PHYSICS OPPORTUNITIES @FUTURE CIRCULAR COLLIDER

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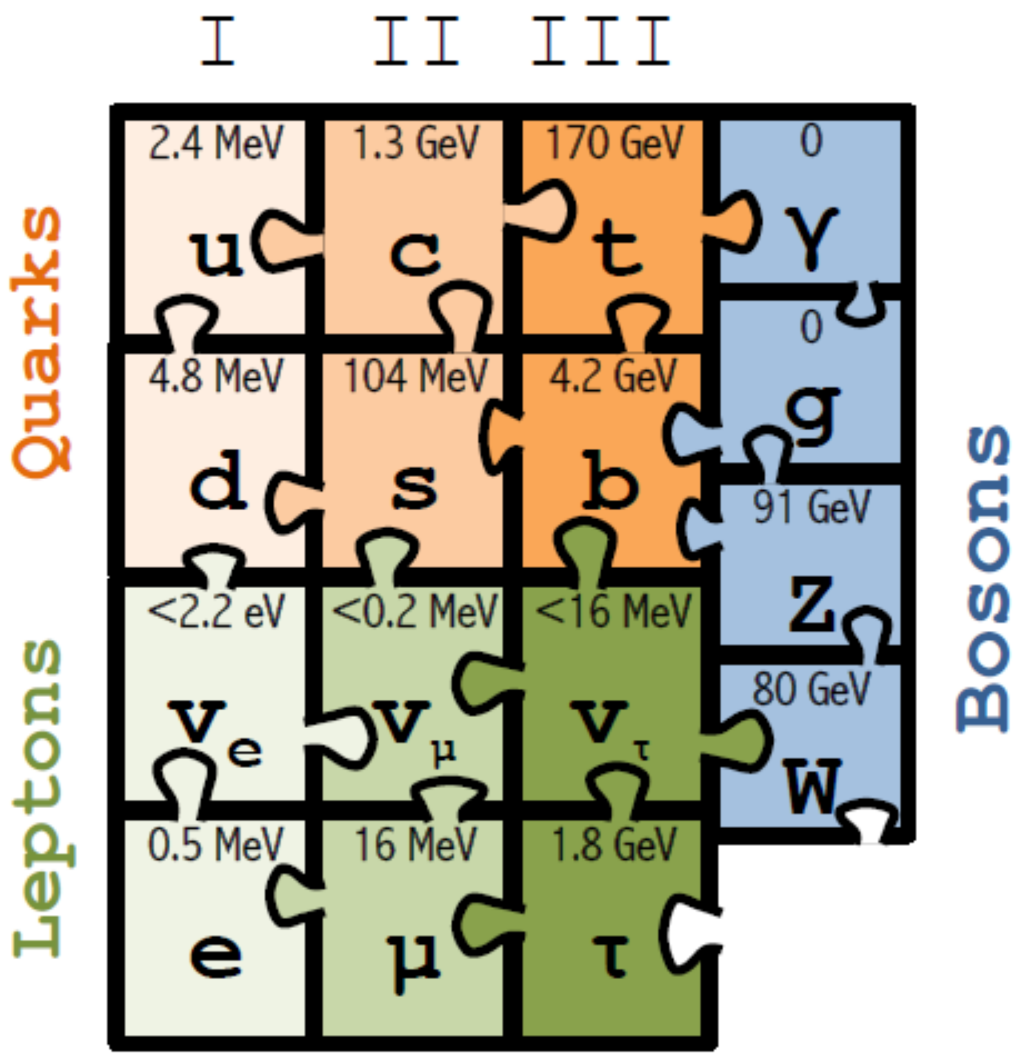
1st FCC Nordic Days - 22 March 2021

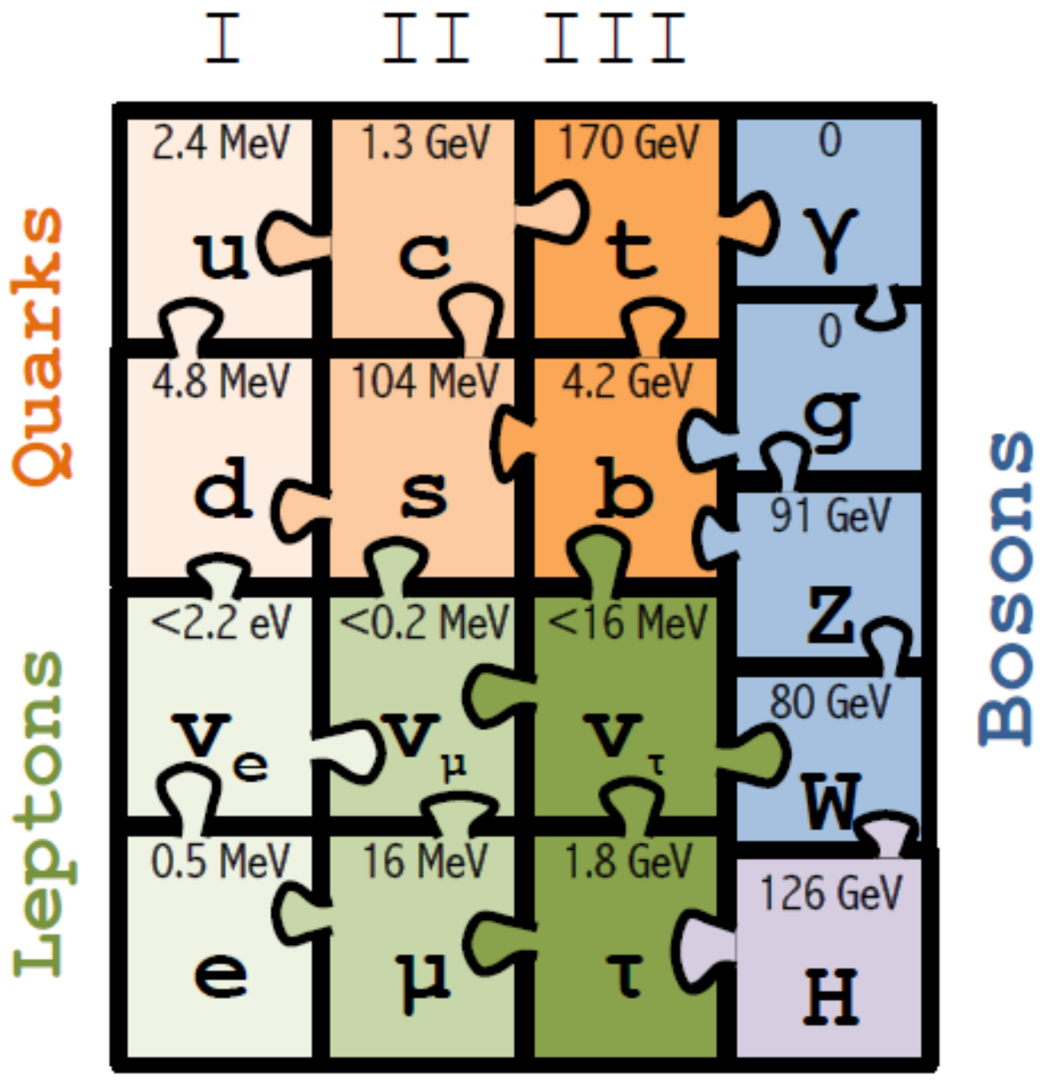
THE PHYSICS LANDSCAPE

- Particle Physics has arrived at an important moment of its History:

1989-1999:
Top mass predicted
(LEP mZ and ΓZ)
Top quark observed
at the right mass
(Tevatron, 1995)
Nobel Prize 1999
(t'Hooft & Veltman)



1997-2013:
Higgs mass cornered
(LEP EW + Tevatron mtop , mW)
Higgs boson observed
at the right mass
(LHC 2012)
Nobel Prize 2013
(Englert & Higgs)



- It looks like the Standard Model is complete and consistent theory
- It describes all observed collider phenomena – and actually all particle physics (except neutrino masses)
  - Was beautifully verified in a complementary manner at LEP, SLC, Tevatron, and LHC
  - EWPO radiative corrections predicted top and Higgs masses assuming SM and nothing else
- With mH = 125 GeV, it can even be extrapolated to the Plank scale without the need of New Physics.

- Is it the *END* ?

WHY NEW COLLIDER(S) / EXPERIMENTS?

- We need to extend mass & interaction reach for those phenomena that SM cannot explain:
  - Dark matter
    - SM particles constitute only 5% of the energy of the Universe
  - Baryon Asymmetry of the Universe
    - Where is anti-matter gone?
  - Neutrino Masses
    - Why so small? Dirac/Majorana? Heavier right-handed neutrinos? At what mass?

These facts require Particle Physics explanations

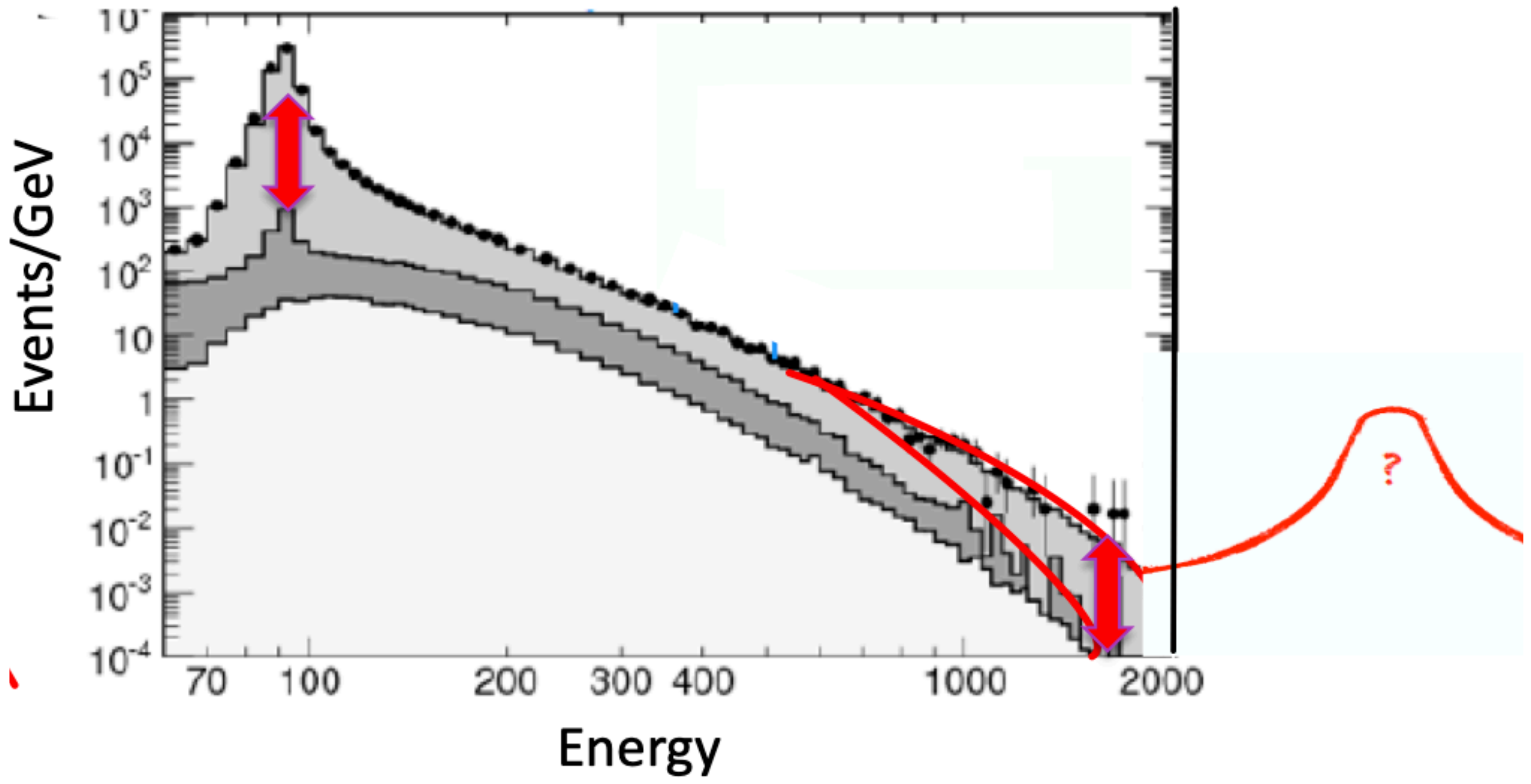
We must continue our quest, but HOW ?

- Possible experimental ways include:
  - Direct search for and observation of new particles (with any mass and any coupling to SM particles)
  - Observation of new phenomena (such as neutrino oscillations, CP violation …)
  - Measurements of deviations from precise predictions (such as top and Higgs mass predictions from loops)

But Where Is Everybody?

WHICH WAY TO GO?

- ➤ Is new physics at larger masses ? Or at smaller couplings ? Or both ?
  - ➤ No experimental hints as to the origin of these observed (unexplained) phenomena
  - ➤ No theoretical hints that would point to one direction more than another
- ➤ Only way to find out: go look, following the historical approach:
  - ➤ Direct searches for new heavy particles ⇒ Need colliders with larger energies
  - ➤ Searches for the imprint of New Physics at lower energies, e.g. on the properties of Z, W, top, and Higgs particles ⇒ Need colliders / measurements with unprecedented accuracy



- **Energy**: direct access to new resonances
- **Precision**: indirect evidence of deviations at low and high energy.

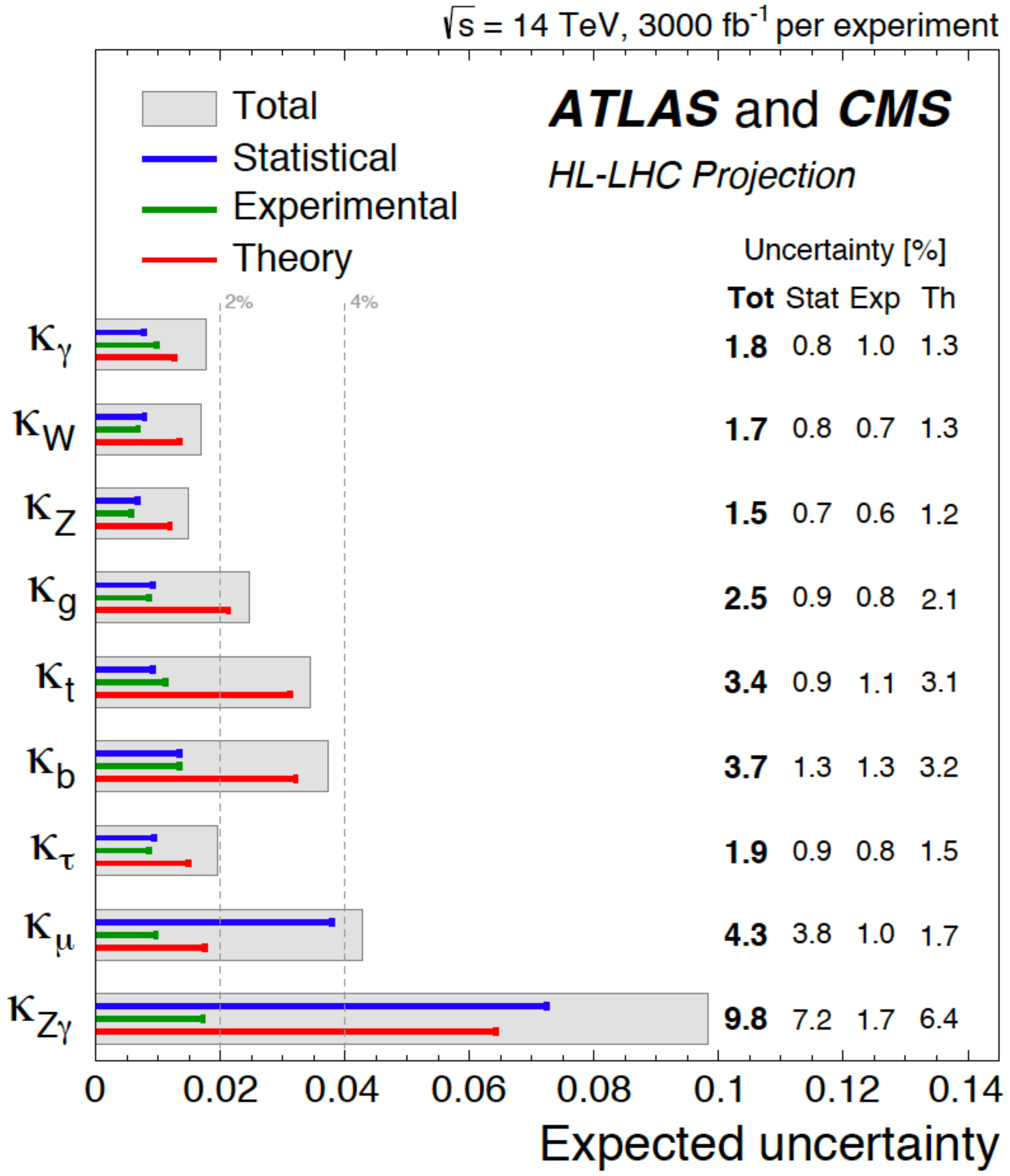
WHICH TYPE OF COLLIDER?

- The next facility must be versatile with a reach as broad and as powerful as possible – as there is no specific target

More SENSITIVITY, more PRECISION, more ENERGY

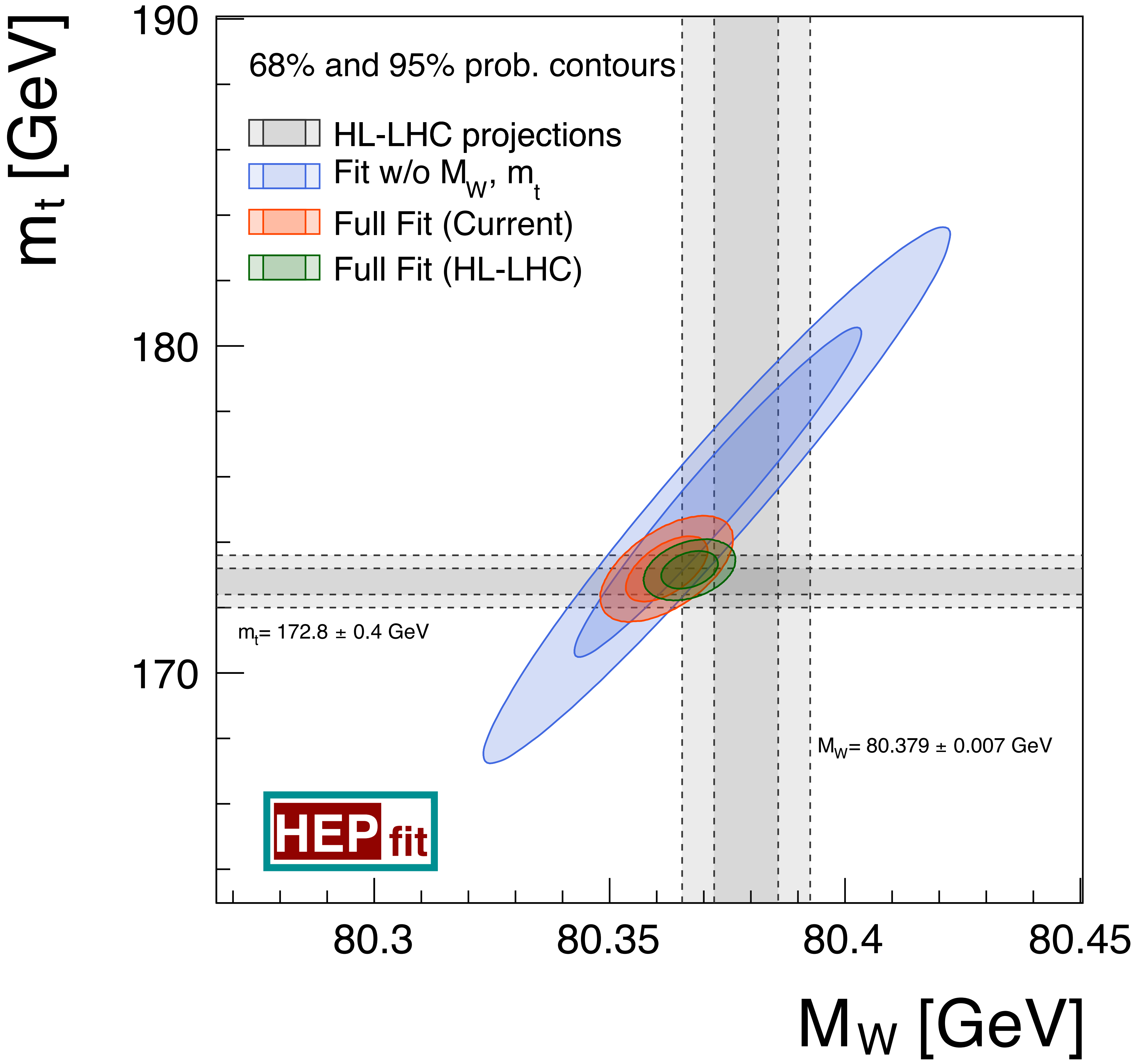
- Future Circular Colliders (FCC) offer the most adapted response to this situation
  - Largest luminosity
  - highest parton energy
  - synergies and complementarities between ee and pp, etc

AFTER HL-LHC



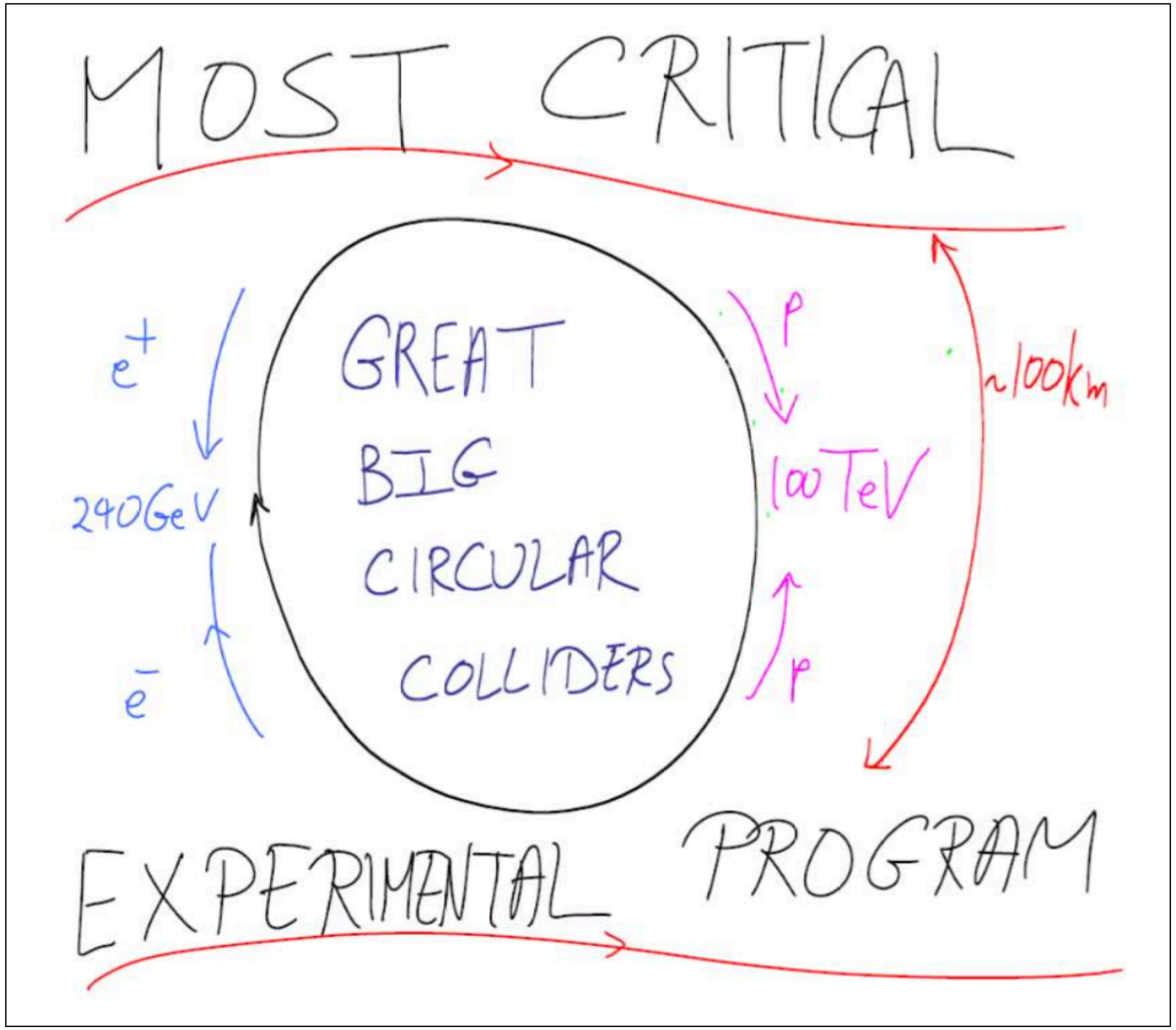
Uncertainty [%]

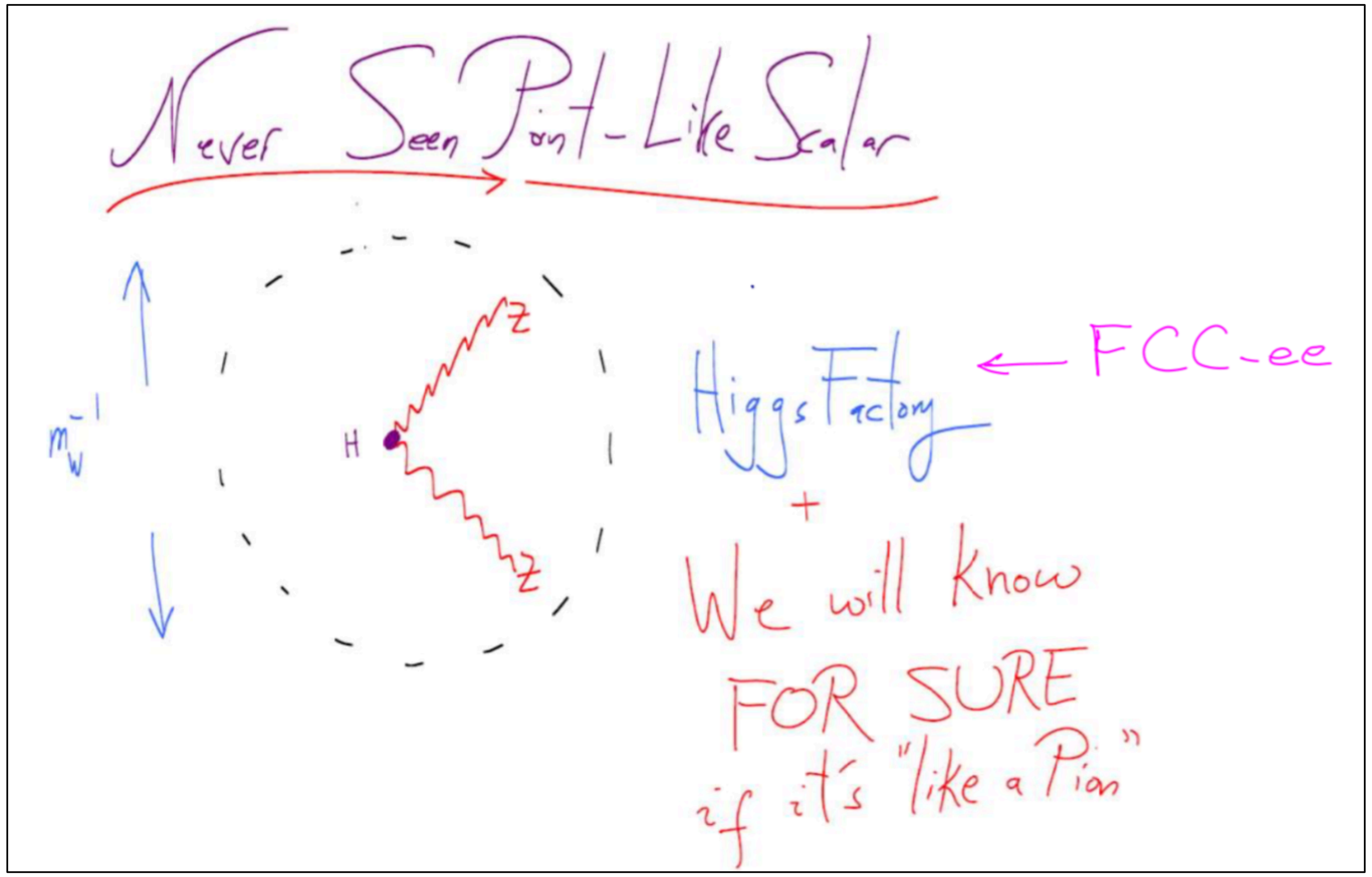
	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

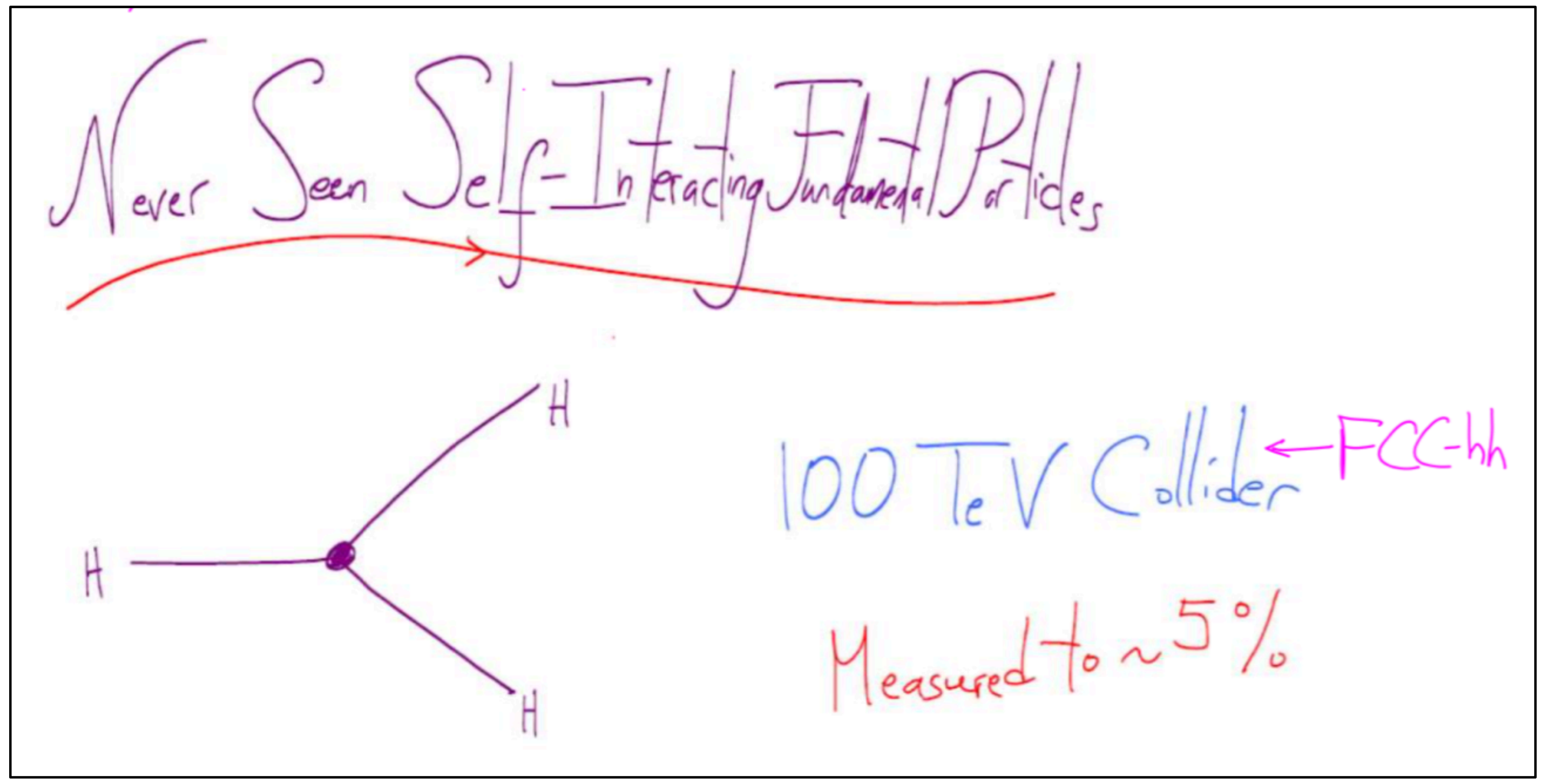


- Careful studies and projections for the physics at the HL-LHC we have shown:
  - we have designed amazing detectors that will be able to fully mitigate the 200PU conditions
  - uncertaintities on Higgs couplings of the order of 2-4% and top mass about ~200MeV
  - This precision might still not be sufficient to show the effect of new physics…

