



FCC-ee physics overview

FCC week 2018

Amsterdam, 9th April 2017

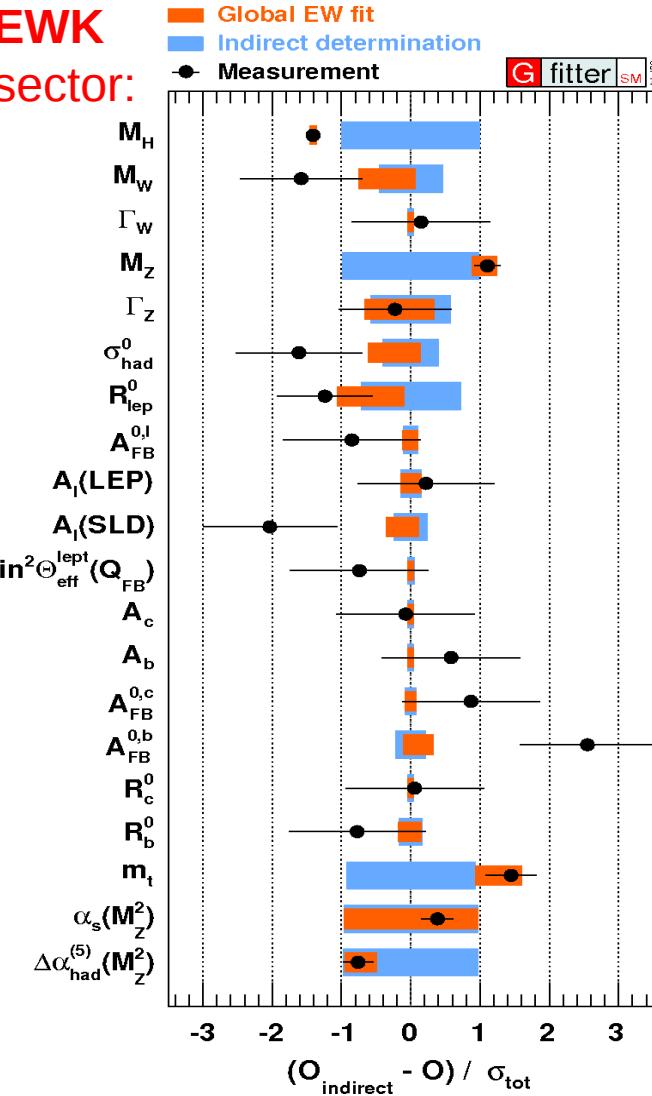
David d'Enterria
(on behalf of the FCC-ee study group)

CERN

Standard Model of particles & interactions

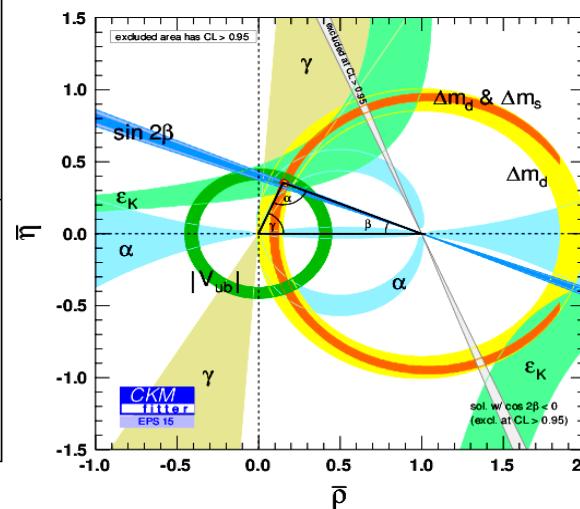
- Renormalizable QFT of electroweak $SU(2)_L \times U(1)_Y$ & strong $SU(3)_c$ gauge interactions
- O(20) parameters:** Couplings, H mass&vev, H-f Yukawa, CKM mix., CP phases.
- Experimentally confirmed to great precision for over ~50(!) years:

EWK sector:

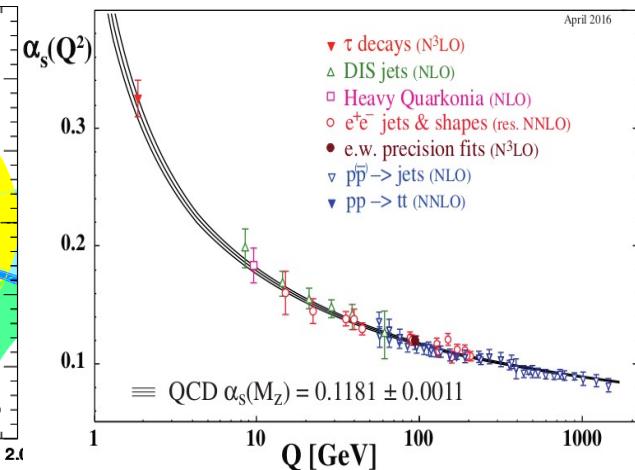


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Flavour sector:



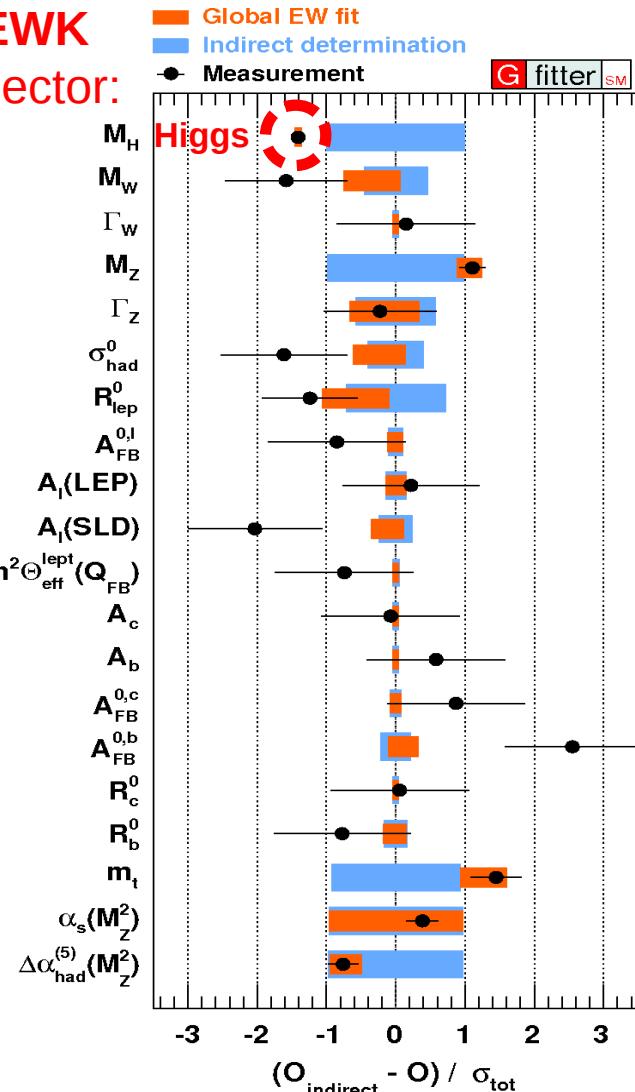
QCD sector:



Standard Model of particles & interactions

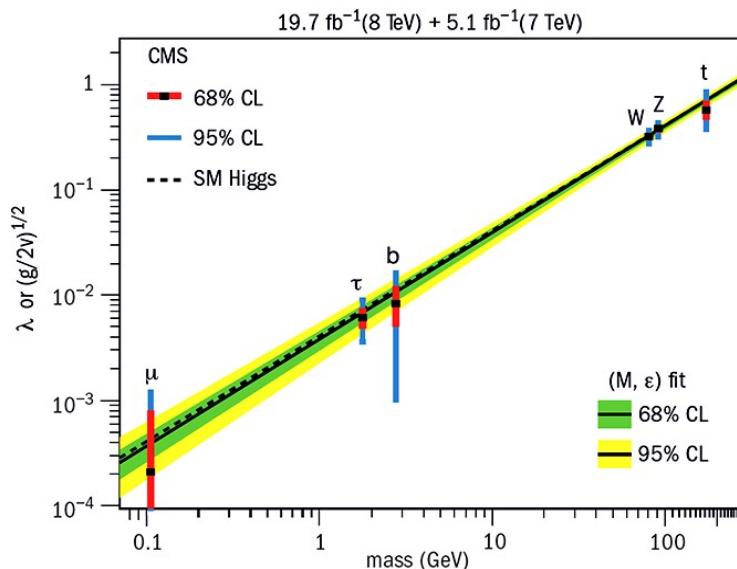
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sector:**



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**Higgs
sector:**



Open questions in the SM (1)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\text{tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}\text{tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \quad [\text{Gauge interactions: U(1}_Y, \text{SU(2}}_L, \text{SU(3}}_C]$$

$$+(\bar{\nu}_L, \bar{e}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R \sigma^\mu iD_\mu e_R + \bar{\nu}_R \sigma^\mu iD_\mu \nu_R + (\text{h.c.}) \quad [\text{Lepton dynamics}]$$

$$-\frac{\sqrt{2}}{v} \left[(\bar{\nu}_L, \bar{e}_L) \phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[(-\bar{e}_L, \bar{\nu}_L) \phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix} \right] \quad [\text{Lepton masses}]$$

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$$-\frac{\sqrt{2}}{v} \left[(\bar{u}_L, \bar{d}_L) \phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[(-\bar{d}_L, \bar{u}_L) \phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix} \right] \quad [\text{Quark masses}]$$

$$+\overline{(D_\mu \phi)} D^\mu \phi - m_h^2 [\bar{\phi} \phi - v^2/2]^2 / 2v^2. \quad [\text{Higgs dynamics \& mass}]$$

✗ Light-masses generation: 1st-gen. fermion (and all ν's) masses Yukawas?

Open questions in the SM (2)

$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\text{tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}\text{tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) & [\text{Gauge interactions: U(1}_Y, \text{SU(2)}_L, \text{SU(3)}_C] \\
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 \end{aligned}$$

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Open questions in the SM (3)

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Open questions in the SM (5)

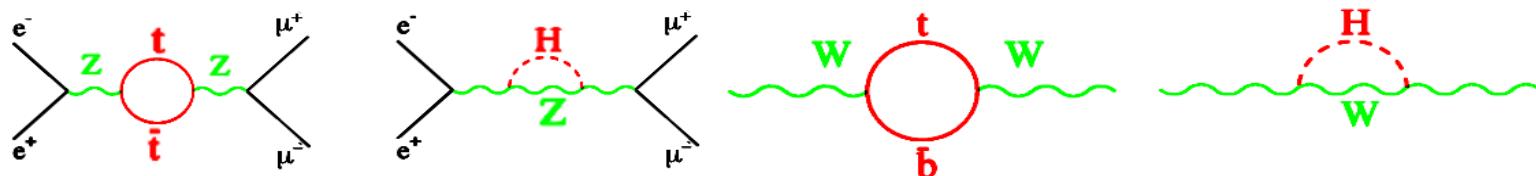
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- ✗ Flavour: SM cannot generate observed matter-antimatter imbalance
- ✗ Dark matter: SM describes only 4% of Universe (visible fermions+bosons)
- ✗ Others: Strong CP, quantum gravity, cosmological const, dark energy, inflation,...

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

BSM physics at e^+e^- colliders

- New physics: Beyond present reach? Hiding well? At smaller couplings?
- BSM searches at electron-positron colliders:
 - Direct model-indep. discovery of new particles **coupling to Z^*/γ^* up to $m \sim \sqrt{s}/2$**
Small & very-well understood backgrounds: Fill “blind spots” in p-p searches
 - Indirect via high-precision measurements sensitive to **virtual corrections**:



- New physics scale (Λ) limits from generic SM-EFT:

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

HL-LHC: ~5% deviations of Higgs couplings wrt. SM: $\Lambda \gtrsim 1 \text{ TeV}$

FCC(e^+e^-): 10^6 Higgs: ~0.1% Higgs couplings precision: $\Lambda \gtrsim 7 \text{ TeV}$

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

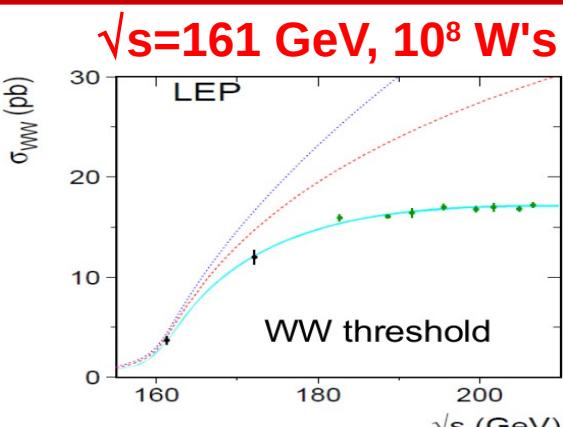
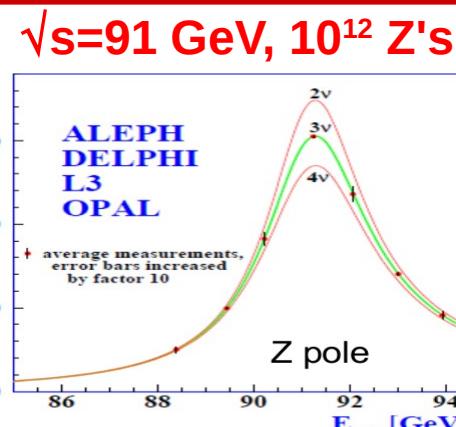
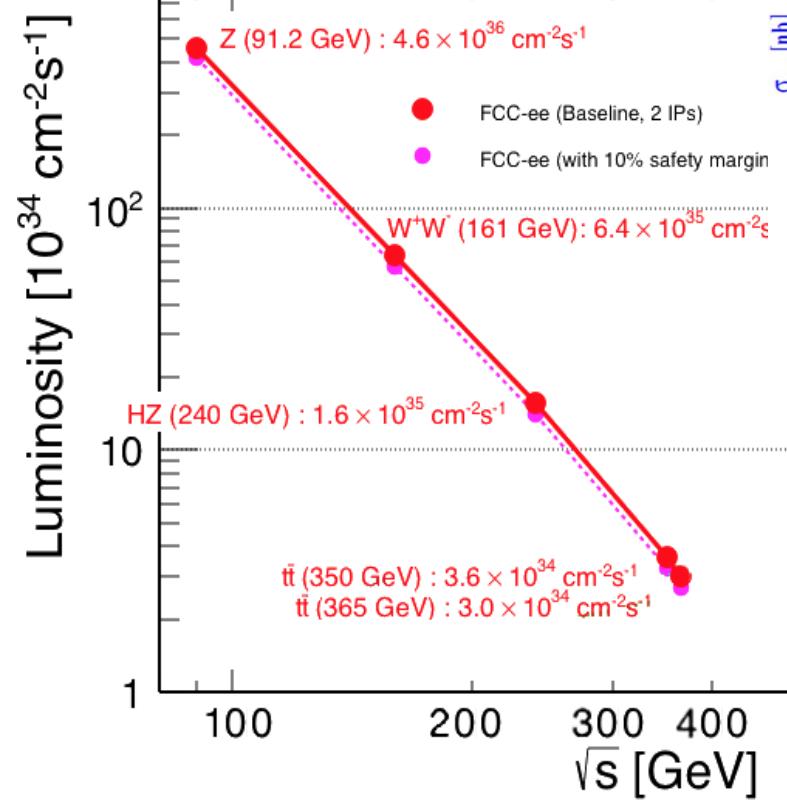
NP excluded below $\Lambda \gtrsim 3 \text{ TeV}$ by current EWK precision fit.

FCC(e^+e^-): $\times 5 \cdot 10^5$ more stats. (10^8 W's, $5 \cdot 10^{12}$ Z's)

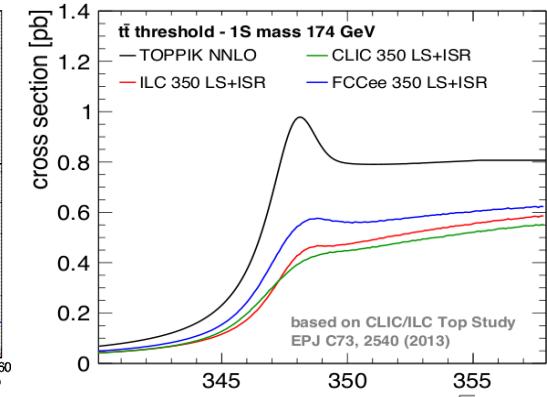
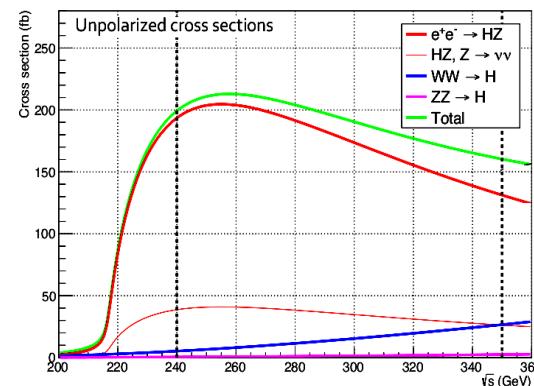
$\times 10^{2.5}$ precision w.r.t. LEP (10^4 W's, 10^7 Z's)

i.e. $\Lambda \gtrsim 45 \text{ TeV}$

FCC-ee: Z($\times 5 \cdot 10^5$ LEP), W($\times 10^4$ LEP), H, top factory



$\sqrt{s}=240 \text{ GeV}, 10^6 H\text{'s}$



Working point	Z, years 1-2	Z, later	WW	HZ	t <bar>t threshold</bar>	365 GeV
Lumi/IP ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$)	100	200	31	7.5	0.85	1.5
Lumi/year (2 IP)	26 ab $^{-1}$	52 ab $^{-1}$	8.1 ab $^{-1}$	1.95 ab $^{-1}$	0.22 ab $^{-1}$	0.39 ab $^{-1}$
Physics goal	150		10	5	0.2	1.5
Run time (year)	2	2	1	3	1	4

■ FCC-ee core physics programme to be completed in ~13 years

FCC-ee detector concept (IDEA)

■ Detector requirements:

