The FCC project - status and Spanish contributions

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1 July 2024

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Future Colliders

- “Raison d’être”: 1 TeV → 10 TeV comprehensive exploration of matter and interactions

- Current scale reach:

  - LEP: ≈ 2.5 TeV (S parameter)

  - LHC:
    - Higgs studies: $\Lambda \gtrsim$ 1 TeV
    - SUSY, related with fermions of third generation, diboson resonances, … : $\Lambda \gtrsim$ 2-4 TeV
    - New gauge boson searches (W’,Z’): $\Lambda \gtrsim$ 5-6 TeV, smaller for composite Higgs models ($\Lambda \gtrsim$ 3-4 TeV)

  - Low energy experiments: ~ TeV reach as soon as minimal conditions are imposed (minimal flavor violation, deviations at loop level, …):
    - Eur. Strat. Briefing Book, 2019: https://arxiv.org/abs/1910.11775

Sensitivity at the Higgs scale

- **Effects at the Higgs scale from a large scale Λ:**

$$\frac{\Delta\sigma_H}{\sigma_H} \approx \frac{v^2}{\Lambda^2}; \quad v = 246 \text{ GeV}$$

- **Precision EWK physics bounds (S-parameter, PDG23):**

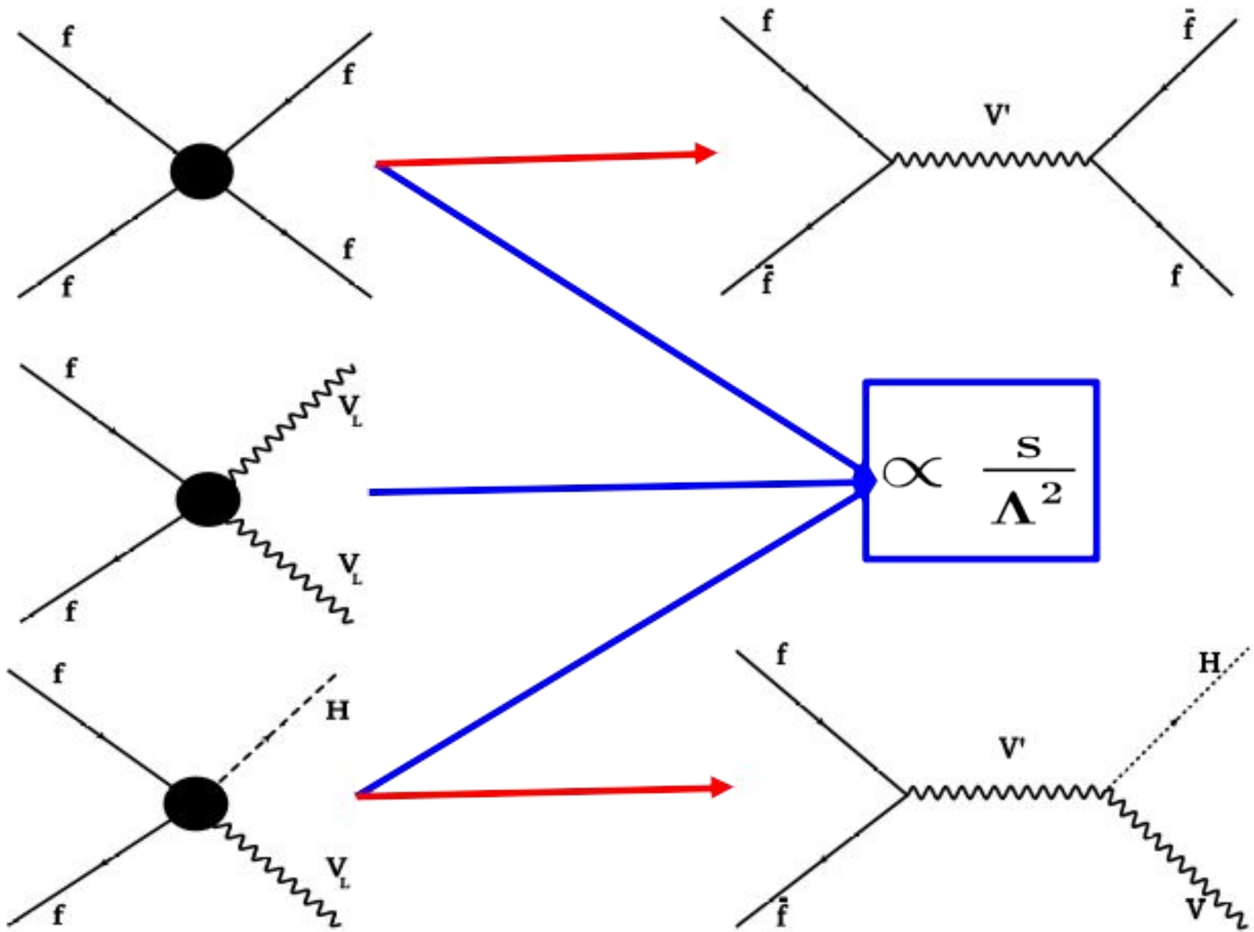
$$\Lambda \gtrsim 2.5 \text{ TeV} \quad \Rightarrow \quad \Delta\sigma_H/\sigma_H \lesssim 1\%$$

Need to search for deviations of the order $\lesssim$ 1% in order to go beyond and unveil the true Higgs nature (composite?, associated to new symmetries/particles?, ...)

Sensitivity when increasing √s

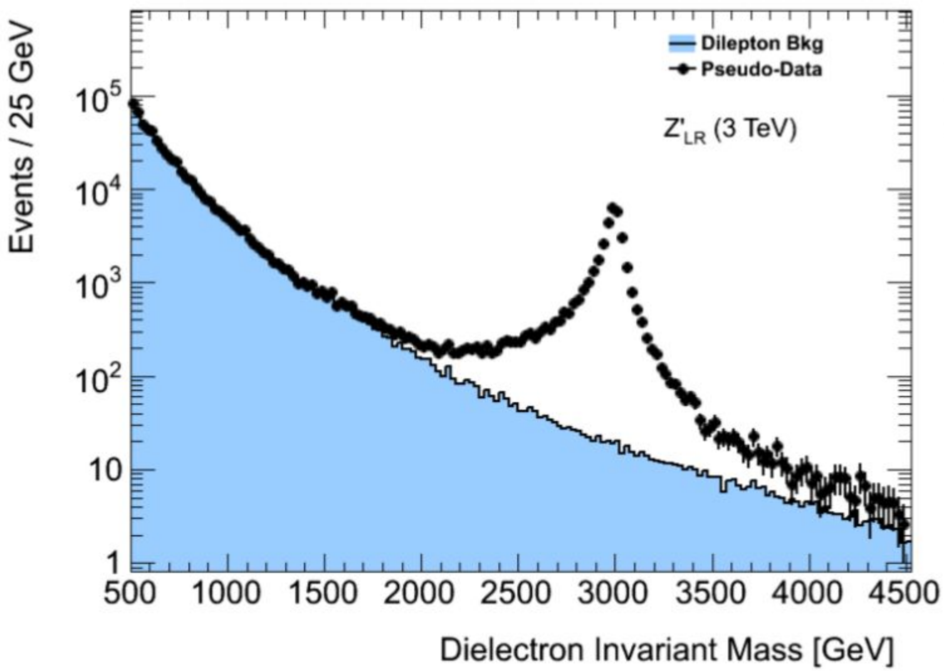
- **Relevant example of new physics effects (direct or indirect) when increasing the center-of-mass energy:**

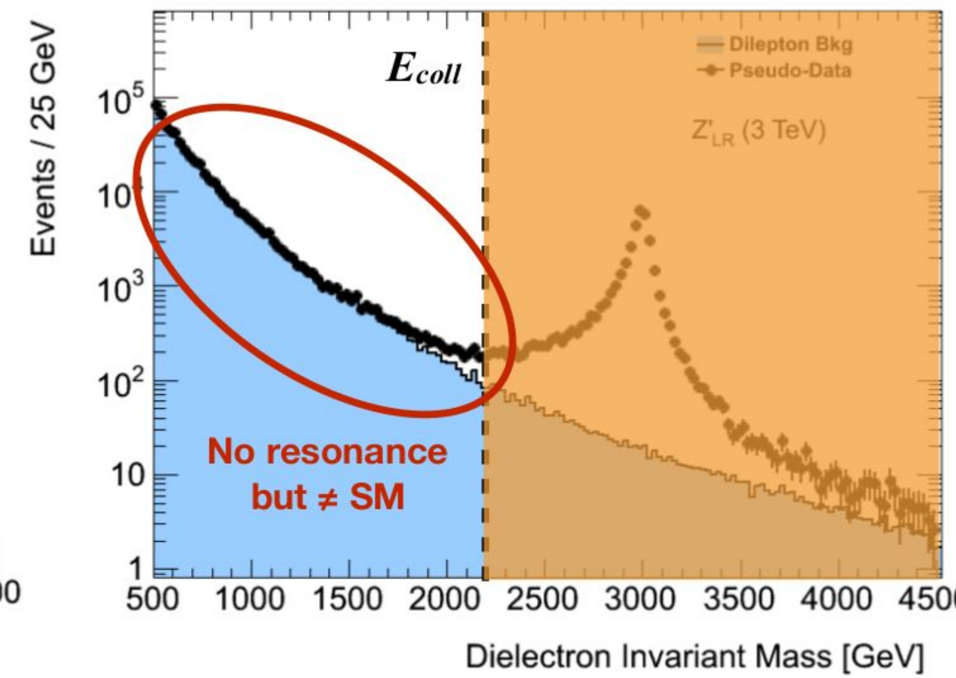
$$\frac{\Delta\sigma}{\sigma_{SM}} \approx \frac{s}{\Lambda^2}$$



Need for "direct" observation

(Plots from J. De Blas from ESG19 discussions)





Seeing the "peak":

- **mass ≲ 0.3-0.5 √s in hadron colliders for "natural" couplings**
- **mass < √s for lepton colliders, but hardly any hope for √s ≲ 3 TeV given current LHC mass limits**

Indirect deviations below "peak":

- **Cleanest in lepton colliders, but only sensitive to the [mass/coupling] ratio via interference, and hypothesis dependent (spin, width, interference) → DIFFICULT TO INFER WHAT IS GOING ON**

Why a circular e^+e^- collider ?

- **Two new pieces of information that were NOT available when the initial proposals of linear colliders took place:**

  a. The Higgs has been now discovered and has a relatively low mass ($m_H \approx 125$ GeV) → it can be precisely study it with a circular e+e- collider using current (well known) technologies

  b. If no new physics found up to the TeV scale → need for a hadron collider to "unambiguously discover" new physics if it lies around the deca-TeV scale

This is the baseline logic - physics driven - behind the FCC proposal, although it offers much more than that (no time to go in much detail on everything in this talk)

European Strategy statements (2020)

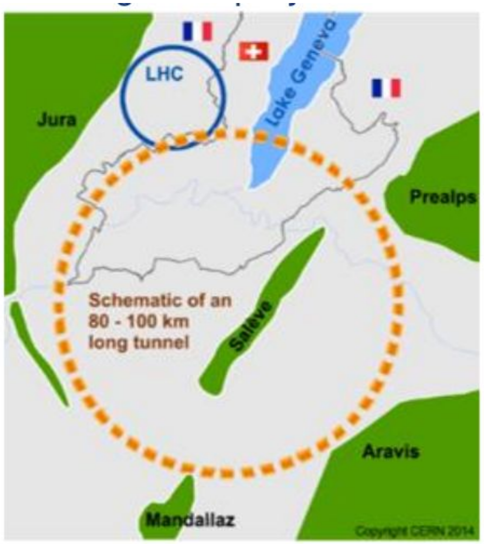
- ***"An electron-positron Higgs factory is the highest-priority next collider."***

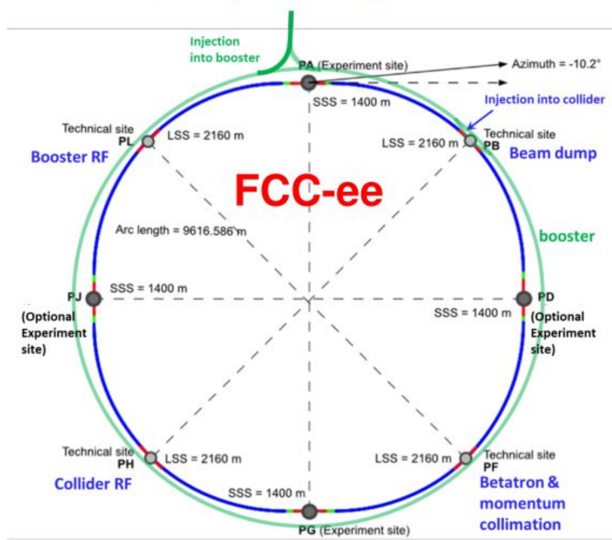
- ***"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV*** *and with an electron-positron Higgs and electroweak factory as a possible first stage.*"

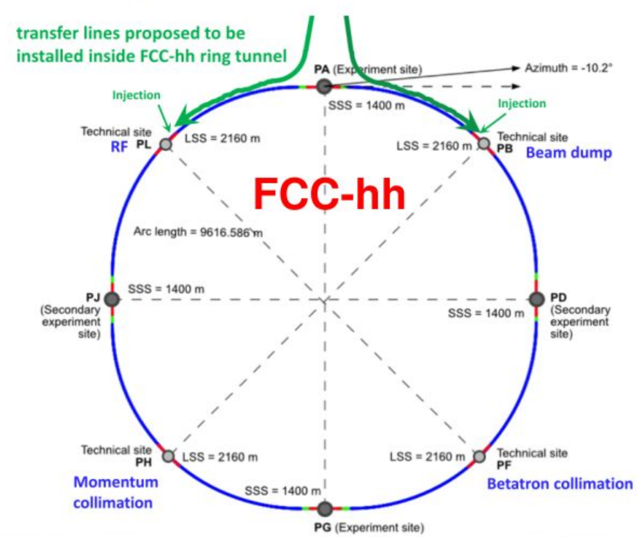
FCC project

- Next CERN accelerator/project after the completion of the HL-LHC program. Two stages in a ≈ 90 km ring:
  - FCC-ee: e^+e^- Higgs (+electroweak+top) factory, $\sqrt{s}$ = 90-365 GeV
  - FCC-hh: pp at $\sqrt{s}$ ≈ 100 TeV (+ possibility of ep and hh collisions)

- FCC-ee technology ready now, no major show-stoppers
- FCC-hh technology requires the development of very high-field magnets (≈14-16 T, ≈20 T with HTS magnets, ≈20 years of R&D)





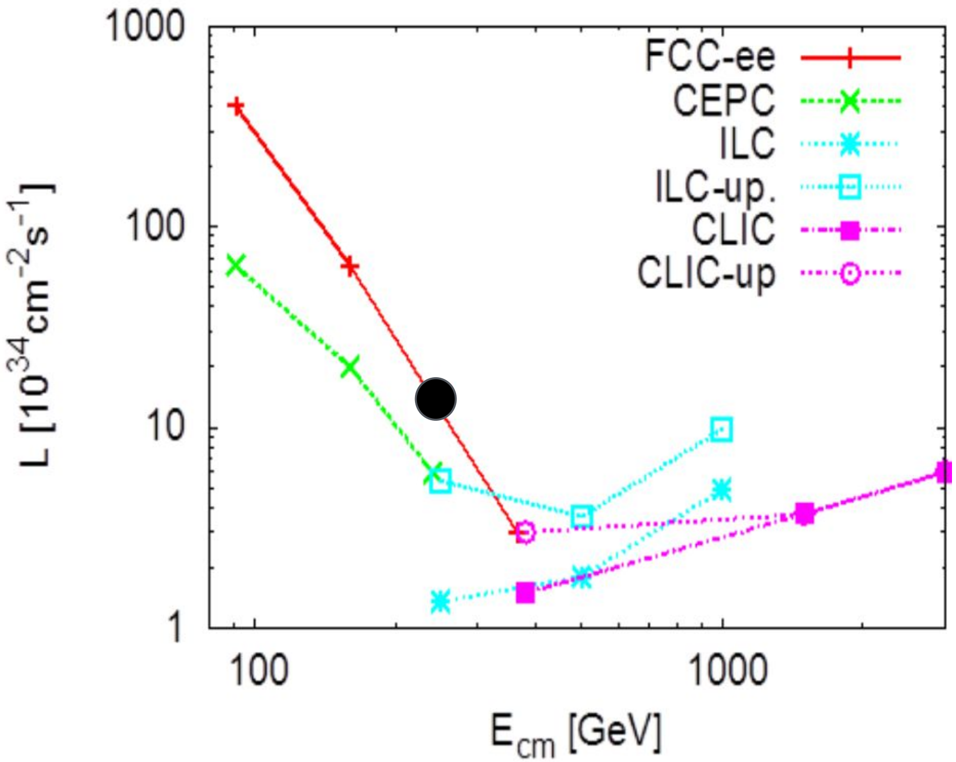


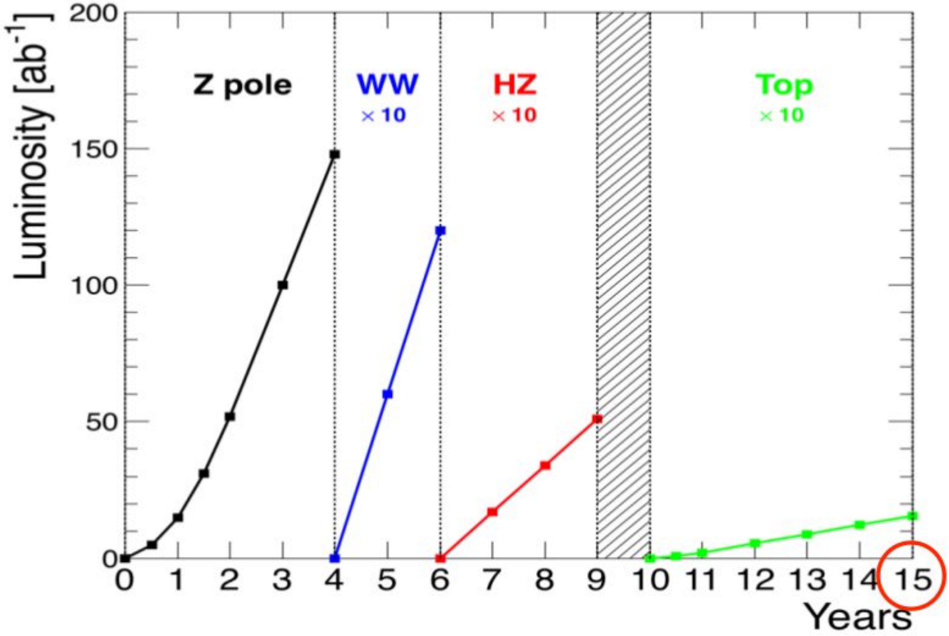
- 2040 | 2045 - 2060 | 2070 - 2095

FCC-ee: huge statistics and precision

[European Strategy Briefing Book: arXiv:1910.11775]

(FCC/CEPC: 2 IPs only)





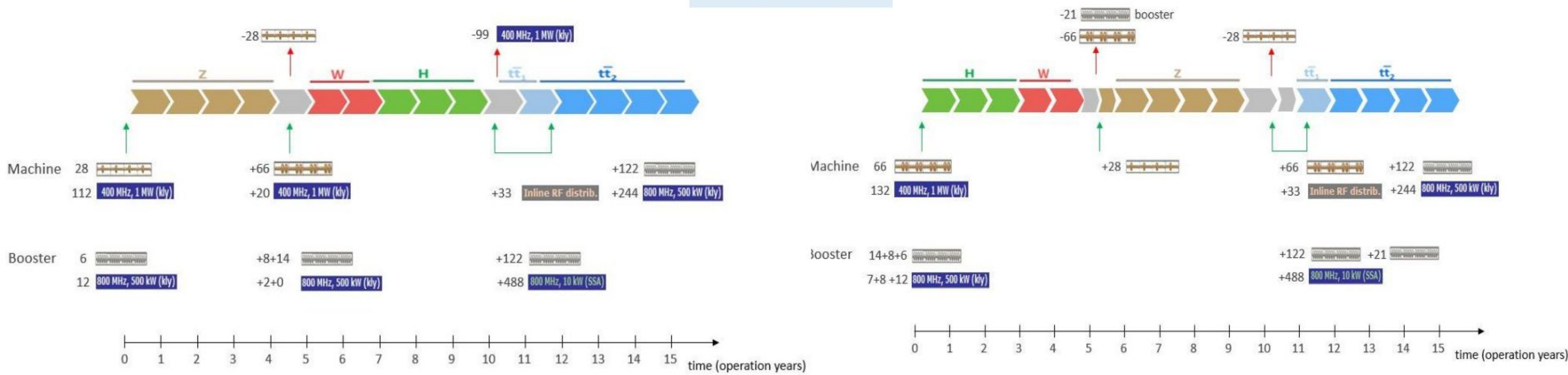
- **4 experiments, now the baseline**
- **Large statistics at $\sqrt{s}$=240 GeV: 5 ab^{-1} in ≈3 years of running for HZ**
- **Tera-Z: 10^{12} Z's in ≈4 years, LEP statistics in a few minutes**
- **Clean, well known environment, precise $\sqrt{s}$ measurements (LEP)**