A CONCRETE TARGET: THE HIGGS BOSON







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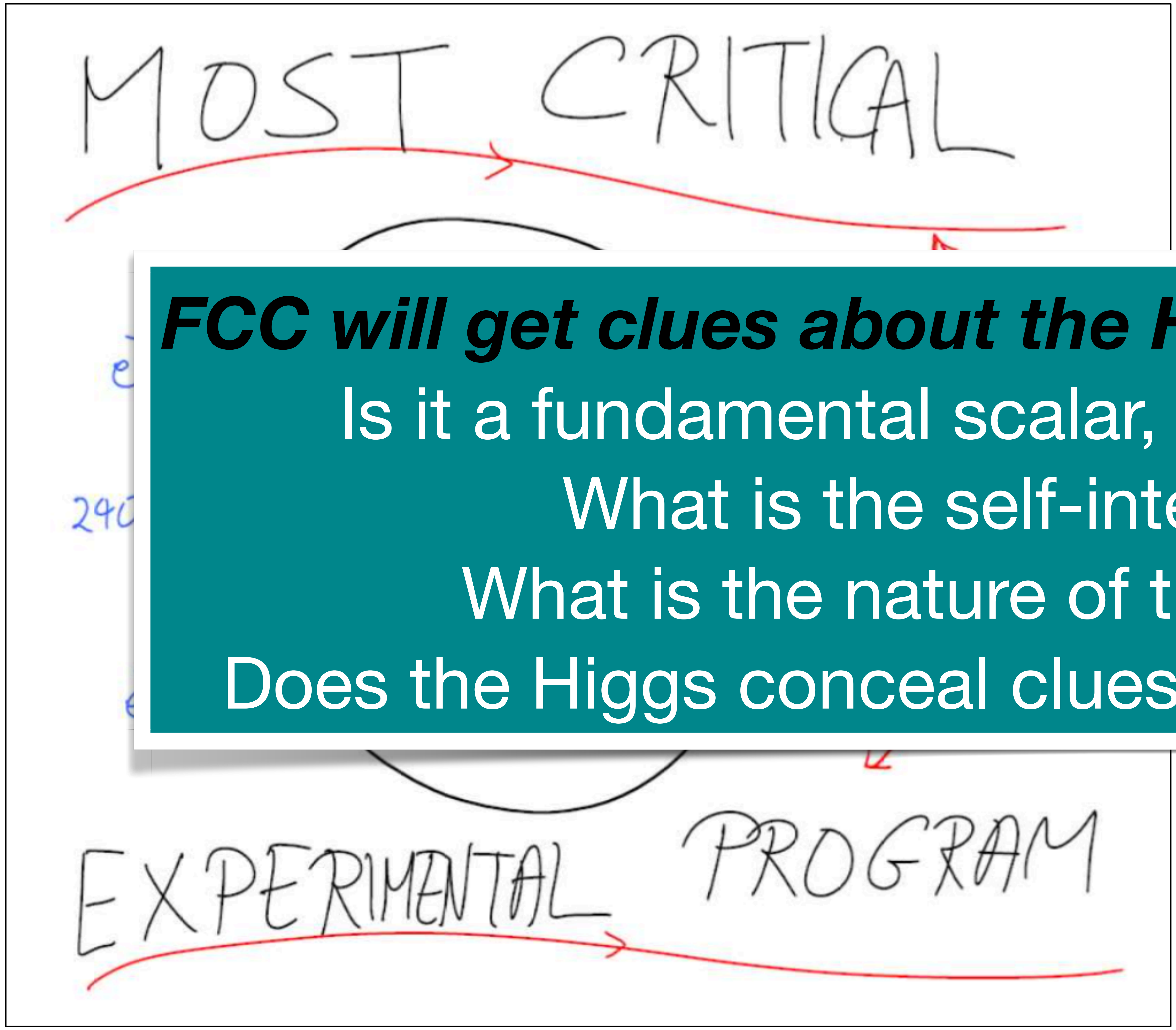
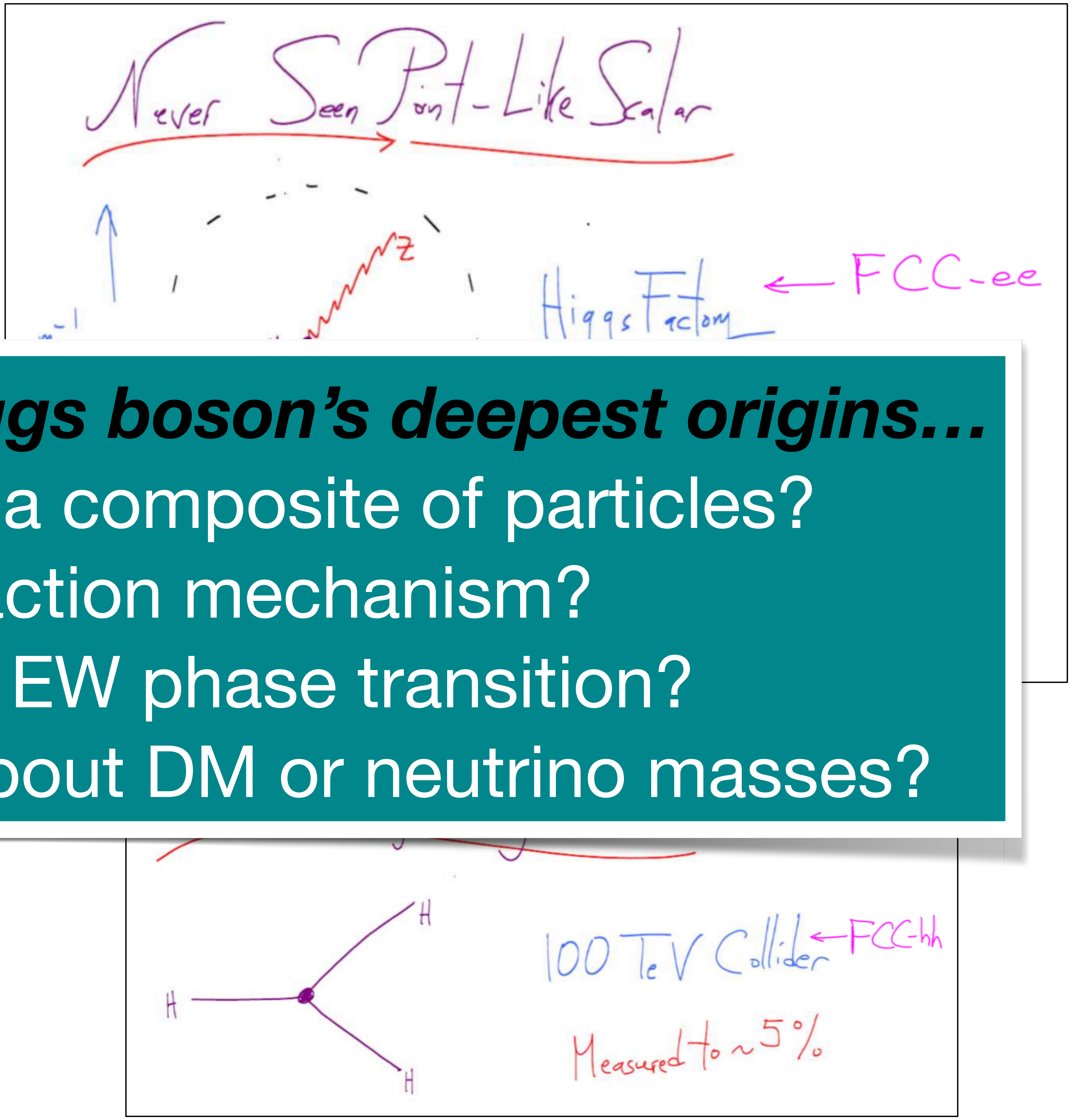




FCC will get clues about the Higgs boson's deepest origins…

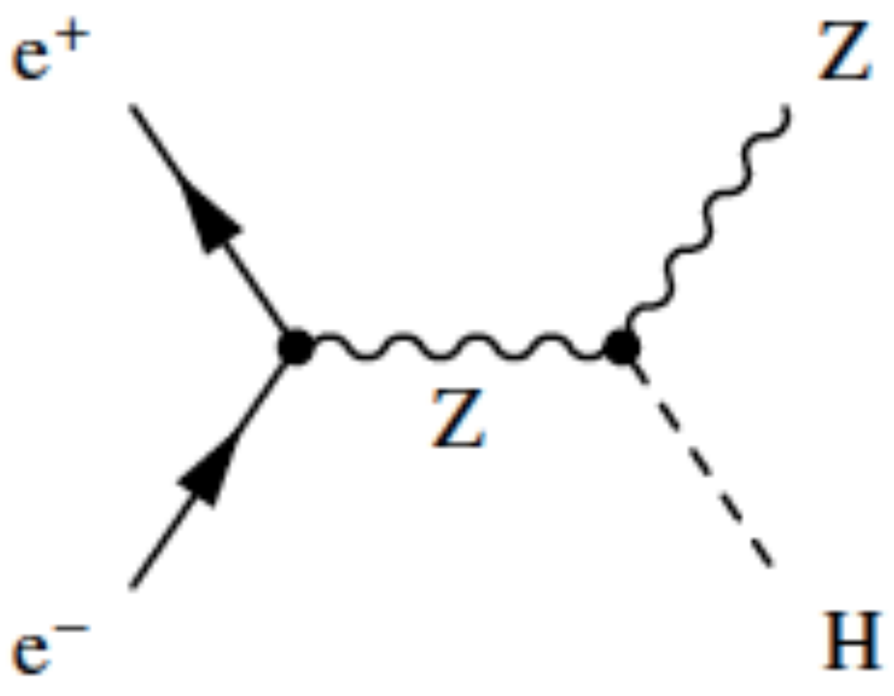
Is it a fundamental scalar, or a composite of particles?

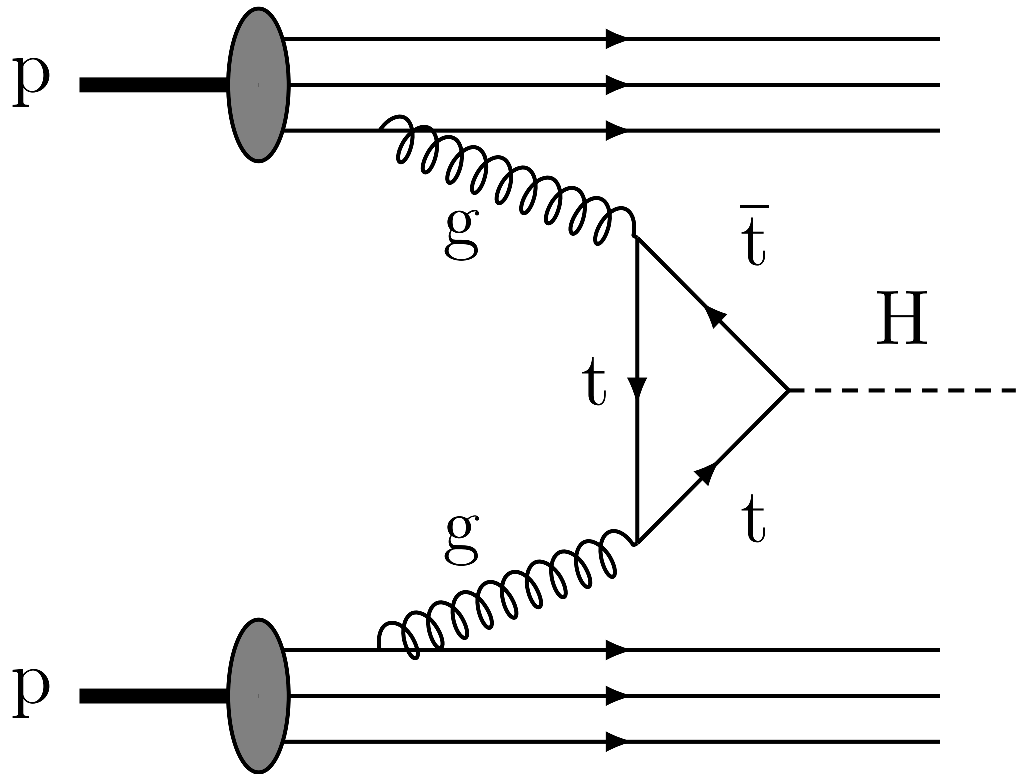
What is the self-interaction mechanism?

What is the nature of the EW phase transition?

Does the Higgs conceal clues about DM or neutrino masses?

e^+e^- VS pp COLLISIONS - THE BASICS





e^+e^- collisions

e^+/e^- are point-like
→ Initial state well defined (E, $\boldsymbol{p}$), polarisation
→ High-precision measurements

Clean experimental environment
→ Trigger-less readout
→ Low radiation levels

Superior sensitivity for **electro-weak states**

- At lower energies (≲ 350 GeV) , **circular** e^+e^- colliders can deliver **very large luminosities.**
- Higher energy (>1TeV) e^+e^- requires **linear** collider.

p-p collisions

Proton is compound object
→ Initial state not known event-by-event
→ Limits achievable precision

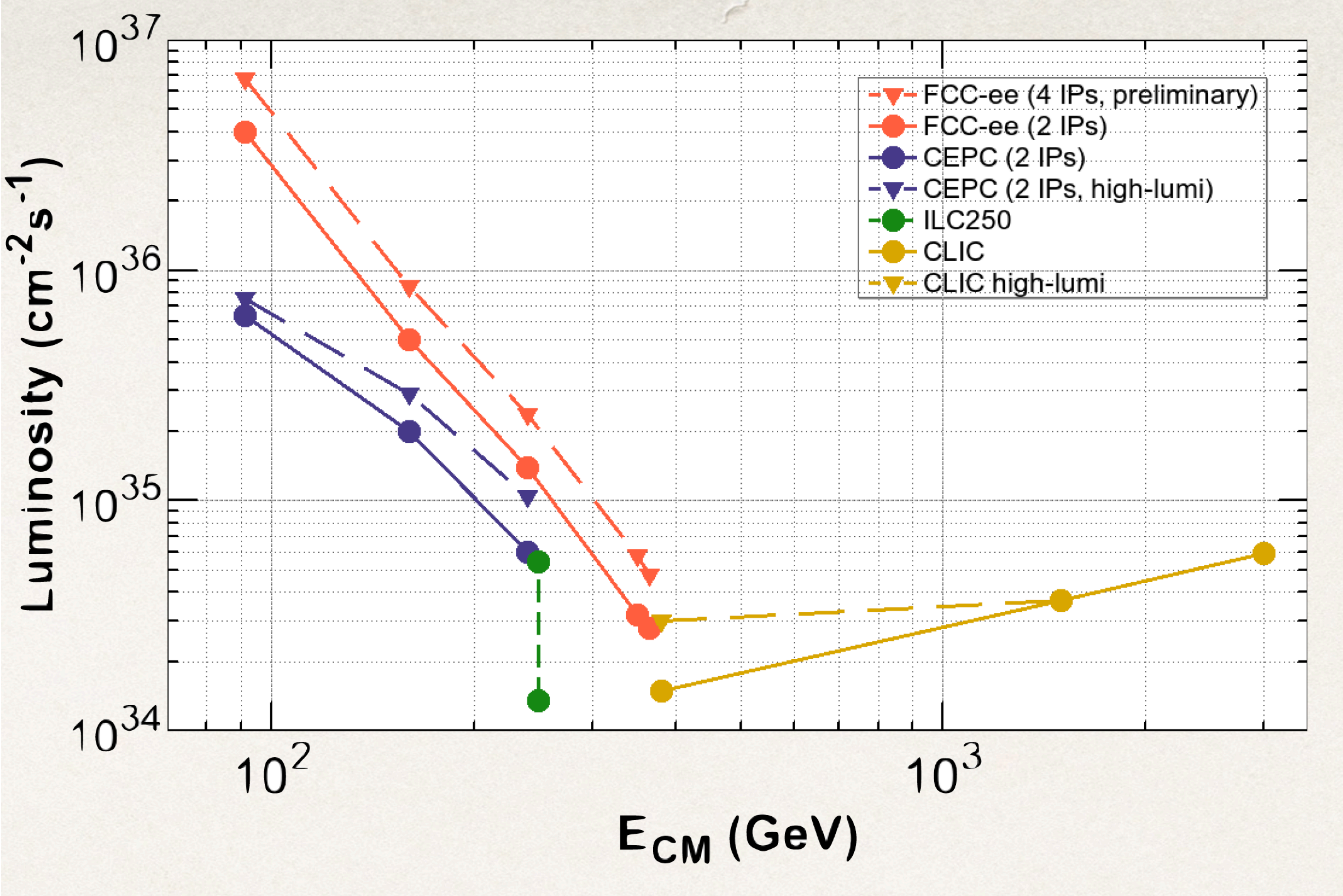
High rates of QCD backgrounds
→ Complex triggering schemes
→ High levels of radiation

High cross-sections for **colored-states**

High-energy **circular** pp colliders feasible

THE FCC-EE

FCC-ee ENERGY RANGE AND LUMINOSITY



- ➤ High integrated luminosity at the needed E_{cm}
- ➤ Clean environment
- ➤ precise knowledge of the center-of-mass energy and of the luminosity
- ➤ precise detectors offering plenty of redundancy (and more than one)

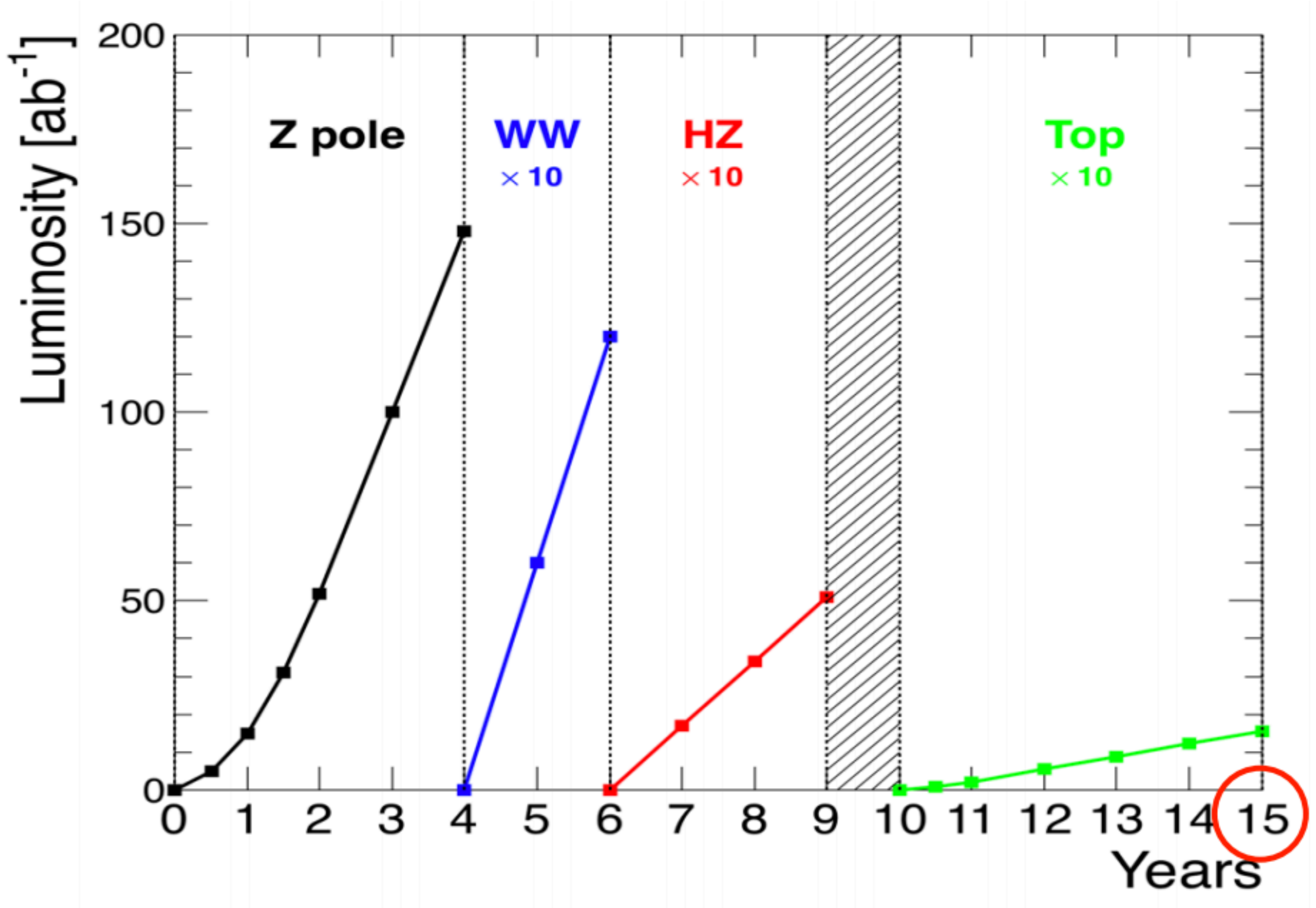
Can produce all the heaviest particles of the Standard Model

FCC-ee RUN PLAN

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

	√s uncertainty
LEP x 10^5	<100keV
LEP x $2 \cdot 10^3$	<300keV
Never done	~2MeV
Never done	~5MeV

- Total running time 14(+1)years (~LEP)
  - longer shutdown to install the 196 RF for operation at the top threshold



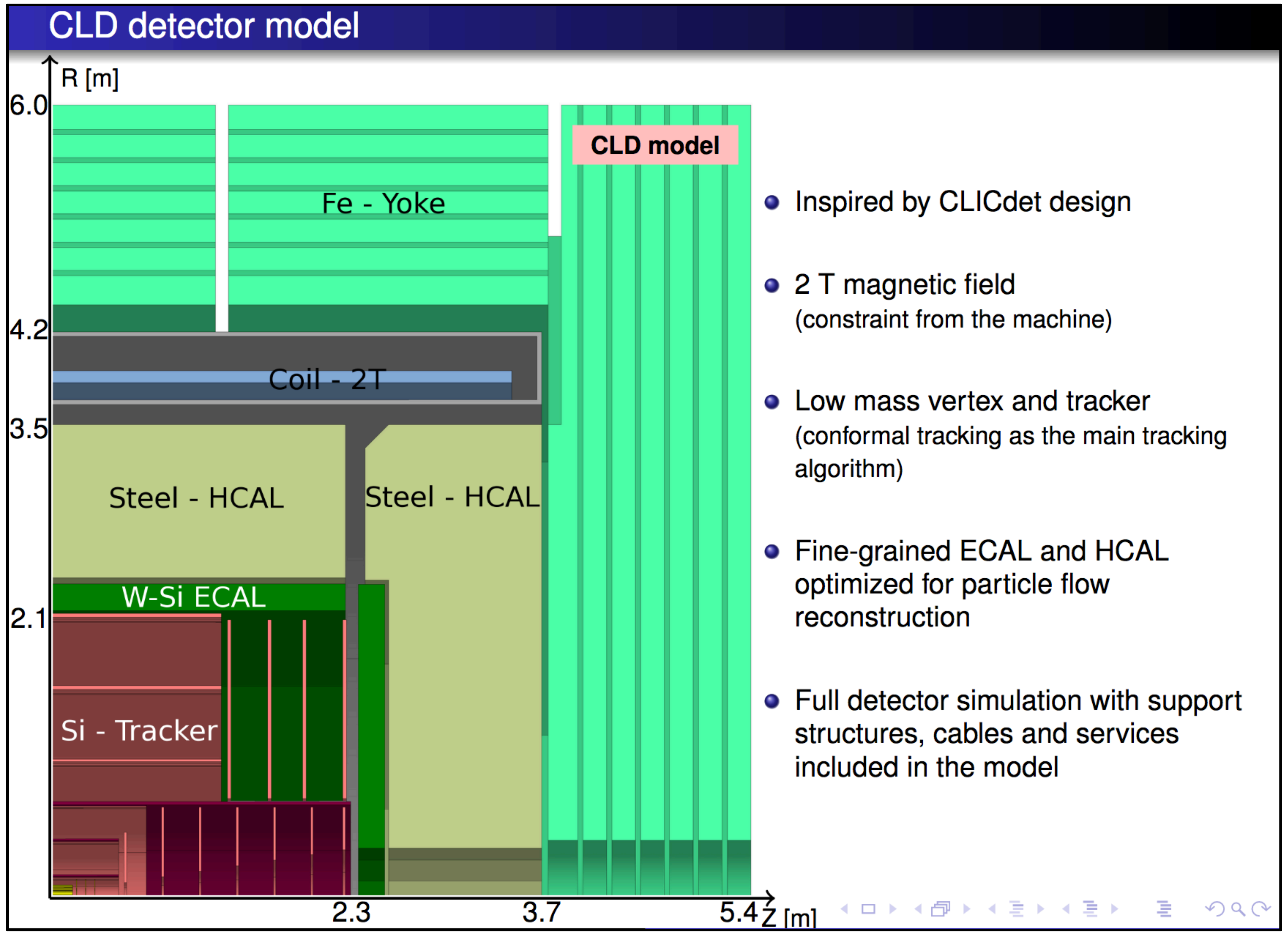
The FCC-ee unique discovery potential is multiplied by the access to the four heaviest particles of the Standard Model in its energy range

FCC-ee: A 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
  - Allows understanding of the underlying physics structure
- **DISCOVER** a violation of flavour conservation/universality
  - Flavour physics in 1012 bb events (B0 → K*0τ+τ− , BS→ τ+τ− , …)
- **DISCOVER** dark matter as invisible decays of the Z or Higgs
- **DISCOVER** feebly coupled particles in the 5-100 GeV mass range
  - Such as right handed neutrinos, dark photons, …

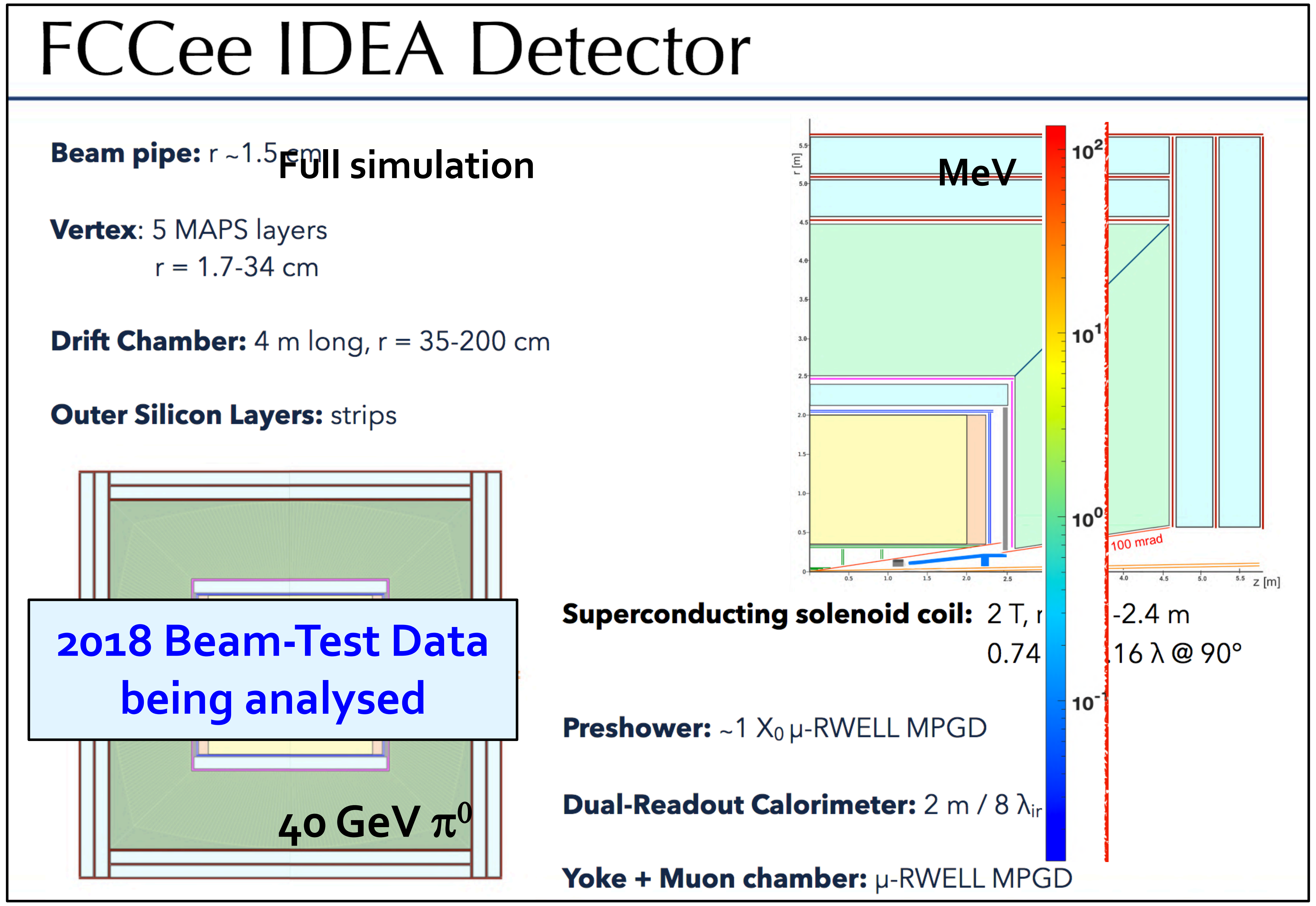
TWO DETECTOR CONCEPTS FOR THE CDR

- It was demonstrated that detectors satisfying the requirements are feasible. Two options considered for now with complementary designs
    - physics performance, beam background, invasive MDI event rates…



CLD detector model

- Inspired by CLICdet design
- 2 T magnetic field (constraint from the machine)
- Low mass vertex and tracker (conformal tracking as the main tracking algorithm)
- Fine-grained ECAL and HCAL optimized for particle flow reconstruction
- Full detector simulation with support structures, cables and services included in the model



FCCee IDEA Detector

Beam pipe: r ~1.5 cm

Vertex: 5 MAPS layers
r = 1.7-34 cm

Drift Chamber: 4 m long, r = 35-200 cm

Outer Silicon Layers: strips

Superconducting solenoid coil: 2 T, r -2.4 m
0.74 16 λ @ 90°

Preshower: ~1 X_0 μ-RWELL MPGD

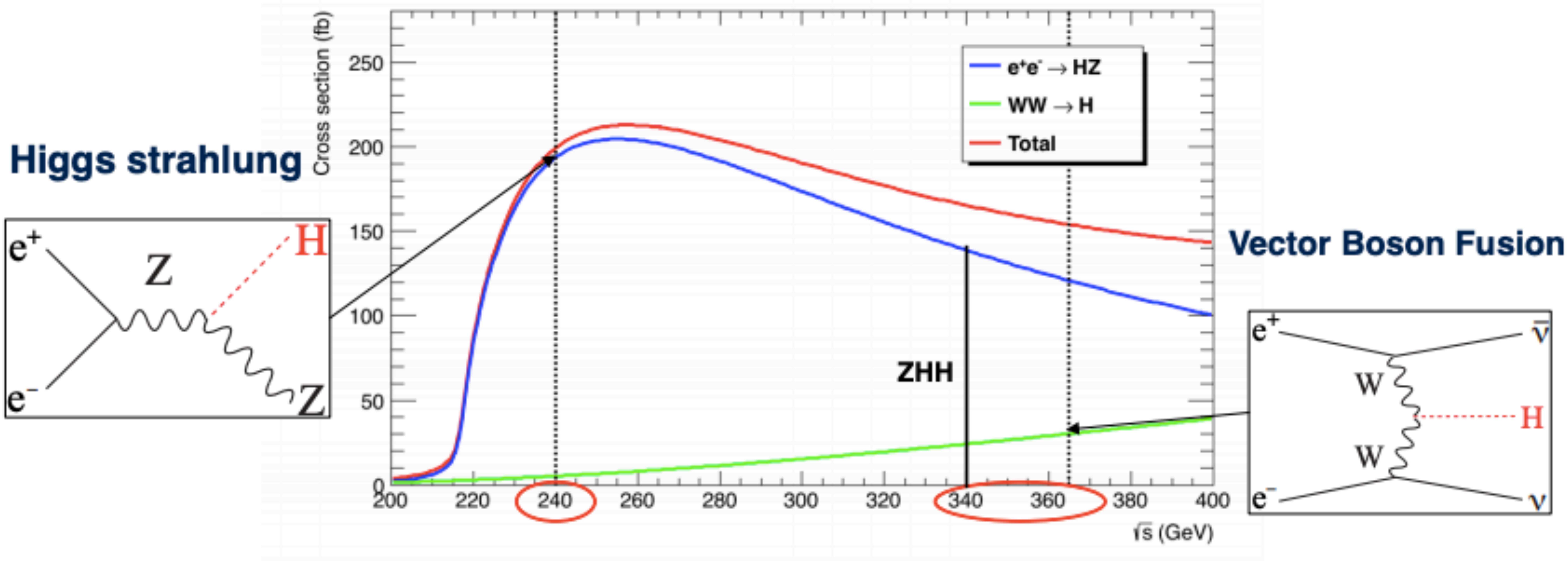
Dual-Readout Calorimeter: 2 m / 8 λ_{ir}

