Future colliders

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University of Chicago

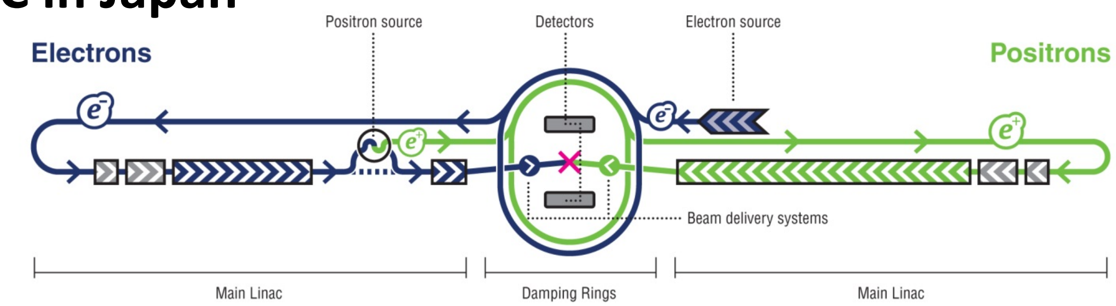
BOOST 2019, July 22 MIT

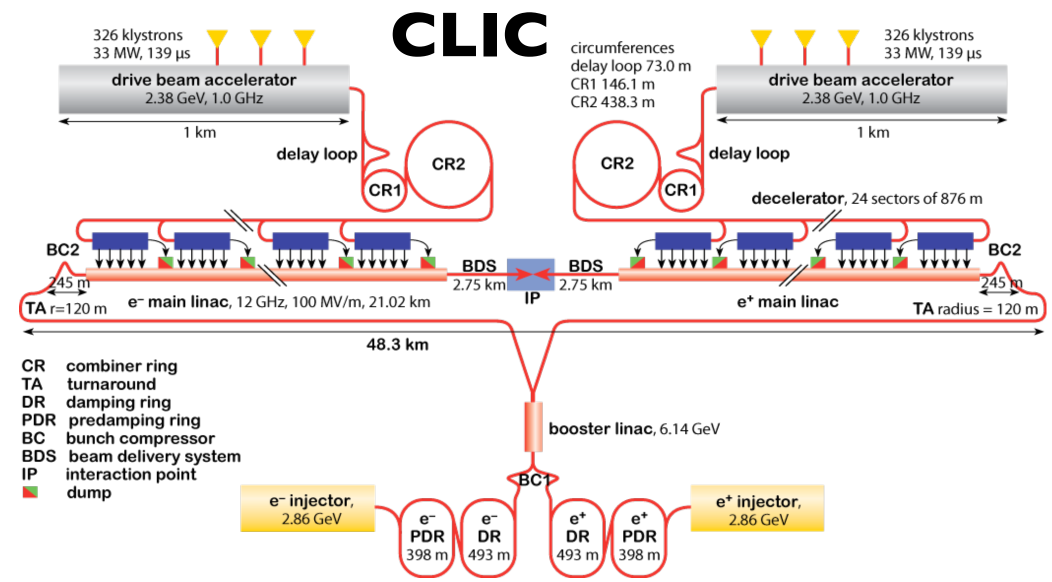
My talk

- Summary of the status of future collider proposals.
- Brief overview of the physics potential.

Future Colliders

ILC in Japan



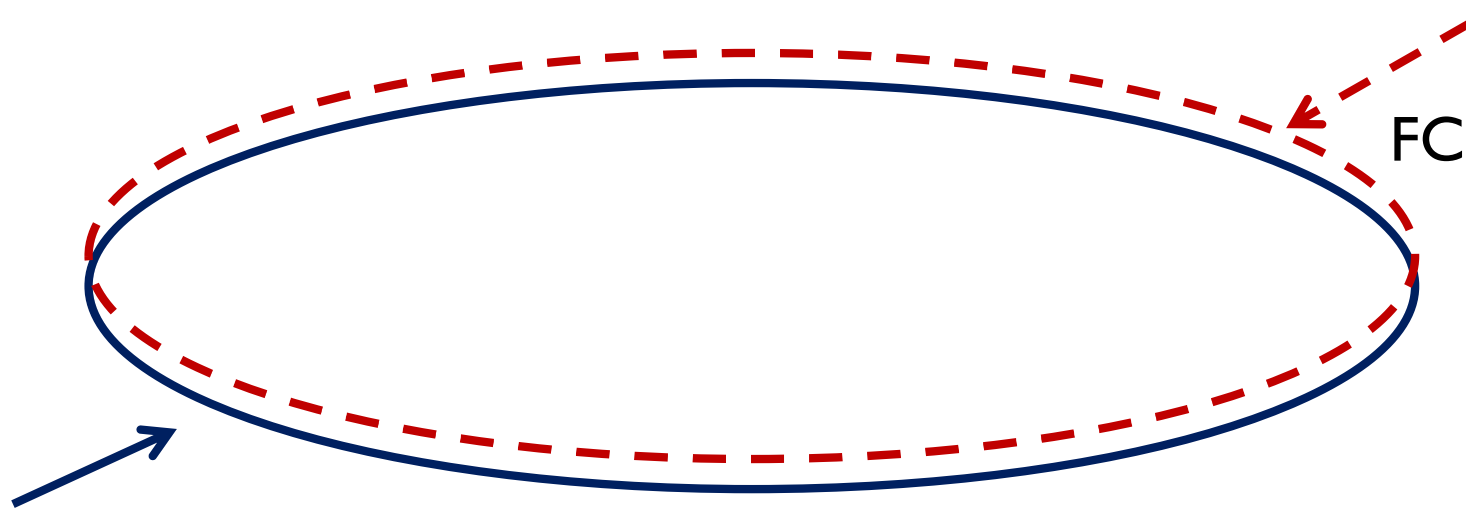


Circular. "Scale up" LEP+LHC

~100 TeV

pp collider

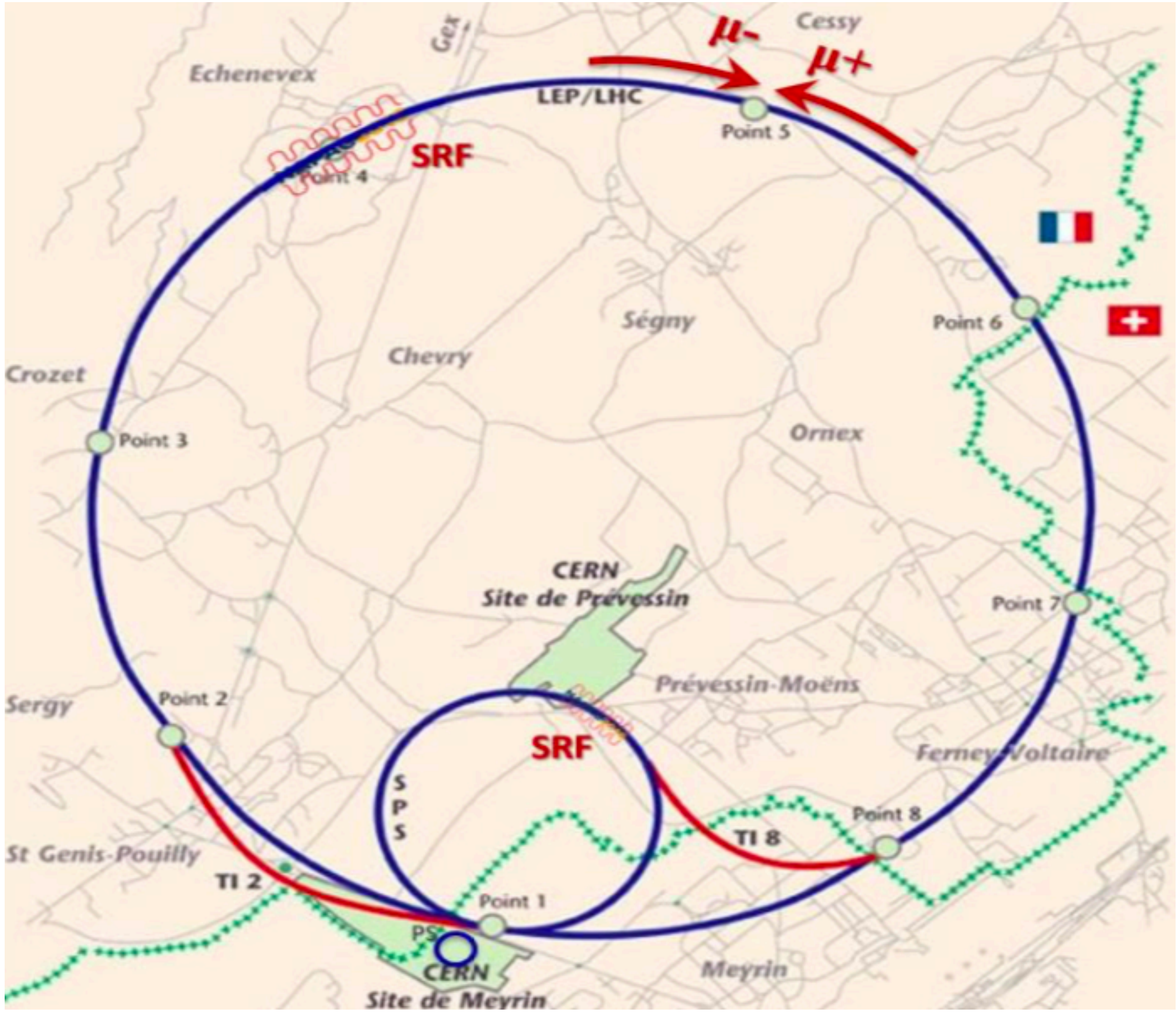
FCC-hh (CERN), SppC(China)

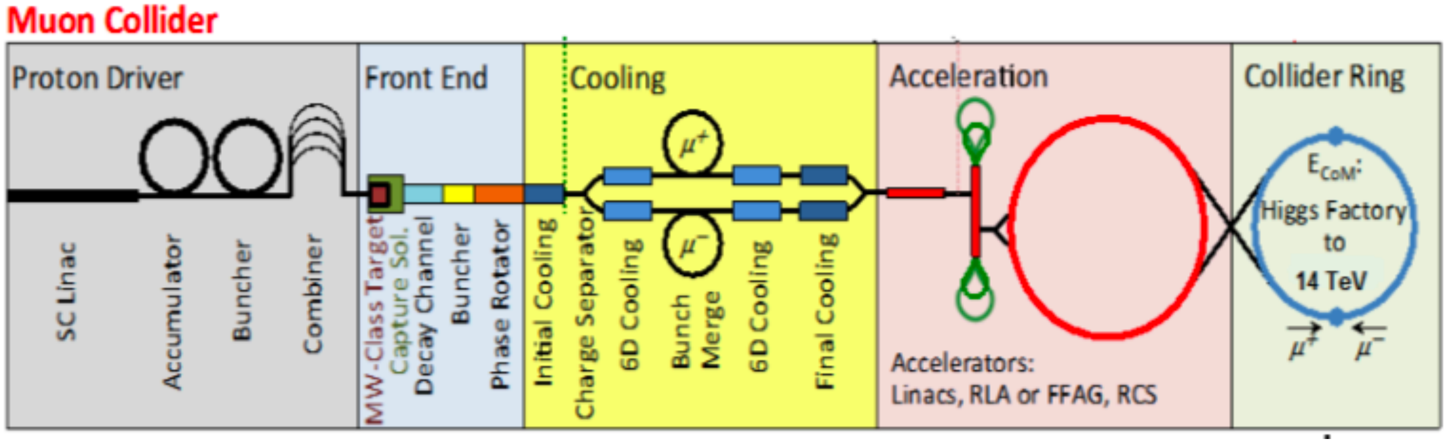


250 GeV **e^-e^+ Higgs Factory**

FCC-ee (CERN), CEPC(China)

muon collider





more exciting

From: "Peskin, Michael E." <mpeskin@slac.stanford.edu>
Subject: lepton collider physics at 10- 50 TeV

Dear Colleague,

I am starting a new community study in particle theory. I hope you will be interested in it, and it would be great if you would participate. There is a serious purpose, but, for the moment, it is an excuse to have fun

• • •

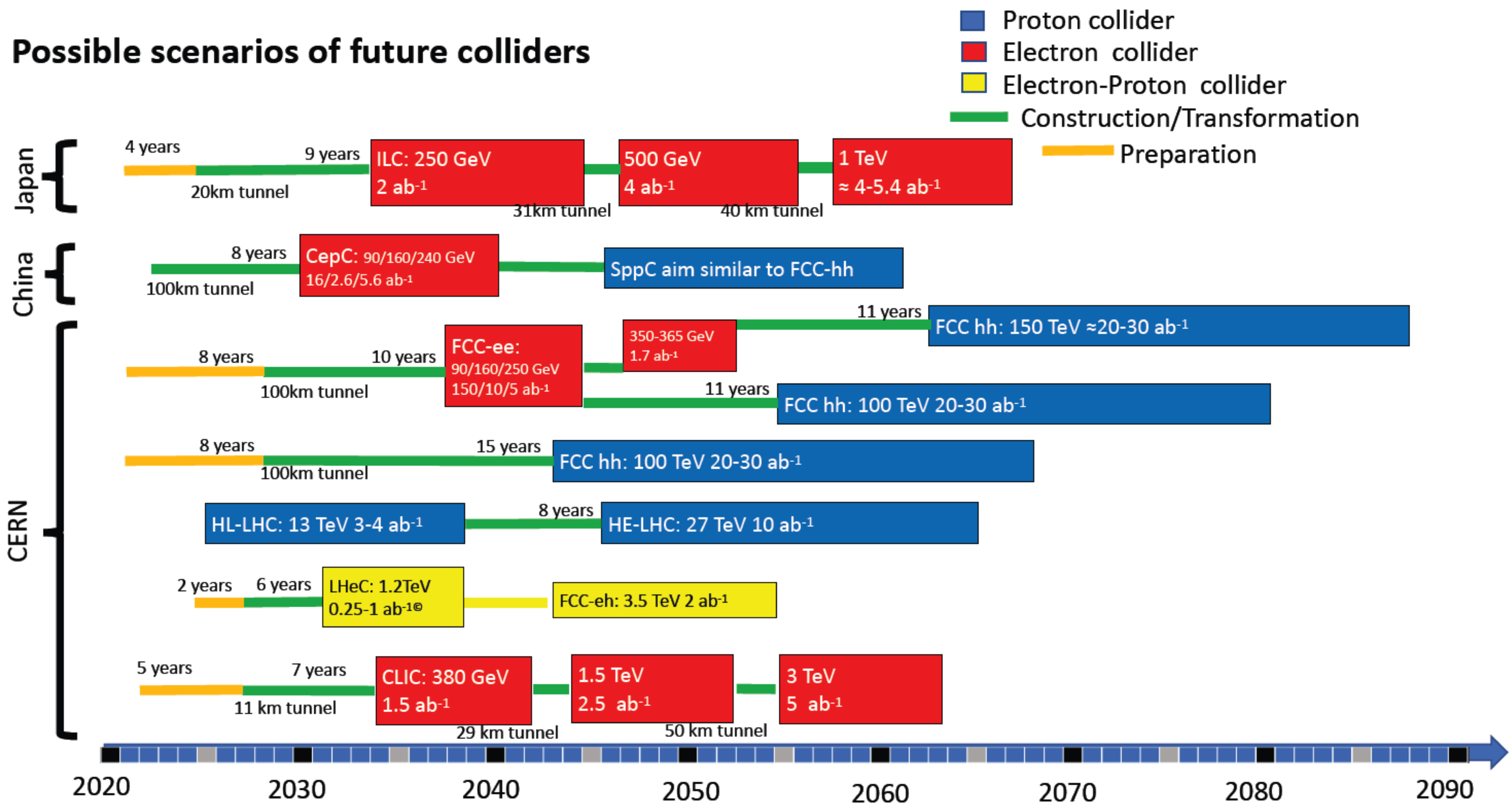
5 GeV/m is SLAC in 10m. In a 10 km accelerator, such as one might envision for a new global facility in the 2040's, it would give a 50 TeV beam energy.

I think it is important that the development of these technologies should be pushed by theorists. To motivate this program, we need to answer the question: What would we learn from an electron accelerator of energy 10 - 50 TeV? This question is also relevant for thinking about future muon colliders and hadron colliders. We have studied the TeV range of energies for a long time, but future facilities might vault us into the tens of TeV. What then?

• • •

My focus here

- More "near future".
- Circular: FCC-ee/FCC-hh, CEPC/SppC
- Linear: ILC, CLIC



Future = 0, 1, 2... colliders?

Main goal to keep in mind: at least 1

FCC-ee: ambitious program

FCC-ee:

FCC-ee possible operation model

working point	luminosity/IP $[10^{34}\ cm^{-2}s^{-1}]$	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
Z later	200	52 ab^{-1}/year		
W	32	8.3 ab^{-1}/year	**10 ab^{-1}**	**1**
H	7.0	1.8 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: **1 year**				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.5	0.38 ab^{-1}/year	**1.5 ab^{-1}**	**4**

$$\sim 10^6 \text{ Higgses}, \ \sim 10^{13} \text{ Zs}, \ldots$$

13 yr run plan: Higgs=3 yr, Z=4 yr, top=5 yr, W=1 yr

Hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

Goal: 20-30 ab^{-1} during the collider lifetime

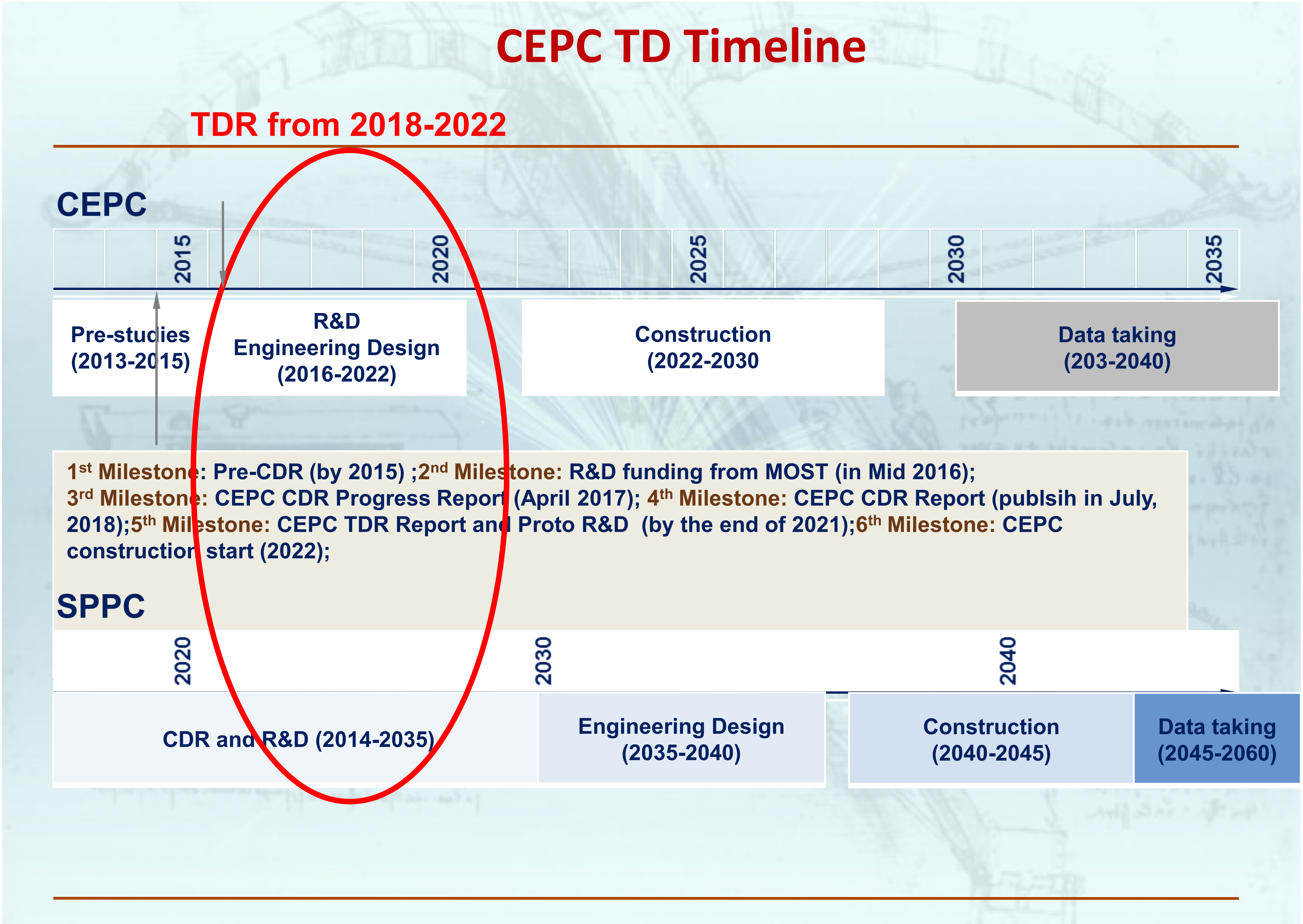
A new possibility

ESG request for parameters of a lower-energy hadron collider

parameter	FCC-hh		FCC-hh-6T	HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		37.5	27	14	14
dipole field [T]	16		6	16	8.33	8.33
beam current [A]	0.5		0.6	1.1	1.1	0.58
synchr. rad. power/ring [kW]	2400		57	101	7.3	3.6
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	10 (lev.)	16	5 (lev.)	1
events/bunch crossing	170	1000	~300	460	132	27
stored energy/beam [GJ]	8.4		3.75	1.4	0.7	0.36

