Physics At Future Colliders
In Light of the Higgs Boson

PASCOS 2017, IFT, June 23, 2017

Tao Han
University of Pittsburgh

TLEP Report 1308.6176; CEPS pre-CDR; Snowmass Reports;
N. Arkani-Hamed, T. Han, M. Mangano, L.T. Wang, Phys. Rep.;
More refs: CERN Yellow Reports, 2017.

High Energy Physics IS at an extremely interesting time:

The completion of the SM:

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

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. "

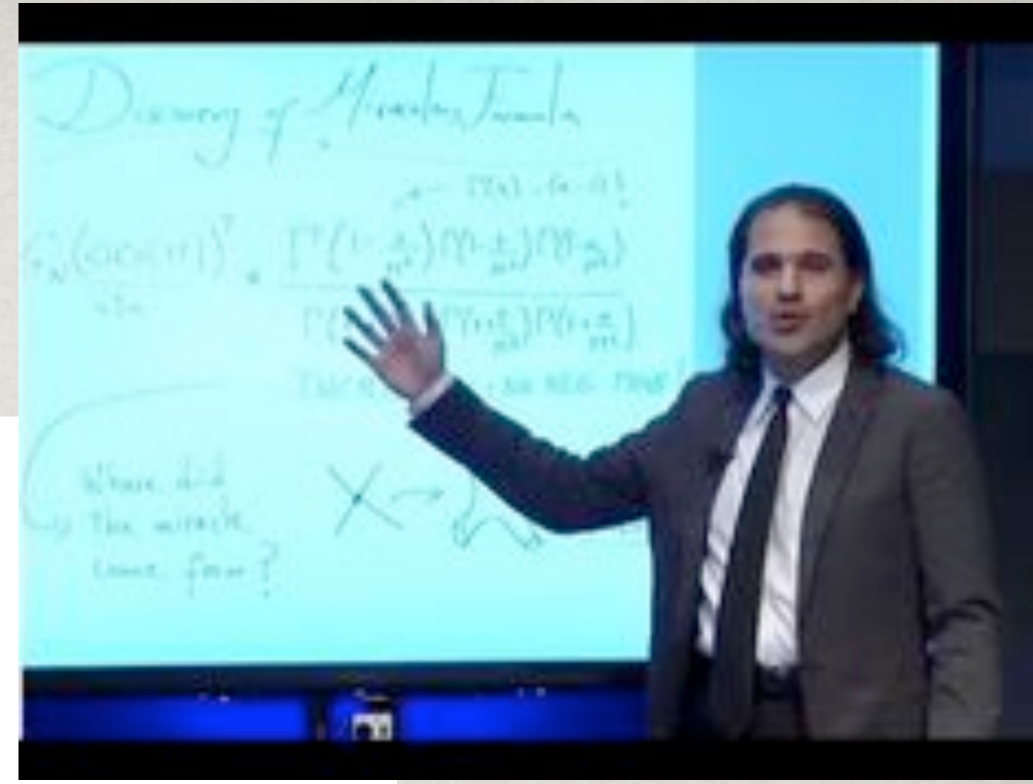
"… most of the grand underlying principles have been firmly established. (An eminent physicist remarked that) the future truths of physical science are to be looked for in the sixth place of decimals. "

--- Albert Michelson (1894)

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

Will History repeat itself (soon)?

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

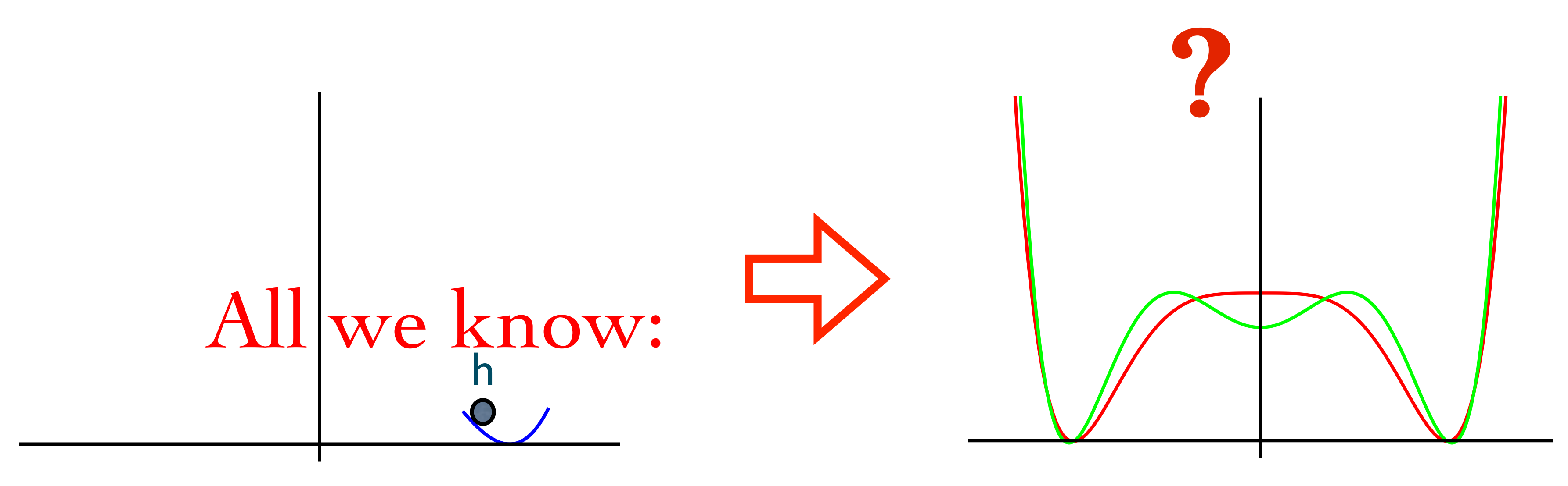


New Era:
Under the Higgs lamp post

Question 1: The Nature of EWSB ?

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

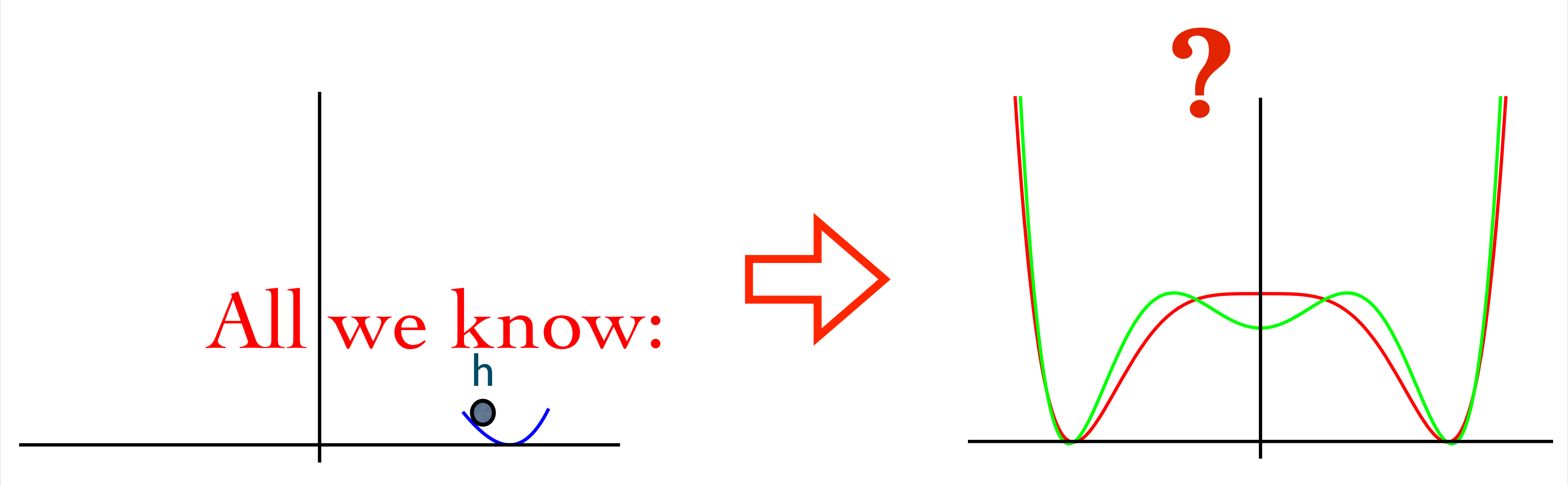
underwent a 2nd order phase transition (?)



Question 1: The Nature of EWSB ?

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

underwent a 2nd order phase transition (?)



With new physics near the EW scale:

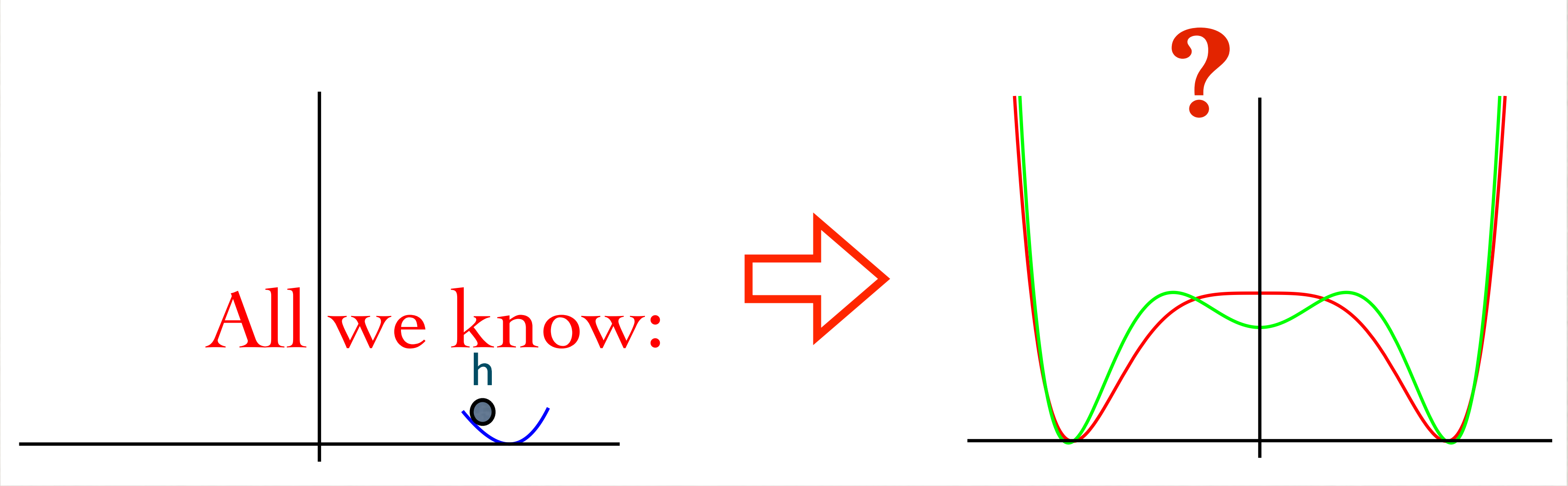
$$V(h) \to m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3, \quad \rightarrow \lambda_{hhh} = (7/3)\lambda_{hhh}^{SM}$$

$$\to \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right] \quad \rightarrow \lambda_{hhh} = (5/3)\lambda_{hhh}^{SM}$$

Question 1: The Nature of EWSB ?

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

underwent a 2$^{\text{nd}}$ order phase transition (?)



With new physics near the EW scale:

$$V(h) \to m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3, \quad \to \lambda_{hhh} = (7/3)\lambda_{hhh}^{SM}$$

$$\to \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right] \quad \to \lambda_{hhh} = (5/3)\lambda_{hhh}^{SM}$$

EW phase transition strong 1$^{\text{st}}$ order!

→ O(1) deviation on λ_{hhh}

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

Question 2: The "Naturalness"

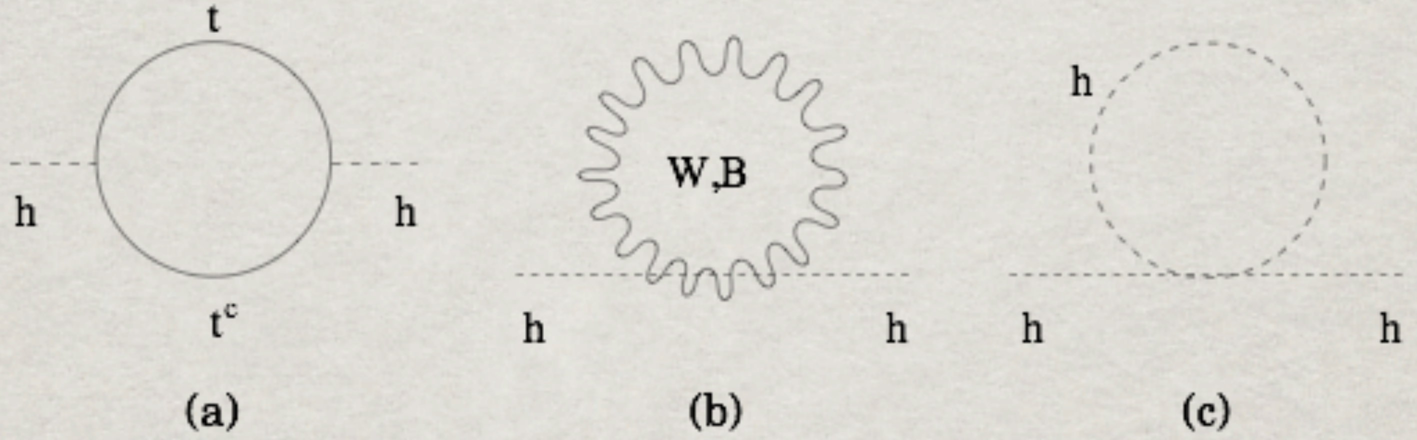
"… scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry."

Ken Wilson, 1970

Question 2: The "Naturalness"

"… scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry."
Ken Wilson, 1970

"unnatural" in the 't Hooft sense:



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

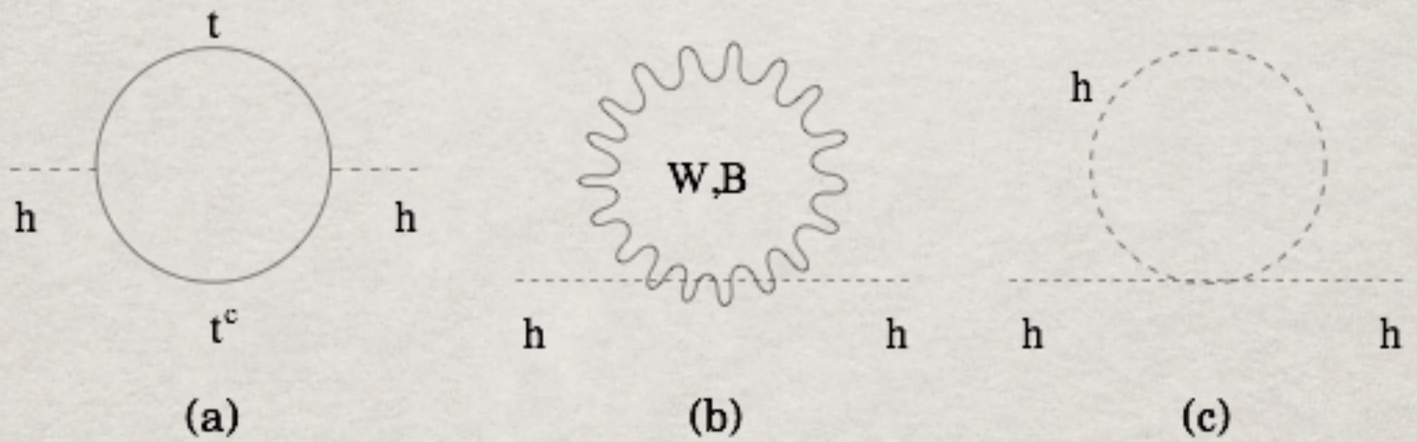
If $\Lambda^2 \gg m_H^2$, then unnaturally large cancellations must occur.

Question 2: The "Naturalness"

"… scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry."

Ken Wilson, 1970

"unnatural" in the '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.

- Natural: O(1 TeV) new physics, associated with ttH.
- Unknown: Deep UV-IR correlations: gravity at UV?
- Agnostic: Multiverse/anthropic?

A "natural" EW theory?

- "Natural SUSY":

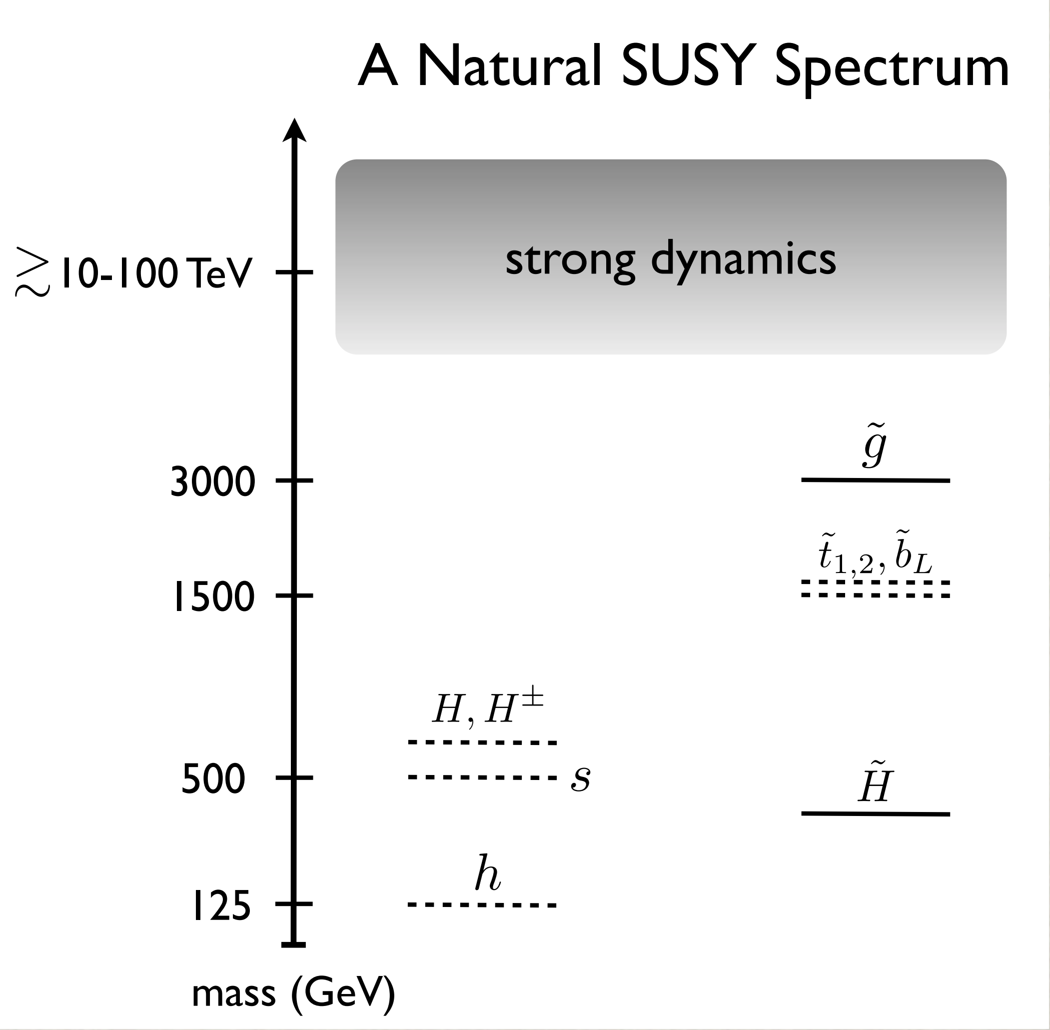
Relevant to the Higgs and the "Most Wanted":

$\tilde{H}^{0,\pm},\ \tilde{t},\ \tilde{b},\ (\tilde{g});\ S,\ \tilde{S}...$

LHC Run 2 bounds:

$m_{\tilde{t}} > 800 - 1100\ \mathrm{GeV}$

$m_{\tilde{\chi}^{\pm}} > 600 - 1100\ \mathrm{GeV}$



A "NATURAL" EW THEORY?