Yoke + Muon chamber: μ-RWELL MPGD

2018 Beam-Test Data being analysed

HIGGS PRODUCTION AT FCC-ee

Higgs boson production through Higgs strahlung and VBF



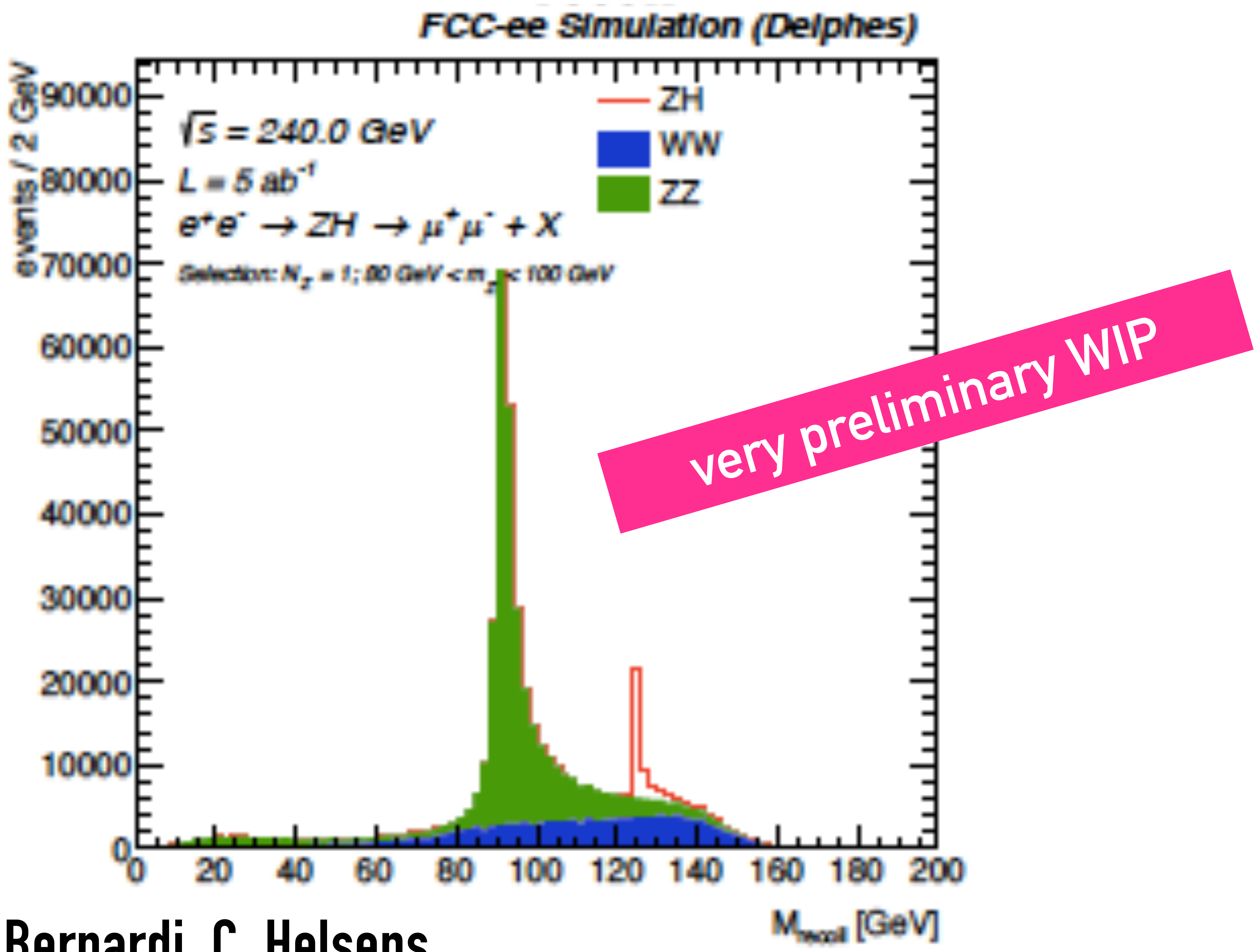
- maximum ZH cross section value at √s = 255 GeV
- luminosity drops with √s at constant ISR dissipation power

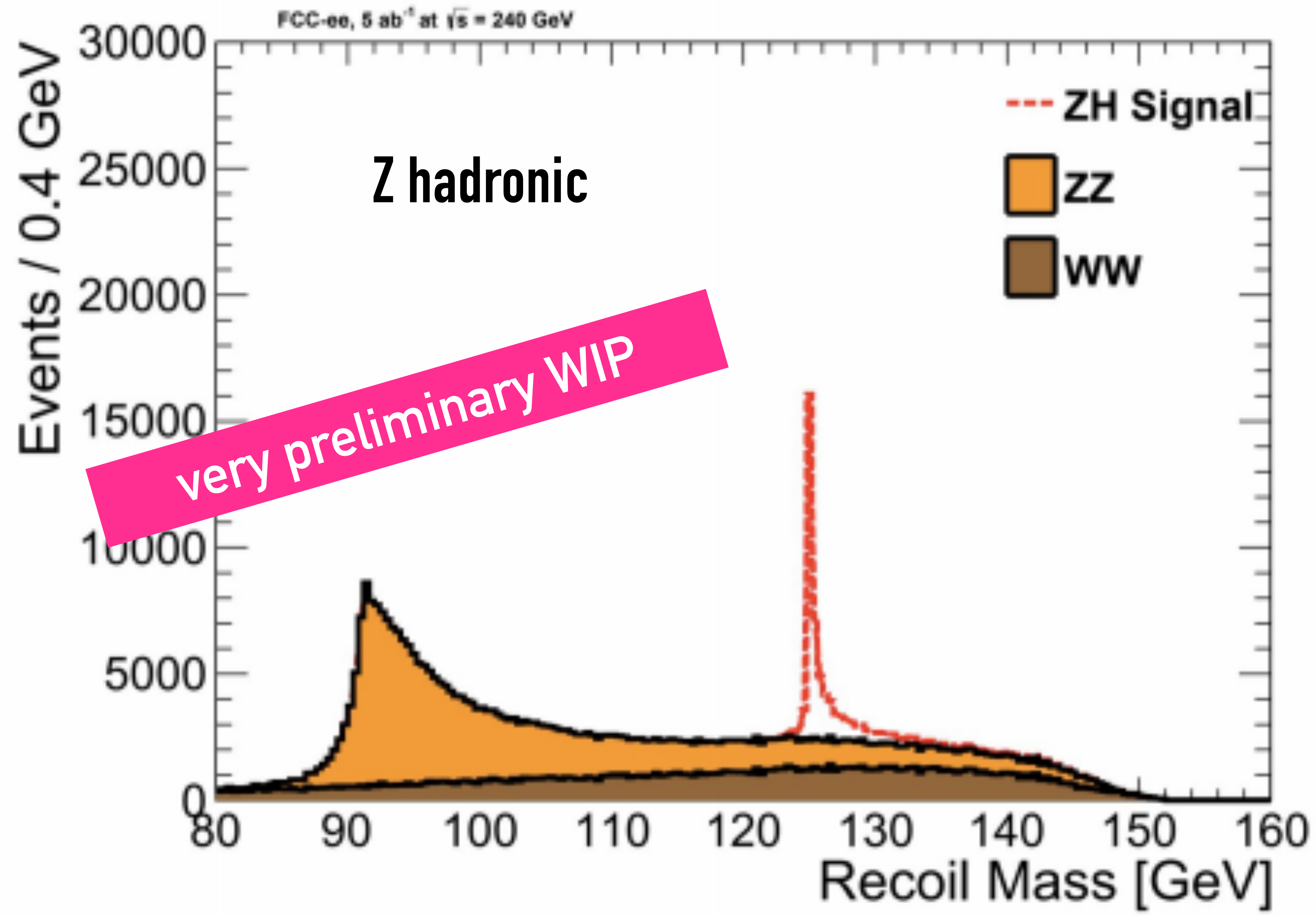
maximum event production at √s = 240 GeV

- higher energy points available for other physics targets (top physics), but they can be used to improve Higgs measurements (in particular Γ_H and Higgs self-coupling)

HIGGS PHYSICS - THE RECOIL METHOD

- Recoil method unique to lepton collider, it allows to tag Higgs event independent of decay mode:
    - Precision measurements: couplings, mass, width
    - Searches for Exotic Higgs, invisible decays
- Traditionally Z « tagged » via its leptonic decays
    - large FCC-ee statistics and improved detectors will allow to profit also of hadronic decays of Z
    - New analyses in progress with the latest software framework

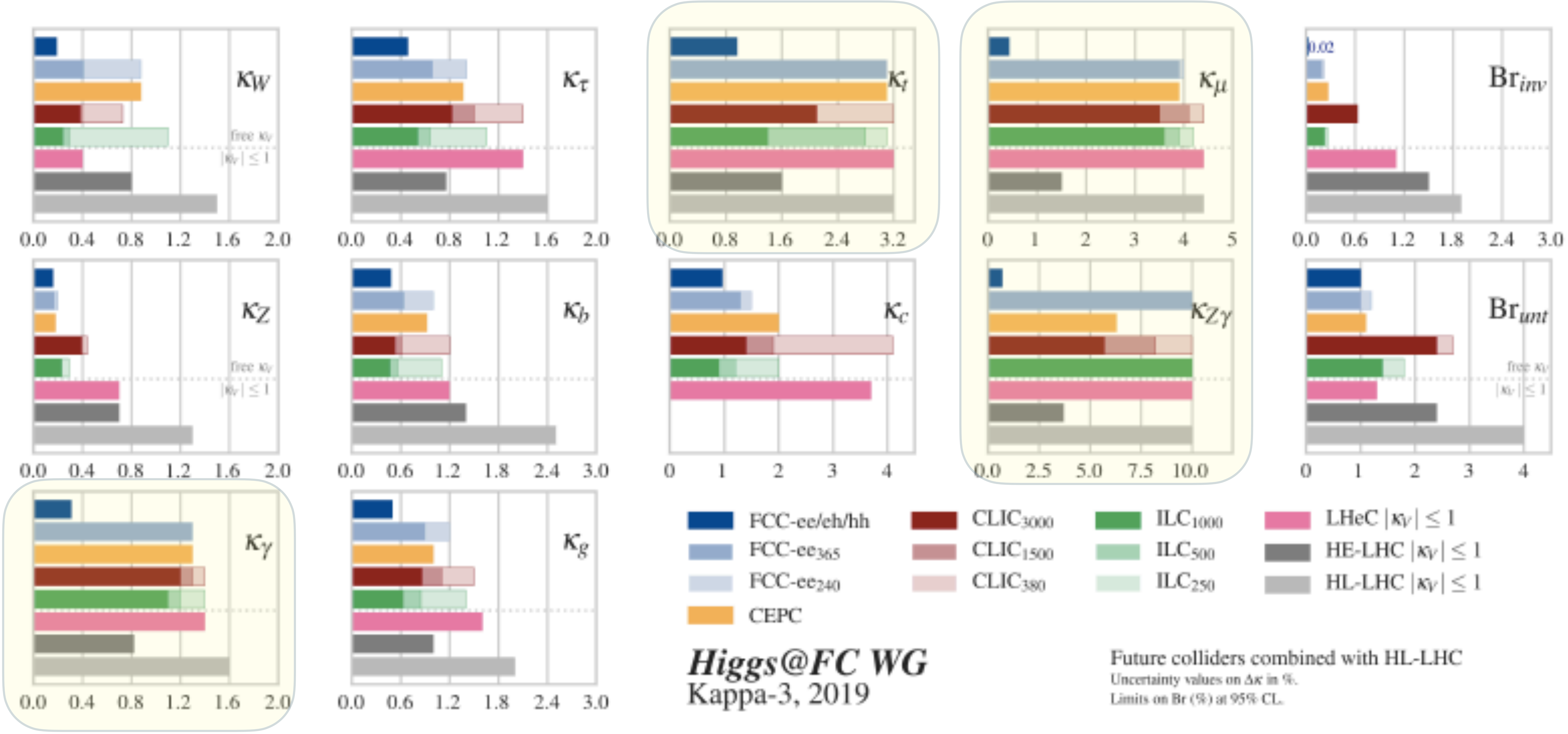




Ang Li, G. Bernardi, C. Helsens

HIGGS COUPLINGS

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



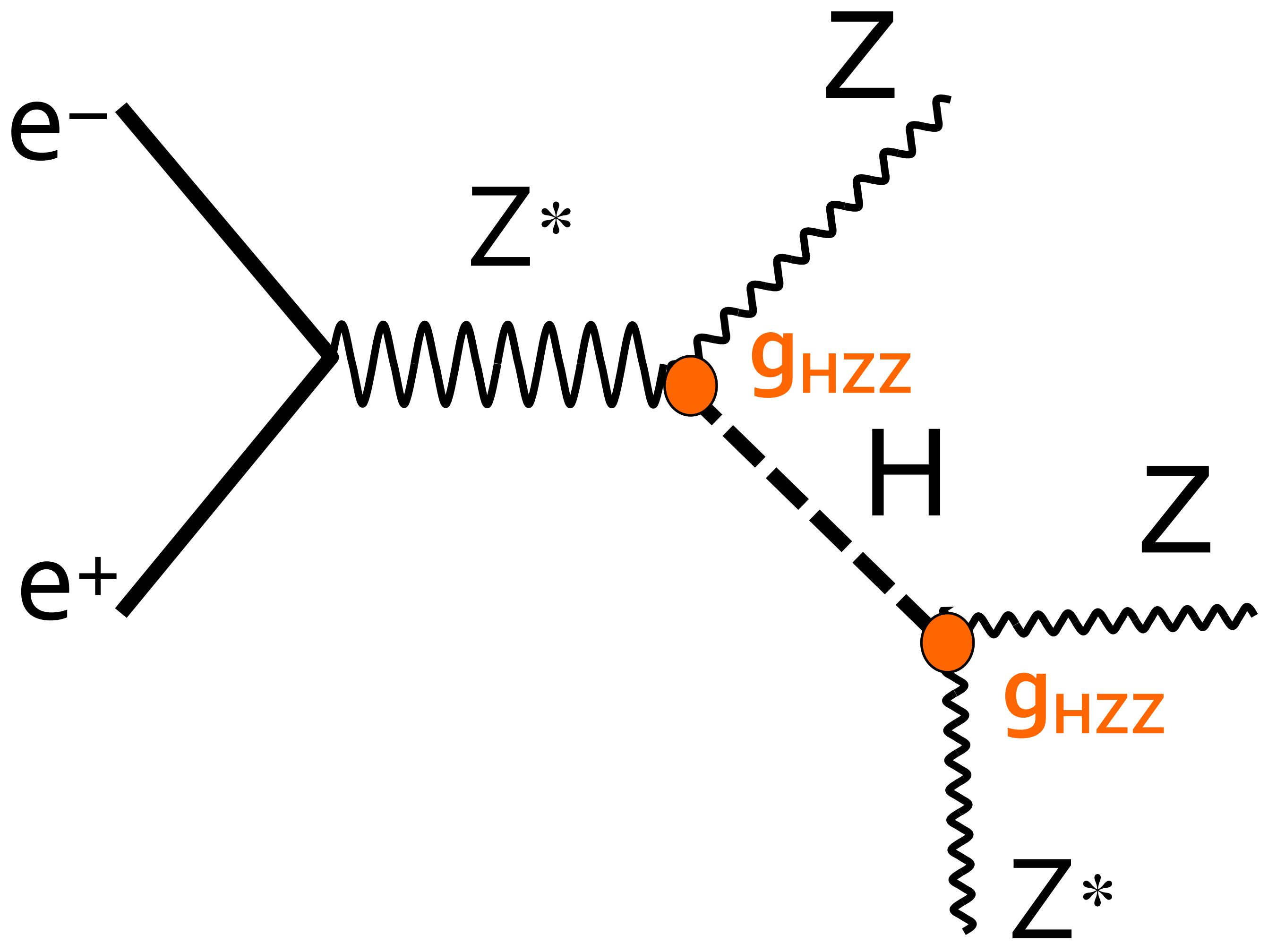
Yellow highlight for those couplings best measured with FCC-hh

FCC

HIGGS WIDTH

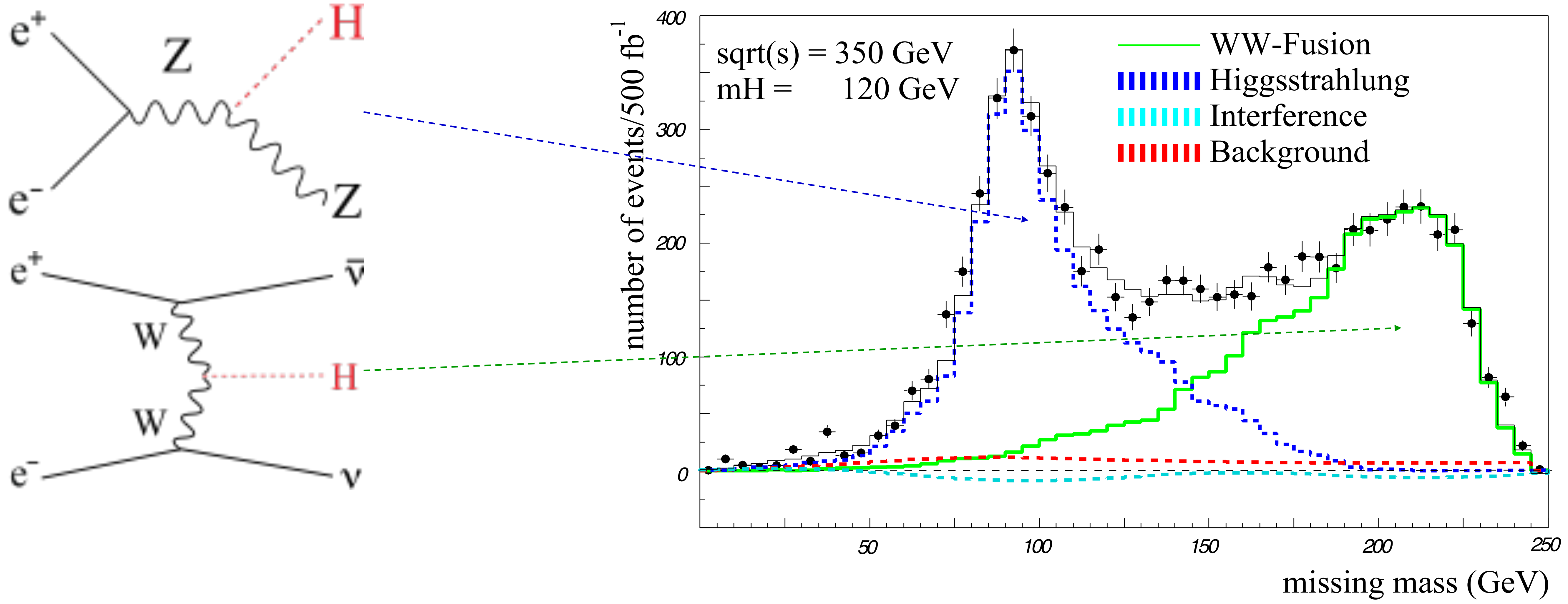
- ➤ Model independent determination of the total Higgs decay width down to 1.3% with runs at √s=240 and √s=365 GeV

ee →HZ & H → ZZ at √s = 240 GeV



- ❖ σ_{HZ} is proportional to g_{HZZ}^2
- ❖ BR(H → ZZ) = Γ(H → ZZ) / Γ_H is proportional to g_{HZZ}^2/Γ_H
  - ▪ σ_{HZ} × BR(H → ZZ) is proportional to g_{HZZ}^4/Γ_H
- ❖ Infer the total width Γ_H

WW → H νν→ bbνν at √s = 365 GeV



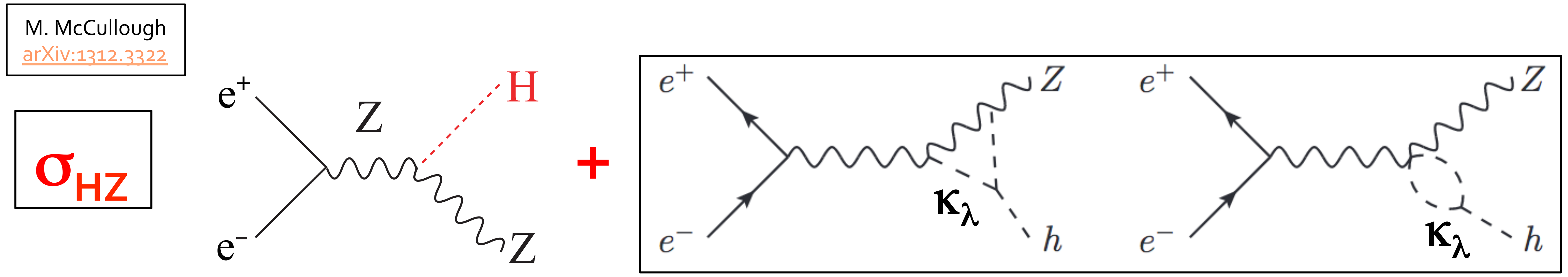
$$\Gamma_H \propto \frac{\sigma_{WW\to H}}{BR(H\to WW)} = \frac{\sigma_{WW\to H\to b\bar{b}}}{BR(H\to WW)\times BR(H\to b\bar{b})}$$

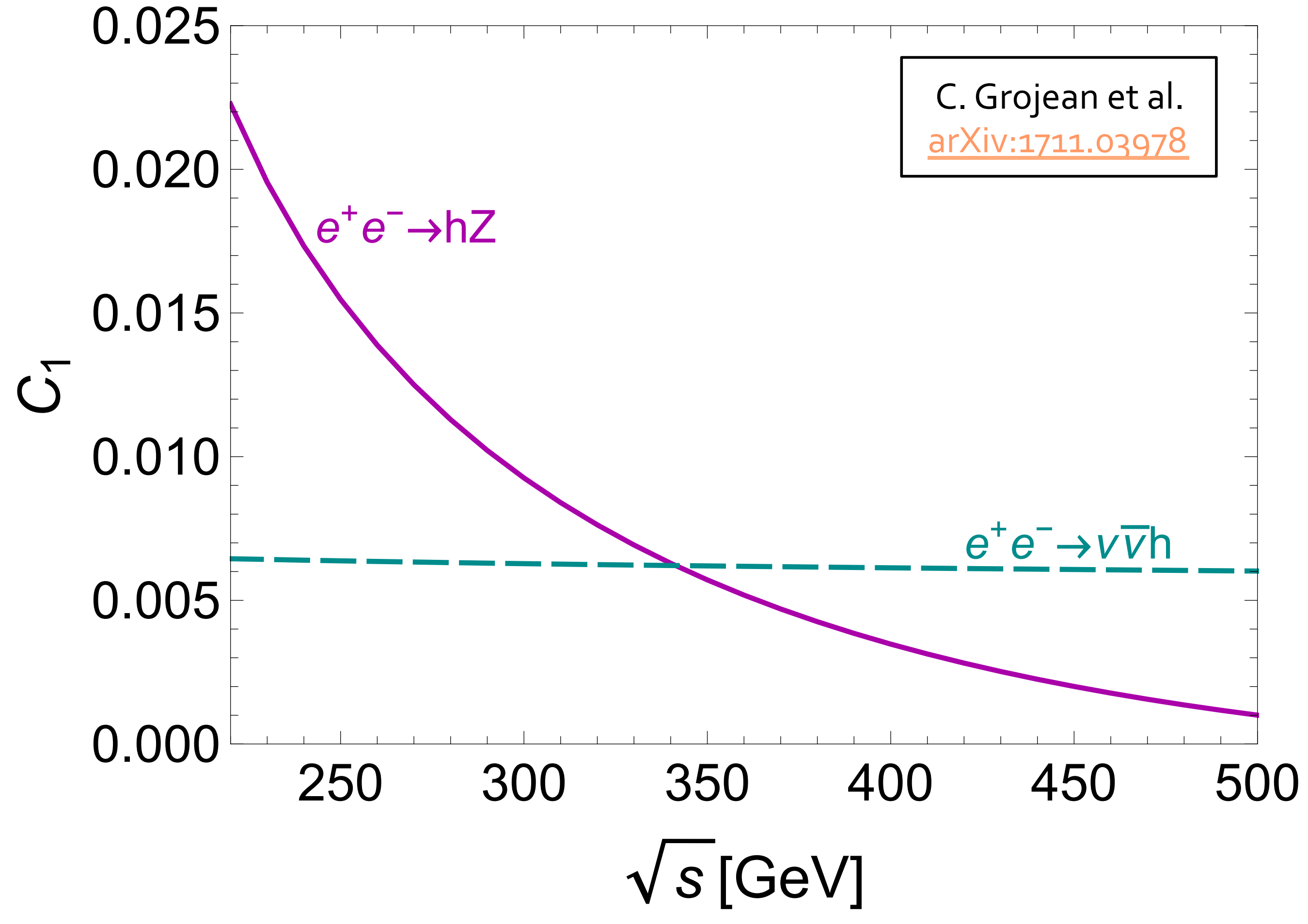
HIGGS SELF-COUPLING WITH SINGLE HIGGS

patrizia azzi -1st FCC Nordi Day -22/03/2021

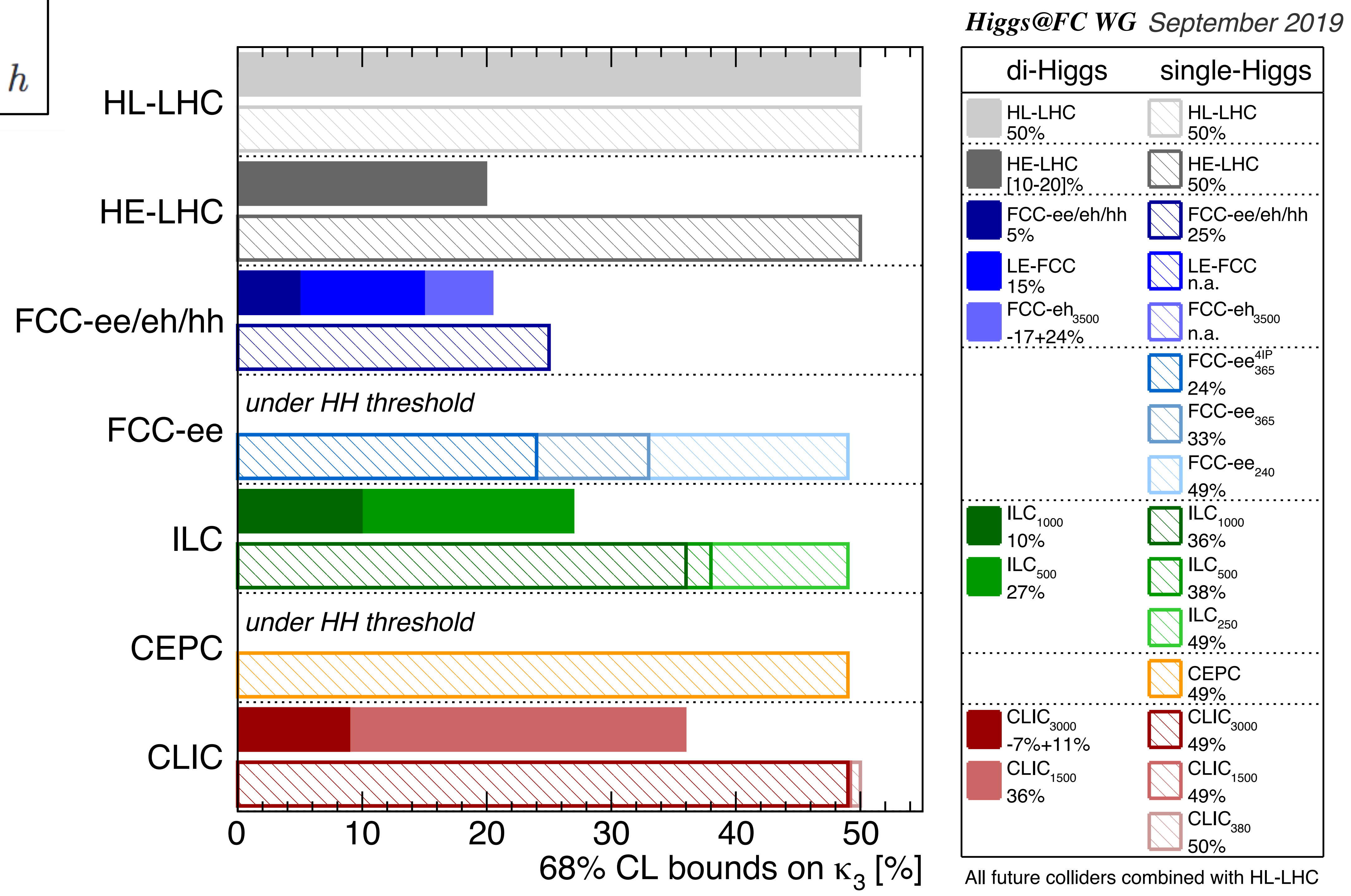
- Traditionally kλ measured in double Higgs production at higher energies. FCC-ee can profit of the significant effect on single Higgs production

