Higgs physics at the FCC

ICHEP'16

Chicago, 3th–10th August 2016

David d'Enterria
(on behalf of FCC-ee,hh study group)
CERN

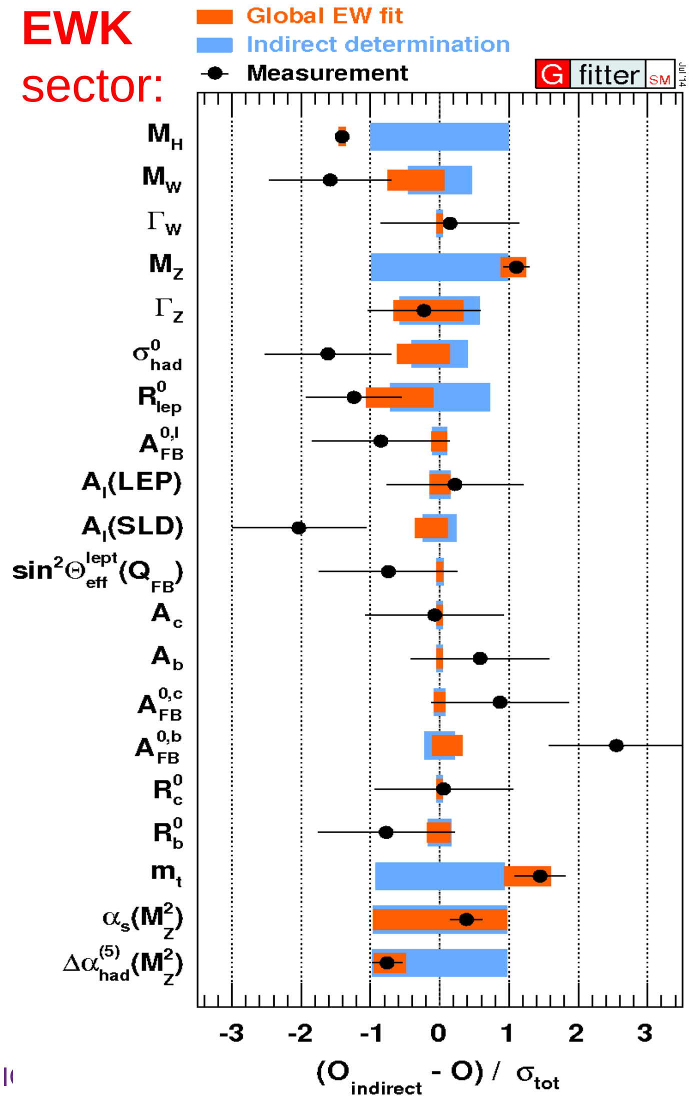
Standard Model of particles & interactions

- Renormalizable QFT of electroweak $SU(2)_L \times U(1)_Y$ & strong $SU(3)_c$ gauge interactions

  O(20) parameters: Couplings, H mass&vev, H-f Yukawa, CKM mix., CP phases.

  Experimentally confirmed to great precision for over 40(!) years:

EWK sector:



$$
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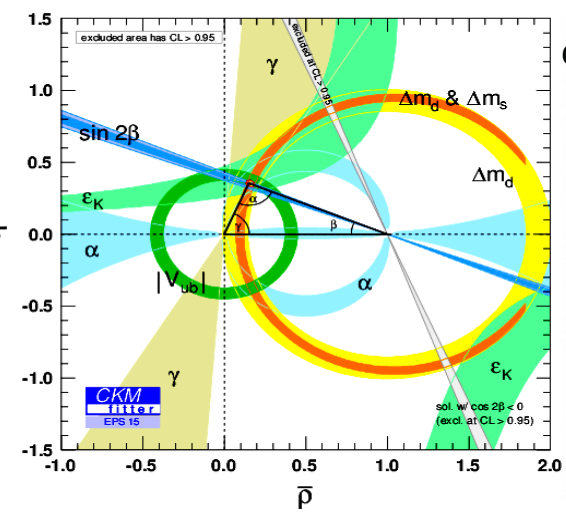
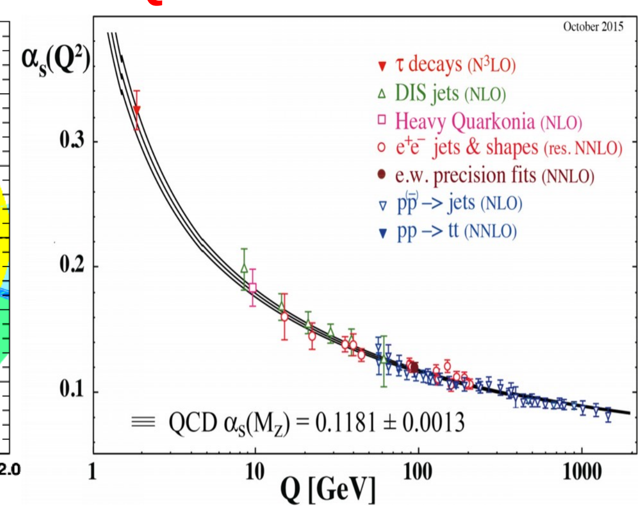
Flavour sector:



QCD sector:



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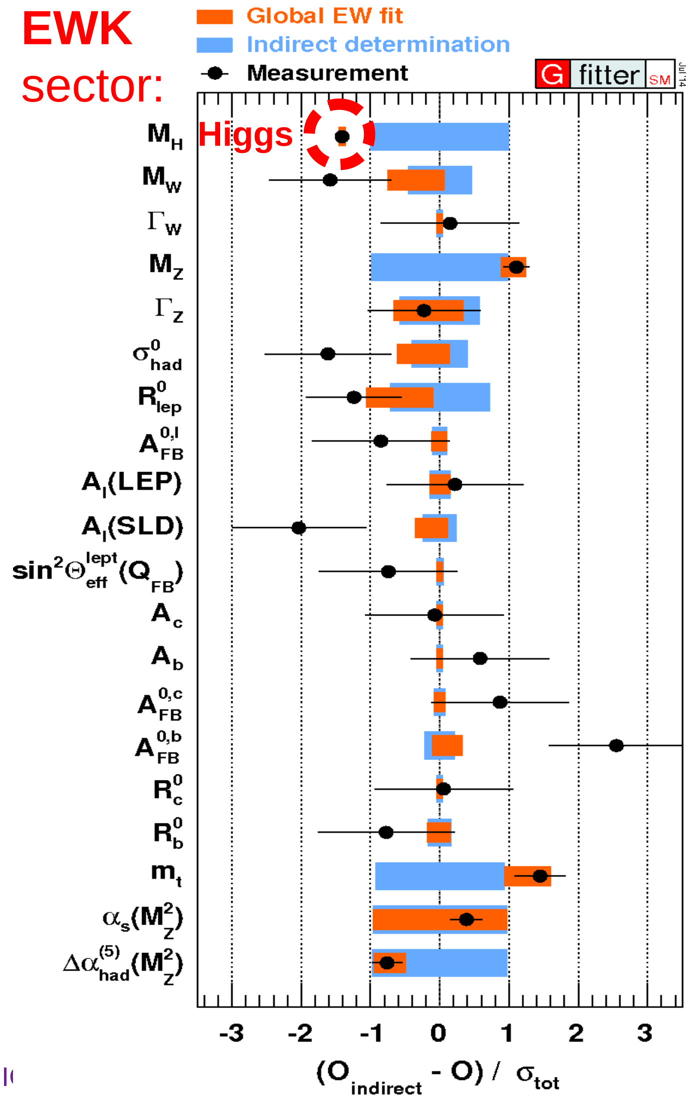

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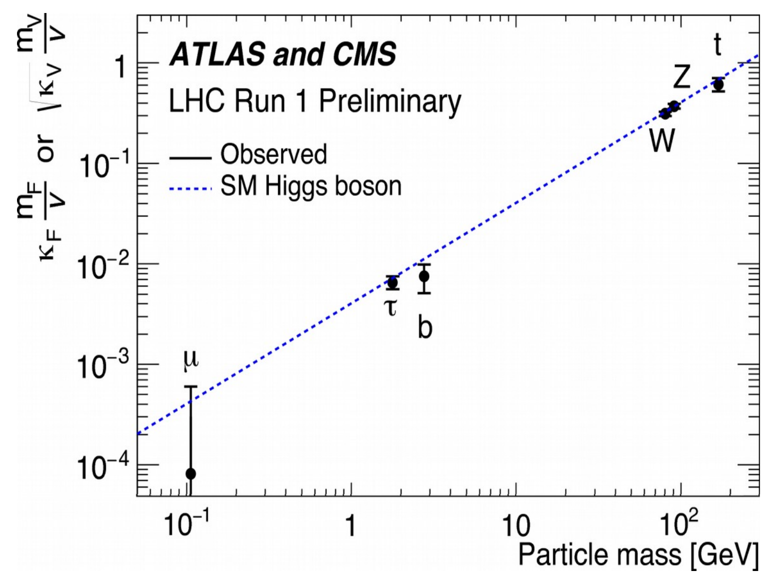
Higgs sector:



Open questions in the SM (1)

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- ✘ Light masses: Higgs mechanism for lightest fermions (u,d,s,e,ν's) to be proven
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- ✘ Fine-tuning: Higgs mass virtual corrections «untamed» up to Planck scale

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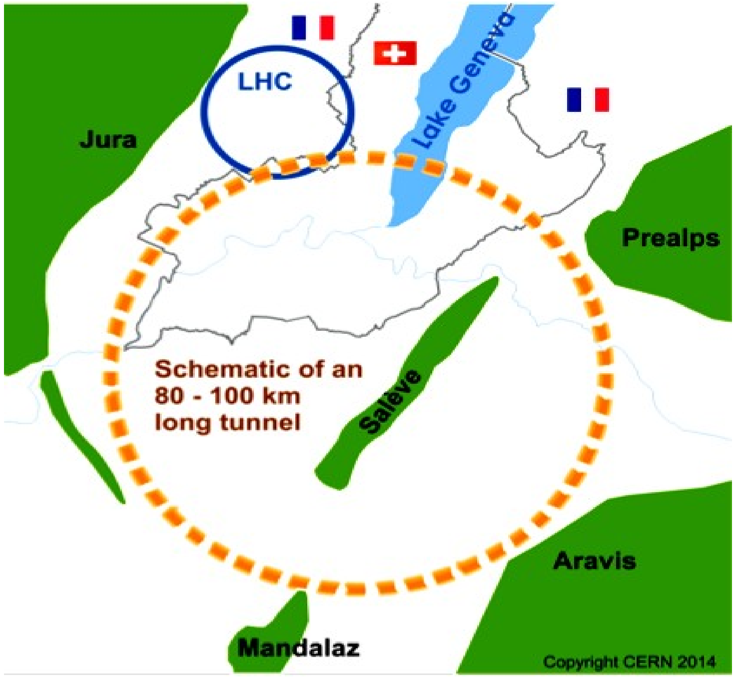
Some/Most(?) of these questions will not be fully answered at the LHC

CERN Future Circular Collider (FCC) project

- Solving those & others HEP open problems requires higher-energy collider:

- 100 km ring, Nb_3Sn 16 T magnets, LHC used as injector:
  - pp at $\sqrt{s}$=100 TeV, L~2x10^{35}, L_{int}=2 ab^{-1}/yr
  - e^+e^- option (before pp) at $\sqrt{s}$=90–350 GeV L~10^{35}–4·10^{36}, L_{int}=1–40 ab^{-1}/yr for H, Z
  - e-h collider option at $\sqrt{s}$=3.5 TeV, L~10^{34}



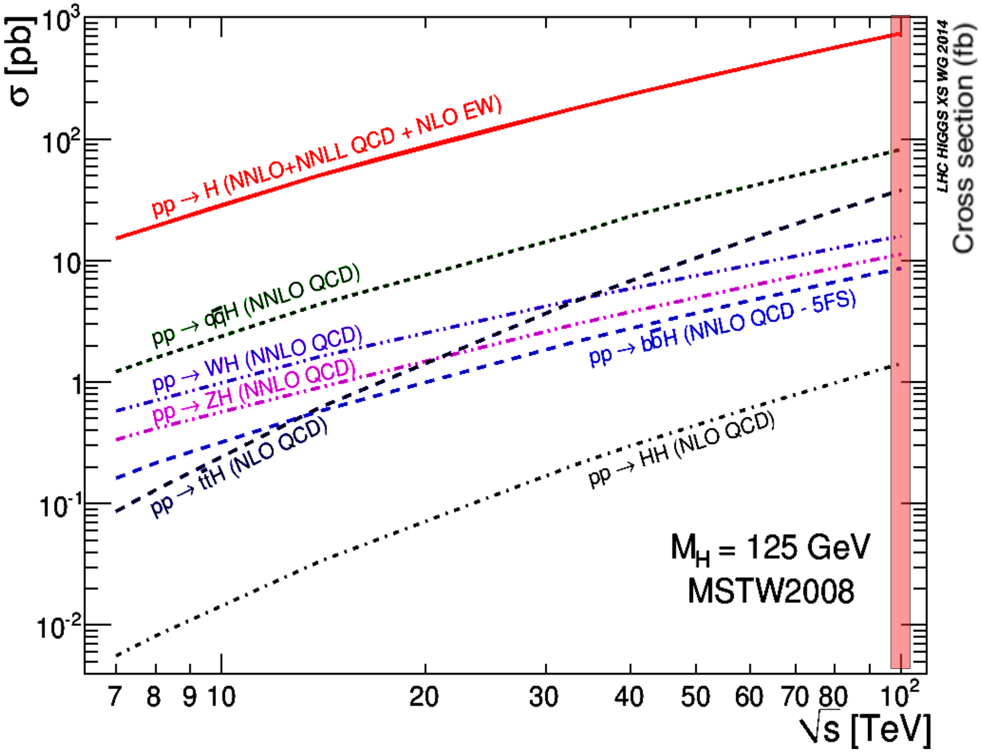
[Talk mostly focused on FCC-ee.
See M.Mangano: FCC-pp, B.Mellado: FCC-eh]

