PHYSICS OPPORTUNITIES @FUTURE CIRCULAR COLLIDER

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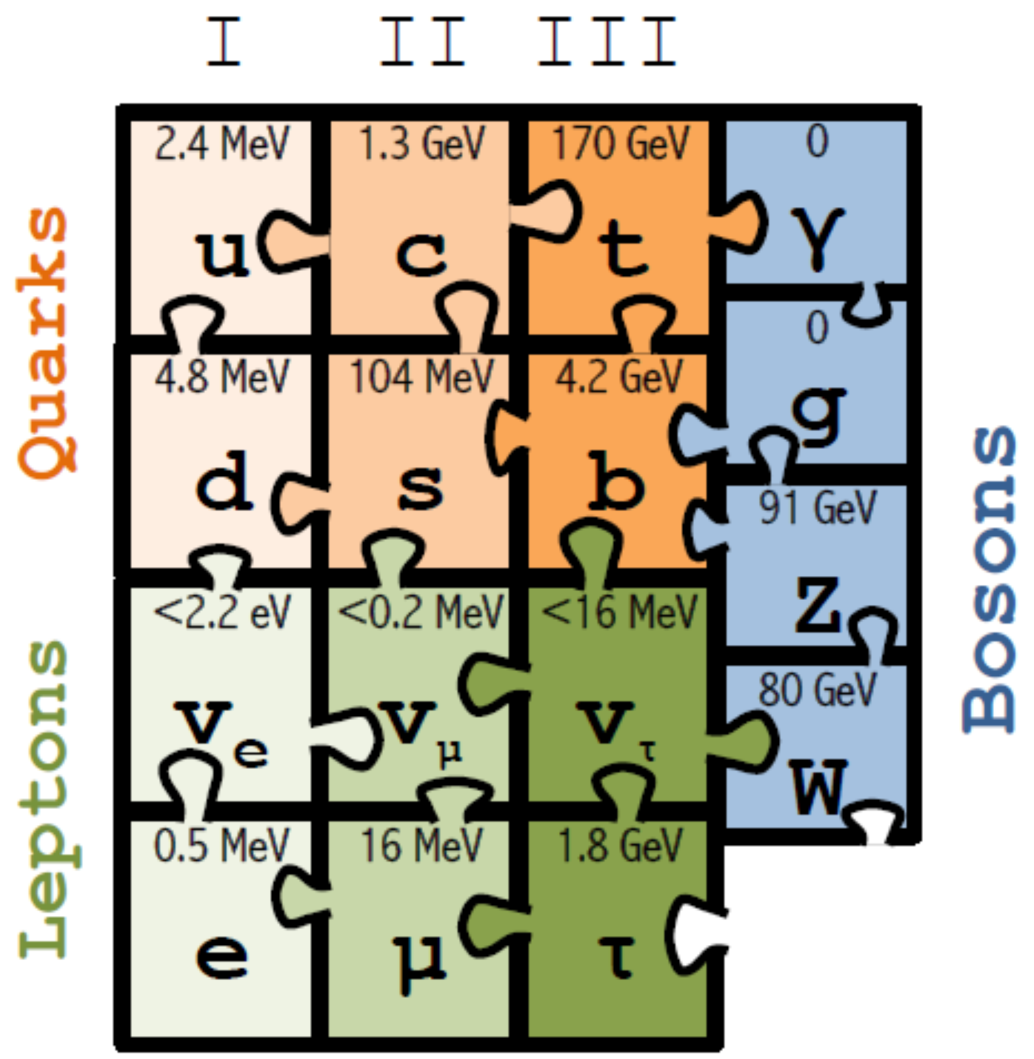
FCC

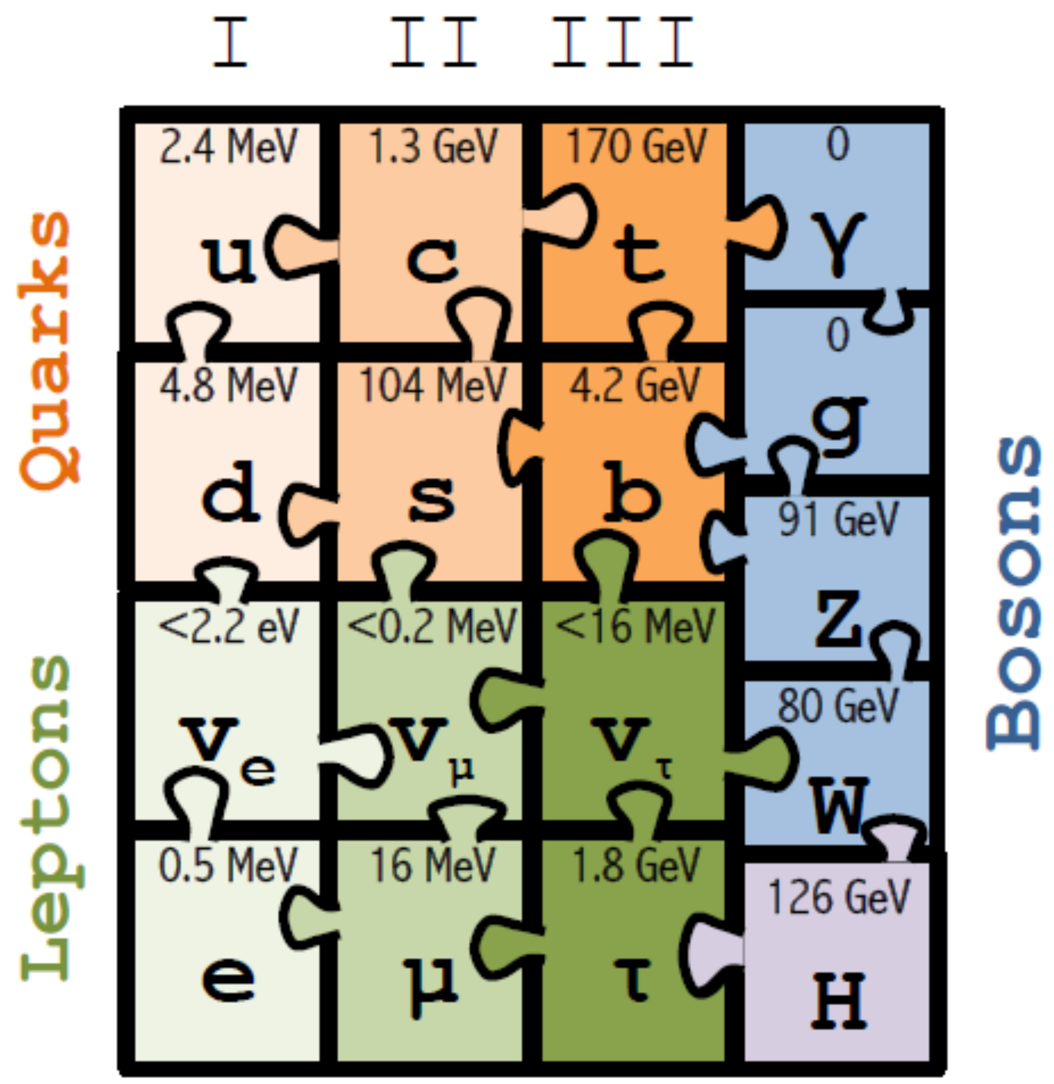
THE PHYSICS LANDSCAPE

➤ 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 ?

WHICH TYPE OF COLLIDER?

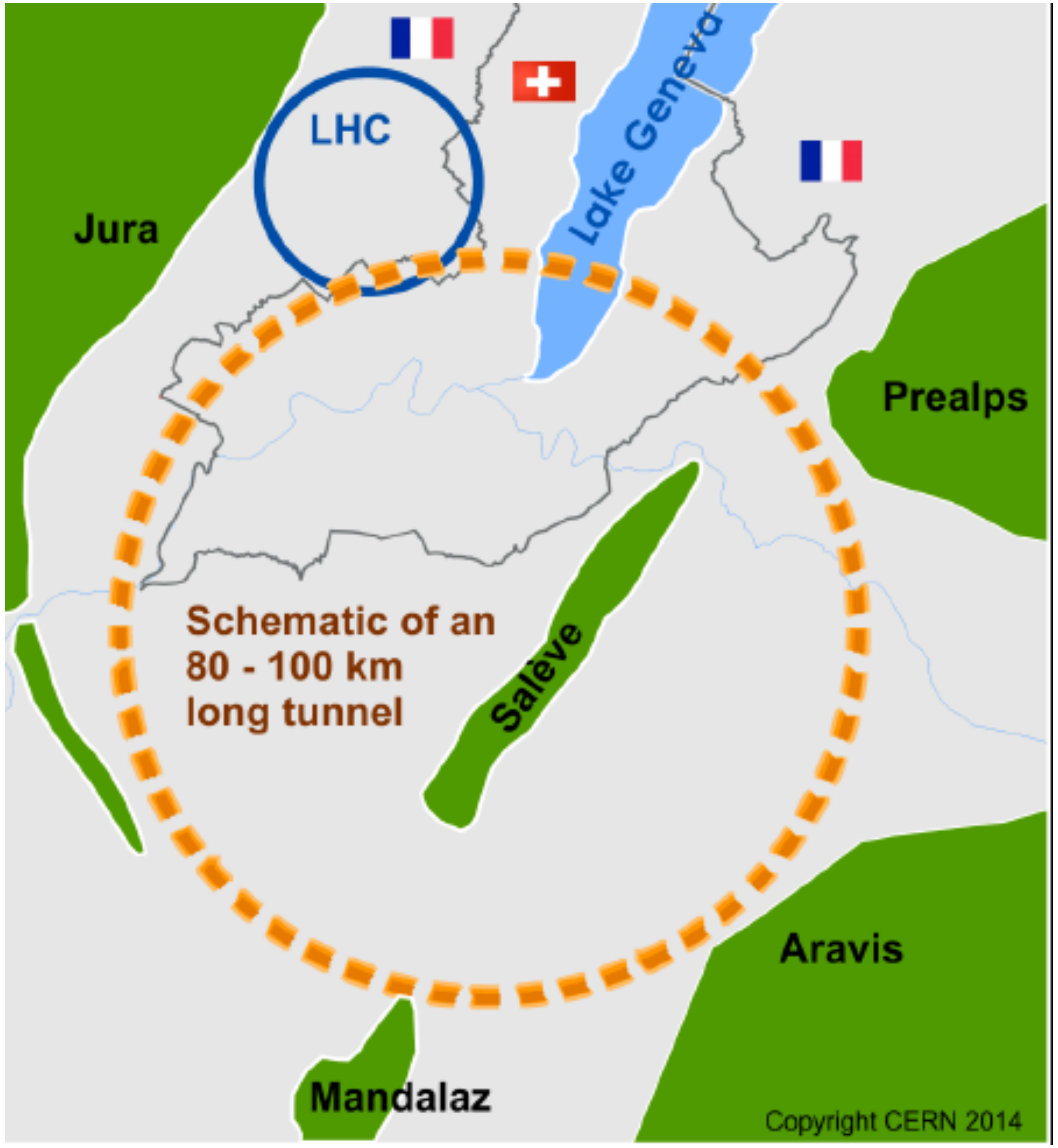
- Energy: direct access to new resonances
- Precision: indirect evidence of deviations at low and high energy.

More SENSITIVITY, more PRECISION, more ENERGY

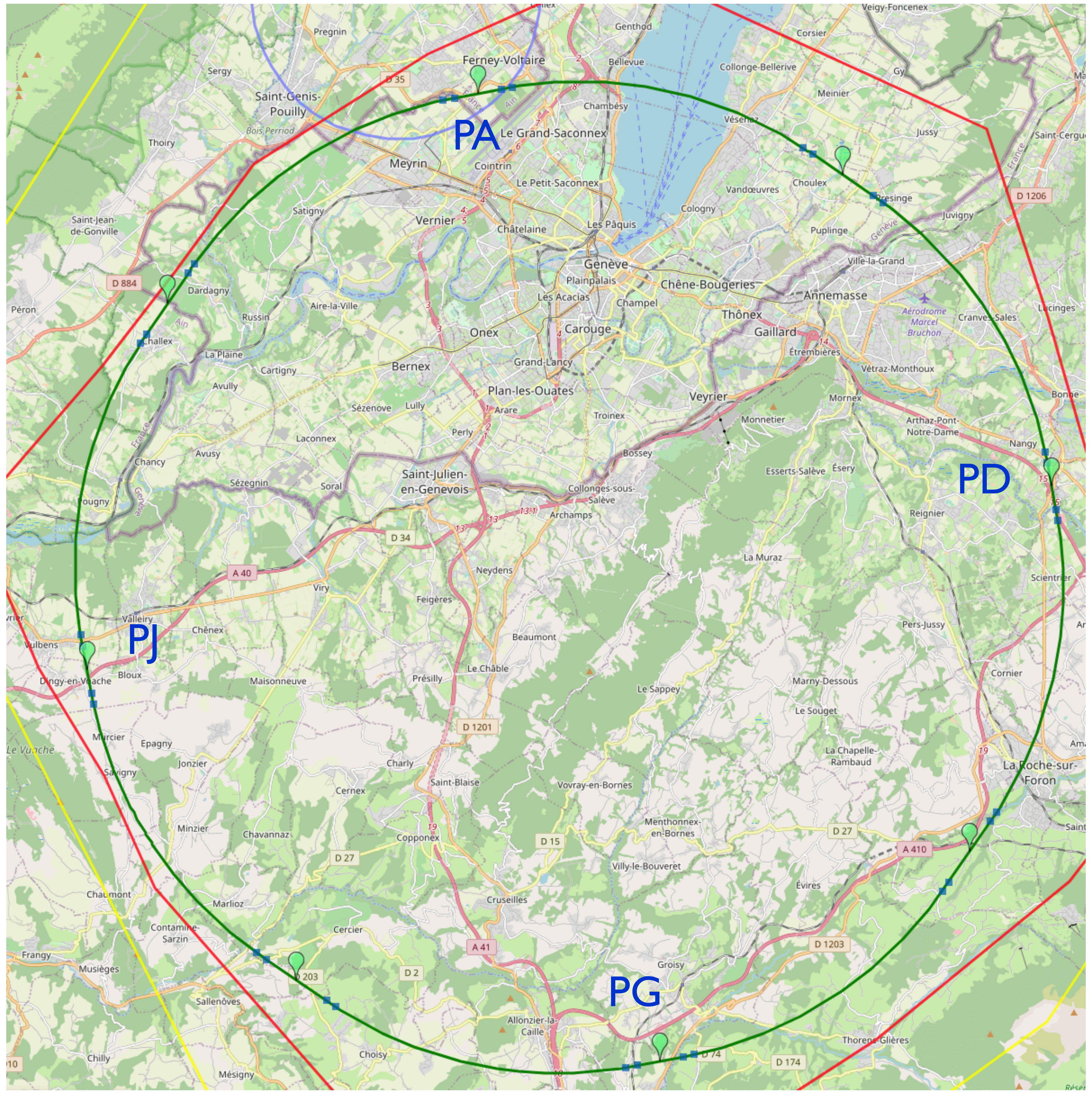
- A combination of lepton and hadron colliders provides:
  - Largest luminosity
  - highest parton energy
  - synergies and complementarities between e^+e^- and pp (and more…)
- FCC integrated project offers an appropriate answer to these needs

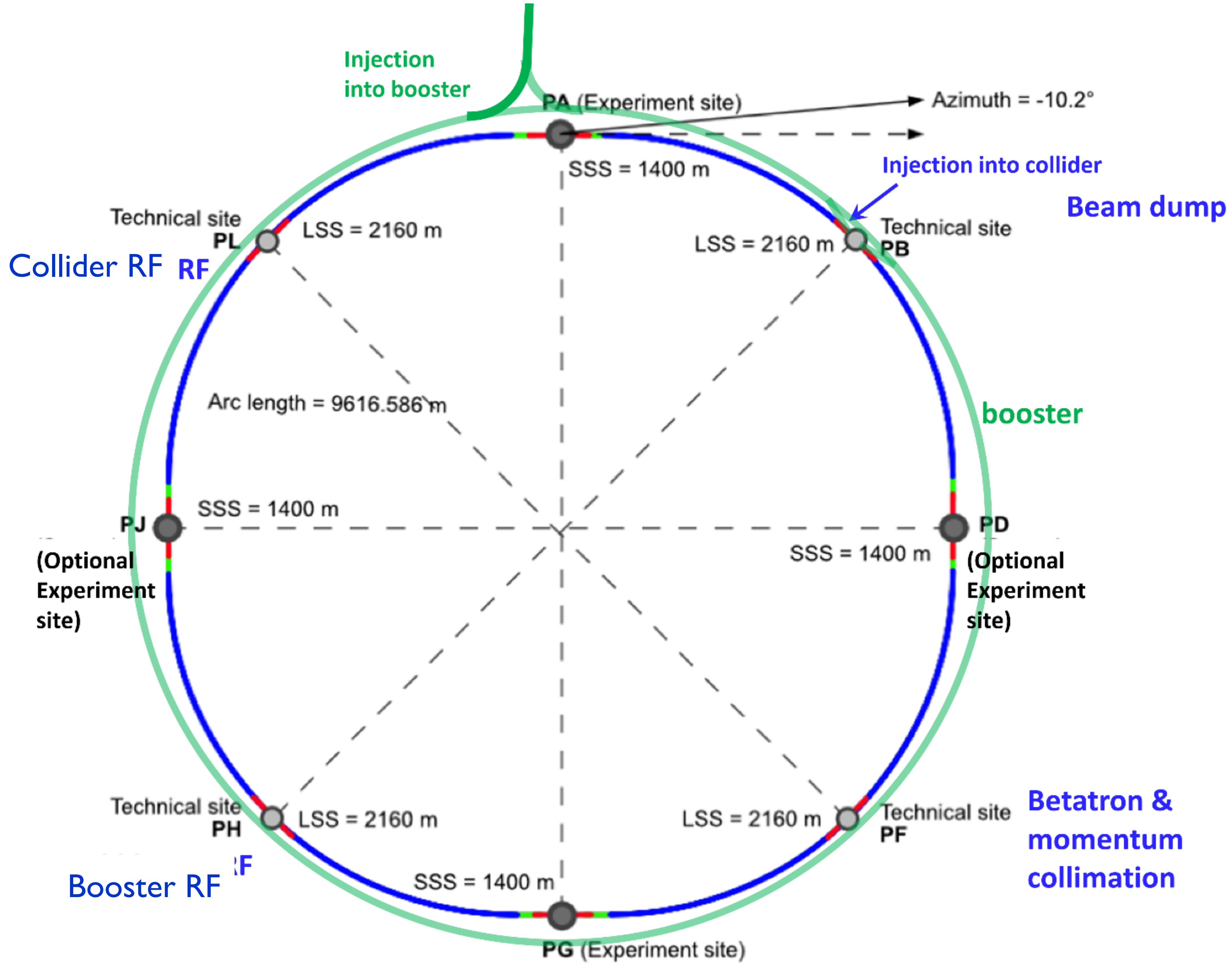
THE FUTURE: THE FCC INTEGRATED PROJECT

- Build a new 91km tunnel in the Geneva region
- Ultimate goal: highest energy reach in pp collisions, 100 TeV
  - need time to develop the technology to get there
- First step: extreme precision circular e^+e^- collider (FCC-ee)
  - variable collision energy from 90-360 GeV (beyond top threshold)
- **As for the LEP+LHC, one tunnel for two complementary machines covering the largest phase space in the high energy frontier**
  - a complete physics program until the end of the century



OPTIMIZED PLACEMENT AND NEW LAYOUT: ~91 KM



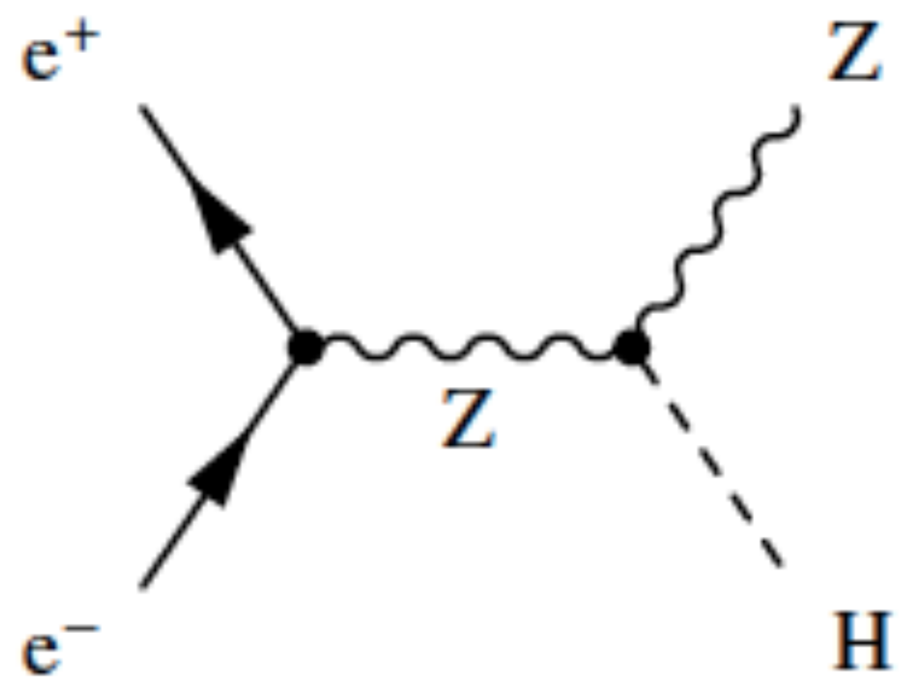


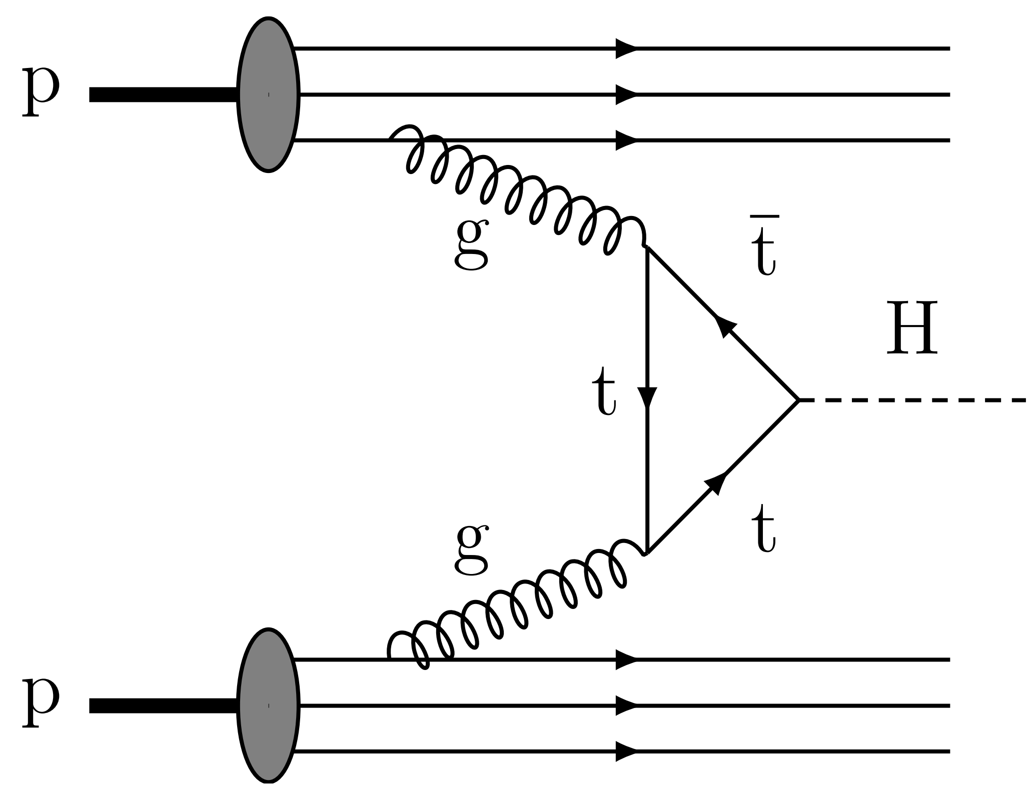
- New four-fold periodicity and increased FCC-ee / FCC-hh synergies: opens the possibility of four experiment sites at FCC-ee
  - Same experimental areas and positions for FCC-ee and FCC-hh interaction points