- **NbTi technology from LHC, magnet with single-layer coil providing 6 T at 1.9 K:**
  - → Corresponding beam energy 18.75 TeV or 37.5 TeV c.m.
  - → Significant reduction of synchrotron radiation wrt FCC-hh (factor 50) and corresponding cryogenic system requirements.
- **Luminosity goal 10 ab^{-1} over 20 years or 0.5 ab^{-1} annual luminosity:**
  - → Beam current 0.6 A or 20% higher than for FCC-hh, 1.2E11 ppb (FCC-hh: 1.0 ppb).
  - → Stored beam energy 3.75 GJ vs 8.4 GJ for FCC-hh.
- **Analysis of physics potential, technology requirements and cost ongoing.**

M. Benedikt and F. Zimmermann, FCC week



Design effort focusing on CEPC

CEPC Operation Plan

Particle type	Energy (c.m.) (GeV)	Luminosity per IP (10^{34} $cm^{-2}s^{-1}$)	Luminosity per year (ab^{-1}, 2 IPs)	Years	Total luminosity (ab^{-1}, 2 IPs)	Total number of particles
H	240	3	0.8	**7**	5.6	1×10^{6}
Z	91	32	8	**2**	16	7×10^{11}
W	160	10	2.6	**1**	2.6	8×10^{6}

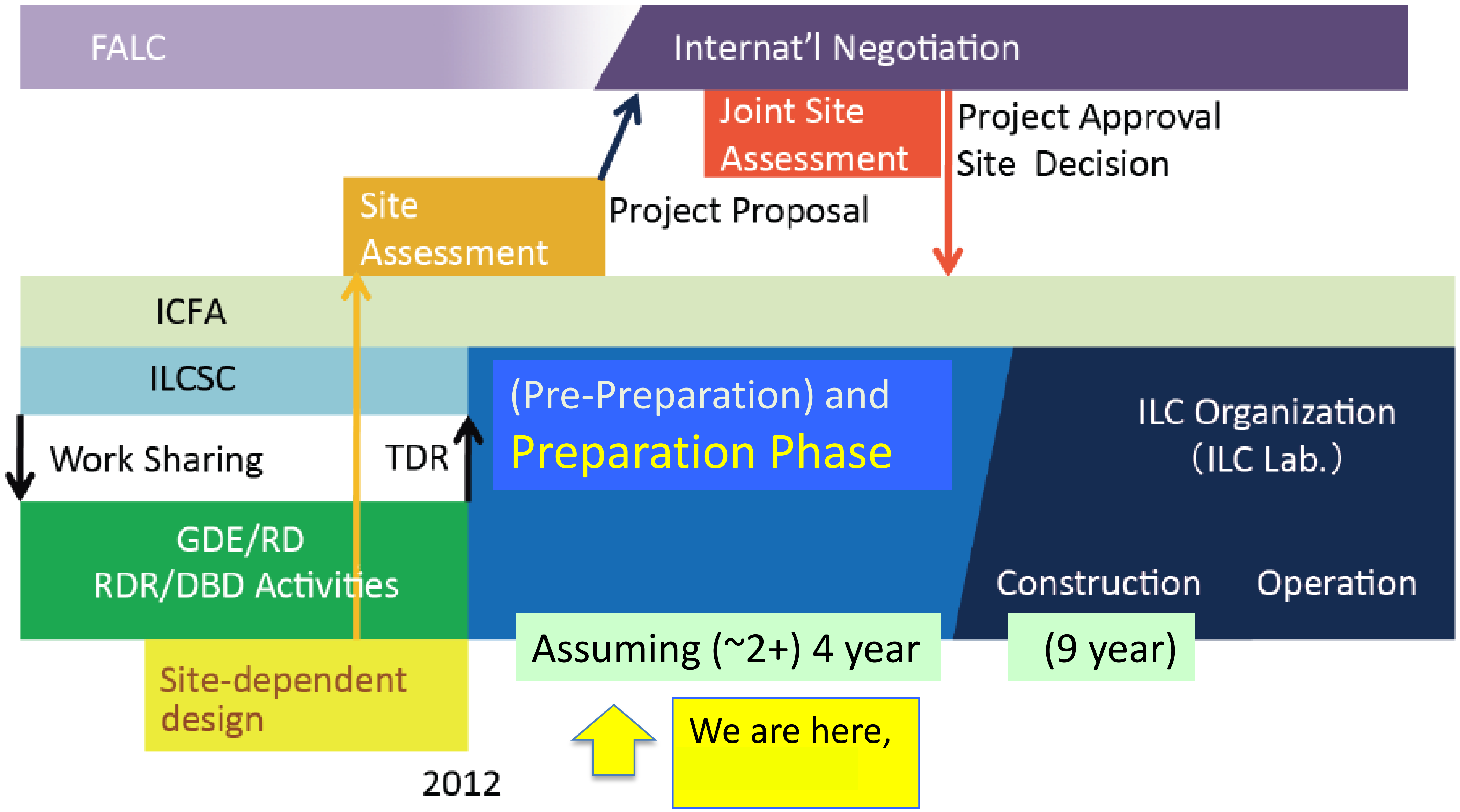
CEPC yearly run time assumption:

- Operation – 8 months, or 250 days, or 6,000 hrs
- Physics (60%) – 5 months, or 150 days, or **3,600 hrs**, or 1.3 Snowmass Unit.

CEPC

staging scheme	physics focus
7 year at Higgs **~1M events** 240 GeV (initial stage)	H indir. BSM
2 years at Z **upto 10^{12} events** 1 year at WW **~20M events**	Z, W EW Physics

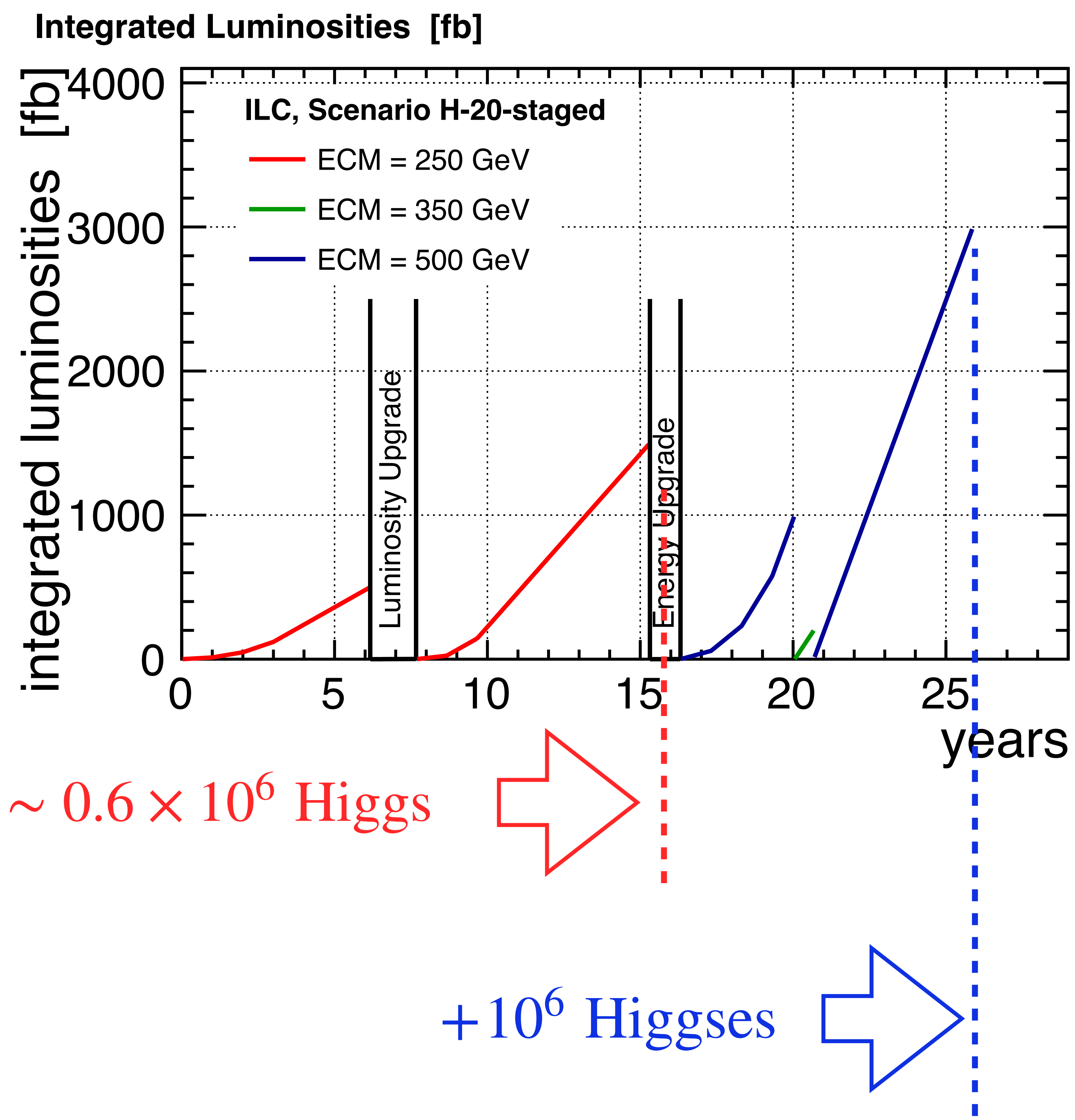
ILC Time Line: Progress and Prospect



Shin Michizono, HK IAS conference 2018 and 2019

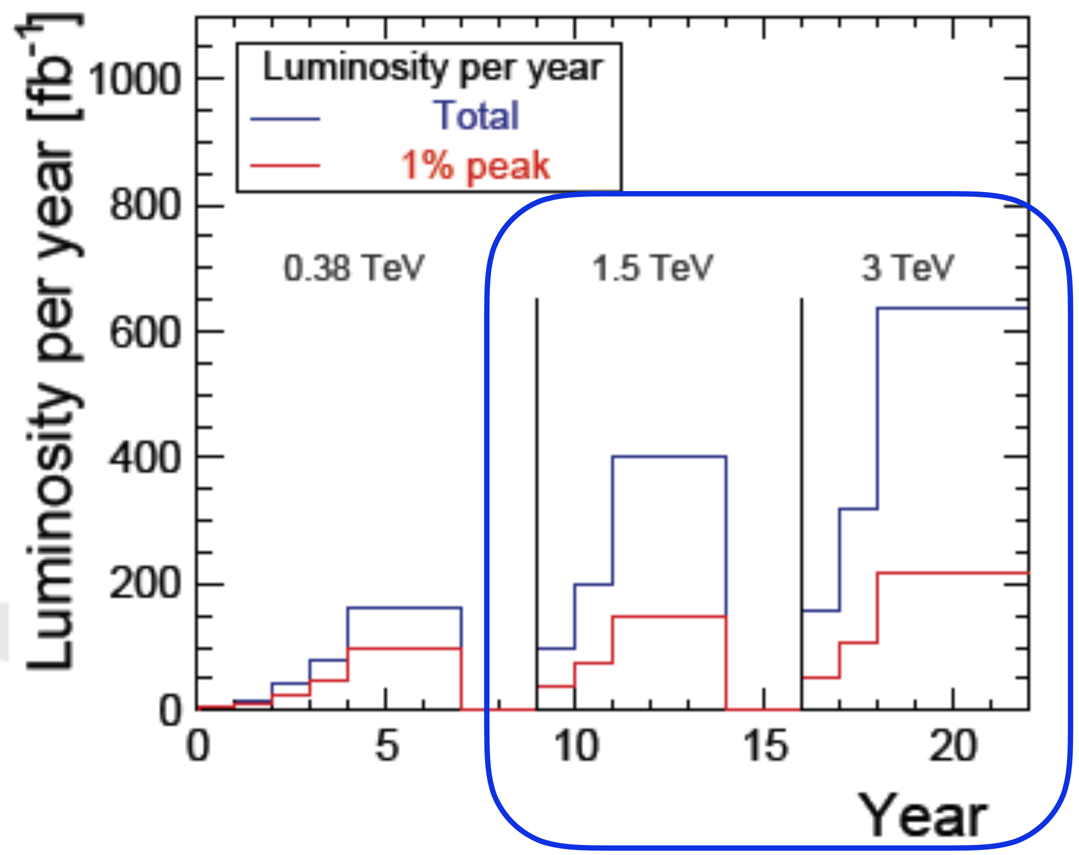
Next key step: European strategy 2020, and some further decision from Japan

ILC run plan



No Z-pole or WW run planned

CLIC



Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

$\sim 2 \times 10^5$ Higgs

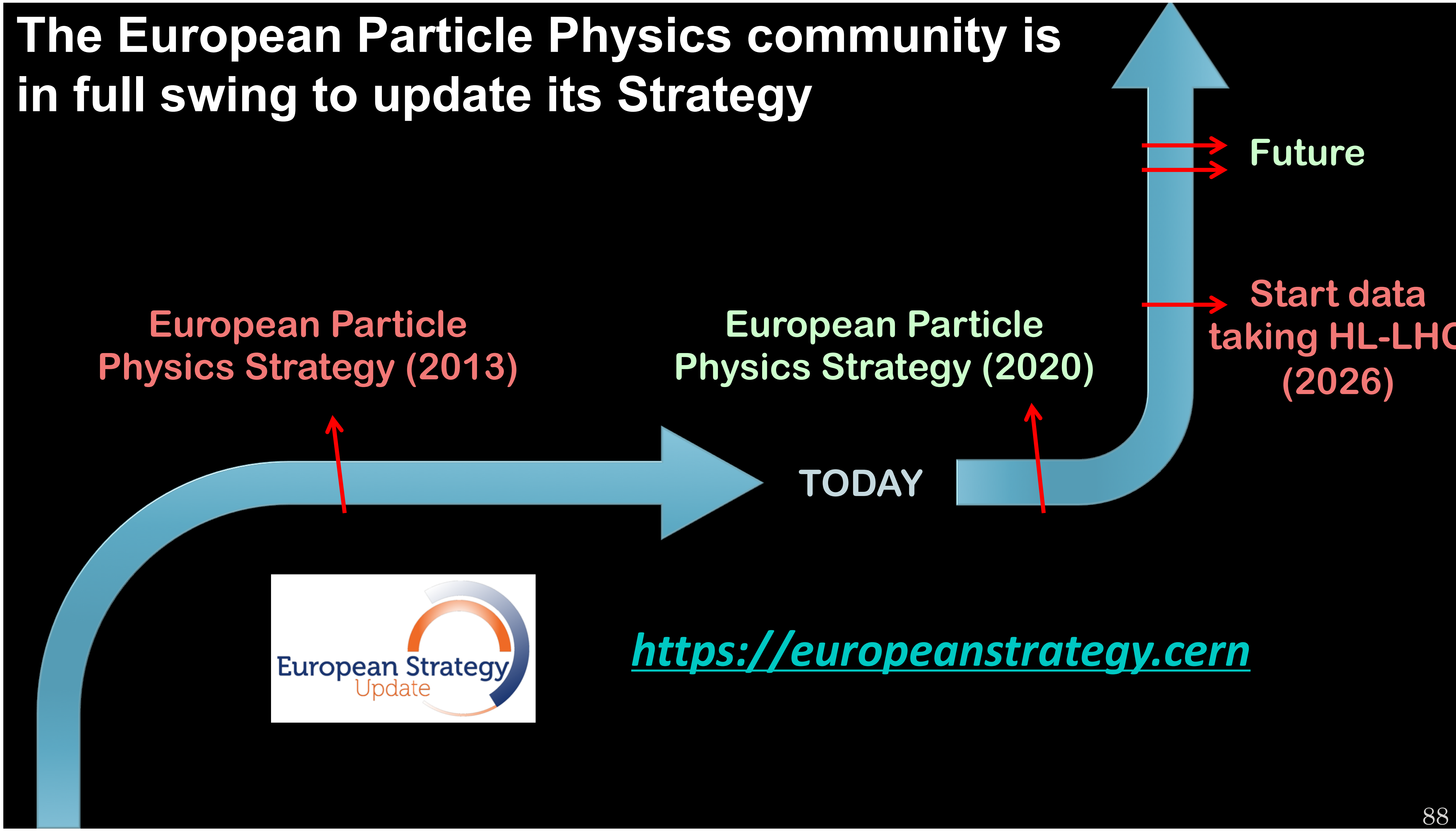
higher energies!

Based on national inputs.

Open symposium on European strategy update. Bethke

summary:

- clear preference for an e^+e^- collider as the next h.e. collider:
  - as H-factory and for precision e.w. measurements (ILC, CEPC, FCC-ee, CLIC)
  - significant demands for upgradeability to access $t\bar{t}$ (ILC, CEPC, FCC-ee, CLIC) and also HH and ttH final states (ILC+; CLIC)
- second priority: R&D for future h.e. collider: h.f. s.c. magnets for hadron colliders, and also novel accelerator techniques (PWA, μ-collider)
- third priority: future hadron collider beyond LHC (FCC-hh; fewer demands for he-LHC and eh-collider)
- large diversity of other, "smaller" projects (PBC, neutrino, DM searches, precision/intensity frontier, astro-particle, …



Jorgen D'Hondt, FCC week

Physics potential

Physics potential for future collider

- Basic physics studies have been finished
  - ILC physics case well studied.
  - CDR for CEPC and FCC published recently.
  - A clear picture has emerged. The basis for the strategic decisions.
- More detailed studies needed/on-going
  - Potential of flavor physics at Z-factory
  - QCD measurements
  - ...
  - Goal: further inputs for detector and machine design

Assumption:

- LHC will not make discovery of new physics.
  - Otherwise, great!!!.
  - We need to completely re-think.

Probing NP with precision measurements

- Lepton colliders: ILC, FCC-ee, CEPC, CLIC

  clean environment, good for precision.

