PHYSICS OPPORTUNITIES @FUTURE CIRCULAR COLLIDER

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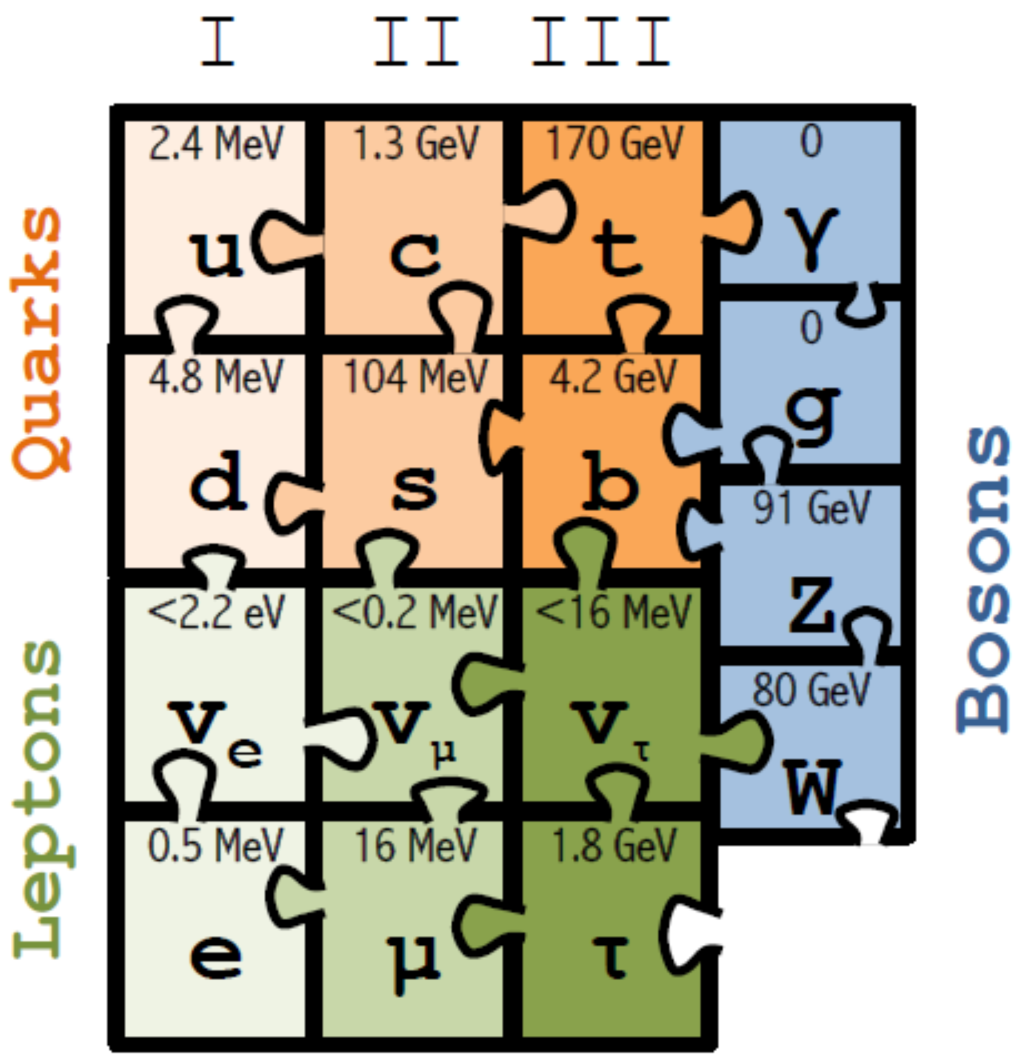
FCC

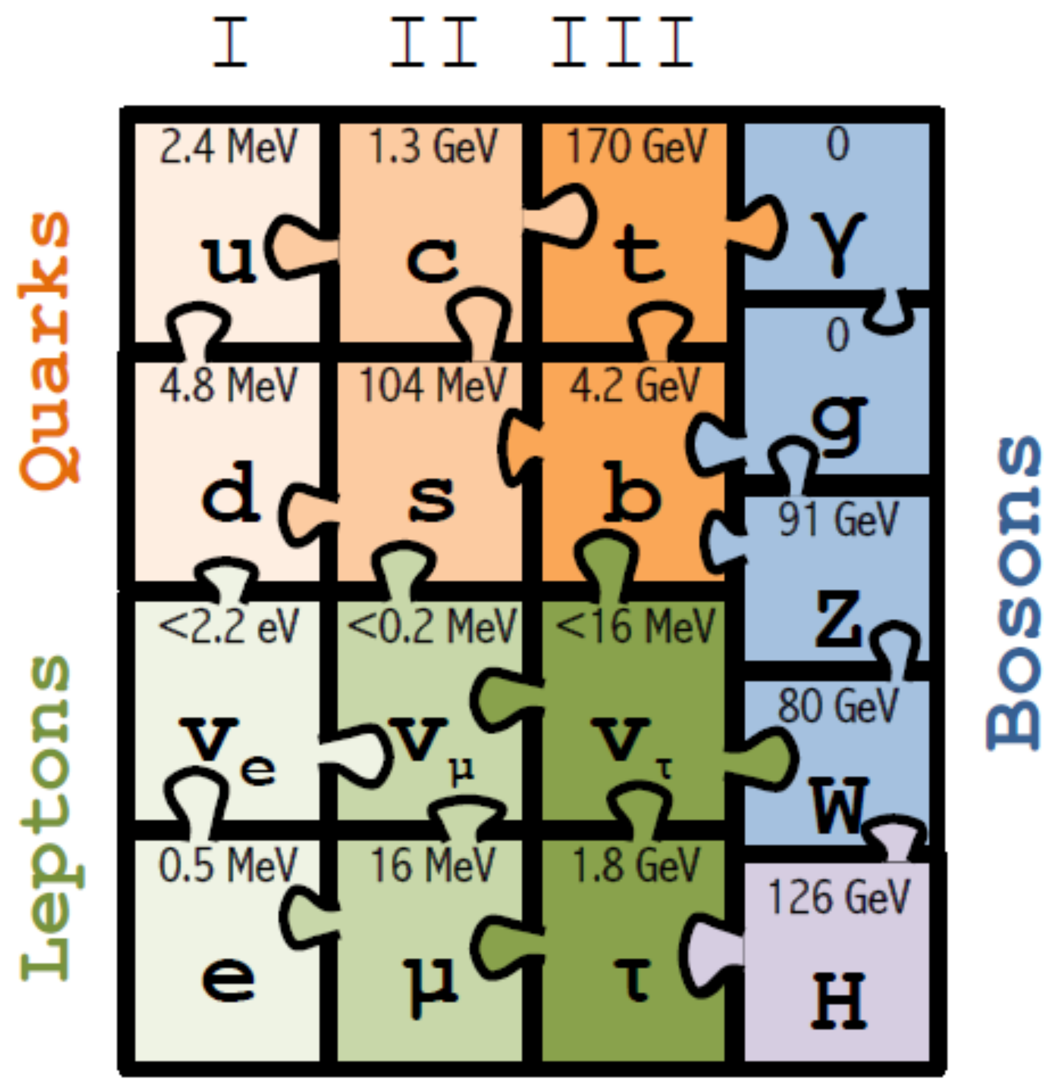
THE PHYSICS LANDSCAPE

➤ 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* ?

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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 ?

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WHICH TYPE OF COLLIDER?

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

- 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

- The Future Circular Collider (FCC-ee,hh,eh) integrated project offers the most adapted response to this situation:
  - Largest luminosity
  - highest parton energy
  - synergies and complementarities between the machines (past, and future)

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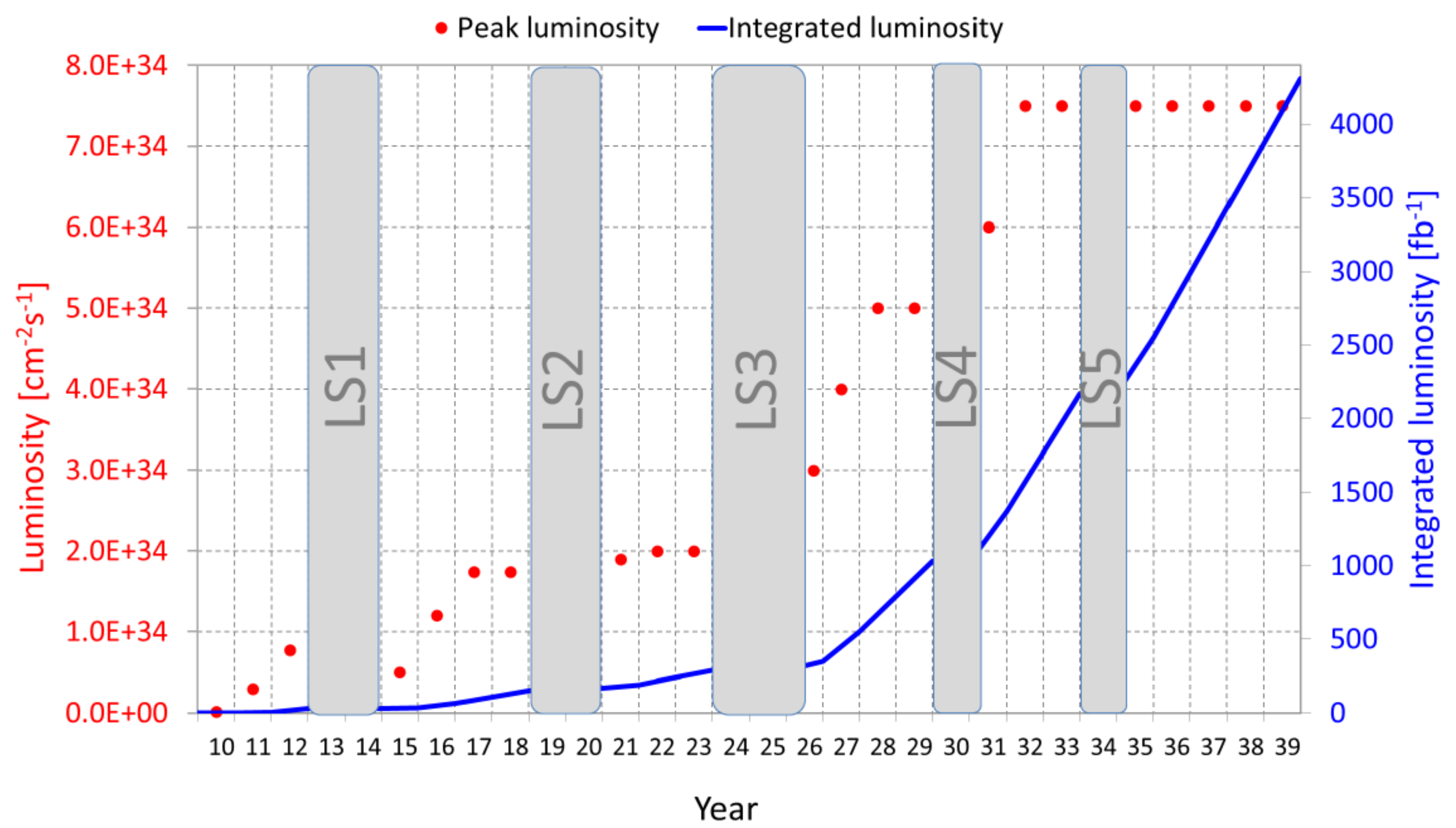
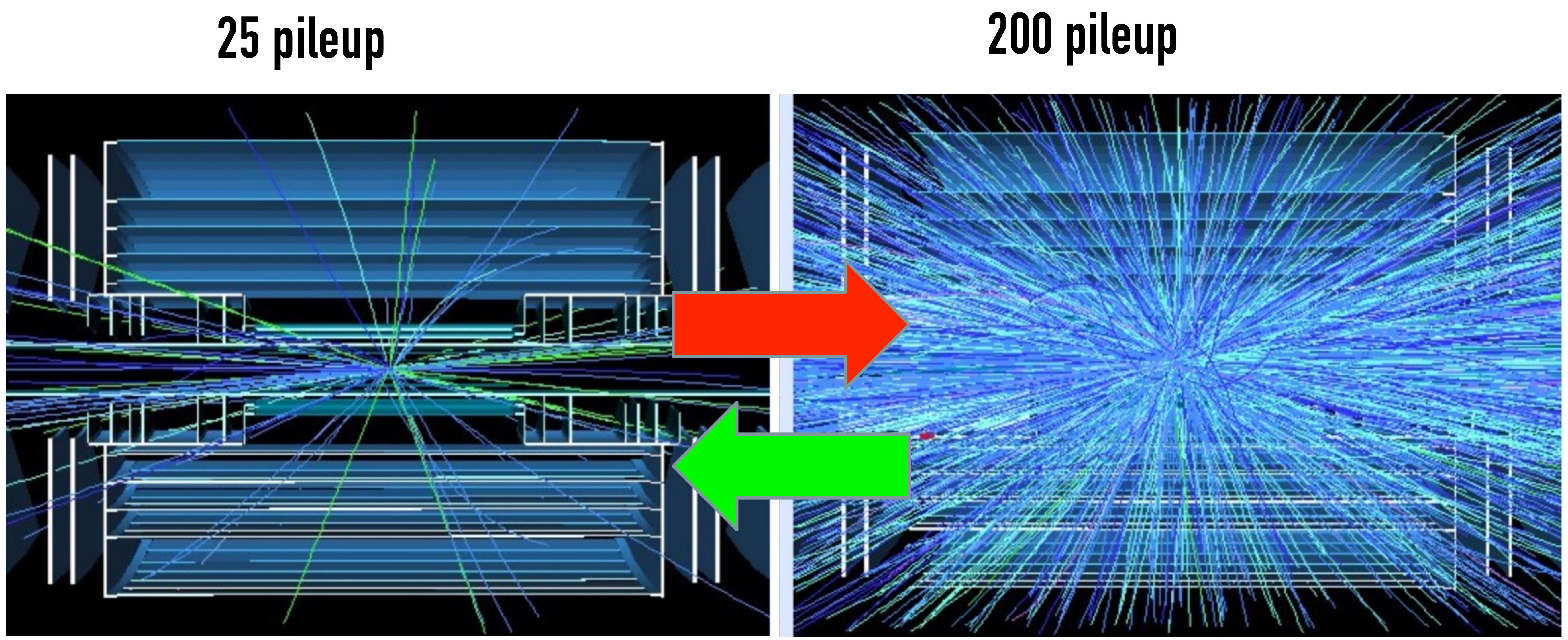
- **The LHC is still pretty much in its childhood: factor 10 more luminosity to be collected with HL-LHC**





- High luminosity ➔ 200 soft pp interactions per crossing
- Detector elements and electronics are exposed to high radiation dose : requires new tracker, endcap calorimeters, forward muons, replacing readout systems
- We have demonstrated that the new detectors will be able to explore the full physics potential of HL-LHC even in these conditions.

Expected HL-LHC results used as starting point for future machines performance!

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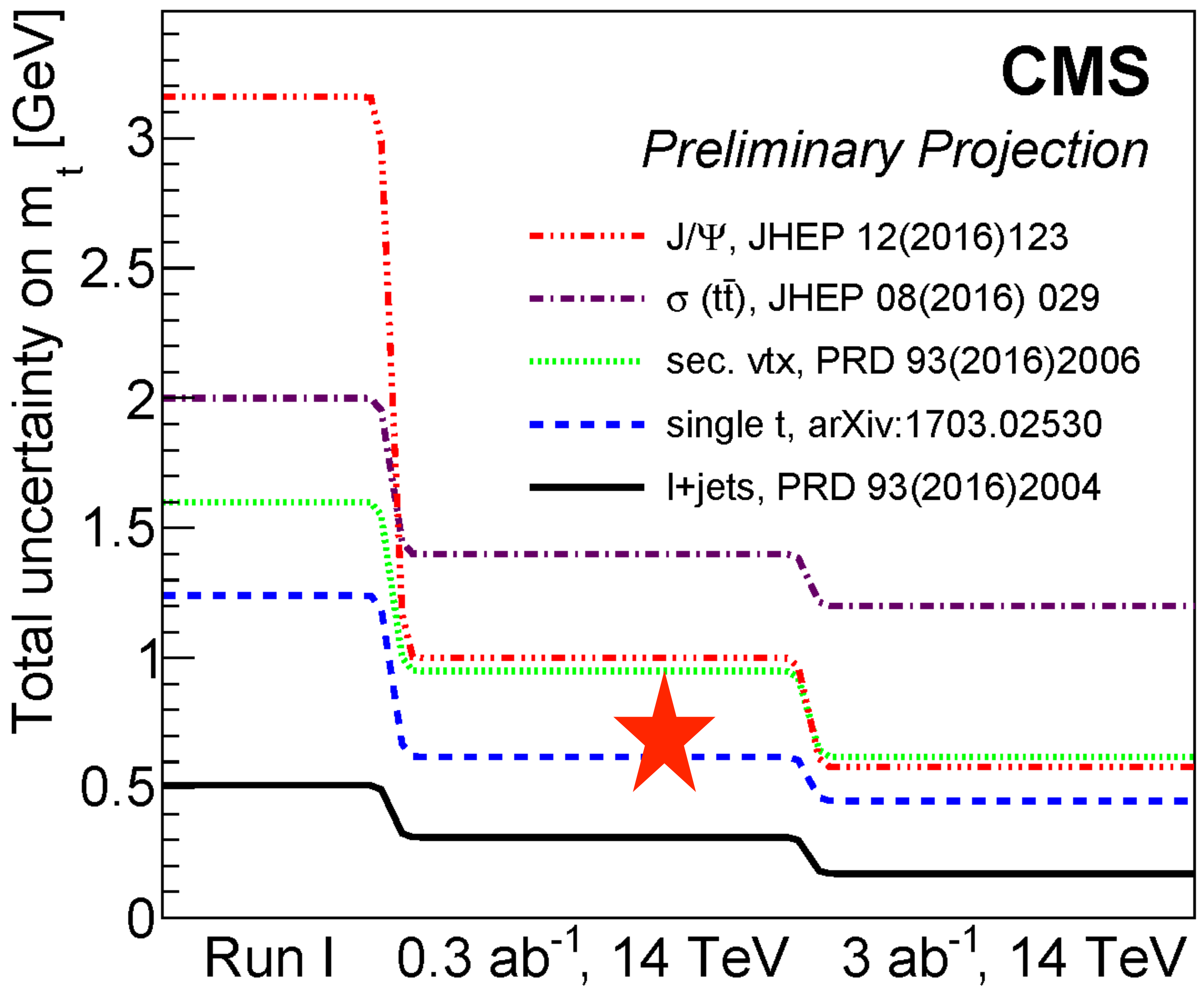
AFTER HL-LHC: SM & TOP



Predicted reach for top mass uncertainty of 0.17GeV.
Experiments catching up with predictions already:
Brand new CMS top mass 171.77 ± 0.38 GeV

$sin^2\theta_{eff}$ direct measurement better than $5 \cdot 10^{-5}$

Thanks to higher eta acceptance

	ATLAS $\sqrt{s} = 8$ TeV	ATLAS $\sqrt{s} = 14$ TeV	ATLAS $\sqrt{s} = 14$ TeV
$\mathcal{L}$ [fb^{-1}]	20	3000	3000
PDF set	MMHT14	CT14	PDF4LHC15$_{HL-LHC}$
$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ [$\times 10^{-5}$]	23140	23153	23153
Stat.	± 21	± 4	± 4
PDFs	± 24	± 16	± 13
Experimental Syst.	± 9	± 8	± 6
Other Syst.	± 13	-	-
Total	± 36	± 18	± 15

Observation of Diboson scattering and 3σ evidence for longitudinal scattering

Process	$W^{\pm}W^{\pm}$	WZ	WV	ZZ	WWW	WWZ	WZZ
Final state	$\ell^{\pm}\ell^{\pm}jj$	$3\ell jj$	$\ell jjjj$	$4\ell jj$	$3\ell 3\nu$	$4\ell 2\nu$	$5\ell\nu$
Precision	6%	6%	6.5%	10–40%	11%	27%	36%
Significance	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	3.0σ	3.0σ

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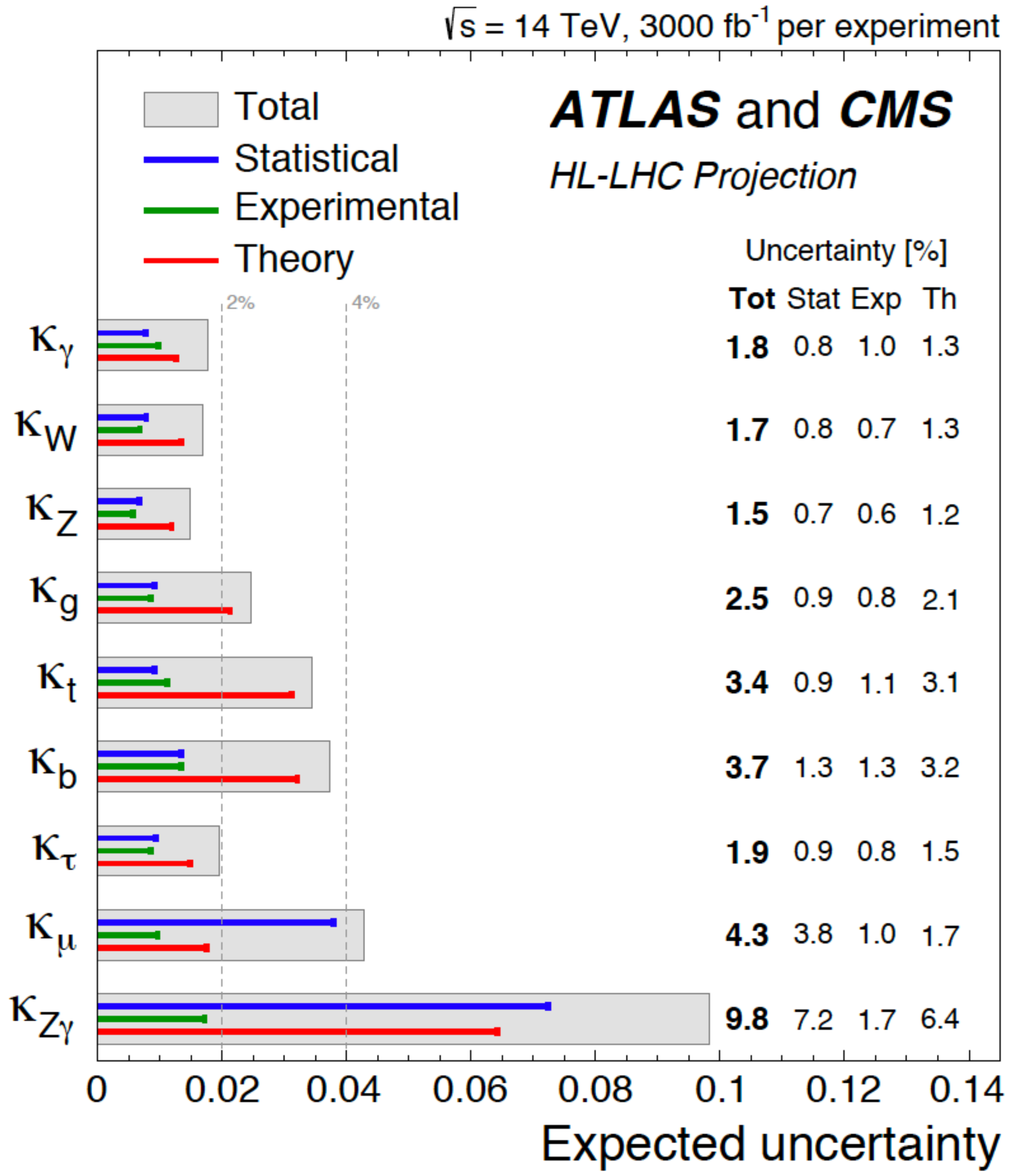
AFTER HL-LHC : HIGGS

Uncertainties on Higgs couplings of the order of 2-4%



HH production σ~ 39.5 fb@14TeV

Combined sensitivity on λ_3 above 4σ

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \rightarrow b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \rightarrow b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \rightarrow b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

- **Careful studies and projections for the physics at the HL-LHC have shown the upgraded detectors will be able to deal with the 200PU conditions**
  - This precision might still not be sufficient to show the effect of new physics…
- Let's not forget that Run3 might still bring more improvements and surprises…!

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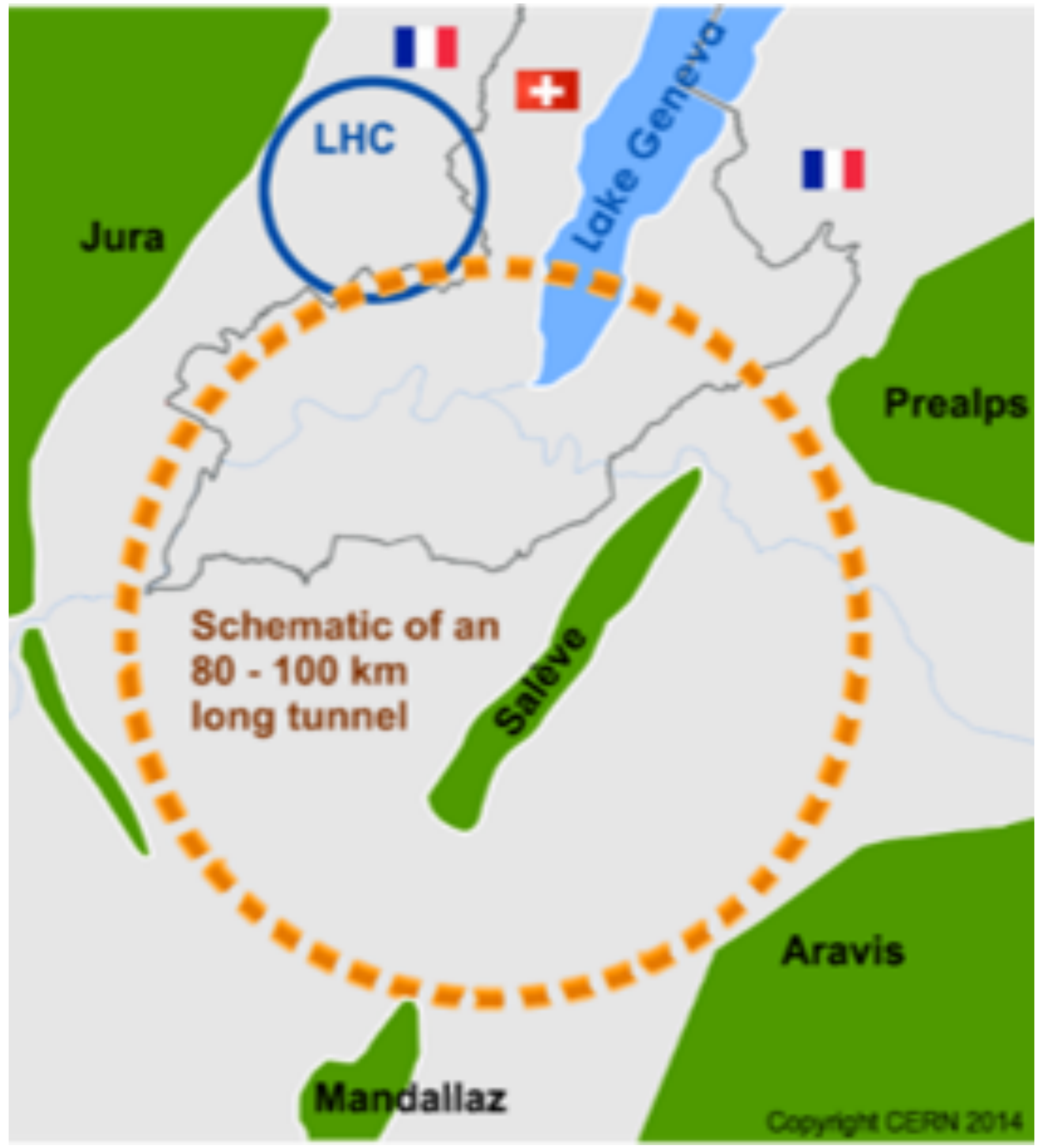
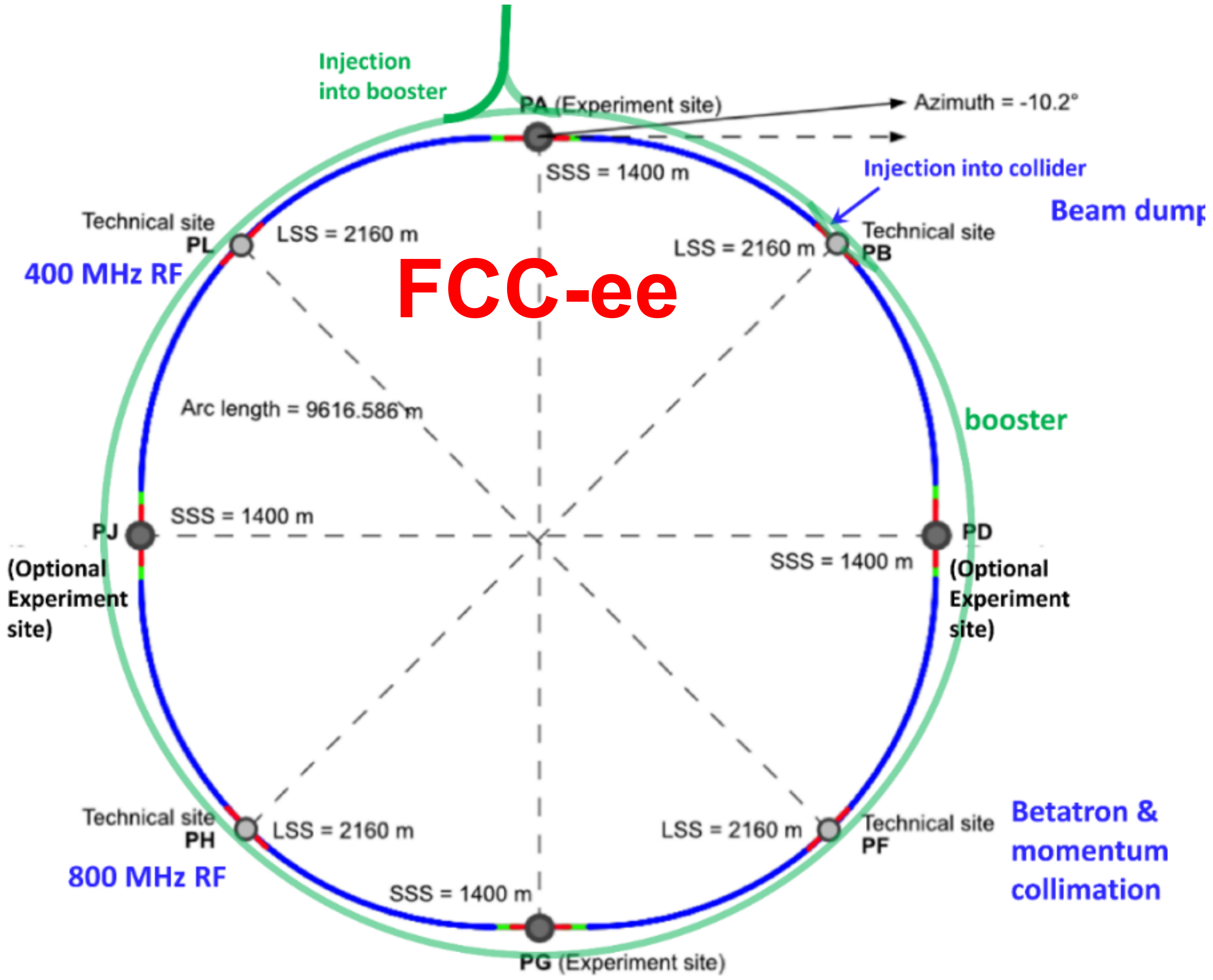
THE FCC INTEGRATED PROGRAM: INSPIRED BY SUCCESSFUL LEP – LHC PROGRAMS AT CERN

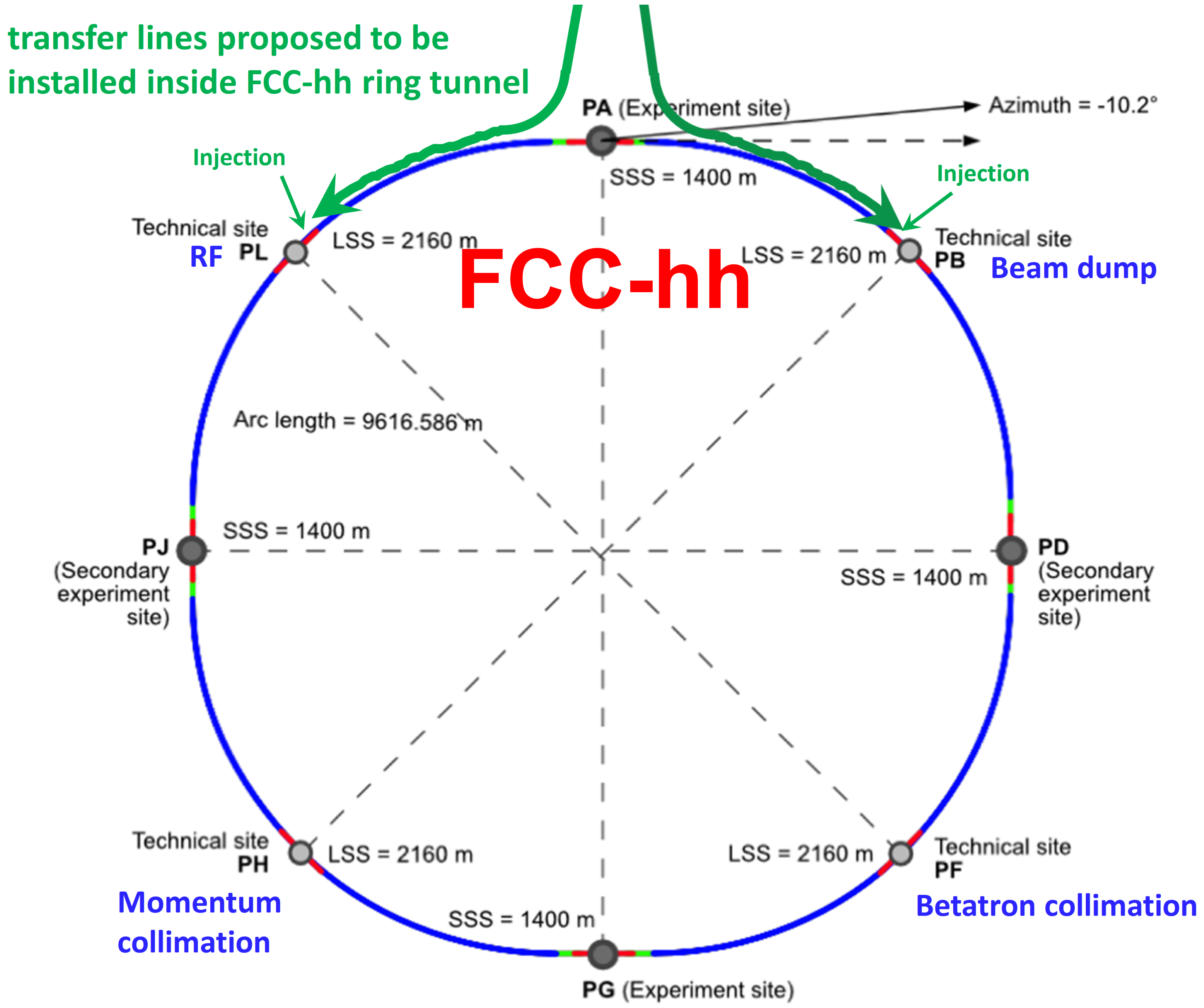
M. Benedikt

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program







2020 - 2040 | 2045 - 2060 | 2070 - 2090++

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8-SITE BASELINE "PA31"

Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2143 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**91.1 km**

- 8 sites – less use of land, <40 ha instead 62 ha
- **Possibility for 4 experiment sites in FCC-ee**
- All sites close to road infrastructures (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP

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J. Gutleber

M. Boscolo

INTERACTION REGION DESIGN - FCC-ee

FCC-ee collider

Double ring e+ e- collider

Common footprint with FCC-hh, except around IPs

Asymmetric IR layout and optics to limit synchrotron radiation towards the detector

