FUTURE CIRCULAR COLLIDER STUDY

FCC-ee PROJECT

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On behalf of the FCC Collider Study Group

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DISCOVERY MACHINE AND MORE

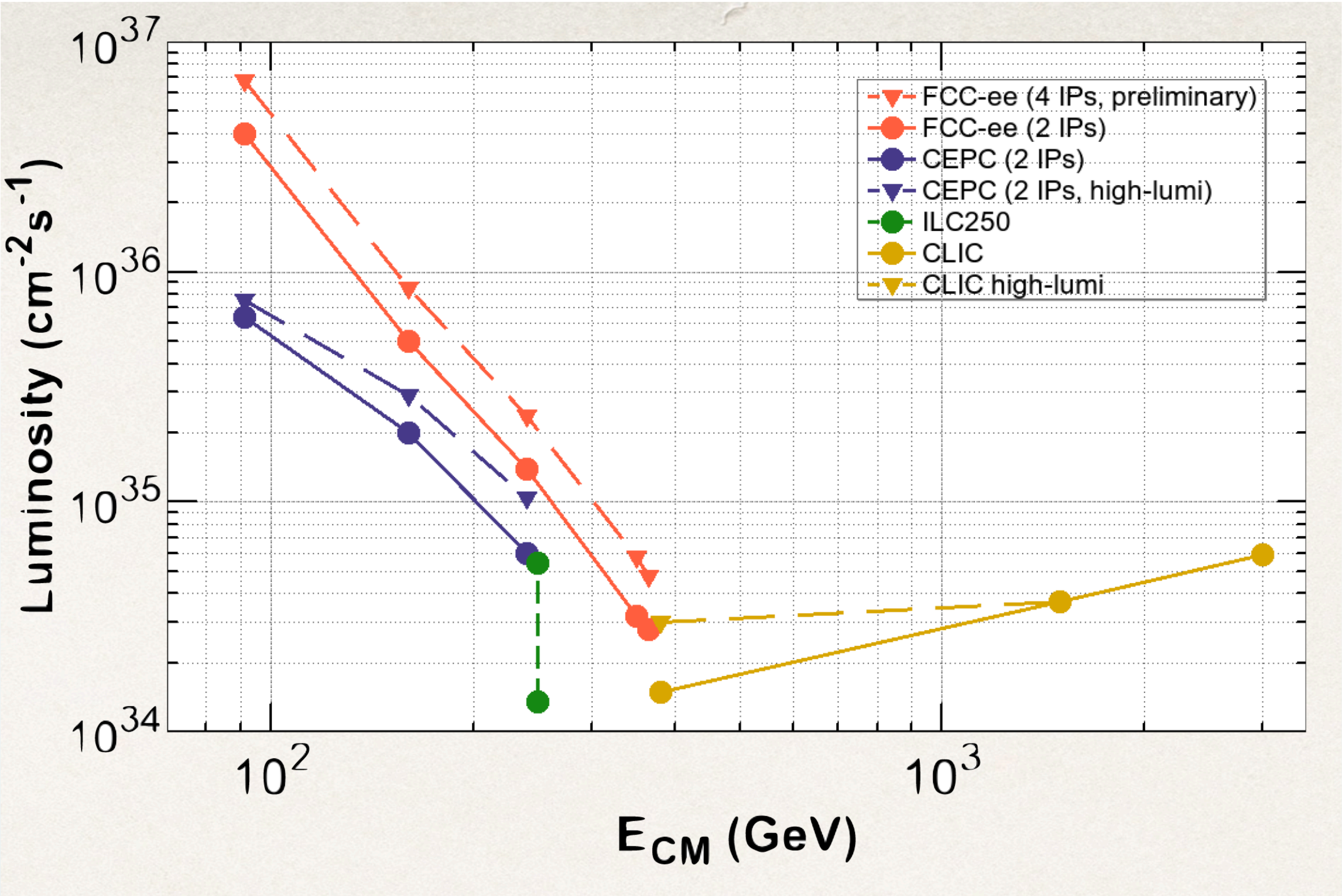
- **EXPLORE** the 10-100 TeV energy scale region with precision measurements of the properties of the Z,W,Higss and top particles
  - 20-50fold improved precision on EWK observables
  - 10 fold more precise and model-independent Higgs coupling measurements
- **DISCOVER** that the Standard Model does not fit
  - Existence of extra-weakly-coupled and Higgs-coupled particles
  - Understanding of the underlying physics structure
- **DISCOVER** a violation of flavour conservation/universality
- **DISCOVER** very weakly coupled particles in the 5-100 GeV mass range
  - Such as right handed neutrinos, dark photons, …
- **DISCOVER** dark matter as invisible decays of the Z or Higgs

PHYSICS DRIVEN NEEDS

- 100 ab^{-1} at the Z pole ($\sqrt{s}$=91.2 GeV,)
- 30 ab^{-1} around the Z pole ($\sqrt{s}$=88 and 94 GeV)
- 10 ab^{-1} around the WW threshold ($\sqrt{s}$~161 GeV)
- 5 ab^{-1} at the HZ cross section max. ($\sqrt{s}$=240 GeV)
- 0.2 ab^{-1} around the top threshold ($\sqrt{s}$=350 GeV)
- 1.5 ab^{-1} above the top threshold ($\sqrt{s}$~365 GeV)

The FCC-ee unique discovery potential is multiplied by the presence of the four heaviest particles of the standard model in its energy range

The FCC-ee measurements help shape up the FCC-hh program and detectors



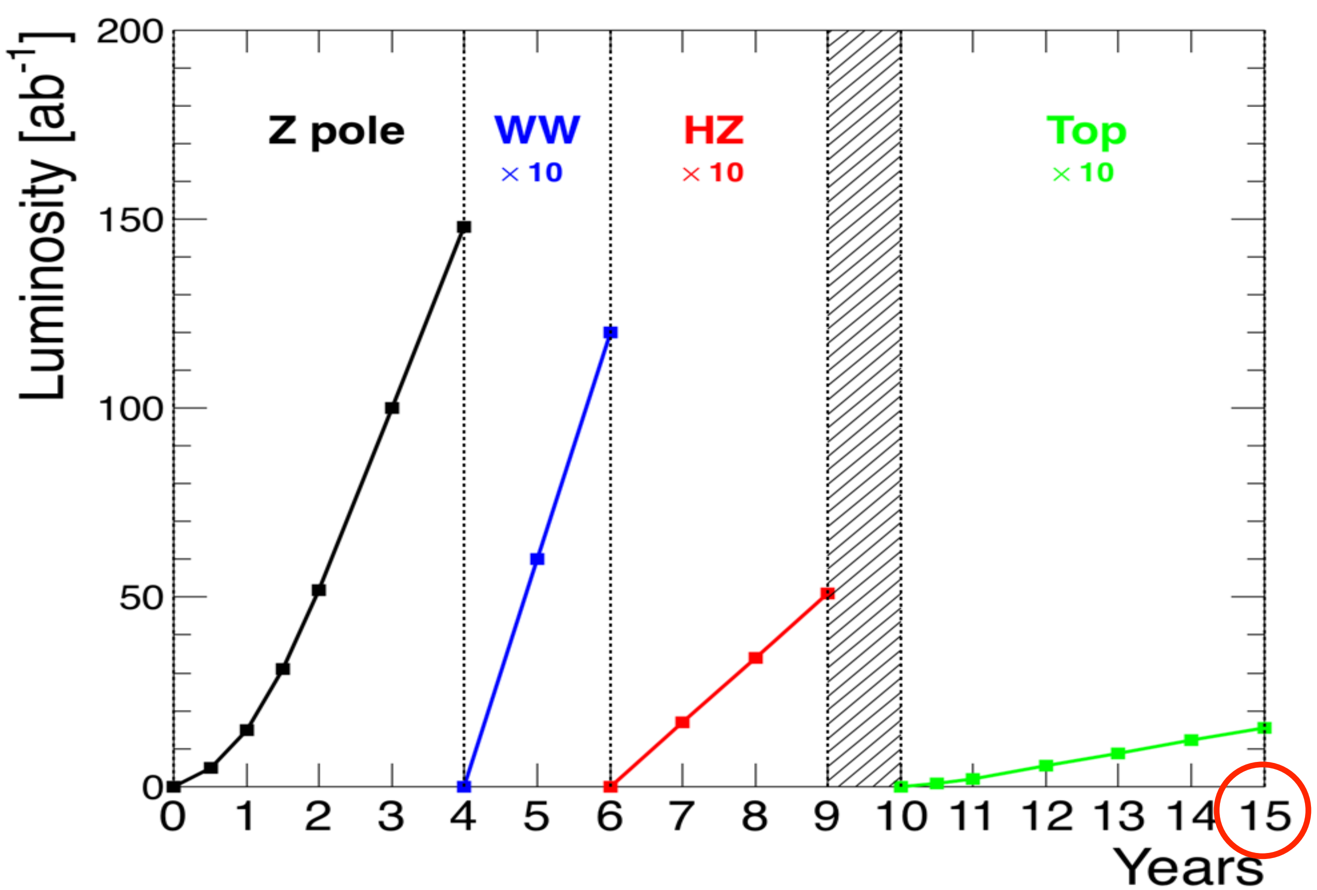
- High integrated luminosity at the needed E_{cm}
- Clean e^+e^- environment
- Precise knowledge of the center-of-mass energy and of the luminosity
- Precise detectors to be designed offering plenty of redundancy (and more than one)

OPERATION MODEL AND STATISTICS

- 185 physics days / year, 75% efficiency, 10% margin on luminosity

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold…	… and above
√s (GeV)	88, 91, 94		157, 163	240	340 – 350	365
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	100	200	25	7	0.8	1.4
Lumi/year (2 IP)	24 ab^{-1}	48 ab^{-1}	6 ab^{-1}	1.7 ab^{-1}	0.2 ab^{-1}	0.34 ab^{-1}
Physics goal	150 ab^{-1}		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4

Total : 15 years



Event statistics

5×10^{12} $e^+e^- \to Z$
10^8 $e^+e^- \to W^+W^-$
10^6 $e^+e^- \to HZ$
10^6 $e^+e^- \to t\bar{t}$

√s precision

100 keV
300 keV
2 MeV
5 MeV

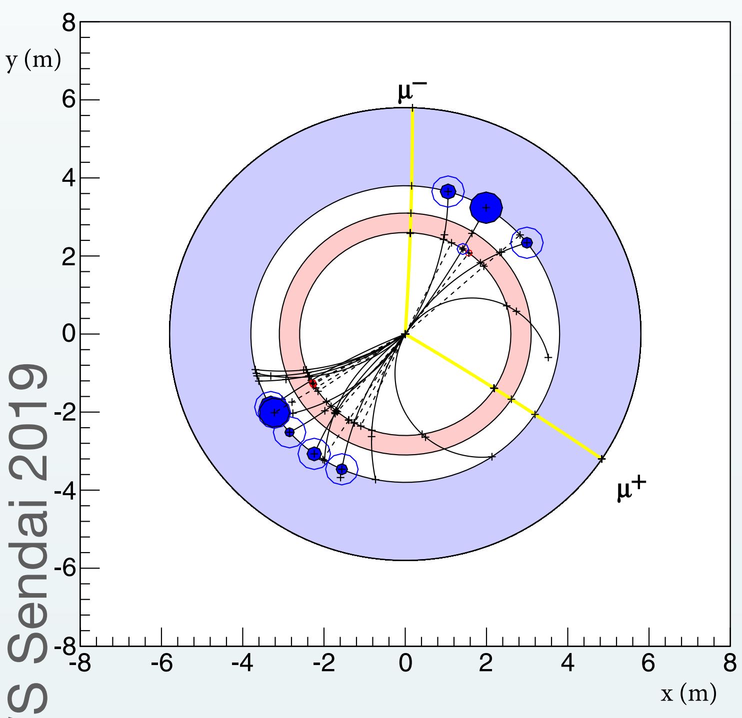
Transverse polarization (E_{beam} calib.),
No longitudinal polarization.

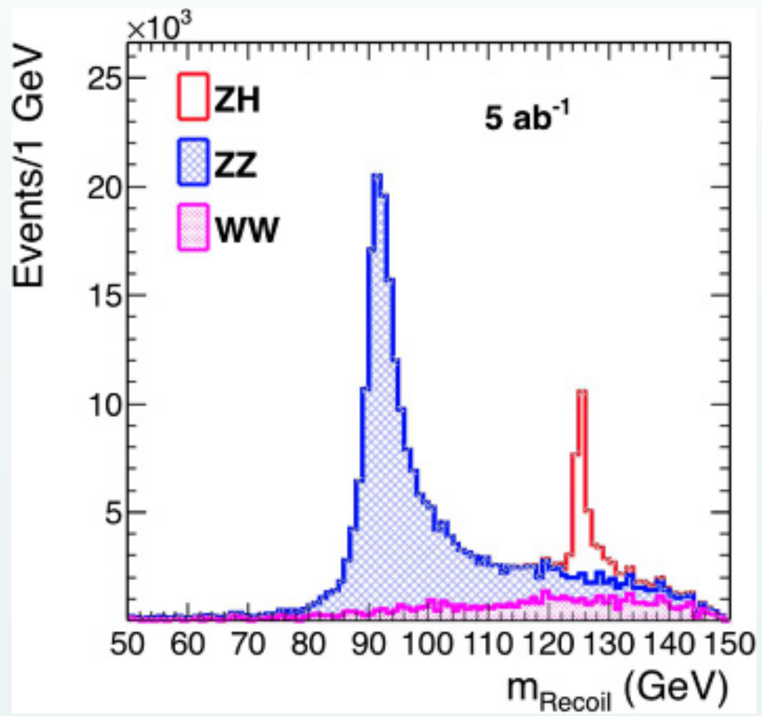
HIGGS STUDIES

➤ Ultimate precision on Higgs couplings below 1% (and measurement of the total width) a milestone of the FCC physics program.

