The Need for a Higgs, Electroweak and Top Factory

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Paris

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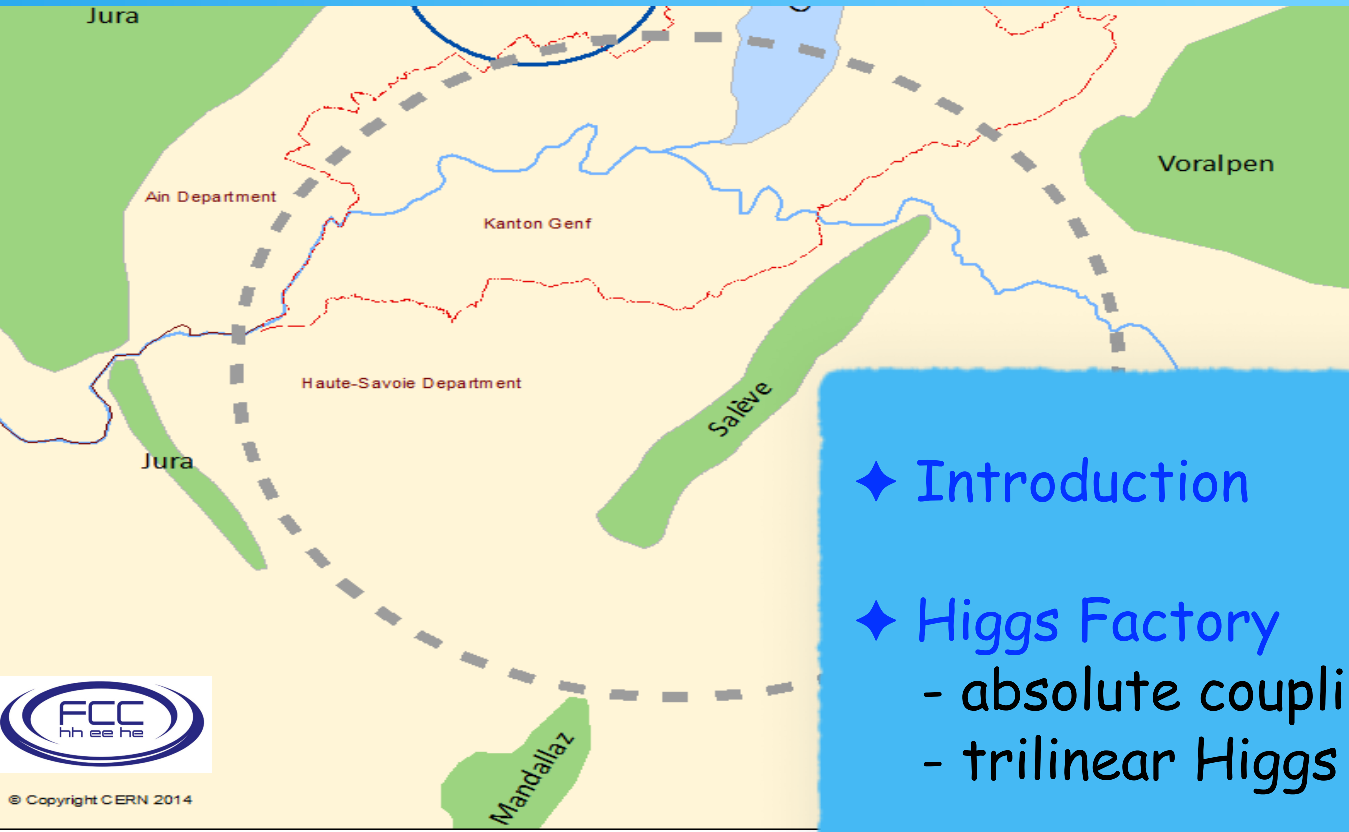
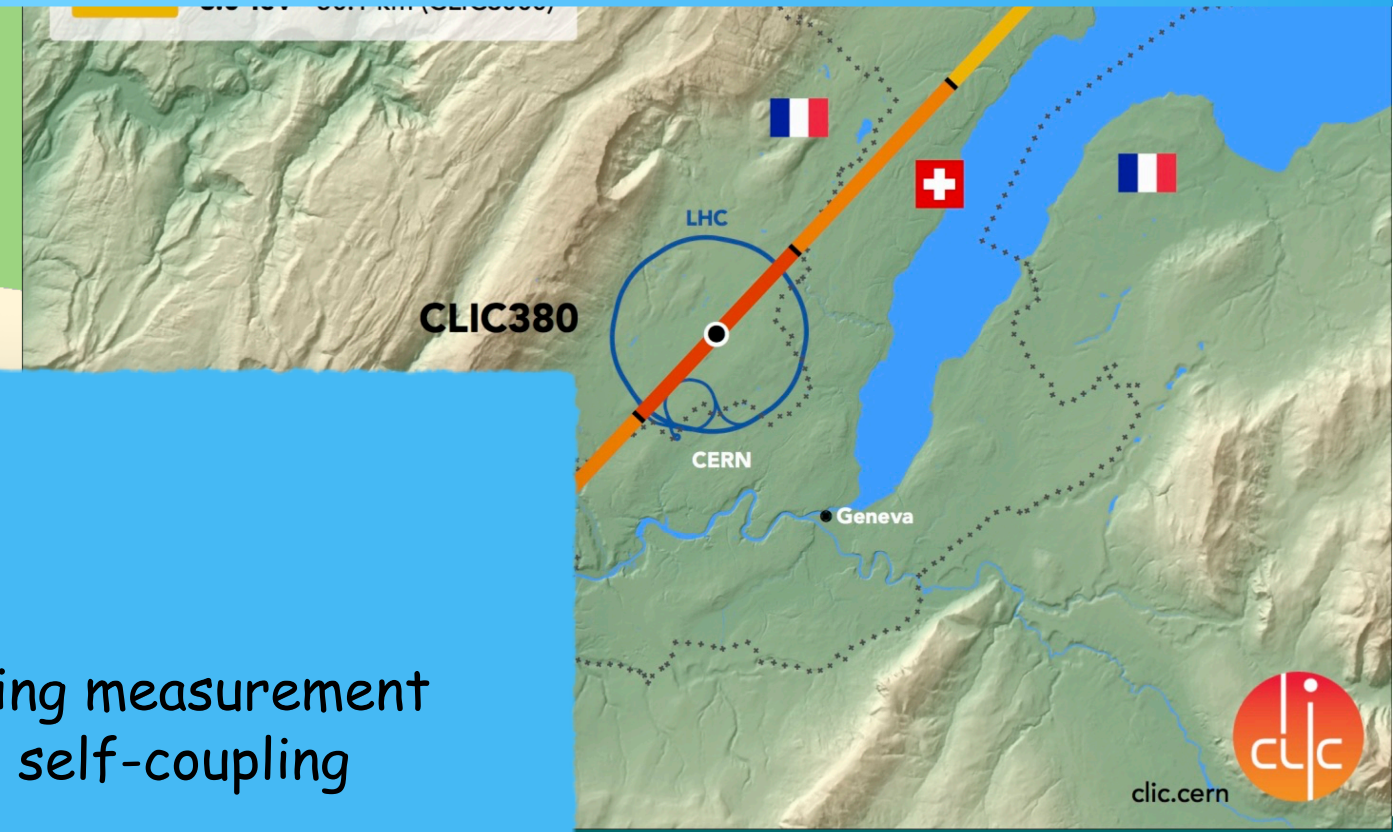
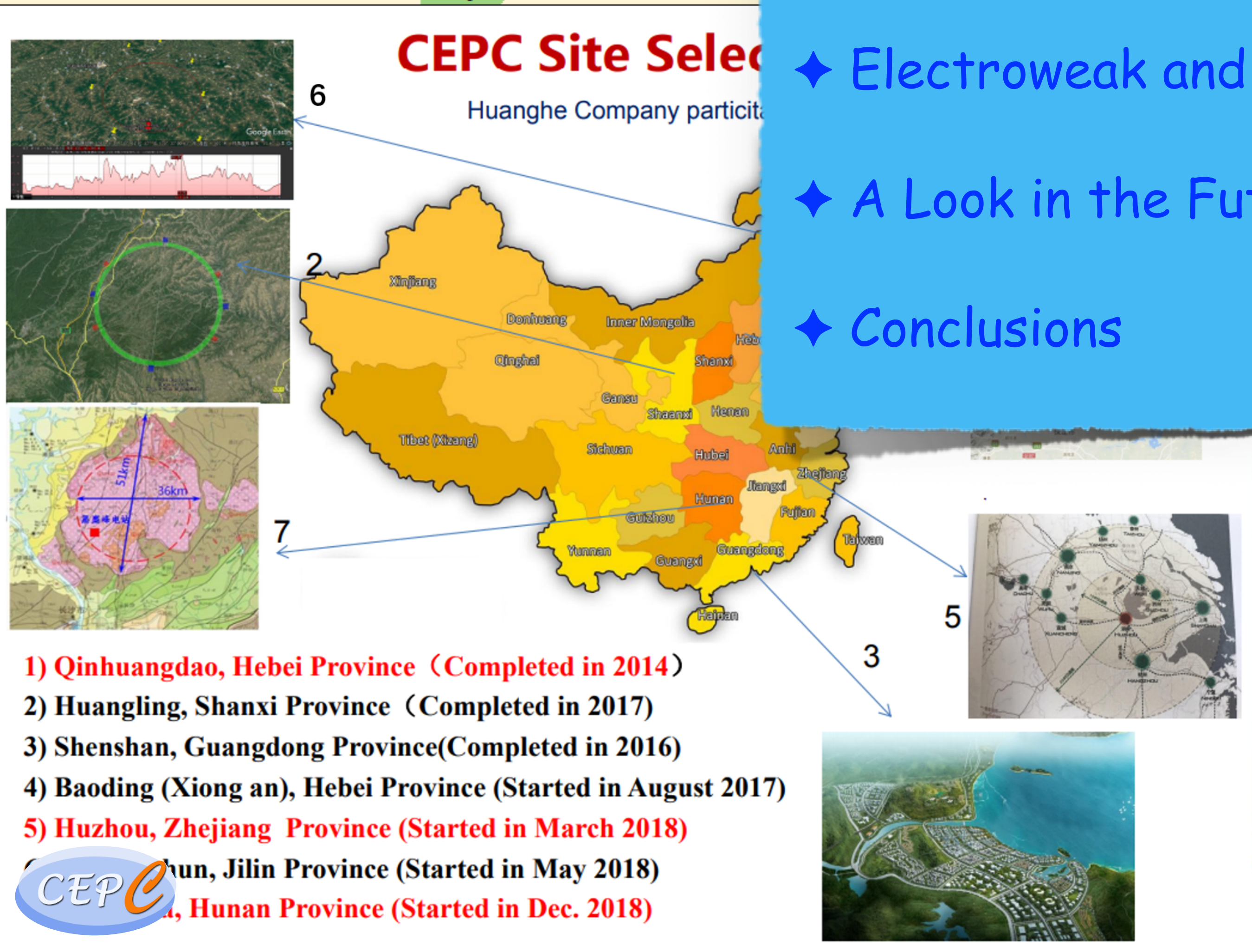
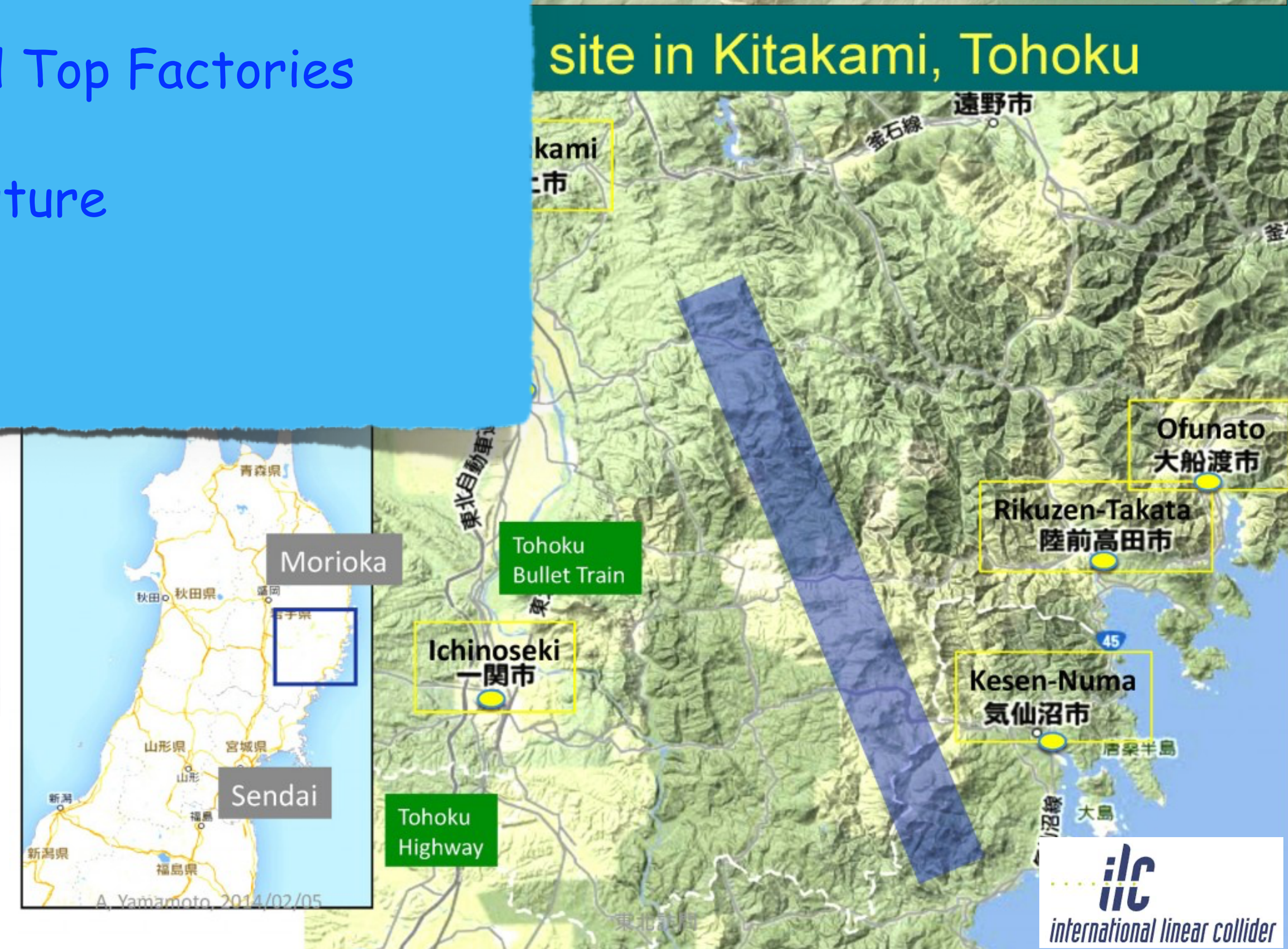
Outline





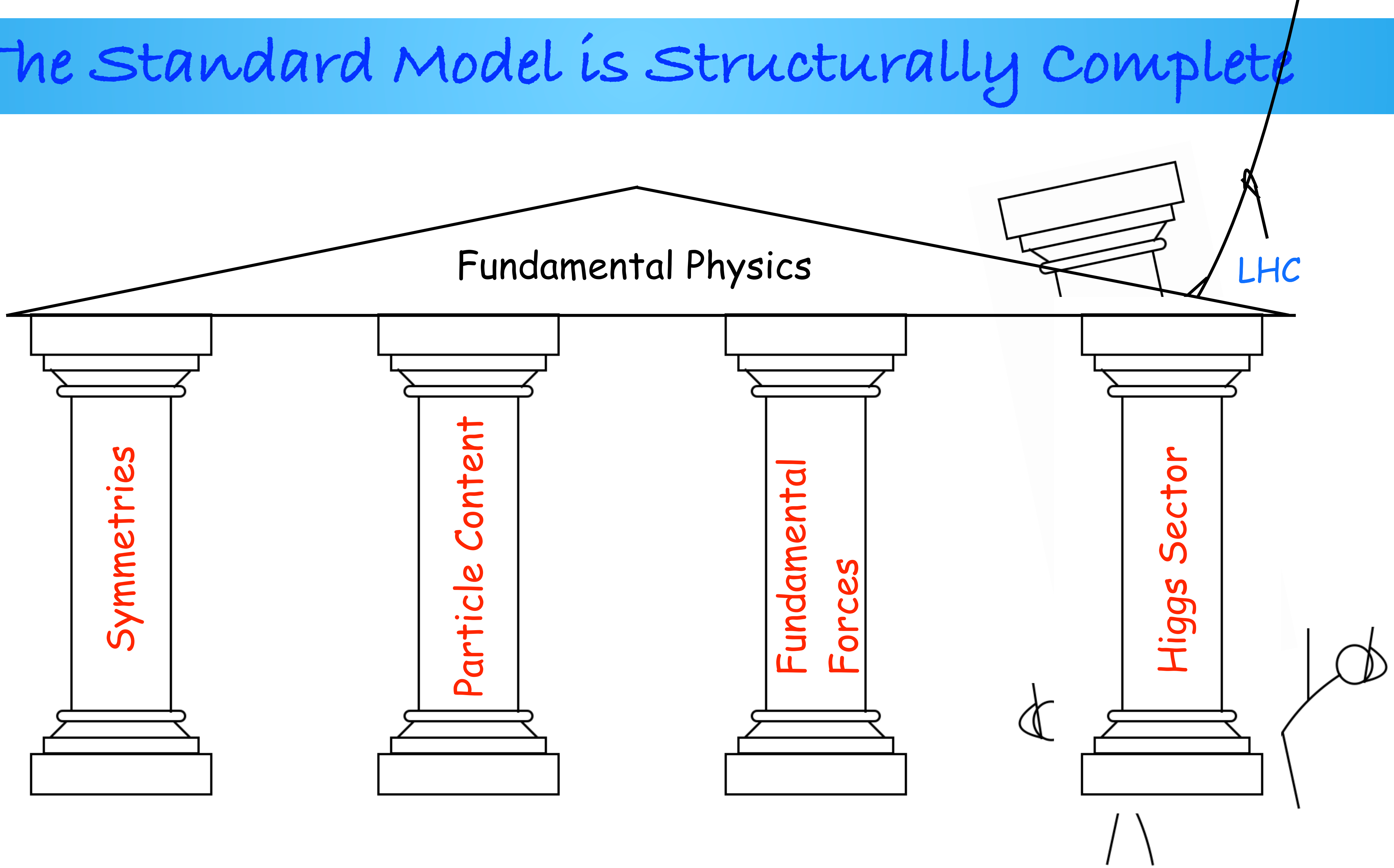
- ✦ Introduction
- ✦ Higgs Factory
  - absolute coupling measurement
  - trilinear Higgs self-coupling
- ✦ Electroweak and Top Factories
- ✦ A Look in the Future
- ✦ Conclusions



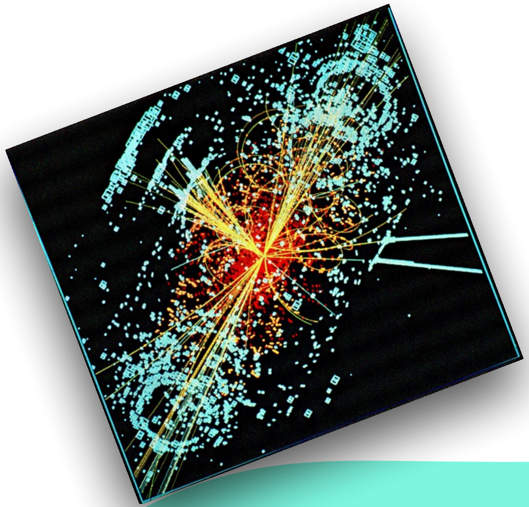


Introduction

The Standard Model is Structurally Complete



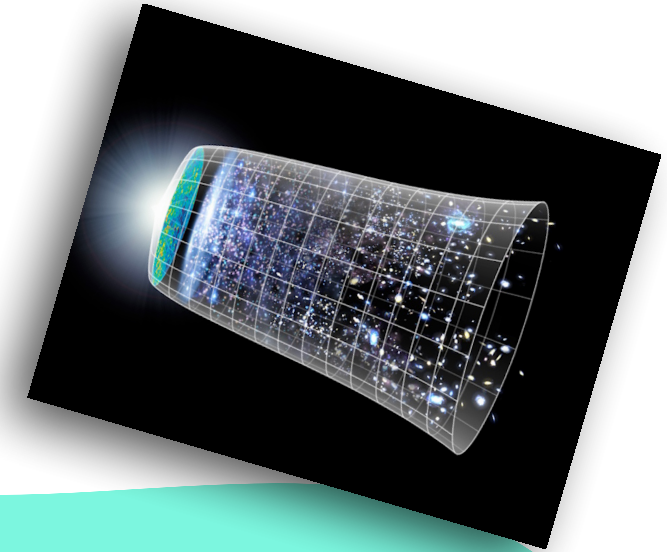
Open Questions



Particle physics

- ❖origin of electroweak symmetry breaking
- ❖hierarchy problem
- ❖nature of the Higgs boson
- ❖fermion mass and flavor puzzle
- ❖origin of neutrino masses

Cosmology

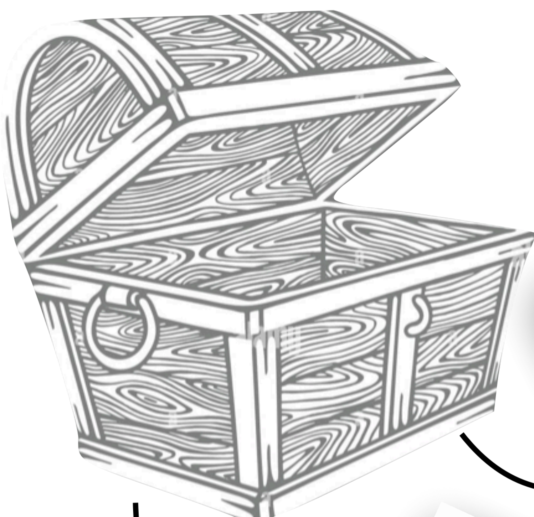


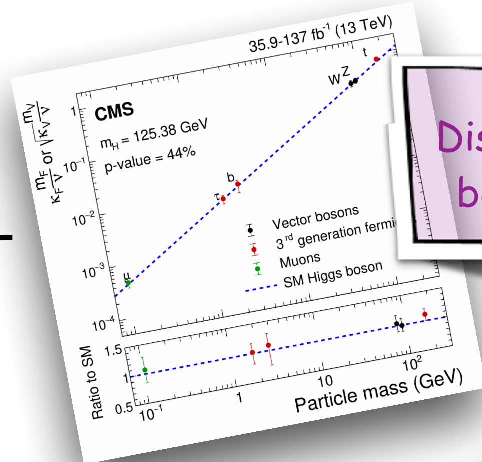
- ❖nature of Dark Matter
- ❖matter-antimatter asymmetry
- ❖dark energy
- ❖inflation
- ❖how to incorporate gravity

Decipherment of fundamental laws of nature:
judicious combination of
theoretical methods/interpretation
and experimental input/scrutiny

New physics is required, but there is no clear indication at which energy scale

The Challenge





Discovered Higgs Boson behaves very SM-like

Consistency Test of the SM at the quantum level

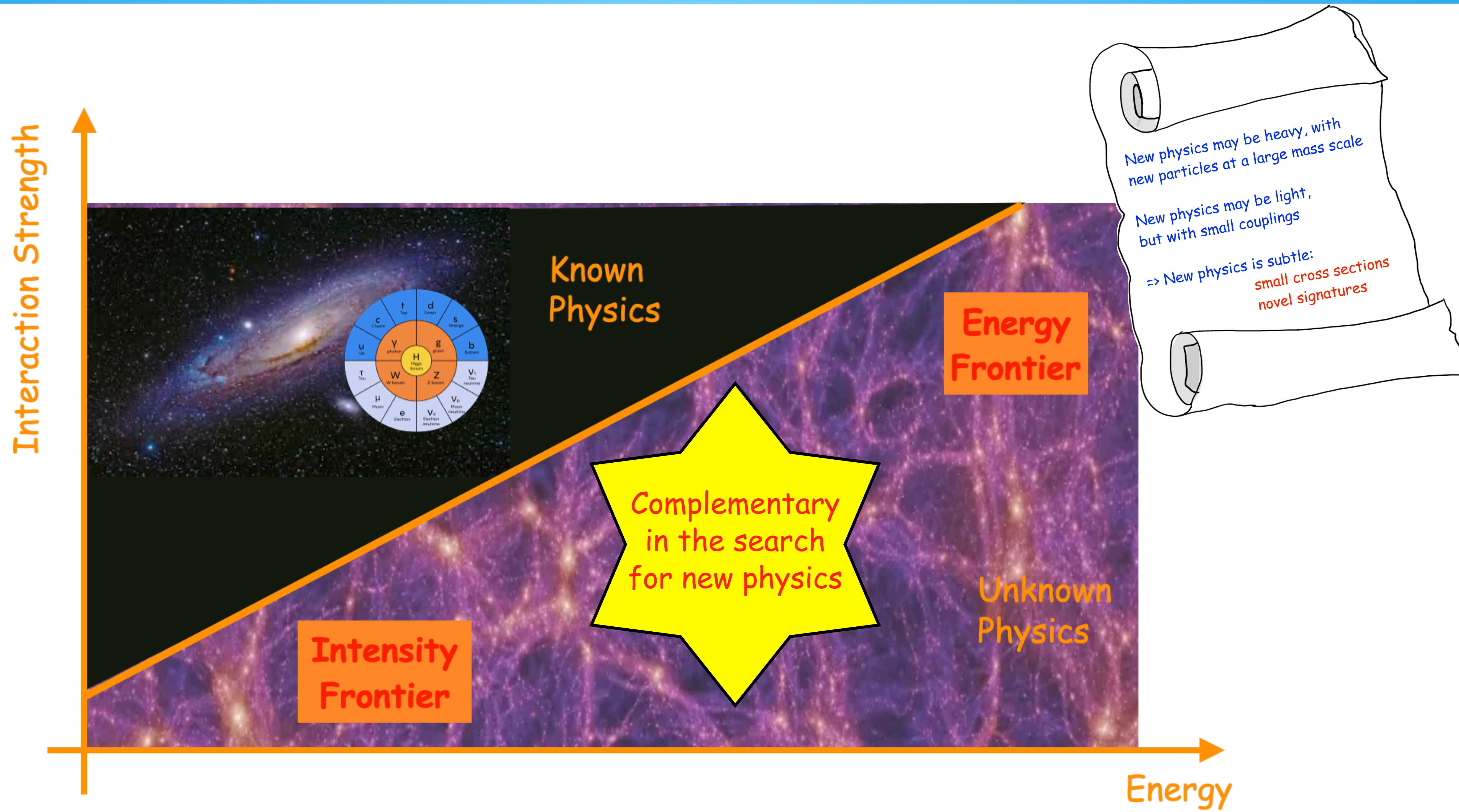
No direct discovery of New Physics so far

New physics may be heavy, with new particles at a large mass scale

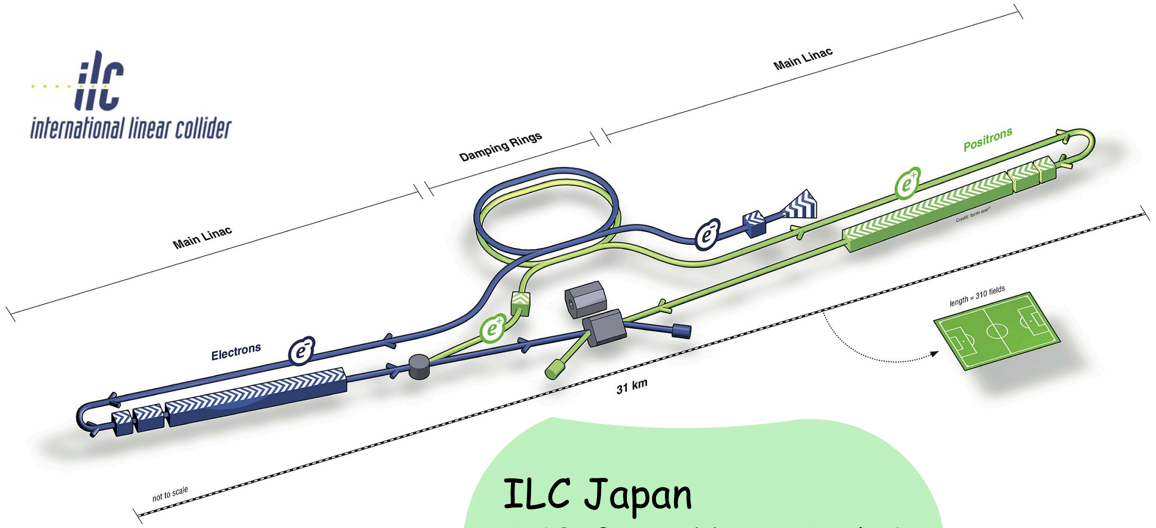
New physics may be light, but with small couplings

=> New physics is subtle:
small cross sections
novel signatures

Search for New Physics

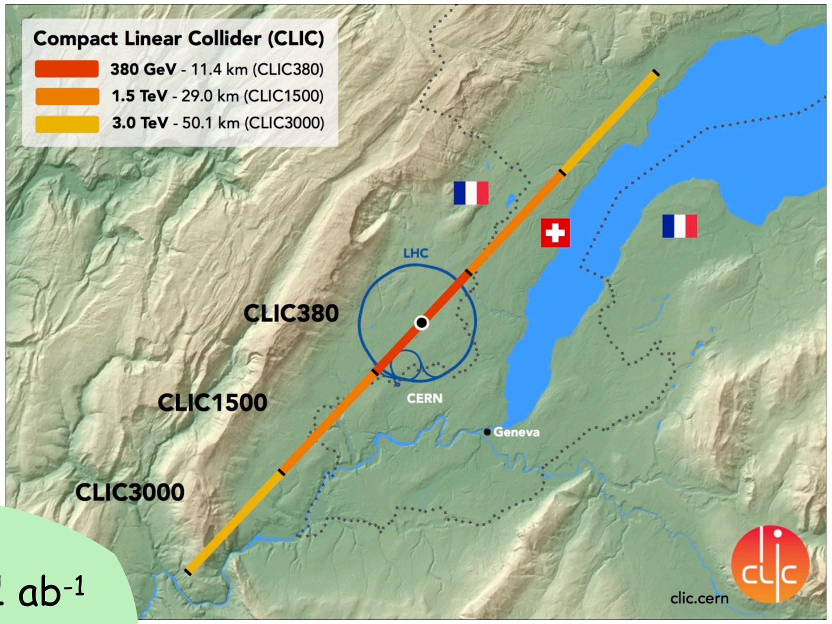


Future e^+e^- Collider Projects

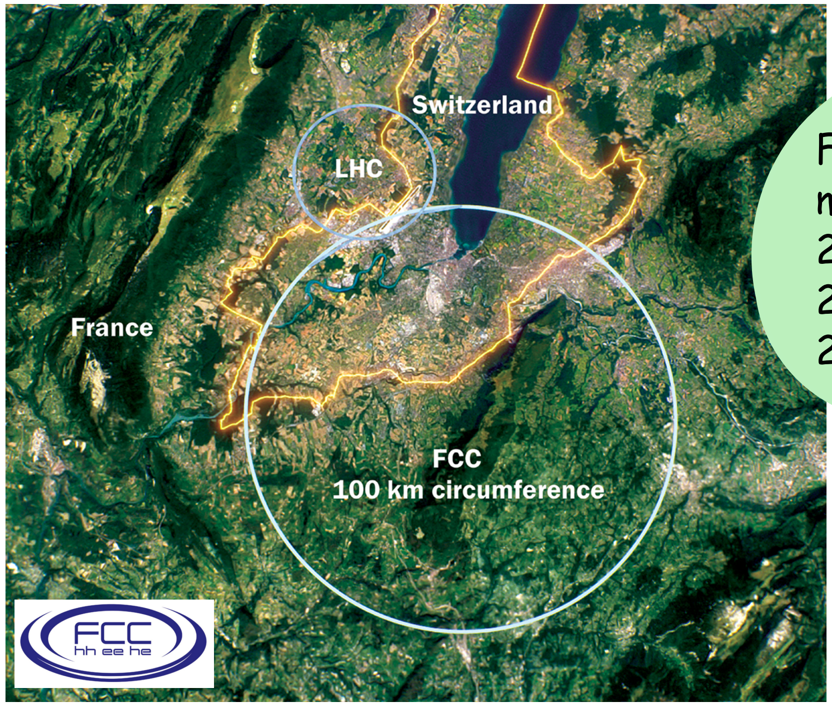


ILC Japan
250 GeV, 11y -> 2 ab^{-1}
500 GeV, 8.5y 4 ab^{-1}
1000 GeV, 8.5y 8 ab^{-1}

