Exploring the Electroweak Scale with Precision

Patrick Meade
C.N.Yang Institute for Theoretical Physics
Stony Brook University

Thank you to the organizers for the invitation to come to talk about CEPC again (12 years later)





Note: As a physics convener for US-FCC many of my plots will be FCC-ee based but the translation should be straightforward

What makes CEPC so exciting?

Exploring the Electroweak Scale with Precision

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It *better be* exciting given the scales!





Why build any collider?

Contrarian(social media clickbait) version:

“Collider physicists just want bigger colliders”

Not *entirely* untrue, but for a very good ***physics*** reason Quantum Field Theory implies ***Decoupling***

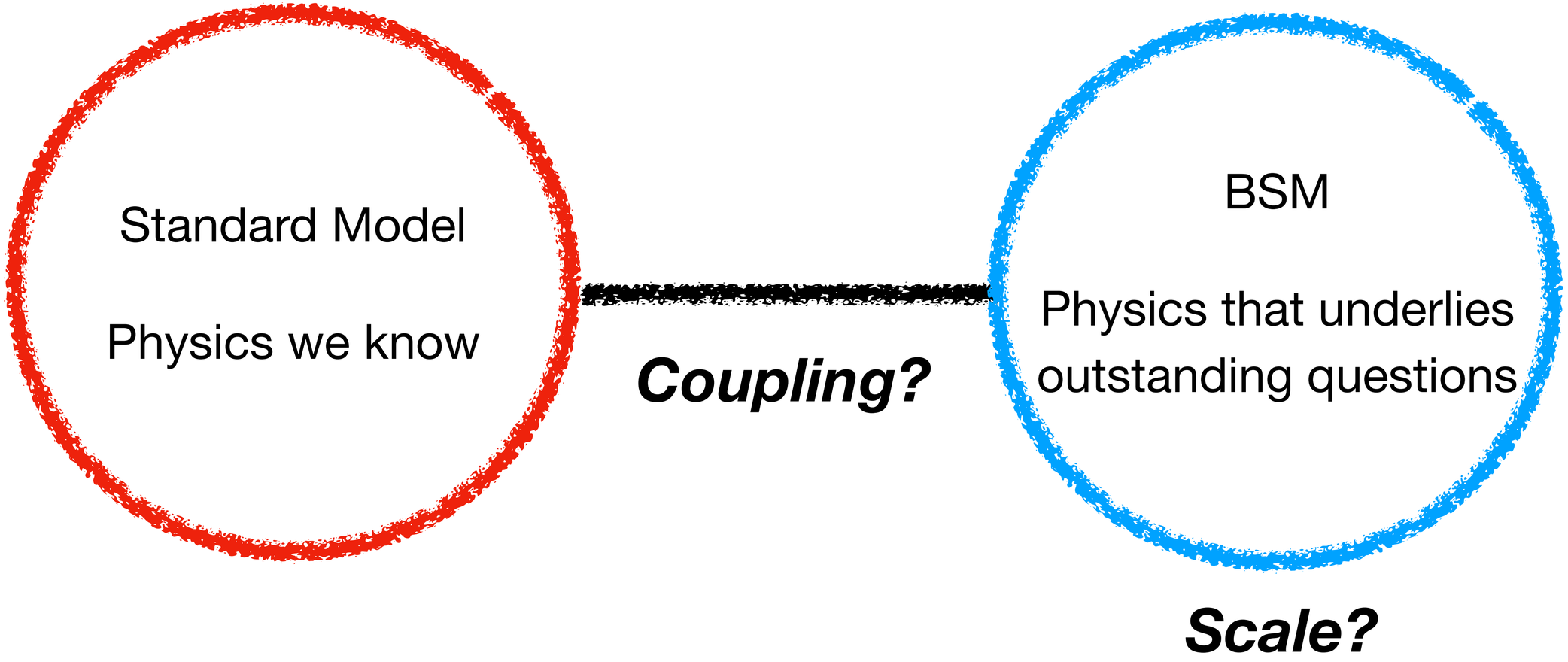


Tabletop experiments would require ridiculous precision to test the Electroweak scale

$$\sim \left(\frac{\mathrm{eV}}{100\,\mathrm{GeV}} \right)^2 \approx 10^{-22}$$

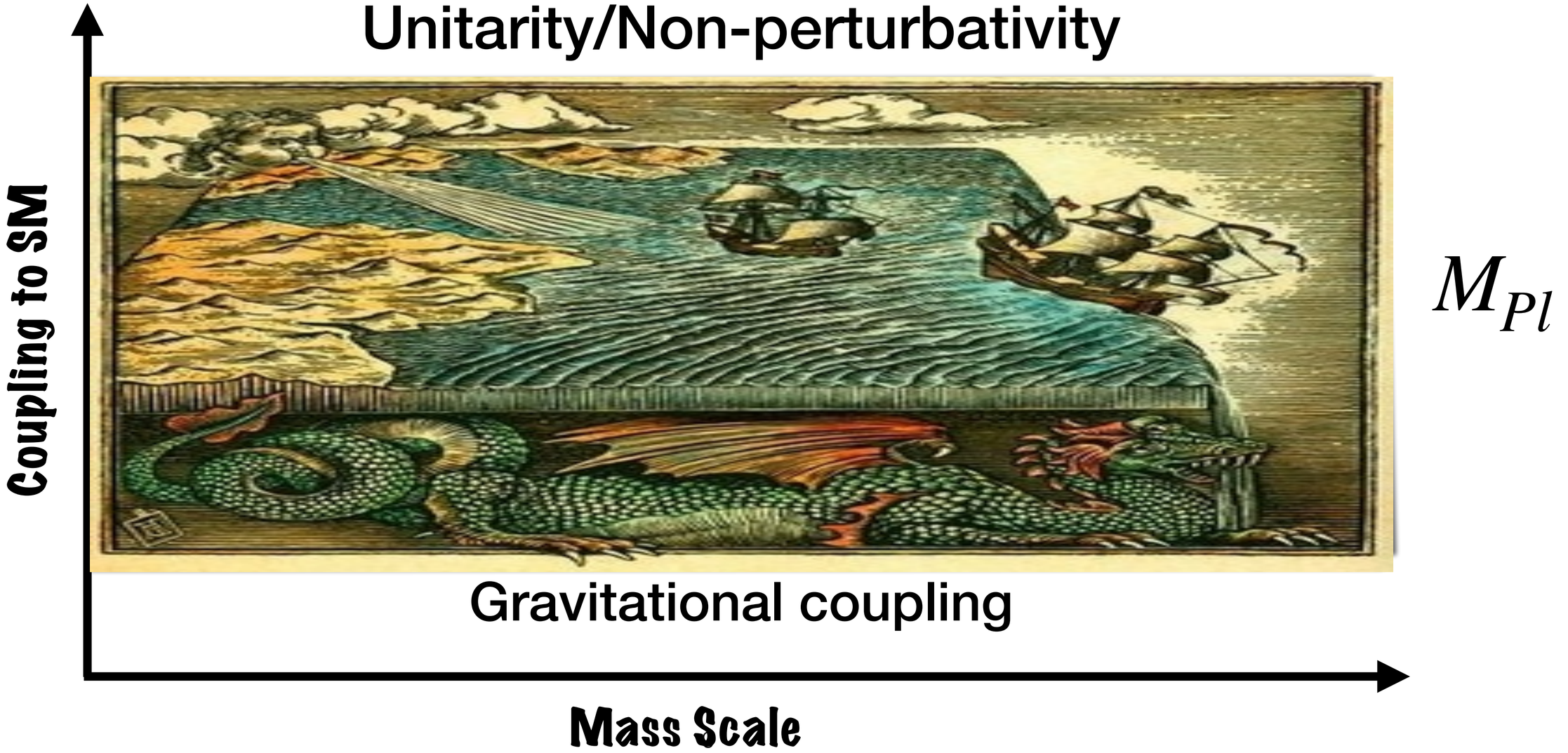
Colliders ***<u>are</u>*** our ***<u>needed</u>*** modern microscopes

Is this a never ending pursuit?



Gauge theories naturally factorize, but all is not lost!

All the Universe's secrets are contained in this bounded space (but very large space) to explore



Curiosity driven research pushes ***accelerator*** research to enable this exploration

Cost limits what we can implement at a given time

Is there a compelling enough cost/benefit ratio for a particular collider?

Cost/Benefit analysis depends on perspective at a given time

Science

SCIENCEINSIDER | ASIA/PACIFIC

Debate signals cloudy outlook for Chinese supercollider

Nobel laureate blasts proposal for world's biggest particle accelerator

12 SEP 2016 • BY HAO XIN

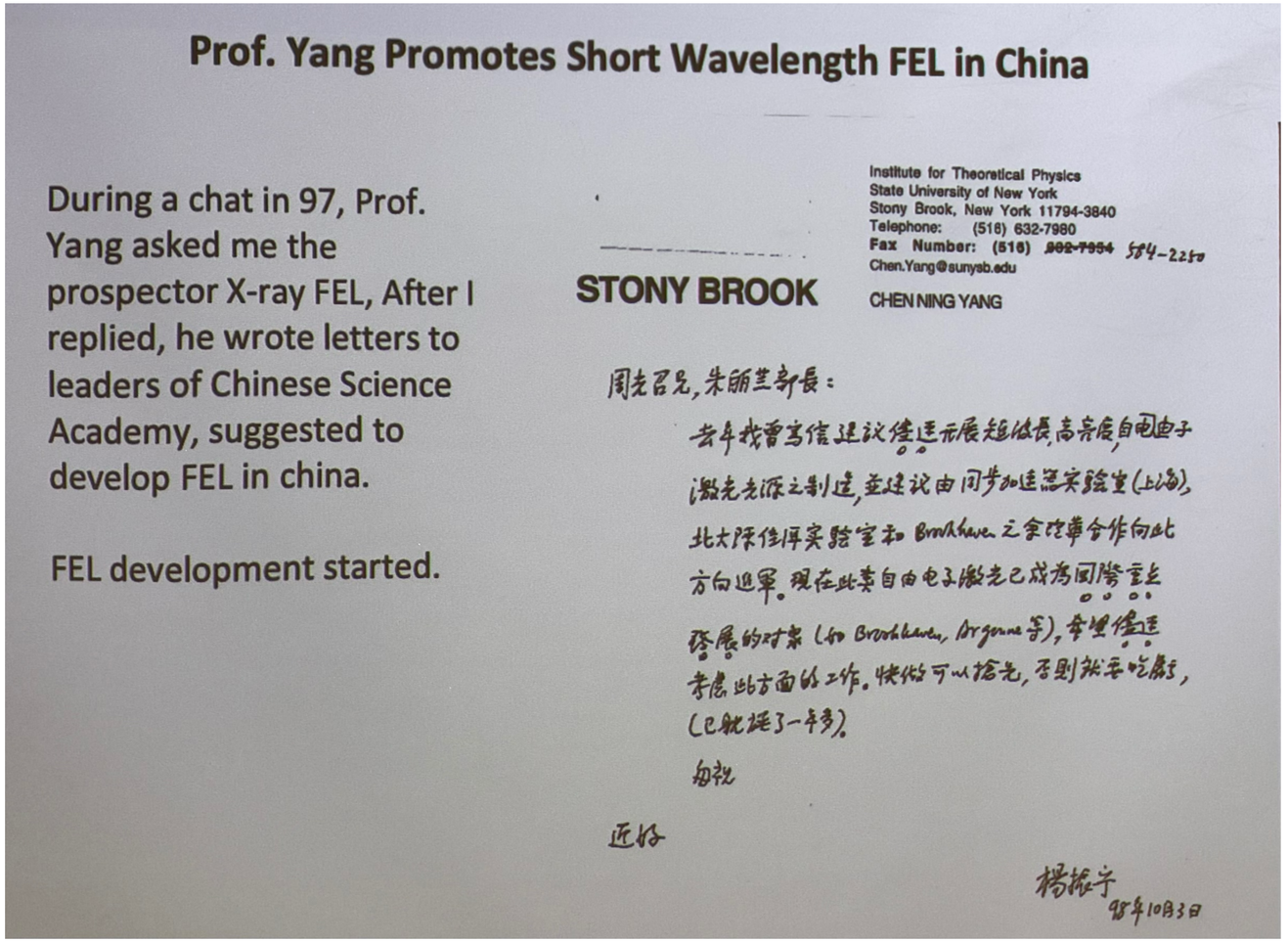


Yang Chen-ning does not believe that a Chinese supercollider will deliver enough bang for the billions of bucks it will cost to build. XINHUA/ALAMY STOCK PHOTO

Prof. Yang Promotes Short Wavelength FEL in China

During a chat in 97, Prof. Yang asked me the prospector X-ray FEL, After I replied, he wrote letters to leaders of Chinese Science Academy, suggested to develop FEL in china.

FEL development started.



