THE FUTURE CIRCULAR COLLIDER PROJECT: GOALS & CHALLENGES

FUTURECIRCULARCOLLIDER
CONCEPTUAL DESIGN REPORT
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Istituto Nazionale di Fisica Nucleare

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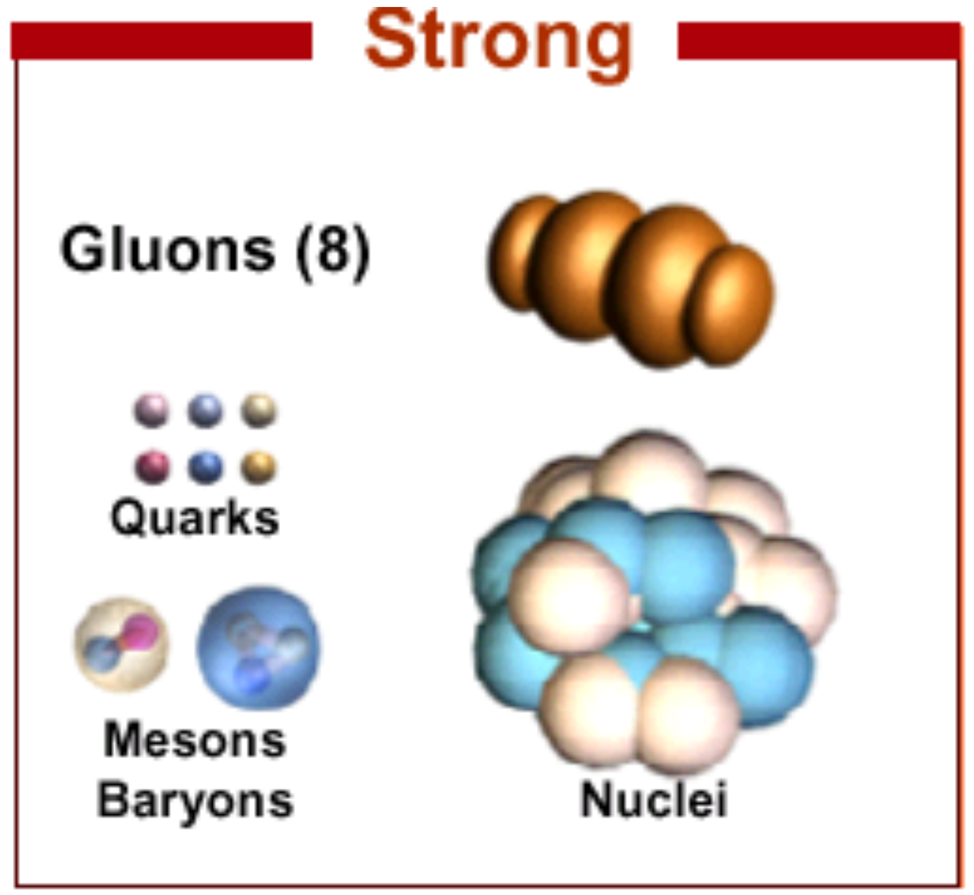
EASITrain School - Oct 2020

THE STANDARD MODEL OF PARTICLE PHYSICS



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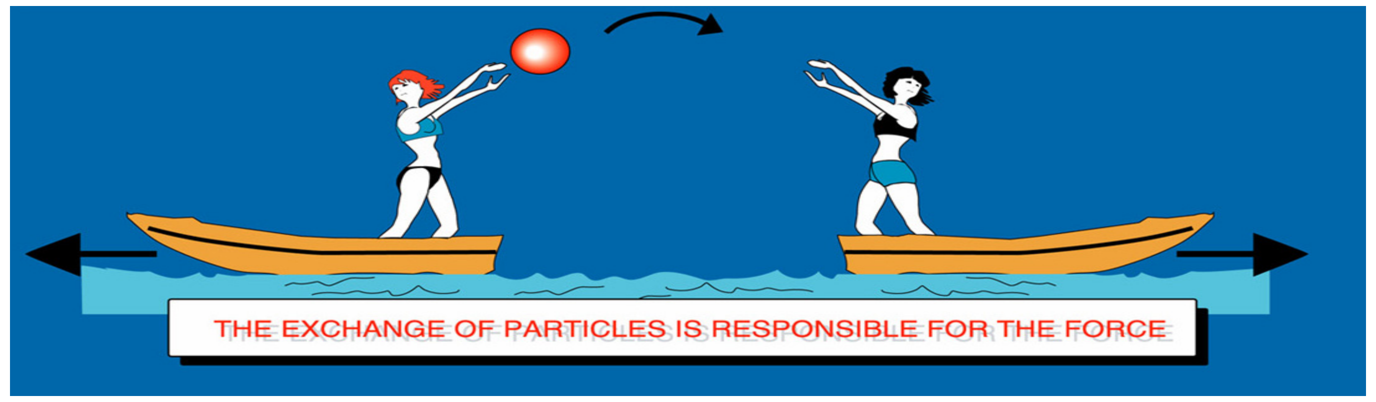
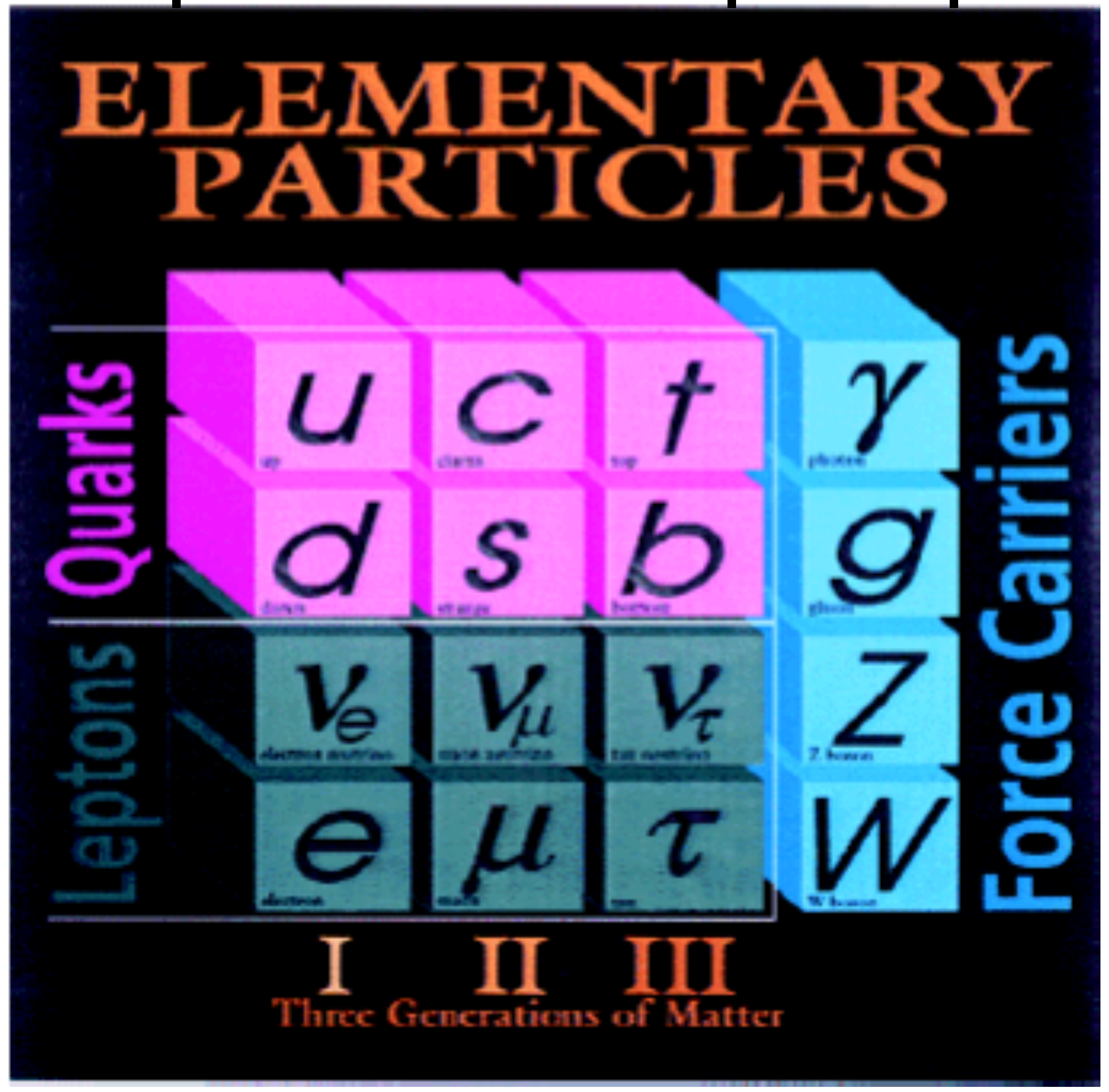


Matter
fermions

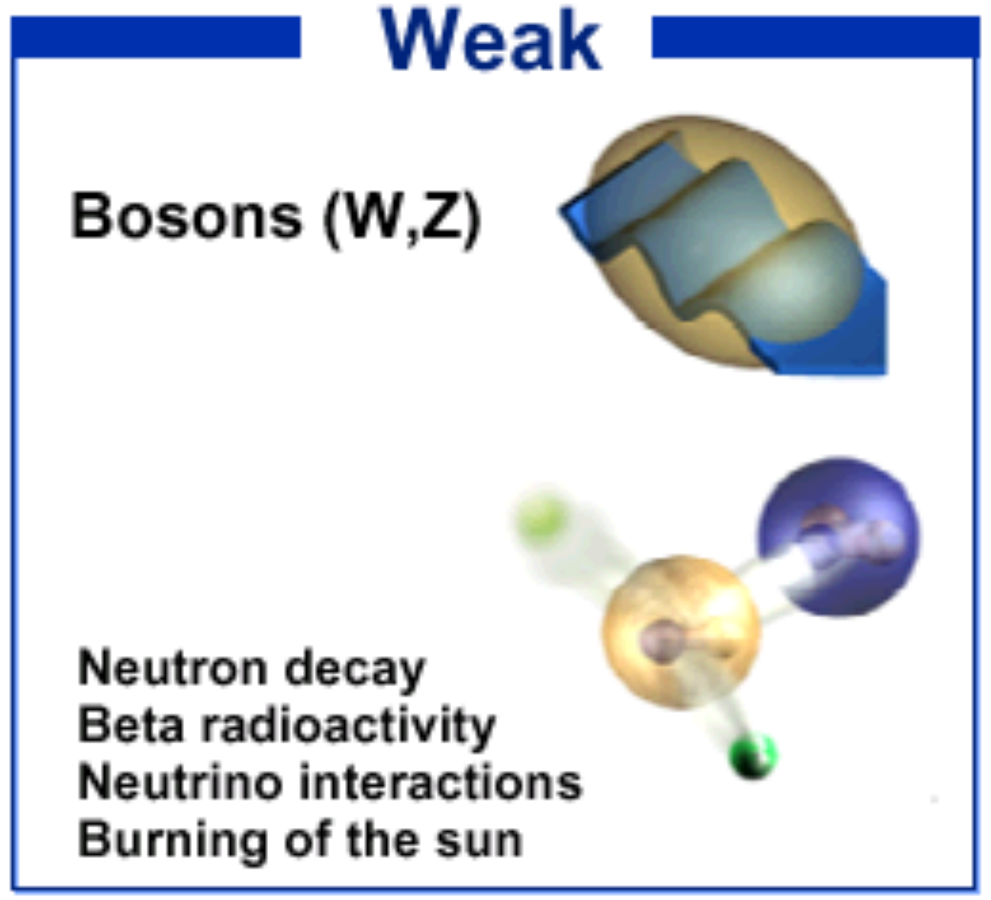
Force
carriers
bosons



+ antiparticles

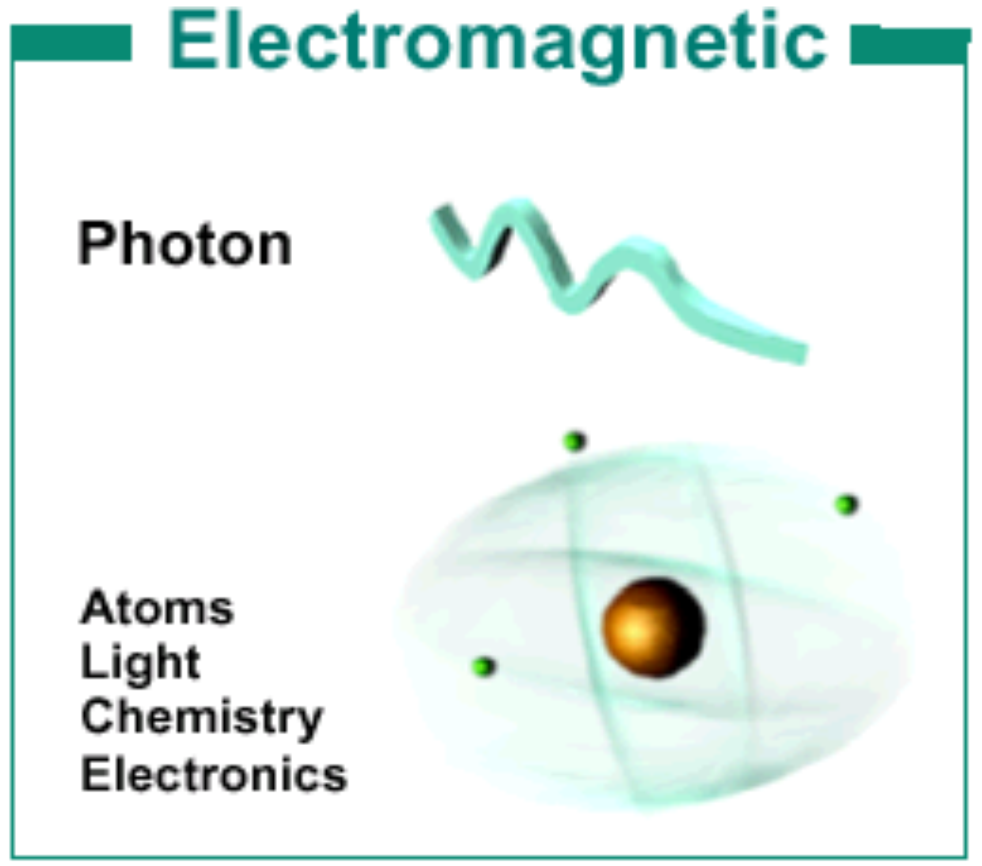
e.g : p=uud ; Λ^0=uds ; Λ^0_b=udb

π^+=u$\underline{d}$; ψ =c$\underline{c}$; Υ=b$\underline{b}$

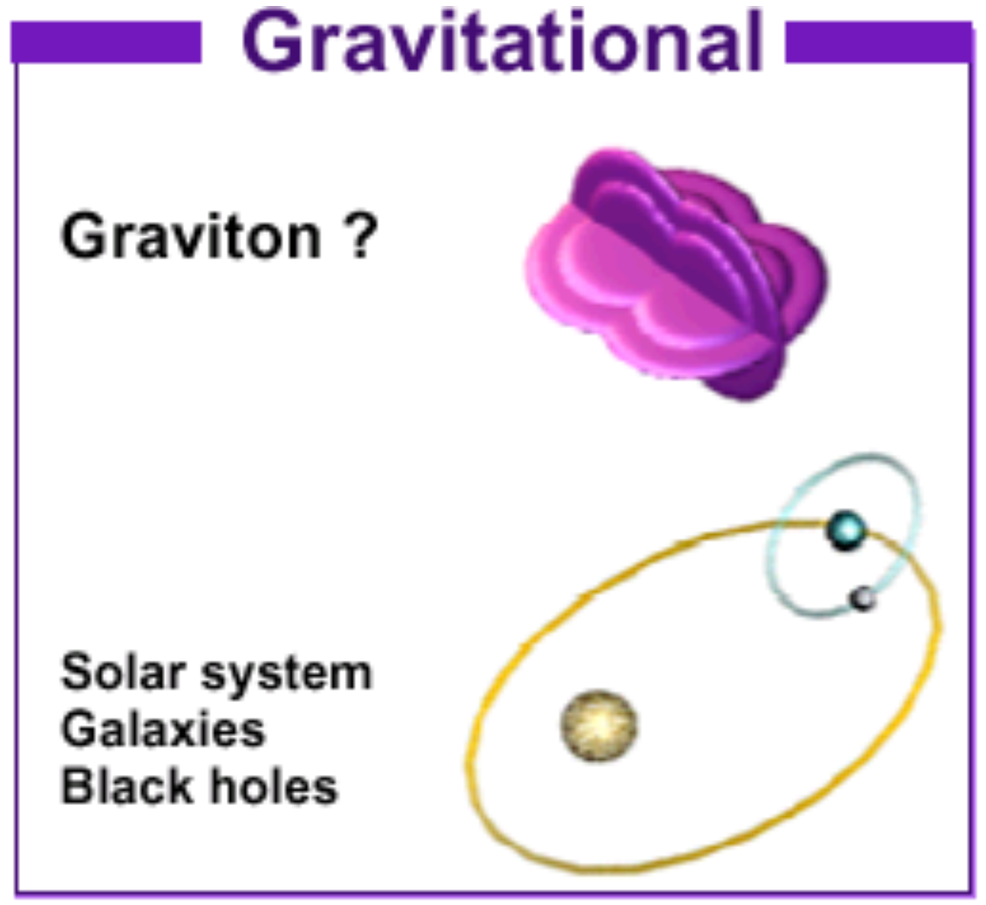


10^{-13}

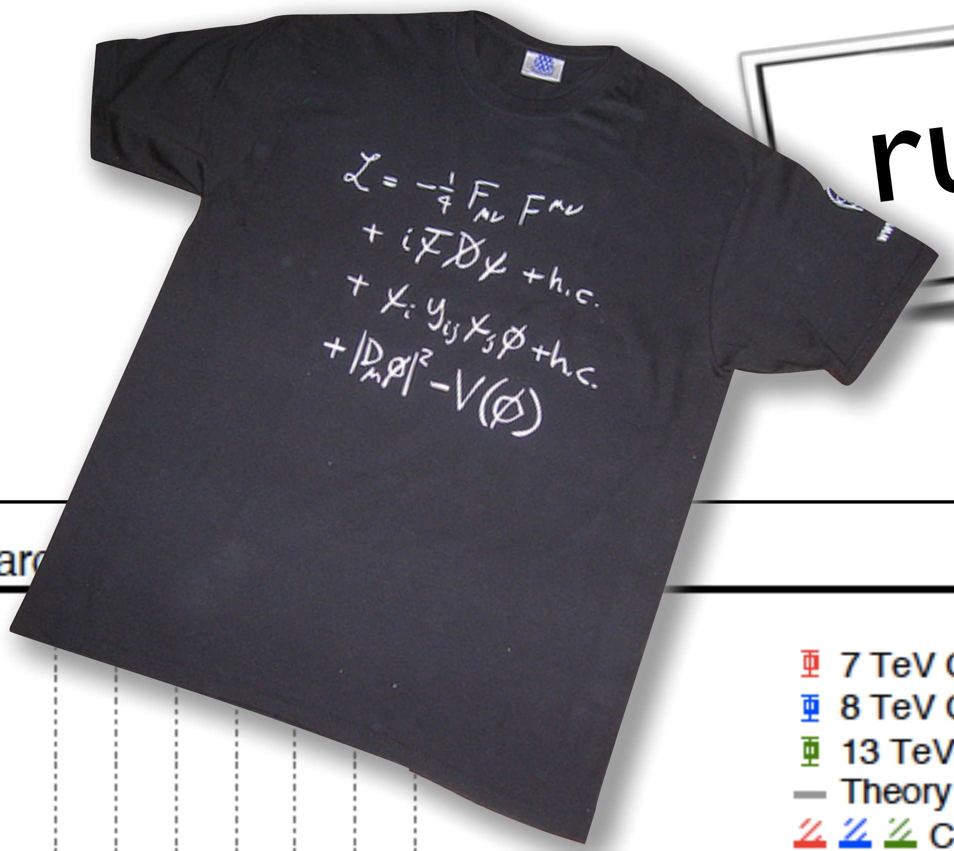
10^{-2}



10^{-38}

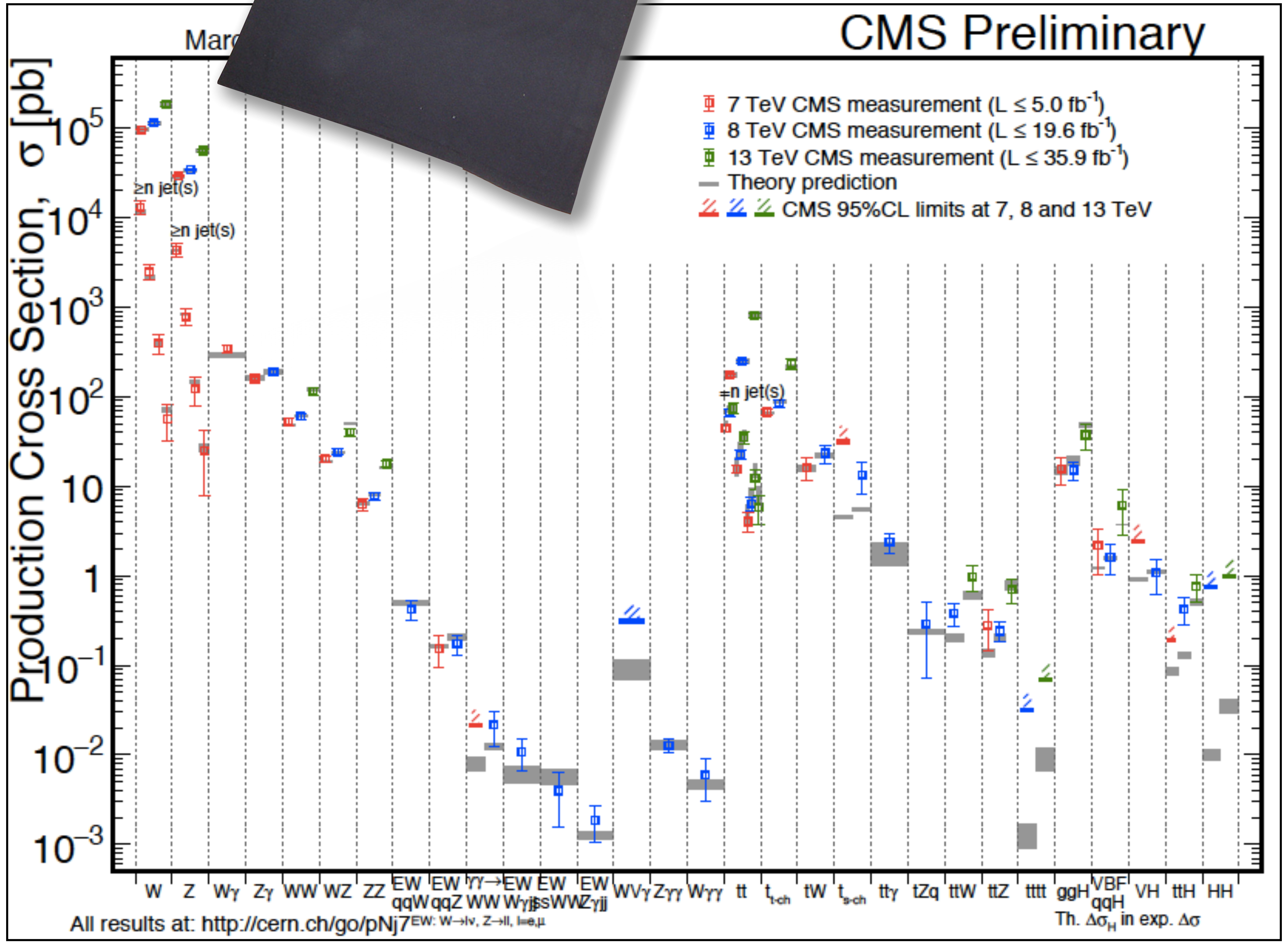


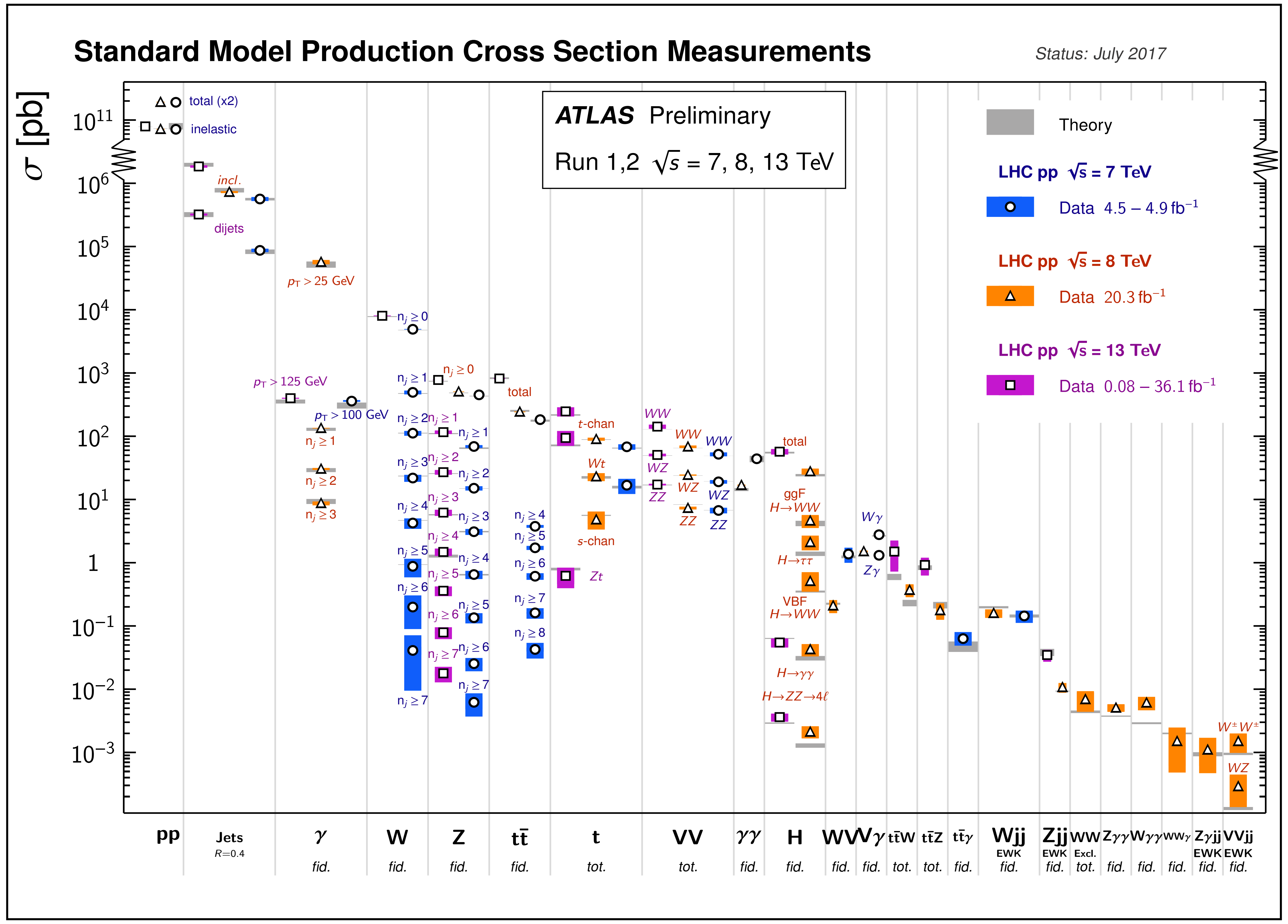
The SM and... the LHC data so far



rules the world!