FCC-ee: order

FUTURE CIRCULAR COLLIDER

operation sequences for FCC-ee

O. Brunner, F. Peauger



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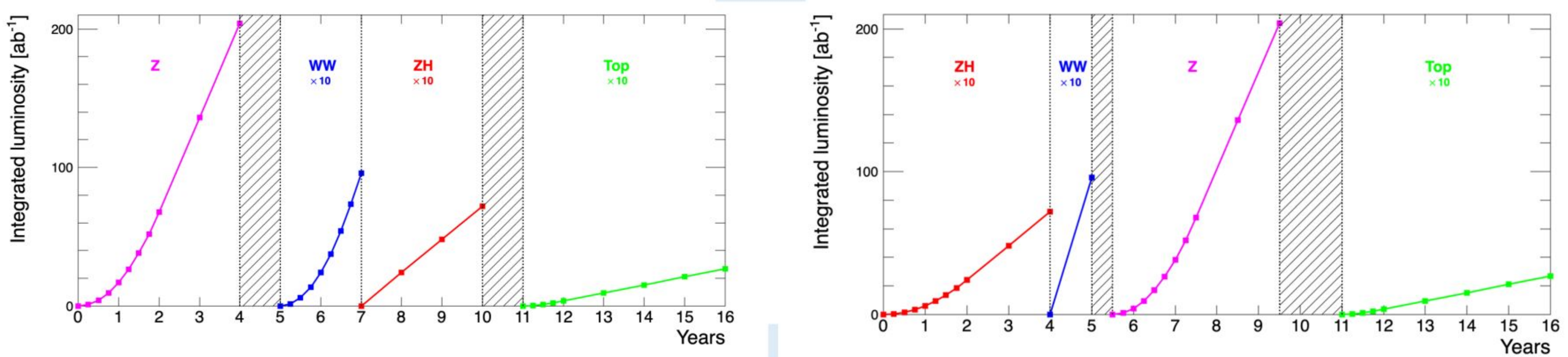
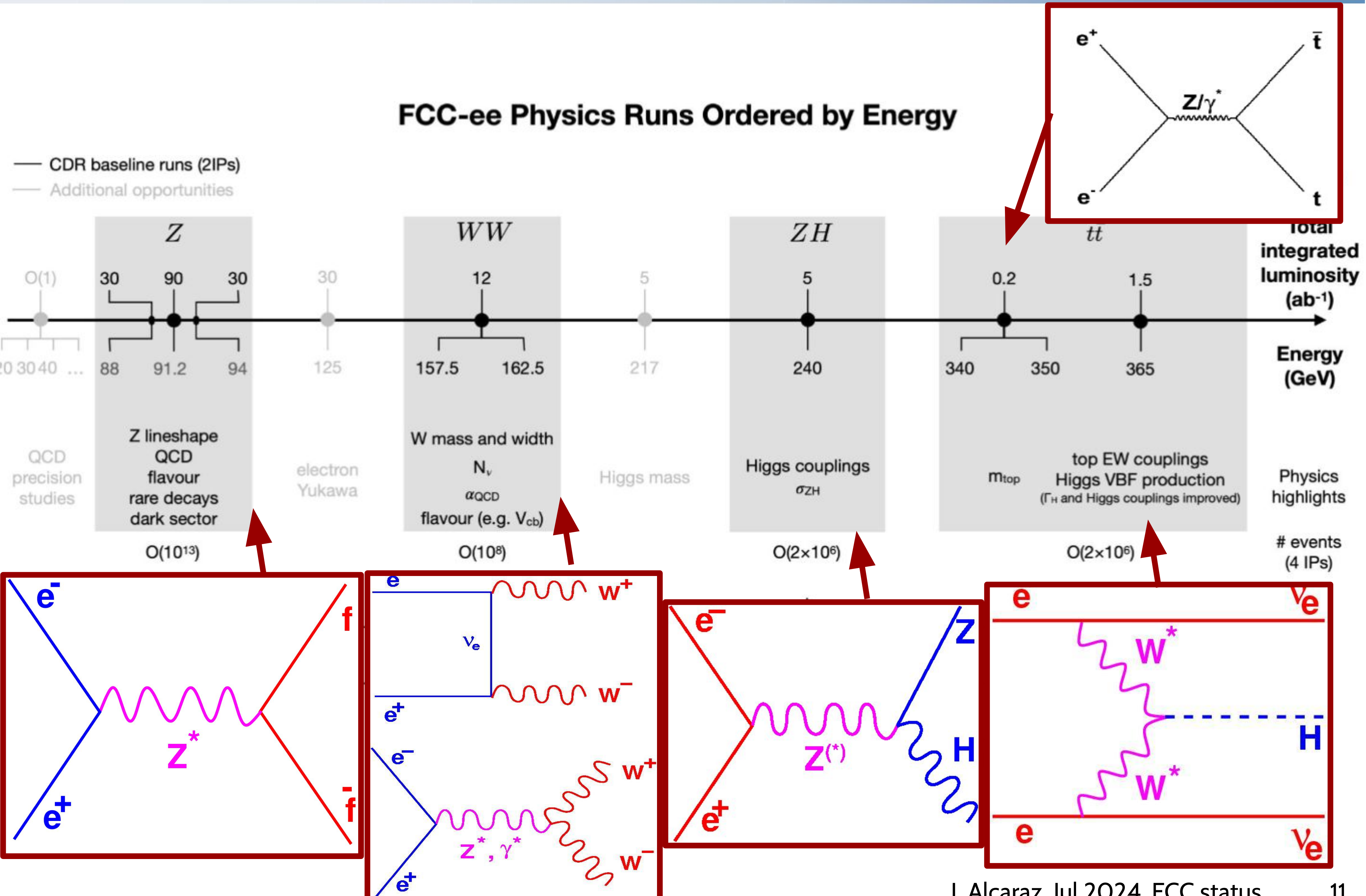
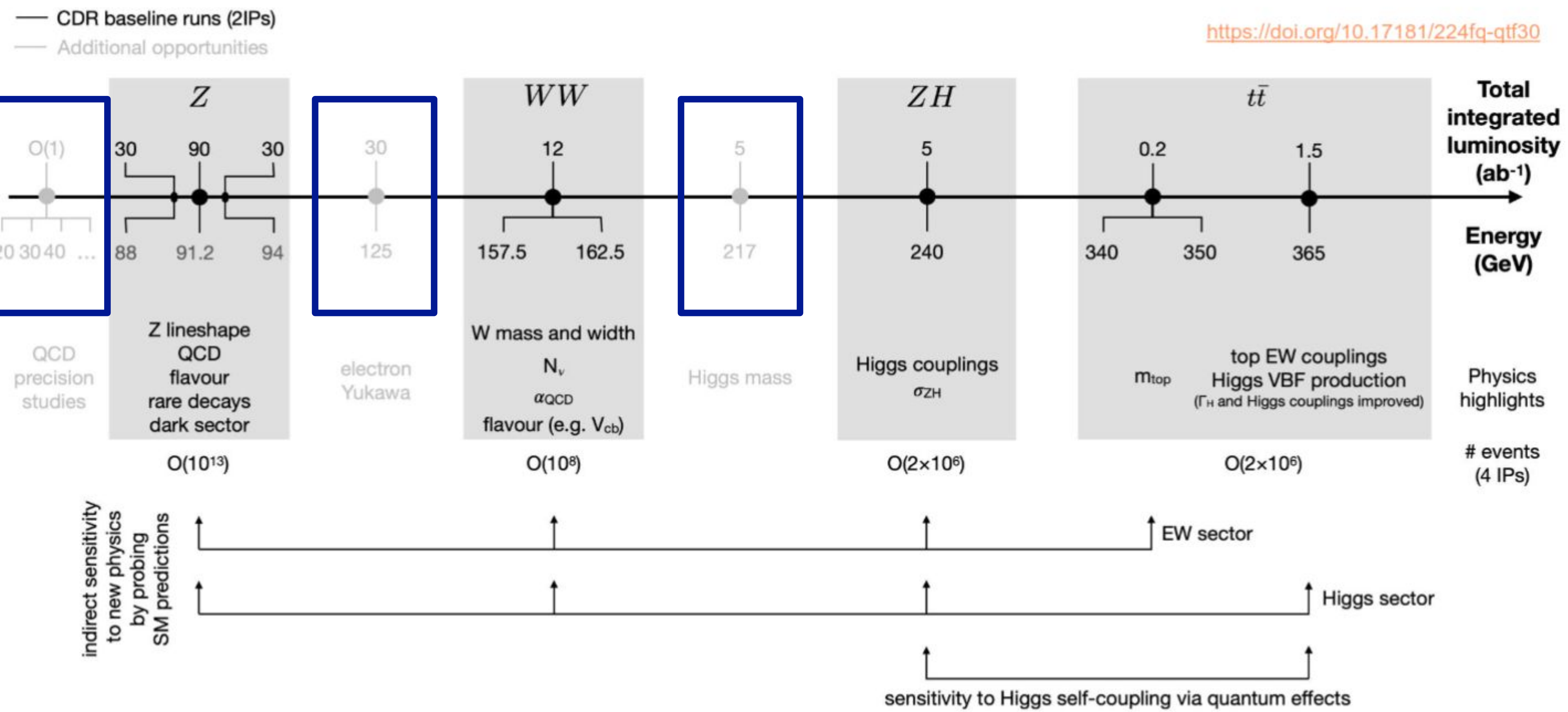


Global view of the FCC-ee program



Possible extensions (not the baseline)

- **Additional "opportunities: QCD studies, ee→H, more precise m_H**



Some strengths of FCC-ee

(many more details on the physics with FCC-ee/FCC-hh in the backup)

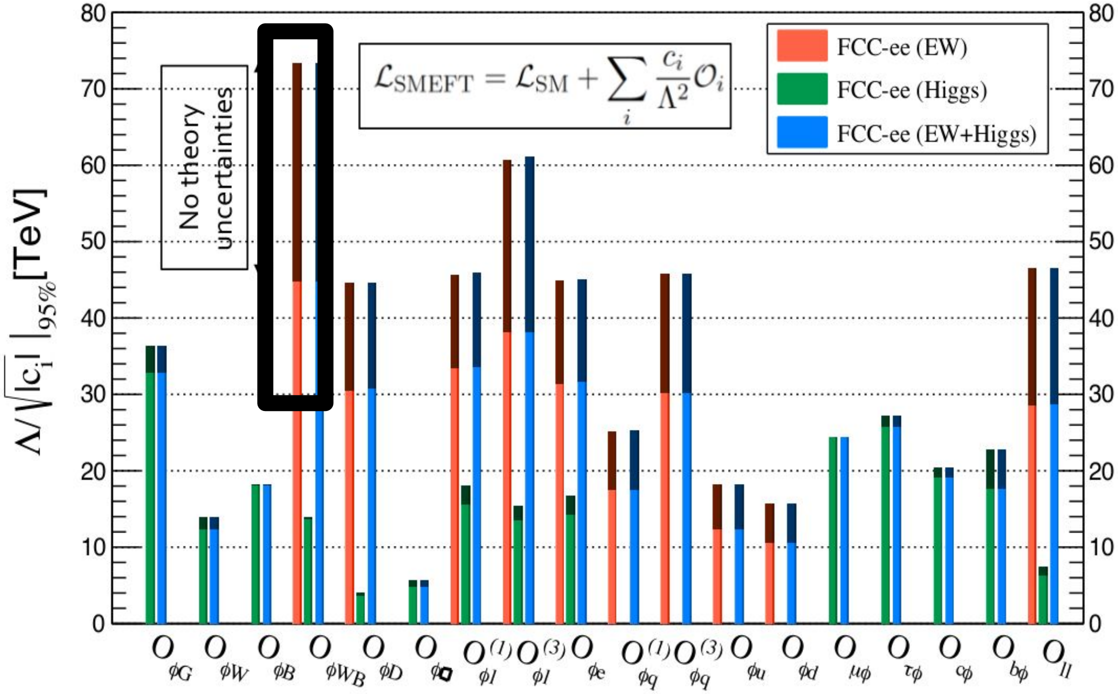
FCC-ee strengths: Z pole, SM parameters

- **At the Z pole: 150 ab^{-1}, 5 x 10^{12} Z decays in ≈ 4 years of running**
- **Exquisite control of beam uncertainties (average, width, systematics):**
  - **Extraordinary √s precision ("resonant depolarization")**
    - **100 keV at the Z, 300 keV at WW threshold**
  - **No need for longitudinal beam polarization (FB τ polarization asymmetry does the job of measuring A_e with almost zero systematics)**

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 leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	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
$\sin^2\theta_W^{\mathrm{eff}}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{\mathrm{QED}}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	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 $A_{FB}^{\mathrm{pol},\tau}$; systematics from non-$\tau$ 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

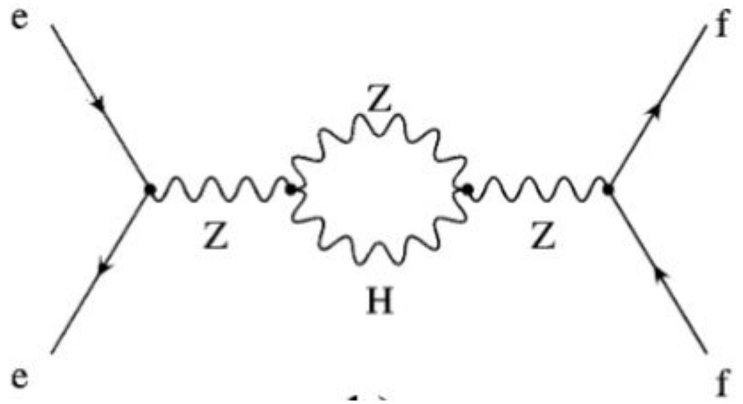
≈ two orders of magnitude improvement expected for Γ_Z, R_l, α_s, $\sin^2\theta_W^{\mathrm{eff}}$

FCC-ee: scale reach from EWK precision

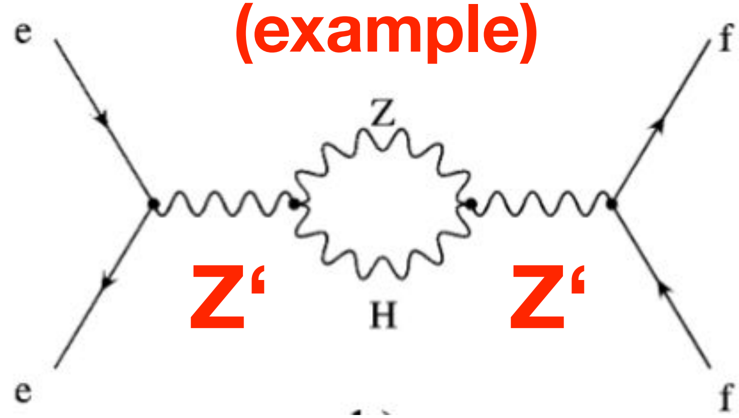


- **Probing the 10-TeV scale for new-physics effects with just a few years of FCC-ee EW running**
- **≈ 70 TeV reach corresponds to the 95% CL expected constraint on the S oblique parameter**

SM corrections



BSM corrections (example)



FCC-ee as HF/tau factory (S. Monteil, M. Chrzaszcz)

A- Particle production at the *Z* pole:

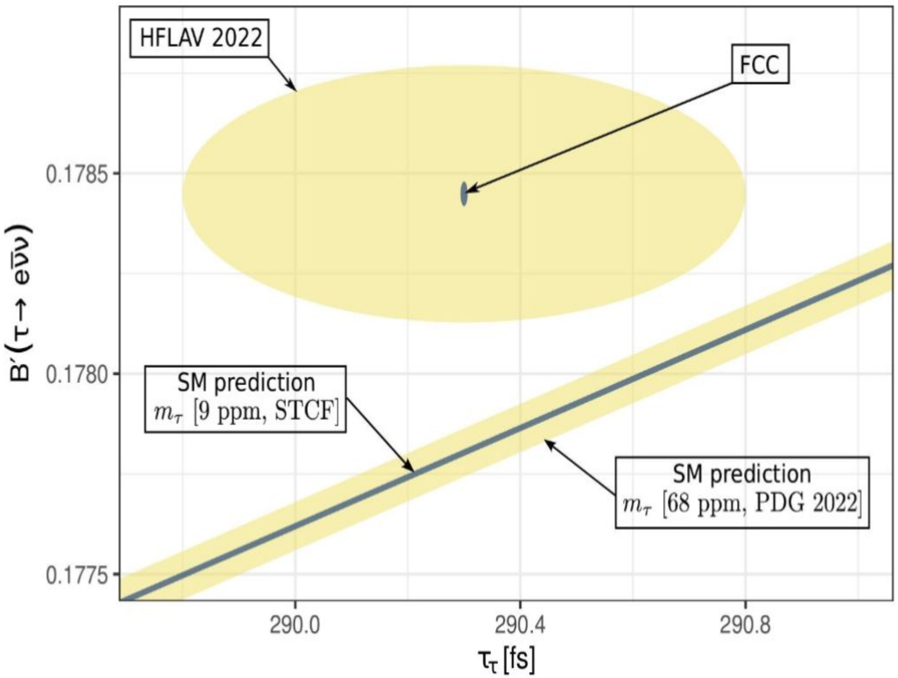
- About 15 times the Belle II anticipated statistics for B^0 and B^+.
- All species of *b*-hadrons are produced.
- Expect ~4.10^9 B_c-mesons assuming $f_{B_c}/(f_{B_u}+f_{B_d}) \sim 3.7 \cdot 10^{-3}$

Comparison w/ LHCb and Belle II. Advantageous attributes:

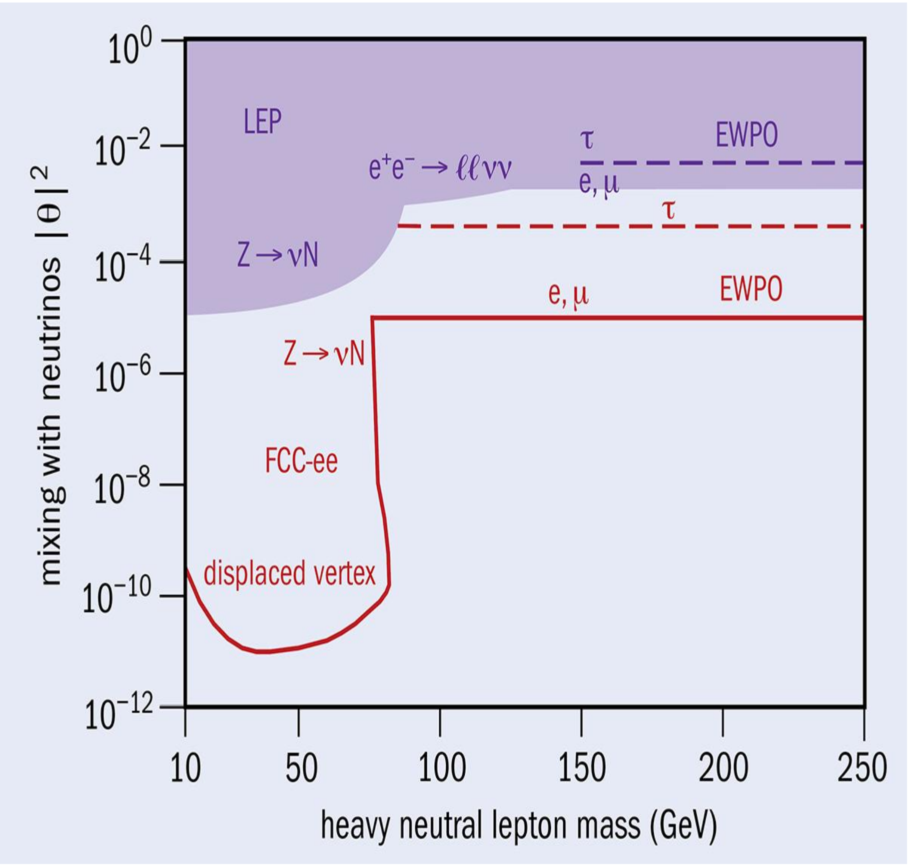
Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

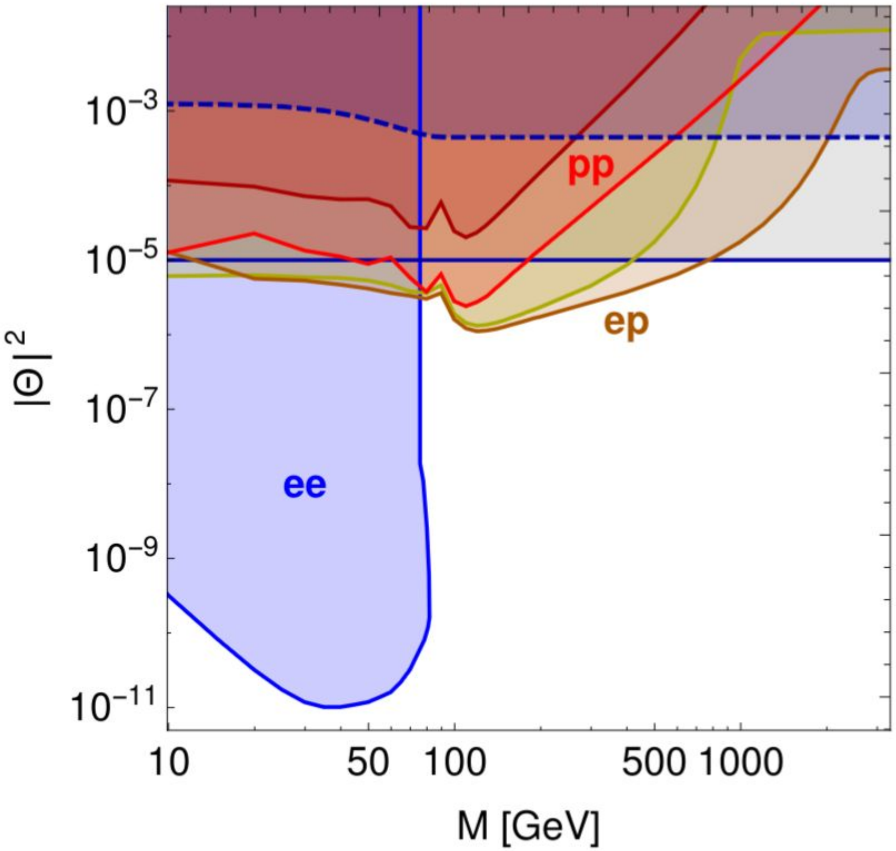
Canonical Tau Lepton Universality test

HFLAV 2022 in yellow, FCC estimates in blue



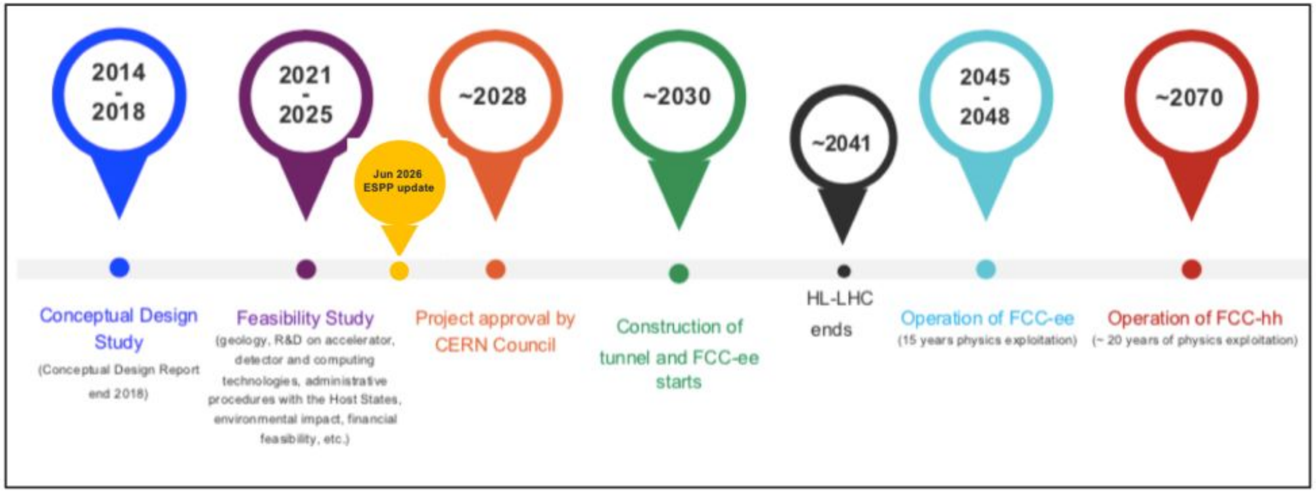
FCC-ee: rare / axion / HNL / FIP “factory”





- Reaching see-saw limit (≈ 10^{-11} mixing) for masses < m_Z
- Extended beyond 90 GeV via electroweak-precision observables

FCC timeline (F. Gianotti, FCC Week 2024)



1st stage collider FCC-ee: electron-positron collisions 90-360 GeV: electroweak and Higgs factory
2nd stage collider FCC-hh: proton-proton collisions at ~ 100 TeV

Next steps:

- ❑ Complete Feasibility Study by March 2025
- ❑ ESPP update: process started by Council in March → to be completed in June 2026 → see next slide
- ❑ Preparation for Council decision on FCC end 2027/beg 2028: “pre-TDR phase”

FCC project: feasibility study

Deliverables (approved by Council in Sept 2022):
D1 : Definition of the baseline scenario
D2 : Civil engineering
D3 : Processes and implementation studies with the Host States
D4 : Technical infrastructure
D5 : FCC-ee accelerator
D6: FCC-hh accelerator
D7: Project cost and financial feasibility
D8: Physics, experiments and detectors

Documents:
- ❑ Mid-term report (all deliverables except D7; ~ 700 pages)
- ❑ Executive Summary of mid-term report (~ 50 pages)
- ❑ Updated cost assessment (D7)
- ❑ Funding model (D7)

DONE and approved

Cost/funding (F. Gianotti, FCC Week 2024)

FCC-ee construction cost up to operation at ZH : ~ 15 BCHF

Includes:
- ❑ Civil engineering (tunnel, experimental caverns, surface sites, etc.)
- ❑ FCC-ee collider and injectors
- ❑ Technical infrastructure
- ❑ Other infrastructure (roads, power lines, land, etc.)
- ❑ 4 detectors

Does not include upgrade to ttbar operation (~ 1.5 BCHF)

Updated cost assessment made in 2023, reviewed by dedicated Cost Review Panel of experts (chair N. Holtkamp), which concluded:
- ❑ cost estimates are appropriate for this stage of the study
- ❑ uncertainty estimates are realistic; most items are class 4 (- 30% to + 50%) or class 3 (-20% to +30%).
  Aim at class 3 for all main items at the end of the Feasibility Study

Note: **care should be taken when comparing with other proposed future colliders, whose cost estimates are in most cases not so detailed and complete, and have not been re-assessed recently** (high inflation over past years!)