4 IPs

large horizontal crossing angle 30 mrad,

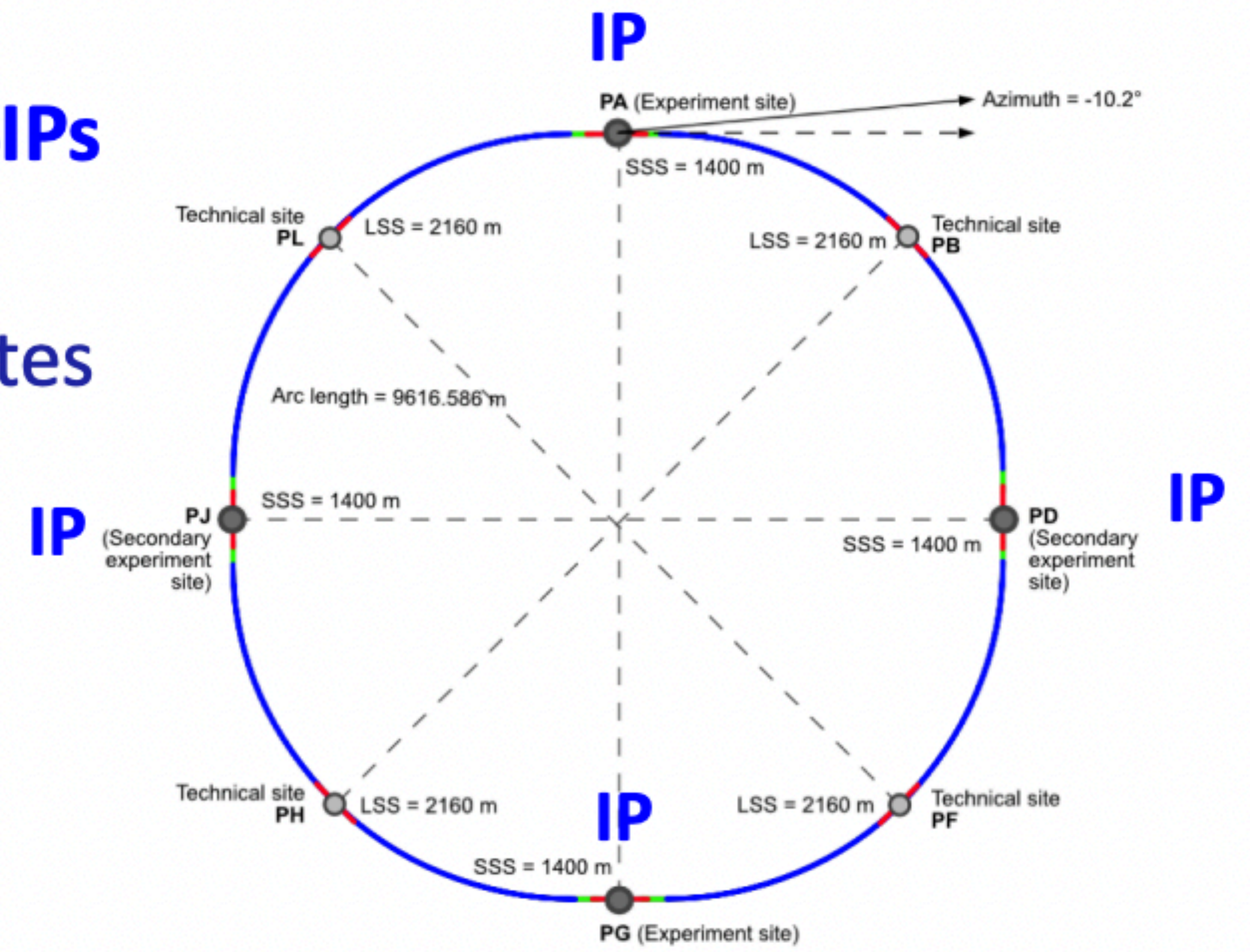
crab-waist collision optics

Synchrotron radiation power **50 MW/beam** at all beam energies

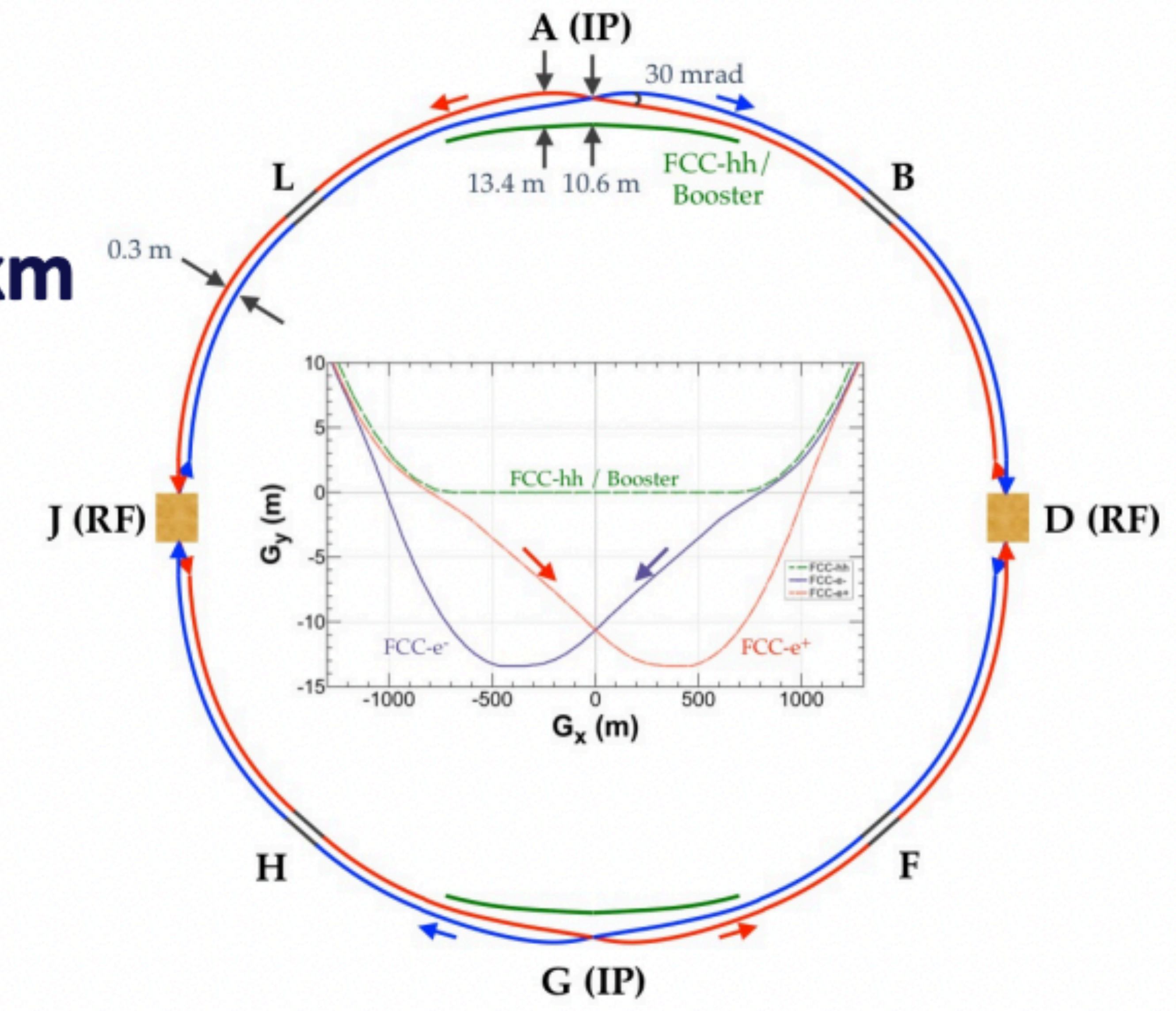
Top-up injection scheme for high luminosity requires booster synchrotron in collider tunnel

"**Tapering**" of magnets along the ring to compensate the sawtooth effect

evolution 4IPs
C=91 km
8 surface sites



CDR
C=97 km



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MANY REQUIREMENTS FOR THE IR & MDI REGION

- One common IR for all energies, flexible design, with a constant detector field of 2T (physics impact of this choice):
  - At Z pole: crab-waist, nano-beams & large crossing angle
  - At tt threshold SR and BS dominate the lifetime
- Solenoid compensation scheme: to compensate the detector field
- Synchrotron radiation control in the IR
- 100mrad of physics cone: trade off accelerator/detector
- Luminosity monitor for low angle Bhabhas:
  - construction precision at the micron level!
- Low X/X0 vacuum chamber & cooling to keep low material budget
- Background suppression and radiation shielding
- Accessibility to inner detector for maintenance
- etc….

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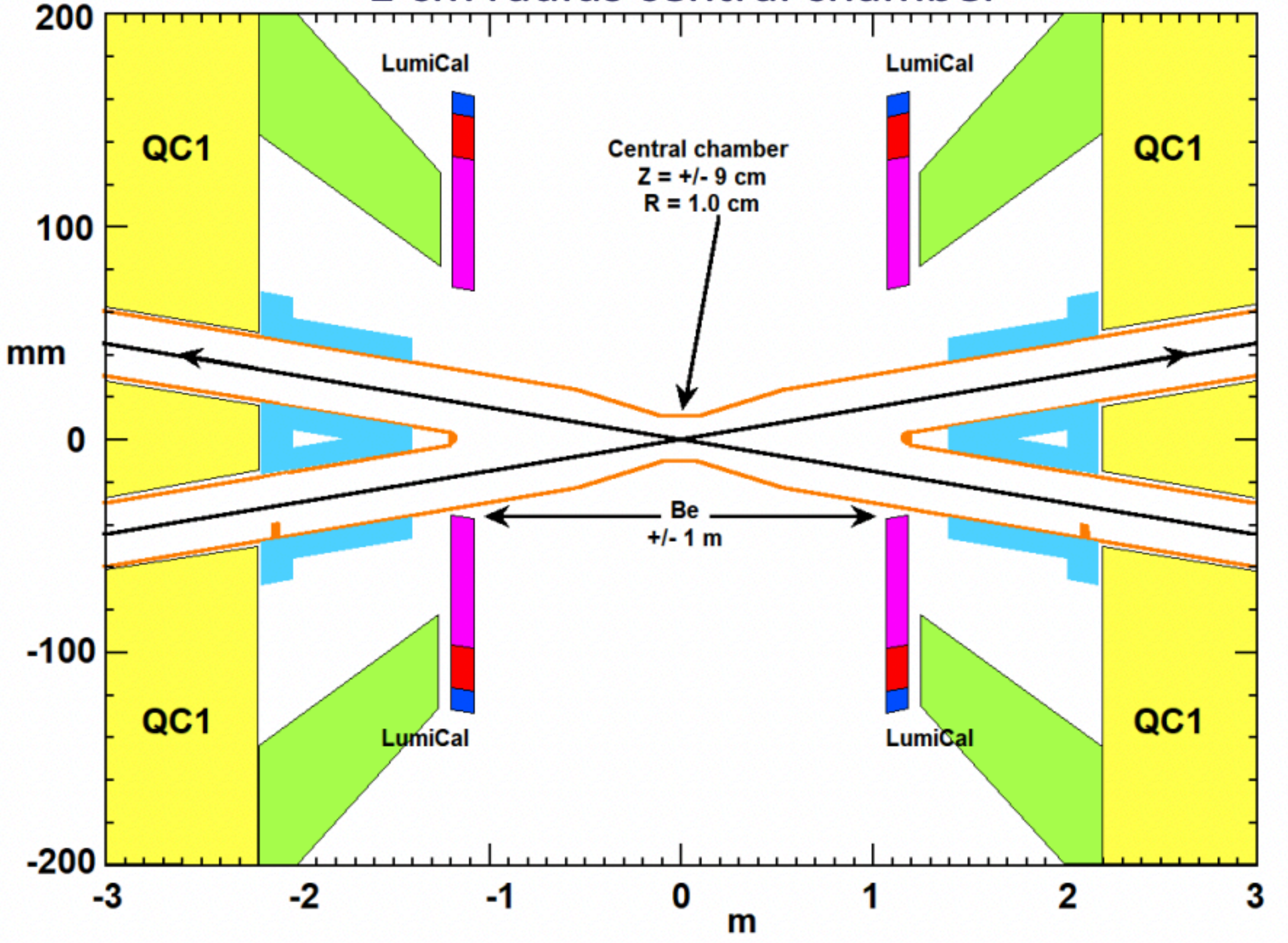
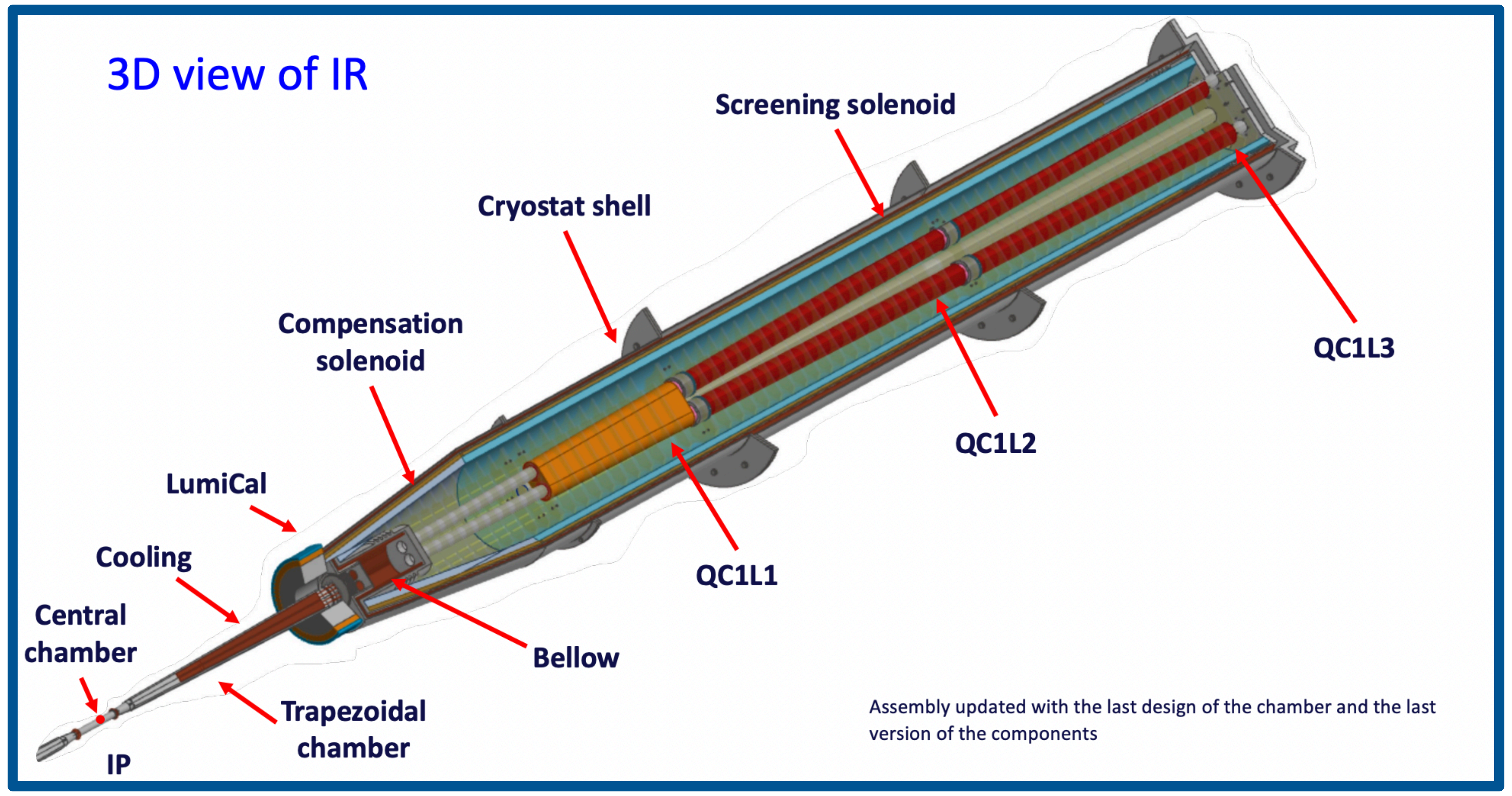
FCC-ee INTERACTION REGION DESIGN

present low impedance beam pipe
1 cm radius central chamber



a smaller central vacuum chamber allows for a smaller radius of the innermost vertex detector layer



- Design has evolved from the CDR one

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Stage 1: FCC-ee updated parameters

Parameter [4 IPs, 91.2 km, T_{rev}=0.3 ms]	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
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
luminosity per IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

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K. Oide, D. Shatilov,

Stage 1: FCC-ee updated parameters

FUTURE CIRCULAR COLLIDER

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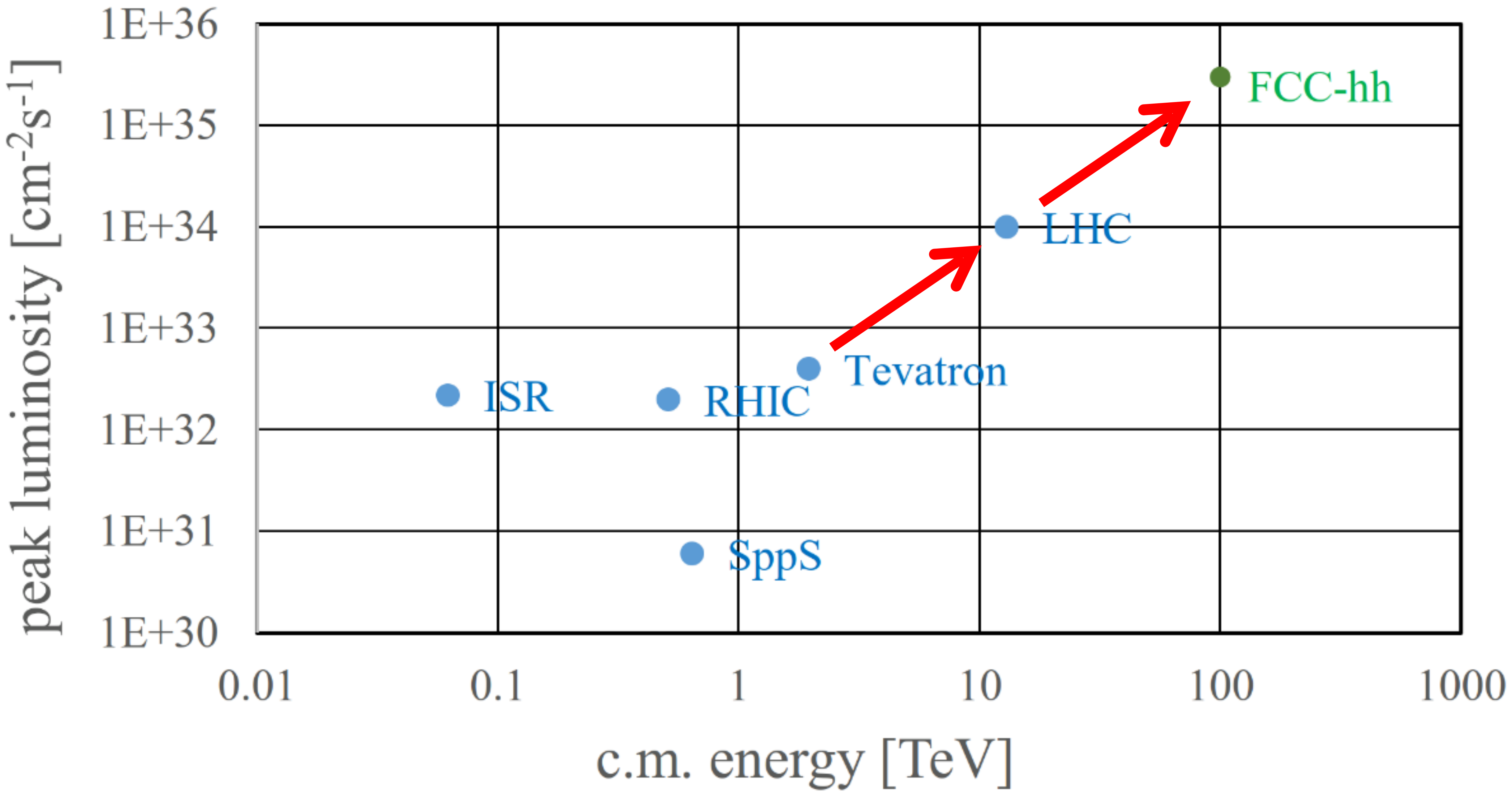
Stage 2: FCC-hh (pp) collider parameters

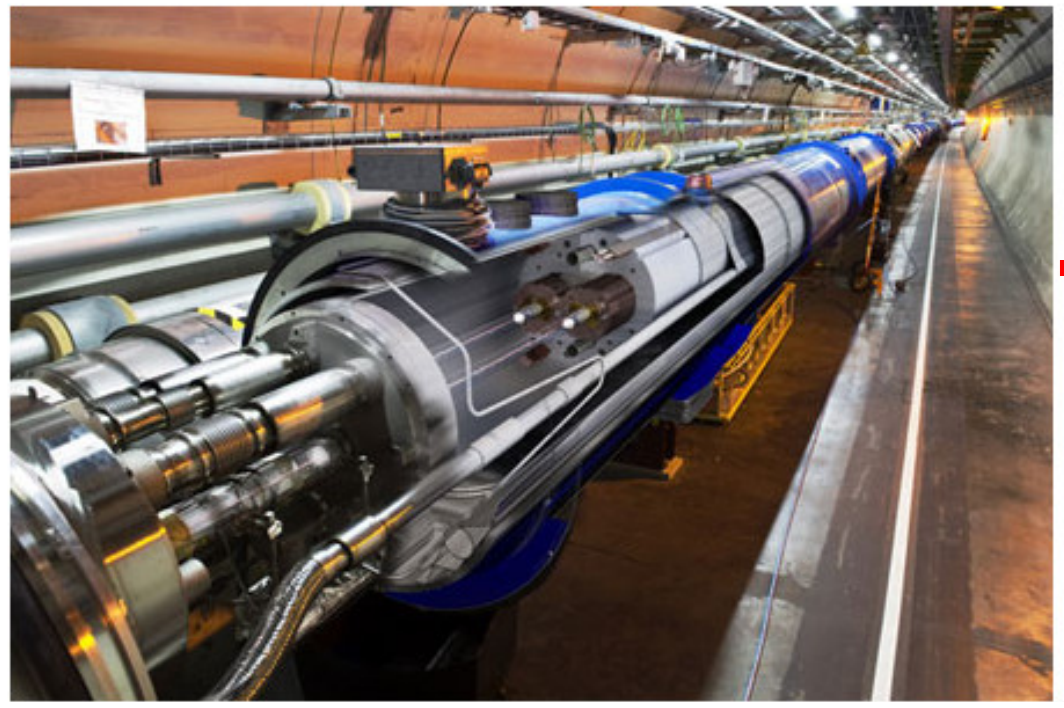
parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	~17 (~16 comb.function)		8.33	8.33
circumference [km]	91.2		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2700		7.3	3.6
SR power / length [W/m/ap.]	32.1		0.33	0.17
long. emit. damping time [h]	0.45		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	7.8		0.7	0.36

FCC-hh: HIGHEST COLLISION ENERGIES

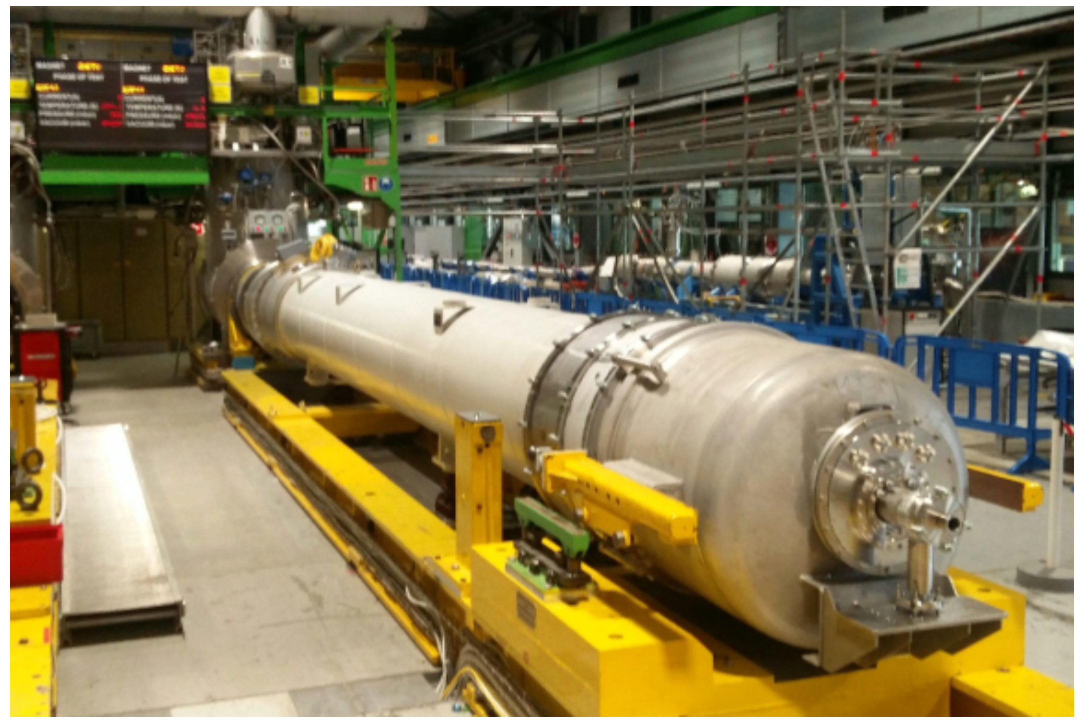


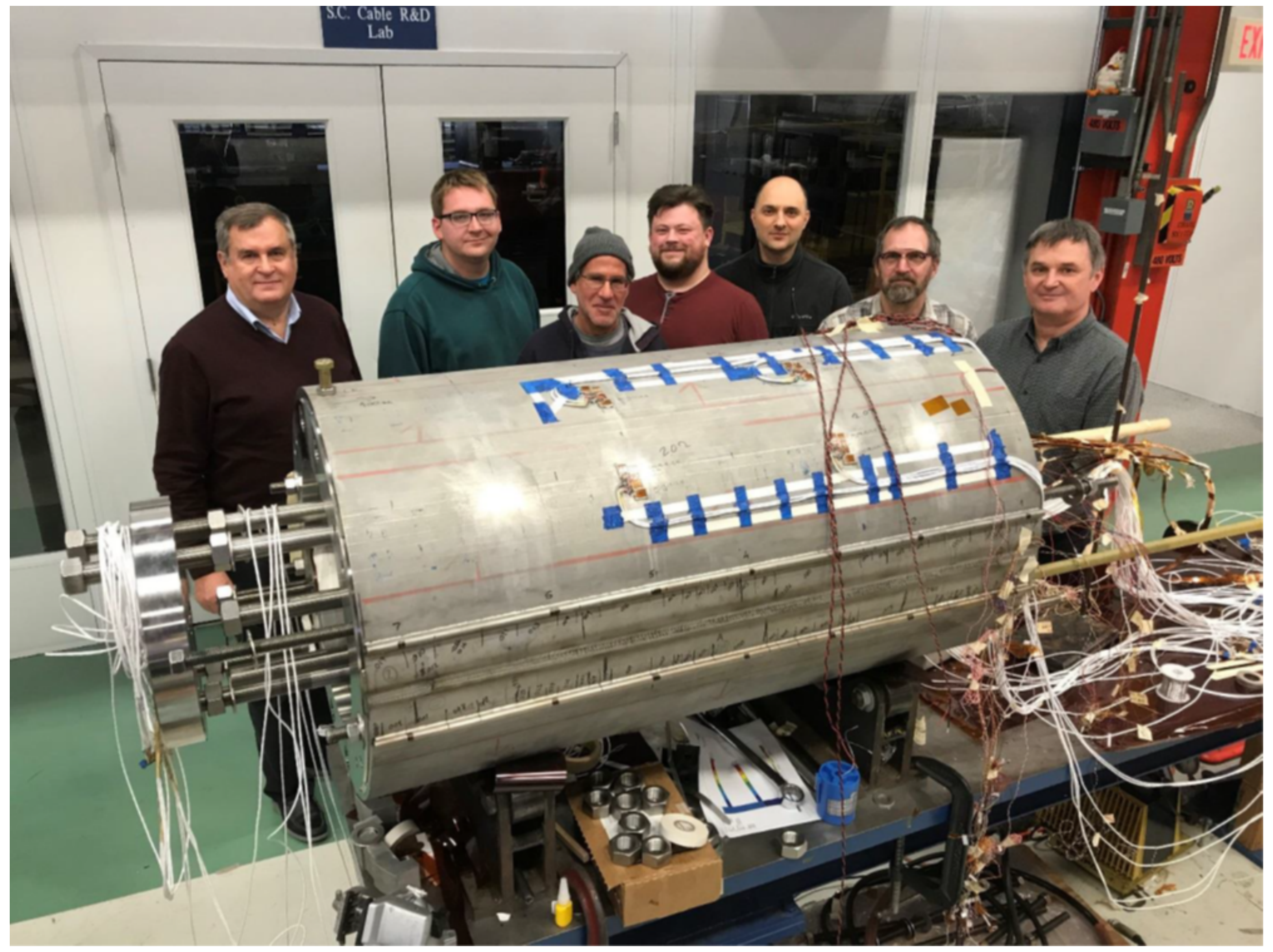
- **order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab-1 per experiment collected over 25 years** of operation (vs 3 ab^{-1} for LHC)
- similar performance increase as from Tevatron to LHC
- **key technology: high-field magnets**

from
LHC technology
8.3 T NbTi dipole



via
HL-LHC technology
12 T Nb_3Sn quadrupole

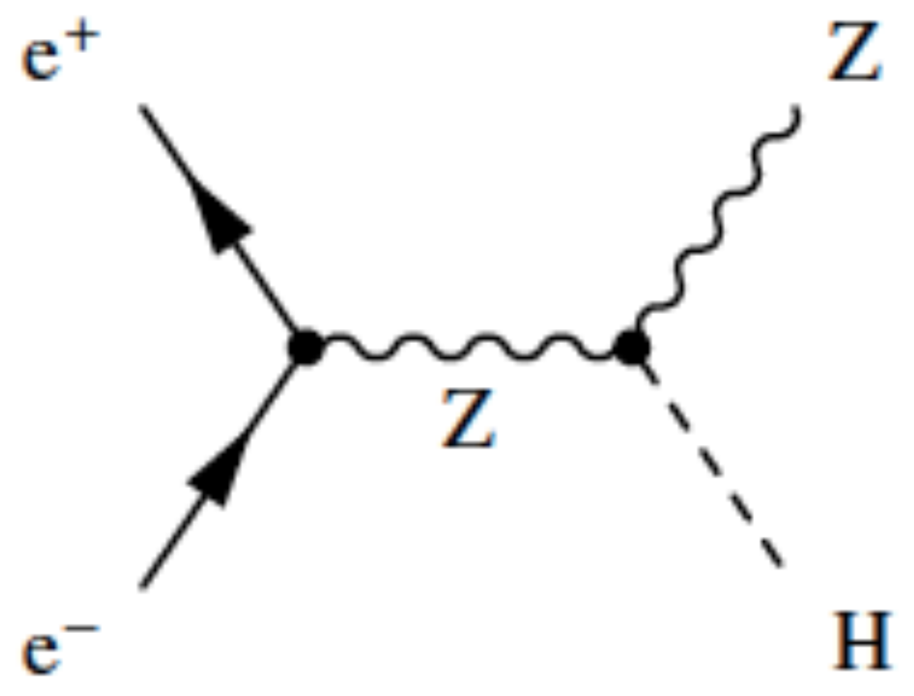


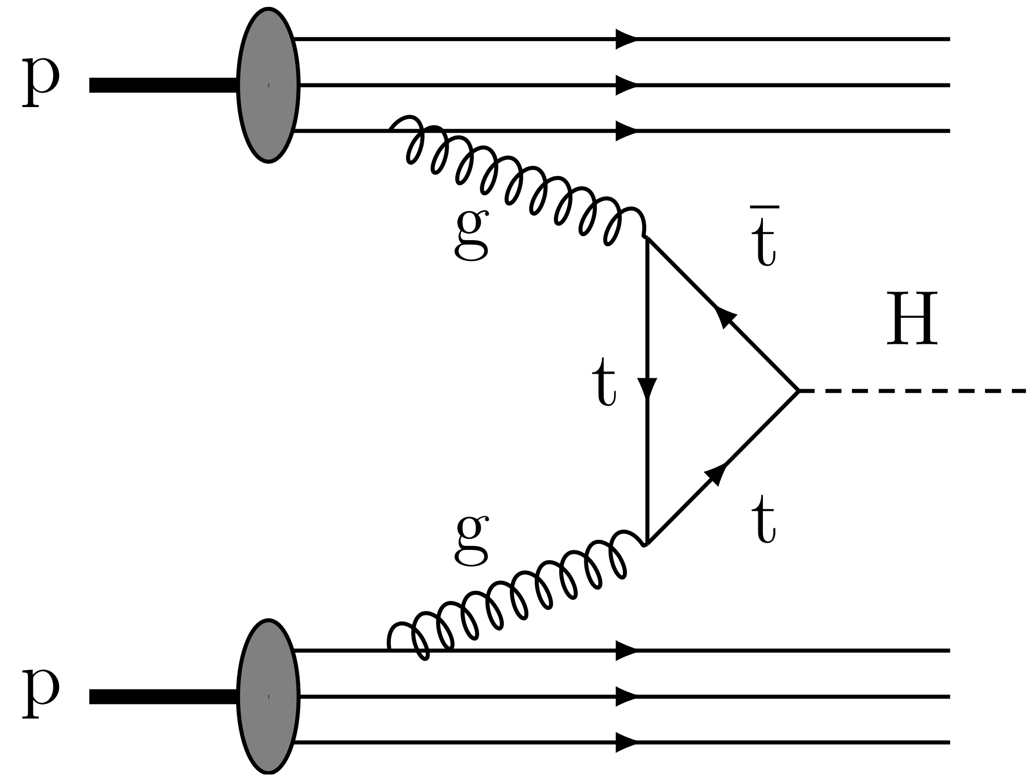


FNAL dipole demonstrator 4-layer cosϑ 14.5 T Nb_3Sn in 2019

THE FCC-ee

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





e^+e^- collisions	p-p collisions
e^+/e^- are point-like → Initial state well defined (*E*, ***p***), polarisation → High-precision measurements	**Proton is compound object** → Initial state not known event-by-event → Limits achievable precision
Clean experimental environment → Trigger-less readout → Low radiation levels	**High rates of QCD backgrounds** → Complex triggering schemes → High levels of radiation
Superior sensitivity for **electro-weak states**	High cross-sections for **colored-states**
- At lower energies (≲ 350 GeV) , **circular** e^+e^- colliders can deliver **very large luminosities.** - Higher energy (>1TeV) e^+e^- requires **linear** collider.	High-energy **circular** pp colliders feasible

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INTRODUCTION TO THE FCC-ee:

- The physics landscape of the FCC-ee program extends in all possible directions:
  - the difference in the physics focus at the different $\sqrt{s}$
  - the difference in the event kinematic of running from 90GeV (and possibly below) up to 365GeV
  - the challenge of being able to achieve superbe precision on SM processes but also perform unique direct searches for new physics
- *The list of interesting processes and measurement is extensive, and it has not been fully explored yet, even in terms of sensitivity.*
- From this richness, during the Feasibility Study, we need to extract concrete benchmark measurements, the « case studies »
  - They will be used to extract requirements on what is missing to achieve our ambitious goals: detector requirements, reconstruction tools, calibration techniques.

