

Physics at the CERN Future Circular Collider

Korean Phys. Society Fall Meetg.

Jeju Island, 21st Oct 2026

David d'Enterria

CERN

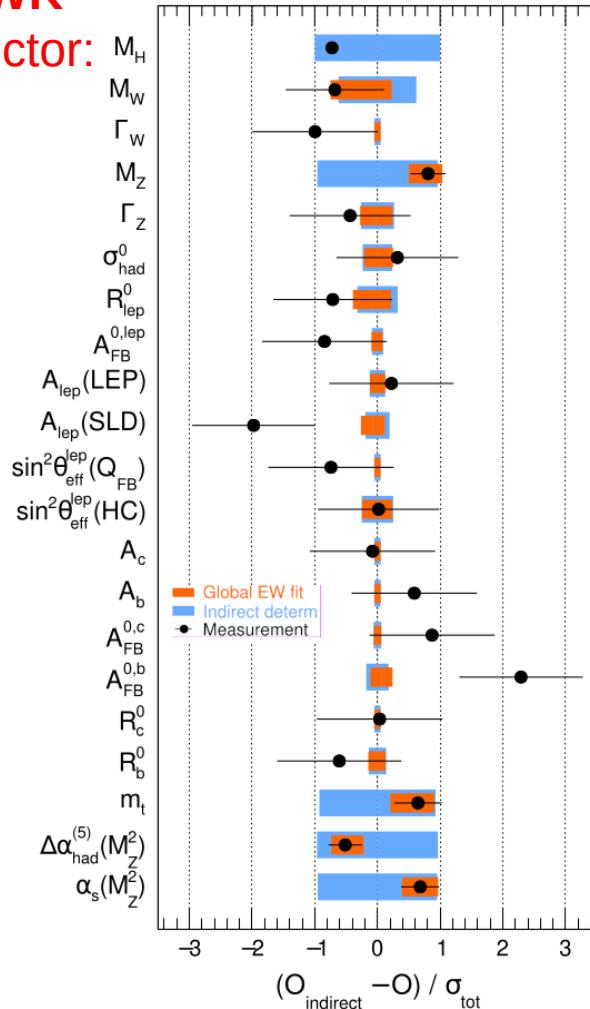


For the FCC approval & detectors concepts:
See presentation by Paolo Giacomelli

Standard Model of particles & interactions

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

EWK sector:

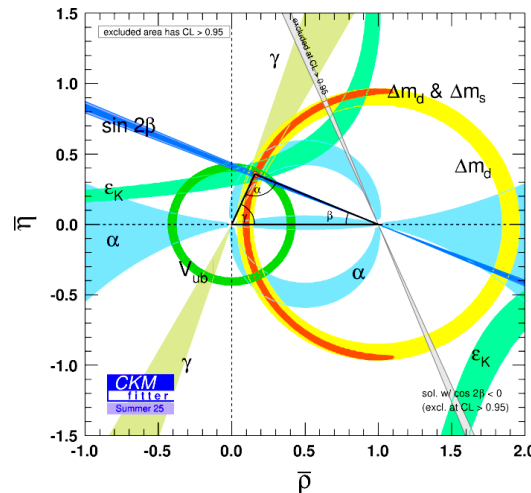


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} D\psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

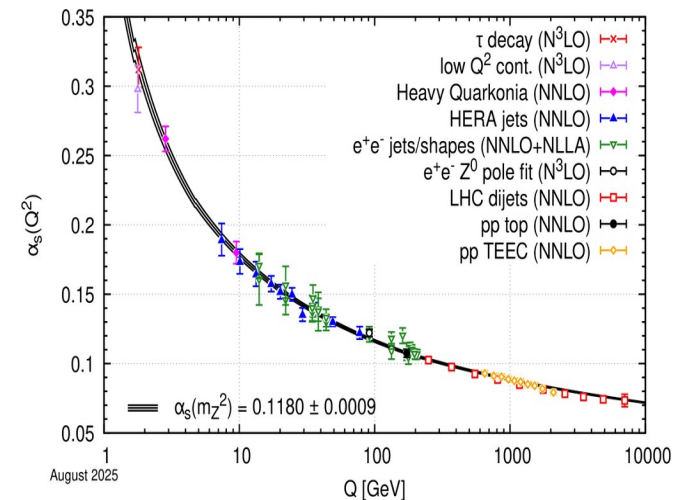
Diagram illustrating the Lagrangian components and their corresponding Feynman diagrams:

- GAUGE FIELDS**: $-\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$ (Gauge Field Kinetic Term)
- FERMION FIELDS**: $+i\bar{\psi} D\psi + h.c.$ (Feynman diagram showing a fermion line with a derivative)
- YUKAWA COUPLINGS**: $+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$ (Yukawa Interactions)
- HIGGS SECTOR**: $+ |D_\mu \phi|^2 - V(\phi)$ (Higgs Sector)

Flavour sector:



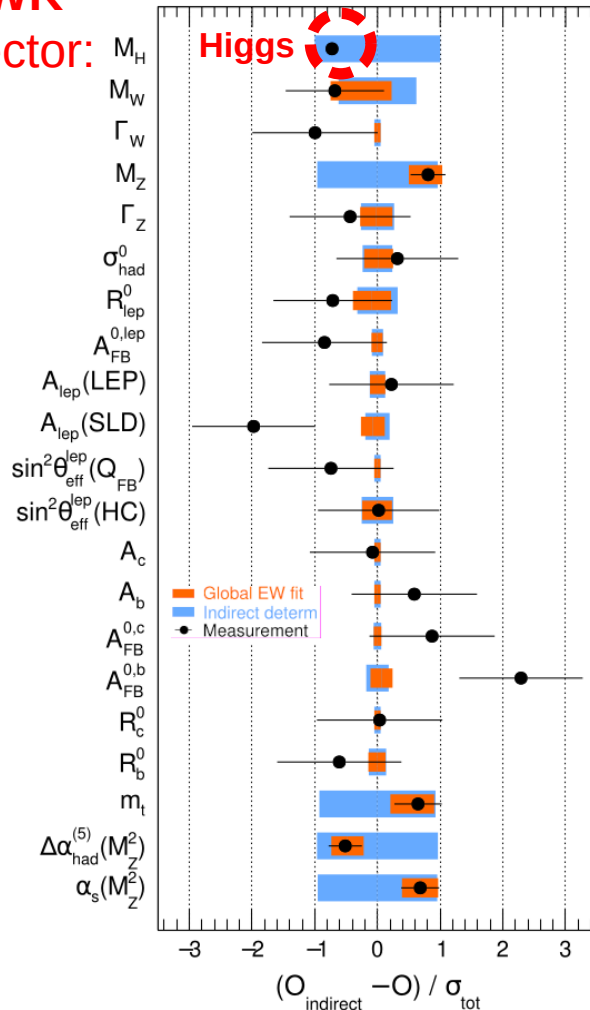
QCD sector:



Standard Model of particles & interactions

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- $\mathcal{O}(20)$ parameters: Couplings, H mass & vev, H-f Yukawas, CKM mix., CP phases.
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EWK sector:



Gauge Fields

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

Gauge Field Kinetic Term

Fermion Fields

$$+ i\bar{\psi} D\psi + h.c.$$

Fermions

Yukawa Couplings

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

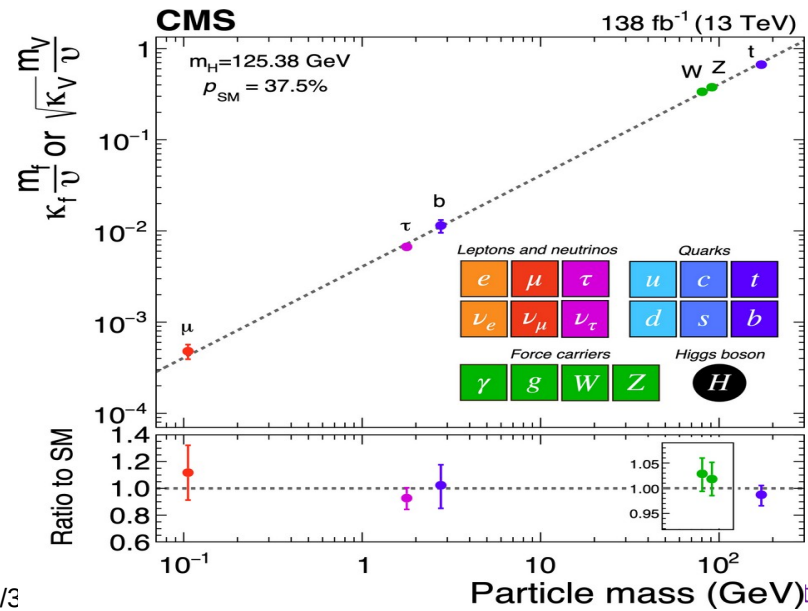
Yukawa Interactions

Higgs Sector

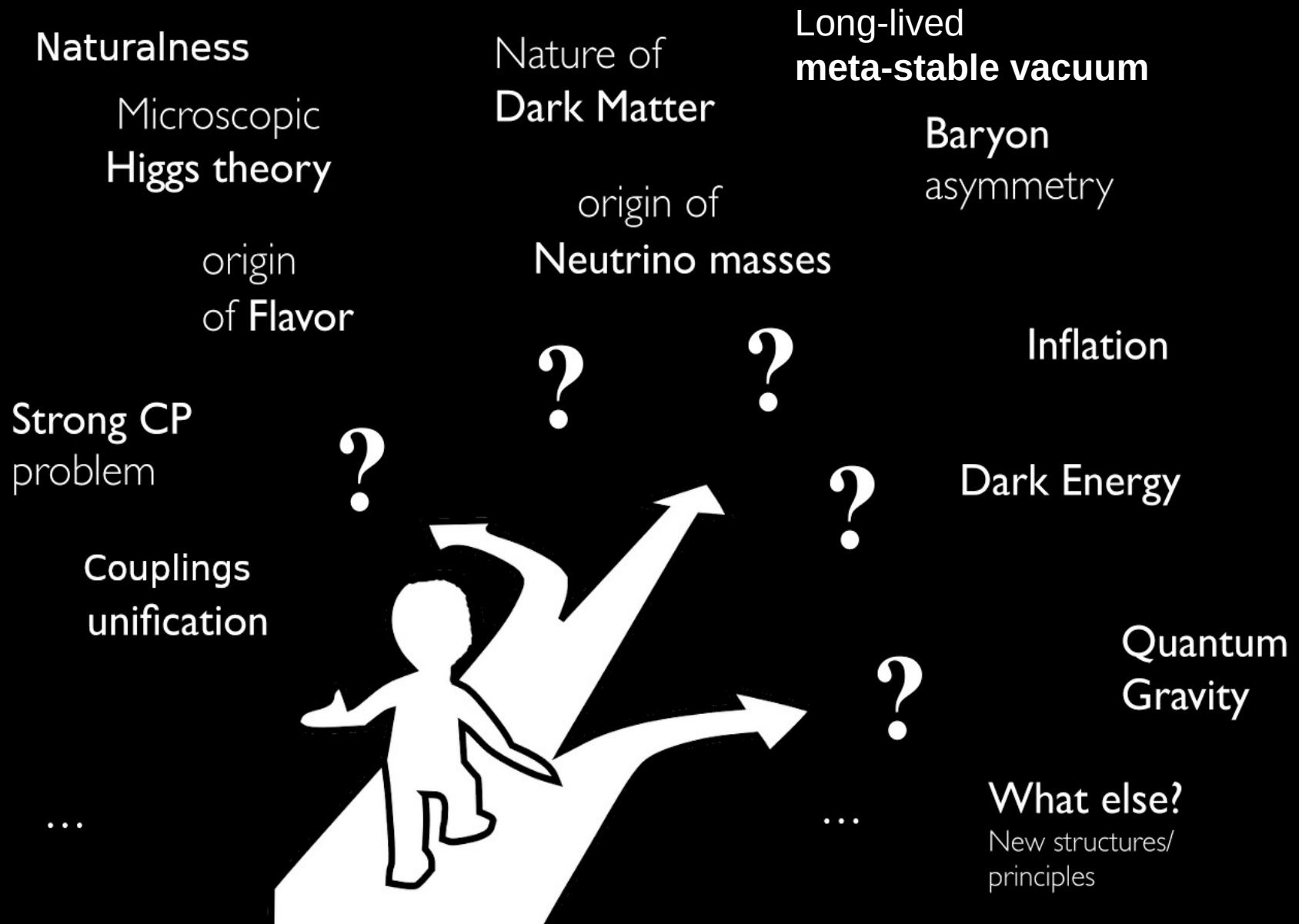
$$+ |D_\mu \phi|^2 - V(\phi)$$

Higgs Sector

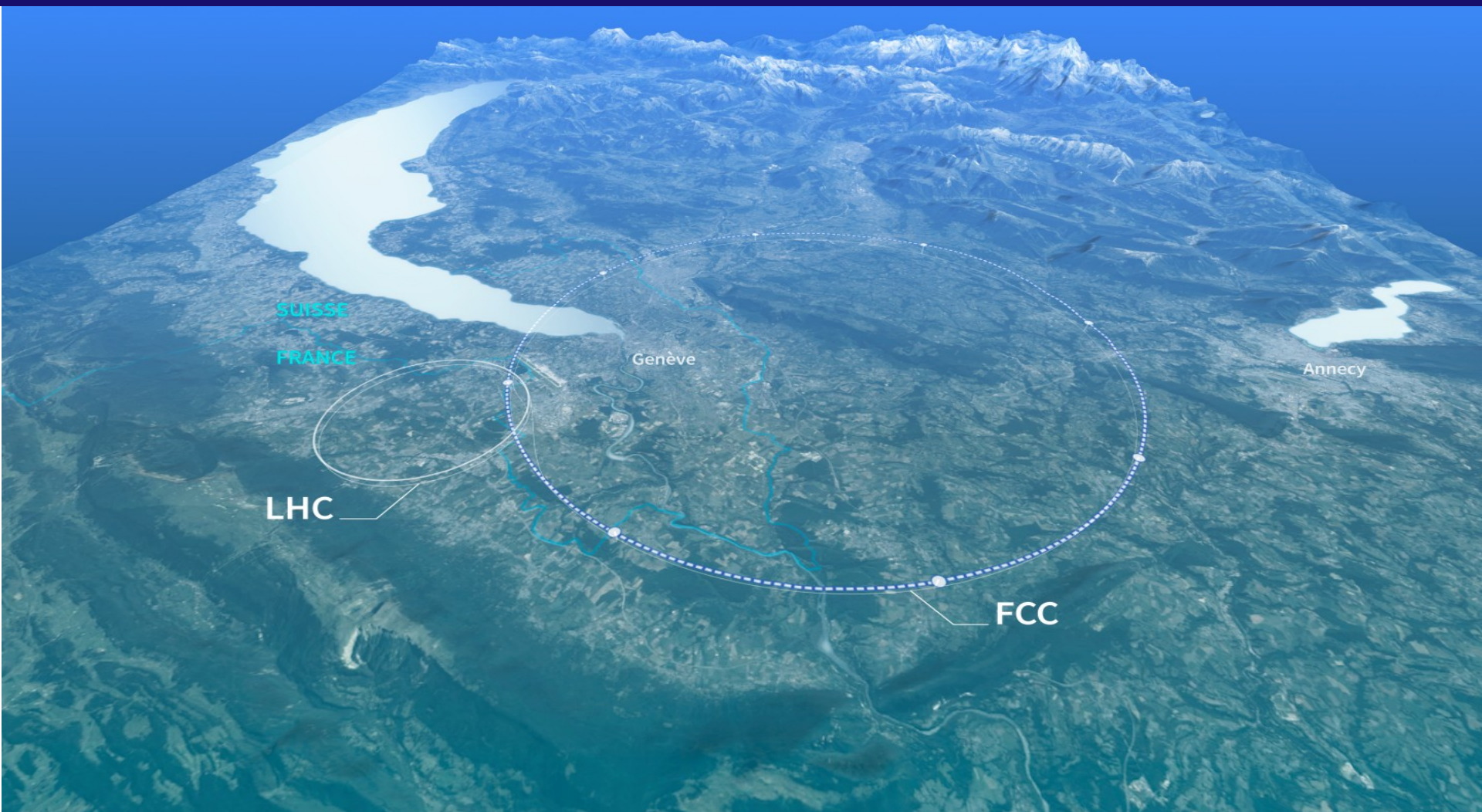
Higgs sector:



Why do we need a new collider ?



LHC has discovered Higgs + “nothing else” = Higher precision & energy needed

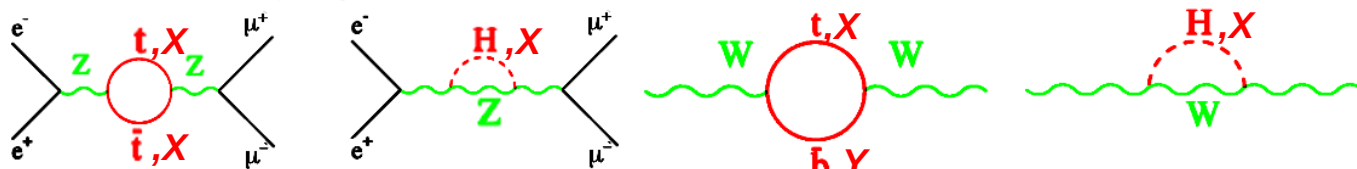


Particle collider with **4 interaction points** in **91-km** (200m-undergnd) **ring**:

- ▶ **FCC-ee**: e^+e^- Higgs/EW/Flavour/top/QCD factory at $\sqrt{s} = 90\text{--}365$ GeV
- ▶ **FCC-hh**: Energy frontier **pp** collider reaching $\sqrt{s} \approx 100$ TeV

Indirect & Direct BSM searches

- Cover the broadest possible range of BSM scenarios:
Heavier than LHC reach → Produce it at **FCC-hh** (energy frontier $\times 10$)
Small couplings / hiding well → Find it at **FCC-ee** (precision $\times 300$)
- BSM searches at FCC-ee:
 - ➔ **Direct** model-indep. discovery of particles **from Z,W,H decays up to $m \sim \sqrt{s}/2$**
Small & well understood backgrounds: Fill “blind spots” in p-p searches
 - ➔ **Indirect** via high-precision SM measurements sensitive to **virtual corrections**:



- BSM scale Λ (from generic SMEFT) via precision measurements:

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

HL-LHC: $\pm 5\%$ Higgs couplings precision: $\Lambda \gtrsim 1 \text{ TeV}$

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

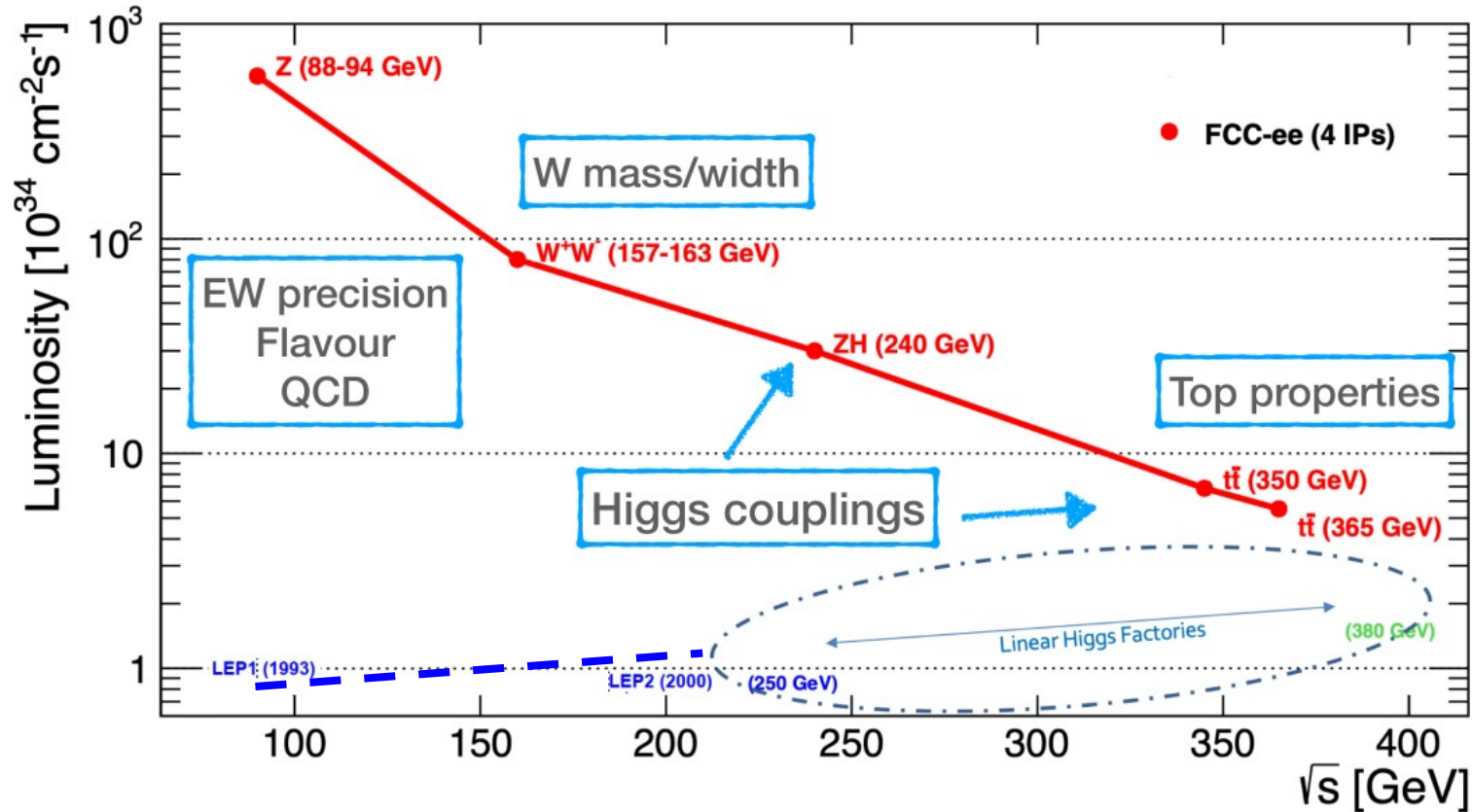
➔ **New electroweak-coupled** physics: $\Lambda \propto (1 \text{ TeV}) / \sqrt{\delta X}$