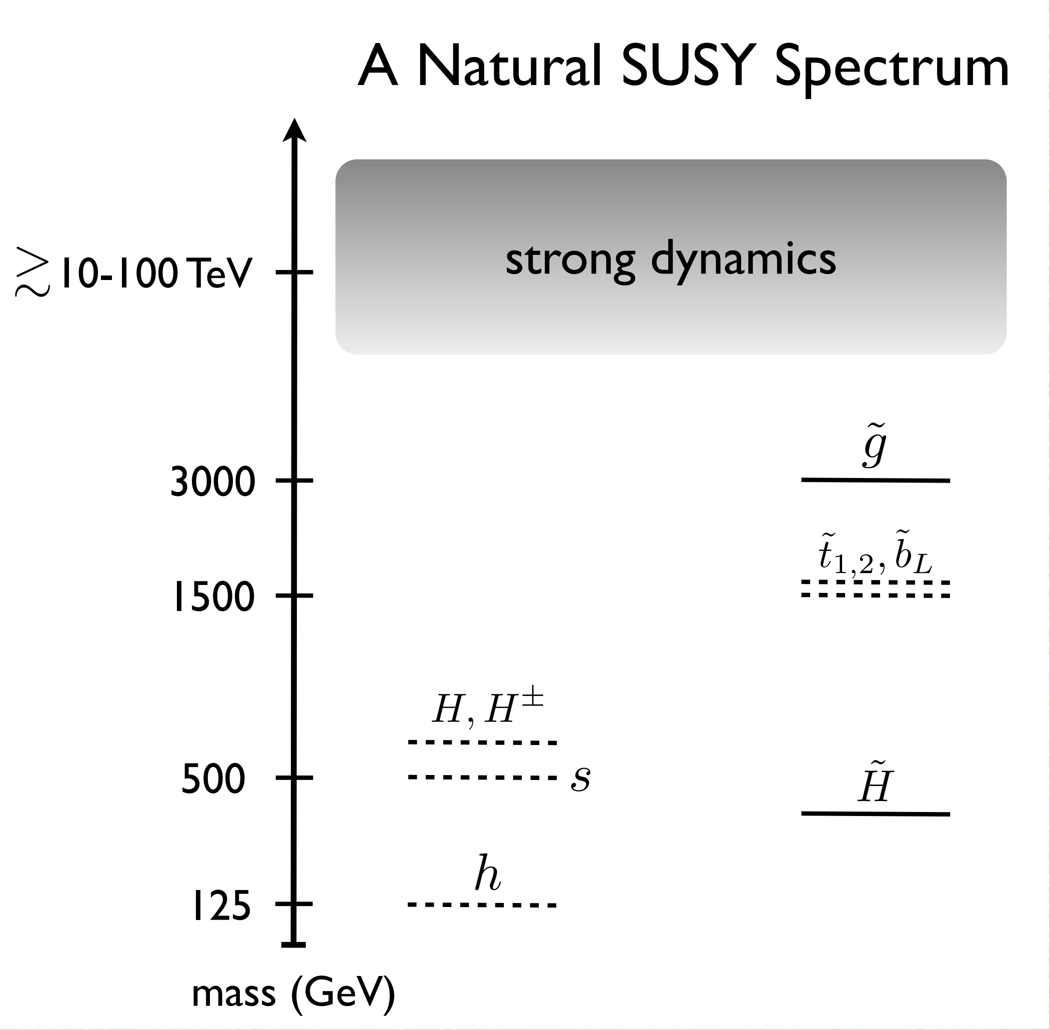
- "Natural SUSY":

Relevant to the Higgs and the "Most Wanted":
$\tilde{H}^{0,\pm},\ \tilde{t},\ \tilde{b},\ (\tilde{g});\ S,\ \tilde{S}\ldots$

LHC Run 2 bounds:

$m_{\tilde{t}} > 800 - 1100$ GeV

$m_{\tilde{\chi}^{\pm}} > 600 - 1100$ GeV

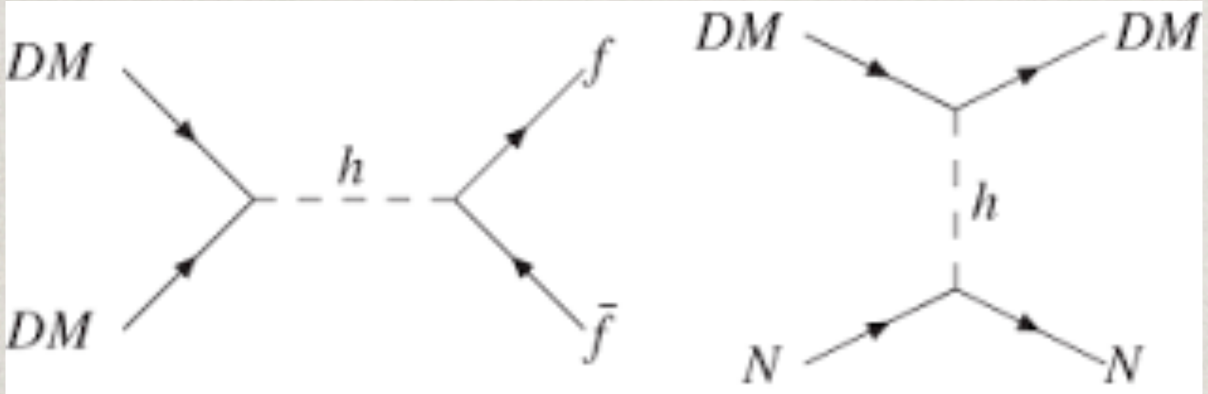


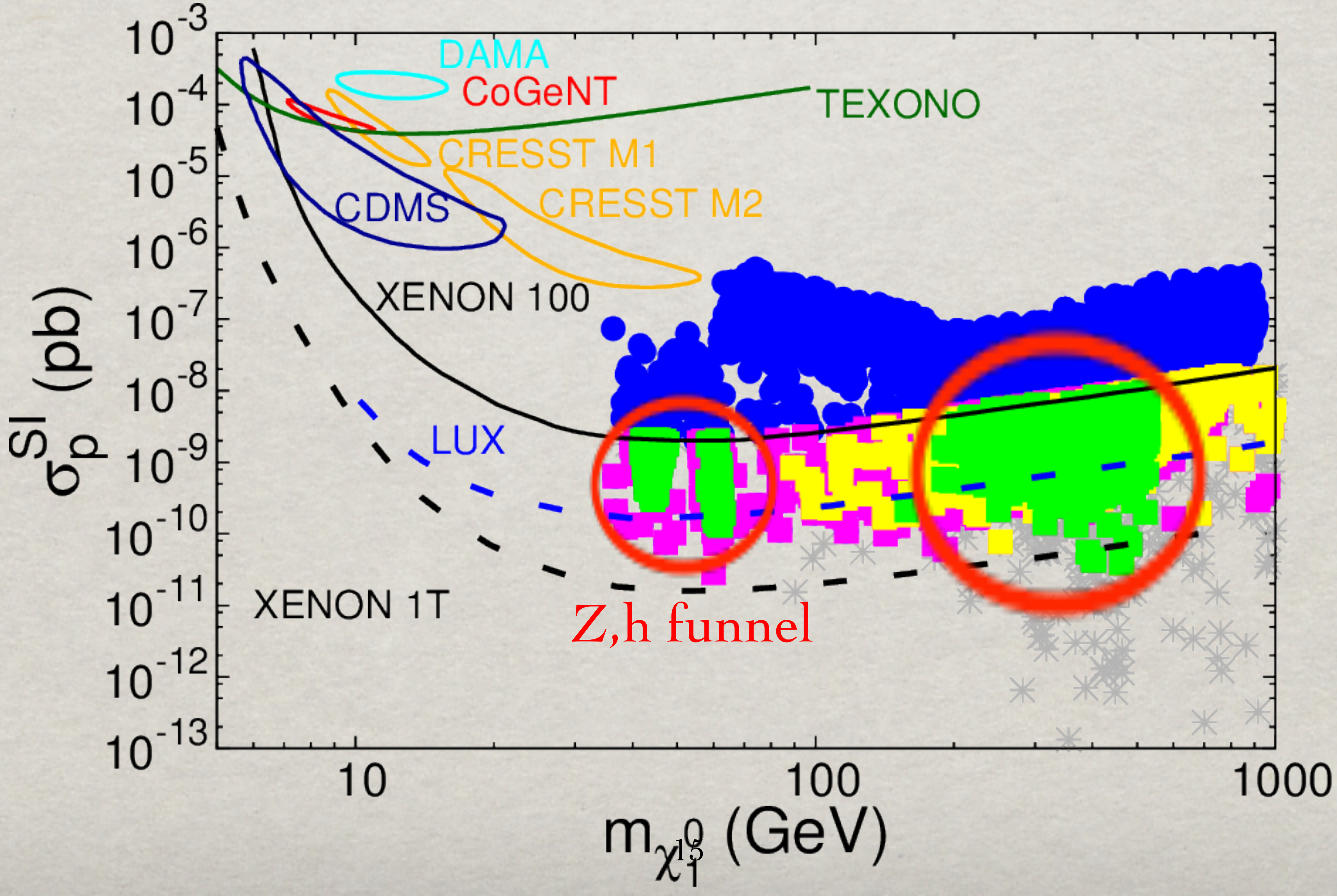
- New strong dynamics, "Compositeness":
The top-quark partner T',
Current ATLAS/CMS limit:
$M_T > 1400$ GeV, for $M_A < 100$ GeV.

Question 3: The Dark Sector

The un-protected operator may reveal secret

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

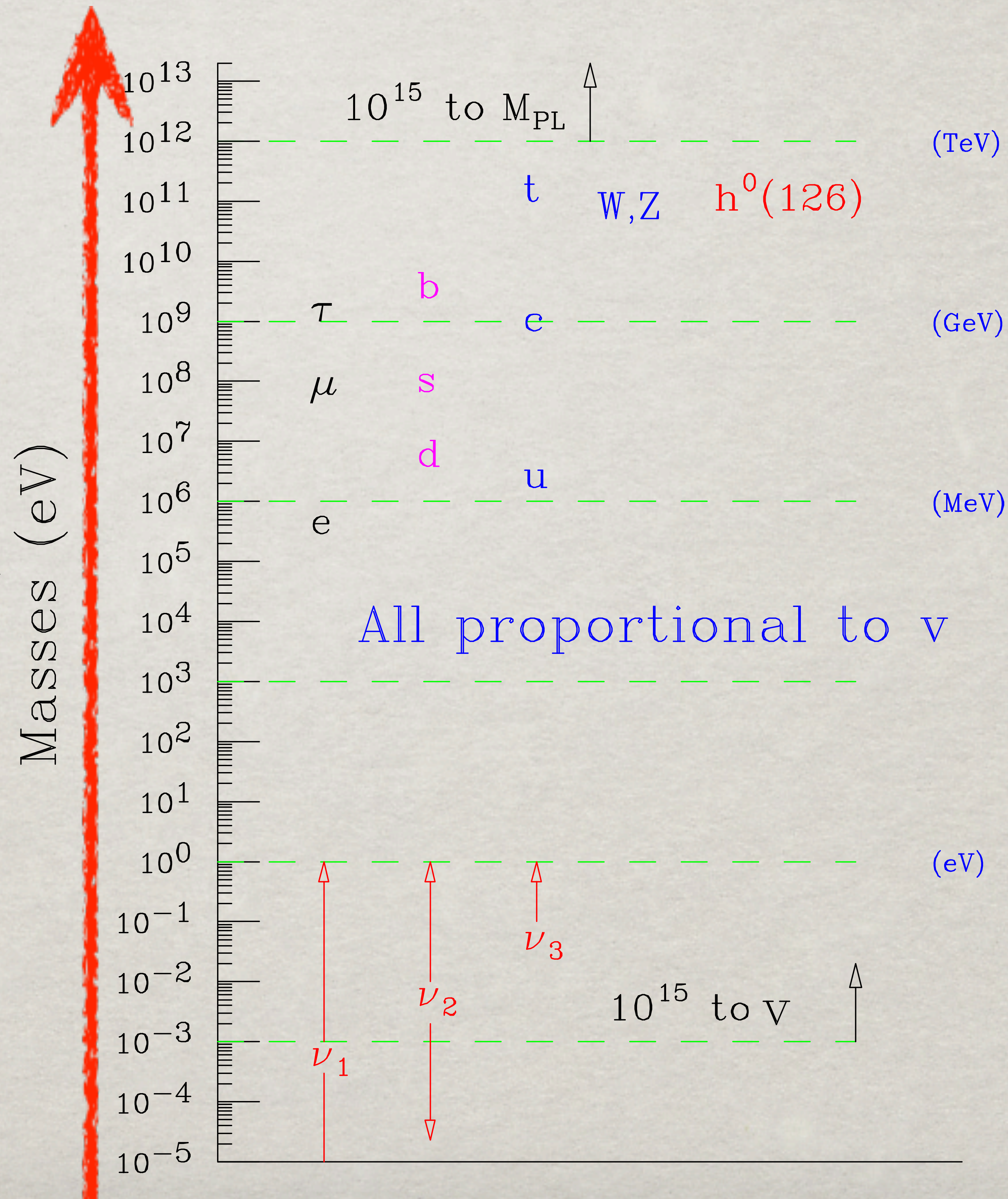




Question 4: The "Flavor Puzzle"

- Particle mass hierarchy
- Patterns of quark, neutrino mixings
- New CP-violation sources?

Higgs Yukawa couplings as the pivot!

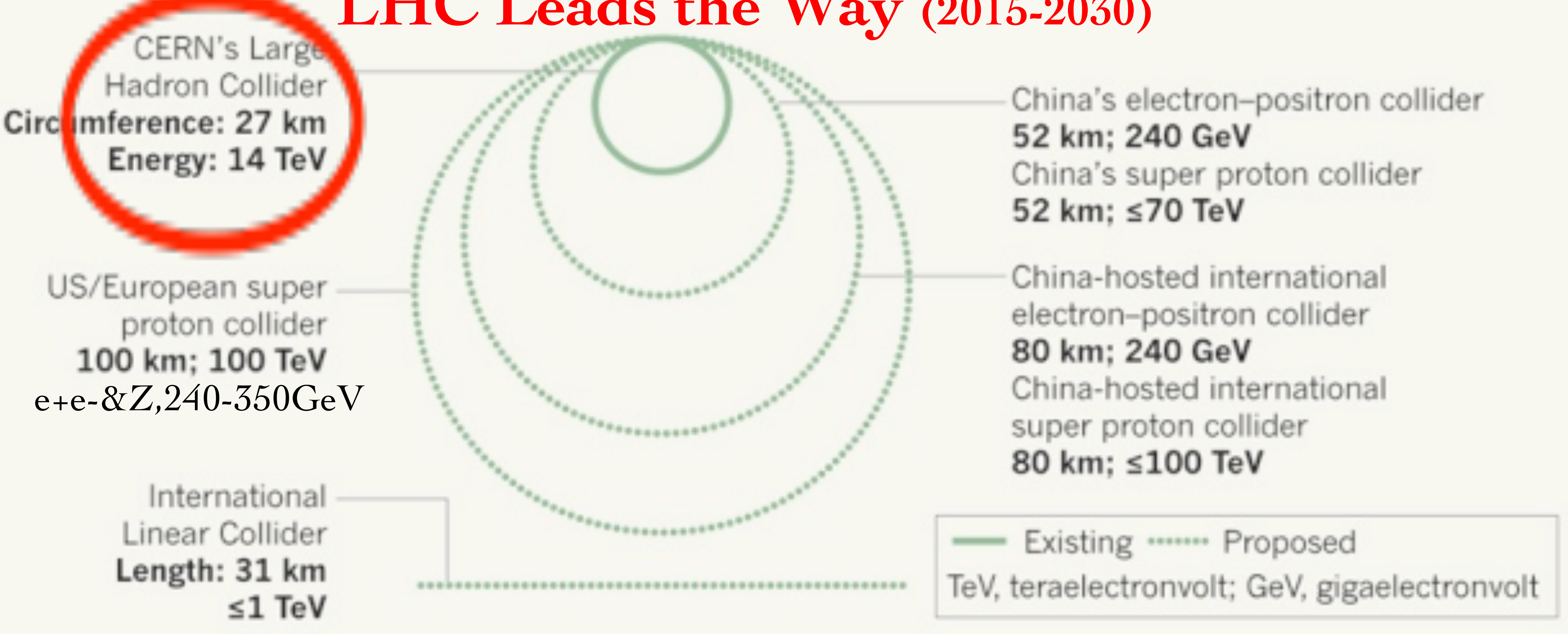


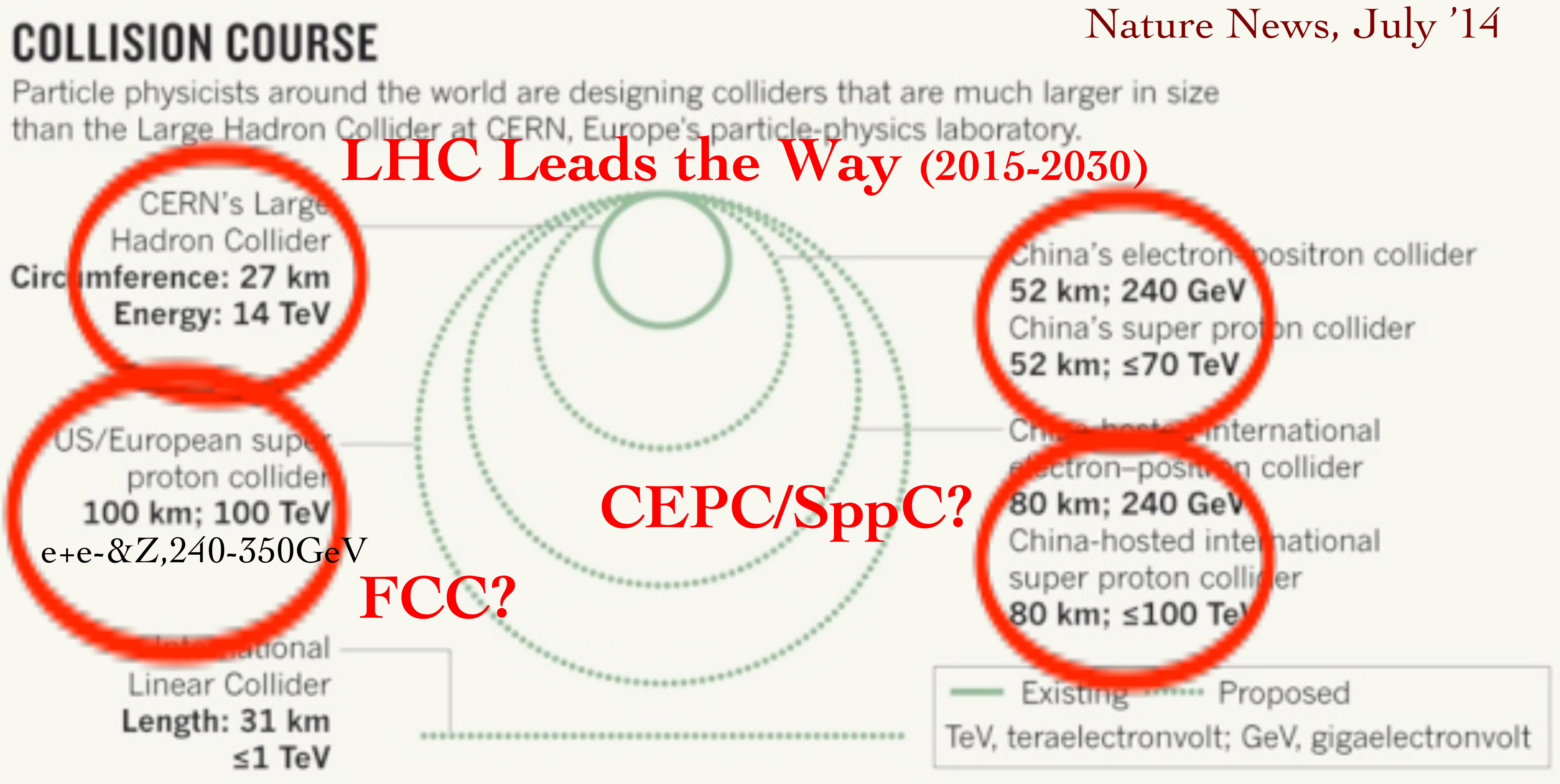
Nature News, July '14

LHC Leads the Way (2015-2030)

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.





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 Larg
Hadron Collider
Circ mference: 27 km
Energy: 14 TeV
US/European sup
proton collide
100 km; 100 TeV
e+e-&Z,240-350GeV
FCC?
Linear Collider
Length: 31 km
≤1 TeV
CEPC/SppC?
hina's electron positron collider
52 km; 240 GeV
China's super pro n collider
52 km; ≤70 TeV
nternational
ctron–posi n collider
80 km; 240 GeV
China-hosted inte national
super proton colli er
80 km; ≤100 Te
Existing
Proposed
TeV, teraelectronvolt; GeV, gigaelectronvolt

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?

International Linear Collider
Length: 31 km
≤1 TeV

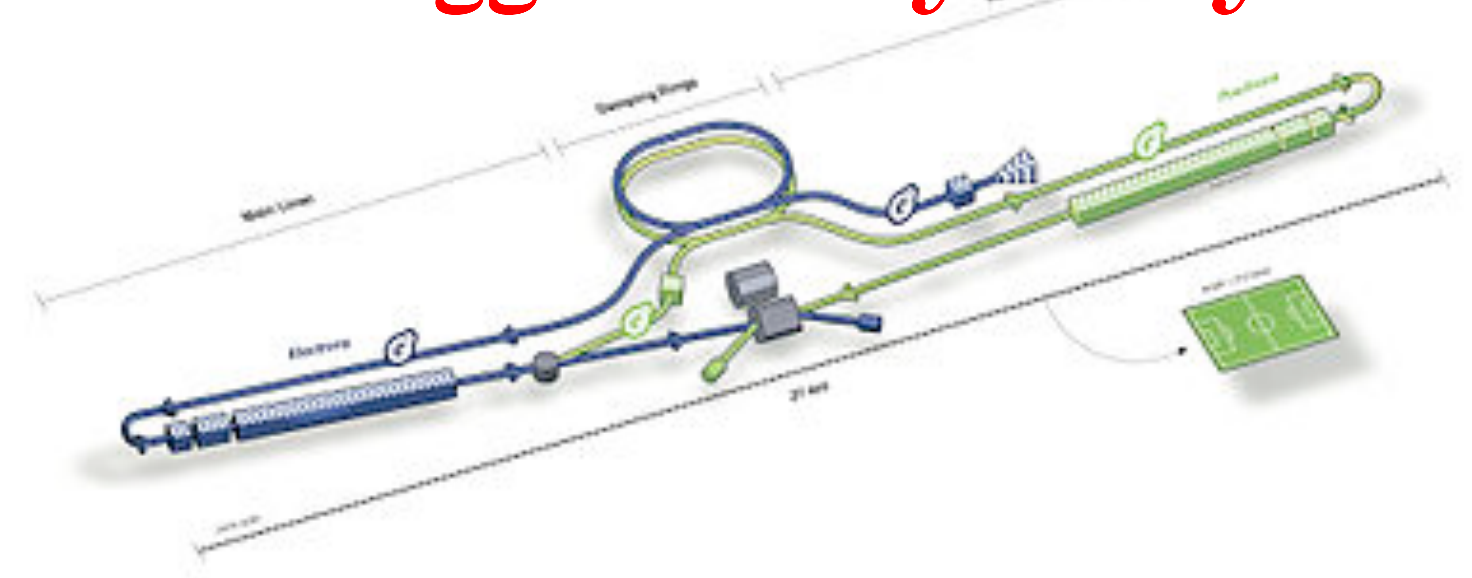
CEPC/SppC?