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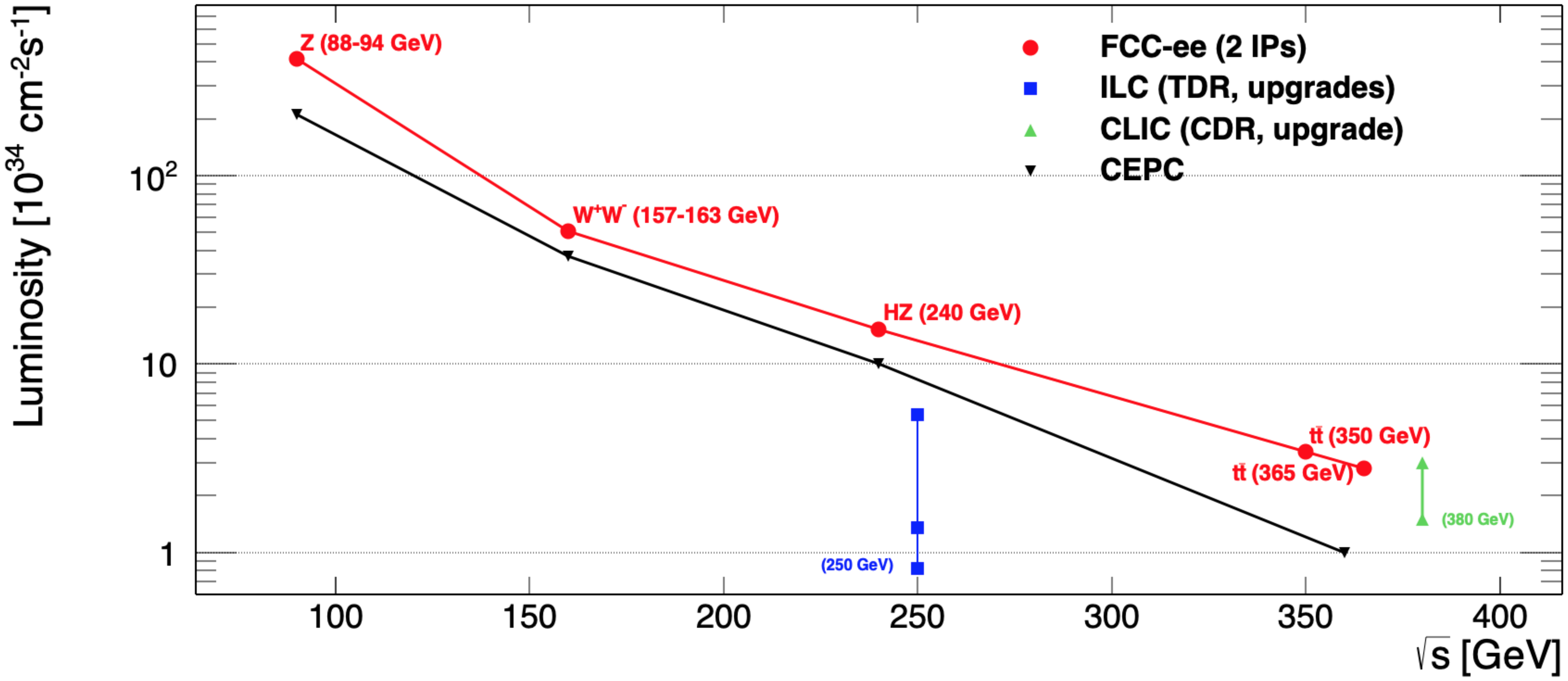
ENERGY RANGE & LUMINOSITY



Can produce all the heaviest particles of the Standard Model: Z, W, H and top

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics		√s uncertainty
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays	LEP x 10^5	<100keV
FCC-ee-W	2	158-162	12	10^8 WW events	LEP x $2 \cdot 10^3$	<300keV
FCC-ee-H	3	240	5	10^6 ZH events	Never done	~2MeV
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events	Never done	~5MeV
s-channel H	???	125 GeV		~5000 $e^+e^- \to$ H events	Never done	< 200 keV

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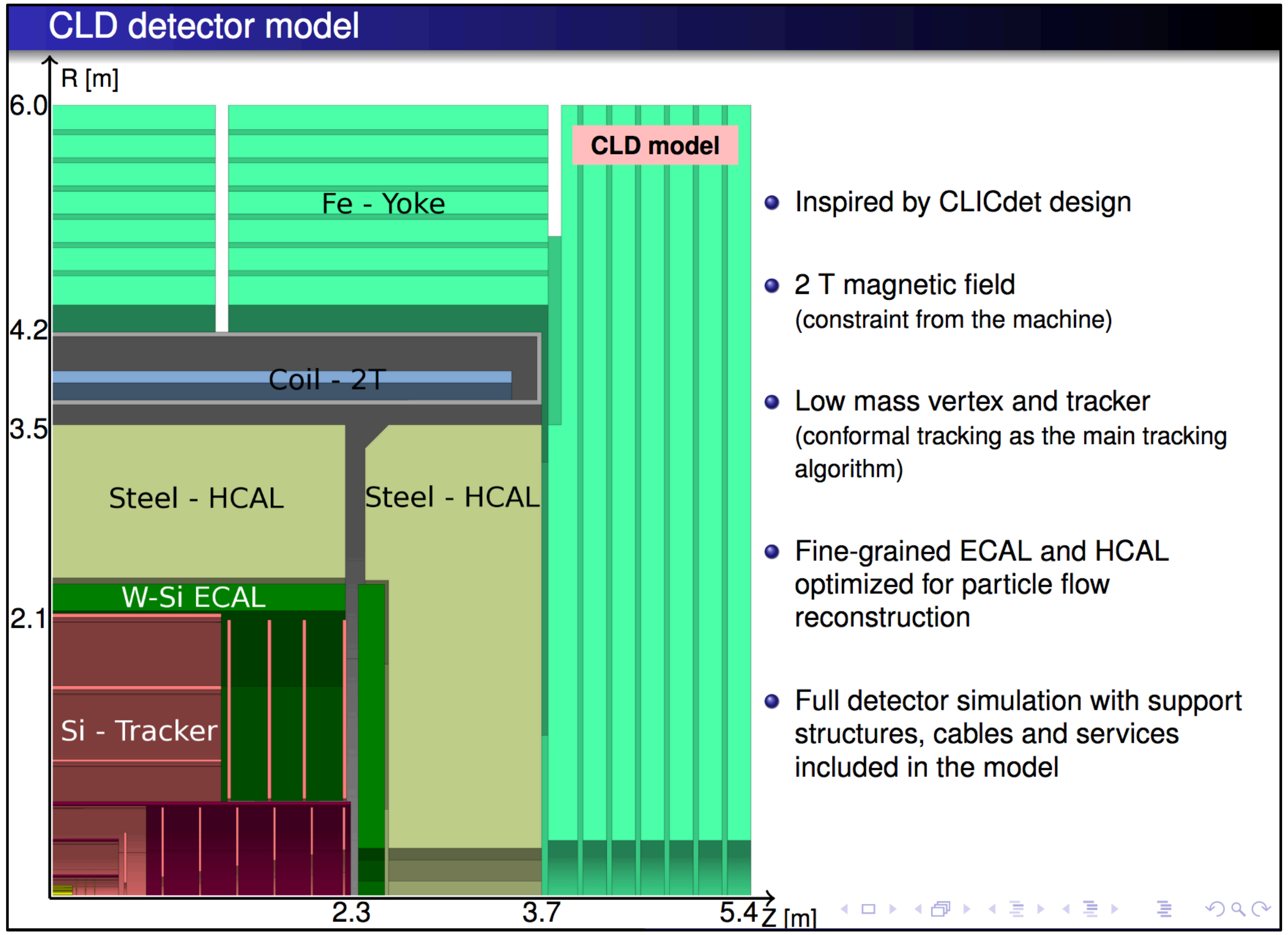
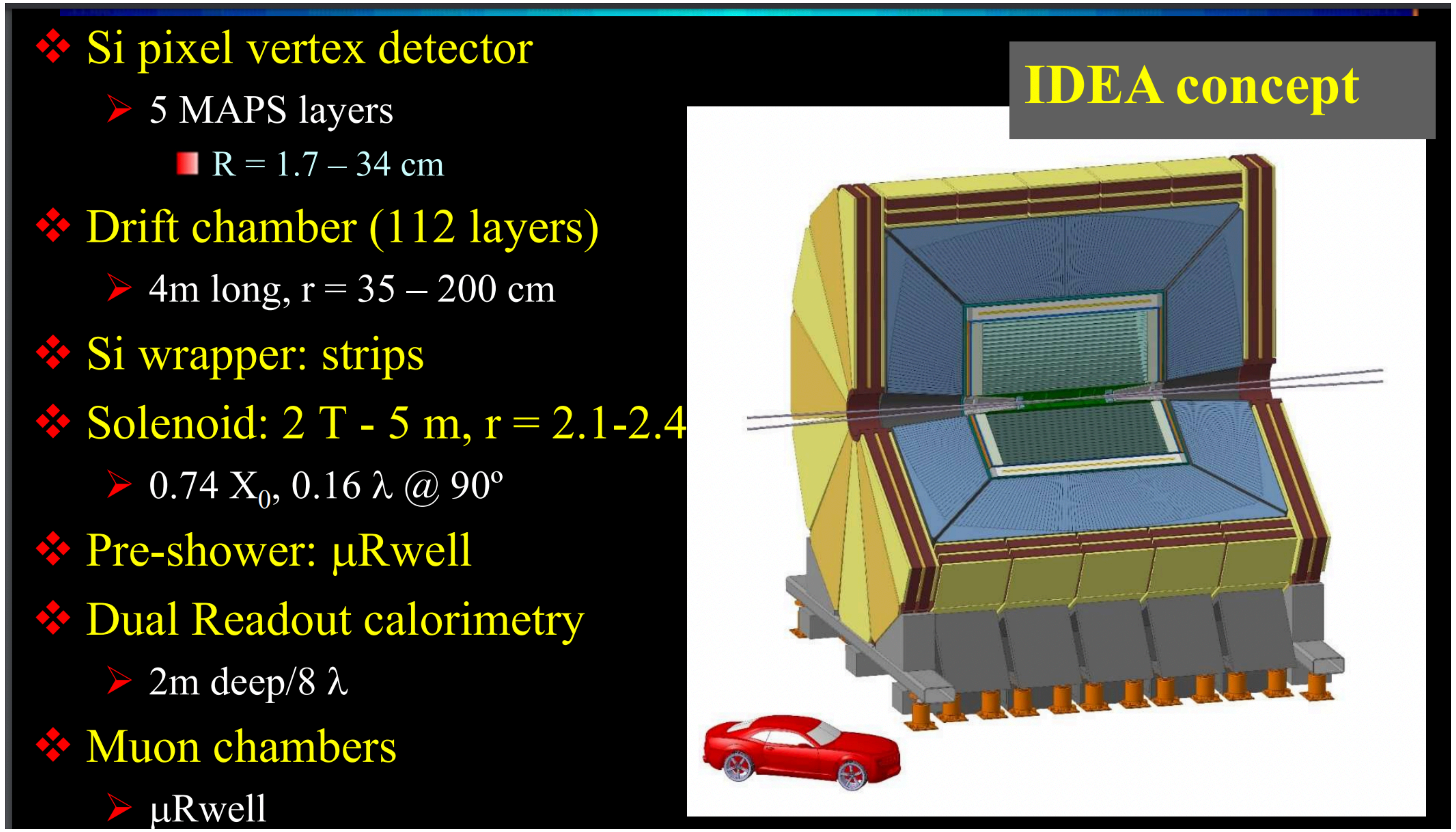
TWO BASELINE DETECTOR CONCEPTS FOR THE CDR

- 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…
- New detector design ideas are coming and being tested





DETECTOR REQUIREMENTS TO GUIDE NEW IDEAS

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

LC-inspired.
Update from physics studies ongoing

Ultra Precise EW Programme & QCD

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) 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 √s meast.

It is not unlikely that the most stringent requirements will come from the intensity frontier
Just pick up a case study in the TeraZ programme, and you'll make a unique contribution

Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

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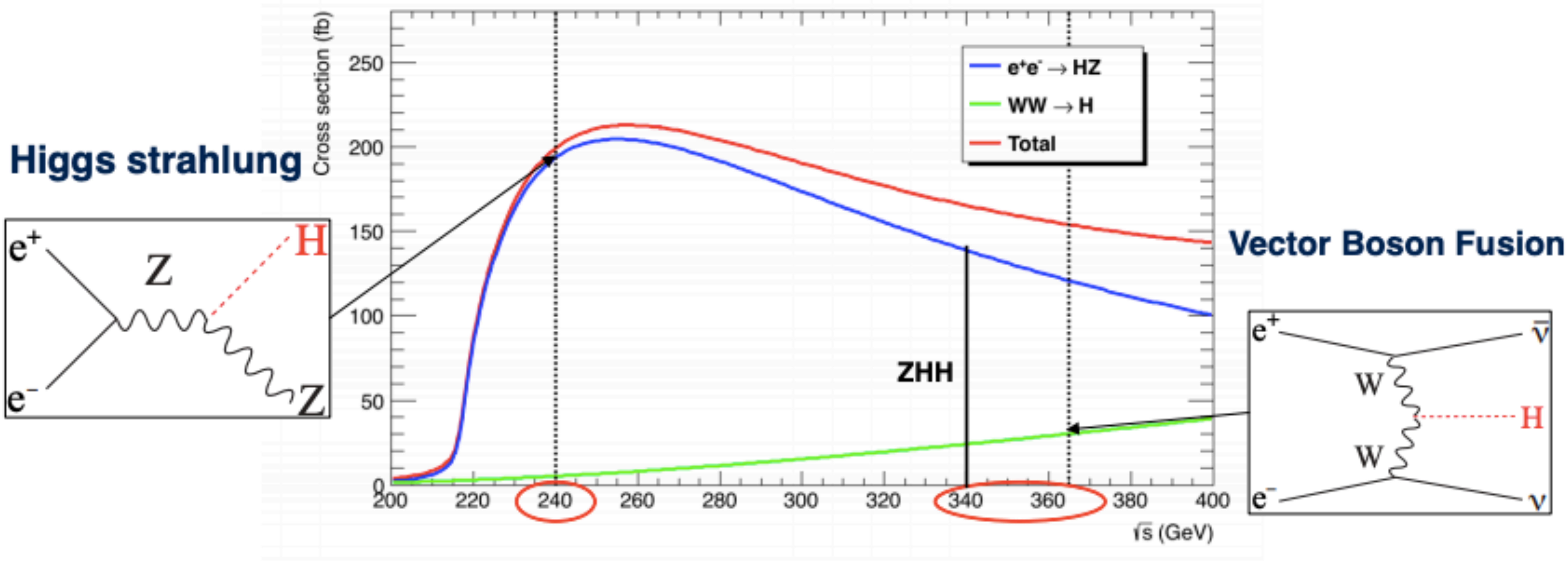
M. Dam, P. Janot

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)

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FCC-ee AS A HIGGS FACTORY AND BEYOND

FCC

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
  - (1st 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
  - (2nd 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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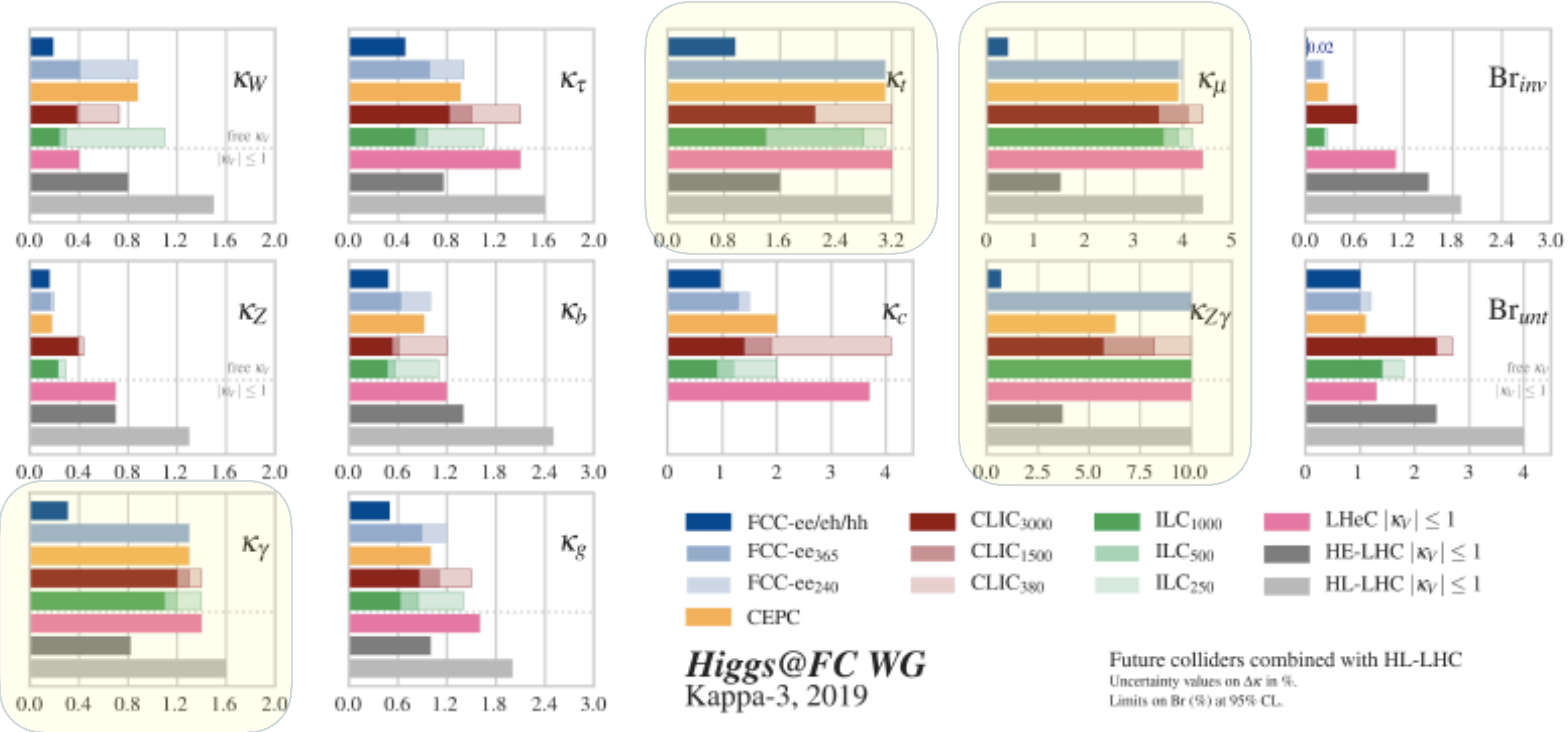
HIGGS COUPLINGS

➤ 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

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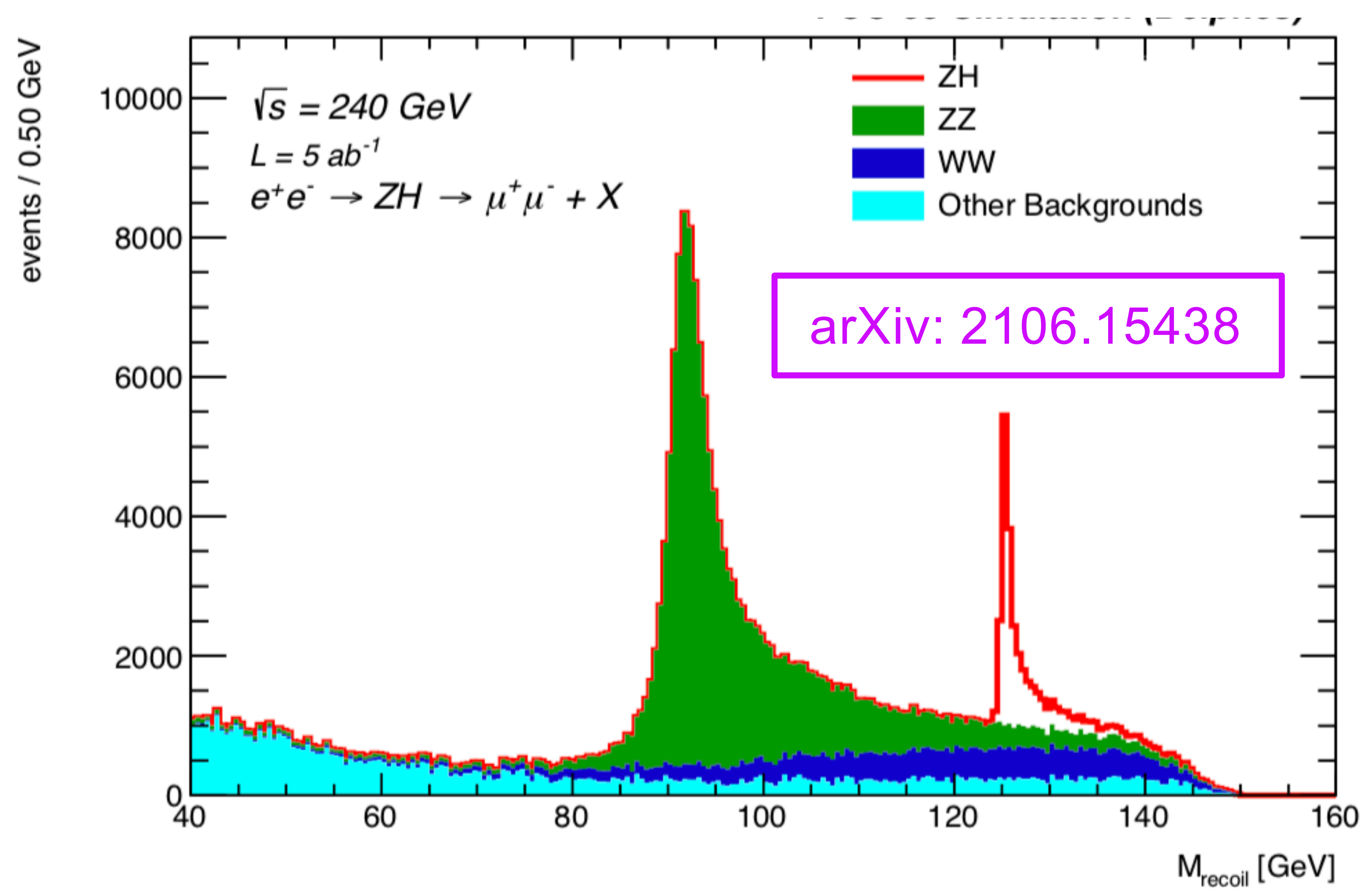
HIGGS FACTORY “CASE STUDIES”

➤ To have a concrete path toward the precision we plan to reach. With complete analysis and realistic detectors

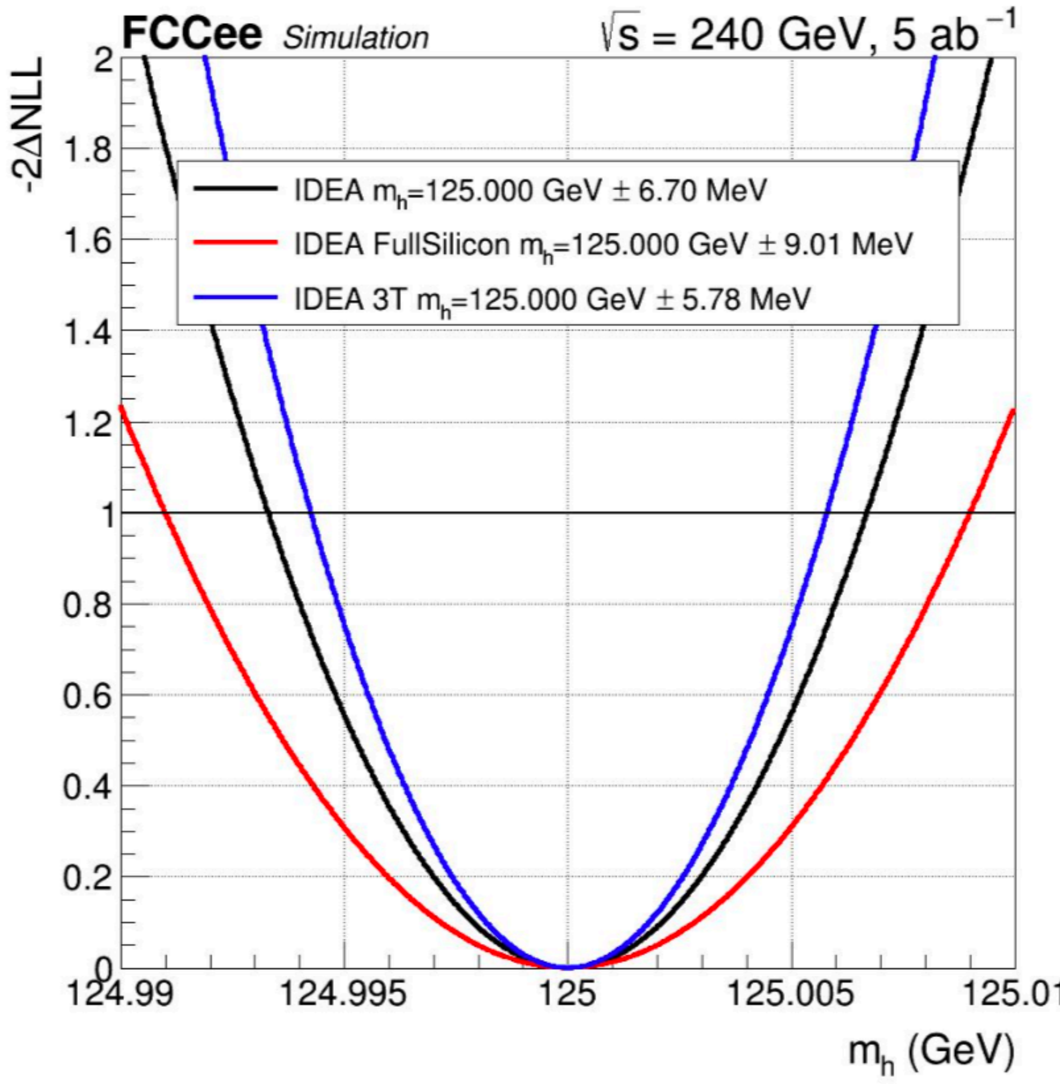
Higgs mass and inclusive cross section measurement

Recoil mass fit in $e^+e^- \to ZH$ with $Z \to \mu^+\mu^-$

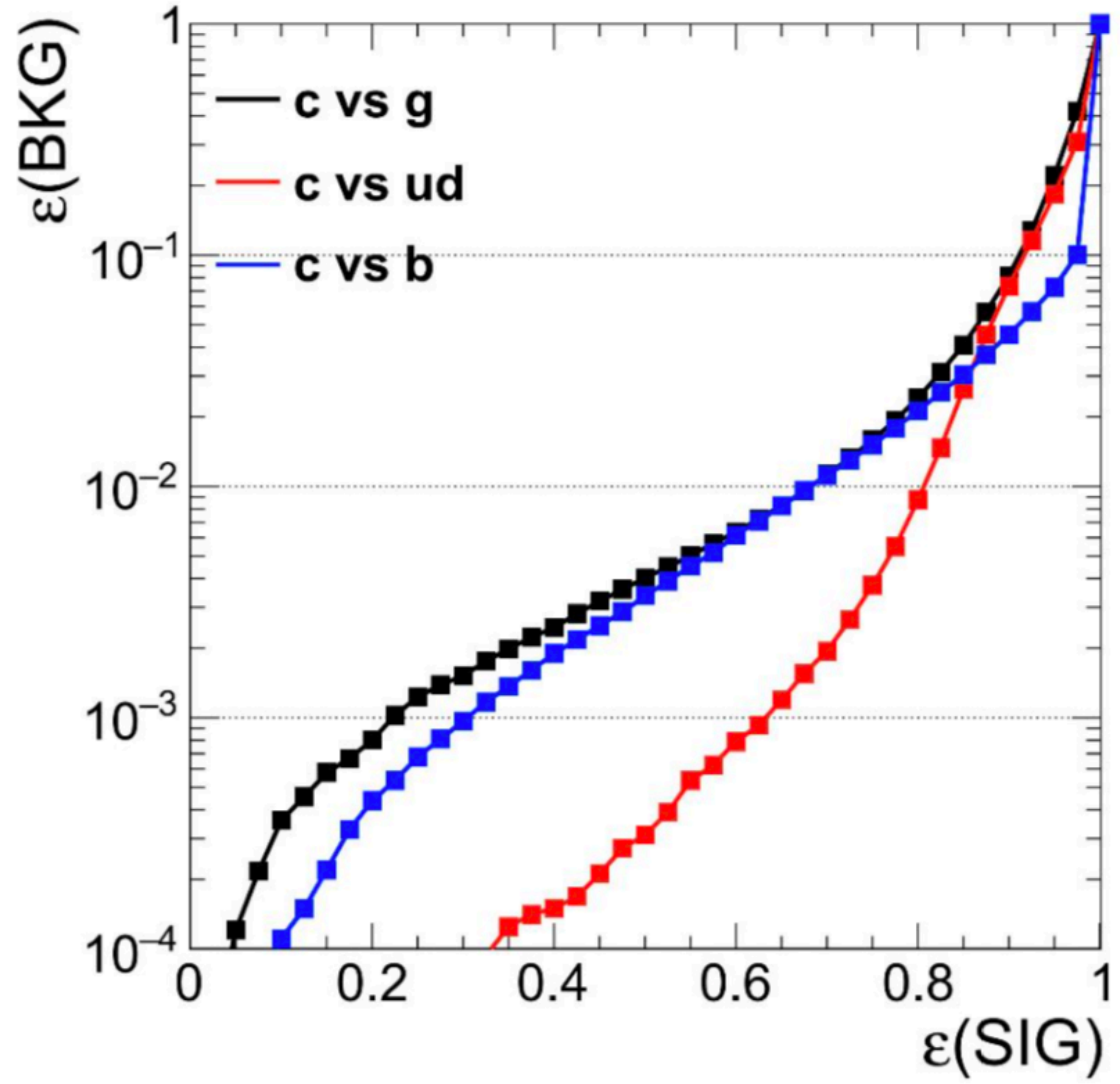


Gentle beamstrahlung
→ limited mass tail

Light tracker much better
Mag. Field of 3T helps a bit



Flavour tagging



- Advanced flavour-tagging algorithm based on a Dynamic Graph Convolutional Neural Network.
- Very promising c-tagging
- Innovative developments on s-tagging too

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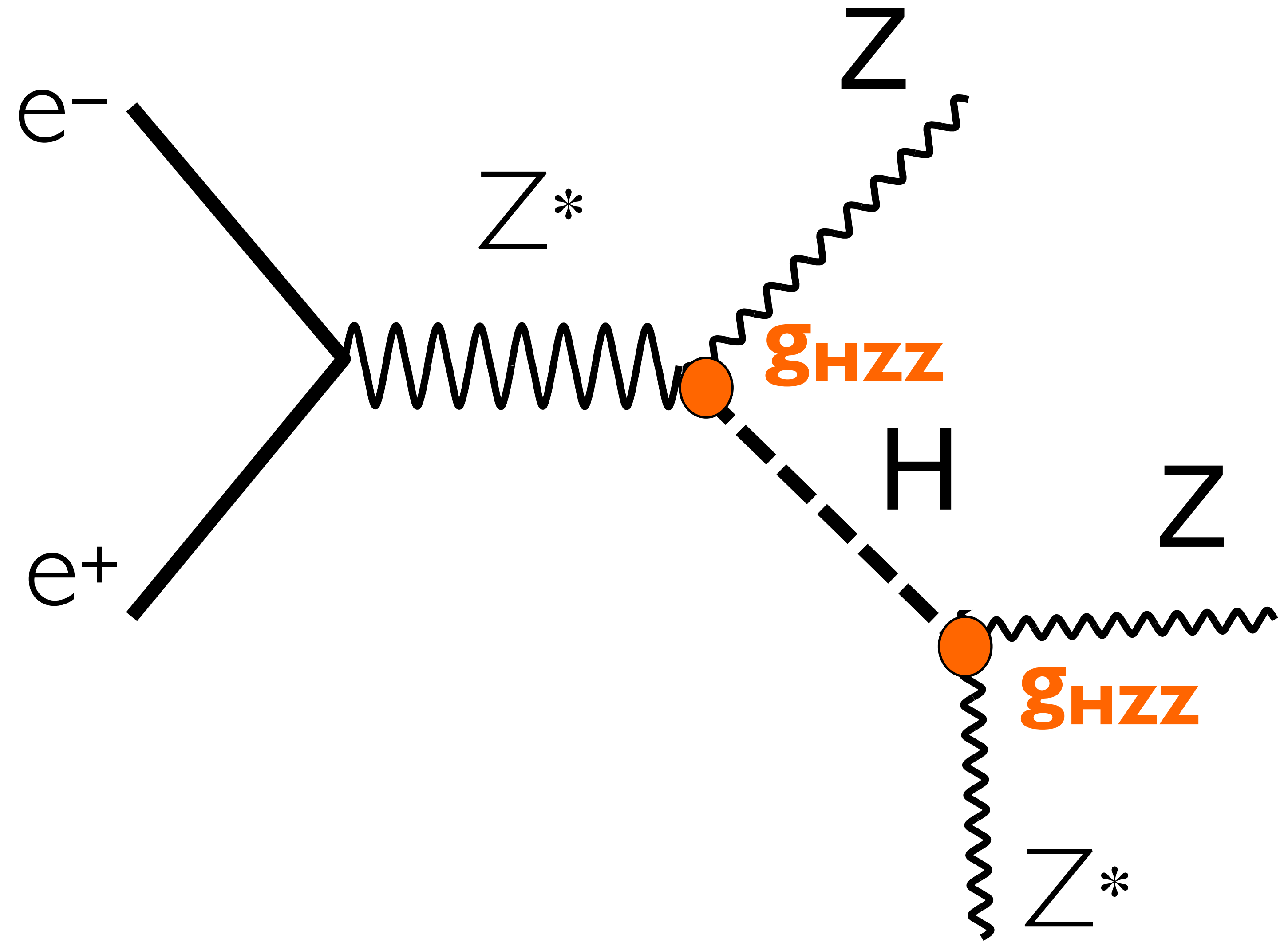
HIGGS WIDTH

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

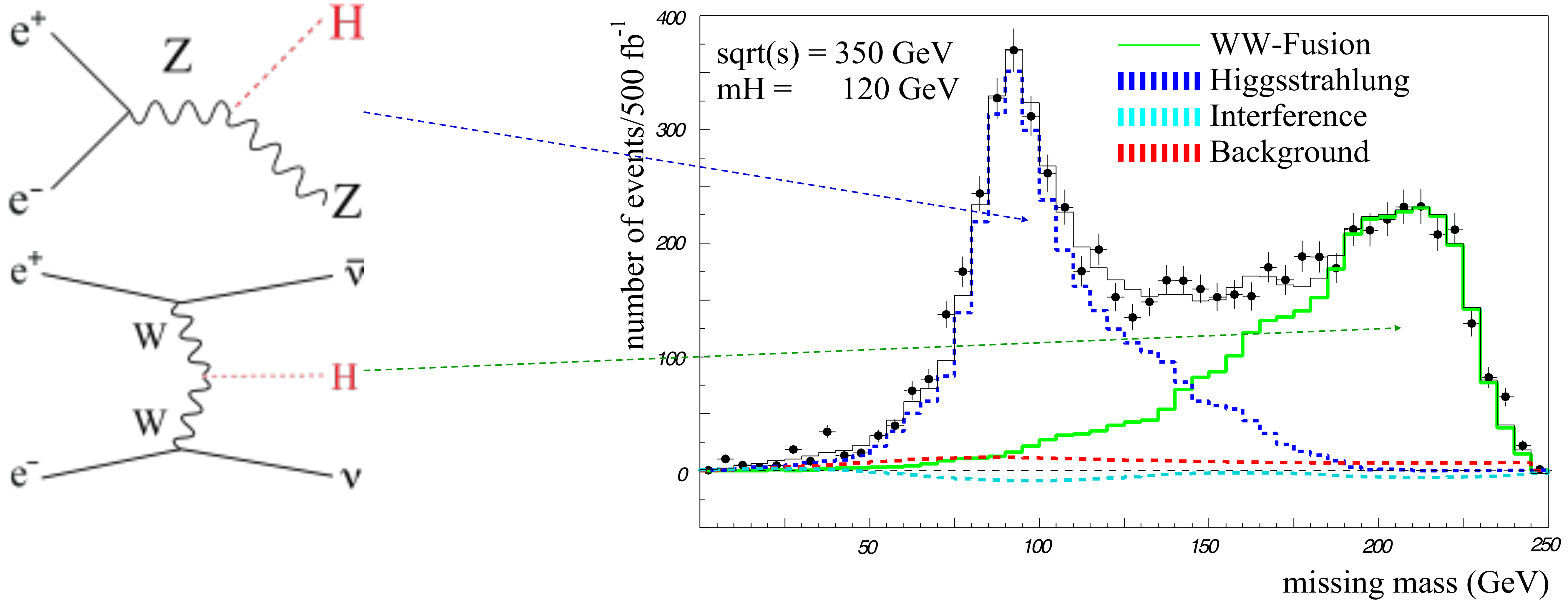
√s=365 not just for Top physics!