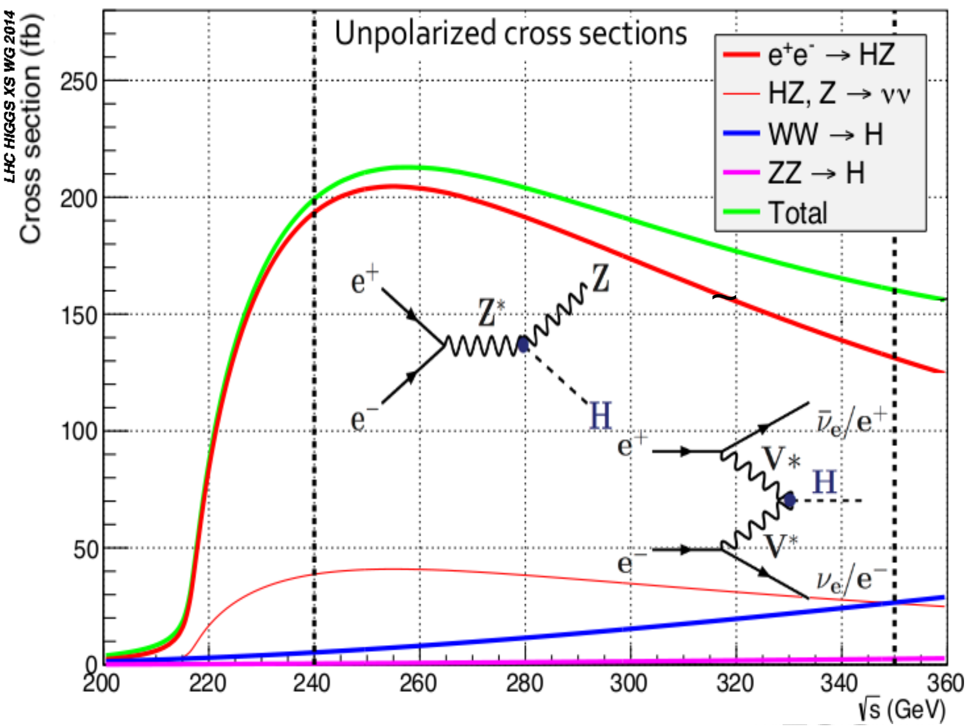
Higgs physics at FCC-pp & FCC-ee

- Huge number of Higgs expected: $2\cdot10^{10}$ (FCC-pp), $2\cdot10^{6}$ (FCC-ee)

$\sigma(pp\to H+X) \approx 0.9$ nb (ttH/HH/HHH access)

$\sigma(e^+e^-\to H+X)\approx200$ fb (low bckgd, no pileup)



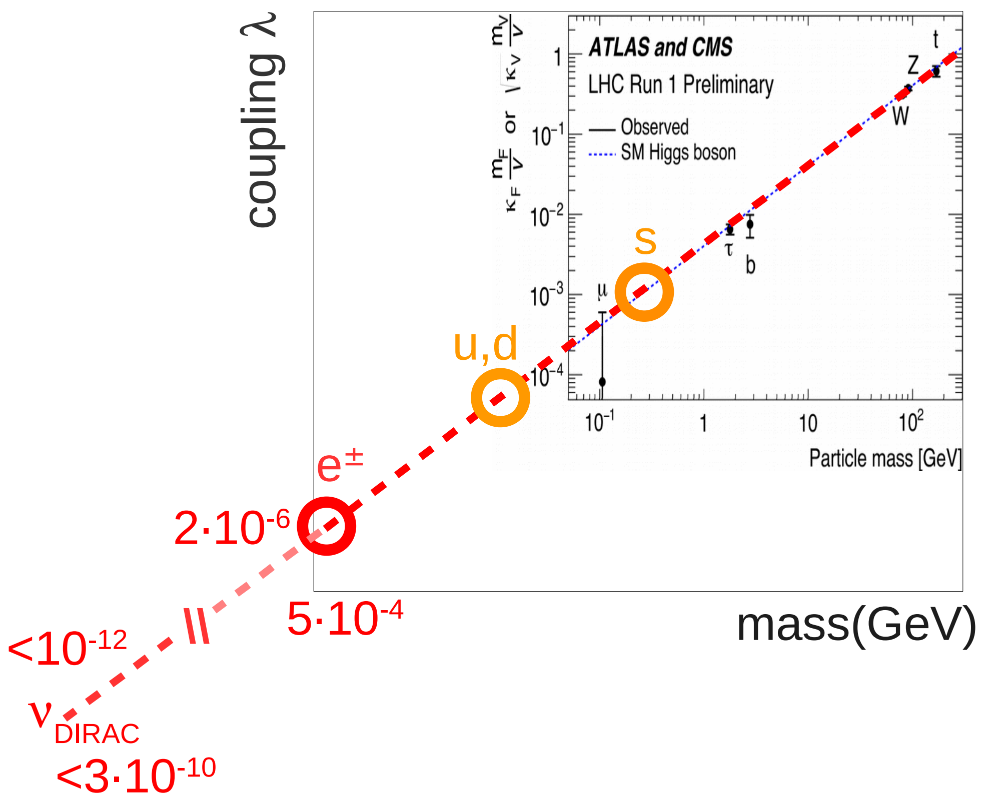


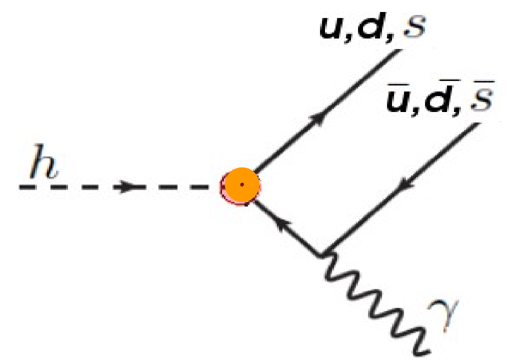
	gg→H	VBF	WH	ZH	ttH	HH
σ_{100} [pb]	802	69	16	11	32	1.9
σ_{100}/σ_{14}	x17	x16	x10	x11	x52	x40

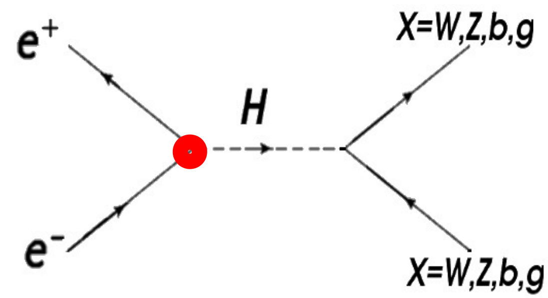
Total Integrated Luminosity (ab^{-1})	10
Number of Higgs bosons from $e^+e^- \to HZ$	2,000,000
Number of Higgs bosons from boson fusion	50,000

- Access to precision (<1%) Higgs couplings, and rare & BSM decays

Open issue in the SM (1): Generation of lightest fermion masses (u,d, e,ν's)

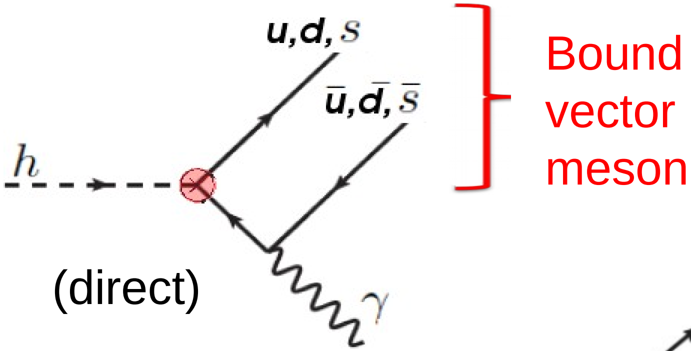






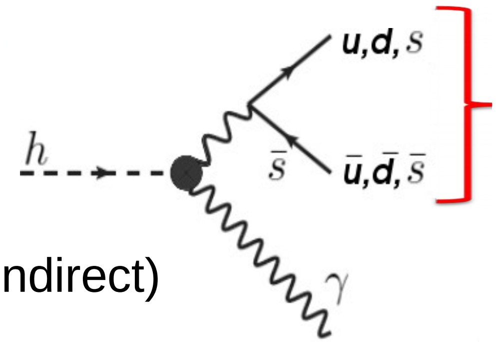
1^{st}-gen. quark Yukawa couplings at FCC-ee

- 1^{st} & 2^{nd} gen. quark Yukawa accessible via exclusive H→Vγ , V=ρ,ω,ϕ



(direct)

Interferes with:



(indirect)

[G. Perez et al, arXiv:1505.06689]

Mode	Branching Fraction $[10^{-6}]$	
Method	LCDA LO [170]	LCDA NLO [173]
$\mathrm{Br}(H \to \rho^0 \gamma)$	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(H \to \omega \gamma)$	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(H \to \phi \gamma)$	3.00 ± 0.13	2.31 ± 0.11

- H→ρ(ππ)γ channel most promising: N~40 counts expected, low backgds
- Sensitivity to u/d quark Yukawa couplings:

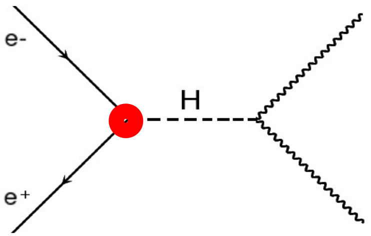
$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2} \times 10^{-5}$$

$(k_q = y_q/y_b)$

- All channels accessible with higher stats at FCC-pp. But much worse backgrounds (QCD and pileup).

$e^{\pm}$ Yukawa coupling at FCC-ee(125)

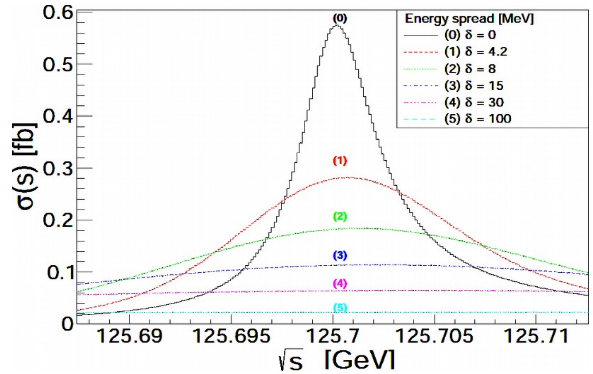
- Resonant s-channel Higgs production at $\sqrt{s}$ = 125 GeV has tiny x-sections:



$\sigma(e^+e^-\rightarrow H)_{\text{Breit-Wigner}}$ = 1.64 fb

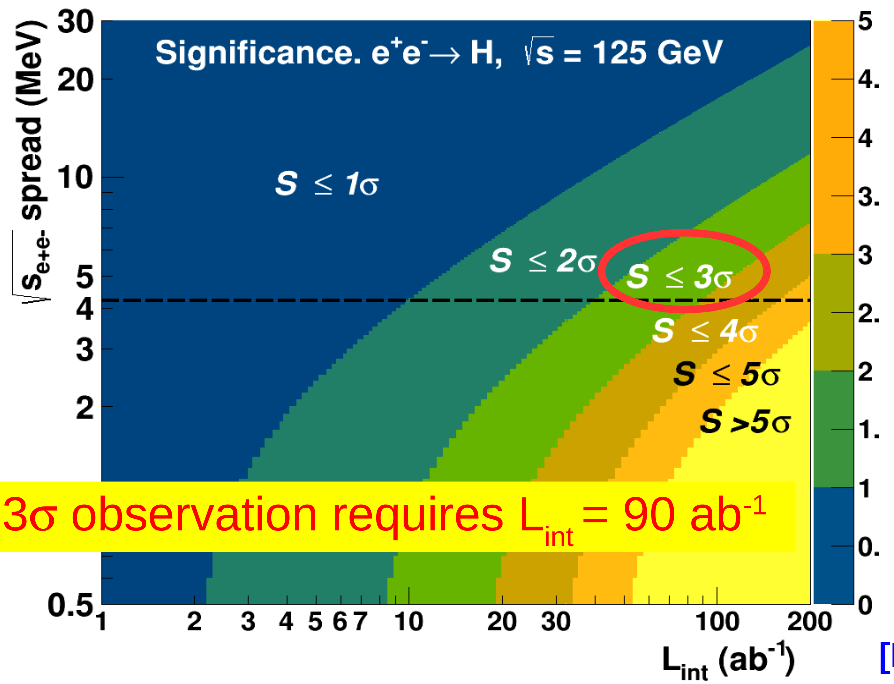
$\sigma(e^+e^-\rightarrow H)_{\text{visible}}$ = 290 ab