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

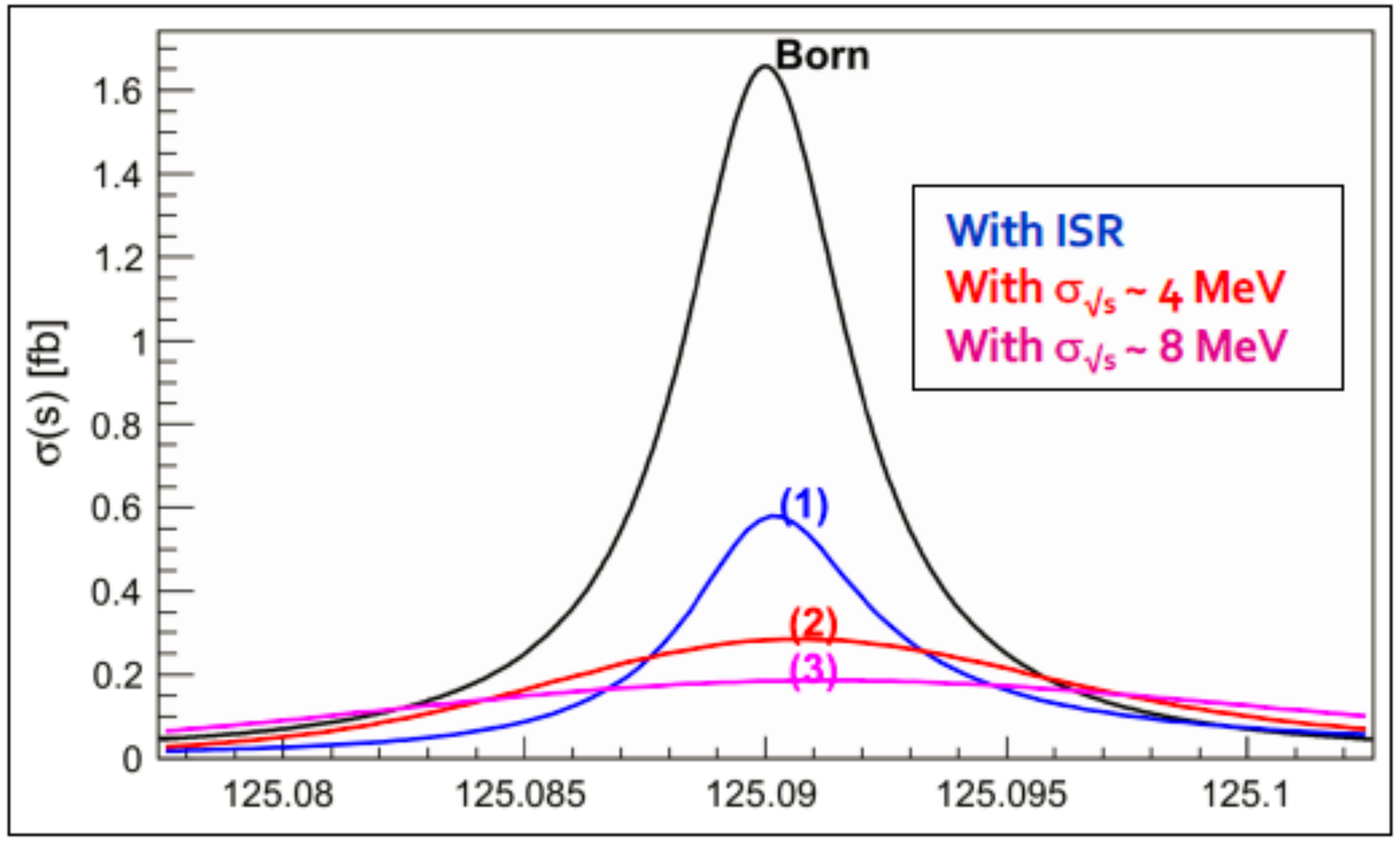

M. McCullough
arXiv:1312.3322

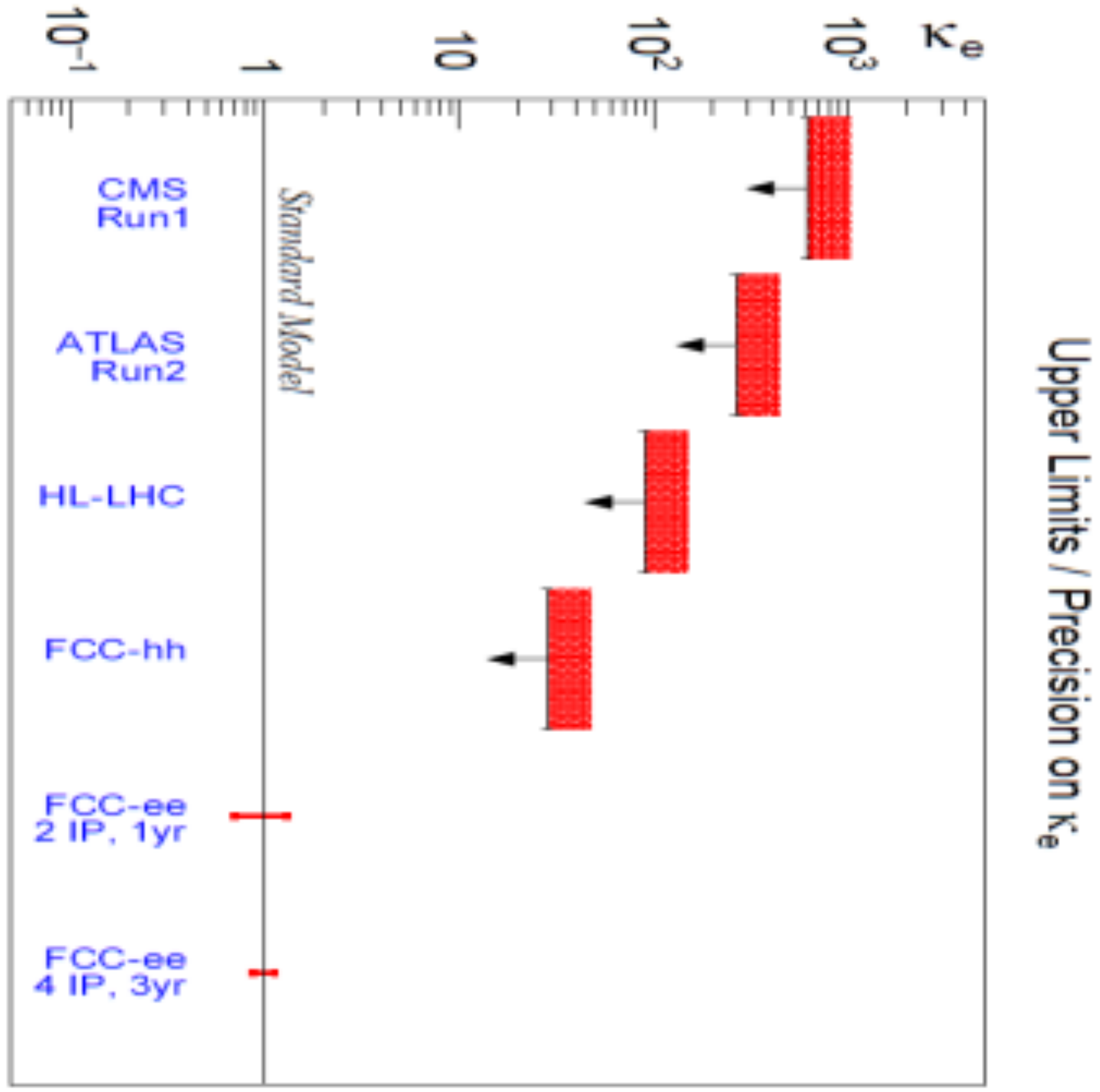

C. Grojean et al.
arXiv:1711.03978

Measurements at different √s also help to lift degeneracy between processes



SOMETHING UNIQUE: ELECTRON YUKAWA COUPLING



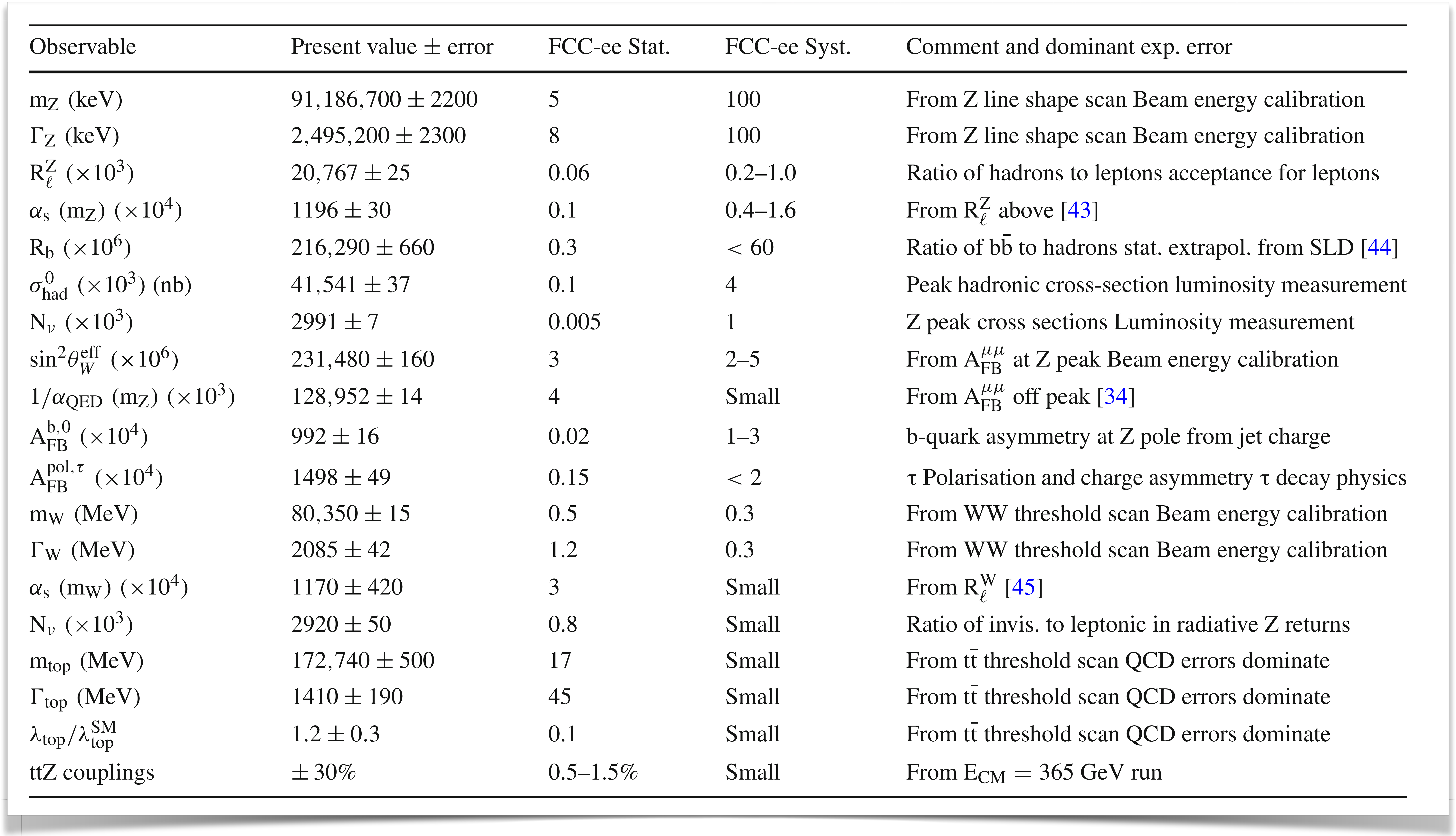


HUGE CHALLENGE

e+e- → H @ 125.xxx GeV requires:

- Higgs mass to be known to <5 MeV from 240 GeV run (CEPC group almost there)
- Huge luminosity
- monochromatization (opposite sign dispersion using magnetic lattice) to reduce σECM
- continuous monitoring and adjustment of ECM to MeV precision (transv. Polar.)
- an extremely sensitive event selection against backgrounds
- a generous lab director to spend 3 years doing this and neutrino counting

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	± 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.

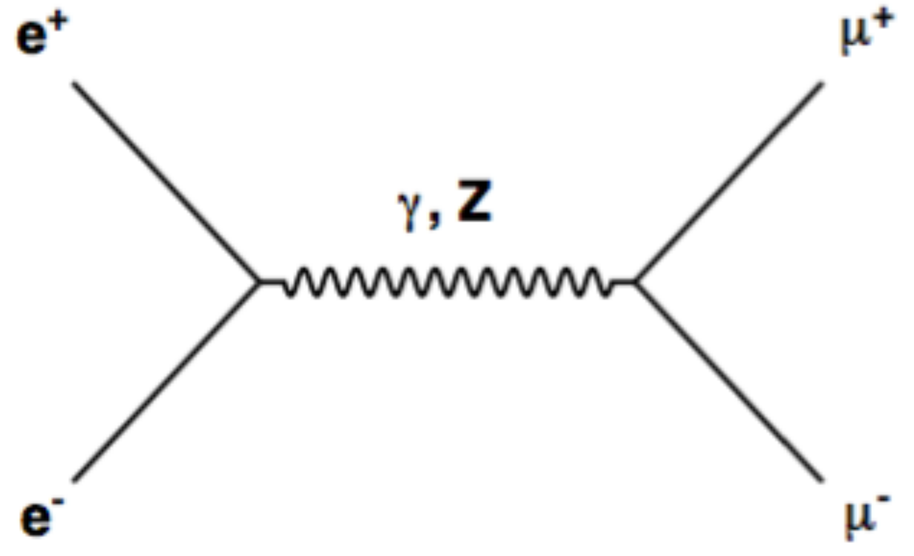
ELECTROWEAK PRECISION MEASUREMENTS

TeraZ (5 X 10^{12} Z)

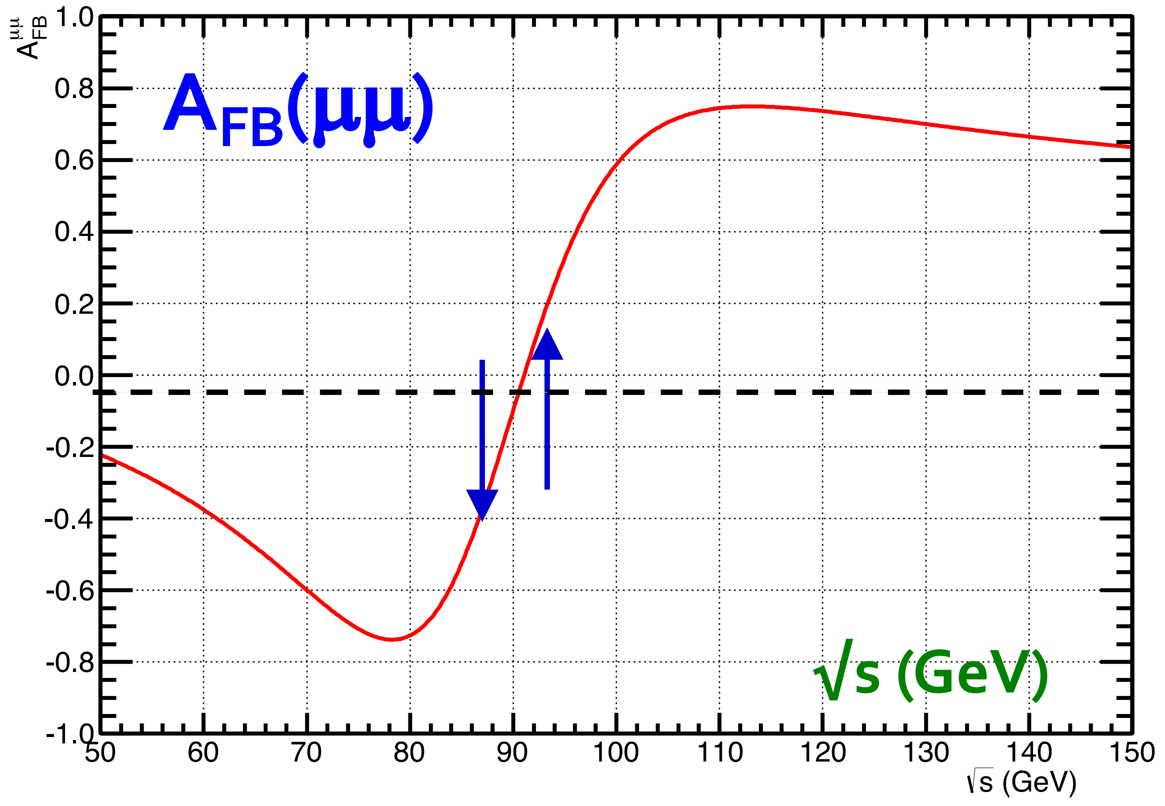
From data collected in a lineshape energy scan:

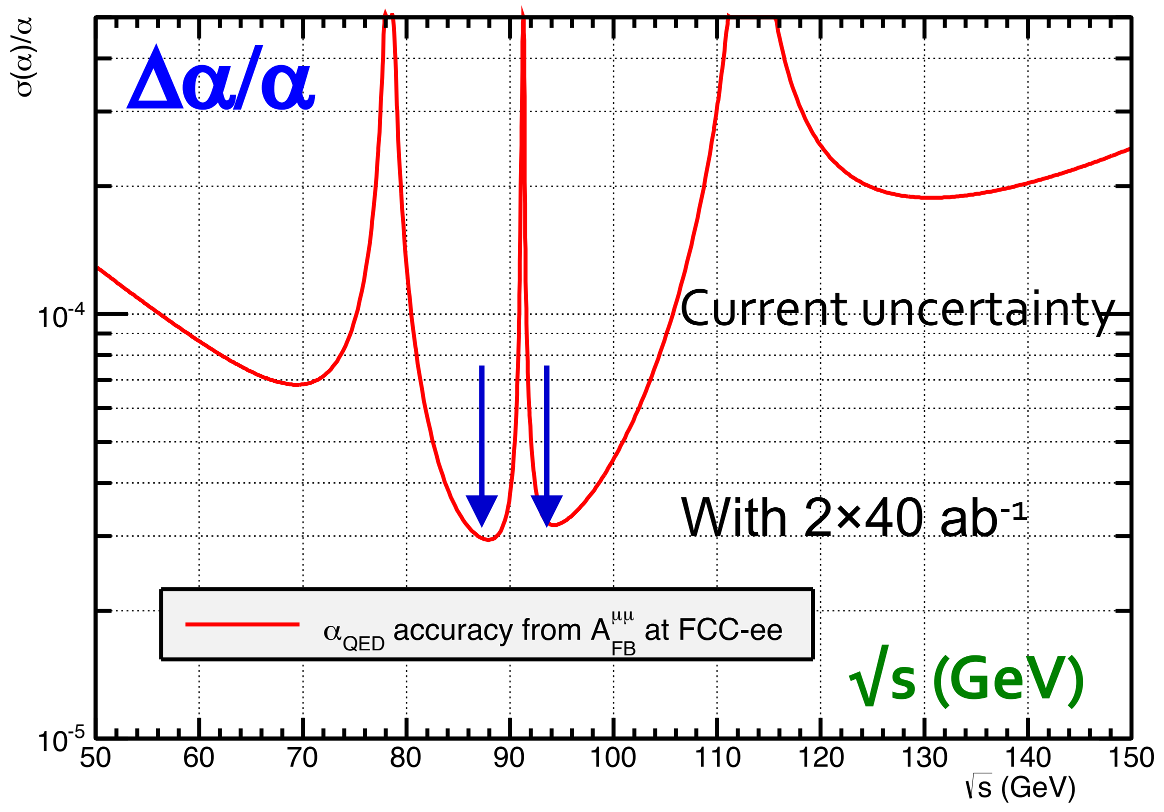
- Z mass (key for jump in precision for ewk fits)
- Z width (jump in sensitivity to ewk rad corr)
- R_l = hadronic/leptonic width ($\alpha_s(m^2_Z)$, lepton couplings, precise universality test)
- peak cross section (invisible width, N_ν)
- $A_{FB}(\mu\mu)$ ($\sin^2\theta_{eff}$, $\alpha_{QED}(m_Z^2)$,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

- Boils down to measuring cross sections and asymmetries
  - The dominant experimental uncertainties come from the beam energy knowledge



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





NEUTRAL COUPLINGS AND EWK ANGLE

$$A_e = \frac{2g_{V_e}g_{A_e}}{(g_{V_e})^2 + (g_{A_e})^2} = \frac{2g_{V_e}/g_{A_e}}{1 + (g_{V_e}/g_{A_e})^2}$$

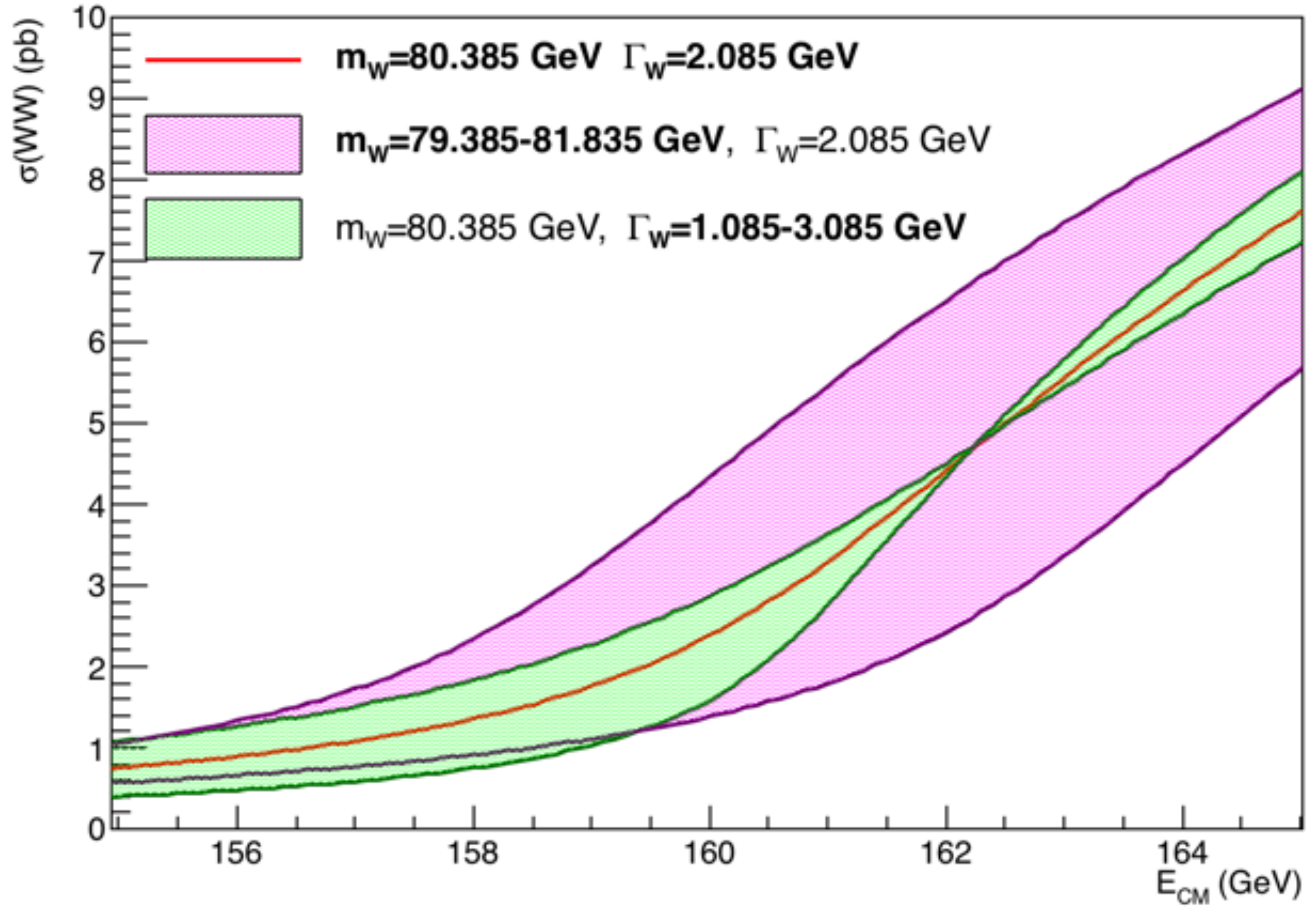
- $\sin^2\theta_{eff}$ can be measured with 5x10^{-6} (at least) from:
  - **Muon forward-backward asymmetry at pole $A_{FB}^{\mu\mu}(m_Z)$ assuming muon-electron universality**
    - uncertainty driven by knowledge of CM energy (point to point errors)
  - **Tau polarization without assuming lepton universality**
    - Tau polarization measures A_e and A_τ, can input to $A_{FB}^{\mu\mu} = \frac{3}{4}A_eA_\mu$ to measure separately e, μ and τ coupling (with $\Gamma_e, \Gamma_\mu, \Gamma_\tau$)
      - 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^o
      - Preliminary estimate to measure $\sin^2\theta_{eff}$ with 6.6x10^{-6} precision
- Asymmetries A_{FB}^{bb}, A_{FB}^{cc} provide input to quark couplings (together with Γ_b, Γ_c)

THE WW THRESHOLD

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)



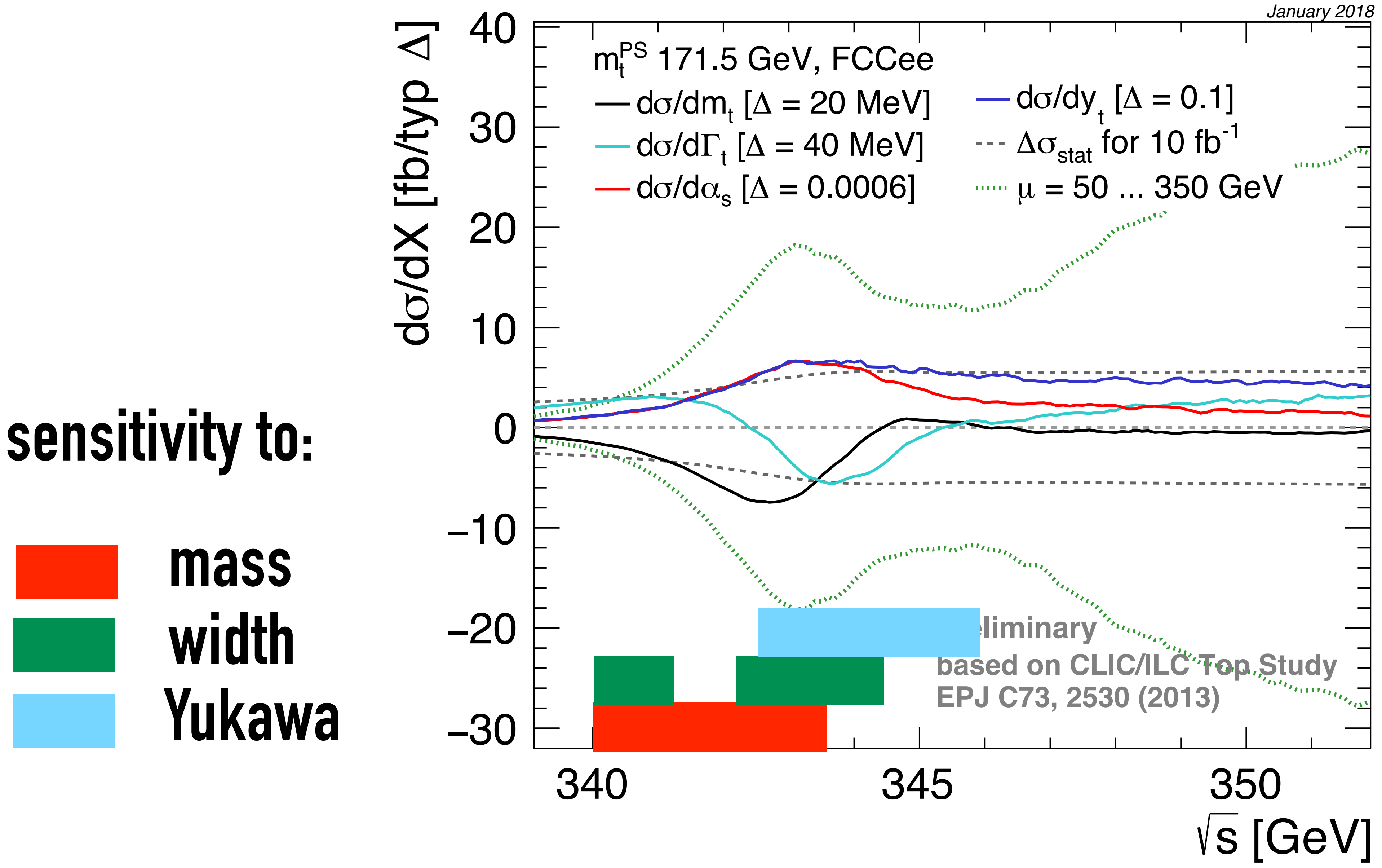
with E_1=**157.1** GeV E_2=**162.3** GeV f=**0.4**
Δm_W=0.62 $\Delta\Gamma_W$=1.5 (MeV)

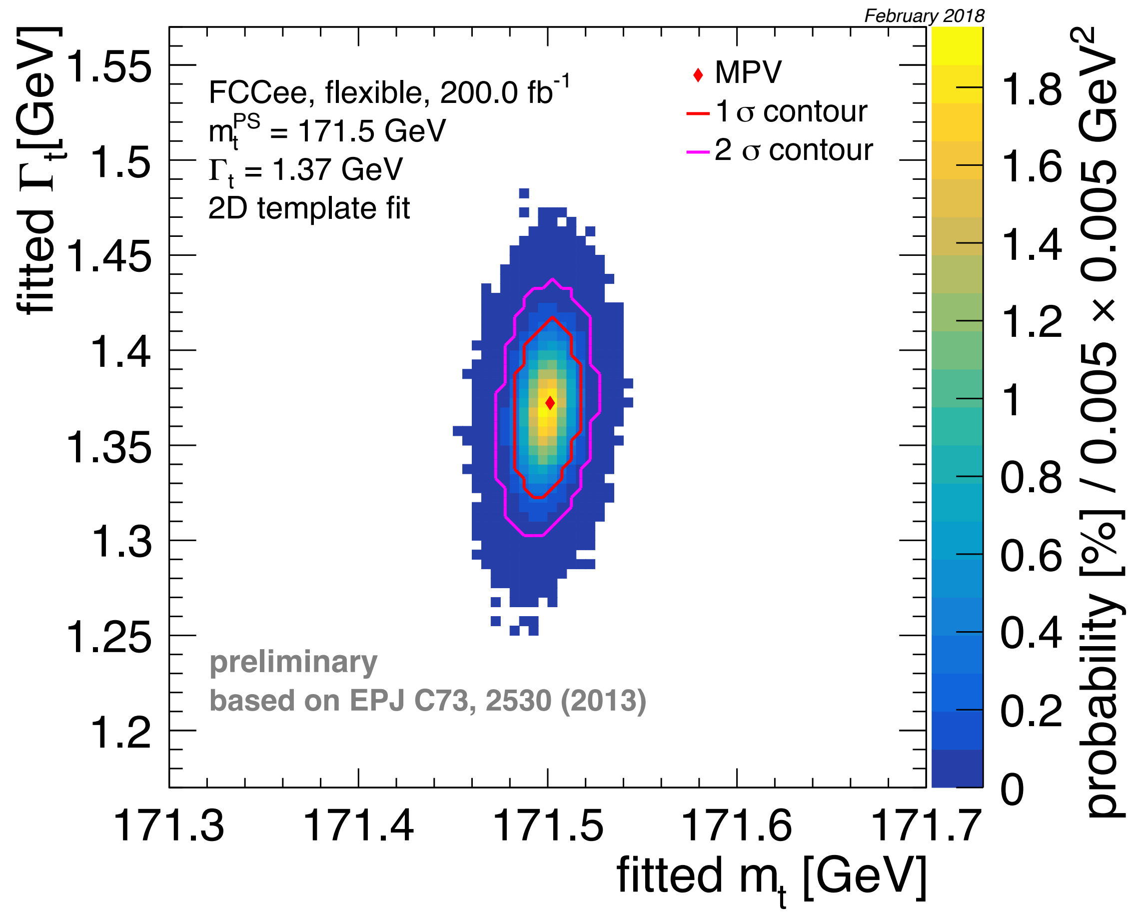
need syst control on :

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

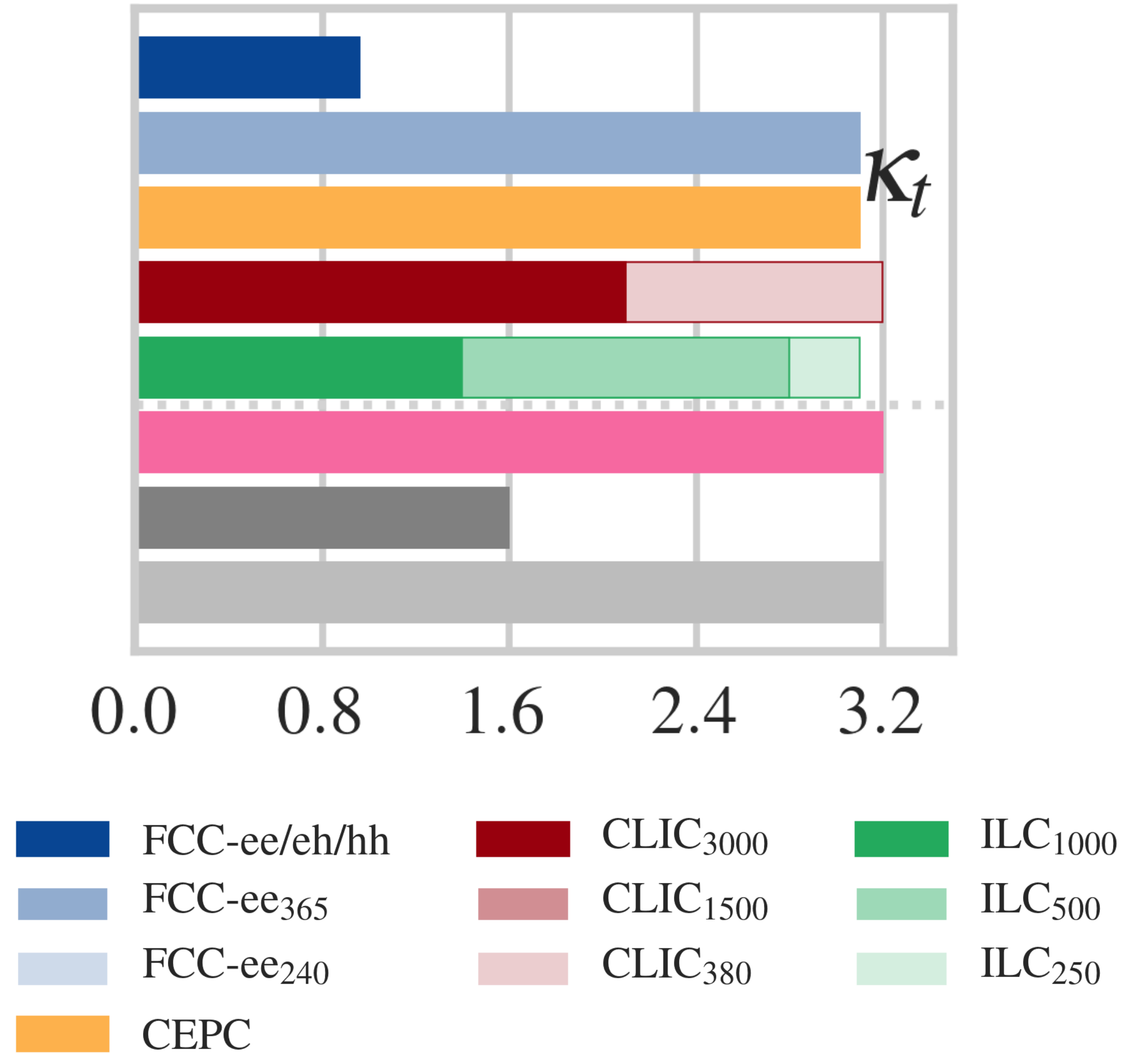
TOP PHYSICS AT FCC-ee

- 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 αS).
    - But, HL-LHC result of about 3.1% already better (with FCC-ee Higgs measurements removing the model dependence)





Mass only: 8.8 MeV (stat), 5.4 MeV (αs [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)