Institute for Theoretical Physics
State University of New York
Stony Brook, New York 11794-3840
Telephone: (516) 632-7980
Fax Number: (516) ~~632-7954~~ 584-2250
Chen.Yang@sunysb.edu

STONY BROOK CHEN NING YANG

周光召兄，朱丽兰部长：

去年我曾写信建议修建千展超微长高亮度自由电子激光光源之制造，并建议由同步加速器实验室(上海)，北大陈佳洱实验室和 Brookhaven 之金改革合作向此方向迈进。现在此类自由电子激光已成为国际重点发展的对象 (如 Brookhaven, Argonne 等)，希望修建考虑此方面的工作。快做可以搭先，否则就要吃亏，(已就延了一年多)。

匆祝

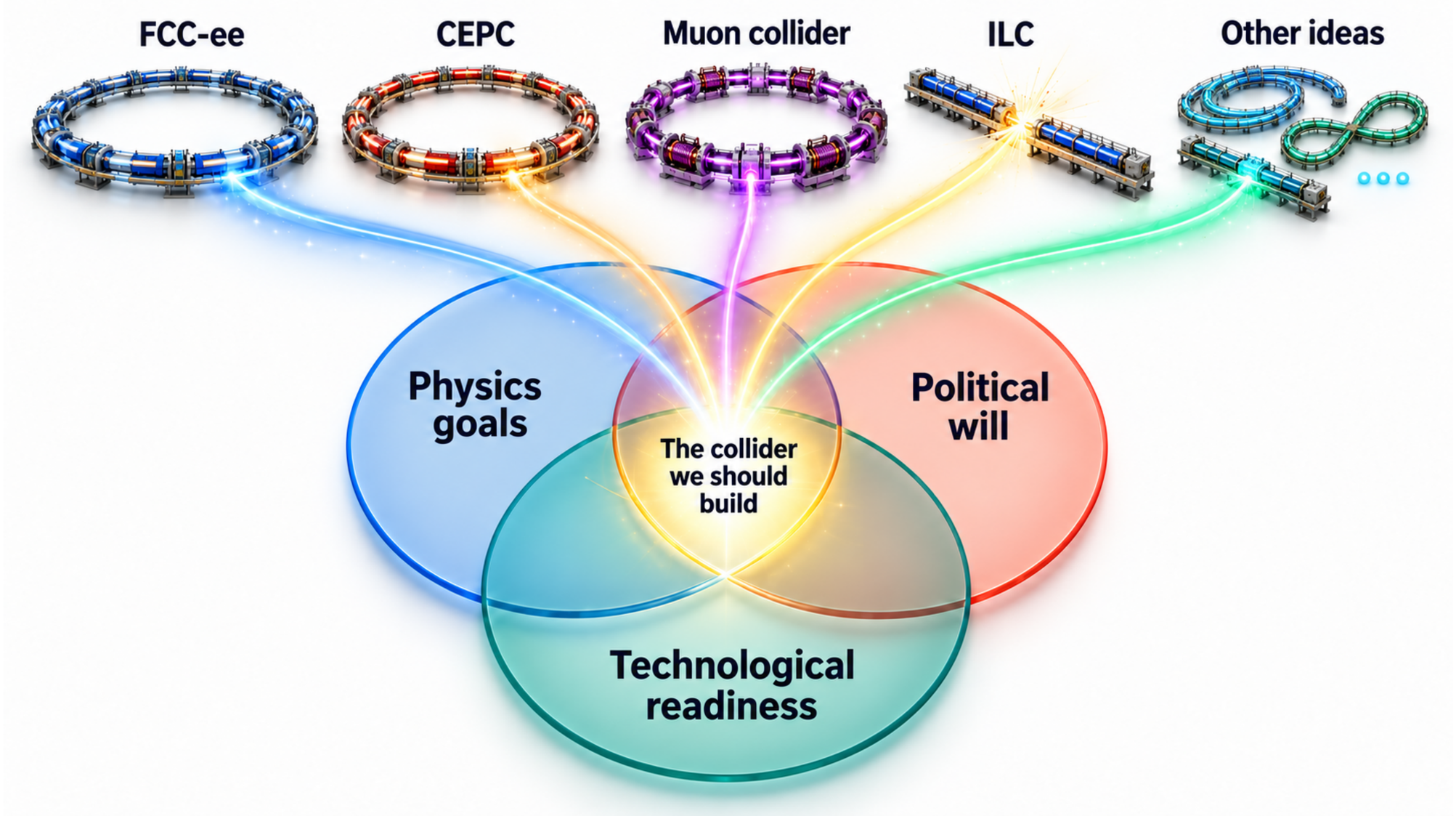
近好

杨振宁
98年10月3日

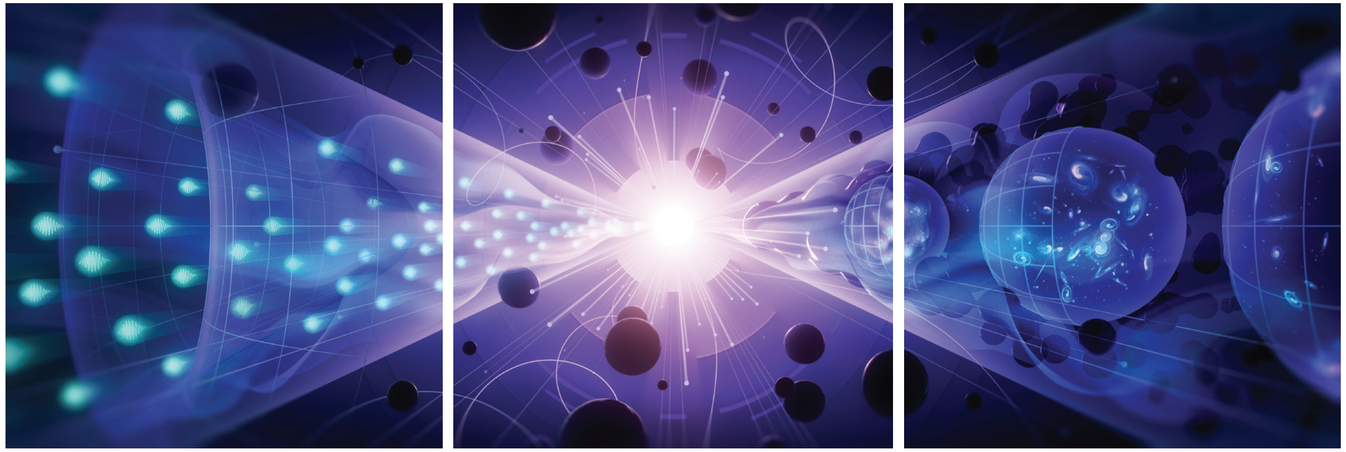
Li Hua Yu
C.N. Yang Memorial Symposium Oct 2026

Yang's perspective was far more nuanced than I appreciated

Even if you believe colliders are worth pursuing now, why CEPC/FCC-ee rather than something else?



IF the USA were <u>ever</u> to build another Energy Frontier collider



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

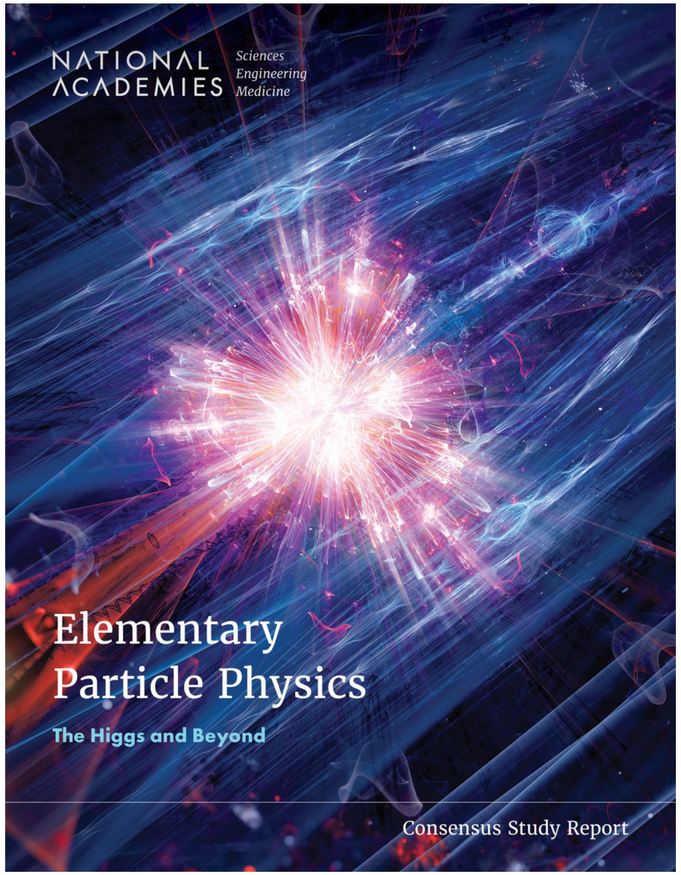
Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

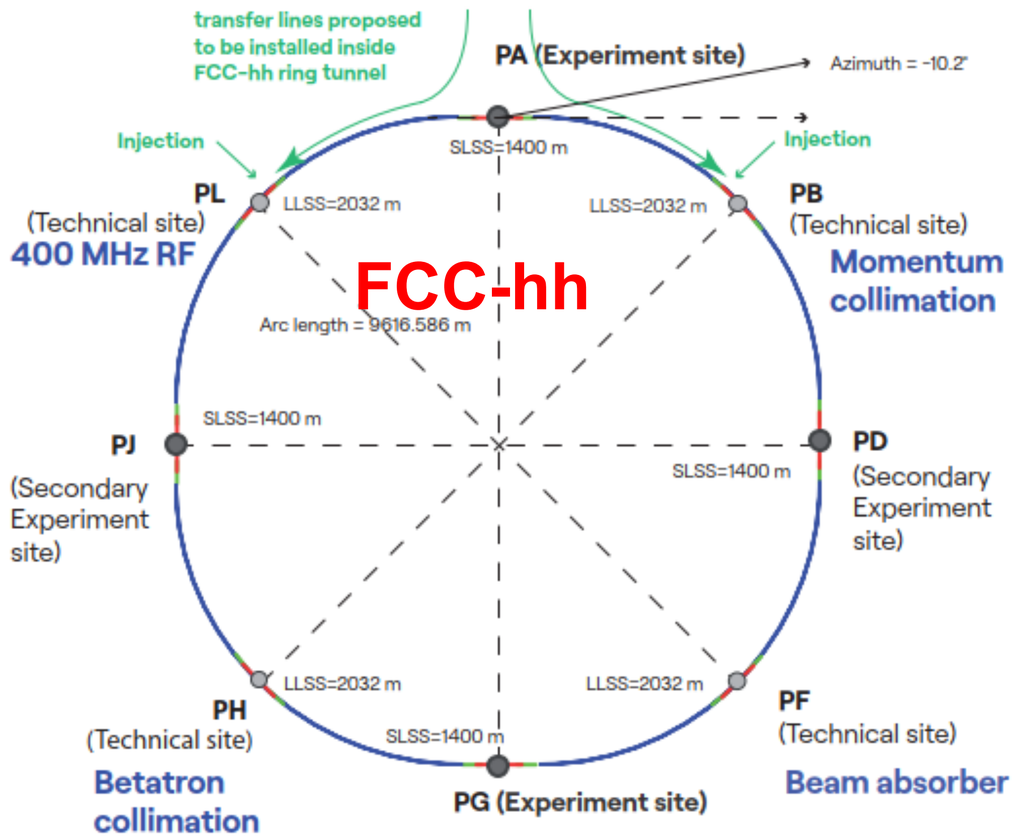
“Muon Shot” in P5



Highest priority in National Academy report

However the technological readiness isn’t there <u>yet</u>

Similarly FCC-ee/CEPC are not envisioned as the endpoint



~2075 ?

However, magnet technology/cost isn't feasible yet…

Conclusion slide from my talk at IHEP in 2014

Certain questions require more energy to fully explore the possibilities

In US this motivated the "10 TeV pcm" target from P5 process

CONCLUSIONS

- EWBG provides a potential no-lose theorem for future colliders to test - Everything is tied to a low scale!
- We've explored a "nightmare scenario" for testing the EWPT of EWBG and although you will NEVER see it at the LHC, you CAN see it with a 100 TeV pp machine!!
- CEPC not as important as SPPS! (at least for this)

So what makes CEPC so compelling ***now***?

