Theoretical Challenges and Physics potential at FCC-ee

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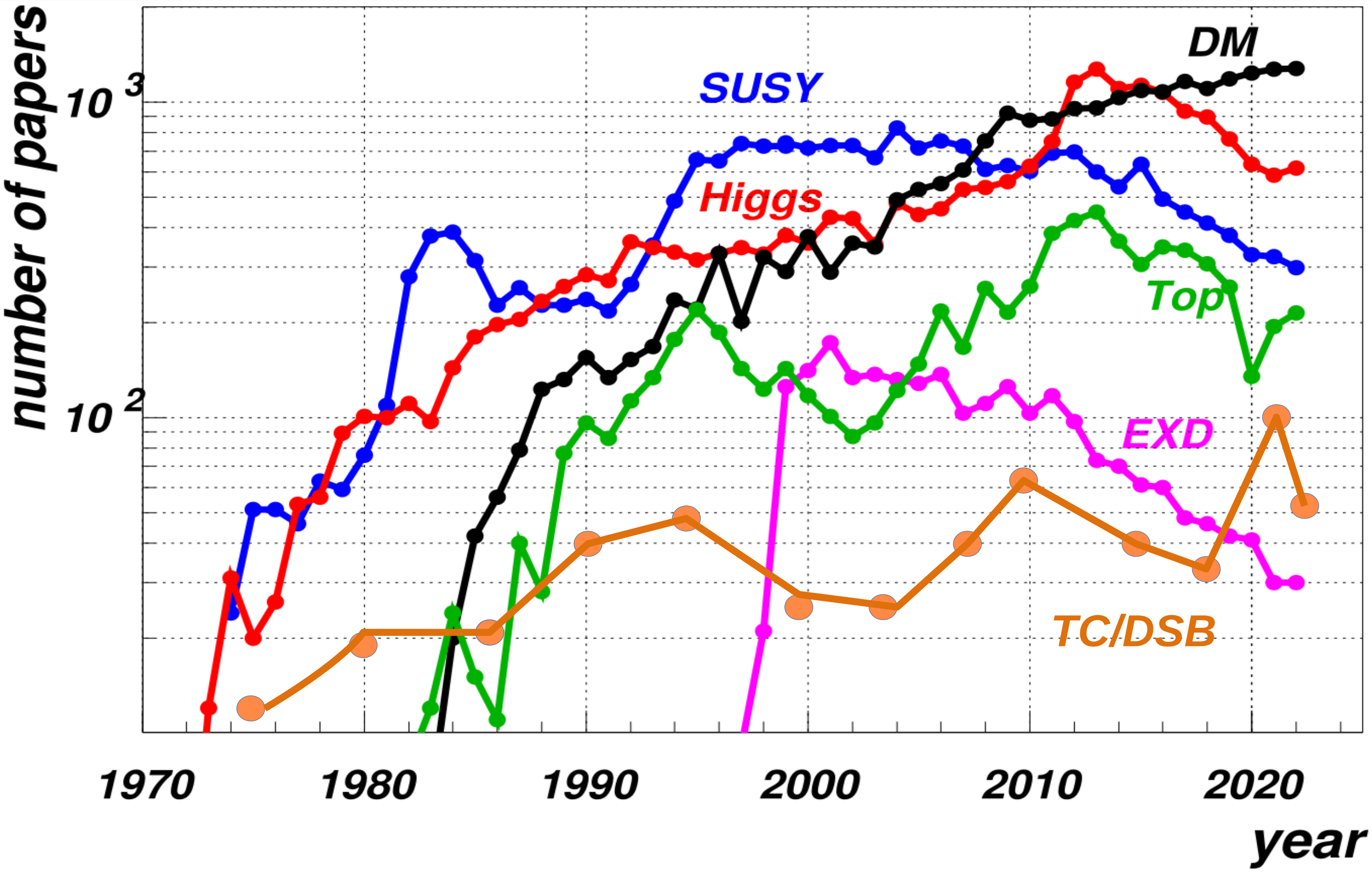
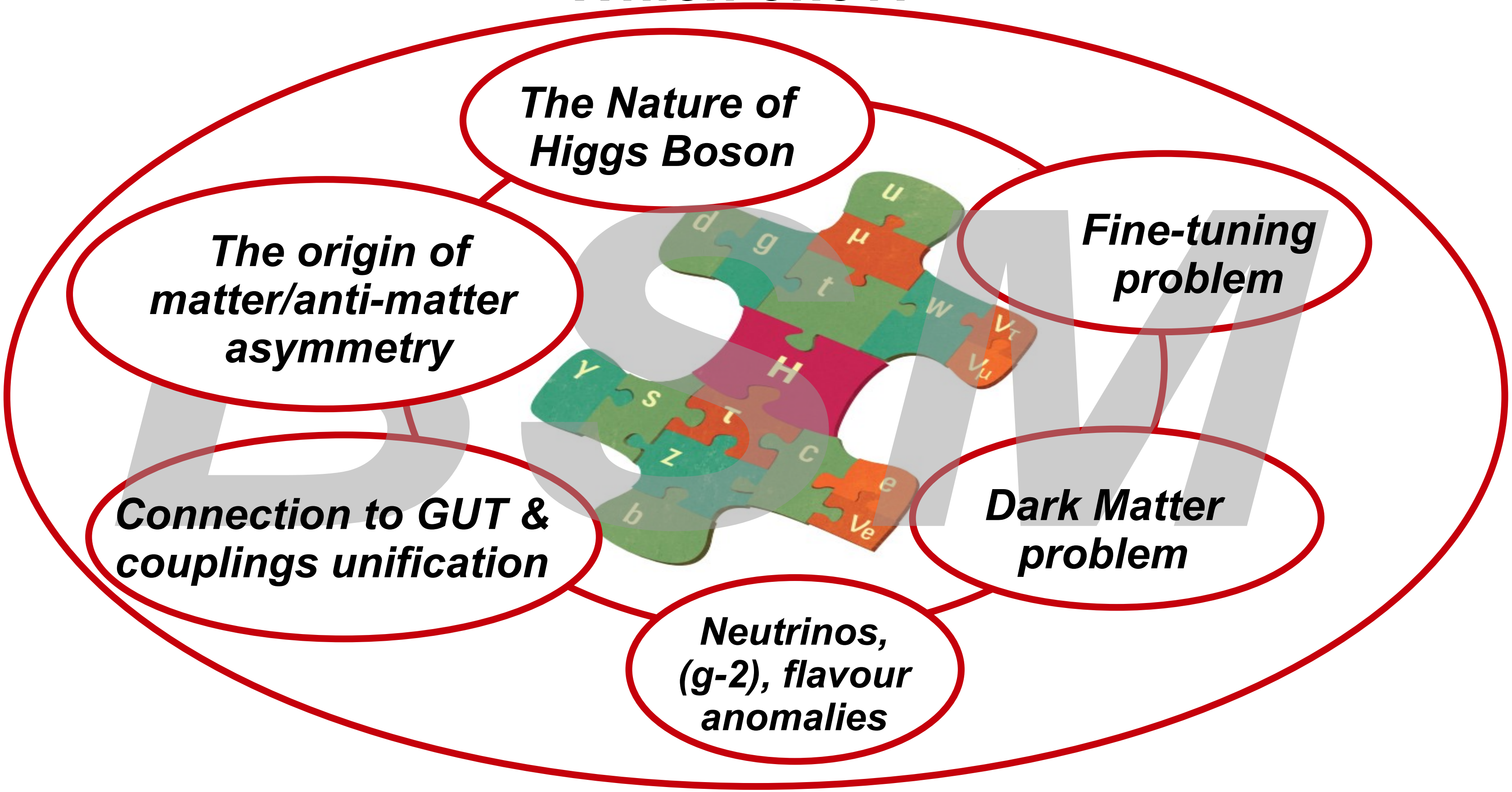
IP2I perspectives for FCC-ee
13th of September 2023

Popular directions in Particle Physics. Which ones FC-ee can explore?



