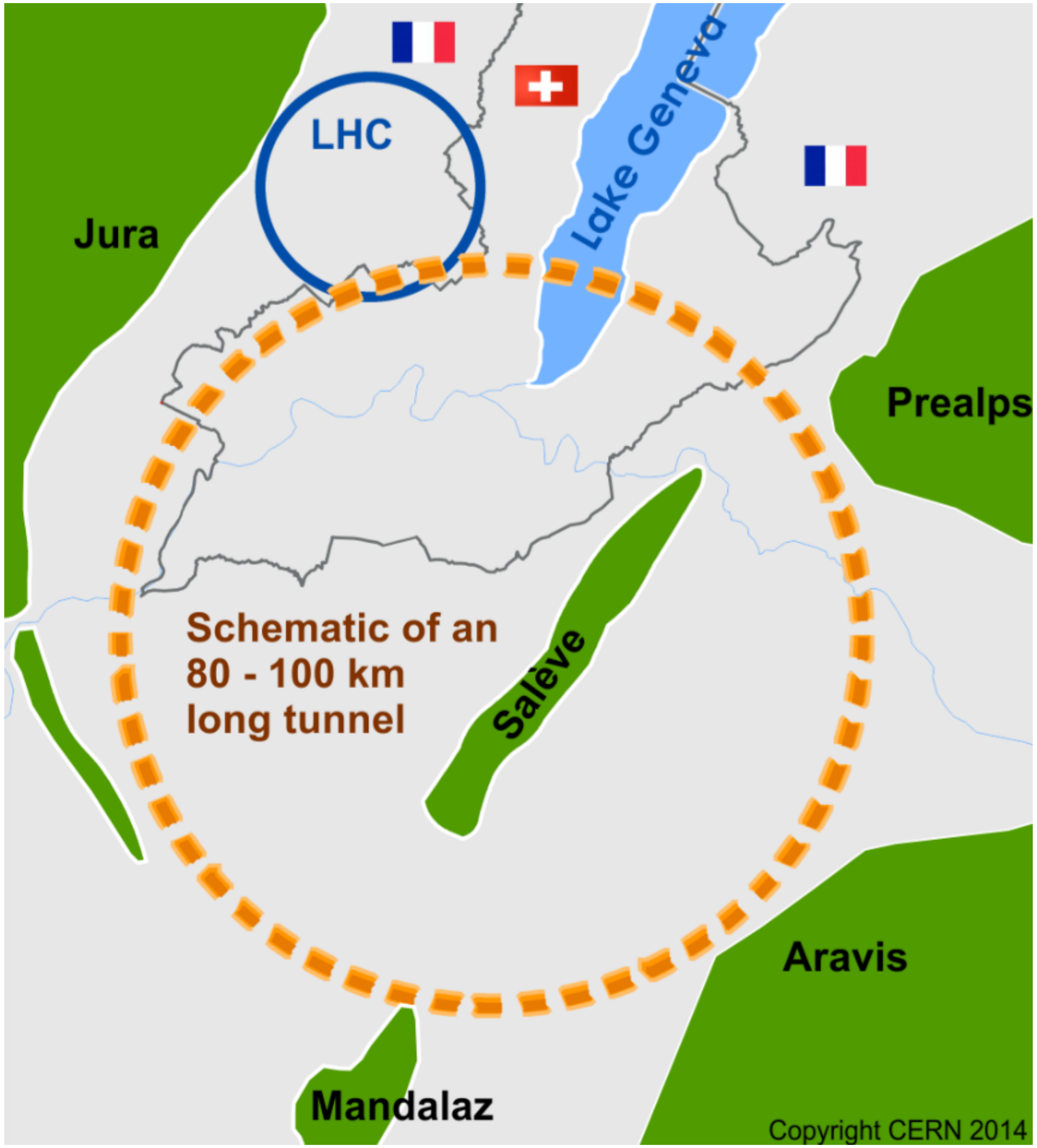
Overview of Higgs Physics at Future Circular Colliders

Anadi Canepa (Fermilab)

Double Higgs Production at Colliders Workshop

4-9th September 2018

FUTURE COLLIDERS (AT CERN) - I



- FCC: HADRON-HADRON
- THE ENERGY FRONTIER
- THE CHALLENGE: MAGNETS & PILEUP

parameter	FCC-hh	
collision energy cms [TeV]	100	
dipole field [T]	16	
circumference [km]	97.75	
beam current [A]	0.5	
bunch intensity [10^{11}]	1	1
bunch spacing [ns]	25	25
synchr. rad. power / ring [kW]	2400	
SR power / length [W/m/ap.]	28.4	
long. emit. damping time [h]	0.54	
beta* [m]	1.1	0.3
normalized emittance [μm]	2.2	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30
events/bunch crossing	170	1000
stored energy/beam [GJ]	8.4	

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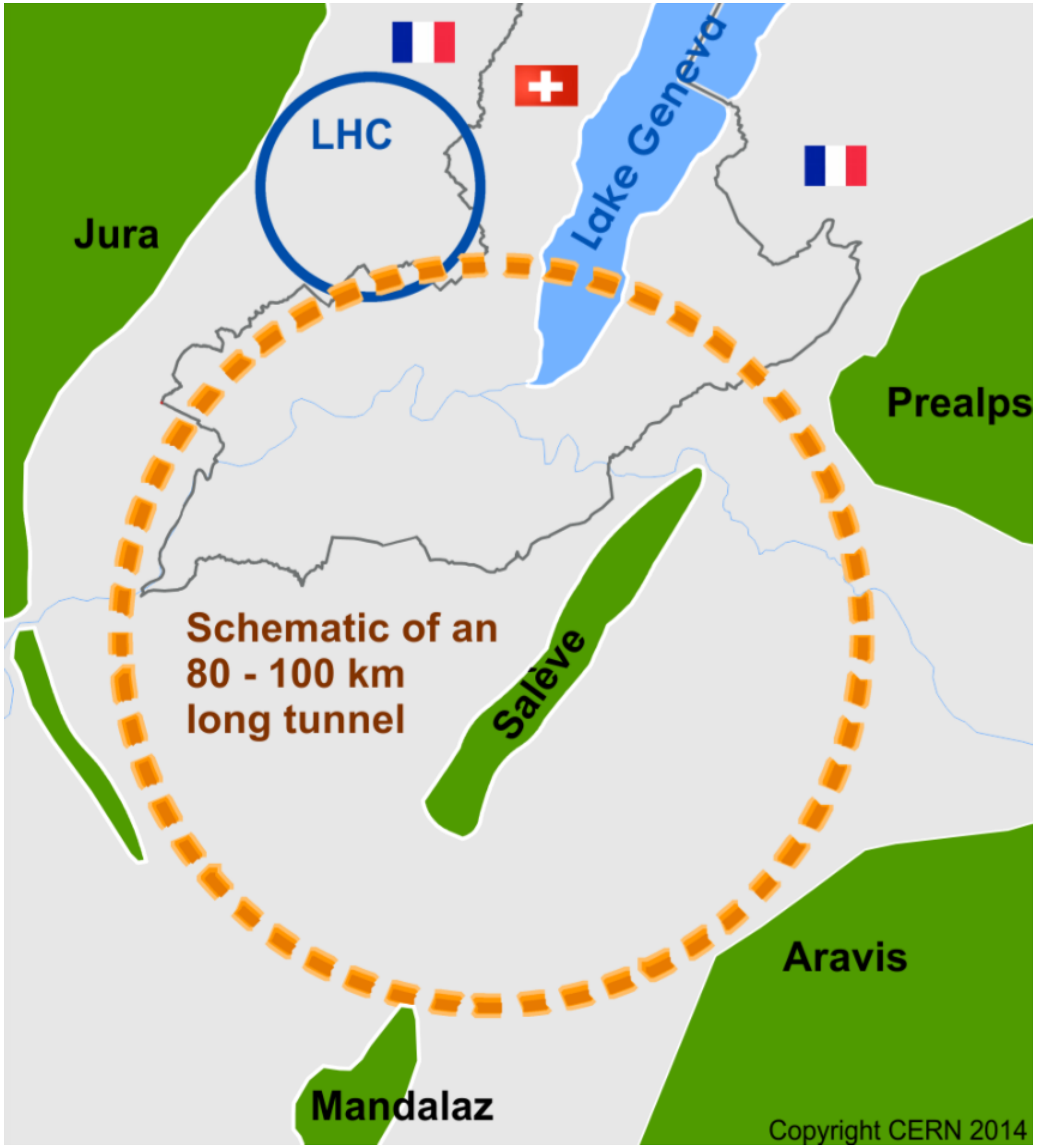
FUTURE COLLIDERS (AT CERN) - II

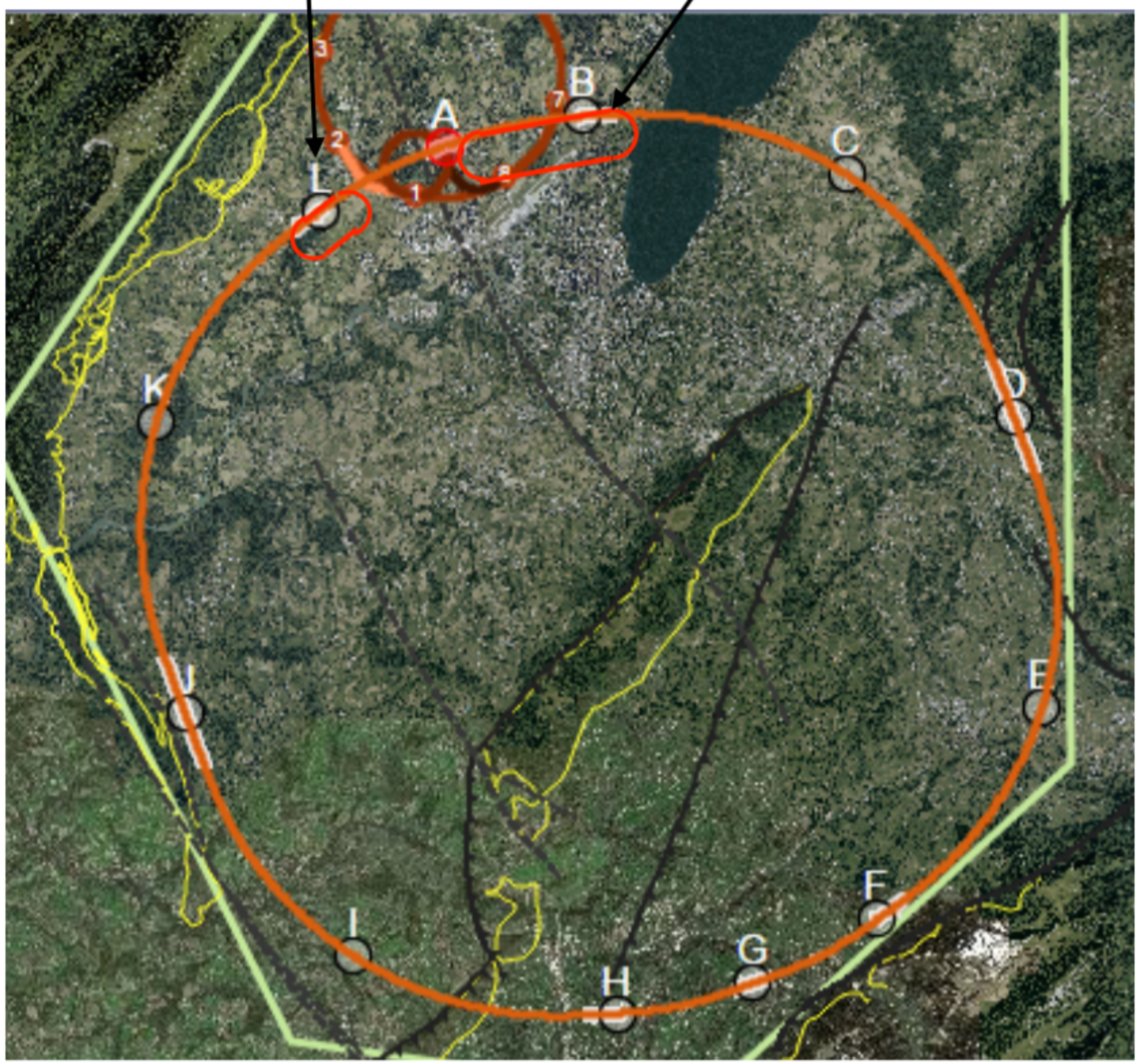


- FCC: ELECTRON-POSITRON
- THE PRECISION MACHINE
- *IN THE HH TUNNEL*
- ENERGY SCAN UP TO 365GEV
- THE CHALLENGE: CONTROL OF MACHINE OPERATING POINT

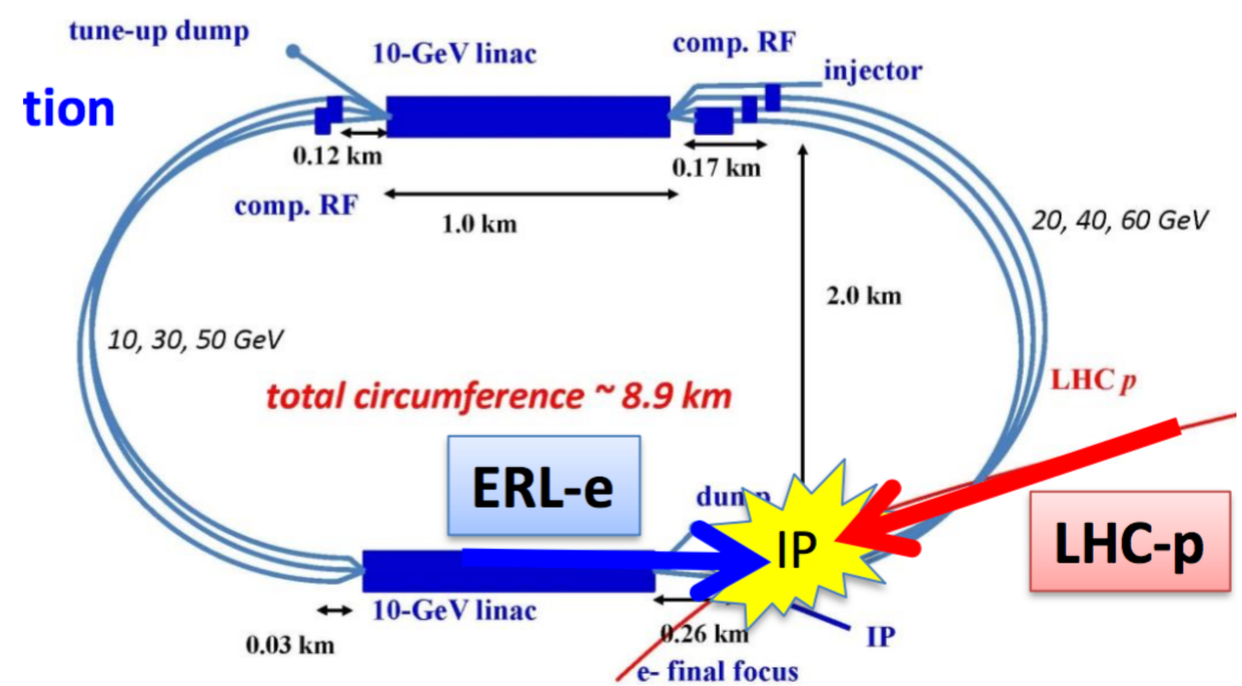
FUTURE COLLIDERS (AT CERN) - III

Independent FCC-he
Point L, F, H or B

LHeC / FCC-he
LHC P8 & FCC PB

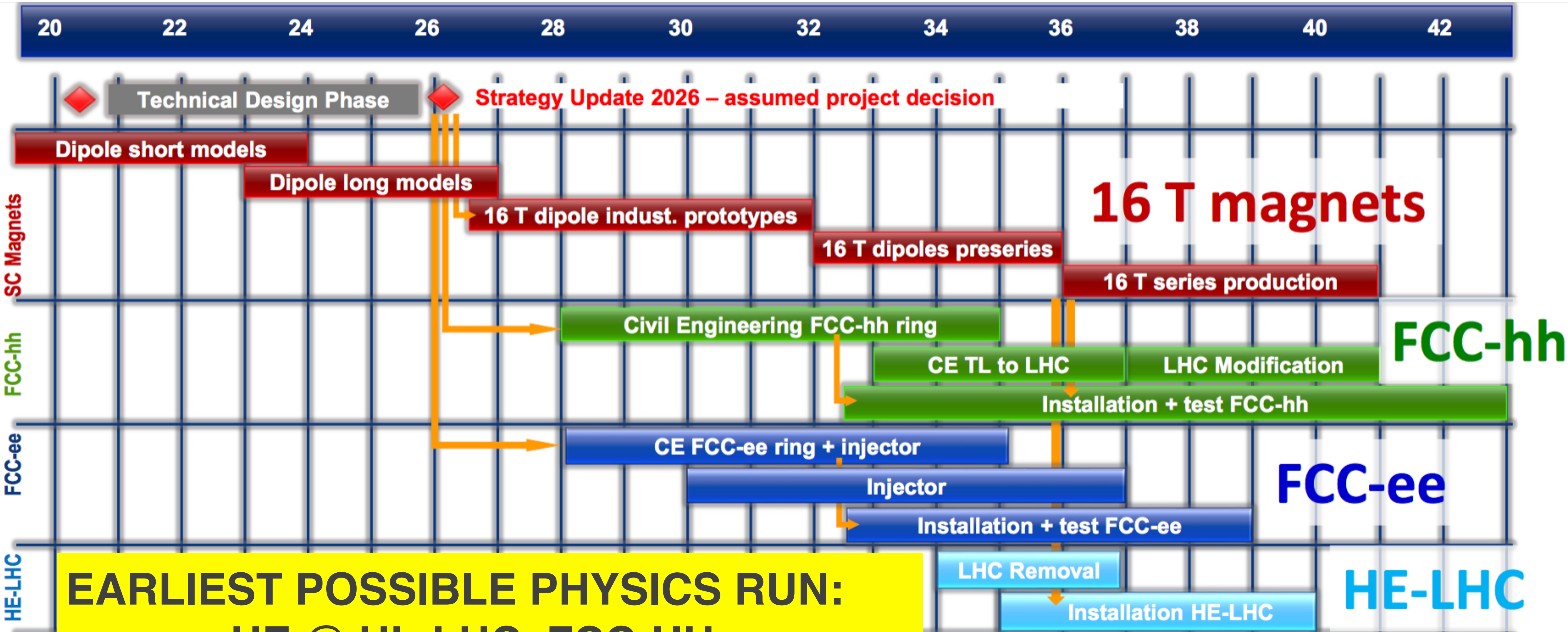


- FCC: LEPTON-HADRON
- THE PRECISION MACHINE UP TO 3.5TEV
- *HIGHER ENERGY THAN FCC-EE AND CLEANER THAN FCC-HH*



https://arxiv.org/pdf/1801.07394.pdf

TIMESCALE



EARLIEST POSSIBLE PHYSICS RUN:

- **HE @ HL-LHC, FCC-HH**
- **FCC-EE 2039**
- **FCC-HH 2043**

M. Benedikt,
FCC Week 2018, Amsterdam

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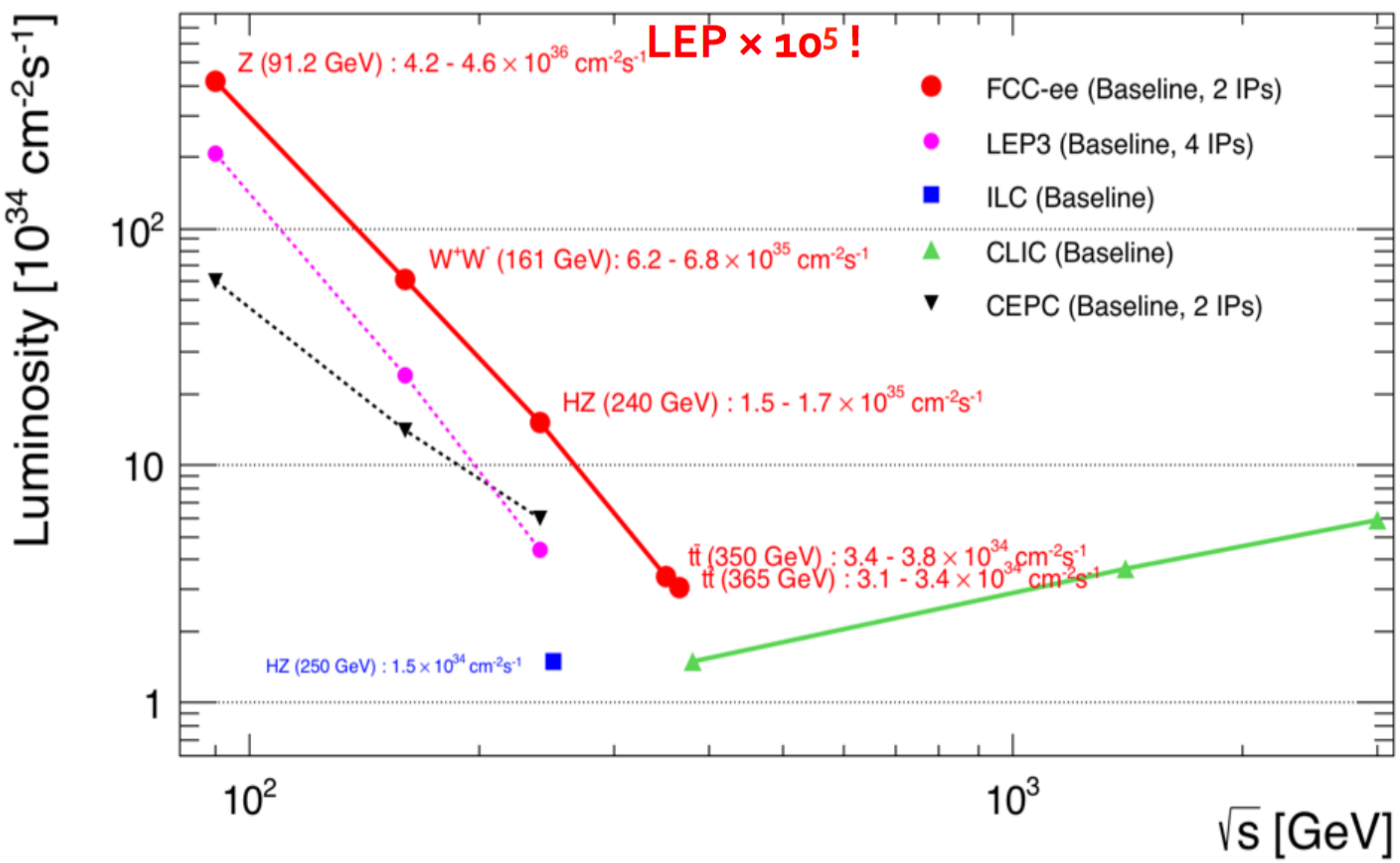
OUTLINE