[and we, HEP practitioners, are all entitled for some royalties!]



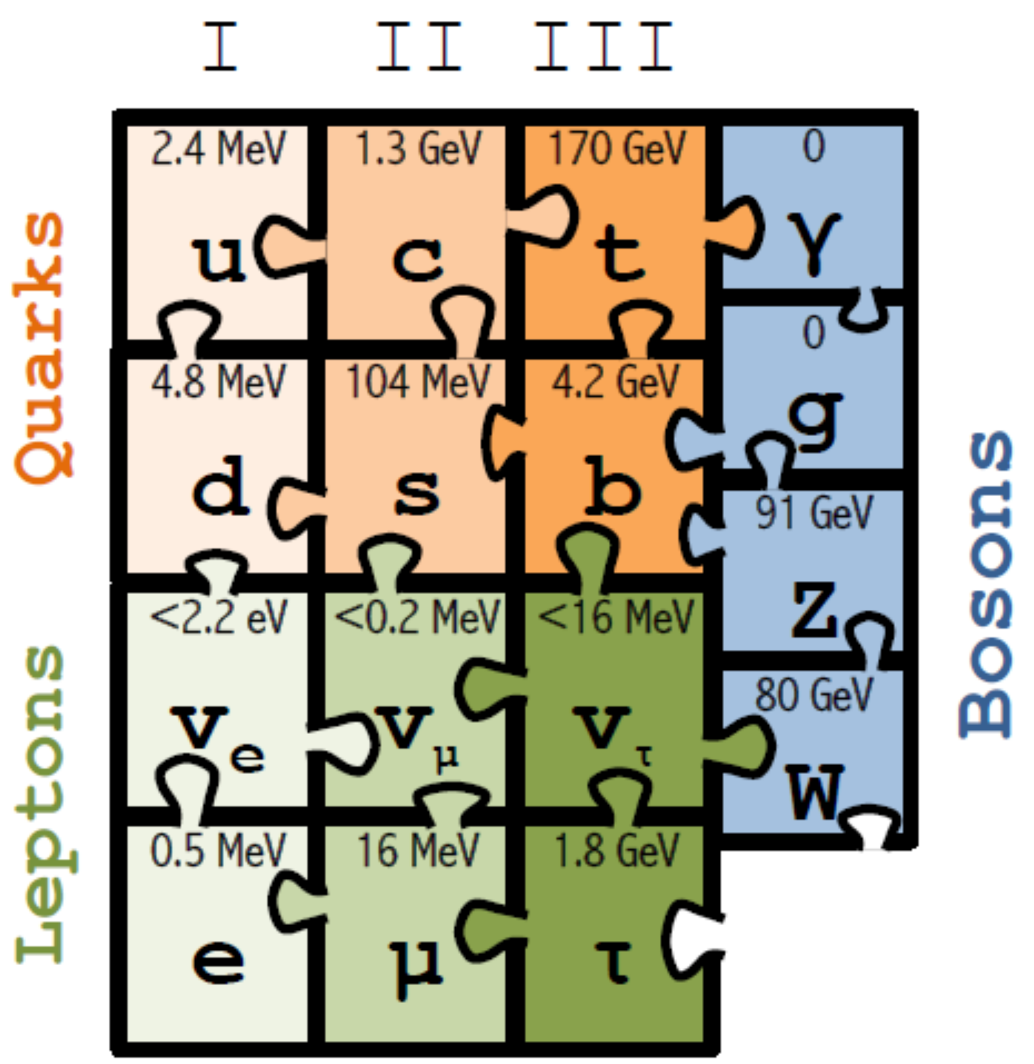


[slide of C. Grojean]

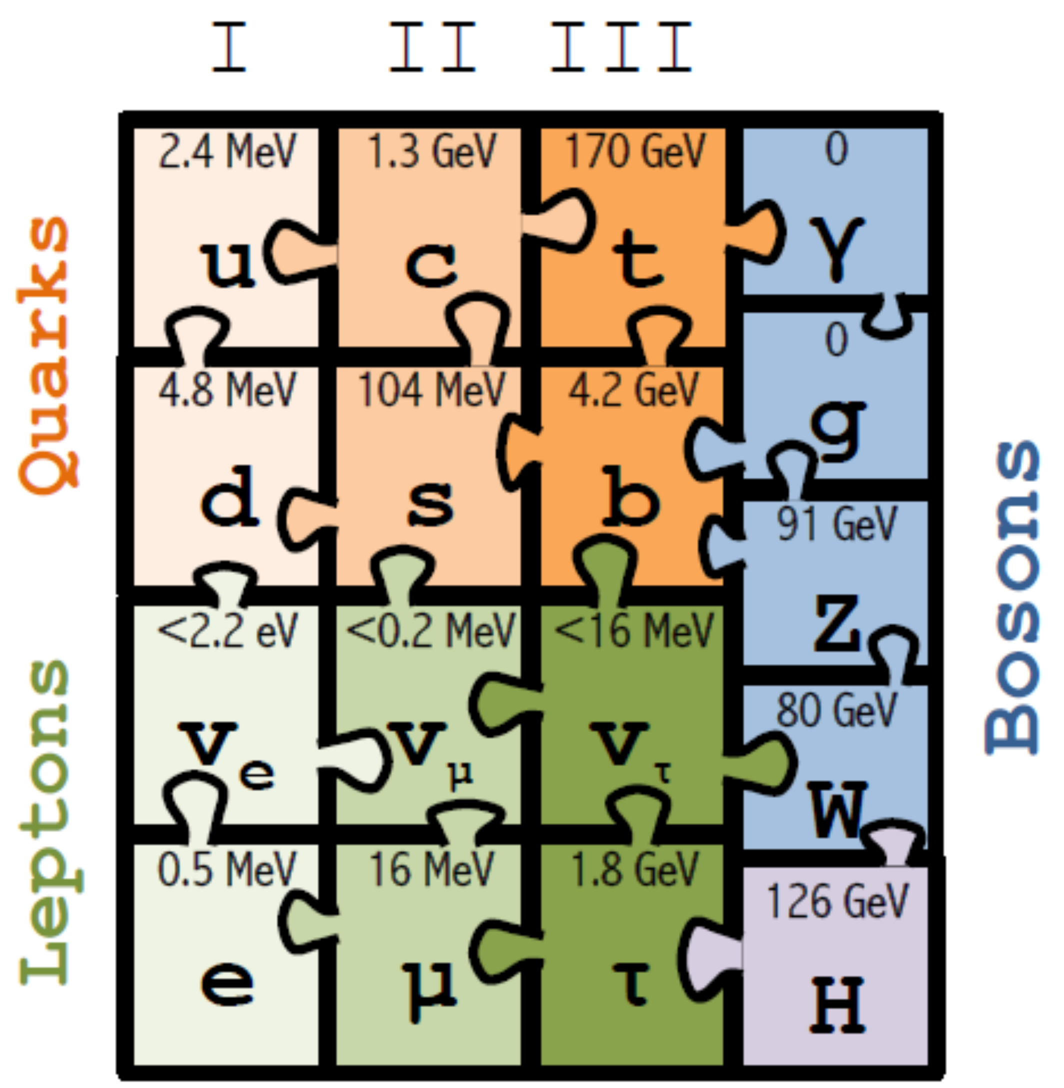
THE PHYSICS LANDSCAPE

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

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



1997-2013:
- Higgs mass cornered
  (LEP EW + Tevatron m_{top}, m_W)
- Higgs boson observed *at the right mass*
  (LHC 2012)
- Nobel Prize 2013
  (Englert & Higgs)

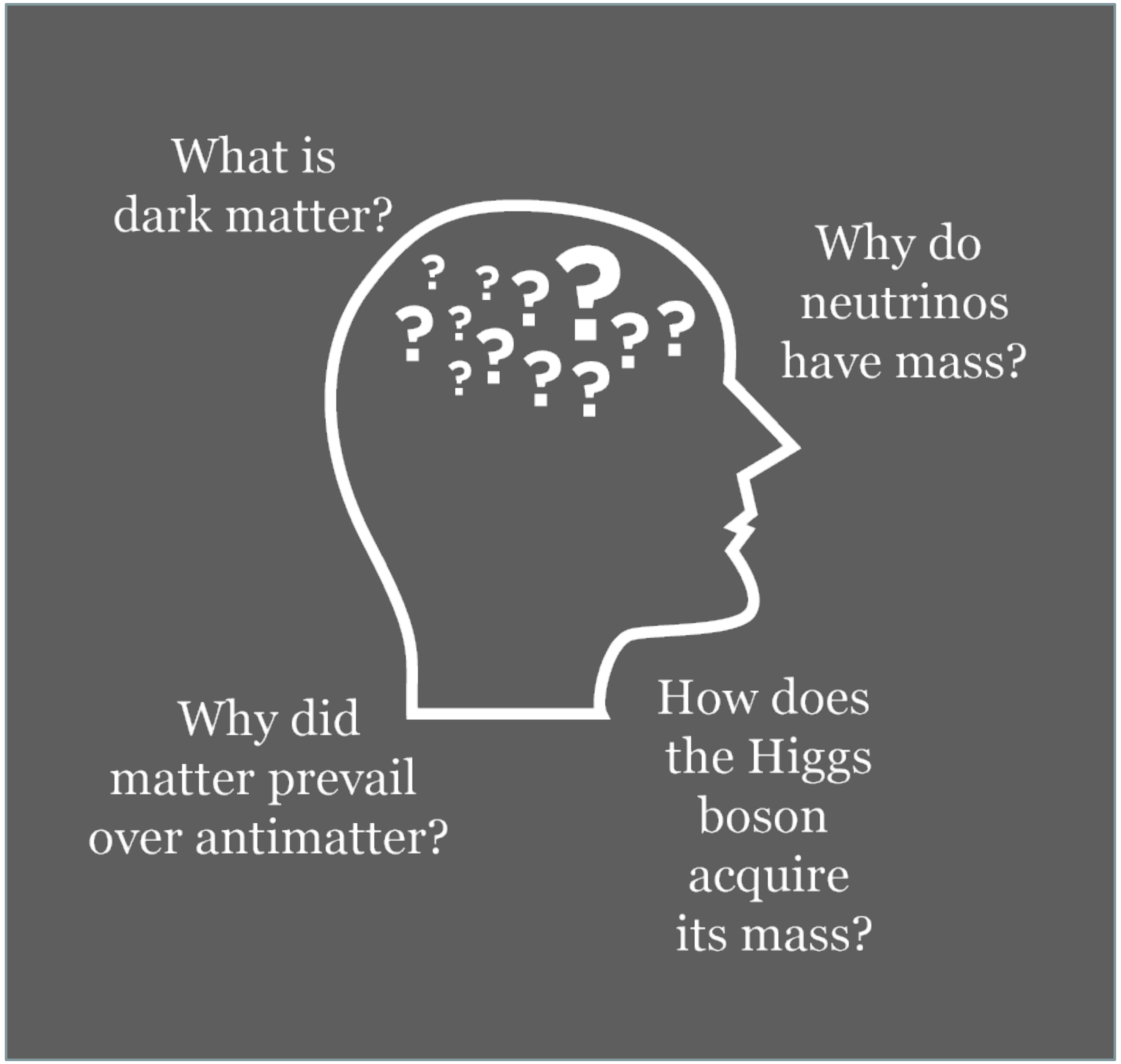


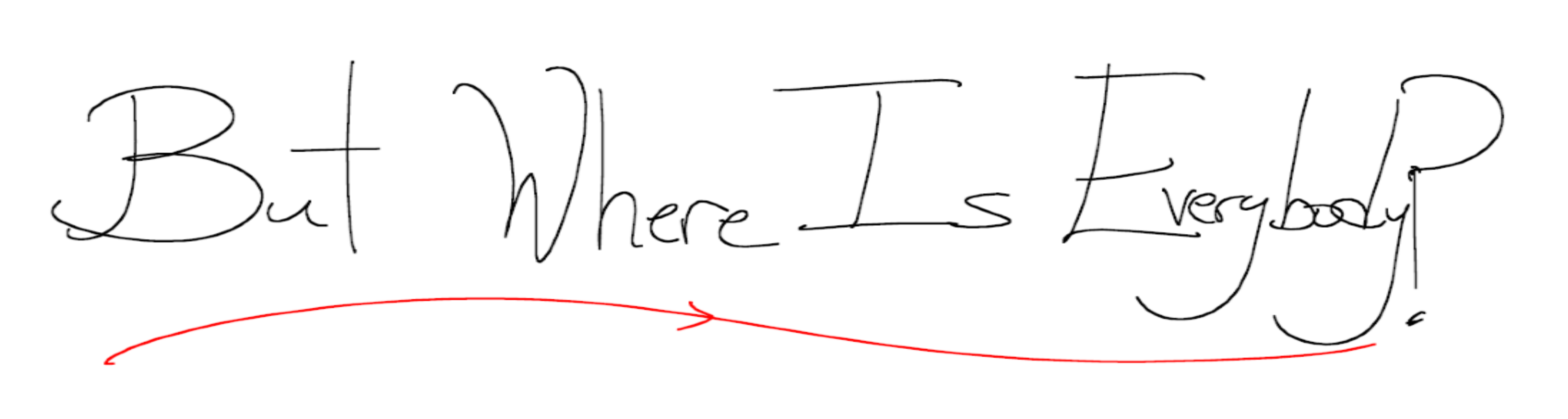
- It looks like the Standard Model is complete and consistent theory
- It describes all observed collider phenomena – and actually all particle physics (except neutrino masses)
  - Was beautifully verified in a complementary manner at LEP, SLC, Tevatron, and LHC
  - EWPO radiative corrections predicted 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 ?

SO MANY OPEN QUESTIONS!

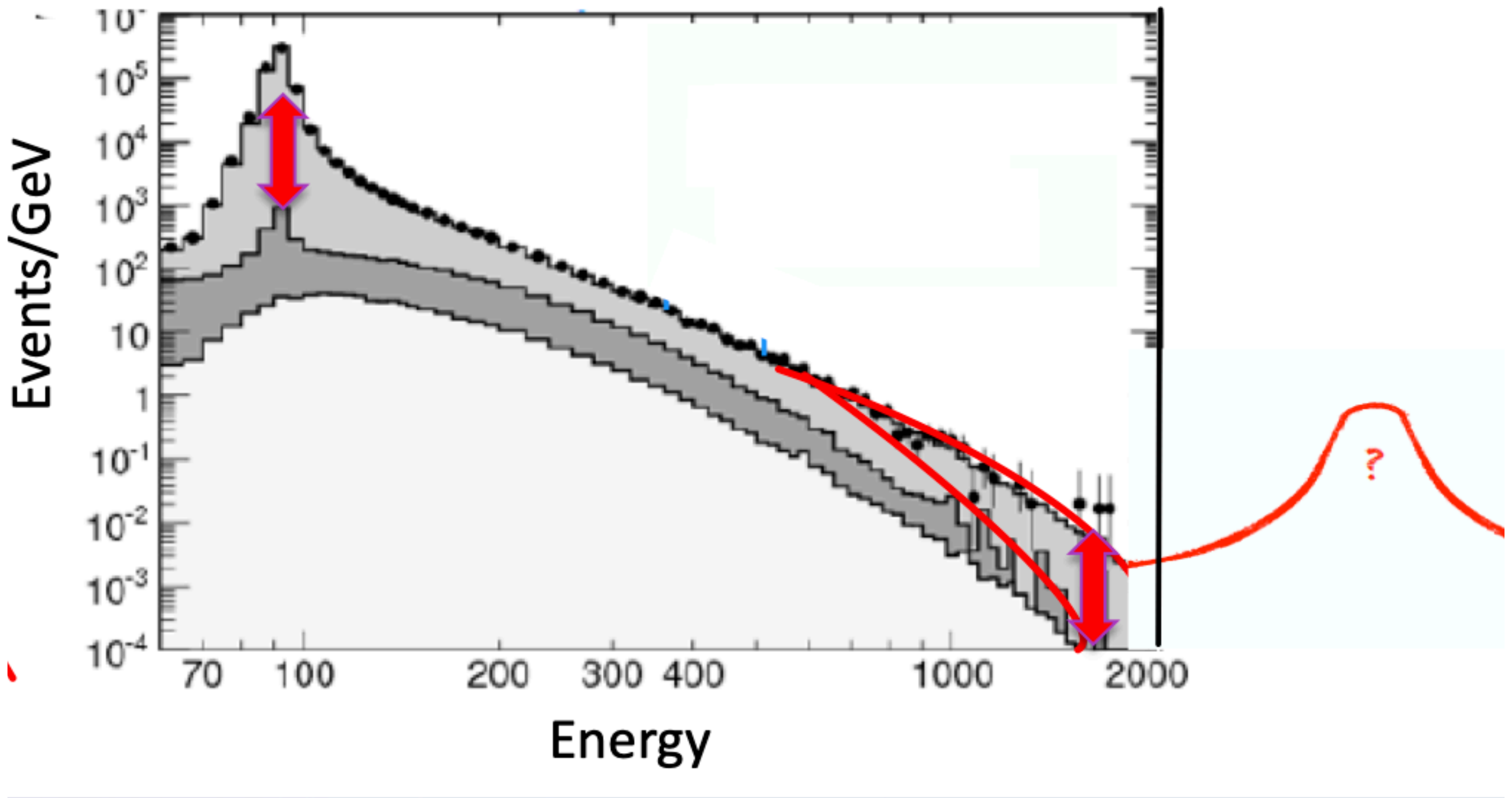
- Yet the Standard Model cannot explain certain experimental observations, such as:
  - the striking evidence for dark matter
    - SM Particles make up only 5% of Universe!
  - the abundance of matter over antimatter
  - the non-zero neutrino masses.
- Plus, the small Higgs boson mass hints to crucial questions specific to the nature of the theory at TeV scale
- All these point to the existence of physics beyond the Standard Model.





WHICH WAY TO GO?

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



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

WHICH TYPE OF COLLIDER?

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

More SENSITIVITY, more PRECISION, more ENERGY

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

THE COLLIDERS OF TODAY AND TOMORROW

NOW (LHC) : pp 13 TeV, 300 fb^{-1}

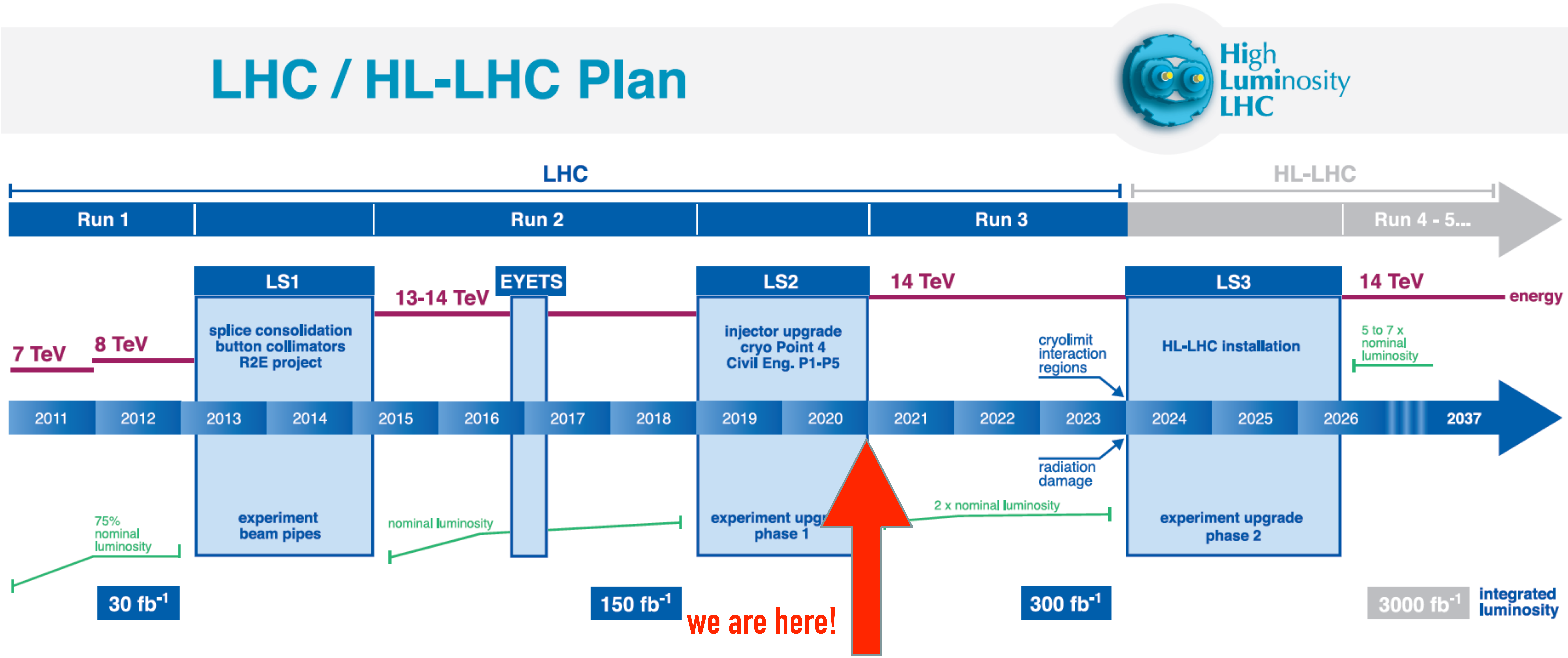
NEXT FUTURE (HL-LHC) : pp 14 TeV, 3000 fb^{-1}