Slide from P. Janot

THE FCC-ee

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 UNIQUENESS OF FCC-ee

With respect to linear collider's 1st stage

Optimal energy range for SM particles

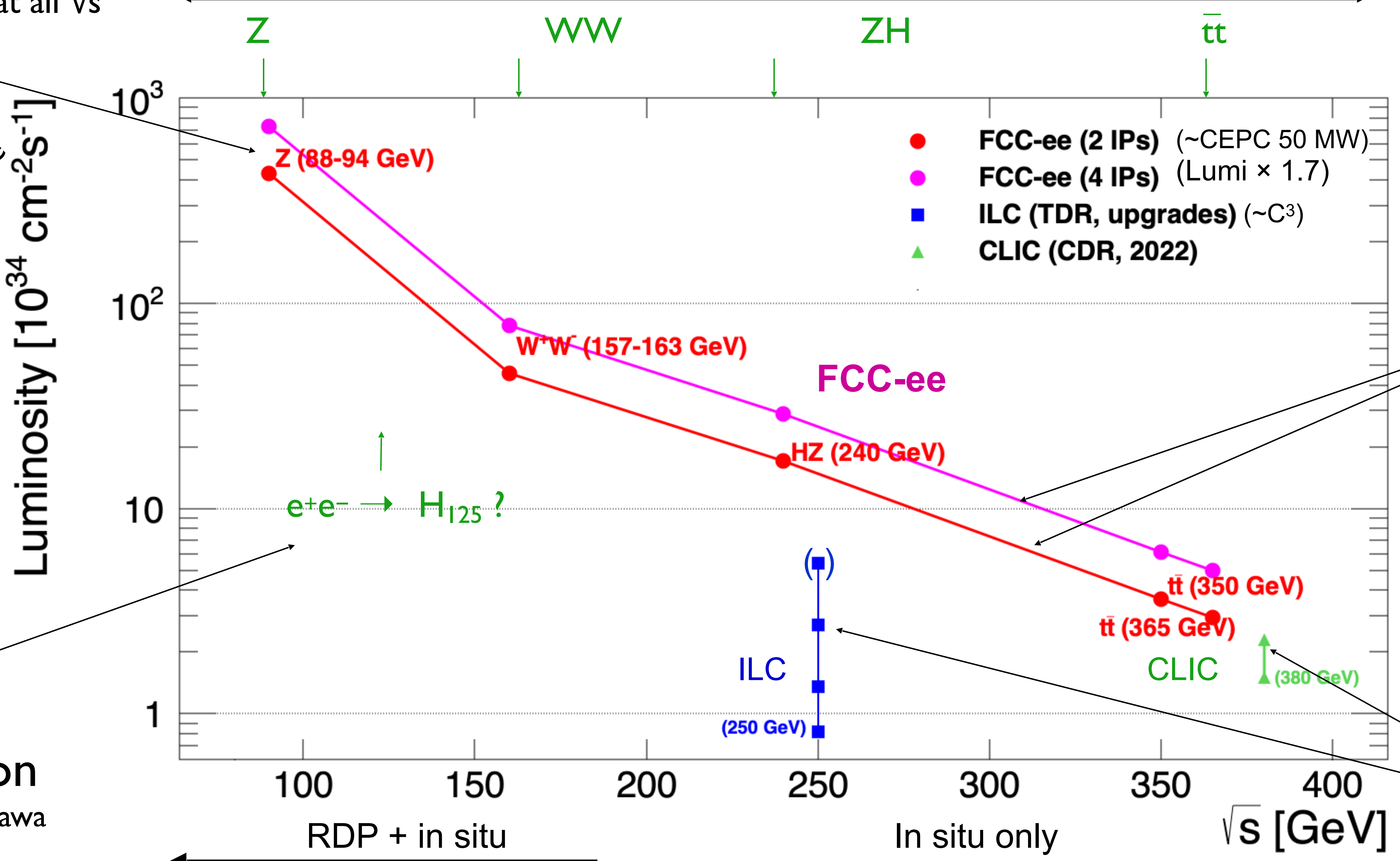
Sharpen and challenge our knowledge of already existing physics

LEP1 statistics in a few minutes

Detector calibration/alignment at all √s

Highest luminosities

Less running time for a given physics outcome
Better physics outcome for a given running time
Increase discovery potential



Serve up to 4 interaction points

Net overall gain in MW/ab-1 or CO2-eq/ab-1
Essential redundancy for precision measurements
May satisfy all detector requirements
Increase discovery potential
Enhance the community (FCC/CERN clients)

√s Monochromatisation

Unique opportunity for electron Yukawa

Motivates the competition

Luminosity is the name of the game

Precise and continuous √s, √s spread, boost determination

Both with resonant depolarisation (RDP) and with collision events in up to four detectors
Essential for precision measurements

Slide from P. Janot

BASELINE RUN SCENARIO WITH 2IPs (FROM CDR)

- Numbers of events in 15 years, tuned to maximise the physics outcome:

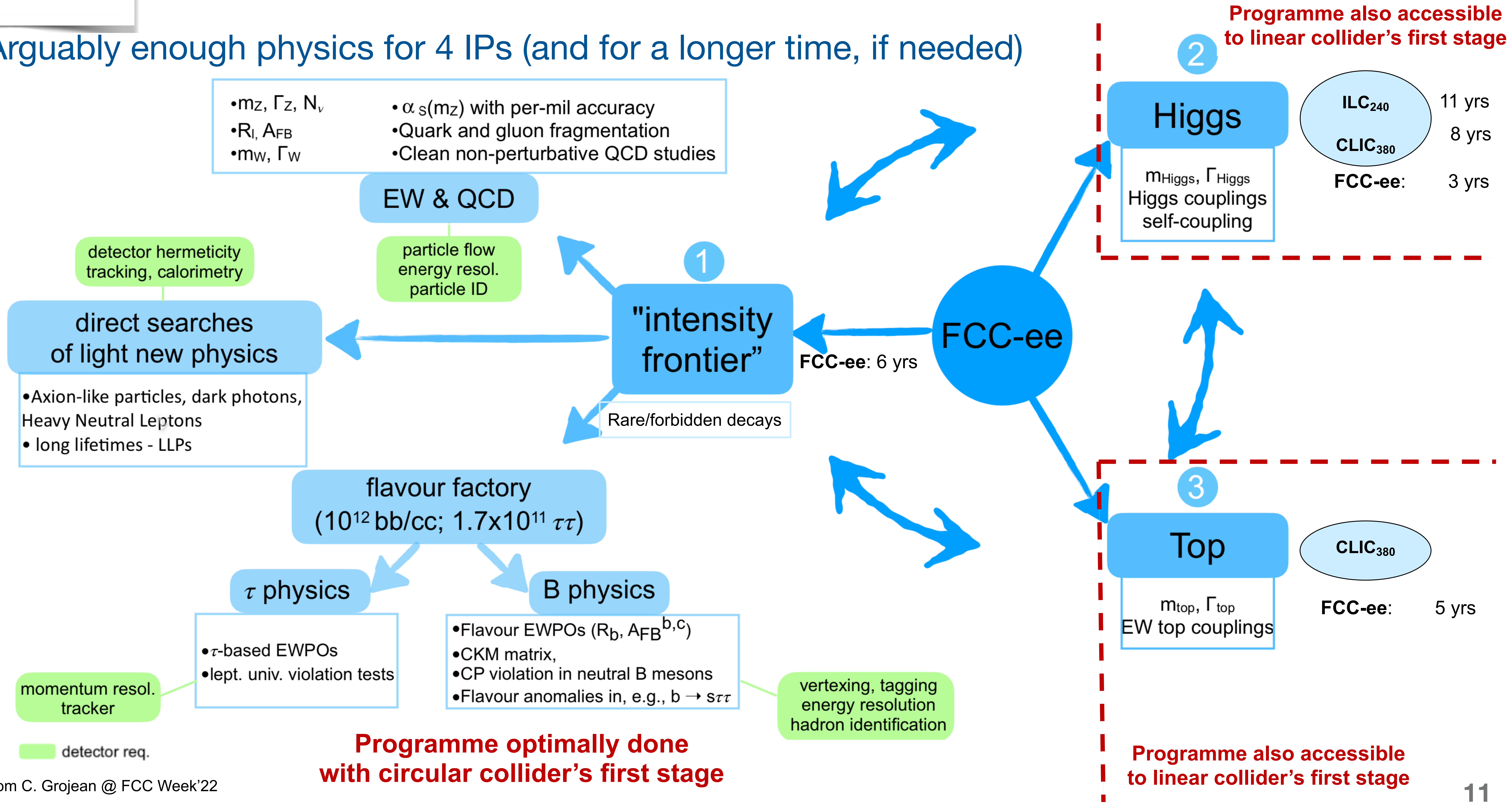
						$\sqrt{s}$ uncertainty
ZH maximum	$\sqrt{s}$ ~ 240 GeV	3 years	10^6	$e^+e^- \to ZH$	Never done	2 MeV
$t\bar{t}$ threshold	$\sqrt{s}$ ~ 365 GeV	5 years	10^6	$e^+e^- \to t\bar{t}$	Never done	5 MeV
Z peak	$\sqrt{s}$ ~ 91 GeV	4 years	5×10^{12}	$e^+e^- \to Z$	LEP x 10^5	< 50 keV
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$	LEP x 10^3	< 200 keV
[s-channel H	$\sqrt{s}$ = 125 GeV	5? years	~5000	$e^+e^- \to H_{125}$]	Never done	< 100 keV

- Exact durations depend on a number of factors (to be studied by the FCCC in 2048-2063)
  - Overall duration: Are the FCC-hh magnets ready ? New physics in FCC-ee data ?
  - Step duration: What is the actual luminosity at each √s? How many IPs? Alternative physics optimization?

- Exact sequence of events is a multi-faceted issue (which can also be decided later)

FCC-ee PHYSICS PROGRAMME WITH 2 IPs AND 15 YEARS

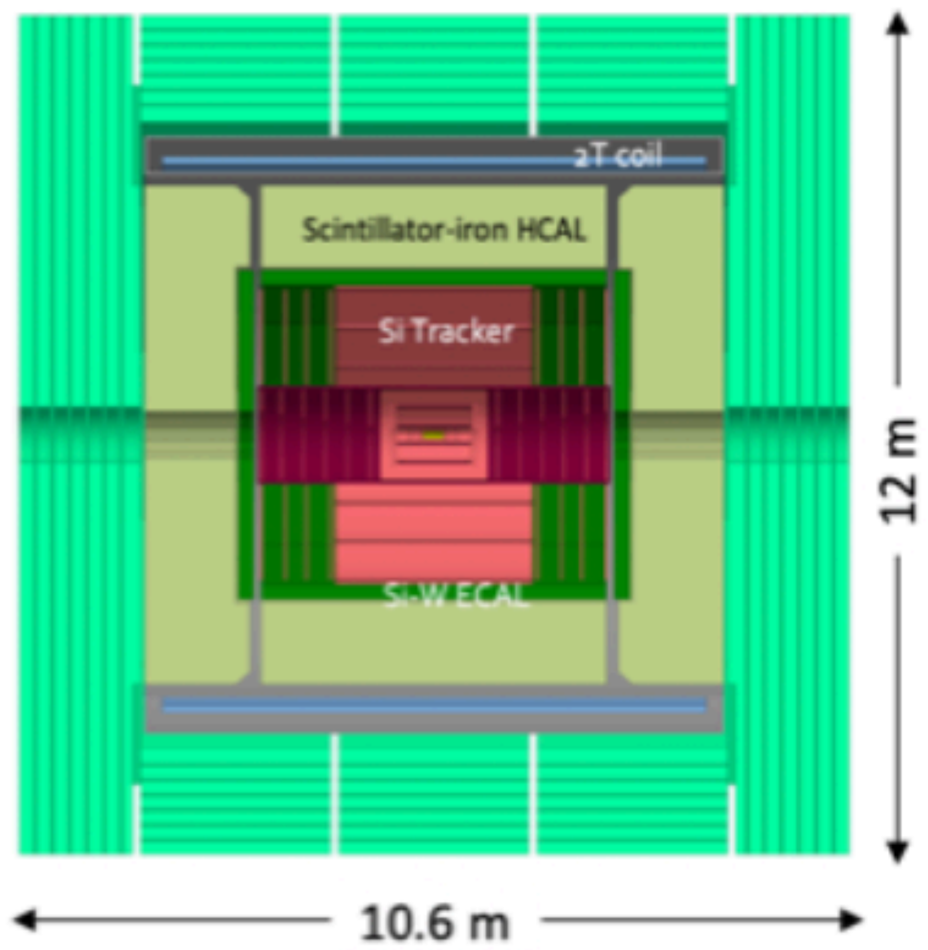
- Arguably enough physics for 4 IPs (and for a longer time, if needed)



Slide from C. Grojean @ FCC Week'22

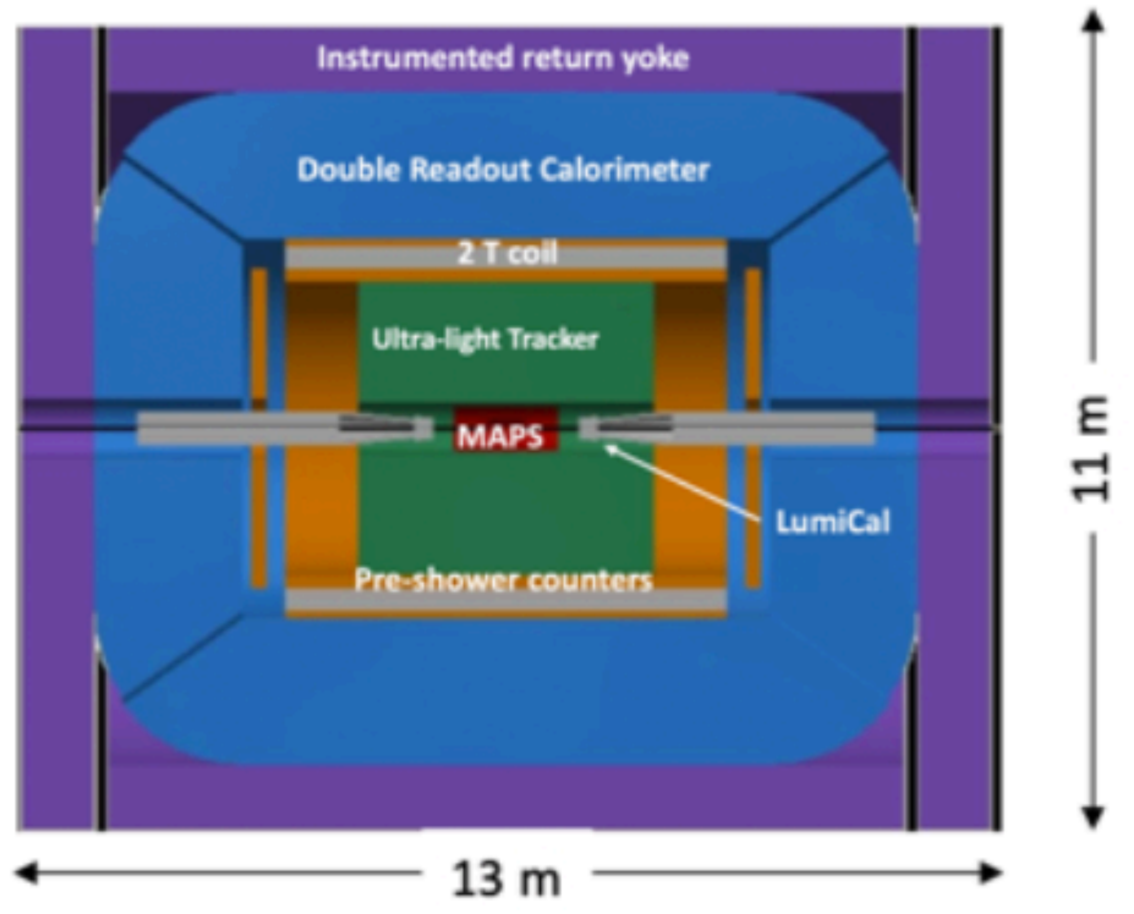
PROTO-DETECTOR CONCEPTS

CLD

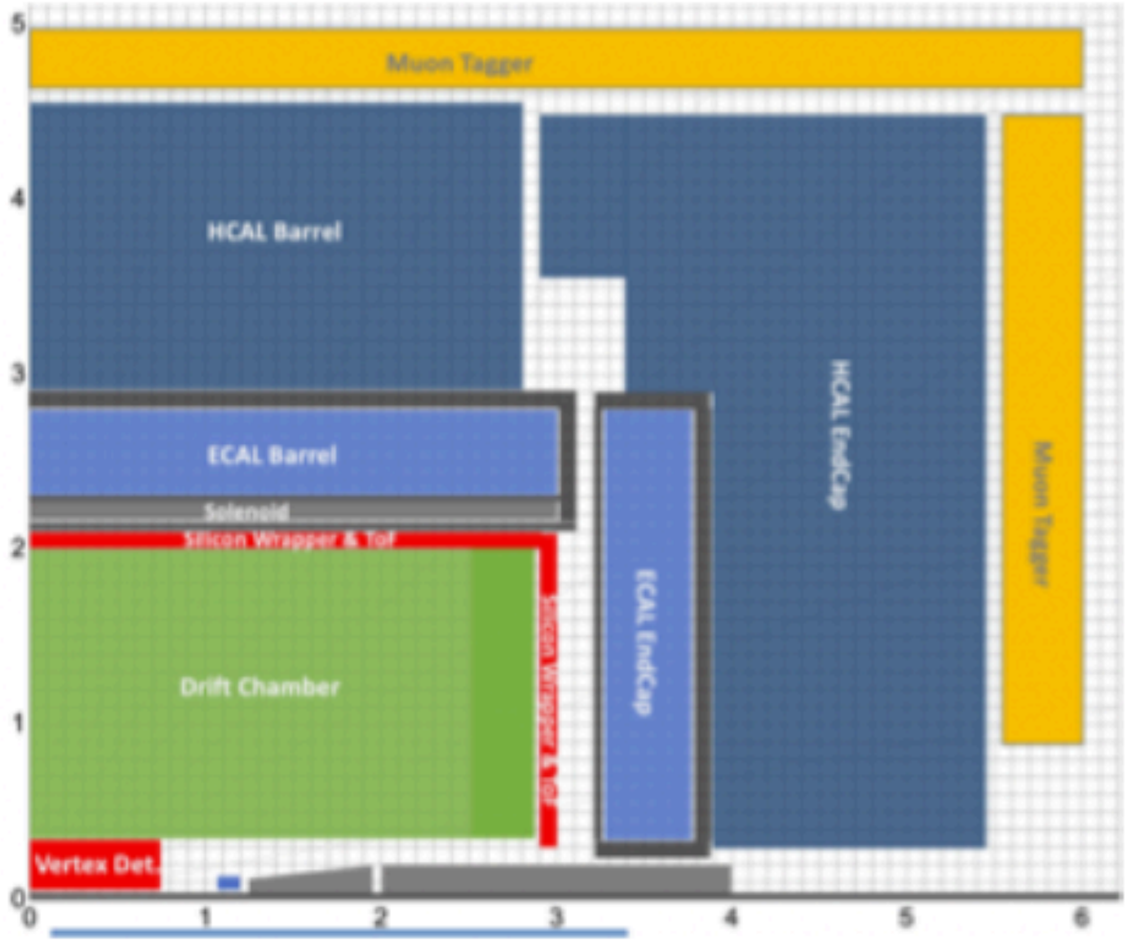


CDR

IDEA



Noble Liquid ECAL based



new

- CLIC detector -> CLD
- 2T solenoid outside Calo
- Full Si vtx + tracker
- CALICE-like calo
- RPC muon system

1911.12230, 1905.02520

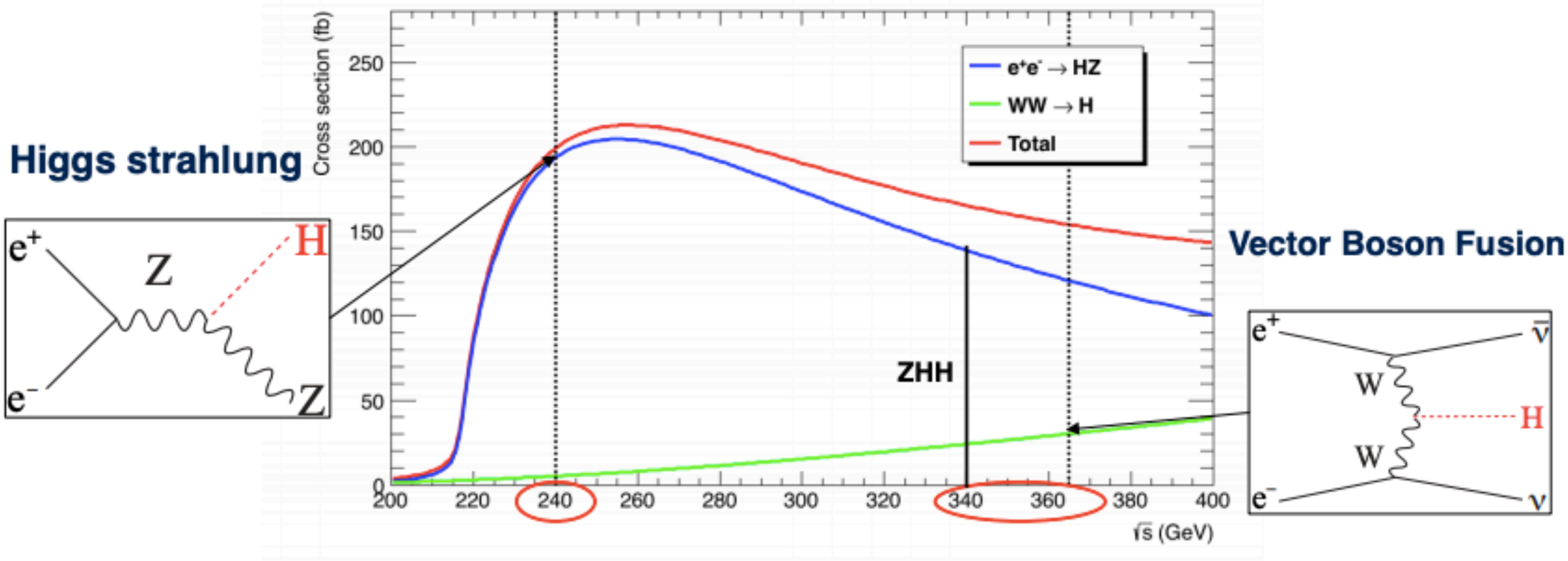
- 2T thin solenoid within Calo
- Si vtx detector
- Ultra light drift chamber
- Dual Readout calo+preshower
- Possible crystal ECAL
- MPGD (μ-rwell) muon system

CERN-ACC-2018-0057

- High granularity ECAL
  - Pb+Lar (or W+LKr)
- Drift chamber (or Si) tracker; CALICE-like HCAL; muon sys.
- Coil in same cryostat as LAr

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)

FCC-ee AS A HIGGS FACTORY AND BEYOND

Higgs provides a very good reason why we need both e^+e^- AND pp colliders

- **FCC-ee measures g_{HZZ} to 0.2% (absolute, model-independent, standard candle) from σ_{ZH}**
  - Γ_H, g_{Hbb}, g_{Hcc}, $g_{H\tau\tau}$, g_{HWW} follow
  - Standard candle fixes all HL-LHC couplings
- FCC-hh produces over 10^{10} Higgs bosons
  - (1^{st} standard candle →) $g_{H\mu\mu}$, $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, Br_{inv}
- FCC-ee measures top EW couplings ($e^+e^- \to t\bar{t}$)
  - Another standard candle
- FCC-hh produces 10^8 ttH and 2. 10^7 HH pairs
  - (2^{nd} standard candle →) g_{Htt} and g_{HHH}

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT	
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30	
Years	10	3 + 1 + 4	25	
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16	ee
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19	ee
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	ee
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96	ee
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5	ee
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46	ee
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43	pp
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32	pp
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7	pp
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95	pp
g_{HHH} (%)	50.	44./33. 27./24.	2-3	pp
Γ_H (%)	SM	1.1	0.91	ee
BR_{inv} (%)	1.9	0.19	0.024	pp
BR_{EXO} (%)	SM (0.0)	1.1	1	ee

- FCC-ee + FCC-hh is outstanding
  - All accessible couplings with per-mil precision; self-coupling with per-cent precision

