FCC-UK Meeting, Virtual, September 2020

FCC-ee Higgs physics

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The European strategy:

- "..a new electron-positron collider operating as a "Higgs factory". Such a collider would produce copious Higgs bosons in a very clean environment, would make dramatic progress in mapping the diverse interactions of the Higgs boson with other particles and would form an essential part of a research programme.."

The ground-rules

- Fcc-ee producing 10^6 ee→Zh @ 240 GeV events means $5ab^{-1}$
  - Aim to deliver in 3 years
  - With additional samples at $t\bar{t}$ threshold
- A decade after LHC has delivered 160M Higgs bosons to each of ATLAS and CMS
- Why is this interesting?

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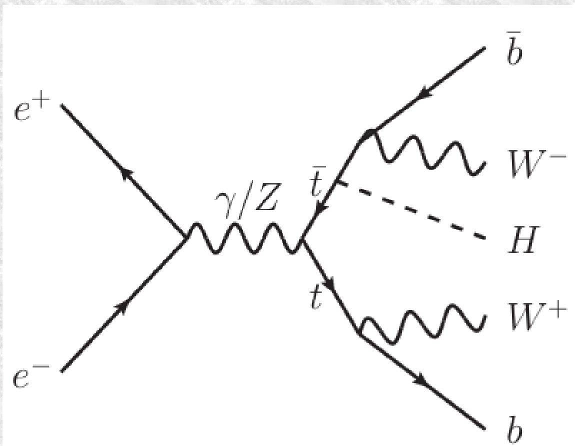
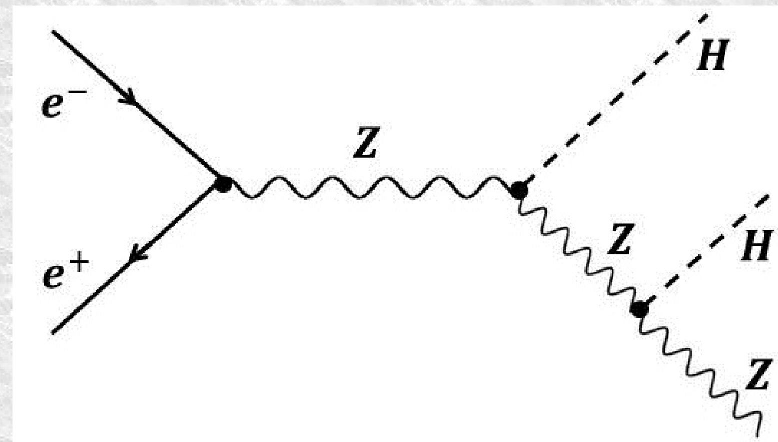
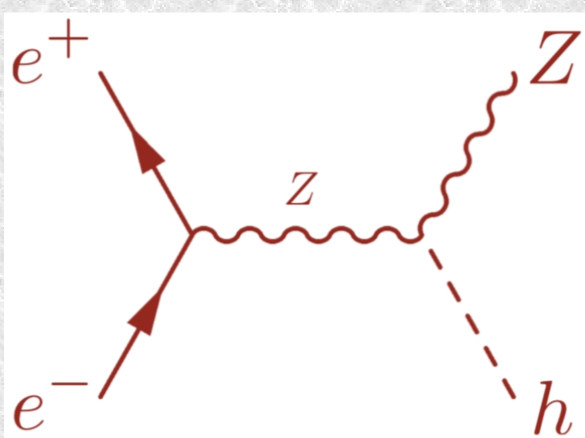
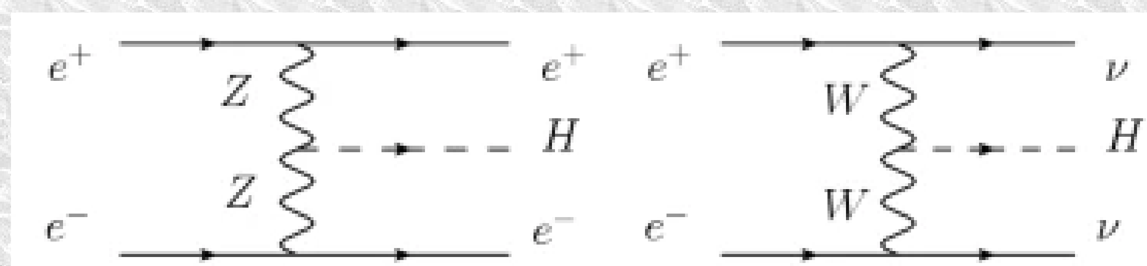
Higgs production in ee