Current EWK fit excludes new physics below: $\Lambda \gtrsim 3 \text{ TeV}$

FCC(e^+e^-): $\times 300$ times more precise: $\Lambda \gtrsim 50 \text{ TeV}$

FCC-ee = Z, W, H, top factory

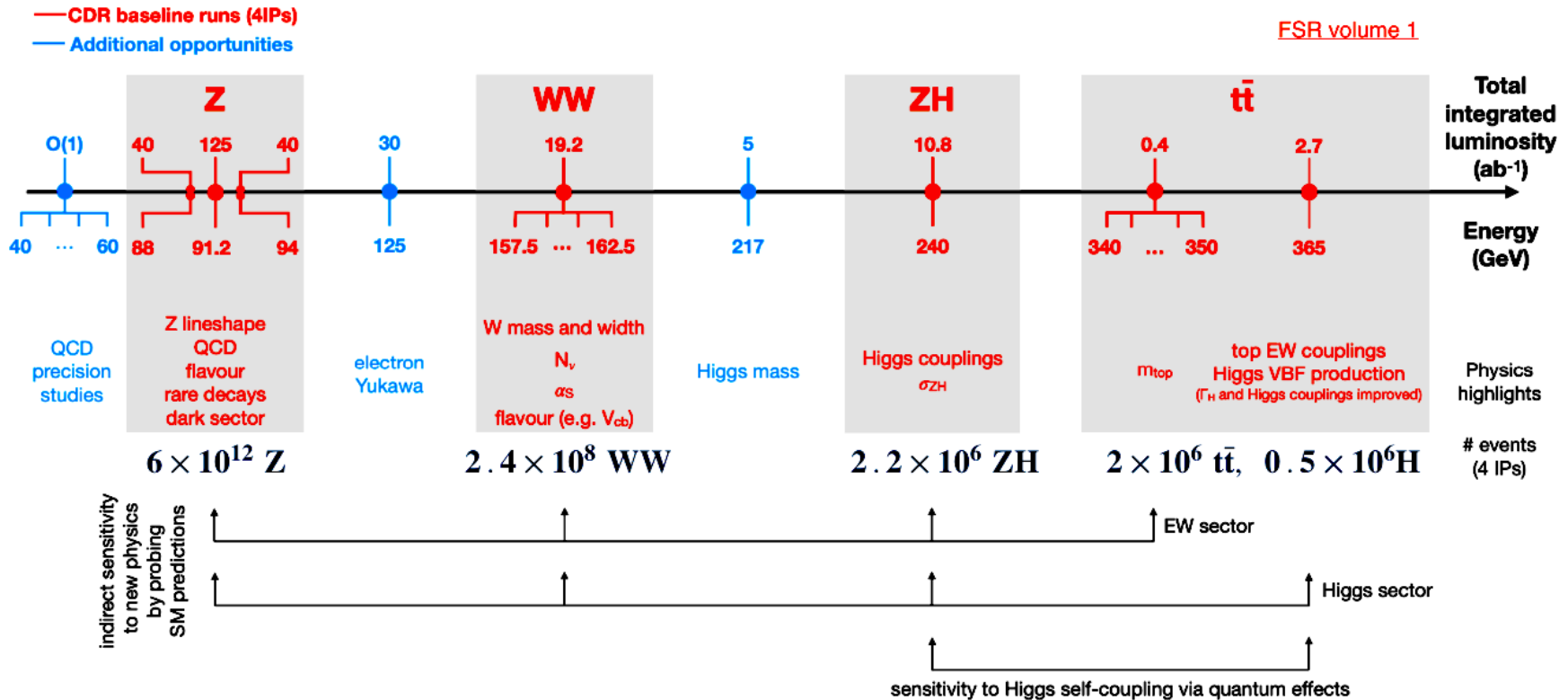
- The FCC-ee features **unparalleled luminosities**:



- ➡ Full LEP program in 1 minute: $Z (\times 5 \cdot 10^5 \text{ LEP})$, $W (\times 10^4 \text{ LEP})$, plus 2M Higgs, 2M top quarks
- ➡ Indirect **exploration of the 10–100 TeV energy scale** through SM “stress tests” via high-precision studies of the **4 heaviest particles: W,Z,H,top**

FCC-ee = Z, W, H, top factory

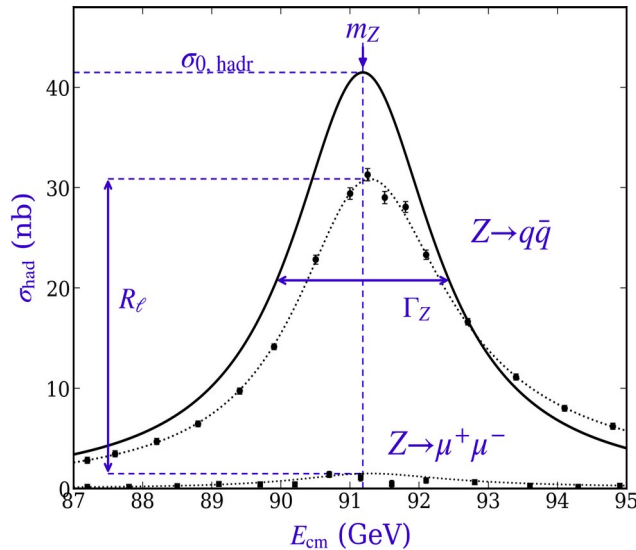
■ Physics programme in 4 baseline runs:



- ➡ Full LEP program in 1 minute: Z (× 5 · 10⁵ LEP), W (× 10⁴ LEP), plus 2M Higgs, 2M top quarks
- ➡ Indirect exploration of the 10–100 TeV energy scale through SM “stress tests” via high-precision studies of the 4 heaviest particles: W, Z, H, top

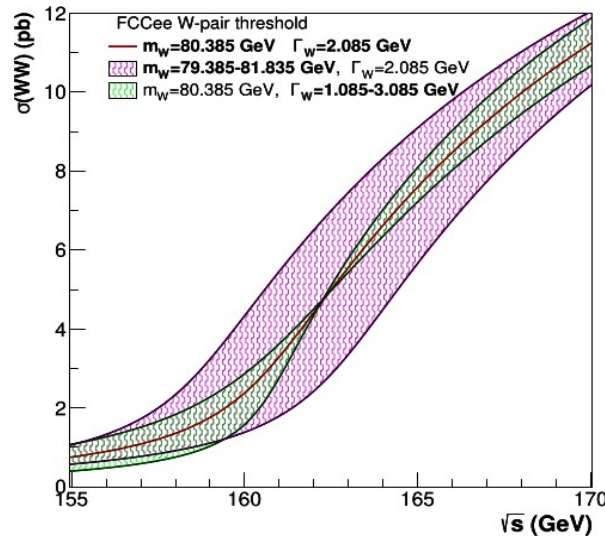
FCC-ee: High-precision W, Z, top

Z resonance: $6 \cdot 10^{12}$ Z



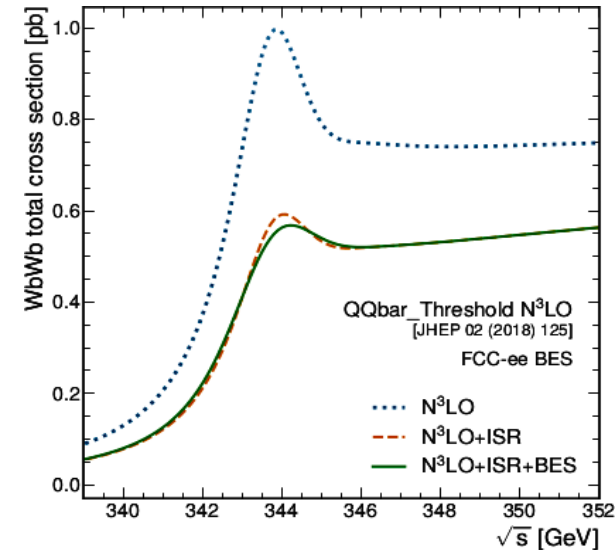
- **Lineshape:**
Exquisite E_{beam} (RDP)
 M_Z, Γ_Z to 10 keV (stat)
- **Asymmetries:**
 $\sin^2\theta_W$ to $1e-6$
 α_{em} to $8e-5$
- **Branching fractions, R_l, R_b :**
 $\alpha_s(m_Z)$ to 0.1%
- Predict m_{top}, m_W in SM

WW thresh. scan: $2 \cdot 10^8$ W



- **Threshold scan:**
 m_W to 200 keV
 Γ_W to 300 keV
- **Branching fractions:**
 $\alpha_s(m_W)$ to 0.2%
- **Radiative returns:** $e^+e^- \rightarrow Z(\nu\nu)\gamma$
 N_ν to 0.0005

tt thresh. scan: $2 \cdot 10^6$ tops



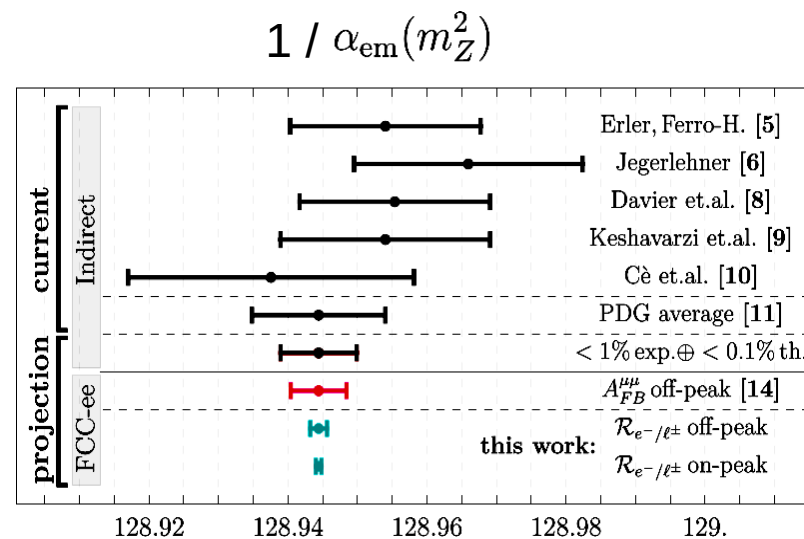
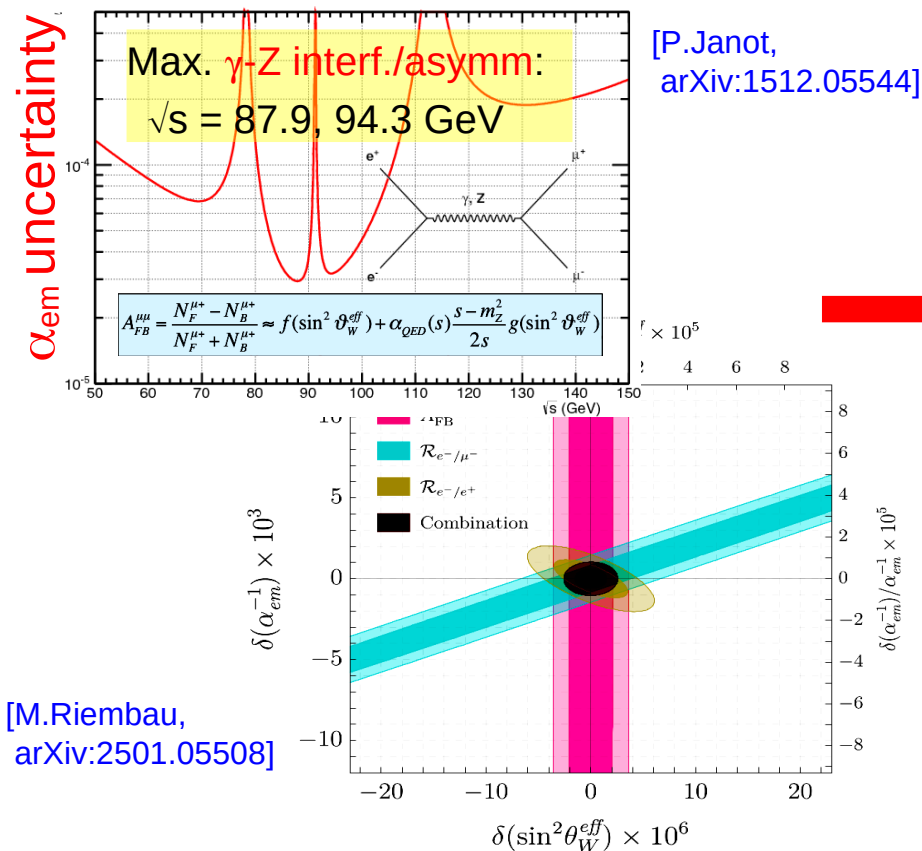
- **Threshold scan:**
 m_{top} to 7 MeV
 Γ_{top} to 11 MeV
 λ_{top} to 1.5% (4D fit)
EW couplings to 1%

■ Mostly thanks to: (i) Huge statistics

(ii) Exquisite beam energy calib: $\delta E_{\text{cm}} \approx 0.1, 0.15, 1$ MeV (Z,W,t)

FCC-ee: $\alpha_{em}(m_Z)$ coupling

- The QED coupling at m_Z is a large **parametric uncertainty** in EWPO fits.
- Slope of $\mu\mu$ fwd-bckwd asymmetry off-peak and fwd. Bhabha/ $\mu\mu$ ratio on-peak have very strong sensitivity to **QED coupling & weak mixing angle**:



- FCC-ee will reduce the current **QED coupling** uncertainty by up to a factor $\times 20$: $\delta\alpha/\alpha(m_Z) \sim 6 \cdot 10^{-6}$ (stat. uncert., syst. cancel in ratios)

FCC-ee: $\alpha_s(m_Z)$ coupling

EW boson hadronic widths known at N³LO in pQCD:

- The W and Z hadronic widths :

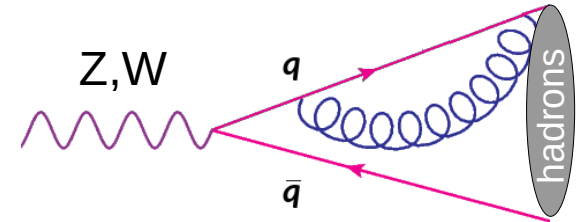
$$\Gamma_{W,Z}^{\text{had}}(Q) = \Gamma_{W,Z}^{\text{Born}} \left(1 + \sum_{i=1}^4 a_i(Q) \left(\frac{\alpha_S(Q)}{\pi} \right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\text{EW}} + \delta_{\text{mix}} + \delta_{\text{np}} \right)$$

- The ratio of W, Z hadronic-to-leptonic widths :

$$R_{W,Z}(Q) = \frac{\Gamma_{W,Z}^{\text{had}}(Q)}{\Gamma_{W,Z}^{\text{lep}}(Q)} = R_{W,Z}^{\text{EW}} \left(1 + \sum_{i=1}^4 a_i(Q) \left(\frac{\alpha_S(Q)}{\pi} \right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\text{mix}} + \delta_{\text{np}} \right)$$

- In the Z boson case, the hadronic cross section at the resonance peak in e^+e^- :

$$\sigma_Z^{\text{had}} = \frac{12\pi}{m_Z} \cdot \frac{\Gamma_Z^e \Gamma_Z^{\text{had}}}{(\Gamma_Z^{\text{tot}})^2}$$



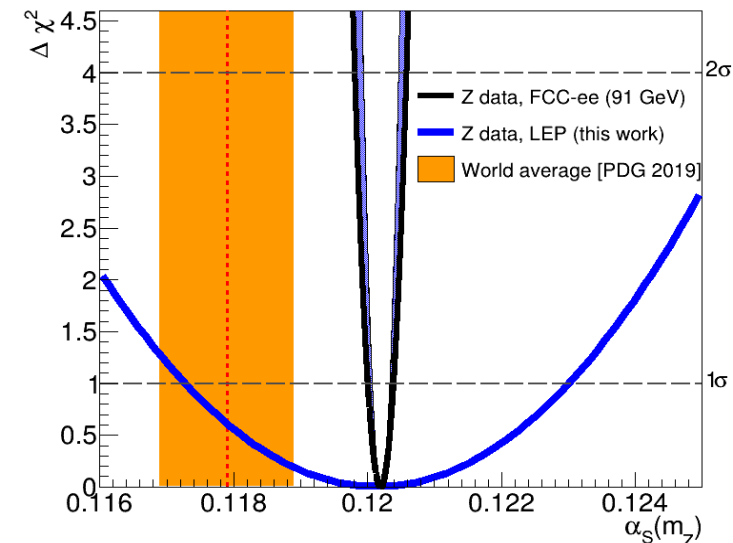
Sensitivity to $\alpha_s(m_Z)$ via
 $\mathcal{O}(4\%)$ higher-order corr.

[DdE, Jacobsen
arXiv:2005.04545]

FCC-ee will reach 0.1% precision on $\alpha_s(m_Z)$ ($\times 20$ better than LEP):

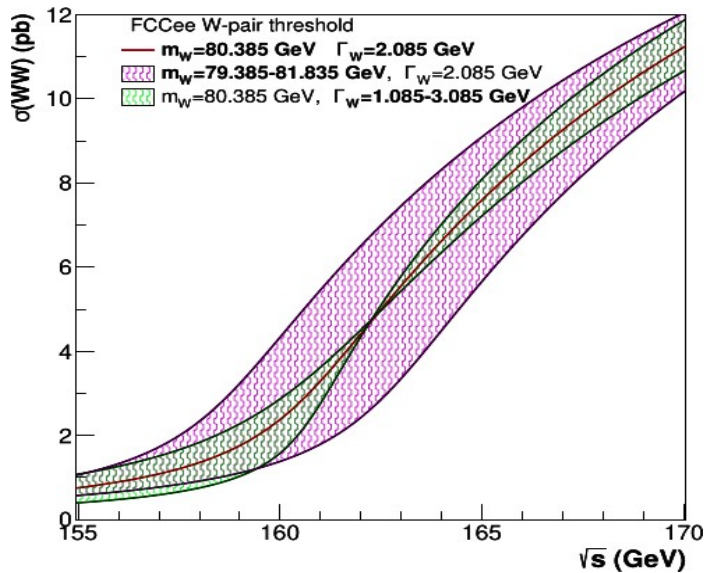
- Huge Z pole statistics
- Exquisite syst./parametric precision:

$$\begin{aligned} \Delta R_Z &= 10^{-3}, & R_Z &= 20.7500 \pm 0.0010 \\ \Delta \Gamma_Z^{\text{tot}} &= 0.1 \text{ MeV}, & \Gamma_Z^{\text{tot}} &= 2495.2 \pm 0.1 \text{ MeV} \\ \Delta \sigma_Z^{\text{had}} &= 4.0 \text{ pb}, & \sigma_Z^{\text{had}} &= 41\,494 \pm 4 \text{ pb} \\ \hline \Delta m_Z &= 0.1 \text{ MeV}, & m_Z &= 91.18760 \pm 0.00001 \text{ GeV} \\ \Delta \alpha &= 3 \cdot 10^{-5}, & \Delta \alpha_{\text{had}}^{(5)}(m_Z) &= 0.0275300 \pm 0.0000009 \end{aligned}$$



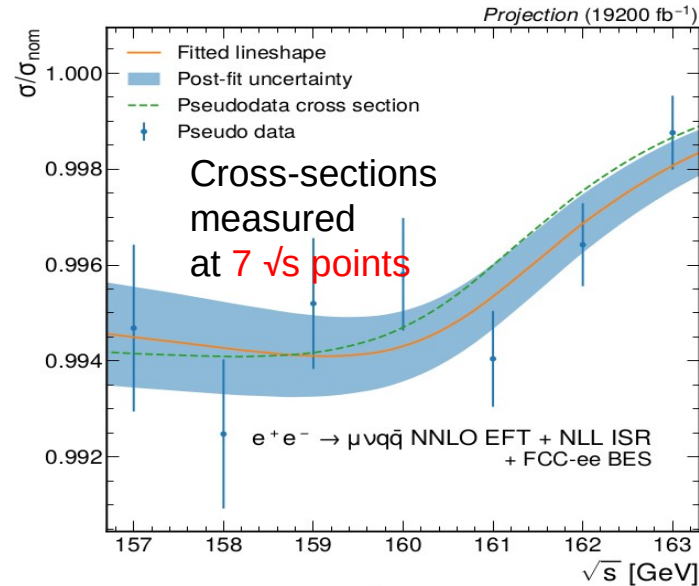


- **Threshold scan** over $\sqrt{s} \approx 155\text{--}170$ GeV for W **mass & width** extraction:



[P.Azzurri,
arXiv:2107.04444]

m_W : position of rise
 Γ_W : curvature of rise

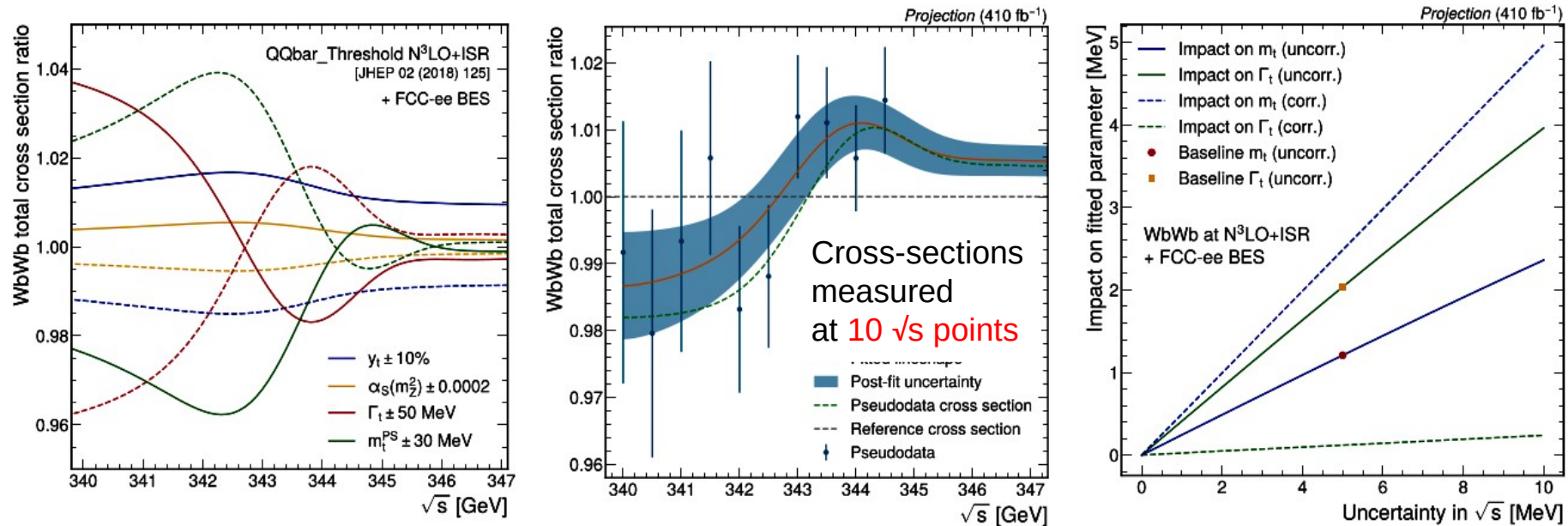


[M.Defranchis, work in progress]

- Experimental **uncertainties**: $\delta m_W \sim 0.2$ MeV (vs. ± 9 MeV today)
 $\Delta \Gamma_W \sim 0.3$ MeV (vs. ± 42 MeV today)
- **Theoretical** NNLO+NLL ISR uncertainties are today at the $\mathcal{O}(3$ MeV) level.
- Also, W mass with $\mathcal{O}(1$ MeV) from $W \rightarrow qq, q+\nu\ell$ inv. mass (kin. constraints)



- **Threshold scan** over $\sqrt{s} = 340\text{--}345$ GeV for **top mass & width** extraction:



Uncertainty source	m_t^{PS} [MeV]	Γ_t [MeV]	y_t [%]
Experimental (stat. $\times 1.2$)	4.2	10.0	1.5
Total profiled	6.5	11.7	2.1
Theory	35	25	?