(incl. ISR + $\sqrt{s}_{\text{spread}} = \Gamma_H$ = 4.2 MeV)

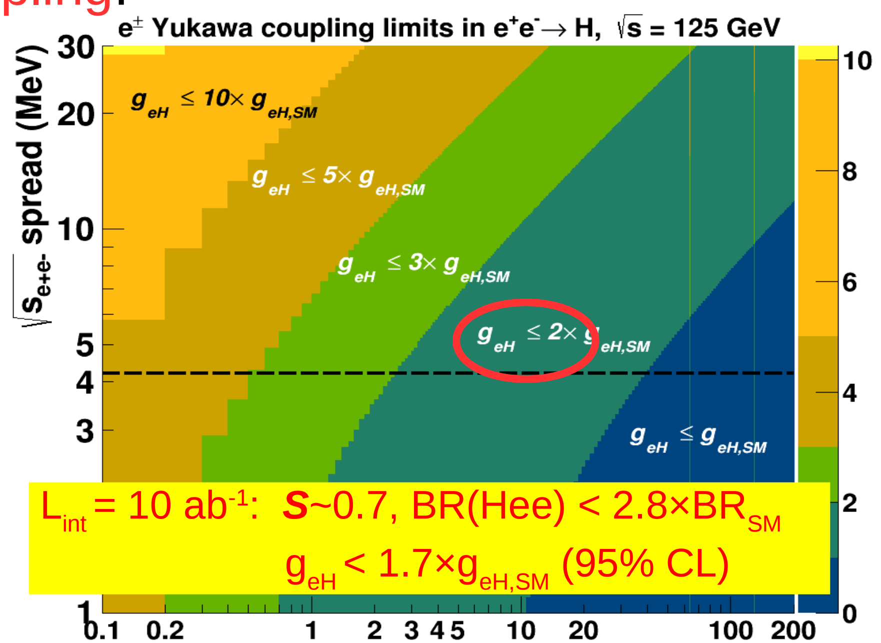


Mono-chromatization required to achieve $\sqrt{s}_{\text{spread}} \approx \Gamma_H$

- Preliminary study for signal + backgrounds in 10 Higgs decay channels.
- Significance & limits on e-Yukawa coupling:



3σ observation requires L_{int} = 90 ab^{-1}



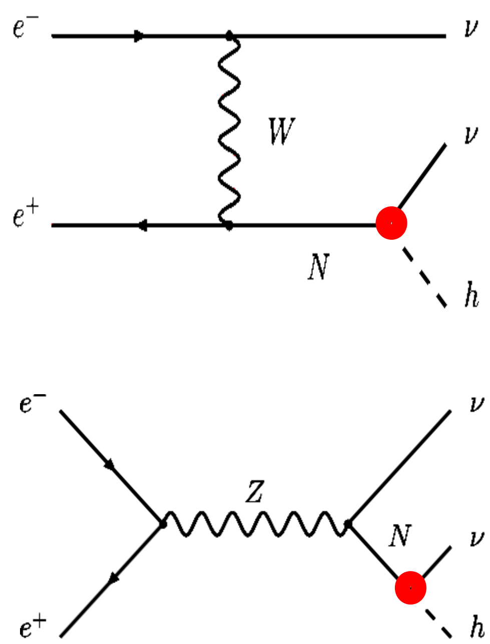
L_{int} = 10 ab^{-1}: ***S***~0.7, BR(Hee) < 2.8×BR_{SM}

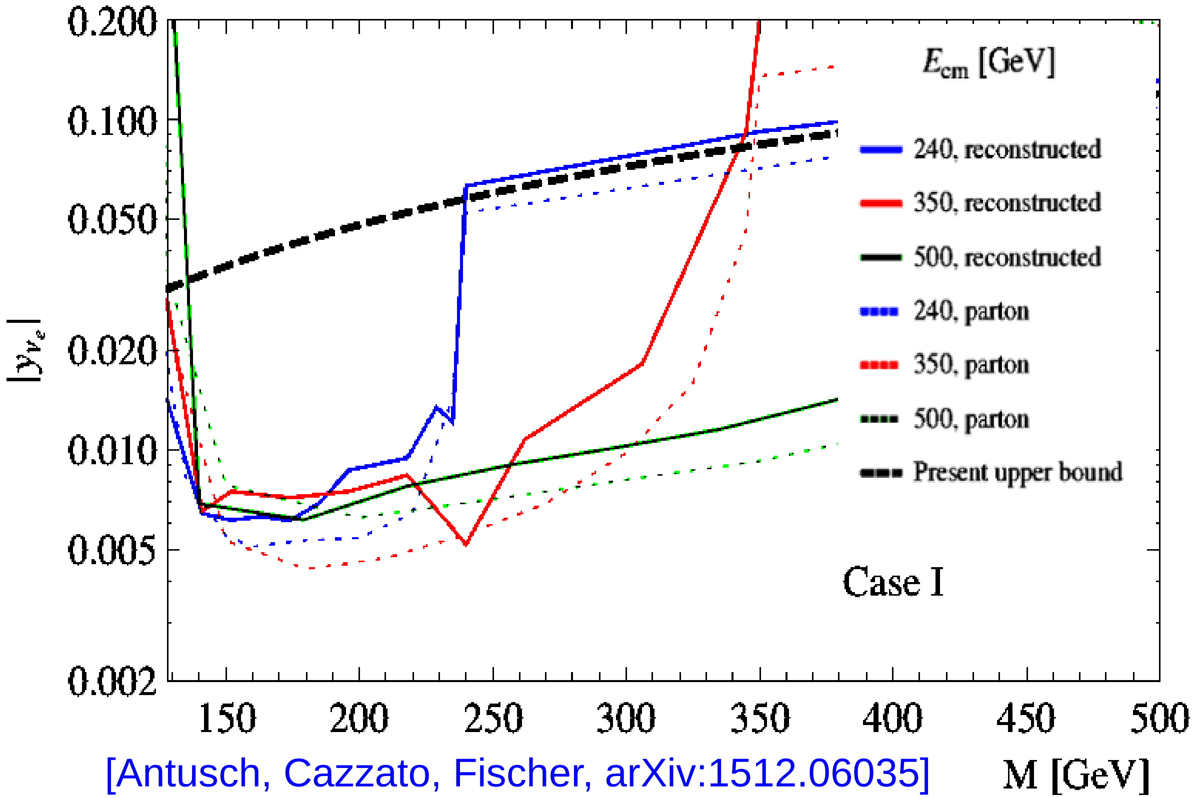
$g_{eH} < 1.7 \times g_{eH,SM}$ (95% CL)

[D.d'E., Wojcik, Aleksan]

Higgs couplings to heavy-neutrinos at FCC-ee

- Consider (symmetry-protected) seesaw scenario with 2 sterile ν (N_i): large neutrino Yukawa couplings & masses: $y_\nu \approx 10^{-3}$, $m_N \approx 10^2$ GeV
- N_i decay to Higgs+ν. Signature: mono-Higgs(jj) plus missing energy



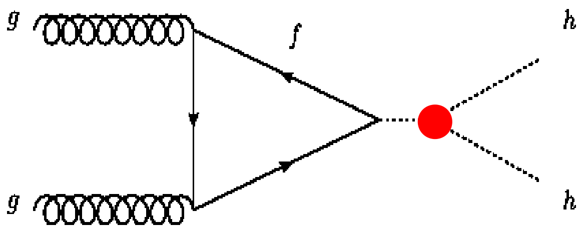


[Antusch, Cazzato, Fischer, arXiv:1512.06035]

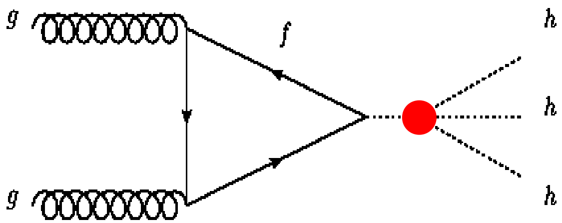
- FCC-ee sensitivity down to $|y_{\nu e}|\sim 5 \times 10^{-3}$ for unexplored $m_N \sim 100$–300 GeV

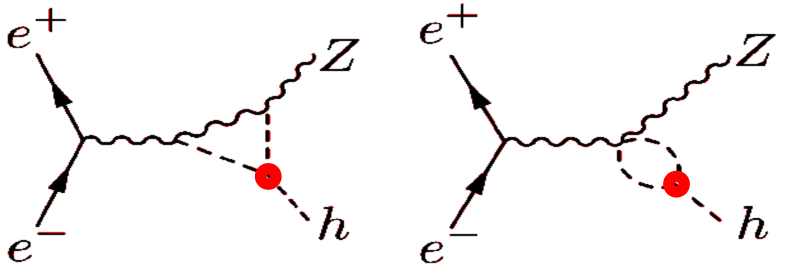
Open issue in the SM (2): Higgs potential (triple & quartic self-couplings)

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



(direct, pp at √s=100 TeV)



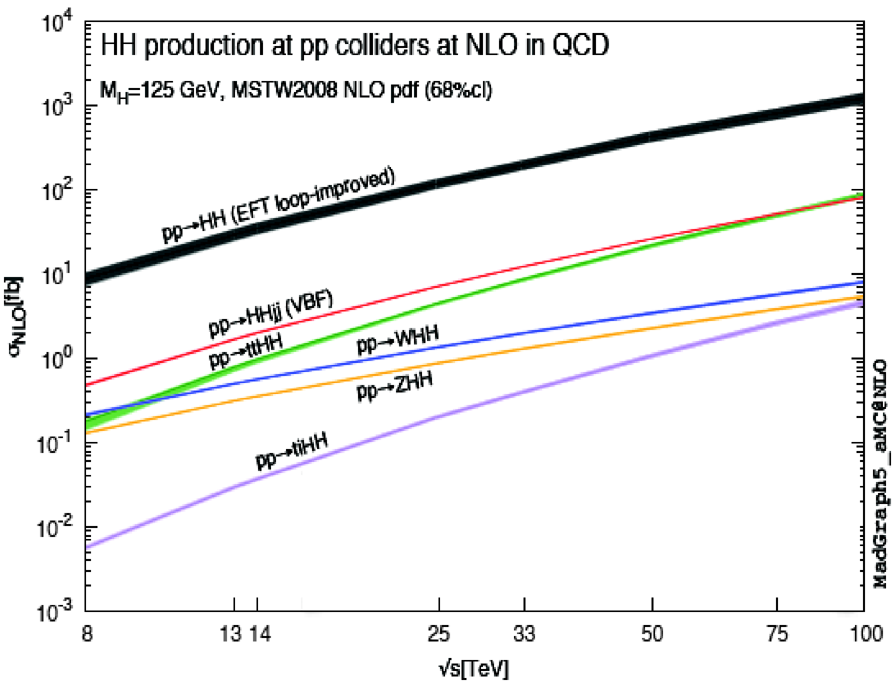


(indirect, e^+e^- at √s=240–350 GeV)

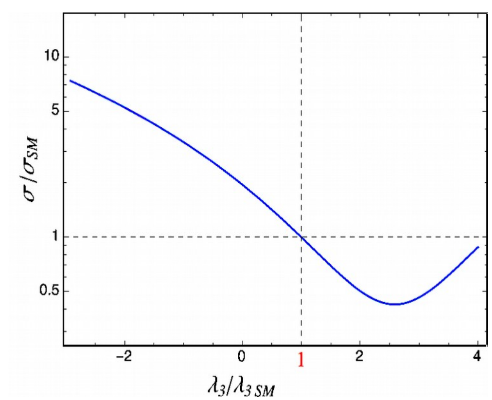
Higgs self-couplings (λ_3,λ_4) at FCC-pp

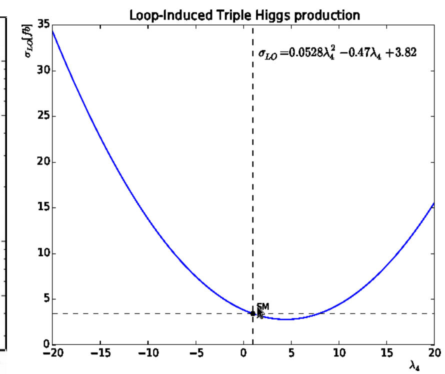
[R. Contino et al., arXiv:1606.09408]

- Double (triple) Higgs cross section ≈ 1.9 pb (5 fb)



But various diagrams contribute to σ_{HH},σ_{HHH}: ~diluted sensitivity to λ_3, λ_4





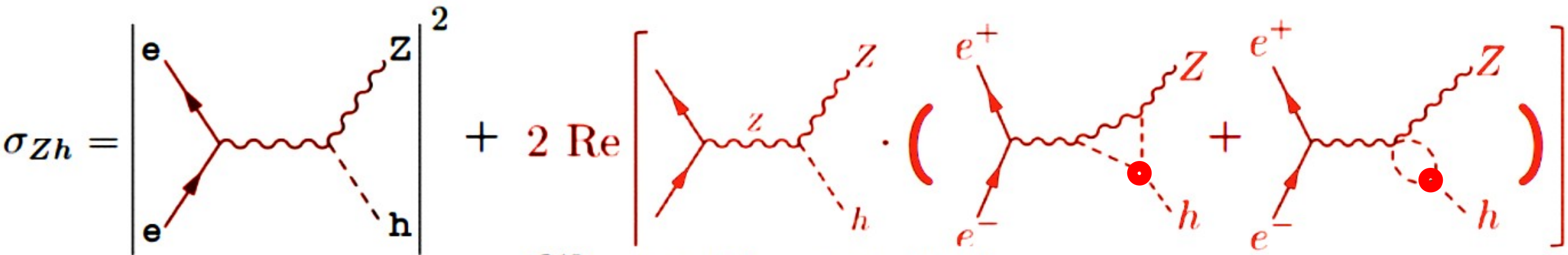
process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH\to b\bar{b}\gamma\gamma$	3%	$\lambda_3\in[0.97,1.03]$
$HH\to b\bar{b}b\bar{b}$	5%	$\lambda_3\in[0.9,1.5]$
$HH\to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3\in[0.6,1.4]$
$HH\to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3\in[0.8,1.2]$
$HH\to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH\to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4\in[-4,+16]$

- bb(bb)ɣɣ most sensitive channel:
  Critical flavor-tagging performances.