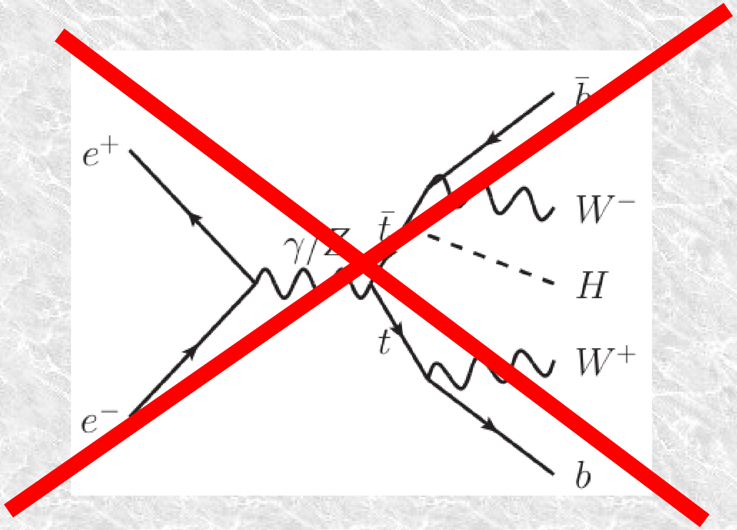


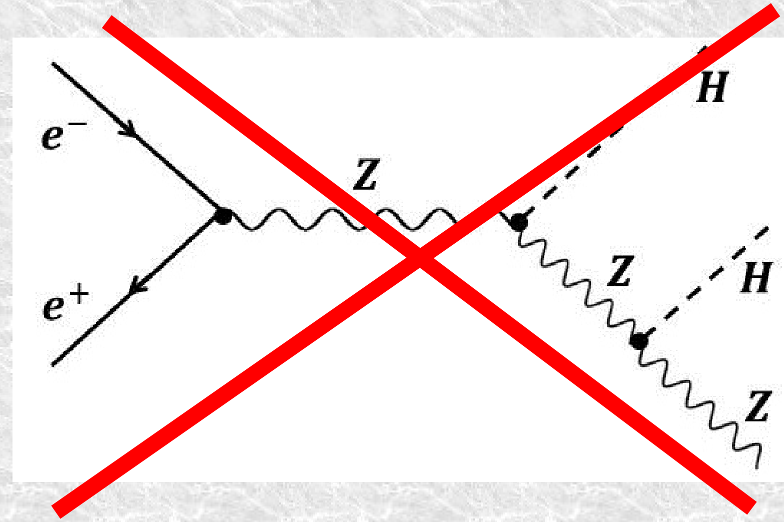


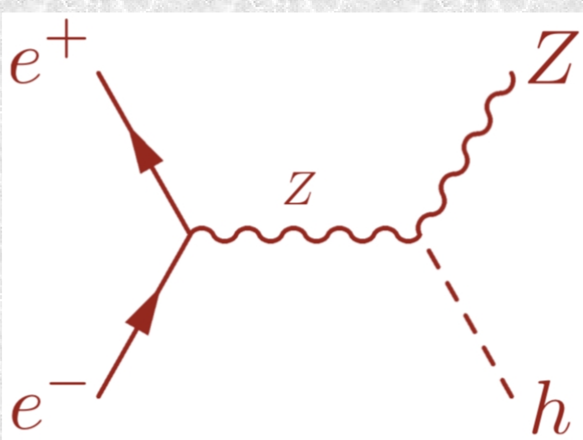


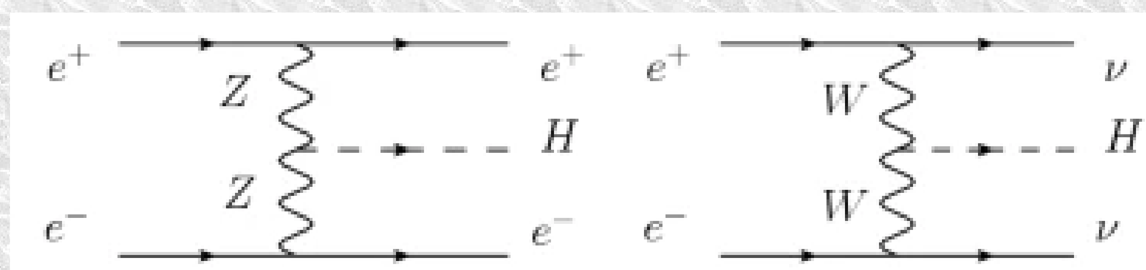


Higgs production in FCC-ee







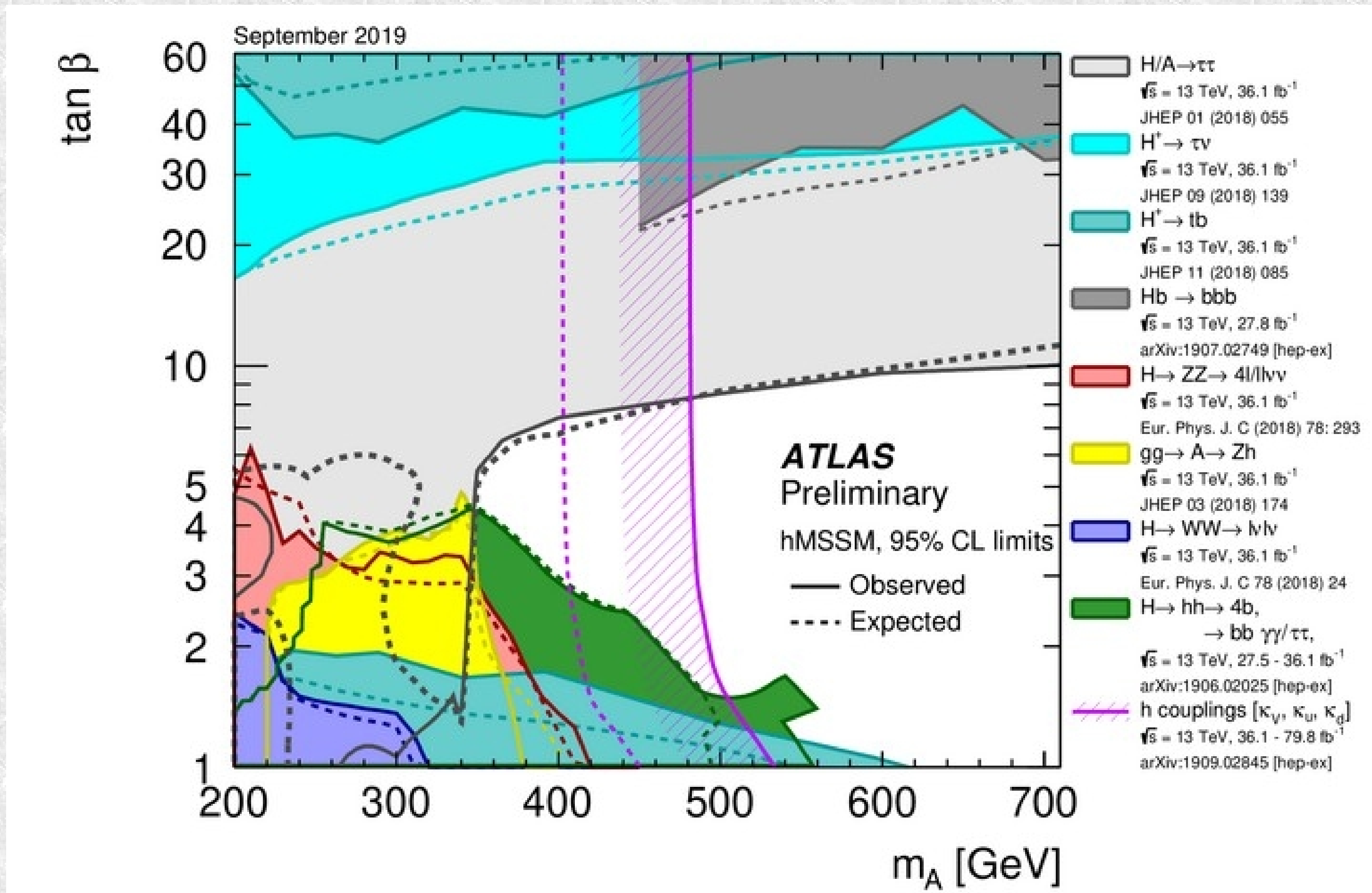


I was amused by ArXiv yesterday:

- Two papers, next to each other in the mailing:
  - "Prospects of measuring the branching fraction of the Higgs boson decaying into muon pairs at the International Linear Collider"
    - https://arxiv.org/abs/2009.04285
    - Shin-ichi Kawada, Jenny List, Mikael Berggren
    - 6 ab^{-1} @250/500 GeV → 17% precision
  - "Evidence for Higgs boson decay to a pair of muons"
    - https://arxiv.org/abs/2009.04363
    - CMS Collab.
    - 0.16ab^{-1} @ 7/8/13 TeV → 40% precision
- Focus on what you are good at!

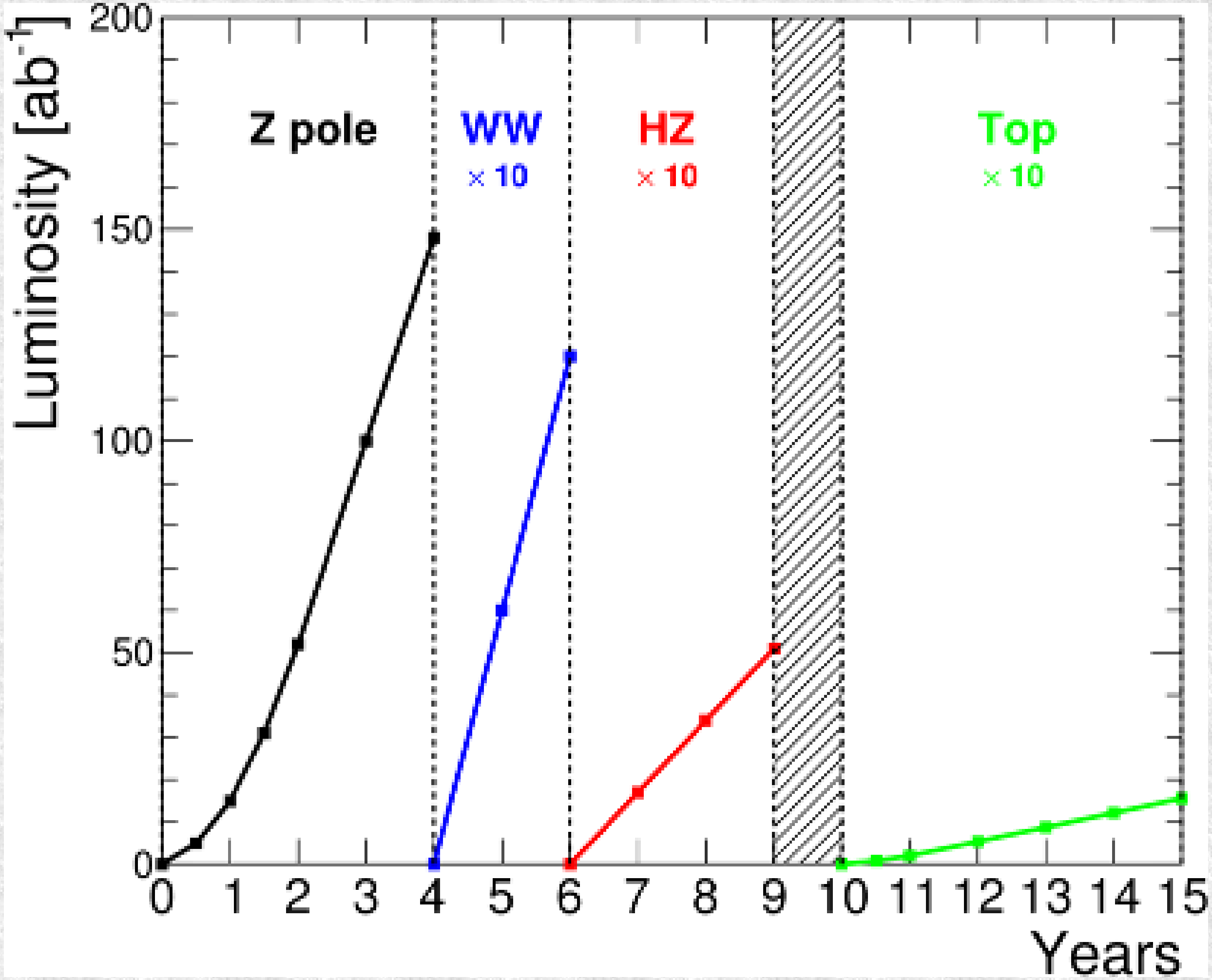
Direct v Indirect studies

- Example: SUSY Higgs sector, m_A and tan β
- Direct searches (solid) and indirect (purple line) have comparable impact on plane
- We learn a lot from Higgs couplings