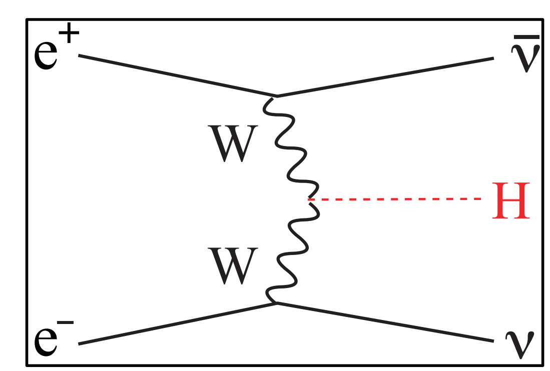
$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
H $\rightarrow$ any	± 0.5		± 0.9	
H $\rightarrow$ $b\bar{b}$	± 0.3	± 3.1	± 0.5	± 0.9
H $\rightarrow$ $c\bar{c}$	± 2.2		± 6.5	± 10
H $\rightarrow$ gg	± 1.9		± 3.5	± 4.5
H $\rightarrow$ W^+W^-	± 1.2		± 2.6	± 3.0
H $\rightarrow$ ZZ	± 4.4		± 12	± 10
H $\rightarrow$ $\tau\tau$	± 0.9		± 1.8	± 8
H $\rightarrow$ $\gamma\gamma$	± 9.0		± 18	± 22
H $\rightarrow$ $\mu^+\mu^-$	± 19		± 40	
H $\rightarrow$ invisible	<0.3		<0.6	

Statistical precision with 2IPs





- **Added value from WW fusion (mostly at 350-365 GeV)**
  - **H$\nu\nu$ → bb$\nu\nu$ final state, rate $R_2 \propto g_{HWW}^2\, g_{Hbb}^2 / \Gamma_H$**
    - **bb$\nu\nu$ / (Zbb × ZWW) $\propto g_{HZZ}^4 / \Gamma_H$** → **$\Gamma_H$ to ~1 %**
  - **H$\nu\nu$ → WW$\nu\nu$ final state, rate $R_1 \propto g_{HWW}^4 / \Gamma_H$** → **$g_{HWW}$ to a few per mil**

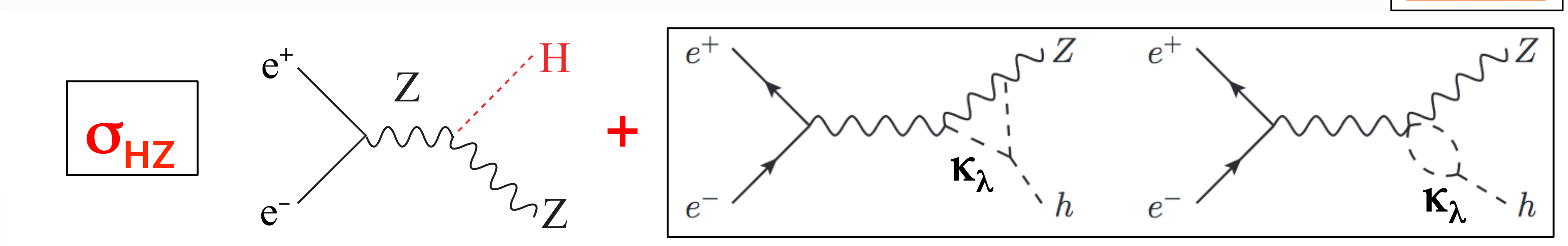


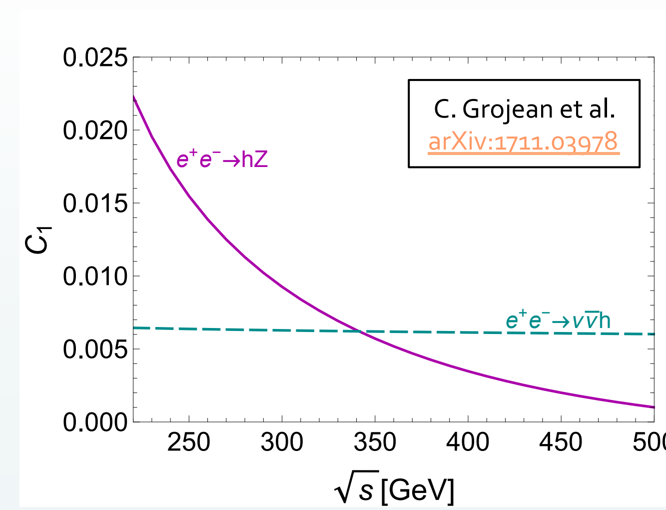
➤ Model independent determination of the total Higgs decay width at 1.3% at √s=240 and 365.

HIGGS SELF-COUPLING

- Traditionally k_λ measured in double Higgs production at higher energies. FCC-ee can profit of the significant effect on single Higgs production

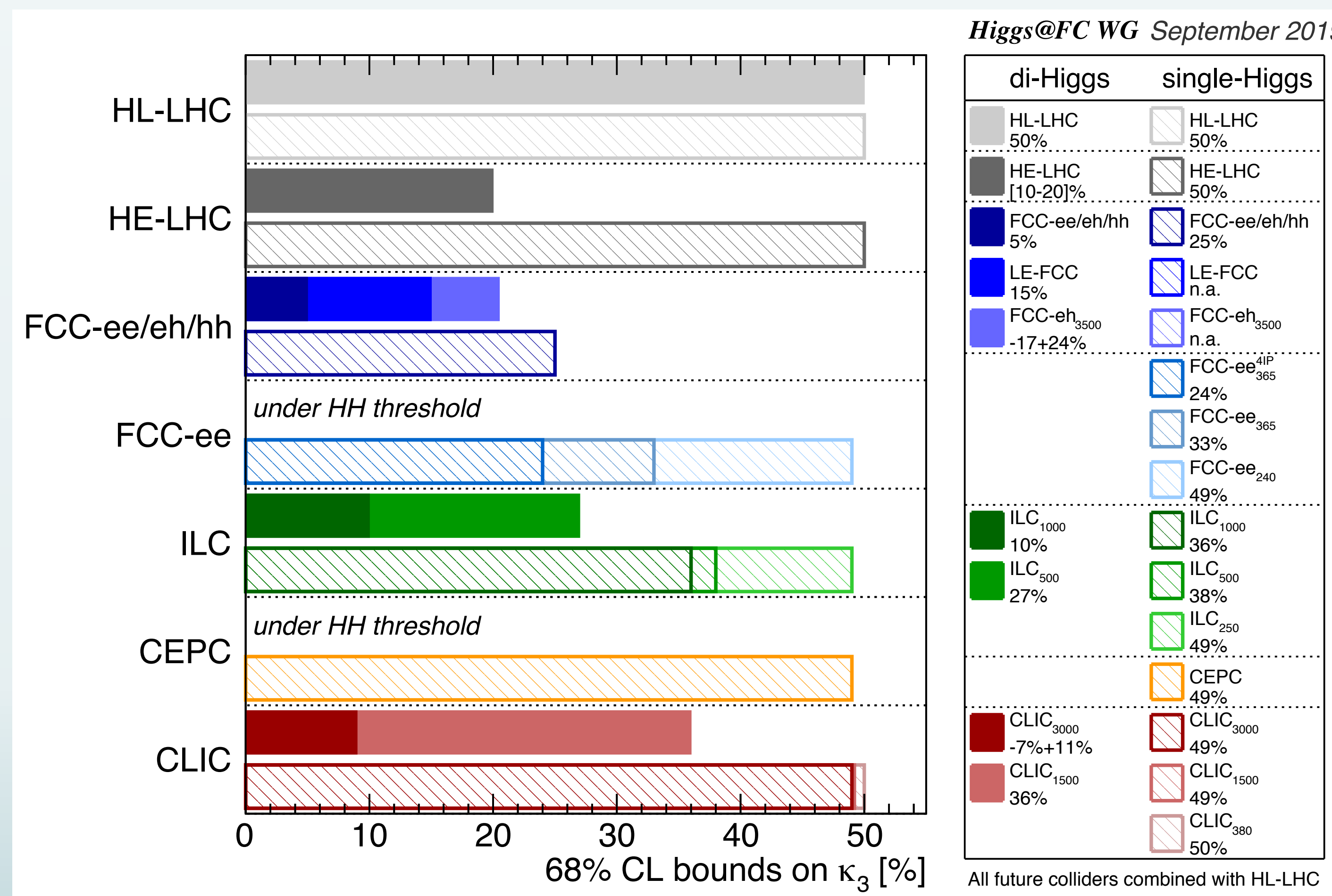
M. McCullough
arXiv:1312.3322





- Plus measurements at different $\sqrt{s}$ also help to lift degeneracy between processes in the fit

Precision on k_λ	
FCC-ee	33%
FCC-ee(4IP)	24%
FCC(ee+hh)	5%



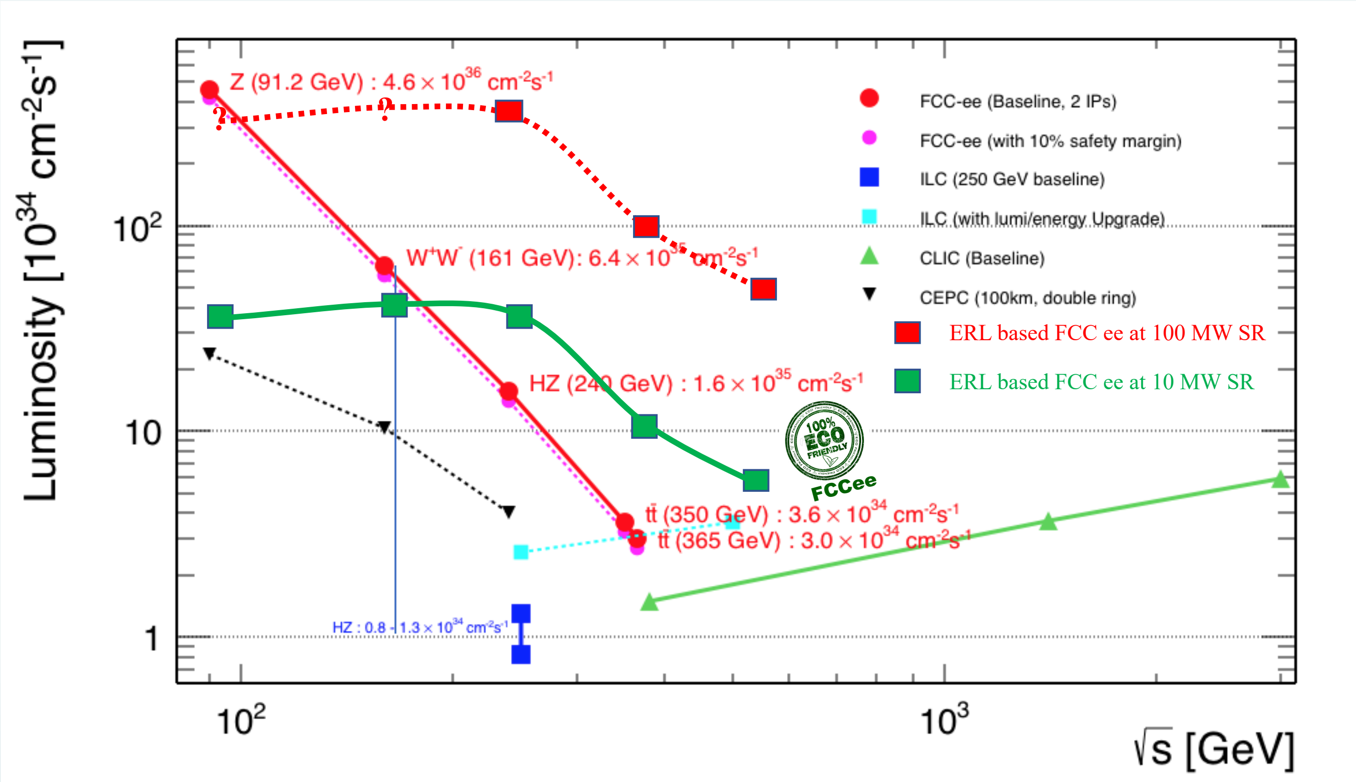
https://arxiv.org/pdf/1905.03764.pdf

AN INTERESTING IDEA: FCC-ERL

https://arxiv.org/abs/1909.04437

- The FCC baseline strategy to access the HH production is to replace electron/positrons with protons fat 100 TeV (FCC-hh). However, the project is still open to the influence of technological developments.
- If scientifically needed, and as an intermediate step, it could be imagined to upgrade the FCCee with Energy Recovery Linac technology and run at 500 GeV or more with a luminosity $4.5(45)\times10^{34}$ $cm^{-2}s^{-1}$ 10(100) MW of synchrotron radiation power.
  - Corresponding to 5-50 ab^{-1} in 10 years
  - This might allow a statistical precision on the Higgs self coupling of about 10%

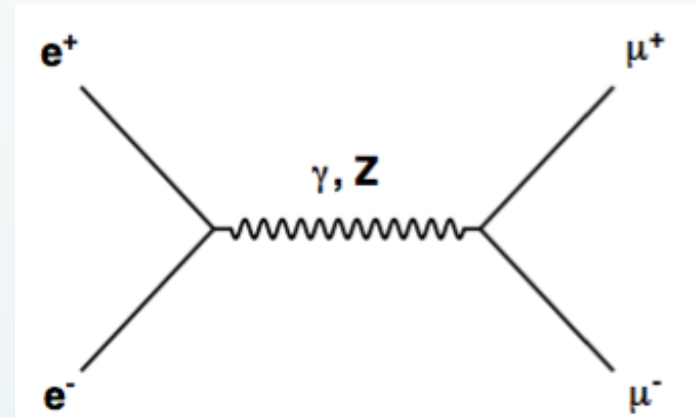
Of course this is just a sketch for now. Realistic, in-depth studies are needed. Plan to include them in the TDRs