- Precisions on coupling:
  Trilinear (g_{HH})~3–4%
  Quartic (g_{HHH}) mildly constrained

Higgs self-coupling at FCC-ee

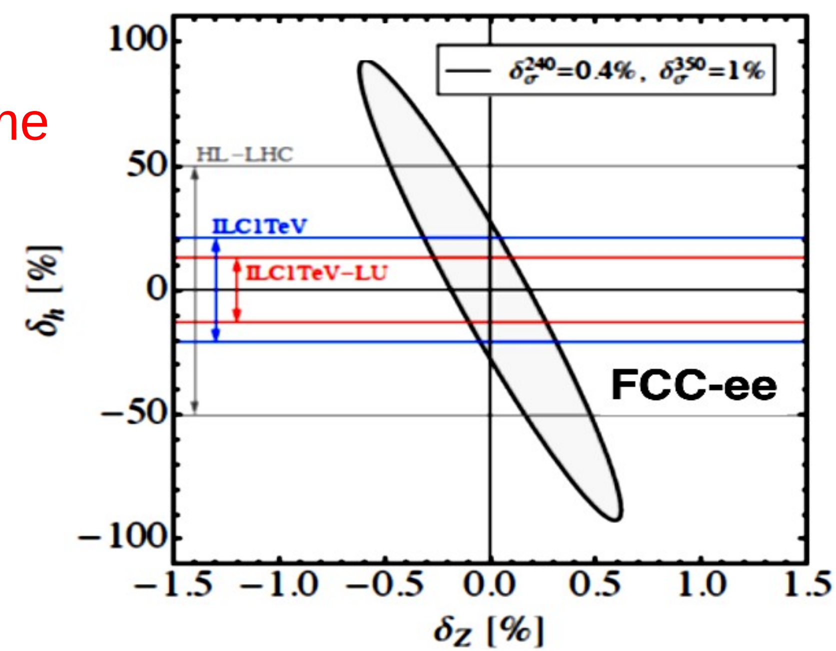
- Higgs self-coupling indirectly through loop corrections to σ(H+Z):



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

Self-coupling correction δ_h: energy-dependent
δ_Z: energy-independent (distinguishable).

[M. McCullough, 2014]



- Tiny effect, but visible thanks to extreme precision on σ_{ZH} (0.4%) coupling reachable at FCC-ee.

- Indirect and model-dependent limits on trilinear Higgs coupling can be set (~70% level) comparable to HL-LHC

Open issue in the SM (3): Hierarchy/Naturalness (BSM scalar-coupled physics)

- Solved via many BSM realizations: SUSY, little-H, hidden sectors,...
- Parametrize (B)SM as an Effective Theory:

$$\mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad\qquad [\mathcal{O}_i] = d$$

- Indirect (loop) constraints on new physics coupled to Higgs:

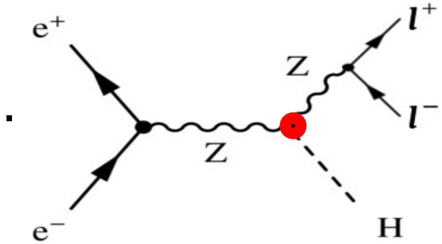
$$\Lambda \gtrsim (1\,\mathrm{TeV})/\sqrt{(\delta g_{\rm HXX}/g^{\rm SM}_{\rm HXX})/5\%}$$

~5% deviations of Higgs couplings wrt. SM: Λ >1 TeV

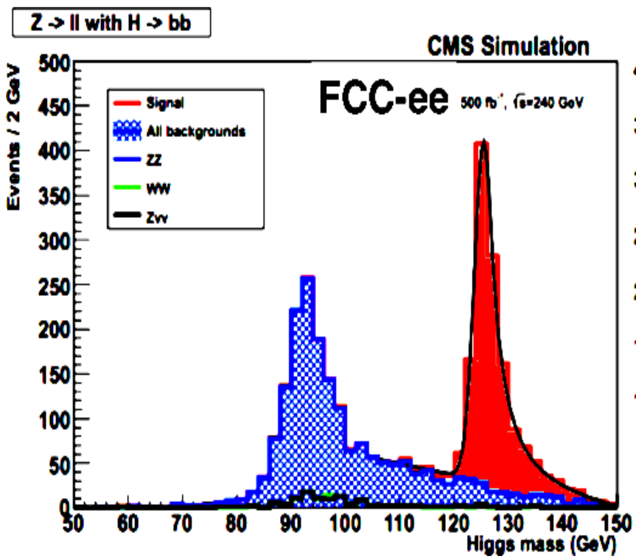
~0.1% Higgs couplings precision (~10^6 Higgs) ⇒ Λ>7 TeV

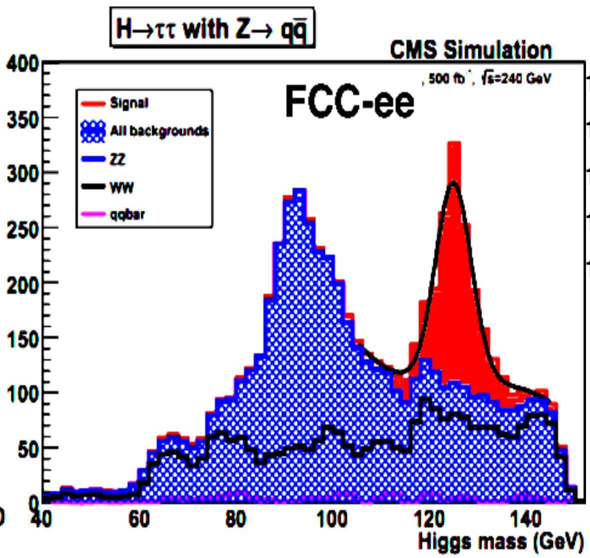
Precision H couplings, width, mass at FCC-ee

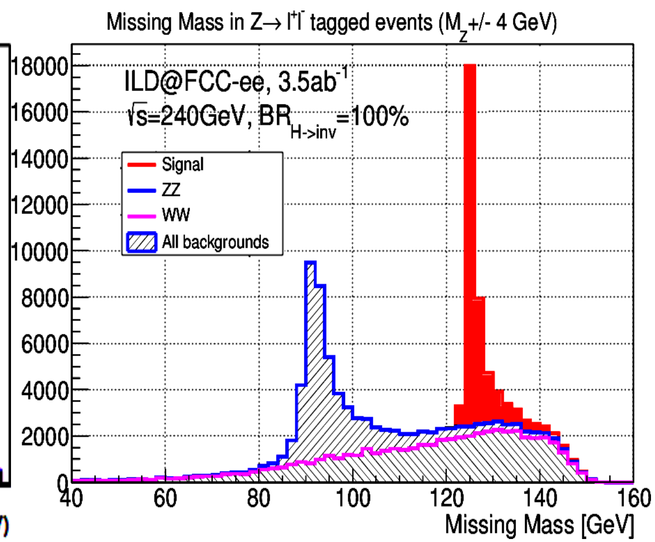
- Recoil method in H-Z unique to lepton collider: reconstruct H 4-mom. independent of H decay mode.
- High-precision (0.4%) σ_{ZH} provides model-indep. value of g_Z coupling: $\sigma(ee\rightarrow ZH) \propto g_Z^2$



$$m^2_{\rm recoil} = (\sqrt{s} - E_{f\bar{f}})^2 - p^2_{f\bar{f}}$$







- Total width (Γ_H) with ~1% precision from combination of measurements: $\sigma(ee\rightarrow ZH(\rightarrow X)) \propto \Gamma_{H\rightarrow X}$, plus known BR ($H\rightarrow X$): Obtain Γ_H
- Branching fraction to invisible can be tested directly to 0.2% @ 95% CL
- Higgs mass (m_H) from recoil mass in $Z\rightarrow\mu\mu$,ee.

Precision H couplings, width, mass at FCC-ee

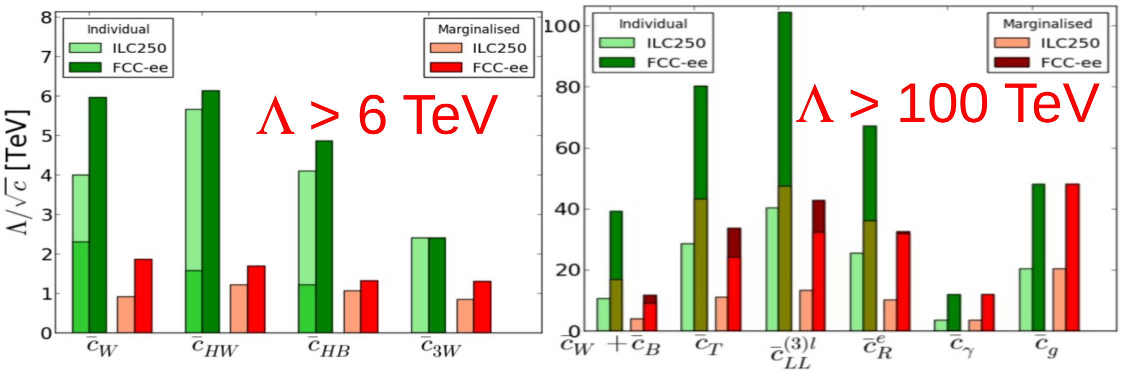
- e^+e^- colliders provide factor >10 improvement in precision w.r.t. HL-LHC.
- FCC-ee has typically highest precision:

	ILC	FCC-ee	CEPC	CLIC
$\sigma(ZH)$	0.7%	0.4%	0.51%	1.65%
g_{bb}	0.7%	0.42%	0.57%	0.9%
g_{cc}	1.2%	0.71%	2.3%	1.9%
g_{gg}	1.0%	0.80%	1.7%	1.4%
g_{WW}	0.42%	0.19%	1.6%	0.9%
$g_{\tau\tau}$	0.9%	0.54%	1.3%	1.4%
$g_{\mu\mu}$	9.2%	6.2%	17%	7.8%
g_{inv}	<0.29%	<0.45%	<0.28%	<0.97%
Δm_H (MeV)	15	11	5.9	44
Γ_H	1.8%	1%	2.8%	3.6%

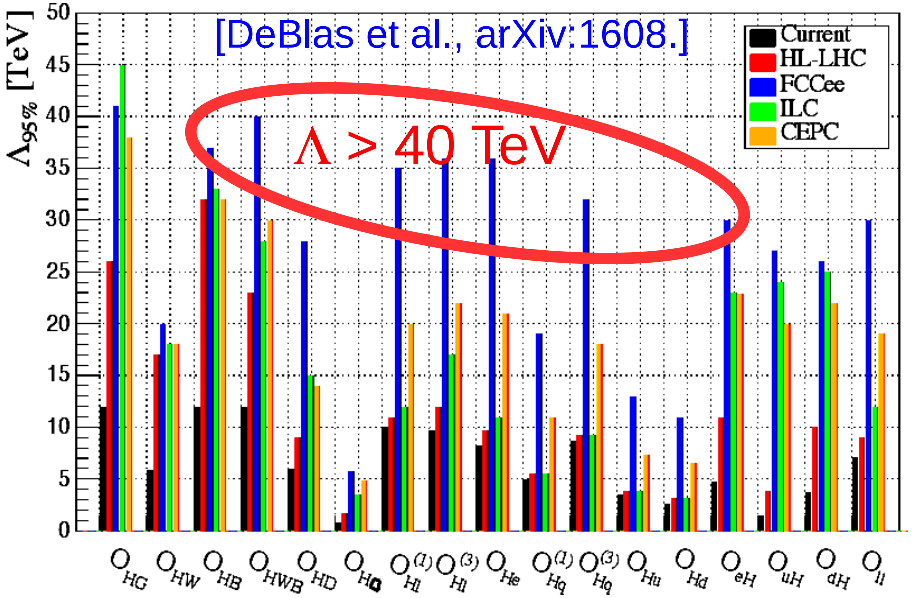
- Most precise (g_Z) ~0.1% coupling sets limit on new scalar-coupled physics at: $\Lambda \gtrsim (1\,\mathrm{TeV})/\sqrt{(\delta g_{HXX}/g^{SM}_{HXX})/5\%}$ >7 TeV