Funding

CERN Budget can cover more than half of the cost. Contributions expected from non-Member States with interested communities (e.g. US) and from Member States (beyond their contributions to CERN Budget).
Other contributions may come from the European Commission and private donors.

Preliminary funding model (including construction and operation expenses) and funding scenarios studied
→ will be further developed in the coming year based on discussions in Council and with potential partners.

Important notes:
- **current step is the solid assessment of the cost**
- **funding model to be established in the coming year**

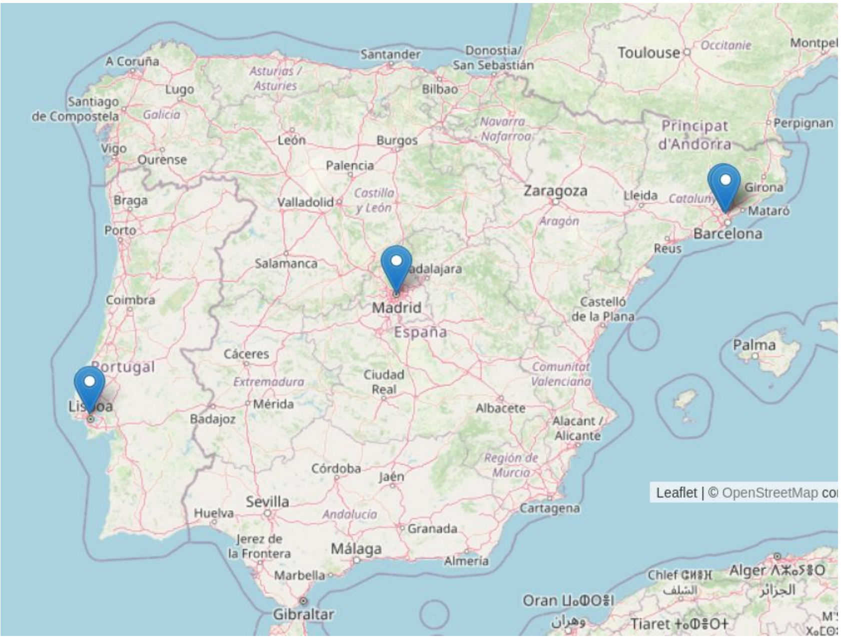
Spanish contributions

- FCC is a relatively new project, with initial studies around the last European Strategy (CDRs released for 2019 meetings), and a Horizon EU Innovation Study Feasibility project started in 2021.

- FCC is a global collaboration, with ~ 150 institutions (https://fcc.web.cern.ch/collaboration)

  - FCC MoU signed by several Spanish Institutes. Significant technological contributions, centered mostly around FCC-hh for the moment:

    - CIEMAT-CDTI (dipole magnets)
    - ICMAB-UPC-ALBA-IFAE (HTS coated conductors for beam screens)



Spanish contributions

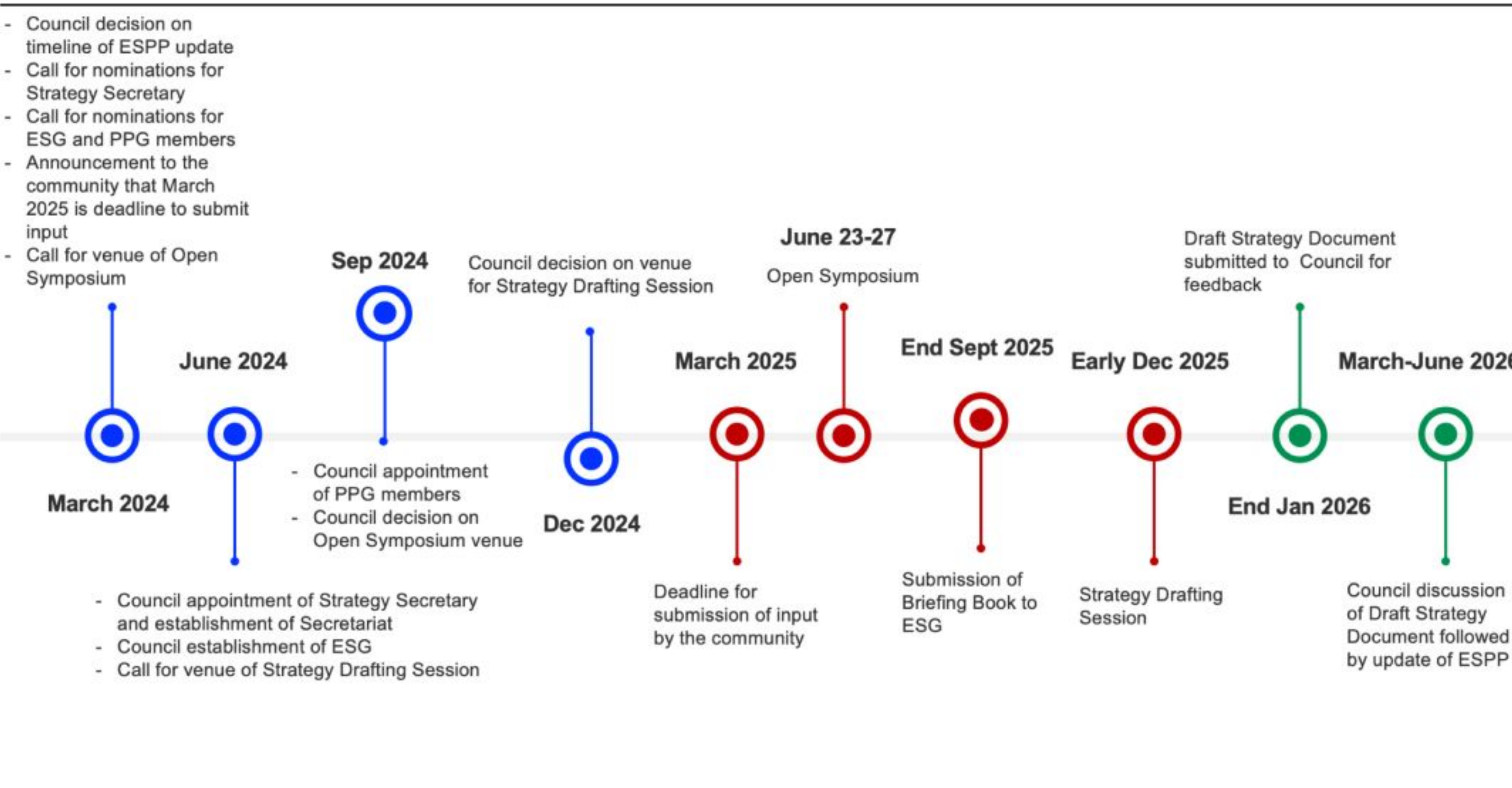
- **Specific Physics contributions by Spanish physicists. mostly centered around FCC-ee:**
  - **FCC-ee Snowmass White Paper, signed by: J. Alcaraz (EWK-tables, A_{FB}(b), A. Pich (flavour b→ll, taus), M. Vos (Top-EWK couplings), S. Heinemeyer (BSM-Higgs), J. De Blas (EWK-global fit)**
  - **FCC PED (Phys/Exp/Det) organizational structure:**
    - **J. De Blas: Higgs**
    - **S. Heinemeyer: BSM**
    - **(J.A.: EWK in the past)**
  - **CIEMAT group fully involved in PED (Phys/Exp/Det) FCC-ee activities:**
    - **J.A.: A_{FB}(b), $\gamma\gamma$, EWK precision measurements, HZ studies**
    - **M. Cepeda: Tau polarization, HZ studies**
    - **MC. Fouz, J.A., M. Cepeda, …: ILD detector integration in FCC-ee (just started)**
- **Many specific theory contributions/papers are focusing frequently on FCC (ee or hh)**
- **Also contributions to other accelerator/detector modes (IGFAE: FCC-eh, FCCb)**
- **Several Spanish people involved in the FCC mid-term report (from CIEMAT, UGR, USC, IFIC/UVAL, …)**

Spanish contributions

- Many of these activities are synergistic and can also profit from the ECFA Hifggs/EWK/TOP (HET) Factory Studies, where Spain has a key participation:
  - M.C. Cruz: WG3 (detector R&D) coordinator
  - J. De Blas: WG1 (Physics Potential) coordinator (also J.A. until 2023)
  - A. Irles: WG1-precision group convener
  - M. Vos, S. Heinemeyer: WG1-global interpreteations group conveners
- Outcome of HET studies: focus topics, covering all accelerator options for a Higgs factory
  - https://arxiv.org/abs/2401.07564

Backup

European Strategy Update timeline



Physics outlook

- **We are facing a new period of challenges in Particle Physics. Next priorities at laboratory (accelerators) are:**
  - Deep study of the Higgs sector
  - Detailed exploration of what is beyond the SM at the 10 TeV scale

- **FCC is a unique machine for this purpose, and much more:**
  - FCC-ee:
    - Measurements in the Higgs sector with < % precision
    - A Z/b/c/τ factory
    - Most sensitive search for very rare decays via Z production
    - Ultimate precision on m_W, m_t, m_H, α_S, $\sin\theta_W$(eff) parameters of the SM
    - Most sensitive “indirect” exploration of the 10 TeV scale via precision electroweak measurements

  - FCC-hh (+eh):
    - Unique way to “directly” explore of the 10 TeV scale,
    - Complementary to FCC-ee: ‰ Higgs measurements, comprehensive picture of deviations from SM

FCC-ee parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr] 4 IPs	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10

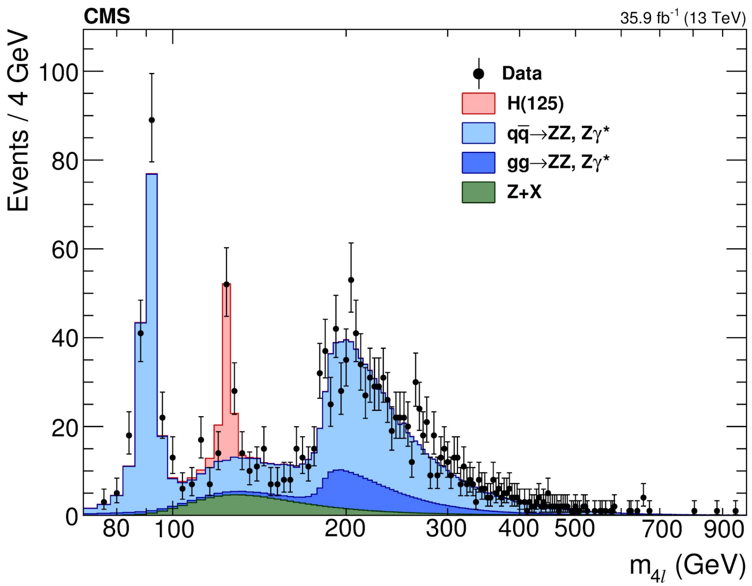
FCC-hh parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 (Nb_3Sn) - 20 (HTS)	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

SM, LHC, the Higgs and beyond

Now the Standard Model (SM) has become an extremely solid baseline:

- We have discovered a particle that matches the properties of the Higgs boson – the last missing piece of the SM puzzle



- No apparent deviations from SM predictions, but the mere existence of an "elementary" scalar is theoretically disturbing → suggesting new physics
- No clear theoretical path to go beyond the SM: a "leap in the dark"

- **D. Arkani-Jamed: "*... when theorists are more confused, it's time for more, not less, experiments*"**

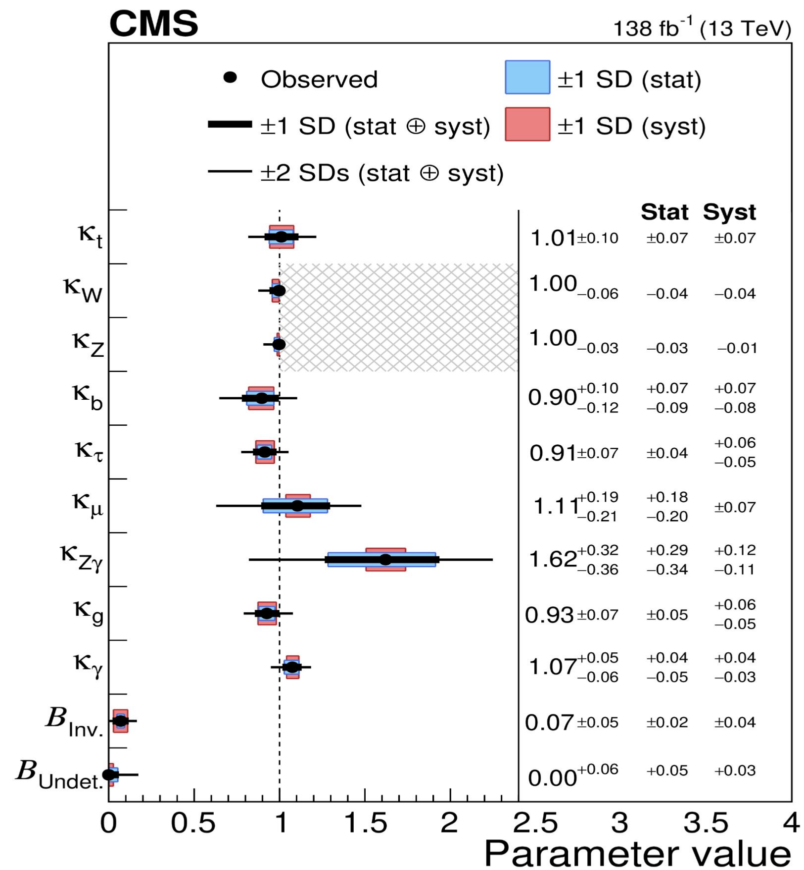
What we know about the Higgs

- Its mass (≈ 125 GeV) known with per mille precision
- Quantum numbers consistent with a scalar particle: $J^{PC} = 0^{++}$
- Structure and size of the couplings consistent with the one predicted by the SM

- Observed couplings to:
  - a) massive bosons,
  - b) third generation quarks (top, bottom)
  - c) third generation leptons (tau)

- Evidence for its coupling to 2^{nd}-generation fermions ($H\rightarrow\mu\mu$)

- **We know these couplings at the ~10% level**

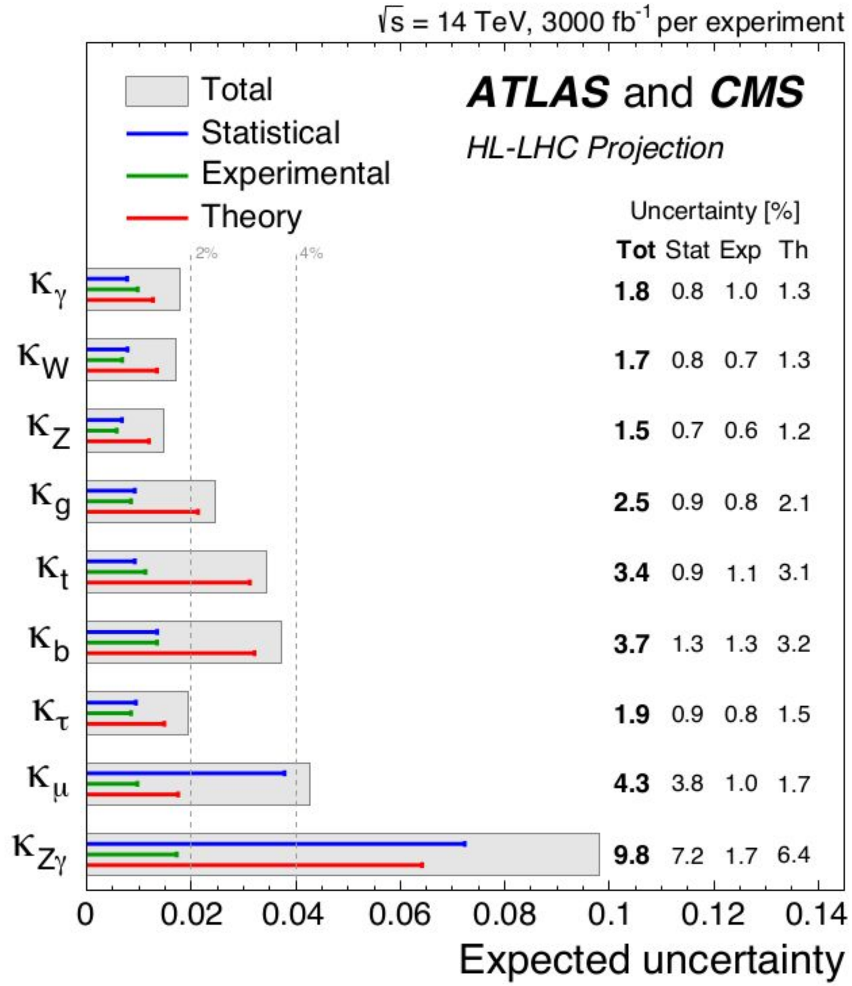


CMS-HIG-22-001

HL-LHC Higgs improvements

- “Extrapolated” precisions of order of a few percent in some channels, but:
    - Dominated by theoretical uncertainties (assumed to be ½ of current values !)
    - with large experimental systematics
- **Should we improve the precision on the Higgs couplings,? YES**

arxiv:1902.00134



Some Higgs numbers ("kappa" fits)

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years	10	11.5	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5	0.30 / 0.29	0.50 / 0.44	0.19 / 0.18	0.18 / 0.17
g_{HWW} (%)	1.7	1.8 / 1.0	0.86 / 0.73	1.3 / 0.88	0.44 / 0.41
g_{Hbb} (%)	5.1	1.8 / 1.1	1.9 / 1.2	1.3 / 0.92	0.69 / 0.64
g_{Hcc} (%)	SM	2.5 / 2.0	4.4 / 4.1	2.2 / 2.0	1.3 / 1.3
g_{Hgg} (%)	2.5	2.3 / 1.4	2.5 / 1.5	1.5 / 1.0	1.0 / 0.89
$g_{H\tau\tau}$ (%)	1.9	1.9 / 1.1	3.1 / 1.4	1.4 / 0.91	0.74 / 0.66
$g_{H\mu\mu}$ (%)	4.4	15. / 4.2	– / 4.4	9.0 / 3.9	8.9 / 3.9
$g_{H\gamma\gamma}$ (%)	1.8	6.8 / 1.3	– / 1.5	3.7 / 1.2	3.9 / 1.2
$g_{HZ\gamma}$ (%)	11.	– / 10.	– / 10.	8.2 / 6.3	– / 10.
g_{Htt} (%)	3.4	– / 3.1	– / 3.2	– / 3.1	10. / 3.1
g_{HHH} (%)	50.	– / 49.	– / 50.	– / 50.	44./33. 27./24.
Γ_H (%)	SM	2.2	2.5	1.7	1.1
BR_{inv} (%)	1.9	0.26	0.65	0.28	0.19
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	1.1

- **Huge statistics is key to go below % uncertainties**
- **FCC-ee measurements dominated by statistical uncertainties !!**
  - **Frequent high-statistics calibrations at the Z peak**
  - **Luminosity well below permille uncertainty (⇒ relevant for cross sections)**
  - **Also, theoretical uncertainties will be smaller than stat. uncs. in the future**

FCC-hh will complement the FCC-ee

Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50
$g_{\mathrm{H}\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46
$g_{\mathrm{H}\mu\mu}$ (%)	9.4 / 3.9	6.3 / 3.6	5.9 / 3.5	0.43 / 0.43
$g_{\mathrm{H}\gamma\gamma}$ (%)	3.5 / 1.2	1.9 / 1.1	2.3 / 1.1	0.32 / 0.32
$g_{\mathrm{HZ}\gamma}$ (%)	– / 10.	– / 10.	7. / 5.7	0.71 / 0.70
g_{Htt} (%)	6.9 / 2.8	1.6 / 1.4	2.7 / 2.1	1.0 / 0.95
g_{HHH} (%)	27.	10.	9.	5.
Γ_{H} (%)	1.1	1.0	1.6	0.91
$\mathrm{BR}_{\mathrm{inv}}$ (%)	0.23	0.22	0.61	0.024
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	1.4	1.4	2.4	1.0

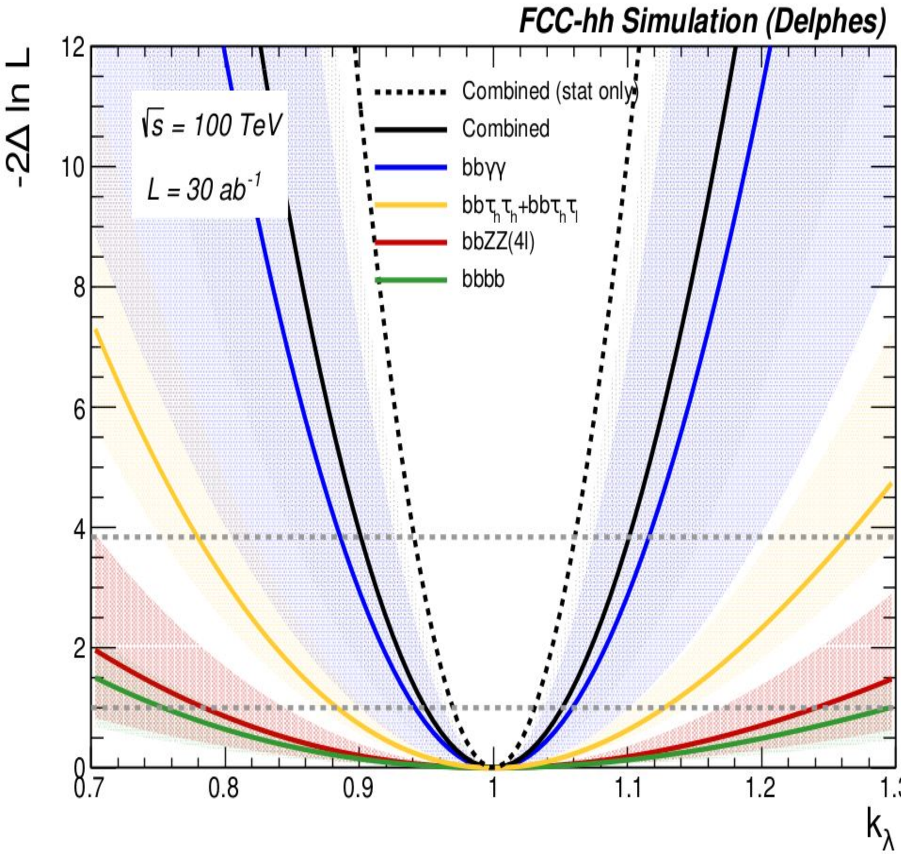
- **Relative rare decay channels that are clean and observable at LHC and FCC: Γ(H→$\mu\mu$,$\gamma\gamma$,Zγ)/Γ(H→ZZ) become precise measurements when referred to the FCC-ee Γ(H→ZZ) measurements**