We are confident that the SM itself is the piece of the underlying complete and consistent theory! Which one?!

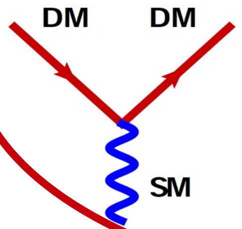


The ingredients of the BSM theory space

Gauge Invariant, Renormalizable, Anomaly Free

DM

Z2 symmetry, an upper limit on the mass from relic density



mono-X, invisible Higgs decays, disappearing tracks, multi-leptons, Z', VLQs, ...

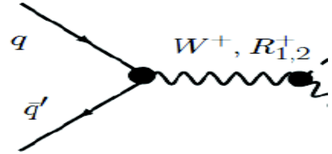
HIGGS

Which one?

Fundamental: SUSY, UED, …

OR

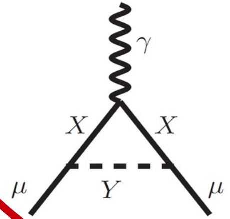
Composite: CHM, Technicolor, RS, ...



VBF/VH resonances, deviations from SM couplings, ttH, invisible decays, Z', VLQs, ...

$(g\text{-}2)_\mu$ and flavour

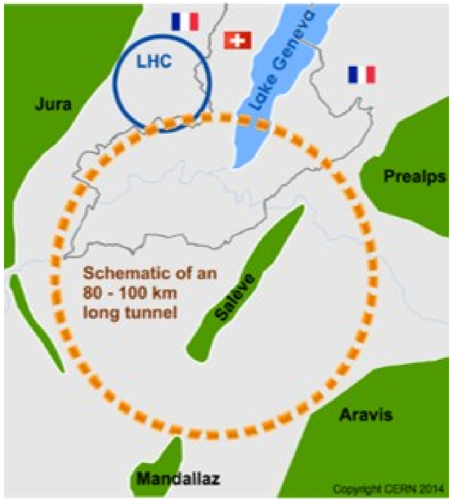
An upper limit on the scale of new physics

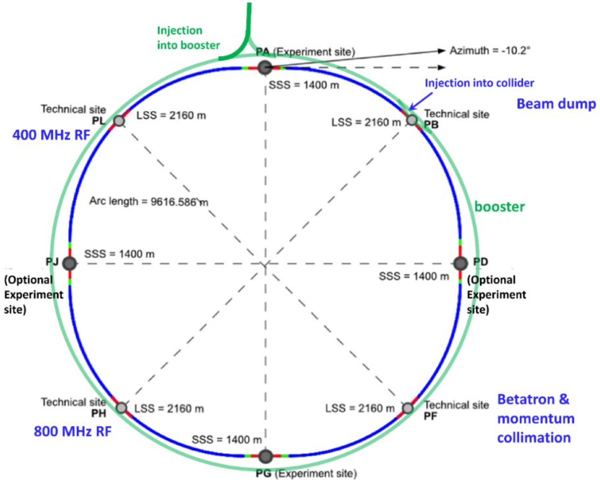


multi-leptons, LVUV, LQ's, Z', ...

FCC-ee: main characteristics

- **CDRs**
  - “FCC-ee: the lepton collider”, EPJ Special Topics 228 (2019) 26
  - “FCC physics opportunities: future circular collider conceptual design report” v1 EPJ C 79 (2019) 474
- **The first stage of FCC**
- **Two or Four Interaction Points (IPs)**
- **High Luminosity:** ~20ab/IP @ m_Z
- **CME’s:** 91, (125), 160, 240, 365 GeV
- **Fixed CME and precise CME calibration:** ~100 keV@m_Z,~300 keV@m_{WW}
- **European Strategy for Particle Physics** CERN-ESU-015 (2020) *“An electron-positron Higgs factory is the highest-priority next collider”*





2020 - 2040

2045 - 2060

c.m. energy [GeV]	lum./ IP [10^{34} cm^{-2}s^{-1}]	int. lum./year (2 IPs) [ab^{-1}/yr]	run time [yr]	power [MW]
91	200	48	4	259
160	20	6	1–2	277
240	7.5	1.7	3	282
365	1.3	0.34	5	354

FCC-ee: physics opportunities

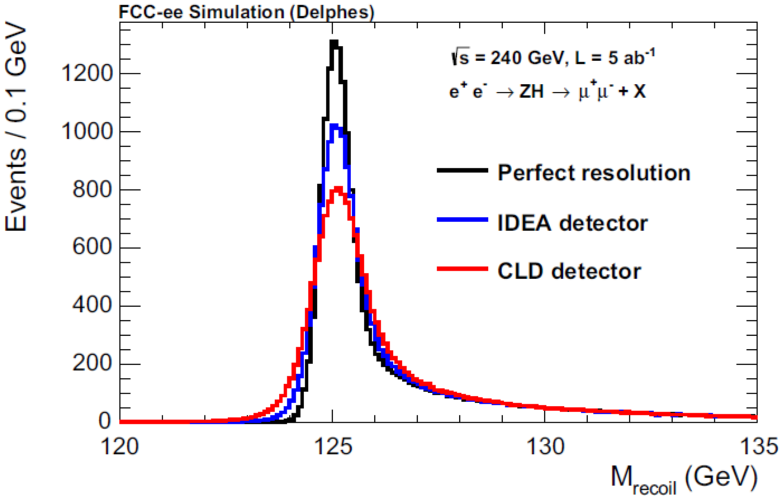
Higgs Physics: HZ

- the precision is based on the measurement the mass recoiling Z-bozon in $\mathrm{e^+e^-} \to \mathrm{HZ}$ process and the accuracy of CME calibration

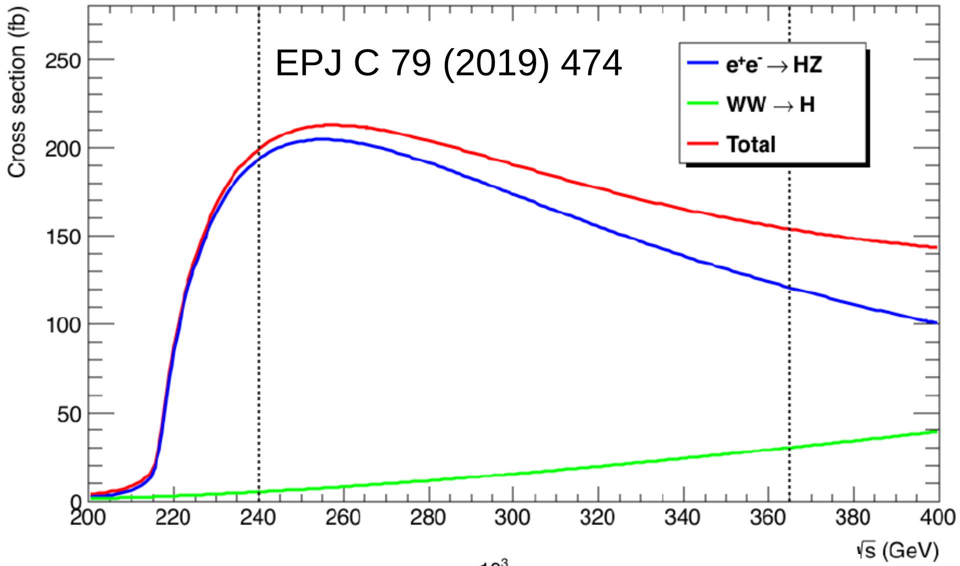
$$m^2_{\mathrm{Recoil}} = s + m^2_{\mathrm{Z}} - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