Precision H properties: BSM bounds

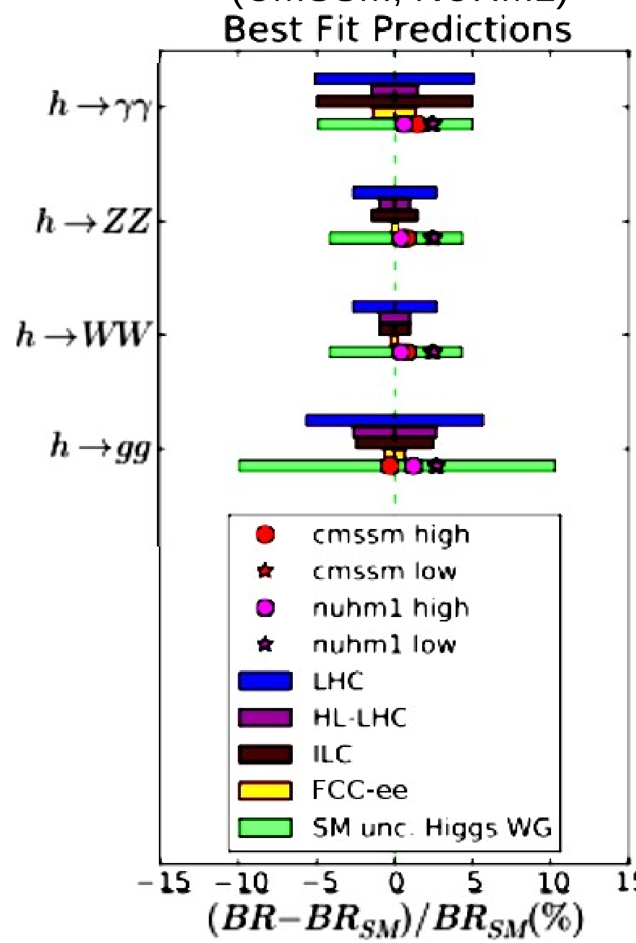
- FCC-ee precision measurem. improve greatly scalar-coupled BSM limits.
- NP bounds: Higgs & Higgs+EWPO combined



[J.Ellis and T.You, arXiv:1510:04561]

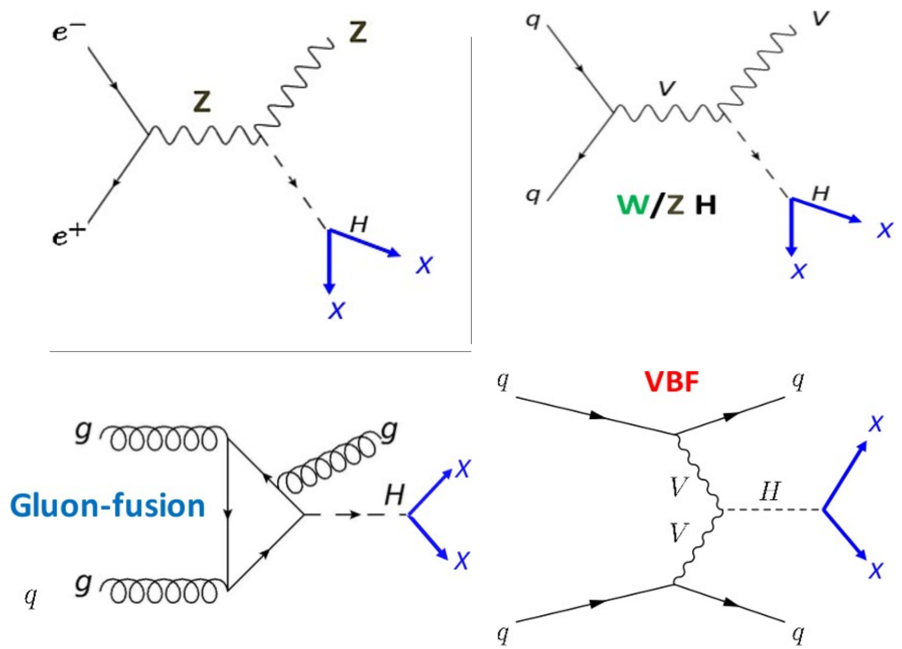


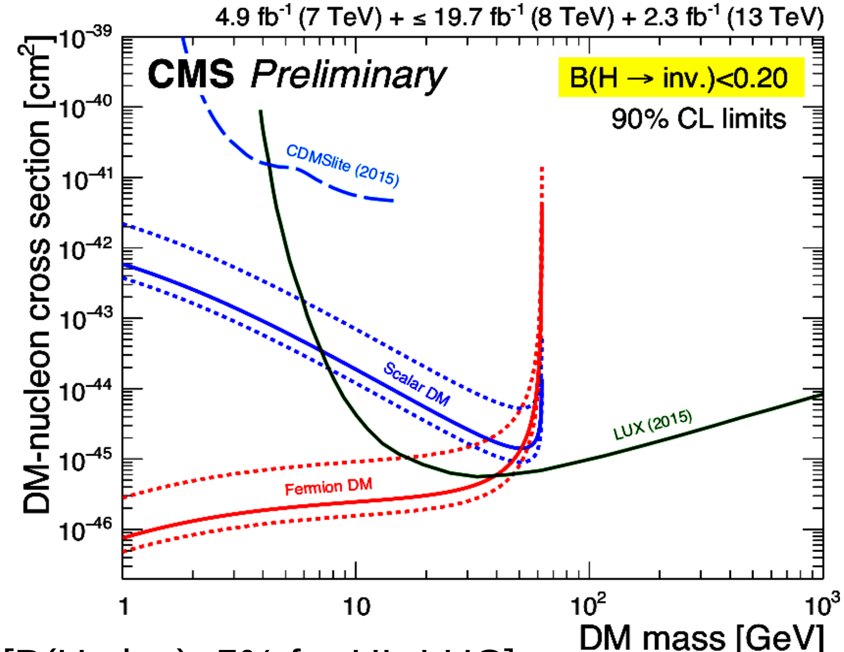
Benchmark SUSY models
(CMSSM, NUHM1)



[arXiv:1308.6176]

Open issue in the SM (4): Dark matter (Higgs-portal)

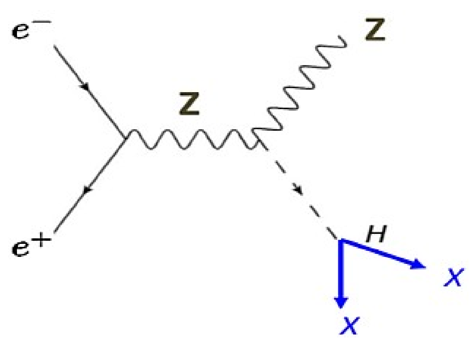


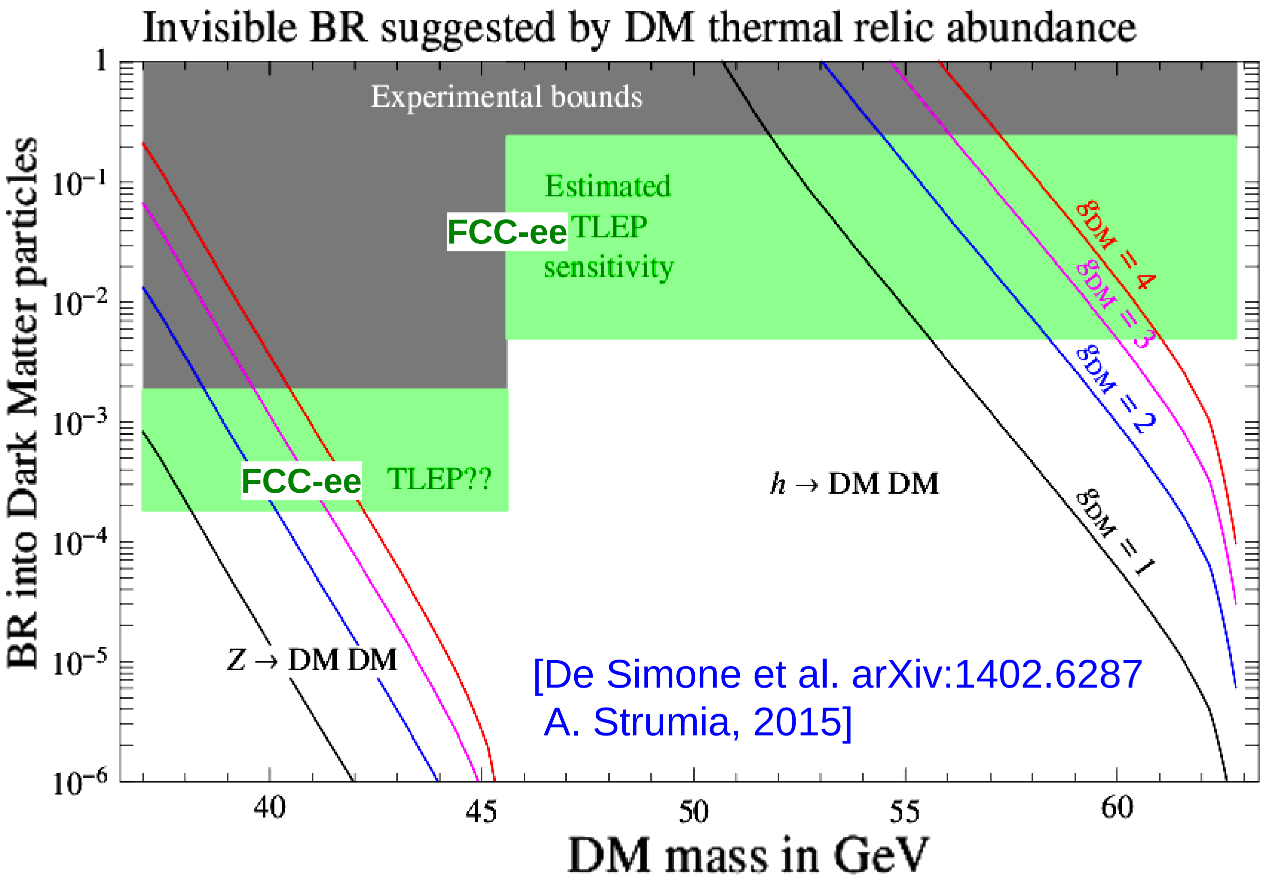


[B(H→inv)>5% for HL-LHC]

Dark Matter ($m_{DM}<m_H/2$) via H decays at FCC-ee

- DM freeze-out fixes σv ≈ 3 10^{-26}cm³/s. If m_{DM} is just below $m_{Z,H}/2$, DM freeze-out dominated by resonant Z,H exchange, fixing $\Gamma_{Z,H}$.

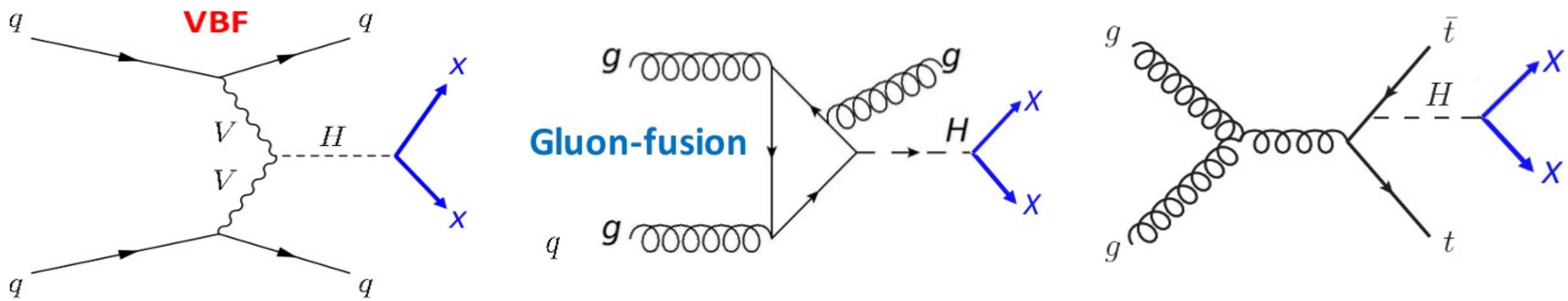




- <10^{-3} and <10^{-1} precision measurements of invisible Z & H widths are best collider option to test any $m_{DM}<m_{Z,H}/2$ that couples via SM mediators.