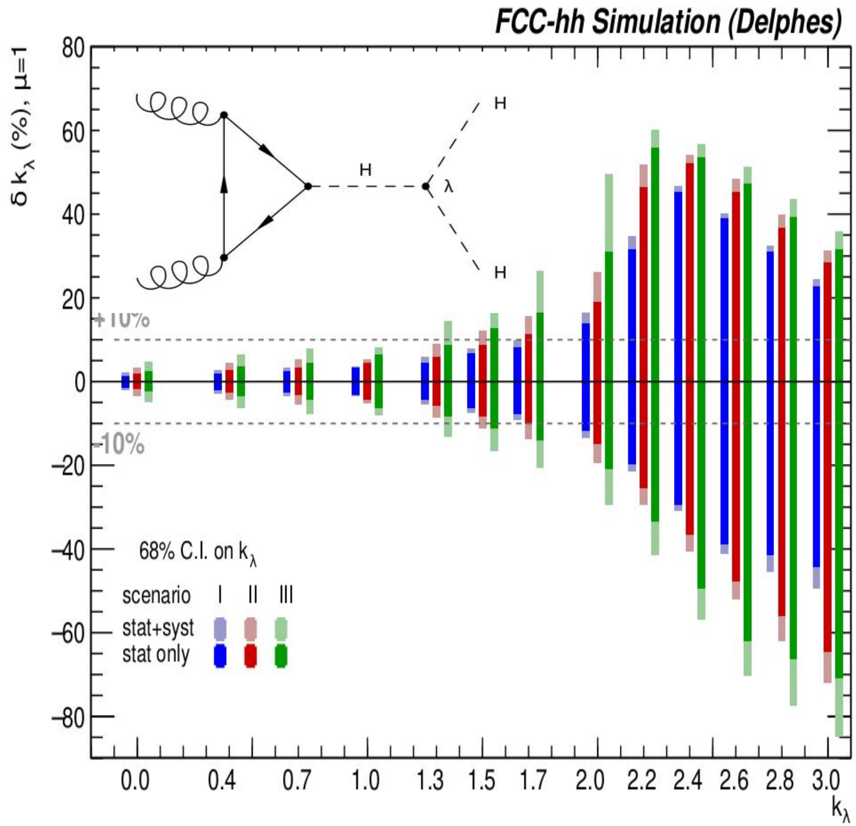
- **Great complementarity of FCC-ee and FCC-hh: all HVV and Hff couplings with precision <1% !!**

Higgs self-coupling measurement at FCC-hh

- **Measurement the Higgs self-coupling via HH production with 3-5% precision**

arXiv:2004.03505





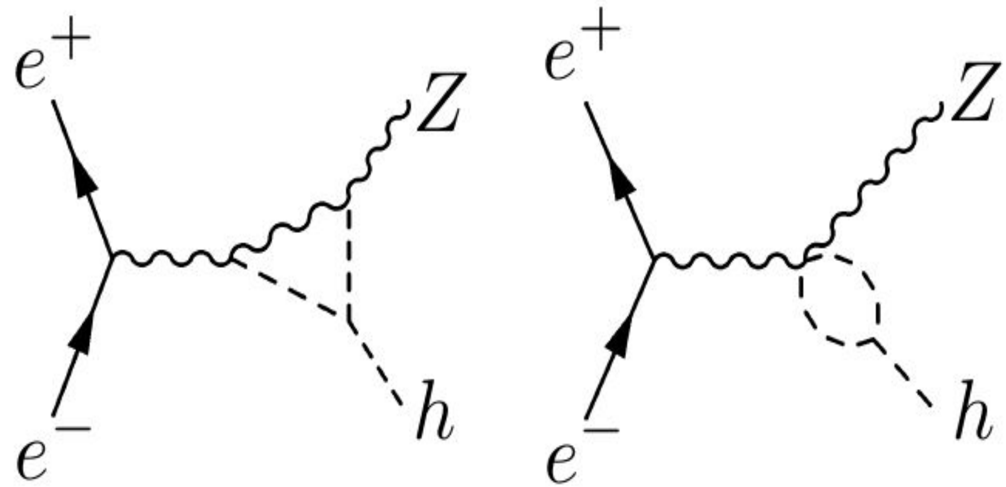
scenario I: Run2 performance (optimal)

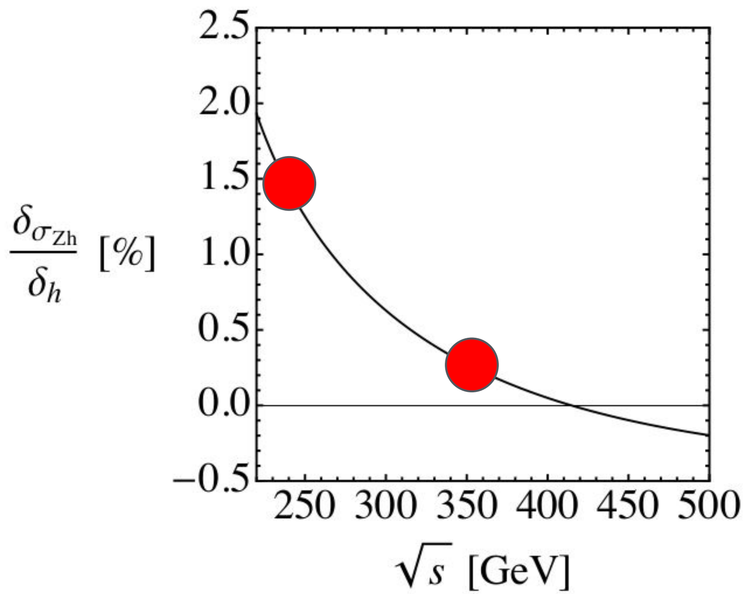
scenario III: HL-LHC conditions with performance degradation (pessimistic)

scenario II: intermediate case (assumed for left plot above)

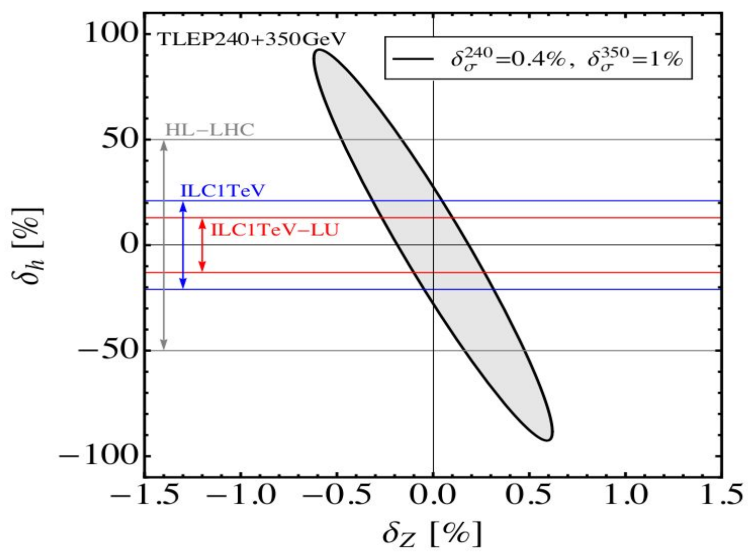
Higgs self-coupling also at FCC-ee: ee→HZ channel

arXiv:1312.3322

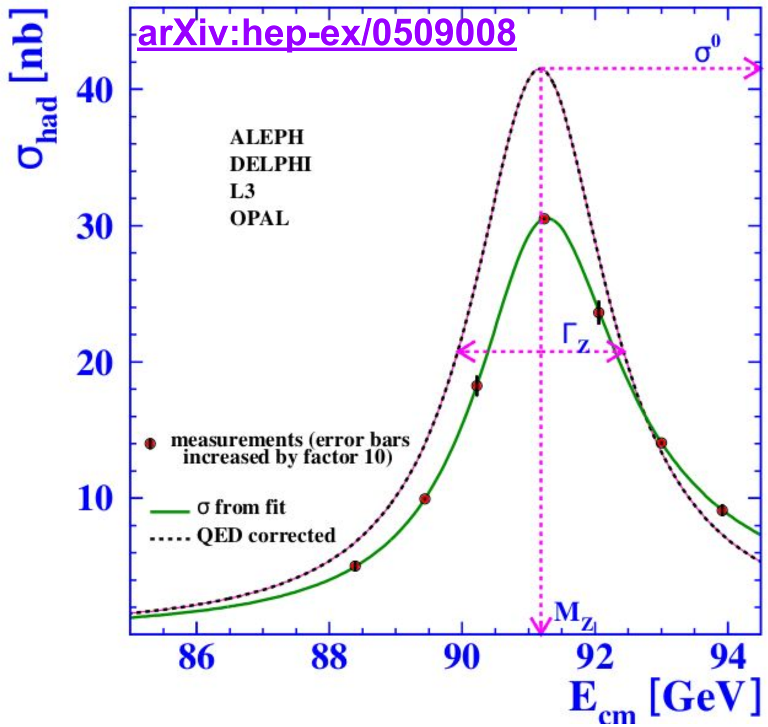


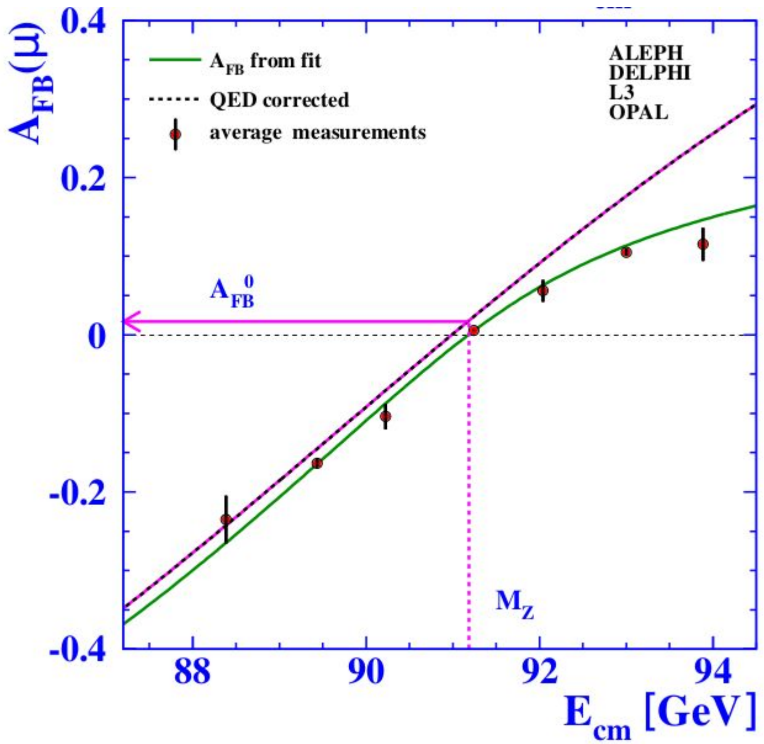


- If one includes NLO effects ⇒
  - HHH coupling (δ_h) effects are √s-dependent
  - HZZ coupling (δ_Z) effects may be constant with √s (composite Higgs, for instance)
- Aim: 30% precision (dedicated analysis ongoing)



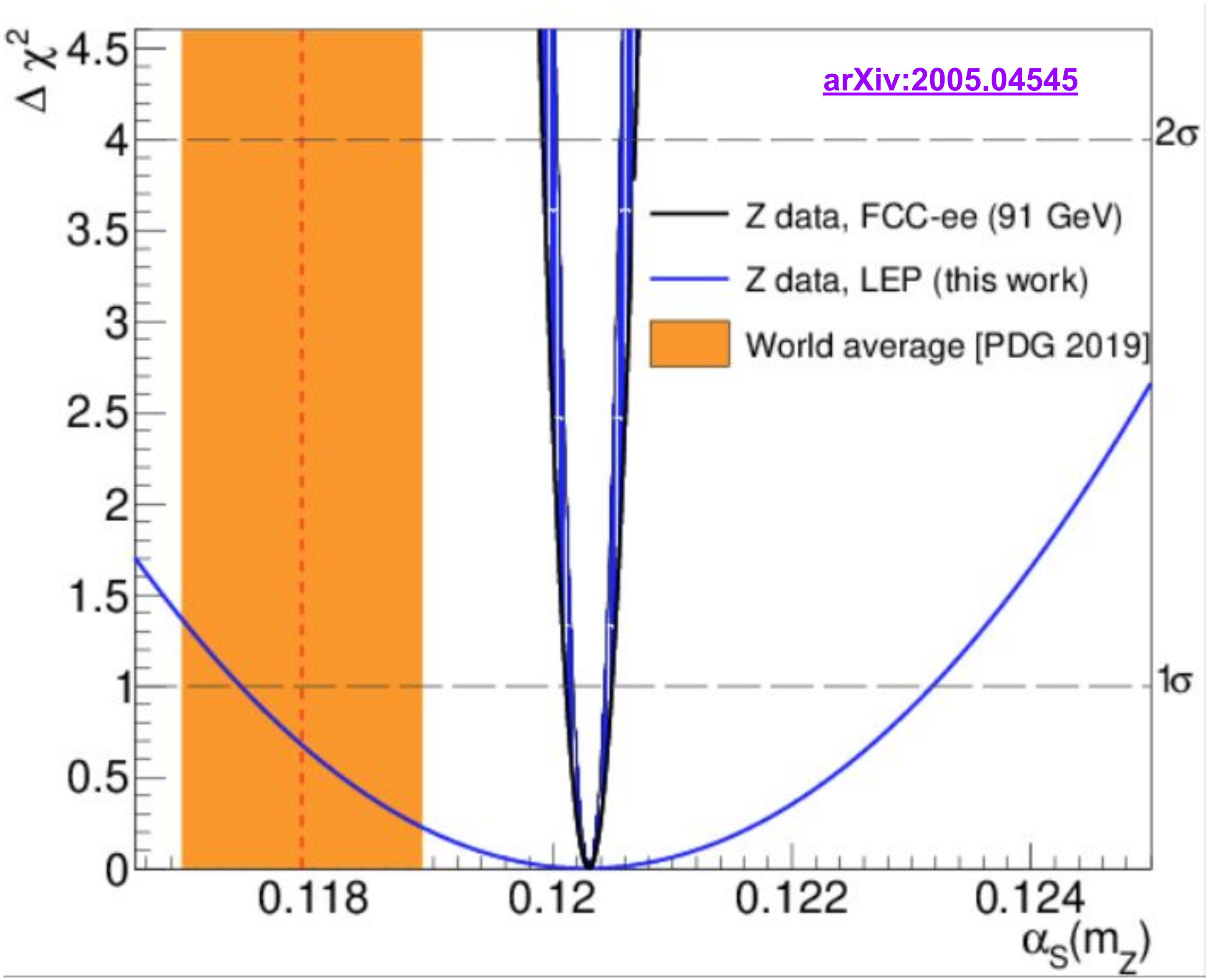
Z pole scan: cross sections, asymmetries



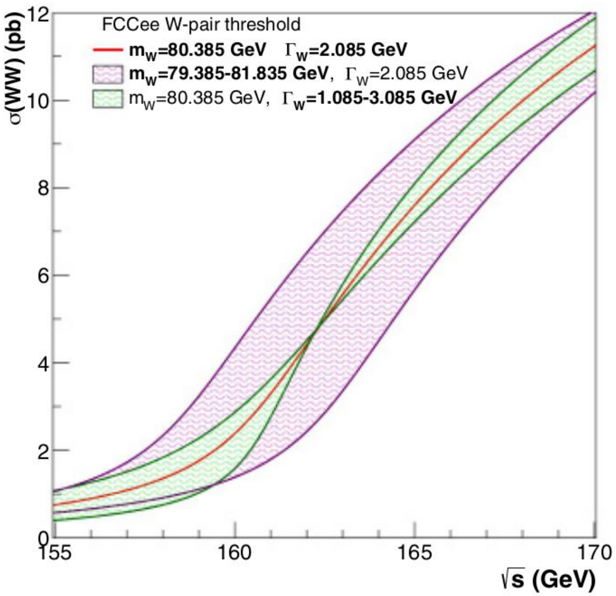


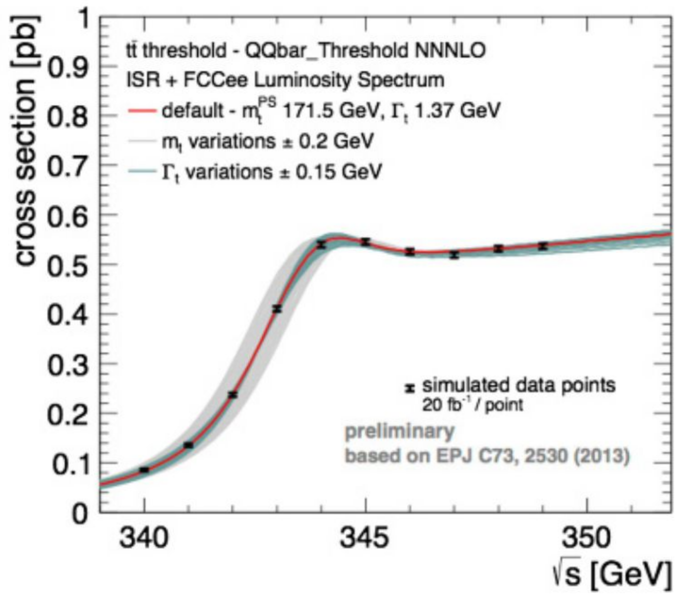
- **≈ 10^{-4} precision on cross sections due to luminosity uncertainty:**
  - **possibility to reduce it by an order of magnitude using the measured $\sigma(ee\rightarrow\gamma\gamma)$ as reference**
- **≈ 10^{-6} statistical uncertainties (≈ $1/\sqrt{N}$) on relative measurements:**
  - **Forward-backward charge asymmetries, cross-section ratios**

Z pole: α_s at FCC-ee (from $R_l \equiv \Gamma_{had}/\Gamma_l$)



More EWK physics: W, top masses/widths





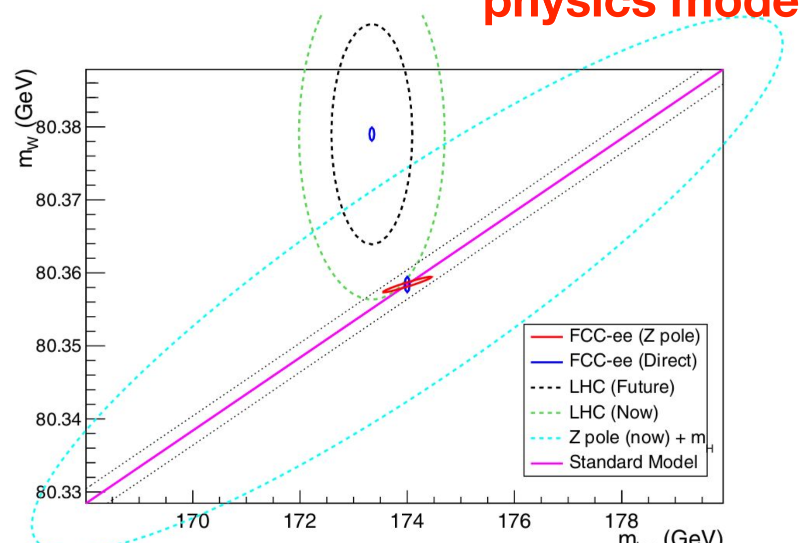
√s scans at production thresholds

Strong constraining power on new physics models

- **Expectations:**
  - **ΔM_W = 0.5 MeV, $\Delta\Gamma_W$ = 1.5 MeV**
  - **$\Delta M_t \approx$ 17 MeV, $\Delta\Gamma_t \approx$ 45 MeV**

[arxiv:2107.04444](https://arxiv.org/abs/2107.04444)

CERN-ACC-2018-0057



Heavy flavours at FCC-ee (from S. Monteil)

B- The Boost at the *Z*:

$$\langle E_{X_b} \rangle = 75\% \times E_{\text{beam}}; \langle \beta\gamma \rangle \sim 6.$$

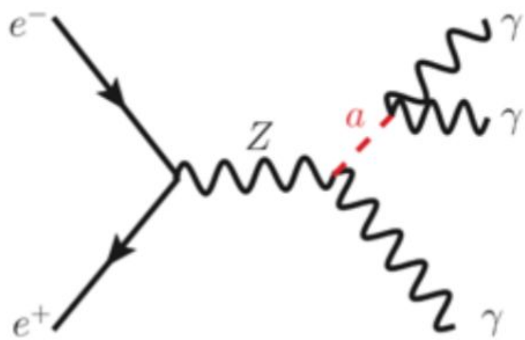
- Fragmentation of the *b*-quark:
- Makes possible a topological rec. of the decays w/ miss. energy.

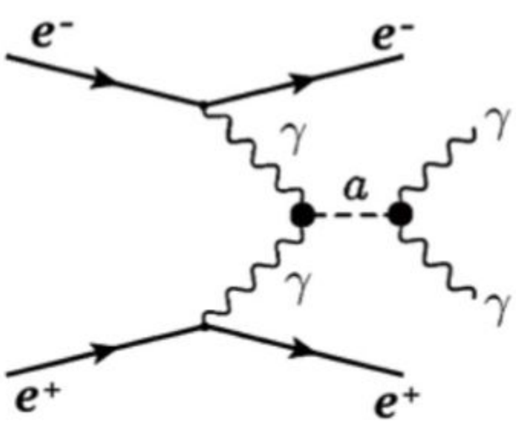
C- Comparison w/ LHCb and Belle II. Advantageous attributes:

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

D- Versatility : the *Z* pole does not saturate all Flavour possibilities. Beyond the obvious flavour-violating Higgs and top decays, the *WW* operation will enable to collect several 10^8 *W* decays on-shell AND boosted.