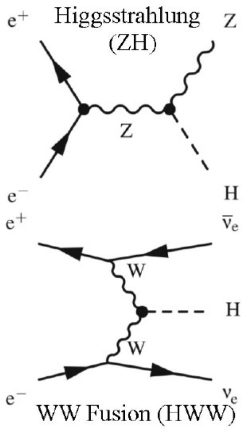
- counting m_{Recoil} around the Higgs mass allows to determine σ_{HZ}

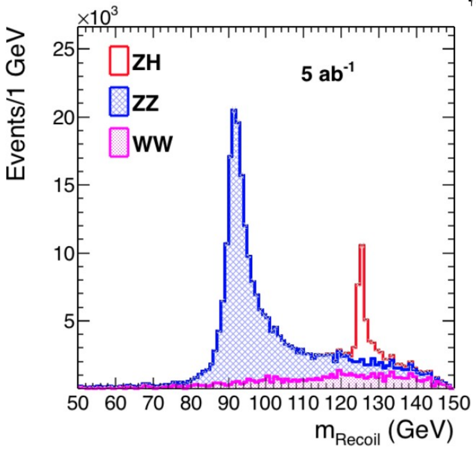
Azzi,Perez, EPJ (2021) 136:1195



EPJ C 79 (2019) 474







FCC-ee: physics opportunities

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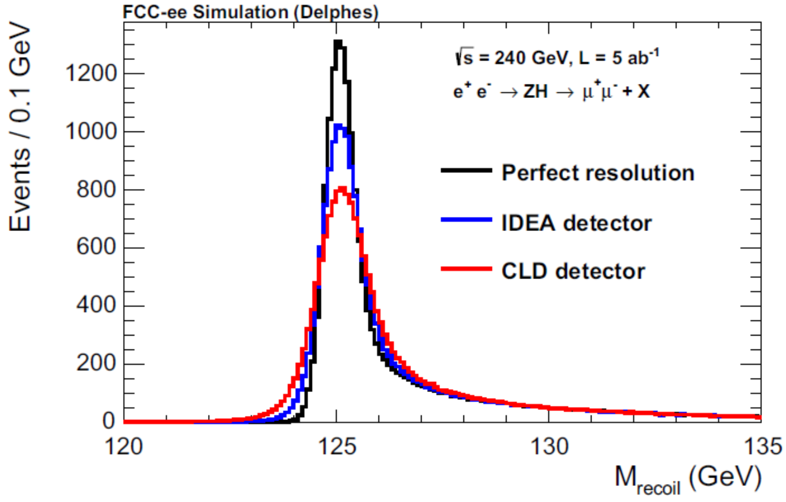
  - counting $m_{\rm Recoil}$ around the Higgs mass allows to determine σ_{HZ}

- Determination of Higgs couplings
  - HZZ – per mille precision
  - HWW, Hbb, Hcc, Hgg – percent precision
  - Hμμ – 10% precision, Hγγ – 5% precision
- **Challenge for theory to match HZ precision**
  - N3LO QCD + N2LO EW
  - "precision calculations for future e+e– colliders" workshop (indico.cern.ch/event/1140702/)

Azzi,Perez, EPJ (2021) 136:1195

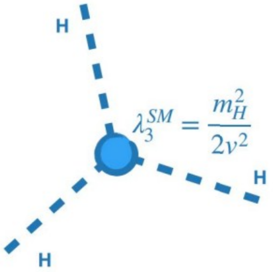


Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	7	3	+4	—	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.8	6.3	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.35	0.80	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.7	1.3	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.8	2.8	1.3	**0.61**	0.55	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	6.8	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	2.2	3.8	1.6	**1.01**	0.83	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.9	4.2	1.4	**0.74**	0.64	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	13	n.a.	10.1	**9.0**	3.9	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	6.4	n.a.	4.8	**3.9**	1.1	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	–	–	2.4	1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	$< \mathbf{1.0}$	< 1.0	n.a.

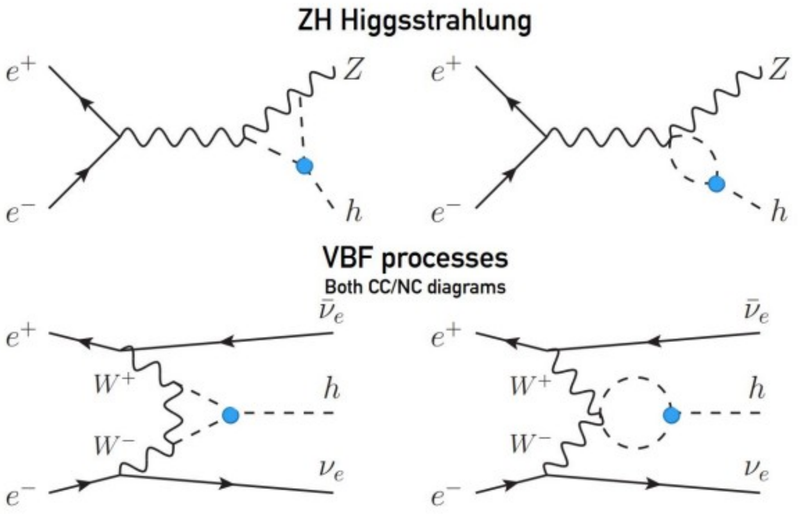
FCC-ee: physics opportunities

- **Higgs Physics: Higgs self coupling**
  - Can be probed indirectly via single Higgs boson production

$$\Sigma_{\rm NLO} = Z_H \Sigma_{\rm LO}(1+\kappa_\lambda C_1) \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$



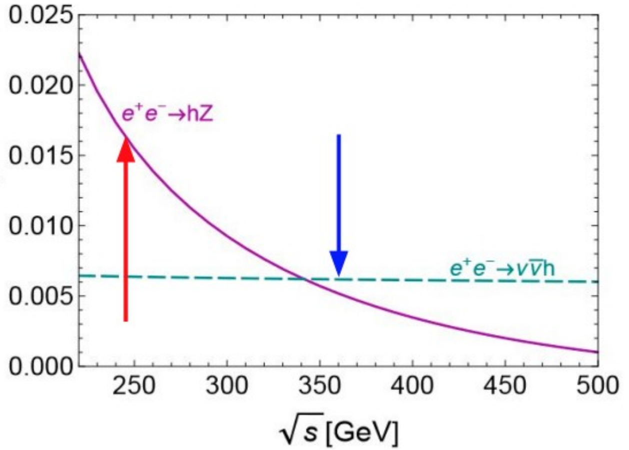
McCullough, 2013

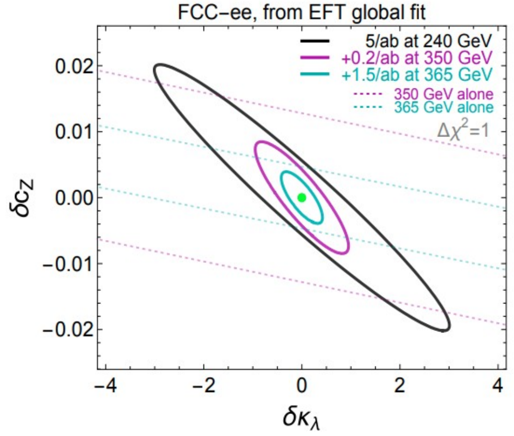


  - Sensitivity to NLO = via NLO processes
  - C_1 varies with CME
  - The combination of HL-LHC and FCC-ee brings sensitivity to **g_{HHH} down to 33%**