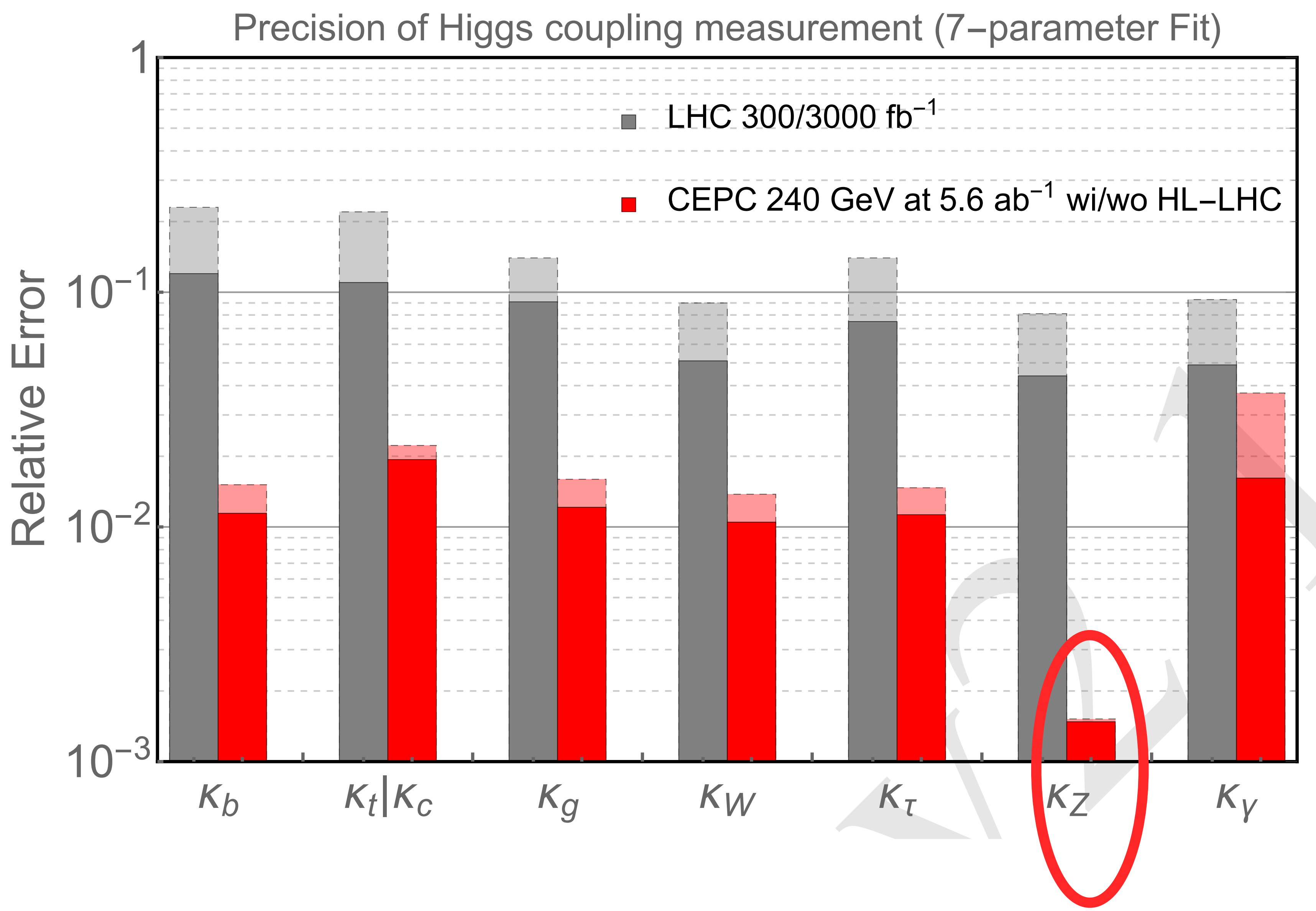
- We are going after deviations of the form

$$\delta \simeq c\frac{v^2}{M_{\rm NP}^2}$$

M_{NP} : mass of new physics
c: $O(1)$ coefficient

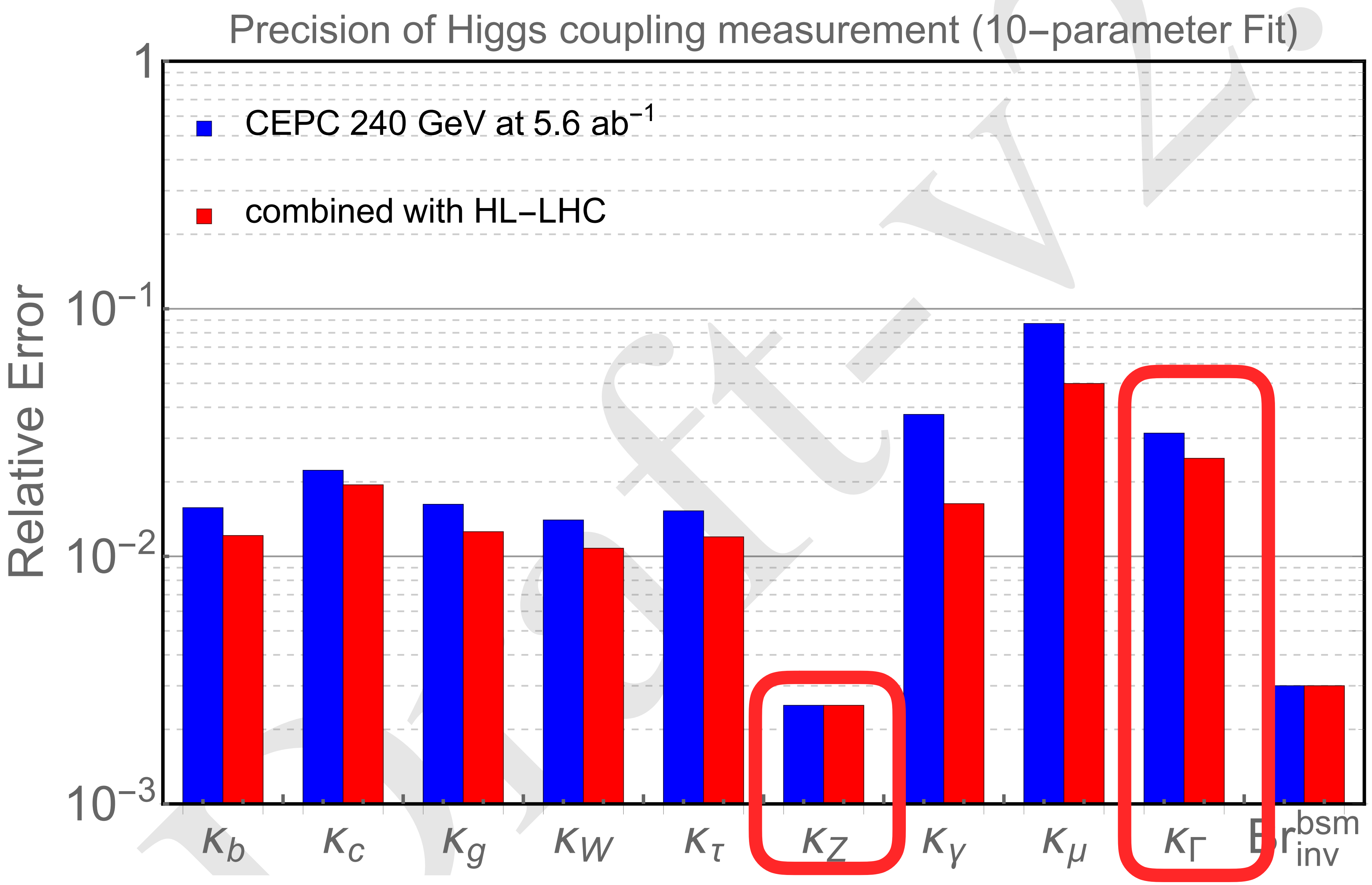
- Take for example the Higgs coupling.
  - LHC precision: 5-10% $\Rightarrow$ sensitive to M_{NP} < TeV
  - However, M_{NP} < TeV largely excluded by direct NP searches at the LHC.
  - To go beyond the LHC, need 1% or less precision.

Higgs coupling measurements at the CEPC



Up to sub percent precision, reach to new physics at multi-TeV scale. Far beyond the reach of LHC.

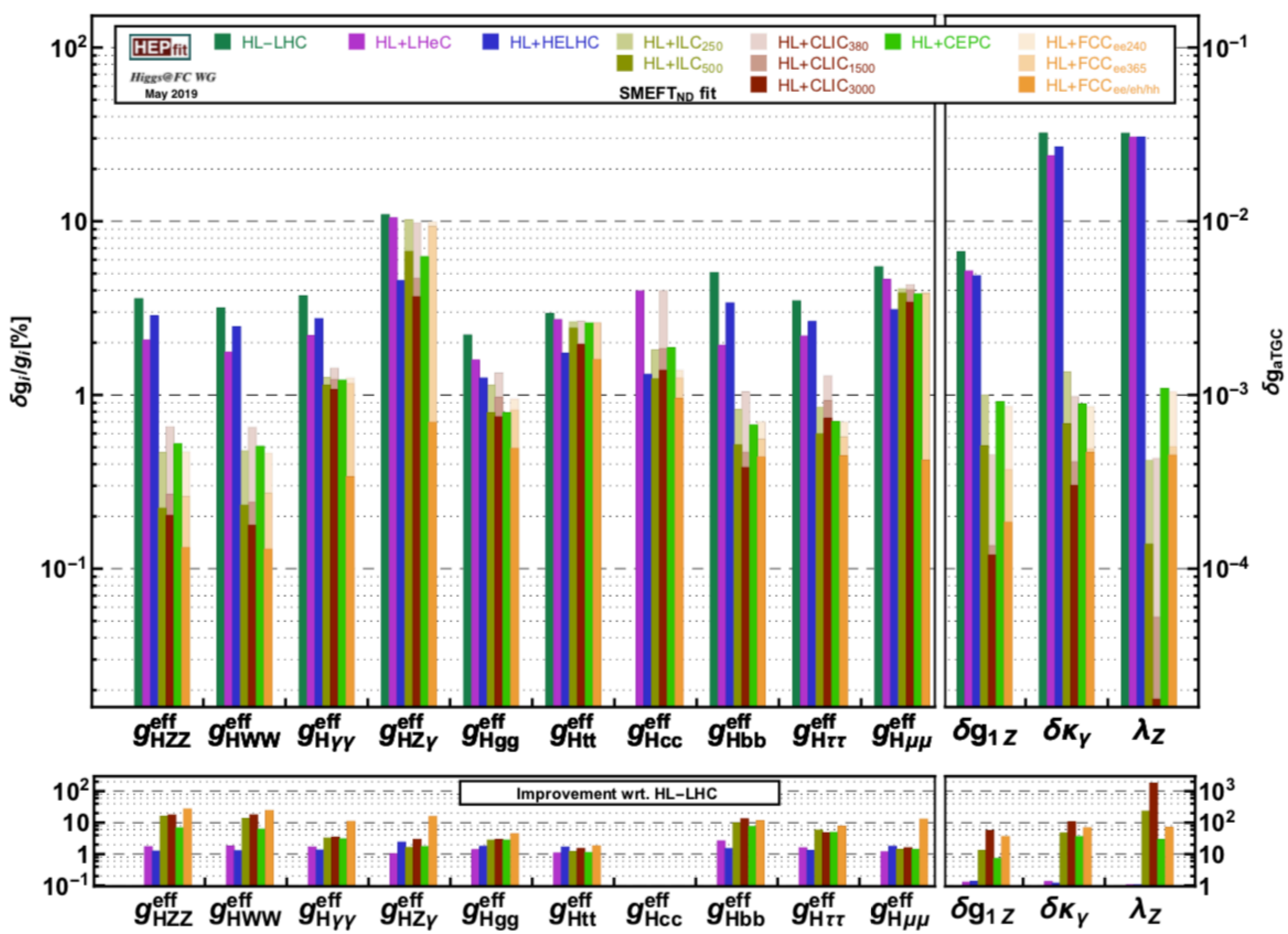
Measurements at Higgs factories



Allows model independent determination of Higgs width and Higgs-Z coupling

Beyond basic Higgs factory

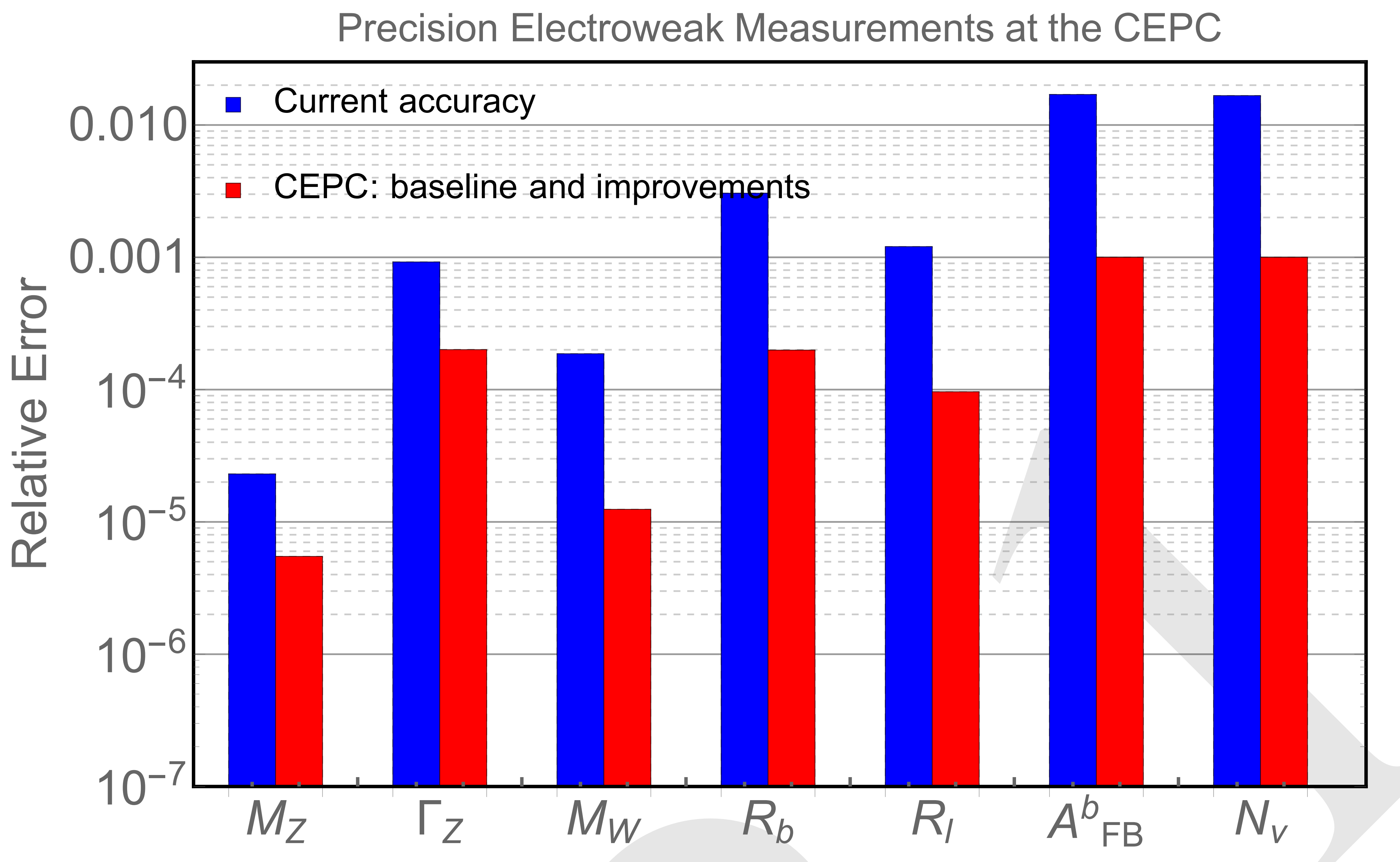
- Higher energies can help.
- Additional handle such as polarization helps with distinguish different new physics effects.



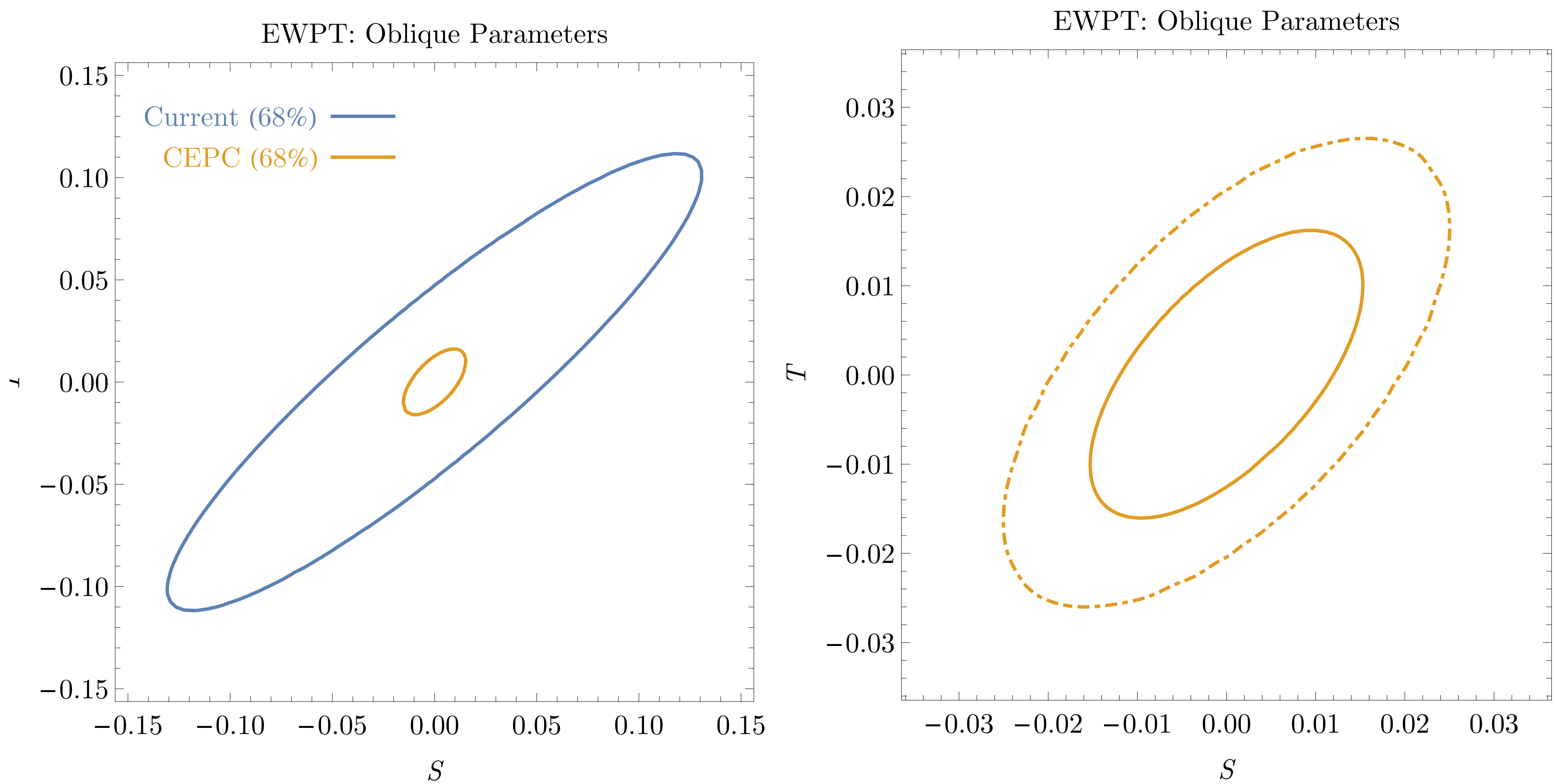
Why is Higgs measurement crucial?

- EWSB is one of the most pressing questions
  - How should we predict the Higgs mass?
- We may not have the right idea. No confirmation of any of the proposed models.
- Need experiment!
- Fortunately, with Higgs, we know where to look.
- And, the clue to any possible way to address naturalness problem must show up in Higgs coupling measurement.

A big advance in electroweak precision

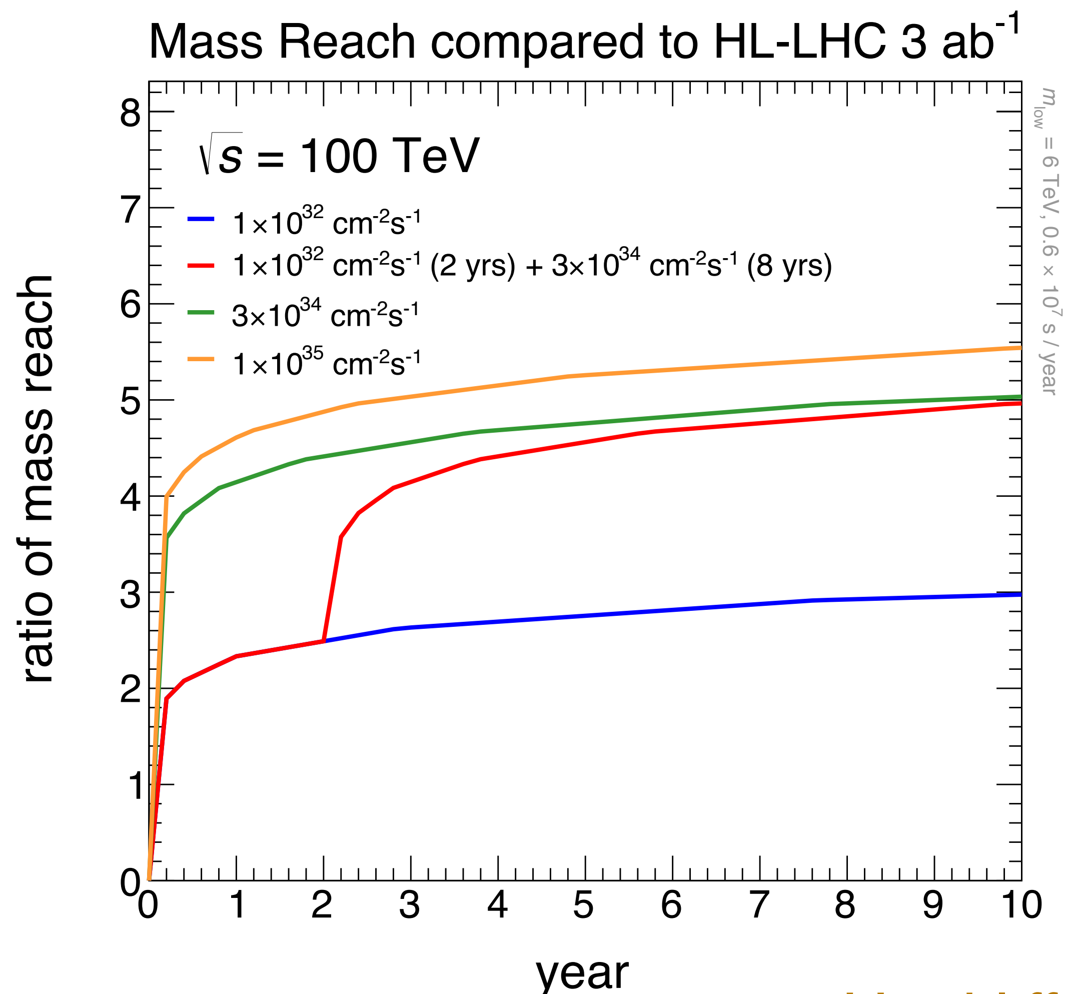


Big step in Electroweak precision



FCC can do even better (by a factor of a few)