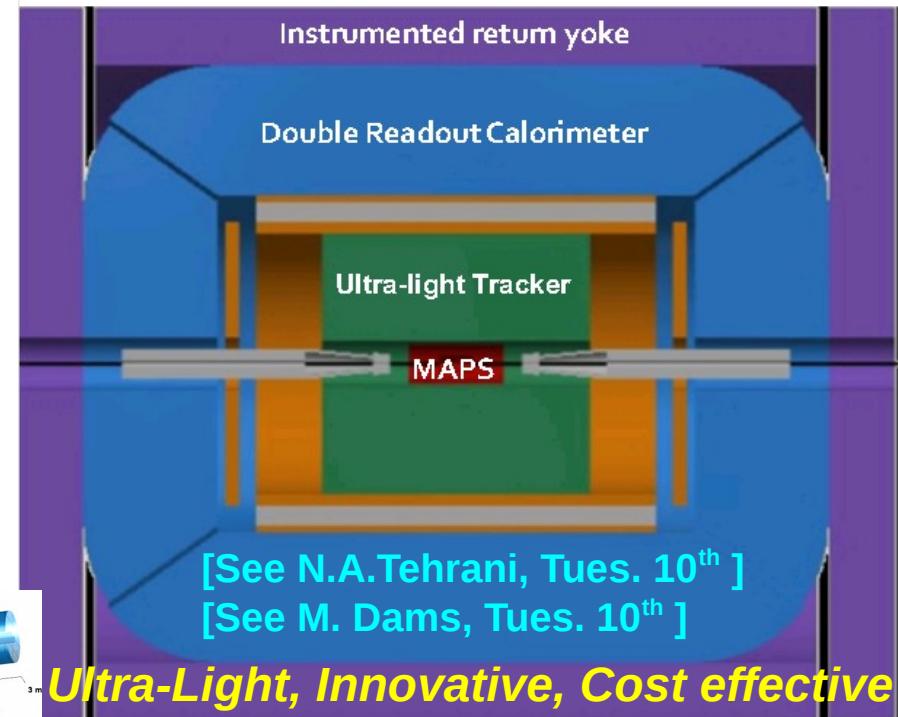
- Track p resolution: $\sigma_{1/p} = 3 \cdot 10^{-5} \text{ GeV}^{-1}$ [comparable to e^+e^- beam energy spread at Z]
- Jet E resolution: $\delta E/E = 30\%/\sqrt{E(\text{GeV})}$ [comparable to natural $Z(qq)$ width]
- Impact-param. resol: $\sigma_{d_0} = a + b / (p \cdot \sin^{3/2}\theta)$; $a=5\mu\text{m}$, $b=15\mu\text{m}$ [b,c,τ tagging]
- PID: γ/π^0 , $e/\mu/h$, $\pi/k/p$ separation (high granularity)

■ IDEA detector concept based on current state-of-the-art technologies:

- Beam pipe: ~1.5 cm ($0.5\% X_0$)
- Vertex detector: MAPS (ALICE ITS)
5 layers ($3\% X_0$). Point resol.: $5\mu\text{m}$
- Ultralight Drift Chamber: MEG2-type
 $\text{He-iC}_4\text{H}_{10}$ (90:10); 110 layers ($1.5\% X_0$)
Point resol.: $\sim 100(xy), 700(z) \mu\text{m}$
PID: via cluster counting
- Preshower counter: $2X_0/\text{SiStrip}/1X_0/\text{SiStrip}$
- Dual readout Pb/fiber calorimeter ($d=1.6\text{m}$):
 $\sim 6-8\lambda_{\text{int}}$, Scintillation/Cherenkov signals.
- B-field: 2 T. Instrumented return yoke for μ
- Forward (<150 mrad):
MDI & LumiCal (1.2m)



Two Options: Coil inside or outside calorimetry



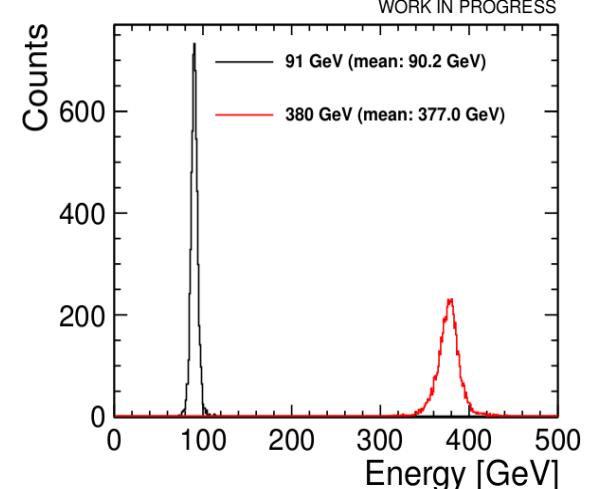
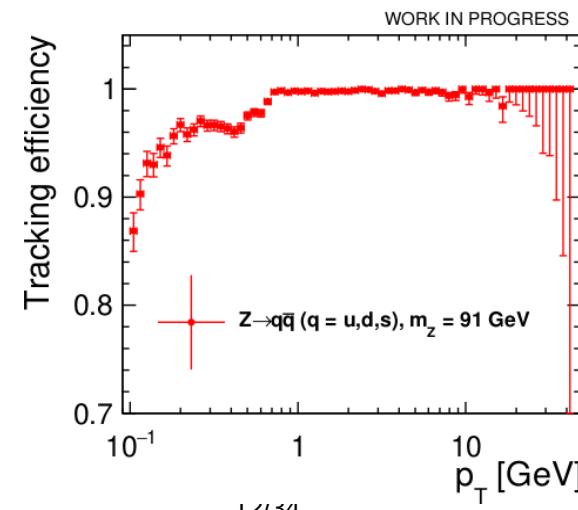
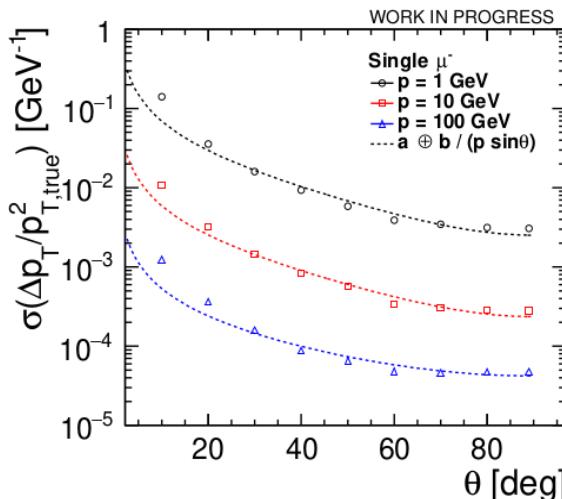
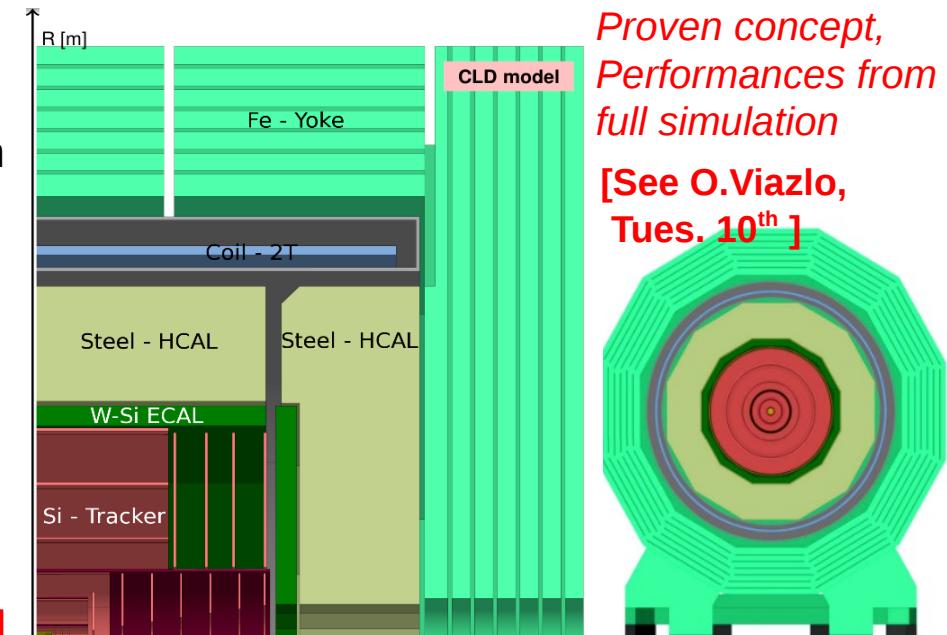
[See N.A.Tehrani, Tues. 10th]
[See M. Dams, Tues. 10th]

Ultra-Light, Innovative, Cost effective

FCC-ee detector concept (CLD)

■ CLD ($L=10.6$ m) inspired in CLIC/ILC detectors & optimized for FCC-ee conditions:

- Beam pipe: ~1.5 cm ($0.5\% X_0$)
- Vertex detector: Si pixels
3x2 double-layers ($1\% X_0$). Point resol.: $3\mu\text{m}$
- Tracker detector: Si pixels & microstrips
6 layers ($8\% X_0$). Point resol.: $7 \times 90\ \mu\text{m}$
- EM & HCAL Calorimeters:
Si-W sampling calo ($22\ X_0$, $1\lambda_{\text{int}}$)
Sci/Steel sampling calo ($5.5\ \lambda_{\text{int}}$)
- B-field: 2 T (superconducting coil)
- Muon system: 6 RPCs
- Forward region (<150 mrad): MDI & LumiCal



David d'Enterria (CERN)

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:

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

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

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

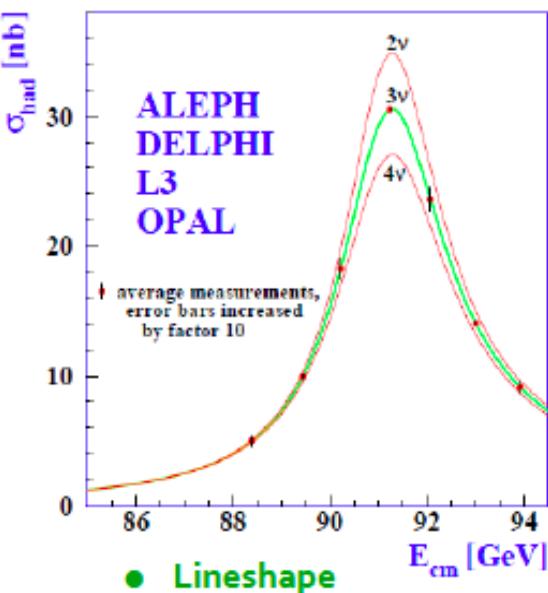
$$\Lambda \propto (1 \text{ TeV}) / \sqrt{\delta X}$$

~0.1% precision of W,Z couplings ($10^{4,6}$ W,Z LEP): $\Lambda \gtrsim 3 \text{ TeV}$

~0.0005% W,Z couplings precision (~ $10^{8,12}$ W,Z): $\Lambda \gtrsim 45 \text{ TeV}$

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

Z resonance: TeraZ

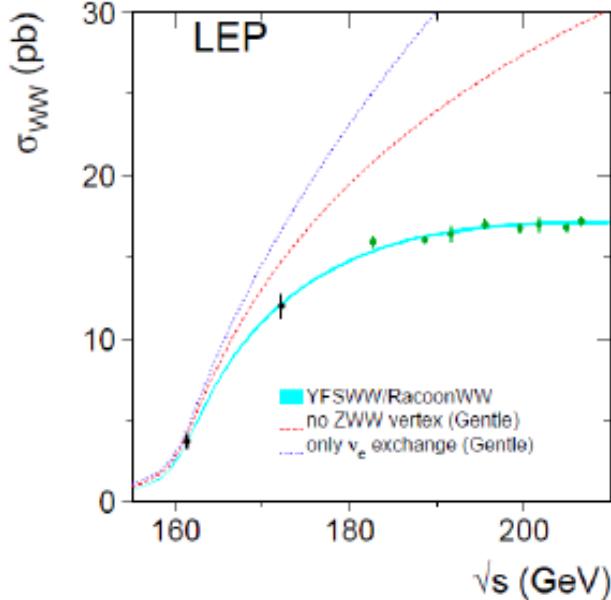


- Lineshape
 - Exquisite E_{beam} (unique!)
 - m_Z, Γ_Z to 10 keV (stat.)
- Asymmetries 100 keV (syst.)
 - $\sin^2 \theta_W$ to 5×10^{-6}
- Branching ratios, $R_l l$, R_b
 - $\alpha_s(m_Z)$ to 0.0002
- Predict m_{top}, m_W in SM

■ Mostly thanks to:

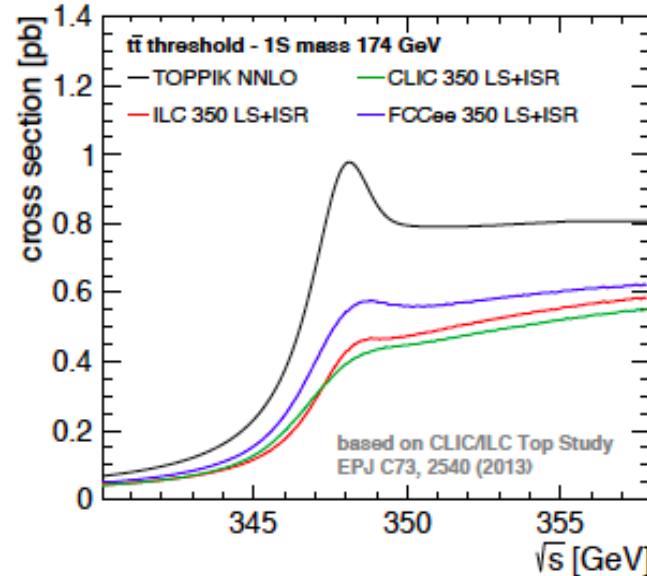
- (i) huge statistics,
- (ii) threshold scans with $\delta E_{\text{cm}} \sim 0.1, 0.3, 2., 4.$ MeV (Z, W, ZH, t)

WW threshold scan: OkuW



- Threshold scan
 - m_W to 500 keV
- Branching ratios $R_l l, R_{\text{had}}$
 - $\alpha_s(m_W)$ to 0.0002
- Radiative returns $e^+e^- \rightarrow \gamma Z$ ($Z \rightarrow \nu\nu, \mu^+\mu^-$)
 - N_ν to 0.001

tt threshold scan: MegaTops



- Threshold scan + 4D fit
 - m_{top} to 10 MeV (stat.)
 - 40 MeV (th.)
 - λ_{top} to 13%
 - EWK couplings to 1–10%

[See A. Blondel,
Tues. 10th]

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

■ Exp. uncertainties (stat.uncert. ~negligible) improved wrt. LEP by factors $\times 20$:

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1 *	QED / EW
R_i	Peak	20.767 ± 0.025	0.001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \rightarrow bb$
N_v	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\sin^2\theta_W^{\text{eff}}$	A_{FB}^{WW} (peak)	0.23148 ± 0.00016	0.000003	< 0.000005 *	Beam energy
$1/\alpha_{\text{QED}}(m_z)$	A_{FB}^{WW} (off-peak)	128.952 ± 0.014	0.004	< 0.004	QED / EW
$\alpha_s(m_z)$	R_i	0.1196 ± 0.0030	0.00001	< 0.0002	New Physics
m_w (MeV)	Threshold scan	80385 ± 15	0.6	< 0.6	EW Corr.
Γ_w (MeV)	Threshold scan	2085 ± 42	1.5	< 1.5	EW Corr.
N_v	$e^+e^- \rightarrow \gamma Z, Z \rightarrow vv, ll$	2.92 ± 0.05	0.001	< 0.001	?
$\alpha_s(m_w)$	$B_{\text{had}} = (\Gamma_{\text{had}}/\Gamma_{\text{tot}})_W$	$B_{\text{had}} = 67.41 \pm 0.27$	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	$173340 \pm 760 \pm 500$	20	< 40	QCD corr.
Γ_{top} (MeV)	Threshold scan	?	40	< 40	QCD corr.
λ_{top}	Threshold scan	$\mu = 1.2 \pm 0.3$	0.08	< 0.05	QCD corr.
ttZ couplings	$\sqrt{s} = 365$ GeV	~30%	~2%	< 2%	QCD corr

* work to do: check if we can't improve

■ Theoretical developments needed to match expected experimental uncertainties

High-precision W, Z, top: Theory uncertainties

- Current TH uncertainties to be improved by $\sim \times 5$ to match expected exp. ones:

- Today

$$m_W = 80.3584 \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \\ \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{\text{theory}} \text{ GeV} \\ = 80.358 \pm 0.008_{\text{total}} \text{ GeV},$$