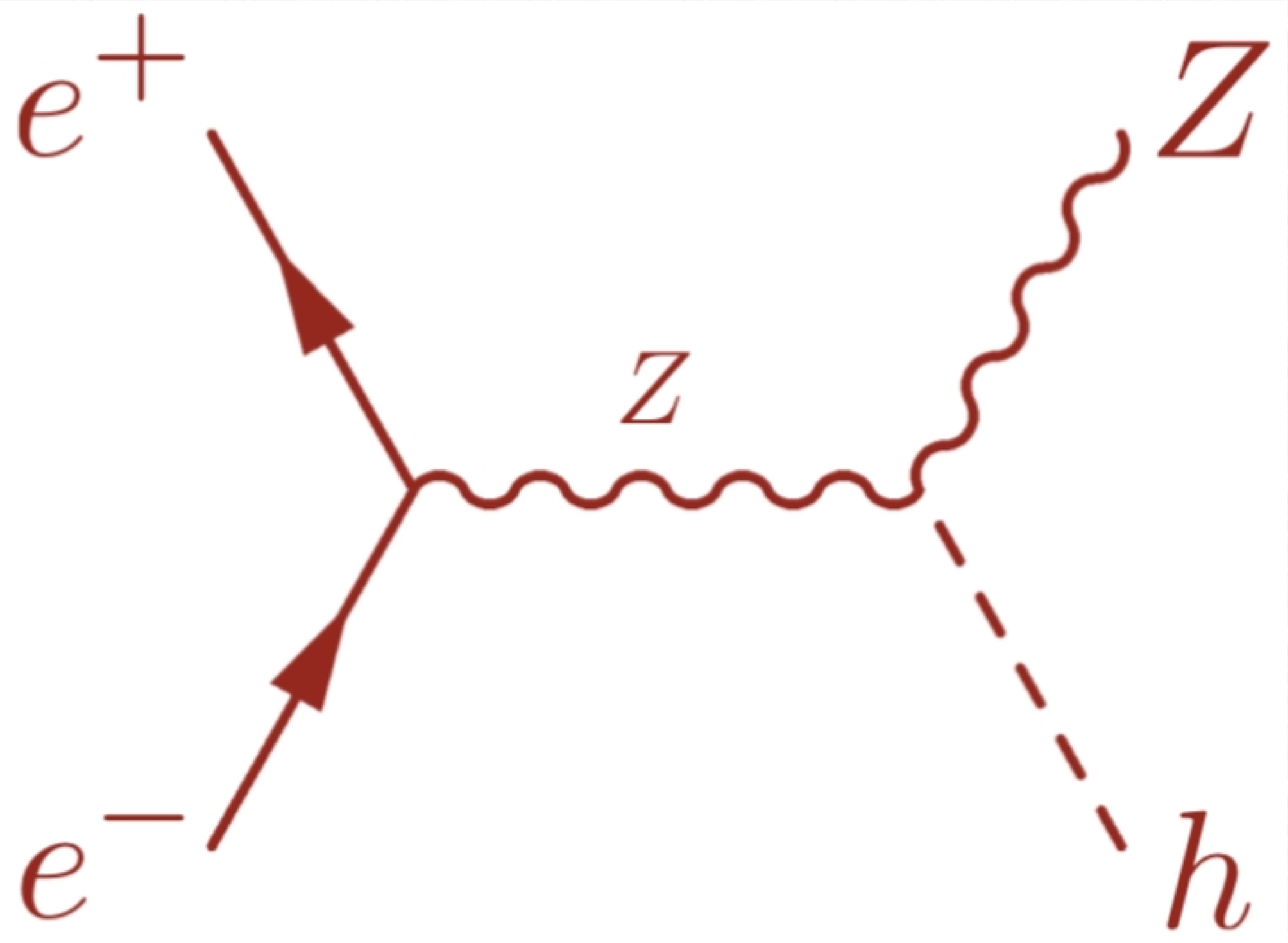


Reminder: the run plan

- Nominal plan 3 years in Higgs
  - With tt run after

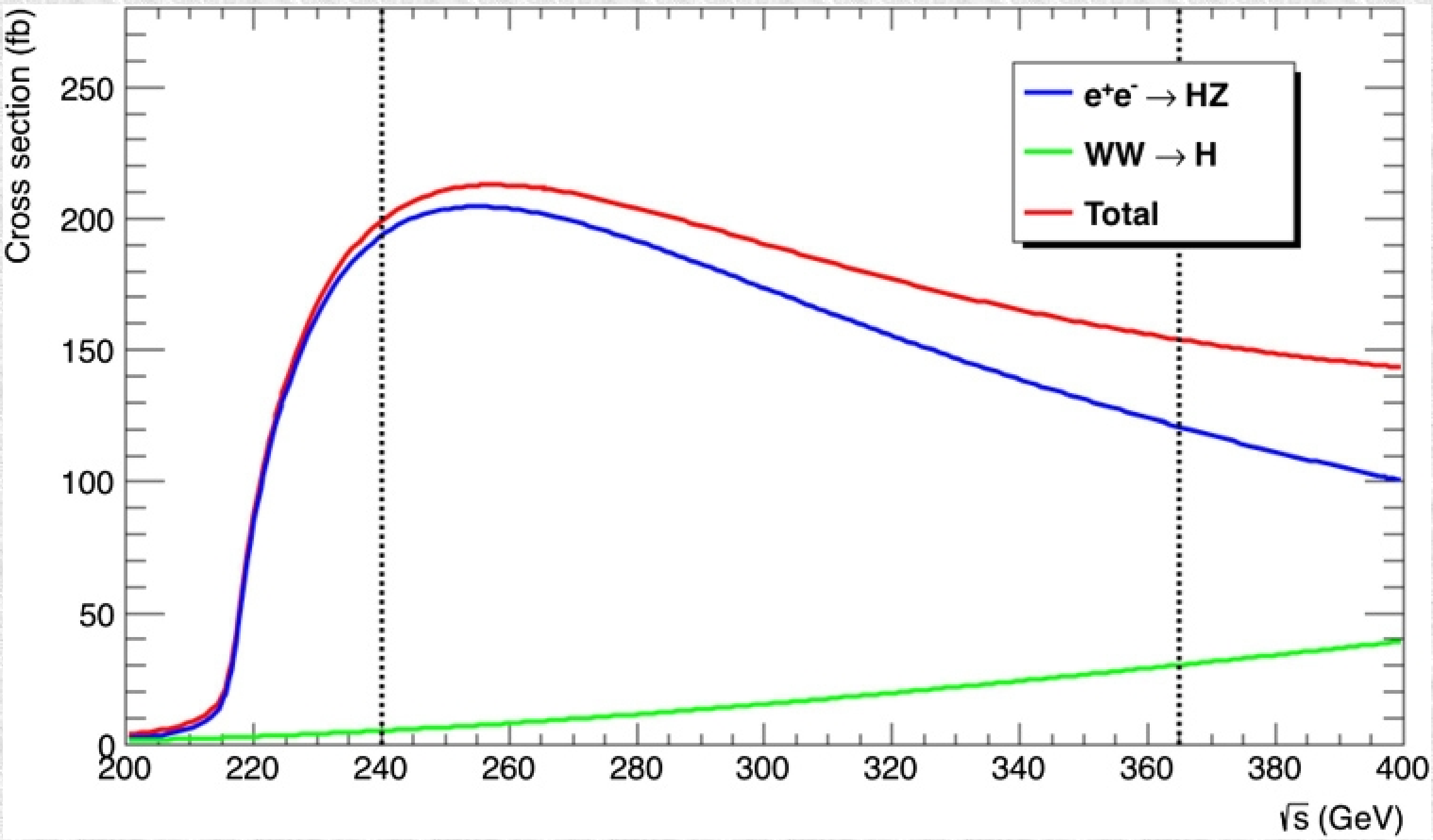


The 240 GeV run



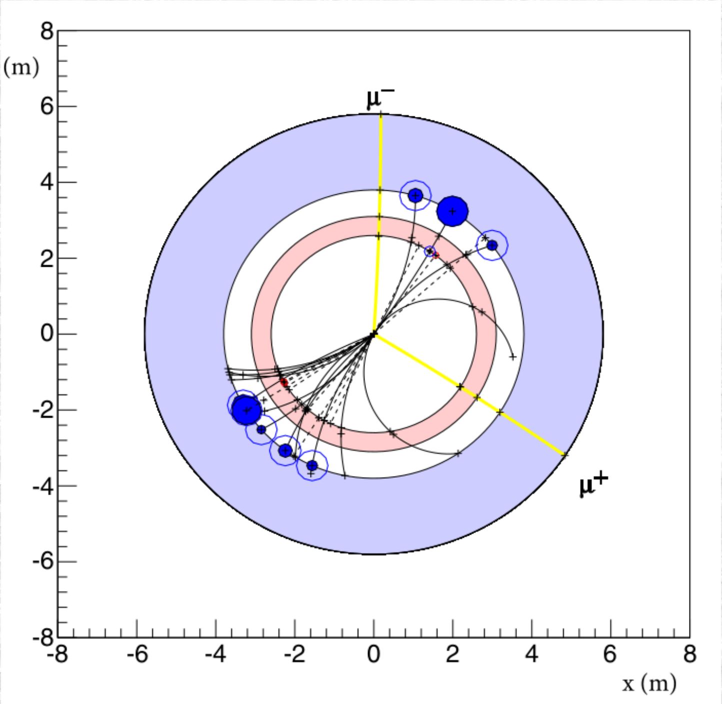
Why 240 GeV?

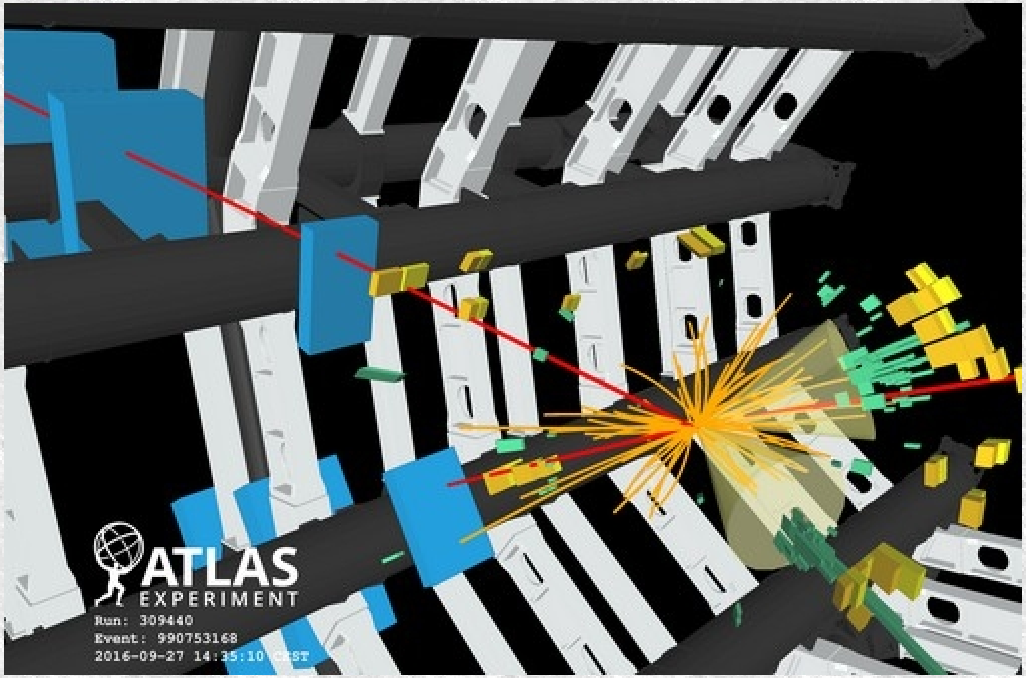
- The cross-section peaks at 260 GeV
  - But in a circular collider luminosity~ 1/energy
  - Resulting in a peak rate at 240 GeV