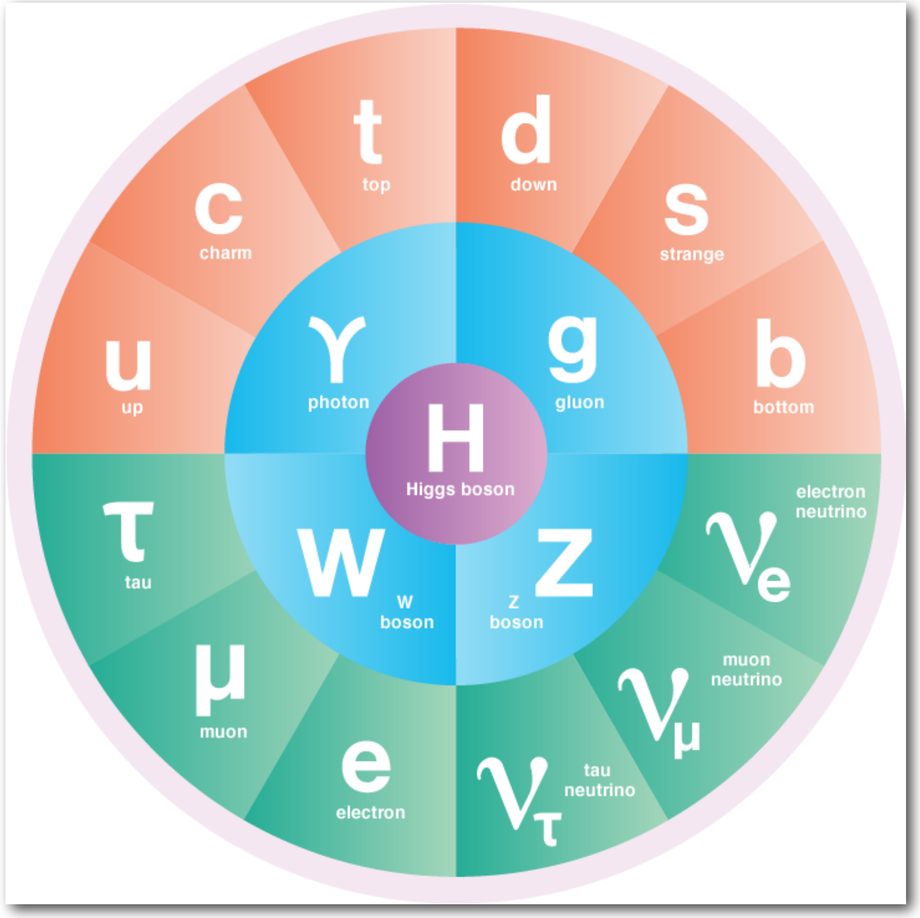
<u>Standard Answer:</u>

A Higgs Factory we can build with *current* technology "to unlock the secrets of the Higgs boson"

Absolutely True - but other "Higgs Factories" possibilities also do this, so is it just who has the political will or something else?

The really exciting thing about CEPC or FCC-ee is that it can do ***<u>much</u>*** more than other options!

What secrets do we think the Higgs boson holds?



Isn’t the SM complete? Shouldn’t we look for new physics answers to our questions elsewhere?

The SM has a very rigid structure (QFT+symmetry), but with many parameters!

g_1, g_2, g_3 3 gauge couplings

+QCD vacuum angle θ_{QCD}

θ_{ij}, δ_{CP} 3 CKM angles +1 phase

m_{q_i}, m_{l_j} 6 quark masses+3 charged leptons

m_h, v Higgs mass and VEV

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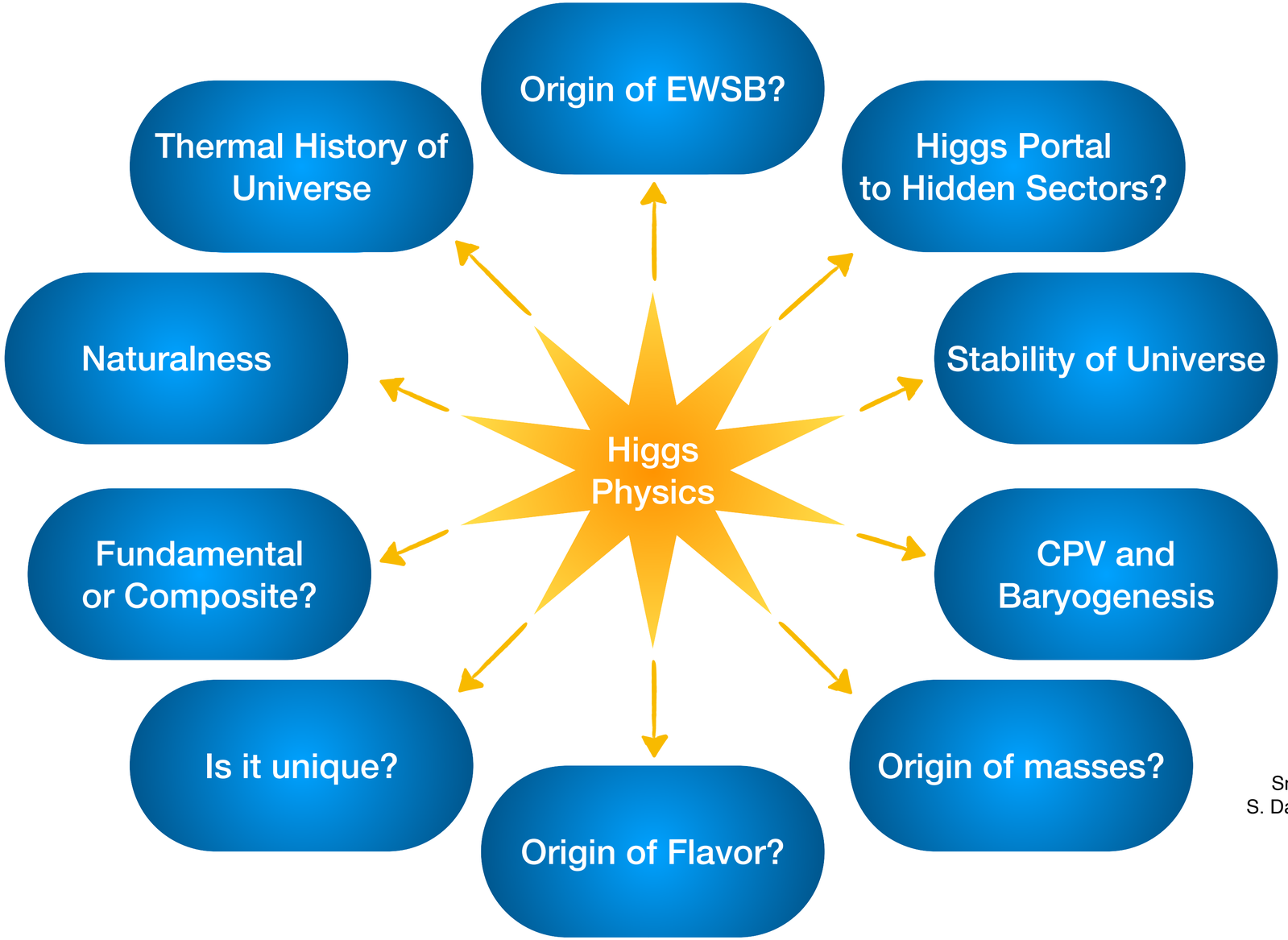
m_{q_i}, m_{l_j} 6 quark masses+3 charged leptons

m_h, v Higgs mass and VEV

15/19 tied to the Higgs, 22/26 if we include neutrinos *or* there must be a *new* "Higgs"

Precision + *Prediction* is a powerful tool!

Inherent to being so central to the SM, the Higgs is tied to so many questions that the SM can't answer itself



Snowmass EF Higgs Topical Report
S. Dawson, PM, I. Ojalvo, C. Vernieri et al
2209.07510

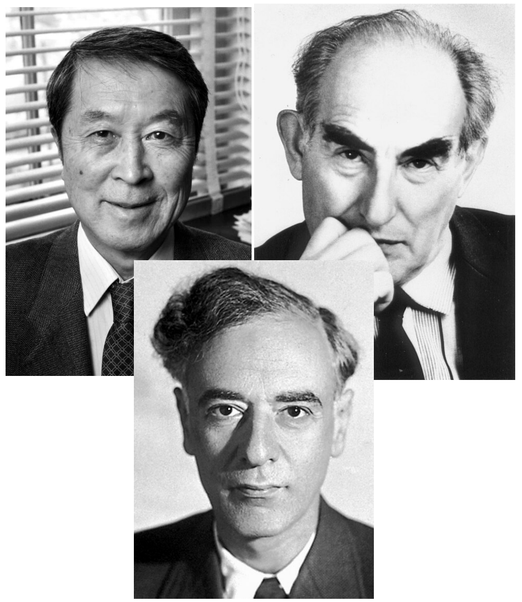


Why are we here?

Where did we come from?

Where are we going?

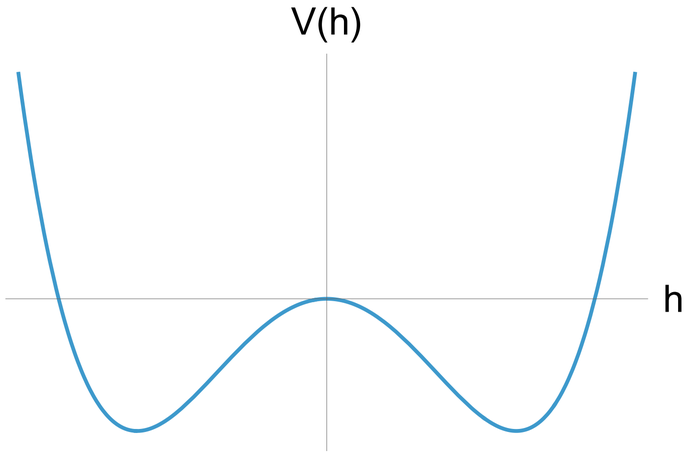
The Higgs can be ***quantitatively*** tied to all these through QFT+GR



Spontaneous Symmetry Breaking and *our* place in the universe

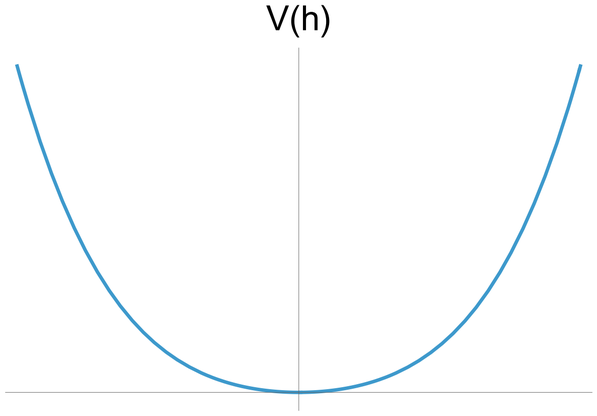


Why

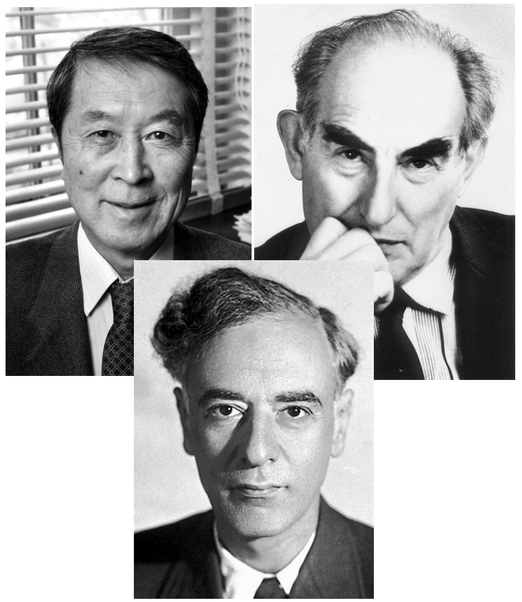


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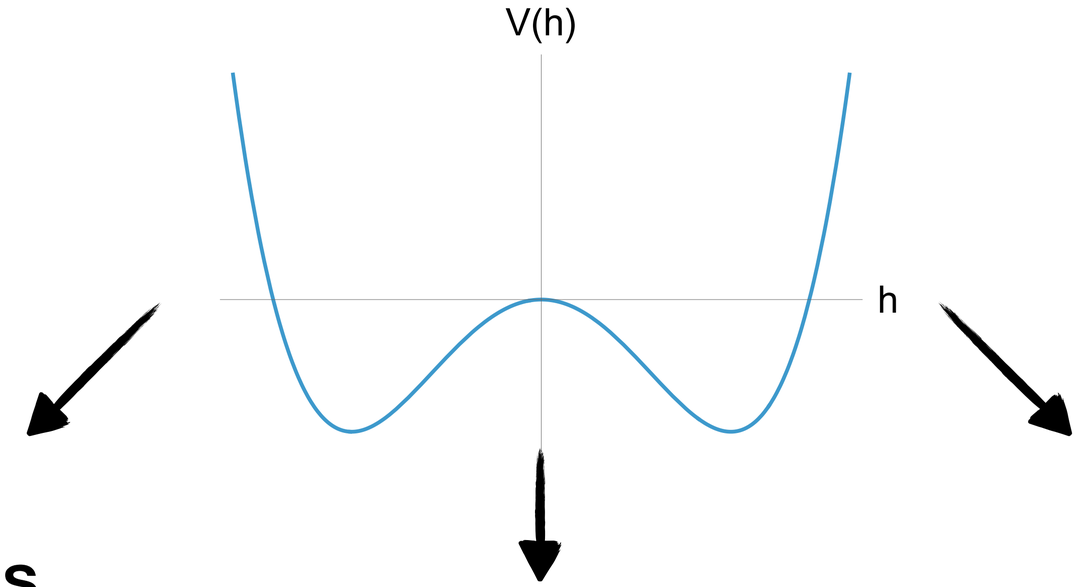