- **Higgs program at FCC-ee**
  - Leading couplings
  - Electron Yukawa coupling
  - Self coupling
- **Higgs program at FCC-eh**
  - Leading couplings
  - Top Yukawa coupling
  - Self coupling
- **Contrasting HL vs FCC-ee vs FCC-eh**
- **Higgs program at FCC-hh**
  - Rare Modes
  - Self coupling
- **Conclusions**

THE FCC-EE

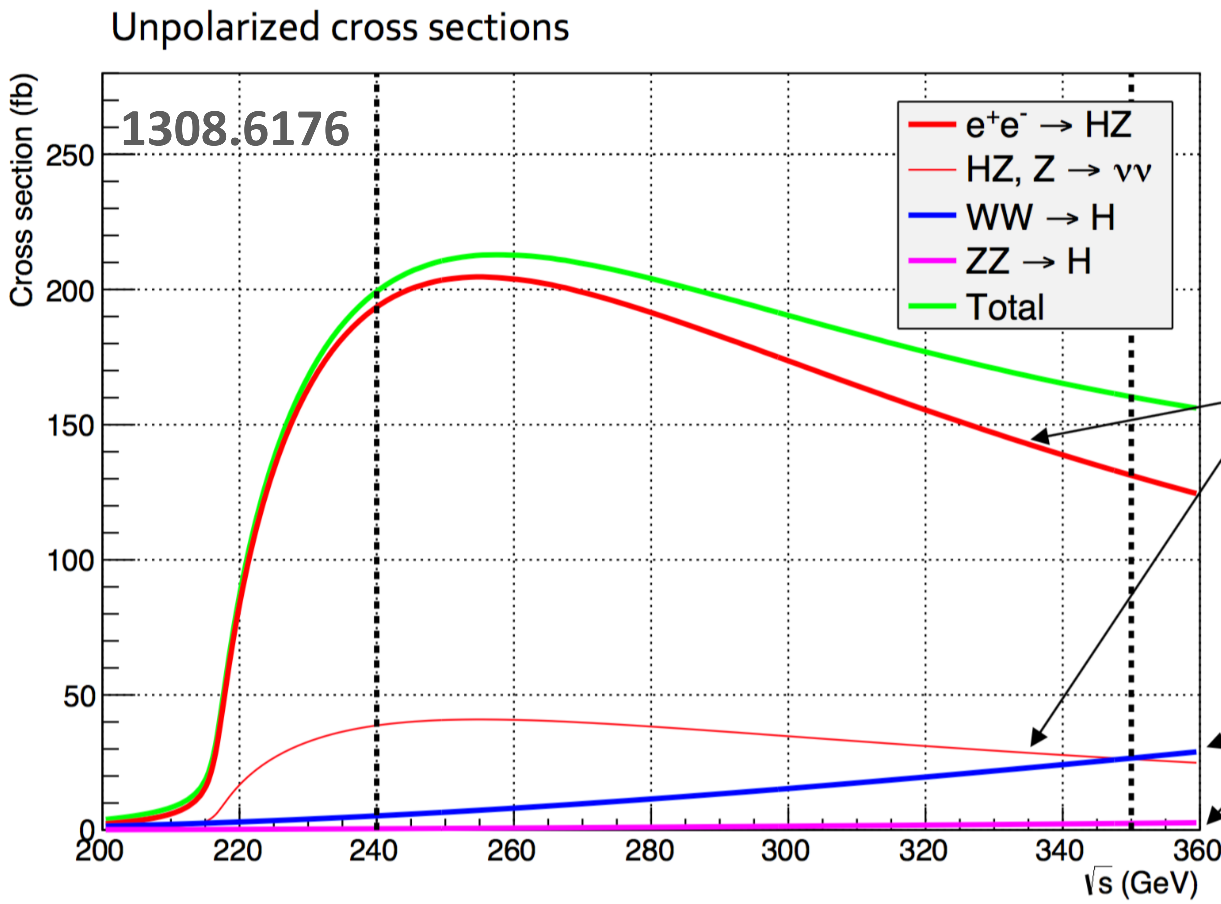
(GeV)	91.2	91.2	161	240	350	365
Lumi/yr (2 IP)	26/ab	52/ab	8/ab	1.95/ab	0.22/ab	0.39/ab
Physics Goals	150/ab		10/ab	5/ab	0.2/ab	1.5/ab
Run time (yr)	2	2	1	3	1	4

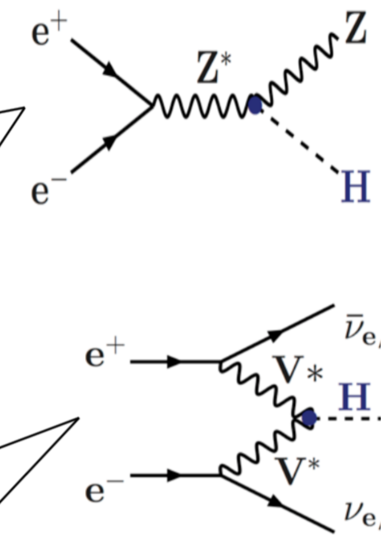
- Physics run from 2039 for ~13+1 years (similar to the LEP run time)



- Precise knowledge of the center of mass energy and luminosity
- Clean environment
- Independent measurement of SM parameters (*e.g.* m_t, m_H, …)

HIGGS PRODUCTION @ THE FCC-EE



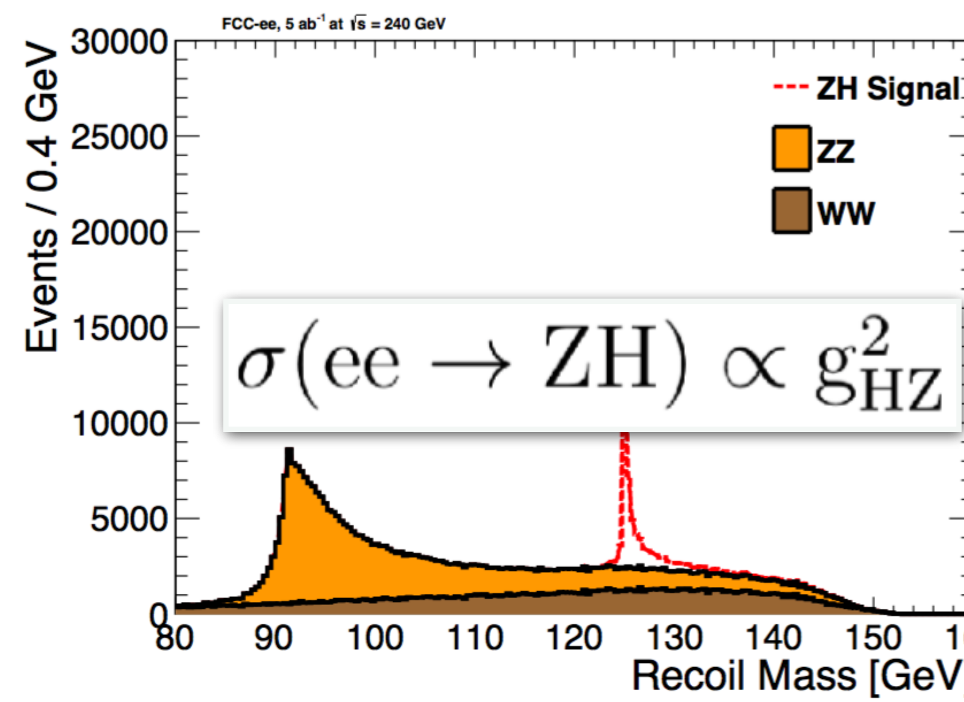


- **Higgstrahlung dominating the Higgs production with small contributions from VBF**

	240GeV	350GeV
Tot. Lumi	5/ab	1.5/ab
# ZH	1M	200k
# VBF H	25k	40k

- **<u>At 240 GeV</u>, measurement of the recoil mass allowing for an independent measurement of the ZH cross-section and thus of the g_{ZH} coupling (precision in 0.5-0.7% range)**

$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



LEADING HIGGS COUPLINGS @ FCC-EE

- Higgs width measured for the first time, indirectly from

$$\sigma(ee \to ZH) \cdot BR(H \to ZZ) \propto \frac{g_{HZ}^4}{\Gamma}$$

%	240GeV	+350GeV
Γ	2.61	1.55

- Absolute coupling measurements into various Higgs decay modes enabled by measurement of the g_{ZH} and Higgs width
- Extended dataset at 365GeV improving precision and offering sensitivity to y_t

Observable	Expected uncertainty
σ_{HZ}	0.57%
$\sigma_{HZ}\,\mathrm{Br}(H \to b\bar{b})$	0.28%
$\sigma_{HZ}\,\mathrm{Br}(H \to c\bar{c})$	1.7%
$\sigma_{HZ}\,\mathrm{Br}(H \to gg)$	2.0%
$\sigma_{HZ}\,\mathrm{Br}(H \to W^{\pm}W^{\mp *})$	1.3%
$\sigma_{HZ}\,\mathrm{Br}(H \to \tau^{+}\tau^{-})$	1.0%
$\sigma_{HZ}\,\mathrm{Br}(H \to ZZ^{*})$	4.4%
$\sigma_{HZ}\,\mathrm{Br}(H \to \gamma\gamma)$	4.2%
$\sigma_{HZ}\,\mathrm{Br}(H \to \mu^{+}\mu^{-})$	18.4%

Observable	Expected uncertainty
$\sigma_{WBF}^{(240\mathrm{GeV})}\,\mathrm{Br}(H \to b\bar{b})$	3.1%
$\sigma_{WBF}^{(350\mathrm{GeV})}\,\mathrm{Br}(H \to b\bar{b})$	0.79%

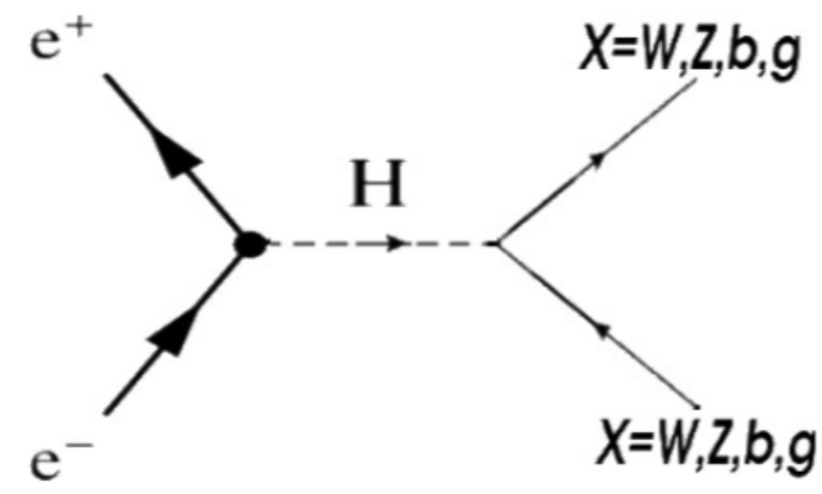
M. Klute, FCC Week 2018 Amsterdam

ELECTRON YUKAWA COUPLING @ FCC-EE (I)

- **Branching ratio H(ee) ~ 5 x 10^{-9}, observation beyond the reach of HL-LHC and FCC-ee via ZH**
- **Exploration of Yukawa coupling via resonant s-channel**

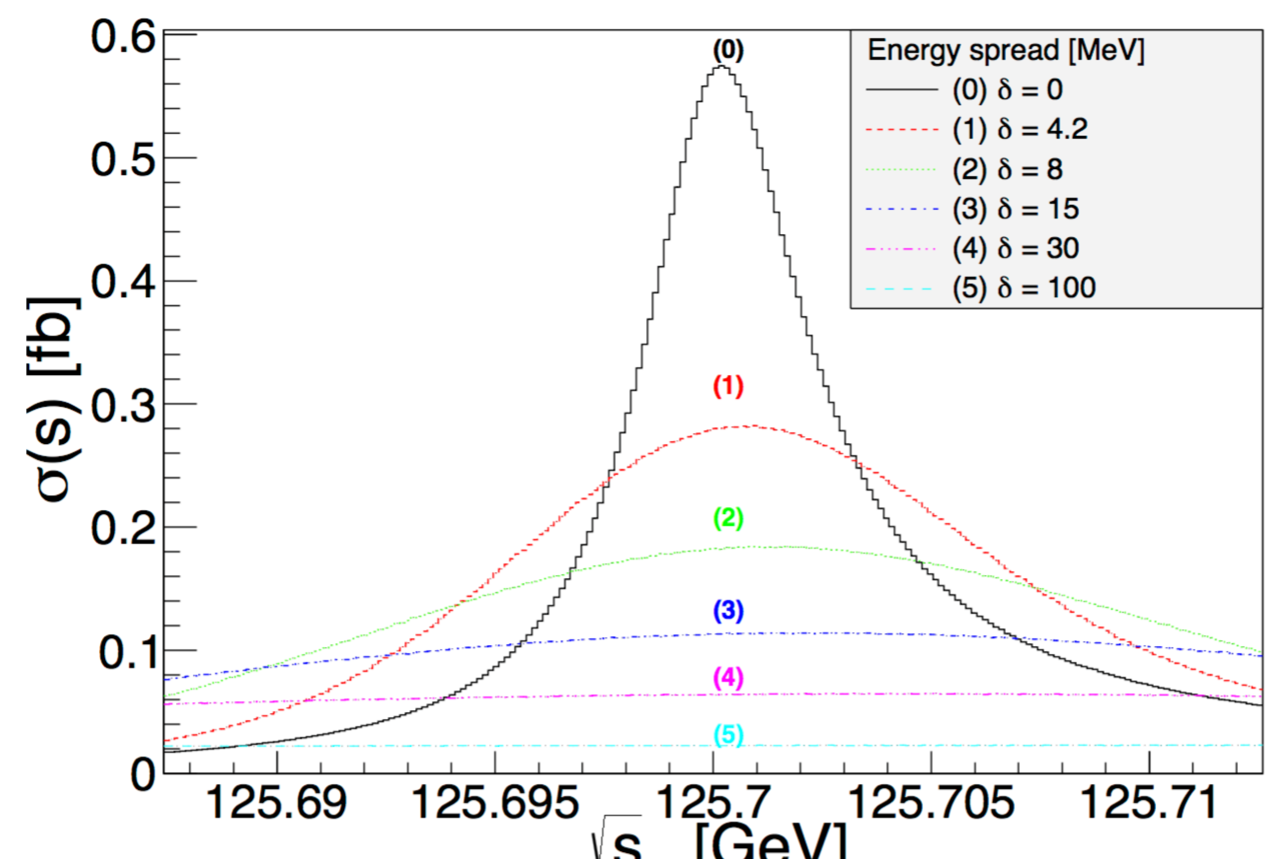
σ(eeH)	1.64fb

← Born cross-section



- **However, Higgs production greatly suppressed off resonant peak**
  - Cross-section reduced by beam energy spread and energy loss due to QED (ISR, FSR)
  - 1.64 fb → 50ab
- **Excellent control of beam energy critical**
  - baseline 6 MeV energy spread, L = 2/ab
  - optimized 10 MeV energy spread, L = 7/ab

https://arxiv.org/pdf/1509.02406.pdf

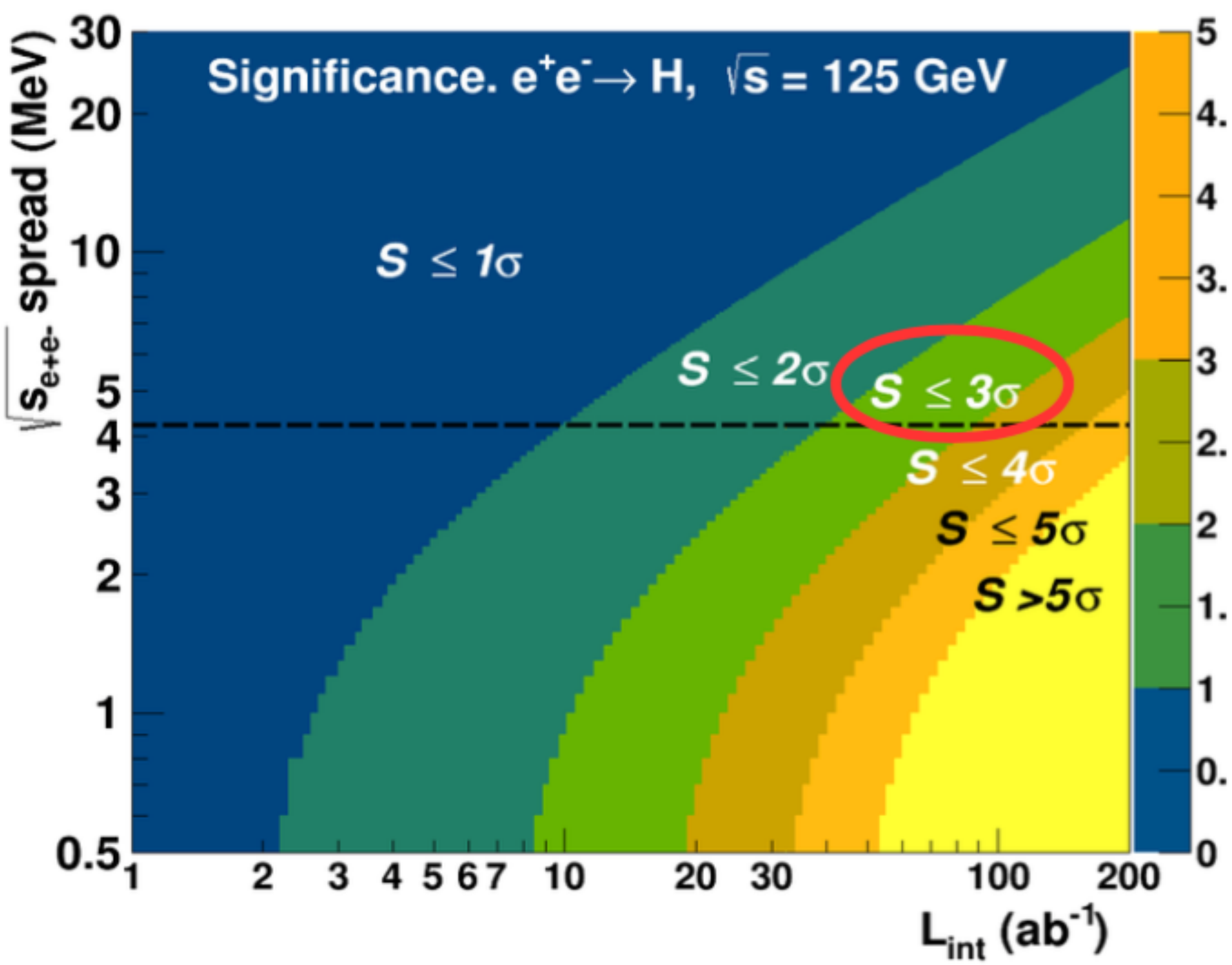


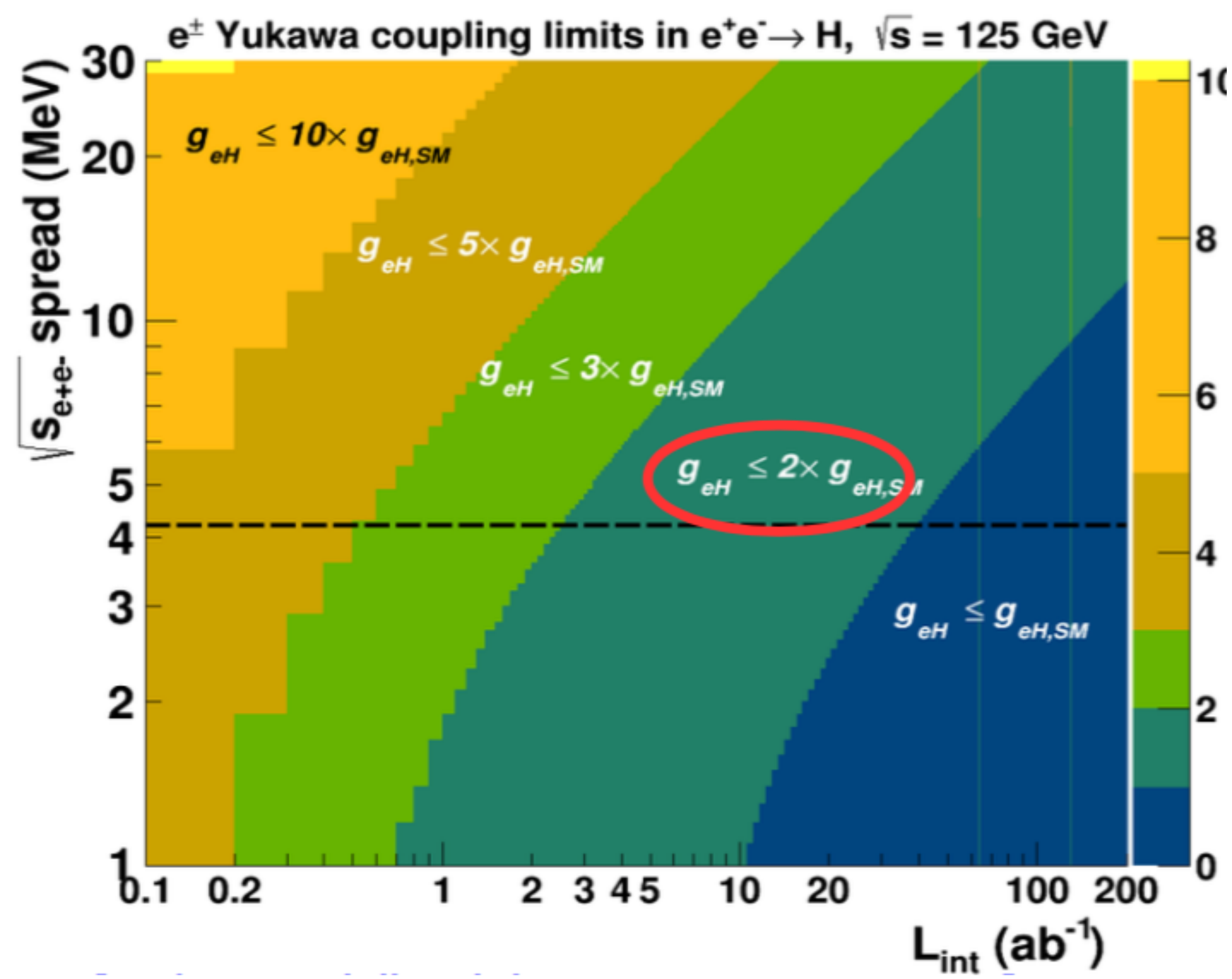
Garcia et al, WEPMW009 Proceedings of IPAC2016, Busan, Korea