ee →HZ & H → ZZ at √s = 240 GeV



- σ_{HZ} is proportional to g_{HZZ}^2
- $BR(H \to ZZ) = \Gamma(H \to ZZ) / \Gamma_H$ is proportional to g_{HZZ}^2 / Γ_H
  - $\sigma_{HZ} \times BR(H \to ZZ)$ is proportional to g_{HZZ}^4 / Γ_H
- Infer the total width Γ_H

WW → H νν→ bbνν at √s = 365 GeV



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

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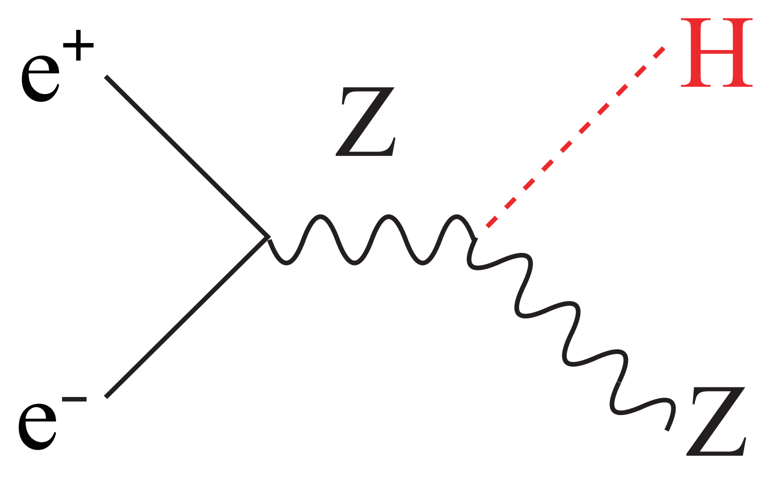
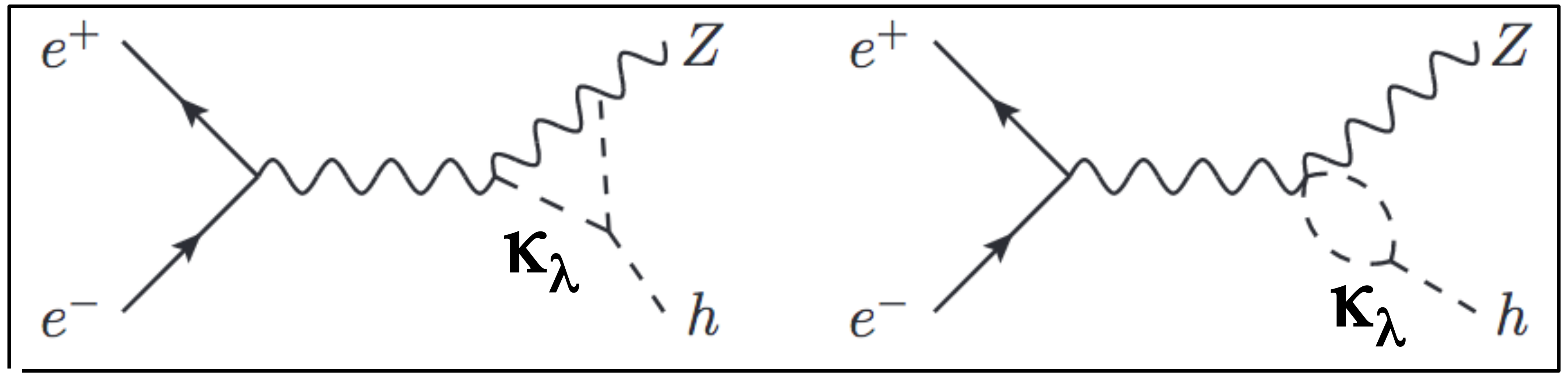
HIGGS SELF-COUPLING WITH SINGLE HIGGS

- Higgs self-coupling, λ_3, is a fundamental parameter of the SM whose value should be checked against prediction
- e+e- colliders with $\sqrt{s}$<500 GeV can profit of the significant effect on single Higgs production

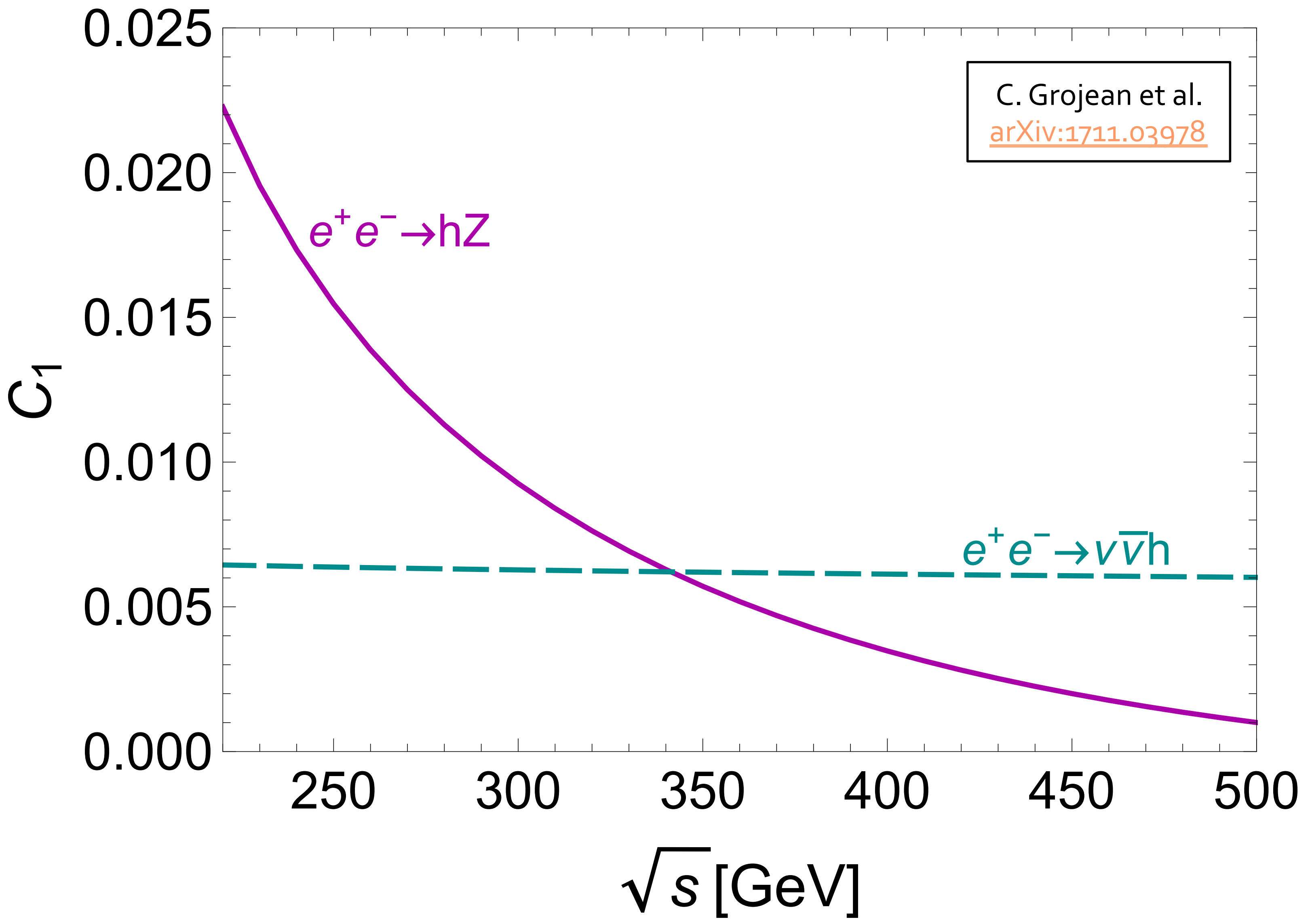
σ_{HZ}



+



M. McCullough
arXiv:1312.3322



Measurement at different $\sqrt{s}$ also helps to lift degeneracy between processes

$\sqrt{s}$=365 not just for Top physics!

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

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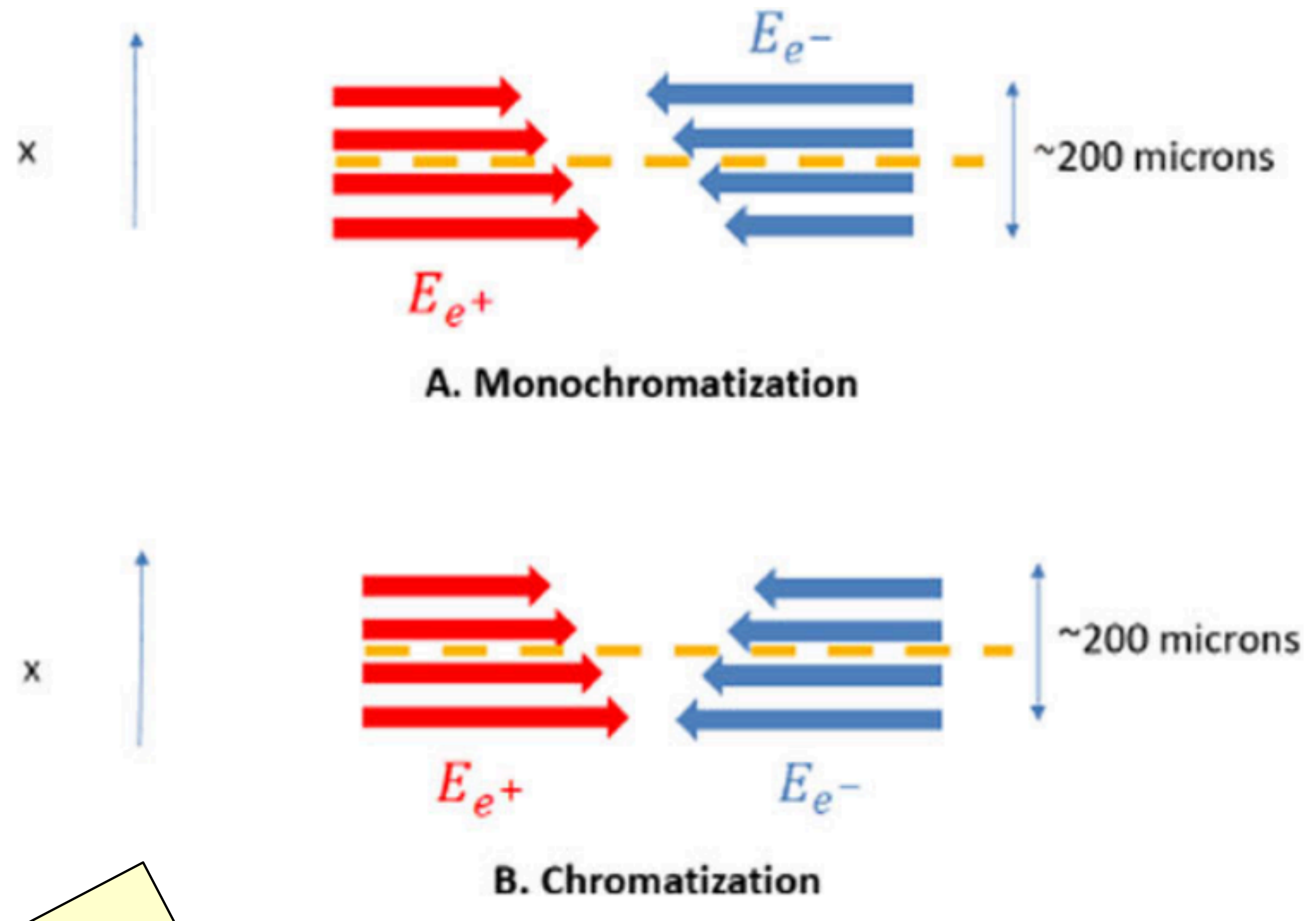
ELECTRON YUKAWA COUPLING

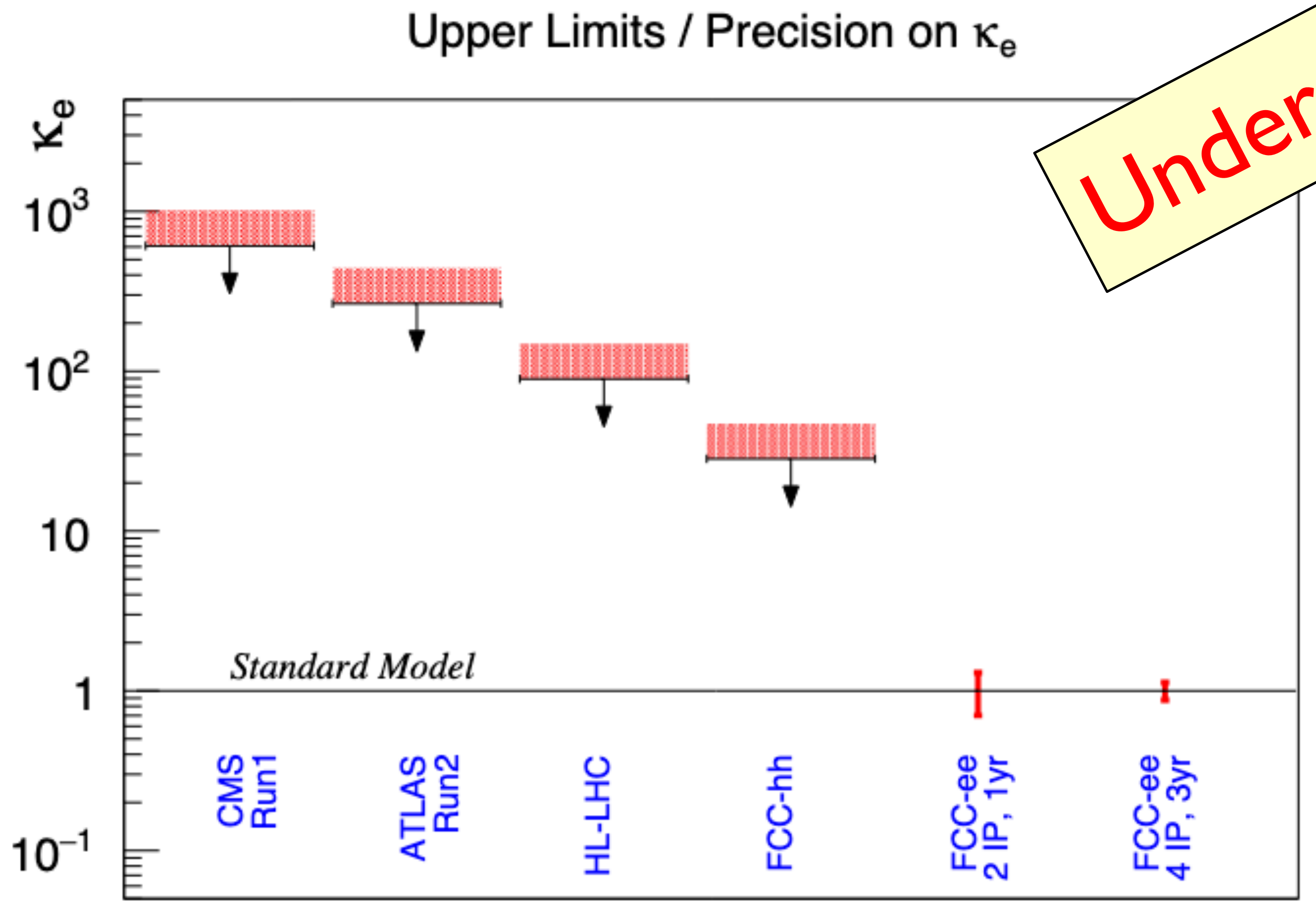
- Something unique: electron Yukawa coupling from $e^+e^- \to H$
  - One of the toughest challenges, which requires:
    - Higgs boson mass prior knowledge to a couple MeV
    - Huge luminosity (i.e., several years with possibly 4 IPs)
    - (Mono)chromatisation: Γ_H (4.2 MeV) $\ll \delta_{\sqrt{s}}$ (100 MeV)
    - Continuous monitoring and adjustment of $\sqrt{s}$
    - Different e^+ and e^- energies (to avoid integer spin tune)
    - Extremely sensitive event selection against SM backgrounds
      - For all Higgs decay channels



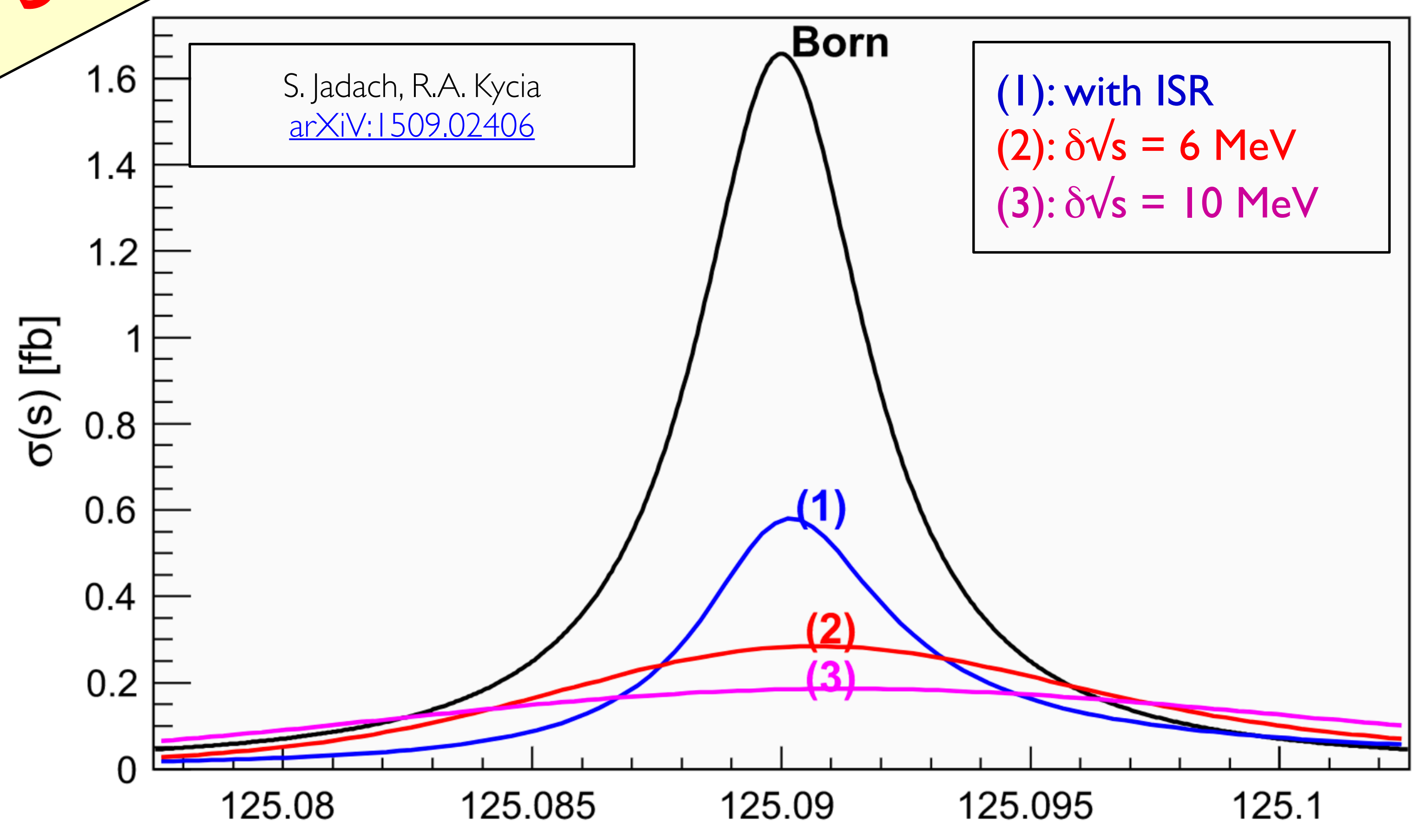
Uncertainty at the SM level

(IF everything works nominally)

Indicates whether the Higgs boson (also) gives mass to ordinary matter.



Under Study



Very very challenging

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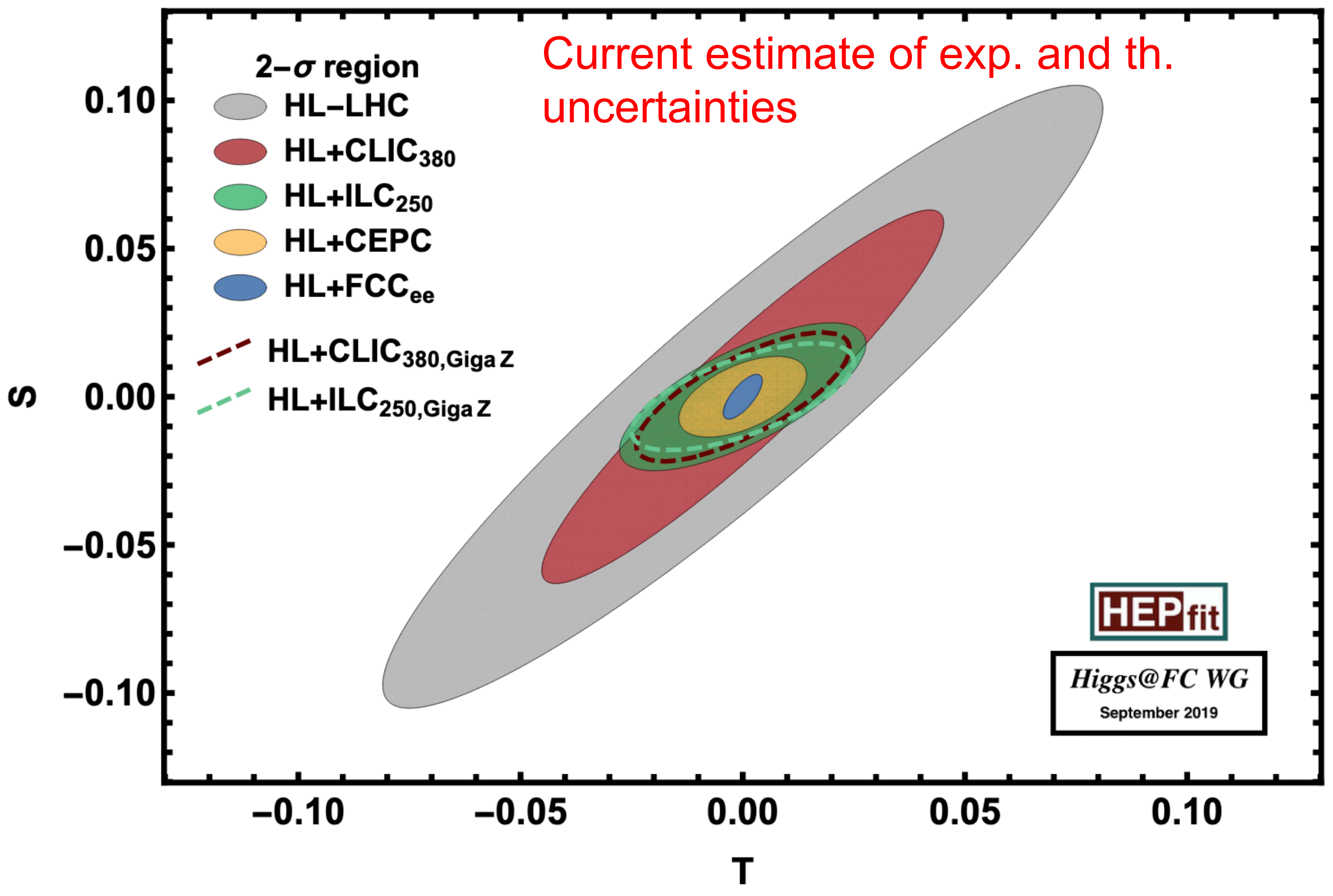
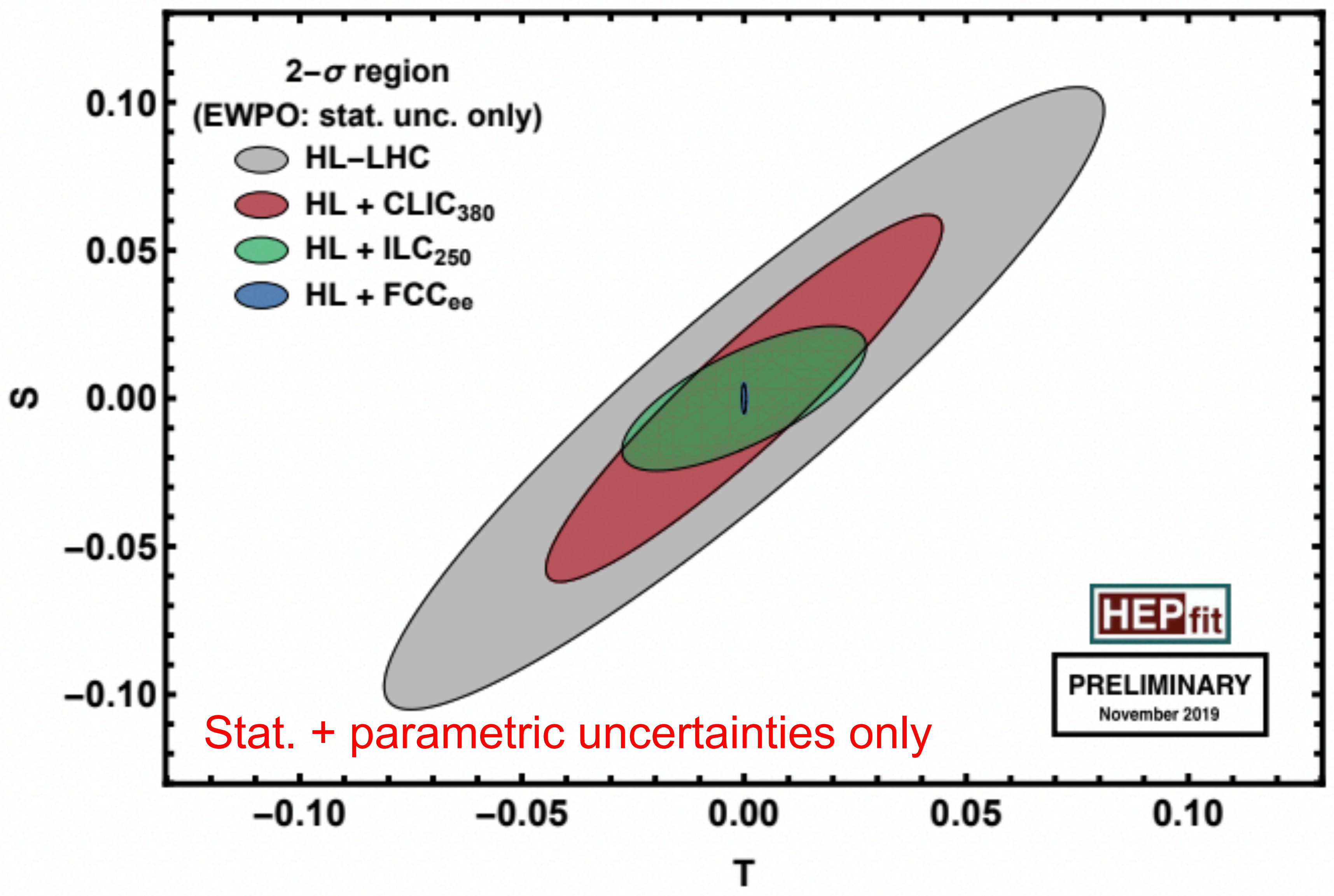
FCC-ee AS AN ELECTROWEAK FACTORY

- With highest luminosities at 91, 160 and 350 GeV
  - Complete set of EW observables can be measured
    - Precision (10^{-3} today) down to few 10^{-6}



- Precision unique to FCC-ee, with smallest parametric errors
  - Challenge: match syst. uncertainties to the stat. precision
    - A lot more potential to exploit with good detector design than the present treatment suggests
    - Theory work is critical and initiated
- Precision = discovery potential (e.g., NP in Z/W propagators)



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SELECTED ELECTROWEAK QUANTITIES (FROM FCC-ee)

Orders of magnitudes reduction of statistical uncertainties

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above [43]
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]
σ^0_{had} ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$231,480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	$128,952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak [34]
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV)	$80,350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R_ℓ^W [45]
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	$172,740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{CM} = 365$ GeV run

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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.

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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^0
      - 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)

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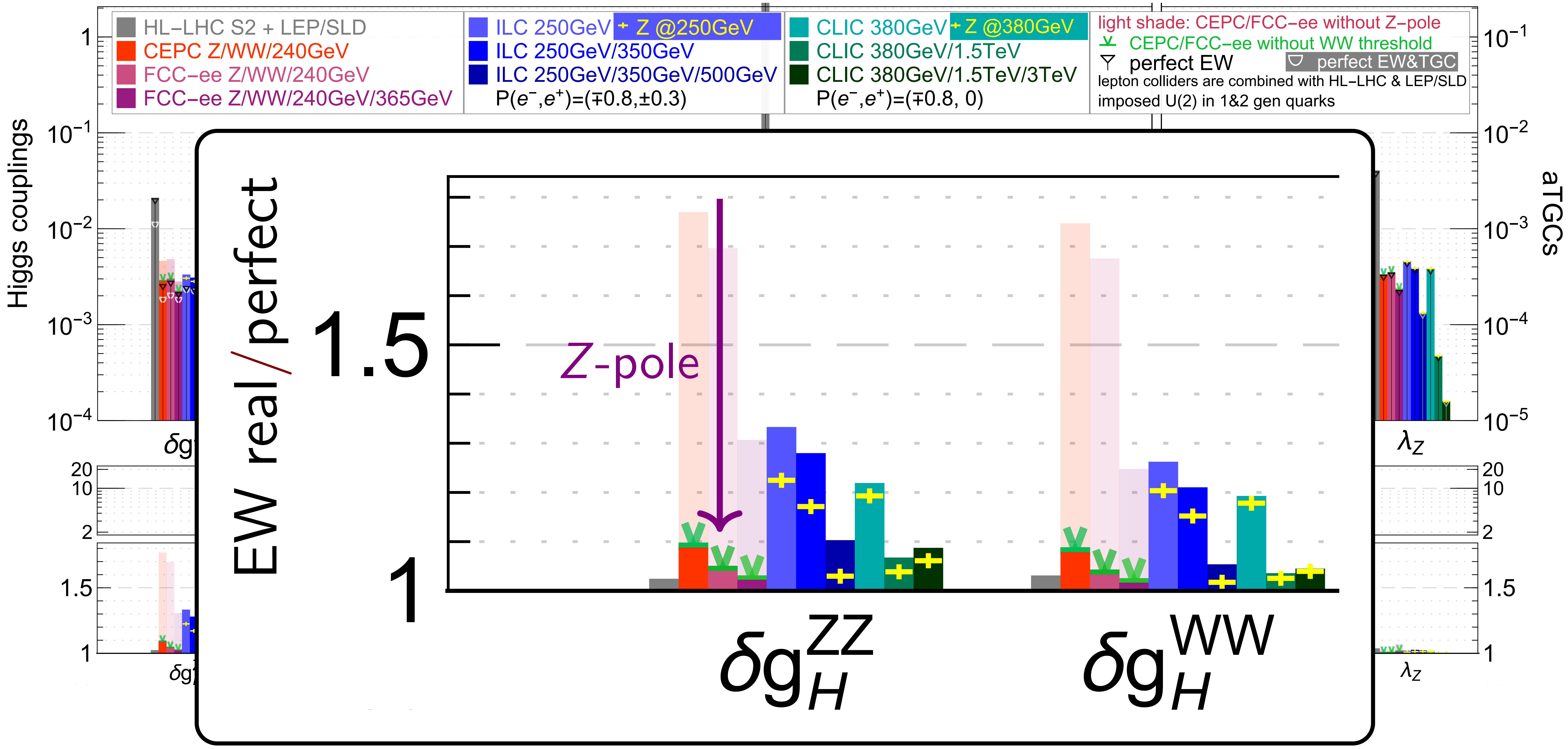
IMPACT OF Z POLE RUN ON HIGGS

- Z-pole run and precise EWK observables have a big impact also on the Higgs effective couplings