FCC-ee is also the most effective way toward FCC-hh

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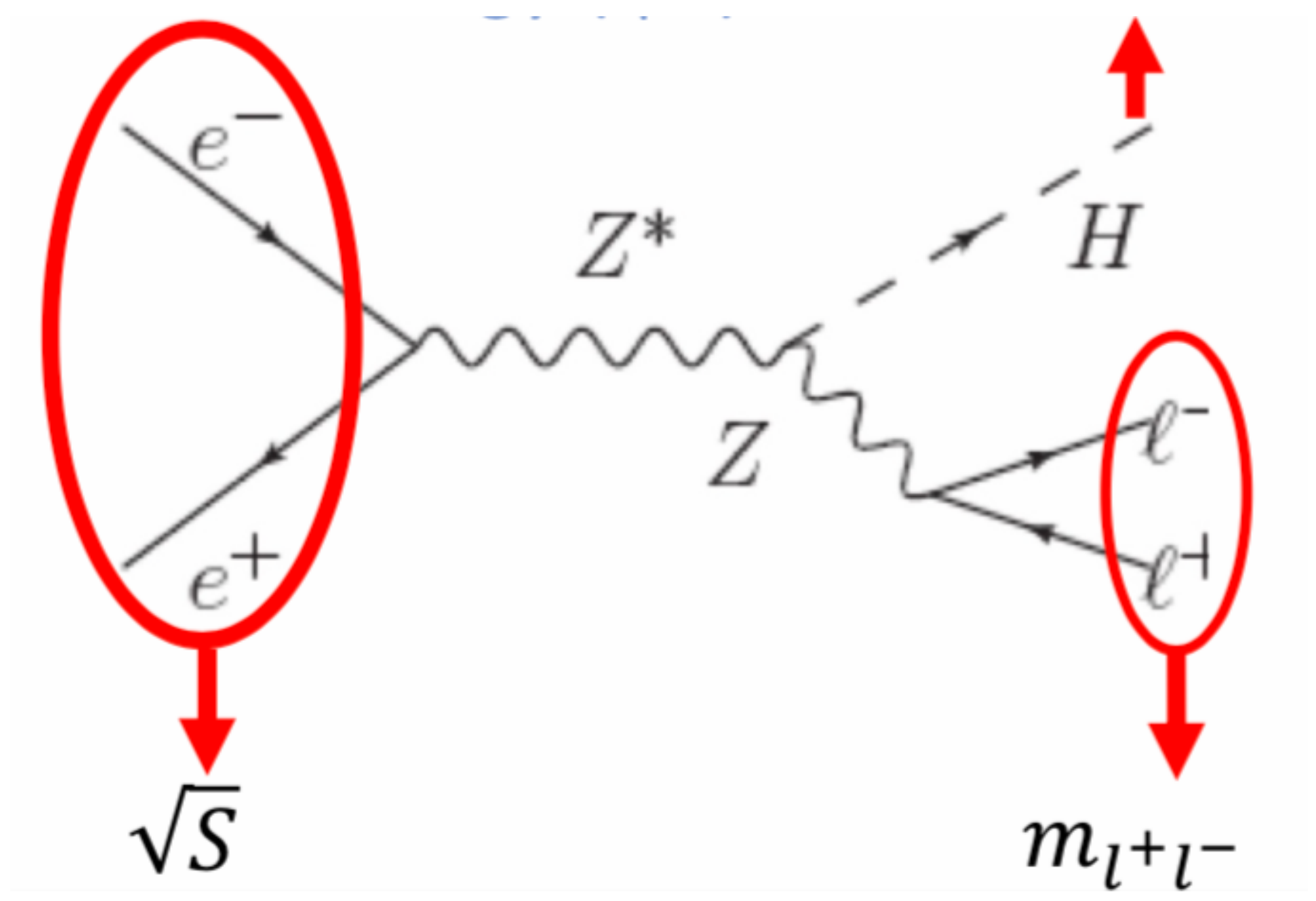
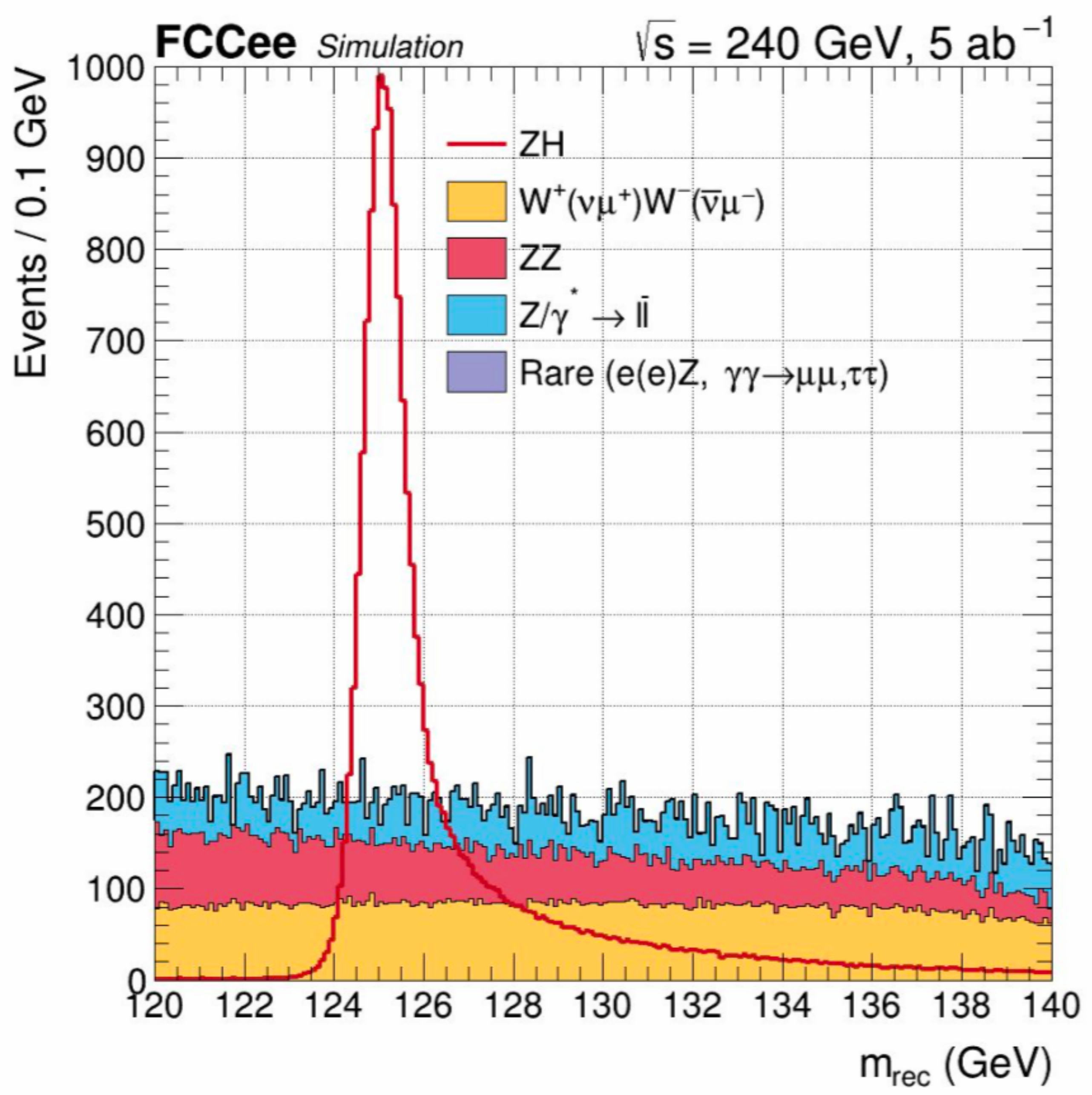
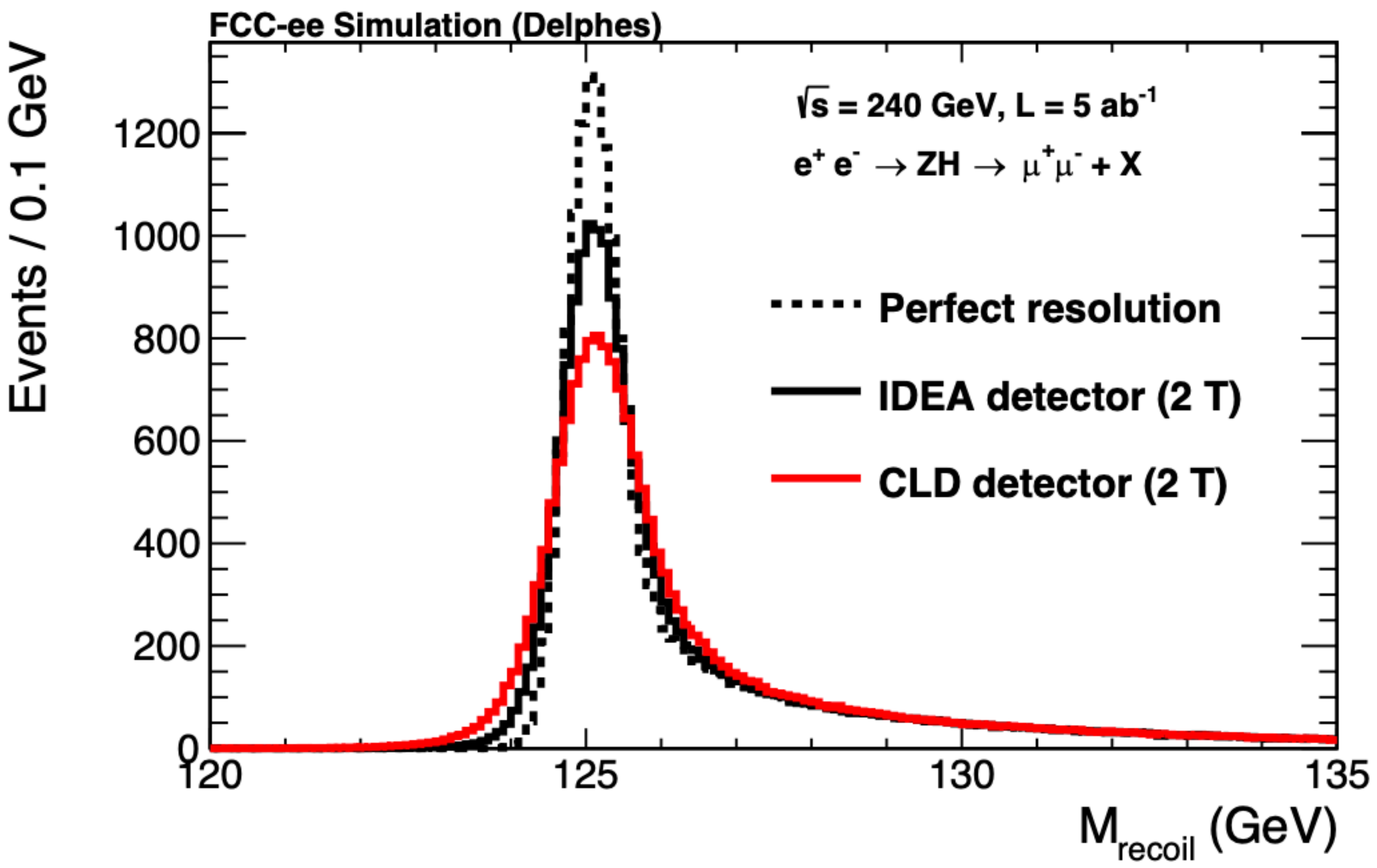
EXAMPLE "CASE STUDY": HIGGS MASS AND CROSS SECTION

$e^+e^- \to ZH, Z \to \mu\mu$

2107.04509







$$m^2_{\text{recoil}} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$

Recoil mass affected by :
- The beam energy spread
- The momentum resolution (and the ISRs for the tail)

Higgs mass measurement:

$\Delta(m_H) < O(\Gamma_H)$ i.e. 4 MeV desirable in view of $e^+e^- \to H$

Main TK	Δm_H (MeV)	$\Delta\sigma$ (%)
IDEA 2T	6.70	1.07
CLD 2T	9.01	1.12
IDEA 3T	5.78	1.06
Perfect resol	4.75	1.04

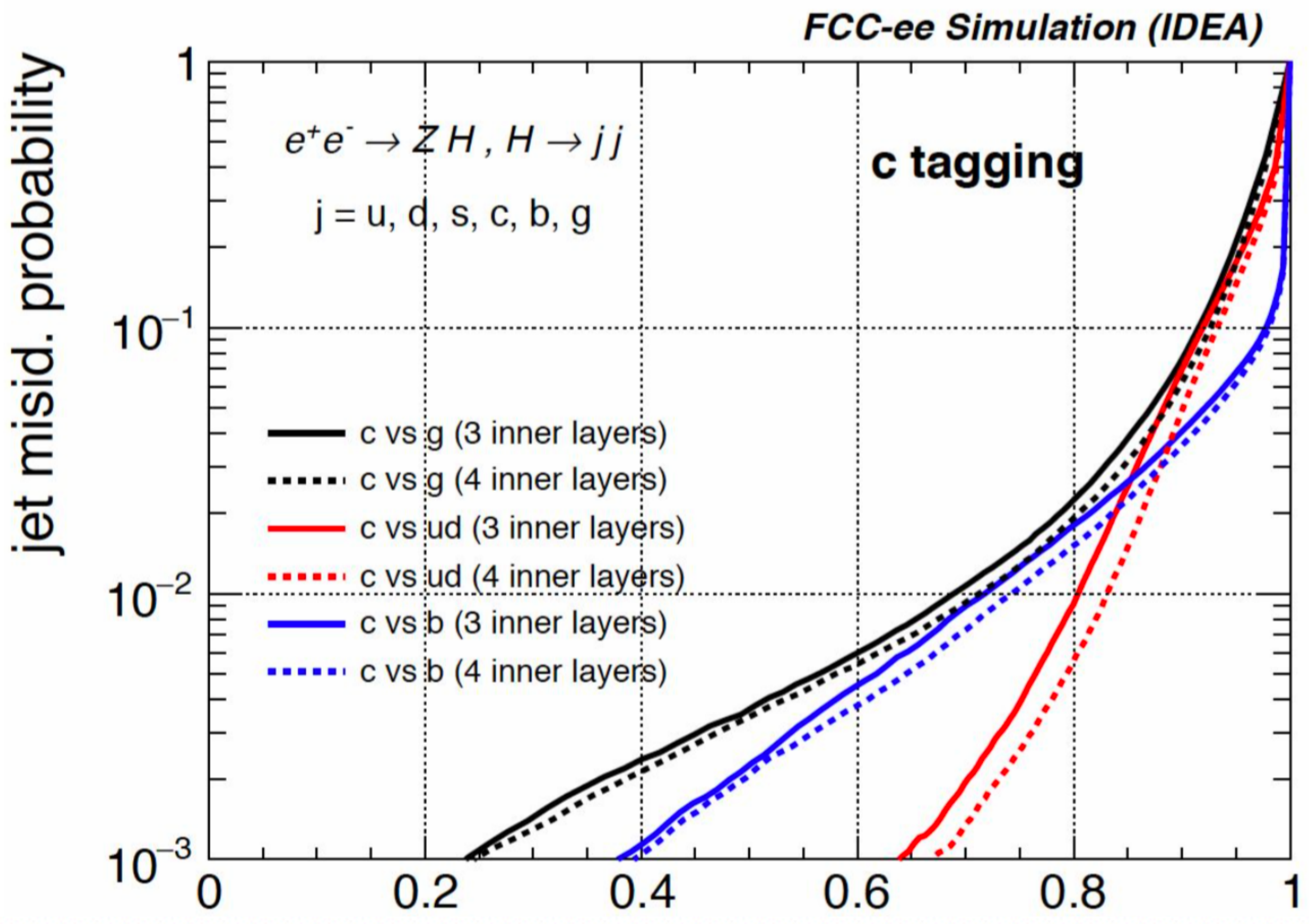
EXAMPLE "CASE STUDY": HIGGS COUPLINGS TO b/c/s-QUARKS AND GLUONS

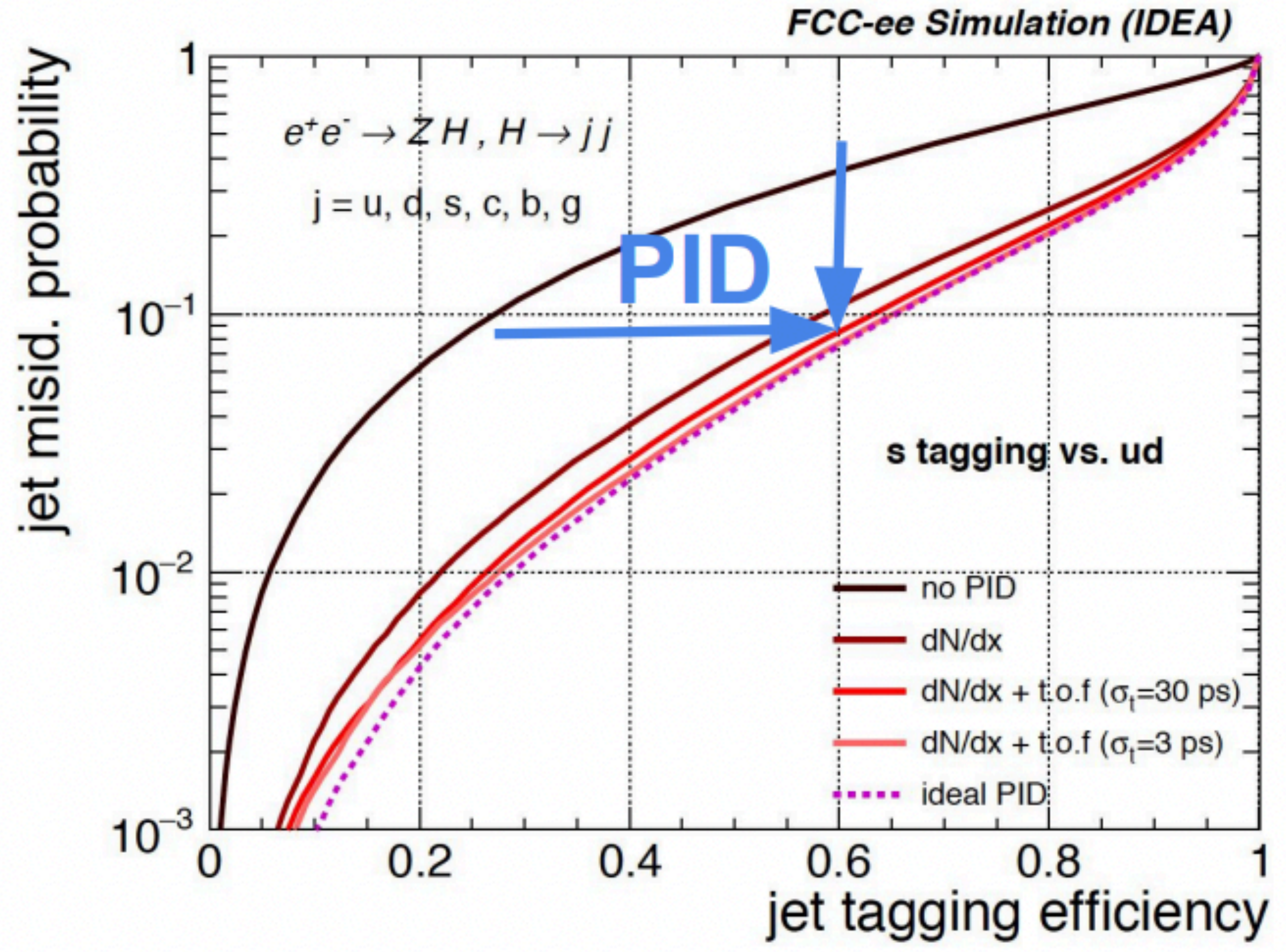
2202.03285

- A must for any Higgs factory
  - Precise measurement of all Higgs couplings to ff, VV
  - H(cc), H(gg) won't be measured at HL-LHC

- **Flavour tagging is the key**
  - Algorithms based on state-of-the-art advanced Neural Networks

- **Requirements on Detector:**
  - Position of innermost layer of vertex
  - Particle ID capabilities (timing?)



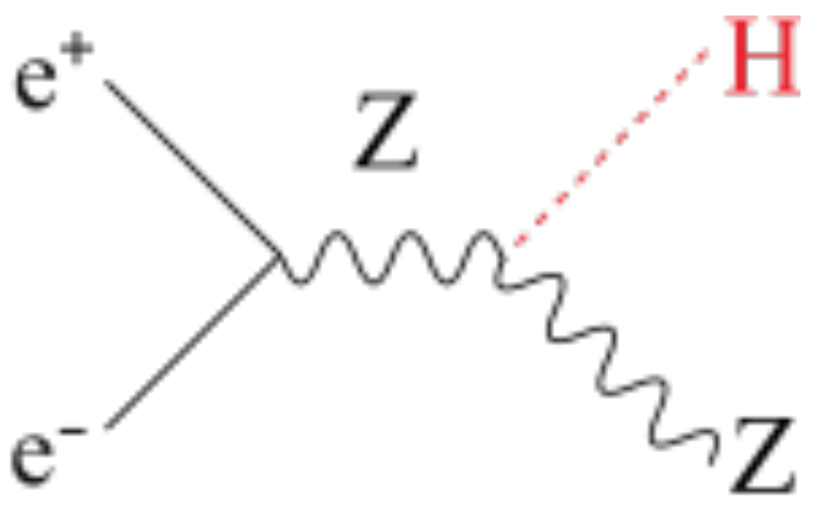


Benchmarks for flavour tags

- Final states:
  - Z(ll) H(qq) : clean, use the recoil mass a
  - Z(vv) H(qq) : probably drives the sensitivi
  - Z(qq) H(qq) : performance depends in addi on jet pairing, see later

HIGGS SELF-COUPLING

- Traditionally kλ measured in double Higgs production at higher energies.
- Statistics-limited sensitivity comes from $\sigma_{ee\to ZH}$ measurements at 240 and 365 GeV
  - Thanks to the relative change with centre-of-mass energy



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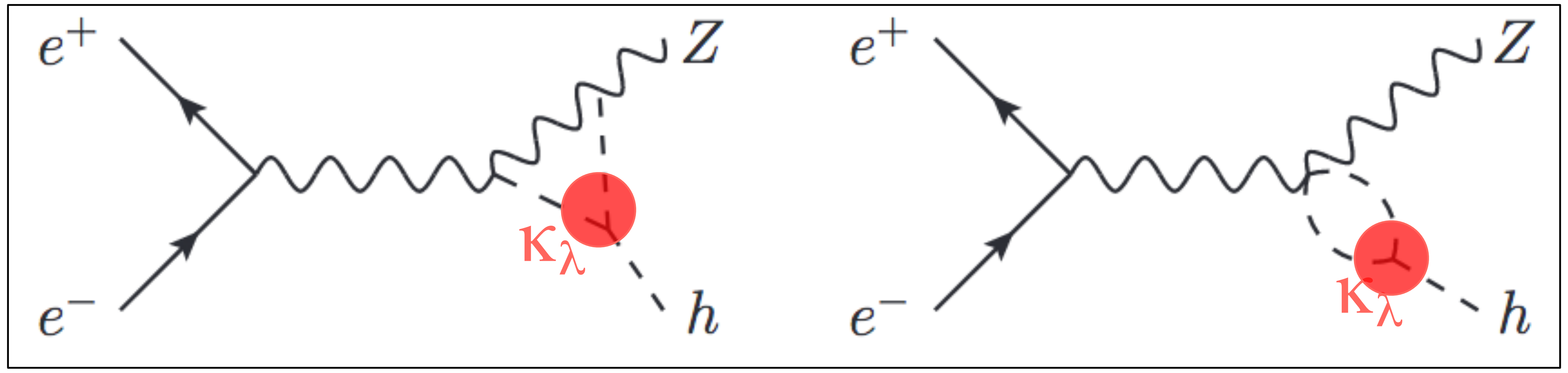
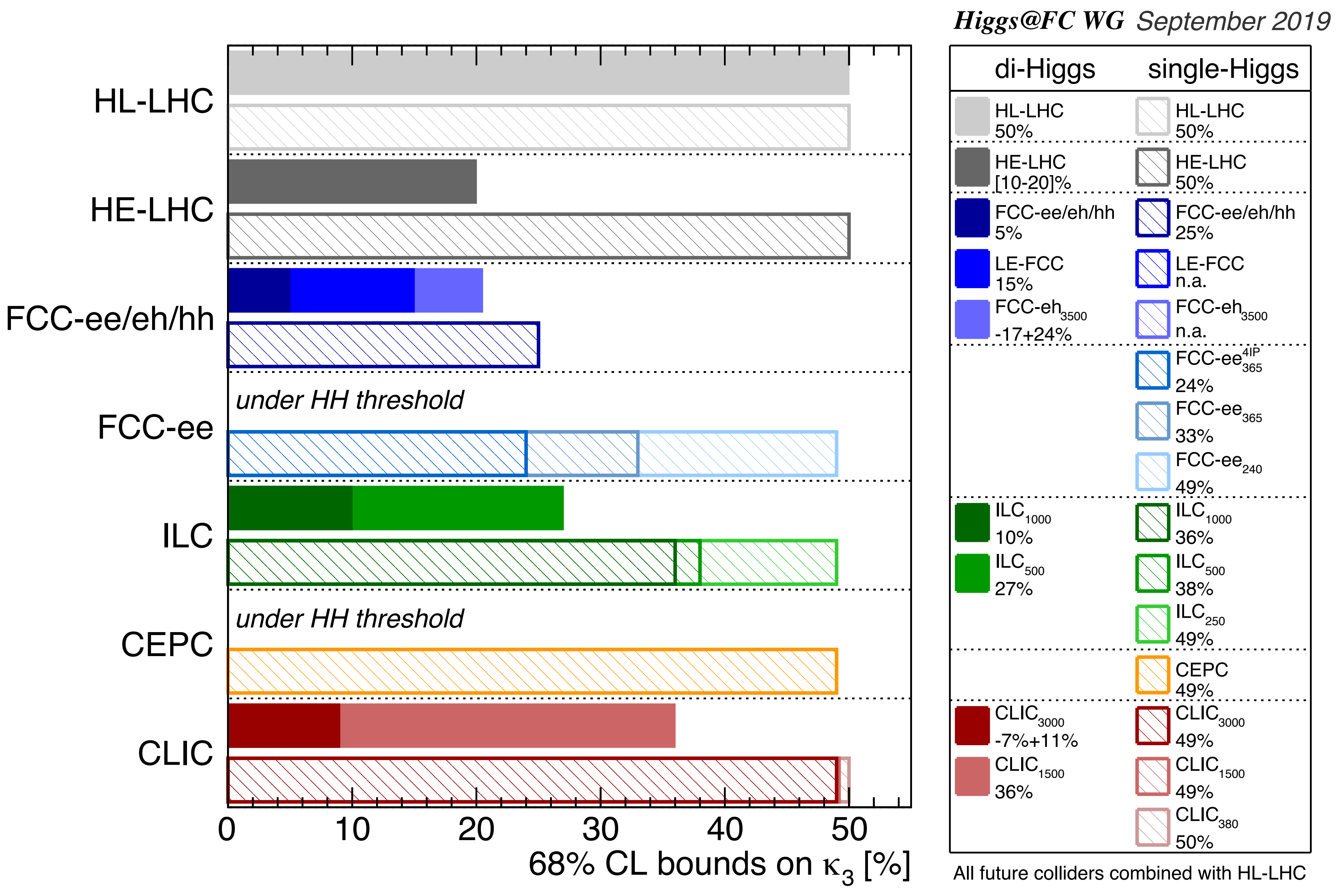


