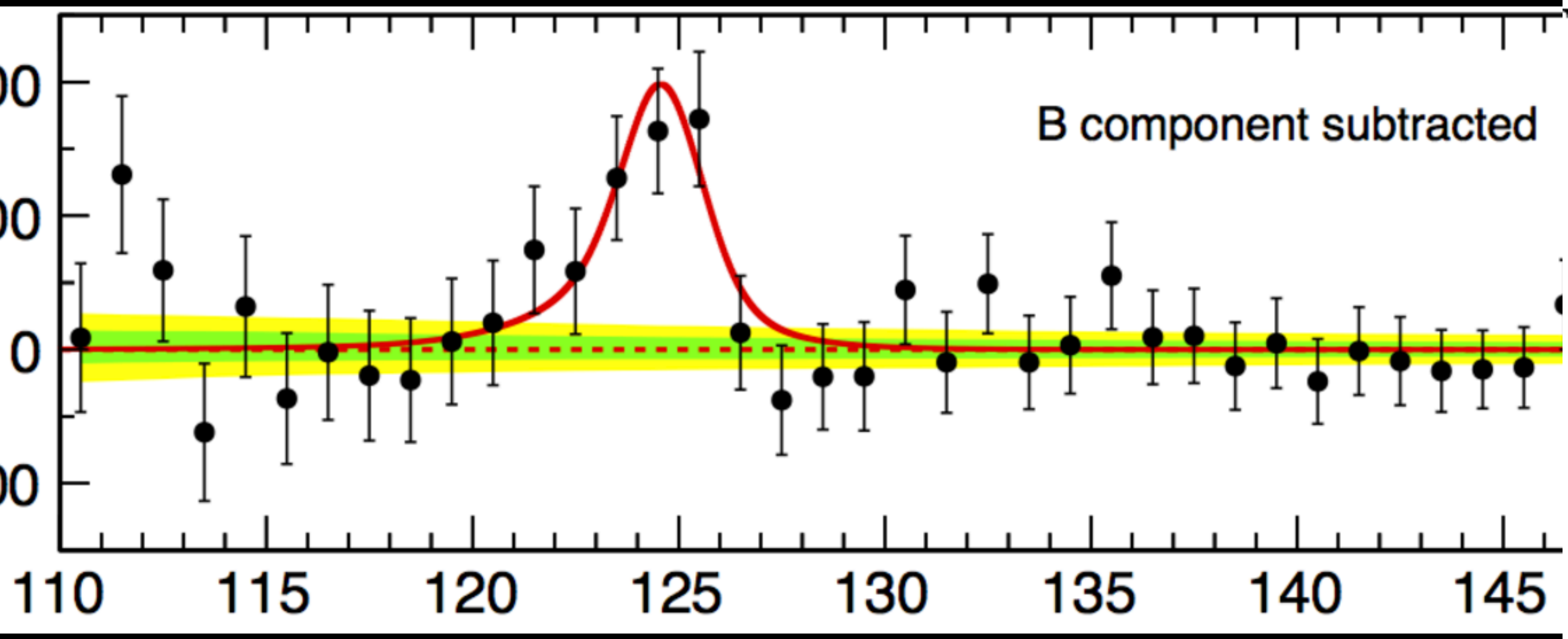
Prospects and new viewpoints of Future Collider Probes

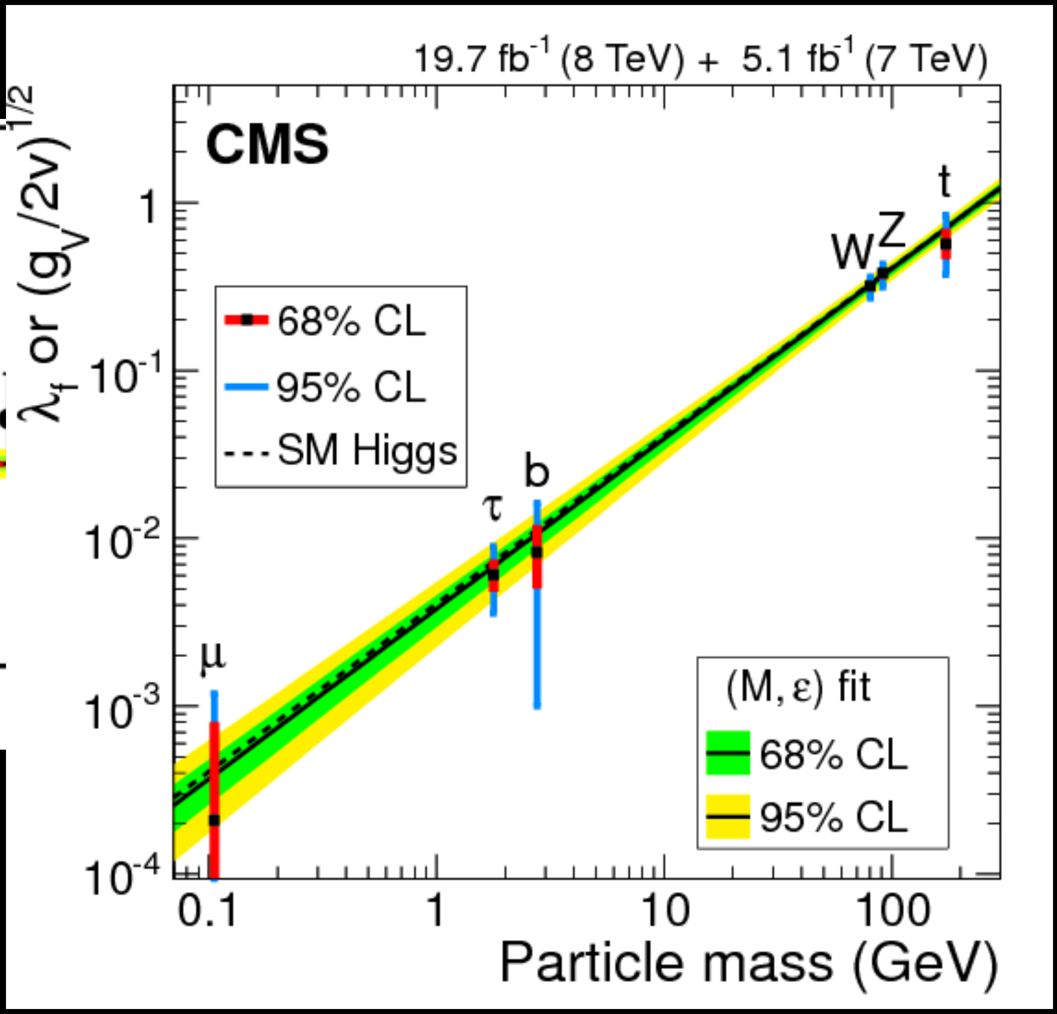
Sunghoon Jung

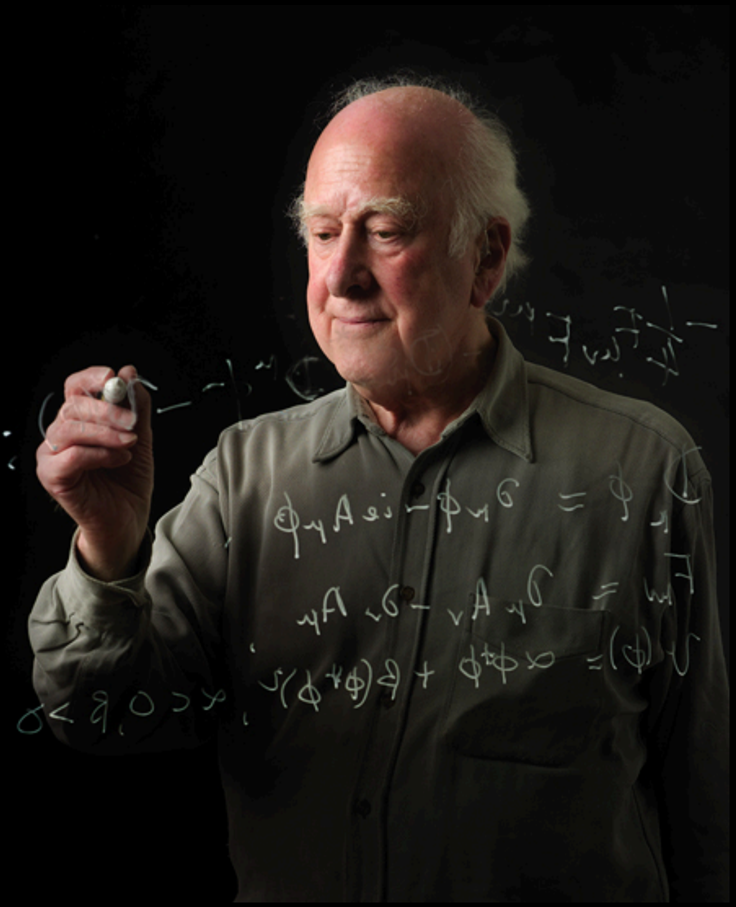
Seoul National University

입자분과 General Meeting, 2019/09/21

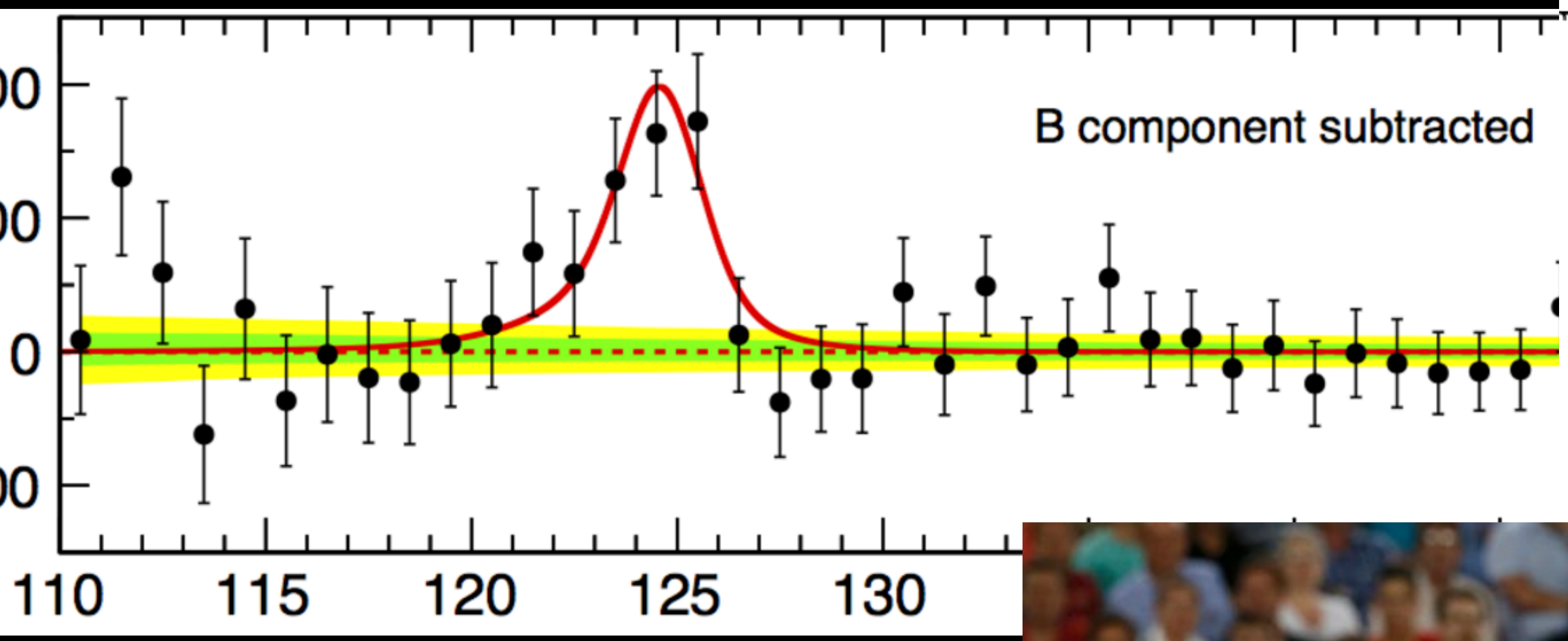
It all starts with the Higgs boson

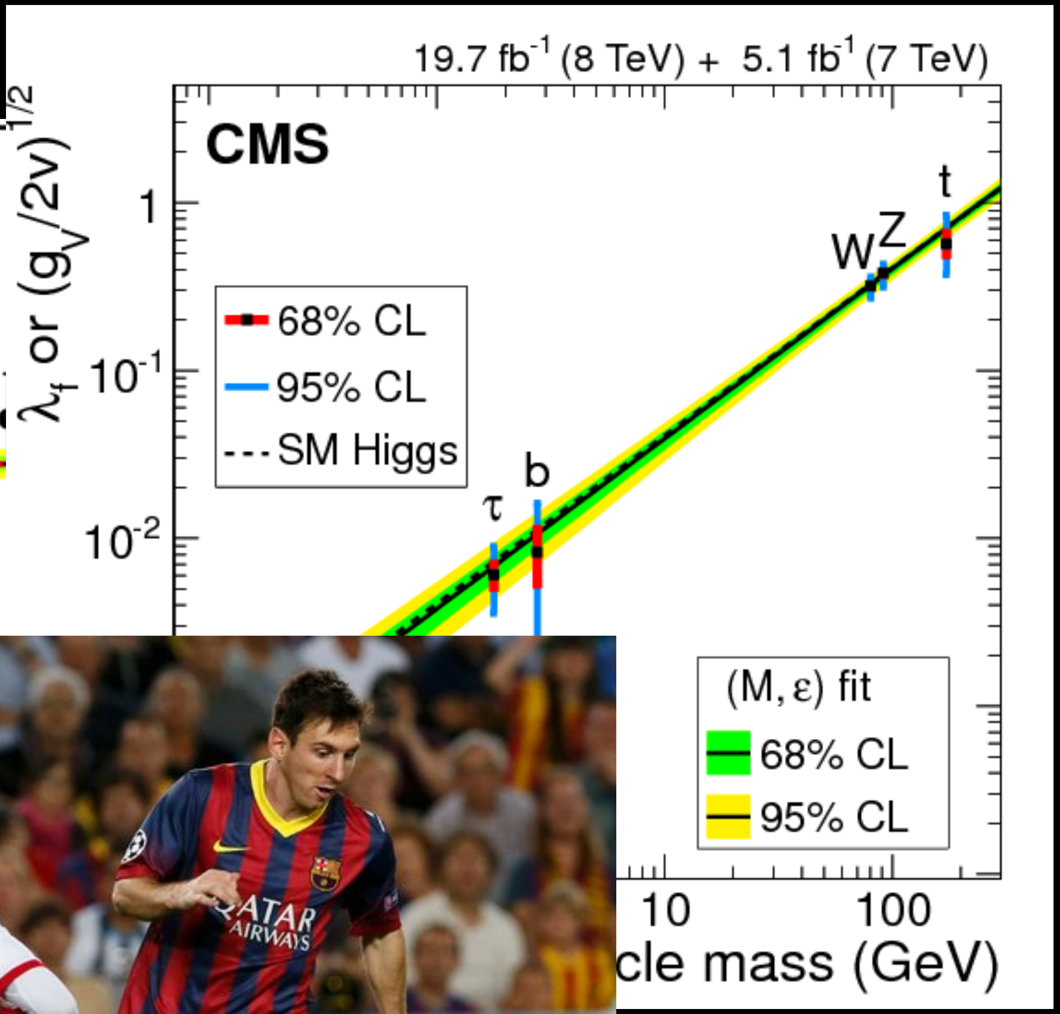


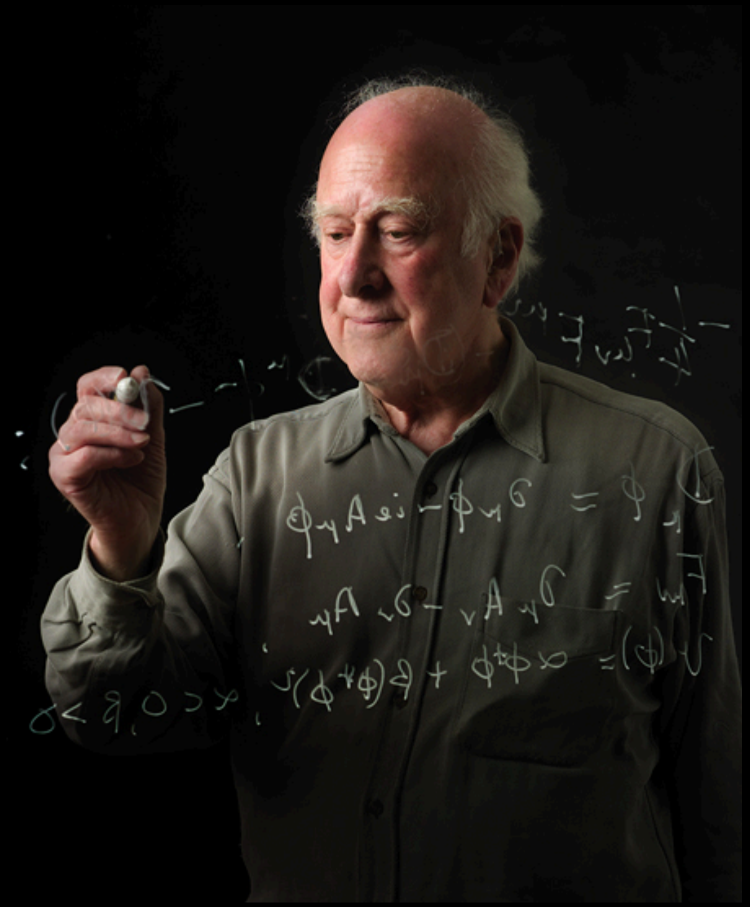




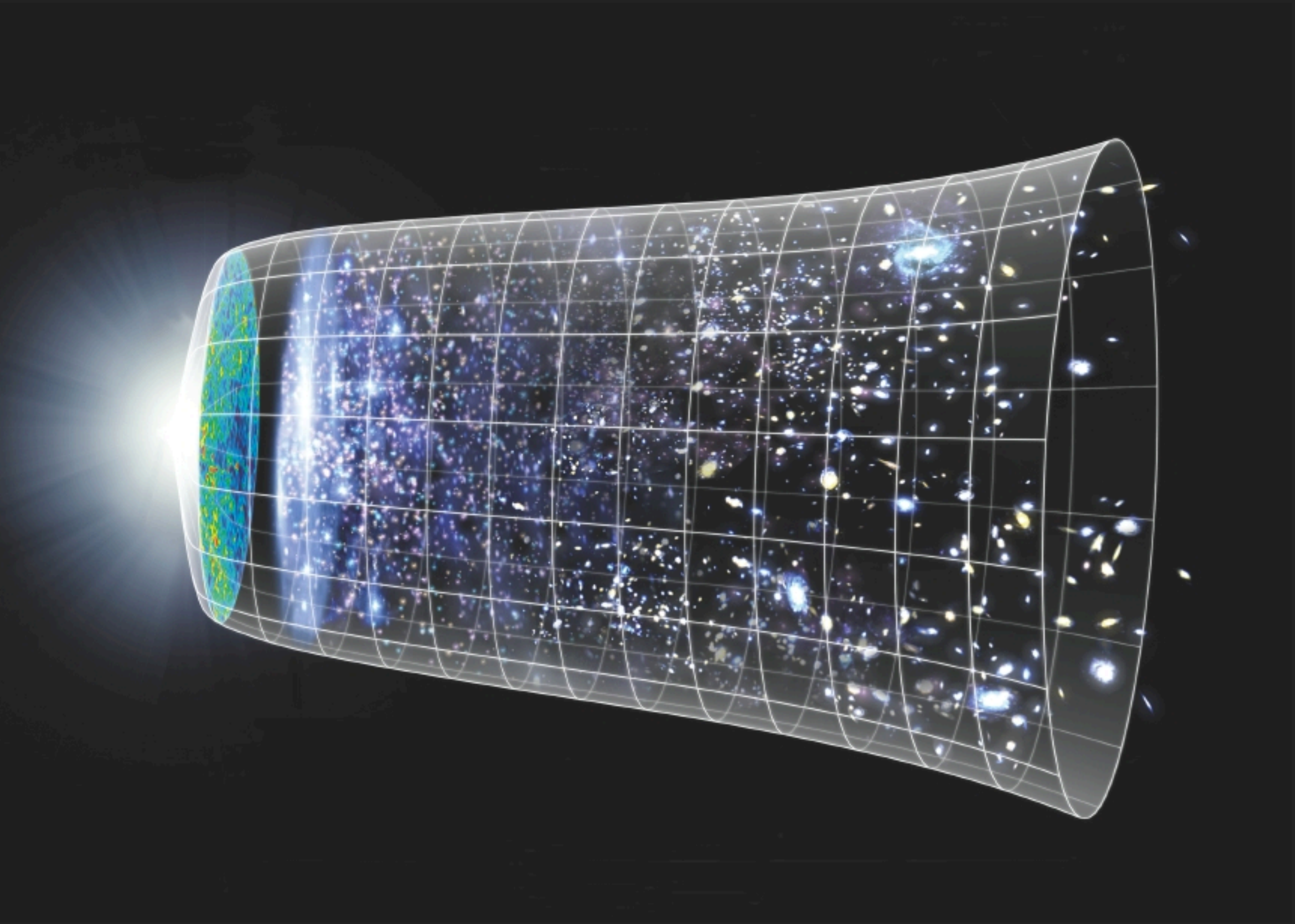
Post Higgsism





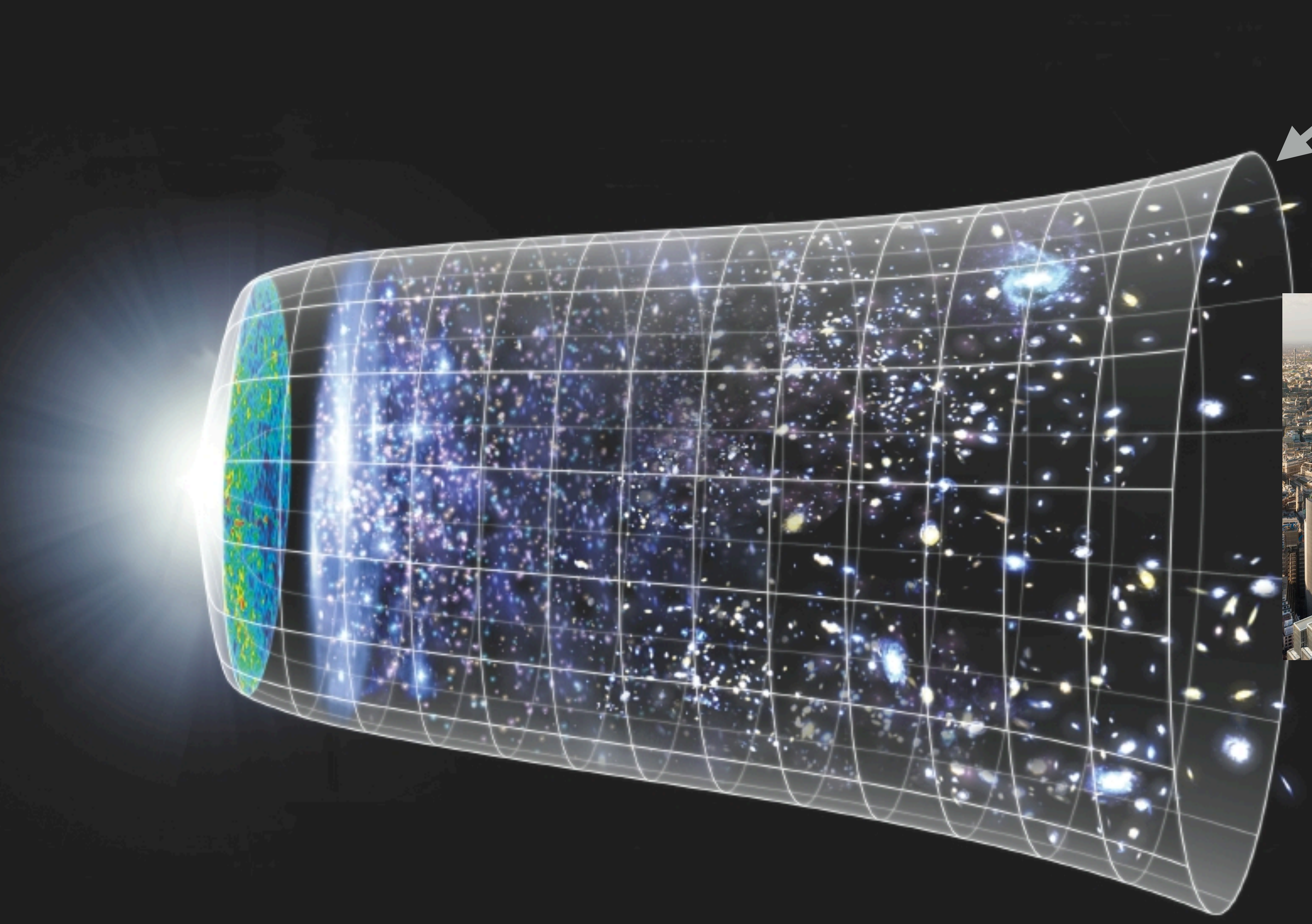


Questions now became real too.



