Physics at FCC-ee

Séminaire CP3 (UCL)

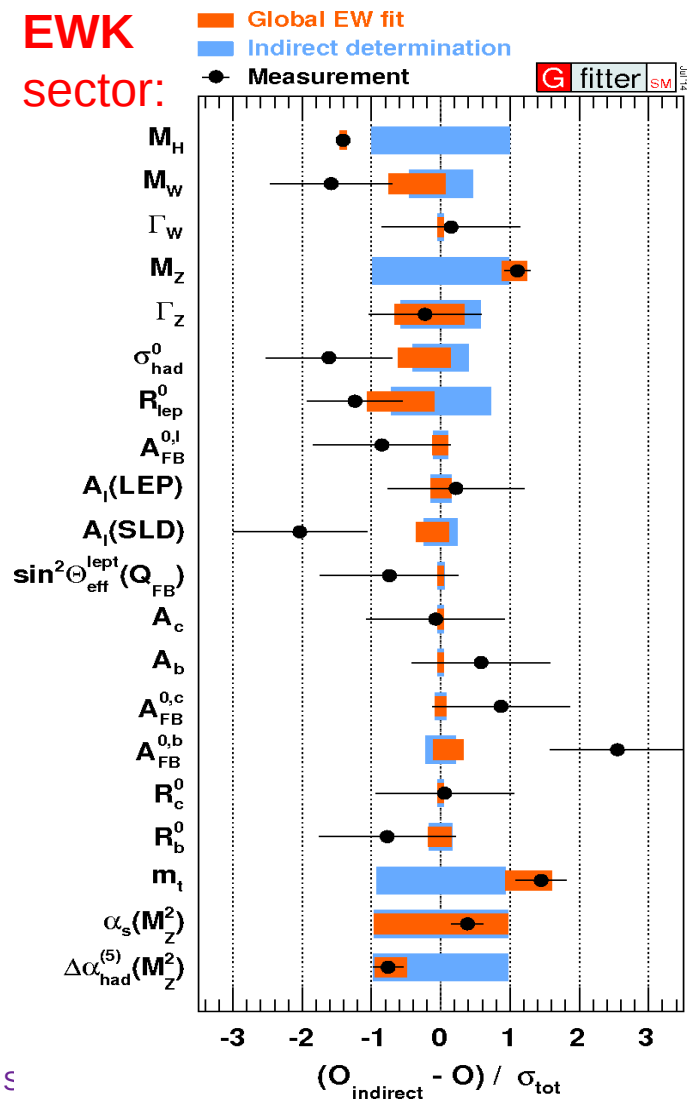
UC Louvain, 11th January 2017

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

Standard Model of particles & interactions

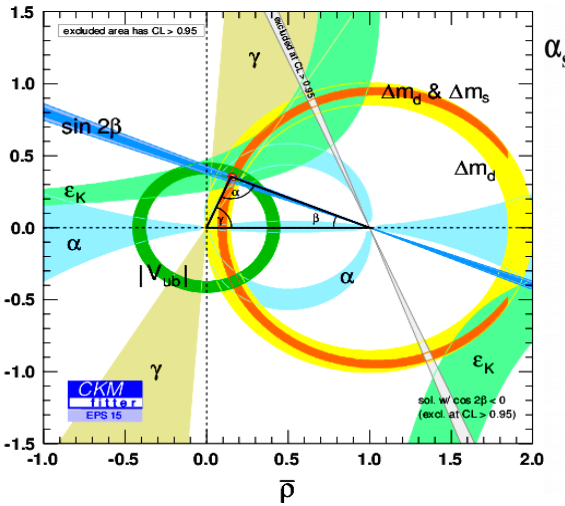
- Renormalizable QFT of electroweak $SU(2)_L \times U(1)_Y$ & strong $SU(3)_c$ gauge interactions
  O(20) parameters: Couplings, H mass&vev, H-f Yukawa, CKM mix., CP phases.
  Experimentally confirmed to great precision for over 40(!) years:

EWK sector:

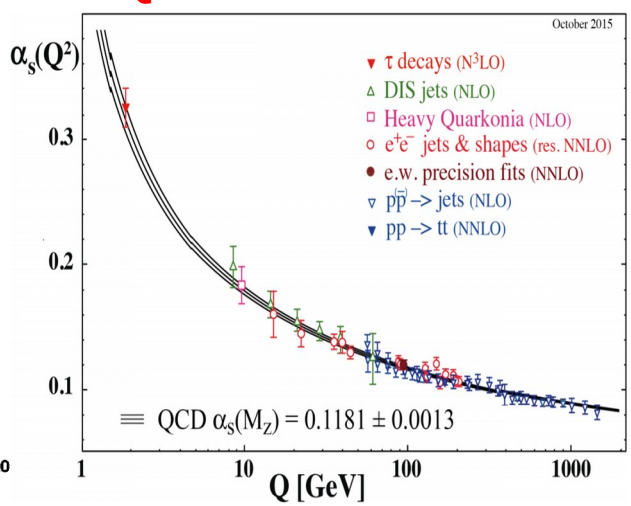


$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$
$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu i D_\mu \begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu i D_\mu e_R + \bar{\nu}_R\sigma^\mu i D_\mu \nu_R + (\text{h.c.})$$
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Flavour sector:



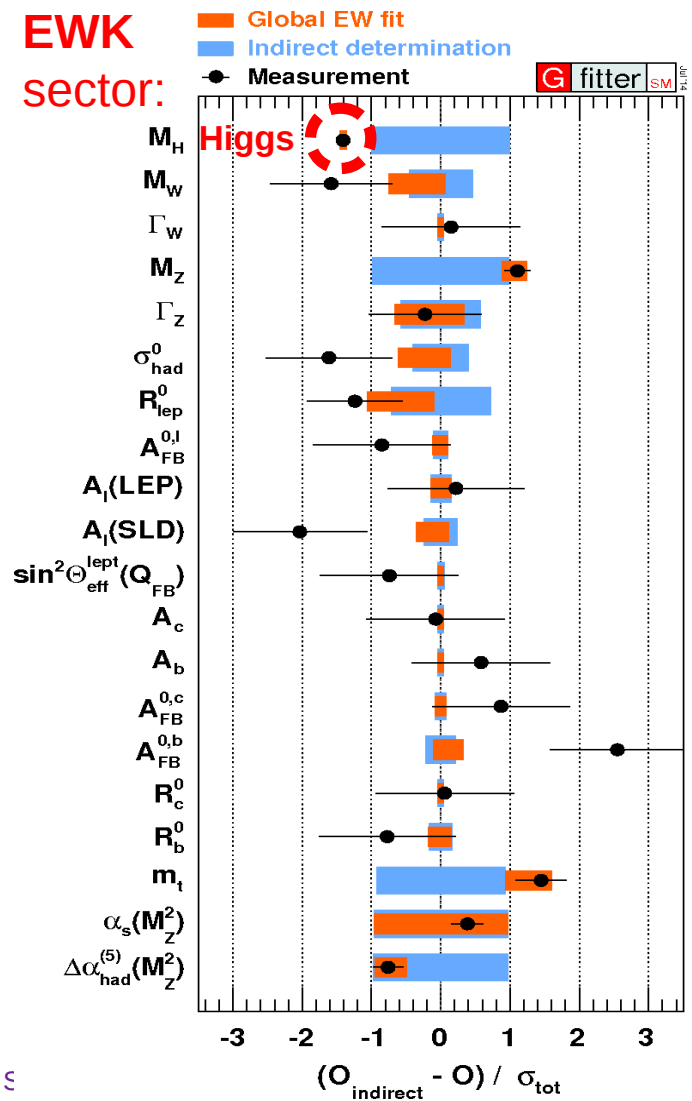
QCD sector:



Standard Model of particles & interactions

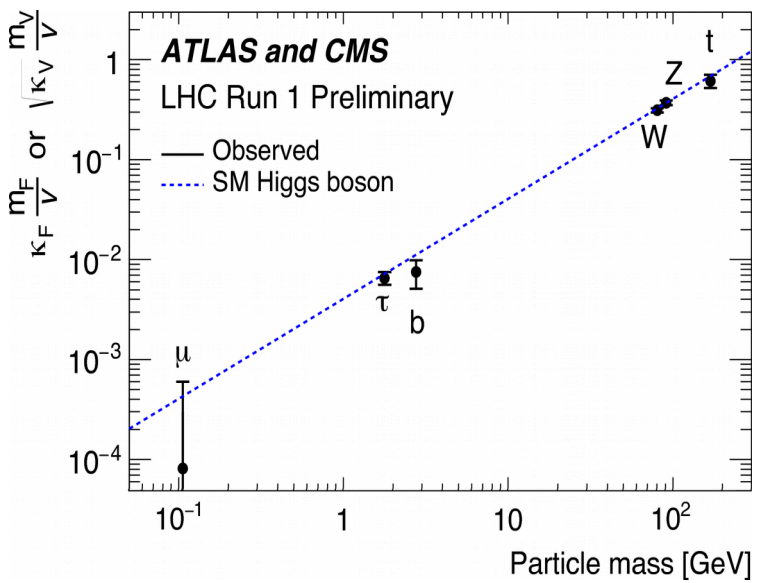
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Higgs sector:



Open questions in the SM (1)

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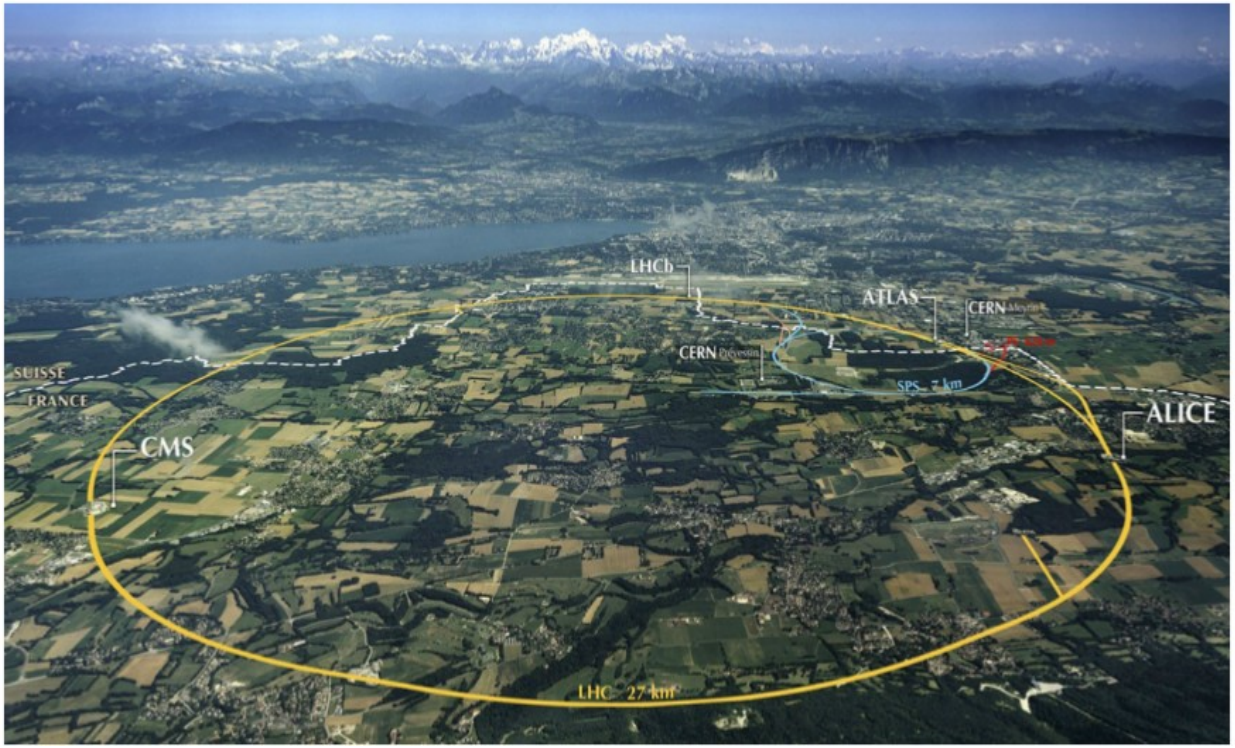
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- ✘ Flavour: SM cannot generate observed matter-antimatter imbalance
- ✘ Dark matter: SM describes only 4% of Universe (visible fermions+bosons)
- ✘ Others: Strong CP, quantum gravity, cosmological const, dark energy, inflation,...

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

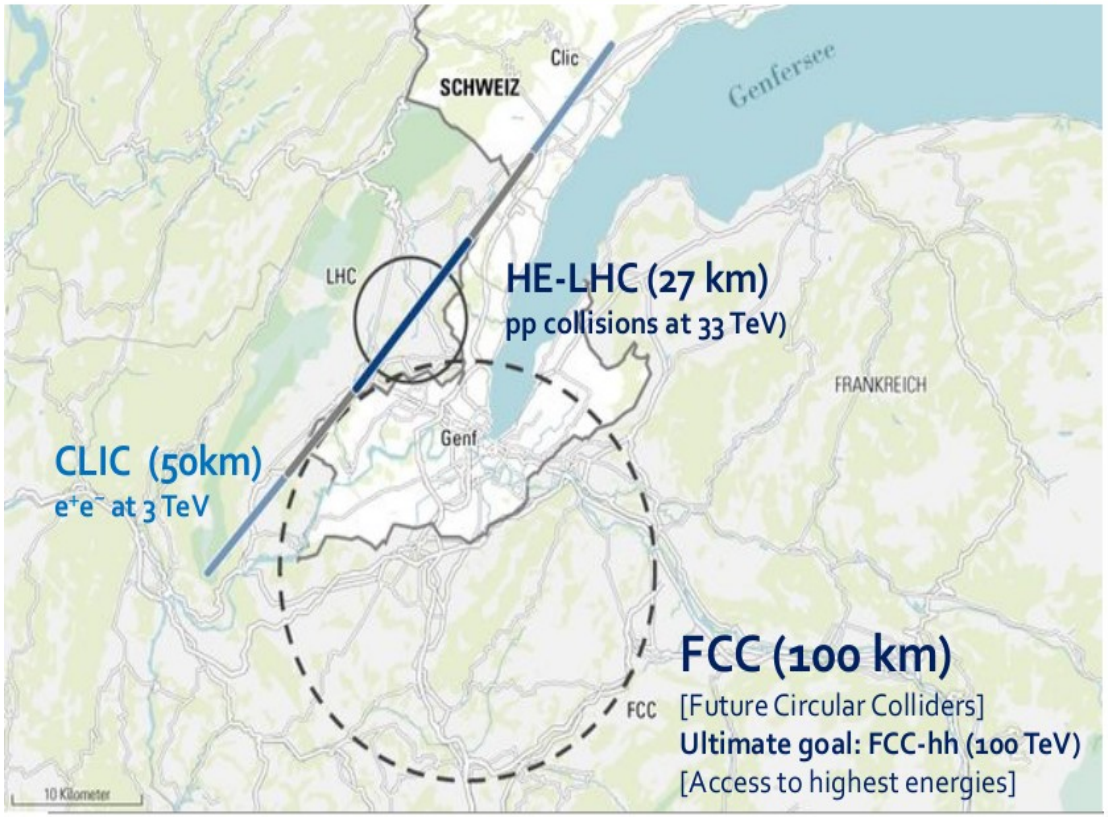
EU short-term HEP perspectives (2020-2030)

- In May 2013, European Strategy said (very similar statements from US)
  - Exploit the full potential of the LHC until ~2030 as the highest priority
    - Get 75-100 fb^{-1} at 13-14 TeV by 2018 (LHC Run2: running)
    - Get ~300 fb^{-1} at 14 TeV by 2022 (LHC Run3: approved)
    - Upgrade machine and detectors to get 3 ab^{-1} at 14 TeV by 2035 (HL-LHC: project)
      - A first step towards both energy and precision frontier



EU long-term HEP perspectives (2040-2060)

- In May 2013, European Strategy said (very similar statements from US)
  - Perform R&D and design studies for high-energy frontier machines at CERN
    - HE-LHC, a programme for an energy increase to 33 TeV in the LHC tunnel
    - FCC, a 100-km circular ring with a pp collider long-term project at $\sqrt{s}$ = 100 TeV
    - CLIC, an e^+e^- collider project with $\sqrt{s}$ from 0.3 to 3 TeV



Similar circular projects
(50 or 70km) in China
pp collisions at $\sqrt{s}$ ~ 50 or 70 TeV





EU mid-term HEP perspectives (2030-2040)

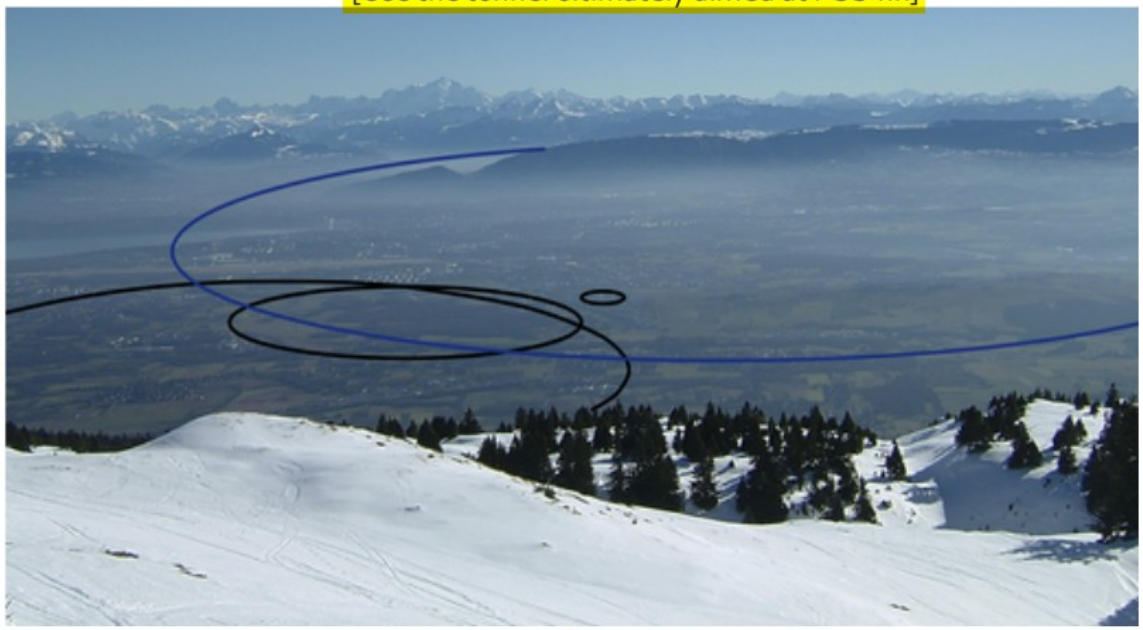
- In May 2013, European Strategy said (very similar statements from US)
  - Acknowledge the strong physics case of e^+e^- colliders with intermediate $\sqrt{s}$
    - Participate in ILC if Japan government moves forward with the project
    - In the context of the FCC, perform accelerator R&D and design studies
      - In view of a high-luminosity, high-energy, circular e^+e^- collider as a first step



FCC (100 km)

