Discussions on Future Facilities for Higgs Physics

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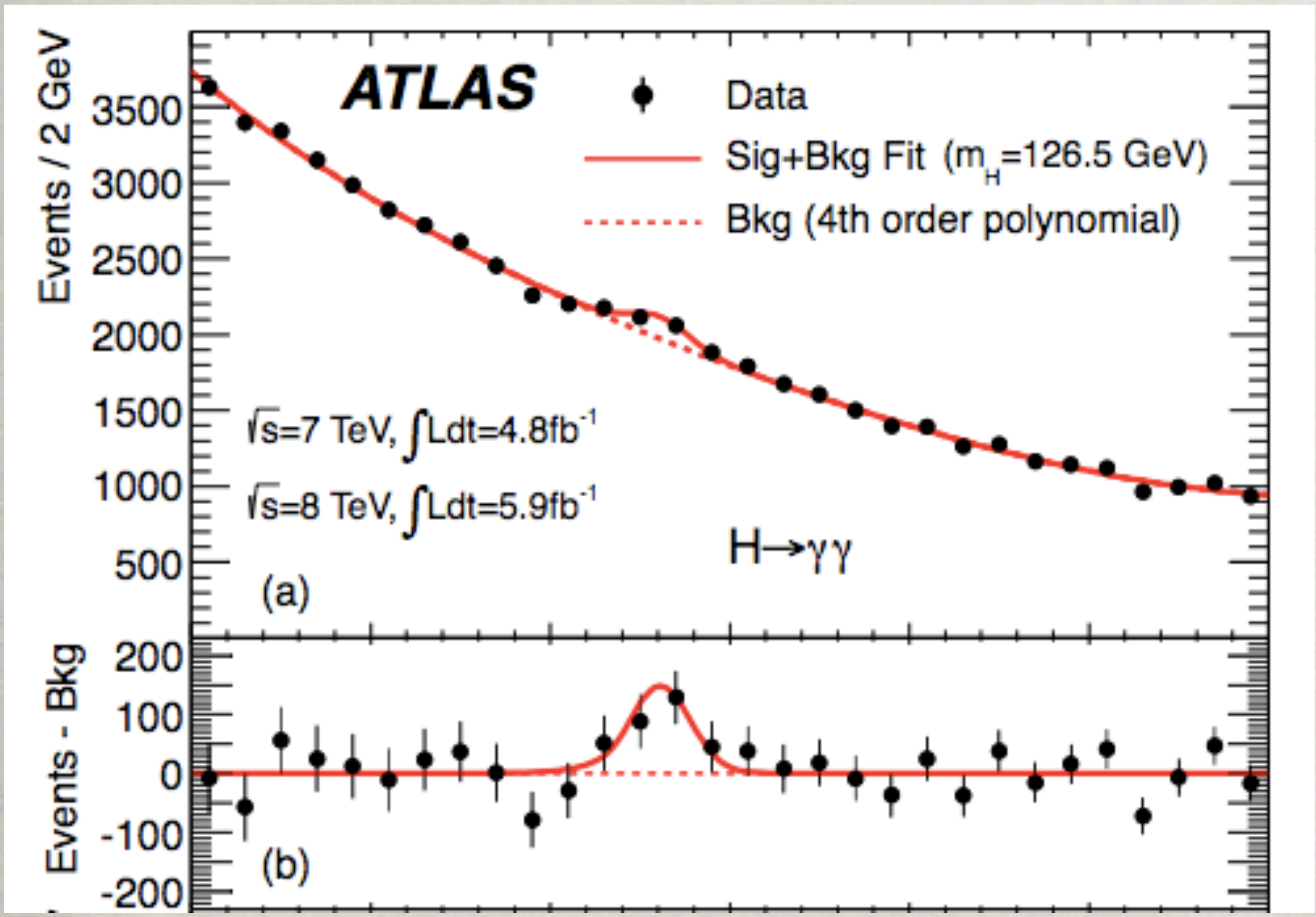
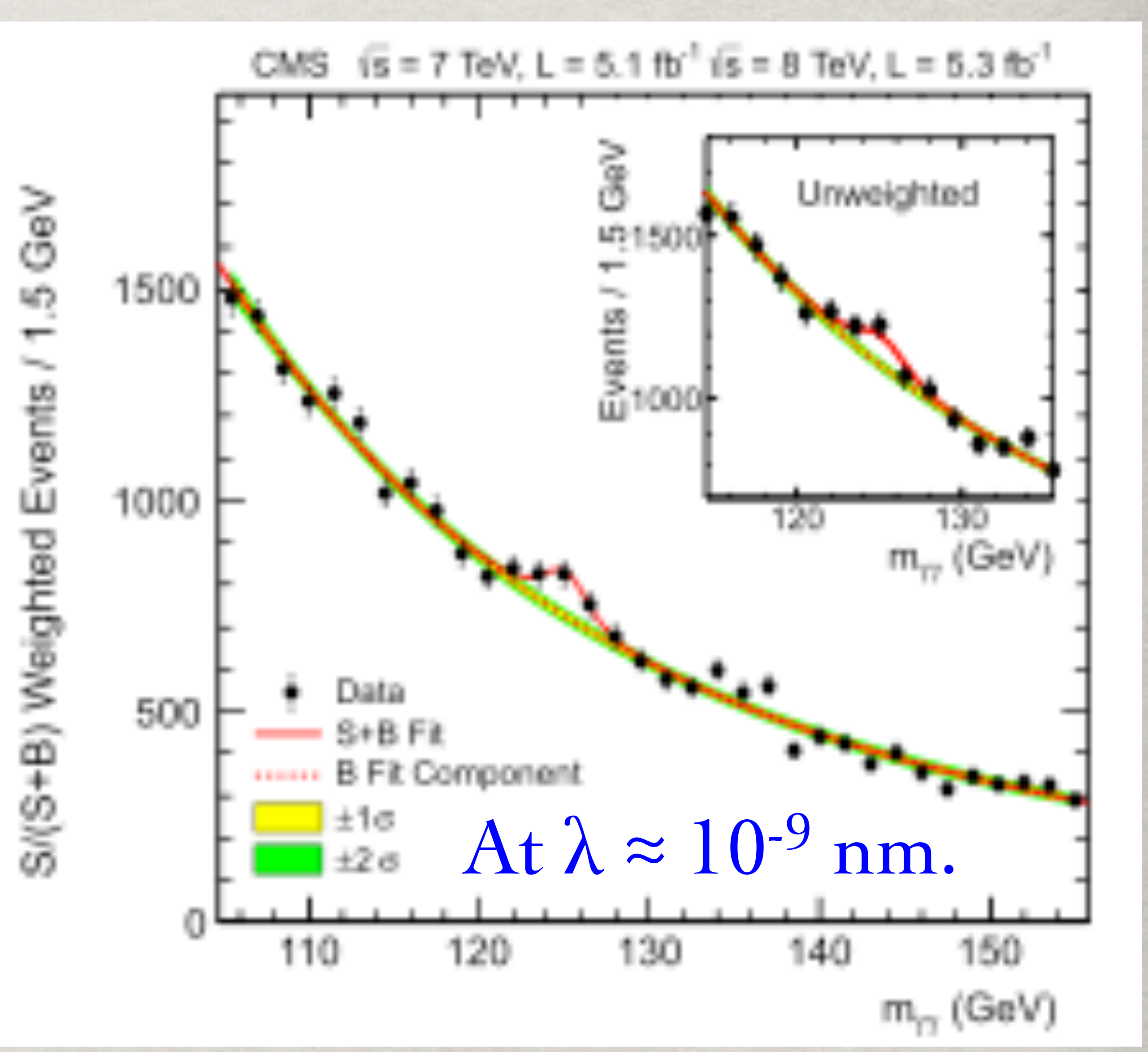
ISHP 2013, IHEP, Beijing
August 16, 2013

The field is rejuvenated on the 4th of July, 2012:

A neutral boson decay to two photons





At $\lambda \approx 10^{-9}$ nm.

The combined signal significance:

ATLAS: 5.9σ

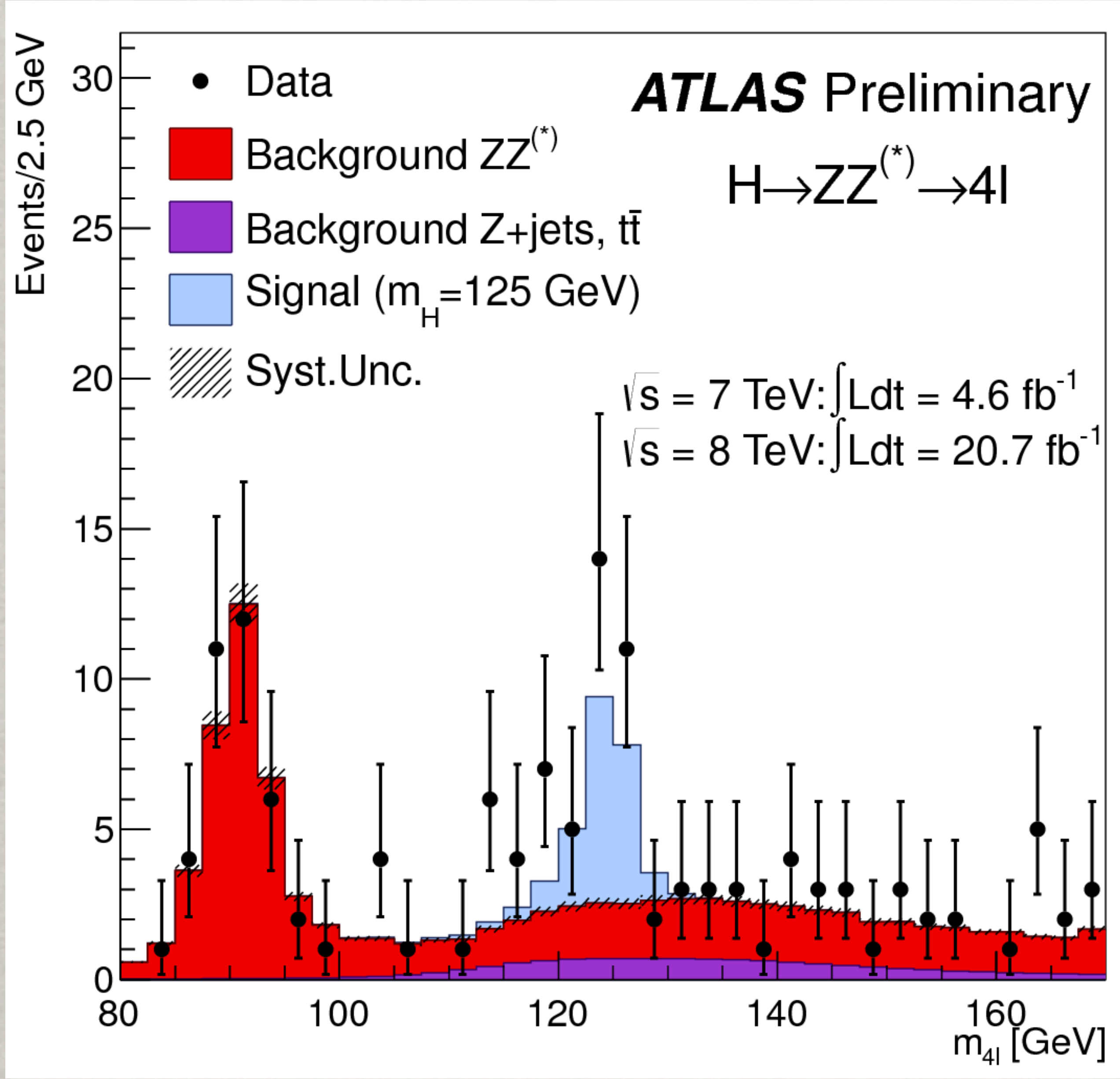
CMS: 5.0σ

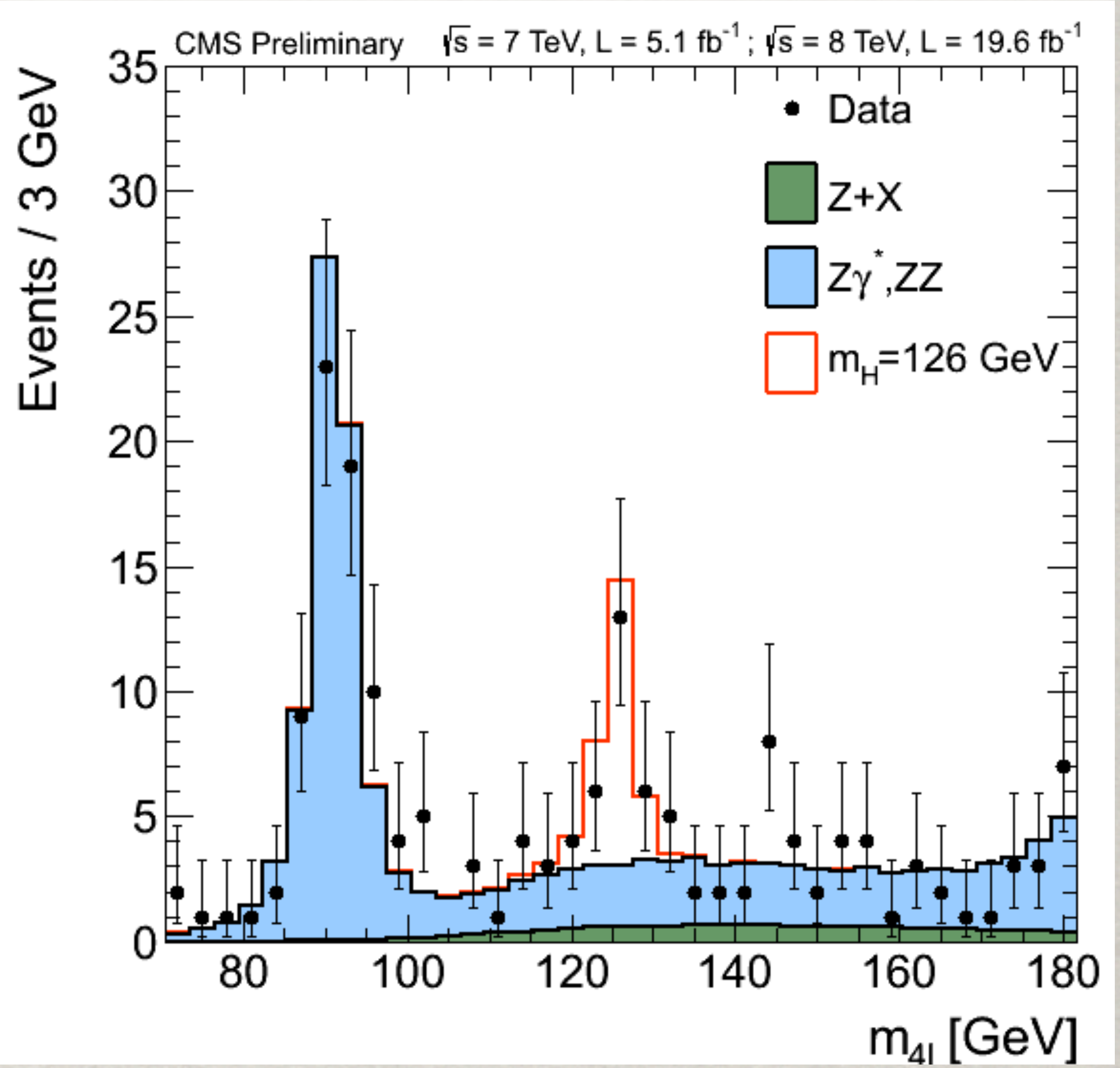
Phys. Lett. B716, 1 (2012)

Phys. Lett. B716, 30 (2012)

2013 Moriond Update:

The "Gold plated" channel:





CMS/ATLAS Signal significance: **ZZ(4l): 6.7/6.6σ; ϒϒ: 3.2/7.4σ; WW: 3.9/3.8σ; bb+ττ: 3.4σ**

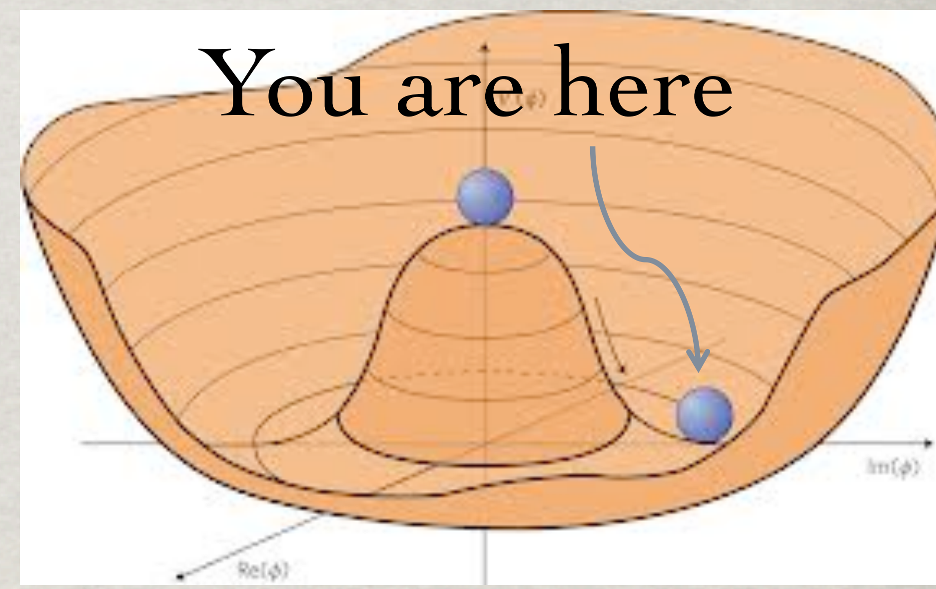
We Now Know

$m_H \approx 126$ GeV !

In the SM, the EWSB is parameterized as

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

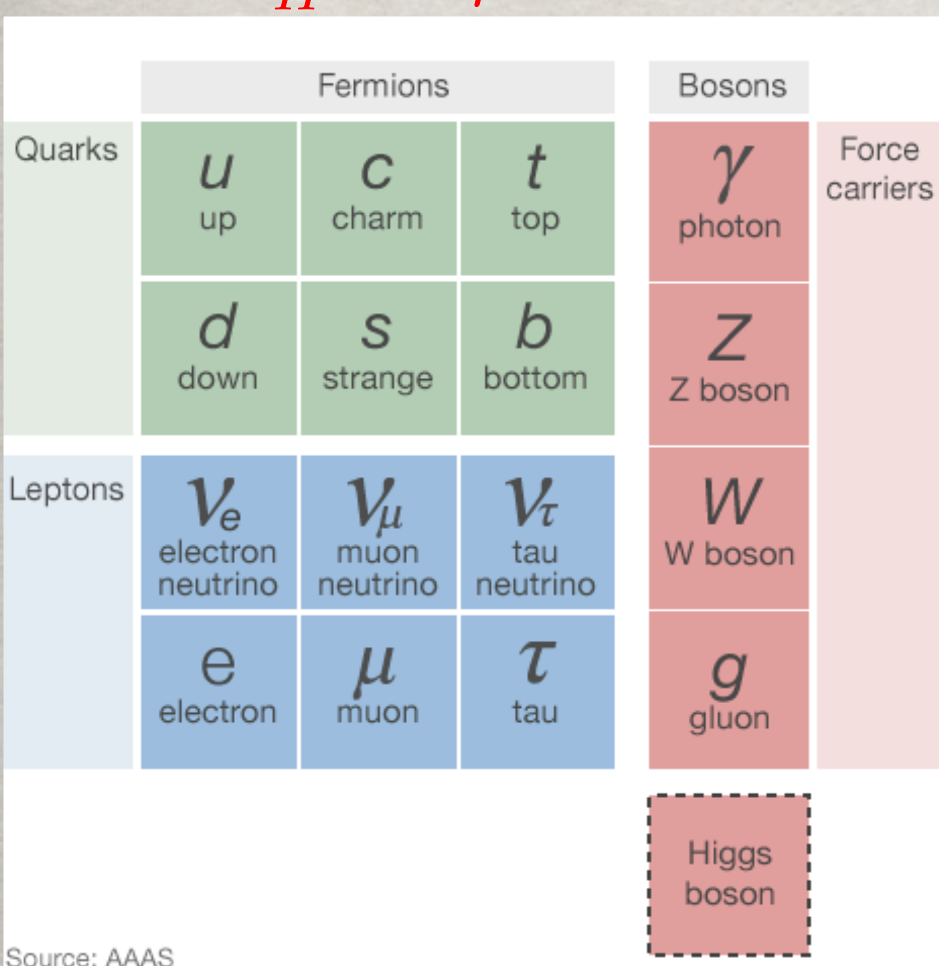
$$\Rightarrow \quad \mu^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$



Consequently,

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

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



Completion of the SM:

A perturbative, renormalizable theory, valid up to a scale of

TeV ? …, M_{Pl} ?

New Era: Under the Higgs lamp post

The "Observation" papers: now about 1500 cites each!

The discovery has rejuvenated the field and for years to come!

A Reminder

The Higgs mechanism ≠ a Higgs boson !

From theoretical point of view,
3 Nambu-Goldstone bosons were all we need!
(non-linear realization of the gauge symmetry)

With no Higgs, the theory is valid only
to a unitarity bound ~ 2 TeV

The existence of a light, weakly coupled Higgs boson carries important message for our understanding & theoretical formulation in & beyond the SM.

What It tells us

$$V = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

the only dimensional parameter allowed by SM symmetry.

The "large hierarchy":

$$\mathrm{m}_h^2 - m_{h^0}^2 \sim -\frac{3}{8\pi^2} y_t^2 \Lambda^2$$

Michael Dine's cancelation at Planck scale:

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

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

10^{-3} fine-tune

"Naturalness" → TeV scale new physics.

The "Little hierarchy":

- **In SUSY,** $m_H^2 \approx M_Z^2 \cos^2 2\beta + \Delta m^2_{SUSY}$

  Tree-level $< (80\ \text{GeV})^2$ + loop-level: $> (45\ \text{GeV})^2$

  → Need large tanβ; m_{stop} & mixing $X_t >> m_t$

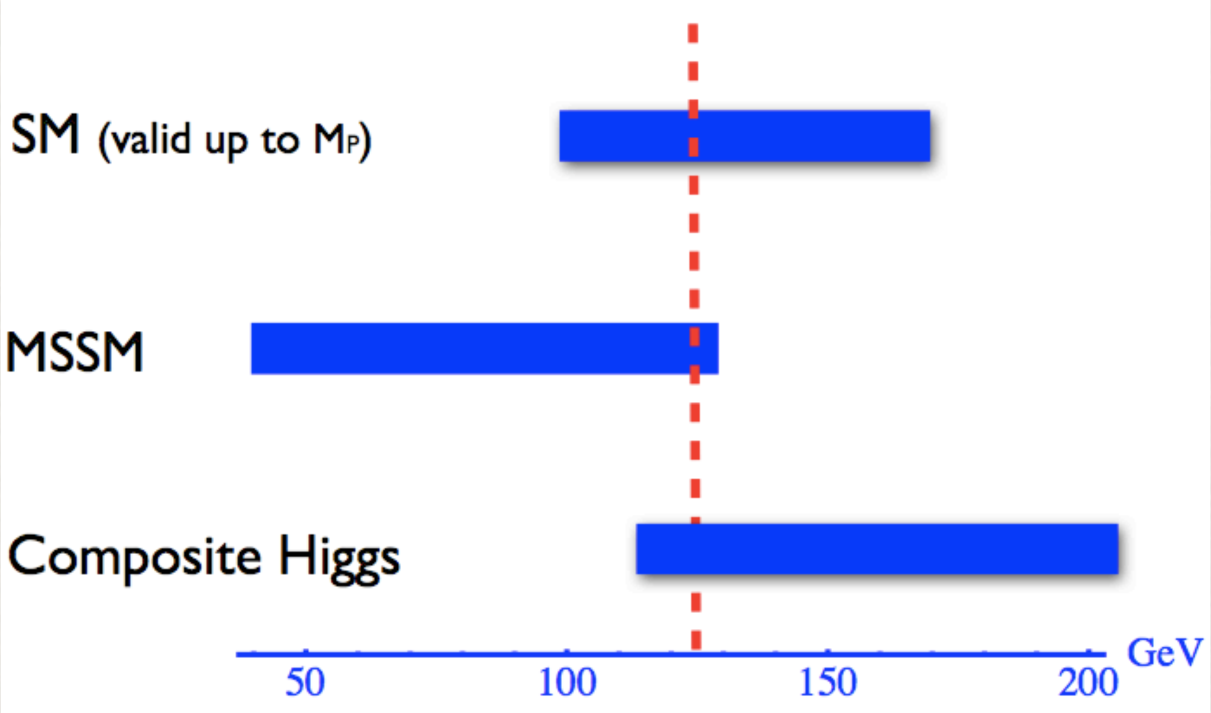
- **In composite/strong dynamics:**

  (dual of extra dimension theory)

The Higgs boson as a pseudo-Goldstone boson:

$$m_H^2 \sim \frac{f^2}{(4\pi)^2} \sim \frac{m_t^2 M_T^2}{f^2}.$$

→ "naturally light": Need low scale f, M_T .



Both SUSY/Compositeness suffer from some degree of "fine-tune": < 1% .

Pomarol, ICHEP'12

What We Wish to Know

1. A "natural" EW theory ?

- "Natural SUSY":

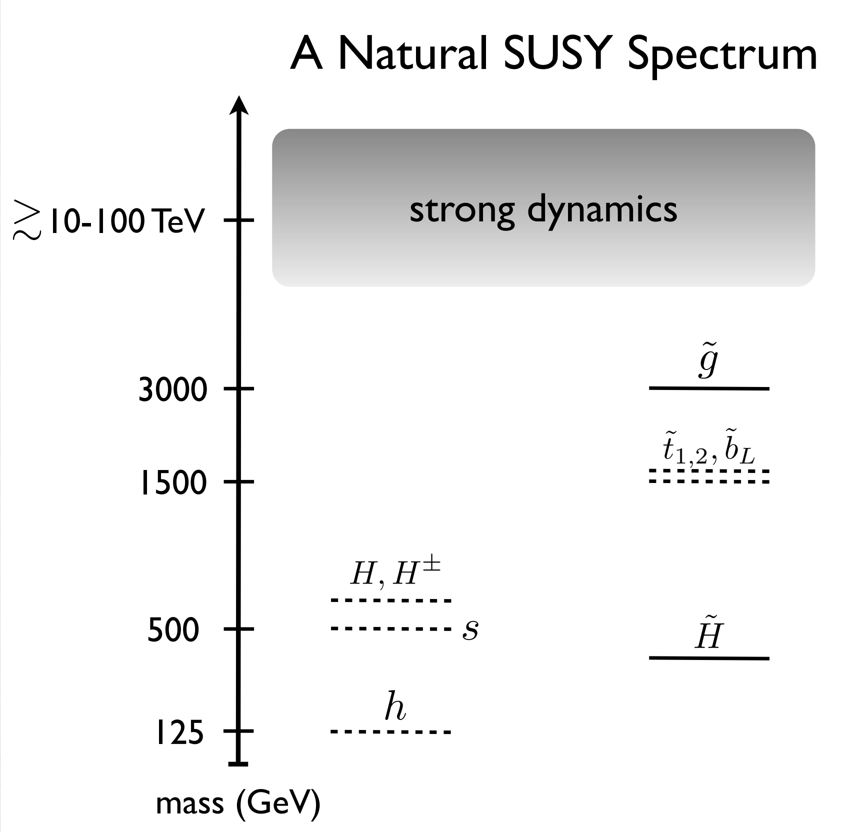
Relevant to the Higgs and the "Most Wanted":

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

Current LHC bounds:

$m_{\tilde{t}} > 200 - 680\ \mathrm{GeV},$

$m_{\tilde{\chi}^{\pm}} > 100 - 600\ \mathrm{GeV}\ \ (\mathrm{depending\ on}\ m_{\chi^0})$



- "Compositeness": the T', current ATLAS limit:

$M_T > 480$ GeV, for $M_A < 100$ GeV.

2. Extended Higgs sector?

The Higgs boson should have not only relatives:

$$\tilde{t},\ \tilde{b},\ \tilde{H}^{\pm,0};\ \ T',$$

But also siblings: $\mathrm{H}_j^0,\ A_j^0,\ H^\pm,\ H^{\pm\pm},\ S, \ldots$

- Two Higgs Doublet Model (2HDM):
  rich phenomenology, Type II SUSY option …

- Plus a singlet:
  NMSSM, solve the μ-problem, relax fine-tune, light DM...

- Triplet Model:
  m_ν , L-R symmetric theories, Little Higgs …

3. The Higgs portals to Cosmos?

(a). Dark Matter

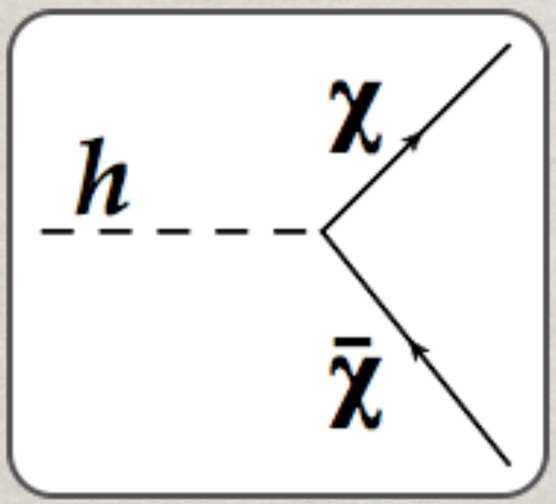
$H^\dagger H$ is the only bi-linear SM gauge singlet.

Bad: May lead to hierarchy problem with high-scale physics;

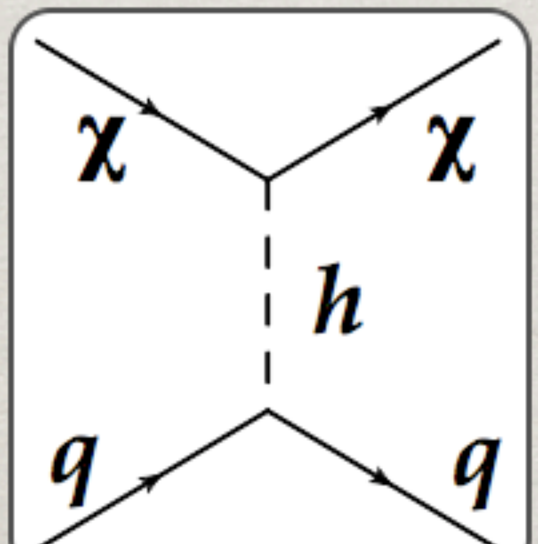
Good: May readily serve as a portal to the dark sector:

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

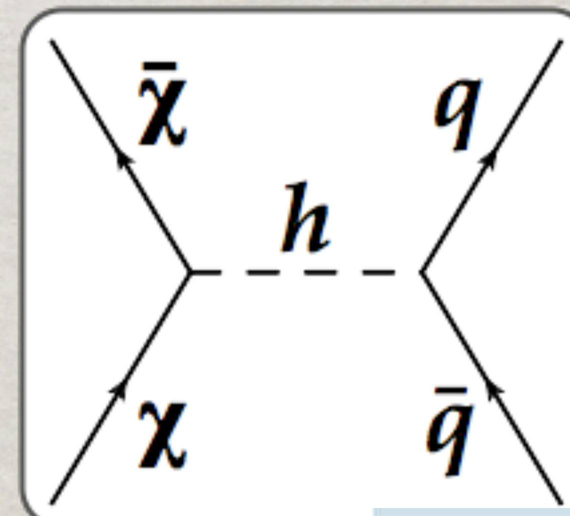
Missing energy at LHC

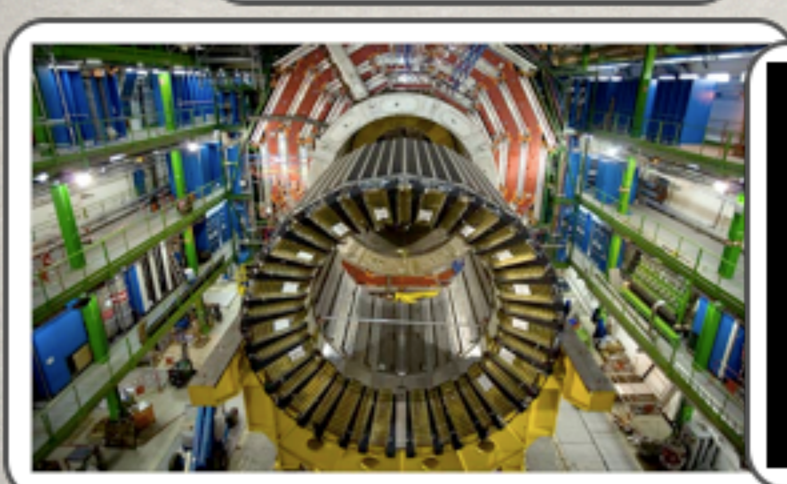


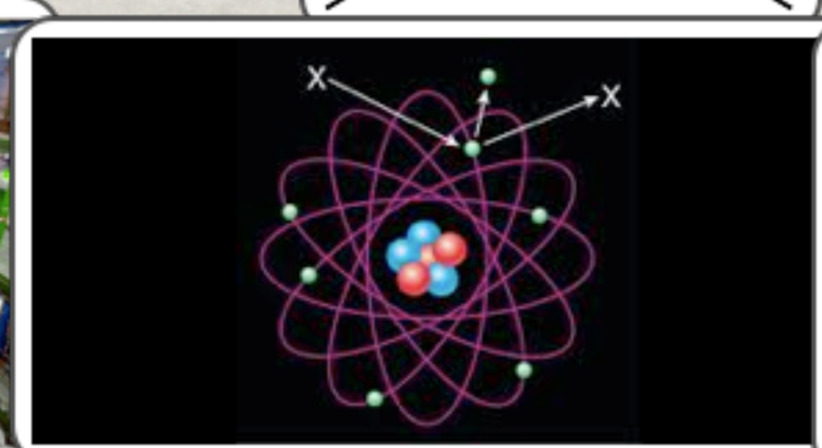
Direct detection

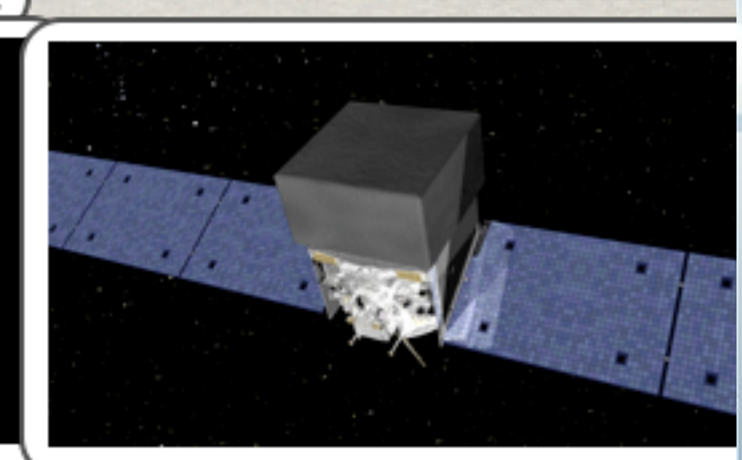


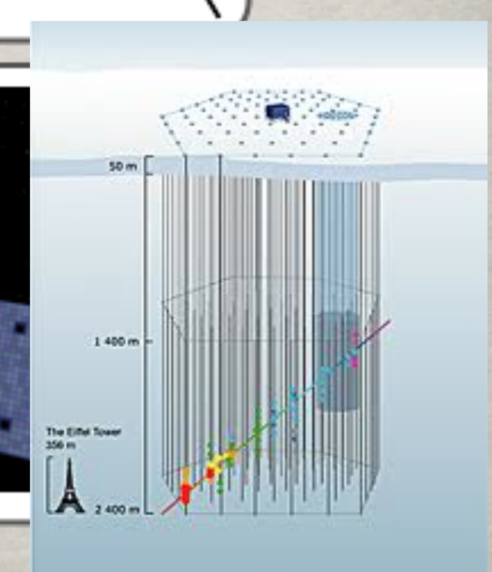
Indirect detection





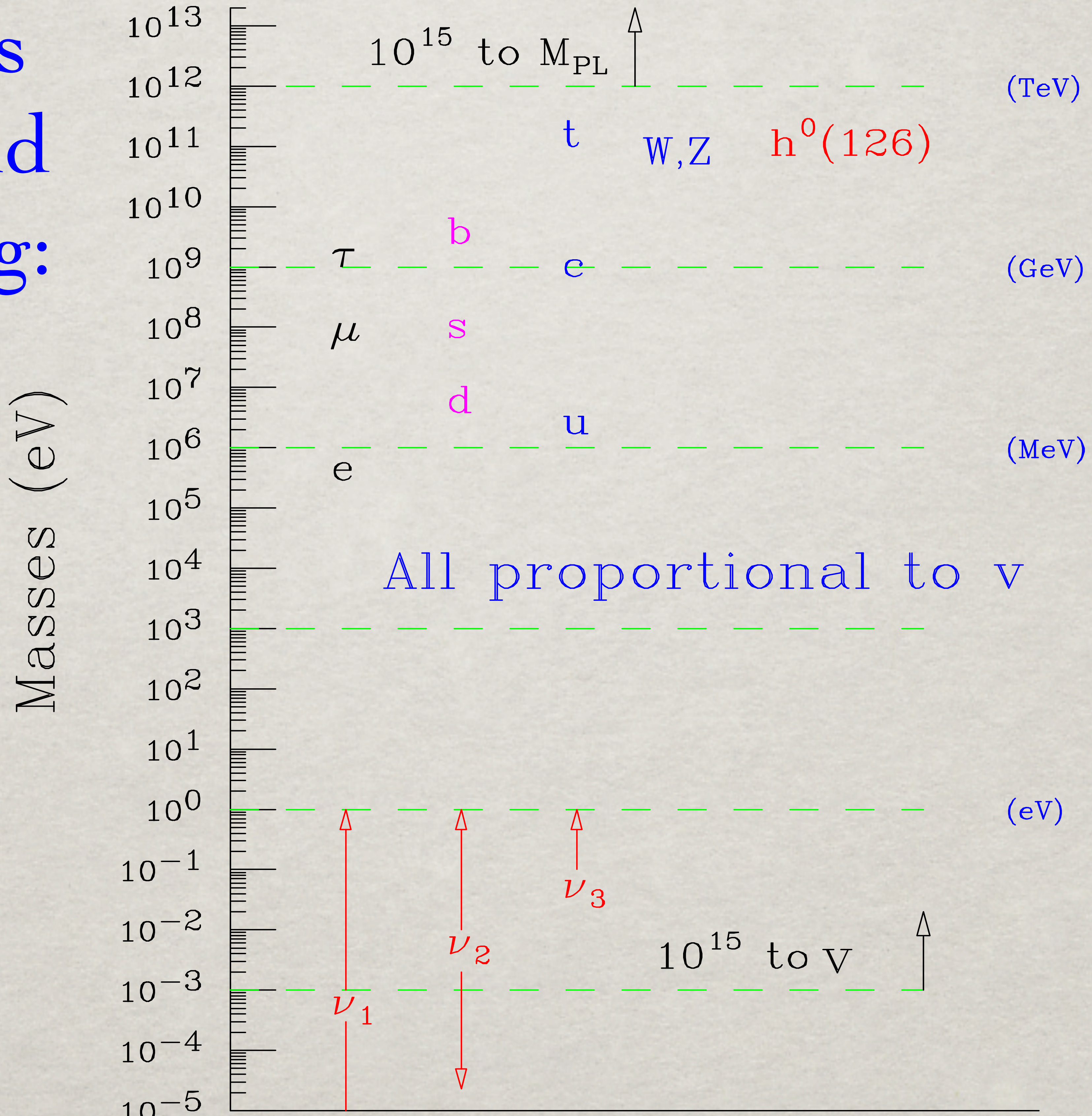






4. Flavor & ν Masses

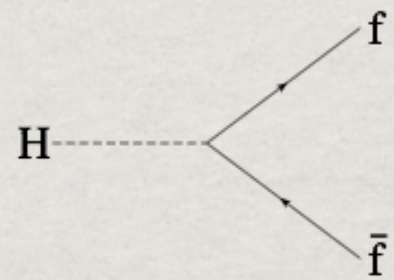
Particle mass hierarchy and flavor mixing:



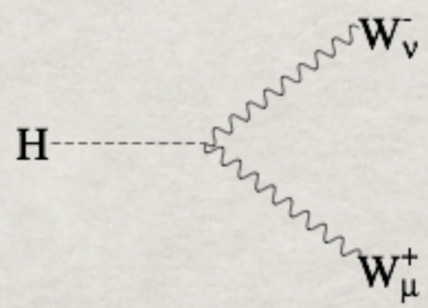
5. Couplings & Width

Higgs boson couplings encode its properties:

Yukawa coupling

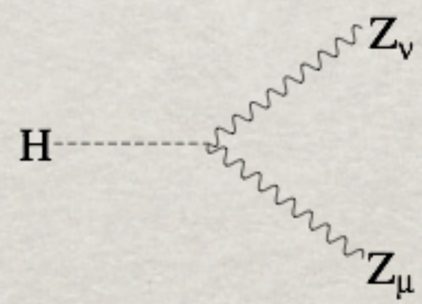


$-i\frac{m_f}{v}\left(1+\Delta_f\right)$



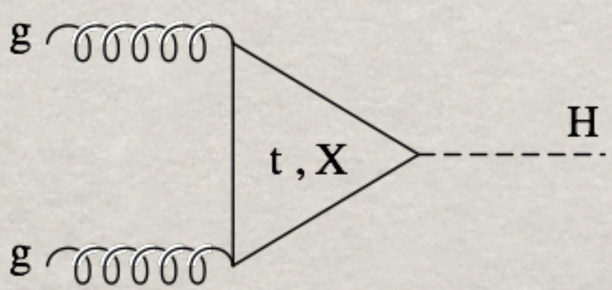
$ig\, m_W\, (1+\Delta_W) g_{\mu\nu}$

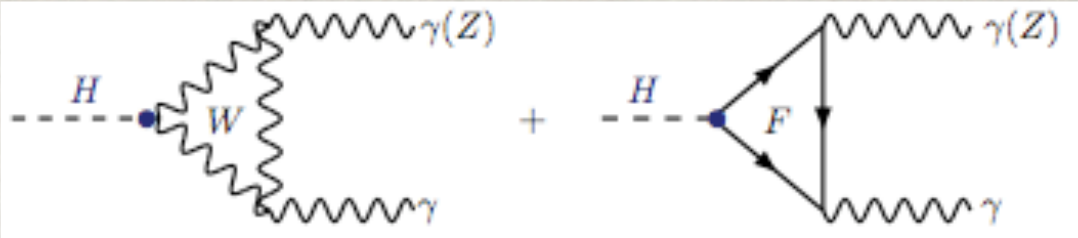
EWSB



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

Color/charged particles in loops:





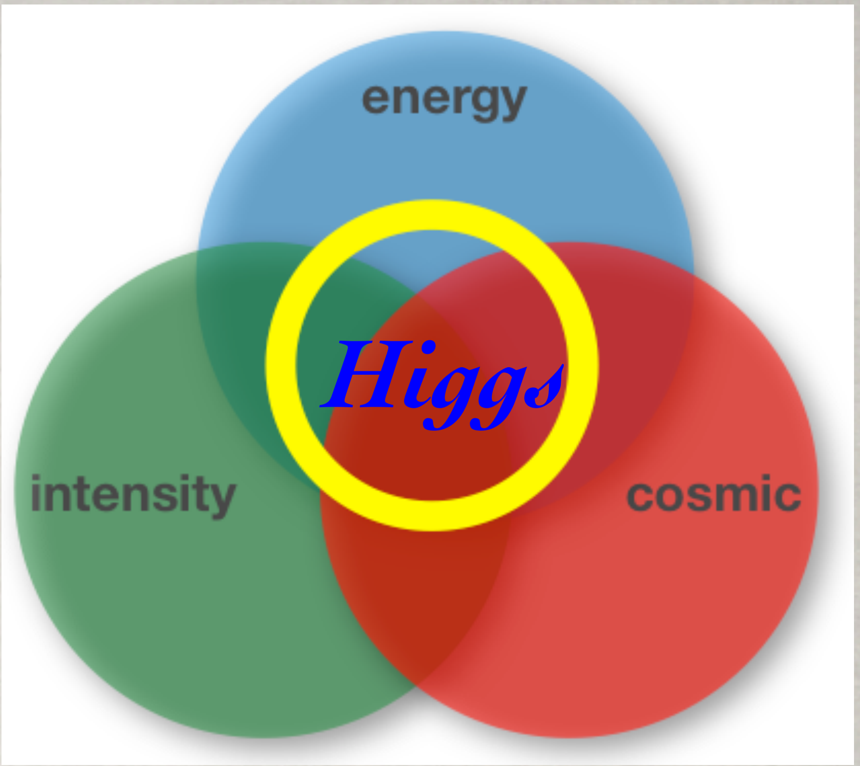
In a pessimistic scenario, the LHC does not see a new particle associated with the Higgs sector, then the effects of a heavy state on g_i at the scale M:

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

Higgs coupling deviations:

Δ:	VVH	$b\bar{b}H+\tau\bar{\tau}H$	$ggH,\gamma\gamma H$
Composite	(3-9)% $(1 \text{ TeV}/f)^2$		
H^0, A^0		6% $(500 \text{ GeV}/M_A)^2$	
T’			-10% $(1 \text{ TeV}/M_T)^2$

Summary:



- The Higgs boson is a new class, at a pivotal point of energy, intensity, cosmic frontiers.

"Naturally speaking":

- It should not be a lonely solitary particle; has an "interactive friend circle": $t,\ W^{\pm},\ Z$
"relatives": $\tilde{H}^{0,\pm},\ \tilde{t},\ \tilde{b},\ (\tilde{g});\ S,\ \tilde{S}...$
"siblings": $H^0,\ A^0,\ H^{\pm},\ H^{\pm\pm},\ S...$
- LHC lights the way for the searches.
- Higgs factory may reveal their properties from Higgs coupling measurements at 1%-level.

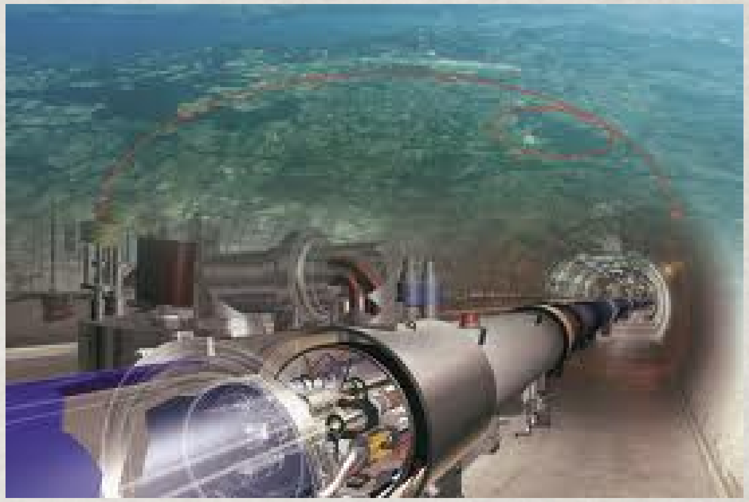
Future Facilities:

pp colliders:

LHC at 14 TeV with 300 fb^{-1}

HL-LHC at 14 TeV with 3000 fb^{-1}

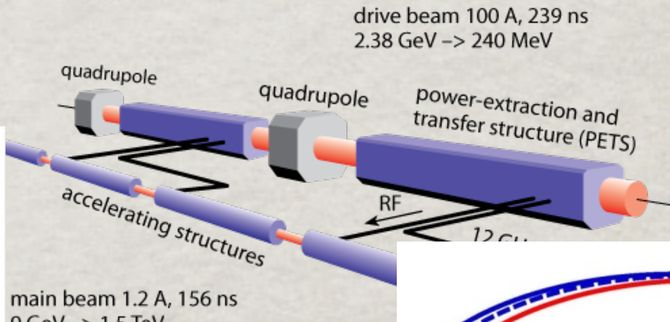
HE-LHC at 33 TeV and VLHC at 100 TeV

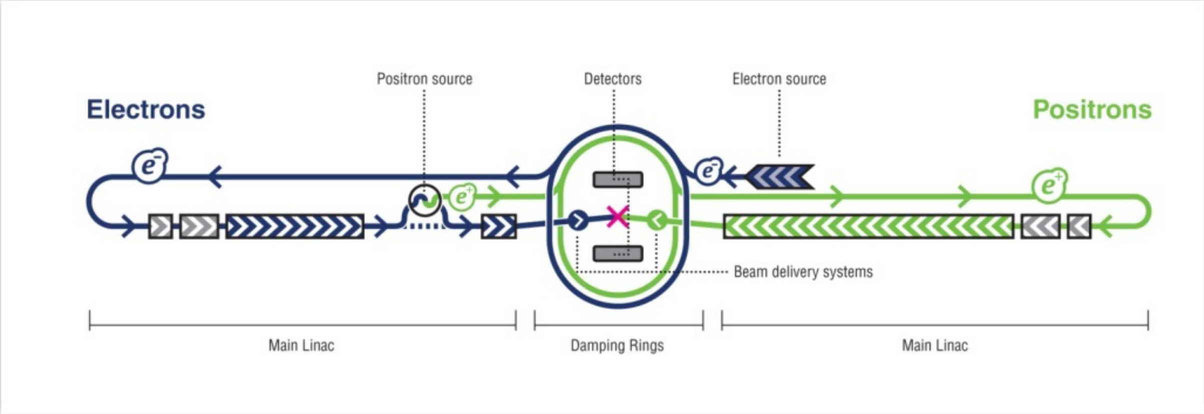


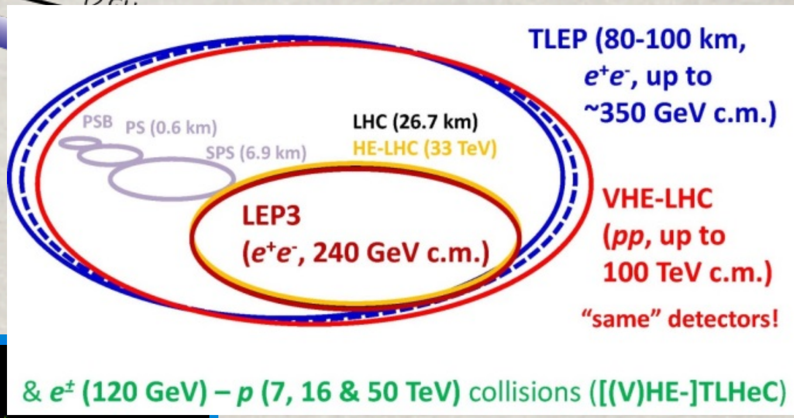
e^+e^- colliders:

Linear: ILC 250/500/1000 GeV, CLIC 350/1400/3000 GeV

Circular: TLEP @ 240 and 350 GeV



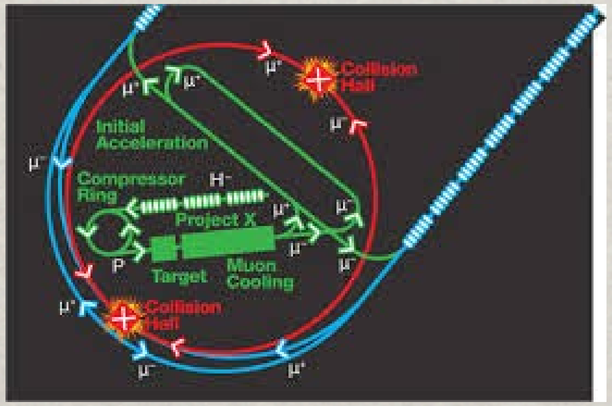


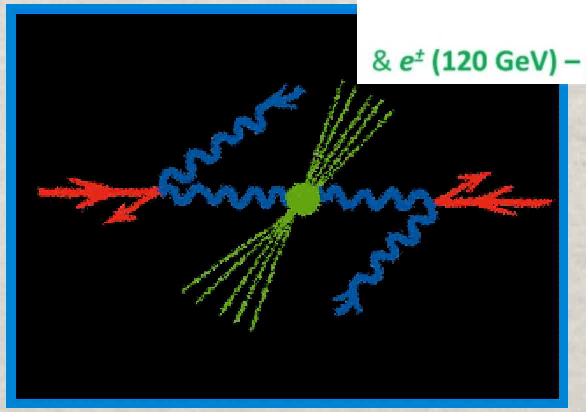


Others:

$\mu^+\mu^-$ collider

$\gamma\gamma$ collider





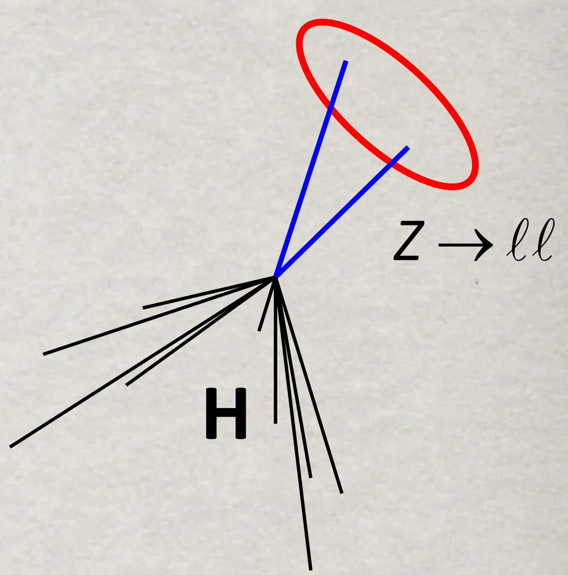
Accuracies & complementarity:

Facility	Δm_H (MeV)	$\Delta\Gamma_H/\Gamma_H$
LHC	100	–
HL-LHC	50	–
ILC500	35	5.9%
ILC1000	35	5.6%
ILC1000-up		2.7%
CLIC	33	8.4%
TLEP (4 IP)	7	0.6%
μC	0.06	4.3%

$e^+e^- \to ZH$ with

$Z \to \ell^+\ell^-$

$H \to X$



$$m^2_{\text{recoil}} = \left(\sqrt{s} - E_{\ell\ell}\right)^2 - \left|\vec{p}_{\ell\ell}\right|^2$$

μμ collider:

resonance scan for both the mass and the width

$$\sigma\left(\sqrt{s}\right) \sim \frac{1}{\left(s - m_H^2\right)^2 + \Gamma_H^2 m_H^2}$$

pp collisions:

Higgs candidates are selected from their decays $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell, \ldots \Rightarrow$ always measure $\sigma \times$BR, not possible to separate the two without assumptions

Facility Summary

Jianming Qian's talk

LHC at 14 TeV with 300 fb^{-1} of data is essential to firmly establish the five major production mechanisms of a Higgs boson (ggH, VBF, WH, ZH, $t\bar{t}H$) and the main bosonic and fermionic decay modes $\left(\gamma\gamma, ZZ^*, WW^*, \tau\tau, b\bar{b}\right)$. This will lead to about a factor of $3-5$ improvements in the most precise measurements compared to the 8 TeV run of LHC. It will also lead to about 100 MeV precision on the Higgs boson mass and the measurement of the boson spin.

HL-LHC provides unique capabilities to measure rare statistically limited SM decay modes such as $\mu\mu$ and Zγ and make the first measurement of the Higgs self-coupling. The high luminosity program increases the precision on the couplings compared to the LHC with 300 fb^{-1} by roughly a factor of $2-3$ and has a high discovery potential for heavy Higgs bosons.

TeV-scale *ee* linear colliders (ILC and CLIC) offer the full menu of measurements of the 126 GeV Higgs Higgs boson with better precision than the LHC, though their mass reach for heavy Higgs bosons are generally weaker than the high-energy *pp* colliders, except for CLIC running at 3 TeV. The two linear colliders have different capabilities – the ILC can run on the Z peak while CLIC has a higher mass reach and better precision in Higgs self-coupling measurement when operating at 3 TeV.

Facility Summary

TLEP offers the best precisions for most of the Higgs coupling measurements because of its projected integrated luminosity and multiple detectors. This program also includes high luminosity operation at the Z peak and top threshold. There is no sensitivity to *ttH* and Higgs self-coupling at these center-of-mass energies.

A higher energy *pp* collider such as a 33 TeV (HE-LHC) or 100 TeV (VLHC) hadron collider provides high sensitivity to the Higgs self-coupling as well as the highest discovery potential for heavy Higgs bosons.

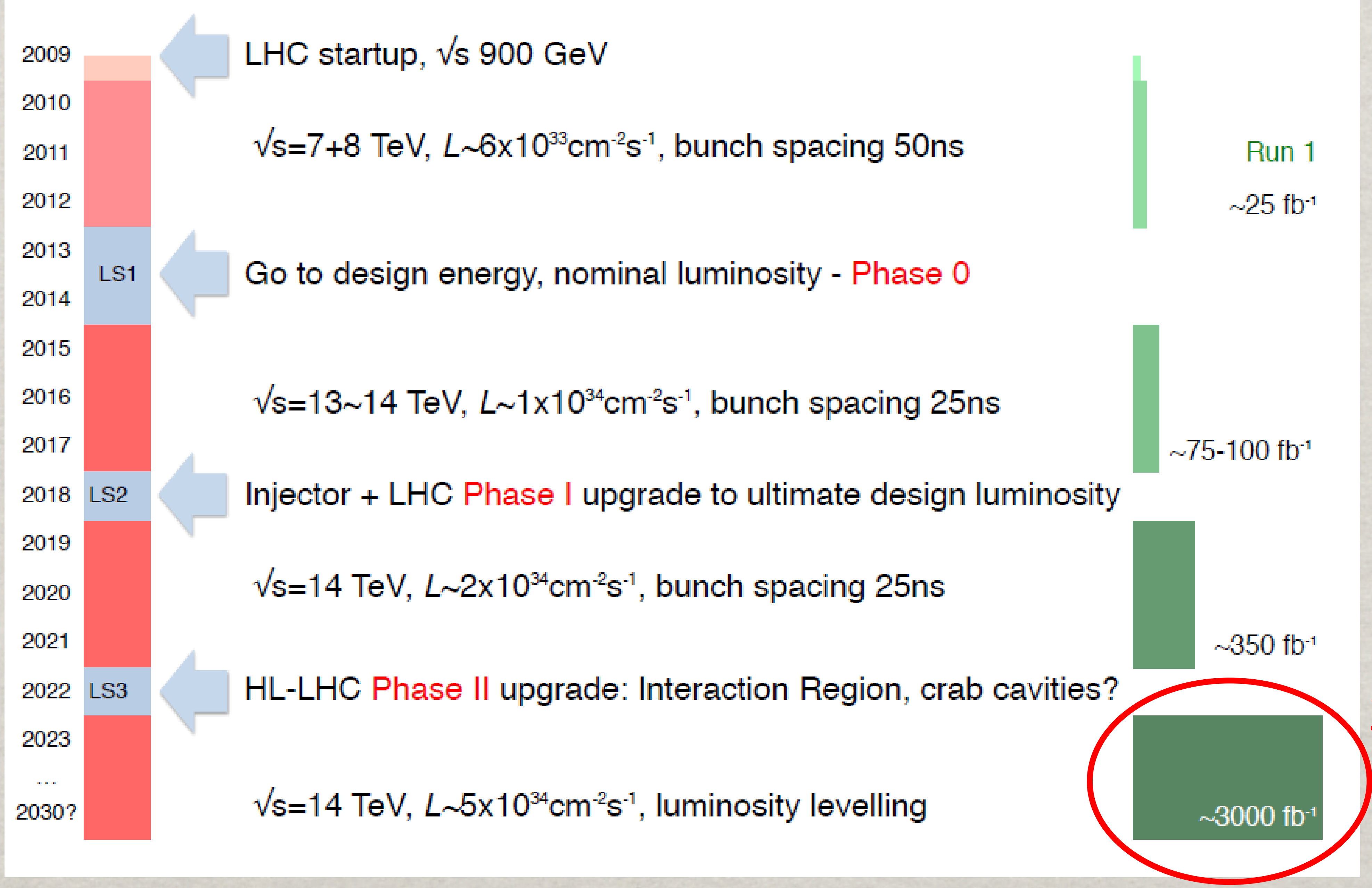
A TeV-scale muon collider should have similiar physics capabilities as the ILC and CLIC with potentially higher energy reach, but this needs to be demonstrated with more complete studies. The muon collider also has the potential for resonant production of heavy Higgs bosons. CP measurements are possible if a beam polarization option is included.

A $\gamma\gamma$ collider is able to study CP mixture and violation in the Higgs sector with polarized photon beams. It can improve the precision of the effective $\gamma\gamma H$ coupling measurement through s-channel production.

LHC: Time lines:

Update of European Strategy for Particle Physics:

"Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030."



$3000\ \text{fb}^{-1}$!

ILC:

H. Yamamoto's talk @LP13

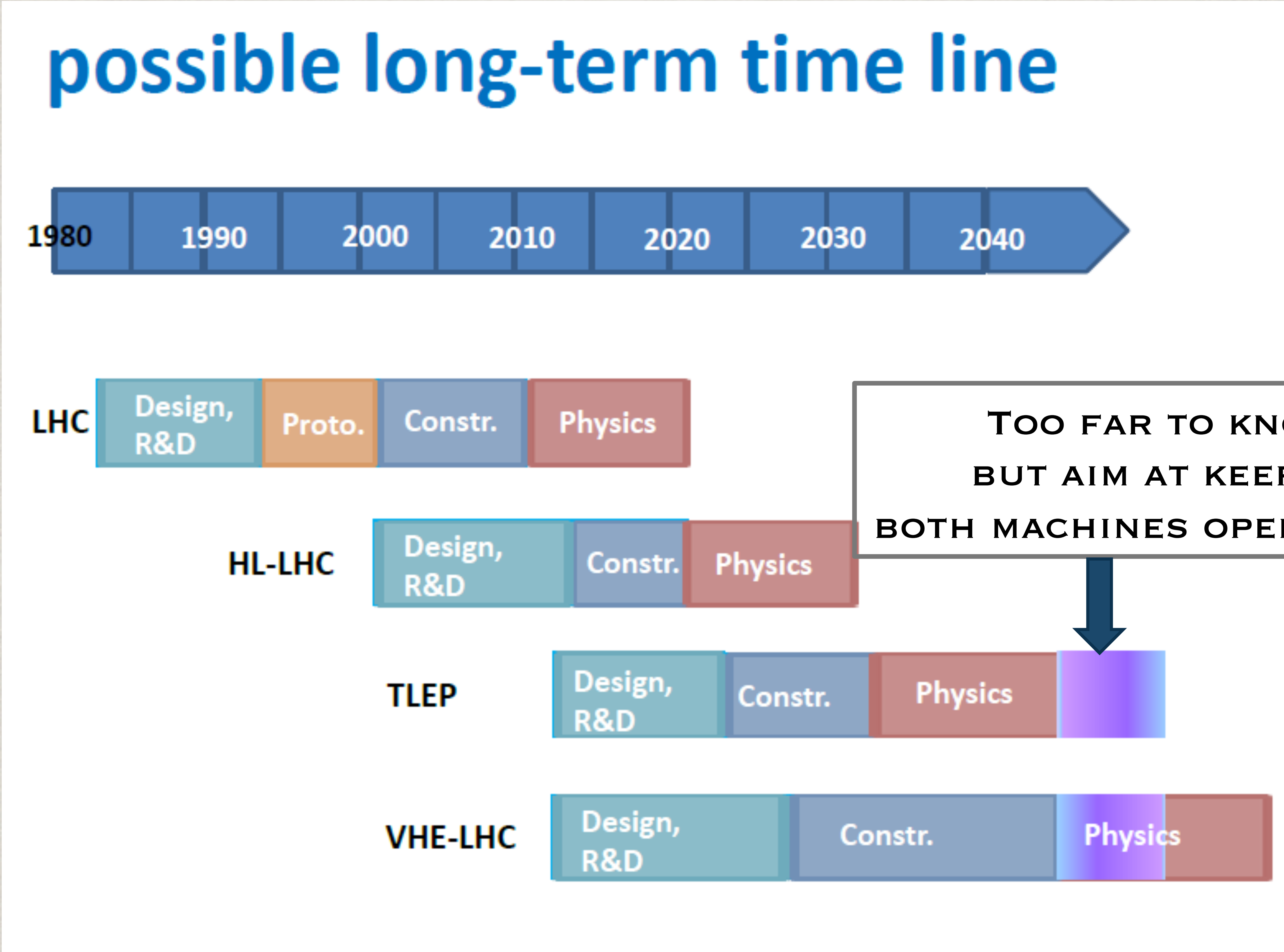
Times line

(The possible best scenario)

- End 2013
  - Japanese government announces its intention to host the ILC. It will start negotiation with other government.
- 2013-2015
  - Negotiations among governments
  - Finish R&Ds. Prepare for the international lab.
- 2015-2016
  - Bidding for construction, start construction
- 2026-2027
  - Start operation

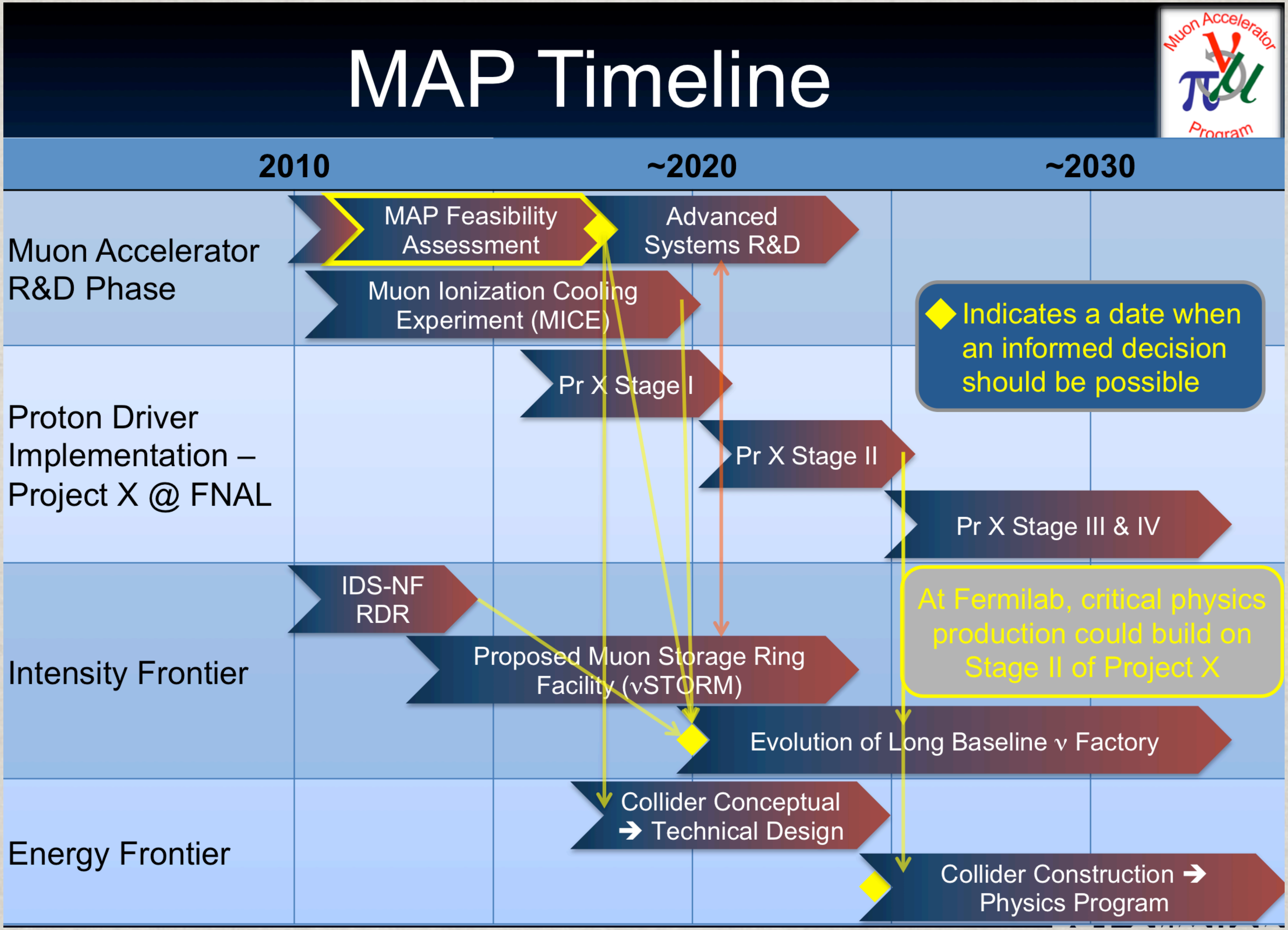
TLEP/VHE-LHC:

F. Zimmermann



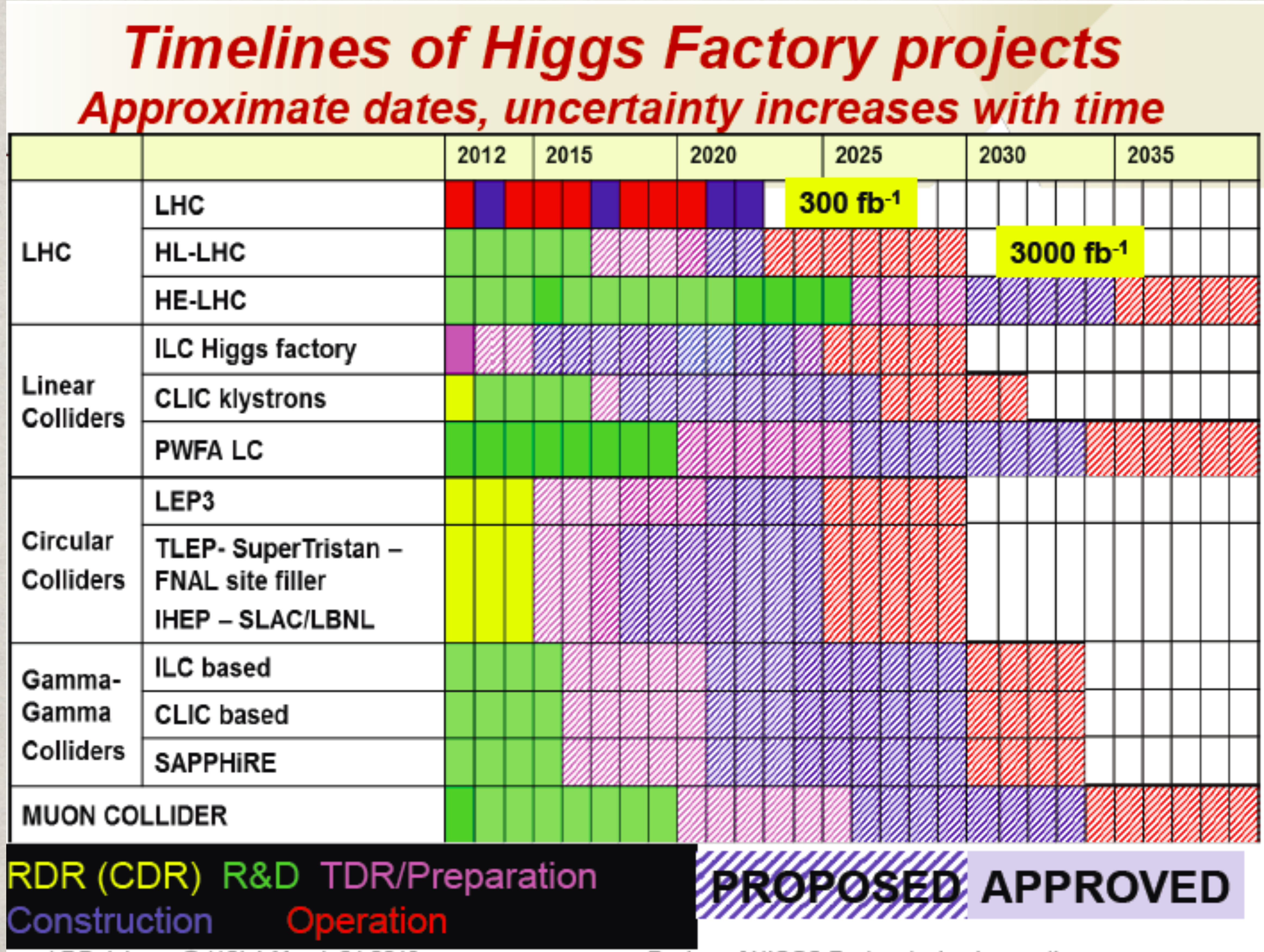
Too far to know,
but aim at keeping
both machines operationa

Muon-C: Mark Palmer's talk@Snowmass



MAP has been supported by US DOE
at a leverl of $13M/yr.

SUMMARY:



Timelines of Higgs Factory projects
Approximate dates, uncertainty increases with time
2012
2015
2020
2025
2030
2035
LHC
LHC
300 fb-1
HL-LHC
3000 fb-1
HE-LHC
Linear Colliders
ILC Higgs factory
CLIC klystrons
PWFA LC
Circular Colliders
LEP3
TLEP- SuperTristan – FNAL site filler IHEP – SLAC/LBNL
Gamma-Gamma Colliders
ILC based
CLIC based
SAPPHiRE
MUON COLLIDER
RDR (CDR) R&D TDR/Preparation
Construction Operation
PROPOSED
APPROVED
J.P.Delahaye @ UCLA March 21,2013
Review of HIGGS Factory technology options
36

Other Remarks/Issues:

Timing: 时机

We are in an exciting era,
The "Higgs era"!

LHC/HL-LHC lead the way.

Higgs factory a must!
Best time to argue for it!

Collaboration: 合作

The HEP programs could be successful only with international collaboration!

In a project:

- Joint R & D
- Technology sharing!

Among projects:

- Mutual supports!
- Encourage LOCAL CONTRIBUTION!

Diversity: 百花齐放

Geographical locations:

Tevatron: US
LHC: Europe
ILC: Asia
TLEP/VHE-LHC: Europe or China
Muon-C: US

Technologies, research frontiers:
Healthy, balabced programs.
(CERN, FNAL, KEK, IHEP, …)

Theory support: 理论先行

"Theory is a strong driver for particle physics…"

Theory takes the lead:

Motivation; inspiration; design guidance …

Facing budgetary constraints

Engaging general public

Dealing with politics

Last, but not the least:

On behalf of the organizers:

Thank you all for presenting the great talks;
for participating the discussions!

As a participant, Thank the local organizers:

Yaquan Fang, Shan Jin, Guoming Chen;
Jianming, Liantao, Shufang, …
and many others …

In particular: ***Tianhong Xing,***
Plus Ying Cui + students

Hope to see you often in Beijing,
A nice trip home!

Accuracies & Complementarity:

Collider	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	250	350	500	1,000	126	126	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	250	350	500	1,000	250		
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			$>5\sigma$
ZZH	$0.07^\dagger$	$0.02^\dagger$	$7\cdot 10^{-4}$	$1.1\cdot 10^{-4}$	$4\cdot 10^{-5}$	$7\cdot 10^{-6}$	✓	✓	$< 10^{-5}$
WWH	$3\cdot 10^{-3\ddagger}$	$5\cdot 10^{-4\ddagger}$	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
ggH	✓	✓	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$< 10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	–	–	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

pp colliders

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

e^+e^- colliders

	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	$1600^\ddagger$	500+1000	$1600+2500^\ddagger$
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma(ZHH)$	42.7%		42.7%	23.7%
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%

Future Measurements:

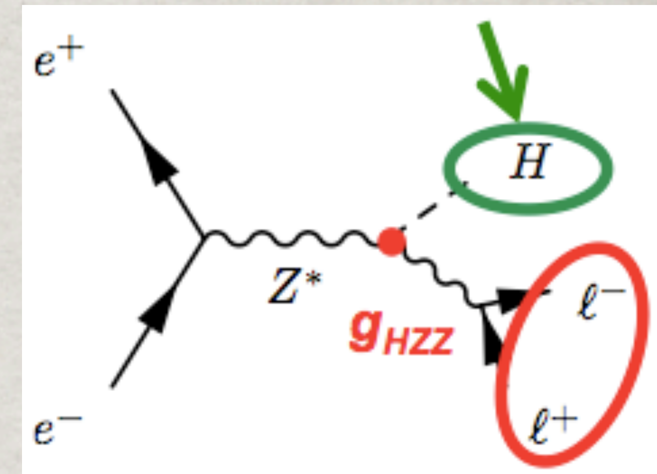
(from Roy Aleksan)

With M_H all parameters of SM are known!
What do we need to measure now?

	LHC(300)	LHC (3000)	ILC (250+350+500)	TLEP (240+350)	Comment
Δm_H (MeV)	~100	~50	~30	~7	Overkill for now
$\Delta\Gamma_H/\Gamma_H (\Delta\Gamma_{inv})$			5.5(1.2)%	1.1(0.3)%	
H spin	✓	✓	✓	✓	
Δm_W (MeV)	~10	~10	~6	<1	Theo. limits
Δm_t (MeV)	800-1000	500-800	20	15	~100 from theo.
$\Delta g_{HVV}/g_{HVV}$	2.7-5.7%*	1-2.7%*	1-5%	0.2-1.7%	
$\Delta g_{Hff}/g_{Hff}$	5.1-6.9%*	2- 2.7%*	2-2.5%	0.2-0.7%	
$\Delta g_{Htt}/g_{Htt}$	8.7%*	3.9%*	~15%	~30%	
$\Delta g_{HHH}/g_{HHH}$	--	~30%	15-20%**	--	Insufficient ?

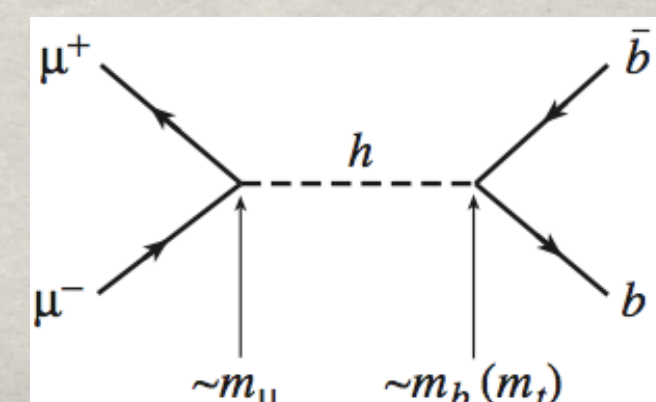
*Assuming systemaical errors scales as statistical and theoretical errors divided by 2 compared to now

**Sensibility with $2ab^{-1}$ at 500 GeV (TESLA TDR) and needs to be comfirmed by on-going more detailed studies



e^+e^- Higgs factory: model-independent

$\mu^+\mu^-$ Higgs factory: Model-independentpe line-shape for Γ_H



LHC results need assumptions: SM-like, no-missing mode, etc.