15 EW param. also marginalized over / assumed perfectly constrained

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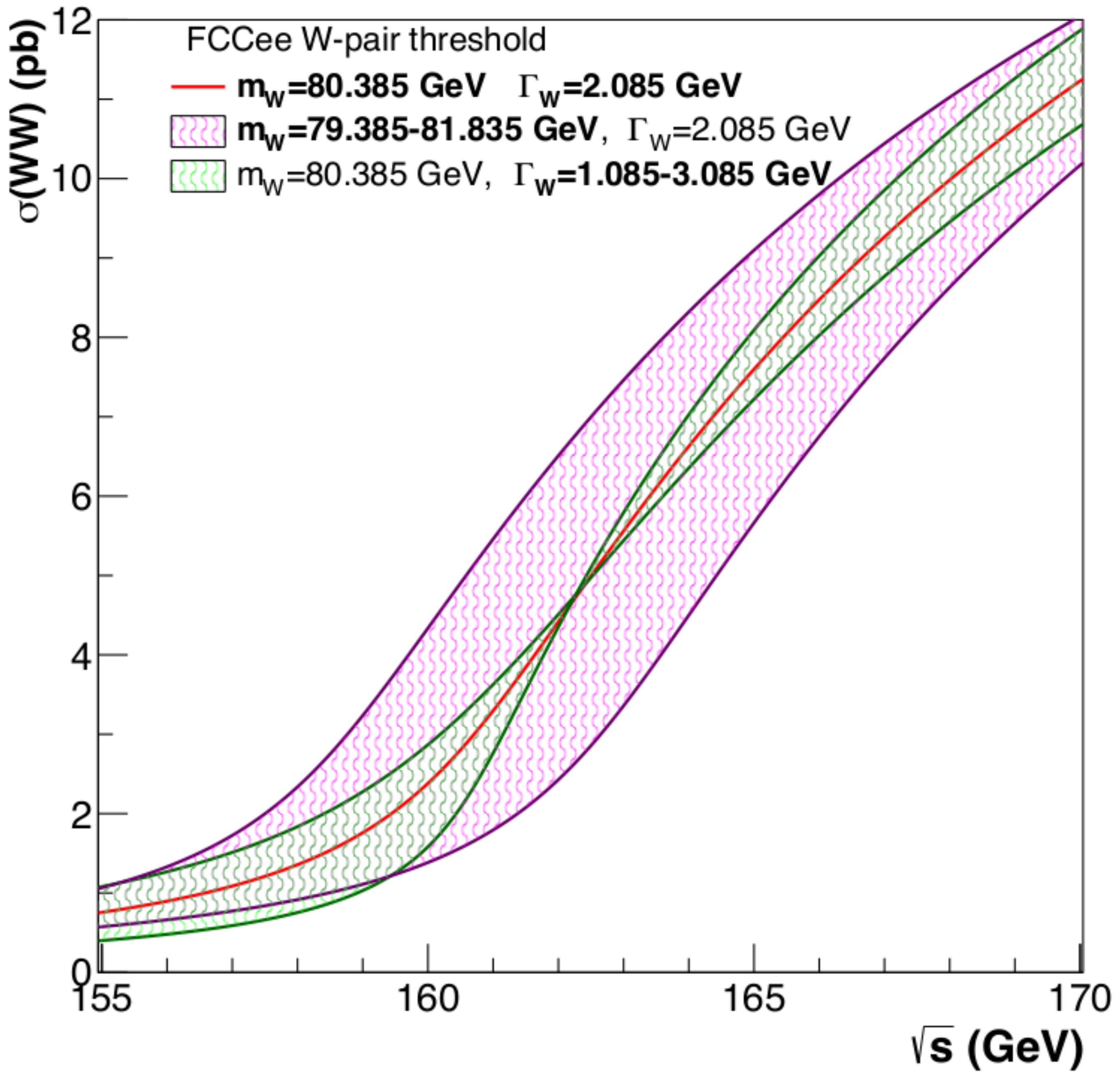
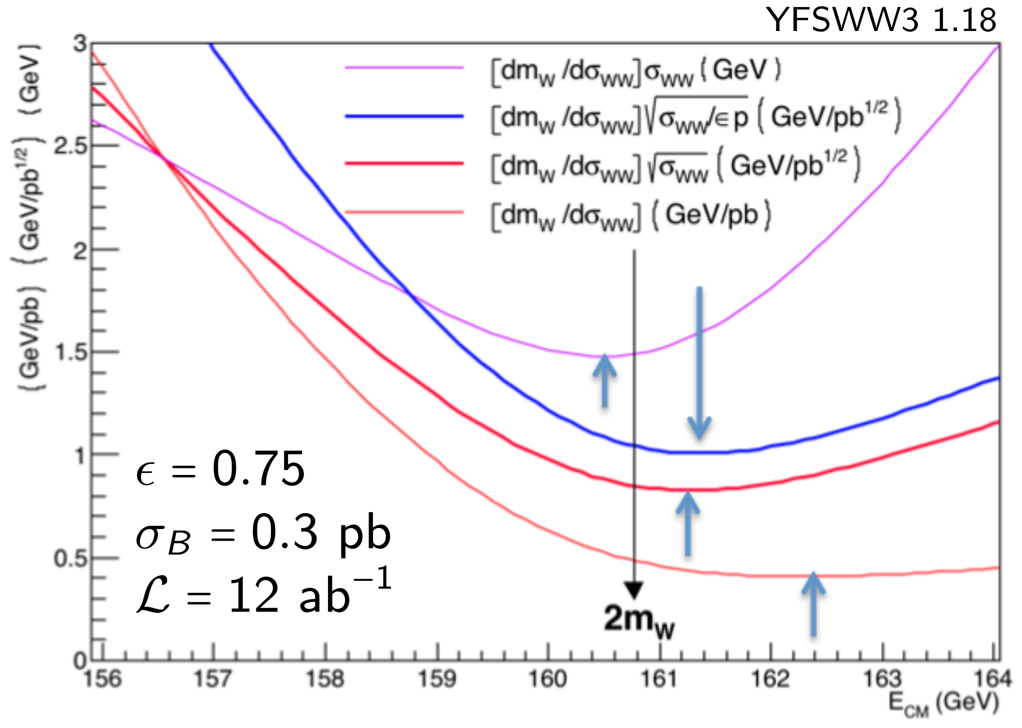
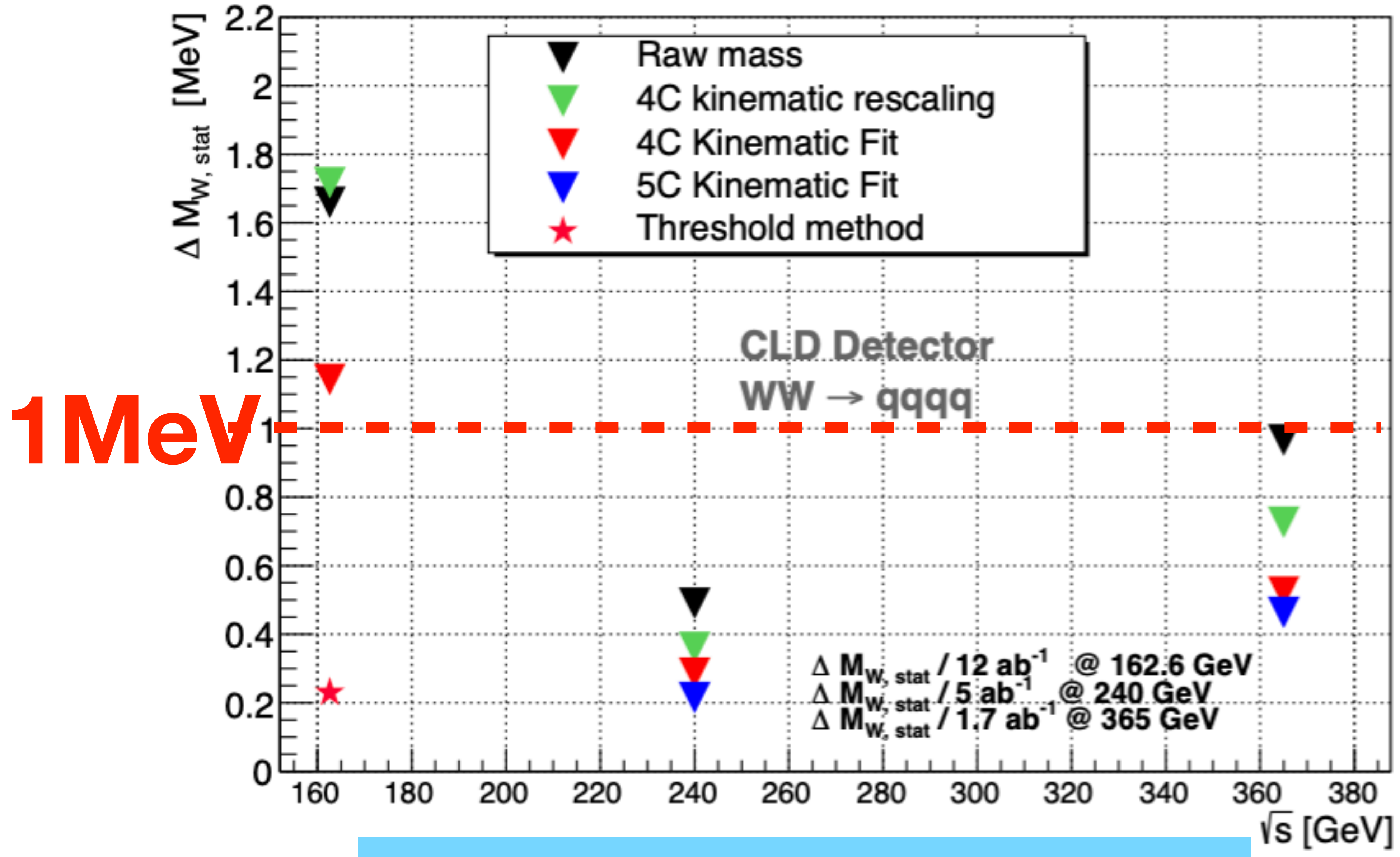
FCC **AT THRESHOLD**

HOT TOPIC: W MASS AND WIDTH







ABOVE THRESHOLD

Optimal energy : E = 161.4 GeV
$\mathbf{\Delta M_W}$ **= 0.23 MeV**

LEP : ΔM_W = 210 MeV
$\mathcal{L}$ = 10 pb^{-1}

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

- Precise M(W) from threshold run
- **M(W) direct reconstruction from decay products useful/needed at any √s>threshold**
- Competitive as statistical uncertainty but different challenges to be considered:
  - Event reconstruction, choice of jet algorithms
  - Lepton momentum scale and resolution
  - Kinematical fitting

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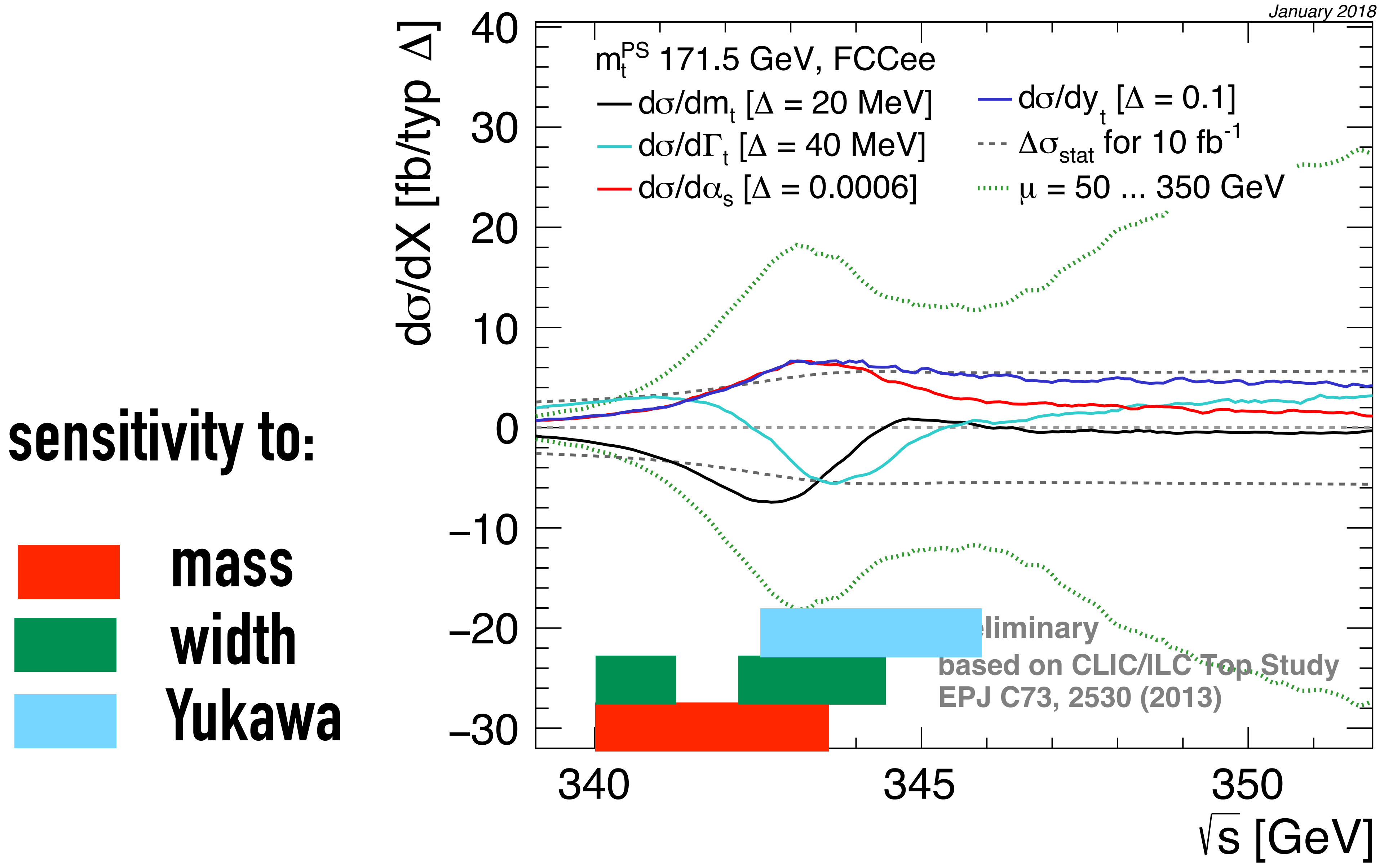
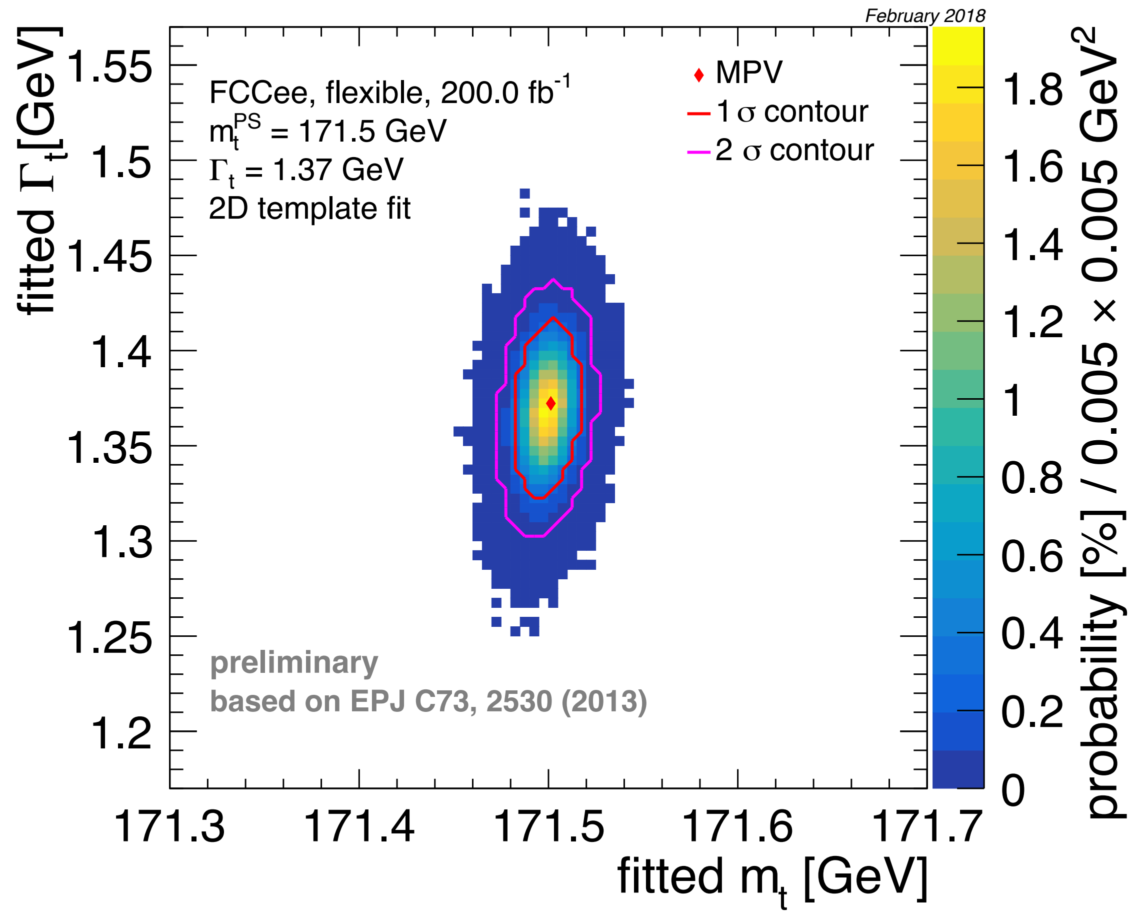
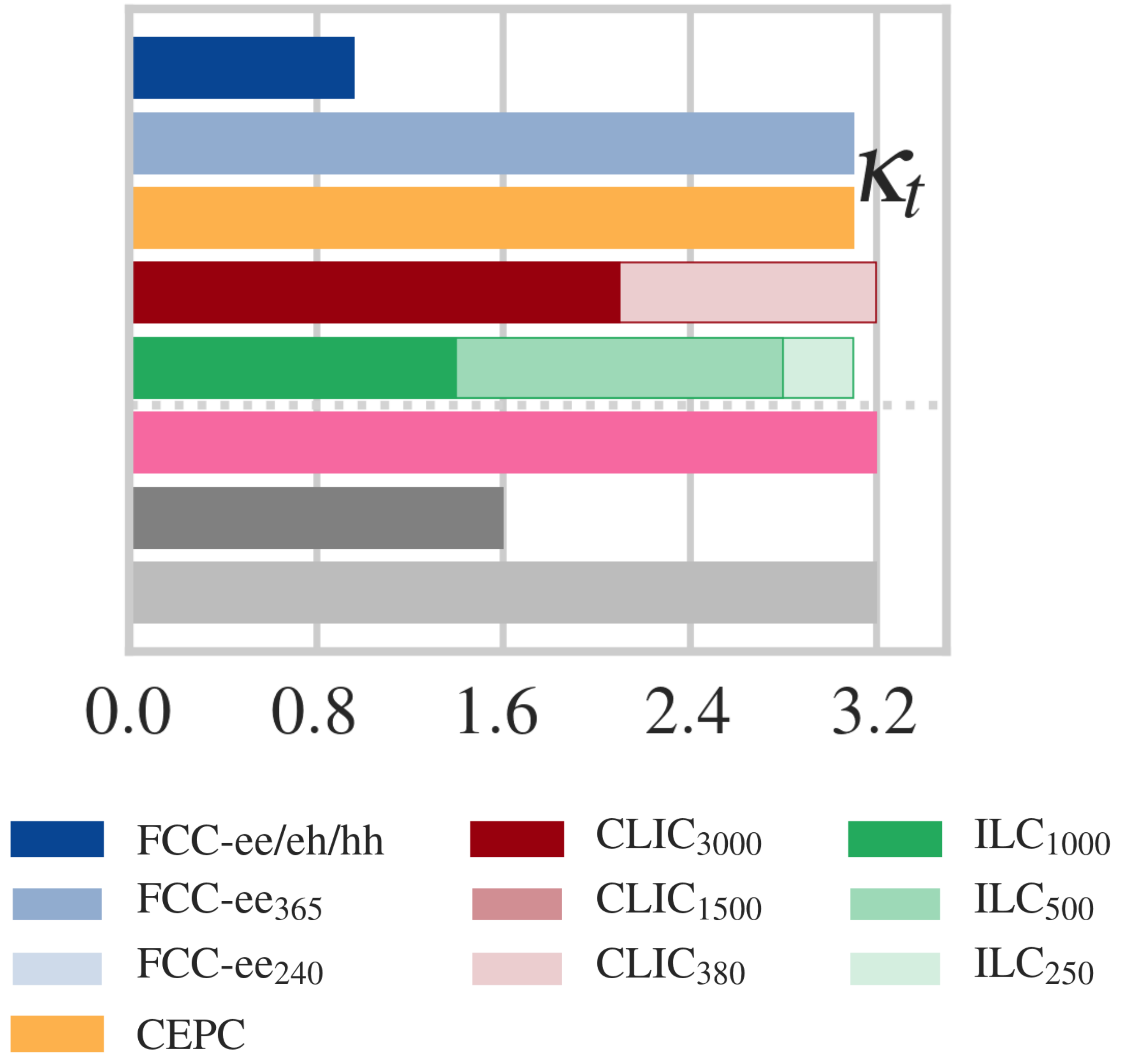
TOP PHYSICS AT FCC-ee

- 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.**

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FCC

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_s^0	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	$\sim$ 2 000	$\sim$ 10	n/a (5)
LHCb Run I	150	-	$\sim$ 15 (–)
LHCb Upgrade	$\sim$ 5000	-	$\sim$ 500 (50)
FCC-ee	$\sim$ 200000	$\sim$ 1000	$\sim$1000 (100)

Yelds for flavor anomalies studies:

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

Full reconstruction possible

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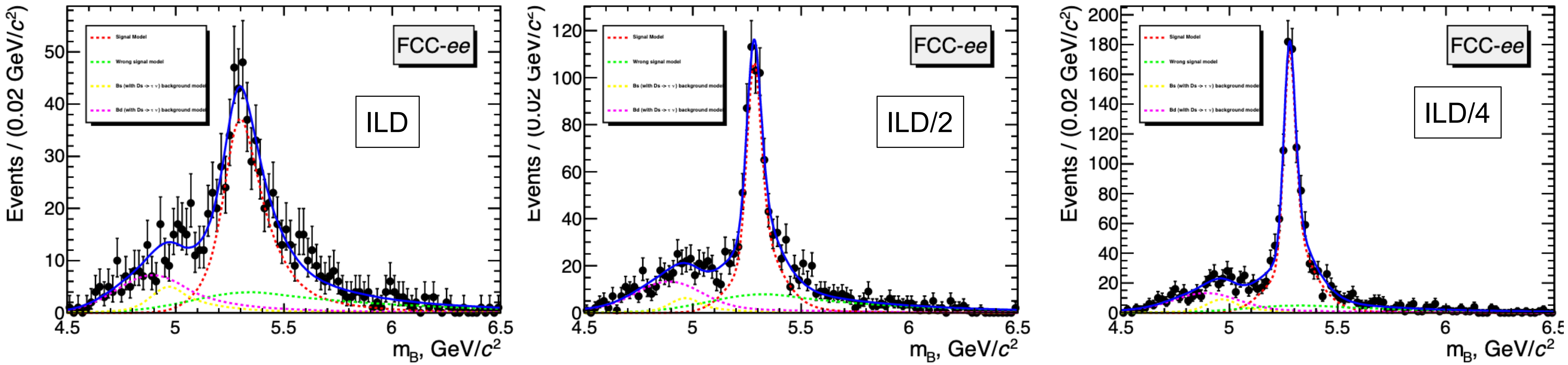
FCC

FLAVOR PHYSICS CASE STUDIES

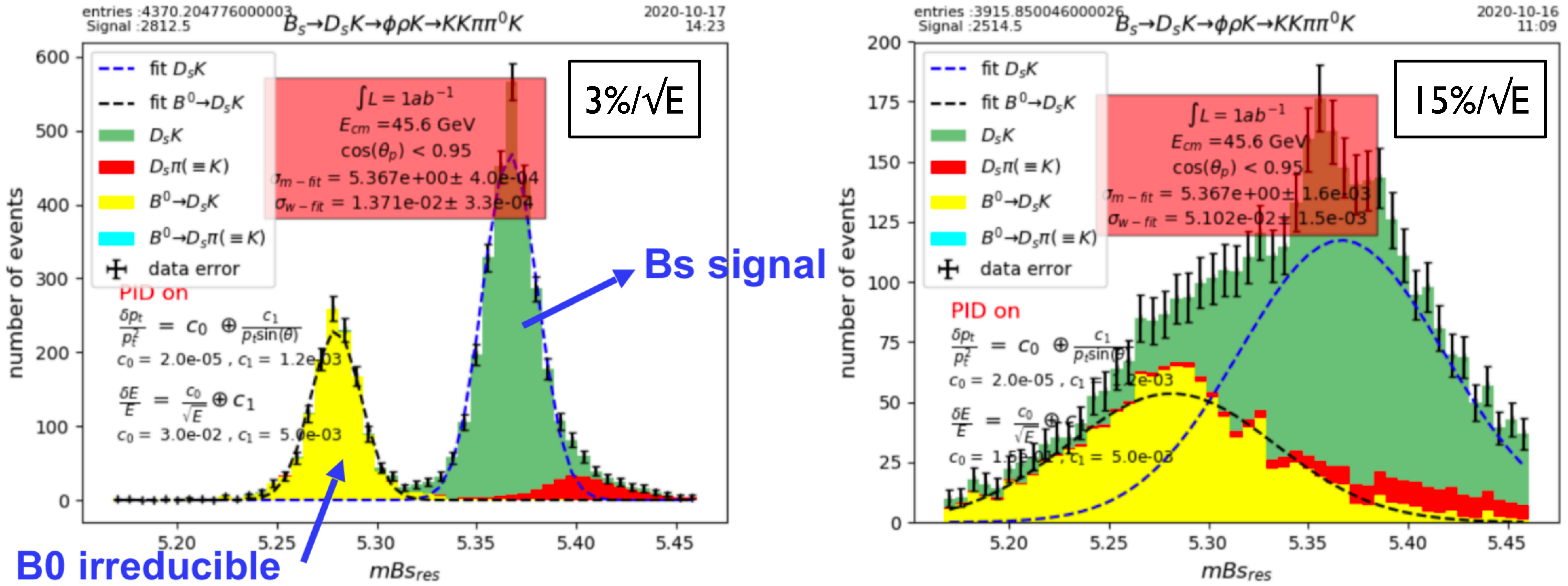
A major background missing in these plots

$B^{*0} \to K^{*0} D_s D_s (D_s \to \pi\pi\pi\pi^0\pi^0)$

- $B^0 \to K^{*0}\tau^+\tau^-$: need excellent Vertexing

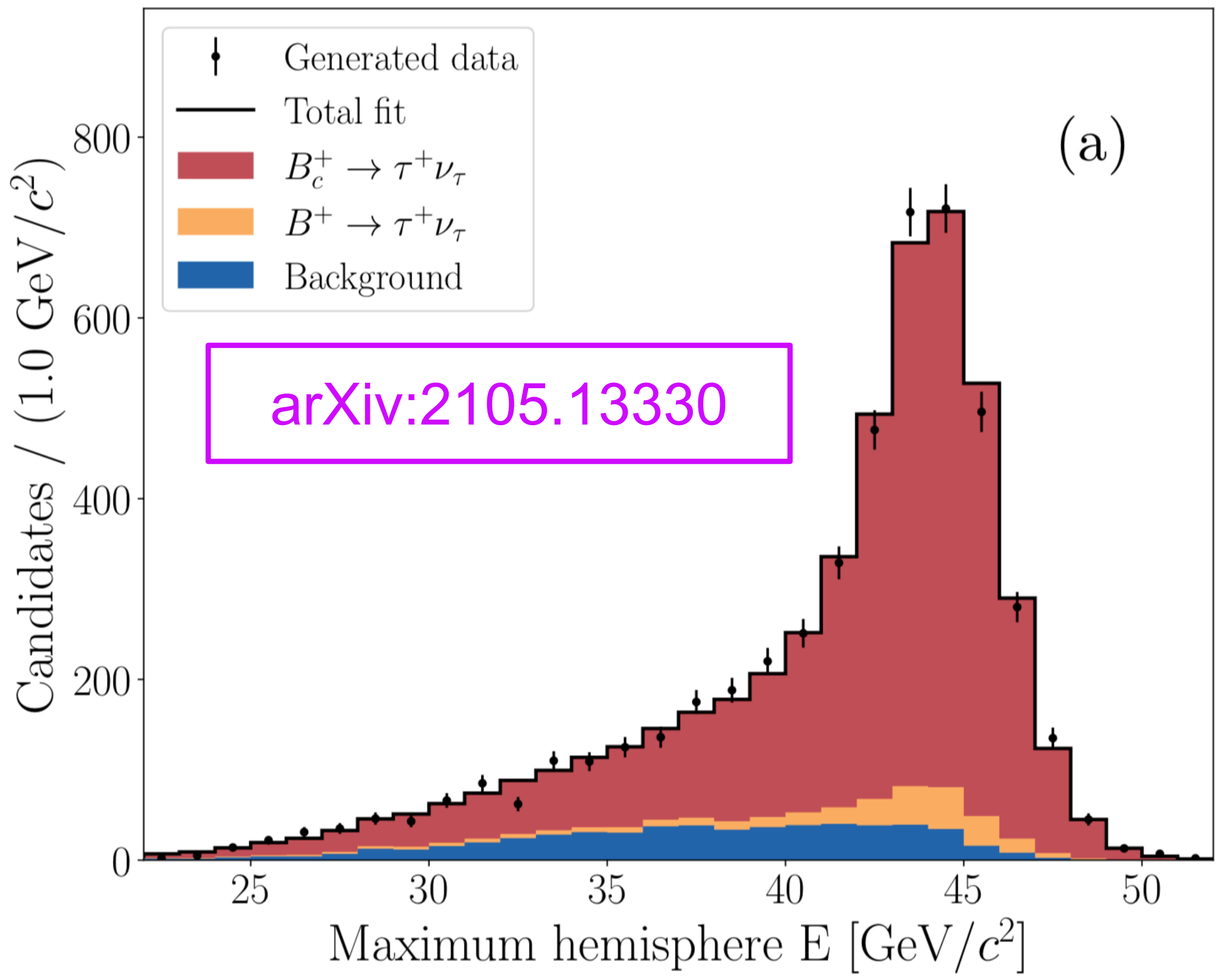


- $B_s \to D_s K$, modes with neutrals : ECAL energy resolution prospects



State-of-the-art Xtal-type to HGCal-type : $\sigma(D_s^\pm(\phi\rho^\pm)K^\mp) \approx 14MeV \to 51MeV$

$B_c \to \tau\nu$:



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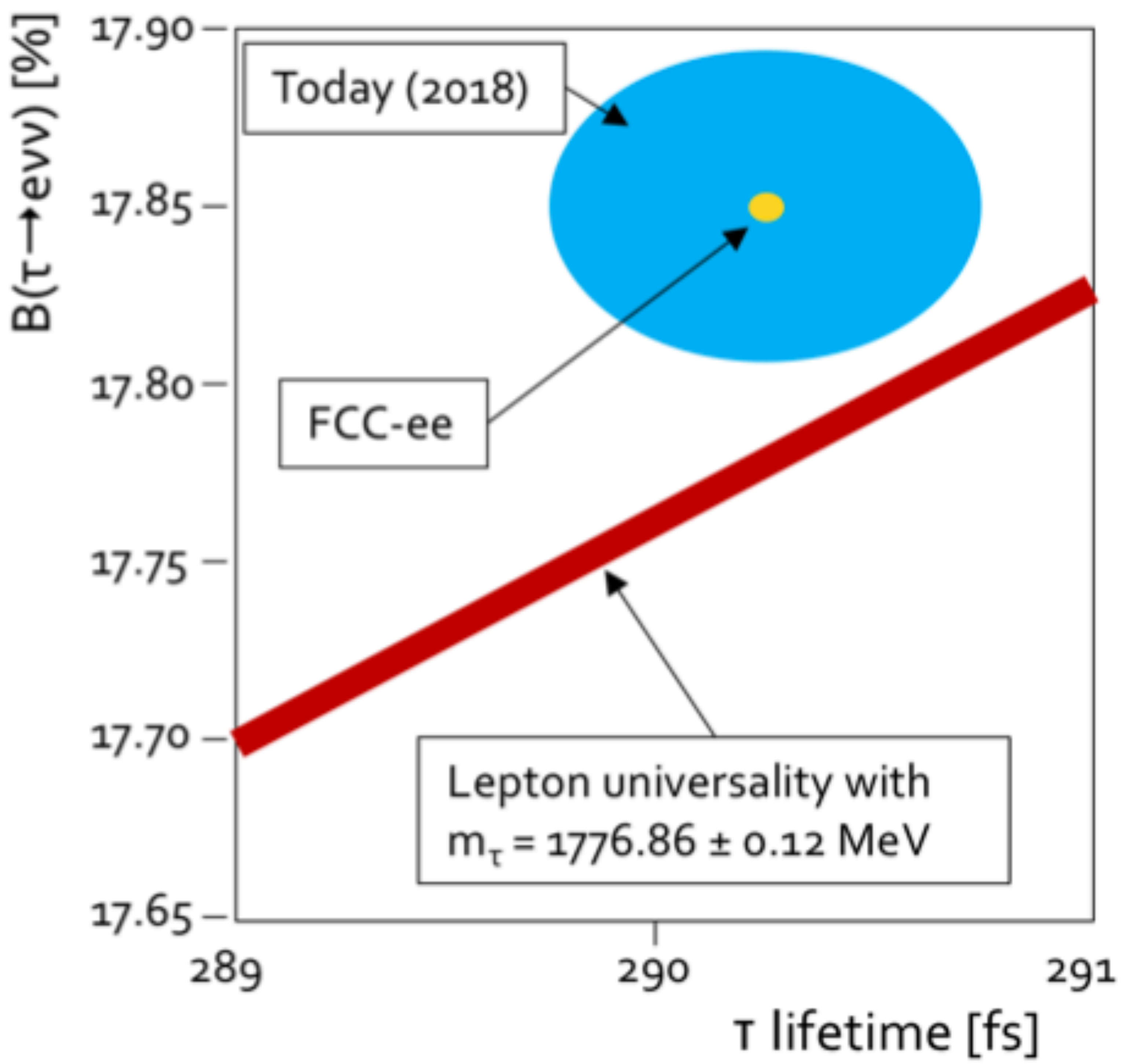
THE INTENSITY FRONTIER - TAU PHYSICS

- Enormous statistics: 1.7 10^{11} ττ events
- Clean environment, boost, vertexing
- Much improved measurement of tau mass, lifetime, BR's will be crucial for:
  - τ-based EWPOs (R_τ, A_{FB}^{pol}, P_τ)
  - Lepton universality violation tests
  - PMNS matrix unitarity
  - Constraints on Light-heavy neutrino mixing



Detector Requirements

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

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BSM PHYSICS: RARE PROCESSES FIP

- Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m(Z). They could be also DM candidates.
- Signatures explored: photons and long lifetimes (LLP's).
  - Axion-like particles
  - Dark photons
  - Heavy Neutral Leptons

More "extravagant" signatures can be studied in the future profiting of the clean environment

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

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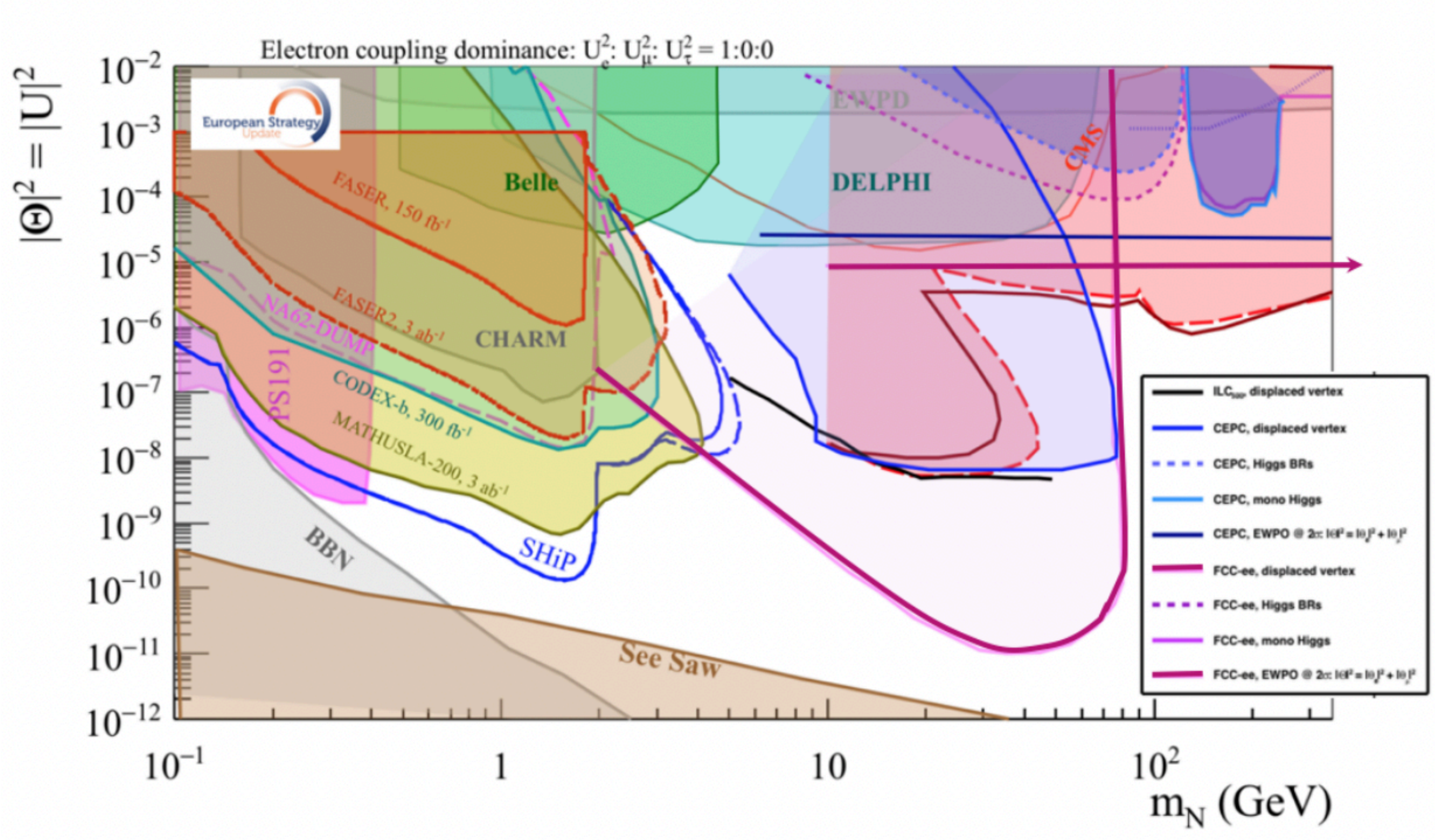
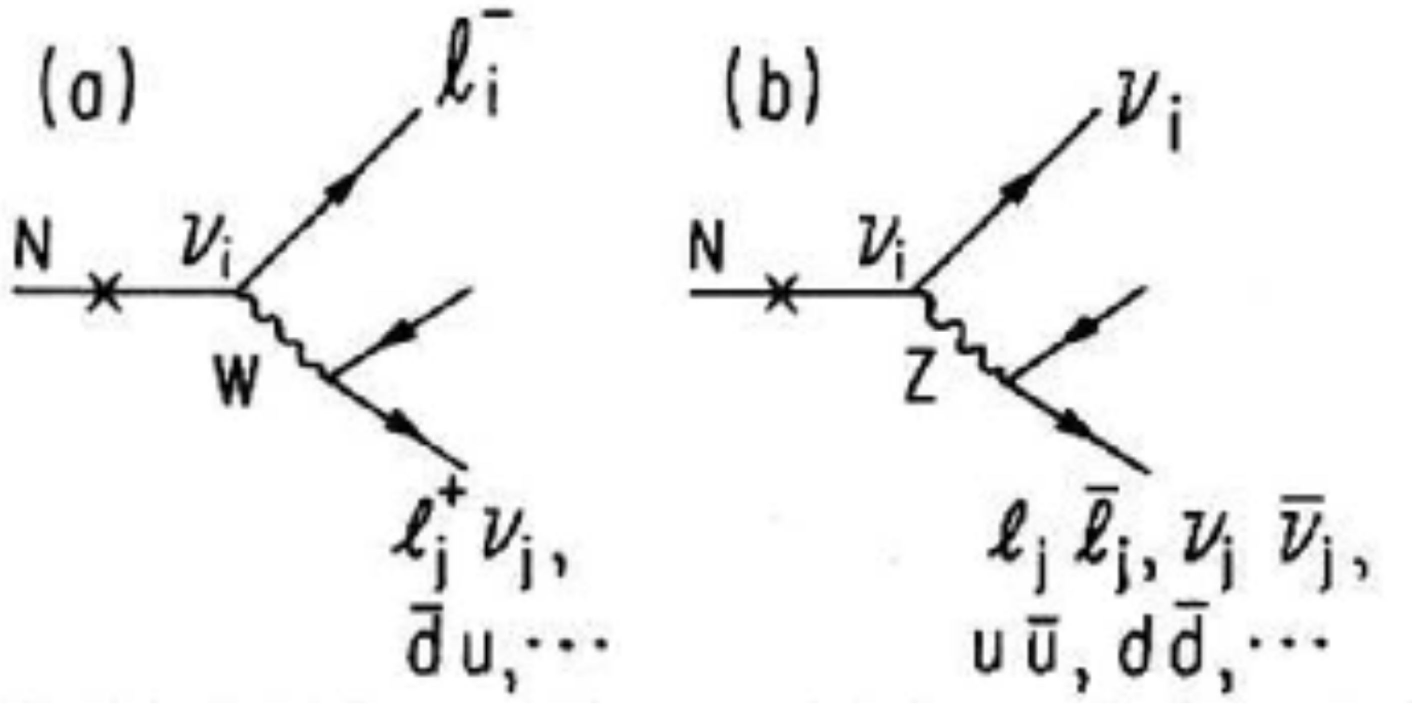
BSM DIRECT SEARCHES - HEAVY NEUTRAL LEPTONS