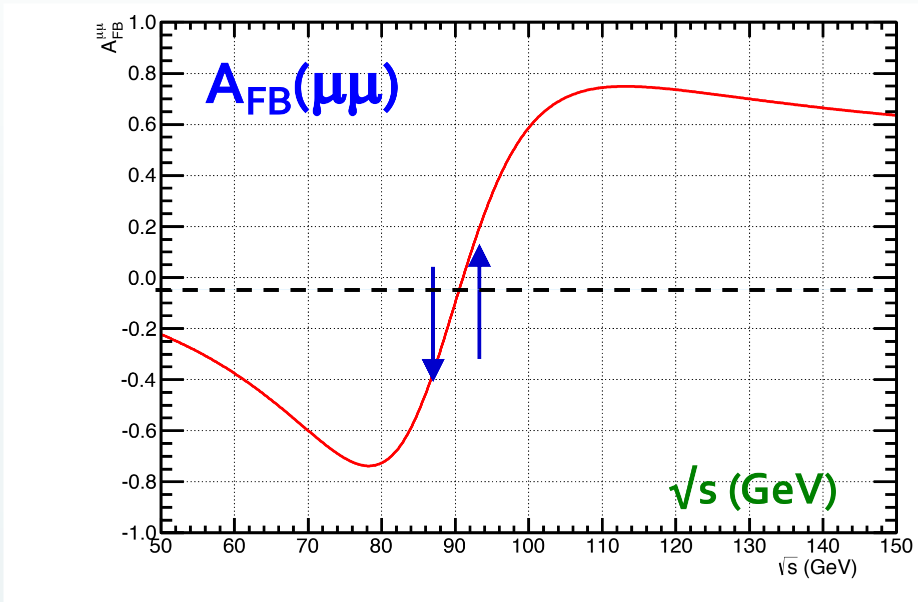


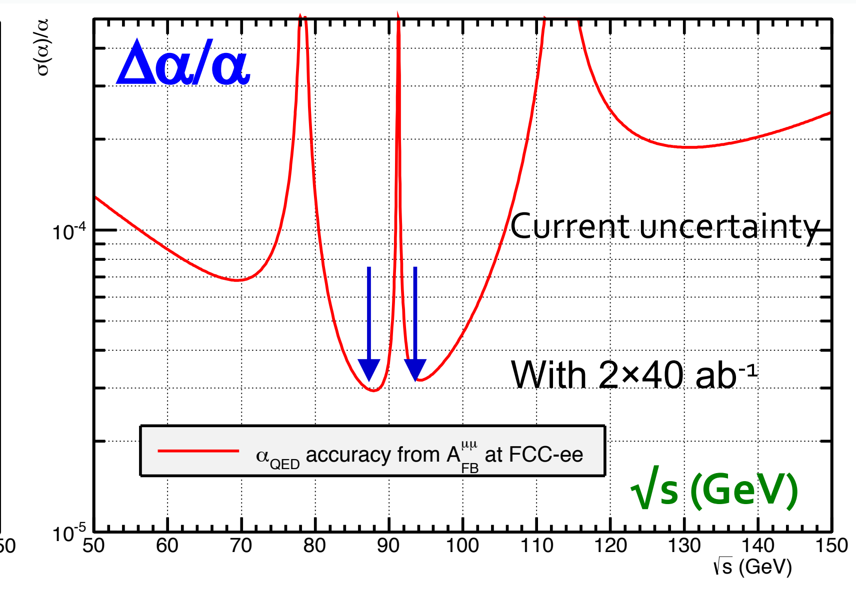
ELECTROWEAK PRECISION MEASUREMENTS

- Boils down to measuring cross sections and asymmetries
  - The dominant experimental uncertainties come from the beam energy knowledge
  - Detailed studies in new paper: **ArXiv:1909.12245v1 A.Blondel et al.**

$e^+e^- \rightarrow \mu^+\mu^-$







TeraZ (5×10^{12} Z)

From data collected in a lineshape energy scan:

- Z mass (key for jump in precision for ewk fits)
- Z width (jump in sensitivity to ewk rad corr)
- R_l = hadronic/leptonic width ($\alpha_s(m^2_Z)$, lepton couplings, precise universality test)
- peak cross section (invisible width, N_ν)
- $A_{FB}(\mu\mu)$ ($\sin^2\theta_{eff}$, $\alpha_{QED}(m_Z^2)$, lepton couplings)
- Tau polarization ($\sin^2\theta_{eff}$, lepton couplings, $\alpha_{QED}(m_Z^2)$)
- R_b, R_c, $A_{FB}(bb)$, $A_{FB}(cc)$ (quark couplings)

OkuWW (10^8 WW)

From data collected around and above the WW threshold:

- W mass (key for jump in precision for ewk fits)
- W width (first precise direct meas)
- $R^W = \Gamma_{had}/\Gamma_{lept}$ ($\alpha_s(m^2_Z)$)
- Γ_e , Γ_μ , Γ_τ (precise universality test)
- Triple and Quartic Gauge couplings (jump in precision, especially for charged couplings)

SELECTED ELECTROWEAK QUANTITIES

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	8	100	From Z line shape 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 leptons
α_s (m_Z) $(\times 10^4)$	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above [43]
R_b $(\times 10^6)$	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]
σ^0_{had} $(\times 10^3)$ (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν $(\times 10^3)$	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$ $(\times 10^6)$	$231,480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) $(\times 10^3)$	$128,952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak [34]
$A_{FB}^{b,0}$ $(\times 10^4)$	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV)	$80,350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
α_s (m_W) $(\times 10^4)$	1170 ± 420	3	Small	From R_ℓ^W [45]
N_ν $(\times 10^3)$	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	$172,740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{CM} = 365$ GeV run

In this context would need from theory full 3-loop calculations for the Z pole and propagator EWK corrections and probably 2-loop for EWK corrections to the WW cross section. Matching these experimental precisions motivates a significant theoretical effort.

NEUTRAL COUPLINGS AND EWK ANGLE

$$\mathcal{A}_e = \frac{2 g_{Ve} g_{Ae}}{(g_{Ve})^2 + (g_{Ae})^2} = \frac{2 g_{Ve}/g_{Ae}}{1 + (g_{Ve}/g_{Ae})^2}$$

- Muon forward backward asymmetry at pole, $A_{FB}^{\mu\mu}$ (m_Z) gives $\sin^2\theta_{eff}$ with 5 10^{-6} precision (at least)
  - **uncertainty driven by knowledge on CM energy (**point to point energy errors **)**
  - **assumes muon-electron universality**
- **Tau polarization can reach similar precision without universality assumption**
  - tau pol measures A_e and A_τ, can input to **$A_{FB}^{\mu\mu} = 3/4\, A_e\, A_\mu$** to measure separately electron, muon and tau couplings, (together with Γ_e, Γ_μ, Γ_τ)
- Asymmetries A_{FB}^{bb}, A_{FB}^{cc} provide input to quark couplings together with Γ_b, Γ_c

➤ **Tau polarization has a central role at FCC-ee**

➤ Very large tau statistics and improved knowledge of parameters (BF, decay modeling).

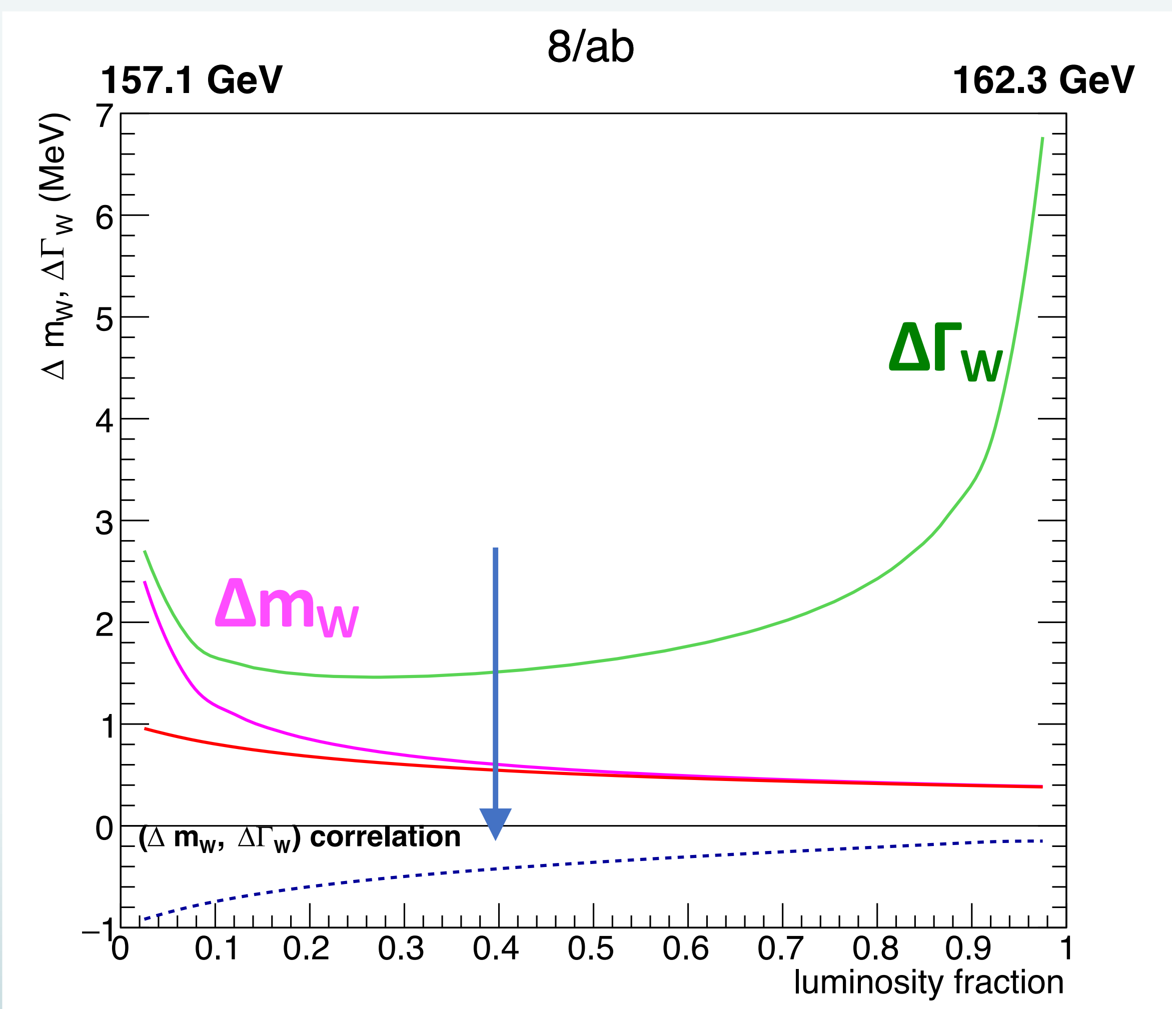
➤ Also use best decay channels, $\tau \rightarrow \rho\nu_\tau$. Constraint on detector performance for γ/π^0

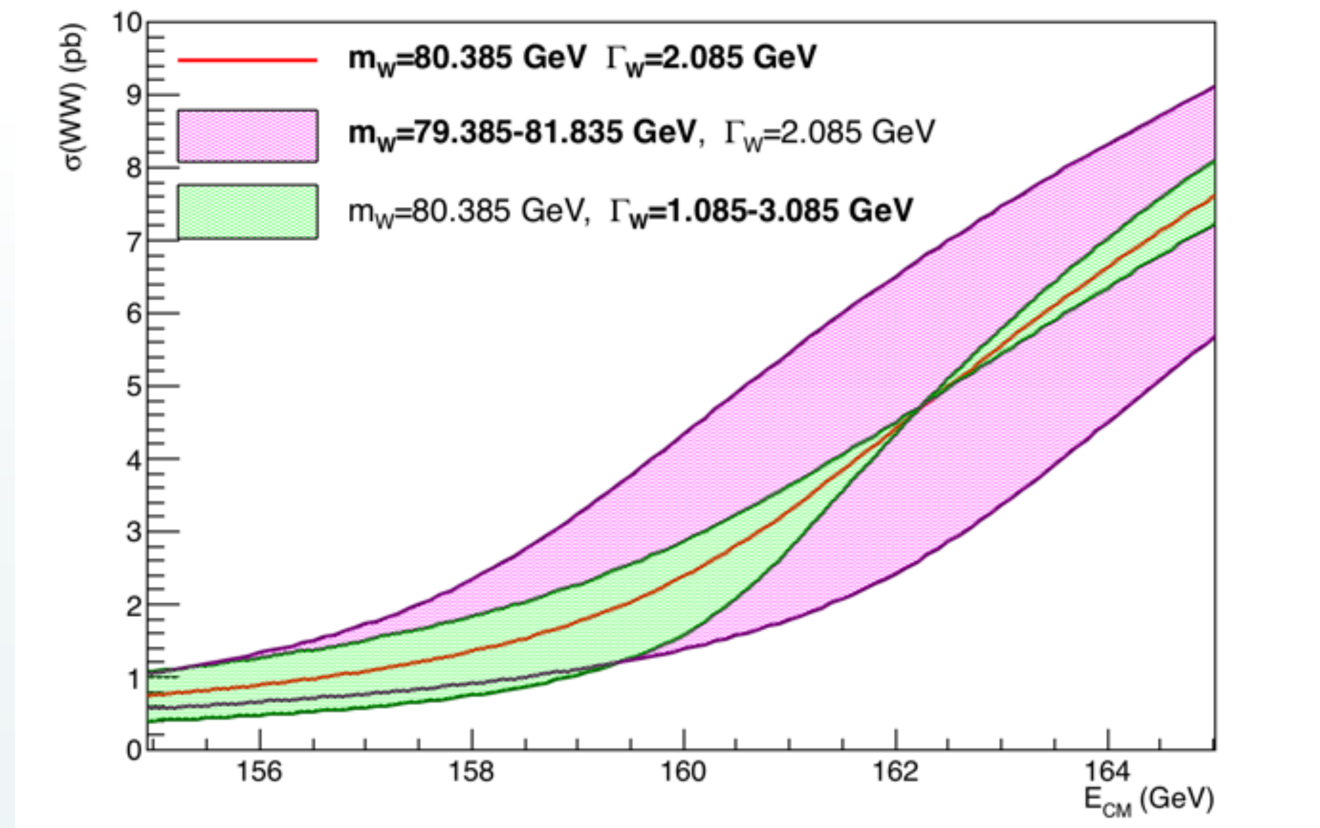
➤ **Measure $\sin^2\theta_{eff}$ with $6.6\mathrm{x}10^{-6}$ precision**

W MASS AND WIDTH

Sensitivity to mass and width is different at different E_{CM}: can optimize mass AND width by choosing carefully two energy points.