[M.Defranchis et al., arXiv:2503.18713]

- Cross section measurements stat. limited
- **b-tagging** uncertainty can be controlled in-situ exploiting WbWb topology
- Challenge: control of **point-to-point correlations** (luminosity, beam energy spread, beam energy calibration)

- Today, **theoretical** N³LO+ISR uncertainties are at the **$\mathcal{O}(35 \text{ MeV})$ level**.

- Experimental **uncertainties**: $\delta m_{\text{top}} \sim 7 \text{ MeV}$ (vs. $\pm 290 \text{ MeV}$ today)

$\delta \Gamma_{\text{top}} \sim 12 \text{ MeV}$ (vs. $\pm 190 \text{ MeV}$ today)

■ Stat. uncertainties **very small**. Syst. ones **reducible in-situ** (statistics-driven).

Observable	Measurement	Current precision	FCC-ee stat.	Approx. syst.	Challenge
m_Z (MeV)	Lineshape	91187.6 ± 2.0	0.004	≤ 0.1	Beam energy calib.
Γ_Z (MeV)	Lineshape	2495.5 ± 2.3	0.004	≤ 0.012	Beam energy calib.
R_ℓ	Peak	20.767 ± 0.025	0.00005	≤ 0.00005	Lepton acceptance
σ_{had}^0 (nb)	Peak	41.4802 ± 0.0325	0.00003	≤ 0.0008	Lumi meas.
R_b	Peak	0.21629 ± 0.00066	0.00000025	≤ 0.0000003	$g \rightarrow b\bar{b}$
$A_{FB}^{b,0}$	Jet charge	0.0992 ± 0.0016	0.00004	≤ 0.00004	Jet charge
$A_{FB}^{pol, \tau}$	τ polarisation	0.1498 ± 0.0049	0.00007	≤ 0.0002	τ decay physics
N_ν	Peak	2.9963 ± 0.0074	0.00009	≤ 0.00012	Lumi meas.
$\sin^2 \theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.0000012	≤ 0.0000012	Beam energy
$1/\alpha_{QED}(m_Z^2)$	$A_{FB}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	0.0039	TBD	QED / EW
$1/\alpha_{QED}(m_Z^2)$	$A_{FB}^{\mu\mu}$ (on-peak)	128.952 ± 0.014	0.0008	TBD	QED / EW
$\alpha_s(m_Z^2)$	R_ℓ	0.1196 ± 0.0030	0.00001	≤ 0.0001	New Physics
τ lifetime	τ decays (fs)	290.3 ± 0.5	0.001	≤ 0.005	ISR, τ mass
τ mass (MeV)	τ decays	1776.93 ± 0.09	0.002	≤ 0.02	Estimator bias, ISR, FSR
$B(\tau \rightarrow \mu \nu \bar{\nu})$ (%)	$\tau \rightarrow \mu \nu_\mu \bar{\nu}_\tau$	17.38 ± 0.04	0.00007	≤ 0.003	PID, π^0 efficiency
m_W (MeV)	Threshold scan	80360.2 ± 9.9	0.18	≤ 0.16	Beam energy calib.
Γ_W (MeV)	Threshold scan	2085 ± 42	0.27	≤ 0.2	QED / EW
N_ν	$e^+ e^- \rightarrow \gamma Z, Z \rightarrow \nu \nu, \ell \ell$	2.92 ± 0.05	0.0005	TBD	TBD
$\alpha_s(m_W^2)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	$B_{had} = 67.41 \pm 0.27$	0.0002	0.0002	CKM Matrix
m_{top} (MeV)	Threshold scan	172570 ± 290	4.2	≤ 4.9	QCD uncert.
Γ_{top} (MeV)	Threshold scan	1420 ± 190	10	≤ 6	QCD uncert.
λ_{top}	Threshold scan	$\mu = 1.2 \pm 0.3$	0.015	≤ 0.015	QCD uncert.
ttZ coupl.	$\sqrt{s} = 365$ GeV	$\pm 30\%$	0.5–1.5 %	TBD	QCD corr.

■ Complete, self-calibrating observables **sensitive to huge set of BSM** scenarios

- Today

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

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

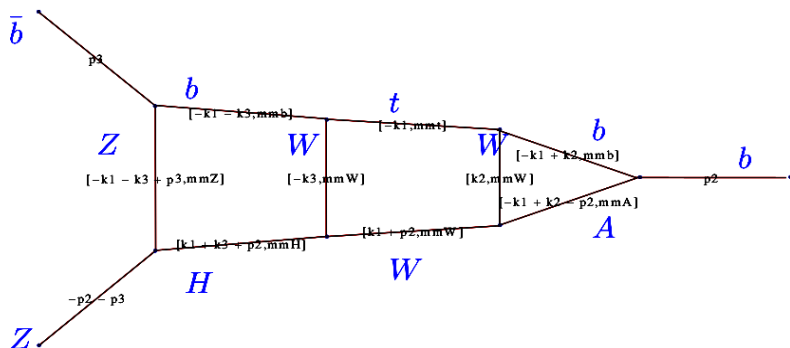
- **With FCC-ee**

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

$$= 80.3584 \pm 0.0006_{\text{exp}} \pm 0.0040_{\text{theory}} \text{ GeV},$$

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

- Theory R&D



Required N³LO SM corrections of EWPOs theoretically doable in ~10 years (with appropriate financial support and training programs)

■ Current TH uncertainties to be improved by $\times 5\text{--}10$ to match expected exp. ones:

■ **Today**

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

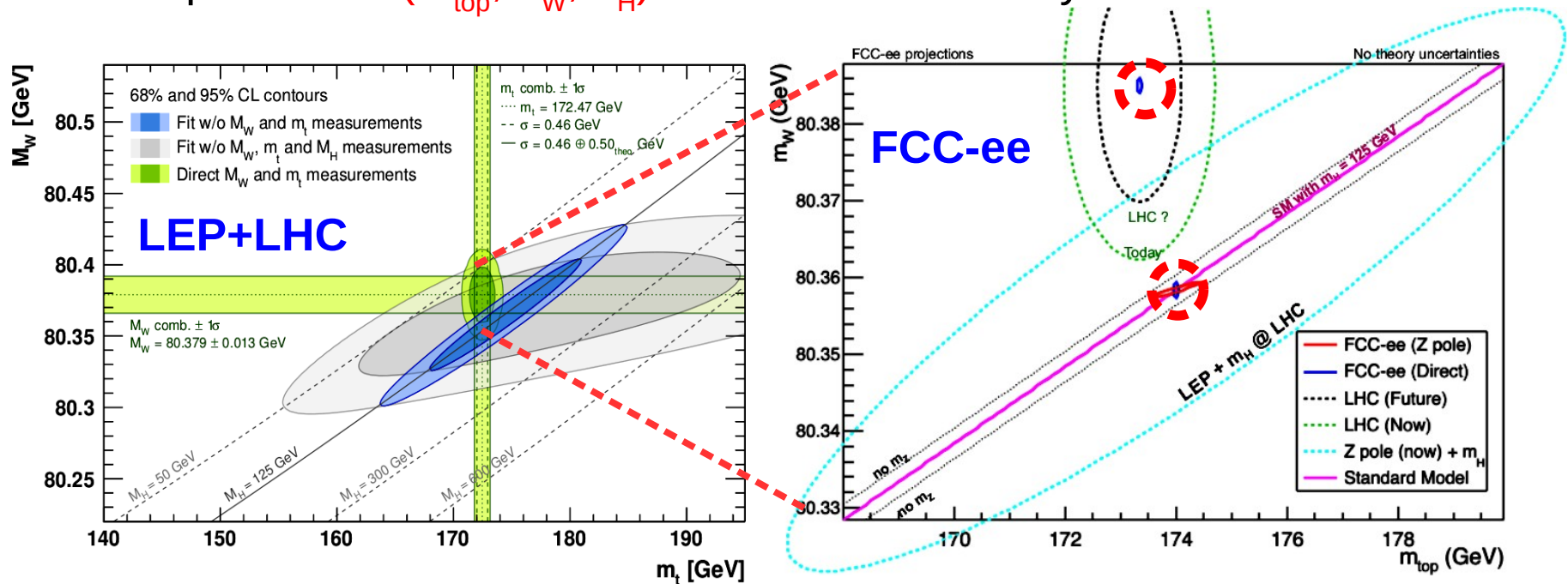
$$m_W^{\text{direct}} = 80.385 \pm 0.015 \text{ GeV},$$

■ Theory calculations wish-list for FCC-ee:

[ESPPU'25 Phys. Book, arXiv:2511.03883]

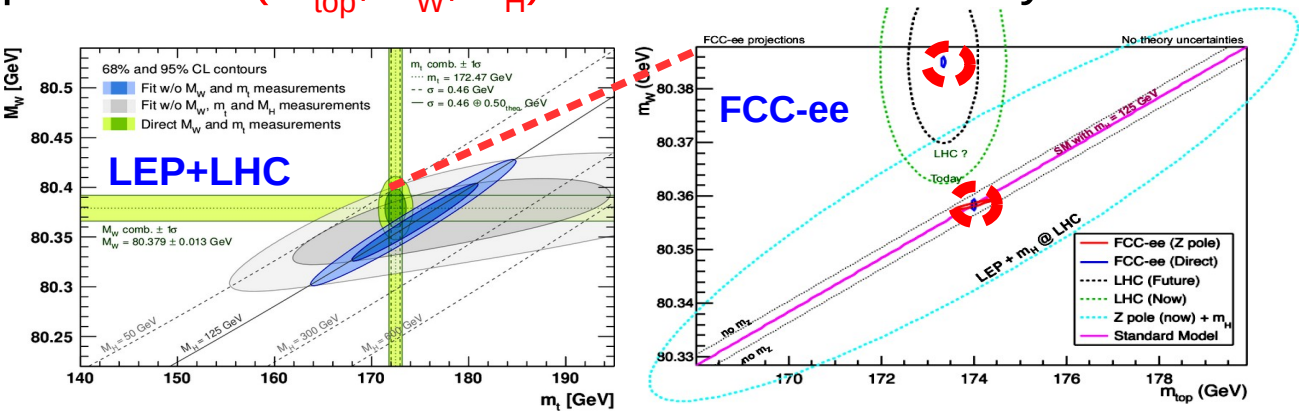
Observable	Missing higher-order & power-suppressed corrections
Hadronic Z width	$\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha_s^6)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s \alpha^3)$, $\mathcal{O}(\alpha_s^2 \alpha^2)$
Hadronic W width	$\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha_s^2 \alpha)$
Hadronic τ width	$\mathcal{O}(\alpha_s^5)$
Hadronic event shapes (Z, W, H decays)	$N^3\text{LO}$ differential, $N^{3,4}\text{LL}$ resummation, power corrections
Inclusive jet rates	3-jet cross-sections at $N^3\text{LO}$, 4-jets at $N^2\text{LO}$, 5-jets at NLO
Lattice QCD results (α_s extr.; quark masses m_c, m_b)	$\mathcal{O}(\alpha_s^6)$ β -function; $\mathcal{O}(\alpha_s^5)$ heavy quark decoupling; $\mathcal{O}(\alpha_s^4)$ static potential $\mathcal{O}(\alpha_s^3)$ lattice perturbation theory matching (lattice coupling to $\alpha_s^{\overline{MS}}$ etc.)
$\sigma(e^+e^- \rightarrow W^+W^-)$ vs. $\sqrt{s}$	EW $N^2\text{LO}$: $\mathcal{O}(\alpha^2)$, Mixed EW-QCD: $\mathcal{O}(\alpha_s \alpha^2)$, $\mathcal{O}(\alpha_s^2 \alpha)$
$\sigma(e^+e^- \rightarrow t\bar{t})$ vs. $\sqrt{s}$	NRQCD: $\mathcal{O}(\alpha_s^5)$, Non-resonant: $\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha_s^3)$ differential; QED: $\mathcal{O}(\alpha^3)$ at NNLL
$H \rightarrow b\bar{b}$ width	$N^4\text{LO}$ ($m_b \neq 0$); $N^4\text{LO}$ differential ($m_b = 0$)
$H \rightarrow gg$ width	$N^5\text{LO}$ (heavy-top limit), $N^4\text{LO}$ ($m_t \neq 0$); $N^4\text{LO}$ differential, $N^3\text{LO}$ differential ($m_t \neq 0$)
MC simulations for $e^+e^- \rightarrow X$ processes	$N^{2,3}\text{LO}$ matched to $N^{2,3}\text{LL}$ PS. Per mille control of non-pQCD effects (hadronization, CR, ...)

■ Comparison of $(m_{\text{top}}, m_W, m_H)$ electroweak fit today and at FCC-ee:



■

Comparison of $(m_{\text{top}}, m_W, m_H)$ electroweak fit today and at FCC-ee:



■

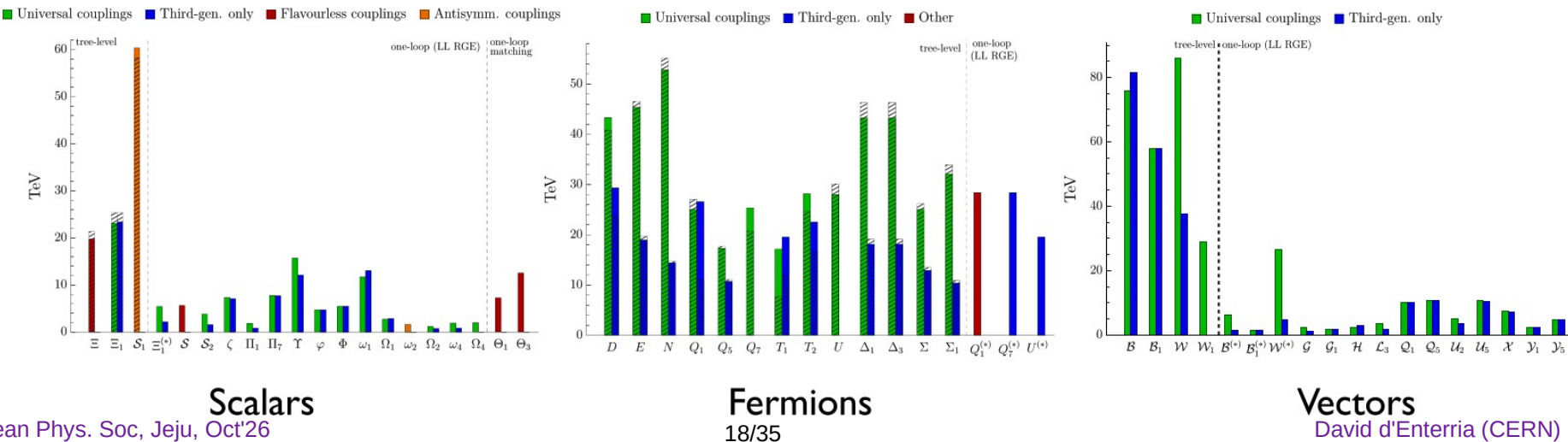
Constraints on generic BSM SMEFT dim-6 operators at scale Λ :

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

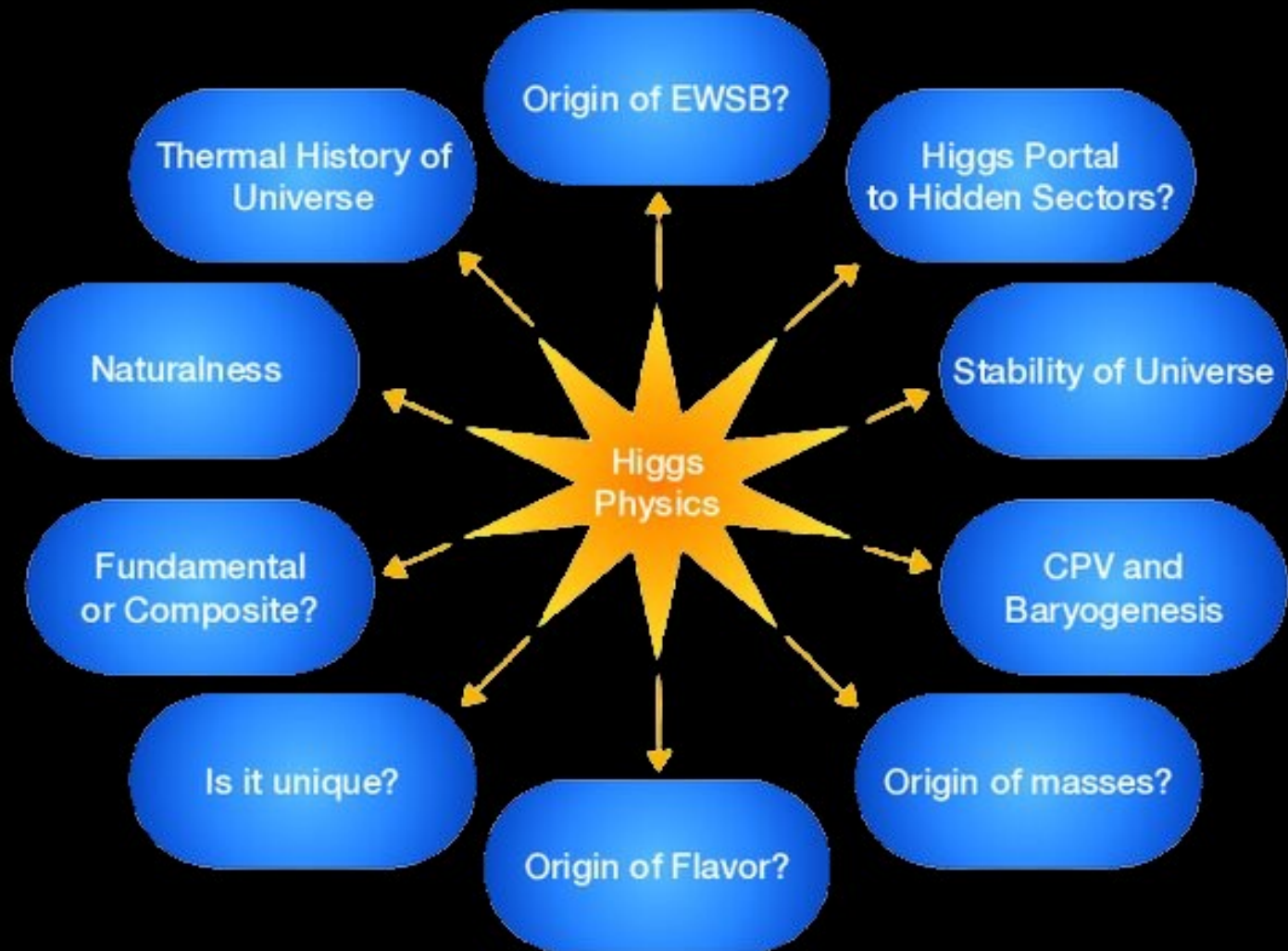
LEP constraints: $\Lambda > 3\text{--}10$ TeV

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

[Allwicher, McCullough, Renner, arXiv:2408.03992]

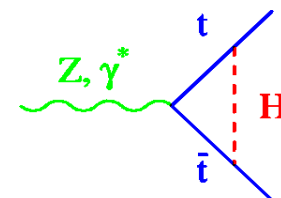
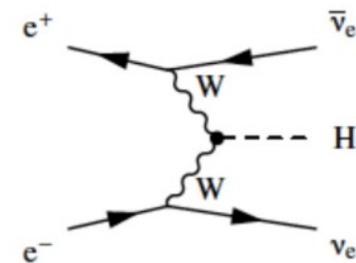
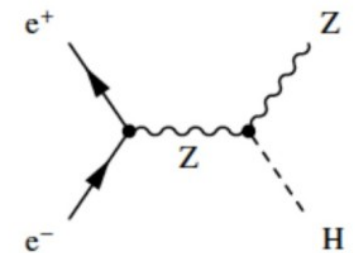
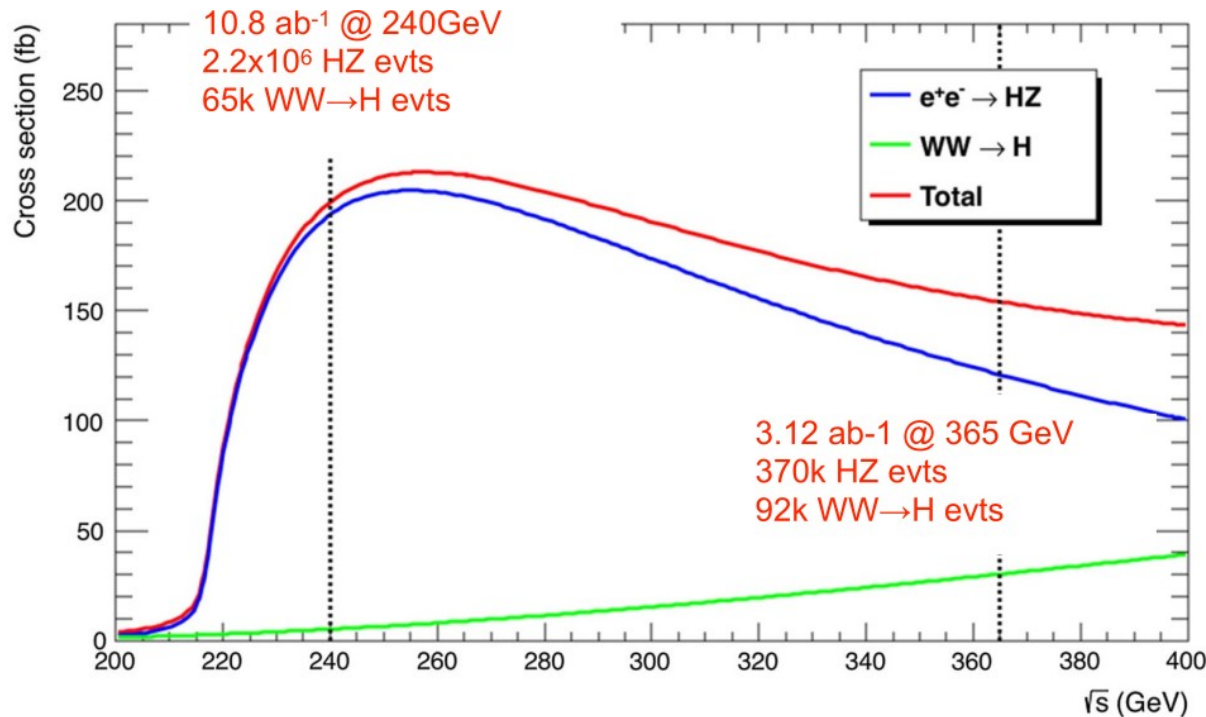


Higgs boson as the keystone of (B)SM



FCC-ee = Higgs boson factory

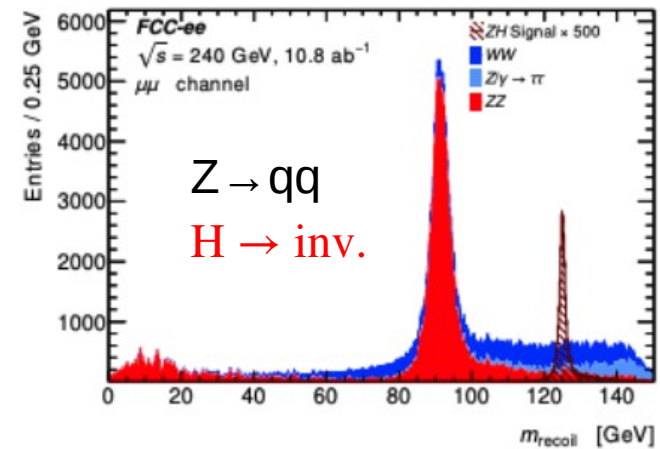
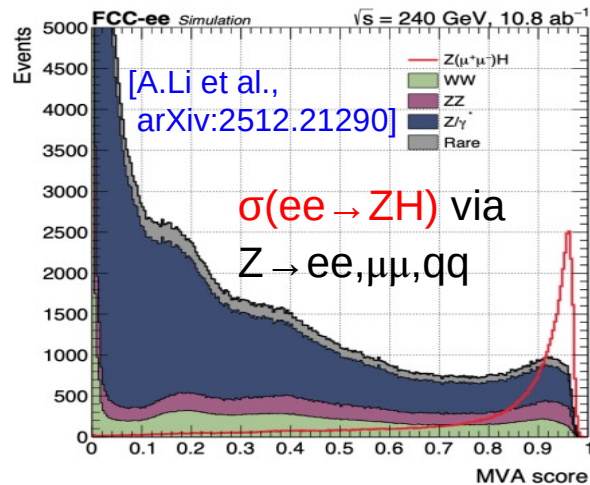
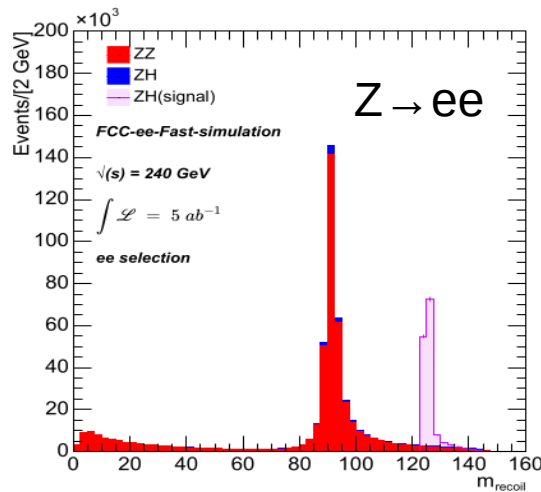
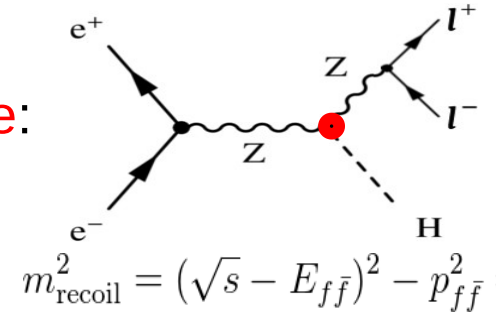
- Cross section (HZ+VBF): $\sigma(e^+e^- \rightarrow H+X) \approx 200 + 50 \text{ fb}$
- 2+ million Higgs bosons produced with small & controlled backgrounds and no pileup:



(also sensitivity to y_t)

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

- Recoil method in $H\text{-}Z(l\bar{l})$ unique to lepton collider: reconstruct H 4-mom. independent of H decay mode:
- High-precision (0.2%) σ_{ZH} provides model-indep. g_Z coupling $\sigma(ee \rightarrow ZH) \propto g_Z^2$, with $\pm 0.1\%$ uncert.