First step: FCC-ee (91-400GeV)

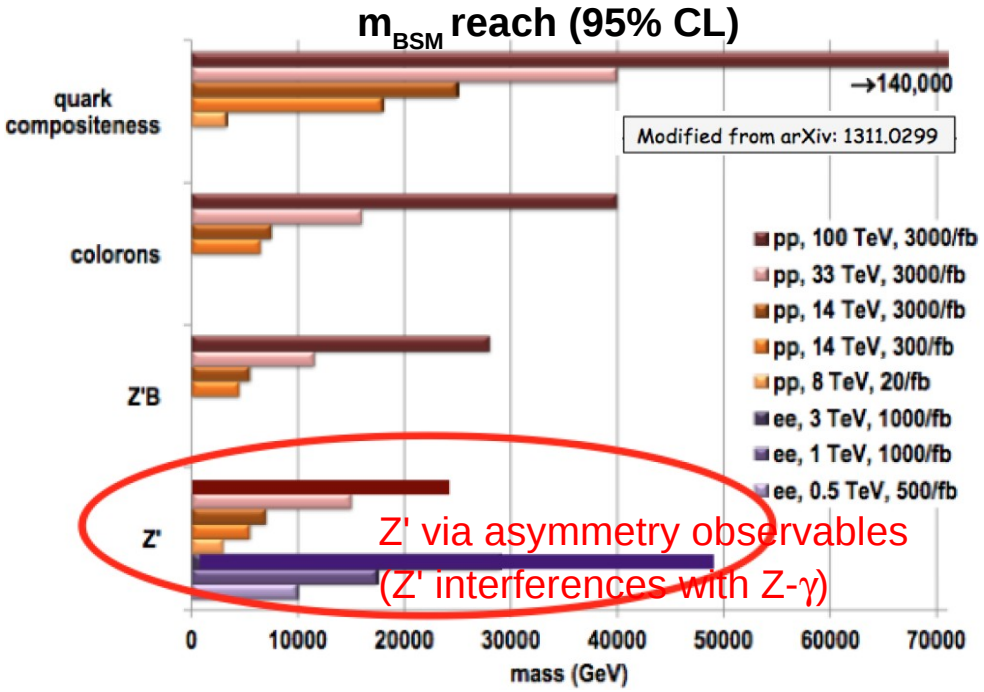
[Use the tunnel ultimately aimed at FCC-hh]

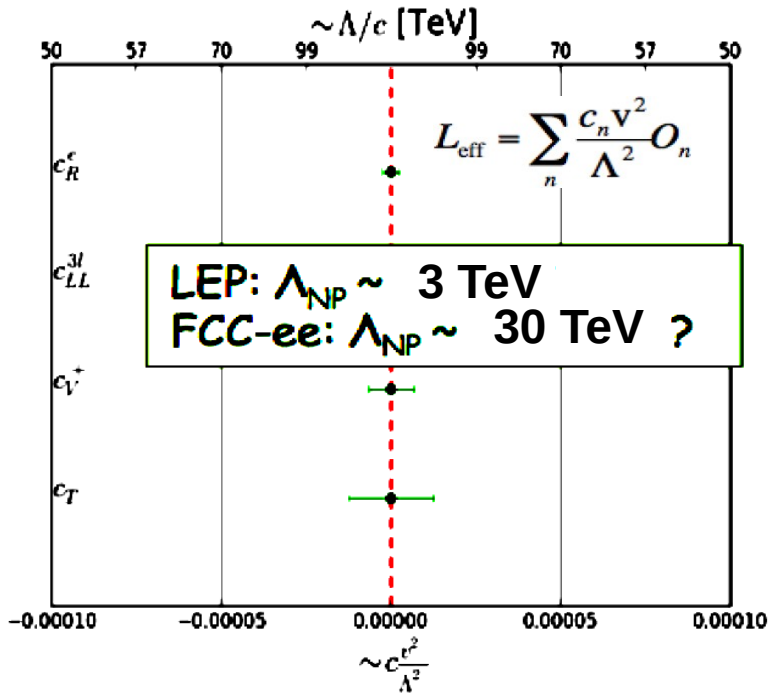


Note: CLIC can also run at $\sqrt{s}$ ~ 350 GeV in ~2035-2040

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 NP constraints via virtual corrections to parameters X: $\Lambda_{NP} \sim 1\ \text{TeV}/\sqrt{\delta X}$





BSM reach at e^+e^- colliders

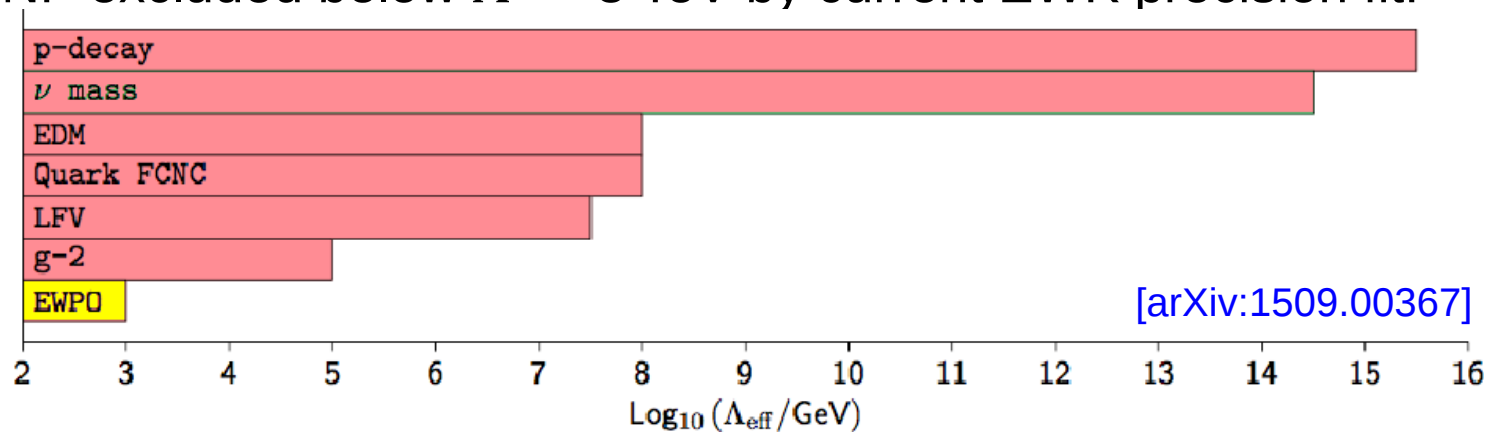
- Indirect searches through loops in high-stats W, Z, H, top precision studies (<<1% accuracy) in very high-luminosity e^+e^- collisions.
- Indirect constraints on new physics (from generic EFT $L_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^2} O_n$)

New scalar-coupled physics: $\Lambda \gtrsim (1\,\text{TeV})/\sqrt{(\delta g_{\text{HXX}}/g^{\text{SM}}_{\text{HXX}})/5\%}$

HI-LHC: ~5% deviations of Higgs couplings X wrt. SM ⇒ Λ > 1 TeV
With 10^6 Higgs: ~0.1% stat. Higgs couplings precision ⇒ Λ > 7 TeV

New electroweak-coupled physics: $\Lambda \propto (1\,\text{TeV})/\sqrt{\delta X}$

NP excluded below Λ^{NP}~ 3 TeV by current EWK precision fit:



[arXiv:1509.00367]

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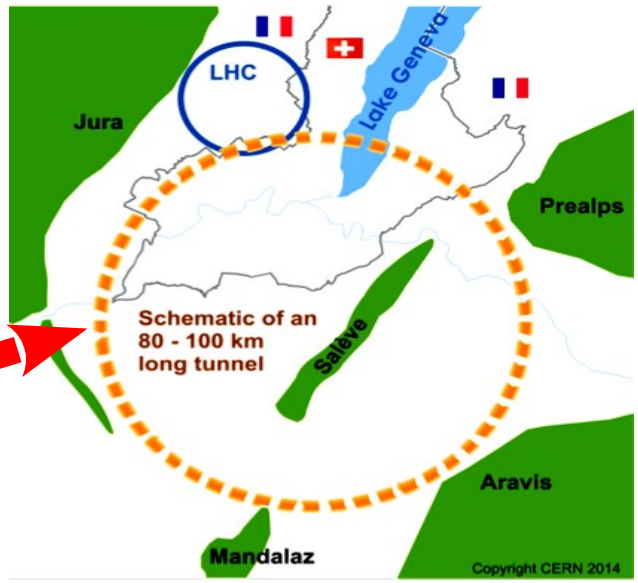
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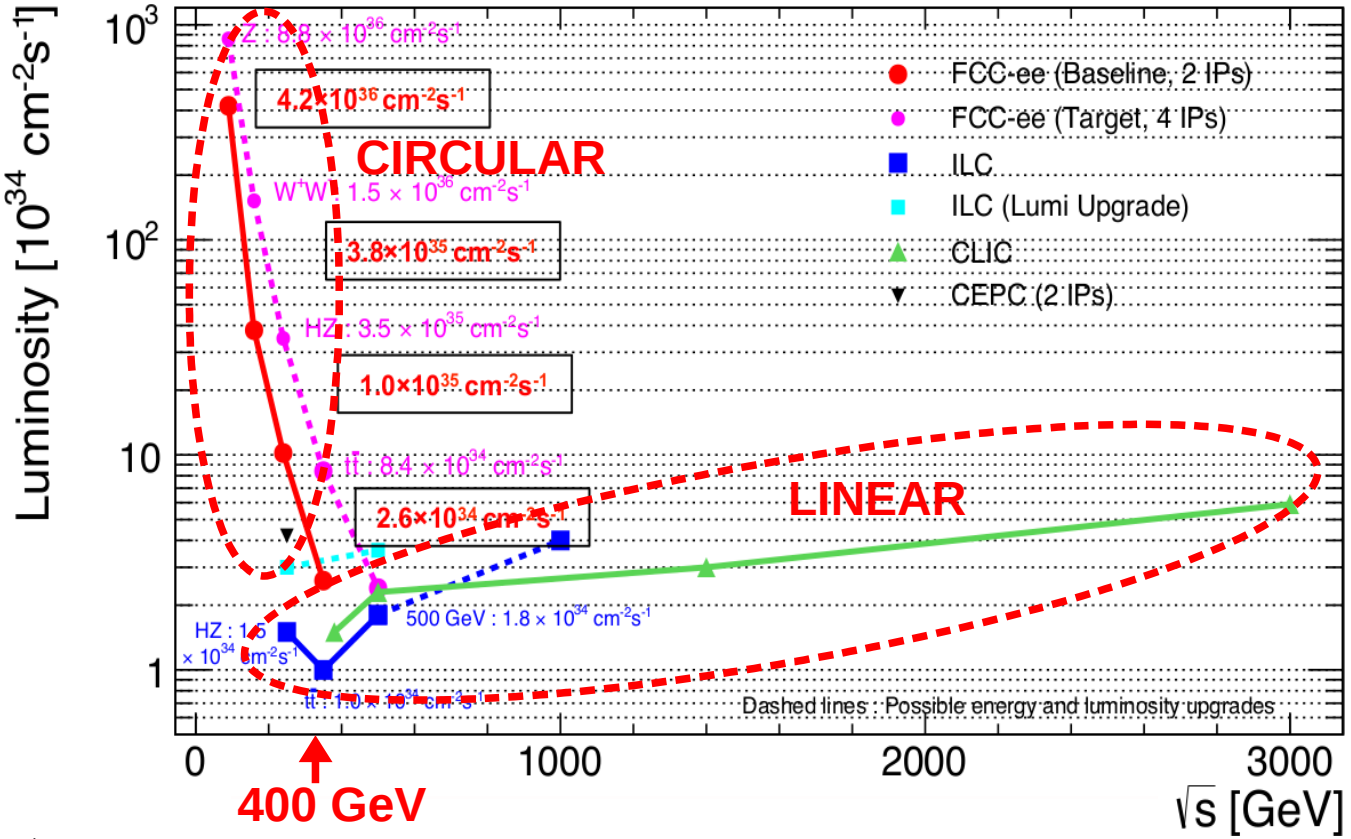
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NP excluded below Λ_{NP} ~ 3 TeV by current EWK precision fit:

Λ^{NP} ~30 TeV requires: ×10^2 precision w.r.t. LEP (10^4 W's, 10^7 Z's), i.e. ×10^4 more stats. (10^8 W's, 10^{11} Z's) reachable in e^+e^- circular collider with R~80–100 km



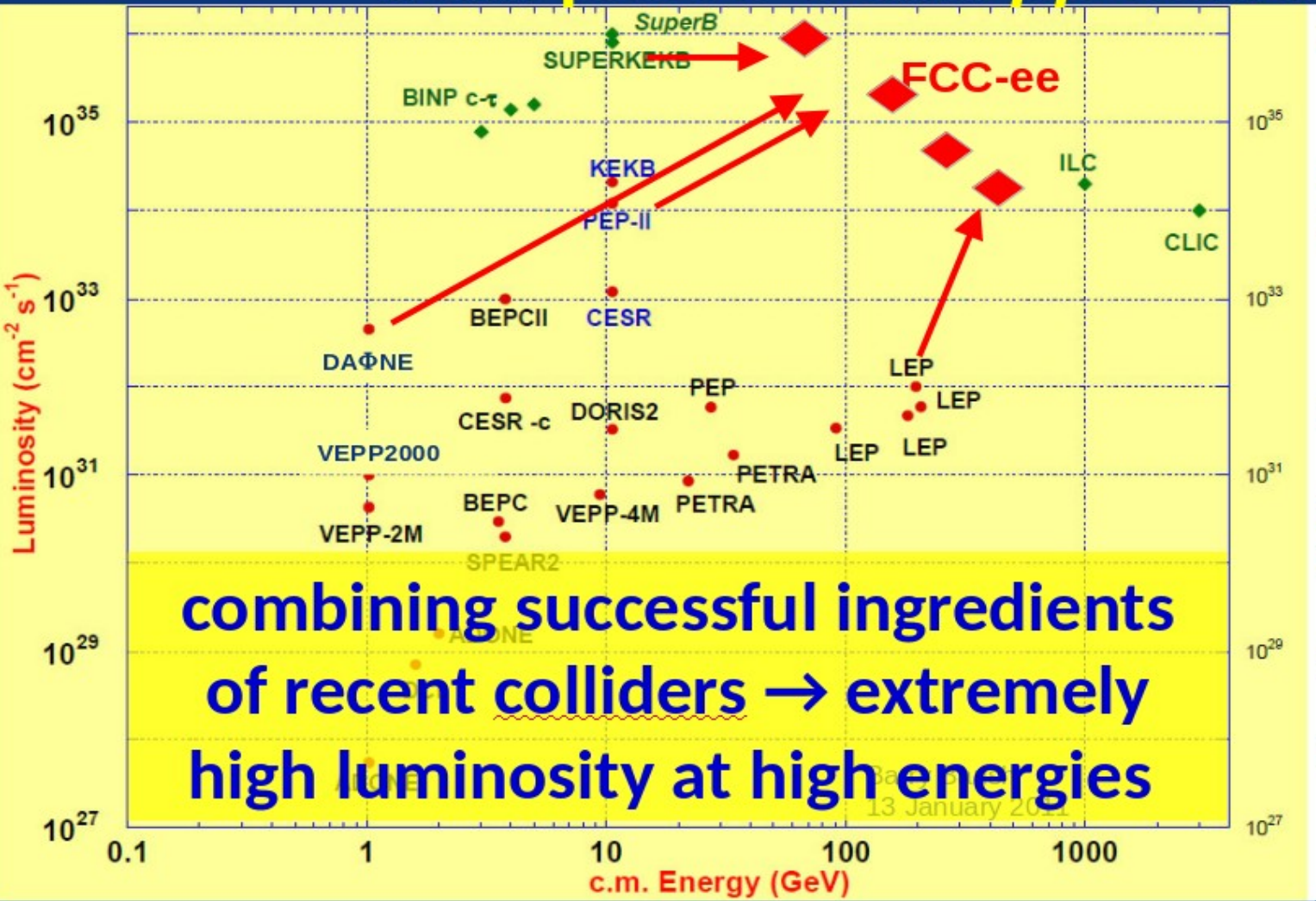
Circular or linear e^+e^- colliders ?



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

- Larger √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



combining successful ingredients of recent colliders → extremely high luminosity at high energies

LEP:
- high energy
- SR effects

B-factories:

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

DAFNE:
- crab waist

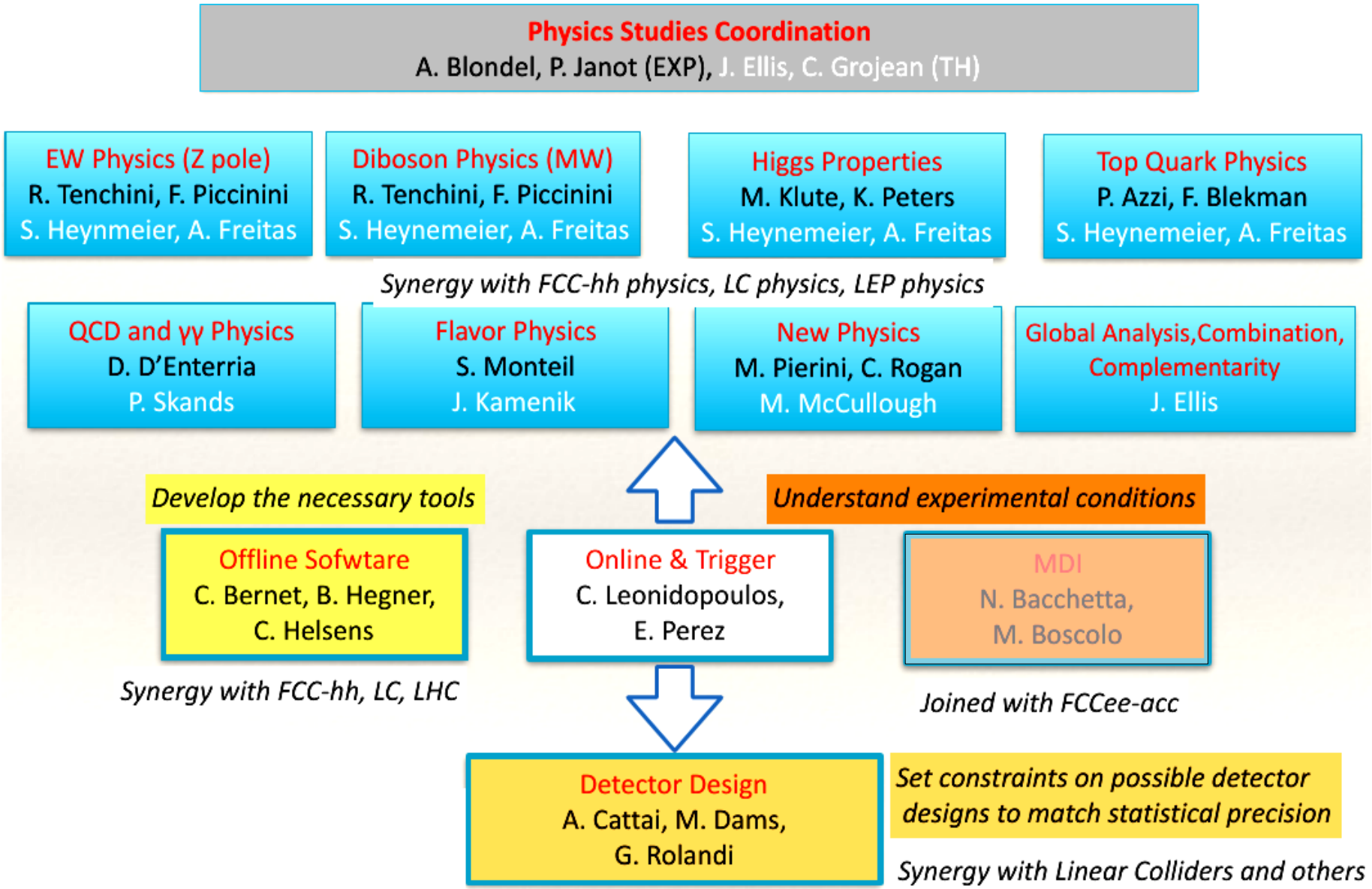
Super B-factories

S-KEKB:
- low β_y^*

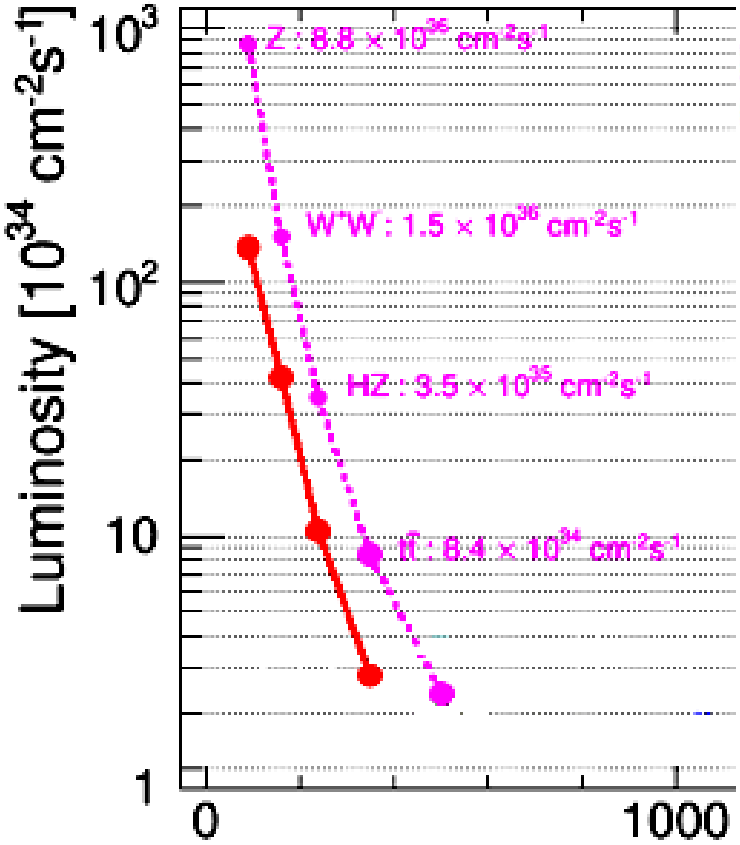
KEKB:
- e^+ source

HERA, LEP, RHIC:
- spin gymnastics

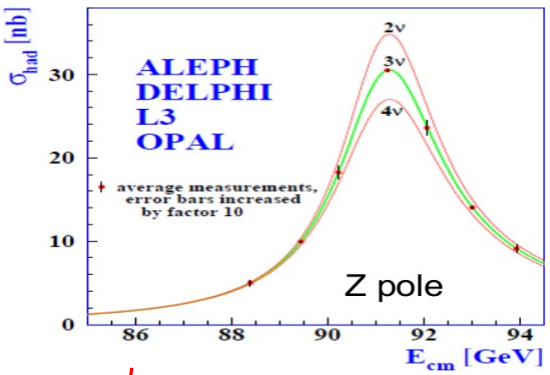
FCC-ee: CERN study project



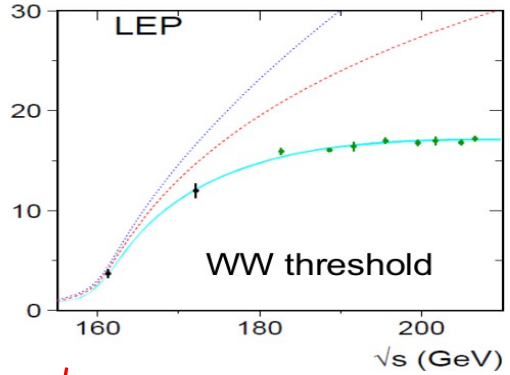
FCC-ee physics programme in a nutshell



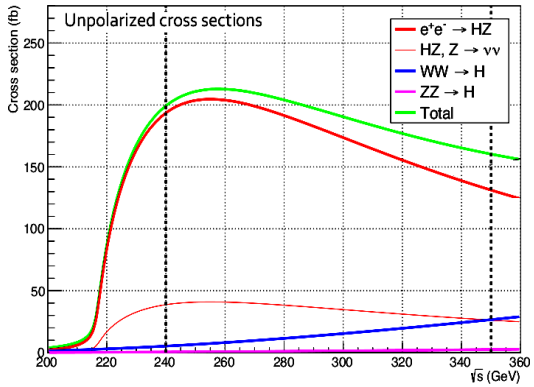
√s=91 GeV, 10^{12} Z's



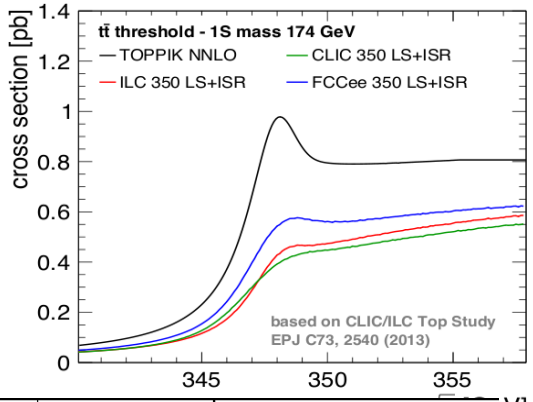
√s=161 GeV, 10^8 W's



√s=240 GeV, 10^6 H's



√s=350 GeV, $5{\cdot}10^5$ t's



$\sqrt{s}$ (GeV):	90 (Z)	125 (eeH)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350 (WW→H)
σ	43 nb	290 ab	4 pb	200 fb	0.5 pb	25 fb
$\mathcal{L}$/IP ($cm^{-2}\,s^{-1}$)	$4.3{\cdot}10^{36}$	$2.2{\cdot}10^{36}$	$7.6{\cdot}10^{35}$	$1.8{\cdot}10^{35}$	$5{\cdot}10^{34}$	$5{\cdot}10^{34}$
$\mathcal{L}_{int}$ (ab^{-1}/yr, 2 IPs)	86	45	15	3.5	1.0	1.0
Events/year (2 IPs)	$3.7{\cdot}10^{12}$	$1.3{\cdot}10^{4}$	$6.1{\cdot}10^{7}$	$7.0{\cdot}10^{5}$	$5{\cdot}10^{5}$	$2.5{\cdot}10^{4}$
Years needed (2 IPs)	2.5	1.5	1	3	0.5	3

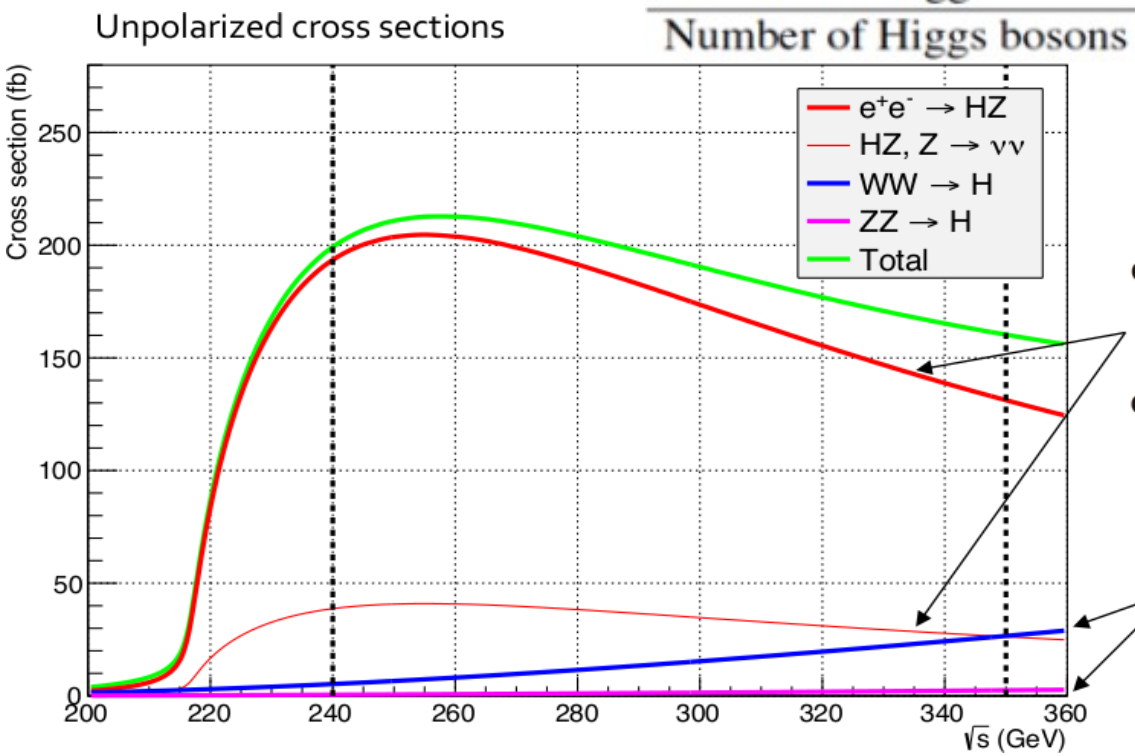
- FCC-ee core physics programme to be completed in 10–15 yrs

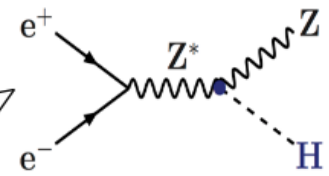
FCC-ee physics: High-precision Higgs boson

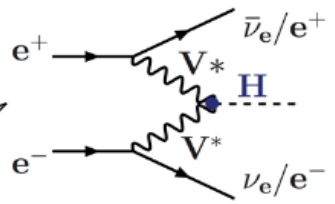
- 1st (ud, e±) and 2nd (s) generation Yukawa couplings, (heavy) ν.
- Precision (<1%) Higgs couplings studies, plus total width.
- Rare and exotic decays, in particular DM decays.
- Higgs self-coupling constrain through loop corrections.

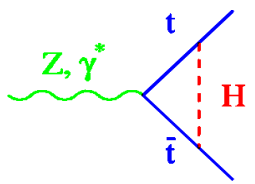
Thanks to huge, clean datasets:

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









(also sensitivity to y_t)

Open issue in the SM (1): Hierarchy problem solved via BSM W,Z,t -coupled physics

- Many BSM realizations: SUSY, Z', composite top,...
- Parametrize (B)SM as an Effective Field Theory:

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

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

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

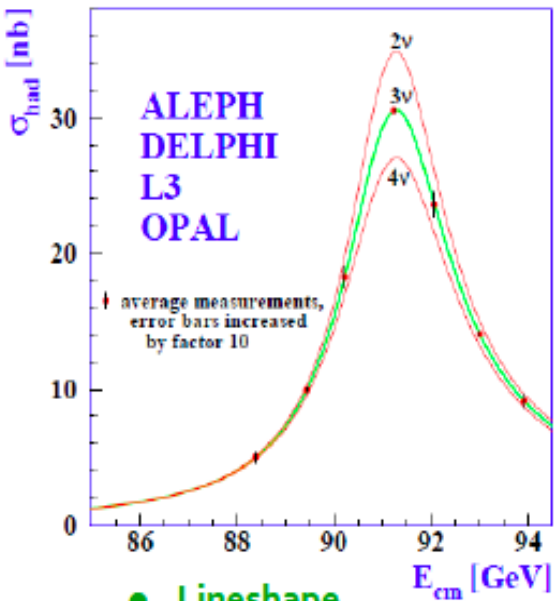
$$\Lambda \propto (1\ \text{TeV})/\sqrt{\delta X}$$

~0.1% precision of W,Z couplings ($10^{4,6}$ W,Z LEP): Λ >3 TeV

~0.001% W,Z couplings precision (~$10^{8,12}$ W,Z) ⇒ Λ>30 TeV

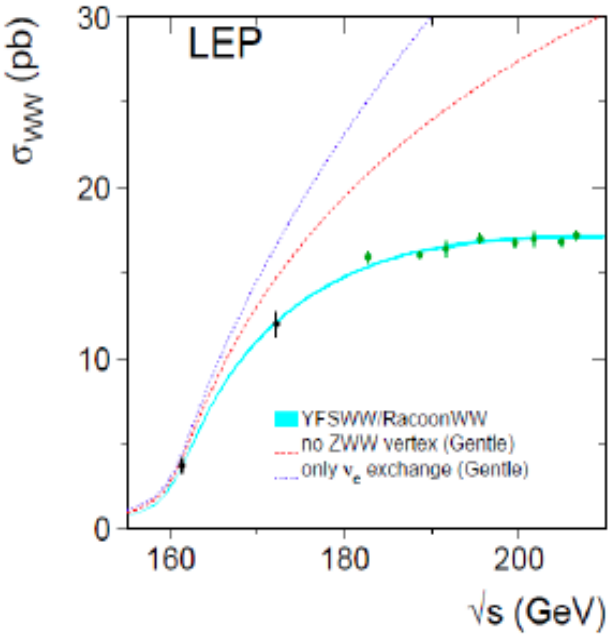
FCC-ee physics: High-precision W, Z, top

Z resonance: TeraZ



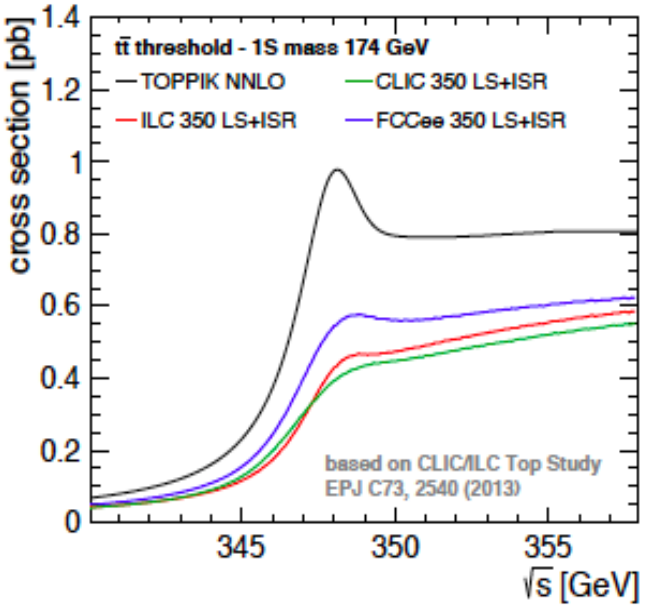
- Lineshape
  - Exquisite E_{beam} (unique!)
  - m_Z, Γ_Z to 10 keV
- Asymmetries
  - $\sin^2\theta_W$ to 2×10^{-6}
- Branching ratios, R_l, R_b
  - $\alpha_S(m_Z)$ to 0.0002
- Predict m_{top}, m_W in SM

WW threshold scan: OkuW



- Threshold scan
  - m_W to 500 keV
- Branching ratios R_l, R_{had}
  - $\alpha_S(m_W)$ to 0.0002
- Radiative returns $e^+e^-\to\gamma Z$ $(Z\to\nu\nu, \mu^+\mu^-)$
  - N_ν to 0.0004

tt threshold scan: MegaTops



- Threshold scan + 4D fit
  - m_{top} to 10 MeV
  - λ_{top} to 13%
  - EWK couplings to 1–10%

[arXiv:1308.6176]

■ Mostly thanks to: (i) huge stats, (ii) threshold scans with E_{beam} ~ 0.1 MeV

High-precision W, Z, top: FCC-ee uncertainties

[D.d'E., arXiv:1602.05043]

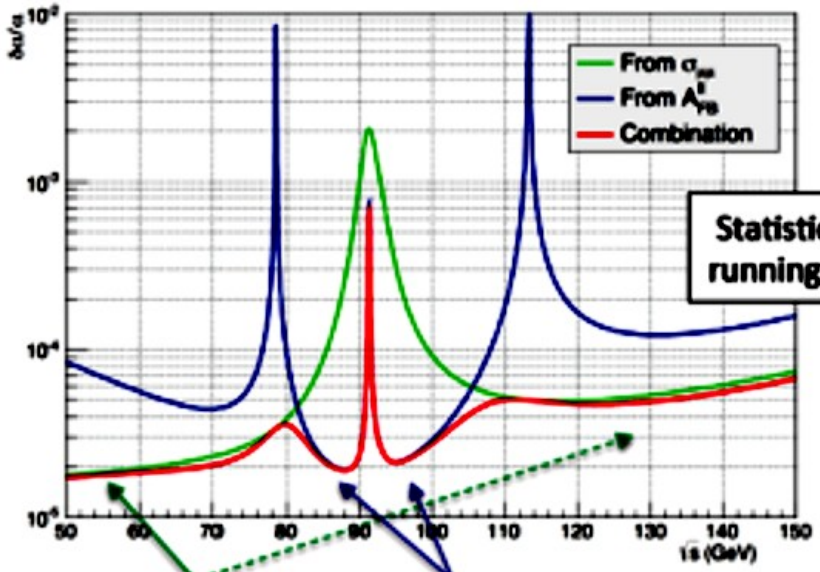
- Exp. uncertainties (stat. uncert. ~negligible) improved by factors ×3–100:

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_{Z} (MeV)	Z lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_{Z} (MeV)	Z lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_ℓ	Z peak	20.767 ± 0.025	0.0001	< 0.001	QED corr.
R_{b}	Z peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \to \mathrm{b\bar{b}}$
N_ν	Z peak	2.984 ± 0.008	0.00004	0.004	Lumi meas.
N_ν	$\mathrm{e^+e^-} \to \gamma\,\mathrm{Z(inv.)}$	2.92 ± 0.05	0.0008	< 0.001	–
$A_{\mathrm{FB}}^{\mu\mu}$	Z peak	0.0171 ± 0.0010	0.000004	< 0.00001	E_{beam} meas.
$\alpha_{\mathrm{s}}(m_{\mathrm{Z}})$	$R_\ell, \sigma_{\mathrm{had}}, \Gamma_{\mathrm{Z}}$	0.1190 ± 0.0025	0.000001	0.00015	New physics
$1/\alpha_{\mathrm{QED}}(m_{\mathrm{Z}})$	$A_{\mathrm{FB}}^{\mu\mu}$ around Z peak	128.952 ± 0.014	0.004	0.002	EW corr.
m_{W} (MeV)	WW threshold scan	80385 ± 15	0.3	< 1	QED corr.
$\alpha_{\mathrm{s}}(m_{\mathrm{W}})$	$\Gamma_{\mathrm{W}}, B_{\mathrm{had}}^{\mathrm{W}}$	$B_{\mathrm{had}}^{\mathrm{W}} = 67.41 \pm 0.27$	0.00018	0.00015	CKM matrix
m_{t} (MeV)	$\mathrm{t\bar{t}}$ threshold scan	173200 ± 900	10	10	QCD
Γ_{t} (MeV)	$\mathrm{t\bar{t}}$ threshold scan	1410^{+290}_{-150}	12	?	$\alpha_{\mathrm{s}}(m_{\mathrm{Z}})$
y_{t}	$\mathrm{t\bar{t}}$ threshold scan	$\mu = 2.5 \pm 1.05$	13%	?	$\alpha_{\mathrm{s}}(m_{\mathrm{Z}})$
$F_{\mathrm{1V,2V,1A}}^{\gamma\,t, Z\,t}$	$\mathrm{d}\sigma^{t\bar{t}}/\mathrm{dx}\,\mathrm{dcos}(\theta)$	4%–20% (LHC-14 TeV)	(0.1–2.2)%	(0.01–100)%	–

- Theoretical developments needed to match expected experimental uncertainties

High-precision (around) Z: α_{QED} coupling

- BSM searches require reduced SM parametric uncertainties (α,α_s,m_W,..)
- $\mu\mu$ forward-backward asymmetry around Z pole: sensitive to QED coupling



Statistical uncertainty for one year of running at any centre-of-mass energy.

