Physics At Future Colliders

KIAS/Univ. of Pittsburgh, PITT PACC
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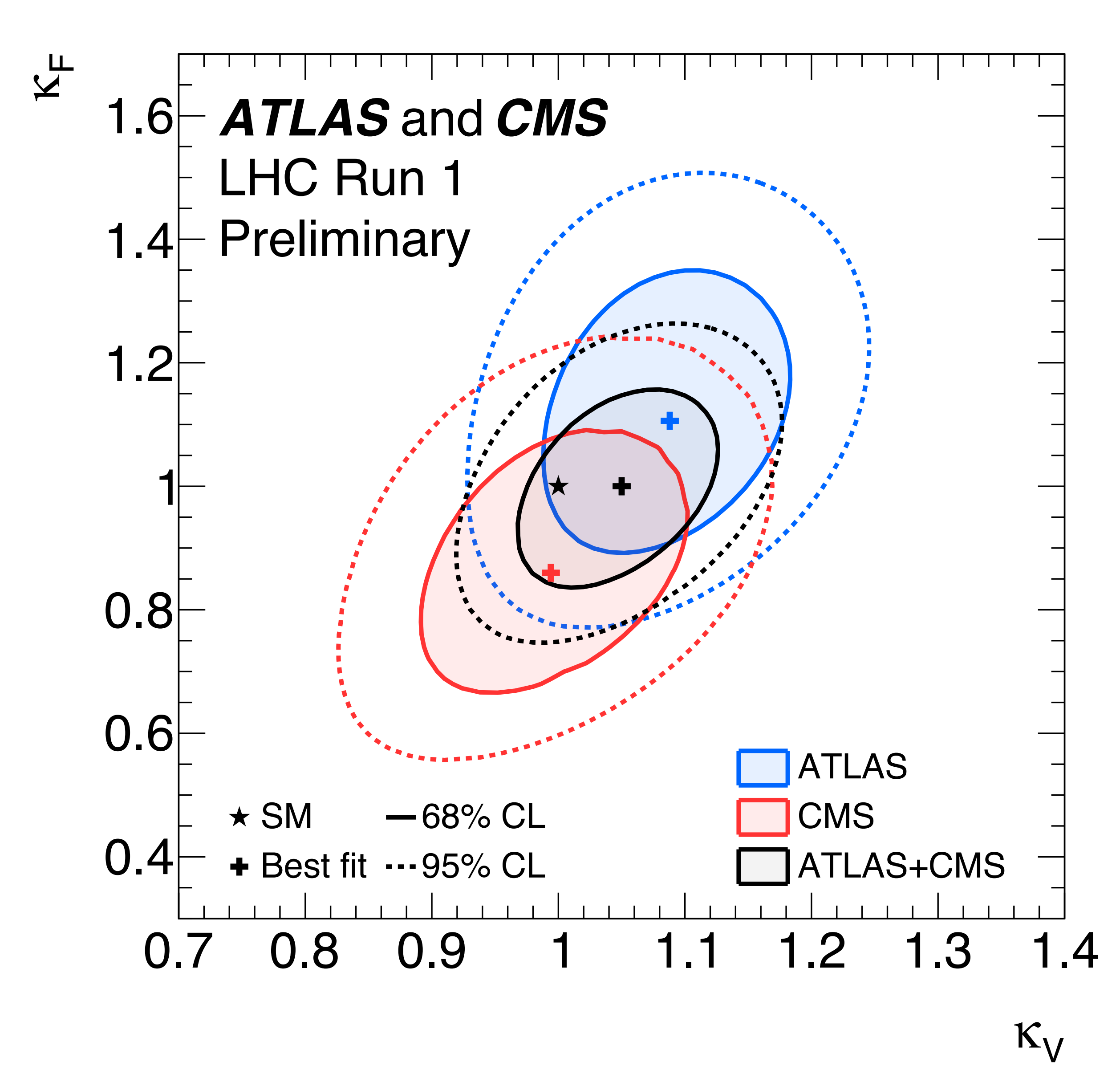
IBS Center for Theoretical Physics of the Universe
Oct. 28, 2015

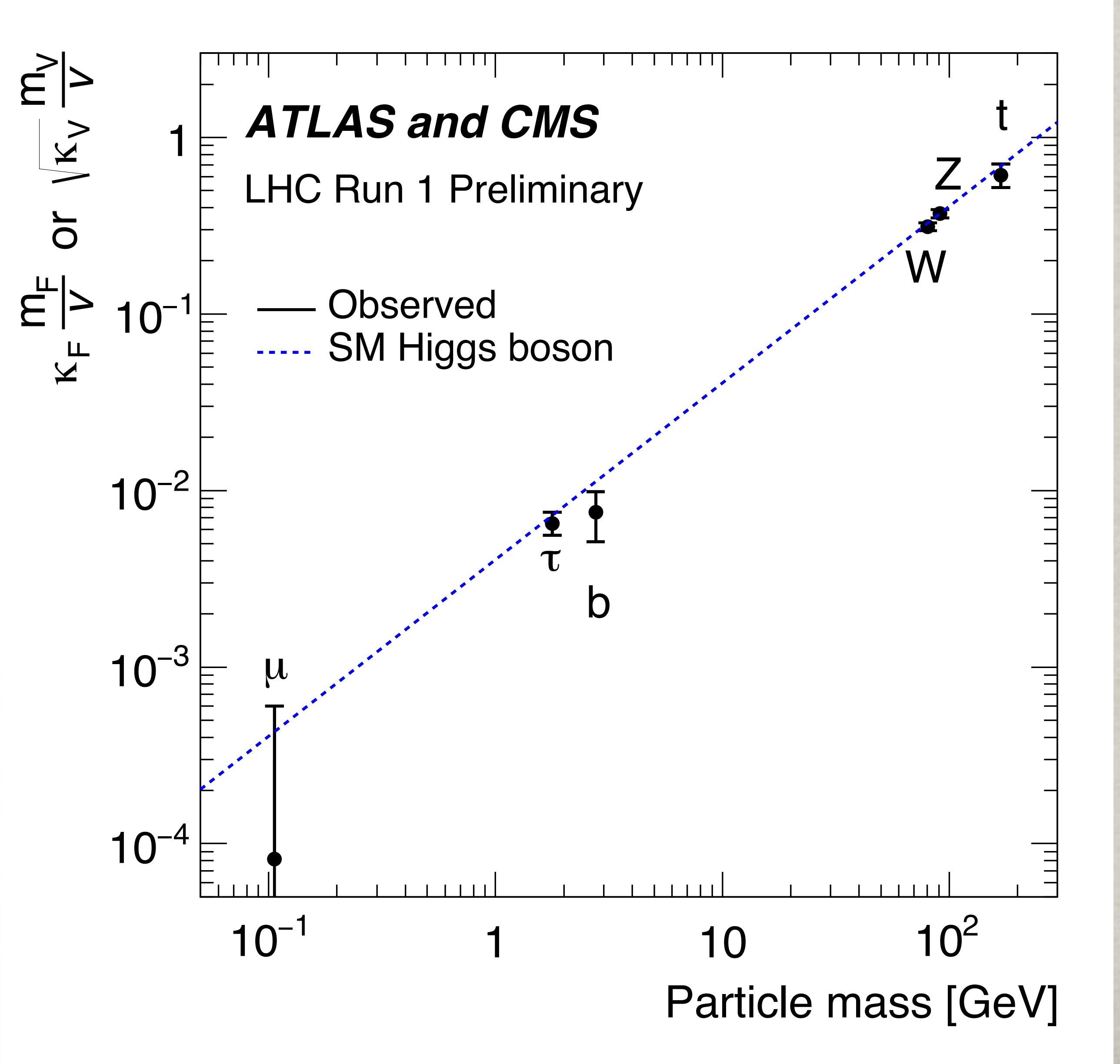
N. Arkani-Hamed, T. Han, M. Mangano, L.T. Wang, in prep

High Energy Physics IS at an extremely interesting time:

2012: The milestone discovery:

2015: 5σ for both h → ττ; WW→h Very SM-like





The completion of the SM:

First time ever, we have a consistent relativistic/quantum mechanical theory: weakly coupled, unitary, renormalizable, vacuum (quasi?)stable.

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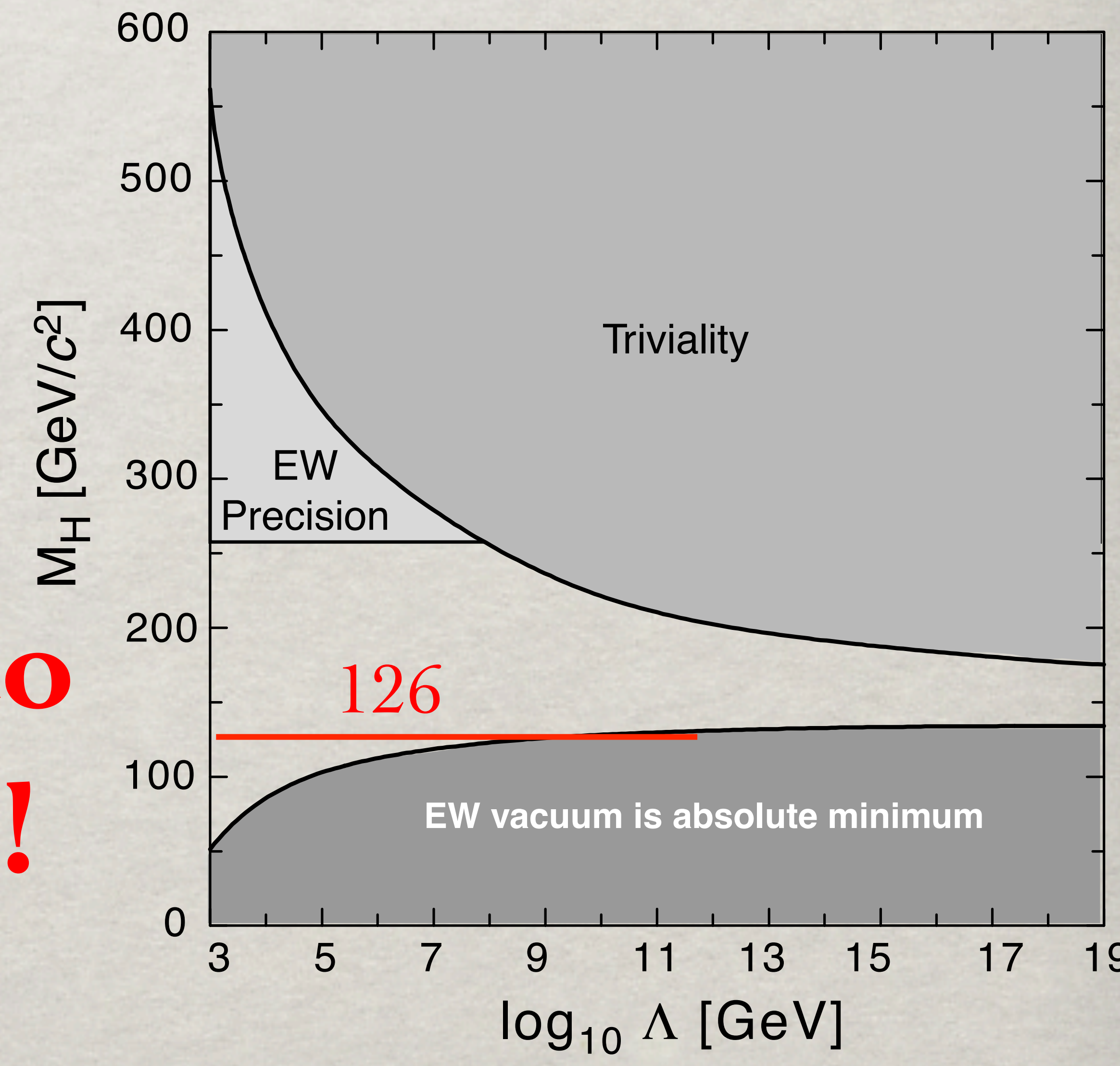

Valid up to an exponentially high scale, perhaps to the Planck scale M_{Pl}!

"... most of the grand underlying principles have been firmly established. An eminent physicist remarked that the future truths of physical science are to be looked for in the sixth place of decimals. "

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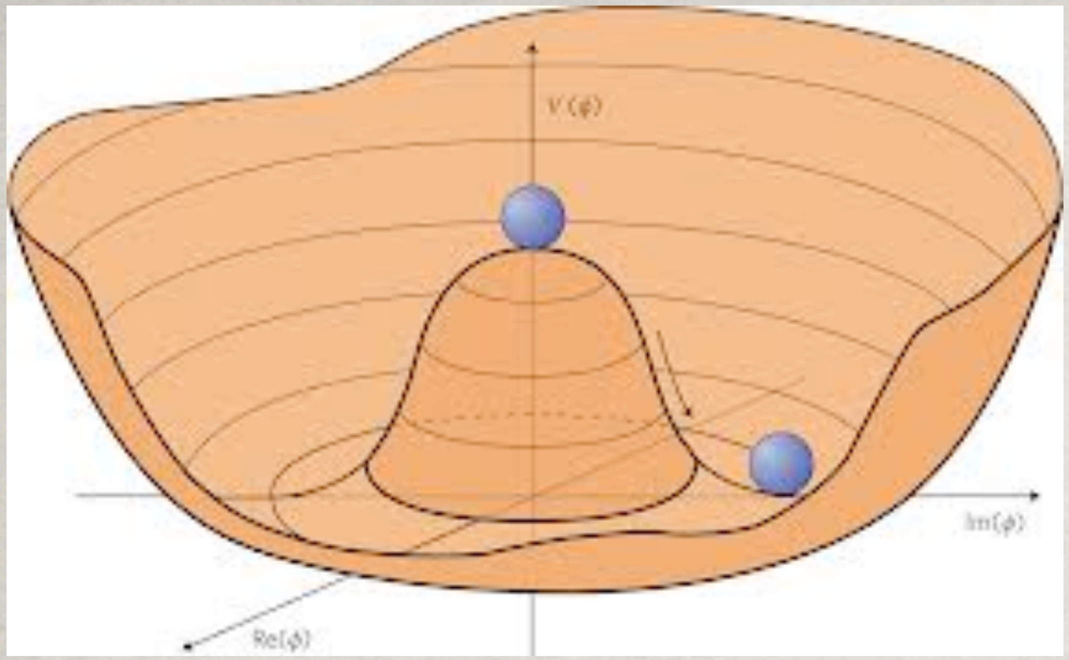
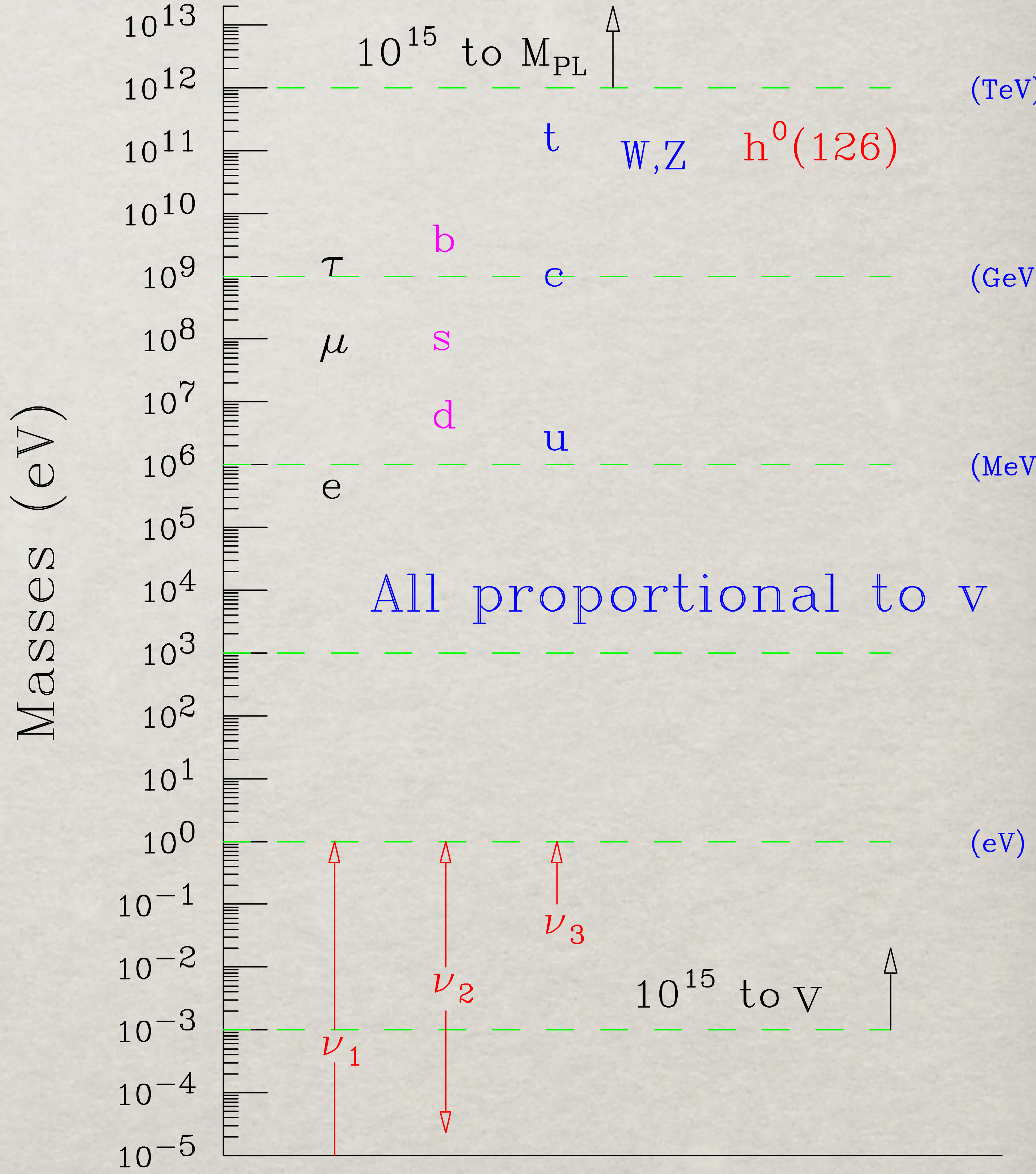
Michelson–Morley experiments (1887):
"the moving-off point for the theoretical aspects of the second scientific revolution"

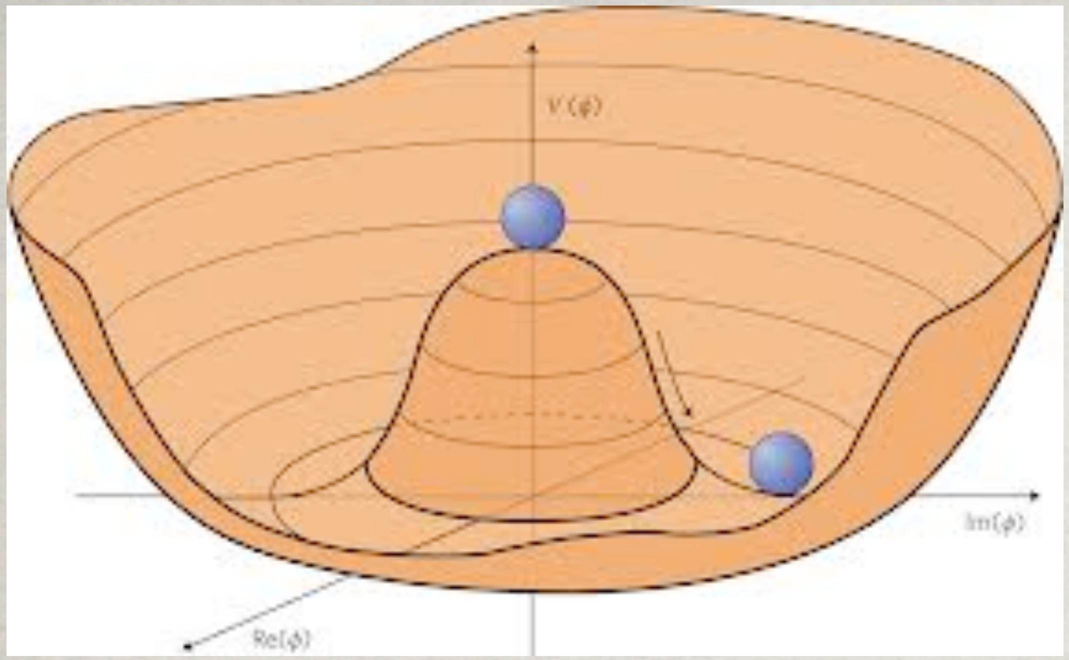
Will History repeat itself (soon)?



$v = m_H/\sqrt{(\sqrt{2}\,\lambda)} = 2M_W/g$

SM UV complete!





$v = m_H/\sqrt{(\sqrt{2}\,\lambda)} = 2M_W/g$

The nature of the EW phase transition?

Where is the next scale?

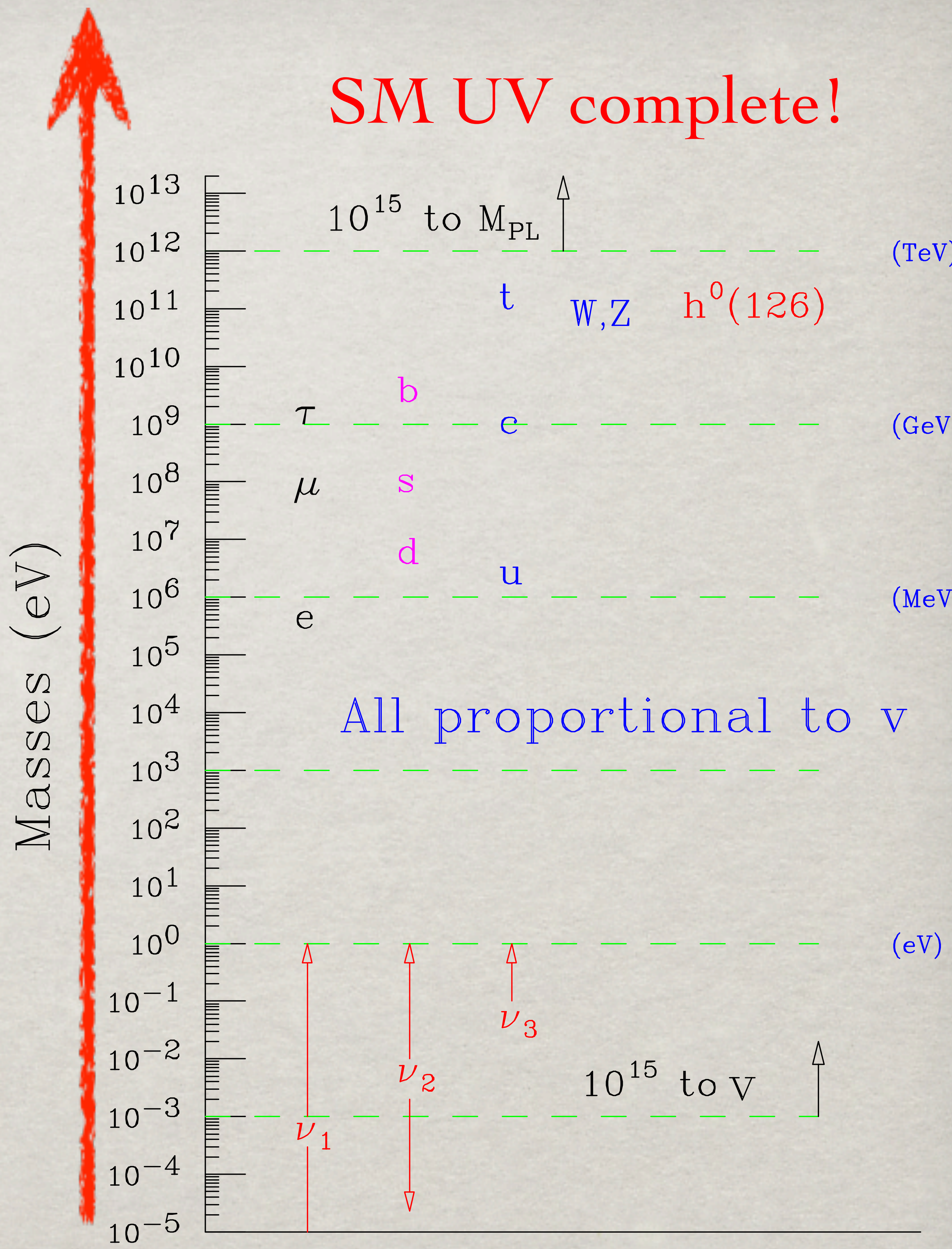
O(TeV)? M_{GUT}? M_{planck}?

$\Lambda \sim M/g$:

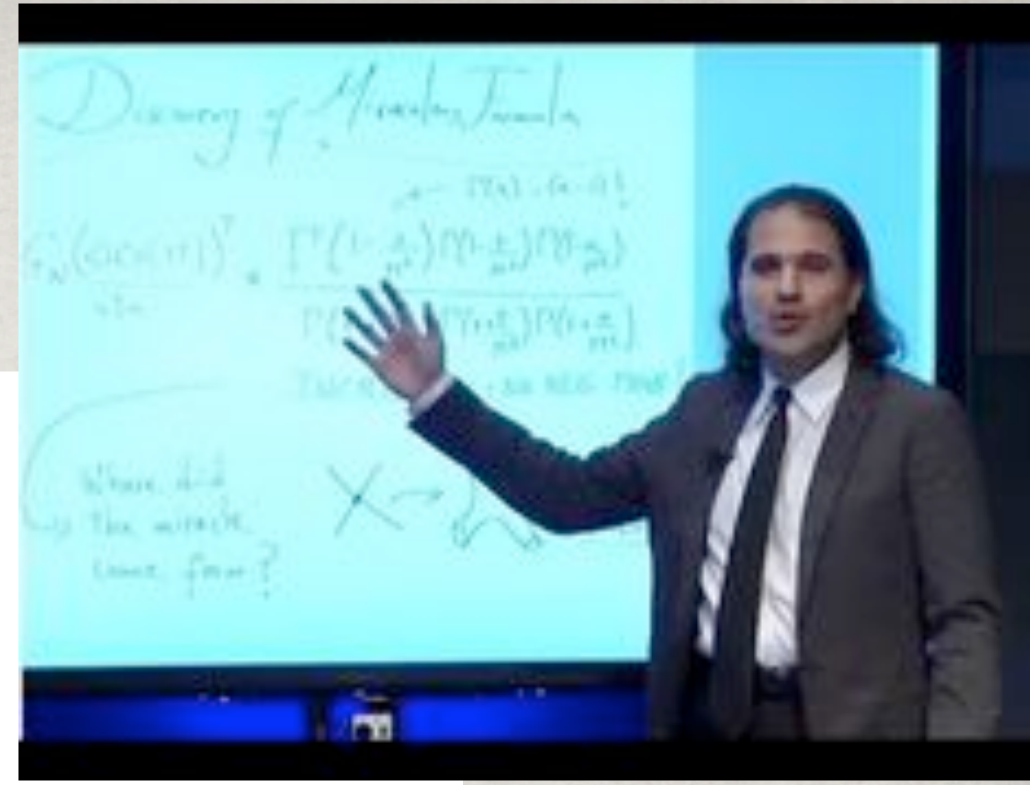
Higher mass?

Weaker coupling?

SM UV complete!

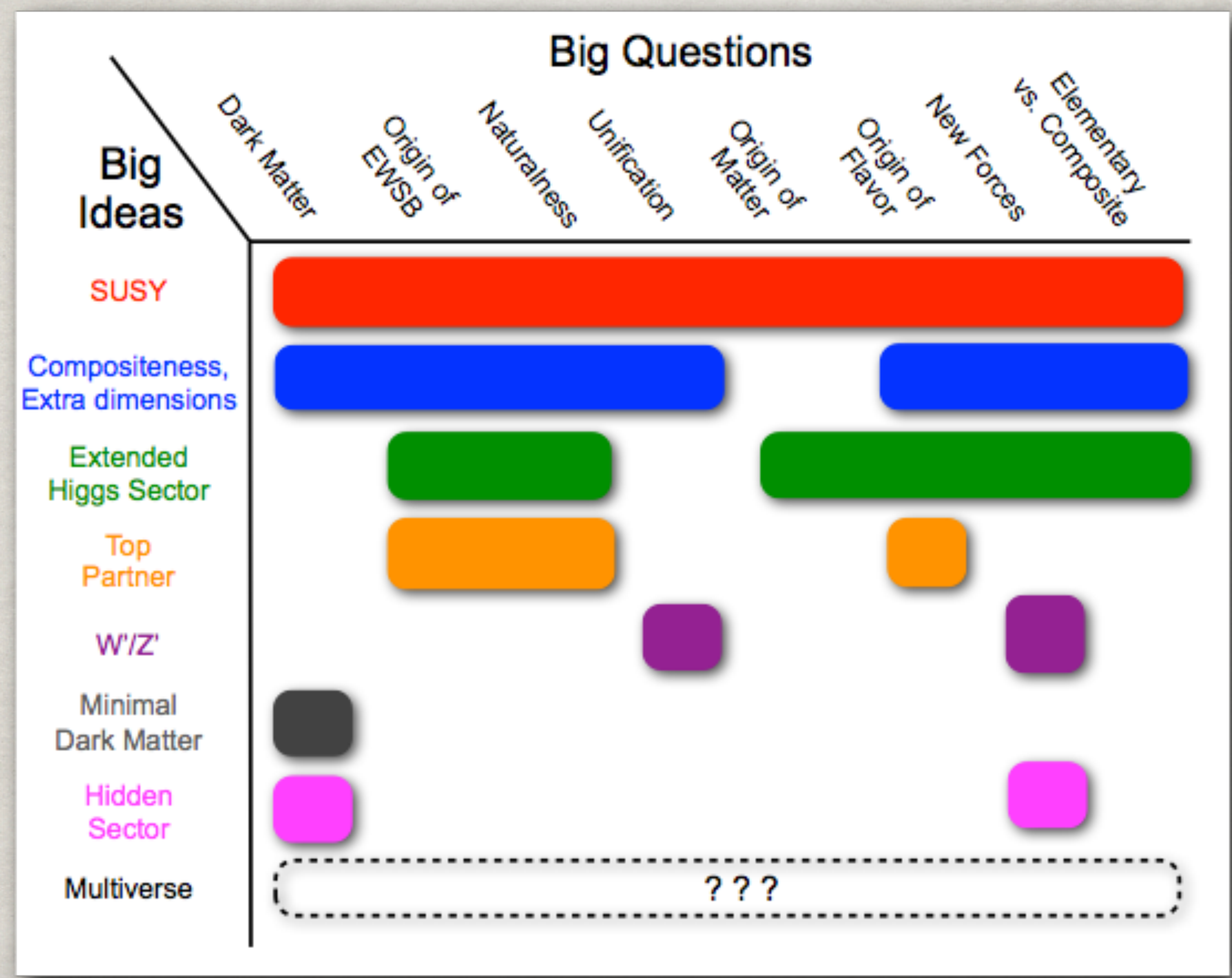


Nima Arkani-Hamed
(Director of CFHEP, Beijing)



The central questions today are not details — but structural: origin of spacetime, UV/IR connection, standard model → real theory

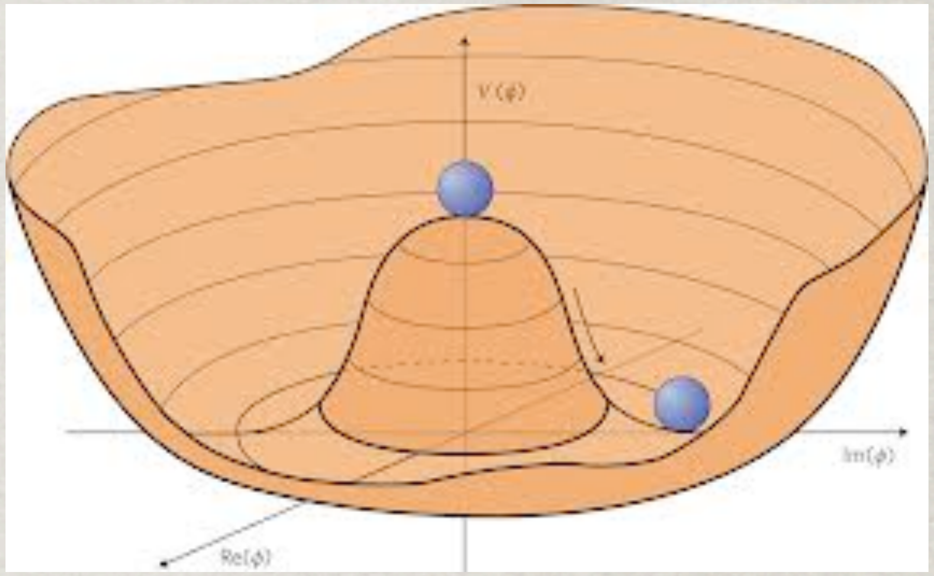
Snowmass NP report, 1311.0299



New Era:
Under the Higgs lamp post

Question 1: The Nature of EWSB ?