High Luminosity LHC

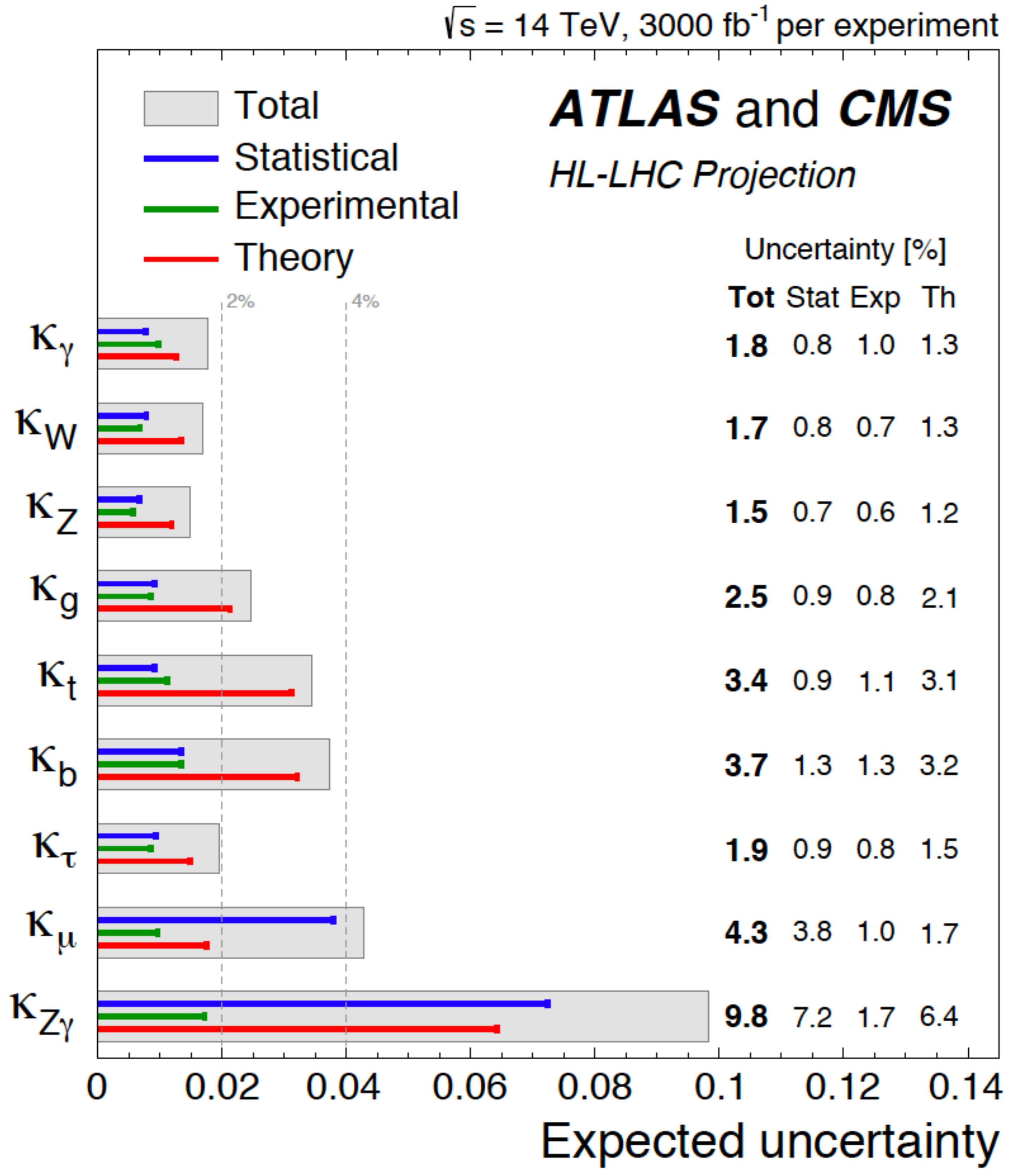
- (2024) The LHC tunnel will be used once again for another machine: the HL-LHC. To be able to function with the new accelerator the experiments will be upgraded as well

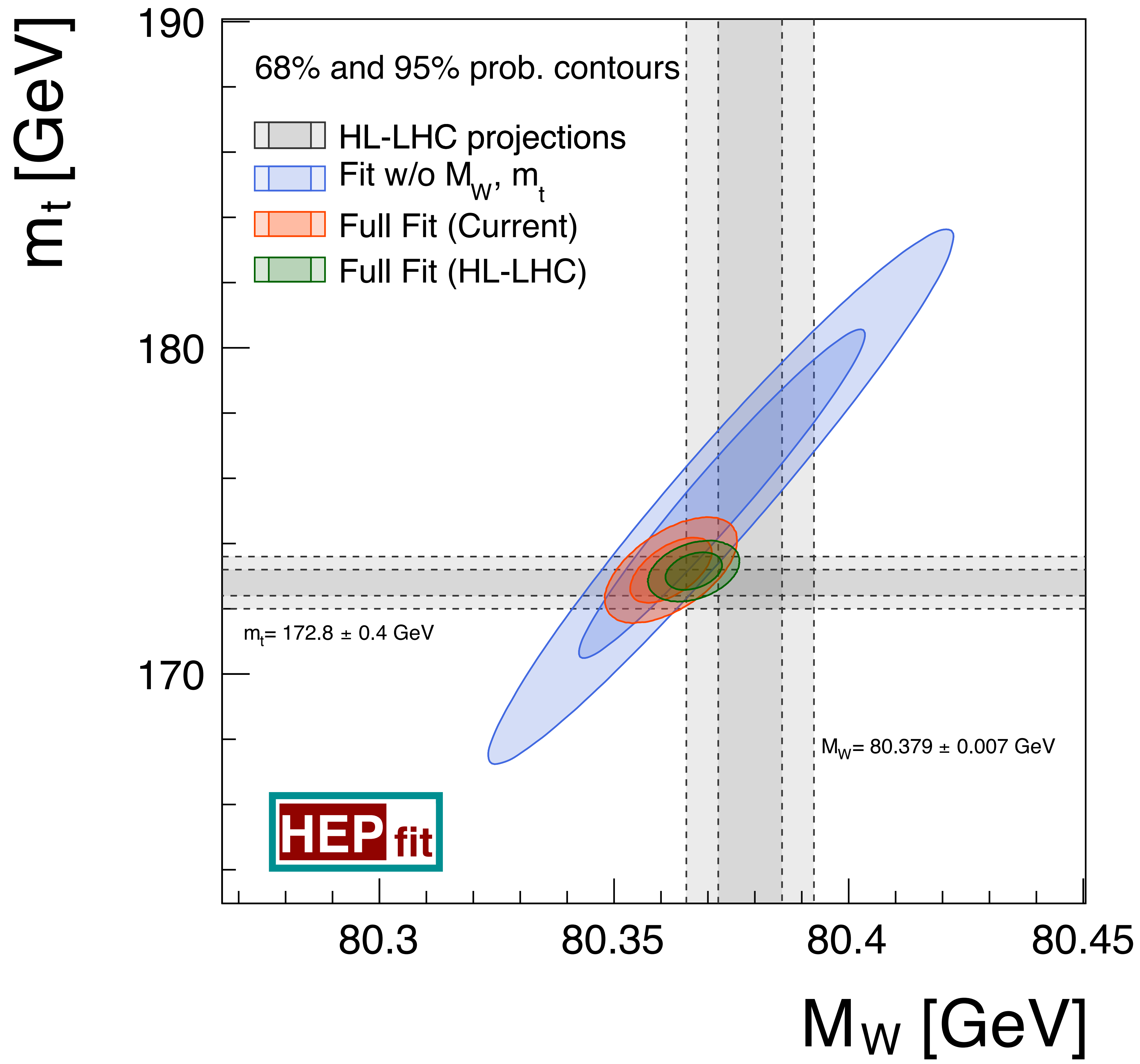
THE NEXT FUTURE (2024): HL-LHC

- Aim at 3000 fb^{-1} pp collisions at $\sqrt{s}$ = 14 TeV
- Higher luminosity means a large number of extra-interactions per bunch crossing
  - to be precise <μ> = 200 more extra collision overlapping with the « interesting one » (pile-up)



AFTER HL-LHC

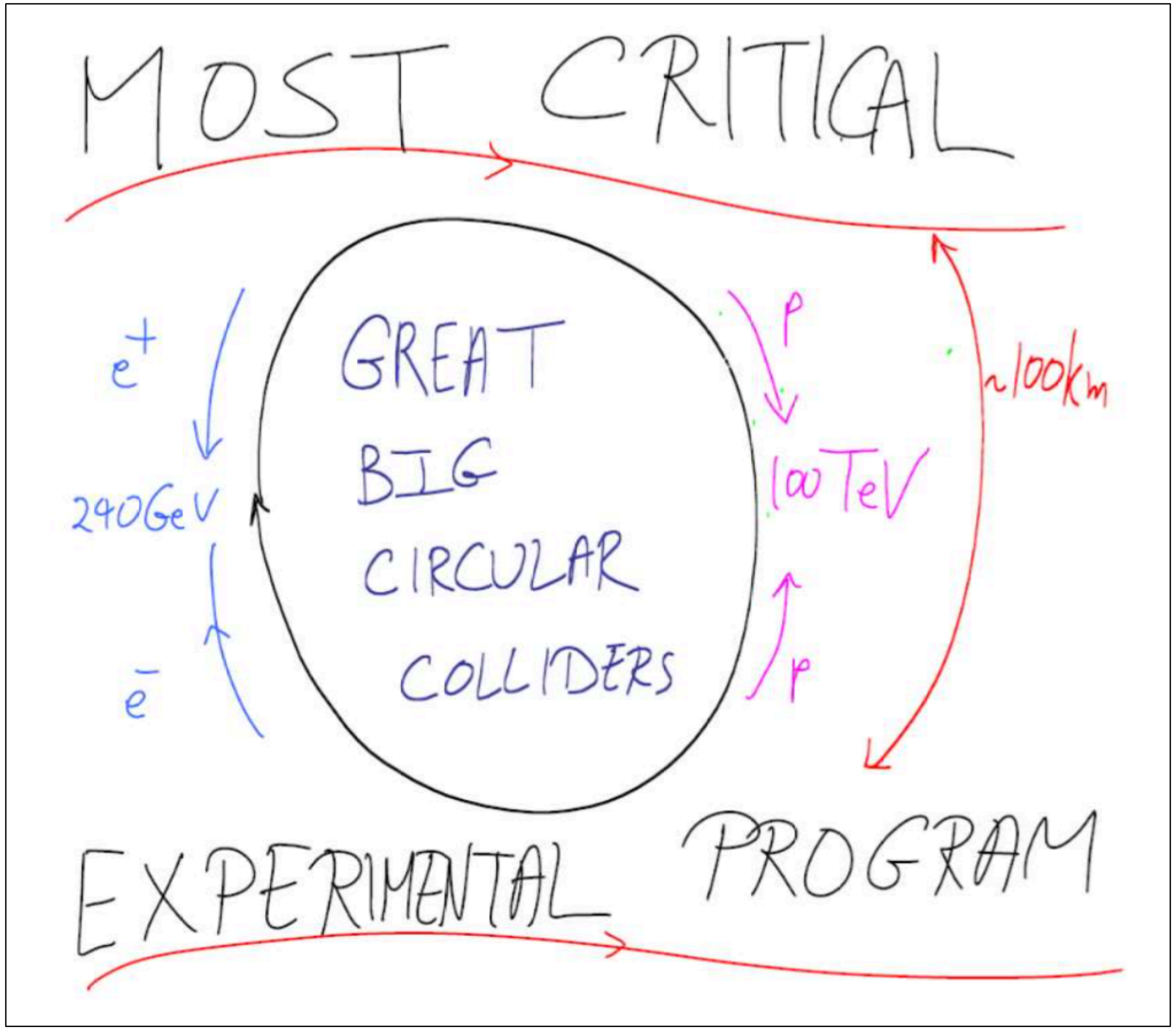


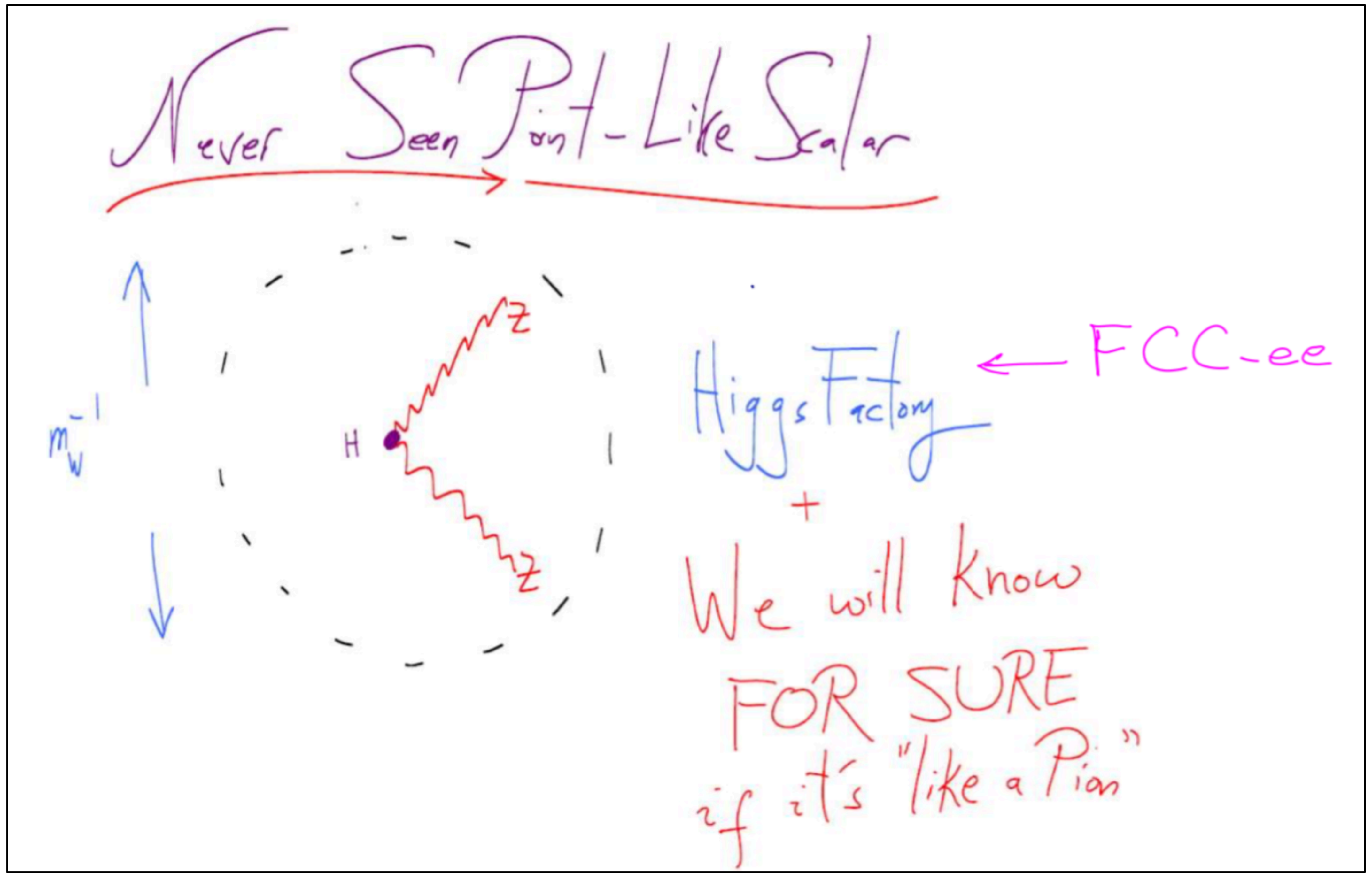


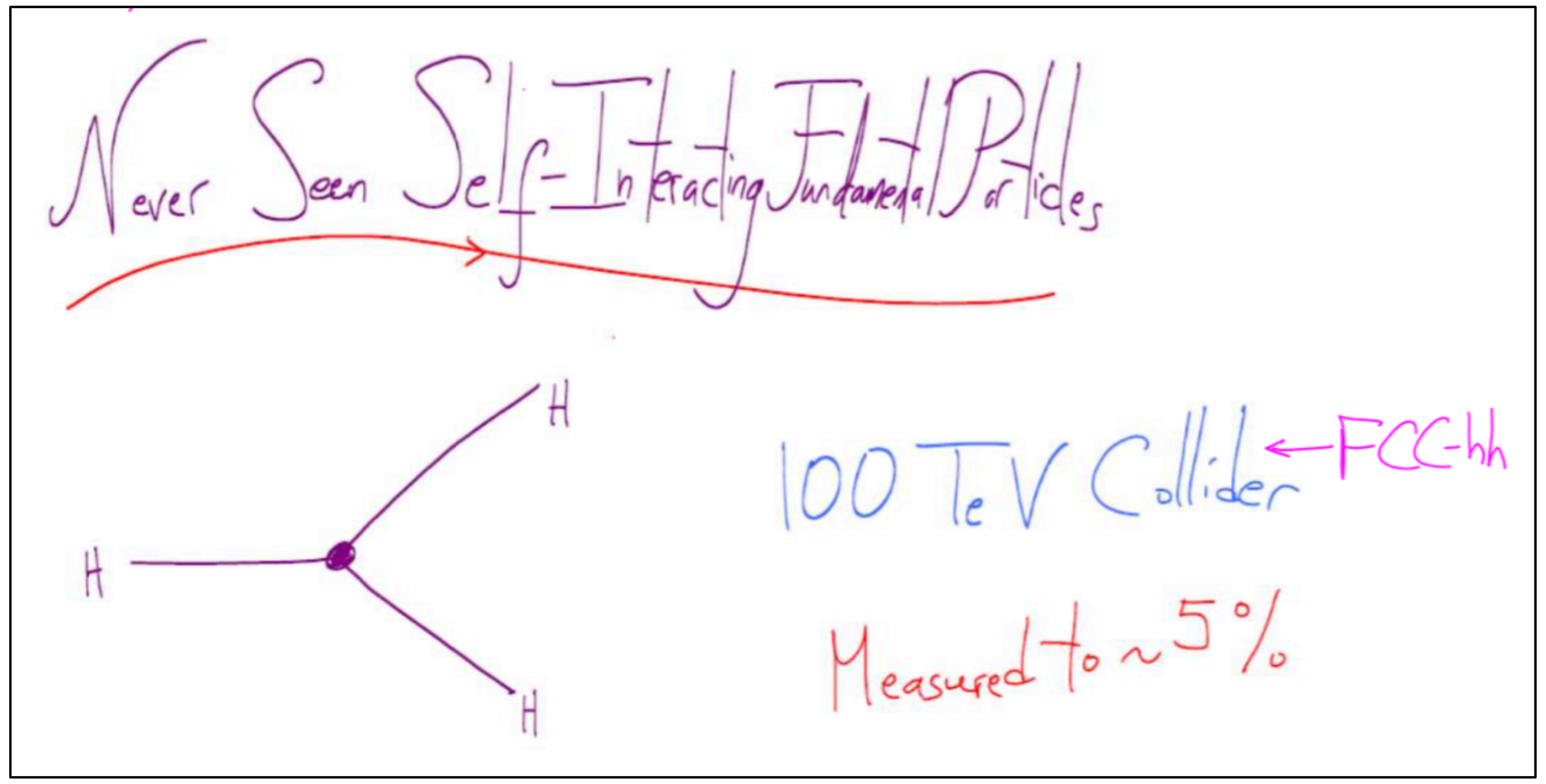
- Careful studies and projections for the physics at the HL-LHC we have shown:
  - we have designed amazing detectors that will be able to fully mitigate the 200PU conditions
  - uncertaintities on Higgs couplings of the order of 2-4% and top mass about ~200MeV
  - This precision might still not be sufficient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