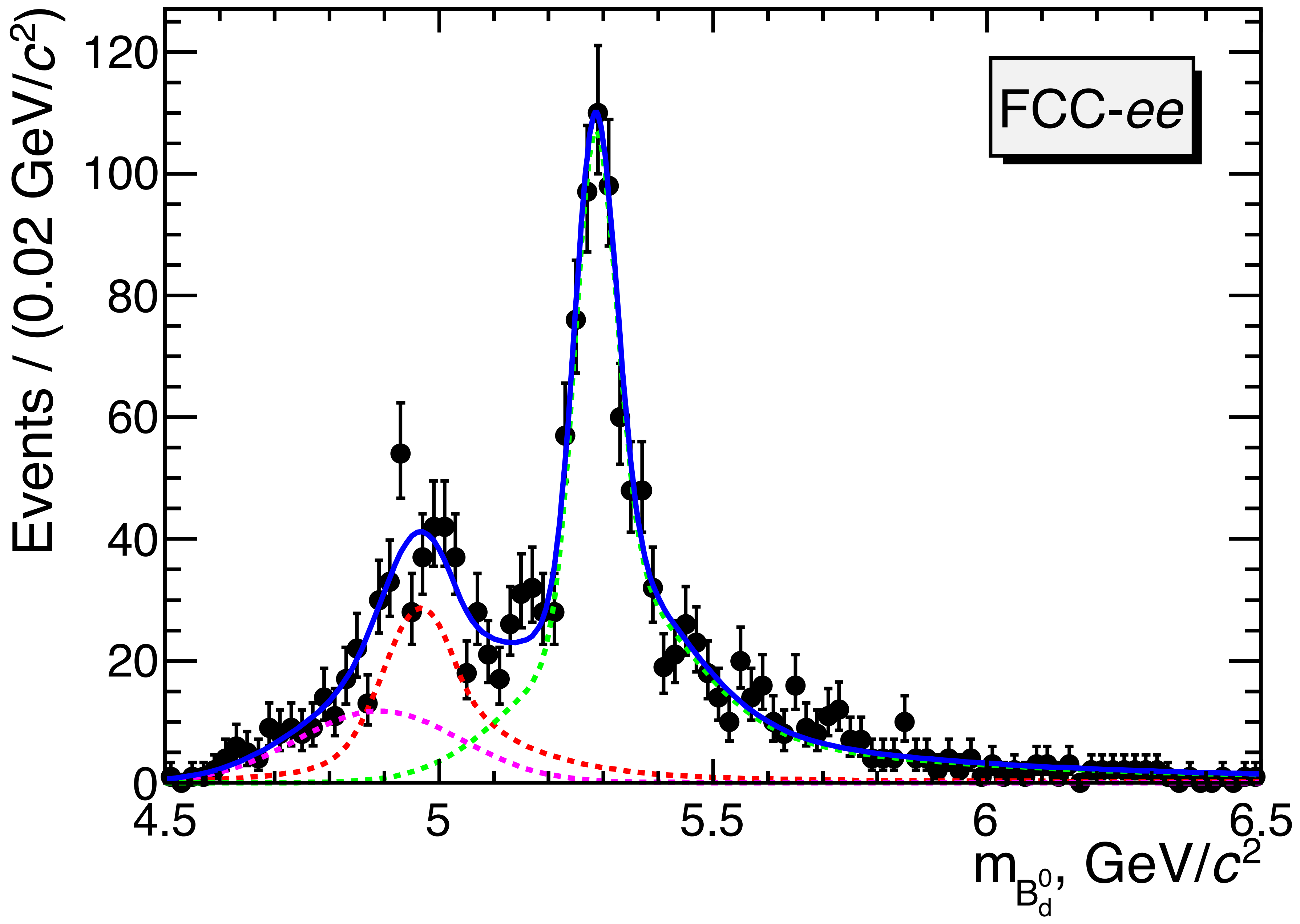
Working point	Lumi. / IP $[10^{34}\ \text{cm}^{-2}.\text{s}^{-1}]$	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

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 $B^0 \to K^{*0}\tau^+\tau^-$👍

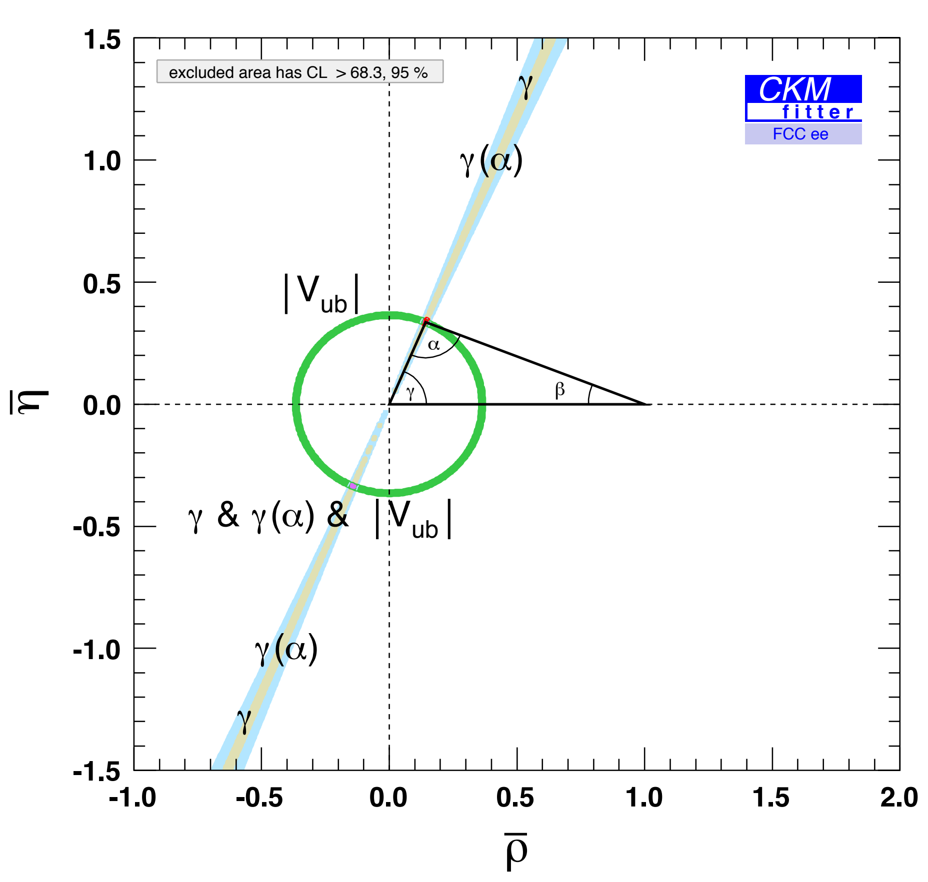
Full reconstruction possible

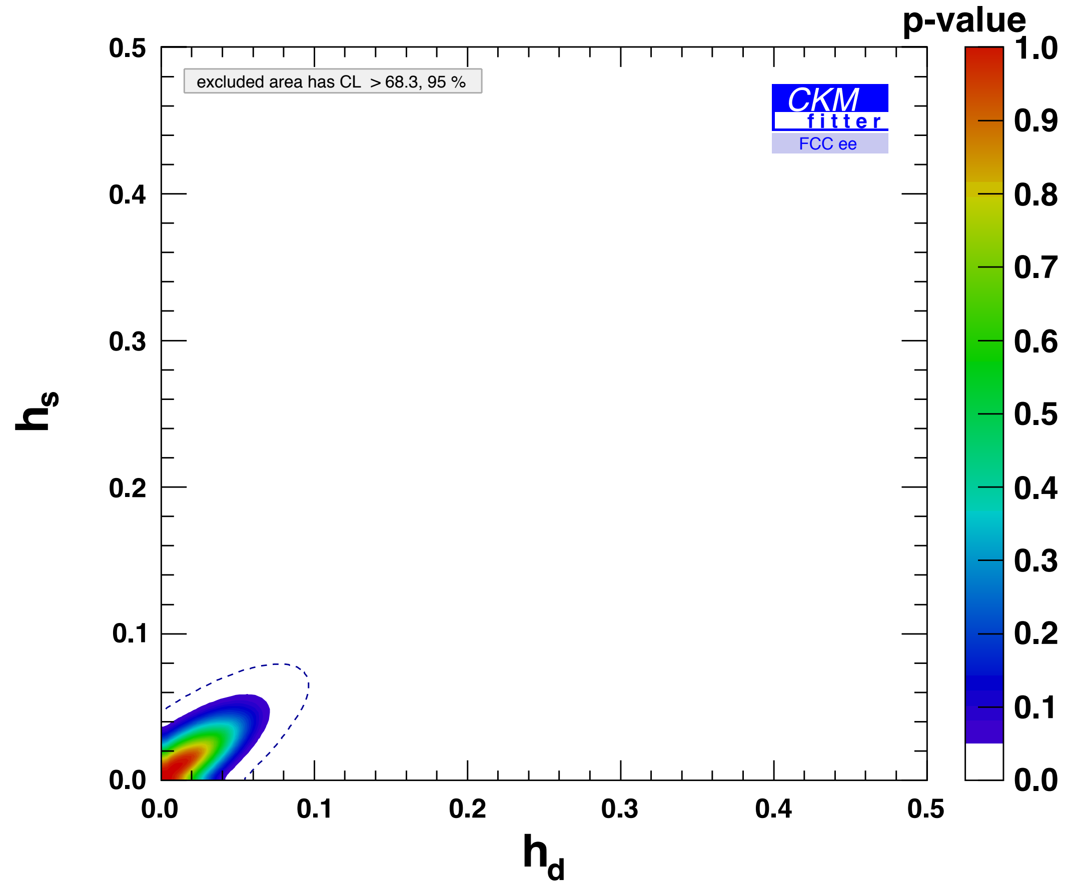
TERA-Z - FLAVOR PHYSICS(2)

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	?

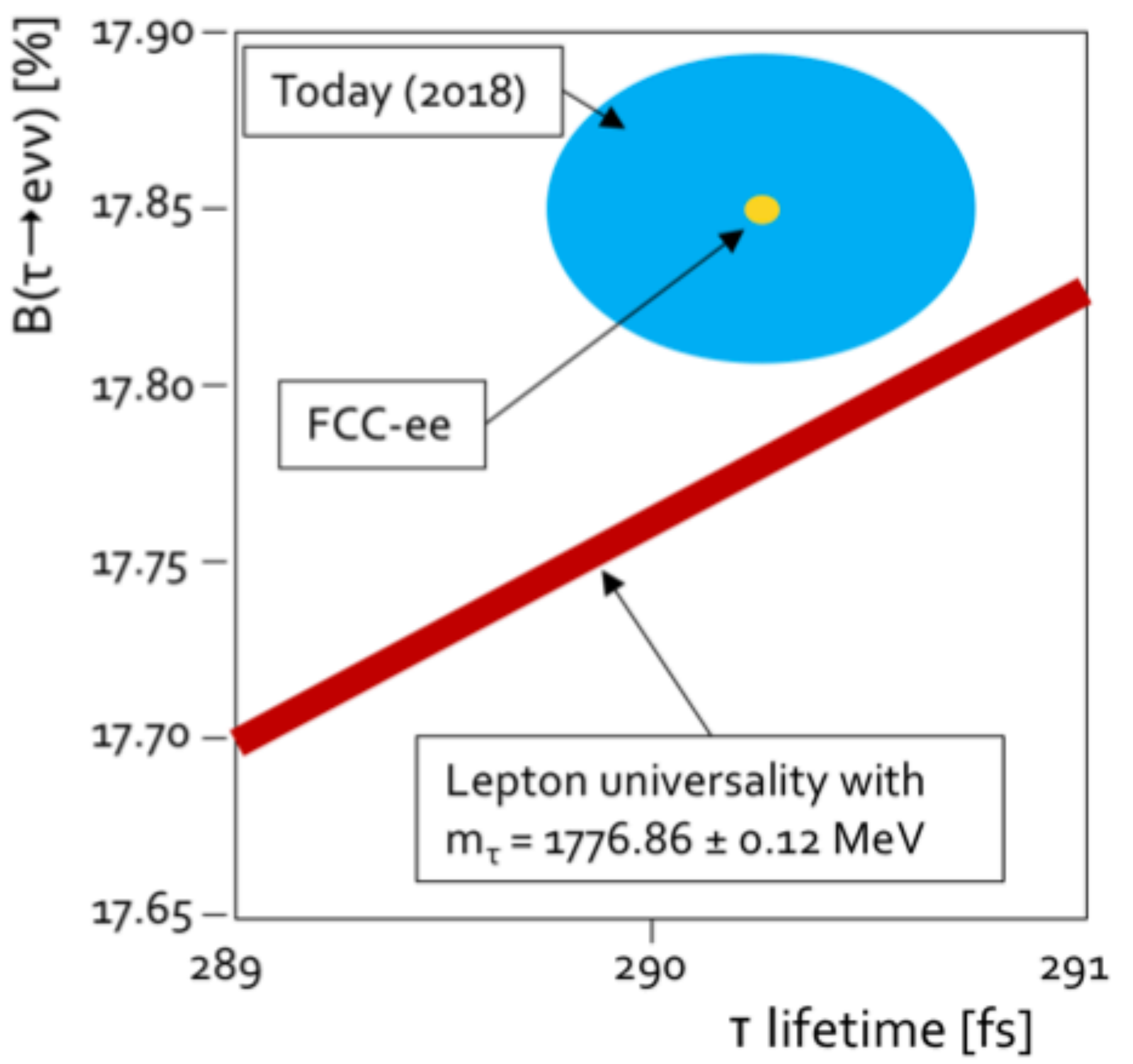
CLFV *Z* decays:

in SM $<10^{-50}$

Decay	Current bound	FCC-ee sensitivity
$Z \rightarrow e\mu$	$0.75 \times ^{-6}$	10^{-8}
$Z \rightarrow \mu\tau$	12×10^{-6}	10^{-9}
$Z \rightarrow e\tau$	9.8×10^{-6}	10^{-9}

CLFV *τ* decays:

Decay	Current bound	FCC-ee sensitivity
$\tau \rightarrow \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \rightarrow 3\mu$	2×10^{-8}	10^{-10}

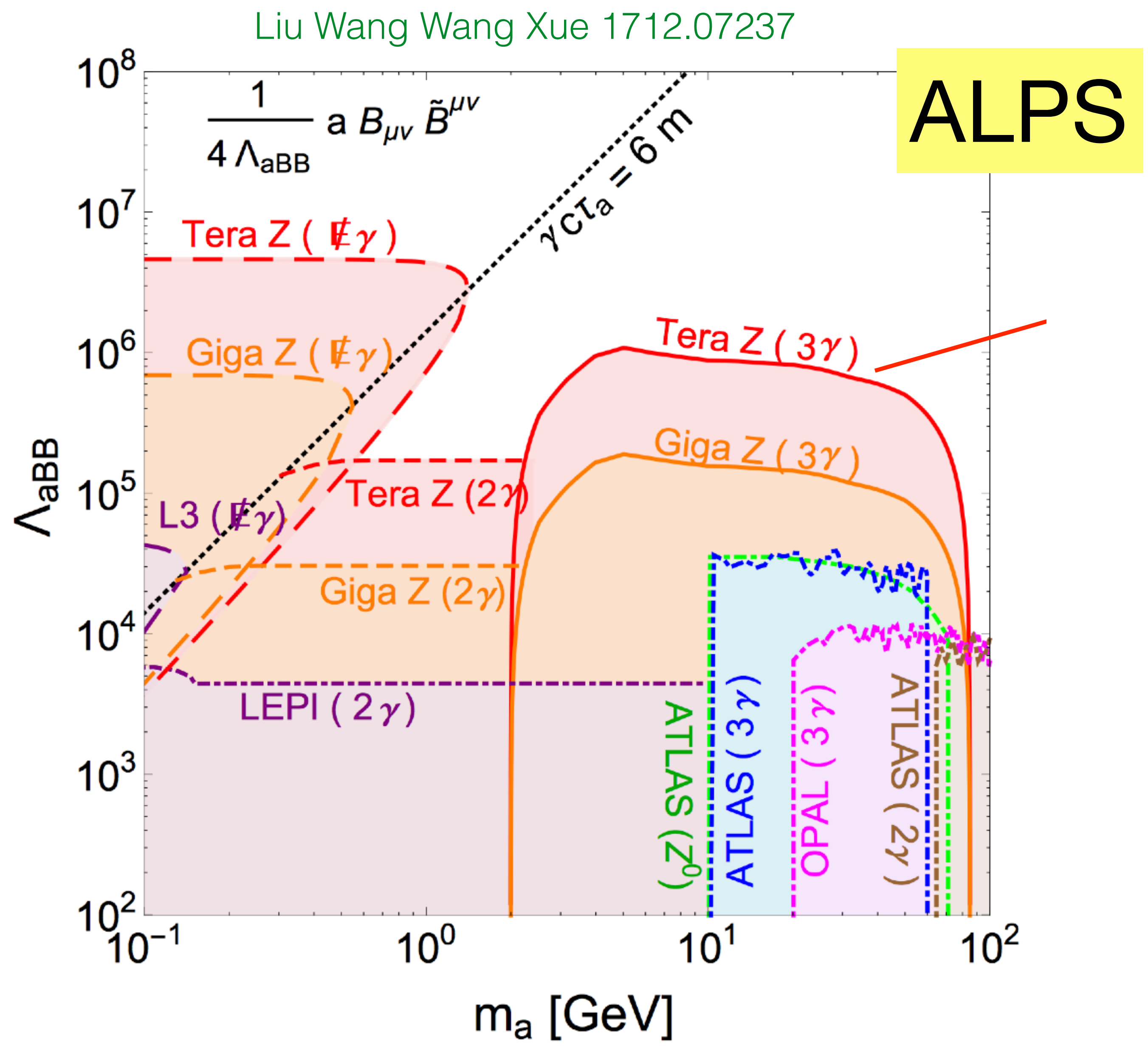


Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04

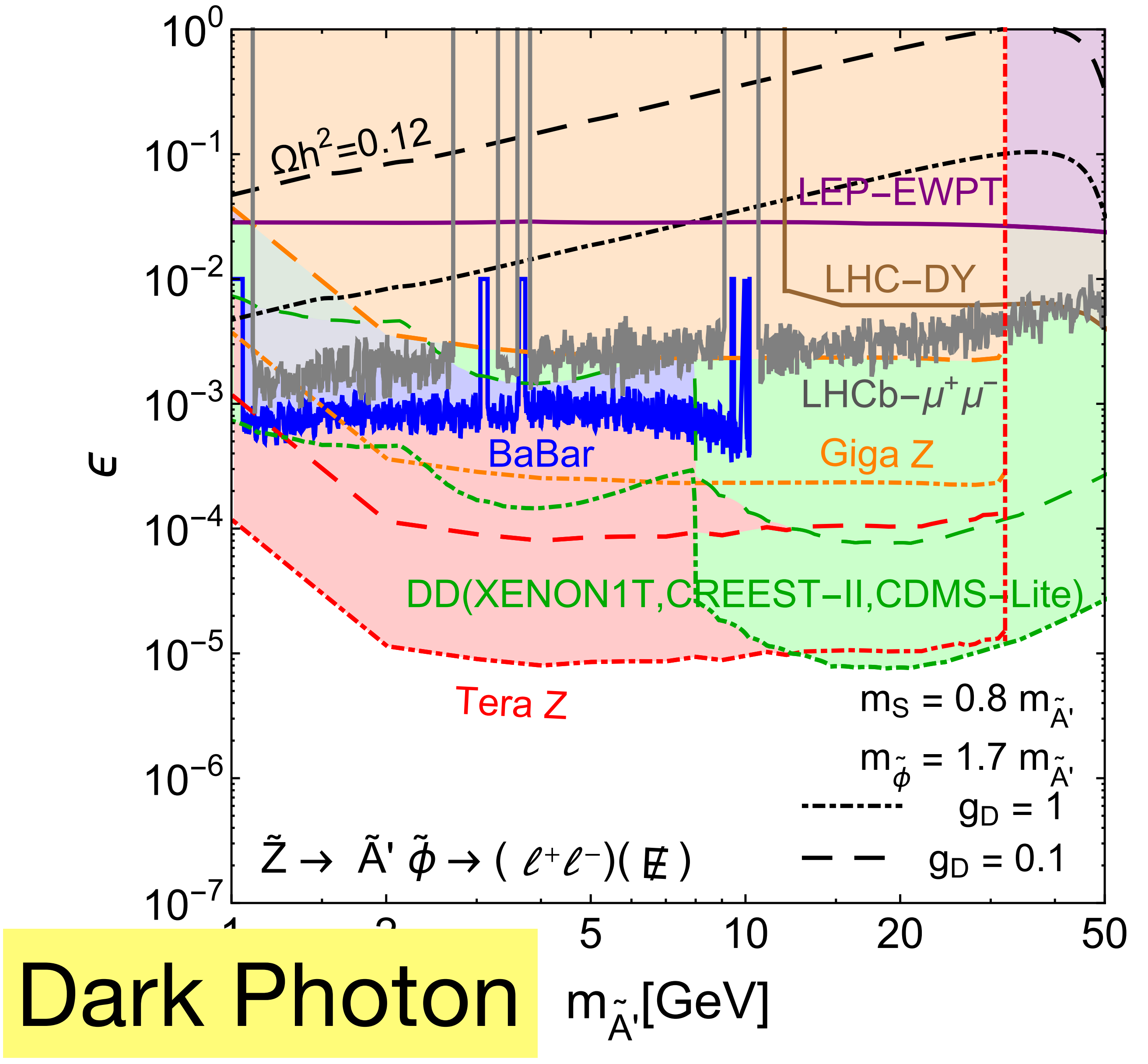
more unique opportunities in backup

BSM DIRECT SEARCHES - Z EXOTIC DECAYS

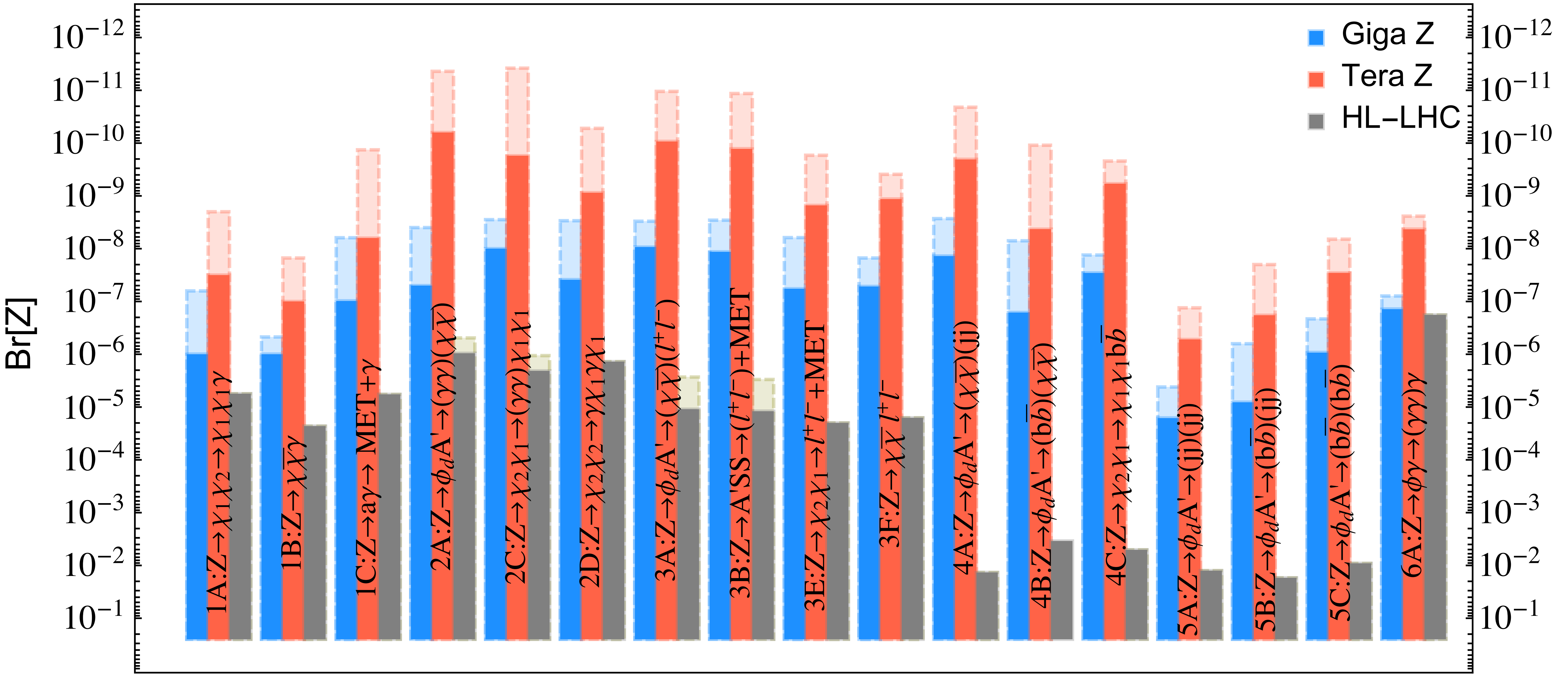
- Several models that describe possible exotic Z decays in dark sector candidate particles have been studied
- Complementarity between experiments depending on the parameter space
- Also comparison with HL-LHC



ALPS

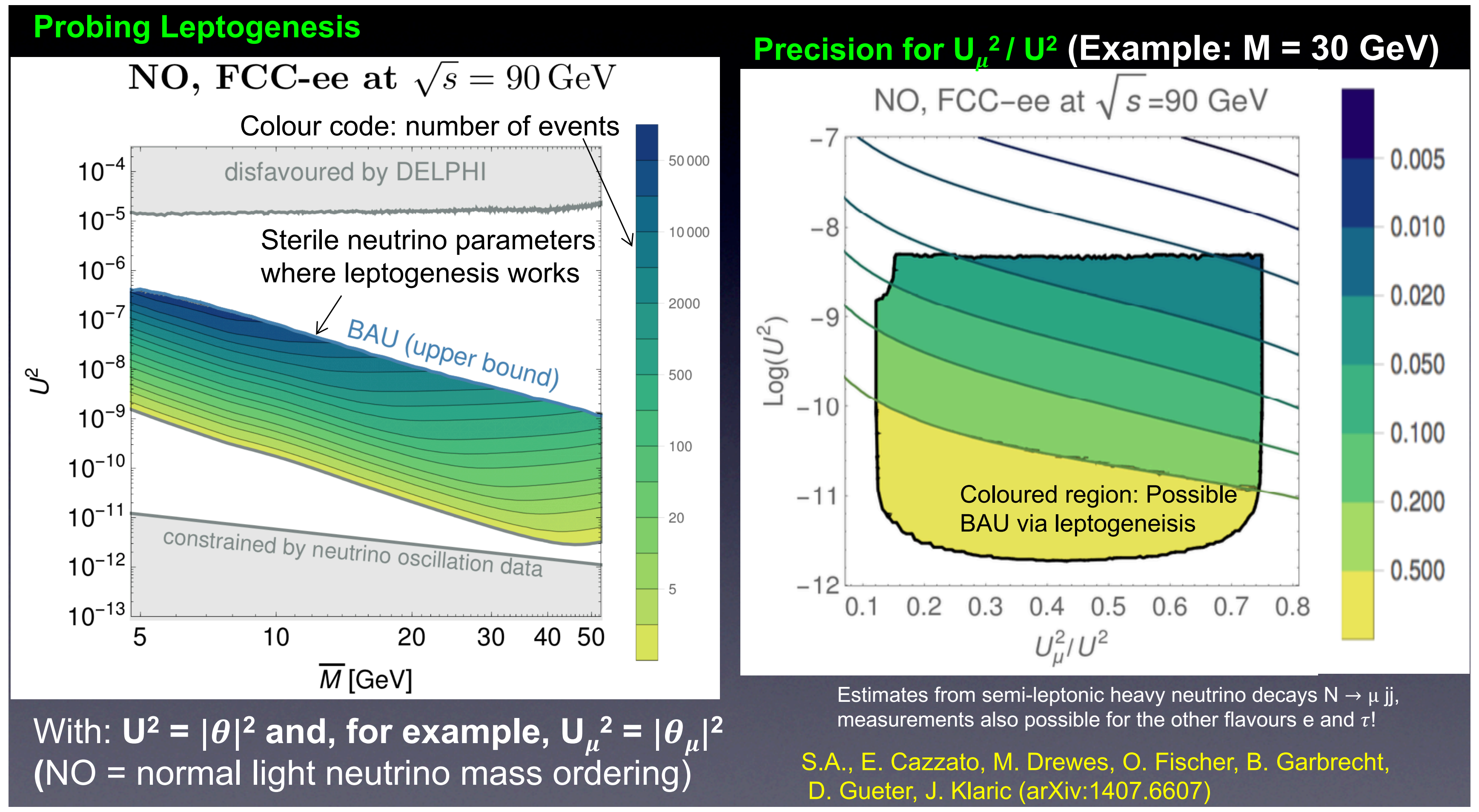


Dark Photon



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 hypothesis
- Together with ΔM also tests the compatibility with leptogenesis



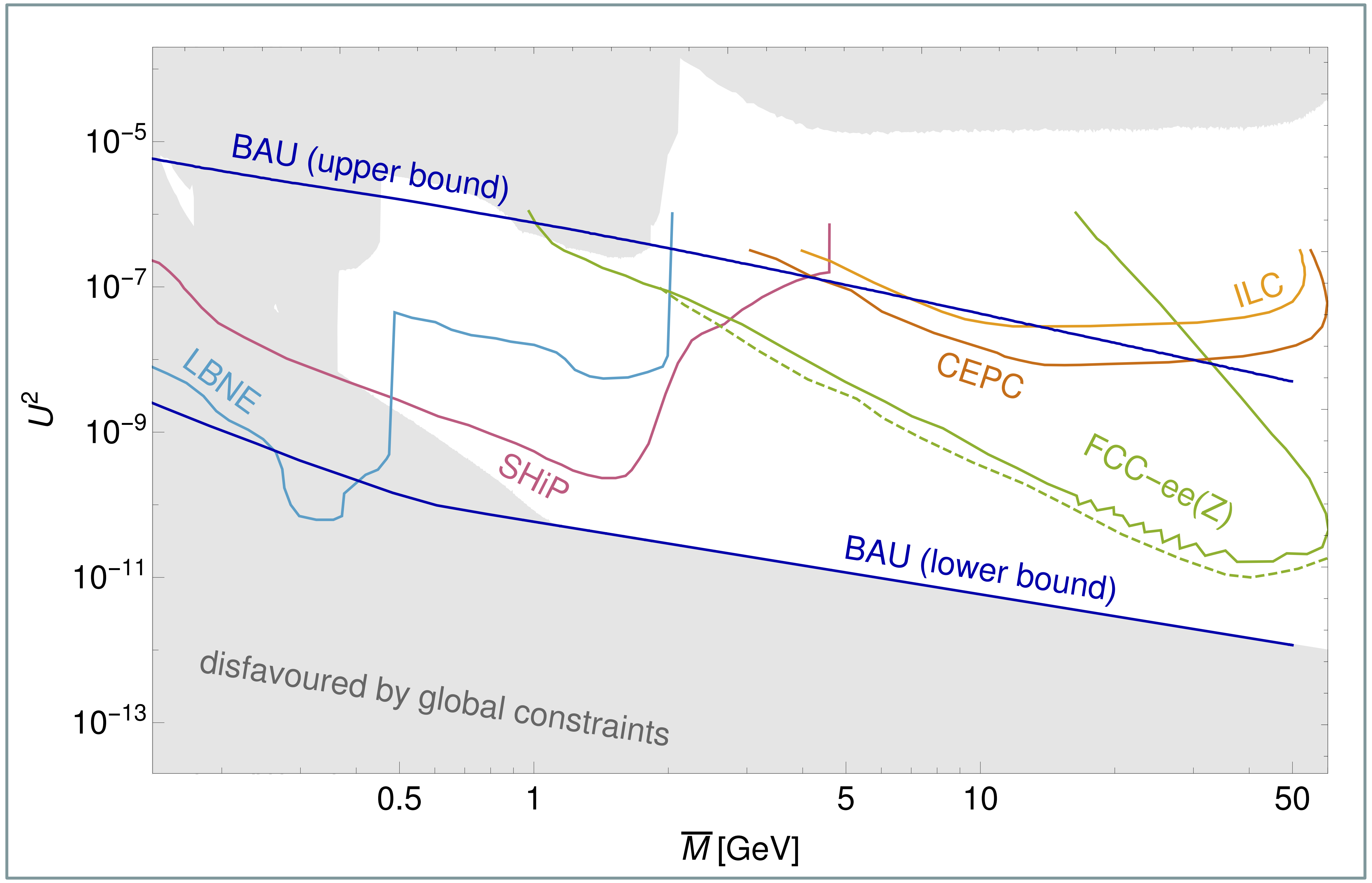
Probing Leptogenesis

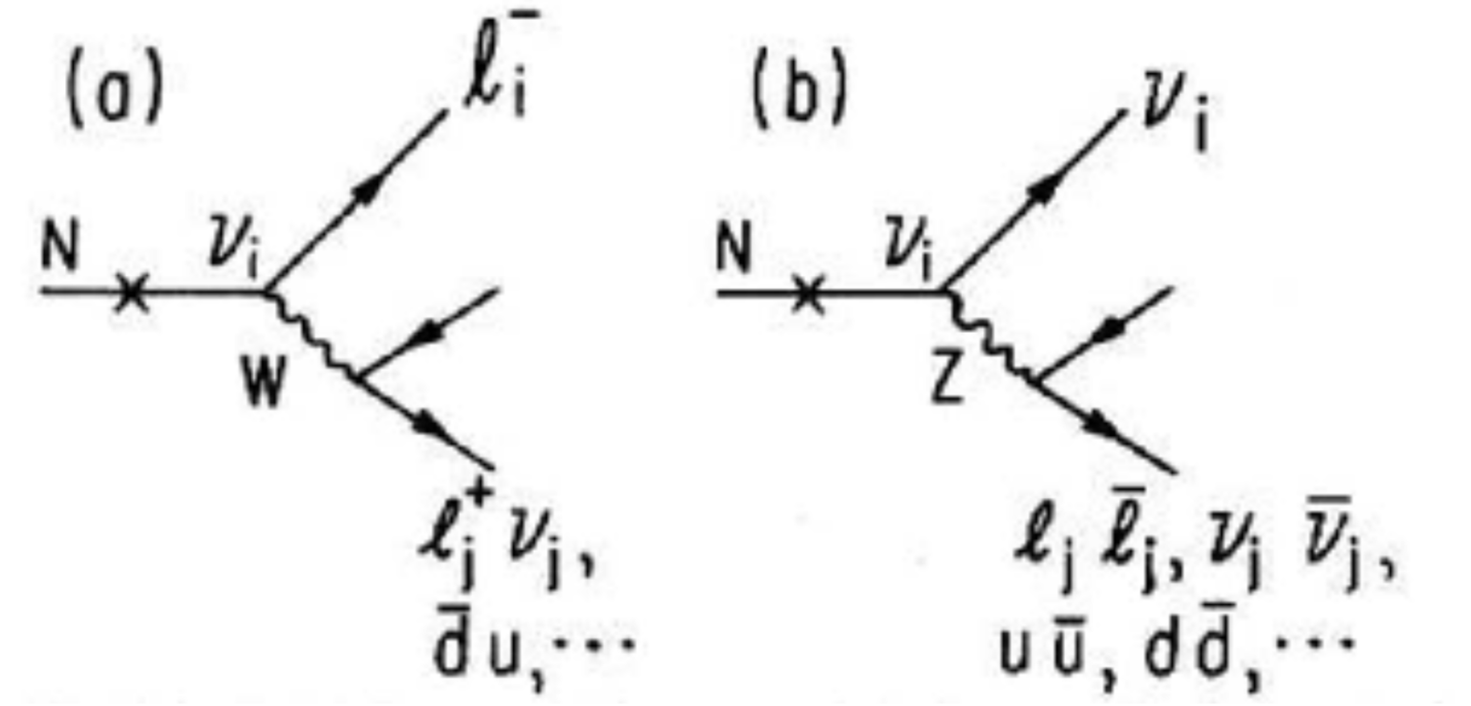
Precision for U_μ^2 / U^2 (Example: M = 30 GeV)

With: **$U^2 = |\theta|^2$ and, for example, $U_\mu^2 = |\theta_\mu|^2$**
(NO = normal light neutrino mass ordering)

Estimates from semi-leptonic heavy neutrino decays N → μ jj, measurements also possible for the other flavours e and τ!