ELECTRON YUKAWA COUPLING @ FCC-EE (II)

- **10 Higgs decay modes combined together, with the WW*(lvjj) final state providing best sensitivity**
  - 3 sigma achievable with 90/ab at 4MeV beam spread
  - BR(Hee) < 2.8×SM (95% CL)
  - g_{eH} < 1.7×SM (95% CL) with 10/ab

1701.02663

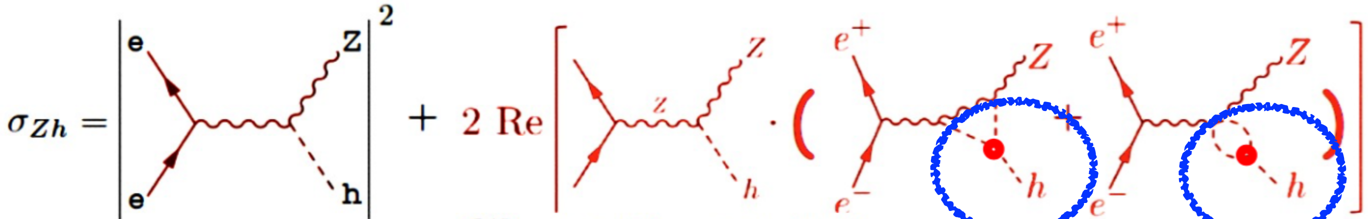


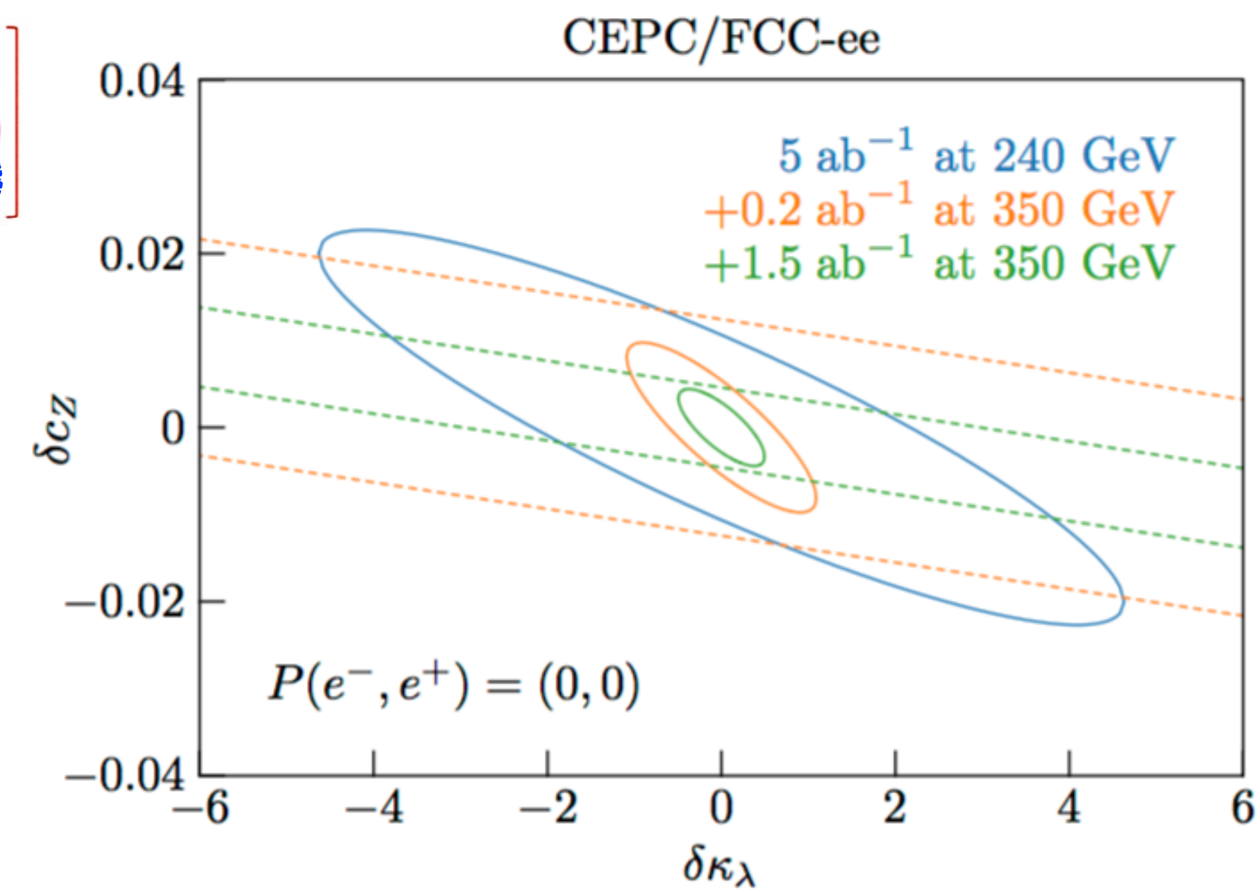


SELF COUPLING @ FCC-EE (INDIRECT)

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

- At FCC-ee, Higgs trilinear indirectly constrained through loop corrections to σ(H+Z)





- **Testing possible only thanks to excellent precision on the ZH cross-section measurement**
- **~40% precision on trilinear coupling from global fit and combination of 240 and 350 GeV datasets**
  - HH cross-section at the HL-LHC ~ 50 fb (150k events) corresponding to an uncertainty on trilinear coupling to ~ 50%

1711.03978, 1701.02663

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THE FCC-EH

	@LHeC	@HL-LHC	@HE-LHC	FCC-he
Ep [TeV]	7	7	12.5	50
Ee [GeV]	60	60	60	60
√s [TeV]	1.3	1.3	1.7	3.5
Luminosity [$10^{33}/cm^2s$]	1	8	12	15

- **High electron polarisation of 80-90% possible**
  - higher electron energy also considered, up to 120GeV
- **Clean environment for reconstruction**

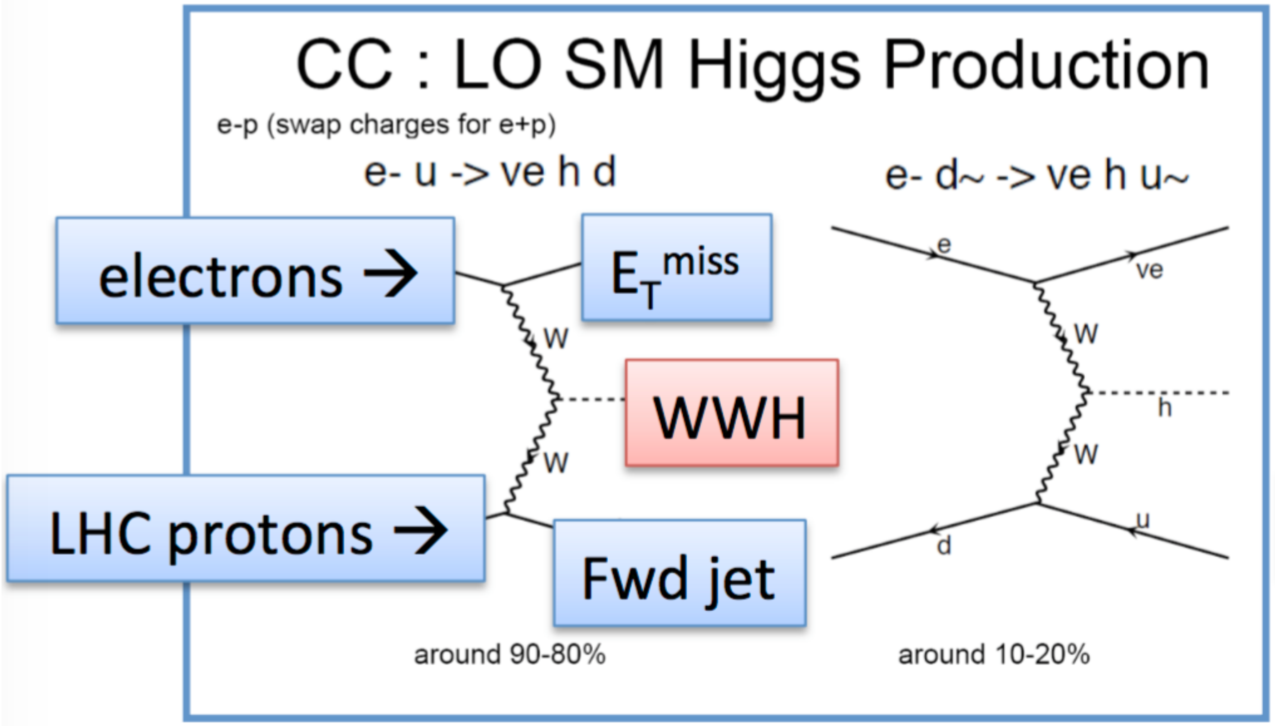
  < 0.1 PU @LHeC and up to 1 PU @FCC-eh
- **100/fb per year over 10 years, total 1/ab**
- **Luminosity to 0.5-1%.**

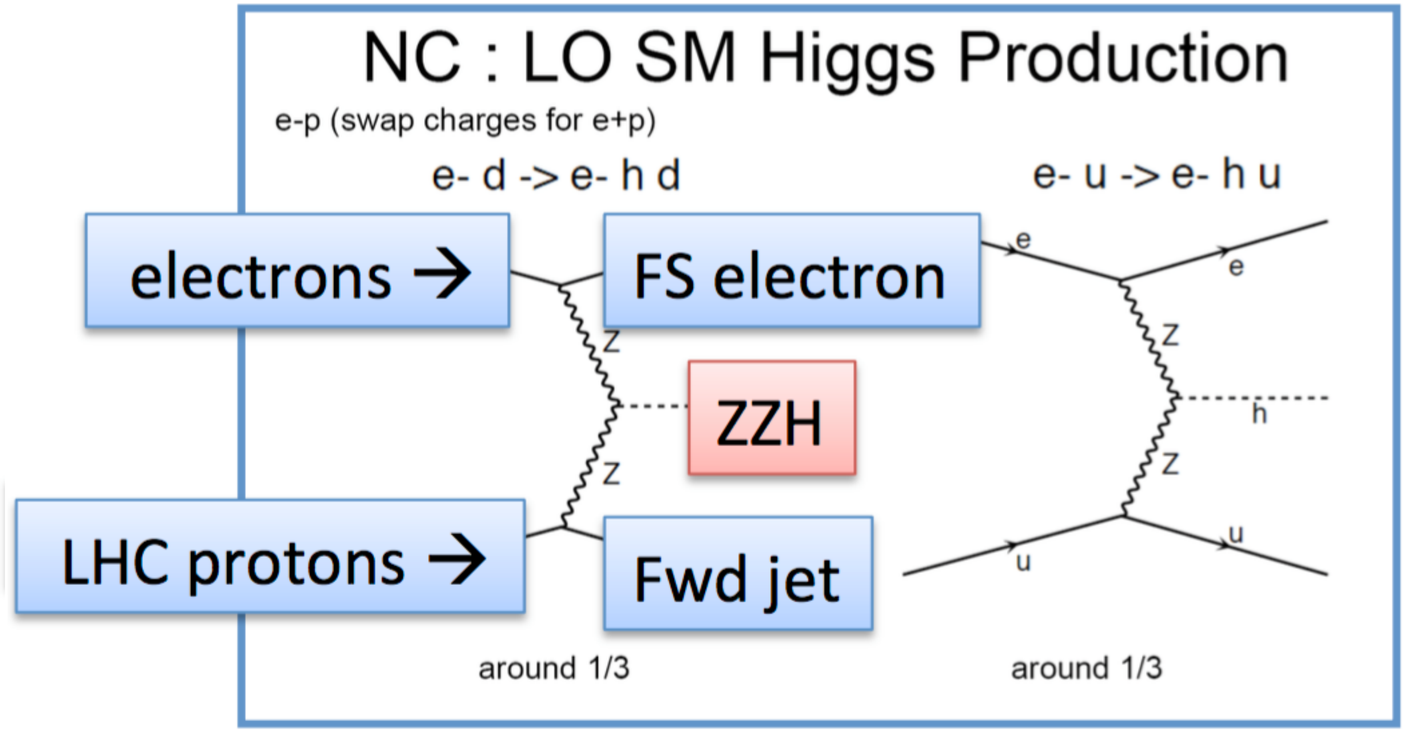
LHeC CDR: arXiv:1206.2913

HIGGS PRODUCTION @ THE FCC-EH

- **LO Higgs production uniquely from either CC or NC DIS via VBF**

Courtesy of U. Klein



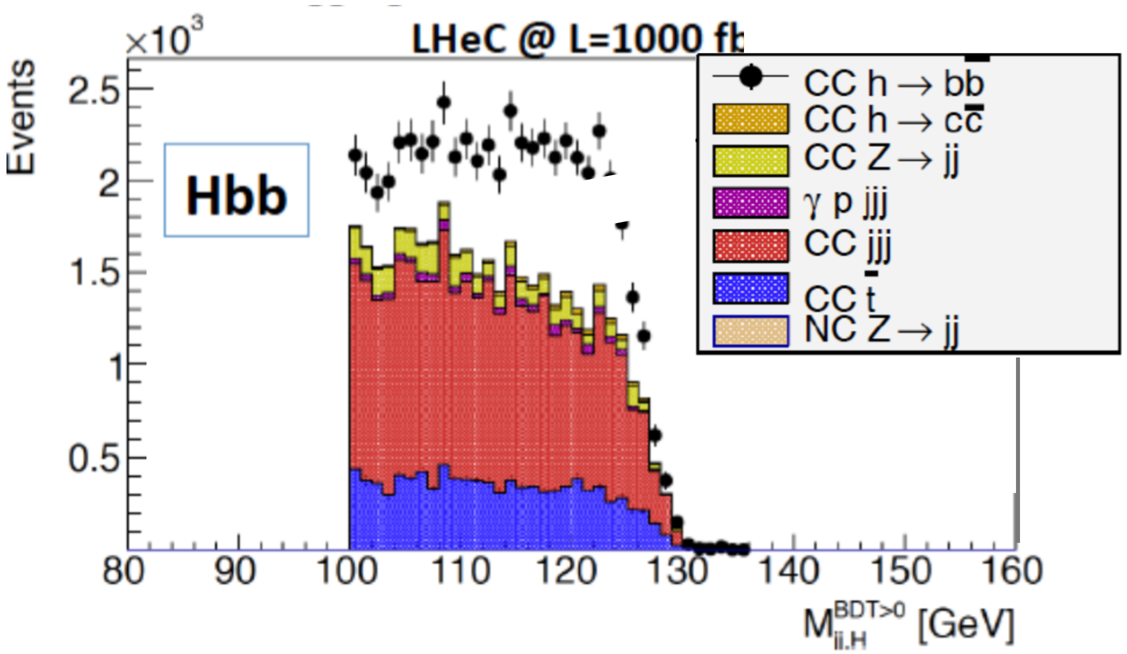


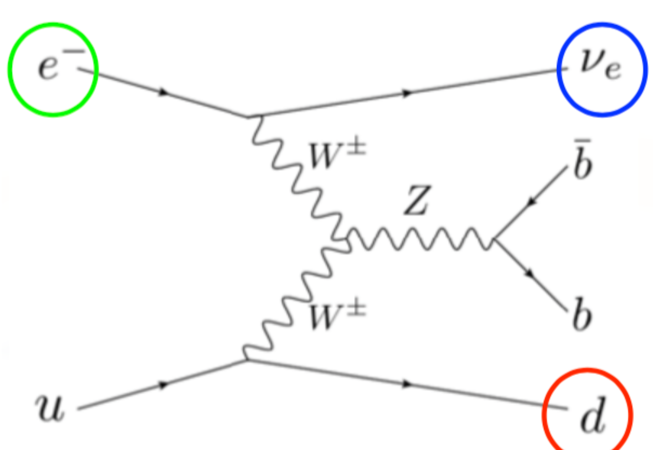
Cross-Section	LHeC	FCC-eh
CC	109 fb	560 fb
NC	21 fb	127 fb
CC (P=-80%)	196 fb	1008 fb
NC (P=-80%)	25 fb	148 fb

- **Scale dependencies of the LO calculations 5-10%; small QCD corrections for NLO (but up to 20% impact on kinematics)**
- **Large dataset with up to 2M Higgs events from CC**

LEADING HIGGS COUPLINGS @ FCC-EH

- **Forward lepton tagging to discriminate CC Higgs production**





CC Z production

Observable	Expected uncertainty
$\sigma_{WBF}\,\mathrm{Br}(H \to b\bar{b})$	0.27%
$\sigma_{WBF}\,\mathrm{Br}(H \to c\bar{c})$	2.36%
$\sigma_{WBF}\,\mathrm{Br}(H \to gg)$	1.78%
$\sigma_{WBF}\,\mathrm{Br}(H \to W^\pm W^{\mp *})$	2.45%
$\sigma_{WBF}\,\mathrm{Br}(H \to \tau^+\tau^-)$	1.65%
$\sigma_{WBF}\,\mathrm{Br}(H \to ZZ^*)$	3.94%
$\sigma_{WBF}\,\mathrm{Br}(H \to \gamma\gamma)$	4.7%

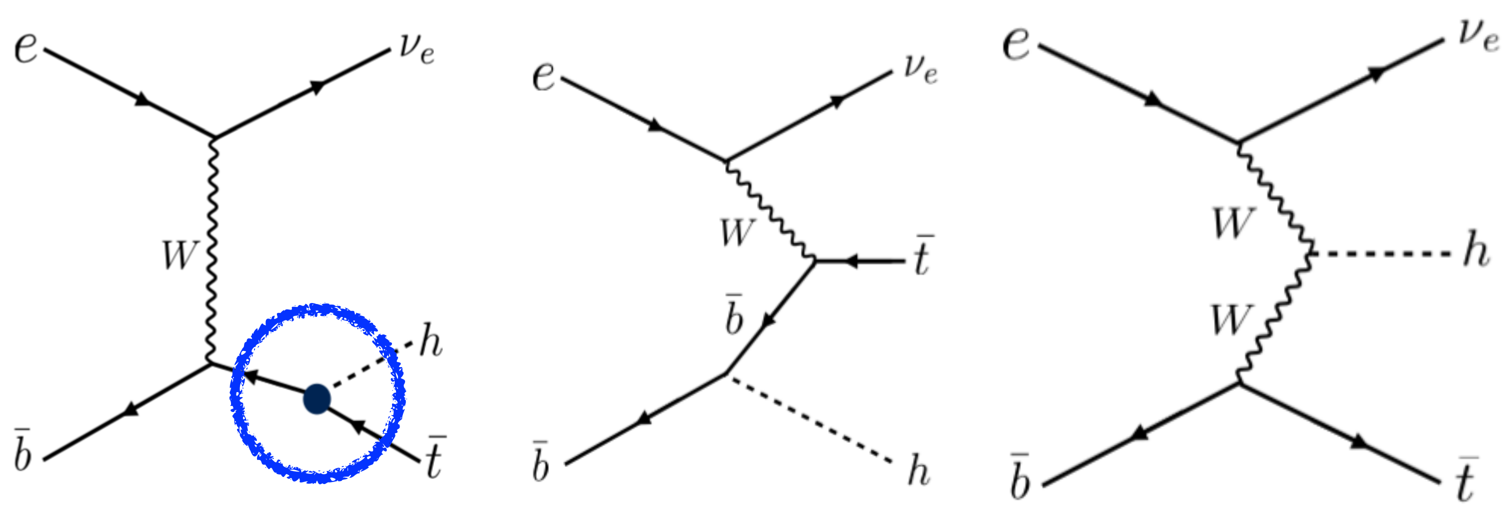
Observable	Expected uncertainty
$\sigma_{ZBF}\,\mathrm{Br}(H \to b\bar{b})$	0.83%
$\sigma_{ZBF}\,\mathrm{Br}(H \to c\bar{c})$	7.08%
$\sigma_{ZBF}\,\mathrm{Br}(H \to gg)$	5.62%
$\sigma_{ZBF}\,\mathrm{Br}(H \to W^\pm W^{\mp *})$	4.29%
$\sigma_{ZBF}\,\mathrm{Br}(H \to \tau^+\tau^-)$	5.25%
$\sigma_{ZBF}\,\mathrm{Br}(H \to ZZ^*)$	11.8%
$\sigma_{ZBF}\,\mathrm{Br}(H \to \gamma\gamma)$	14.1%