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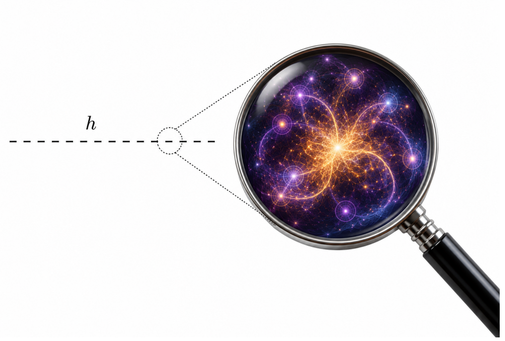
Spontaneous Symmetry Breaking and *our* place in the universe



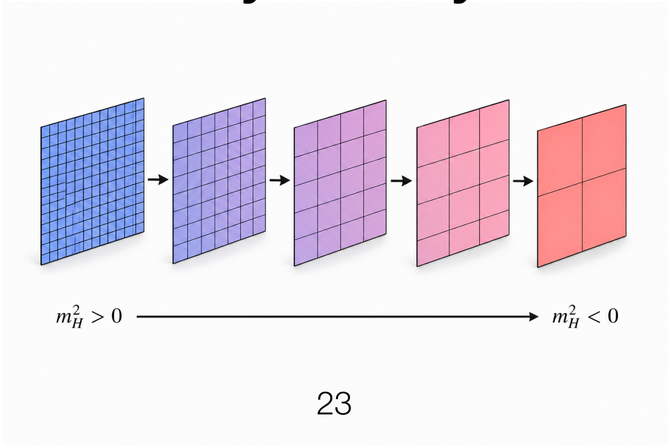


Underlying dynamics

Composite Higgs

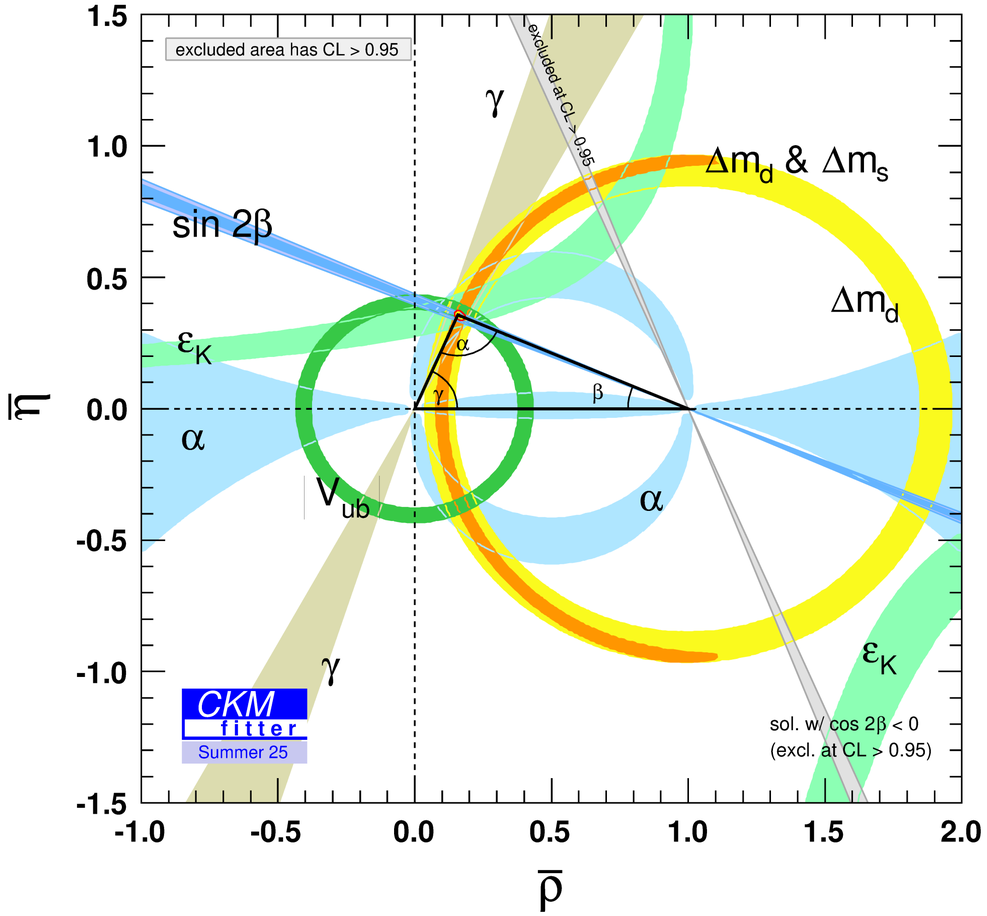


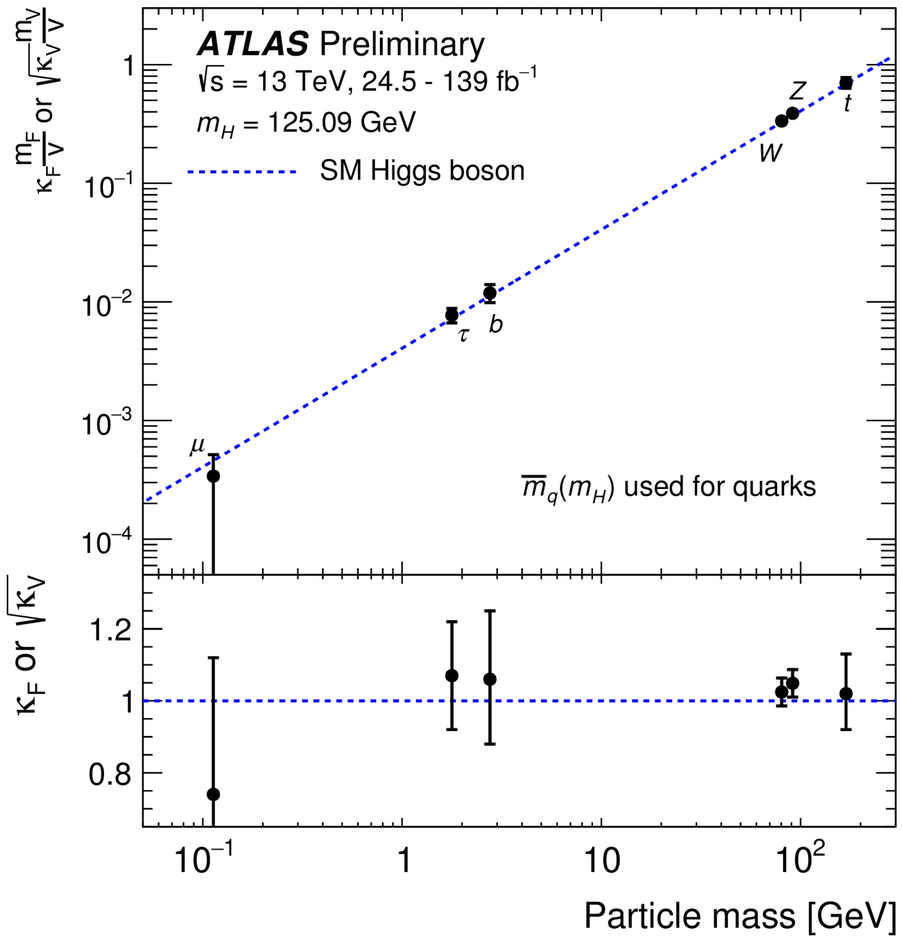
Radiative Symmetry Breaking



. . .

Flavor and Mass?

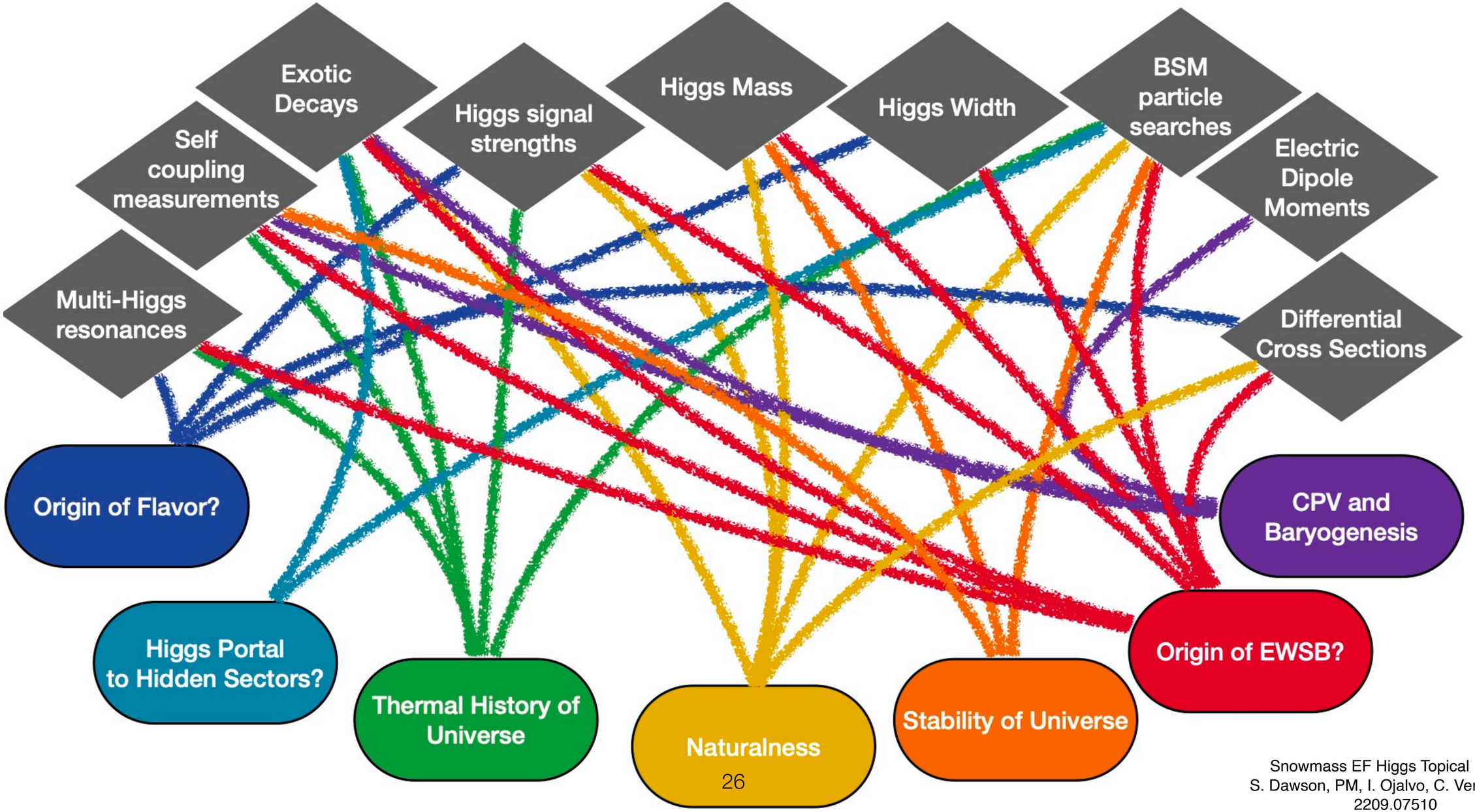




Despite beautiful tests of the Unitarity of the CKM matrix, until we were able to probe the Higgs directly we didn't *know* the origin of charged fermion masses!

