Physics at FCC-ee

Zoltan Ligeti
Lawrence Berkeley Lab

FCC week, June 10–14, 2024

Some Physics at FCC

Zoltan Ligeti
Lawrence Berkeley Lab

FCC week, June 10–14, 2024

Preliminaries

- Building a $10\times$ better microscope than the LHC is a clear case
- If a deviation from SM in flavor is established, it would make a clear case for tera-Z
- We don't know where and how new physics will show up

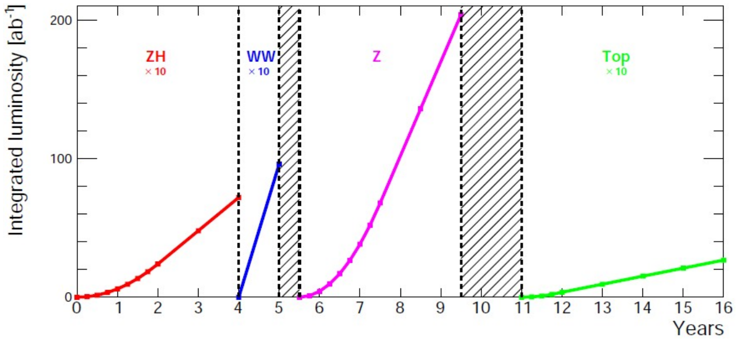
  Broad program is essential, but I cannot cover the plethora of interesting processes

  (If I do not talk about your favorite topic, it does not mean that I think it's less important!)
- FCC-ee can be a discovery machine; very rich and challenging physics program

  FCC-ee measurements will be essential to fully explot FCC-hh (α_s, m_t, etc.)

Outline

- Higgs is new physics
  - Complementarities, intertwined
  - It's not only the ZH run, multiple energies important
- Precision electroweak: enormous (10^5) jump from LEP



- Flavor: only way to go order(s) of magnitude beyond Belle II & LHCb in many channels
- Light BSM scenarios: much improved probes of many models with new light particles
- Many interesting topics I have no time to cover
- Experimental and theoretical challenges (opportunities!) everywhere

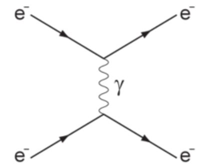
Higgs and superconductivity

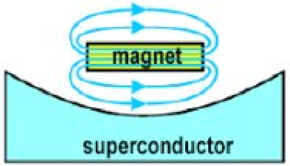
- Gauge symmetry forbids γ, W, Z masses, Coulomb's law, infinite range

  Meissner effect: photon acquires a mass, $\mathbf{B}$ field falls off exponentially

  Higgs mechanism: nonabelian analog to give masses to $W^\pm, Z^0$ (spontaneously breaking of gauge symmetry)

  The vacuum in our Universe is in a superconducting state below 10^{15} K





- Superconductivity: microscopic theory, Cooper pairs ("new physics")
- Higgs mechanism: Is it totally different?

  As for superconductivity, microscopic explanations have phenomena at nearby scales
  (supersymmetry, little higgs, technicolor, extra dimensions, strongly interacting sectors, etc.)

- It would be unprecedented to have no "new physics" at nearby scales (nearby $=$?)

Before Higgs, we only knew there was a VEV

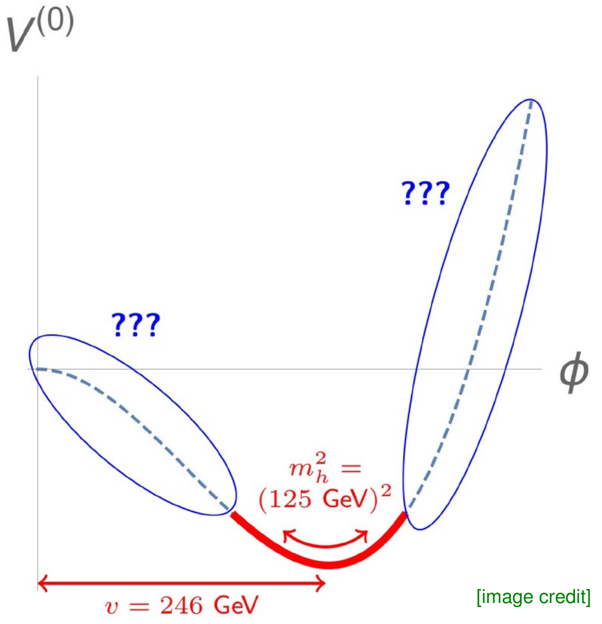
- Before 2012, we only knew there was a condensate, which broke electroweak symmetry:

$$\langle \phi(1,2)_{1/2} \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

- Higgs was one option: "derive" $v^2 = m^2/\lambda$ (λ: quartic)
  expand about min., cubic: $\lambda v h^3$

  Is it just the Higgs self-interaction that generates the potential and breaks electroweak symmetry? We have no clue!

- BCS-like: compositeness
  SUSY: λ related to gauge couplings g, g'
  ... etc.



[image credit]

Higgs is new physics!

Higgs is new physics!

- Don't believe me...? Higgs is Really New Physics! [Arkani-Hamed, 10th anniversary]

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Higgs is new physics!

- Don't believe me...?

[Arkani-Hamed, 10th anniversary]

- Was not guaranteed that LHC discovers a Higgs (many said the same about SUSY)

  Never saw before a point-like elementary scalar, cannot overstate importance of Higgs

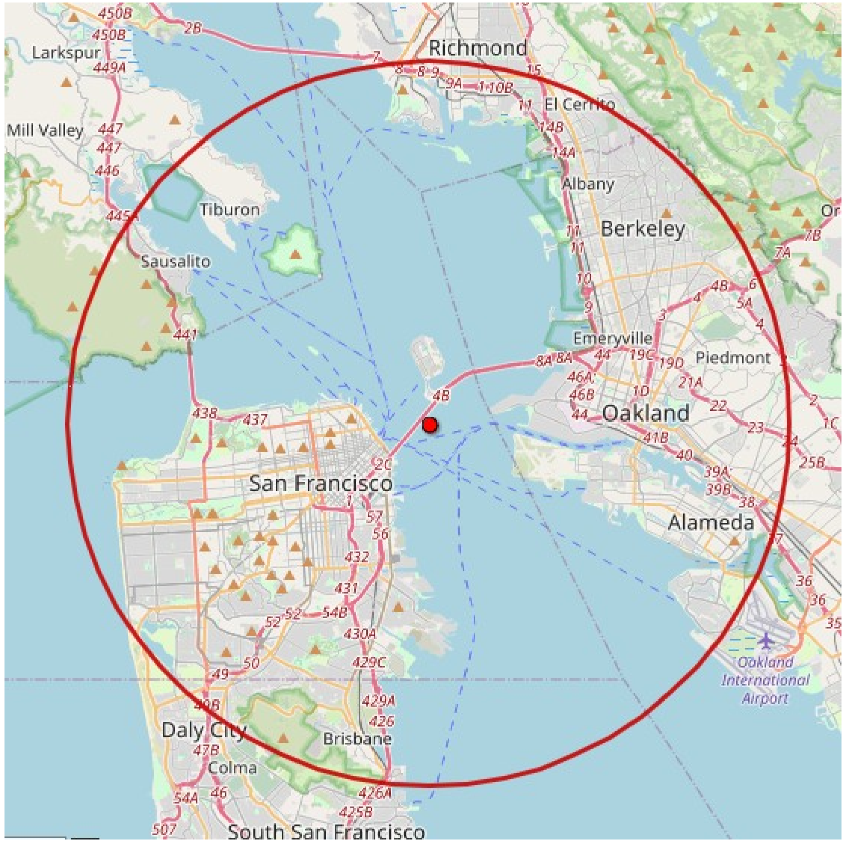
  Major questions about Higgs:
  – elementary or composite?
  – one or several particles?
  – couplings as predicted?
  – only source of flavor violation?