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

Existing ······ Proposed
GeV, gigaelectronvolt

ILC as Higgs Factory & beyond



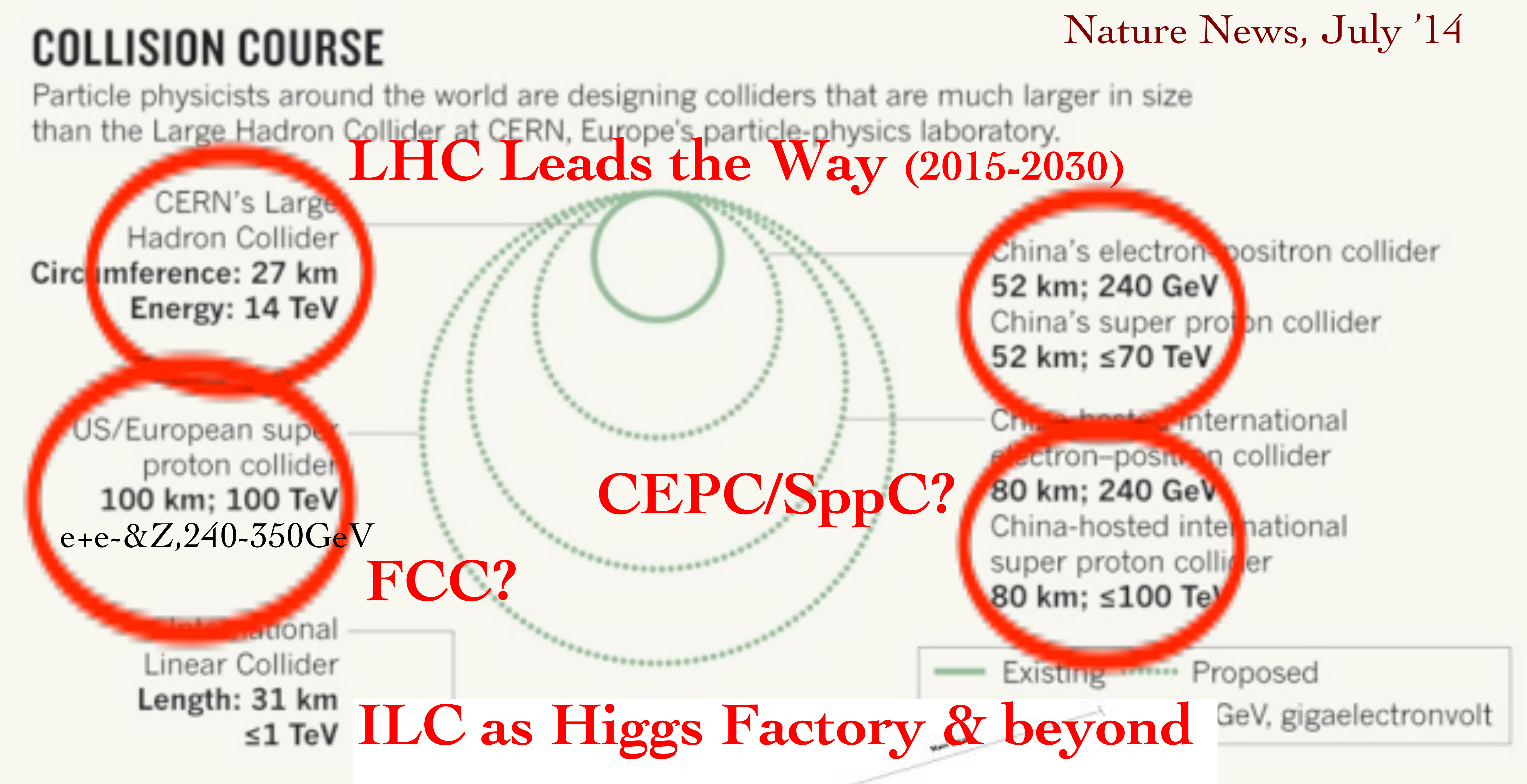


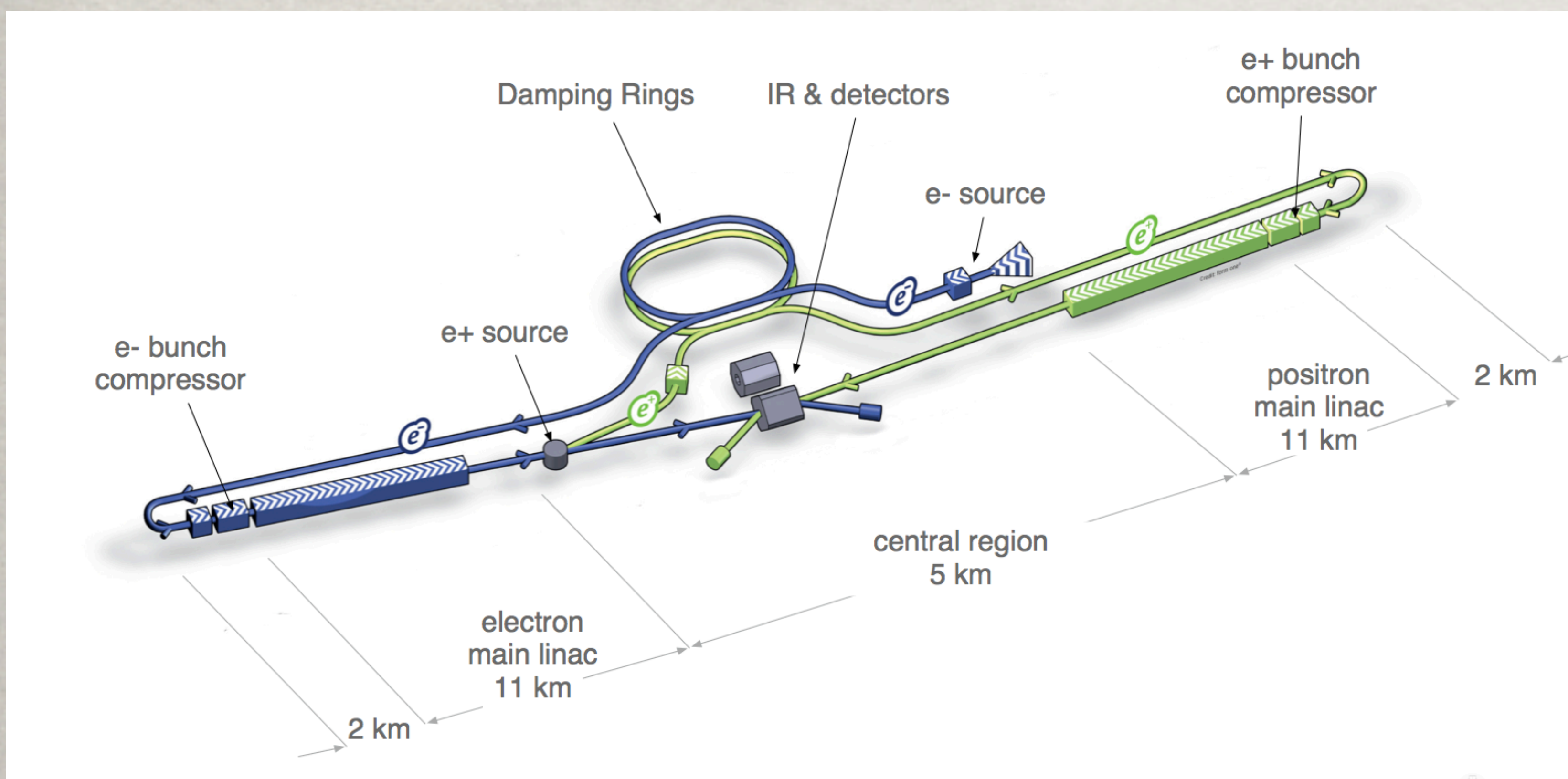
Table 1-1. *Proposed running periods and integrated luminosities at each of the center-of-mass energies for each facility.*

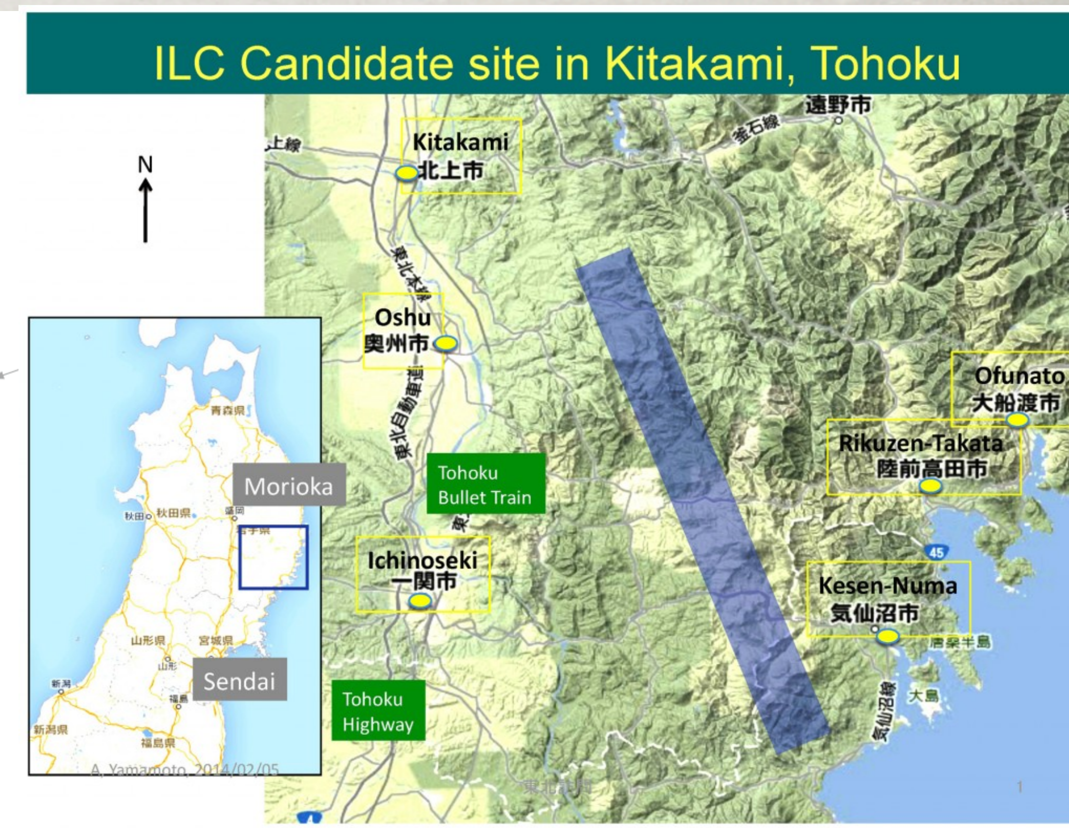
Snowmass 1310.8361

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

International Linear Collider as a Higgs Factory & beyond

Under serious consideration in Japan:

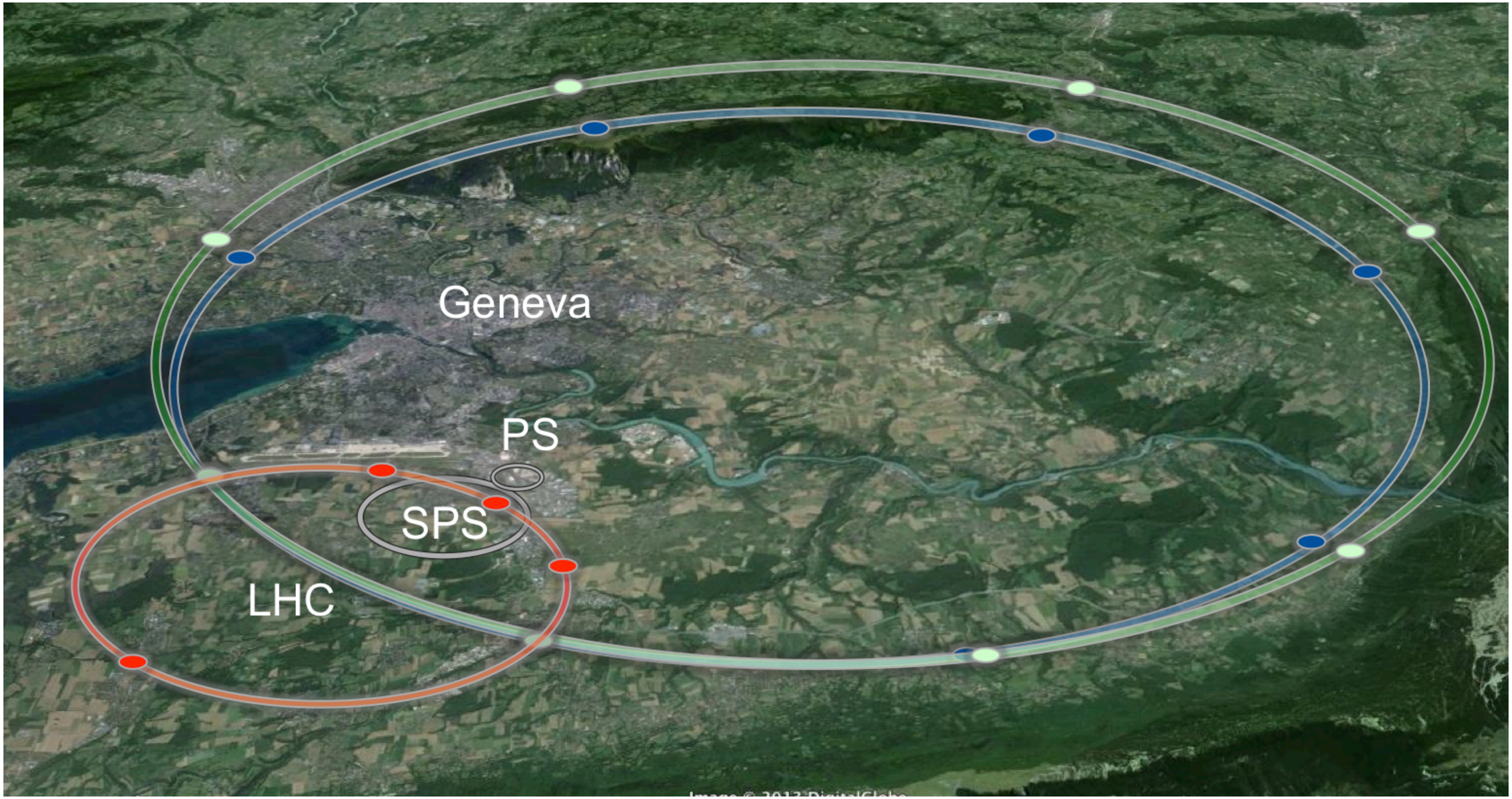




Ecm (GeV) = 250 (Higgs), 500 (top), 1000 (new particles)

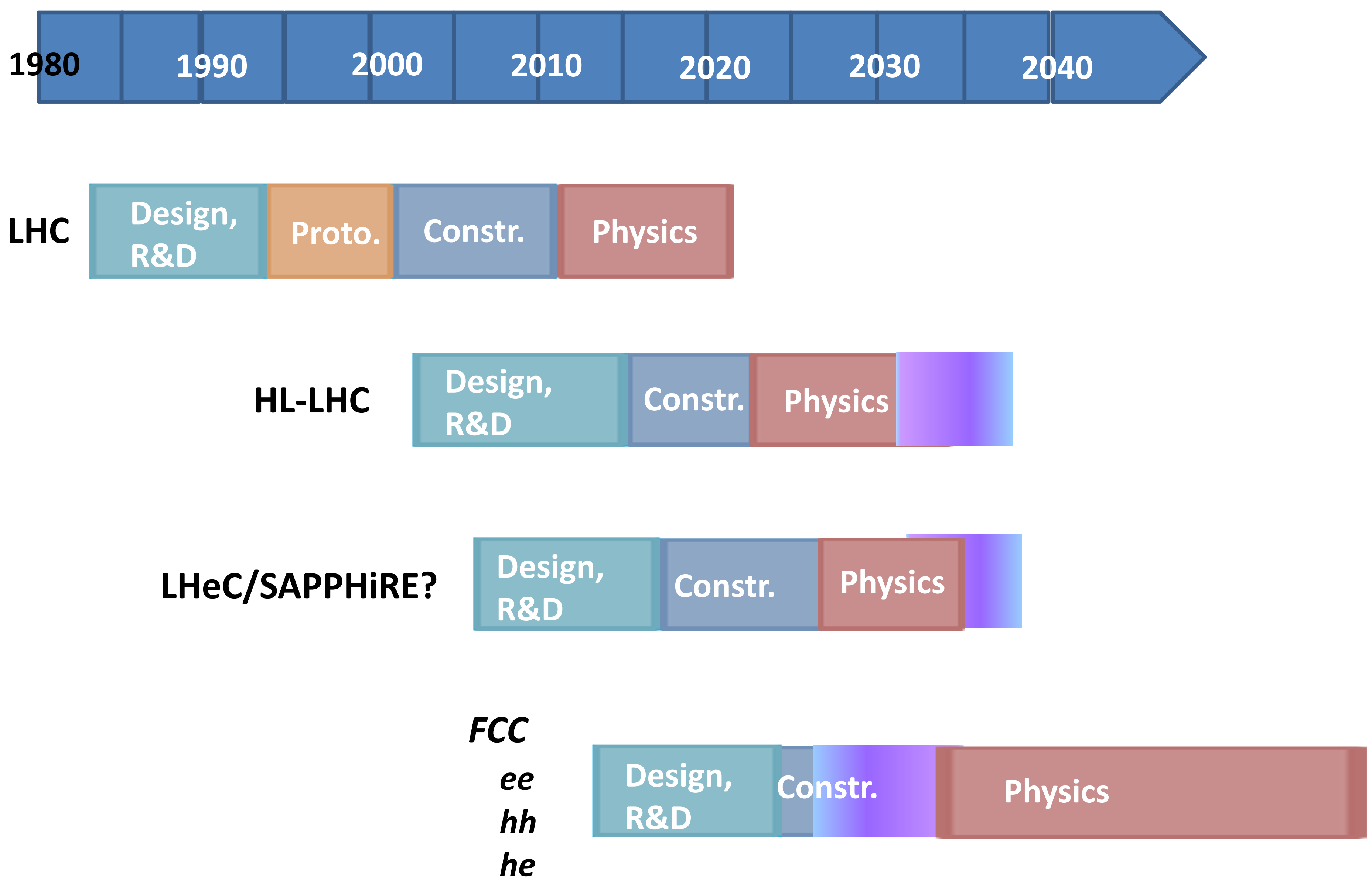
Lumi (ab^{-1}) = 0.25 - 2

FCC (future circular collider): CERN



HE-LHC	FCC-ee	FCC-hh
27 km, 20T	80/100 km	80 /100 km, 16/20T
33 TeV	90 - 400 GeV	100 TeV