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-ee + HL-LHC
Int. Lumi (ab^{-1})	3	5 + 0.2 + 1.5	–
Years	10	3 + 1 + 4	–
$g_{\rm HHH}$ (%)	50.	44.	33.
$\Gamma_{\rm H}$ (%)	SM	1.1	1.1

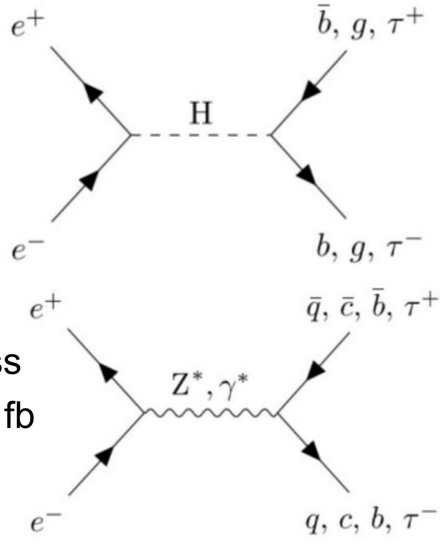
arXiv:2203.06520 FCC Snowmass 2021 summary

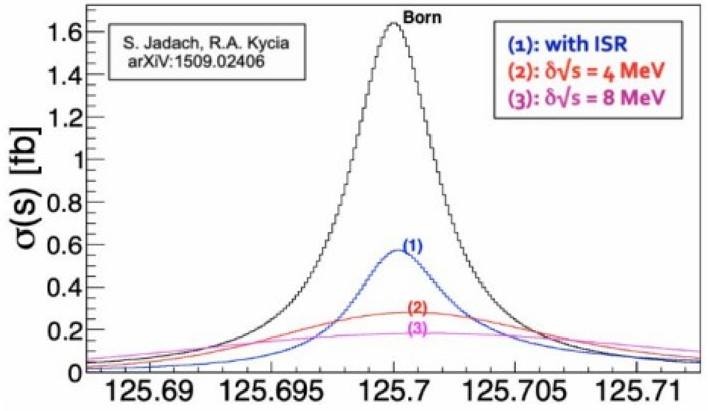


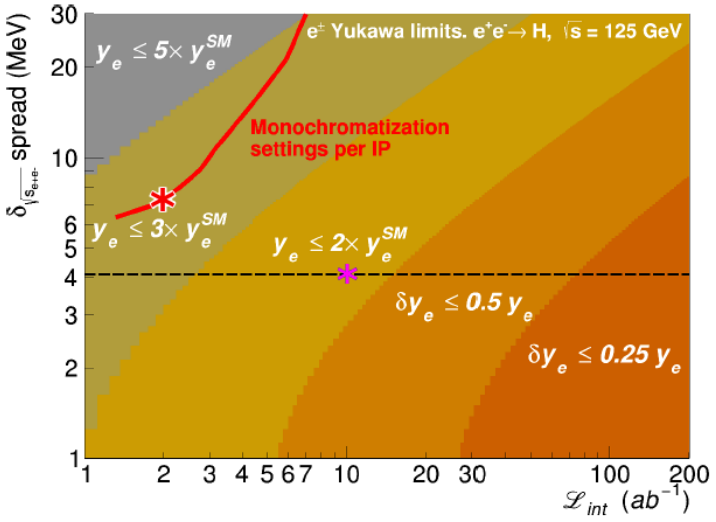


FCC-ee: physics opportunities

- **Higgs Physics: Higgs coupling to electrons**
  - Using monochromatic resonant Higgs production at $\sqrt{s} = 125$ GeV
  - Challenges:
    - ISR+FSR → 40% reduction
    - beam energy speread ~ 4 MeV → 45% reduction
    - potential uncertainty of the Higgs mass
    - total convoluted cross section: ~ 0.28 fb
    - large backgrounds
  - Expected
    - 20 ab^{-1}/y @ √s = 125 GeV → ~ 6k ee→ H bosons /y
    - after 2 years running with 4 IP → **limit $y_e < 1.6 \times y_e$** (1.2 σ)





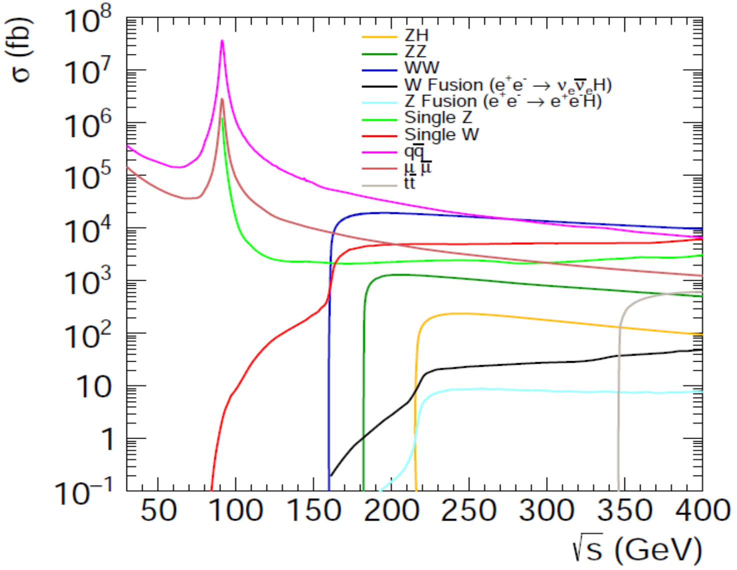


d'Enterria, Poldaru, Wojcik arXiv:2107.02686

FCC-ee: physics opportunities

- **EW precision program around Z pole and WW**

Working point	Z years 1-2	Z, later	WW
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	115	230	28
Lumi/year (ab^{-1}, 2 IP)	24	48	6
Physics goal (ab^{-1})	150		10
Run time (year)	2	2	2
Number of events	5×10^{12} Z		10^{8} WW