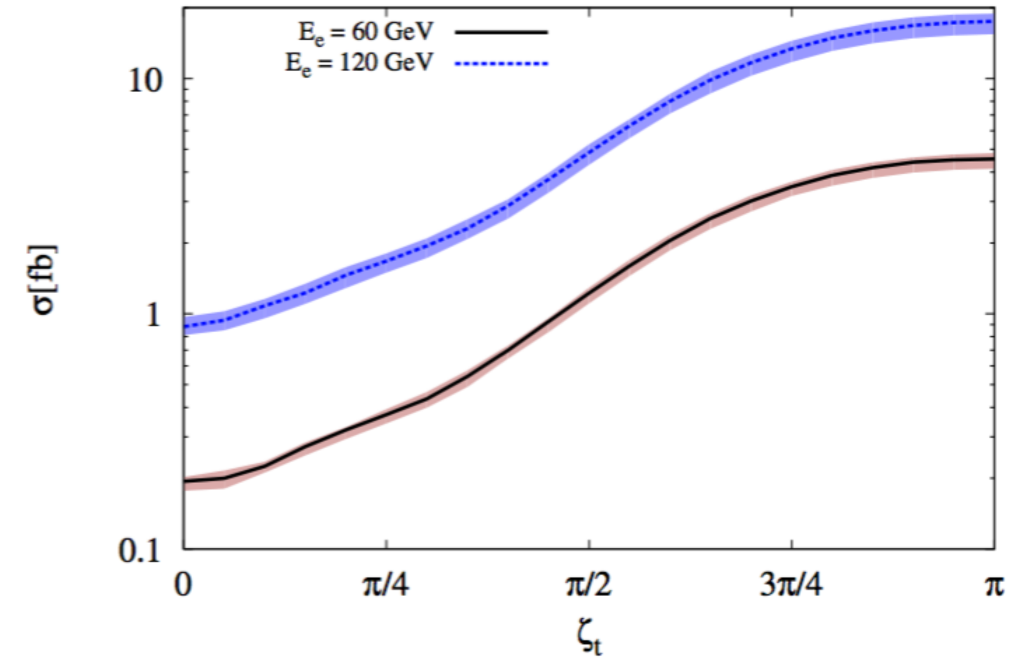
U. Klein, FCC Week 2018 Amsterdam

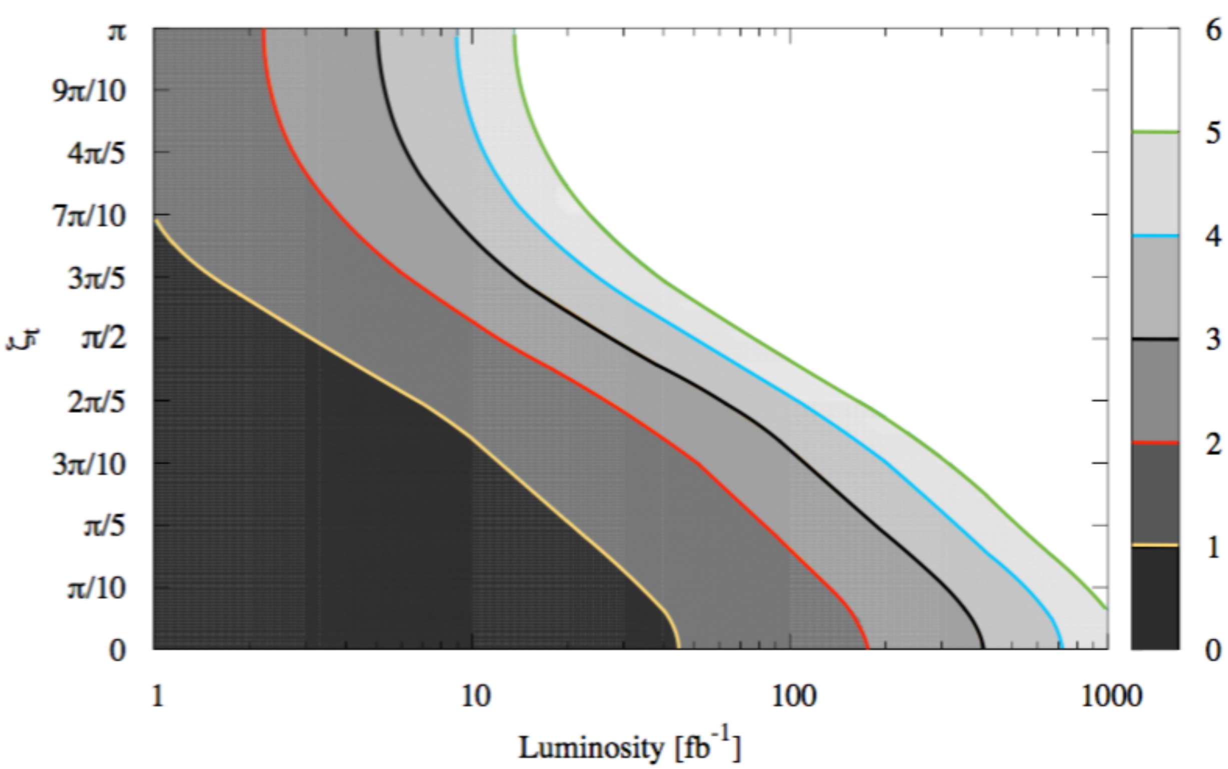
TOP YUKAWA COUPLING @ FCC-EH

- **Top Yukawa coupling probed in events where Higgs boson is radiated off a top quark**

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



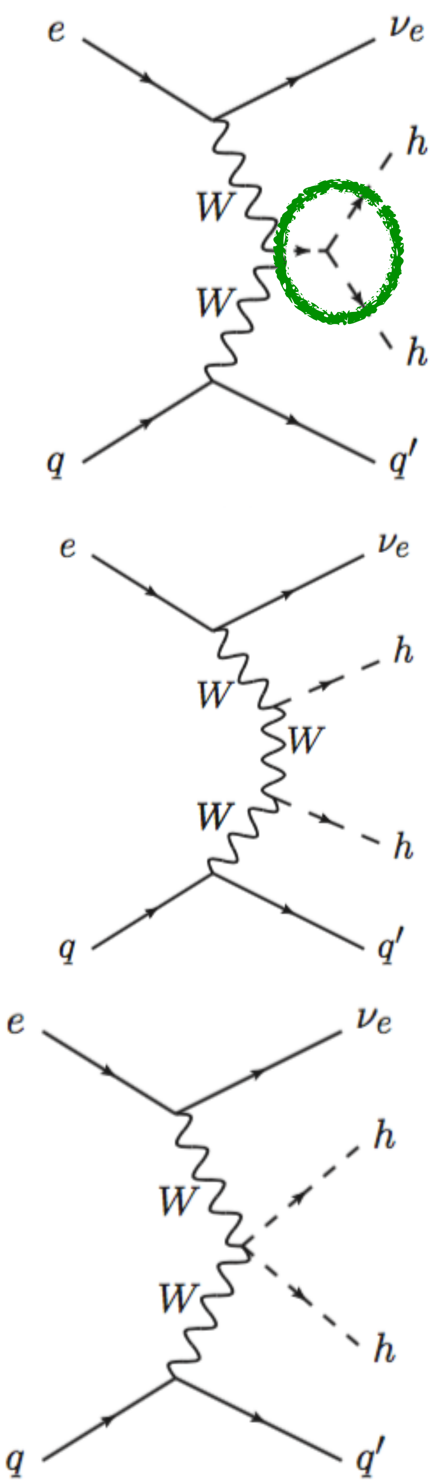


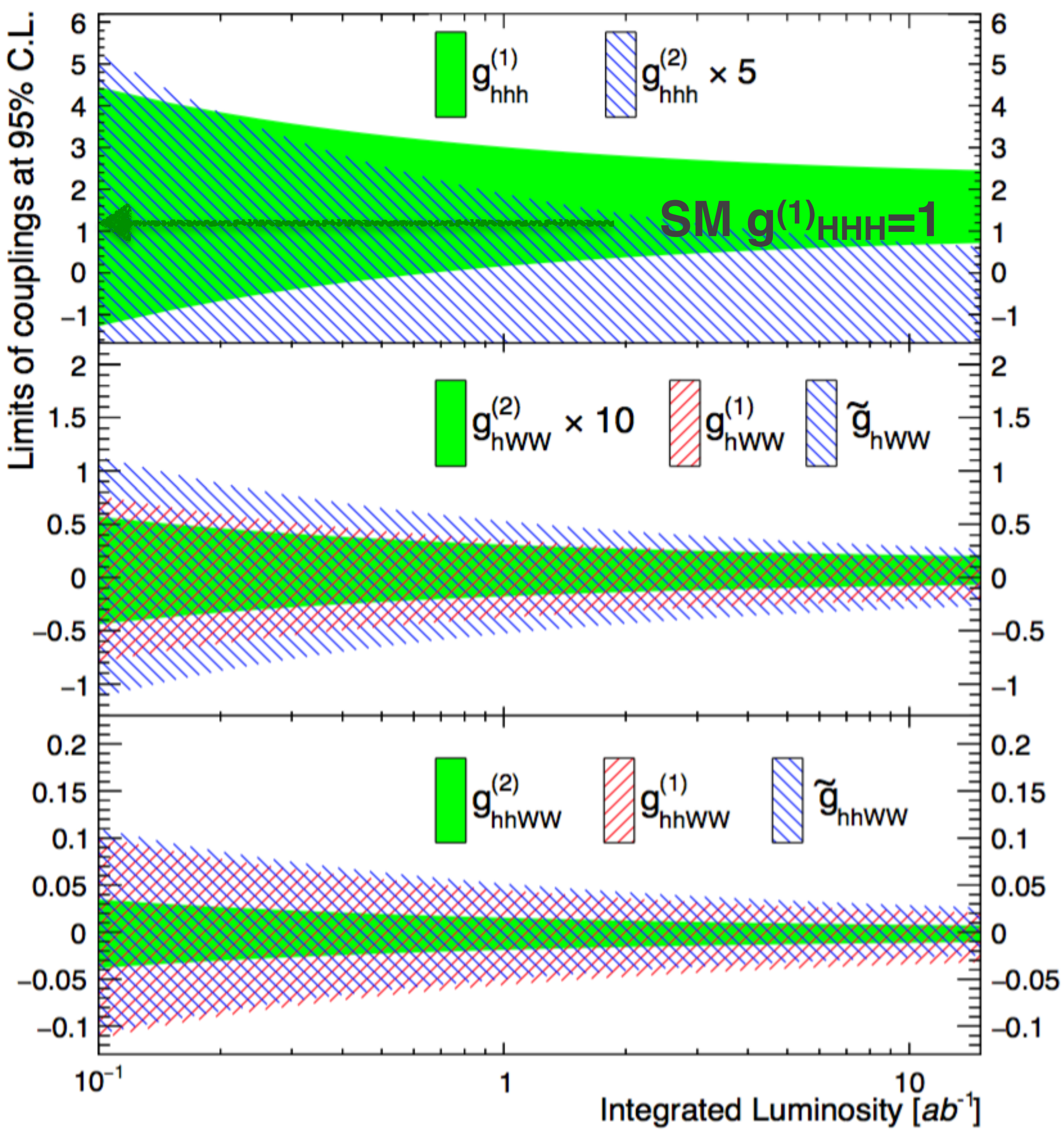


- **Accuracy of top Yukawa coupling ~17% with 1/ab at LHeC**
- **Extrapolated to 1.85% at FCC-eh**

1702.03426
Presentation from U. Klein at FCC Week 2018, Amsterdam

TRILINEAR COUPLING @ FCC-EH





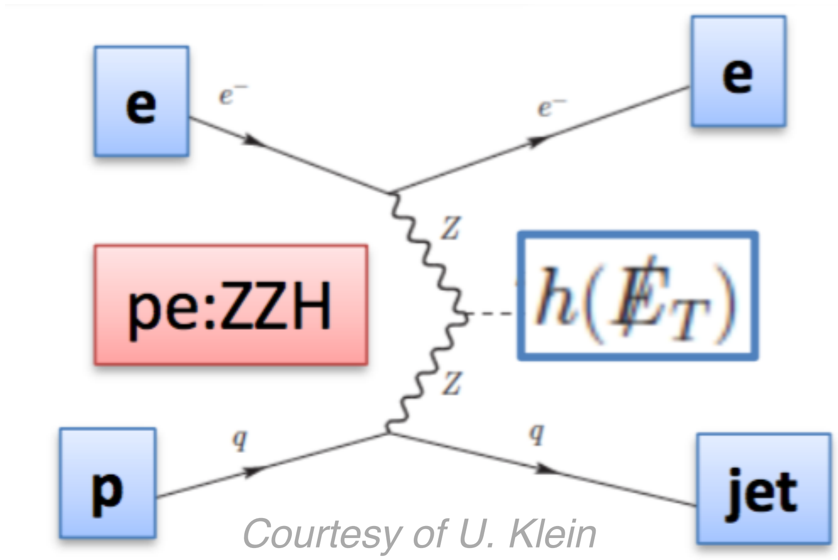
- **Precision on the trilinear coupling is determined for two electron energy hypotheses, 60 and 120 GeV:**

$$g^{(1)}_{hhh} = 1.00^{+0.24(0.14)}_{-0.17(0.12)}$$

1509.04016

INVISIBLE HIGGS DECAY @ FCC-EH AND FCC-EE

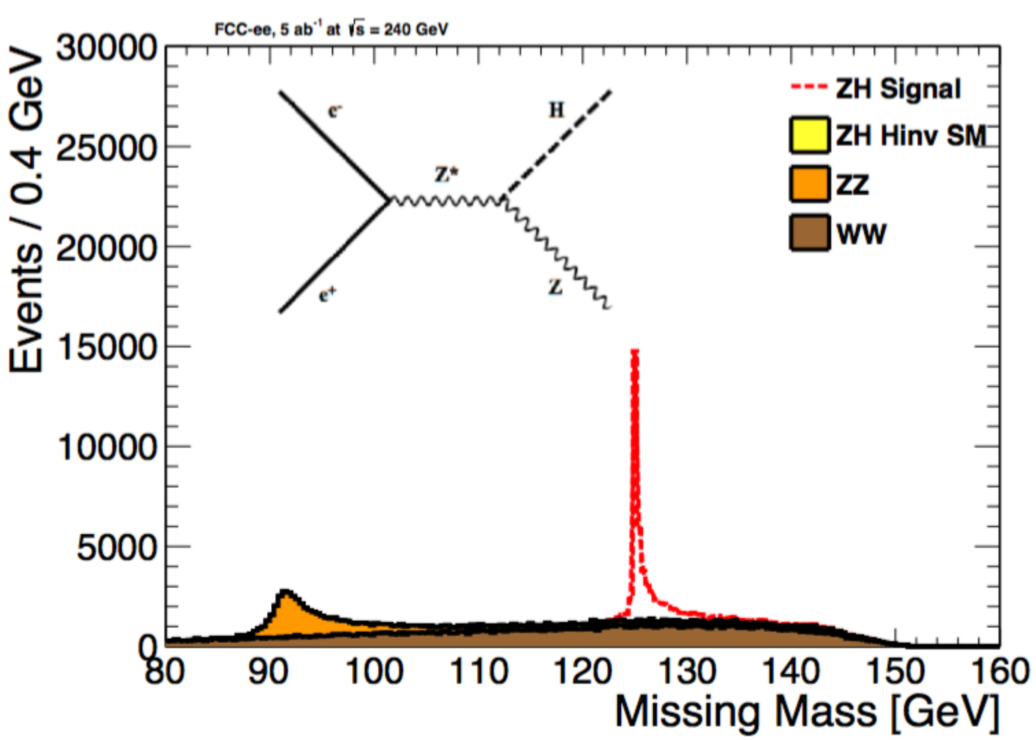
Probing invisible decay through NC production at FCC-eh



	95% C.L. limit on BR
HL-LHC	< 3.5% (3/ab), 1411.7699
FCC-eh	< 1.7% (1/ab)

Presentation from U. Klein at FCC Week 2018, Amsterdam

Extension of the ZH measurement at FCC-ee

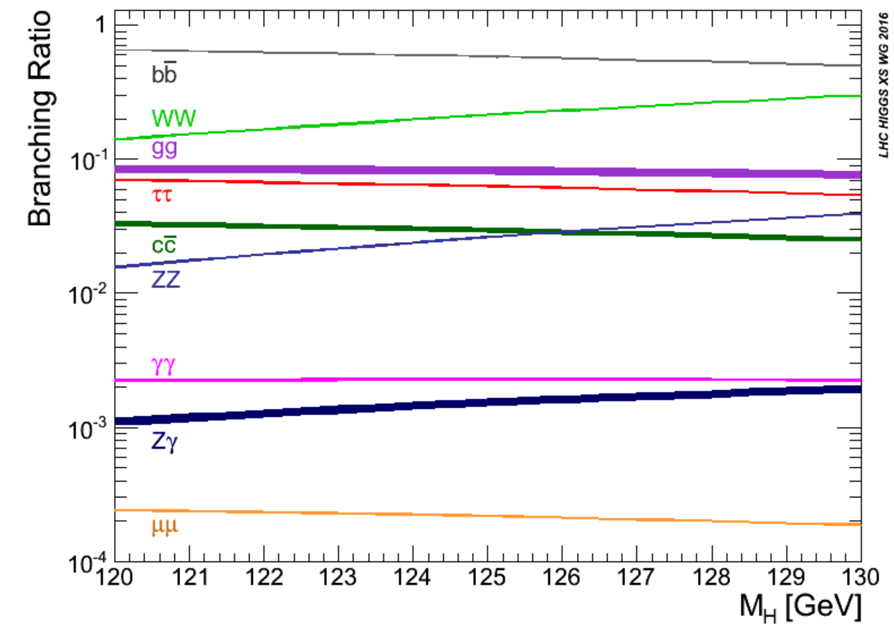


	$BR_{95\% limit}$	$BR_{5\sigma}$
CMS-like	$0.92 \pm 0.32\%$	$2.5 \pm 0.2\%$
ILD-like	$0.63 \pm 0.22\%$	$1.7 \pm 0.1\%$

https://link.springer.com/content/pdf/10.1140/epjc/s10052-017-4680-5.pdf

OVERVIEW OF THE FCC-EE AND FCC-EH PROGRAM

- **Kappa framework used to determine and compare precision on couplings are various machines**
  - *significant progress in EFT not shown today*
- **Both FCC-ee and FCC-eh pushing the boundaries on knowledge of Higgs sector reaching (sub) % precision for high statistics modes**



HLLHC (ATLAS)		FCC-ee		FCC-eh	
Coupling	Relative precision	Coupling	Relative precision	Coupling	Relative precision
κ_b	10.4%	κ_b	0.58%	κ_b	0.74%
κ_t	7.6%	κ_t	—	κ_t	—
κ_τ	9.43%	κ_τ	0.78%	κ_τ	1.10%
κ_c	—	κ_c	1.05%	κ_c	1.35%
κ_μ	7.4%	κ_μ	9.6%	κ_μ	—
κ_Z	3.7%	κ_Z	0.16%	κ_Z	0.43%
κ_W	4.2%	κ_W	0.41%	κ_W	0.26%
κ_g	5.2%	κ_g	1.23%	κ_g	1.17%
κ_γ	4.3%	κ_γ	2.18%	κ_γ	2.35%
$\kappa_{Z\gamma}$	15%	$\kappa_{Z\gamma}$	—	$\kappa_{Z\gamma}$	—

Global fits to Higgs observables at the FCC by Jorge de Blas

OVERVIEW OF THE FCC-EE AND FCC-EH PROGRAM

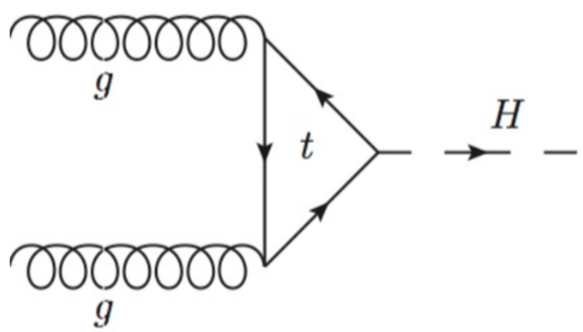
- **Limited knowledge of the trilinear coupling with precision in the 20% range**
- **Rare modes (*e.g.* μμ and Zγ) unaccessible at FCC-ee an FCC-eh**
  - BR(H→ μμ ~2.18 10^{-4})
  - BR(H→ Zγ ~1.5 10^{-3})