INFN
PADOVA

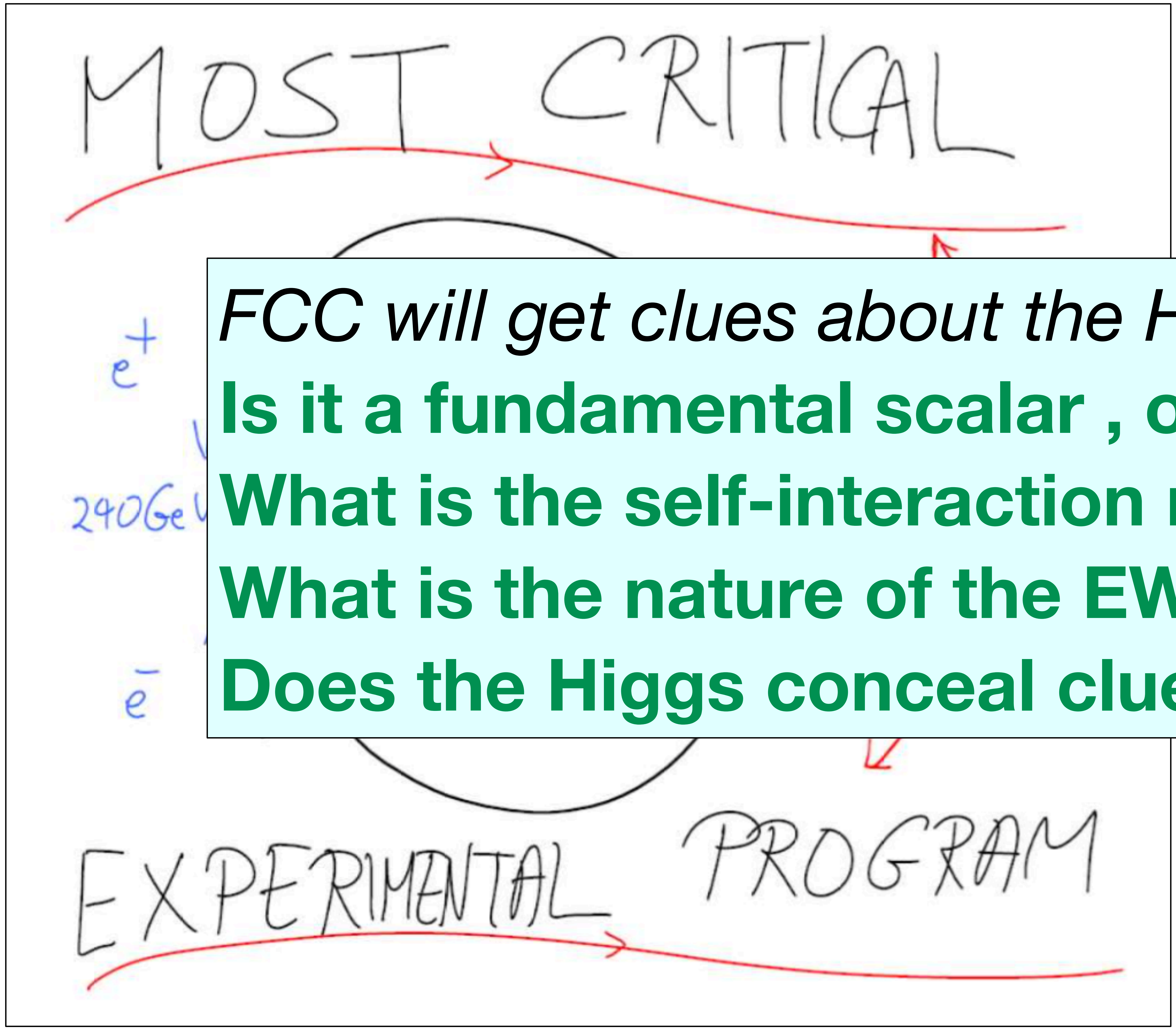
A CONCRETE TARGET: THE HIGGS BOSON

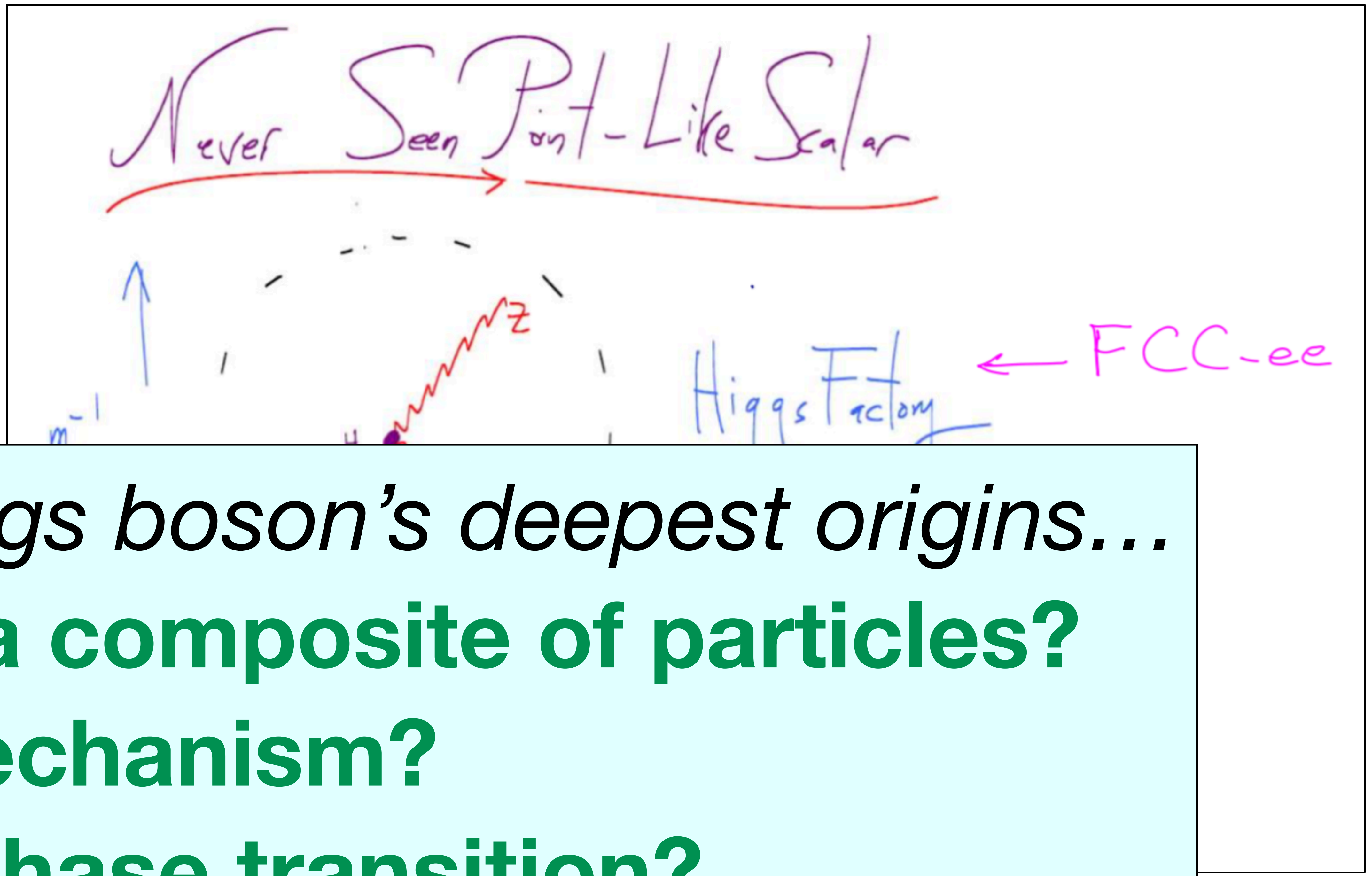


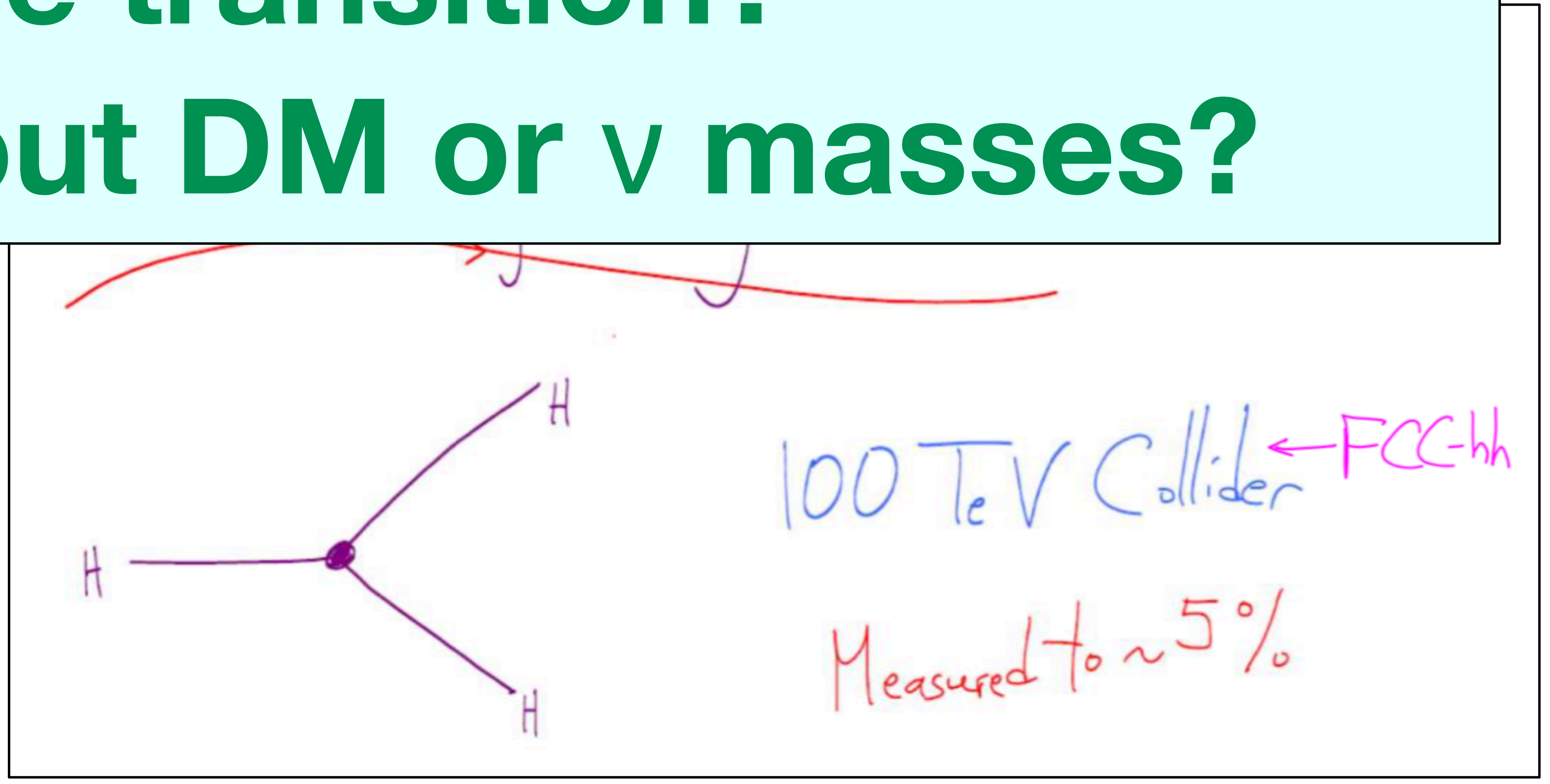




A CONCRETE TARGET: THE HIGGS BOSON







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

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

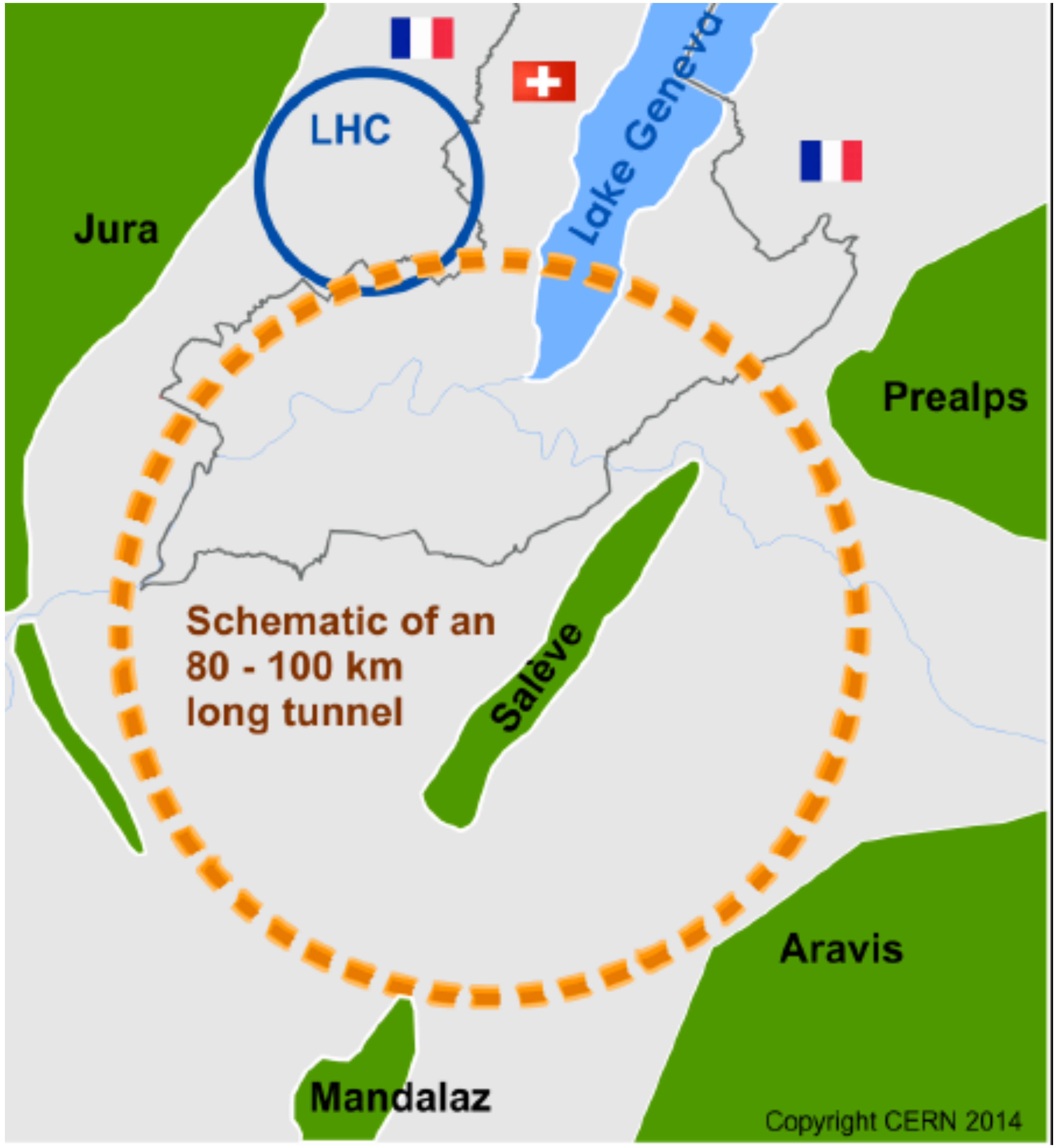
What is the self-interaction mechanism?

What is the nature of the EW phase transition?

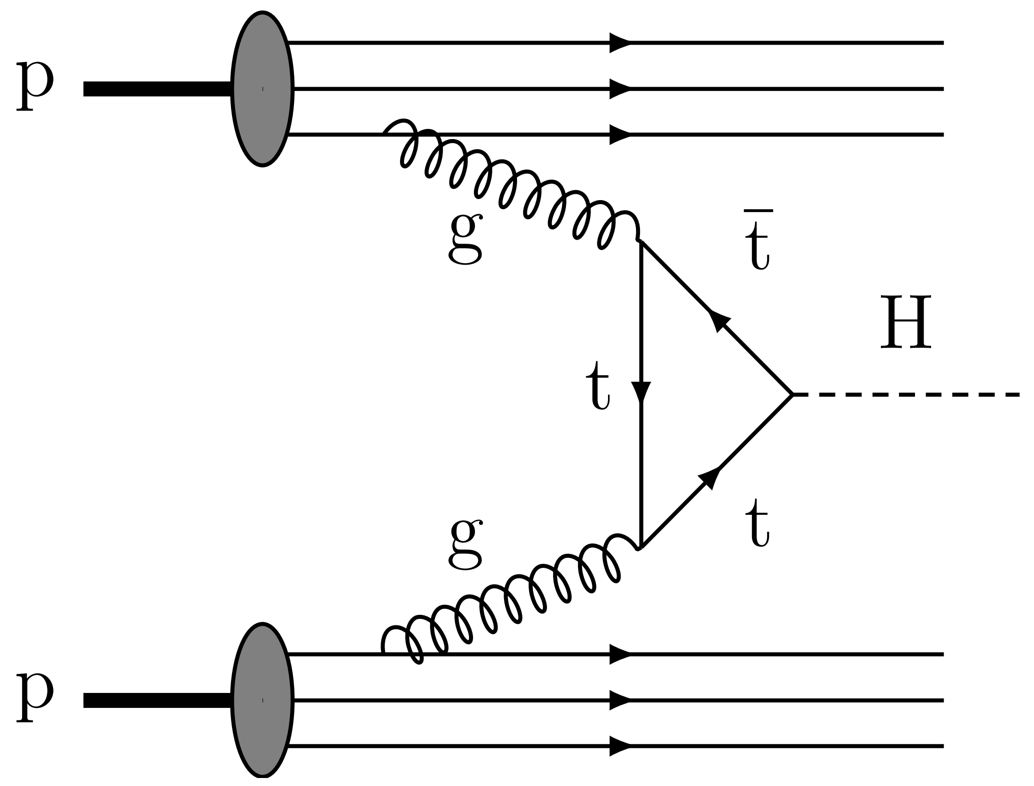
Does the Higgs conceal clues about DM or ν masses?

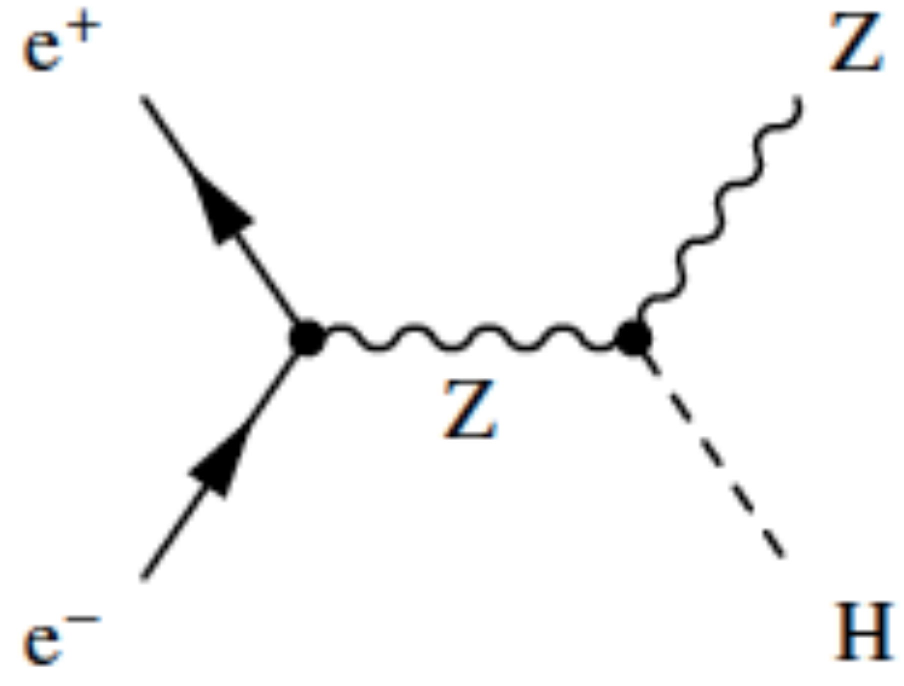
THE FUTURE: THE FCC INTEGRATED PROJECT

- Build a new 100 km 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 for the next 50 years



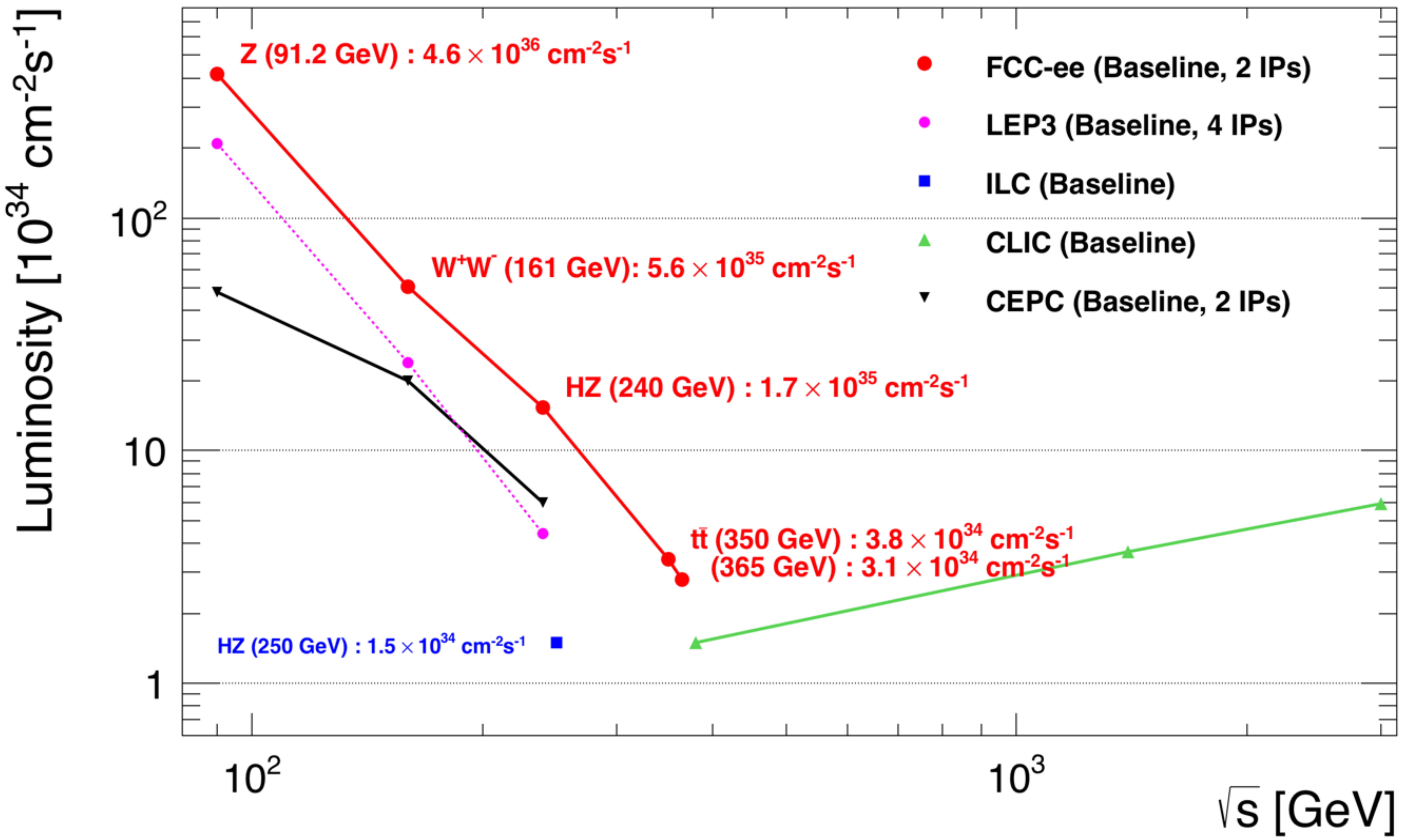
e^+e^- VS pp COLLISIONS - EVENT CHARACTERISTICS





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

FCC-ee ENERGY RANGE AND LUMINOSITY



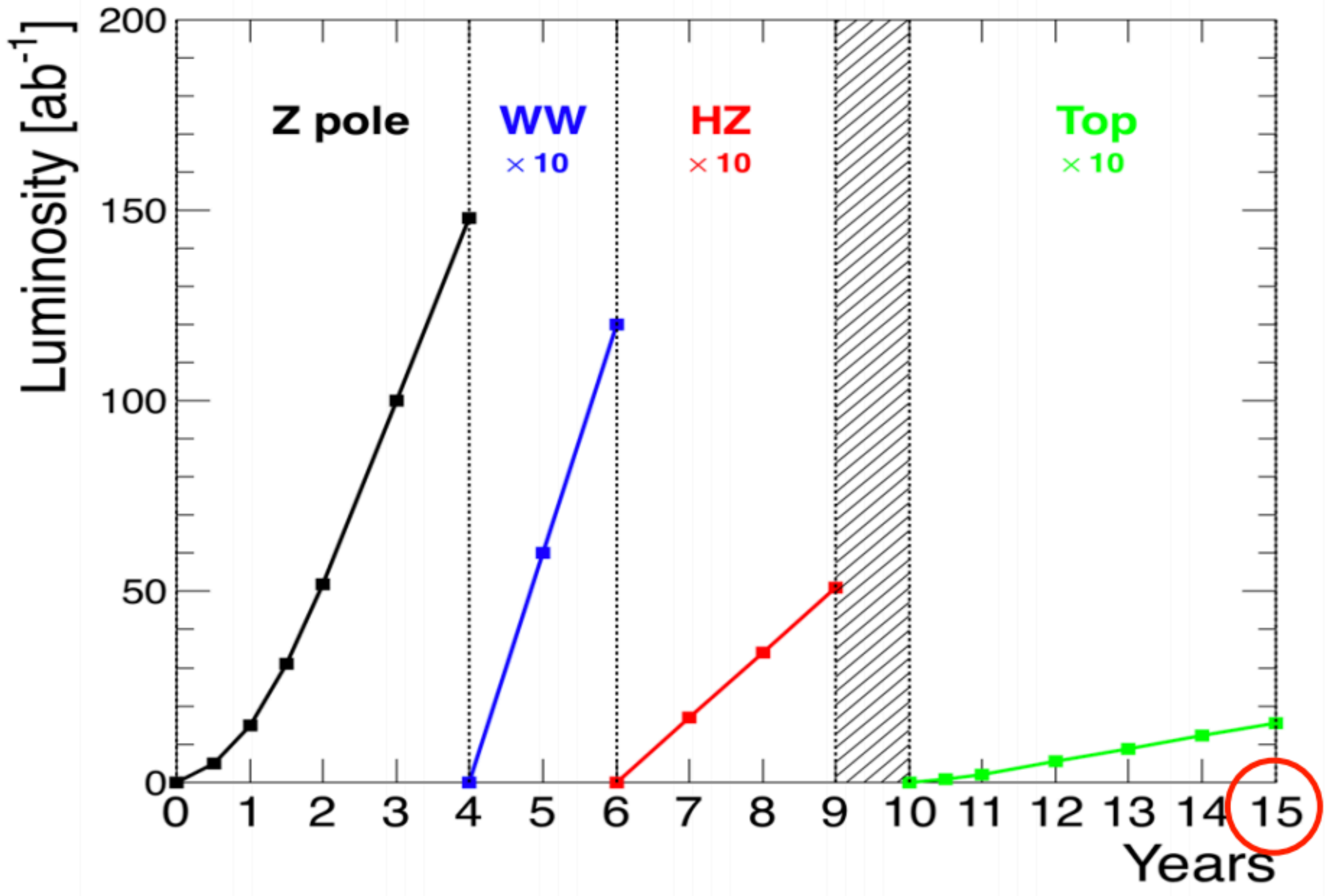
- High integrated luminosity at the needed E_{cm}
- Clean environment
- precise knowledge of the center-of-mass energy and of the luminosity
- precise detectors offering plenty of redundancy (and more than one)

Can produce all the heaviest particles of the Standard Model

FCC-ee RUN PLAN

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics	
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays	LEP x 10^5
FCC-ee-W	2	158-162	12	10^8 WW events	LEP x $2 \cdot 10^3$
FCC-ee-H	3	240	5	10^6 ZH events	Never done
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events	Never done