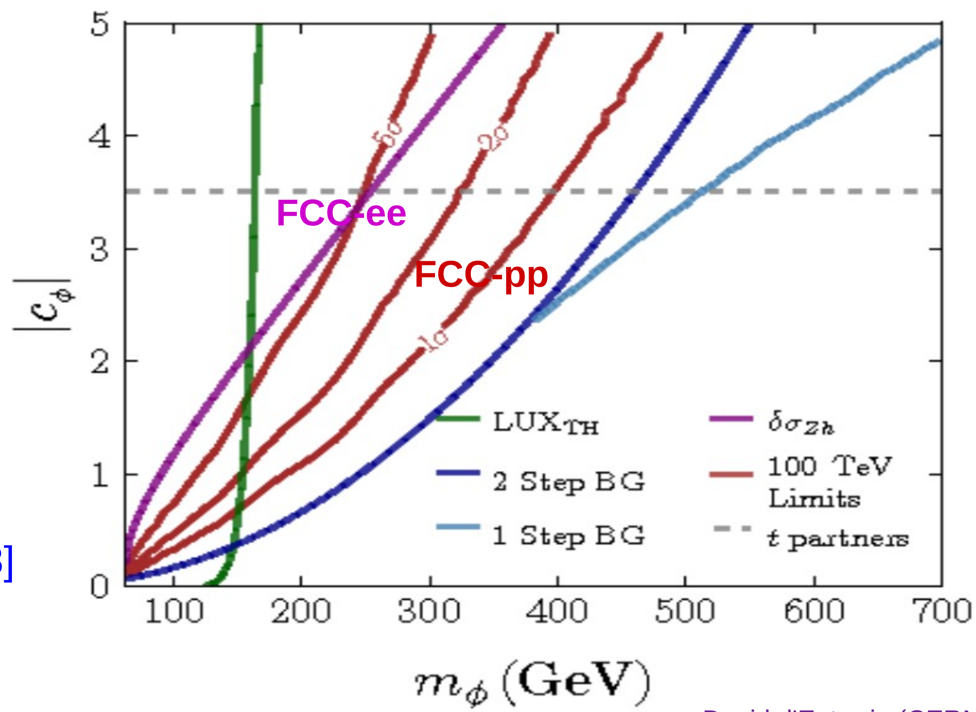
Dark Matter (m_{DM}>m_H) via offshell H at FCC-pp

- If DM heavier than Higgs, offshell H decays into DM, can be tagged with extra associated production: jet, VBF-jets, ttbar,... like at LHC:



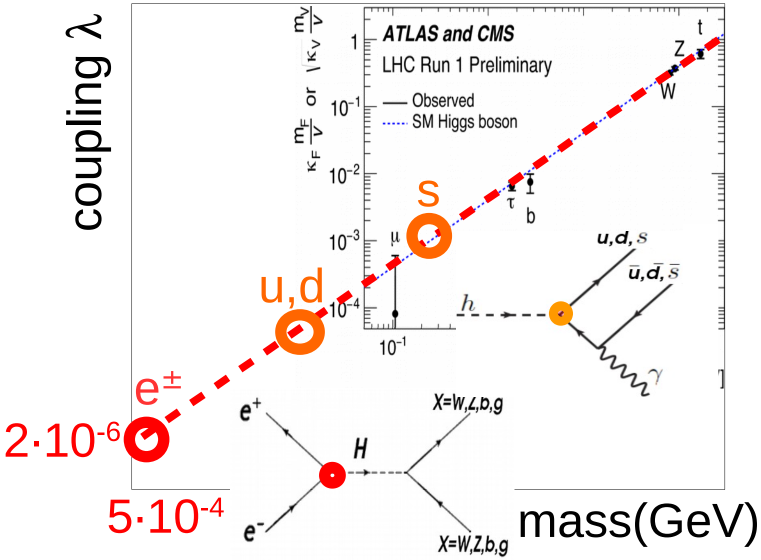
- Strong constraints on the Higgs portal coupling $|c_\phi|$ for unexplored DM masses M_{DM}~ 150–500 GeV:

[N. Craig et al. arXiv:1412.0258]



Summary

- FCC provides unparalleled luminosities O(1–20 ab^{-1}) in pp at √s=100 TeV & e+e- at √s=125–350 GeV for high-precision Higgs studies (<1% uncert.) fully closing SM ($g_{1st\text{-}gen}$,$\lambda_{3,4}$) & constraining scalar-coupled BSM to multi-TeV



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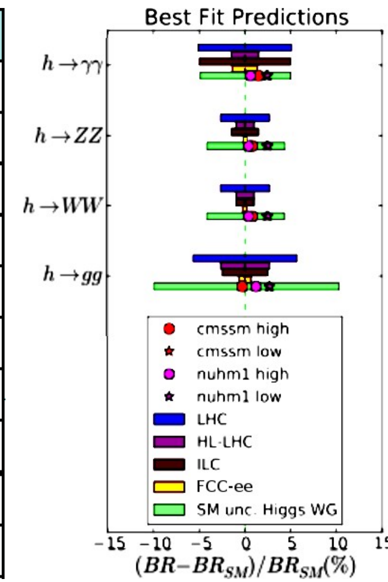
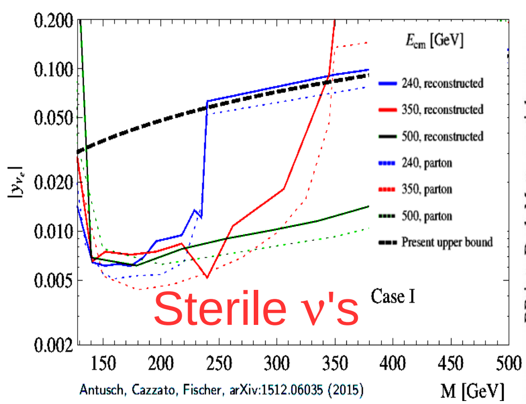
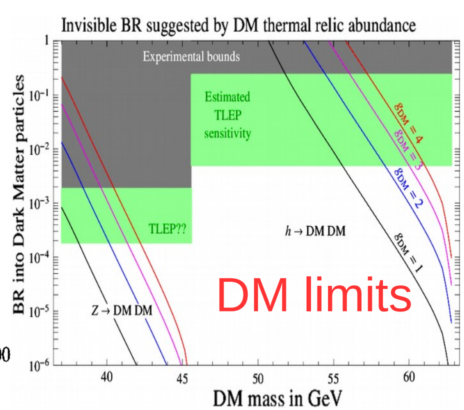
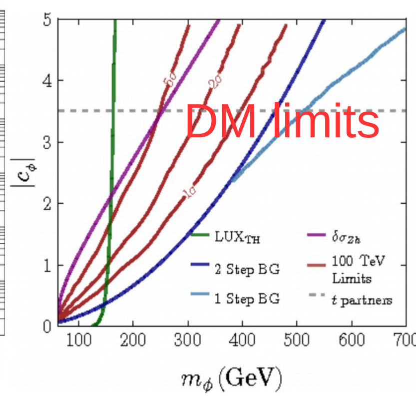
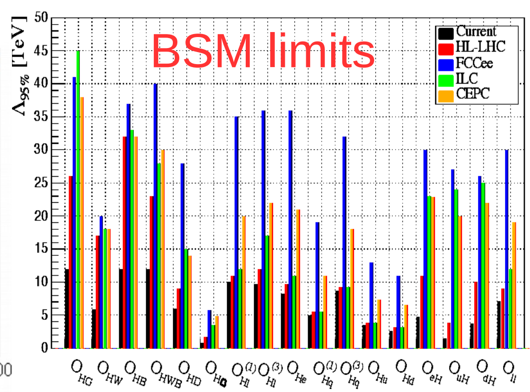










Backup slides

ee→H significance: Multi-Channel Combination

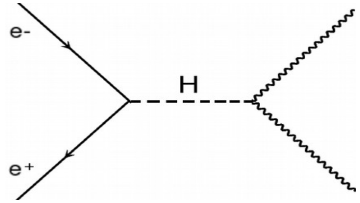
- Channels combination using Roostats-based tool for LHC Higgs analyses: Profile likelihood & hybrid significances all give ~identical results, which are also very close to naive S/√B expectation (no background uncertainty).

Channel	Significance (1 ab^{-1})	Significance (10 ab^{-1})
$WW\to l\nu 2j, 2l2\nu, 4j$	$0.15\oplus0.09\oplus0.03$	$0.50\oplus0.30\oplus0.08$
$ZZ\to 2j2\nu, 2l2j, 2l2\nu$	$0.07\oplus0.05\oplus0.01$	$0.21\oplus0.16\oplus0.03$
bb	0.03	0.10
gg	0.03	0.09
$\tau\tau$	–	0.02
$\gamma\gamma$	–	0.01
Combined	0.2	0.7

- For 10 ab^{-1}: Significance ≈ 0.7 (preliminary, optimizations under study)
  Limit (95% CL) for branching ratio: $BR(H\to ee) < 2.8\times BR_{SM}(H\to ee)$
  Limit (95% CL) for SM Yukawa: $g_{eH} < 1.7\times g_{eH,SM}$

Higgs physics at FCC-ee(125): H-e Yukawa

- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125 GeV):



$\sigma(e^+e^-\to H)_{B\text{-}W} \sim 1.64$ fb

$\sigma(e^+e^-\to H)_{visible} \sim 280$ ab (ISR + $E_{beam\text{-}spread} \sim \Gamma_H = 4.2$ MeV)

- Signal + backgrounds study for 7 decay channels:
  WW*(2j,lν) (σ = 28 ab), WW*(2l2ν) (σ = 6.7 ab),
  WW*(4j) (σ = 29.5 ab), ZZ*(2j2ν) (σ = 2.3 ab), ZZ*(2l2j) (σ = 1.14 ab),
  bb (2j) (σ = 156 ab), gg (2j) (σ = 24 ab)

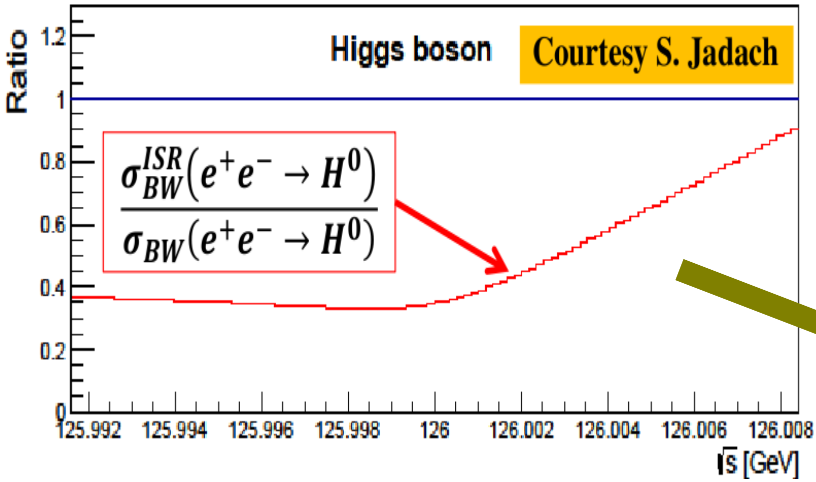
- Preliminary analysis:
  $L_{int} = 10\ ab^{-1}$, S=0.65: BR(Hee) < 4.63×BR_{SM} (3σ), $g_{hee} < 2.15 \times g_{Hee,SM}$ (3σ)
  Evidence (observation?) will require further improvements in large-BR (huge background) jet channels: H→ bb, H → WW → 4j

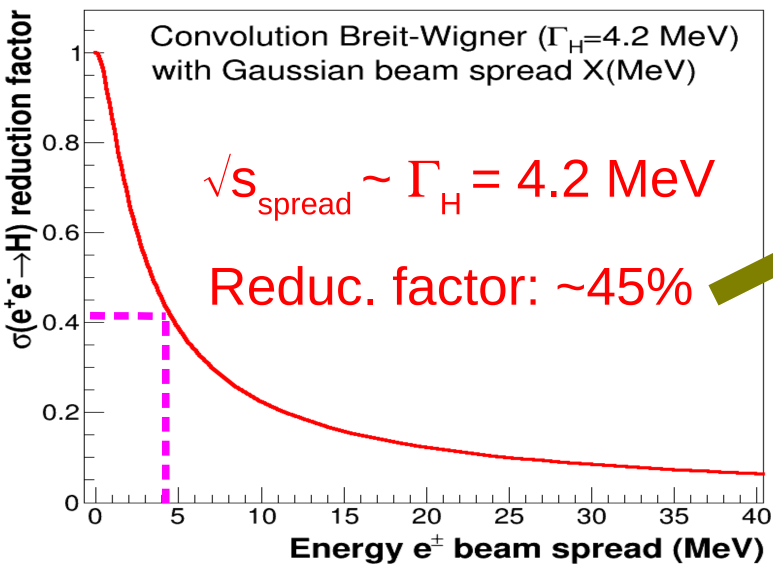
- Challenging accelerator conditions: mono-chromatization, huge lumi

- Fundamental & unique physics accessible if measurement feasible:
  → Electron Yukawa coupling
  → Higgs width measurable ("natural" threshold scan)