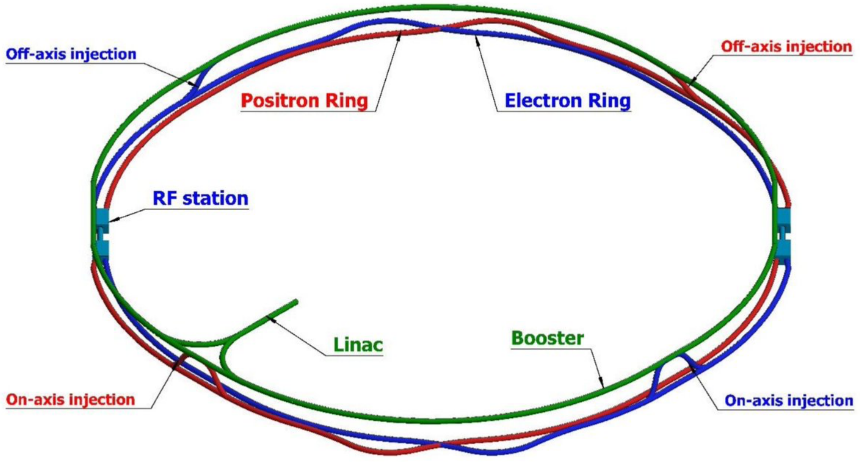
Cool Copper Collider
250 GeV -> 1.3×10^{34}/cm^{2}s
550 GeV 2.4×10^{34}/cm^{2}s



CLIC, CERN
380 GeV, 8y -> 1 ab^{-1}
1500 GeV, 7y 2.5 ab^{-1}
3000 GeV, 8.5y 5 ab^{-1}

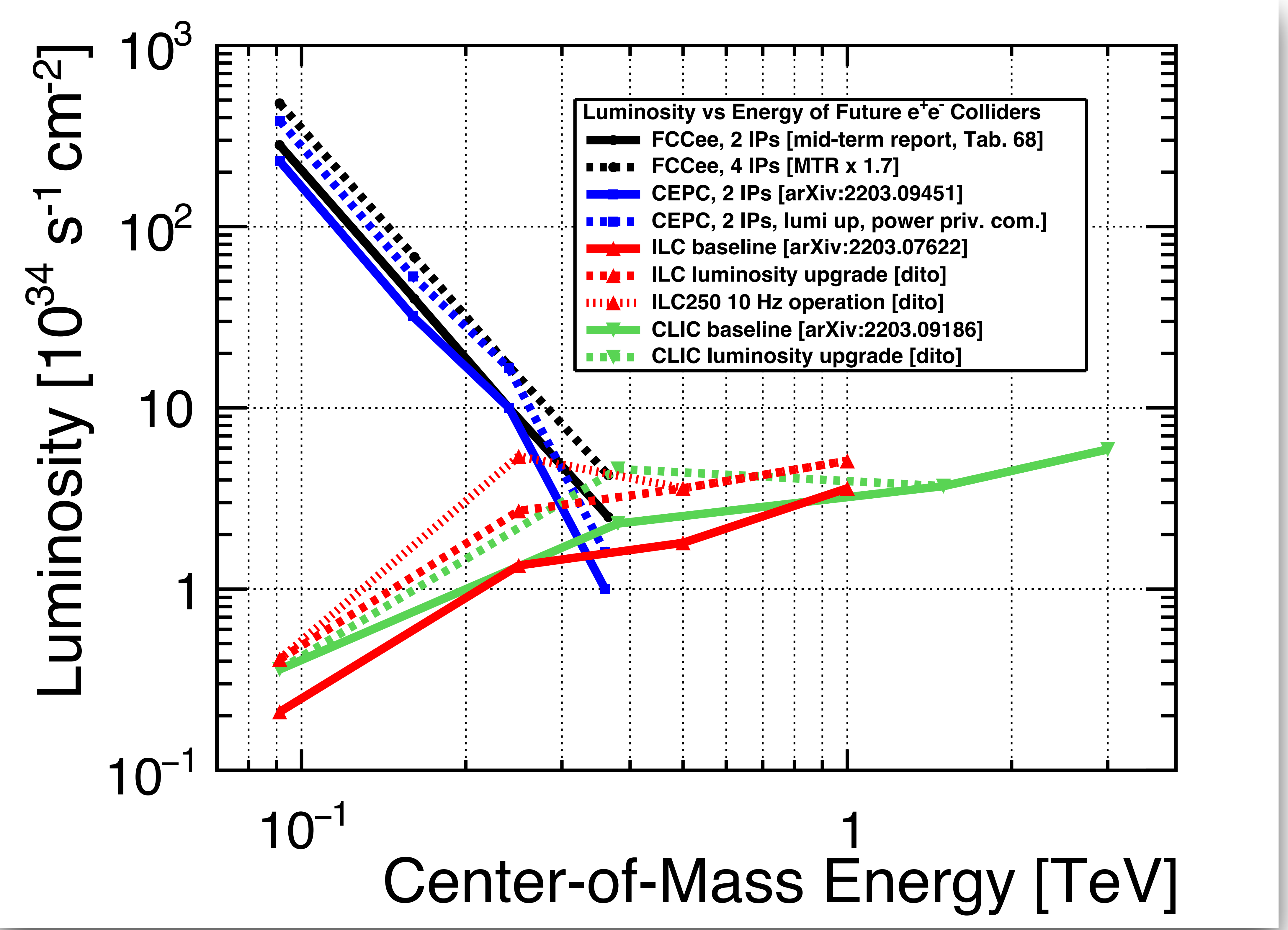


FCC-ee, CERN
m_Z, 4y -> 150 ab^{-1}
2 m_W, 1-2y 10 ab^{-1}
240 GeV, 3y 5 ab^{-1}
2 m_{top}, 5y 1.5 ab^{-1}



CEPC, China
m_Z, 2y -> 16 ab^{-1}
2 m_W, 1y 2.6 ab^{-1}
240 GeV, 7y 5.6 ab^{-1}

ee-Colliders Energy Range & Luminosity



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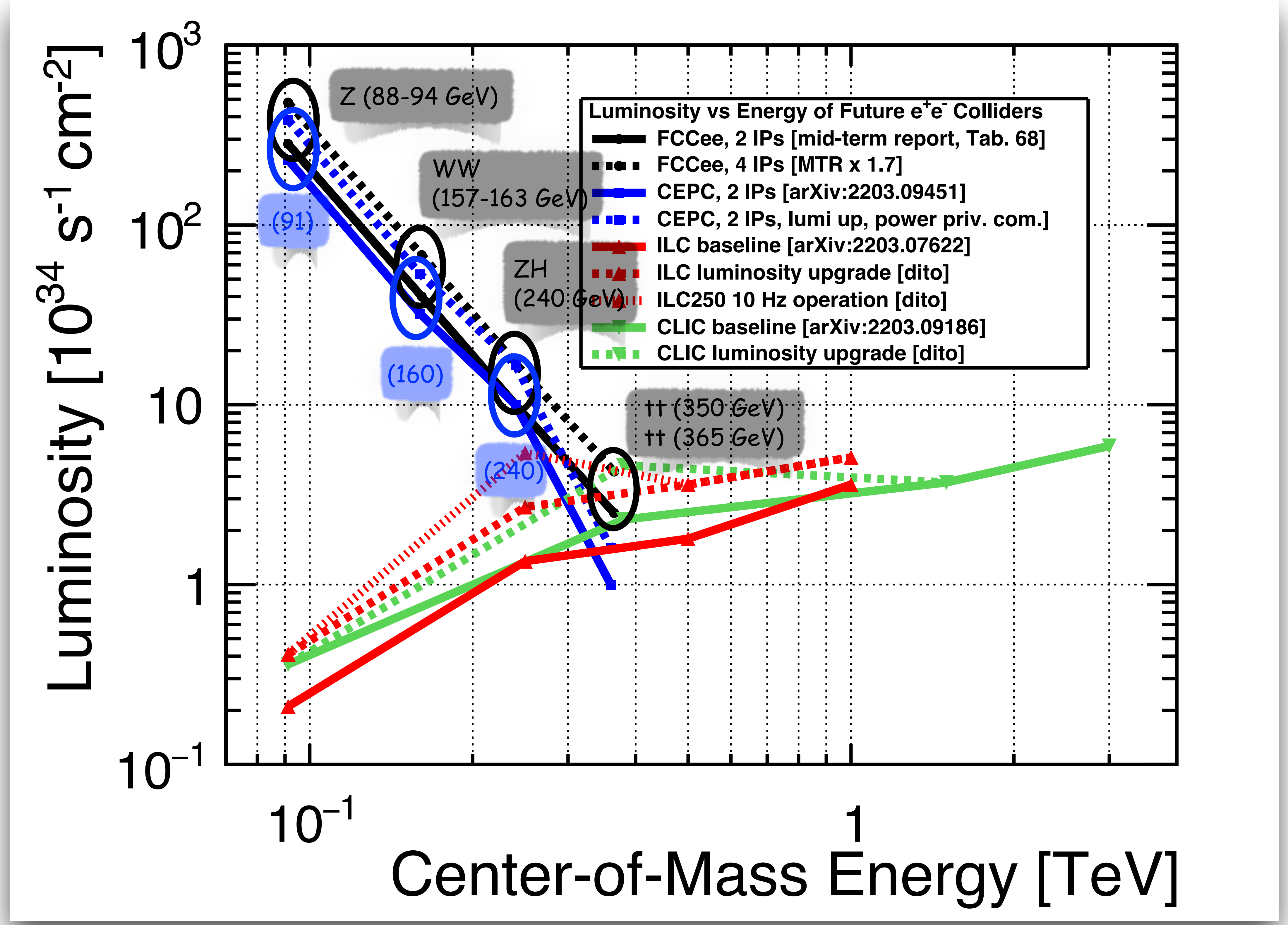

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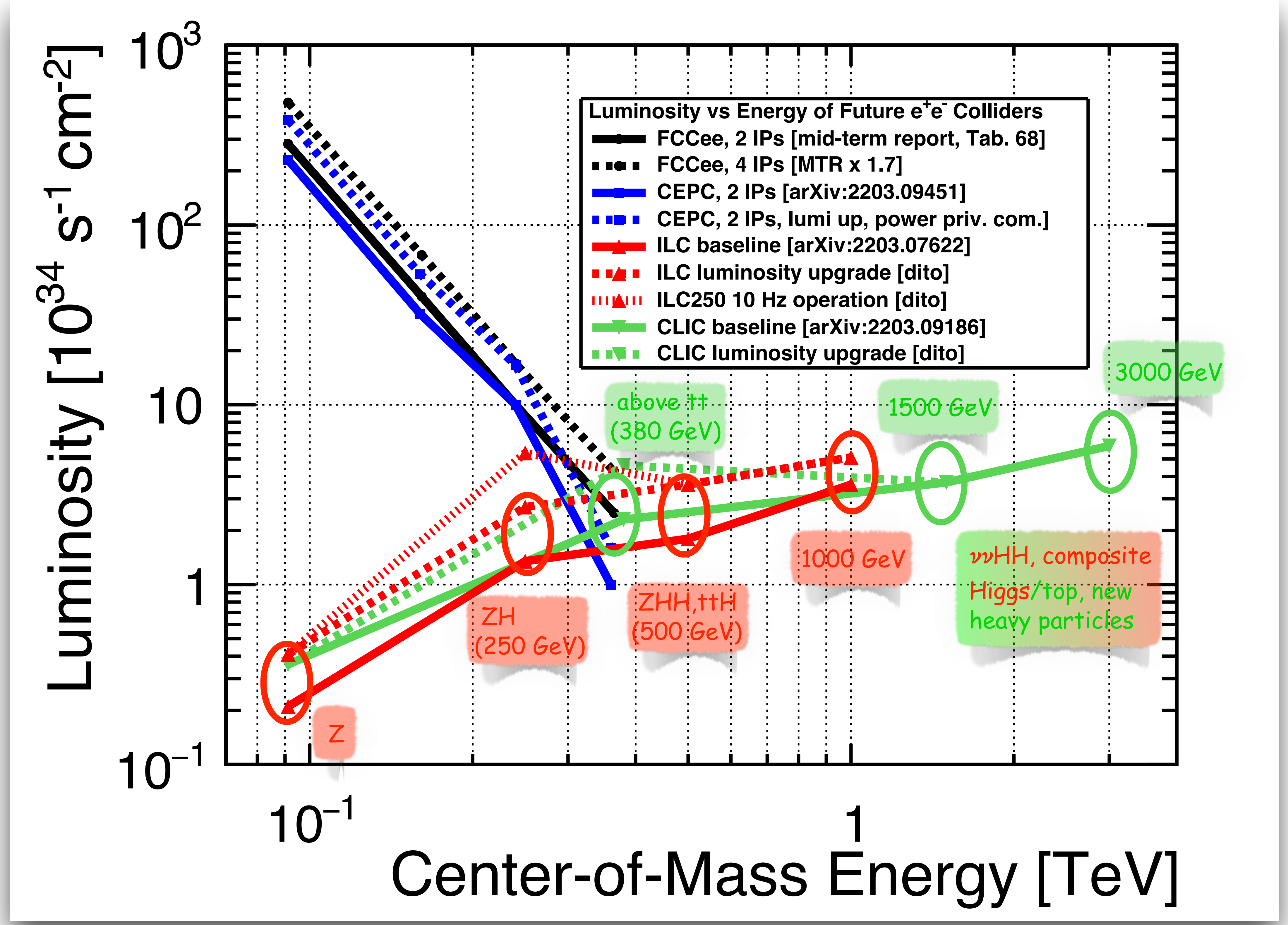
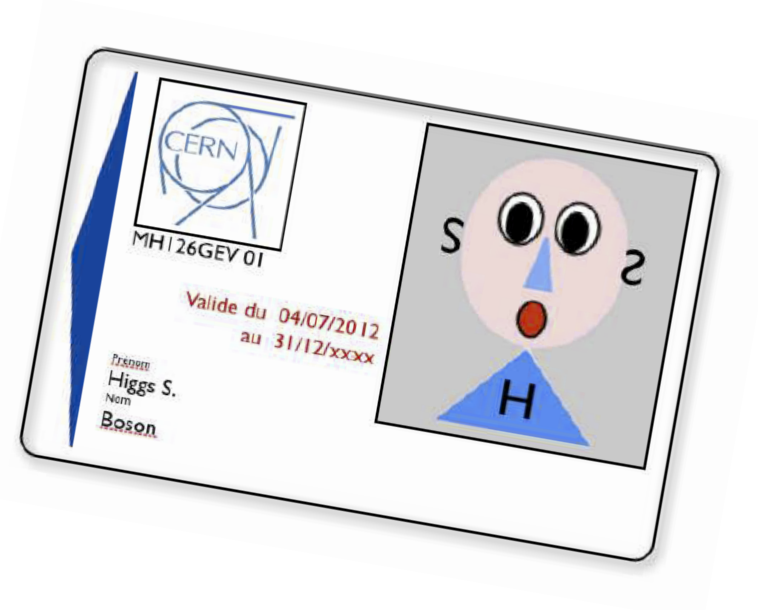



Higgs Factory

Establishing the Higgs Mechanism



4th July 2012

Discovery of new particle announced by CERN!!

But how can we be sure that it is a Higgs? We must

- Measure its couplings to the other SM particles
- We must determine its spin and CP quantum numbers
- We must measure the Higgs potential, I.e. its self-couplings

My Diary

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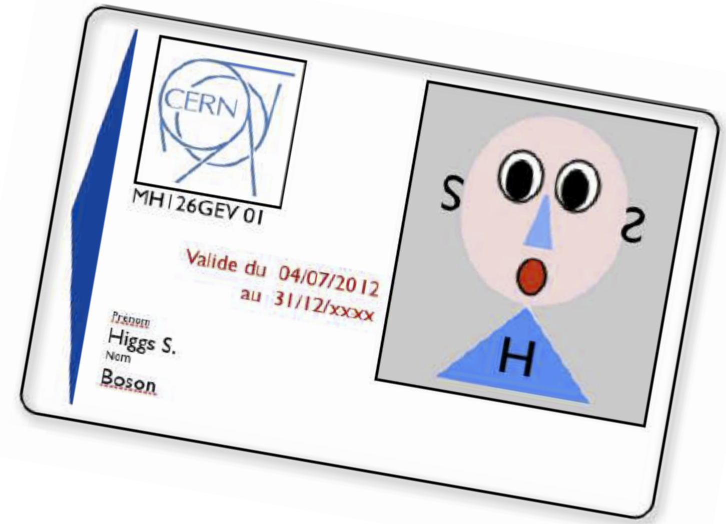
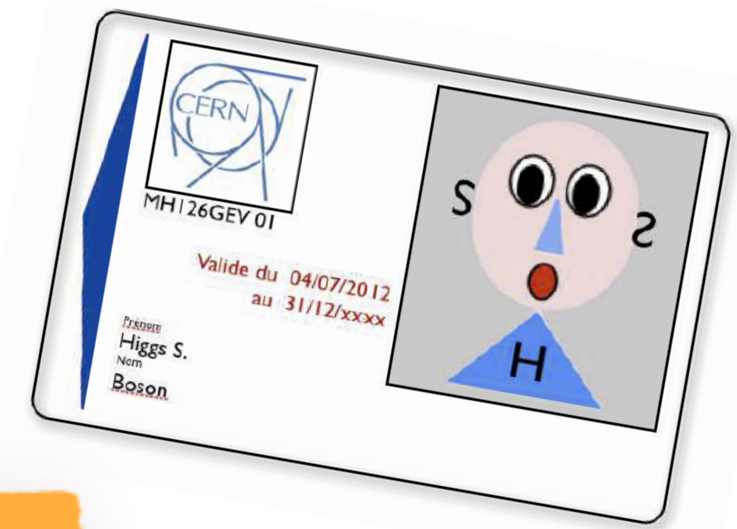
My Diary

Precise measurements may give hints to beyond-SM physics (BSM)



Role of the Higgs Boson



- We have the SM-like Higgs boson

  What can we learn from Higgs physics?

- Corner new physics with the Higgs:

$$\mathscr{L}_{\text{Higgs}} = (\mathscr{D}_\mu \Phi_i)(\mathscr{D}^\mu \Phi_i)^\dagger - V(\Phi_i) + \mathscr{L}_{\text{Yukawa}}$$

- anomalous Higgs gauge couplings
- CP violation

✏ New Physics & DM
✏ Compositeness
✏ Baryogenesis

- coupling relations $g_X \sim m_X^{(2)}$

✏ **Establish Higgs mechanism/Unique?**
✏ **Compositeness**

- Higgs mass
- Higgs self-interaction
- vacuum structure
- CP violation
- portal to hidden sector

✏ **Self-consistency SM**
✏ **Ultimate test Higgs mechanism**
✏ **Vacuum stability**
✏ **New Physics**
✏ **Dark Matter**
✏ **Matter asymmetry**
✏ **Evolution of Universe**
✏ **Baryogenesis**

- anomalous Higgs fermion couplings
- CP violation

✏ **Flavor/Matter puzzle**
✏ **Unique?**
✏ **New Physics**
✏ **Compositeness**
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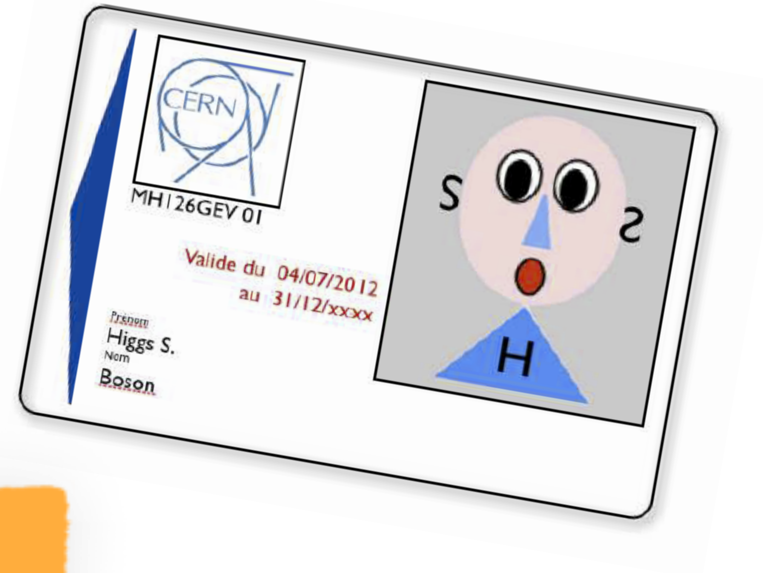

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Establish Higgs Mechanism

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New Physics

- Higgs mass
- Higgs self-interaction
- vacuum structure
- CP violation
- portal to hidden sector

✏ **Self-cons... ...ncy SM**
✏ **Ult...**
Higg...
✏ **Vac...**
✏ **N...**
✏ **Dark ...**
✏ **Matte... ...ry**
✏ **Evolution of Universe**
✏ **Baryogenesis**

Matter-Antimatter Asymmetry

Dark Matter

- anomalous Higgs fermion couplings
- CP violation

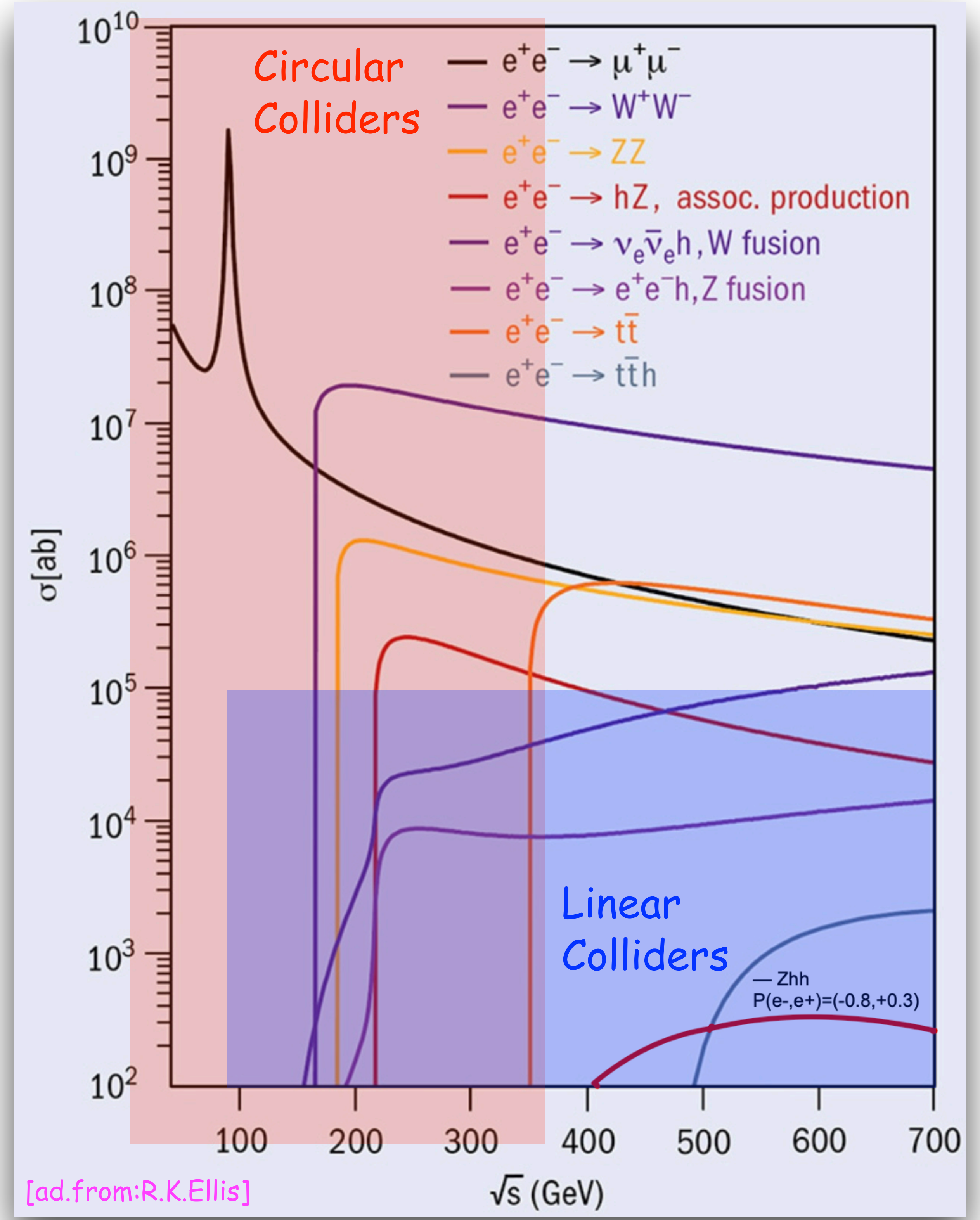
✏ **Flavor/Matter puzzle**
✏ **Unique?**
✏ **New Physics**
✏ **Compositeness**
✏ **Baryogenesis**