All the possible answers we've come up with leave quantum imprints on the SM Higgs couplings

Different questions/answers map to different observables



Snowmass EF Higgs Topical Report
S. Dawson, PM, I. Ojalvo, C. Vernieri et al
2209.07510

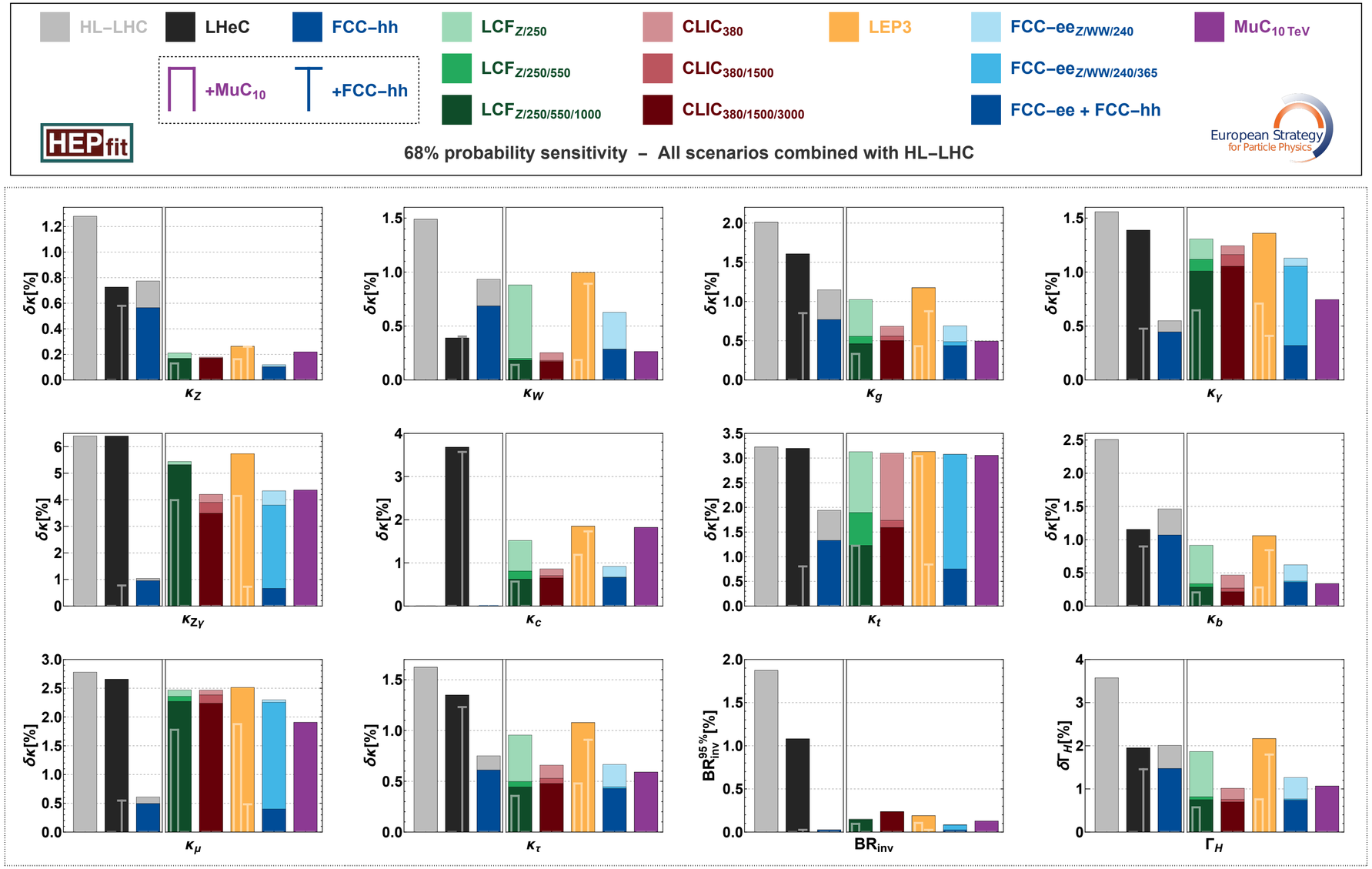
And even more exciting… the possibilities *we haven't thought of* do so as well!



ANY deviation from predictions implies a *revolution* in our understanding of the universe

CEPC/FCC-ee is a powerful Higgs precision probe!

$$\kappa_X \equiv \frac{g_{hXX}}{g_{hXX}^{SM}}$$

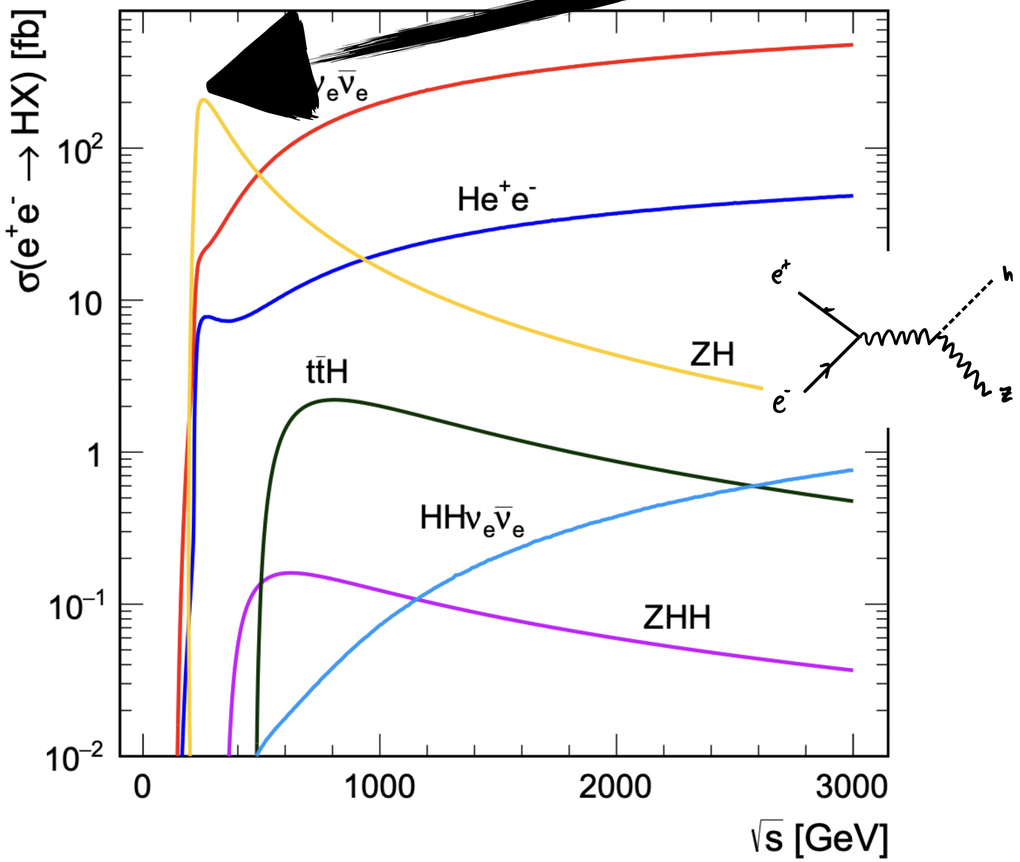


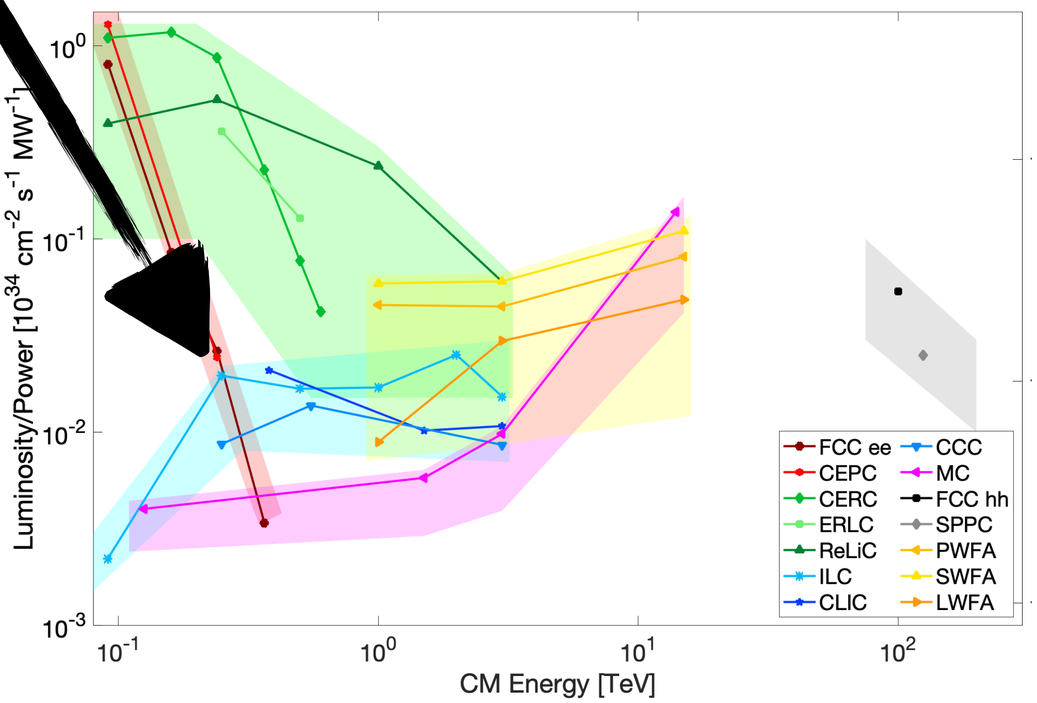
An order of magnitude or more sensitivity gain from the HL-LHC for many couplings

What enables this sensitivity?

The run plan at 240 GeV gives $\mathcal{O}(10^6)$ clean Higgs events $\rightarrow \delta\kappa_i \sim 10^{-3}$ precision

$$N_{ev} = \sigma\mathscr{L}$$





Snowmass Accelerator Implementation Task Force

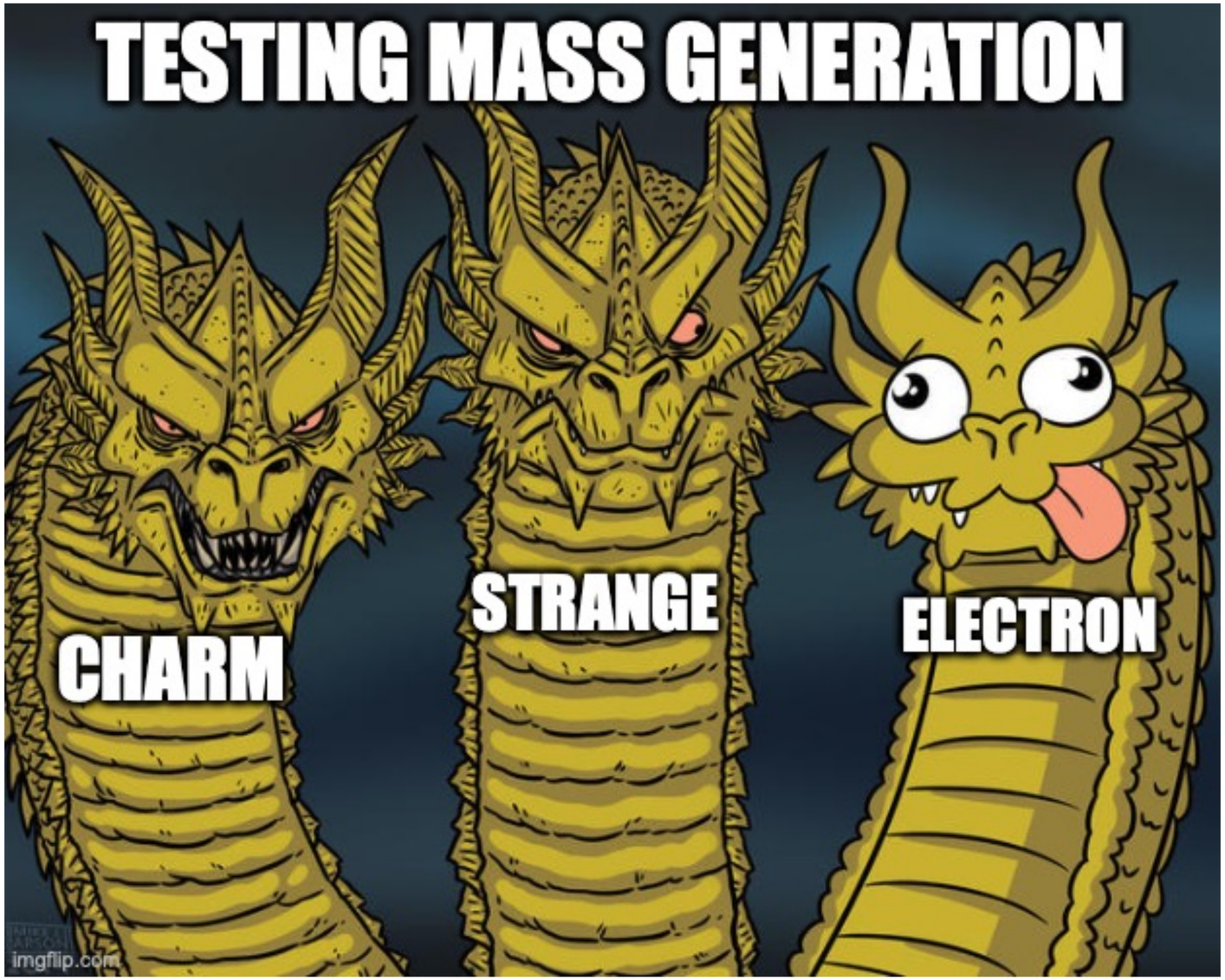
Is improving precision sufficient to justify building CEPC/FCC-ee?