[H. Abidi et al., arXiv:2504.11103]

- Total width (Γ_H) with 0.8% 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: $< 0.05\%$ (95% CL)
- Higgs mass from recoil mass in $Z \rightarrow \mu\mu, ee$: $\delta m_H \sim 4$ MeV

FCC: Higgs couplings, width, mass

- FCC will improve by **factor ~10** the precision in Higgs properties **wrt. (model-dependent) HL-LHC** results:

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh	
κ_Z (%)	1.3*	0.10	0.10	
κ_W (%)	1.5*	0.29	0.25	
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45	
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44	
κ_τ (%)	1.6*	0.46	0.40	
κ_c (%)	—	0.70 / 0.87	0.68 / 0.85	First meas. of 2nd-gen. quark Yukawa's
κ_γ (%)	1.6*	1.1	0.30	
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67	
κ_t (%)	3.2*	3.1	0.75	
κ_μ (%)	4.4*	3.3	0.42	1 st model-indep total width (0.8%). Invisible width to ~0.05%
$ \kappa_s $ (%)	—	+29 -67	+29 -67	
Γ_H (%)	—	0.78	0.69	
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}	2.3×10^{-4}	
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}	6.7×10^{-3}	

FSR volume 1

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

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FCC-hh will
further improve
loop/rare/heavy
couplings ($\gamma, Z\gamma, \mu, t$)

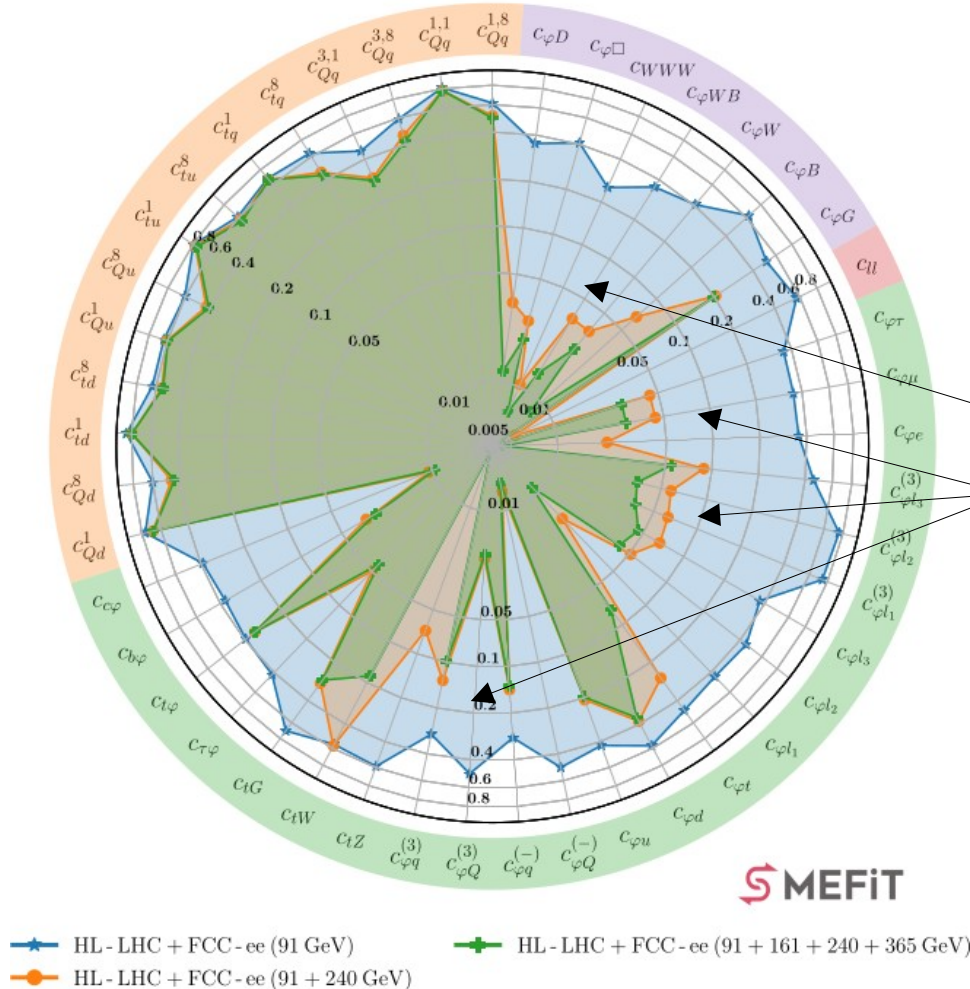
[FSR volume 1](#)

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FCC-ee: Indirect new physics reach

- FCC-ee Higgs boson precision measurements will **greatly improve scalar-coupled BSM limits:**

Ratio of Uncertainties to SMEFT3.0 Baseline, $\mathcal{O}(\Lambda^{-2})$, Marginalised



- **Big gains** on SMEFT ops. bounds:

LHC+EWPO

LHC+EWPO+Higgs:

Bosonic/Higgs-gauge ops

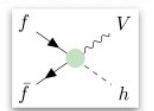
Higgs-fermion (Yukawa)

LHC+EWPO+Higgs+top

Bosonic



2-fermion

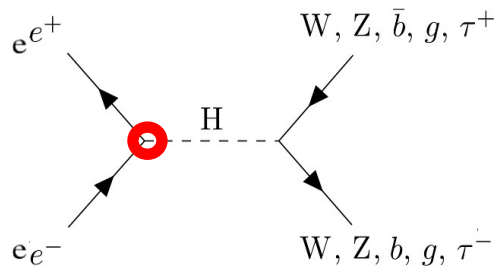


MEFIT

[E.Celada et al., arXiv:2404.12809]

FCC-ee: $e^\pm$ Yukawa coupling

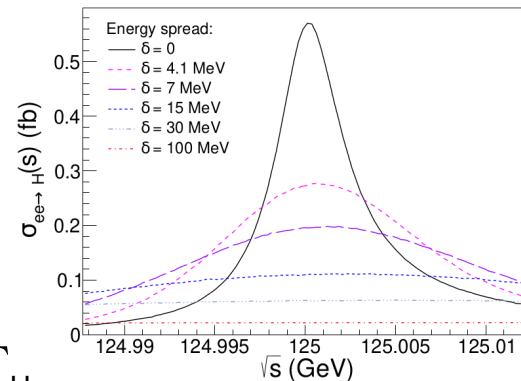
- Resonant s-channel Higgs prod. at $\sqrt{s} = 125$ GeV :



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

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

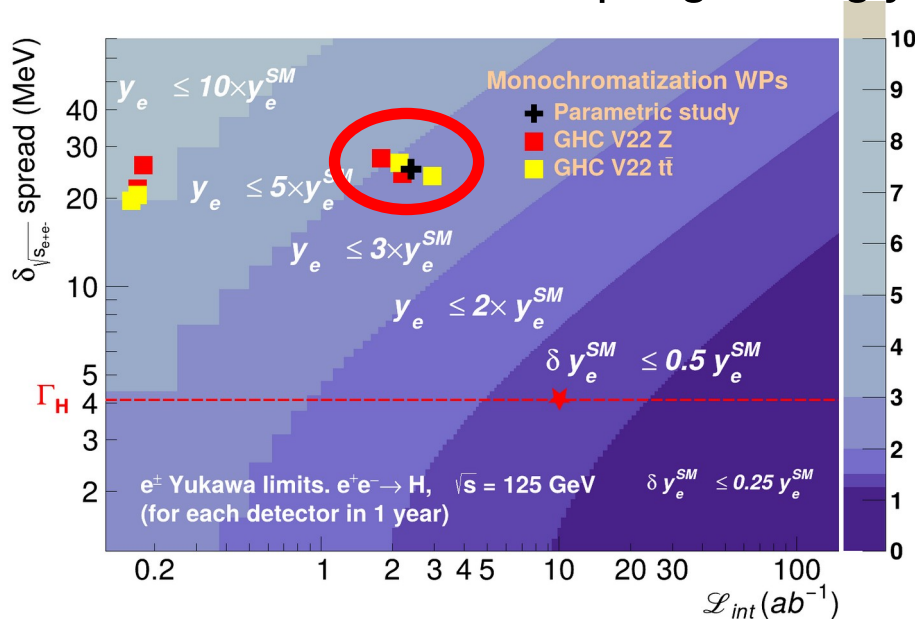
$$(\text{incl. ISR} + \sqrt{s}_{\text{spread}} = \Gamma_H = 4.2 \text{ MeV})$$



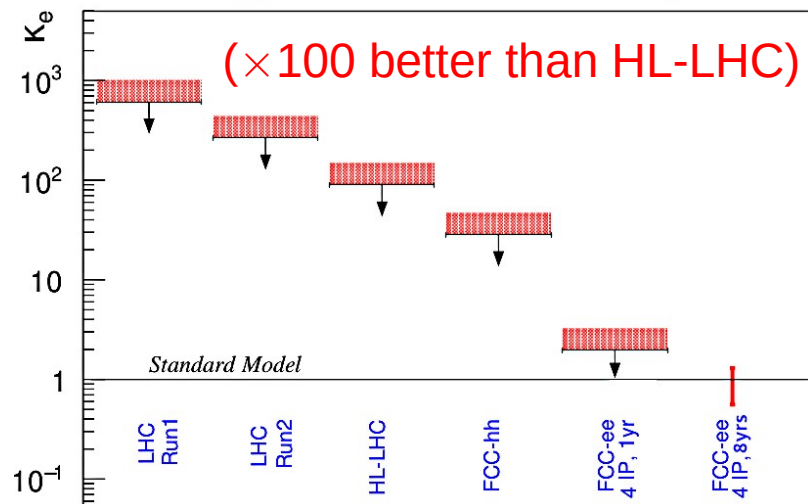
Beams mono-chromatization required to achieve $\sqrt{s}_{\text{spread}} \sim \Gamma_H$

- “Counting exp.”: Tiny signal excess above huge backgds in 10 Higgs decays

- Limits on e-Yukawa coupling strongly depend on Lumi + spread:



[D. d'Enterria et al., arXiv:2107.02686]



$y_e < 2 (1.5) \times y_{e,SM}$ at 95% CL, for 4 IPs in 1 (4) years (improvements ongoing)

Neutrino masses

Naturalness

Microscopic
Higgs theory

origin
of Flavor

Nature of
Dark Matter

origin of
Neutrino masses

Long-lived
meta-stable vacuum

Baryon
asymmetry

Inflation

Strong CP
problem

Couplings
unification

Dark Energy

Quantum
Gravity

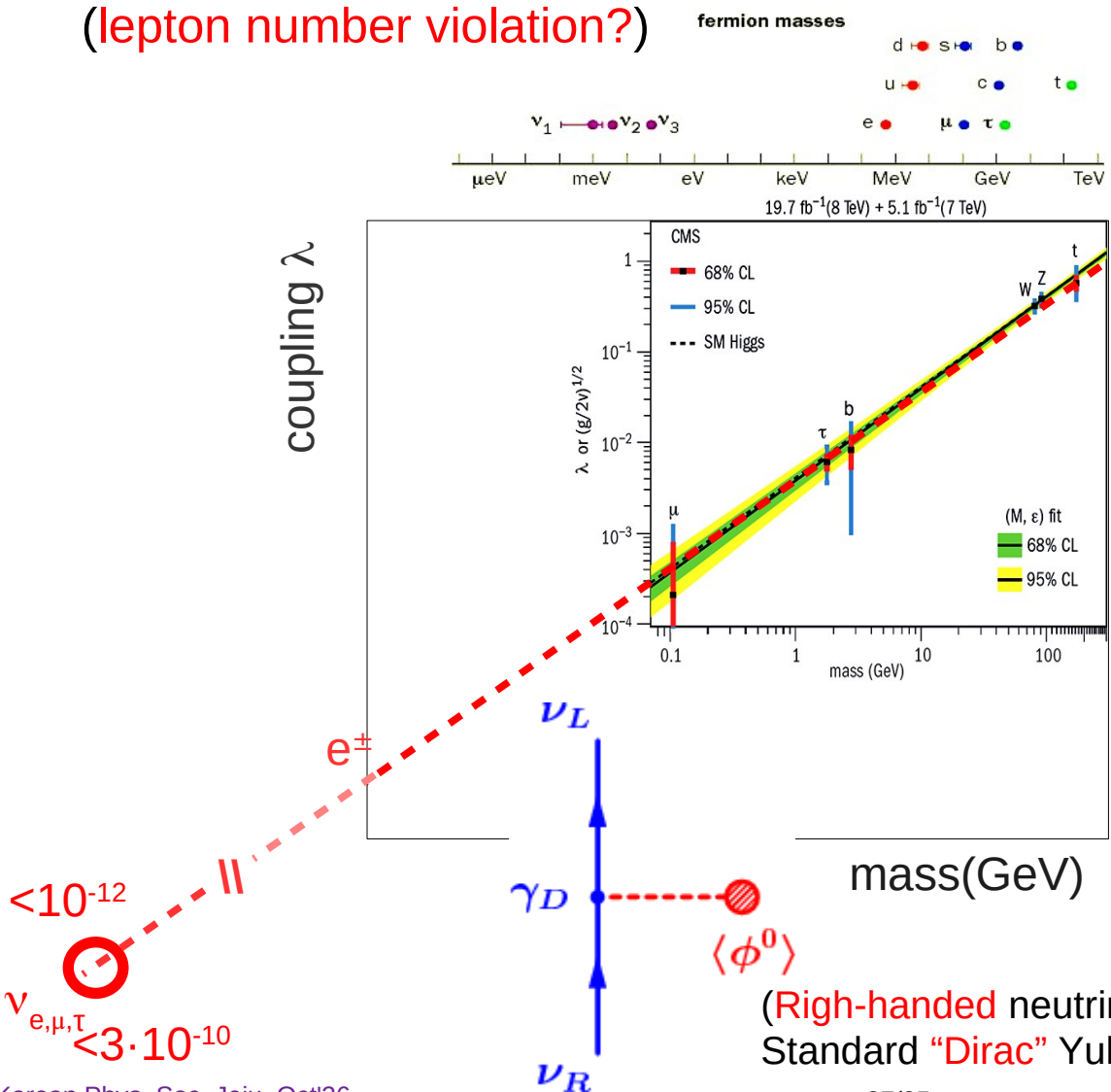
What else?

New structures/
principles

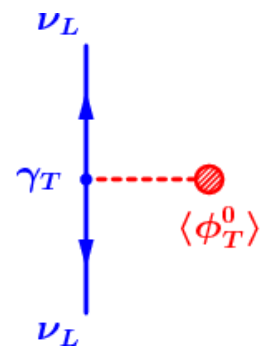


Generation of neutrino masses

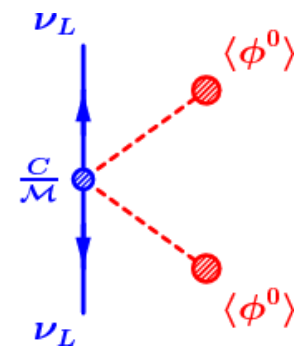
■ Lightness of m_ν , coupling of ν 's to Higgs (or other scalar vev), their nature (lepton number violation?) are big open mysteries:



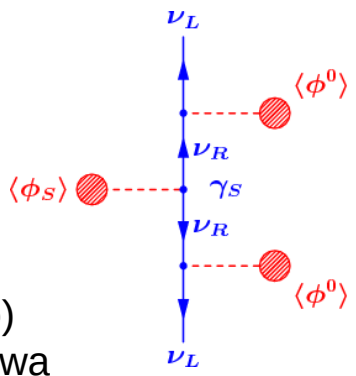
(Majorana)
Type-II seesaw



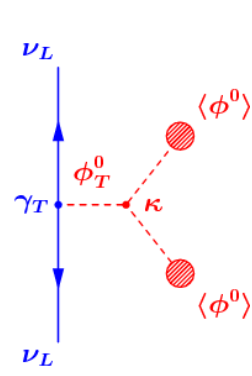
(Dim-5 Weinberg)
Type-I,III seesaw



Inverse seesaw



Radiative Zee-like



FCC-ee: Heavy neutrinos sensitivity

[A. Blondel et al. arXiv:1411.5230]

- Direct searches for heavy-neutrinos in $Z \rightarrow N\nu$ decays with displaced $N \rightarrow Z(jj, ll)\nu$, $W(jj, l\nu)$ events:

Production in Z decay via mixing with light neutrinos

$$\text{BR}(Z \rightarrow \nu N) = \frac{2}{3} |U_N|^2 \text{BR}(Z \rightarrow \text{invisible}) \left(1 + \frac{m_N^2}{2m_Z^2}\right) \left(1 - \frac{m_N^2}{m_Z^2}\right)$$

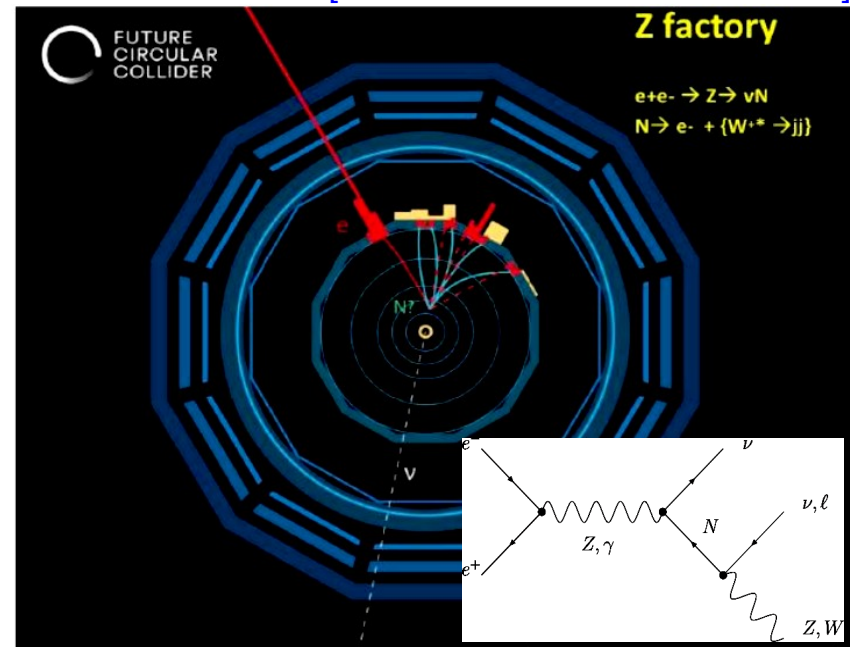
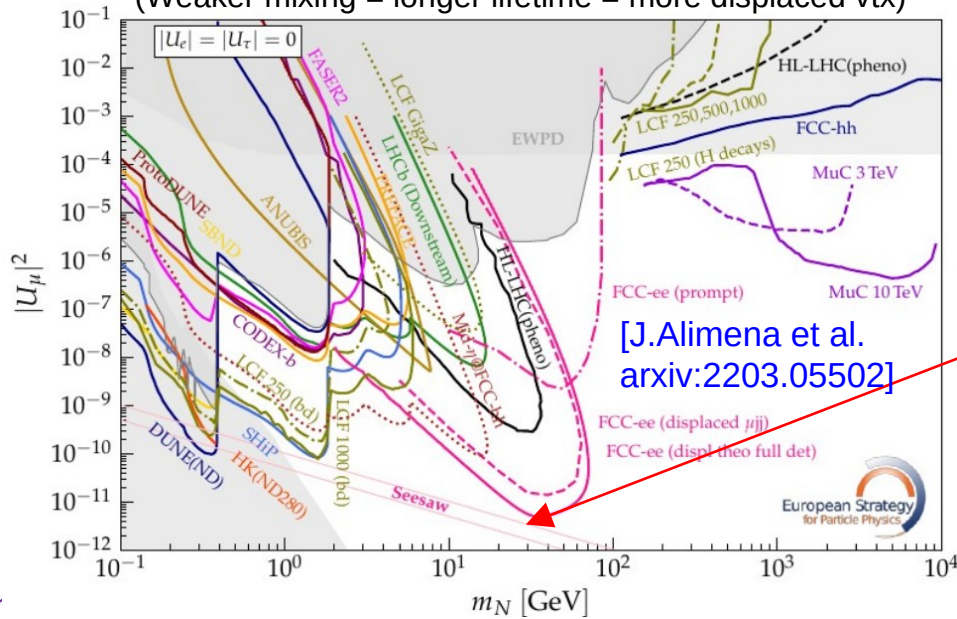
$$|U_N|^2 \equiv \sum_{\ell=e,\mu,\tau} |U_{\ell N}|^2 \quad (\text{for Majorana, } \frac{1}{2} \text{ for Dirac})$$

Decay: three-body decay into 3 fermions via virtual W/Z

Decay length:

$$L_{N_i} \simeq \frac{1.6}{U_i^2} \left(\frac{M_i}{\text{GeV}} \right)^{-6} (1 - (M_i/M_Z)^2) \text{ cm}$$

(Weaker mixing = longer lifetime = more displaced vtx)



(Also in W,H decays)

- FCC-ee sensitivity down to $|\mathbf{U}_\mu|^2 \sim 10^{-11}$ for $m_N \sim 10\text{--}100$ GeV:
Approaching **minimal Type-I seesaw**
(smallest mixing for which the minimal seesaw still produces neutrino masses of the measured size).
- Possible **Dirac/Majorana separation**:
HNL decay/prod. angles, HNL oscil.