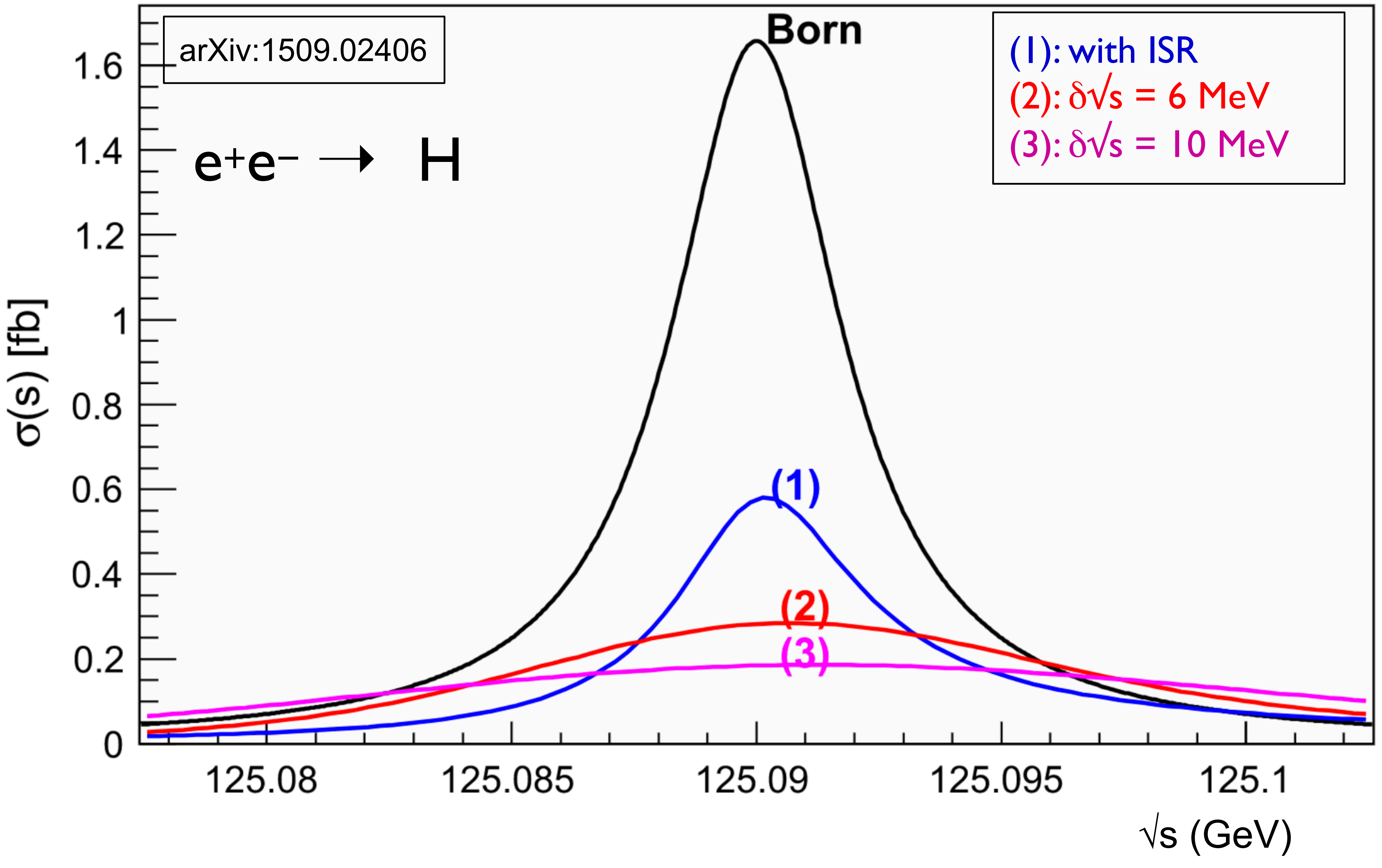


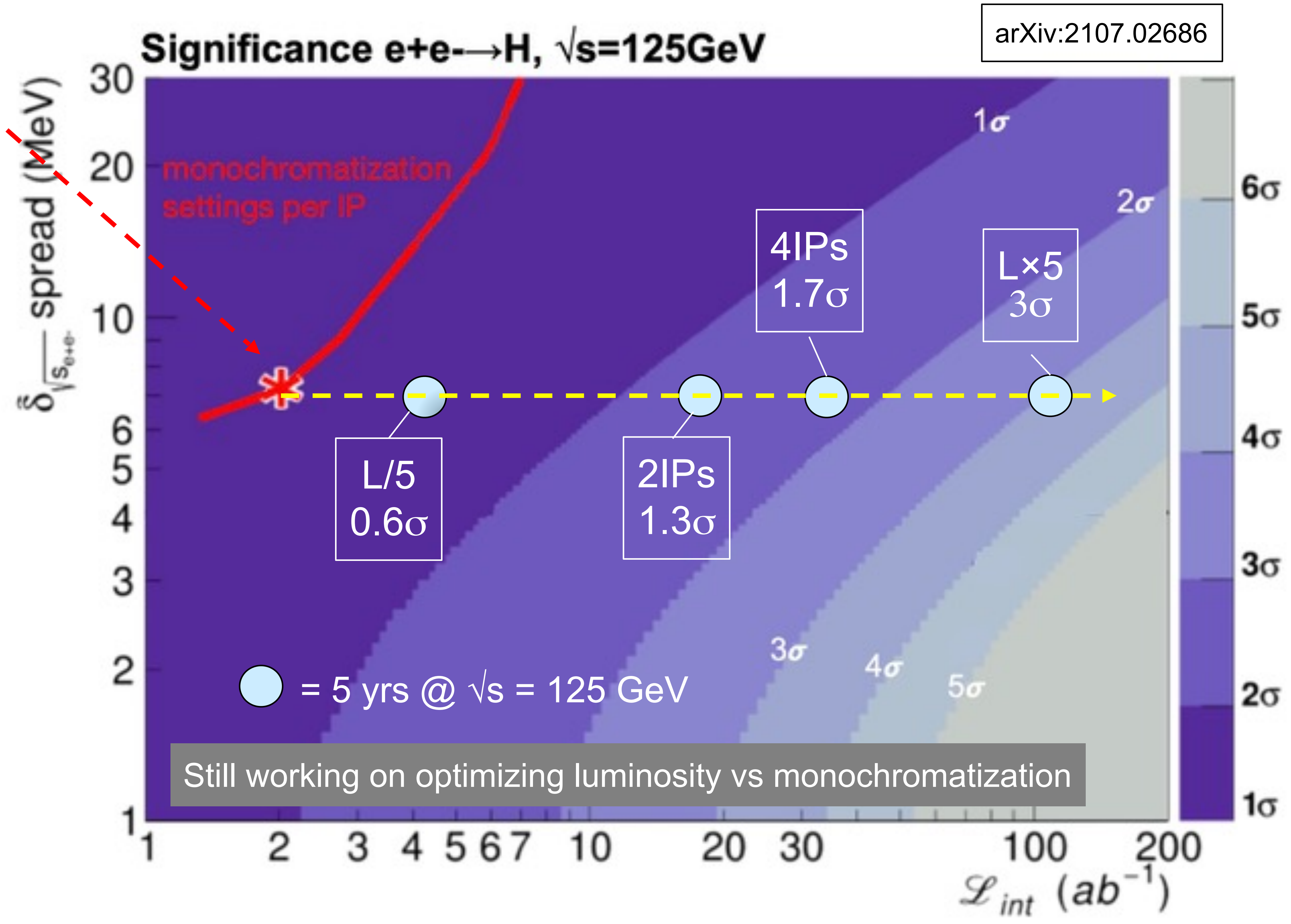
- Estimate with present run plan and 2 IPs: ≥ 2σ from κλ=0
  - With 4 IPs and optimization of run plan: target ≥ 5σ, δκλ~20%
  - With FCC-hh can reach the few % level

ELECTRON YUKAWA COUPLING: UNIQUE @ FCC-ee

(not yet in the baseline)

- One of the toughest challenges, which requires in particular, at √s = 125 GeV
  - Higgs boson mass prior knowledge to a couple MeV, requires at least the design lumi at √s = 240 GeV
  - Huge luminosity, achievable with with several years of running and possibly 4 IPs
  - √s monochromatisation : Γ_H (4.2 MeV) ≪ natural beam energy spread (~100 MeV)
- First studies indicate a significance of 0.4σ with one detector in one year



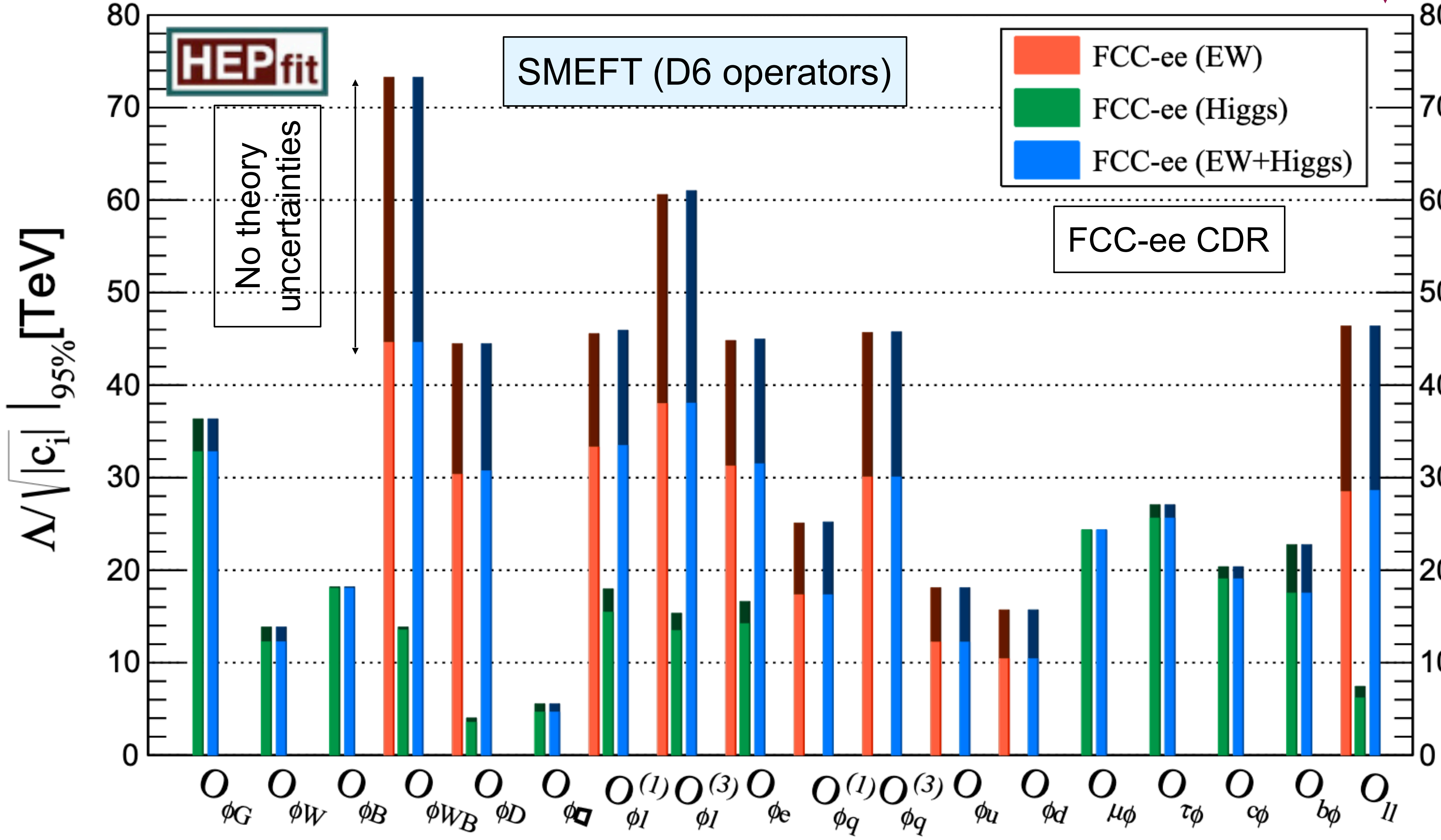


PRECISION EW MEASUREMENTS

arXiv:2106.13885

- Many interconnected measurements
  - The whole FCC-ee run plan is essential (Z,W,top)
  - Complementary to Higgs for New Physics
  - Huge statistics → precision
    - Real chance of discovery
  - Most of the work is (will be) on systematics
    - Experimental and theoretical

	Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
Z	m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Z	Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
Z	$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
Z	$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
Z	R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
Z	$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
Z	σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
Z	$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
Z	R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
Z	$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
Z	$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
Z	τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
Z	τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
Z	τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
W	m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
W	Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
W	$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
W	$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
top	m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
top	Γ_{top} (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
top	$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
top	ttZ couplings	± 30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run



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M(W) FROM HL-LHC TO FCC-ee

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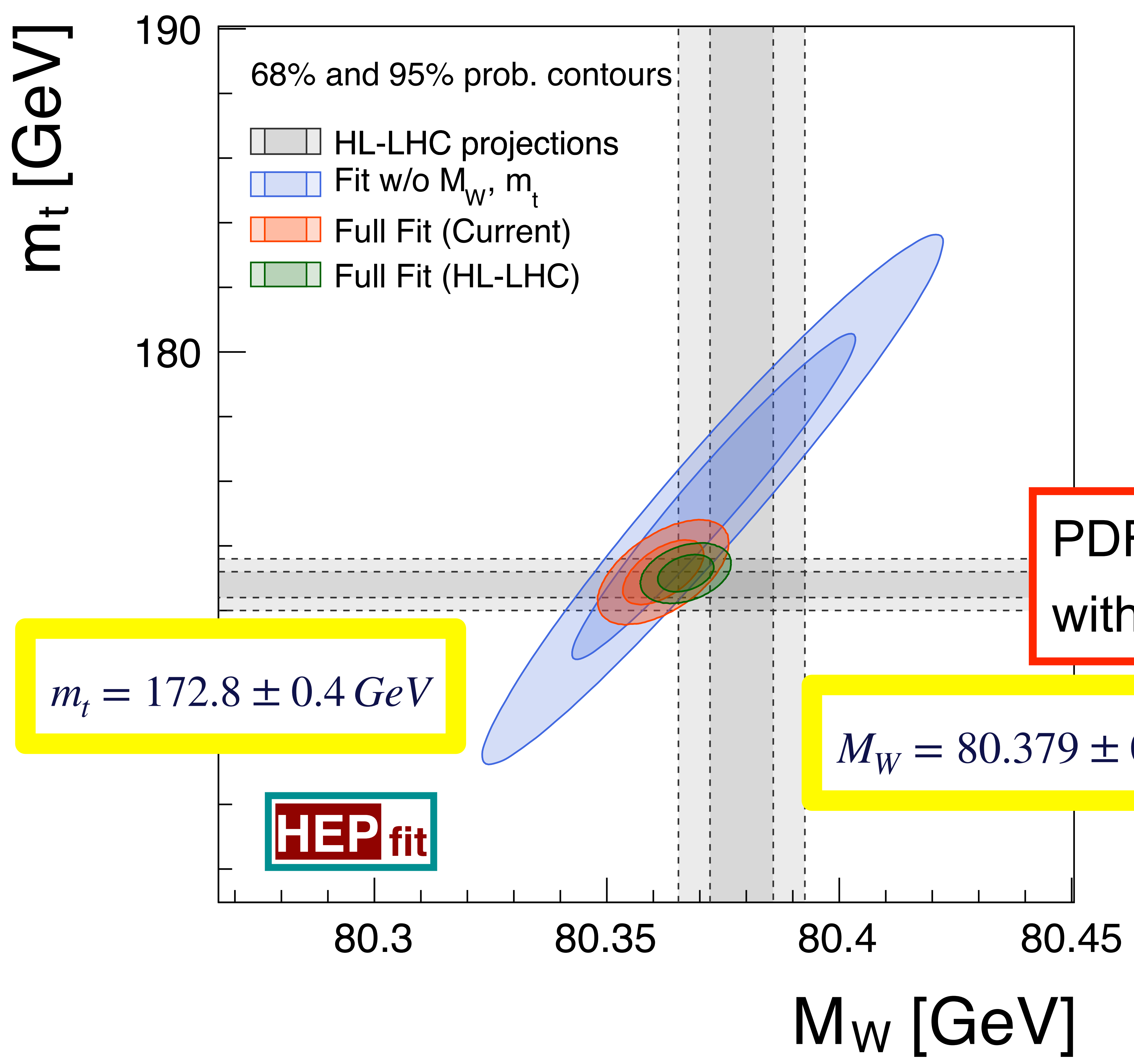
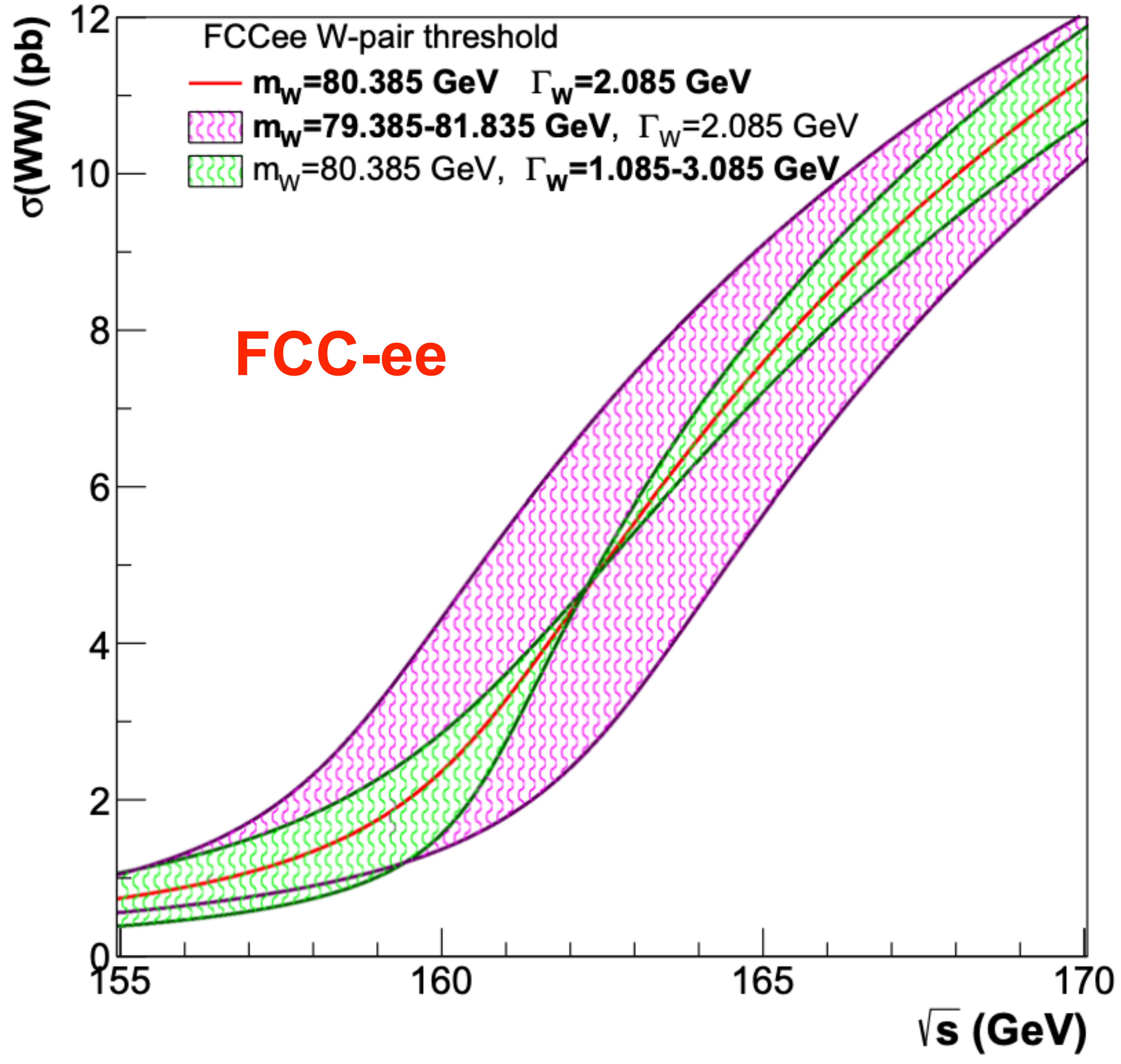
HL-LHC extrapolations



$m_t = 172.8 \pm 0.4\, GeV$

$M_W = 80.379 \pm 0.007\, GeV$

PDF syst on M_W ~2MeV with LHeC PDF set



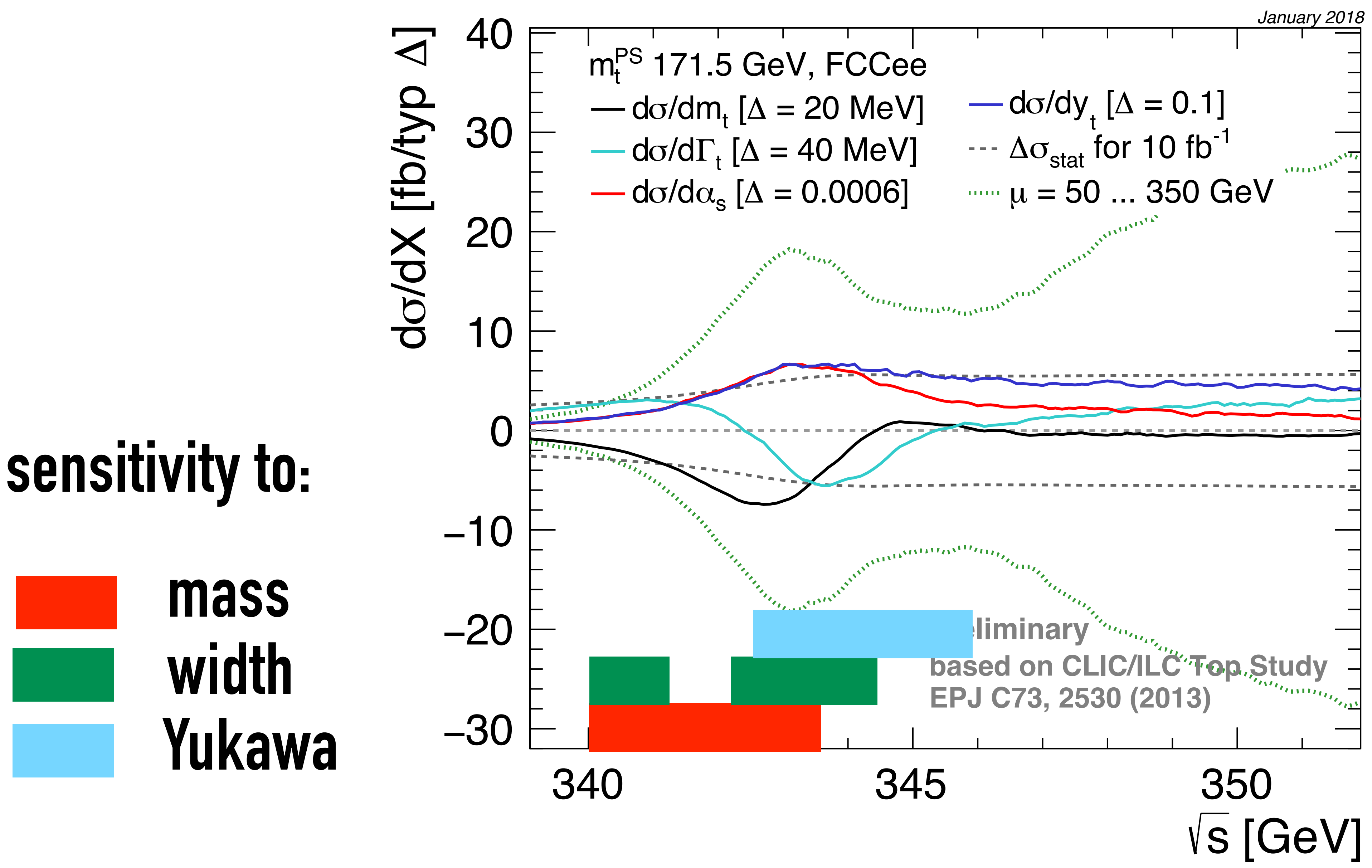
From threshold measurement:
L_{int}=12ab^{-1} E1=157, E2=163
$\Delta M(W) = 0.5 MeV$ & $\Delta\Gamma(W) = 1.2 MeV$