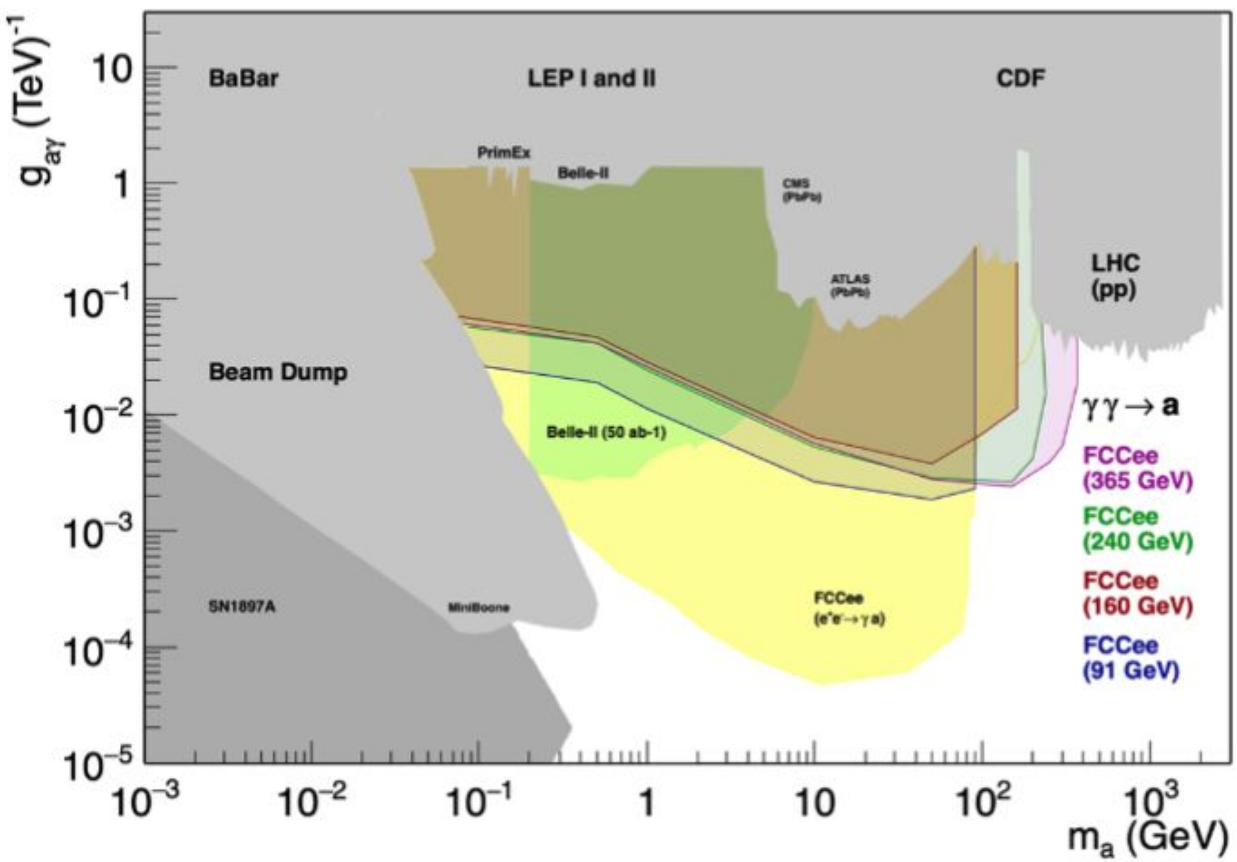
Feebly Interacting Particles at FCC-ee: axions





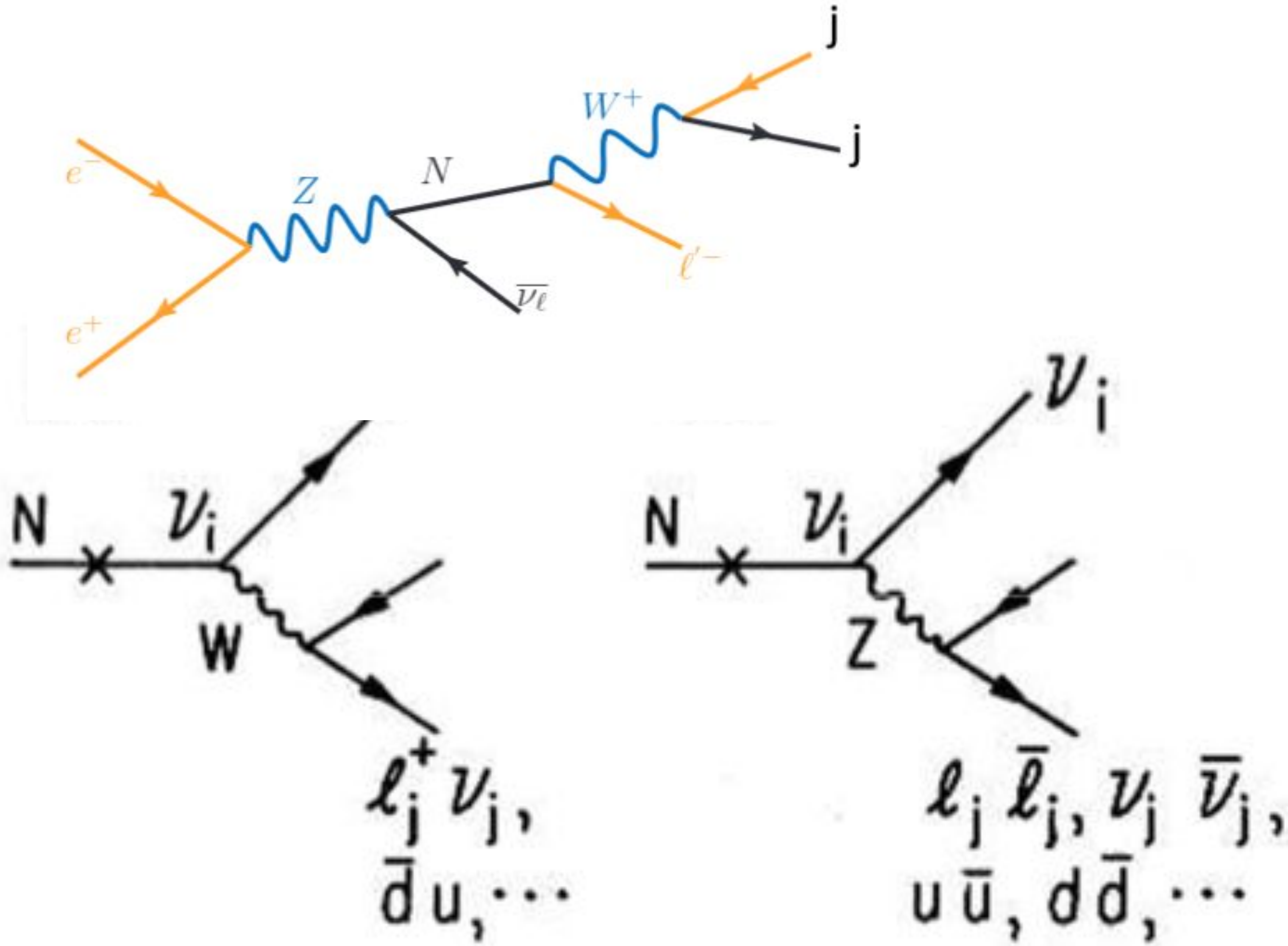
Eur. Strat.: arXiv:1910.11775

arXiv:2310.17270



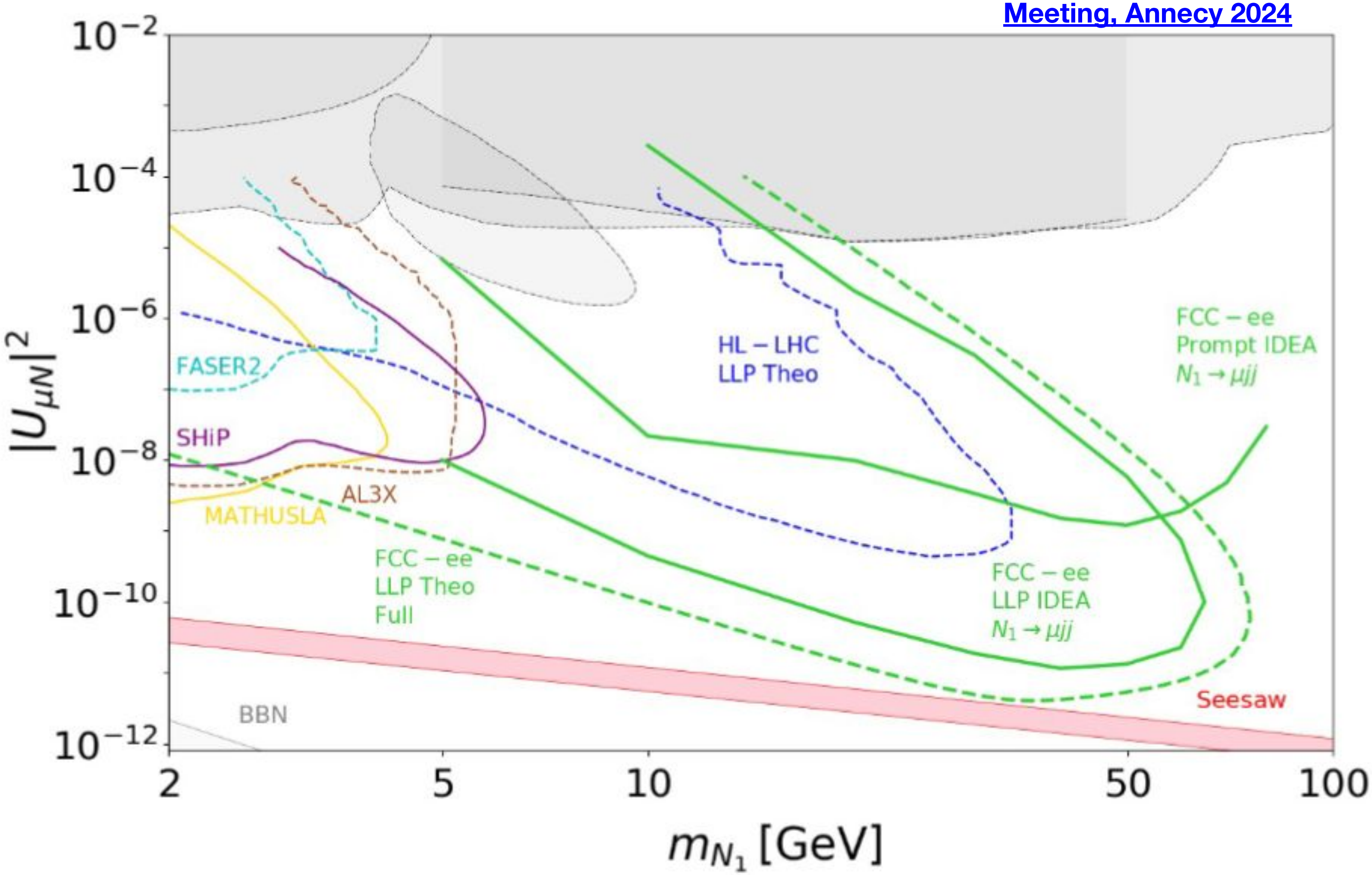
- **$Z \to a\gamma$: FCC-ee unbeatable in the m_A=1-100 GeV range**
- **$\gamma\gamma$ fusion: FCC-ee also better for $m_a \lesssim 350$ GeV**

Heavy Neutrinos at FCC-ee (FIP regime again)



Heavy Neutrinos at FCC-ee (FIP regime again)

from G. Polesello at FCC Physics Meeting, Annecy 2024

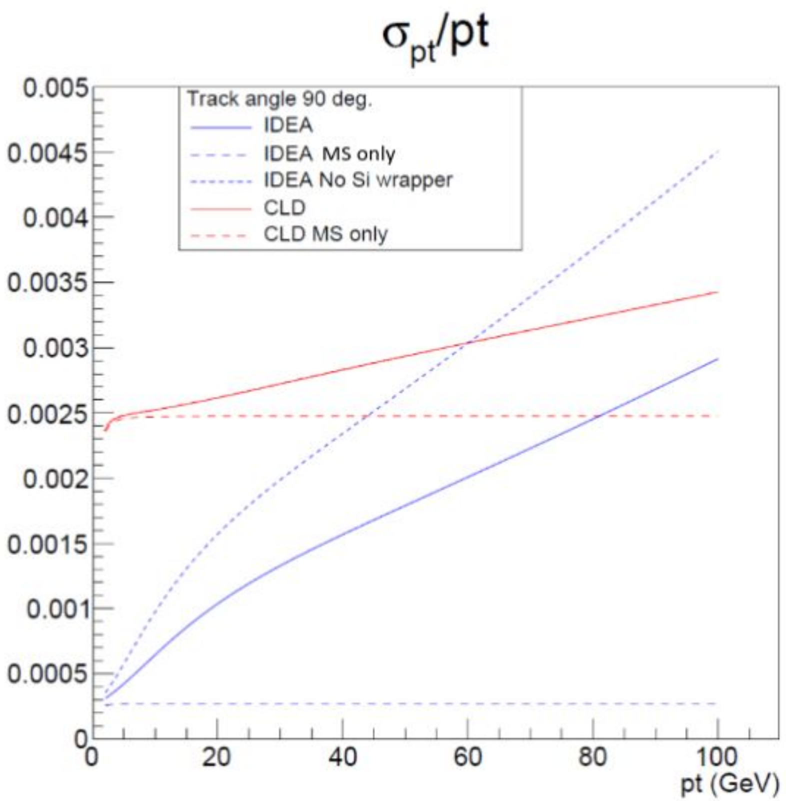


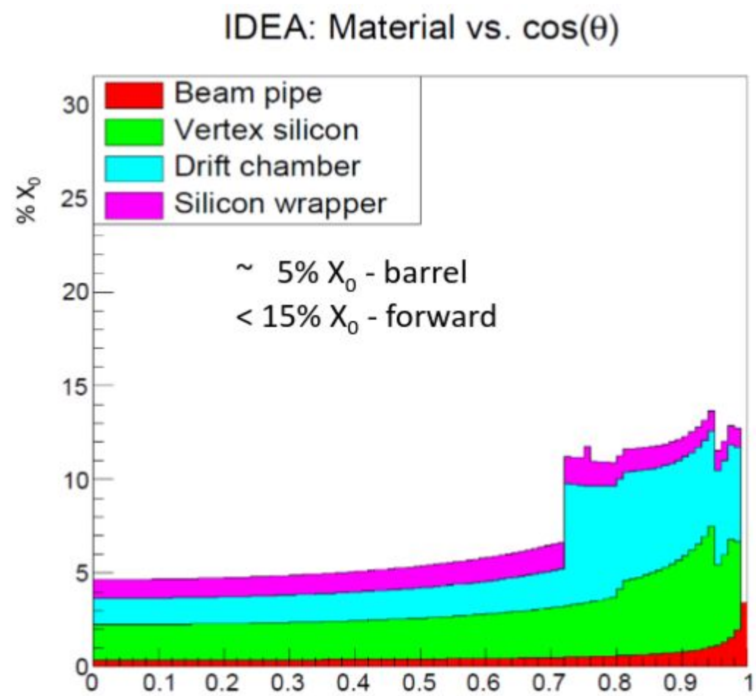
- **$U_{\mu N} \neq 0$: FCC-ee almost reaching the see-saw limit for $m_N < m_Z$**

FCC-ee detector challenges: central drift chamber

IDEA DCH designed to provide **efficient tracking, high precision momentum measurement and excellent particle identification** for particles of low and medium momenta. Main features:

- *High granularity*
- *Transparency*
- *Cluster counting technique*





Particle momentum range far from the asymptotic limit where MS is negligible

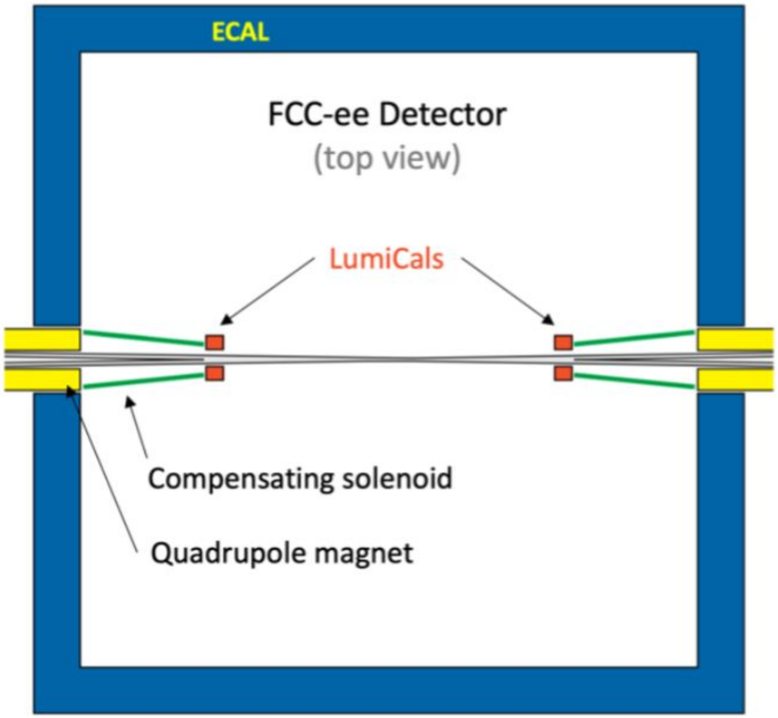
$$\frac{\Delta p_T}{p_T}\Big|_{res.} \approx \frac{12\,\sigma_{r\phi}\,p_T}{0.3\,B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\,B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

Drasal, Riegler,
https://doi.org/10.1016/j.nima.2018.08.078

FCC-ee detector challenges: luminosity monitor

LumiCal Challenges

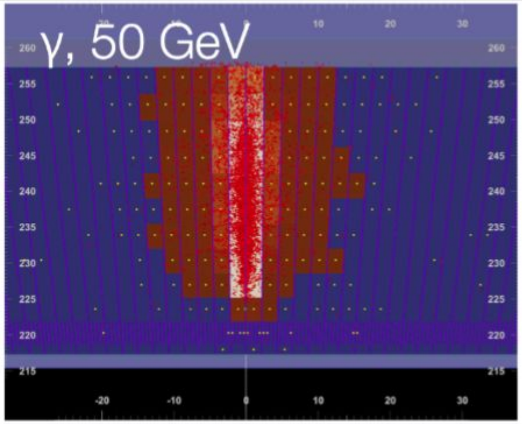


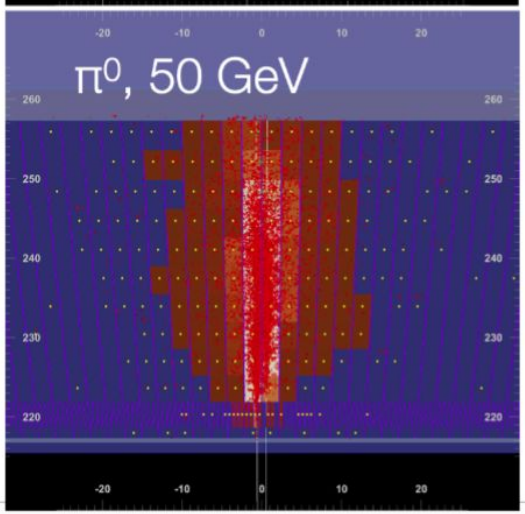
- Geometrical constraints:
  - Stay away from beampipe
  - Stay away from tracker acceptance
  - Continuity of calorimetry below forward ECAL acceptance
- Precision constraints for 10^{-4} measurement:
  - Radial dimension of monitors to be controlled to $\mathcal{O}(1\ \mu m)$
  - Distance between two monitors to be controlled to 100 μm
  - System of two monitors to be centred about collision point to precision of
    - few mm in z
    - few tenths on mm in xy plane
  - Well understood energy respons allowing good control of efficiency and background
    - Dominant single uncertianty contribution for OPAL (1.8×10^{-4})
- Pile up considerations (new wrt LEP):
  - Non-negligible probability to have two overlapping events (signal + signal/background) in the same bunch crossing

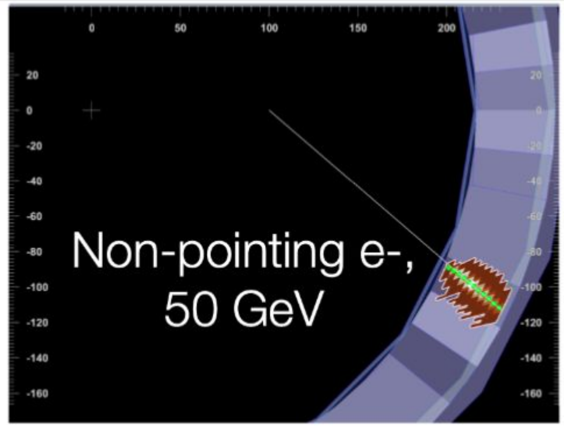
Mogens Dam / NBI Copenhagen 7th FCC Physics Workshop, Annecy 31.01.2024

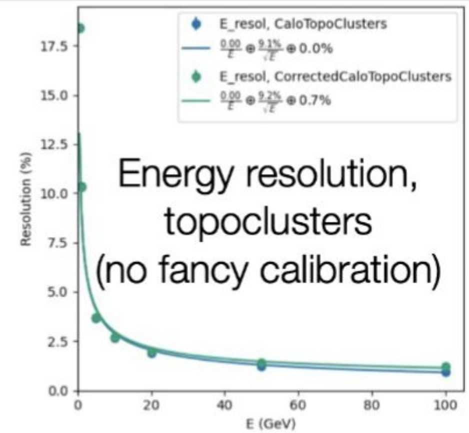
FCC-ee detector challenges: γ/π^0 separation