FCC-ee: physics opportunities

arXiv:2203.06520

- **EW precision program around Z pole and WW**

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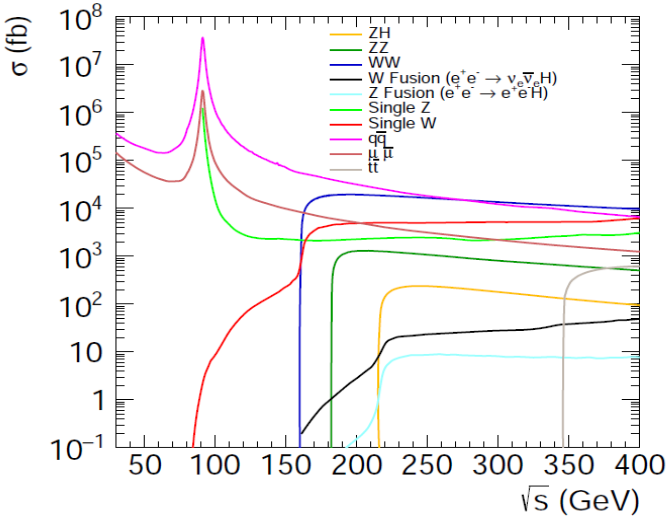
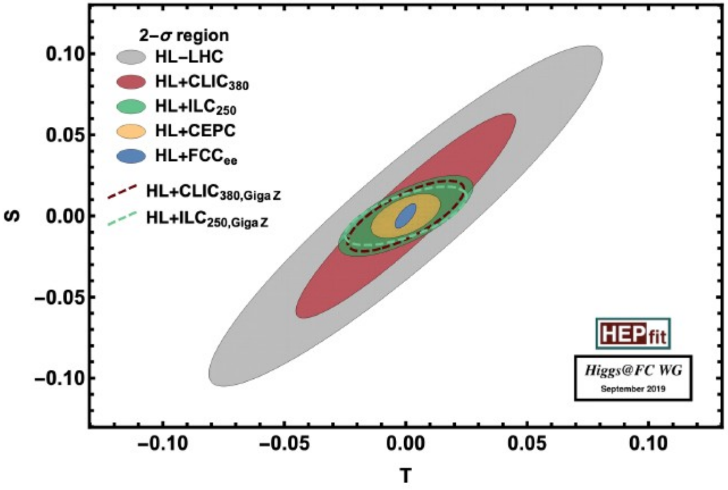
Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	4	100	From Z lineshape scan; beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	4	25	From Z lineshape scan; beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	0.2 – 1.0	Ratio of hadrons to leptons; acceptance for letpons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	0.1	0.4 – 1.6	From R_ℓ^Z above
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons; stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross section; luminosity measurement
N_ν ($\times 10^3$)	$2,996 \pm 7$	0.005	1	Z peak cross sections; luminosity measurement
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	3.8	1.2	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1.3	b-quark asymmetry at Z pole; from jet charge
A_e ($\times 10^4$)	$1,498 \pm 49$	0.07	0.2	from $A_{FB}^{\text{pol},\tau}$; systematics from non-τ backgrounds
m_W (MeV)	$80,350 \pm 15$	0.25	0.3	From WW threshold scan; beam energy calibration
Γ_W (MeV)	$2,085 \pm 42$	1.2	0.3	From WW threshold scan; beam energy calibration
N_ν ($\times 10^3$)	$2,920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$\alpha_S(m_W^2)$ ($\times 10^4$)	$1,170 \pm 420$	3	Small	From R_ℓ^W





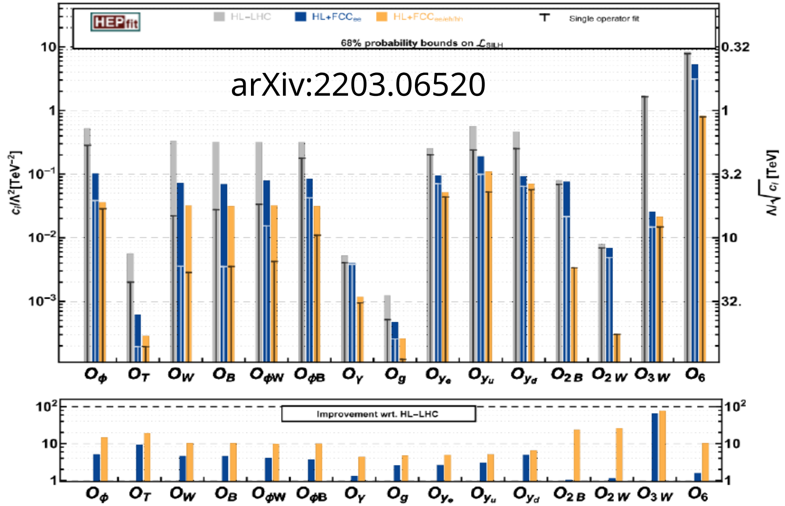
FCC-ee: physics opportunities

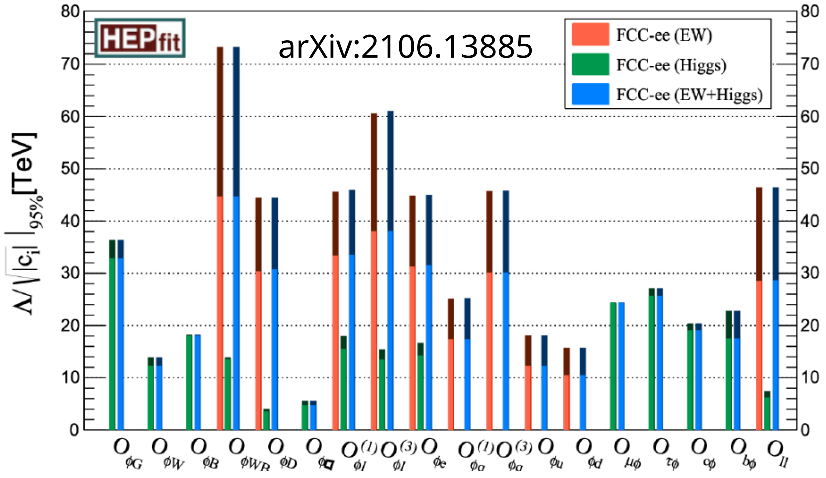
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

- **EW precision program around Z pole and WW**
  - Improvement in our understanding of SM or BSM by at least one order of magnitude
  - Theory challenges:
    - Theory must be matched with EWPO at least at the same level of accuracy

Quantity	FCC-ee	Current intrinsic theory uncertainty	Projected intrinsic theory uncertainty
m_W (MeV)	$0.5-1$	$4\ (\alpha^3,\ \alpha^2\alpha_S)$	1
$\sin^2\theta_{\mathrm{eff}}^{\ell}\ (10^{-5})$	0.6	$4.5\ (\alpha^3,\ \alpha^2\alpha_S)$	1.5
Γ_Z (MeV)	0.1	$0.4\ (\alpha^3,\ \alpha^2\alpha_S,\ \alpha\alpha_s^2)$	0.15
$R_b\ (10^{-5})$	6	$11\ (\alpha^3,\ \alpha^2\alpha_S)$	5
$R_\ell\ (10^{-3})$	1	$6\ (\alpha^3,\ \alpha^2\alpha_S)$	1.5

- This requires not only N^{3}LO and leading N^{4}LO QED corrections – at least one order beyond the current state of art, but also respective MC generators



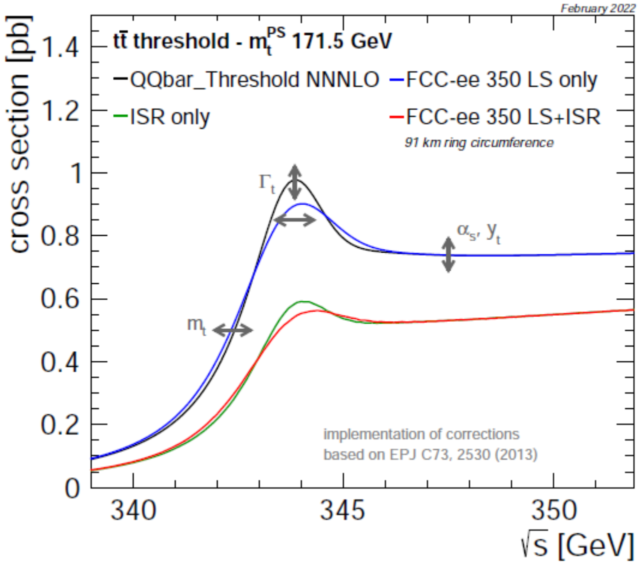


FCC-ee: physics opportunities

- **Top quark physics**
  - per mille precision for anomalous vector and percent precision for anomalous axial coupling