Unparalleled Flavour physics

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Microscopic
Higgs theory

origin
of **Flavor**

Nature of
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origin of
Neutrino masses

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What else?

New structures/
principles

Strong CP
problem

Couplings
unification

...

...



FCC-ee: Flavour physics

- Flavour remains a sector with enormous physics motivations:
 - ➔ **Baryogenesis** unexplained without extra CP Violation
 - ➔ Pattern of **fermion masses & mixings** unexplained.
 - ➔ **New physics** contributing to higher-order (Penguin, box) loops in **flavour-changing** processes.
- FCC-ee has an enormous leverage for flavour physics:
 - ➔ **Unparalleled b-, c-quark, tau stats** with $6 \cdot 10^{12}$ Z bosons:

Particle species	B^0	B^-	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^- \tau^+$
Yield (10^9)	740	740	180	160	3.6	720	200

- ➔ **Unique experimental conditions** compared to LHCb/Belle-II

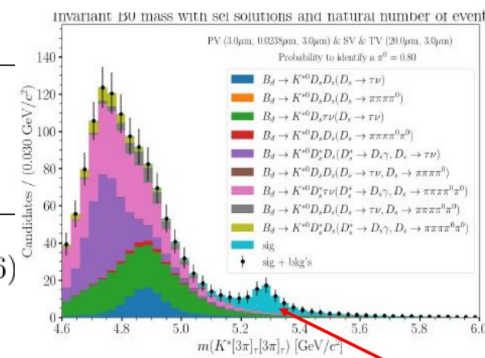
Boost, no trigger loss,
higher accept., initial state
flavour tagging, a very clean
environment:

Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

- Access to very rare heavy-Q and tau decays, BRs, decays asymmetries, oscil. freqs., inclusive & exclusive CKM elements, ...

Boosted b's & taus:

$\langle\beta\gamma\rangle \approx 6$: topological
reco of decays w/ ME

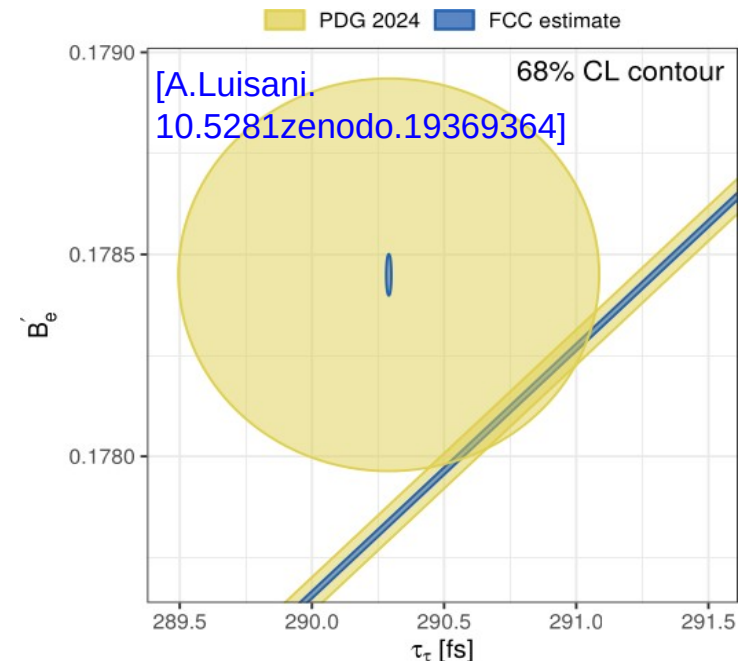
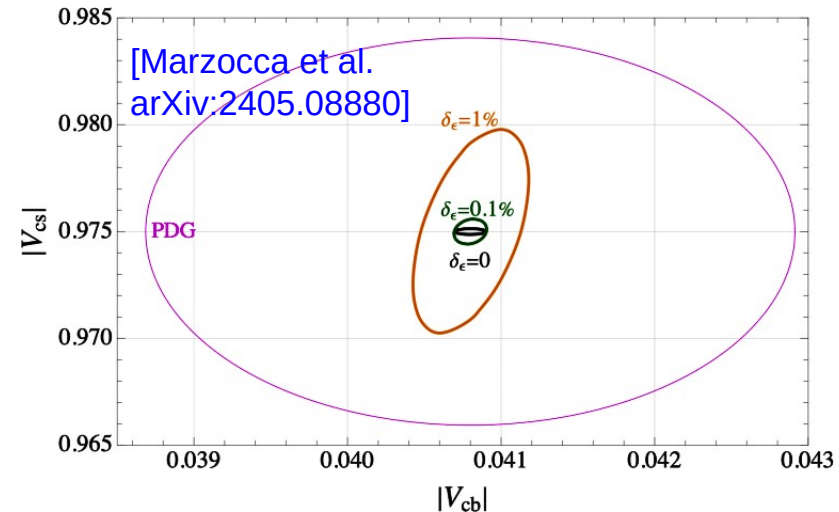


■ CKM elements:

- CPV angles (γ, β, ϕ_s) at permille
- $V_{cb,cs}$ from inclusive $W \rightarrow cb, cs$ in WW run.
Also V_{ts} from top $t \rightarrow Ws$ decays

■ Tau physics (10^{11} from $Z \rightarrow \tau\tau$)

- Tests of **Lepton Flavour Universality**:
 m_τ @ 10 ppm
 τ lifetime @ 20ppm
 G_F from τ @ 10 ppm ($\times 10$ Belle-II)
 $B(\tau \rightarrow l\nu\nu)$ @ 200 ppm
- Searches for **Lepton Flavour Violation**:
 $\tau \rightarrow \mu\gamma$ @ 10^{-9}
 $\tau \rightarrow 3\mu$ @ 10^{-11} ($\times 10$ Belle-II)
 $\tau \rightarrow 3e$ at 10^{-11}



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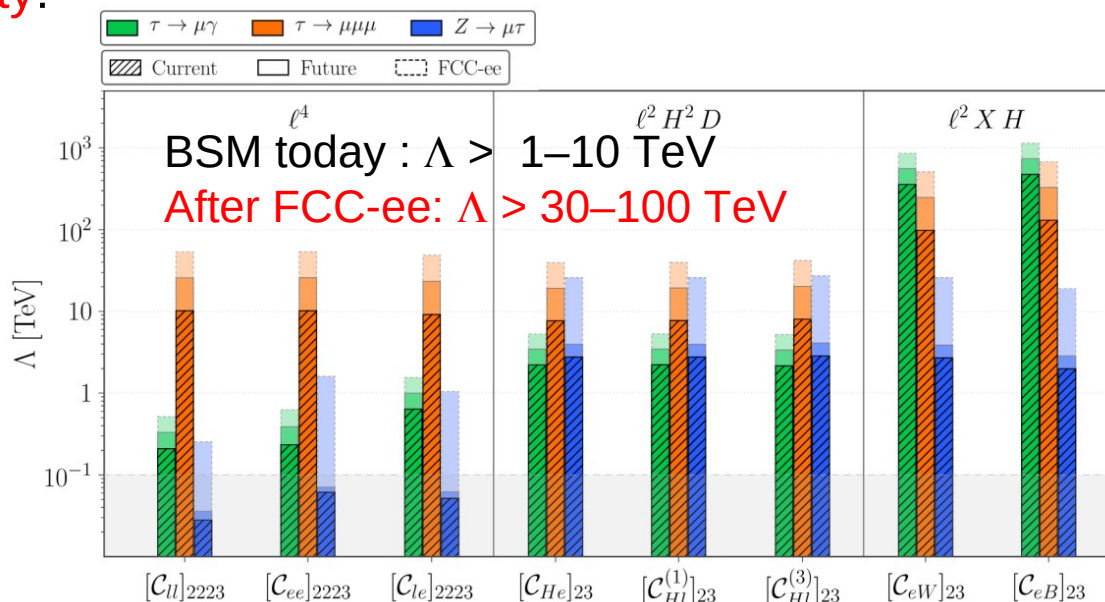
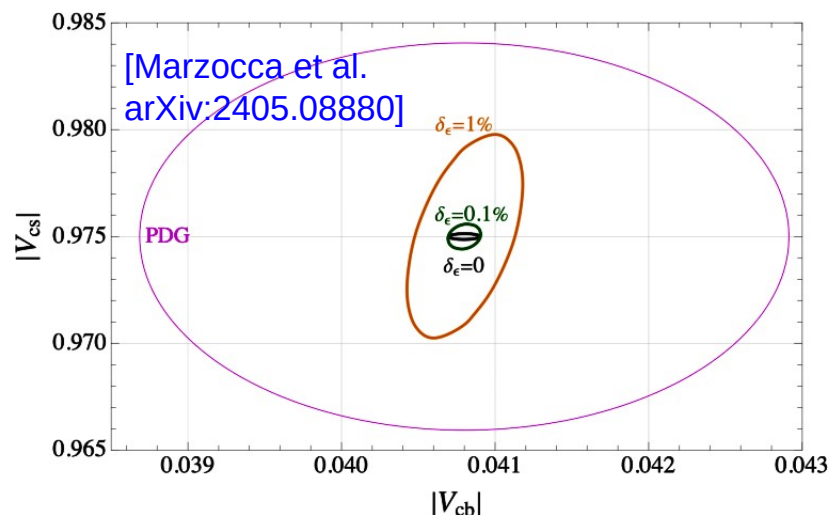
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$\tau \rightarrow 3\mu$ @ 10^{-11}

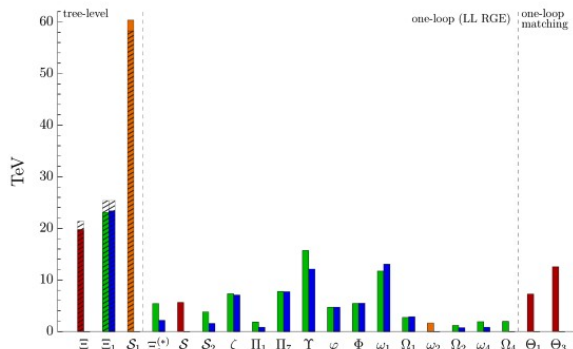
$\tau \rightarrow 3e$ at 10^{-11}



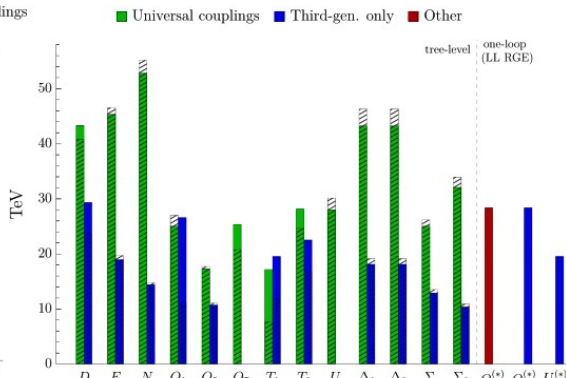
Summary

- FCC-ee provides **unparalleled luminosities** 3–200 ab^{-1} at $\sqrt{s}=90\text{--}365$ GeV for **high-precision** (down to 10^{-5} uncert.) **W, Z, H, top** studies, setting unique indirect constraints on **new physics** up to $\Lambda \gtrsim 30\text{--}100$ TeV:

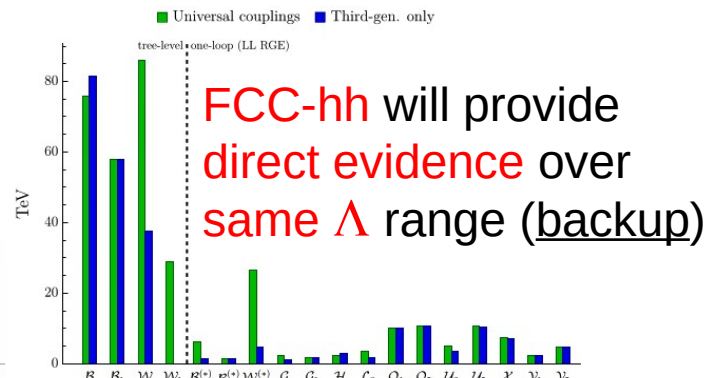
■ Universal couplings ■ Third-gen. only ■ Flavourless couplings ■ Antisymm. couplings



Scalars

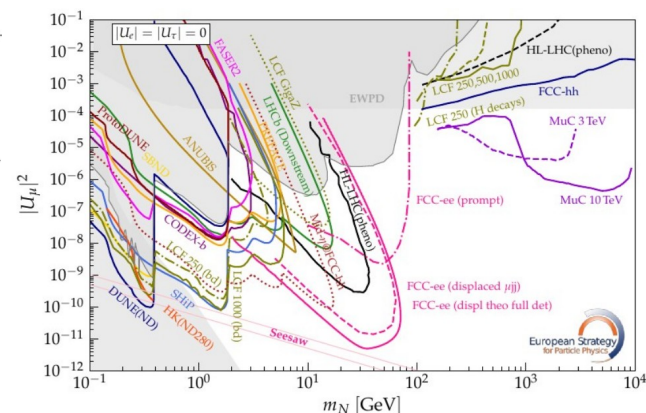
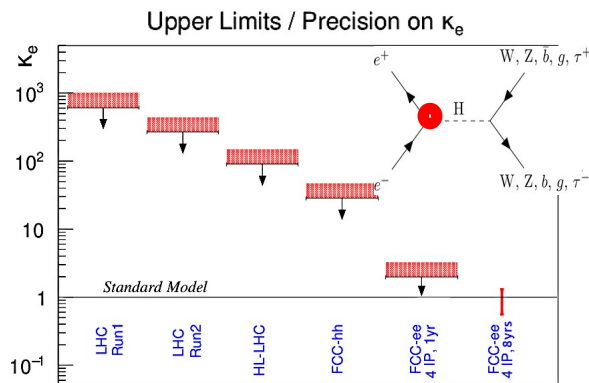
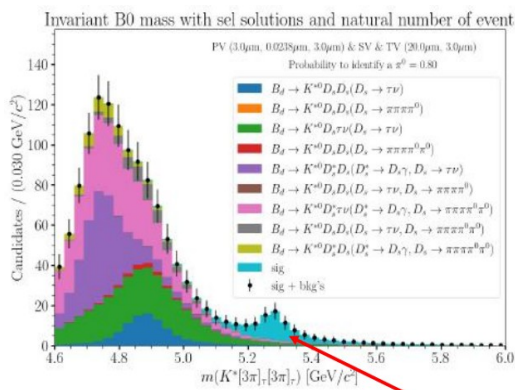


Fermions



Vectors

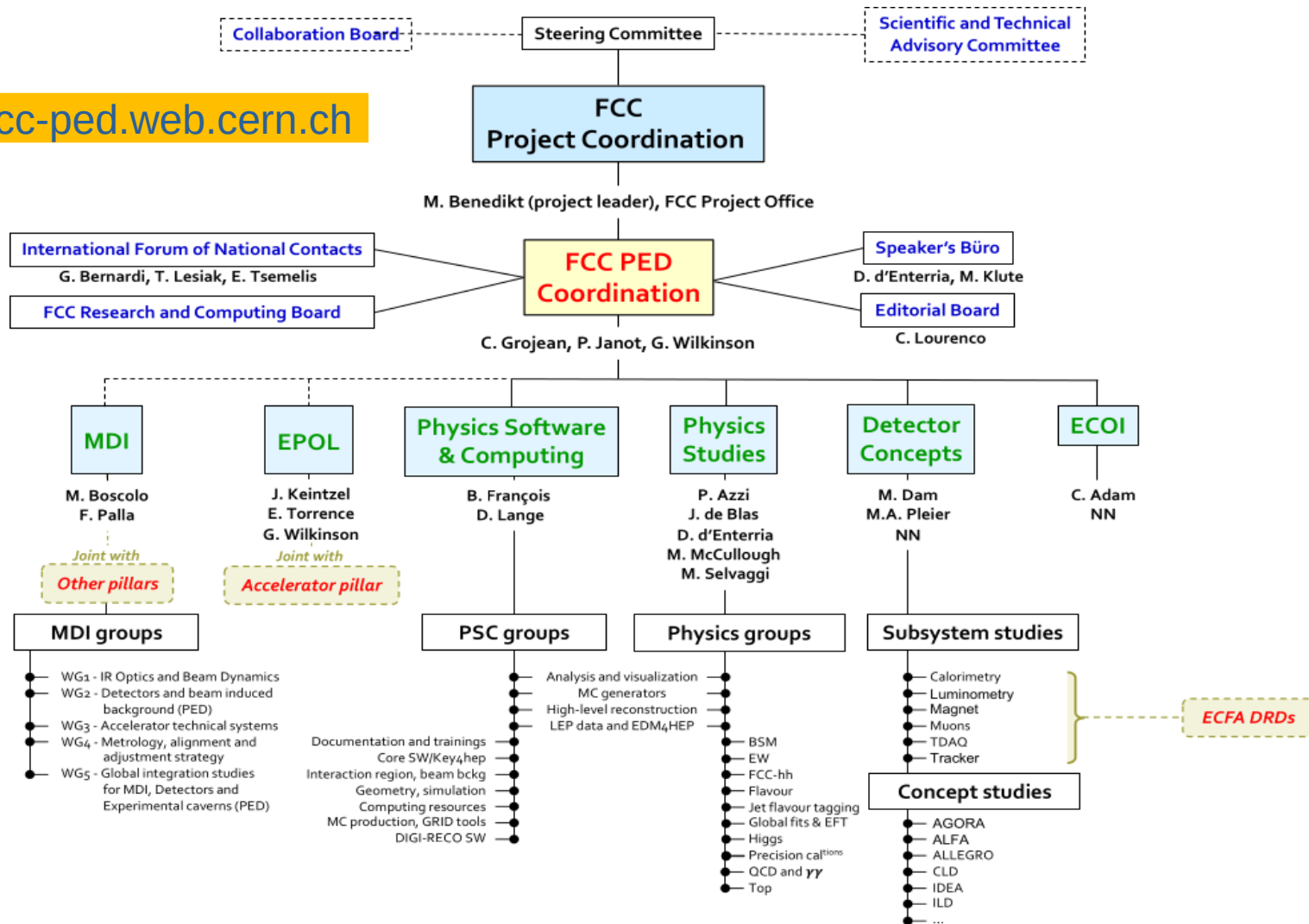
- Plus unique measurements: **Electron Yukawa, heavy ν 's, Flavour, QCD,...**



Summary

Lots of interesting exp. & theory physics to do ! **Come join the effort !**
Activity areas of **FCC Physics, Experiments & Detectors (PED)**:

<https://fcc-ped.web.cern.ch>



Backup slides

Dark matter searches at FCC

Naturalness

Microscopic
Higgs theory

origin
of Flavor

Strong CP
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Couplings
unification

...

Nature of
Dark Matter

origin of

Neutrino masses

Long-lived
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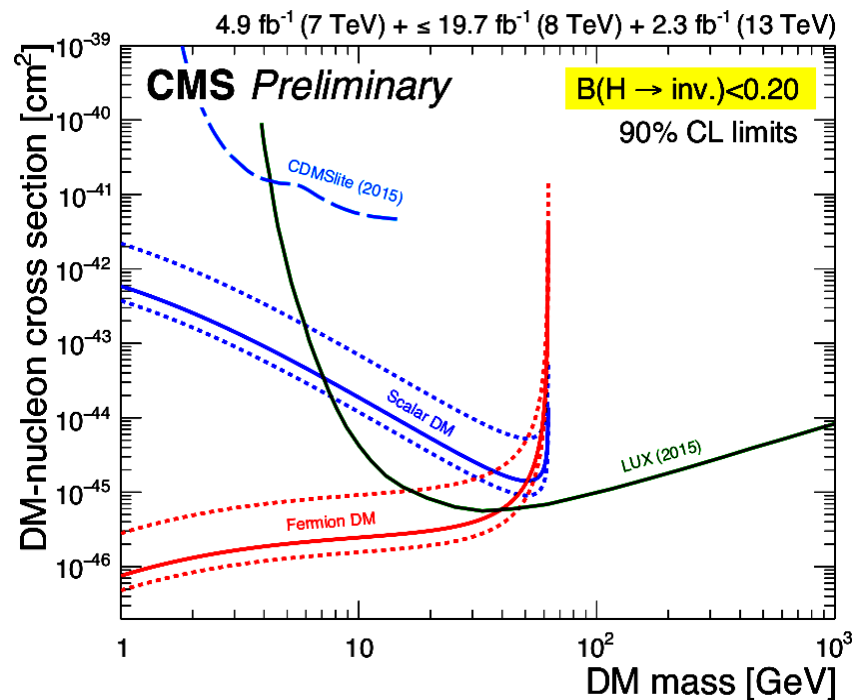
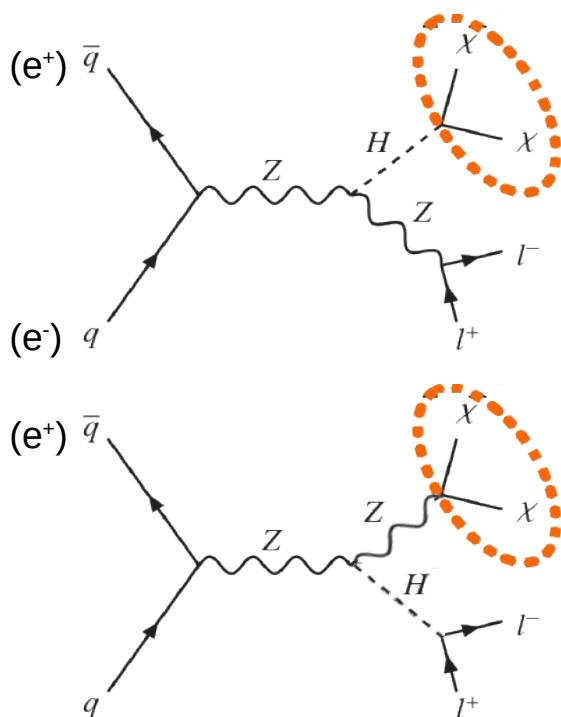
What else?