- Same concept can be used to minimize systematics (e.g. due to backgrounds)
- Centre-of-mass known by resonant depolarization (available at ≈ 160 GeV)
- Luminosity from Bhabha, requirements similar to Z pole case



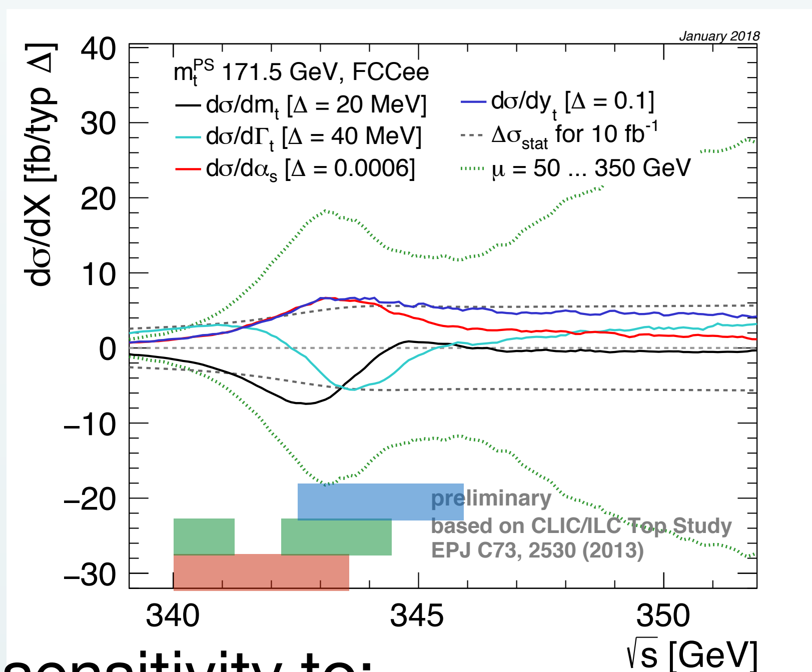


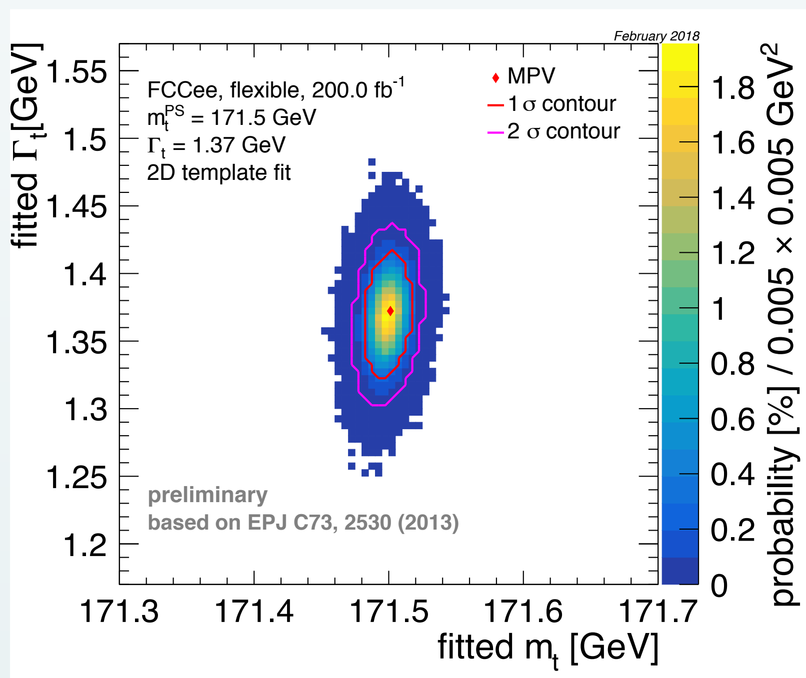
with E_1=**157.1** GeV E_2=**162.3** GeV f=**0.4**
Δm_W=0.62 $\Delta\Gamma_W$=1.5 (MeV)

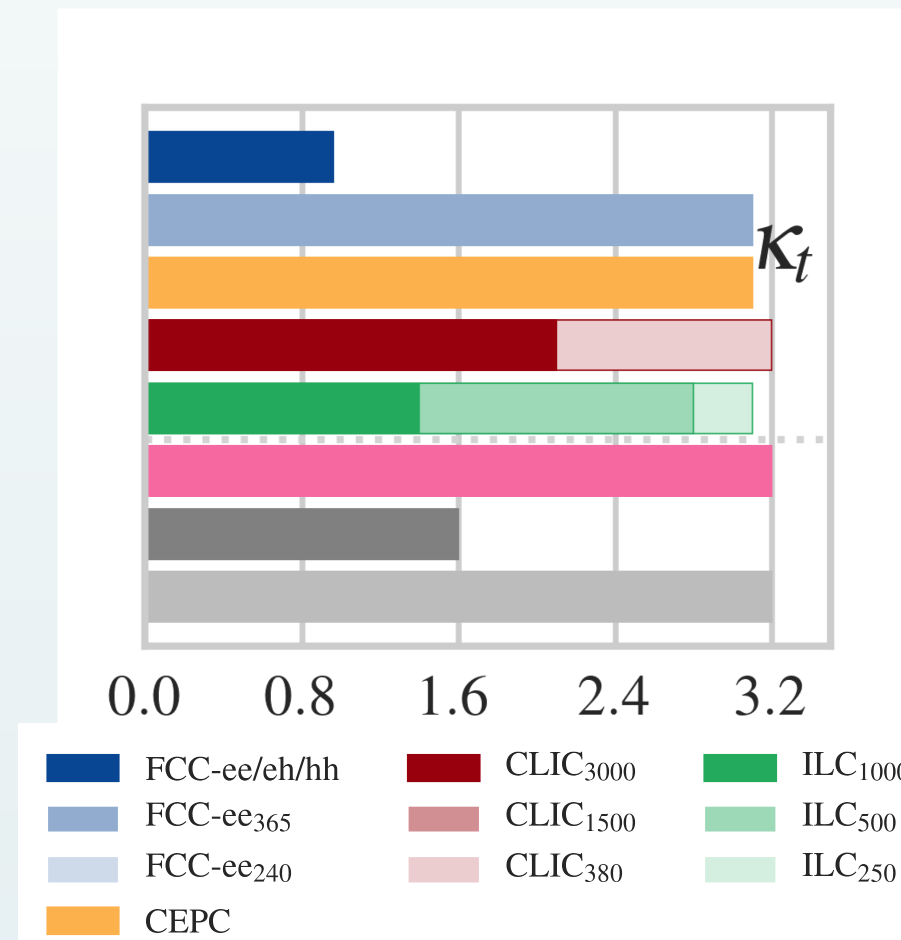
need syst control on :

- **ΔE(beam)<0.35 MeV (4×10^{-6})**
- **$\Delta\varepsilon/\varepsilon$, $\Delta L/L < 2\ 10^{-4}$**
- **$\Delta\sigma_B$<0.7 fb ($2\ 10^{-3}$)**

- Threshold region allows most precise measurements of top mass, width, and estimate of Yukawa coupling. Scan strategy can be optimized
  - FCC-ee has some standalone sensitivity to the top Yukawa coupling from the measurements at thresholds for a 10% precision (profiting of the better α_S).
    - But, HL-LHC result of about 3.1% already better (with FCC-ee Higgs measurements removing the model dependence)







sensitivity to:
- mass
- width
- Yukawa

- Mass only: **8.8 MeV** (stat), **5.4 MeV** (α_s [2 x 10^{-4}]), **44 MeV** (theo)

- Run at 365 GeV used also for measurements of top EWK couplings (at the level of 10^{-2}-10^{-3}) and FCNC in the top sector.

TERA-Z - FLAVOR PHYSICS (1)

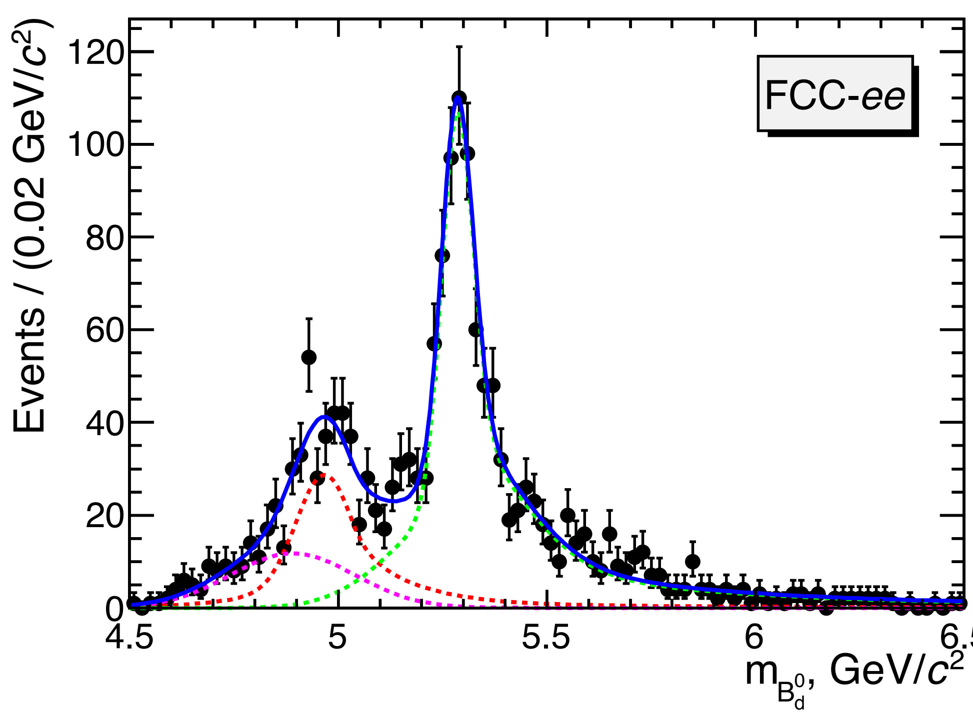
Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0	B^-	B^0_s	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

~15 times Belle's stat

Boost at the Z!

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	~ 2 000	~ 10	n/a (5)
LHCb Run I	150	-	~ 15 (–)
LHCb Upgrade	~ 5000	-	~ 500 (50)
FCC-ee	~ 200000	~ 1000	~1000 (100)



Yelds for flavor anomalies studies:

b→sll yelds and $B^0 \to K^{*0}\tau^+\tau^-$

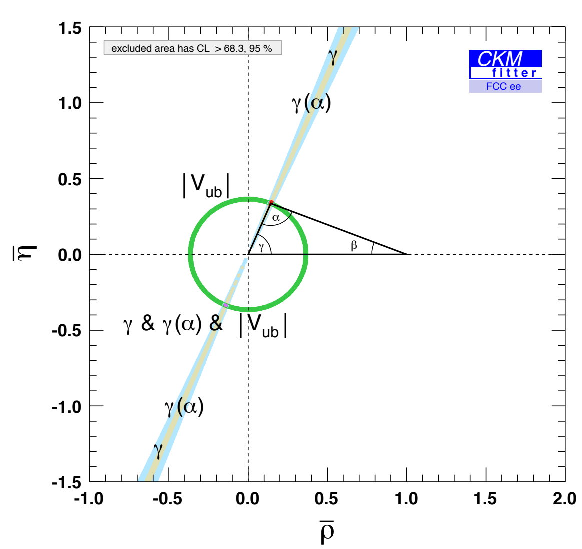
👍 Full reconstruction possible

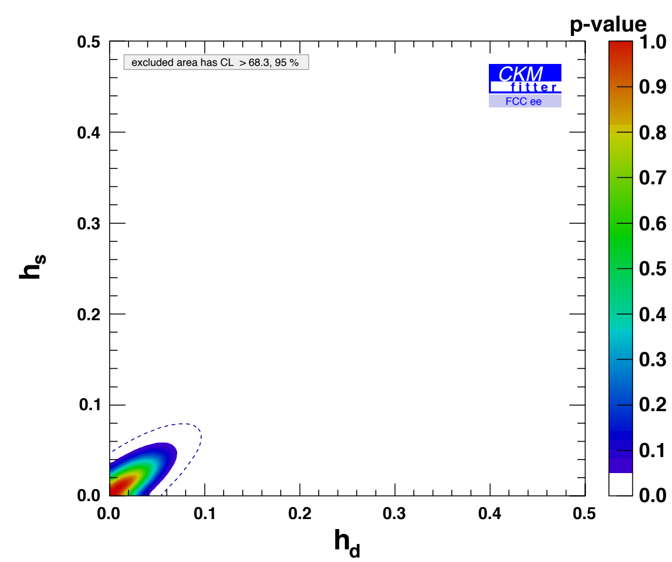
TERA-Z - FLAVOR PHYSICS(2)

CKM and CP-violation in quark mixings

- Expected precisions scaled with statistics and anticipated flavour tagging performance when necessary.
- First observation of *CP* violation in *B* mixing is at reach.
- A global analysis of BSM contributions in box mixing processes, assuming *Minimal Flavour Violation* pushes the BSM energy scale to 20 TeV.

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
$\lvert V_{ub}\rvert$ (precision)	5.9%	2.5%	6%	1%
Mixing-related inputs				
$\sin(2\beta)$	0.691 ± 0.017	0.691 ± 0.008	0.691 ± 0.009	0.691 ± 0.005
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	n/a	-3.65 ± 0.05	-3.65 ± 0.01
Δm_d (ps^{-1})	0.5065 ± 0.0020	same	same	same
Δm_s (ps^{-1})	17.757 ± 0.021	same	same	same
$a^d_{\rm fs}$ (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	-7 ± 2
$a^s_{\rm fs}$ (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	0.3 ± 2





global analysis

Bottomline: the constraints on BSM scale issued from *B*-mesons mixing observables with Minimal Flavour Violation $\Lambda_{\rm NP}(\Delta F = 2) > 20\ {\rm TeV}$

TERA-Z - TAU PHYSICS

Visible Z decays	3×10^{12}
$Z \rightarrow \tau^+\tau^-$	1.3×10^{11}
1 vs. 3 prongs	3.2×10^{10}
3 vs. 3 prong	2.8×10^{9}
1 vs. 5 prong	2.1×10^{8}
1 vs. 7 prong	< 67,000
1 vs 9 prong	?