Working point	$t\bar{t}$	
$\sqrt{s}$ (GeV)	340-350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	0.95	1.55
Lumi/year (ab^{-1}, 2 IP)	0.2	0.34
Physics Goal (ab^{-1})	0.2	1.5
Run time (year)	1	4
Number of events	10^6 $t\bar{t}$ +200k HZ +50k WW $\rightarrow$ H	

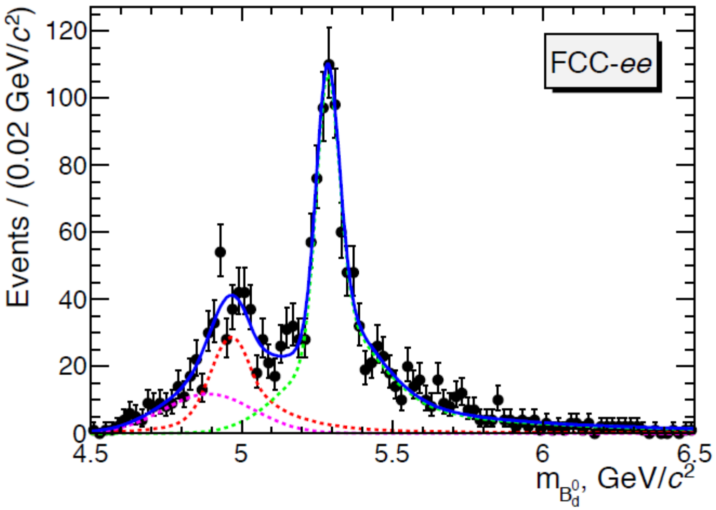
m_{top} (MeV/c^2)	172740 ± 500	20	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	40	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.08	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	<2%	small	From E_{CM} = 365GeV run



FCC-ee: physics opportunities

- **Flavour physics**
  - FCC-ee will be able to measure rare B-meson decays which are inaccessible at present

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	$\sim 2\,000$	~ 10	n/a (5)
LHCb Run I	150	-	~ 15 (–)
LHCb Upgrade	~ 5000	-	~ 500 (50)
FCC-ee	~ 200000	~ 1000	~ 1000 (100)

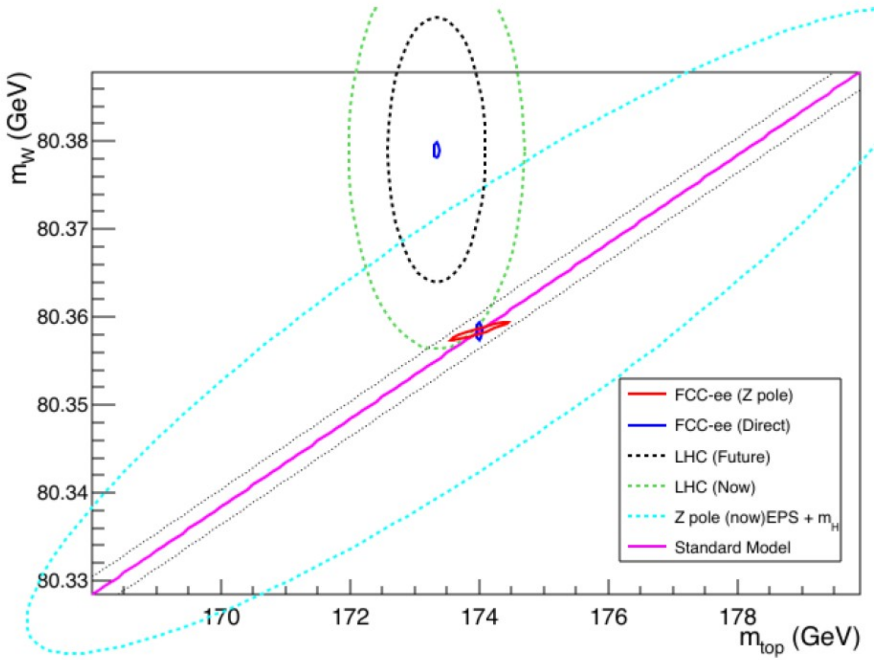


  - LVF in Z-decay will be probed down to 10^{-9}
  - CKM probes

Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-*ee*
CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	1.136 ± 0.004
$\|V_{ub}\|$ (precision)	5.9%	2.5%	6%	1%

FCC-ee: physics opportunities

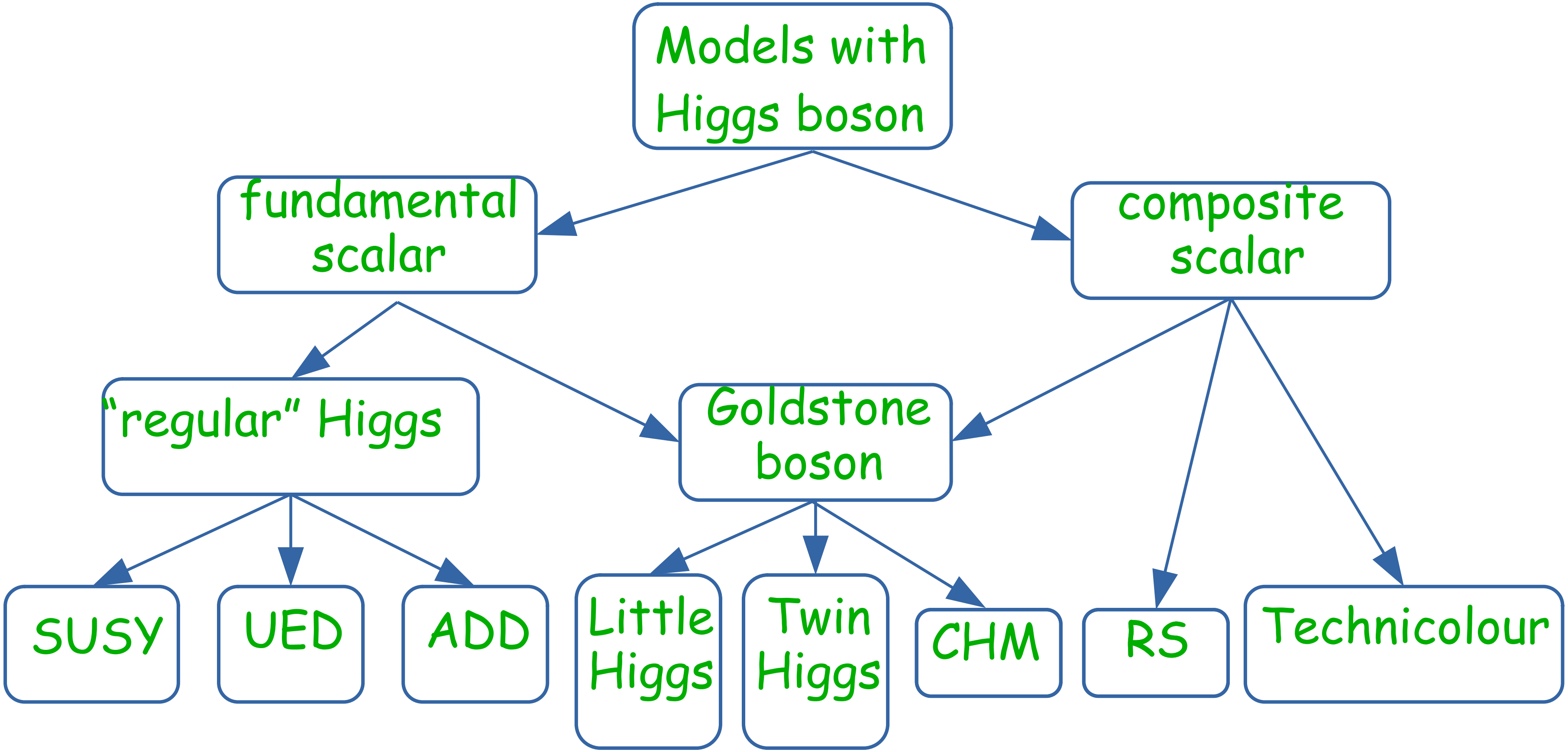
- **EW global fits**
  - m_W vs m_{top} plane