[P.Janot, JHEP 1602 (16) 053]

From $\sigma_{\mu\mu}$ measurement
- Sensitivity best "far" away from Z peak, particularly at the low side
- Systematics (normalisation) probably a killer

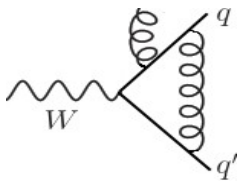
From $A_{FB}^{\mu\mu}$ measurement
- Sensitivity best at points $\sqrt{s}$ = 87.9 and 94.3 GeV
- Theoretical systs. largely cancel by "averaging" over 87.9 and 94.3 GeV points.
  - Higher order EW to be calculated (few x 10^{-4})
- Experimental systs. controlable; dominant contribution from knowledge of E_{BEAM}: 1 x 10^{-5}

- 6 months at $\sqrt{s}$ = 87.9, 94.3 GeV reduces current uncert. by factor $\times$3: $\delta\alpha/\alpha(m_Z)\sim3\cdot10^{-5}$ (mostly statistical)

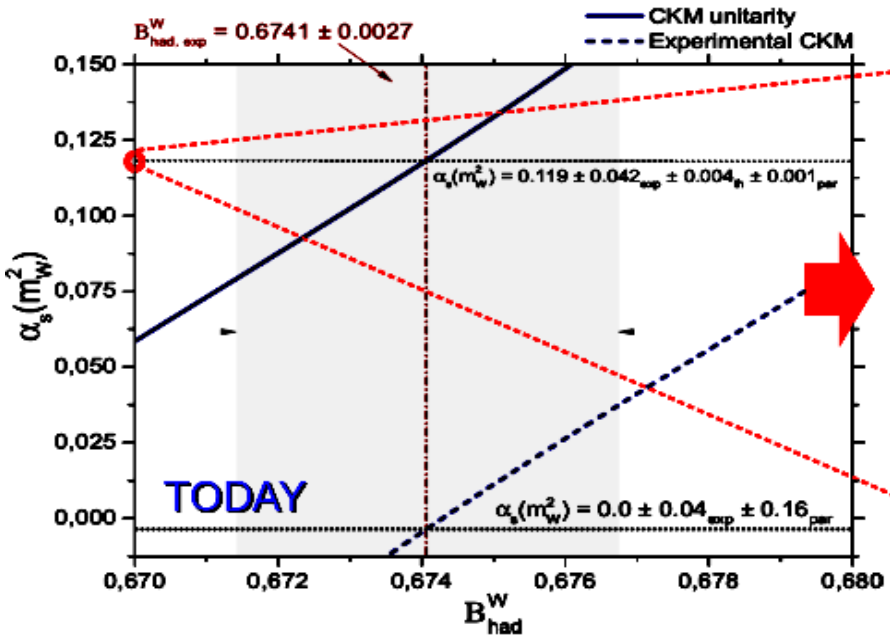
High-precision W, Z: α_s coupling

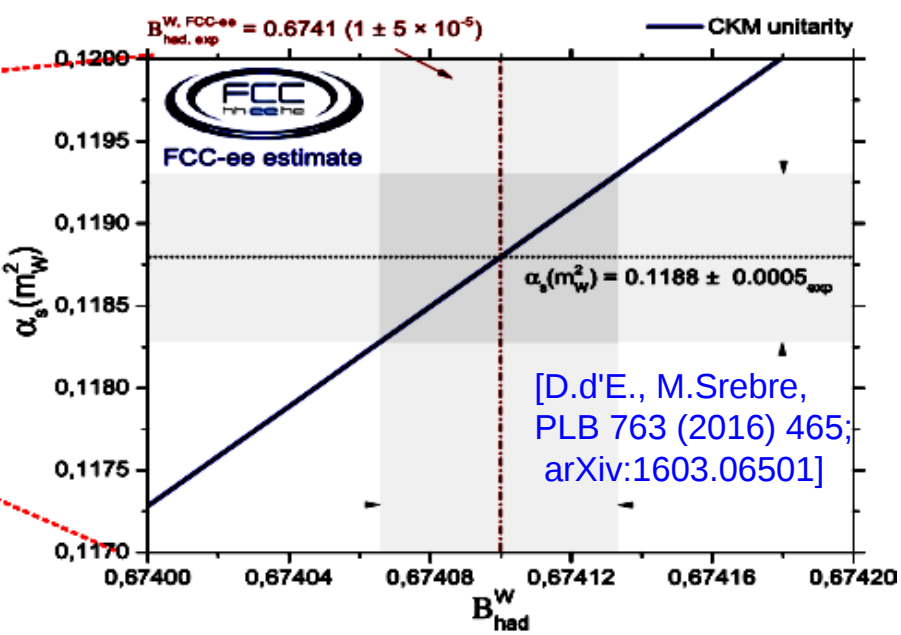
- BSM searches require reduced SM parametric uncertainties (α,α_s,m_W,..)
  - Hadronic W width (BR) known at N³LO (NNLO). Sensitivity to α_s (only beyond Born) requires exquisite experimental uncertainties:

$$\Gamma_{W,had} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks i,j}} |V_{i,j}|^2 \left[1 + \sum_{k=1}^{4} \left(\frac{\alpha_s}{\pi} \right)^k + \delta_{\text{electroweak}}(\alpha) + \delta_{\text{mixed}}(\alpha\alpha_s) \right]$$



  - Current Γ_W measurement yields poor extraction: $\delta\alpha_s$~25%
  - FCC-ee prospects: Huge $e^+e^- \to WW$ stats (10^8, $\times 10^3$ LEP): $\delta\alpha_s < 0.2\%$





[D.d'E., M.Srebre, PLB 763 (2016) 465; arXiv:1603.06501]

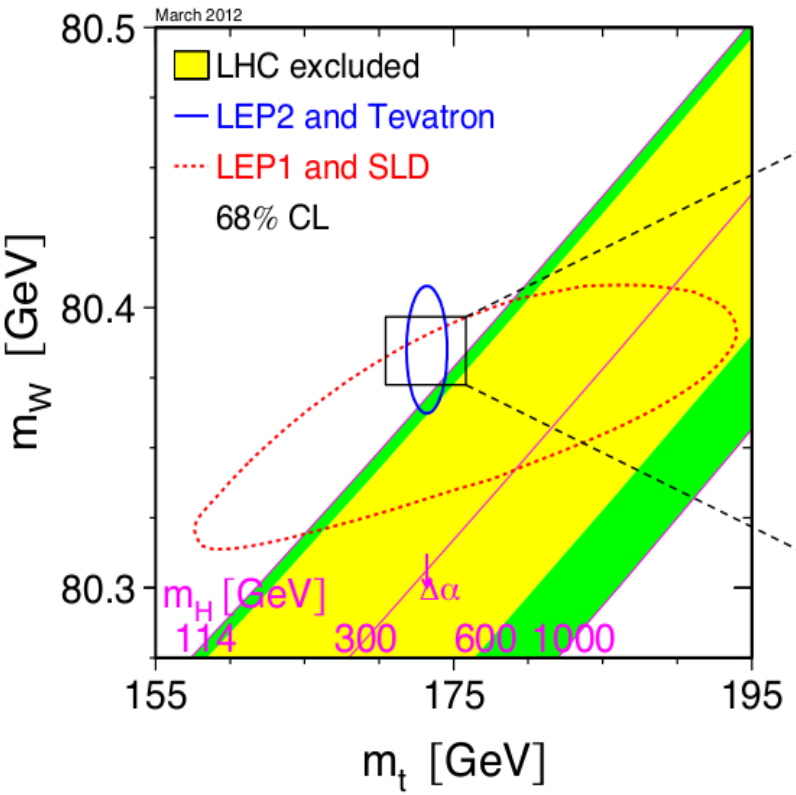
$$\alpha_s(M_Z) = 0.117 \pm 0.030_{(exp)} \pm 0.003_{(th)} \pm 0.001_{(par,CKM=1)}$$

$$\alpha_s(M_Z) = 0.1188 \pm 0.0002_{(exp)}$$

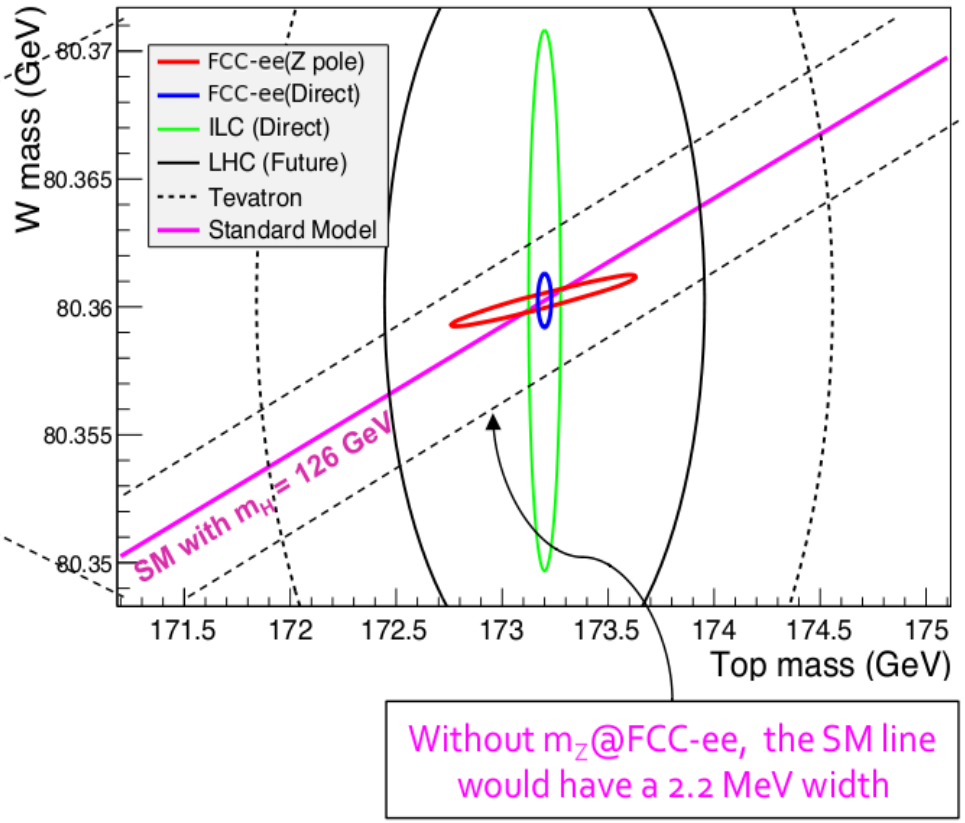
$R_W \equiv \mathcal{B}^W_{had}/\mathcal{B}^W_{lep} = \mathcal{B}^W_{had}/(1 - \mathcal{B}^W_{had})$ in three $e^+e^- \to W^+W^-$ final states ($\ell\nu\,\ell\nu$, $\ell\nu\,qq$, $qq\,qq$)

High-precision W, Z, top: BSM constraints

- **Combination of all precision electroweak measurements (Z, W, top)**
  - **In absence of new physics, the (m_{top}, m_W) plot would look like this**



[arXiv:1308.6176]



- Indirect constraints on new weakly-coupled physics:
  Precision ~ $1/\Lambda^2_{NP}$, i.e. Λ^2_{NP} ~ O(30–100 TeV)

High-precision W, Z, top: Weakly-coupled BSM

- Higher-dimensional operators as relic of new physics
  - Possible corrections to the Standard Model Lagrangian

$$L_{\text{eff}} = \sum_n \frac{c_n v^2}{2} O_n$$

$$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$

$$\mathcal{O}_{LL}^{(3)l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$

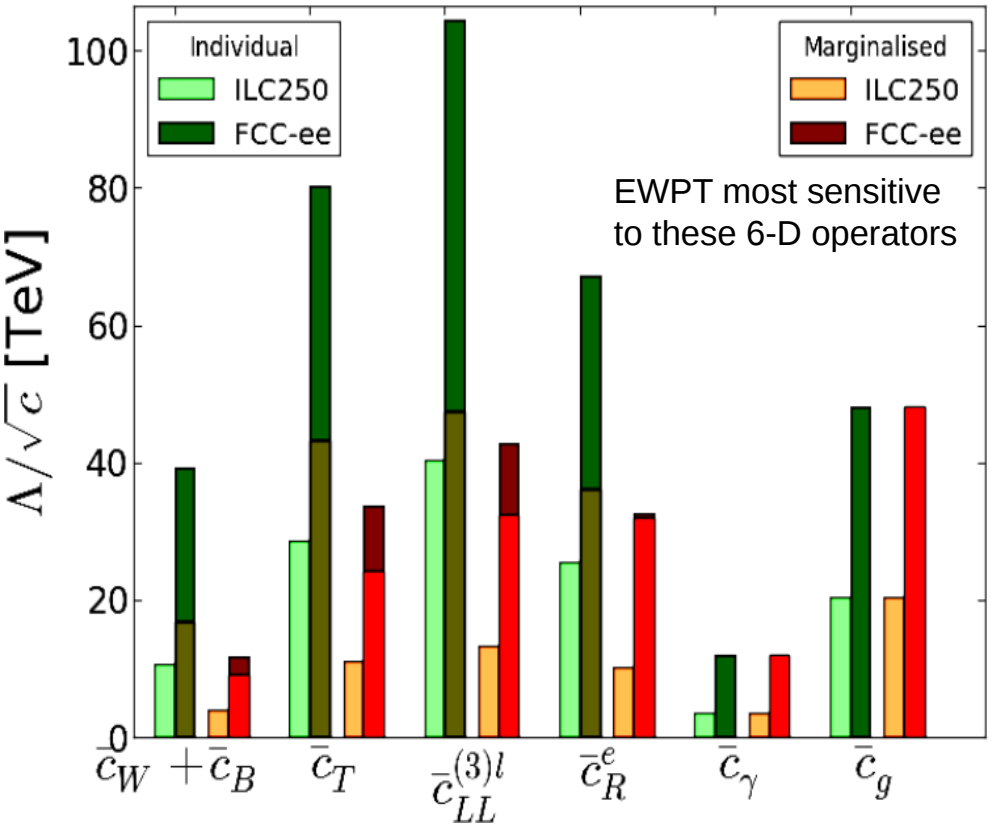
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

LEP constraints: Λ_{NP} >3-10 TeV

After FCC-ee: Λ_{NP} > 30-100 TeV

Sensitivity to Weakly-coupled NP

Dim-6 operators
Pomarol & Riva basis
[arXiv:1308.1426]



[J. Ellis and T. You, arXiv:1510.04561]

Open issue in the SM (1): Hierarchy problem solved via BSM scalar-coupled physics

- Many BSM realizations: SUSY, little-H, 2HDM, composite H,...
- Parametrize (B)SM as an Effective Field 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:

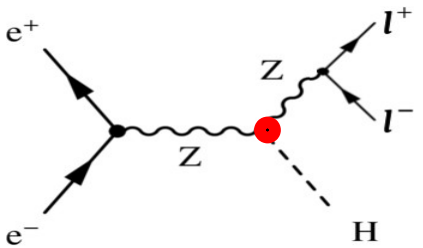
$$\Lambda \gtrsim (1\,\text{TeV}) / \sqrt{(\delta g_{\rm HXX}/g_{\rm HXX}^{\rm SM})/5\%}$$

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

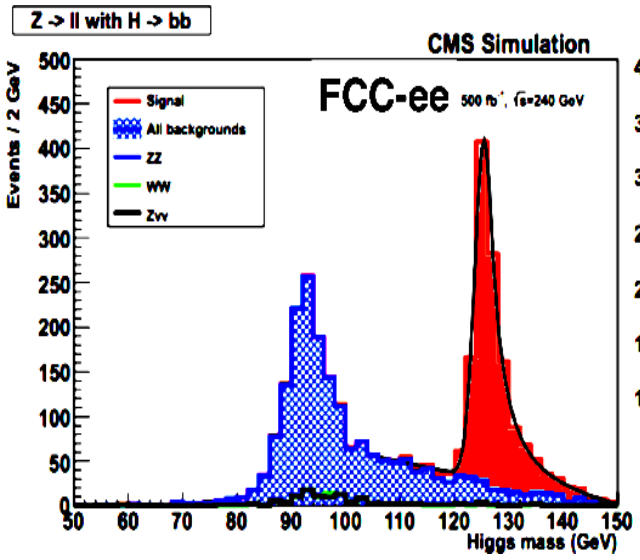
~0.1% Higgs couplings precision (~10^6 Higgs) ⇒ Λ>7 TeV

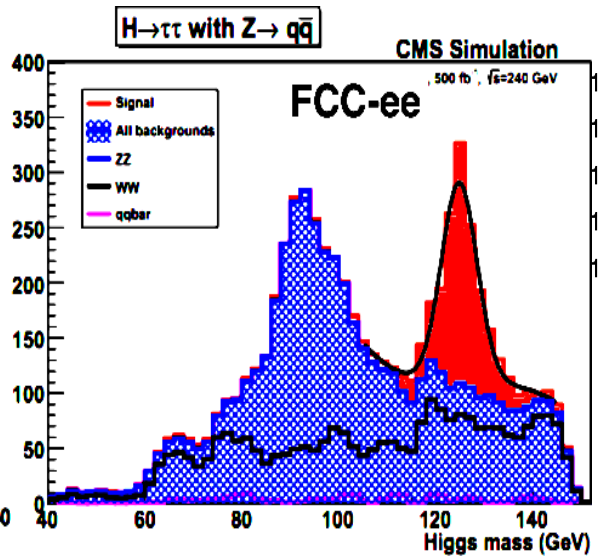
Precision H couplings, width, mass at FCC-ee

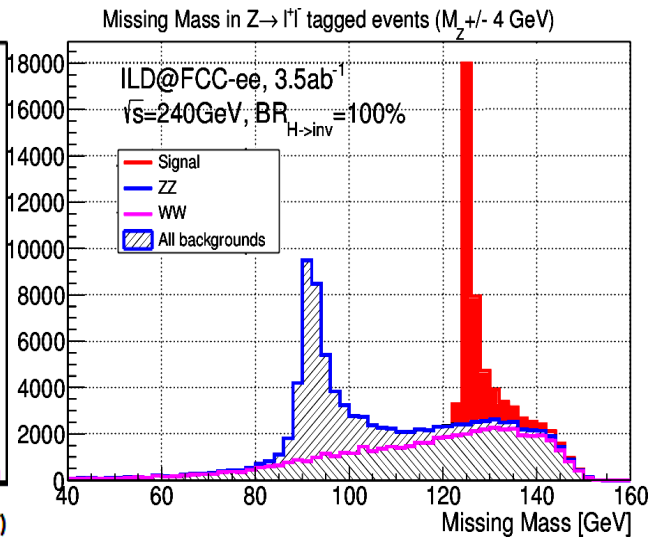
- Recoil method in H-Z(ll) unique to lepton collider: reconstruct H 4-mom. independent of H decay mode.
- High-precision (0.4%) σ_{ZH} provides model-indep. g_Z coupling ($\sigma(ee \to ZH) \propto g_Z^2$), with ±0.2% uncert.