Flavor Matter Puzzle

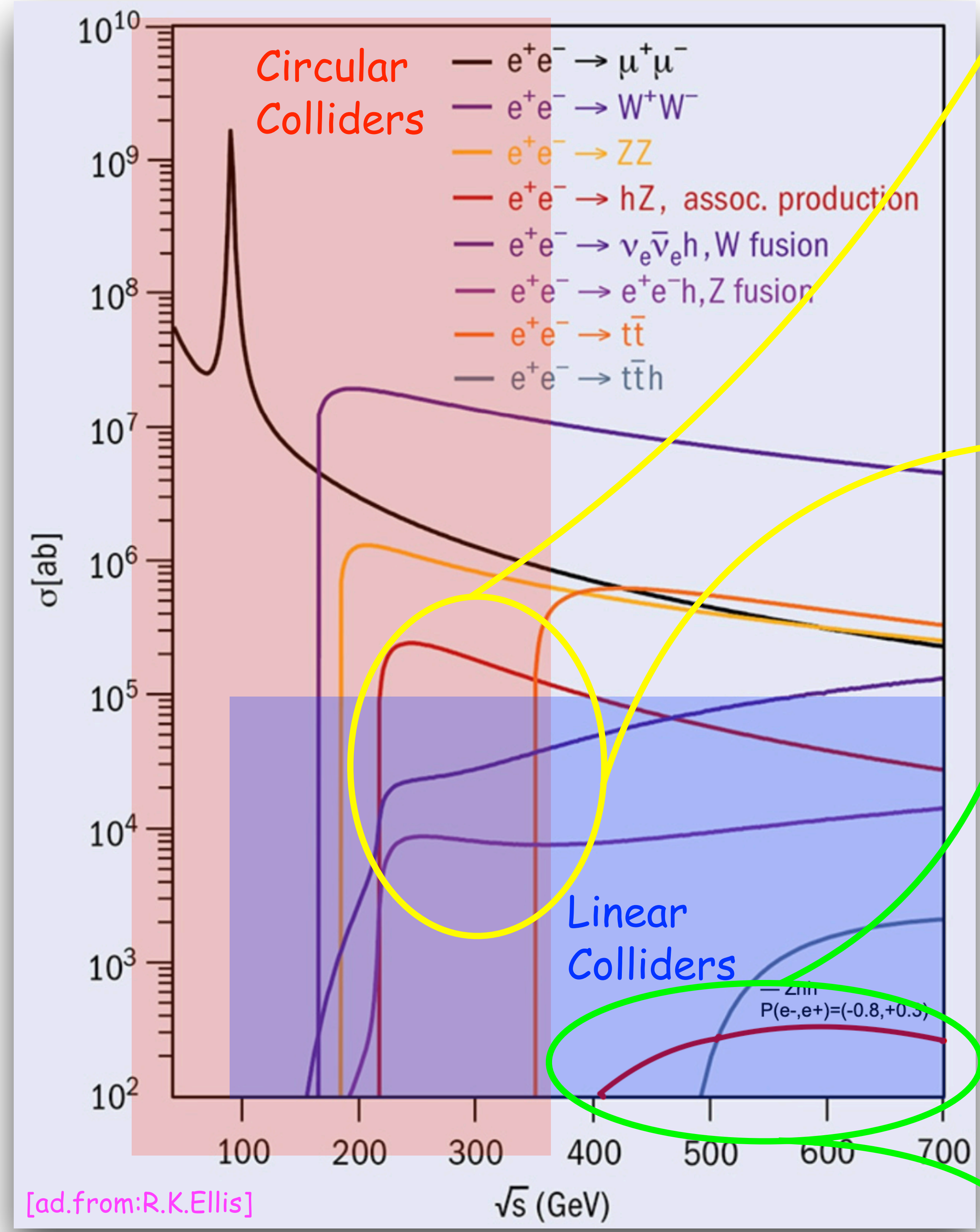
Evolution of the Cosmos

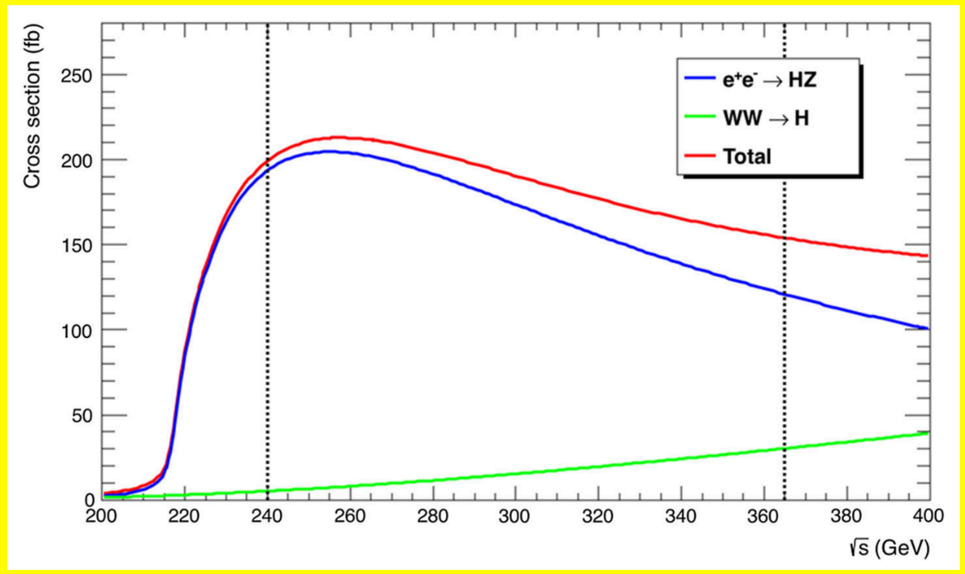
The Higgs Factory

NEED

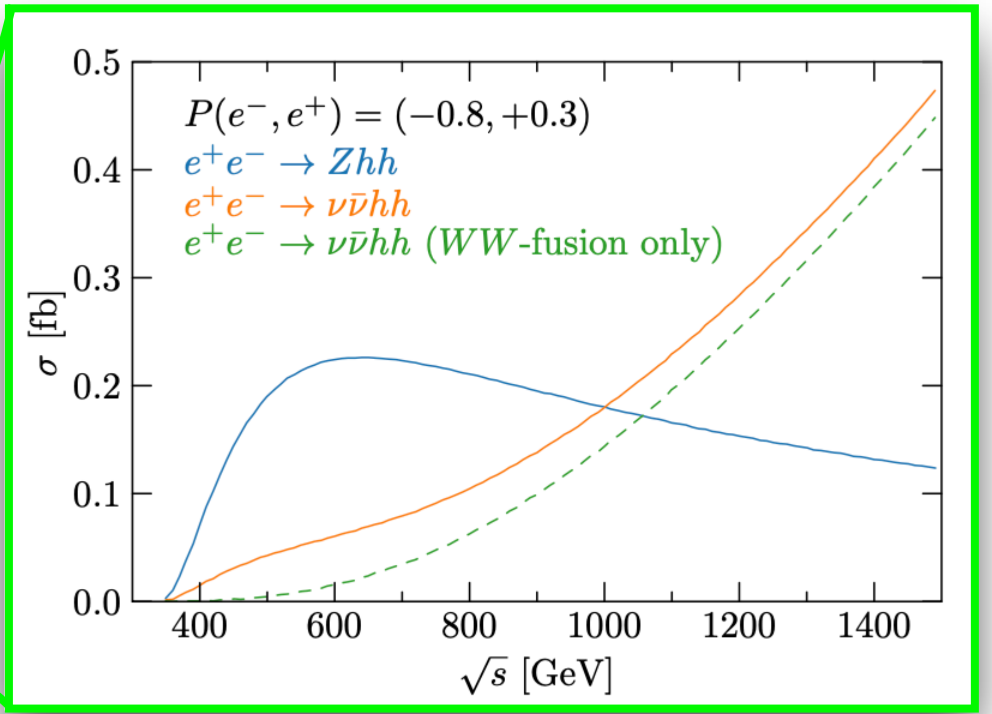


The Higgs Factory





Single Higgs Production



Double Higgs Production

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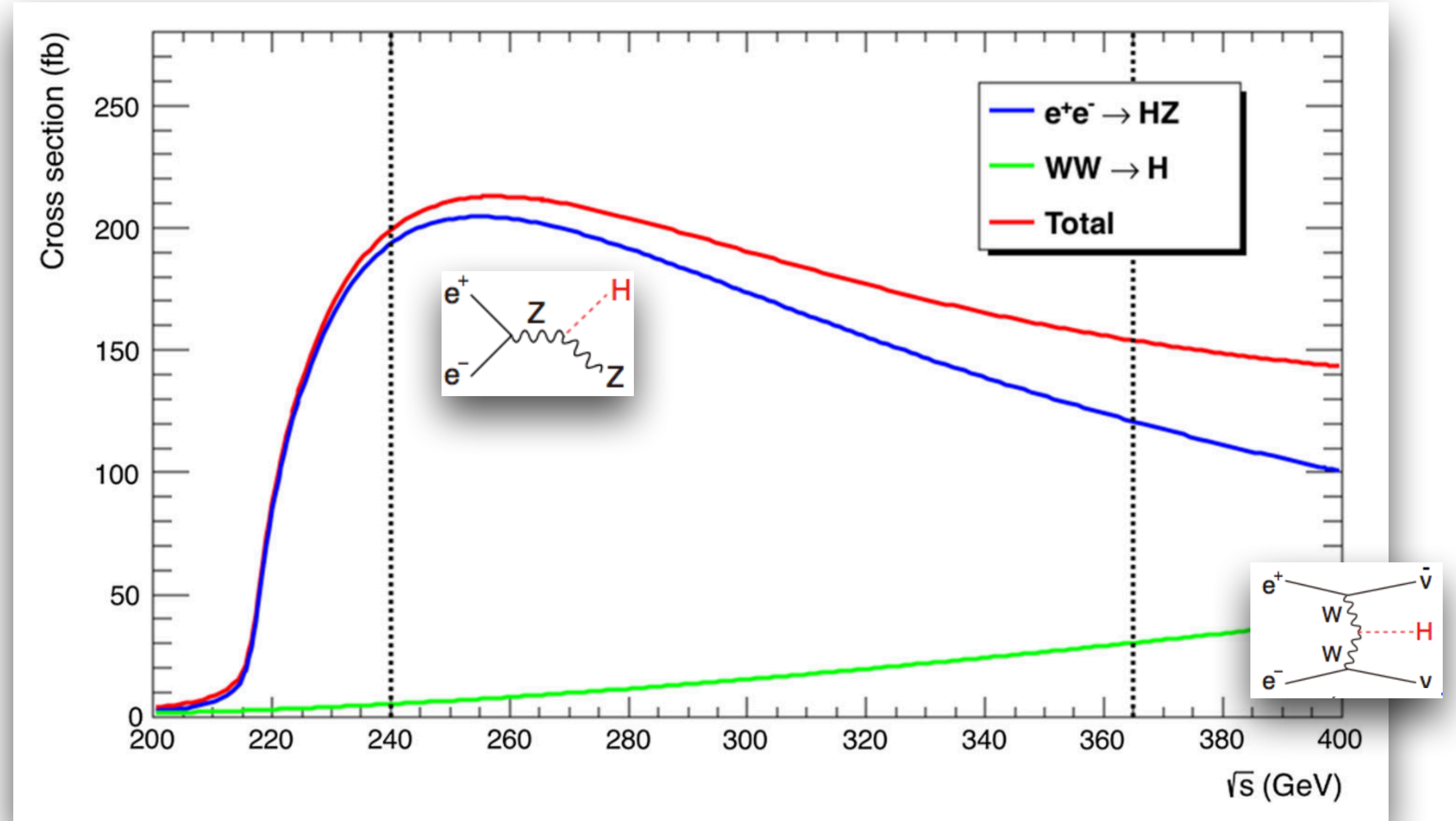
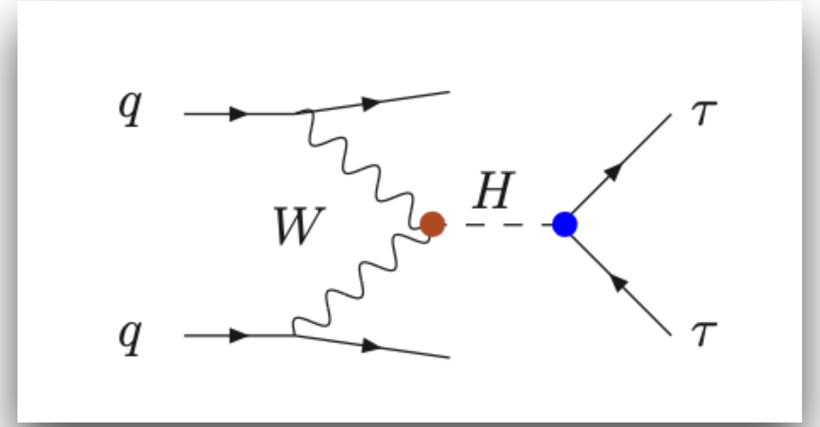


O(10^6) Higgs bosons from ZH
O(10^5) Higgs bosons from H$\nu\nu$

Higgs Coupling Measurements

- **Higgs mechanism:** Higgs couplings to SM particles ~ to masses of the particles
- **Experimental test:** various production and decay channels ~> extract couplings

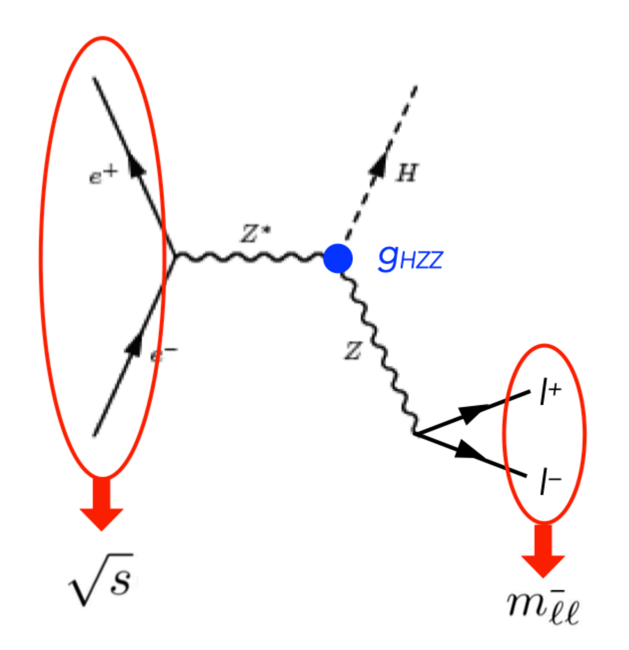


~ Γ_{WW} x BR(H->ττ) ~ Γ_{WW} x Γ(H->ττ)/Γ_{tot}

at LHC: not all final states are accessible
small SM Γ_{tot} non measurable

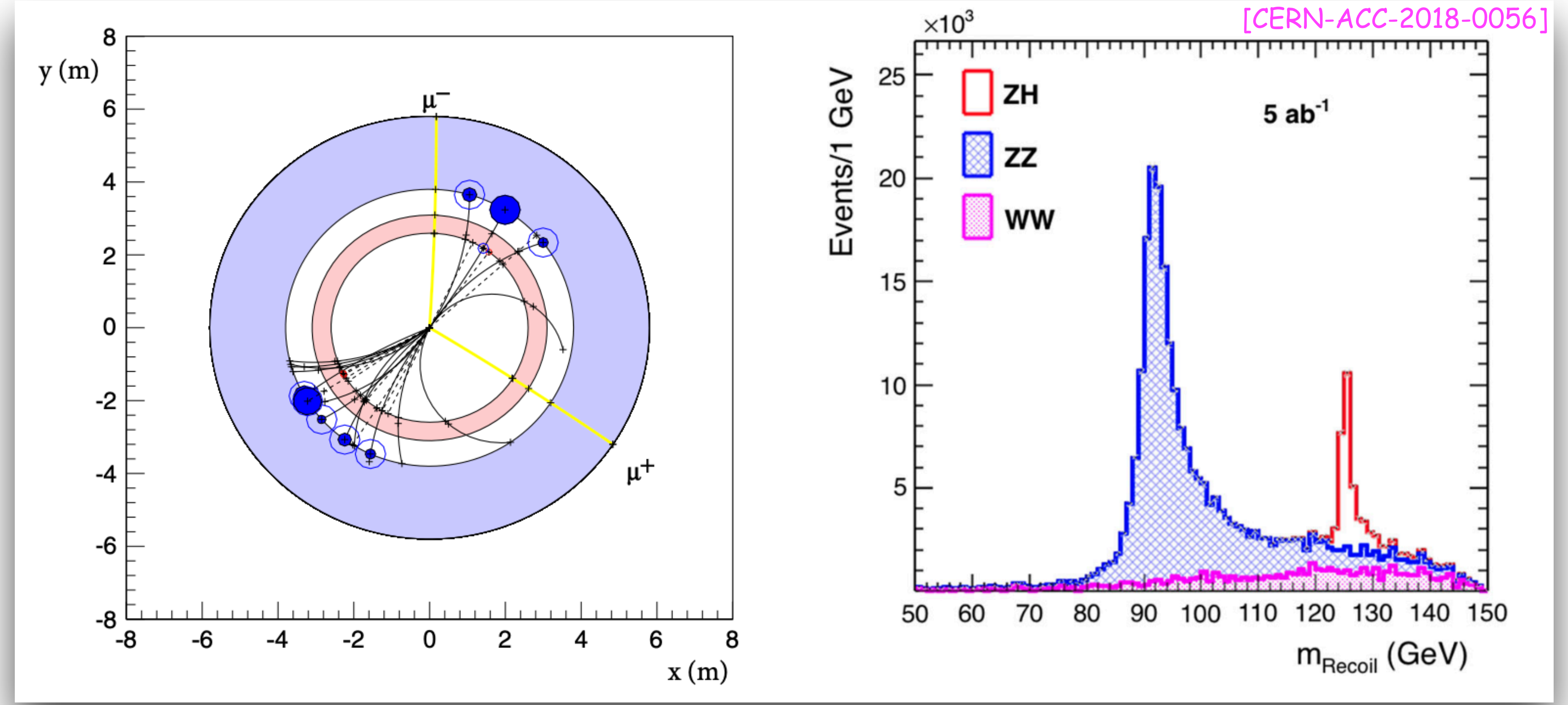
Higgs Coupling Measurements

❖ e^+e^- Collider: Absolute coupling measurement



$$m^2_{\rm recoil} = s + m^2_{\ell\ell} - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

Fit to recoil mass distribution:
- σ(ZH) measurement independent of Higgs decay
  ⇒ absolute determination of g_{HZZ}



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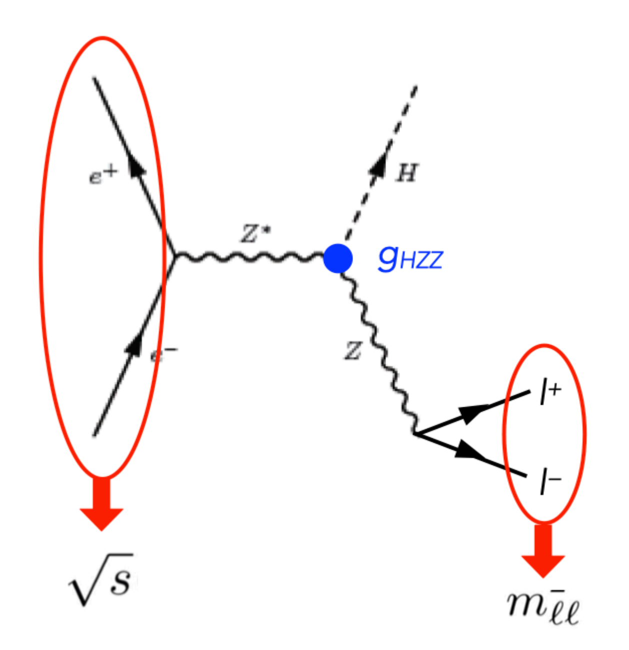

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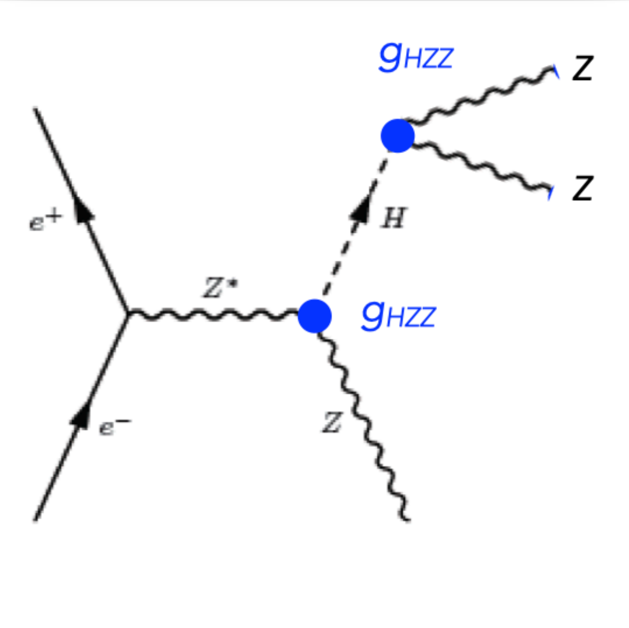
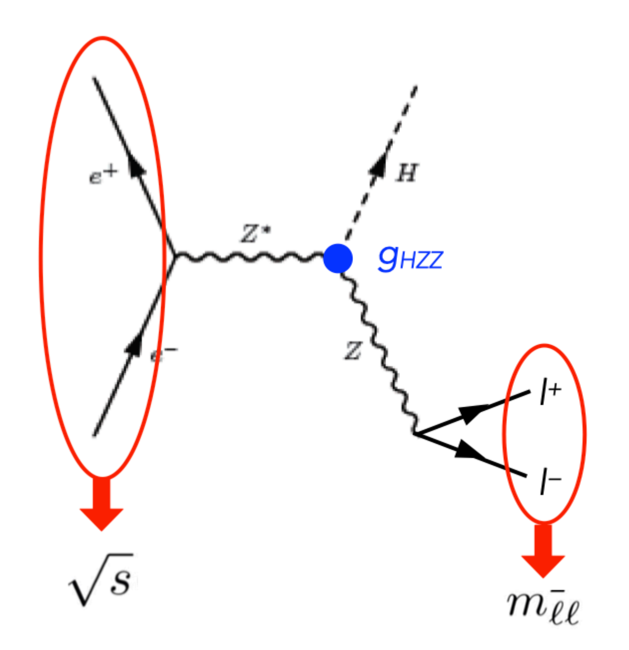


$$\sigma_{HZ} \times \Gamma(H \to ZZ)/\Gamma_H \sim (g_{HZZ})^4/\Gamma_H$$

⇒ extraction of Γ_H

Higgs Coupling Measurements

❖ e⁺e⁻ Collider: Absolute coupling measurement



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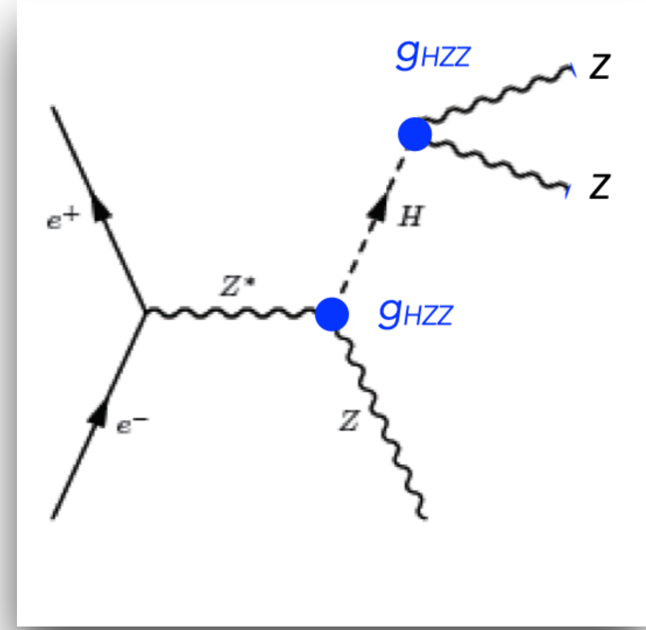
Exclusive decays into XX = bb, cc, gg, ττ, μμ, WW, γγ, Zγ, invisible, other new BSM states ⇒ absolute coupling extraction g_{HXX}



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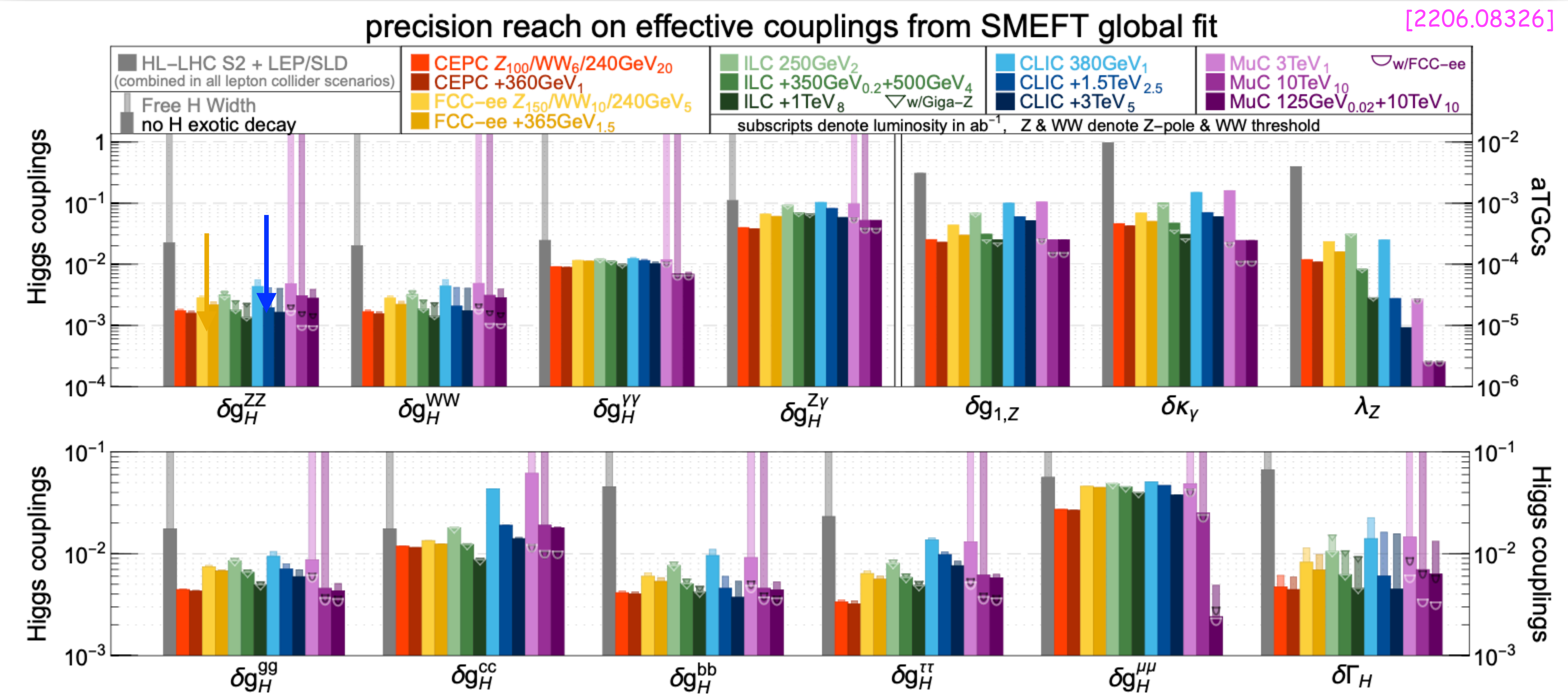
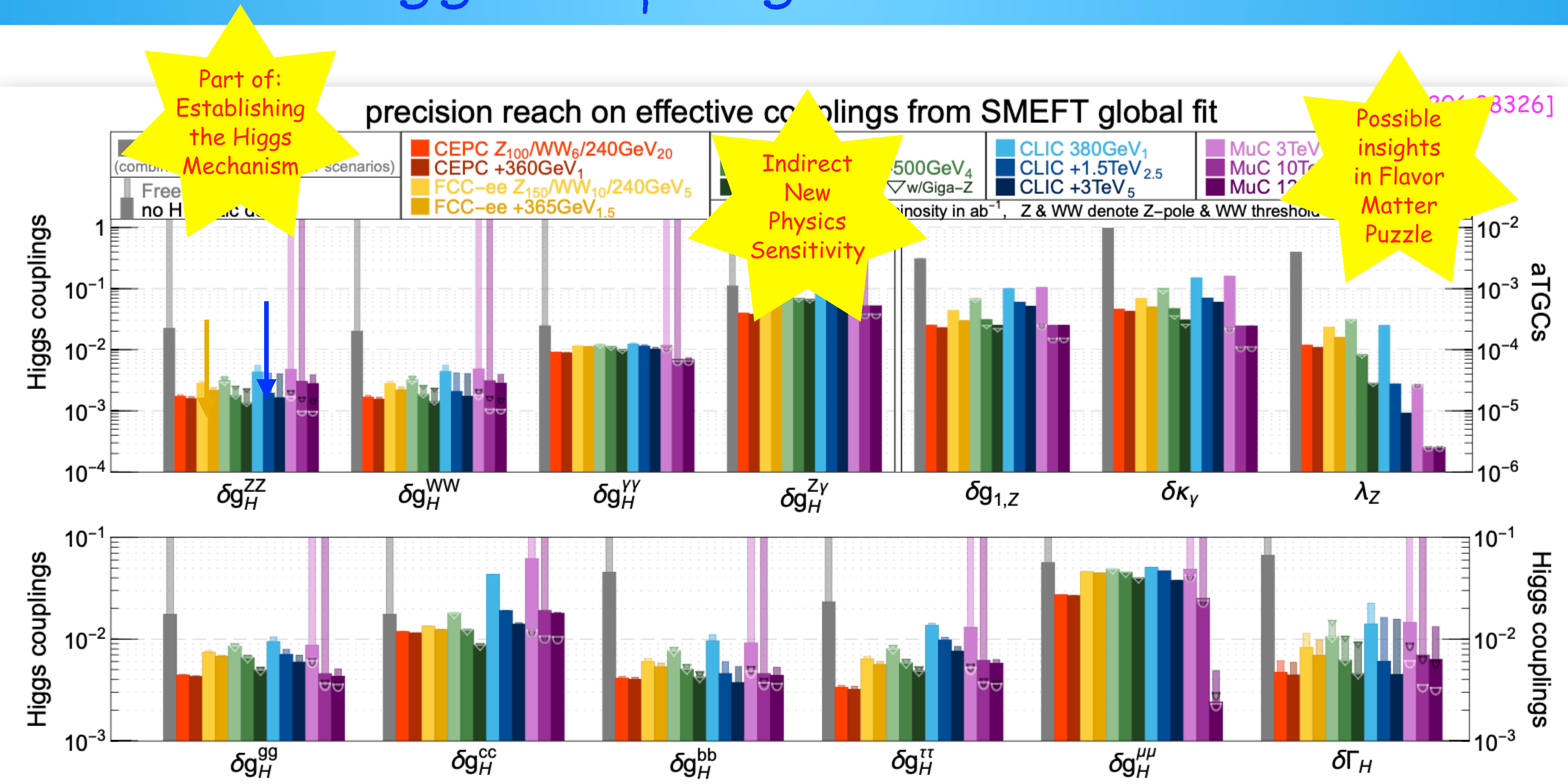


- ✏ all Higgs factories perform similar: luminosity vs. polarization
- ✏ couplings will be pushed to single percent - few per mille
- ✏ at least 1 order of magnitude precision gain compared to HL-LHC

Higgs Coupling Measurements



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What do we Learn?

✻ **What do we learn about new physics from indirect measurements** through enhanced precision (~factor 10 better than HL-LHC) in comparison to direct new physics searches at the HL-LHC?

✻ Which **new physics scales** can we probe?

✻ What can we learn from the patterns of the coupling deviations about the **underlying model**?

✻ How well can we **distinguish between different realizations** of possible BSM physics?

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✏ Coupling deviations due to new physics*: $g = g_{SM}[1 + \Delta] \; : \; \Delta = O(v^2/\Lambda^2)$

Experimental accuracy O(0.2) … O(0.01) =>
Probed new physics scale: $\Lambda = 550$ GeV … 2.5 TeV

* Unless violation of decoupling theorem

What do we Learn?

✏ Coupling deviations due to new physics: $g = g_{SM}[1 + \Delta]\ :\ \Delta = O(v^2/\Lambda^2)$

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Mixing effects: $\sim v^2/M^2$
- Higgs mixes w/ other high-mass scalar fields
- singlet, doublet, triplet extensions
- strongly interacting

Loop effects: $\sim 1/(16\pi^2)\, v^2/M^2$
- from new gauge bosons, scalars, fermions
- supersymmetry, strong dynamics, extra dimensions, see-saw, extended gauge groups

⇝ $\Lambda = 200$ GeV for $\Delta = 0.01$

What do we Learn?

[Englert,Freitas,MM,Plehn,Rauch,Spira,Walz,'14]

Scenario/framework	LHC	HL-LHC	LC	HL-LC
Higgs portal	0.23	0.28	0.44	0.56
2HDM type-II ($\tan\beta \approx 1$)	0.52	0.58	1.15	1.6
2HDM type-II ($\tan\beta \approx 10$)	0.33	0.36	0.7	1.0
$D = 6$ effective operators:				
hVV	0.78	0.87	2.6	3.3
hff	0.45	0.50	1.0	1.4
hgg contact	0.55	1.1	1.3	1.8
$h\gamma\gamma$ contact	0.15	0.18	0.24	0.36
Strong interactions	0.9	1.1–2.0	2.8–5.1	3.4–5.6
hgg loop effects:				
scalar triplet	0.16	0.31	0.37	0.52
scalar octet	0.39	0.75	0.92	1.3
vector octet	1.8	3.5	4.2	5.8
$h\gamma\gamma$ loop effects:				
scalar triplet	0.15	0.18	0.24	0.36
scalar octet	0.25	0.29	0.39	0.60
vector octet	1.1	1.3	1.8	2.7
Vector-like leptons	—	—	1.2	1.5

* LC: 250+500 GeV/250+500 fb^{-1} — HL-LC: 250+500+1000 GeV/ 1150+1600+2500 fb^{-1}

What about Coupling Patterns?

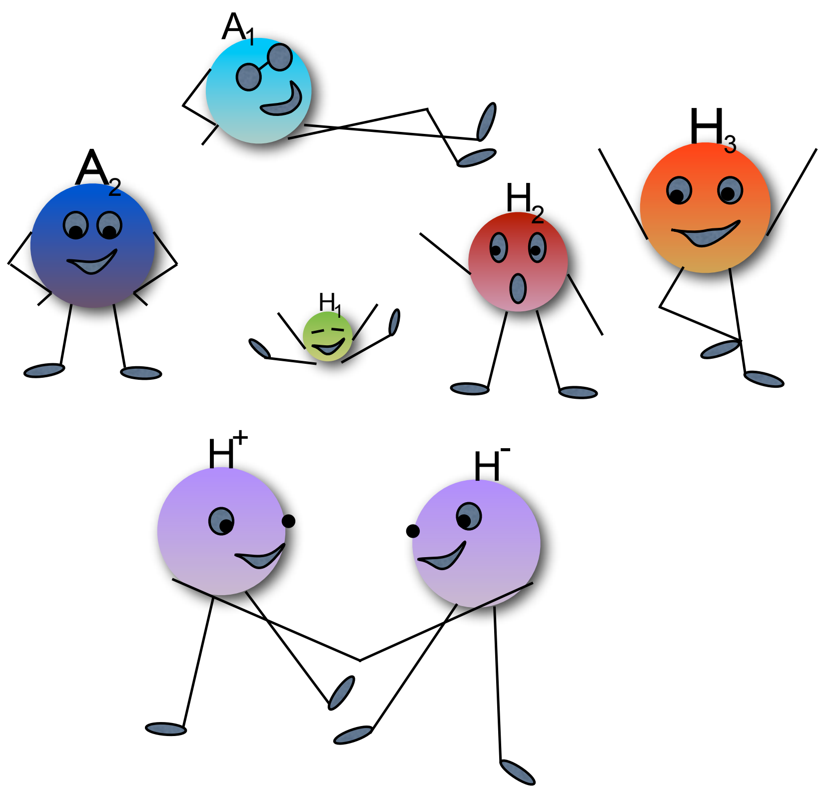
✏ Exploit coupling sum rules!