In the SM:



$$V(|\Phi|) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

$$\Rightarrow \quad \mu^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

Fully determined at the weak scale:

$v = (\sqrt{2}G_F)^{-1/2} \approx 246$ GeV $\quad m_H \approx 126$ GeV

$$m_H^2 = 2\mu^2 = 2\lambda v^2 \quad \Rightarrow \quad \mu \approx 89 \text{ GeV}, \quad \lambda \approx \frac{1}{8}.$$

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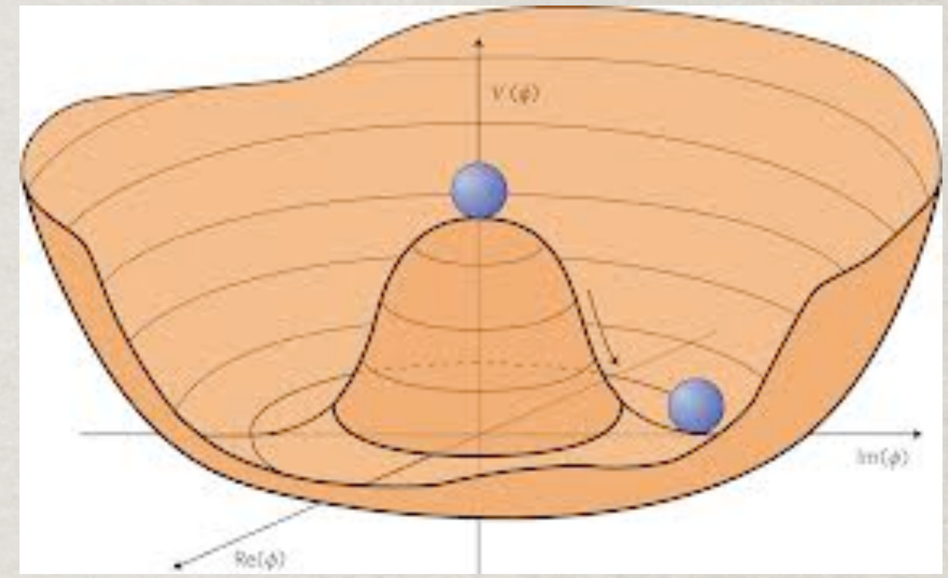

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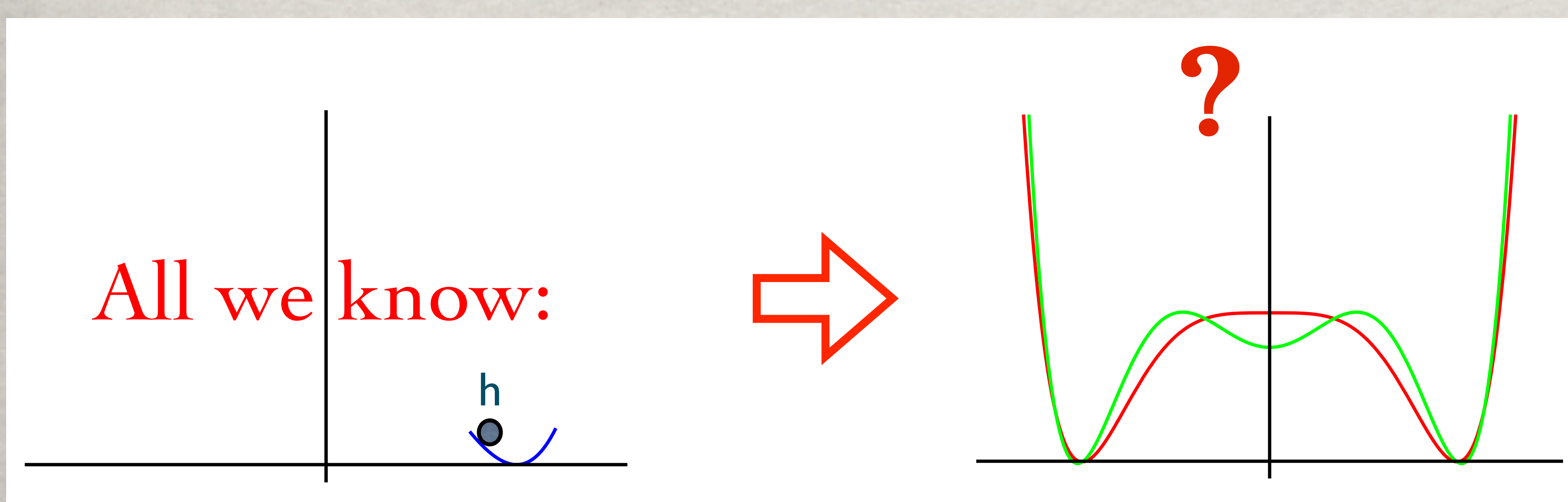
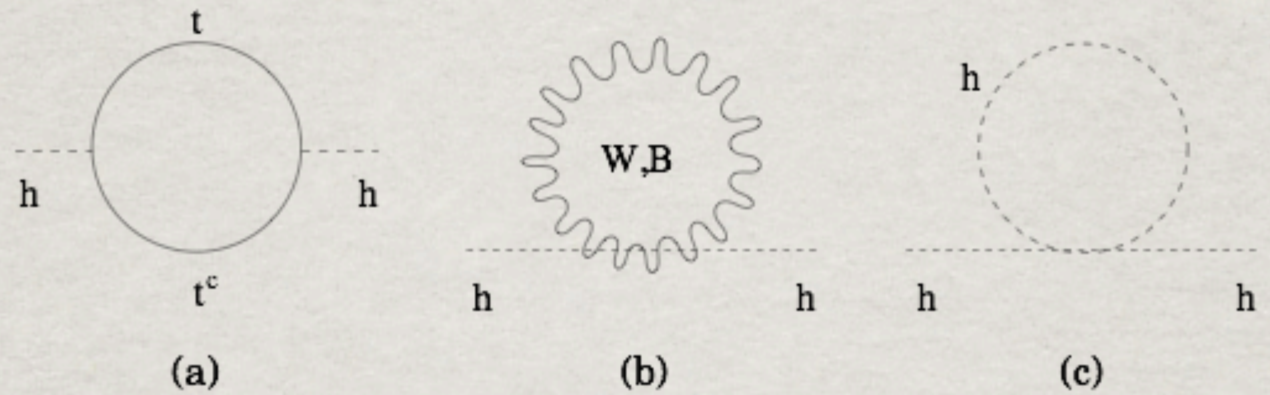


O(1) deviation on λ_{hhh} could make EW phase transition strong 1[st] order!

X.M.Zhang (1993); C. Grojean et al. (2005)

Question 2: The "Naturalness"

Higgs mass is "un-natural" in the Wilson/ 't Hooft sense:



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

If $\Lambda^2 \gg m_H^2$, then unnaturally large cancellations must occur.

Cancelation in perspective:

m_H^2 = 36,127,890,984,789,307,394,520,932,878,928,933,023

–36,127,890,984,789,307,394,520,932,878,928,917,398

= $(125\ \text{GeV})^2$! ?

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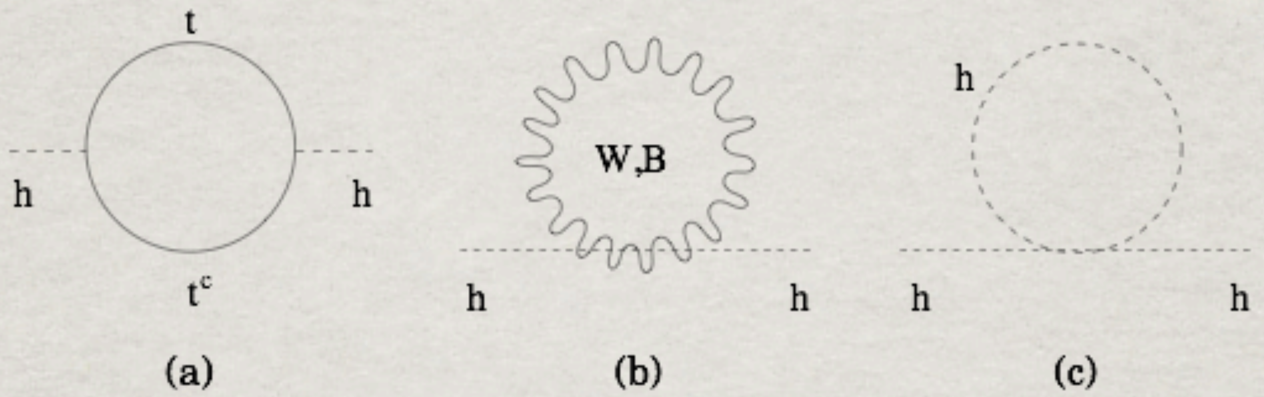

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= $(125\ \text{GeV})^2$! ?

Natural: O(1 TeV) new physics, associated with ttH.

Unknown: Deep UV-IR correlations?

Agnostic: Multiverse/anthropic?

Question 3: The Dark Sector

The un-protected operator may reveal secret

Higgs portal: $k_s H^\dagger H \ S^* S, \quad \frac{k_\chi}{\Lambda} H^\dagger H \ \bar{\chi}\chi.$

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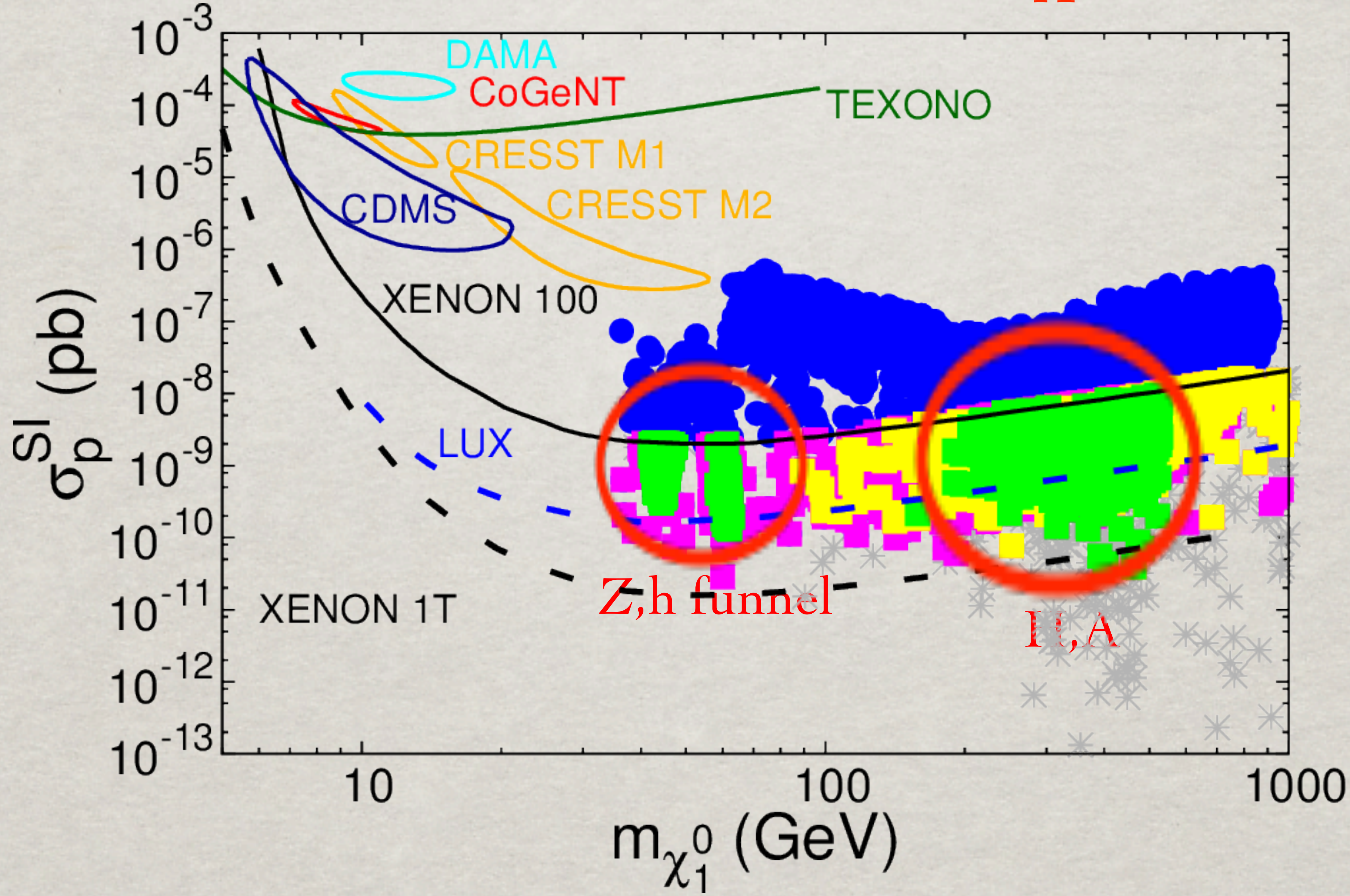
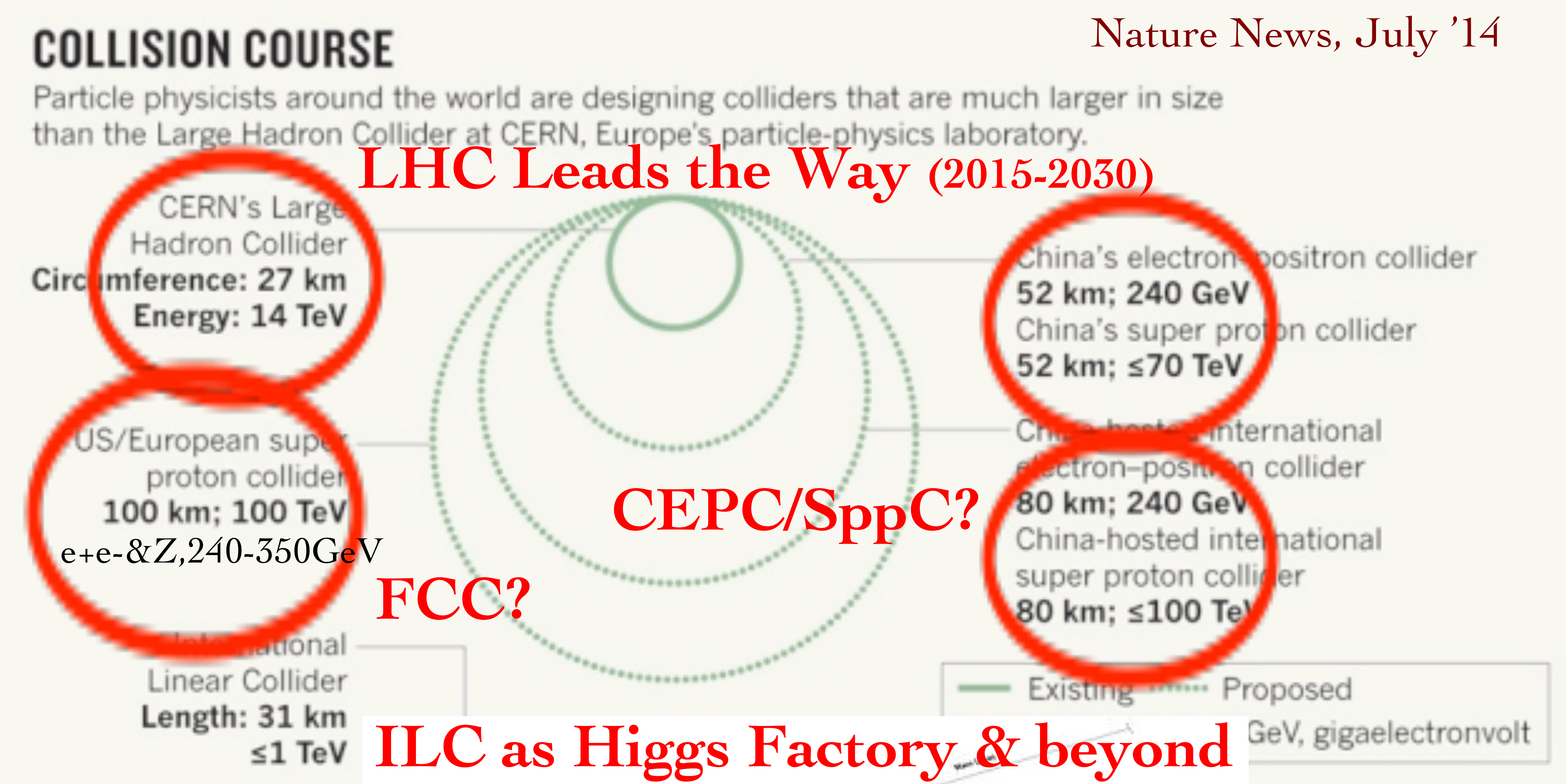
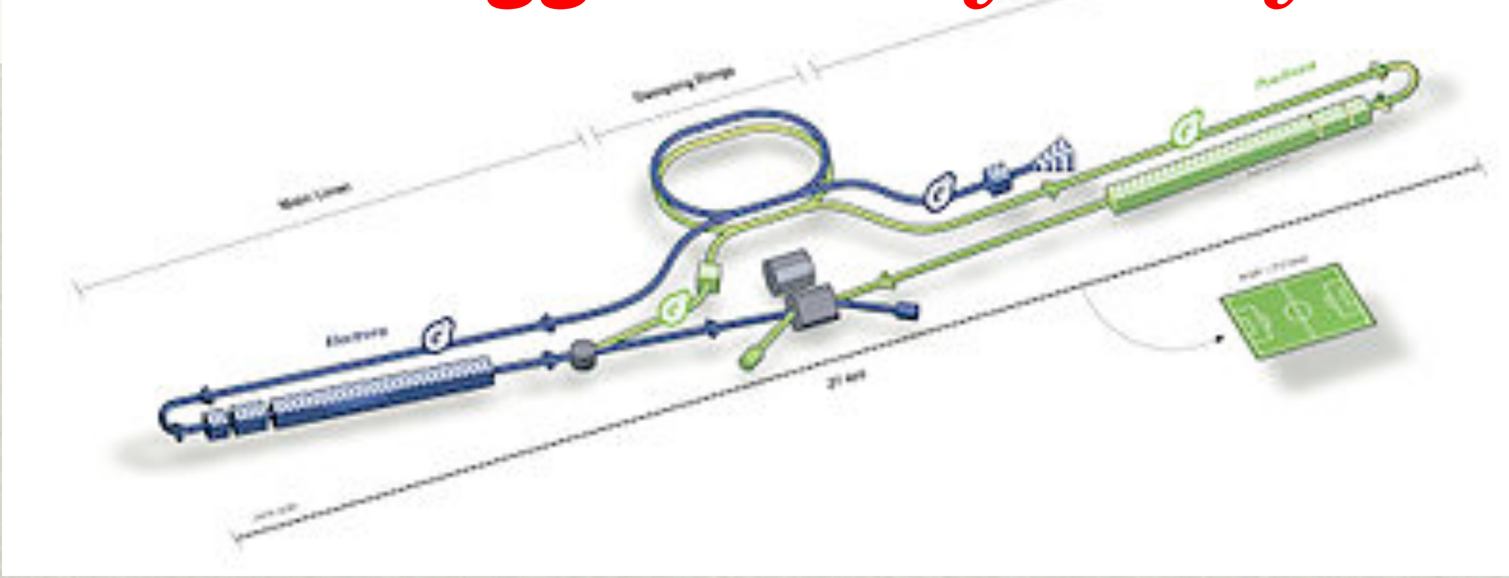


TH, Z.Liu, A.Natarajan, arXiv:1303.3040


Nature News, July '14
COLLISION COURSE
Particle physicists around the world are designing colliders that are much larger in size than the Large Hadron Collider at CERN, Europe's particle-physics laboratory.
LHC Leads the Way (2015-2030)
CERN's Large Hadron Collider
Circumference: 27 km
Energy: 14 TeV
US/European super proton collider
100 km; 100 TeV
e+e-&Z,240-350GeV
FCC?
CEPC/SppC?
China's electron-positron collider
52 km; 240 GeV
China's super proton collider
52 km; ≤70 TeV
China-hosted international electron–positron collider
80 km; 240 GeV
China-hosted international super proton collider
80 km; ≤100 TeV
International Linear Collider
Length: 31 km
≤1 TeV
Existing
Proposed
GeV, gigaelectronvolt
ILC as Higgs Factory & beyond



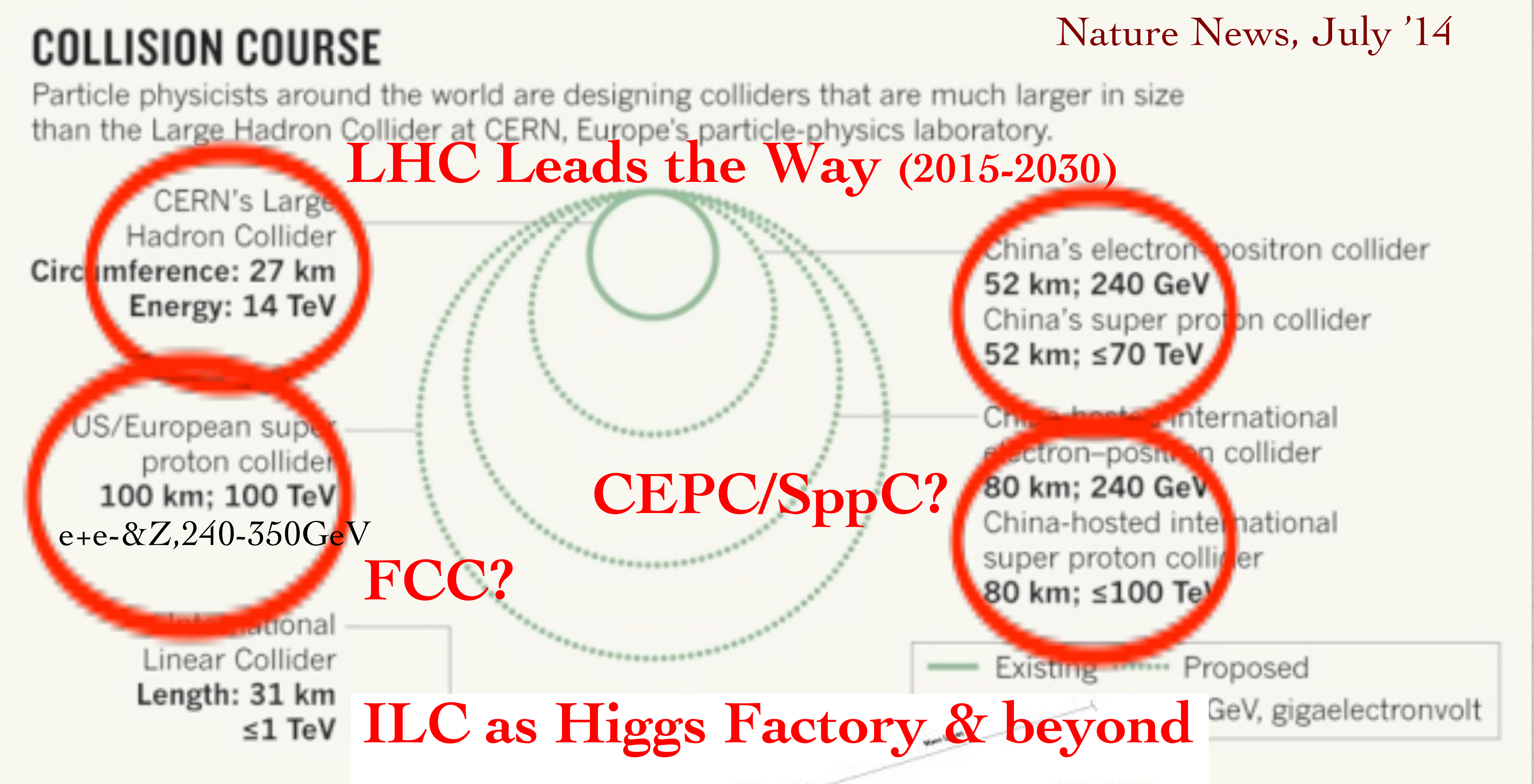


Table 1-1. *Proposed running periods and integrated luminosities at each of the center-of-mass energies for each facility.*

Snowmass 1310.8361

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\overline{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
dt (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

ILC:
(Hitoshi Yamamoto, 2015)

Academic Experts Committee Interim Summary

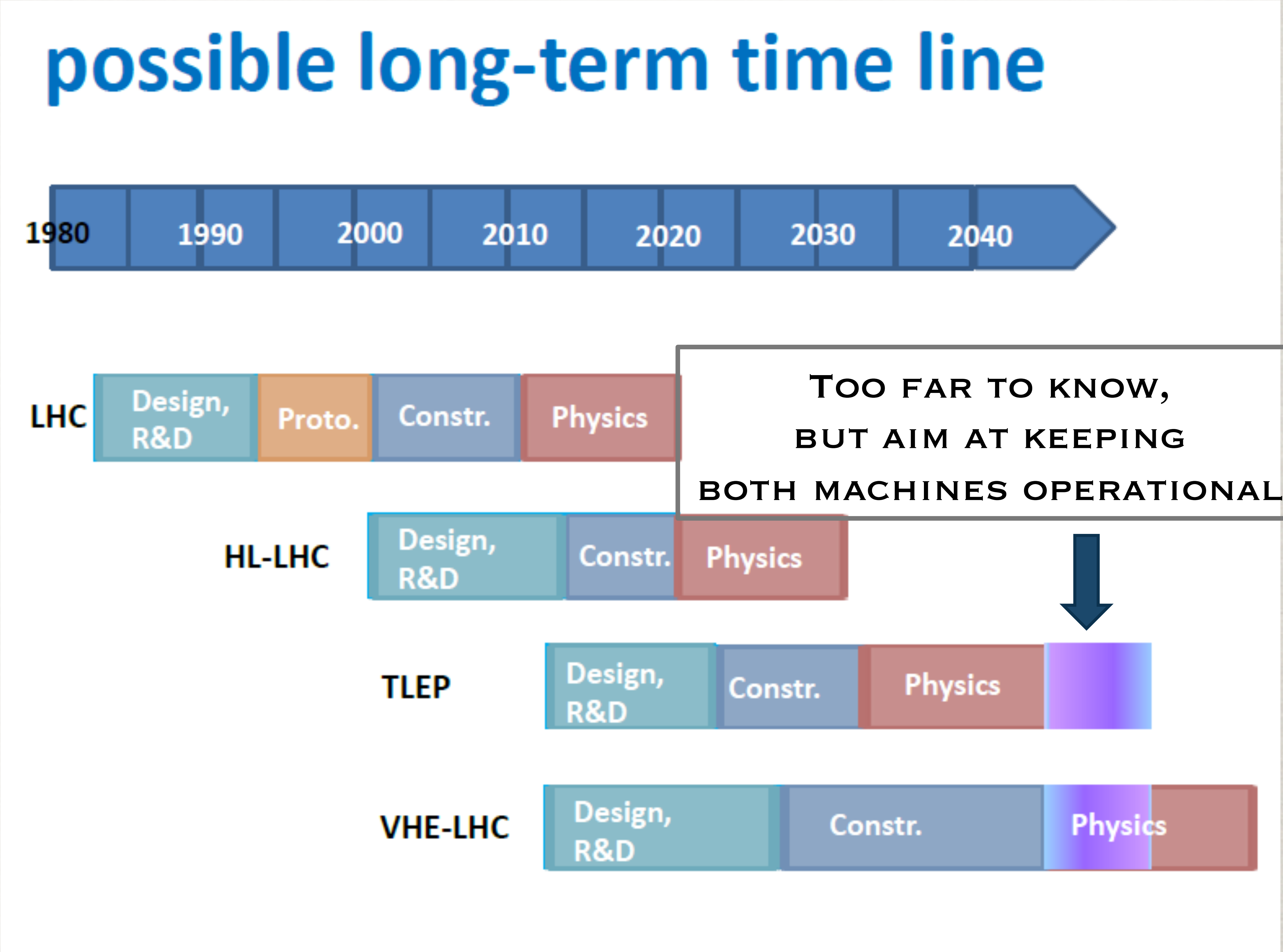
Recommendation 1: The ILC project requires huge investment that is so huge that a single country cannot cover, thus it is indispensable to share the cost internationally. From the viewpoint that the huge investments in new science projects must be weighed based upon the scientific merit of the project, a clear vision on the discovery potential of new particles as well as that of precision measurements of the Higgs boson and the top quark has to be shown so as to bring about novel development that goes beyond the Standard Model of the particle physics.

Recommendation 2: Since the specifications of the performance and the scientific achievements of the ILC are considered to be designed based on the results of LHC experiments, which are planned to be executed through the end of 2017, it is necessary to closely monitor, analyze and examine the development of LHC experiments. Furthermore, it is necessary to clarify how to solve technical issues and how to mitigate cost risk associated with the project.