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







- Total width (Γ_H) with ~1% precision from combination of measurements: $\sigma(ee \to ZH(\to X)) \propto \Gamma_{H\to X}$, plus known BR $(H \to X) = \Gamma_{H\to X}/\Gamma_H$: Obtain Γ_H
- Limits in branching fraction to invisible down to <0.5% @ 95% CL
- Higgs mass (m_H) from recoil mass in $Z \to \mu\mu$,ee.

Precision H couplings, width, mass at FCC-ee

- e^+e^- colliders provide factor > 50 (10) improvement in precision w.r.t. Model-dependent! LHC (HL-LHC) expectations:

[DdE, arXiv:1701.02663]

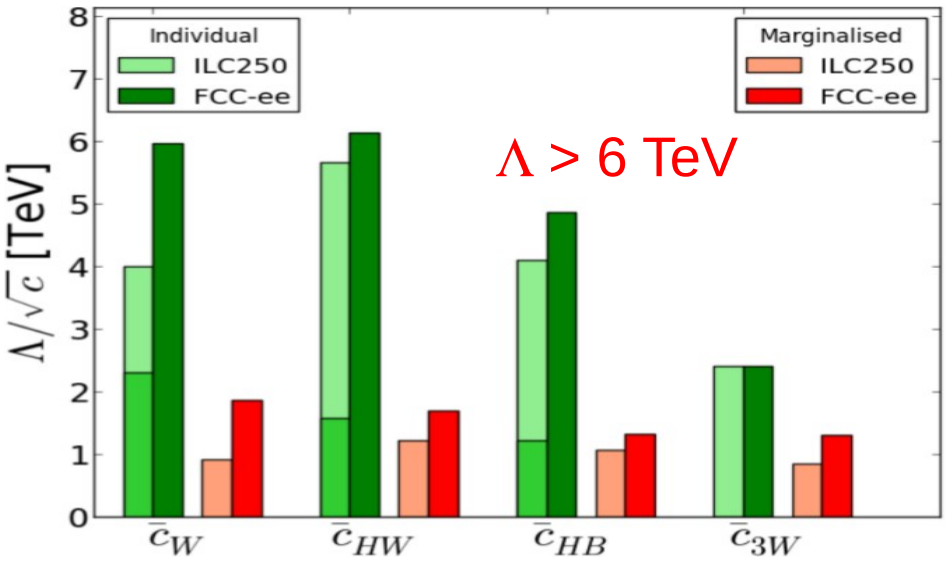
Parameter	Current* 7+8+13 TeV $\mathcal{O}$ (70 fb^{-1})	HL-LHC* 14 TeV (3 ab^{-1})	FCC-ee Baseline (10 yrs)	ILC Lumi upgrade (20 yrs)	CEPC Baseline (10 yrs)	CLIC Baseline (15 yrs)
σ(HZ)	–	–	0.4%	0.7%	0.5%	1.6%
g_{ZZ}	10%	2–4%	0.15%	0.3%	0.25%	0.8%
g_{WW}	11%	2–5%	0.2%	0.4%	1.6%	0.9%
g_{bb}	24%	5–7%	0.4%	0.7%	0.6%	0.9%
g_{cc}	–	–	0.7%	1.2%	2.3%	1.9%
$g_{\tau\tau}$	15%	5–8%	0.5%	0.9%	1.4%	1.4%
$g_{t\bar{t}}$	16%	6–9%	13%	6.3%	–	4.4%
$g_{\mu\mu}$	–	8%	6.2%	9.2%	17%	7.8%
$g_{e^+e^-}$	–	–	<100%	–	–	–
g_{gg}	–	3–5%	0.8%	1.0%	1.7%	1.4%
$g_{\gamma\gamma}$	10%	2–5%	1.5%	3.4%	4.7%	3.2%
$g_{Z\gamma}$	–	10–12%		(to be determined)		9.1%
Δm_H	200 MeV	50 MeV	11 MeV	15 MeV	5.9 MeV	32 MeV
Γ_H	<26 MeV	5–8%	1.0%	1.8%	2.8%	3.6%
Γ_{inv}	<24%	<6–8%	<0.45%	<0.29%	<0.28%	<0.97%

- Most precise g_{ZZ} ~0.2% coupling sets limit on new scalar-coupled physics at: $\Lambda \gtrsim (1\,\mathrm{TeV})/\sqrt{(\delta g_{HXX}/g_{HXX}^{SM})/5\%}$ > 6 TeV

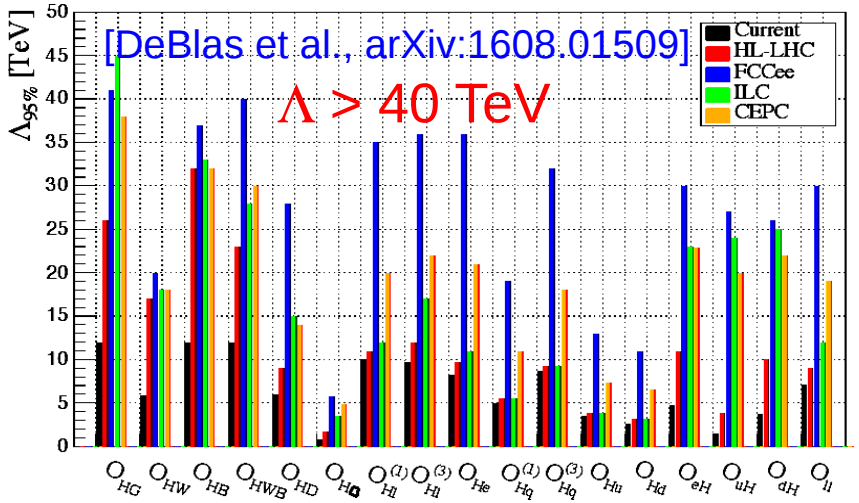
Precision H+EWK properties: BSM bounds

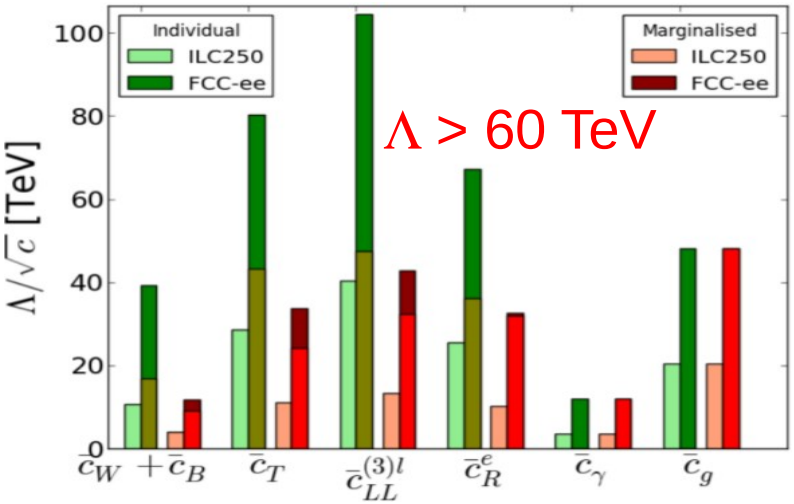
- FCC-ee Higgs boson precision measurements improve greatly scalar-coupled BSM limits.

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



- NP bounds: Higgs & Higgs+EWPO combined

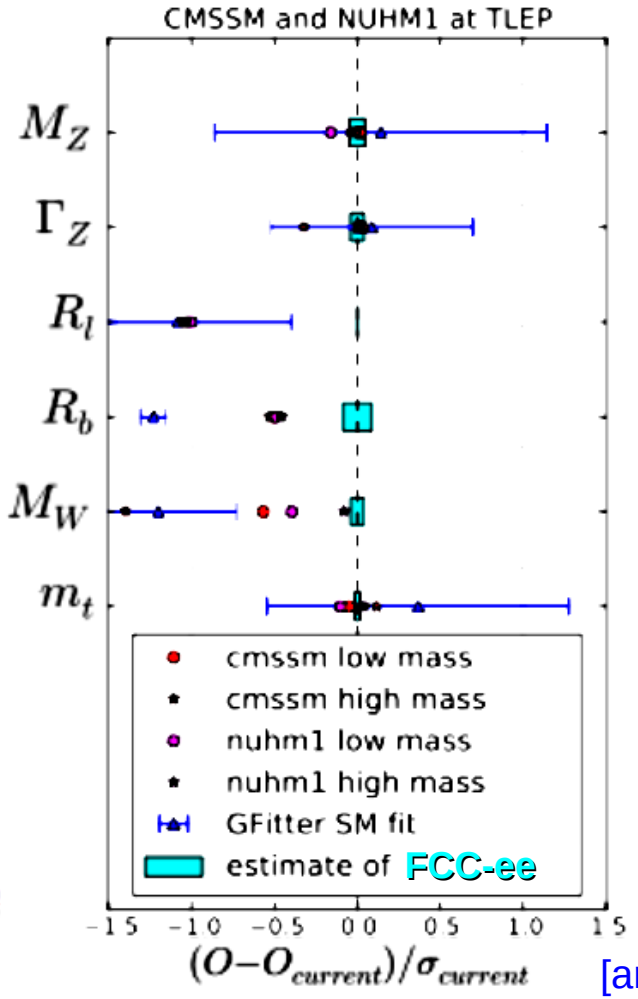




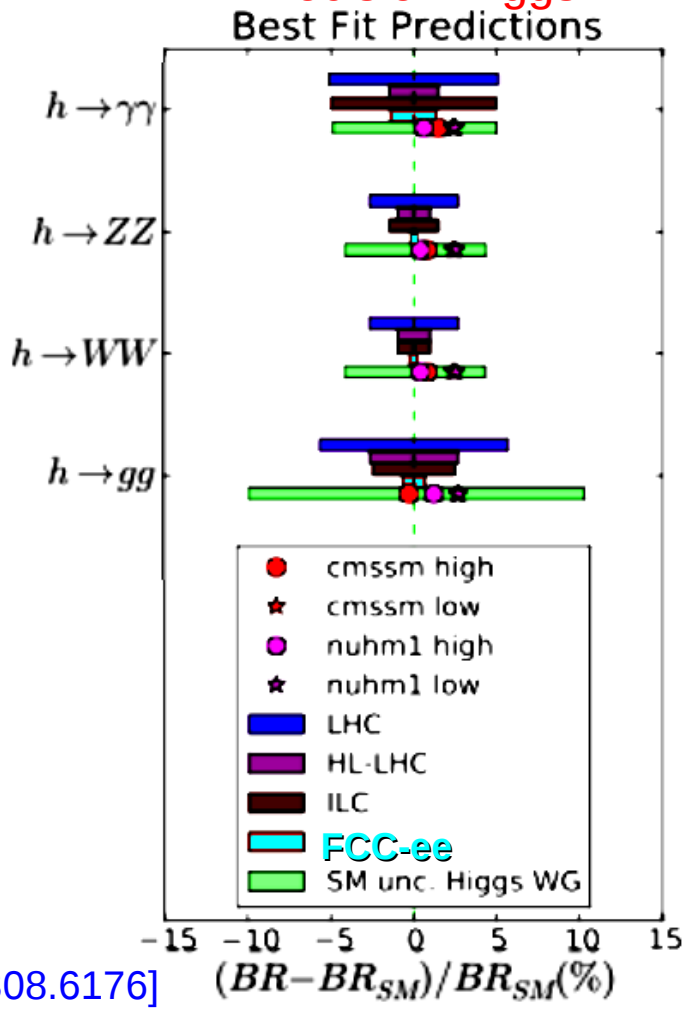
New physics constraints: SUSY

- FCC-ee measurements significantly improve limits in benchmark SUSY models (CMSSM, NUHM1):

Precision Electroweak

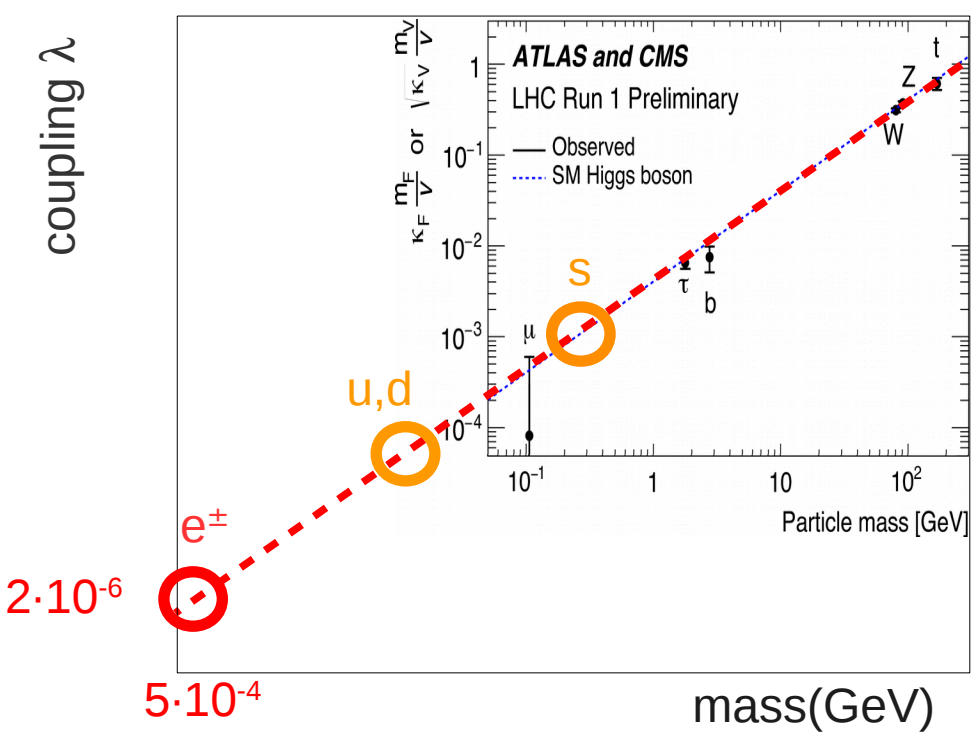


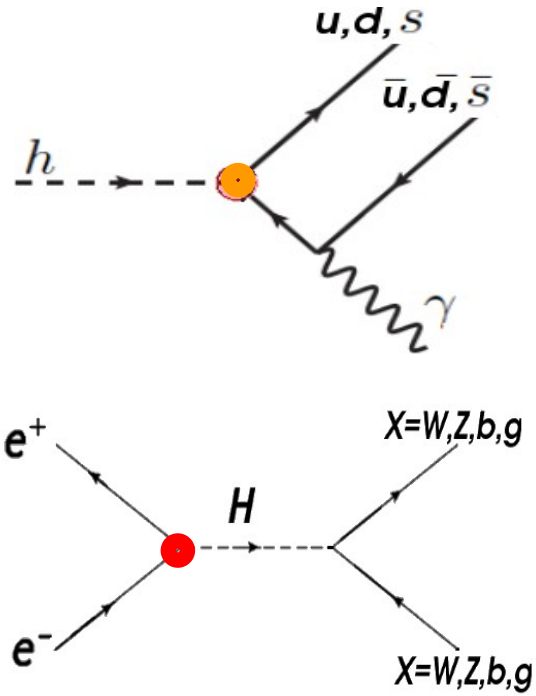
Precision Higgs



[arXiv:1308.6176]

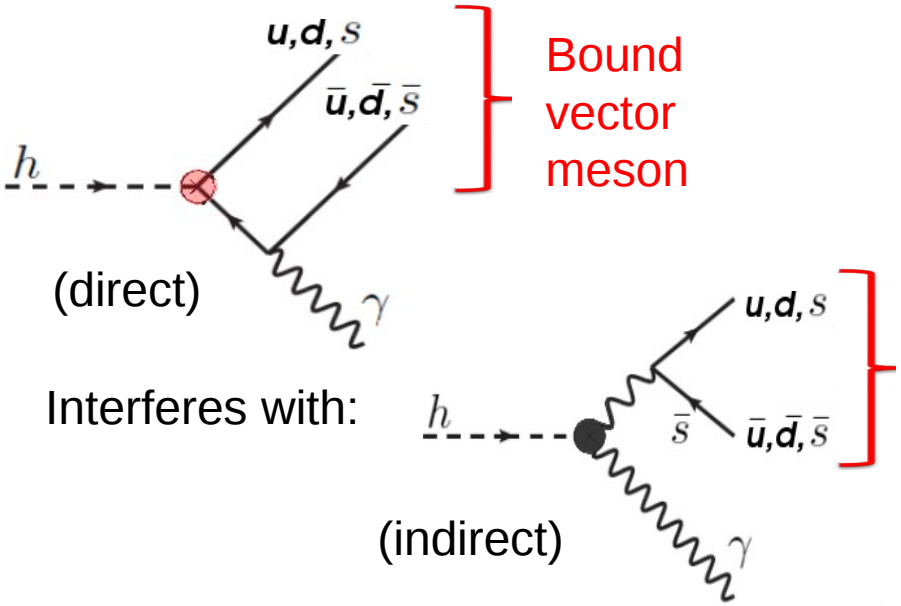
Open issue in the SM (3): Generation of lightest fermion masses (u,d, e)





1st-gen. quark Yukawa couplings at FCC-ee

- 1st & 2nd gen. quark Yukawa accessible via exclusive $H \to V\gamma$, $V=\rho,\omega,\phi$



[G. Perez et al, arXiv:1505.06689]

Mode / Method	Branching Fraction $[10^{-6}]$ 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

- $H \to \rho(\pi\pi)\gamma$ channel most promising: N~40 counts expected, low backgds
- Sensitivity to u/d quark Yukawa couplings:

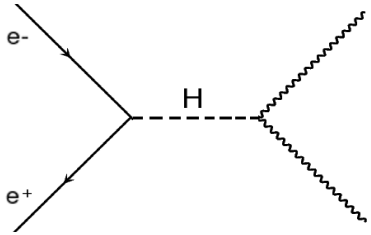
$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2} \times 10^{-5}$$

($k_q = y_q/y_b$)

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

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

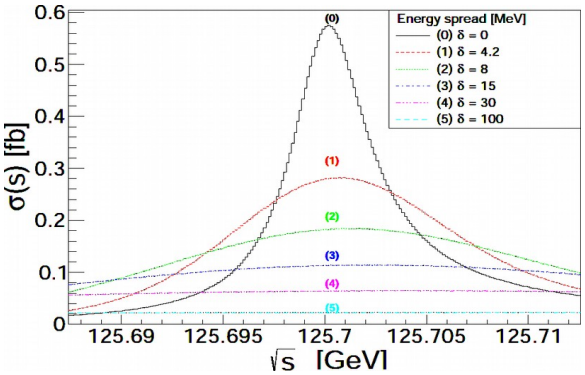
- Resonant s-channel Higgs production at $\sqrt{s}$ = 125 GeV has tiny x-sections:



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

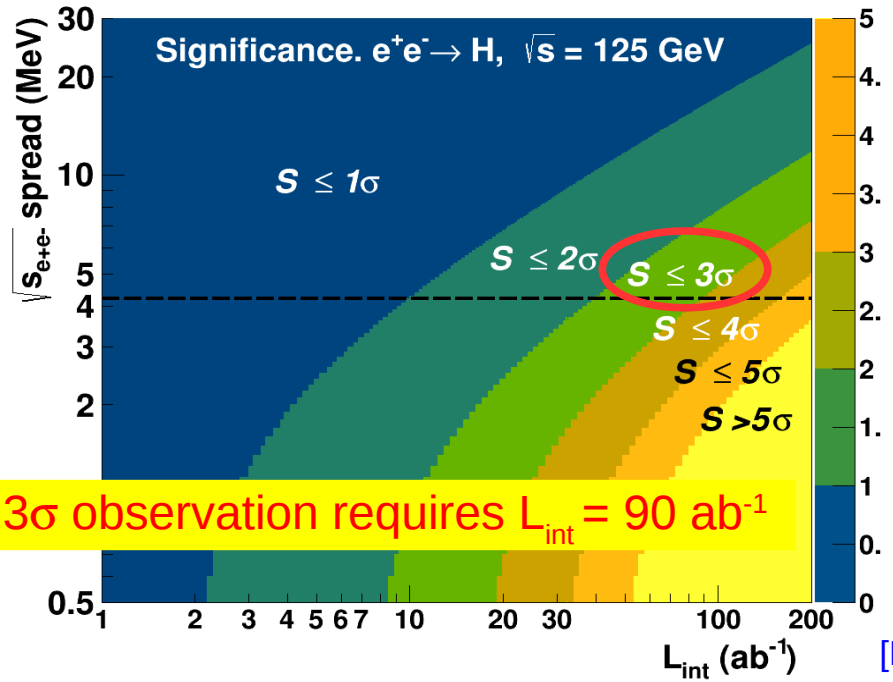
$\sigma(e^+e^- \to H)_{\text{visible}} = 290$ ab

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

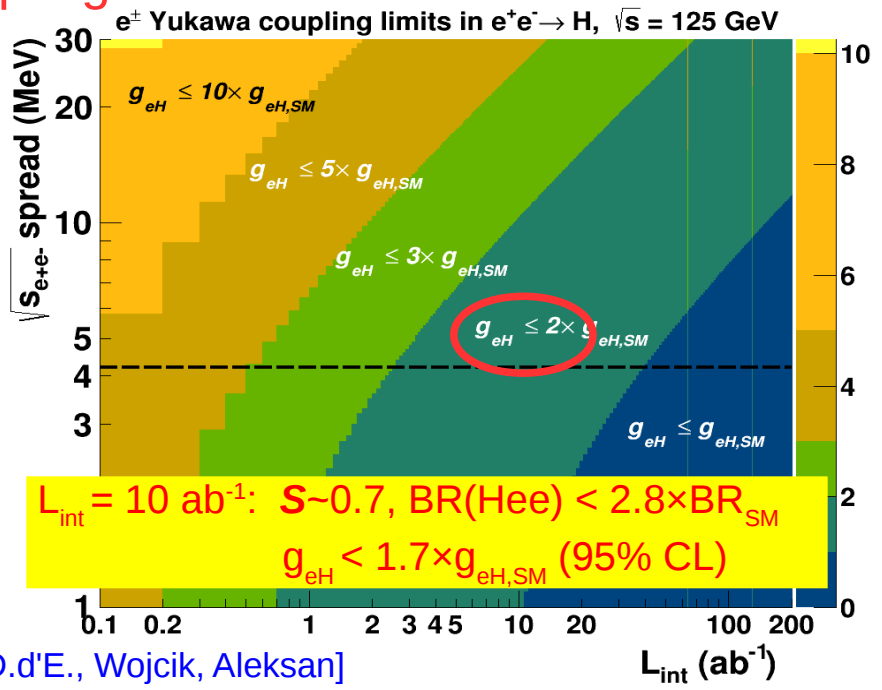


Mono-chromatization required to achieve $\sqrt{s}_{\text{spread}} \sim \Gamma_H$

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



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

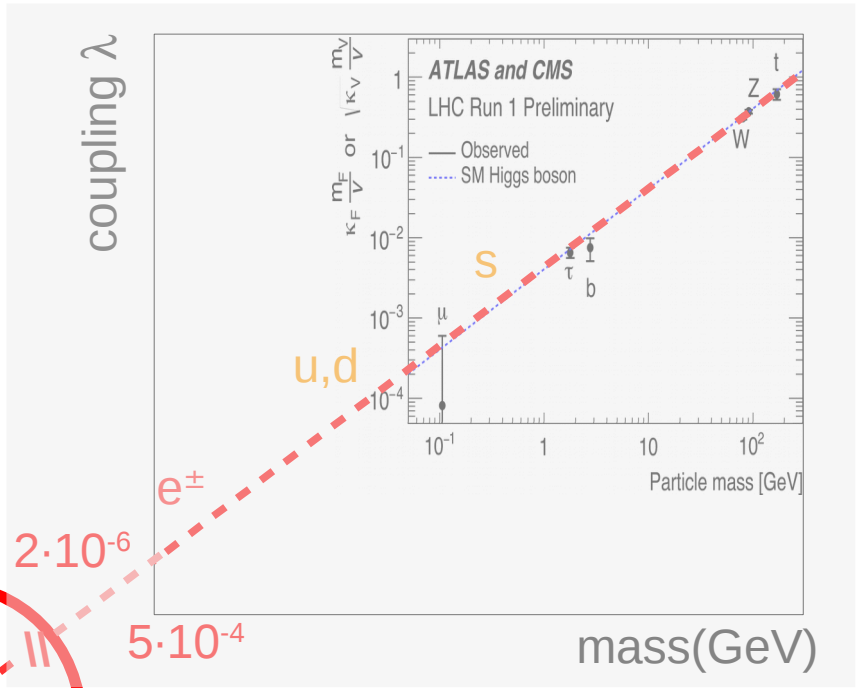


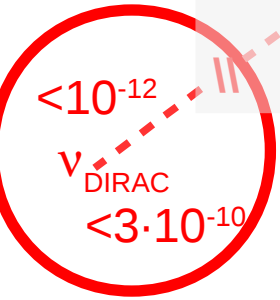
L_{int} = 10 ab^{-1}: S~0.7, BR(Hee) < 2.8×BR$_{SM}$

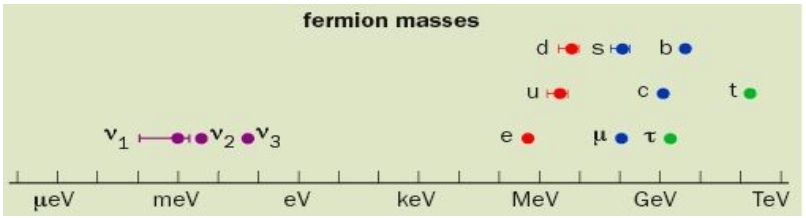
$g_{eH} < 1.7 \times g_{eH,SM}$ (95% CL)

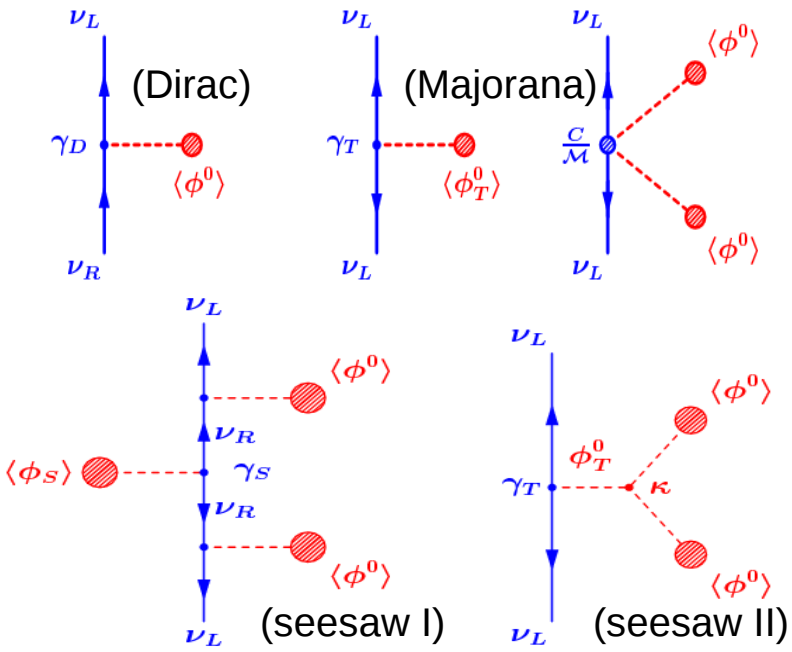
[D.d'E., Wojcik, Aleksan]

Open issue in the SM (4): Generation of neutrino masses



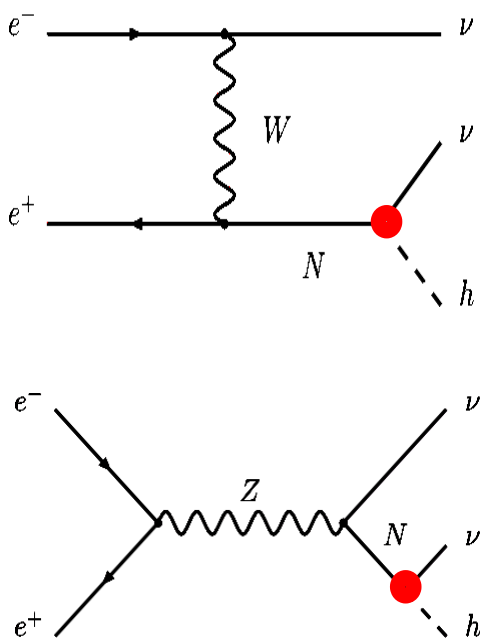


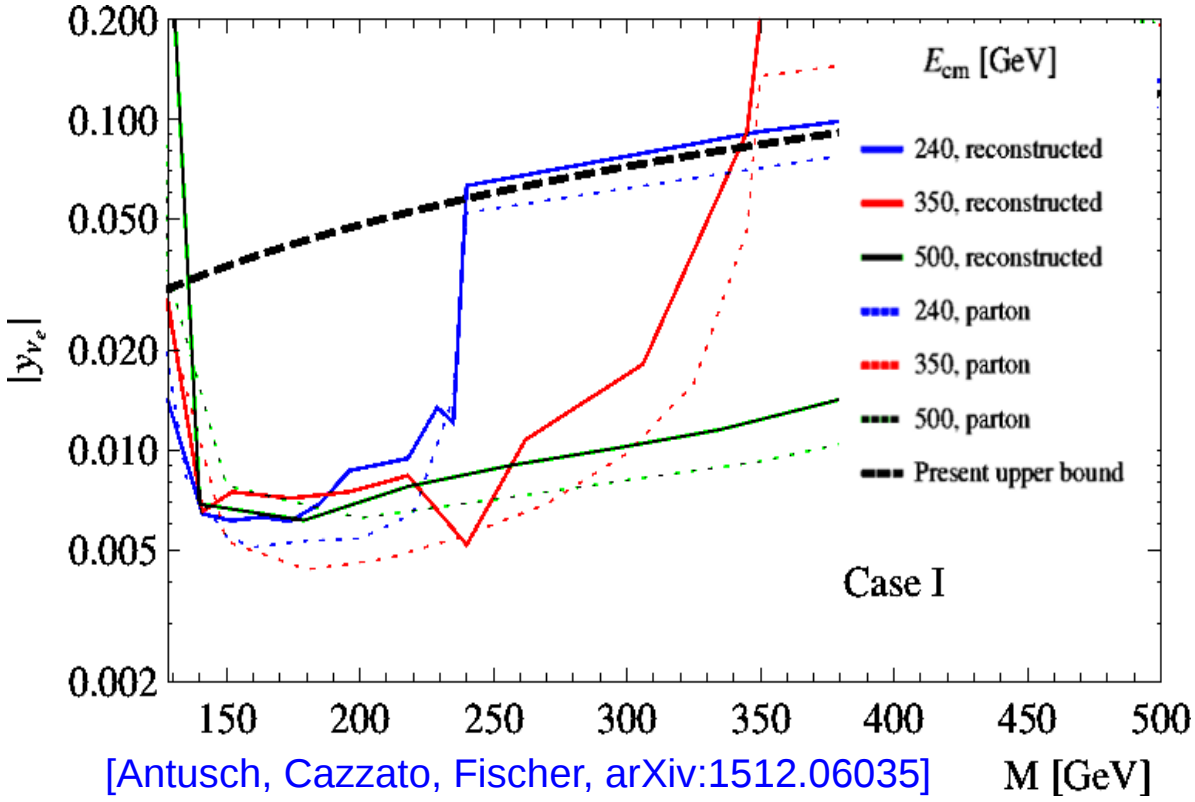




Righ-handed neutrinos decaying into Higgs

- 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]

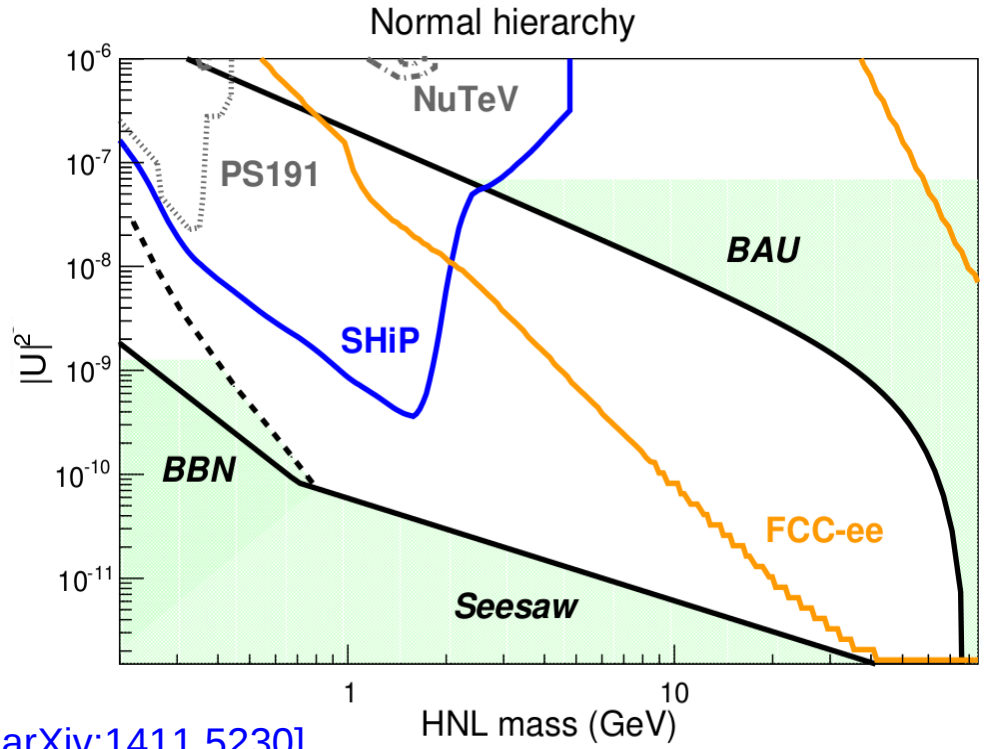
- FCC-ee sensitivity down to $|y_{\nu e}| \sim 5 \times 10^{-3}$ for unexplored $m_N \sim 100$–300 GeV

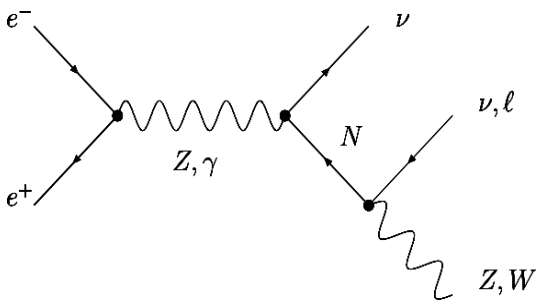
Righ-handed neutrinos via Z decays

- **Opportunities for direct searches for new physics through rare decays**
  - 10^{12} (10^{13}) Z, 10^{11} b, c or τ : A fantastic potential that remains to be explored.
  - E.g, search for right-handed neutrino in Z decays

$$Z \rightarrow N\nu_i, \text{ with } N \rightarrow W^{*}l \text{ or } Z^{*}\nu_j$$