Clean events

- ZH→ μμbb at Fcc-ee and LHC

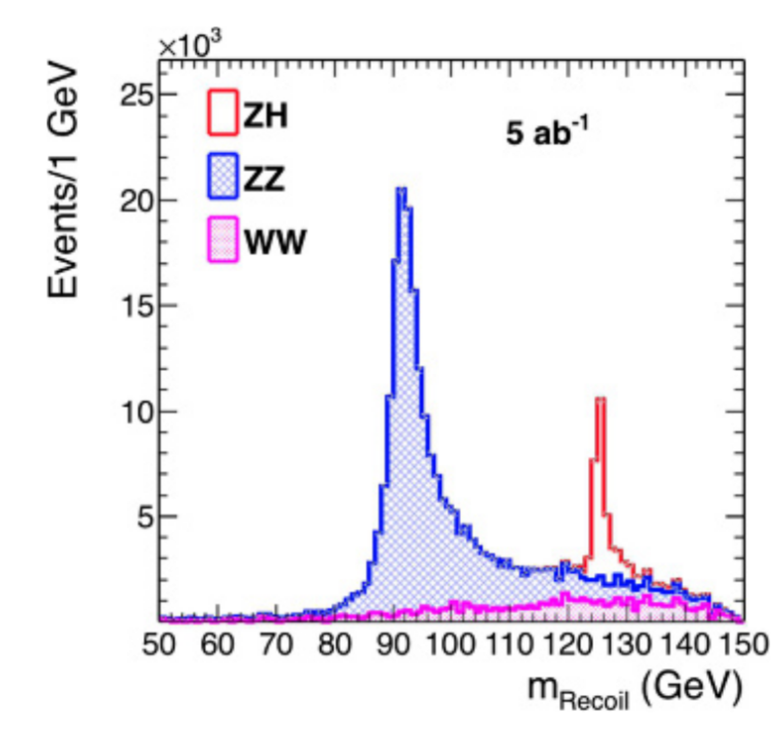




- Negligible pileup and conservation of energy are huge advantages

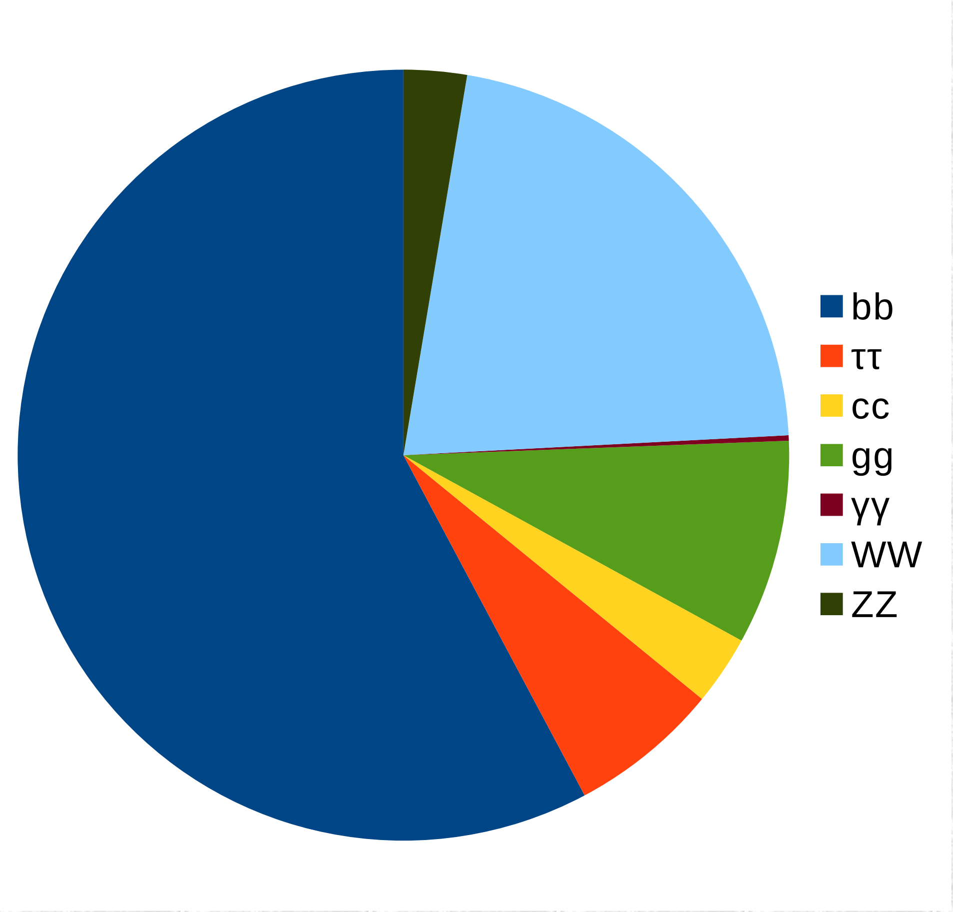
The method

- The Higgs-strahllung from known initial state is the unique and best feature of the Higgs factory
  - Reconstruct the Z and the recoil mass shows you the Higgs
    - Extract cross-section σ_{HZ}
    - Assume SM coupling form & measure g_{HZZ}
  - Right is $Z \rightarrow \mu\mu$
    - Maximise sensitivity using also hadronic Z decays
- Measure BR to ZZ to extract Γ_H, the width



Higgs decay modes

- All the Higgs decay modes shown can be studied
  - Unlike LHC where gg and cc are not measurable
- And the tagging opens the door for new & unexpected decays



Errors on branching ratios

- 1M ZH events at 240 GeV
  - + 180K ZH, 45K WW fusion in top run
- ZH run dominates branching ratio measurements
- The BR to invisible is very exciting, 3 per mille
  - C/f 2-3% from HL-LHC

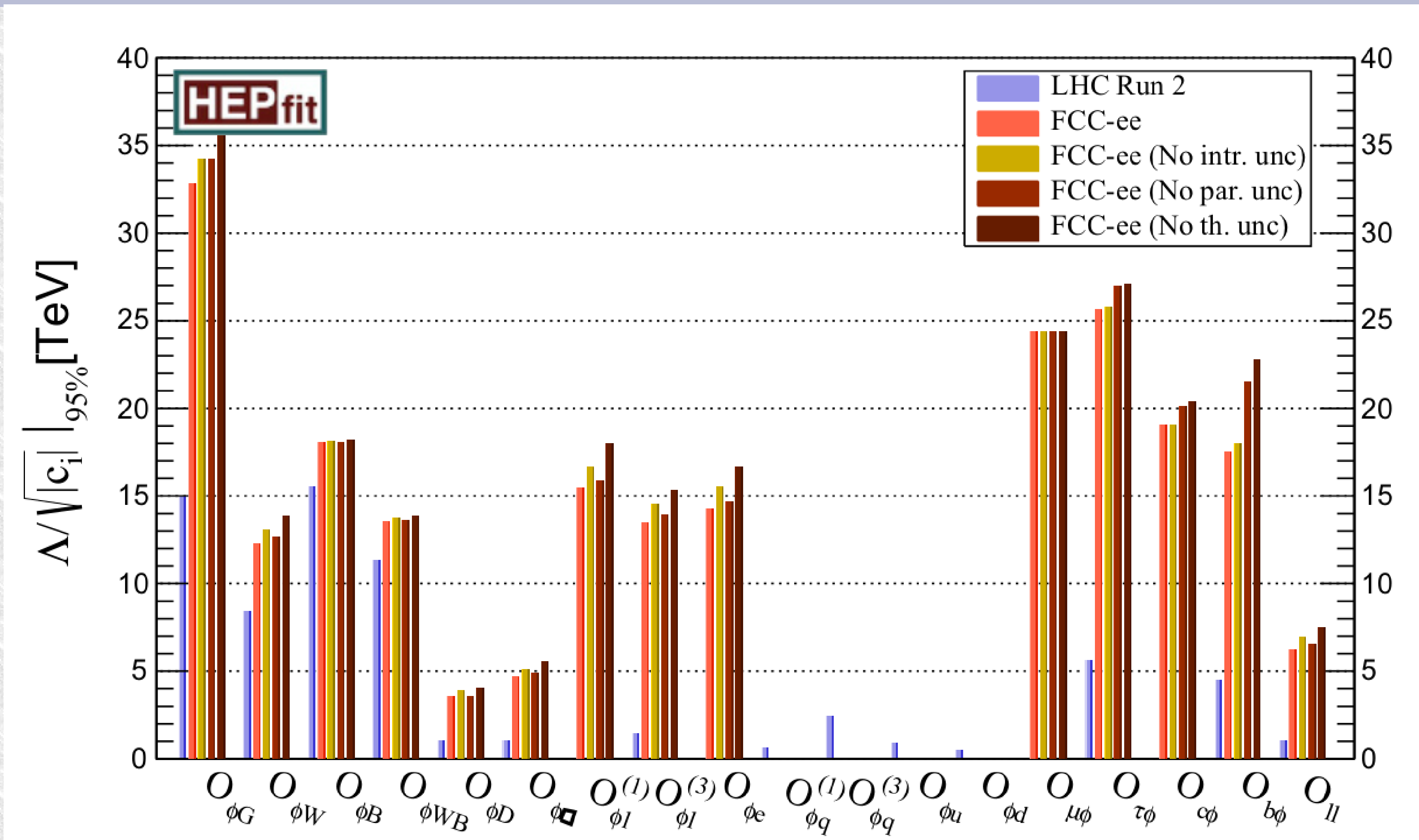
$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to$ any	± 0.5		± 0.9	
$H \to b\bar{b}$	± 0.3	± 3.1	± 0.5	± 0.9
$H \to c\bar{c}$	± 2.2		± 6.5	± 10
$H \to gg$	± 1.9		± 3.5	± 4.5
$H \to W^+W^-$	± 1.2		± 2.6	± 3.0
$H \to ZZ$	± 4.4		± 12	± 10
$H \to \tau\tau$	± 0.9		± 1.8	± 8
$H \to \gamma\gamma$	± 9.0		± 18	± 22
$H \to \mu^+\mu^-$	± 19		± 40	
$H \to$ invisible	<0.3		<0.6	

Kappa fit from various colliders

kappa-0	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 15000	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

- Charm coupling measured for first time
- Huge gain in Higgs coupling to Z
- But b and W improve almost as much after $t\bar{t}$ run
  - VBF and better kinematics

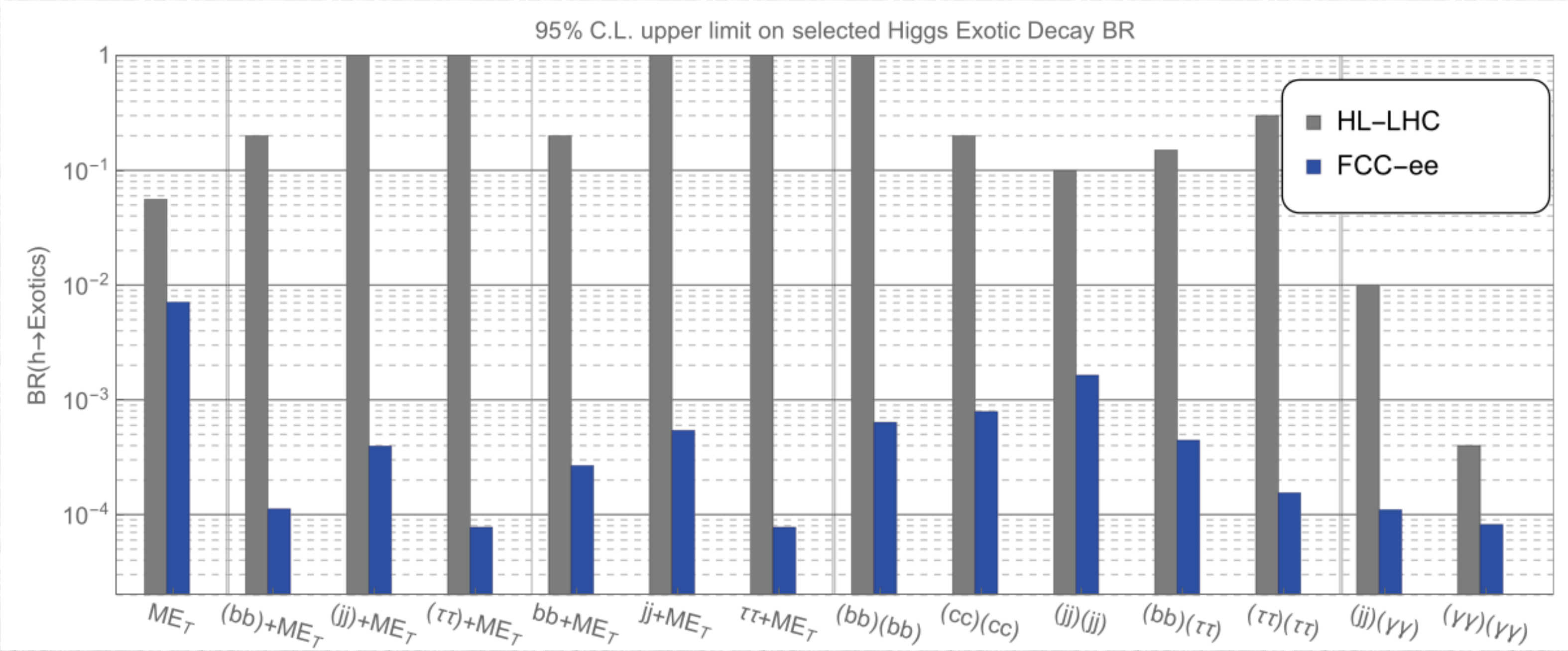
Higgs constraints on EFT



- Definition of EFT coefficients in CDR vol 2

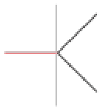
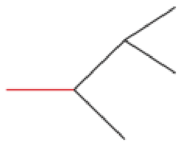
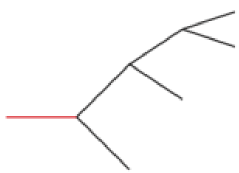
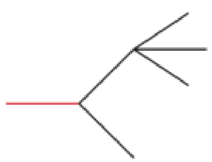
Exotic Higgs decays

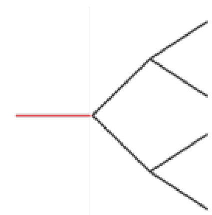
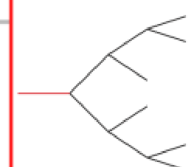
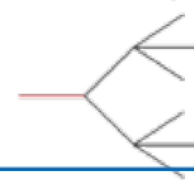
- Huge potential for unexpected Higgs decay modes



- Fcc-ee delivers up to 10^4 improvement over LHC
- This is testing the couplings & mixings of the only fundamental scalar

There are many more ….