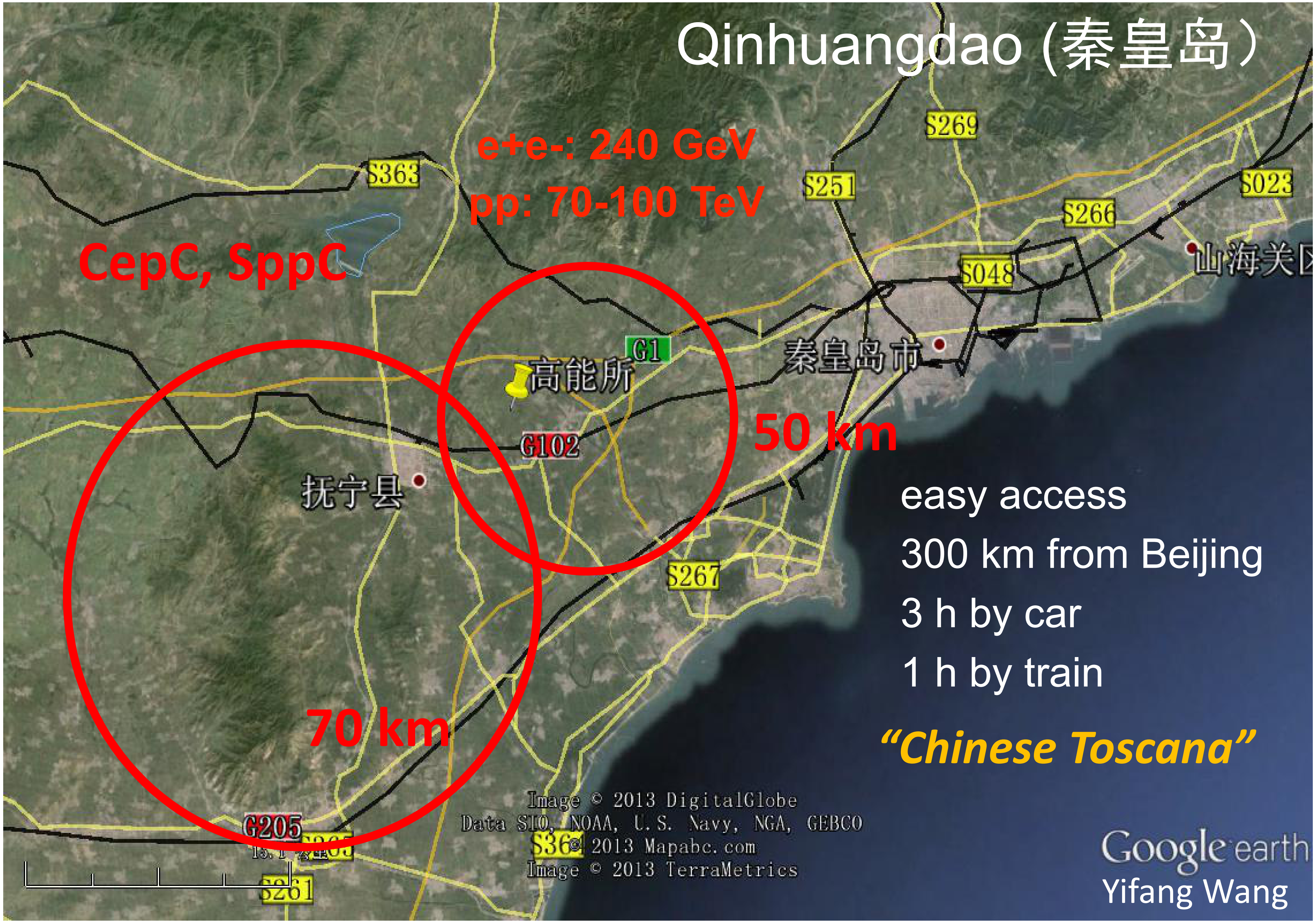
FCC Timeline



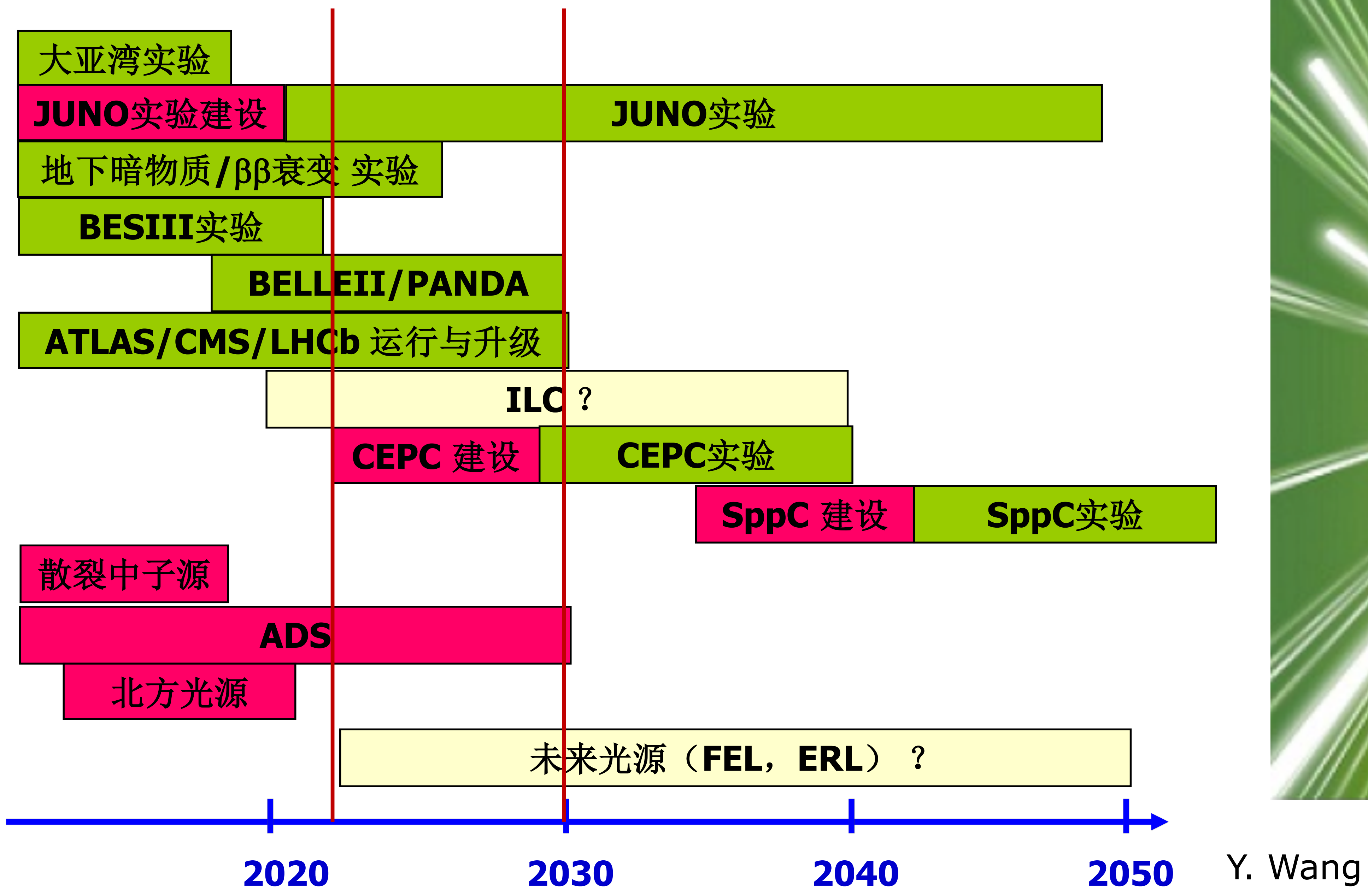
M. Benedikt

CERN Yellow Reports on “a 100 TeV pp Collider”:
Vol. 1. SM; 2. Higgs; 3. BSM; 4. Accelerator

CEPC (circular e^-e^+)/SppC: China

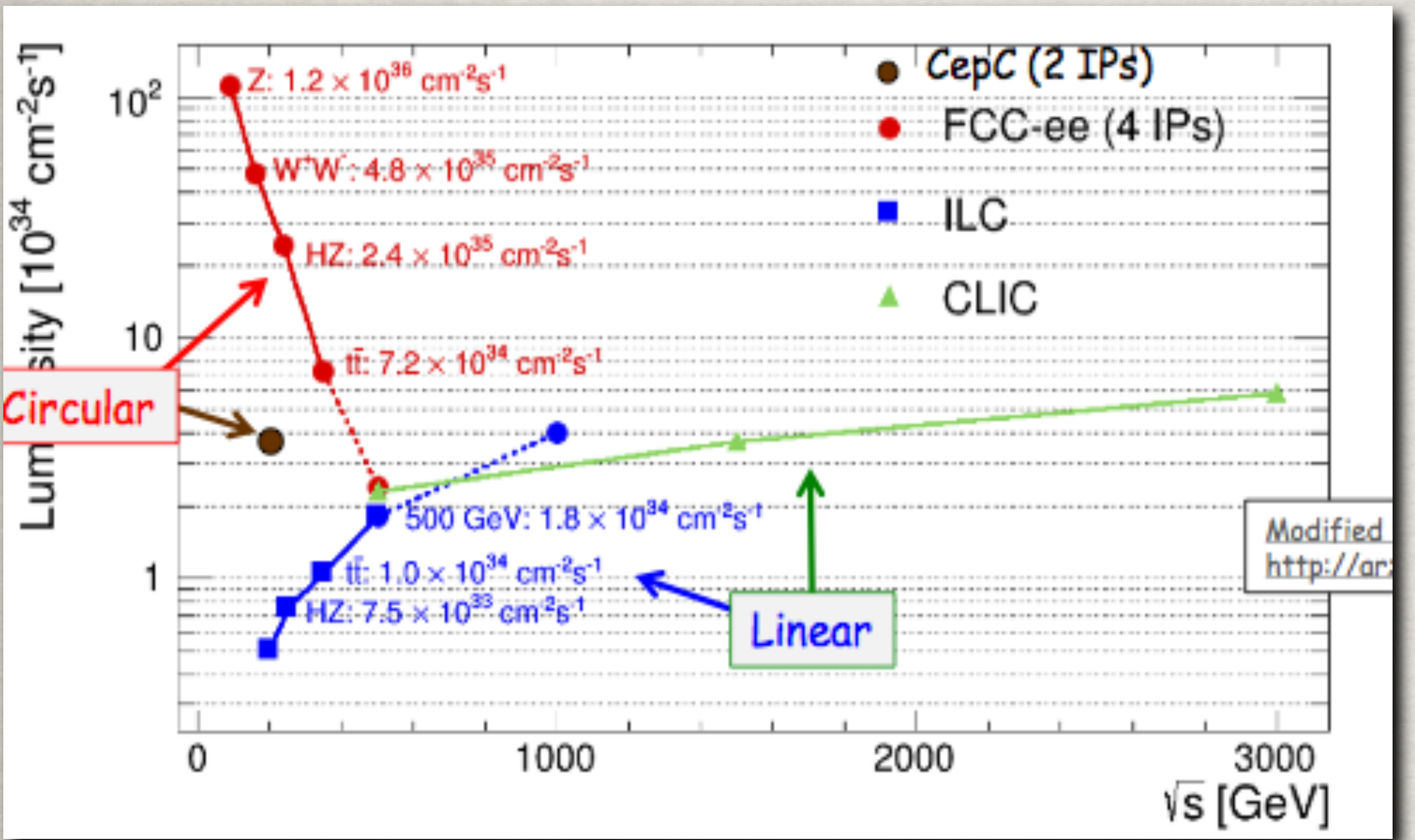


CEPC-SPPC Timeline



CEPC/SppC Preliminary Conceptual Design Reports:
Vol. 1: Physics & Detector; Vol. 2: Accelerator
http://cepc.ihep.ac.cn/preCDR/volume.html

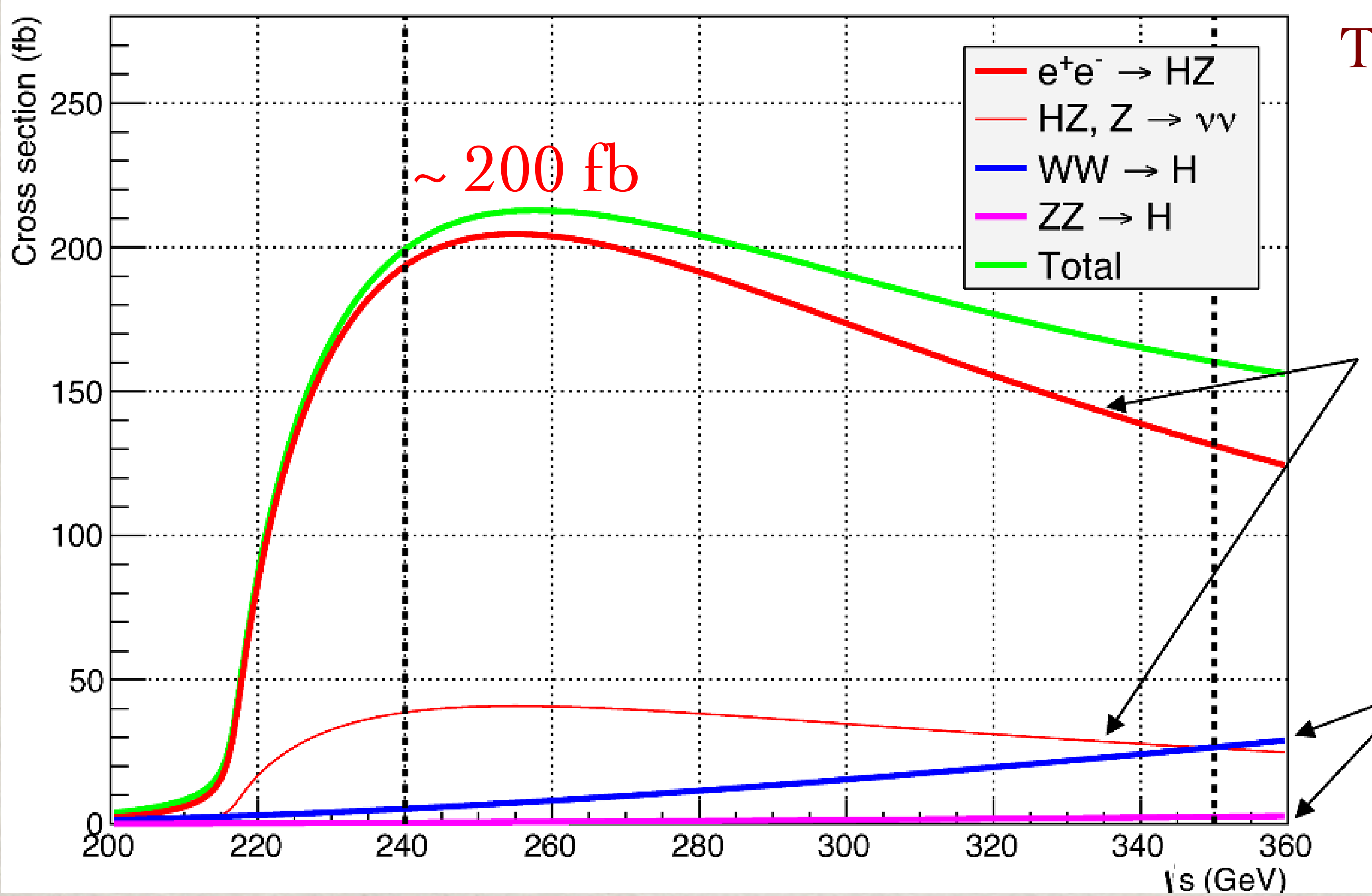
e^+e^- colliders: Energy/Lumi projection



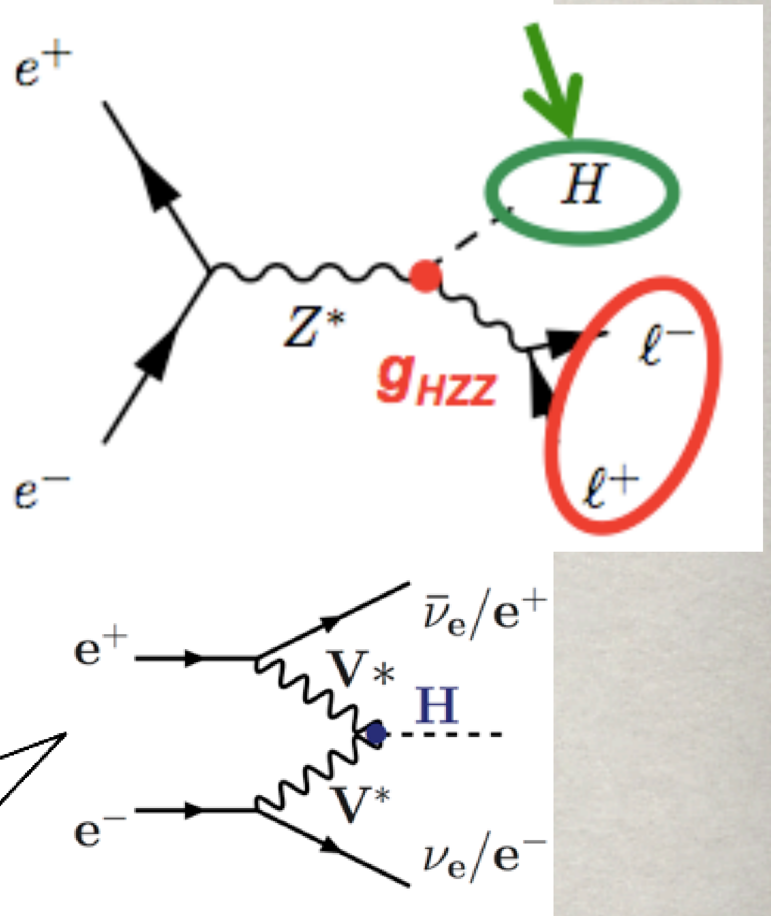
TLEP Report: 1308.6176

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	2×10^6 ZH (Mega H)
350 GeV	4-5 yrs	10^6 tt (Mega top)

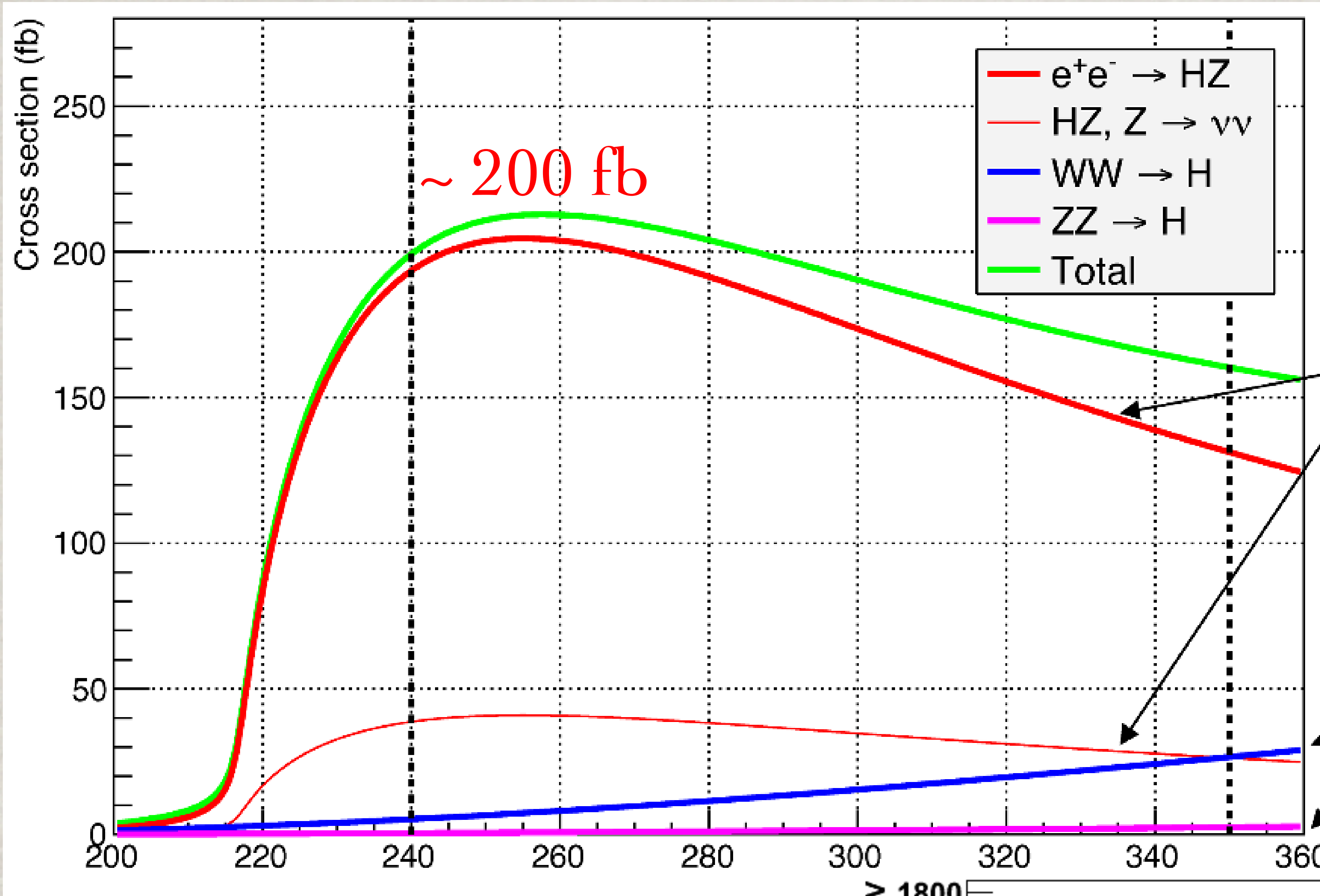
Higgs-Factory: Mega (10^6) Higgs



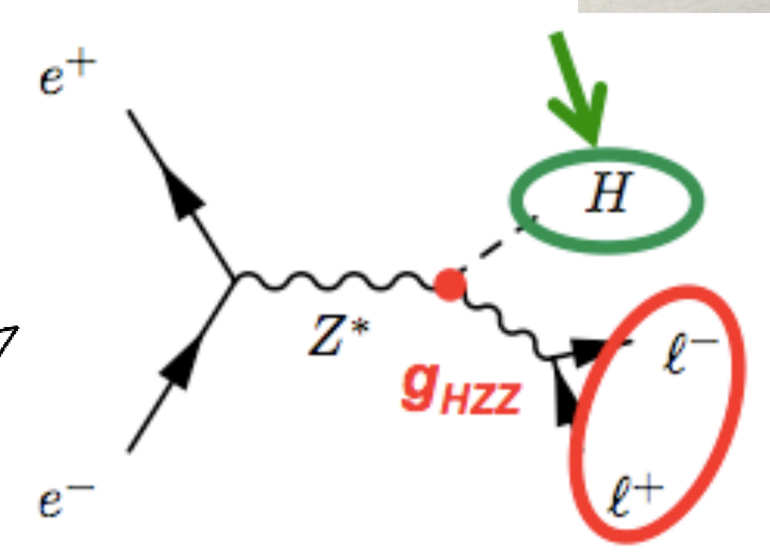
TLEP Report: 1308.6176

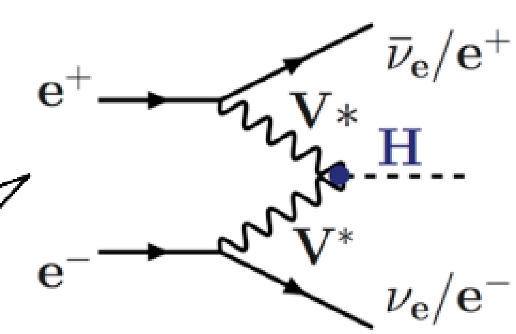


HIGGS-FACTORY: MEGA (10^6) HIGGS



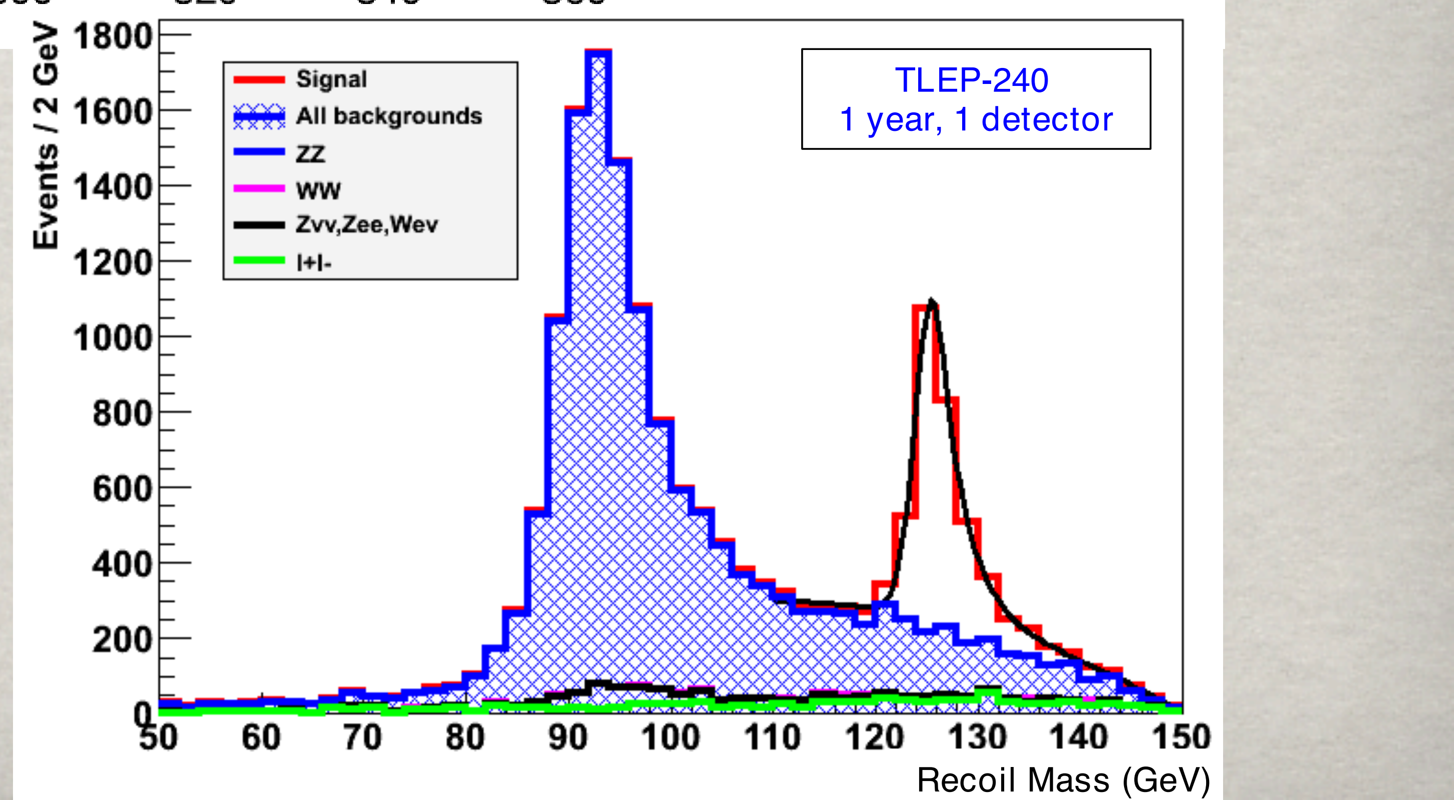
TLEP Report: 1308.6176





"Recoil mass"

$$m_h^2 = (p_{e^-} + p_{e^+} - q_{\mu^-} - q_{\mu^+})^2$$



Higgs-Factory:

- ILC: E_{cm} = 250 (500) GeV, 250 (500) fb^{-1} (0.5×10^5 Higgs)

Model-independent measurement:

ILC Report: 1308.6176

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

(HL-LHC: assume SM, $\Gamma_H \sim 5\text{-}8\%$, $\Delta m_H \sim 50$ MeV)

- FCCee/CEPC **10^6** Higgs: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

Higgs-Factory:

- ILC: E_{cm} = 250 (500) GeV, 250 (500) fb^{-1} (0.5x10^5 Higgs)

Model-independent measurement:

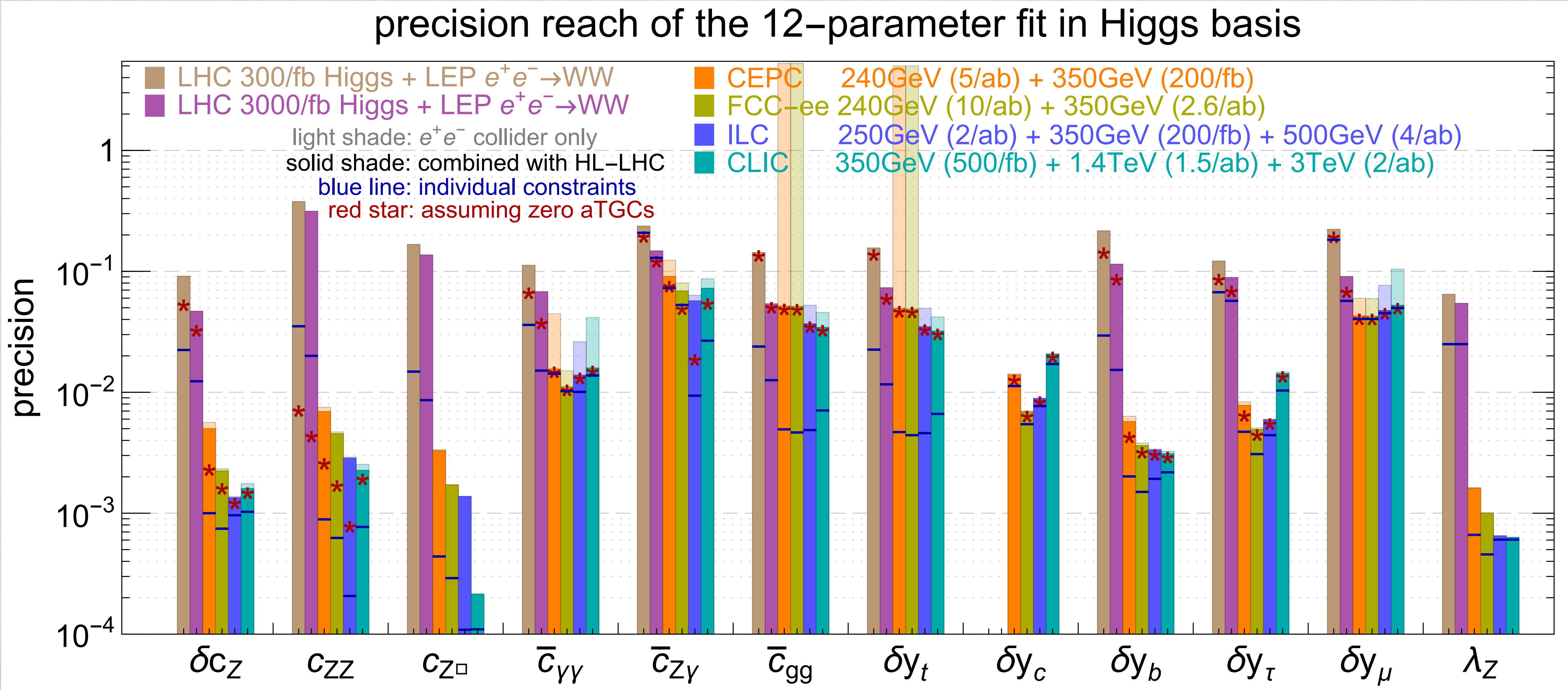
ILC Report: 1308.6176

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

(HL-LHC: assume SM, $\Gamma_H \sim$ 5-8%, $\Delta m_H \sim 50$ MeV)

- FCC/CEPC **10^6** Higgs: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

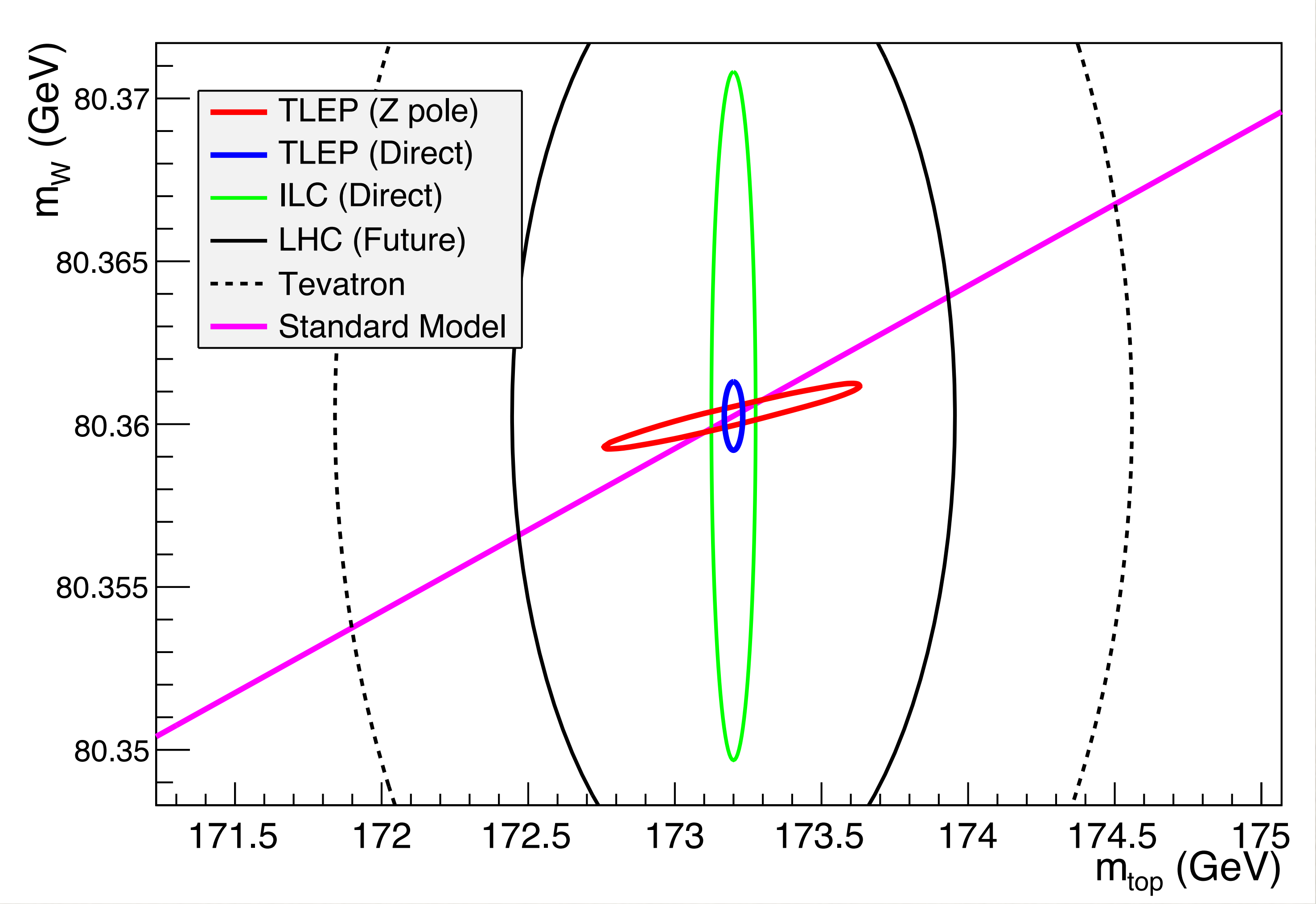
Couplings to sub-percent: Peskin et al. 1704.02333



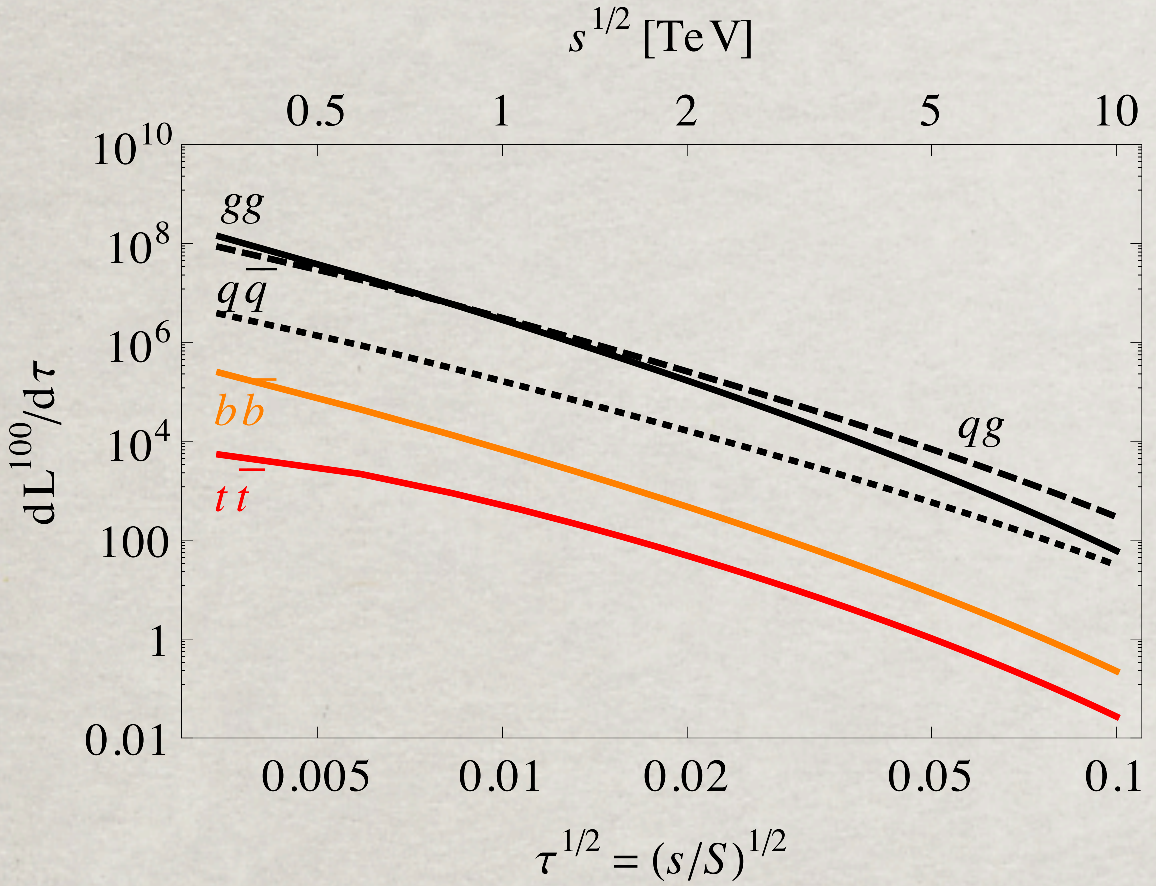
Z-Factory: Tera (10^{12}) Z Physics

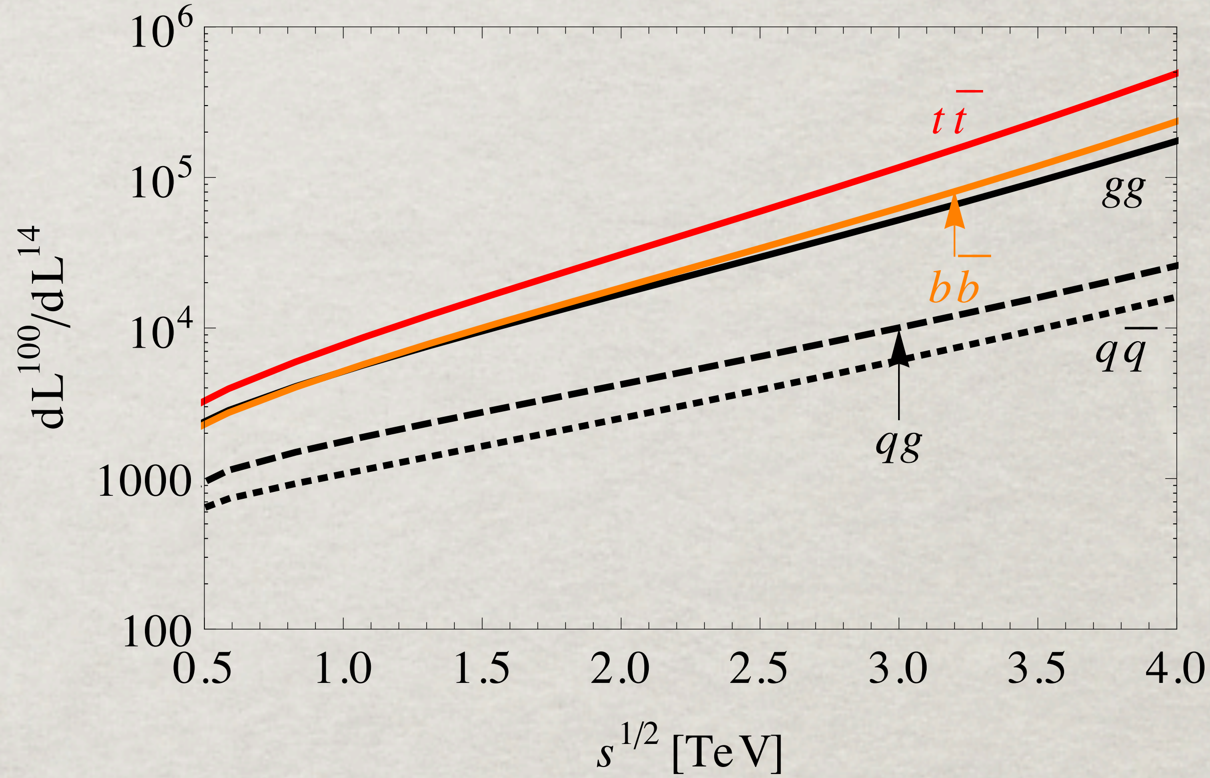
TLEP Report: 1308.6176

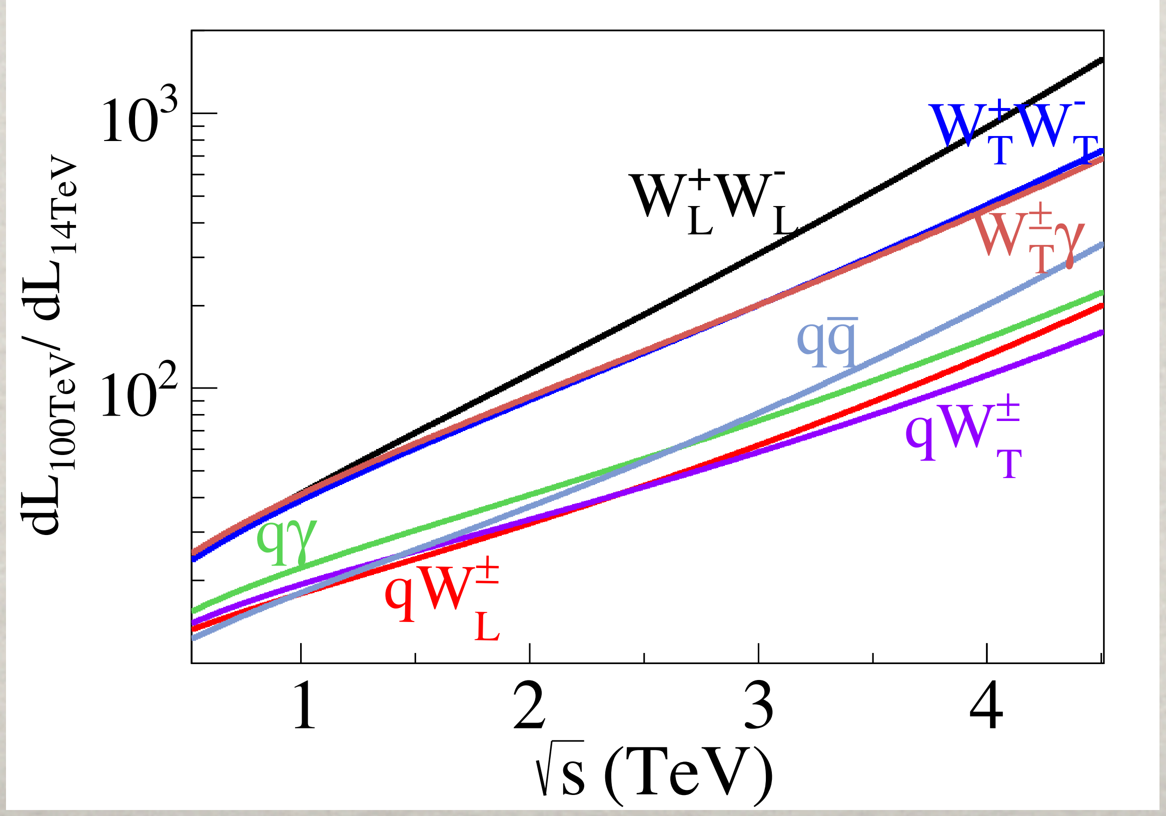
- Clean environment, $\Delta E_{cm} < 1$ MeV, 10^5 x LEP-I
- possible longitudinal polarization
- Z-ploe: ΔM_Z, $\Delta\Gamma_Z < 0.1$ MeV, $\Delta\sin^2\theta_w < 10^{-6}$;
- Thr. scan: $\Delta M_W \sim O(1$ MeV), $\Delta m_t \sim O(10$ MeV), $\Delta m_H \sim O(10$ MeV).



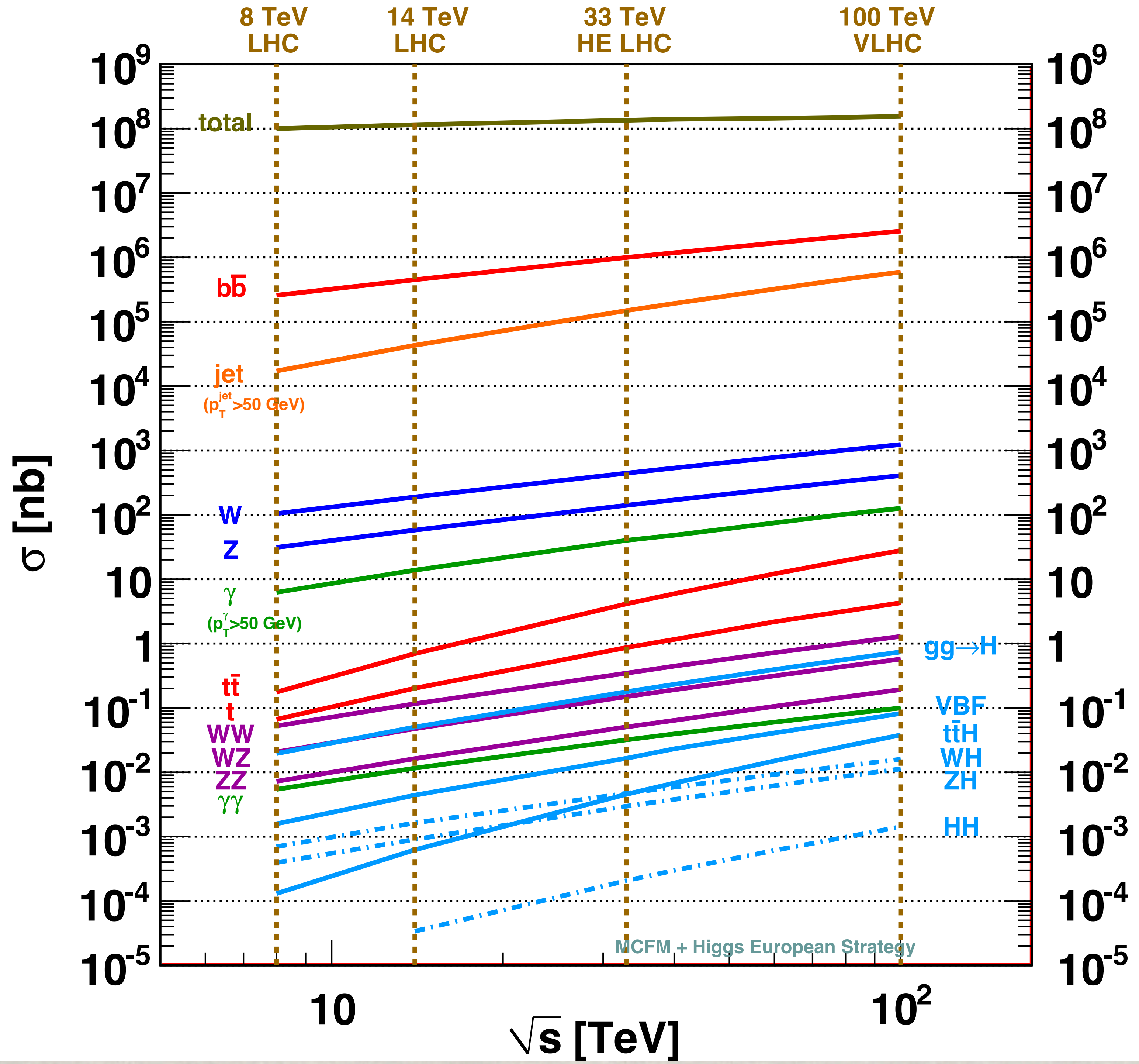
The Next Energy Frontier: 100 TeV Hadron Collider







Higgs Production @ FCC_{hh}/SPPC



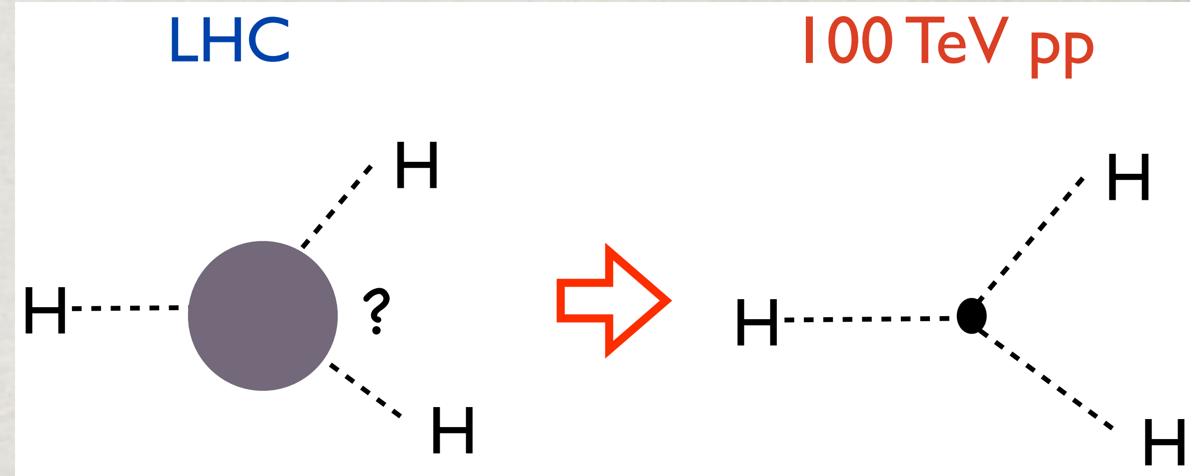
Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

Snowmass QCD Working Group: 1310.5189

Higgs Self-couplings:

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

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

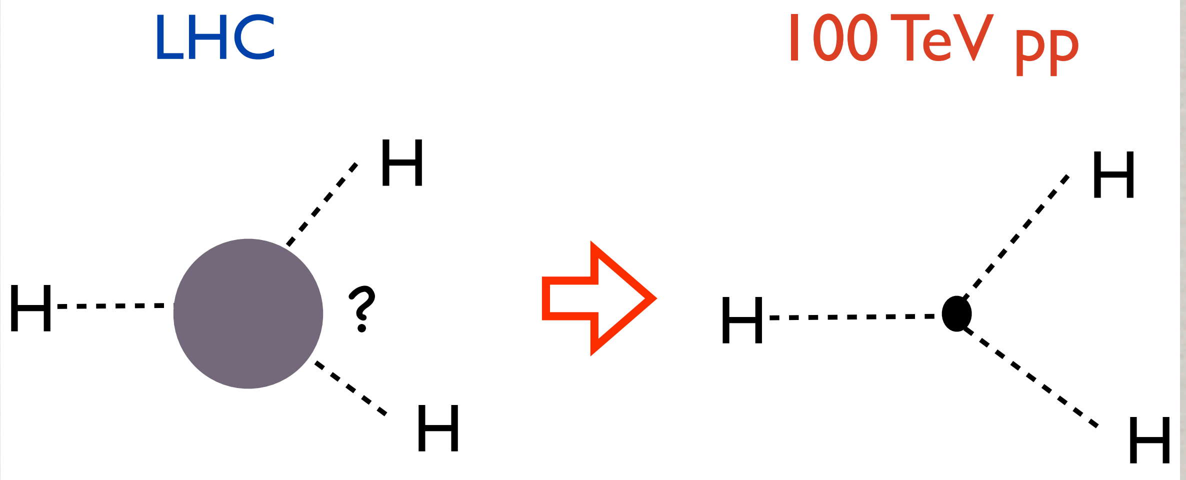


Triple Higgs boson coupling λ_{hhh} :
Test the shape of the Higgs potential,
and the fate of the EW-phase transition (EWPT):
O(100%) deviation needed for 1^{st} order EWPT;
O(10%) accuracy needed for a conclusive test.

Higgs Self-couplings:

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

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



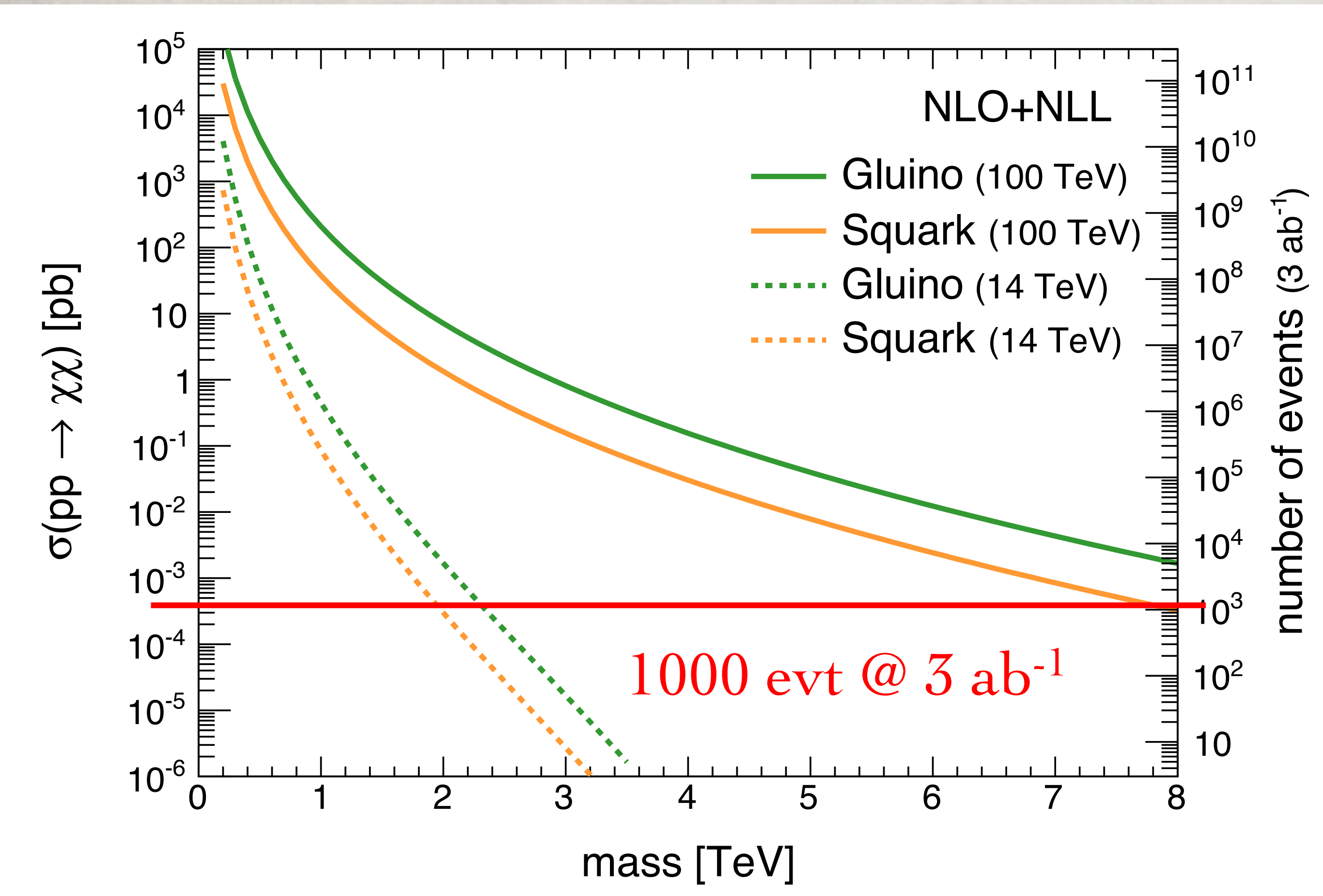
Triple Higgs boson coupling λ_{hhh} :
Test the shape of the Higgs potential,
and the fate of the EW-phase transition (EWPT):
O(100%) deviation needed for 1st order EWPT;
O(10%) accuracy needed for a conclusive test.

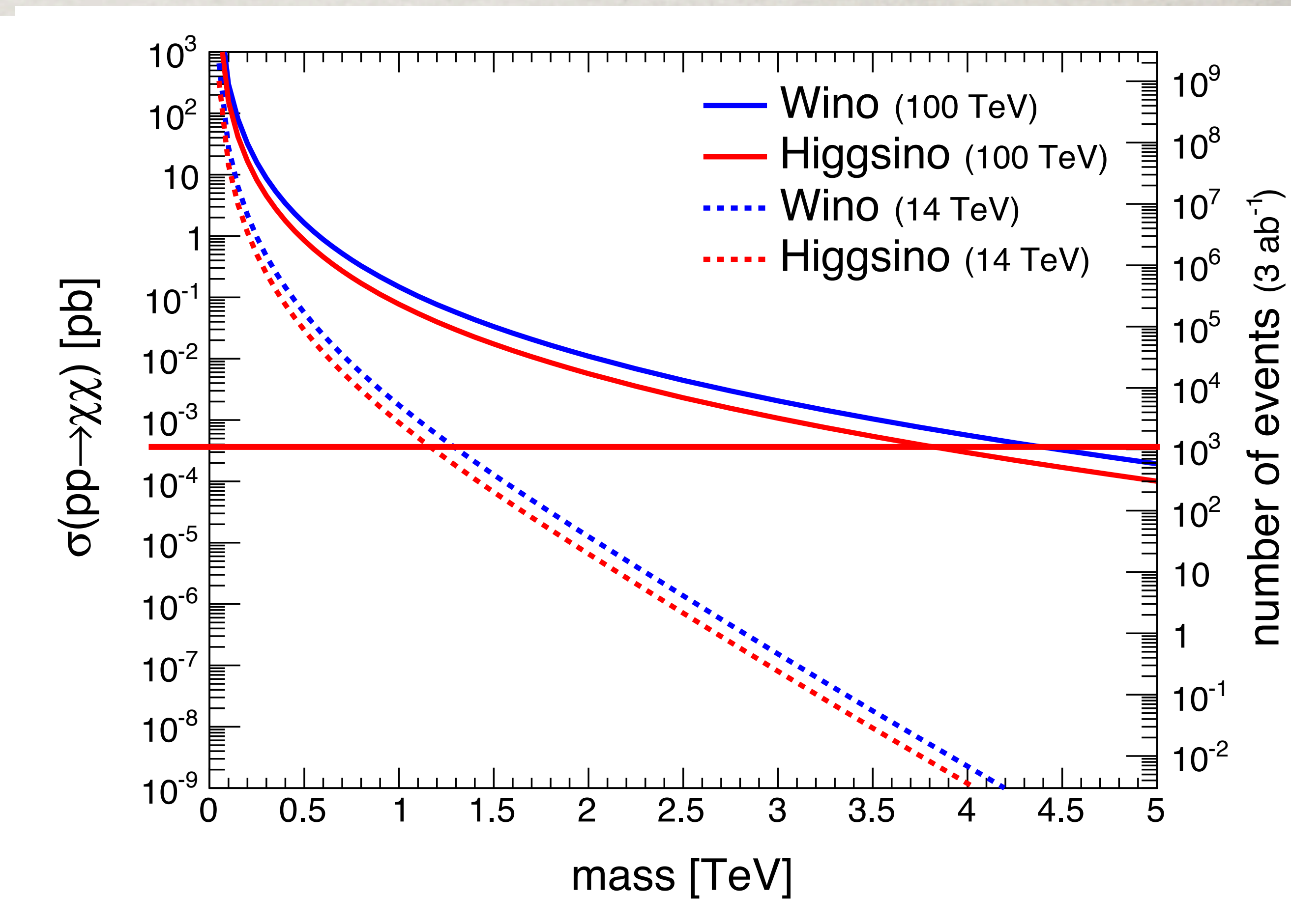
HL-LHC ~ 50%; ILC(1 TeV), CLIC(3 TeV) ~ 10%;

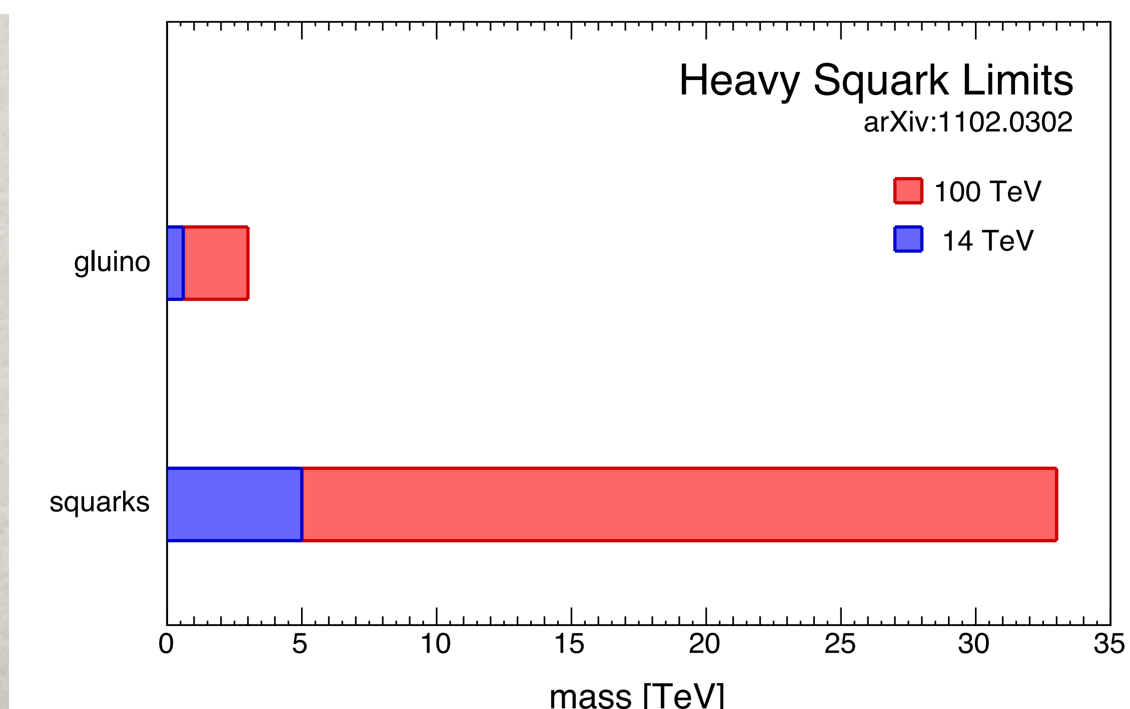
FCC$_{hh}$ @ 3 ab^{-1}: ~ 8%

SUSY @ FCC_{hh}/SPPC

M.Mangano et al.: 1407.5066

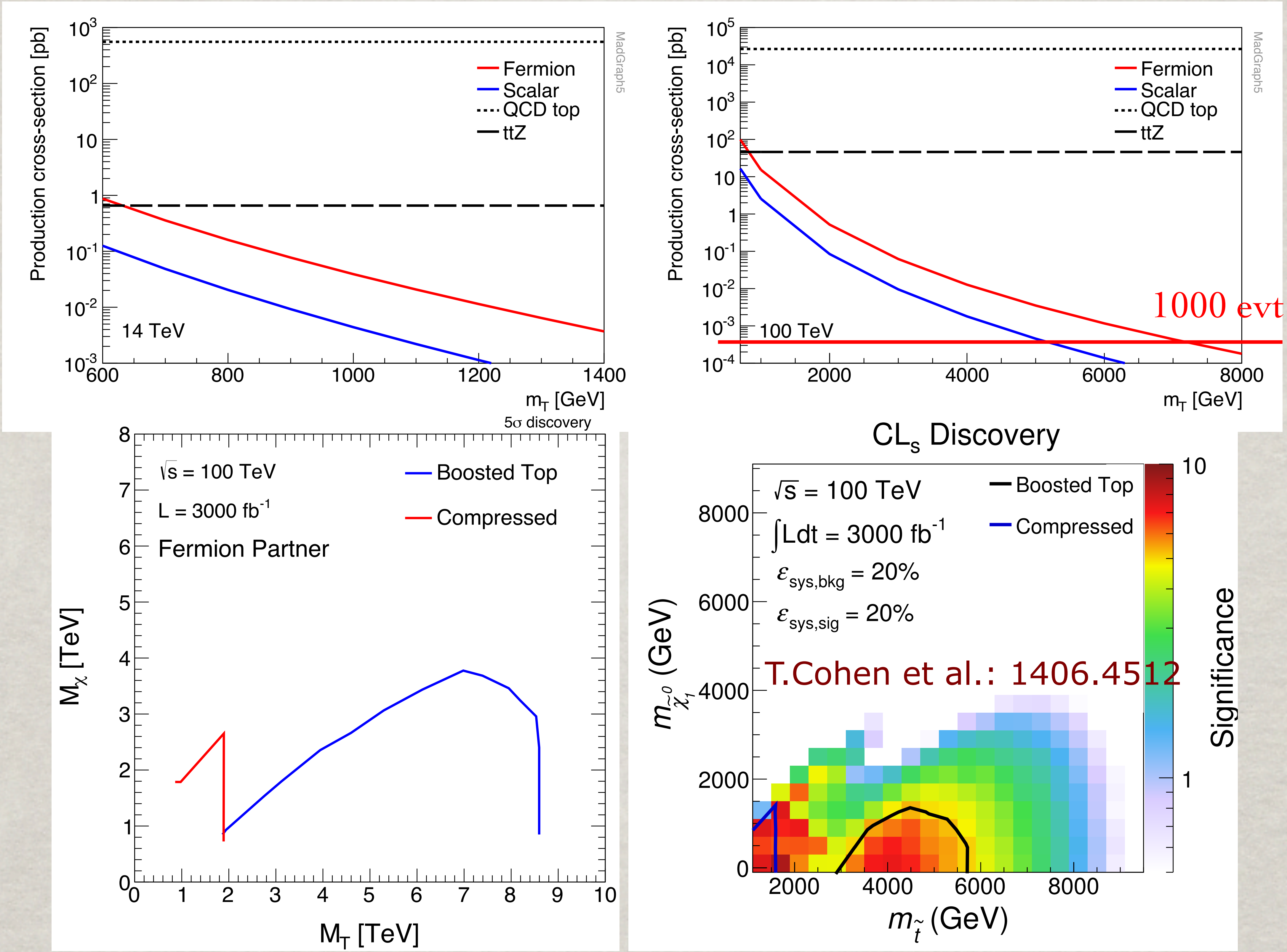






Mass reach at 100 TeV:
~ 7x over LHC

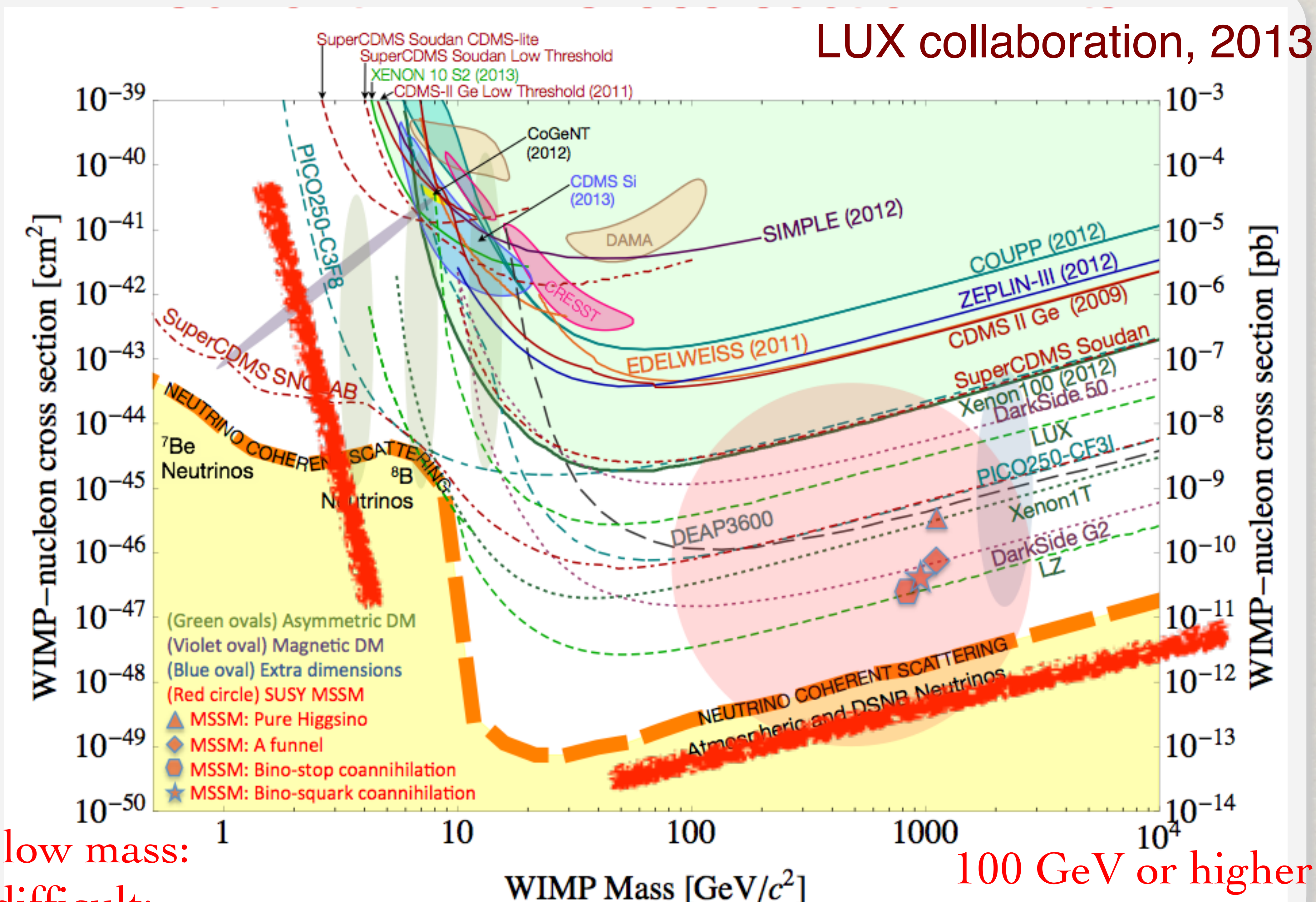
Pushing the "Naturalness" limit



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!

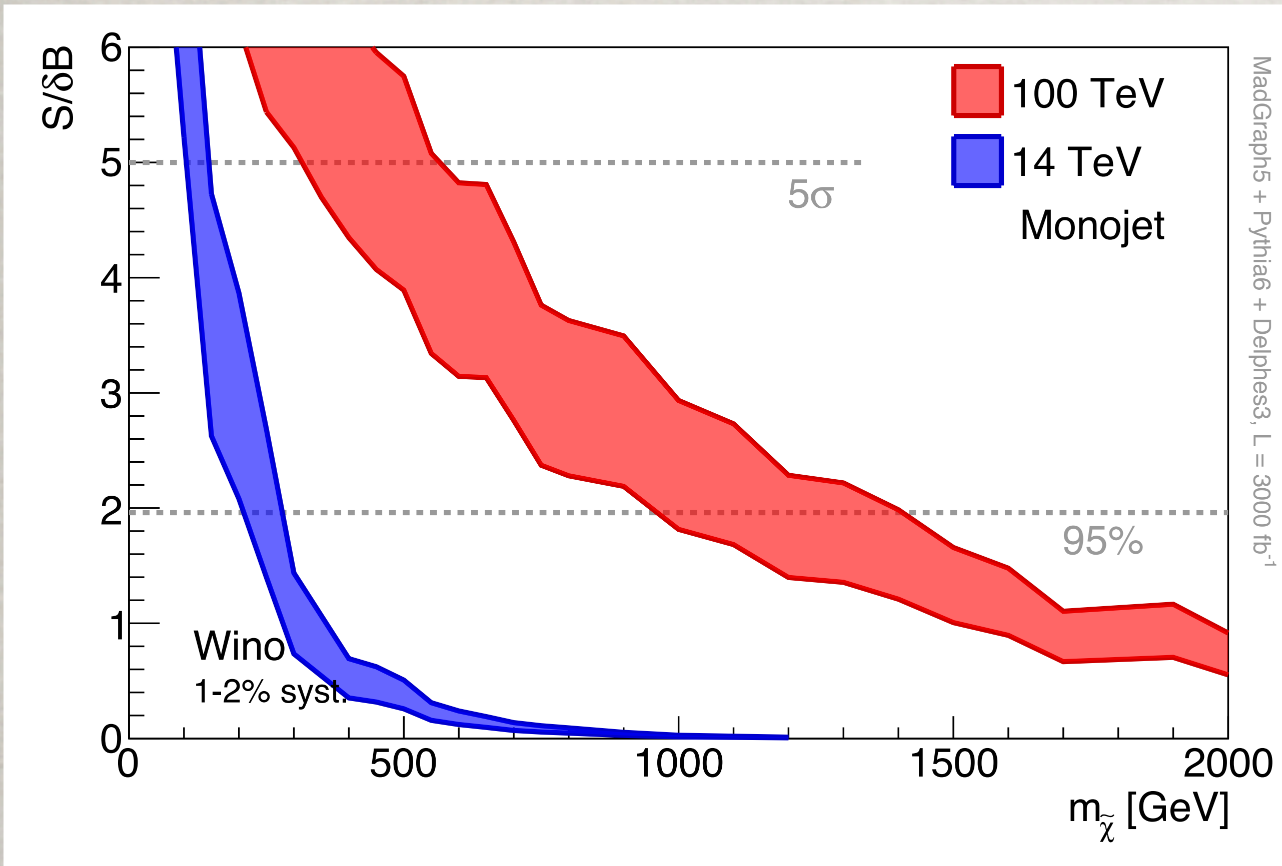
DM Searches

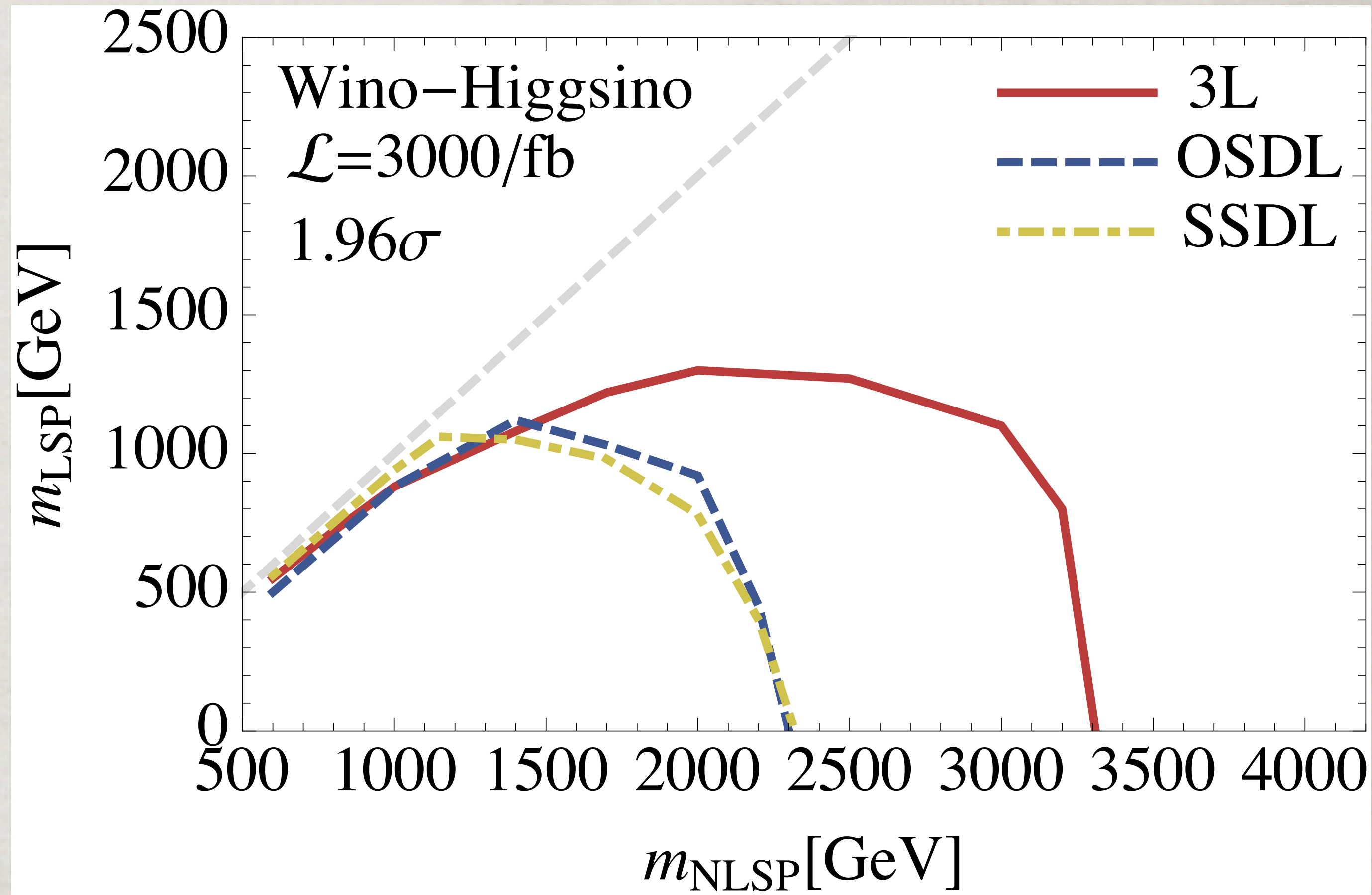


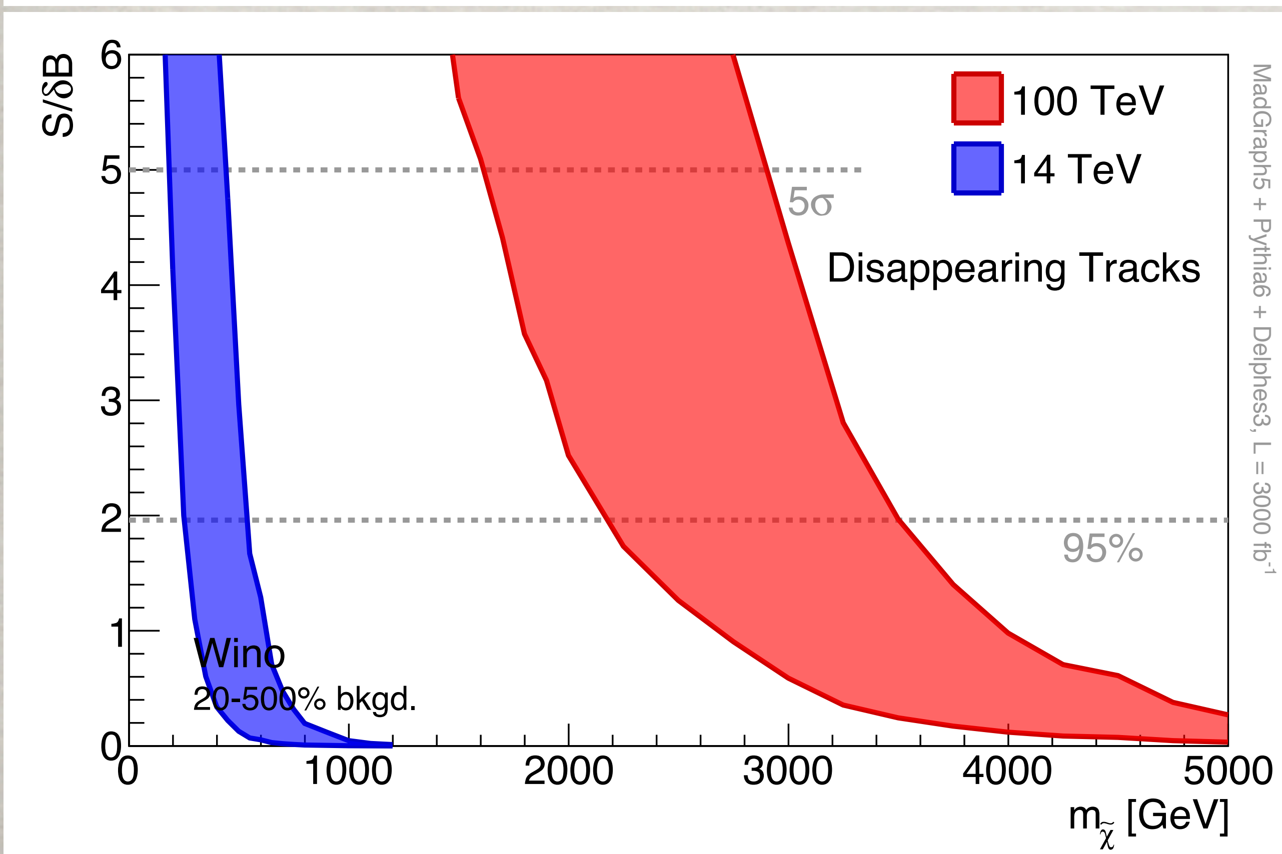
GeV low mass:
DD difficult;
Collider complementary

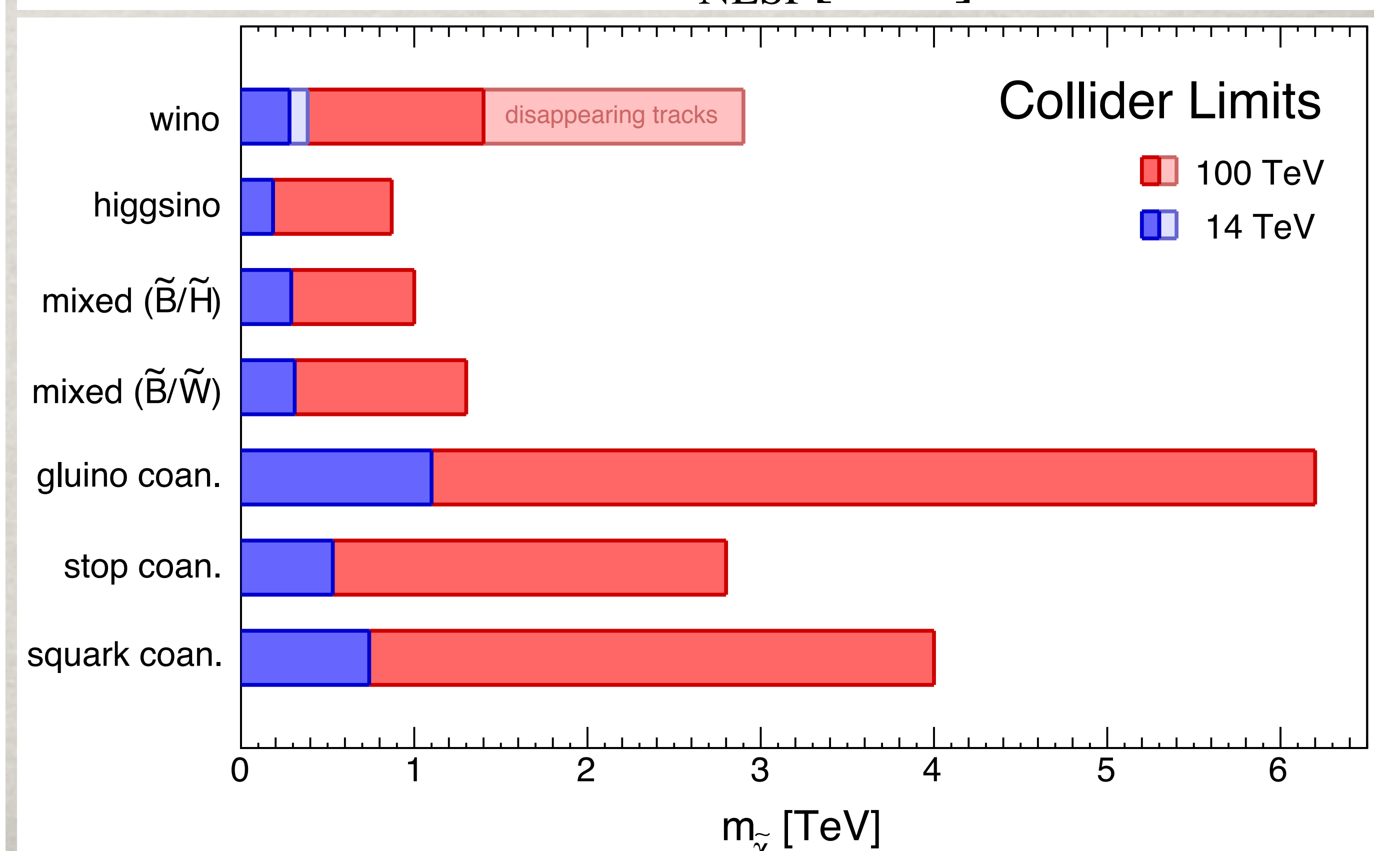
100 GeV or higher mass:
DD + ID + HE Collider

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



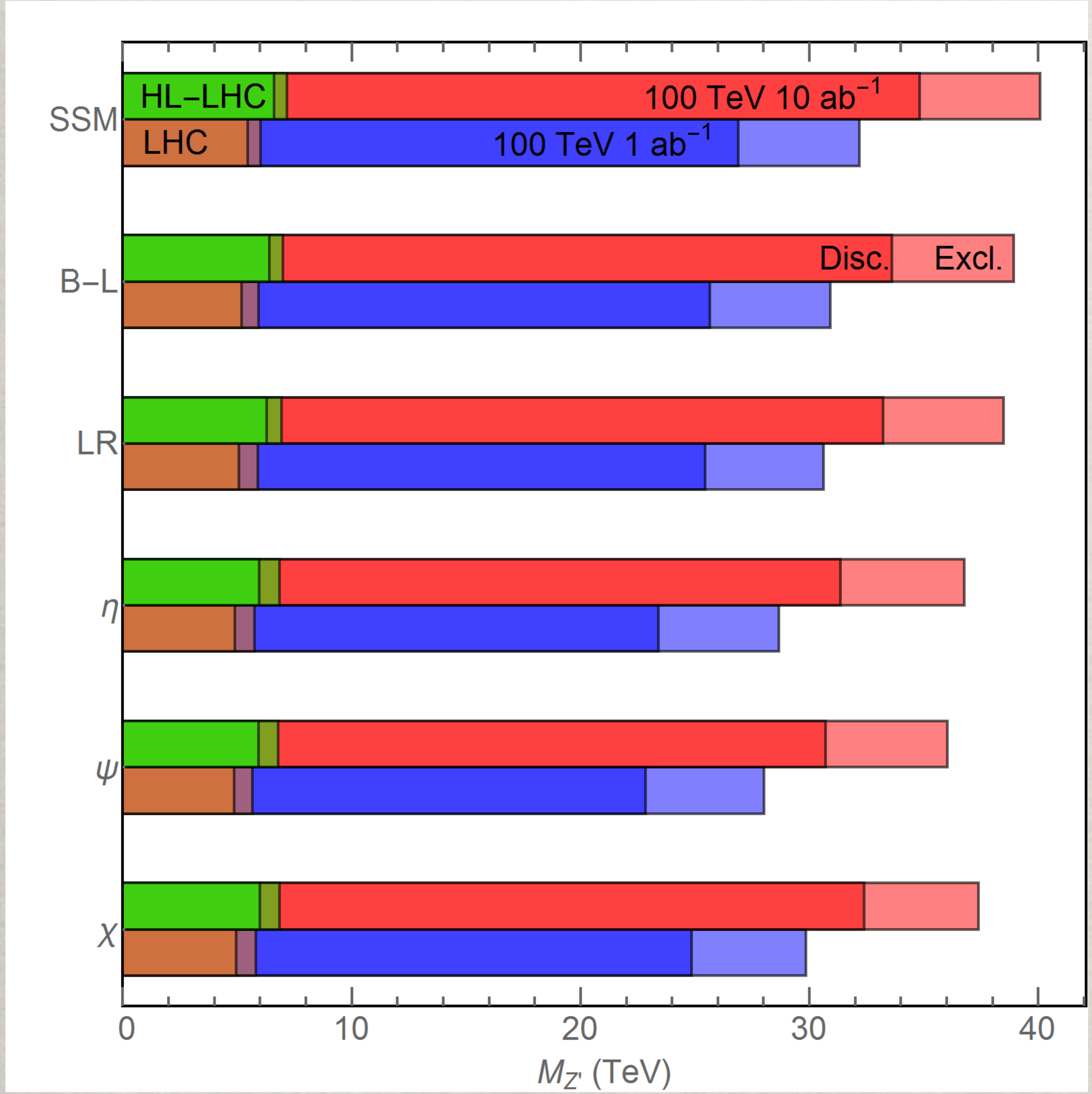






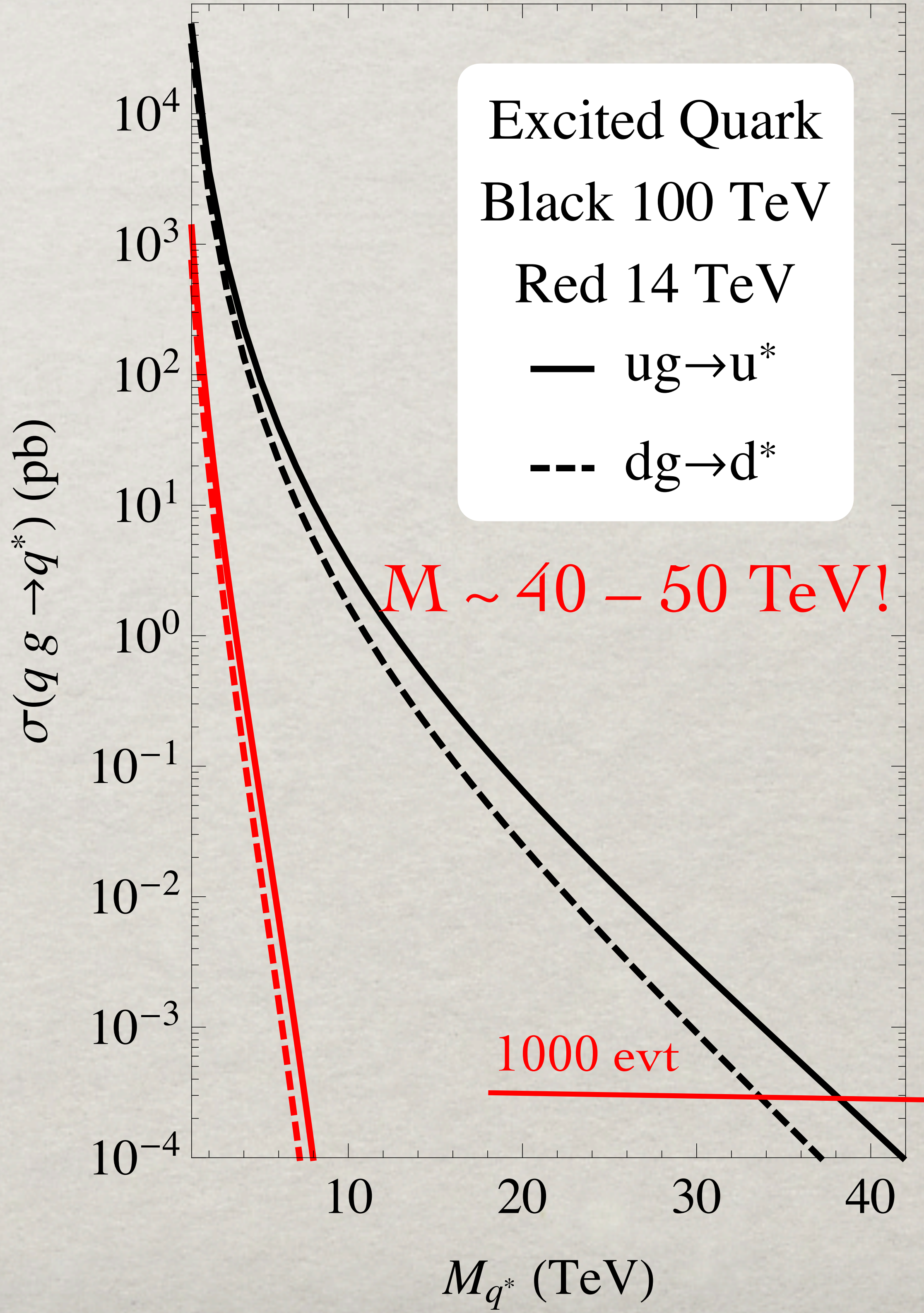
New Particle Searches

Electroweak Resonances: Z',W'



~ 6x over LHC

Colored Resonances:



SM Bread & Butter Physics

e.g., Electroweak symmetric phase:

$$\frac{m_t}{100\ \mathrm{TeV}} \sim \frac{m_b}{2\ \mathrm{TeV}}$$

$$\frac{v}{100\ \mathrm{TeV}} \sim \frac{\Lambda_{QCD}}{100\ \mathrm{GeV}}$$

v^2/E^2 only "higher twist" effects!

Chen, TH, Tweedie: arXiv:1611.00788

SM Bread & Butter Physics

e.g., Electroweak symmetric phase:

$$\frac{m_t}{100\ \text{TeV}} \sim \frac{m_b}{2\ \text{TeV}}$$

$$\frac{v}{100\ \text{TeV}} \sim \frac{\Lambda_{QCD}}{100\ \text{GeV}}$$

v^2/E^2 only "higher twist" effects!

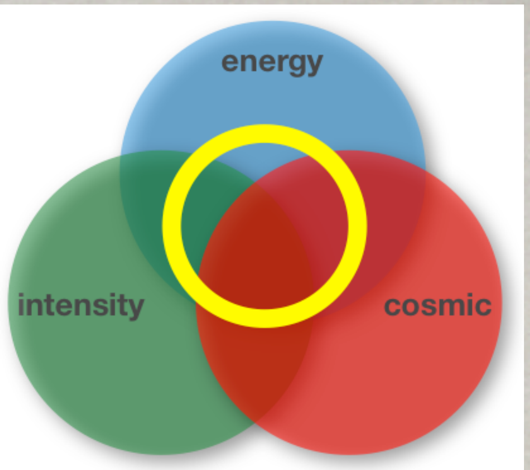
Electroweak splitting/showering:

"Color factors" : $\frac{C_A}{C_F} = \frac{2N^2}{N^2-1} \Rightarrow (\frac{9}{4})_{N=3}$ and $(\frac{8}{3})_{N=2}$.

→ new perspectives in the EW sector.

Chen, TH, Tweedie: arXiv:1611.00788

Conclusions



- Higgs boson is a new class.

NP BSM → "under the Higgs lamppost"

LHC will lead the way: g~10%; λ_{HHH} ~ 50%; $Br_{inv.}$~ 20%

but it also calls for new colliders:

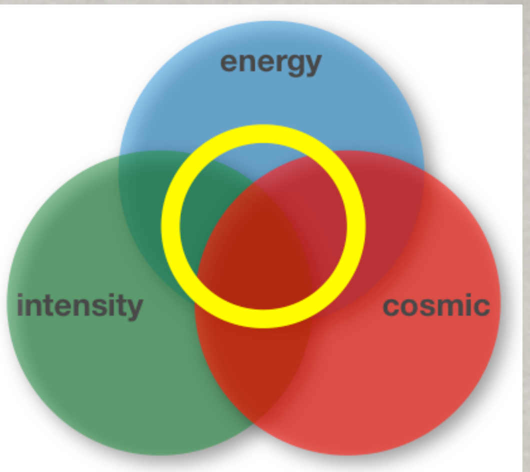
Precision: FCC_{ee}/CEPC

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

At thresholds: ΔM_W ~ 1 MeV, Δm_t ~ 10 MeV

Mega Higgs: κ_v ~ 0.2%, Γ_H ~ 1%, $Br_{inv.}$ ~ 1%, Δm_H ~ 5 MeV.

Conclusions



- Higgs boson is a new class.

NP BSM → "under the Higgs lamppost"

LHC will lead the way: $g\sim 10\%$; $\lambda_{HHH} \sim 50\%$; $Br_{inv.} \sim 20\%$

but it also 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: $\kappa_v \sim 0.2\%$, $\Gamma_H \sim 1\%$, $Br_{inv.} \sim 1\%$, $\Delta m_H \sim 5$ MeV.

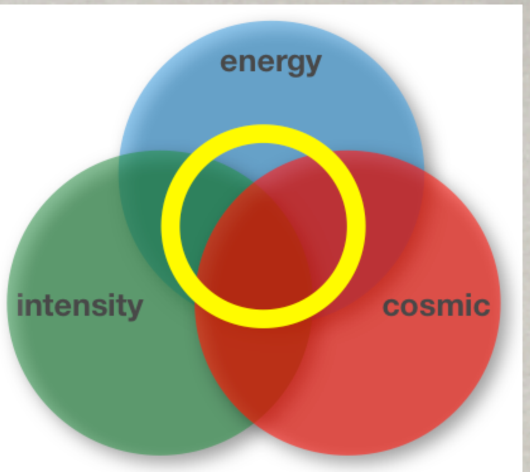
Energy frontier: FCC_{hh}/SPPC

$g\sim 10\%$; $\lambda_{hhh} < 10\%$ → Conclusive for EWPT

6x LHC reach: 10 – 30 TeV → fine-tune < 10^{-4}

WIPM DM mass ~ 1 – 5 TeV

Conclusions



- Higgs boson is a new class.

NP BSM → "under the Higgs lamppost"

LHC will lead the way: g~10%; λ_{HHH} ~ 50%; $Br_{inv.}$~ 20%

but it also 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: ΔM_W ~ 1 MeV, Δm_t ~ 10 MeV

Mega Higgs: κ_v ~ 0.2%, Γ_H ~ 1%, $Br_{inv.}$ ~ 1%, Δm_H ~ 5 MeV.

Energy frontier: FCC_{hh}/SPPC

g~10%; λ_{hhh} < 10% → Conclusive for EWPT

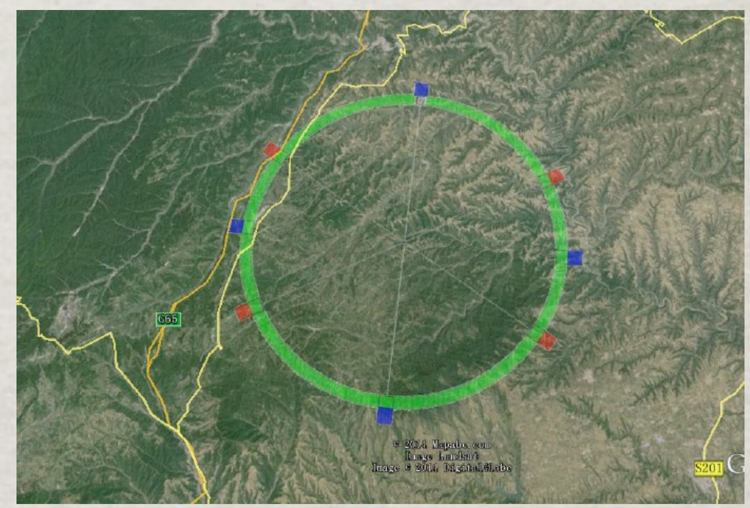
6x LHC reach: 10 – 30 TeV → fine-tune < 10^{-4}

WIPM DM mass ~ 1 – 5 TeV

An exciting journey ahead!

Site selections (a few main candidates)

1)



2)

3)

1) Qinhuangdao

2) Shaanxi Province

3) Near Shenzhen and Hongkong

“Canonical” energy / luminosity: **100 TeV, 3 – 30 ab^{-1}**

(Perhaps)

- Technology limitation (high field magnets?)
- Budgetary consideration (> 10 B$?)
- Geological / geographic consideration

Higgs Factories:

- ILC: 250 GeV, 2 ab^{-1}, 80% / 30% polarization.
- CEPC: 240 GeV, 5 ab^{-1} .
- FCC_{ee}: 250 GeV, 20 ab^{-1} .

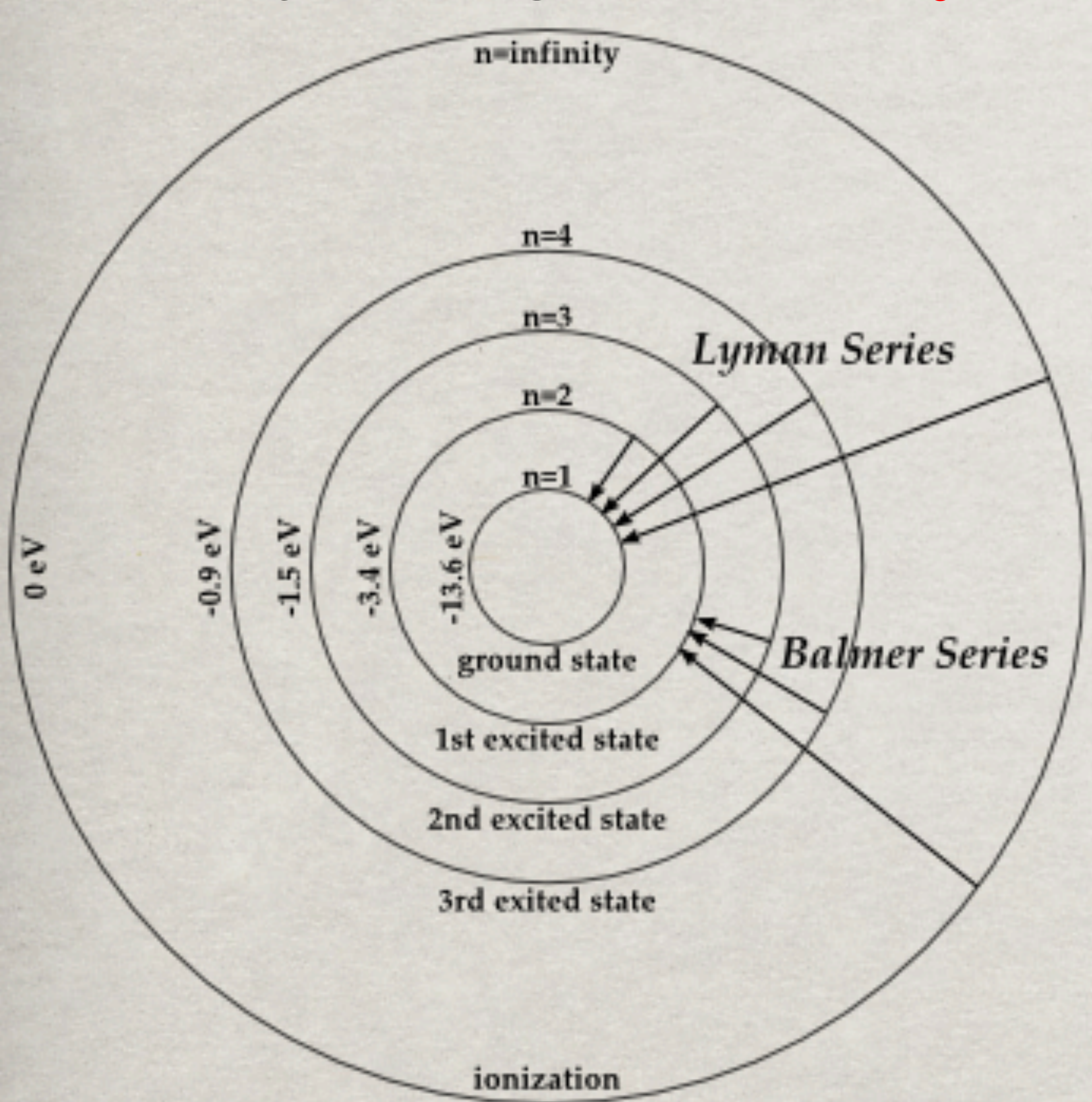
Z Factory : at M_Z, 20 ab^{-1} .

Higher Energy e^+e^- Colliders:

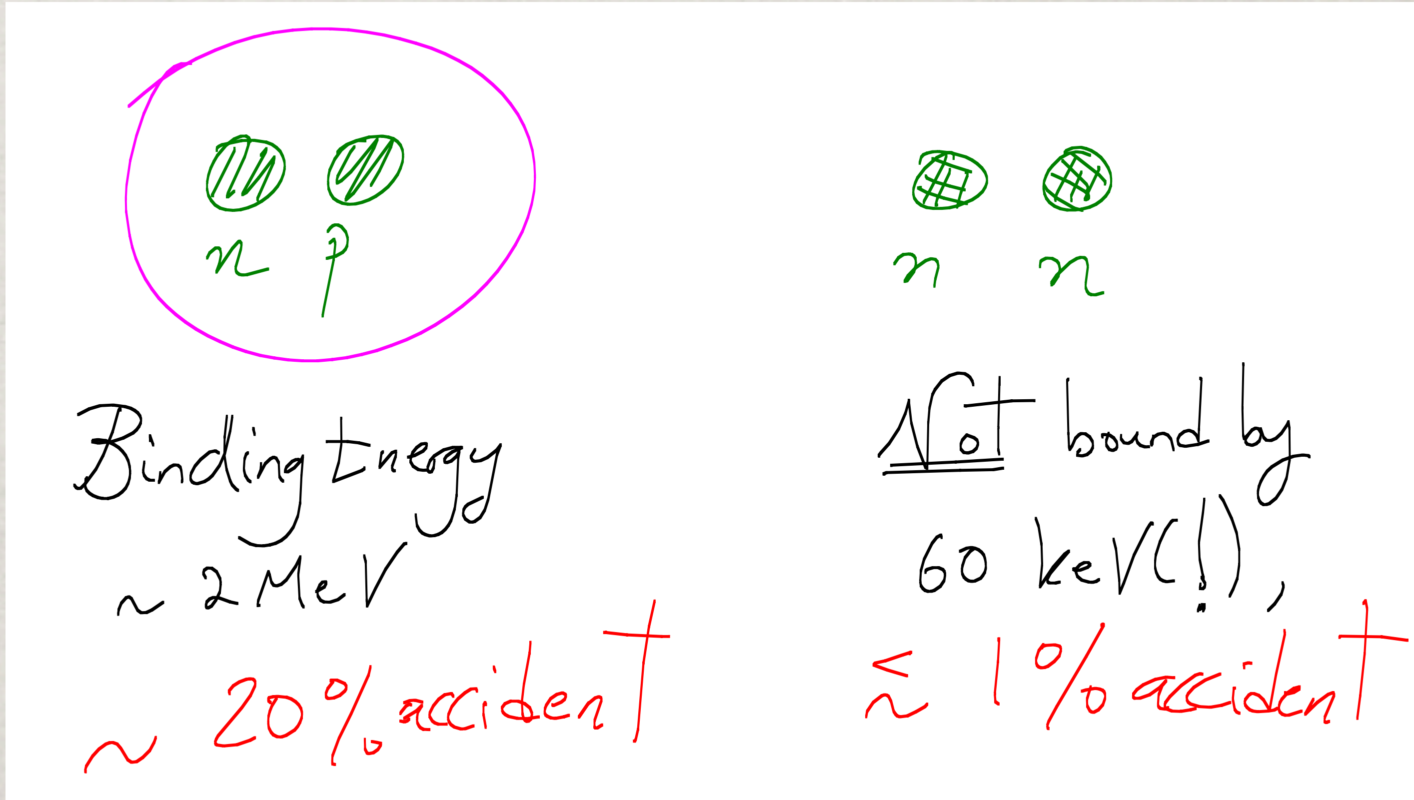
- ILC: 500 GeV, 4 ab^{-1}, 80% / 30% polarization.
- CLIC: 380 GeV, 0.5 ab^{-1}, 80% / 0 polariation.
- 1.5 TeV, 1.5 ab^{-1};   3 TeV, 3 ab^{-1}.

Atomic physics:

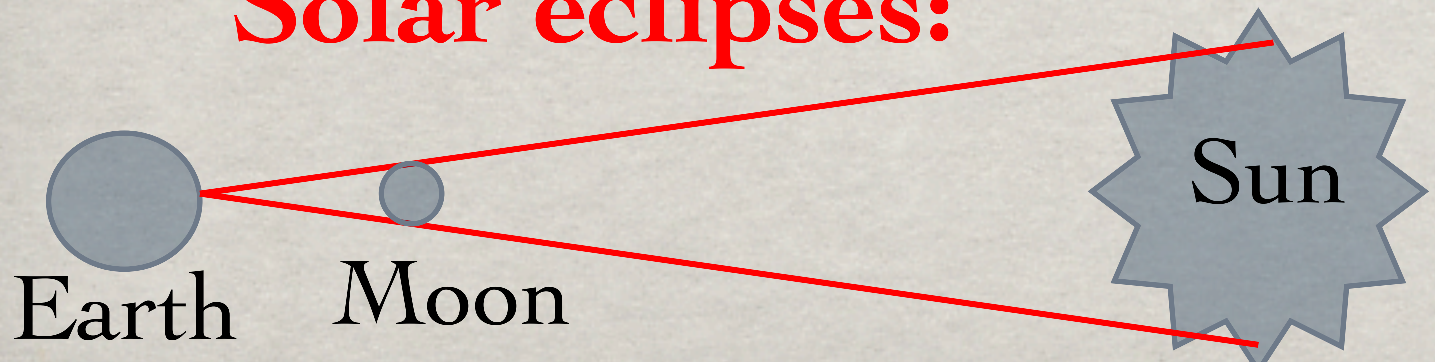
Rydberg const. $E_0 \sim \alpha^2 m_e \rightarrow O(25\ eV)$, very natural!



Nuclear physics?



Solar eclipses:



$\delta\theta/\theta \sim 10^{-2}$

rather unnatural!