Is precision the only thing improved for the Higgs compared to the LHC/HL-LHC?

Do we ***care*** about this precision threshold?

What does it mean in the context of any larger questions?

Fundamental new tests and new territory



Fundamental new tests and new territory

Charm Yukawa

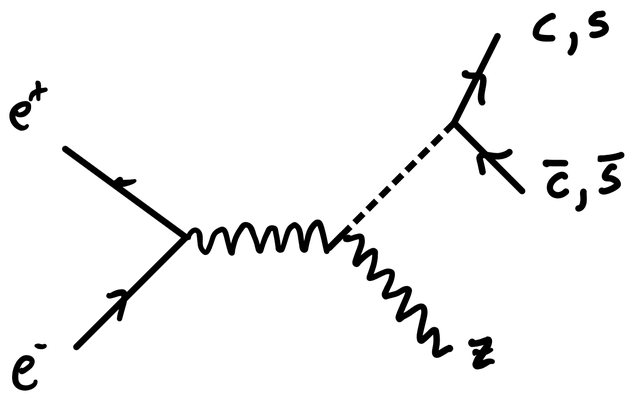
HL-LHC: $|\kappa_c| < 1.5$

FCC-ee: $\delta\kappa_c = 1.8\,\%$

Strange Yukawa

HL-LHC: N/A

FCC-ee: $\kappa_s \in [.4, 1.3]$

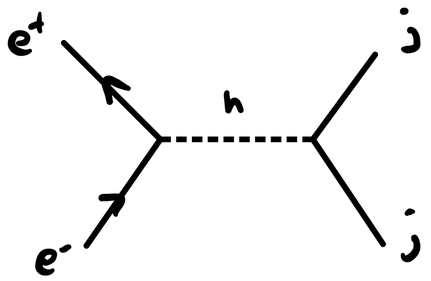


ESPPU Briefing Book
2511.0388

Electron Yukawa

HL-LHC: $|\kappa_e| \lesssim \mathcal{O}(10^2)$

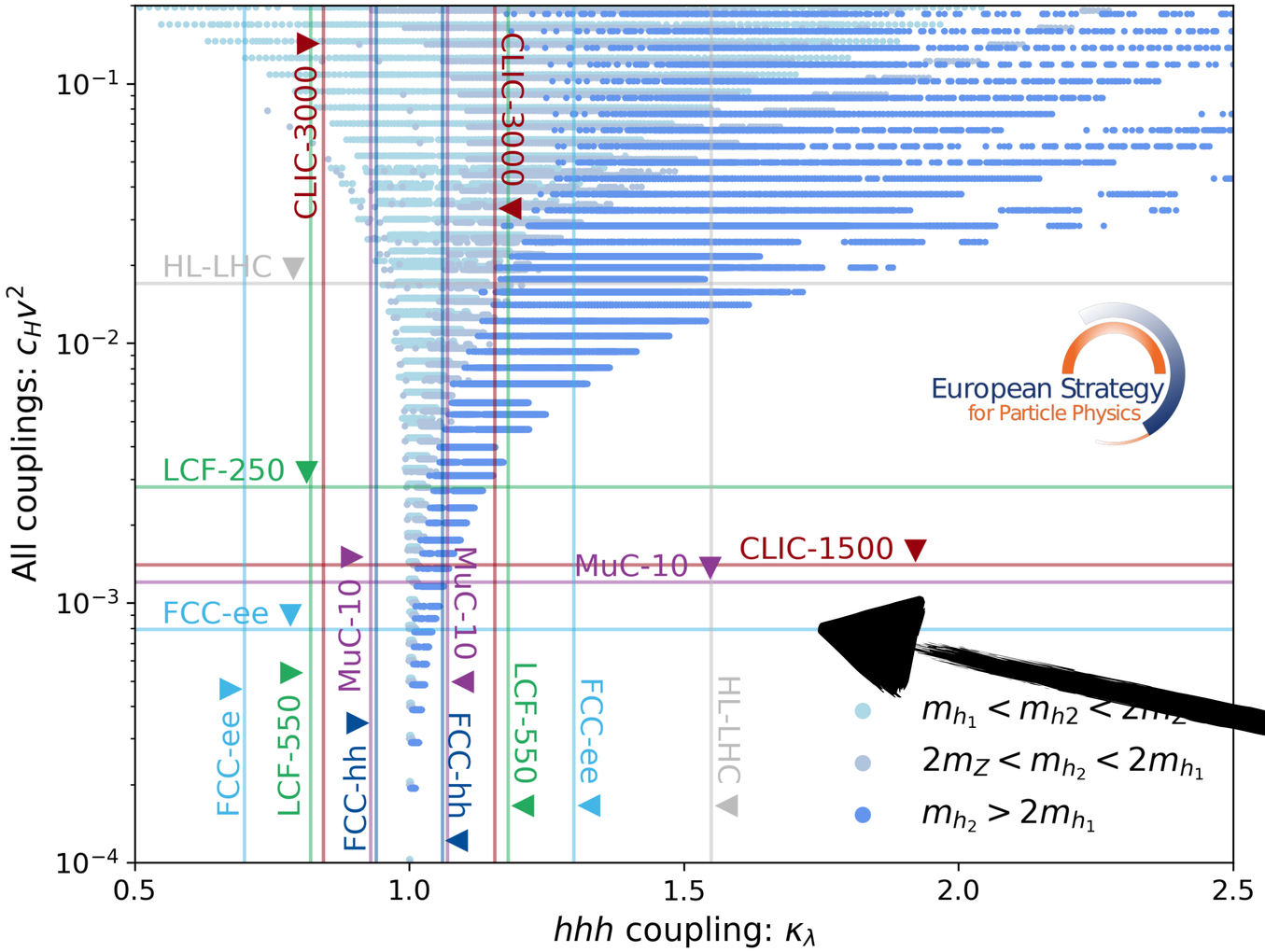
FCC-ee*: $|\kappa_e| \lesssim \mathcal{O}(1)$



*not officially in run plan

ECFA report
2506.15390

Does this precision matter for the big questions?



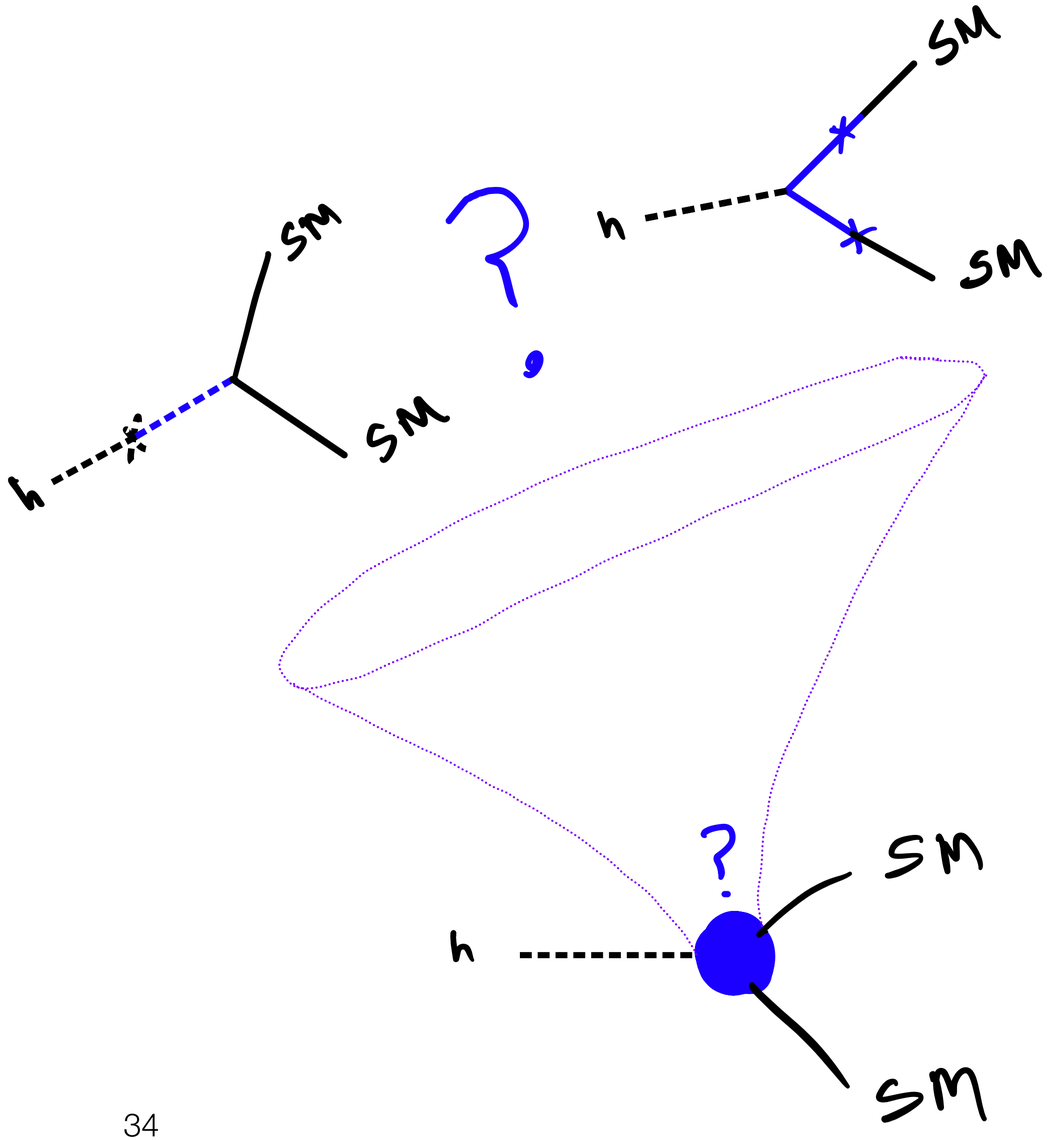
CEPC/FCC-ee can't map the Higgs potential well directly, but the quantum imprints affect how it couples to ***other*** SM particles as well!

CEPC/FCC-ee Higgs couplings can have big implications

Scalar singlet driven first order EW phase transition

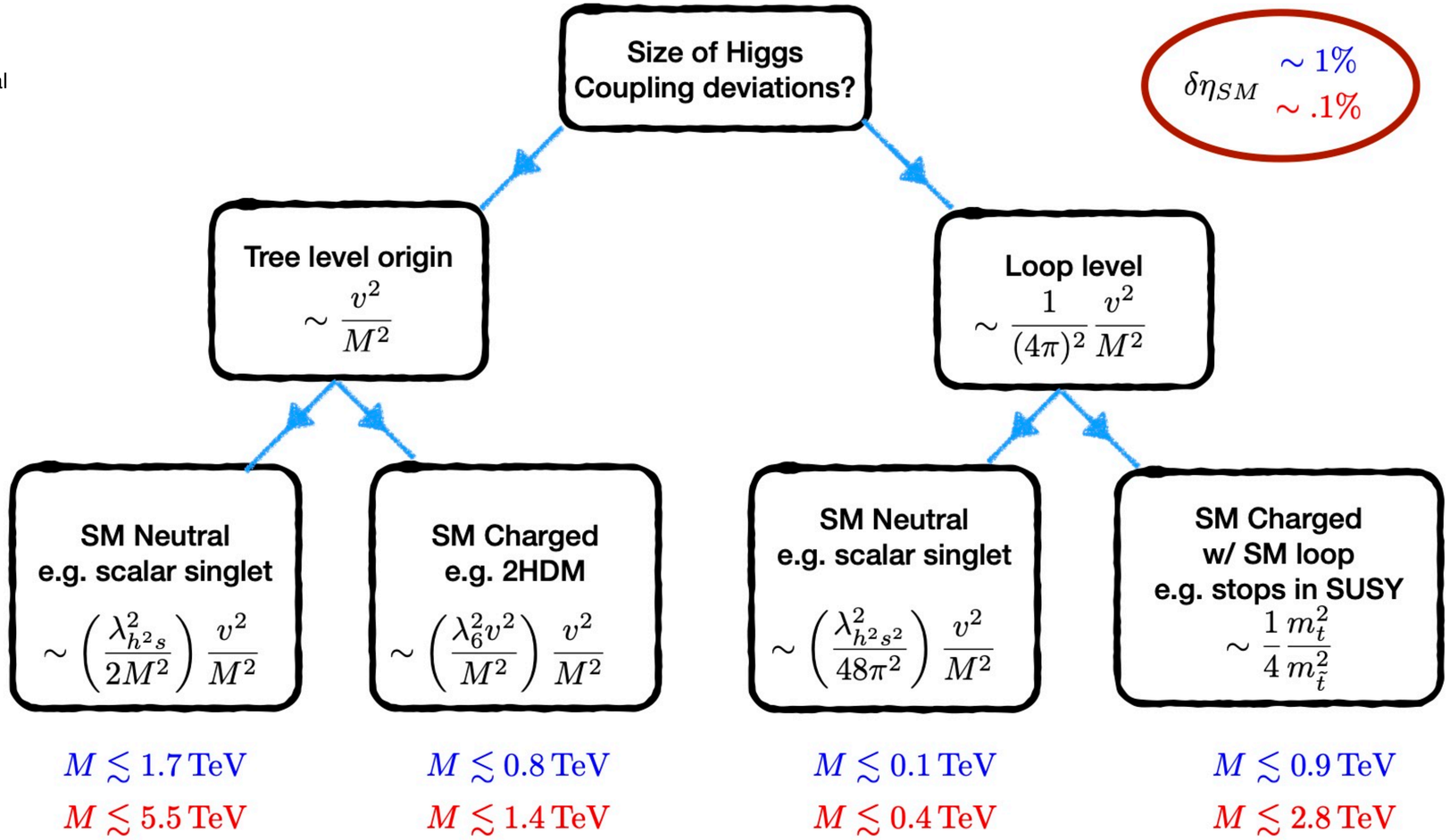
What does this precision translate to more generically and does it extend beyond LHC direct reach?