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

Strong areas of Higgs factories

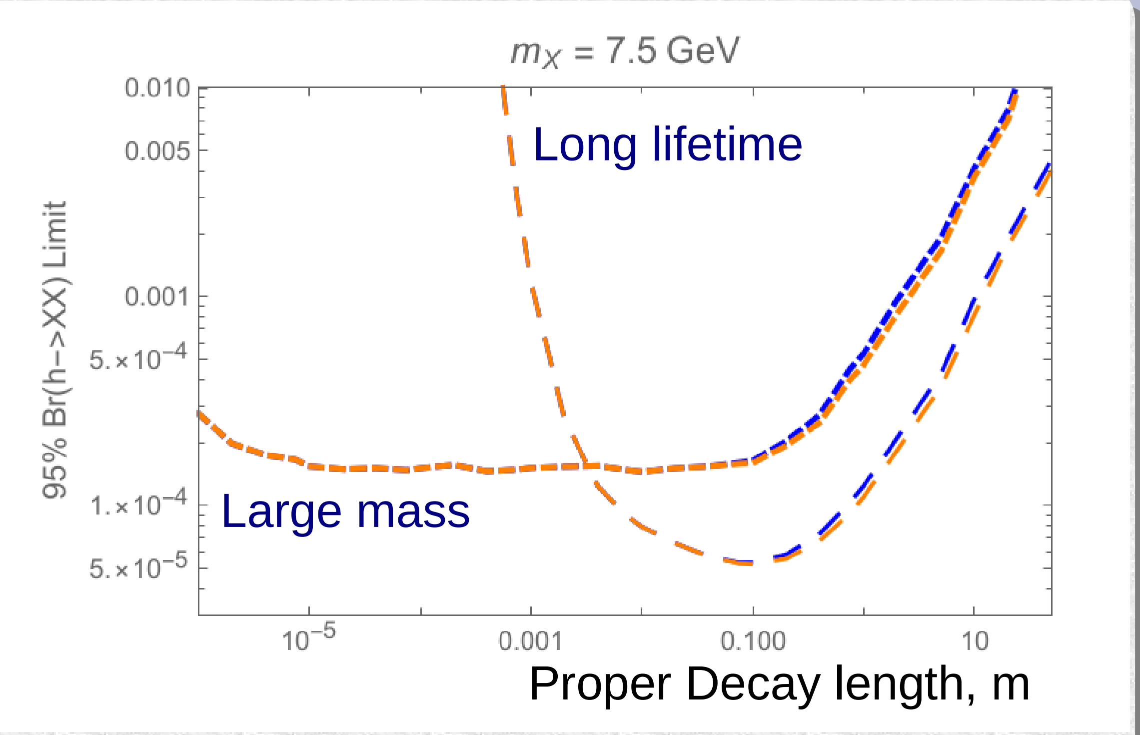
More hadronic

With MET, less lepton

Great sensitivity from the LHC

Higgs to long lived particles

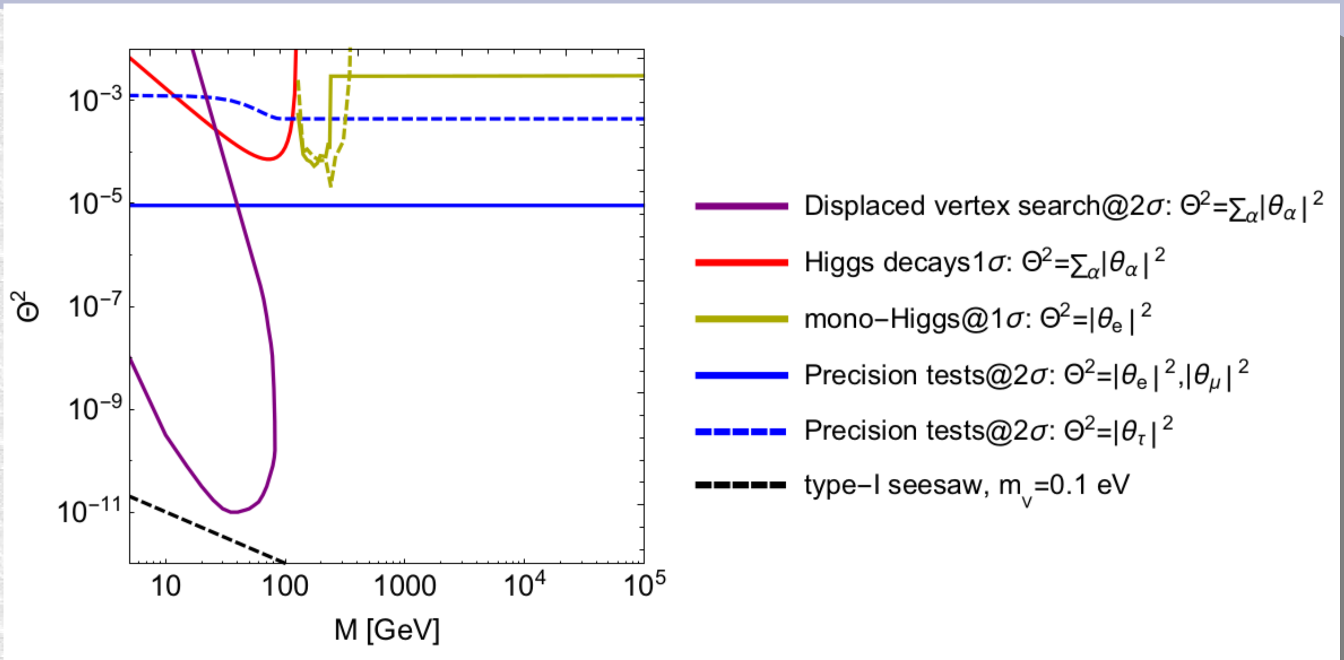
- Assume Higgs decay to long lived particles
  - Decaying to hadrons
- Two search strategies
  - Both exploit displacement
- Projected h → XX BR limits FCC-ee/CepC shown
- BR 10^{-4} accessible



https://arxiv.org/abs/1812.05588

Sterile right-handed neutrinos

- Assume RH neutrino, mixing with left handed
- Multiple different sensitivities



- If θ^2 above 10^{-5} EW will see it
  - Maybe Higgs
- Z decay to LLP give 6 orders magnitude more reach for tens of GeV mass

Rare Z decays

- $Z \rightarrow \mu e$, $e\tau$ or $\mu\tau$
  - Sensitivity is 2 orders of magnitude better than HL-LHC
  - There are constraints from $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$ etc
    - Strongly constraining for μe case
    - But not so for decays with taus
- Lepton universality in Z decay
  - 1.5×10^{11} μμ & ττ pairs
    - 3 per mille constraints from LEP
    - These are important constraints on the B flavour anomalies
  - Fcc-ee will have to understand e/μ/τ efficiency well
    - This is a question of ID systematic errors

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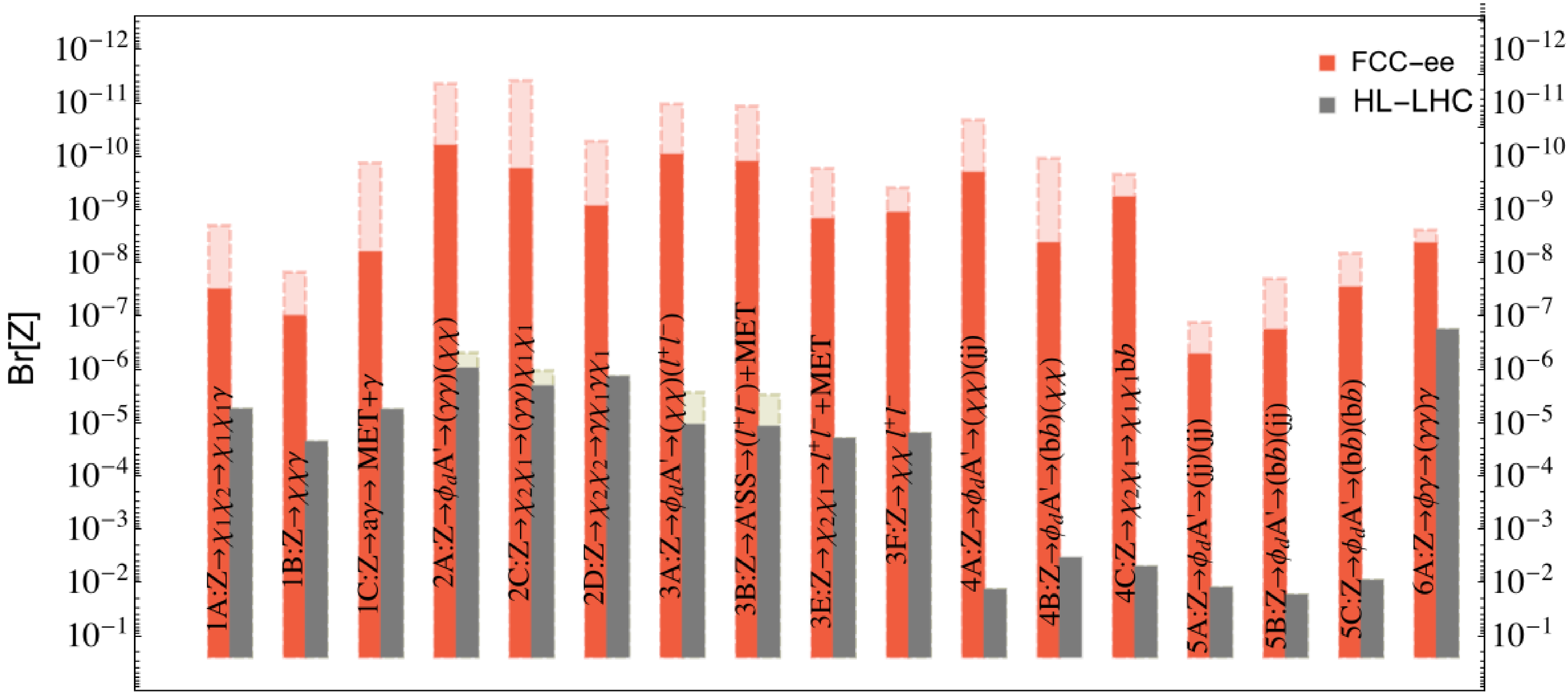
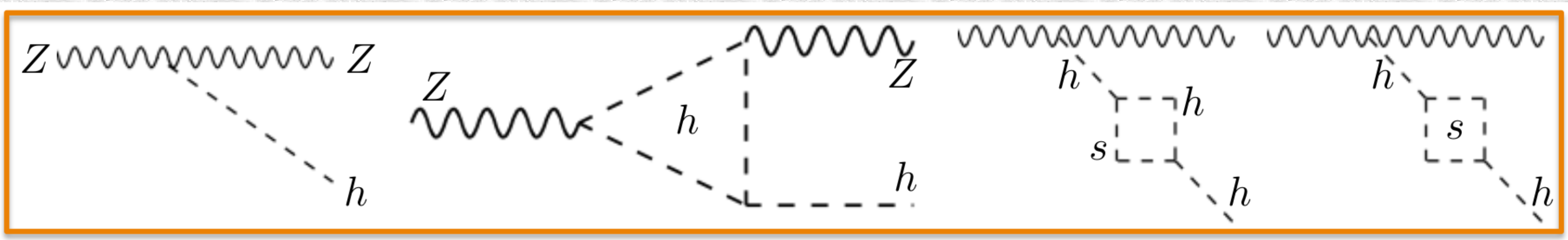
Rare Z decays