  - order of magnitude improvement – the story behind m_W will become transparent

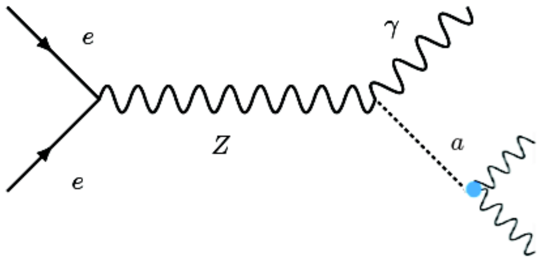
FCC-ee: prospects for direct test of new physics

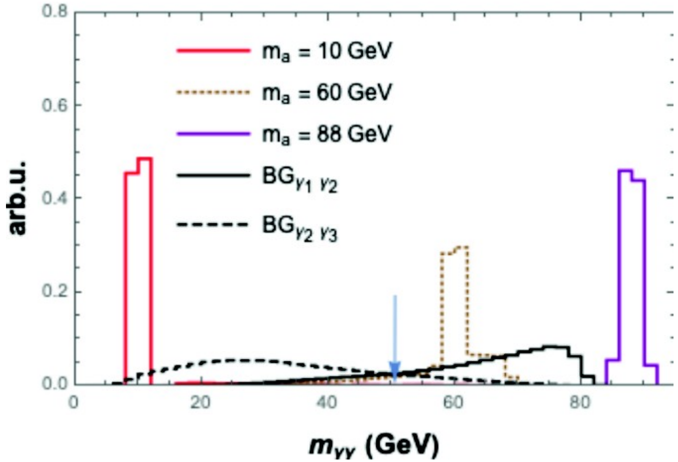
- **The new physics scale can be quite low, at least for some particles**

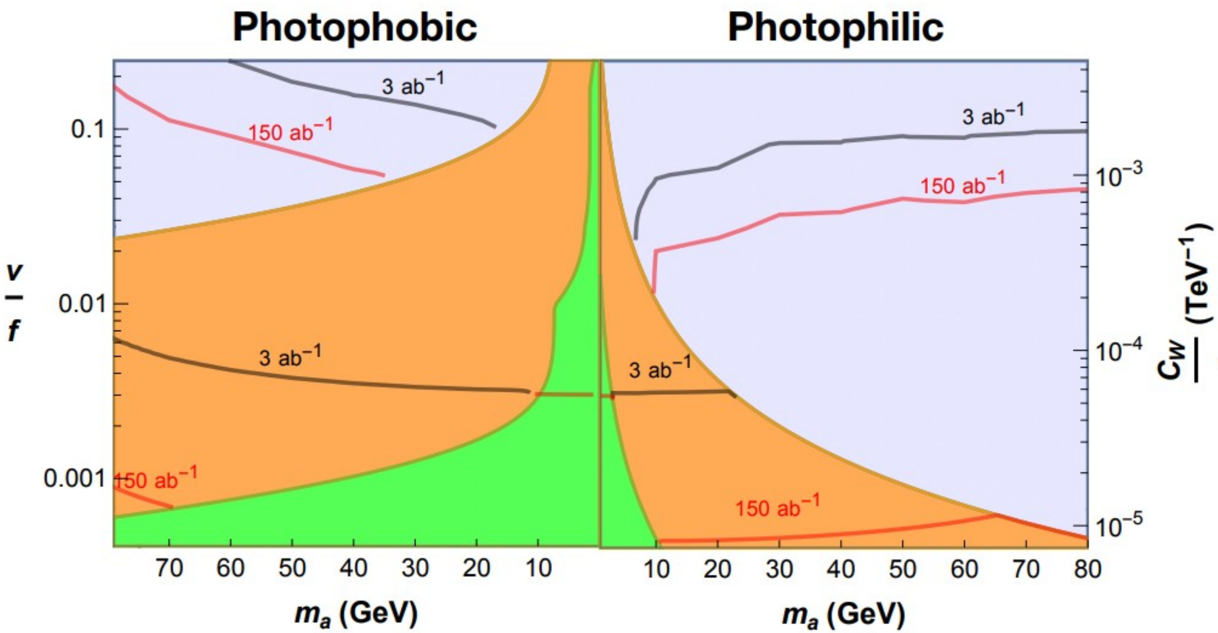


FCC-ee: prospects for direct test of new physics

- **In particular in models with partial Higgs compositeness, there could be light pseudo scalars**
- 1312.5330, 1610.06591
- 2104.11064 Cacciapaglia, Deandrea, Iyer, Sridhar