- Number of events depend on mixing between N and ν, and on m_N

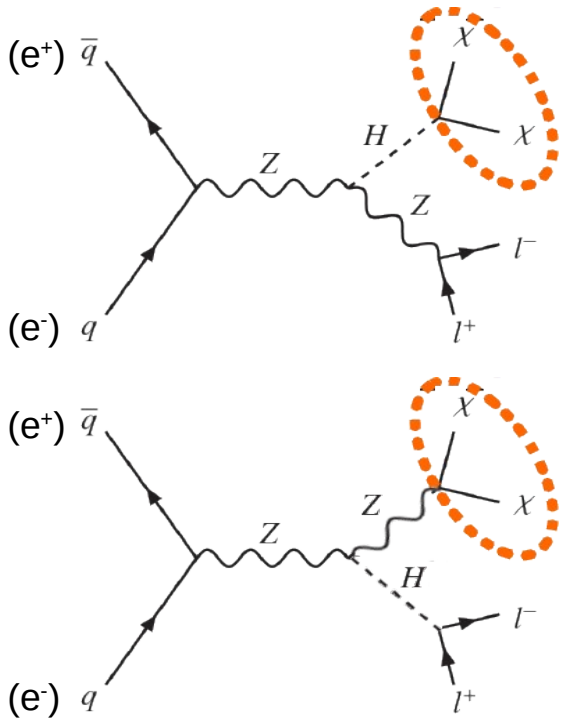


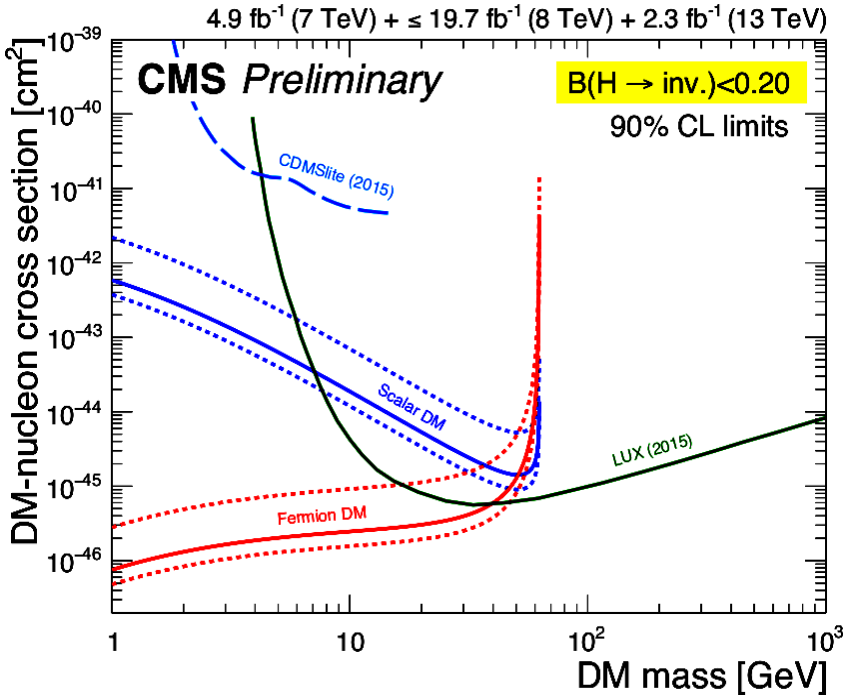


[A. Blondel et al. arXiv:1411.5230]

Open issue in the SM (5): Dark matter

For $M_{DM}<M_{H,Z}/2$:

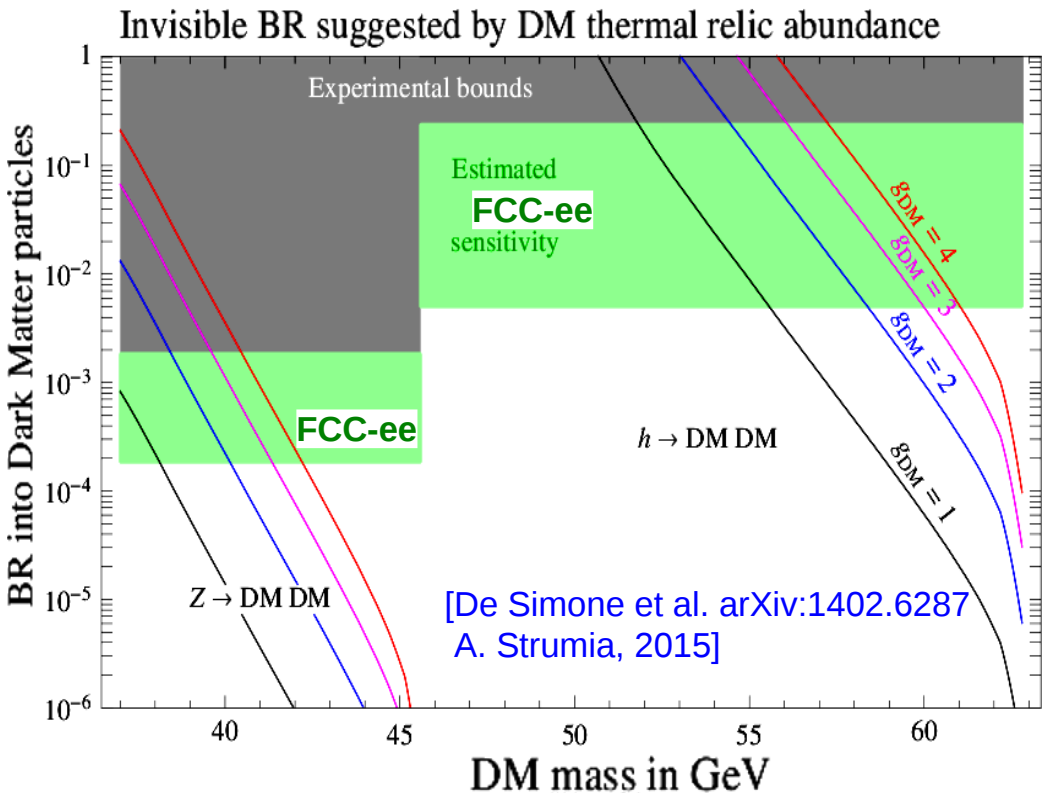


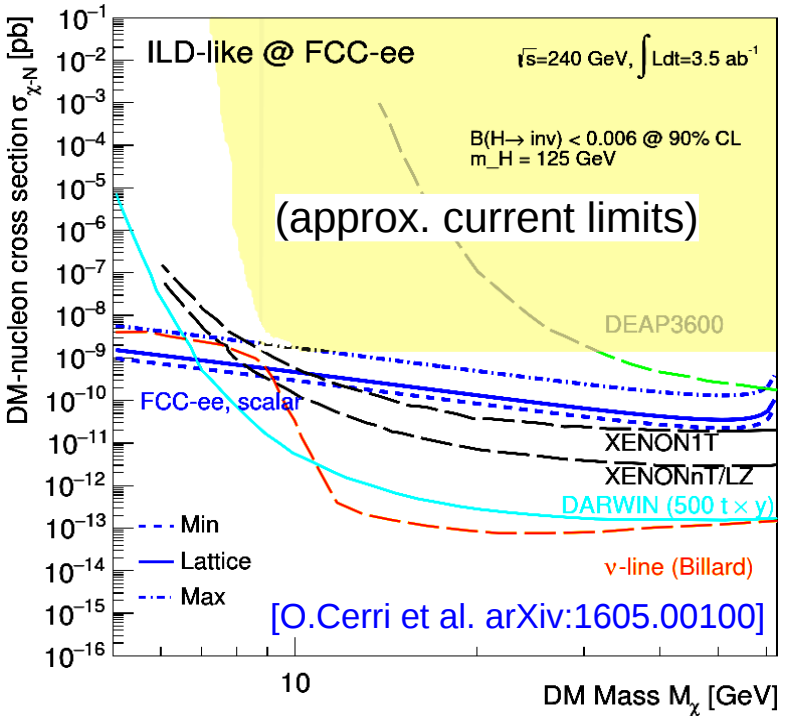


[B(H→inv)>5% for HL-LHC]

Dark Matter via invisible Z & H decays

- DM freeze-out fixes $\sigma \cdot v \approx 3\ 10^{-26} cm^3/s$. If m_{DM} is just below $m_{Z,H}/2$, then DM freeze-out dominated by resonant Z,H exchange, fixing $\Gamma_{Z,H}$.



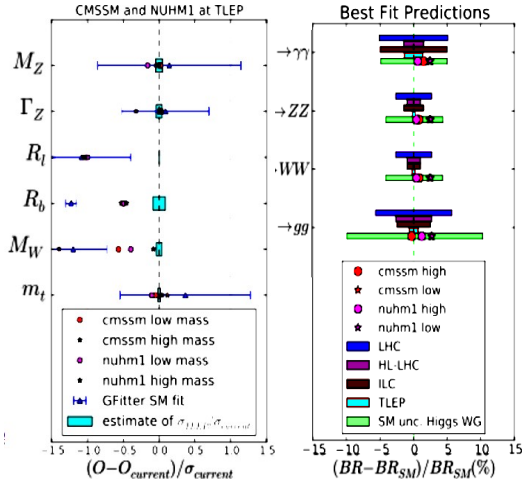


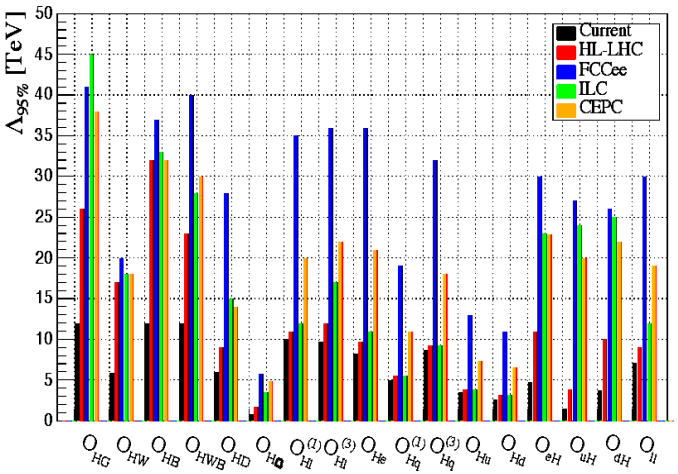
- <10^{-3},<10^{-1} precision measurements of Z & H inv. widths are best collider option to test any $m_{DM}<m_{Z,H}/2$ coupling via SM mediators

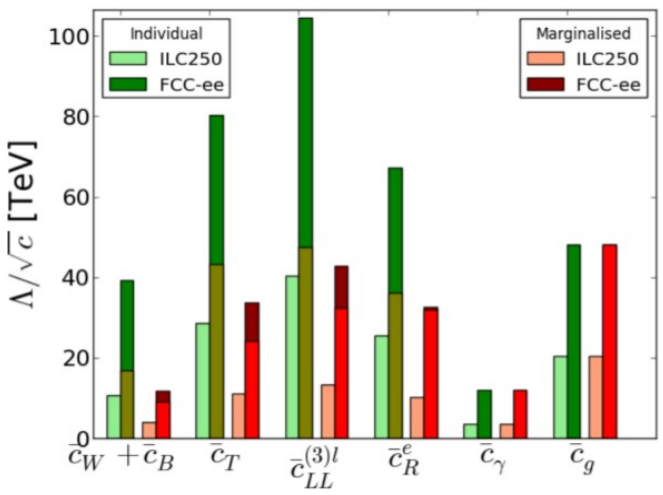
- Limits on σ(DM-nucleon) vs. m_{DM} in Higgs-portal models competitive with future direct DM-searches experiments.

Summary

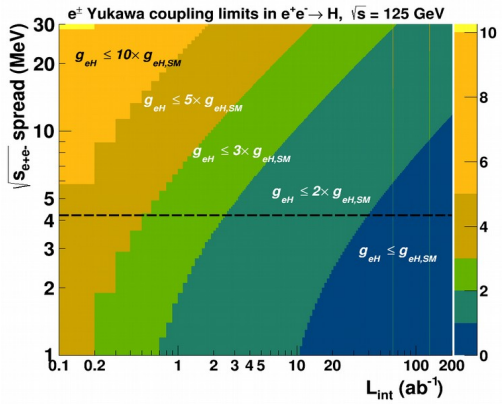
- FCC-ee circular (R~100 km) collider provides unparalleled luminosities O(1–100 ab^{-1}) at √s = 90–350 GeV for high-precision W,Z,H,t studies (<<1% uncert.) setting unique new physics constraints up to O(6–100 TeV)

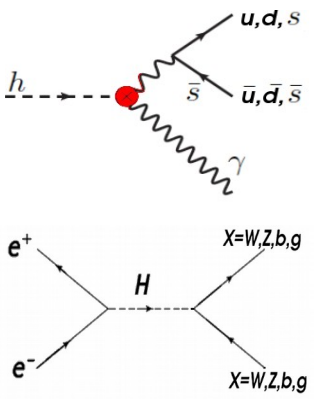


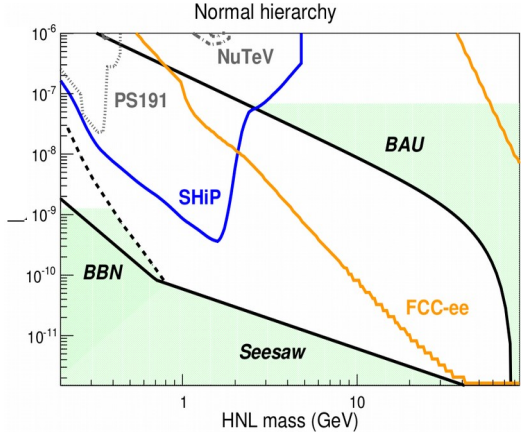


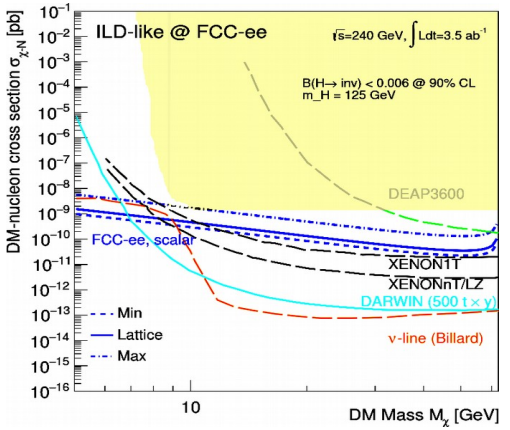


- Plus: 1st gen. Yukawas, right-handed ν's, dark matter, …









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→lν2j,2l2ν,4j	0.15⊕0.09⊕0.03	0.50⊕0.30⊕0.08
ZZ→2j2ν,2l2j,2l2ν	0.07⊕0.05⊕0.01	0.21⊕0.16⊕0.03
bb	0.03	0.10
gg	0.03	0.09
ττ	–	0.02
γγ	–	0.01
Combined	**0.2**	**0.7**

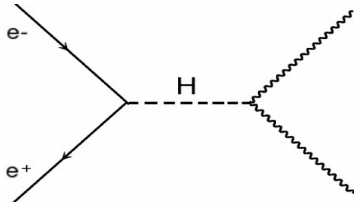
- For 10 ab^{-1}: Significance ≈ 0.7 (preliminary, optimizations under study)

  Limit (95% CL) for branching ratio: $BR(H\rightarrow ee) < 2.8\times BR_{SM}(H\rightarrow ee)$

  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):



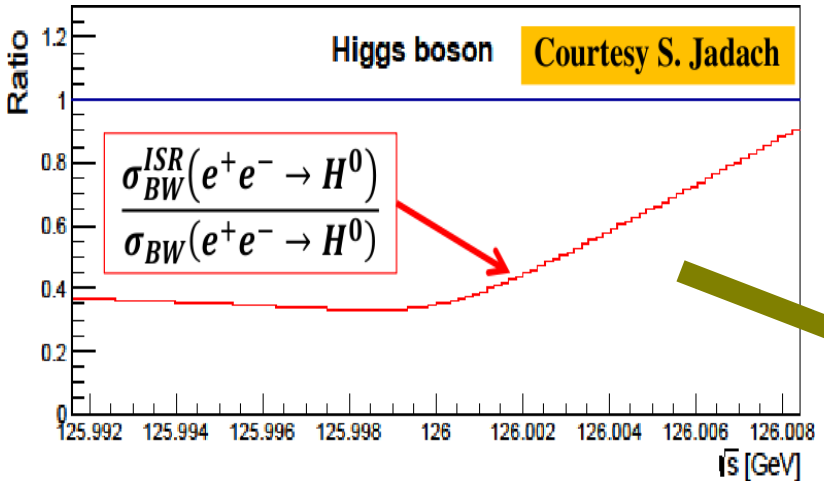
$\sigma(e^+e^- \to H)_{B\text{-}W} \sim 1.64$ fb

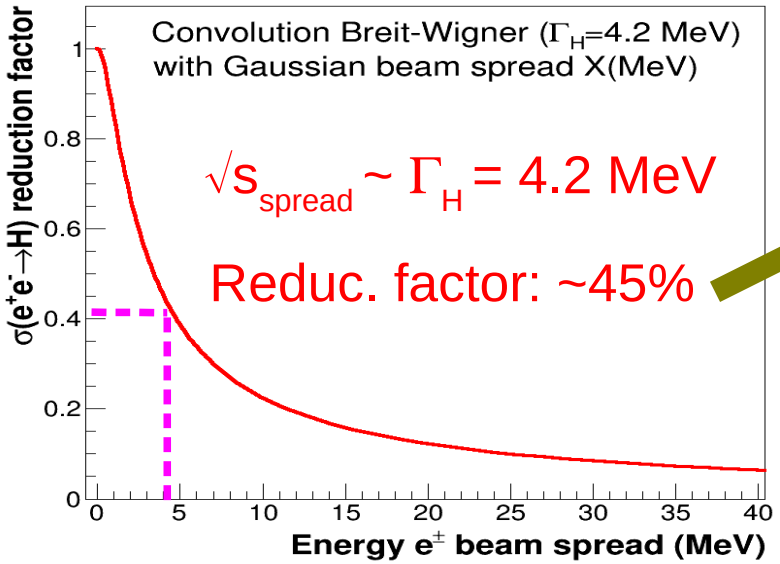
$\sigma(e^+e^- \to H)_{visible} \sim 280$ ab (ISR + $E_{beam\text{-}spread} \sim \Gamma_H = 4.2$ MeV)

- 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)

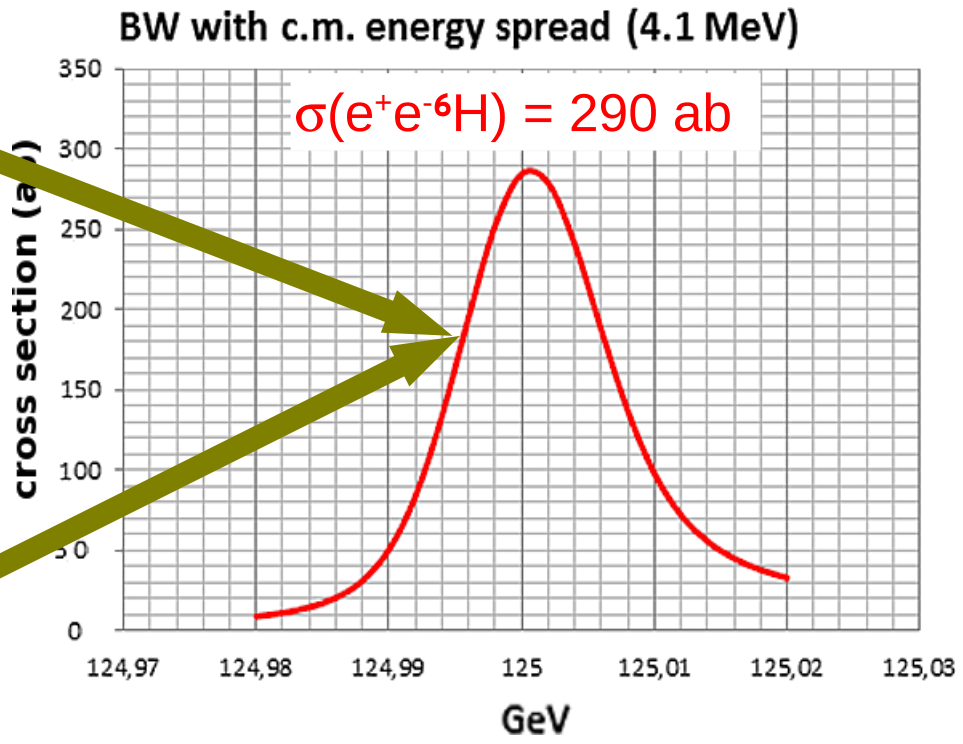
$\sigma(e^+e^- \to H)$ reduction: Beam energy spread + ISR

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





- Combined reduction factors:



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

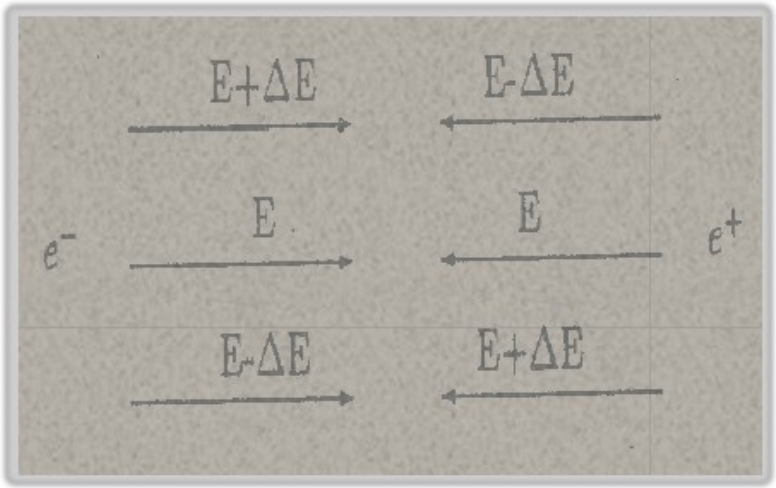
mono-chromatization at 2x63 GeV?