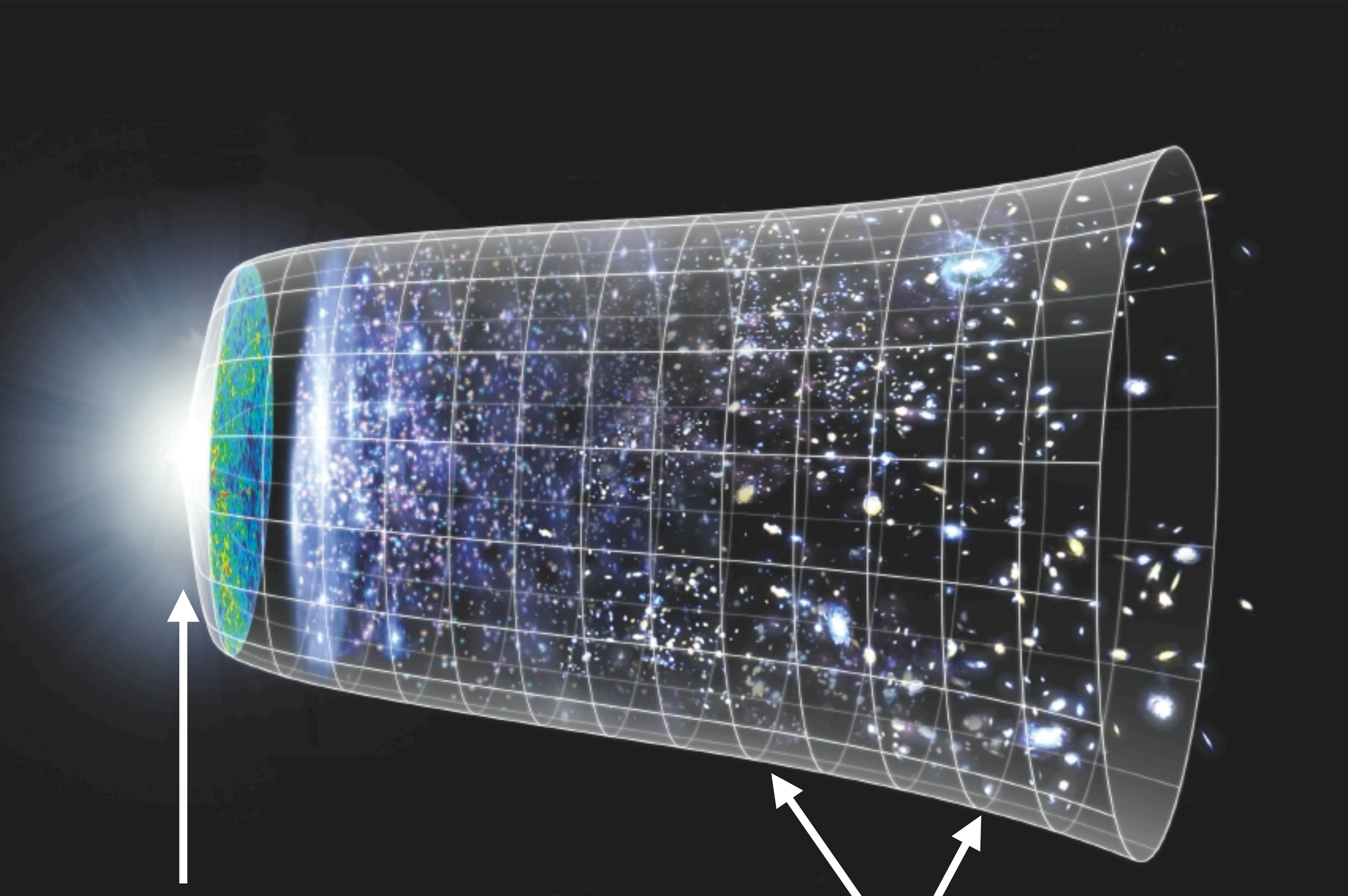
Questions

Why do we exist as we do today?

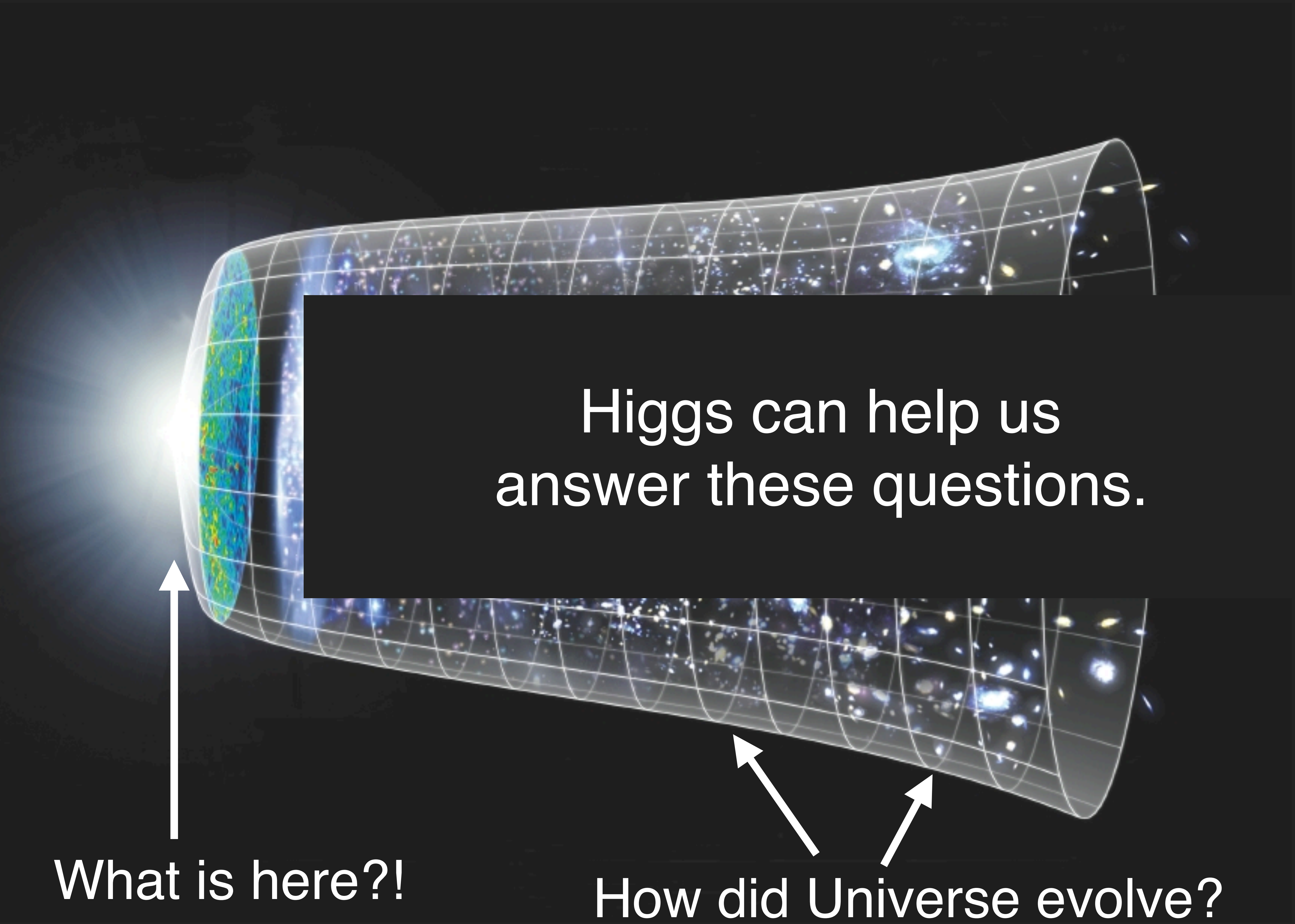


Our existence and shape today all depend on
the history of the Universe and Higgs properties.

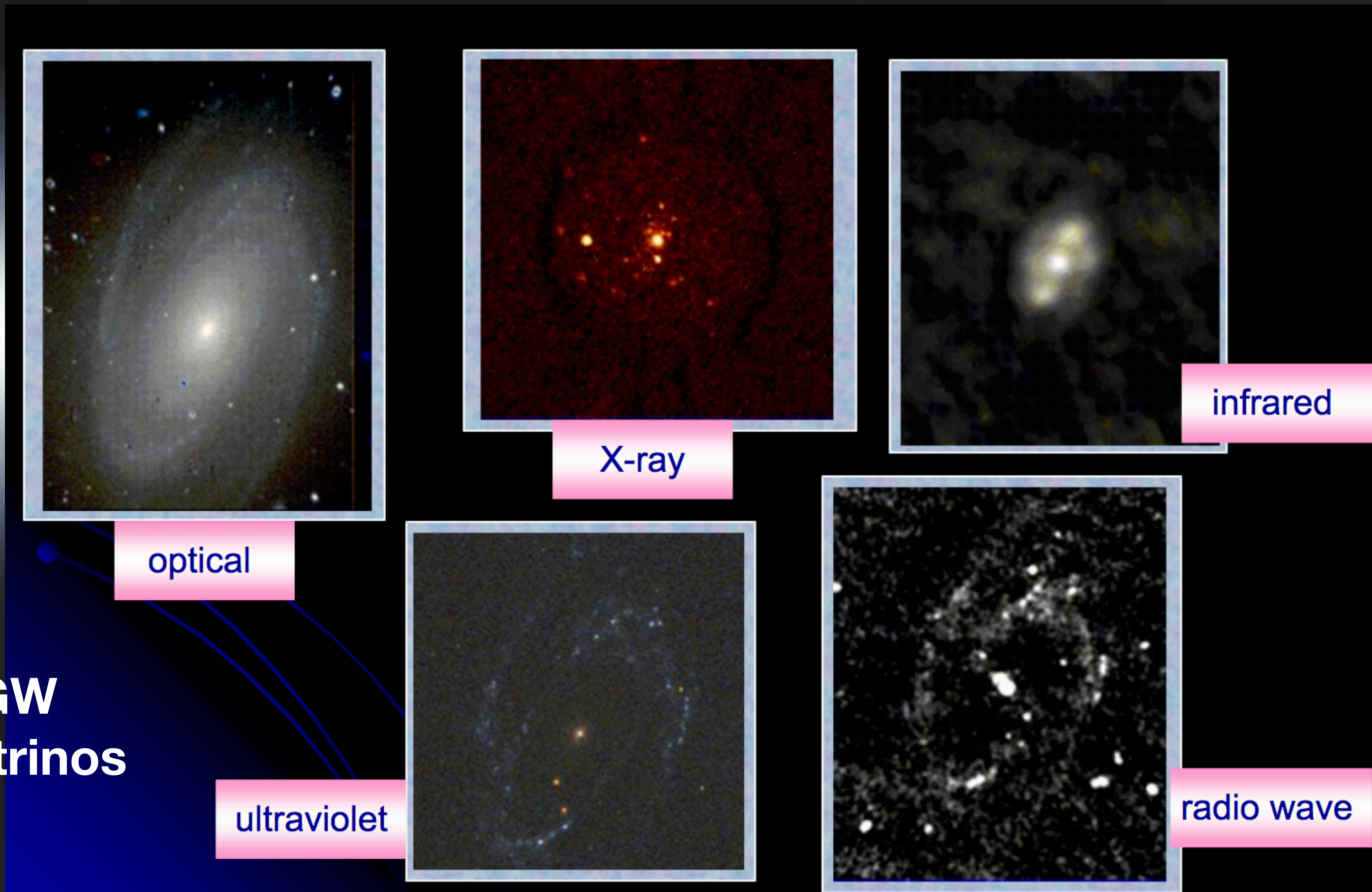
We are so eager to see the Early Universe



Higgs as a new probe

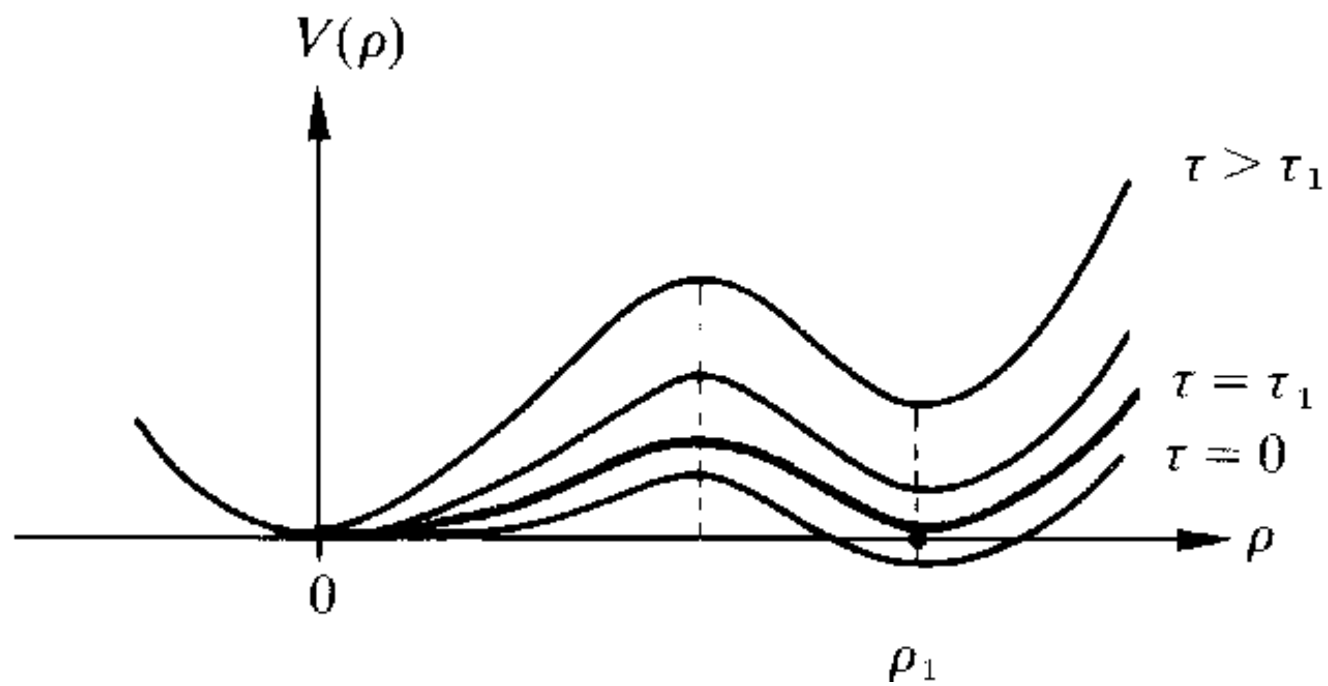


Higgs can open up whole new ways to see and understand the Universe



GW
neutrinos

Higgs potential has evolved over a long time with Universe



- A long way from the Big Bang (10^19 GeV) down to the subatomic scale (GeV).
- Must be sensitive to the initial condition and evolution history of the Early Universe.

Energy scales of the Universe

M_planck	10^19 GeV	initial condition
GUT	10^16 GeV	
electroweak	246 GeV	Higgs
QCD	200 MeV	fm
Supernova T	60 MeV	heavy nucleus
nuclear BE	10 MeV	BBN
Sun’s core	1 keV	
atomic	1 eV	CMB
room T	3*10^-2 eV	
m_neutrino	10^-2 eV	<< CMB
DE	10^-3 eV	
H0	10^-33 eV	10^18 sec size/age of Univ.

The Higgs cannot withstand this huge hierarchy with QM.

M_planck	10^19 GeV	initial condition
GUT	10^16 GeV	
electroweak	246 GeV	Higgs
QCD	200 MeV	fm
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Source: P.W.Graham

In all, the big question is

What causes the electroweak symmetry breaking at such a low energy scale?

More specific questions relevant to collider physics are

Is there naturalon? Which naturalon is realized in nature?
(SUSY, composite Higgs, neutral naturalness, and even relaxions!)

How did the Higgs look like in the Early Universe?
(Higgs potential/phase transition, relaxion, DM)

Takehome messages

- Future TeV-scale SUSY is *qualitatively different*, requiring new viewpoints, insights and works.

- Higgs precision largely prefers to *polarization!* (of linear e+e- colliders.)

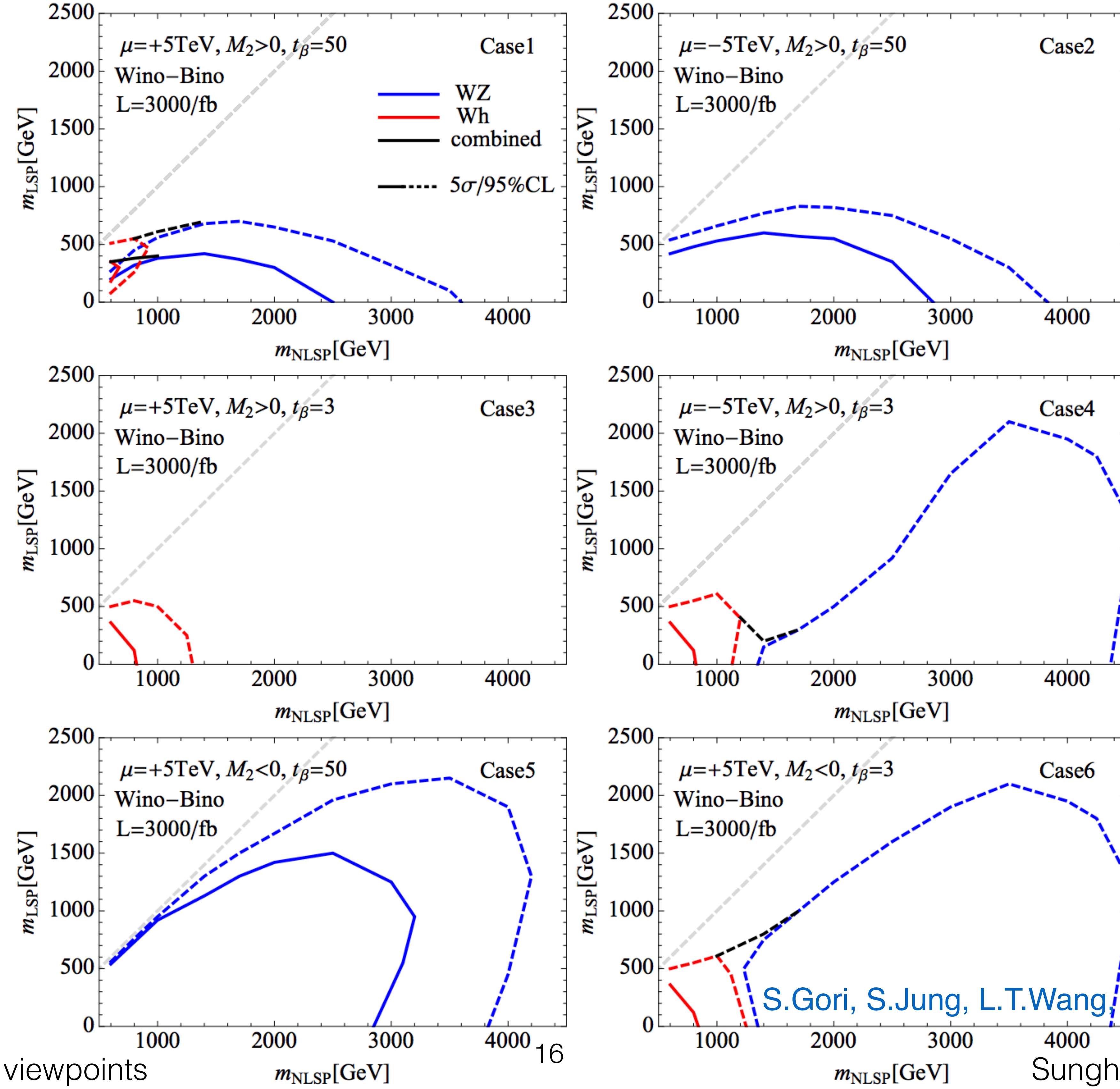
- Relaxion solutions are also *uniquely testable* at colliders.

- "Alpha Go sensei never speaks."

1. Future SUSY

Higgsino vs. gaugino
What is a resonance?

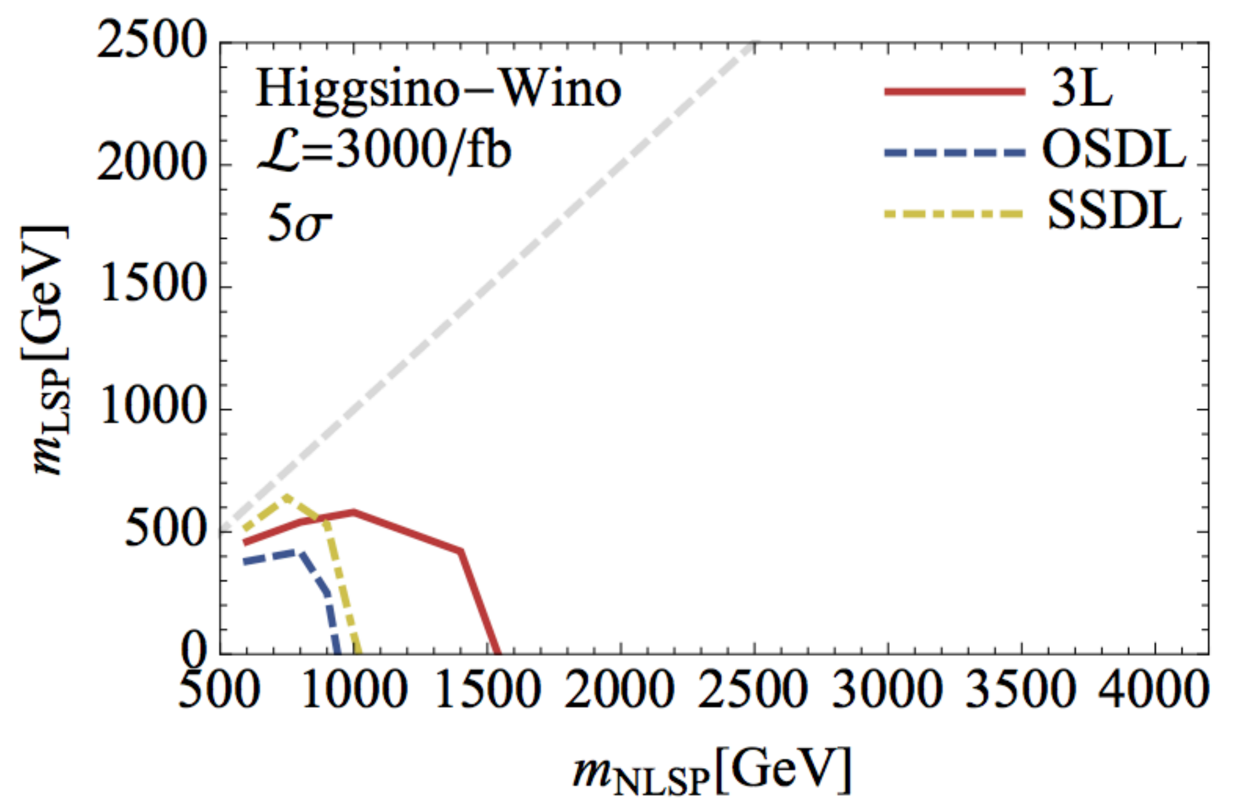
Even for TeV SUSY, pure Wino-Bino exhibit so much varieties of results!



S.Gori, S.Jung, L.T.Wang, J.D.Wells, 1410.6287

But Higgsino is different;
One plot is enough!

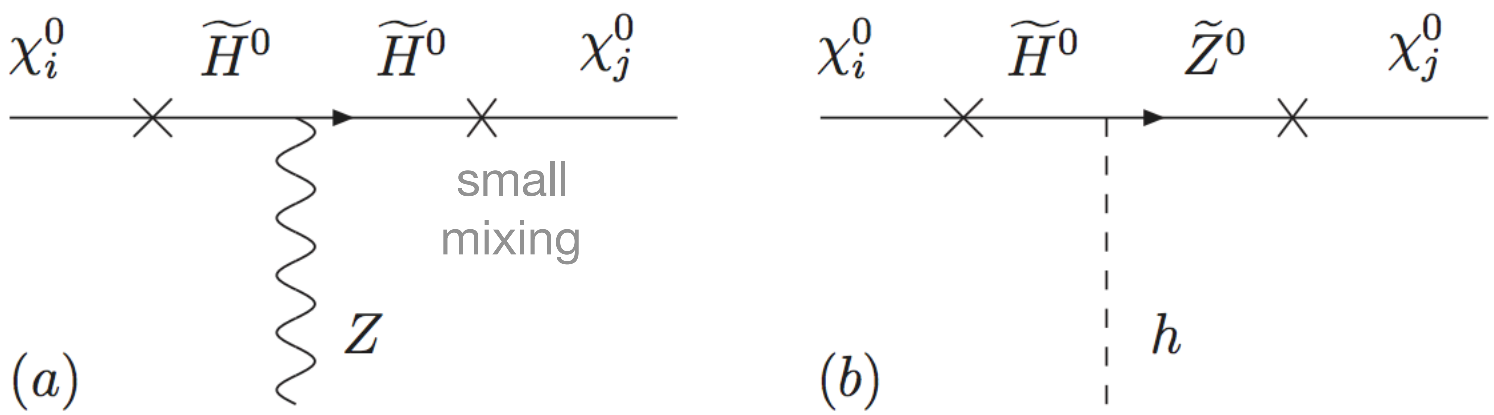
One plot is enough with Higgsino (if either LSP or NLSP).



BR(h) = BR(Z) (~0.5 instead of 1), always!

The reason is that Higgsino's couplings to h and Z are inherited by the same one.

Higgsino **Zino**



(a) << (b) ?

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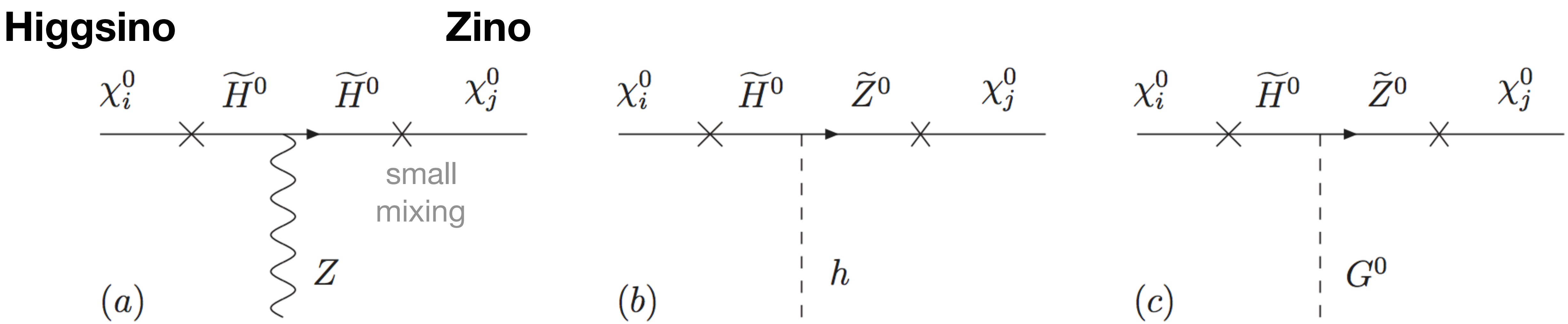


(a) << (b) ?

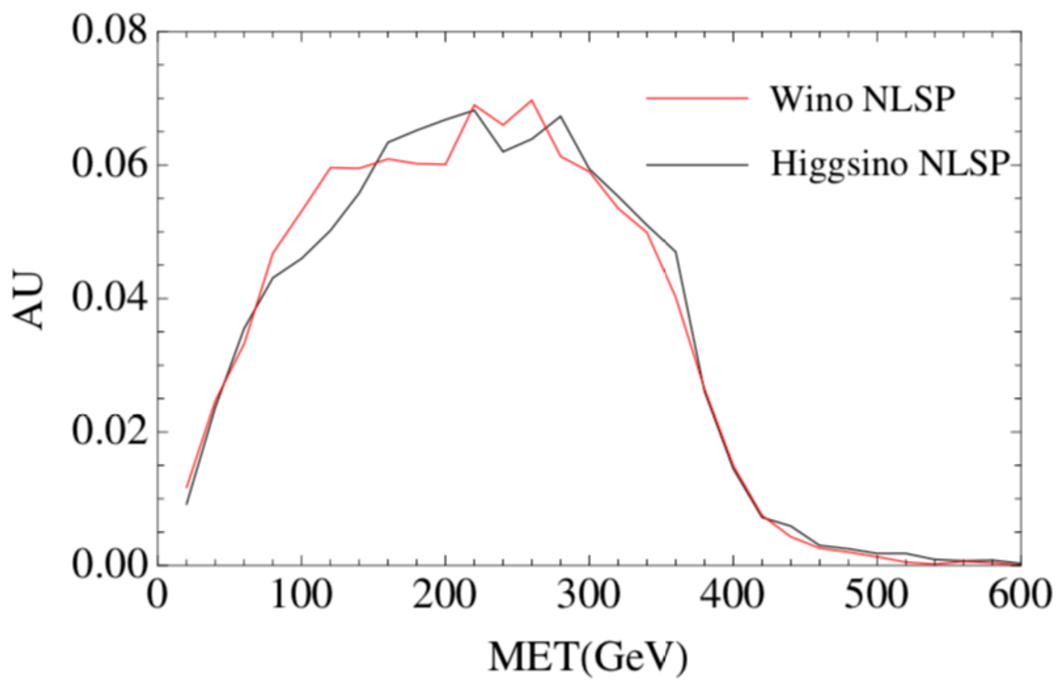
No. (a) = (c) ~ (b).