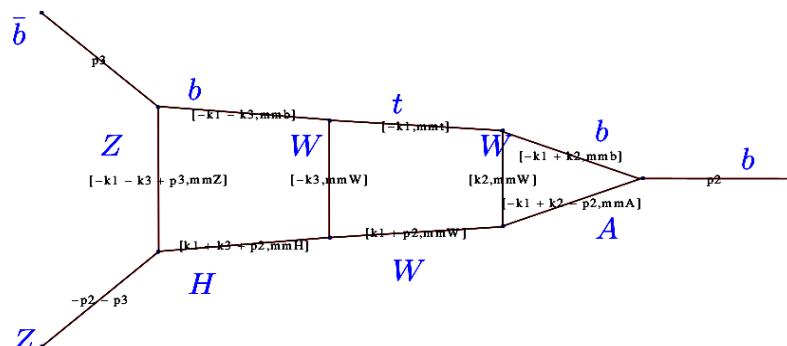
- With FCC-ee

$$m_W^{\text{direct}} = 80.385 \pm 0.015 \text{ GeV},$$

$$m_W = 80.3584 \pm 0.0002_{m_{top}} \pm 0.0001_{m_Z} \pm 0.0005_{\alpha_{QED}} \\ \pm 0.0002_{\alpha_S} \pm 0.0000_{m_H} \pm 0.0040_{\text{theory}} \text{ GeV} \\ = 80.3584 \pm 0.0006_{\text{exp}} \pm 0.0040_{\text{theory}} \text{ GeV},$$

$$m_W^{\text{direct}} = 80.385 \pm 0.0006 \text{ GeV}$$

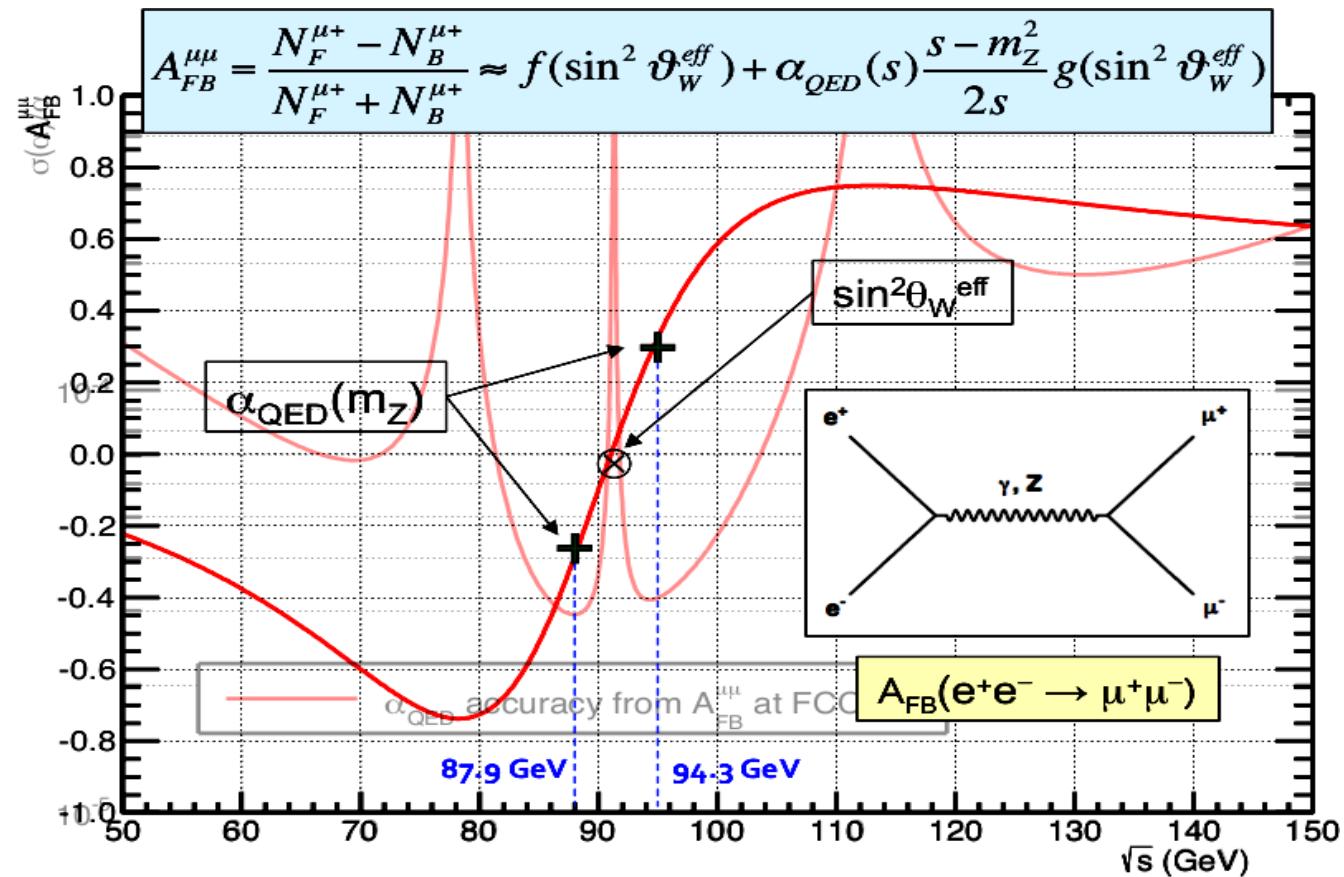
- Theory R&D



"Precision EW Calculations Mini-Workshop"
 [Jan. 2018]: Required N³LO SM corrections
 of EWPOs are theoretically doable in
**5–10 years (with appropriate financial
 support and training programs)**

High-precision Z pole measurements: α_{QED} coupling

- BSM searches require reduced SM parametric uncertainties ($\alpha, \alpha_s, m_W, m_t, \dots$)
- $\mu\mu$ forward-backward asymmetry around Z pole: Unparalleled sensitivity to QED coupling & weak mixing angle:

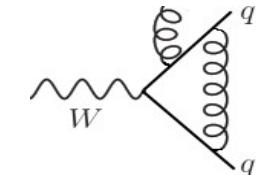


- 6 months at $\sqrt{s} = 87.9, 94.3$ GeV reduces current e.m. coupling uncertainty by factor $\times 3$: $\delta \alpha / \alpha(m_Z) \sim 3 \cdot 10^{-5}$ (mostly statistical)

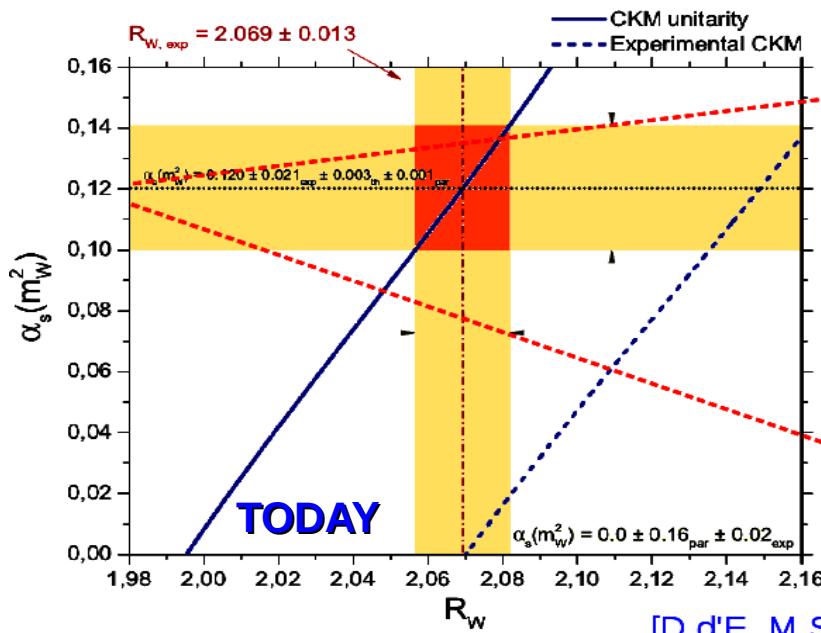
High-precision W,Z measurements: α_s coupling

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

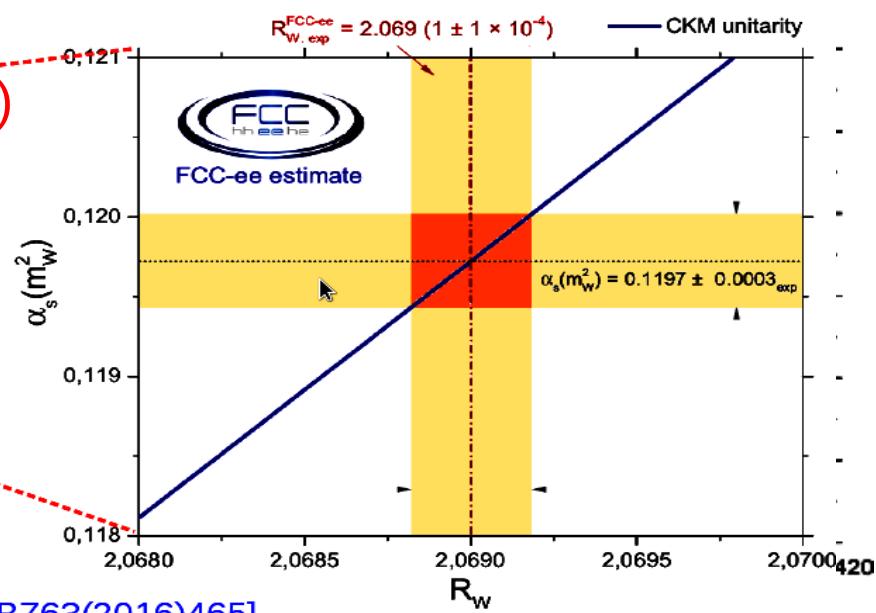
$$\Gamma_{W,\text{had}} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks } i,j} |V_{i,j}|^2 \left[1 + \sum_{k=1}^4 \left(\frac{\alpha_s}{\pi} \right)^k + \delta_{\text{electroweak}}(\alpha) + \delta_{\text{mixed}}(\alpha \alpha_s) \right]$$



- Current Γ_W measurement yields poor extraction: $\delta \alpha_s \sim 25\%$



- FCC-ee prospects: Huge $e^+e^- \rightarrow WW$ stats ($10^8, \times 10^3$ LEP): $\delta \alpha_s < 0.2\%$



[See DdE,
Tues. 10th]

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

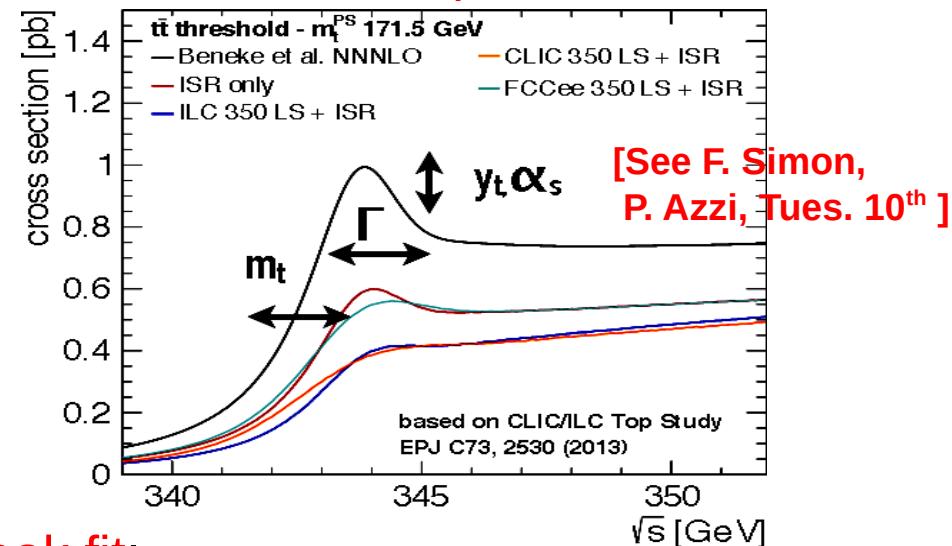
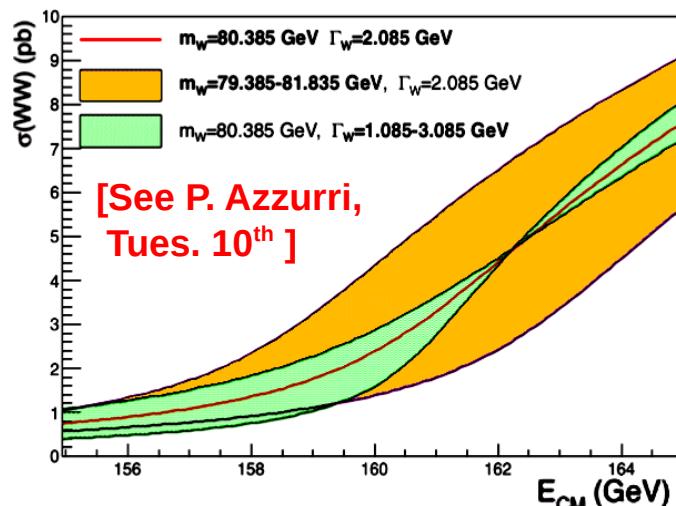
$$\alpha_s(M_Z) = 0.1188 \pm 0.0002_{\text{(exp)}}$$

$R_W = \mathcal{B}_{\text{had}}^W / \mathcal{B}_{\text{lep}}^W = \mathcal{B}_{\text{had}}^W / (1 - \mathcal{B}_{\text{had}}^W)$ in three $e^+e^- \rightarrow W^+W^-$ final states ($\ell\nu\ell\nu, \ell\nu qq, qq\bar{q}\bar{q}$)

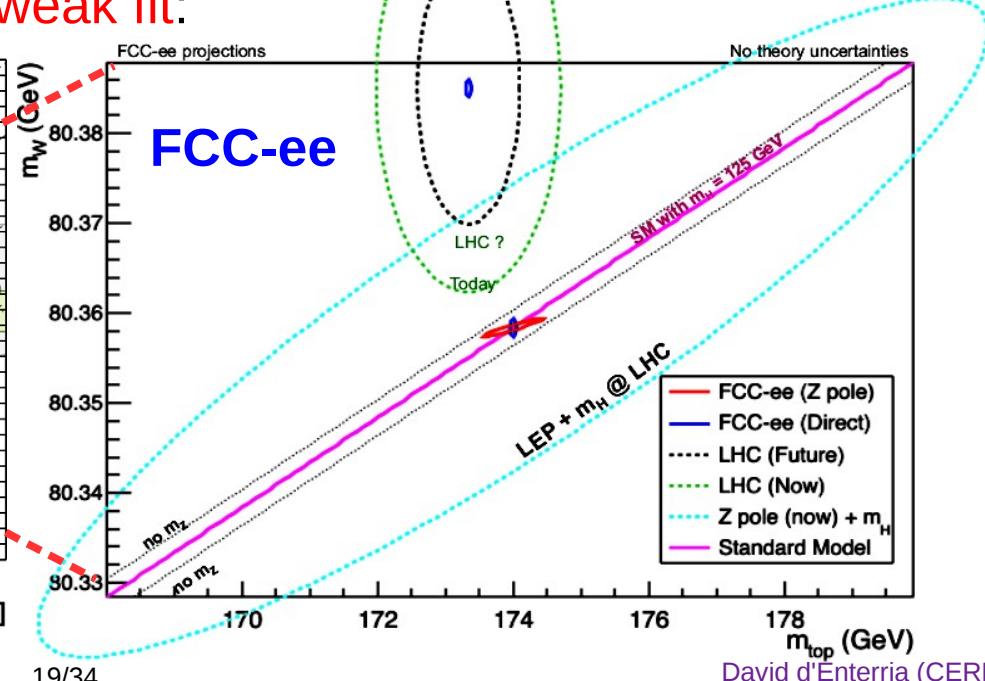
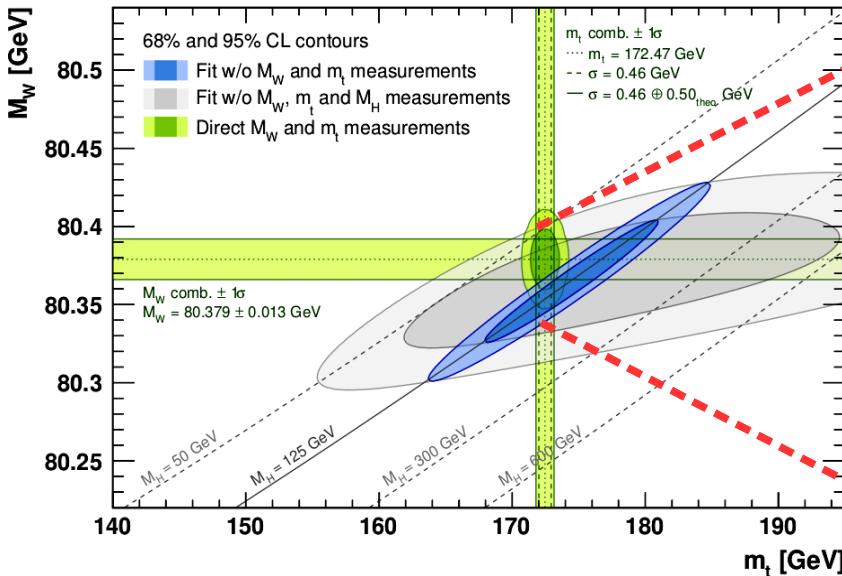
David d'Enterria (CERN)

High-precision W,top measurements: masses,widths

■ Threshold scans for high-accuracy extraction of W, top masses & widths:



■ Combined (m_{top}, m_W, m_H) electroweak fit:



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

- Higher-dimensional operators as relic of new physics

Generic BSM corrections to the SM Lagrangian at scale Λ :

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

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

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

$$\mathcal{O}_W = \frac{ig}{2} \left(H^\dagger \sigma^a \overset{\leftrightarrow}{D}^\mu H \right) D^\nu W_{\mu\nu}^a$$

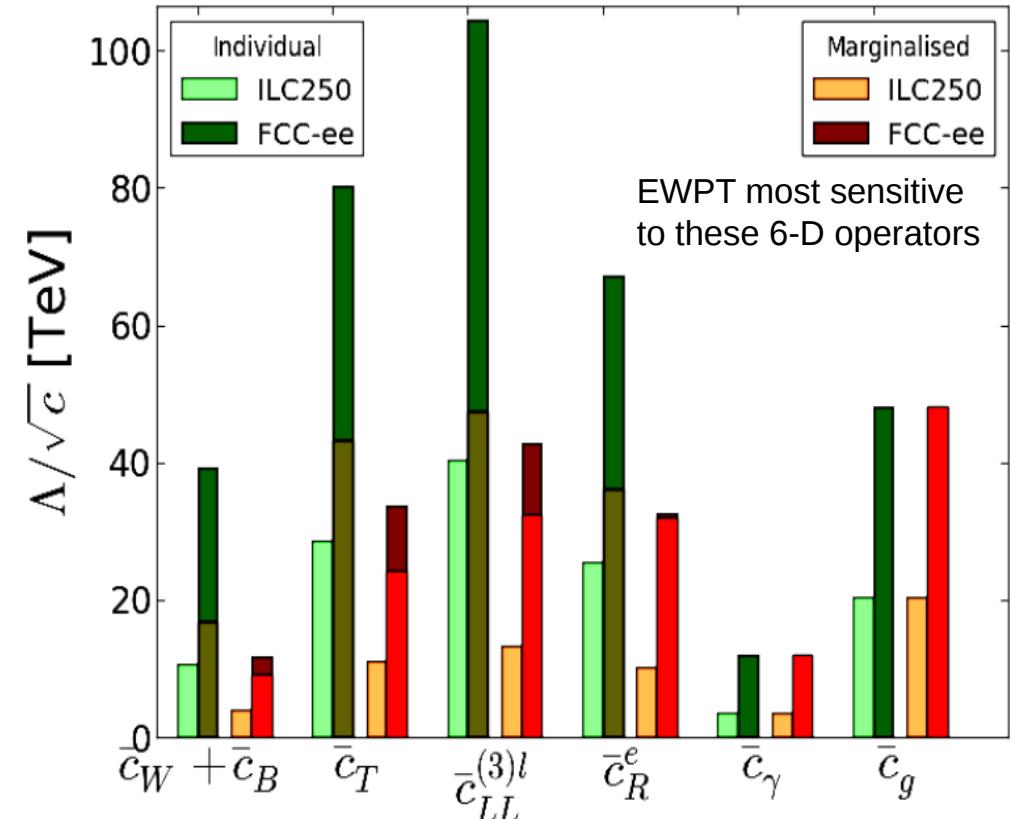
$$\mathcal{O}_B = \frac{ig'}{2} \left(H^\dagger \dot{D}^\mu H \right) \partial^\nu B_{\mu\nu}$$