- The 10^{11} clean Z's give a phenomenal reach for many possible particle
  - With a range dependent on your experimental optimism

EW phase transition

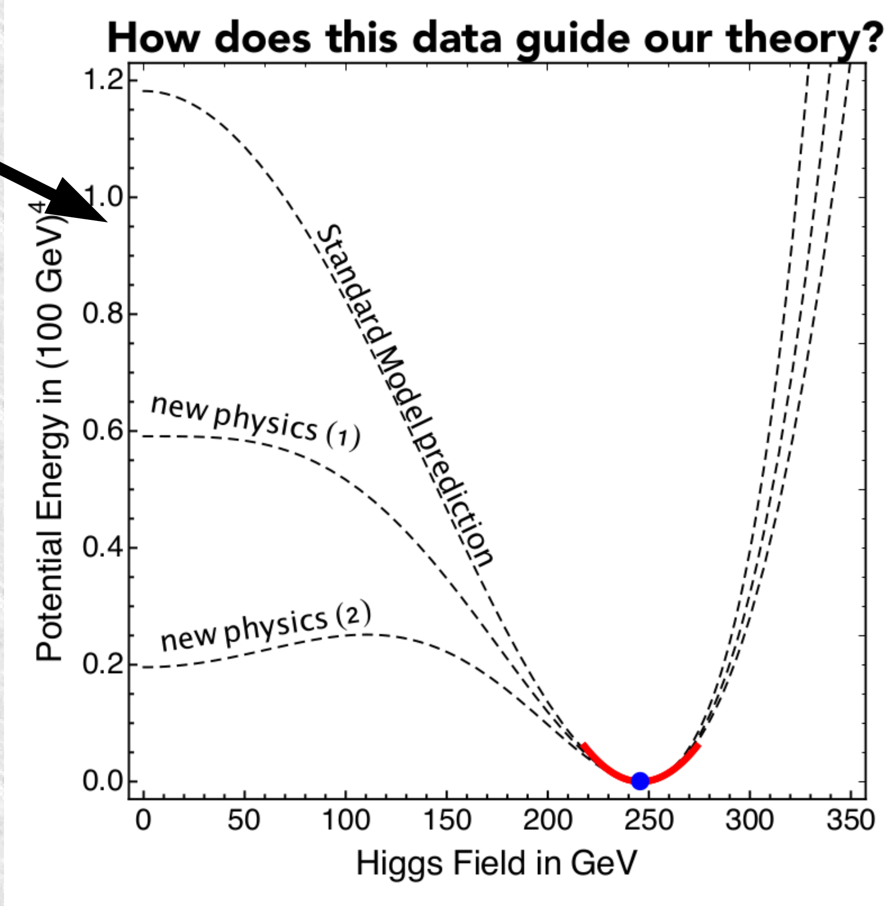
- Baryogenesis needs a strong 1st order EW phase transition
- This in turn requires new physics interacting with Higgs
  - effects must exist in Higgs couplings
  - The question is are they visible?
- Real scalar singlet (no colour/EM) interactions can do it
  - And mixes with Higgs; changes ZZH coupling



Long

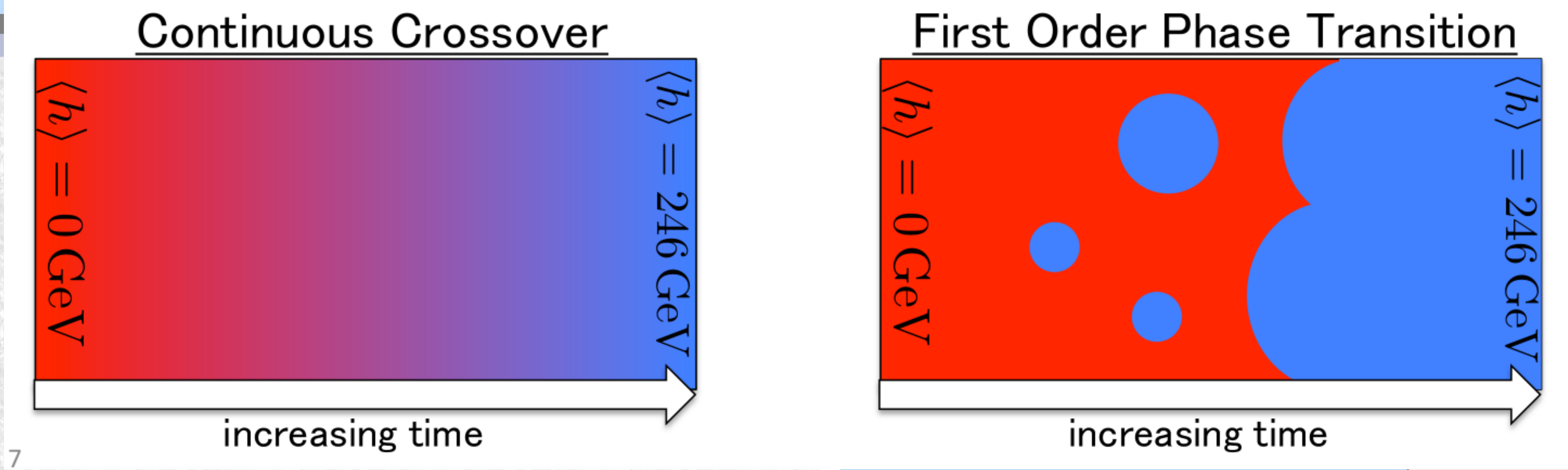
First order phase transition

- So far we probe the Higgs potential near 250GeV
- There could be a barrier between the origin and vacuum?
- If so the symmetric vacuum is meta-stable
- Universe does not smoothly evolve to the observed Higgs VeV
- But will start from local fluctuations which spread

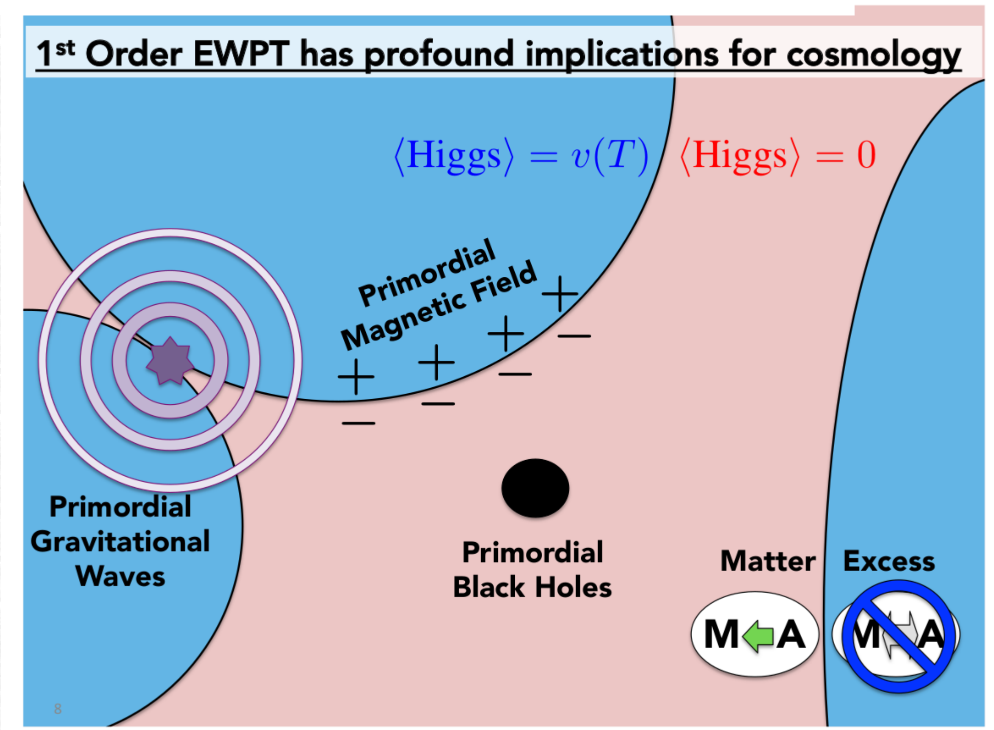


Long

Why do we care?