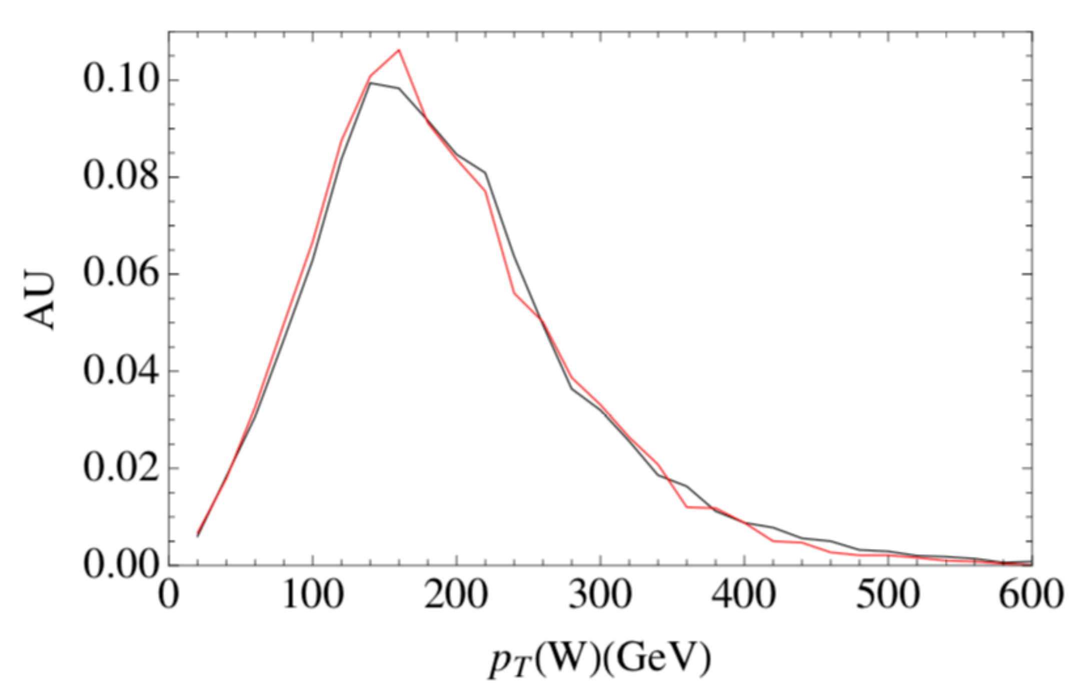
"Goldstone equivalence theorem"
inherently relates the Higgsino couplings to Z and h.

This becomes more and more accurate at higher energy,
hence more relevant at future collider experiments.

Implication to LHC Inverse Problem

Typical LHC Inverse Problem.



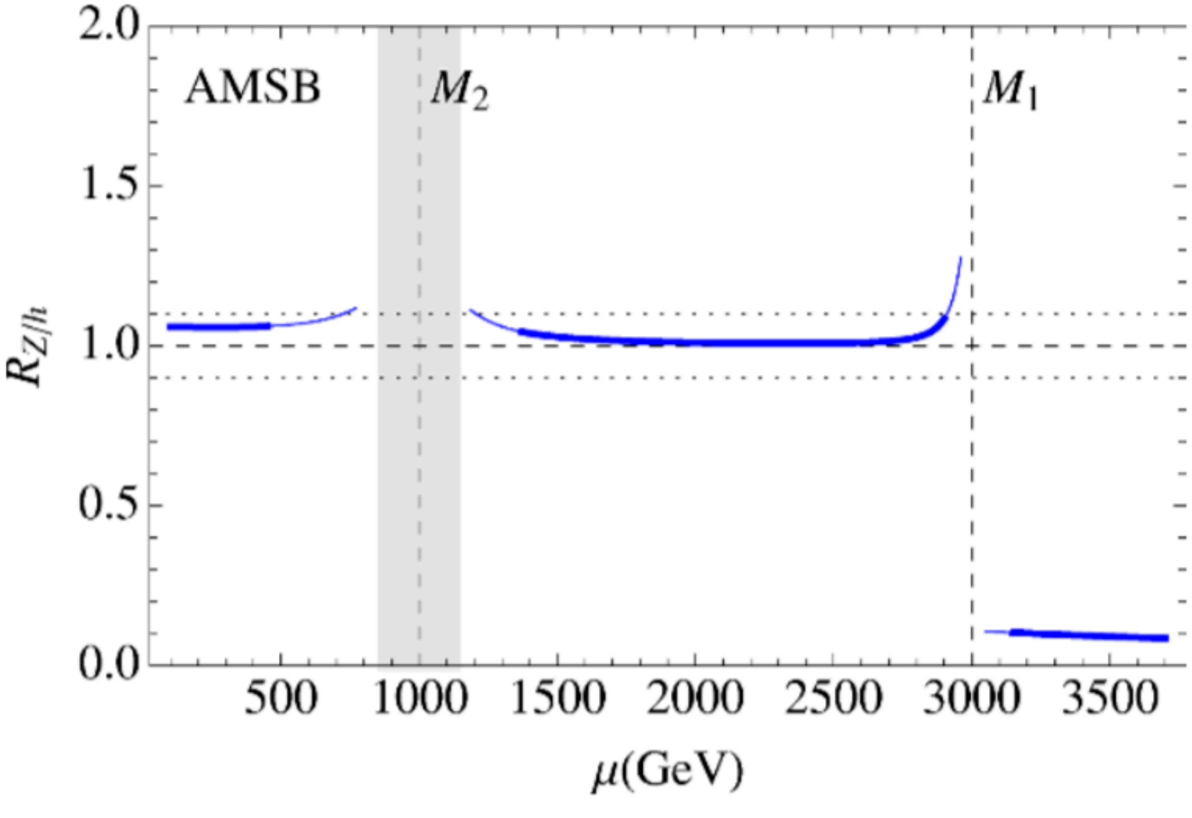


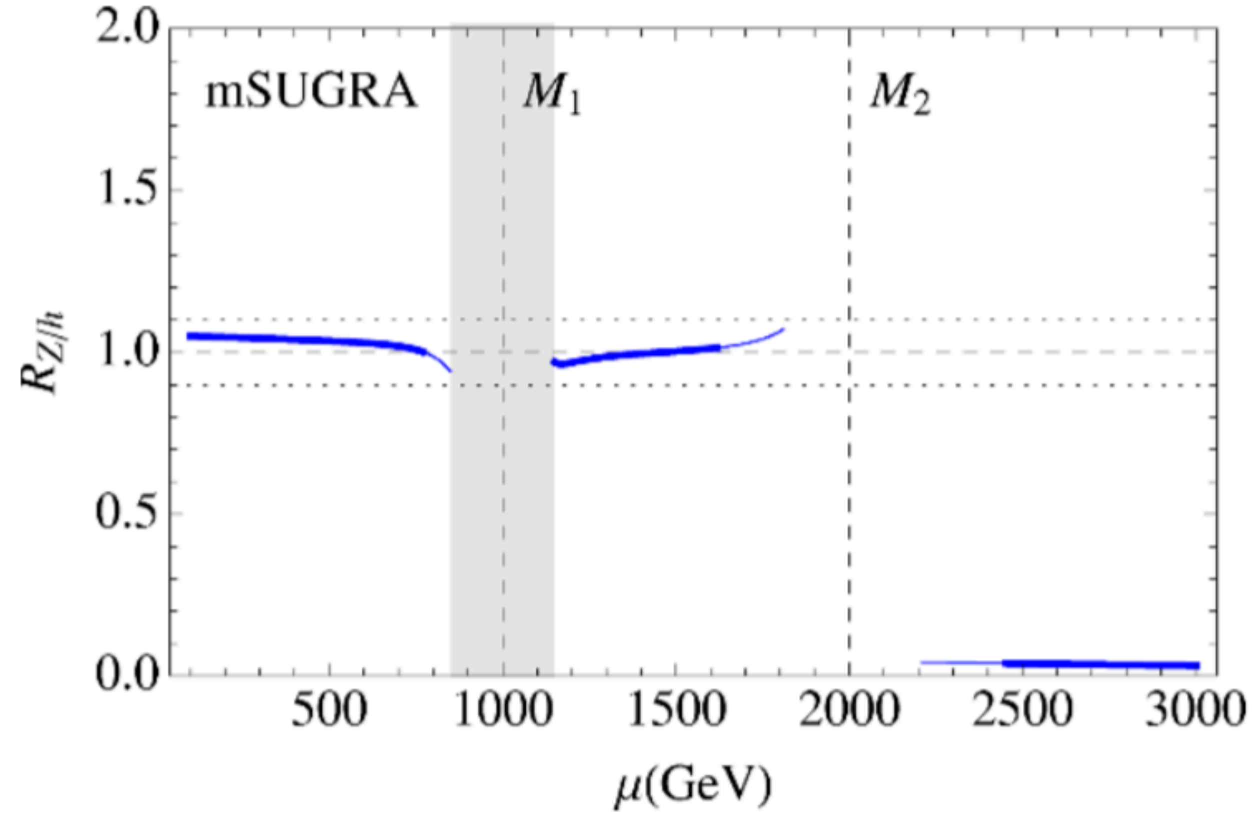
Model	parameters (M_1, M_2, μ, t_β)	$\sigma(W^+W^-)$	$\sigma(W^\pm Z)$	$\sigma(ZZ)$
Wino-NLSP	0.5 TeV, 1.0 TeV, −2.0 TeV, 4.3	0.60 fb	1.1 fb	0 fb
Higgsino-NLSP	0.2 TeV, 2.0 TeV, 0.8 TeV, 2.0	0.61 fb	1.1 fb	0.02 fb

S.Jung, 1404.2691

LHC Inverse Problem with Higgsinos can be resolved.

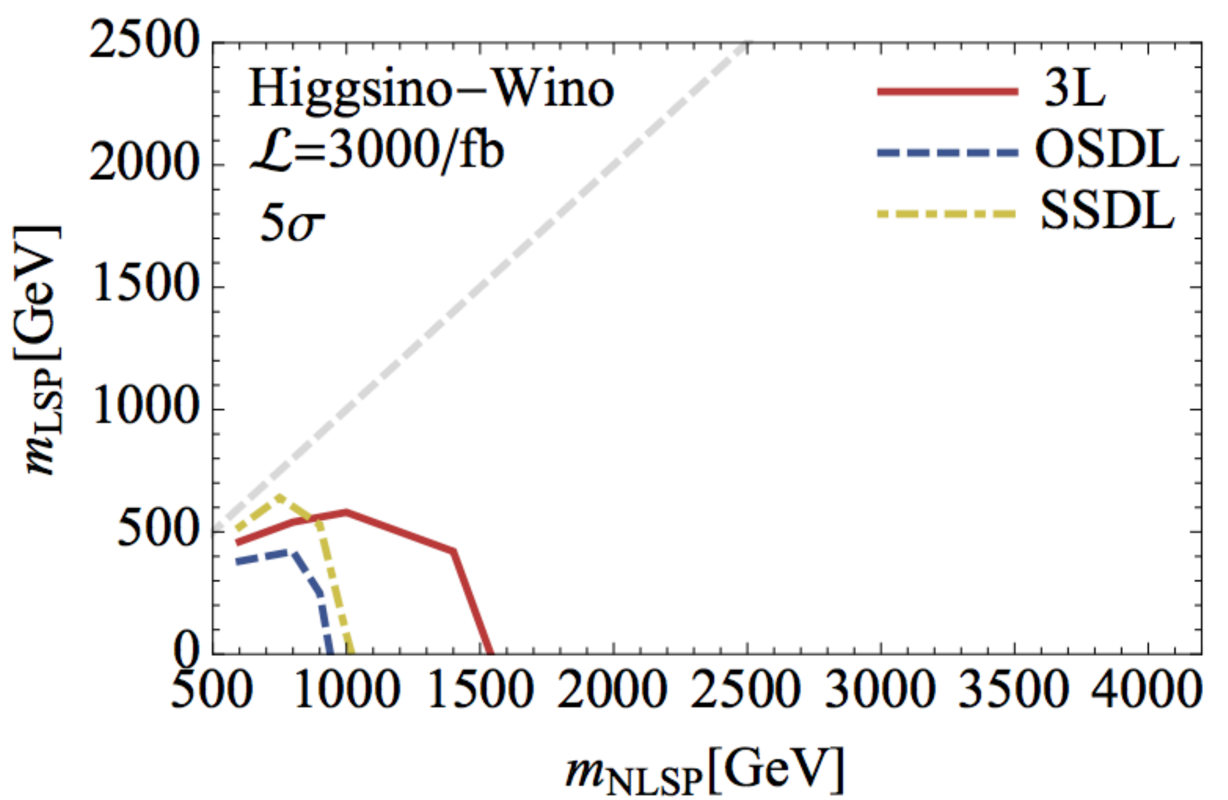
But the existence of Higgsinos lead to the same number of h and Z!





TeV SUSY comes with the electroweak symmetry restored.

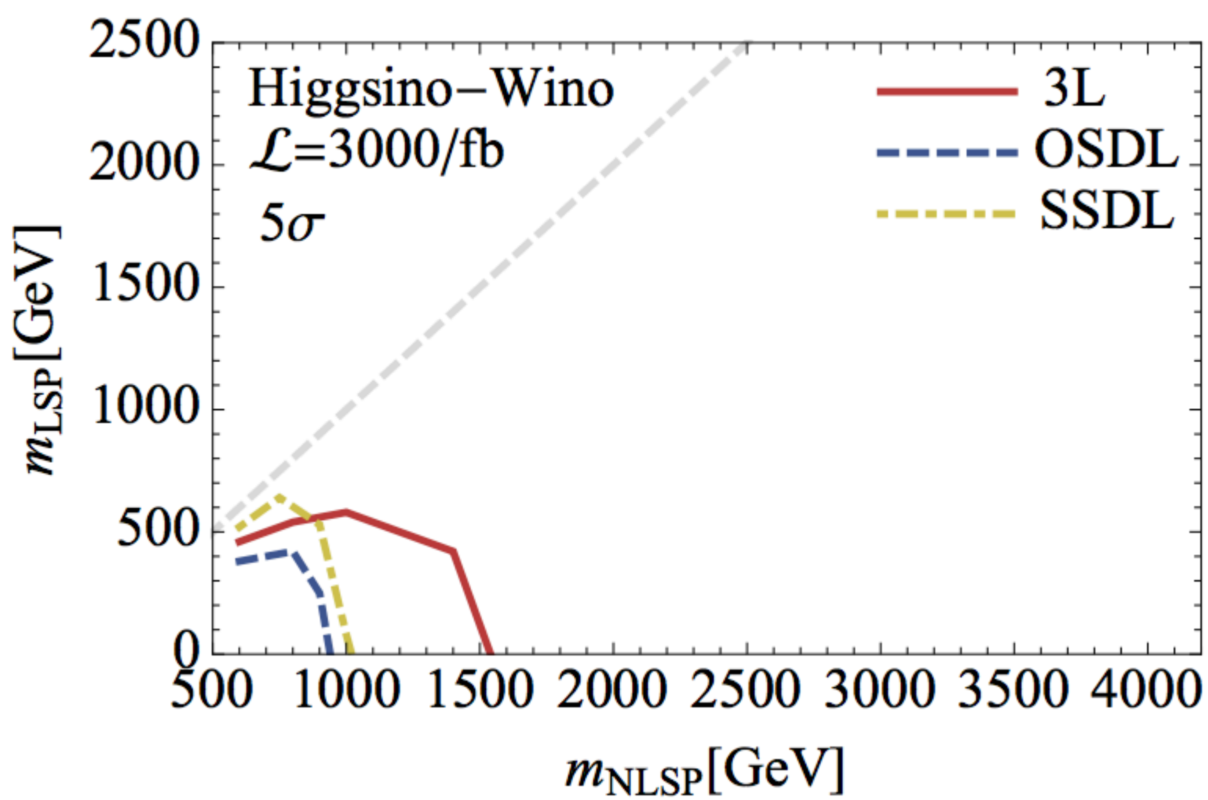
making Higgsino simplified
and unique,



Always, BR(h) = BR(Z).

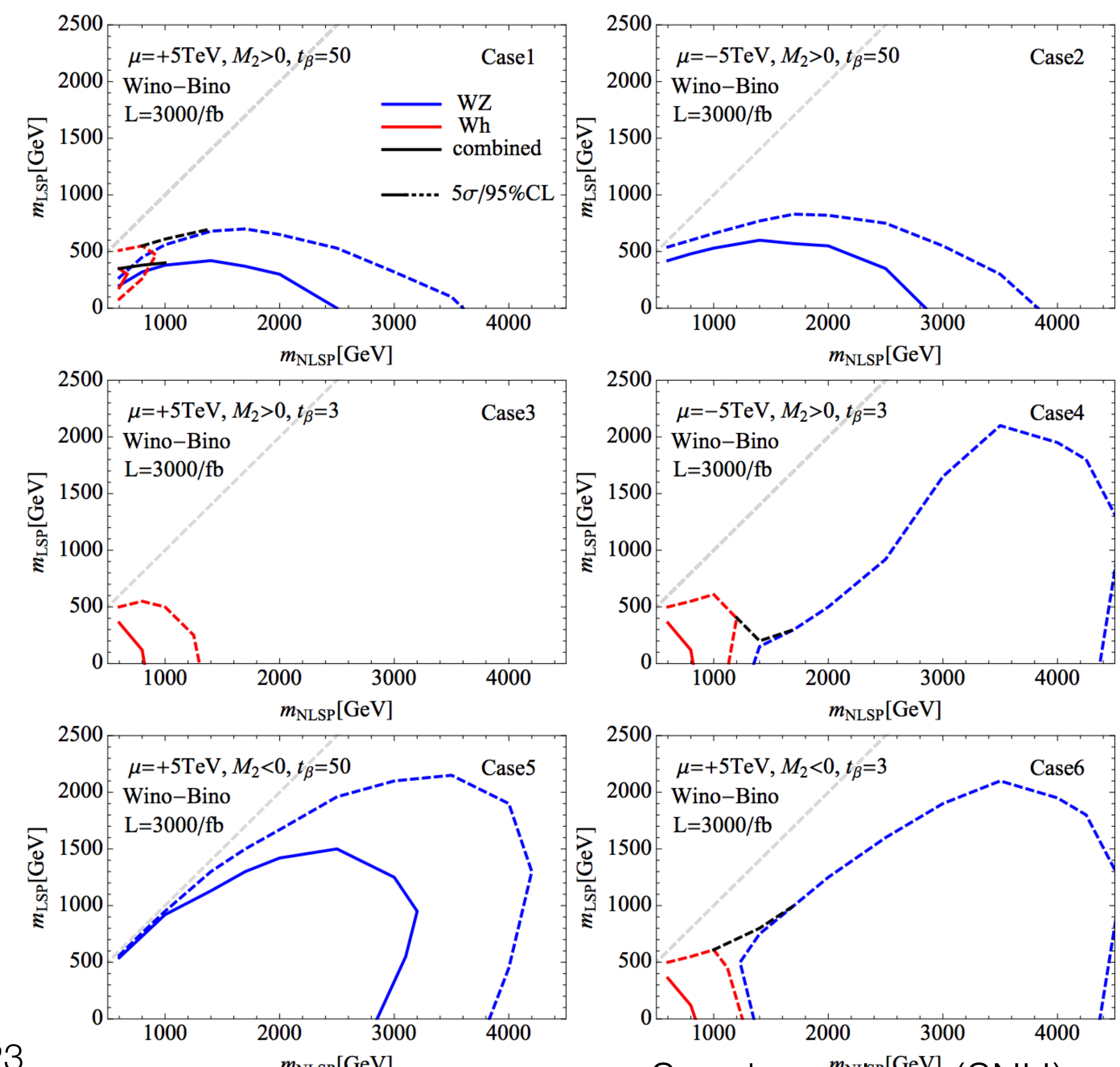
TeV SUSY comes with the electroweak symmetry (almost) restored.

making Higgsino simplified and unique,

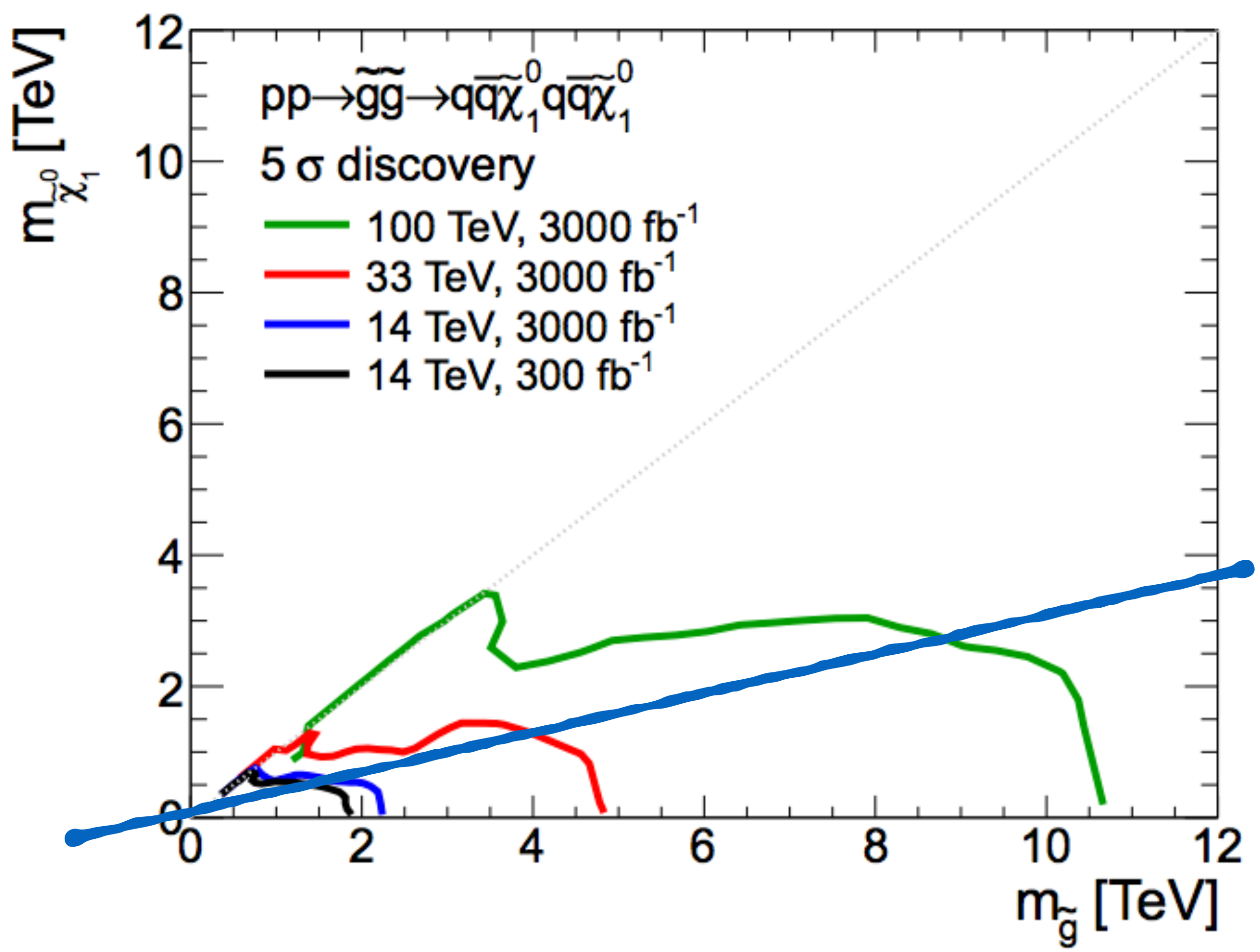


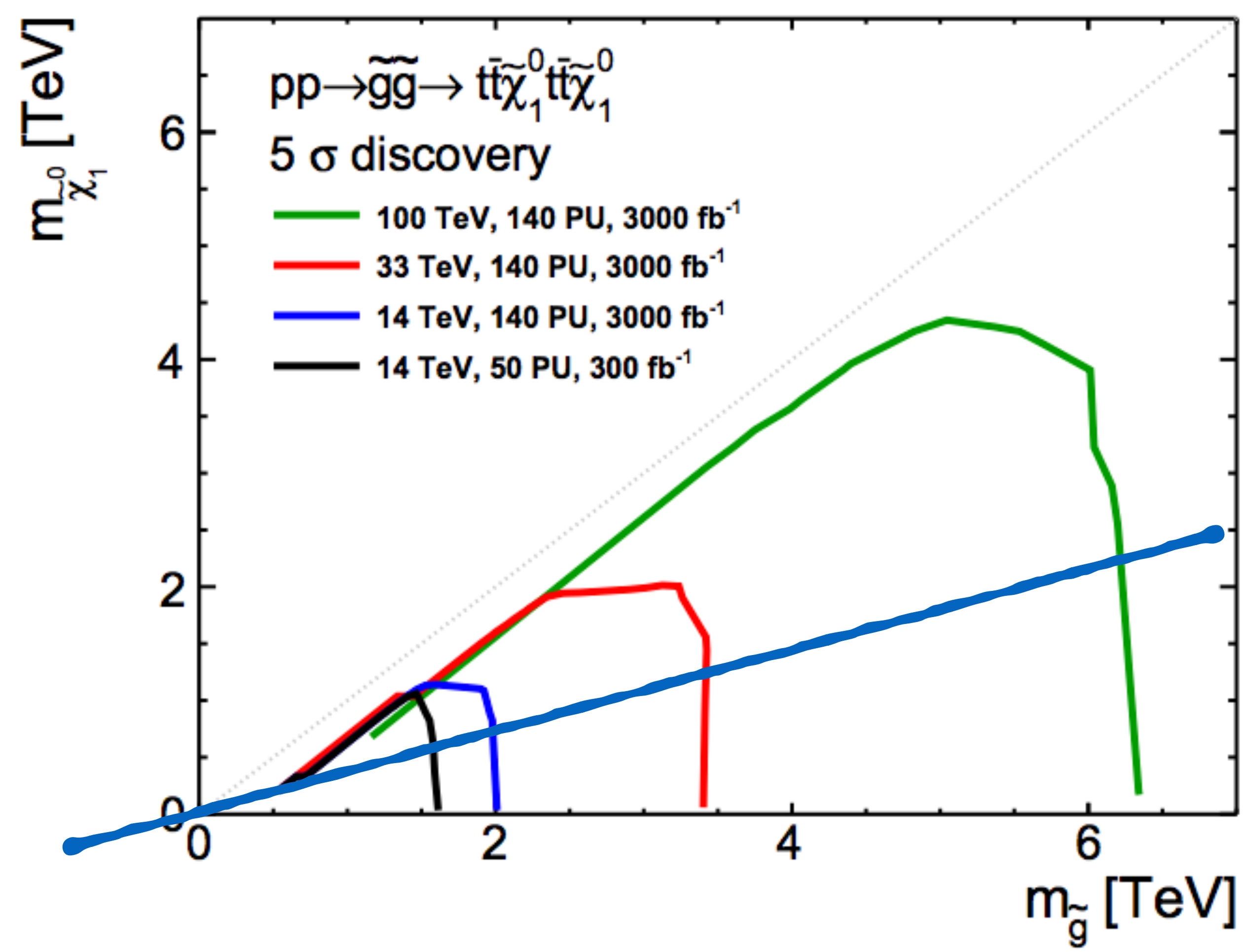
Always, BR(h) = BR(Z).

but retaining the trace of its breaking as small mixing.