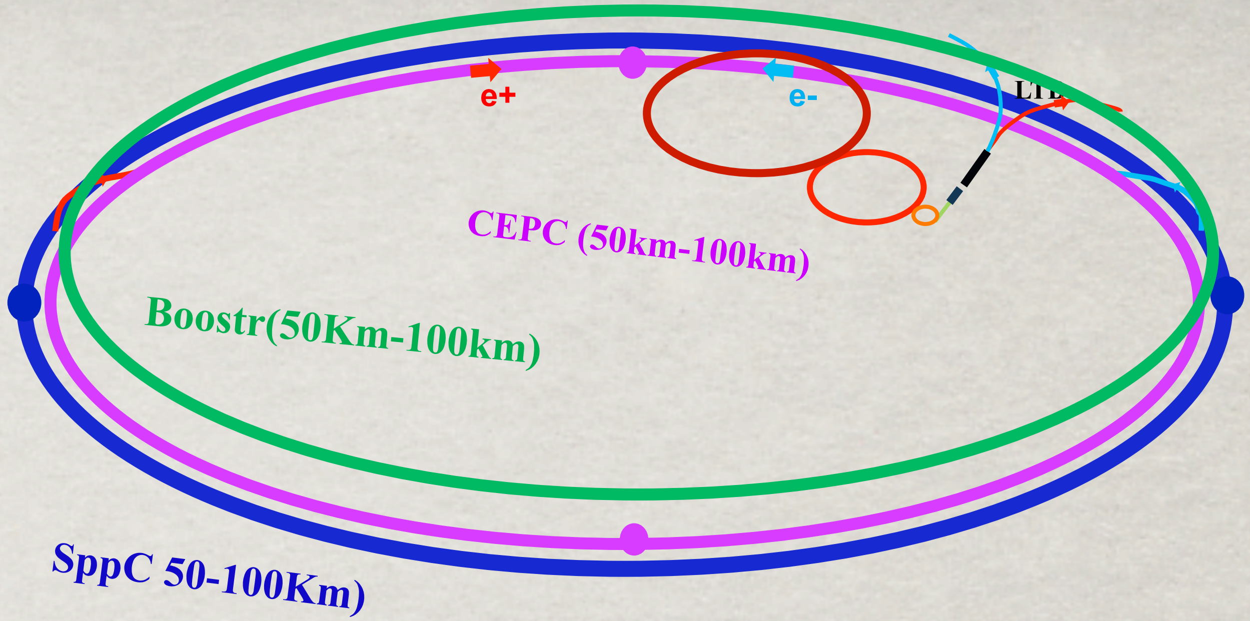
Recommendation 3: While presenting the total project plan, including not only the plan for the accelerator and related facilities but also the plan for other infrastructure as well as efforts pointed out in Recommendations 1 & 2, it is important to have general understanding on the project by the public and science communities.

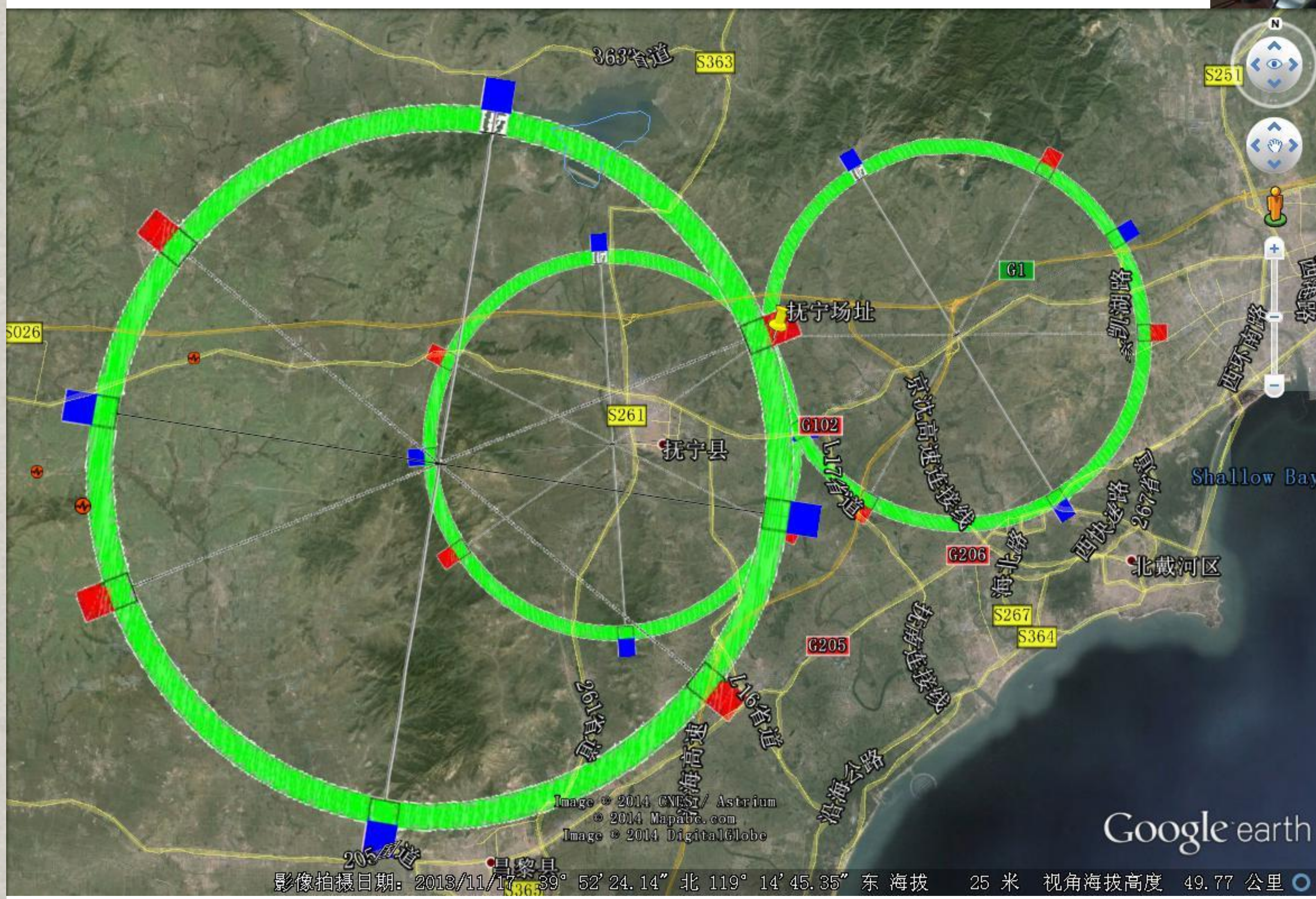
TLEP/VHE-LHC:

F. Zimmermann



CEPC/SPPC





QingHuangDao site Investigation

- 300km from Beijing
- Geo well suited
- Great environment

CEPC/SPPC:

Yifang Wang

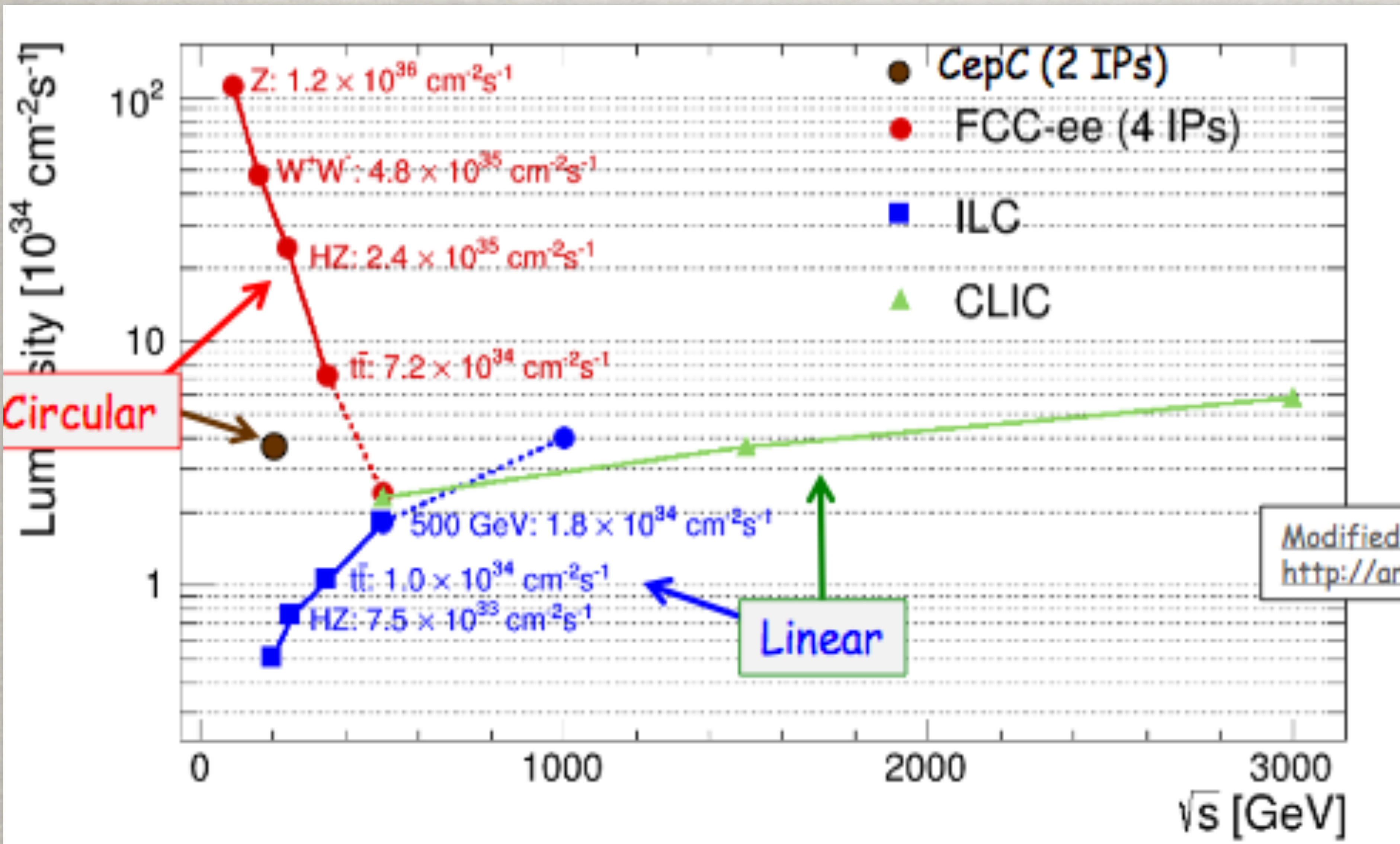
技术上

(理想的) 时间进度安排

- **CEPC（建设：2021-2028）**
  - 预先研究及准备工作
    - 2014年底之前完成 pre-CDR，争取纳入十三五规划
    - 预研：2016-2020
    - 工程设计: 2016-2020
  - 建设: 2021-2027
  - 数据获取: 2028-2035
- **SppC（建设：2035-2042）**
  - 预先研究及准备工作
    - 预先研究：2014-2030
    - 工程设计: 2030-2035
  - 建造: 2035-2042
  - 数据获取: 2042 - 2055

显然具体过程不会如此简单，应该有：
概念设计评审
预研项目申请与审批
项目建议书评审
工程设计评审
国际评审
。。。

e^+e^- colliders: Energy/Lumi projection



TLEP Report: 1308.6176

E_{cm}	running time	statistics (FCC-ee)
	b,c,τ	10^{11} b,c,τ
90 GeV	1-2 yrs	10^{12} Z (Tera Z)
160 GeV	1-2 yrs	10^8- 10^9 WW(Oku W)
240 GeV	4-5 yrs	$2x10^6$ ZH (Mega H)
350 GeV	4-5 yrs	10^6 tt (Mega top)

Precision Higgs Physics

In a pessimistic scenario, the LHC does not see a new particle associated with the Higgs sector, then the effects of a heavy state on Higgs coupling g_i at the scale M:

$$\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2)$$ ≈ a few % for M ≈ 1 TeV

If no deviations, I'd DEFINE it THE SM Higgs!

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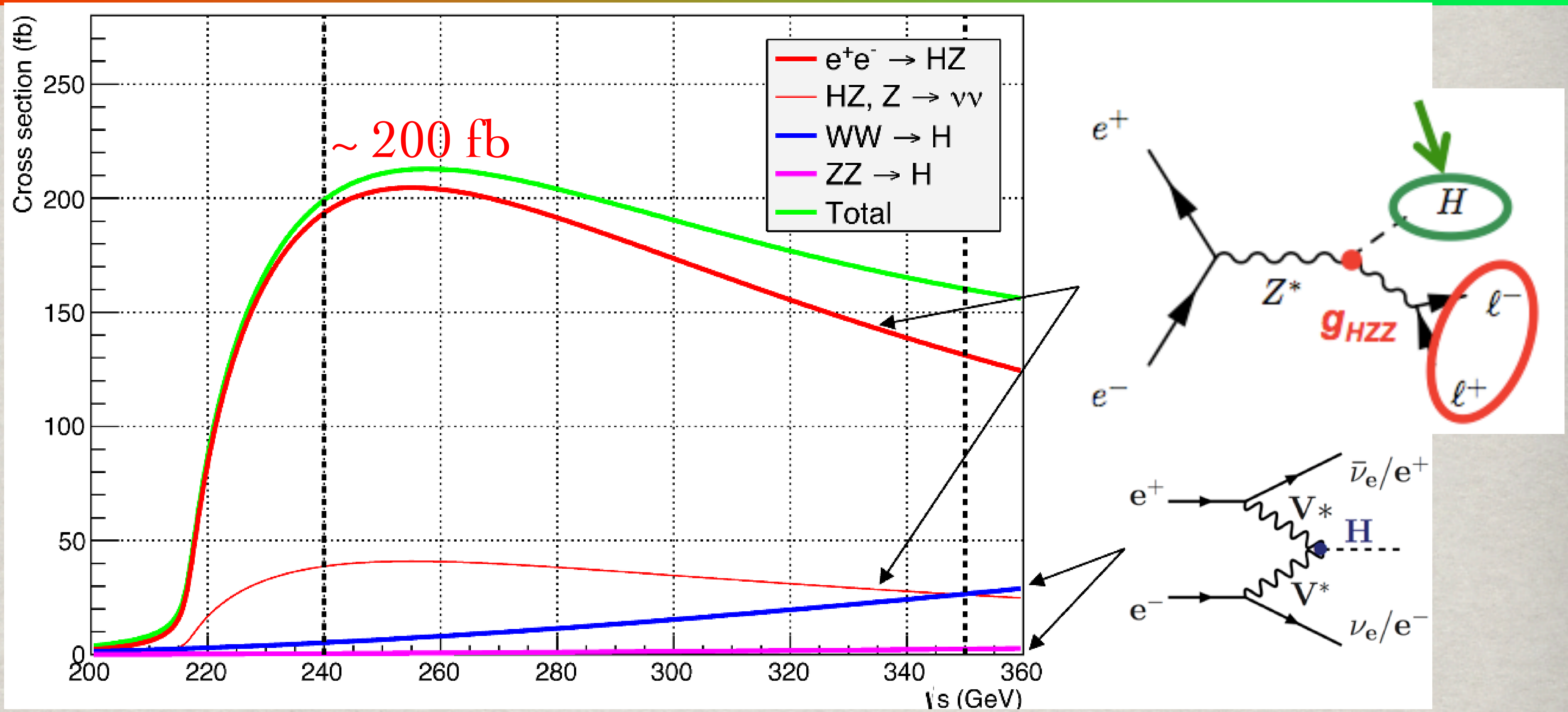
$$\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2) \approx \text{a few \% for } M \approx 1 \text{ TeV}$$

If no deviations, I'd DEFINE it THE SM Higgs!

Higgs coupling deviations:

Δ:	VVH	bbH,ττH	ggH,γγH	HHH
Composite	(3-9)%	$(1\ \text{TeV}/f)^2$	(tree-level)	100%
H^0, A^0		$6\%\ (500\ \text{GeV}/M_A)^2$		
T'			$-10\%\ (1\ \text{TeV}/M_T)^2$ (loop)	
LHC 14 TeV, $3ab^{-1}$:	8%	15%	few%	50%

Higgs-Factory: Mega (10^6) Higgs Physics



ILC Report: 1308.6176

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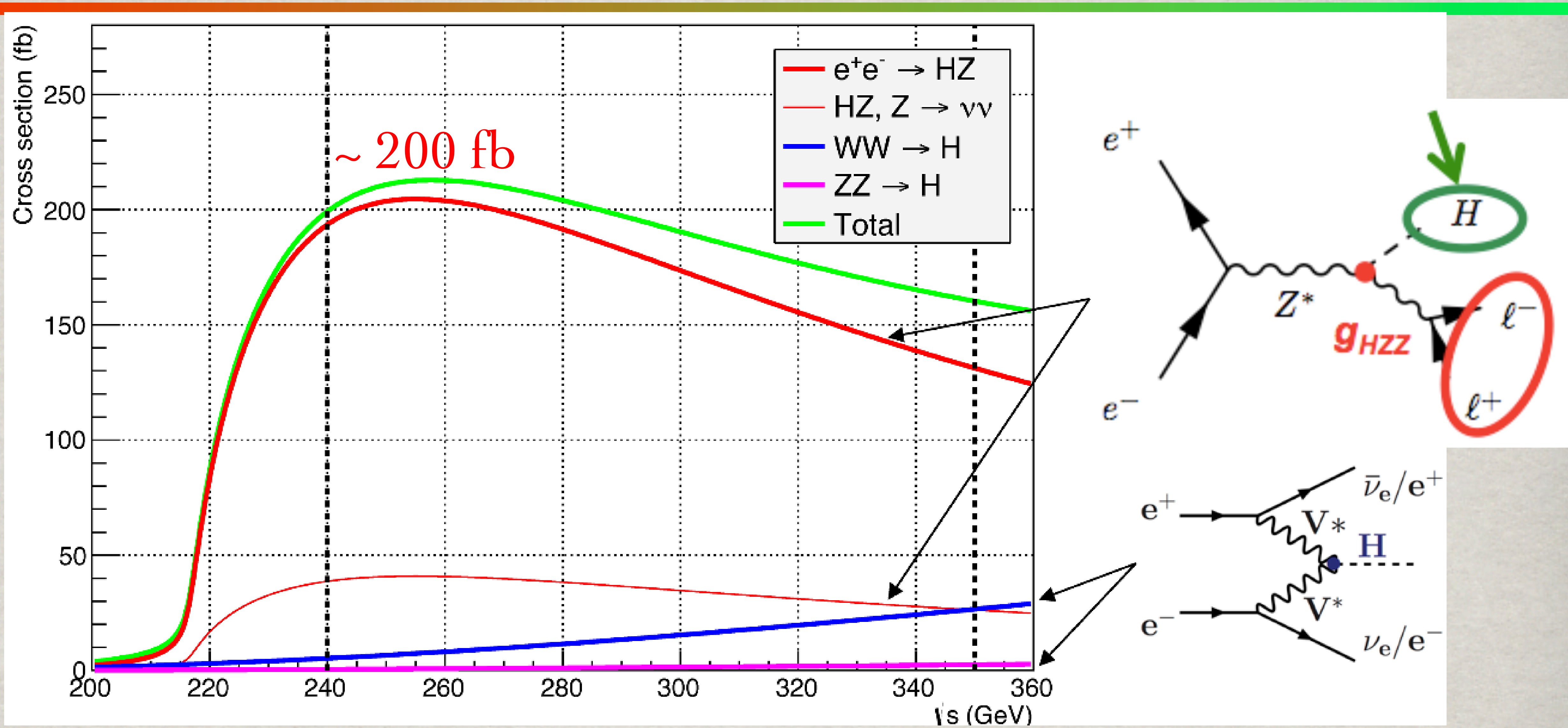


ILC: E_{cm} = 250 (500) GeV, 250 (500) fb^{-1}

- Model-independent measurement: ILC Report: 1308.6176

  $\Gamma_H \sim 6\%$, $\Delta m_H \sim 30$ MeV

  (HL-LHC: assume SM, $\Gamma_H \sim$ 5-8%, $\Delta m_H \sim 50$ MeV)
- TLEP 10^6 Higgs: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

TLEP Report: 1308.6176

• Comparison (FCC_{ee}/TLEP 4IP)

Snowmass Higgs Working Group: 1310.8361

Coupling	HL-LHC	ILC	FCC-ee
k_W	2-5%	1.2%	0.19%
k_Z	2-4%	1.0%	0.15%
k_b	4-7%	1.7%	0.42%
k_c	–	2.8%	0.71%
k_τ	2-5%	2.4%	0.54%
k_μ	~10%	91%	6.2%
k_g	2-5%	8.4%	1.5%
k_γ	3-5%	2.3%	0.8%
k_{Zg}	~12%	?	?
BR_{invis}	~10-15%?	< 0.9%	< 0.19%
Γ_H	~50%?	5.0%	1.0%
k_t	7-10%	14%	13% (*)
k_H	30-50% ?	80%	80%(*)

Model-independent results
HL-LHC(3 ab^{-1}),
ILC(0.25,0.5,1 ab^{-1}), TLEP(10 ab^{-1})

Sensitive to new physics at tree level
Expected effects < 5% / Λ^2_{NP}

Sensitive to new physics in loops

Sensitive to light dark matter; exotic decays

Need higher energies

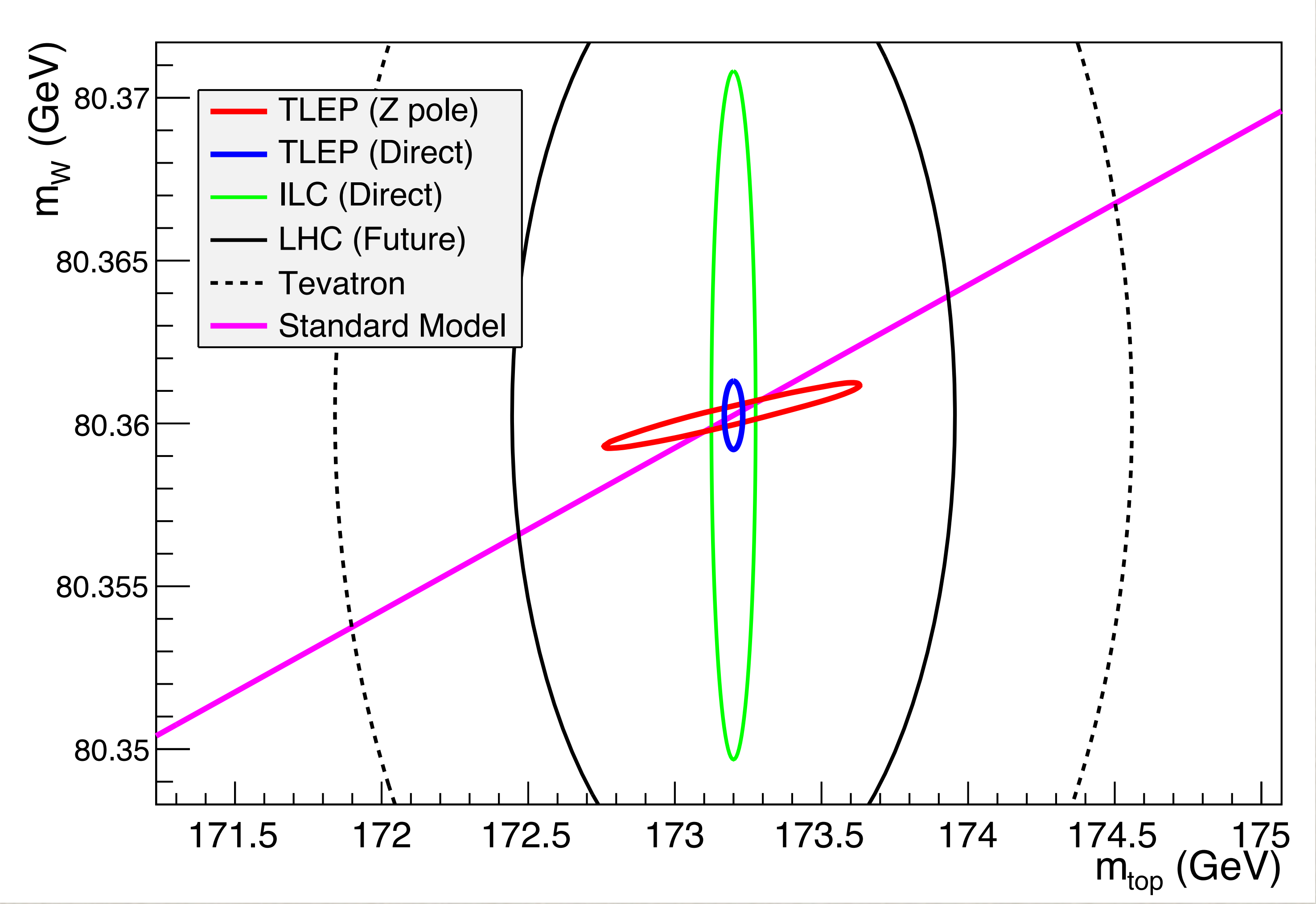
Z-Factory: Tera (10^{12}) Z Physics

TLEP Report: 1308.6176

- Clean environment, $\Delta E_{cm} < 1$ MeV, 10^5 x LEP-I
- possible longitudinal polarization
- Precision measurements (statistical):

Z-ploe: ΔM_Z, $\Delta \Gamma_Z < 0.1$ MeV, $\Delta \sin^2\theta_w < 10^{-6}$;

$\Delta M_W \sim O(1\ \text{MeV})$, $\Delta m_t \sim O(10\ \text{MeV})$, $\Delta m_H \sim O(10\ \text{MeV})$.



Z-Factory: Tera (10^{12}) Z Physics

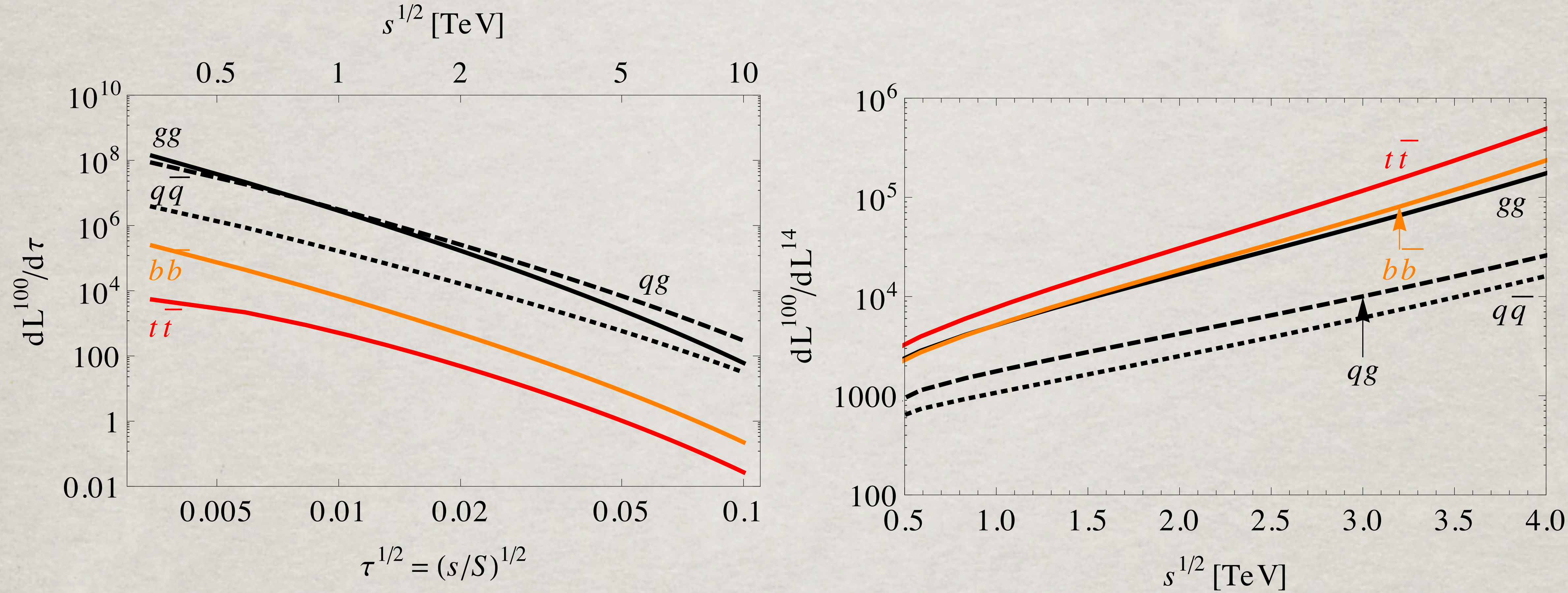
- Flavor physics & CP violation:
  with $O(10^{11})$ B-hadrons: Bs oscillation, Bc …
  complementary to LHCb, Belle II.

- Indirect new physics probe (Z'…):
  $\delta \sim (v/\Lambda)^2$, sensitivity reach $\Lambda \sim 10$ TeV.

- However, systematics dominance!
  must control theoretical errors!