New structures/
principles



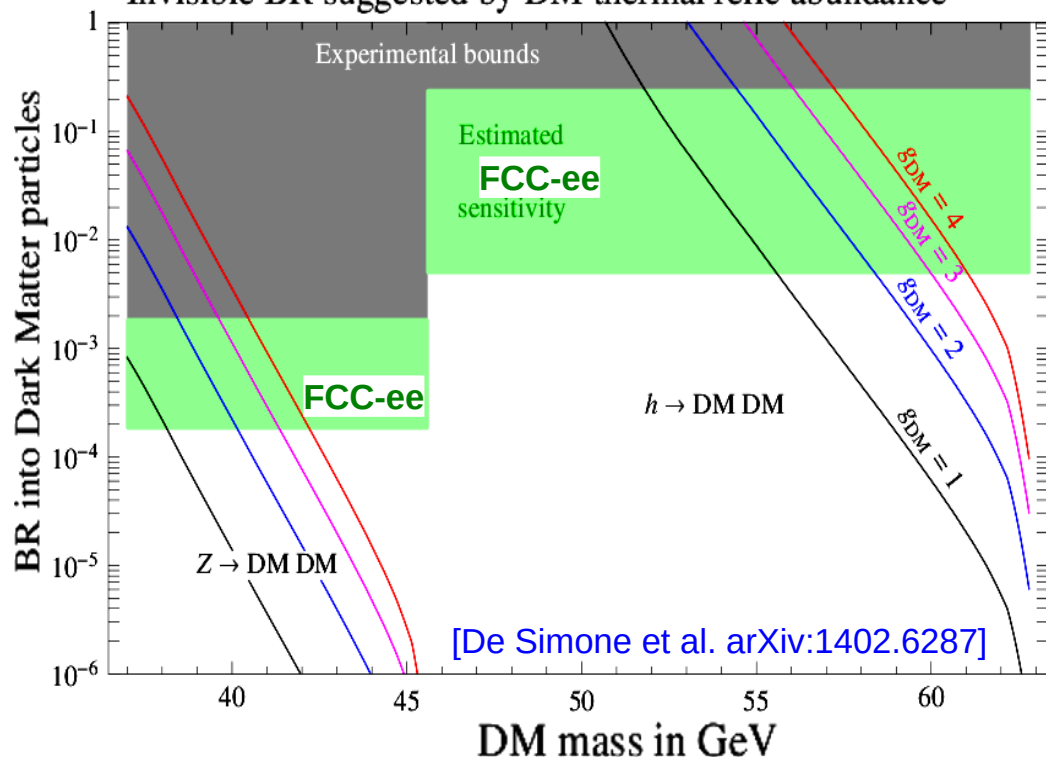
- DM freeze-out fixes $\sigma \cdot v \approx 3 \cdot 10^{-26} \text{cm}^3/\text{s}$. If m_{DM} is just **below** $m_{Z,H}/2$, then **DM freeze-out dominated by resonant Z,H exchange**, fixing $\Gamma_{Z,H}$.

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

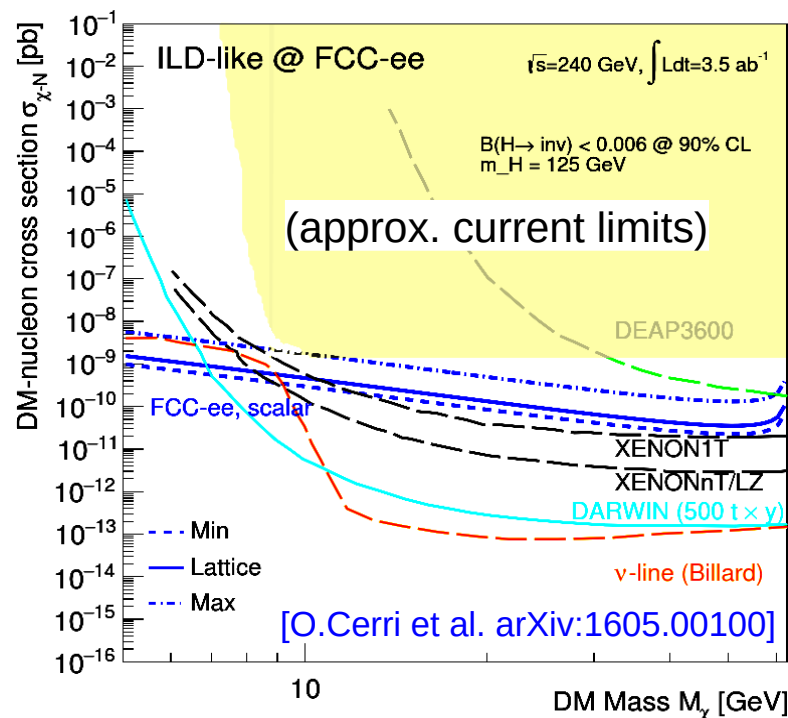


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Invisible BR suggested by DM thermal relic abundance



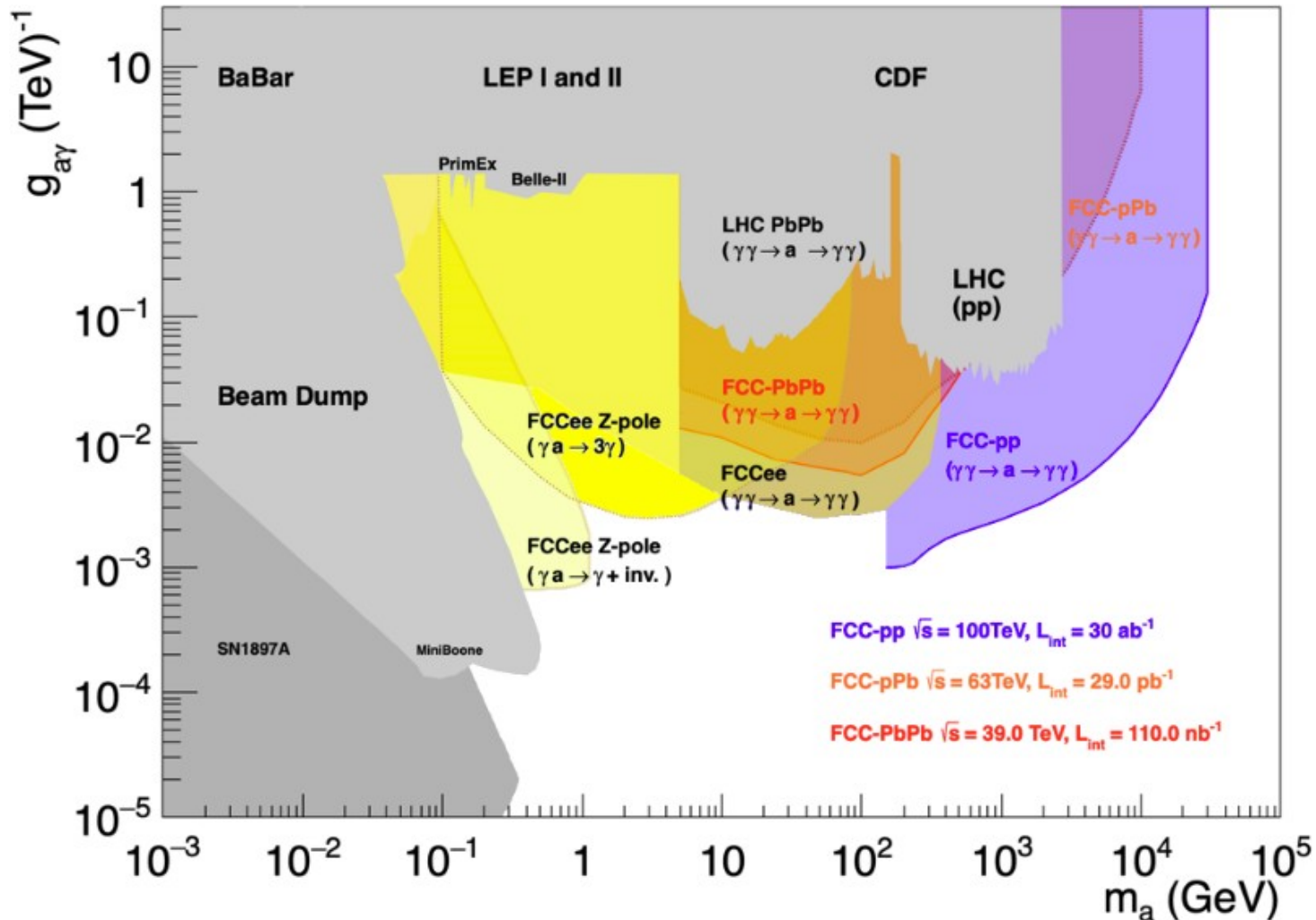
- $\sim 10^{-4}, \sim 5 \cdot 10^{-3}$ precision measurements of **Z & H invisible widths** are **best collider option** to test any $m_{\text{DM}} < m_{Z,H}/2$ coupling via SM mediators



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

FCC: Axion-Like Particles

- FCC-ee will provide the best direct searches for ALPs over $m_a \approx 1\text{--}300\text{ GeV}$, FCC-hh will extend this to $m_a \approx 30\text{ TeV}$:

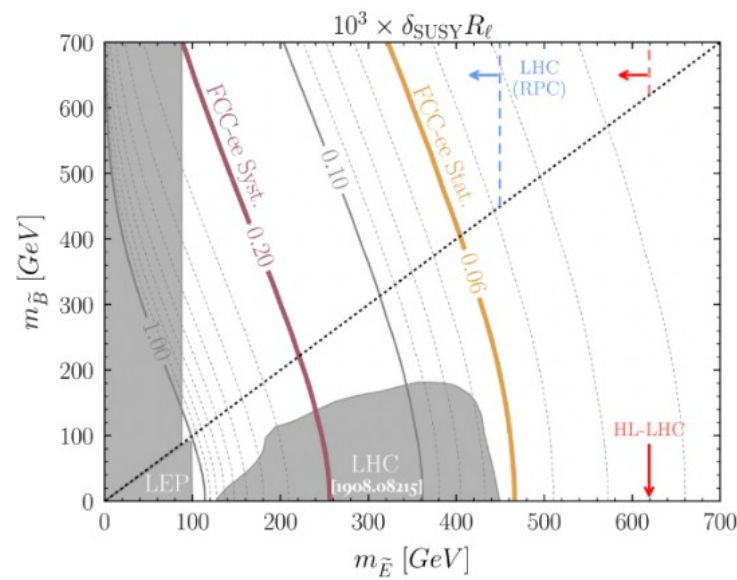


■ FCC-ee measurements significantly **improve SUSY searches**:

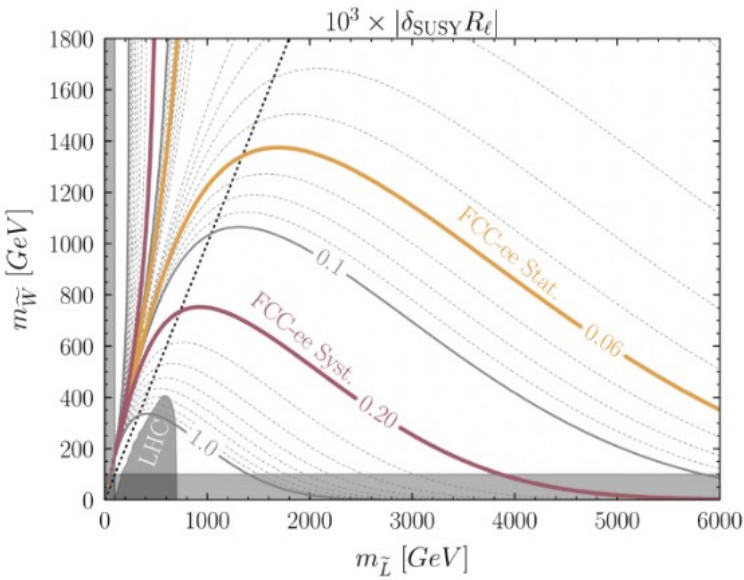
SUSY discovery via EW precision measurements

$$\frac{\Gamma_{Z\rightarrow\ell\ell} - \Gamma_{Z\rightarrow\ell\ell}^{(SM)}}{\Gamma_{Z\rightarrow\ell\ell}^{(SM)}} \propto \frac{g^2}{16\pi^2} \left(\frac{m_Z}{M_{\text{SUSY}}} \right)^2 \longrightarrow \boxed{M_{\text{SUSY}}^{\text{probed}} \sim 1 \text{ TeV} \times \left(\frac{\delta\Gamma/\Gamma}{10^{-5}} \right)^{-1/2}}$$

25 keV (10^{-5}) syst. uncertainty on Γ_z probes M_{SUSY} in the TeV region



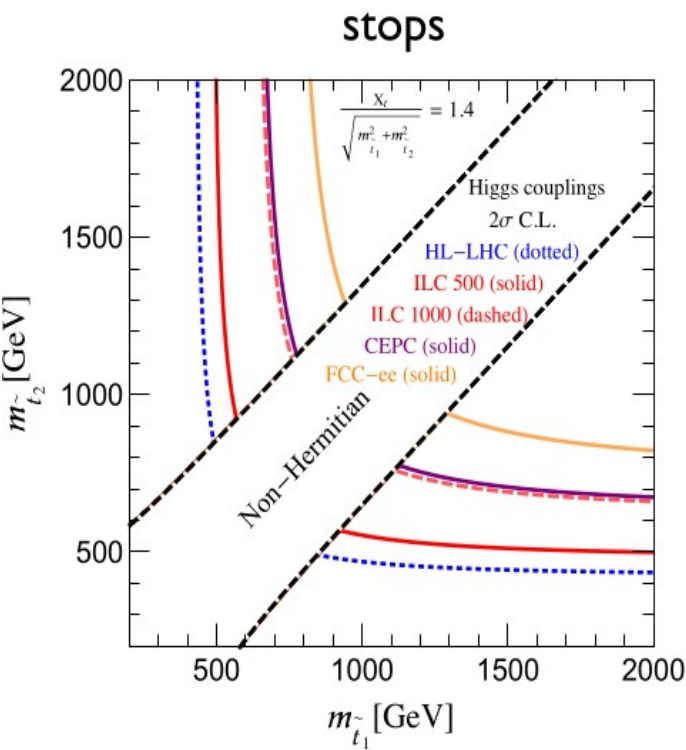
Bino + RH slepton model



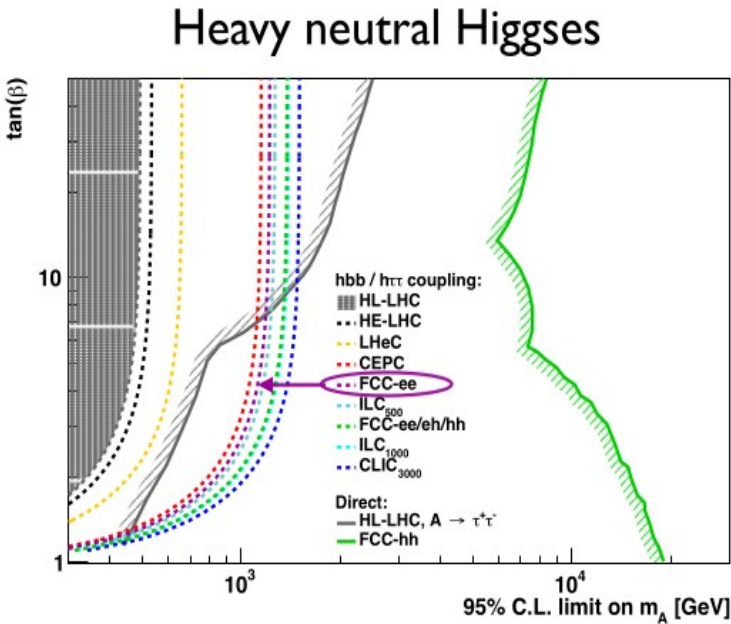
Wino + LH slepton model

Knapen, Langhoff, Liqeti: 2407.13815

- FCC-ee measurements significantly **improve limits** in **benchmark SUSY models** :
- Precisely measured EW and Higgs observables are sensitive to heavy New Physics
- Examples of improved sensitivity wrt direct reach @ HL-LHC: SUSY



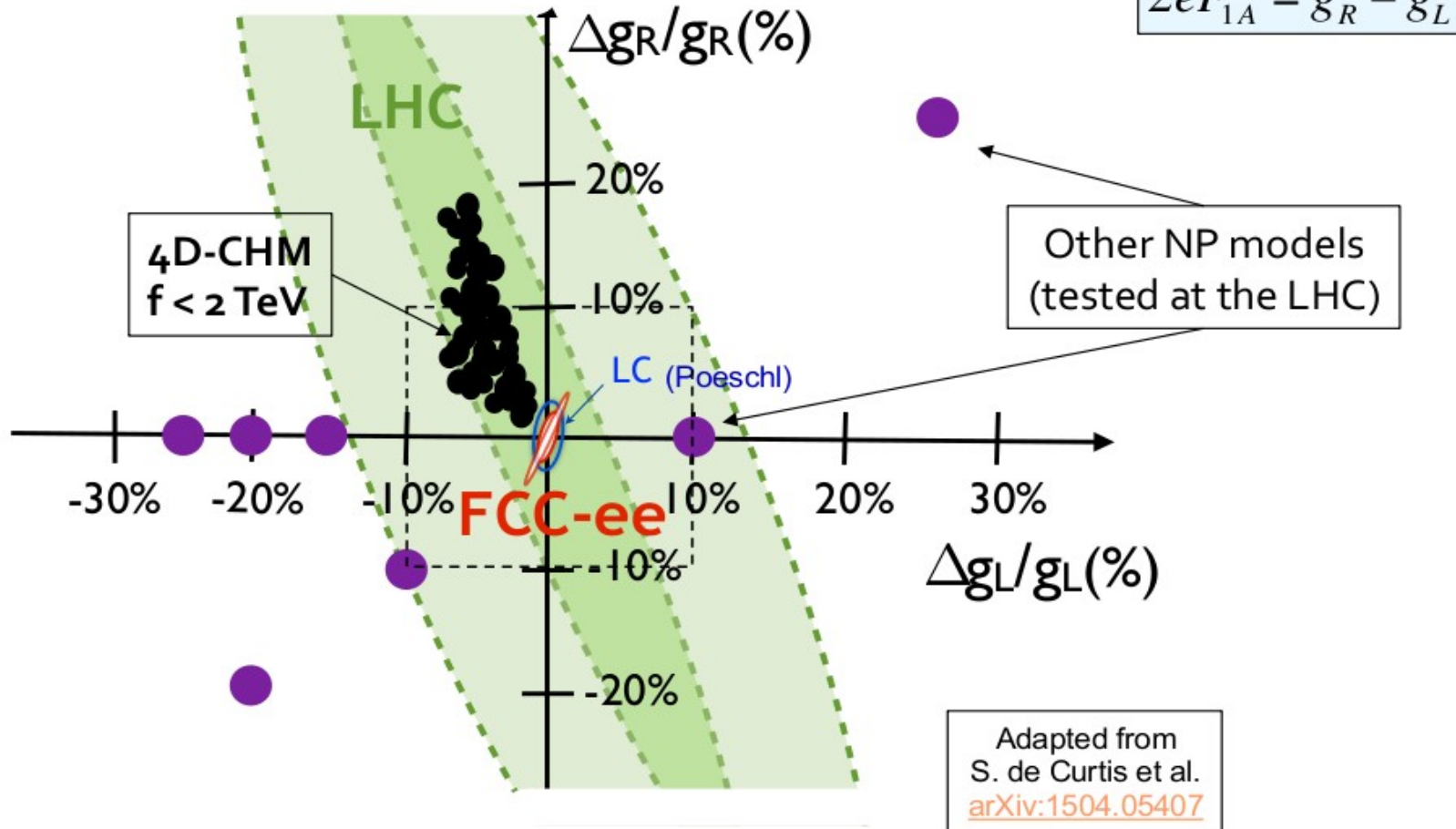
Fan, Reece, Wang '14



ESU Physics BB '19

FCC-ee: Composite Higgs constraints

- 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



FCC-ee: Higgs self-coupling via $\sigma(H+Z)$

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

$$\sigma_{Zh} = \left| \begin{array}{c} e \\ \nearrow \\ \text{---} \\ \nwarrow \\ e \end{array} \begin{array}{c} Z \\ \nearrow \\ \text{---} \\ \nwarrow \\ h \end{array} \right|^2 + 2 \operatorname{Re} \left[\begin{array}{c} \text{---} \\ \nearrow \\ Z \\ \text{---} \\ h \end{array} \cdot \left(\begin{array}{c} e^+ \\ \nearrow \\ \text{---} \\ \nwarrow \\ e^- \end{array} \begin{array}{c} Z \\ \nearrow \\ \text{---} \\ \nwarrow \\ h \end{array} \right) + \begin{array}{c} e^+ \\ \nearrow \\ \text{---} \\ \nwarrow \\ e^- \end{array} \begin{array}{c} Z \\ \nearrow \\ \text{---} \\ \nwarrow \\ h \end{array} \right] \right]$$

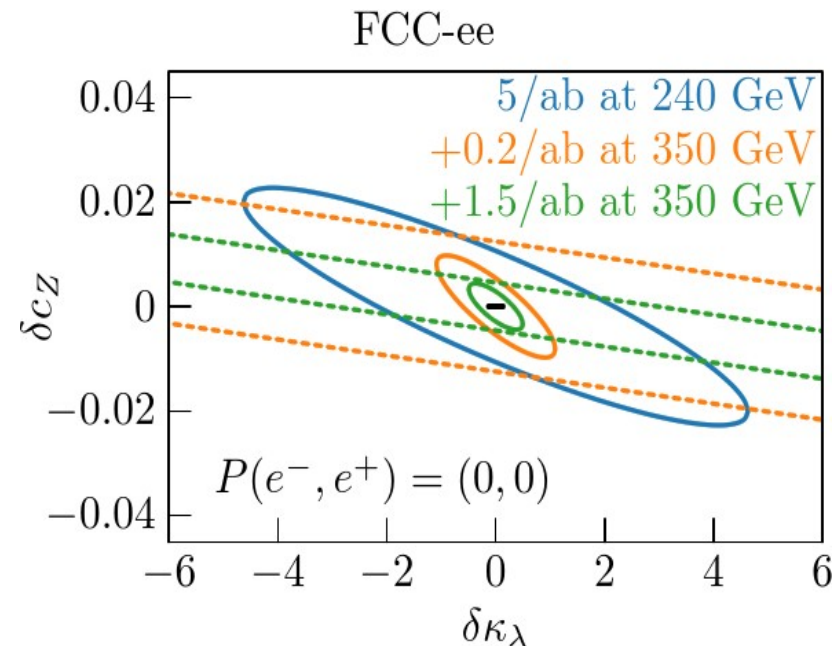
$\delta_{\sigma}^{240} = 100 (2\delta_Z + 0.014\delta_h) \%$

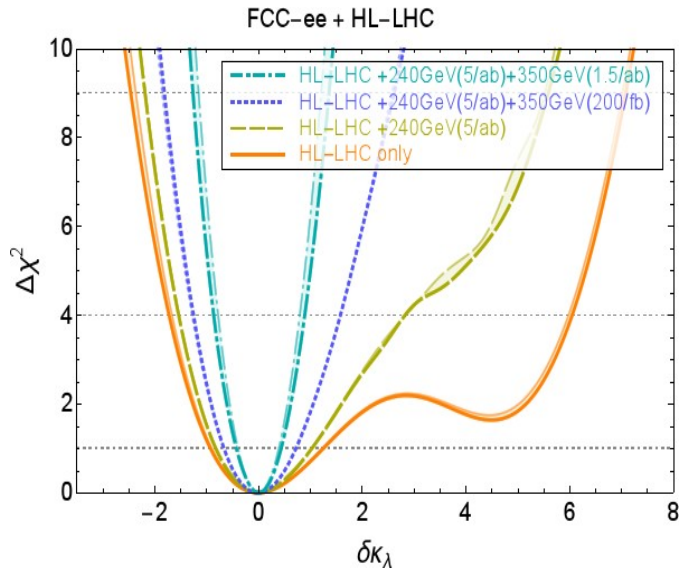
[M. McCullough, 2014]

Self-coupling correction δ_h : **energy-dependent**

δ_Z : energy-independent (distinguishable).