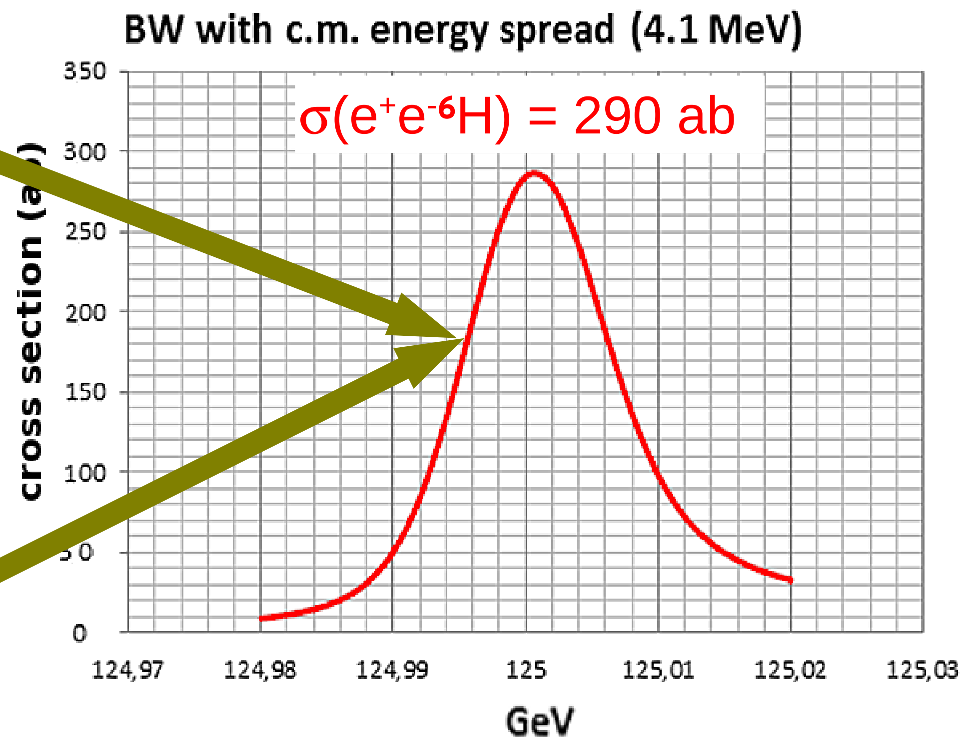
$\sigma(e^+e^- \to H)$ reduction: Beam energy spread + ISR

- Extra ~40% reduction also due to initial state radiation:





- Combined reduction factors:



$$\sigma_{beam\text{-}spread+ISR}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H)$$

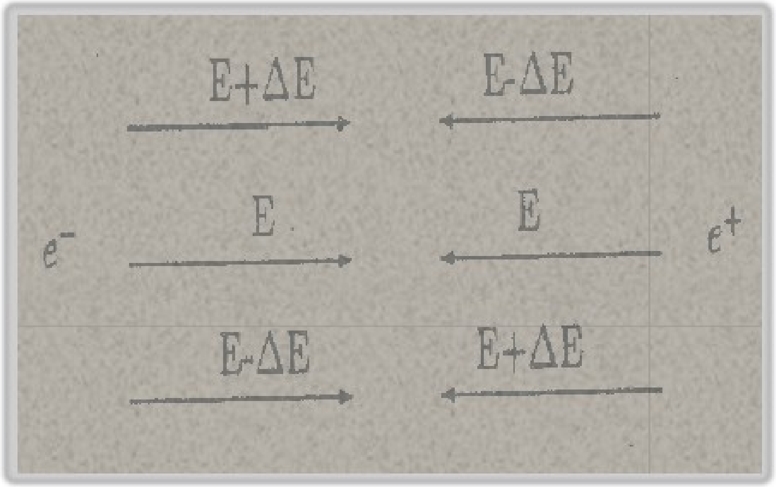
mono-chromatization at 2x63 GeV?

direct *s* channel Higgs production $e^+e^- \rightarrow H$

rms beam energy spread at 63 GeV ~30 MeV
total width of SM Higgs Γ ~ 4 MeV

effective collision energy spread is decreased by introducing opposite-sign IP dispersion

$$\frac{\sigma_W}{W} = \sqrt{\frac{2\varepsilon_x}{\left(\frac{{D^*_x}^2}{\beta^*_x} + \frac{\varepsilon_x}{{\sigma_\epsilon}^2}\right)}}$$

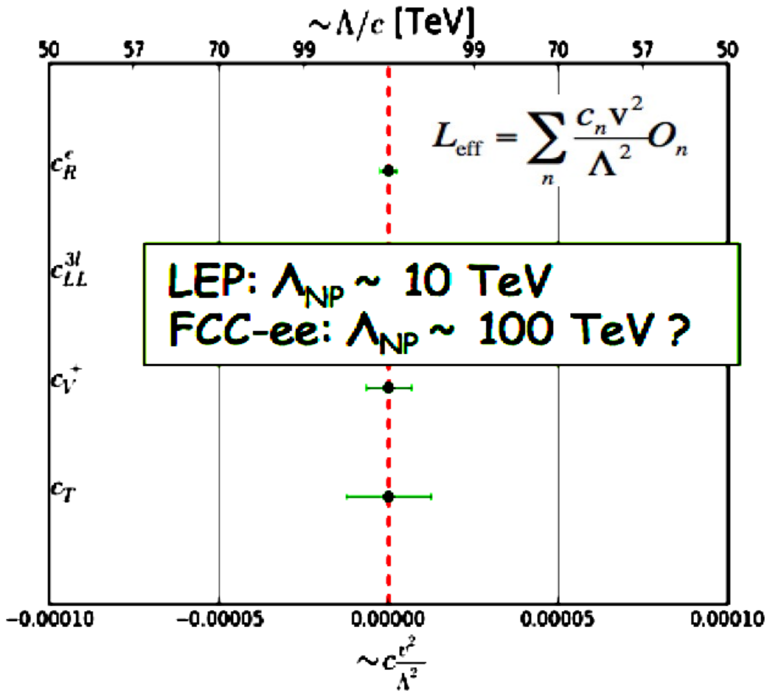


first proposed by A. Renieri (1975); historical studies for VEPP4, SPEAR, LEP, τ-c factory;never tested experimentally

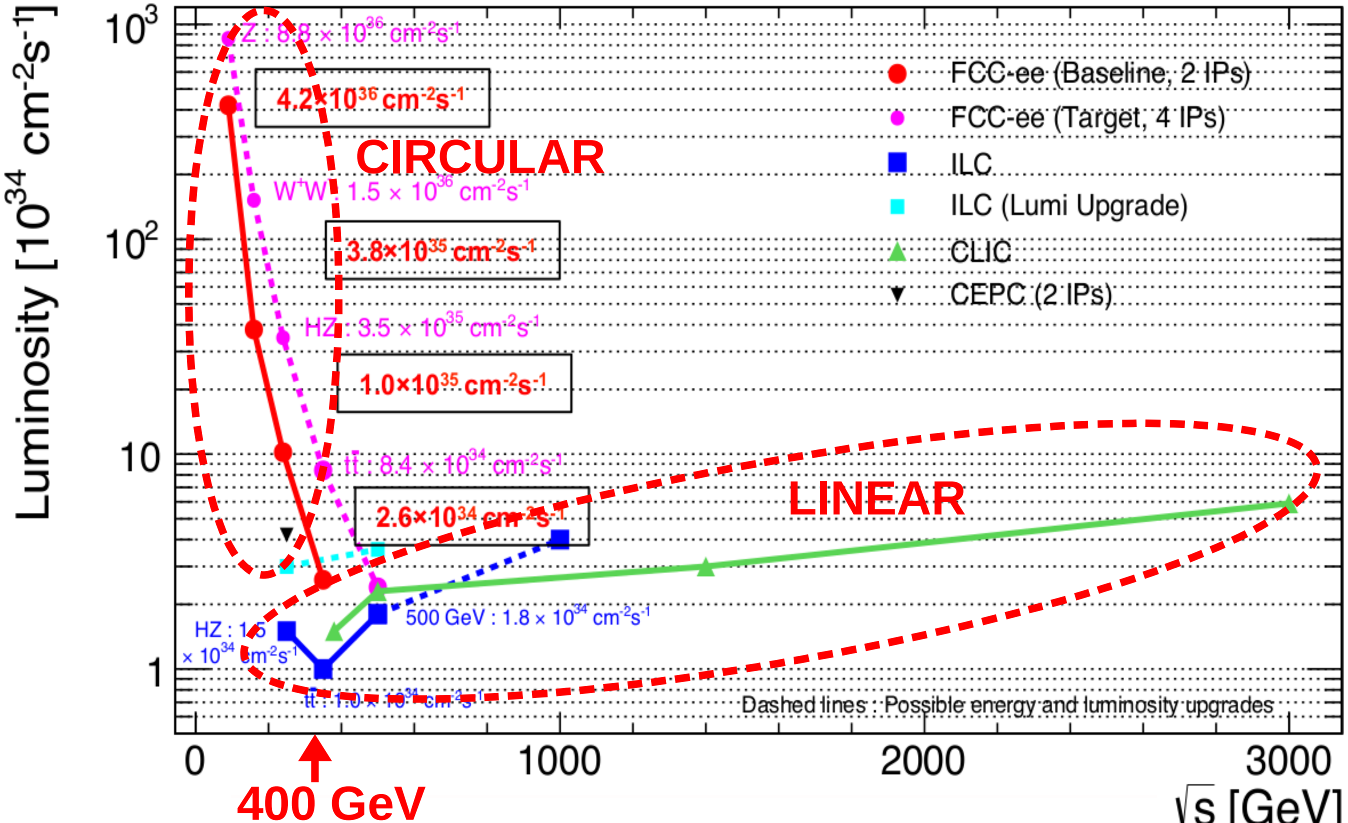
reducing cm energy spread x1/10 w/o loss of luminosity?!
implementation for crab-waist scheme?

Why new e^+e^- colliders ?

- New physics (NP): Hiding well ? Or beyond present reach ?
  At larger masses? Or at smaller couplings? Or both?
- Electron-positron colliders:
  - ➡ Direct model-indep. discovery of new particles coupling to Z*/γ* up to m~√s/2
  - ➡ Low, very-well understood backgrounds: Fill "blind spots" in p-p searches
  - ➡ Polarised beams: Extra handle to constrain theory underlying any NP
  - ➡ Indirect constraints on new physics via virtual corrections: Λ_{NP}~ 1 TeV/√δX



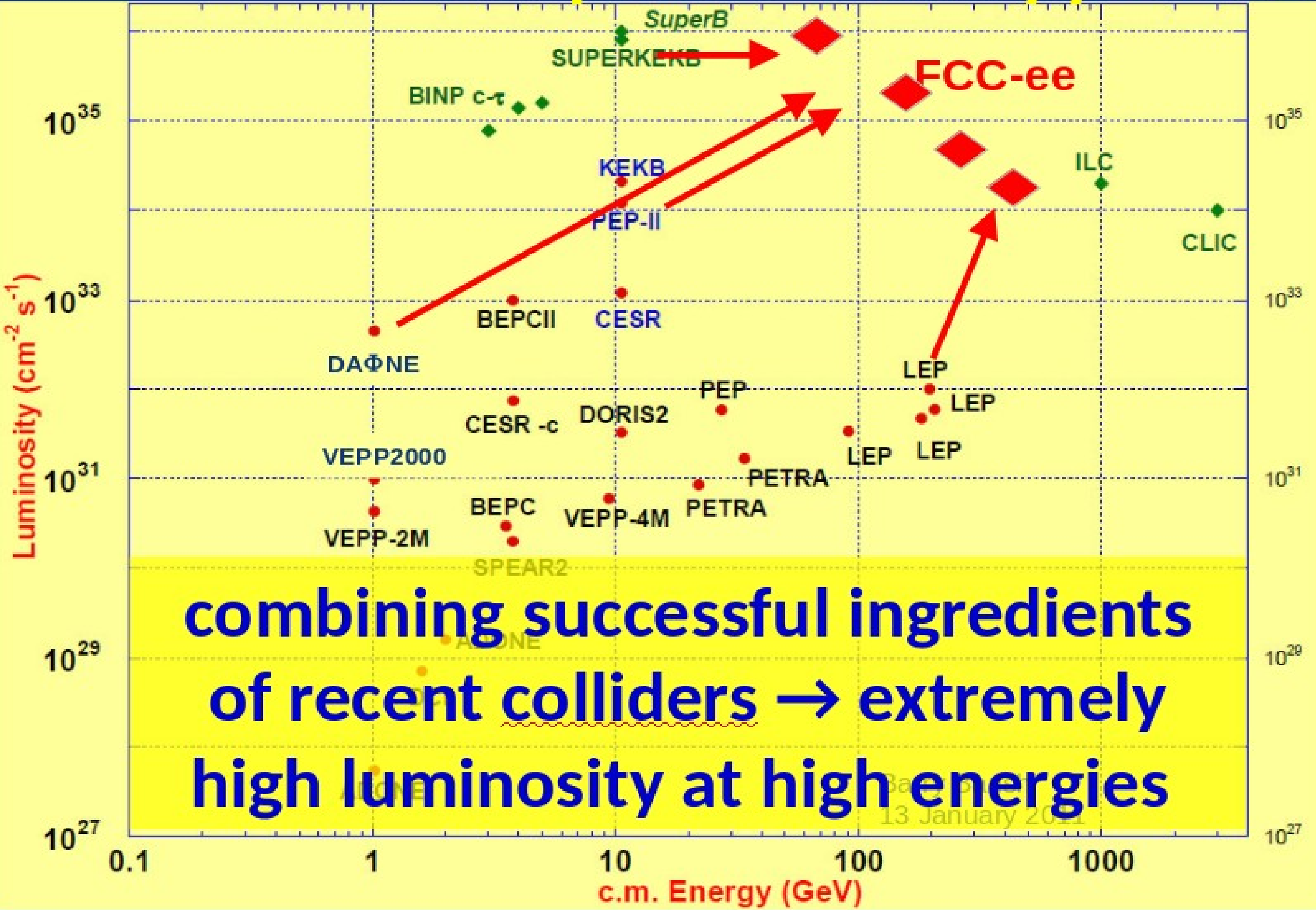
Circular or linear e^+e^- colliders ?