  Major questions Higgs impacts:
  – is electroweak baryogenesis viable?
  – vacuum stability?
  – understand naturalness?
  – portal to hidden sector?

- It is imperative to study the Higgs as precisely as we possibly can

- LHC $\Rightarrow$ need a much better microscope to understand electroweak superconductivity

FCC doesn’t look that big in the Bay Area



US units for FCC week:

X mile radius $\Leftrightarrow 10X$ km circumference

(2π miles = 10 km)

Units for flavor: m_B/MeV = mile / foot

10^{-2} and 10^{-4} coincidences, respectively

Where are we now? The highway 50 analogy...

We have just passed Austin (Nevada), approaching Eureka!

1 mile $\Leftrightarrow$ 1 fb^{-1}

Physics in 20 years may be very different

- Will LHC see NP beyond the Higgs? (new particle $\Rightarrow$ new flavor sector, recall $H\tau\mu$ anomaly)
- Will NP be seen in the quark sector? (Current data: hints of possible deviations from SM)
- Will NP be seen in charged lepton sector? $\mu N \to eN$, $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to 3\mu$?
- Will DM be discovered? Axions? EDMs? Something else?
- Neutrinos: Does 3 flavor paradigm hold? What is the nature of ν mass?

- No one knows — an exploratory era! Any BSM discovery would be a game changer

  Michelson 1894: "... it seems probable that most of the grand underlying principles have been firmly established ..."
- While Higgs is an obvious place to look for BSM, want broad searches on all fronts

What is the scale of new physics?

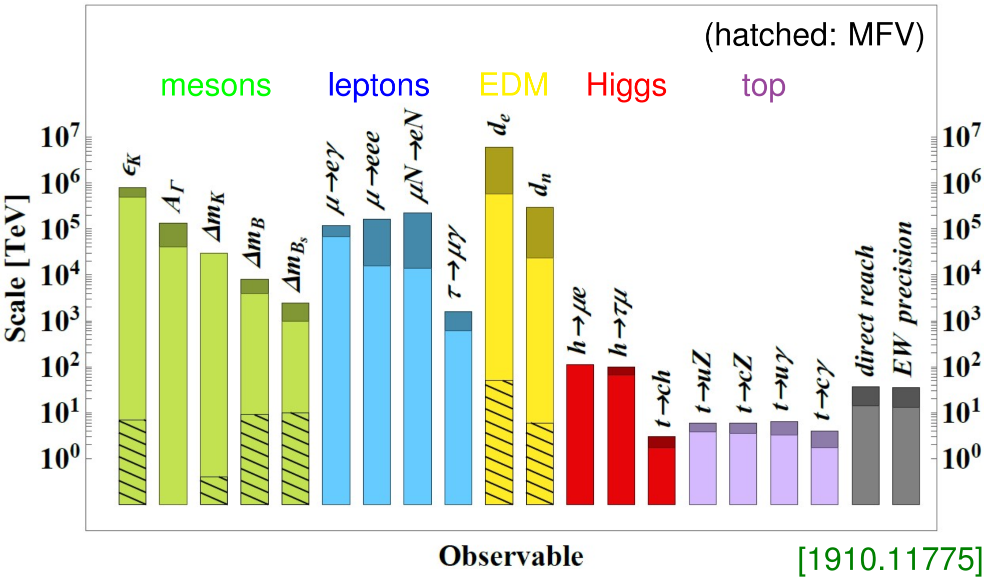
- Flavor, K, B, D: $\dfrac{(\bar{b}\,\Gamma d)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2 - 10^5\ \text{TeV}$

  (Note special sensitivity of meson mixings)

- Electroweak: $\dfrac{(H^\dagger D_\mu H)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10\ \text{TeV}$

- Actual scales may be much less; e.g., in SM:

$$\frac{\Delta m_K}{m_K} \sim \frac{g_2^4}{16\pi^2}\,|V_{cs}V_{cd}|^2\,\frac{m_c^2}{m_W^4}\,f_K^2 \sim 7\times 10^{-15}$$



[1910.11775]

- Lack of NP in flavor tells us something; motivates tera-Z part of comprehensive search

- If NP is within any collider's reach, it must possess nontrivial structures (e.g., MFV-like)

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

How much improvement needed? E.g.: CP violation

ANNALS OF PHYSICS: 5, 156–18 (1958)

Long-lived Neutral K Mesons*

M. BARDON, K. LANDE, AND L. M. LEDERMAN

Columbia University, New York, New York, and Brookhaven National Laboratories, Upton, New York

AND

WILLIAM CHINOWSKY

Brookhaven National Laboratories, Upton, New York

set an upper limit <0.6% on the reactions

$$K_2^0 \to \begin{cases} \mu^\pm + e^\mp \\ e^+ + e^- \\ \mu^+ + \mu^- \end{cases}$$

and on $K_2^0 \to \pi^+ + \pi^-$.

VOLUME 6, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 1, 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3% for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our

"At that stage the search was terminated by administration of the Lab."
[Okun, hep-ph/0112031]

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

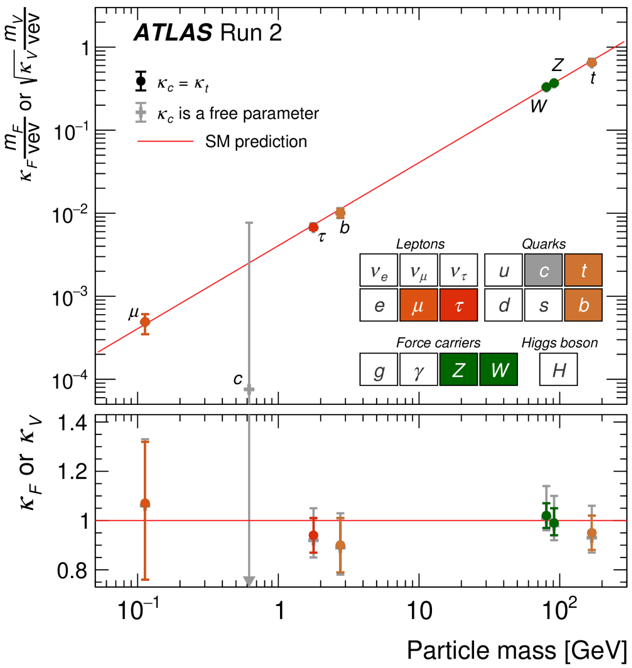
J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

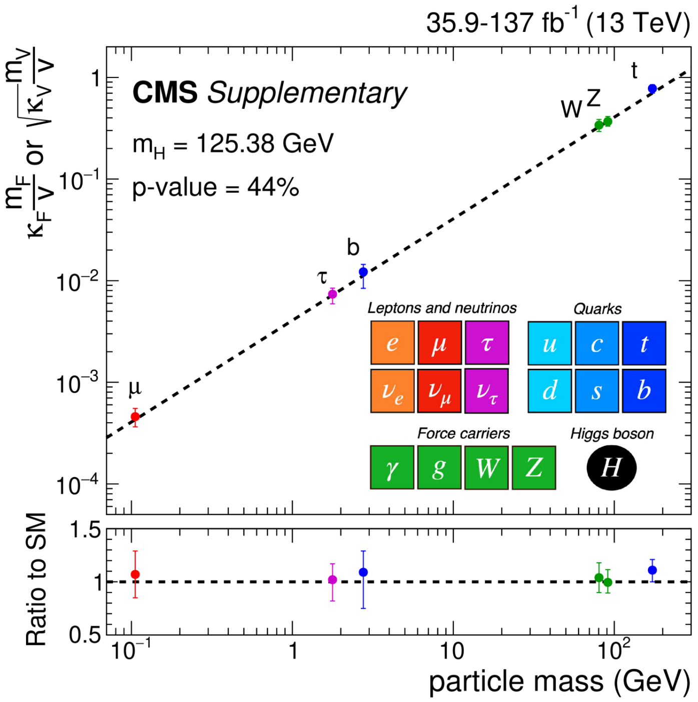
We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As empha-

Unexpected discovery from minor improvements. Not what the goal was. Are we looking at all places?