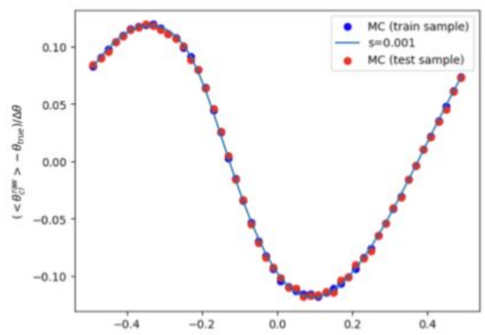
ECAL barrel simulation

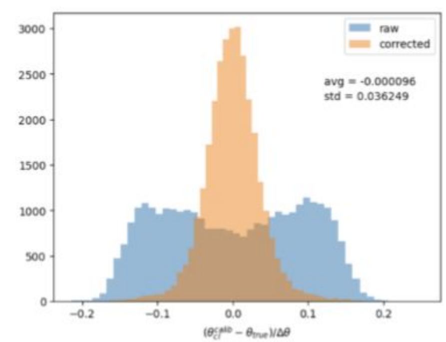










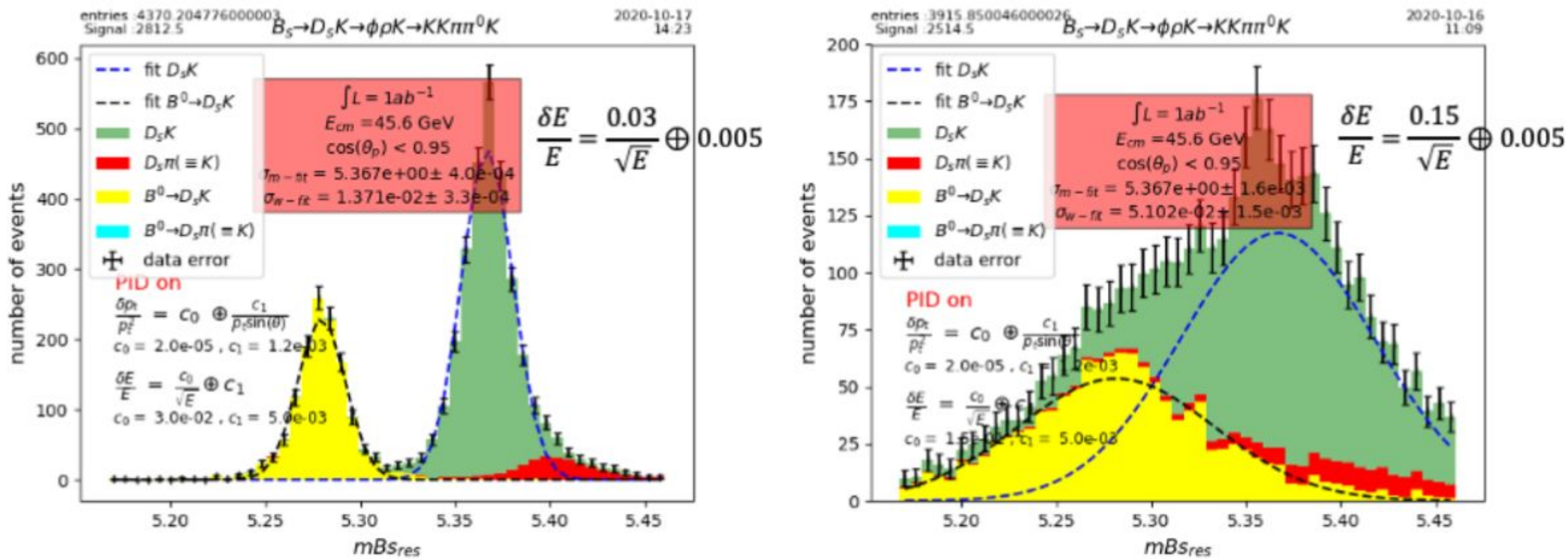


Position/direction reconstruction: S-curve
θ correction and resolution

Progress on ALLEGRO calorimeters implementation - Giovanni Marchiori -

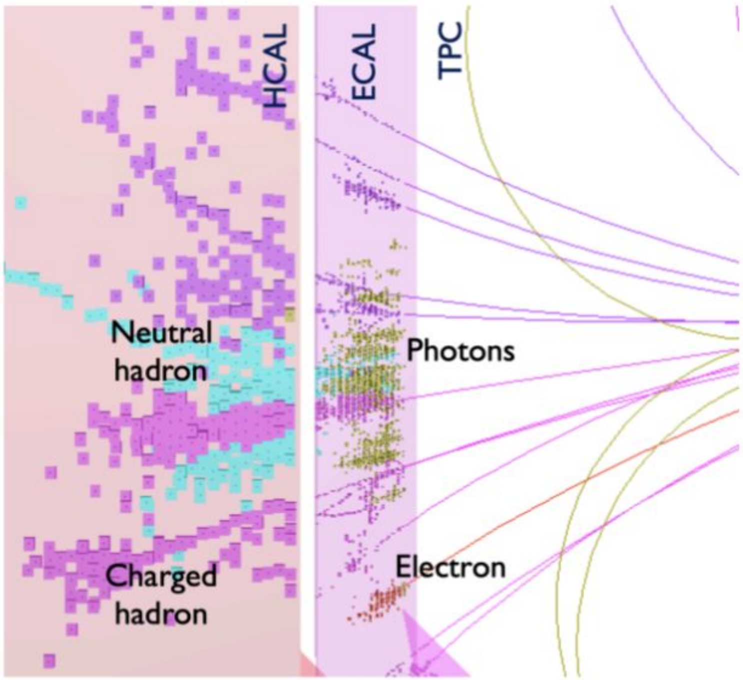
FCC-ee detector challenges: ECAL resolution

- 1) From R. Aleksan: CKM angle γ (D_sK w/ $D_s \to \phi\rho$ ($\to \pi\pi^0$))



FCC-ee detector challenges: get best Particle Flow

- Particle flow: requires the reconstruction of all individual particles
  - Charged particles (62%) through the tracker, photons (27%) through the ECAL and neutral hadrons (10%) through HCAL
- Particle Flow Objects (PFO) built from tracks and (associated) clusters:
  - Calorimeter energy resolution not critical - most energy obtained from tracks

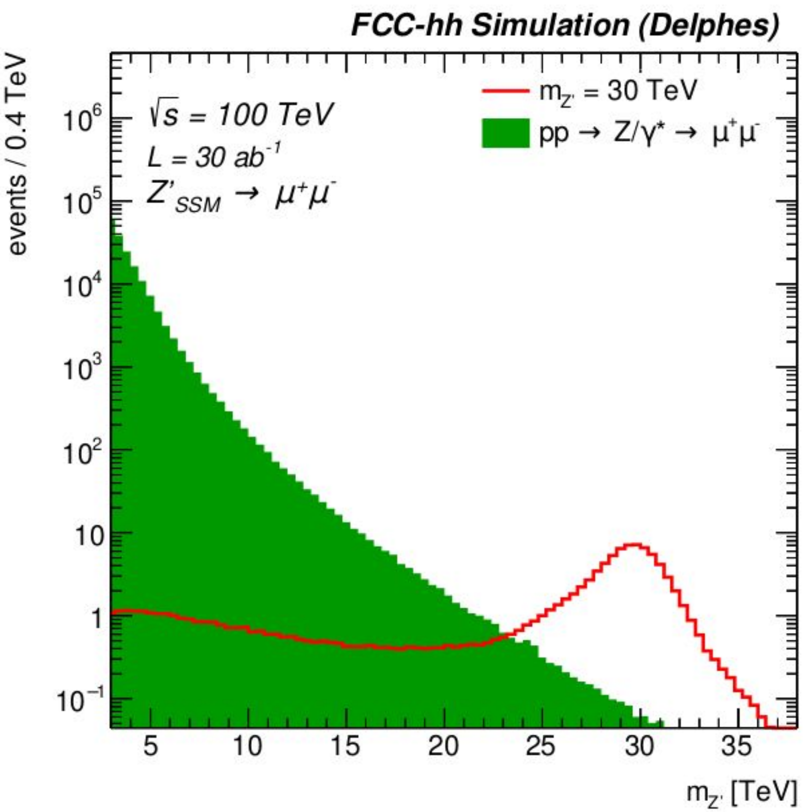


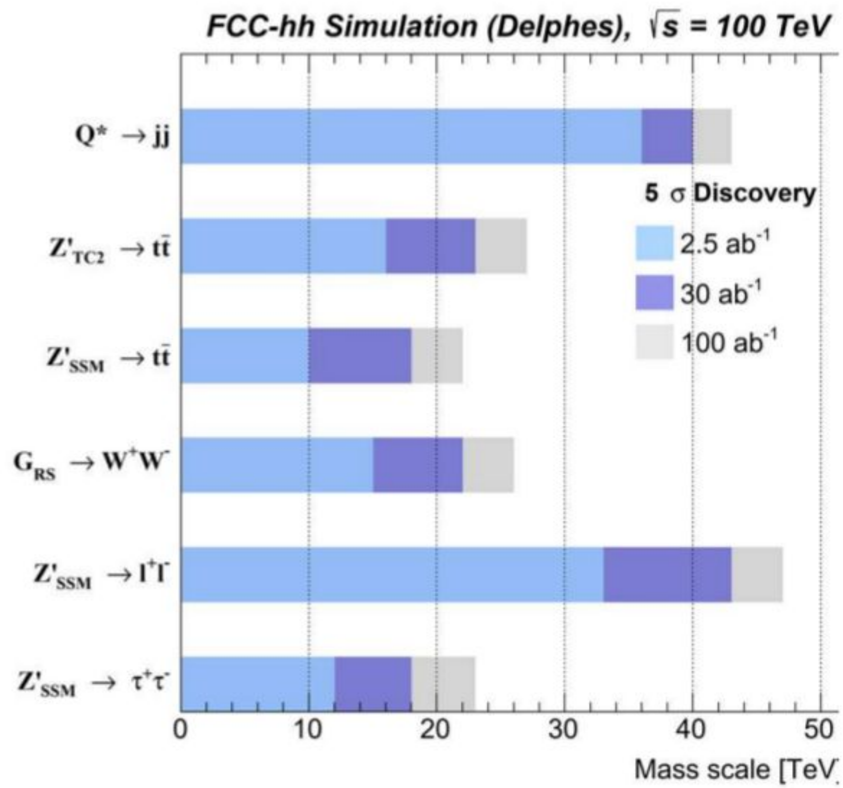
Swathi Sasikumar | Pandora Particle Flow Concept in Key4hep

1 February 2024

FCC-hh: search for new resonances

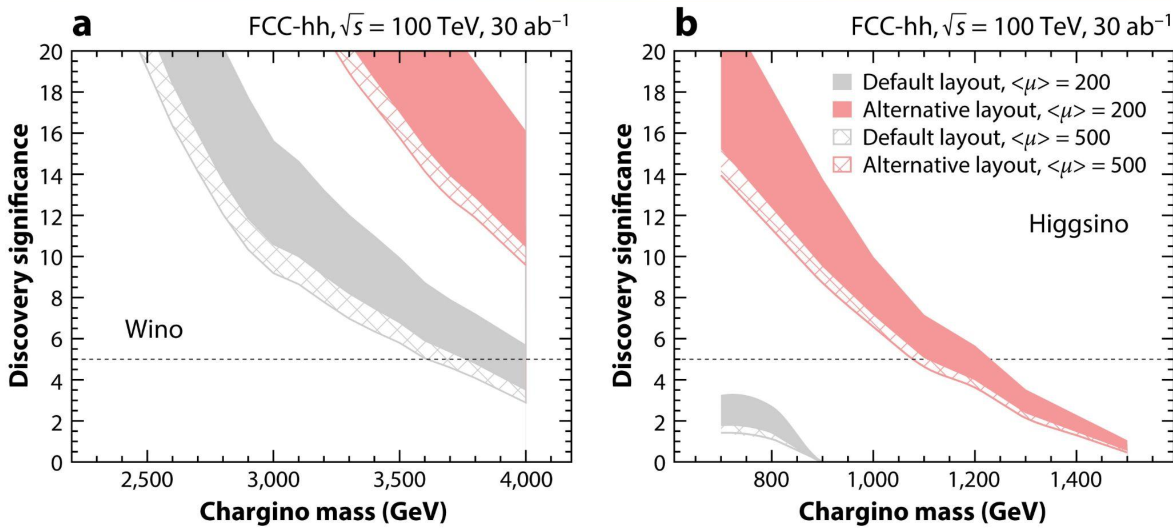
- **Direct discoveries of new particles in the 20-40 TeV range, thus becoming the ideal microscope to explore the unknown physics at the 10 TeV scale**



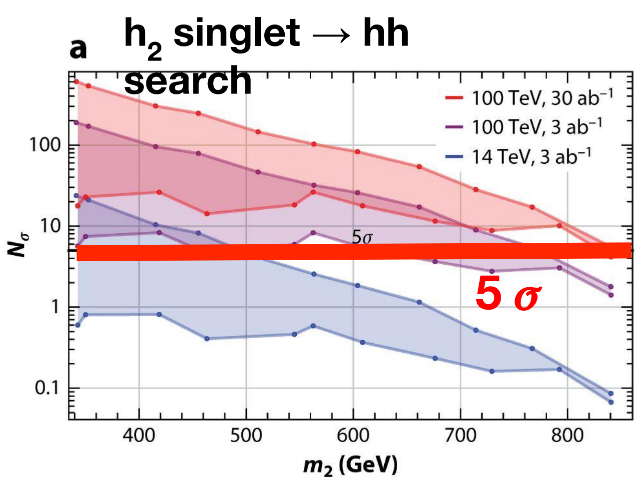


FCC-hh: dark matter, EWSB

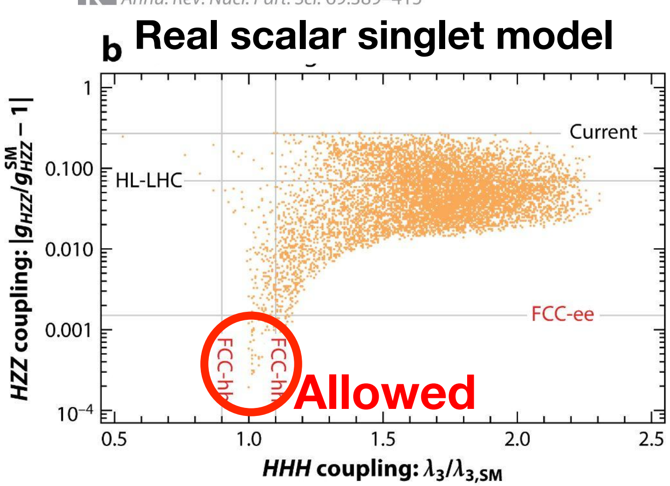
Dark matter up to ≈1-3 TeV masses (≈ upper edge of WIMPs)



Benedikt M, et al. 2019.
Annu. Rev. Nucl. Part. Sci. 69:389–415



Benedikt M, et al. 2019.
Annu. Rev. Nucl. Part. Sci. 69:389–415

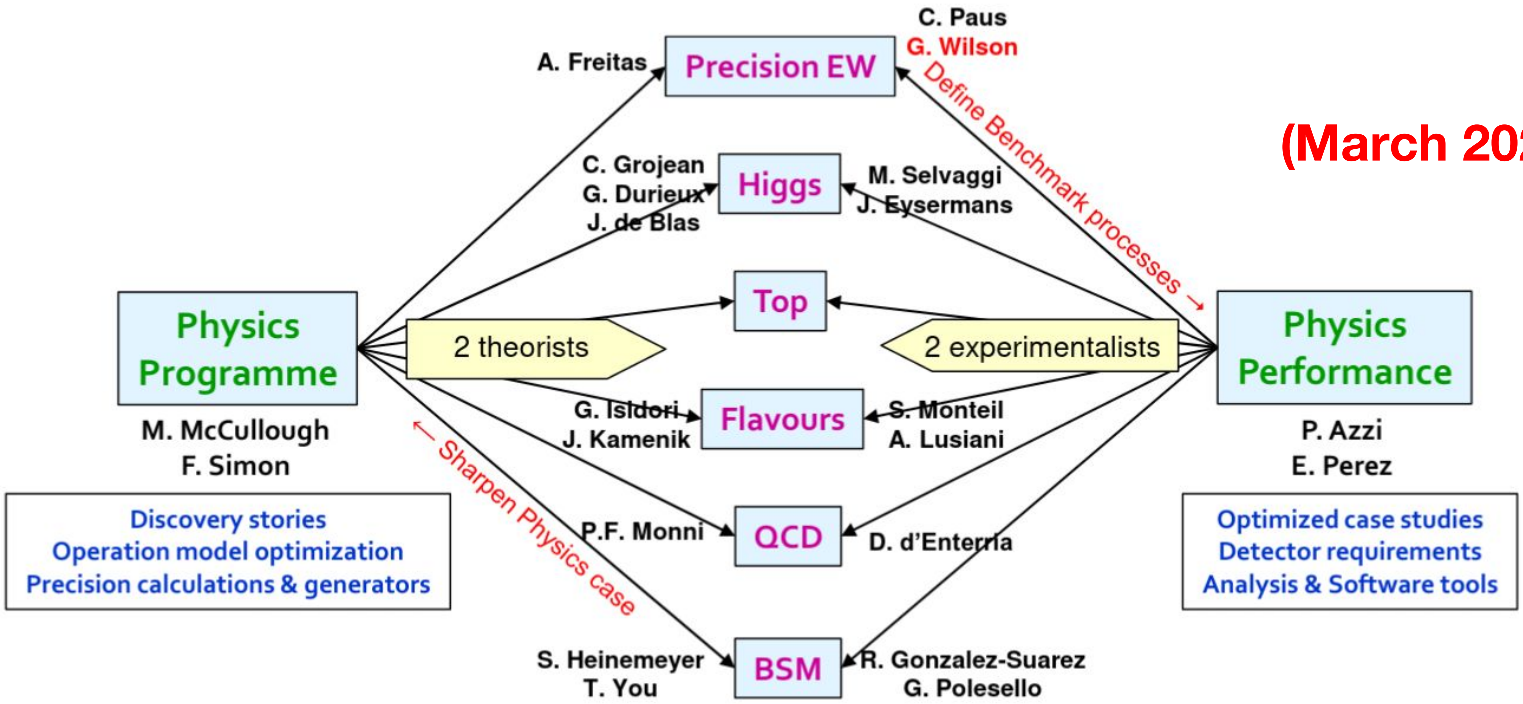


Electroweak 1st order transition with SM + real scalar singlet

Participating in FCC studies

- **Many physics subgroups have been formed to study the FCC physics potential, experiment and detector requirements (PED). Feel free to join the effort:**
  - **E-group lists at CERN to subscribe to: fcc-experiments-lepton, fcc-experiments-hadron**
  - **Meetings: https://indico.cern.ch/category/5251/**

(March 2022)



FCC-hh: which exact $\sqrt{s}$?

from M. Mangano at FCC Physics Meeting, Annecy 2024

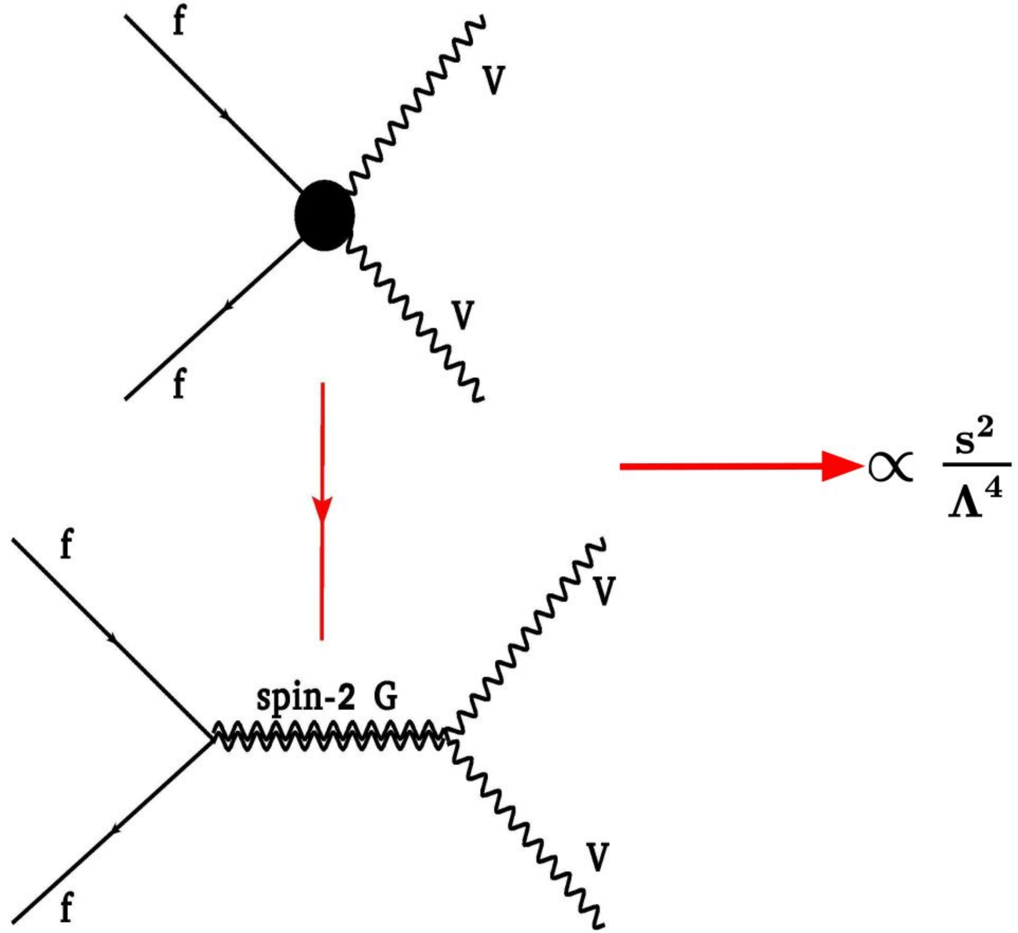
100 vs 80 vs 120: food for thought

- For the key "guaranteed deliverables", the difference between 100 and 80 TeV is comparable to the detector performance projection uncertainties. The loss in rate is in the range of 20-30% for key observables, with minor impact on measurements that by and large tend to be systematics-dominated
  - ➡ investing in detector performance is more effective than pushing the magnet technology 14→16 T
- Discovery reach at the largest masses vary at the level of –20% to +15% for the 80 and 120 TeV options. No obvious case today of critical thresholds to push for, or exclude, either option.
  - ➡ unless a specific BSM case arises, the upgrade from 80 (or 100) to 120 TeV doesn't lead to clear progress justifying the potential cost and refurbishment time loss: running at 80(100) TeV longer might be wiser …
  - ➡ the decision of 80 vs 120 vs 100 is probably final, and unlikely to lead to an upgrade path

What else?