Back to gauginos, in TeV SUSY, what matters is the m(gluino).





T. Cohen et al.

As long as m(gluino) > (2~3) m(LSP), only m(gluino) matters in the search kinematics.

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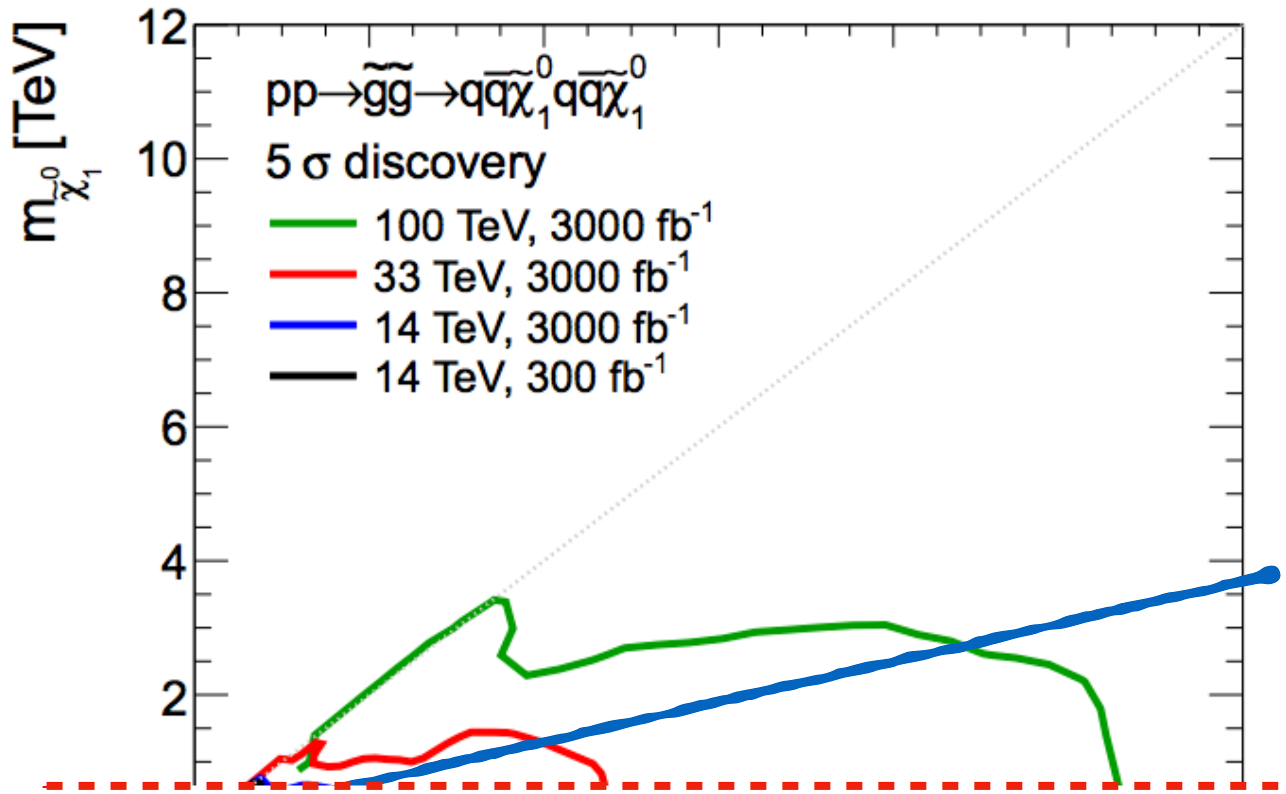
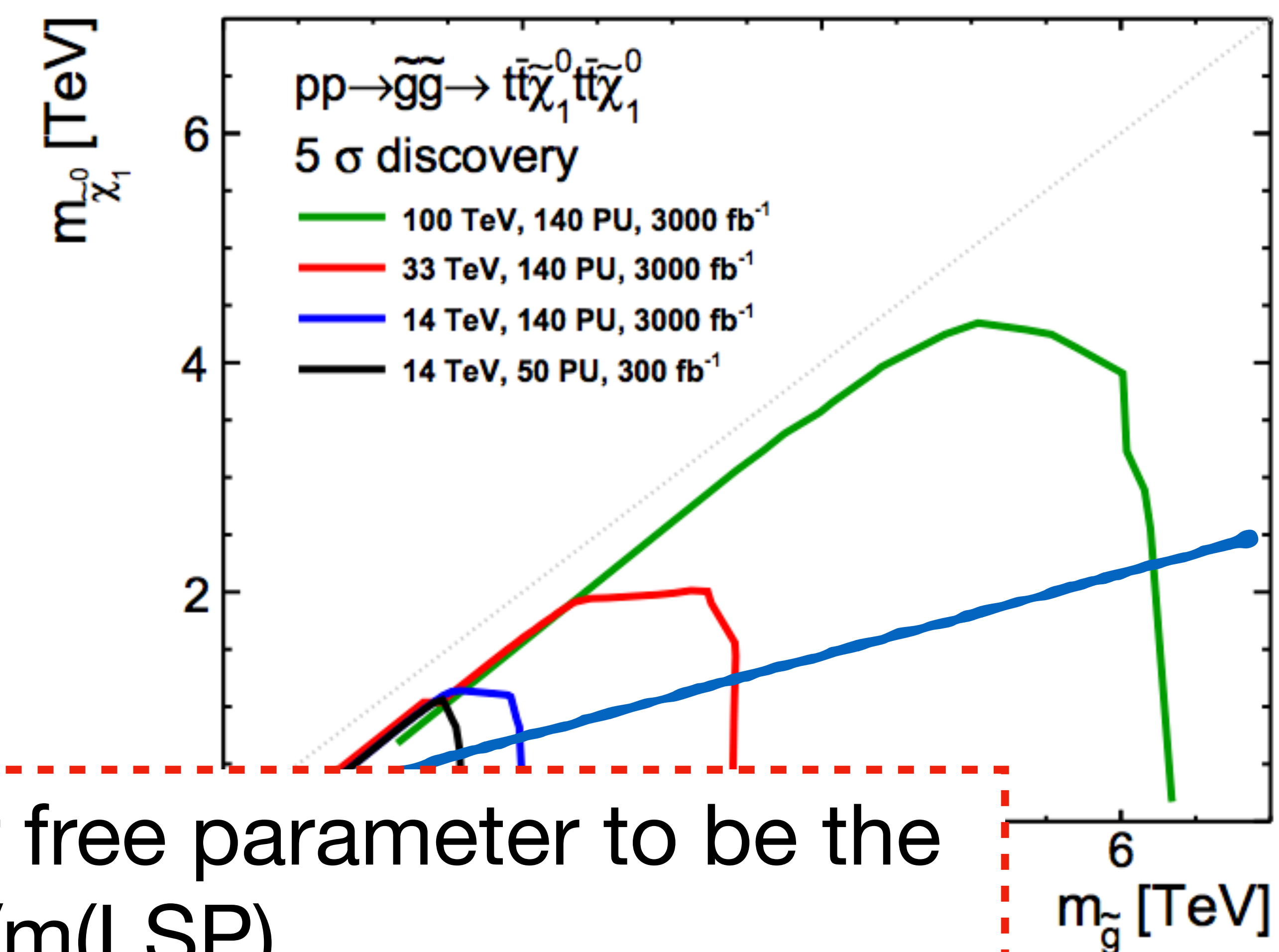




It is useful to exchange the other free parameter to be the "gaugino mass ratio": m(gluino)/m(LSP).

As long as m(gluino) > (2~3) m(LSP),
only m(gluino) matters in the search kinematics.

Gaugino code

K.Choi, H.P.Nilles, 0702146

$$\text{mSUGRA pattern} \;:\quad M_a \propto \frac{\alpha_a}{4\pi}\Lambda$$

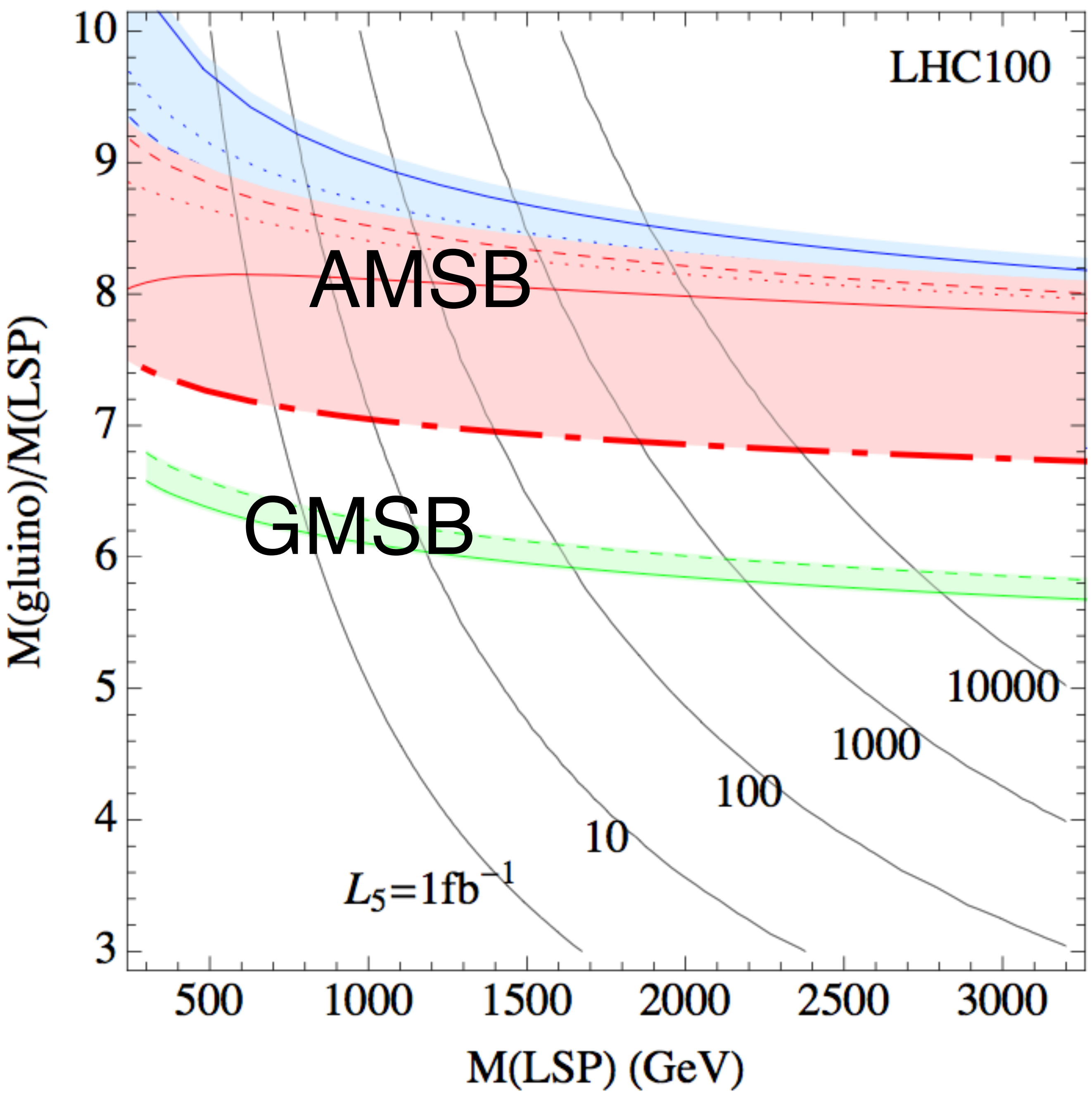
$$\text{AMSB pattern} \;:\quad M_a \propto \frac{b_a \alpha_a}{4\pi} m_{3/2}$$

$$\text{mirage pattern} \;:\quad M_a \propto \frac{\alpha_a}{4\pi}\left(b_a + \frac{1}{0.1\alpha}\right) m_{3/2}$$

Gaugino mass ratios are characteristic variables of ~~SUSY~~ mediation.

Gauginos are most model-independent fields.

A useful presentation, probing ~~SUSY~~ mediation

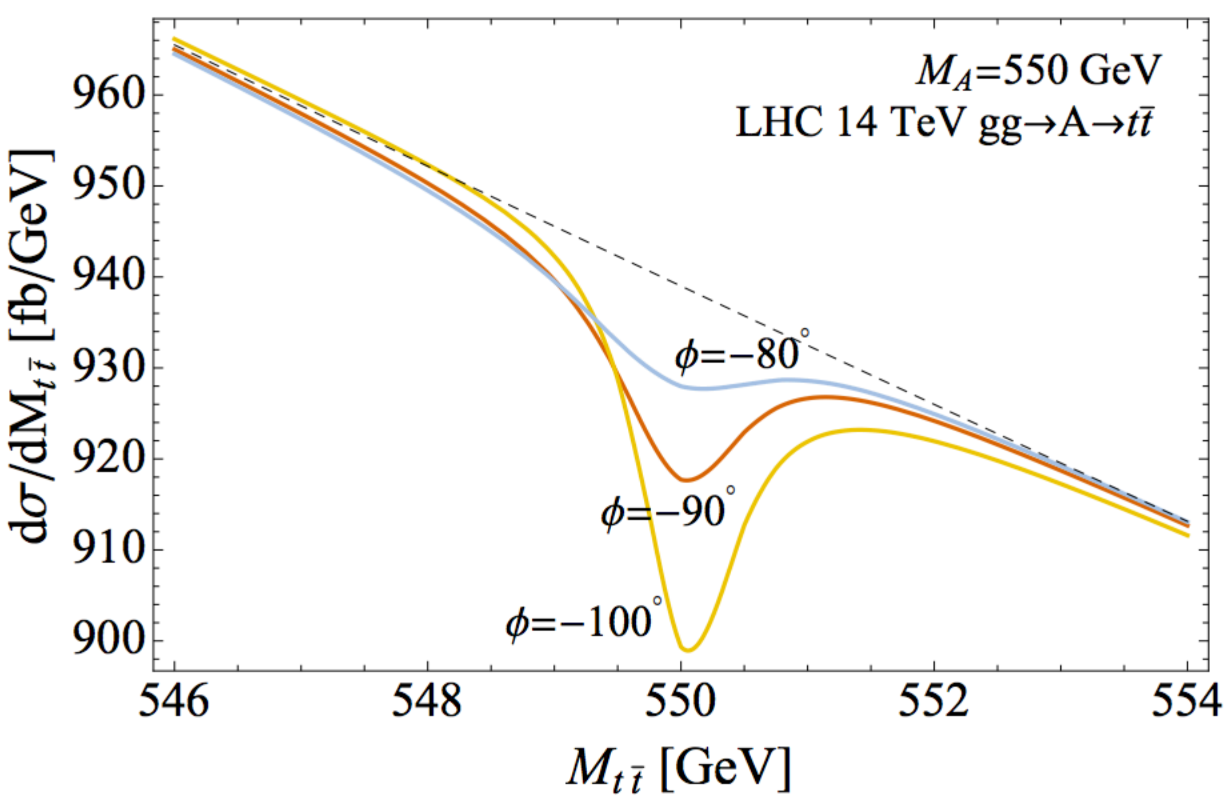


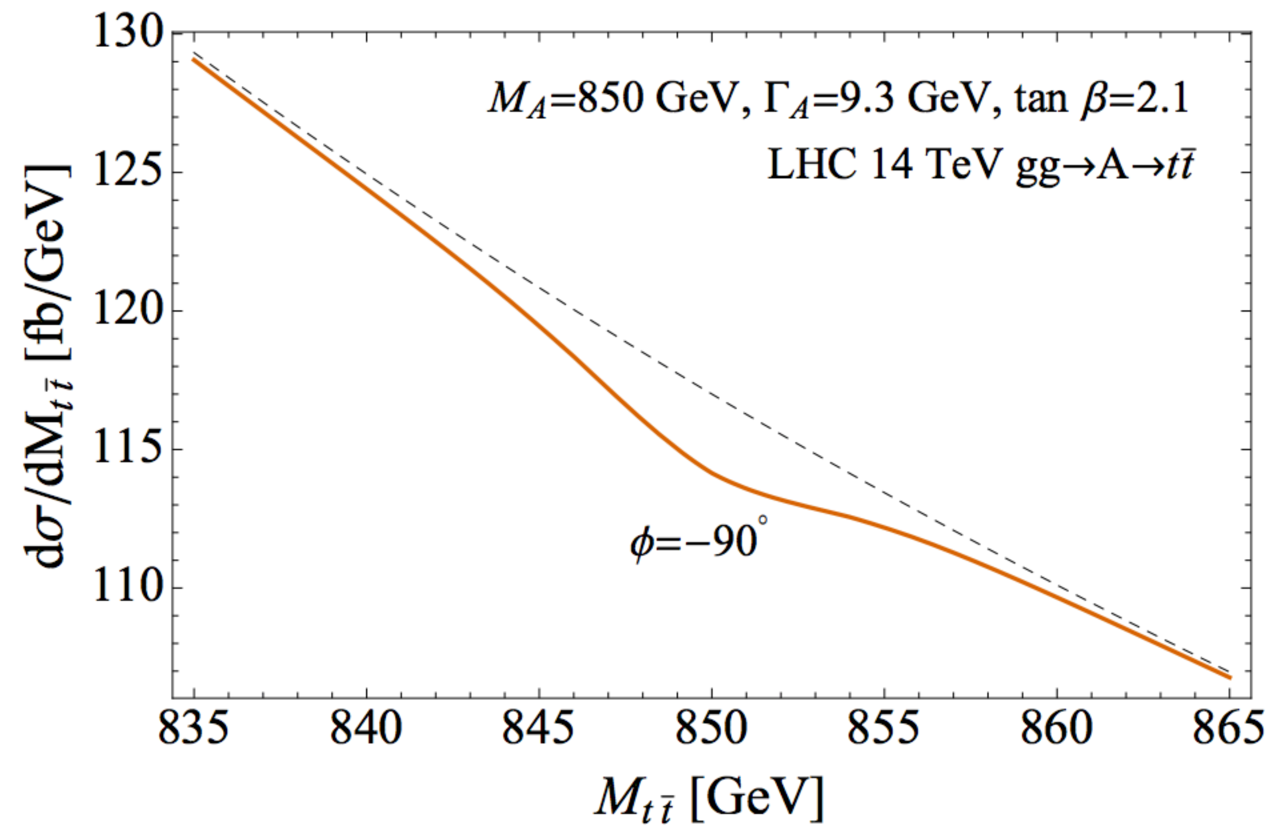
This is a useful way to present SUSY search results (gluino pair in this case).

S.Jung and J.D.Wells, 1312.1802

In TeV SUSY, heavy Higgs bosons are generically NOT resonance peaks.

gg > H, A > ttbar

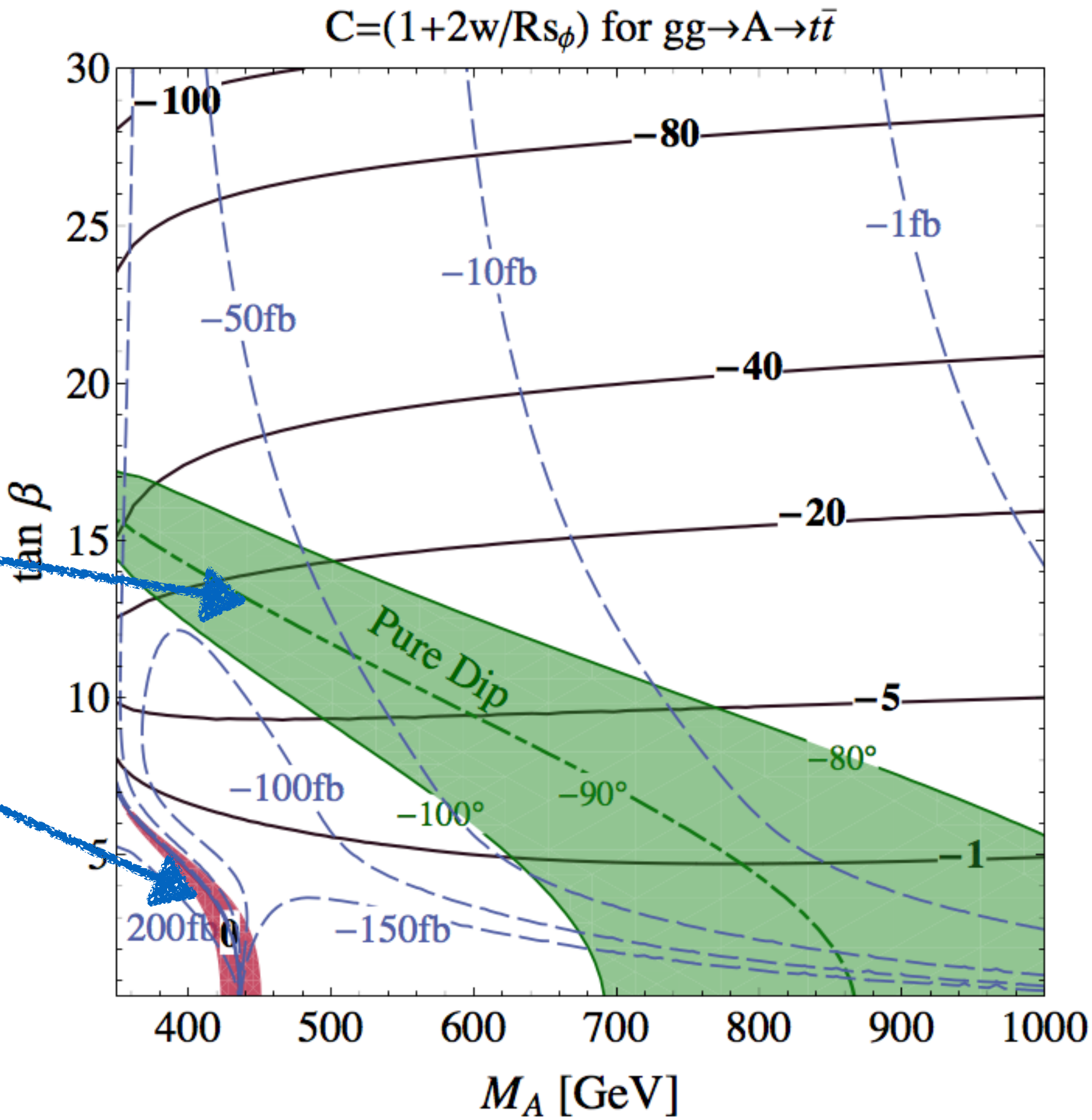




Even a pure dip or nothingness is not only possible but generic.

In TeV SUSY, they are generically NOT resonance peaks.

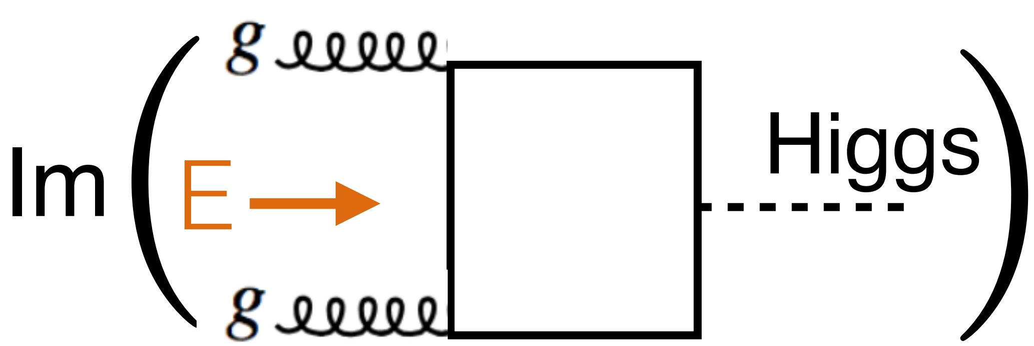
- No pure peak anywhere!
- Pure dip and nothingness regions.
- Generic in energy-frontier future colliders.