100-ish TeV pp collider



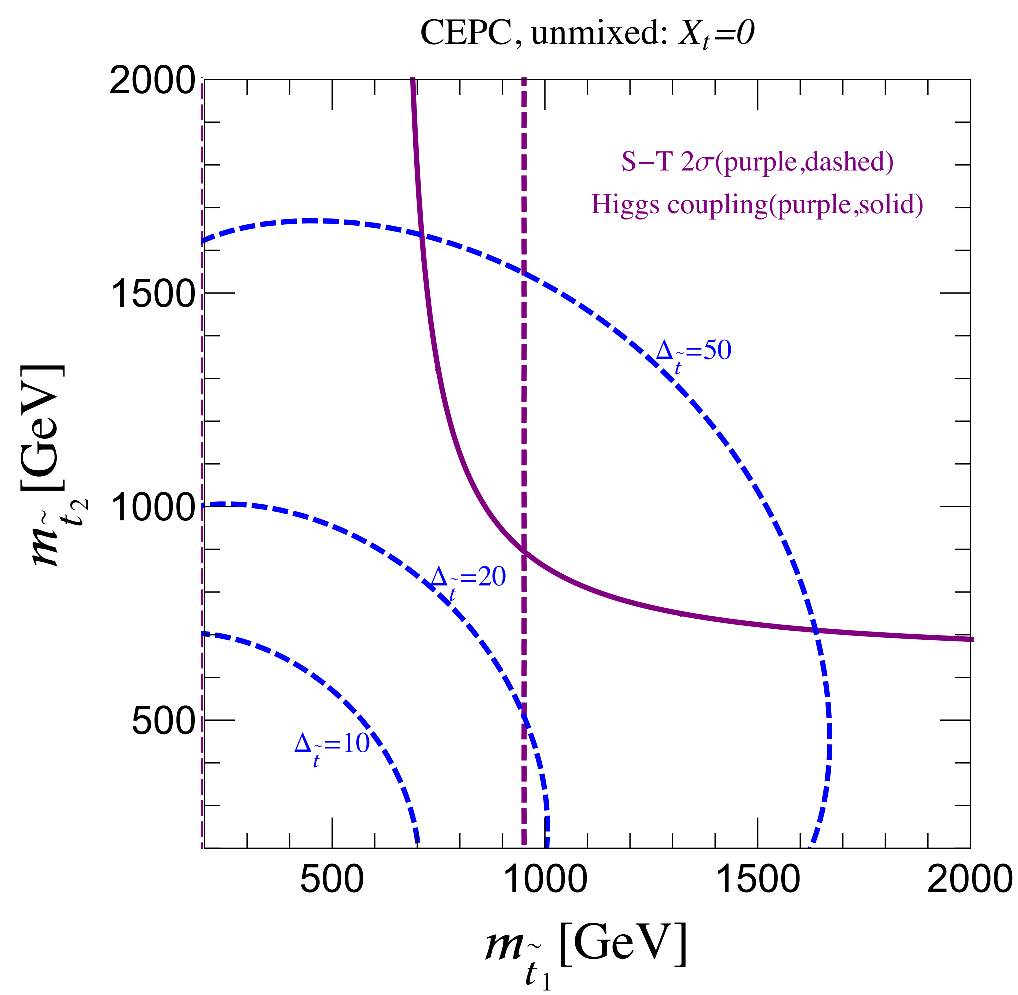
Hinchliffe, Kotwal, Mangano, Quigg, LTW

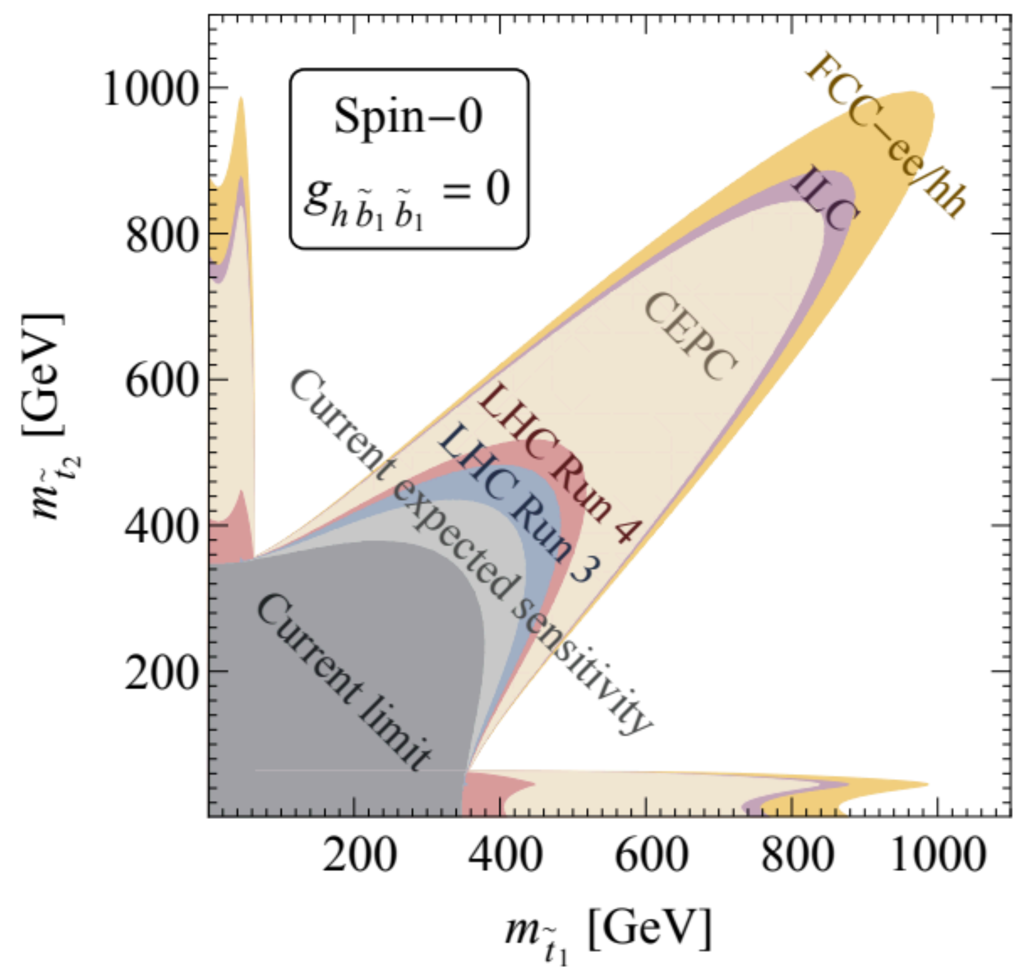
A factor of at least 5 increase in reach beyond the LHC, with modest luminosity

Some examples

Naturalness in SUSY

- LHC searches model dependent, many blind spots.

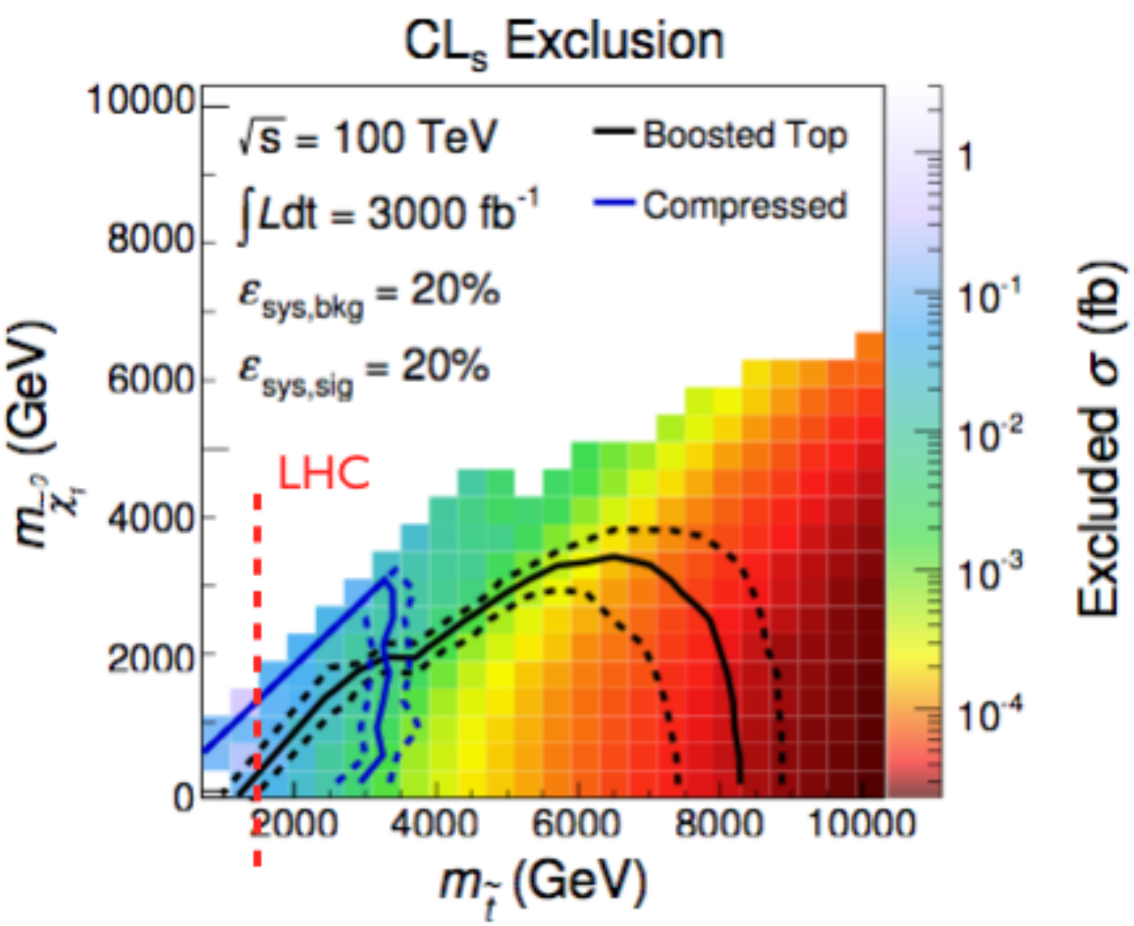




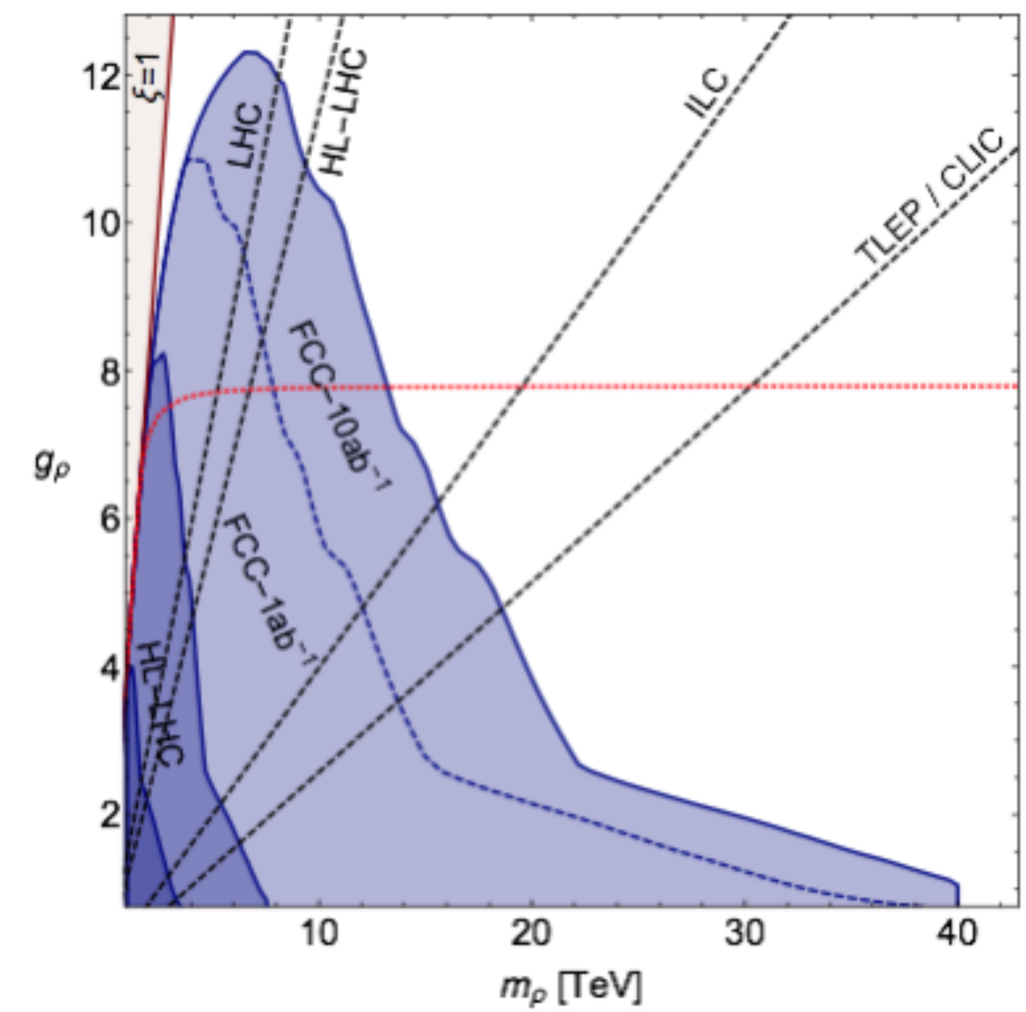
- Testing fine-tuning down to percent level.

Testing naturalness at 100 TeV pp collider

Cohen et. al., 2014



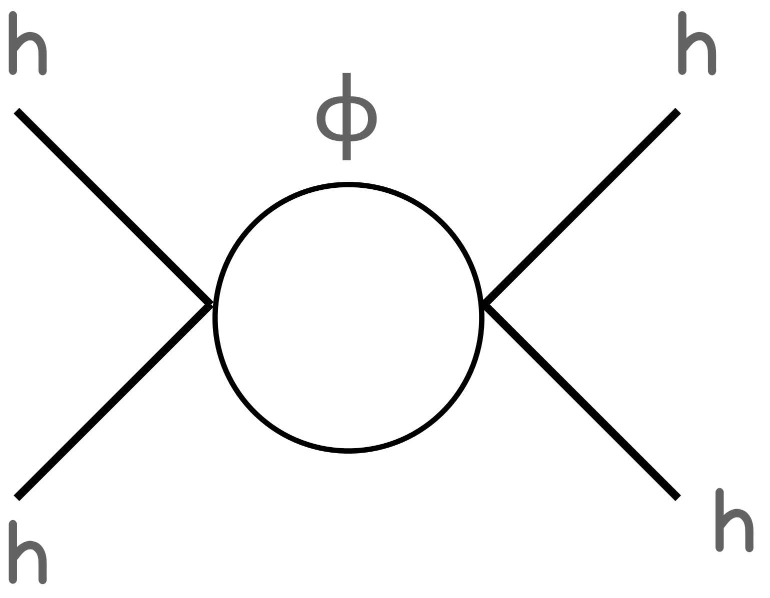
Pappadopulo, Thamm, Torre, Wulzer, 2014

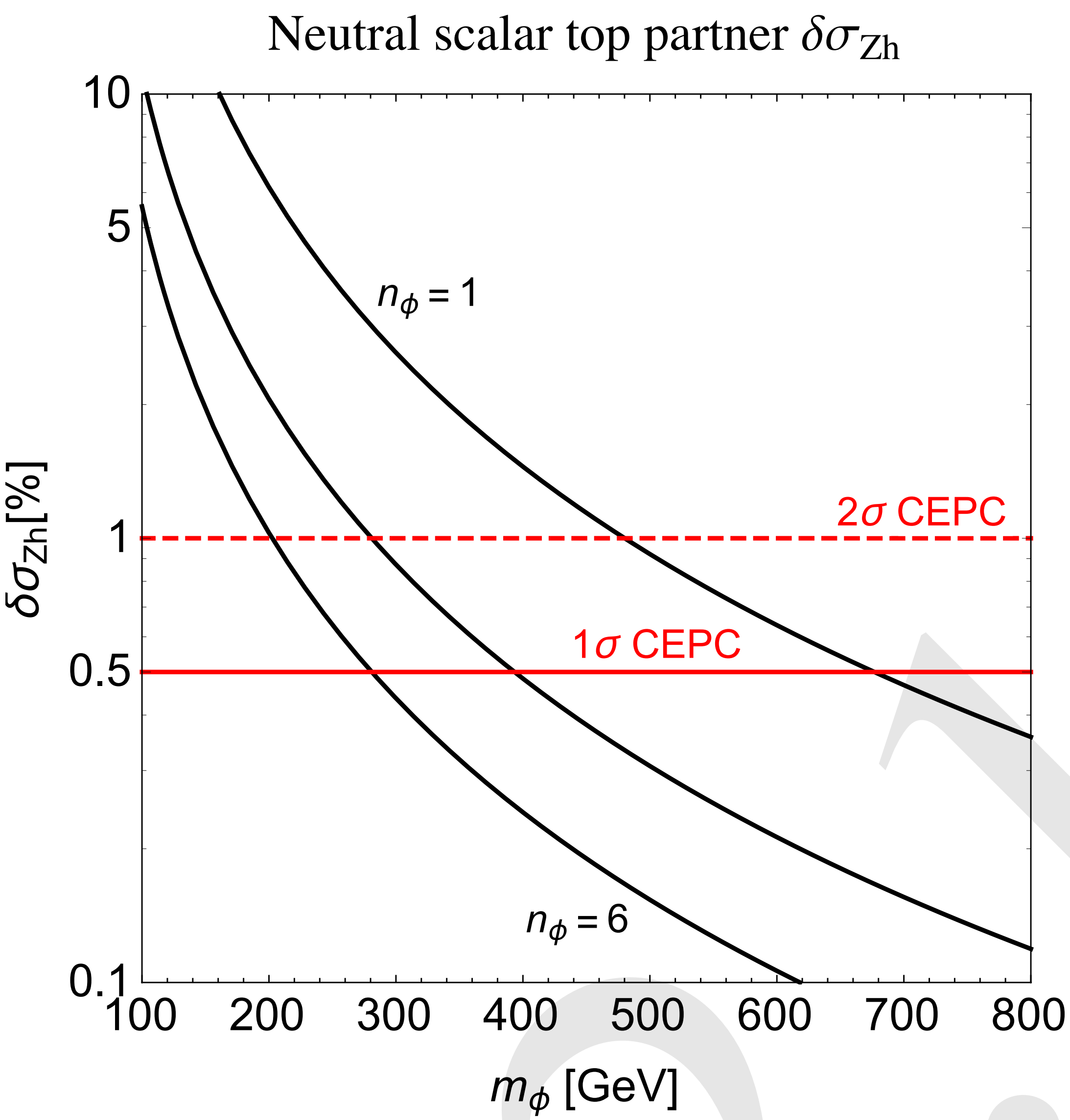


Fine tuning $\propto M_{\mathrm{NP}}^2$

Go much beyond the LHC.

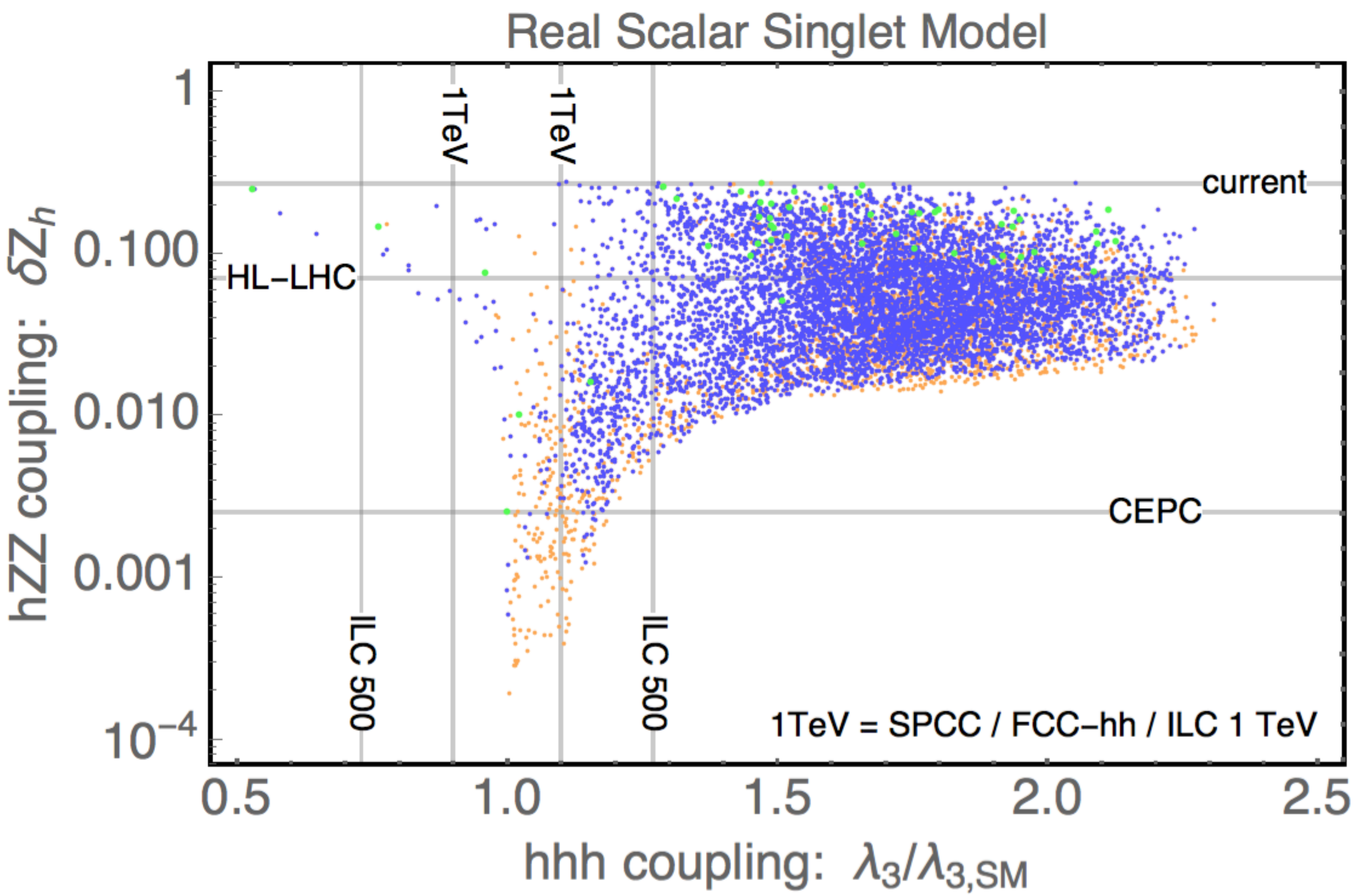
Neutral naturalness.