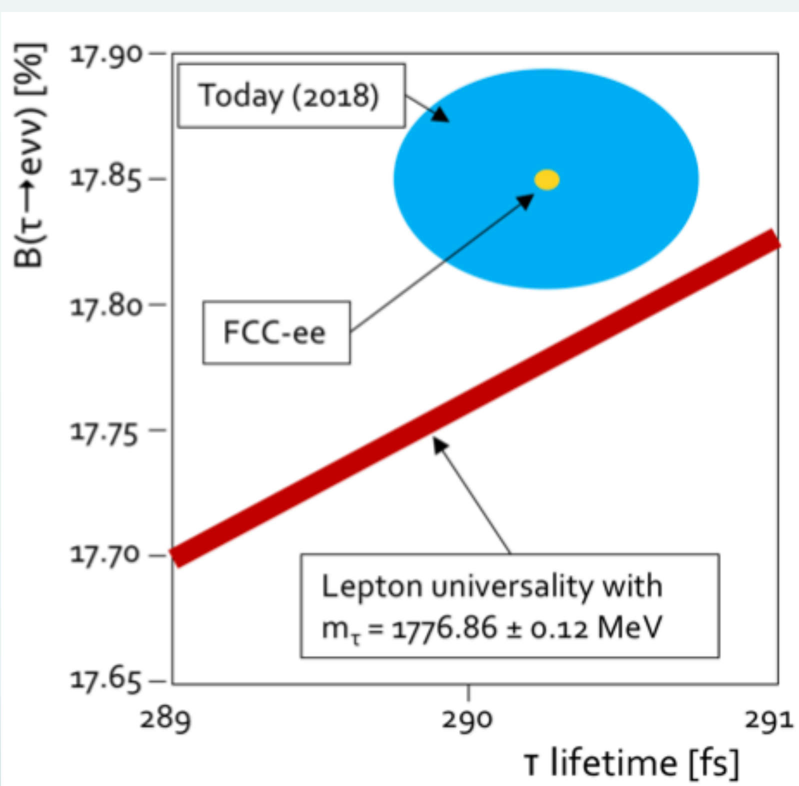
CLFV *Z* decays:

in SM <10-50

Decay	Current bound	FCC-ee sensitivity
Z -> eμ	$0.75 \times {}^{-6}$	10^{-8}
Z -> μτ	12×10^{-6}	10^{-9}
Z -> eτ	9.8×10^{-6}	10^{-9}

CLFV *τ* decays:

Decay	Current bound	FCC-ee sensitivity
τ -> μγ	4.4×10^{-8}	2×10^{-9}
τ -> 3μ	2×10^{-8}	10^{-10}

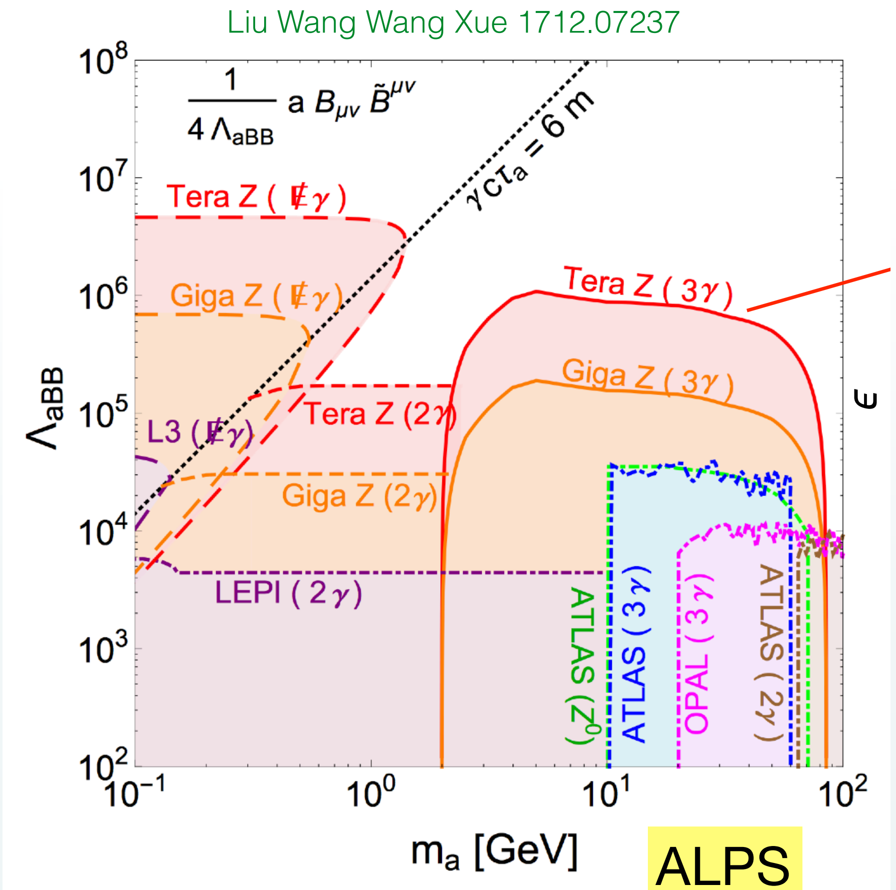


Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04

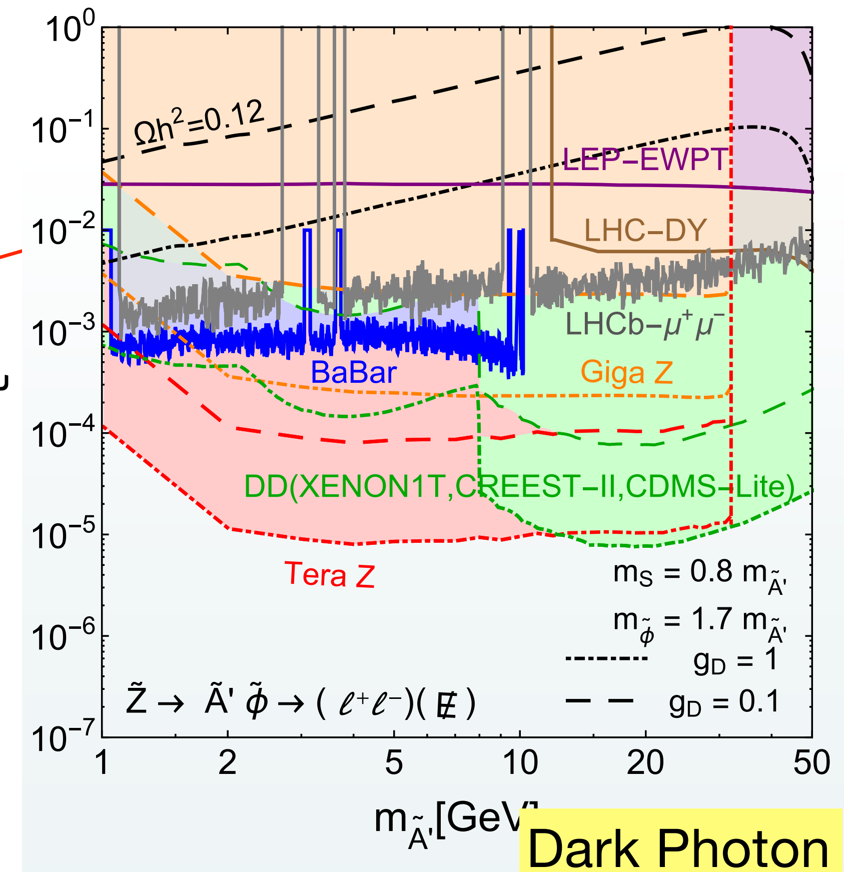
more unique opportunities in backup

BSM DIRECT SEARCHES - Z EXOTIC DECAYS

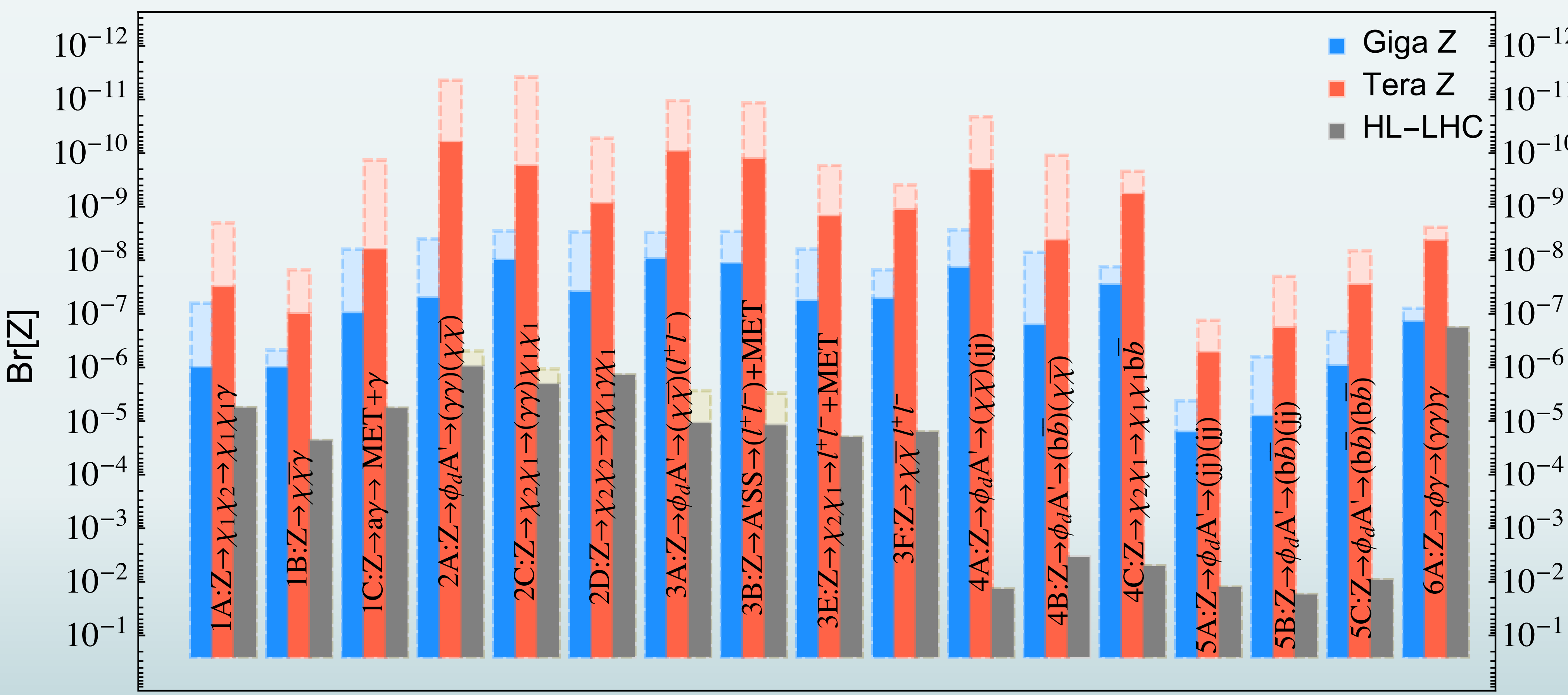
- Several models that describe possible exotic Z decays in dark sector candidate particles have been studied
- Complementarity between experiments depending on the parameter space
- Also comparison with HL-LHC