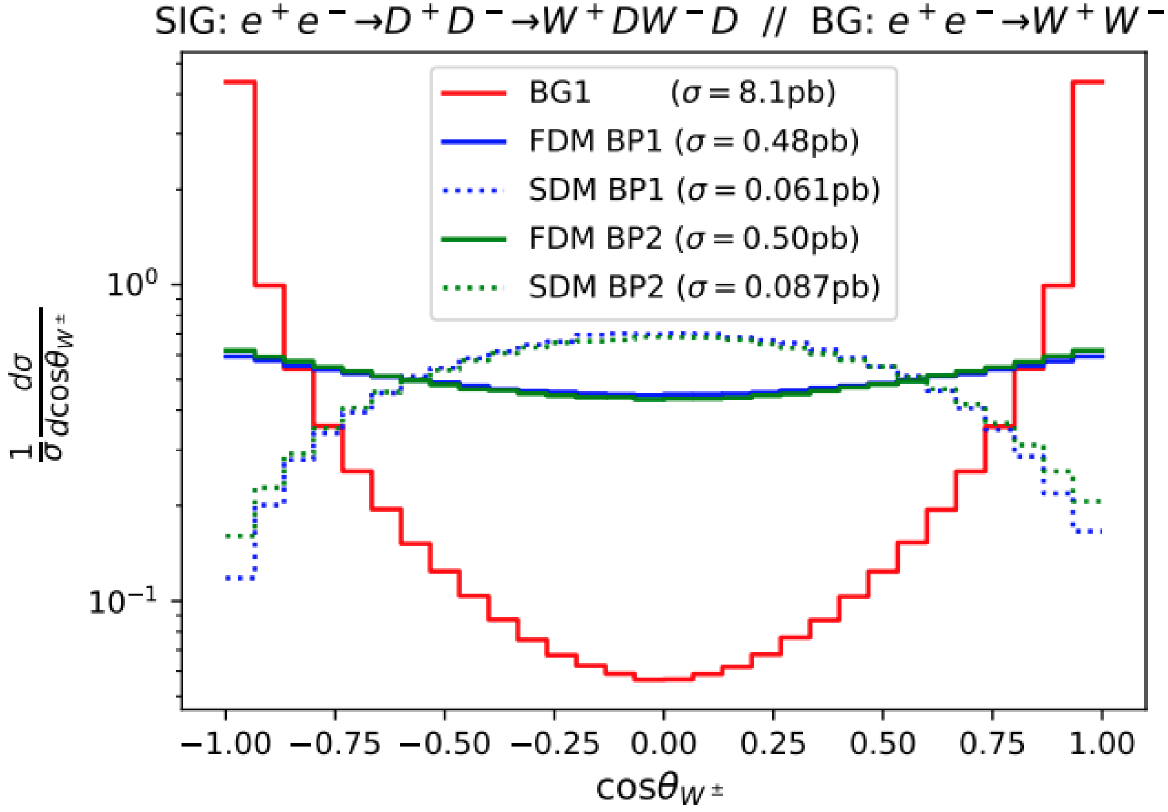






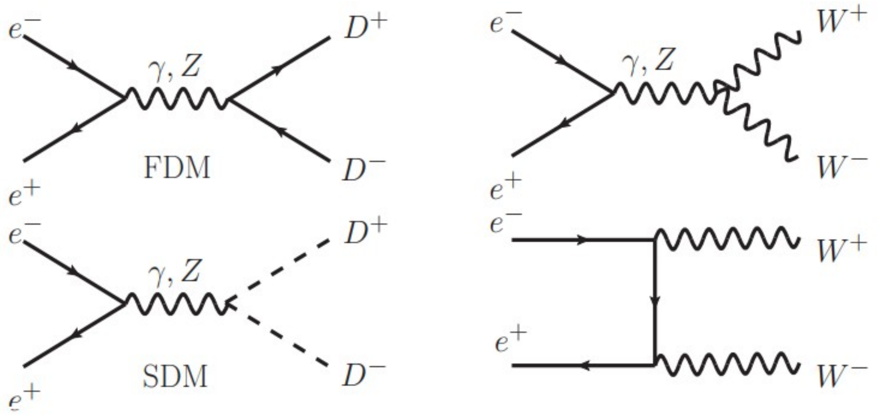
FCC-ee: prospects for direct test of new physics

- **Light Dark Matter case (~ 100-160 GeV)**



AB, Ginzburg, Locke, Freegard, Pukhov arXiv:**2112.15090**

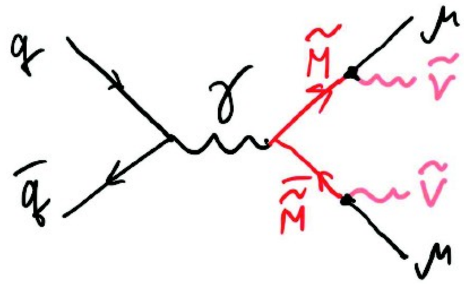
$$\frac{d\sigma}{d\cos\theta_{D^\pm}} \propto \begin{cases} 1 - \cos^2\theta_{D^\pm}, & \text{for SDM} \\ 1 + \frac{s - 4M_+^2}{s + 4M_+^2}\cos^2\theta_{D^\pm} & \text{for FDM} \end{cases}$$



- The angular W-boson distribution (either for real or virtual W) is found to be very important discriminator between DM spin as well as the main BG
- The shape of angular W-boson distribution is the same for two benchmarks for DM of the same spin

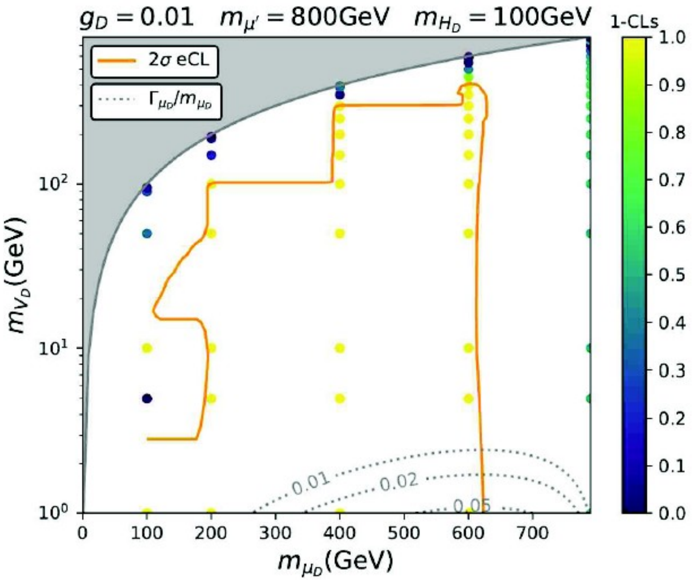
FCC-ee: prospects for direct test of new physics

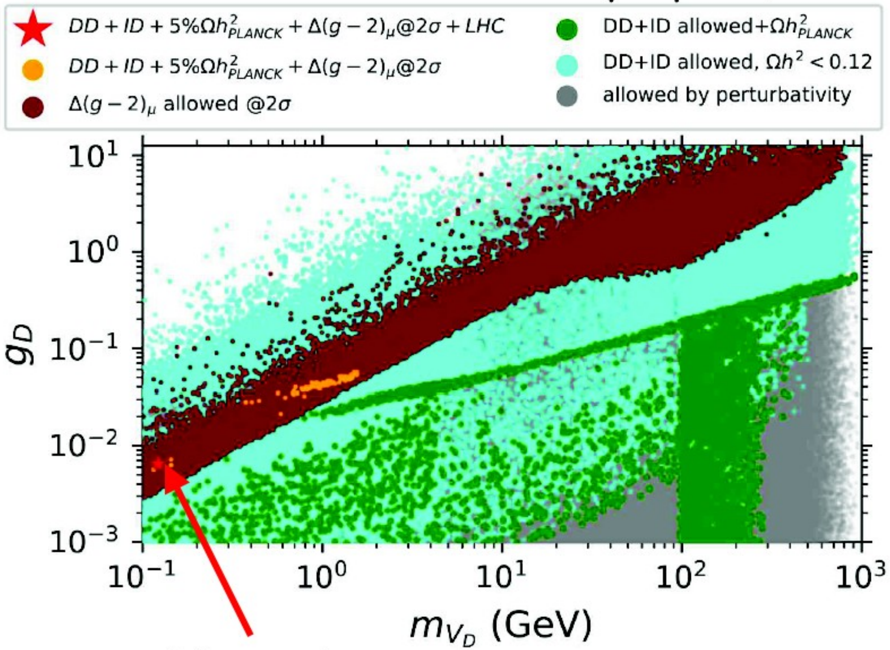
- **Sub-GeV vector DM: Vector-like fermion portat to dark SU(2)** (AB, Panizzi, Thonguoi, work in progress)



$$pp \to \tilde{M}^- \tilde{M}^+ \to \tilde{V}_D \tilde{V}_D \mu^+ \mu^-$$

- Madgraph + PTHIA+Delphes + Madanalysis
- $\tilde{M} > 600$ GeV comes from the main $\mu^+ \mu^- + MET$





- surviving region
- Δaμ parameter space is further constrained

Summary

- FCC-ee could the first machine coming after the LHC
  - It is unique collider, which provides incredible opportunities which come with challenges for theory and experiment
  - We should seriously consider FCC-ee not only as a precision collider, but also as a discovery machine

- New signals are likely to appear, at least we strongly feel that it is around the corner
  - From my point of view what is missing now is the strategy of mapping of the signal space into the space of concrete models (not only EFT's!)
  - This reverse engineering program should be taken very seriously