Based on ***how*** NP couples to the Higgs we can translate precision to mass scales using EFT



Remarkably there aren't *that* many relevant ways to couple at this level of precision!

Snowmass EF Higgs Topical Report
S. Dawson, PM, I. Ojalvo, C. Vernieri et al
2209.07510



Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

CEPC breaks new ground even *beyond* Higgs coupling comparisons!

CEPC/FCC-ee is clearly a powerful tool for Higgs properties…

What really excites me is the run at the Z-pole

Isn't that just LEP from long ago?

Yes, but LEP produced ~10^7 Z bosons

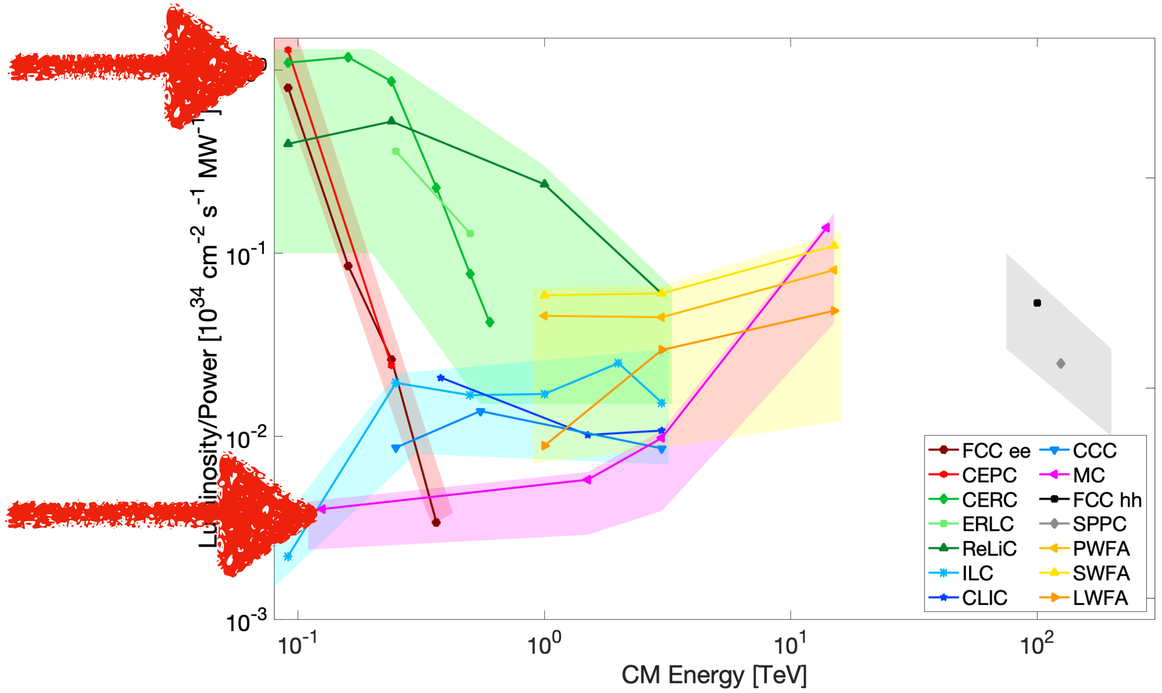
CEPC/FCC-ee will produce ~10^{12} Z bosons "TeraZ"

*Cool thing is it's mostly **technology** driven!*

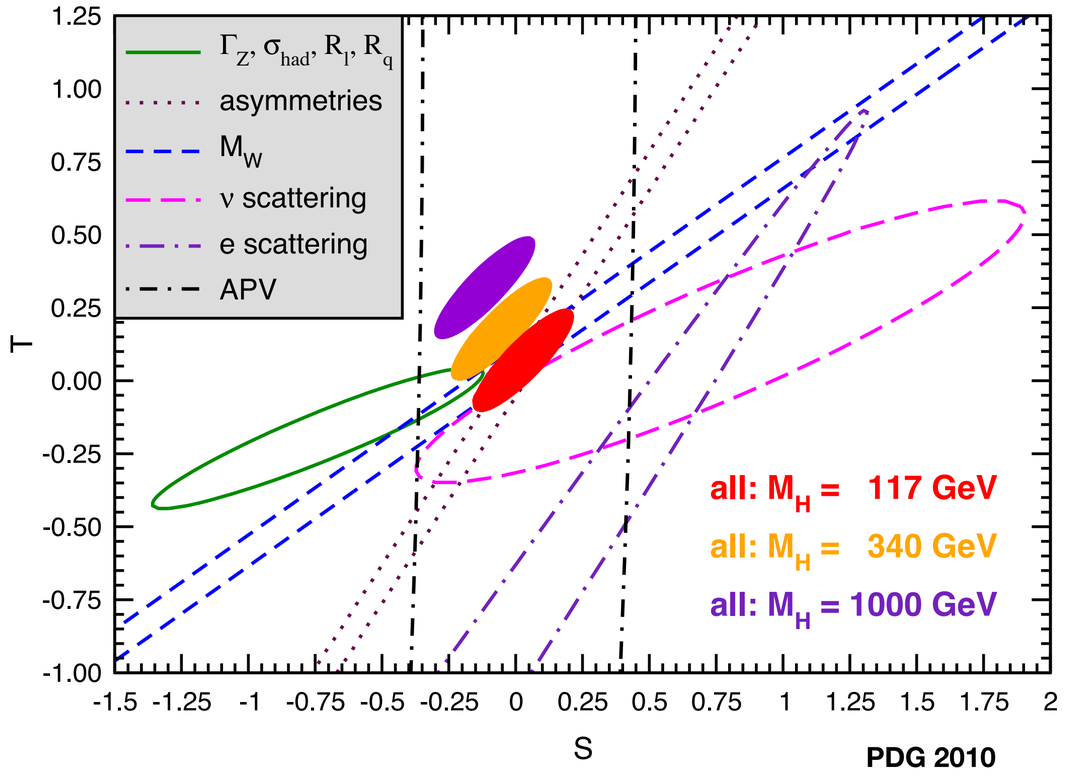
TeraZ

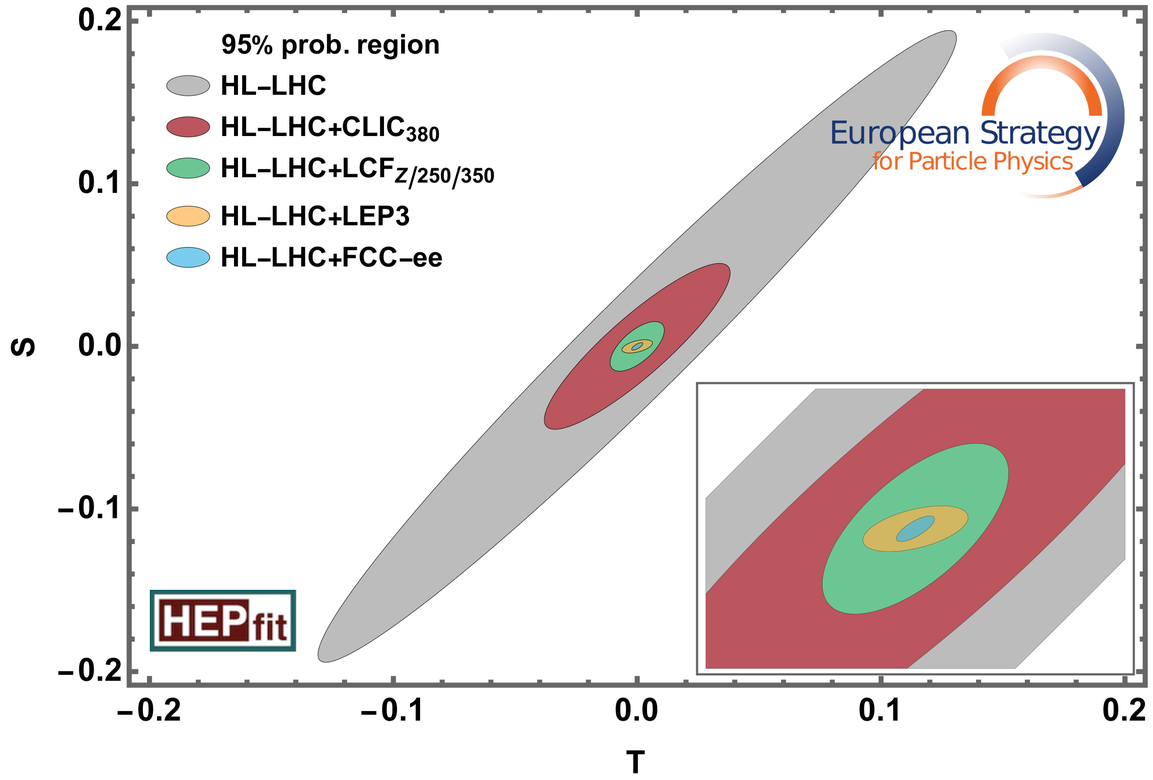
GigaZ

This demonstrates the power of ***circular*** e^+e^- colliders at "low" energy compared to ***linear*** colliders



Naively not directly testing “Higgs” physics… but LEP strongly constrained the properties of EWSB *before* the LHC





Projected sensitivities increase another 2 orders of magnitude from LEP to the 10^{-5} level!

What does this mean *generically* for the scale of new physics?

LEP EWPT $\frac{C_T}{\Lambda^2}(H^\dagger D_\mu H)^2 \longrightarrow$

Why did it make sense to proceed with the LHC?

$C_T \sim \mathcal{O}(1) \longrightarrow \Lambda \gtrsim 10\,\text{TeV}$ **“Tree”**

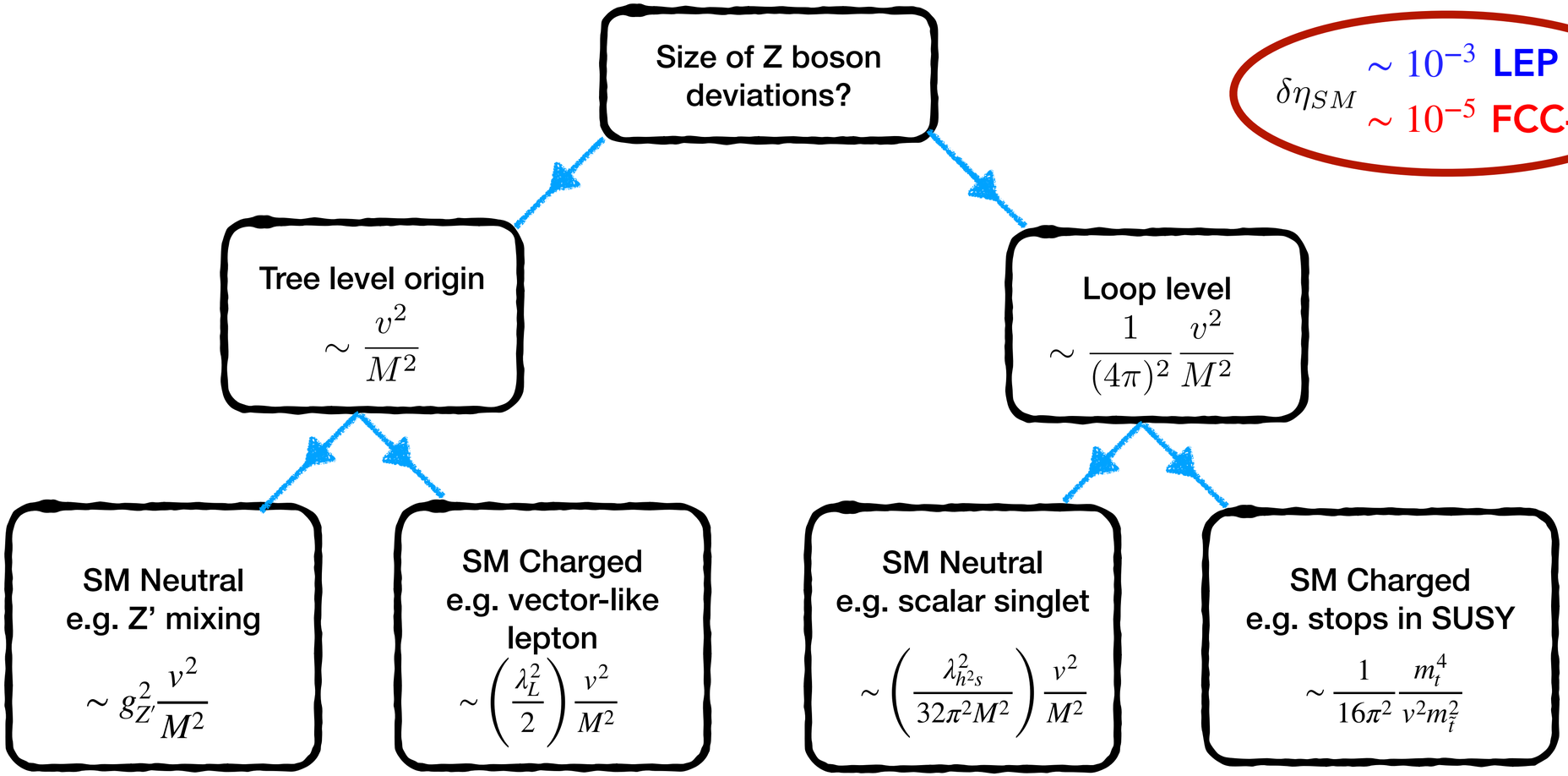
Loop + weak coupling $\longrightarrow \Lambda \gtrsim v$

CEPC increasing EW precision by *2* orders of magnitude

$C_T \sim \mathcal{O}(1) \longrightarrow \Lambda \gtrsim 100\,\text{TeV}$ **“Tree”**

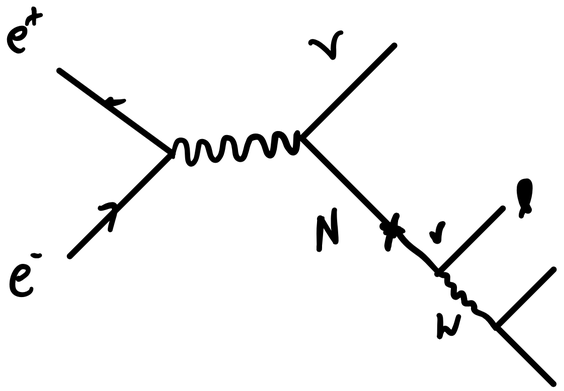
Loop + weak coupling $\longrightarrow \Lambda \gtrsim 2.5\,\text{TeV}$

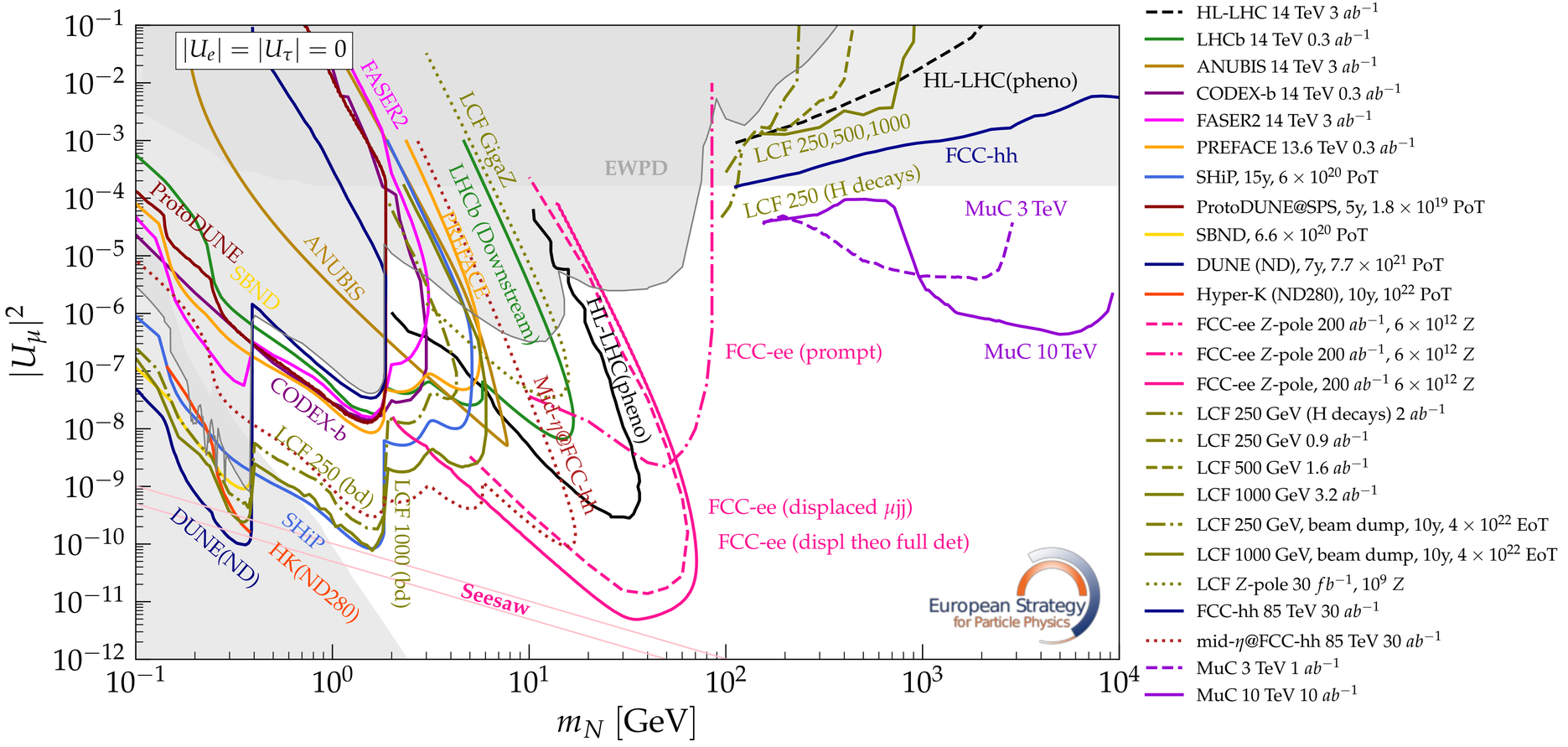
Translating to mass reach like the Higgs



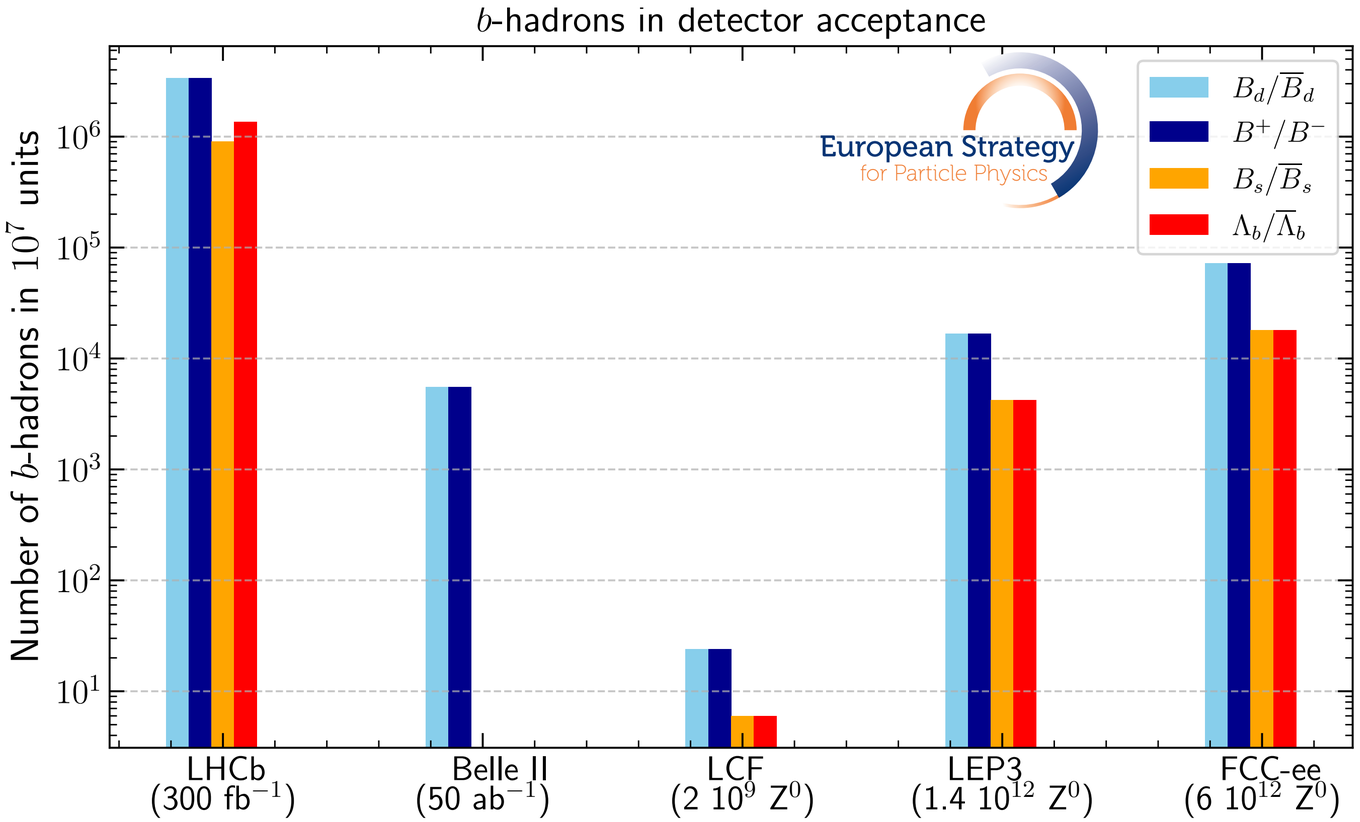
Conservative Scaling for Upper Limit on Mass Scale Probed by Z-pole Precision

Direct Windows also from big samples of Z bosons! HNL… and neutrino mass?





Huge samples of Z bosons aren't only good for exotic decays but a "Super-Duper" B-Factory...



Belle II ~ 70 times Belle dataset - TeraZ run gives *another* order of magnitude!

An e^+e^- collider *enables* precision but you have to control systematics - both experimental and theoretical!

Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}$ $(\times 10^6)$	231,480	±	160	**1.2**	1.2	From $A_{\rm FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)$ $(\times 10^3)$	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{\rm FB}^{\mu\mu}$ off peak From $A_{\rm FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z $(\times 10^3)$	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ $(\times 10^4)$	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, $\Gamma_{\rm tot}^Z$, $\sigma_{\rm had}^0$ fit
$\sigma_{\rm had}^0$ $(\times 10^3)$ (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
$N_\nu(\times 10^3)$	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
$R_{\rm b}$ $(\times 10^6)$	216 290	±	660	**0.25**	0.3	Ratio of $\rm b\bar{b}$ to hadrons
$A_{\rm FB}^{\rm b,0}$ $(\times 10^4)$	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{\rm FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2)$ $(\times 10^4)$	1 010	±	270	**2**	2	Combined R_ℓ^W, $\Gamma_{\rm tot}^W$ fit
N_ν $(\times 10^3)$	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV)	172 570	±	290	**4.2**	4.9	From $\rm t\bar{t}$ threshold scan QCD uncert. dominate
$\Gamma_{\rm top}$ (MeV)	1 420	±	190	**10**	6	From $\rm t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2	±	0.3	**0.015**	0.015	From $\rm t\bar{t}$ threshold scan QCD uncert. dominate
ttZ couplings		±	30%	**0.5–1.5** %	small	From $\sqrt{s} = 365$ GeV run

Current: NNLO + m_t-enhanced N3LO*

"Conservative": N3LO with $N_f \geq 2$ or $N(\alpha_S) \geq 1$ + m_t-enhanced N4LO + α_S^5 FSR

"Aggressive": N4LO with $N_f \geq 2$ or $N(\alpha_S) \geq 2$ + partial m_t-enhanced N5LO + α_S^6 FSR

Theory needs @ Z-pole,
A. Freitas LoopFest 2026

An enormous amount of work is needed to pull off physics at the 10^{-5} precision - but the payoff is worth it!

Conclusions

- CEPC represents a significant leap beyond the LHC for ***Higgs*** physics but that's only *part* of the story

- A wide array of runs/energies can explore many different types of physics, with TeraZ as an incredibly compelling component!

- There is still a lot of work to do to make it a reality, but the physics payoff is enormous

- A project that pushes the ***precision*** boundaries will guide the way for future decades or uncover new physics before we can directly produce it