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?

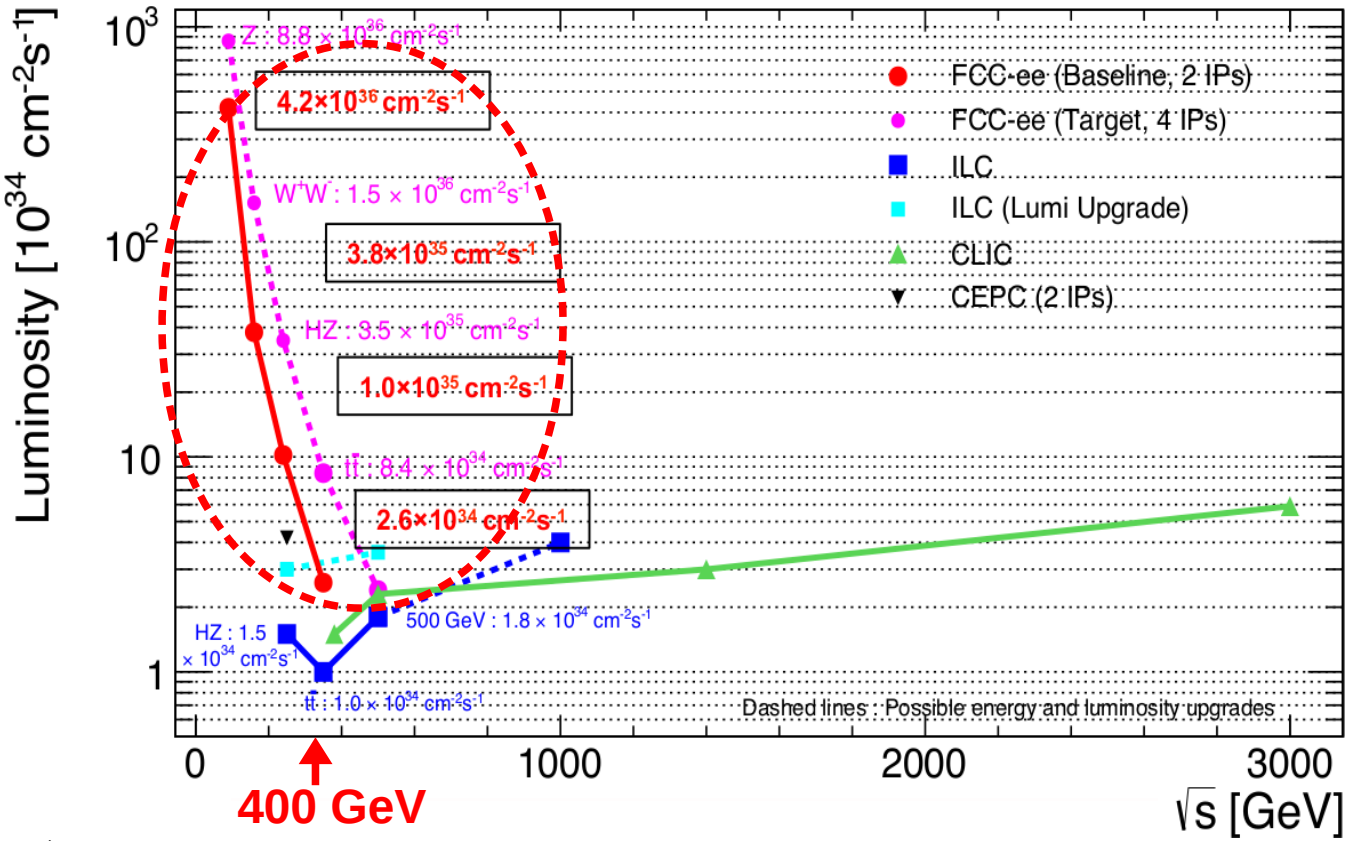
e+e- colliders: FCC-ee vs. LEP, CepC

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**

FCC-ee characteristics

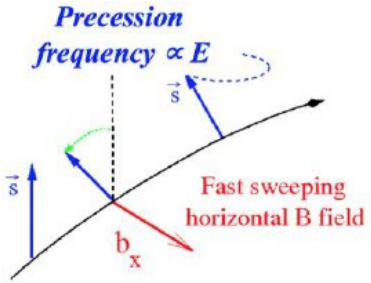


- √s limited to ~400 GeV by SR~E^4/R: R~80 km (×3 LEP radius)
- Large # of circulating bunches: ×10^4 LEP bunches +crab-waist collisions
  - → High Lumi (better at low √s): ×10^4–10 more lumi than ILC for √s = 90–400 GeV
  - → Top-up injection ring to compensate L burnoff
- Various Interaction Points possible: 2 baseline, 4 target
- Precise E_{beam} from resonant depolarization: ±0.1 MeV (2 MeV at LEP)

Beam energy spread via resonant depolarization

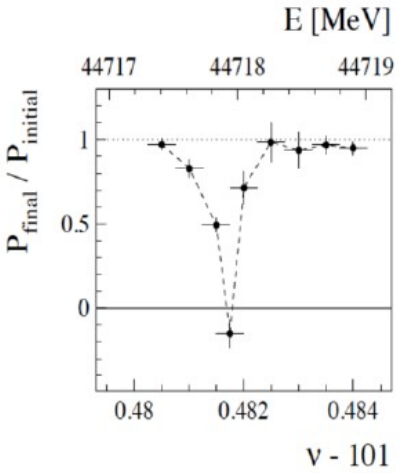
Resonant depolarization

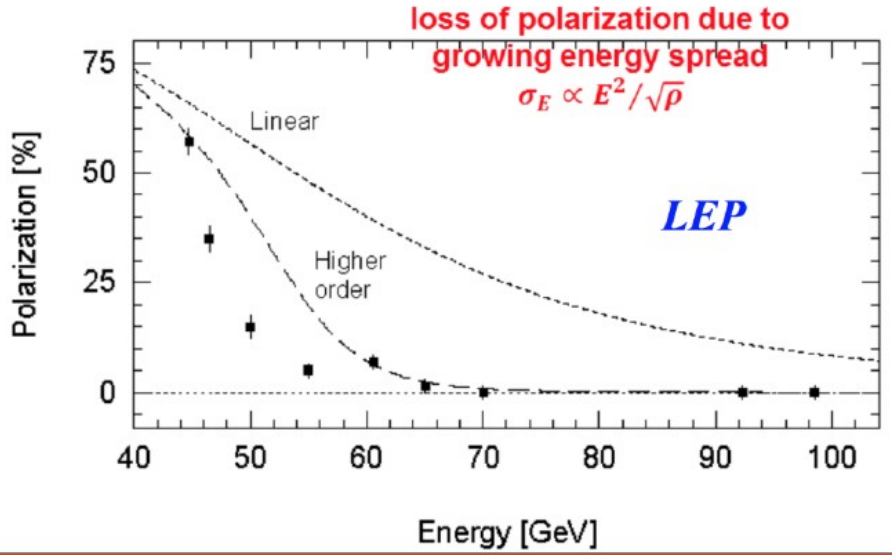
- use naturally occuring transverse beam polarization
- add fast oscillating horizontal B field to depolarize at Thomas precession frequency



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:

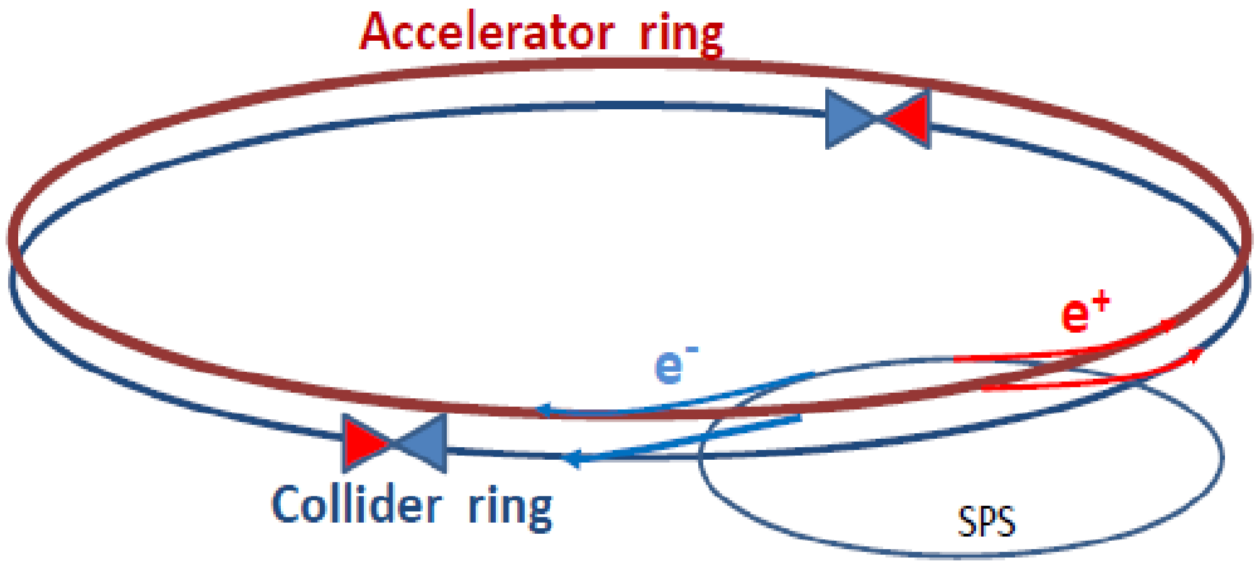
- Polarization expected up to the WW threshold

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

Luminosity gain: FCC-ee vs. LEP

Employ B-factory design to gain factor ~500 w.r.t. LEP:
Low vertical emittance combined small value of β^*_y (very strong focussing in vertical plane):

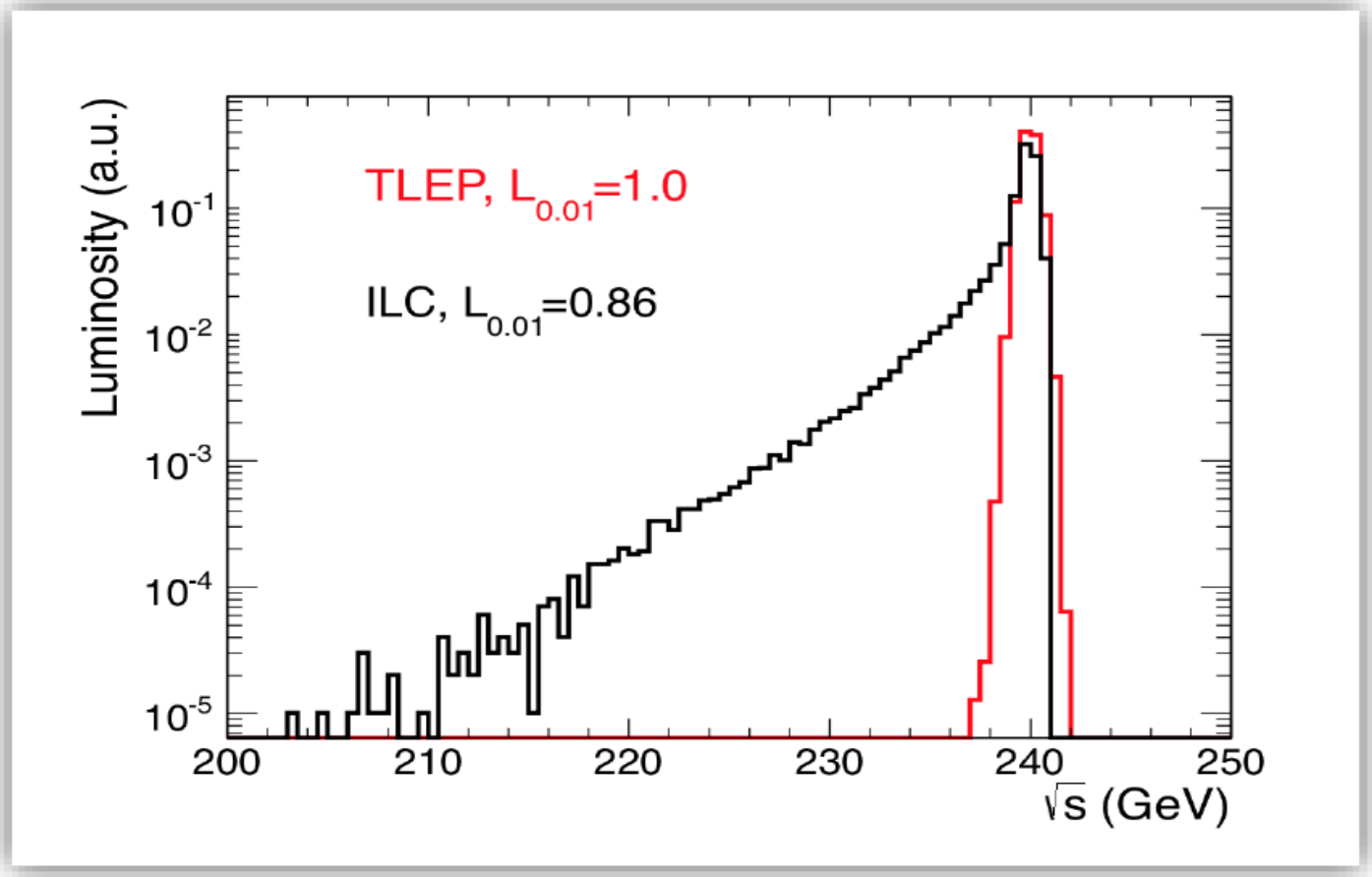
- Electrons and positrons have a much higher chance of interacting
- ➢ Very short beam lifetimes (few minutes)
- ➢ Top-up injection: feed beam continuously with an ancillary accelerator



Two separate beam pipes for e^+ and e^- to avoid collisions away from IPs

Hence, a total of three beam pipes

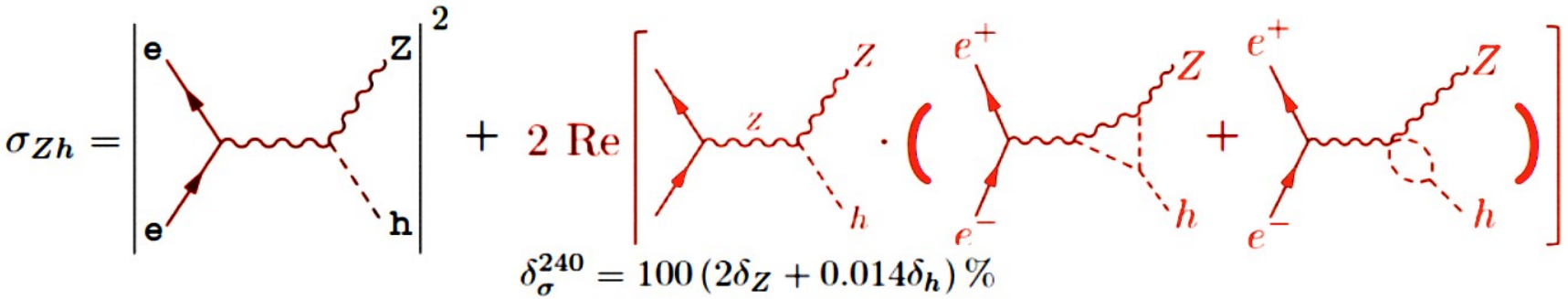
FCC-ee beam energy spread



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

Higgs physics at FCC-ee(240): Self-coupling

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

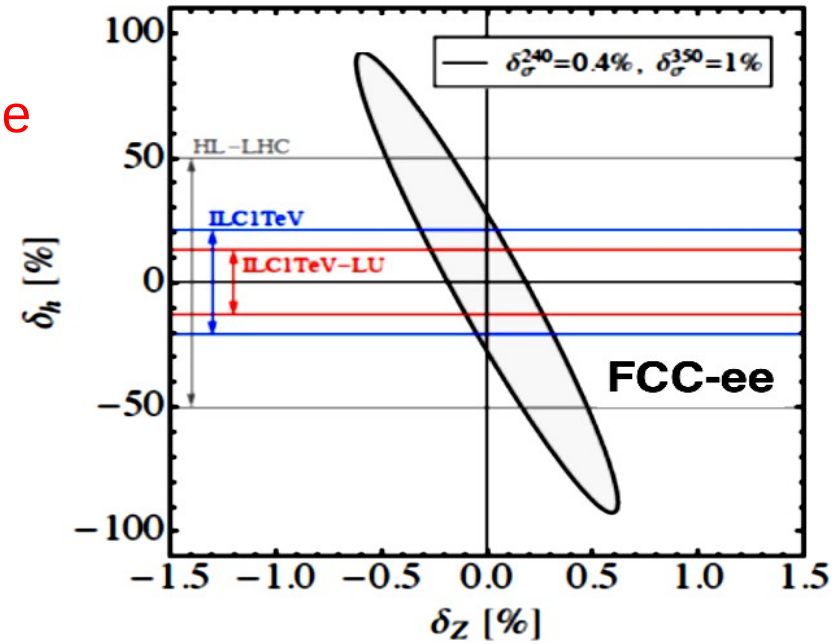


Self-coupling correction δ_h: energy-dependent
δ_Z: energy-independent (distinguishable).

- Tiny effect but visible thanks to extreme precision on g_{ZH} (0.05%) coupling reachable at FCC-ee.

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

[M. McCullough, 2014]



FCC-ee sensitivity to new physics: Composite Higgs

- Example: $t_L t_L Z$ and $t_R t_R Z$ couplings, g_L and g_R
  - Couplings most sensitive to composite Higgs models

$$2eF^Z_{1V} = g_R + g_L$$
$$2eF^Z_{1A} = g_R - g_L$$