- **Even larger sensitivity for other deviations, like neutral triple-gauge couplings, $f\bar{f}\rightarrow\gamma\gamma$, or spin-2 exchanges (basically invisible in low-energy experiments)**

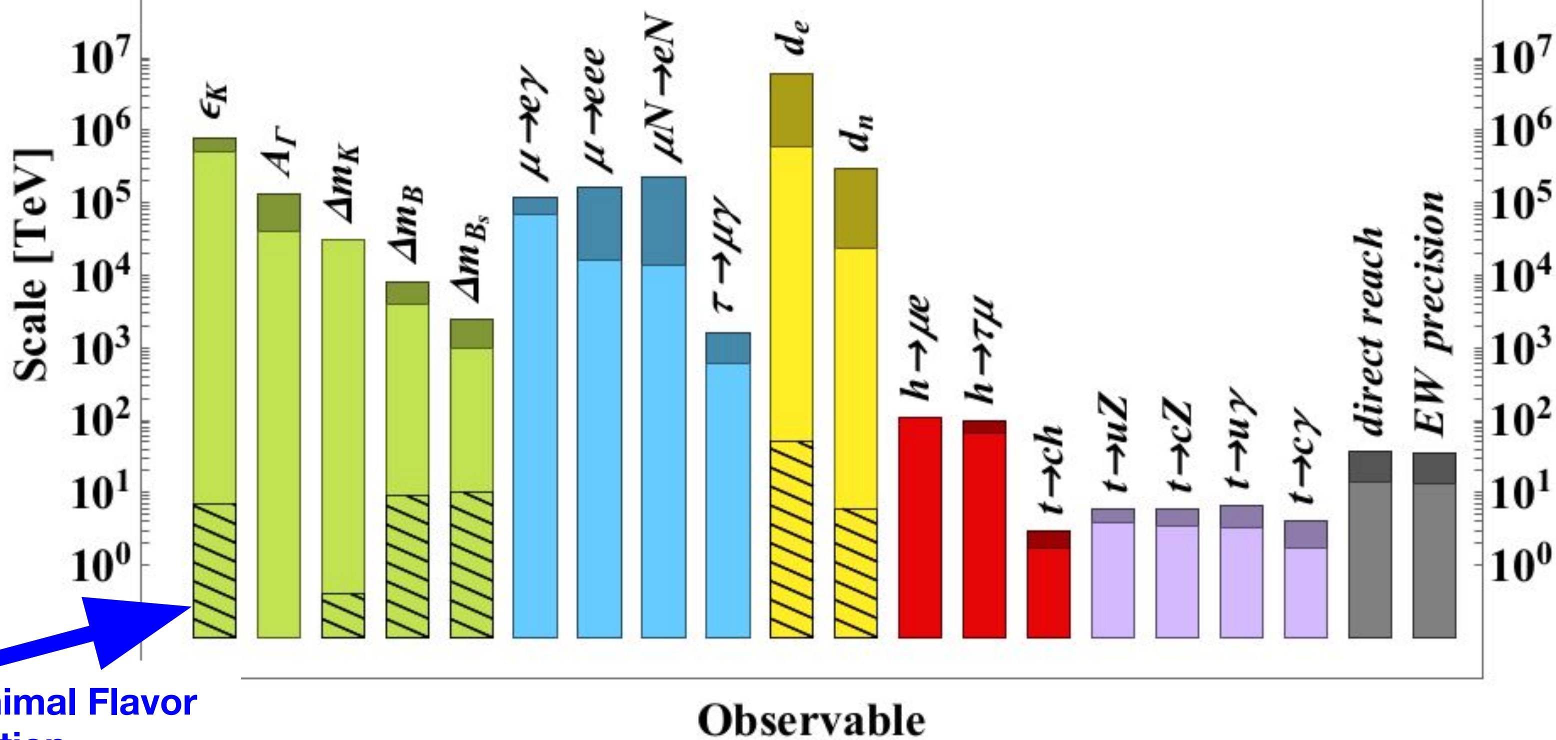
$$\frac{\Delta\sigma}{\sigma_{SM}} \approx \frac{s^2}{\Lambda^4}$$



B factories and low-energy constraints

European Strategy Briefing Book: arXiv:1910.11775

All limits suppressed by a factor 10^2-10^3 in many cases (by $1/(4\pi)^2$ due to loops and by α for electroweak-type couplings)



Dashed: Minimal Flavor Violation

- **Low energy experiment do not really explore comprehensively beyond the TeV scale, once some (reasonable) a priori assumptions are made**

Need of a "thorough" exploration of the 10 TeV range

FCC project: baseline placement, length

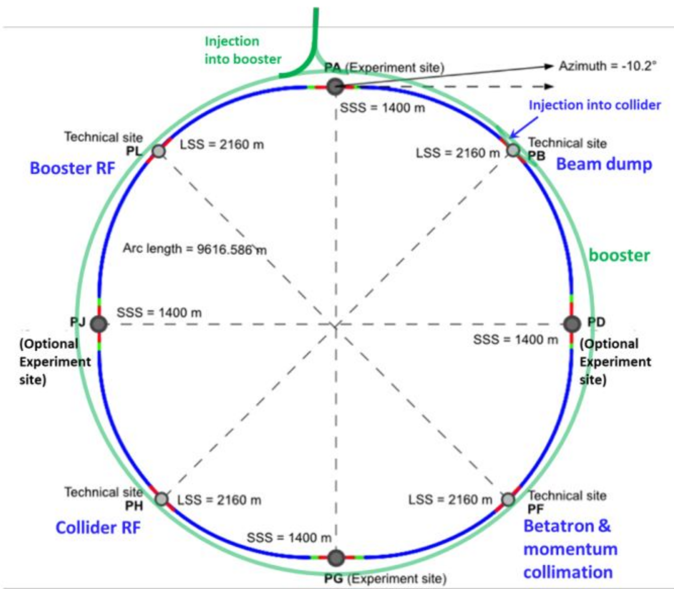
FUTURE CIRCULAR COLLIDER

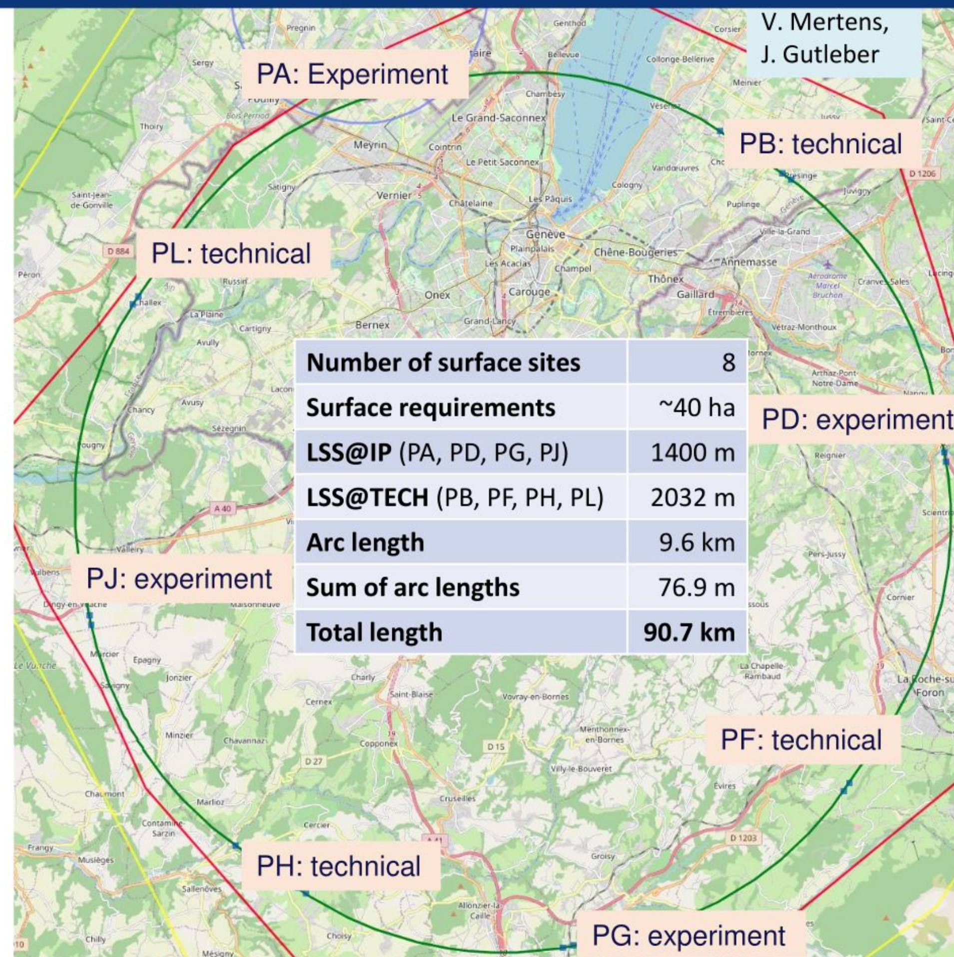
optimized placement and layout for feasibility study

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

"Avoid-reduce -compensate" principle of EU and French regulations

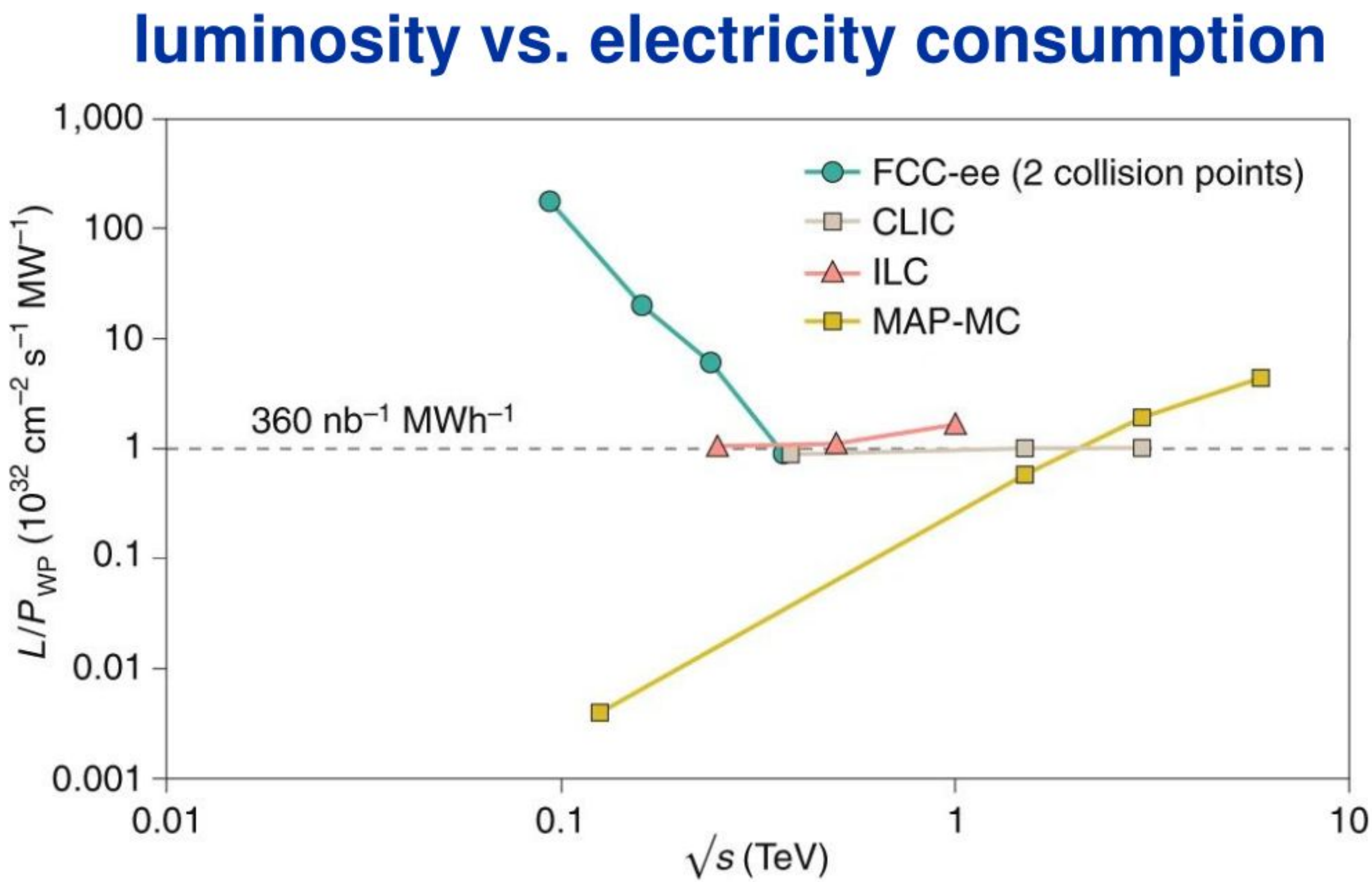
Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement





Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

FCC-ee: most efficient option



highest lumi/power of all *H* fact. proposals

Nature Physics 16, 402–407 (2020)

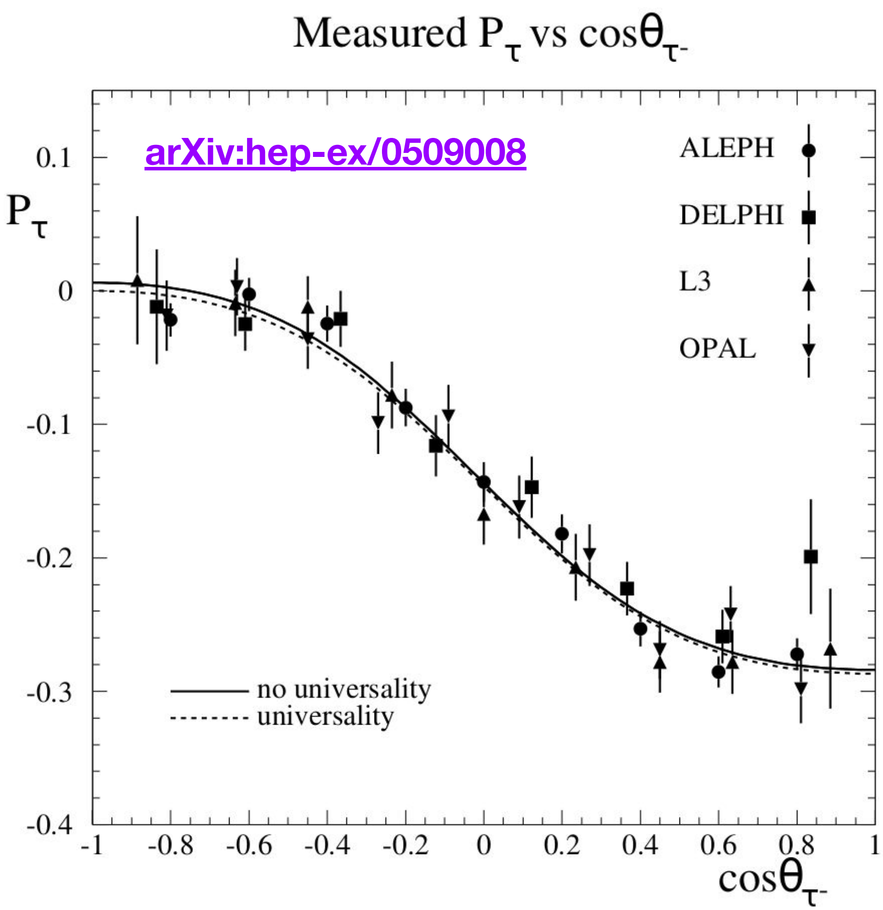
Z pole summary table (cont.)

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
$A_{FB}^{b},0$ ($\times 10^4$)	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 polarization asymmetry τ decay physics
R_b ($\times 10^6$)	216290 ± 660	**0.3**	<60	ratio of bb to hadrons stat. extrapol. from SLD

- **Objective: ≳ 20 times better than current precision**

- **A^{b}_{FB}: measurement showing ~3σ deviation at LEP:**
  - intrinsic theoretical systematics reducible via angular cuts
- **$A^{pol,\tau}_{FB}$: equivalent to the Z polarization (A_e):**
  - key input that avoids the need of polarized beams at FCC-ee (see next slides)

Tau polarization: key measurement



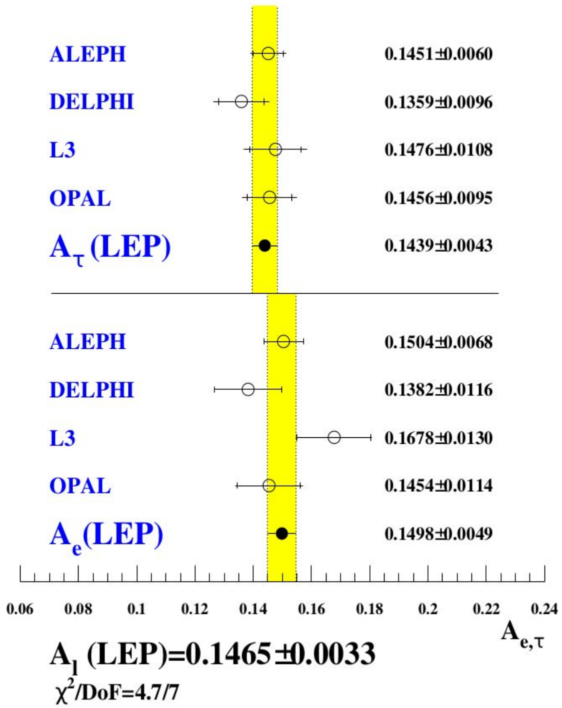
$$P(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

- **The FCC-ee baseline does not use longitudinal beam polarization:**
  - Although feasible, It would reduce too much the available luminosity
  - Not needed: tau polarization input is enough to facilitate precise measurements of the L-R asymmetry parameters for all fermions: A_e,A_μ,A_τ, A_b,A_c

$$\mathcal{A}_{FB}(f) = ¾\, \mathcal{A}_e\mathcal{A}_f$$

- **Measuring very precisely A_e is the key to extract A_f from $A_{FB}(f)$!!**

A_e is a precise / safe measurement



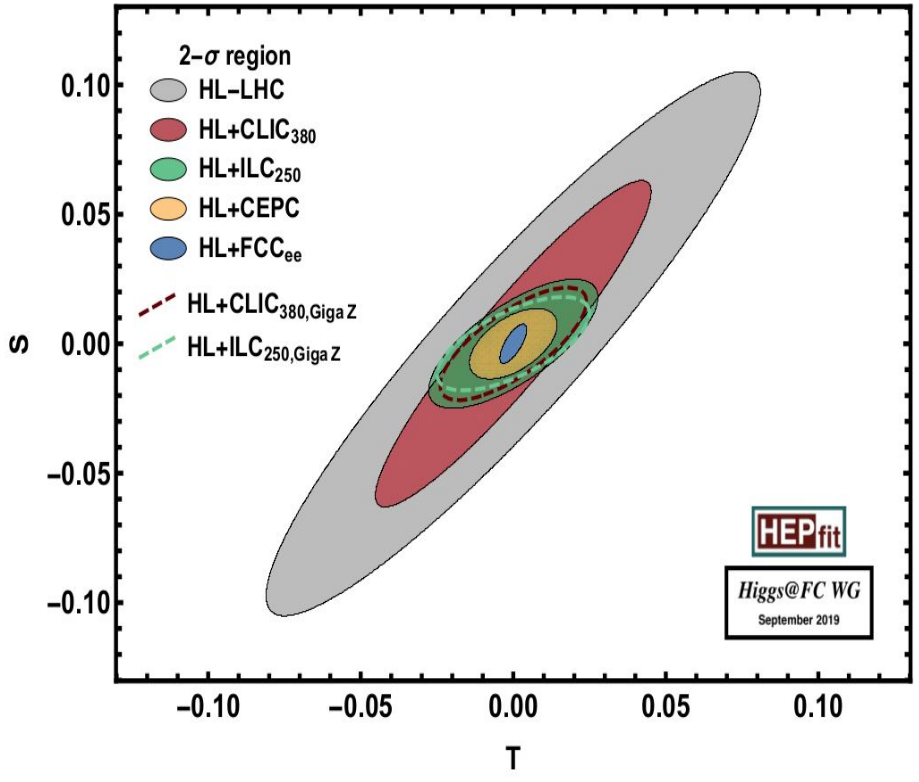
Experiment	$\mathcal{A}_\tau$	$\mathcal{A}_e$
ALEPH	$0.1451 \pm 0.0052 \pm 0.0029$	$0.1504 \pm 0.0068 \pm 0.0008$
DELPHI	$0.1359 \pm 0.0079 \pm 0.0055$	$0.1382 \pm 0.0116 \pm 0.0005$
L3	$0.1476 \pm 0.0088 \pm 0.0062$	$0.1678 \pm 0.0127 \pm 0.0030$
OPAL	$0.1456 \pm 0.0076 \pm 0.0057$	$0.1454 \pm 0.0108 \pm 0.0036$
LEP	$0.1439 \pm 0.0035 \pm 0.0026$	$0.1498 \pm 0.0048 \pm 0.0009$

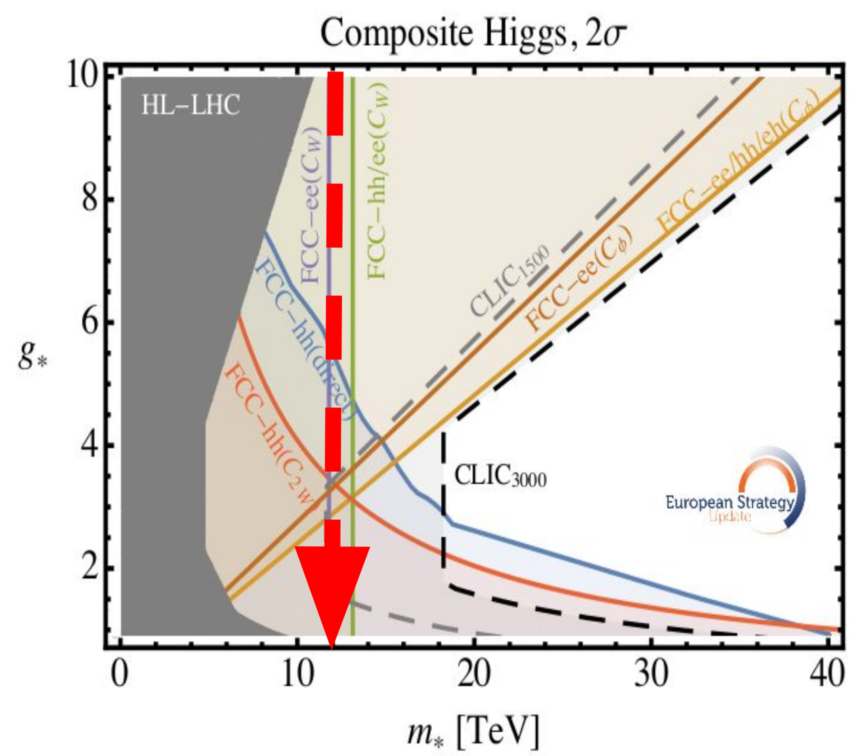
	A_e						
Systematic effect	h	ρ	$3h$	$h2\pi^0$	e	μ	acol
tracking	0.04	-	-	-	-	0.05	-
non-τ background	0.13	0.08	0.02	0.07	1.23	0.24	0.24
modelling	-	-	0.40	0.40	-	-	-
TOTAL	0.13	0.08	0.40	0.41	1.23	0.24	0.24

- A_e ($\equiv$ $-P_\tau^{FB}$) is much less affected by systematic uncertainties, because forward-backward asymmetry measurements are largely independent of (charge symmetric) acceptance uncertainties
- Dominant systematic uncertainty will be basically the non-tau background (just 0.08% in the $\tau\rightarrow\rho\nu$ channel).
- How low can in uncertainty can we go ? Current rough estimates assume a ≈⅓ reduction in systematic uncertainty w.r.t. LEP. Studies going on

Physics potential

Eur. Strat.: arXiv:1910.11775



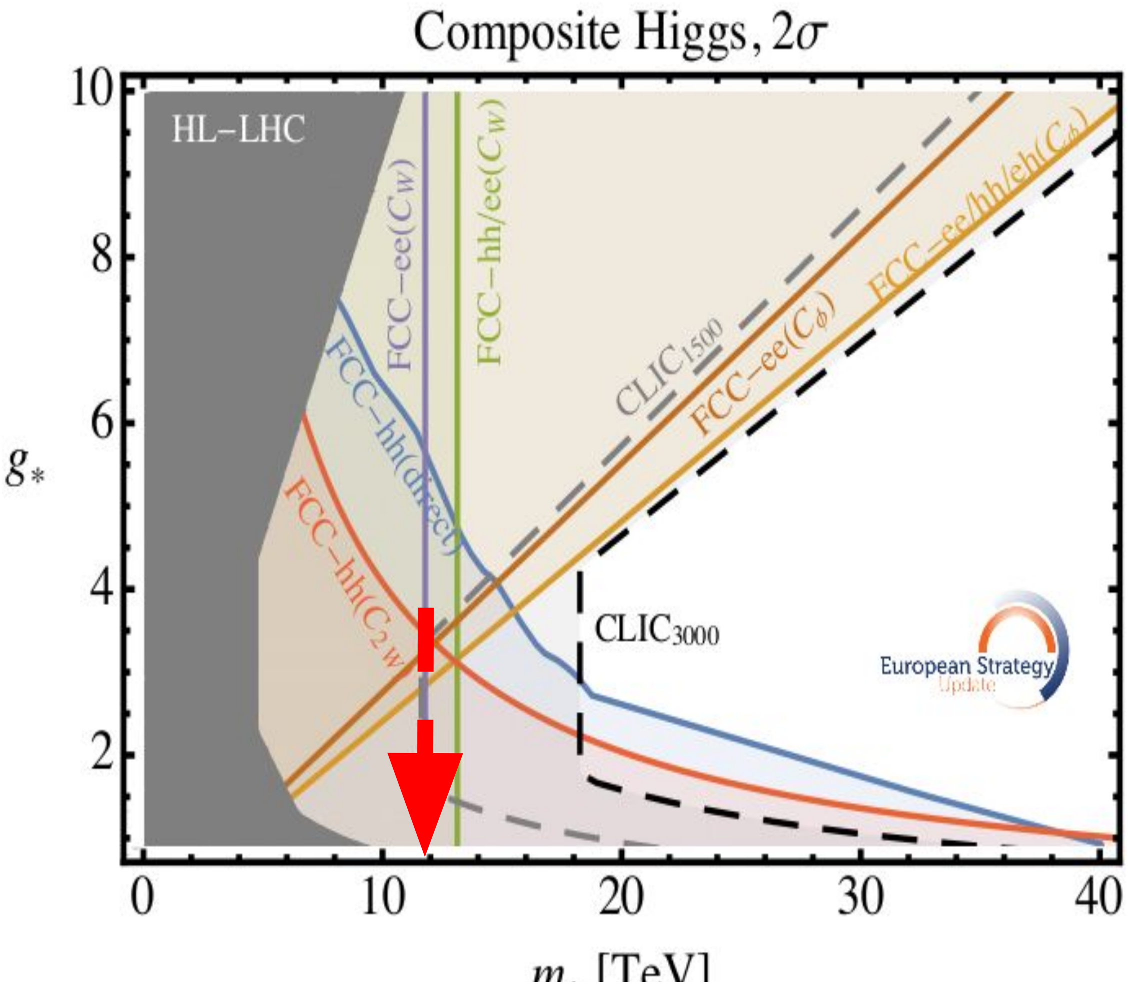


Constraints on the S parameter from FCC-ee are > 1 order of magnitude better than those of HL-LHC

Higgs compositeness reach (from S-parameter constraint)

FCC-ee physics potential

Eur. Strat.: arXiv:1910.11775



Higgs compositeness reach ≈12 TeV (S-parameter constraint)

Heavy flavours at FCC-ee

from C. Grojean, Status of the FCC Feasibiility Study (2024)

See S. Monteil, Flavour@FCC '22

At present (Z/h/NewPhysics) FCNCs mostly constrained by low energy observables.
The large statistics of FCC will open on-shell opportunities.