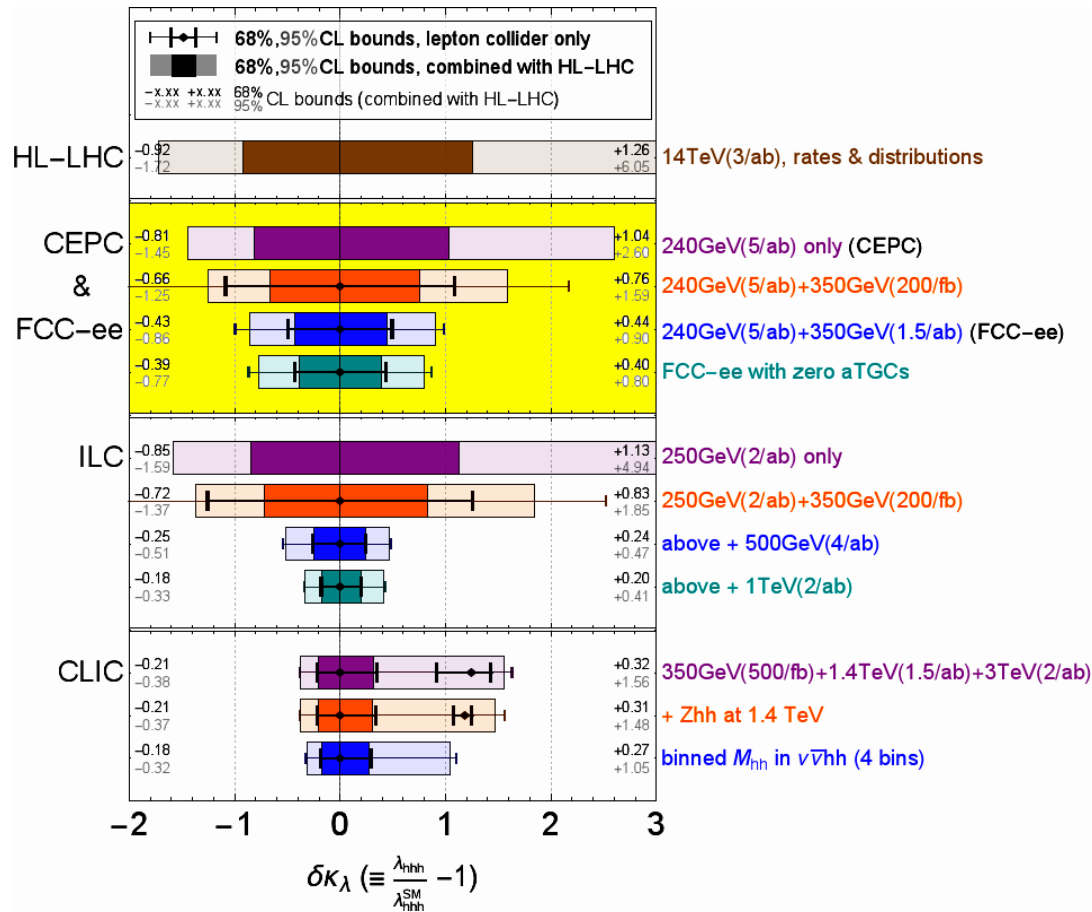
- Tiny effect, but visible thanks to **extreme (0.4%) precision on σ_{Zh}** coupling reachable at FCC-ee.
- Indirect **limits on trilinear λ coupling** at **$\sim 30\%$ level** combining HL-LHC+ FCC-ee at 240+350GeV





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

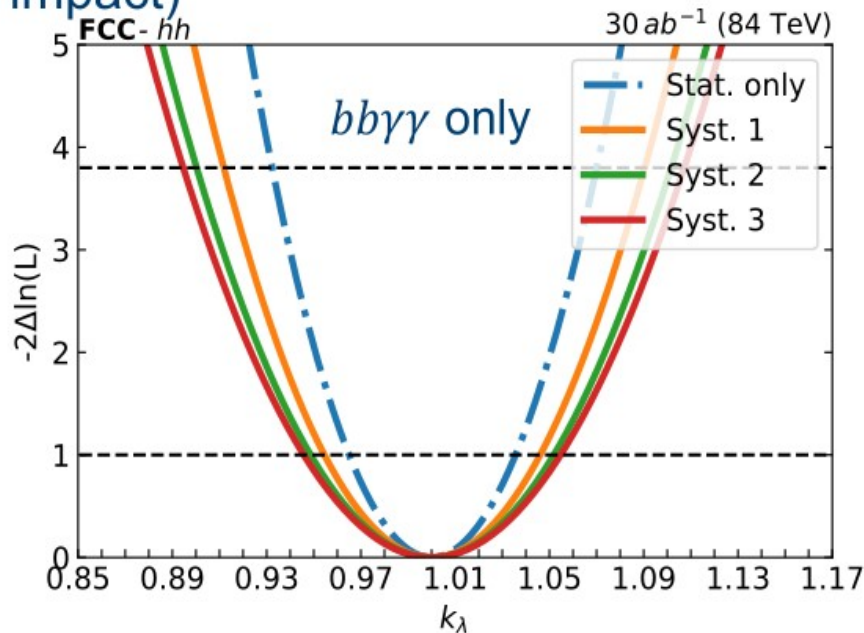
- Addition of FCC-ee 240+350GeV Higgs cross section solves 2nd minimum on λ from HL-LHC data alone.



- FCC-hh will measure self-coupling to $\delta\kappa_\lambda < 5\%$: Probe Higgs potential.

1. Higgs self-coupling

(Combine $bb\gamma\gamma$ with $bb\tau\tau$ for maximal impact)

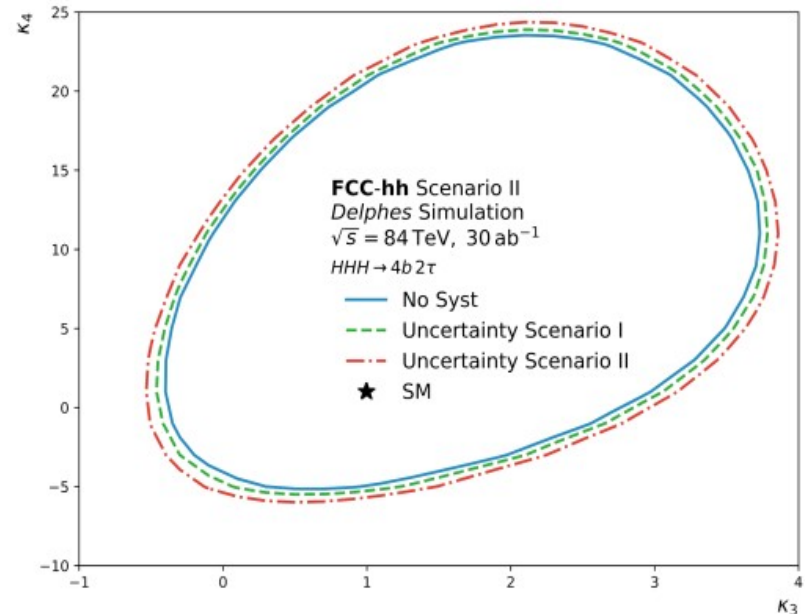


$bb\tau\tau$ [CDS note](#) by M. D'Onofrio et. al.

$bb\gamma\gamma$ [CDS note](#) by P. Mastrapasqua et al.

2. Higgs quartic coupling

(Using $hhhh \rightarrow 4b2\tau$)

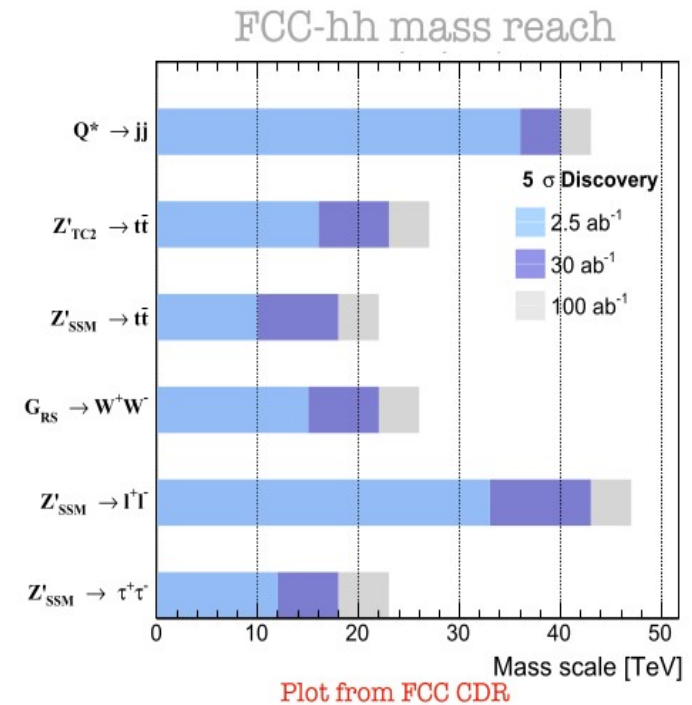
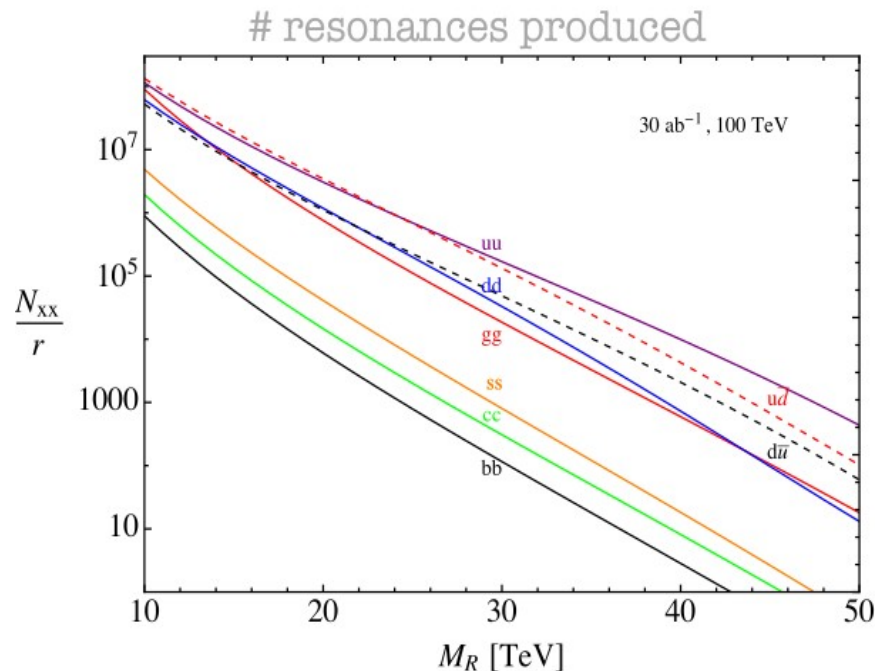


[CDS note](#) by T. Dingley et. al.v

- FCC-hh will allow directly producing **BSM multi-TeV resonances**:

Protons are made of 5 quarks, gluons, photons, W/Z

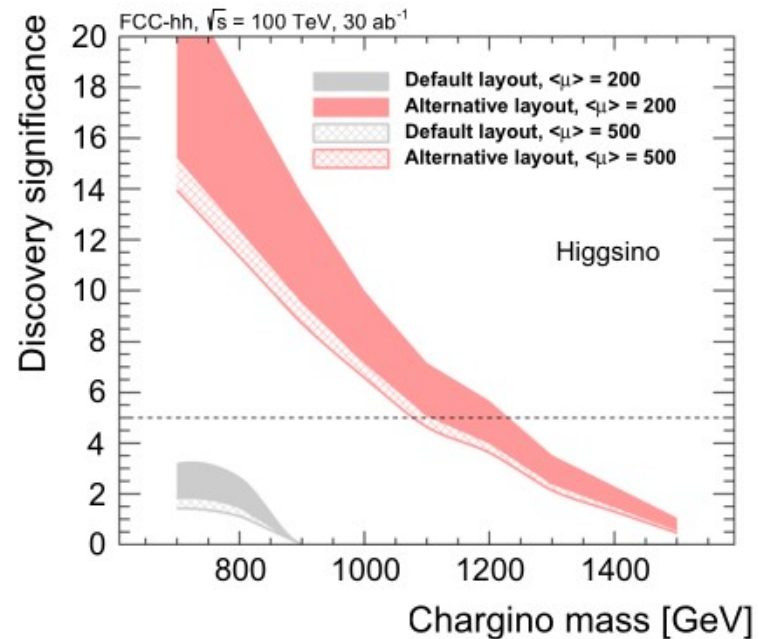
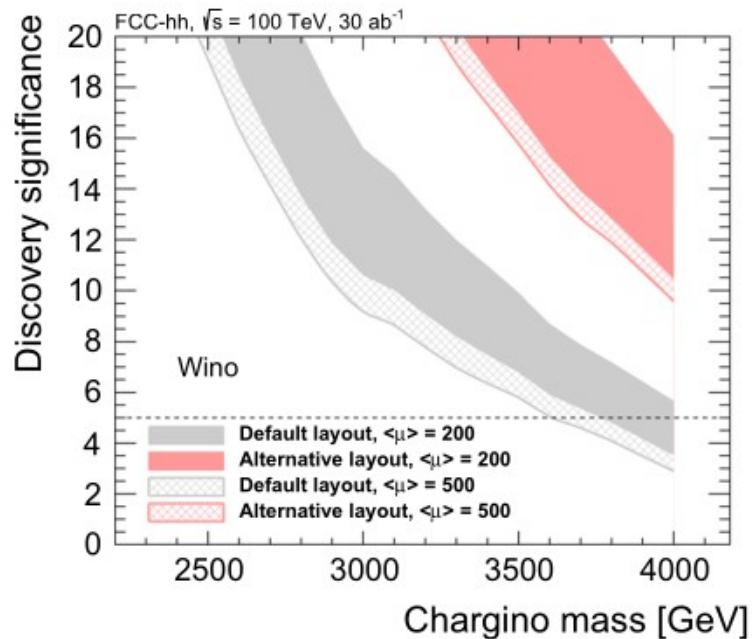
FCC-hh effectively collides 196 different initial states = perfect exploratory machine



FCC-hh: Direct SUSY searches

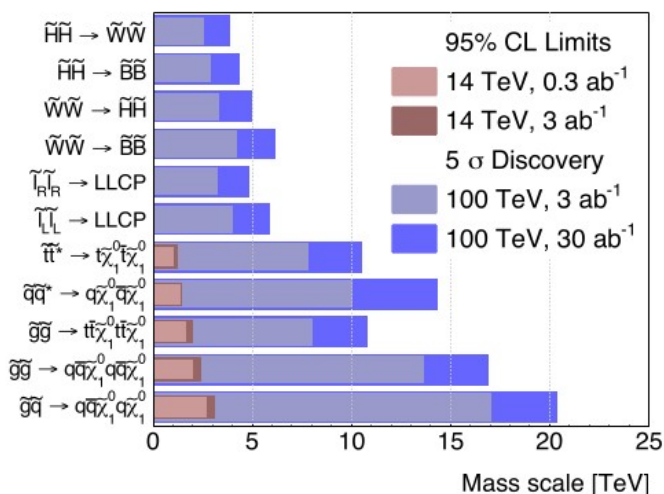
■ FCC-hh will allow directly producing **SUSY multi-TeV particles**:

- Direct searches for heavy resonances and WIMP dark matter provide natural benchmarks to study detector design.



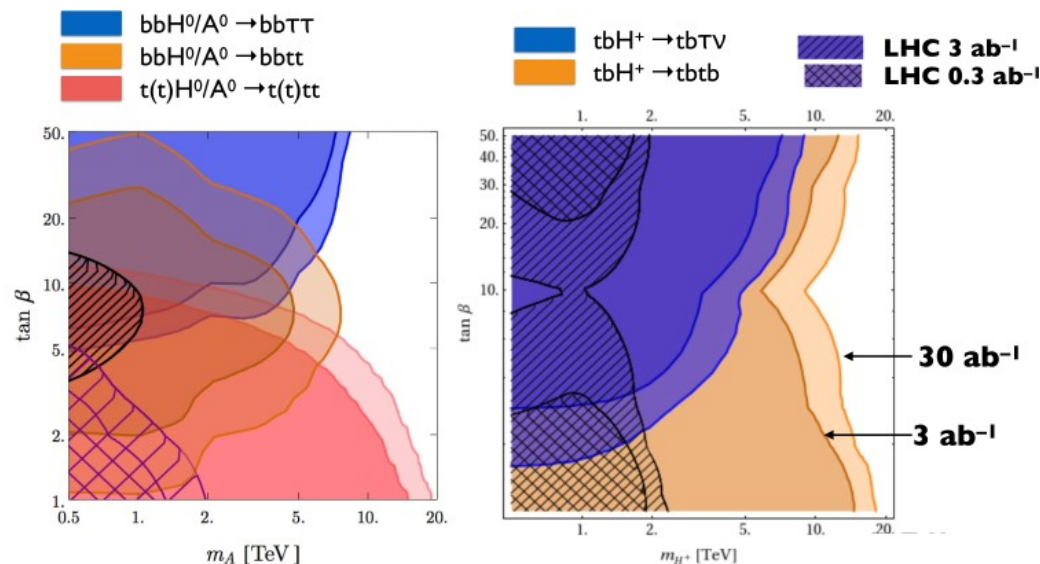
FCC-hh: Direct SUSY searches

■ FCC-hh will allow directly producing **SUSY multi-TeV particles**:



Plot from [arXiv:1606.00947](https://arxiv.org/abs/1606.00947)

15-20TeV squarks/gluinos
require kinematic threshold 30-40TeV:
FCC-hh is more than a $\sqrt{s} \sim 10\text{TeV}$ factory



Plot from [arXiv:1605.08744](https://arxiv.org/abs/1605.08744) and [arXiv:1504.07617](https://arxiv.org/abs/1504.07617)

Factor 10 increase on the HL-LHC limits.

Open questions in the SM (1)

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

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

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

$$+(\bar{u}_L, \bar{d}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) \quad [\text{Quark dynamics}]$$

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

$$+(\overline{D_\mu\phi})D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. \quad [\text{Higgs dyn. \& mass}] \quad \boxed{+ \text{ new particles/symmetries ?}}$$

✗ Light-masses generation: 1st-gen. fermion + all ν 's Yukawa couplings?

Open questions in the SM (2)

$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\text{tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}\text{tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && [\text{Gauge interactions: } U(1)_Y, SU(2)_L, SU(3)_c] \\
 & +(\bar{\nu}_L, \bar{e}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.}) && [\text{Lepton dynamics}] \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{\nu}_L, \bar{e}_L)\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[(-\bar{e}_L, \bar{\nu}_L)\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix} \right] && [\text{Lepton masses}] \\
 & +(\bar{u}_L, \bar{d}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) && [\text{Quark dynamics}] \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{u}_L, \bar{d}_L)\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[(-\bar{d}_L, \bar{u}_L)\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix} \right] && [\text{Quark masses}] \\
 & +(\overline{D_\mu\phi})D^\mu\phi \left(-m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2 \right) && [\text{Higgs dyn. \& mass}] \quad \left(+ \text{ new particles/symmetries ?} \right)
 \end{aligned}$$

- ✗ Light-masses generation: 1st-gen. fermion + all ν 's Yukawa couplings?
- ✗ Naturalness: Higgs mass virtual corrections «untamed» up to Planck scale

Open questions in the SM (3)

$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\text{tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}\text{tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && [\text{Gauge interactions: } U(1)_Y, SU(2)_L, SU(3)_c] \\
 & +(\bar{\nu}_L, \bar{e}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.}) && [\text{Lepton dynamics}] \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{\nu}_L, \bar{e}_L)\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[-\bar{e}_L, \bar{\nu}_L\right]\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix} && [\text{Lepton masses}] \\
 & +(\bar{u}_L, \bar{d}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) && [\text{Quark dynamics}] \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{u}_L, \bar{d}_L)\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[-\bar{d}_L, \bar{u}_L\right]\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix} && [\text{Quark masses}] \\
 & +(\overline{D_\mu\phi})D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && [\text{Higgs dynamics \& mass}]
 \end{aligned}$$

- ✗ Light-masses generation: 1st-gen. fermion + all ν 's Yukawa couplings?
- ✗ Naturalness: Higgs mass virtual corrections «untamed» up to Planck scale
- ✗ Flavour: SM cannot generate observed matter-antimatter imbalance

Open questions in the SM (4)

$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\text{tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}\text{tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && [\text{Gauge interactions: } U(1)_Y, SU(2)_L, SU(3)_c] \\
 & +(\bar{\nu}_L, \bar{e}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.}) && [\text{Lepton dynamics}] \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{\nu}_L, \bar{e}_L)\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[(-\bar{e}_L, \bar{\nu}_L)\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix} \right] && [\text{Lepton masses}] \\
 & +(\bar{u}_L, \bar{d}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) && [\text{Quark dynamics}] \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{u}_L, \bar{d}_L)\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[(-\bar{d}_L, \bar{u}_L)\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix} \right] && [\text{Quark masses}] \\
 & +(\overline{D_\mu\phi})D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && [\text{Higgs dyn. \& mass}] \quad \boxed{+ \text{ new particles/symmetries ?}}
 \end{aligned}$$

- ✗ Light-masses generation: 1st-gen. fermion + all ν 's Yukawa couplings?
- ✗ Naturalness: Higgs mass virtual corrections «untamed» up to Planck scale
- ✗ Flavour: SM cannot generate observed matter-antimatter imbalance
- ✗ Dark matter: SM describes only 4% of Universe (visible fermions+bosons)

Open questions in the SM (5)