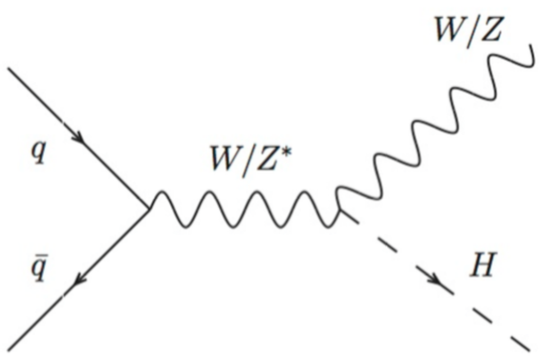
HLLHC (ATLAS)		FCC-ee		FCC-eh	
Coupling	Relative precision	Coupling	Relative precision	Coupling	Relative precision
κ_b	10.4%	κ_b	0.58%	κ_b	0.74%
κ_t	7.6%	κ_t	—	κ_t	—
κ_τ	9.43%	κ_τ	0.78%	κ_τ	1.10%
κ_c	—	κ_c	1.05%	κ_c	1.35%
κ_μ	7.4%	κ_μ	9.6%	κ_μ	—
κ_Z	3.7%	κ_Z	0.16%	κ_Z	0.43%
κ_W	4.2%	κ_W	0.41%	κ_W	0.26%
κ_g	5.2%	κ_g	1.23%	κ_g	1.17%
κ_γ	4.3%	κ_γ	2.18%	κ_γ	2.35%
$\kappa_{Z\gamma}$	15%	$\kappa_{Z\gamma}$	—	$\kappa_{Z\gamma}$	—

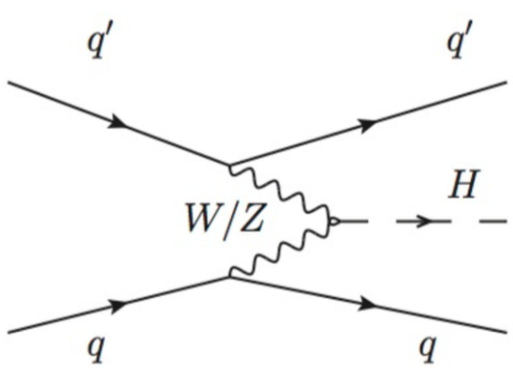
Global fits to Higgs observables at the FCC by Jorge de Blas

HIGGS PRODUCTION AT THE FCC-HH (I)

- **The INTENSITY FRONTIER (WITH 20 TO 30/AB)**
  - unprecedented dataset enabling high precision program (but PU challenge)
  - probing rare processes (receiving significant boost w.r.t HL-LHC)



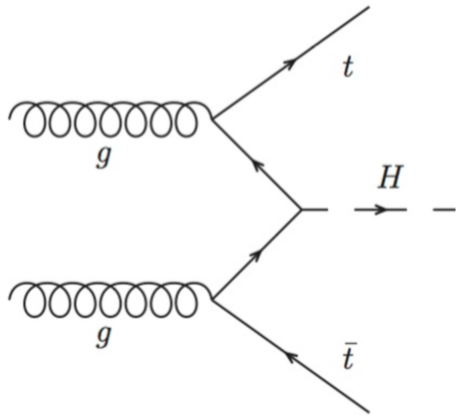




	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

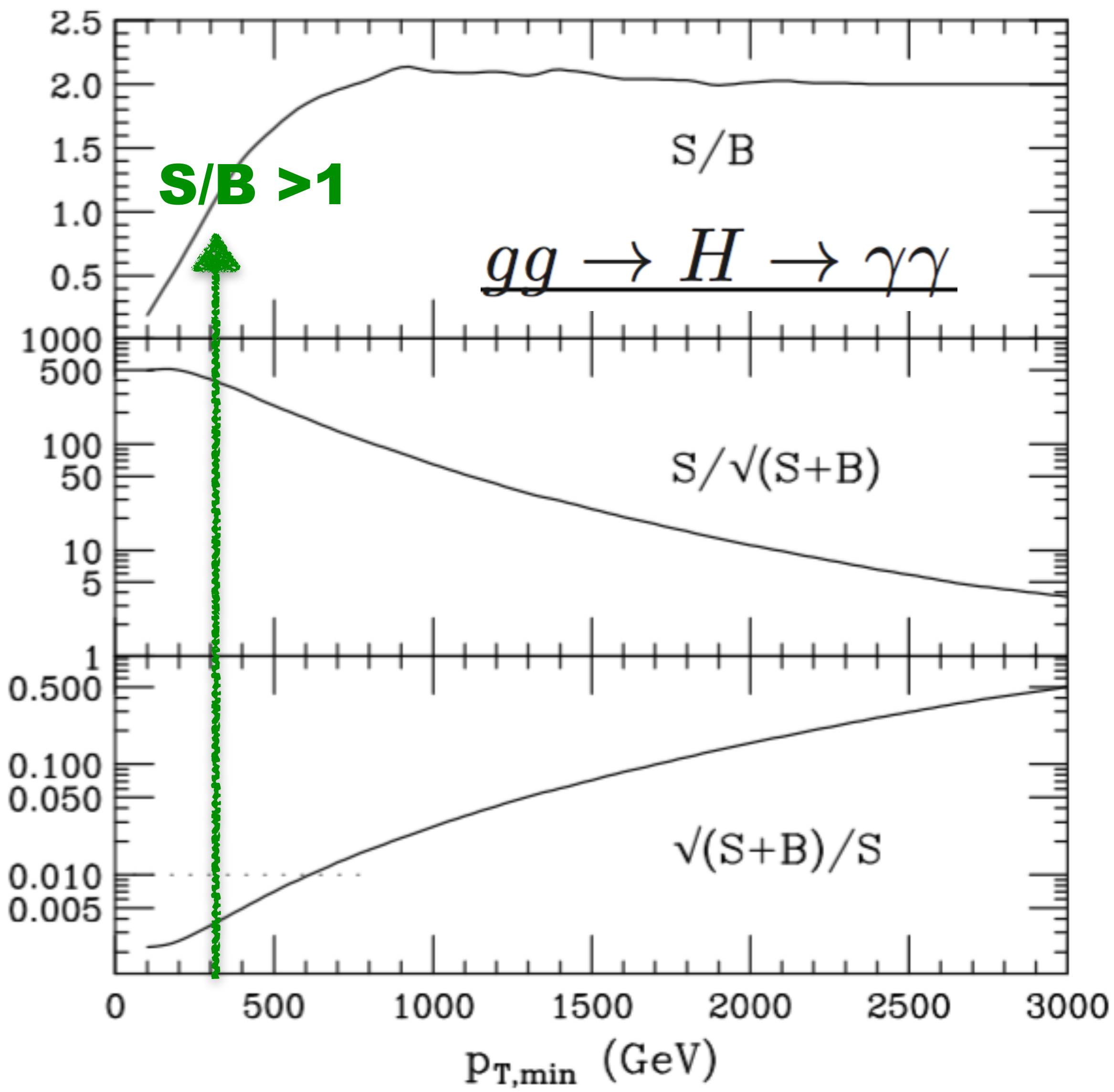
assuming nominal 20/ab @ FCC-hh

~1M Higgs @ FCC-ee, FCC-eh



HIGGS PRODUCTION AT THE FCC-HH (II)

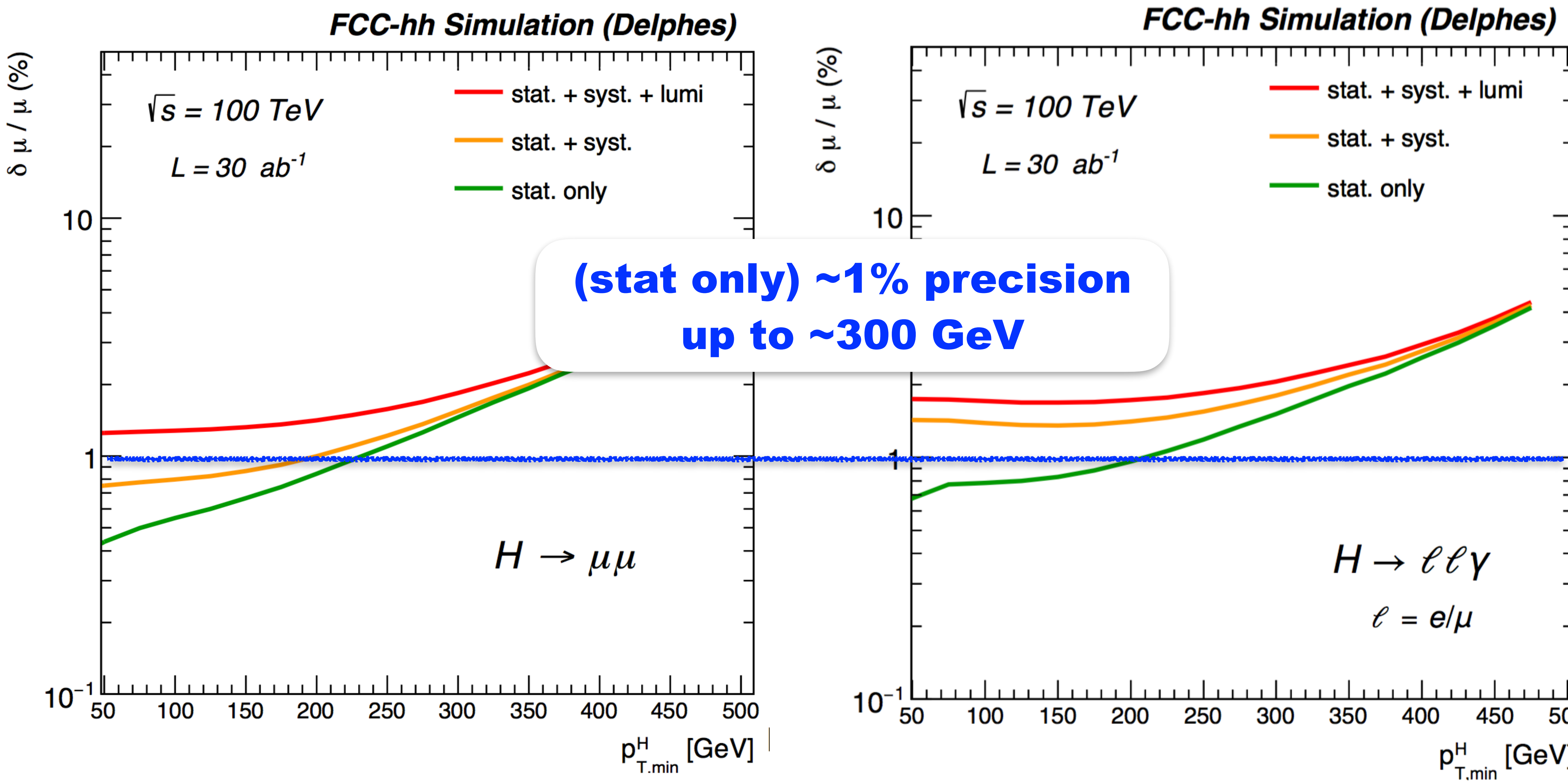
- **The ENERGY FRONTIER**
  - exploration of tail of the distributions (1M Higgs with pT > 1TeV)



- **Good control of systematic uncertainties**
- **But complex detector and sophisticated algorithms required to identify highly boosted objects**
- **LHC and HL-LHC essential machines to develop and validate these techniques**

COUPLING TO MUONS AND ZGAMMA (I)

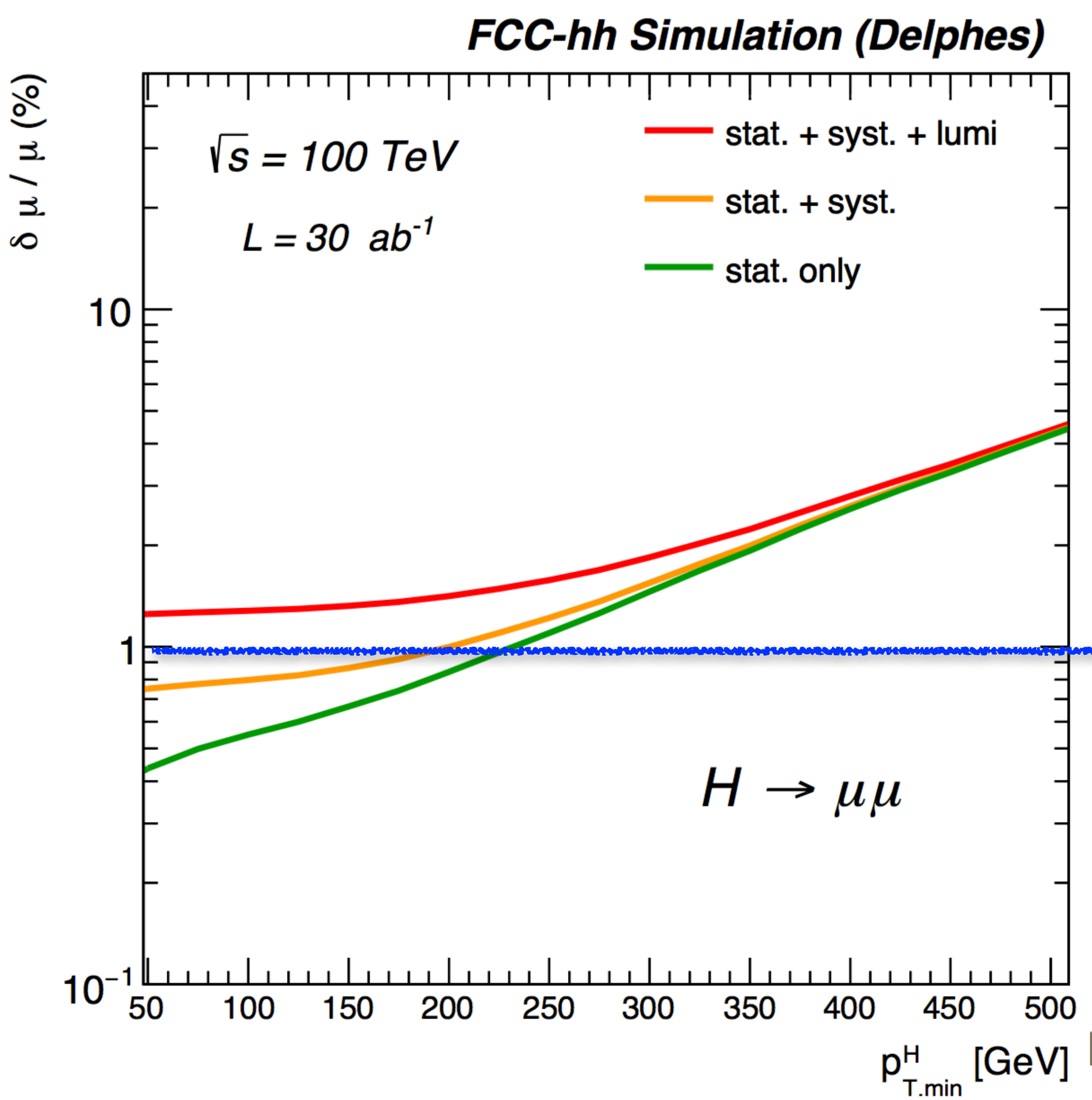
- Exploiting the large gluon fusion cross section (803 pb >> 55pb @ 14 TeV) and excellent S/B up to large Higgs p_T

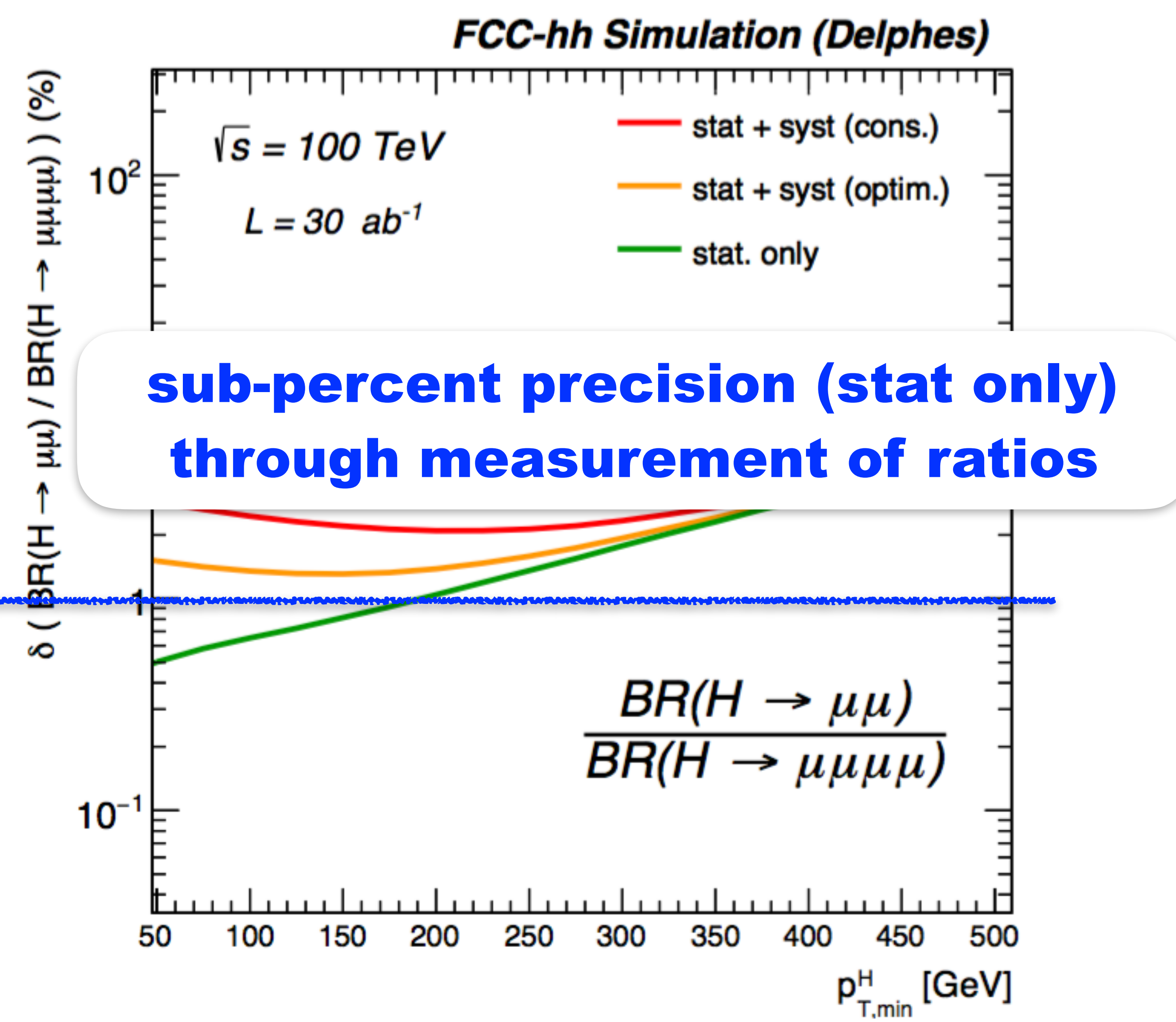


M. Selvaggi, FCC Week 2018, Amsterdam

COUPLING TO MUONS AND ZGAMMA (II)

- **Despite the small BRs, systematically limited measurements before 20-30/ab**





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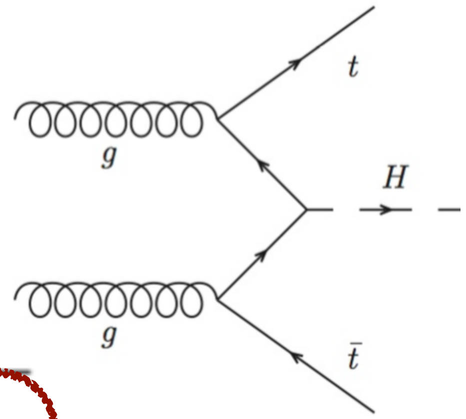
TOP YUKAWA COUPLING

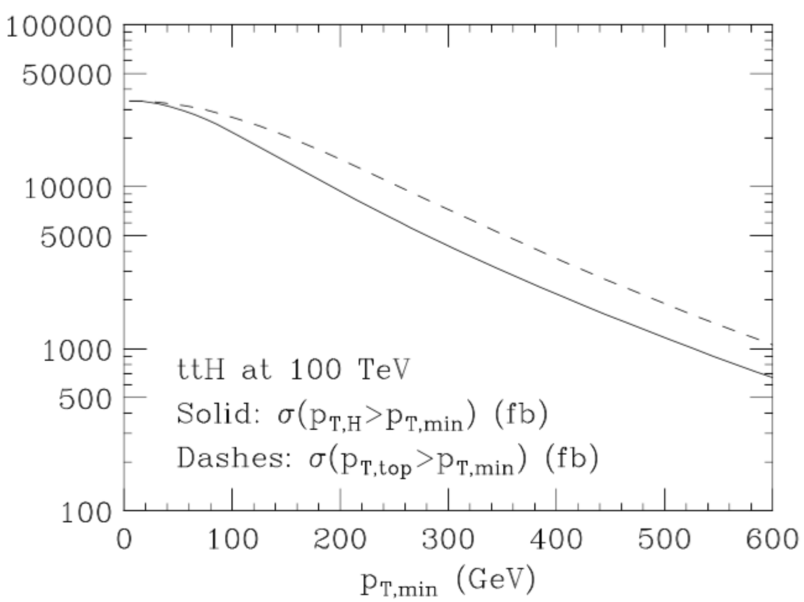
- Cross-section at 100 TeV ~ 34pb >> 0.6 pb @ 14 TeV, all decay modes accessible at the FCC-hh