Top partner not colored. Probed through loop correction to h-Z coupling.

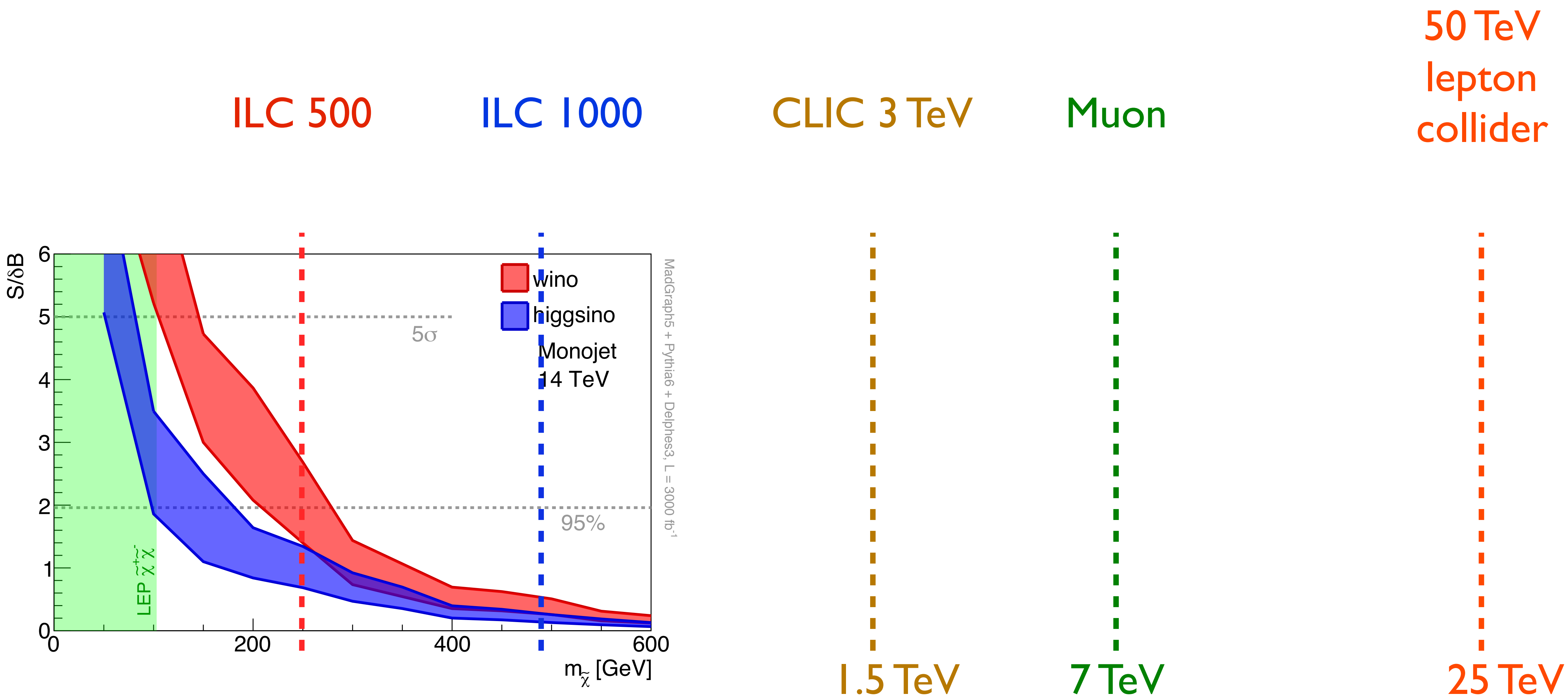
Probing EW phase transition



Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

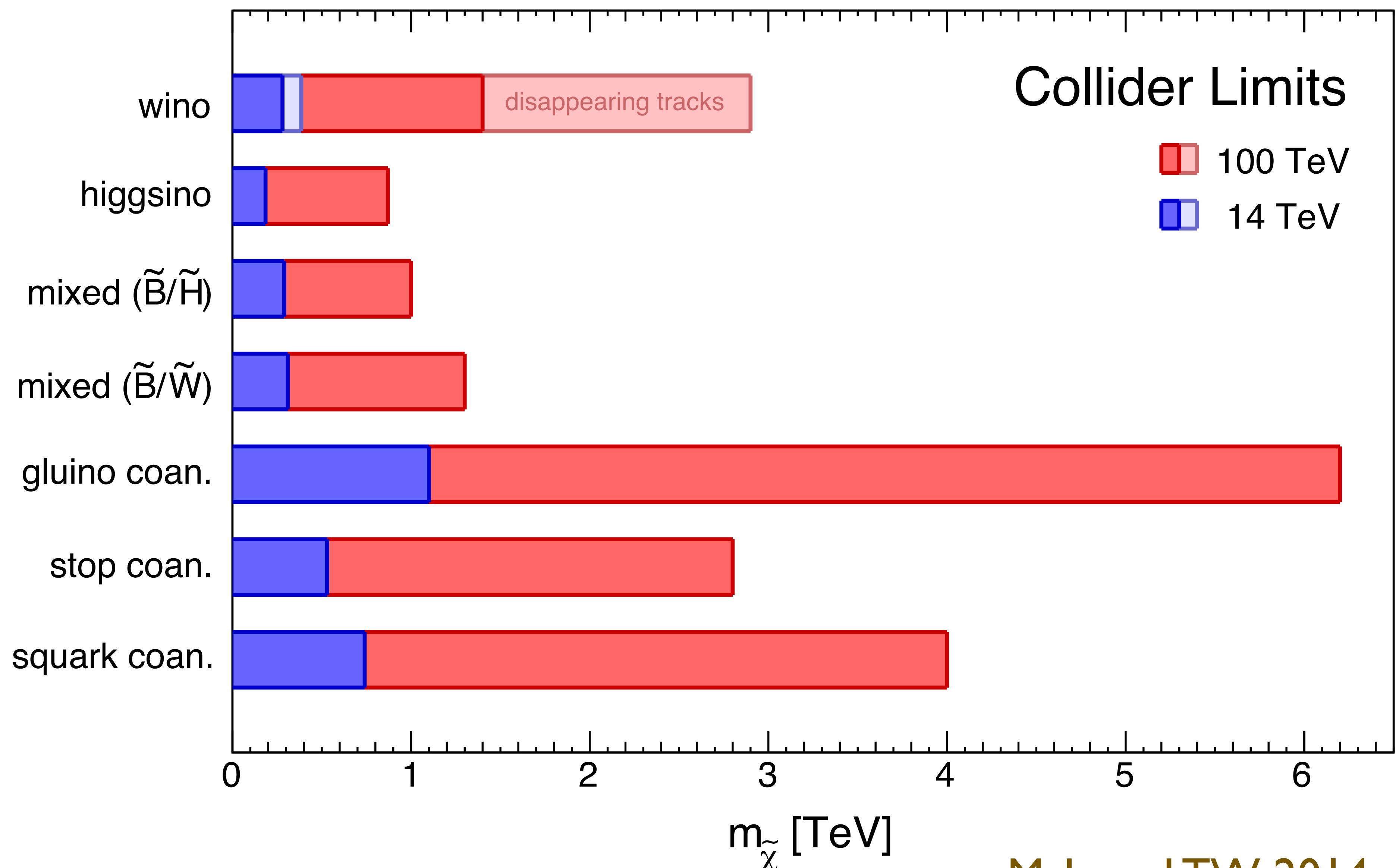
Huang, Long, LTW, 1608.06619

Mono-X



- Reach at lepton collider, about 1/2 E_{CM}.

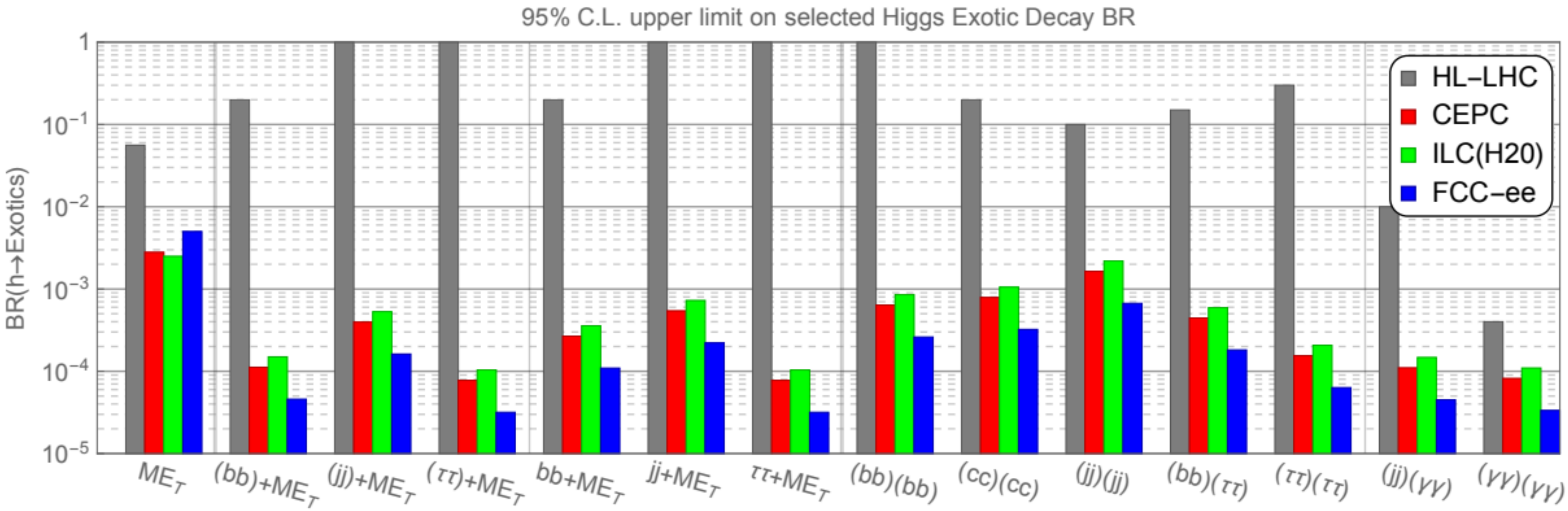
Dark matter with Mono-jet



M. Low, LTW 2014

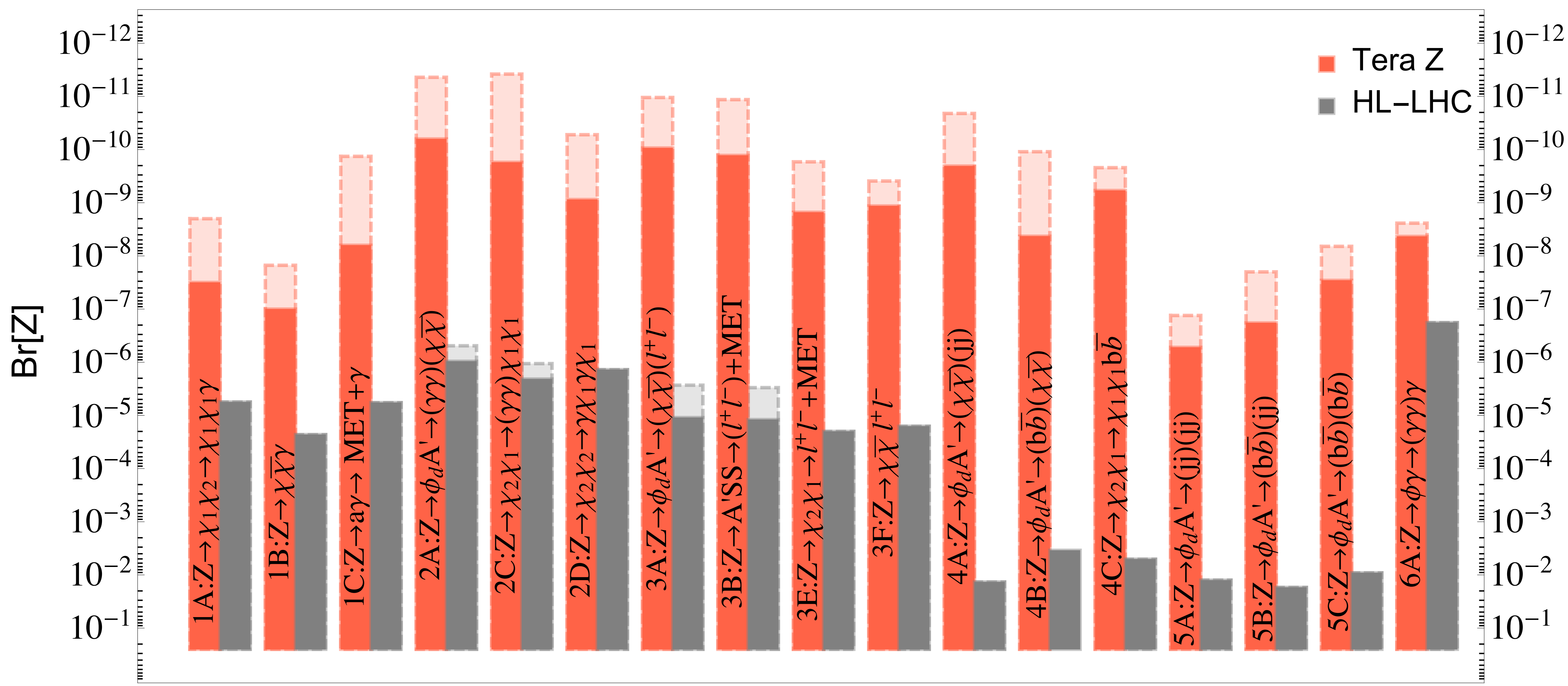
$$M_{\mathrm{WIMP}} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

Higgs exotic decay



Complementary to hadron collider searches

Rare Z decay



Can get to BR≈10^{-10} in some cases.
Gain from large statistics, clean environment

Flavor

Particle production

Particle	@ Tera-Z	@ Belle II		@ LHCb
b hadrons				
B^+	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B^0	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B_s	2×10^{10}	3×10^{8}	$(5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S))$	8×10^{12}
b baryons	1×10^{10}			1×10^{13}
Λ_b	1×10^{10}			1×10^{13}
c hadrons				
D^0	2×10^{11}			
D^+	6×10^{10}			
D_s^+	3×10^{10}			
Λ_c^+	2×10^{10}			
τ^+	3×10^{10}	5×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	

From CEPC's CDR using fragmentation ratios from Amhis et al, 17

- Similar statistical sample of $B^{0,\pm}$, τ's at Belle 2 and CEPC
- Two order of magnitude more B_s at CEPC wrt to Belle 2
- b-baryon physics possible at the CEPC
- Limited possibilities for charm physics at Belle 2

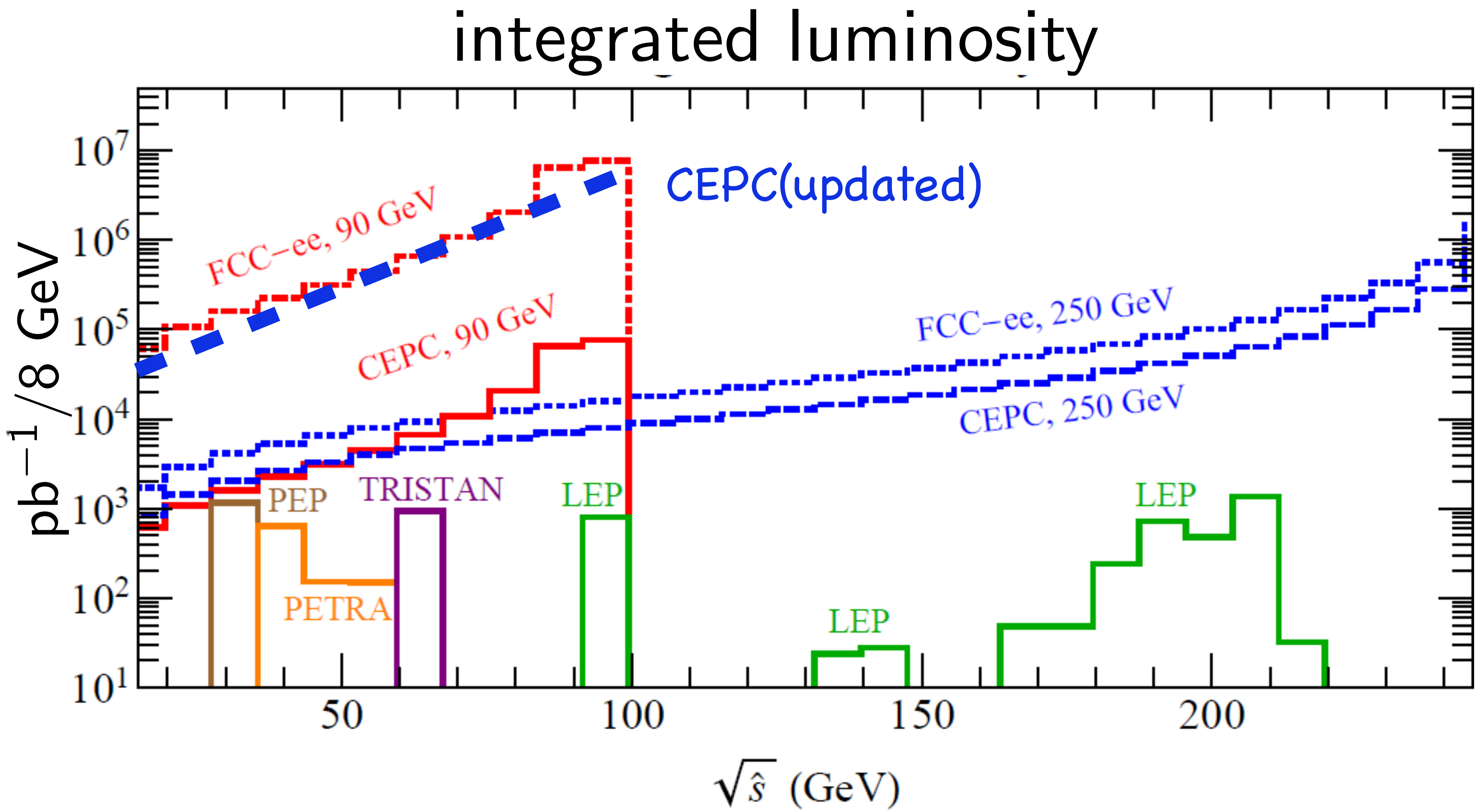
Flavor physics at Z-factory

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathrm{BR}(B_s \to \tau\tau)$	5.2×10^{-3} (LHCb)	$\sim 5 \times 10^{-4}$ (LHCb)	$\sim 10^{-5}$
$\mathrm{BR}(B \to K^*\tau\tau)$	–	$\sim 10^{-5}$ (Belle II)	$\sim 10^{-8}$
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\tau \to \mu\gamma)$	4.5×10^{-8} (Belle)	$\sim 10^{-9}$ (Belle II)	$\sim 10^{-9}$
$\frac{\mathrm{BR}(\tau\to\mu\nu\bar{\nu})}{\mathrm{BR}(\tau\to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar)	$\sim 10^{-3}$ (Belle II)	$\sim 10^{-4}$
$\mathrm{BR}(Z \to \mu e)$	1.7×10^{-6} (LEP)	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP)	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8}$
$\mathrm{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP)	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8}$

More detailed study needed to understand its full potential

Filling gaps with radiative return

M. Karliner, M. Low, J. Rosner, LTW



Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

How can we best use this?