- It calls for heroic theory efforts:
  largest uncertainty from running α_{QED}
  (low energy hadronic contributions)
  3-loop EW; multi-loop QCD …

The Next Energy Frontier:
100 TeV Hadron Collider



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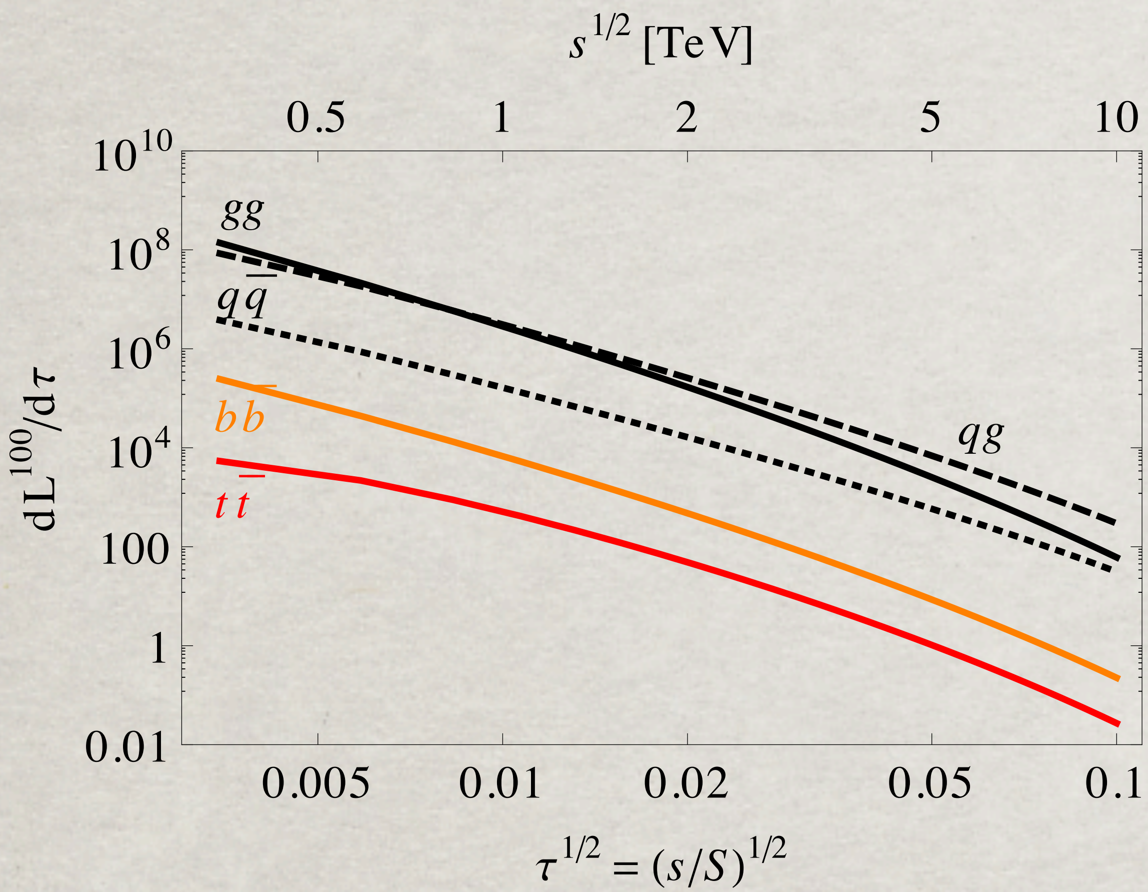
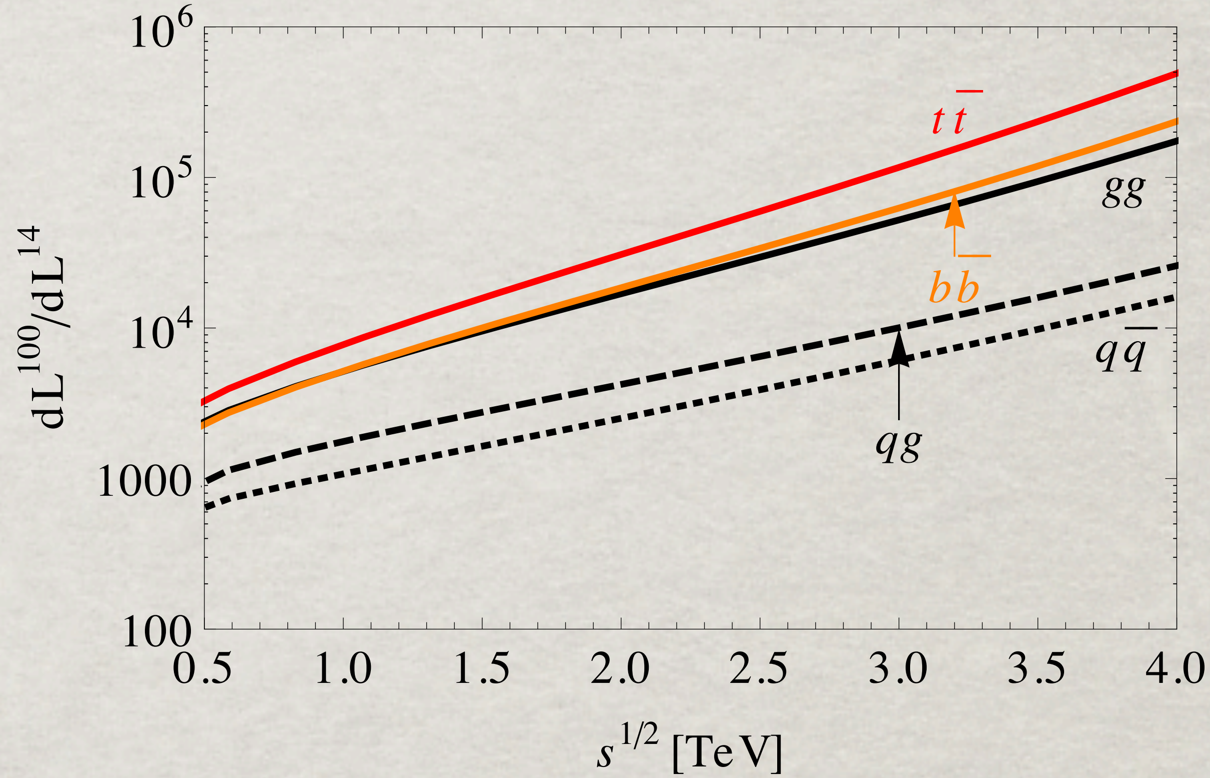
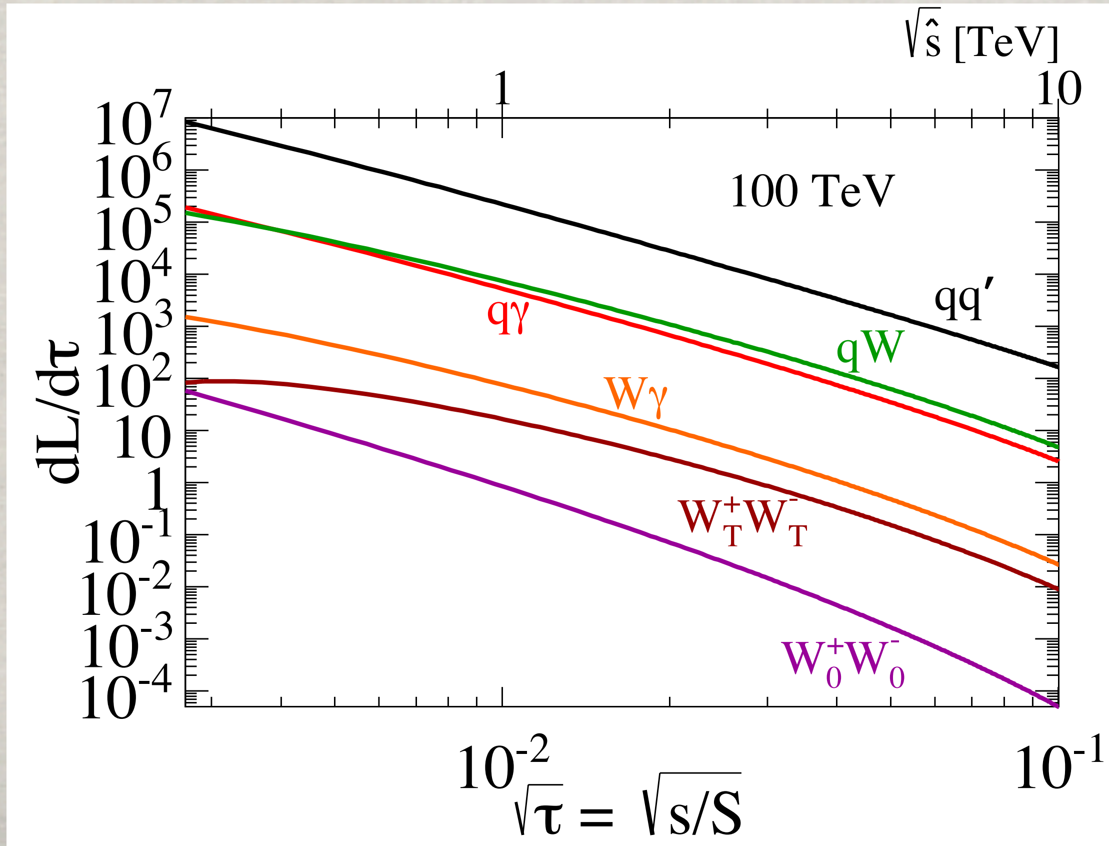
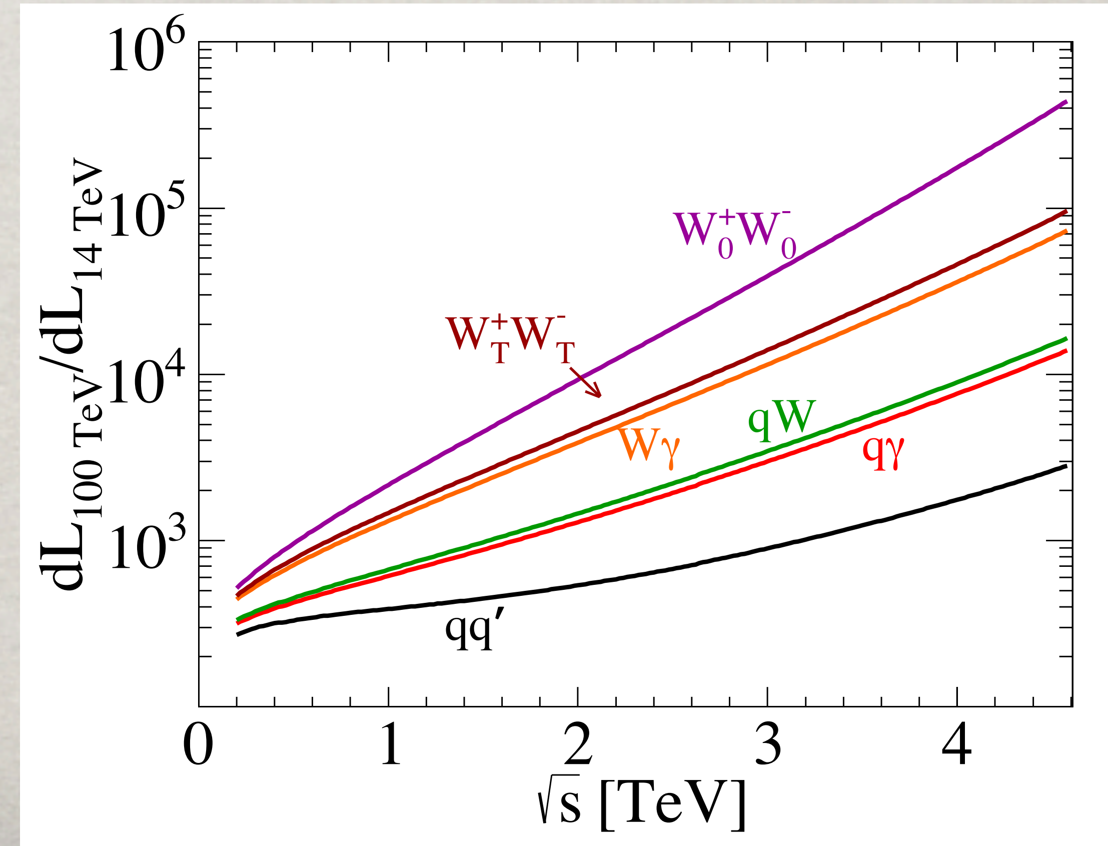
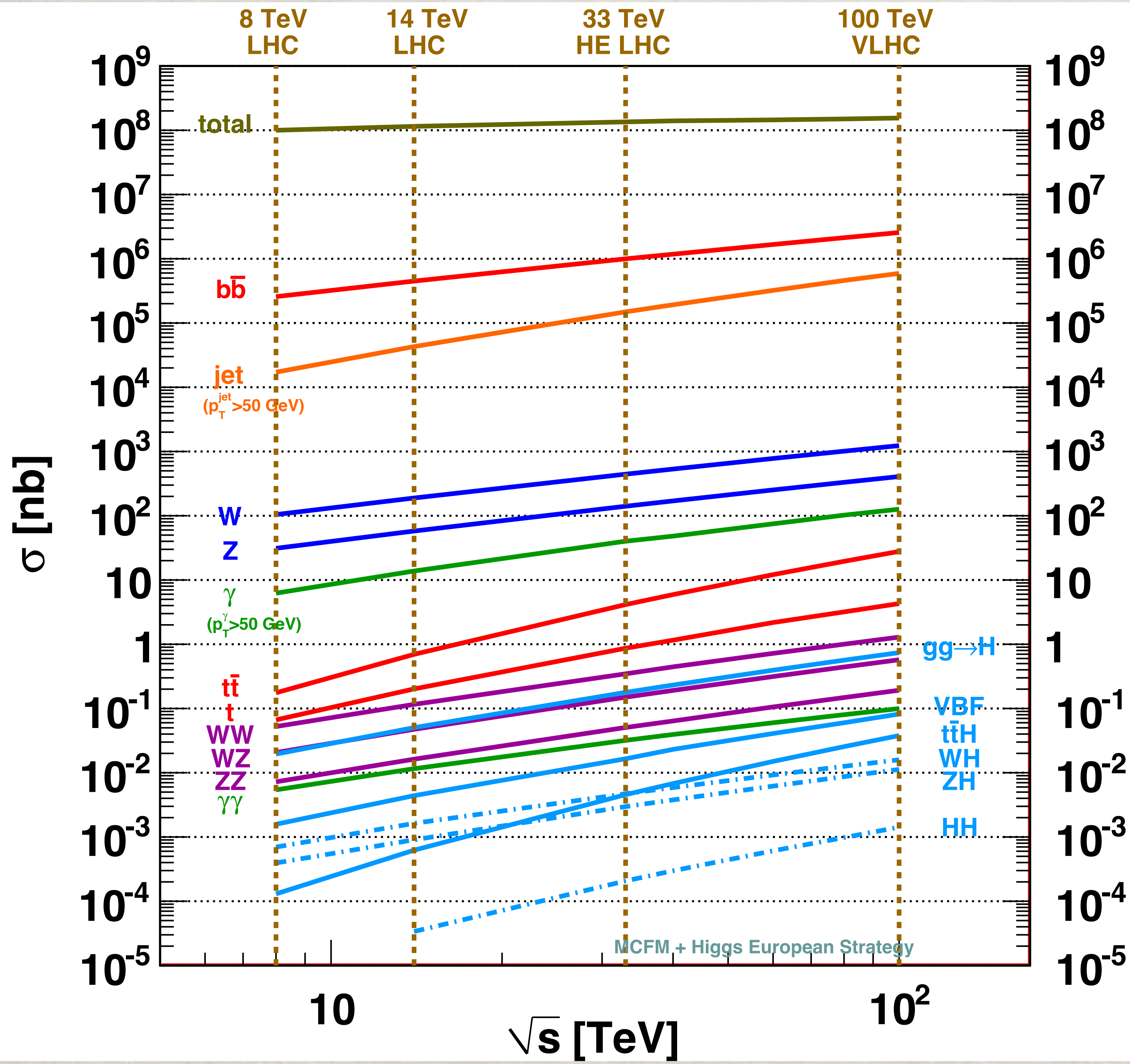








Higgs Production @ FCC_{hh}/SPPC



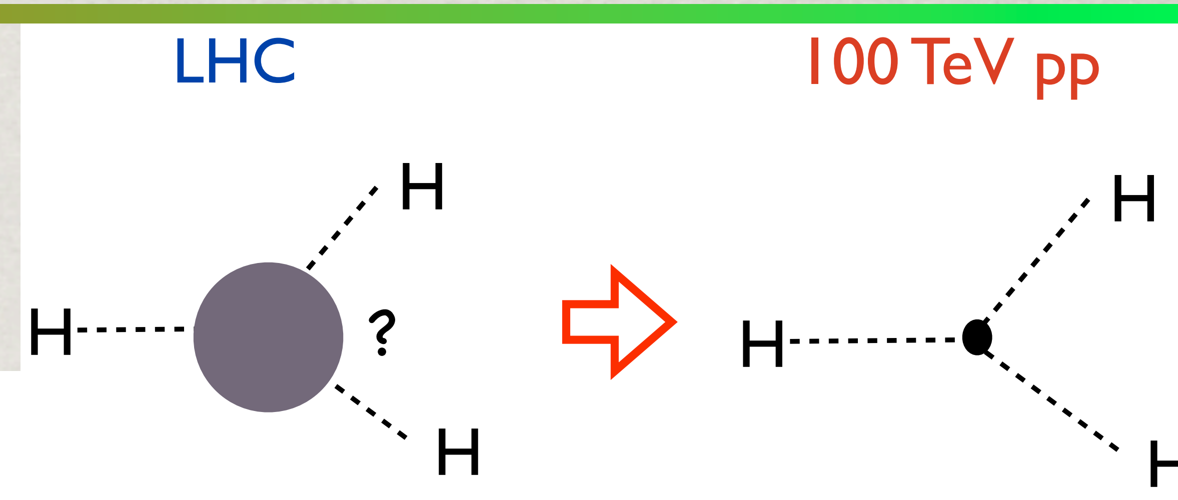
Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

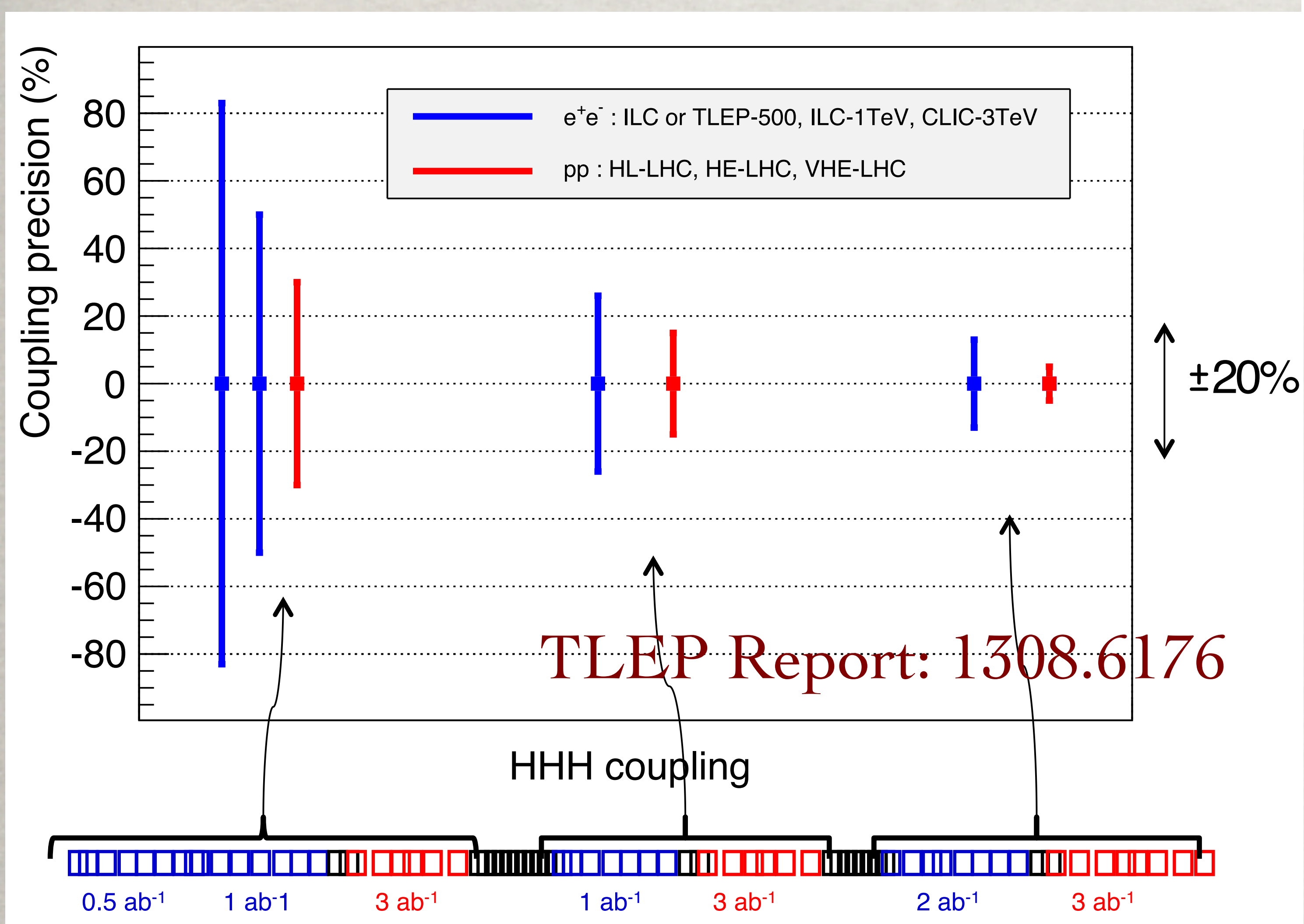
Snowmass QCD Working Group: 1310.5189

Higgs Self-couplings:

$$\mathcal{L} = -\frac{1}{2} m_H^2 H^2 - \frac{g_{HHH}}{3!} H^3 - \frac{g_{HHHH}}{4!} H^4$$

$$g_{HHH} = 6 \;\; v = \frac{3m_H^2}{v}, \qquad g_{HHHH} = 6 \;\; = \frac{3m_H^2}{v^2}.$$





Triple coupling sensitivity:

Test the shape of the Higgs potential, and the fate of the EW-phase transition!

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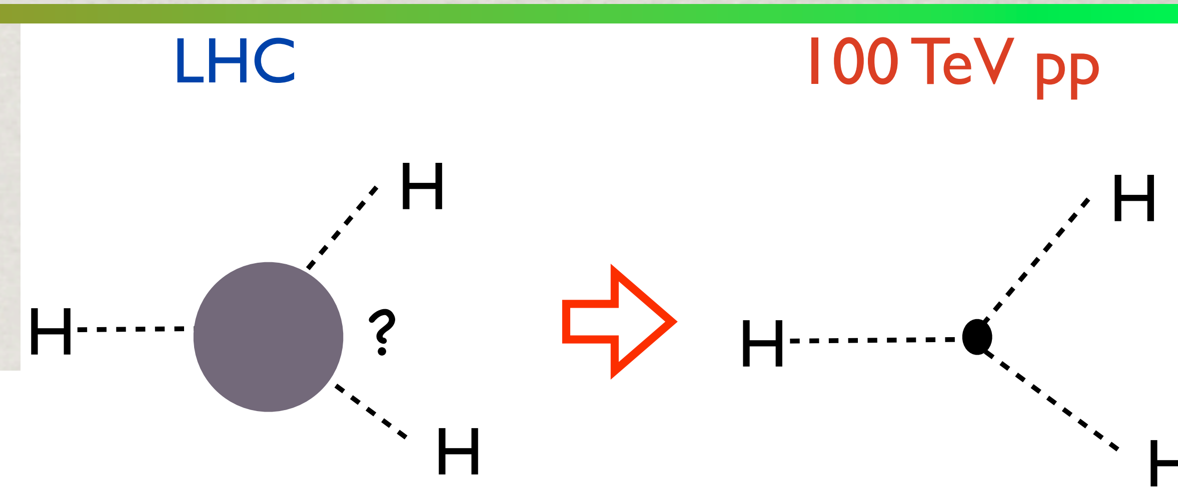
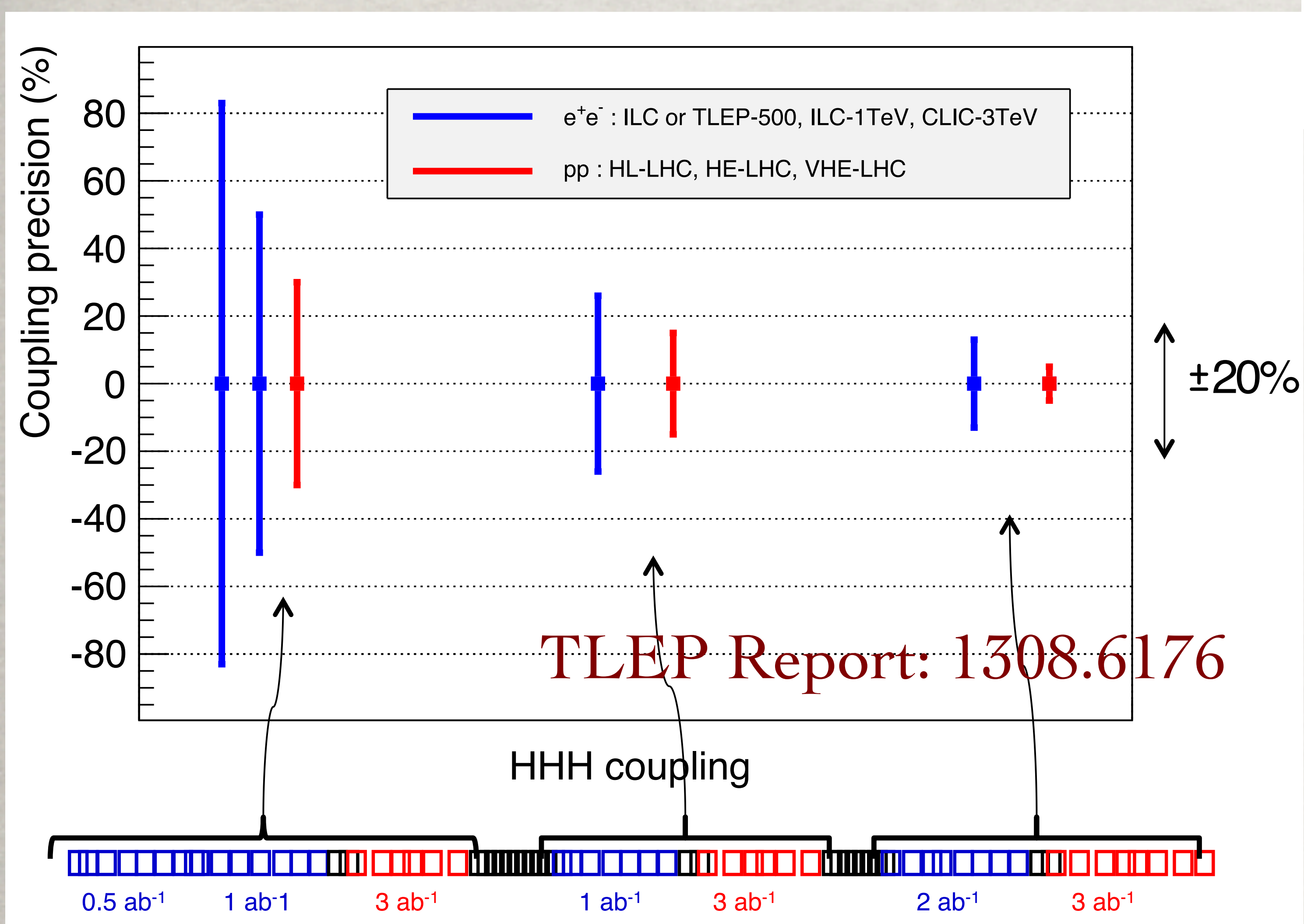
$$g_{HHH} = 6 \;\; v = \frac{3 m_H^2}{v}, \qquad g_{HHHH} = 6 \;\; = \frac{3 m_H^2}{v^2}.$$





TLEP Report: 1308.6176

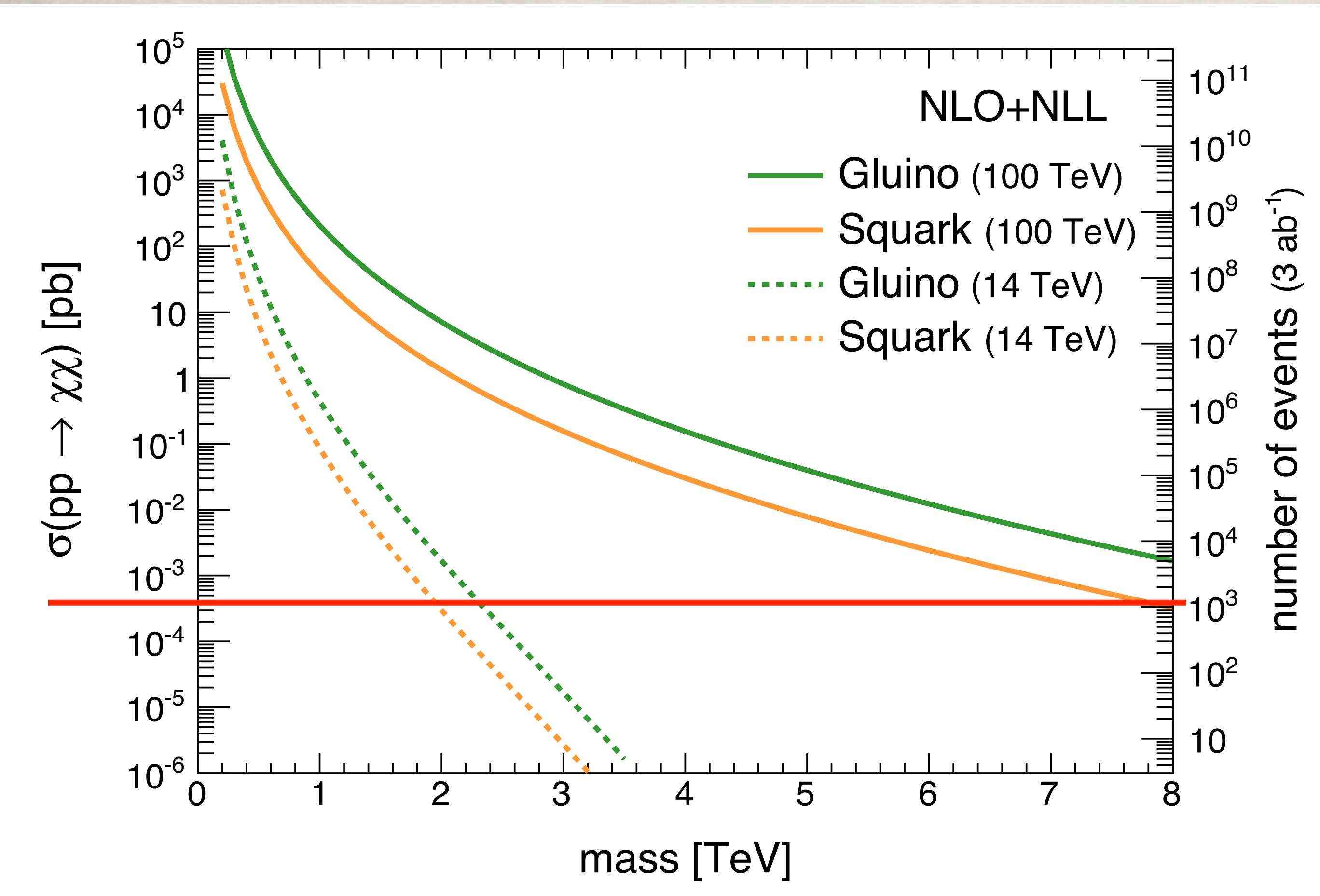
Triple coupling sensitivity:
Test the shape of the Higgs potential, and the fate of the EW-phase transition!