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

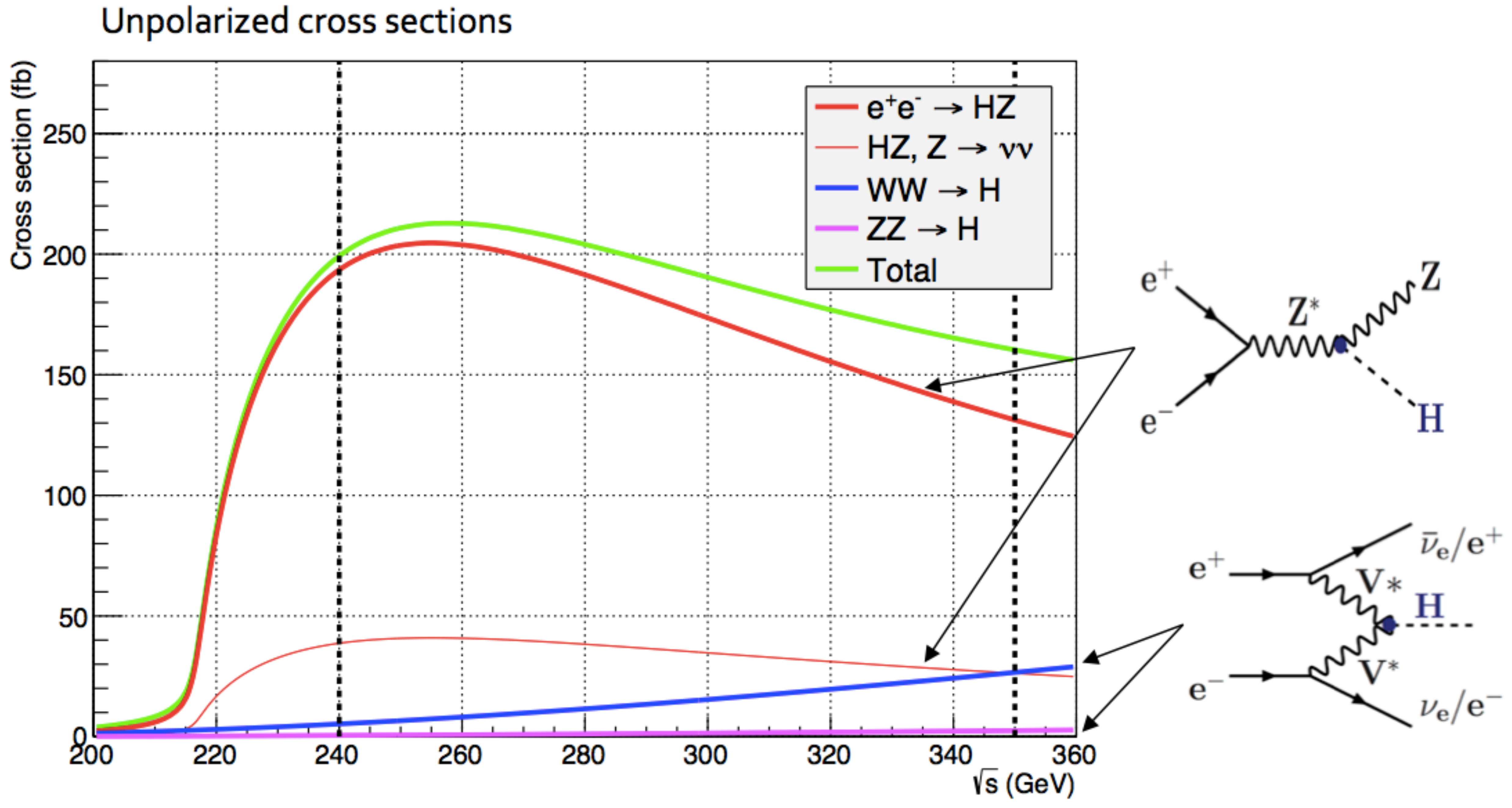


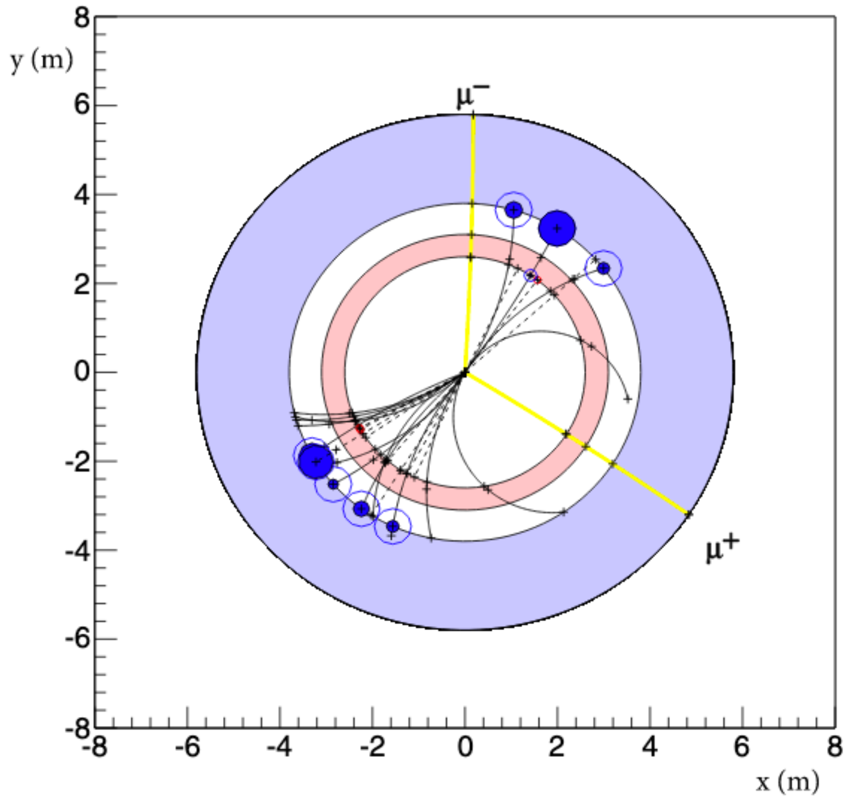
patrizia azzi - EASISchool3 - 8/10/2020

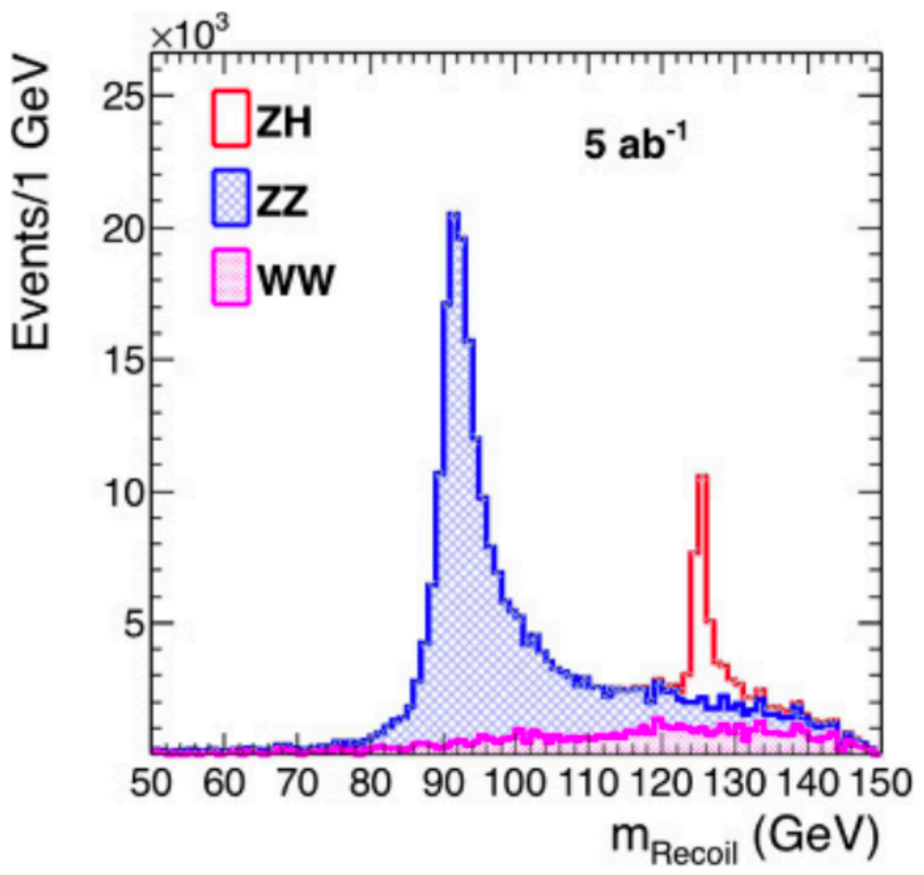
FCC-ee: A DISCOVERY MACHINE AND MORE

- ***EXPLORE** the 10-100 TeV energy scale region with precision measurements of the properties of the Z,W,Higss and top particles*
  - 20-50fold improved precision on EWK observables
  - 10 fold more precise and model-independent Higgs coupling measurements
- **DISCOVER** that the Standard Model does not fit
  - Allows understanding of the underlying physics structure
- **DISCOVER** a violation of flavour conservation/universality
  - Flavour physics in 1012 bb events (B0 → K*0τ+τ− , BS→ τ+τ− , …)
- **DISCOVER** dark matter as invisible decays of the Z or Higgs
- **DISCOVER** feebly coupled particles in the 5-100 GeV mass range
  - Such as right handed neutrinos, dark photons, …

HIGGS PHYSICS AT THE FCC-EE



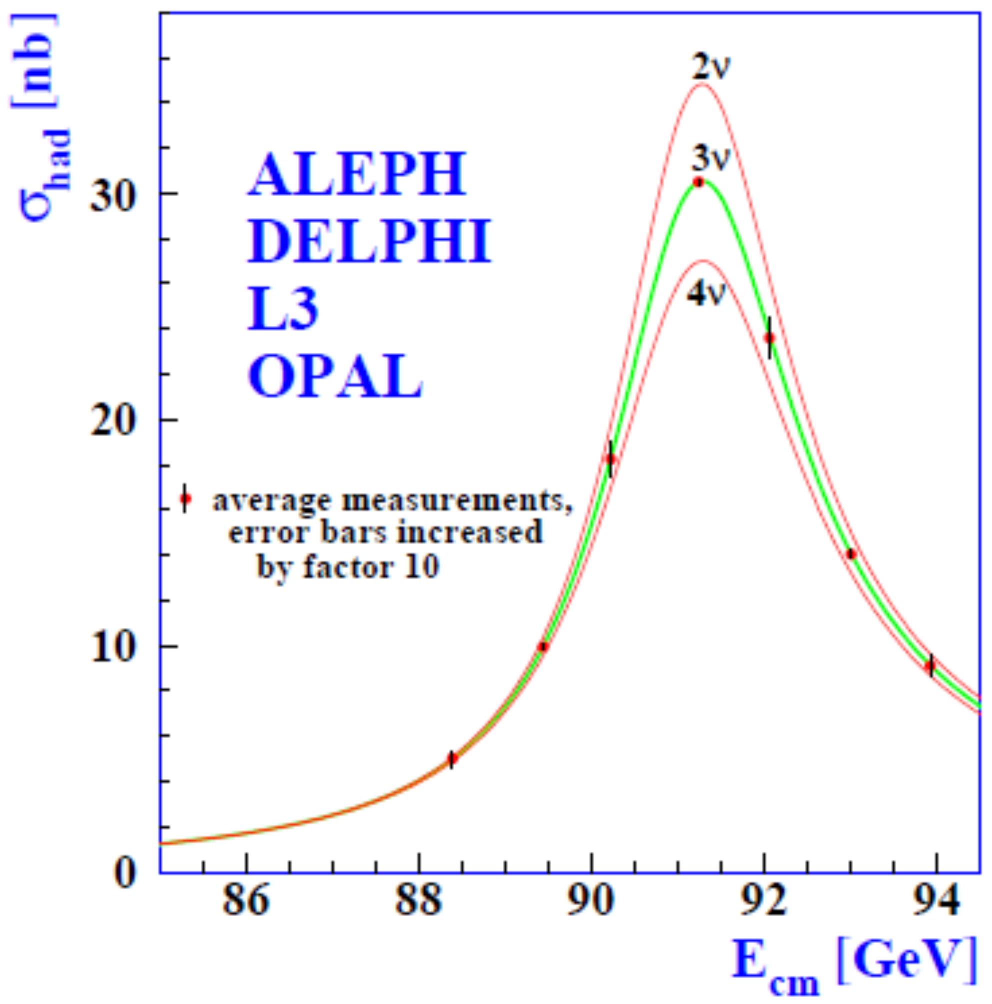




- ➤ Recoil method unique to lepton collider:
  - ➤ Tag Higgs event independent of decay mode
- ➤ Precision measurements: couplings, mass, width
- ➤ Searches for Exotic Higgs, invisible decays

PRECISION ELECTROWEAK MEASUREMENTS

Z resonance: TeraZ



Lineshape

- Extremely precise E_{beam}
- m_Z, Γ_Z to < 100 keV (2.2 MeV)

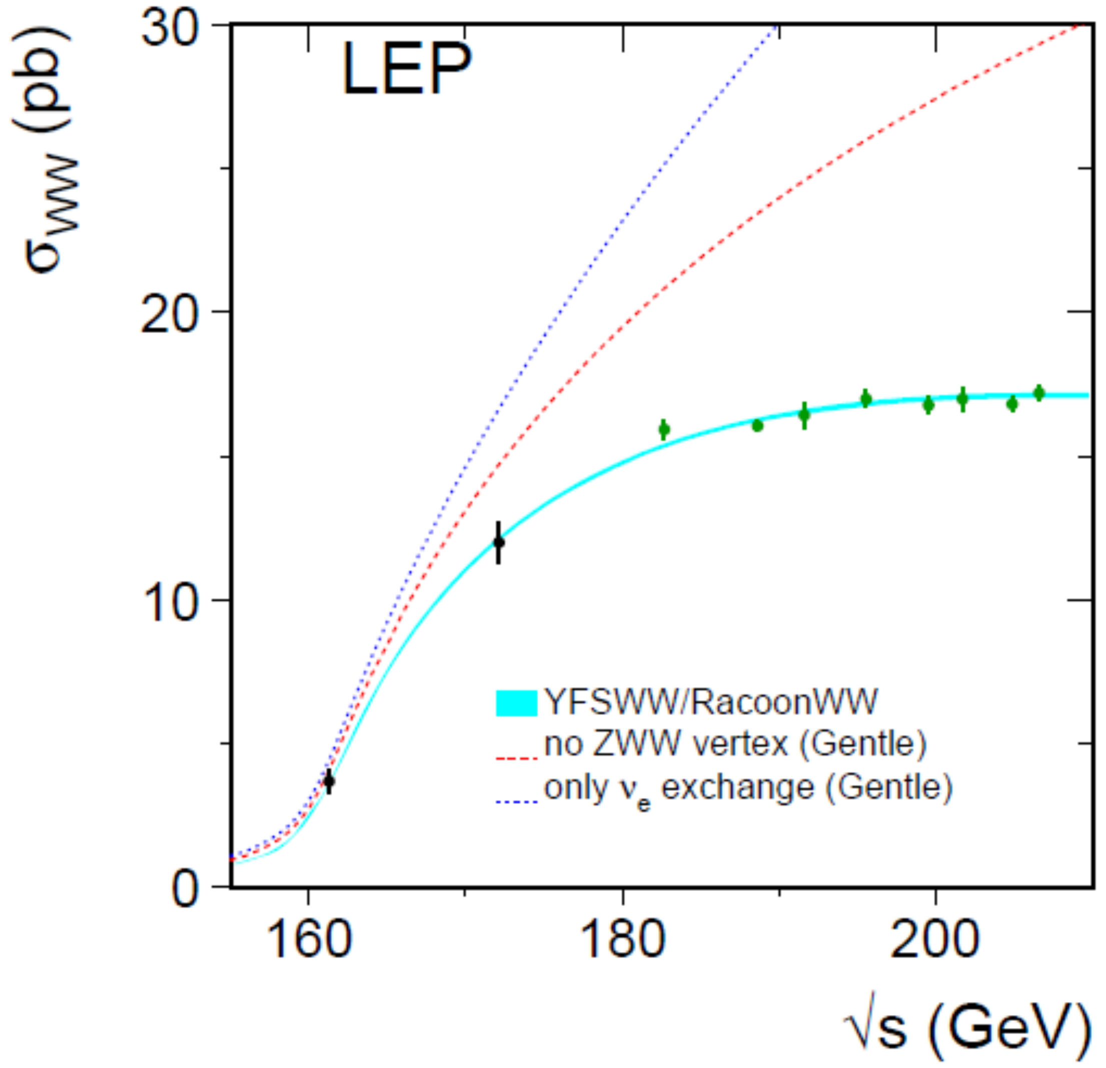
Asymmetries

- $\sin^2\theta_W$ to 6×10^{-6} (1.6×10^{-4})
- $\alpha_{QED}(m_Z)$ to 3×10^{-5} (1.5×10^{-4})

Branching ratios R_l, R_b

- $\alpha_S(m_Z)$ to 0.0002 (0.002)

WW threshold scan: OkuW



Threshold scan

- m_W to 0.5 MeV (12 MeV)

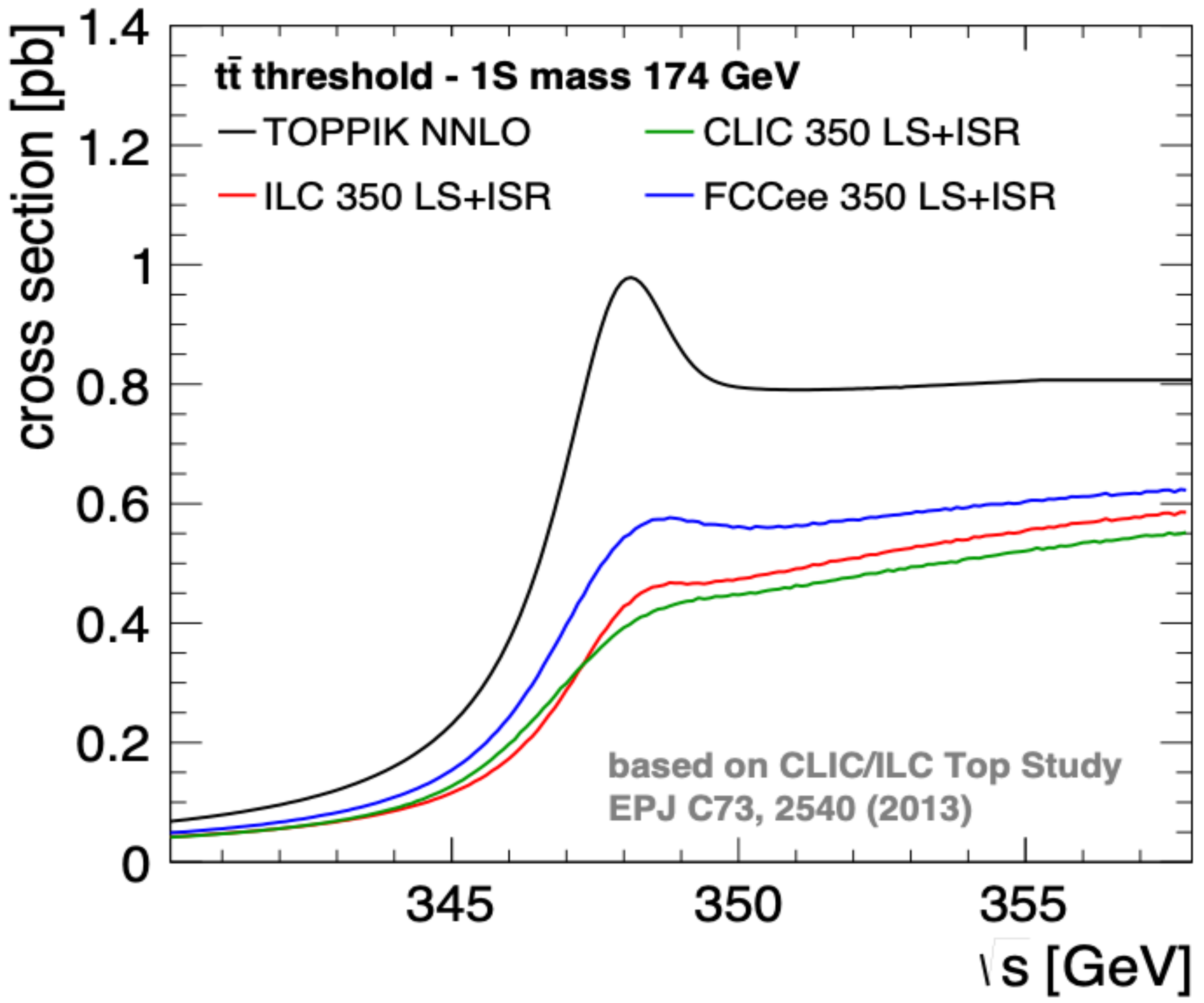
Branching ratios R_l, R_b

- $\alpha_S(m_Z)$ to 0.0002

Radiative return $e^+e^- \rightarrow Z\gamma$

- N_ν to 0.0004 (0.008)

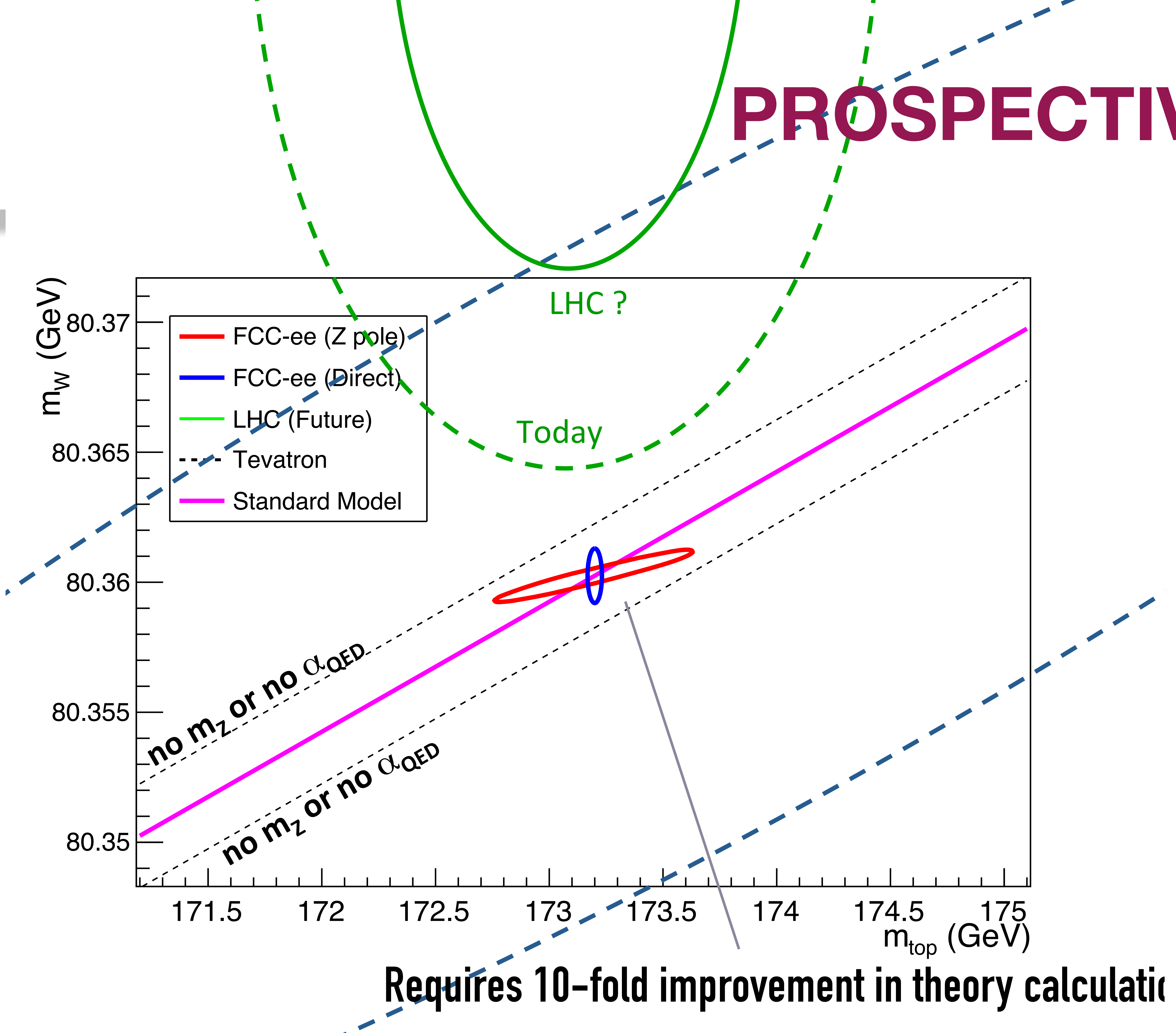
tt threshold scan: MegaTop



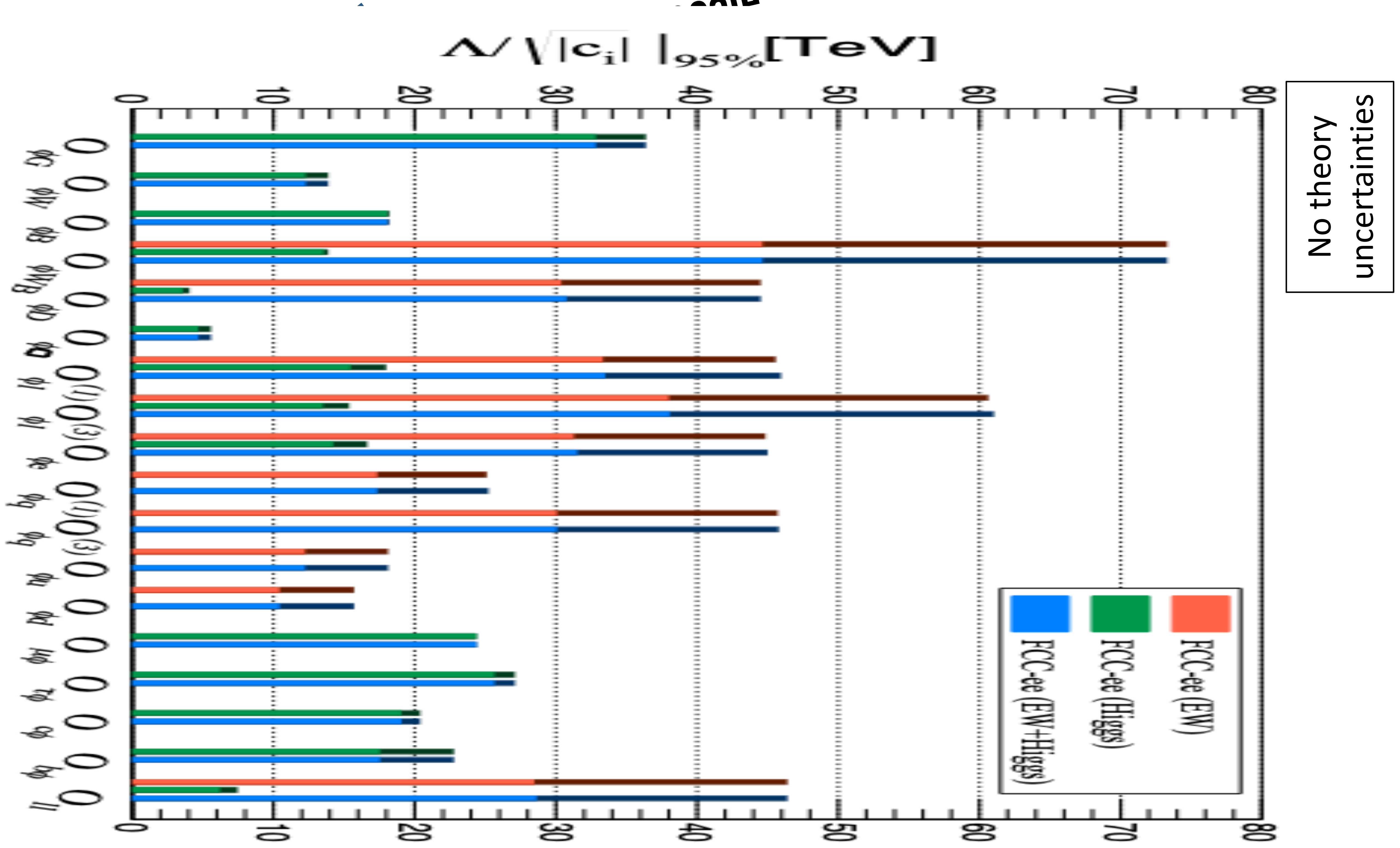
Threshold scan

- m_{top} to 10 MeV (500 MeV)
- λ_{top} to 10%
- EW couplings to 1%

PROSPECTIVES FOR SM FITS AFTER FCC-ee



$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$



- Today Λ_{NP}>5-10 TeV, after FCC-ee Λ_{NP}>50-100 TeV
  - Points to the physics to be studied with FCC-hh

NUMEROLOGY FOR FCC-hh

Numerology for $10ab^{-1}$ @100TeV

- **10^{10} Higgs bosons** => 10^4x today
-
- **10^{12} top quarks** => 5 10^4 x today
  - =>10^{12} W bosons from top decays
  - =>10^{12} b hadrons from top decays
  - =>10^{11} t->W->taus
  - few 10^{11} t->W charm hadrons