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

LEP constraints: $\Lambda_{\text{NP}} > 3\text{-}10 \text{ TeV}$

After FCC-ee: $\Lambda_{\text{NP}} > 30\text{-}100 \text{ TeV}$

Sensitivity to
Weakly-coupled NP



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

Open issue in the SM (2): 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:

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

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

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

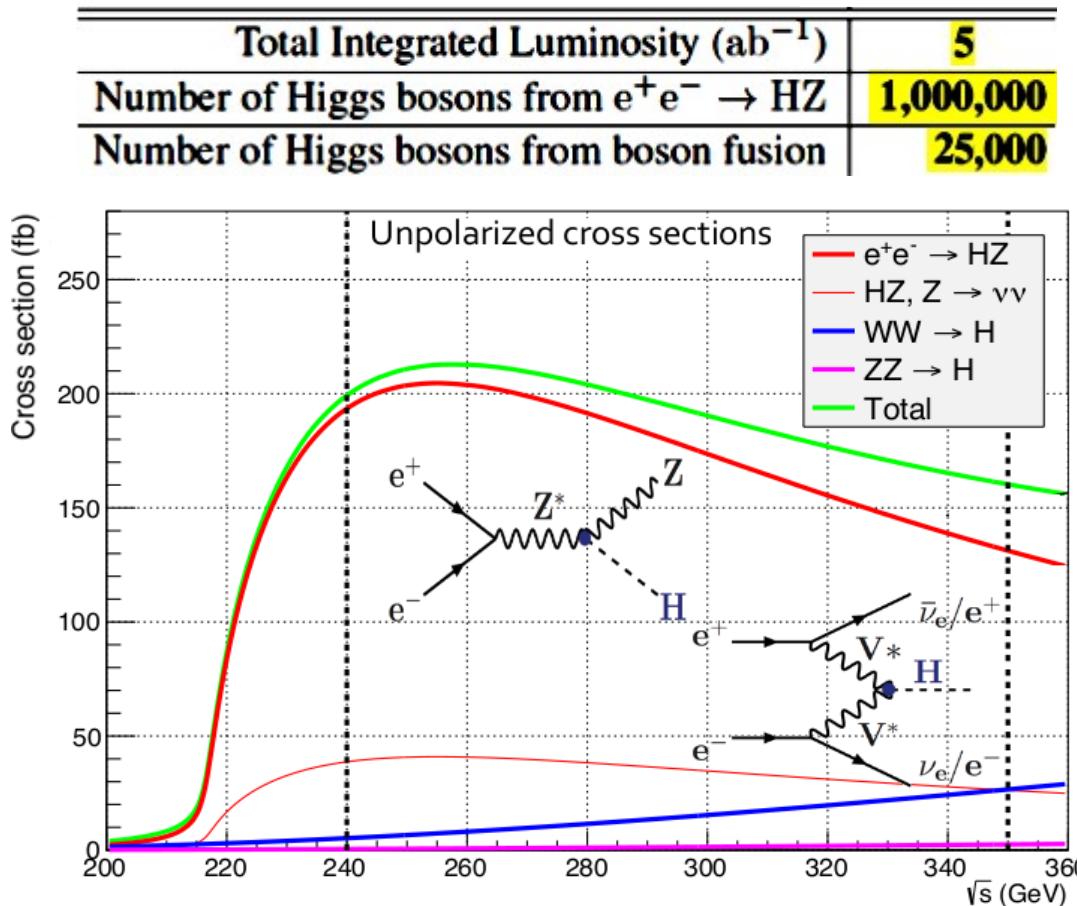
$$\Lambda \gtrsim (1 \text{ TeV}) / \sqrt{(\delta g_{\text{HXX}} / g_{\text{HXX}}^{\text{SM}}) / 5\%}$$

~5% deviations of Higgs couplings wrt. SM: $\Lambda \gtrsim 1 \text{ TeV}$

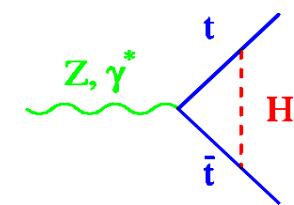
~0.1% Higgs couplings precision (~ 10^6 Higgs): $\Lambda \gtrsim 7 \text{ TeV}$

FCC-ee = Higgs boson factory

- Cross section: $\sigma(e^+e^- \rightarrow H + X) \approx 200 + 50 \text{ fb}$
- 1 million Higgs bosons produced with small & controlled backgrounds, plus no pileup:



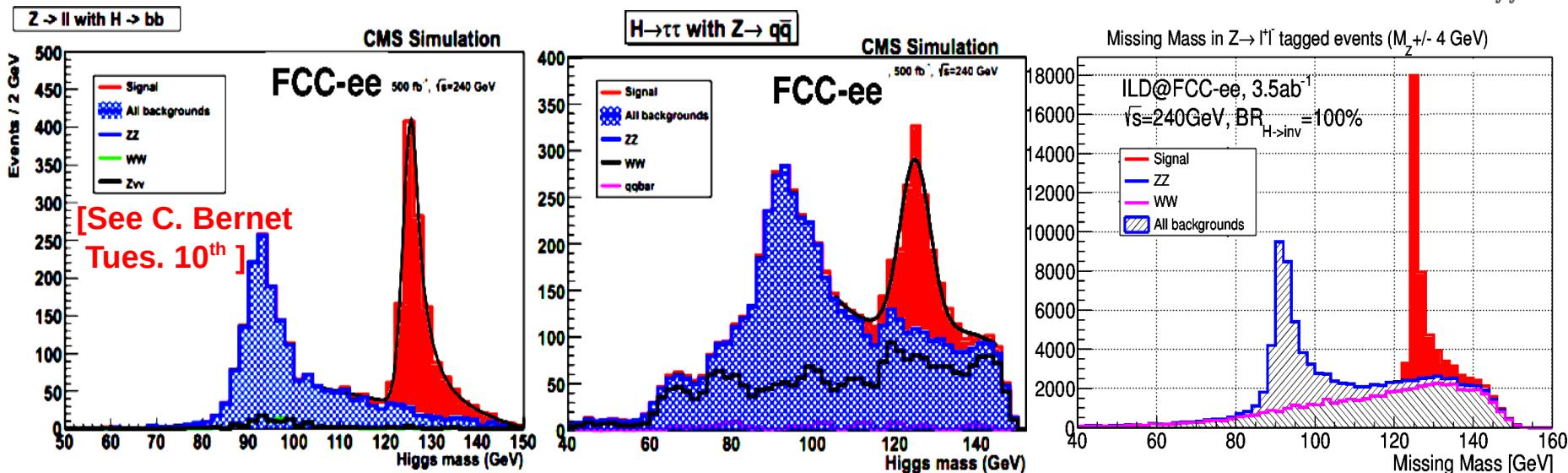
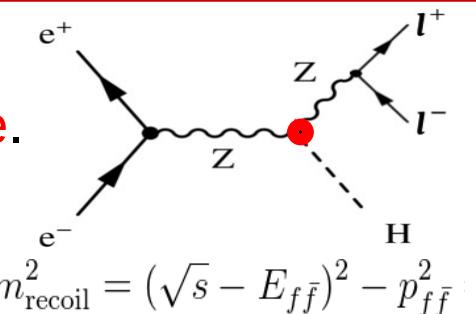
(also sensitivity to y_t)



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

Precision H couplings, width, mass at FCC-ee

- Recoil method in $H-Z(l\bar{l})$ 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 $\sigma(ee \rightarrow ZH) \propto g_z^2$, with $\pm 0.2\%$ uncert.



- Total width (Γ_H) with $\sim 1\%$ precision from combination of measurements
 $\sigma(ee \rightarrow ZH)$, $\sigma(ee \rightarrow ZH \rightarrow ZZ^*)$, $\Gamma_{H \rightarrow ZZ}$: $\sigma(e^+e^- \rightarrow HZ \rightarrow ZZ^*) = \sigma(e^+e^- \rightarrow HZ) \times \frac{\Gamma(H \rightarrow ZZ)}{\Gamma_H}$
- Limits in invisible decay from missing mass: $< 0.5\%$ (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 > 50 (10) improvement in precision w.r.t. model-dependent LHC (HL-LHC) expectations:

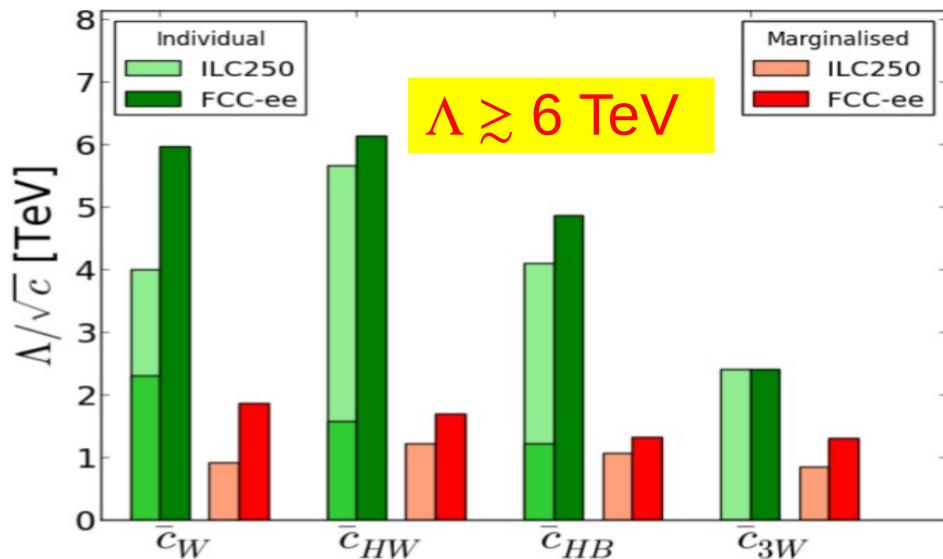
Parameter	Current*	HL-LHC*	FCC-ee Baseline (10 yrs)	ILC	CEPC	CLIC
	7+8+13 TeV $\mathcal{O}(70 \text{ fb}^{-1})$	14 TeV (3 ab ⁻¹)		Lumi upgrade (20 yrs)	Baseline (10 yrs)	Baseline (15 yrs)
$\sigma(\text{HZ})$	—	—	0.4%	0.7%	0.5%	1.6%
g_{zz}	10%	2–4%	0.15%	0.3%	0.25%	0.8%
g_{ww}	11%	2–5%	0.2%	0.4%	1.6%	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_{ee}	—	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 $g_{zz} \sim 0.2\%$ coupling sets limit on new scalar-coupled physics at: $\Lambda \gtrsim (1 \text{ TeV}) / \sqrt{(\delta g_{HXX} / g_{HXX}^{\text{SM}}) / 5\%} \gtrsim 7 \text{ TeV}$

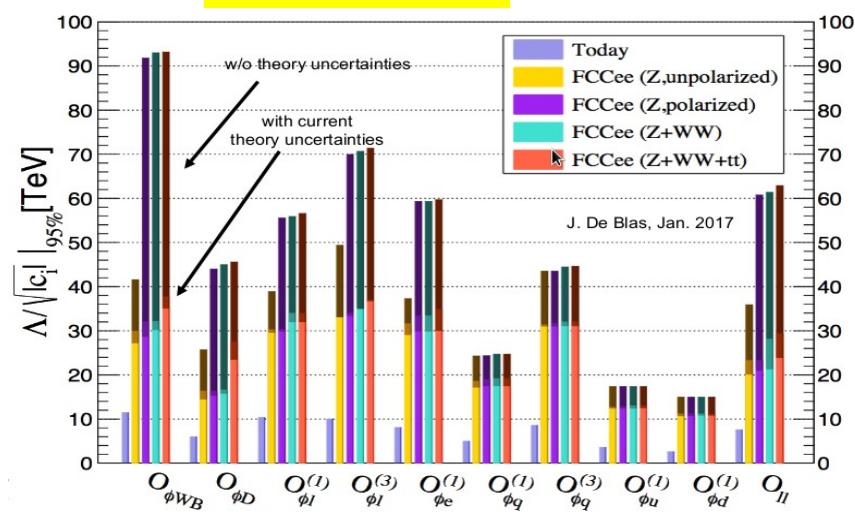
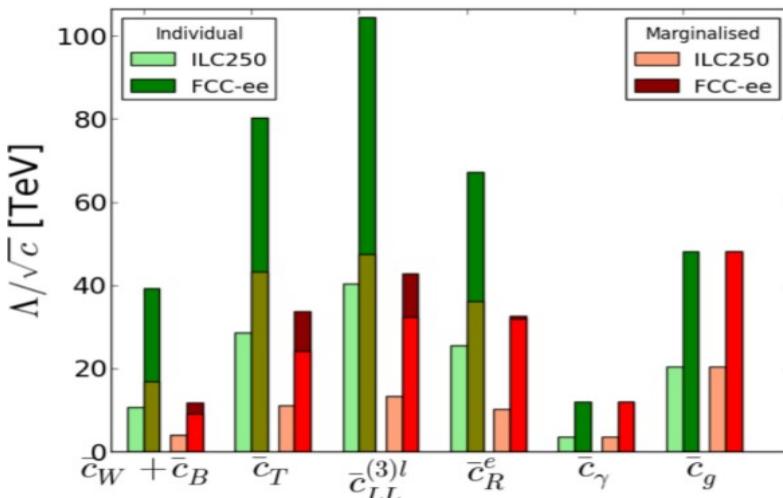
Precision H+EWK measurements: BSM bounds

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

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

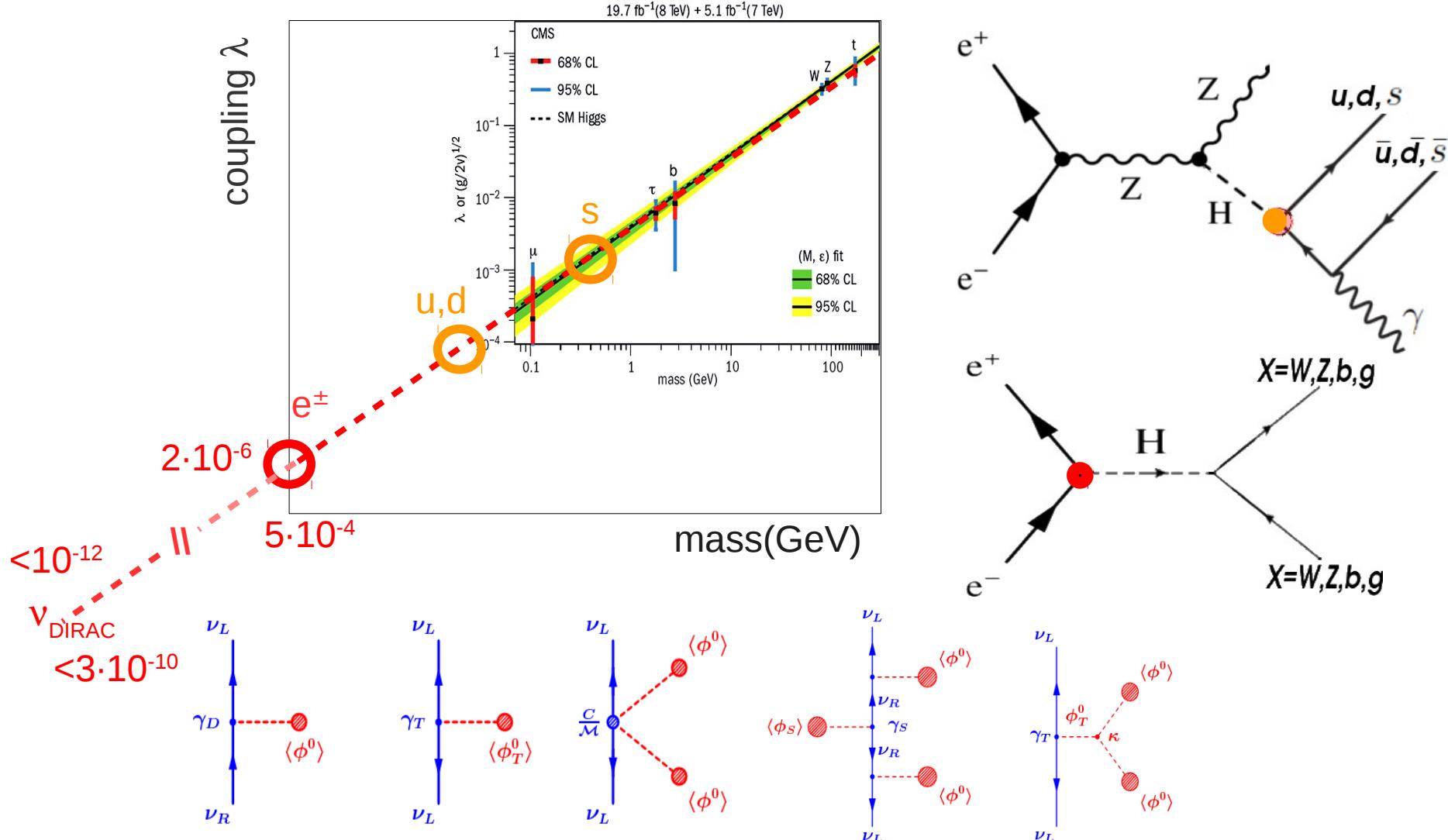


- NP bounds: Higgs+EWPO combined: $\Lambda \gtrsim 50$ TeV



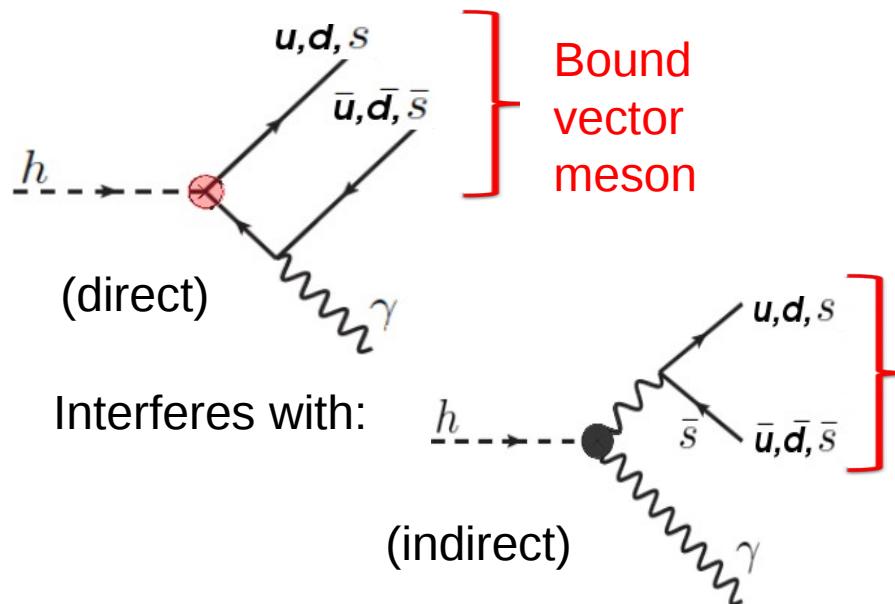
Open SM issue (3): Generation of lightest fermion (u,d,s; e; ν's) masses

■ LHC can only access 3rd (plus few 2nd)-gen. Yukawas. What about the rest?