ALPS

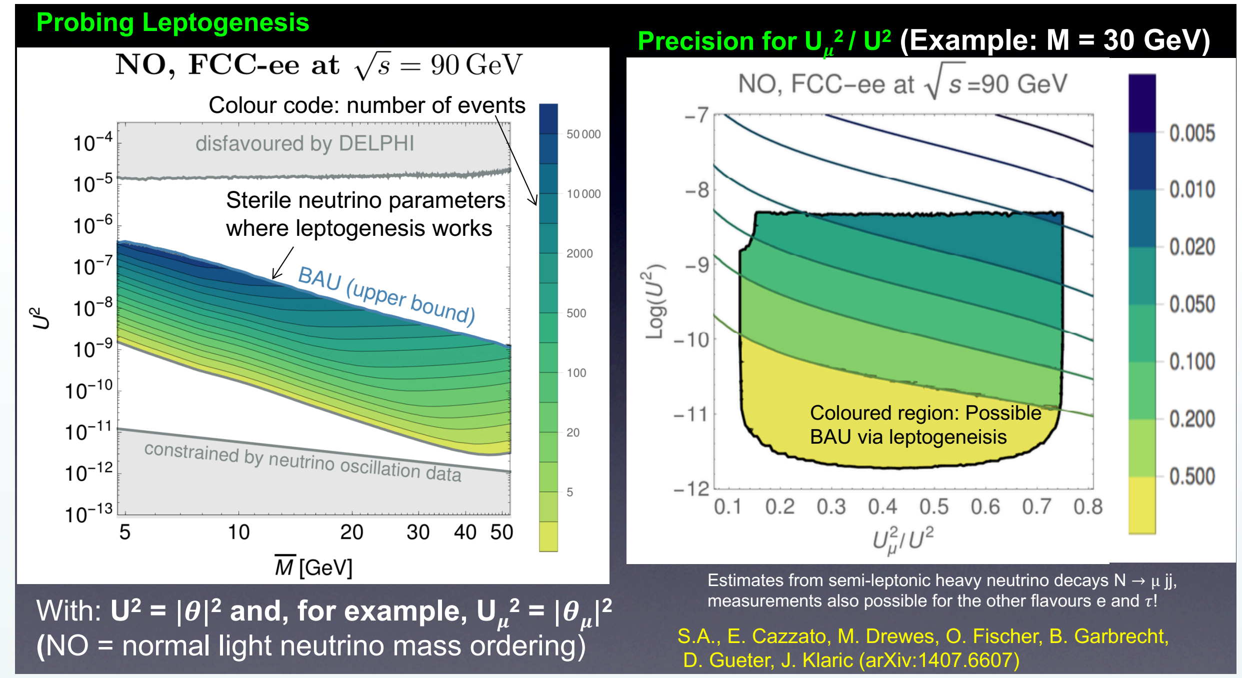


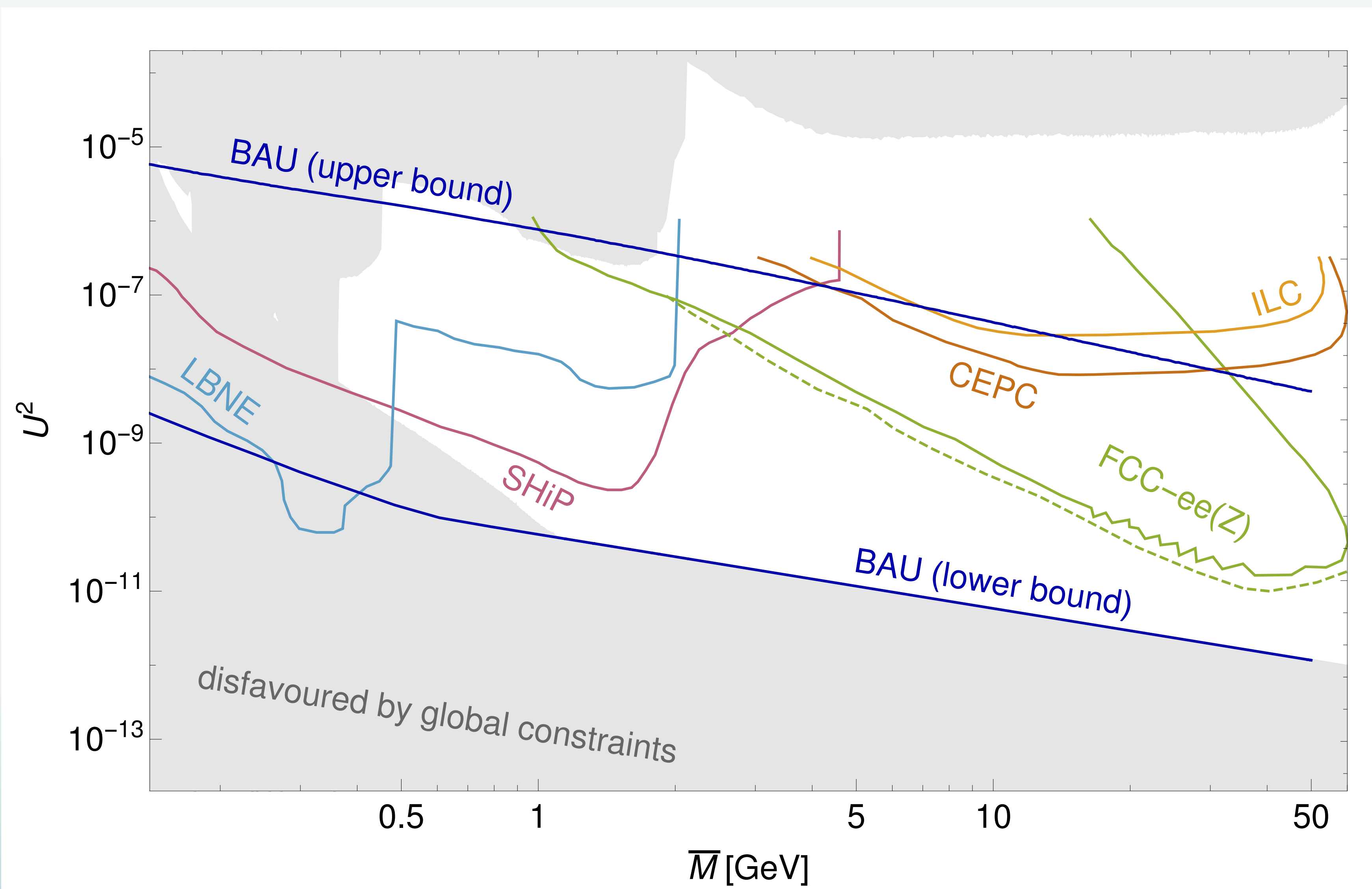
Dark Photon

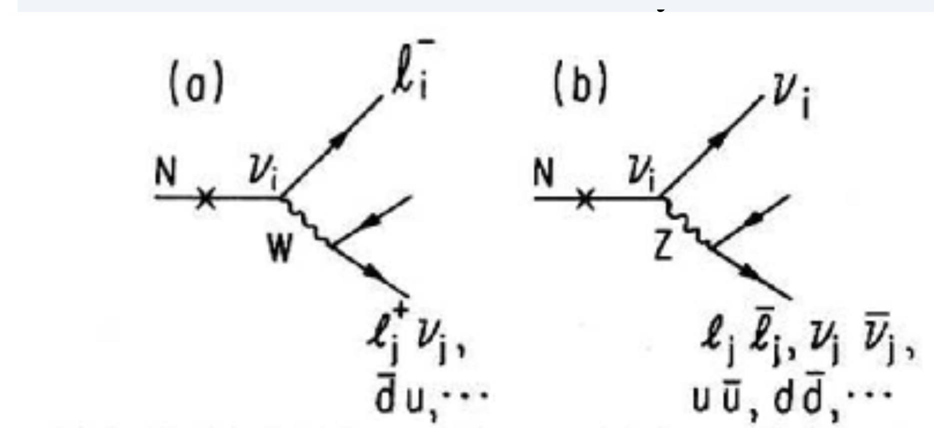


BSM DIRECT SEARCHES - STERILE NEUTRINO LL

- Long Lived Particles: recent study with a SiD inspired detector and 110ab-1 at Z pole 1710.03744
- Rations of θα measureable with high accuracy
- Test minimal type I seesaw hypotesis
- Together with ΔM also tests the compatibility with leptogenesis



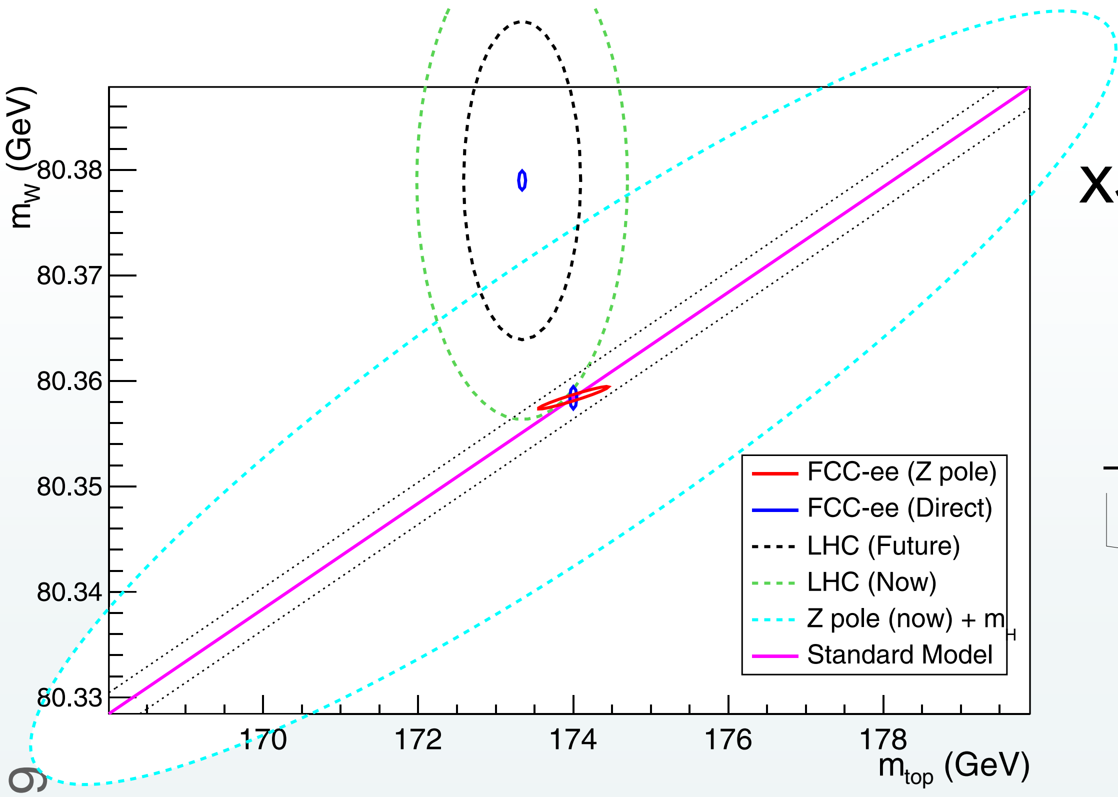


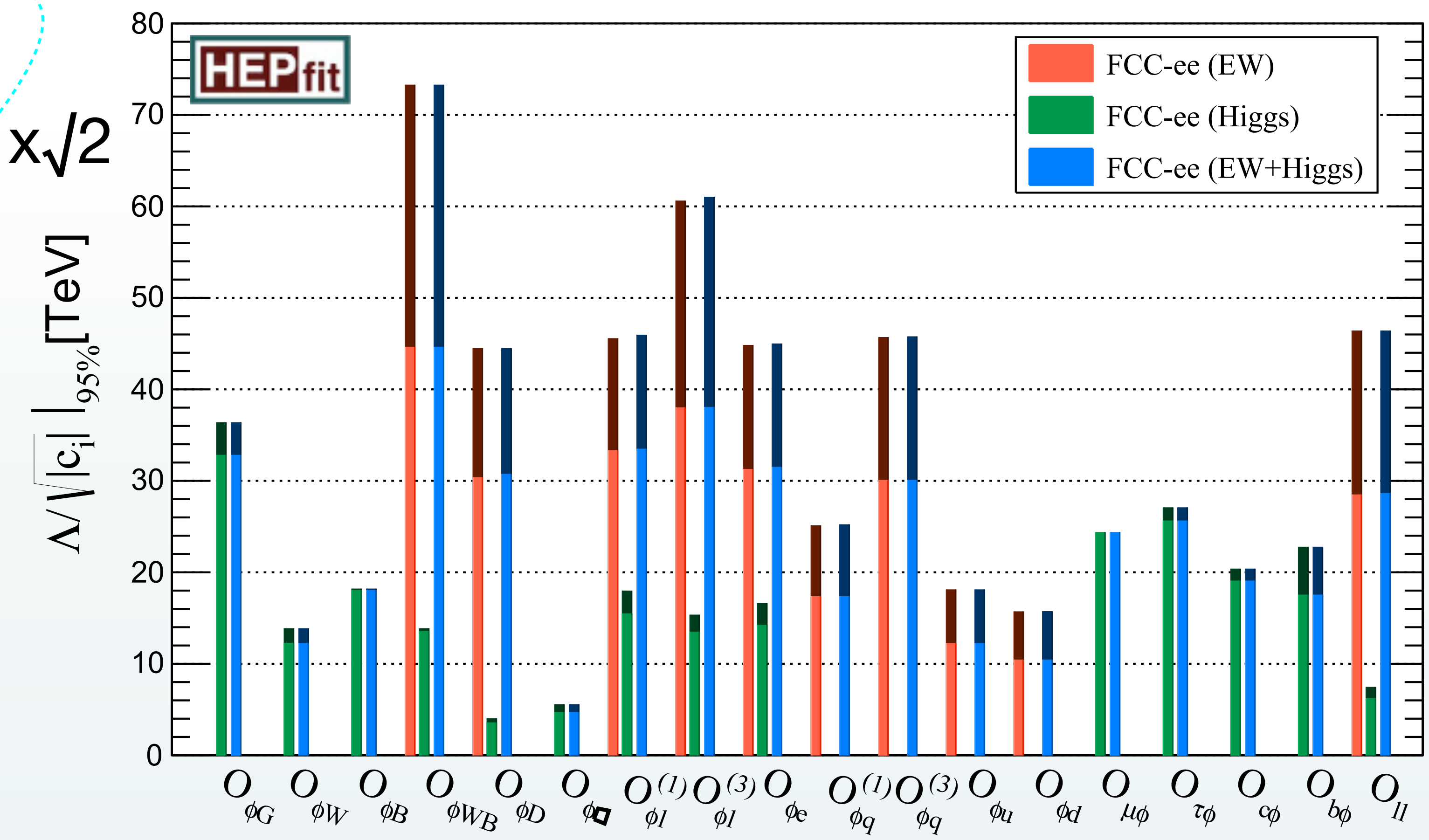


$$L \sim \frac{3\ [cm]}{|U|^2 . (m_N [GeV]\ )^6}$$

L~1m for m_N=50GeV and $|U|^2=10^{-12}$

SUMMARY ON NEW PHYSICS SENSITIVITIES





- ➤ Fit to new physics effects parameterized by dim 6 SMEFT operators
- ➤ single operator fit can be informative
- ➤ model independent result only for global fit

<u>What do we mean by "Sensitivity to NP up the scale of N TeV?" e.g.</u>

$$\frac{c}{\Lambda^2} \sim \frac{g_{\rm NP}^2}{M_{\rm NP}^2} < 0.01\ {\rm TeV}^{-2} \longrightarrow M_{\rm NP} > 10\, g_{\rm NP}\ {\rm TeV}$$

(**Weakly coupled NP** $M_{\rm NP} > 10\ {\rm TeV}\ \ (g_{\rm NP} \sim 1)$)

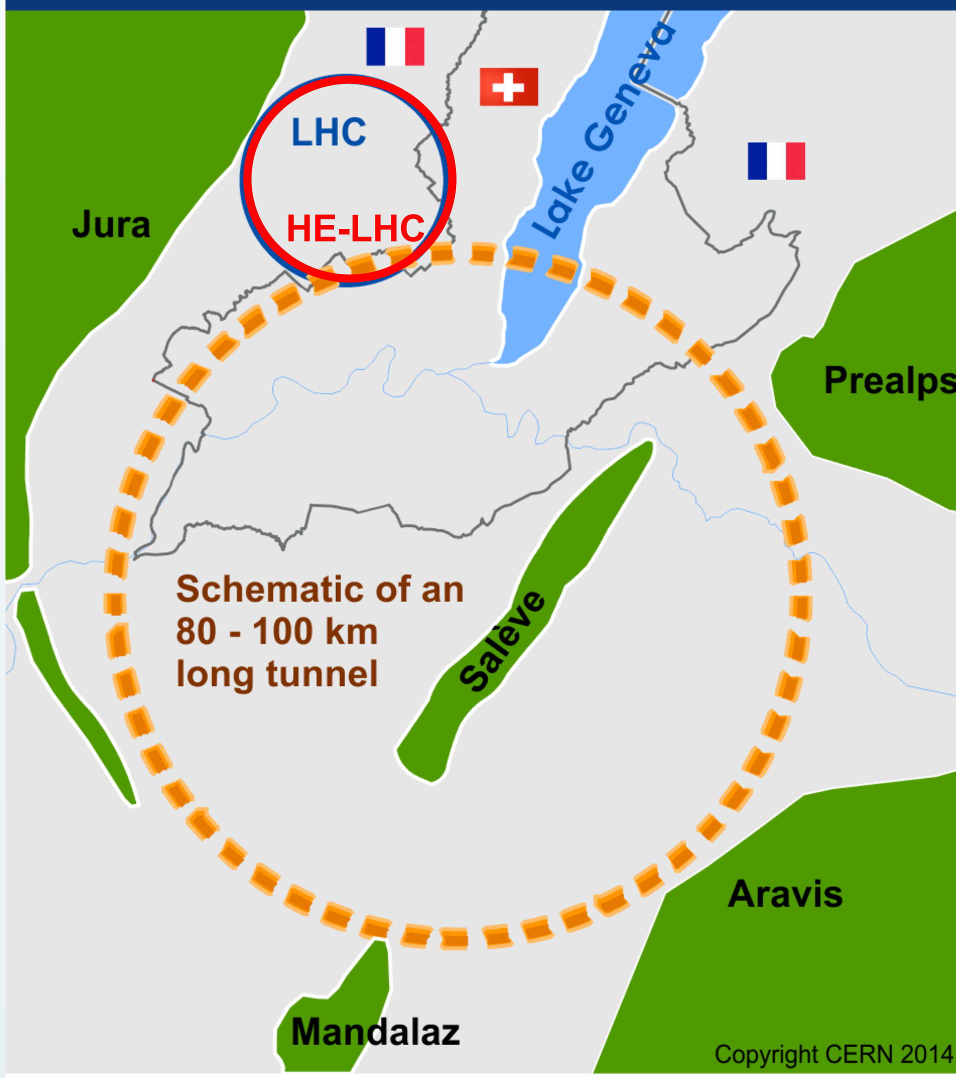
SUMMARY

- **There *must* be something beyond the Standard Theory (or totally different!)**
- Experimental proofs: Cosmological Dark Matter, Baryon Asymmetry of the Universe, non-zero neutrino masses
- Which way to go?
  - **Direct observation of new particles**
  - **New phenomena**
  - **Deviations from precise predictions**
- Physics absolutely needs an e+e- factory that covers the whole range: Z, W, H and top at the highest luminosities
- FCC-ee is the best first step to pave the way for FCC-hh:
  - preview of new physics to be searched for
  - brings a significant reduction of systematics measurements
  - handles to understand underlying theory in case of discovery