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

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

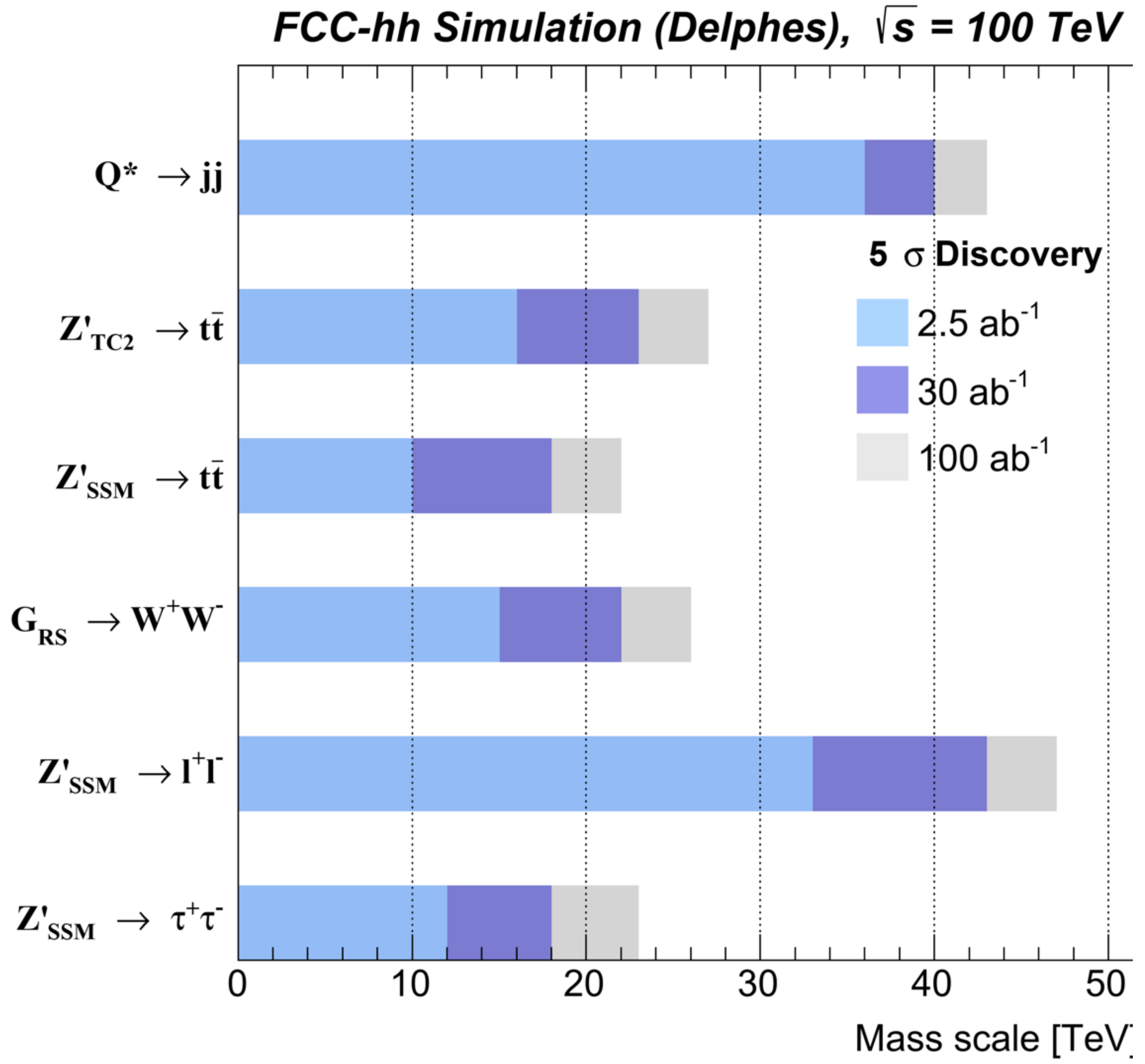
➡rare decays τ->3μ, μγ, CPV

➡rare decays D->$\mu^+\mu^-$,... CPV

Amazing potential, extreme detector and reconstruction challenges

FCC-hh DISCOVERY POTENTIAL (HIGHLIGHTS)

- Highest 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
  - *Direct New Physics production at FCC-hh complemented with quantum effects at FCC-ee*

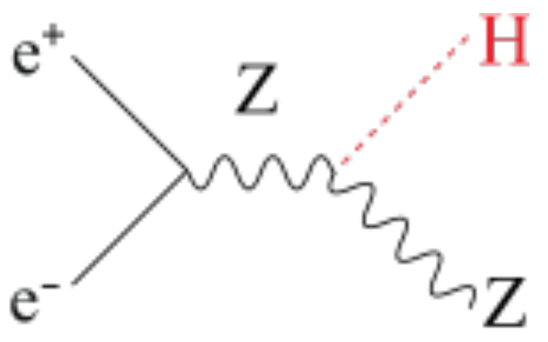


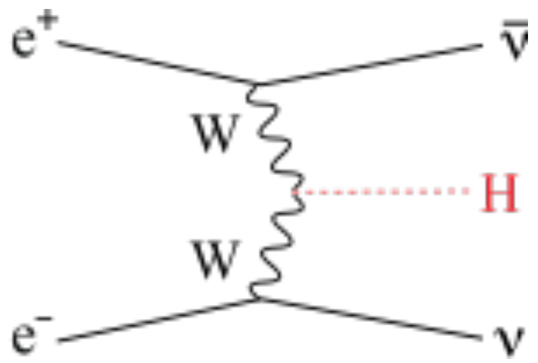
- Huge rates of SM particles (H, W, Z, t, b, …) in single/multiple production
  - Precise determination of triple Higgs coupling; Access to quartic coupling.
  - Rich top and heavy-flavour programme: 10^{12} top quarks and 10^{17} b quarks produced
  - Search for invisibles (invisible Higgs decay [→ 10^{-4}], RH neutrinos in W decays, DM searches) & Long-lived particles
- SM particles produced at high p_T with large statistics
  - Allows cleaner signals for channels that are currently difficult at LHC

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

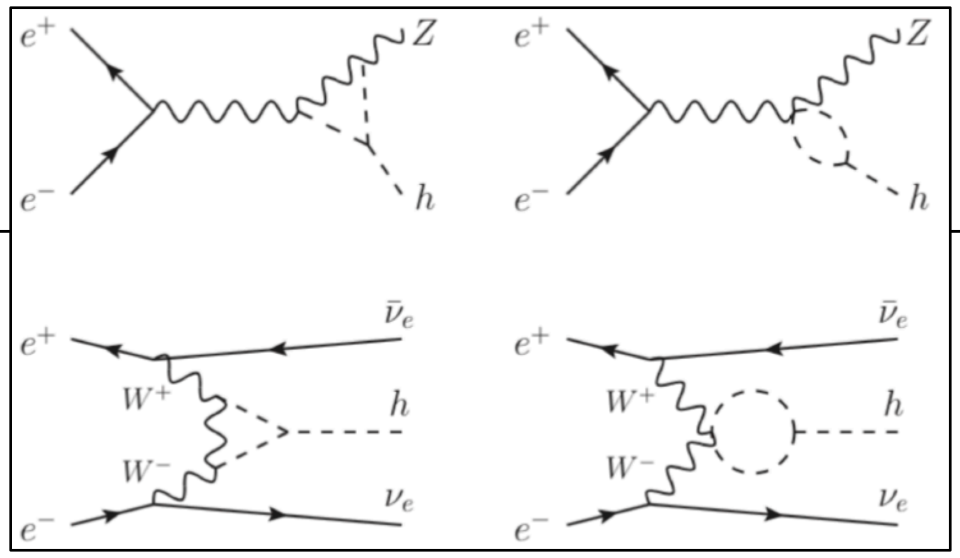
Absolute determination of g_{HZZ} to ±0.17%

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)**



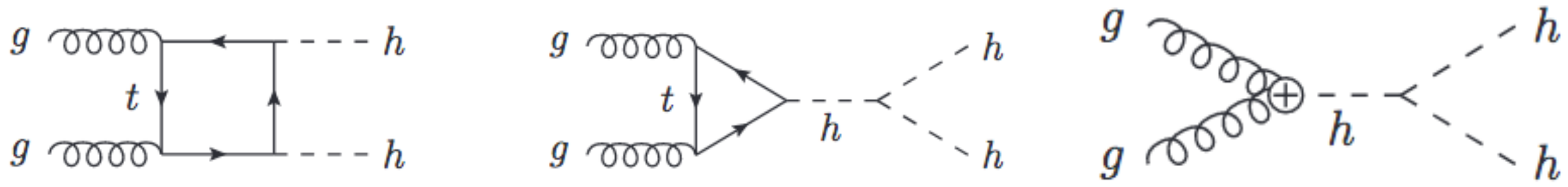
FCC-hh provides 3×10^{10} Higgs bosons

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

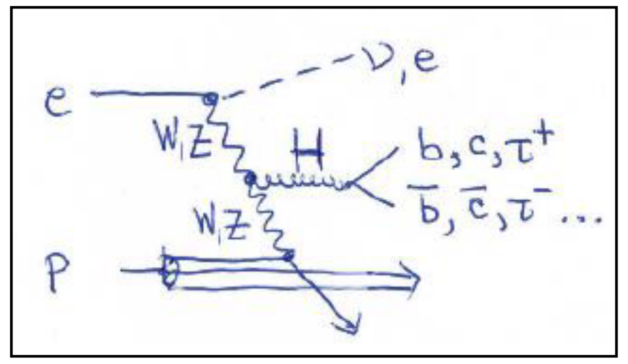
→ **Rare decays: couplings to μμ, γγ, Zγ …**

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



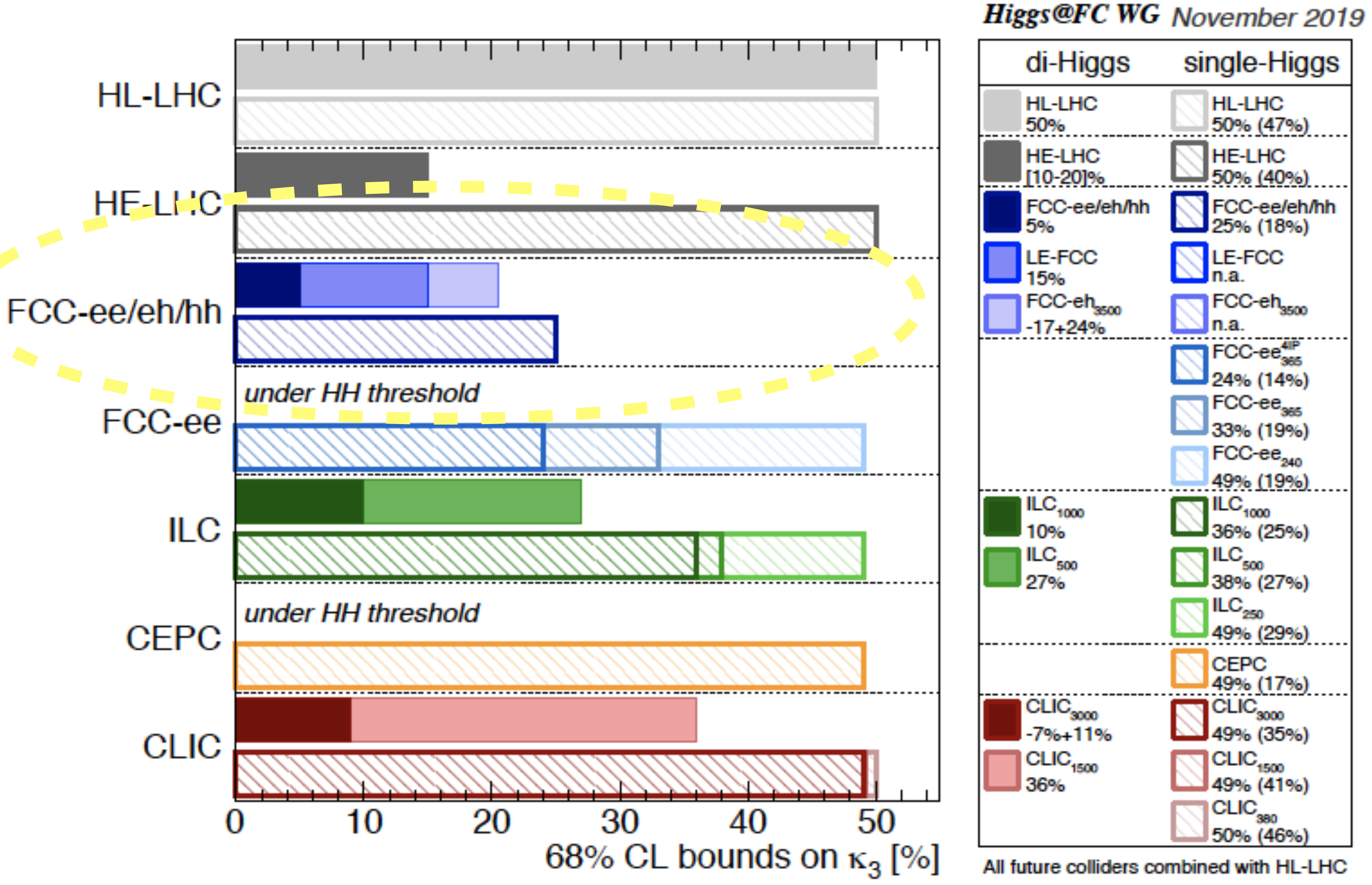
FCC-eh provides 2.5 10^6 Higgs bosons

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



FCC SYNERGIES: TRIPLE HIGGS COUPLING

Projected precision of λ3 measurements

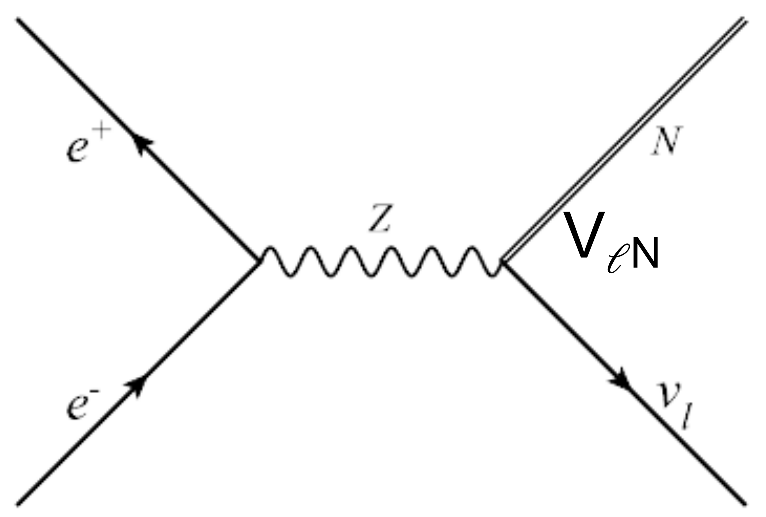


FCC integrated program will measure λ_3 to the 5% level

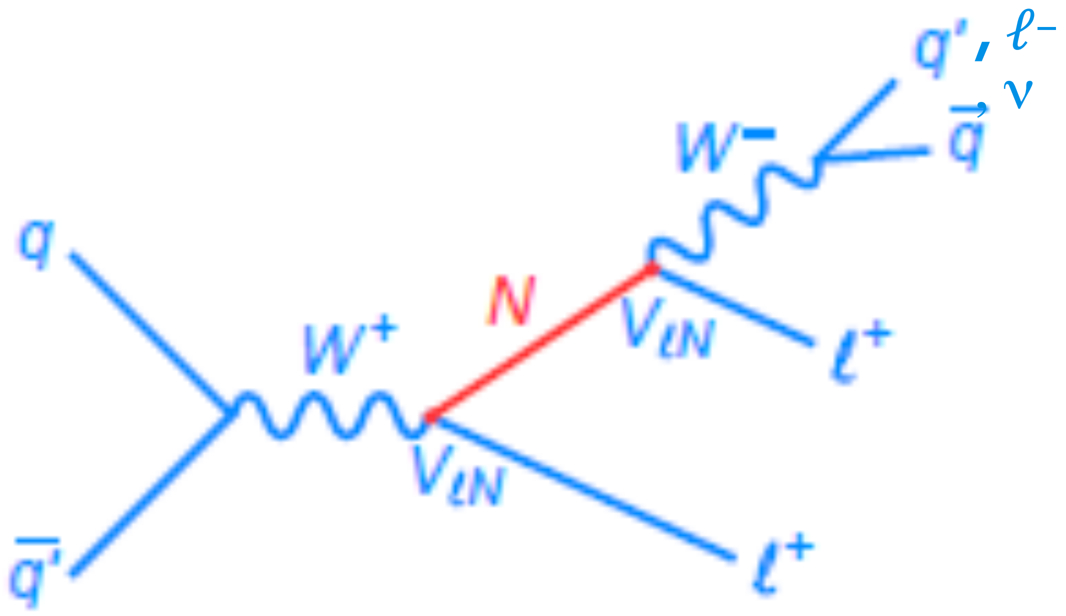
FCC SYNERGIES: FEEBLY INTERACTING PARTICLES

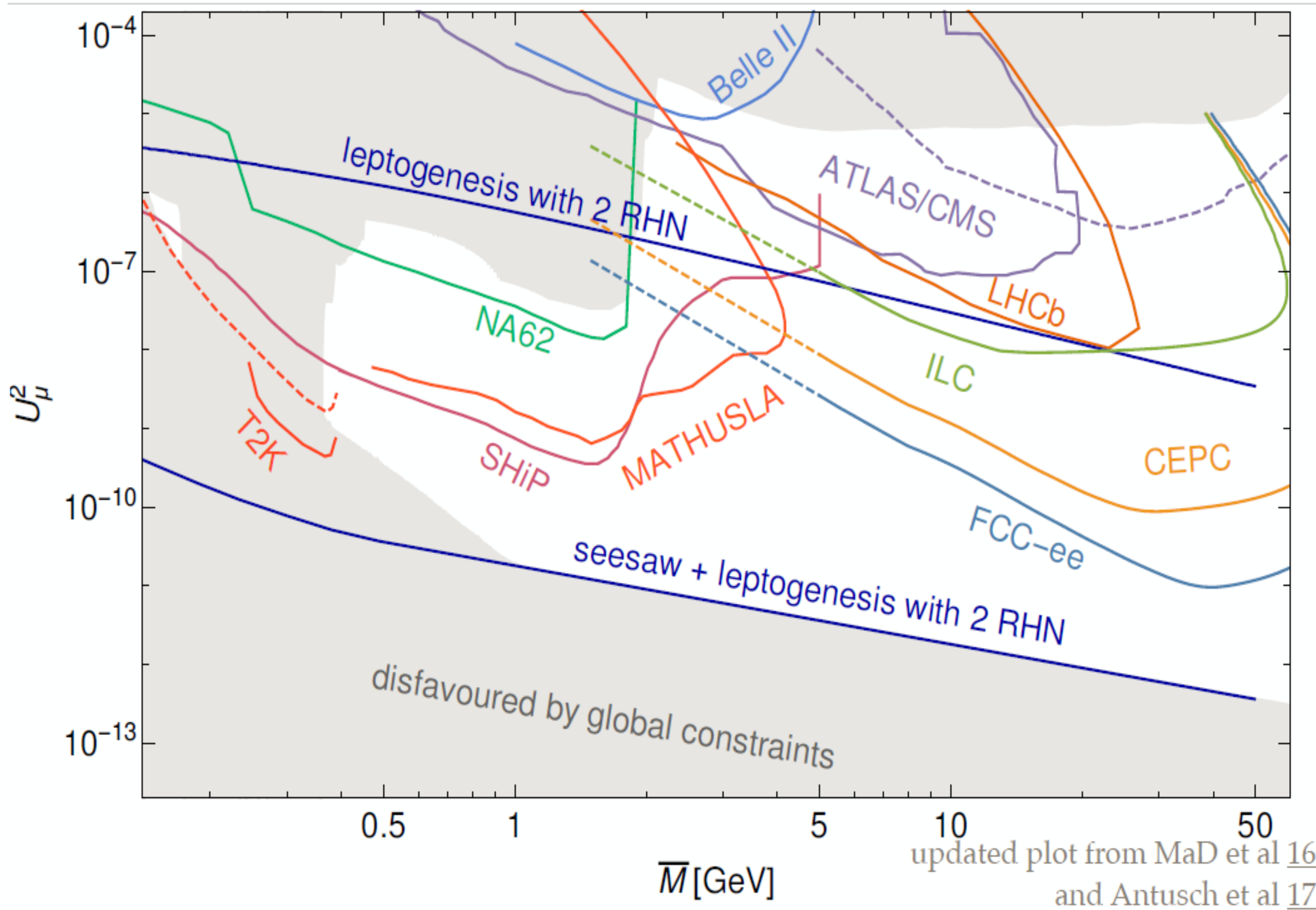
- Heavy Right-Handed Neutrinos
  - Complete SM spectrum – and perhaps explain DM, BAU, ν masses

FCC-ee (Z)



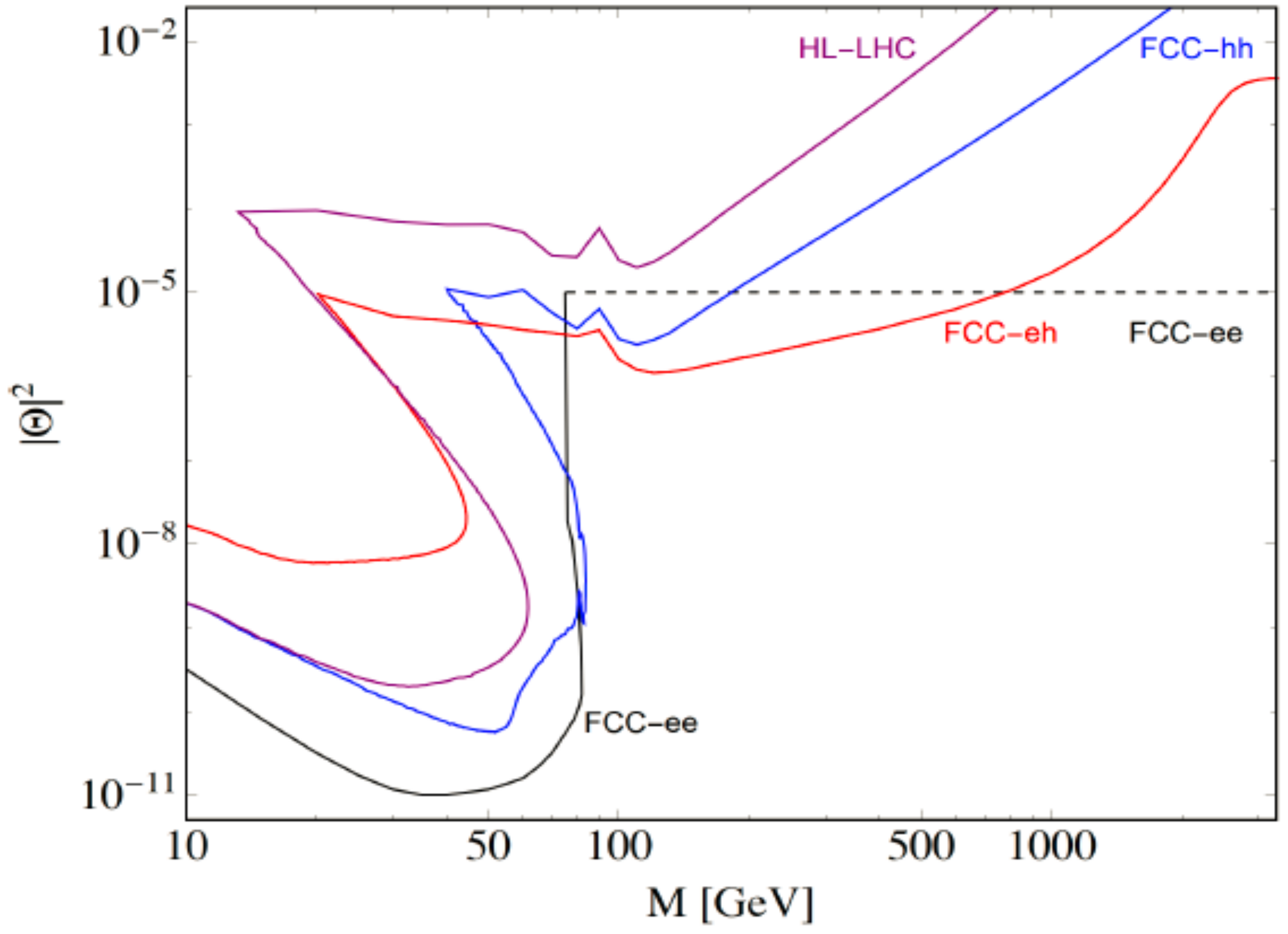
FCC-hh





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 $V_{\ell_1 N}V_{\ell_2 N}$ with lepton charge and flavour
- **FCC-eh sensitivity**
  - Production in charge currents ep → XN (→ℓW)
  - Sensitivity to $V_{eN}V_{\ell N}$
- **Complementarity**
  - Discovery + complementary studies in overlap regions



arXiv:1906.02693, FCC-ee: Your questions answered

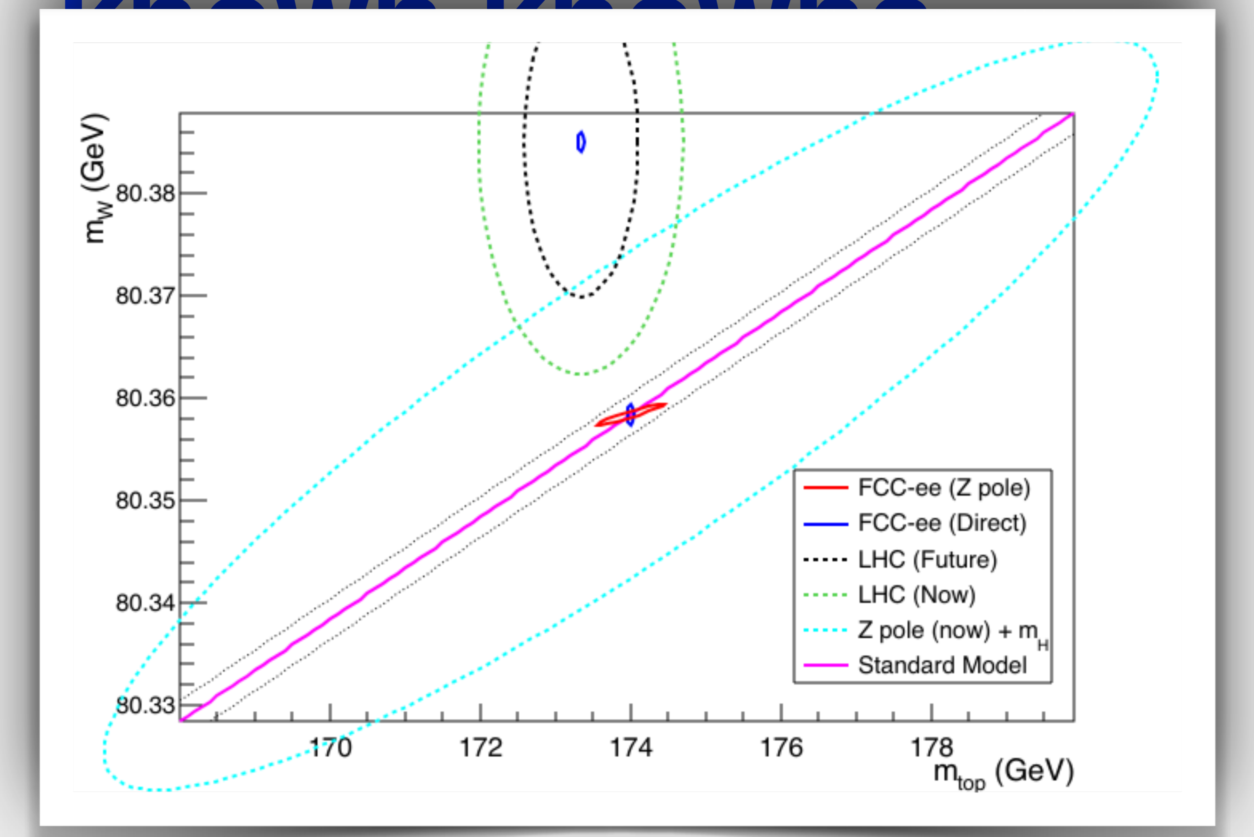
	e^+e^- collisions							pp collisions		
√s → / Physics ↓	m_Z	$2m_W$	HZ max. 240-250 GeV	$2m_{top}$ 340-380 GeV	500 GeV	1.5 TeV	3 TeV	28 TeV 37 TeV 48 TeV	100 TeV	Leading Physics Questions
Precision EW (Z, W, top)	Transverse polarization	Transverse polarization		m_W, α_S						Existence of more SM-Interacting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