Example Next-to-Minimal Supersymmetric Model (NMSSM) w/ 3 Higgs CP-even bosons H_i (i=1,2,3)

$$\sum_{i=1}^{3} g^2_{H_i VV} = 1$$

$$\frac{1}{\sum_{i=1}^{3} g^2_{H_i tt}} + \frac{1}{\sum_{i=1}^{3} g^2_{H_i bb}} = 1$$

Violation of sum rule: - hints to not discovered Higgs boson
- allows distinction from minimal supersymmetric model (MSSM)



Coupling Violation Patterns in BSM Extensions

[MM,Sampaio,Santos,Wittbrodt,'17]

Models w/ H_i (i=1,2,3)
$H_\downarrow, H_{125}, H_\uparrow$:

CxSM:
SM+complex singlet

C2HDM:
CP-violating 2HDM

N2HDM:
Next-to-2HDM

NMSSM

Partial sum Π_{VV}:
$\sum_i g^2_{H_i VV}$ (i=1,2)
in case of only
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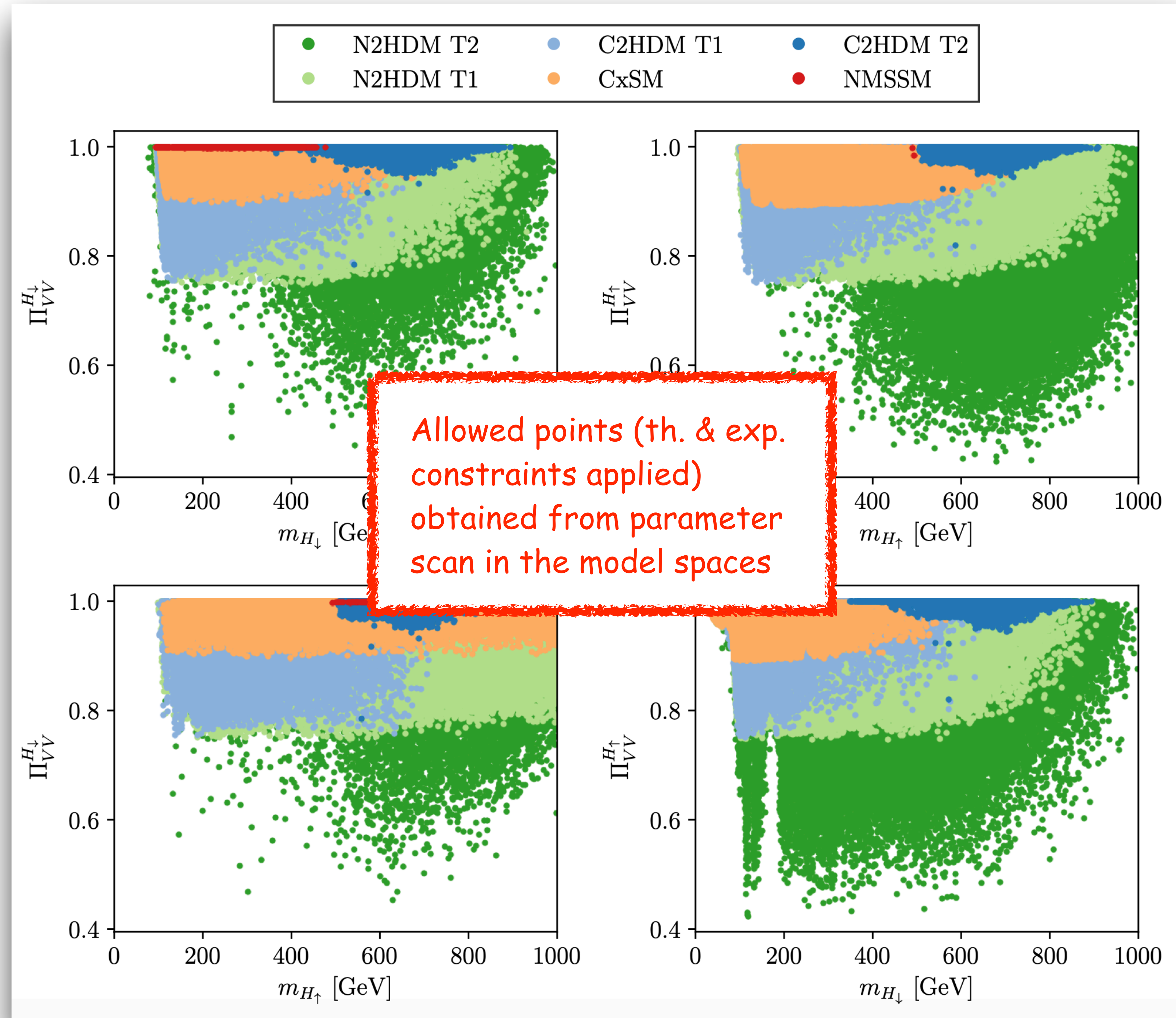

Allowed points (th. & exp. constraints applied) obtained from parameter scan in the model spaces

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Partial sum Π_{VV}:

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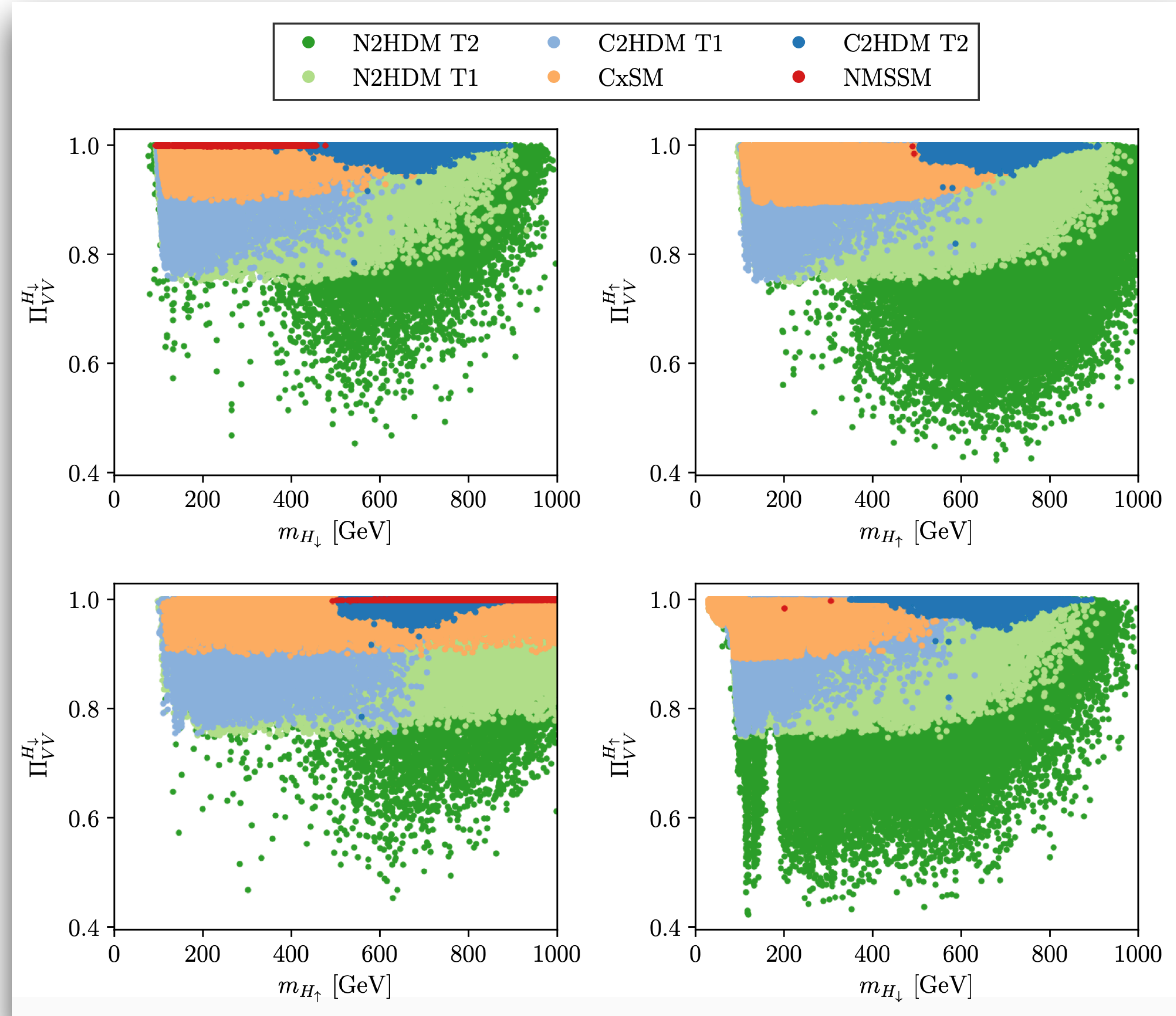
in case of only two out of three discovered Higgs bosons



Trilinear Higgs Self-Coupling

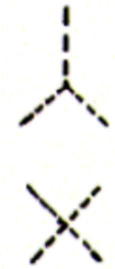
❖ SM Higgs potential: in physical gauge

$$V(H) = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

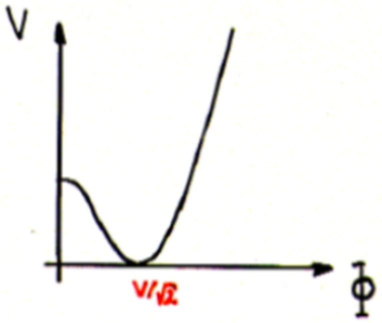
Higgs mass : $M_H = \sqrt{2\lambda}\, v$

trilinear Higgs self-coupling : $\lambda_{HHH} = 3 M_H^2 / M_Z^2$

quadrilinear Higgs self-coupling : $\lambda_{HHHH} = 3 M_H^2 / M_Z^4$



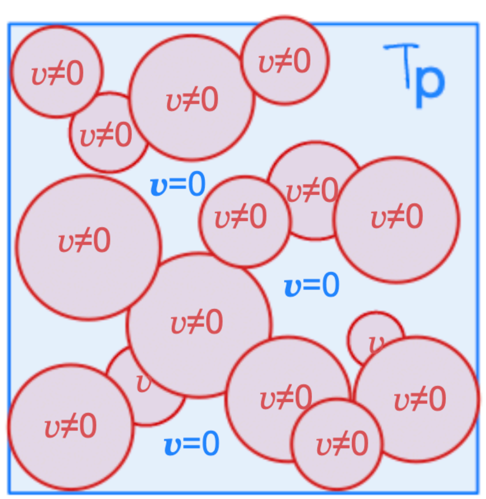
(units $\lambda_0 = 33.8\,\text{GeV}/\lambda_0^2$)



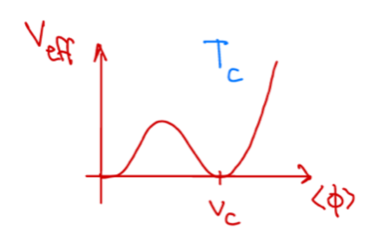
Measurement of the scalar boson self-couplings and Reconstruction of the EWSB potential	Experimental verification Of the scalar sector of the EWSB mechanism

❖ Importance of the trilinear Higgs self-coupling:

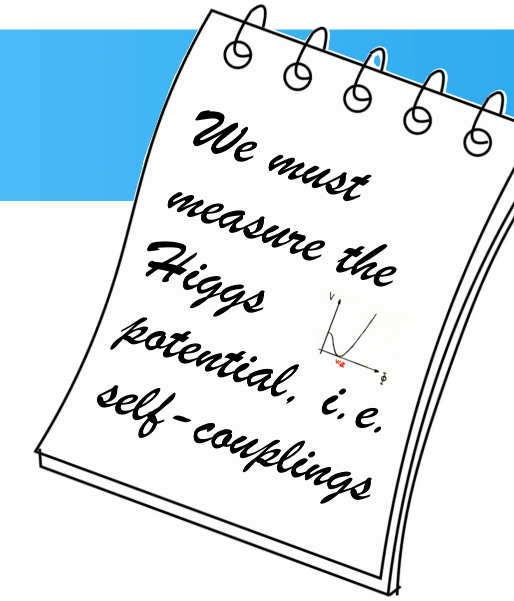
- Determines shape of the Higgs potential
- Sensitive to beyond-SM physics
- Important input for electroweak phase transition*



*matter-asymmetry through electroweak baryogenesis



Trilinear Higgs Self-Coupling



❖ SM Higgs potential: in physical gauge

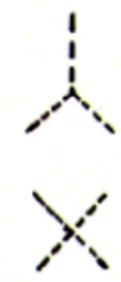
$V(H) = \frac{1}{2} \ldots H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$

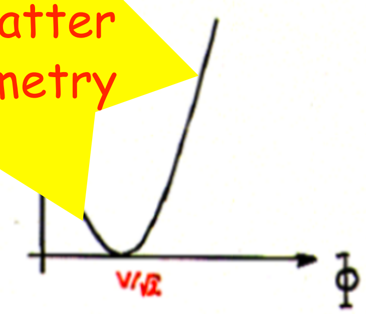
Higgs mass : $M_H = \sqrt{2\lambda}\, v$

tri... upling : $\lambda_{HHH} = 3M_H^2/M_Z^2$

q... coupling : $\lambda_{HHHH} = 3M_H^2/M_Z^4$

(unit... $= 33.8\,\mathrm{GeV}/\lambda_0^2$)





Ultimate test Higgs Mechanism

Matter-Antimatter Asymmetry

New Physics

Evolution of Cosmos

Measurem... ...alar boson self-couplings and Reconstruct... of ...e EWSB potential	Experimental verification Of the scalar sector of the EWSB mechanism

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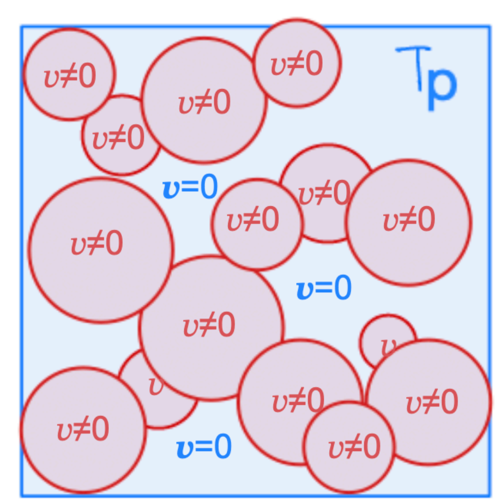

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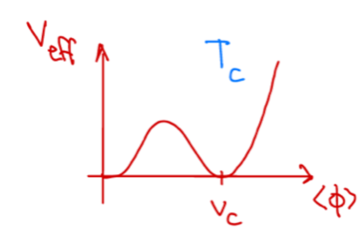
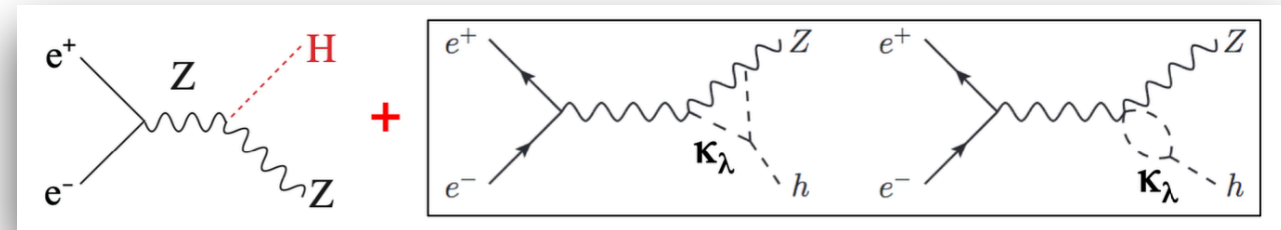
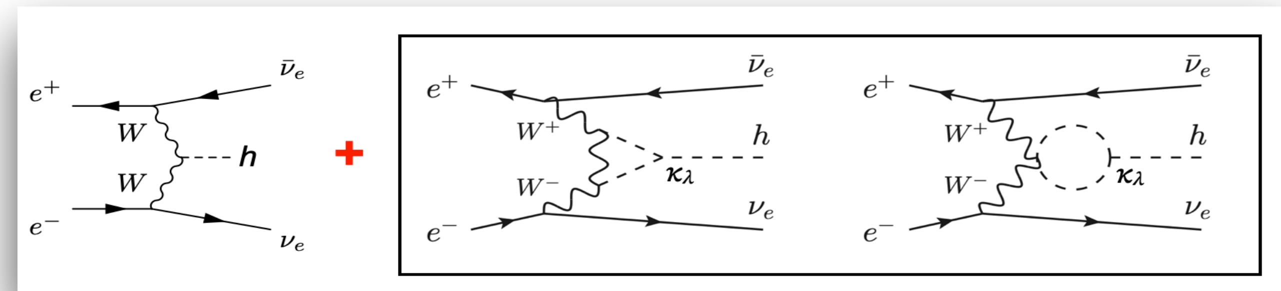


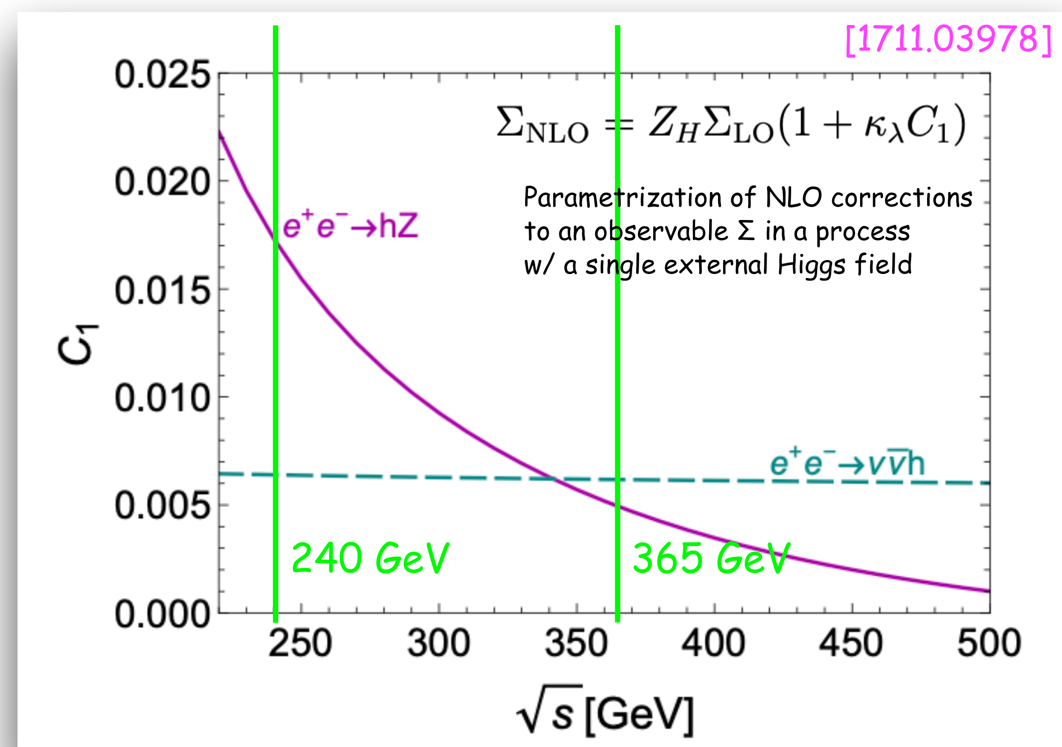
Single-Higgs Access To λ_{HHH}

Indirect Access below Higgs pair threshold



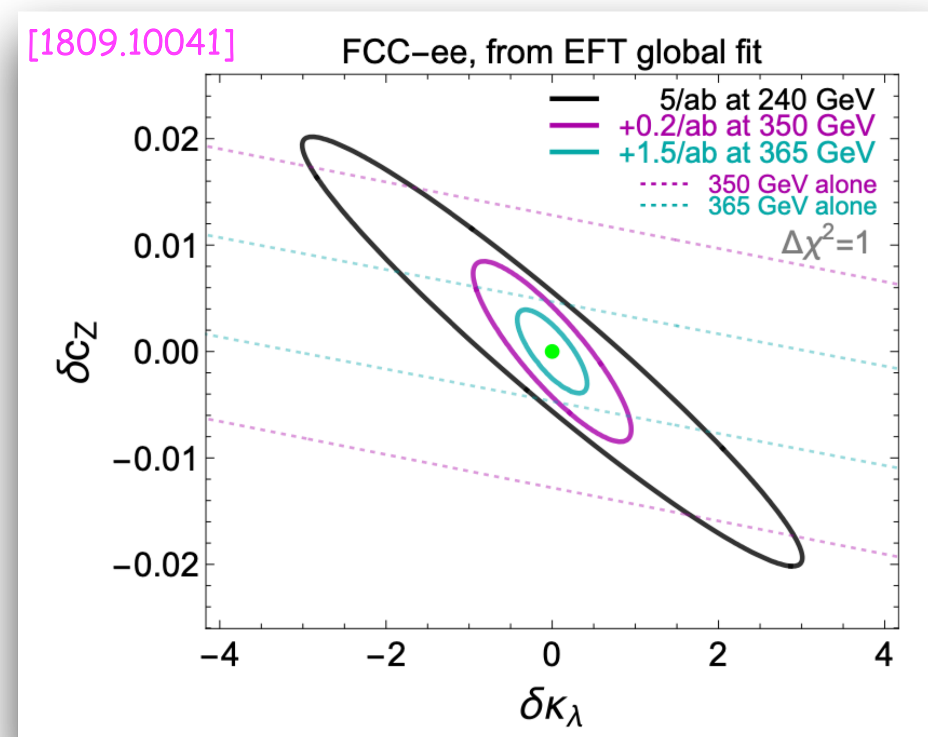


$\kappa_\lambda = \lambda_{HHH}/(\lambda_{HHH})^{SM}$



Single Higgs:

- Global analysis: FCC-ee365, ILC500: ~35% when combined w/ HL-LHC
- FCCee365 w/ 4PIs: ~24%
- Exclusive analysis: too sensitive to other new physics to draw conclusions



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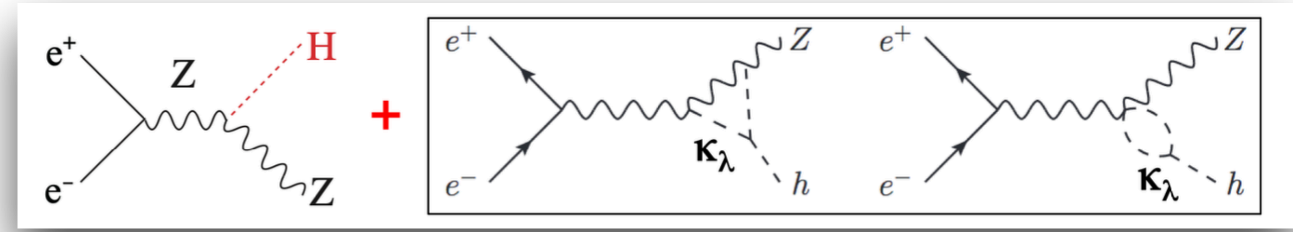
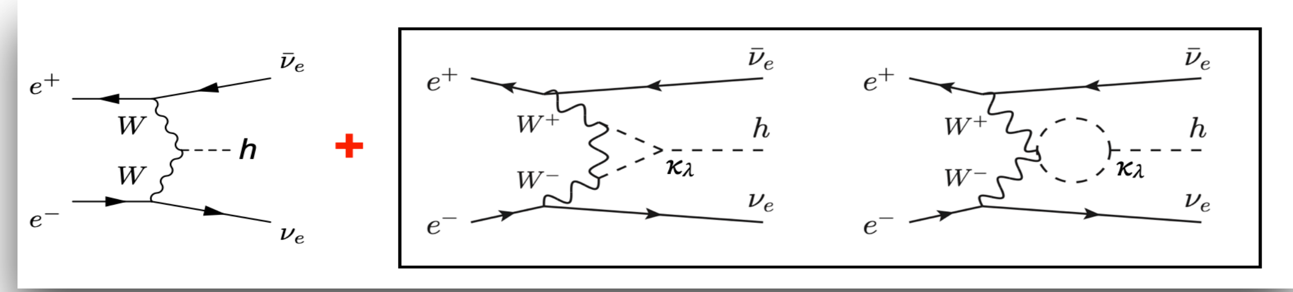
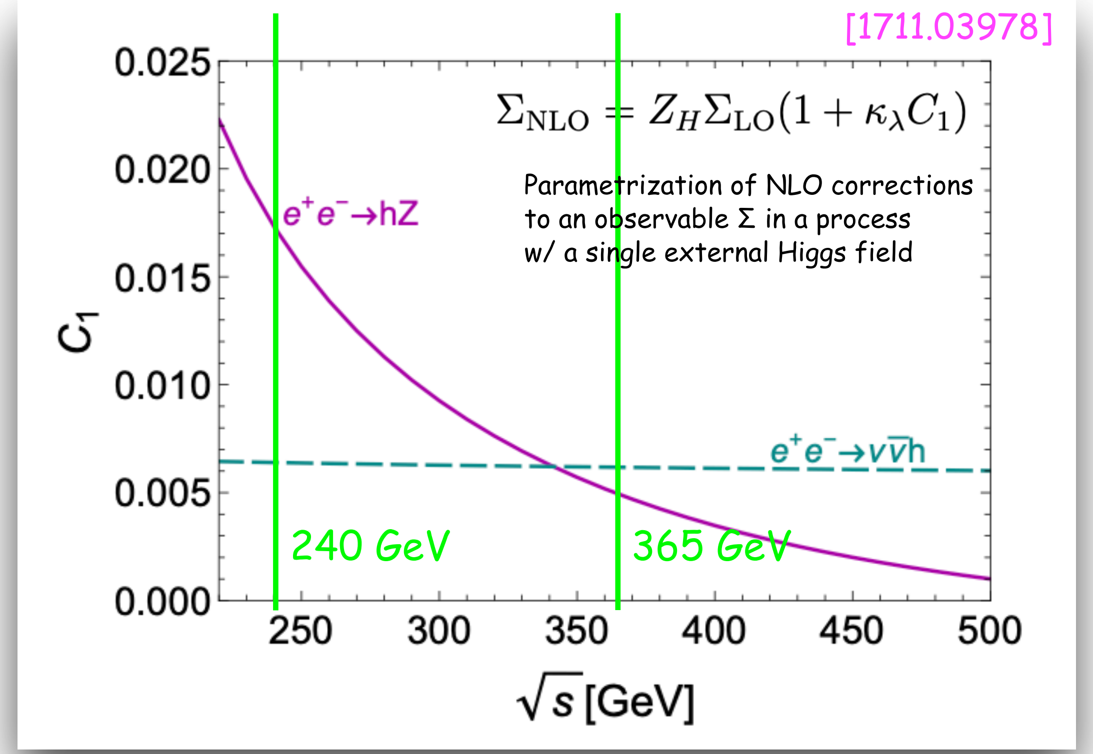




$\kappa_\lambda = \lambda_{HHH}/(\lambda_{HHH})^{SM}$



λ_{hhh} enters at one-loop in single Higgs process

Challenge! Competition with other effects

- competition w/ much larger LO contributions
- other numerically more dominant SM loops
- BSM: modified couplings, loop contributions
- contributions from (poorly constrained) eett operators affect interpretation [Asteriadis eal, 2406.03557]

Sensitivity limitations:

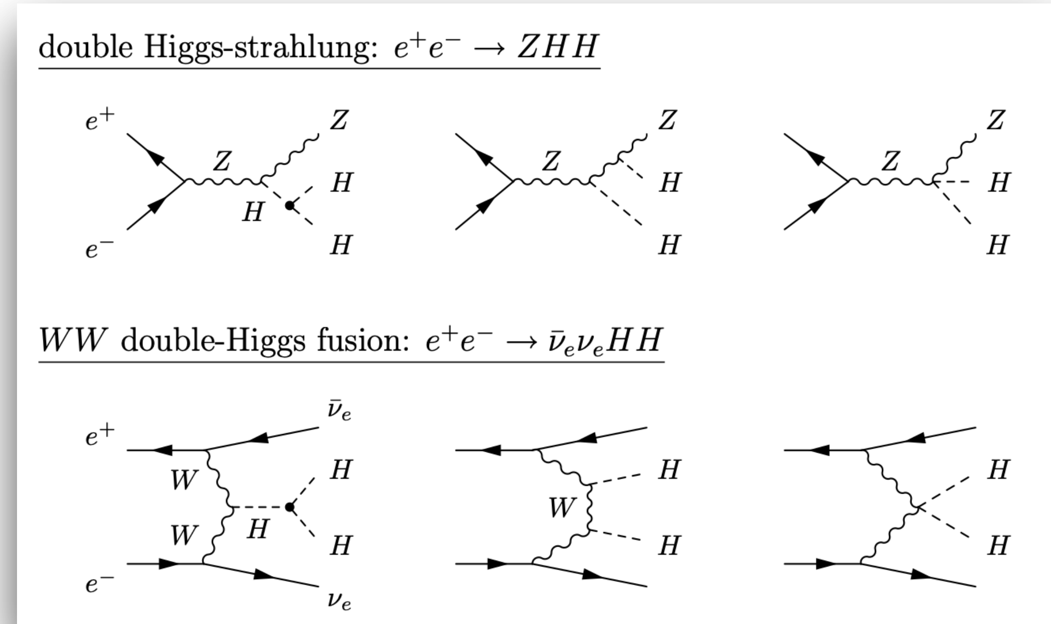
- exp. and theor. uncertainties

Interpretation:

- possibly observed deviation due to λ_{hhh} or other BSM/higher-order contributions?

Di-Higgs Access To λ_{HHH}

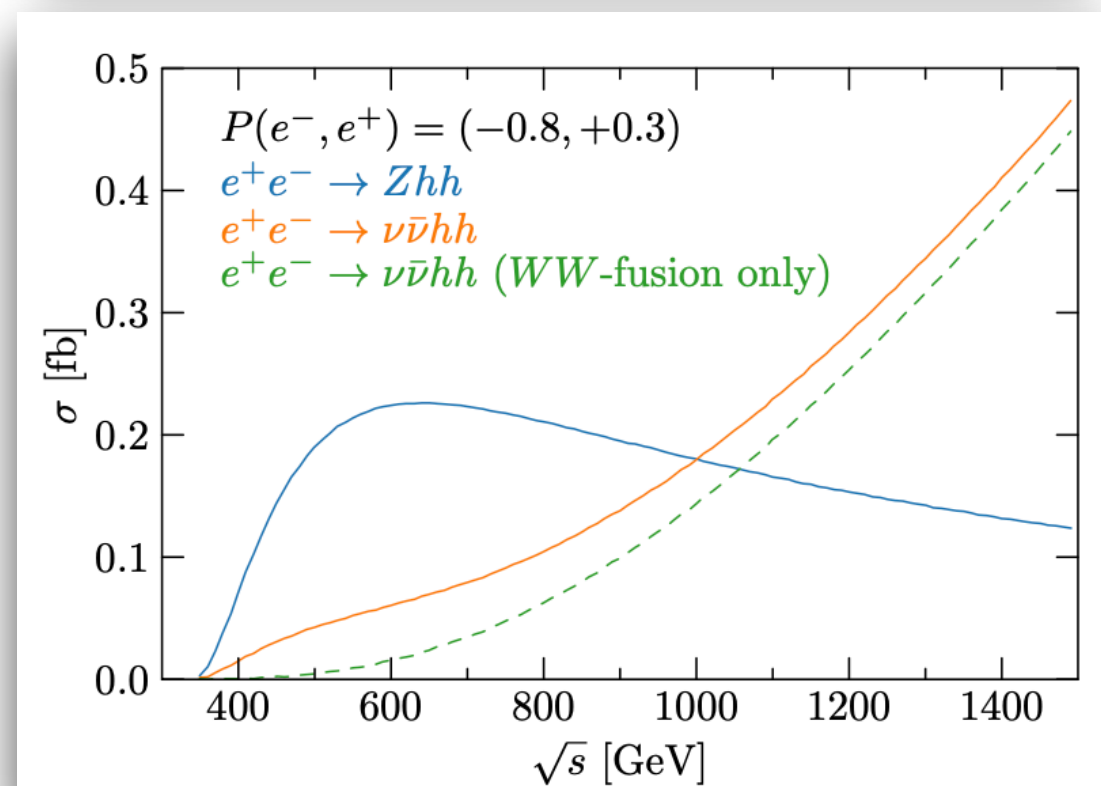
Direct Access above Higgs pair threshold

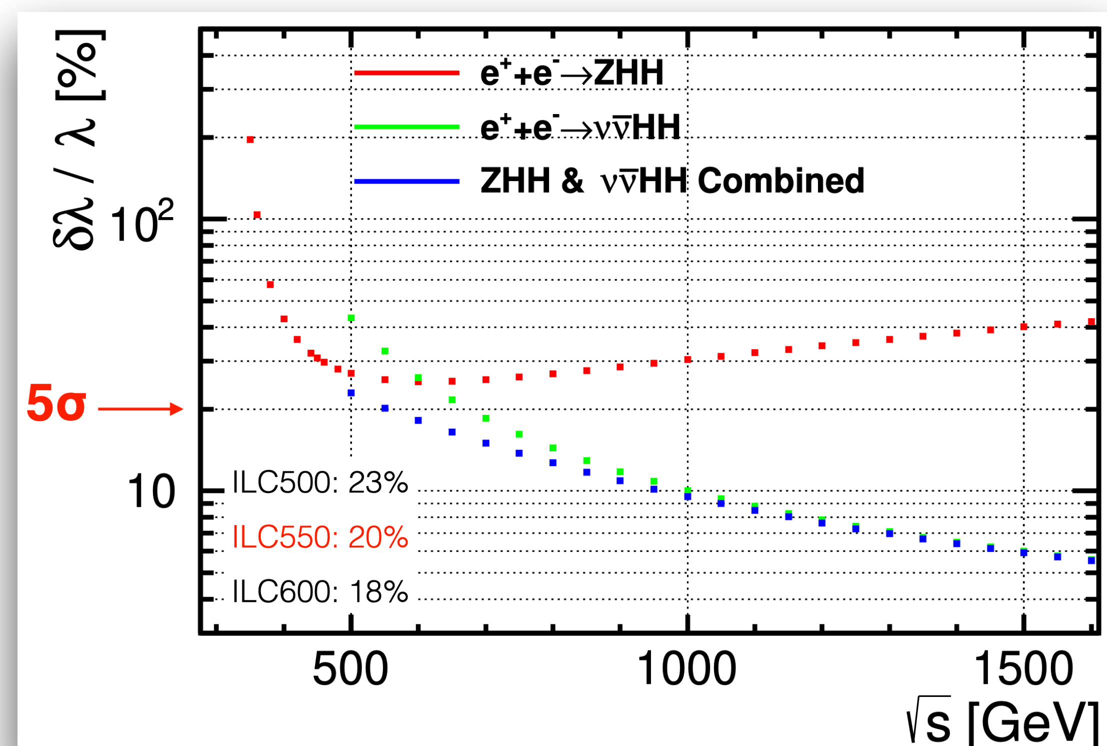


Di-Higgs:

- HL-LHC: ~50% or better?
- improved by HE-LHC (~15%), ILC_{500} (~27%), $CLIC_{1500}$ (~36%)
- Precision by $CLIC_{3000}$ (~ 9%), FCC-hh (~5%)
- Robust w.r.t. other operators

[Taken from J.Tian, LCWS2024]