1st-,2nd-gen. quark Yukawa couplings at FCC-ee

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



[G. Perez et al, arXiv:1505.06689]

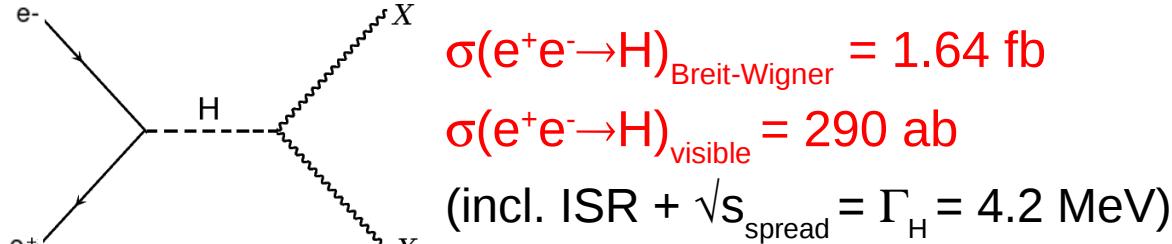
Mode Method	Branching Fraction [10^{-6}]	
	LCDA LO [170]	LCDA NLO [173]
$\text{Br}(H \rightarrow \rho^0 \gamma)$	19.0 ± 1.5	16.8 ± 0.8
$\text{Br}(H \rightarrow \omega \gamma)$	1.60 ± 0.17	1.48 ± 0.08
$\text{Br}(H \rightarrow \phi \gamma)$	3.00 ± 0.13	2.31 ± 0.11

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

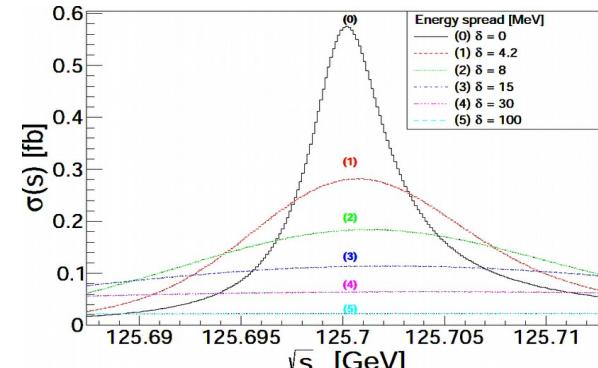
$$\frac{\text{BR}_{h \rightarrow \rho\gamma}}{\text{BR}_{h \rightarrow b\bar{b}}} = \frac{\kappa_\gamma [(1.9 \pm 0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d]}{0.57\bar{\kappa}_b^2} \times 10^{-5}$$
 $(\kappa_q = y_q/y_b)$
- All channels accessible with **higher stats** at FCC-pp.
But **much worse backgrounds** (QCD and pileup).

e^\pm Yukawa via s-channel Higgs at $\sqrt{s}=125$ GeV

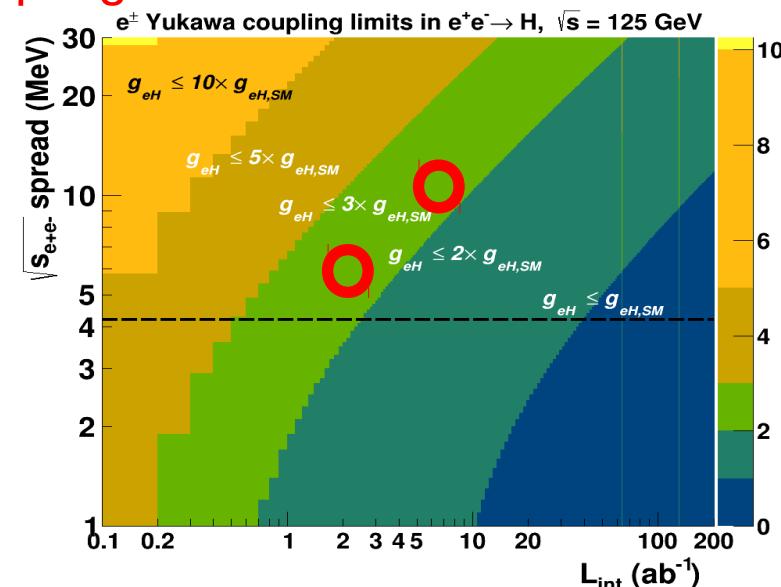
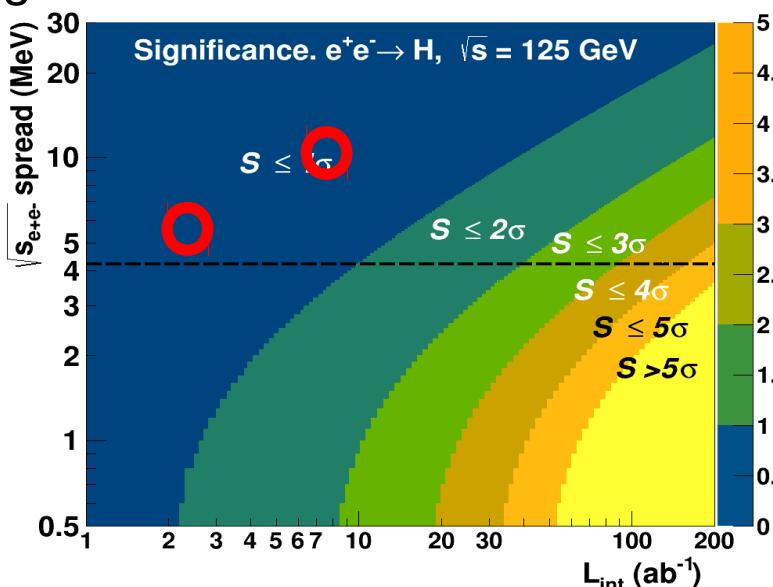
- Resonant s-channel Higgs production at $\sqrt{s} = 125$ GeV has tiny x-sections:



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:



Optimized monochromatization (10 MeV, 7 ab⁻¹): $S=0.43\sigma$, $g_{eH} < 2.2 \times g_{eH,SM}$ (95% CL)

Right-handed neutrinos from Z decays

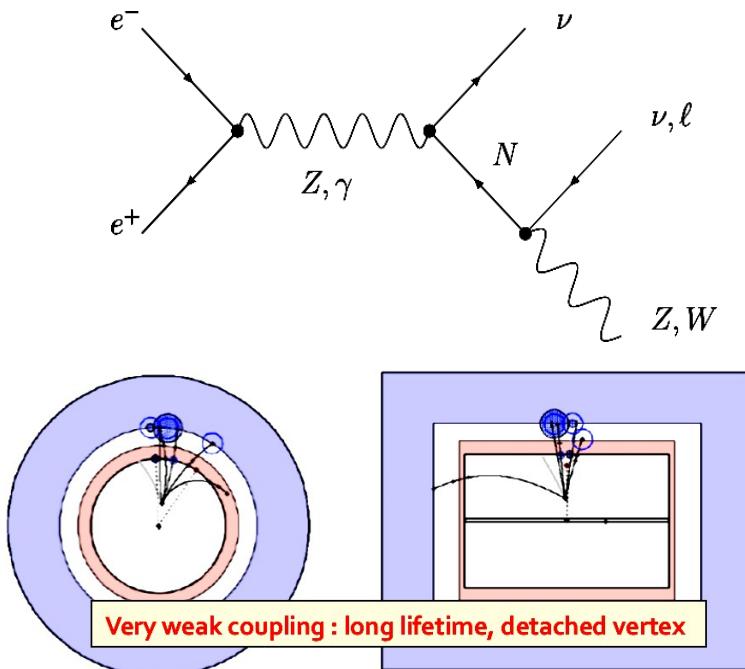
■ Opportunities for direct searches for new physics through rare decays

- ◆ 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

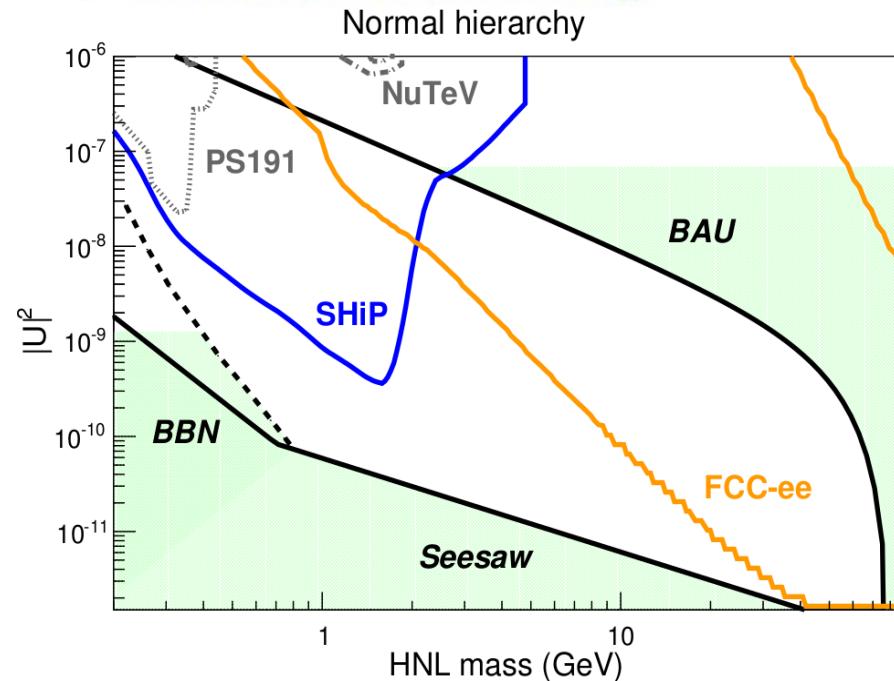
$$Z \rightarrow N\bar{\nu}_i, \text{ with } N \rightarrow W^*\ell \text{ or } Z^*\bar{\nu}_j$$

[See E. Graverini,
Tues. 10th]

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



[A. Blondel et al. arXiv:1411.5230]



- FCC-ee sensitivity down to $|U|^2 \sim 10^{-12}$ for $m_N \sim 1 - 100$ GeV

Open issue in the SM (4):

CP violation, baryon asymmetry, flavour physics

- CP Violation beyond that in the SM is needed in order to explain the baryon asymmetry in universe.
- Pattern of fermion masses & flavour mixings unexplained.
- Indirect searches of new virtual particles contributing to higher-order (Penguin, box) loops in flavour-changing charged current processes.
- Unparalleled b-, c-quark, tau statistics available at FCC-ee:

Particle production (10^9)	B^0 / \bar{B}^0	B^+ / B^-	B_s^0 / \bar{B}_s^0	$\Lambda_b / \bar{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	1000	1000	250	250	1000	500

Access to very rare B-meson: decays, branching fractions, decays asymmetries, oscillation frequencies, ...

Flavour physics at FCC-ee: $B \rightarrow K^* \tau\tau$, $B_s \rightarrow \tau\tau$

■ Current tensions (several $2-3\sigma$ deviations) of LHCb data with SM predictions

- ◆ In particular, lepton flavour universality is challenged in $b \rightarrow s \ell^+ \ell^-$ transitions
 - For example, the rates of $B^0 (B^+) \rightarrow K^{*0} (K^+) \ell^+ \ell^-$ are different for $\ell = e$ and $\ell = \mu$
 - Differences are also observed in the lepton angular distributions
- ◆ This effect, if real, could be enhanced for $\ell = \tau$, in $B \rightarrow K^{(*)} \tau^+ \tau^-$
 - Extremely challenging in hadron colliders
 - With $10^{12} Z \rightarrow b\bar{b}$, FCC-ee is beyond any foreseeable competition
 - Decay can be fully reconstructed
 - Full angular analysis possible

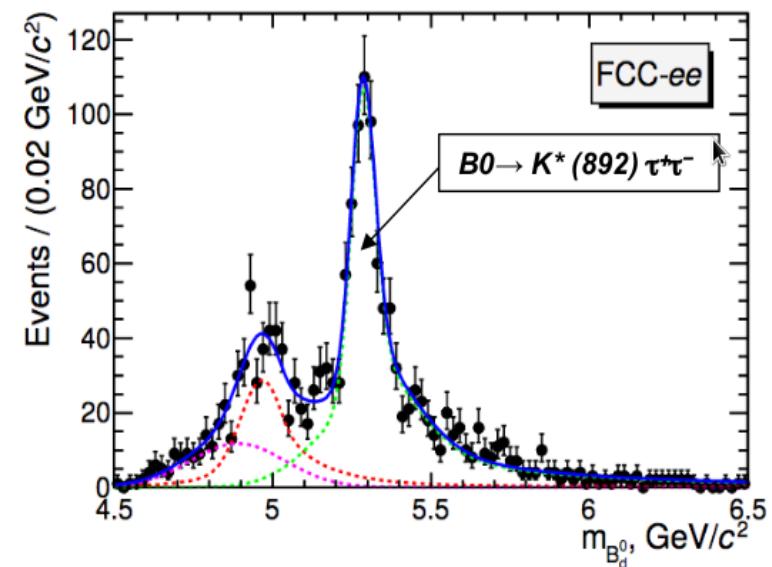
[See S. Monteil,
Tues. 10th]

■ Also sensitive to new physics: $B_s \rightarrow \mu^+ \mu^-$

- ◆ None found yet at the LHC (~ 50 events)

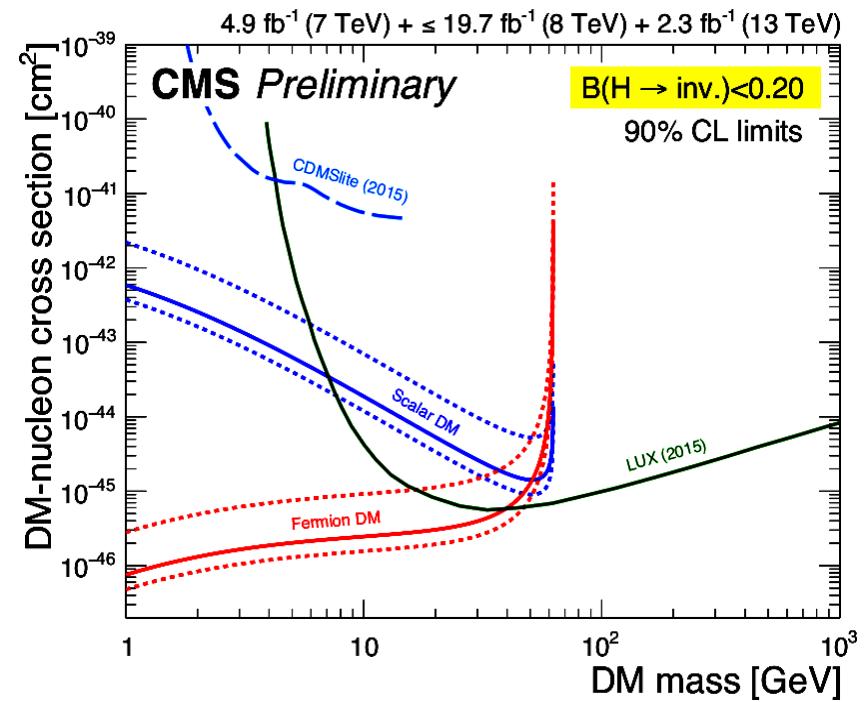
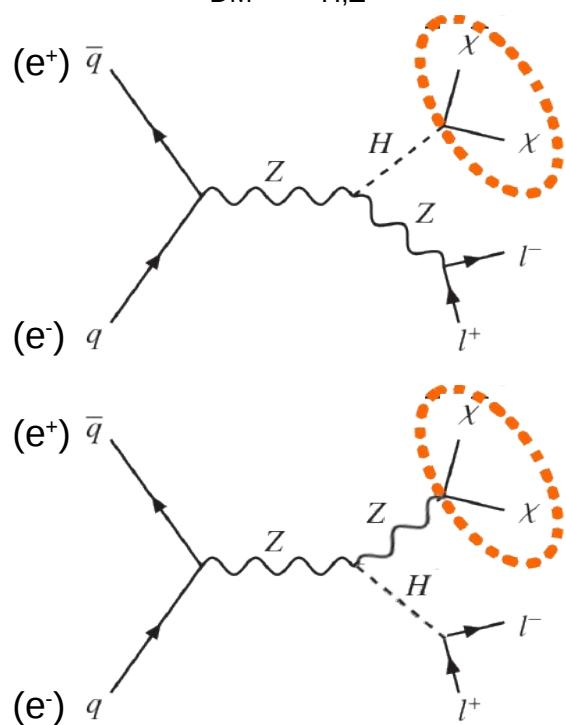
$$BR(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6 {}^{+0.3}_{-0.2}) \times 10^{-9} \sim_{SM}$$

- Expect a few 1000's by the end of LHC
- ◆ $B_s \rightarrow \tau^+ \tau^-$ is 250 times more abundant
 - But almost hopeless at the LHC
- ◆ Again, FCC-ee is beyond any foreseeable competition
 - Several 100,000 events expected – reconstruction efficiency under study