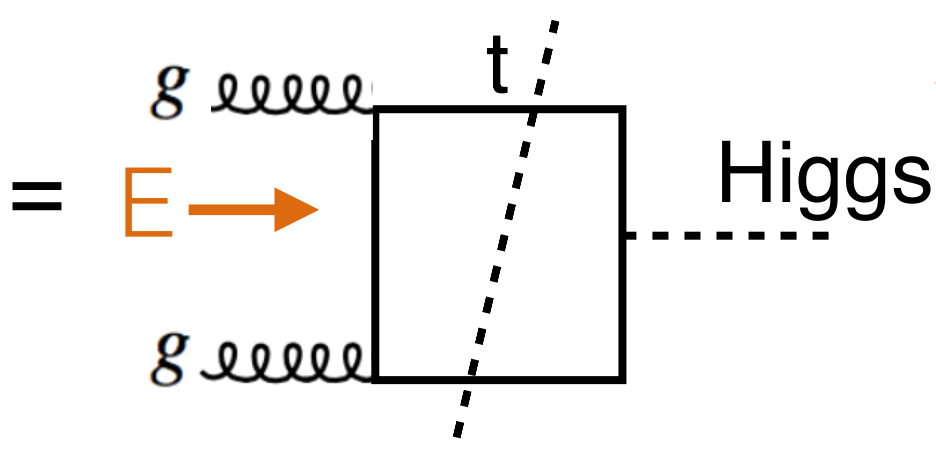


S.Jung, J.Song, Y.W.Yoon, 1505.00291

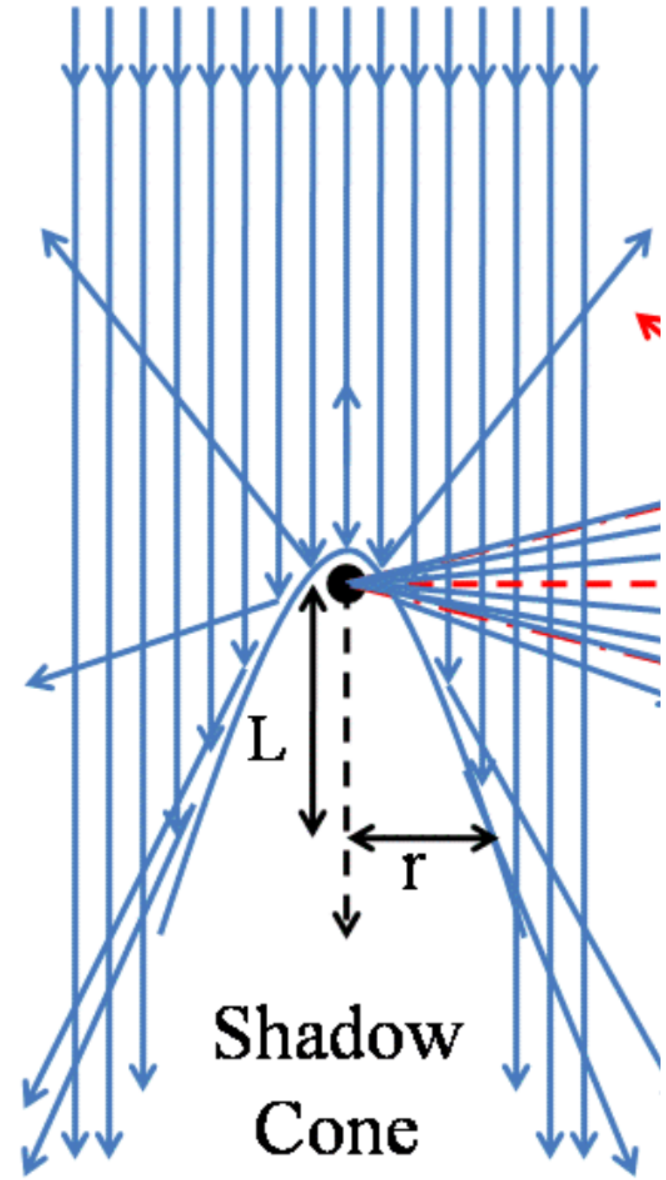
Analogous to Shadow scattering

Attenuation of forward-going wave (shadow)
= Imaginary part of forward-scatt. amplitude





$$E = m_{\text{Higgs}} > 2m_{\text{top}}$$



Above all, new search method is needed.

1. Resonance shape is not Breit-Wigner any more.
2. Peak and dip may cancel in the binning of invariant mass.
3. Narrow-width approximation (NWA) is wrong

   $\sigma(H/A) \cdot BR(H/A \to t\bar{t})$ cannot be used anymore!

Why haven't seen so far?

- 1. Narrow resonances:

  - Complex interference is linear in width.
  - Small width from small mass, small number of decay modes.

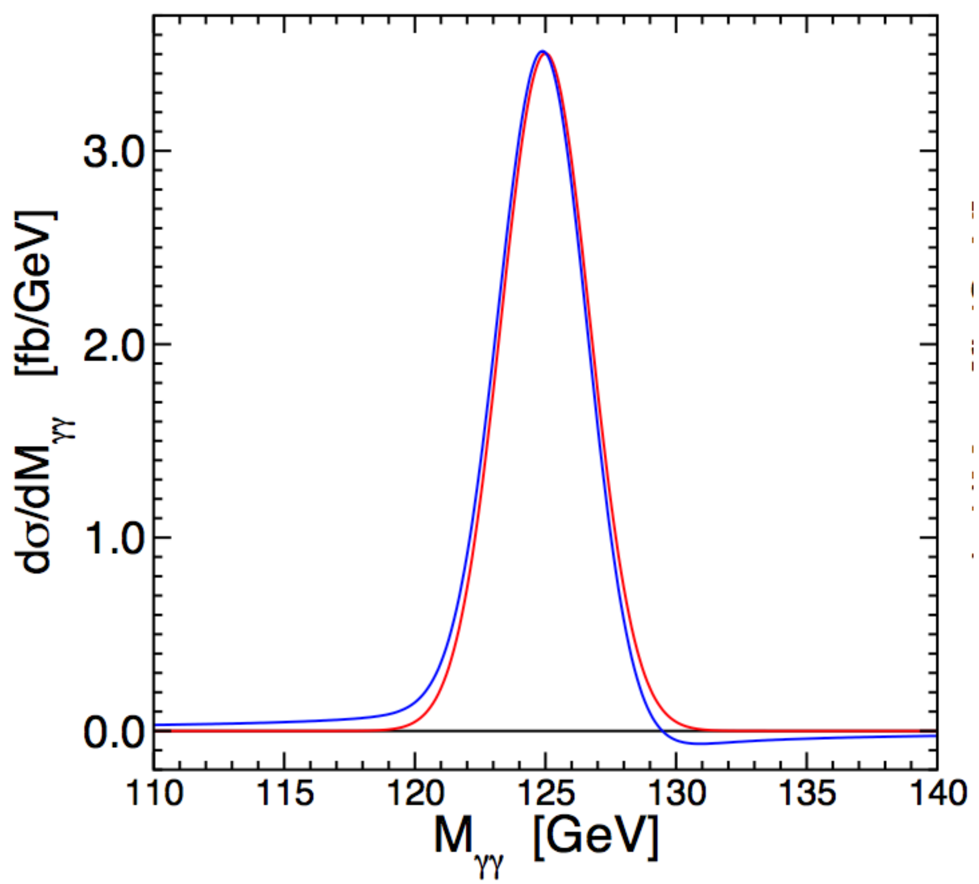
- 2. Small complex phase:

  - Either tree-level decays or no Cutkosky cuts.

Thus, will be generic for future heavy new particles!

Milder interference is also important

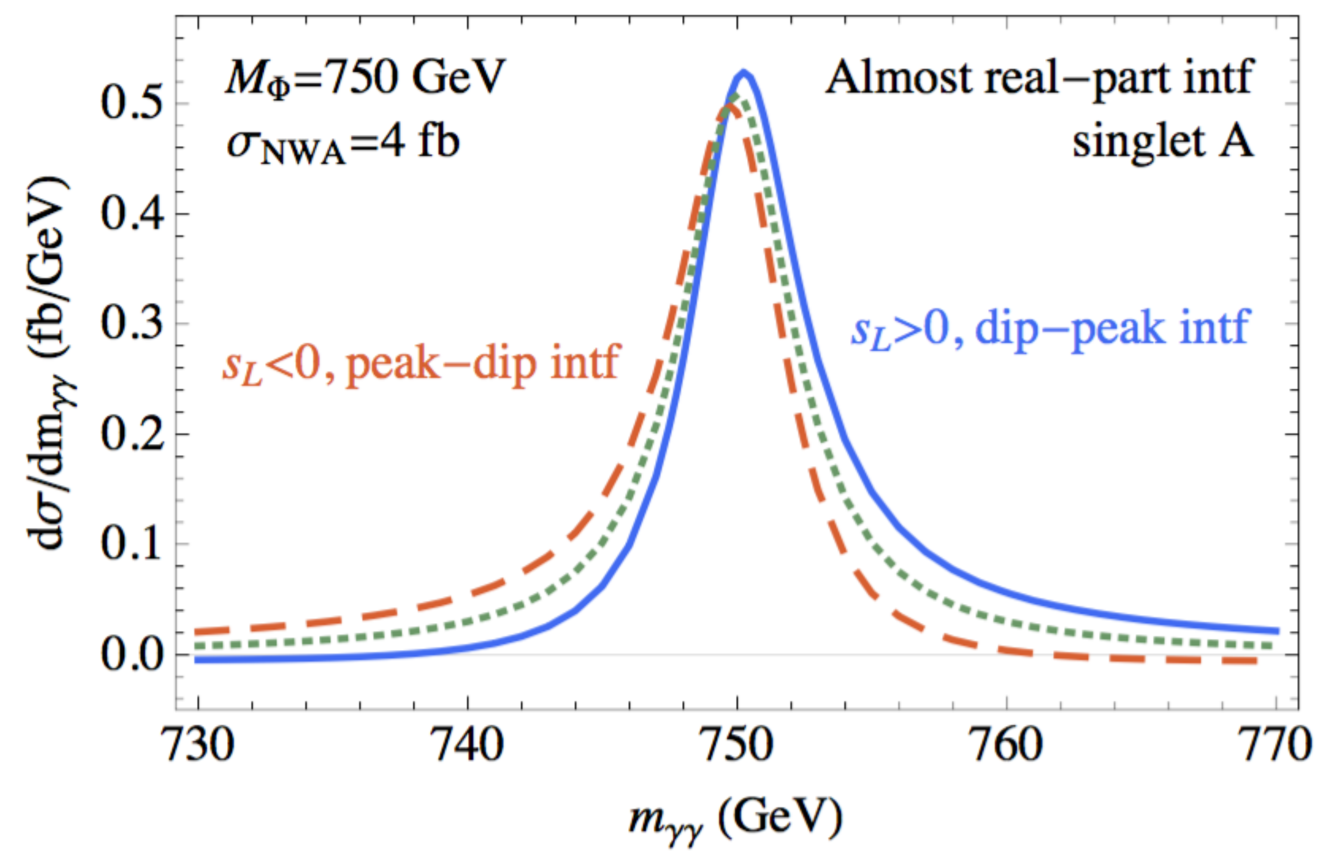
125 GeV SM Higgs



~70 MeV shift to the mass of the (narrow) Higgs.

L.Dixon et al, PRL(2013)

750 GeV diphoton resonance was thought to be *broad*.



Pole shift and peak enhancement had to be accounted, but none did.

S.Jung, J.Song, Y.W.Yoon, 1601.00006

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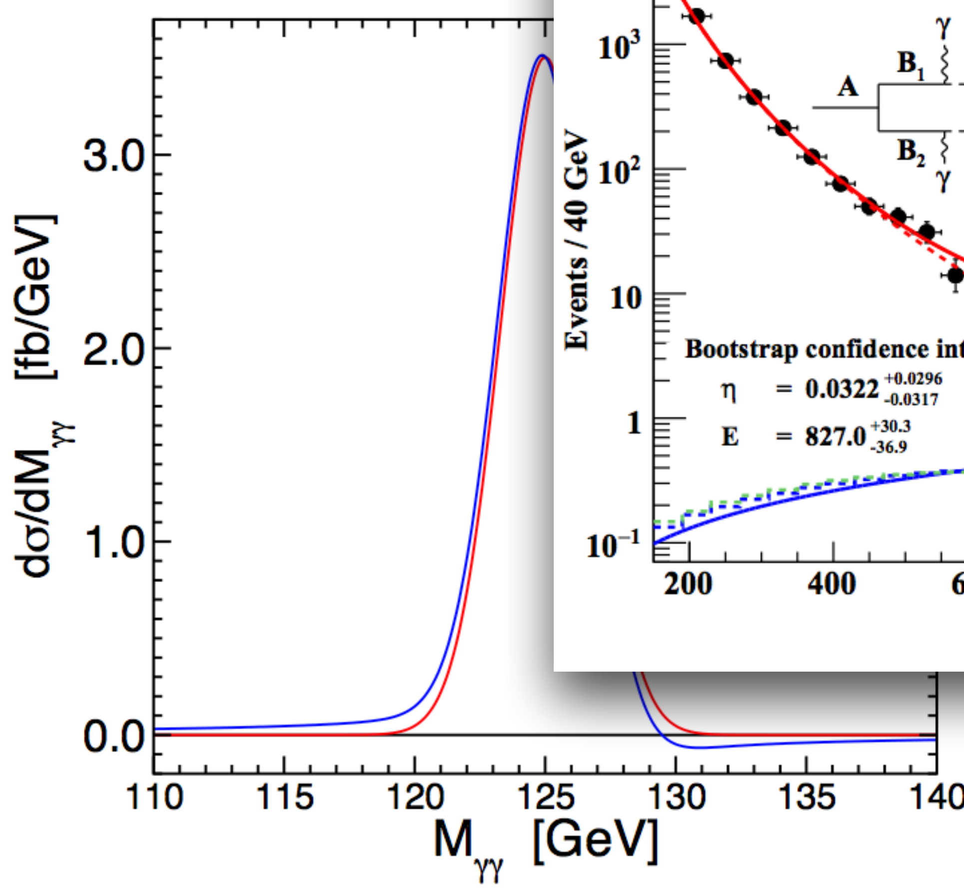
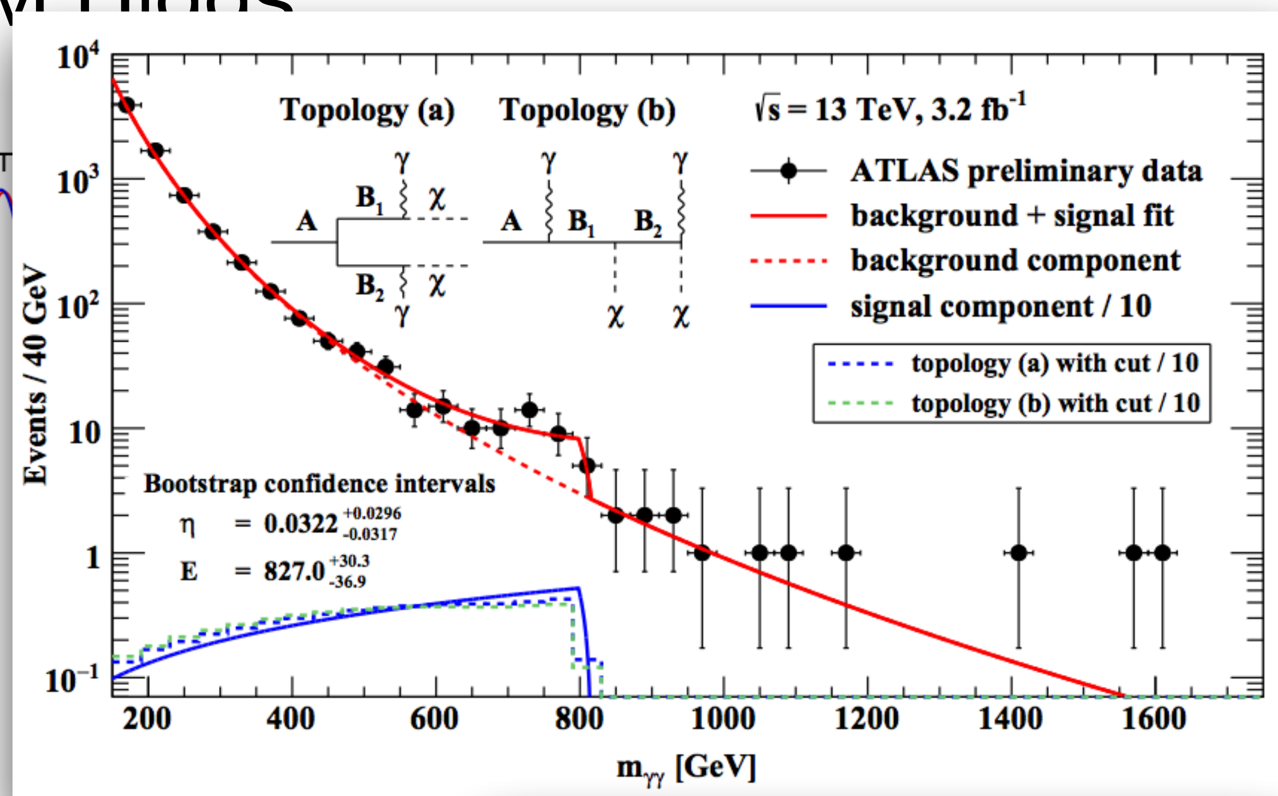
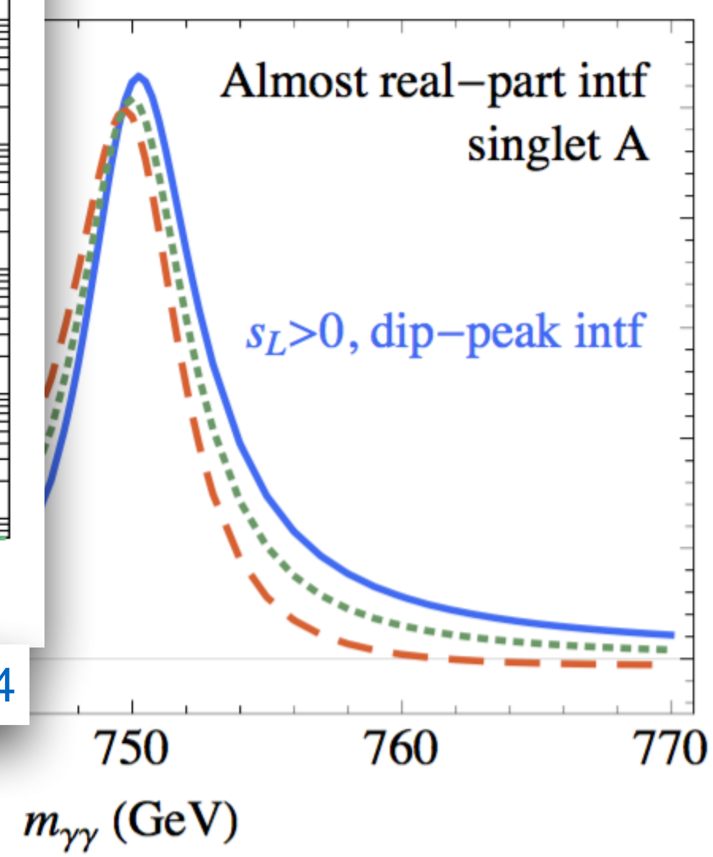




W.S.Cho, J.C.Park et al,1512.06824



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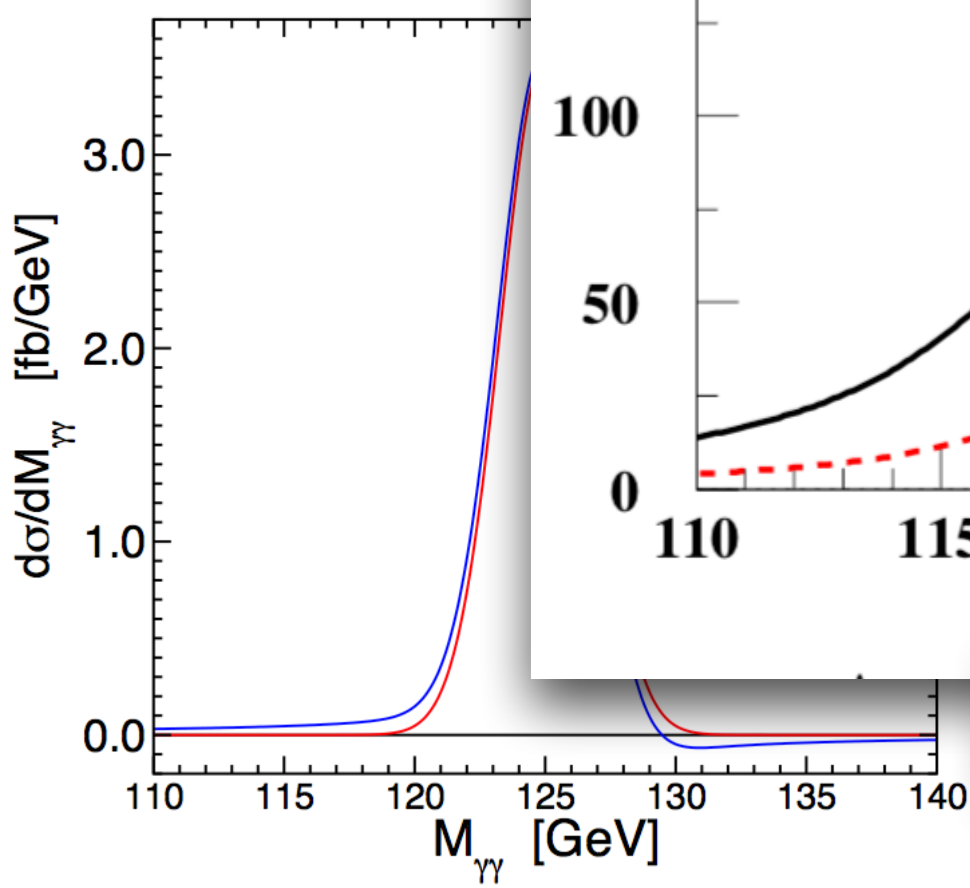
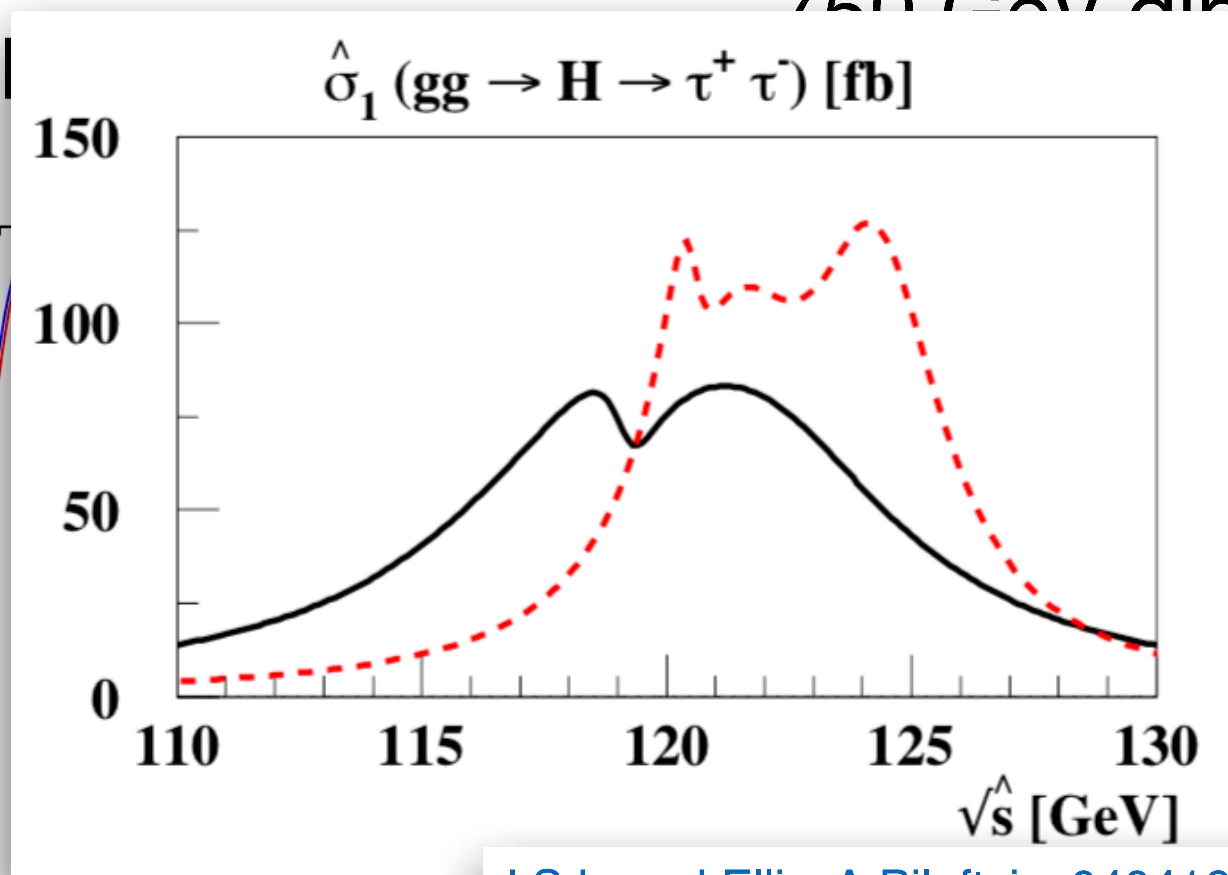
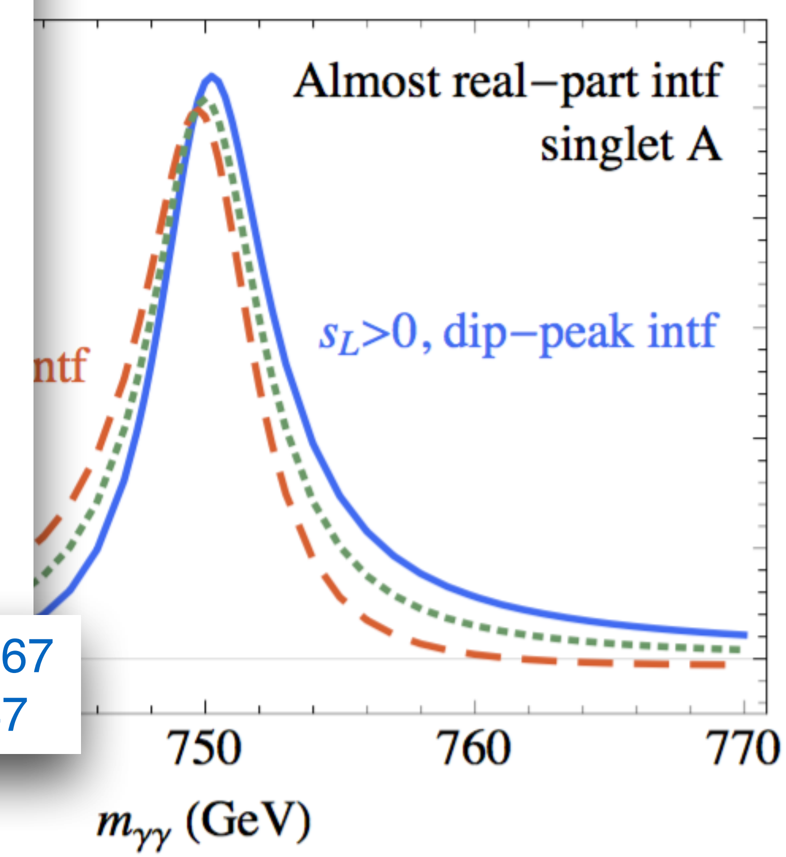