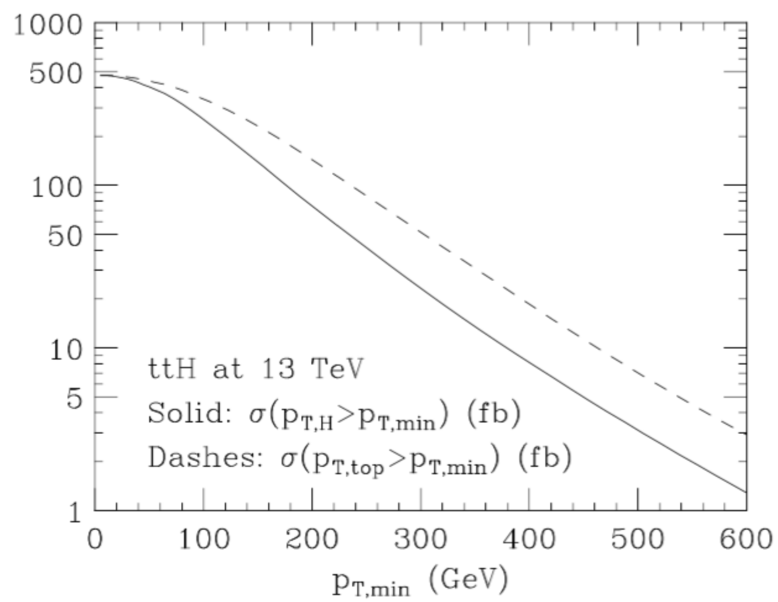


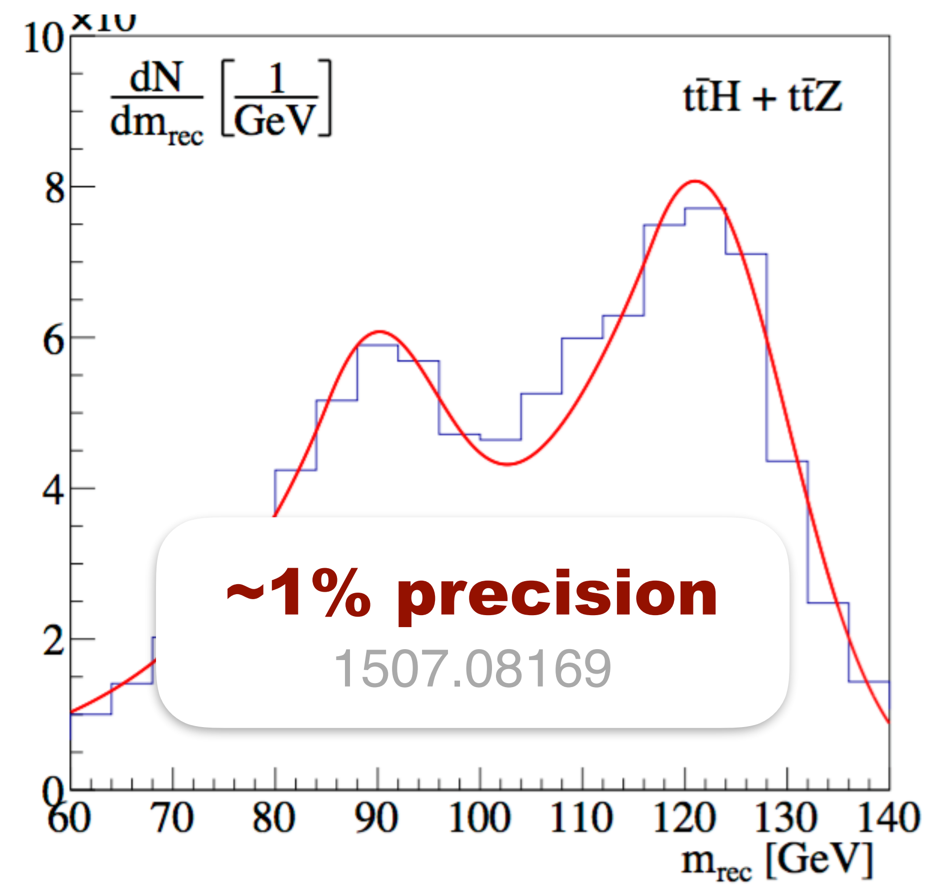
~1% precision thanks to clean final state

$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$

- Full exploitation of the boosted regime in H(bb) mode and of stability of ttZ/ttH ratio







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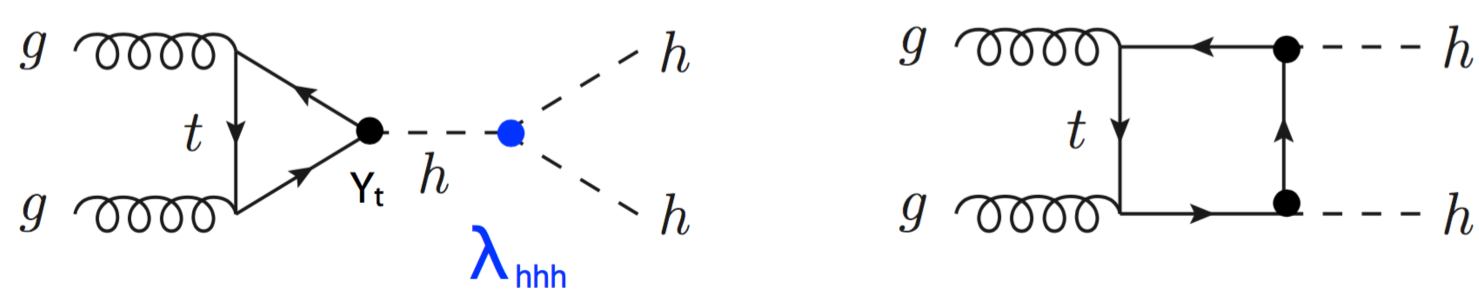
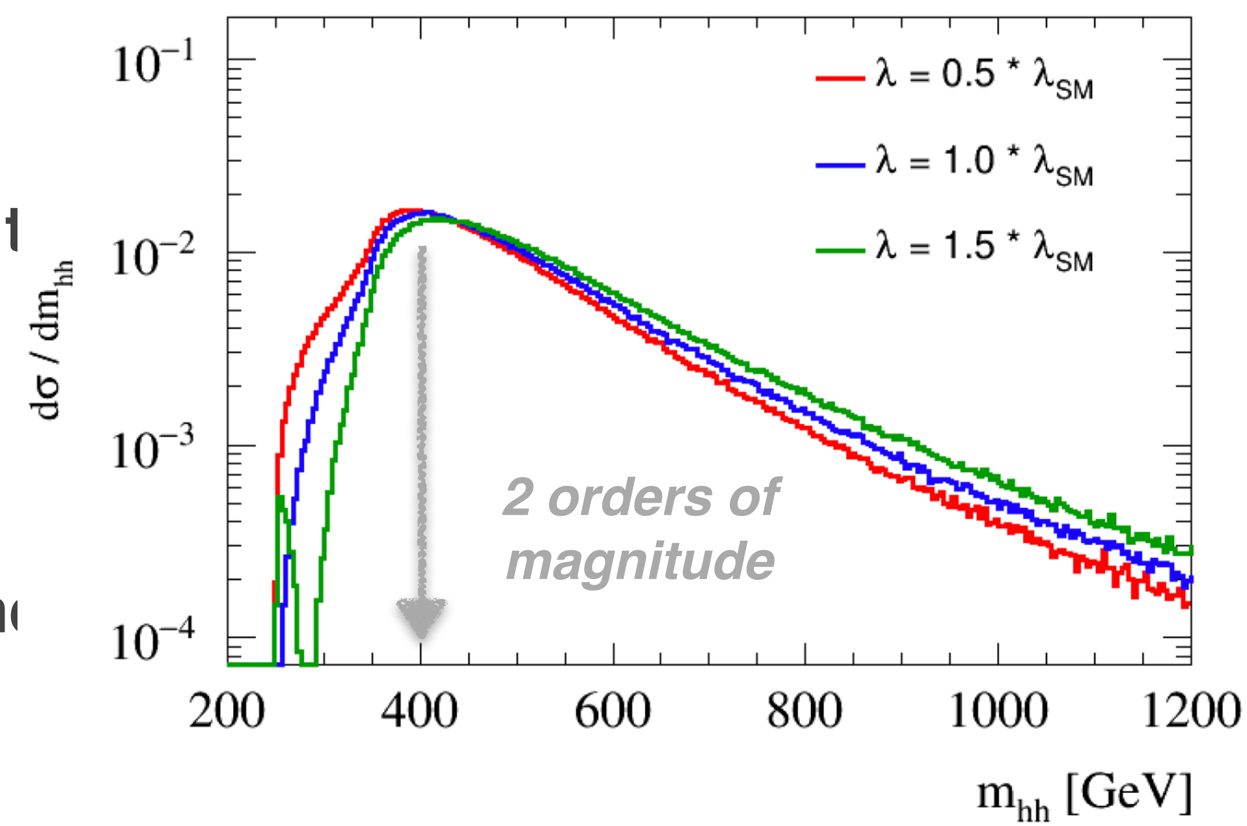
SELF COUPLING AT FCC-HH



1608.04798

$\sqrt{s}$	LO	B-i. NLO HEFT	NLO FT_{approx}	NLO
14 TeV	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	$34.26^{+14.7\%}_{-13.2\%}$	$32.91^{+13.6\%}_{-12.6\%}$
100 TeV	$731.3^{+20.9\%}_{-15.9\%}$	$1511^{+16.0\%}_{-13.0\%}$	$1220^{+11.9\%}_{-10.7\%}$	$1149^{+10.8\%}_{-10.0\%}$

- **With a cross-section ~ 30x HL-LHC and 7x larger dataset, FCC-hh unique opportunity t complete the exploration of the SM Higgs sector**
- **But challenging search due to negative interference between production modes an significant dependence of rate on m_{HH}**



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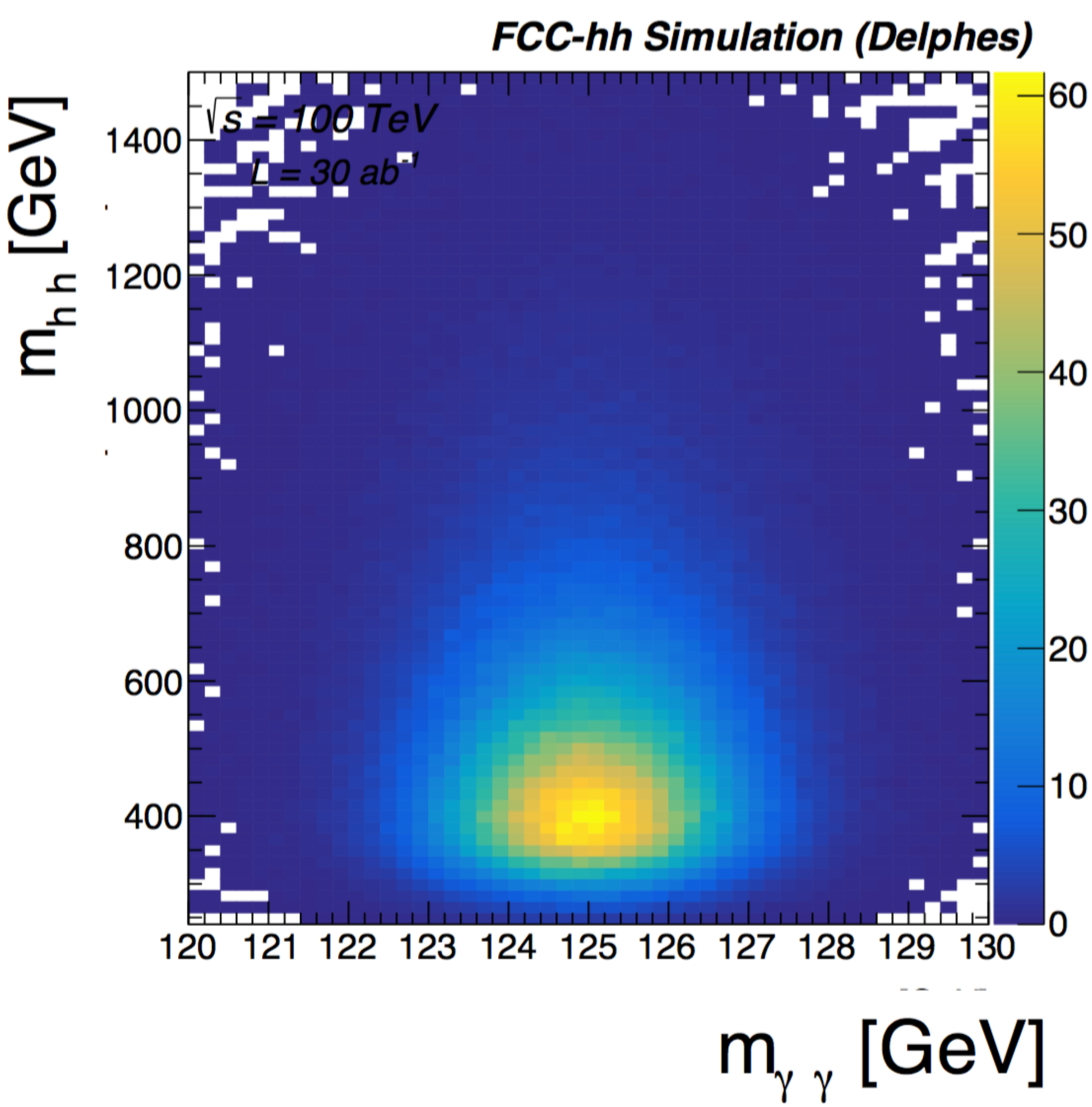
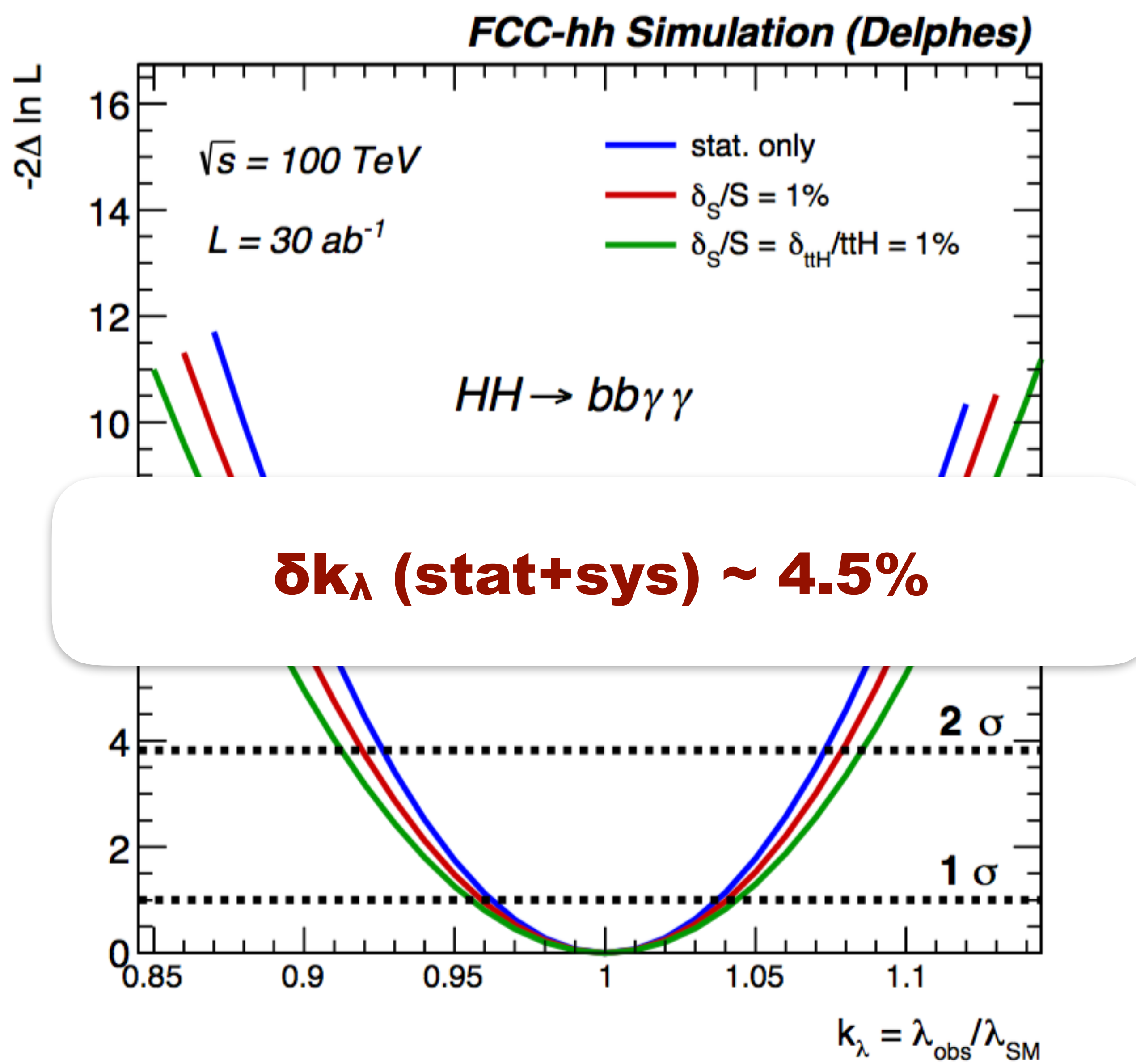
MEASUREMENT IN BB$\gamma\gamma$ FINAL STATE

- **Very small BR (~0.3%)** but narrow clean resonant signal from H($\gamma\gamma$)
- Signal to background discrimination from 2D fits to Higgs boson candidate mass





δk_λ (stat+sys) ~ 4.5%

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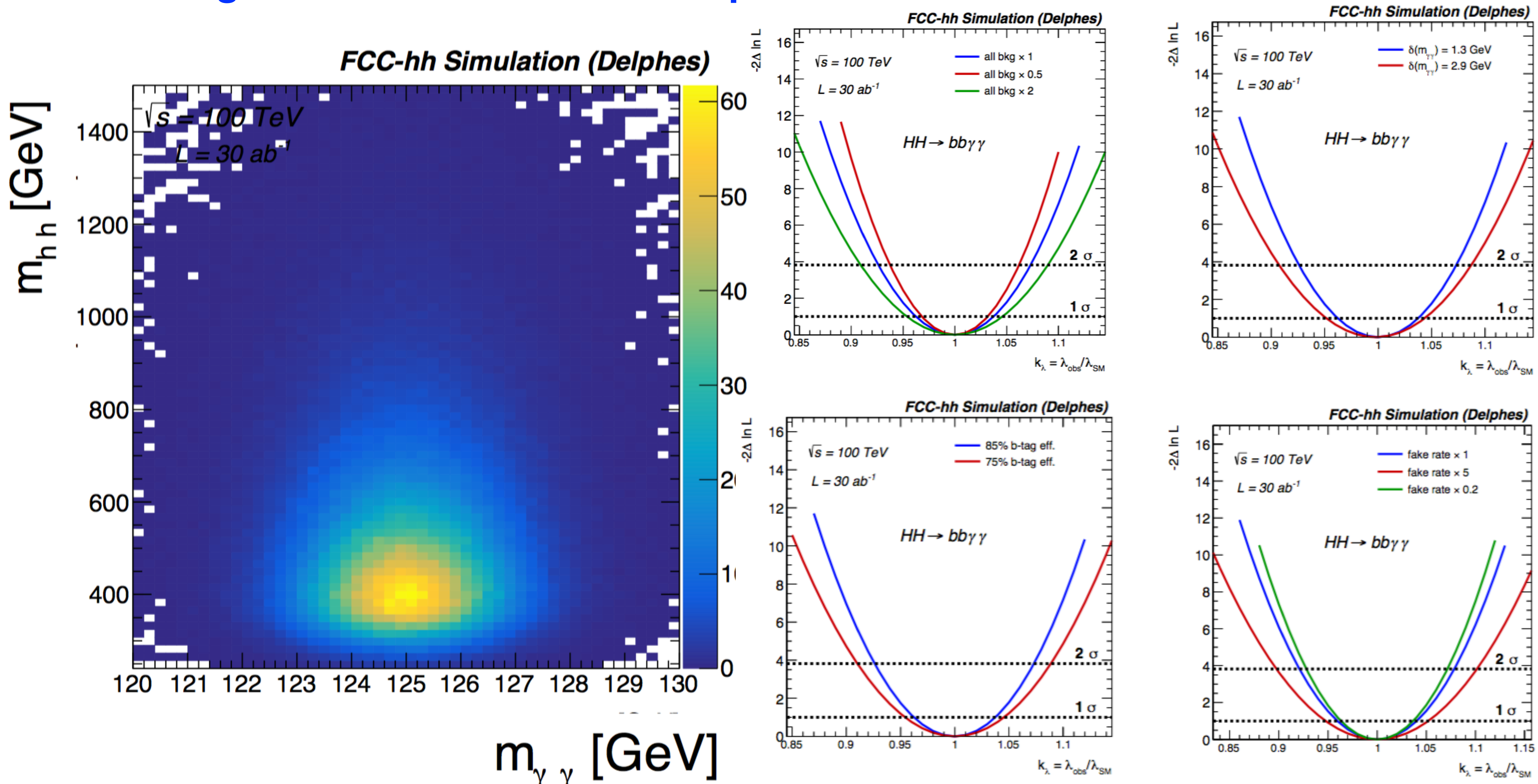
MEASUREMENT IN BB$\gamma\gamma$ FINAL STATE