Open issue in the SM (5): Dark matter

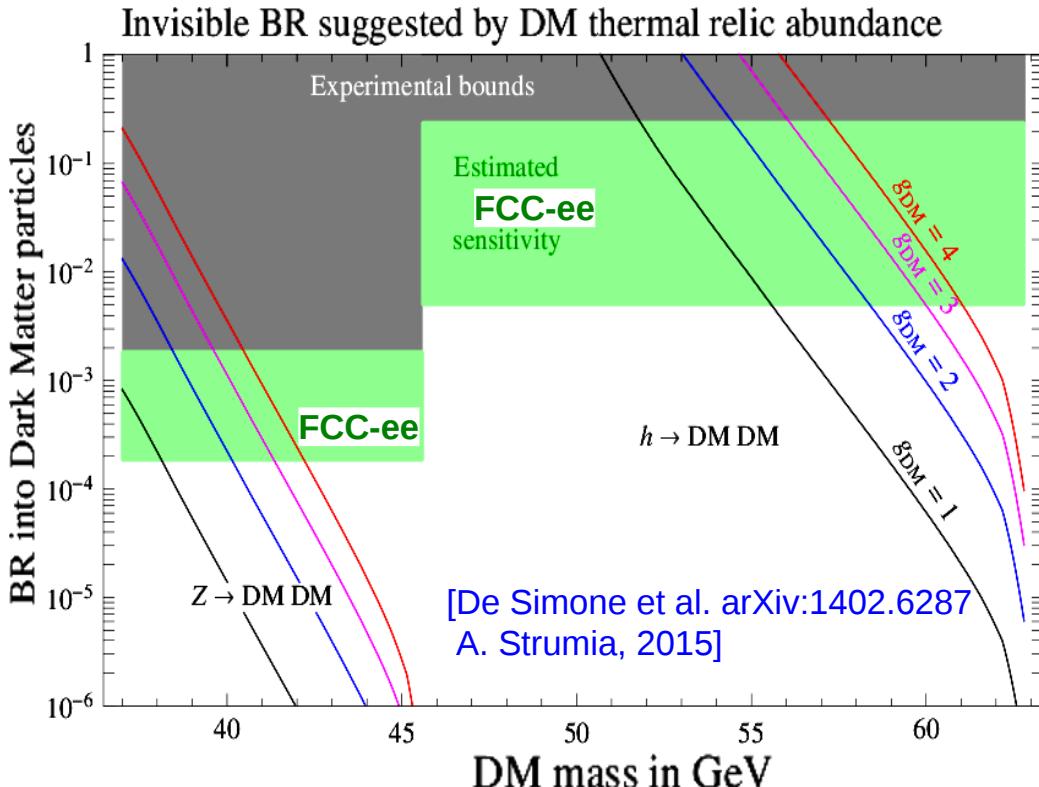
For $M_{\text{DM}} < M_{H,Z}/2$:



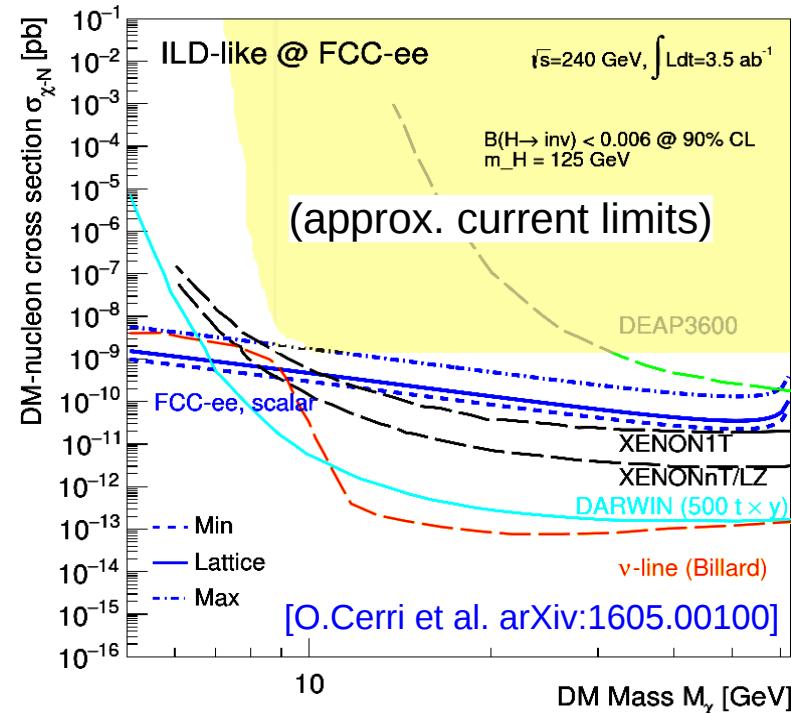
$[B(H \rightarrow \text{inv}) > 5\% \text{ expected for HL-LHC}]$

Dark Matter via invisible $Z, H \rightarrow \chi\chi$ decays

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



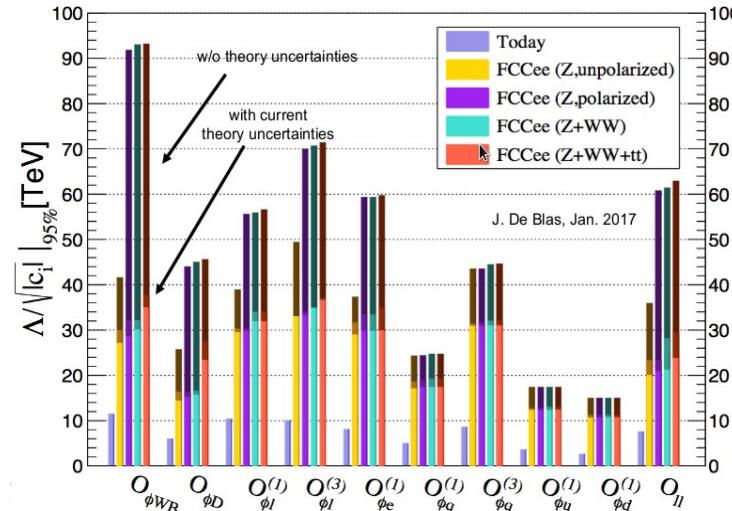
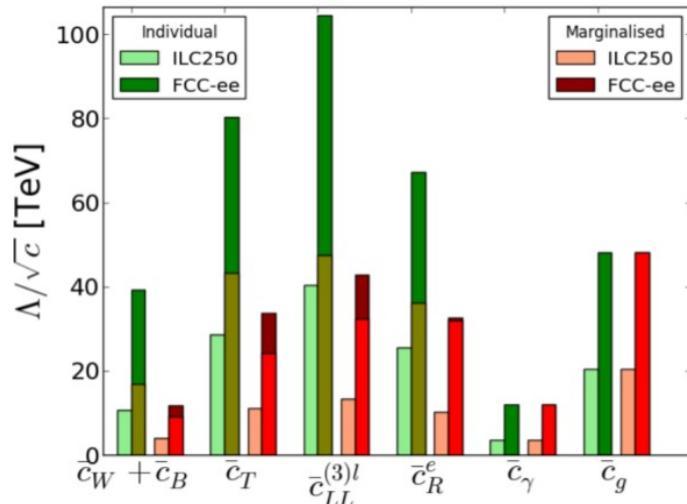
- $\sim 10^{-4}, \sim 5 \cdot 10^{-3}$ precision measurements of Z & H invisible widths are **best collider option** to test any $m_{\text{DM}} < m_{Z,H}/2$ coupling via SM mediators



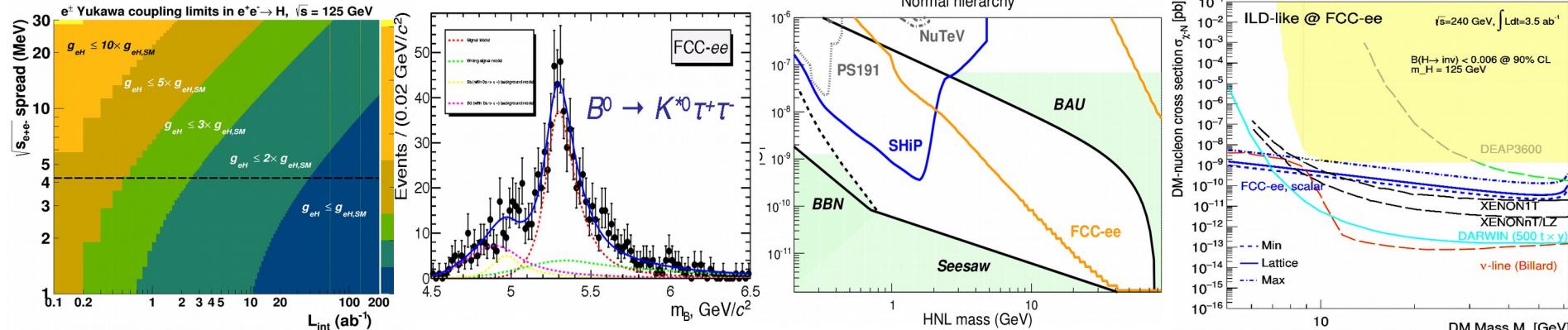
- Limits on $\sigma(\text{DM-nucleon})$ vs. m_{DM} in **Higgs-portal models** competitive with future direct DM-searches experiments.

Summary

- FCC-ee provides unparalleled luminosities $\mathcal{O}(1\text{--}50 \text{ ab}^{-1})$ at $\sqrt{s}=90\text{--}350 \text{ GeV}$ for high-precision ($\ll 0.1\%$ uncert.) W, Z, H, top studies, setting unique constraints on new physics up to $\Lambda \gtrsim 6 \text{ TeV}$ (scalar-), 50 TeV (weak-coupled)



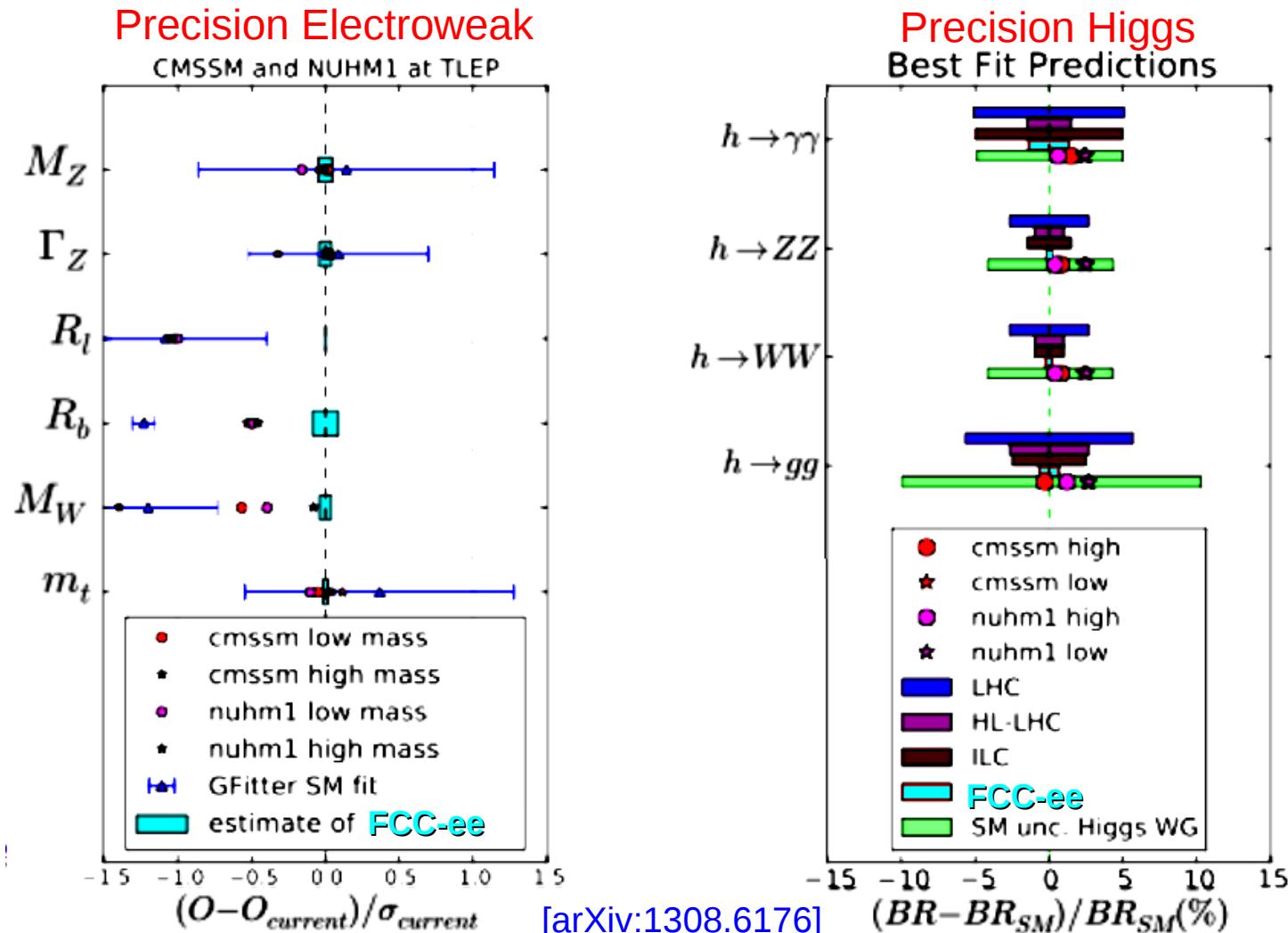
- Plus: 1st gen. Yukawas, right-handed v's, flavour physics, dark matter, ...



Backup slides

New physics constraints: SUSY

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



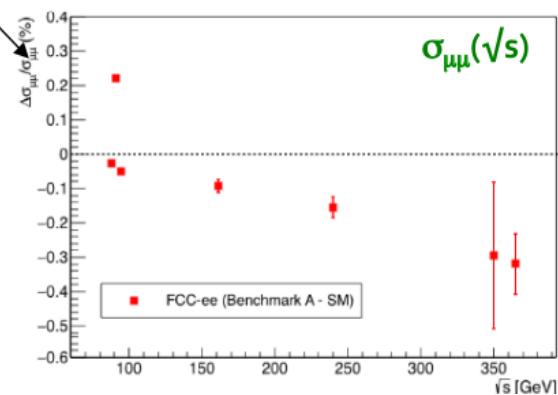
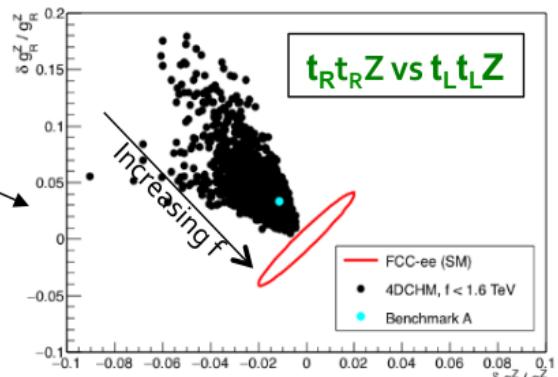
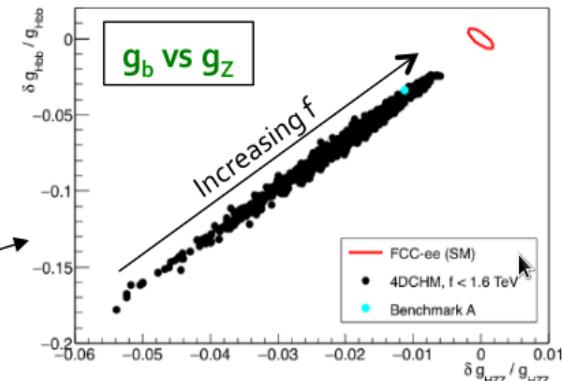
[arXiv:1308.6176]

New physics constraints: Other models

- Higgs-coupled new physics in SMEFT
 - ◆ Probes dim 6 operators for Λ/\sqrt{c} up to 5 – 30 TeV

■ Specific models : pattern of deviations

- ◆ E.g, Composite Higgs Model to solve hierarchy problem
 - Deviations in Higgs couplings
 - Deviations in EW top couplings
 - Deviations in EW lepton couplings
- ◆ Correlations between observations
 - Allow unique characterization of the model
- ◆ For example, gauge sector parameters in benchmark A
 - $f = 1.6 \text{ TeV}$, $g^* = 1.78$, $m_{Z'} \sim 3 \text{ TeV}$, $\Gamma_{Z'} \sim 600 \text{ GeV}$
 - With the FCC-ee precision
 - Z' mass predicted with 2% precision
 - Scale f , coupling g^* predicted with 8% precision



Higgs self-coupling through $\sigma(H+Z)$

- Higgs trilinear indirectly constrained through loop corrections to $\sigma(H+Z)$:

$$\sigma_{Zh} = \left| \text{Feynman diagram with } e\bar{e} \rightarrow Z \rightarrow h \right|^2 + 2 \operatorname{Re} \left[\text{Feynman diagram with } e\bar{e} \rightarrow Z \rightarrow h \cdot \text{(loop correction)} \right]$$

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

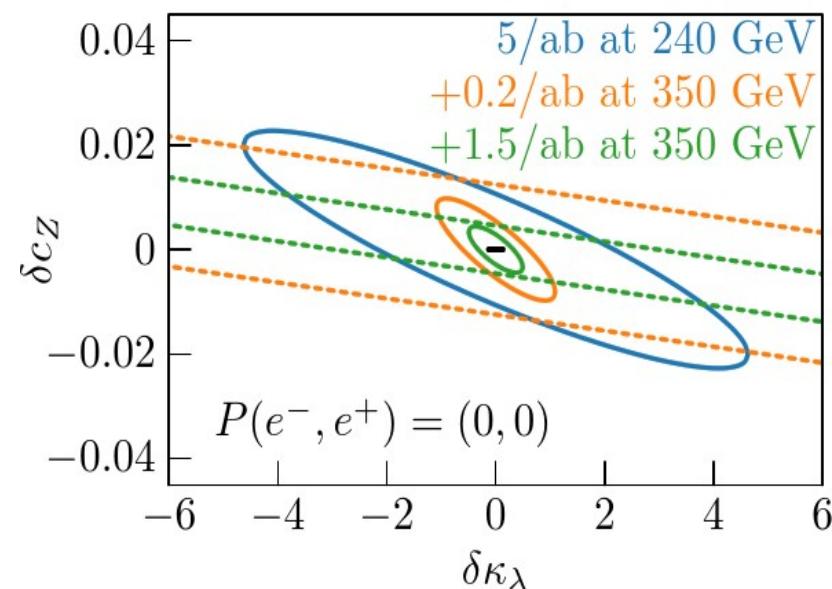
[M. McCullough, 2014]