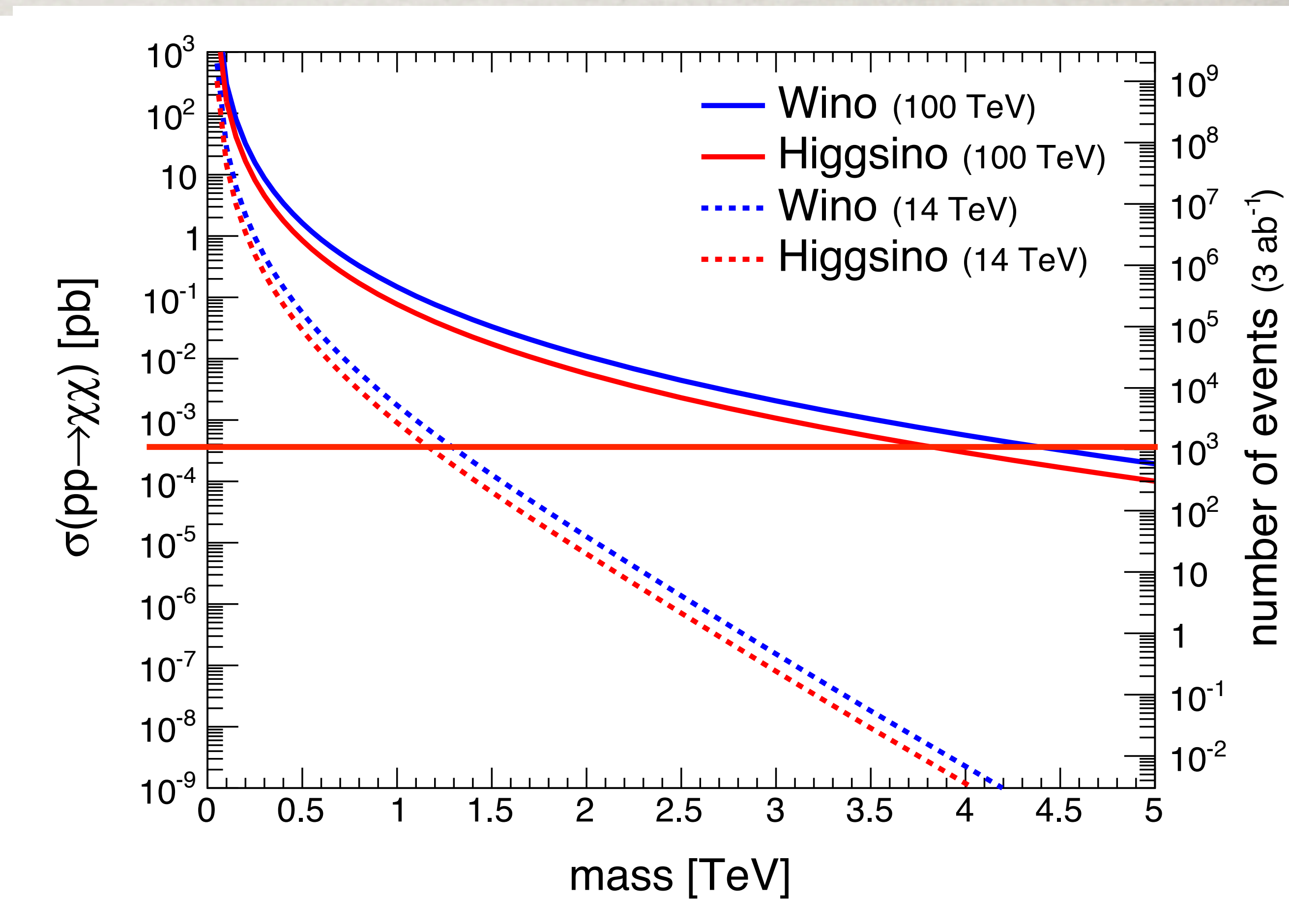
Snowmass 1310.8361

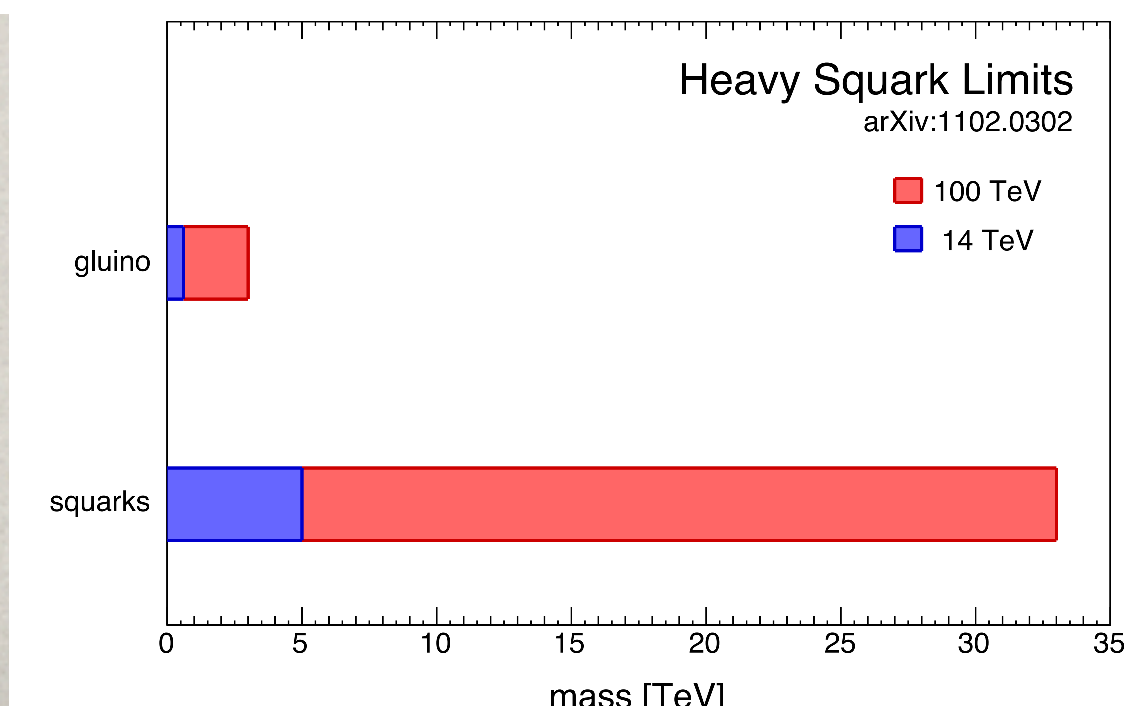
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	1600‡	500+1000	1600+2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

SUSY @ FCC_{hh}/SPPC

M.Mangano et al.: 1407.5066

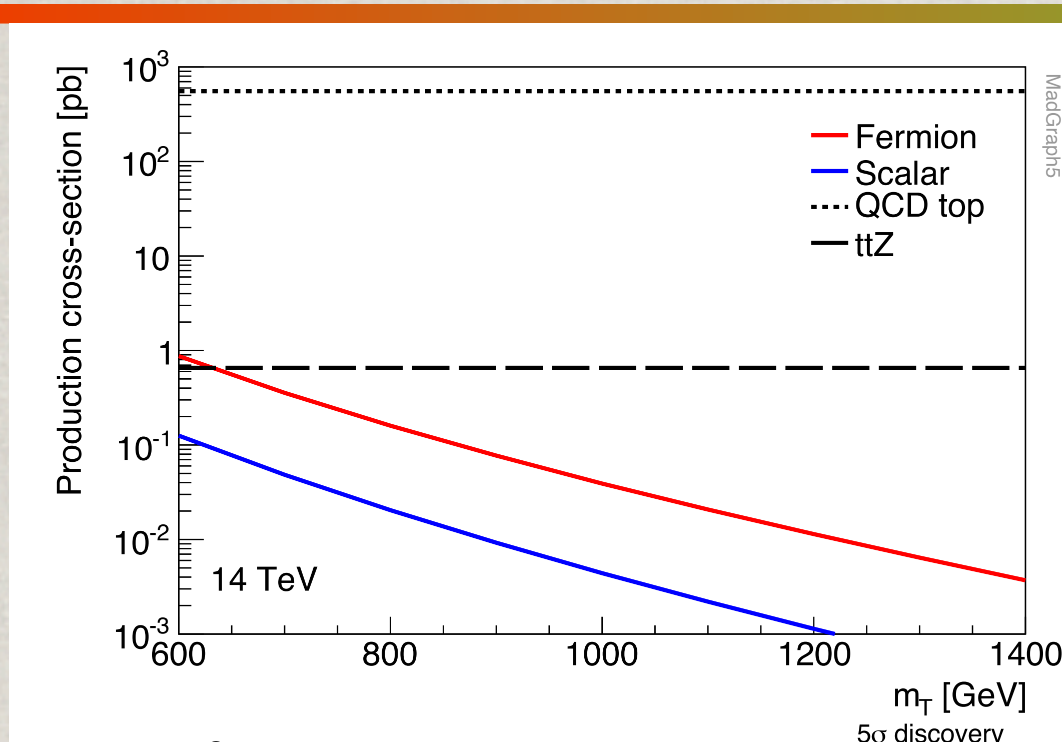


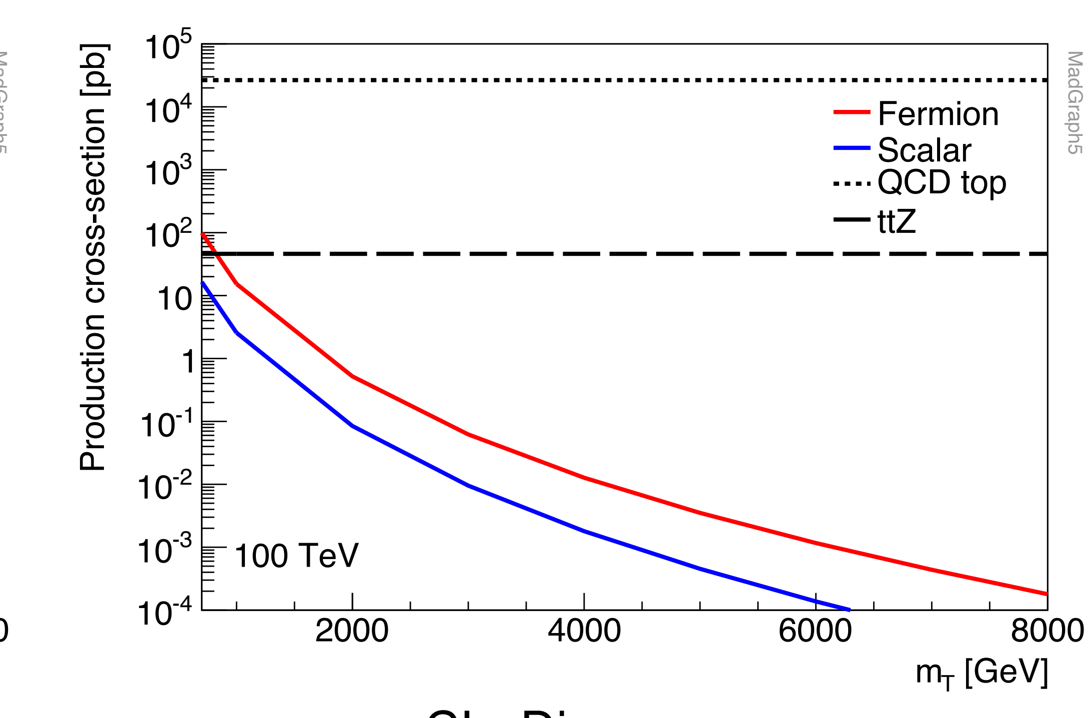


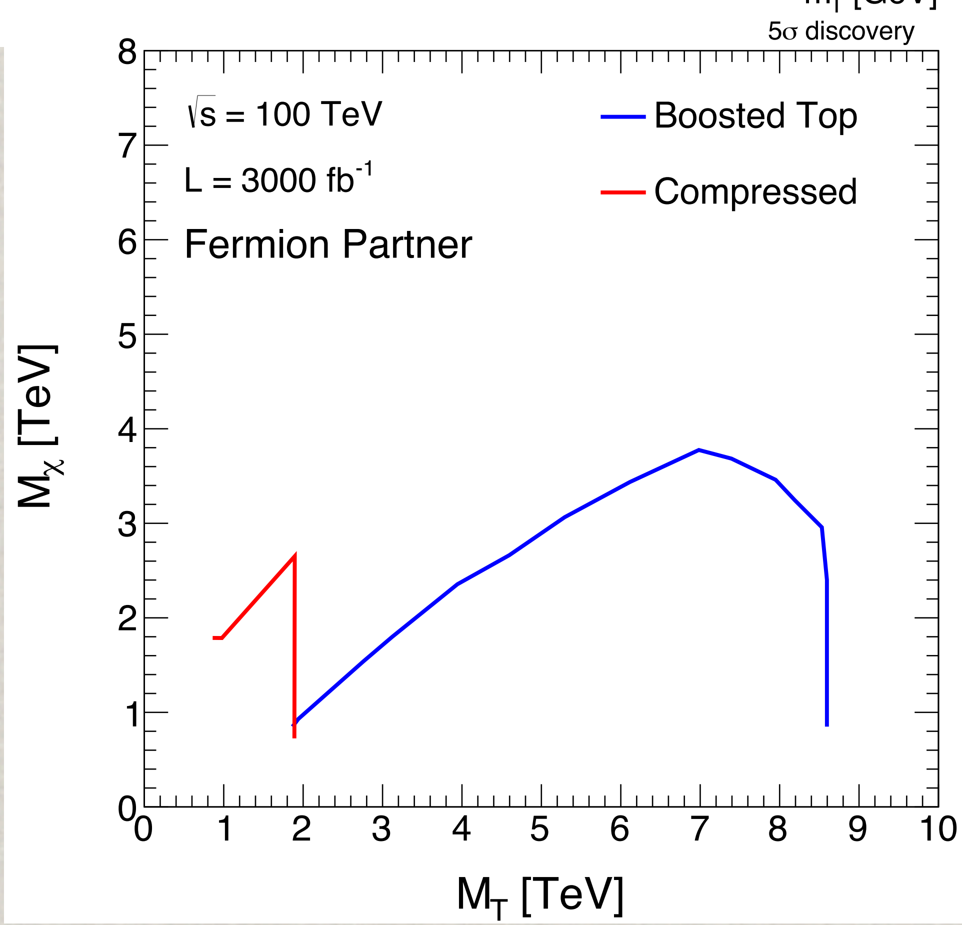


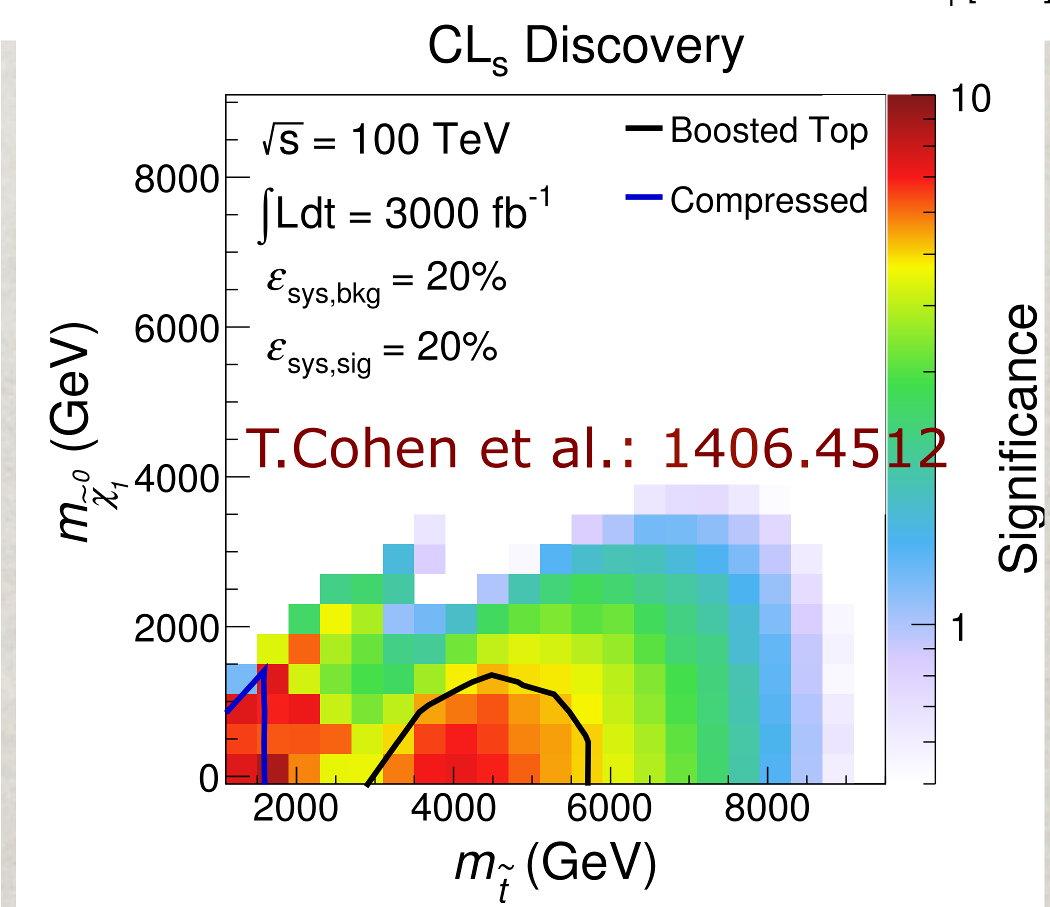
Mass reach at 100 TeV:
~ 7x over LHC

Pushing the “Naturalness” limit









The Higgs mass fine-tune: $\delta m_H / m_H \sim 1\% \, (1 \text{ TeV}/\Lambda)^2$

Thus, $m_{stop} > 8$ TeV → 10^{-4} fine-tune!

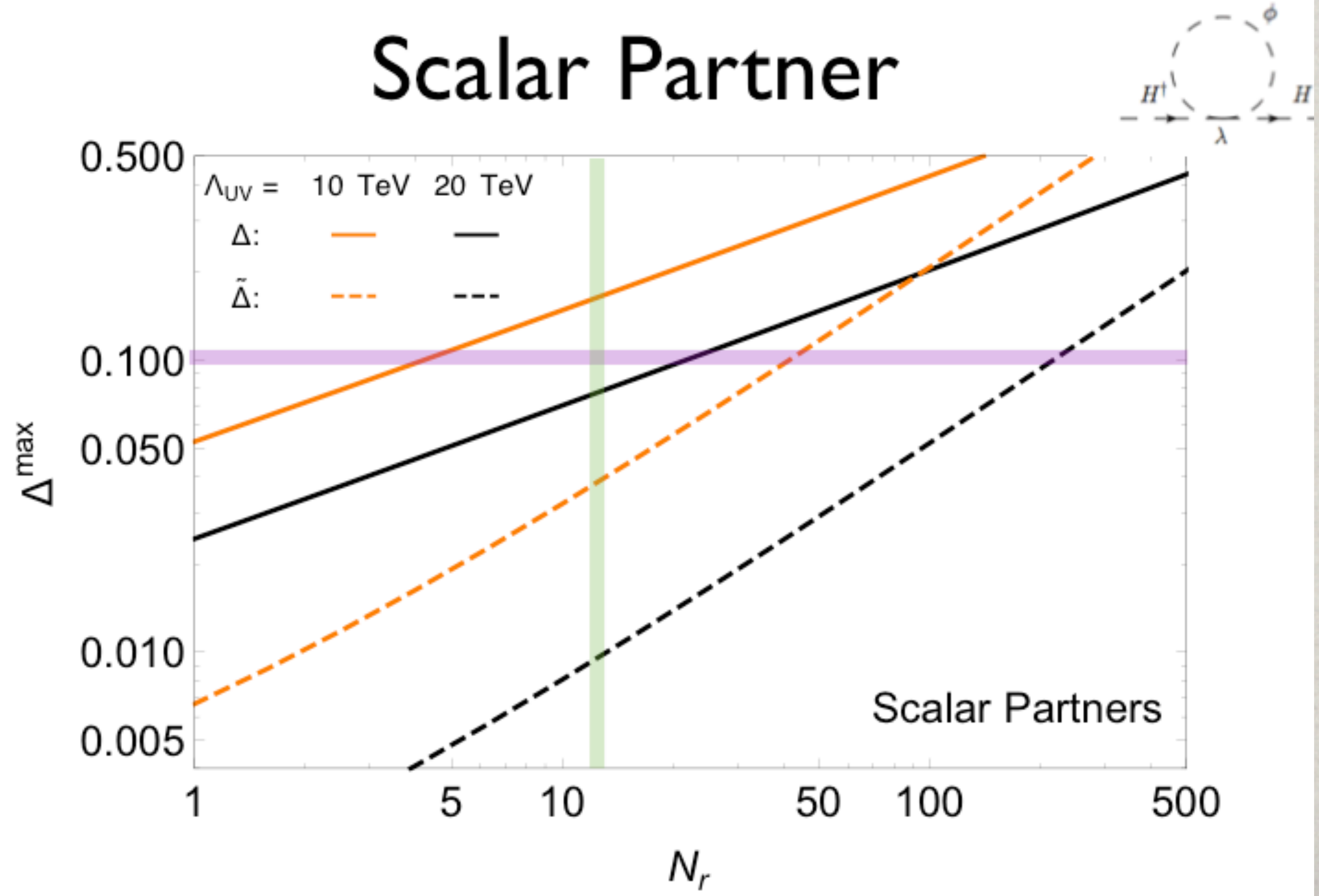
No-Lose(?) for "Natural theory" at $FCC_{ee,hh}$

Irreducible low-E signatures:

- Zh cross section (lepton collider)
- electroweak precision observables (lepton)
- higgs cubic coupling (100 TeV)
- top partner direct production (100 TeV)

1509.04284
(David Curtin's talk)

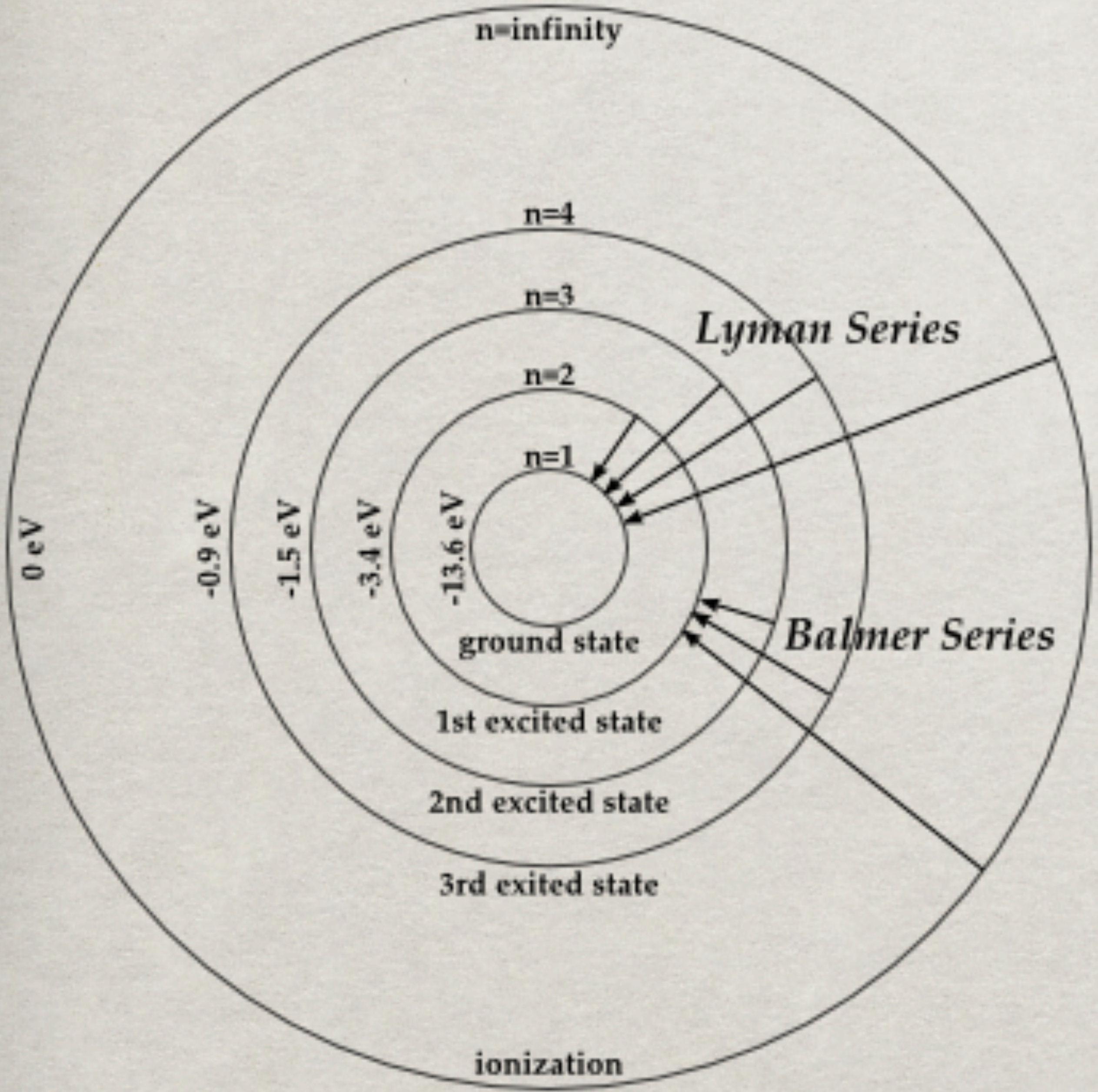
Any theory of ~10% naturalness with O(SM) top partners will be discovered at lepton collider and/or 100 TeV



How much "tune" is fine-tuned?

Atomic physics:

Rydberg const. **$E_0 \sim \alpha^2 m_e \rightarrow O(25\ eV)$,** very natural!



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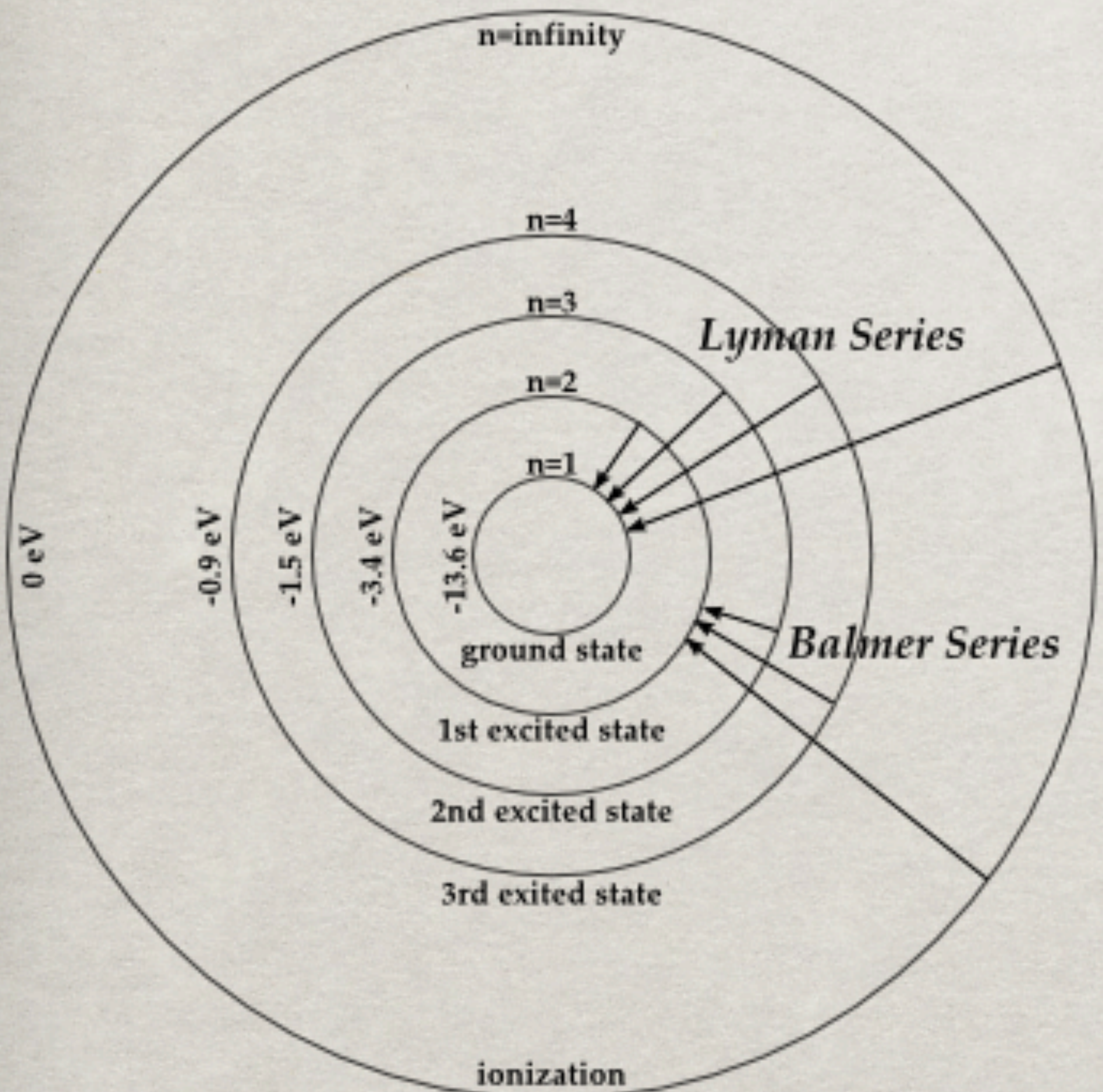
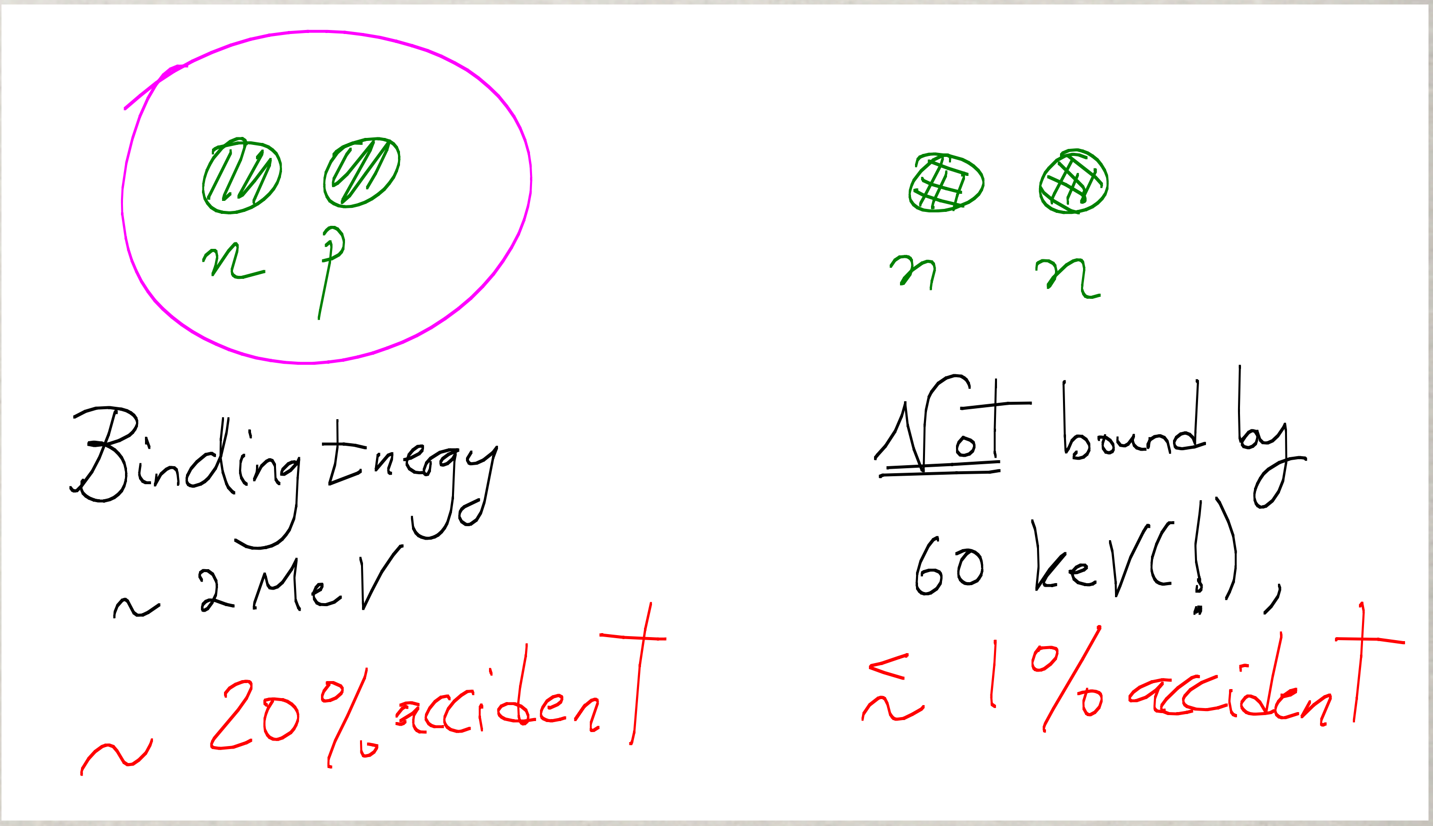
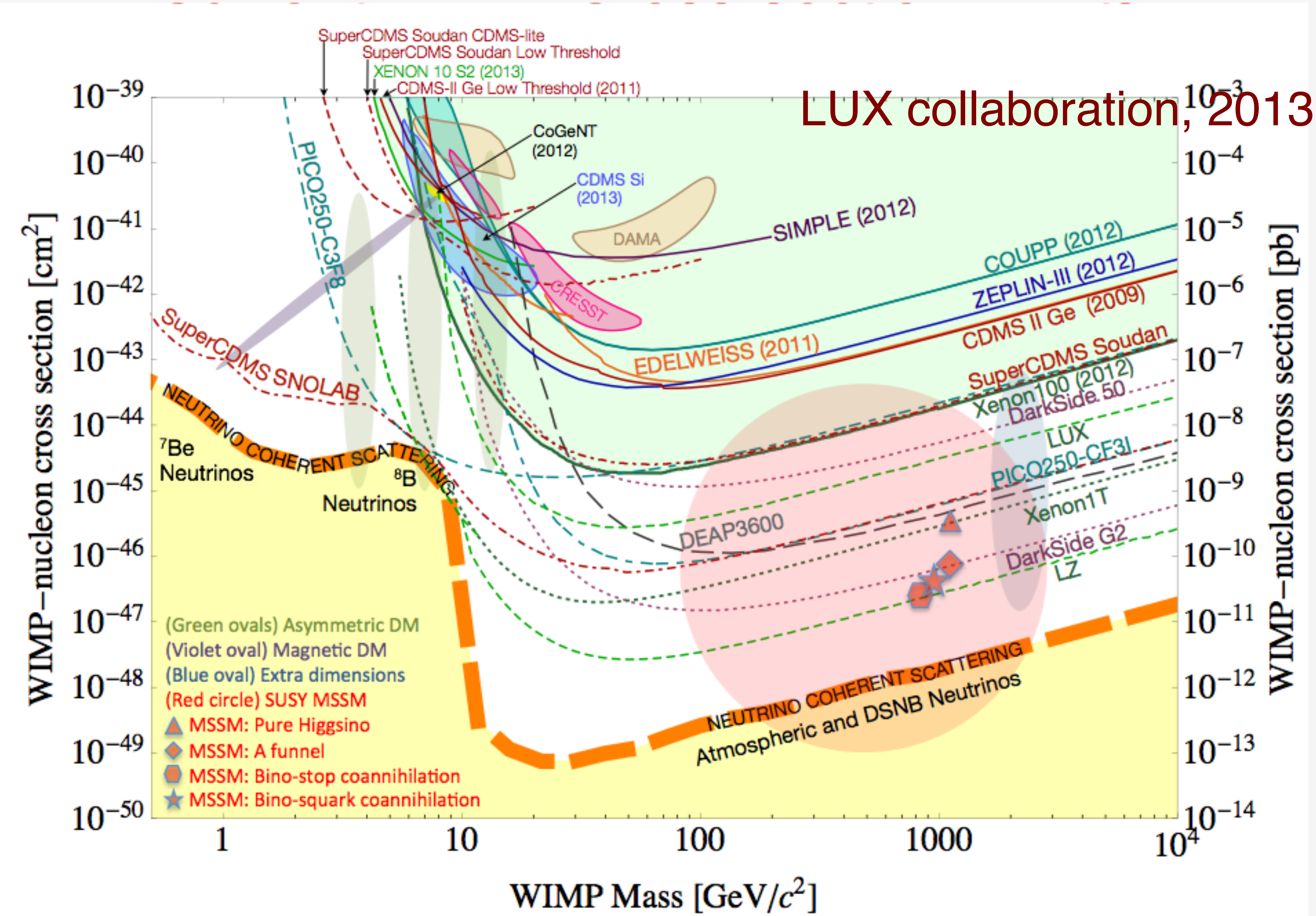


Nuclear physics?