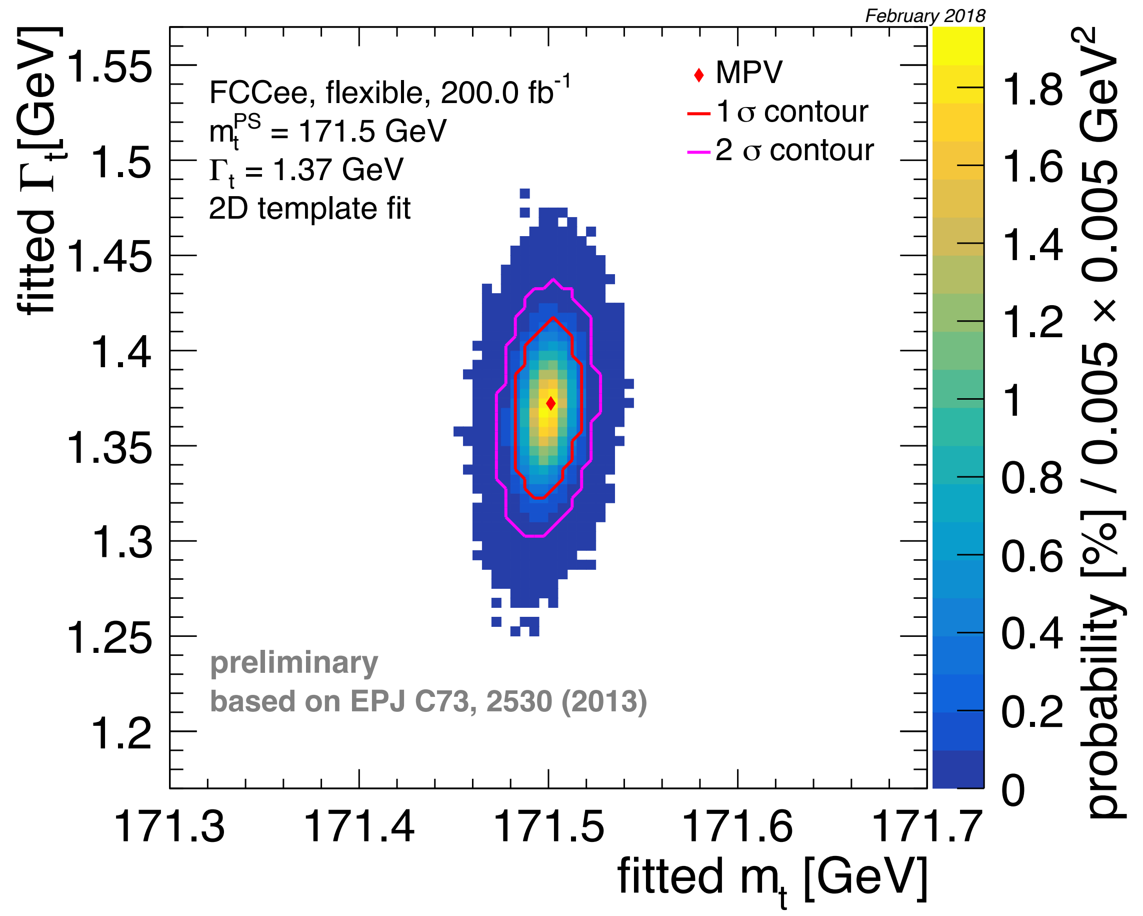
New CMS top mass 171.77 ± 0.38 GeV
New CDF W mass 80433.5 ± 6.4 (stat) ± 6.9 (syst) MeV.

Direct reconstruction of M(W) at other energies (240, 365) similar stat. uncertainty. Different syst.

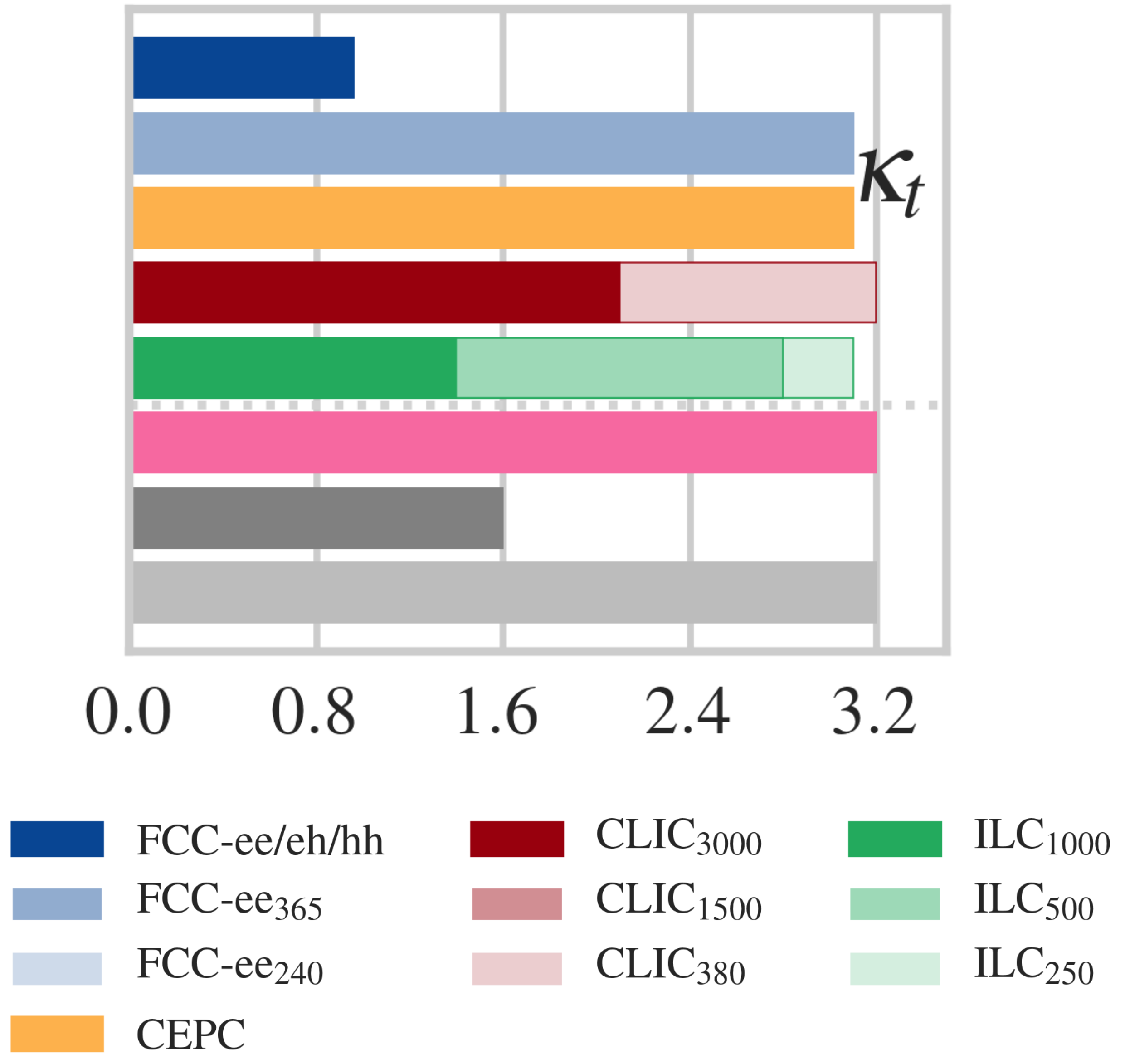
TOP PHYSICS AT FCC-ee

- 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.**

PHYSICS & DETECTOR REQUIREMENTS HIGGS/EW/TOP

M. Dam

"Higgs Factory" Programme

- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

DETECTOR REQUIREMENTS

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of 30%/$\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,...
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale

DETECTOR REQUIREMENTS

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. Γ_{had}/Γ_ℓ) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6}: stability of $\sqrt{s}$ meast.

…are these requirements enough to design our best detector?

FCC-ee AT THE INTENSITY FRONTIER

➤ TeraZ offers four additional pillars to the FCC-ee Higgs/EW/Top physics programme

Flavour physics programme

- Enormous statistics 10^{12} bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs (R_b, $A_{FB}^{b,c}$) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g., $b \to s\tau\tau$

QCD programme

- Enormous statistics with $Z \to \ell\ell$, qq(g)
- Complemented by 100,000 $H \to gg$

1. $\alpha_S(m_Z)$ with per-mil accuracy
2. Quark and gluon fragmentation studies
3. Clean non-perturbative QCD studies

Often statistics-limited
$5. 10^{12}$ Z is a minimum

Tau physics programme

- Enormous statistics: 1.7 10^{11} $\tau\tau$ events
- Clean environment, boost, vertexing
- Much improved measurement of mass, lifetime, BR's

1. τ-based EWPOs (R_τ, A_{FB}^{pol}, P_τ)
2. Lepton universality violation tests
3. PMNS matrix unitarity
4. Light-heavy neutrino mixing

Rare/BSM processes, e.g. Feebly Coupled Particles

Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m_Z

- Signature: long lifetimes (LLP's)
- Other ultra-rare Z (and W) decays

1. Axion-like particles
2. Dark photons
3. Heavy Neutral Leptons

Slide by P. Janot ECFA meeting 19 Nov 2021

FCC-ee AT THE INTENSITY FRONTIER

➤ … which in turn provide specific detector requirements

Flavour physics programme

- Formidable vertexing ability; b, c, s tagging
- Superb electromagnetic energy resolution
- Hadron identification covering the momentum range expected at the Z resonance

QCD + EW programme

- Particle-Flow reconstruction
- Lepton and jet angular and energy resolution ; Lepton ID

More case studies will lead to more detector requirements

Tau physics programme

- Momentum resolution
  Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions
  Lifetime measurement
- Tracker and ECAL granularity and e/μ/π separation
  BR measurements, EWPOs, spectral functions

Rare/BSM processes, e.g. Feebly Coupled Particles

- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity

If all these constraints are met, Higgs and top programme probably OK (tbc)

Slide by P. Janot ECFA meeting 19 Nov 2021

THE INTENSITY FRONTIER - FLAVOR PHYSICS

- Enormous statistics 10^{12} bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs (R_b, $A_{FB}^{b,c}$) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g., b → sττ

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

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

~15 times Belle's stat Boost at the Z!

- **Huge Tau physics program too**
- Much improved measurement of mass, lifetime, BR's, LFV tests
- τ-based EWPOs (R_τ, A_{FB}^{pol}, P_τ)

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)

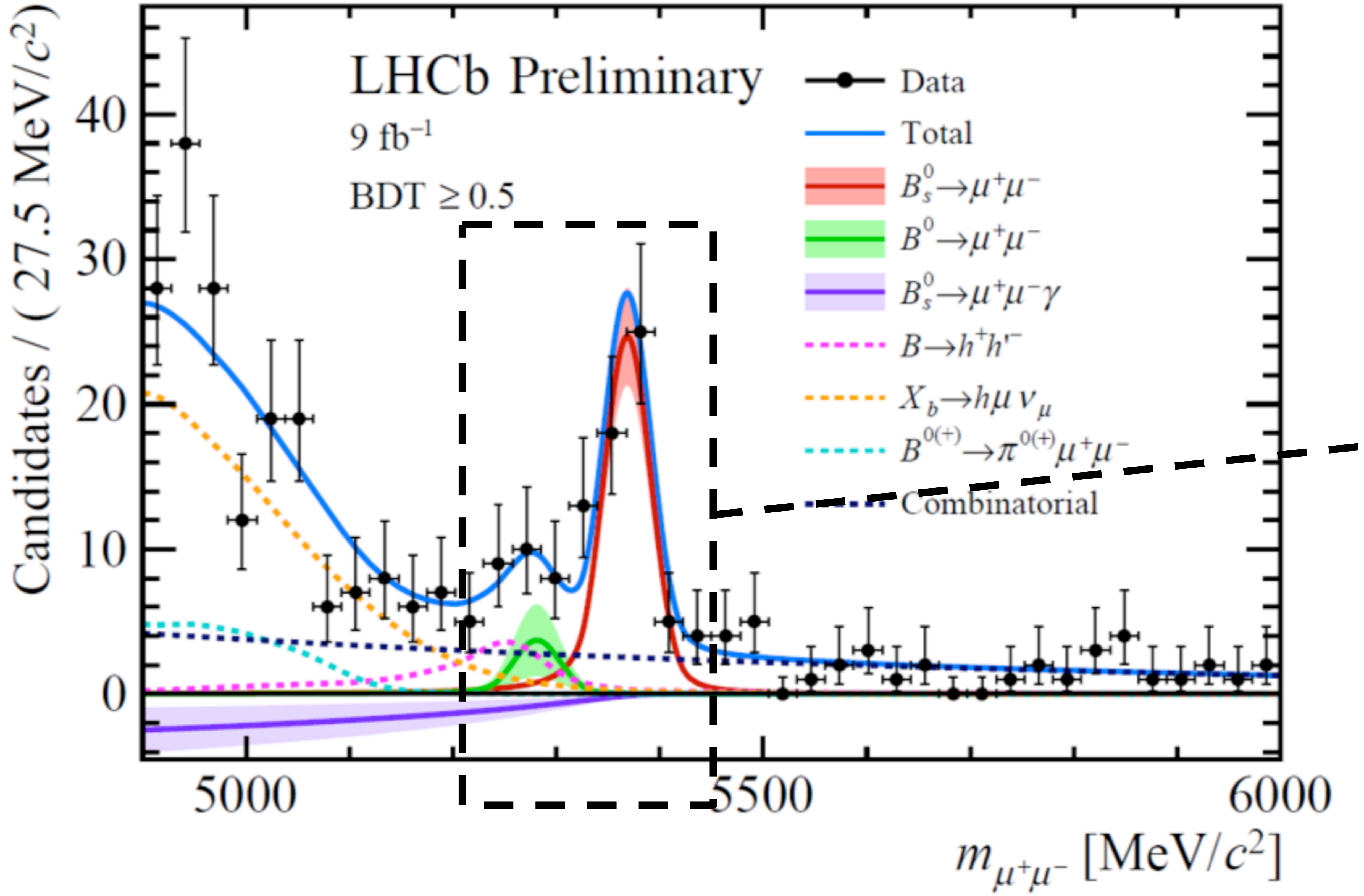
Yelds for flavor anomalies studies:

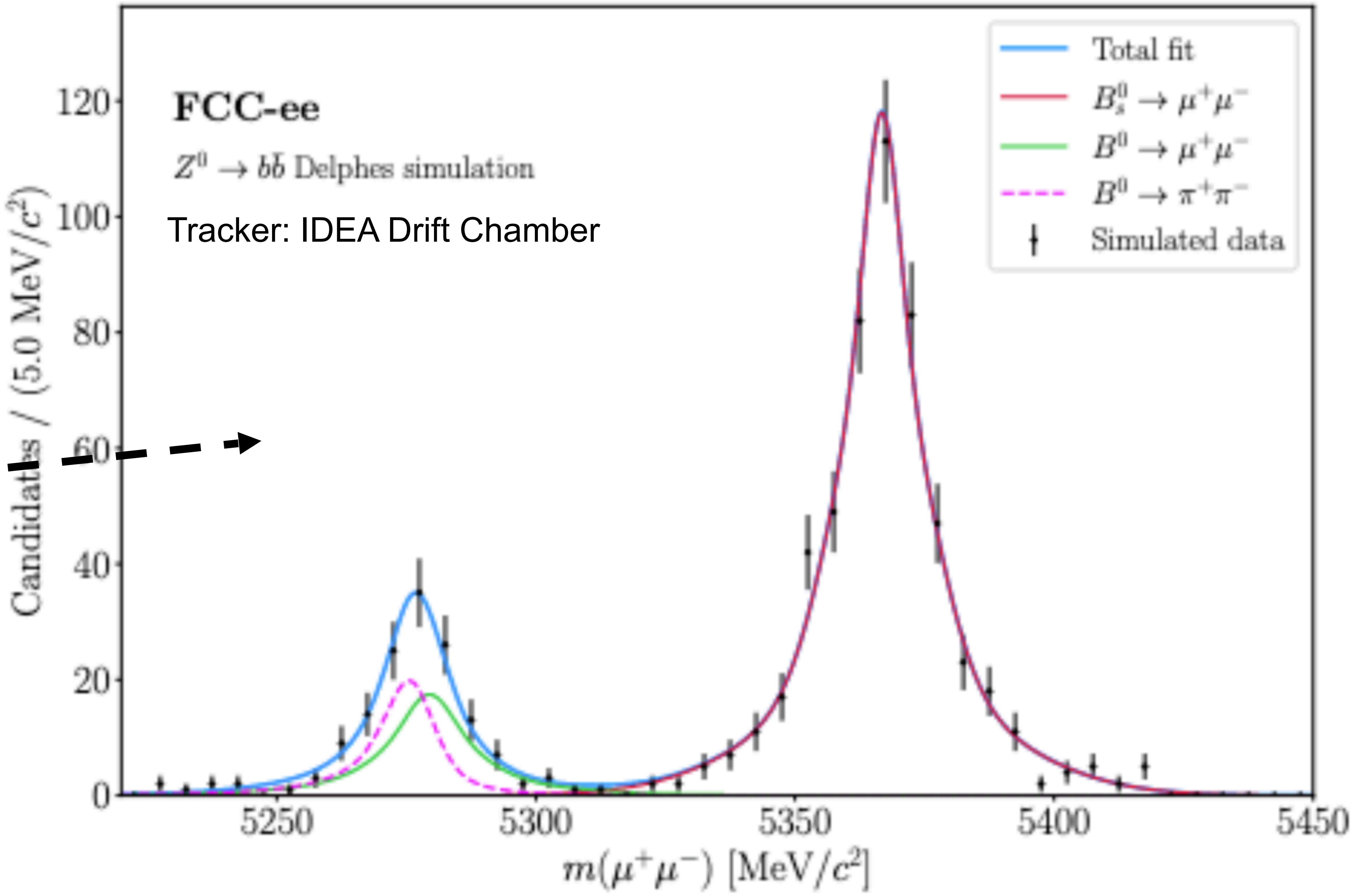
b→sll yelds and $B^0 \to K^{*0}\tau^+\tau^-$ 👍

Full reconstruction possible

INCREDIBLY RICH FLAVOUR PROGRAM

- With 4 IPs, and five years at $\sqrt{s}$ = 91.2 GeV
- Even the $B_{s,d} \to \mu\mu$ sample would be of the same size as that of LHCb Upgrade 2
  - But much better resolved (tracking performance) : more sensitivity to New Physics.





patrizia azzi -15 March 2023

BSM PHYSICS: RARE PROCESSES, FIP

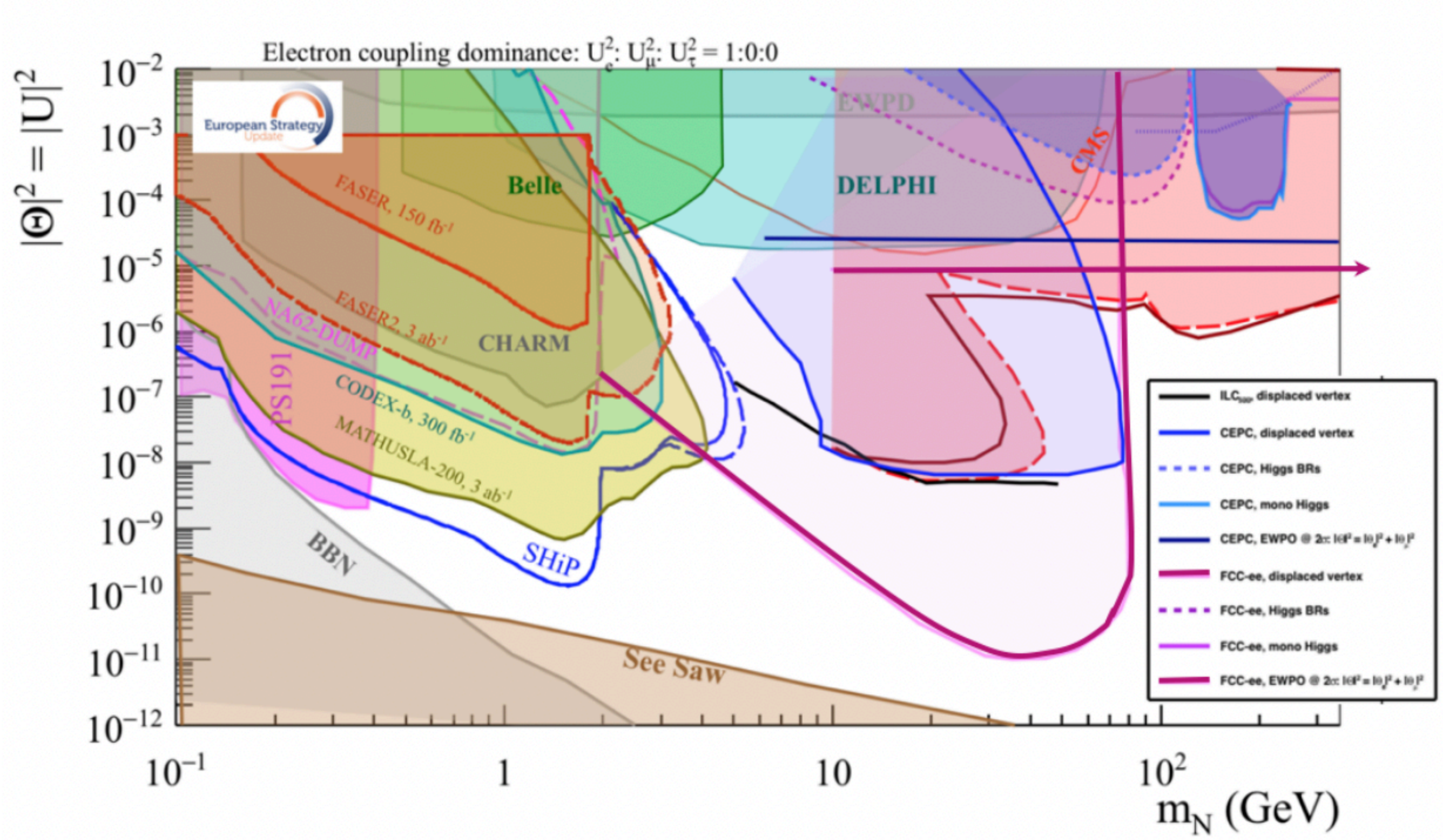
- Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m(Z)
  - Axion-like particles
  - Dark photons
  - Heavy Neutral Leptons
- Exploiting unusual signatures (hard for the HL-LHC), LLP and more

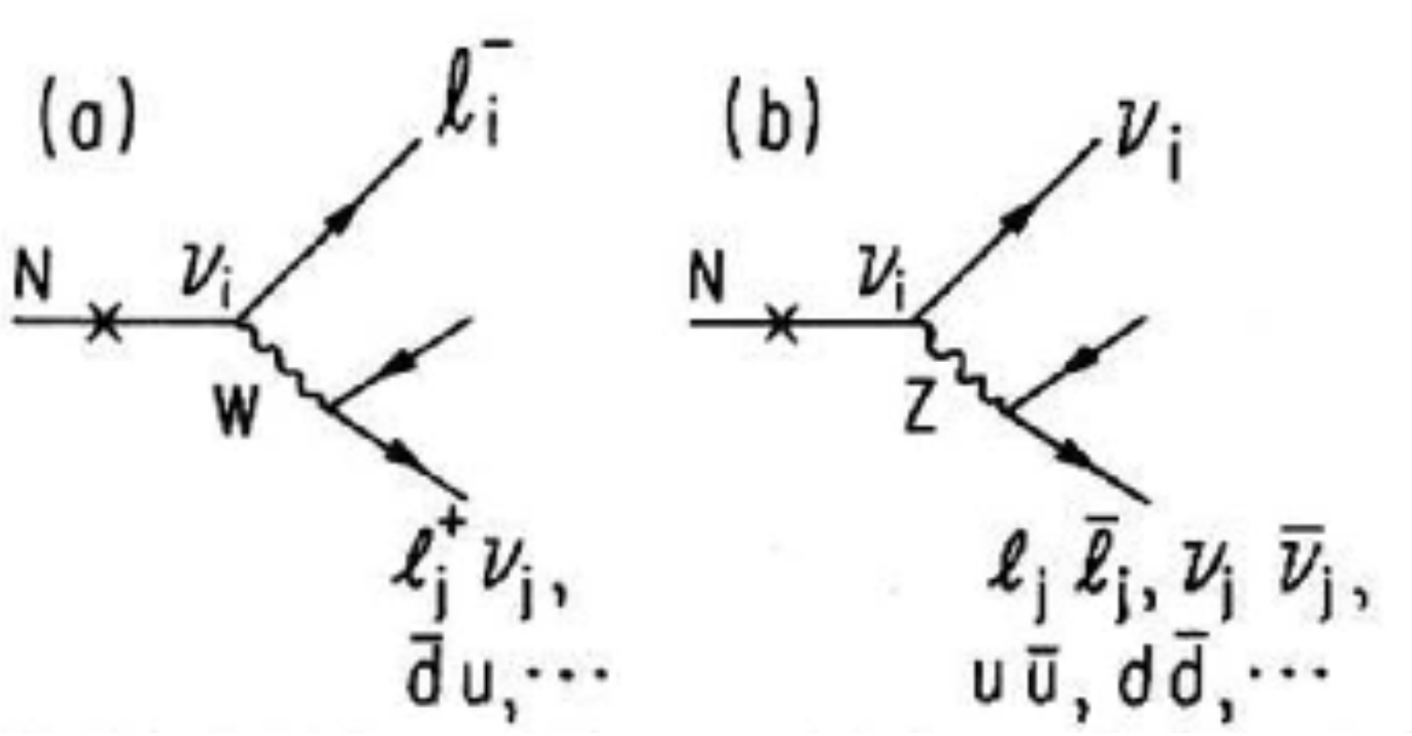
Detector Requirements

- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity

BSM DIRECT SEARCHES - HEAVY NEUTRAL LEPTONS

- Test minimal type I seesaw hypotesis
- Together with ΔM also tests the compatibility with leptogenesis