QCD

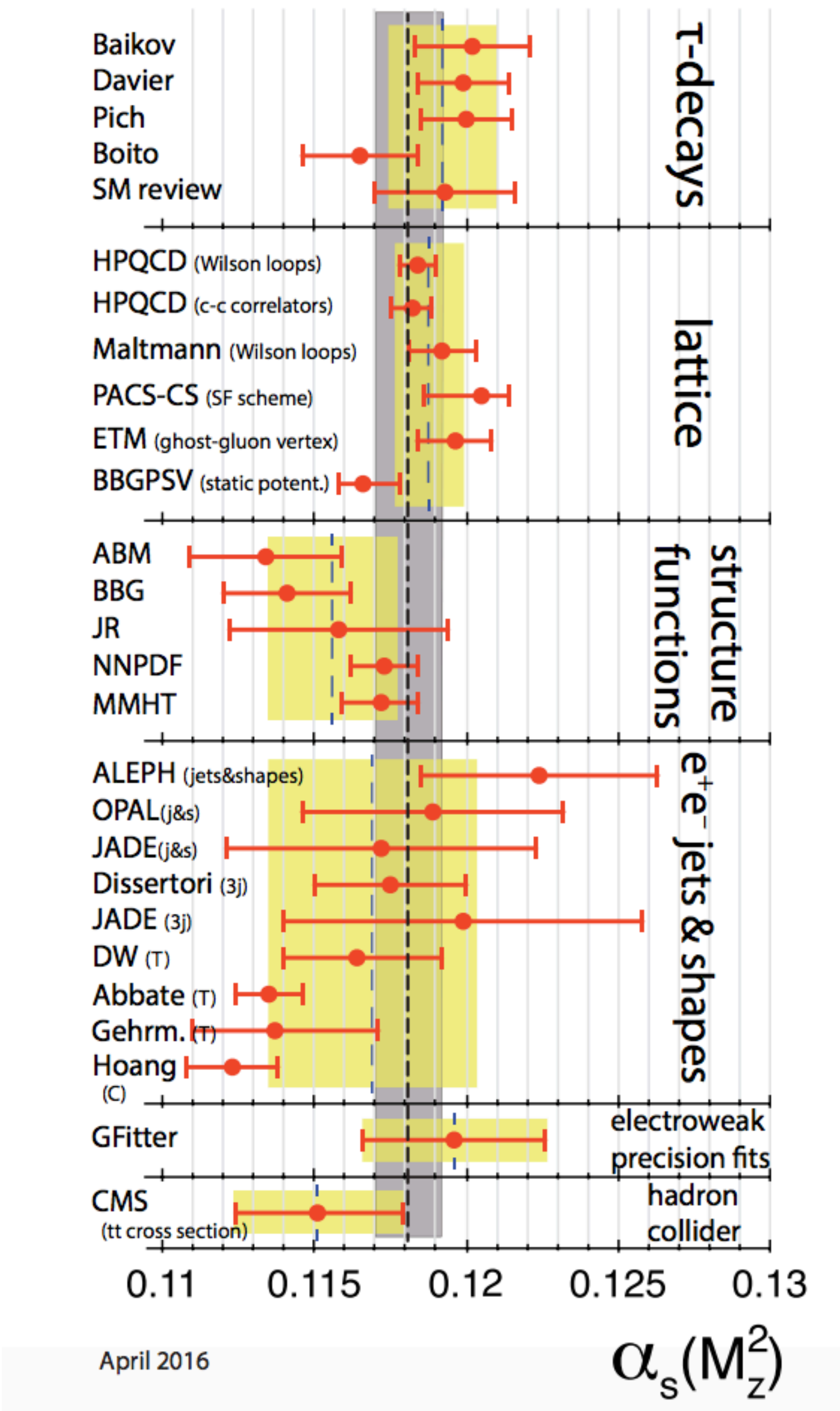
- Essential tool for precision measurements and discoveries at future colliders.

- Future colliders provide unique environment for understanding QCD.

Still a lot of detailed studies to be done to precisely quantify the physics potential in QCD.

See also the next talks in this session

α_S



$$\alpha_s(M_Z^2) = 0.1181 \pm 0.0011$$

Decay	Partial width [keV]	current unc. $\Delta\Gamma/\Gamma$ [%]		
		$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}_{\mathrm{Par}}(m_q)$	$\mathrm{Th}_{\mathrm{Par}}(\alpha_s)$
$H \to b\bar{b}$	2379	< 0.4	1.4	0.4
$H \to c\bar{c}$	118	< 0.4	4.0	0.4
$H \to gg$	335	3.2	< 0.2	3.7

Msbar mass error budget (from threshold scan)

$(\delta M_t^{\mathrm{SD-low}})^{\mathrm{exp}}$	$(\delta M_t^{\mathrm{SD-low}})^{\mathrm{theo}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\mathrm{conversion}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

⇒ improvement in α_s crucial $\delta\alpha_s(M_z) = 0.001$

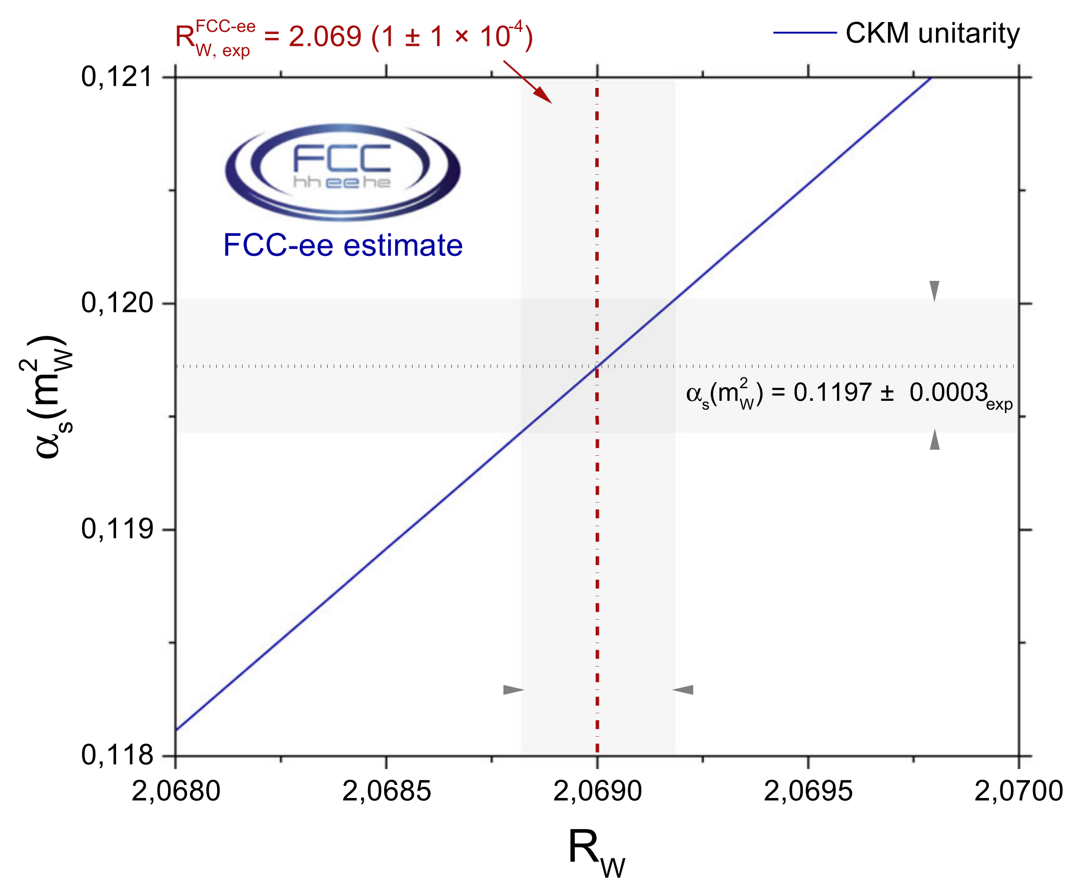
Quantity	FCC-ee	future param.unc.	Main source
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$
R_b [10^{-5}]	6	< 1	$\delta\alpha_s$
R_ℓ [10^{-3}]	1	1.3	$\delta\alpha_s$

Sven Heinemeyer – 1st FCC physics workshop, CERN, 17.01.2017

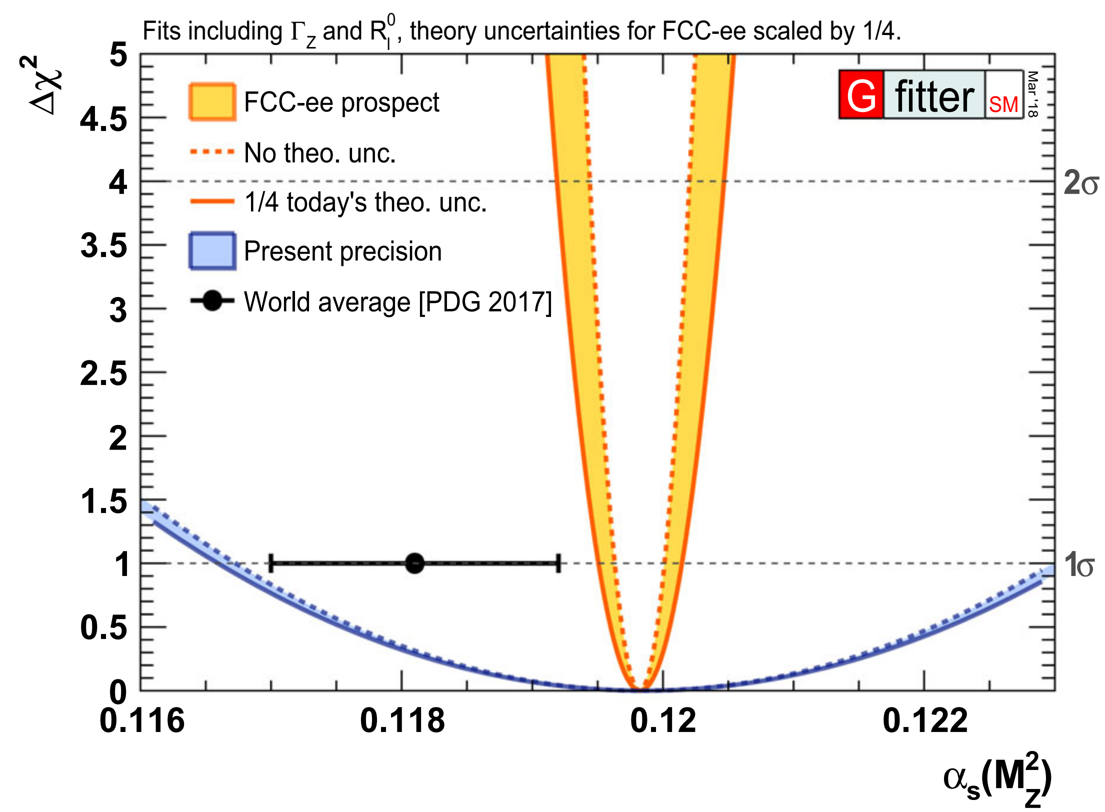
sub-percent determination important for precision measurements

α_S from electroweak measurements

R_W: hadronic/lepton decay ratio



Z decay $$R_Z \equiv \frac{\Gamma(Z \to \mathrm{h})}{\Gamma(Z \to l)}$$



$\delta\alpha_s < 0.2\,\%$

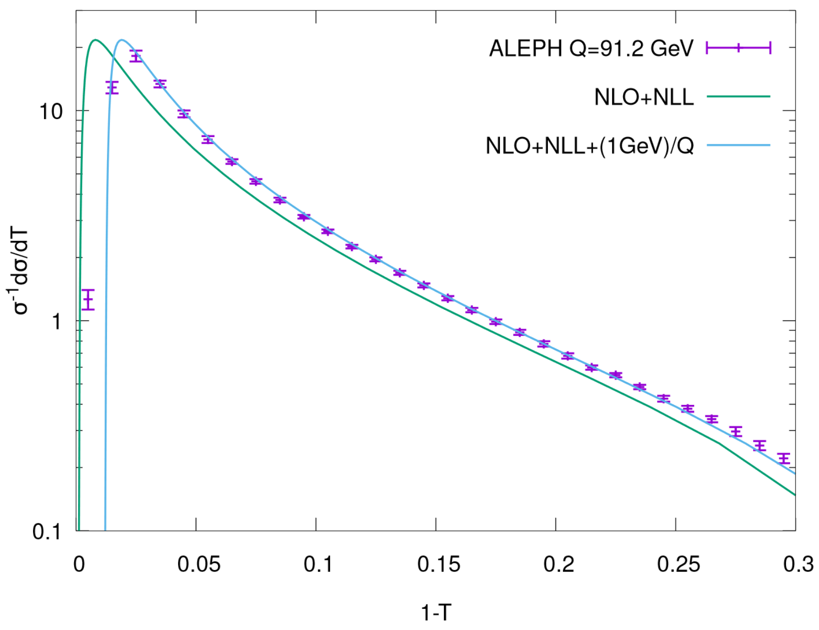
$\delta\alpha_s < 0.15\,\%$

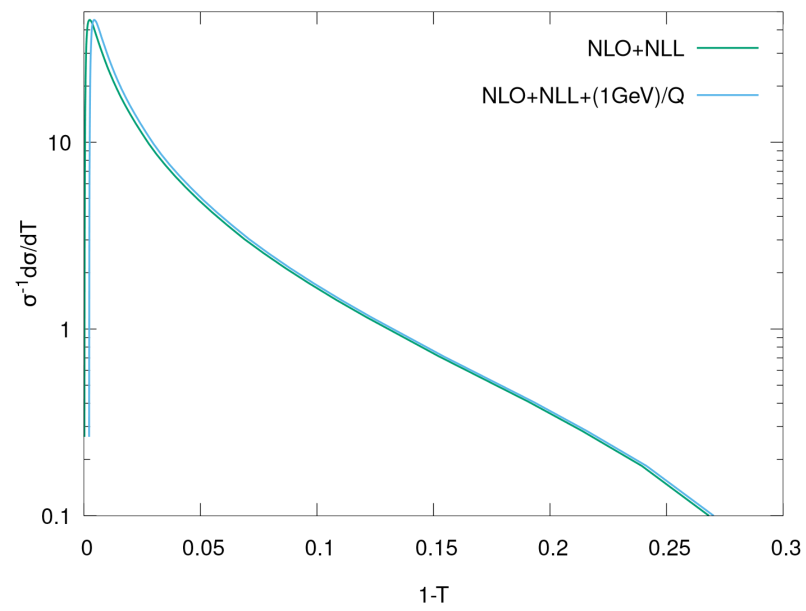
10^4 x LEP

Tera-Z, 10^5 x LEP

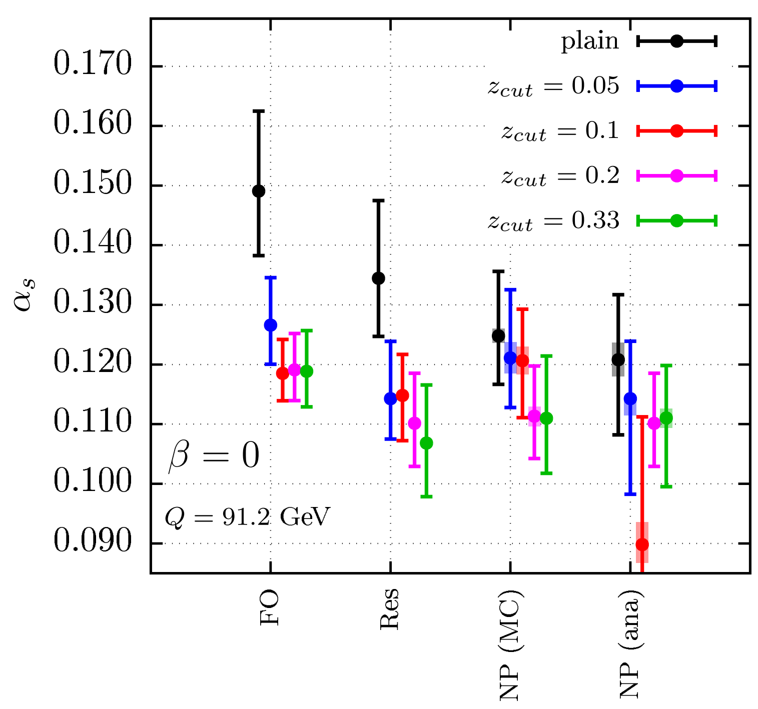
α_S from event shapes

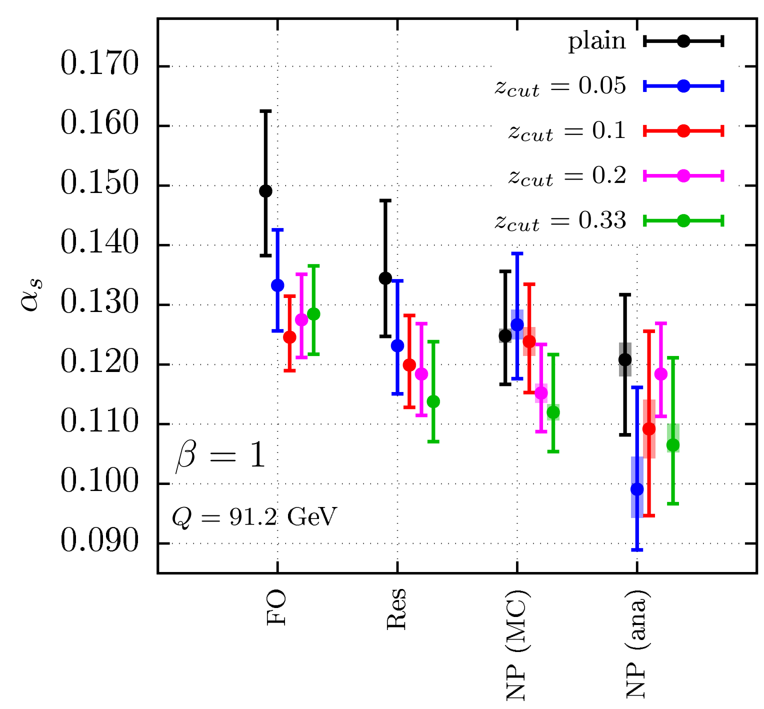
Taming the non-perturbative effects





Less important at higher energies





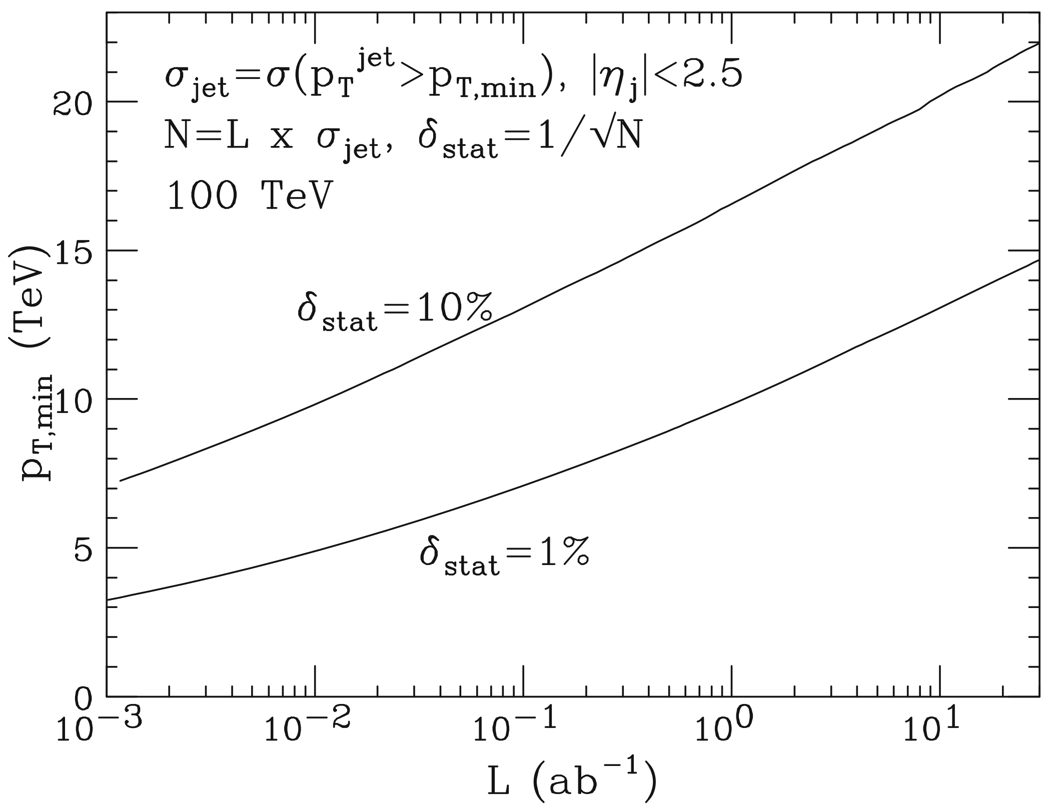
Grooming can help

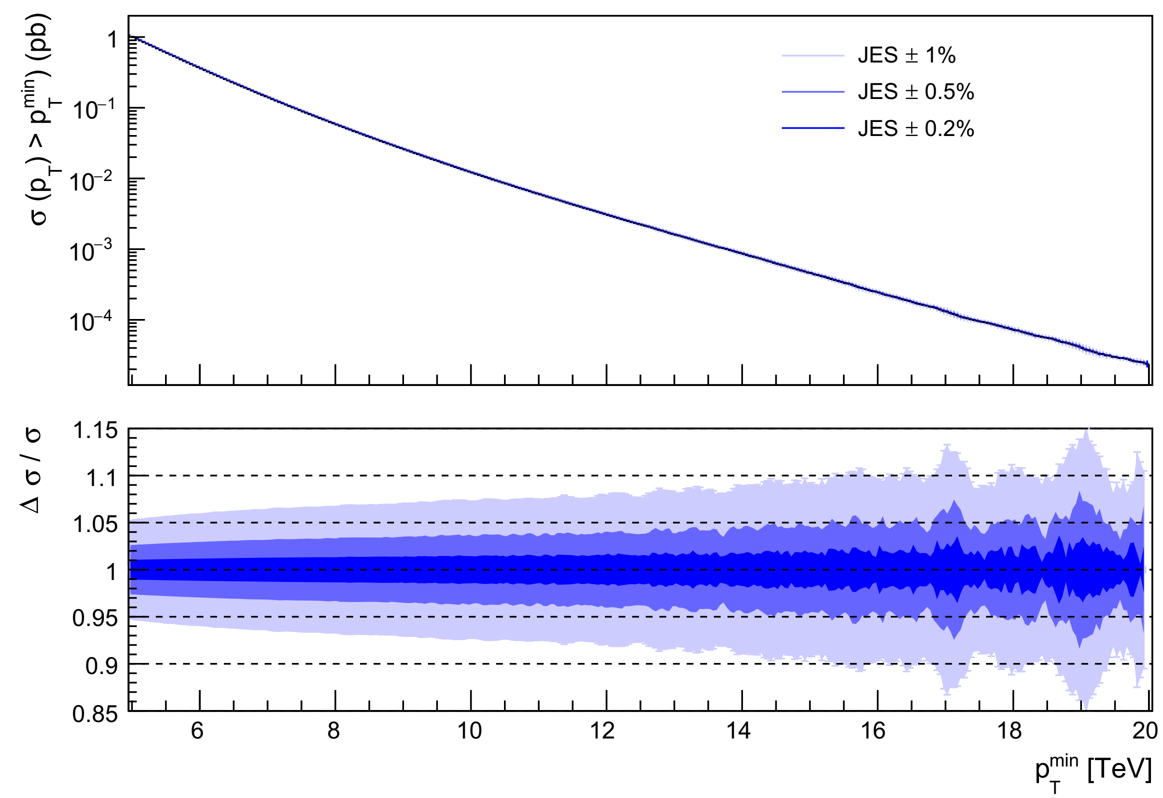
Marzani, Reichelt, Schumann, Soyez, Theeuwes, 1906.10504

QCD at 100 TeV Hadron collider

Crucial for discovery and measurements.