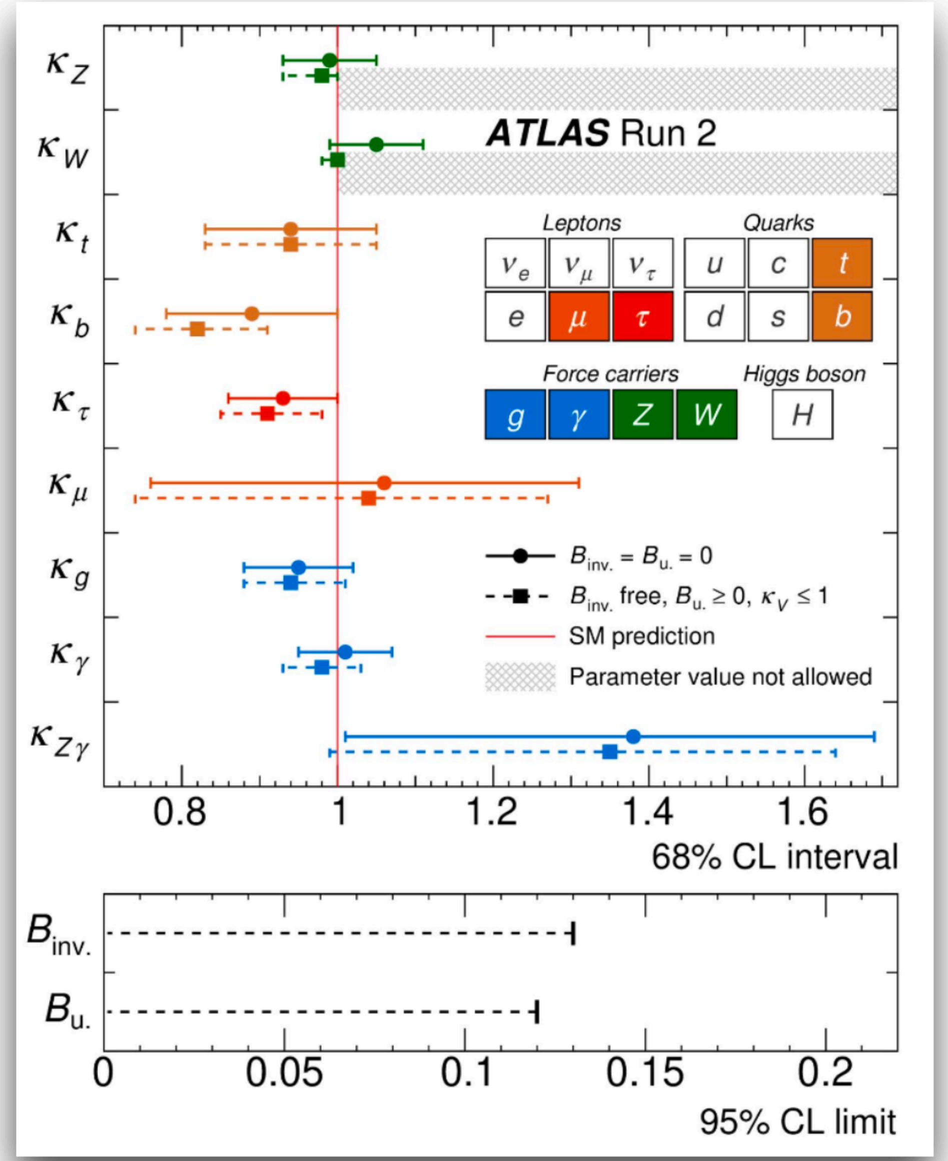


BSM Effects in the Higgs Self-Coupling

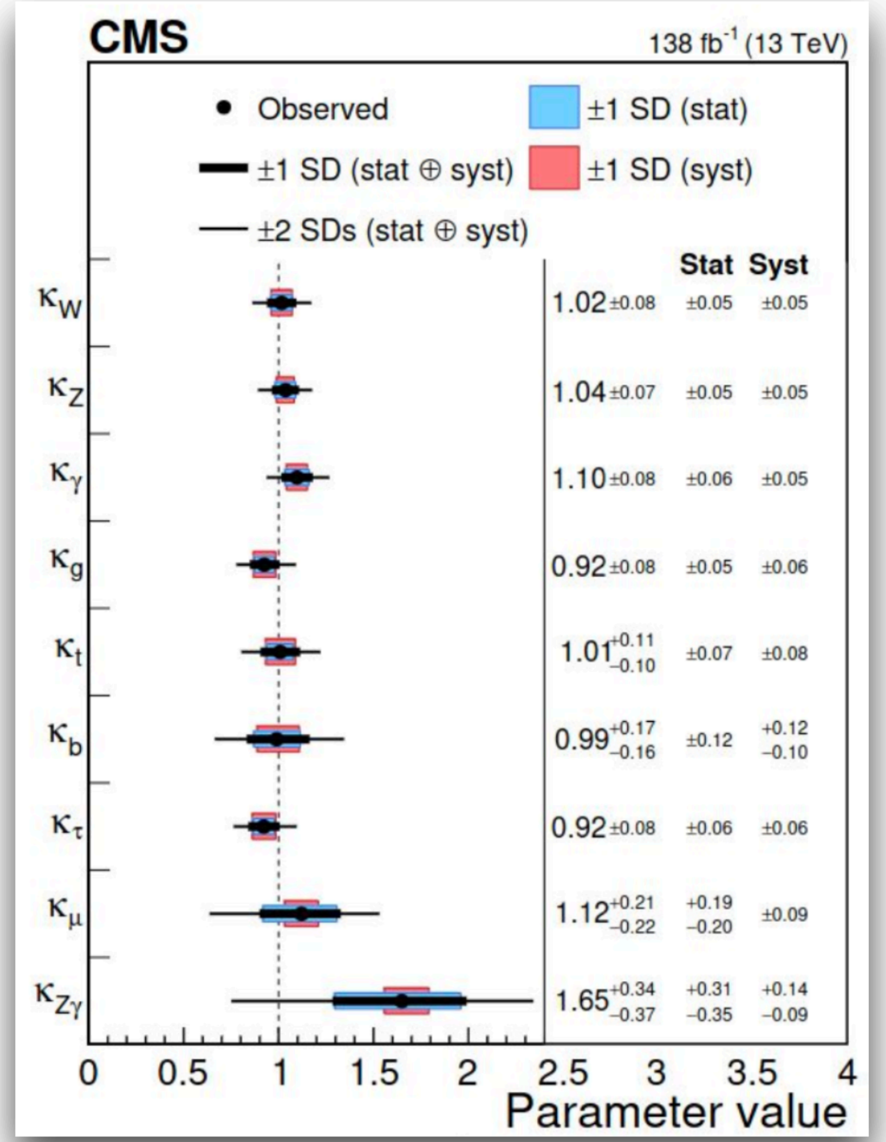
✏ Extended Higgs sectors: mixing effects w/ other Higgs bosons ⇝ coupling deviations
BSM particles: loop contributions

$g_{H\,SM\,SM}$ very SM-like

[ATLAS,Nature607(2022)52]



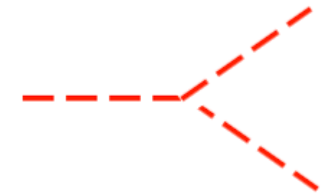
[CMS,Nature607(2022)60]



BSM Effects in the Higgs Self-Coupling

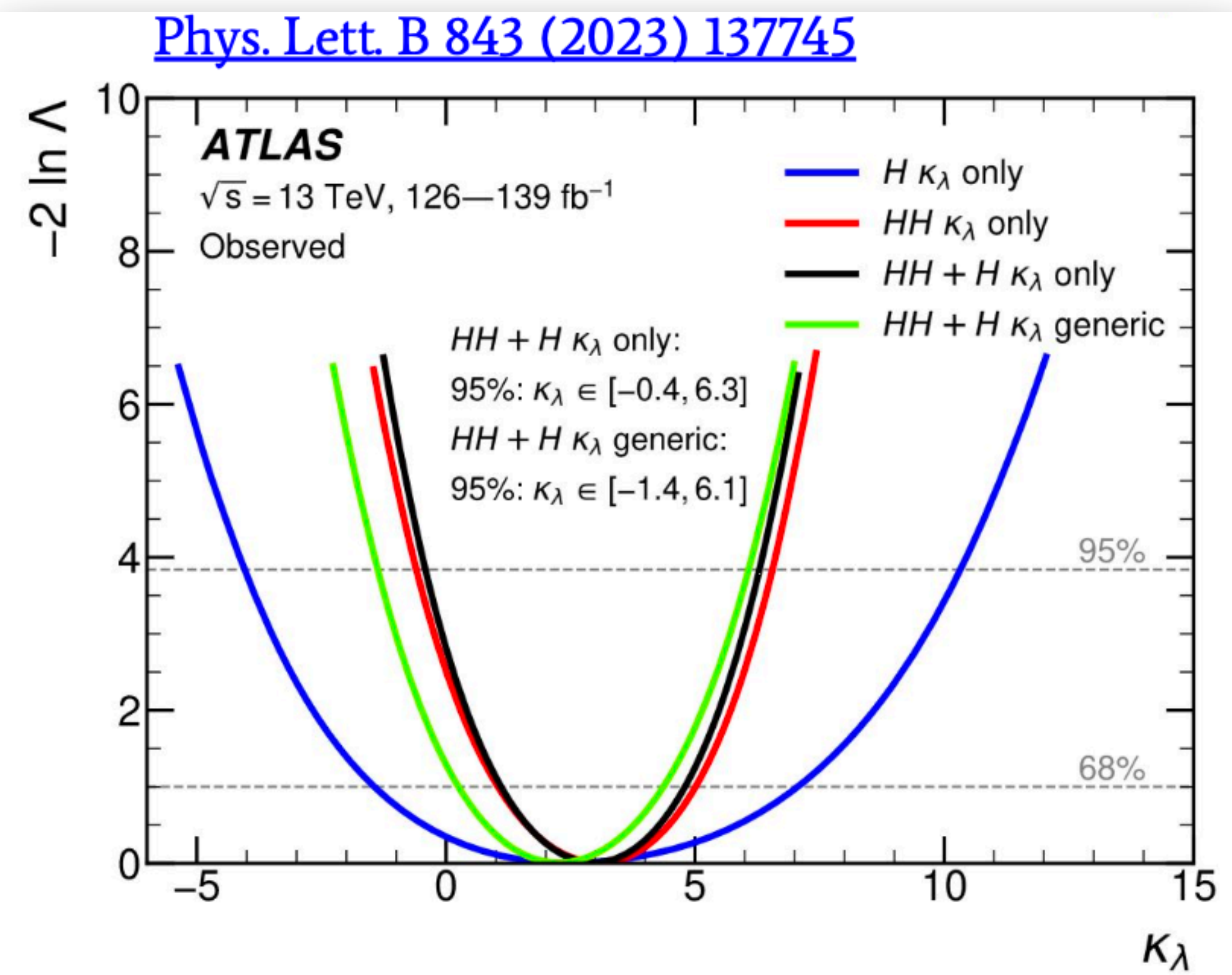
✏ Extended Higgs sectors: mixing effects w/ other Higgs bosons
BSM particles: loop contributions
⇝ coupling deviations

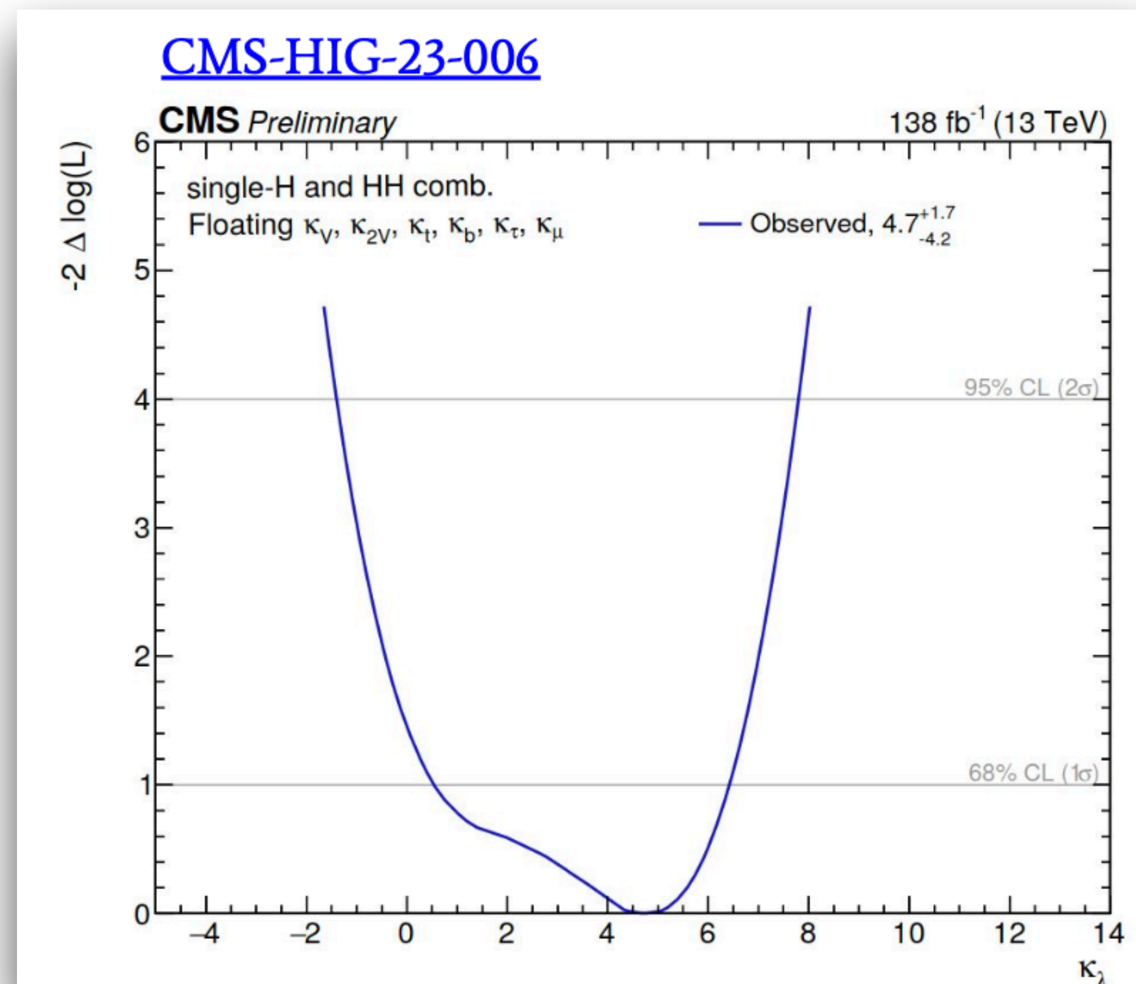
λ_{HHH} can still deviate from SM



ATLAS: $-1.4 < \kappa_\lambda < 6.1$ at 95 % CL

CMS: $-1.2 < \kappa_\lambda < 7.5$ at 95 % CL





BSM Effects in the Higgs Self-Coupling

[Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]

Scan in parameter space of the models check for compatibility w/ relevant theor. and exp. constraints

Special New Physics Offer

	R2HDM		C2HDM	
	$^{R2HDM}_{t,H_{SM}}/y_{t,H}$	$\lambda^{R2HDM}_{3H_{SM}}/\lambda_{3H}$	$y^{C2HDM}_{t,H_{SM}}/y_{t,H}$	$\lambda^{C2HDM}_{3H_{SM}}/\lambda_{3H}$
	.893...1.069	-0.096...1.076	0.898...1.035	-0.035...1.227
	n.a.	n.a.	0.889...1.028	0.251...1.172
heavy I	0.946...1.054	0.481...1.026	0.893...1.019	0.671...1.229
light II	0.951...1.040	0.692...0.999	0.956...1.040	0.096...0.999
medium II	n.a.	n.a.	–	–
heavy II	–	–	–	–

	N2HDM		NMSSM	
	$y^{N2HDM}_{t,H_{SM}}/y_{t,H}$	$\lambda^{N2HDM}_{3H_{SM}}/\lambda_{3H}$	$y^{NMSSM}_{t,H_{SM}}/y_{t,H}$	$\lambda^{NMSSM}_{3H_{SM}}/\lambda_{3H}$
light I	0.895...1.079	-1.160...1.004	n.a.	n.a.
medium I	0.874...1.049	-1.247...1.168	n.a.	n.a.
heavy I	0.893...1.030	0.770...1.112	n.a.	n.a.
light II	0.942...1.038	-0.608...0.999	0.826...1.003	0.024...0.747
medium II	0.942...1.029	0.613...0.994	0.916...1.000	-0.502...0.666
heavy II	–	–	–	–

BSM Effects in the Higgs Self-Coupling

[Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]

	R2HDM		C2HDM	
	$y^{\text{R2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{R2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$	$y^{\text{C2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{C2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$
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heavy II	–	–	–	–

	N2HDM		NMSSM	
	$y^{\text{N2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{N2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$	$y^{\text{NMSSM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{NMSSM}}_{3H_{\text{SM}}}/\lambda_{3H}$
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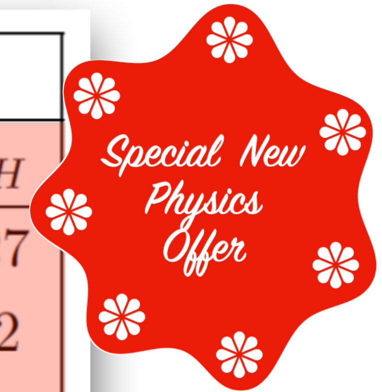
heavy II	–	–	–	–



Effect of Higher-Order Corrections

✏ Higher-order corrections: potentially large in BSM Higgs sectors

e.g. 2HDM: [Kanemura,Kiyoura,Okada,Senaha,Yuan,'02;Braathen,Kanemura,'19,'20]
[Bahl,Braathen,Weiglein,'22]

✏ Example 2HDM: Parameter scan (taking into account theor. & single Higgs constraints)

[Arco,Heinemeyer,MM,in prep.]

Type	LO $\kappa_\lambda^{(0)}$	NLO $\kappa_\lambda^{(1)}$
I	[-0.19, 1.17]	[0.24, 6.79]
II	[0.63, 1.00]	[0.74, 5.66]
LS	[0.48, 1.00]	[0.63, 6.29]
FL	[0.65, 1.00]	[0.76, 5.77]

LHC experiments start being sensitive

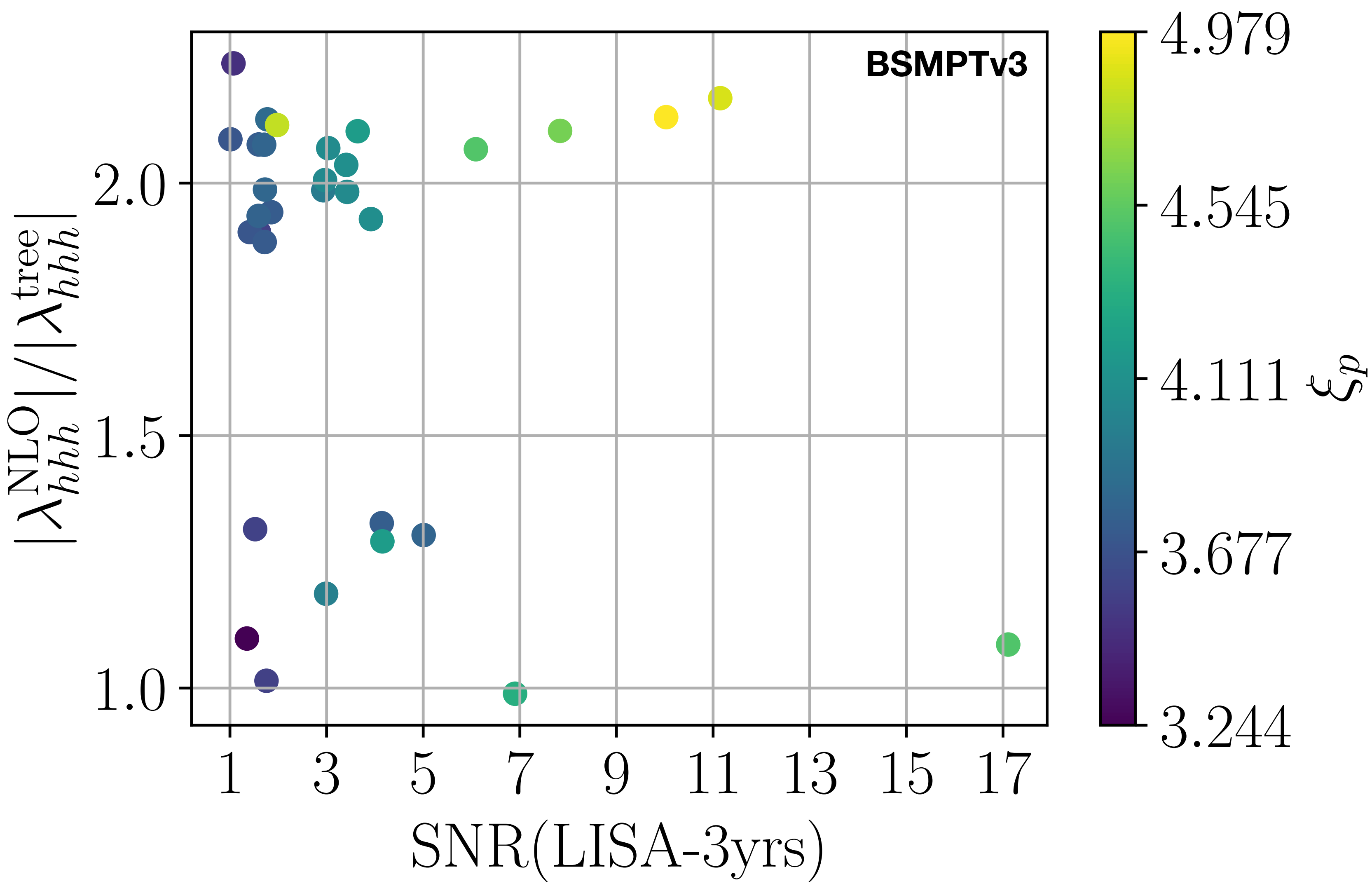
⇝ higher-order corrections important for proper interpretation of limits!

✏ First-order Phase Transition (electroweak baryogenesis): prefers larger λ_{HHH}

Higgs Self-Coupling & Evolution of the Universe

✏ Model CP in the Dark: SM-Higgs ($\lambda_{hhh}^{tree} = \lambda_{hhh}^{SM}$) + Dark Sector
GW signal from strong first-order phase transition

[Basler,Biermann,MM,Müller,Santos,Viana,'24]



[Biermann,Borschensky,Erhardt,MM,Santos,Viana]

✏ Vector DM Model: two visible Higgs bosons + Dark photon
Strong first-order phase transition: $\delta\lambda_{hhh}^{NLO}/\lambda_{hhh}^{LO} = 8\,\%$

Higgs Self-Coupling & Evolution of the Universe

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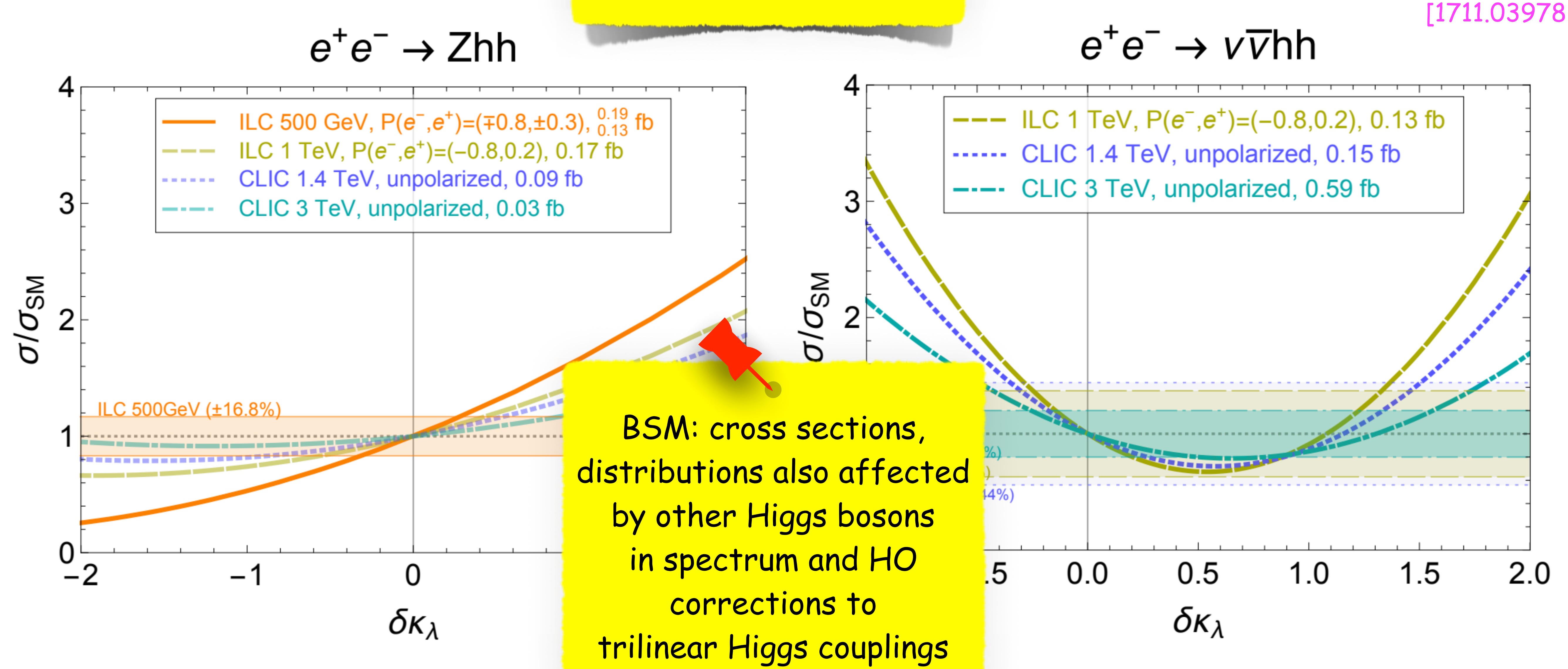
GW signal from strong first-ord...

[Basler,Biermann,MM,Müller,Santos,Viana,'24]

Changes Linear Collider Sensitivities

[1711.03978]



BSM: cross sections, distributions also affected by other Higgs bosons in spectrum and HO corrections to trilinear Higgs couplings

[cf. talk by Arco @LCWS2024]

✏ Vector DM Model: two visible H...
Strong first-order phase transition: $\delta\lambda^{NLO}_{hhh}/\lambda^{LO}_{hhh} = 8\%$

Precision Measurements at Z/WW/tt

Why do we need EWPOs?

- Relations between SM parameters affected by loop corrections =>

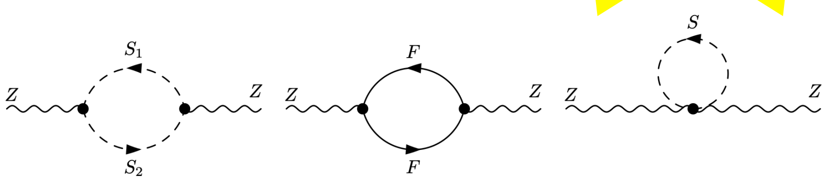
$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2 s_W^2}(1+\Delta r)$$

Consistency test of SM at quantum level

- New particles in the loops =>

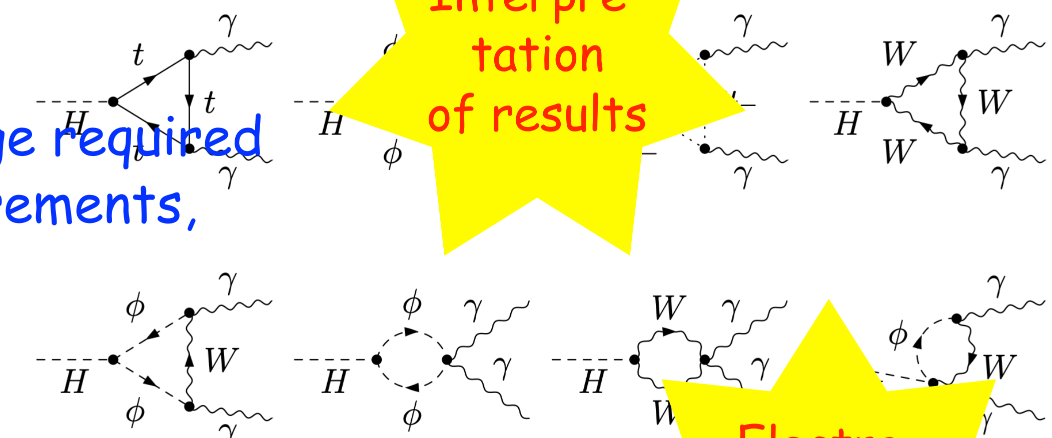
New Physics

$$M_W^2 = \frac{M_Z^2}{2}\left\{1+\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_\mu M_Z^2}\left(1+\Delta^{(n)}_{\text{NMSSMCALC}}r\right)}\right\}$$



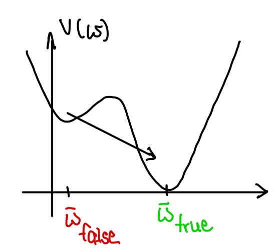
- SM parameters enter observables => precise knowledge required
  for meaningful interpretation of the precision measurements,
  for meaningful predictions of further observables

Interpretation of results

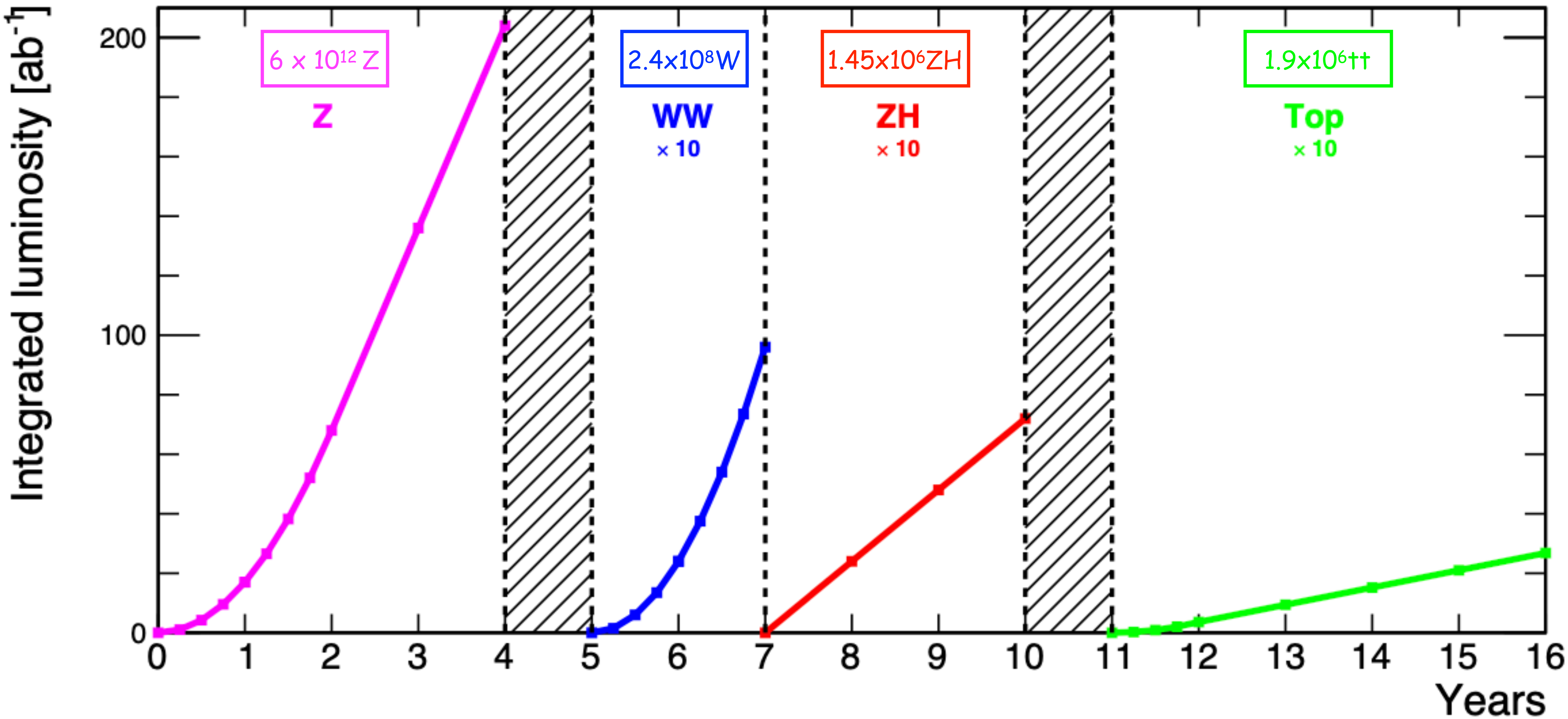


- Parameter values of direct relevance for stability of electroweak vacuum,
  evolution of the universe, matter-antimatter-asymmetry