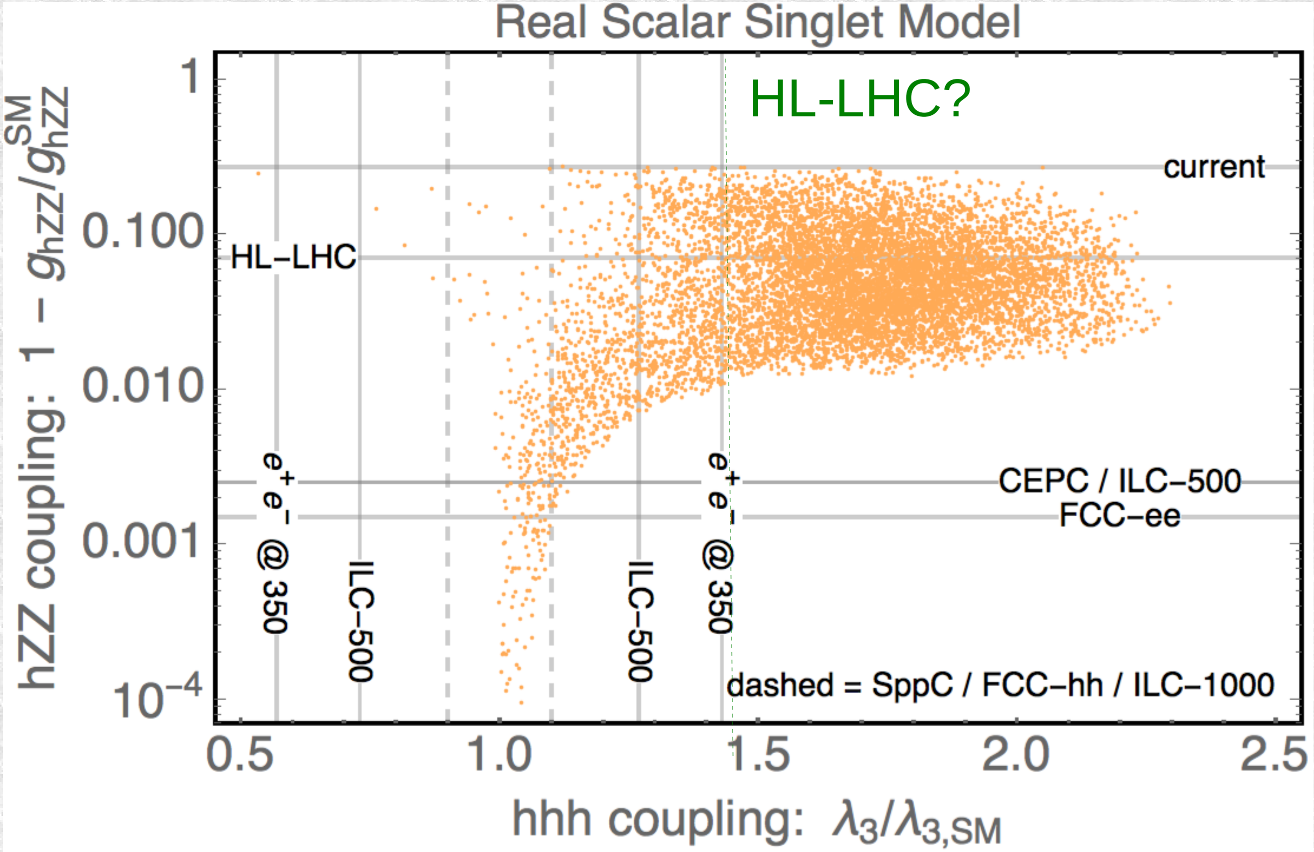
- The inhomogeneities associated could drive matter asymmetry,
- create gravitational waves
- Or seed primordial black holes



Sensitivity to singlet

- Scan of 5 parameters
  - Points give 1st order transition shown
- HL-LHC sel-coupling may give evidence
- FCC-ee has huge sensitivity to a singlet

Huang, Long, & Wang (1608.06619)



But if Lagrangian is $a\Phi^2 + b\Phi^4 + c\Phi^6$ give first-order transition then FCC-ee can definitely see it

Summary

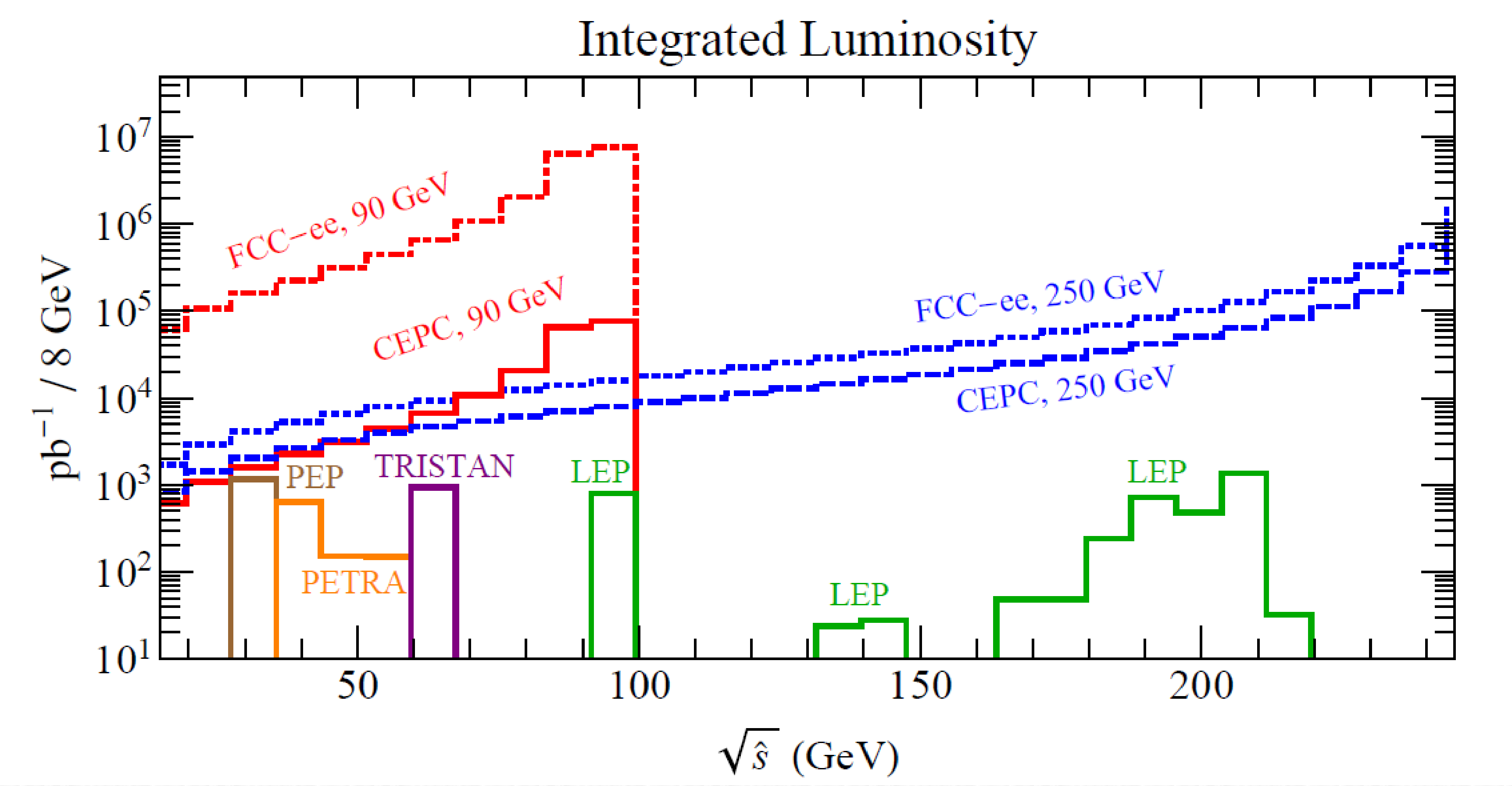
- Fcc-ee will measure charm coupling for first time
  - Only second non-3rd generation coupling known
- The ZH coupling studies are particularly good
  - Discovery potential for 1st order EW phase transition
- Higgs to invisible limits at 0.3%
- Rare decay searches are an enormous opportunity
  - Higgs or Z decays with missing energy especially
  - and great long lived particle sensitivity
- Guaranteed excellent menu

- ..and excellent discovery possibilities

Thanks to all those who's work I stole

Radiative return

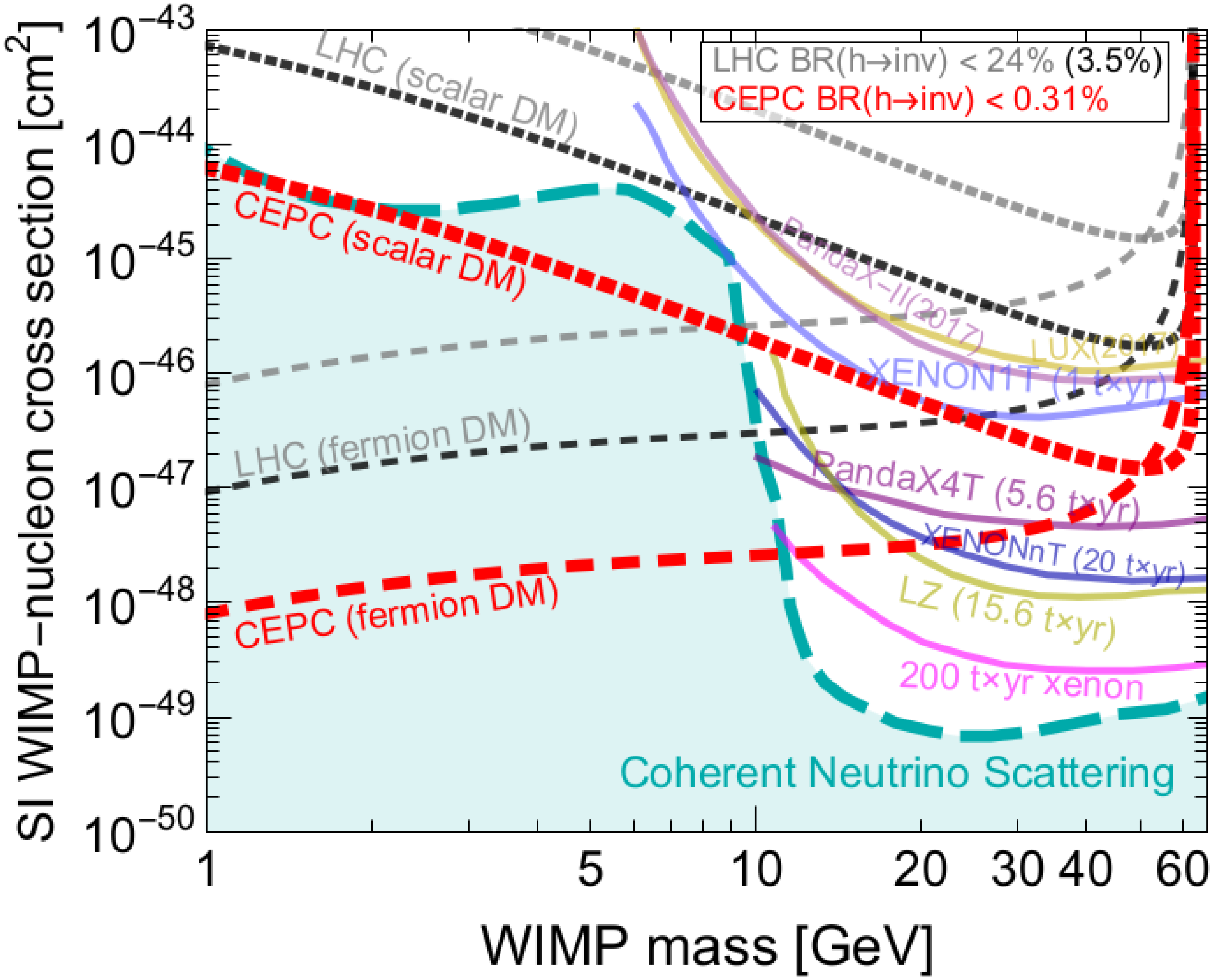
- Many thresholds unexplored. e.g.
  - $B_c\bar{B}_c$ @ 12.551GeV, $\Xi_{bb}\,\bar{\Xi}_{bb}$ @ 20.3GeV