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

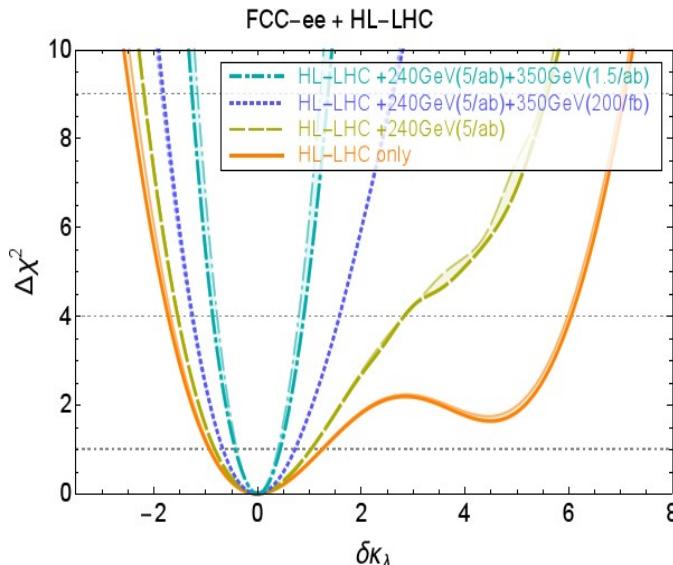
[G. Durieux, Wed. session]

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

- Indirect limits on trilinear λ coupling at ~30% level combining HL-LHC+ FCC-ee at 240+350GeV

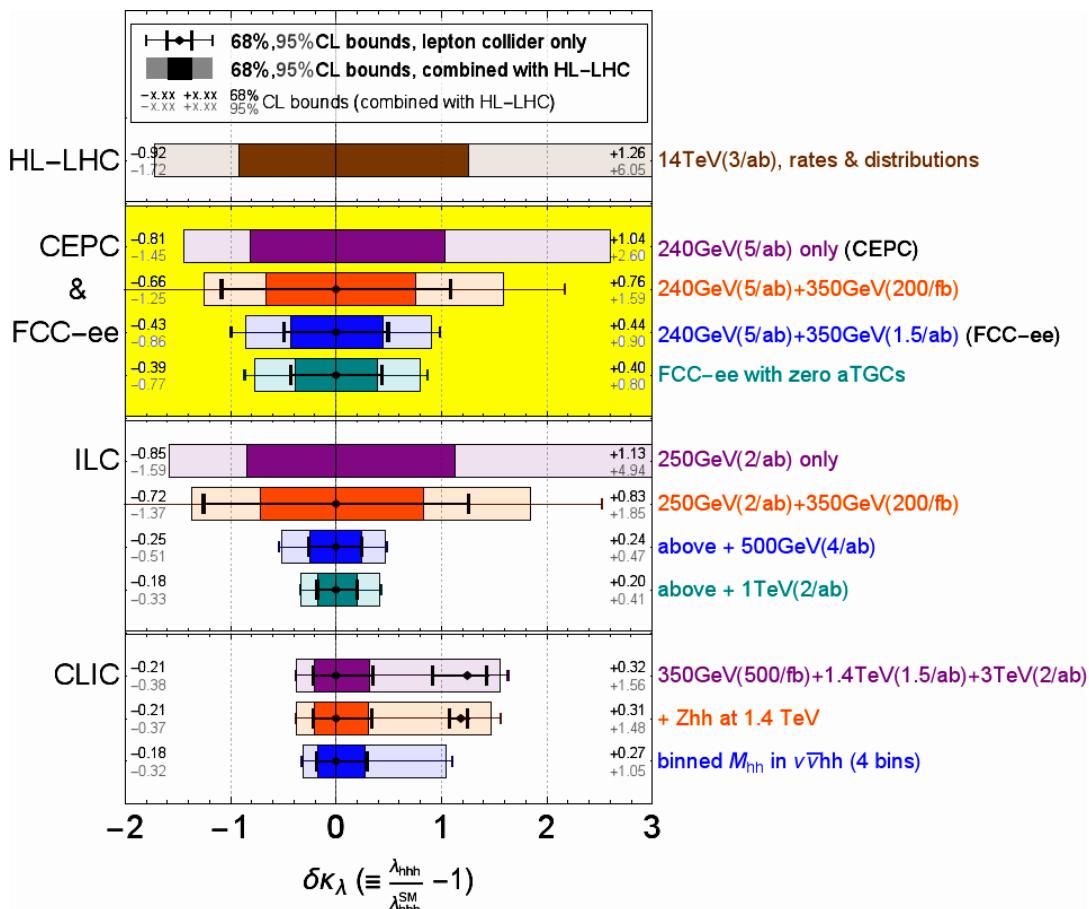


Higgs self-coupling through $\sigma(H+Z)$



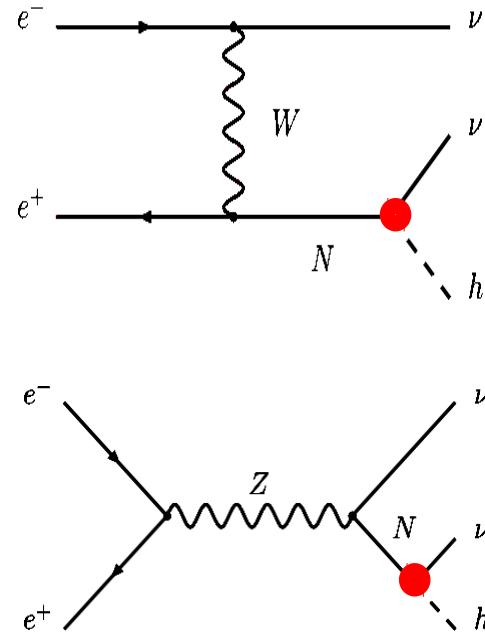
■ Higgs self-coupling constrained to within ~30%. Higher-energy e^+e^- collisions required to reduce it to ~20%

■ Addition of FCC-ee 240+350GeV Higgs cross section **solves 2nd minimum on λ** from HL-LHC data alone.

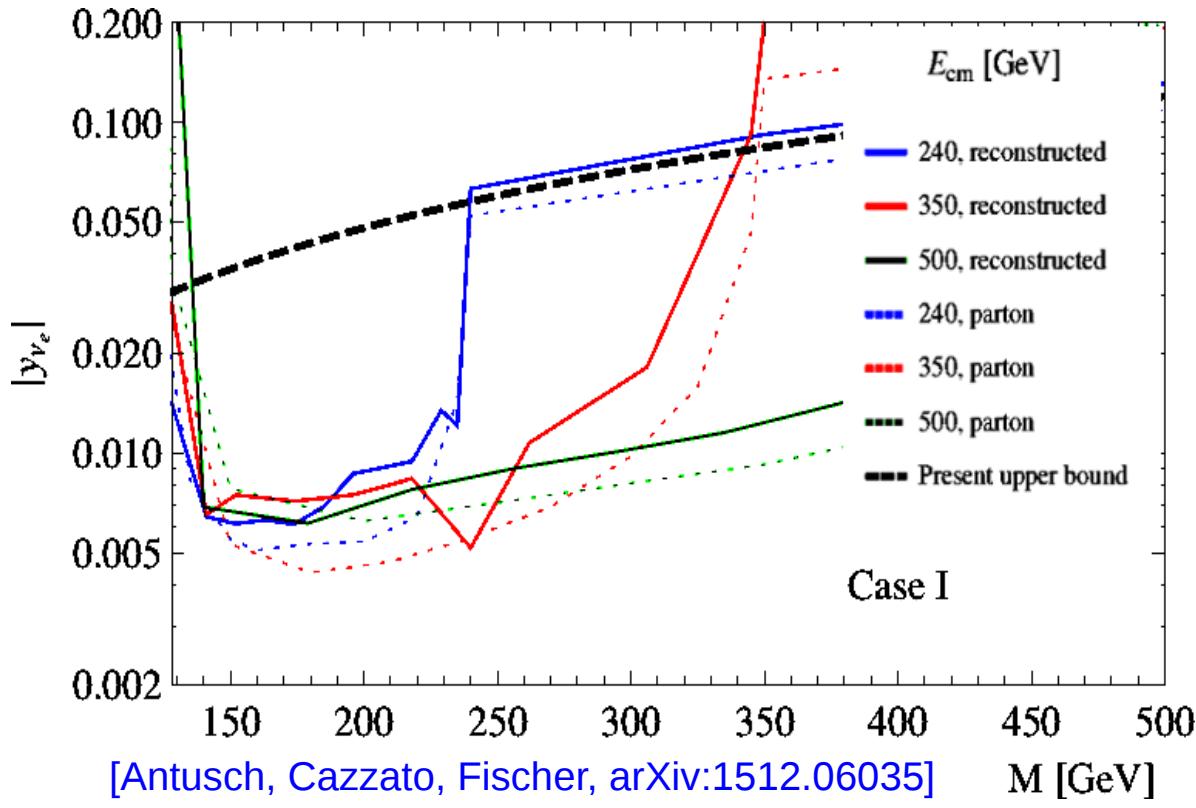


Right-handed neutrinos decaying into Higgs

- 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

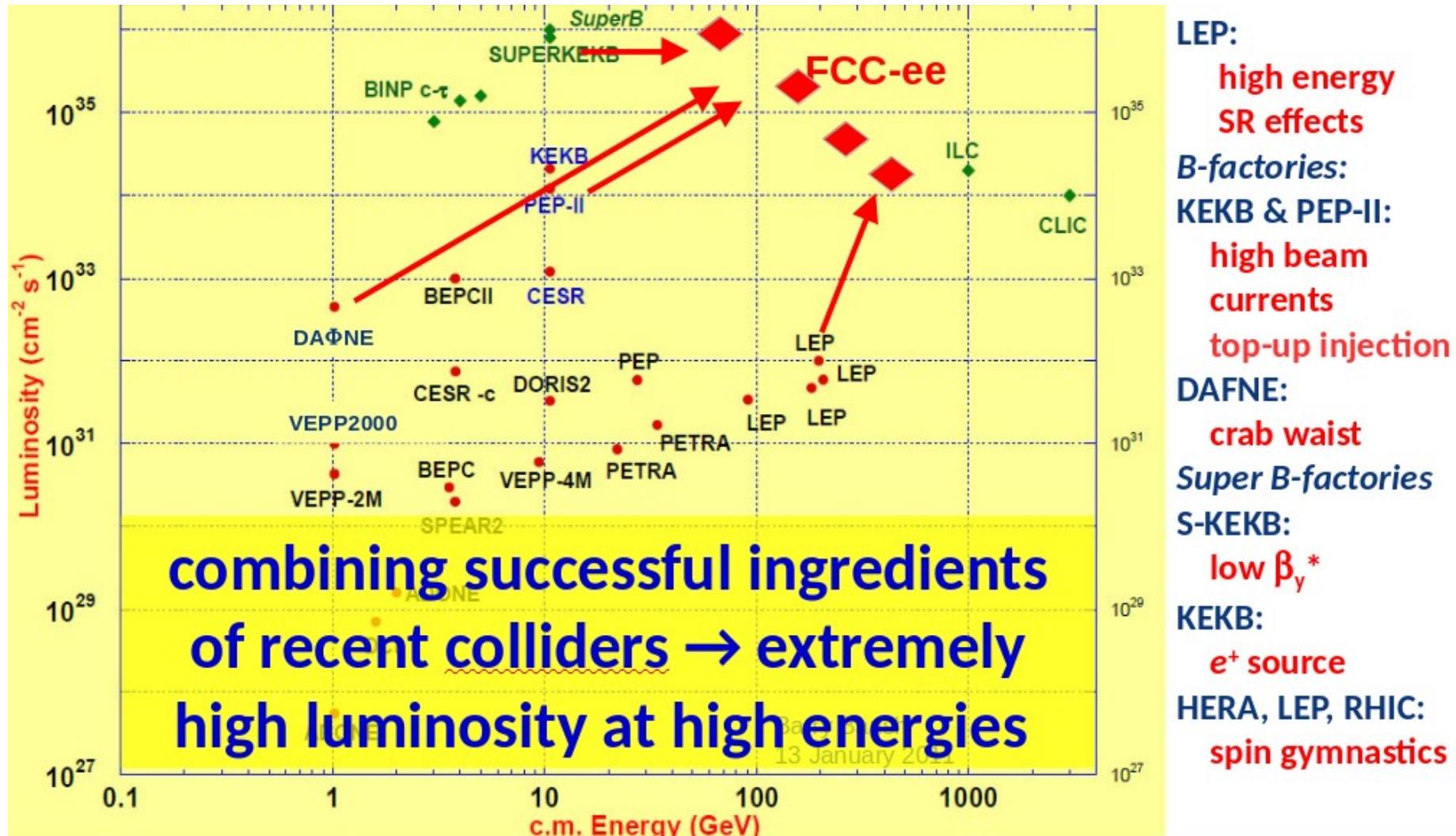


[See E. Graverini,
Tues. 10th]



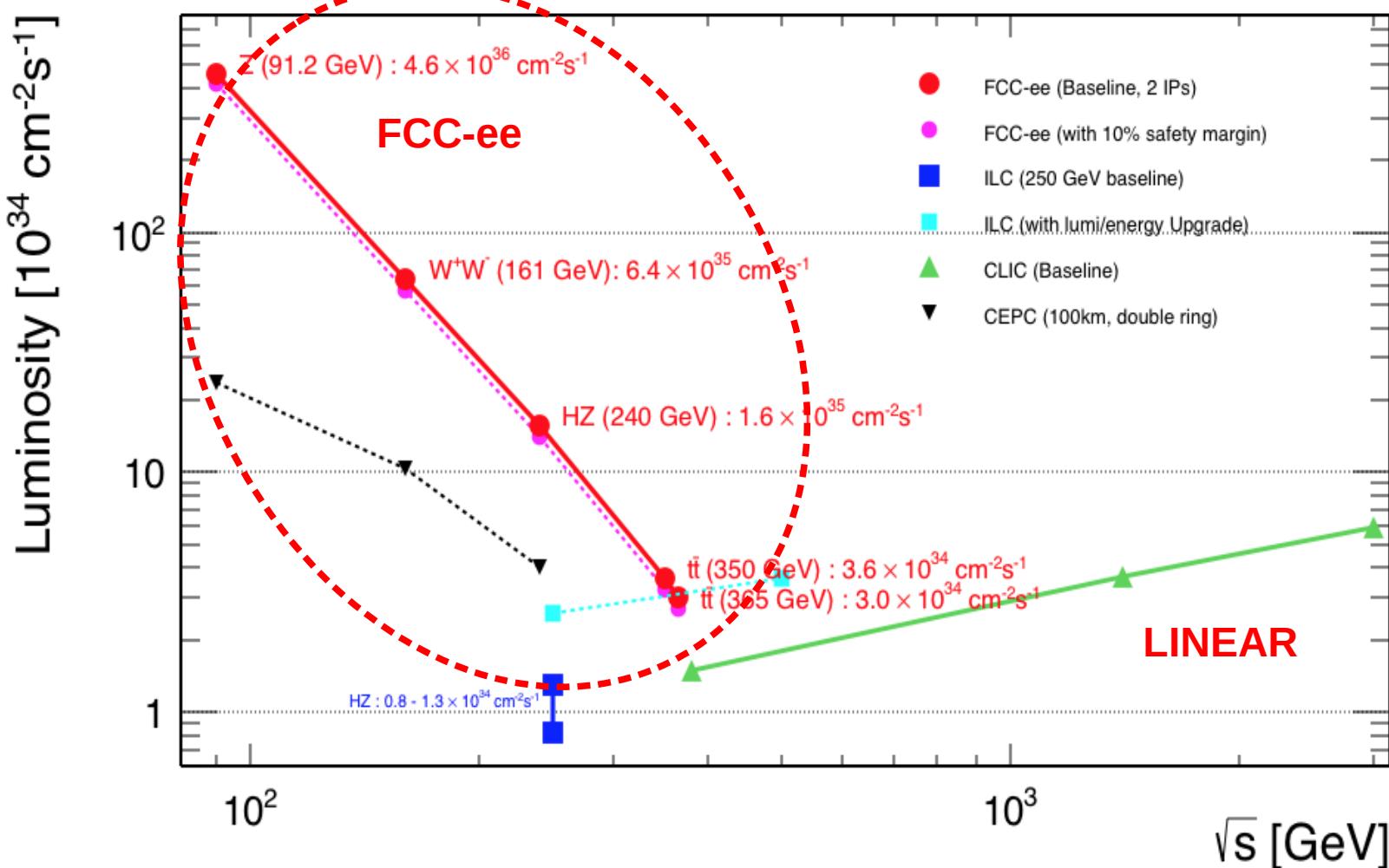
- FCC-ee sensitivity down to $|y_{ve}| \sim 5 \times 10^{-3}$ for unexplored $m_N \sim 100\text{--}350$ GeV

FCC-ee exploits recipes from past e^+e^- , pp colliders



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

FCC-ee: Z($\times 5 \cdot 10^5$ LEP), W($\times 10^4$ LEP), H, top factory



→ Unique exploration of the 10–100 TeV energy scale through high-precision studies of the 4 heaviest fundamental SM particles: W,Z,H,top

FCC-ee beam parameters

	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	175-182.5
arc cell optics	60/60	60/60	90/90	90/90
emittance <u>hor/vert</u> [nm]/[pm]	0.27/1.0	0.84/1.7	0.63/1.3	1.4/2.8
β^* horiz/vertical [m]/[mm]	0.15/.8	0.2/1	0.3/1	1/1.6
SR energy loss / turn (GeV)	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.10	0.75	2.0	8.8-10.3
energy acceptance [%]	± 1.3	± 1.3	± 1.7	$\pm 2.4-2.8$
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.165	0.099 / 0.165	0.15 / 0.20
bunch length (SR / BS) [mm]	3.5 / 12.1	3.0 / 7.5	3.15 / 5.3	2.75 / 3.80
bunch intensity [10^{11}]	1.7	2.3	1.8	3.2-3.35
no. of bunches / beam	16640	1300	328	40-33
beam current [mA]	1390	147	29	6.4-5.4
SR total power [MW]	100	100	100	100
luminosity [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	230	34	8.5	1.9-1.7
luminosity lifetime [min]	70	24	18	25
allowable asymmetry [%]	± 5	± 3	± 3	± 3

FCC-ee: CERN study project

Physics Studies Coordination

A. Blondel, P. Janot (EXP), J. Ellis, C. Grojean (TH) , M.Mccullough

EW Physics (Z pole)

R. Tenchini, F. Piccinini
S. Heynemeier, A. Freitas

Diboson Physics (MW)