Higgs

LHC: impressive map of H couplings





- No constraint yet on origin of 1st generation fermion masses, mainly μ from 2nd gen.
- FCC-ee can establish role of Higgs in y_c, get close to y_s and y_e

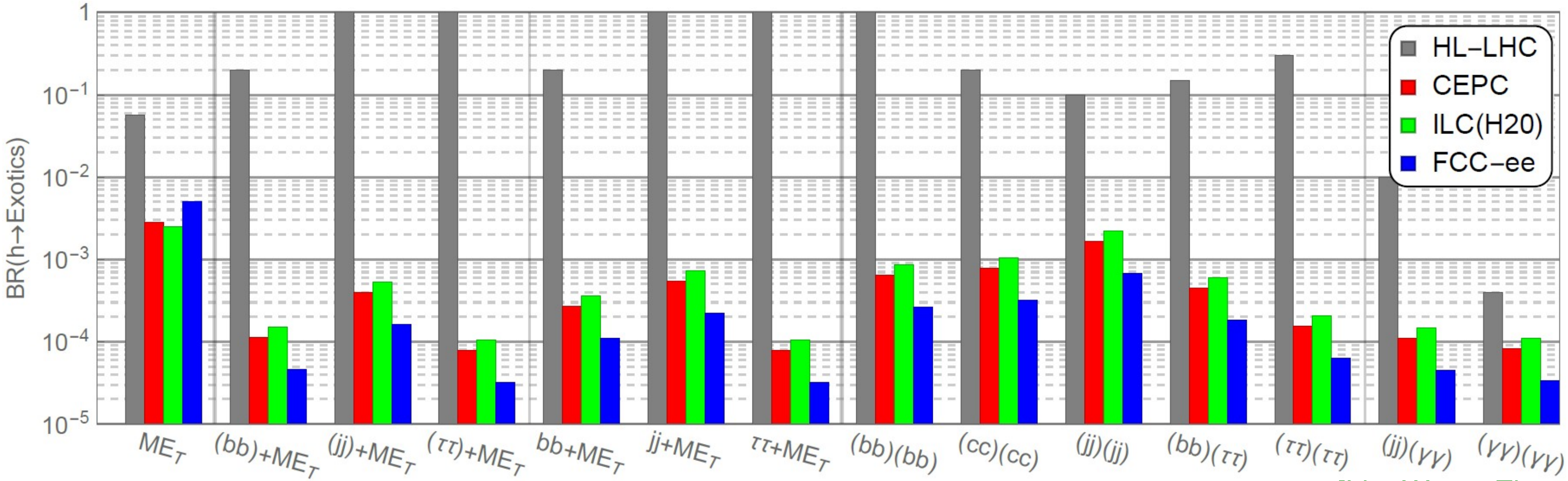
Decays HL-LHC can probe fairly well

- Big improvements for many couplings
- Order of magnitude or more for κ_Z, κ_c, invisible, and "exotic" channels
- κ_Z especially significant
  in many models its modification is correlated with those of self coupling
- Model independent measurement of the Higgs total width is only possible in e^+e^-

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z[%]	1.3*	0.17 / 0.14
κ_g[%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR}_{\mathrm{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR}_{\mathrm{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

($*$: no direct access to H width) [Midterm Report]

“Exotic” decays HL-LHC cannot probe well

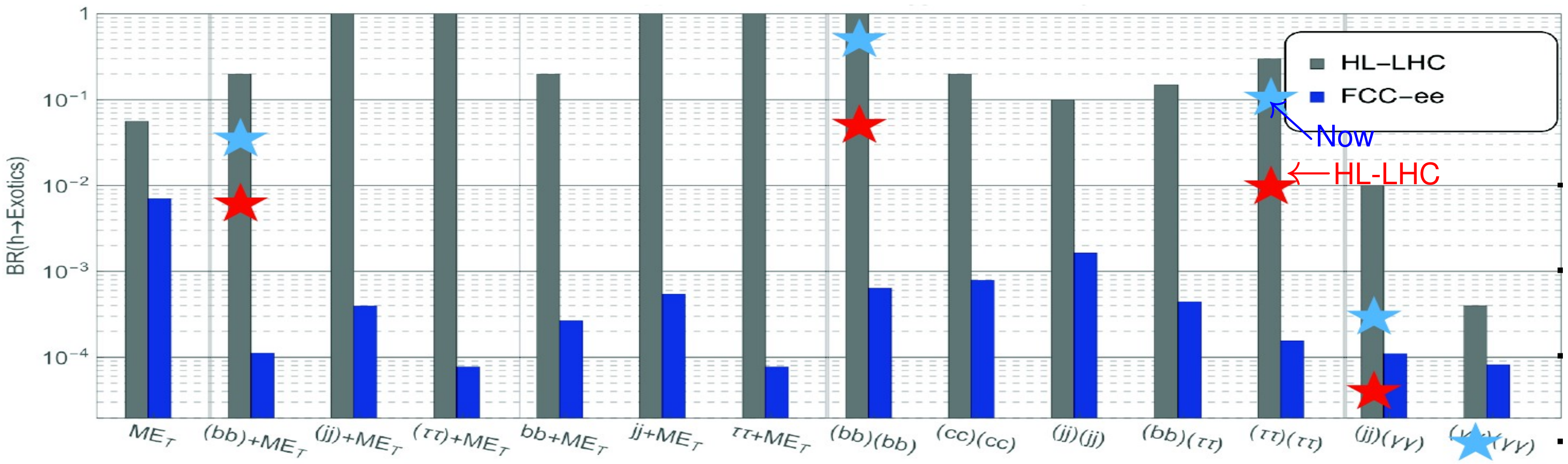


[Liu, Wang, Zhang, 1612.09284]

- Relatively few constraints, many theory papers [E.g., 1312.4992]

  E.g., models like $|H|^2 S^2$, etc., could yield observable rates

"Exotic" decays HL-LHC cannot probe well

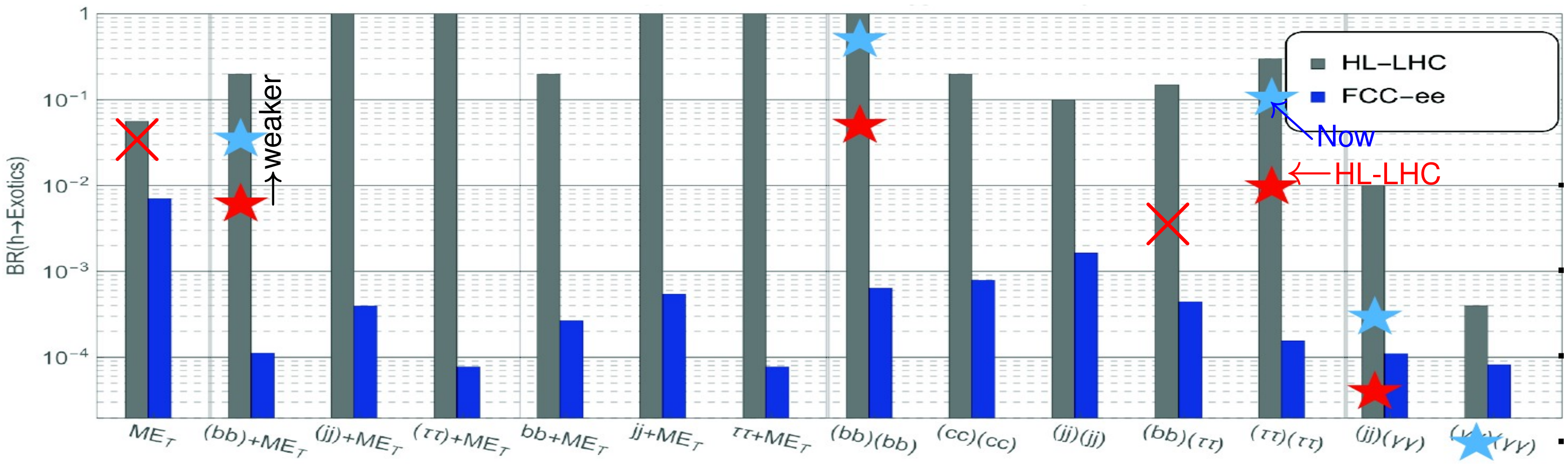


[Lipeles @ Aspen, 3/24]

- As usual, LHC better than predicted, still, huge improvements at FCC in many modes

LHC limits depend on assumptions about models, lifetimes (displacement), etc.