- HNL more new studies in progress: “Snowmass white paper” in preparation.
- 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 $|U|2=10^{-12}$

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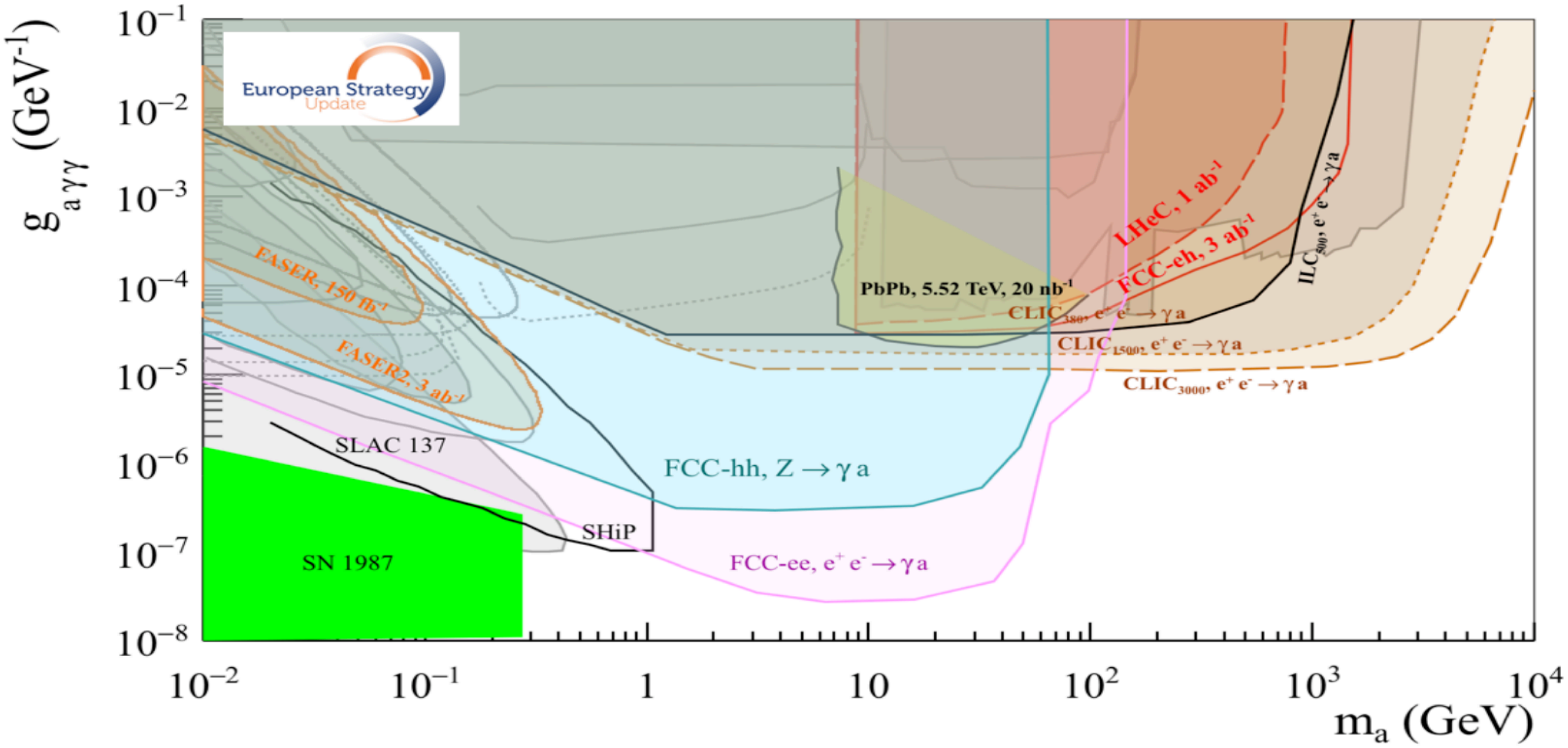
BSM DIRECT SEARCHES - ALPS

- ➤ 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!



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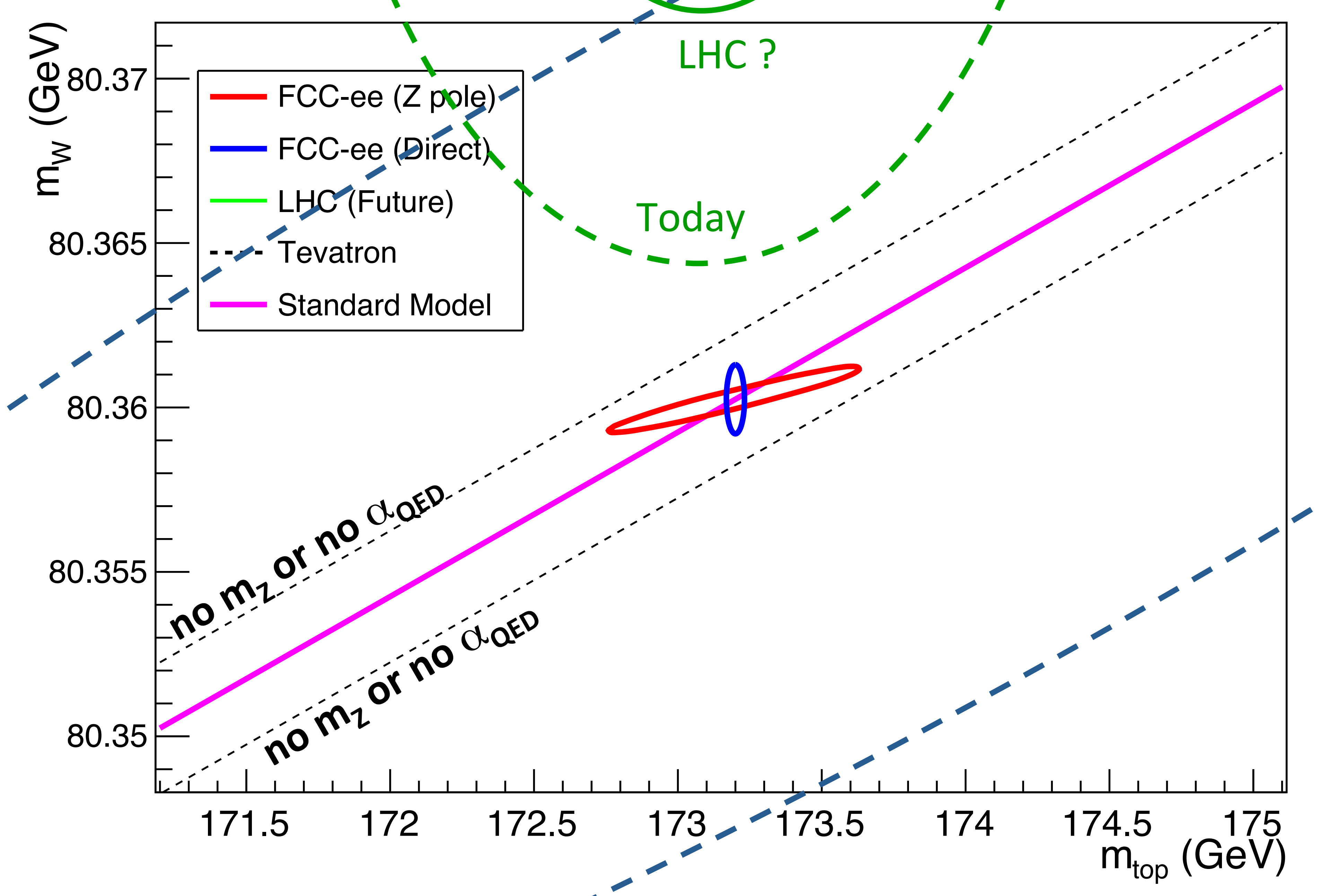
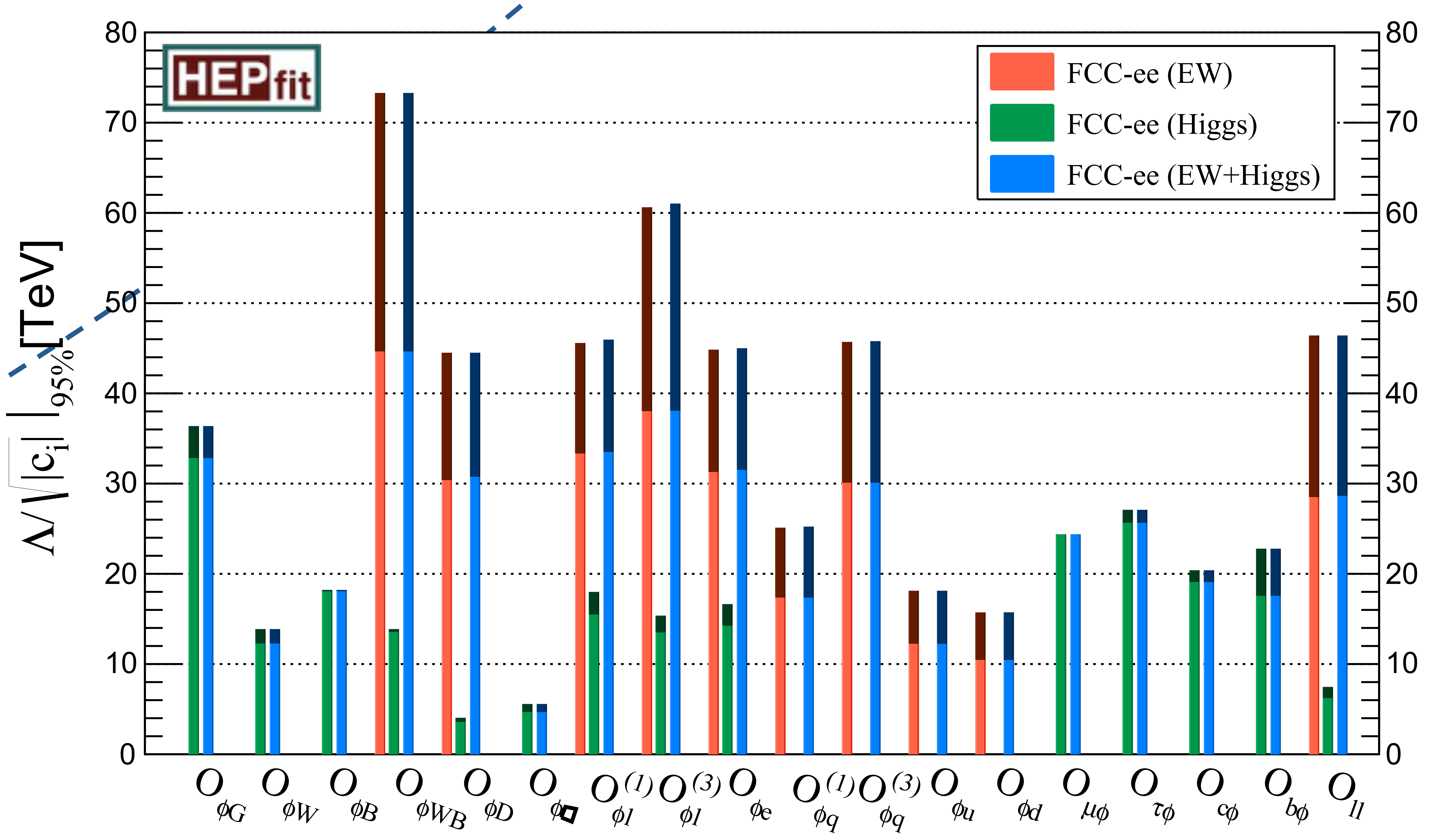
SUMMARY ON NEW PHYSICS SENSITIVITIES

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.

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

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

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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

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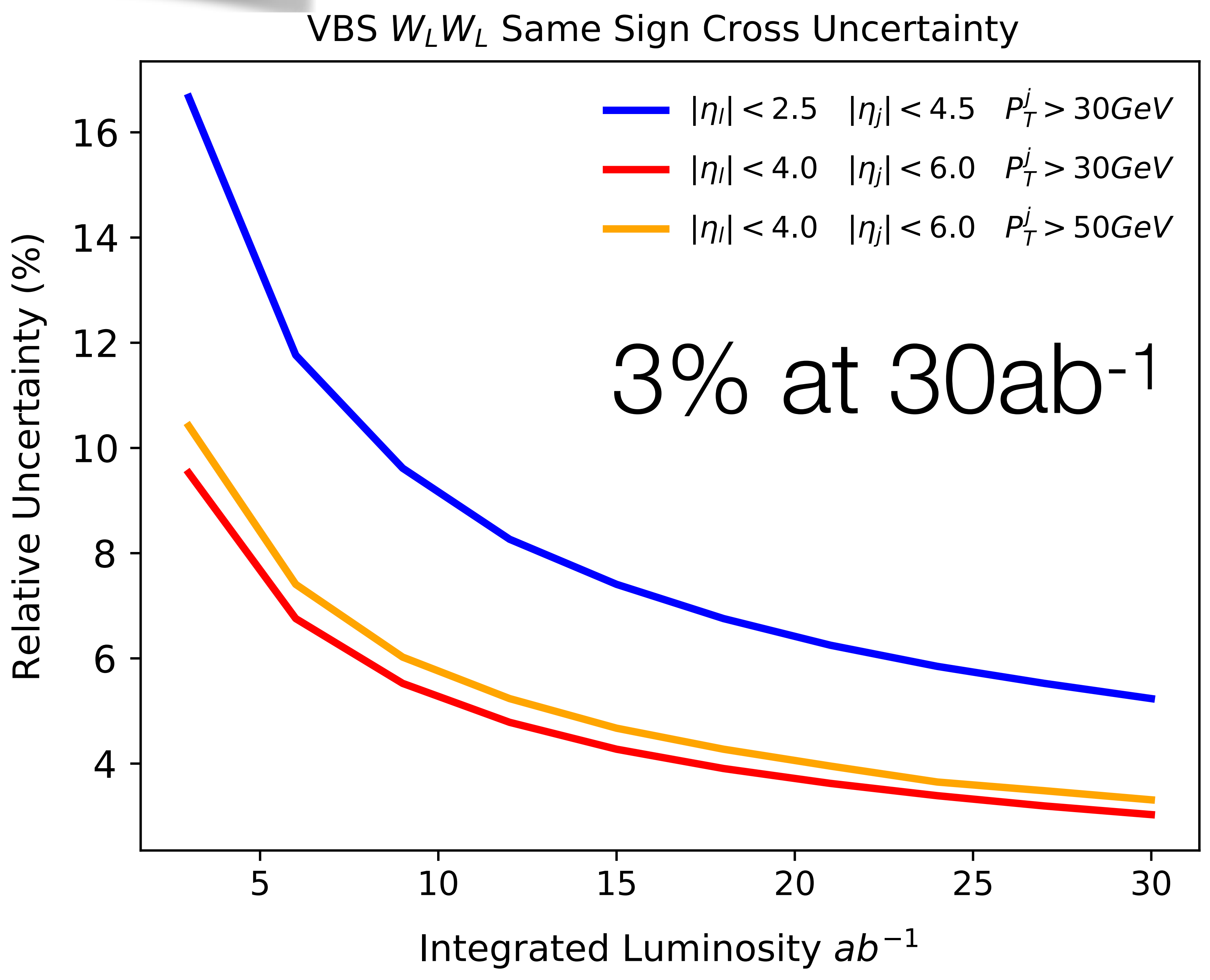
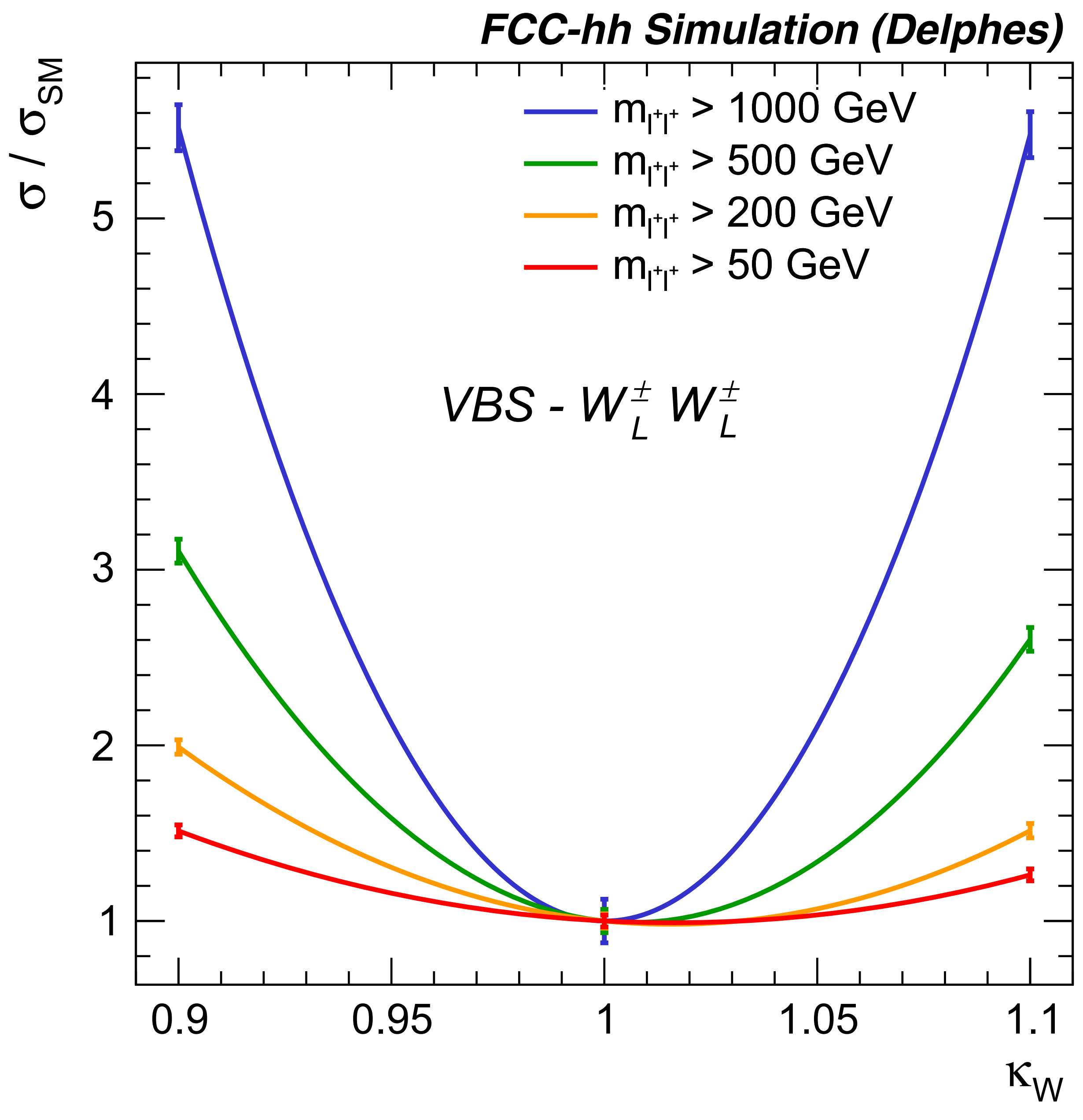
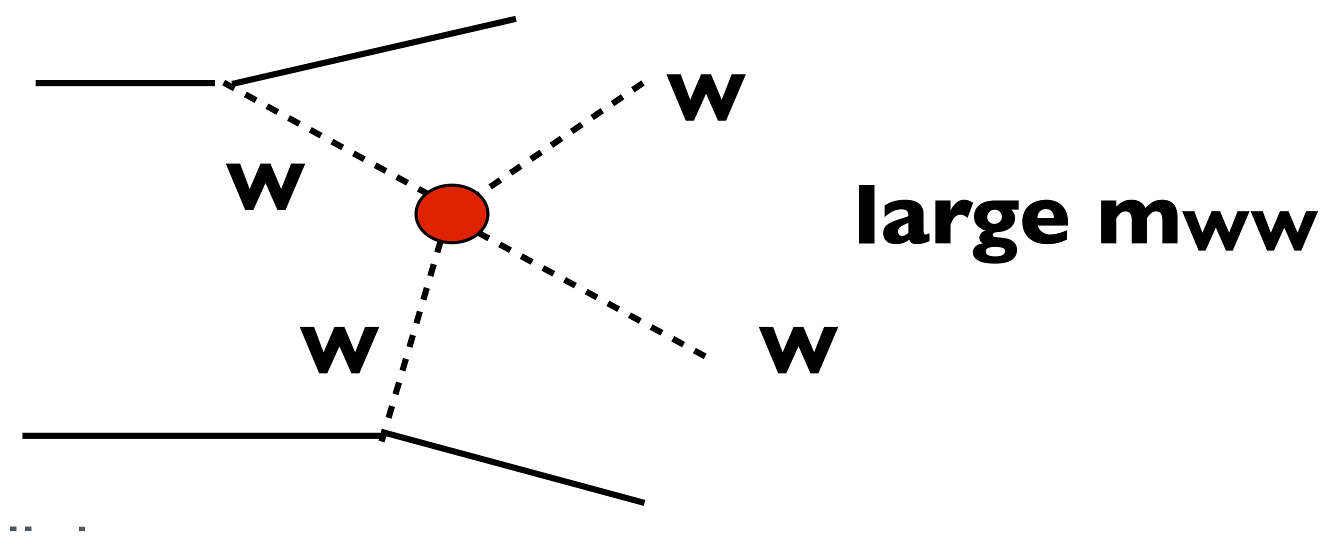
$W_L W_L$ SCATTERING (RELEVANT FOR VVH COUPLING)







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 $W_L W_L \to HH$ 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]

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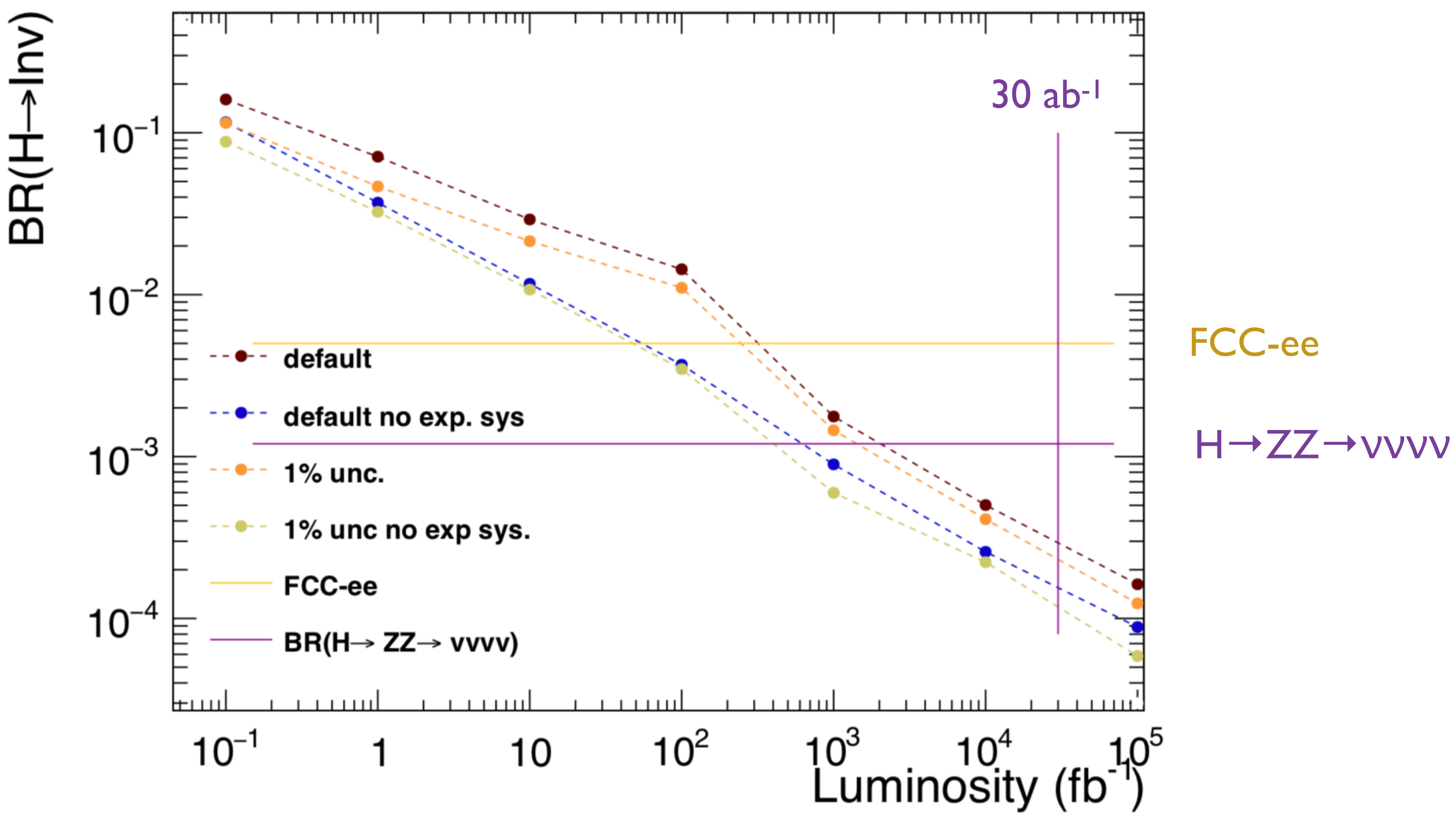
H→INVISIBLE @FCC-hh

- Higgs invisible width can be measured in large missing-E_T signatures
- Derive the BR(H→invisible) from a fit to the missingE_T spectrum
- Constrain background with data driven method using SM W/Z+jets
- $H \rightarrow 4\nu, with\ BR = 1.1 \times 10^{-}$ can be seen after ~1ab^{-1}

P. Harris



Sensitivity down to 2x10^{-4} with full statistics

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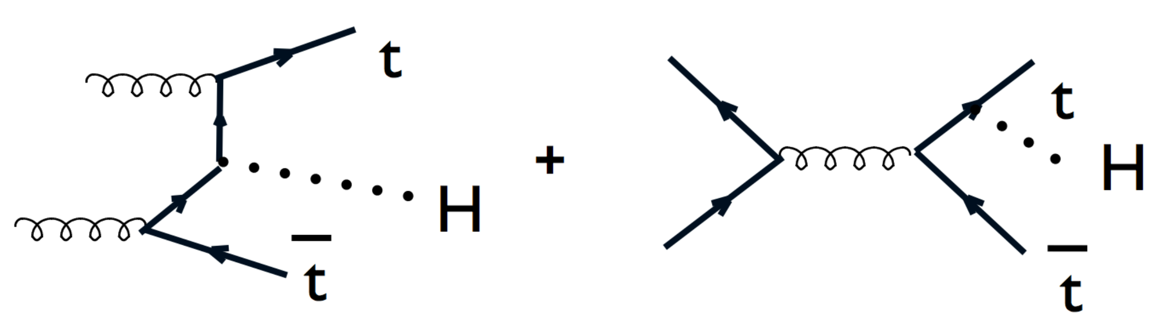
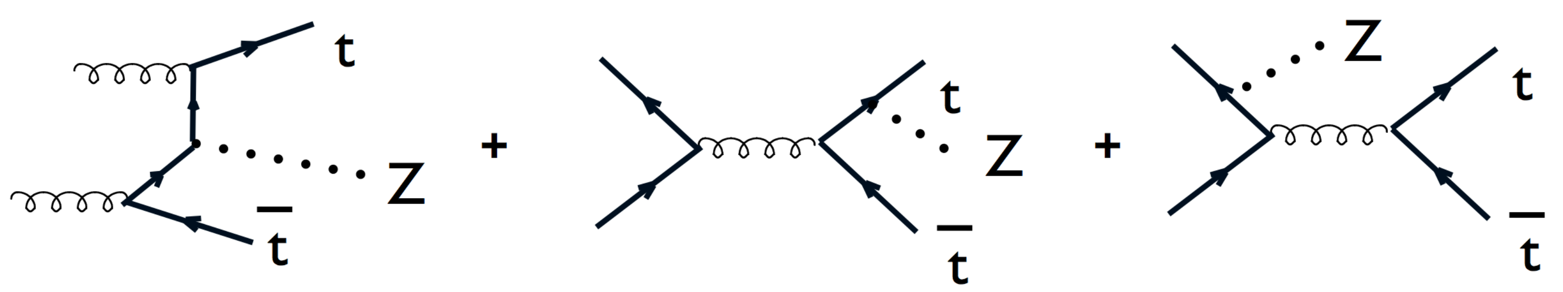
FCC SYNERGIES: TOP YUKAWA COUPLING AT FCC-hh

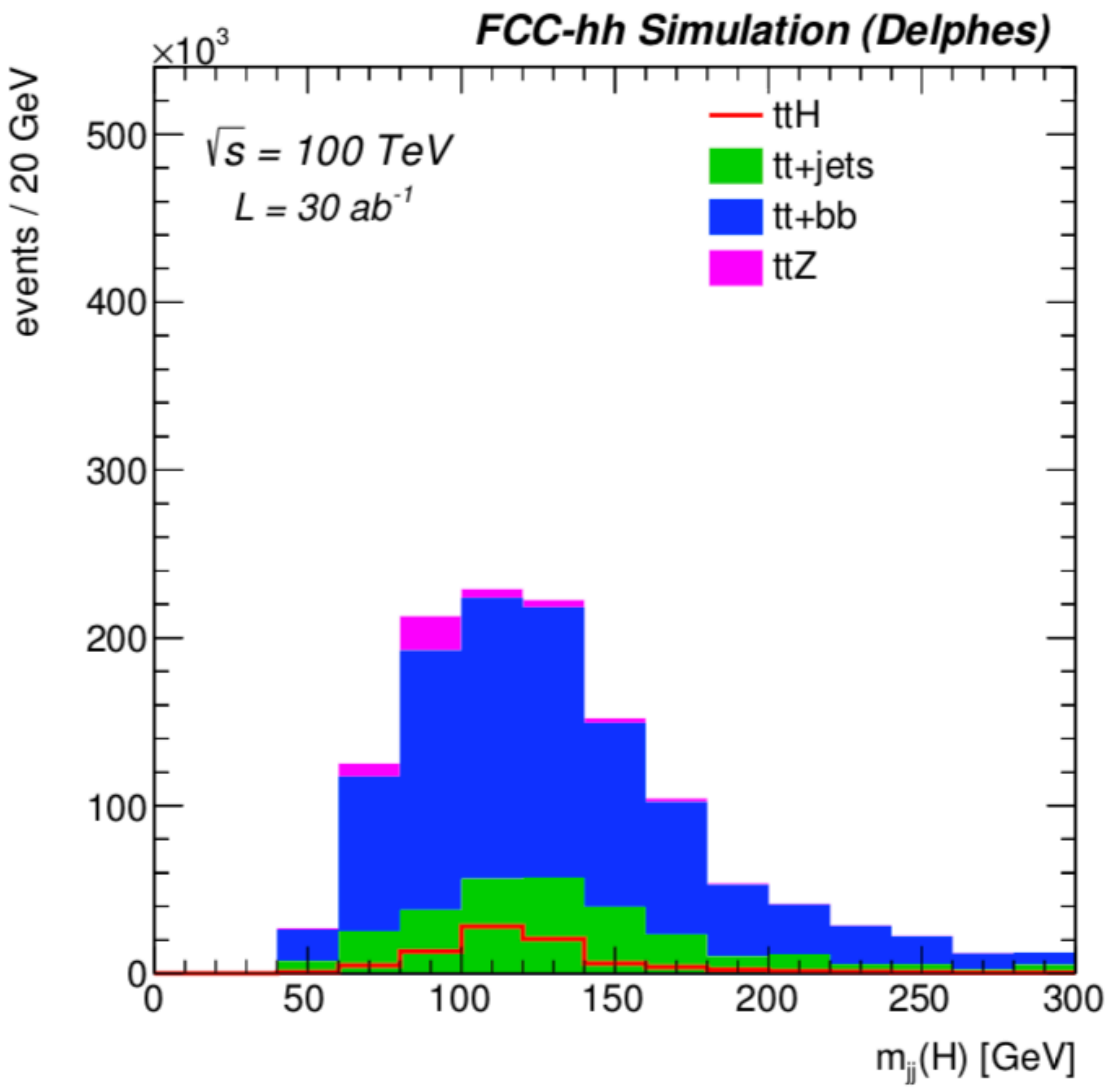
- Measure the production ratio $\sigma(t\bar{t}H)/\sigma(t\bar{t}Z)$ in the boosted regime for $H \rightarrow b\bar{b}$ and in the semi-leptonic top channel. Lumi, PDF, efficiency uncertainties cancel in the ratio
- Perform simultaneous fit of Z and H peak
- **Using g_{ttZ} and k_b measured at 1% by FCC-ee.**
- **Top Yukawa can be measured at 1% and model independent at the FCC-hh**