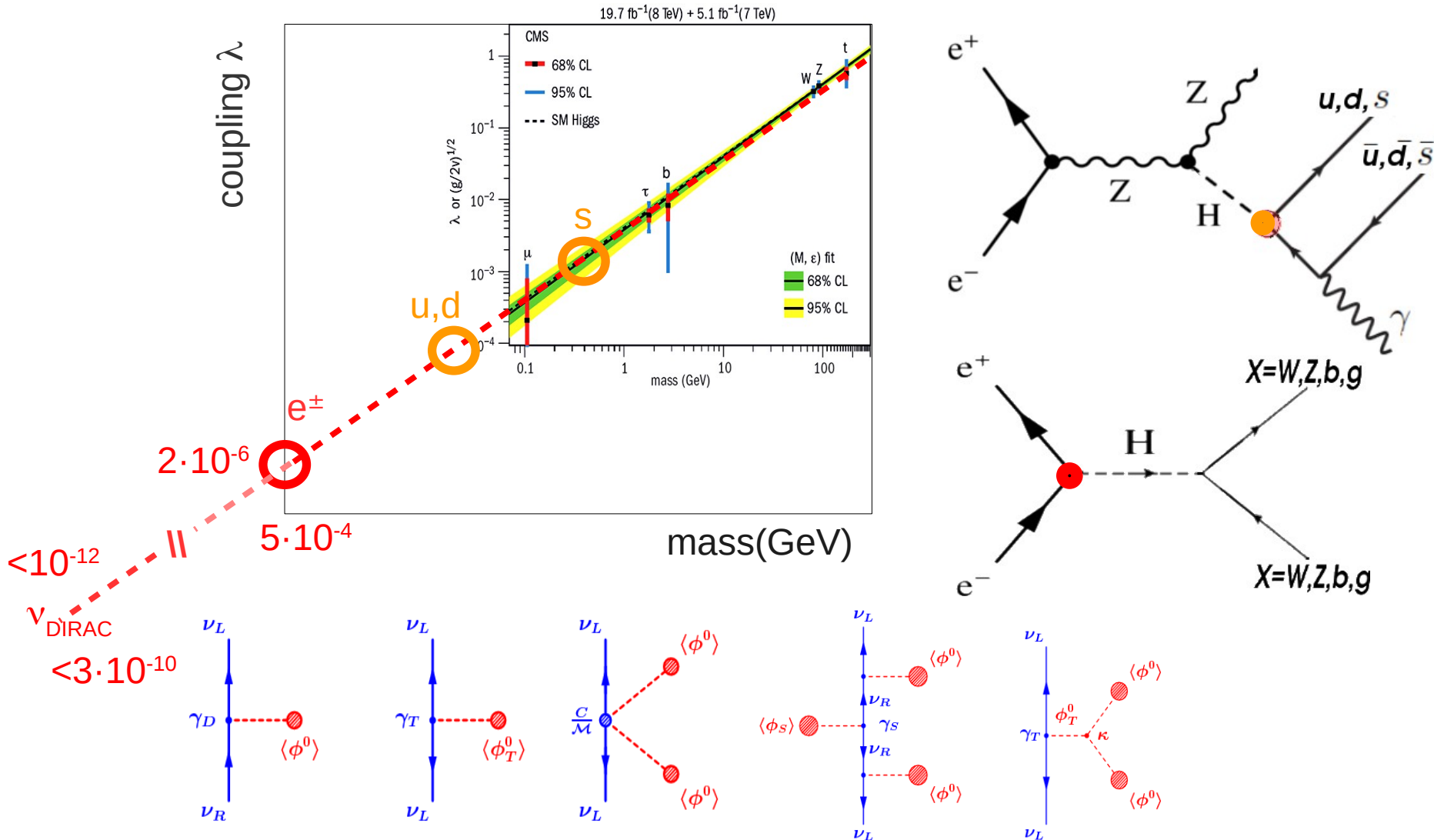
$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\text{tr}(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}\text{tr}(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && [\text{Gauge interactions: } U(1)_Y, SU(2)_L, SU(3)_c] \\
 & +(\bar{\nu}_L, \bar{e}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.}) && [\text{Lepton dynamics}] \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{\nu}_L, \bar{e}_L)\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[(-\bar{e}_L, \bar{\nu}_L)\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix} \right] && [\text{Lepton masses}] \\
 & +(\bar{u}_L, \bar{d}_L)\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) && [\text{Quark dynamics}] \\
 & -\frac{\sqrt{2}}{v} \left[(\bar{u}_L, \bar{d}_L)\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right] - \frac{\sqrt{2}}{v} \left[(-\bar{d}_L, \bar{u}_L)\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix} \right] && [\text{Quark masses}] \\
 & +(\overline{D_\mu\phi})D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && [\text{Higgs dyn. \& mass}] \quad \boxed{+ \text{ new particles/symmetries ?}}
 \end{aligned}$$

- ✗ Light-masses generation: 1st-gen. fermion + all ν 's Yukawa couplings?
- ✗ Naturalness: Higgs mass virtual corrections «untamed» up to Planck scale
- ✗ Flavour: SM cannot generate observed matter-antimatter imbalance
- ✗ Dark matter: SM describes only 4% of Universe (visible fermions+bosons)
- ✗ Many others: Strong CP, quantum gravity, cosmological const, dark energy, inflation,...

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

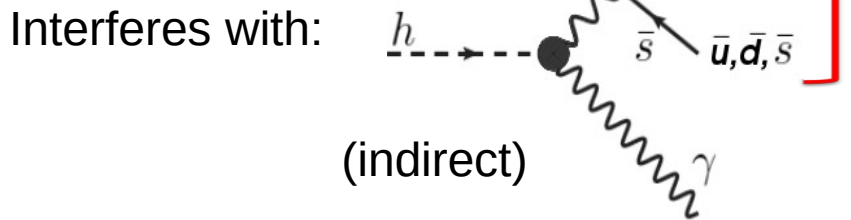
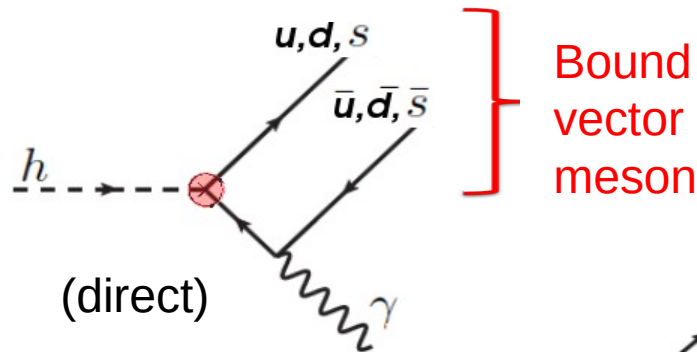
Generation of lightest fermion (u,d,s; e; ν 's) masses

- 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:

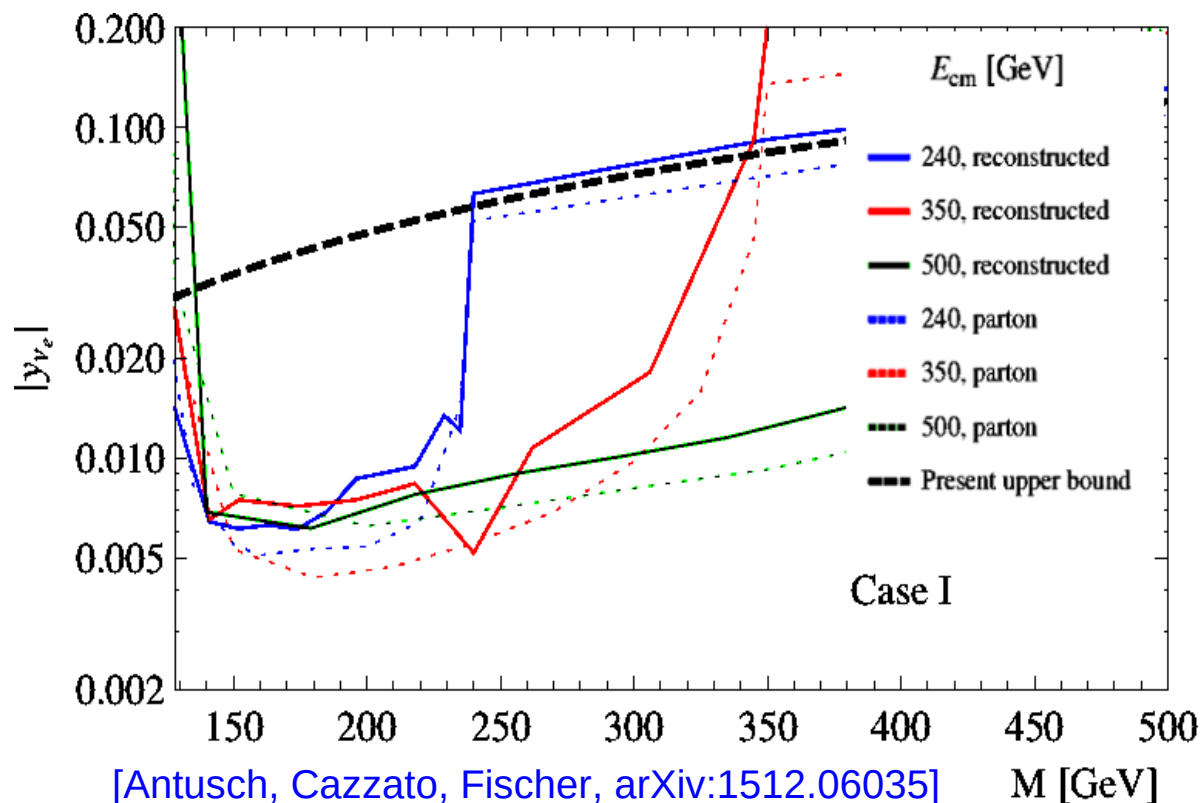
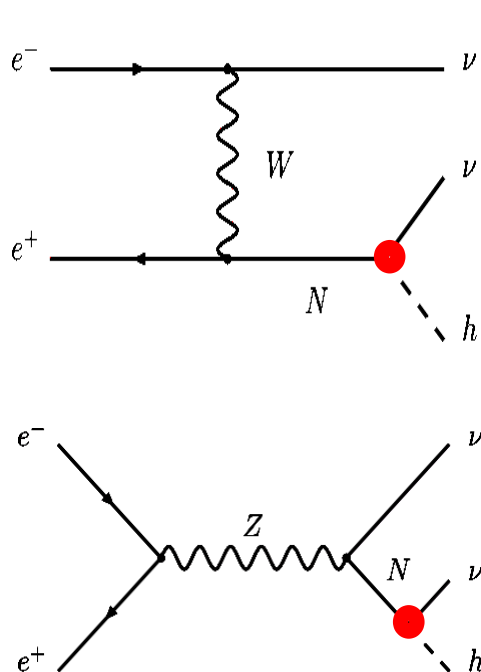
$$\frac{\text{BR}_{h \rightarrow \rho\gamma}}{\text{BR}_{h \rightarrow b\bar{b}}} = \frac{\kappa_\gamma [(1.9 \pm 0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d]}{0.57\bar{\kappa}_b^2} \times 10^{-5}$$

($k_q = y_q/y_b$)

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

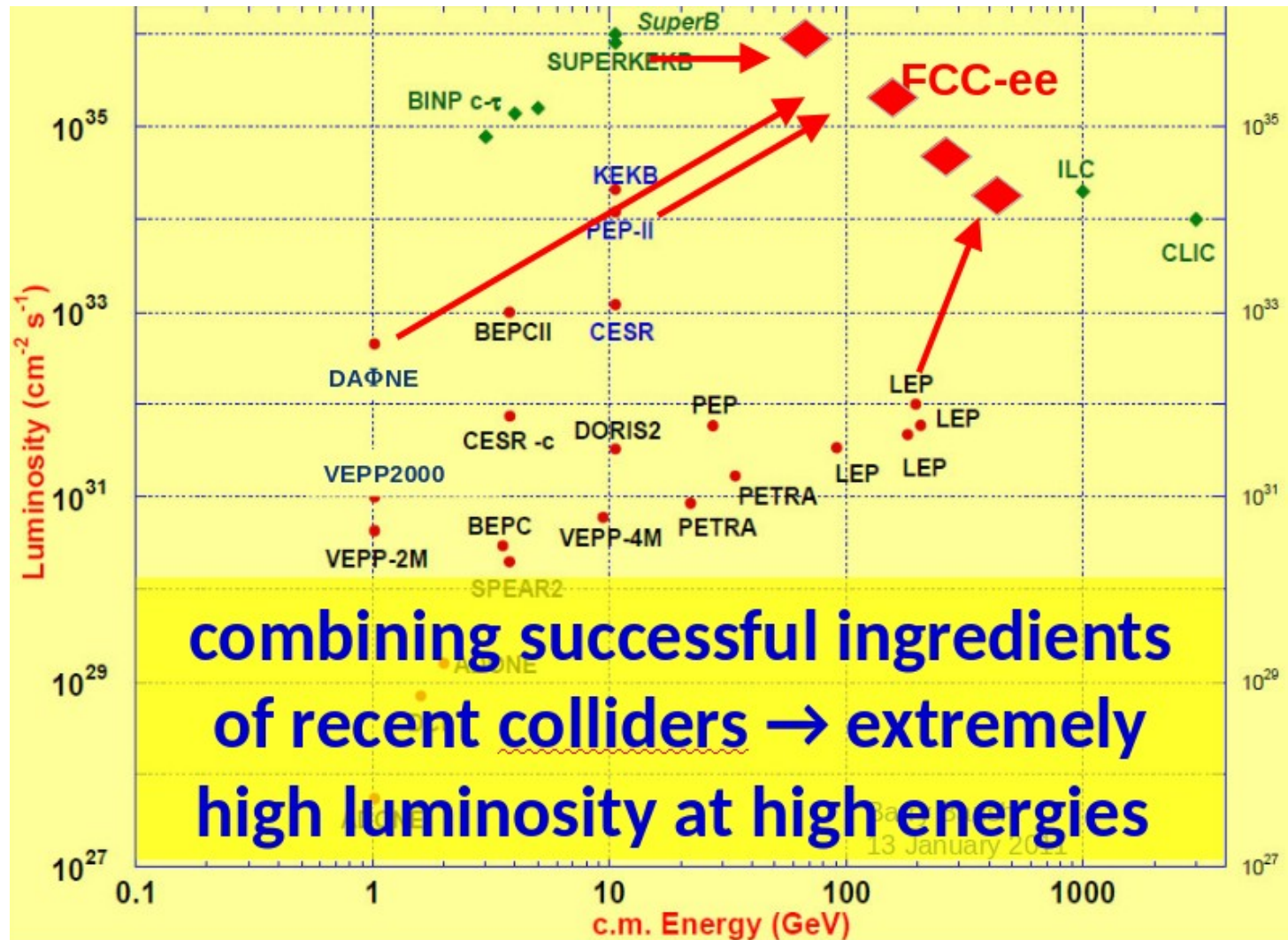
Right-handed neutrinos decaying into Higgs

- 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

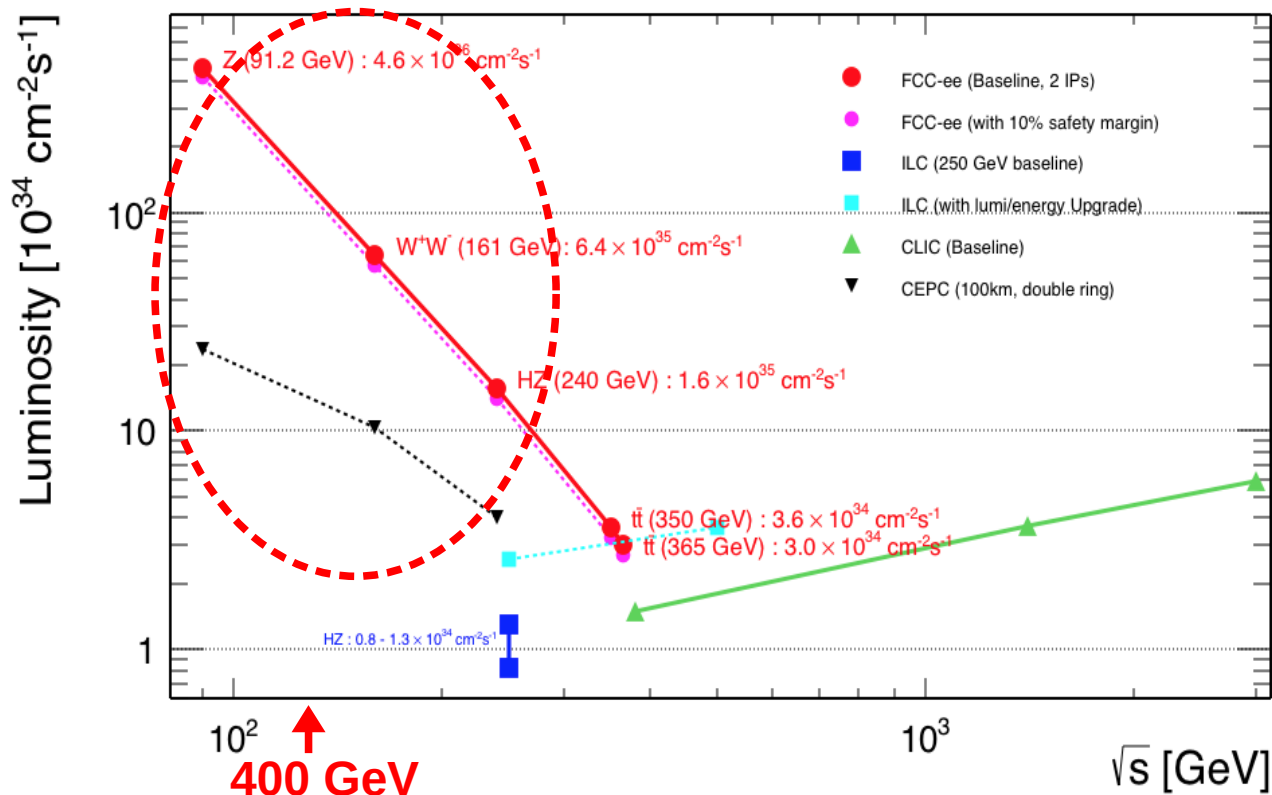


- FCC-ee sensitivity down to $|y_{\nu e}| \sim 5 \times 10^{-3}$ for unexplored $m_N \sim 100-350$ GeV

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



FCC-ee characteristics



- $\sqrt{s}$ limited to ~ 400 GeV by $SR \sim E^4/R$: $R \sim 80$ 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)

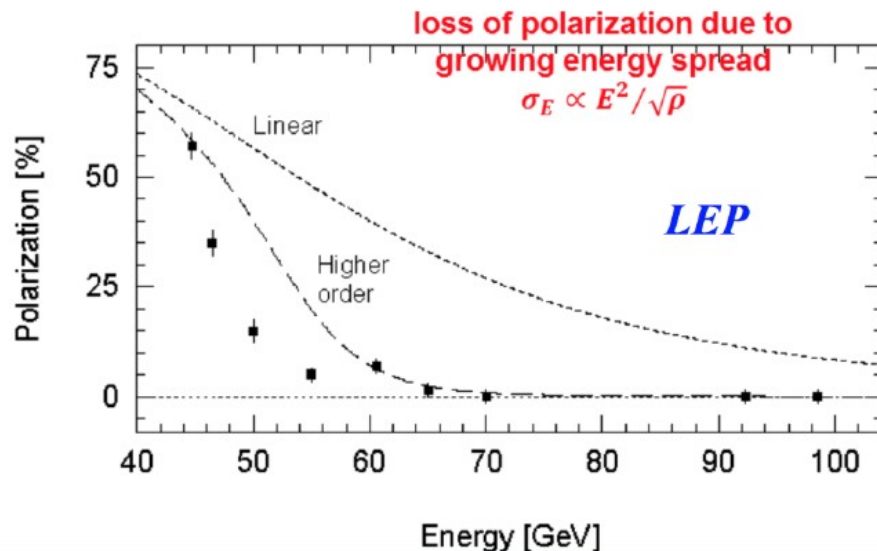
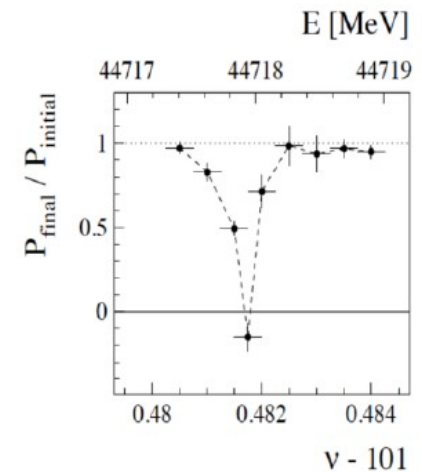
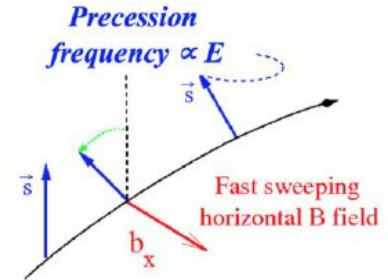
Beam energy spread via resonant depolarization

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

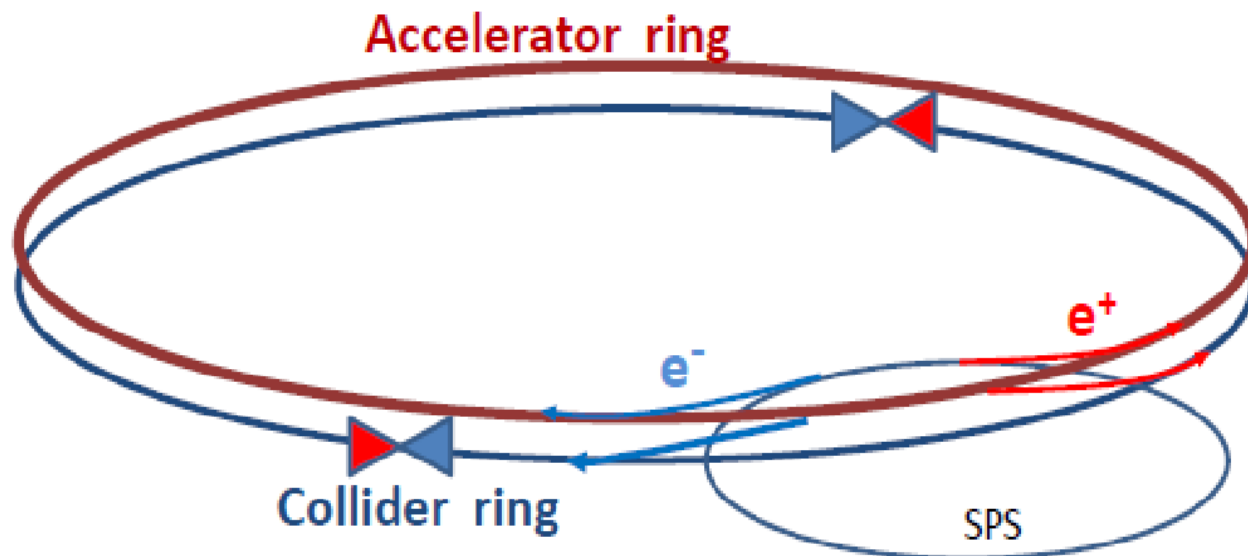
< 100 keV beam energy calibration
at Z peak and at WW threshold

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