S.A., E. Cazzato, M. Drewes, O. Fischer, B. Garbrecht, D. Gueter, J. Klaric (arXiv:1407.6607)



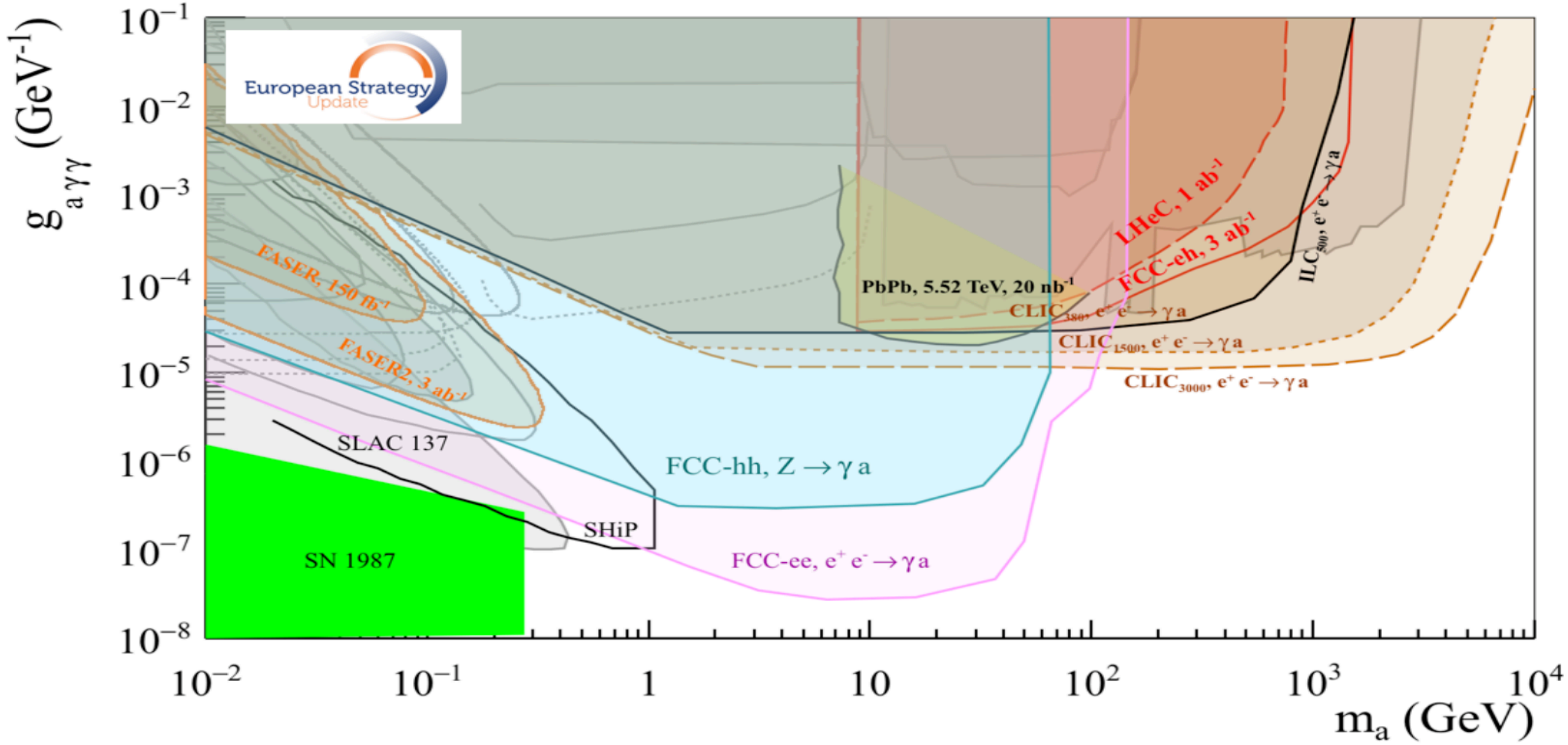


$$L \sim \frac{3\,[cm]}{|U|^2.\,(m_N[GeV]\,)^6}$$

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

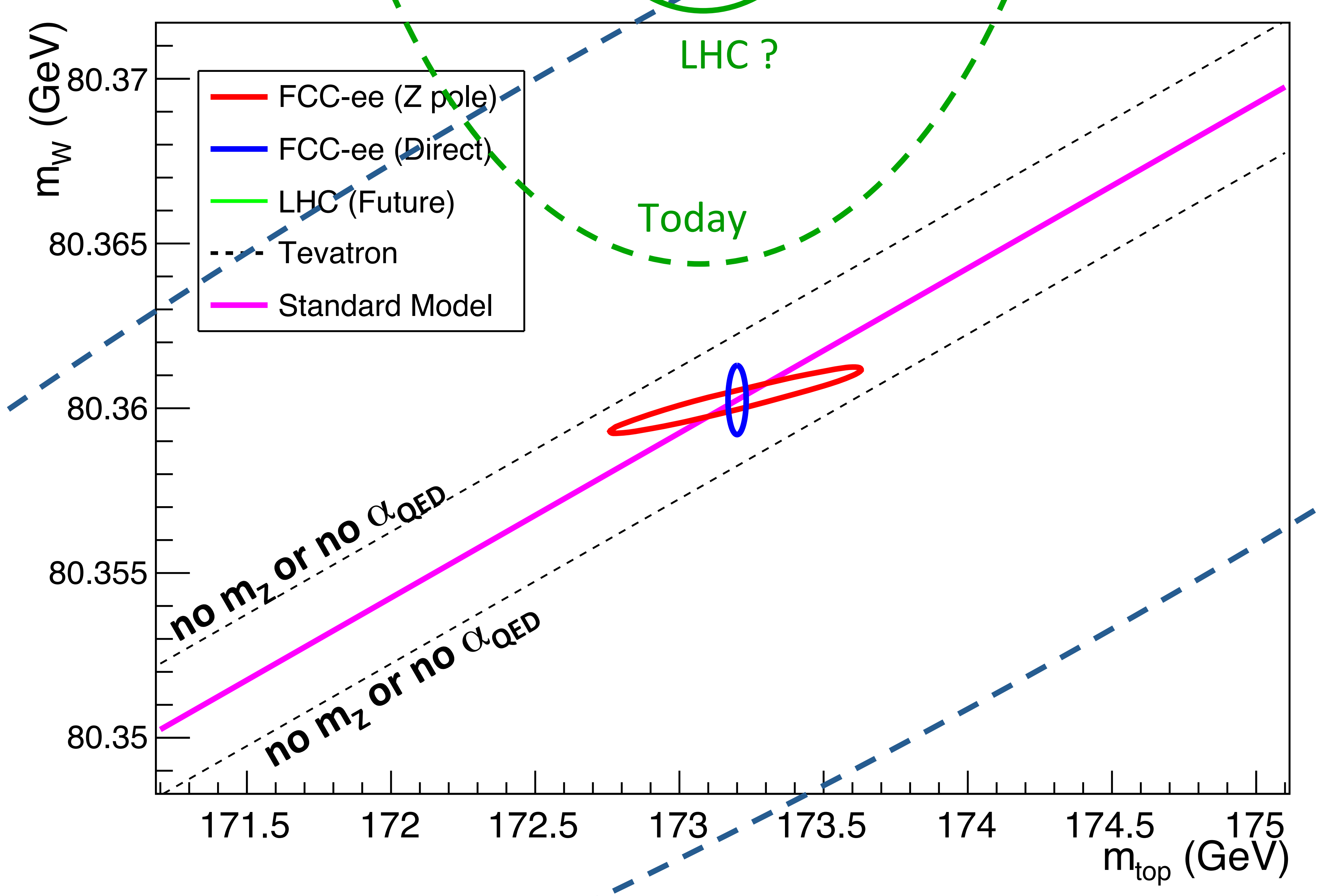
BSM DIRECT SEARCHES - ALPS

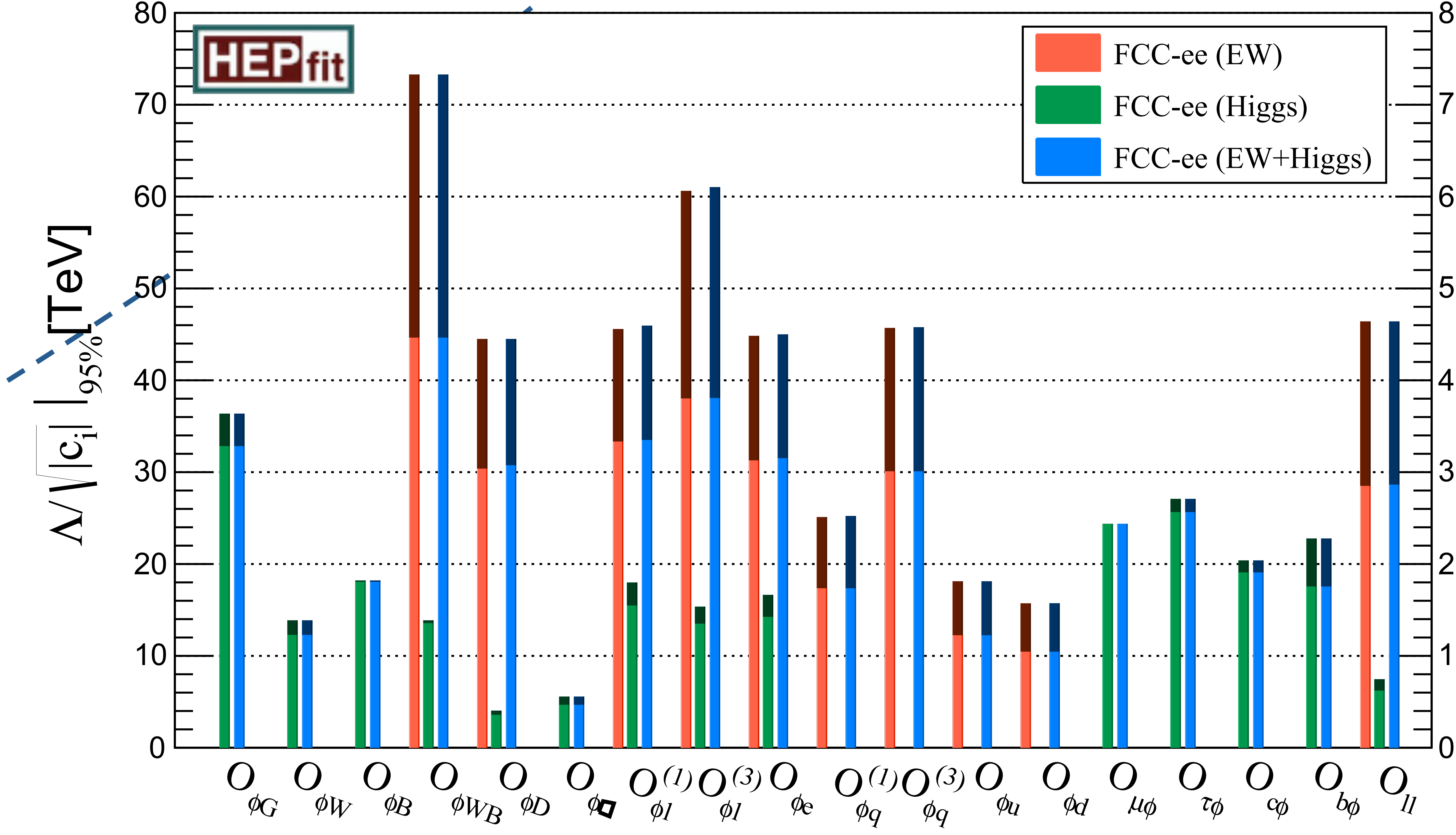
- Similar situation for Axion-like-particles: luminosity is key to the game
- Complementarity with High energy lepton collider
- Much more left to explore at FCC-ee-Z and FCC-hh!
- Fertile ground for development of innovative detector ideas!



SUMMARY ON NEW PHYSICS SENSITIVITIES

Requires 10-fold improvement in theory calculations





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

- **Points to the physics to be studied with FCC-hh**

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

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

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

THE FCC-HH

NUMEROLOGY FOR FCC-hh, 10ab^{-1}, $\sqrt{s}$=100 TeV

- **10^{10} Higgs bosons** => 10^4x today

➡precision measurements
➡rare decays
➡FCNC probes: H->eμ

- **10^{12} top quarks** => 5 10^4 x today
  - =>10^{12} W bosons from top decays
  - =>10^{12} b hadrons from top decays

➡precision measurements
➡rare decays
➡FCNC probes: t->cV (V=Z,g,γ), t->cH
➡CP violation
➡BSM decays ???

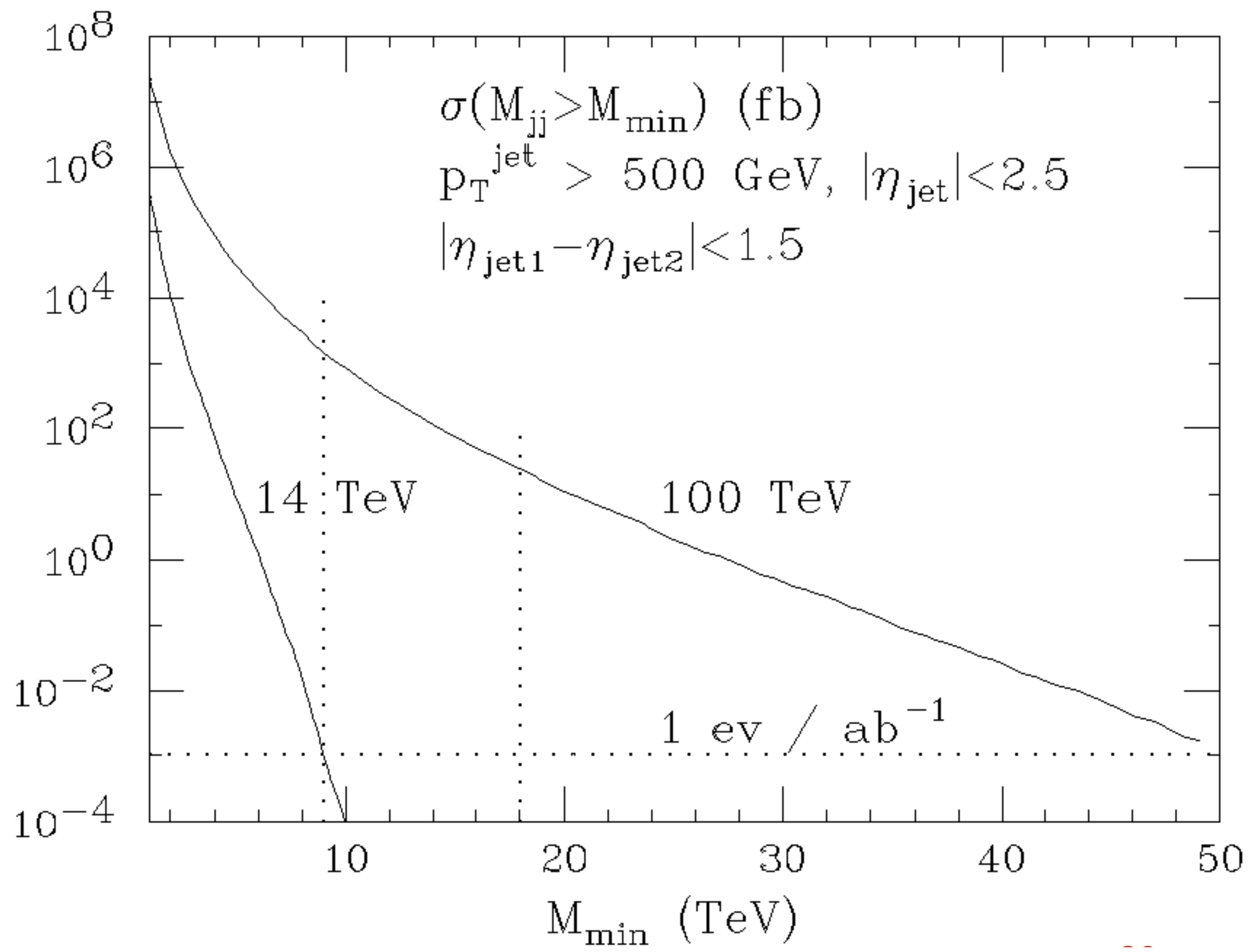
  - =>10^{11} $t \to W \to \tau$
  - few $10^{11} t \to W \to charm\ hadrons$

➡rare decays τ->3μ, μγ, CPV

➡rare decays D->$\mu^+\mu^-$,… CPV

Amazing potential, extreme detector and reconstruction challenges

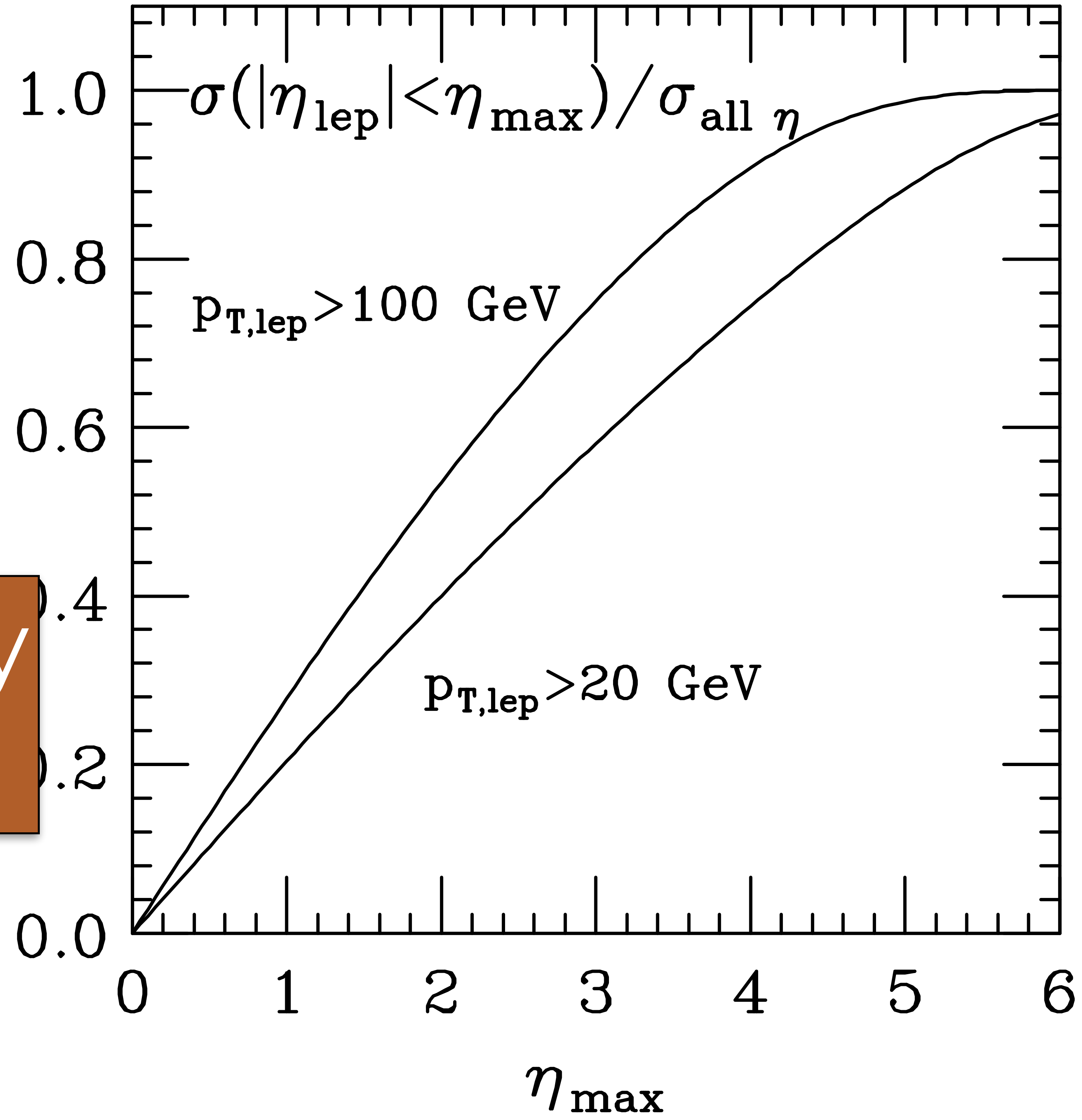
DI-JET PRODUCTION AT LARGE MASS AT FCC-HH



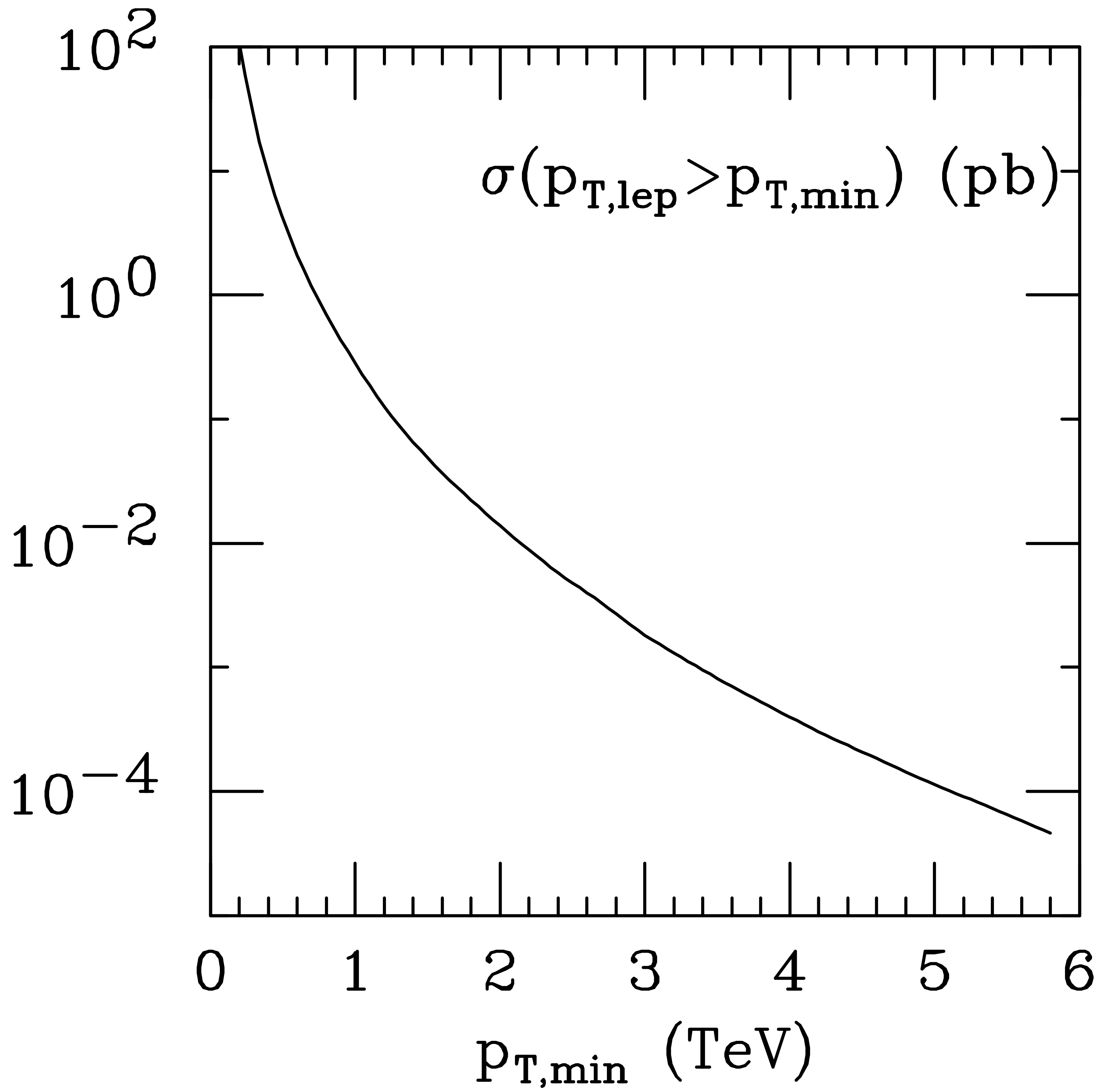
- $1 pb^{-1}$ to recover sensitivity of HL-LHC ==> 1 *day* @ 10^{32}
- $50 pb^{-1}$ to recover 2x sensitivity of HL-LHC ==> 1 *month* @ 10^{32}
- $1 fb^{-1}$ to recover 3x sensitivity of HL-LHC ==> 1 *year* @ $2x10^{32}$

W AND Z PRODUCTION AT FCC-HH

- Production of W and Z bosons is an extremely important probe of EW and QCD dynamics
- The production rate of $W^{\pm}(Z0)$ bosons at 100 TeV is about 1.3(0.4)µb. This corresponds to $O(10^{11})$ leptonic decays per ab^{-1}.

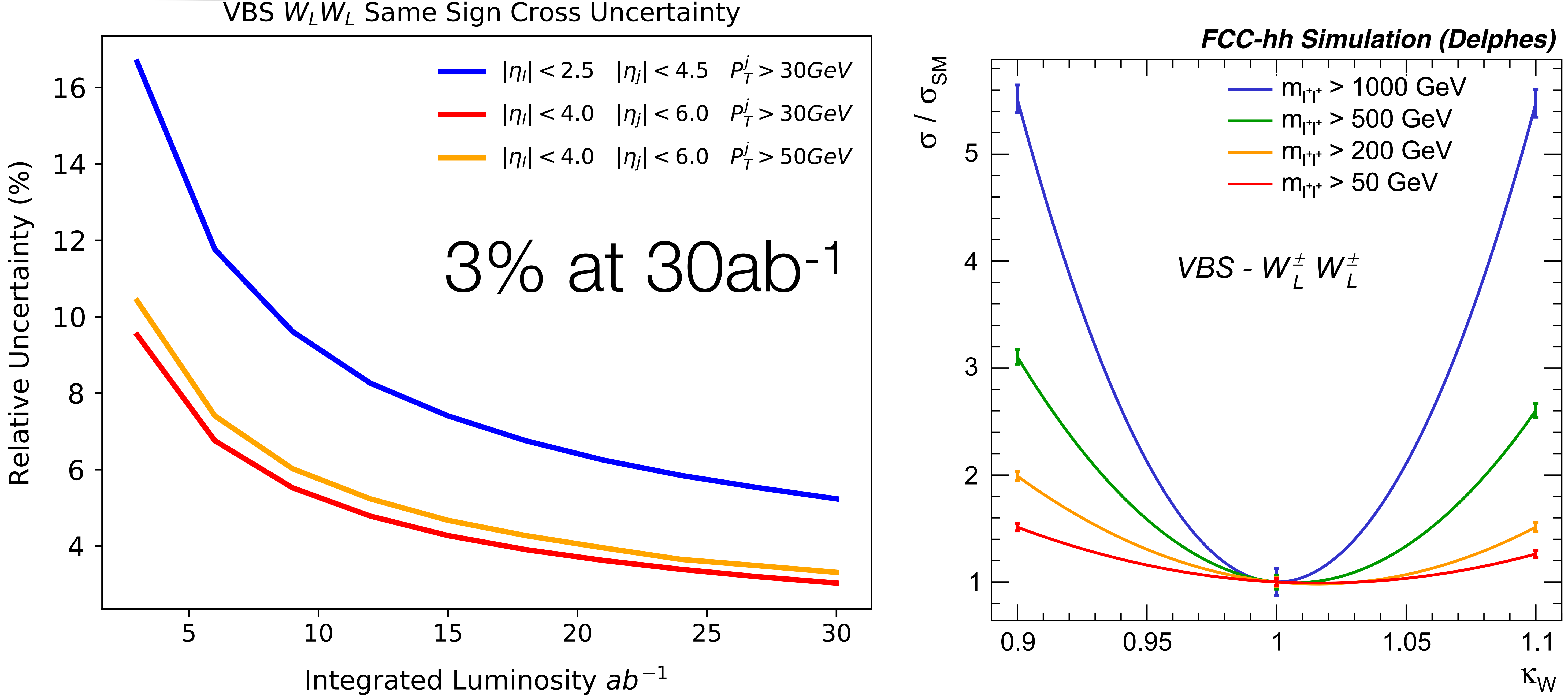


large rapidity distribution!