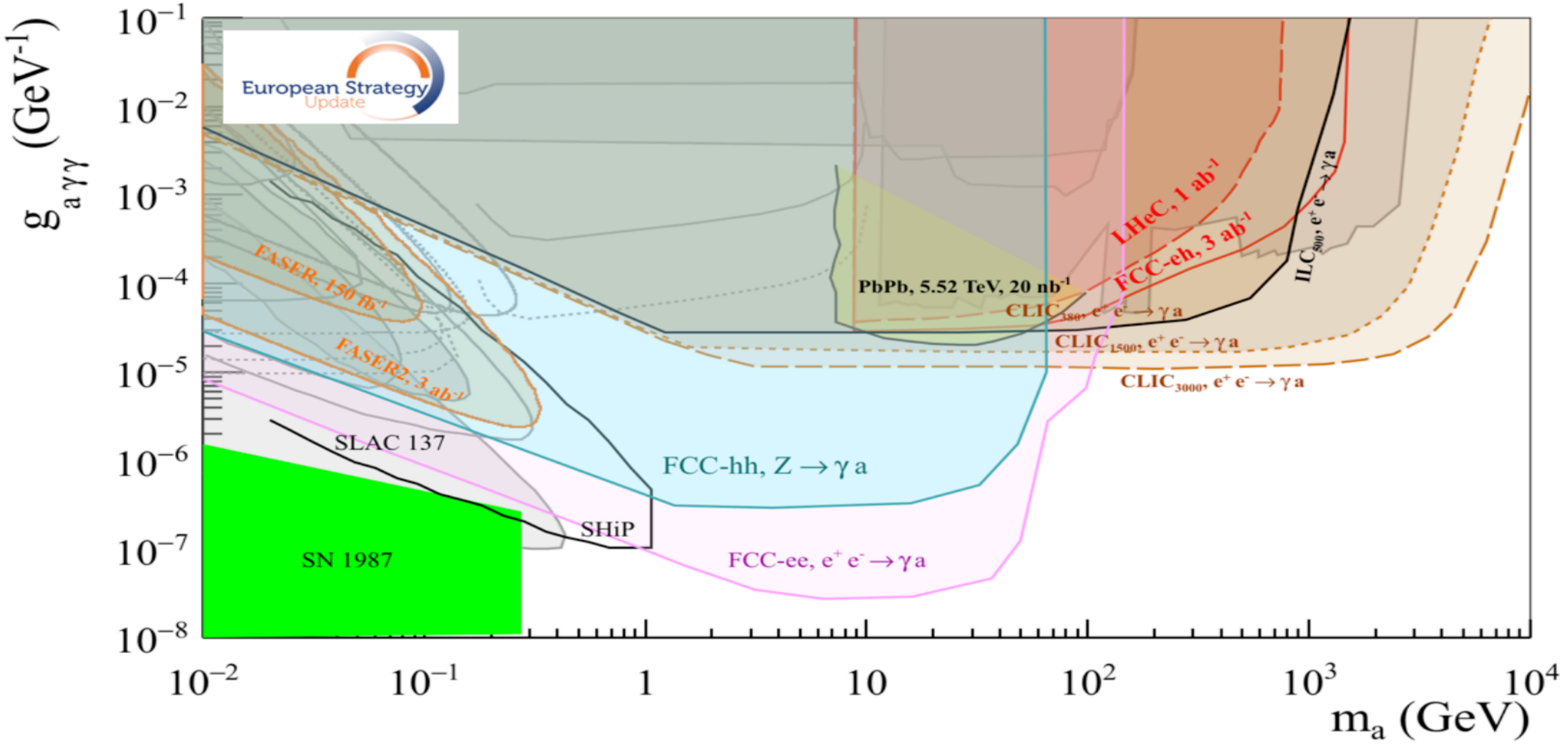
$$L \sim \frac{3\,[cm]}{|U|^2 . (m_N [GeV]\,)^6}$$

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

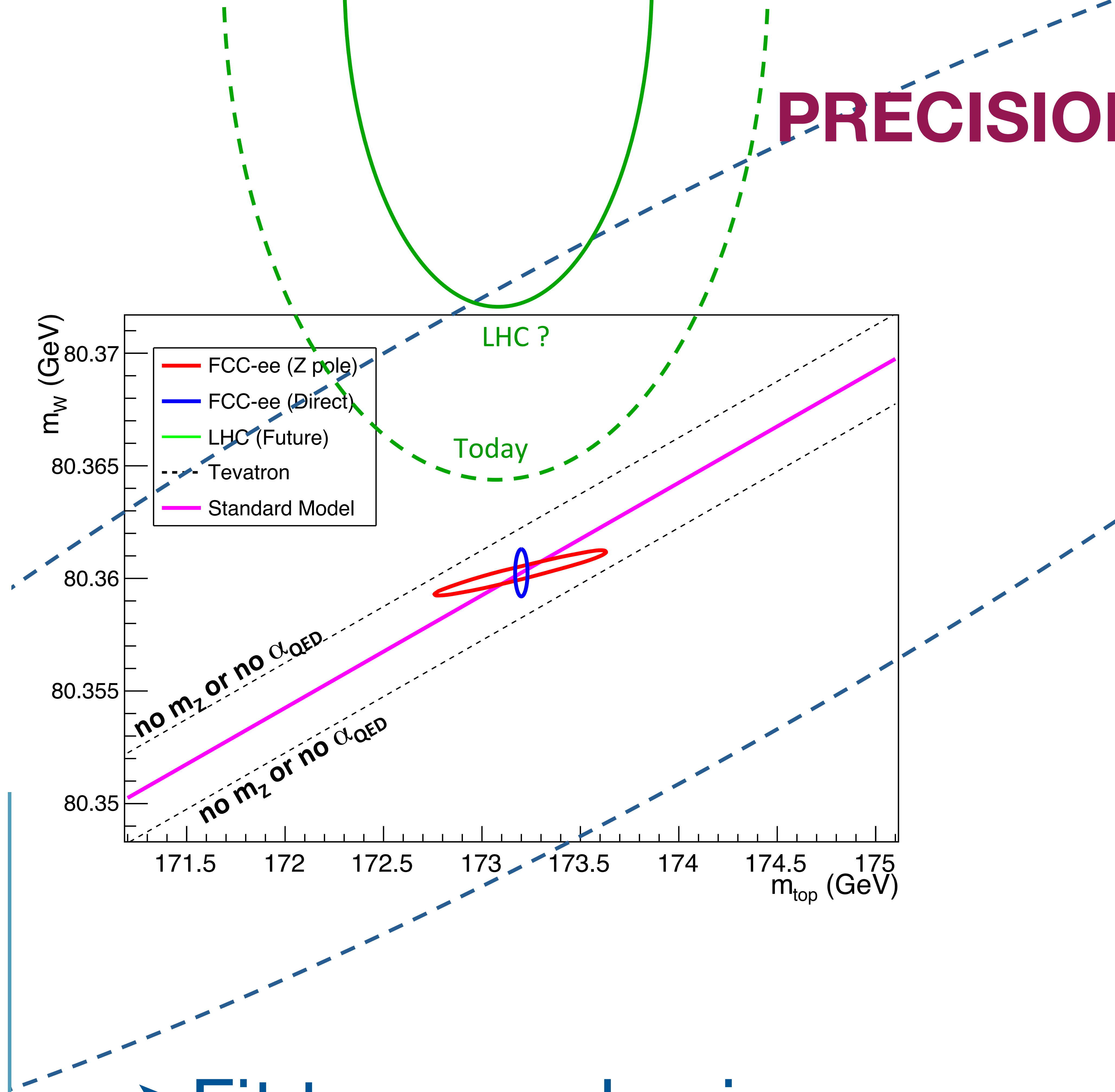
From EPPSU BriefingBook 2019

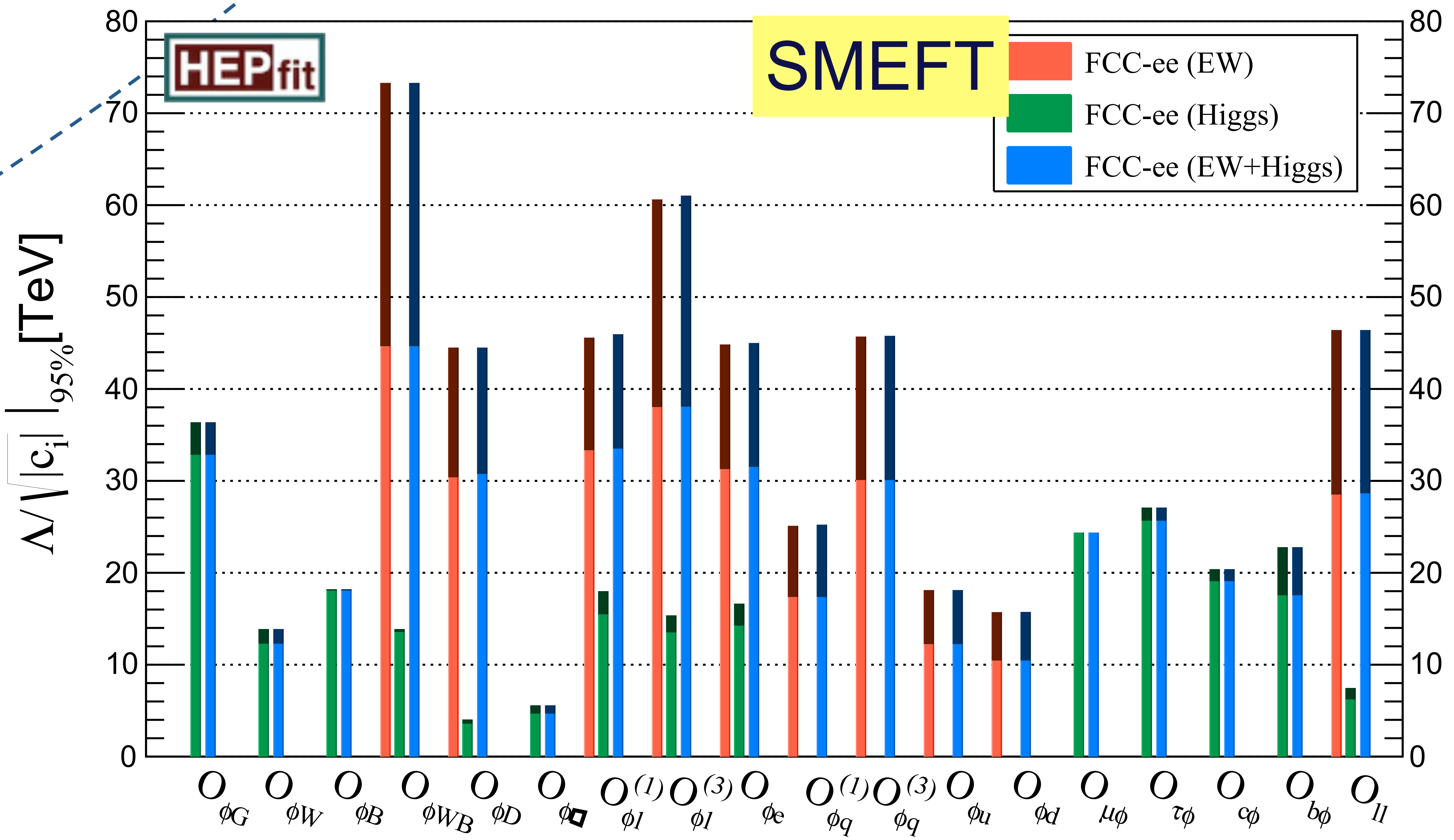
BSM DIRECT SEARCHES - ALPS

- ➤ Similar situation for Axion-like-particles: luminosity is key to the game
- ➤ Complementarity with high energy lepton collider
- ➤ Fertile ground for development of innovative detector ideas: requirements on calorimeter (photon separation) and more…



PRECISION: INDIRECT SENSITIVITY FOR NEW PHYSICS





- ➤Fit to new physics effects parameterized by dim 6 SMEFT operators

Points to the physics to be studied with FCC-hh

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} $t \to W \to \tau$

➡rare decays τ->3μ, μγ, CPV

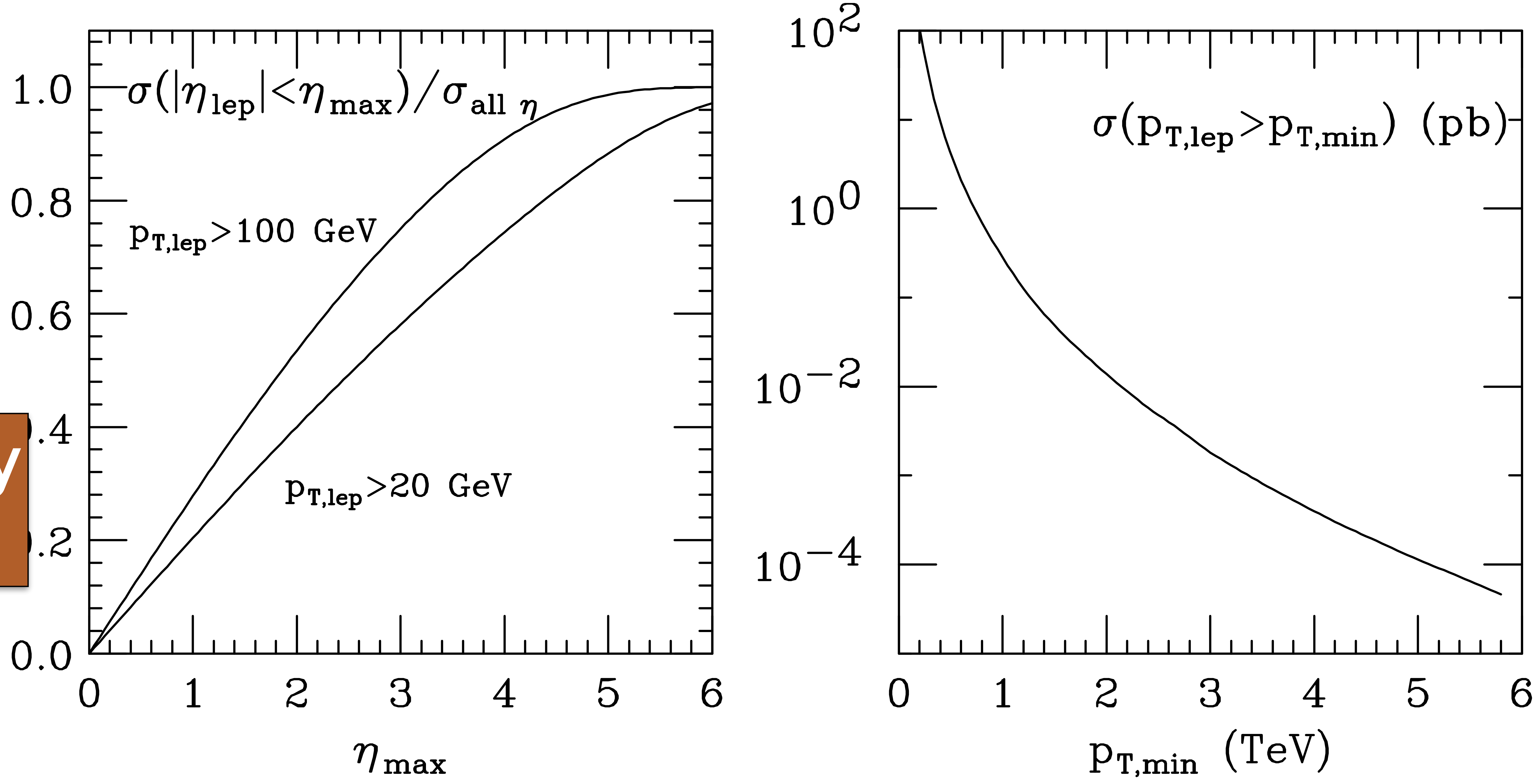
  - few $10^{11} t \to W \to charm\ hadrons$

➡rare decays D->$\mu^+\mu^-$,… CPV

Amazing potential, extreme detector and reconstruction challenges

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}.

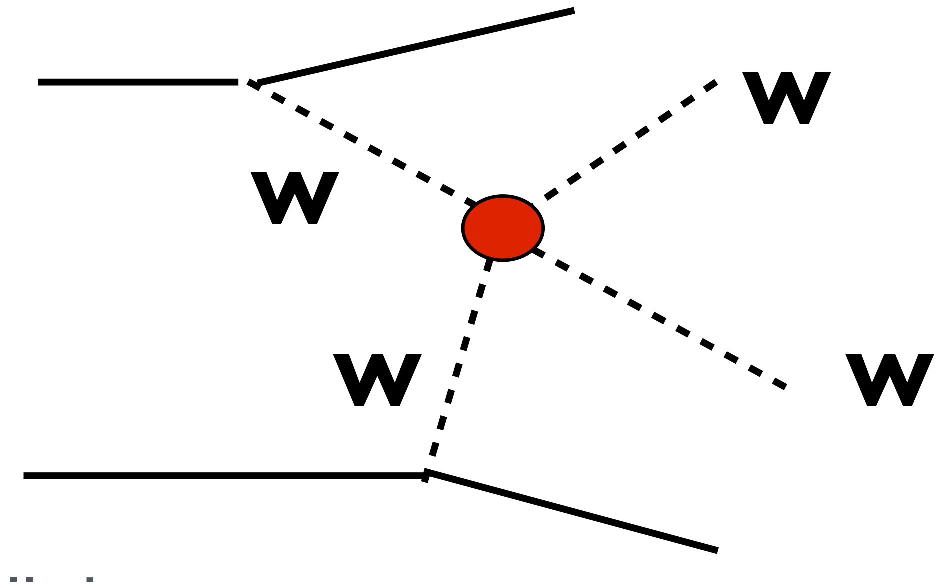


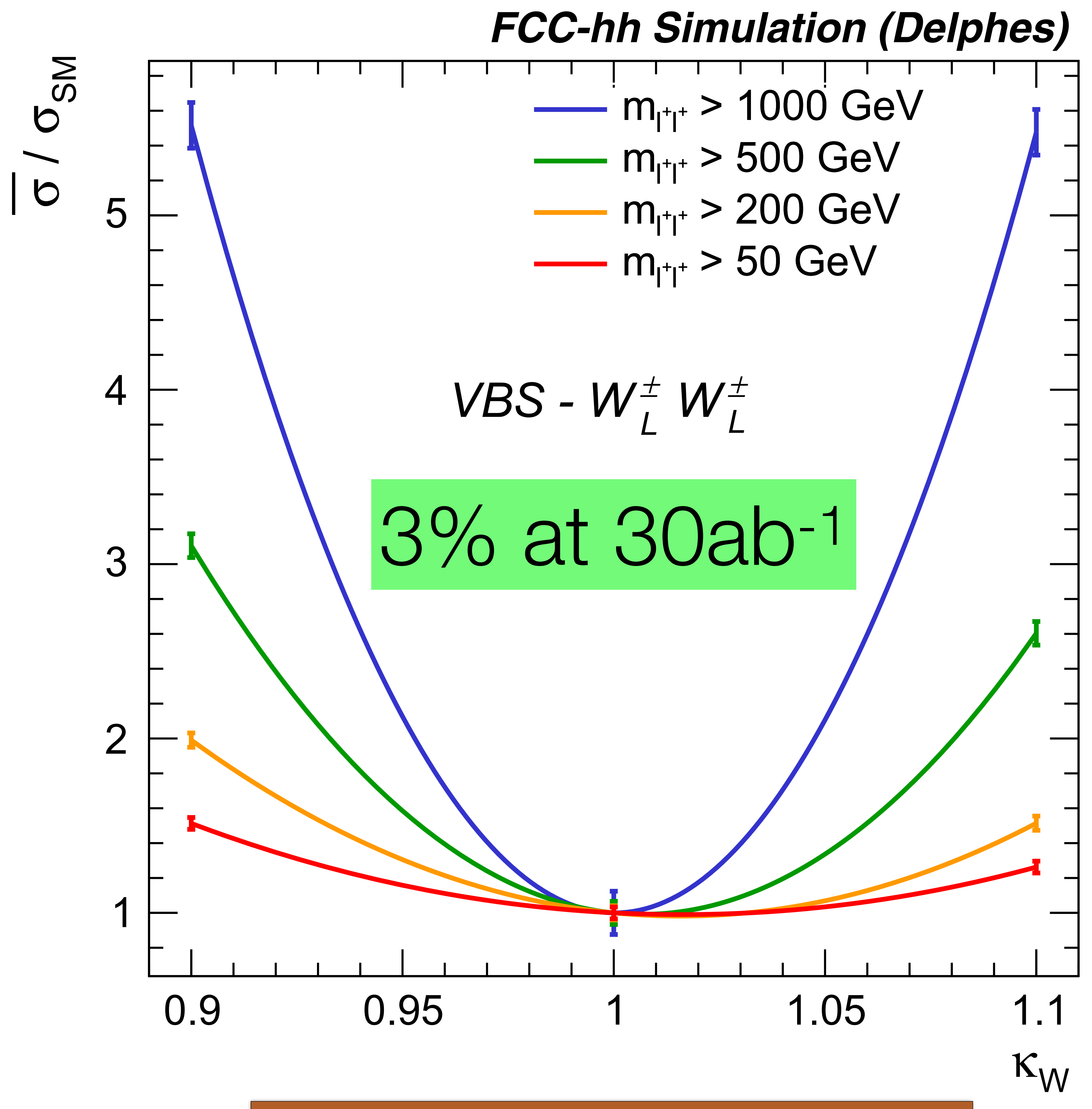
large rapidity distribution!

large p_T

VECTOR BOSON SCATTERING AT HL-LHC & FCC-HH

Process	$W^{\pm}W^{\pm}$	WZ	WV	ZZ
Final state	$\ell^{\pm}\ell^{\pm}$jj	3ℓjj	ℓjjjj	4ℓjj
Precision	6%	6%	6.5%	10–40%
Significance	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$