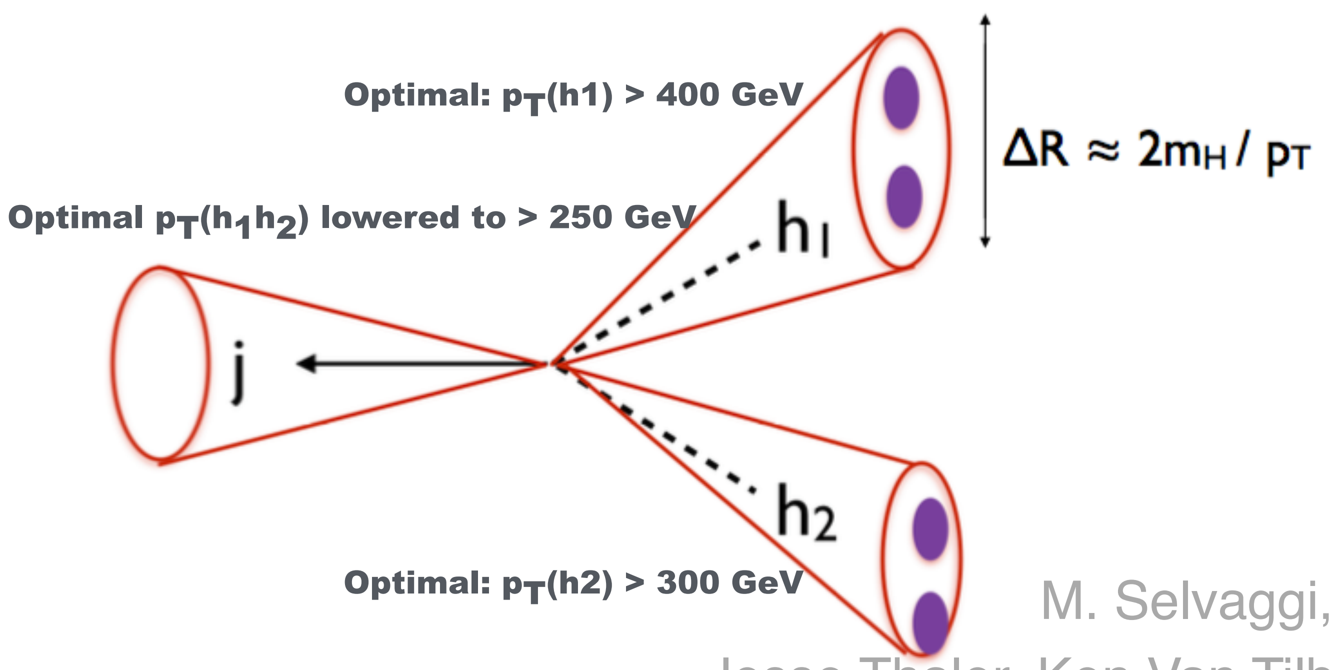
- **Very small BR (~0.3%)** **but narrow clean resonant signal from H($\gamma\gamma$)**
- **Signal to background discrimination from 2D fits to Higgs boson candidate mass**
- **Robust against variation of detector performance**

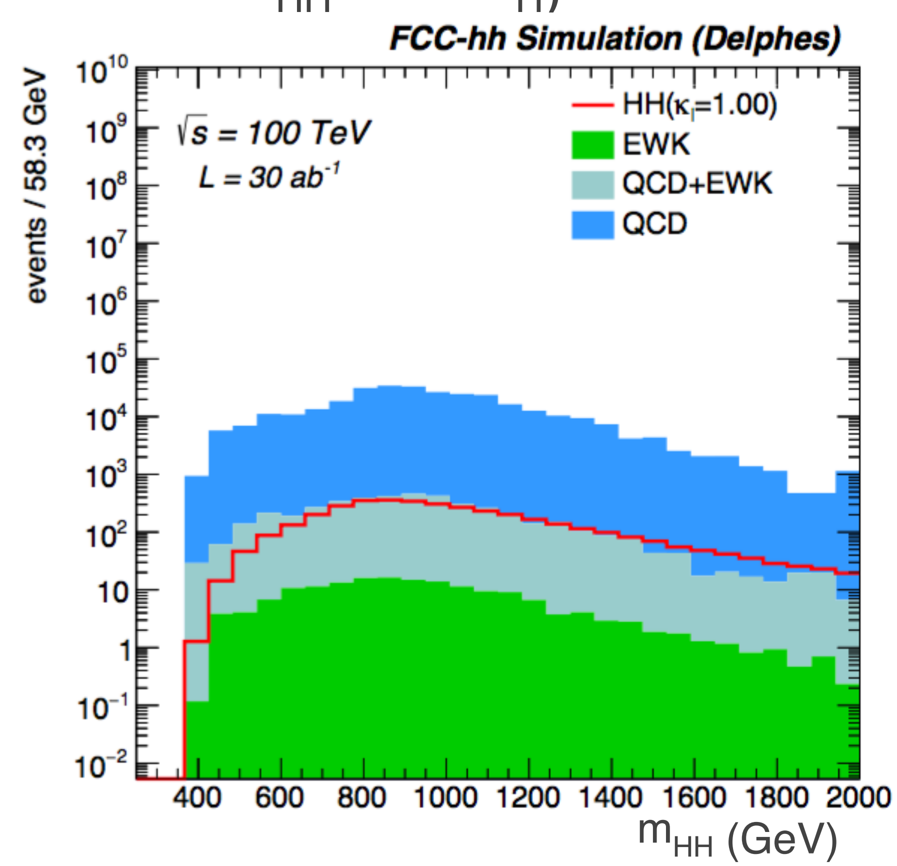


MEASUREMENT IN BBBB FINAL STATE

- **Very large BR (~33%) but very challenging analysis at FCC-hh due to overwhelming QCD background from gluon splitting**
- **Exploiting boosted topology thanks to enhanced cross-section w.r.t 14TeV for high momentum Di-Higgs production**
  - $\sigma(pp \to hhj, 100\ TeV) \approx 100 * \sigma(pp \to hhj, 14\ TeV)$, with $p_T(j) > 100$ GeV
  - Search in final state with one ISR jet and 2 ``fat” jets (sensitive to $m_{HH} \gtrsim 3\text{-}4 m_H$)

	Cross section (pTj > 500GeV)
HH+j	4fb
4b+j	57pb





M. Selvaggi, FCC Workshop June 2018

Jesse Thaler, Ken Van Tilburg, JHEP 1103 (2011) 015

MEASUREMENT IN BBBB FINAL STATE

- **Very large BR (~33%) but very challenging analysis at FCC-hh due to overwhelming QCD background from gluon splitting!**
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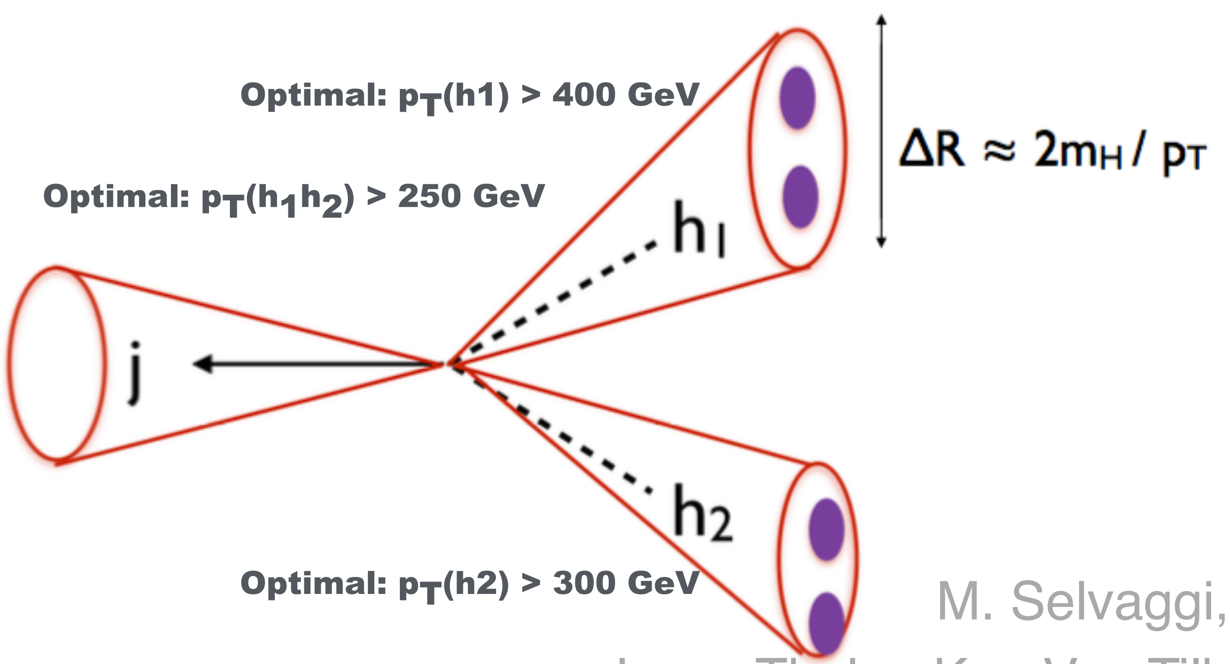
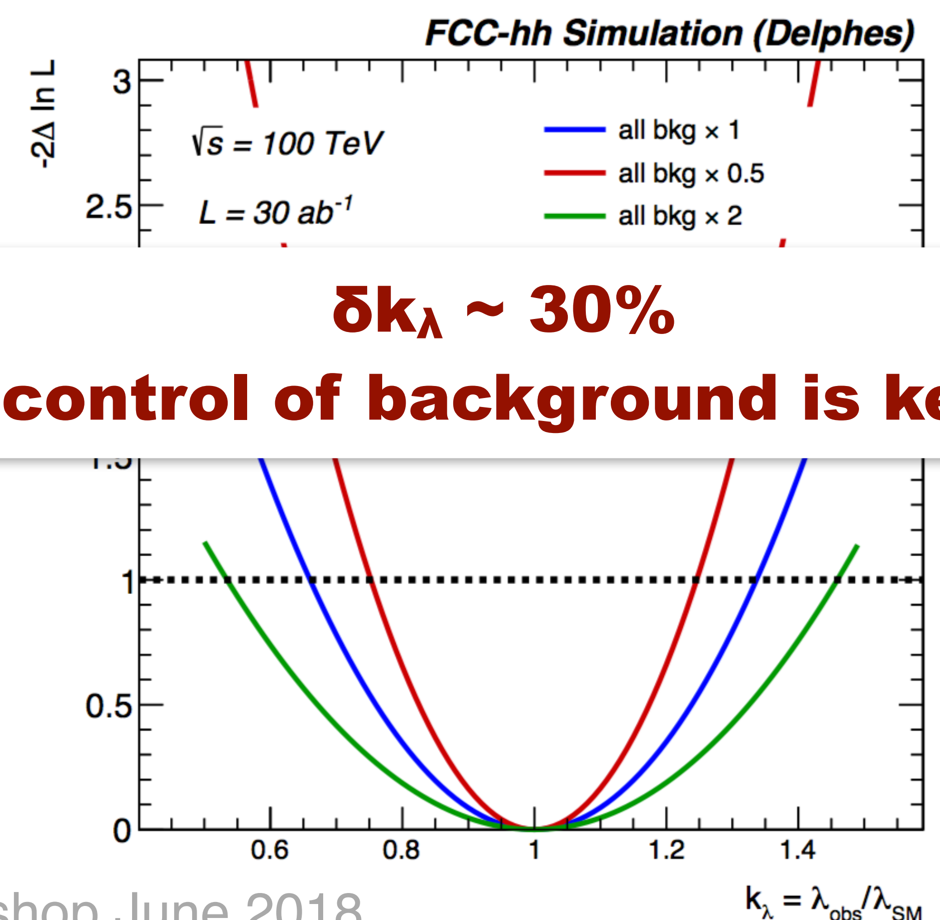




$\delta k_\lambda \sim 30\%$

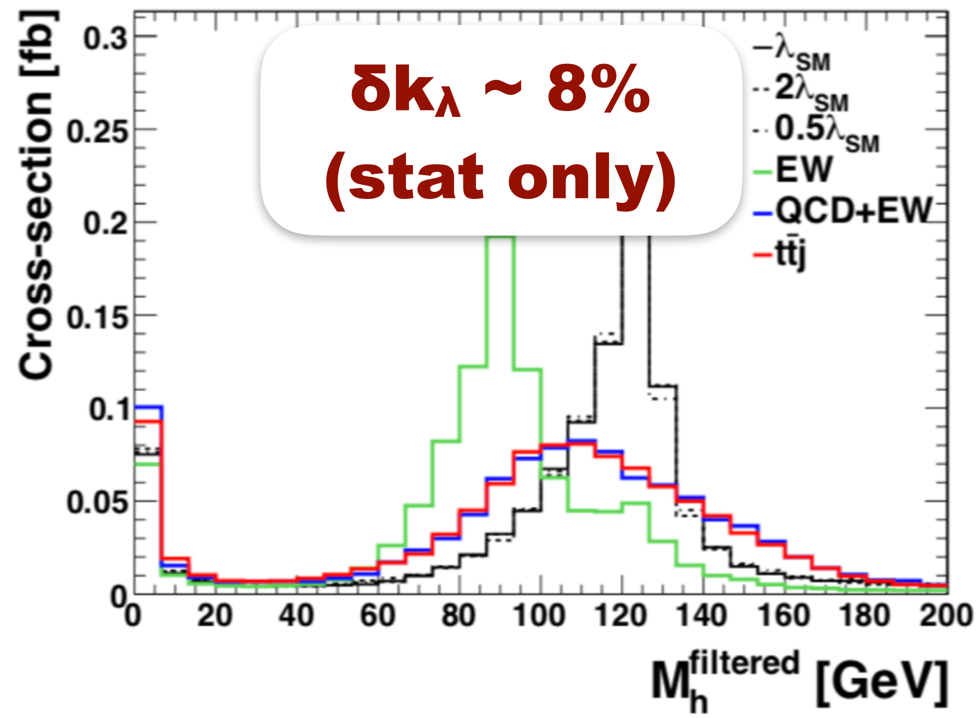
(control of background is key)

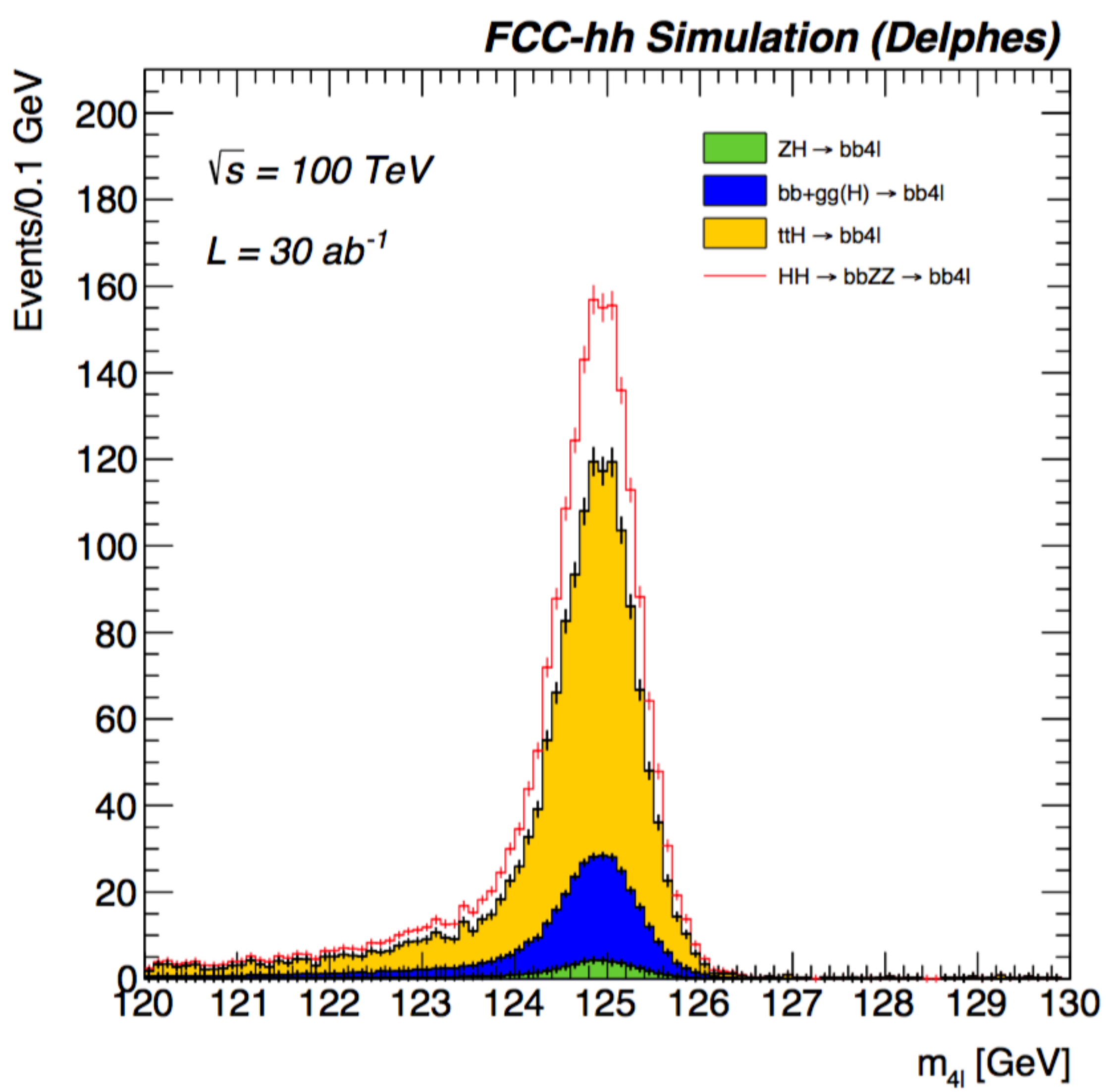
M. Selvaggi, FCC Workshop June 2018

Jesse Thaler, Ken Van Tilburg, JHEP 1103 (2011) 015

ADDITIONAL HH MODES

- **HH(bbττ) with BR ~ 7%**
- 1802.01607
- Boosted topology similar to HH(4b), with sensitivity dominated by the τlτh final state (no detector simulation implemented yet)





- **HH(4l & bb) with BR ~ 0.003%**
- S. Braibant L. Borgonovi E. Fontanesi N. De Filippis A.Taliercio (update to be included in the CDR)
- Expected precision
  - k_λ ~ 14% at 68% C.L (stat)
  - k_λ ~ 15% at 68% C.L (stat+ 1% sys)
  - k_λ ~ 24% at 68% C.L (stat+ 3% sys)

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SUMMARY

- The LHC so far and the HL-LHC in the future set the foundations for the exploration of the Higgs sector
- The FCC (and CepC, SppC in China) will complete the exploration of the Higgs sector and probe the high energy scale for BSM through precision measurement program
  - FCC-ee: precision and absolute measurement of σ_{ZH} and Γ_H
  - FCC-eh: precision
  - FCC-hh: access to rare process and measurement of self coupling
- Comprehensive and integrated program for the future of HEP!