“Exotic” decays HL-LHC cannot probe well



[incl. projections in 1902.10229]

- As usual, LHC better than predicted, still, huge improvements at FCC in many modes

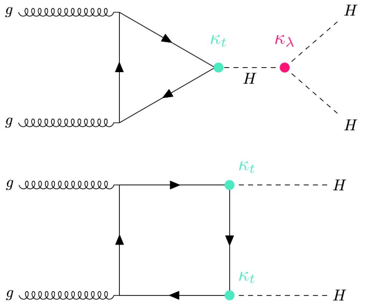
With displacement constraints, 1–10% bounds on $H \to 4q$ & few other modes (not shown)

[2403.15332, 2403.09292, etc.]

Higgs self coupling: the holy grail?

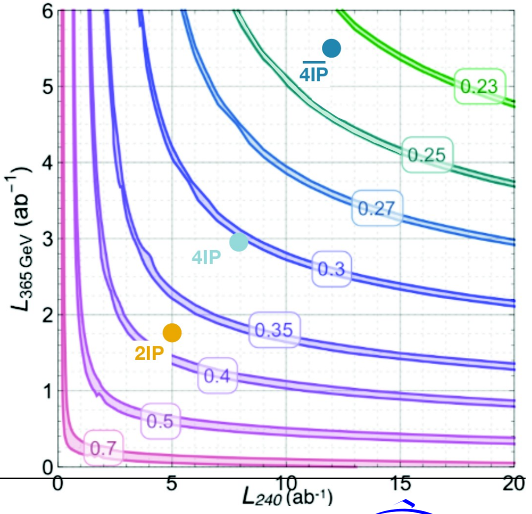
- Measure κ_λ: $\mathcal{O}(5)$ now $\Rightarrow \mathcal{O}(1)$ at HL-LHC $\Rightarrow \mathcal{O}(.25)$ at FCC-ee $\Rightarrow \mathcal{O}(0.03)$ at FCC-hh
- Ultimate FCC-hh sensitivity requires:
  - m_t from FCC-ee
  - $t\bar{t}$ threshold scan needs α_s at max precision from Z (WW?)

destructive interference ↘



- Data at multiple CM energies important for the FCC-ee reach ↘

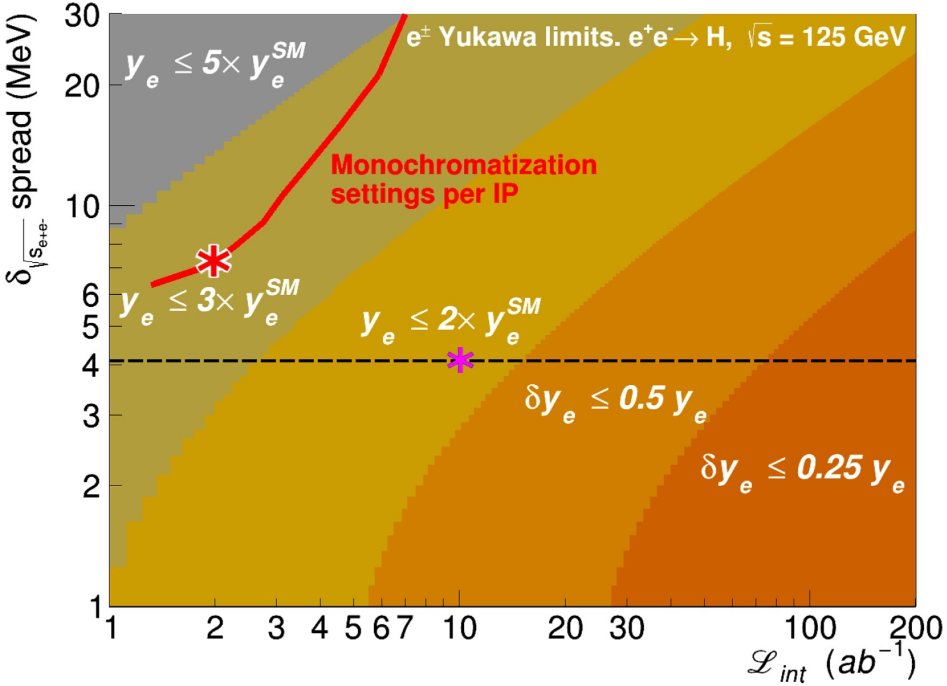
  (Also to constrain different SMEFT operators, resolve degeneracies)



- Precisely mapping out Higgs self-interaction is a well defined target, a “no-lose theorem” for FCC [Salam , last year]
- In many models, correlated modifications of λ and HZZ, which FCC-ee will probe to 0.14%

Approaching electron Yukawa?

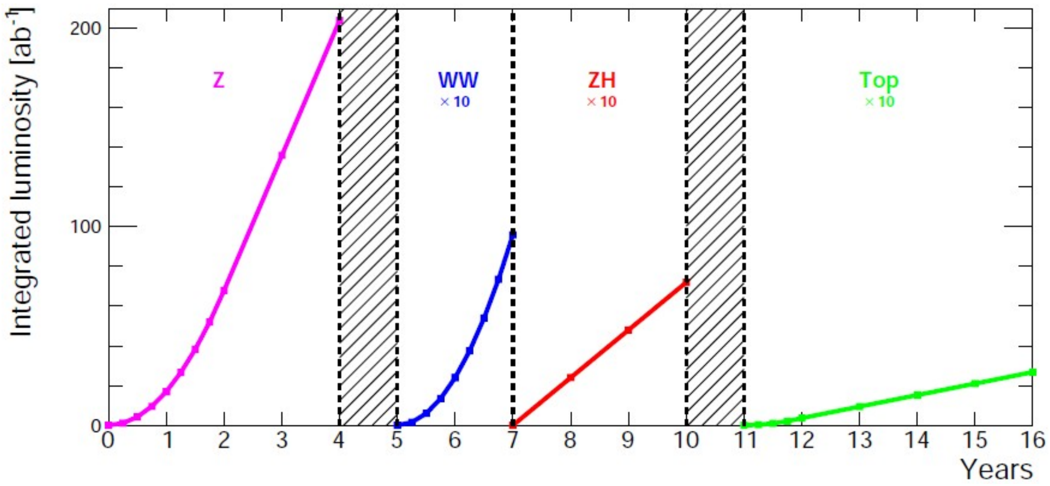
- Probing y_e at $\sqrt{s} = 125\,\mathrm{GeV}$ would be unique to FCC-ee



[2203.06520]

- What additional physics could make this a compelling part of the run plan?