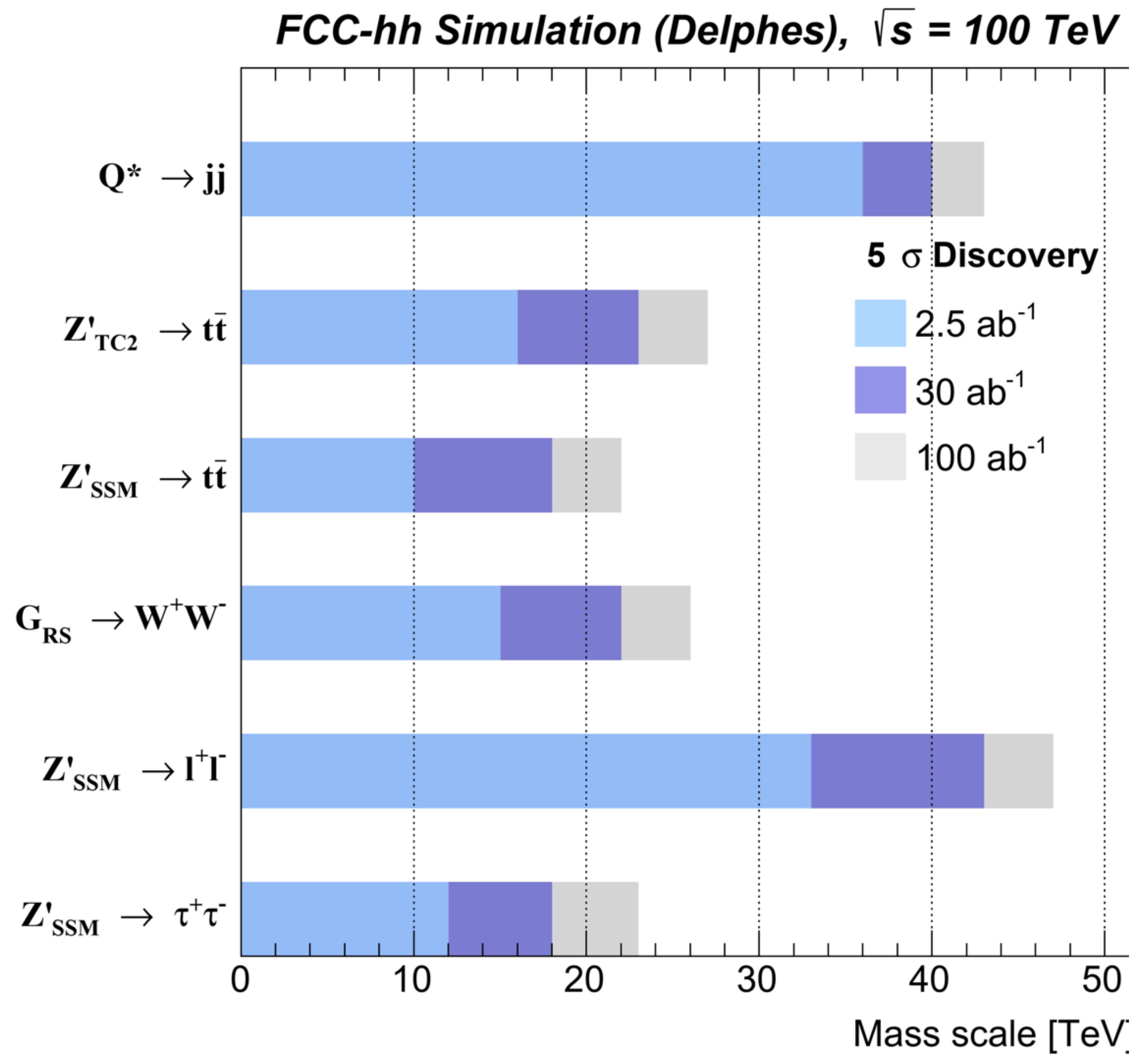


Longitudinal component extracted from angular distribution of the two leptons

- VV production is sensitive to anomalous EWK couplings and effects from new physics at higher scales
  - At HL-LHC 3σ evidence for longitudinal polarization component $V_L V_L$ can be achieved combining channels and experiments
  - At FCC-hh reaching a 3% precision with 30ab^{-1}

FCC-hh DIRECT 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

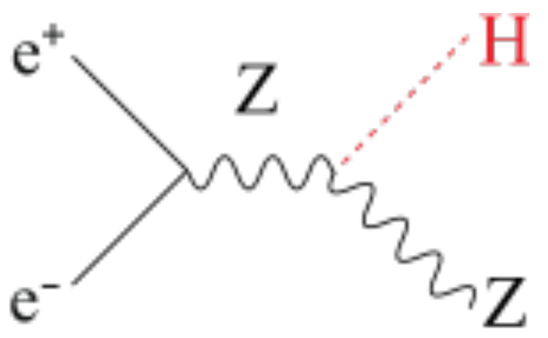


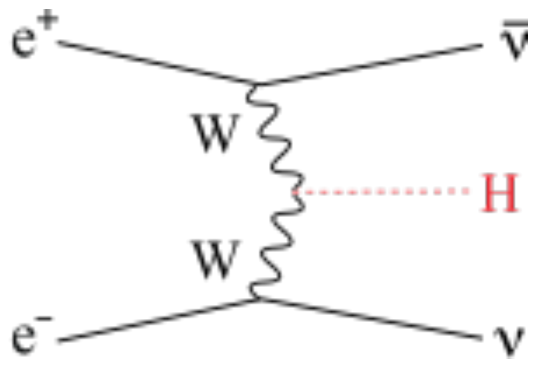
about x6 LHC mass reach at high mass, well matched to reveal the origin of deviations indirectly detected at the FCC-ee

FCC SYNERGIES: 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

$\sqrt{s}$ = 240 GeV





$\sqrt{s}$ = 365 GeV

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

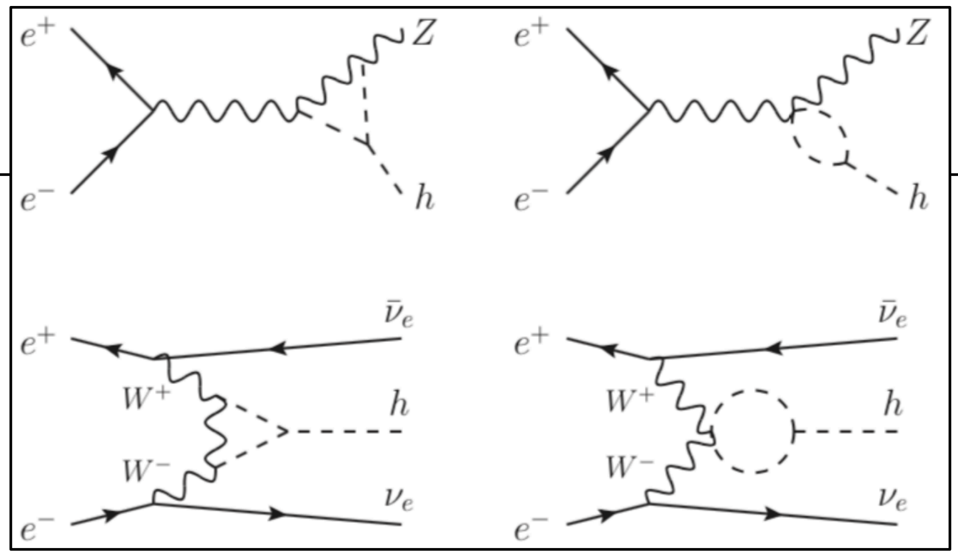
Absolute determination of g_{HZZ} to ±0.17%

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)**



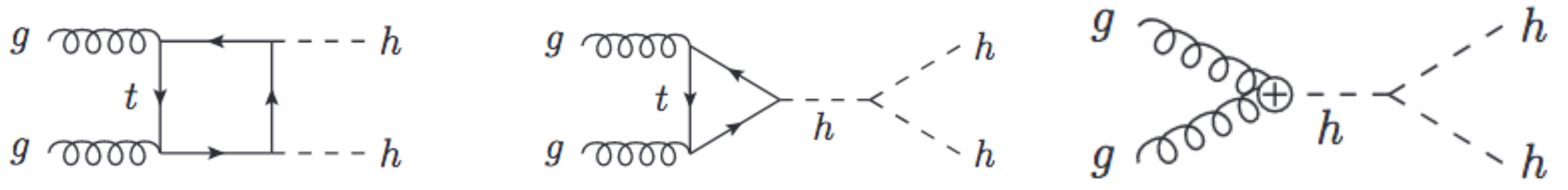
FCC-hh provides 3×10^{10} Higgs bosons

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

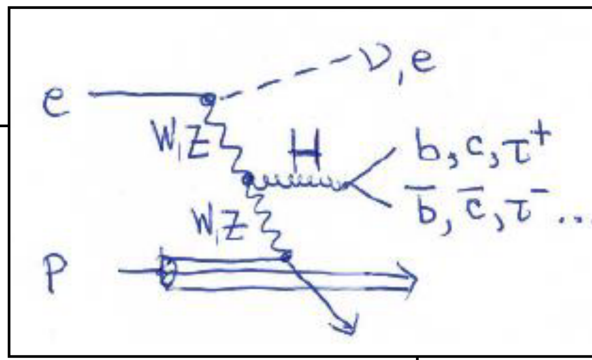
→ **Rare decays: couplings to μμ, γγ, Zγ …**

→ **Higgs self coupling g_{HHH} to ±3%**
With double-Higgs production



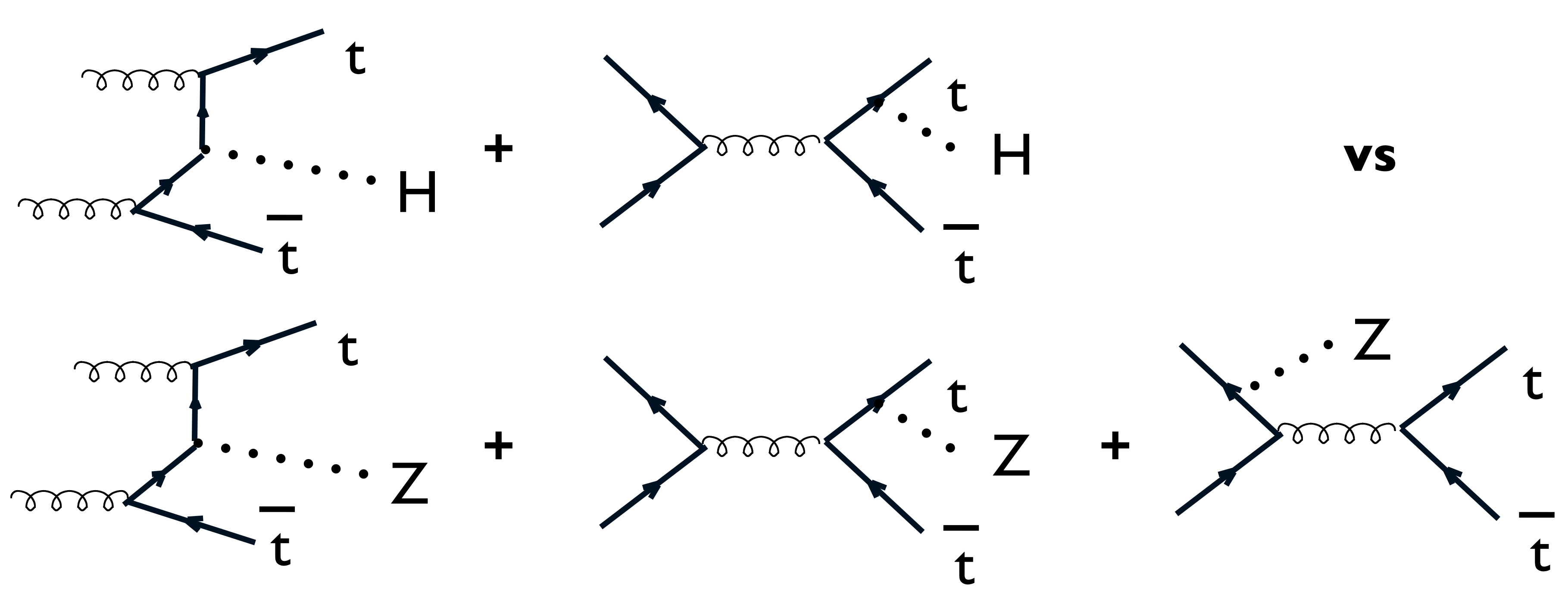
FCC-eh provides 2.5 10^6 Higgs bosons

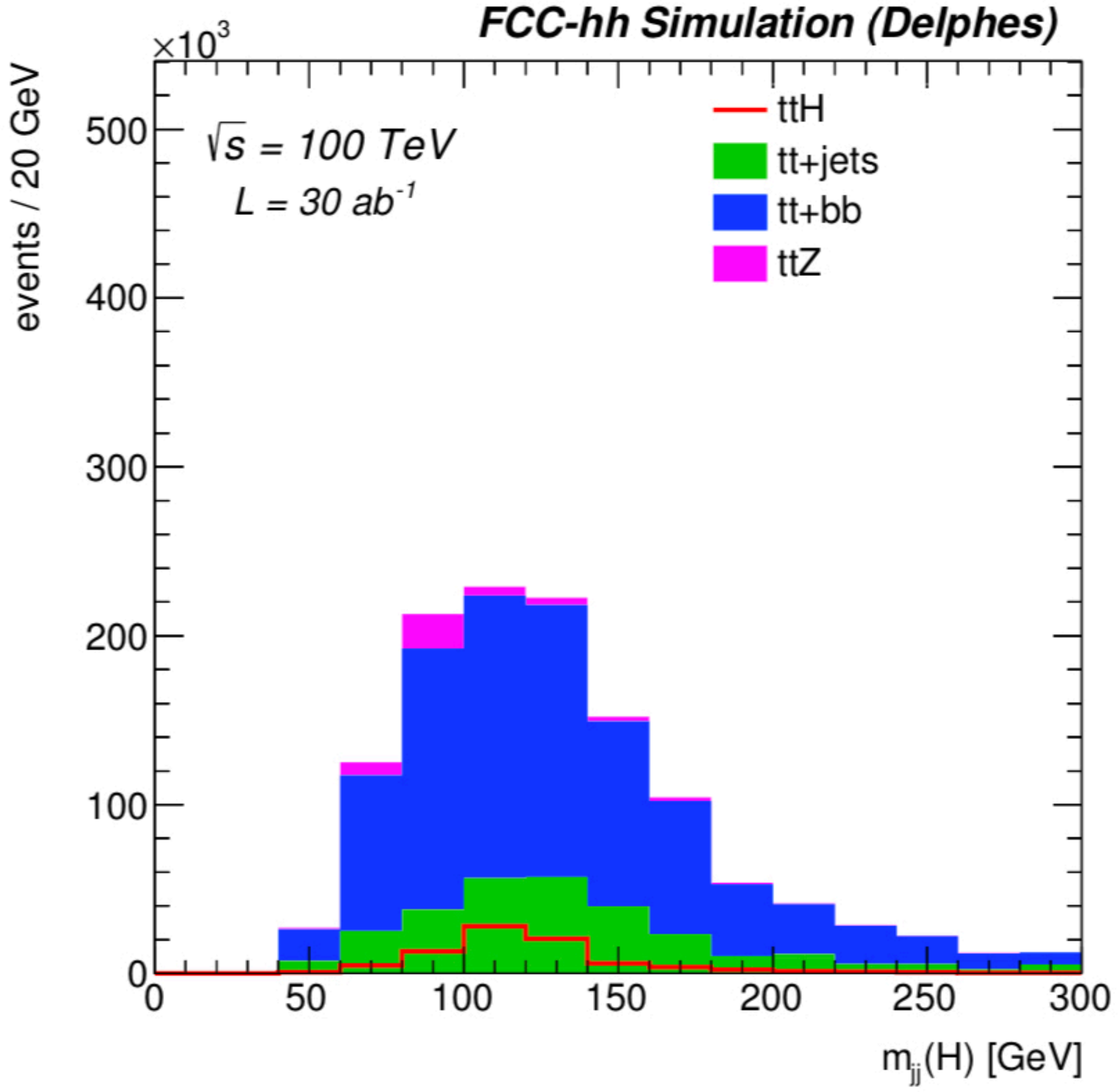
With the FCC-ee candle, further improves on several measurements (e.g., g_{HWW})

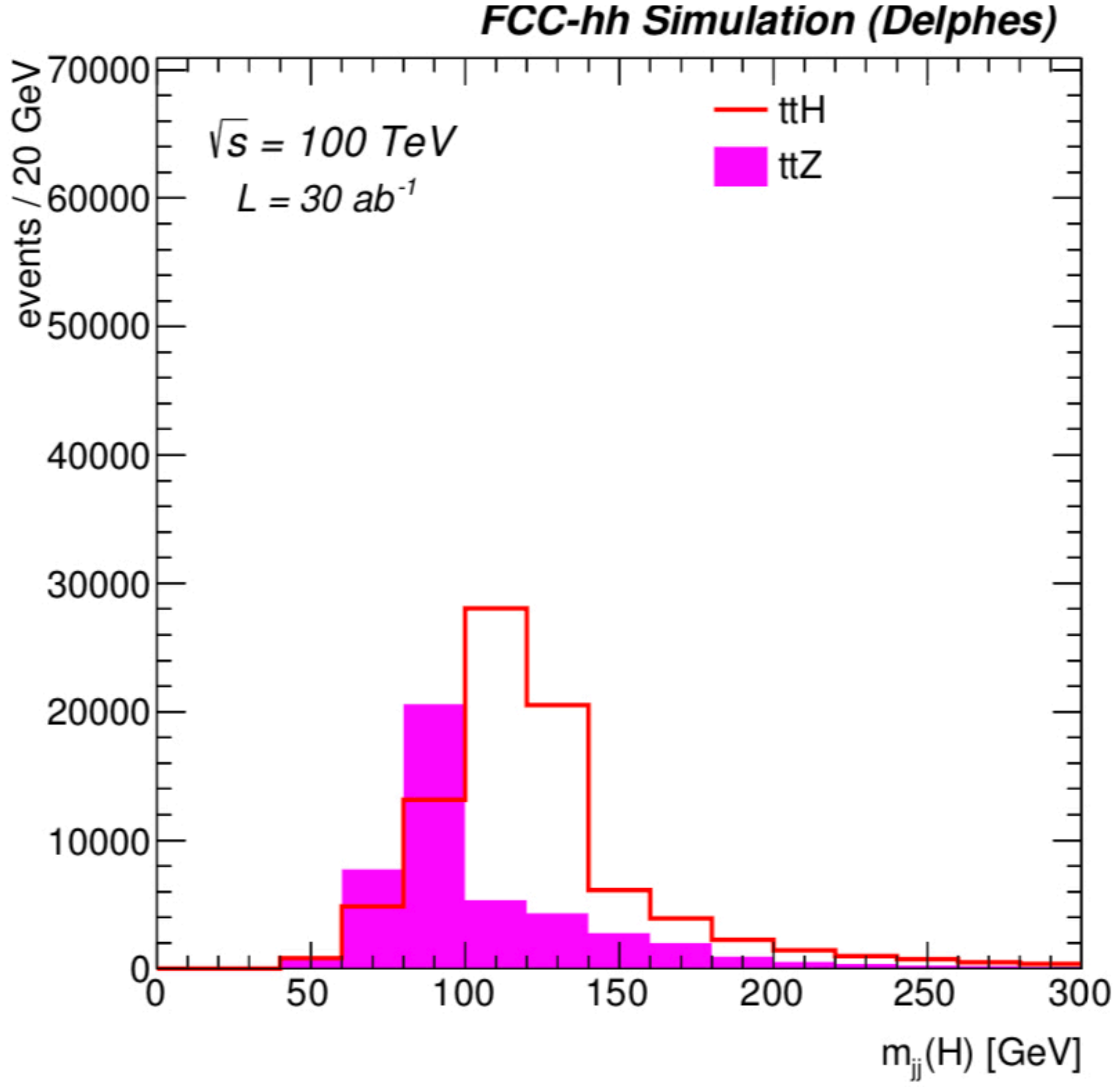


FCC SYNERGIES: TOP - YUKAWA COUPLING

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



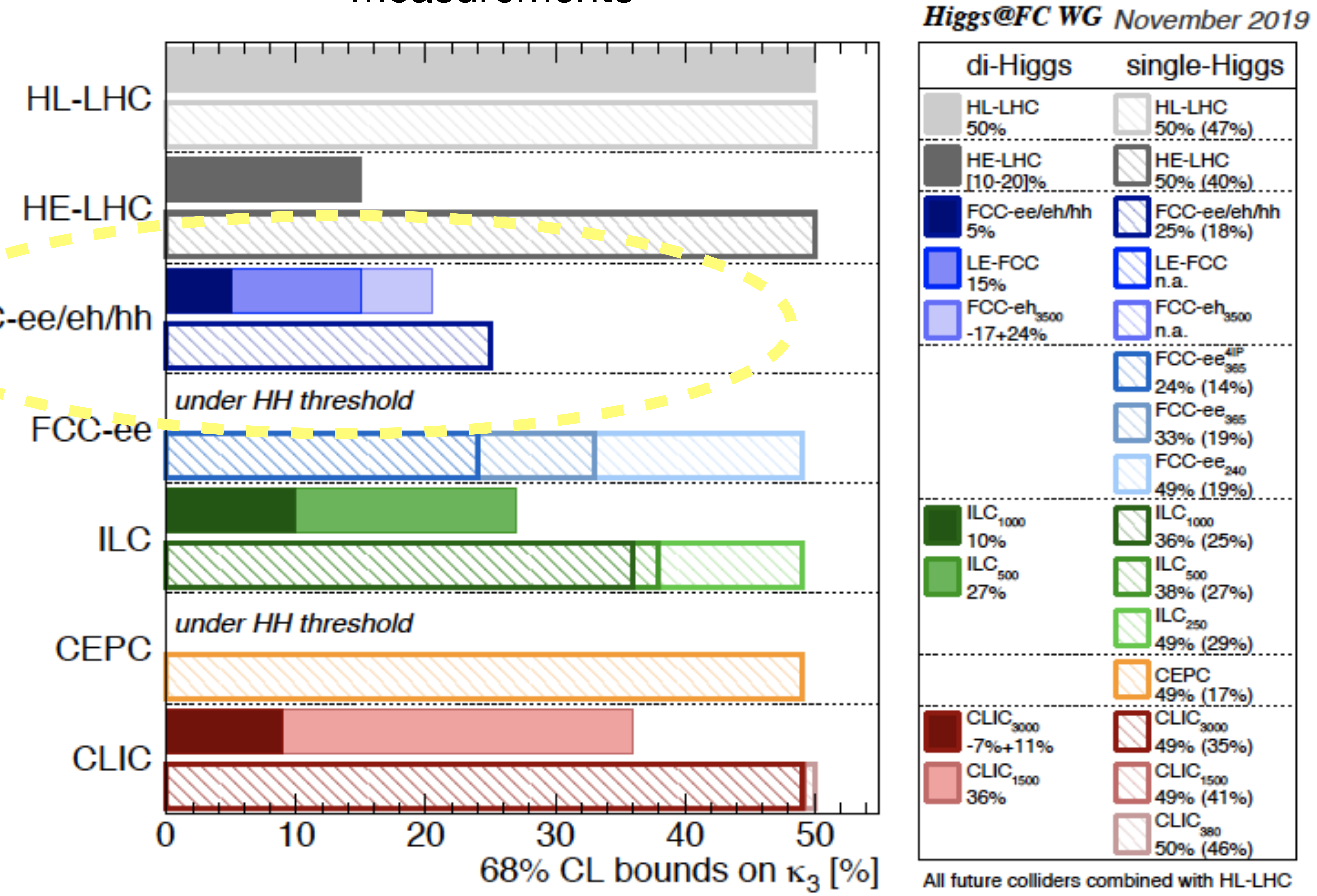




- Use the ratio of $\sigma(ttH)/\sigma(ttZ)$ to cancel many theory uncertainties
- Profit of similar dynamics (QCD Correction, scale, alphas syst.) and kinematical boundaries ($m_Z \simeq m_H$)
- Analysis using boosted $H/Z \to b\bar{b}$ decays (Delphes)
- $\Delta y_t / y_t \approx 1\,\%$ using ttZ EW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