J.S.Lee, J.Ellis, A.Pilaftsis, 0404167
S.Y.Choi, P.Zerwas, et al, 0407347



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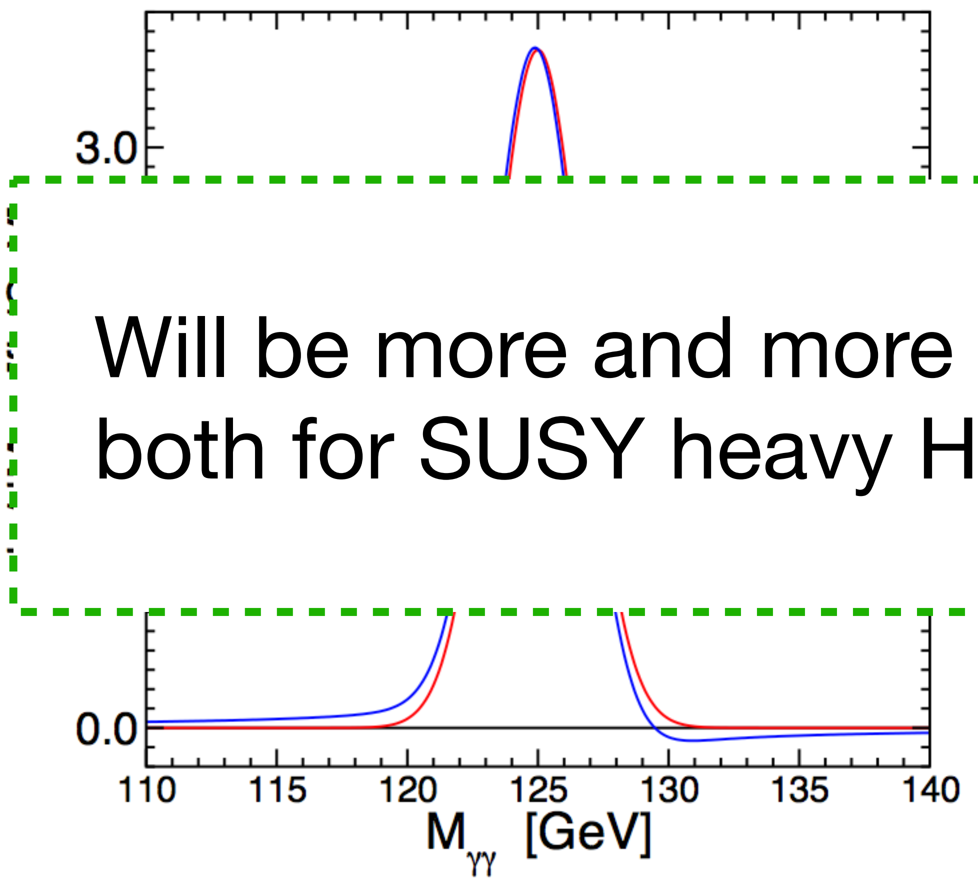
Milder interference is also important

125 GeV SM Higgs



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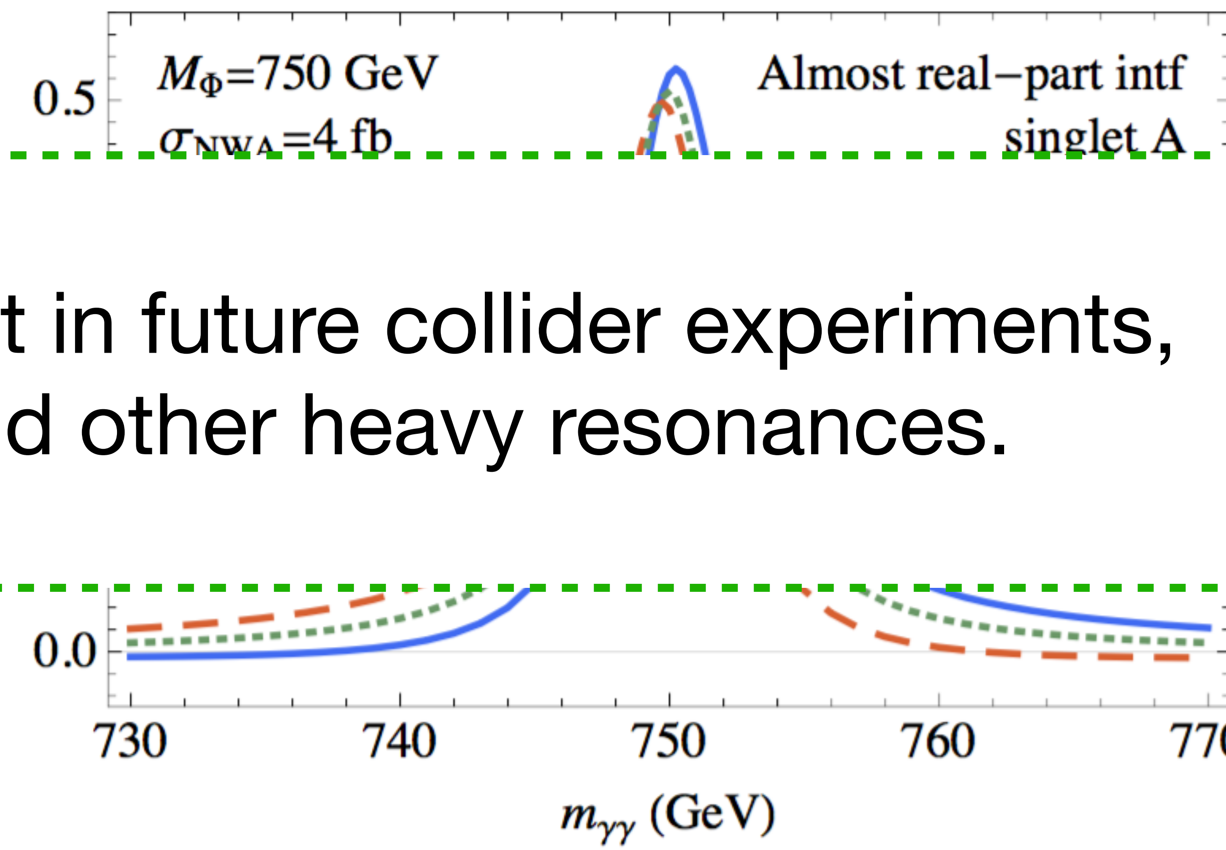

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S.Jung, J.Song, Y.W.Yoon, 1601.00006

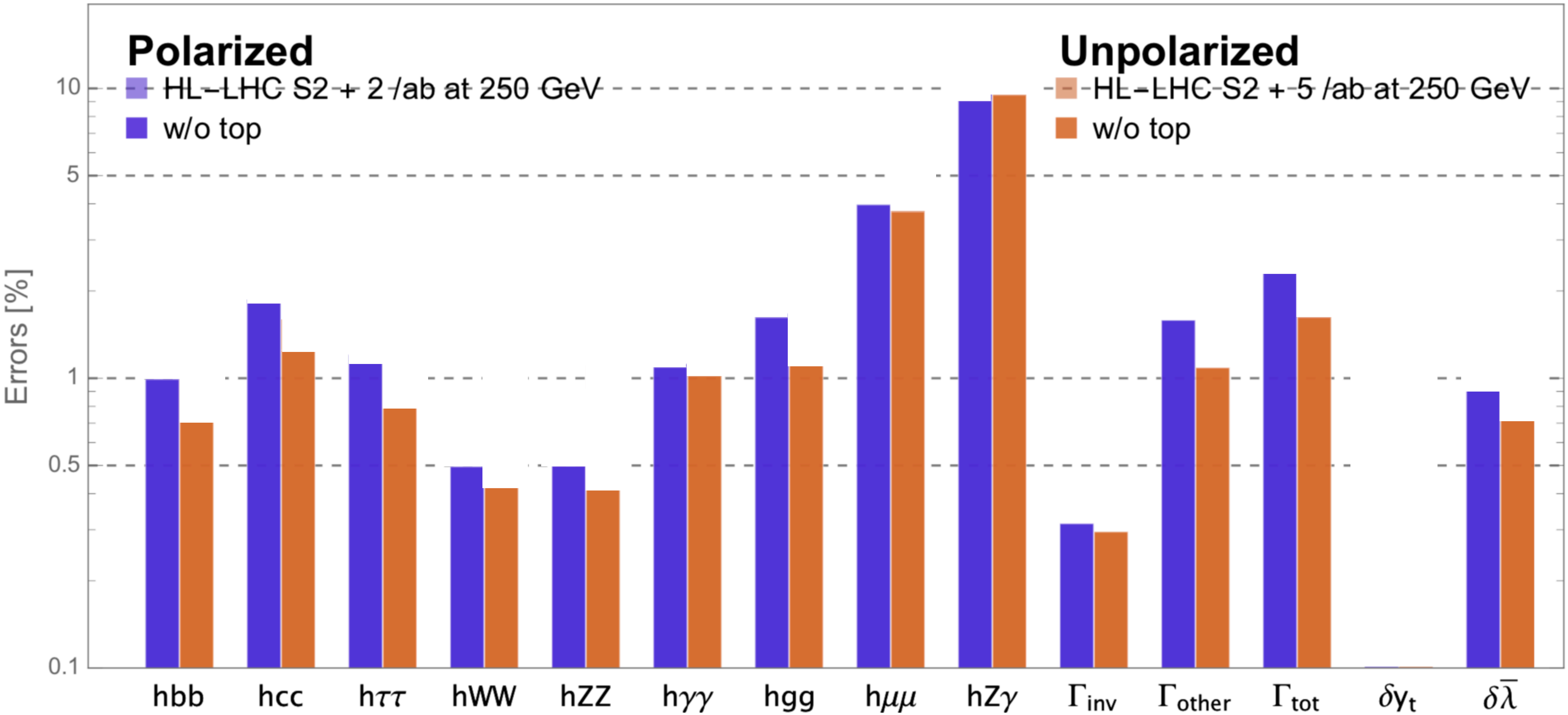
Will be more and more relevant in future collider experiments, both for SUSY heavy Higgs and other heavy resonances.

2. Higgs precision

Polarization!

Model-independent formalism

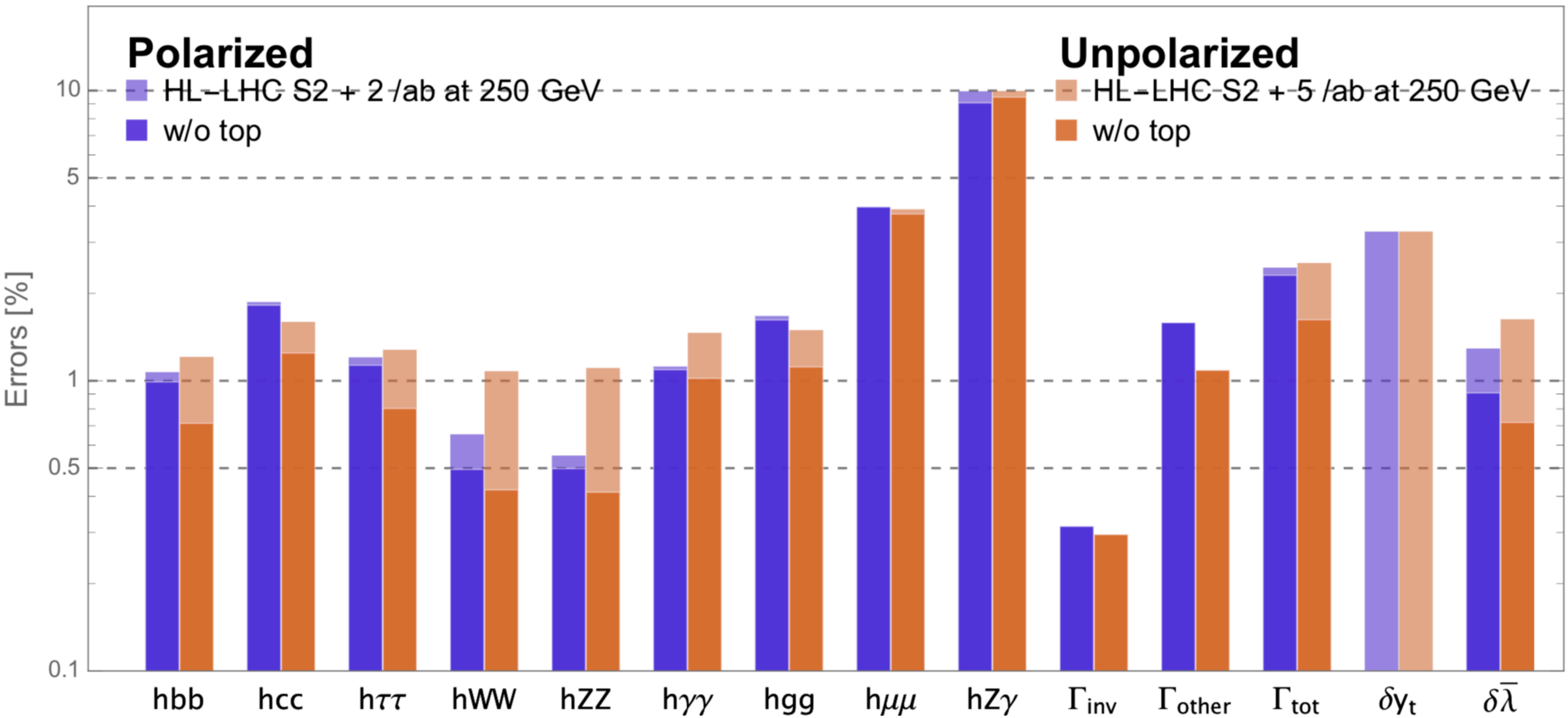
Higgs coupling precision



ILC polarization is thought to be compensated by FCC-ee/CEPC Z-pole and luminosity.

S.Jung, J.Lee, J.Tian, M.Vos, 1909.xxxxx

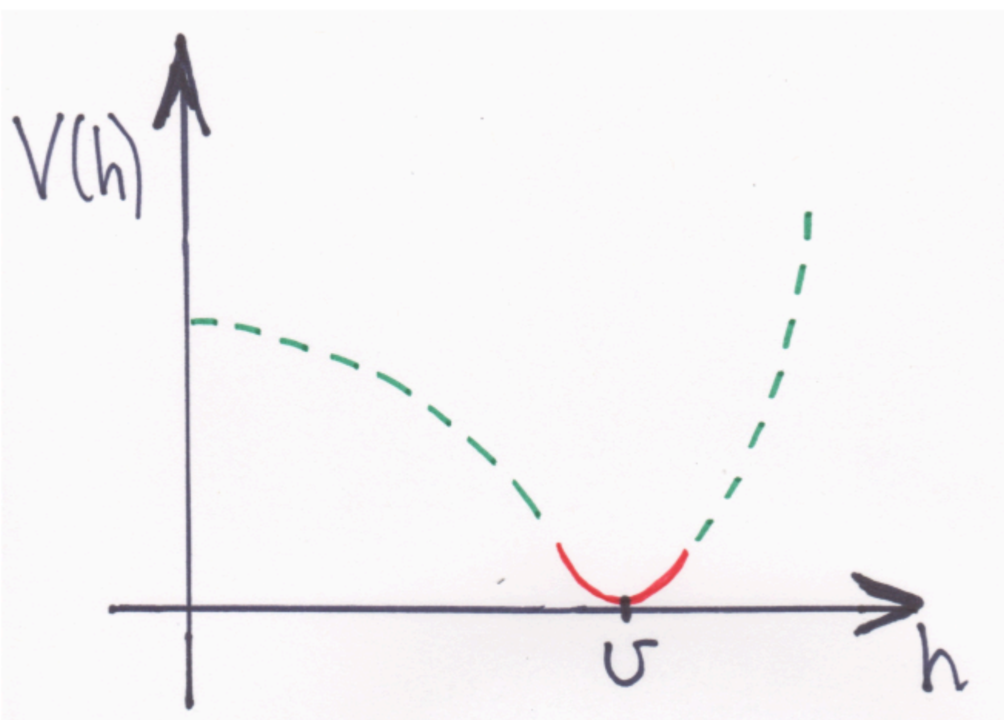
Higgs coupling precision



But once top-quark quantum effects are included, polarization is needed to distinguish Higgs vs. top effects.

S.Jung, J.Lee, J.Tian, M.Vos, 1909.xxxxx

Unknown Higgs self coupling & phase transition



by M.Perelstein

- What we know now:

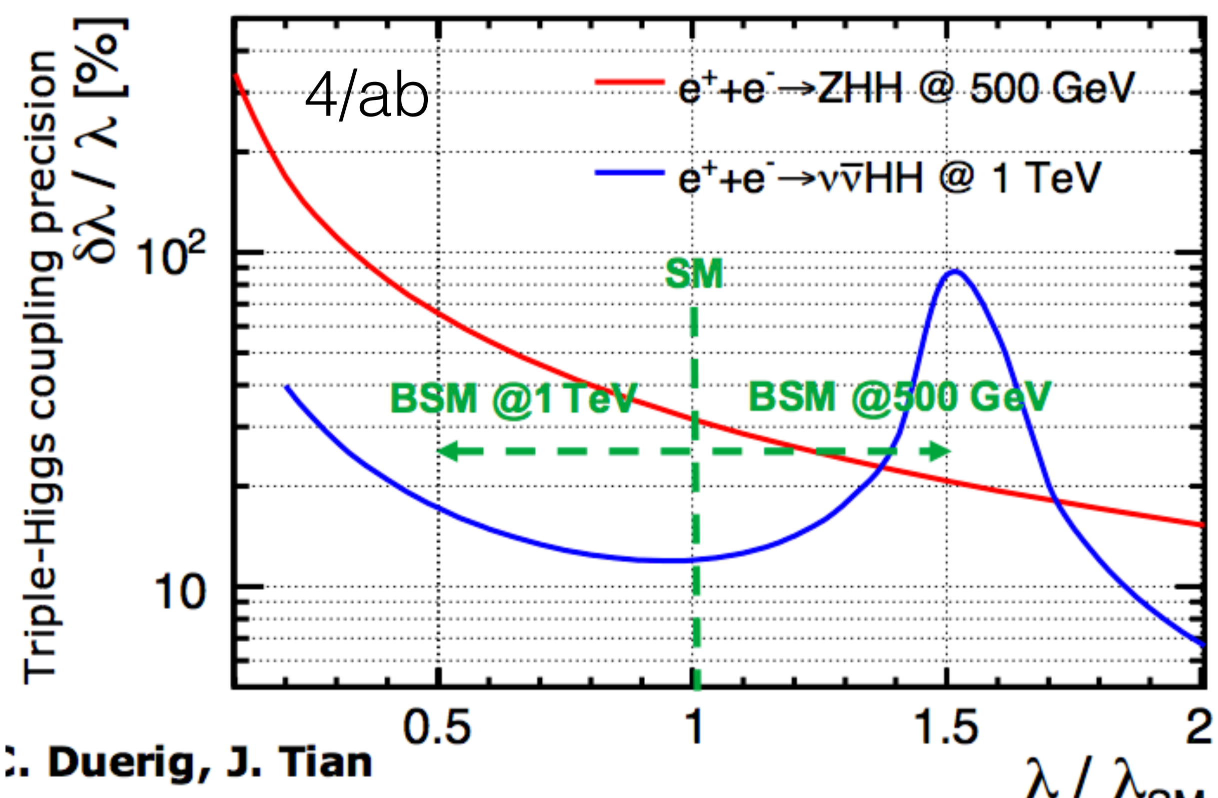
$$V'(h) = 0 \ @ \ h = v \approx 250 \text{ GeV}$$

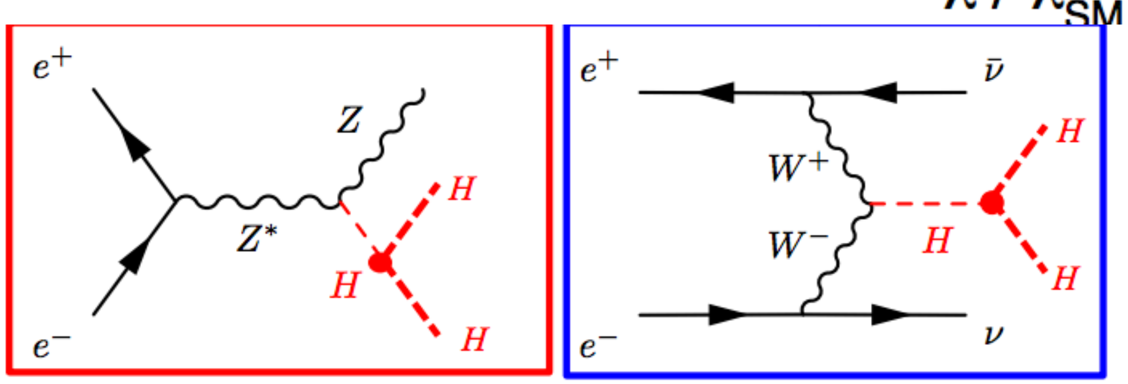
$$m_h^2 = V''(v), \ m_h \approx 125 \text{ GeV}$$

- Measuring Higgs cubic coupling is the next step in extending our knowledge of the shape of V:

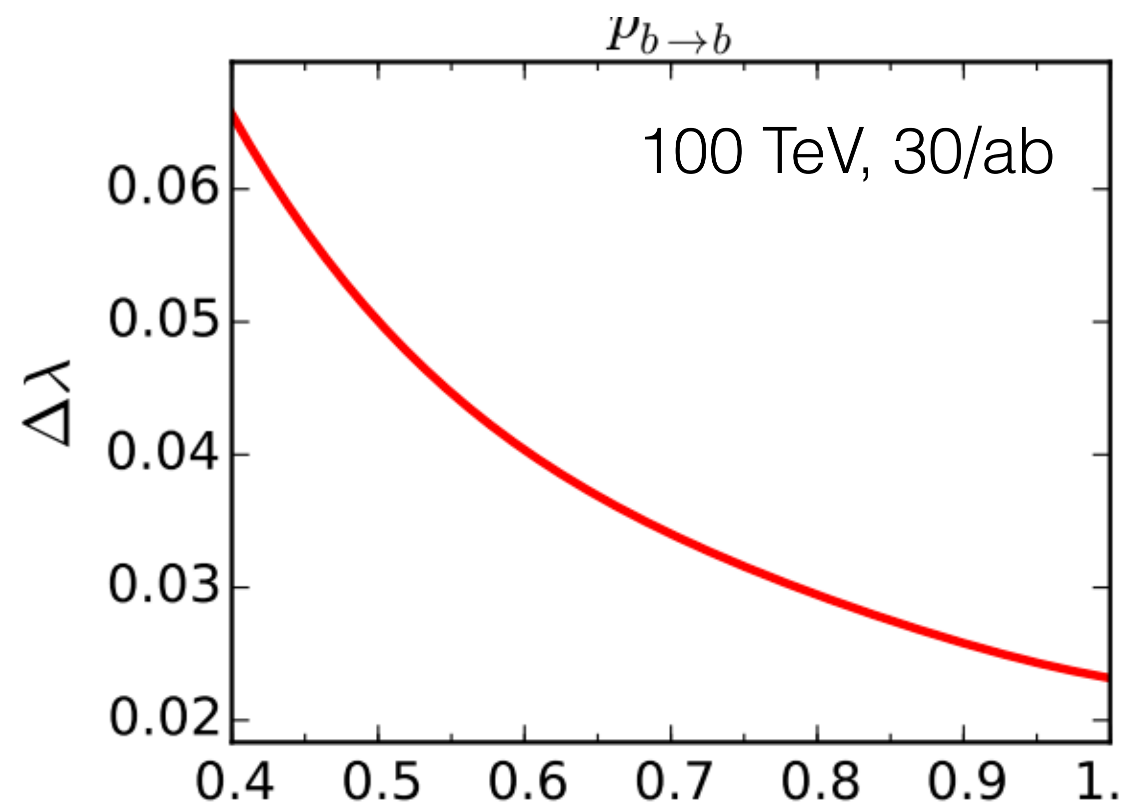
$$\lambda_3 = \frac{1}{6} V'''(v)$$

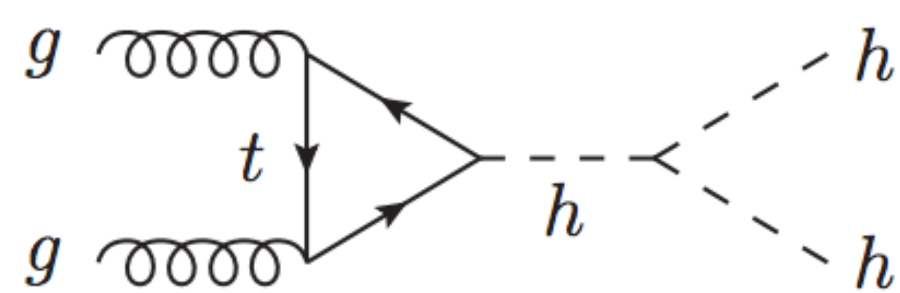
How we usually think about triple-Higgs measurement





Diagrams with triple-Higgs coupling





Extracting triple Higgs

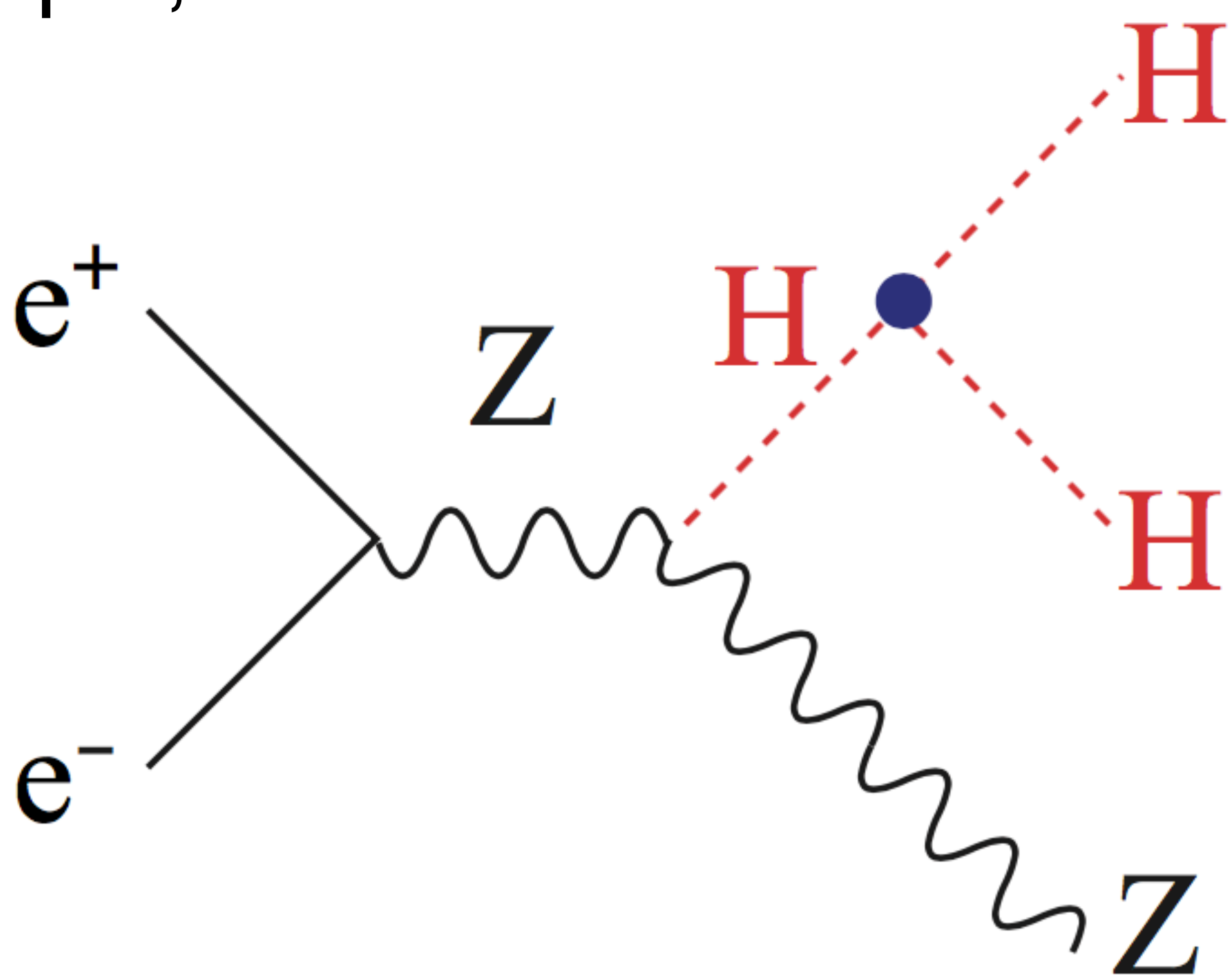
- These results of Delta lambda might be good enough if the only question is to test the SM.