WIMP DM Searches



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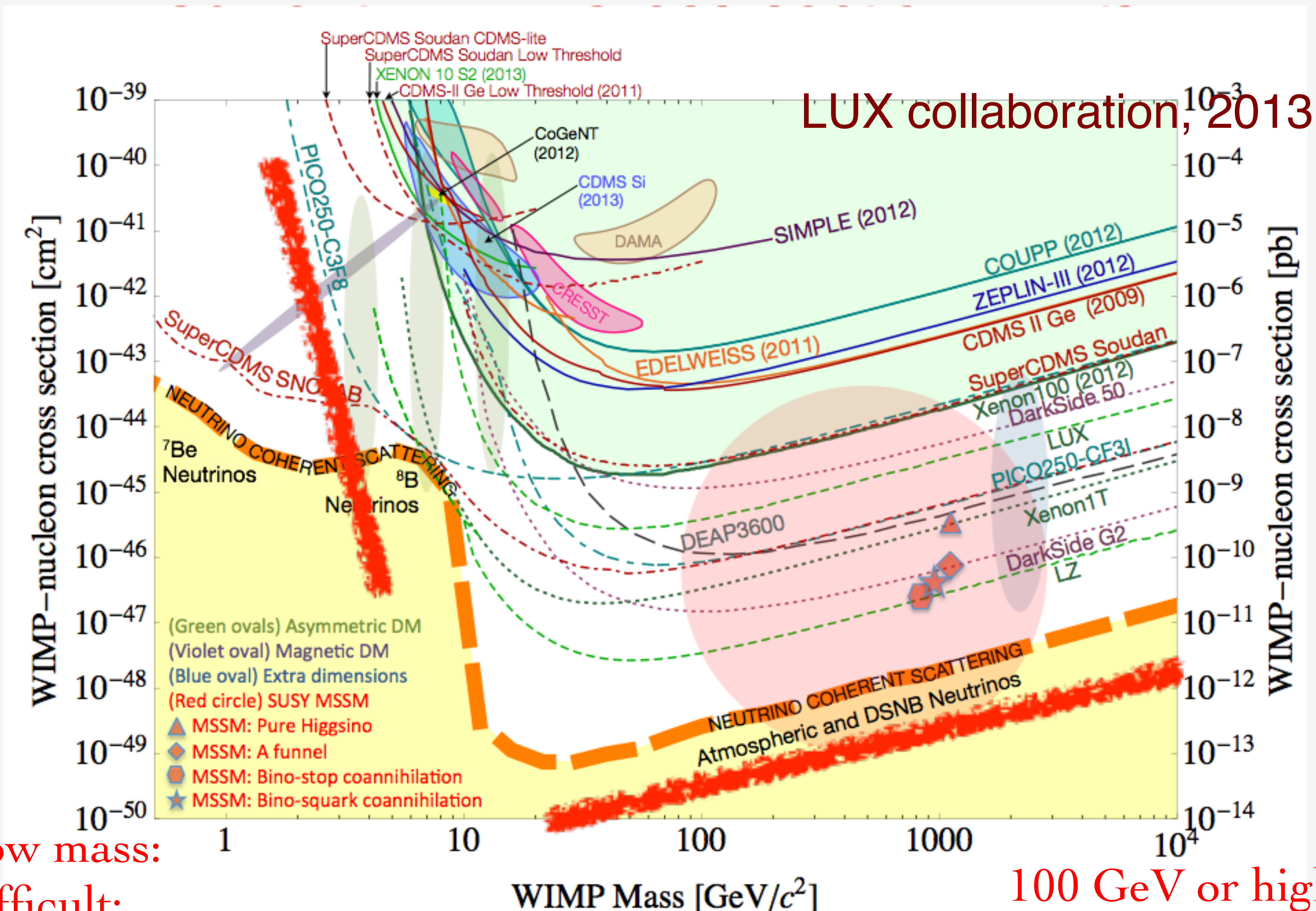


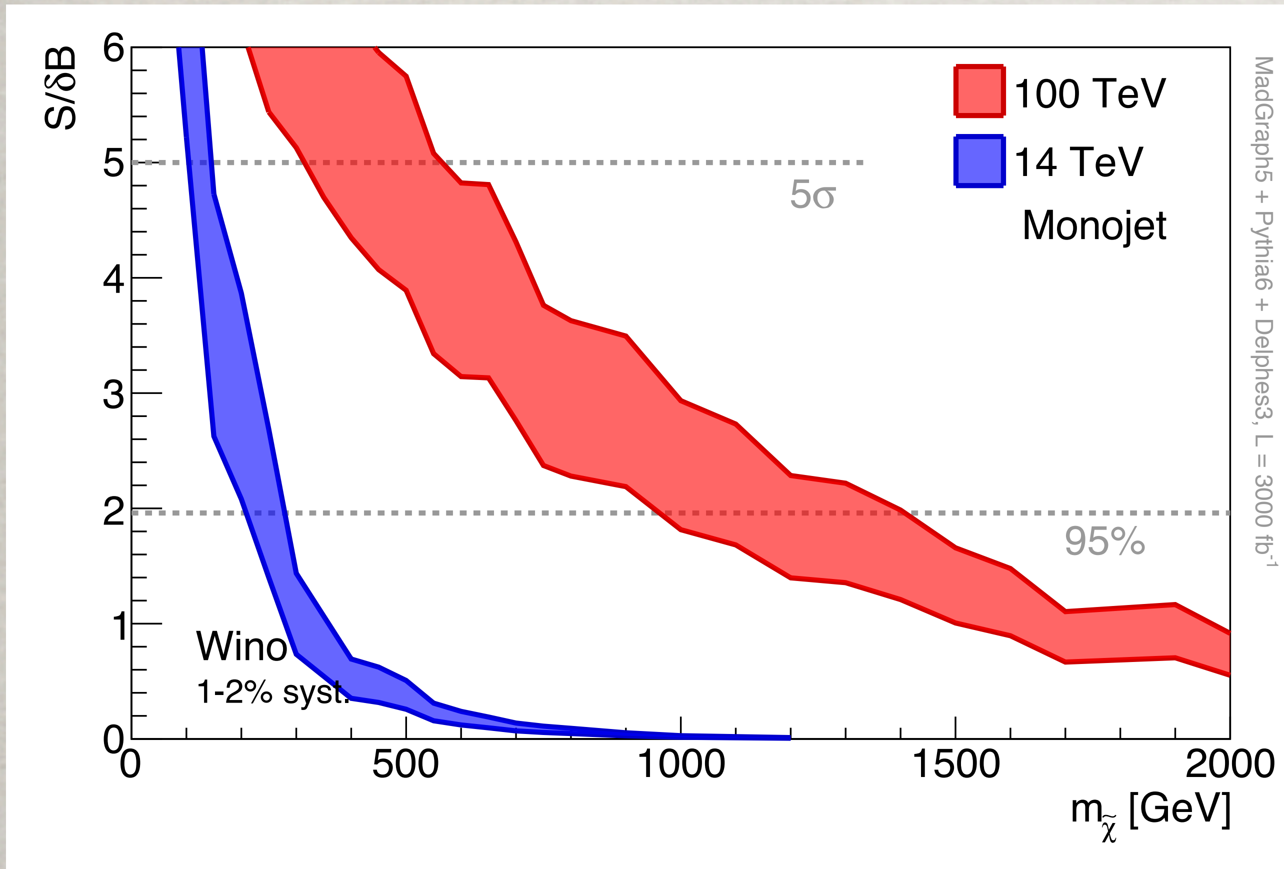
LUX collaboration, 2013

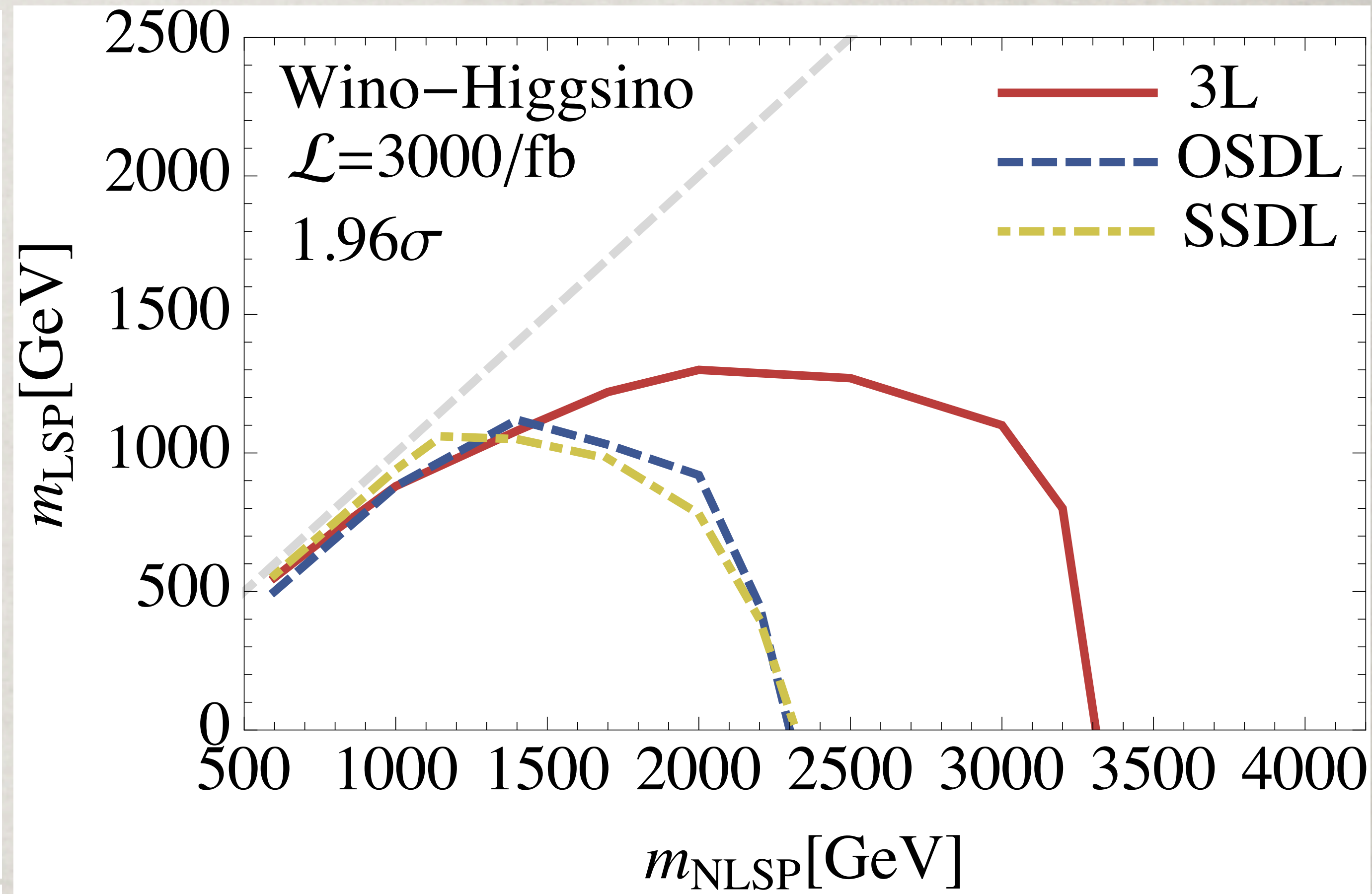
GeV low mass:
DD difficult;
Collider complementary

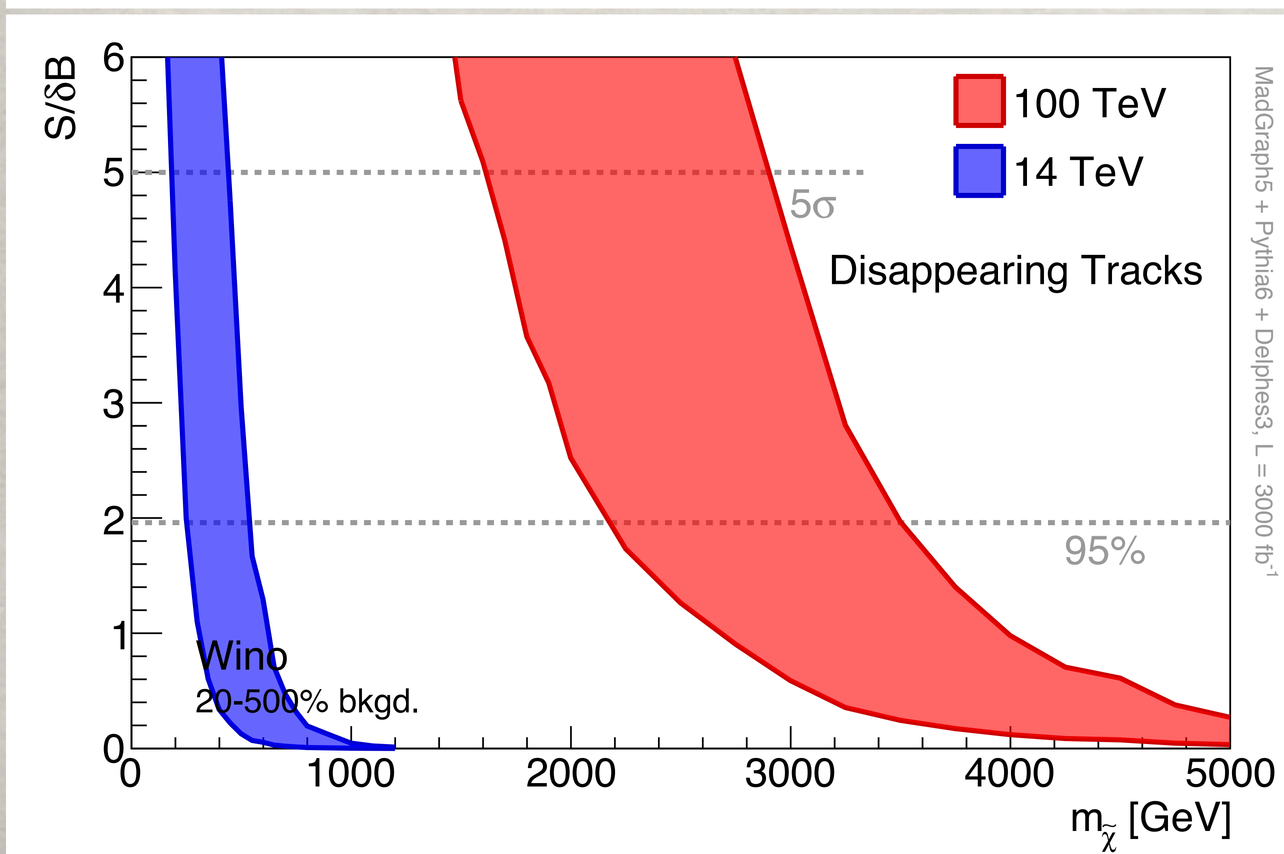
100 GeV or higher mass:
DD + ID + HE Collider
Too hard for O(1) TeV

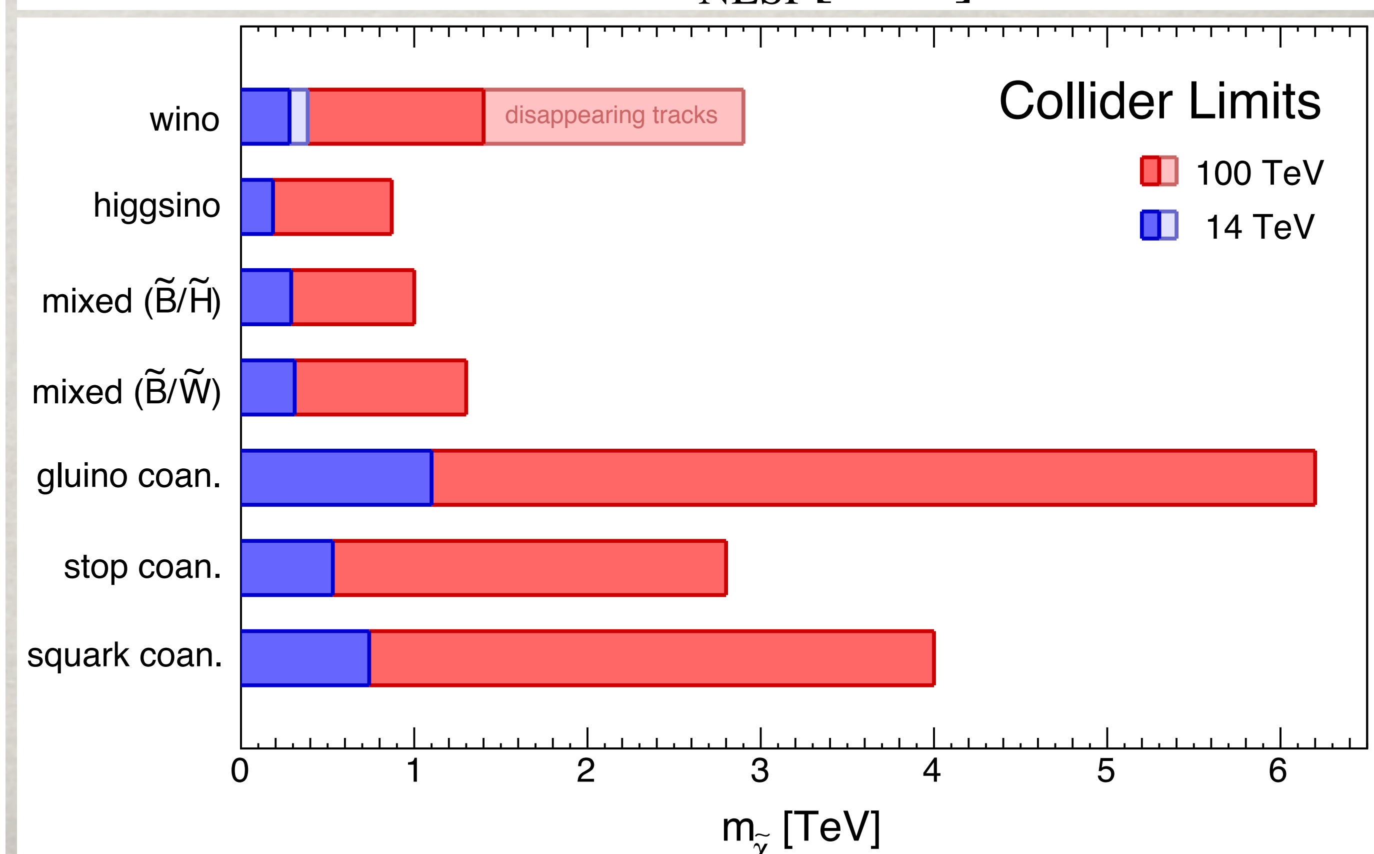
$$\sigma_{\rm SI} \begin{cases} \approx 10^{-47}\ {\rm cm}^2 & \text{for winos,} \\ \leq 10^{-48}\ {\rm cm}^2 & \text{for higgsinos.} \end{cases}$$

WIMP DM: $M_{\rm DM} < 1.8\ \text{TeV} \left(\frac{g_{\rm eff}^2}{0.3}\right)$



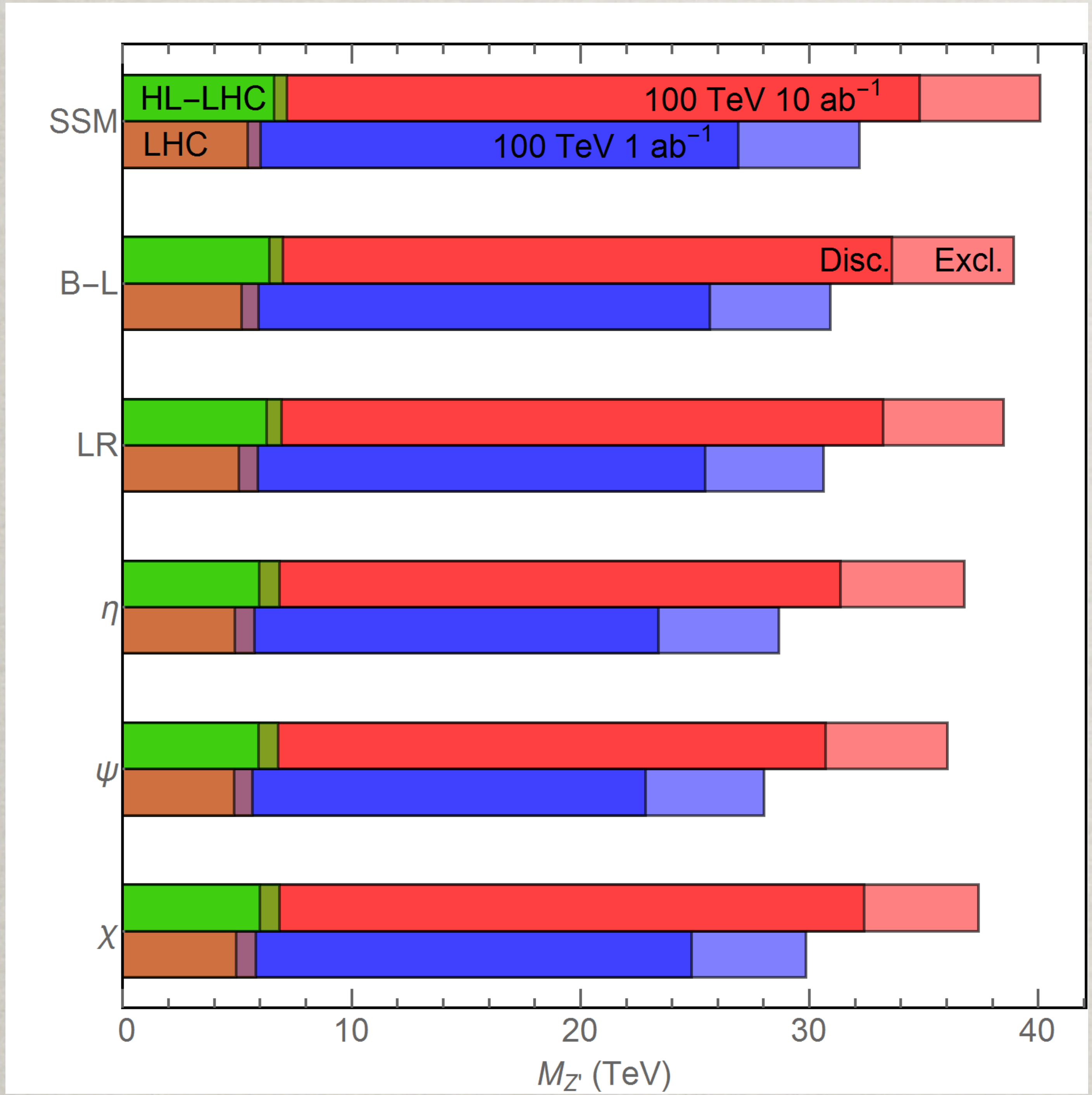




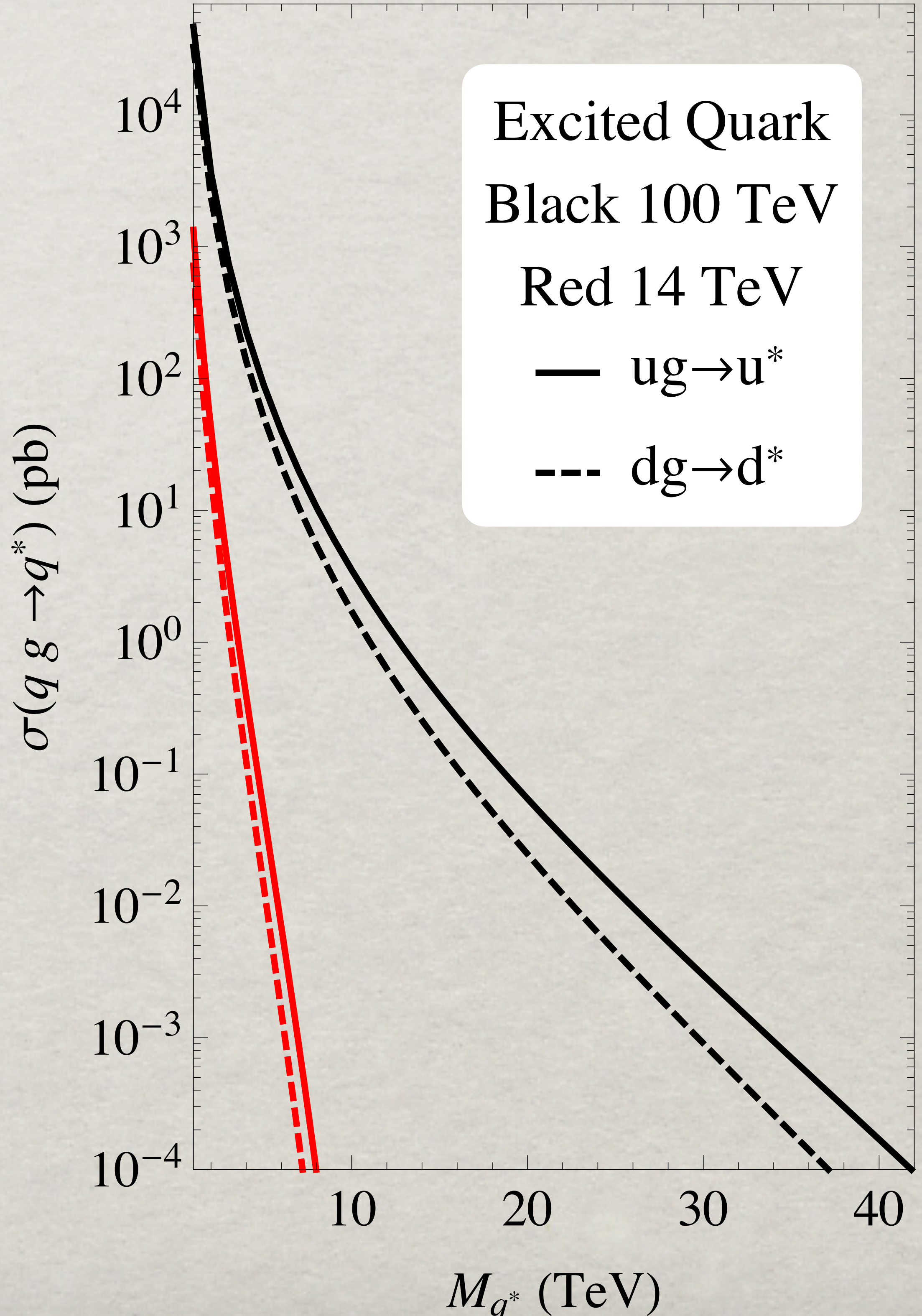


New Particle Searches

Electroweak Resonances: Z',W'



Colored Resonances:



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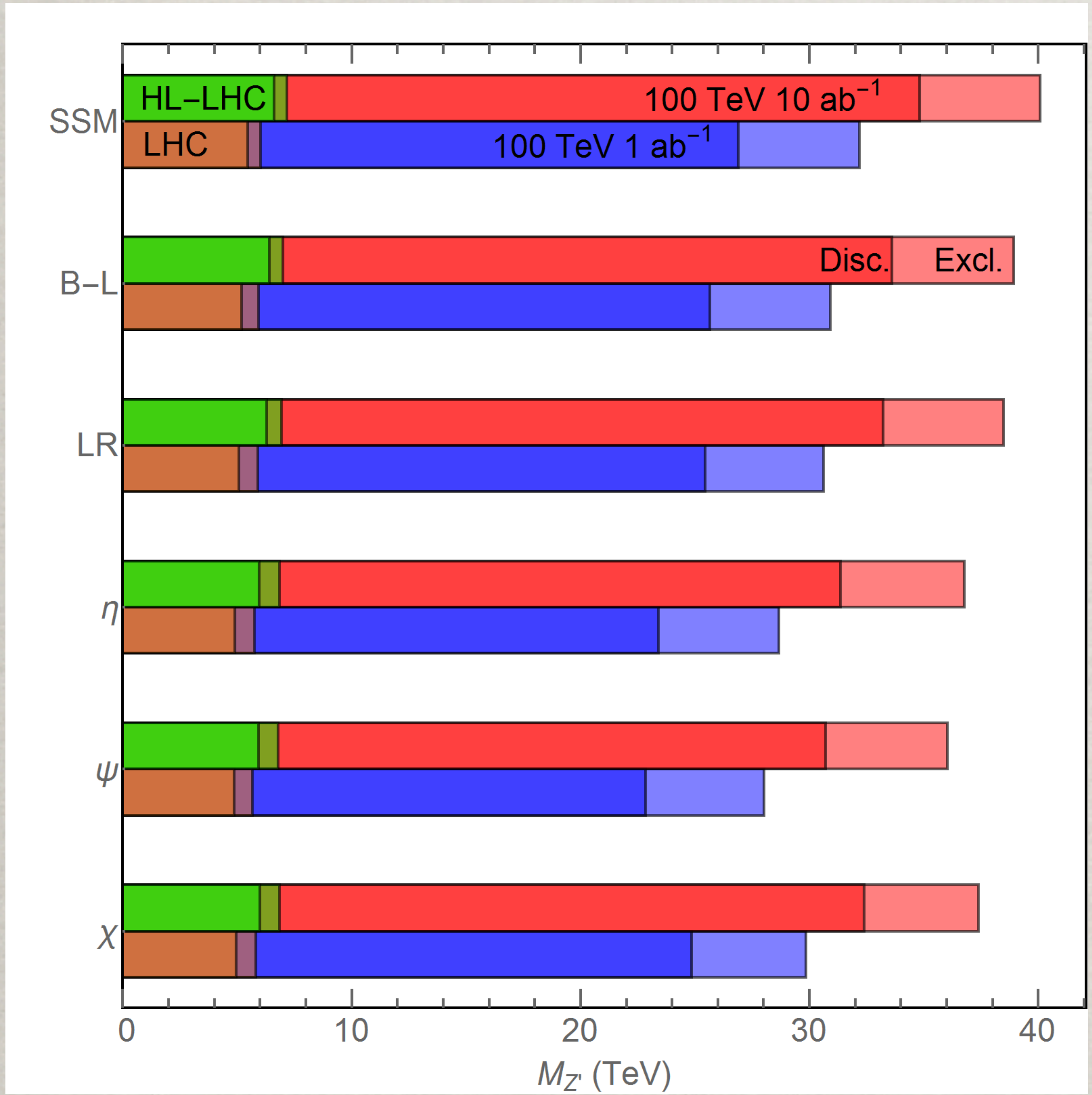
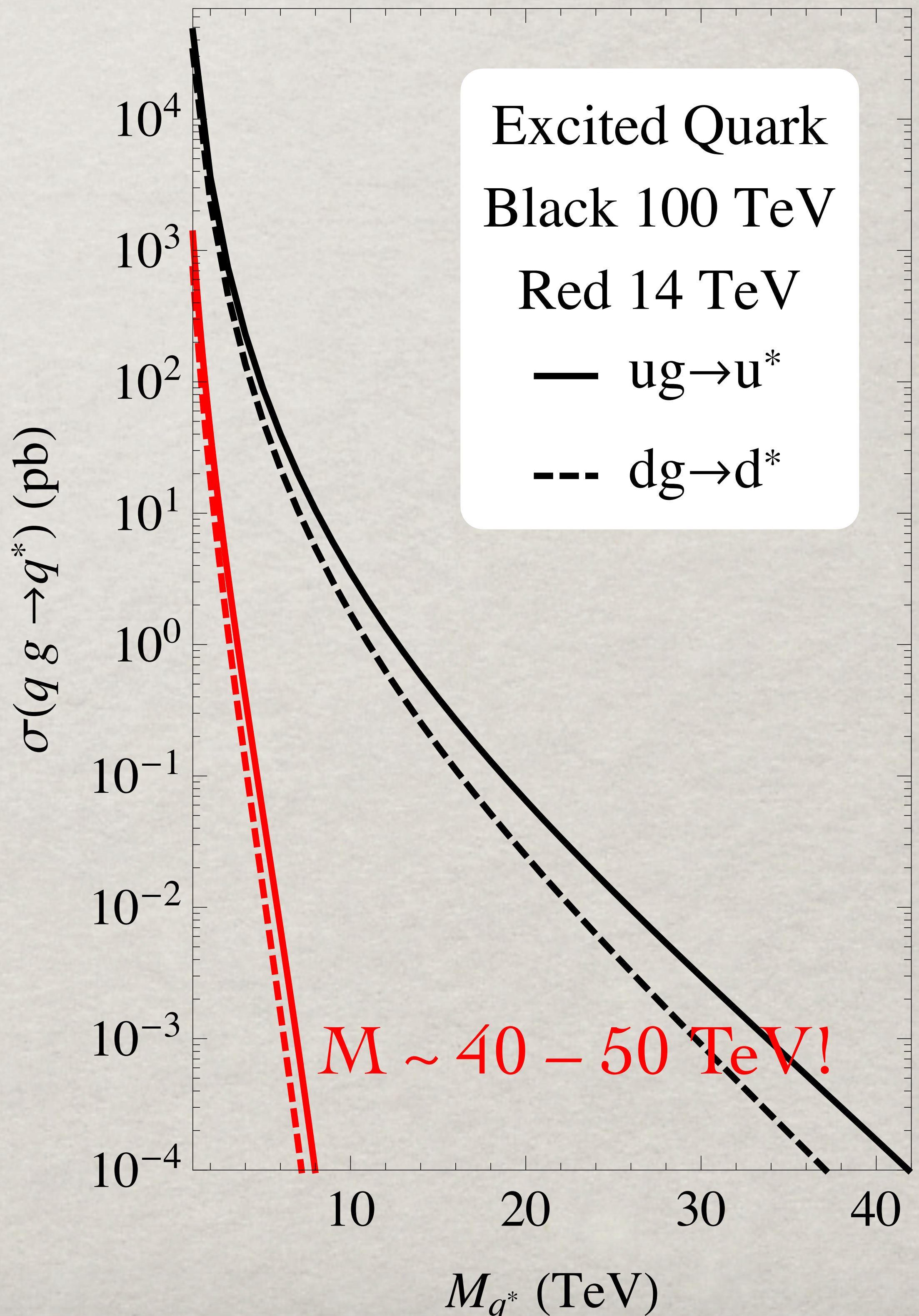


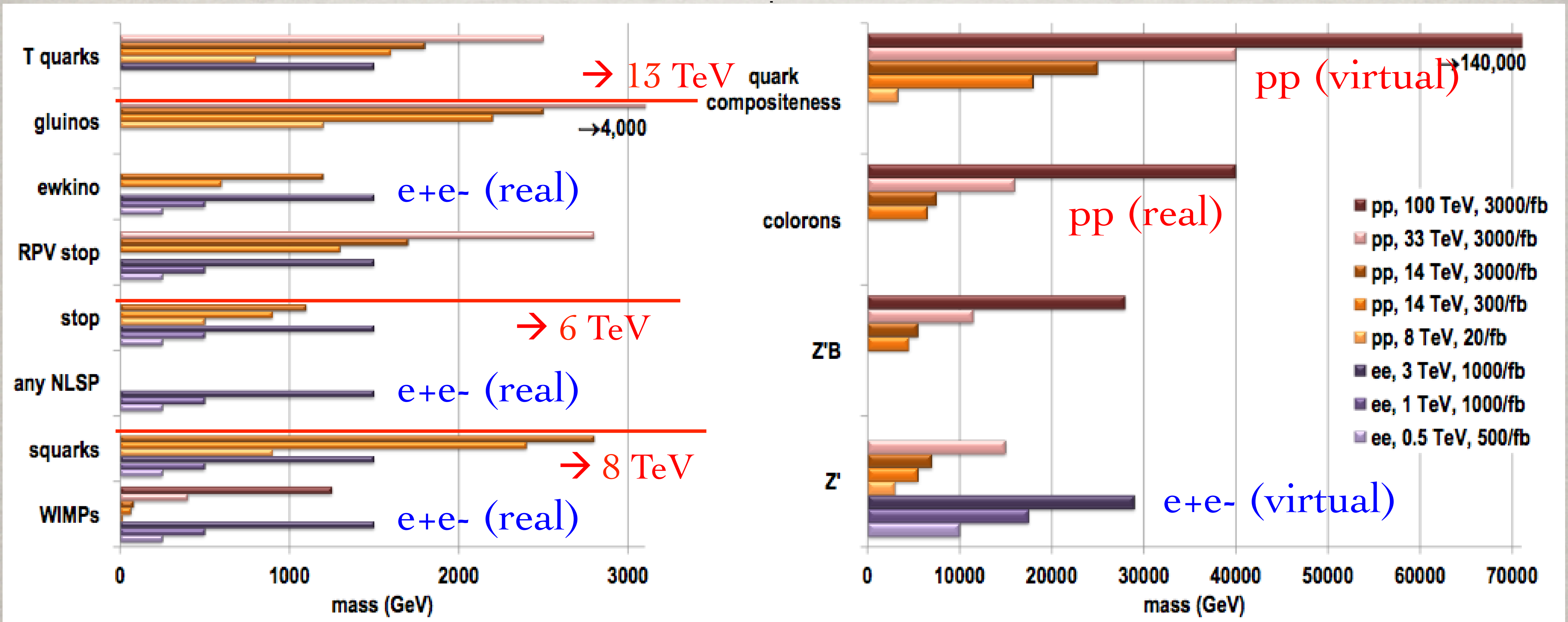
~ 6x over LHC

Colored Resonances:



New Particle Searches

Snowmass NP report, 1311.0299



e+e- & pp complementarity
for a broad range of searches.

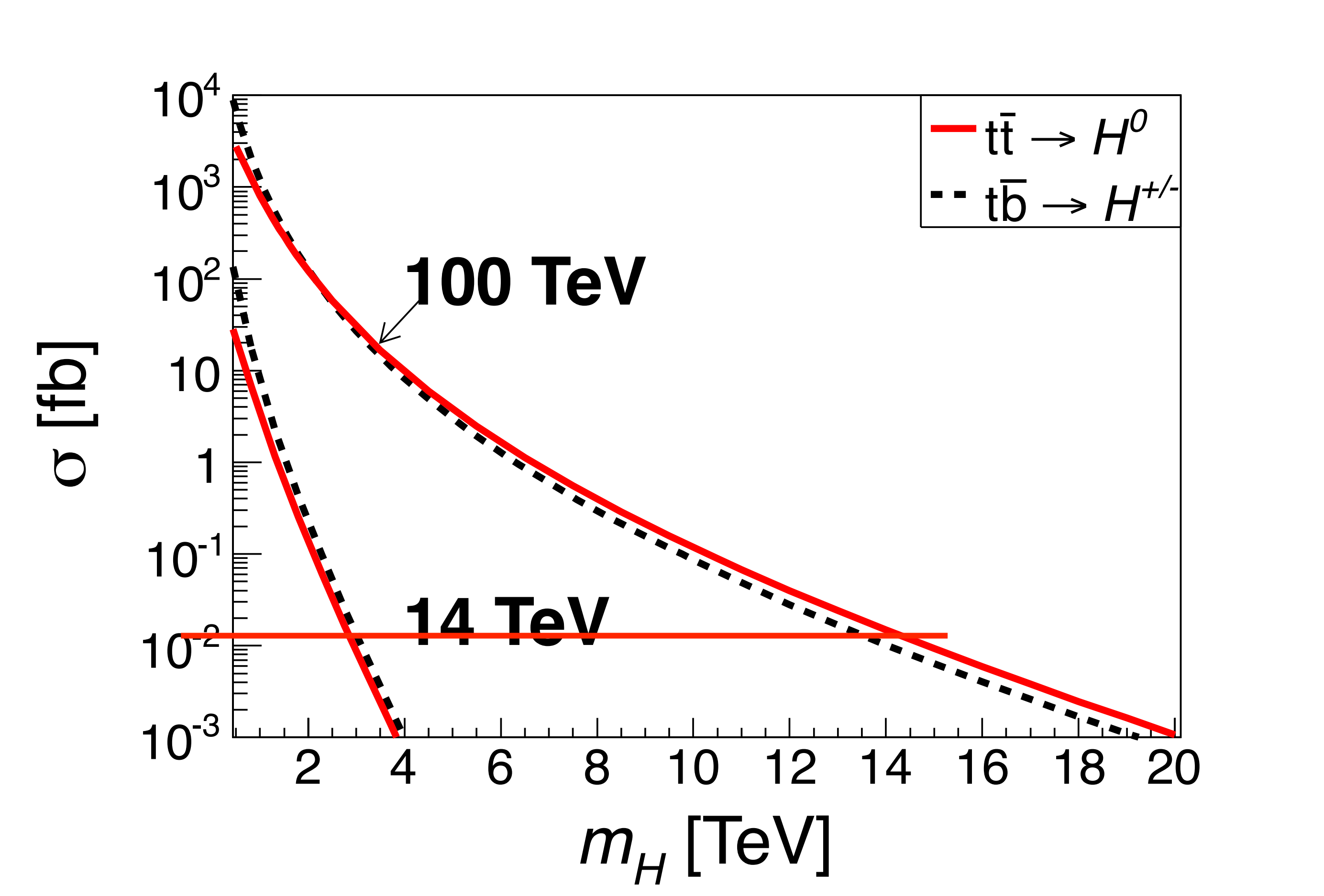
Other Rich Physics Opportunities

- Bread & butter SM physics:
  WW, tt threshold options at FCC_{ee}
  "top window" to new physics at FCC_{hh}
  EW vector boson showering at FCC_{hh}

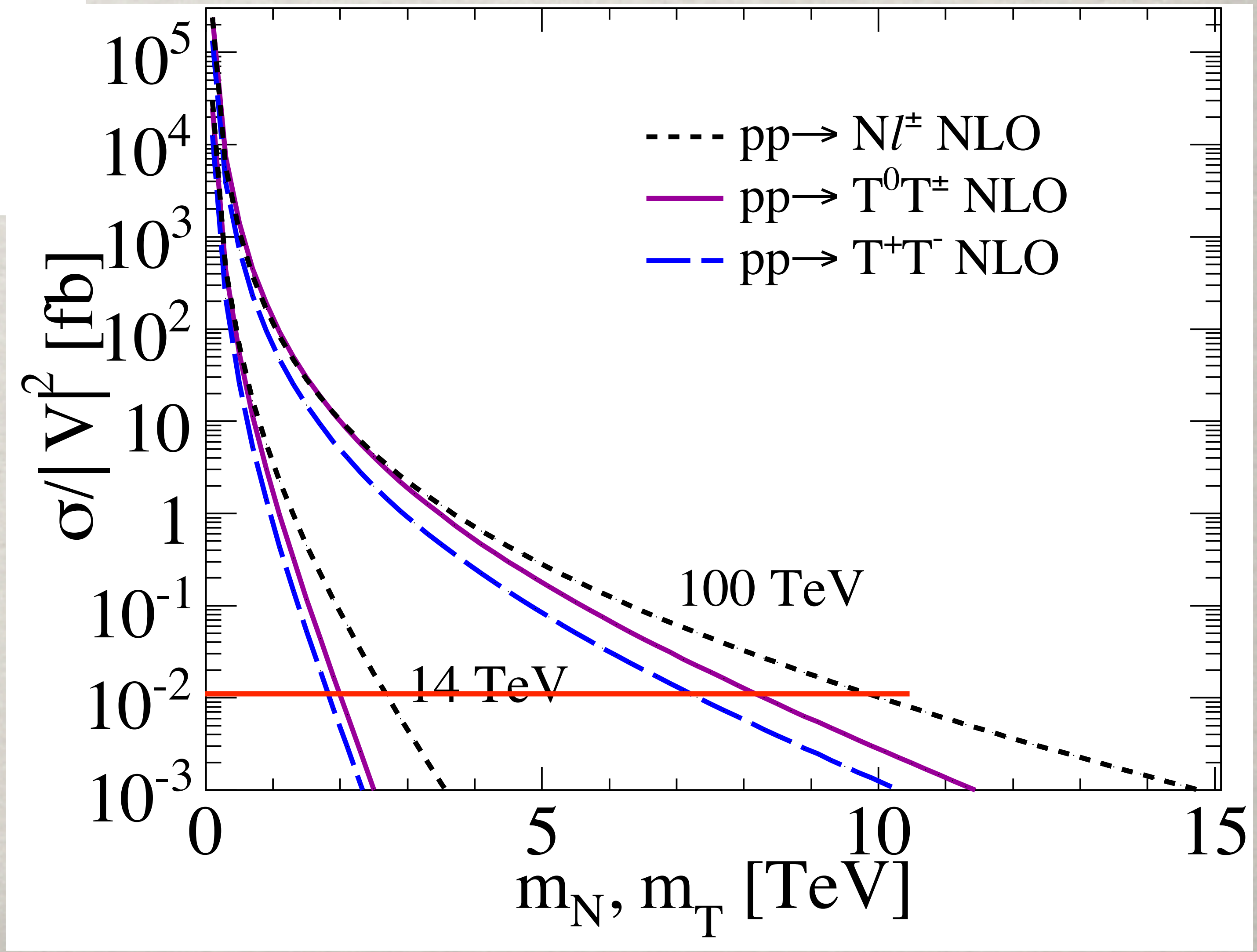
- $W_L W_L$ scattering at E_{ww} > 10 – 20 TeV

- Probe extended Higgs sector
  TeV scale seesaw for neutrino masses …

Heavy Higgs bosons: $H^0, H^\pm$



New (vector-like) leptons



Mass reach at 100 TeV:
~ 5x over LHC

The Higgs as pivot for "seesaw": $m_\nu \sim \kappa \frac{\langle H^0 \rangle^2}{M}$

Type I seesaw: $M = M_N$, right-handed (sterile) N_R^i

$H \to NN$, $N \to H\nu$, …

Yanagida; Ramond et al.; Mohapatra …

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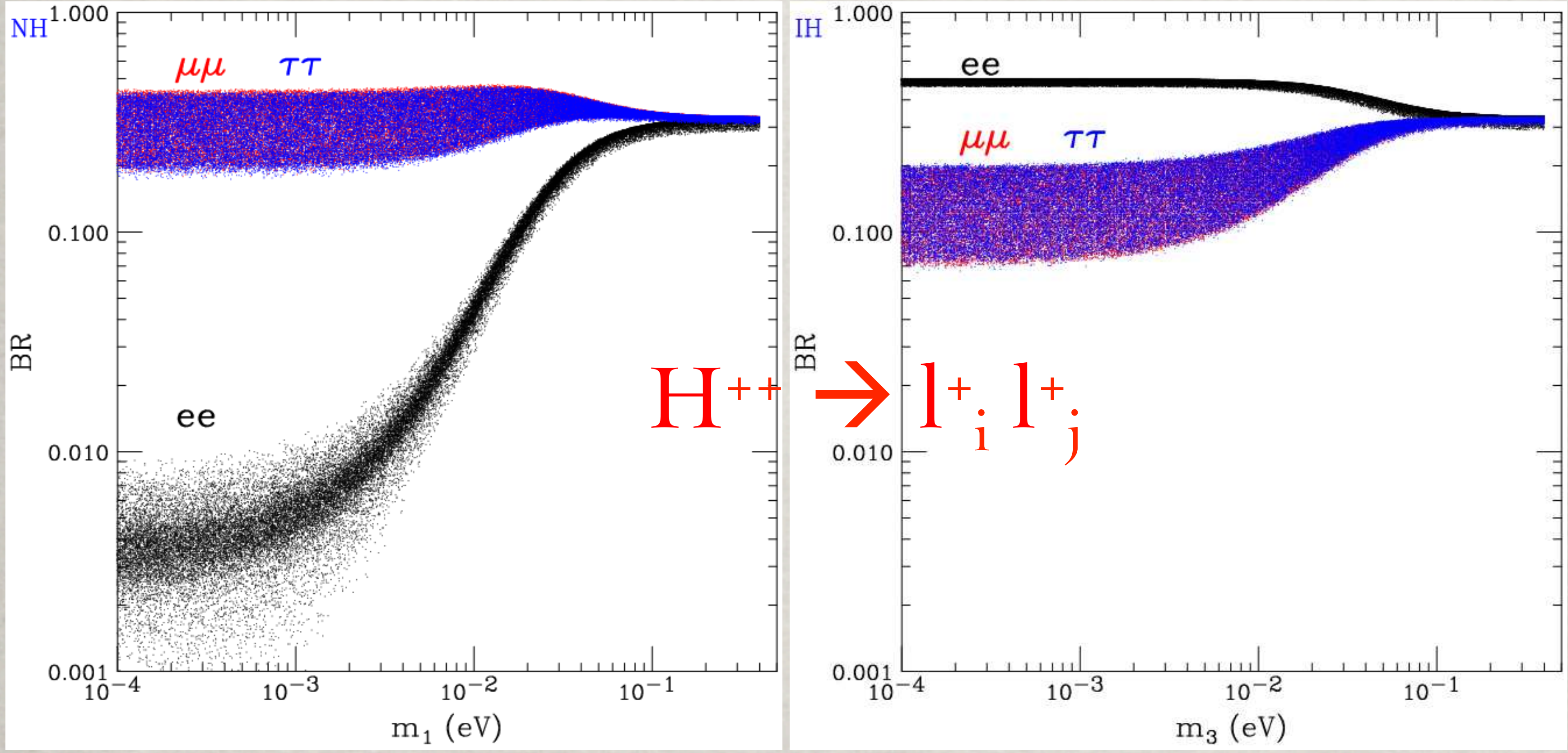
Mohapatra, Senjanovic, …



Fileviez-Perez et al., 2008.
Chaudhuri, Grimus,
Mukhopadyaya, arXiv:1305.5761
Chun et al., arXiv:1305.0329

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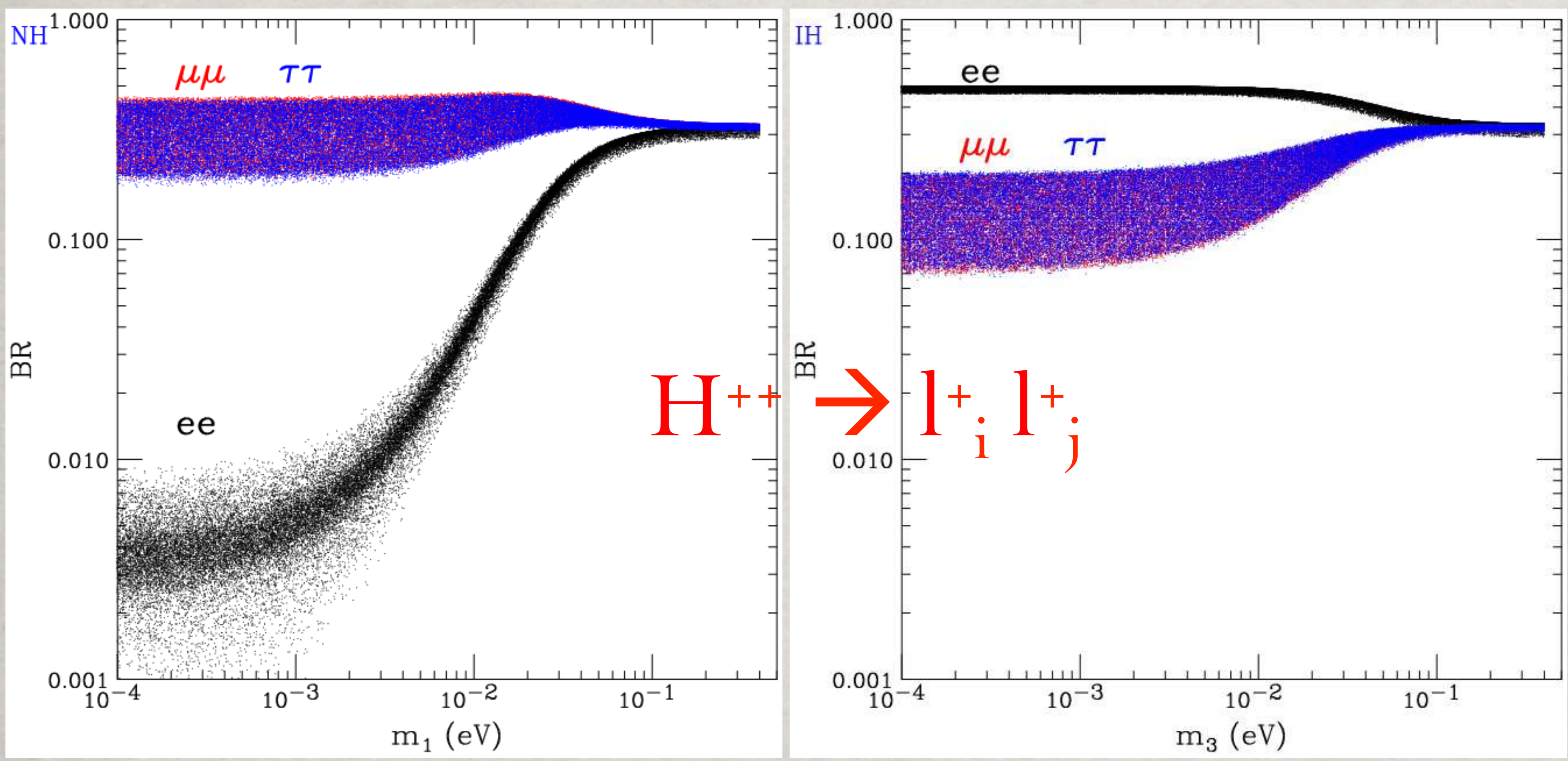

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Fileviez-Perez et al., 2008.
Chaudhuri, Grimus, Mukhopadyaya, arXiv:1305.5761
Chun et al., arXiv:1305.0329

Type III seesaw: $M = M_T$, a fermionic triplet T_3:

$T^+ \to H\, l^+_i$, $T^0 \to W^\pm\, l$

Senjanovic et al., arXiv:0904.2309.

Watch out: $H^0 \to \mu\tau$ $(l^+_i\, l^-_j)$ for BSM flavor physics!

TH, Marfatia, PRL (2001)
Harnik, Kopp, Zupan, 2013

Conclusions

- Higgs boson is a new class. New physics BSM → "under the Higgs lamppost"

- It calls for new colliders:
  Precision: FCC_{ee}/CEPC
  Tera Z: ΔM_Z, $\Delta\Gamma_Z < 0.1$ MeV, $\Delta\sin^2\theta_w < 10^{-6}$.
  At thresholds: $\Delta M_W \sim 1$ MeV, $\Delta m_t \sim 10$ MeV
  Mega Higgs: $\kappa_v \sim 0.2\%$, $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

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  Mega Higgs: $\kappa_v \sim 0.2\%$, $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.
  Energy frontier: FCC_{hh}/SPPC
  $\lambda_{hhh} < 10\%$ → Conclusive for EWPT
  6x LHC reach: 10 – 30 TeV → fine-tune $< 10^{-4}$
  WIPM DM mass ~ 1 – 5 TeV

P5 Five Science Drivers

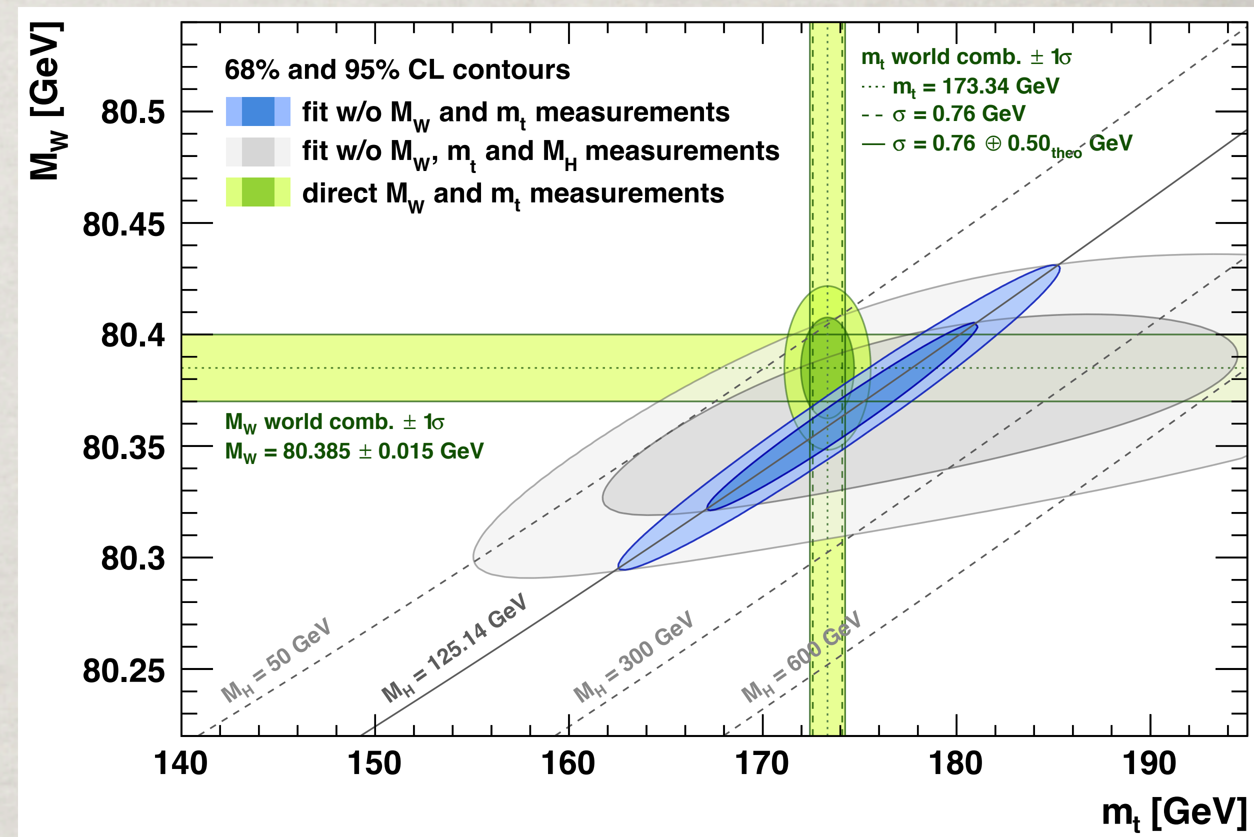
Report of the Particle Physics Project Prioritization Panel, May 2014

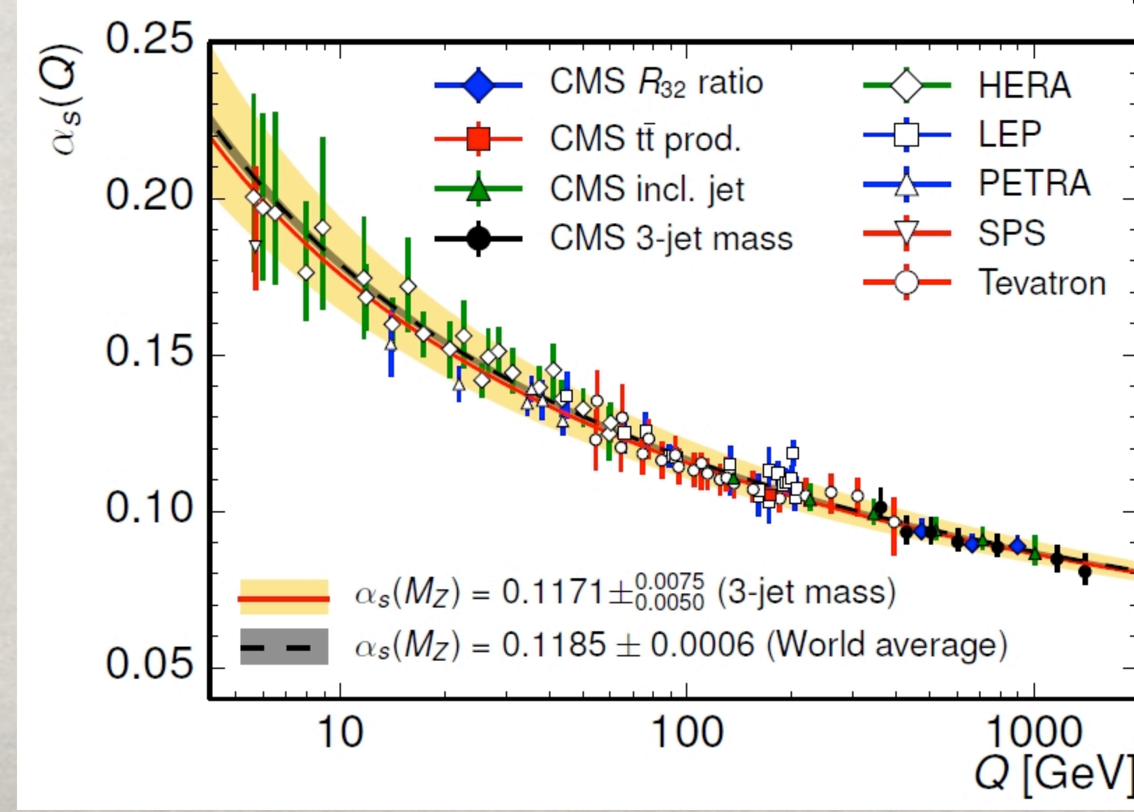
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