FCC SYNERGIES: TRIPLE HIGGS COUPLING

Projected precision of λ3 measurements

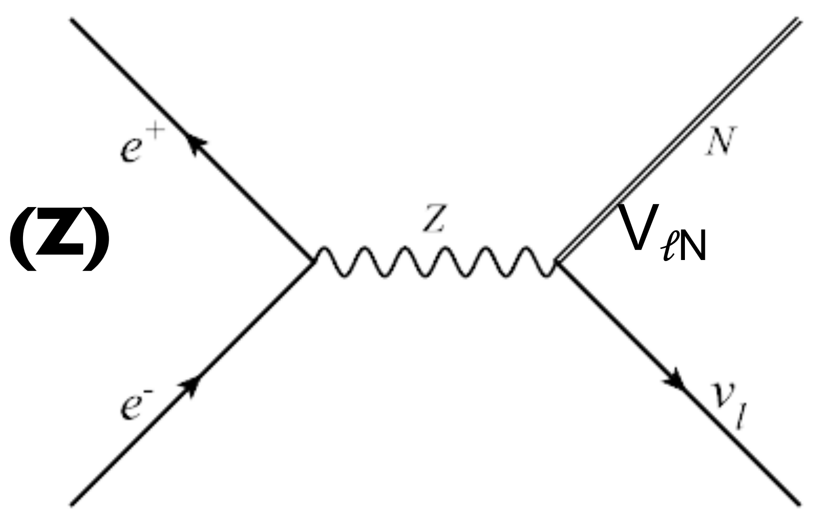


FCC integrated program will measure λ_3 to the "few"% level

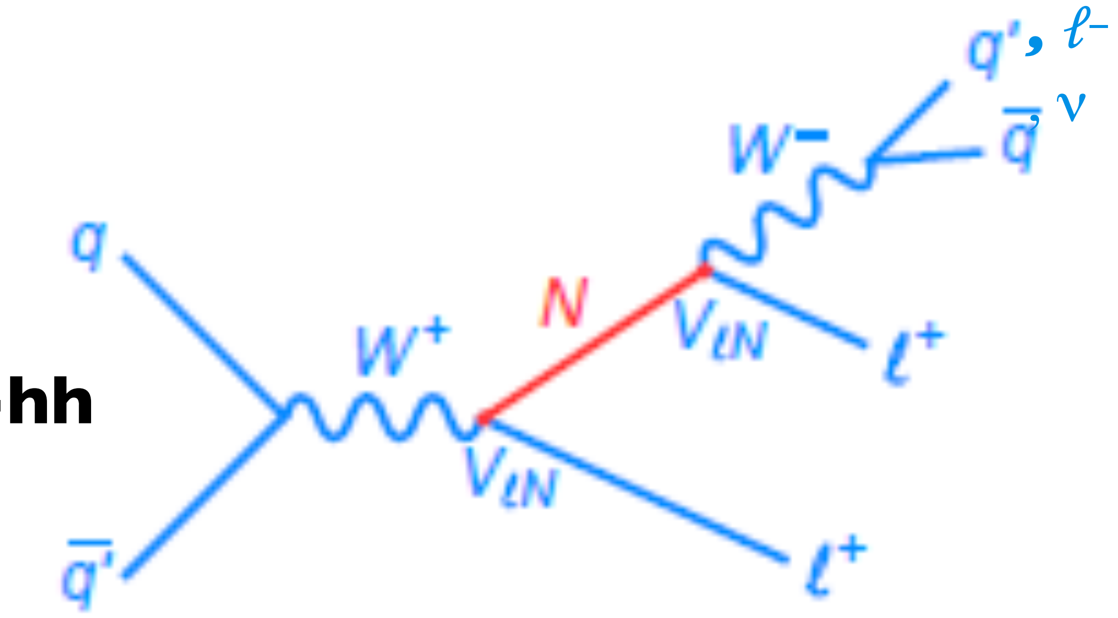
FCC SYNERGIES: FEEBLY INTERACTING PARTICLES

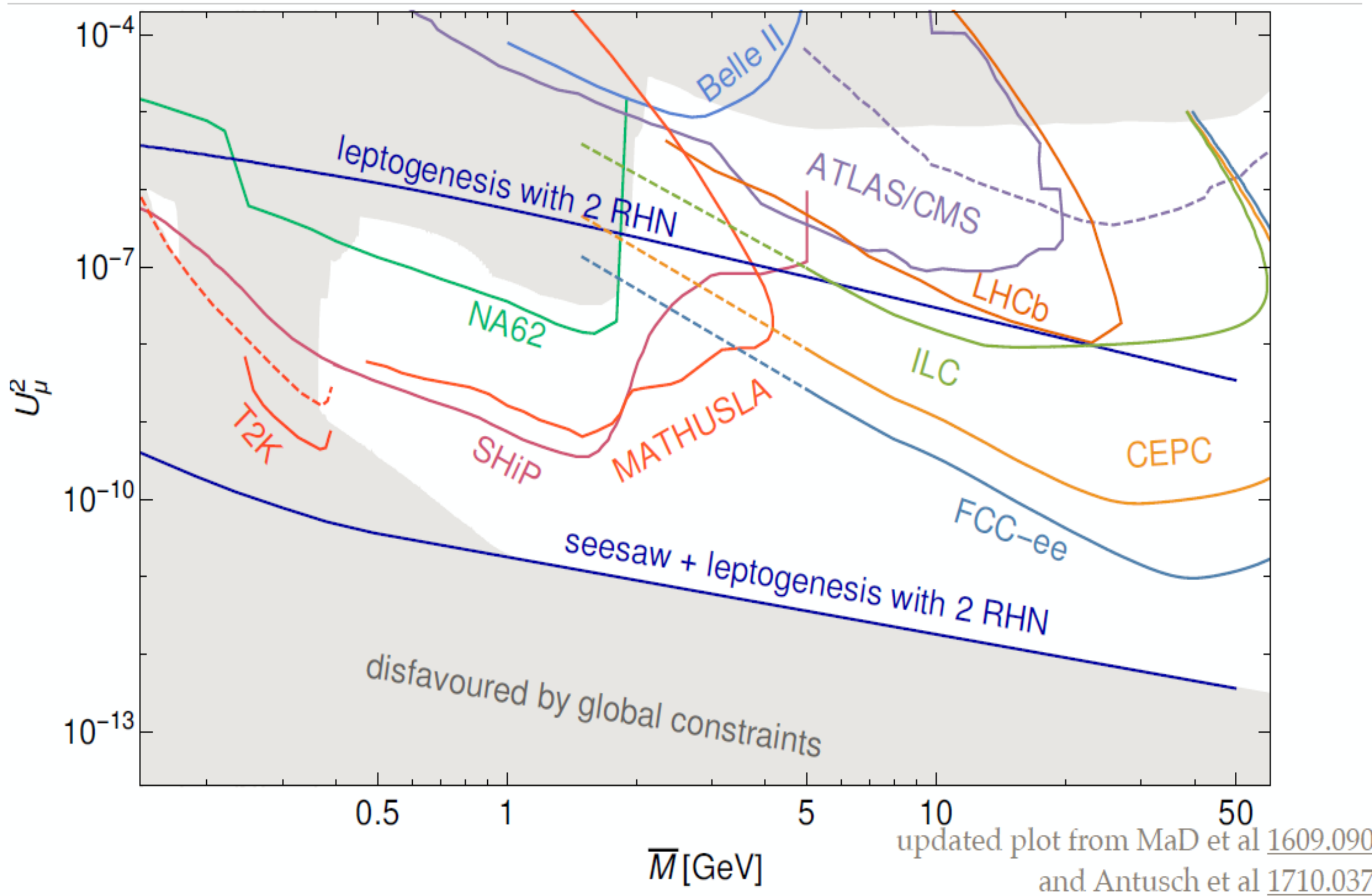
- ➤ Heavy Right-Handed Neutrinos
  - ➤ Complete SM spectrum – and perhaps explain DM, BAU, ν masses

FCC-ee (Z)



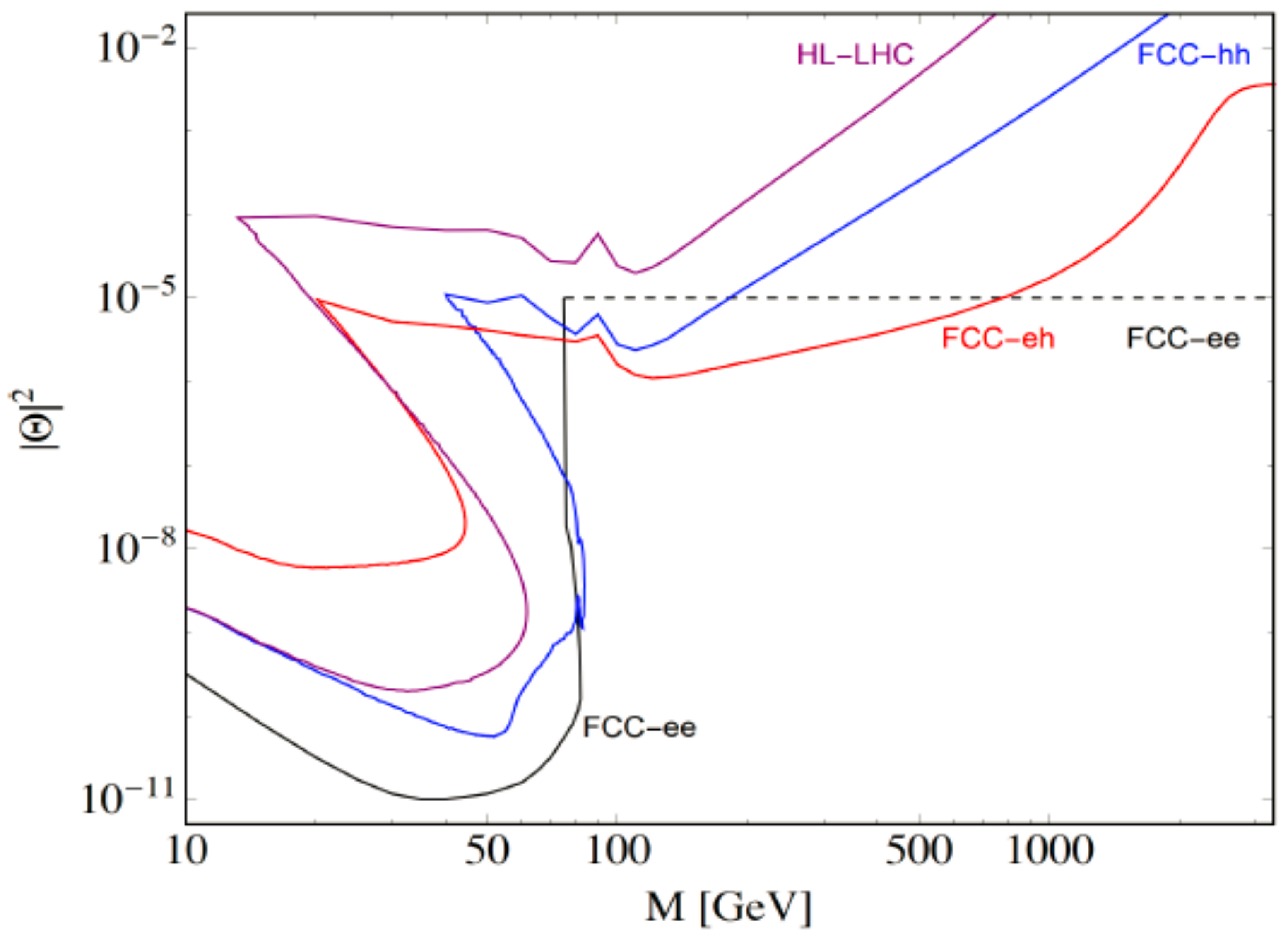
FCC-hh





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: ~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 $V_{\ell 1N} V_{\ell 2N}$ 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**



FCC

FEASIBILITY STUDY LAUNCHED IN 2021

- Case made by the European Strategy, updated by CERN Council in 2020

An electron-positron Higgs factory is the highest priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.

https://cds.cern.ch/record/2721370/

- That's the exact description of FCC
  - FCC-ee is an electron-positron Higgs factory
  - FCC-hh is a proton-proton collider at the highest achievable energy
- The ee → hh sequence (FCC-INT) optimizes the overall investment and its science value
  - Synergistic infrastructure (and related carbon footprint) and advantageous funding profile
  - Time flexibility for R&D towards affordable 16-20T dipole magnet technology
  - Best route towards a 100 TeV hadron collider (see https://arxiv.org/abs/1906.02693)
  - Fundamental physics complementarity/synergy

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. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

Feasibility Study approved by the Council in June 2021: https://cds.cern.ch/record/2774006

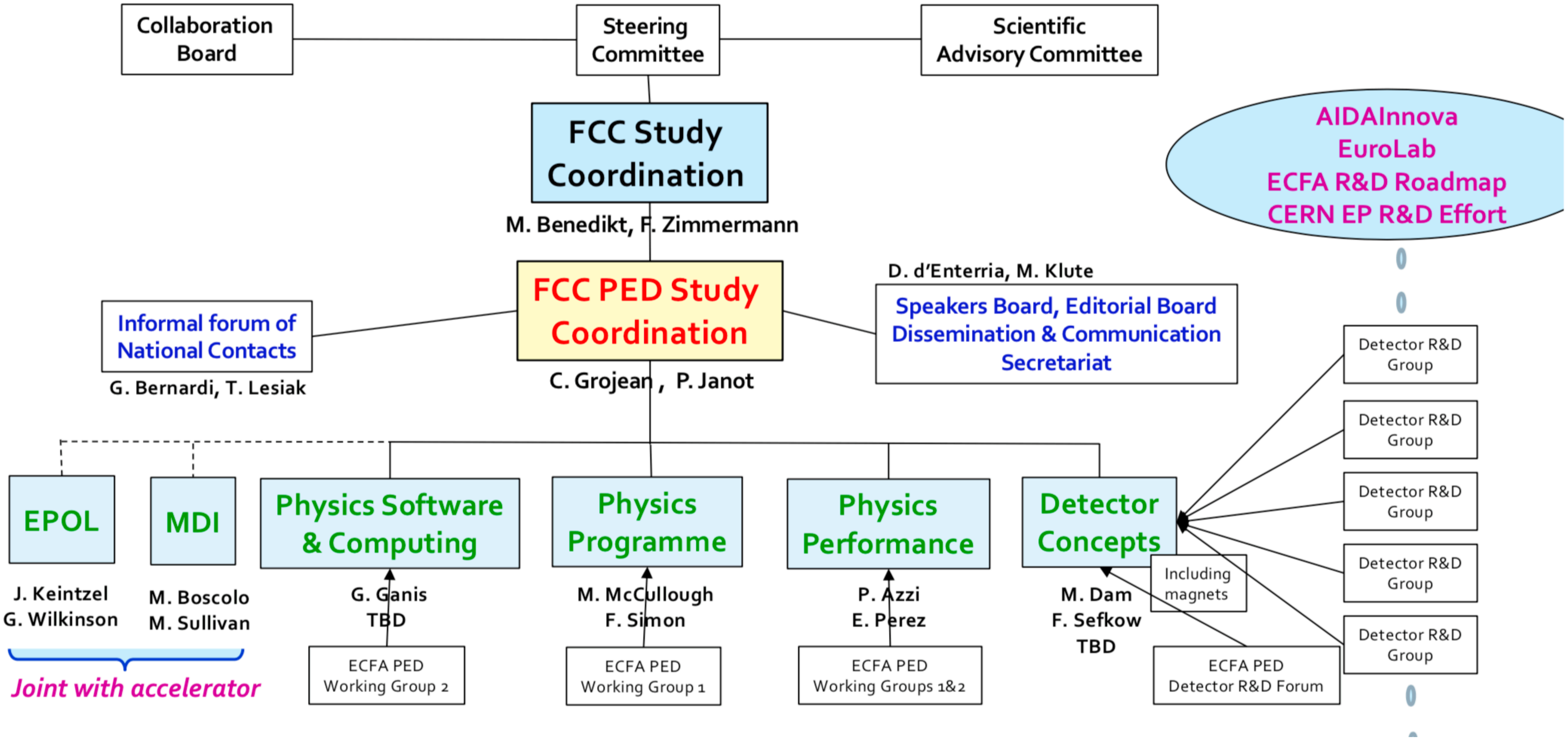
Timeline of the FCC integrated programme

- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

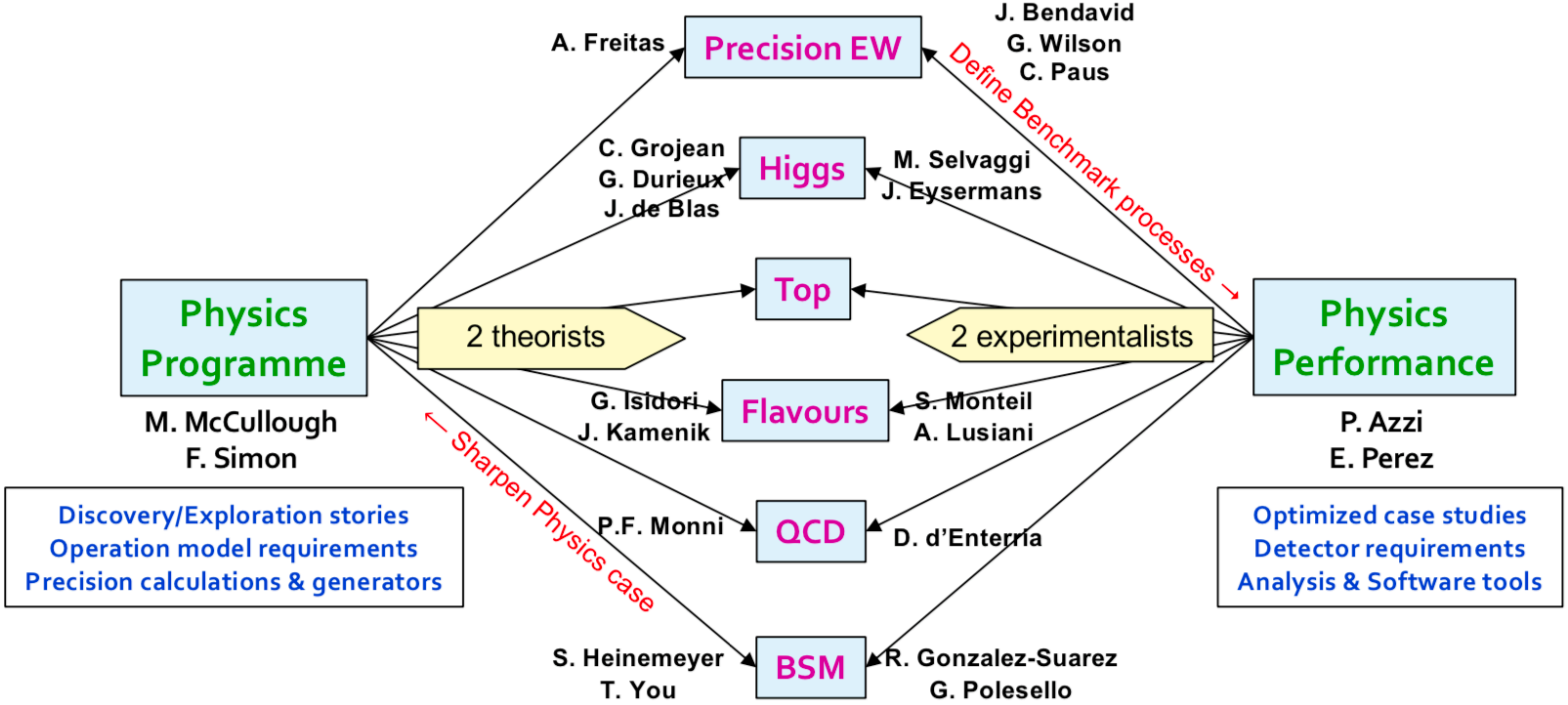
F. Gianotti

➤ *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.*

PED ORGANISATION TO TACKLE THE CHALLENGES



PHYSICS COORDINATION STRUCTURE



RD-FCC INFN ORGANIZATION IN CSN1

- Responsabile Nazionale: Franco Bedeschi (PI)
- WG1 Physics & Software: P. Azzi (PD), N. De Filippis (BA)
- WG2
- WG3
- WG4
- WG5
- WG6

TAKE AWAY MESSAGE

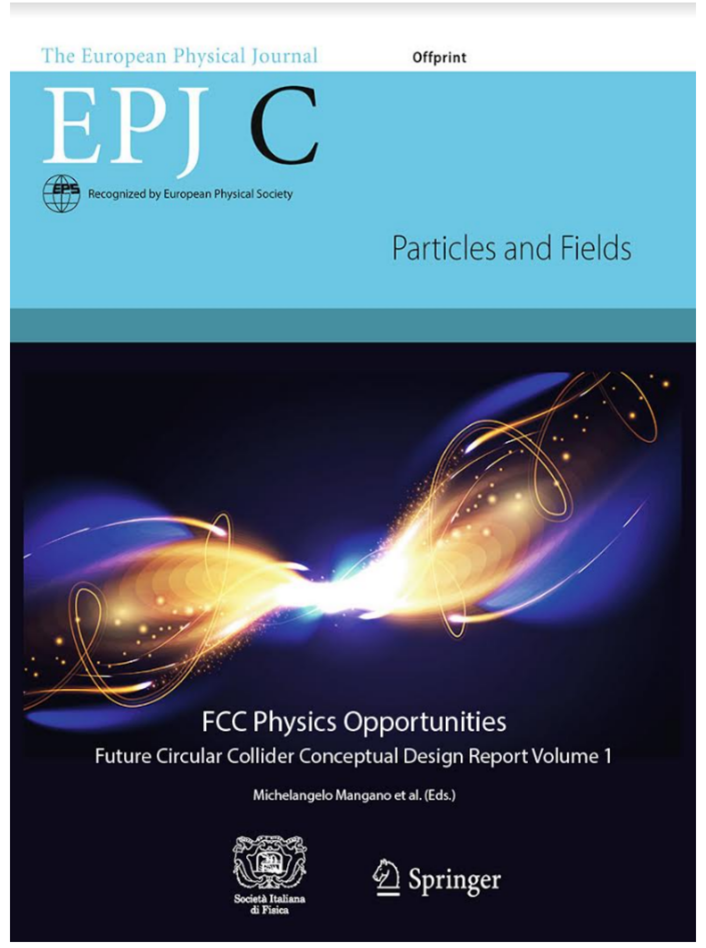
- **The FCC-ee is becoming a very concrete collider project.**
  - The first step of an ambitious integrated project (toward FCC-hh) for HEP until the end of the century
- **FEASIBILITY STUDY focused on the determination of the detector requirements** needed to achieve the desired precision and to inform the technology choices for detector concepts
- **Mid-Term Report of the FCC Feasibility Study to appear at the end of 2023** with new & updated detector concept proposals to realise the needs of the physics programme

FCC integrated project is based on the goal of guaranteed physics deliverables. FCC-ee is a big player in the choice for next lepton collider and requires a significant R&D in all areas to fully exploit its enormous potential

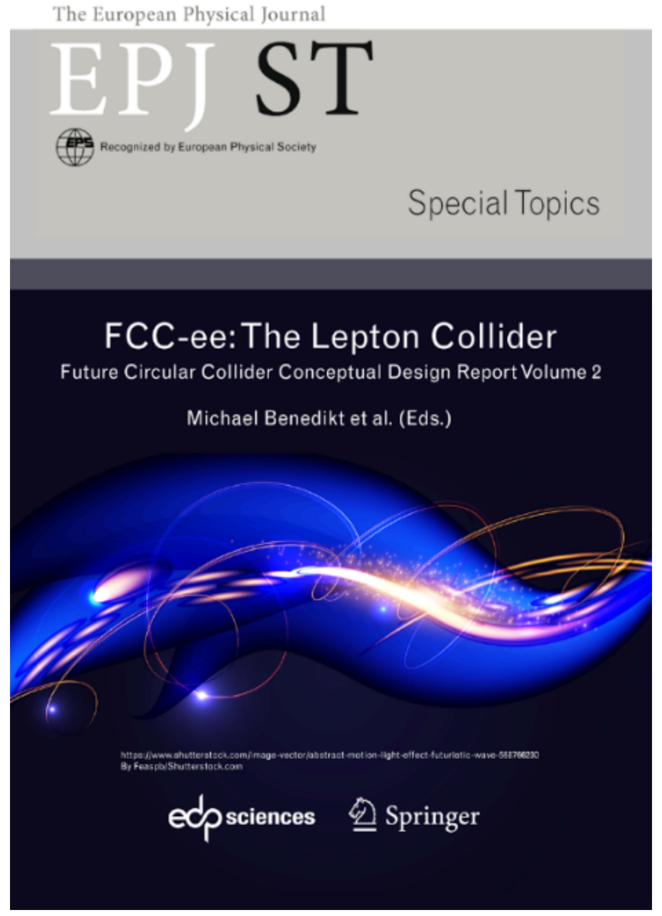
FCC

FIND OUT MORE: CDRS AND PAPERS

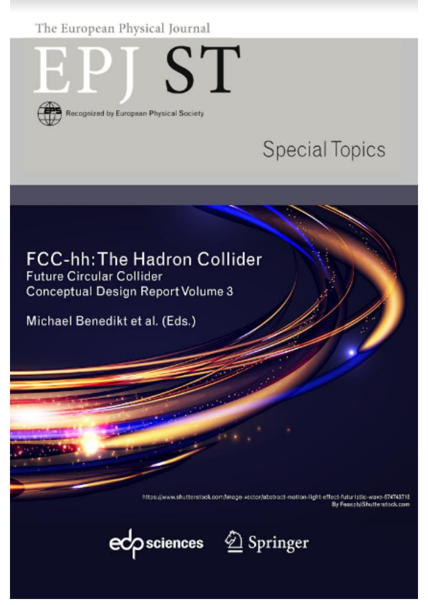
4 CDR volumes published in EPJ



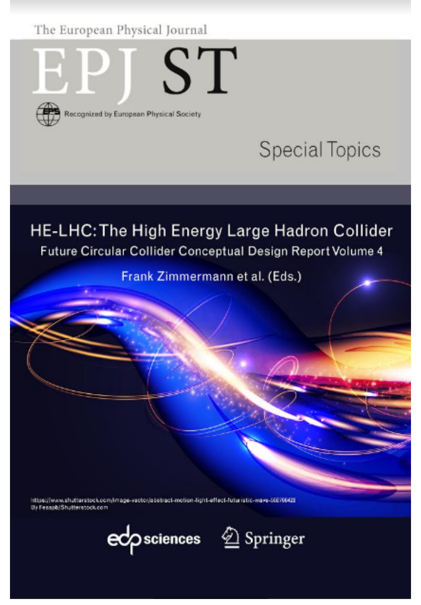
FCC PhysicsOpportunities



FCC-ee: The Lepton Collider



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

FCC

FIND OUT MORE: EPJ+ SPECIAL ISSUE

- EPJ+ special issue "A future Higgs and EW Factory: Challenges towards discovery"

All 34 references in this Overleaf document:
https://www.overleaf.com/read/xcssxqyhtrgt

MDI, √s

Challenges to match statistical precision

Detector requirements & possible solutions

Theory challenges

Software and computing challenges

FIND OUT MORE: FCC PHYSICS WEEK 2023

FCC Week 2023
05-09 June London

Registration:

https://indico.cern.ch/event/1202105/

If you plan to participate in the FCC PED Feasibility Study, you can register to specific working groups here:

https://fcc-ped.web.cern.ch/ , then click on "Contact/Join us", "Join us", "Subscribe to mailing lists"