Tera-Z


Integrated luminosity [ab^{-1}]
200
100
0
Z
WW
× 10
ZH
× 10
Top
× 10
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Years

Precision electroweak observables

- 10^5 improvement over LEP is qualitatively new

  Both a huge leap forward and the right target

  (mass scale) $\propto$ (uncertainty)$^{-1/2}$ $\propto$ (stat)$^{-1/4}$

- Sensitive to order of magnitude heavier NP in loops

  Many interesting observables, complementary sensitivities

- Interesting experimental & theoretical challenges to reduce systematic uncertainties to statistical limits

  E.g., $A^b_{\rm FB}$, largest remaining tension from LEP/SLD

  Must improve: fragmentation, MC, higher orders, jet tagging

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

Can one appreciate / anticipate a 10^5 improvement?

- What might $10^5 \times$ LEP mean? Can we predict it...? (Recall : Belle II / ARGUS $\sim 10^5$!)

  Theory and experimental techniques both changed a lot! (e.g., full hadronic reconstruction)

  Asymmetric B factories at $\Upsilon(4S)$ great for CP violation, less ideal for (semi)leptonic decays

- What was not even tried at LEP? (due to lack of statistics or lack of physics interest)

  Interesting but probably not the best example: $\tau\tau$ spin correlations with 3-prong decays? (0.03×0.1^2)

  Some rare decay sensitivity linear with statistics; e.g., $Z \to \mu\tau, \mu e$, etc.

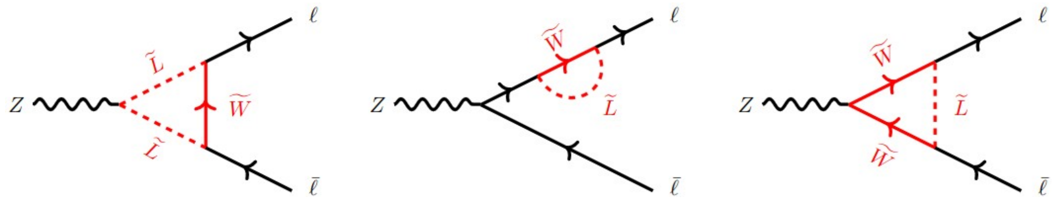
- Some of what's often called precision electroweak, also concerns flavor
  (τ lifetime & mass, R_ℓ for each ℓ flavor, etc.)

A particular sensitivity to SUSY: $Z \to \ell^+\ell^-$

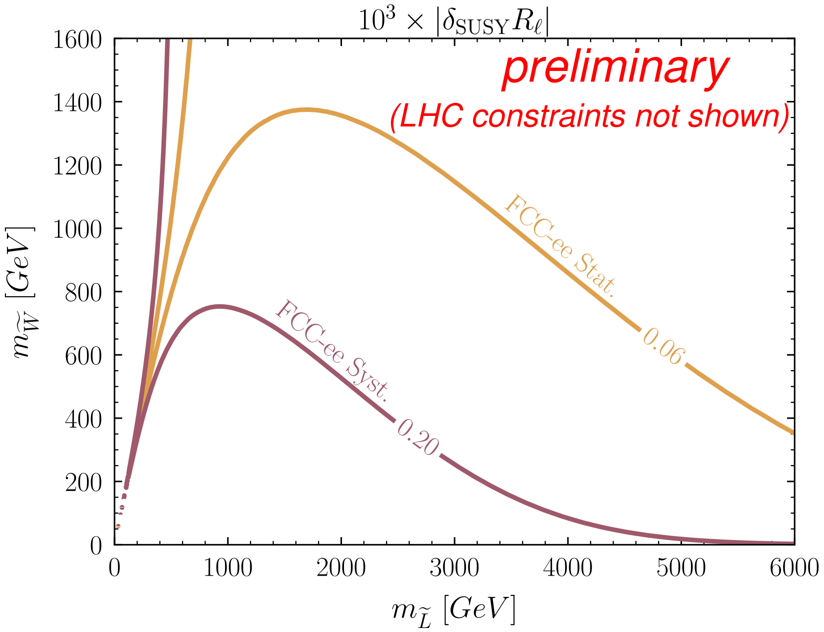
- Precisely measure: $R_\ell = \frac{\Gamma_{\ell^+\ell^-}}{\Gamma_{\text{hadrons}}}$

R_ℓ^Z $(\times 10^3)$	20767	$\pm$	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons

- Consider a SUSY simplified model, with $\tilde{q}, \tilde{g}$ heavy, only electroweakinos & sleptons light



[Knapen, Langhoff, ZL, soon; Langhoff tomorrow 9:40am]



- Ultimate sensitivity: stay tuned (α_s, $\sin^2\theta_w$, etc.)

  Several measurements combined for best physics reach

  Even better sensitivity to flavor violating component (e, μ, τ)

- Complementary to SMEFT based studies, any model may have important correlations

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Some simple takeaways

- Need progress both on experimental and theoretical systematics

  Including: α_s, $\sin^2\theta_w$, luminosity measurements, detector acceptance
- Many theory calculations needed, improvements in Monte Carlo (e.g., for $A^b_{\rm FB}$)
- Not only the "most precise" extraction of parameters matter, but also the "second best"

  (First fixes SM expectations, second to constrain BSM)
- Can probe regions that fall between or outside HL-LHC exclusion regions

Flavor physics at FCC-ee

- Only tera-Z would go well beyond current program — clear case if BSM seen in flavor

Particle production (10^9)	$B^0 + \overline{B}^0$	$B^\pm$	$B^0_s + \overline{B}^0_s$	$\Lambda_b + \bar{\Lambda}_b$	$B^\pm_c$	$c\bar{c}$	$\tau^+\tau^-$
Belle II ($50\,\text{ab}^{-1}$)	27	27	tbd	—	—	65	45
tera-Z $(6\times10^{12}\ Z)$	600	600	150	130	3	600	170

(often the sole focus of talks on flavor @ FCC) [2106.01259]

Comparison with LHCb more complex: roles of trigger, LHCb has advantage if final state is fully reconstructed, if there are neutrals, tera-Z may win

- WW threshold: $W \to b\bar{c}$ can give a qualitatively new determination of $|V_{cb}|$
Estimate 0.2% uncertainty, using 10^8 WW, independent of B measurements
[Monteil @ 7th FCC Physics Workshop, Jan 2024]; also, [2405.08880]

Important, as $|V_{cb}|$ may limit improving BSM sensitivity in $B_{d,s}$ mixing [2006.04824]

Tera-Z: an amazing flavor experiment

- Almost everything about flavor can be done better at tera-Z, focus on few unique points
- $10\times$ Belle II statistics, extra advantage from clean environment and boost of the b

  It will be an exciting program, whether BSM is discovered before, or not

  Flavor probes BSM broadly, relates to most of the parameters of the SM, SMEFT, MSSM, etc.
- Near future: "anomalies" might first become established

  Long term: large increase in discovery potential in many modes
- Hot topics in 2040s are unlikely to be what they are now, or what we can guess now
- For many key measurements we know they won't be systematics limited

Sensitivity to new physics in B mixing

- In many BSM scenarios, dominant deviations from SM may be in neutral meson mixing

  Assume: (i) 3×3 CKM matrix is unitary; (ii) tree-level decays dominated by SM

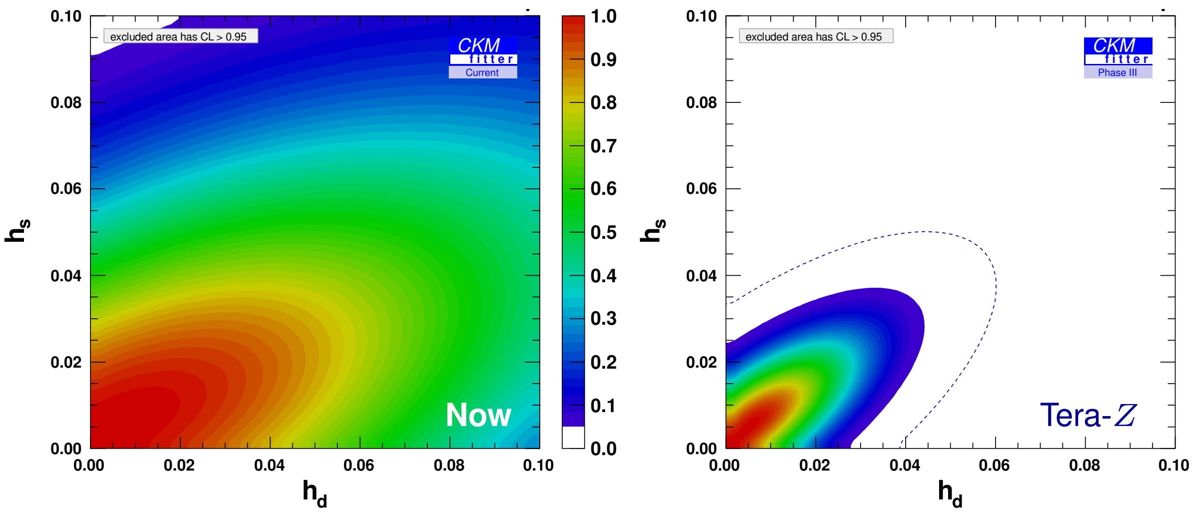
  General parametrization: $h\, e^{2i\sigma} = A_{\rm NP}(B^0 \to \overline{B}^0)/A_{\rm SM}(B^0 \to \overline{B}^0)$ ($h_{d,s}$, $\sigma_{d,s}$: NP param's)

- CKM fit with 4 BSM param's added; combines many measurements and theory inputs [Charles *et al.*, 2006.04824]

  ($\Rightarrow$ conservative view of future progress)

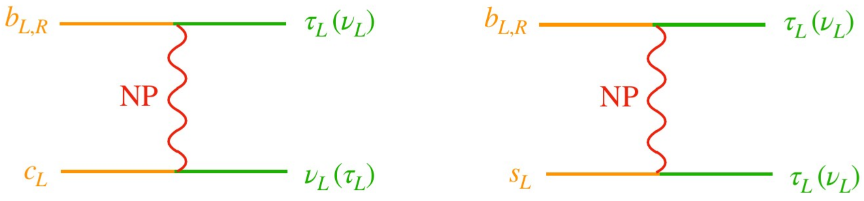
- Sensitive to TeV scale, even if NP is MFV-like

- $|V_{cb}|$ becomes a bottleneck; Tera-Z sensitivity will be better (no LQCD extrapolations)

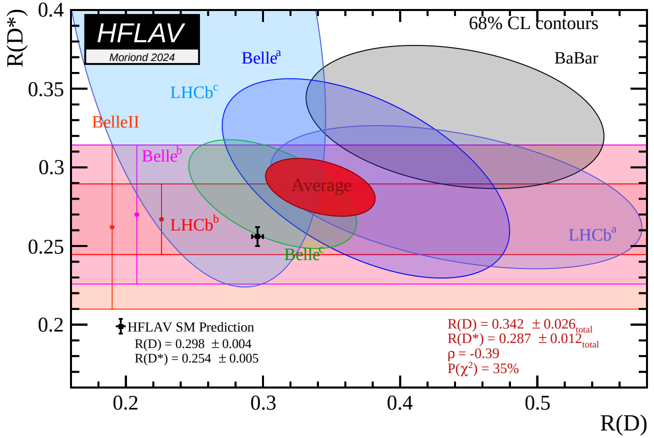


The $b \to c\tau\bar{\nu}$ anomalies could make compelling case

- Over 3σ tension for $R(D^{(*)})$, if it prevails, requires $\mathcal{O}(10\%)$ correction to a tree-level SM process
- If NP is charged under $SU(2)$, unavoidable connection to $b \to s\tau^+\tau^-$ or $b \to s\nu\bar{\nu}$ — correlations distinguish models

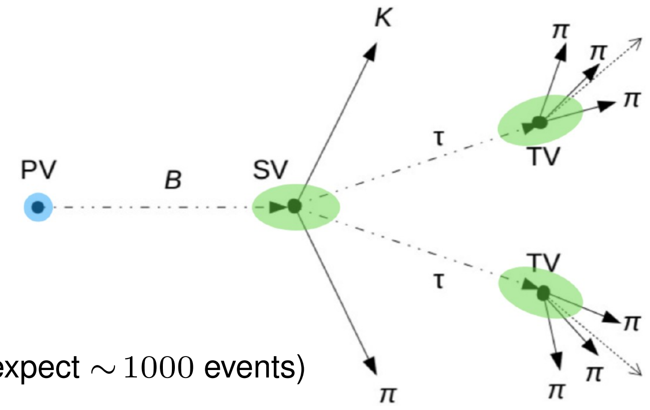


[image credit]



Tera-Z: measure $B \to K^*\tau^+\tau^-$, $K^*\nu\bar{\nu}$ even at SM level

- Boost of B from Z decay provides ideal environment



(expect ~ 1000 events)

(Very) rare (semi)leptonic decays

- Unique capabilities for decays with large missing energy, i.e., ν or τ in final state
  (And better than LHCb for $e^{\pm}$)

- Tera-Z could be the first to measure:
  Many decays mediated by $b \to s\nu\bar{\nu}$ or $b \to s\tau^+\tau^-$, and their $b \to d$ counterparts
  $B \to K^{(*0)}\tau^+\tau^-$, $\Lambda_b \to \Lambda\tau^+\tau^-$, $B \to K^{(*)}\nu\bar{\nu}$, $B_s \to \phi\nu\bar{\nu}$, $\Lambda_b \to \Lambda\nu\bar{\nu}$, $B \to \pi(\rho)\nu\bar{\nu}$, etc.

- Two-body $B \to \ell^+\ell^-$ decays sensitive to very high scales (comparable to $K \to \pi\nu\bar{\nu}$)
  $B_{s,d} \to \mu^+\mu^-$: tera-Z expected to be comparable to HL-LHC for
  $B_{s,d} \to \tau^+\tau^-$: tera-Z is much more sensitive: measure it, if $\geq$ SM level [$\sim 8 \times 10^{-7}$]

- Another important 2-body decay, to be measured by FCC-ee: $B_c \to \tau\bar{\nu}$

- $b \to c\tau\bar{\nu}$ and $s\ell^+\ell^-$ anomalies: in many models, correlated effects in many processes

CP violation in neutral meson mixing: $A_{\rm SL}^{d,s}$

- Only seen in K so far; for $B_{(s)}$, the m_c^2/m_b^2 suppression in the SM may be lifted by BSM

[hep-ph/0202010]

$$A_{\rm SL} = \frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]}$$

- Current status: Data: $A_{\rm SL}^d = -(2.1 \pm 1.7) \times 10^{-3}$ $\quad A_{\rm SL}^s = -(0.6 \pm 2.8) \times 10^{-3}$

  SM: $A_{\rm SL}^d = -(4.7 \pm 0.6) \times 10^{-4}$ $\quad A_{\rm SL}^s = (2.22 \pm 0.27) \times 10^{-5}$ [1603.07770]

  Plenty of room between current sensitivity and the SM predictions

  (Hard to extrapolate whether LHCb becomes systematics limited)

- Unique to Tera-Z: uncertainty $\sim 2.5 \times 10^{-5}$ for both $A_{\rm SL}^d$ and $A_{\rm SL}^s$, reach SM level

Final remarks

It's all connected

CM energy [GeV]	91 (Z)	160 (WW)	240 (HZ)	365 & $t\bar{t}$
Higgs	✓	✓	✓	✓
PEW	✓	✓	✓	✓
Flavor	✓	✓	✓	✓
BSM	✓	✓	✓	✓

- Discovery potential in many channels, in each areas:

  Higgs: precision couplings, discover or bound exotic decays

  PEW: find deviations from BSM or strongly constrain them

  Flavor: “ultimate” B factory, much improved sensitivity in many channels

  Light BSM: dark sectors / photons, feebly interacting particles, HNL, ALPs, etc.

Conclusions

- Very rich physics program

  FCC-ee foundational, complementary to LHC and FCC-hh, necessary for making the most of FCC-hh

- FCC-ee can be a discovery machine

  Much improved sensitivity to: Higgs, PEW, flavor, light particle searches

- Z pole: a leap from LEP, qualitatively new sensitivity

  Probes beyond HL-LHC; deviation from SM would give a target for direct searches later

  In flavor physics, generically, the only way to go well beyond Belle II & LHC(b)

- Interesting challenges to maximize sensitivity, both for experiment and theory

- It's the technology (detector and accelerator) which are the key

  Ample physics reasons to study the largest possible attainable data sets

Thanks ...

For discussions and/or answering my emails:

Mike Chanowitz, David d'Enterria, Heather Gray, Christophe Grojean, Carl Haber, Simon Knapen, Kevin Langhoff, Michelangelo Mangano, Aneesh Manohar, Patrick Meade, Simone Pagan Griso, Michele Papucci, Dean Robinson, Marjorie Shapiro, Benjamin Stefanek, Emily Thompson

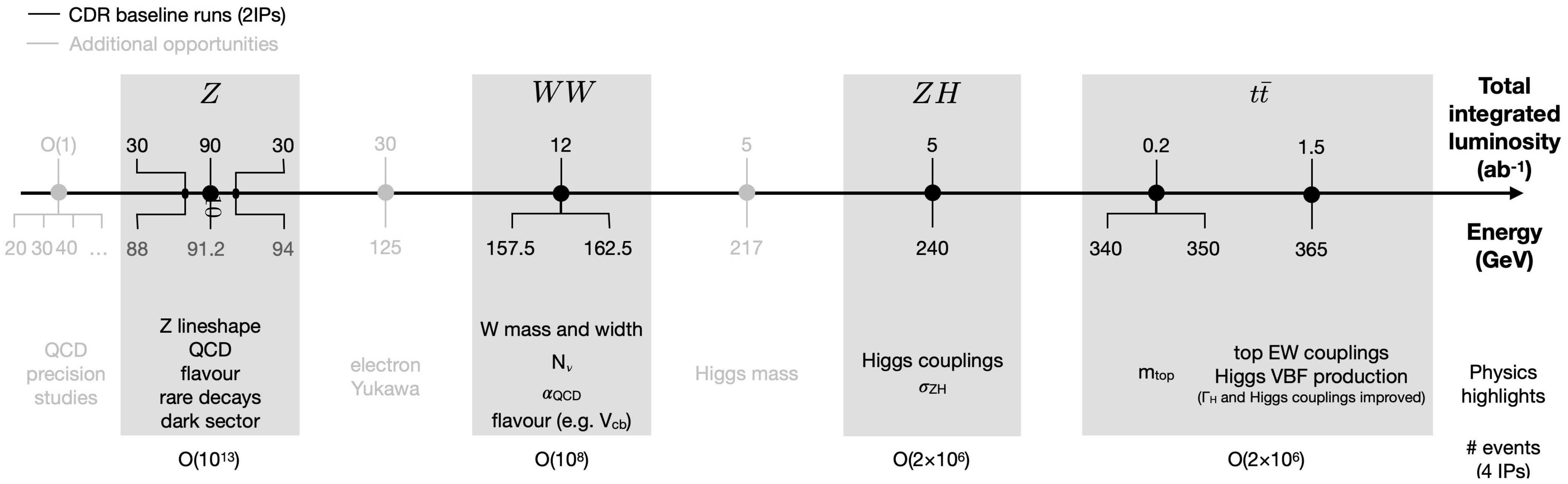
There is exciting physics to be discovered

Just need better resolution

(A diamond field in Namibia)

Extra slides

Run plans and highlights



Flavor physics: many open questions

- Flavor $\equiv$ what distinguishes generations? [break $U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_e$]

  Experimentally, rich and sensitive ways to probe SM, and search for NP

- SM flavor: masses? mixing angles? 3 generations? — most of the SM param's

  Flavor in SM is simple: only Higgs – fermion Yukawa couplings break flavor symm.

- BSM flavor: TeV scale (hierarchy problem) $\ll$ "naive" flavor & CP viol. scale

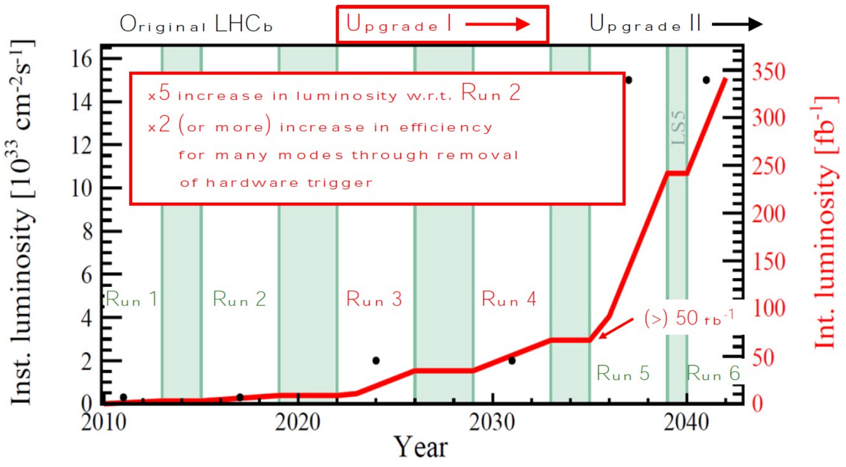
  Any new particle that couples to quarks or leptons $\Rightarrow$ new flavor parameters

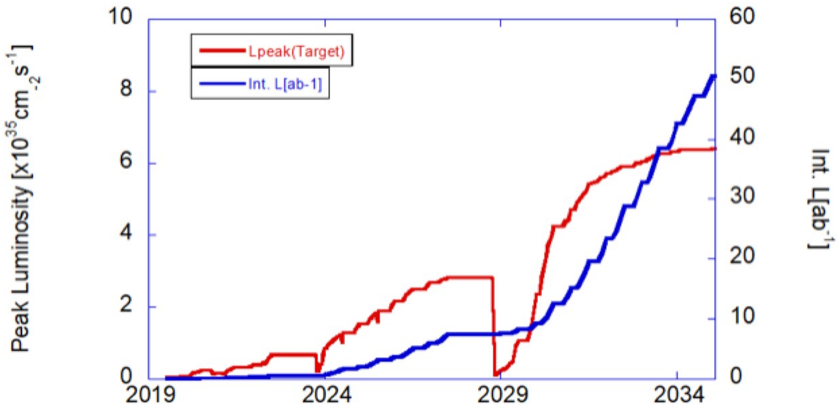
- Baryon asymmetry requires CPV beyond the SM

  (Not necessarily in flavor changing processes, nor necessarily in quark sector)

- If NP is $10 - 100\,\mathrm{TeV}$, flavor especially crucial (less constraints, high reach)

Flavor and future colliders





- LHCb upgrade in LS2 (inst. lumi.: 2×10^{33})
- LHCb Upgrade II in LS4 (inst. lumi.: 1.5×10^{34})

  ATLAS & CMS competitive in some modes

  Extensive sensitivity projections: 1808.08865, 1812.07638

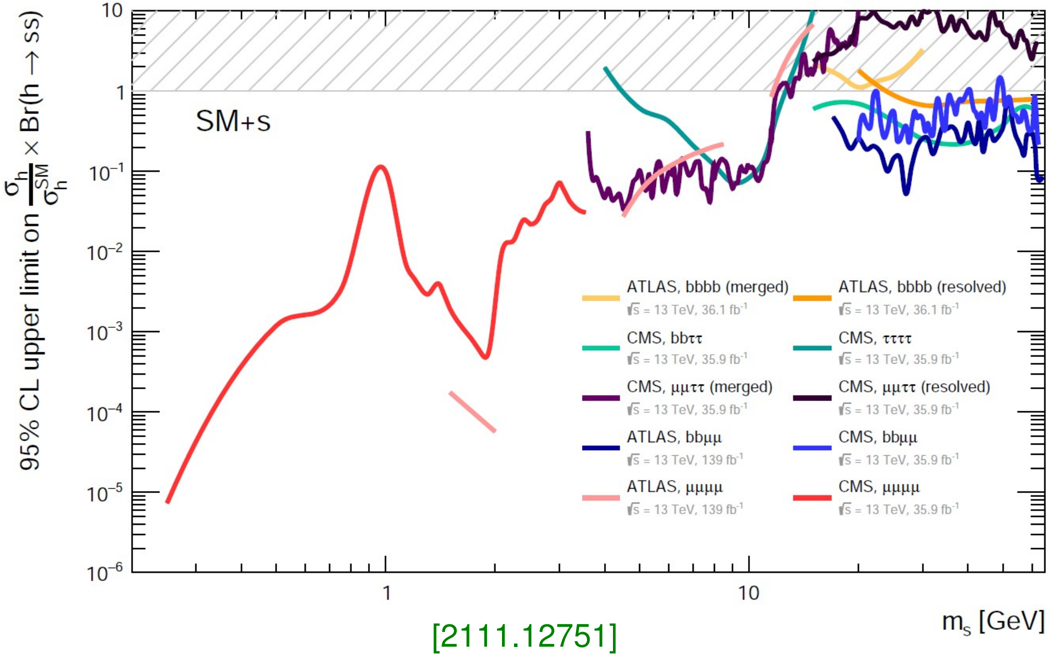
- Goal: over $50 \times$ the Belle data set
- Discussions about physics case and feasibility of an upgrade, aiming 50/ab $\to$ 250/ab (parallel LHCb Upgrade II)

  Extensive sensitivity projections: 1808.10567

- Only Tera-Z would go well beyond current program — clear case if BSM seen in flavor

Higgs is an obvious place to look for NP

$$H \to ss \to f_1\bar{f}_1 f_2\bar{f}_2$$



[2111.12751]

Tidbits of τ physics

- Recent anomalies increased interest in probing lepton flavor universality

  PIONEER will soon improve $\pi \to e\nu$ vs. $\mu\nu$ by factor ~ 15 ($+$ searches for new particles)

- In τ decay, best precision from $\tau \to e\nu\bar{\nu}$ vs. $\mu\nu\bar{\nu}$ — and lifetime (n.b. $e_e \to \mu_\mu \to \tau_\tau$)

  Beyond statistics improvement, many analyses benefit from τ boost

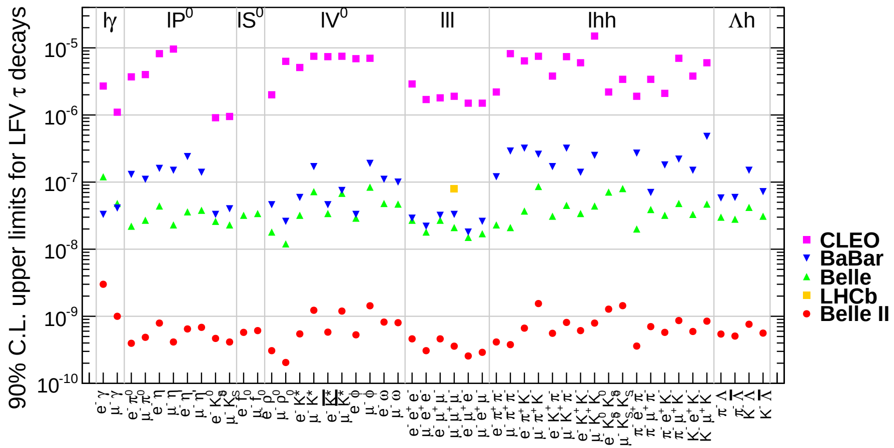
- Large improvements in CLFV τ searches

- Belle II: 2 orders of magnitude; e.g., $\tau \to \mu\gamma, \mu\mu\mu$

  Big model dependence in $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma)$

- FCC would yield further improvement

- Any discovery $\Rightarrow$ broad program to map structure



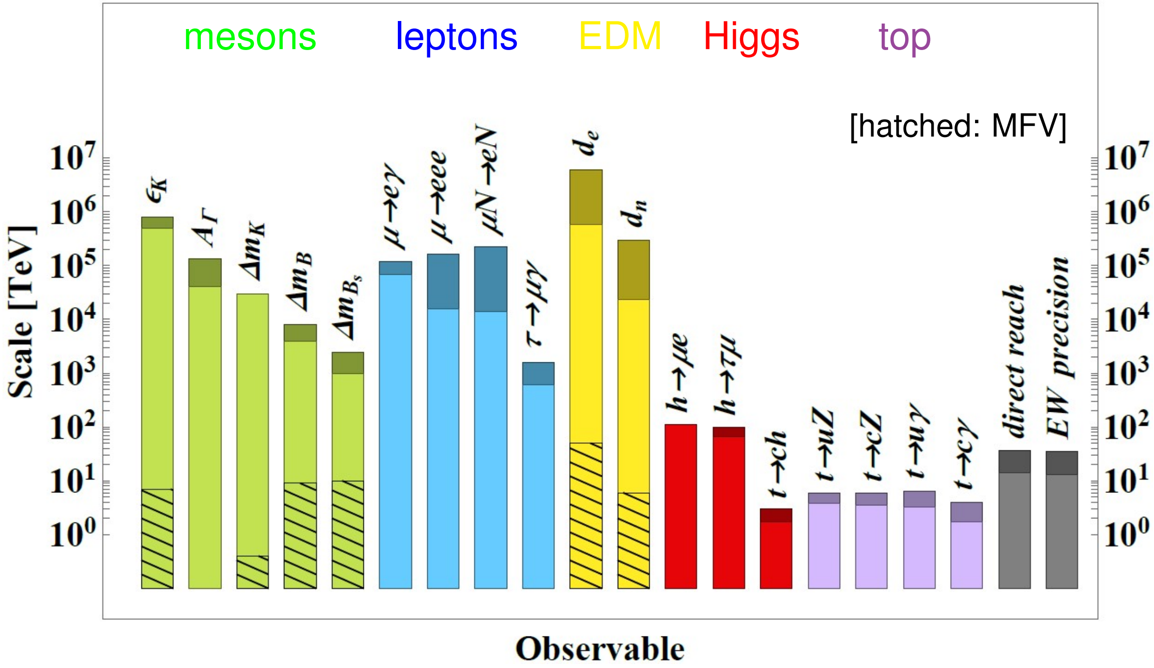
BSM scale sensitivity and structures

- Scales of dim-6 operators probed $\Longrightarrow$

  Various mechanisms devised so that NP obeys these bounds

  (Patterns matter more than precise values; Note special role of meson mixing)

- If NP is within any collider's reach, must possess some structure (MFV?)



[European Strategy Update 2020, arXiv:1910.11775]

- Lack of NP in flavor tells us something; motivates tera-Z, part of comprehensive search

Sensitivity to new physics in B mixing

- $h\, e^{2i\sigma} = A_{\rm NP}(B^0 \to \overline{B}{}^0)/A_{\rm SM}(B^0 \to \overline{B}{}^0)$

  Redo CKM fit w/ 4 BSM param's added

  Relies on many measurements & theory inputs

- Big improvements: Sensitive to TeV scale, even if NP is MFV-like (loop & CKM suppressed)

  Complementary to high-p_T searches

- $|V_{cb}|$ becomes a bottleneck; Tera-Z sensitivity will be better, not lattice QCD extrapolations yet