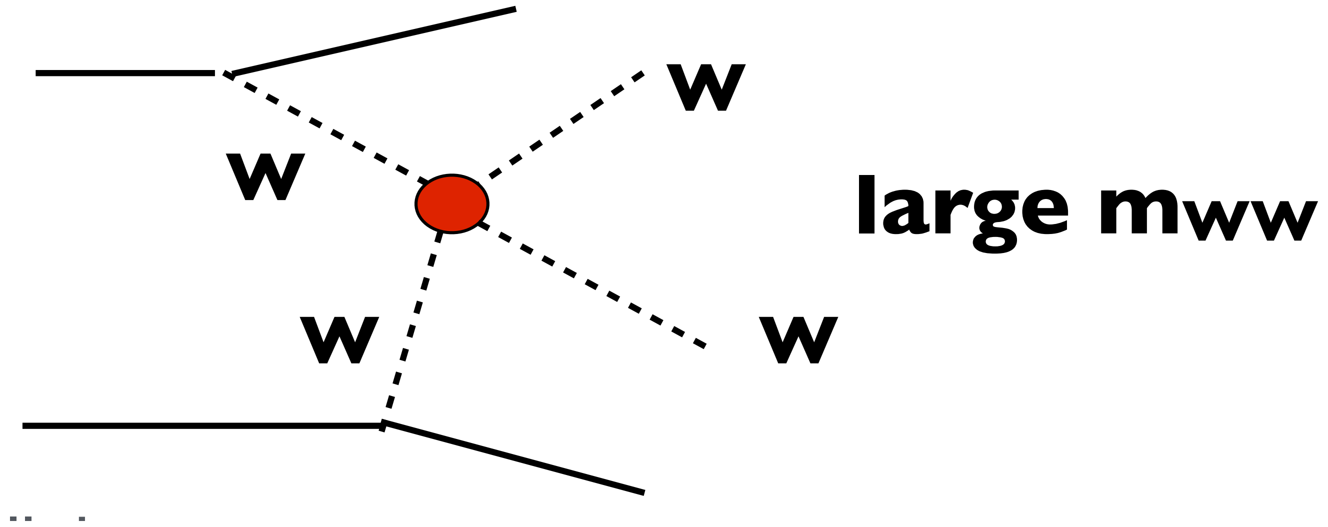


large p_T

W_LW_L SCATTERING (RELEVANT FOR VVH COUPLING)



3% at $30ab^{-1}$



large m_{WW}

Longitudinal component extracted from angular distribution of the two leptons

Fig. 4.9 Left: precision in the determination of the scattering of same-sign longitudinal W bosons, as function of luminosity, for various kinematic cuts. Right: sensitivity of the longitudinal boson scattering cross section w.r.t. deviations of the WWH coupling from its SM value ($\kappa_W = 1$), for various selection cuts on the final-state dilepton invariant mass. The vertical bars represent the precision of the measurement, for 30 ab^{-1}

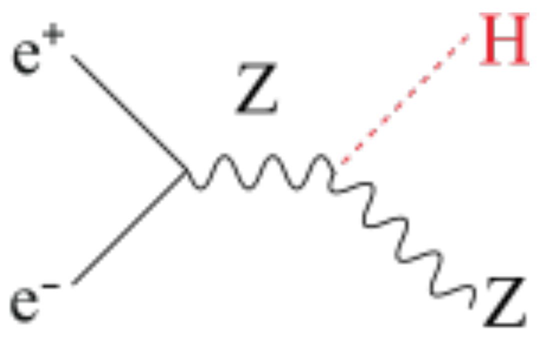
Table 4.5 Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_LW_L \rightarrow HH$ process

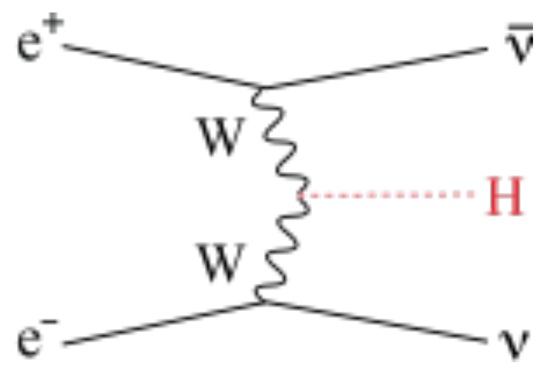
$m_{l^+l^+}$ cut	> 50 GeV	> 200 GeV	> 500 GeV	> 1000 GeV
$\kappa_W \in$	[0.98, 1.05]	[0.99, 1.04]	[0.99, 1.03]	[0.98, 1.02]

FCC SYNERGIES: THE HIGGS BOSON

- The FCC integrated program (ee, hh, eh) has built-in synergies and complementarities
  - It will provide the most complete and model-independent studies of the Higgs boson

√s = 240 GeV





√s = 365 GeV

FCC-ee provides 10^6 HZ + 10^5 WW → H events

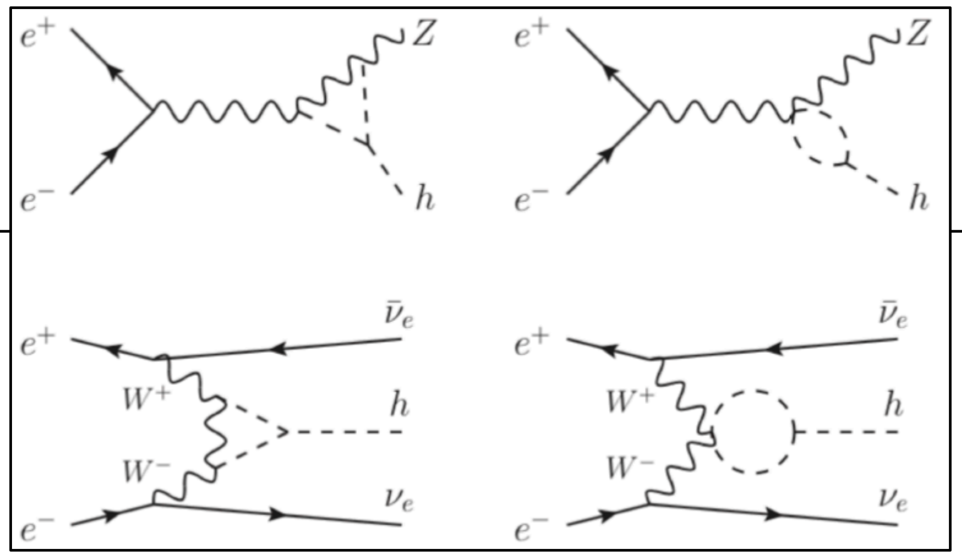
Absolute determination of g_{HZZ} to ±0.17%

Model-independent determination of Γ_H to ±1%

→ Fixed « candle » for all other measurements
including those made at HL-LHC or FCC-hh

→ Measure couplings to WW, bb, ττ, cc, gg, …
Even possibly the Hee coupling!

→ First sensitivity to g_{HHH} to ±34% (±21% with 4IP)



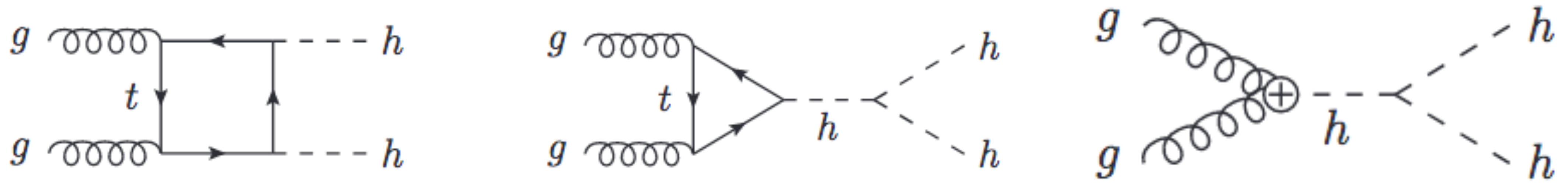
FCC-hh provides 3×10^{10} Higgs bosons

With this huge sample and using the FCC-ee candle

→ Model-independent ttH coupling to < 1%
(HL-LHC and FCC-ee give ±2.6%)
Use ±1% ttZ measurement at FCC-ee

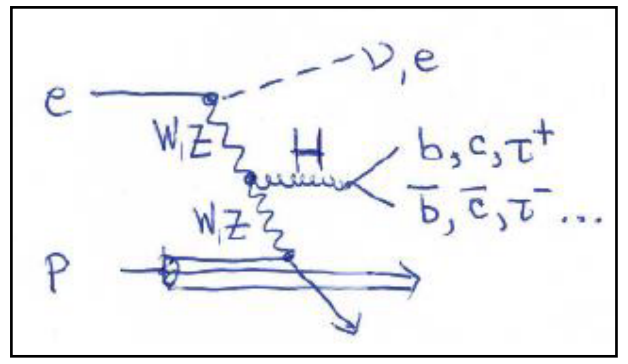
→ Rare decays: couplings to μμ, γγ, Zγ …

→ Higgs self coupling g_{HHH} to ±5%
With double-Higgs production

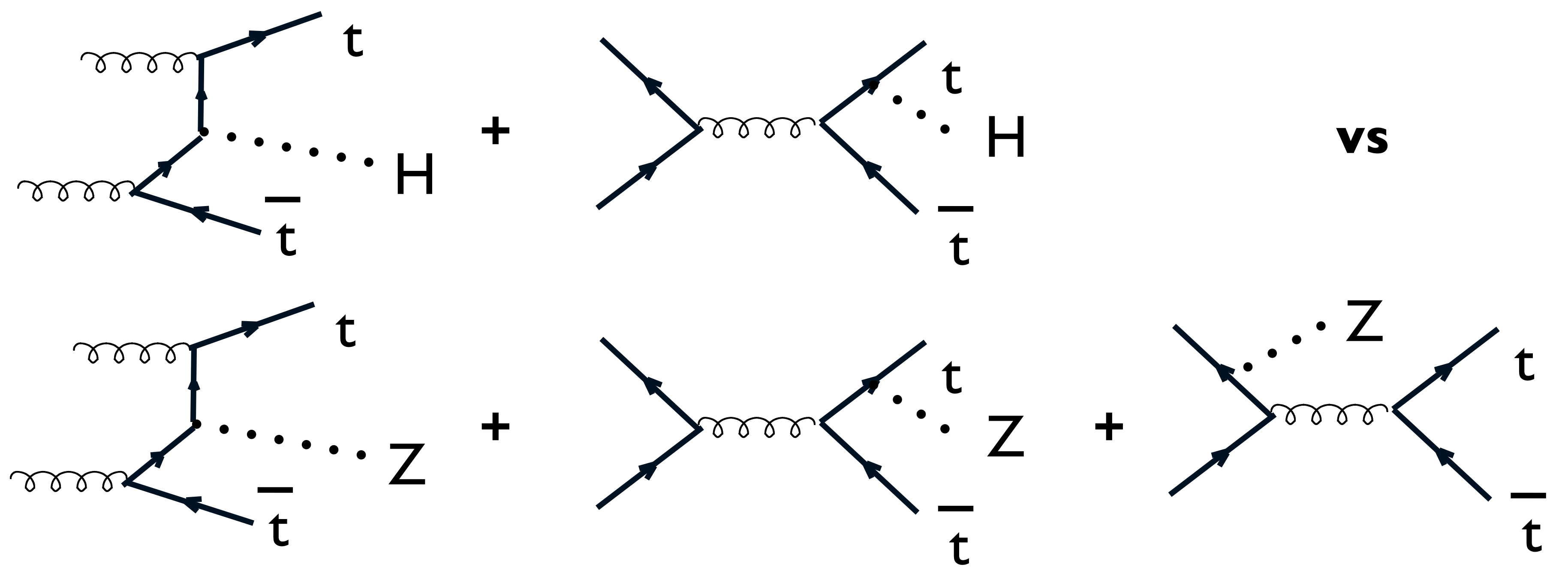


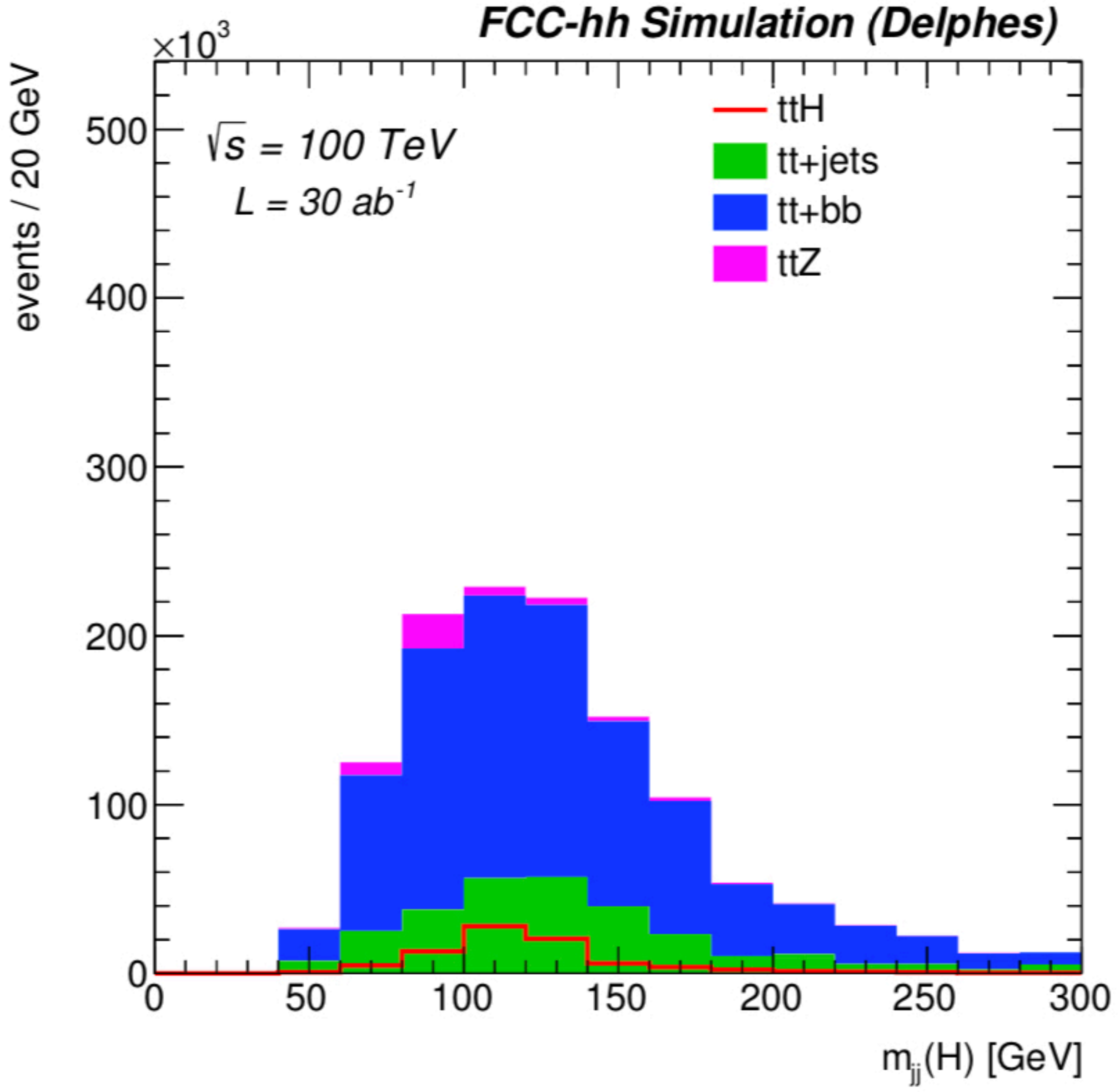
FCC-eh provides 2.5 10^6 Higgs bosons

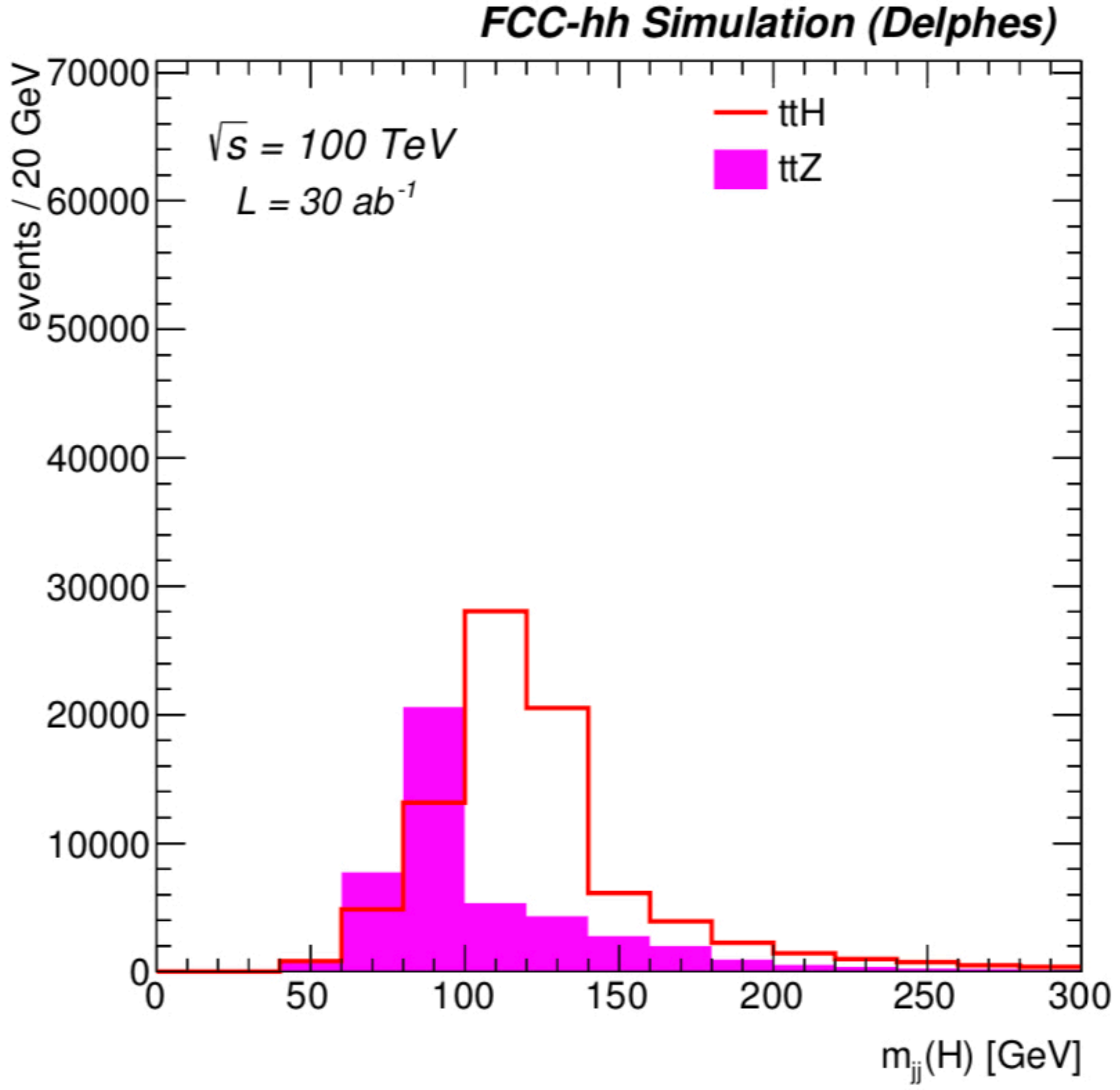
With the FCC-ee candle, further improves
on several measurements (e.g., g_{HWW})



FCC SYNERGIES: TOP - YUKAWA COUPLING







https://cds.cern.ch/record/2642471

- Use the ratio of $\sigma(ttH)/\sigma(ttZ)$.
- Profit of similar dynamics (QCD Correction, scale, alphaS syst.) and kinematical boundaries ($m_Z \simeq m_H$)
- Analysis using boosted $H/Z \to b\bar{b}$ decays (Delphes)
- $\Delta y_t/y_t \approx 1\,\%$ using ttZ EW Coupling and $BR(H \to b\bar{b})$ from FCC-ee

FCC SYNERGIES: HIGGS SELF COUPLING

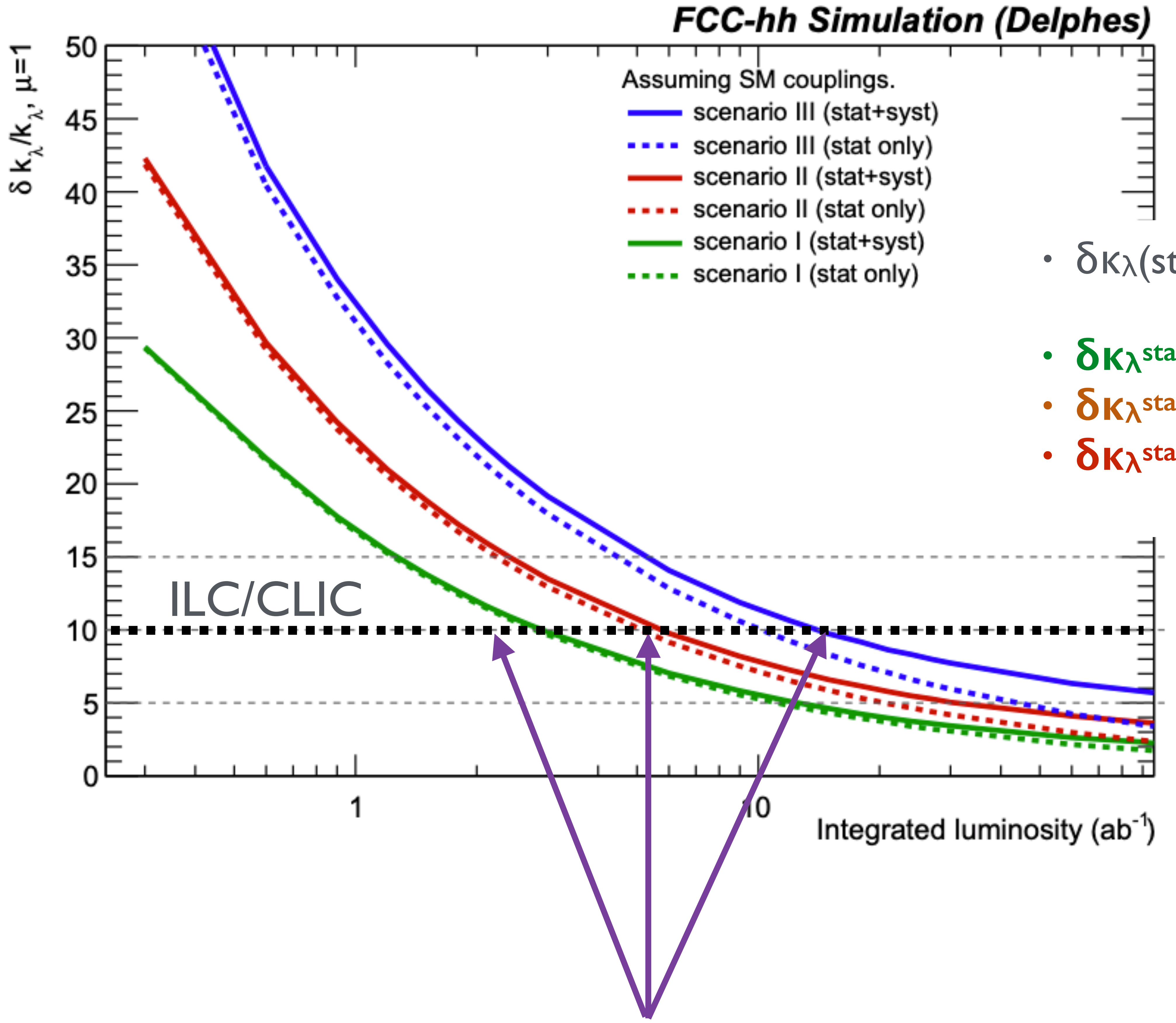
Briefing book

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N_{Det}	$\mathscr{L}_{\text{inst}}$/Det. $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]
HL-LHC	*pp*	14 TeV	–	2	5	6.0	12
HE-LHC	*pp*	27 TeV	–	2	16	15.0	20
FCC-hh	*pp*	100 TeV	–	2	30	30.0	25
FCC-ee	*ee*	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1-2
		240 GeV	0/0	2	7	5	3
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5
		(1y SD before $2m_{top}$ run)					(+1)
ILC	*ee*	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5
		350 GeV	±80/±30	1	1.6	0.2	1
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5
		(1y SD after 250 GeV run)					(+1)
CEPC	*ee*	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	*ee*	380 GeV	±80/0	1	1.5	1.0	8
		1.5 TeV	±80/0	1	3.7	2.5	7
		3.0 TeV	±80/0	1	6.0	5.0	8
		(2y SDs between energy stages)					(+4)
LHeC	*ep*	1.3 TeV	–	1	0.8	1.0	15
HE-LHeC	*ep*	1.8 TeV	–	1	1.5	2.0	20
FCC-eh	*ep*	3.5 TeV	–	1	1.5	2.0	25

→ 16 yrs

→ 22 yrs

→ 27 yrs



- $\delta\kappa_\lambda$(stat) = 3 %
- $\delta\kappa_\lambda^{\text{stat+syst}}$ (sc. I) = 3.4 %
- $\delta\kappa_\lambda^{\text{stat+syst}}$ (sc. II) = 5.1 %
- $\delta\kappa_\lambda^{\text{stat+syst}}$ (sc. III) = 7.8 %

Can reach
expected precision
of ILC/CLIC with 3-5-15 ab^{-1}

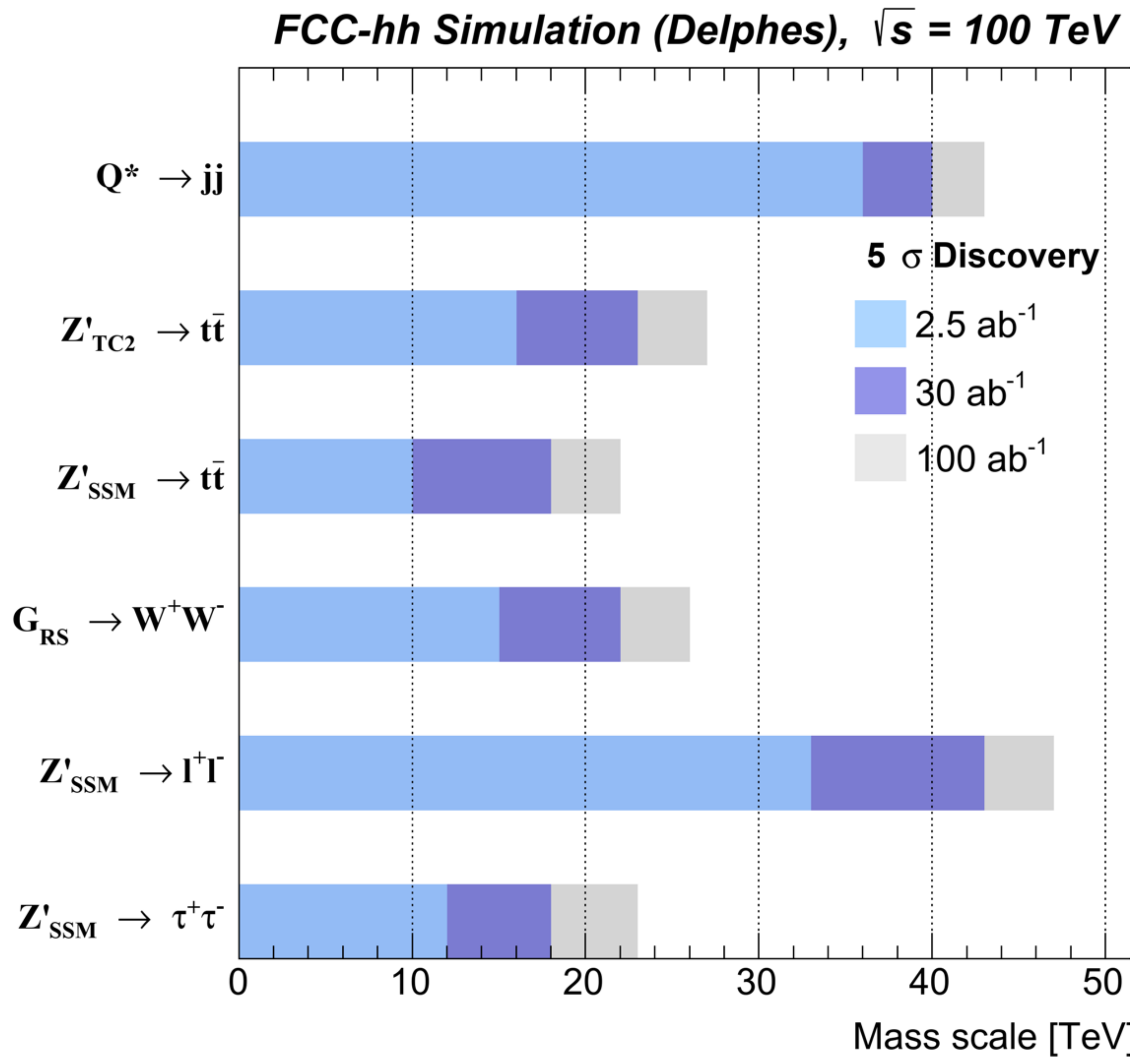
FCC-hh:

- 5 ab-1 during the first 10 years →

10% precision achievable in 10 years (or less)

FCC-HH DISCOVERY POTENTIAL

- Higher parton centre-of-mass energy → A BIG STEP IN HIGH MASS REACH
  - Strongly coupled new particles, new gauge bosons (Z’, W’), excited quarks: up to 40 TeV!
  - Extra Higgs bosons: up to 5-20 TeV
  - High sensitivity to high energy phenomena, e.g., WW scattering, DY up to 15 TeV

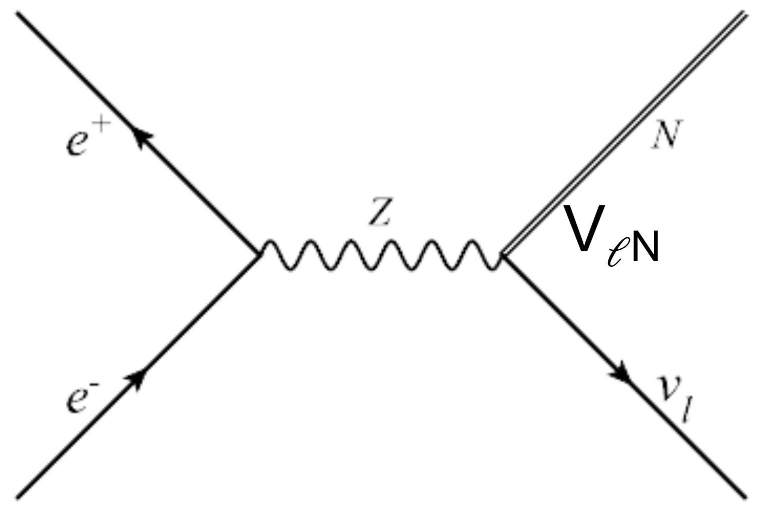


about x6 LHC mass reach at high mass, well matched to reveal the origin of deviations indirectly detected at the FCC-ee

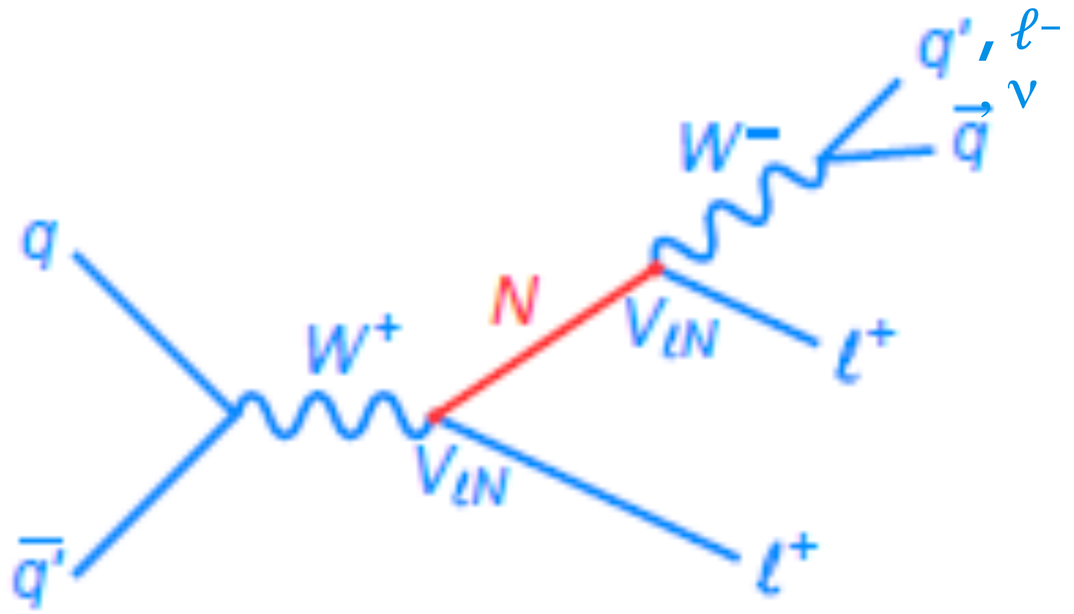
FCC SYNERGIES: FEEBLY INTERACTING PARTICLES

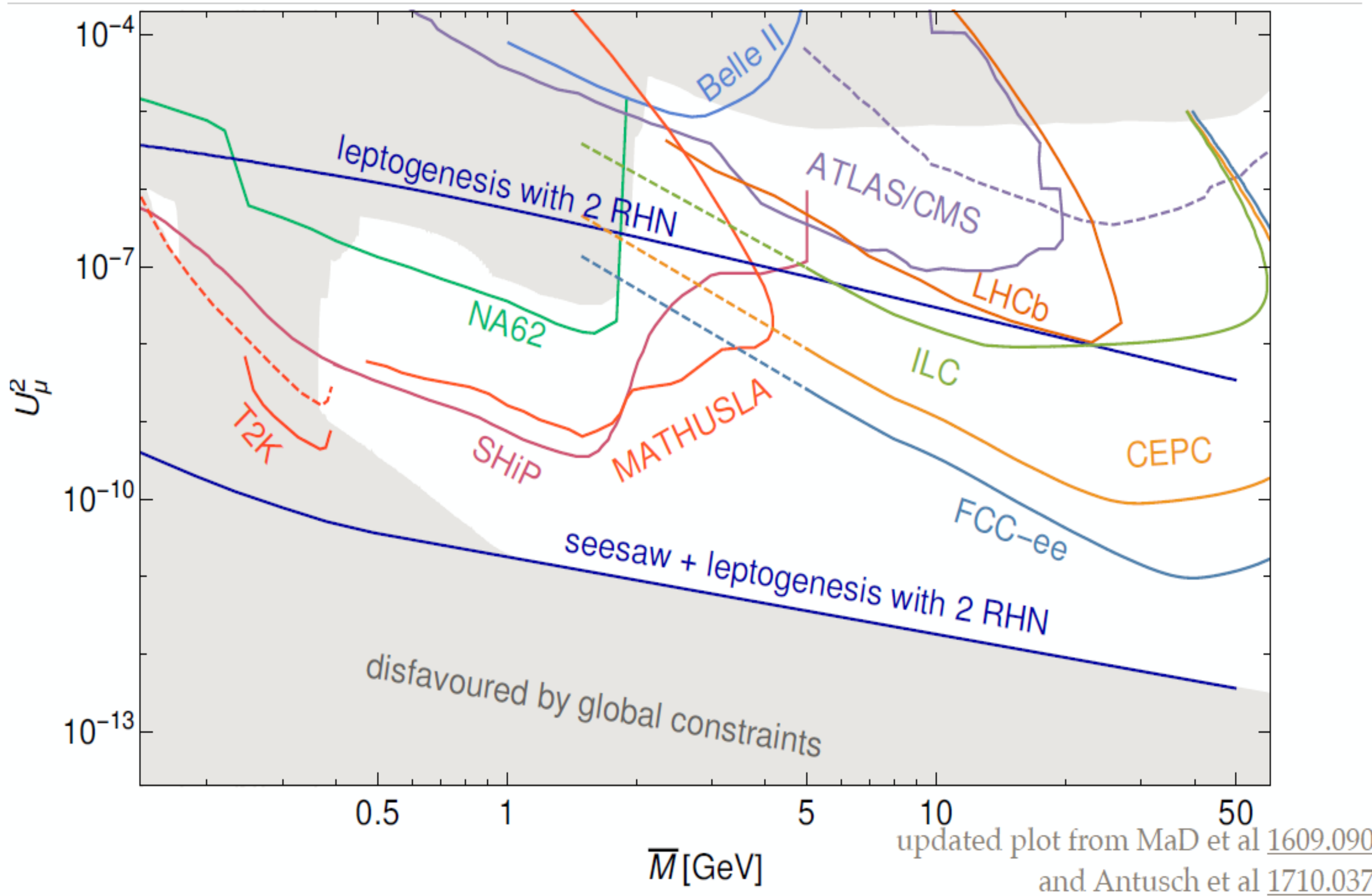
- Heavy Right-Handed Neutrinos
  - Complete SM spectrum – and perhaps explain DM, BAU, ν masses