- If there's a deviation, there's a new physics! Not only lambda, but many others will be non-SM.

- How do we separate the desired deviations in the Higgs triple coupling from those of others?
  We don't even know what are `others'.

How shall we extract Higgs potential?

For example,



HEFT as a model-independent framework

- In the HEFT,
  the deviation of the Higgs potential (triple Higgs coupling in particular) is associated with

$$\Delta\mathcal{L} = -\frac{c_6\lambda}{v^2}|\Phi^\dagger\Phi|^3$$

10 d=6 operators

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

These 10 HEFT ops consist of:
(1) at least one Higgs or EW gauge,
(2) only Higgs, EW gauge and electrons

All 10 ops contribute!

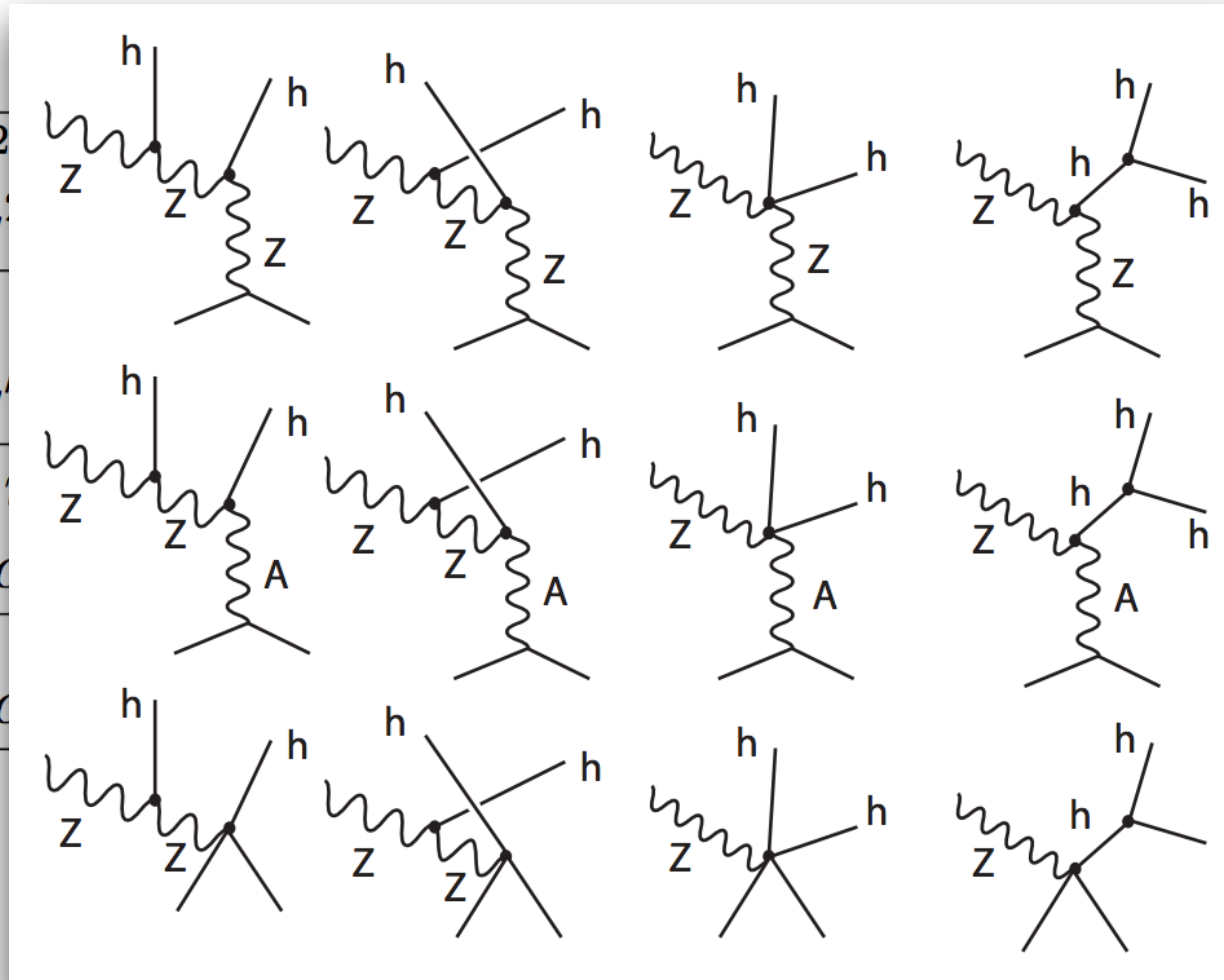
$$\Delta\mathcal{L} = \frac{c_H}{2v^2} \quad \cdots \quad - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$

$+\frac{g}{\cdots}$

$+\frac{g'}{\cdots}$

$+i\frac{c}{\cdots} \quad \cdots \quad \bar{L}\gamma_\mu t^a L)$

$+i\frac{c}{\cdots}$



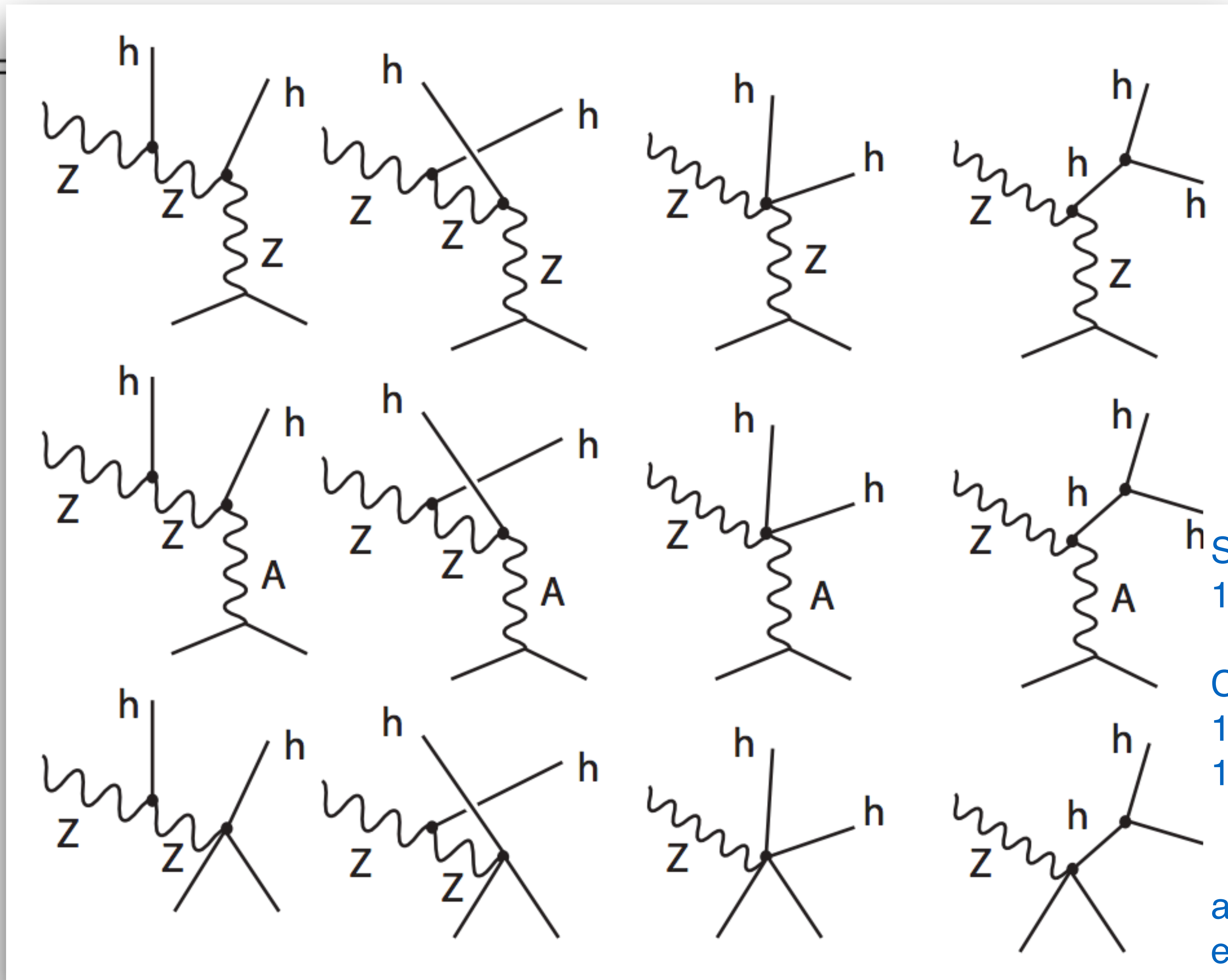
(1) at least one Higgs or EW gauge,
(2) only Higgs, EW gauge and electrons

This was the state-of-the art since 2yrs ago.

$$\Delta\mathcal{L} = \ldots \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$

$B^{\mu\nu}$

$c\rho\mu$



S.Jung, M.Peskin, J.Tian, et al.
1708.09070, 1708.08912

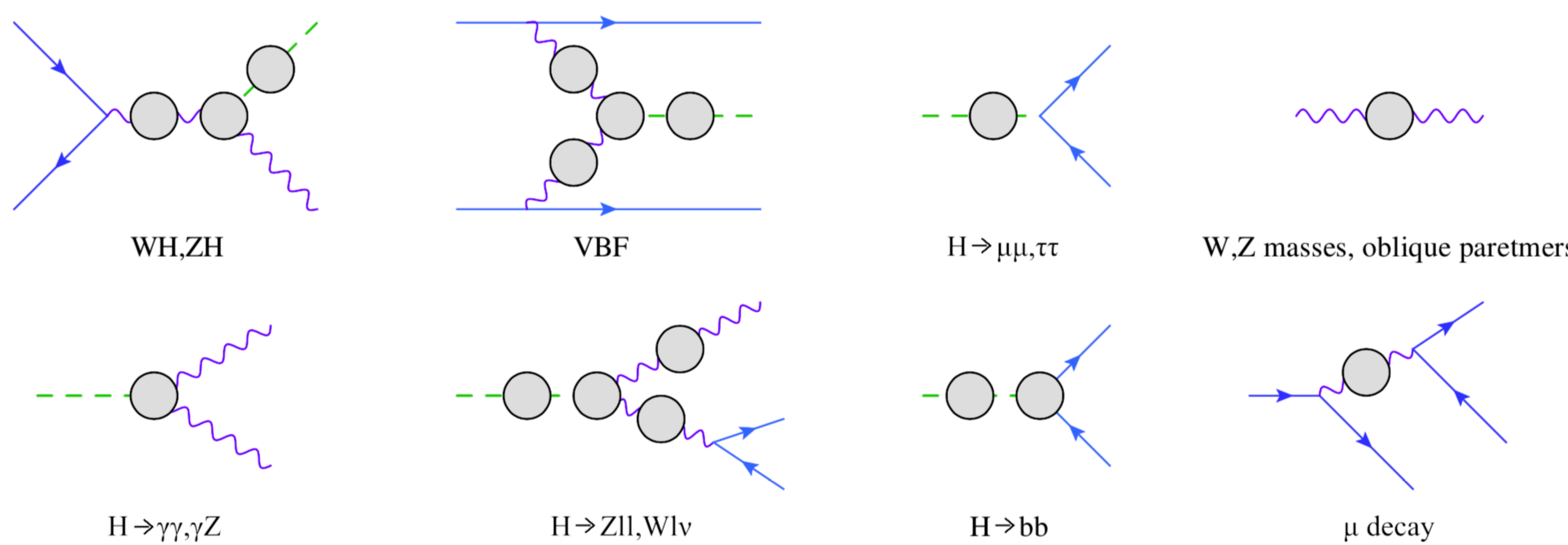
C.Grojean, J.Gu, G.Durieux, et al.
1704.02333, 1711.03978,
1704.01953, 1907.04311

as well as earlier, later works by e.g. J.S.Lee, M.H.Park, P.Ko, S.Y.Choi …

(2) only Higgs, EW gauge and elec

Top quark quantum effects

- At one-loop, top quarks also contribute.
- Small?
  Absolutely can be larger than the desired Higgs precision!



RG operator mixing

- Renormalization group evolution of 10 Higgs and 7 top ops can account for dominant one-loop corrections.

$$\dot{c}_i \equiv 16\pi^2 \frac{dc_i}{d\ln\mu} = \gamma_{ij} c_j,$$

$$\dot{c}_H = (12y_t^2 N_c - 4g^2 N_c) c_{Hq}^{(3)} - 12 y_t y_b N_c c_{Htb}, \tag{2.17}$$

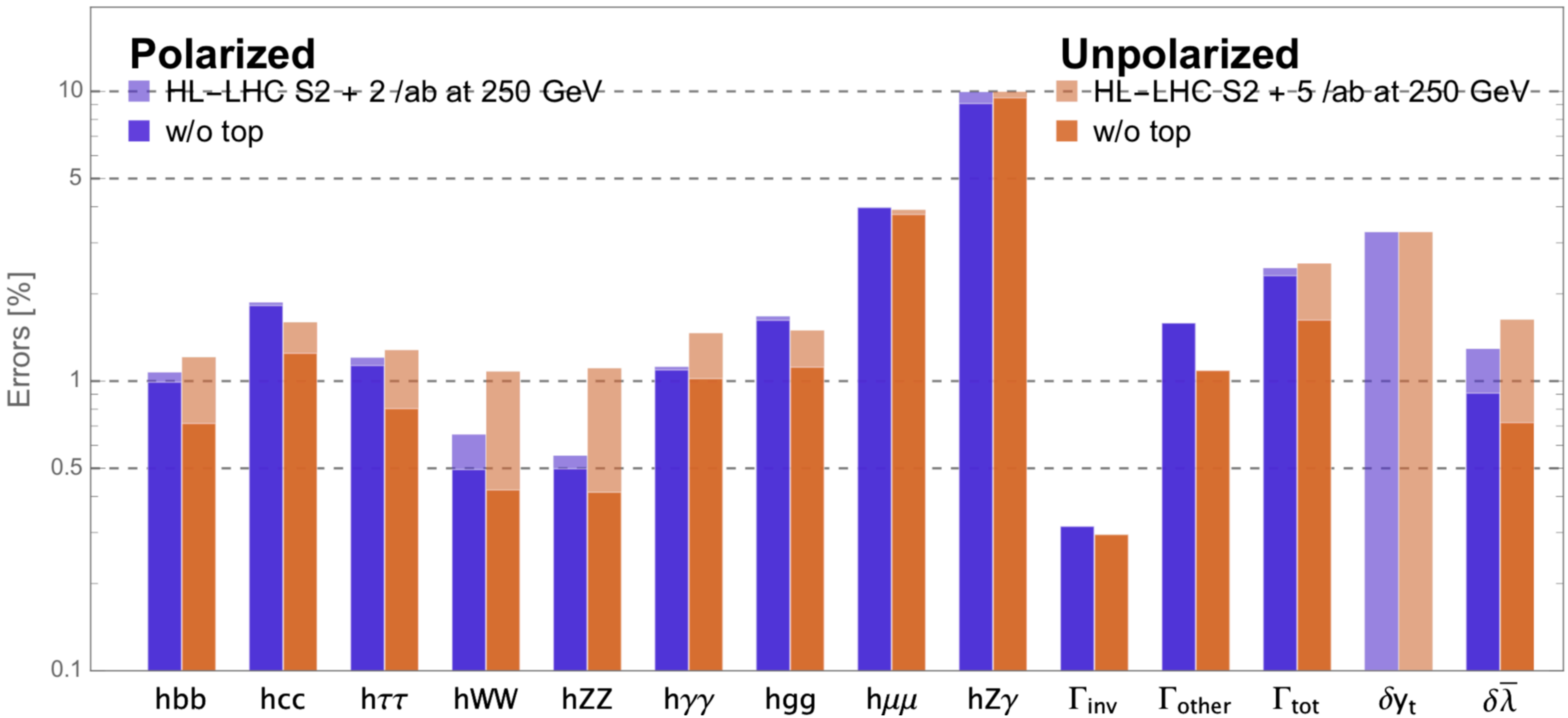
$$\dot{c}_T = (4y_t^2 N_c - \frac{8}{3} g'^2 Y_h Y_u N_c) c_{Ht} - (4y_t^2 N_c + \frac{8}{3} g'^2 Y_h Y_q N_c) c_{Hq}^{(1)} + 4 y_t y_b N_c c_{Htb} \tag{2.18}$$

$$\dot{c}_{WW} = \frac{1}{4}(-2g y_t N_c c_{tW}), \tag{2.19}$$

$$\dot{c}_{BB} = \frac{1}{4t_W^2}\left(-4g' y_t (Y_q + Y_u) N_c c_{tB}\right), \tag{2.20}$$

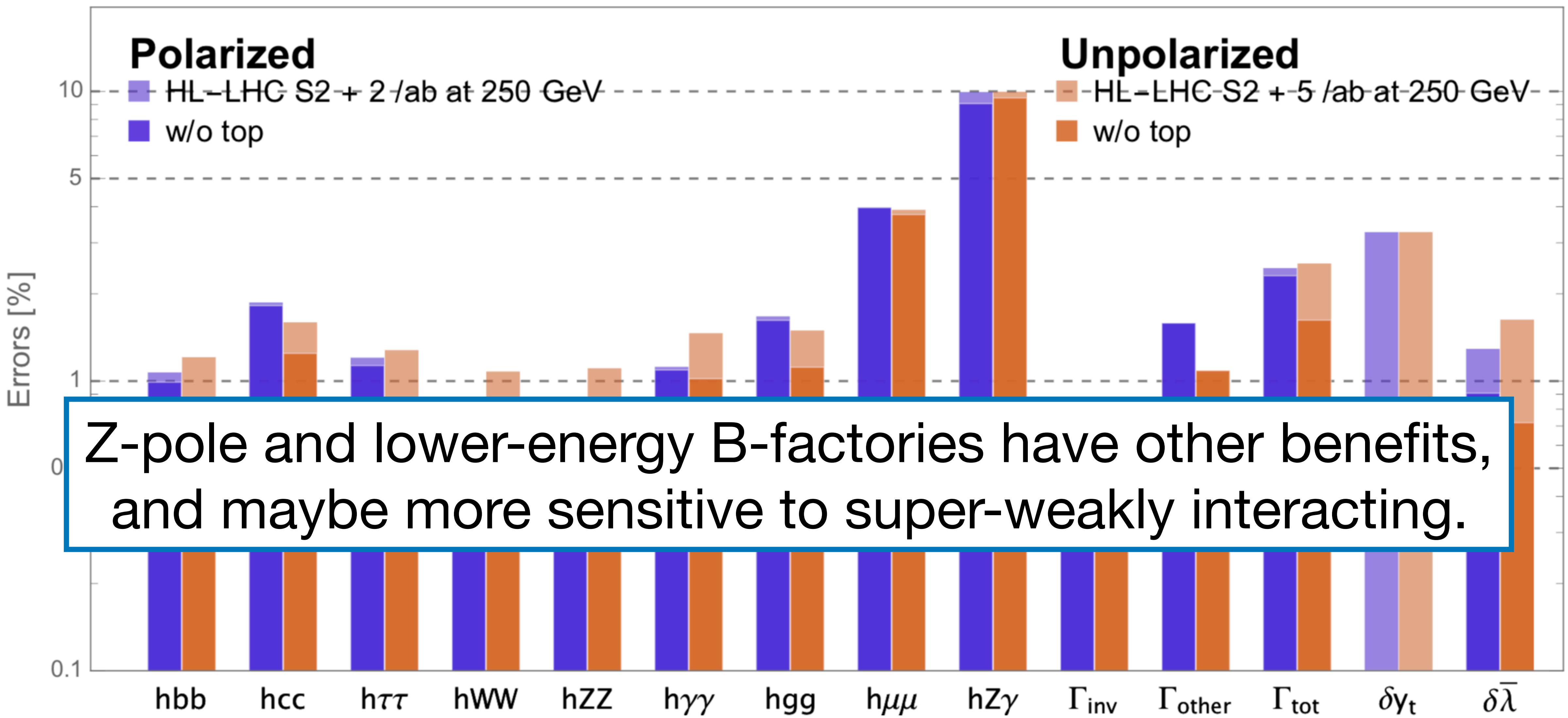
S.Jung, J.Lee, J.Tian, M.Vos, 1909.xxxxx
C.Zhang et al. 1804.09766, 1809.03520

Top-loop now changes quite significantly



Unexpected benefits of polarization.
Model-indep formalism still needs improvements.
LHC precision really needs ingenuities. A lot to learn!

Top-loop now changes quite significantly



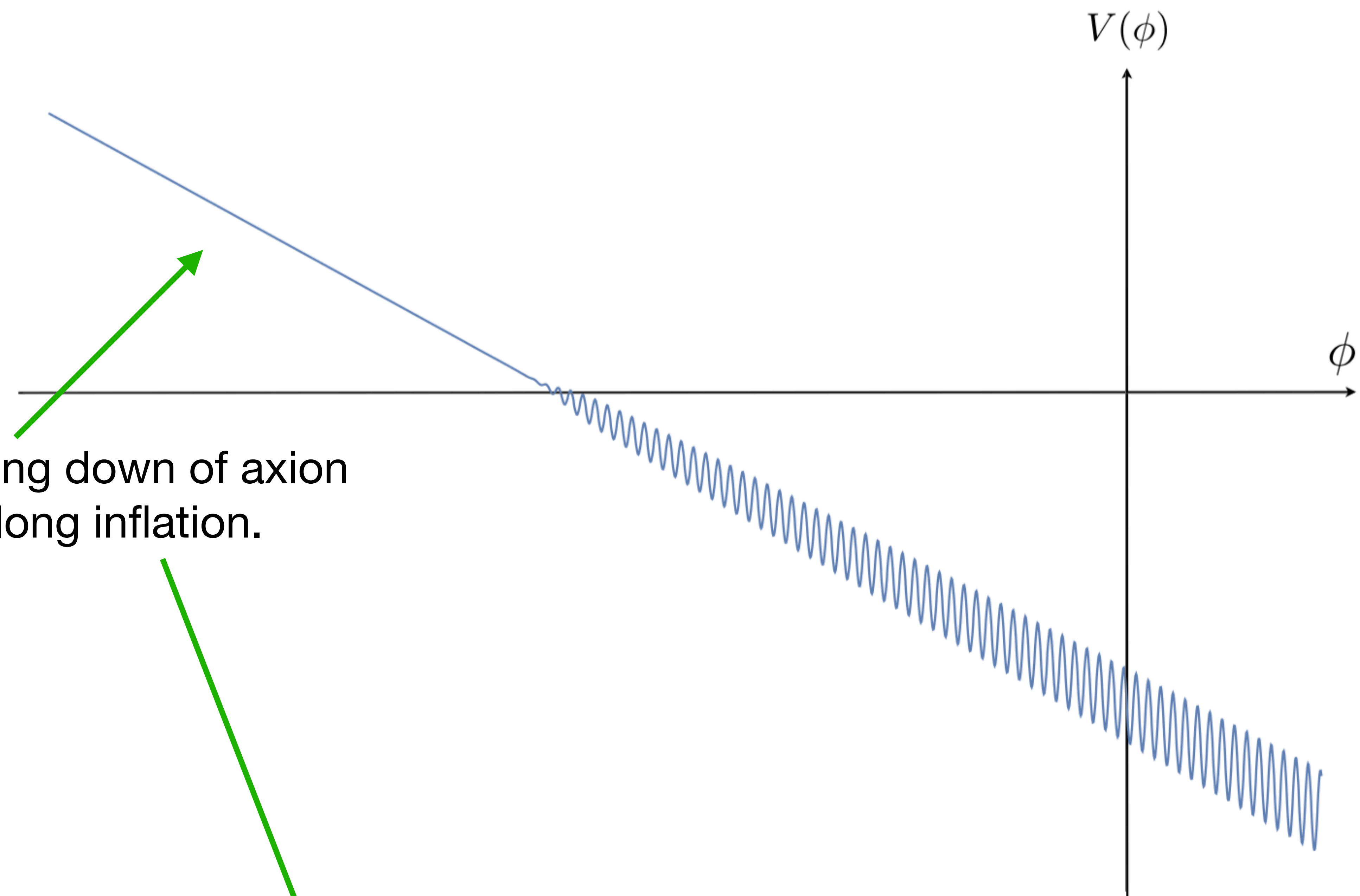
Z-pole and lower-energy B-factories have other benefits, and maybe more sensitive to super-weakly interacting.

Unexpected benefits of polarization.
Model-indep formalism still needs improvements.
LHC precision really needs ingenuities. A lot to learn!