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

FCC-ee = 10 x Belle II

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ ($\sigma_{\sin(2\phi_d)}$)	$\sim 2.*10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

out of reach at LHCb/Belle

boosted b's/τ's at FCC-ee

Makes possible a topological rec. of the decays w/ miss. energy

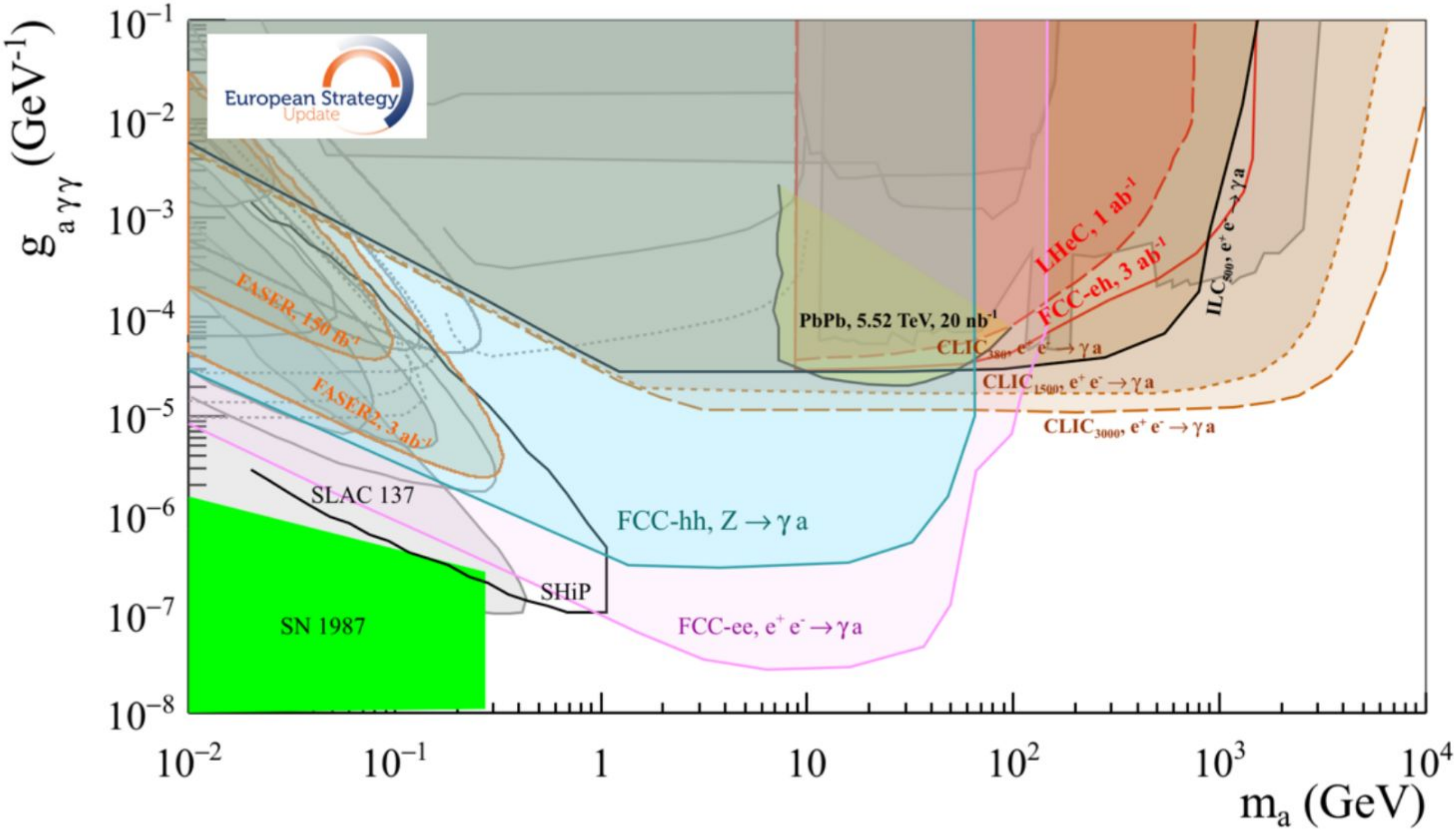
Other flavour opportunities at FCC-ee

[from C. Grojean, Status of the FCC Feasibiility Study (2024)]

FCC-ee flavour opportunities.

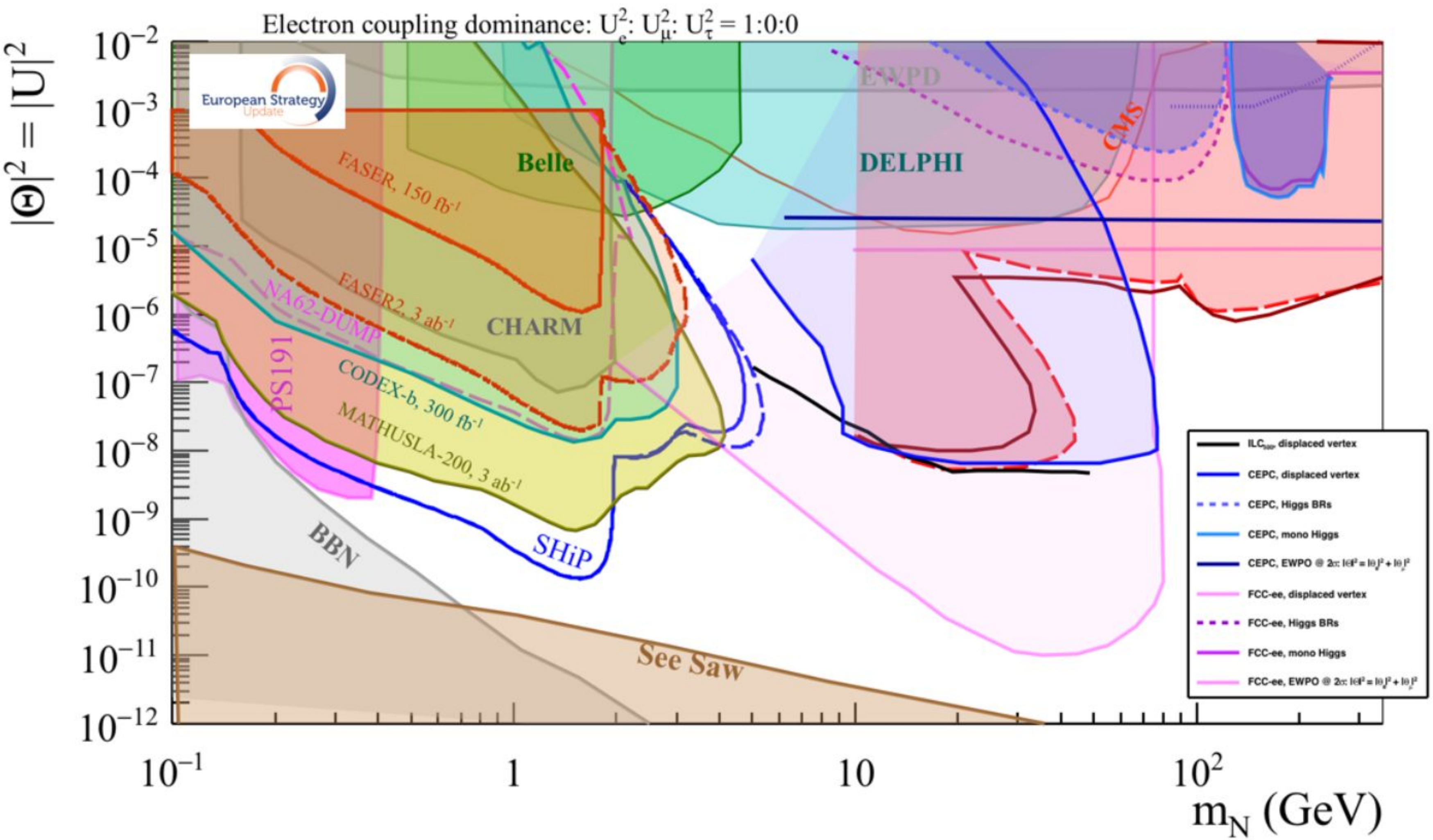
- **CKM element V_{cb}** (critical for normalising the Unitarity Triangle) from WW decays
- **Tau physics** (>10^{11} pairs of tau's produced in Z decays)
  - test of lepton flavour universality: G_F from tau decays @ 10 ppm @ FCC-ee (0.5 ppm from muon decays)
  - lepton flavour violation:
    - $\tau \to \mu\gamma$: $4\text{x}10^{-8}$ @Belle2021→10^{-9} @ FCC-ee
    - $\tau \to 3\mu$: $2\text{x}10^{-8}$ @Belle → $3\text{x}10^{-10}$ @BelleII → 10^{-11} @ FCC-ee
  - tau lifetime uncertainty:
    - 2000 ppm → 10 ppm
  - tau mass uncertainty:
    - 70 ppm → 14 ppm
- **Semi-leptonic mixing asymmetries** a^s_{sl} and a^d_{sl}
- …

FIPs at FCC-ee: axion-like particles ($A \to \gamma\gamma$)



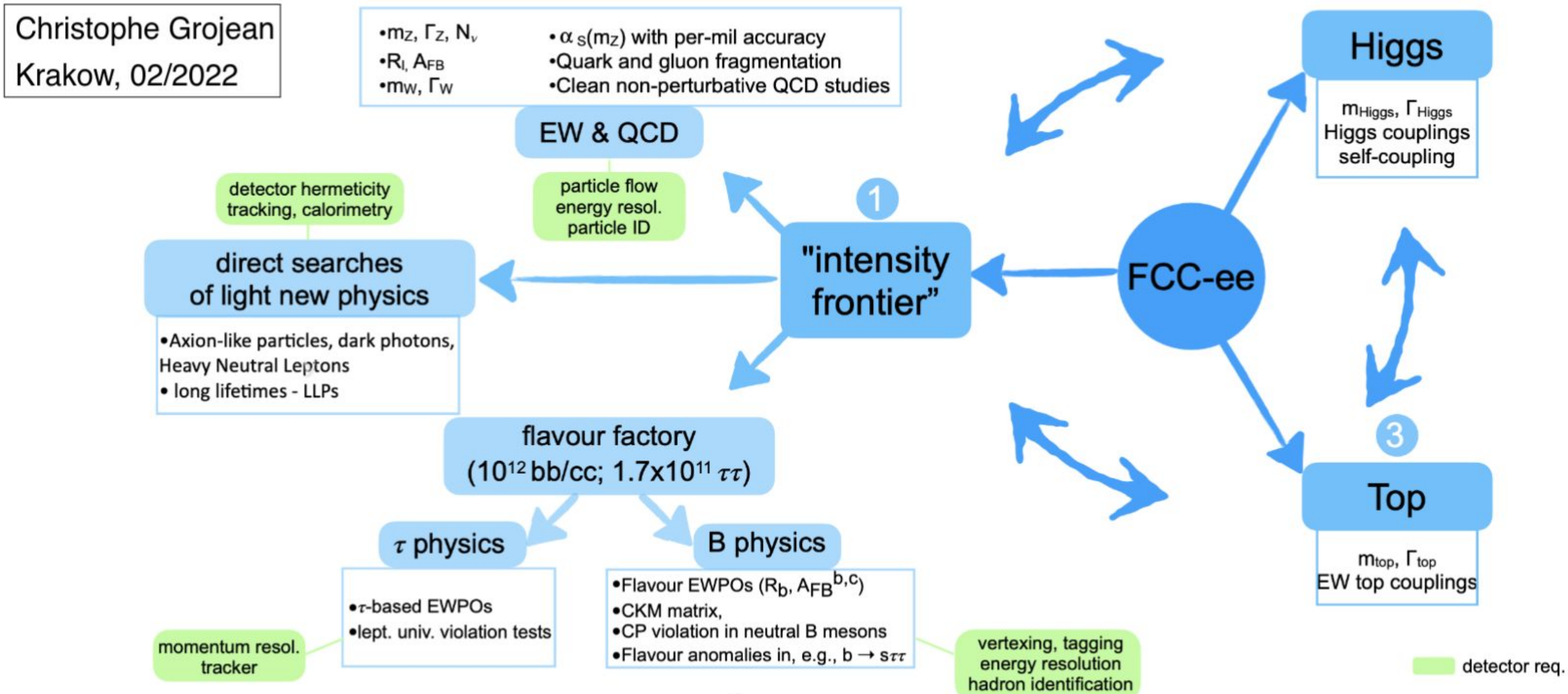
- **FCC-ee unbeatable in the m_A=1-100 GeV range**

Heavy Neutrinos at FCC-ee (FIP regime again)

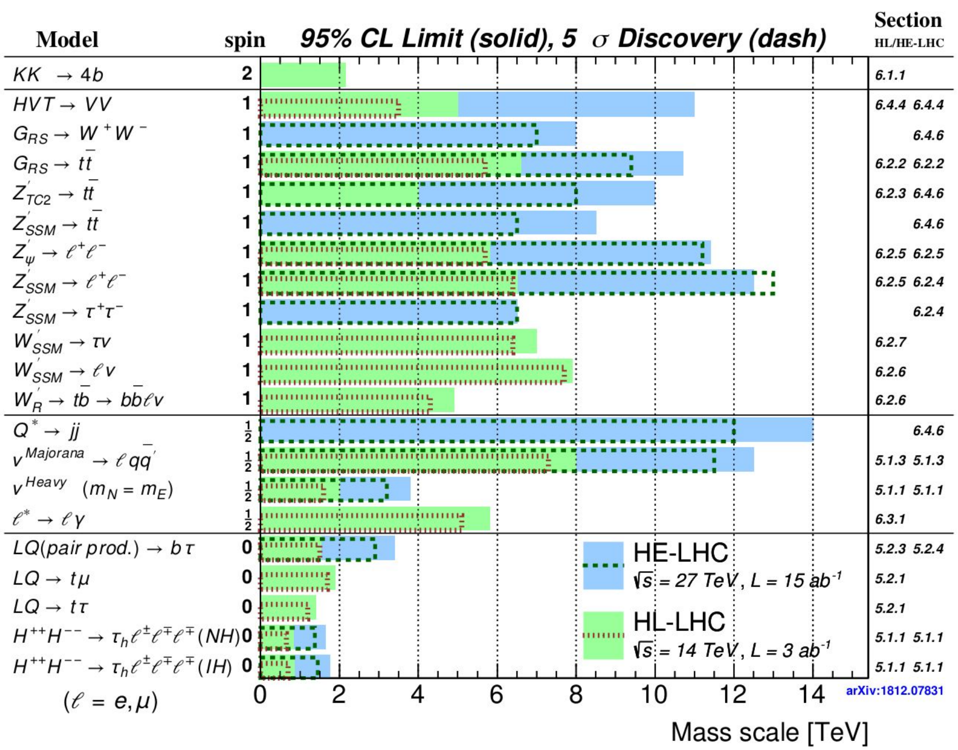


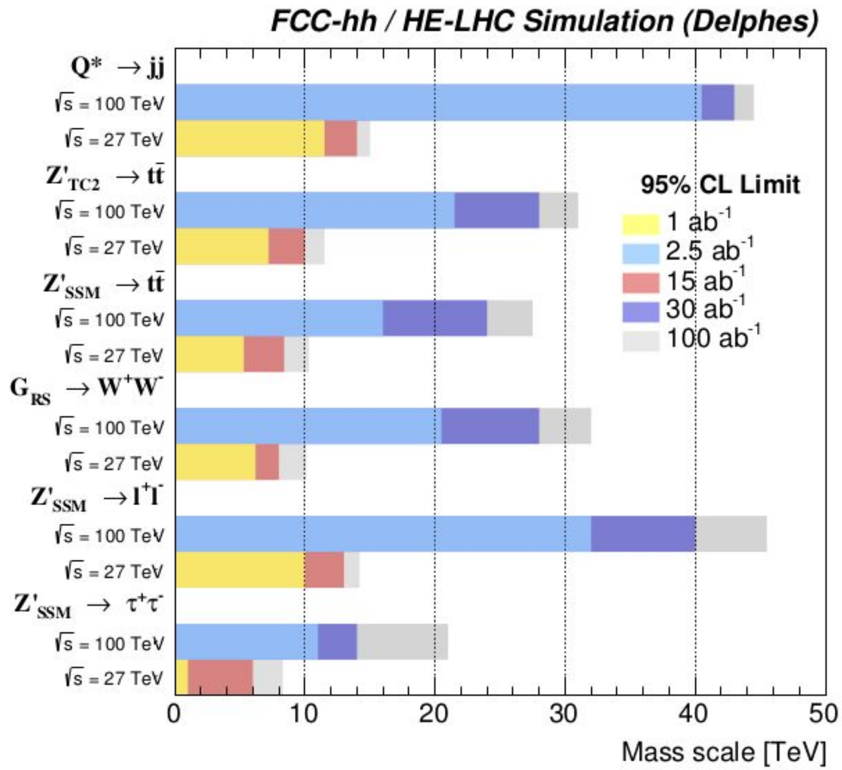
- **U_e=1: FCC-ee unbeatable in the m_N=5-90 GeV range**
- **Approach the see-saw limit in this range**

FCC-ee program: detector performance needs



BSM studies with high-energy probes





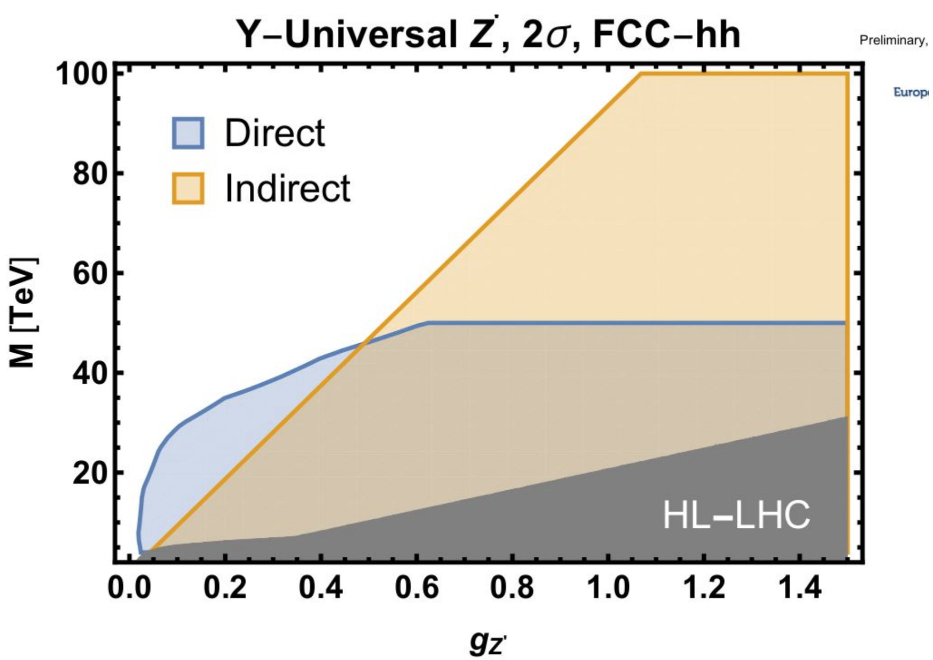
HL-LHC: 14 TeV, 3 ab^{-1}; HE-LHC: 27 TeV, 15 ab^{-1}; FCC-hh: 100 TeV, 30 ab^{-1}

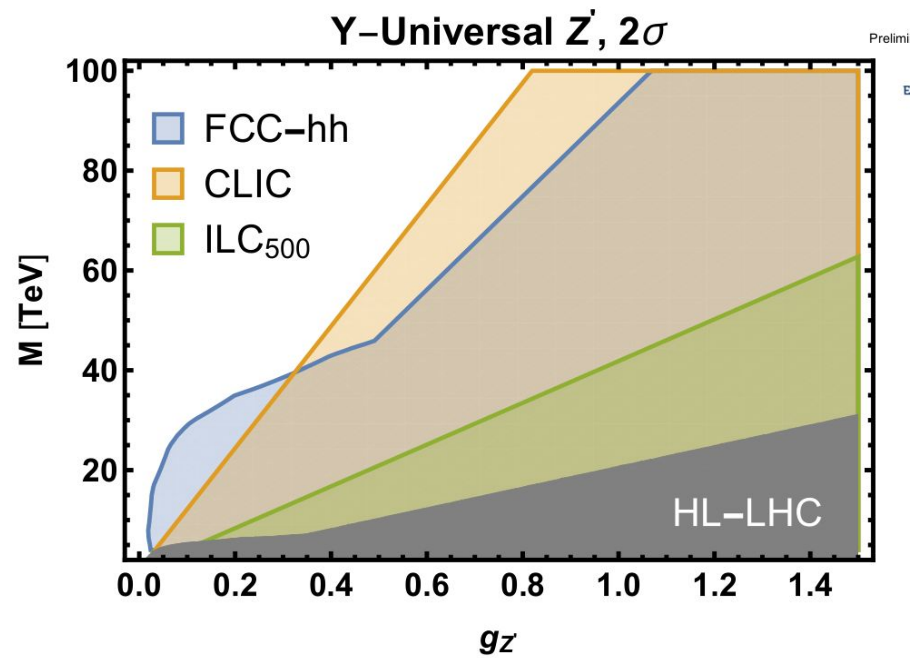
- **Wide exploration of any potential new particle spectra at the ≳ 10 TeV scale**

4-fermion contact interactions (Y-like couplings)

Preliminary, Granada 2019

European Strategy Update





Only FCC provides a "direct" observation for $g_{Z'}=\mathcal{O}(1)$, $M \lesssim 50$ TeV