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

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

FUTURE COLLIDERS TAKE AWAY MESSAGE



known unknowns

“known” new physics

unknown knowns

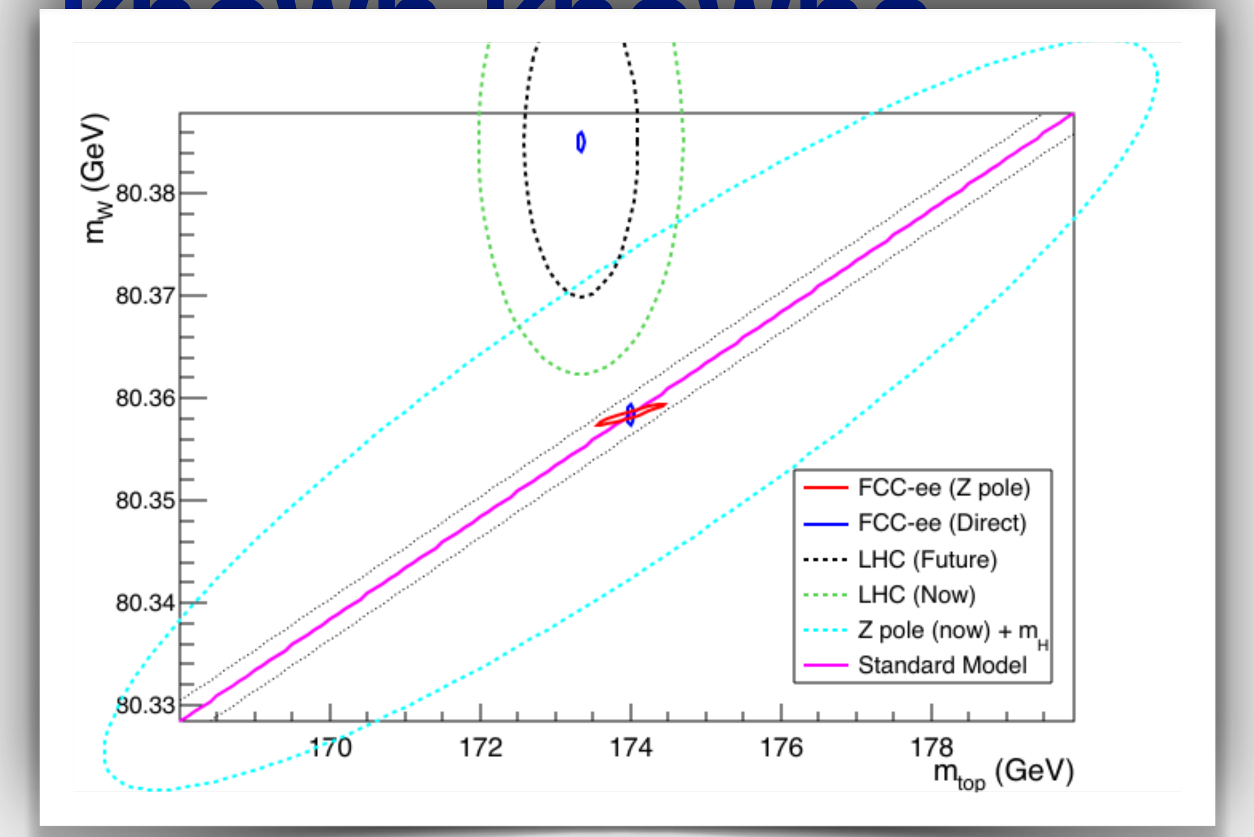
new physics modifies known physics

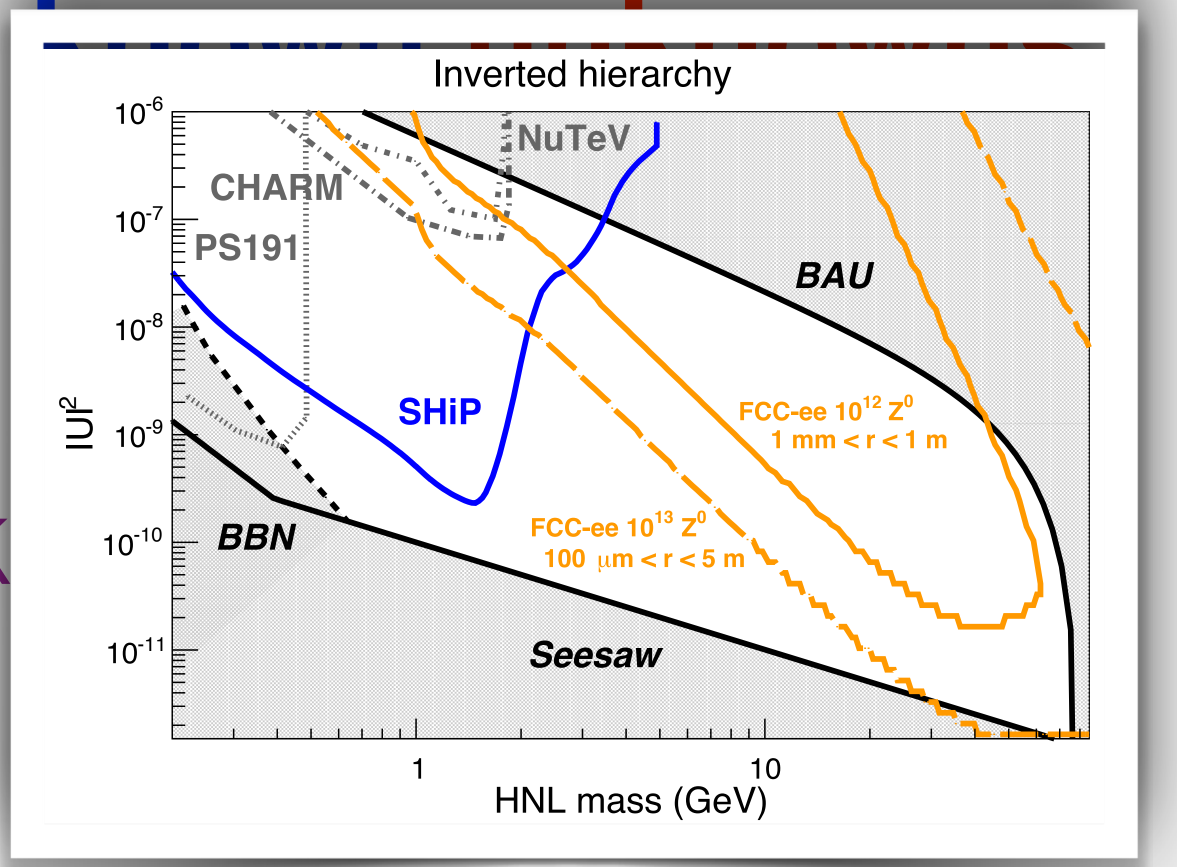
and maybe we already measured it!

unknown unknowns

surprises

FUTURE COLLIDERS TAKE AWAY MESSAGE





unknown knowns

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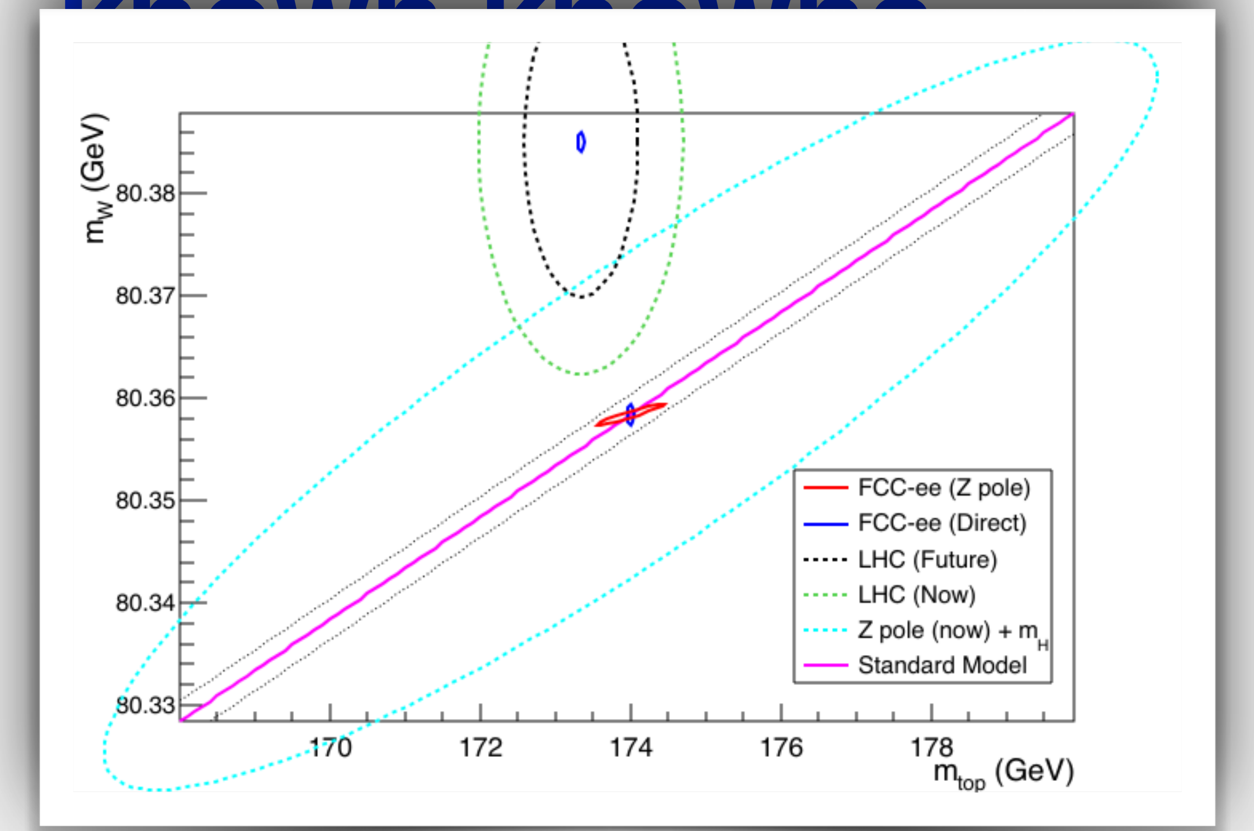
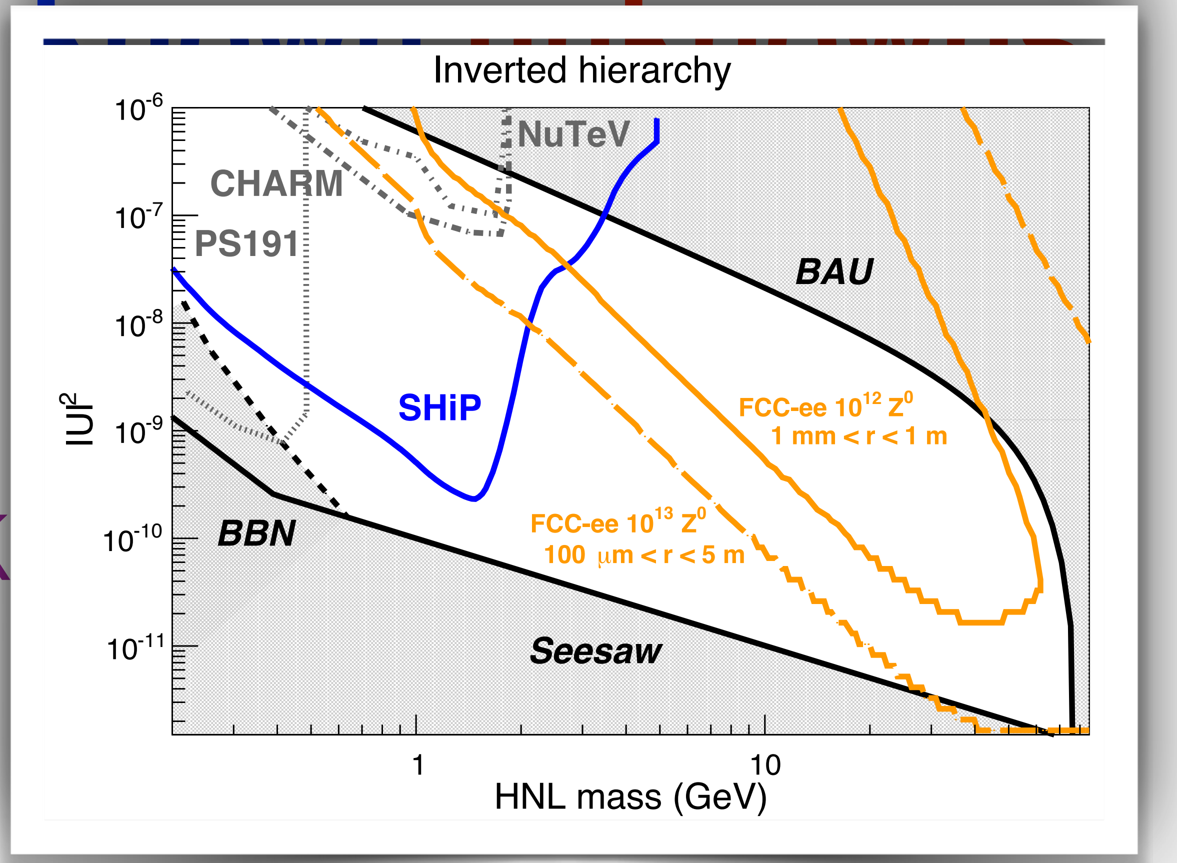
unknown unknowns

surprises

FUTURE COLLIDERS TAKE AWAY MESSAGE





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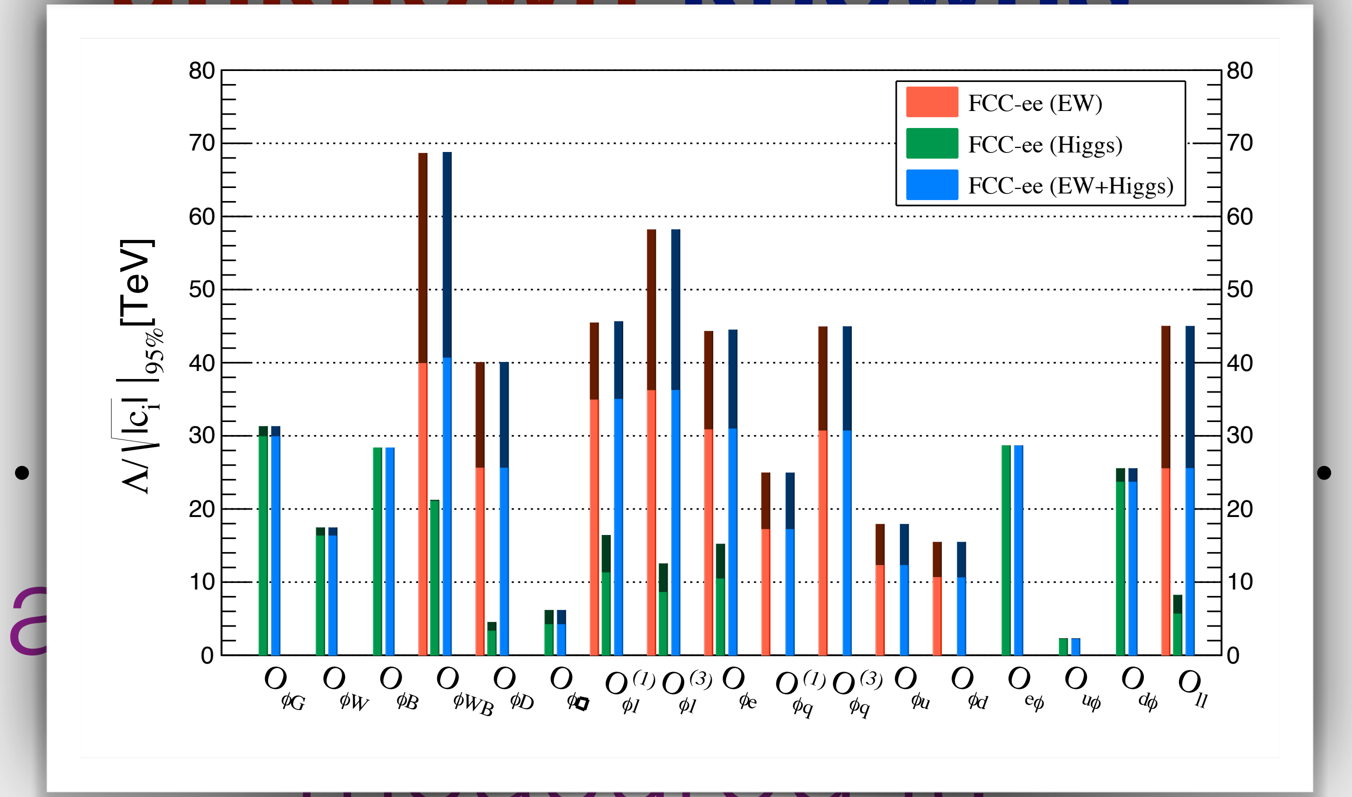
unknown knowns

…  …

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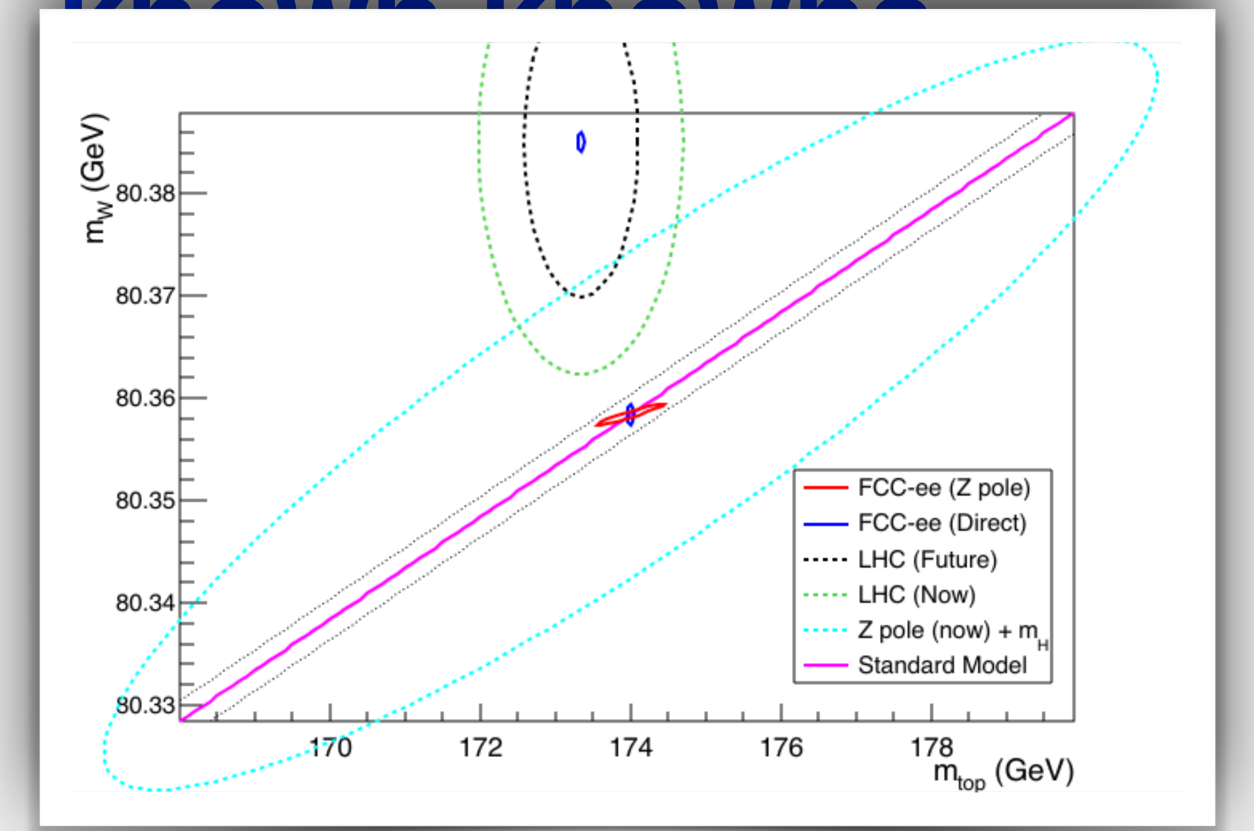
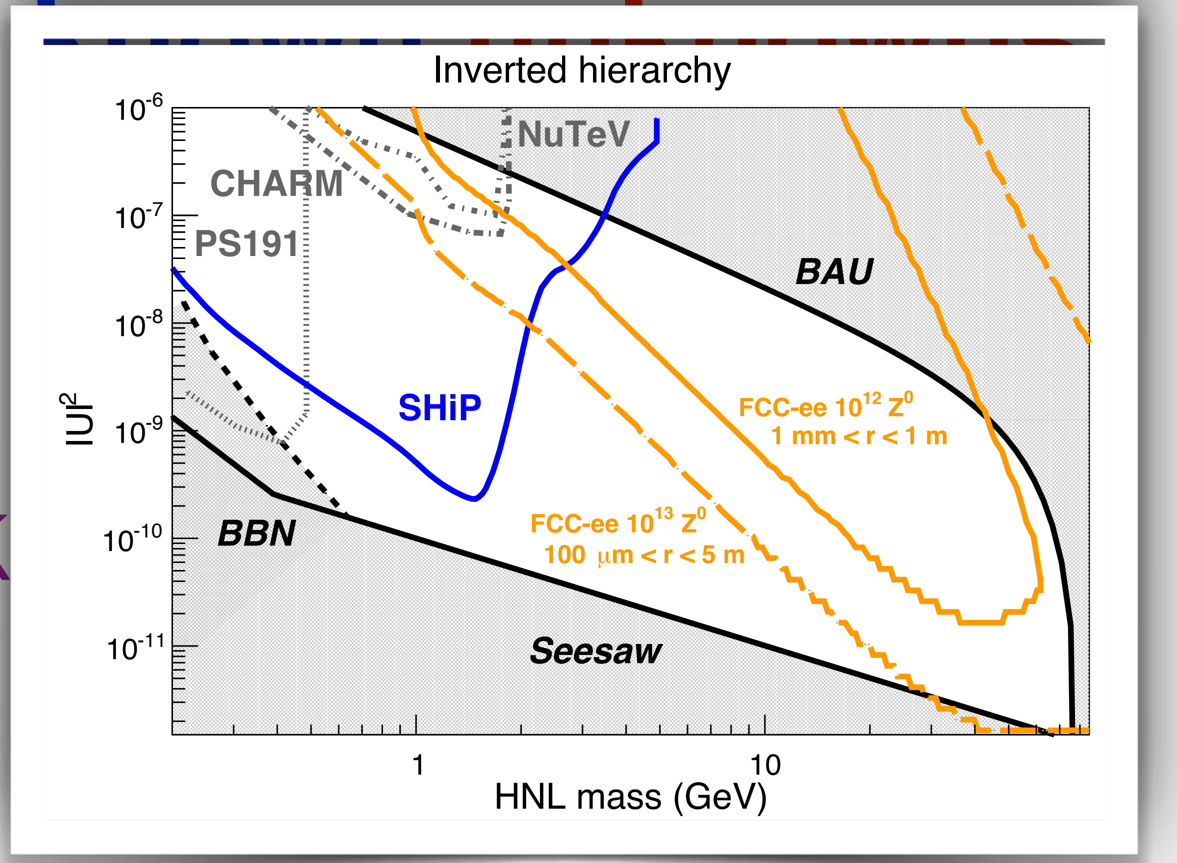
unknown unknowns