NEXT STEPS

➤ **FCC-ee is the first step of the integrated FCC project.**

Future Circular Collider Study - Scope



International FCC collaboration with CERN as host lab to study:

- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- **e^+e^- collider (*FCC-ee*),** → potential first step
- ***pp*-collider (*FCC-hh*)** → long-term goal, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **HE-LHC** with *FCC-hh* technology
- **Ions** and **lepton-hadron** options with hadron colliders

➤ Plan for the next 5 years: write TDRs for the machine and possibly LoI/CDR for the 2(4?) detectors

FUTURE
CIRCULAR
COLLIDER
STUDY

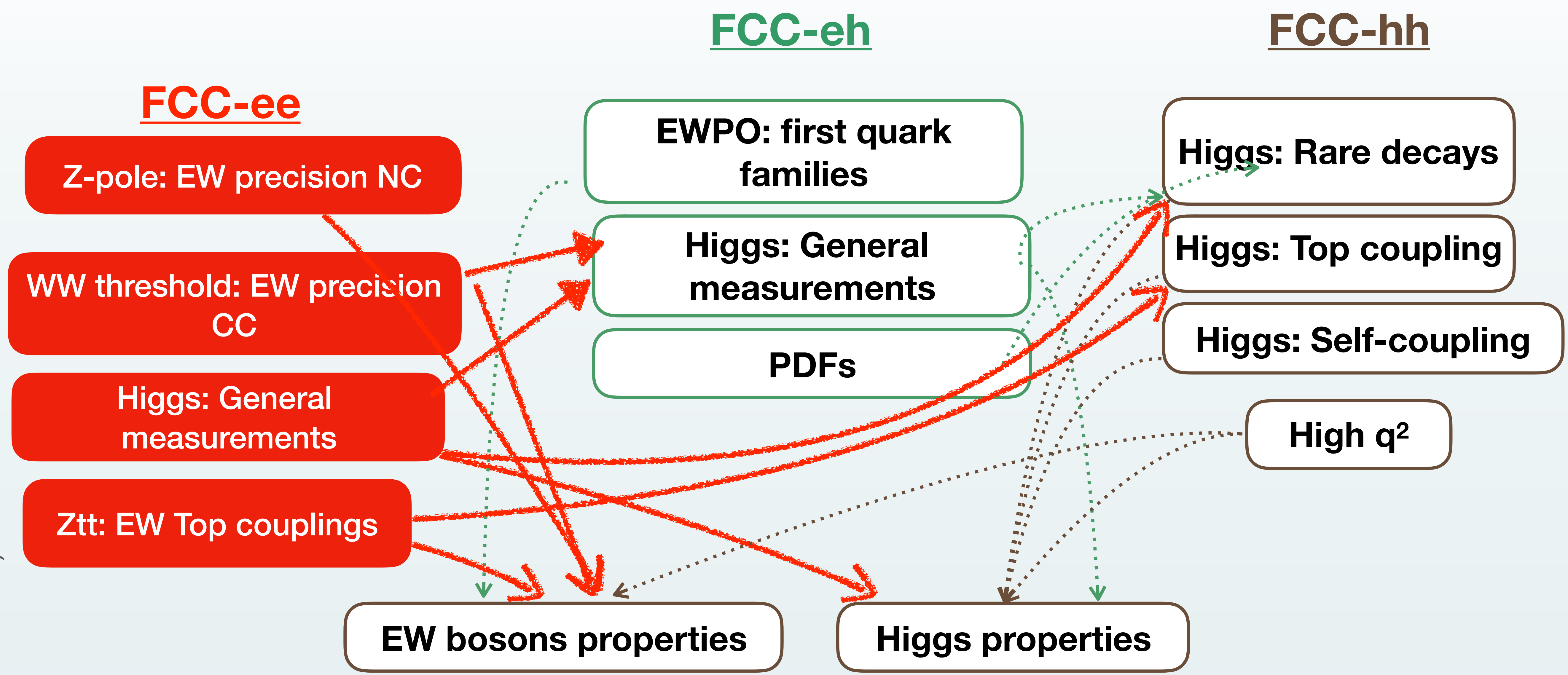
FCC
hh ee he

BACKUP

INFN
PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

COMPLEMENTARITIES IN FCC PROGRAM

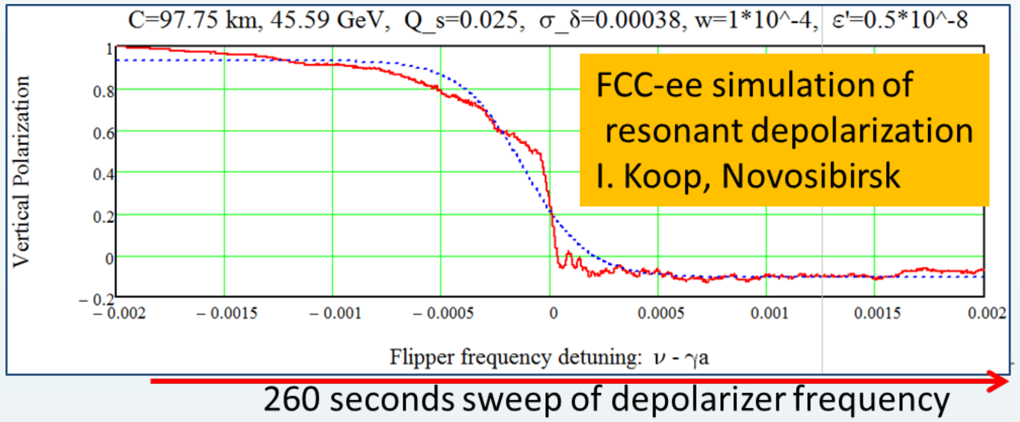
- All three FCC options complement each other very well and are useful to complete the whole picture:



BEAM POLARIZATION AND ENERGY CALIBRATION

- **Requirement from physics**
  - **Center-of-mass energy determination with precision of ±100keV around the Z peak**
  - **Center-of-mass energy determination with precision of ±300keV at W pair threshold**
  - **For Z peak cross-section and width energy spread uncertainty: Δσ/σ=0.2%**

- Use resonant depolarization as main measurement method
- use pilot bunches to calibrate parasitically during physics data taking
- take data at points where self-polarization is expected: easy to accomodate for Z and W
- Lots of details in ArXiv:1909.12245v1 A.Blondel et al.
- ptp energy uncertainty <40KeV and validation of overall centre-of-mass uncertainty of 100KeV



ArXiv:1909.12245v1 A.Blondel et al.

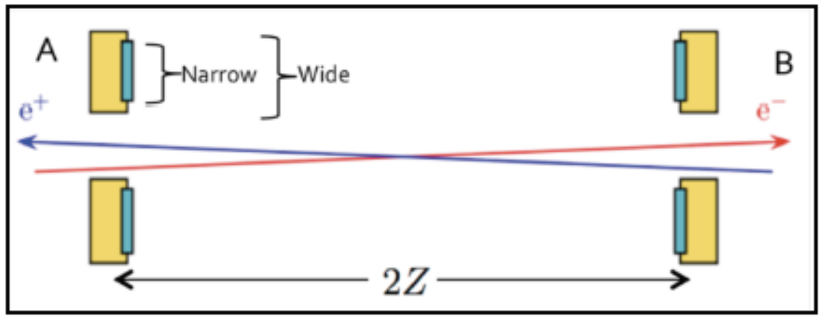
Observable	statistics	$\Delta\sqrt{s}_{abs}$ 100 keV	$\Delta\sqrt{s}_{syst-ptp}$ **40 keV**	calib. stats. $200\,keV/\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ $85 \pm \mathbf{0.05}$ MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	**0.9**	–	**0.1**

MEASUREMENT OF LUMINOSITY, σ_{had}, NEUTRINO FAMILIES

- Realistic goal on theoretical uncertainty from higher order for low angle Bhabha is 0.01% (*), corresponding to a **reduction of a factor 8 in uncertainty on number of light neutrino families, N_ν** (we are already at mid road ≈ 0.04%)
  - Another goal is a point to point relative normalization of 5 10^{-5} for Γ_Z

(*) **Blondel, Jadach et al., arXiv:1812.01004**

- To match this goal an accuracy on detector construction and boundaries of ≈ 2 μm is required
  - clever acceptance algorithms, a la LEP, with independence on beam spot position should be extended to beam with crossing angle



- Can potentially reach an uncertainty of 0.01% also with e+e-→$\gamma\gamma$, statistically 1.4 ab^{-1} are required (theory uncertainty already at this level, requires control of large angle Bhabha)
- Measurement of N_ν with similar precision provided by Zγ, Z→$\nu\nu$ events (above the Z)

➤ Electromagnetic effects caused by the bunch density can affect the acceptance of the luminometers in a non-trivial way. This can provoke a bias one order of magnitude bigger than the desired precision. New study of beam-beam effects in ArXiv:1908.01698

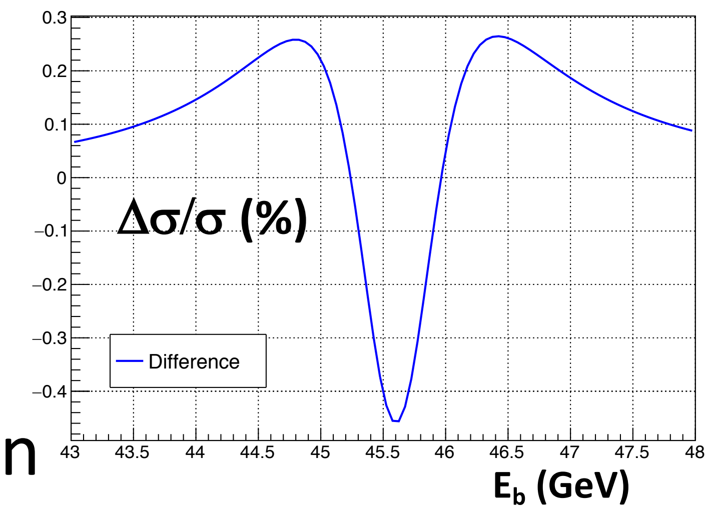
Table 5: Comparisons between the ILC GigaZ and FCC-ee TeraZ for the measurements of left-right coupling asymmetries, tests of lepton universality, and measurements of the effective weak mixing angle at the Z pole. Also indicated is the limiting precision on the effective mixing angle from the precision on $\alpha_{\mathrm{QED}}(m_Z^2)$ taking into account for FCC-ee of the improvement on this quantity from the off-peak measurement of the muon forward-backward asymmetry [63].

Facility	ILC-GigaZ	FCC-ee
Z produced at the peak	10^9	4×10^{12}
Longitudinal polarization (P_{e^-}, P_{e^-})	$(\pm 0.8, 0.0)$	$(0.0, 0.0)$
$\Delta \mathcal{A}_e$	1.2×10^{-4}	1.5×10^{-5}
$\Delta \mathcal{A}_\mu$	3×10^{-4}	5×10^{-5}
$\Delta \mathcal{A}_\tau$	3×10^{-4}	5×10^{-5}
$\Delta \frac{\mathcal{A}_\mu}{\mathcal{A}_e}$	1.6×10^{-3}	2.5 to 4×10^{-4}
$\Delta \frac{\mathcal{A}_\mu}{\mathcal{A}_\tau}$	2.3×10^{-3}	3.3×10^{-4}
$\Delta \sin^2 \theta_W^{\mathrm{eff}}$	1.5×10^{-5}	6×10^{-6}
Hard limit on SM prediction:		
$\Delta \sin^2 \theta_W^{\mathrm{eff}}$ from $\alpha_{\mathrm{QED}}(m_Z^2)$	1.1×10^{-5}	7×10^{-6}

Polarization does compensate for the different statistic but not completely.

Factor 5-10 better for FCC-ee measurement of L-R coupling asymmetries.