Low

Higgs to MET

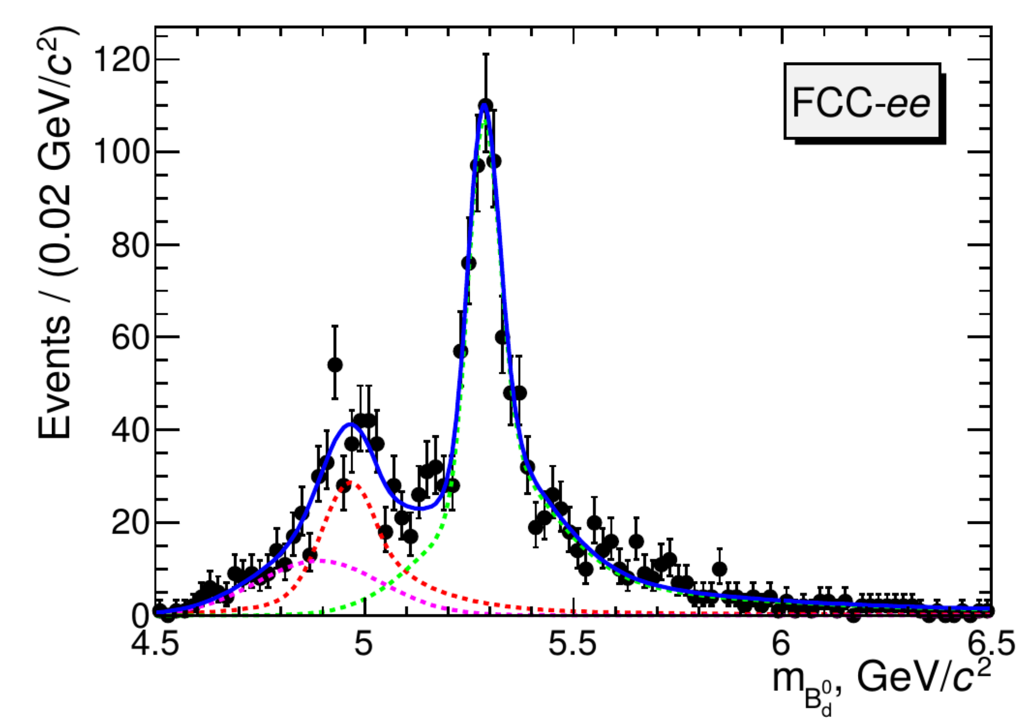
- Higgs to dark matter is 100% invisible
- CepC offers an order of magnitude increase in sensitivity
  - Especially useful at low mass



B hadrons

Altmannshofer & Charles

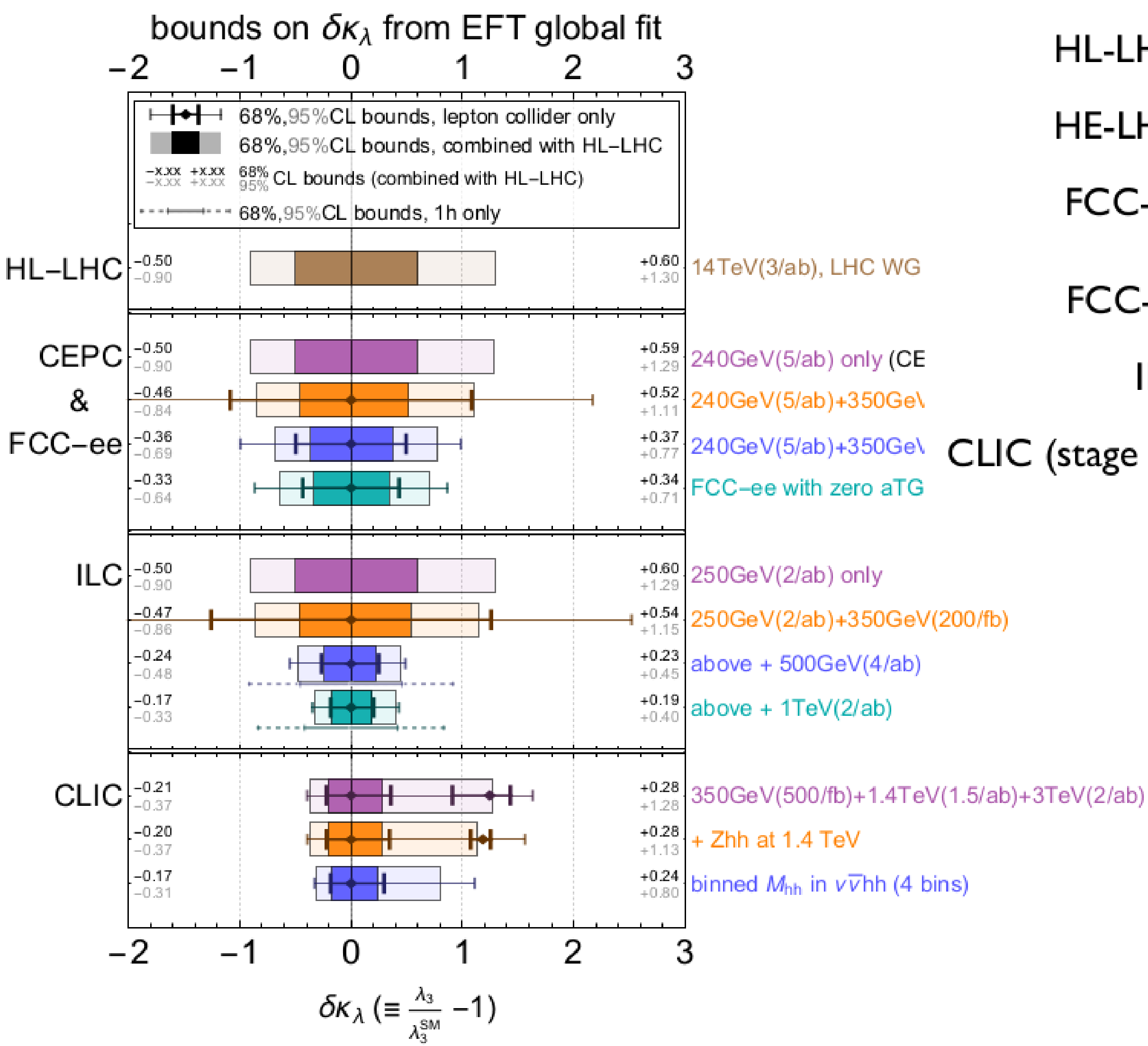
- Tau decay modes might be accessible at Fcc-ee?
  - Bs $\rightarrow \tau\tau$ or B $\rightarrow K\tau\tau$
  - The B flavor anomalies make this very interesting
  - B $\rightarrow K\tau\tau$ with 3-prong tau decays allows 4 vertex positions and thus full mass reconstruction
    - O(100) events seen with Fcc-ee?
    - DD background in LHCb
  - Belle-II/LHCb fail here?
- B to K$\nu\nu$ Fcc-ee can look for MET+K – promising
- $B_c \rightarrow \tau\nu$ also promising

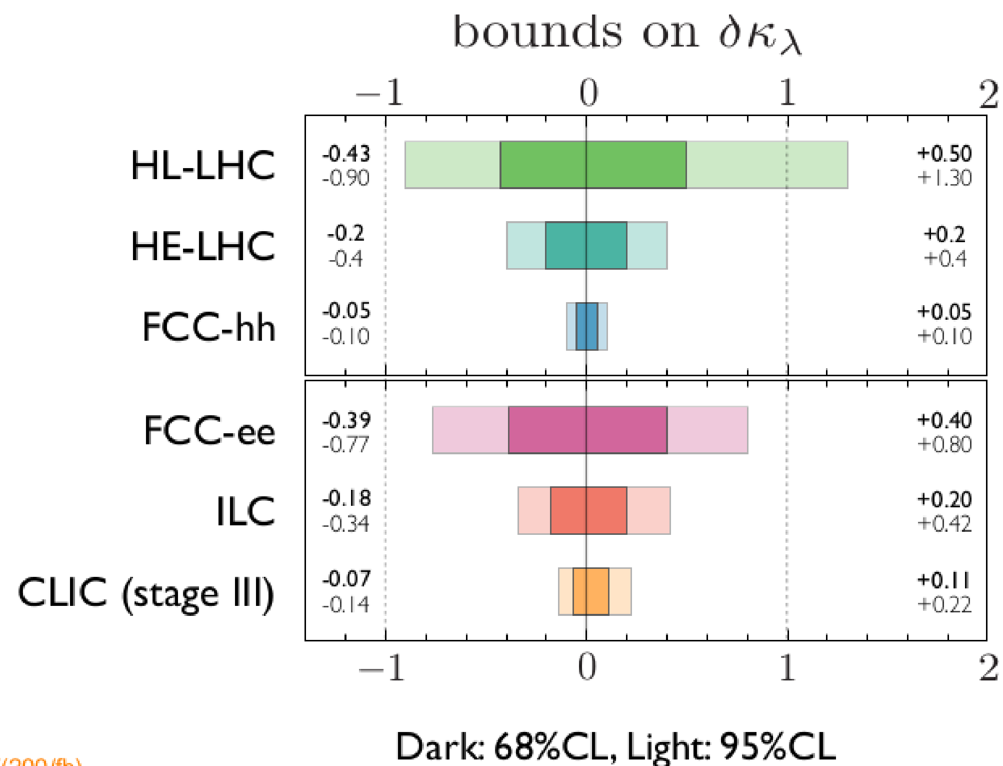


h³ prospects

Grojean

DiVita et al, arXiv: 1711.03978
(updated with latest HL-LHC) projections





ee colliders
will establish at 95%CL that the Higgs self-coupling exists
ILC will establish it at 5σ
FCC-hh will probe the quantum corrections of the Higgs potential

Higgs mass and width

- Higgs mass in 4-lepton from will improve
  - ATLAS currently 240 MeV error
  - 52 MeV if no improvements made
  - 47 MeV if ITk yields 30% resolution improvement
  - 33-38 MeV If also scale uncertainty reduced 50-80%
  - *No current theory need for better*
- $H \rightarrow \gamma\gamma$ systematics more important
- Width from off-shell couplings
  - CMS project range 2-6 MeV @95%CL
    - S1/S2 similar here
    - Statistics are important