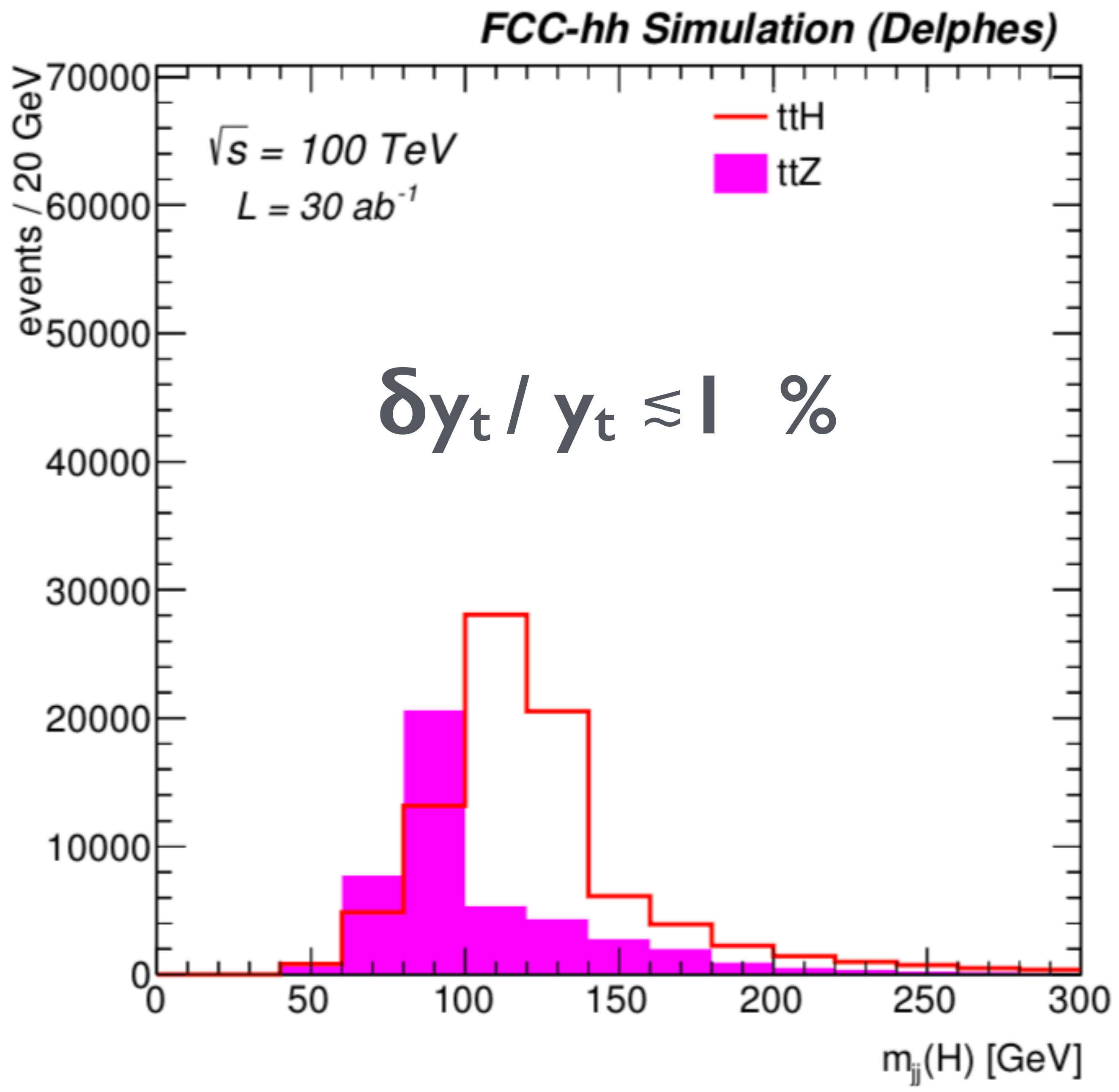
ttH



ttZ







- **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.**

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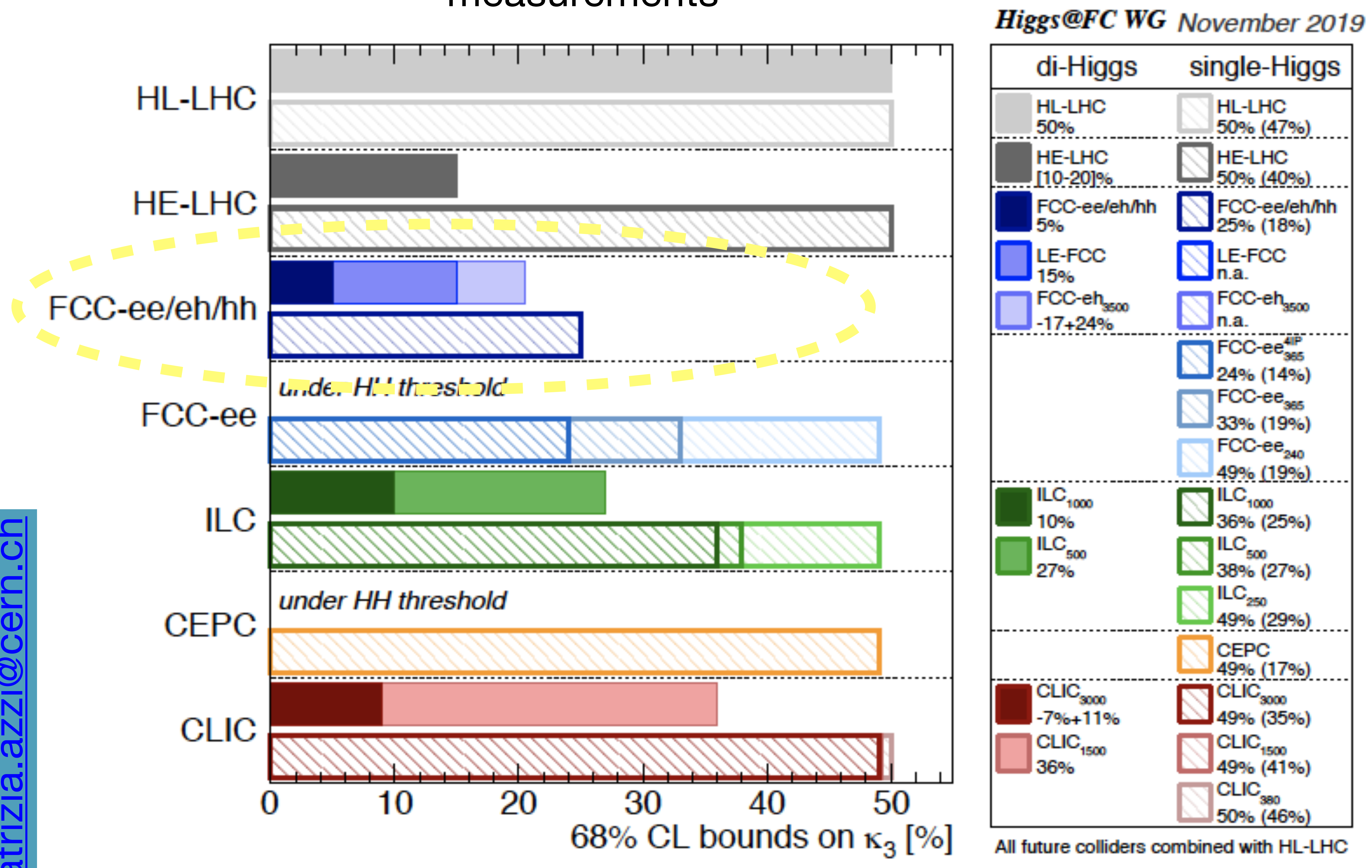
FCC SYNERGIES: TRIPLE HIGGS COUPLING

Projected precision of λ3 measurements



FCC integrated program will measure λ_3 to the 5% level

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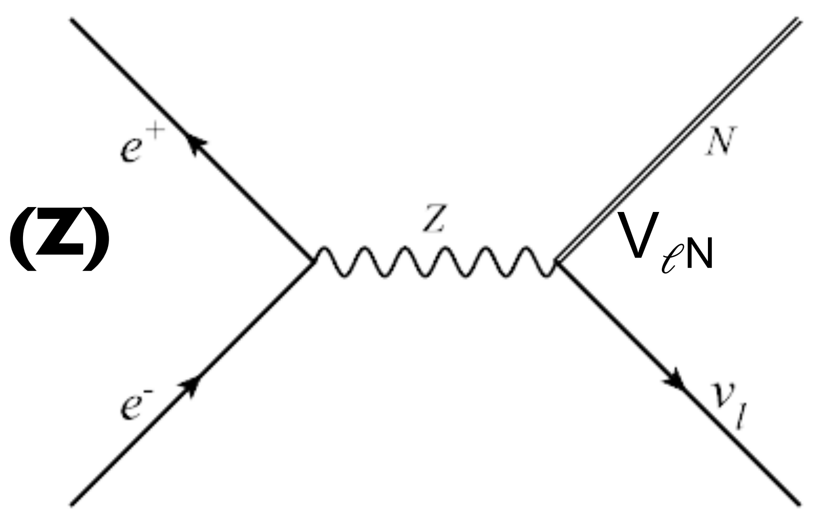
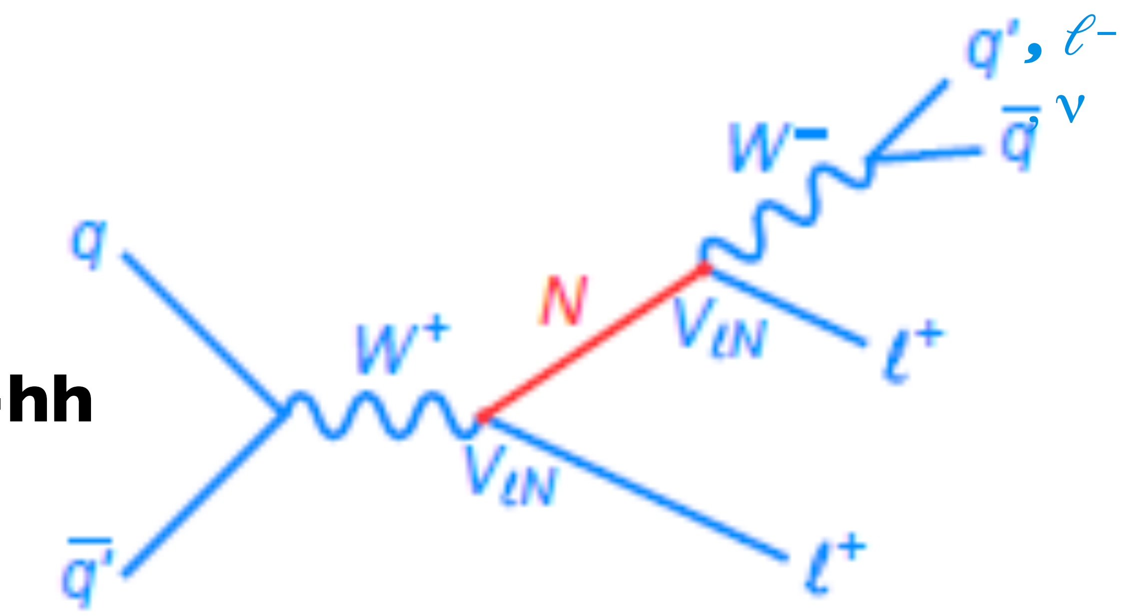
FCC SYNERGIES: FEEBLY INTERACTING PARTICLES

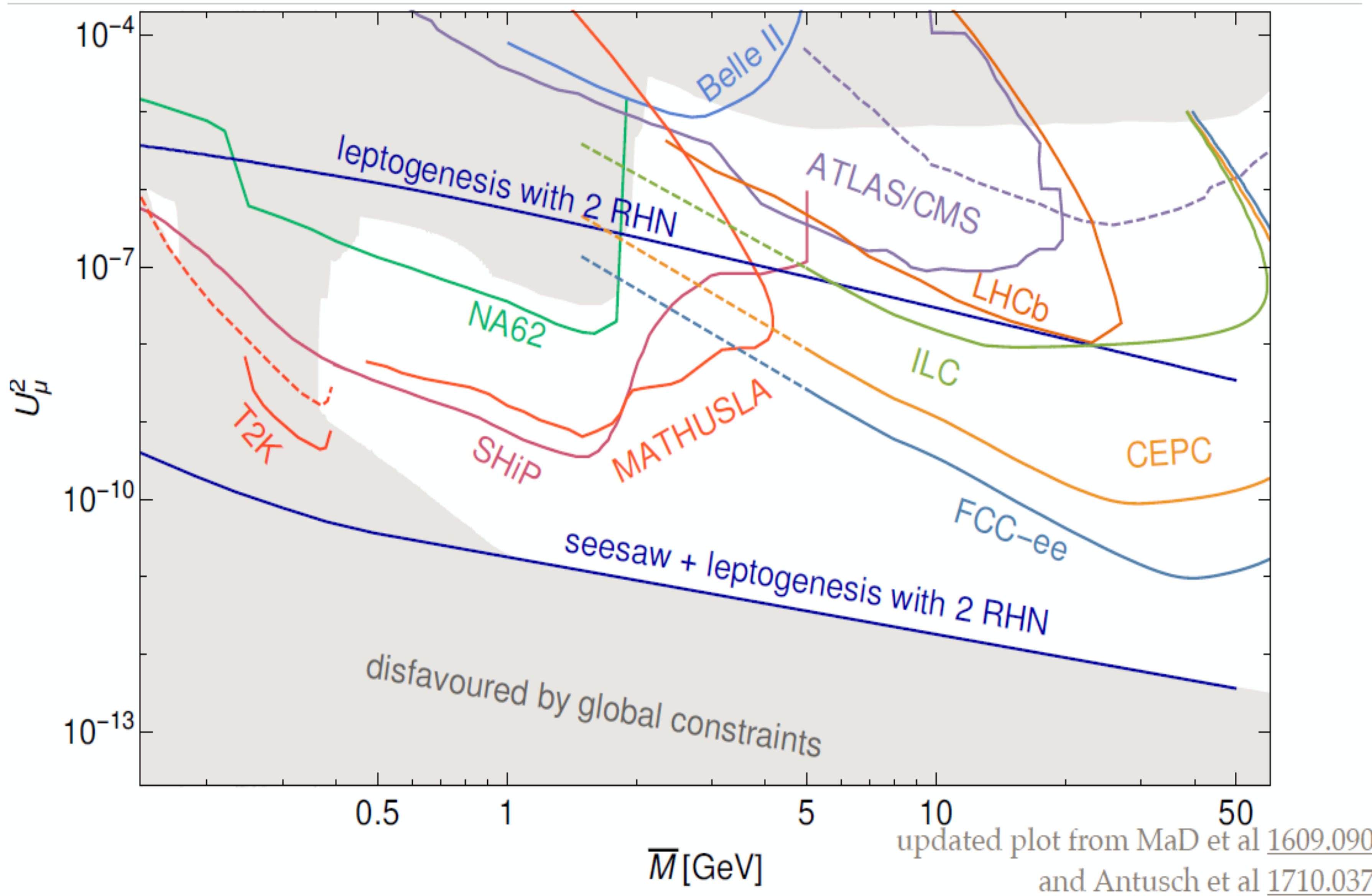
- Heavy Right-Handed Neutrinos
  - Complete SM spectrum – and perhaps explain DM, BAU, ν masses

FCC-ee (Z)



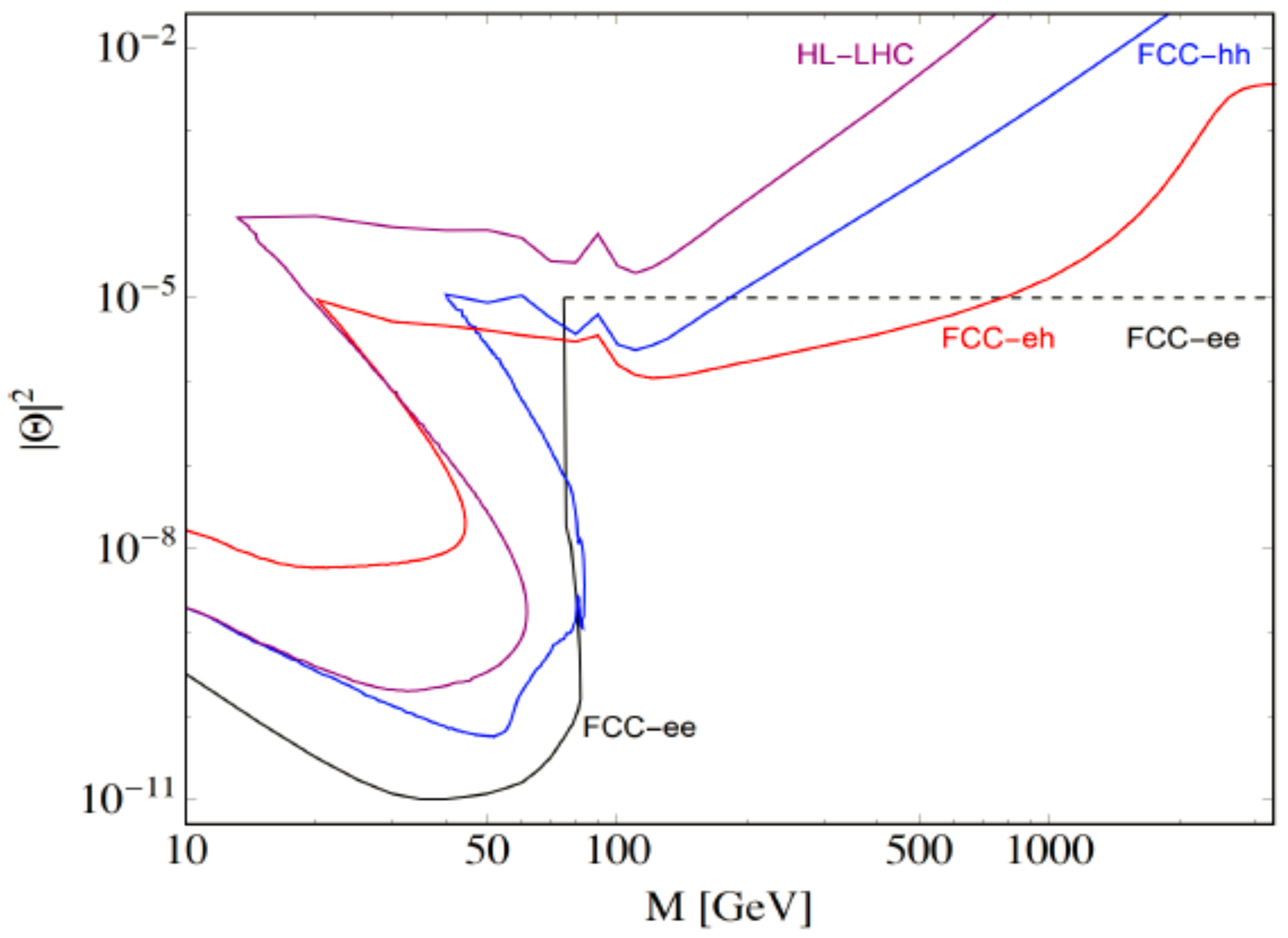
FCC-hh





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**



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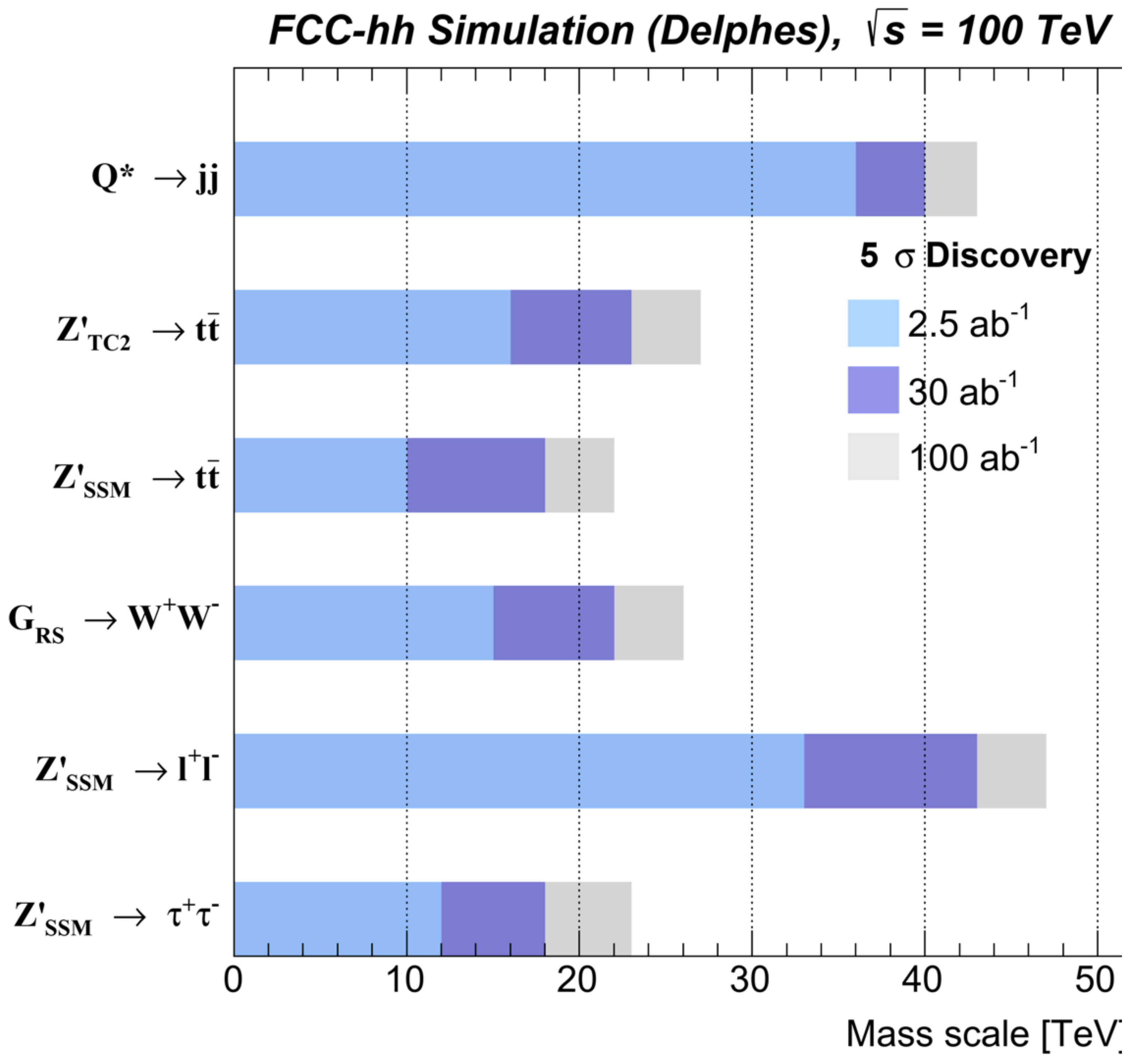
FCC SYNERGIES: FCC-hh DIRECT DISCOVERY POTENTIAL

- ➤ 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

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FCC FEASIBILITY STUDY

TIMELINE OF THE FCC INTEGRATED PROGRAMME

F. Gianotti

- 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++

➤ 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!

FUTURE COLLIDERS TAKE AWAY MESSAGE

known knowns	known unknowns
Standard Model	"known" new physics
unknown knowns	**unknown unknowns**
new physics modifies known physics .... and maybe we already measured it!	surprises

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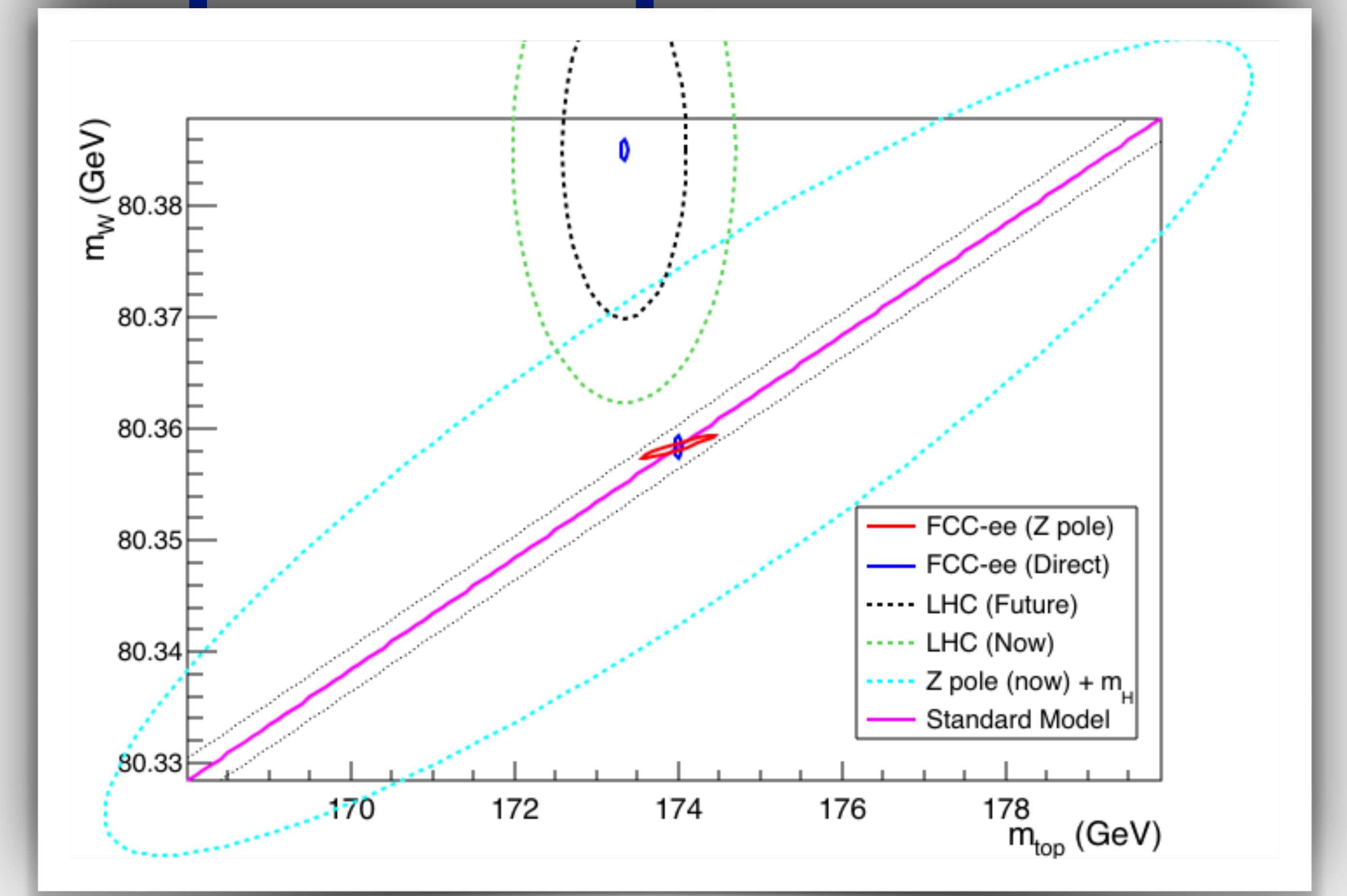
FUTURE COLLIDERS TAKE AWAY MESSAGE



known unknowns

"known" new physics

unknown knowns

new physics modifies known physics

and maybe we already measured it!

unknown unknowns

surprises

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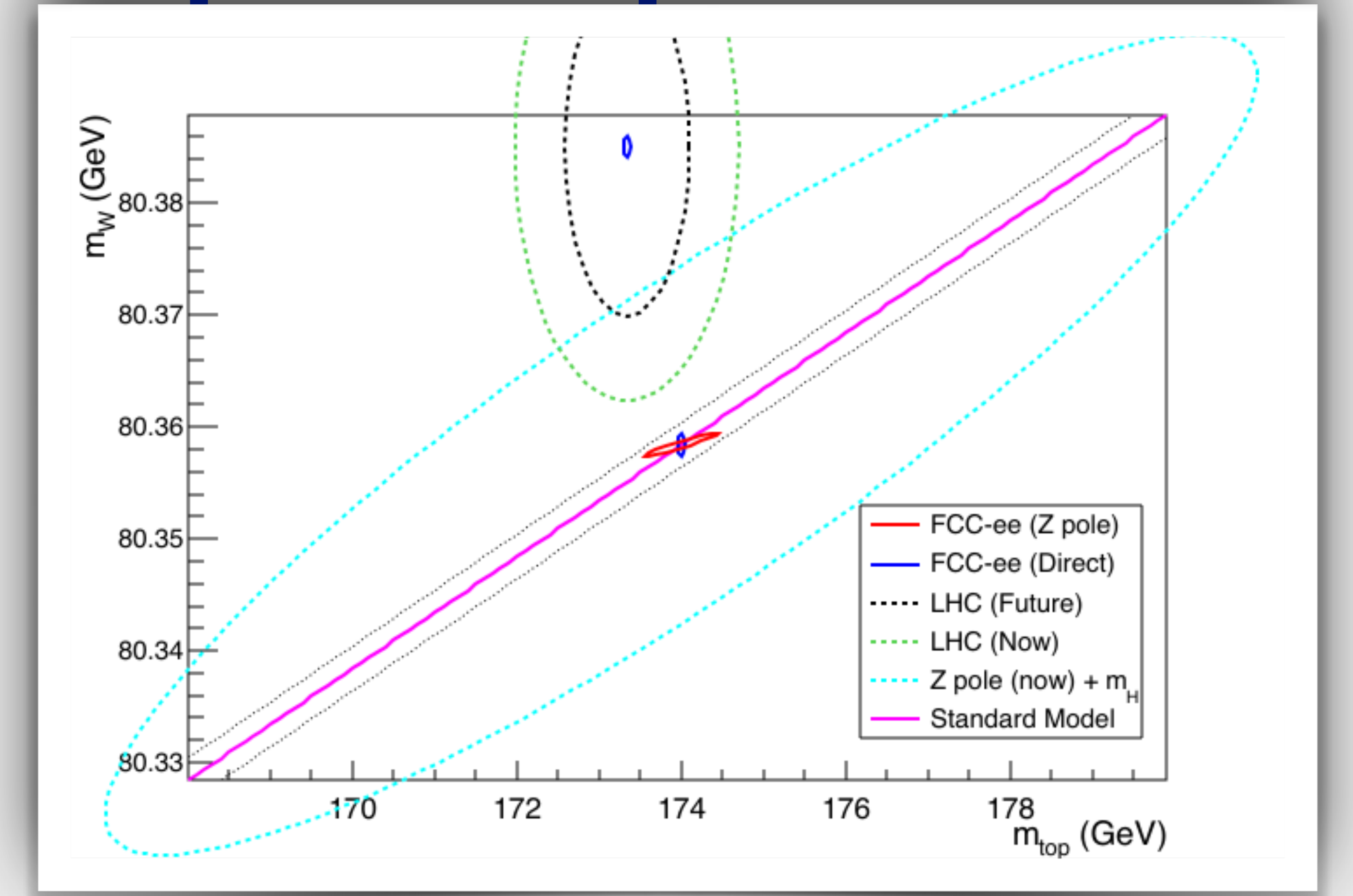
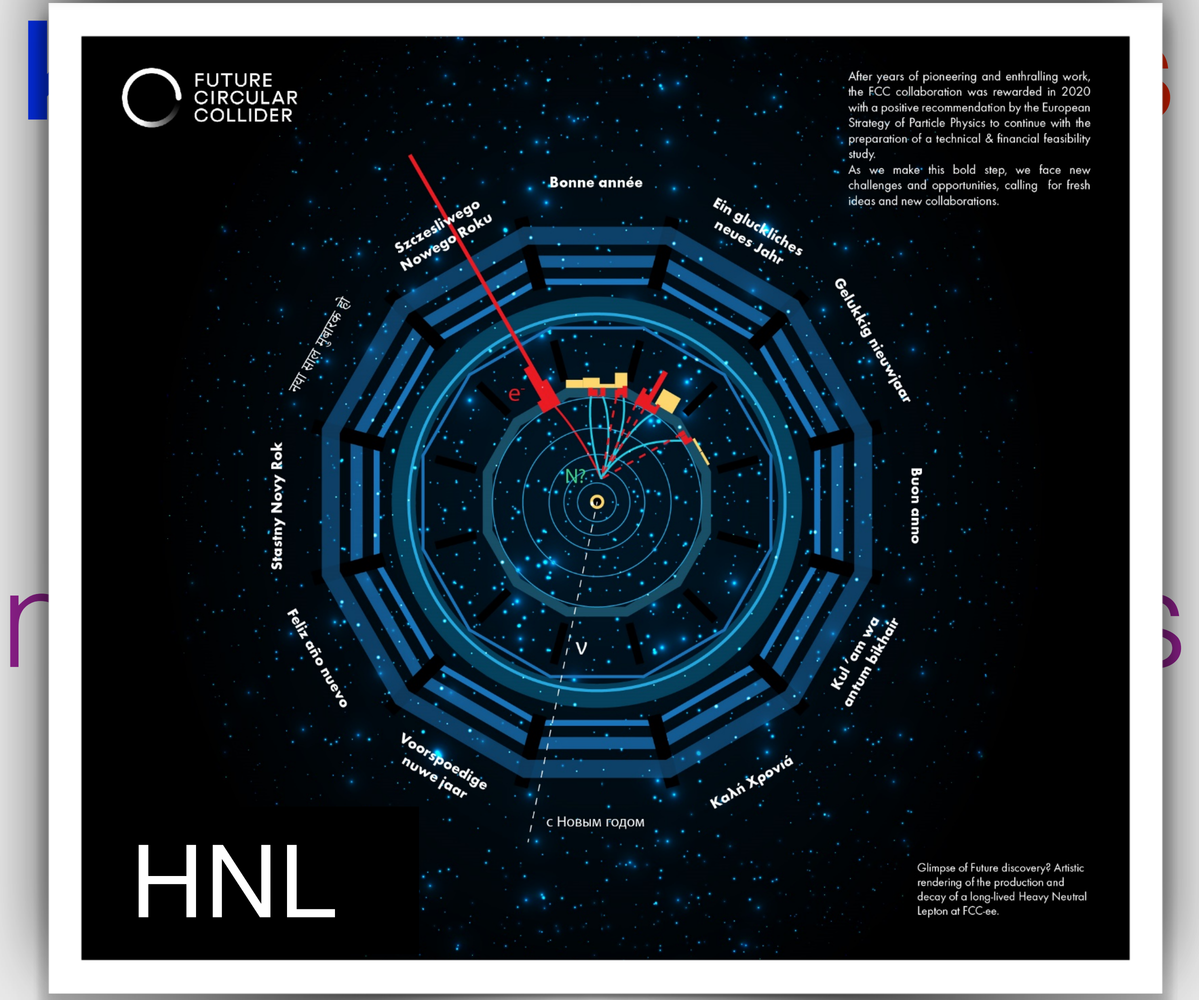
FUTURE COLLIDERS TAKE AWAY MESSAGE





unknown knowns	unknown unknowns
new physics modifies known physics …………………… and maybe we already measured it!	surprises