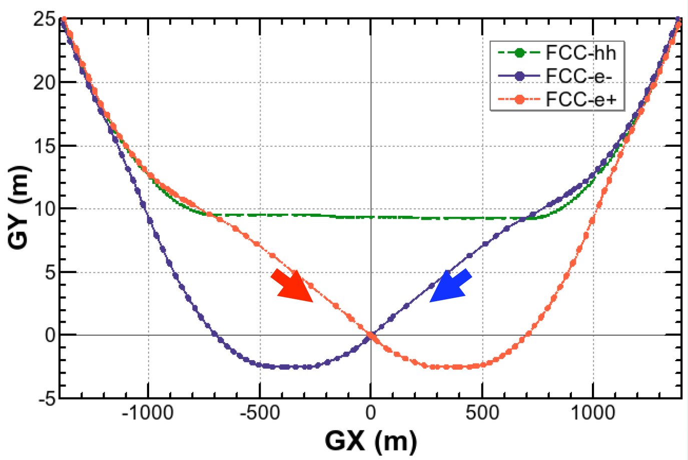
Γ_Z and beam energy spread



- The beam energy spread affects the lineshape changing the cross section by

$$\delta\sigma \simeq 0.5 \frac{d^2\sigma}{dE^2}\epsilon^2_{CMS}$$

- The size of the energy spread (≈ 60 MeV) and its impact on Γ_Z (≈4 MeV) is similar to LEP, but the approach to tackle the corresponding systematic uncertainty different because of FCC-ee beam crossing angle
- At LEP it was controlled at 1% level by measuring the longitudinal size of the beam spot, at FCC-ee can be measured with similar precision from the scattering angles of $\mu^+\mu^-$ events



➤ **Using 10^6 dimuon events (4 min @FCC-ee) can measure the energy spread at 0.1% of its value**

➤ *Detector requirement on muon angular resolution of 0.1mrad*

tau polarization plays a central role at FCC-ee

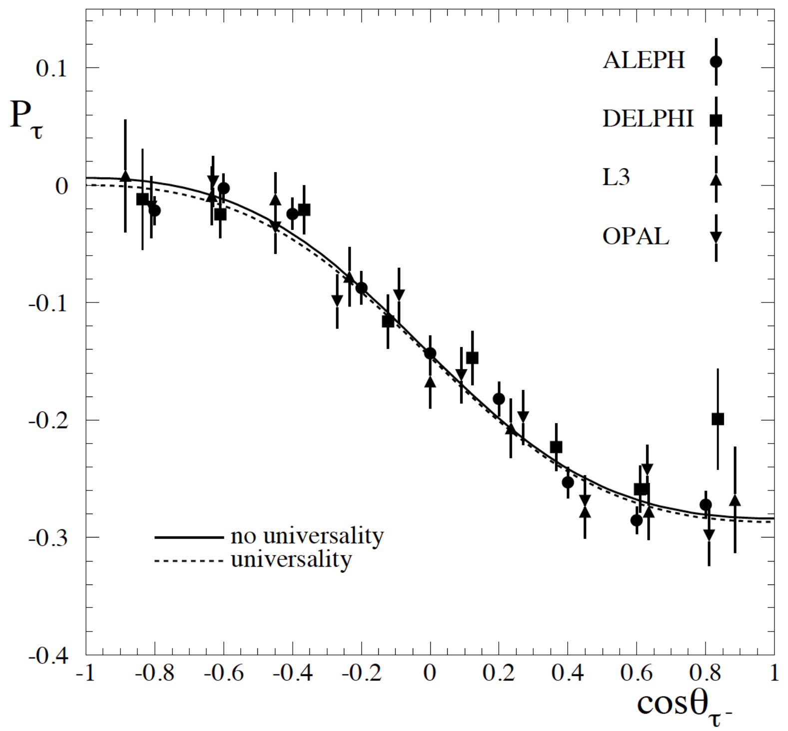
- Separate measurements of A_e and A_τ from

$$P_\tau(\cos\theta) = \frac{A_{pol}(1+\cos^2\theta) + \frac{8}{3}A_{pol}^{FB}\cos\theta}{(1+\cos^2\theta) + \frac{8}{3}A_{FB}\cos\theta}$$

$$A_{pol} = \frac{\sigma_{F,R} + \sigma_{B,R} - \sigma_{F,L} - \sigma_{B,L}}{\sigma_{tot}} = -A_f$$

$$A_{pol}^{FB} = \frac{\sigma_{F,R} - \sigma_{B,R} - \sigma_{F,L} + \sigma_{B,L}}{\sigma_{tot}} = -\frac{3}{4}A_e$$

Measured P_τ vs $\cos\theta_{\tau^-}$



At FCC-ee

- very high statistics: improved knowledge of tau parameters (e.g. branching fraction, tau decay modeling) with FCC-ee data
- use best decay channels (e.g. $\tau \rightarrow \rho\nu_\tau$ decay very clean), note that detector performance for photons / π^0 very relevant

→ **measure $\sin^2\theta_{eff}$ with 6.6 10^{-6} precision**

Precisions on coupling ratio factors, A_f

$$\mathcal{A}_e = \frac{2 g_{Ve} g_{Ae}}{(g_{Ve})^2 + (g_{Ae})^2} = \frac{2 g_{Ve}/g_{Ae}}{1 + (g_{Ve}/g_{Ae})^2}$$

	Statistical uncertainty	Systematic uncertainty	improvement w.r.t. LEP
$\mathcal{A}_e$	$5. \times 10^{-5}$	$1. \times 10^{-4}$	50
$\mathcal{A}_\mu$	2.5×10^{-5}	1.5×10^{-4}	30
$\mathcal{A}_\tau$	$4. \times 10^{-5}$	$3. \times 10^{-4}$	15
$\mathcal{A}_b$	2×10^{-4}	30×10^{-4}	5
$\mathcal{A}_c$	3×10^{-4}	80×10^{-4}	4
$\sin^2\theta_{W,eff}$ (from muon FB)	10^{-7}	$5. \times 10^{-6}$	100
$\sin^2\theta_{W,eff}$ (from tau pol)	10^{-7}	6.6×10^{-6}	75

Relative precisions, but for $\sin^2\theta_{eff}$

Precisions on vector and axial neutral couplings

fermion type	g_a	g_v
e	1.5×10^{-4}	2.5×10^{-4}
μ	2.5×10^{-5}	$2. \times 10^{-4}$
τ	0.5×10^{-4}	3.5×10^{-4}
b	1.5×10^{-3}	1×10^{-2}
c	2×10^{-3}	1×10^{-2}

Relative precisions

Improvements 1 – 2 orders of magnitudes with respect to LEP, depending on the fermion
(Still need to explore the potential for a measurement of the s quark coupling)

7) A (partial) selection of unique opportunities

- The search for the decay $B_s \to \tau^+\tau^-$, as the next rare dileptonic decay. Produced number of events at FCC-ee: $O(2.10^5)$. Can be studied with a topological reconstruction of the kinematics of the decay.

- The search for the decay $B^0 \to \mu^+\mu^-$, expect $O(100)$ clean events.

  - Incidentally, the CKM matrix element $|V_{ub}|$ can be determined theory free (up to the assumption of SU(2)$_{strong}$!) at 5% precision through:

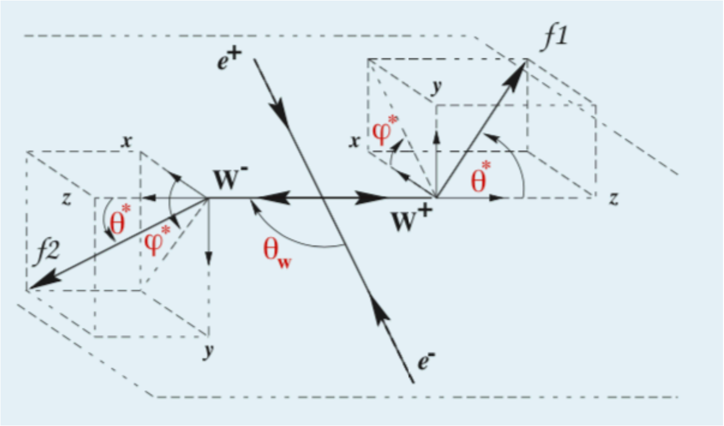
$$\frac{\mathcal{B}(B^+ \to \mu^+\nu)}{\mathcal{B}(B^+ \to \mu^+\mu^-)} \propto \frac{f_{B^+}}{f_{B^0}} \frac{|V_{ub}|}{|V_{td}|}$$

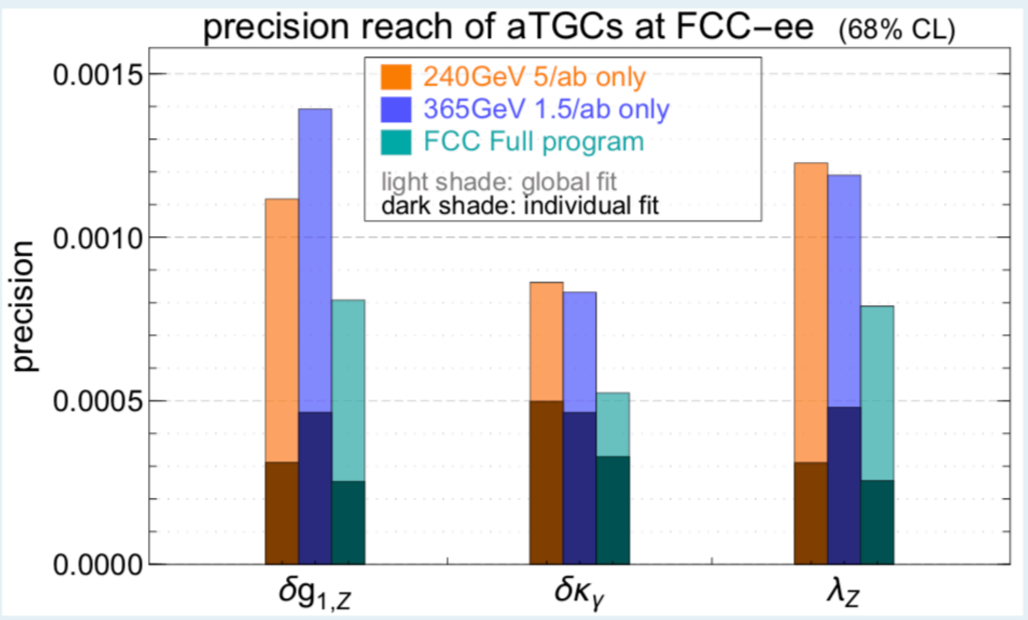
  - The leptonic decay $B^+_c \to \tau^+\nu_\tau$ is diagrammatically similar to the presently anomalous decay $B^0 \to D^{(*)}\tau^+\nu_\tau$. Expect $O(10^6)$!

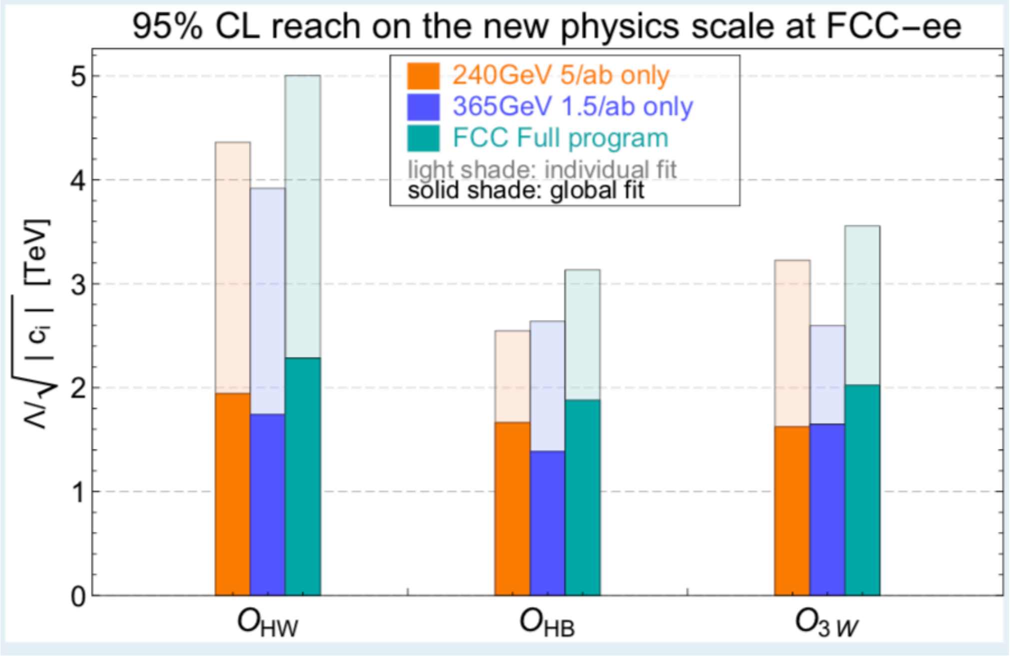
- *CP* violation in neutral *B*-mesons mixing is unobserved to date. The SM predictions are $O(10^{-4})$ [$O(10^{-5})$]

SENSITIVITY TO ATGCS

- Based on expected luminosity at 161, 240, 350 and 365 GeV
- Consider CP-even dimension 6 operators, SU(2)XU(1) symmetry leaves three independent anomalous couplings
- Include both total cross section and angles
- For the moment only statistical uncertainties
- **One order of magnitude improvement with respect to LEP**







Analysis performance

- **Full Sim, Fast Sim, Extrapolation**
  - We have developed benchmark analyses with CMS full sim analyses (2012)
    - $H \to bb, \tau\tau, WW, ZZ, \gamma\gamma, \mu\mu, \ldots$
  - We have checked a few of them with CLICDet full sim (2013)
    - Improves over CMS precisions by 20% (for those channels accessible to CMS)
  - We have developed a fast simulation able to reproduce CMS and CLICDet performance
    - Validated on full simulation
  - We have checked that the fast simulation gives the same results as ILC/CLIC analyses
    - For a number of benchmark analyses
  - For the final FCC-ee numbers, we have conservatively assumed same detector performance as ILC and CLIC detectors in our fast simulation (CLD)
    - We expect better performance
      - ➨ Smaller beam pipe – currently checking if 10 mm radius is feasible
      - ➨ Ten years to develop innovative detectors at up to 4 IPs
      - ➨ Better calibration, new analysis techniques, etc.
  - We have extrapolated statistical precision from ILC (250 GeV) and CLIC (380 GeV)
    - For those channels not fully analysed by the FCC-ee team
      - ➨ Note: $H \to Z\gamma$ final state not yet in the tables, but can be included as well.

Experimental uncertainties

- **Many sources were examined, and solutions exist for all of them**
  - Centre-of-mass energy can be calibrated to ~2-5 MeV with Zγ, WW, and ZZ events
    - From the knowledge of m_Z and m_W to 0.1 and 0.5 MeV
      - ➨ Negligible impact on m_H and on Higgs branching fractions
  - Beam energy spread can be measured continuously (1% / √day) with $\mu^+\mu^-$ events
    - Negligible impact on recoil mass uncertainty and on σ_{HZ}
  - Alignment (absolute and relative) and calibration (calo, b-tag, PID, etc)
    - Can be performed with regular runs at the Z pole
      - ➨ Requires 12 hours for setup, e.g., every month
      - ➨ One hour data taking gives 3.10^8 Z in Higgs mode, and 10^7 Z in top mode

        i.e., about 1000 times the monthly Higgs statistics
    - Fermion pairs at 240 and 365 GeV can also be used as a complement
      - ➨ Cross section 300 times the Higgs cross section (3.10^8 events at 240 GeV)
  - Integrated luminosity can be measured fast with 0.01% precision
    - i.e., 10 times better than the ultimate precision expected from 2.5 10^6 Higgs events
  - Magnetic field will not be uniform
    - Will be measured in the tracker volume before tracker installation
    - Will be followed with $\mu^+\mu^-$ events (Z pole) and with coil current measurements

Two detector concepts for the CDR

O. Viazlo, L. Pezzotti

- It was demonstrated that detectors satisfying requirements are feasible
  - Physics performance, beam backgrounds, invasive MDI, event rates, …
    - With two rather complementary designs – see talks of Oleksander and Lorenzo for details