- $\sqrt{s}$ limited to ~400 GeV by SR~E^4/R
- Large # of circulating bunches:
  - → Much higher Lumi (better at low $\sqrt{s}$, lower SR)
  - → Top-up injection ring to compensate L burnoff
- Various Interaction Points possible
- Precise E_{beam} from resonant depolarization

- Larger $\sqrt{s}$ reach (TeV's)
- Low repetition rate
  - → Lumi from nm-size beams
  - → Large bremsstrahlung
  - → Large energy spread
- Longitudinal polarization easier

FCC-ee exploits lessons & recipes from past e^+e^- and *pp* colliders



LEP:
- high energy
- SR effects

B-factories:

KEKB & PEP-II:
- high beam currents
- top-up injection

DAFNE:
- crab waist

Super B-factories

S-KEKB:
- low β_y^*

KEKB:
- e^+ source

HERA, LEP, RHIC:
- spin gymnastics

FCC-ee technologies, time lines, analysis highlights
Frank Zimmermann
KET workshop, Munich, 2 May 2016

e+e- colliders: FCC-ee vs. LEP, CepC

2016 baseline parameters

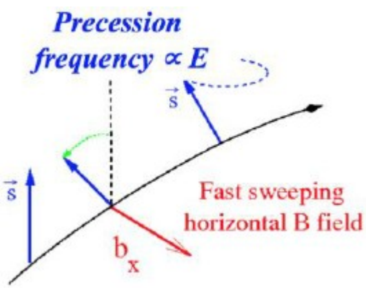
parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**70**	**5**	**1.3**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5
rms bunch length (SR,+BS) [mm]	1.6, 3.8	2.0, 2.4	2.1, 2.5	2.1, 2.6	12, 12
rms emittance $\varepsilon_{x,y}$ [nm, pm]	0.09, 1	0.61, 1	1.3, 2.5	6, 18	22, 250
longit. damping time [turns]	1320	72	23	39	31
crossing angle [mrad]	30	30	30	0	0
beam lifetime [min]	251	75	62	61	434

FCC-ee: 2 separate rings **CEPC: single beam pipe like LEP**

Beam energy spread via resonant depolarization

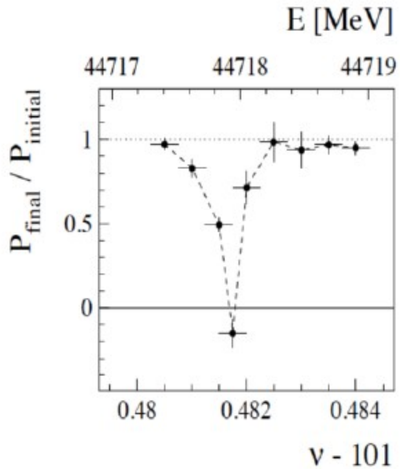
Resonant depolarization

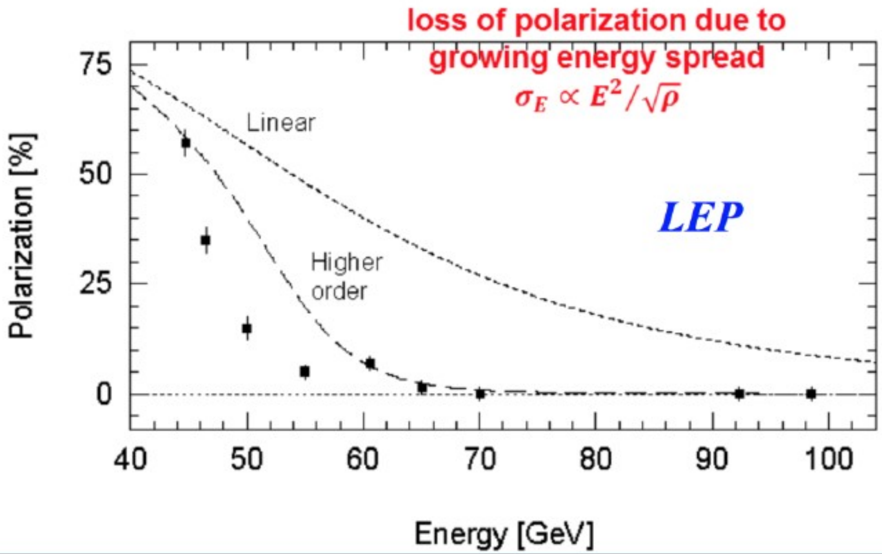
- use naturally occuring transverse beam polarization
- add fast oscillating horizontal B field to depolarize at Thomas precession frequency



Experience from LEP: Depolarization resonance very narrow: ~100 keV precision for each measurement

- However, final systematic uncertainty was 1.5 MeV due to transport from dedicated polarization runs
- At FCC-ee, continuous calibration with dedicated bunches: no transport uncertainty



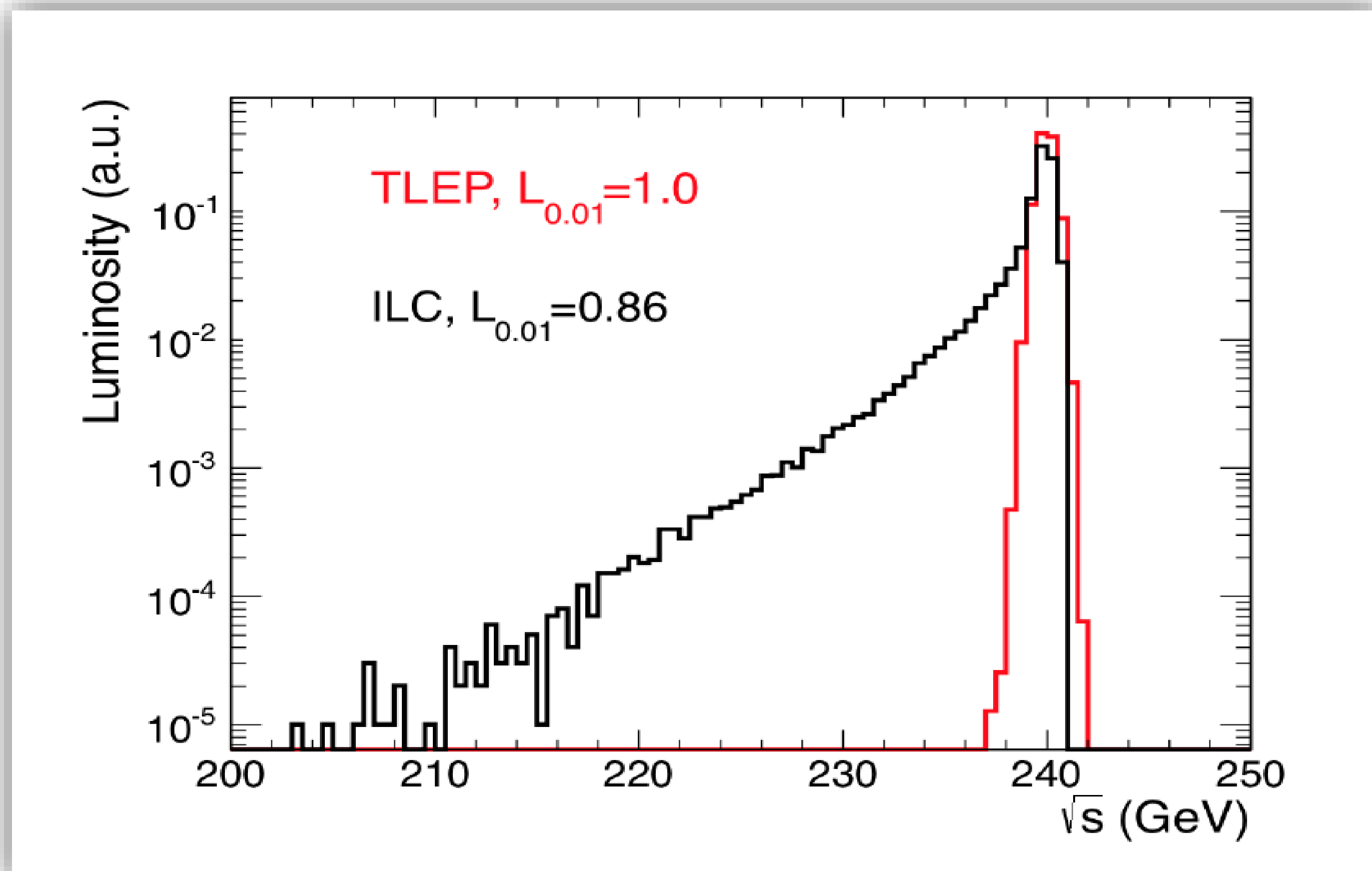


Scaling from LEP experience:

- Polarization expected up to the WW threshold

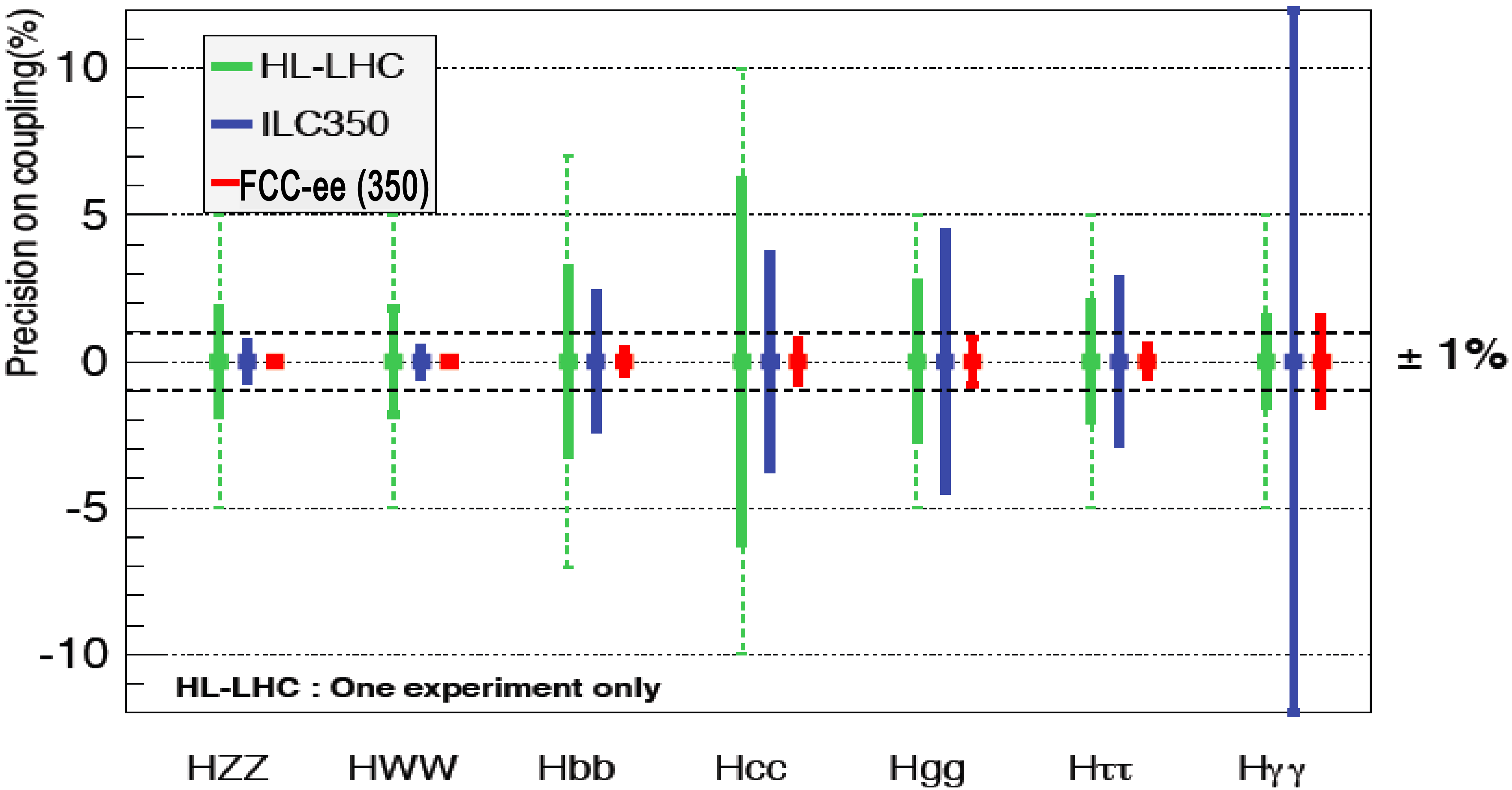
< 100 keV beam energy calibration at Z peak and at WW threshold

FCC-ee beam energy spread



Non-destructive focusing and collision of beams:
- Center-of-mass energy spread by construction modest

Precision Higgs couplings: FCC-ee vs. ILC



- Most precise (g_{HZZ}) ~0.1% coupling sets limit on new scalar-coupled physics at: $\Lambda \gtrsim (1\,\mathrm{TeV})/\sqrt{(\delta g_{HXX}/g_{HXX}^{SM})/5\%}$ >7 TeV