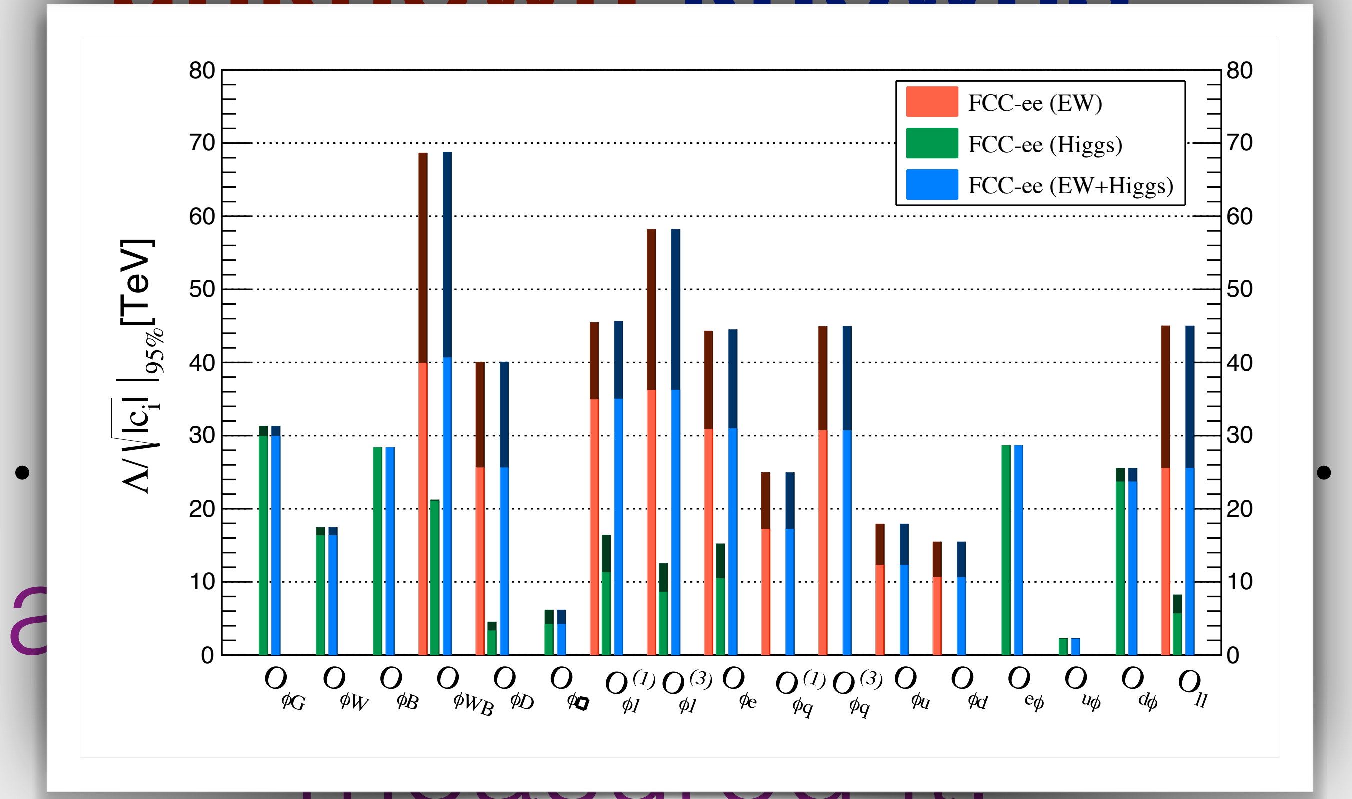
surprises

FUTURE COLLIDERS TAKE AWAY MESSAGE

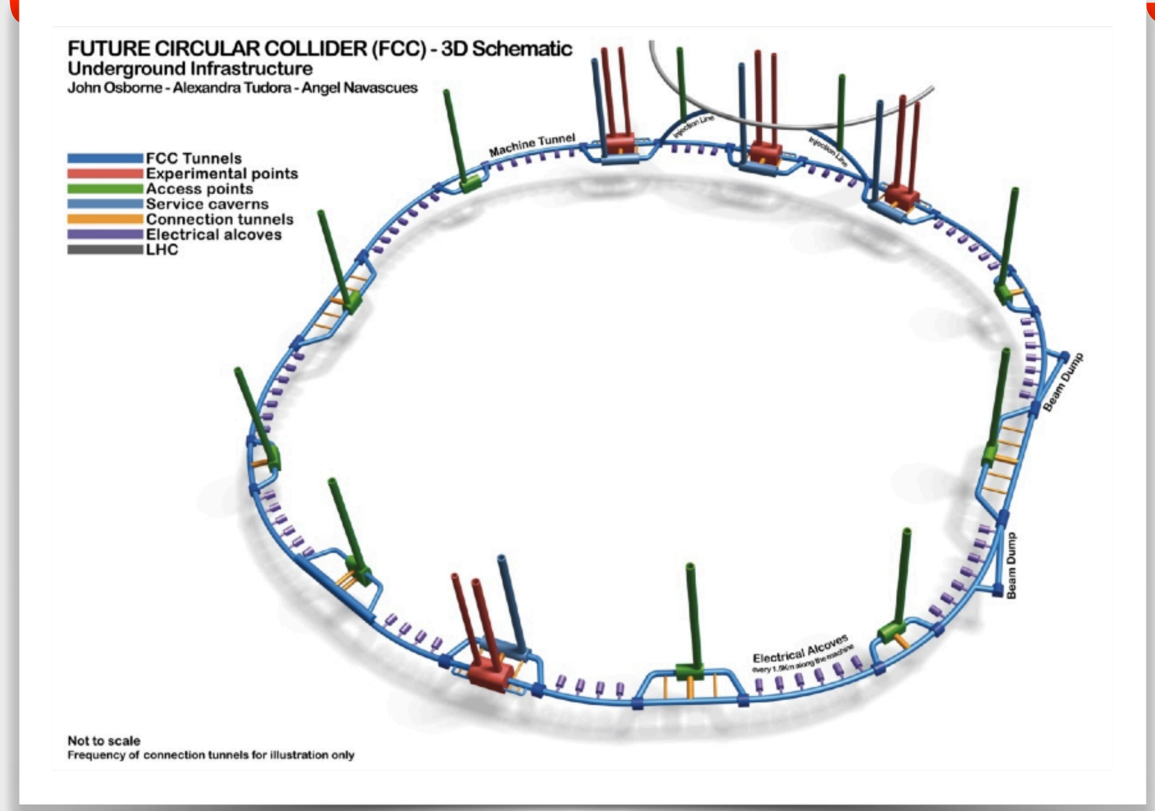




unknown knowns



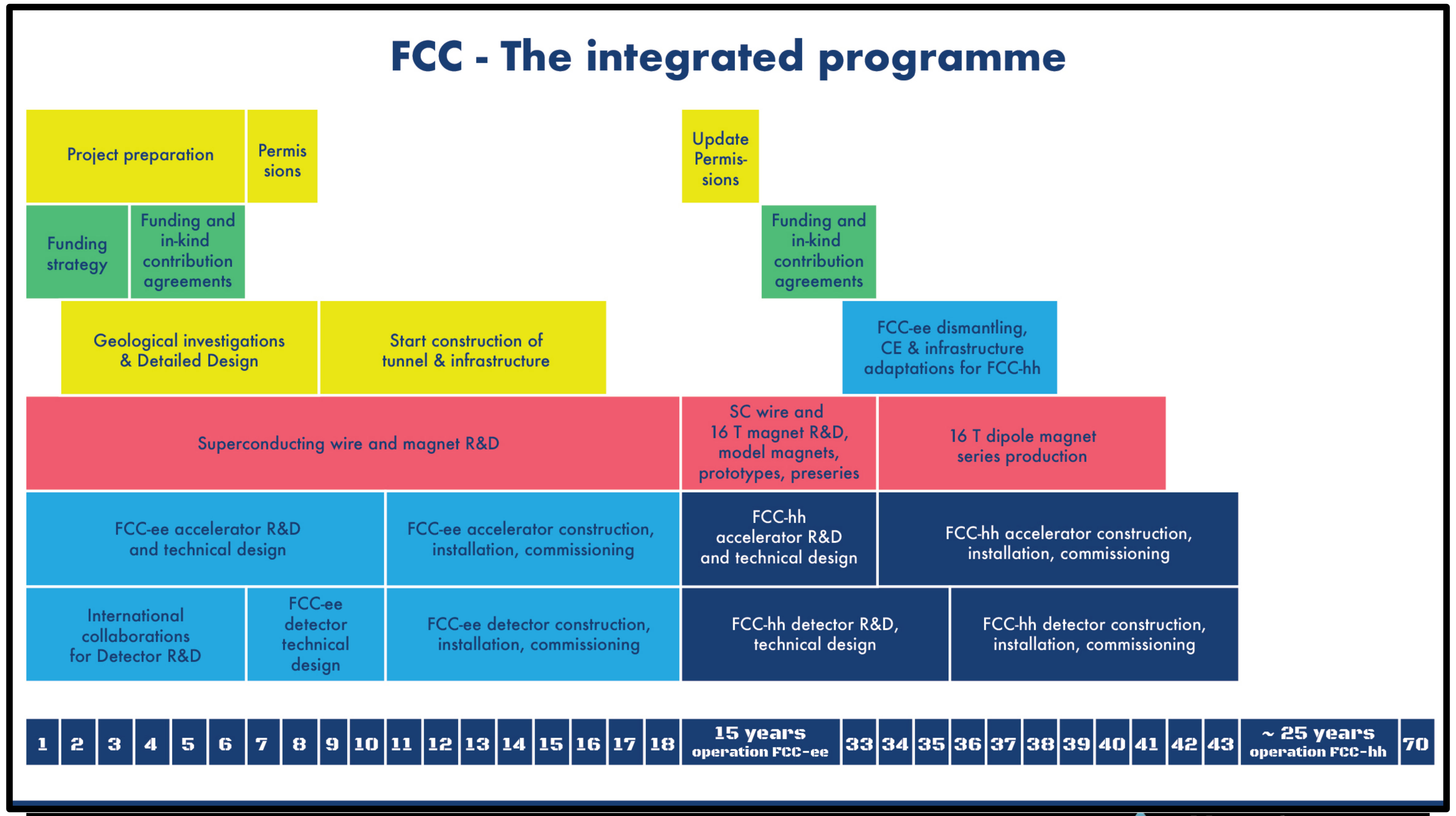
unknown unknowns

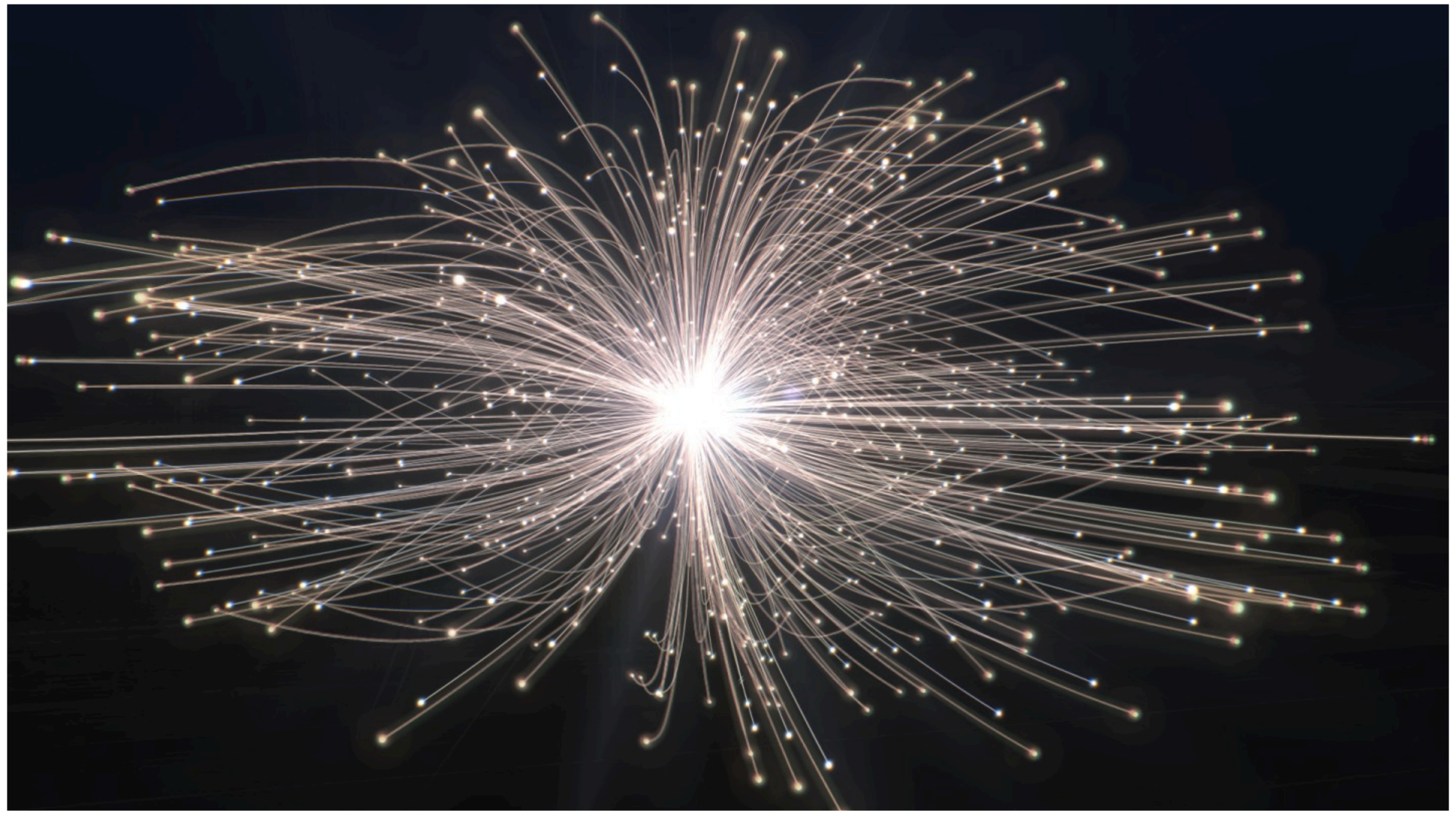


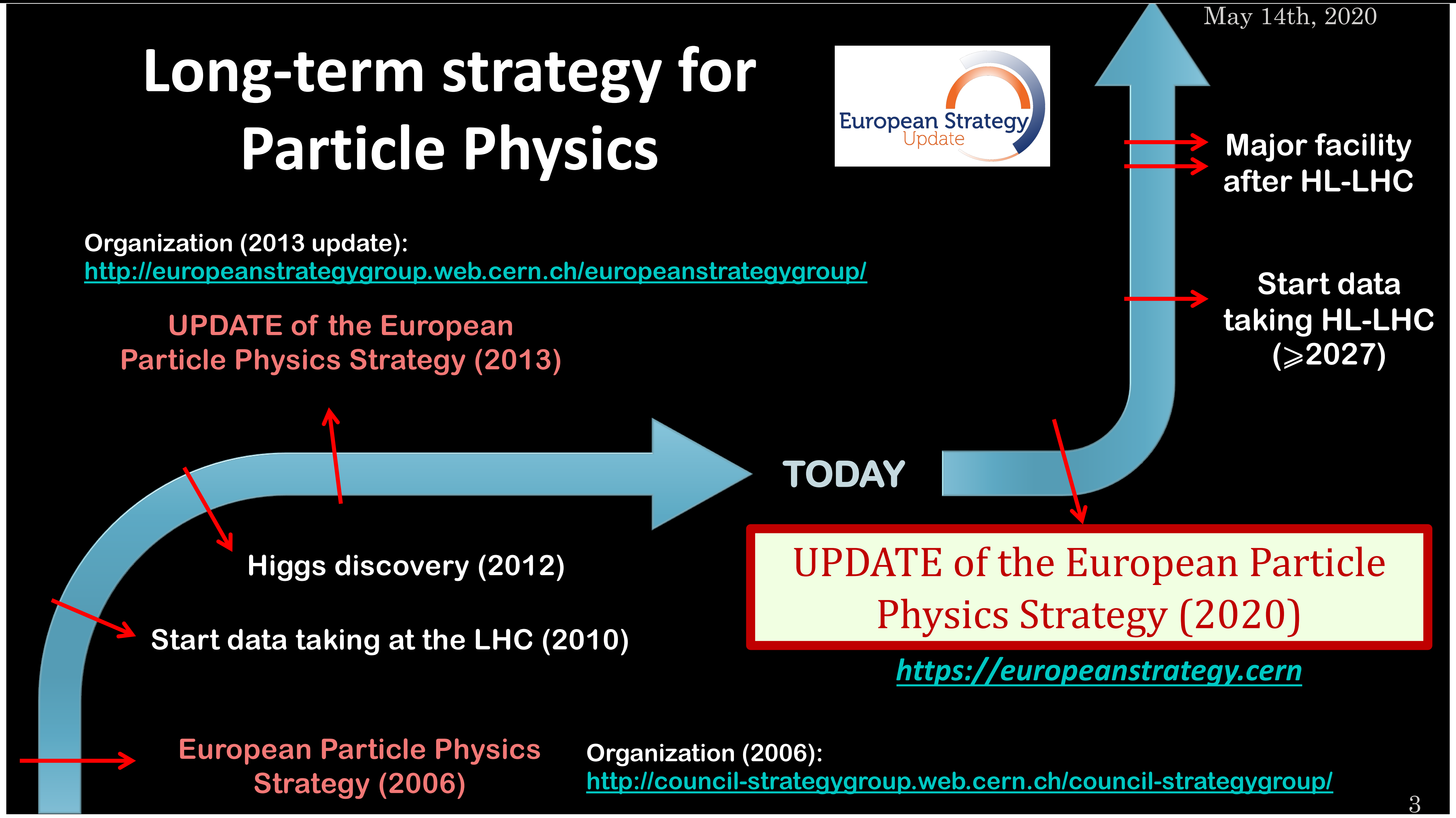
patrizia azzi - EASISchool3 - 8/10/2020

TIMELINE

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

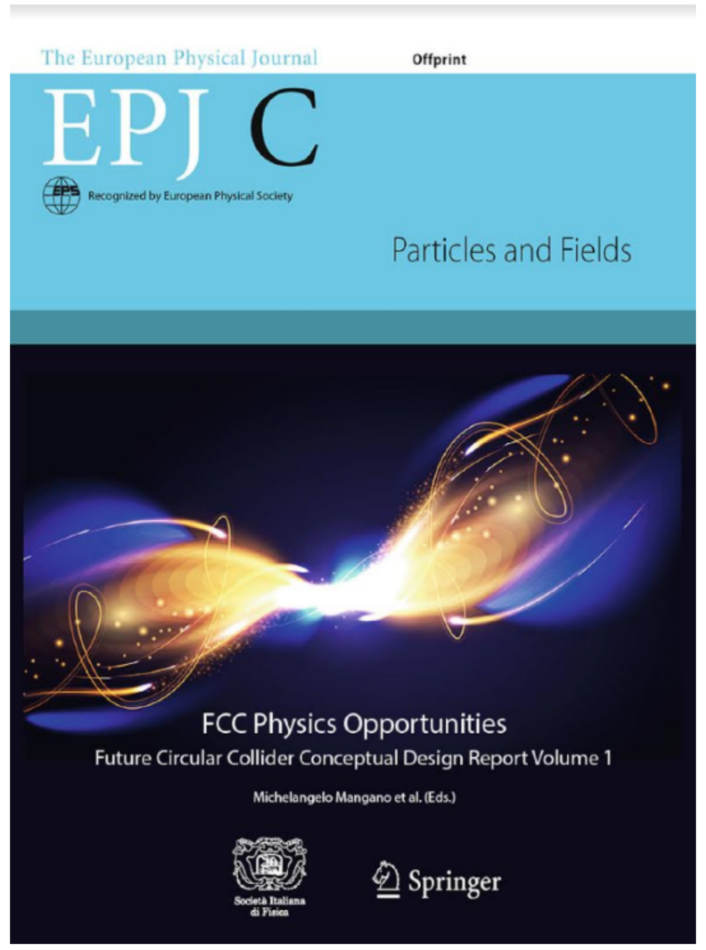




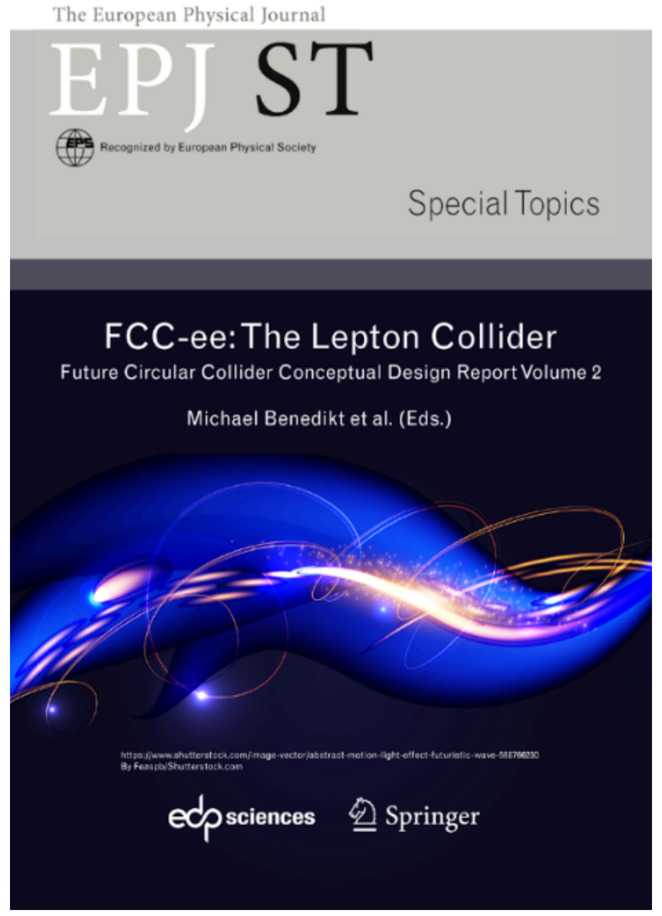


FIND OUT MORE: FCC DOCUMENTATION

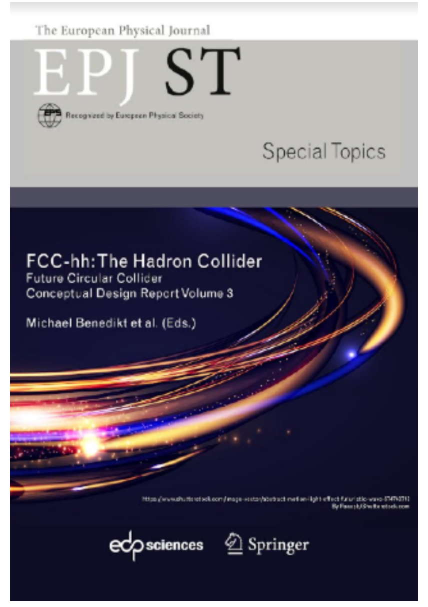
4 CDR volumes published in EPJ



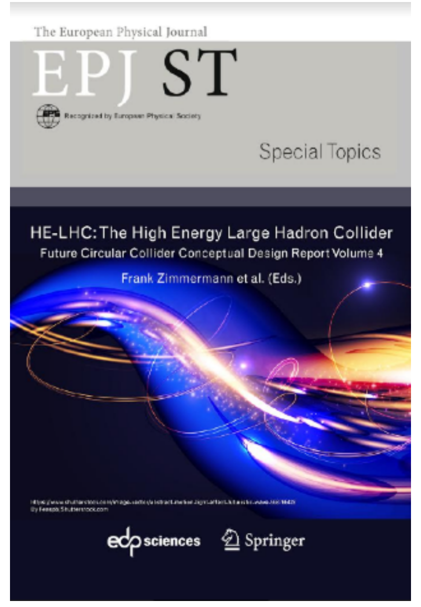
FCC PhysicsOpportunities



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