Courtesy of Jorge de Blas

HLLHC + FCC	
Coupling	Relative precision
κ_b	0.38%
κ_t	0.51%
κ_τ	0.58%
κ_c	0.79%
κ_μ	0.42%
κ_Z	0.14%
κ_W	0.17%
κ_g	0.74%
κ_γ	0.40%
$\kappa_{Z\gamma}$	0.52%

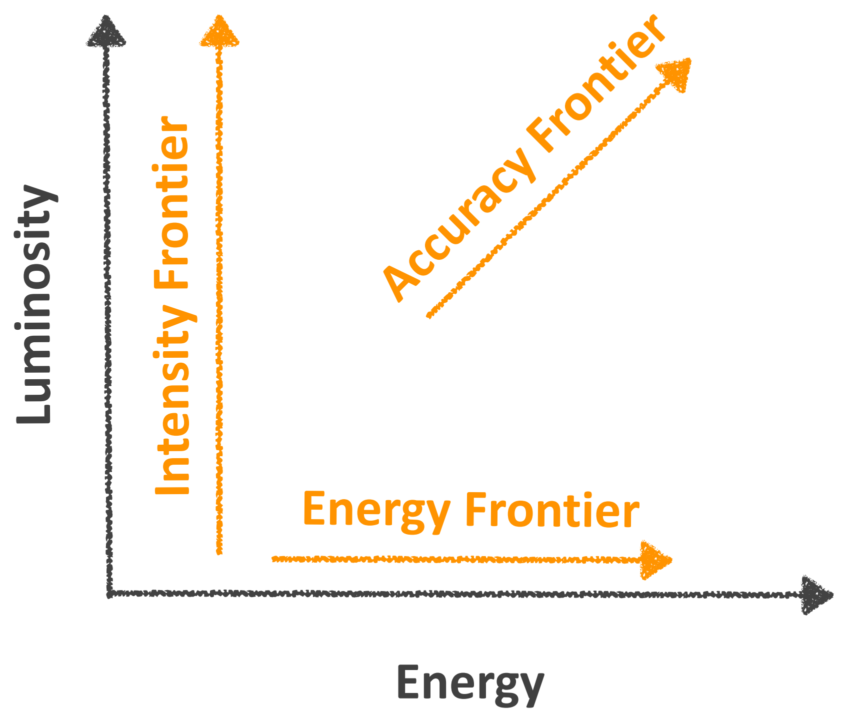
https://fcc.web.cern.ch/Pages/default.aspx

ADDITIONAL MATERIAL

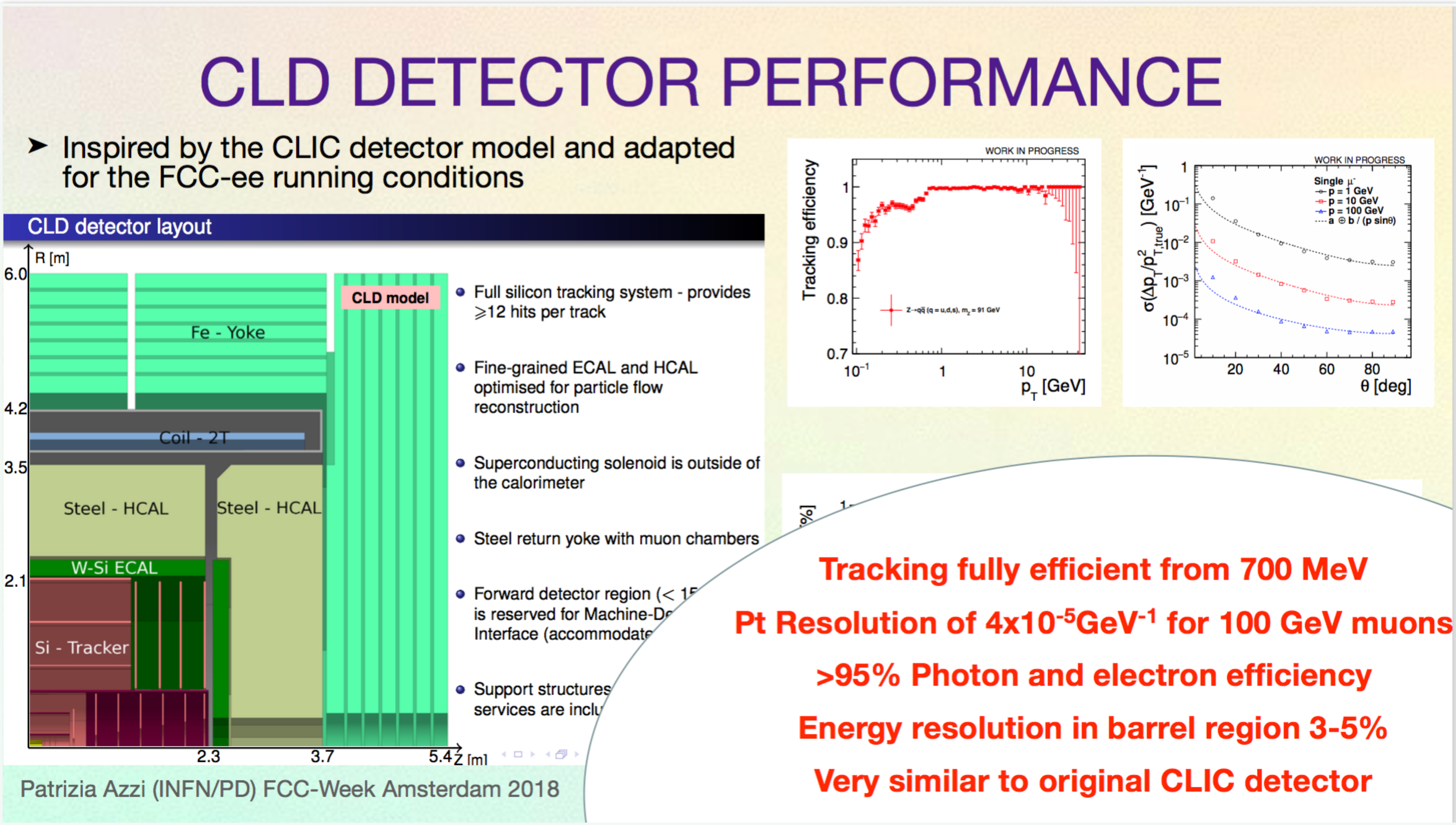
THE FUTURE OF HIGGS PHYSICS

- **The discovery of the Higgs boson represents a historical moment and remarkable achievement in particle physics**
  - It demonstrates that we have a correct effective theory to describe all known fundamental particles
- **The Higgs discovery is also the dawn of a new era for fundamental physics**
  - when we address fundamental questions related to the dynamics of EWKSB, dark sector, neutrino masses, naturalness, unification , …
- **What are the main paths forward in the exploration of the Higgs sector?**

  - Since the Higgs boson is a neutral scalar and it can interact with new particles we may not otherwise detect, a precision measurement program of its properties offers a portal to BSM
  - Mapping the Higgs potential can shed light on how the EWK phase transition occurred in the early Universe and the origin of the matter-antimatter asymmetry



DETECTORS AT FCC-EE (I)



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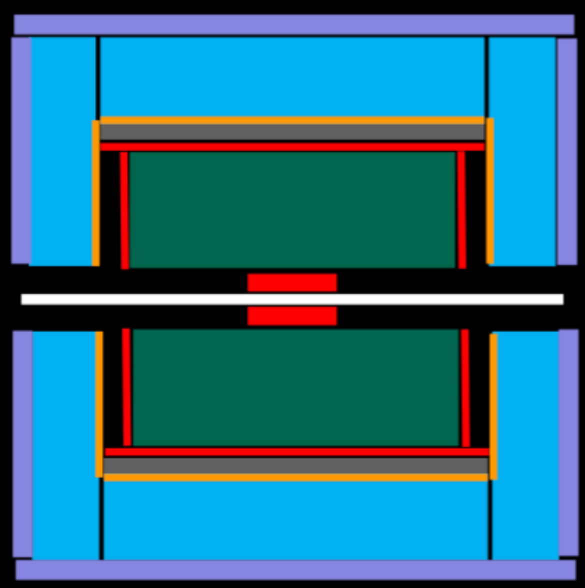
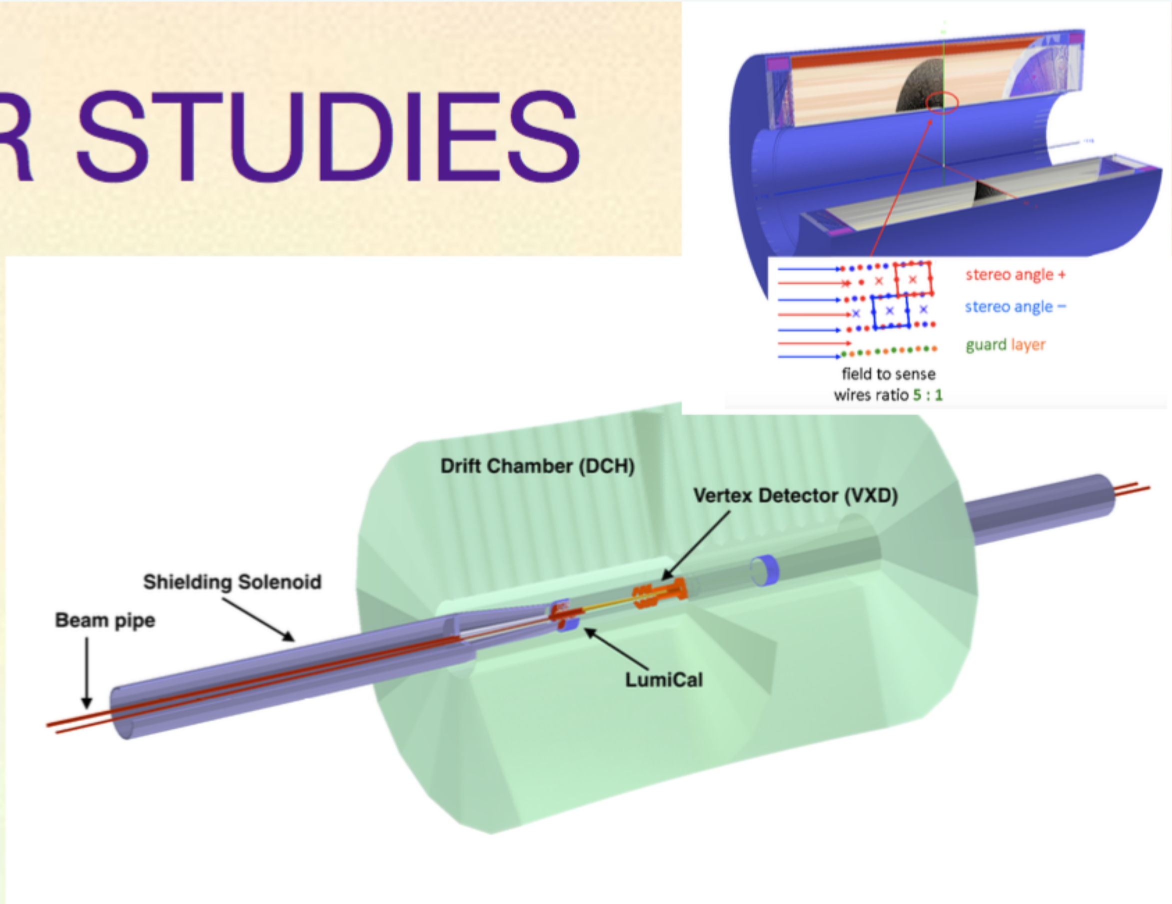
DETECTORS AT FCC-EE (II)

IDEA DETECTOR STUDIES

- Beam pipe (R~1.5 cm)
- VTX: 4-7 MAPS layers
- DCH: 4 m long, R 30-200 cm
- Outer Silicon Layer
- SC Coil : 2 T, R~2.1 m
- Preshower: ~ 1-2 X_0
- DR calorimeter: 2 m/7 λ_{int}
- Yoke + muon chamber





- Significant steps in the simulation of the subdetectors in the FCC-SW. Validation in progress with standalone software
- More detector R&D in progress in all sub-components
- Study of the background effects in the drift chambe
- Next completing simulation of the overall detec

IDEA detector concept becoming a reality in FCC-SW

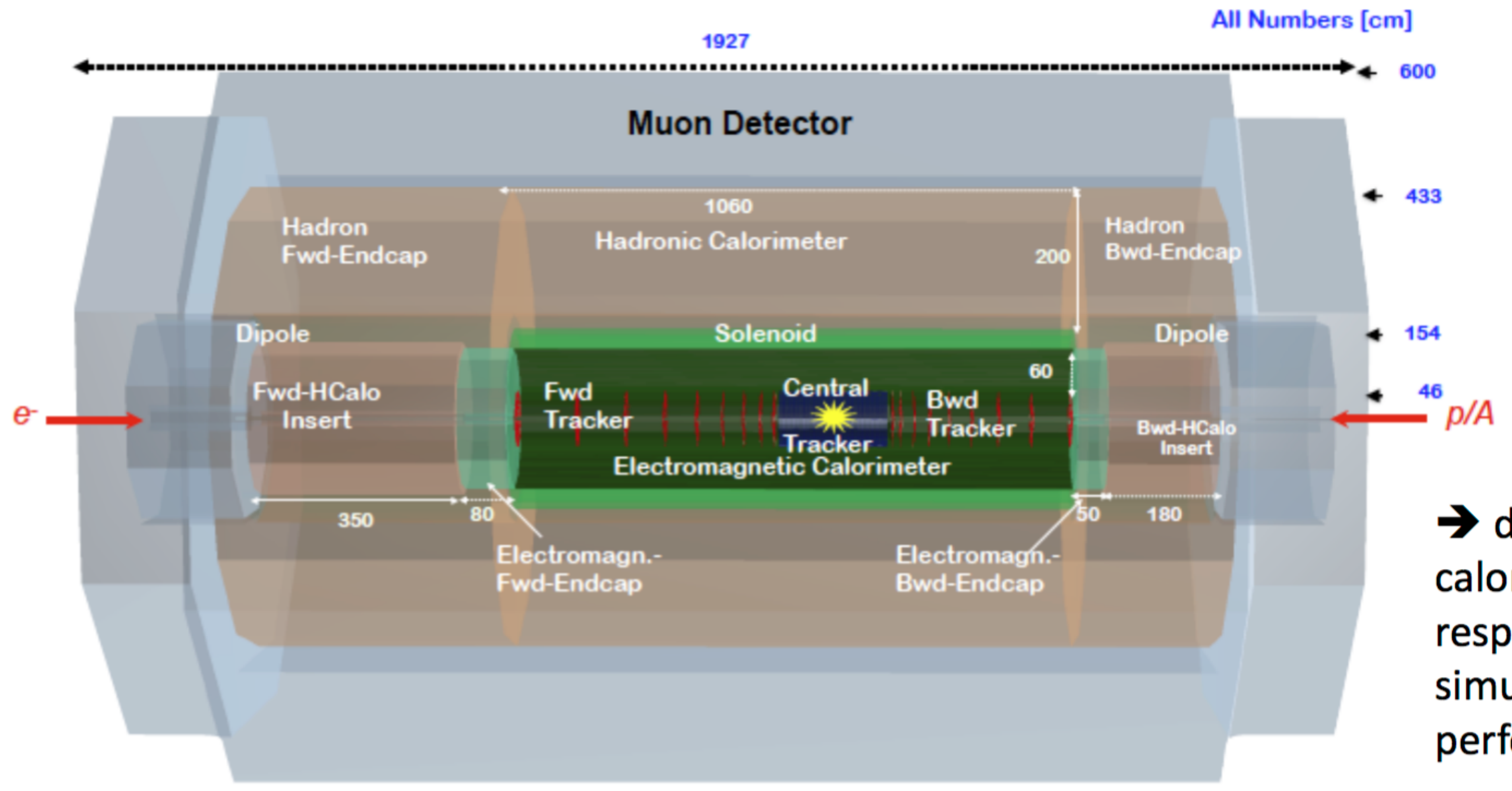
Test beam planned in Fall 2018!

Patrizia Azzi (INFN/PD) FCC-Week Amsterdam 2018

DETECTORS AT FCC-EH

FCC-he Detector Basic Layout

Talk by P Kostka



➔ detailed calorimeter response simulations performed

Based on the LHeC design; Solenoid&Dipoles between Electromagnetic Calorimeter and Hadronic Calorimeter. Length of Solenoid ~11m. detector setup in DD4hep.

https://dd4hep.web.cern.ch/dc

Discussion of ep solenoids by H ten Kate, see CERN March 2018: **No R&D needed**

https://indico.cern.ch/event/696066/

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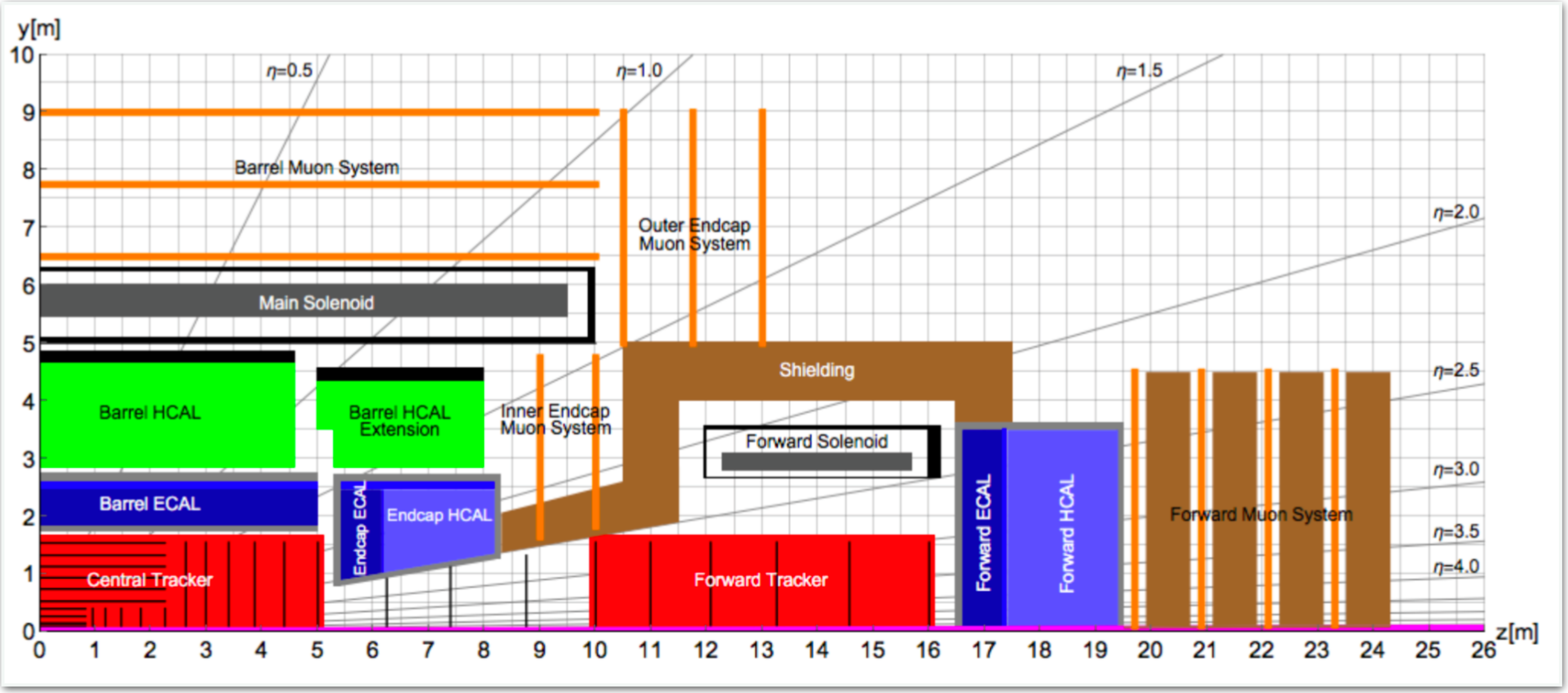
DETECTORS AT FCC-HH



https://indico.cern.ch/event/656491/contributions/2940766/attachments/1632534/2603674/summary_fcchhdet.pdf

EH PARAMETERS

LHeC CDR: arXiv:1206.2913

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

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FCC Week 2018, Amsterdam

HH PARAMETERS

FCC-pp collider parameters

EuroCirCol

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.1	1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	2.2	1.15
bunch spacing [ns]	25	25	25	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	28	5 (lev.)	1
events/bunch crossing	170	1000	800	132	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

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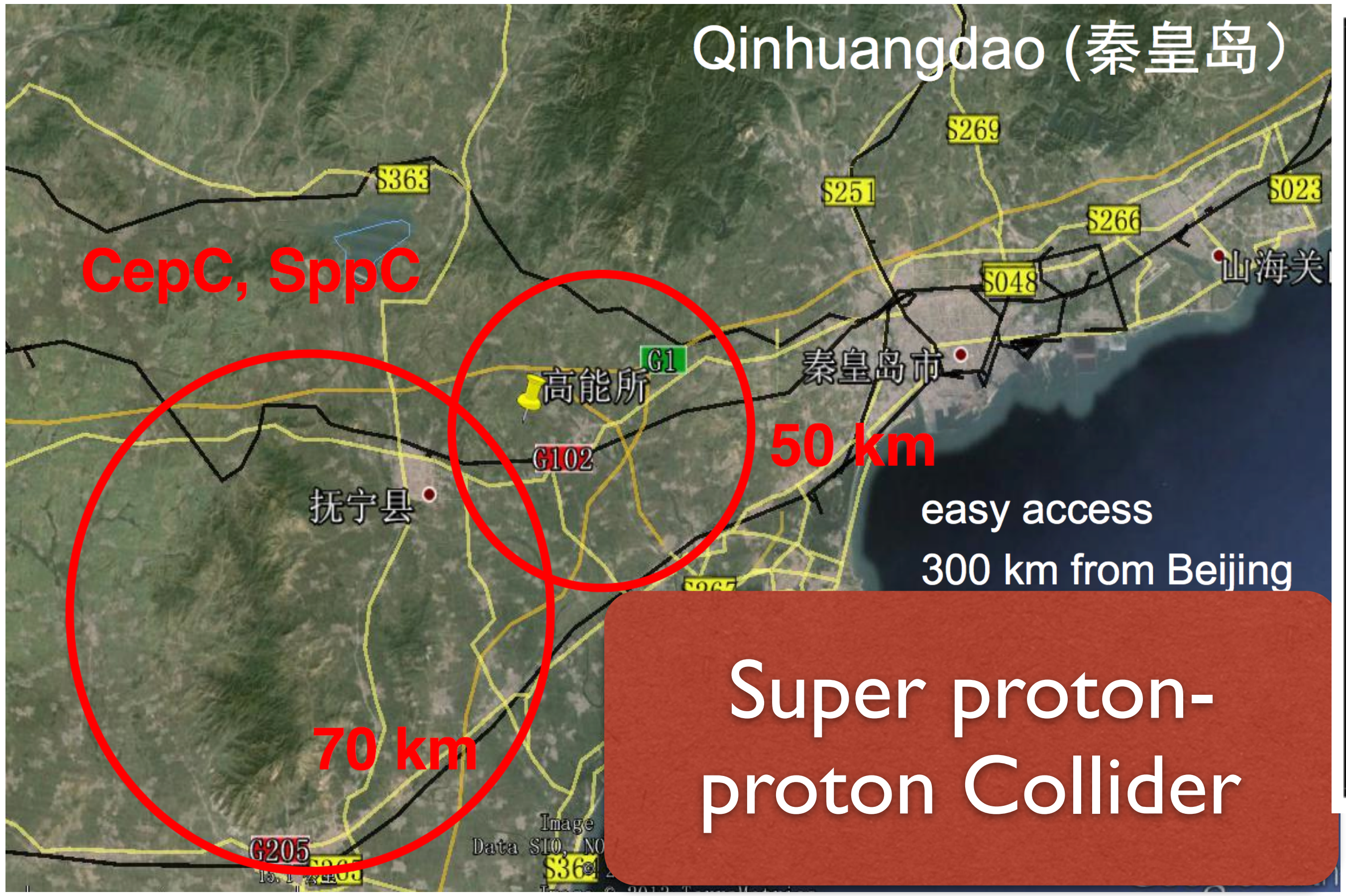
EE PARAMETERS

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	>200	>25	>7	>1.4
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

lepton collider luminosities

SPPC AND CEPC



	Ring, km	Field, T	$\sqrt{s}$, TeV	L, 10^{34}
LHC	27	8.3	14	≤ 5
HE-LHC	27	16	26	5
HE-LHC	27	20	33	5
SppC-1	50	12	50	2
SppC-2	70	19	90	2.8
FCC-hh	80	8.3	42	–
FCC-hh	80	20	100	≥ 5
FCC-hh	100	16	100	≥ 5