FCC CDR

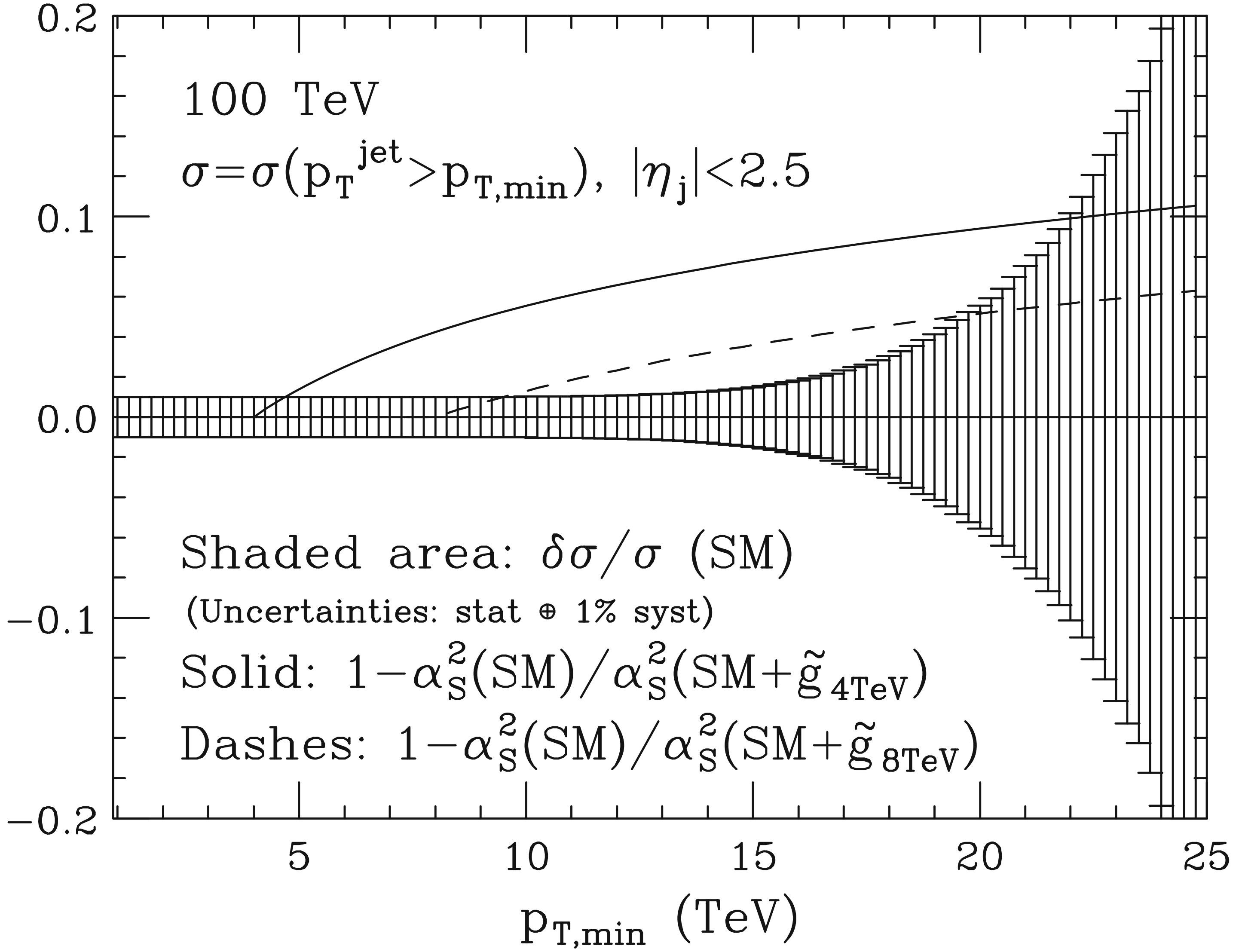




Statistical error small. For 10s ab^{-1}, ≈ 1% for p_T ≈ 10 TeV

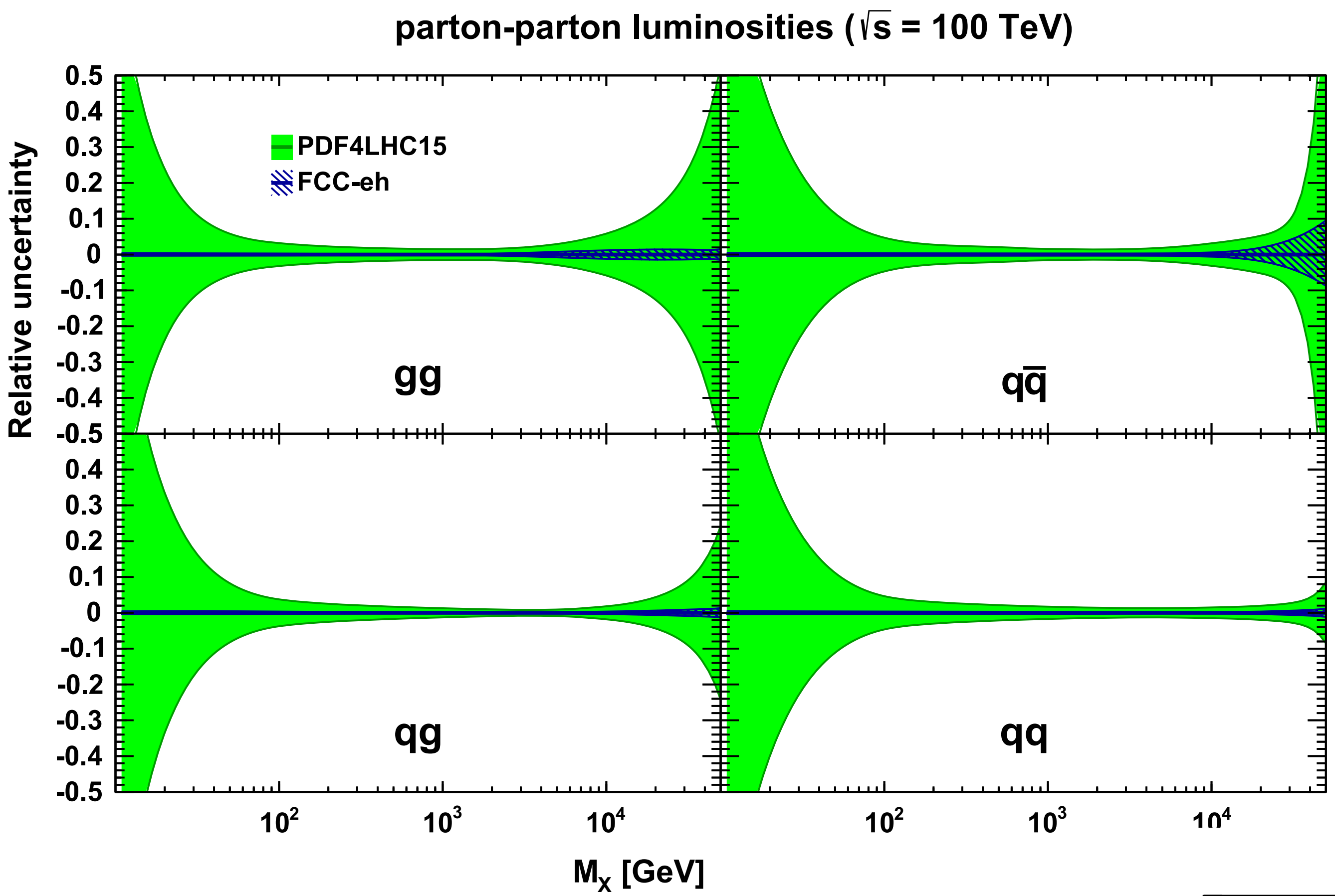
Aiming at 1% systematics for major QCD processes:
Theory, PDF (more later), α_S, better detector,...

Powerful discovery tool

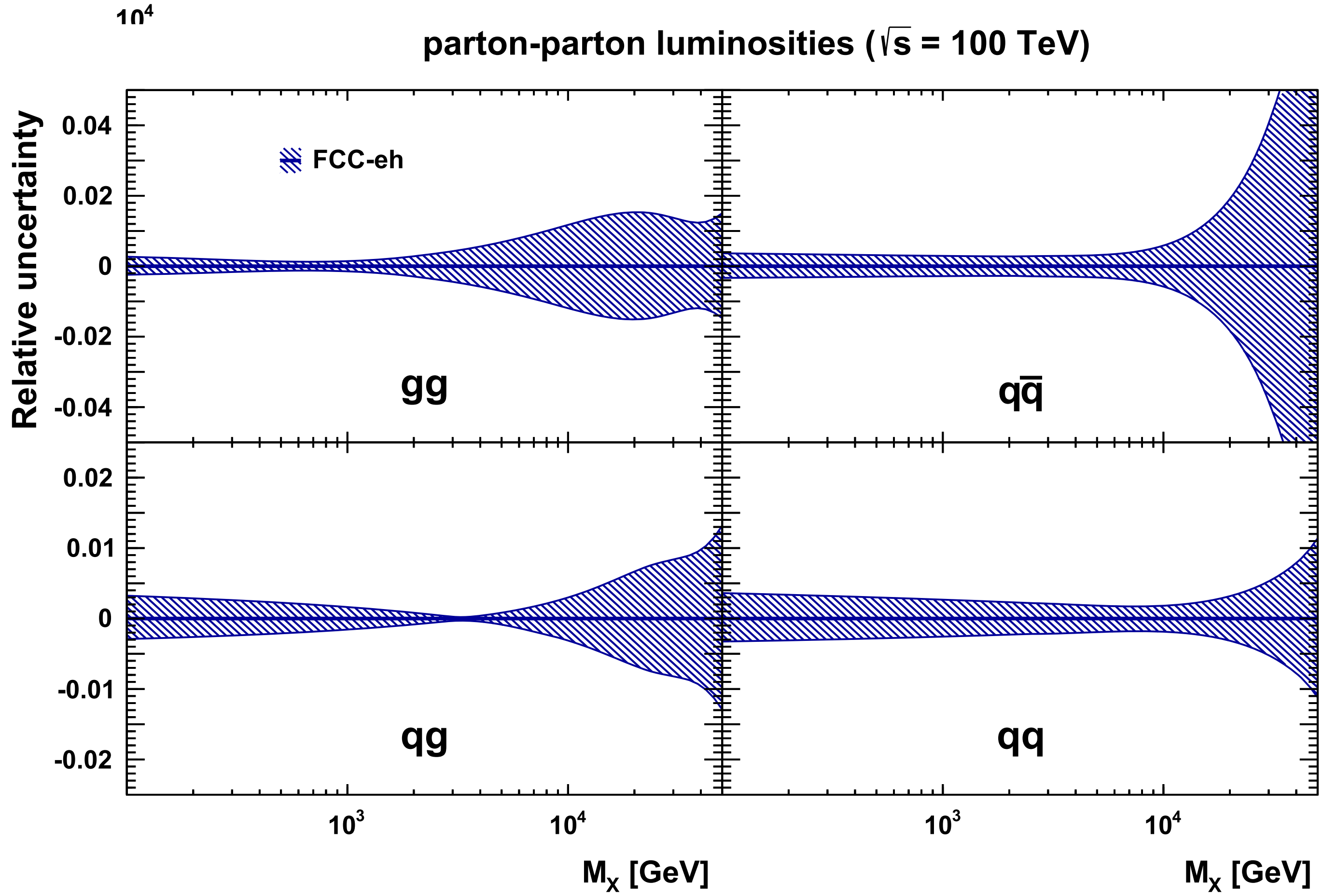


e.g.: gluino changing α_S running

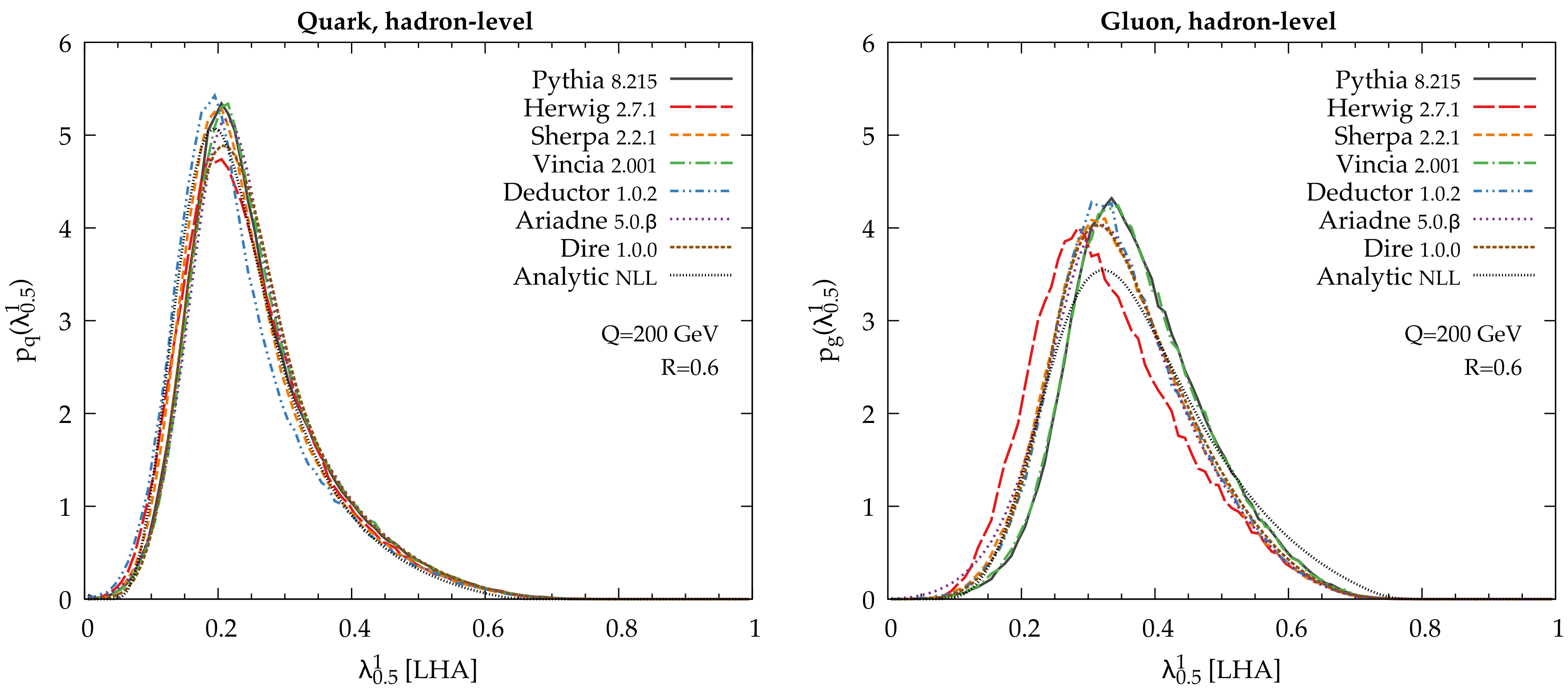
PDF from FCC-eh



Within 1 percent for large range of $\hat{s}$



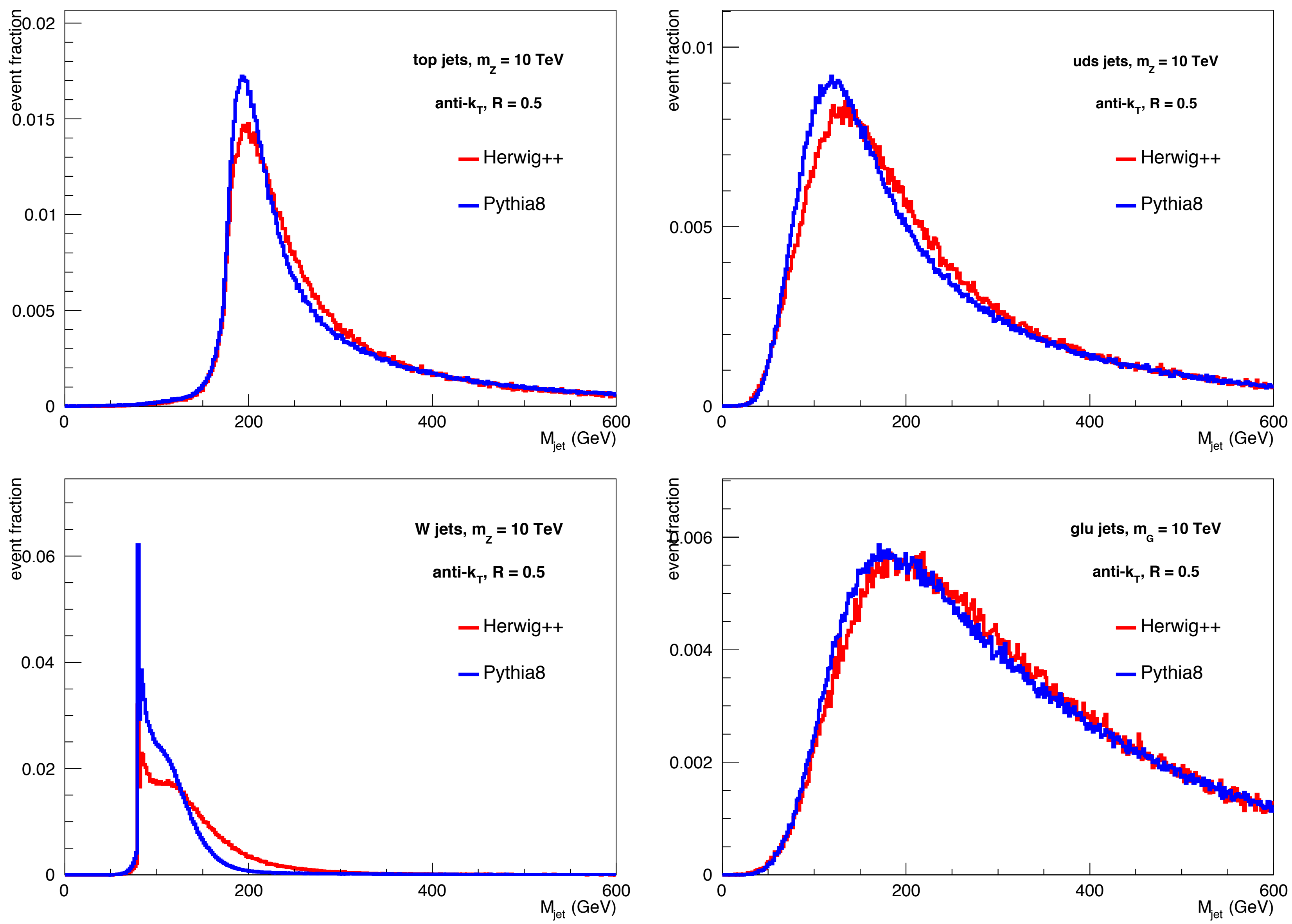
quark gluon differentiation



Dependence on MC generators, in particular for gluon

Large sample of Z→ qq (10^5 x LEP) and h→ gg ($10^{4\text{-}5}$)
Can help build better MC, improve quark-gluon taggers

Boosted top, W, Z at 100 TeV



Many new challenges (next talks in this session)

Some personal thoughts

Lepton collider: Circular vs linear

- Circular.
  - Higher luminosity. More statistics.
  - “Easier” to build
  - 1st stage of a big hadron collider.
- Linear
  - Can get to higher energy.
  - Polarization useful tool to discern new physics.
  - Newer technology
- In an ideal world, good to have both!