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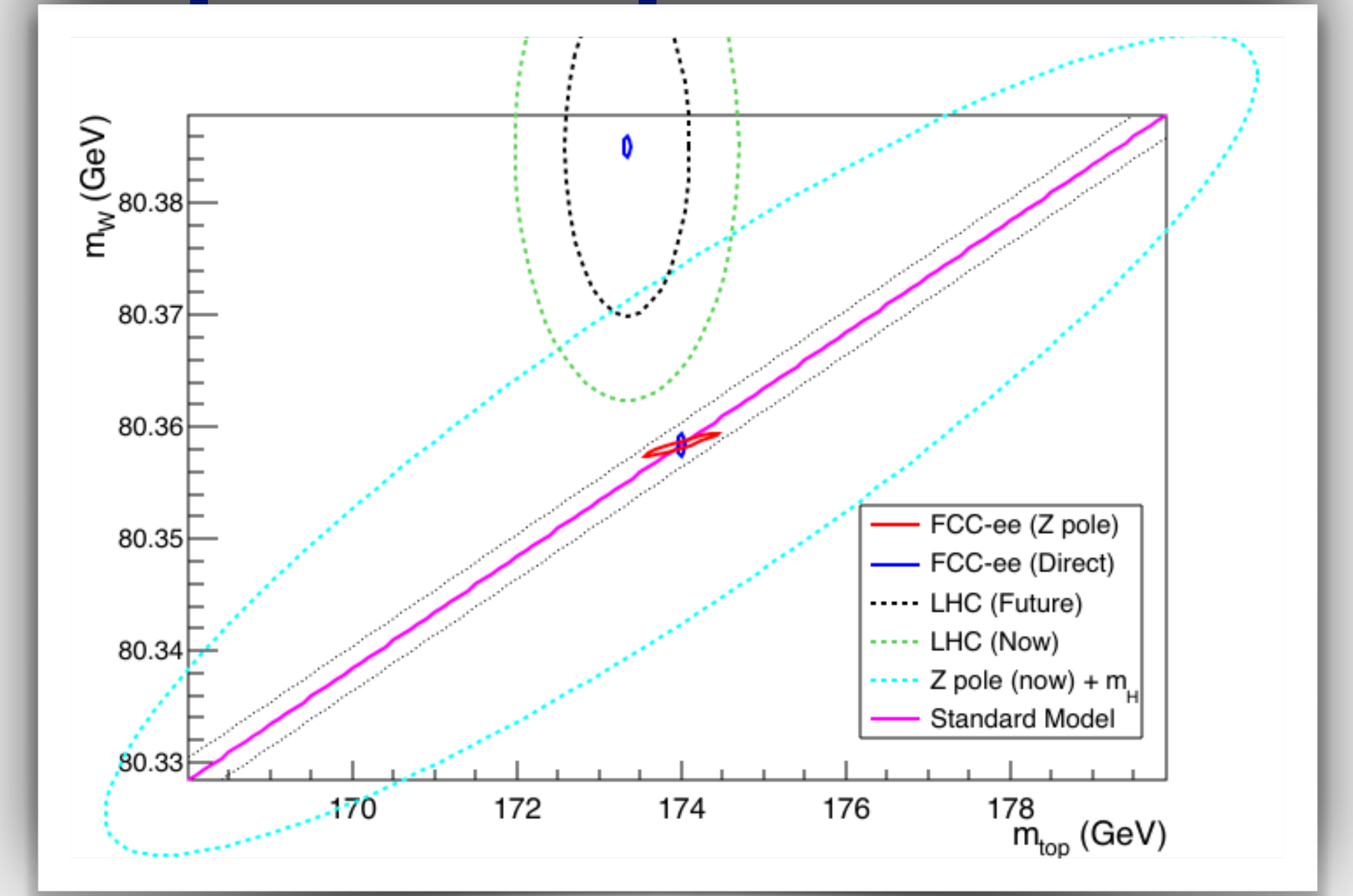
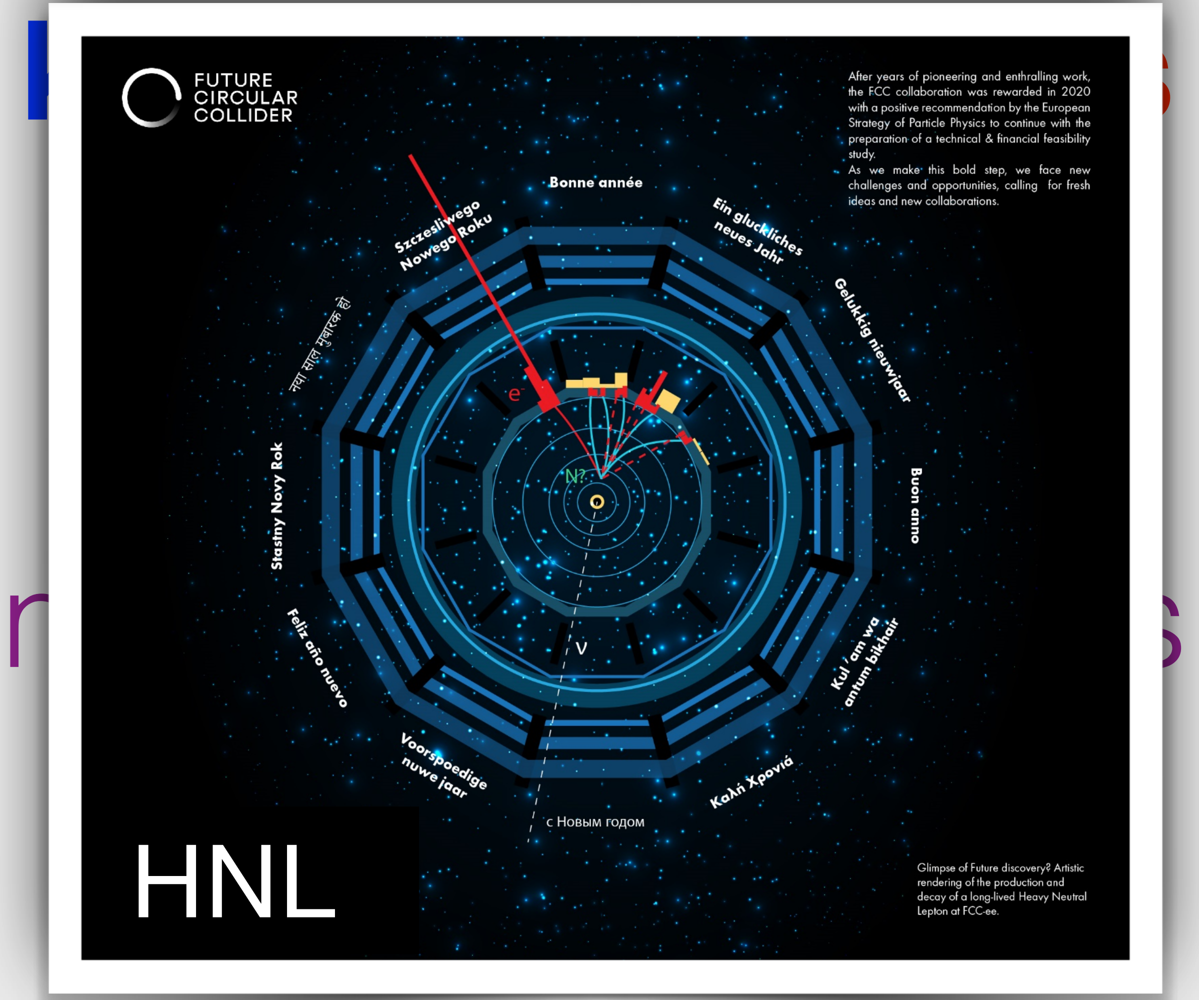
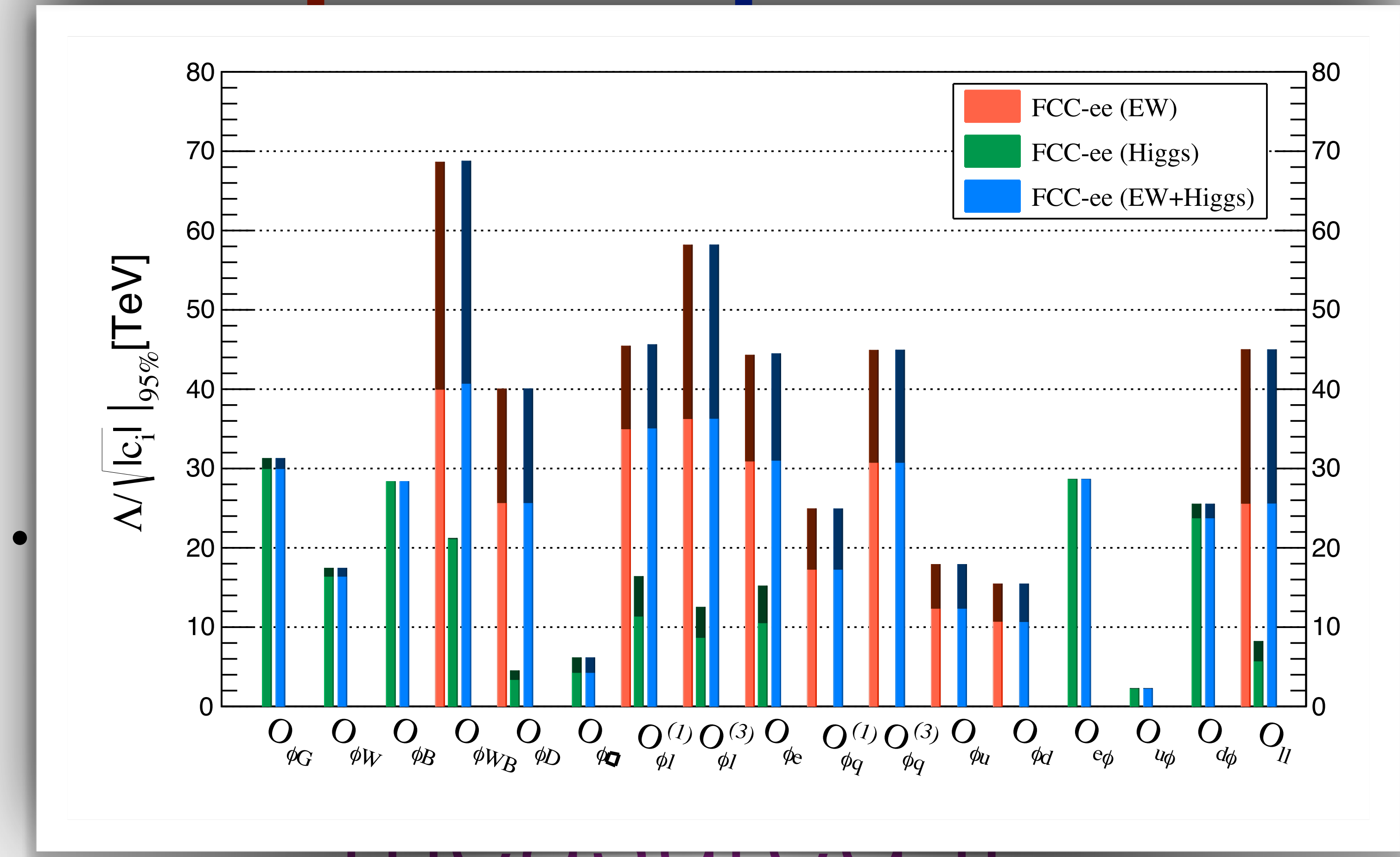
FUTURE COLLIDERS TAKE AWAY MESSAGE







unknown unknowns

surprises

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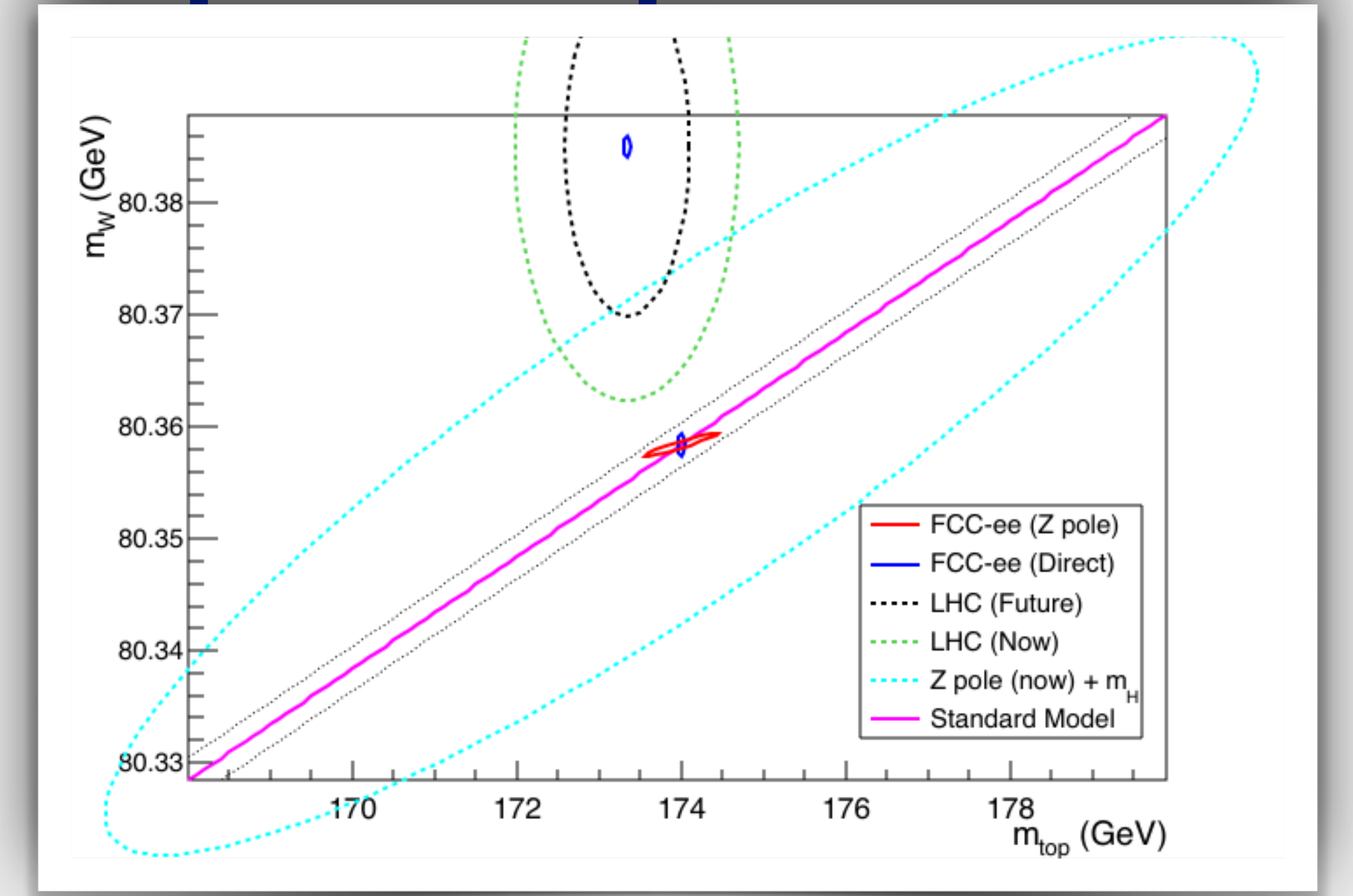
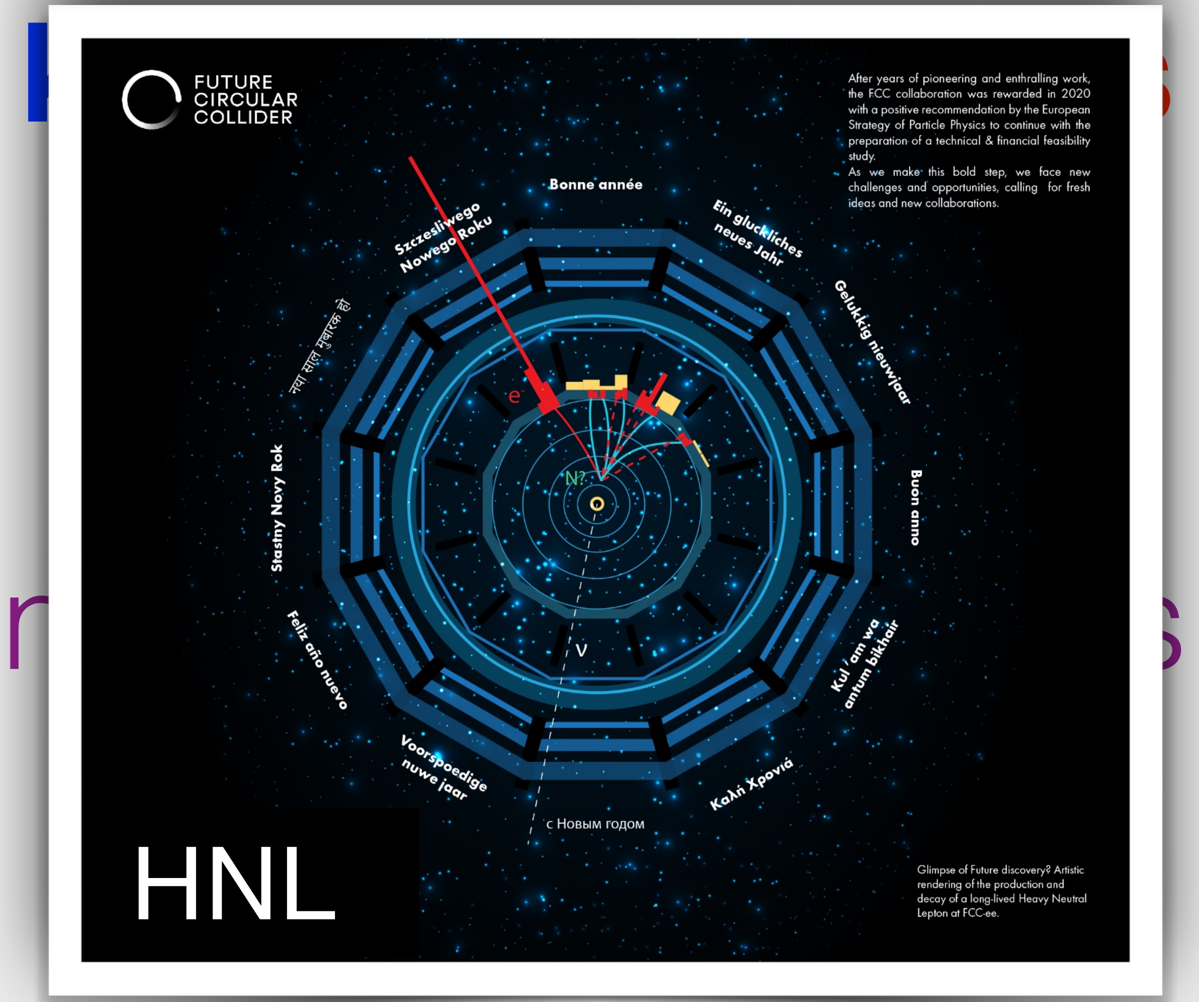
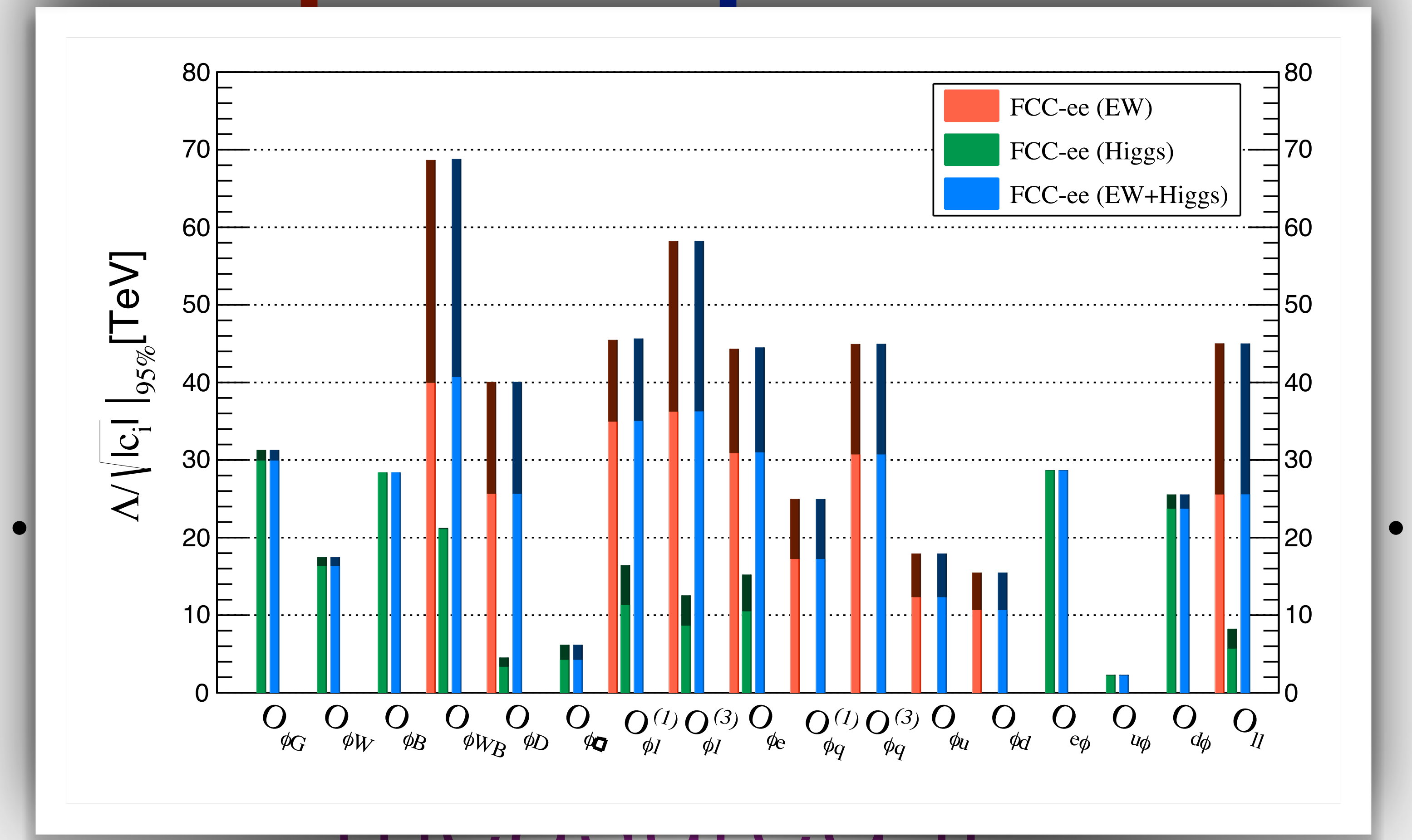
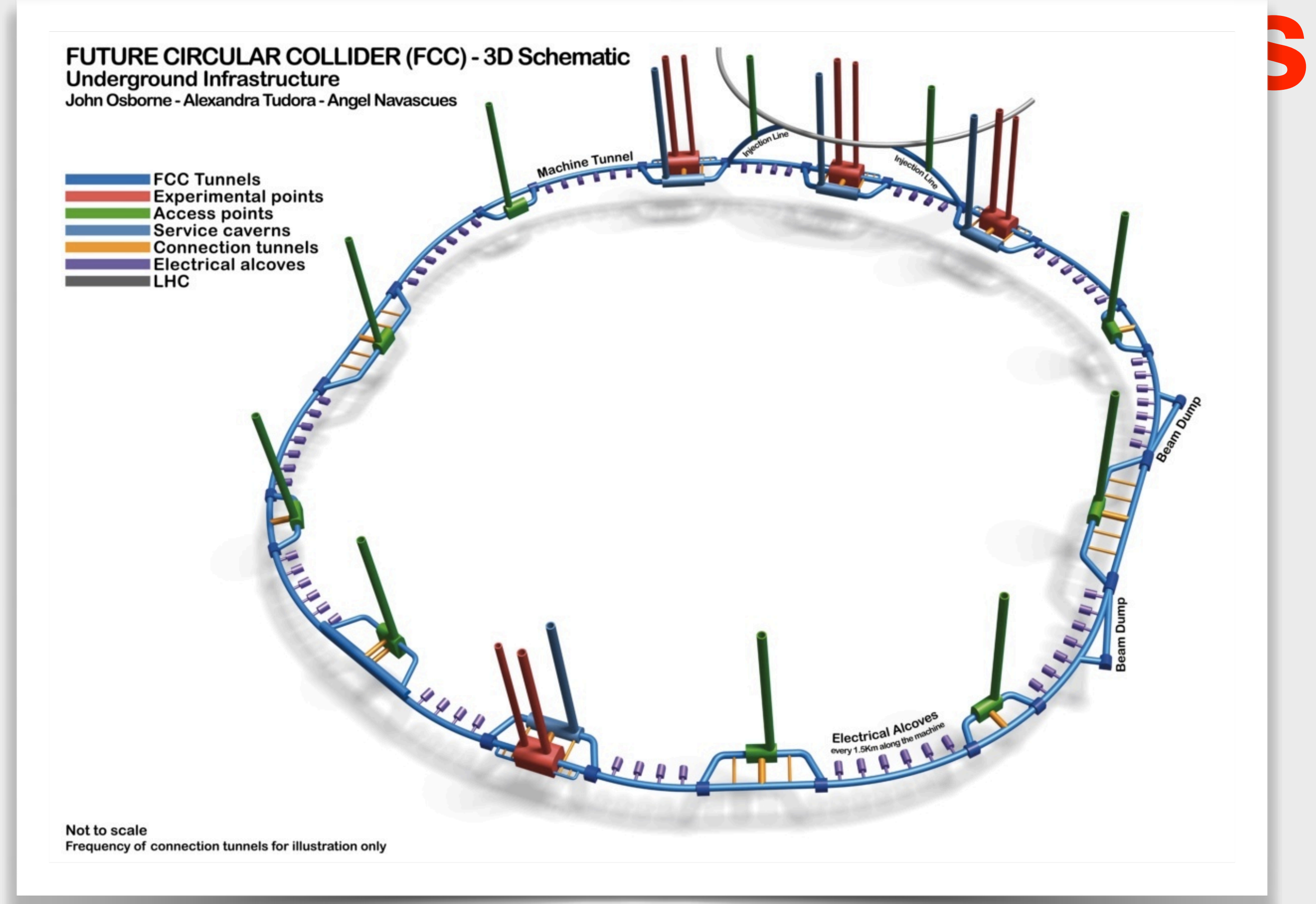
FUTURE COLLIDERS TAKE AWAY MESSAGE









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PRACTICAL INFORMATIONS

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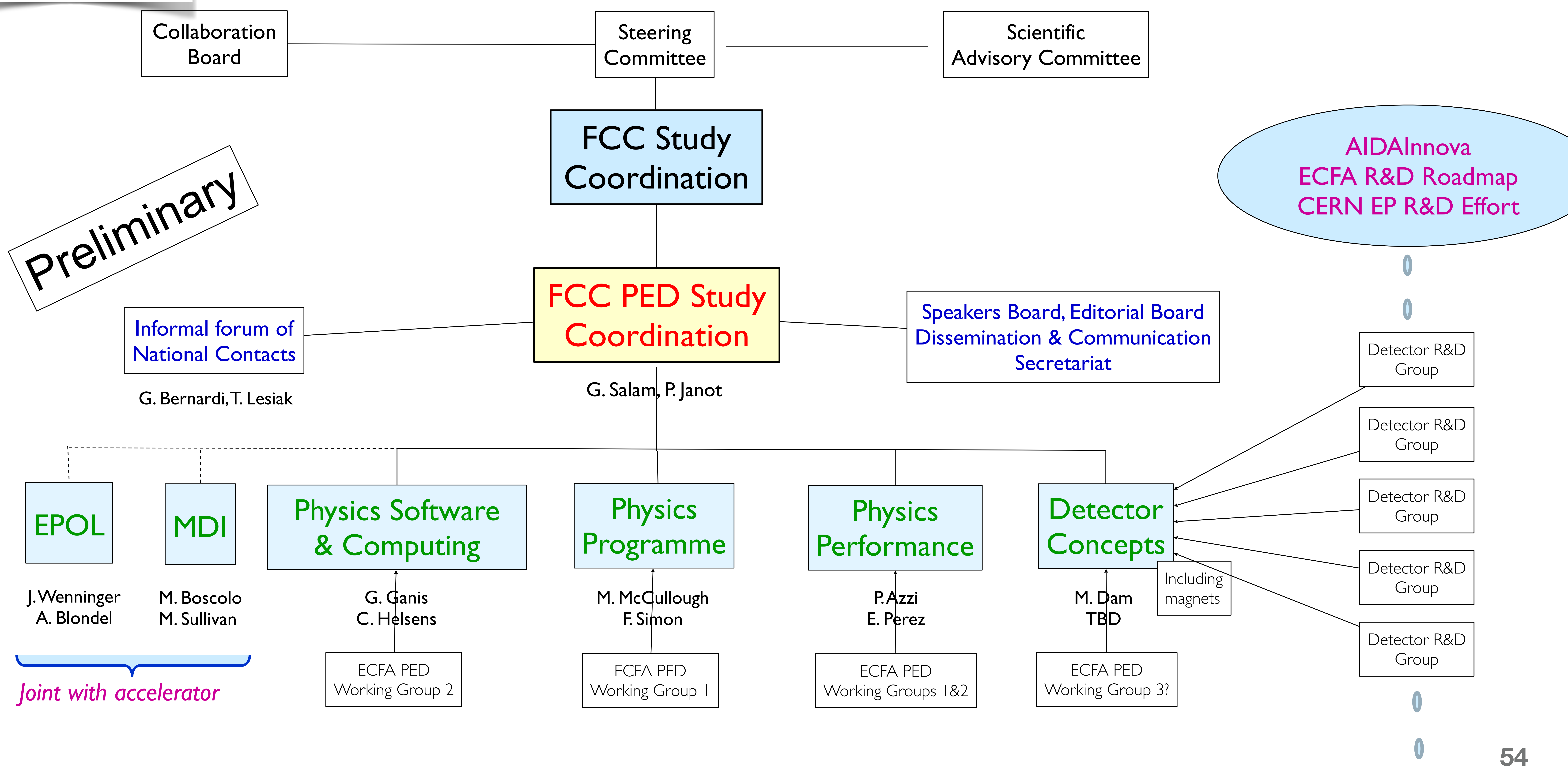
PED ORGANISATION TO TACKLE THE CHALLENGES



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LINKS AND GROUPS

- Al CERN: https://fcc-ped.web.cern.ch/##. CERN main Web page
  - Per iscriversi alle mailing lists fare: Join Us -> Subscribe to mailing lists
- In Italia: Sigla RD-FCC (resp. Naz F. Bedeschi) (include collaborazione con CEPC)
  - https://web.infn.it/RD_FCC/ (per vedere i gruppi di lavoro)
  - Lista generale: rd_fcc@lists.infn.it (chiedere a Bedeschi credo)
    - Meetings di collaborazione 1 o 2 volte l’anno
  - Lista analisi: rd-fcc-simana@lists.infn.it (chiedere a me/DeFilippis)
    - Meetings ~mensili di analisi/software

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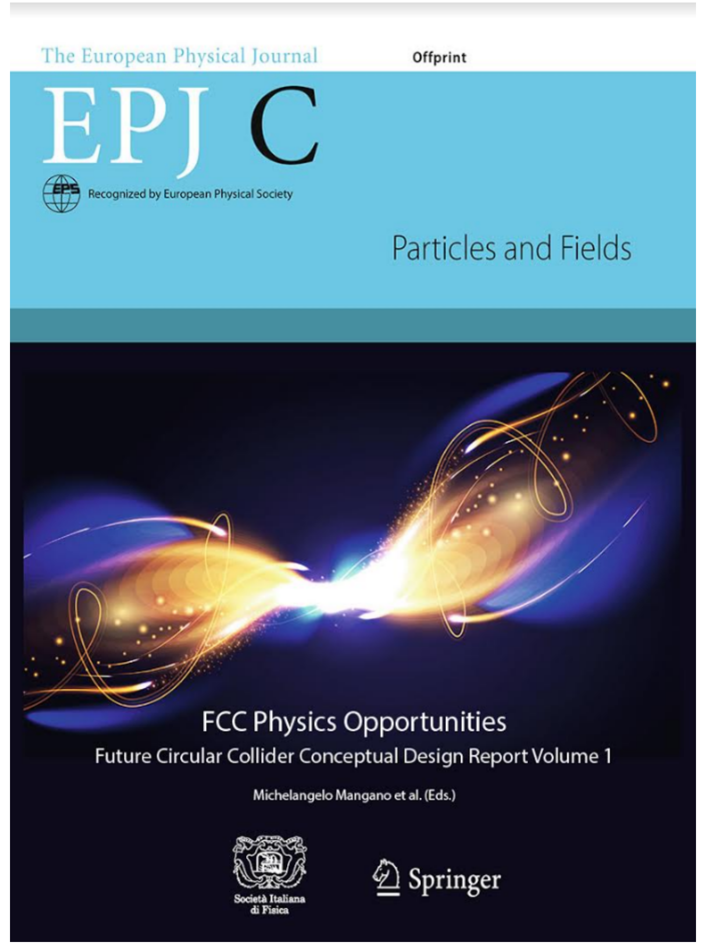
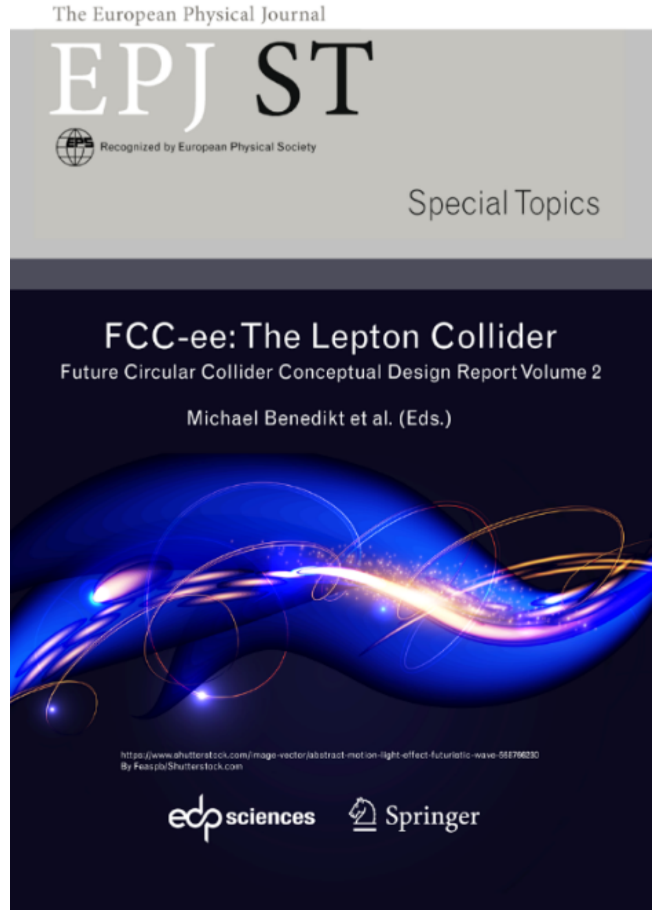
FIND OUT MORE: SOME FCC DOCUMENTATION

FCC

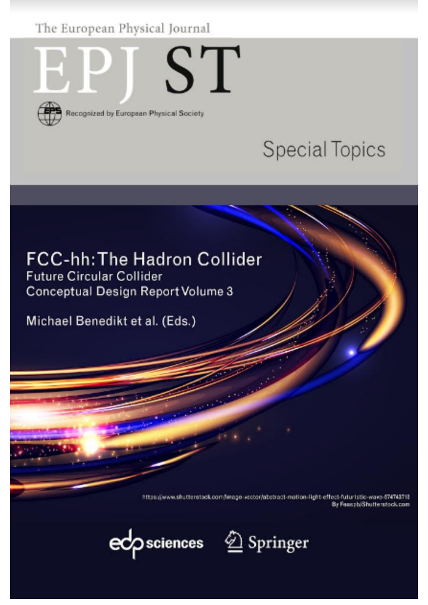
4 CDR volumes published in EPJ



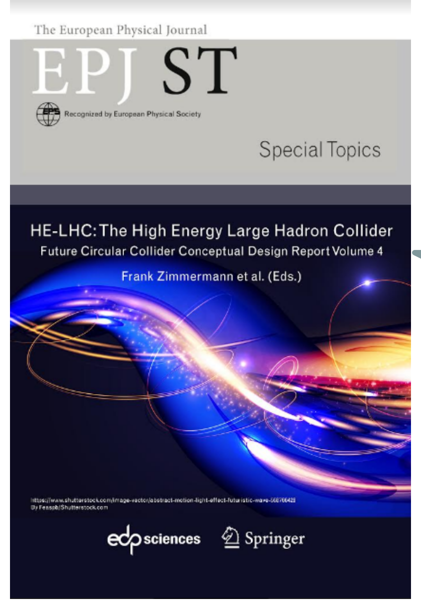
FCC PhysicsOpportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider



NEW

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
- **EPJ+ Collection:**
  - **https://www.epj.org/epjplus-news/2300-epj-focus-point-on-a-future-higgs-electroweak-factory-fcc-challenges-towards-discovery**
- **FCC Week 2022:**
  - **https://indico.cern.ch/event/1064327/timetable/**

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NEW OPPORTUNITIES CREATE NEW CHALLENGES

➤ 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

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