R. Tenchini, F. Piccinini
S. Heynemeier, A. Freitas

Higgs Properties

M. Klute, K. Peters
S. Heynemeier, A. Freitas

Top Quark Physics

P. Azzi, F. Blekman
S. Heynemeier, A. Freitas

Synergy with FCC-hh physics, LC physics, LEP physics

QCD and $\gamma\gamma$ Physics

D. D'Enterria
P. Skands

Flavor Physics

S. Monteil
J. Kamenik

New Physics

M. Pierini, C. Rogan
M. McCullough

Global Analysis, Combination, Complementarity

J. Ellis

Develop the necessary tools

Offline Software

C. Bernet, B. Hegner,
C. Helsens

Online & Trigger

C. Leonidopoulos,
E. Perez

MDI

N. Bacchetta,
M. Boscolo

Synergy with FCC-hh, LC, LHC

Understand experimental conditions

Detector Design

A. Cattai, M. Dams,
G. Rolandi

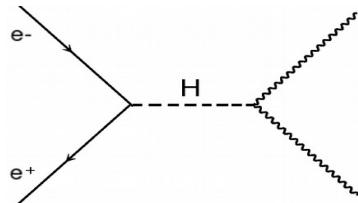
Set constraints on possible detector designs to match statistical precision

Synergy with Linear Colliders and others



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

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



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

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

- Signal + backgrounds study for 7 decay channels:

$WW^*(2j,1\nu)$ ($\sigma = 28$ ab), $WW^*(2l2\nu)$ ($\sigma = 6.7$ ab),

$WW^*(4j)$ ($\sigma = 29.5$ ab), $ZZ^*(2j2\nu)$ ($\sigma = 2.3$ ab), $ZZ^*(2l2j)$ ($\sigma = 1.14$ ab),

bb (2j) ($\sigma = 156$ ab), gg (2j) ($\sigma = 24$ ab)

- Preliminary analysis:

$L_{\text{int}} = 10 \text{ ab}^{-1}$, $S=0.65$: $\text{BR}(\text{Hee}) < 4.63 \times \text{BR}_{\text{SM}}$ (3σ), $g_{\text{hee}} < 2.15 \times g_{\text{Hee,SM}}$ (3σ)

Evidence (observation?) will require further improvements in large-BR (huge background) jet channels: $H \rightarrow bb$, $H \rightarrow WW \rightarrow 4j$

- Challenging accelerator conditions: mono-chromatization, huge lumi

- Fundamental & unique physics accessible if measurement feasible:

→ Electron Yukawa coupling

→ Higgs width measurable (“natural” threshold scan)

$ee \rightarrow H$ significance: Multi-Channel Combination

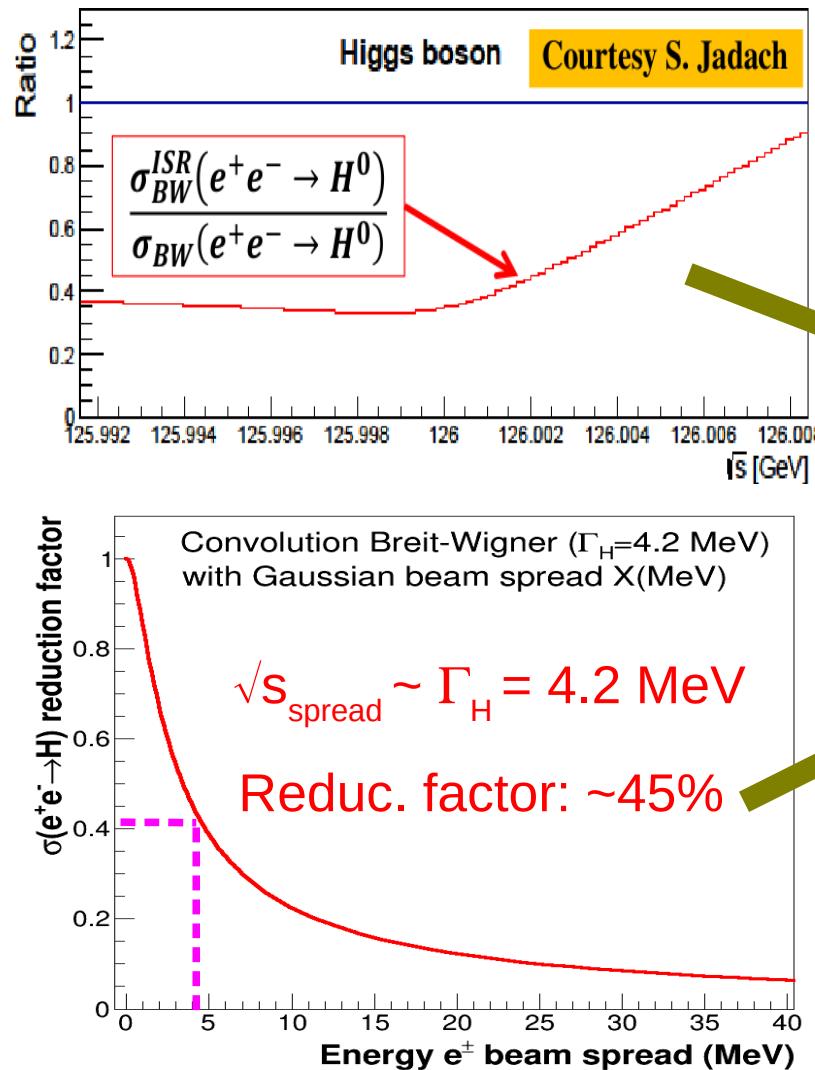
- Channels combination using Roostats-based tool for LHC Higgs analyses: Profile likelihood & hybrid significances all give ~identical results, which are also very close to naive S/ \sqrt{B} expectation (no background uncertainty).

Channel	Significance (1 ab ⁻¹)	Significance (10 ab ⁻¹)
$WW \rightarrow l\nu 2j, 2l 2\nu, 4j$	0.15$\oplus 0.09 \oplus 0.03$	0.50$\oplus 0.30 \oplus 0.08$
$ZZ \rightarrow 2j 2\nu, 2l 2j, 2l 2\nu$	0.07$\oplus 0.05 \oplus 0.01$	0.21$\oplus 0.16 \oplus 0.03$
bb	0.03	0.10
gg	0.03	0.09
$\tau\tau$	–	0.02
$\gamma\gamma$	–	0.01
Combined	0.2	0.7

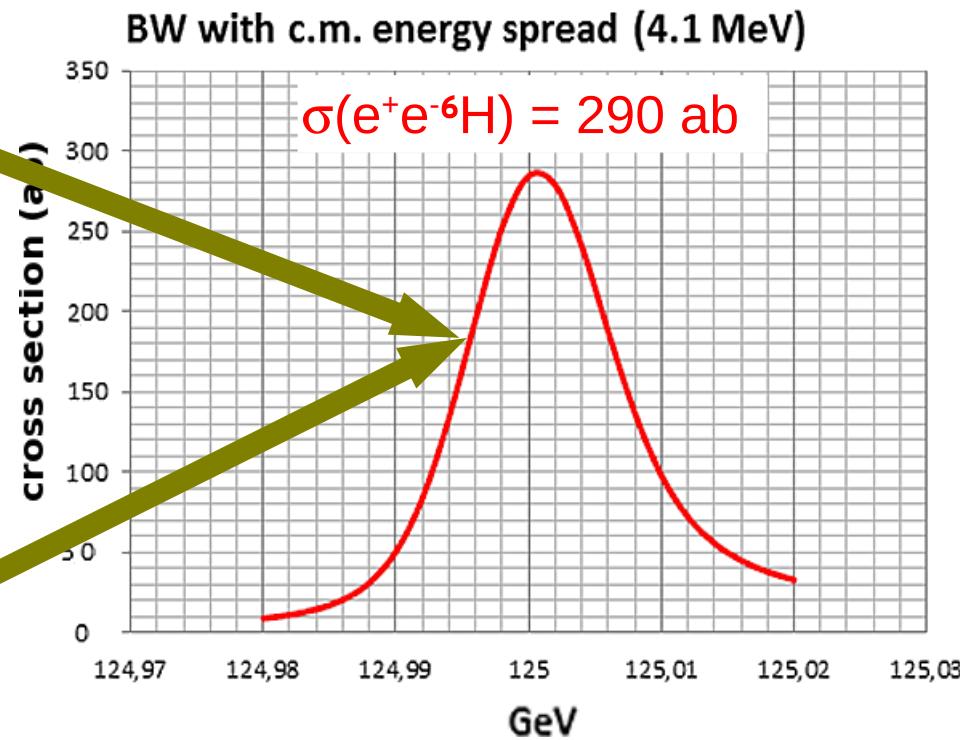
- For 10 ab⁻¹: Significance ≈ 0.7 (preliminary, optimizations under study)
Limit (95% CL) for branching ratio: $BR(H \rightarrow ee) < 2.8 \times BR_{SM}(H \rightarrow ee)$
Limit (95% CL) for SM Yukawa: $g_{eH} < 1.7 \times g_{eH,SM}$

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

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



- Combined reduction factors:



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

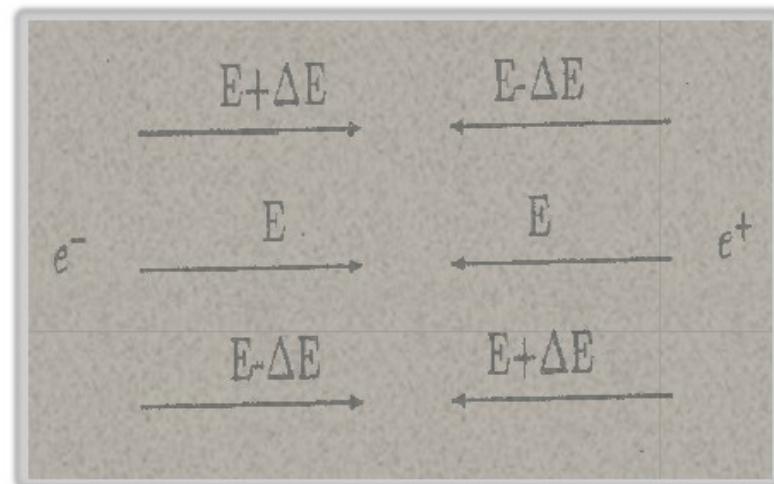
mono-chromatization at 2x63 GeV?

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

rms beam energy spread at 63 GeV ~30 MeV
total width of SM Higgs $\Gamma \sim 4$ MeV

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

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



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



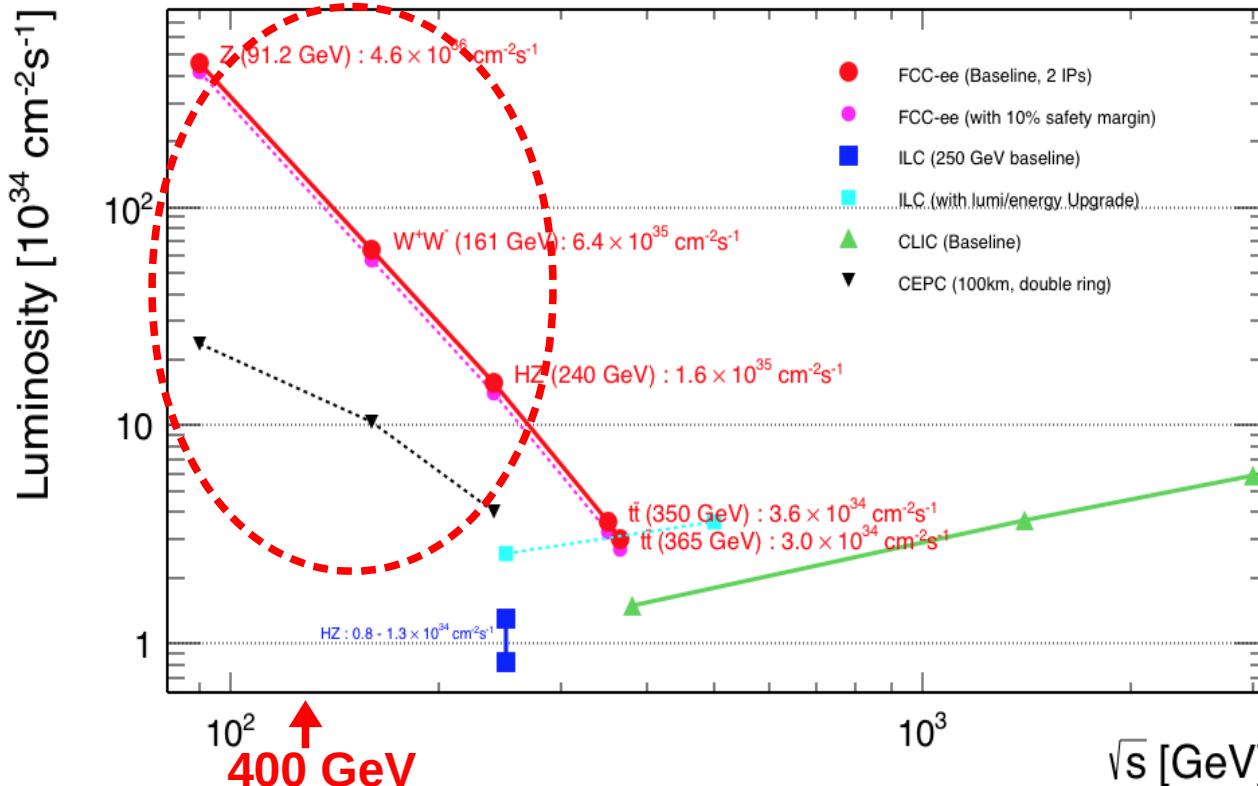
2016 baseline parameters

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 $10^{34} \text{ cm}^{-2}\text{s}^{-1}$	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

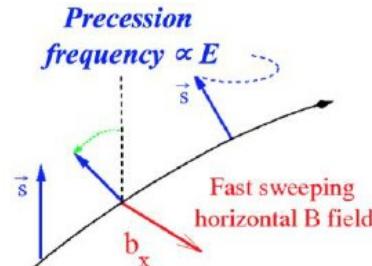


- \sqrt{s} limited to ~ 400 GeV by SR~ E^4/R : $R \sim 80$ km ($\times 3$ LEP radius)
- Large # of circulating bunches: $\times 10^4$ LEP bunches +crab-waist collisions
 - High Lumi (better at low \sqrt{s}): $\times 10^4$ –10 more lumi than ILC for $\sqrt{s} = 90$ –400 GeV
 - Top-up injection ring to 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

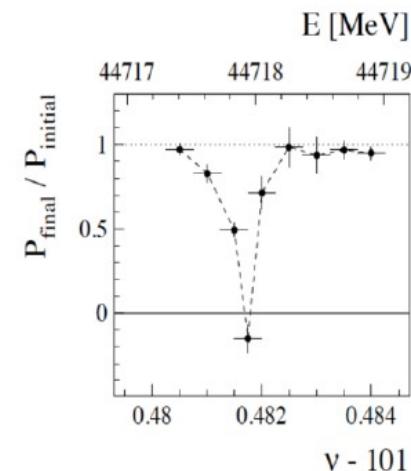
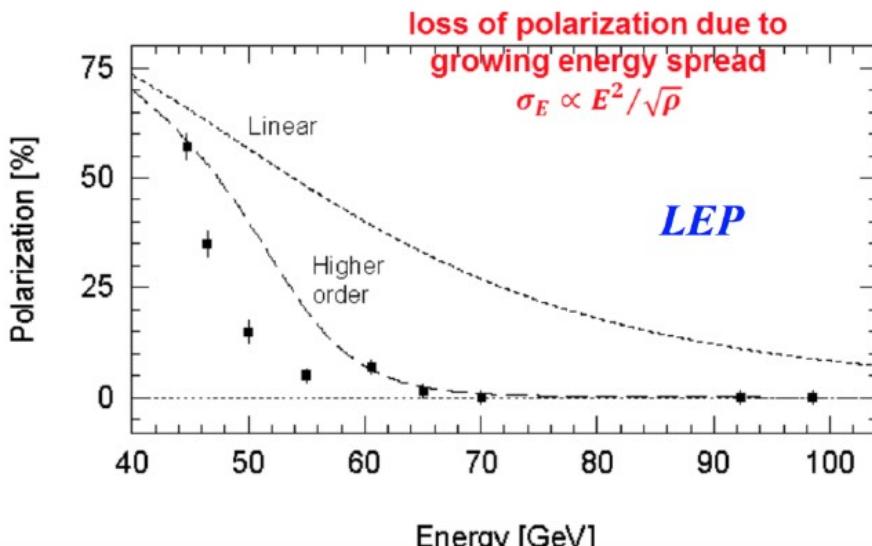
Resonant depolarization

- use naturally occurring 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

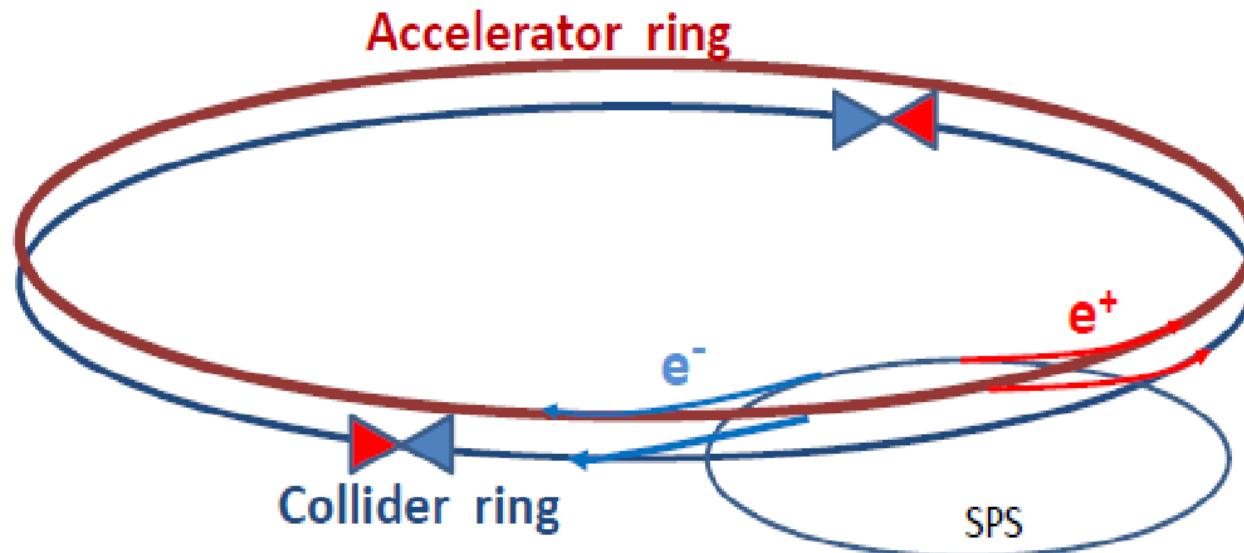
< 100 keV beam energy calibration
at Z peak and at WW threshold

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 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

$$2eF_{1V}^Z = g_R + g_L$$
$$2eF_{1A}^Z = g_R - g_L$$