Why 100 TeV?

- Higher is better.
- This is fixed by reasonable expectation of technology, resource, etc.
- A significant step, factor of 100/14, above LHC.
- Interesting test of naturalness, WIMP dark matter.

40 TeV?

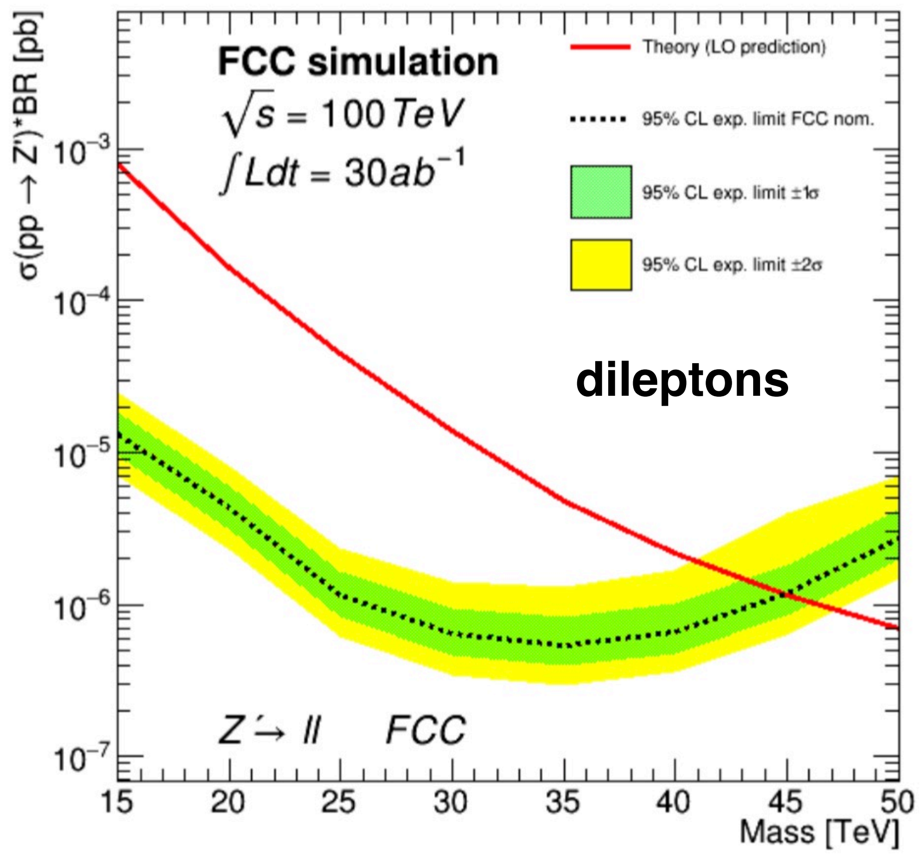
- Worse than 100, by a factor of 40/100.
- Better than the LHC, by a factor of 40/14.
- Good to have of course.
- Is this the most cost effective way of going forward?

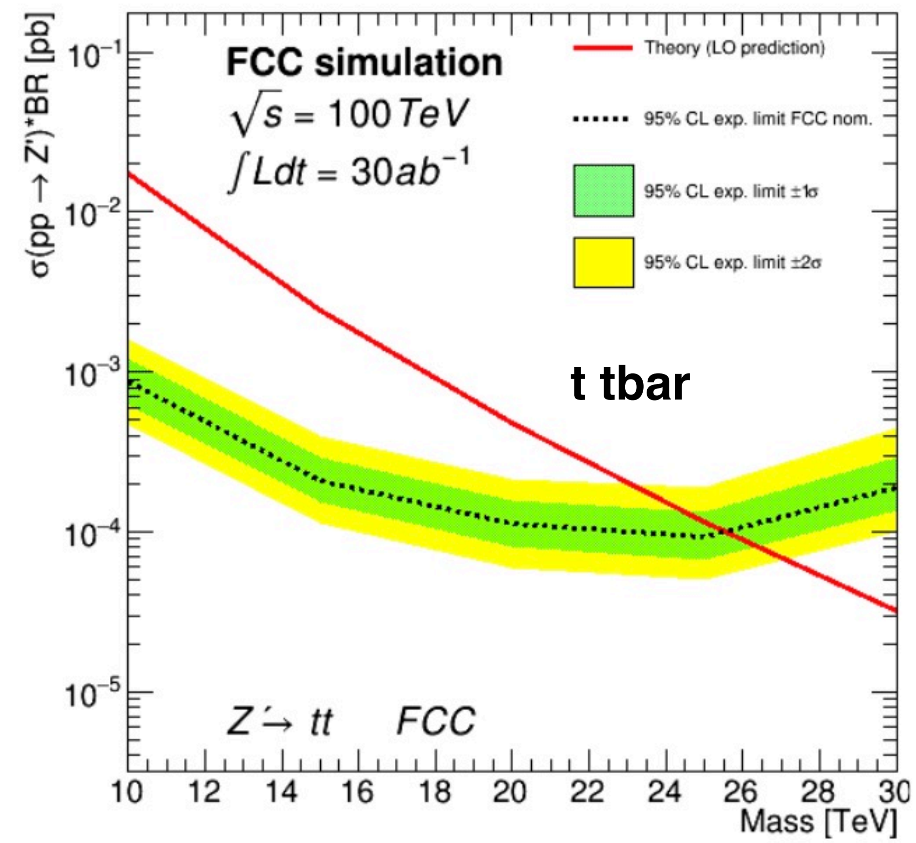
Conclusion

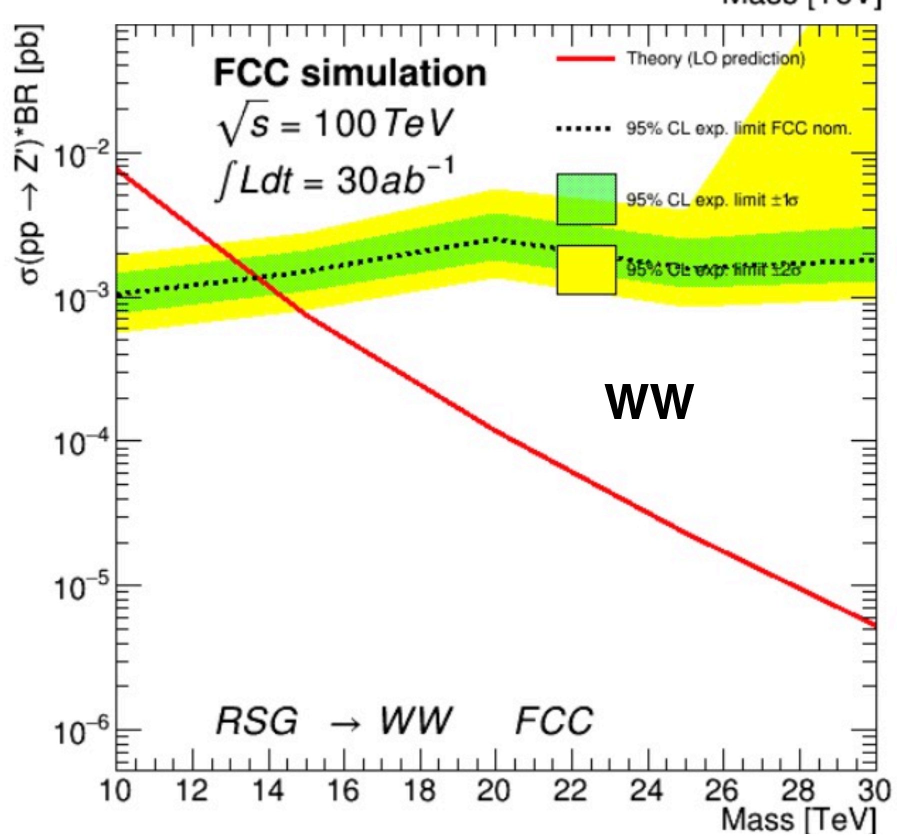
- We are at a special historical juncture. About to make the next step beyond the Standard Model.
- International effort in realizing the future collider(s).
  - European strategy next year (FCC, ILC, CLIC...)
  - CEPC decision early 2020s.
- Hope we have the wisdom and good fortune to converge on the right path.

New physics reach: 10s TeV

Resonances: SSM Z’

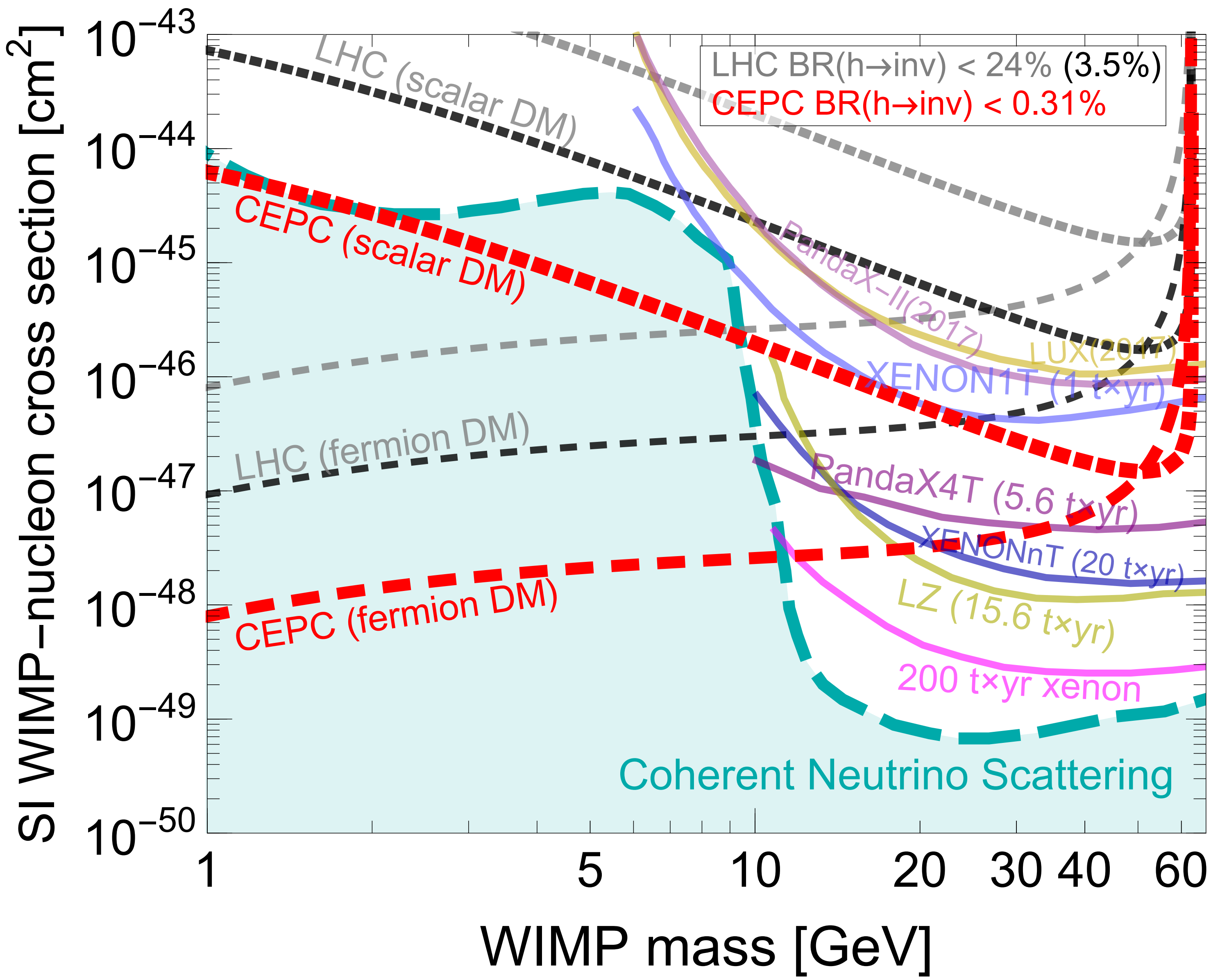






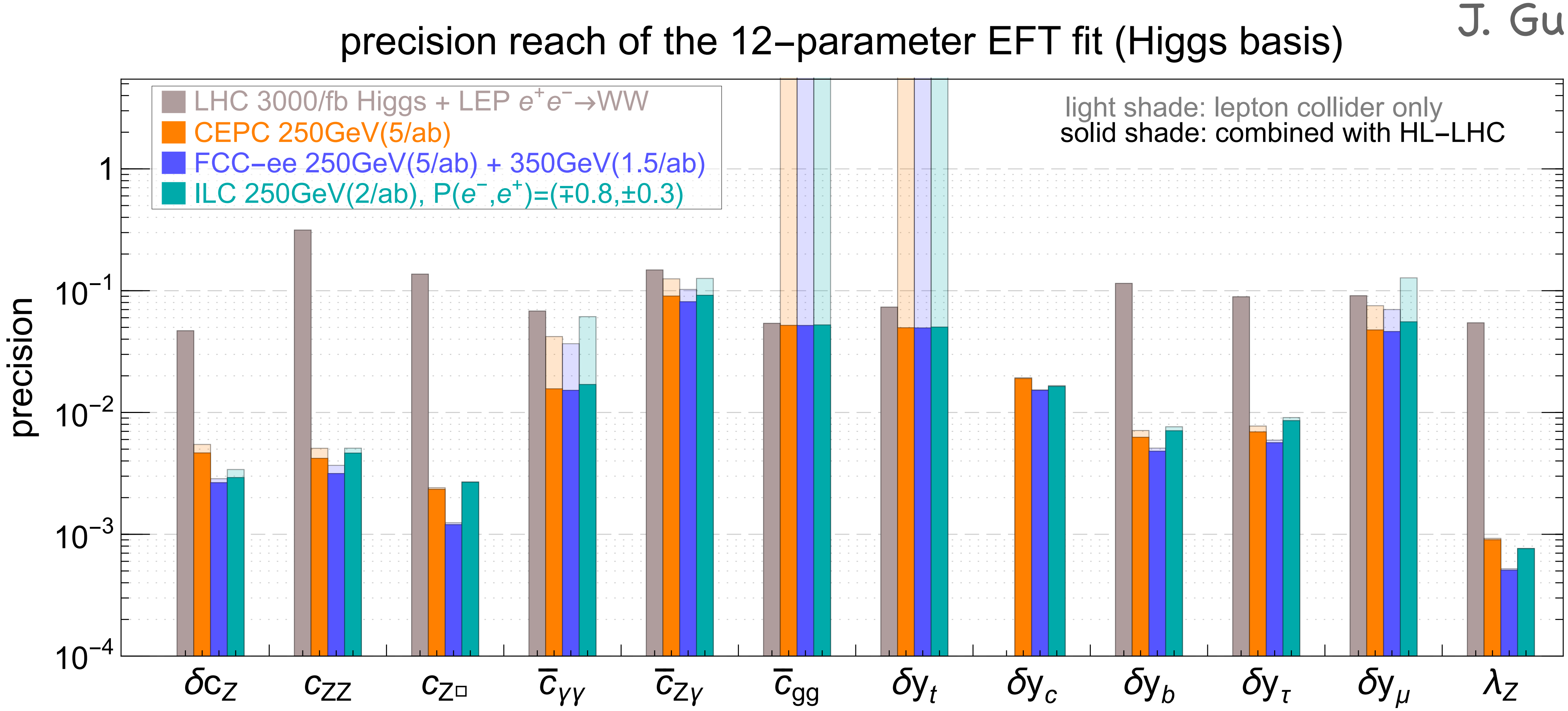
C. Helsens & M. Selvaggi + Summer students
Rachel Smith UIUC and Ine Arts UA

Higgs portal dark matter



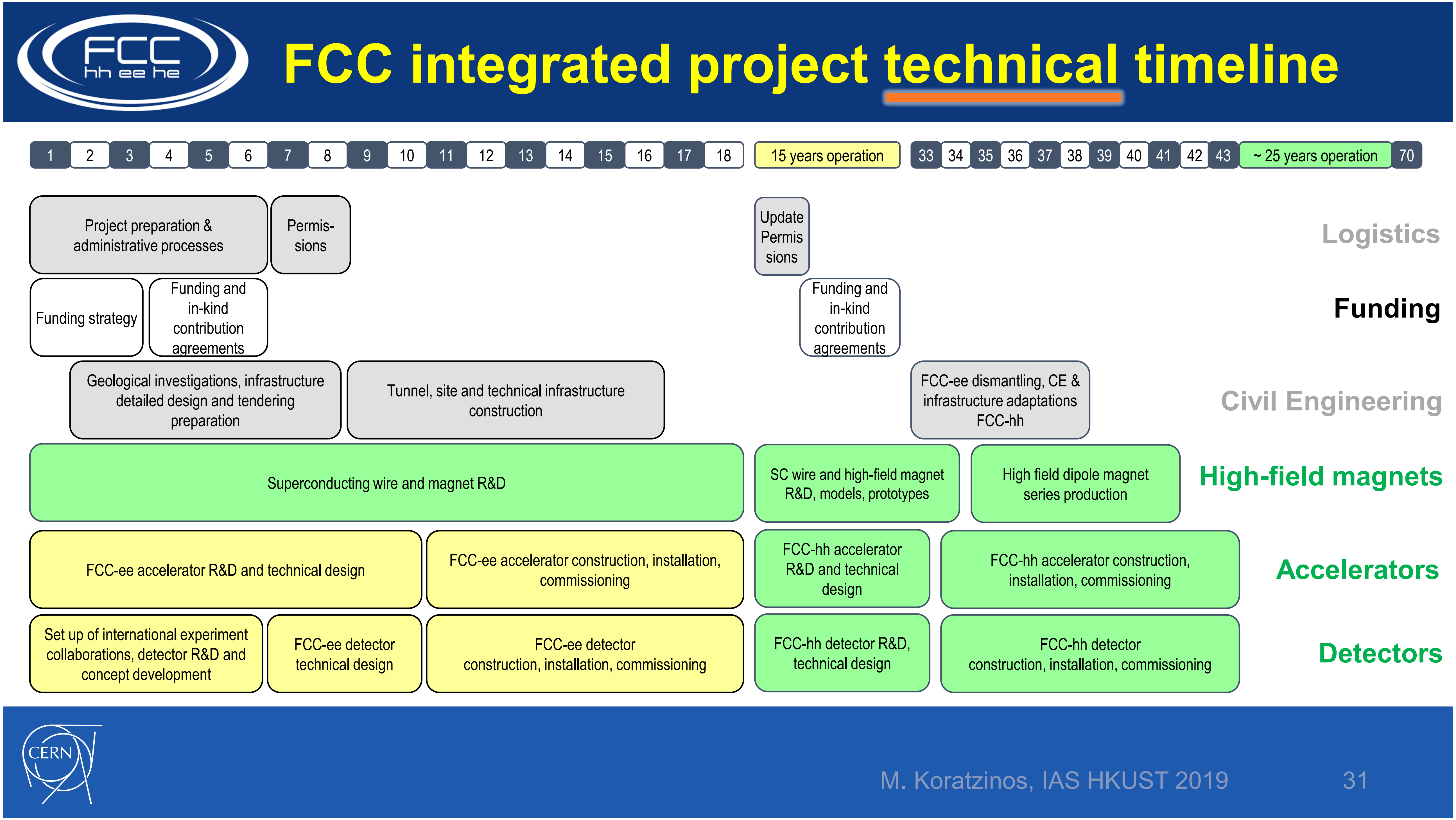
Higgs measurement in EFT

J. Gu



- Both 350 and polarization could help.

FCC time line



FCC-ee: ～2039， FCC-hh: ~2060s