FCC-ee (Z)



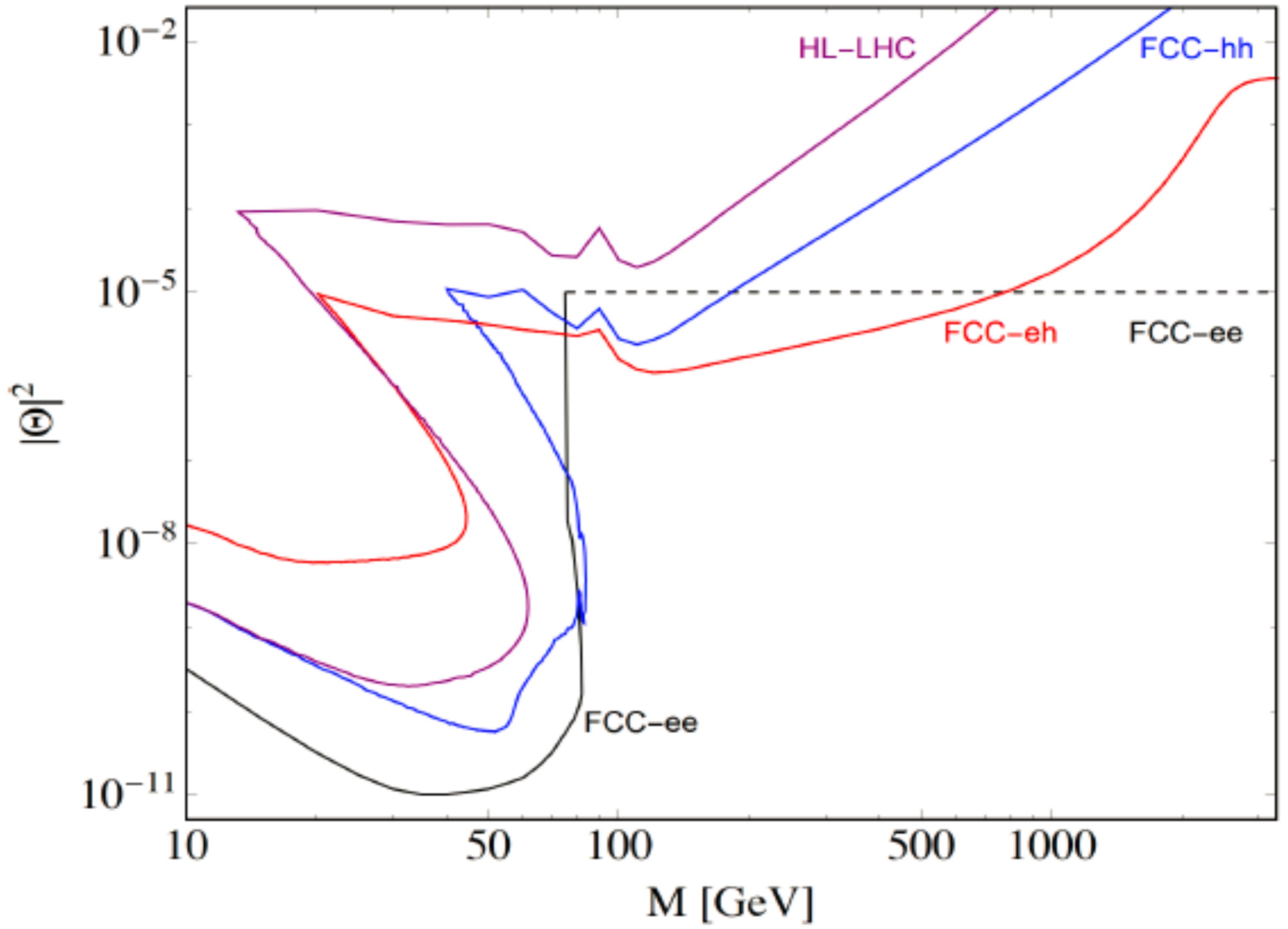
FCC-hh





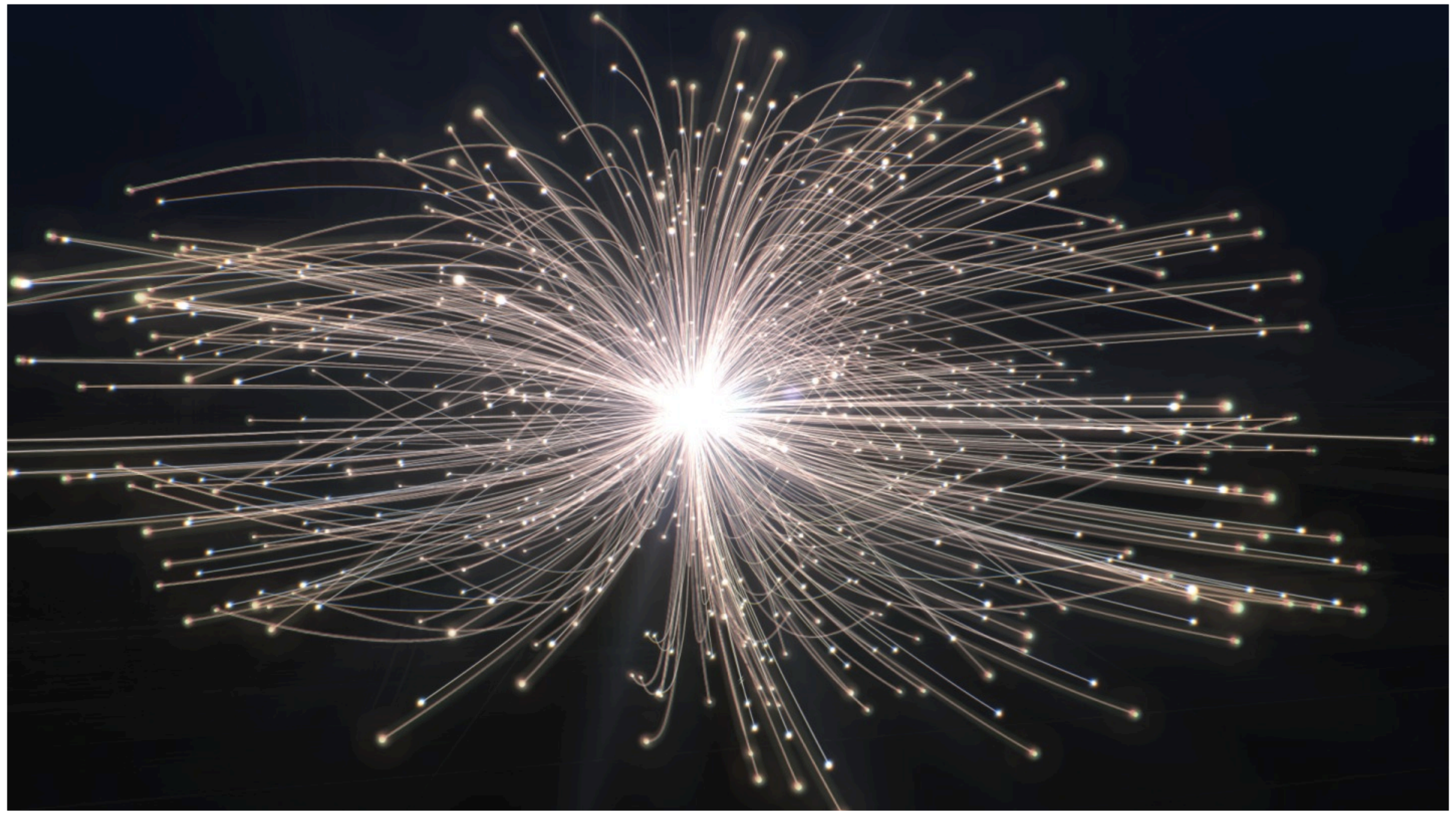
updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

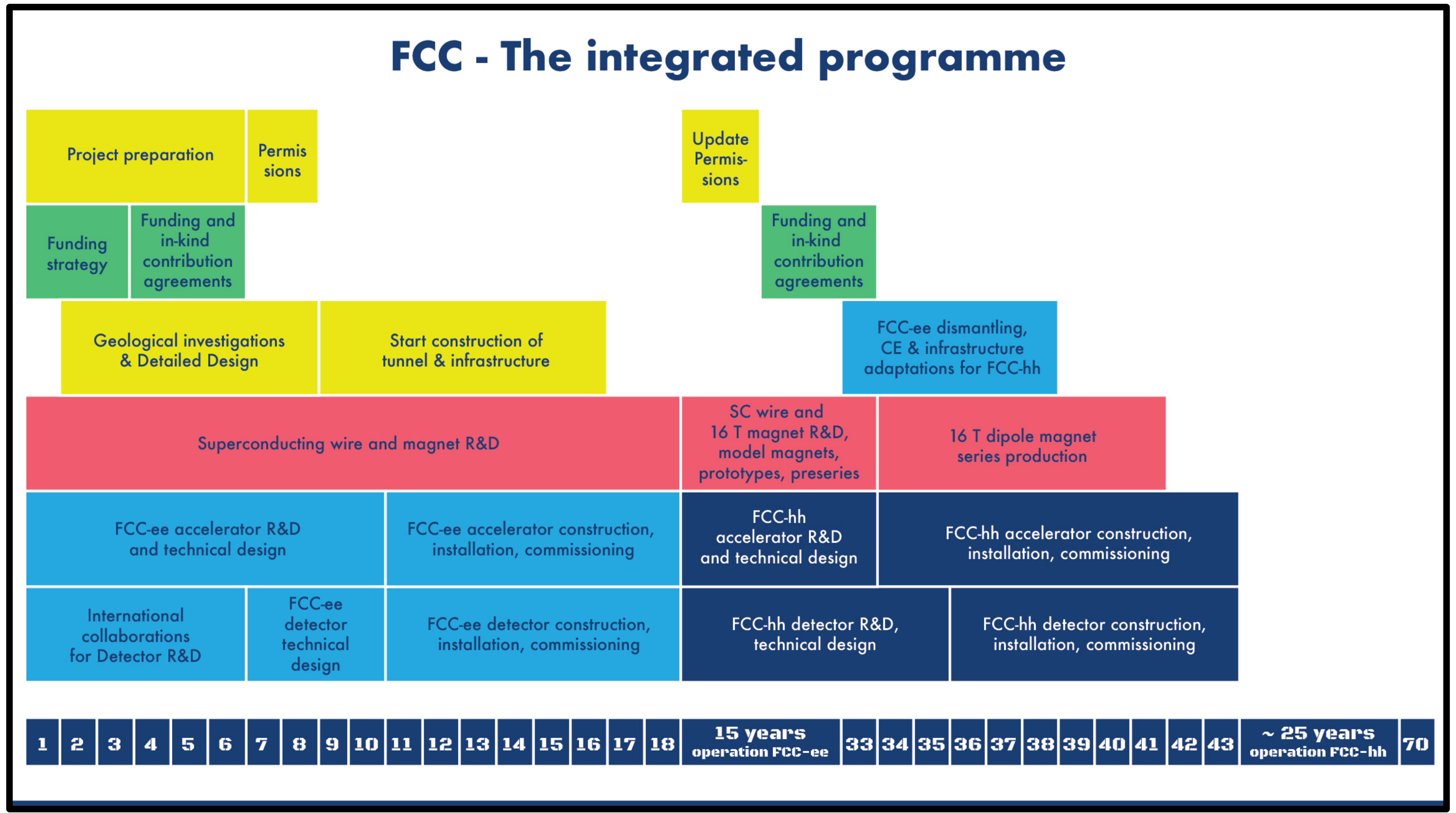
- **FCC-ee sensitivity** (to mixing angle with LH ν)
  - EWPO: $\sim 10^{-5}$ up to very high masses
  - Best, flavour-blind, sensitivity to $\Sigma_\ell |V_{\ell N}|^2$ below 100 GeV
- **FCC-hh sensitivity**
  - Sensitivity to $V_{\ell_1 N} V_{\ell_2 N}$ with lepton charge and flavour
- **FCC-eh sensitivity**
  - Production in charge currents ep → XN (→ℓW)
  - Sensitivity to $V_{eN} V_{\ell N}$
- **Complementarity**
  - Discovery + complementary studies in overlap regions



TIMELINE

- The FCC is an ambitious project for the future of particle physics with concrete goals and deliverables to find the answers that we need from Nature!





FCC - The integrated programme

Project preparation

Permis sions

Funding strategy

Funding and in-kind contribution agreements

Geological investigations & Detailed Design

Start construction of tunnel & infrastructure

Update Permis-sions

Funding and in-kind contribution agreements

FCC-ee dismantling, CE & infrastructure adaptations for FCC-hh

Superconducting wire and magnet R&D

SC wire and 16 T magnet R&D, model magnets, prototypes, preseries

16 T dipole magnet series production

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

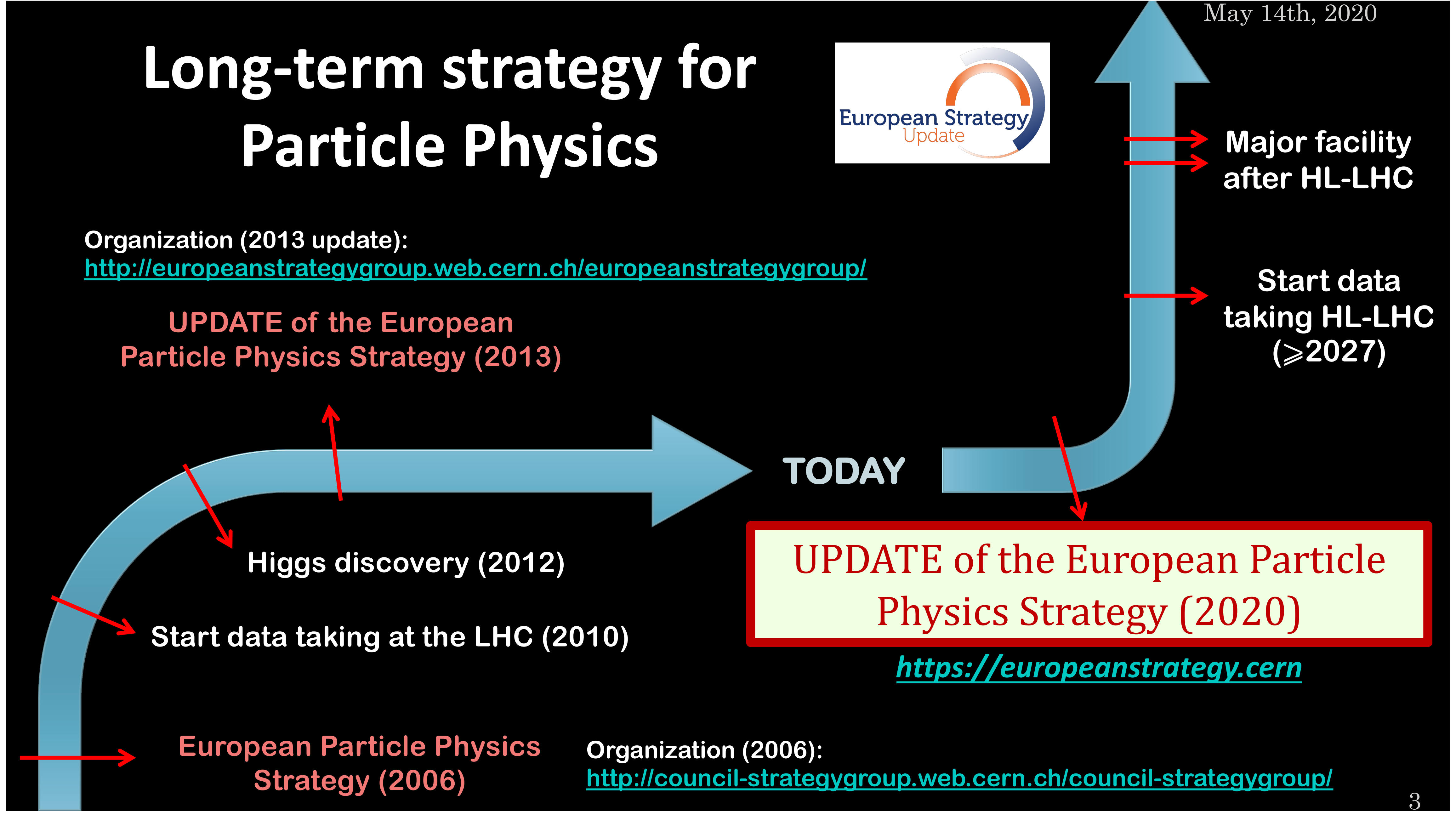
International collaborations for Detector R&D

FCC-ee detector technical design

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning



May 14th, 2020

Long-term strategy for Particle Physics

Organization (2013 update):
http://europeanstrategygroup.web.cern.ch/europeanstrategygroup/

UPDATE of the European Particle Physics Strategy (2013)

Major facility after HL-LHC

Start data taking HL-LHC (⩾2027)

TODAY

Higgs discovery (2012)

Start data taking at the LHC (2010)

UPDATE of the European Particle Physics Strategy (2020)

https://europeanstrategy.cern

European Particle Physics Strategy (2006)

Organization (2006):
http://council-strategygroup.web.cern.ch/council-strategygroup/

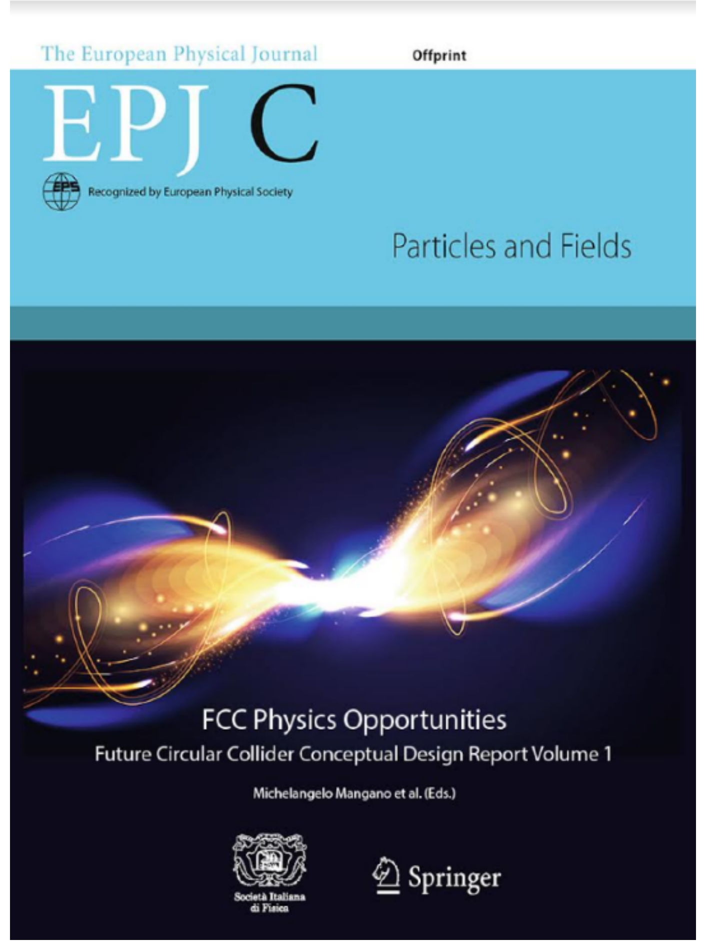
3

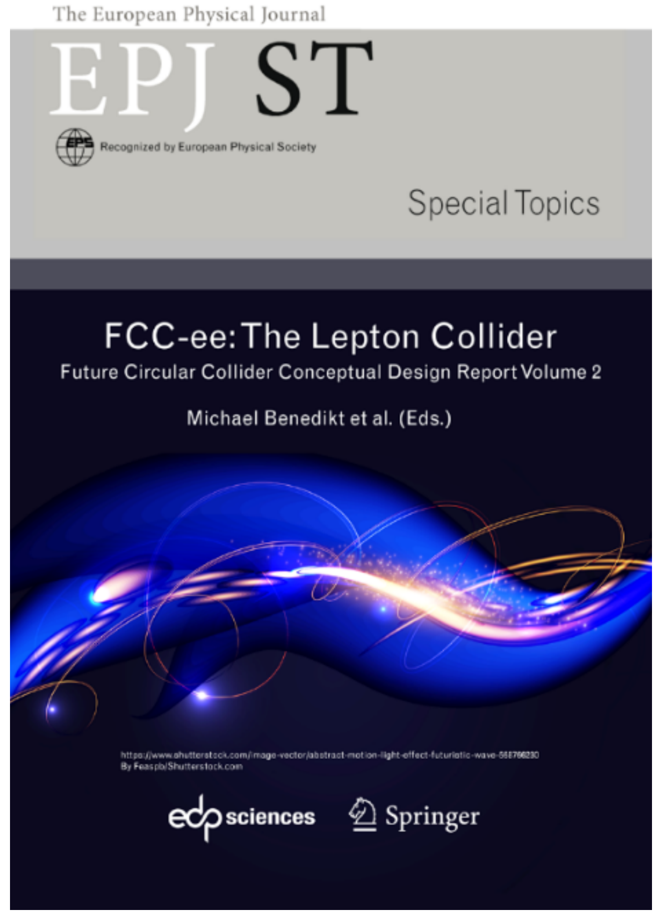
NEXT STEPS

- A first round of analyses to frame the impressive physics case has been summarized in the CDRs
    - of course exploration of the physics potential is continuing
- The focus now is to perform the studies (« case studies ») to determine the detector performance needed to achieve the desired precision and to inform the technology choices
- At the same time a whole revolution is also happening in terms of developing the software framework that will sustain the work in such a long timespan in the future and that is common to all future projects.
    - Our current job is also to develop new reconstruction and analysis tools that fully exploit the detectors of the future
- Physics Performance Group is the place where all this comes together
- Many « Case Studies » in progress: looking forward the FCC-Week 2021

FIND OUT MORE: SOME FCC DOCUMENTATION

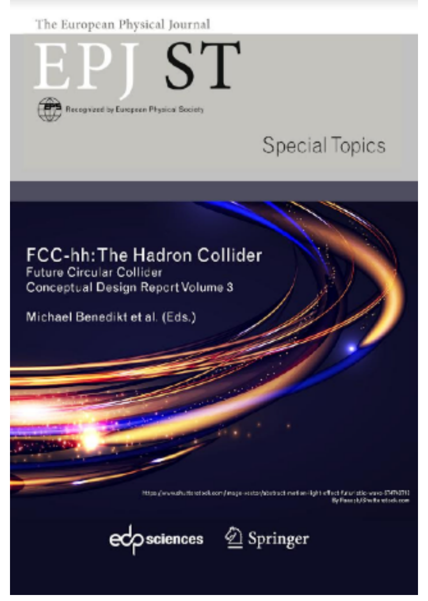
4 CDR volumes published in EPJ

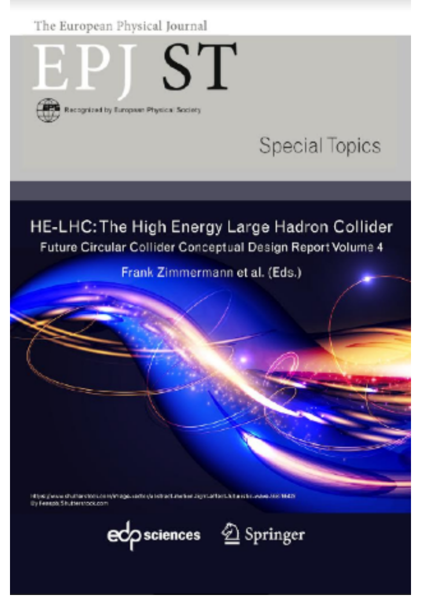

The European Physical Journal
Offprint
EPJ C
Recognized by European Physical Society
Particles and Fields
FCC Physics Opportunities
Future Circular Collider Conceptual Design Report Volume 1
Michelangelo Mangano et al. (Eds.)
Società Italiana di Fisica
Springer


The European Physical Journal
EPJ ST
Recognized by European Physical Society
Special Topics
FCC-ee: The Lepton Collider
Future Circular Collider Conceptual Design Report Volume 2
Michael Benedikt et al. (Eds.)
edp sciences
Springer

FCC PhysicsOpportunities

FCC-ee: The Lepton Collider


The European Physical Journal
EPJ ST
Recognized by European Physical Society
Special Topics
FCC-hh: The Hadron Collider
Future Circular Collider
Conceptual Design Report Volume 3
Michael Benedikt et al. (Eds.)
edp sciences
Springer

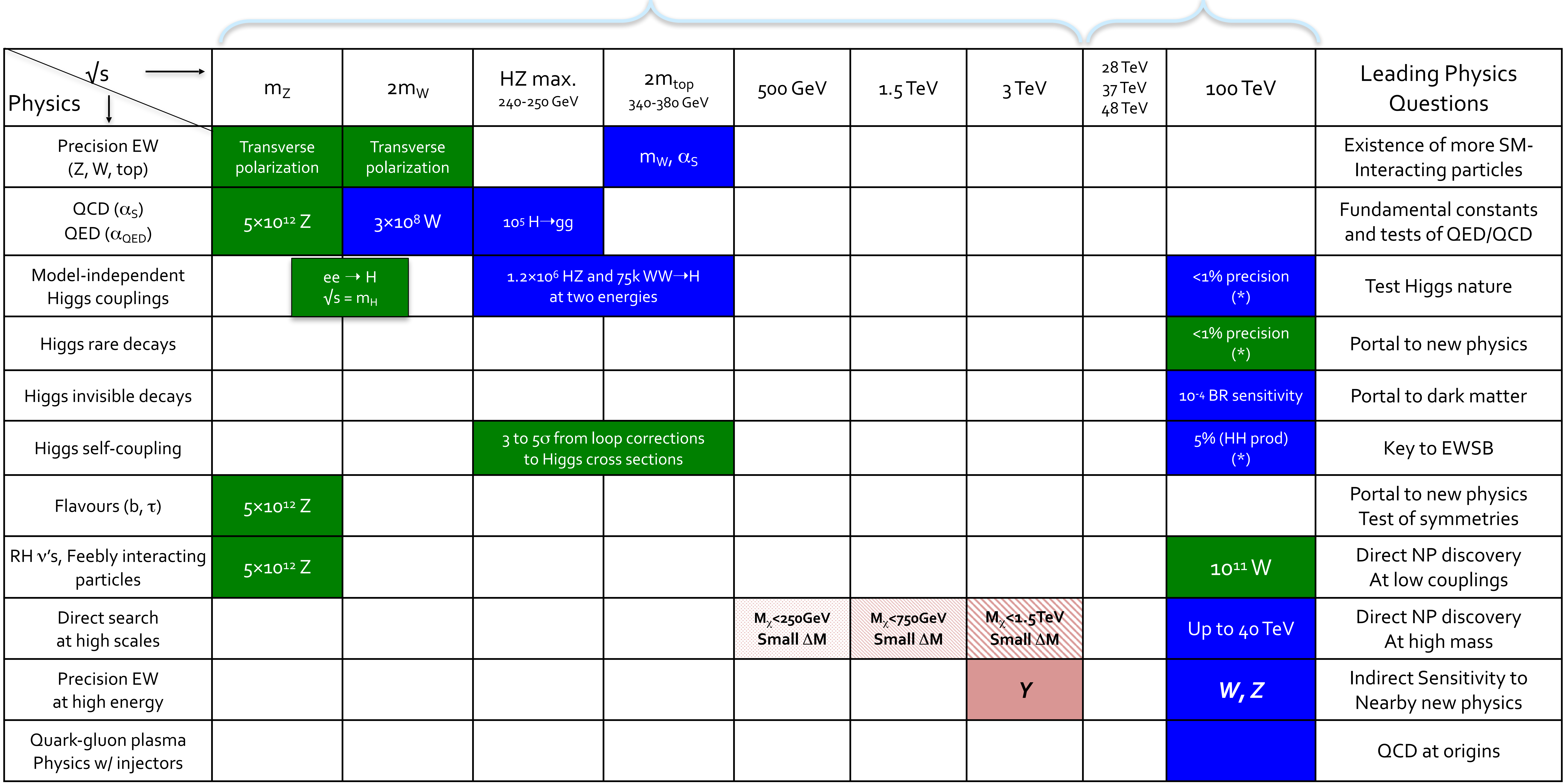

The European Physical Journal
EPJ ST
Recognized by European Physical Society
Special Topics
HE-LHC: The High Energy Large Hadron Collider
Future Circular Collider Conceptual Design Report Volume 4
Frank Zimmermann et al. (Eds.)
edp sciences
Springer

FCC-hh: The Hadron Collider

HE-LHC: The High Energy Large Hadron Collider

- Future Circular Collider - European Strategy Update Documents
  - (FCC-ee), (FCC-hh), (FCC-int)
- FCC-ee: Your Questions Answered
  - arXiv:1906.02693
- Circular and Linear e+e- Colliders: Another Story of Complementarity
  - arXiv:1912.11871
- Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders
  - arXiv:1901.02648
- Polarization and Centre-of-mass Energy Calibration at FCC-ee
  - arXiv:1909.12245

arXiv:1906.02693, FCC-ee: Your questions answered



	e^+e^- collisions							pp collisions		
$\sqrt{s}$ → Physics ↓	m_Z	$2m_W$	HZ max. 240-250 GeV	$2m_{top}$ 340-380 GeV	500 GeV	1.5 TeV	3 TeV	28 TeV 37 TeV 48 TeV	100 TeV	Leading Physics Questions
Precision EW (Z, W, top)	Transverse polarization	Transverse polarization		m_W, α_S						Existence of more SM-Interacting particles
QCD (α_S) QED (α_{QED})	5×10^{12} Z	3×10^8 W	10^5 H→gg							Fundamental constants and tests of QED/QCD
Model-independent Higgs couplings	ee → H $\sqrt{s} = m_H$		1.2×10^6 HZ and 75k WW→H at two energies						<1% precision (*)	Test Higgs nature
Higgs rare decays									<1% precision (*)	Portal to new physics
Higgs invisible decays									10^{-4} BR sensitivity	Portal to dark matter
Higgs self-coupling			3 to 5σ from loop corrections to Higgs cross sections						5% (HH prod) (*)	Key to EWSB
Flavours (b, τ)	5×10^{12} Z									Portal to new physics Test of symmetries
RH ν's, Feebly interacting particles	5×10^{12} Z								10^{11} W	Direct NP discovery At low couplings
Direct search at high scales					M_χ<250GeV Small ΔM	M_χ<750GeV Small ΔM	M_χ<1.5TeV Small ΔM		Up to 40 TeV	Direct NP discovery At high mass
Precision EW at high energy							*Y*		***W, Z***	Indirect Sensitivity to Nearby new physics
Quark-gluon plasma Physics w/ injectors										QCD at origins

Green = Unique to FCC; **Blue = Best with FCC**; **(*) = if FCC-hh is combined with FCC-ee**; **Pink = Best with other colliders**