Electroweak Vacuum



Precision at Electroweak & Top Factories



Precision at Z, WW, tt

[2209.08078]

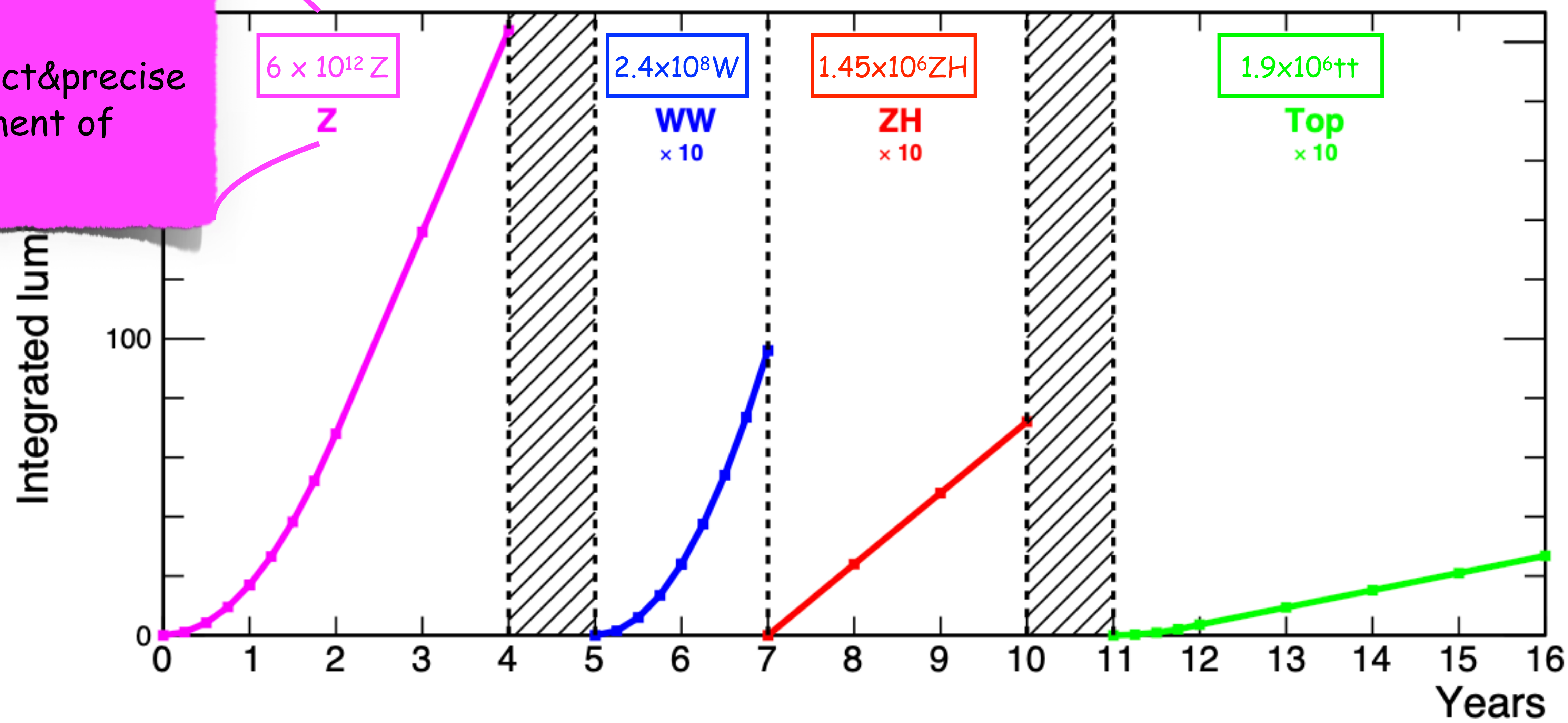
Collider	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
ILC	250 GeV 350 GeV 500 GeV 1 TeV	$\pm 80/\pm 30$ $\pm 80/\pm 30$ $\pm 80/\pm 30$ $\pm 80/\pm 20$	2 0.2 4 8
ILC-GigaZ	m_Z	$\pm 80/\pm 30$	0.1
CLIC	380 GeV 500 GeV 1 TeV	$\pm 80/0$ $\pm 80/0$ $\pm 80/0$	1 2.5 5
CEPC	m_Z $2m_W$ 240 GeV $2m_t$		60 / 100 3.6 / 6 12 / 20 – / 1
FCC-ee	m_Z $2m_W$ 240 GeV $2m_t$		150 10 5 1.5

Electron-positron run scenarios used for the Snowmass 2021 study

Precision at Z, WW, tt

m_Z, Γ_Z, $\alpha_S(m_Z)$, ...
improvement by factor 20-50 w.r.t. today

first direct&precise measurement of $\alpha_{QED}(m_Z)$



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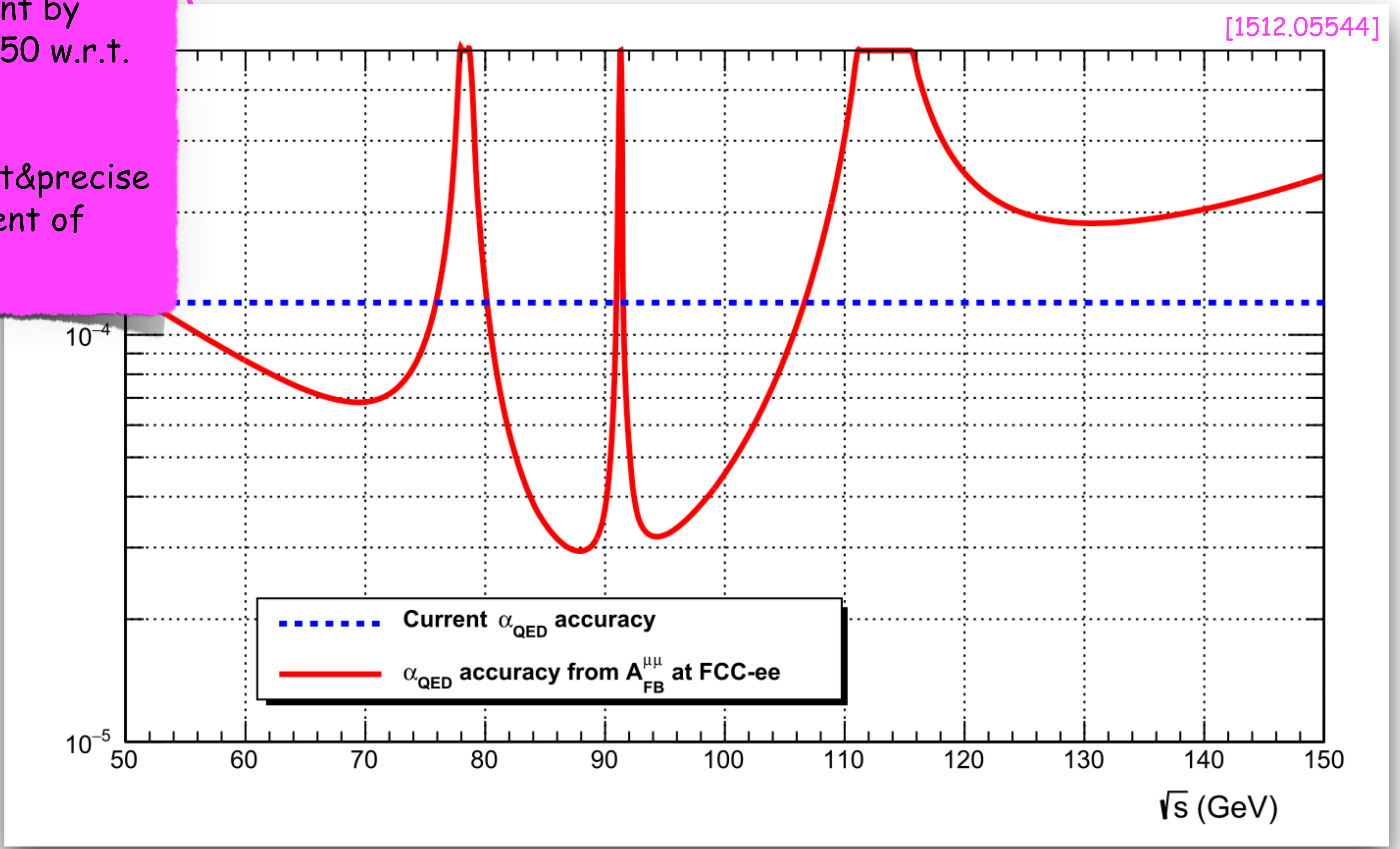
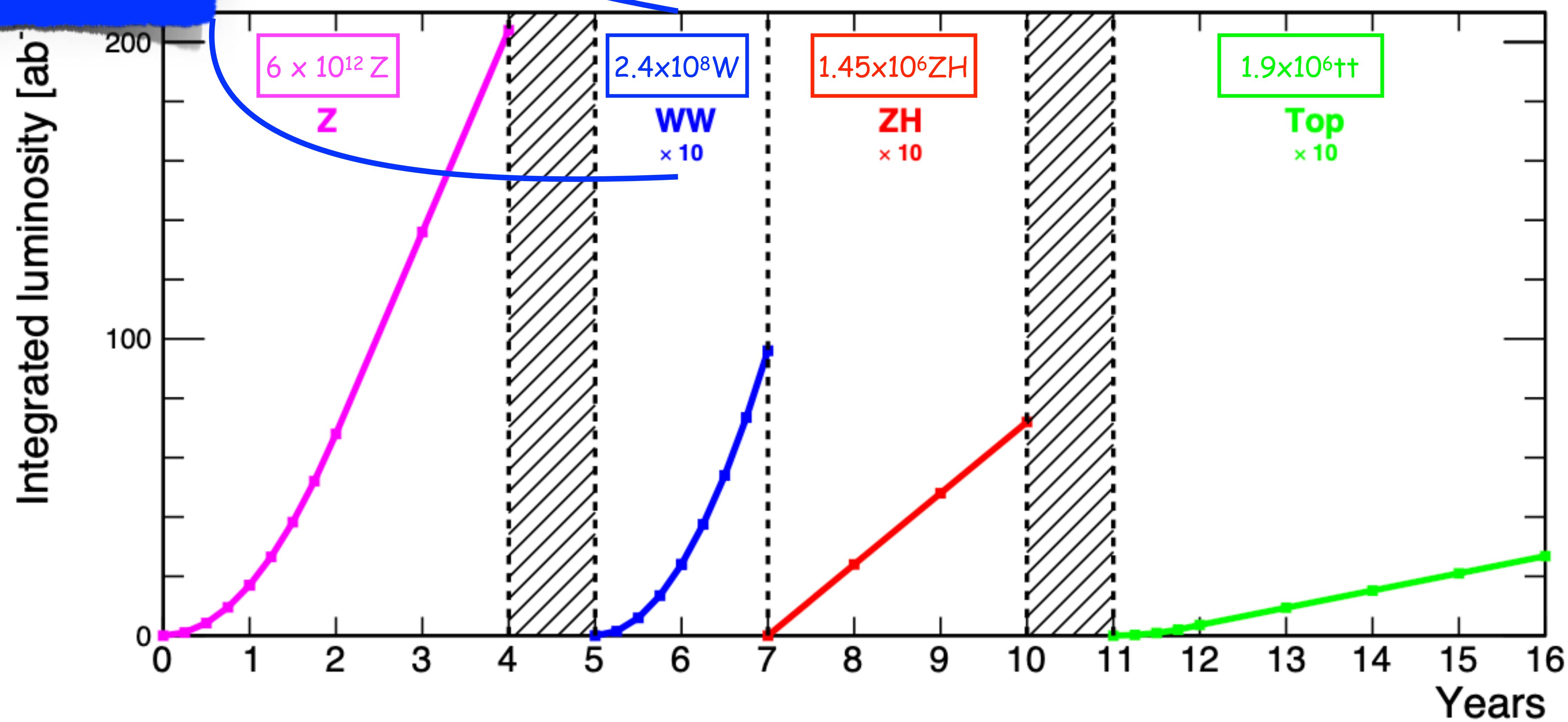


Precision at Z, WW, tt

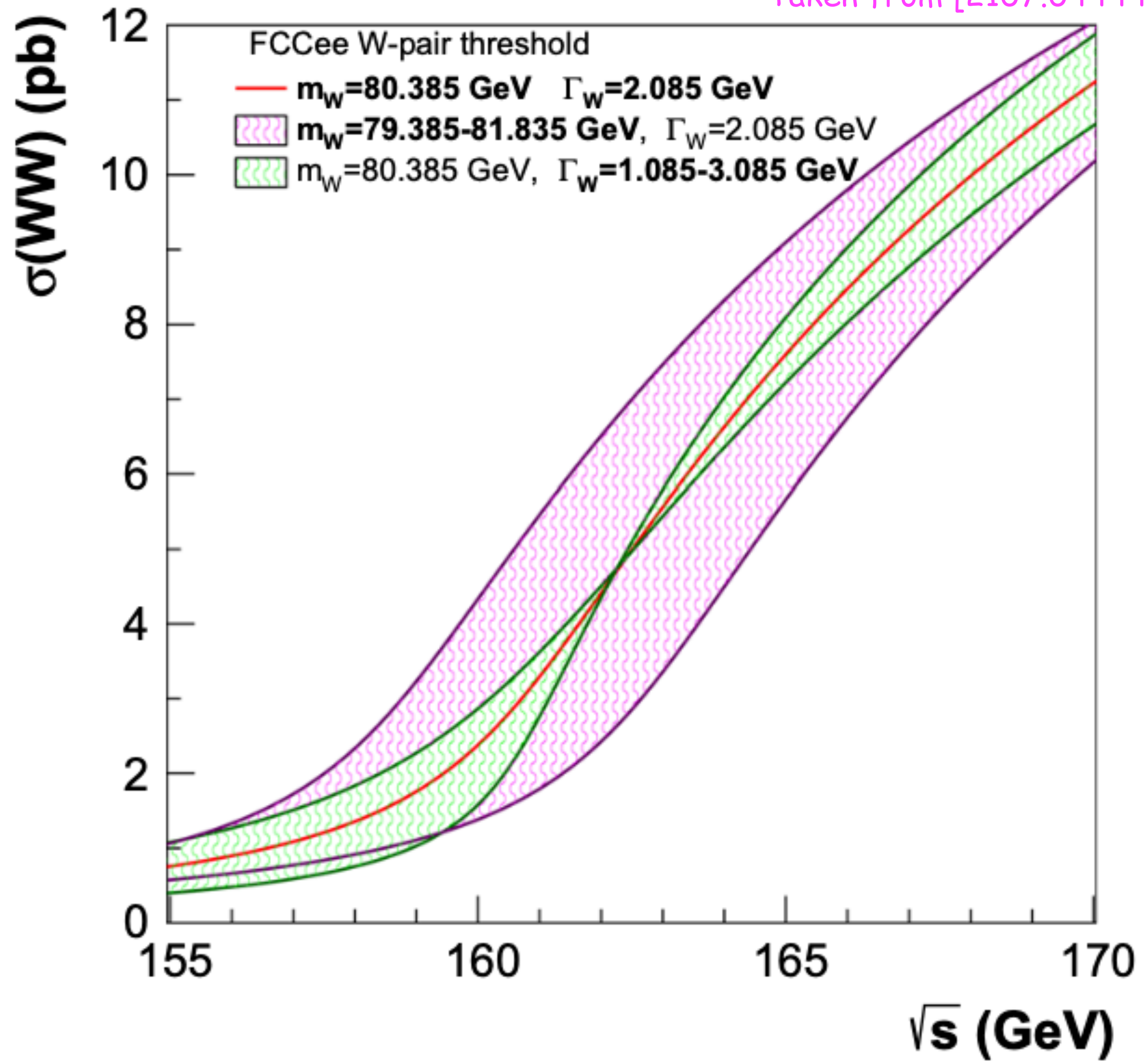
m_W, Γ_W, $\alpha_S(m_W)$, ...
improvement by factor 20-100 w.r.t. today



Precision at Z, WW, tt

m_W, Γ_W, $\alpha_S(m_W)$, ...
improvement by factor 20-100 w.r.t. today

Taken from [2107.04444]

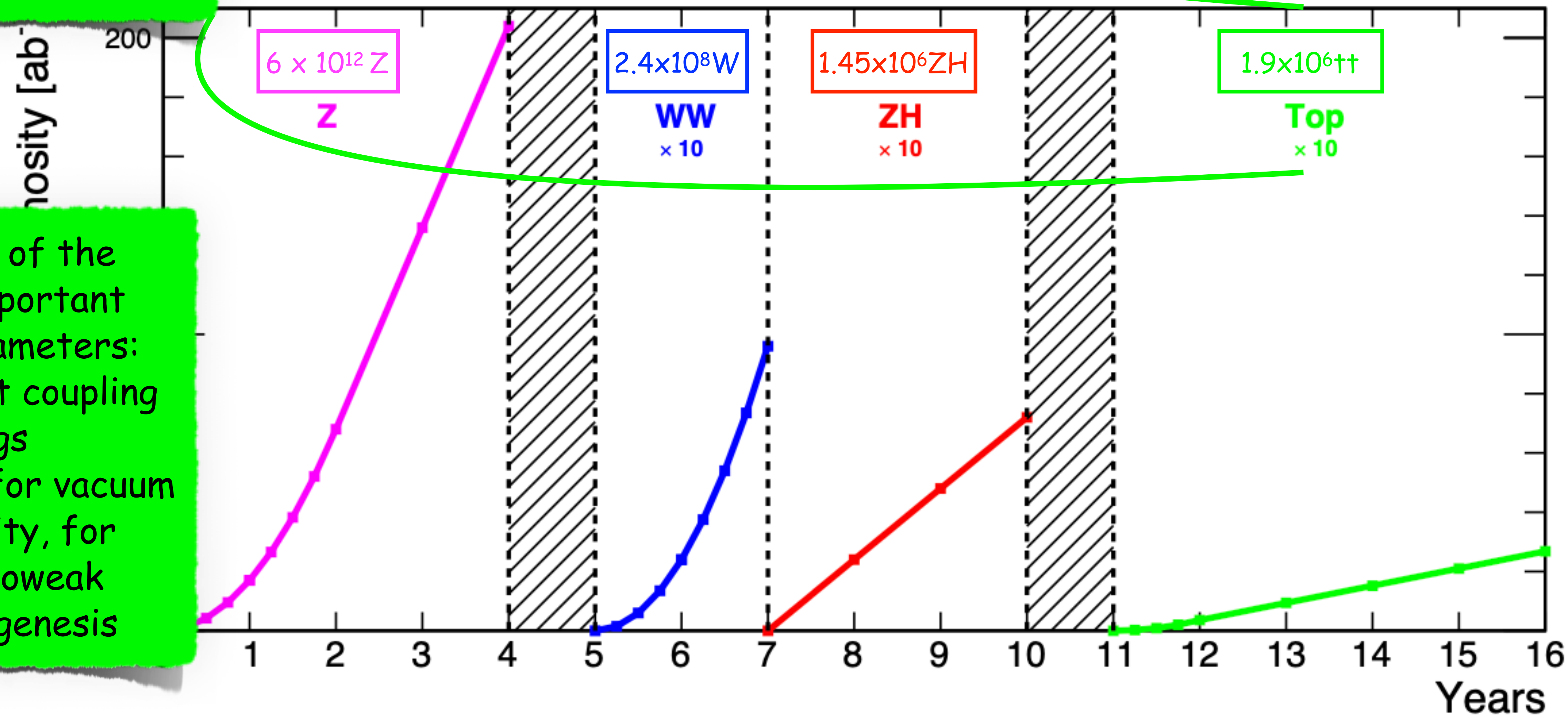


Precision at Z, WW, tt

$\delta m_t \approx$ 50 MeV

$\delta \Gamma_t =$ 45 MeV

theory uncertainty limiting factor



Top one of the most important SM parameters:
- largest coupling to Higgs
- input for vacuum stability, for electroweak baryogenesis

Precision at Z, WW, tt

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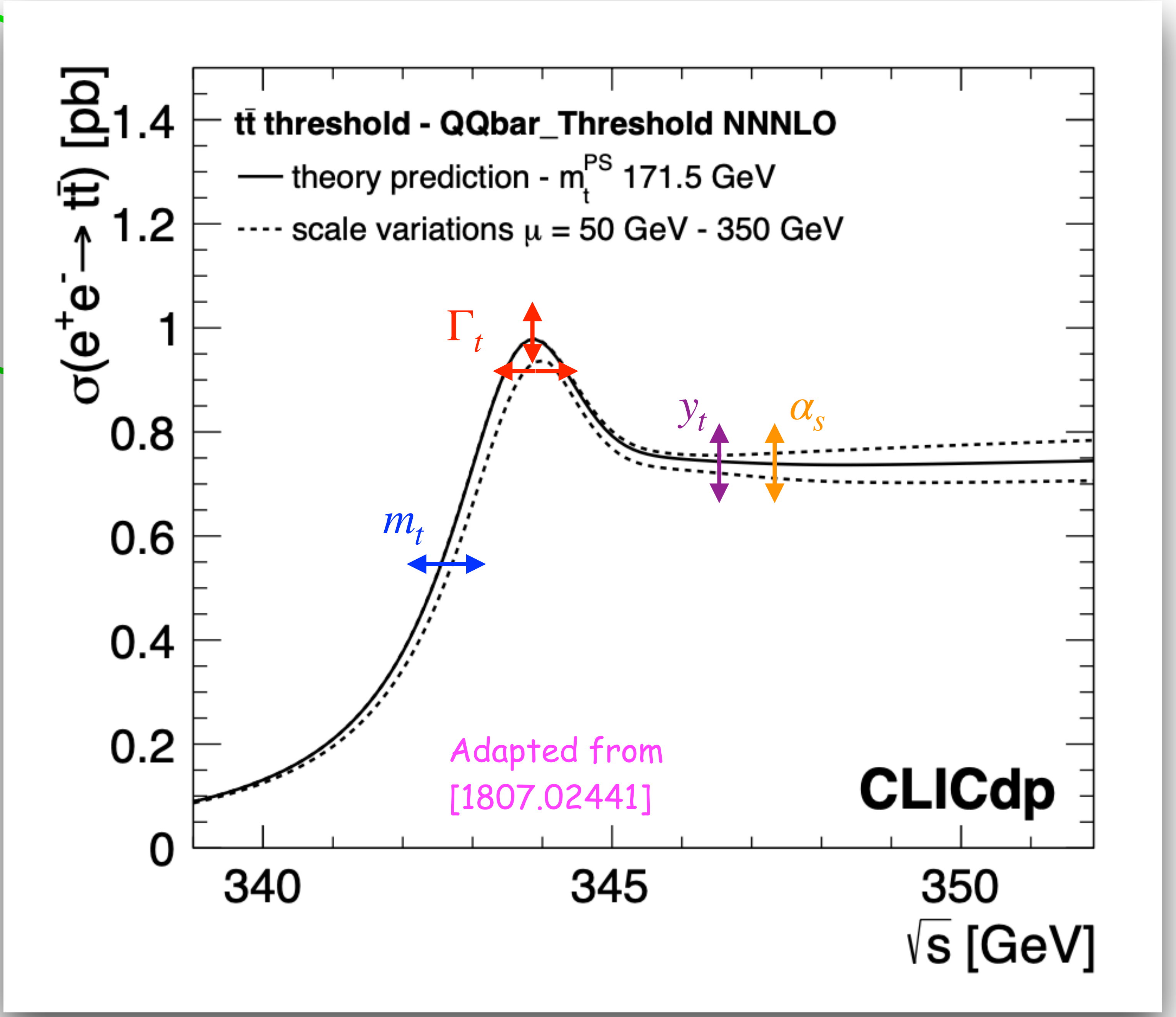

Precision at Z, WW, tt

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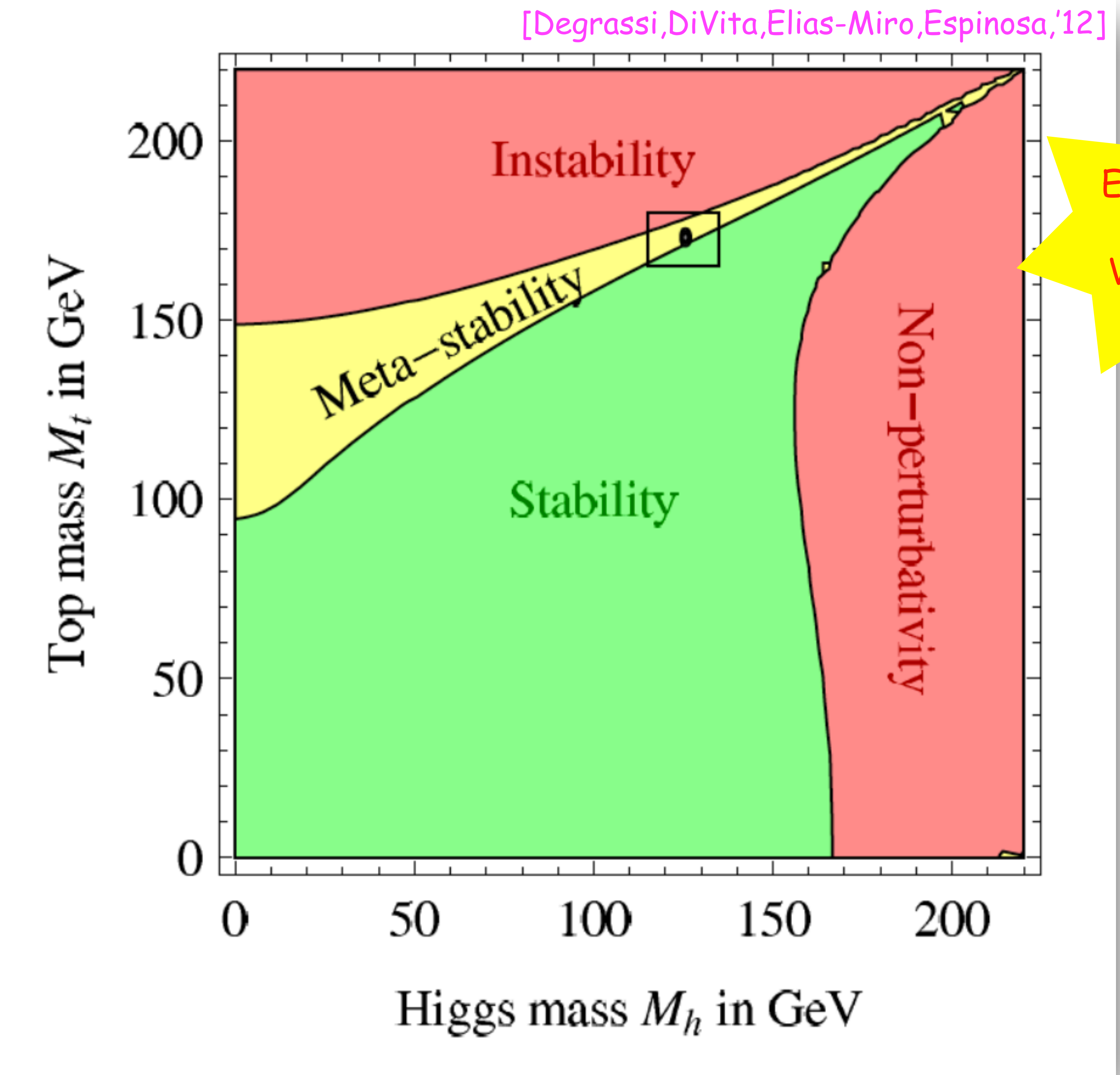


Electro-weak Vacuum

EWPOs at Future e+e- Colliders

[2209.08078]

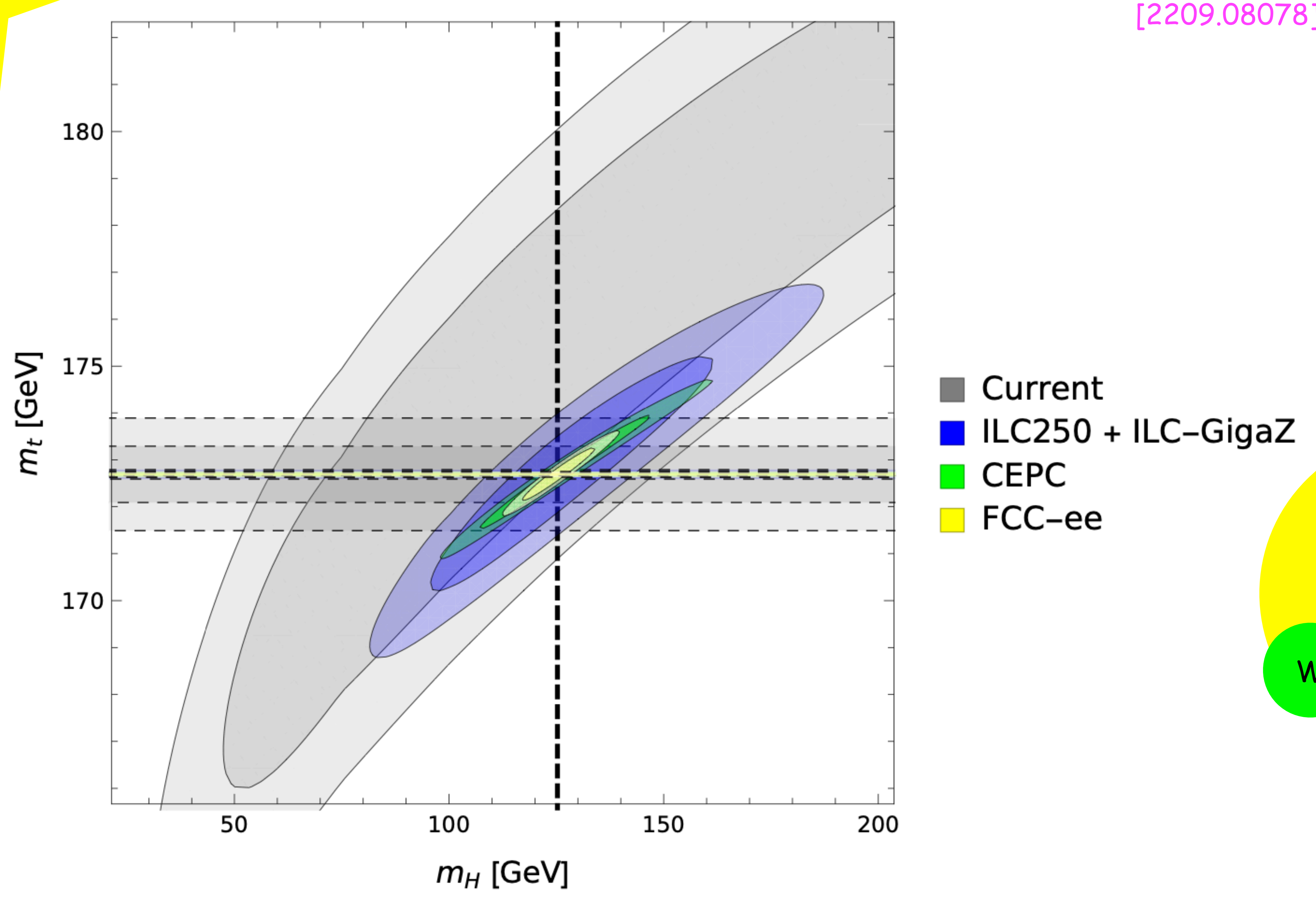
Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	60 (15)
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	390 (14)
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	550 (14)
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	360 (92)
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)	6 (30)	190 (67)
$\Delta\sigma^0_{\rm had}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e ($\times 10^3$)	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.5 (1.0)
δR_μ ($\times 10^3$)	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.5 (1.0)
δR_τ ($\times 10^3$)	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	3.3 (5.0)
δR_b ($\times 10^3$)	3.1*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.5 (1.0)
δR_c($\times 10^3$)	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	2.4 (5.0)

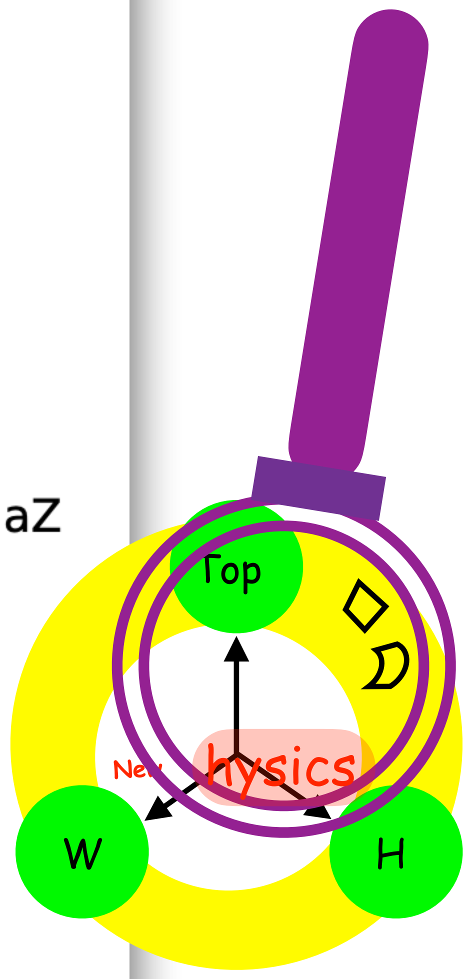
Table 3: EWPOs at future e^+e^- colliders: statistical error (estimated experimental systematic error). Δ (δ) stands for absolute (relative) uncertainty, while * indicates inputs taken from current data [6]. See Refs. [23, 30, 35, 36, 46, 47].

SM Fit to all EWPOs

Consistency test of SM at quantum level

[2209.08078]





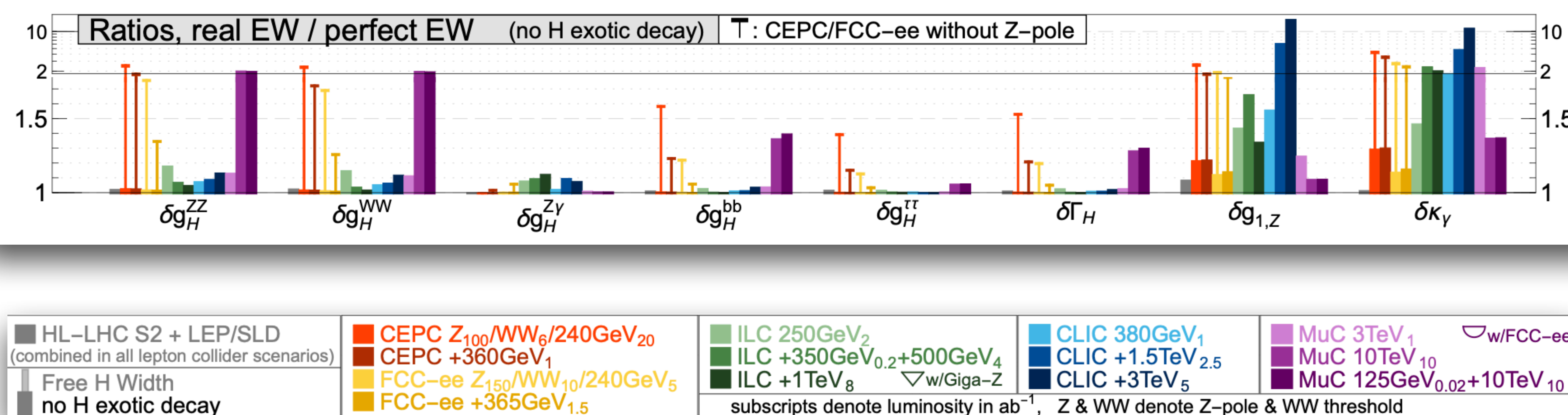
Interplay EW Measurements and Higgs Precision

- Z pole run essential to isolate Higgs measurements and ensure that uncertainties from EW coupling do not affect Higgs couplings

Test of New physics Interpretation of results

- Precision measurements at the Z pole and WW threshold affect significantly achievable precision for Higgs couplings and aTGCs: improvement by about a factor of 2

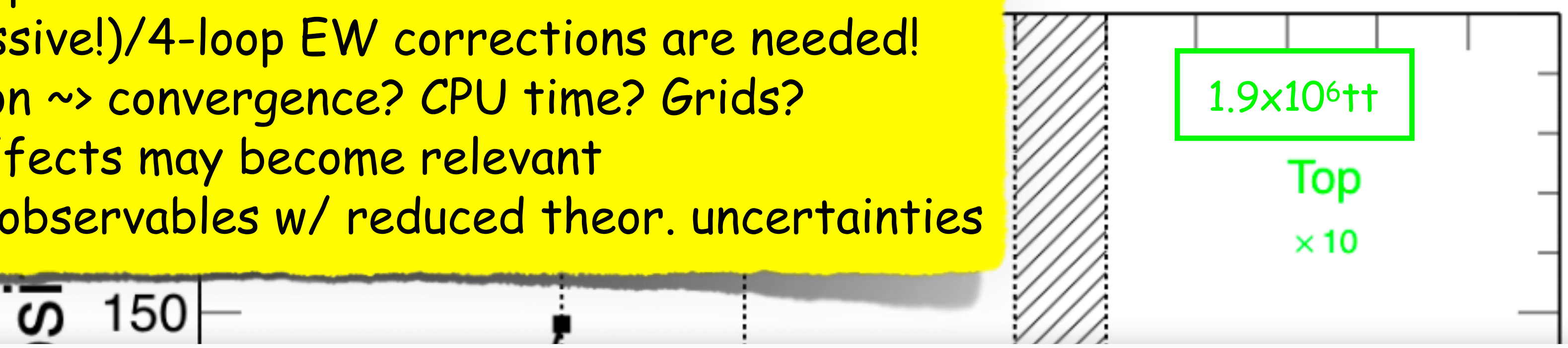
[2209.08078]



Precision at Z, WW, tt

Requirements from Theory:

- Match experimental precision
- At least 3-(fully massive!)/4-loop EW corrections are needed!
- Numerical integration ~> convergence? CPU time? Grids?
  Non-perturbative effects may become relevant
- Identify (ratios of) observables w/ reduced theor. uncertainties



[Freitas,Heinemeyer,Beneke,Blondel,Dittmaier,Gluza,Hoang,Jadach,Janot,Reuter,Reimann;Schwinn,Skrzypek,Weinzierl]

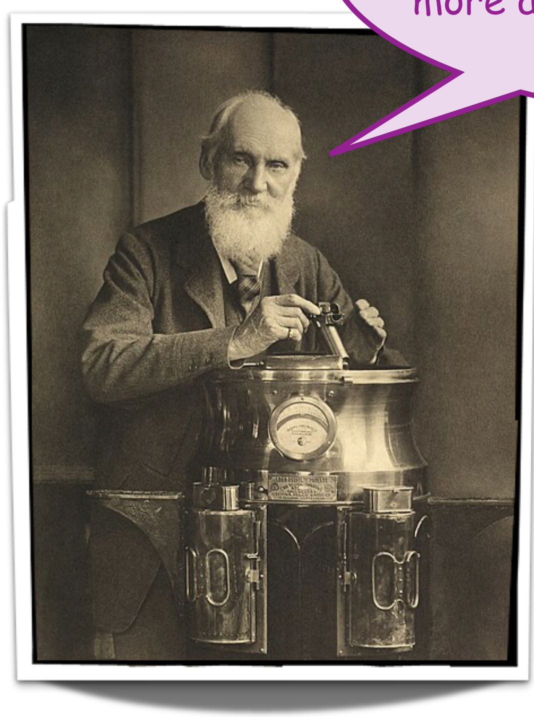
	current exp.	FCCee, CEPC /ILC	current th.	~3(4)-loop
M_W [MeV]	12	0.5/3	4 $(\alpha^3, \alpha^2\alpha_s)$	1
Γ_Z [MeV]	2.3	0.1/1	0.4 $(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.15
R_ℓ $[10^{-3}]$	25	1/10	5 $(\alpha^3, \alpha^2\alpha_s)$	1.5
R_b $[10^{-5}]$	66	6/15	10 $(\alpha^3, \alpha^2\alpha_s)$	5
$\sin^2\theta^\ell_{eff}$ $[10^{-5}]$	~13	0.6/1.3	4.5 $(\alpha^3, \alpha^2\alpha_s)$	1.5

A Look Into the Future

What to Expect?

- Situation at the end of HL-Luminosity LHC:
  suppose: no new physics + Higgs behaves very SM-like

There is nothing new to be discovered
in physics now. All that remains is
more and more precise measurement.
Lord Kelvin (1824-1907)



The most important is
that we never stop asking questions.
Madame Curie, 1867-1934

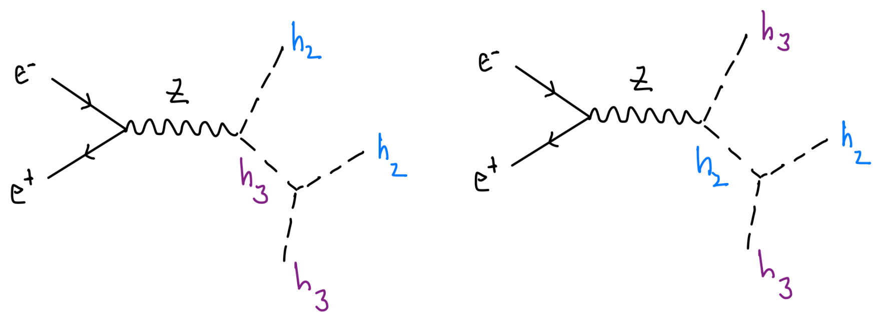
Light on the Horizon

✏ Future colliders may still reveal new physics!

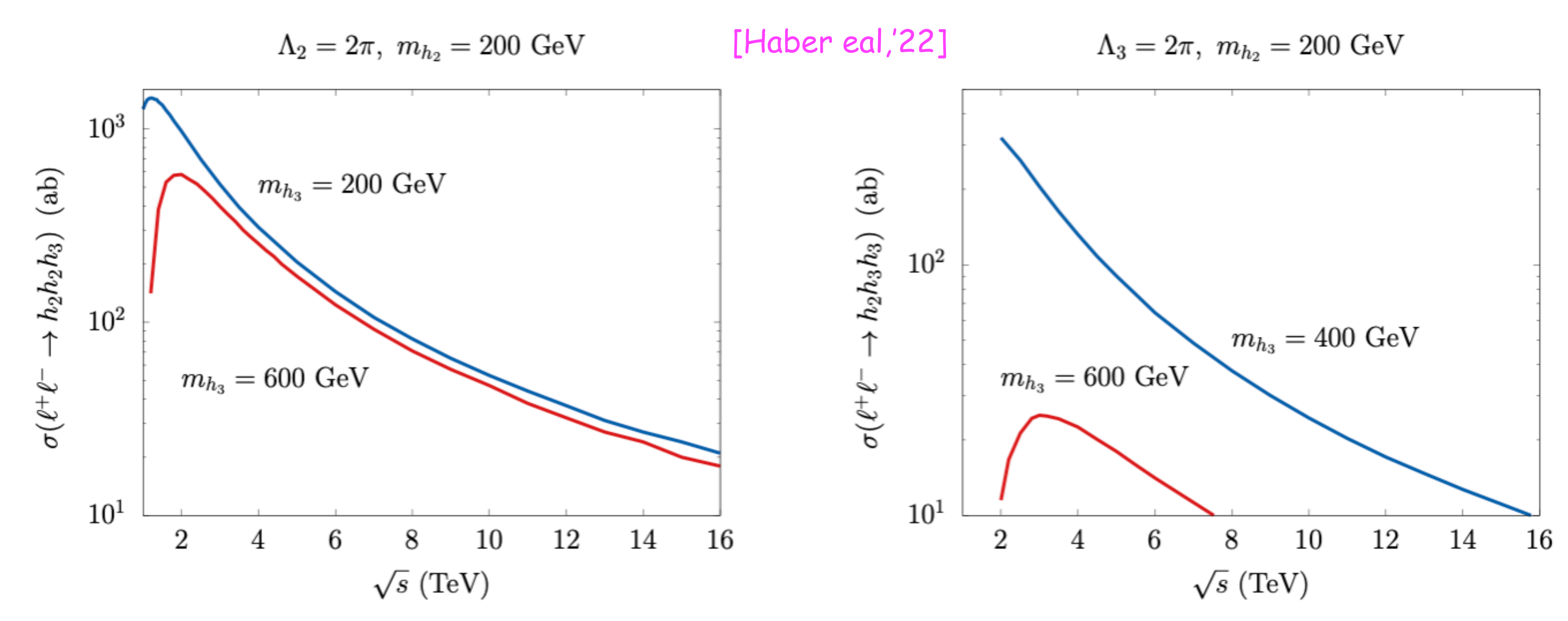
Example CP-violating 2-Higgs-Doublet Model:
Could be that 125 GeV Higgs is very close to the alignment limit and be very CP-even!

Can we still see new physics at future colliders?

Study multi Higgs boson production!



Simultaneous measurement of $Zh_2h_2h_3$, $Zh_2h_3h_3$, Zh_2h_3 sign of CP violation



Still: Extremely hard

Light on

✏ Future colliders n

Example CP-violati

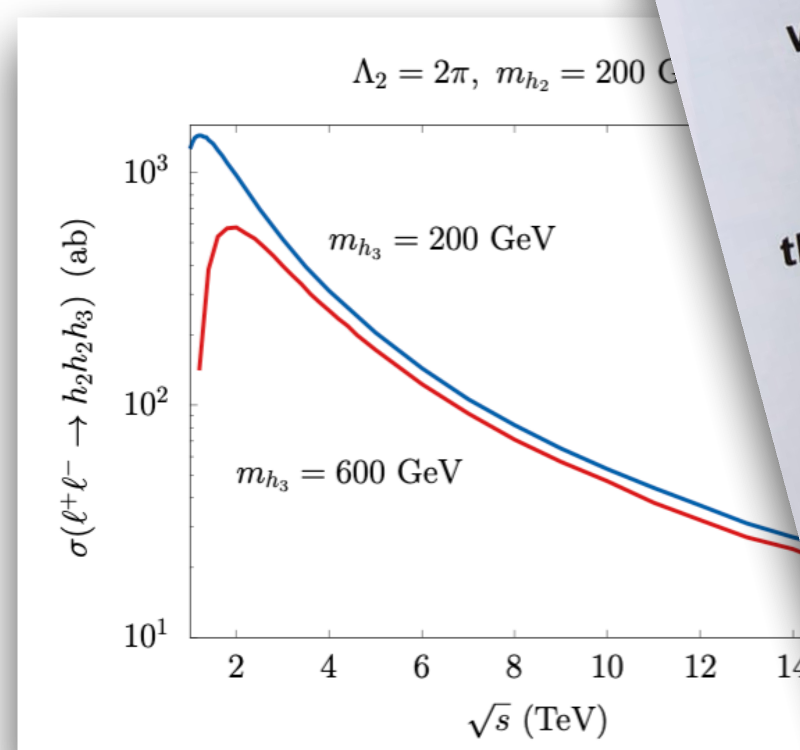
Could be that 125 G   CP-even!

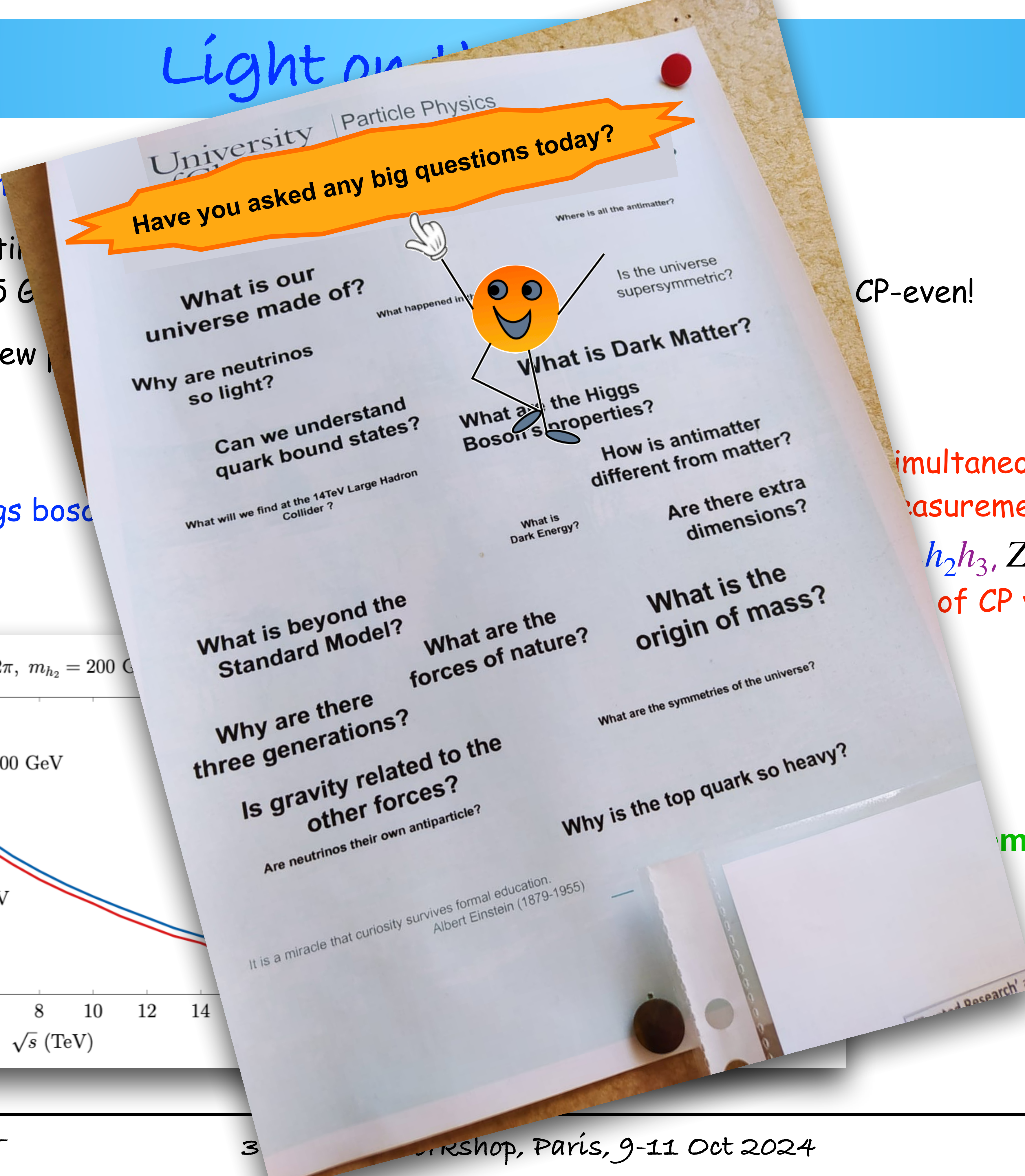
Can we still see new

Study multi Higgs boso
production!

imultaneous
asurement of
h_2h_3, $Zh_2h_3h_3$, Zh_2h_3
of CP violation

mely hard





Focus Topics

[Maestre eal,2401.07564]

In order to stimulate new engagement and trigger some concrete studies in areas where further work would be beneficial towards fully understanding the physics potential of an e^+e^- Higgs / Top / Electroweak factory, we propose to define a set of focus topics. The

HtoSS — $e^+e^- \to Zh$: $h \to s\bar{s}$ ($\sqrt{s} = 240/250\,\text{GeV}$) . . . .

ZHang — Zh angular distributions and CP studies . . . .

Hself — Determination of the Higgs self-coupling . . . .

Wmass — Mass and width of the W boson from the pair-production threshold cross section lineshape and from decay kinematics . . . .

WWdiff — Full studies of WW and $e\nu W$ . . . .

TTthres — Top threshold: Detector-level simulation studies of $e^+e^- \to t\bar{t}$ and threshold scan optimisation . . . .

LUMI — Precision luminosity measurement . . . .

EXscalar — New exotic scalars . . . .

LLPs — Long-lived particles . . . .

EXtt — Exotic top decays . . . .

CKMWW — CKM matrix elements from W decays . . . .

BKtautau — $B^0 \to K^{0*}\tau^+\tau^-$ . . . .

TwoF — EW precision: 2-fermion final states ($\sqrt{s} = M_Z$ and beyond) . . . .

BCfrag and **Gsplit** — Heavy quark fragmentation and hadronisation, gluon splitting and quark-gluon separation . . . .

Conclusions

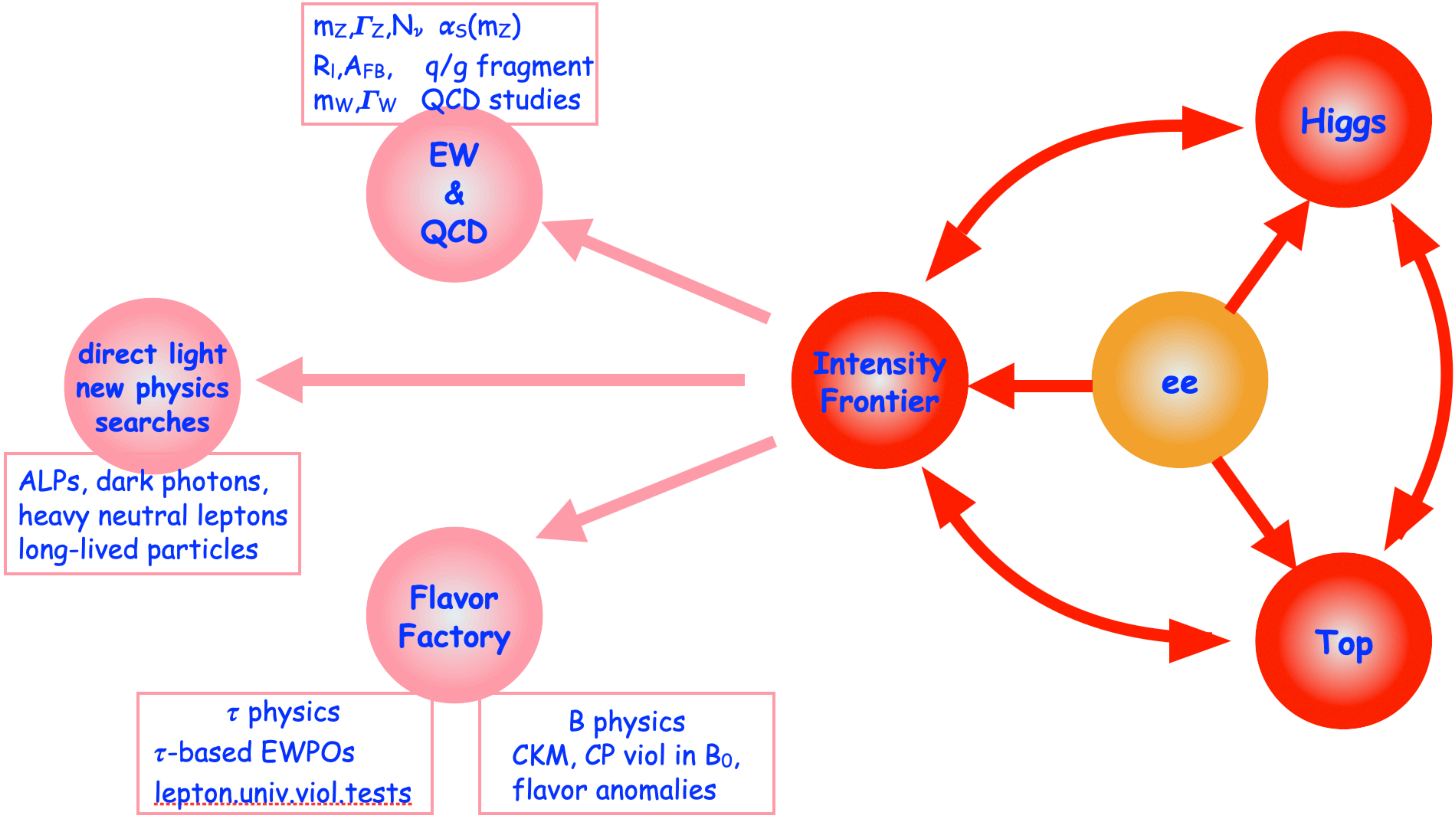
- ✦ e^+e^- Colliders: Higgs/Electroweak/Top Factories in clean e^+e^- environment
- ✦ Absolute Higgs couplings access @ unprecedented precision
- ✦ Unique measurement of He^+e^- coupling
- ✦ Higgs self-coupling measurement
- ✦ EWPOs tremendously improved precision

What do we learn from indirect measurements at Higgs/EW/top factories about the underlying model? How can we combine information from all possible observables, experiments and research areas to get maximum insight?

Lot of work ahead! Exciting times!


Thank you for
your attention!
Tarte de Lima
Tarte de Cereja

Physics Program at ee-Colliders



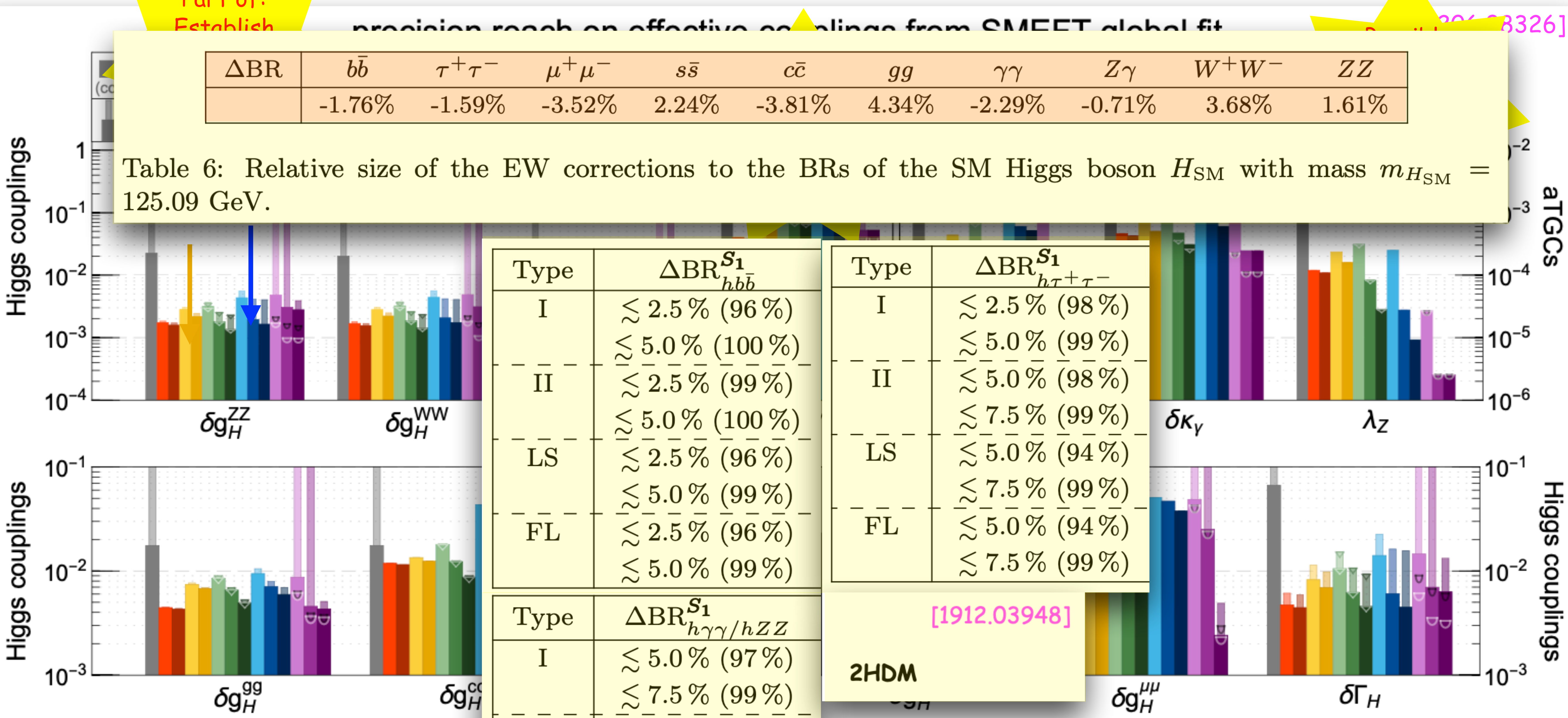
What do we Learn?

[Englert,Freitas,MM,Plehn,Rauch,Spira,Walz,'14]

coupling	LHC	HL-LHC	LC	HL-LC	HL-LHC + HL-LC
hWW	0.09	0.08	0.011	0.006	0.005
hZZ	0.11	0.08	0.008	0.005	0.004
htt	0.15	0.12	0.040	0.017	0.015
hbb	0.20	0.16	0.023	0.012	0.011
$h\tau\tau$	0.11	0.09	0.033	0.017	0.015
$h\gamma\gamma$	0.20	0.15	0.083	0.035	0.024
hgg	0.30	0.08	0.054	0.028	0.024
h_{invis}	—	—	0.008	0.004	0.004

TABLE I: Expected accuracy at the 68% C.L. with which fundamental and derived Higgs couplings can be measured; the deviations are defined as $g = g_{SM}[1 \pm \Delta]$ compared to the Standard Model at the LHC/HL-LHC (luminosities 300 and 3000 fb^{-1}), LC/HL-LC (energies 250+500 GeV / 250+500 GeV+1 TeV and luminosities 250+500 fb^{-1} / 1150+1600+2500 fb^{-1}), and in combined analyses of HL-LHC and HL-LC. For invisible Higgs decays we give the upper limit on the underlying couplings. Constraints on an invisible Higgs decay width involve model-specific assumptions at the LHC, see *e.g.* [15]. Therefore, we allow for additional contributions to the total Higgs width only in the linear collider scenarios, where these can be constrained model-independently by exploiting the recoil measurement [14].

Higgs Coupling Measurements



ΔBR	$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$s\bar{s}$	$c\bar{c}$	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ
	-1.76%	-1.59%	-3.52%	2.24%	-3.81%	4.34%	-2.29%	-0.71%	3.68%	1.61%

Table 6: Relative size of the EW corrections to the BRs of the SM Higgs boson $H_{\rm SM}$ with mass $m_{H_{\rm SM}} =$ 125.09 GeV.

Type	$\Delta\mathrm{BR}^{S_1}_{hb\bar{b}}$
I	$\lesssim 2.5\,\%$ (96 %)
	$\lesssim 5.0\,\%$ (100 %)
II	$\lesssim 2.5\,\%$ (99 %)
	$\lesssim 5.0\,\%$ (100 %)
LS	$\lesssim 2.5\,\%$ (96 %)
	$\lesssim 5.0\,\%$ (99 %)
FL	$\lesssim 2.5\,\%$ (96 %)
	$\lesssim 5.0\,\%$ (99 %)

Type	$\Delta\mathrm{BR}^{S_1}_{h\tau^+\tau^-}$
I	$\lesssim 2.5\,\%$ (98 %)
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Type	$\Delta\mathrm{BR}^{S_1}_{h\gamma\gamma/hZZ}$
I	$\lesssim 5.0\,\%$ (97 %)
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	$\lesssim 7.5\,\%$ (99 %)
FL	$\lesssim 5.0\,\%$ (97 %)
	$\lesssim 7.5\,\%$ (99 %)

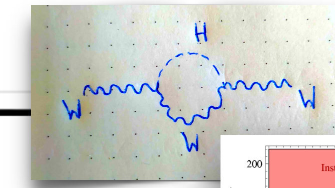
[1912.03948]

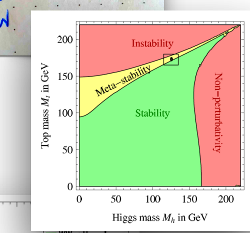
2HDM

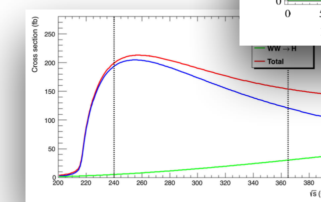
- all Higgs … : luminosity vs. polarization
- couplings … ercent - few per mille precision
- at least … ision gain compared to HL-LHC

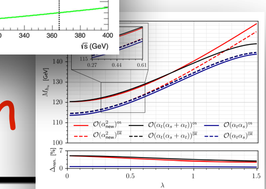
Higgs Mass Measurement

❖ Higgs mass and ZH cross section:





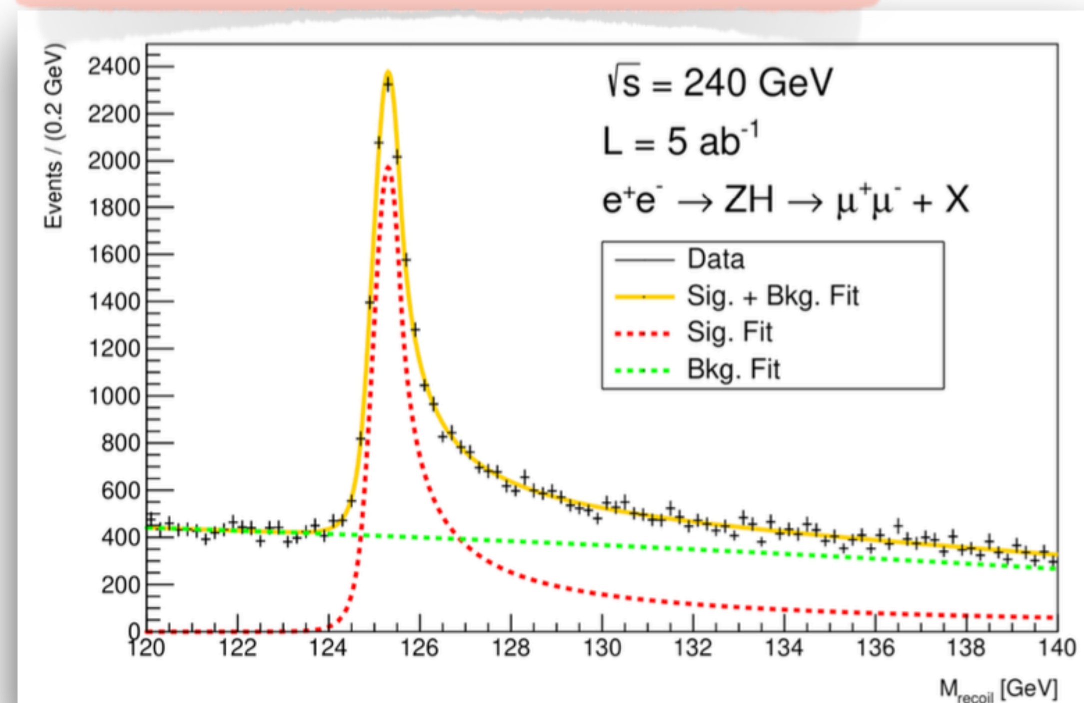




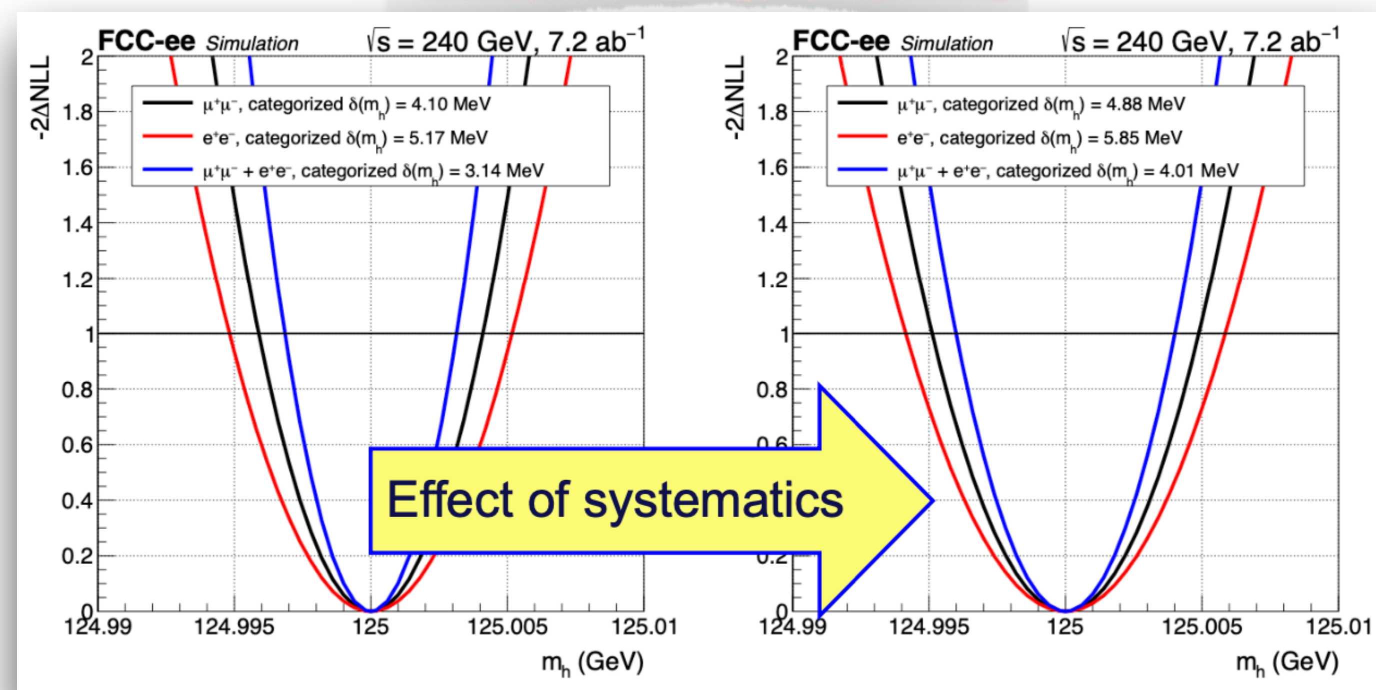
Why precision?

- Self-consistency test of SM at quantum level (e.g.: Higgs loop corrections to EWPOs)
- $M_H \leftrightarrow$ stability of the electroweak vacuum
- Higgs mass uncertainty feeds back in uncertainty on Higgs observables
- Test parameter relations in beyond-SM theories
- Required for electron Yukawa coupling determination from $e^+e^- \to H$ resonant production

M_H fitted from actual exp. m_{recoil} distribution



$\delta(m_H)$ = 3.1 (4.0) MeV stat(syst)



[Eysermans,Bernardi,Li]

Higgs Mass Measurement

❖ Higgs mass and ZH cross section:

Why precision?

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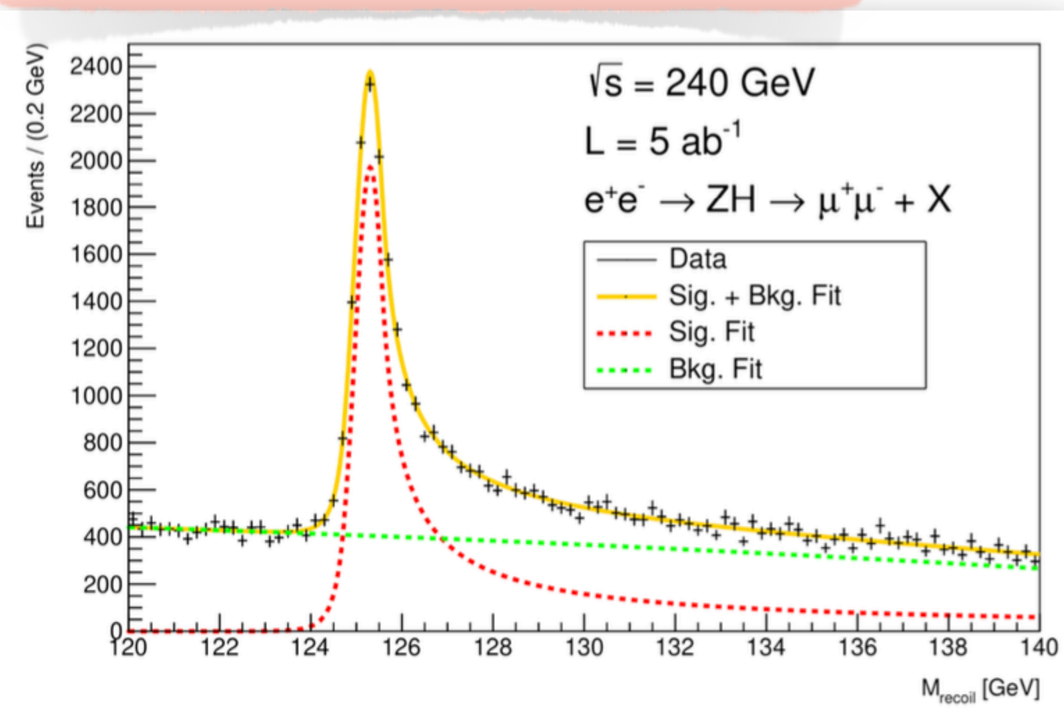
- Higgs mass uncertainty feeds back in uncertainty on Higgs observables
- Test parameter relations in beyond-SM theories
- Required for electron Yukawa coupling determination from $e^+e^- \to H$ resonant p

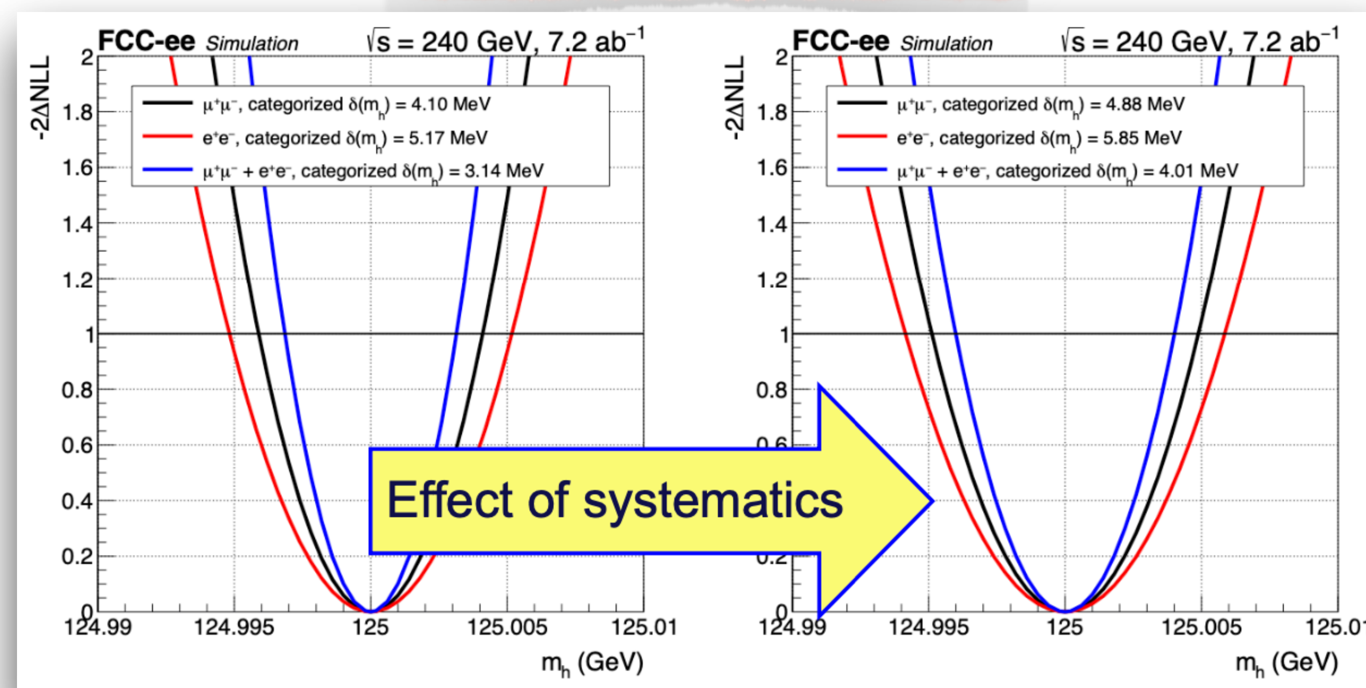
O(10 MeV) need for permille precision of $g_H^{ZZ}, g_H^{WW}, g_H^{Z\gamma}$

O(Γ_H=4 MeV) to measure electron Yukawa coupling

M_H fitted from actual exp. m_{recoil} distribution

$\delta(m_H)$ = 3.1 (4.0) MeV stat(syst)





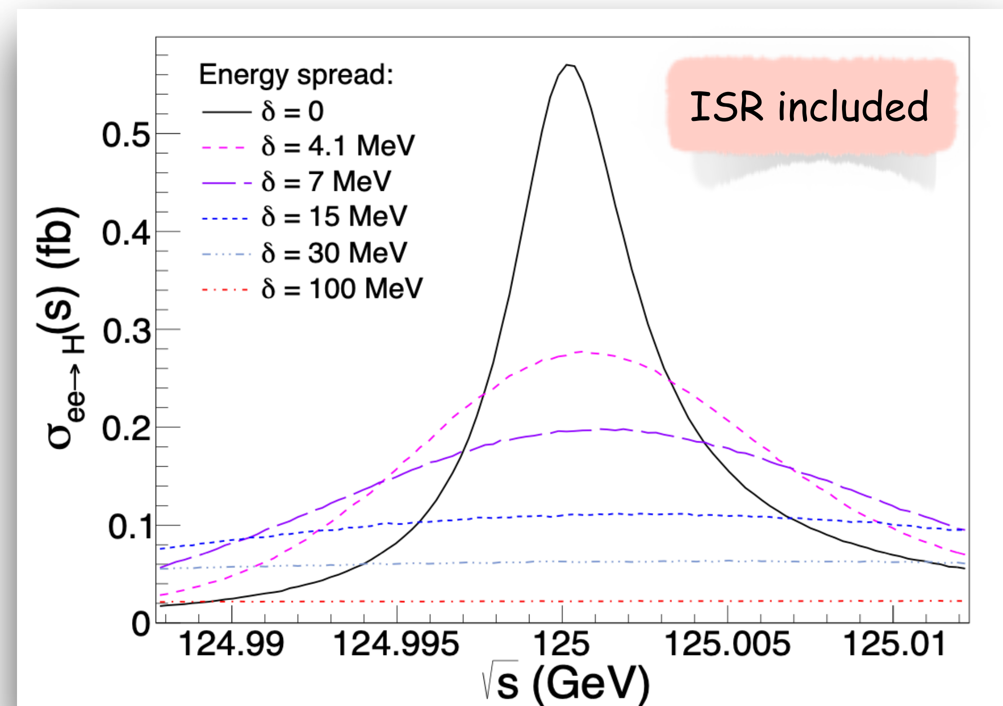
[Eysermans,Bernardi,Li]

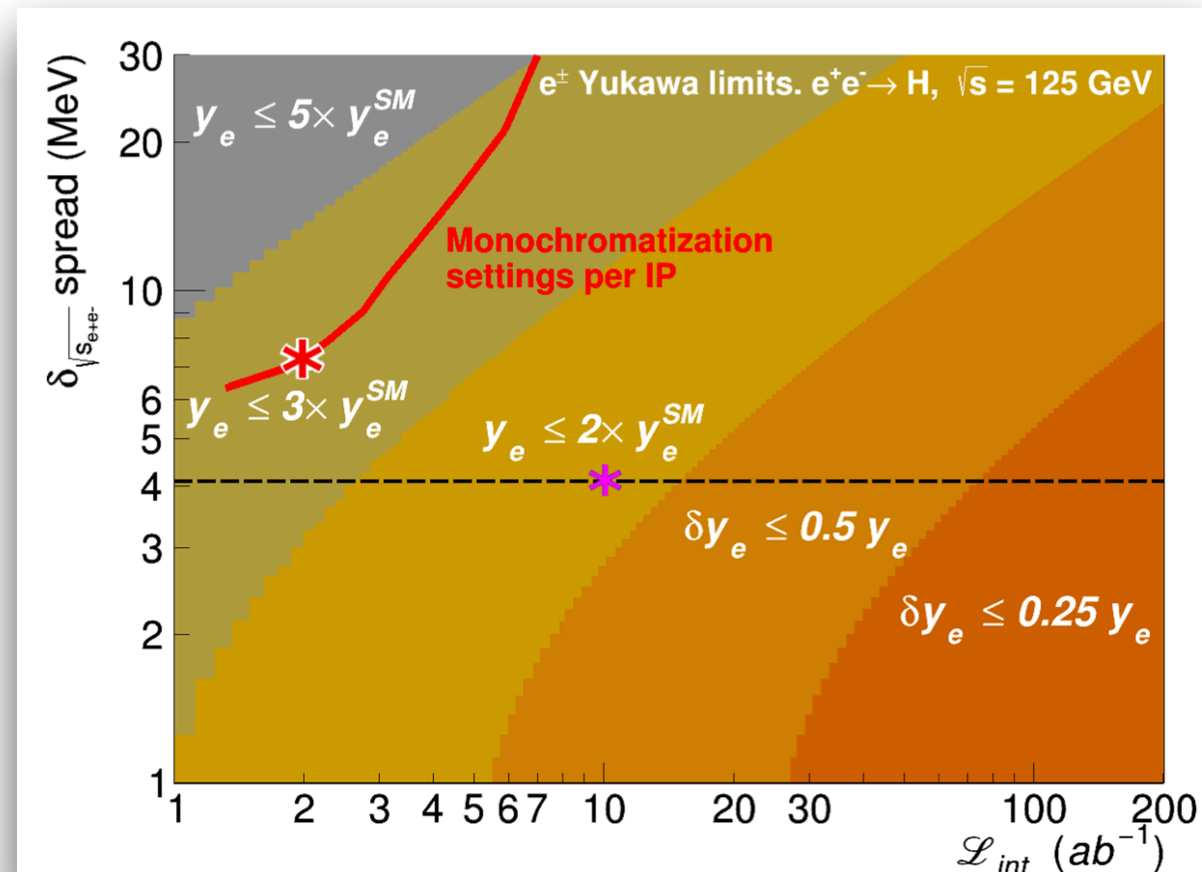
Electron Yukawa Coupling - unique!

- **Why electron Yukawa coupling:** establish experimentally the Higgs coupling to *all* generations ~> also to the *1st* generation!
- **How?:** from $e^+e^- \to H$ at $\sqrt{s} = M_H$
- **Challenge:** coupling extremely tiny

Requirements

- M_H knowledge at $\mathcal{O}$(few MeV) precisely
- Huge luminosity (i.e. several years w/ 4 IPs)
- (Mono)chromatization Γ_H(4.2 MeV)$\ll\delta_{\sqrt{s}}$(100 MeV)
- continuous $\sqrt{s}$ monitoring & adjustment
- extremely sensitive event selection against SM backgrounds





[d´Enterria,Poldaru,Wojcik,2107.02686]

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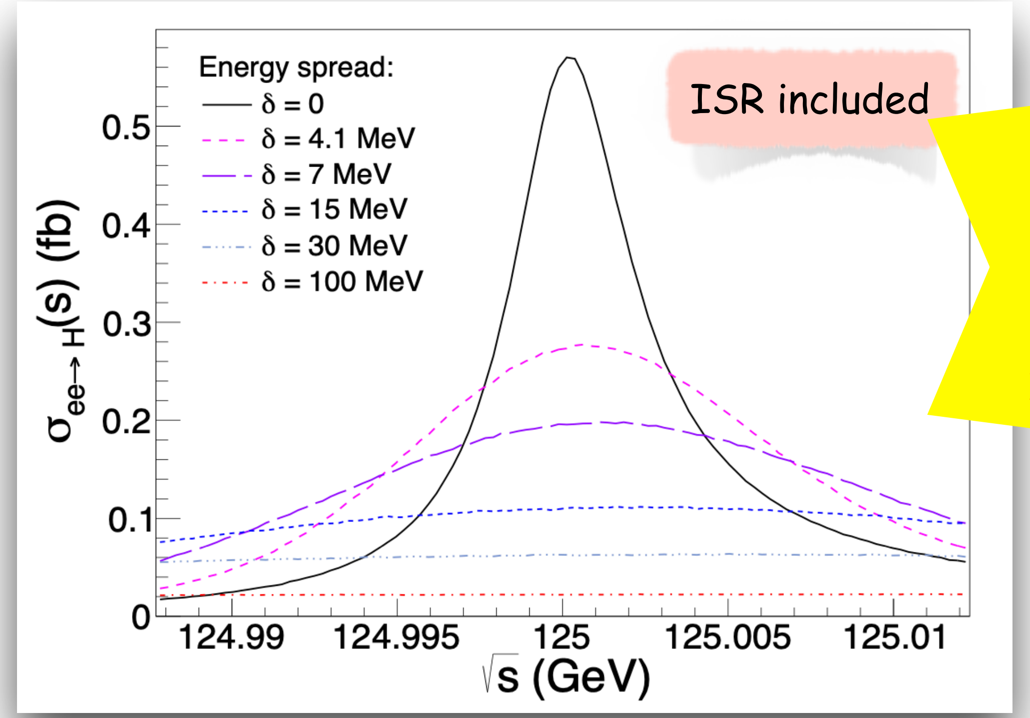
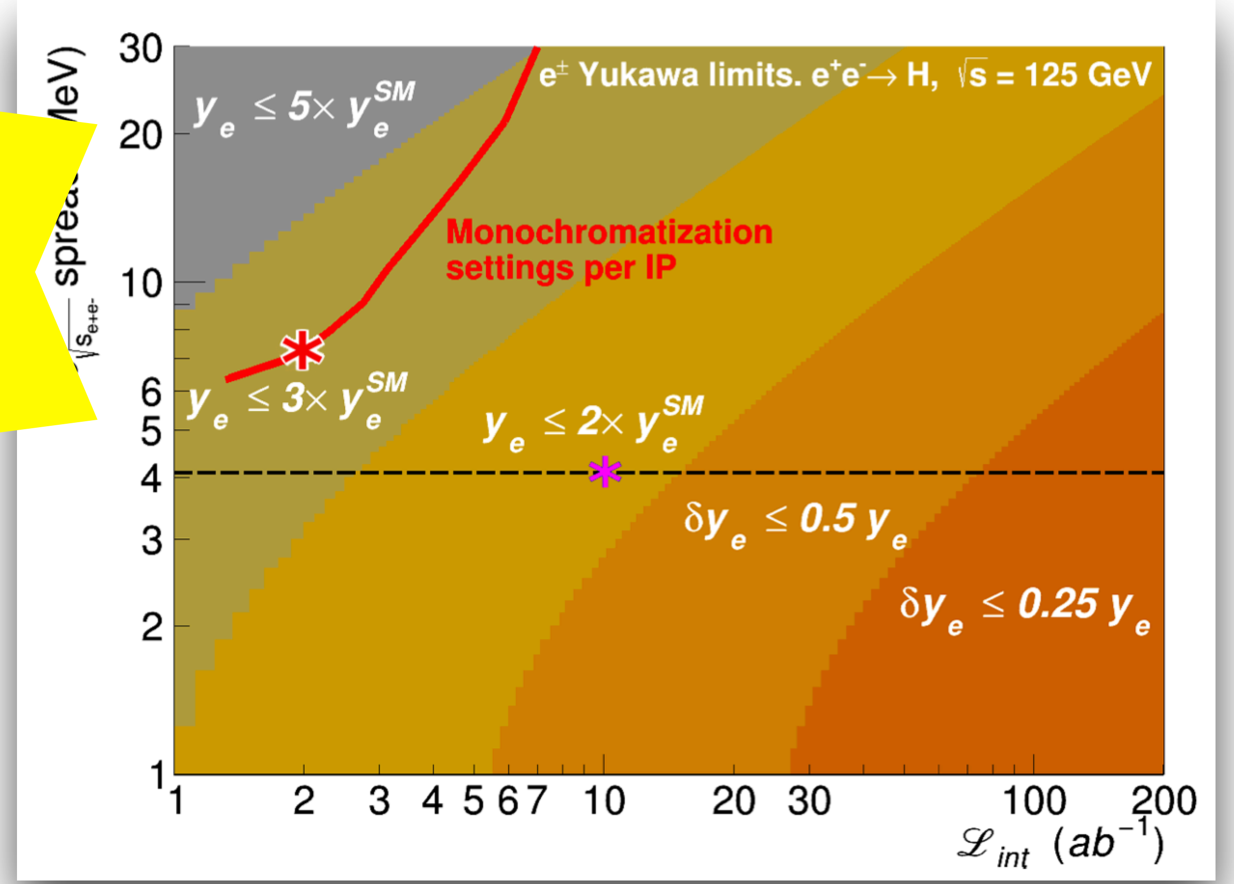


Huge challenge but only place where you can ever measure 1st gen Yukawa!

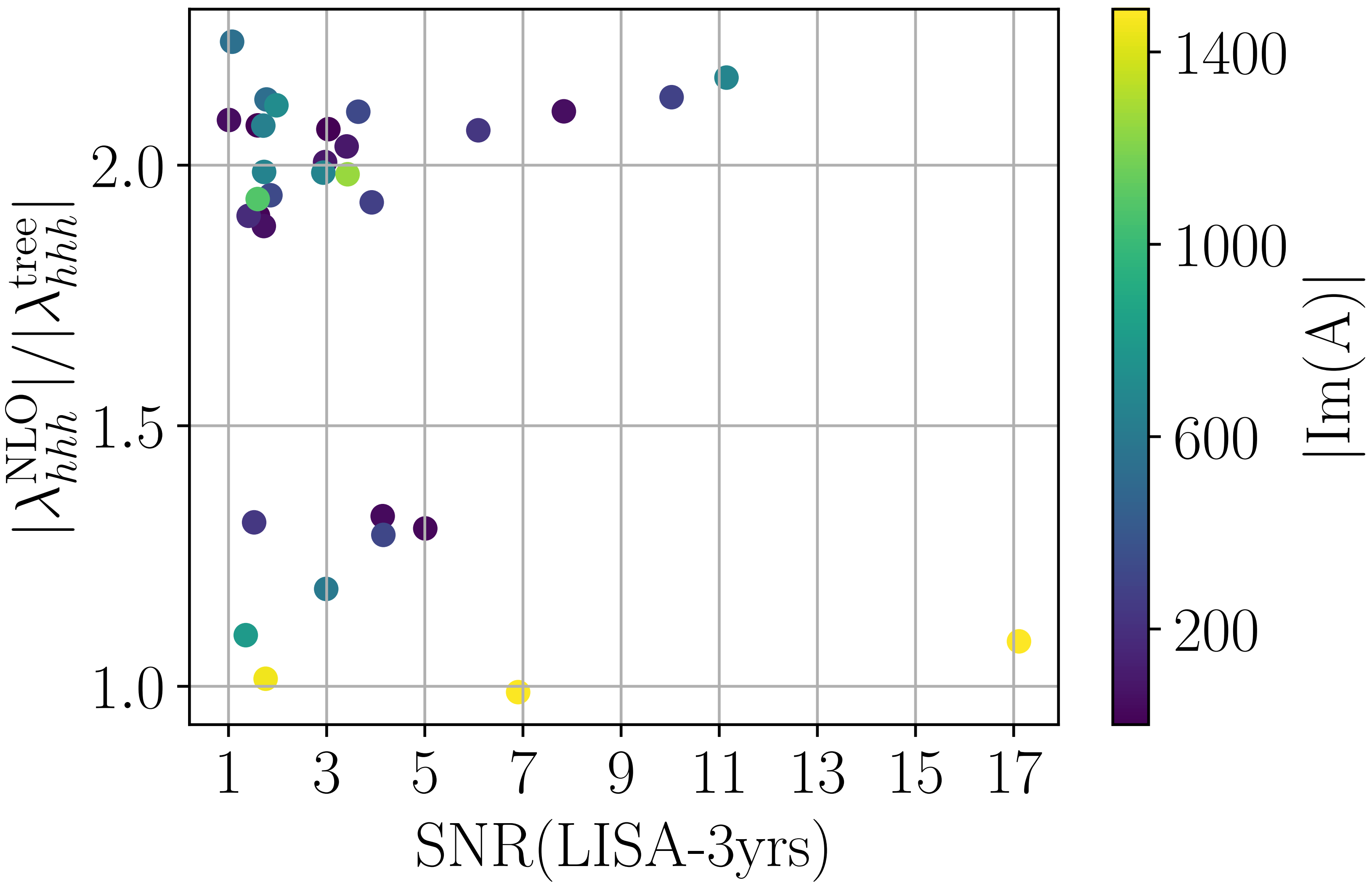


[d´Enterria,Poldaru,Wojcik,2107.02686]

Higgs Self-Coupling & Evolution of the Universe

✏ Model CP in the Dark: SM-Higgs ($\lambda_{hhh}^{tree} = \lambda_{hhh}^{SM}$) + Dark Sector
GW signal from strong first-order phase transition

[Basler,Biermann,MM,Müller,Santos,Viana,'24]

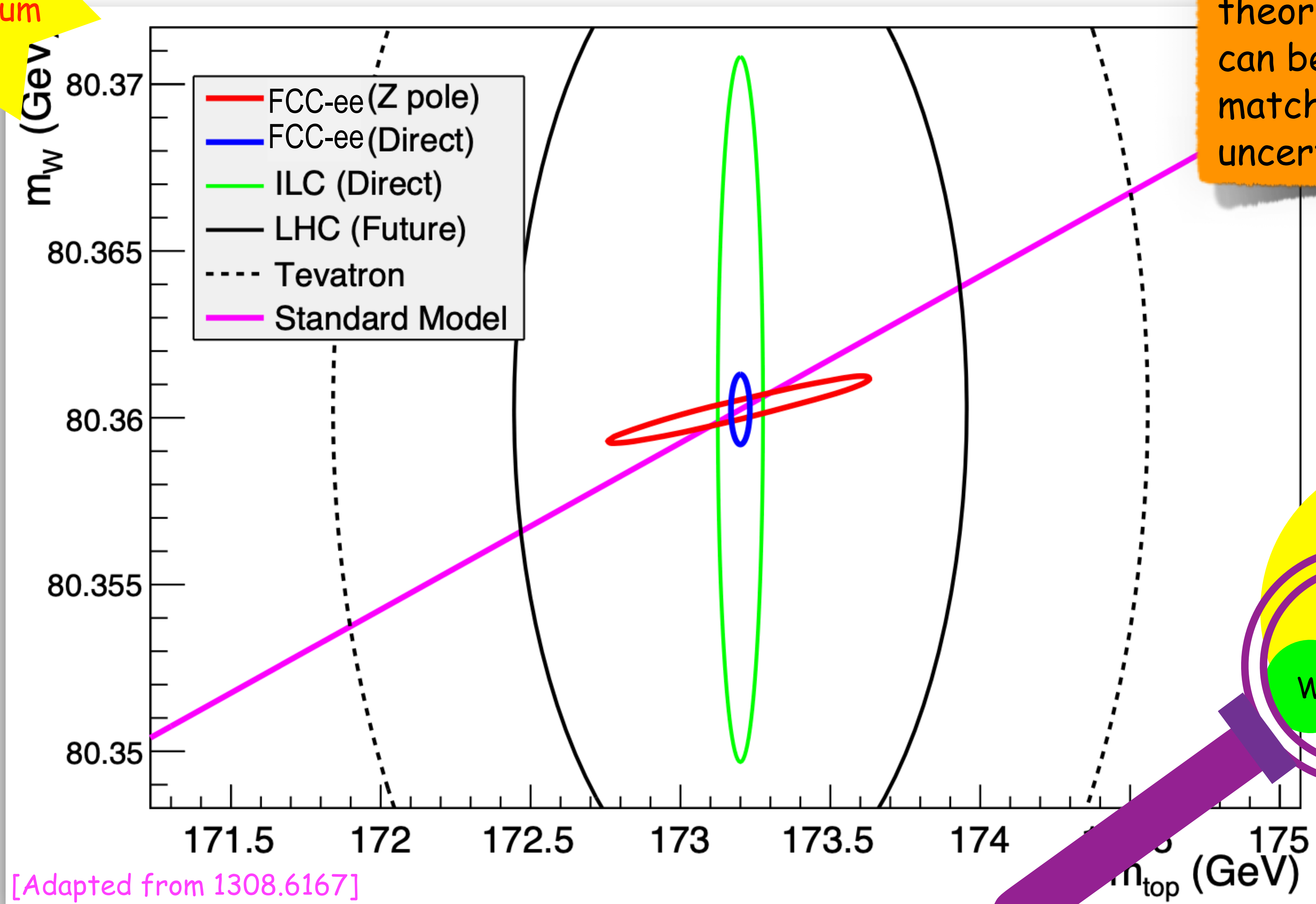


[Biermann,Borschensky,Erhardt,MM,Santos,Viana]

✏ Vector DM Model: two visible Higgs bosons + Dark photon
Strong first-order phase transition: $\delta\lambda_{hhh}^{NLO}/\lambda_{hhh}^{LO} = 8\,\%$

SM Fit to all EWPOs

Consistency test of SM at quantum level



[Adapted from 1308.6167]

Assumes that all theor. uncertainties can be reduced to match the exp. uncertainties!