3. Relaxion test

hh+MET with hidden Nc

Relaxation of Higgs vev

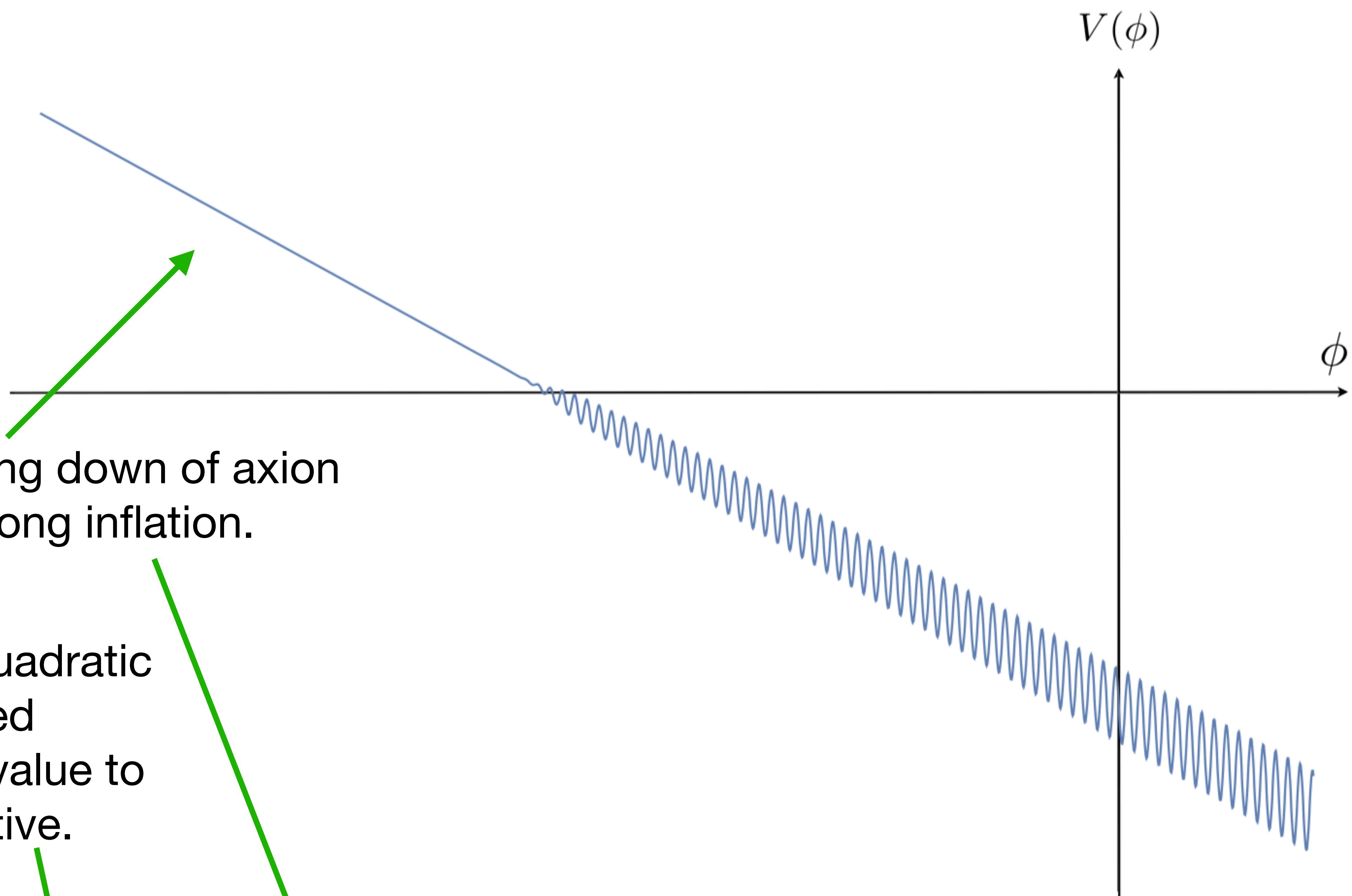


1. Slow rolling down of axion during long inflation.

$$(-M^2 + g\phi)|h|^2 + (gM^2\phi + g^2\phi^2 + \cdots) + \Lambda^4 \cos(\phi/f)$$

P.Graham, D.Kaplan, S.Rajendran, PRL2015

Relaxation of Higgs vev

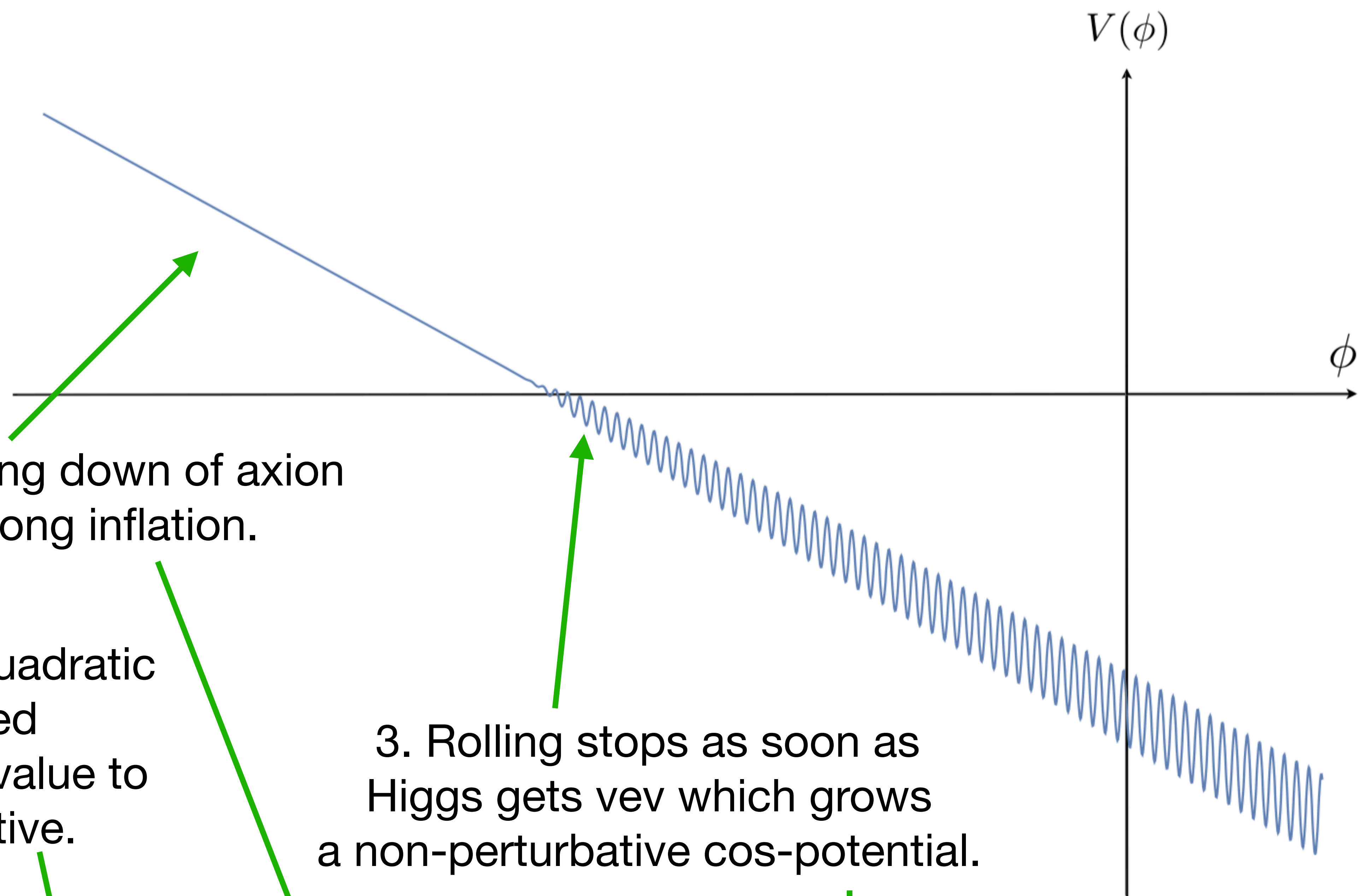


1. Slow rolling down of axion during long inflation.

2. Effective Higgs quadratic term is scanned from large positive value to eventually negative.

$$(-M^2 + g\phi)|h|^2 + (gM^2\phi + g^2\phi^2 + \cdots) + \Lambda^4 \cos(\phi/f)$$

Relaxation of Higgs vev



1. Slow rolling down of axion during long inflation.

2. Effective Higgs quadratic term is scanned from large positive value to eventually negative.

3. Rolling stops as soon as Higgs gets vev which grows a non-perturbative cos-potential.

$$(-M^2 + g\phi)|h|^2 + (gM^2\phi + g^2\phi^2 + \cdots) + \Lambda^4 \cos(\phi/f)$$

Where does relaxion-Higgs coupling come from?

A natural example is

Vector-like lepton (with a hidden confining SU(Nc))

$$y H L N^c + y' H^\dagger L^c N + m_L L L^c + m_N N N^c$$

& relaxion

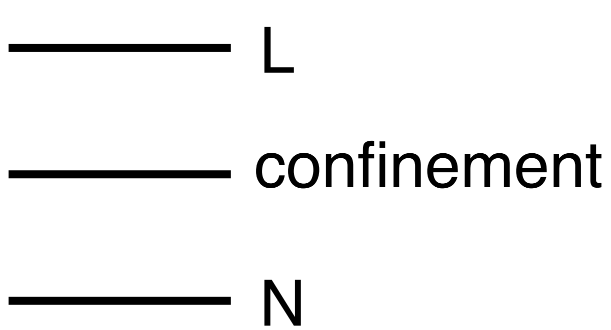
$$\frac{1}{16\pi^2} \frac{\phi}{f} G_H \tilde{G}_H$$

Where does relaxion-Higgs coupling come from?

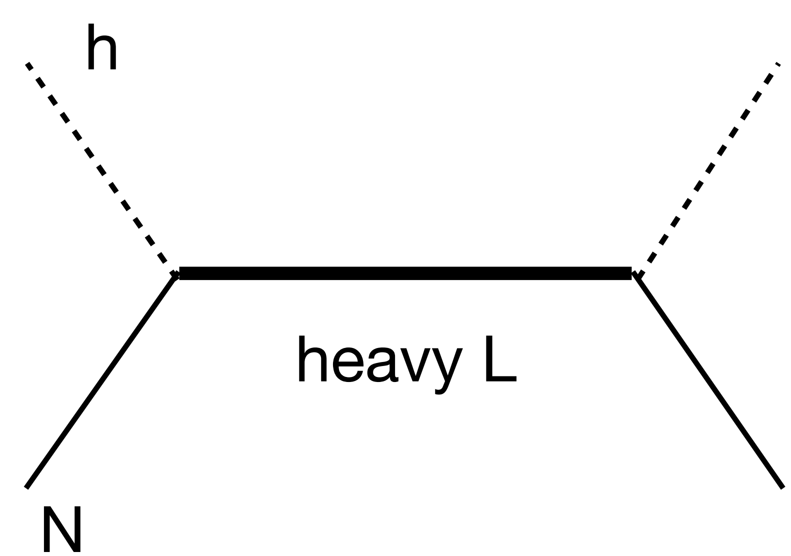
A natural example is

Vector-like lepton (with a hidden confining SU(Nc))

$$yHLN^c + y'H^\dagger L^c N + m_L L L^c + m_N N N^c$$



$$\frac{yy'}{m_L}|H|^2 \quad NN^c.$$



Where does relaxion-Higgs coupling come from?

A natural example is

After NNc condensation,
we obtain the desired relaxion-Higgs coupling.

$$\Delta V = -M^2 \cos\left(\frac{\phi}{f} + \alpha\right) |H|^2 - \Lambda^4 \cos\left(\frac{\phi}{f}\right)$$

L

confinement

N

Unique collider prediction

At leading approximation, L-Z mixing is zero.

Dominant decay mode is thought to be

$$L^0 \rightarrow hN, \qquad L^{\pm} \rightarrow L^0 + \text{soft},$$

so that the collider signal is

$$hh + \text{MET} \quad \Rightarrow \quad 4\text{b} + \text{MET}$$

without corresponding $ZZ+$ MET nor $hZ+$ MET

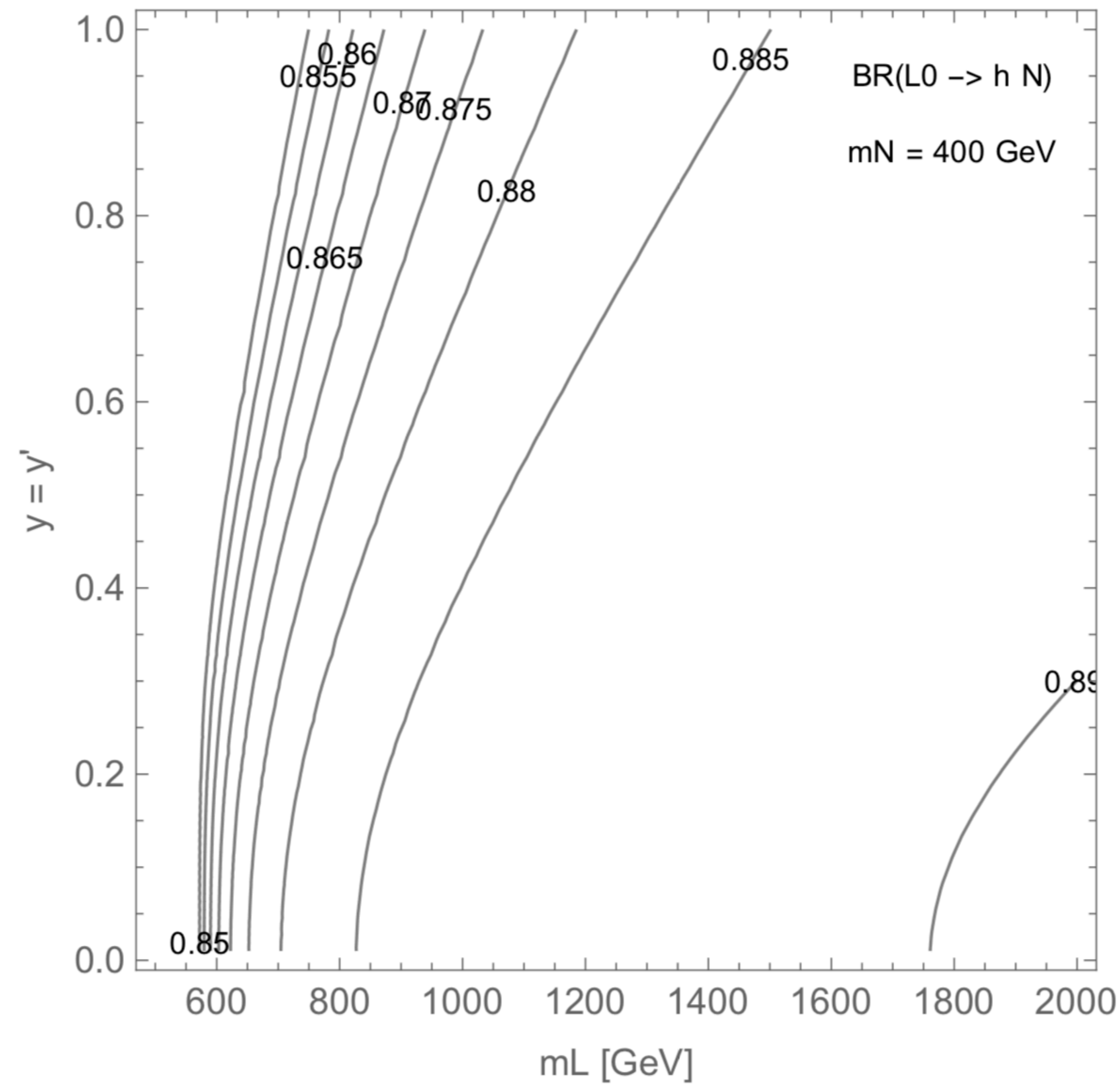
Unique collider prediction

But small L-Z mixing induces

$ZZ+$ MET $\qquad hZ+$ MET

Interestingly,

BR(h) =~ 0.88 is almost fixed!



S.Jung, K.S.Jeong, J.C.Park, S.Shin, 1910.xxxxx

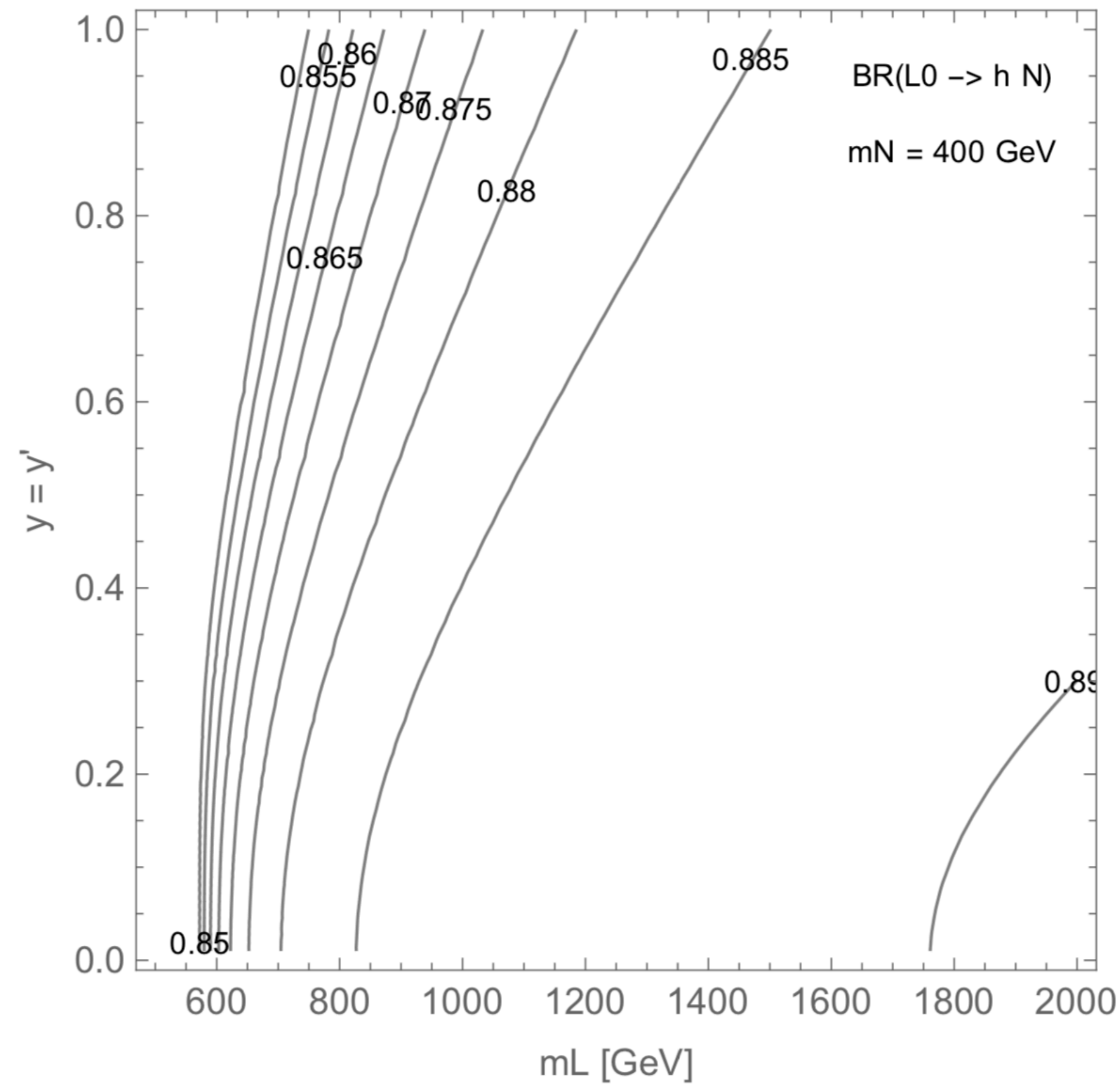
Unique collider prediction

But small L-Z mixing induces

$ZZ+$ MET $\qquad hZ+$ MET

Interestingly,
BR(h) =~ 0.88 is almost fixed!

It's again due to
the Goldstone eq thm,
that overcomes small mixing!



S.Jung, K.S.Jeong, J.C.Park, S.Shin, 1910.xxxxx

Predictions and limits on relaxion

Prediction 1:
Dominant $hh + \mathrm{MET}$.

Prediction 2:
Hidden Nc-enhanced Drell-Yan.

4b+MET at current LHC14 30/fb leads to 1 TeV lower limit.

4. “Alpha Go sensei never speaks”

Before Alpha Go vs. Lee Sedol:

Machine is much better at calculation than human.

But machine does not have intuition and abstraction.

→ “Human will be better in the opening part of a game,

while machine will do better at the ending part.”

After Alpha Go vs. Lee Sedol:

Alpha Go turned out to be much much better
than human in the BEGINNING.

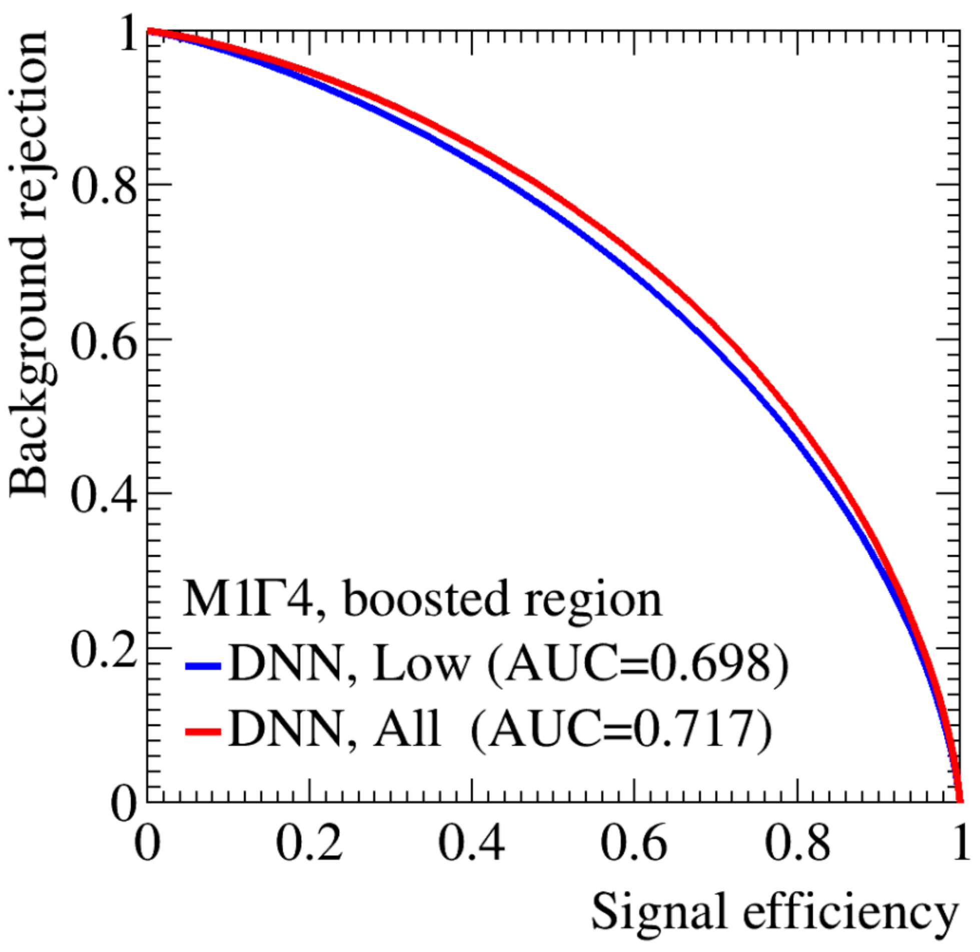
Intuition and abstraction are nothing
but the pattern recognition based on experiences!
→ This is one great lesson that changed my mind.

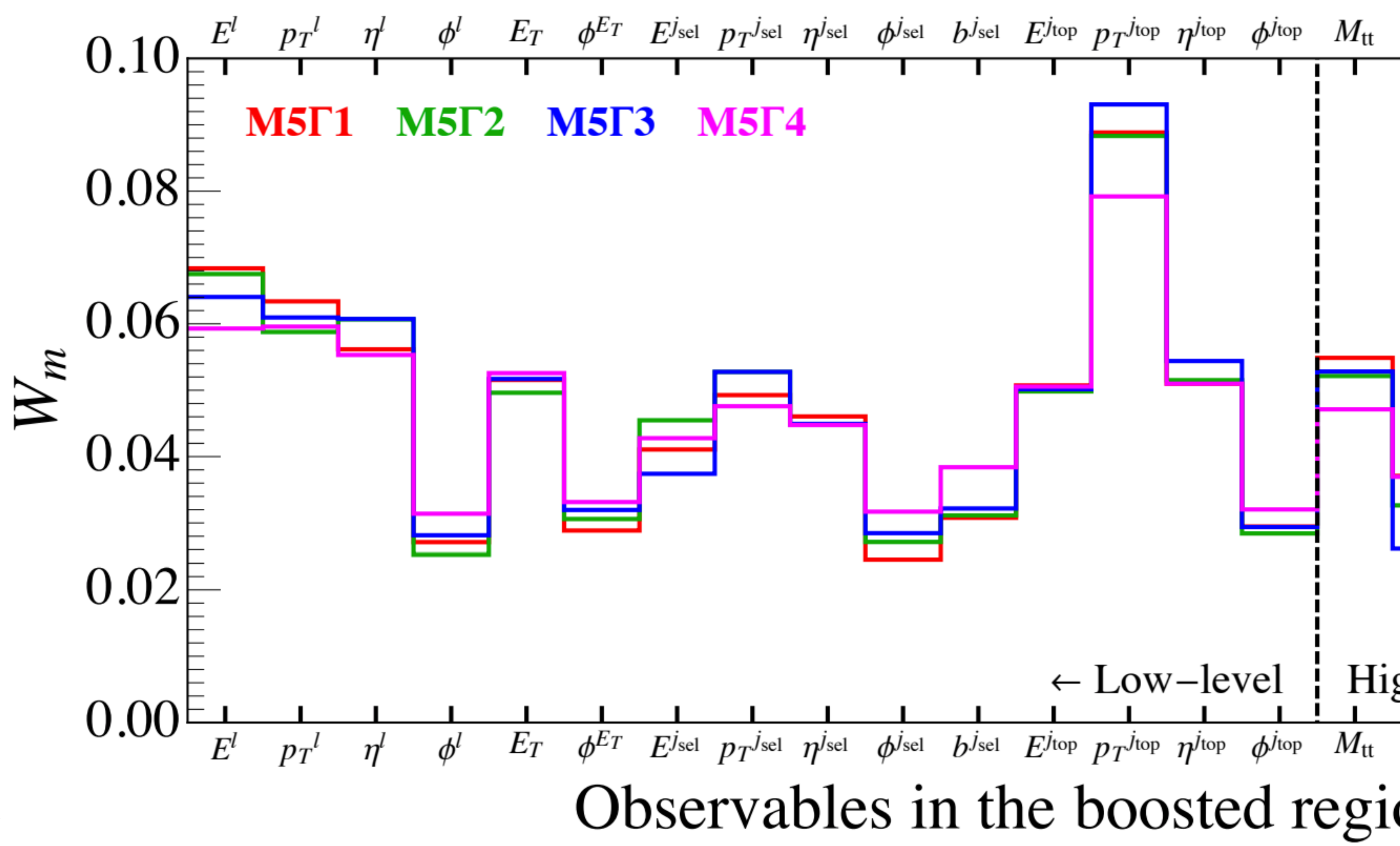
Machine can do the *unexpected*!

Asking to a machine

specialized at signal vs. background,

"Did you learn these observables?
How important are these observables?"





S.Jung, D.Lee, K.Xie, 1906.02810

Remark

But there could still be unknown (to us) info that are not identified in our analysis!!

It’s difficult to find out something that we don’t know even though the machine had learned it.

Lee Changho

“Alpha Go teacher never speaks.”

Being able to communicate with networks will enable better explorations of the Nature, beyond what we know.

Takehome messages

- Future TeV-scale SUSY is *qualitatively different*, requiring new viewpoints, insights and works.

  - Higgsino vs. gaugino exhibit underlying symmetry.
  - What is a resonance?

- Higgs precision largely prefers to *polarization!* (of linear e+e- colliders.)

  - Z-pole or B-factories for super-weakly interacting.
  - Truly model-independent formalism not yet.

- Relaxion solutions are also *uniquely testable* at colliders.

- "Alpha Go sensei never speaks."