High Energy Physics IS at an extremely interesting time:

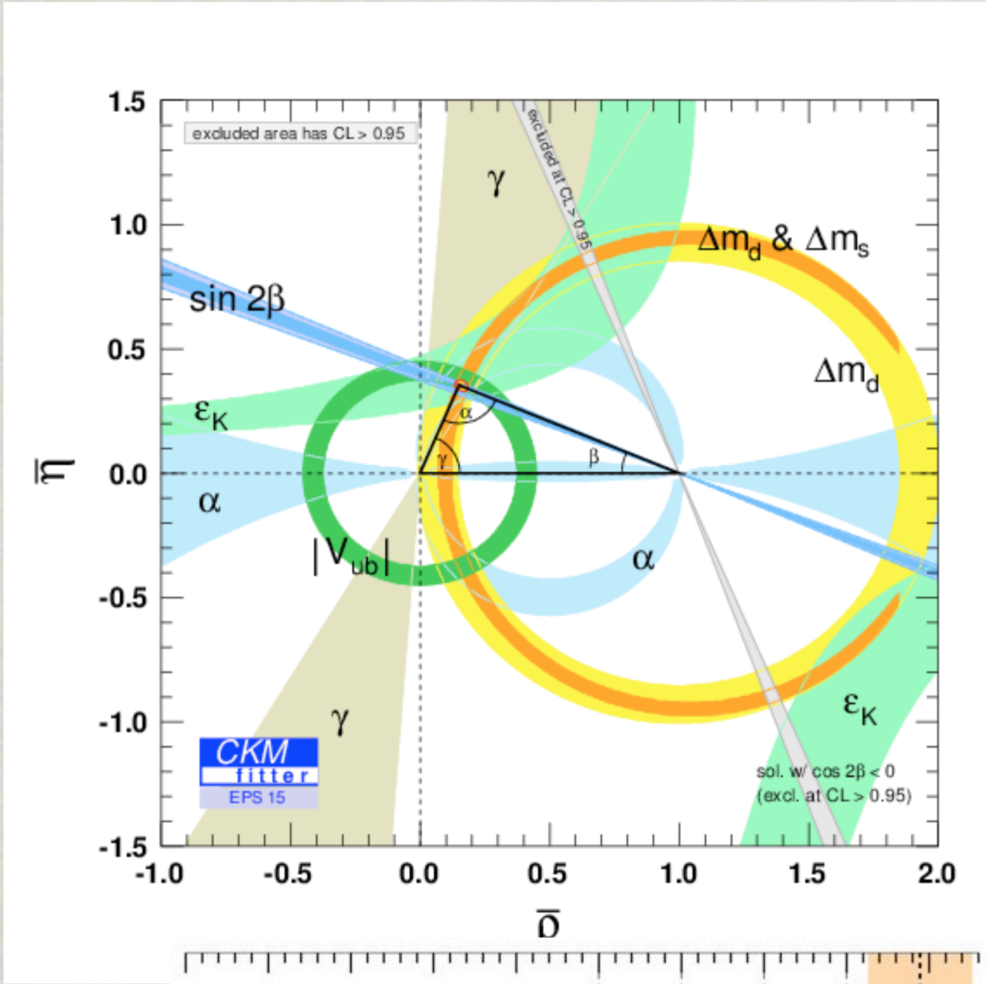
The SM is a triumph:

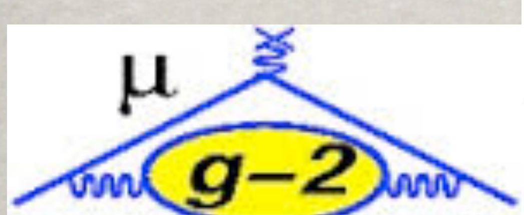
G fitter

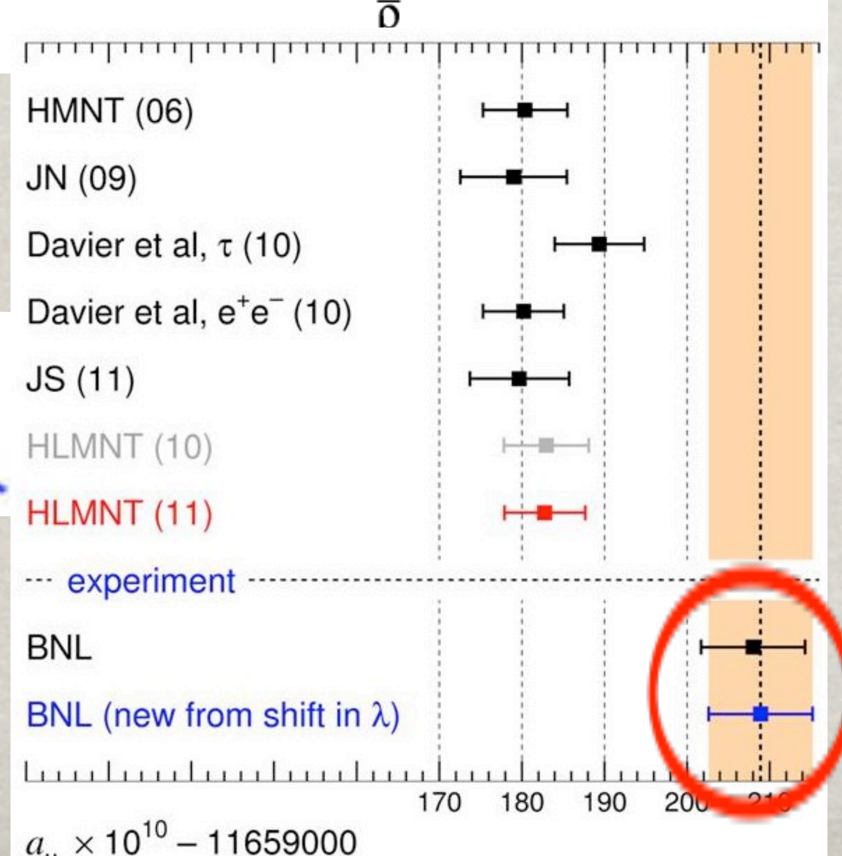


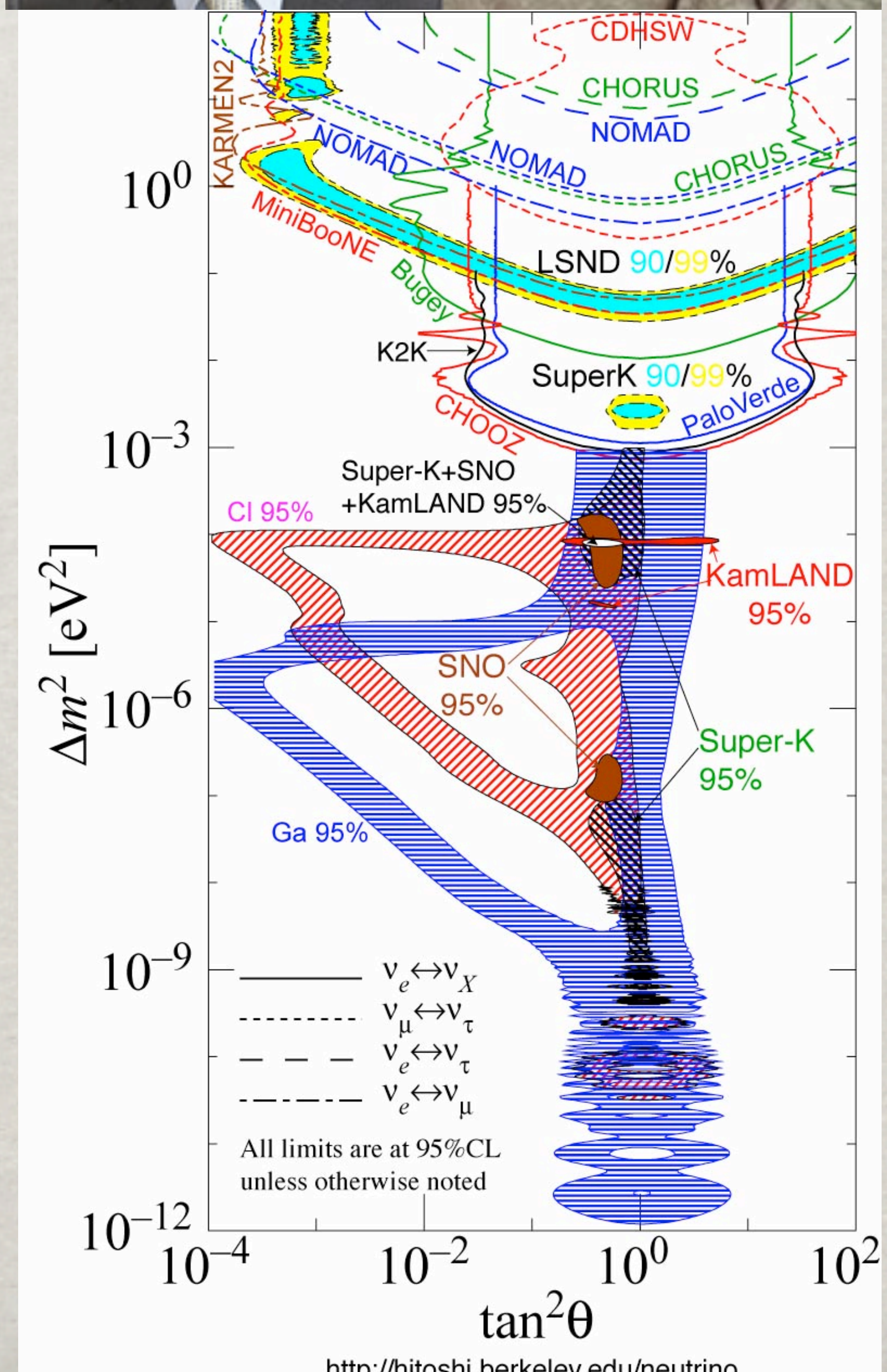


A highly self-consistent flavor sector:









Higgs Report: 1310.8361

Table 1-3. *Theory uncertainties on $M_H = 126$ GeV Higgs partial widths [17].*

Decay	QCD Uncertainty	Electroweak Uncertainty	Total
$H \to b\bar{b}, c\bar{c}$	$\sim 0.1\%$	$\sim 1-2\%$	$\sim 2\%$
$H \to \tau^+\tau^-, \mu^+\mu^-$	–	$\sim 1-2\%$	$\sim 2\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW^*/ZZ^* \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$

Also need to quantify the new physics corrections
(study specific models)

Z-Factory: Z Physics at the pole

EW WG Report: 1310.6708

At e^+e^- colliders, near the Z-peak the differential cross section for $e^+e^- \to f\bar{f}$ can be written as[1]

$$\frac{d\sigma}{d\cos\theta} = \mathcal{R}_{\rm ini}\left[\frac{9}{2}\pi\,\frac{\Gamma_{ee}\Gamma_{ff}(1-\mathcal{P}_e\mathcal{A}_e)(1+\cos^2\theta)+2(\mathcal{A}_e-\mathcal{P}_e)\mathcal{A}_f\cos\theta}{(s-M_Z^2)^2-M_Z^2\Gamma_Z^2}+\sigma_{\rm non-res}\right],$$

where $\Gamma_{ff} = \mathcal{R}_V^f g_{Vf}^2 + \mathcal{R}_A^f g_{Af}^2, \qquad \Gamma_Z = \sum_f \Gamma_{ff},$

$$\mathcal{A}_f = 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2} = \frac{1-4|Q_f|\sin^2\theta_{\rm eff}^f}{1-4\sin^2\theta_{\rm eff}^f+8(\sin^2\theta_{\rm eff}^f)^2}.$$

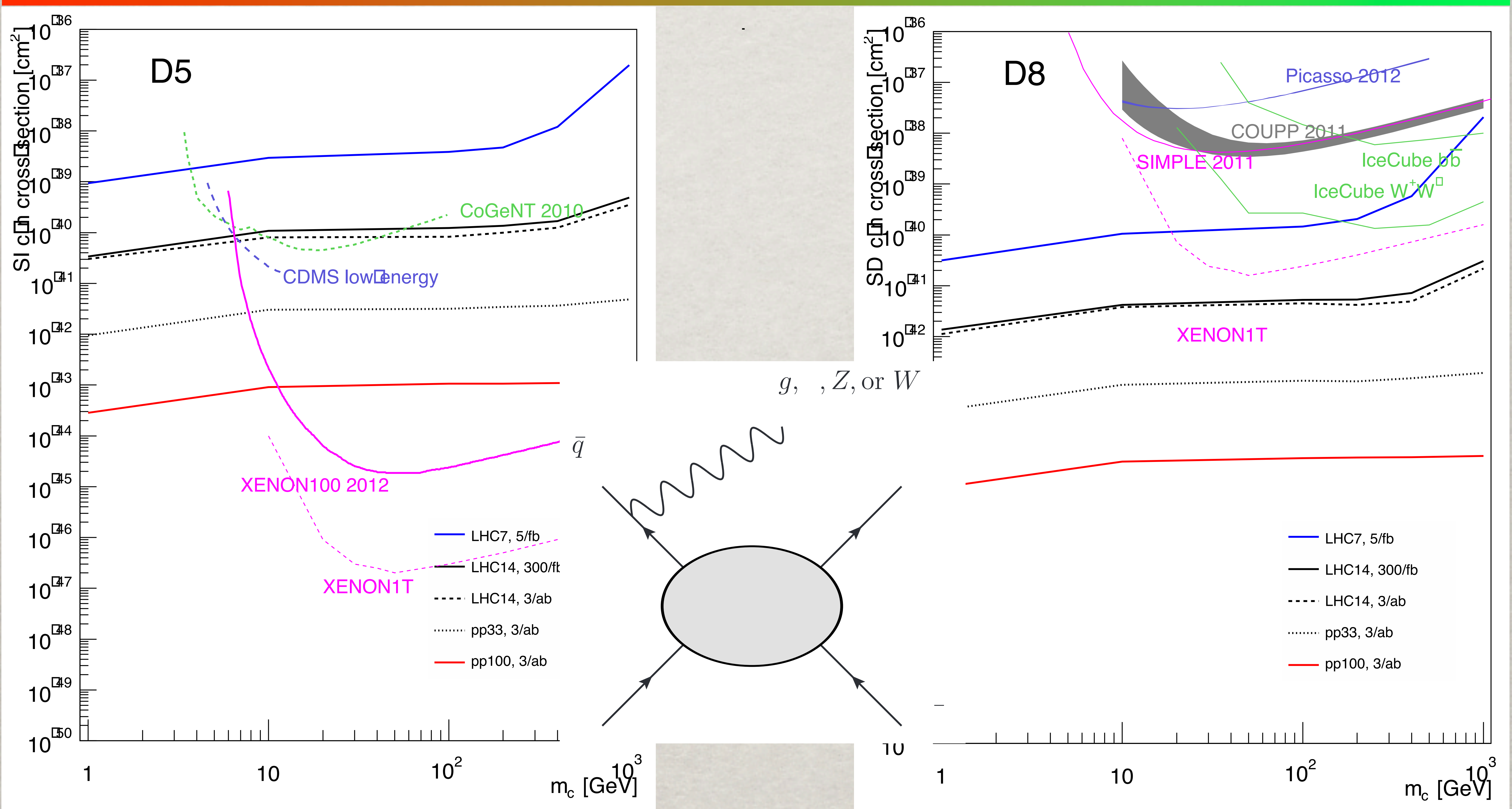
Including all:

	LHC	LHC	ILC/GigaZ	ILC	ILC	ILC	TLEP	SM prediction
$\sqrt{s}$ [TeV]	14	14	0.091	0.161	0.161	0.250	0.161	-
$\mathcal{L}[\,\mathrm{fb}^{-1}]$	300	3000		100	480	500	3000×4	-
ΔM_W [MeV]	8	5	-	4.1-4.5	2.3-2.9	2.8	< 1.2	4.2(3.0)
$\Delta\sin^2\theta_{\rm eff}^\ell$ $[10^{-5}]$	36	21	1.3	-	-	-	0.3	3.0(2.6)

Table 1-12. *Target accuracies for the measurement of M_W and $\sin^2\theta^\ell_{eff}$ at the LHC, ILC and TLEP, also including estimated future theoretical uncertainties due to missing higher-order corrections, and theory uncertainties of their SM predictions. The uncertainties on the SM predictions are provided for $\Delta m_t = 0.5(0.1)$ GeV (see Table 1-3 for details). At present the measured values for M_W and $\sin^2\theta^\ell_{\rm eff}$ are: $M_W = 80.385 \pm 0.015$ GeV [112] and $\sin^2\theta^\ell_{\rm eff} = (23153 \pm 16)\times 10^{-5}$ [3] compared to their current SM predictions of Section 1.2.1: $M_W = 80.360 \pm 0.008$ GeV and $\sin^2\theta^\ell_{\rm eff} = (23127 \pm 7.3)\times 10^{-5}$.*

DM: Collider vs. Direct Direction

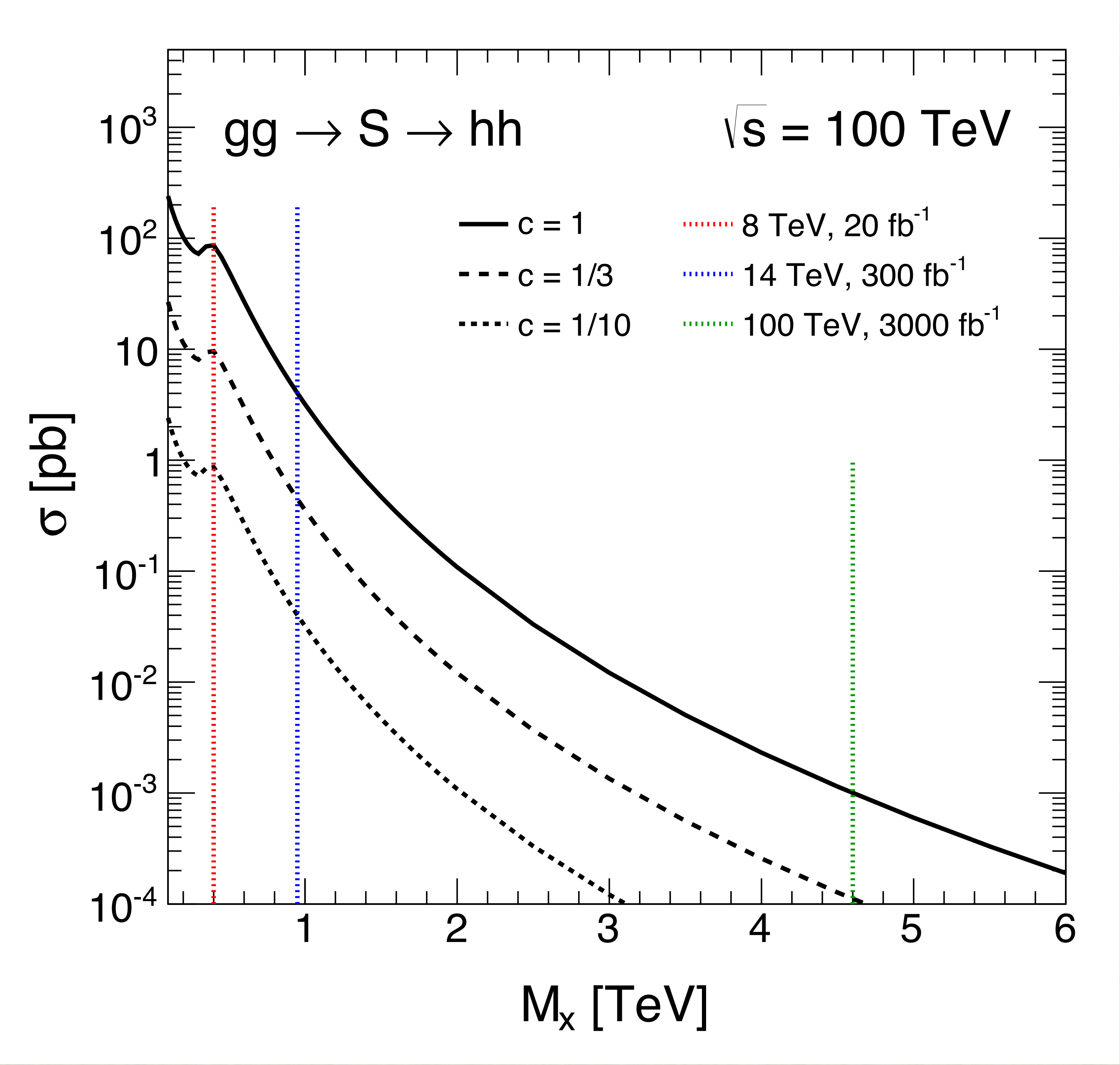
Zhou, Berge, Tait, Wang, Whiteson, 1307.5327



Collider search superior to DD:

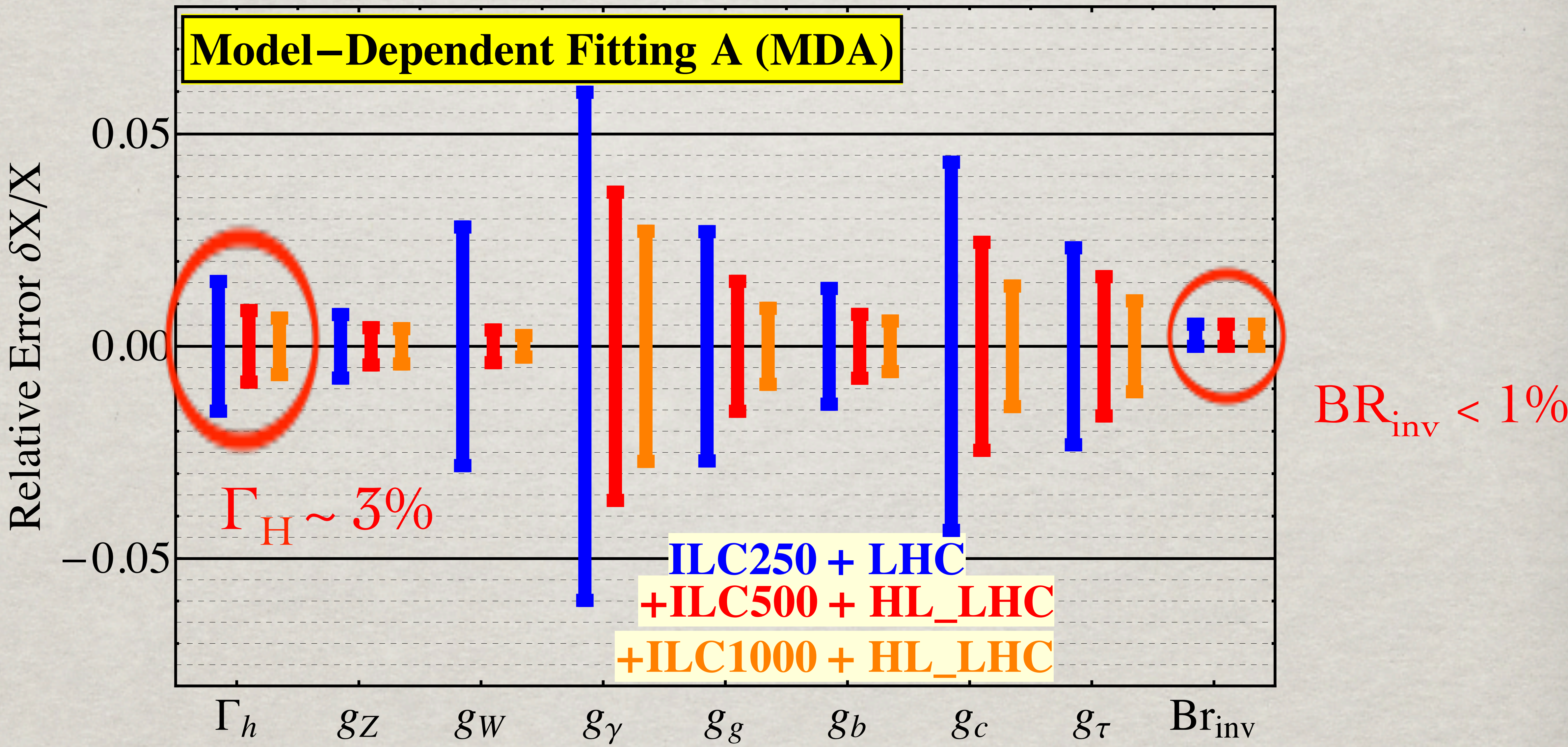
Low mass (larger kinetic MET); Spin-dependent (no N^2)

Higgs Self-couplings & The Nature of EWPT:



Higgs Total Width & Invisible BR:

TH, Z.Liu, J.Sayre, arXiv:1311.7155



Also see, Peskin, arXiv:1312.4974 including ILC luminosity upgrade.

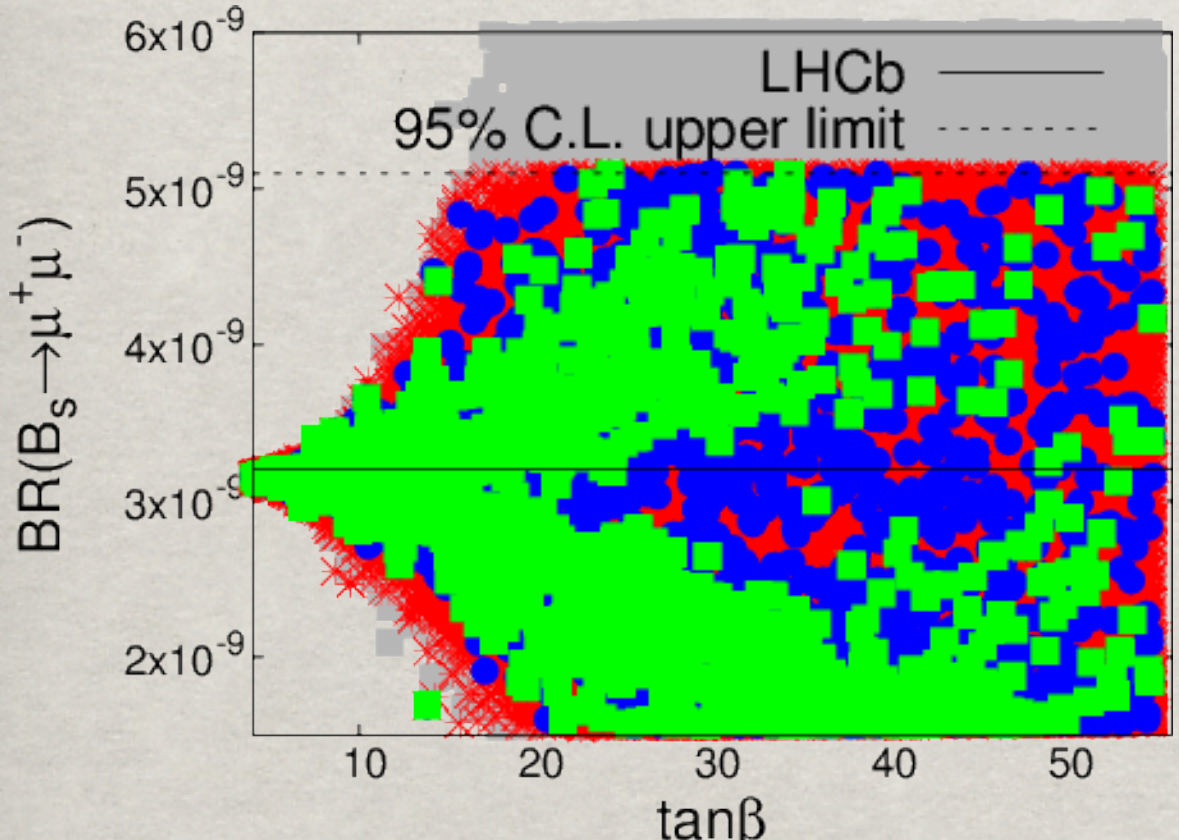
The fermion mass/mixing is a much^n bigger puzzle!

What controls the mixing structure:
"Minimal Flavor Violation" for BSM?

The b rare decays are pushing the limits:

$b \to s\,\gamma$, $B_s \to \mu^+ \mu^-$ BR(Bs) ~ $\tan^6\beta$ / M^4_A

TH, Liu, arXiv:1303.3040
Carena et al., arXiv:1305.5761.



Most recent LHCb+CMS:

arXiv:1411.4413

$$\mathcal{B}(B_s^0 \quad \mu^+\mu^-) = 2.8\,^{+0.7}_{-0.6} \times 10^{-9} \text{ and}$$
$$\mathcal{B}(B^0 \quad \mu^+\mu^-) = 3.9\,^{+1.6}_{-1.4} \times 10^{-10},$$

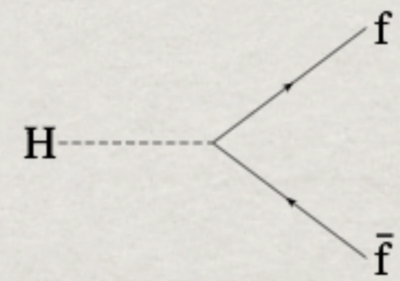
$$\mathcal{S}_{\rm SM}^{B_s^0} = 0.76\,^{+0.20}_{-0.18} \text{ and } \mathcal{S}_{\rm SM}^{B^0} = 3.7\,^{+1.6}_{-1.4}.$$

With Belle 2 as well,
likely a surprise to breakthrough!

5. Couplings & Width

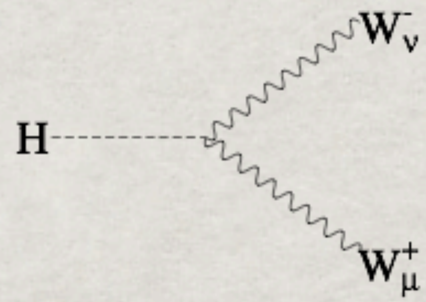
Higgs boson couplings encode its properties:

Yukawa coupling

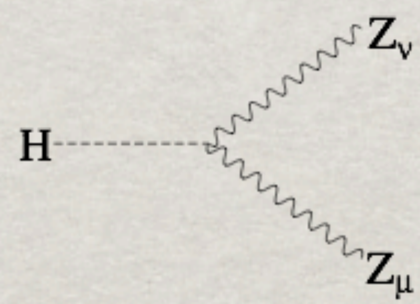


$-i\frac{m_f}{v}\left(1+\Delta_f\right)$

EWSB



$i g\, m_W \,(1+\Delta_W) g_{\mu\nu}$



$i\, g\, \frac{1}{\cos\theta_W}\, m_Z\, (1+\Delta_Z) g_{\mu\nu}$

Color/charged particles in loops: