Physics opportunities at Future Hadron collider

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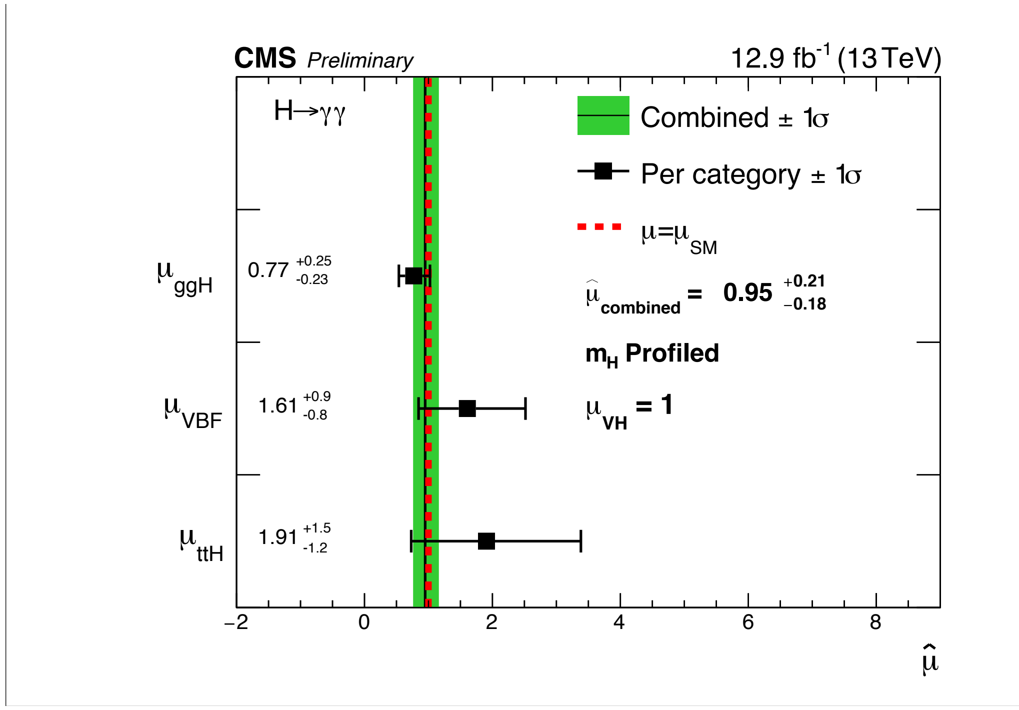
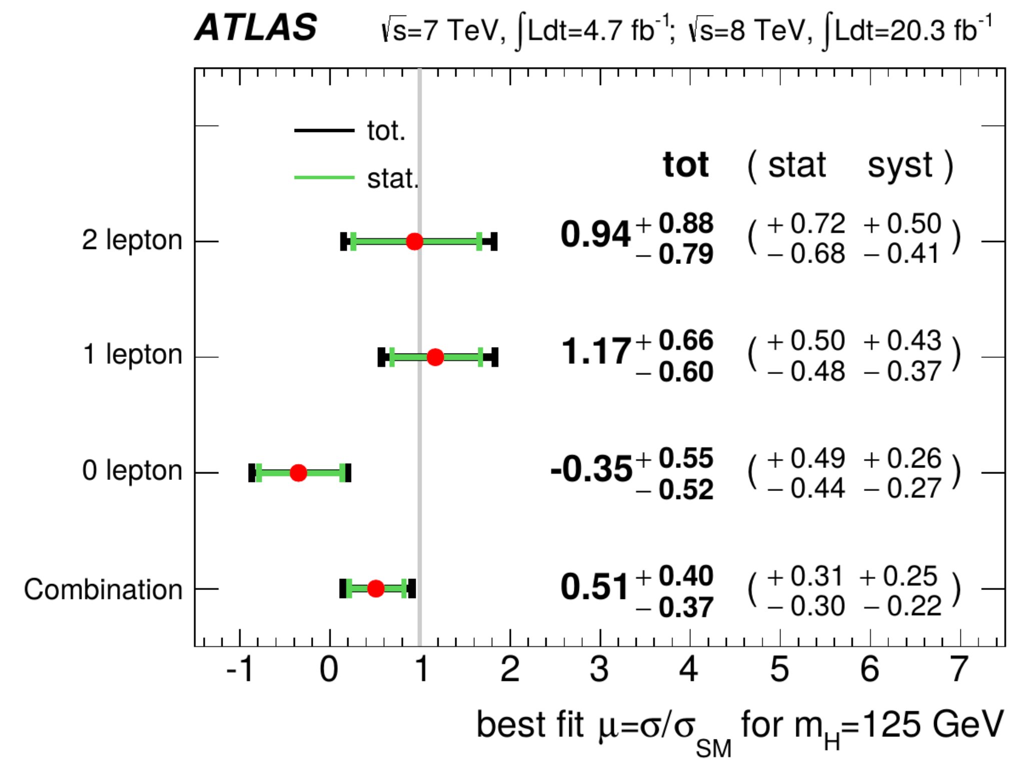
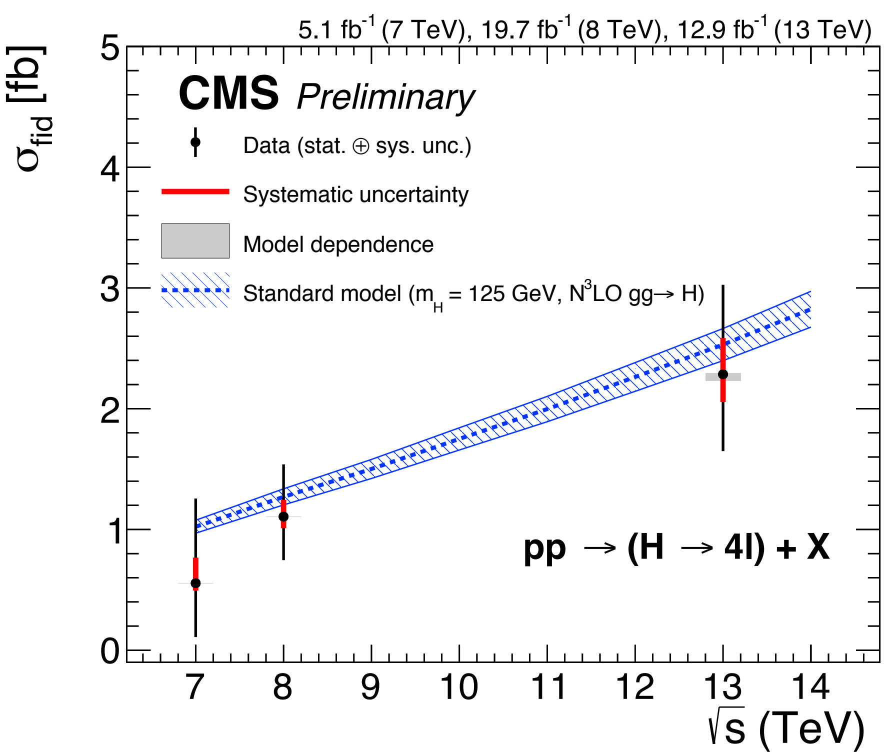
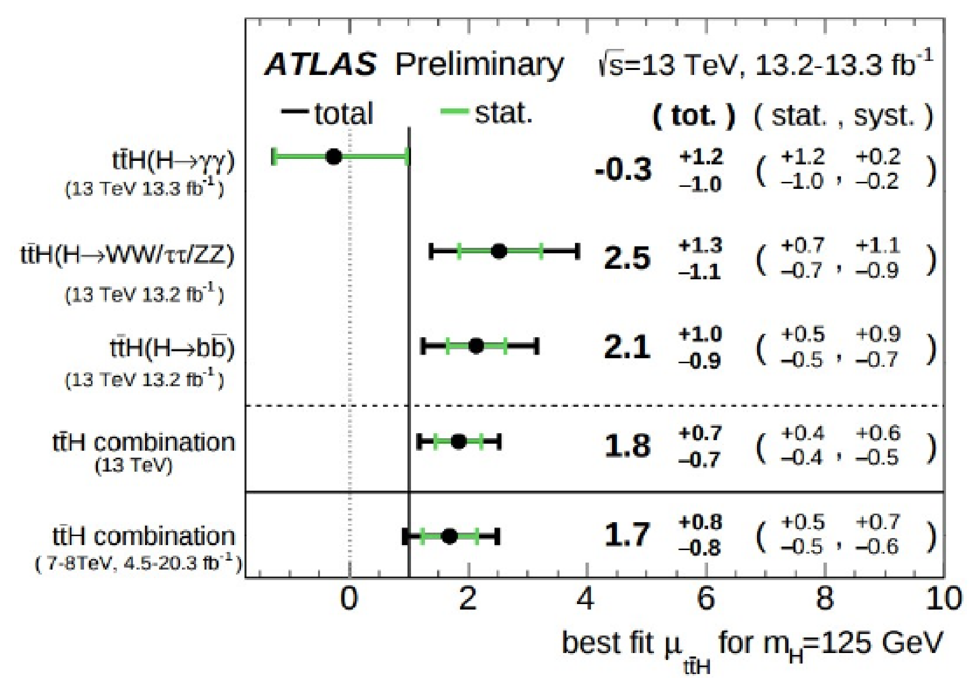
PITP 2017. Princeton July 24-26

Current status



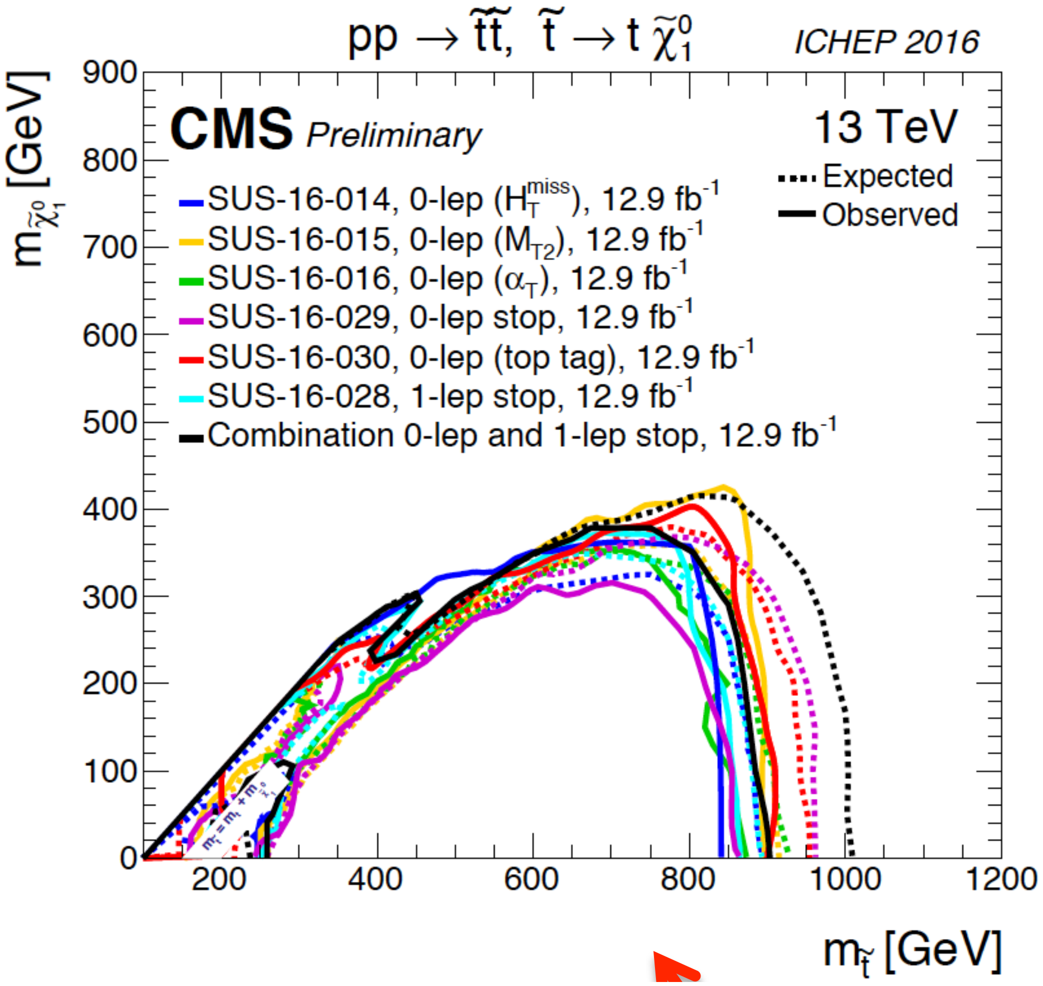


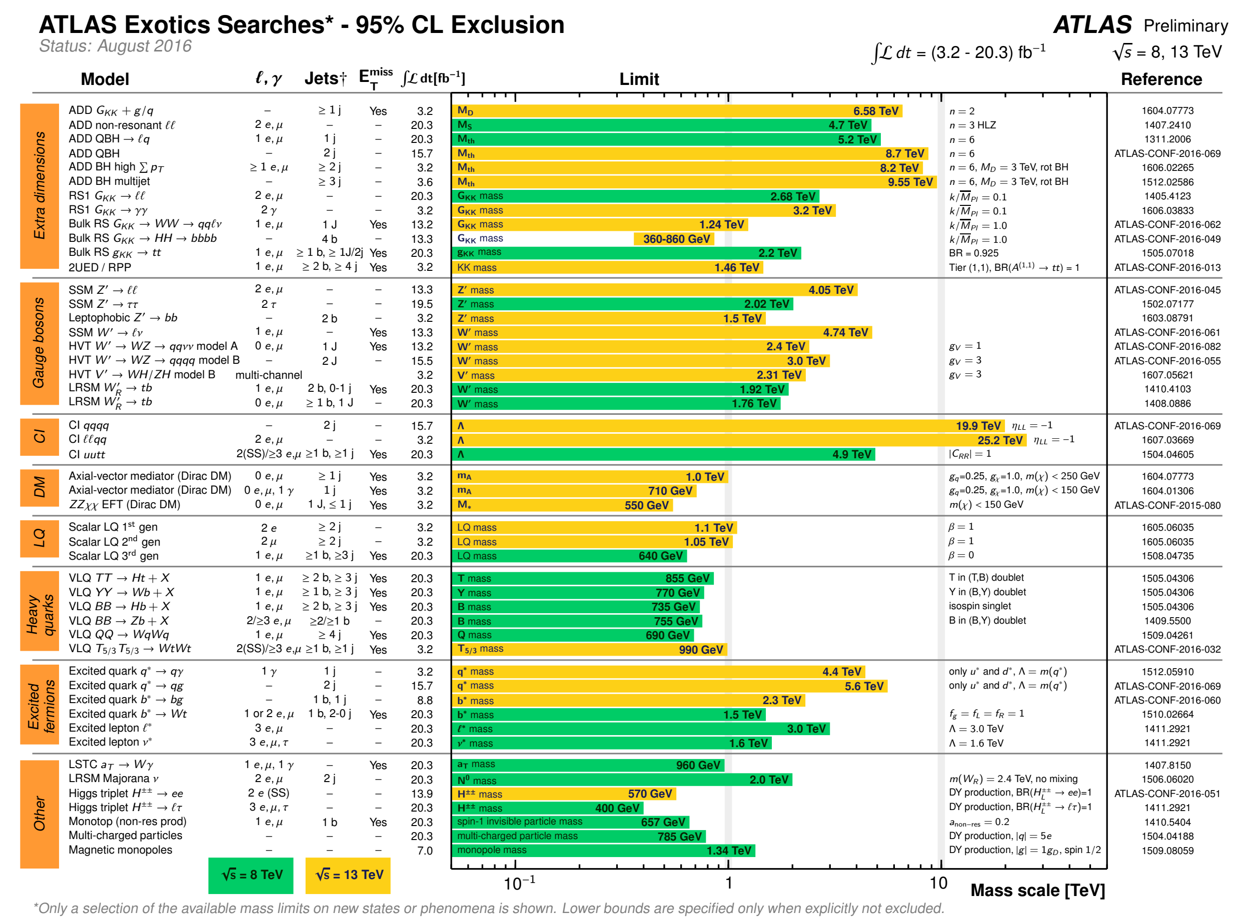




Found Higgs

Current status

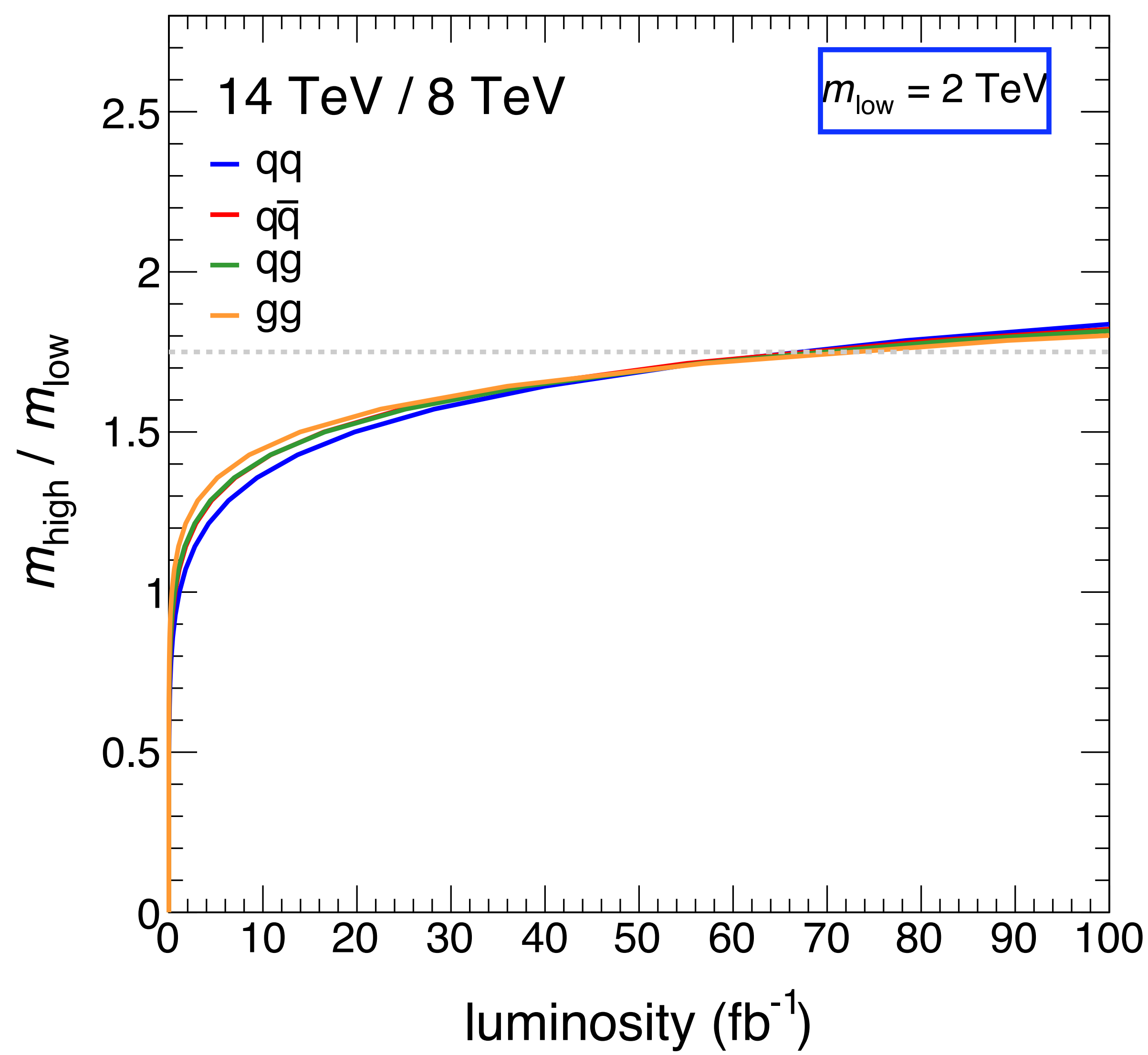




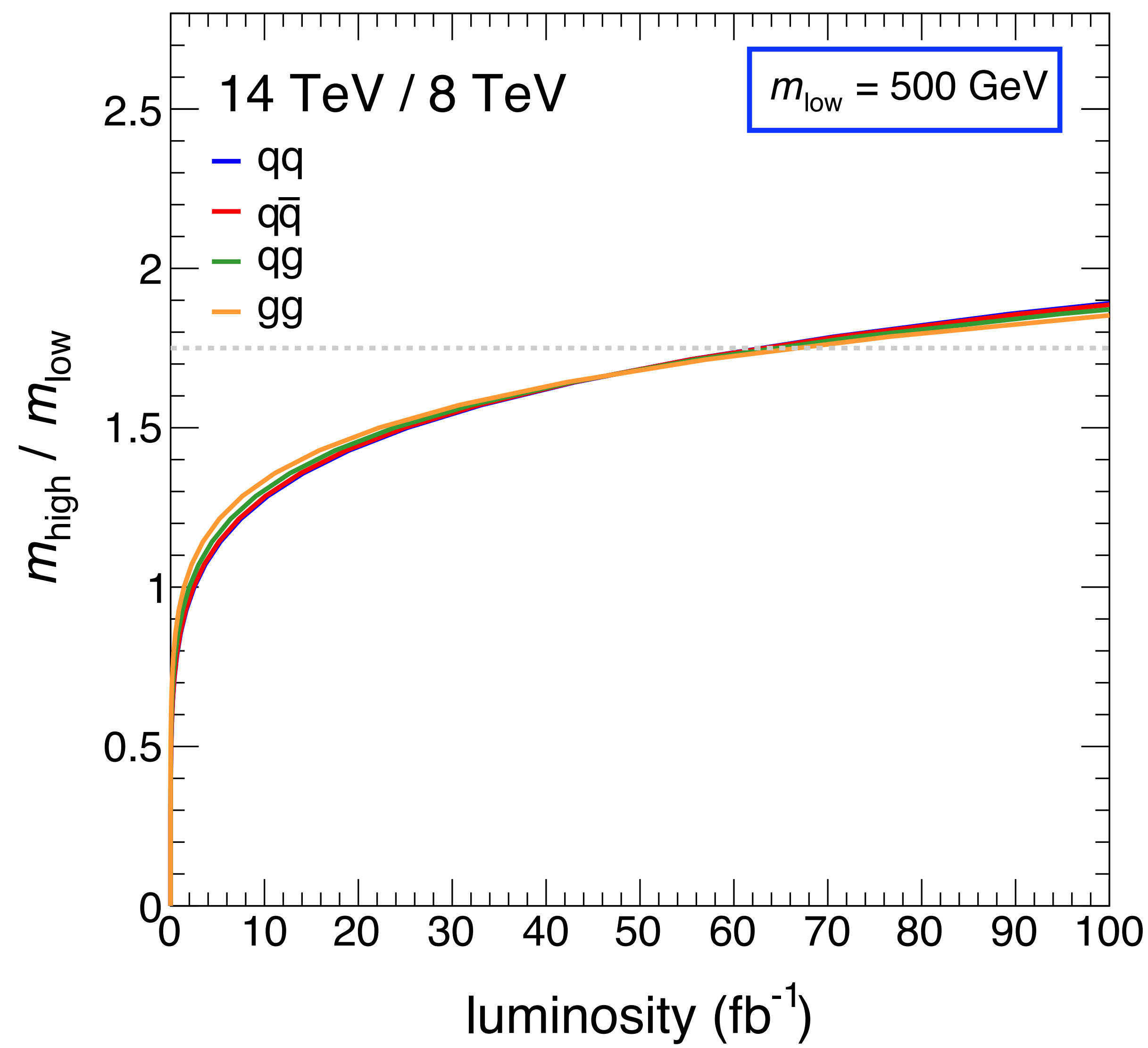
- No "early" discovery.
- Disappointed? Yes.
- Surprised? Not much.

As data accumulates

Run 1 limit 2 TeV, e.g. pair of 1 TeV gluino.



500 GeV, e.g. pair of 250 GeV electroweak-ino



Rapid gain initial 10s fb^{-1}, slow improvements afterwards.

Reaching the "slow" phase after Moriond 2017

LHC Run 2 will continue to pursue a broad physics program.

Of course, there are gaps in to be filled, new signals to be looked at.

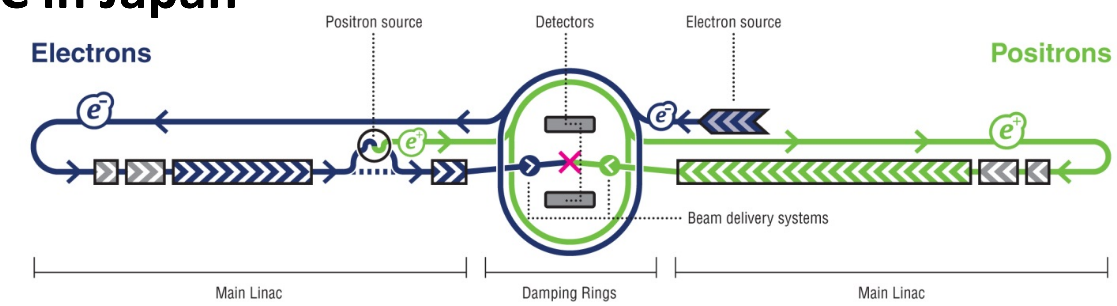
Still room for discovery.

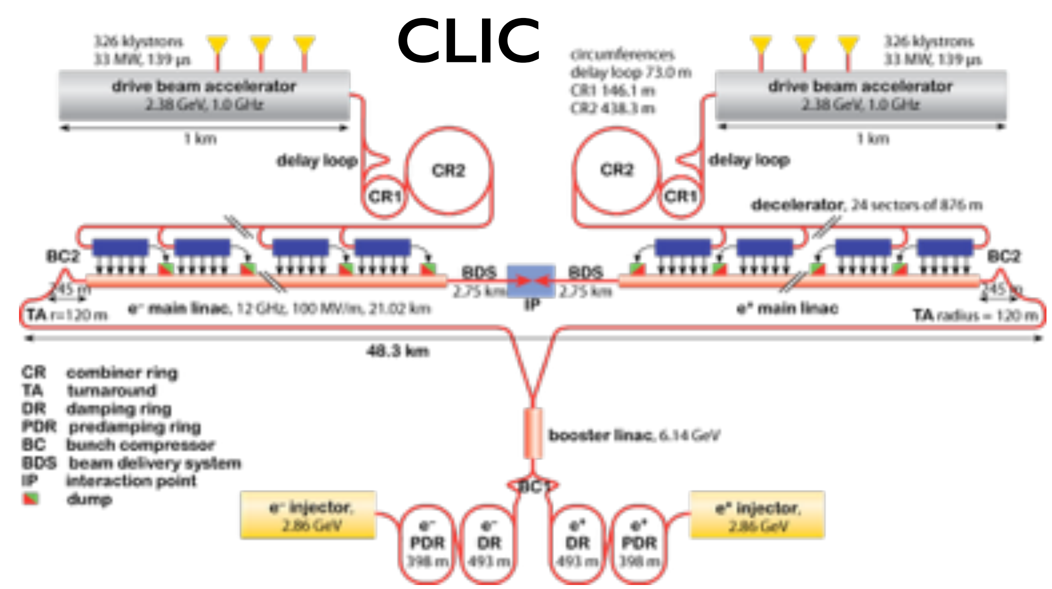
This Lecture

- Focus on longer term future.
- Assuming no discovery of new particle at the LHC.
- Physics case for future hadron collider
  - Cover significant ground beyond the LHC.
  - Answering important questions beyond the reach of the LHC

Beyond the LHC, future facilities

ILC in Japan



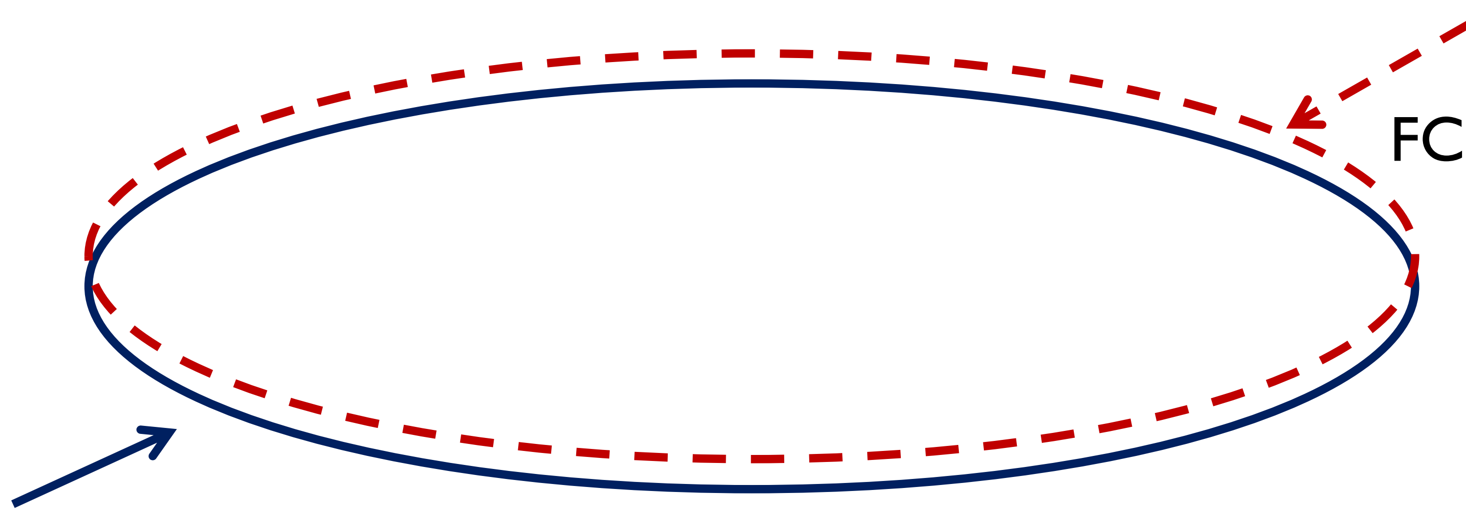


Circular. "Scale up" LEP+LHC

~100 TeV

pp collider

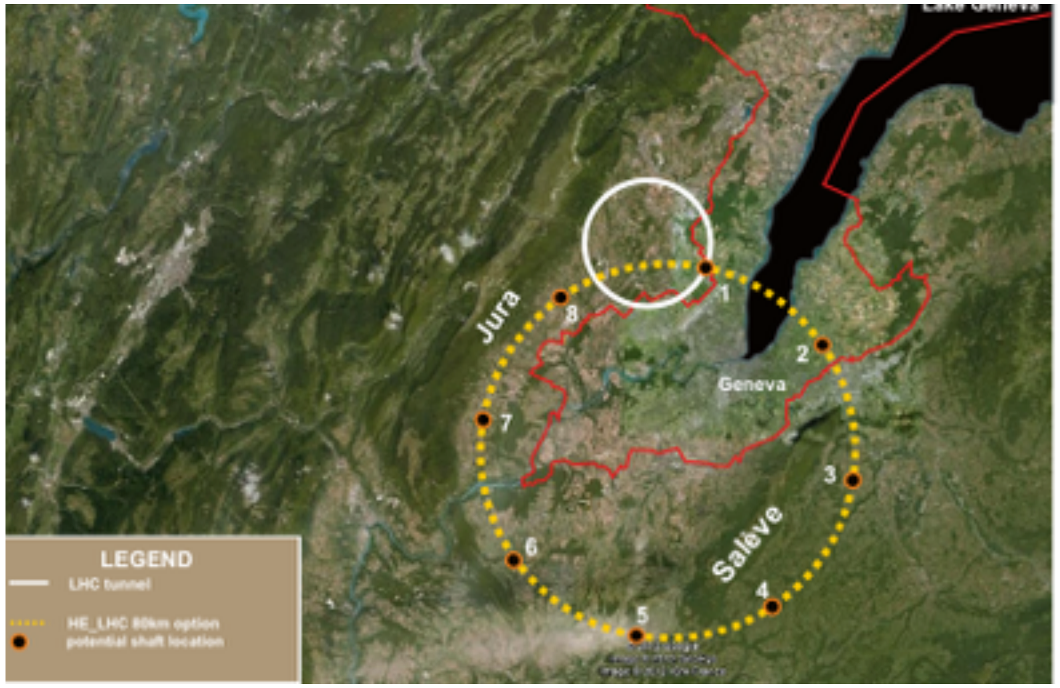
FCC-hh (CERN), SppC(China)



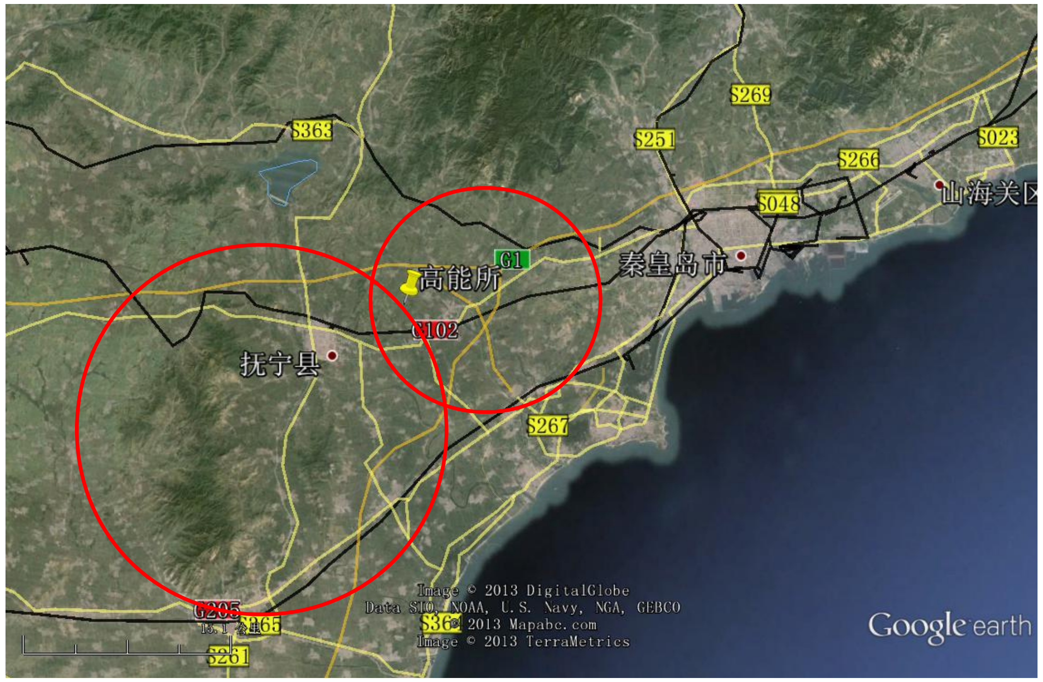
250 GeV **e^-e^+ Higgs Factory**

FCC-ee (CERN), CEPC(China)

Future circular colliders

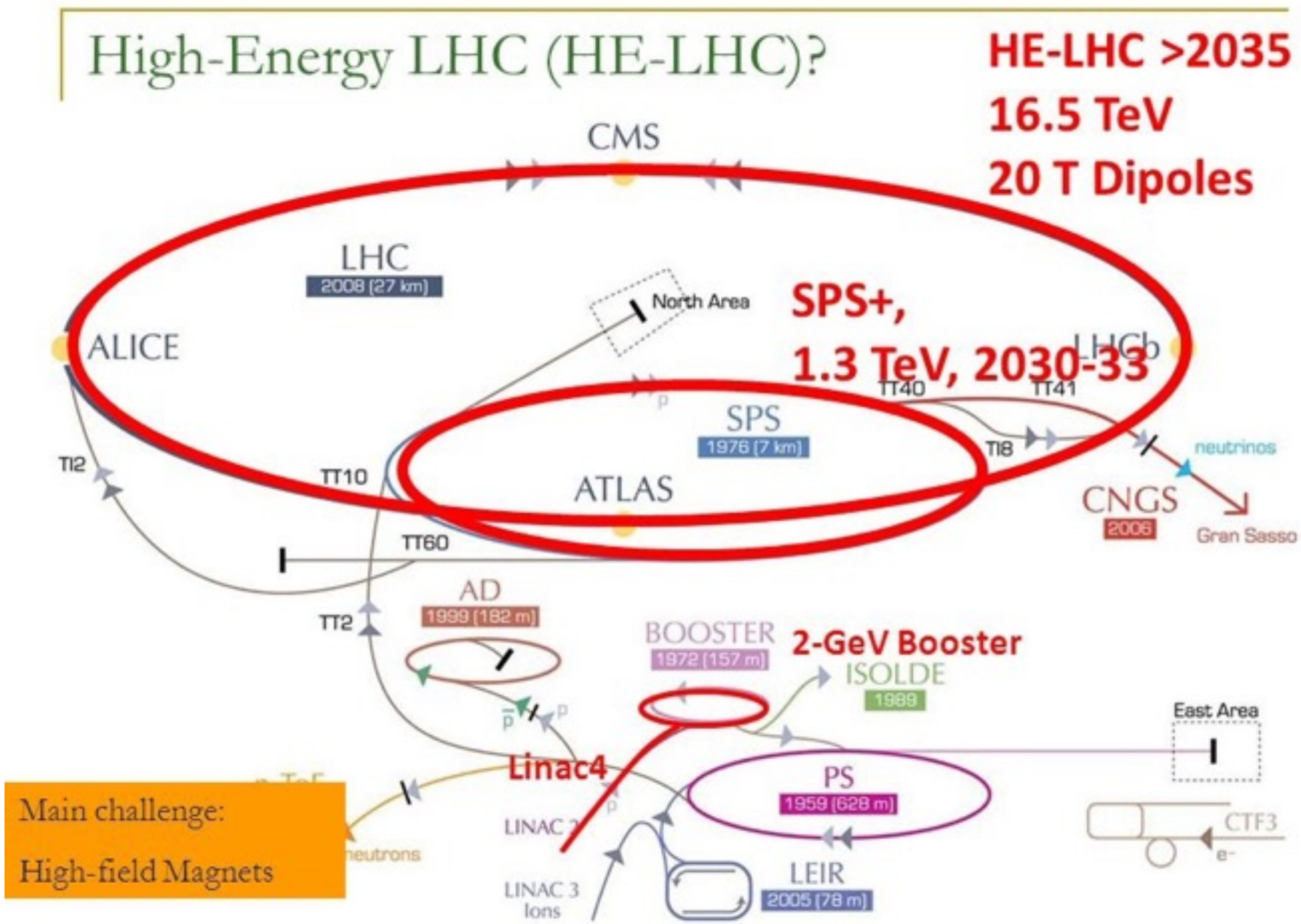


CERN
Higgs factory: FCC-ee
pp Collider: FCC-hh



China.
Higgs factory: CEPC
pp Collider: SppC

HE-LHC



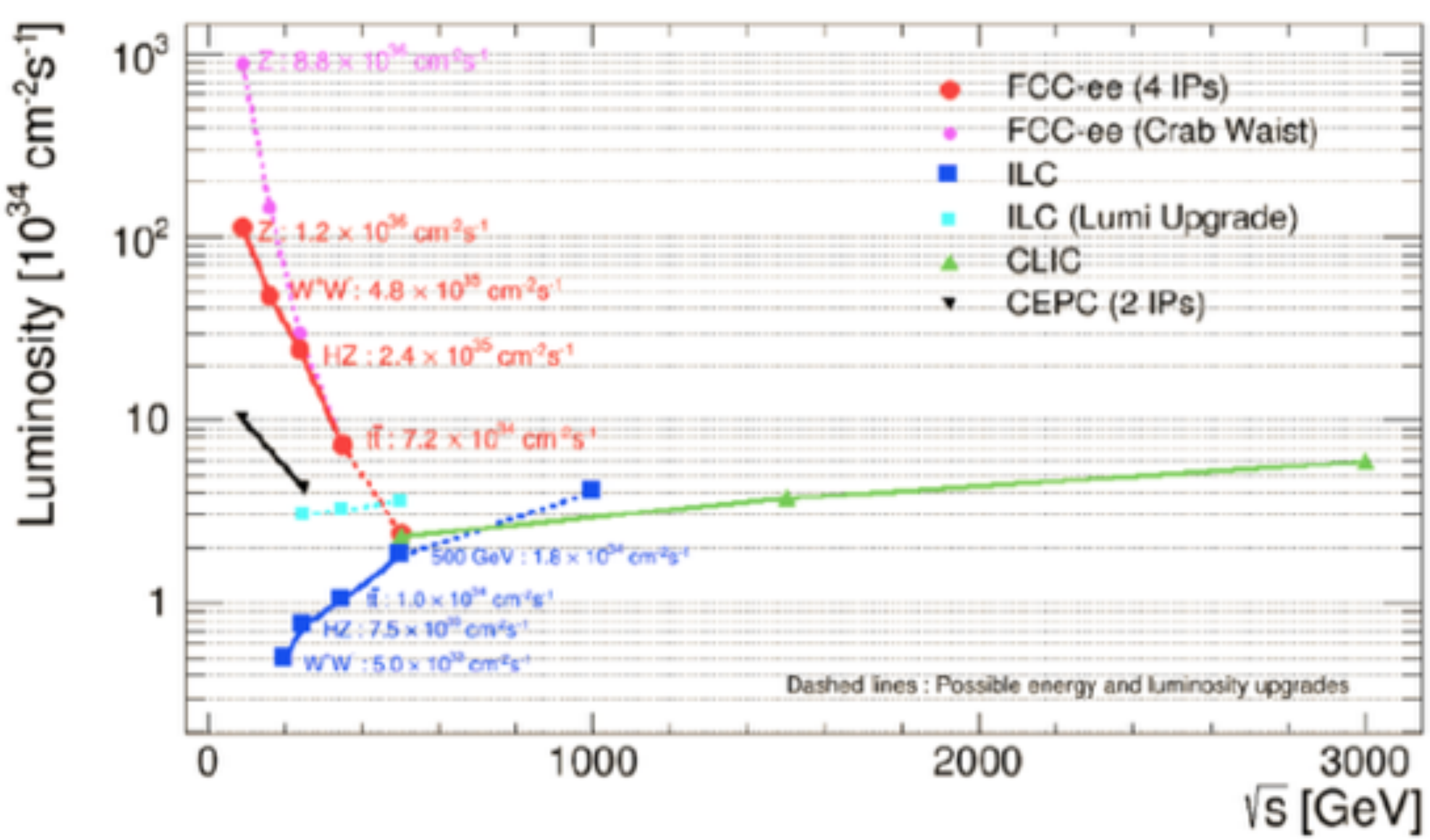
– 28 TeV more realistically?

Will focus on 100 TeV collider here.

Basic physics capability

Higgs factories

- FCC-ee, CEPC, ILC, CLIC.
- Physics case relatively independent of the outcome of the LHC.
  - Reach further than the LHC.
  - Address questions that LHC can't answer.



Probing NP with precision measurements

- CEPC: clean environment, good for precision.

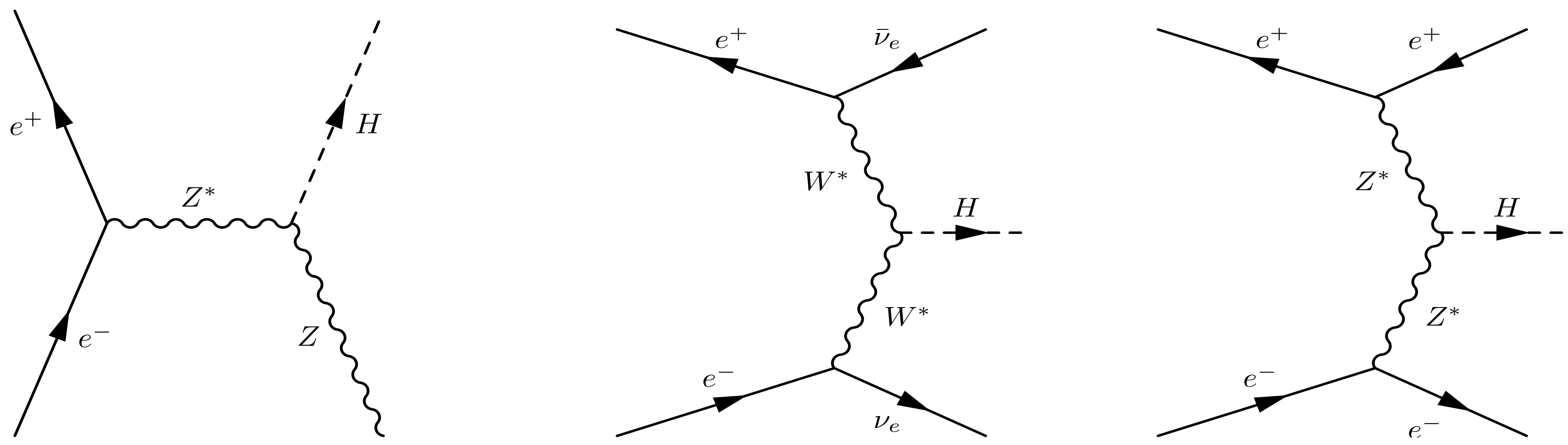
- We are going after deviations of the form

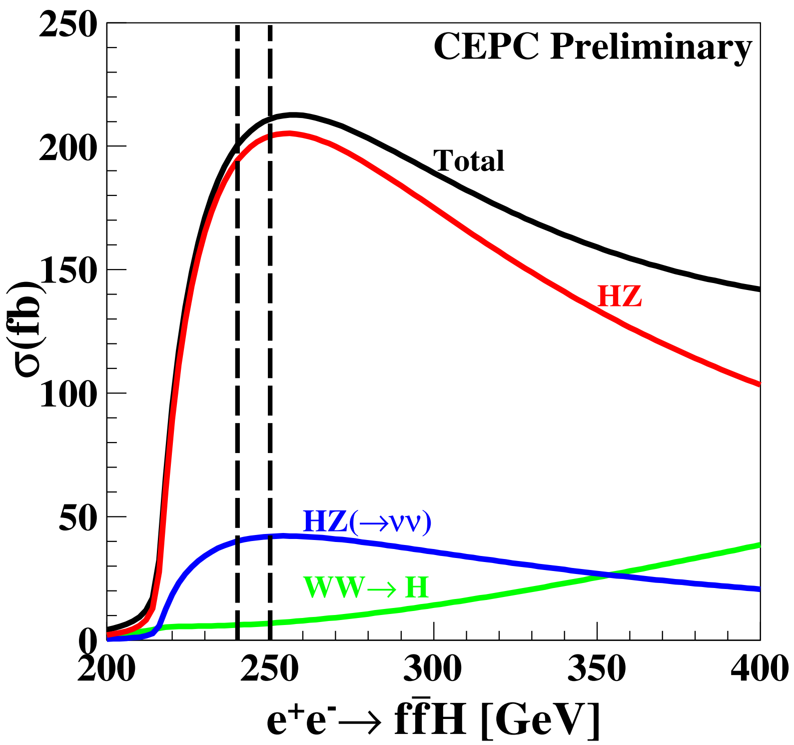
$$\delta \simeq c \frac{v^2}{M_{\rm NP}^2}$$

M_{NP} : mass of new physics
c: $O(1)$ coefficient

- Take for example the Higgs coupling.
  - LHC precision: 5-10% $\Rightarrow$ sensitive to M_{NP} < TeV
  - However, M_{NP} < TeV largely excluded by direct NP searches at the LHC.
  - To go beyond the LHC, need 1% or less precision.

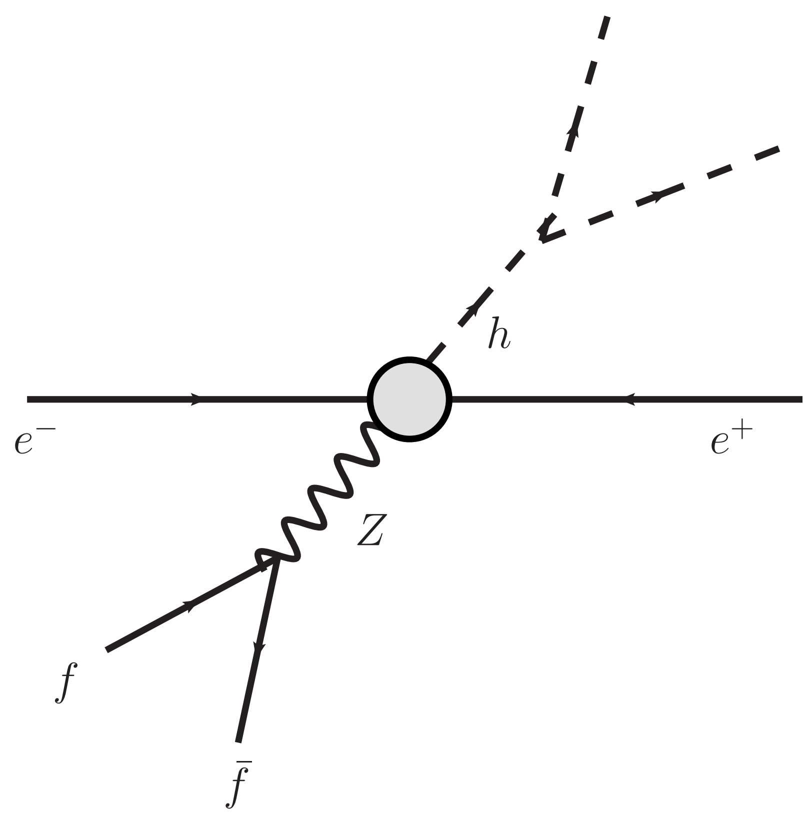
Higgs factory processes

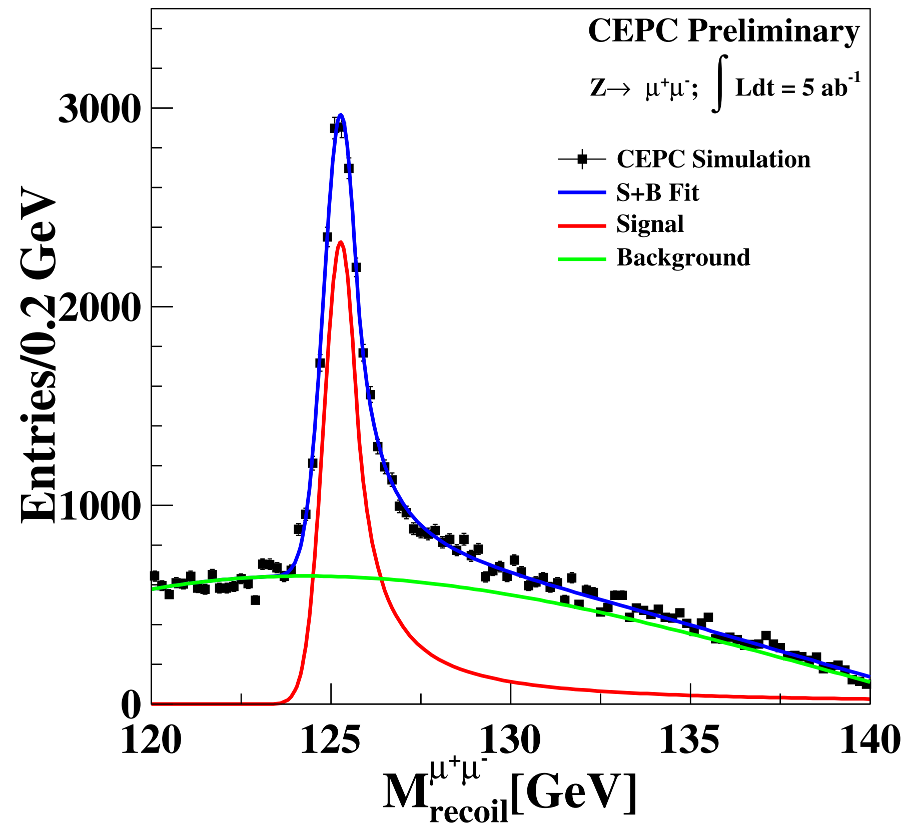




Process	Cross section	Nevents in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\nu H$	6.72	3.36×10^4
$e^+e^- \to eeH$	0.63	3.15×10^3
Total	219	1.10×10^6

Zh cross section



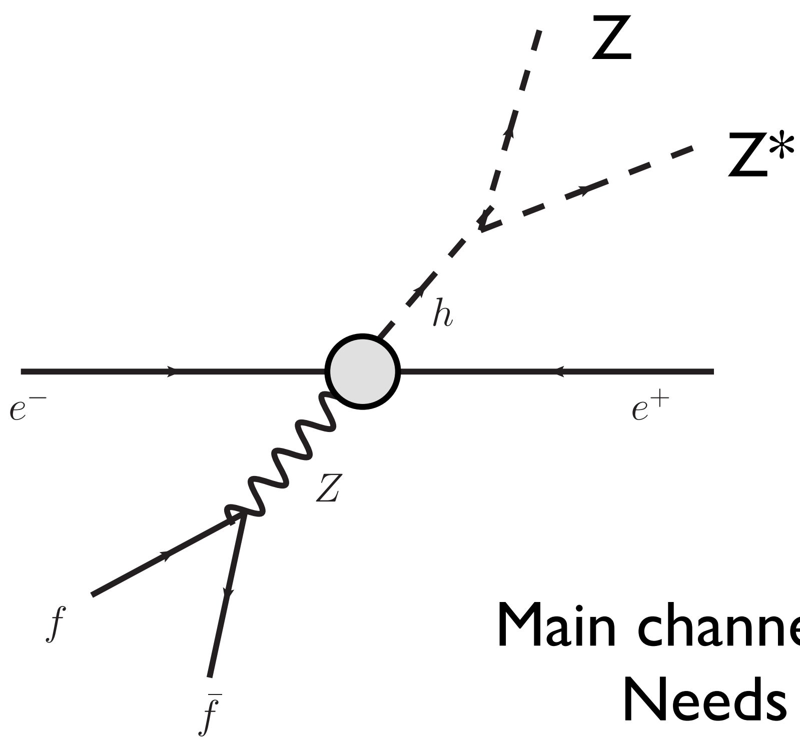


$$M_{\rm recoil}^2 = (\sqrt{s} - E_{ff})^2 - p_{ff}^2 = s - 2E_{ff}\sqrt{s} + m_{ff}^2$$

Can use recoil mass to identify Zh process, independent of Higgs decay

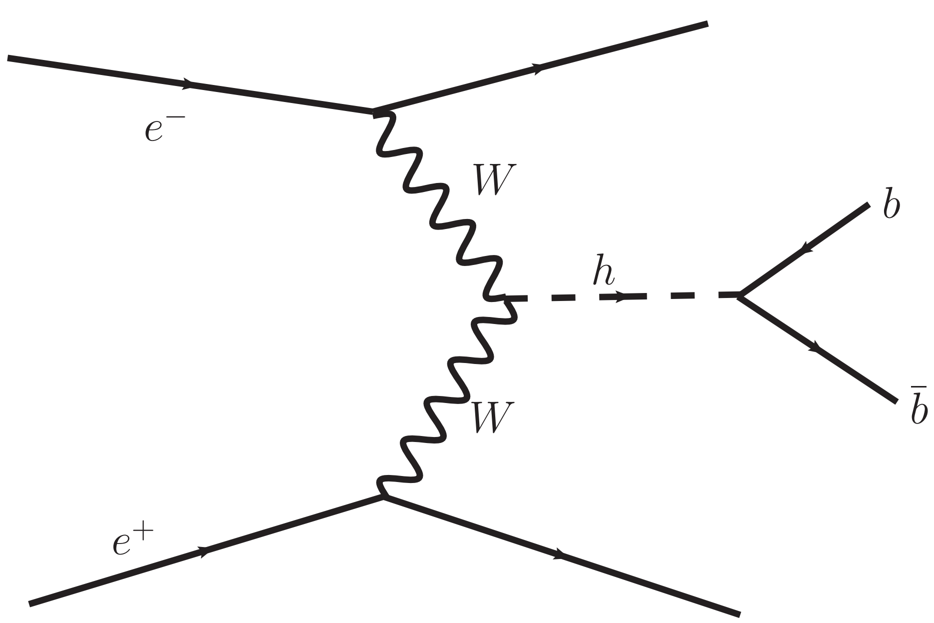
$\Rightarrow$ inclusive measurement of Zh cross section

Higgs width. Unique capability of lepton colliders.



$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$

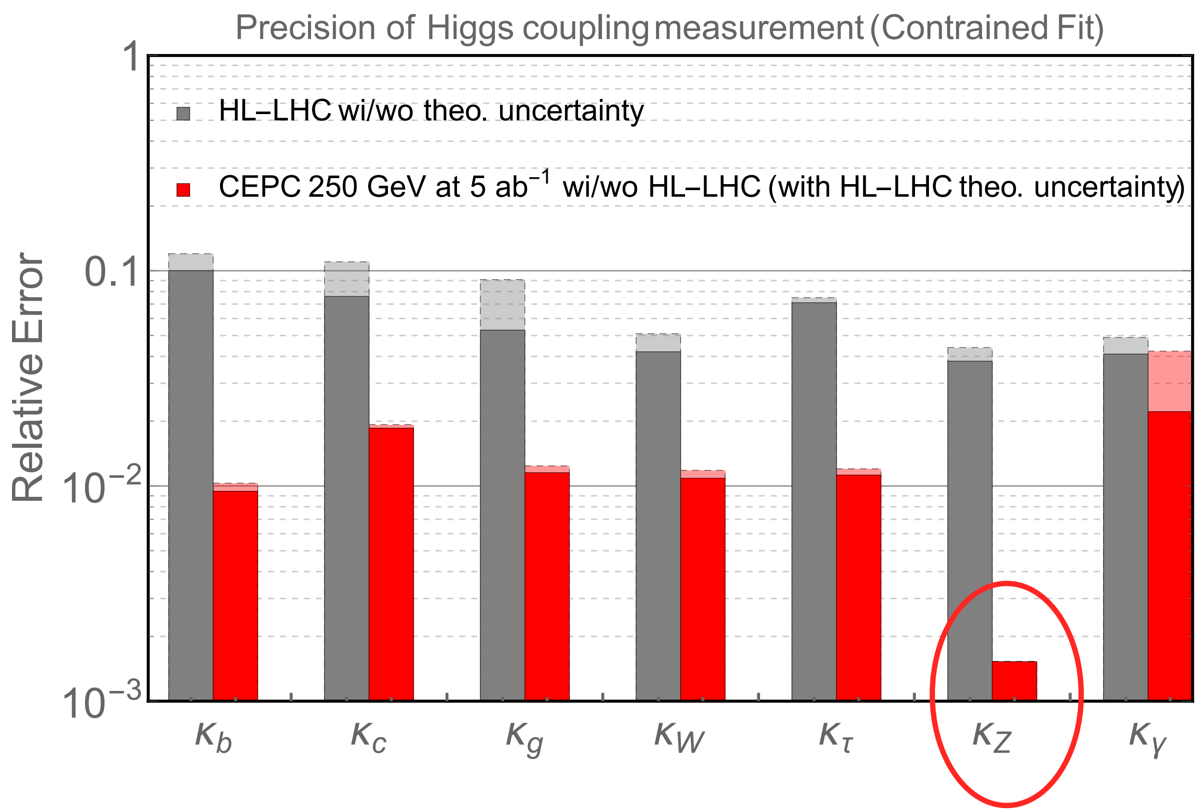
Main channel at 250 GeV.
Needs statistics



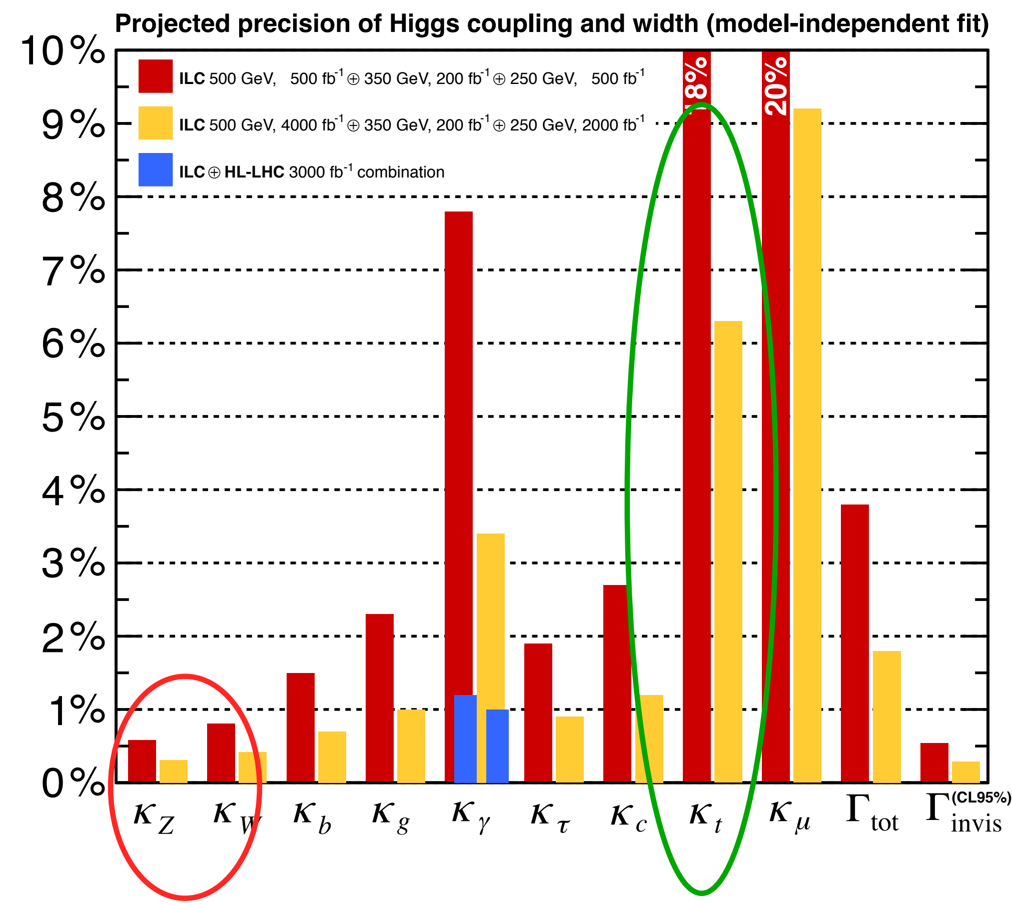
$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\nu H \to \nu\nu bb)}{\mathrm{BR}(H \to bb) \cdot \mathrm{BR}(H \to WW^*)}$$

Needs to go beyond 250.

Higgs factories



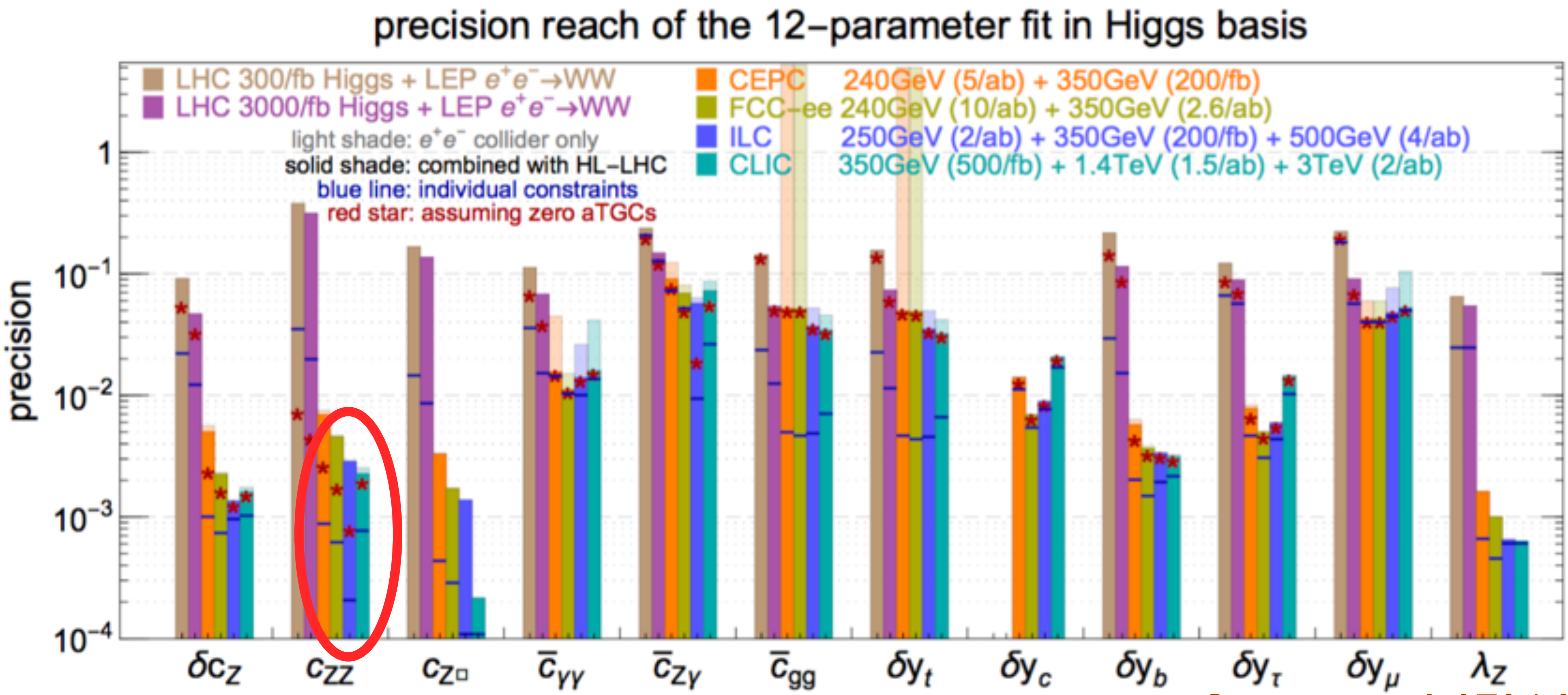
$$\kappa_X = \frac{\text{Measured Higgs-X coupling}}{\text{Standard Model Higgs-X coupling}}$$



Highlights:

HZ coupling to sub-percent level.
Many couplings to percent level.
Model independent measurement of total width.
Sensitive to the triple Higgs coupling: 20-30%

Lepton colliders and precision measurements



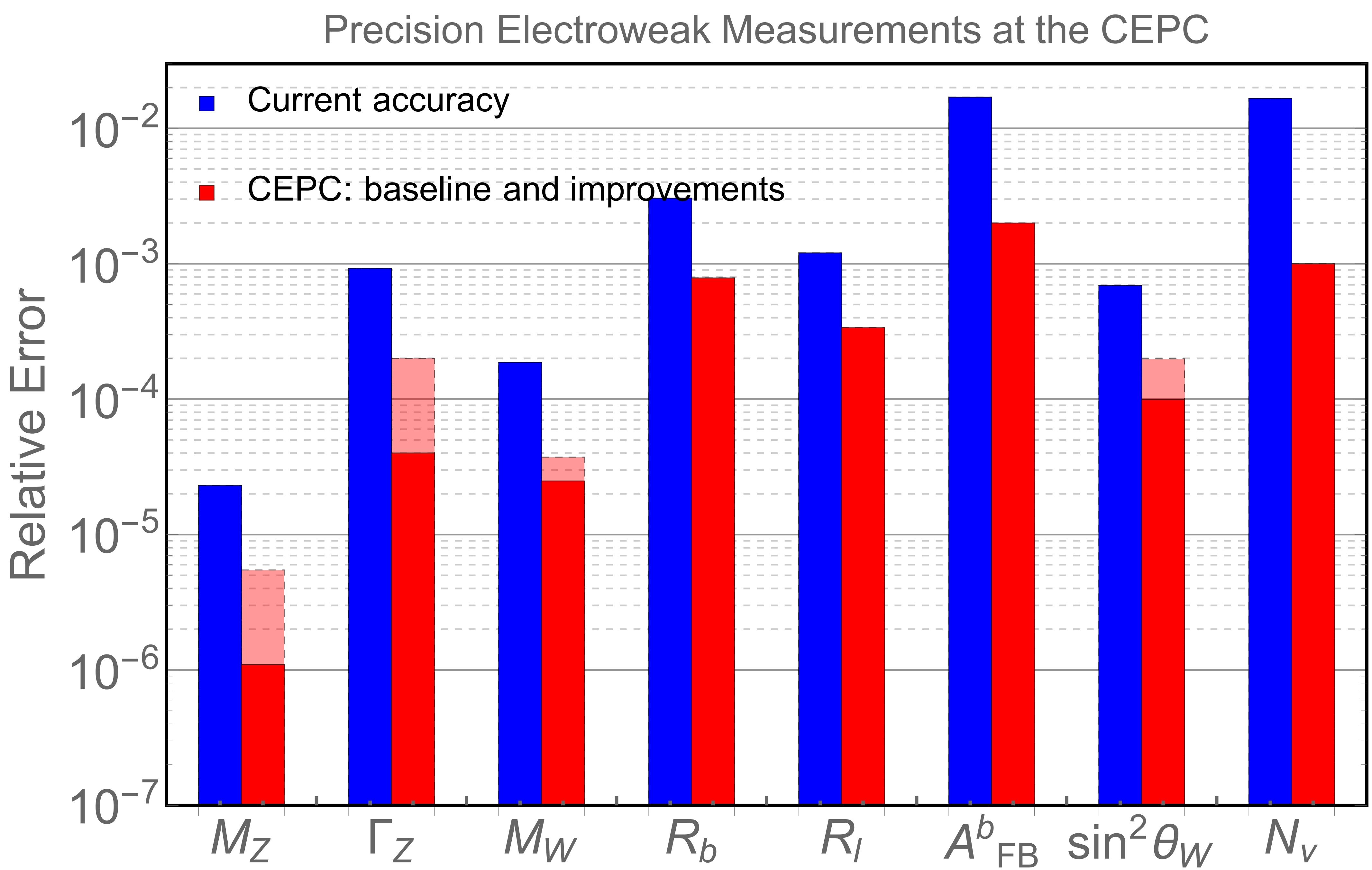
Grojean et al. 1704.02333

New physics with mass M_{NP} can affect Higgs coupling as

$$\delta \sim \frac{m_W^2}{M_{\rm NP}^2}$$

Sub percent precision, reach to new physics at multi-TeV scale.
Far beyond the reach of LHC.

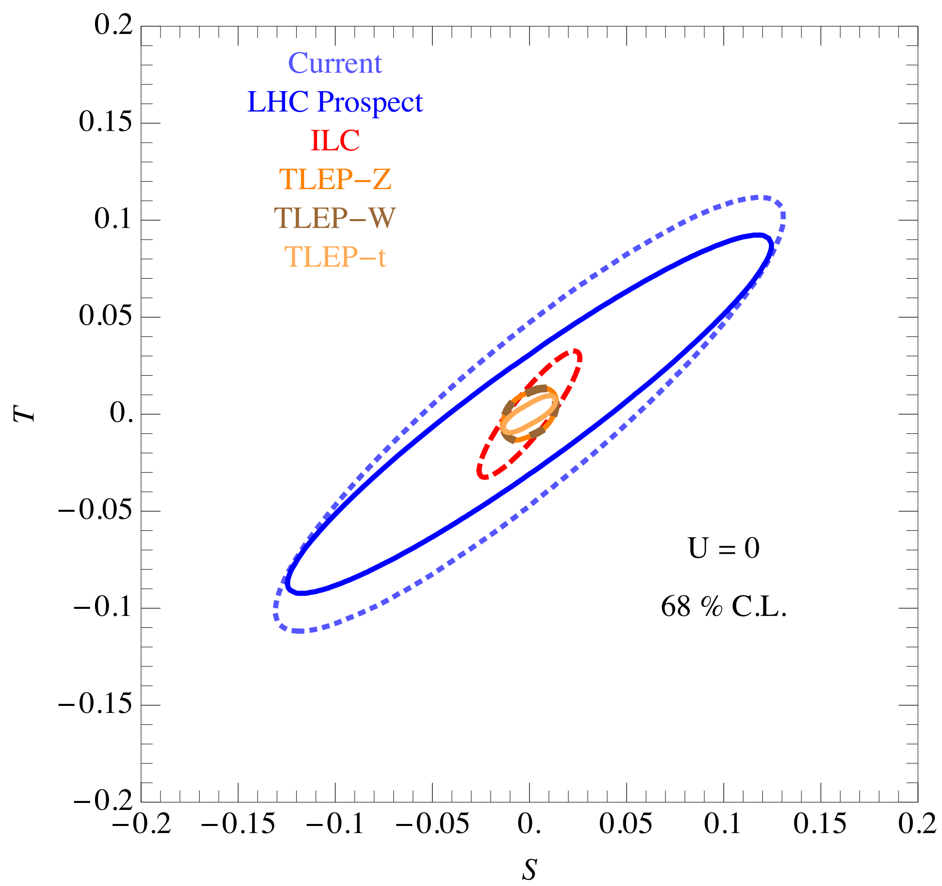
Big advance in electroweak precision

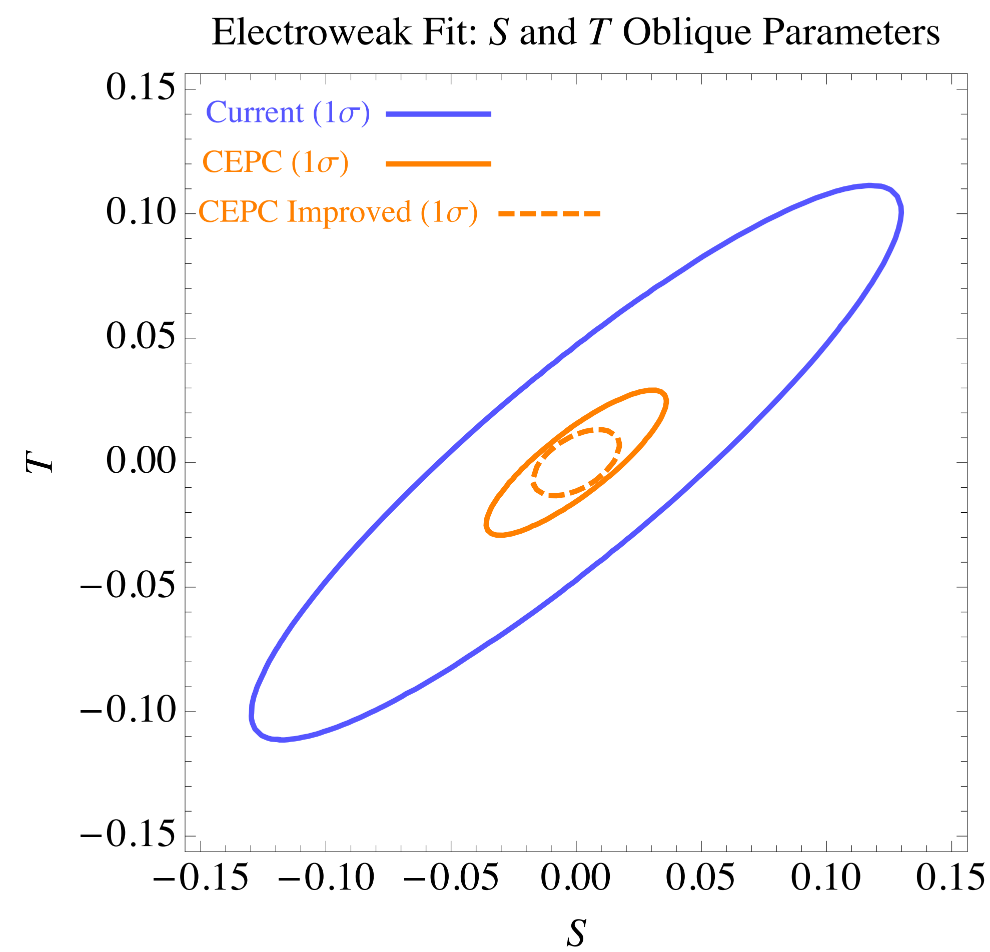


Large improvements across the board

Electroweak precision at CEPC

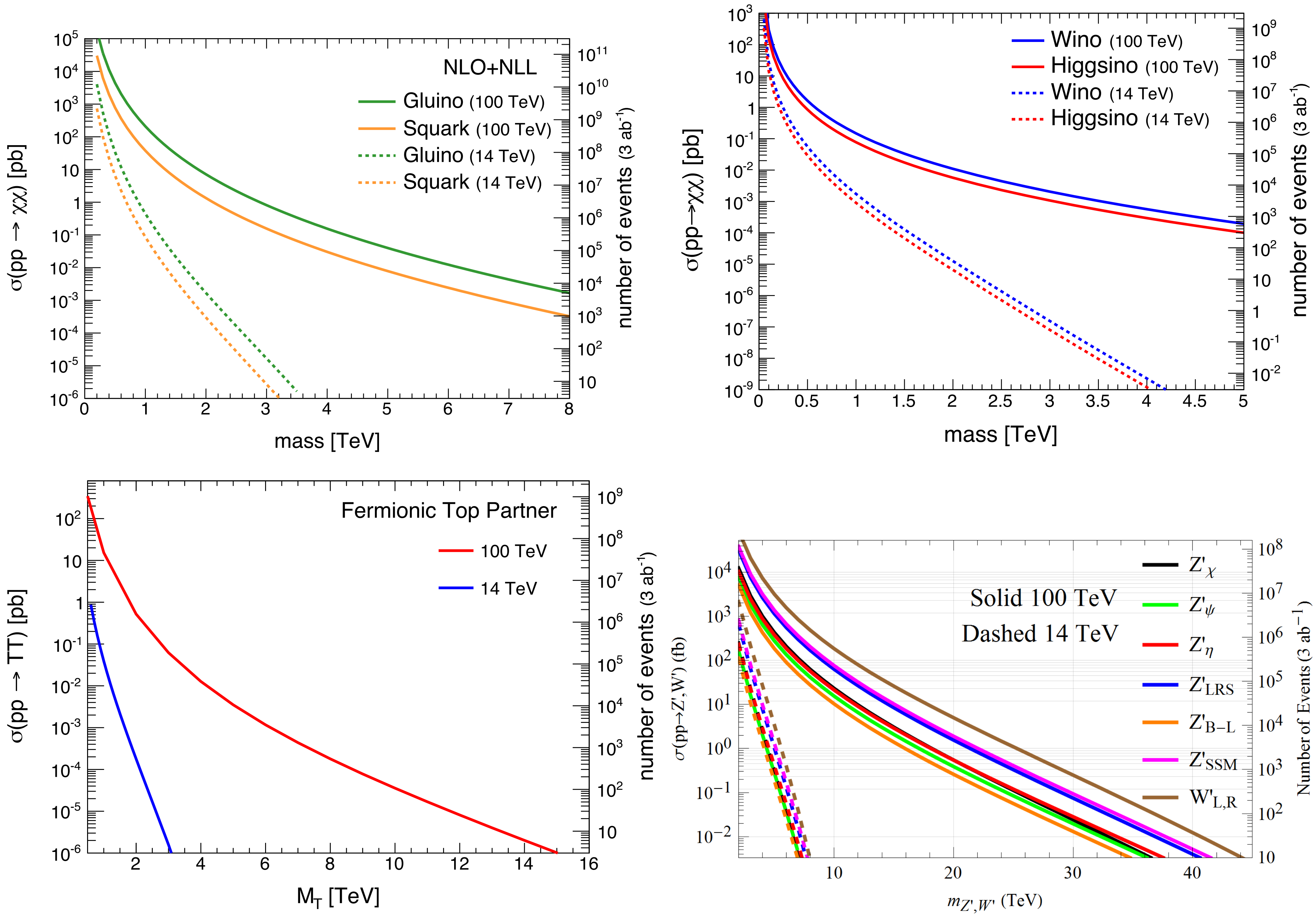
– A big step beyond the current precision.



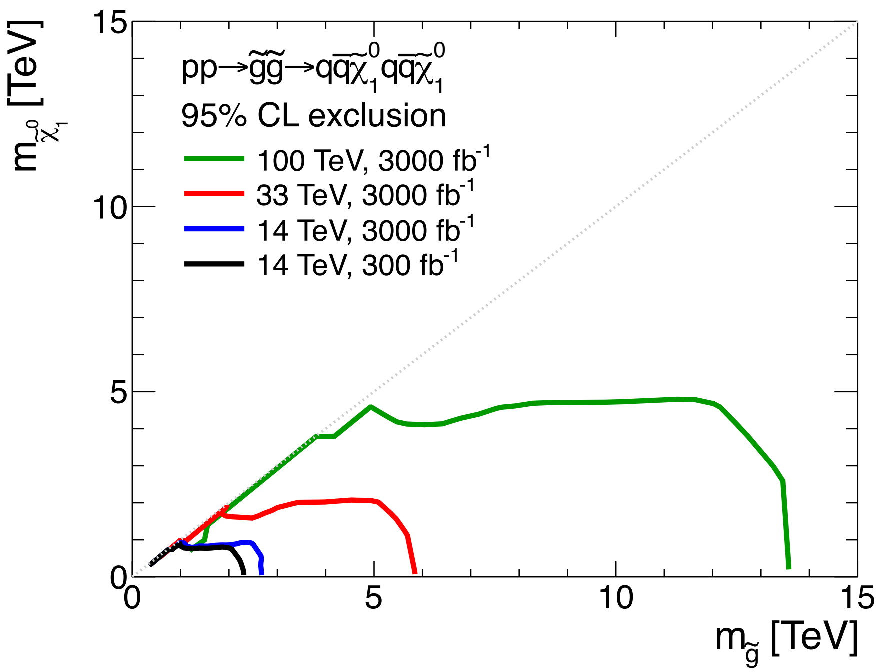


J. Fan, M. Reece, LT Wang, 1411.1054

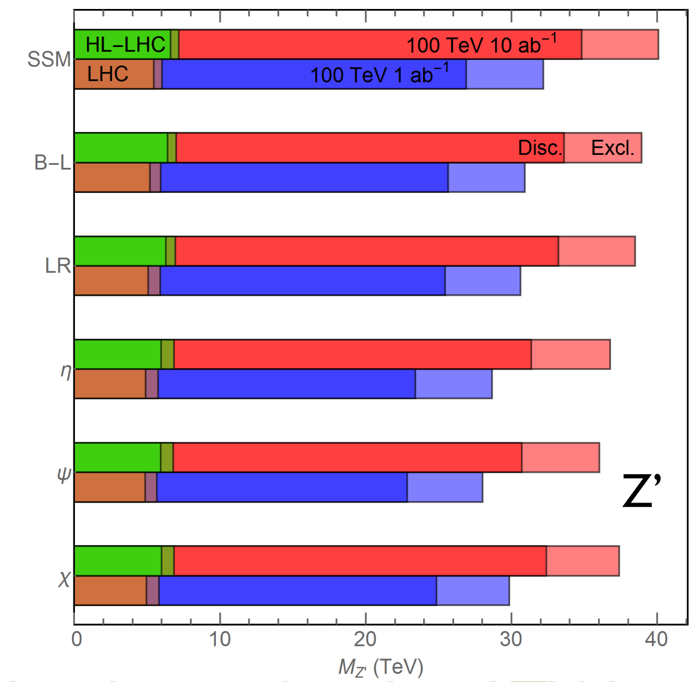
100 TeV pp collider, a big step in energy



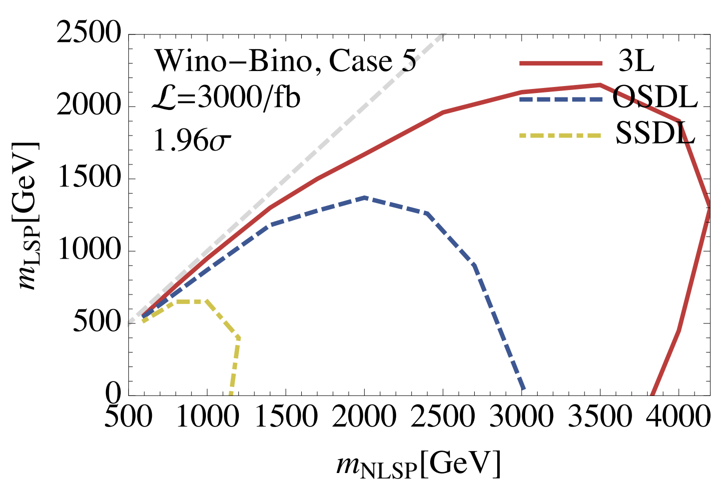
A big step forward in the energy frontier



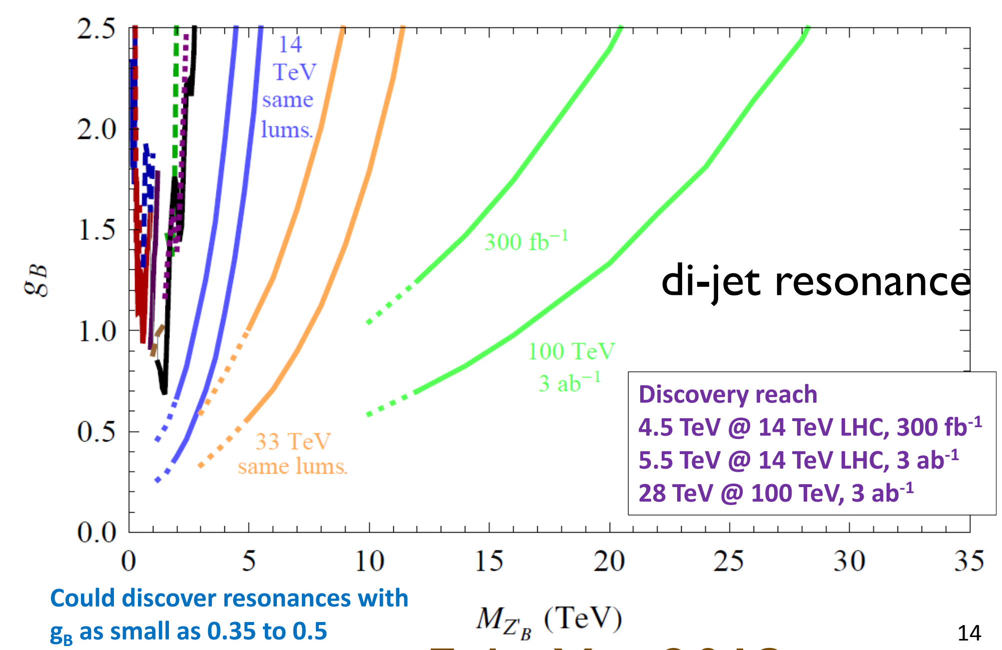
Cohen et al, 2013



Han, Langacker, Liu, LTW, to appear



Gori, Jung, LTW, Wells, 2014



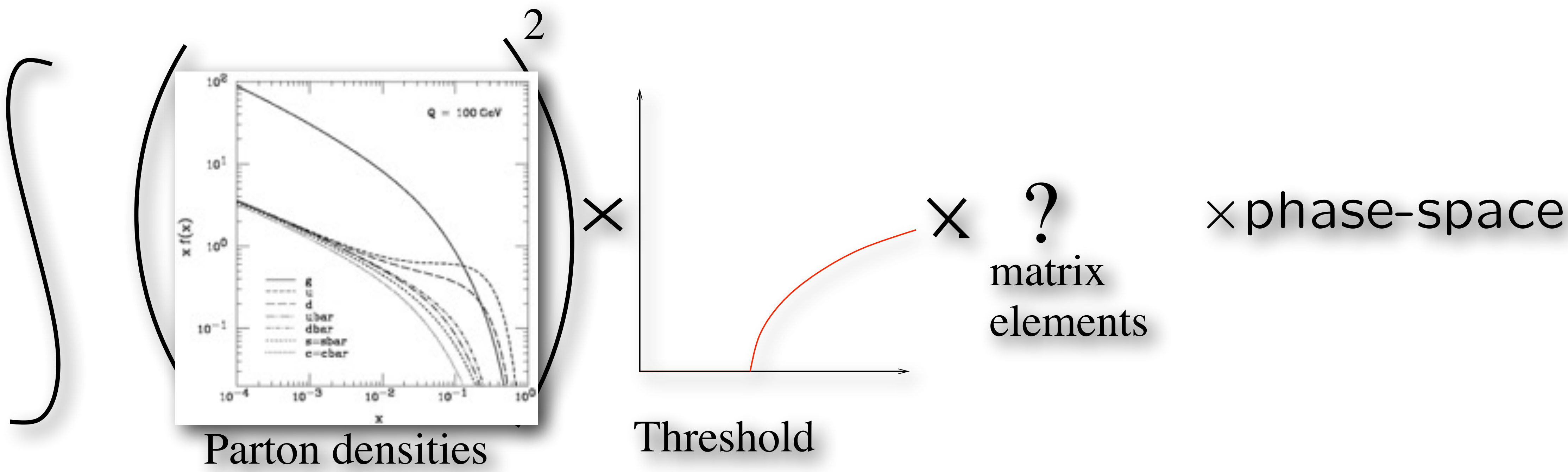
Could discover resonances with g_B as small as 0.35 to 0.5

Felix Yu, 2013

cross the board: x 5(more) improvement, into (10)TeV regime

Production of new physics particles

- Schematics of production at hadron colliders.
  - Dominated by parton densities and thresholds (mass and cut).



$$\frac{d^2\sigma(a,b\to\cdots)}{d\hat{s}\ dY} = \frac{1}{\hat{s}}\sum_{a,b} x_1 f_a(x_1)\ x_2 f_b(x_2)\ \hat{\sigma}(a,b\to\cdots)$$

Partonic cross section

Parton luminosity

- The cross section can be written as

$$\sigma = \sum_{a,b} \int d\tau \boxed{\frac{dL_{ab}}{d\tau}} \hat{\sigma}$$

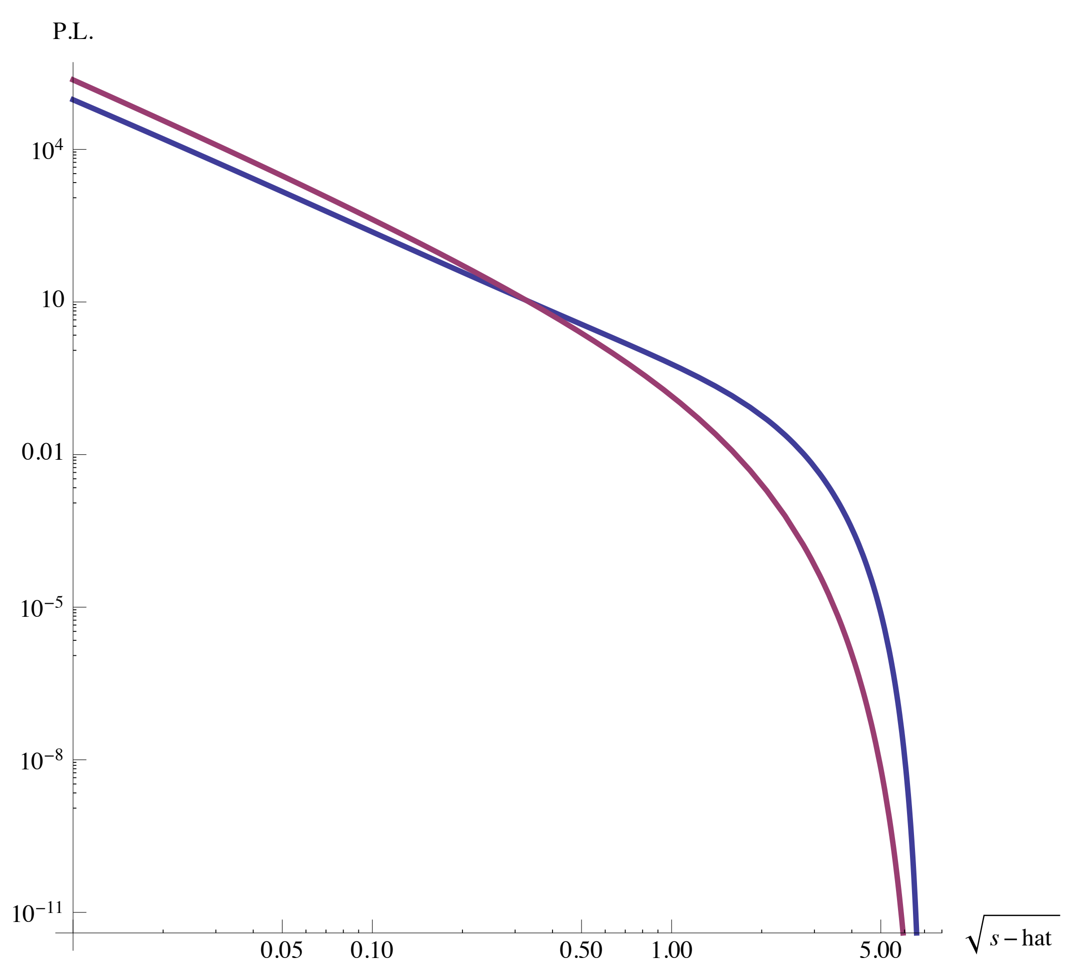
parton luminosity

$$\tau = \frac{\hat{s}}{S} = x_1 x_2$$

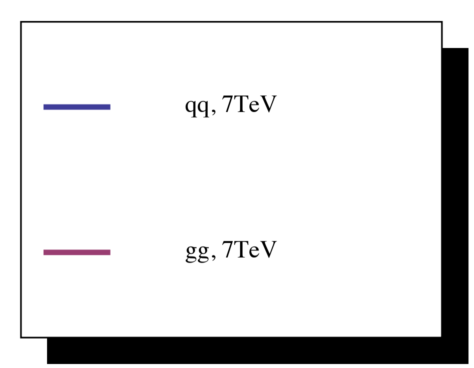
S : center of mass energy

$\hat{s}$: parton center of mass energy

$$L_{ab}(\tau) = \frac{1}{1+\delta_{ab}} \int_\tau^1 \frac{dx}{x} \left[f_a(x) f_b\left(\frac{\tau}{x}\right) + f_a\left(\frac{\tau}{x}\right) f_b(x) \right]$$



TeV, log scale



Very sharp falling

$$\propto \frac{1}{\tau^a}, \quad a \sim 3 - 7$$

Falls by a factor of 10 for every 600 GeV

⇒ Production dominantly on threshold

Rough estimates of discovery reach

$$\sigma \sim L_p \cdot \hat{\sigma} \sim \frac{1}{\tau^a} \hat{\sigma}$$

$$L_p: \text{ parton luminosity}, \ \hat{\sigma}: \text{ parton cross section}$$

Production of new physics particle of mass M

Fast falling parton luminosity ⇒

dominant contribution from
parton cross section near threshold

$$\hat{s} \sim M^2 \to \tau \sim \frac{M^2}{S}$$

$$\hat{\sigma} \sim \frac{1}{M^2}$$

Number of new physics particle produced:

$$N = \sigma \cdot \mathcal{L}$$

$$\mathcal{L}: \text{ luminosity}$$

Discovery reach

Consider 2 colliders.
Collider 1: $E_{cm} = E_1$, or $S_1 = E_1^2$. Collider 2: $E_{cm} = E_2$, or $S_2 = E_2^2$.

$$E_2 > E_1$$

Reach for new physics at these 2 colliders
Collider 1: M_1 . Collider 2: M_2.

Assume the reach is obtained from the same number of signal events

$$\frac{1}{\tau_1^a}\frac{1}{M_1^2}\mathcal{L}_1 = \frac{1}{\tau_2^a}\frac{1}{M_2^2}\mathcal{L}_2 \qquad \text{used} \quad \hat{\sigma} \sim \frac{1}{M^2}$$

We have

$$\frac{M_2}{M_1} = \left(\frac{S_2}{S_1}\right)^{1/2} \left(\frac{S_1}{S_2}\frac{\mathcal{L}_2}{\mathcal{L}_1}\right)^{\frac{1}{2a+2}} \qquad \text{used} \quad \hat{s} \sim M^2 \to \tau \sim \frac{M^2}{S}$$

Discovery reach

$$\frac{M_2}{M_1} = \left(\frac{S_2}{S_1}\right)^{1/2} \left(\frac{S_1}{S_2}\frac{\mathcal{L}_2}{\mathcal{L}_1}\right)^{\frac{1}{2a+2}}$$

$M_2 > M_1$ if $S_2 > S_1$
Large gain with higher energy

If we want $\frac{M_2}{M_1} \sim \frac{E_2}{E_1} = \left(\frac{S_2}{S_1}\right)^{1/2}$ We need $\frac{S_2}{S_1} = \frac{\mathcal{L}_2}{\mathcal{L}_1}$

That is, a factor of 50 more luminosity going from 14 TeV to 100 TeV. From HL-LHC, we will have 3 ab^{-1} . For 100 TeV, we need 150 ab^{-1} . A lot!

However, situation is actually better.

Discovery reach

$$\frac{M_2}{M_1} = \left(\frac{S_2}{S_1}\right)^{1/2} \left(\frac{S_1}{S_2}\frac{\mathcal{L}_2}{\mathcal{L}_1}\right)^{\frac{1}{2a+2}}$$

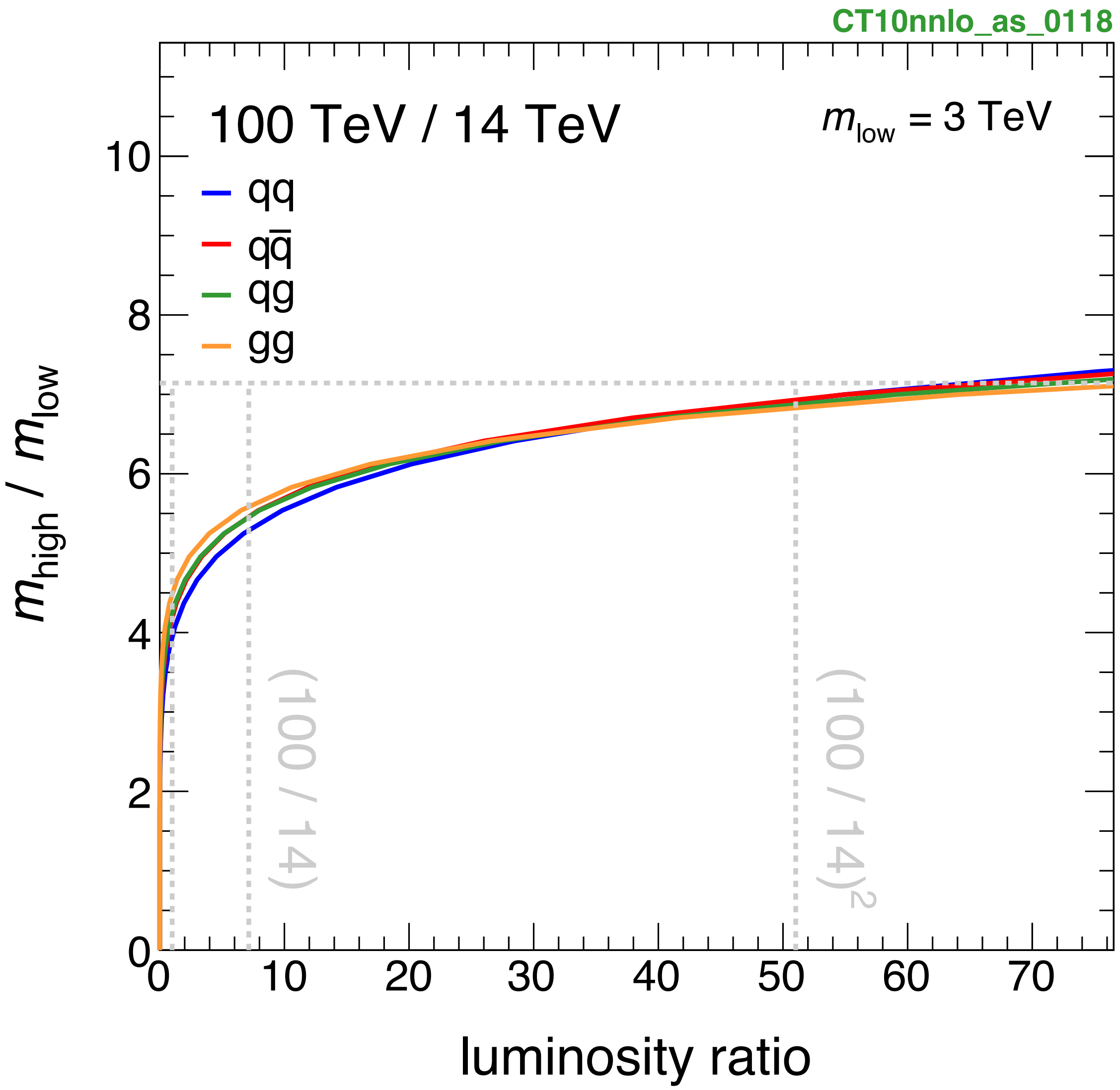
a is large (3-7).

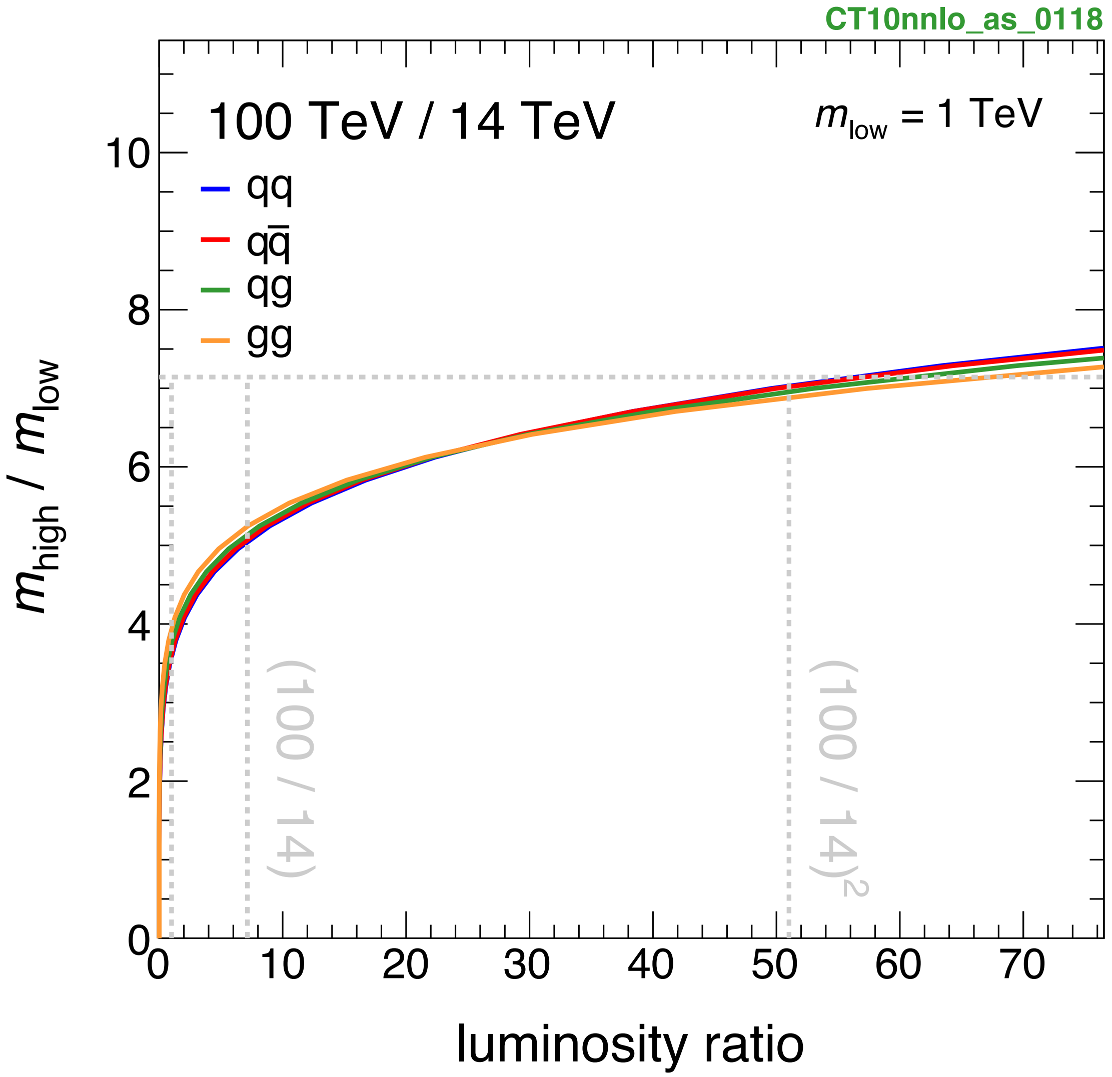
The second factor on r.h.s is increasing slowly with large luminosity i.e., not losing that much without very large luminosity.

In particular, for the same collider, as luminosity increases

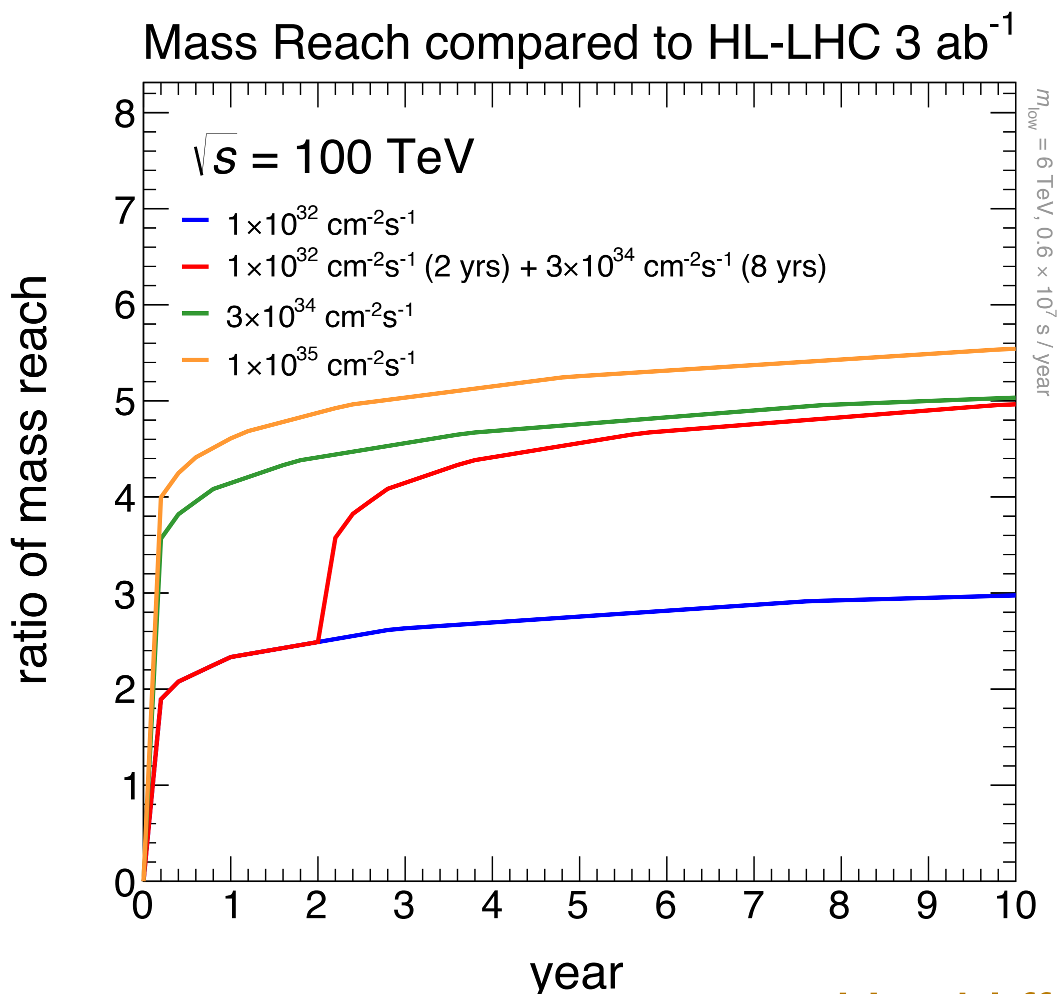
$$\frac{M_2}{M_1} = \exp\left(\frac{1}{2a+2}\log(\mathcal{L}_2/\mathcal{L}_1)\right) \simeq 1 + \frac{1}{2a+2}\log(\mathcal{L}_2/\mathcal{L}_1)$$

Discovery reach





100-ish TeV pp collider



Hinchliffe, Kotwal, Mangano, Quigg, LTW

A factor of about 5 increase in reach with modest luminosity

Status of circular collider studies

- In the past 2 years, many studies of the physics reaches of the circular colliders have been carried out.
  - On both FCC and CEPC/SppC.
- Preliminary physics case has been made. ← rest of this this lecture
- Active efforts in trying to make it happen. Prospect will be clearer in the coming several years.

Open questions beyond LHC

- Nature of electroweak symmetry breaking.
- Naturalness.
- Dark matter.
- ....

Need to go beyond

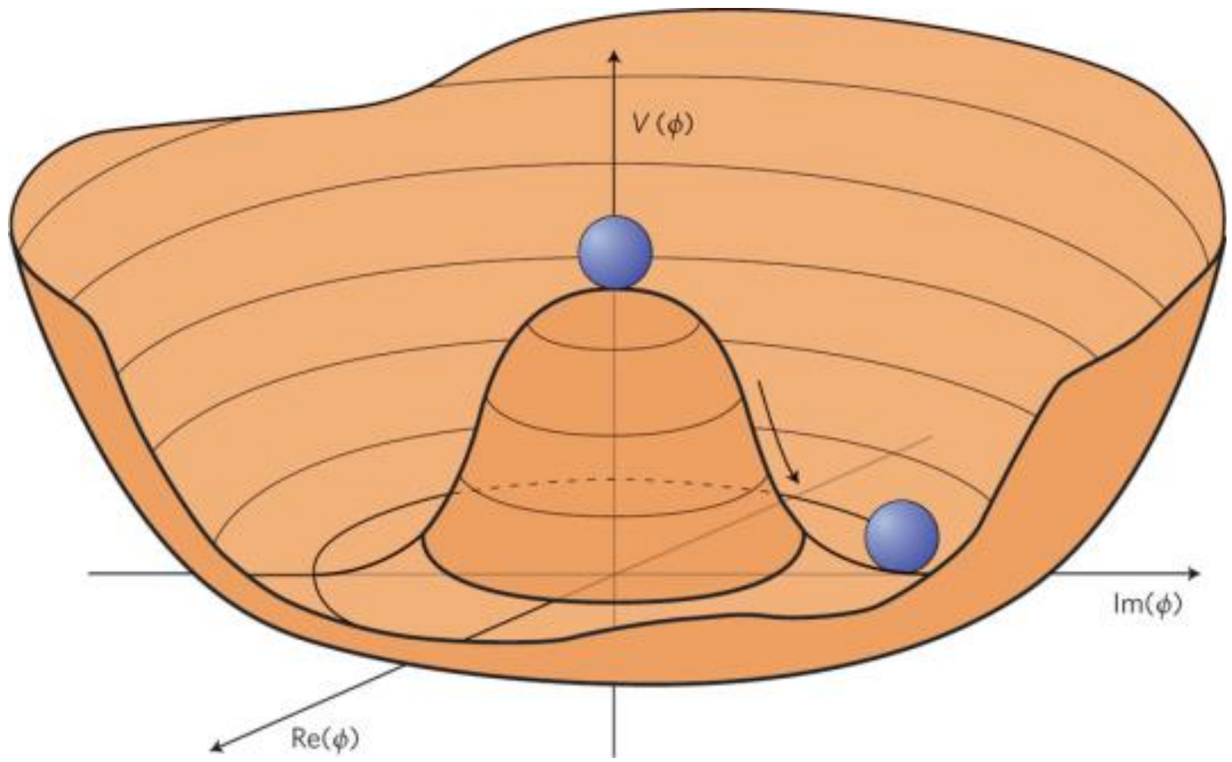
Nature of electroweak symmetry breaking

Higgs is special

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

h: a new kind of
elementary particle

"Simple" picture: Mexican hat



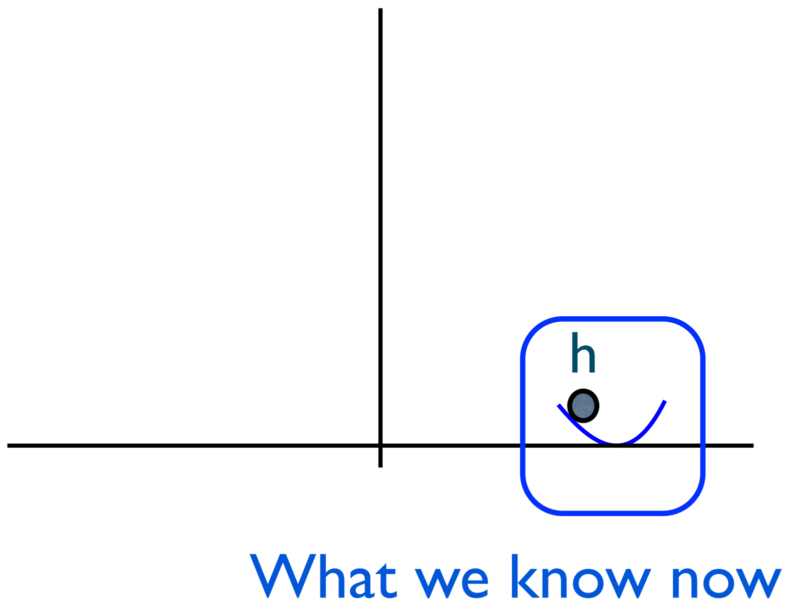
$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

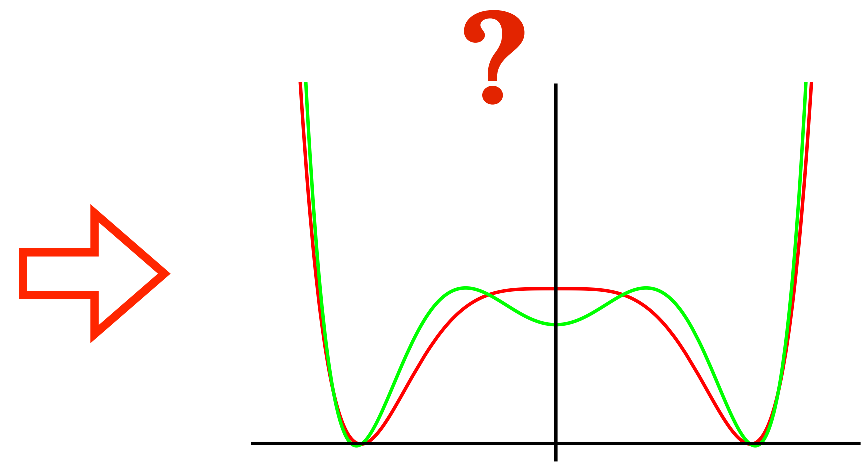
$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

However, this simplicity is deceiving.
Parameters not predicted by theory. Need new physics

Not even sure about "Mexican hat".



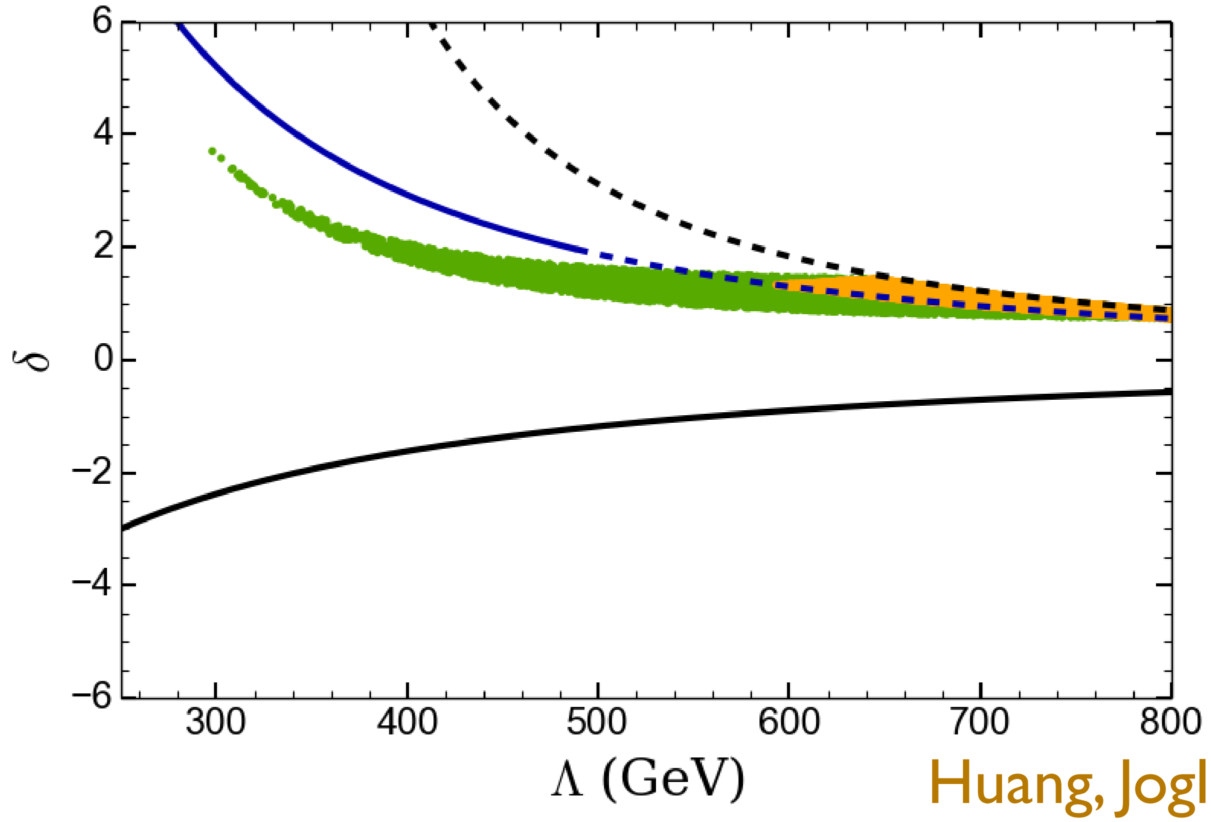


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

Is the EW phase transition first order?

LHC can not distinguish these definitively.

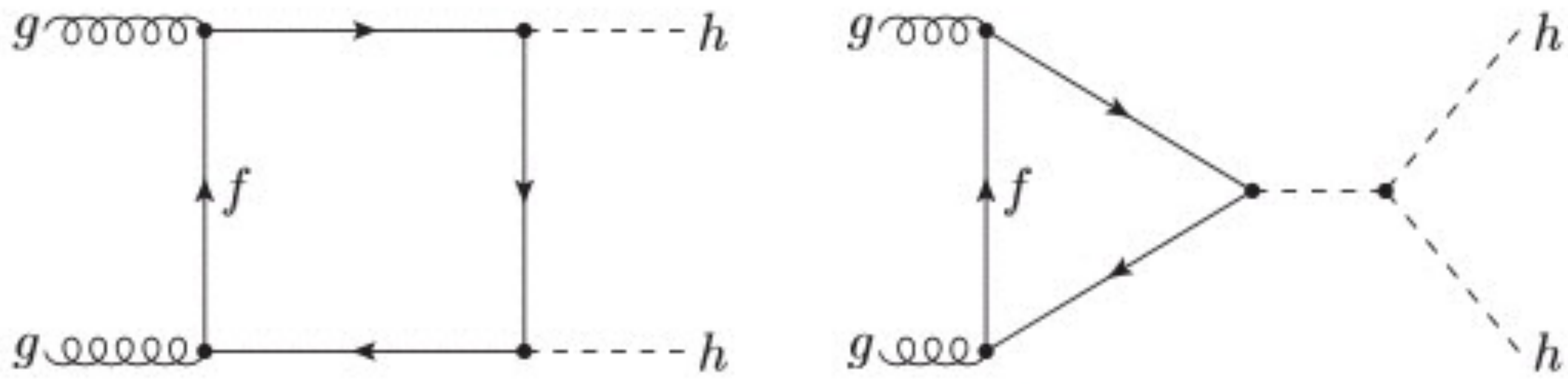
1st order phase transition
$\Rightarrow$ large modification of trilinear coupling



Huang, Joglekar, Li, Wagner, 1512.00068

$$V(h) = \frac{m^2}{2}h^2 + \lambda h^4 + \frac{1}{\Lambda^2}h^6 + \ldots$$

Measuring triple Higgs



f = top, … Many possible final state. Very difficult channel.

LHC at 3 ab^{-1} ≈ 100% .

Triple Higgs coupling at 100 TeV pp collider 30 ab^{-1}
Some preliminary studies, incomplete not fully realistic.

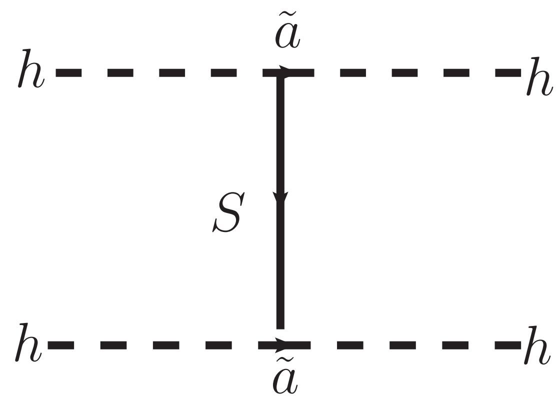
$$\frac{\lambda}{\lambda_{\rm SM}} \in \begin{cases} [0.891, 1.115] & \text{no background syst.} \\ [0.882, 1.126] & 25\%\ hh, 25\%\ hh + \text{jet} \\ [0.881, 1.128] & 25\%\ hh, 50\%\ hh + \text{jet} \end{cases}$$

Barr, Dolan, Englert, de Lima, Spannowsky

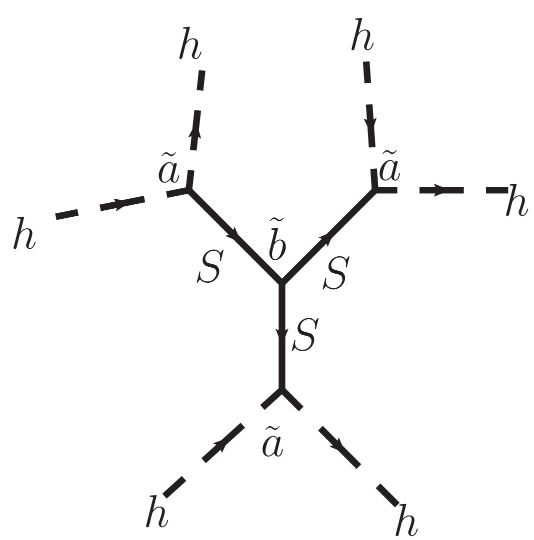
ILC 500: 27%
ILC ultimate, 1 TeV 5 ab-1: 10%

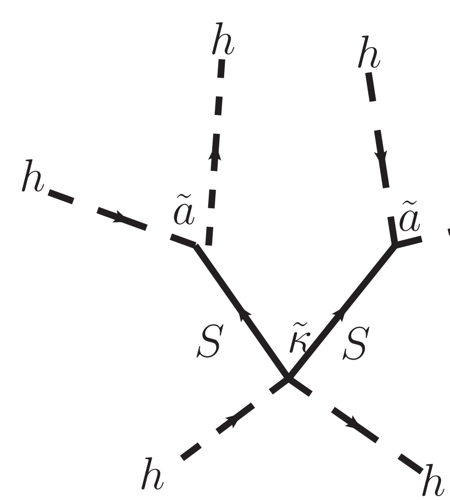
Simple example: Generic singlet model

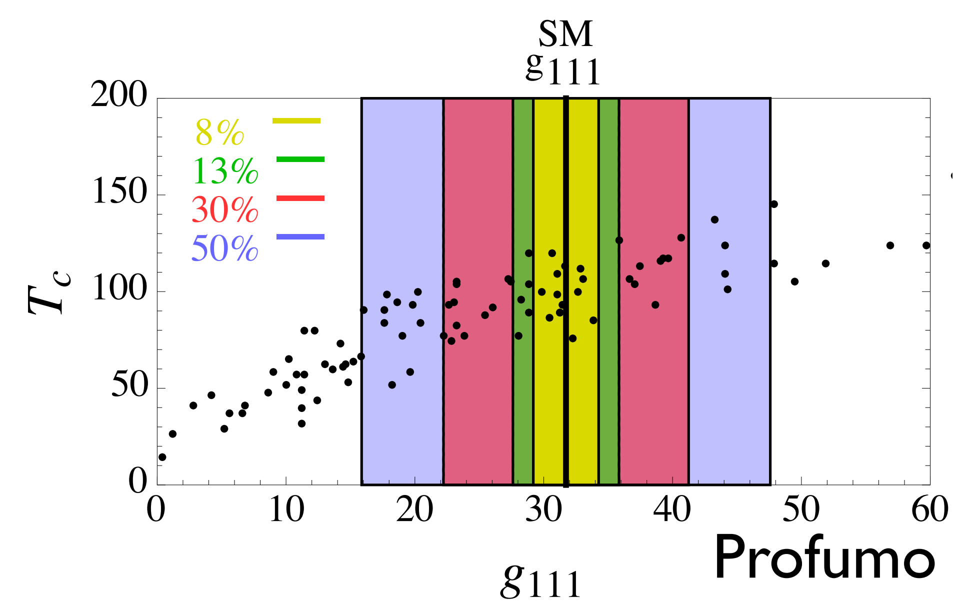
$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$



shift in h-Z coupling > %
Higgs factory important



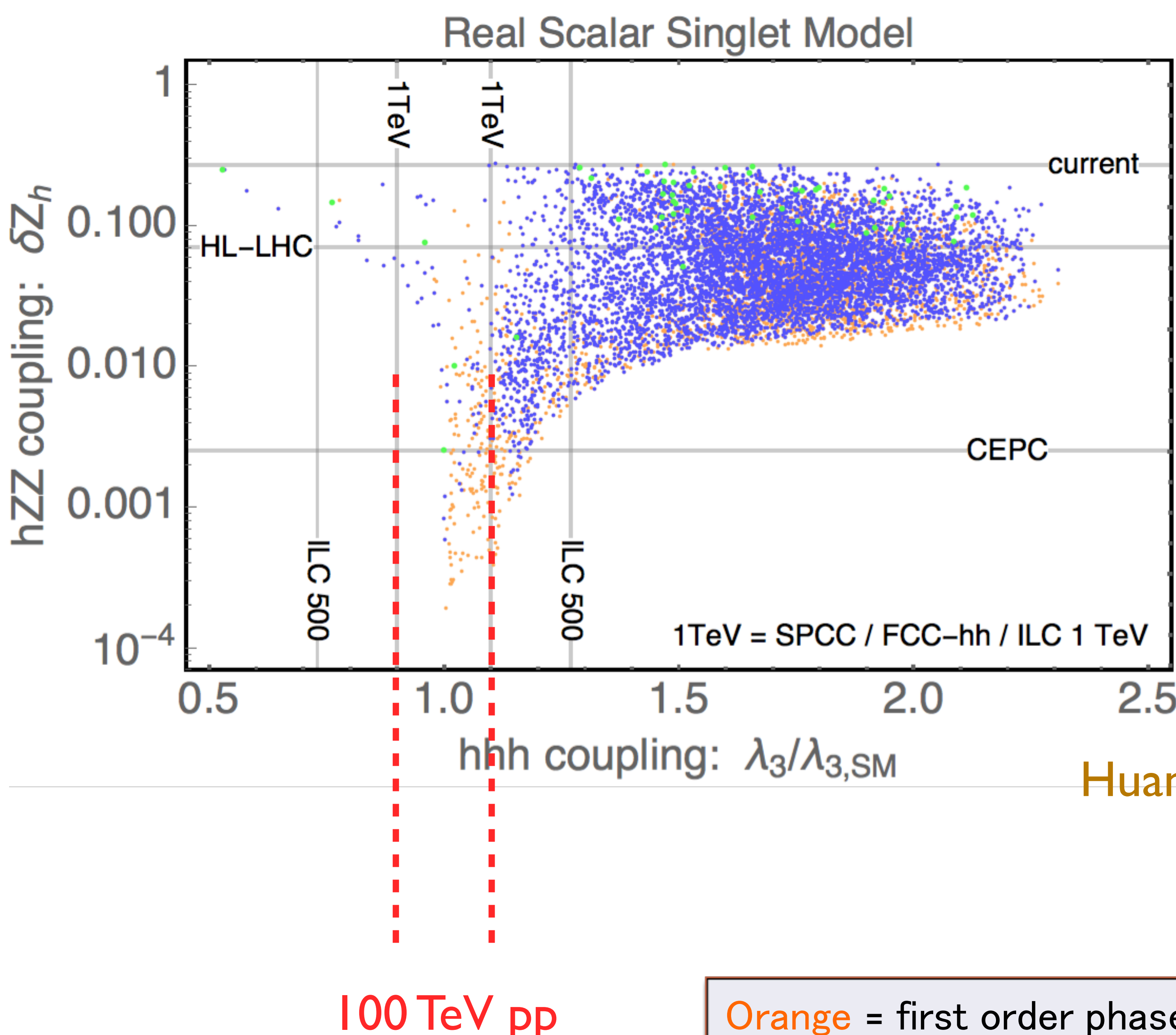




Profumo et al

O(1) devidation in triple Higgs coupling

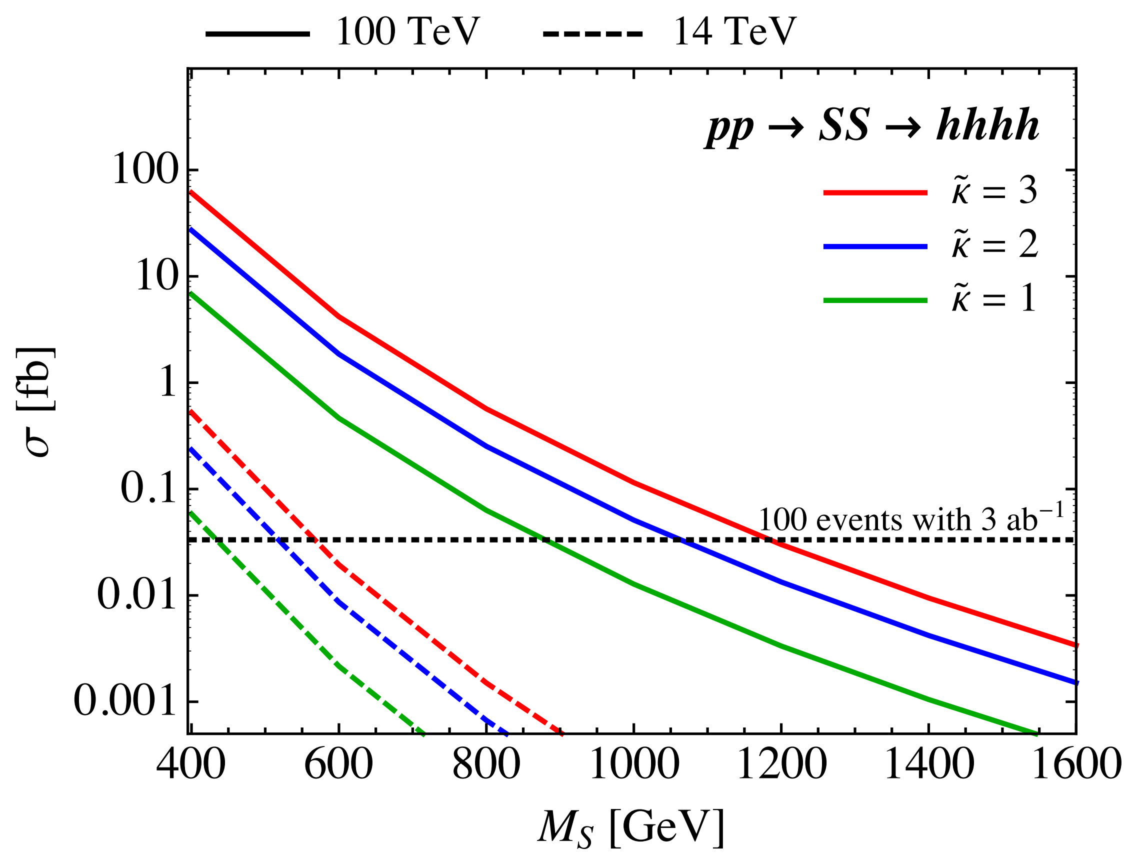
Also considering Higgs factories

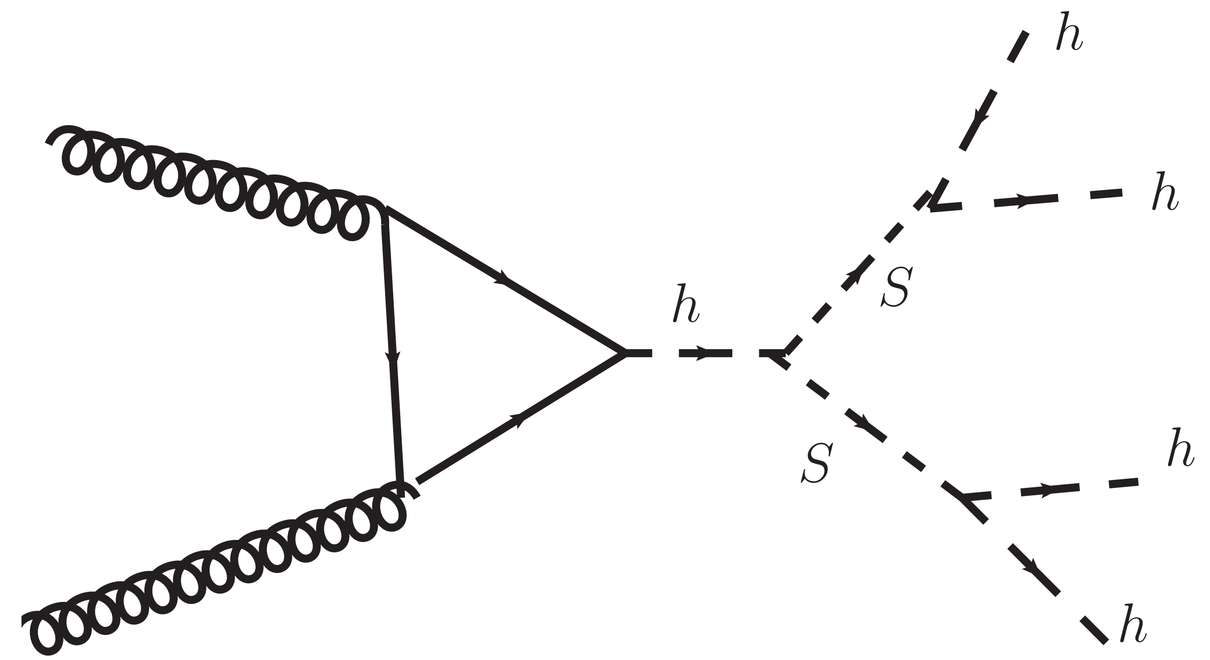


Huang, Long, LTW, in progress

Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

Singlet search at 100 TeV

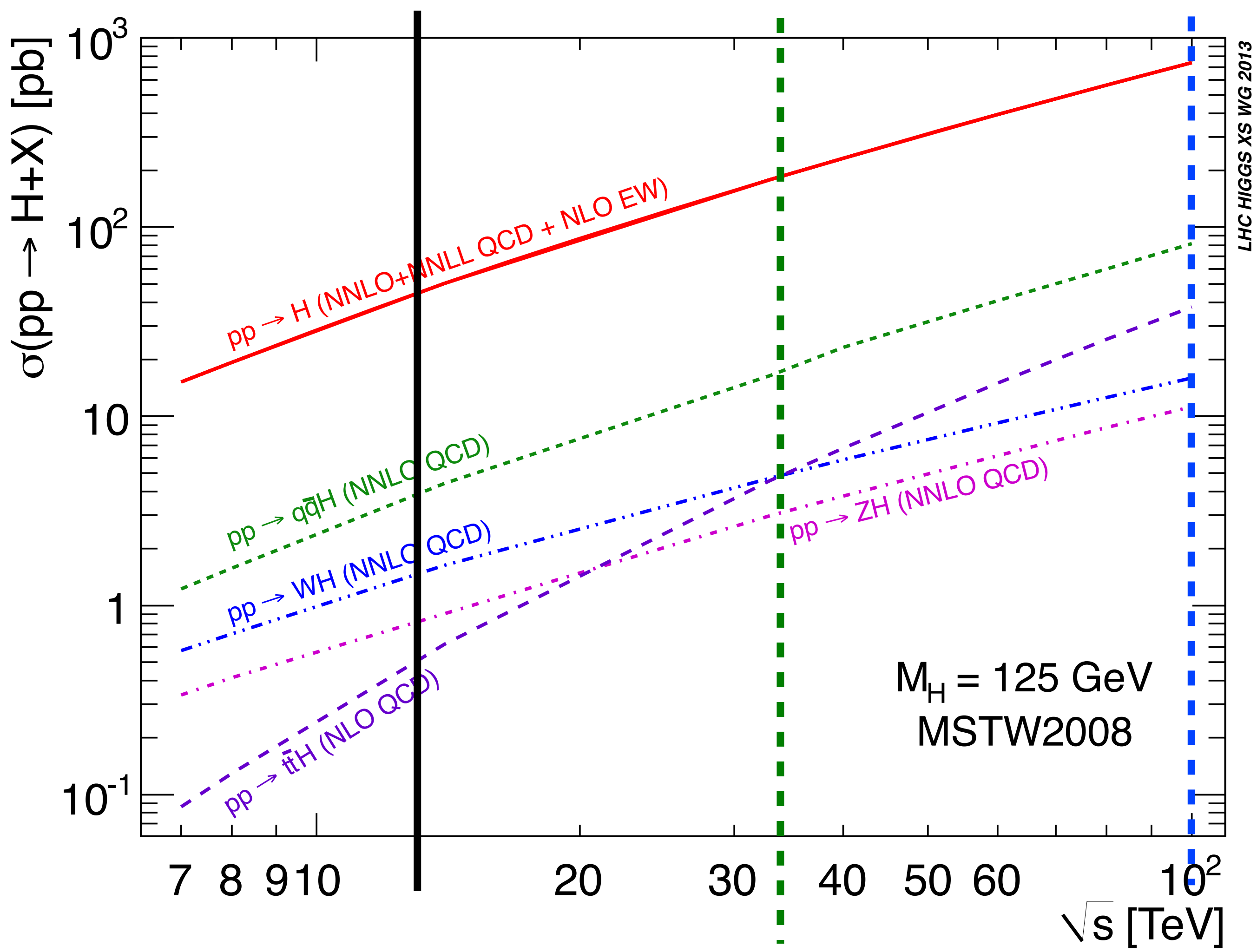




- 4 Higgs final state with decent rate.
- Good discovery potential.

Combination of Higgs factory and 100 TeV pp collider can go very long way in understanding EWSB

More Higgs physics at hadron collider



# of Higgses in 3 ab^{-1}

100 TeV > 2 billion

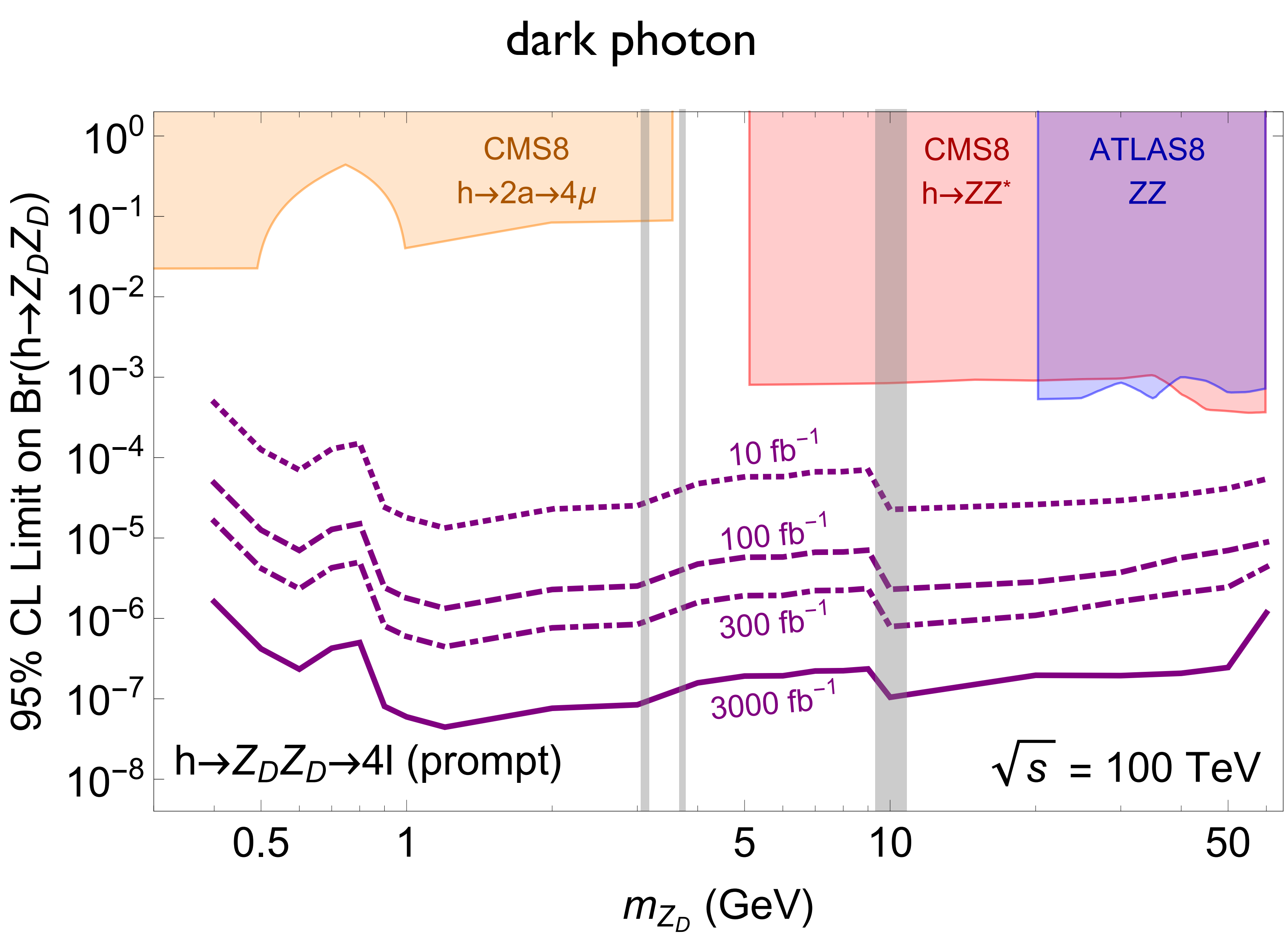
33 TeV > 500 million

14 TeV > 150 million

In comparison, O(million) Higgs at Higgs factories

Can look for very rare and distinct Higgs signal.

New physics Higgs rare decays

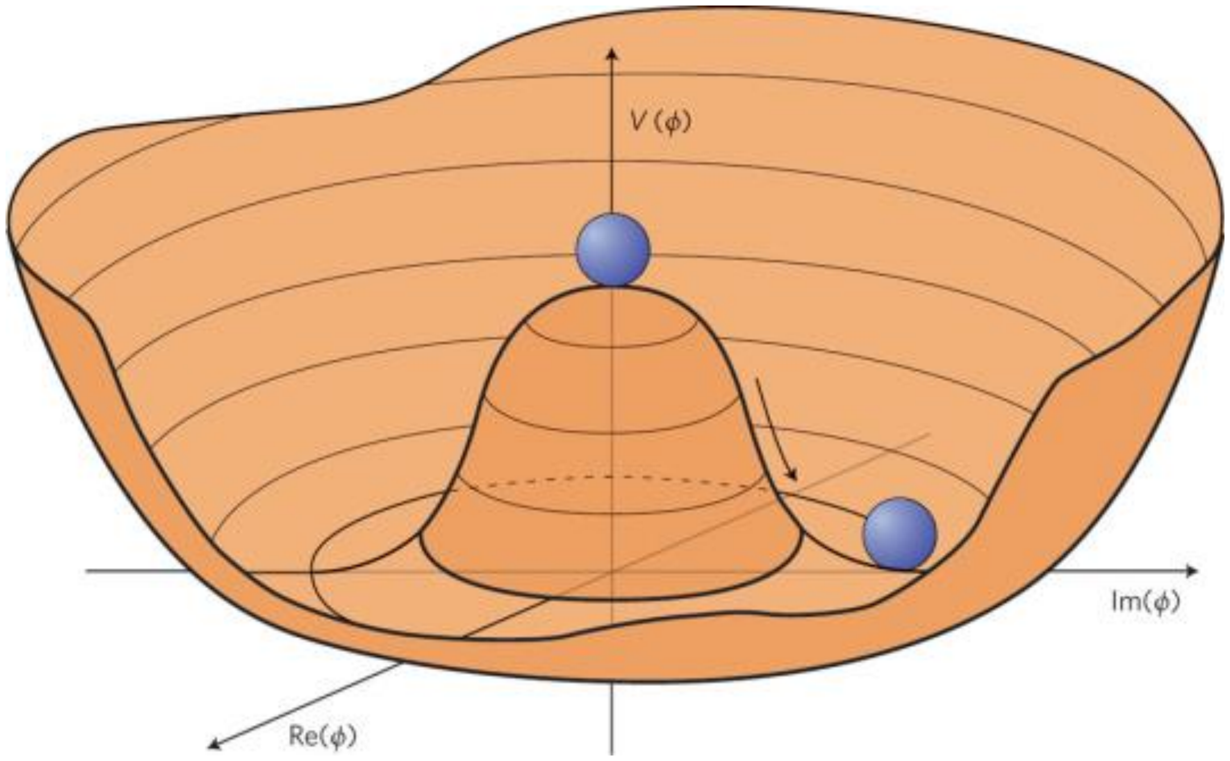


Curtin, Gori, Shelton

There are certainly more examples.

Naturalness

Explaining the Higgs potential.

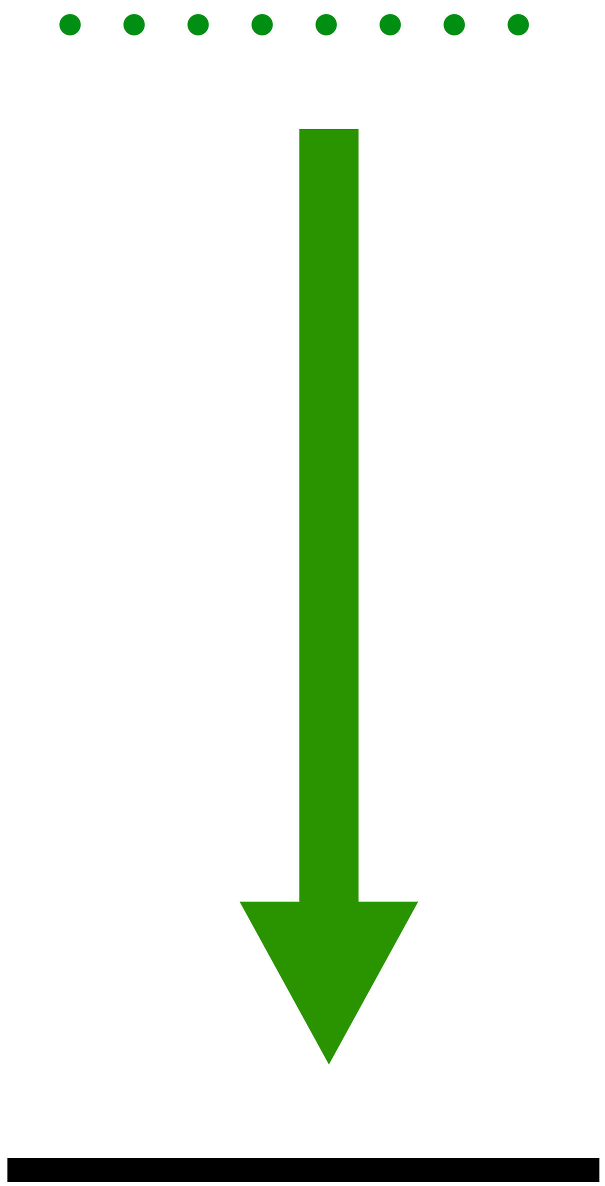


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

Explaining electroweak scale O(100) GeV

Explaining EWSB: naturalness



M: The energy scale of new physics responsible for EWSB

What is M? Can it be very high, such as $M_{Planck} = 10^{19}$ GeV, …?

If so, why is so different from 100 GeV?

Electroweak scale, 100 GeV.

m_h , m_W …

Naturalness of electroweak symmetry breaking

M: The energy scale of new physics responsible for EWSB

What is M? Can it be very high, such as $M_{Planck} = 10^{19}$ GeV, …?

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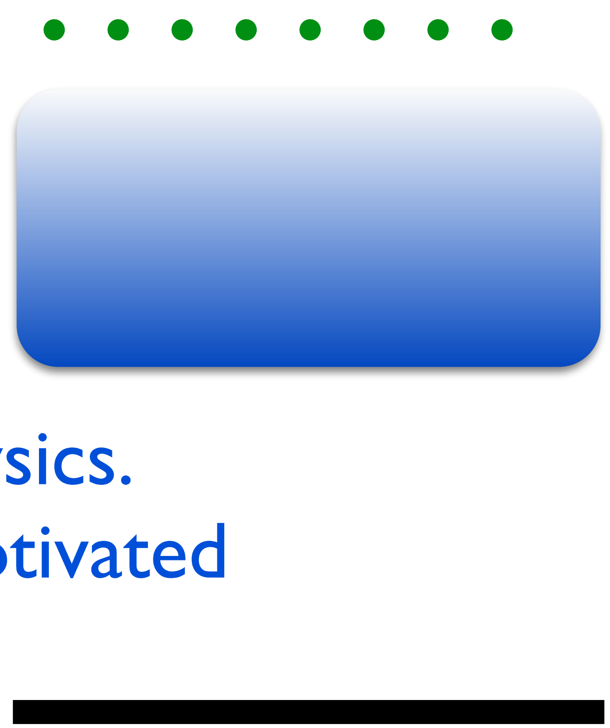


TeV new physics.
Naturalness motivated

Electroweak scale, 100 GeV.
m_h , m_W …

Naturalness problem.

- Dim-analysis, m_h^2 (physical) = $a_1 M_1^2 + a_2 M_2^2 + \ldots$, $a_{1,2} \approx O(1)$

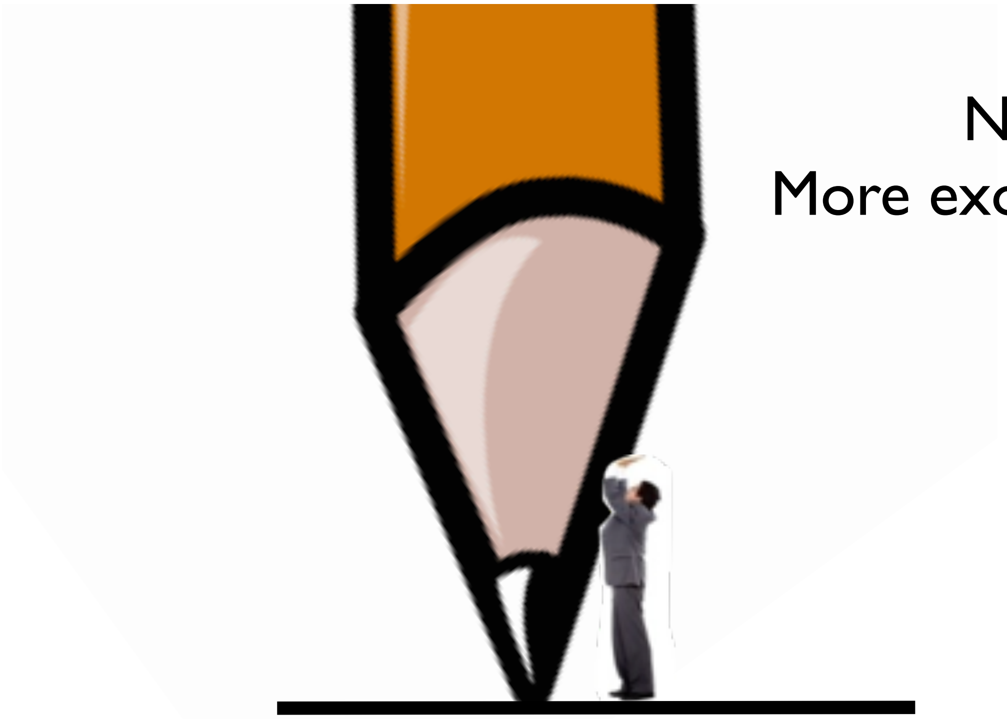
- What is $M_{1,2}$? Or where is new physics?
  - Some fundamental scale beyond the Standard Model. $M \approx M_{Pl} = 10^{19}$ GeV, $M_{unification} = 10^{16}$ GeV...?

- $M_{1,2} \approx M_{Pl}$ At the same time, various terms must cancel to the precision of 10^{-32} to have m_h^2 (physical) $\approx (100 \text{ GeV})^2$, fine-tuning.

- No large cancellation $\Rightarrow m_h^2$ (physical) $\approx (M_{1,2})^2$
  - $M \approx$ 100 GeV - TeV, new physics at TeV scale!

Is fine-tuning ok?

- Mathematically, yes.
  Can always solve m_h^2(physical) = m_h^2 (physical) = $a_1 M_1^2 + a_2 M_2^2 + ...$ But,



No rope?
More exotic possibilities

Similarly, we have been searching for an explanation for the fine-tuning of Higgs mass $O(10^{-32})$

Another fine-tuning problem

Has LHC already told us that electroweak scale is not natural?

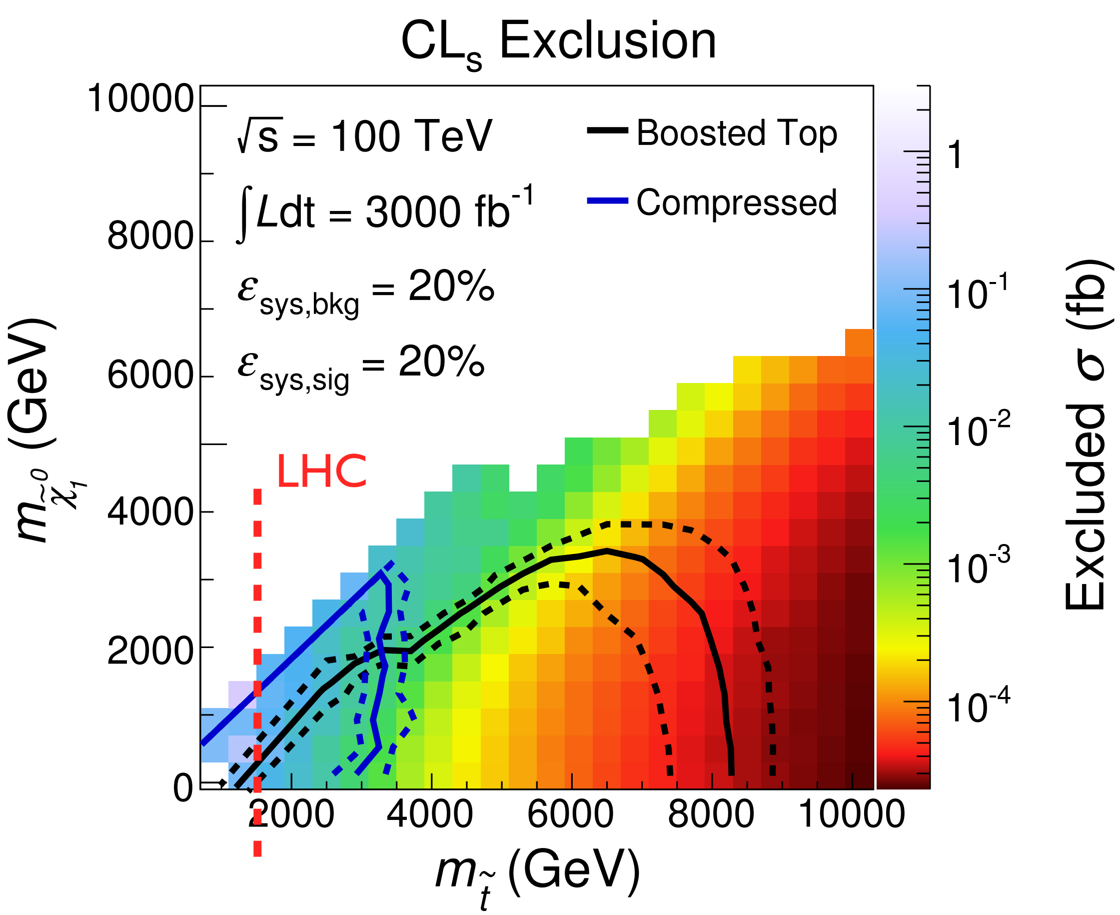
- Certainly put a lot of strain/stress on this notion.
- Actually, before LHC, flavor and electroweak precision tests already "prefer" new physics at 10 TeV scale. "Little hierarchy" problem.
  - Many ugly, but more "natural", models been built.
- Time to think of alternatives? Yes!
- Time to completely give up on this "conventional" naturalness? No!

“Alternatives”

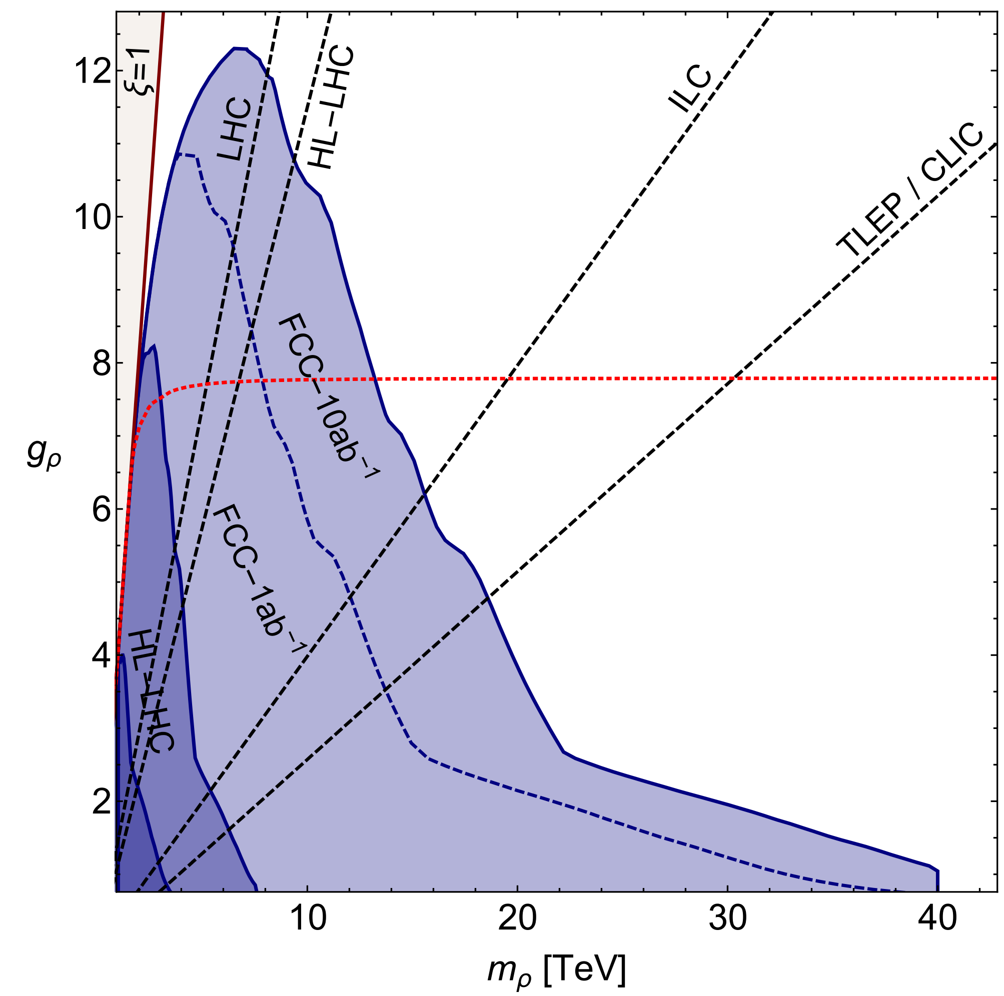
- Connection with cosmological evolution?
- Unique vacuum vs landscape
  - Dynamics vs selection.
- Dramatic new phenomena in quantum field theory
  - UV-IR connection. etc.
- Dramatic paradigm shifts. Very interesting.
- Too important to completely give up on the conventional notion of naturalness after the LHC.

Test naturalness at 100 TeV collider

Cohen et. al., 2014



Pappadopulo, Thamm, Torre, Wulzer, 2014

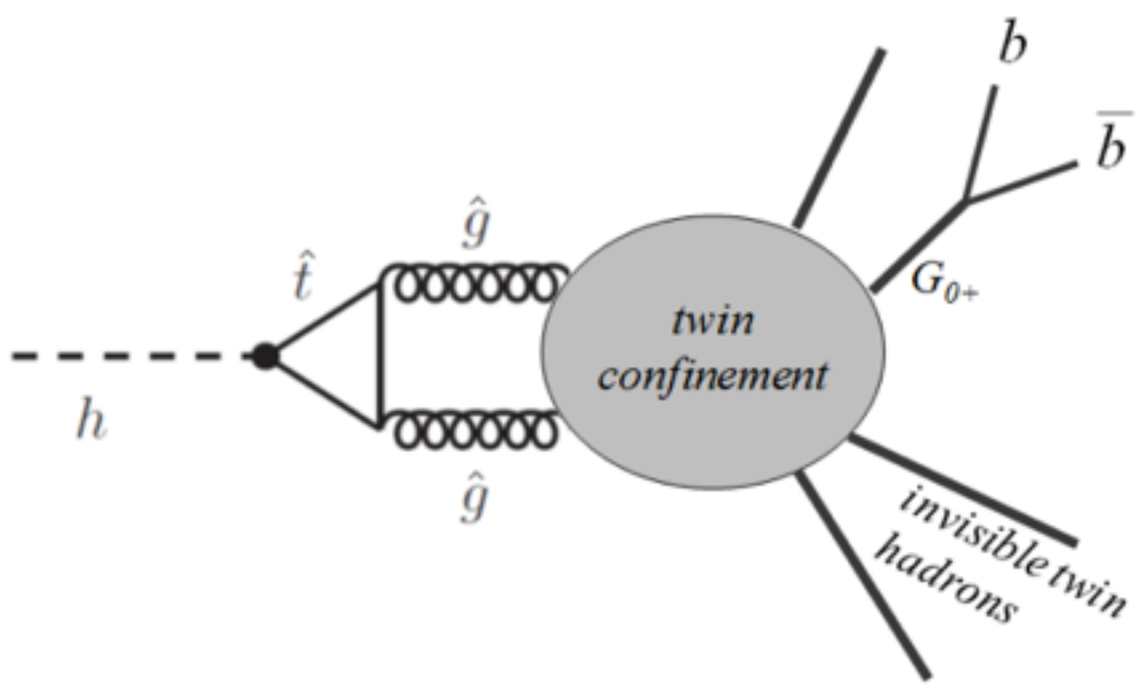


- tune proportional to $(M_{\text{new physics}})^2$.
  - Much better test than LHC, by orders of magnitude!
  - Potential for discovery (would be a victory for naturalness).

Stealthy top partner. "twin"

Chacko, Goh, Harnik

Craig, Katz, Strassler, Sundrum

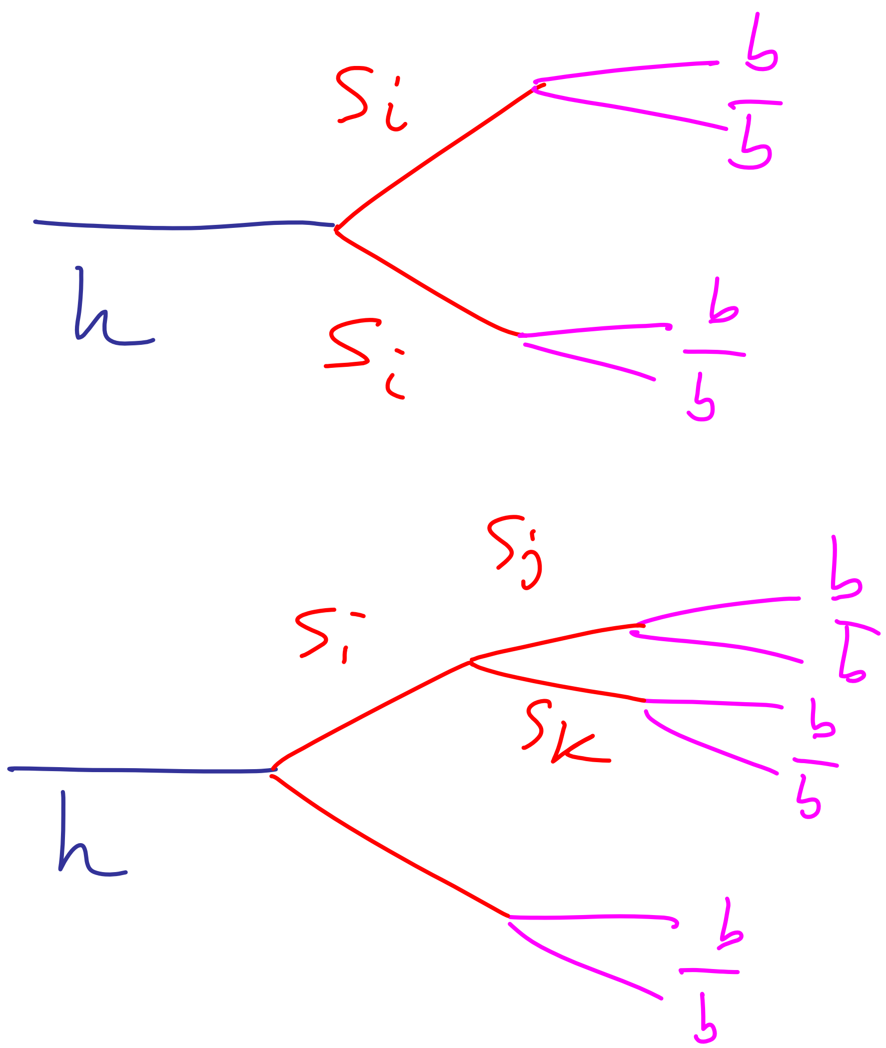


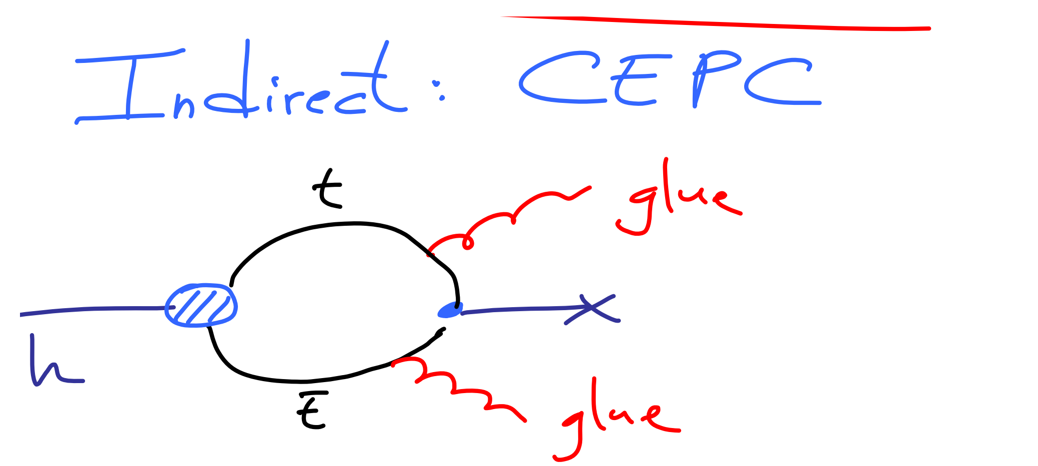
- Top partner not colored. Higgs decay through hidden world and back.

- Lead to Higgs rare decays.

More alternatives

More relevant without discovery at the LHC





$$\kappa_g \sim \left(\frac{m_t^2}{\Lambda^2}\right) \sim 10\%$$ Easy @CEPC

$$\kappa_\gamma \sim \text{few}\ \%$$ Possible@ CEPC

Low scale landscape

Higgs rare decay.

"fat" Higgs

Higgs coupling

Can't hide from the Higgs.

Talk by Arkani-Hamed CEPC workshop Sept. 2016

Bottom line

- Naturalness is the most pressing question of EWSB.
  - How should we predict the Higgs mass?
- We may not have the right idea. No confirmation of any of the proposed models.
- Need experiment!
- Fortunately, with Higgs, we know where to look.
- And, the clue to any possible way to address naturalness problem must show up in Higgs coupling measurement.

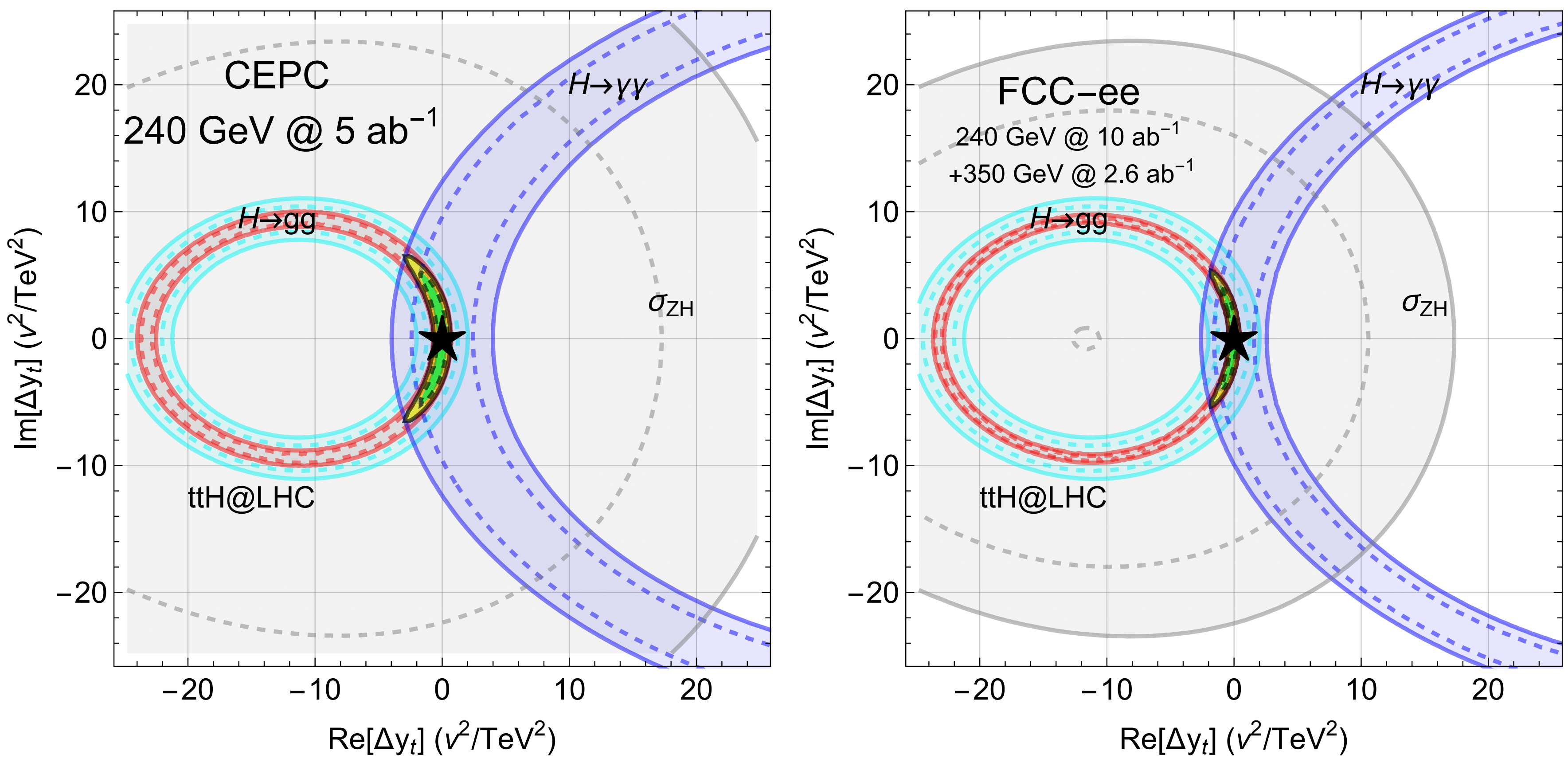
Higgs-top coupling.

Zhen Liu, I. Low, LTW

- Dim-6 operators parameterization.

$$\begin{aligned}
\mathcal{O}_{tH} &= \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R), \\
\mathcal{O}_{bH} &= \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L H b_R), \\
\mathcal{O}_{DHq} &= \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu q_L), \\
\mathcal{O}_{DHq}^{(3)} &= \frac{i}{\Lambda^2}(H^\dagger \tau^I \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu \tau^I q_L), \\
\mathcal{O}_{DHt} &= \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R \gamma^\mu t_R), \\
\mathcal{O}_{DHb} &= \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{b}_R \gamma^\mu b_R),
\end{aligned}$$

$$\mathcal{O}_{tH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R)$$



Coefficient can be complex in general.
Affect h→ gg, although determining CP can be difficult.
h→γγ with a different sign
Sub-leading contribution to hZZ as well.

$$\mathcal{O}_{bH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L H b_R)$$ well constrained by h→bb

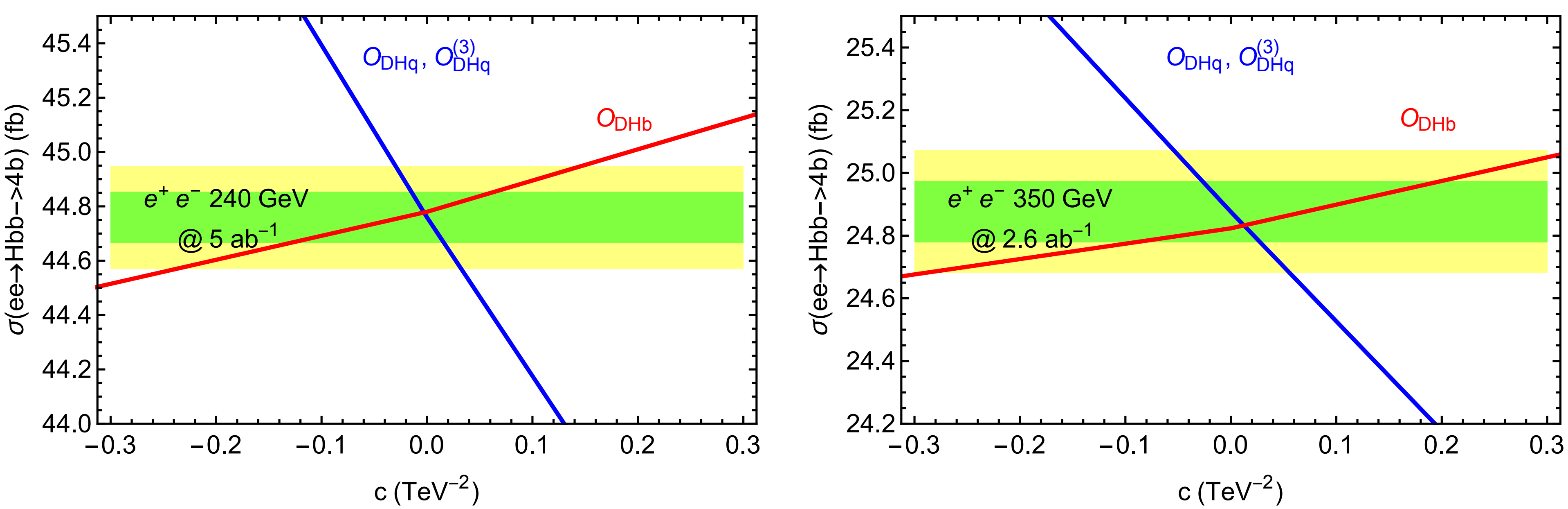
$$\mathcal{O}_{DHq} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu q_L),$$
$$\mathcal{O}^{(3)}_{DHq} = \frac{i}{\Lambda^2}(H^\dagger \tau^I \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu \tau^I q_L),$$
$$\mathcal{O}_{DHt} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R \gamma^\mu t_R),$$
$$\mathcal{O}_{DHb} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{b}_R \gamma^\mu b_R),$$

Do not modify Higgs coupling to tops.

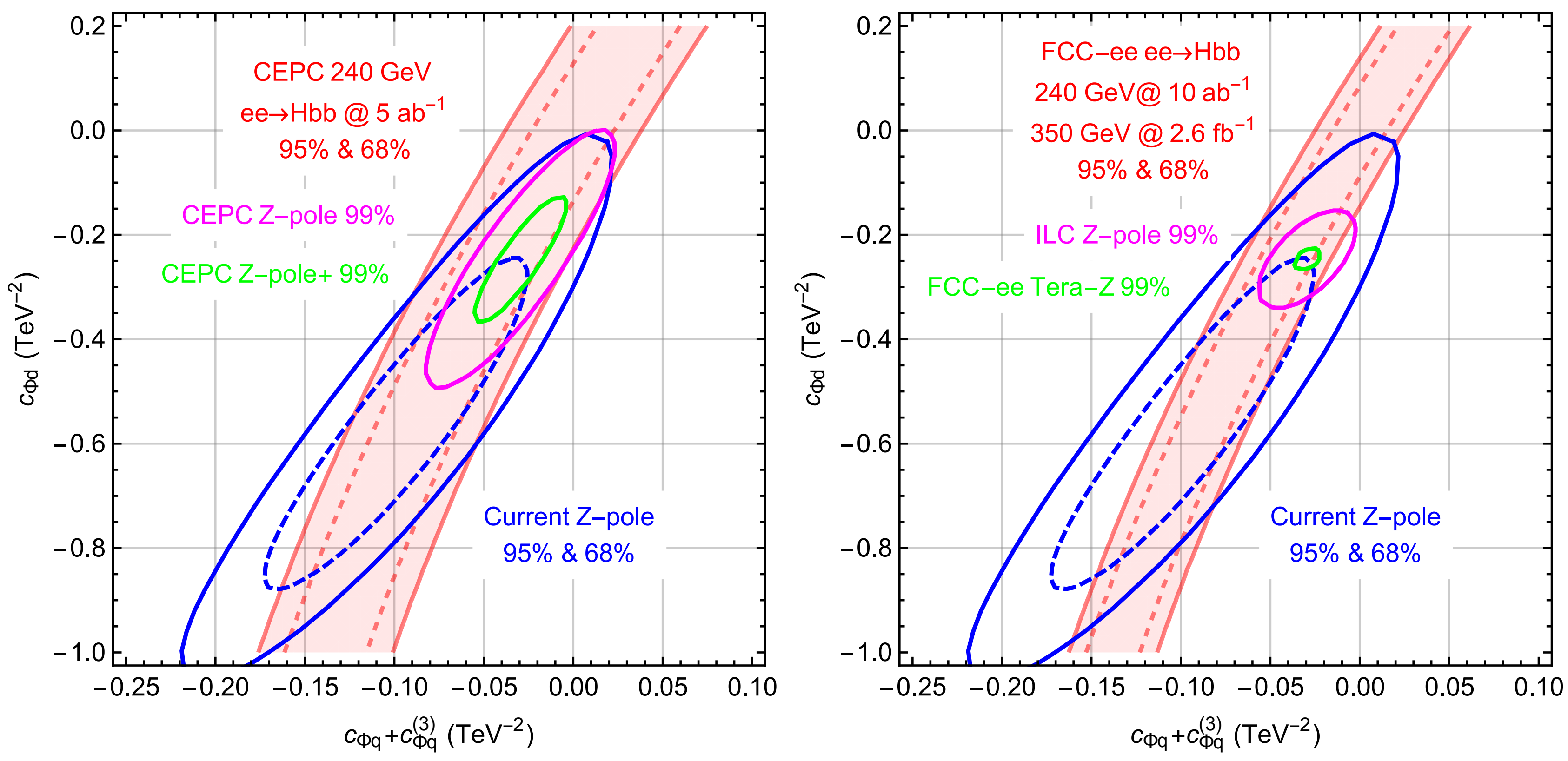
Generate h-Z-bb …

Modify Z-bb and Z-tt couplings

3-body process, ee→hbb



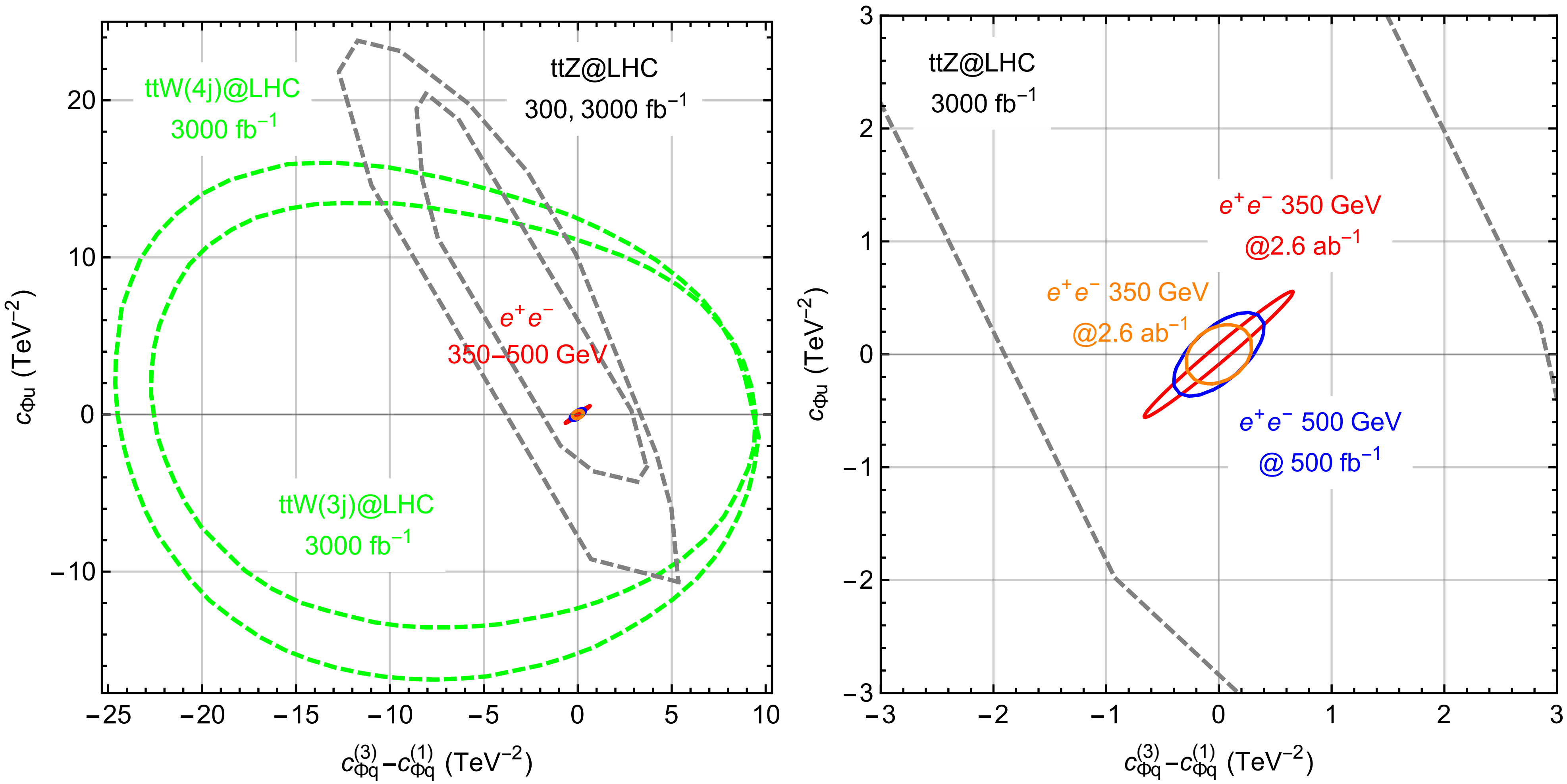
Z-pole



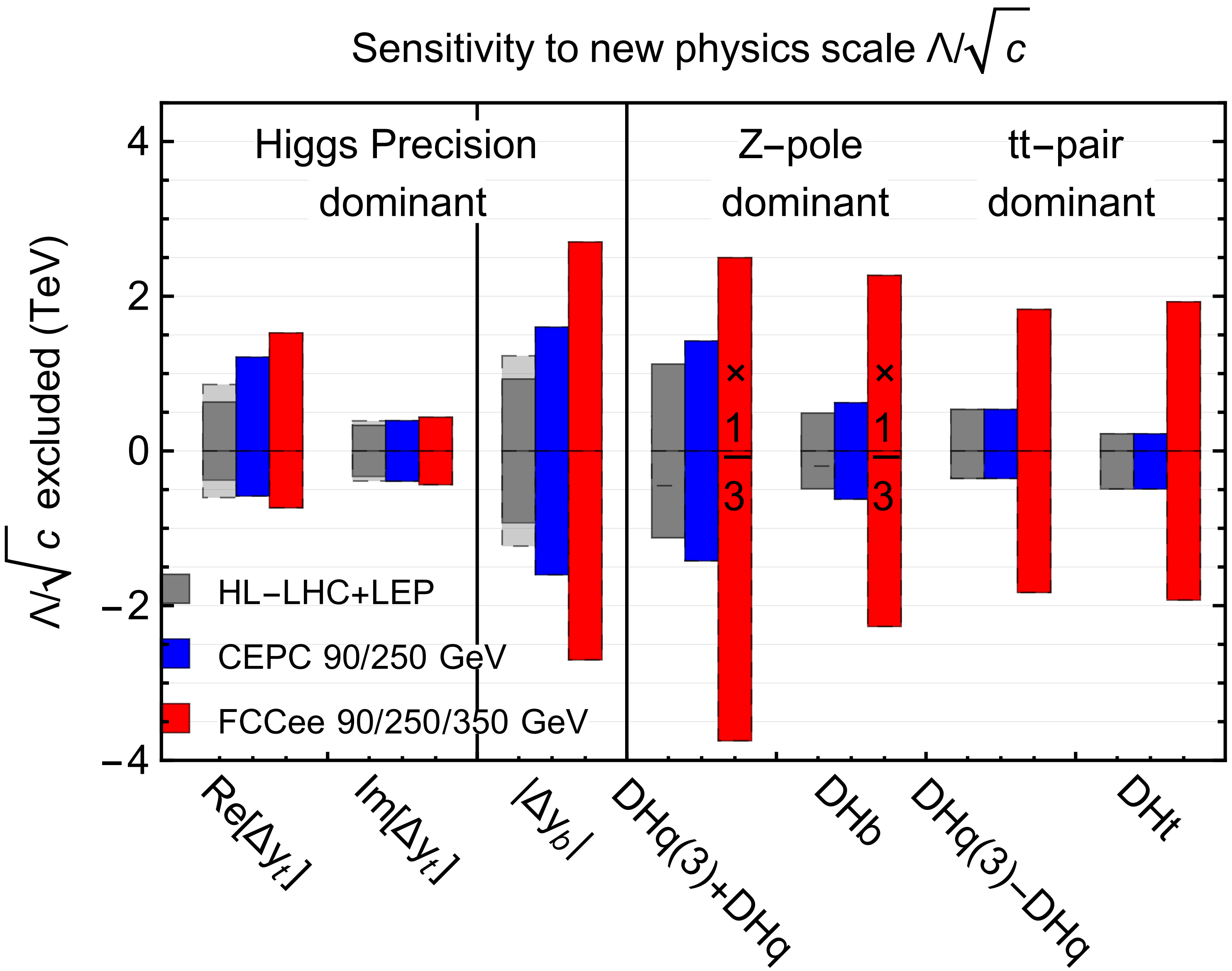
$$\Delta_{Zb\bar{b}} = -\left(C_{DHq} + C^{(3)}_{DHq}\right) \frac{v^2}{\Lambda^2} \frac{\sqrt{g_1^2+g_2^2}}{2} \; Z_\mu \bar{b}_L \gamma^\mu b_L - C_{DHb} \frac{v^2}{\Lambda^2} \frac{\sqrt{g_1^2+g_2^2}}{2} \; Z_\mu \bar{b}_R \gamma^\mu b_R$$

$$\Delta_{Zt\bar{t}} = \left(C^{(3)}_{DHq} - C_{DHq}\right) \frac{v^2}{\Lambda^2} \frac{\sqrt{g_1^2+g_2^2}}{2} \; Z_\mu \bar{t}_L \gamma^\mu t_L - C_{DHt} \frac{v^2}{\Lambda^2} \frac{\sqrt{g_1^2+g_2^2}}{2} \; Z_\mu \bar{t}_R \gamma^\mu t_R$$

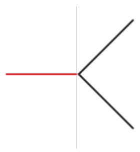
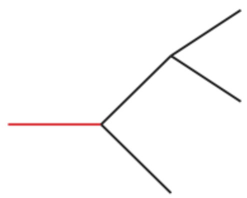
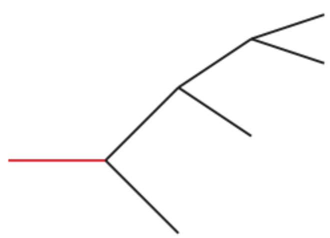
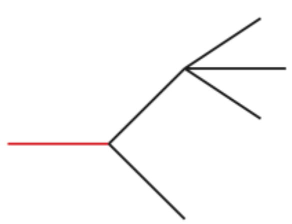
At ttbar threshold

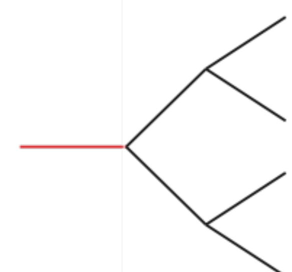
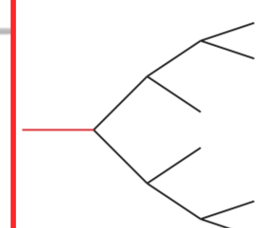
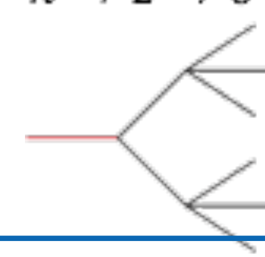


Sensitivity to new physics scales



Some possible channels

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$ $h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$ $h \to jj + \not{E}_T$ $h \to \tau^+\tau^- + \not{E}_T$ $h \to \gamma\gamma + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T + X$

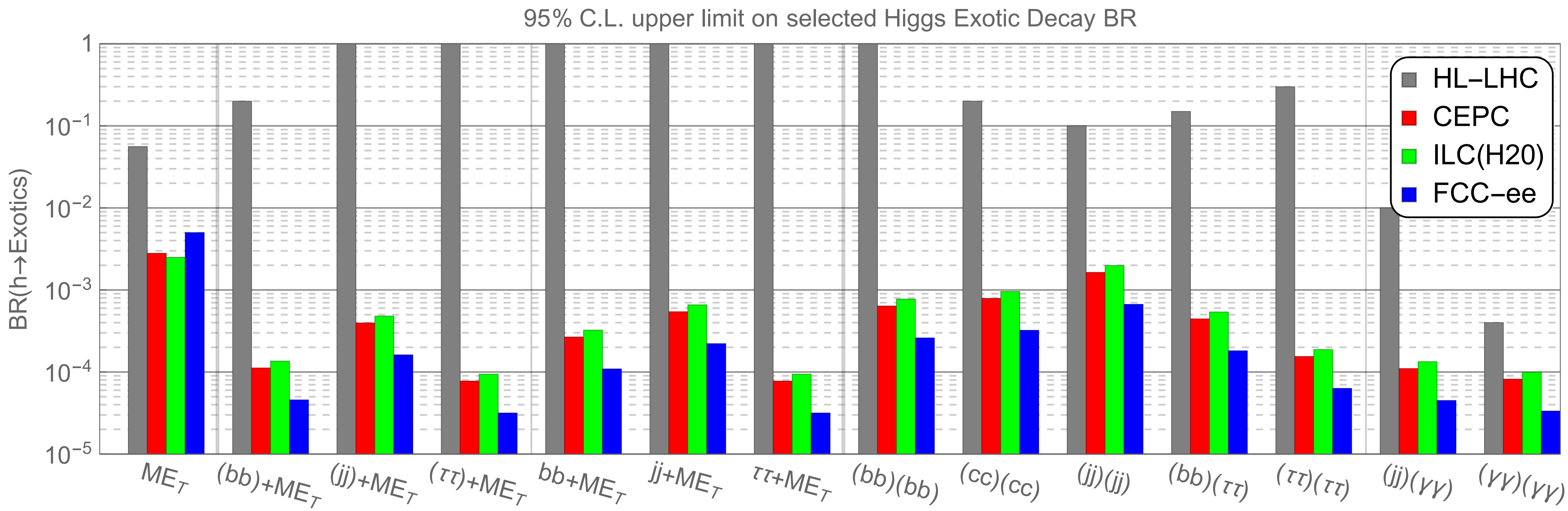
Strong areas of Higgs factories

More hadronic

With MET, less lepton

Great sensitivity from the LHC

Summary

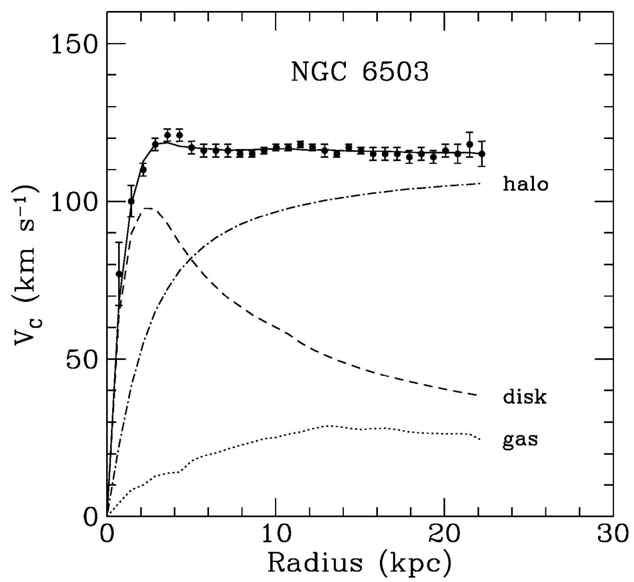


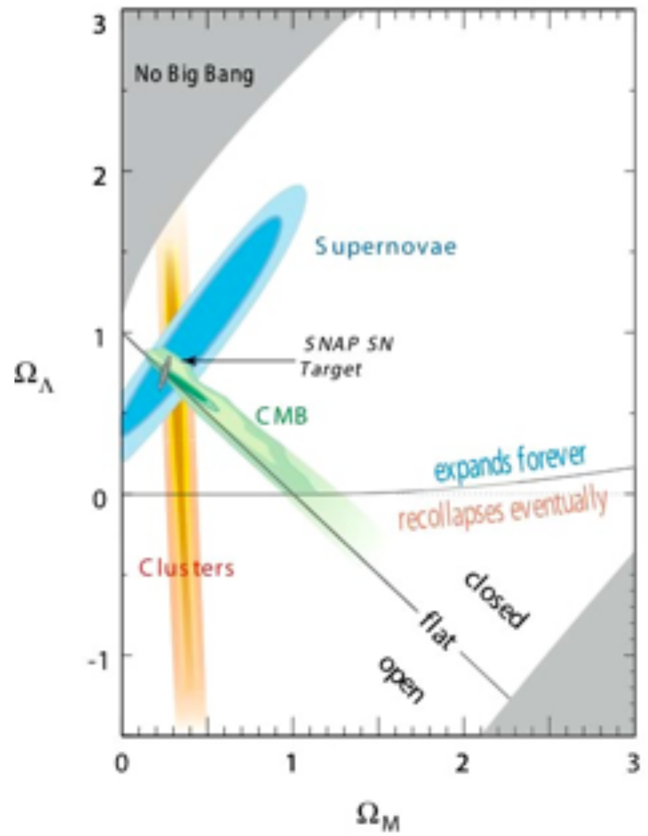
– Higgs factories can push these BR to 10^{-4}. Impressive reach and complementarity with HL-LHC

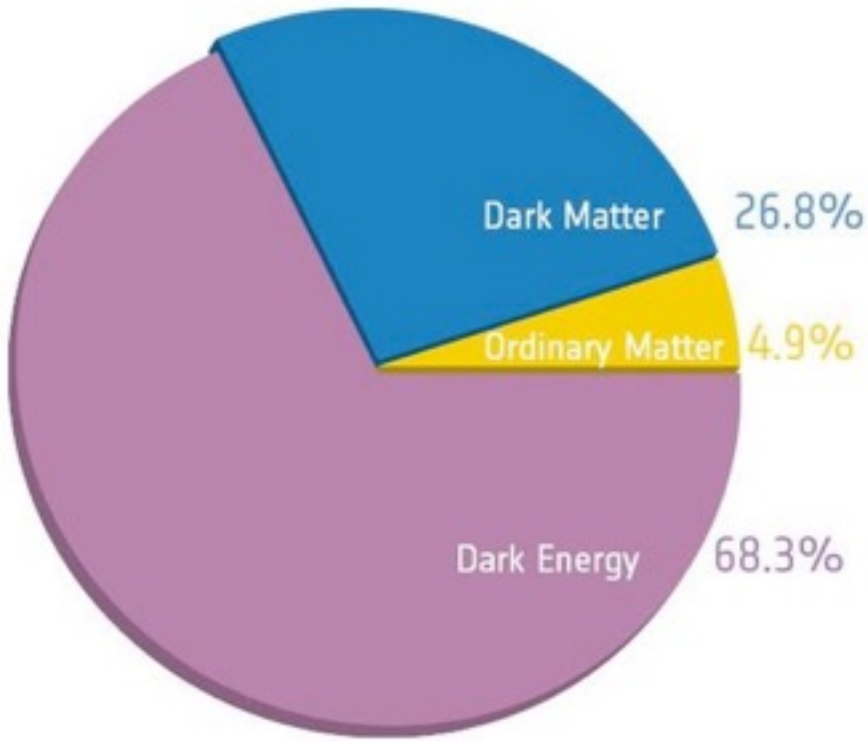
Testing WIMP Dark Matter

$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

Dark matter



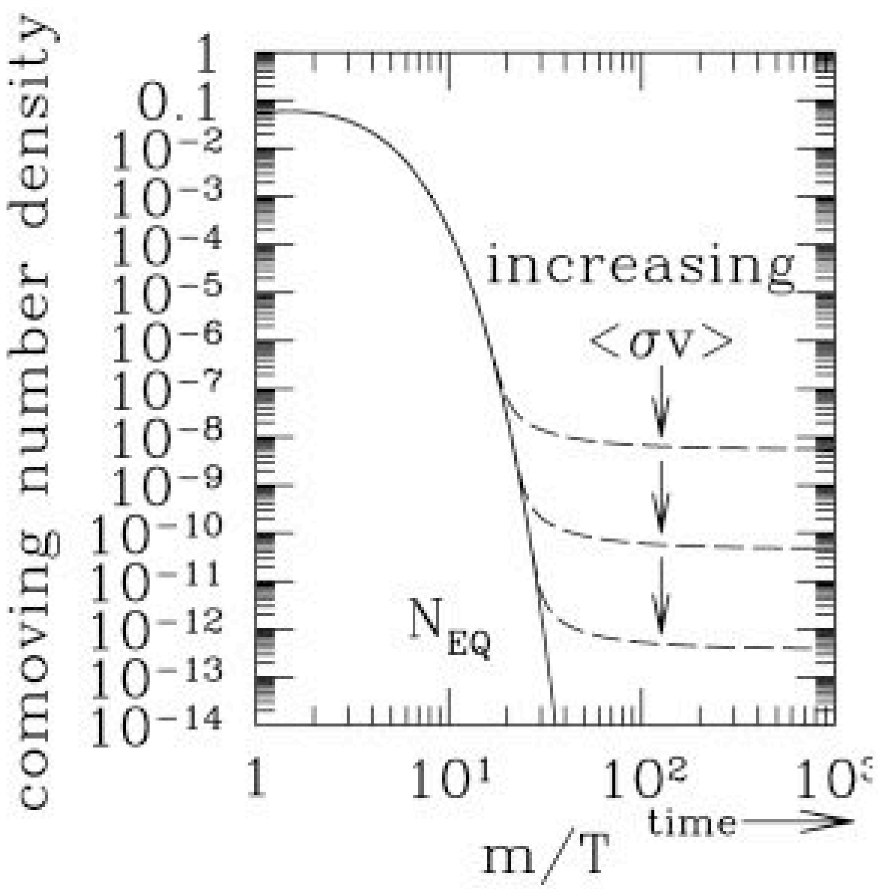


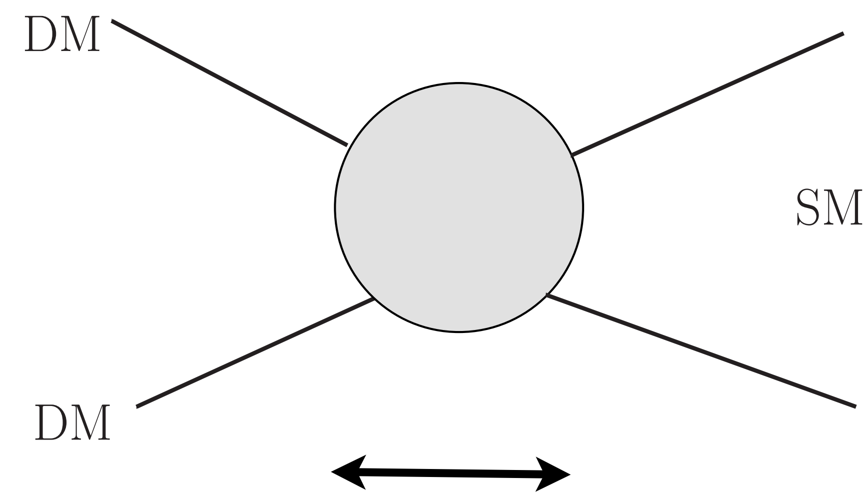


Not required by theory. It is there.
Only seen its gravitational interaction.

We have to understand them better.
Collider search is a key approach.

WIMP scenario.

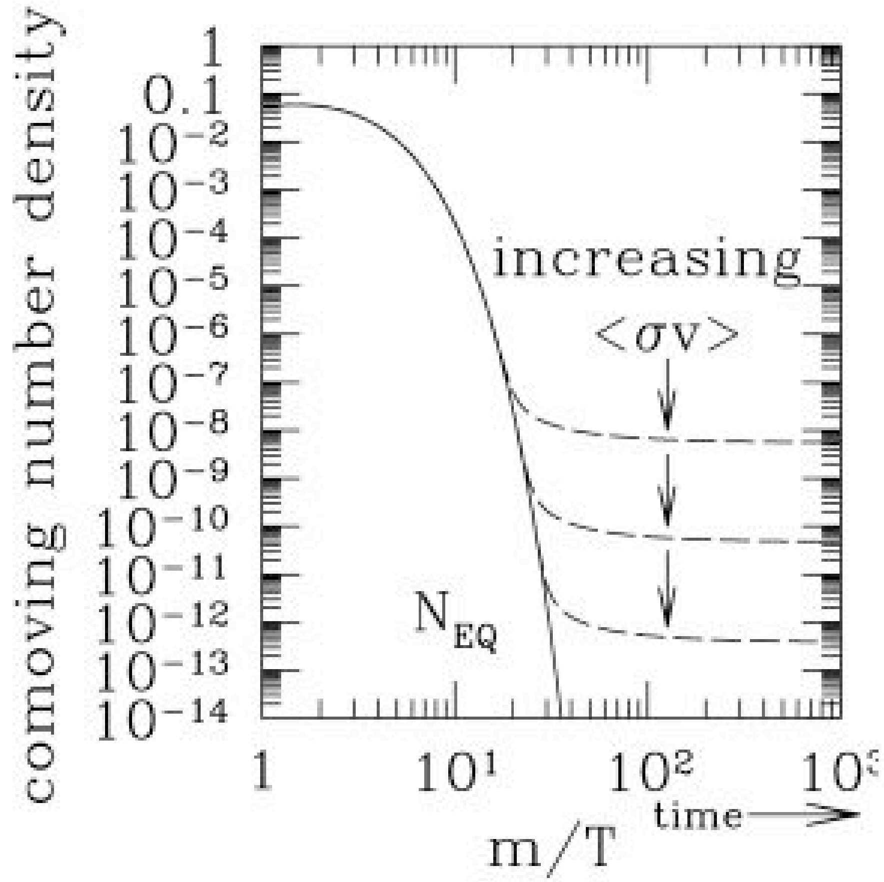


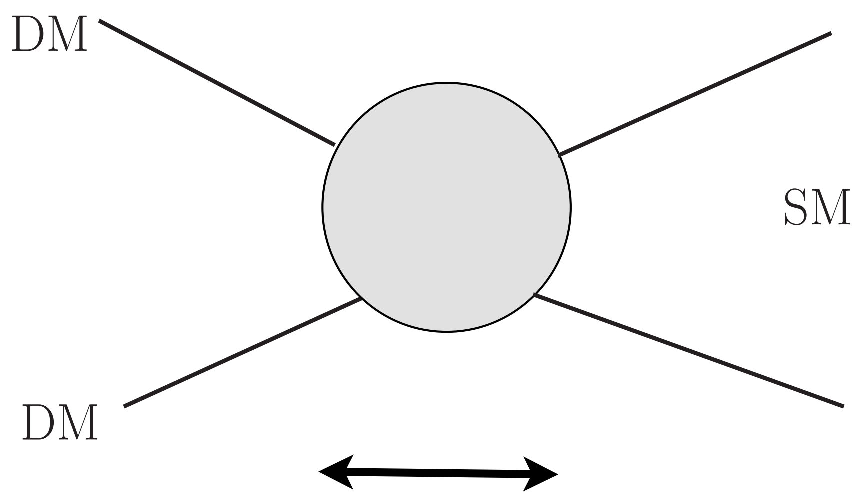


$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- Thermal equilibrium in the early universe.
- If $g_D \sim 0.1$ $M_D \sim 10$s GeV - TeV
  - We get the right relic abundance of dark matter.
- Major hint for weak scale new physics!

WIMP mass





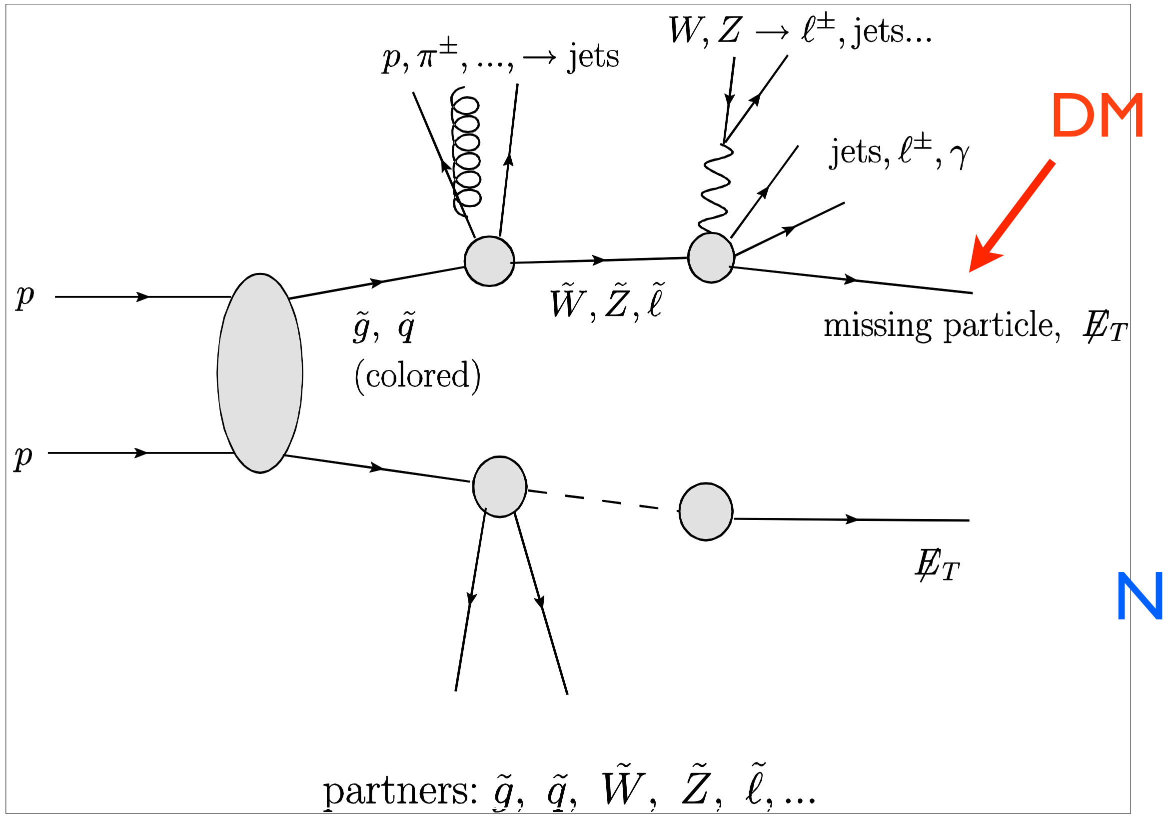
$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- More precisely, to get the correct relic abundance

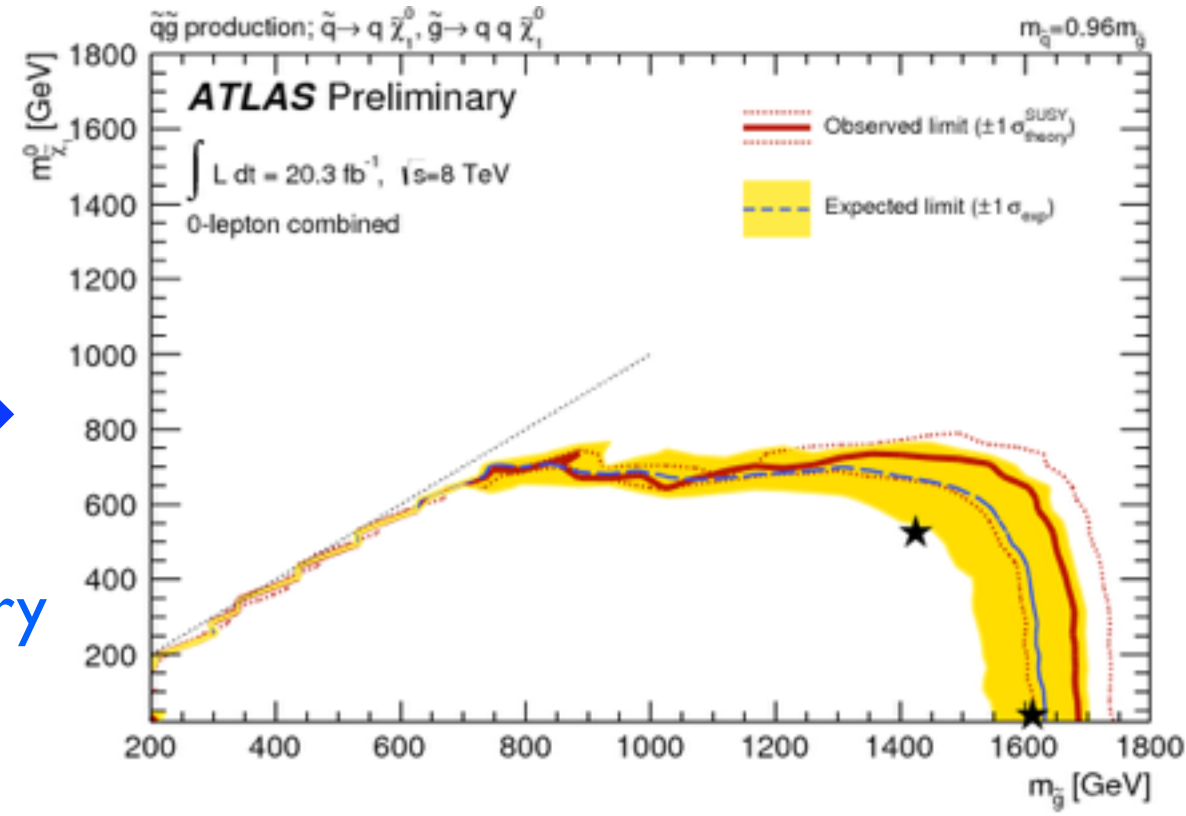
$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

TeV-ish in simplest models

The story I grew up with



No discovery yet



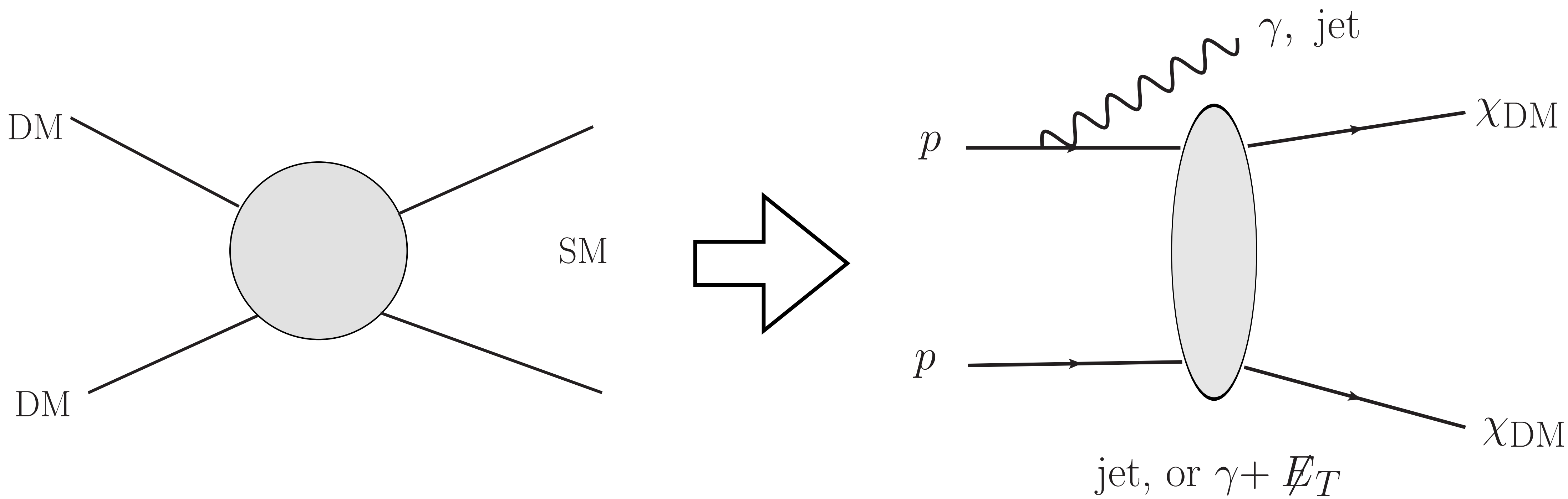
- WIMP is part of a complete model at weak scale.
- It's produced as part of the NP signal, shows up as missing energy.
  - Dominated by colored NP particle production: eg. gluino.
- The reach is correlated with the rest of the particle spectrum.

Of course, still plausible at the LHC, will keep looking.

Higher energy ⇒ higher reach

Basic channel

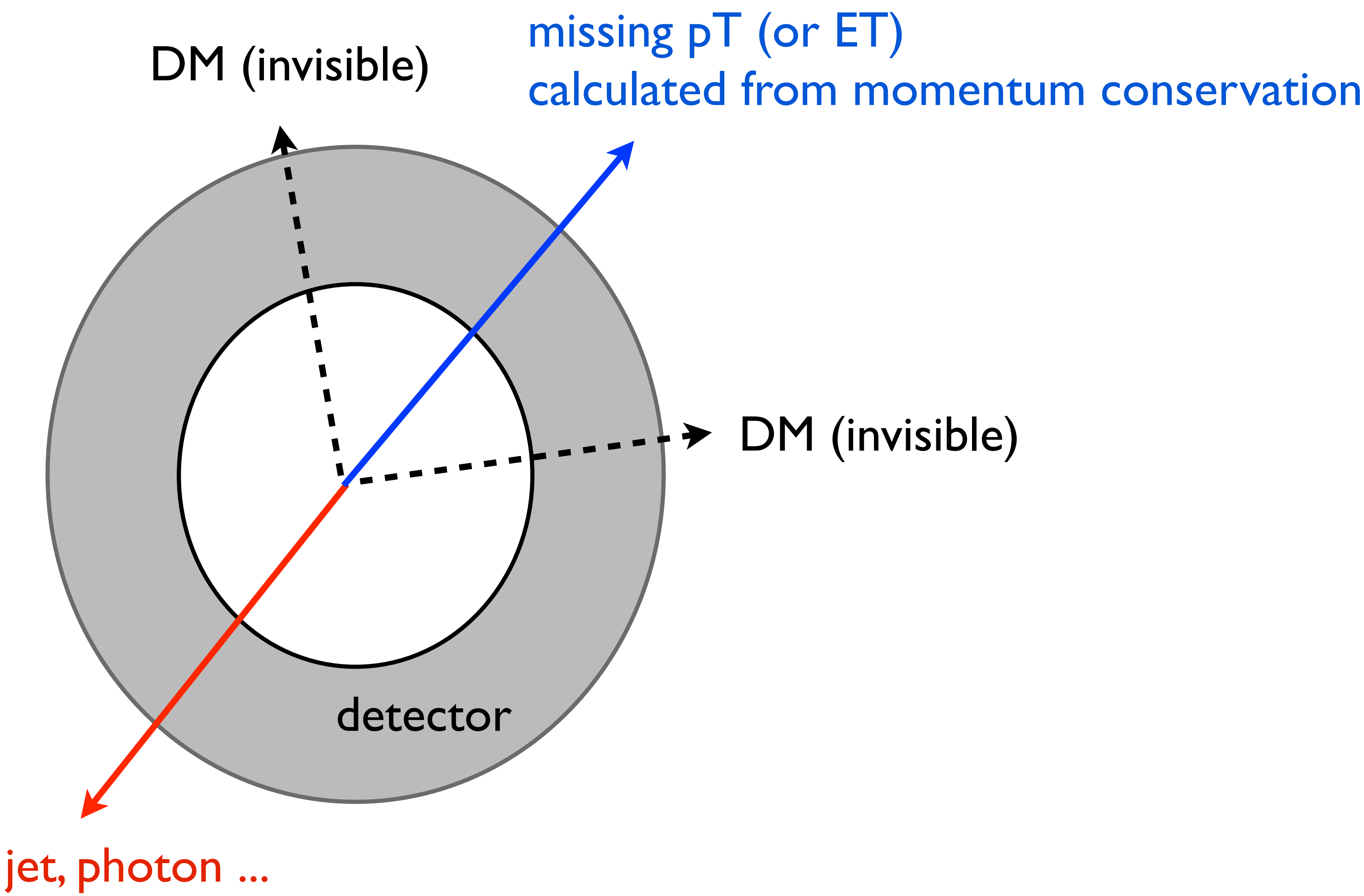
- pair production + additional radiation.



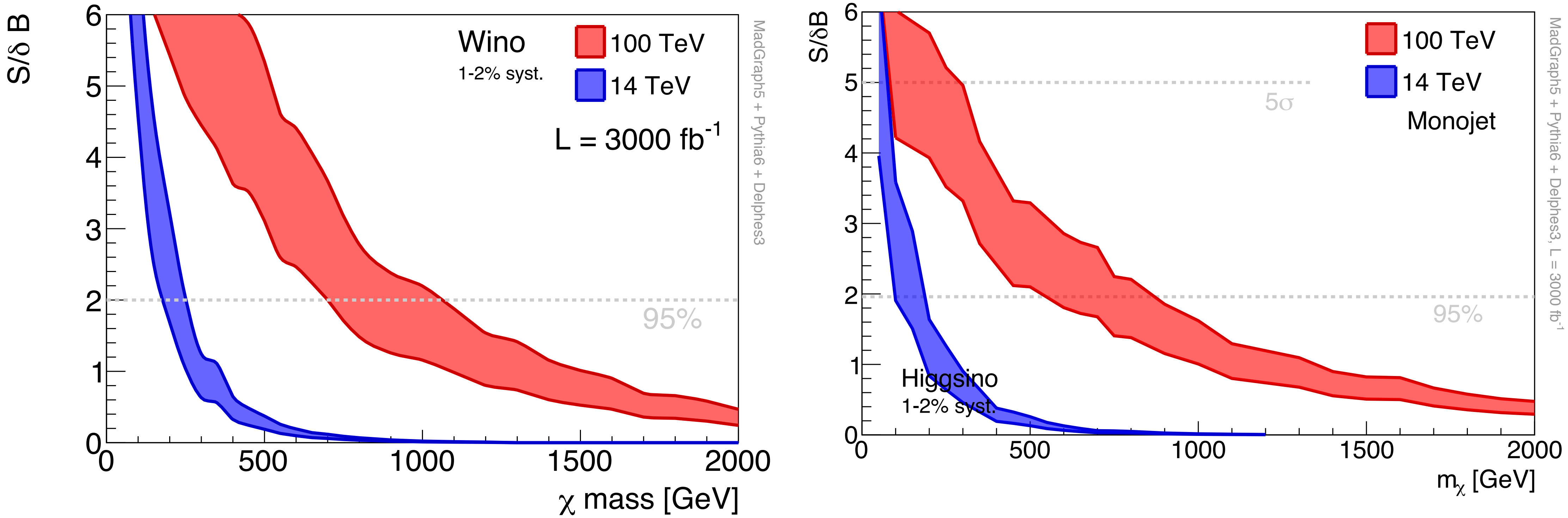
- Mono-jet, mono-photon, mono-...

- Have become "Standard" LHC searches.

Mono-X signature



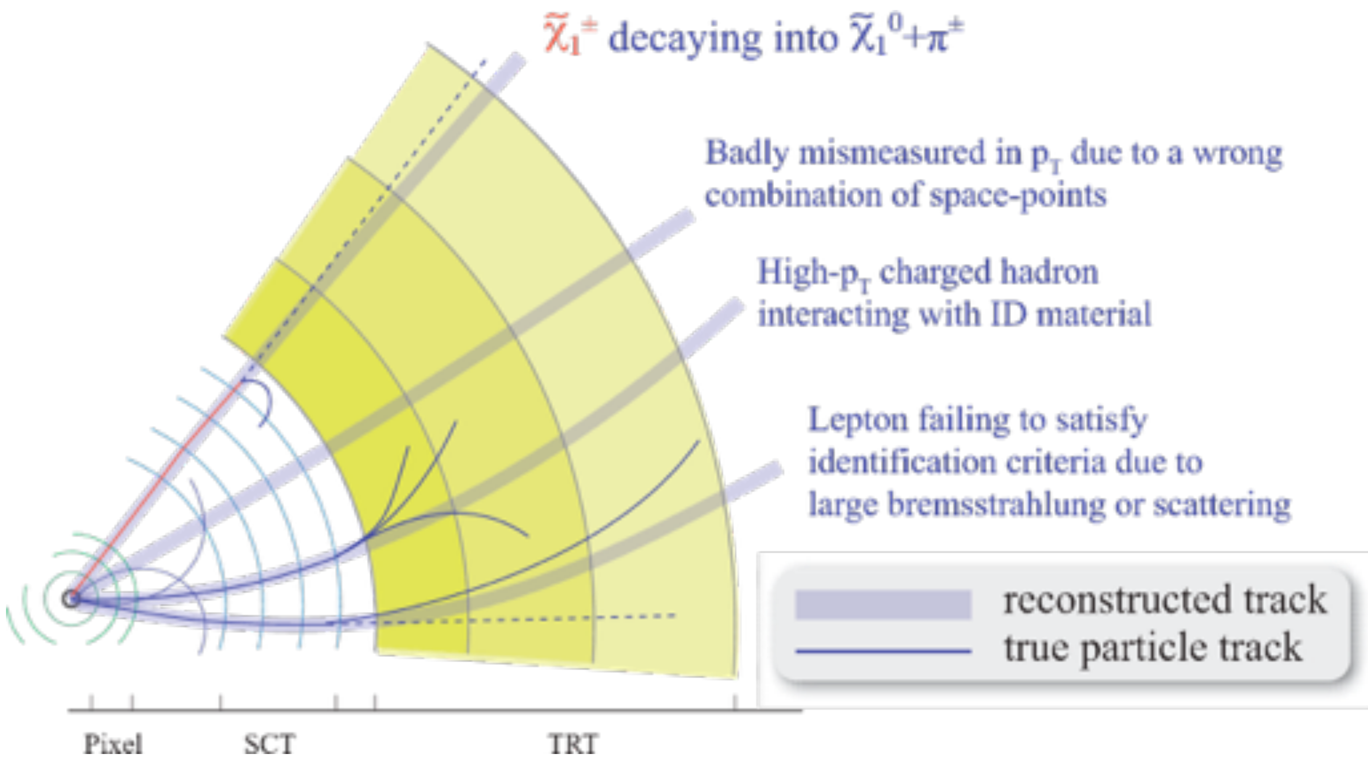
Dark matter (mono-jet)



$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

- LHC only coverage very limited. Rate, systematics...
- 100 TeV pp collider can probe the "bulk" of WIMP parameter space.

Very degenerate, disappearing track.



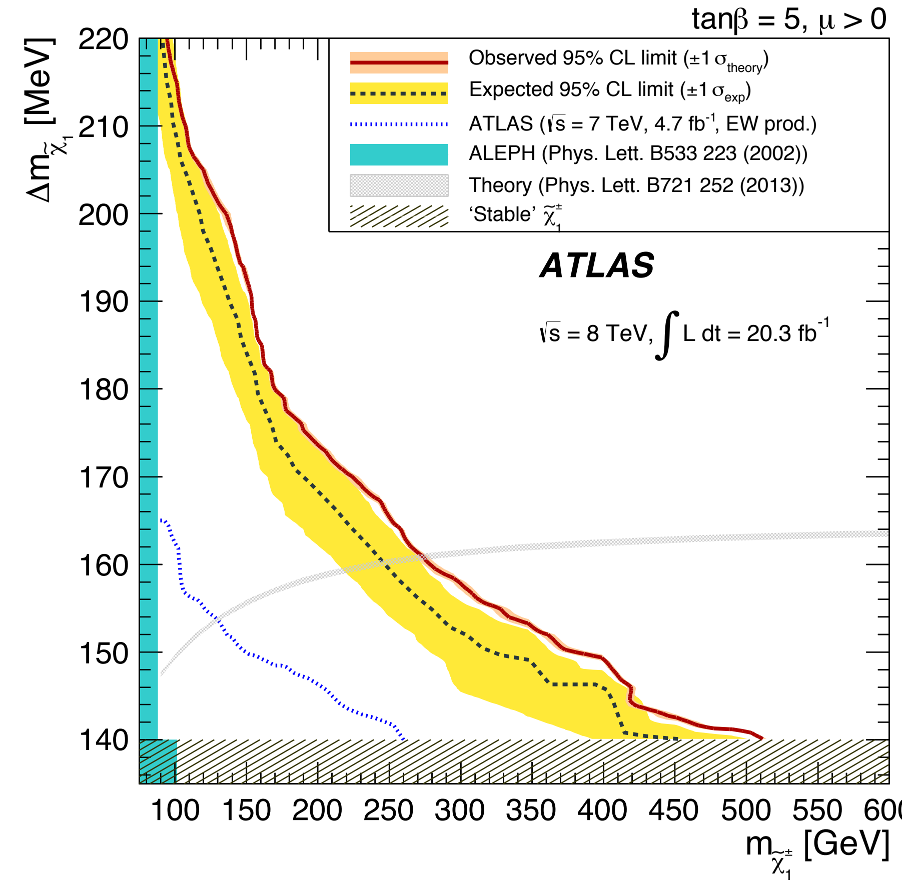
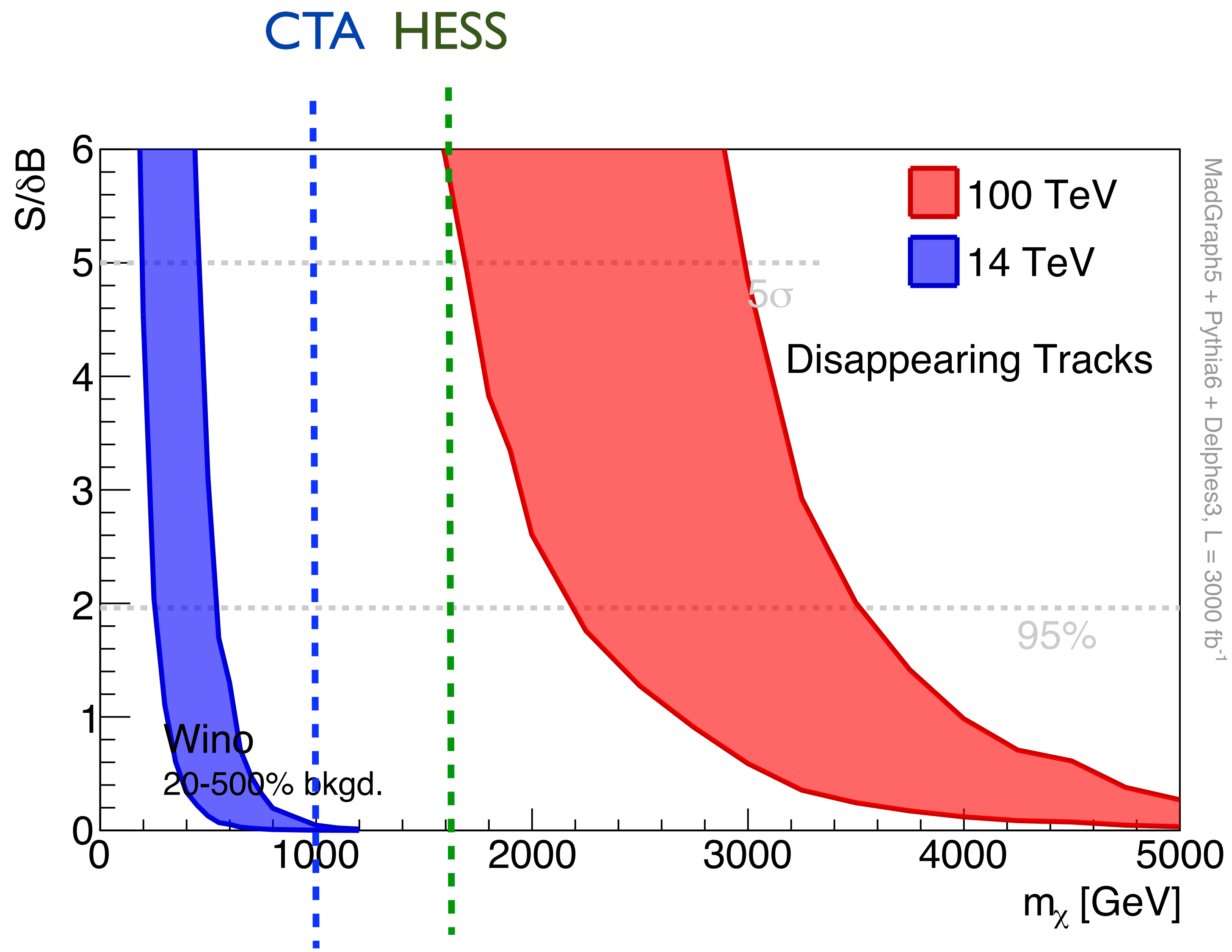


Figure from ATLAS disappearing track search twiki

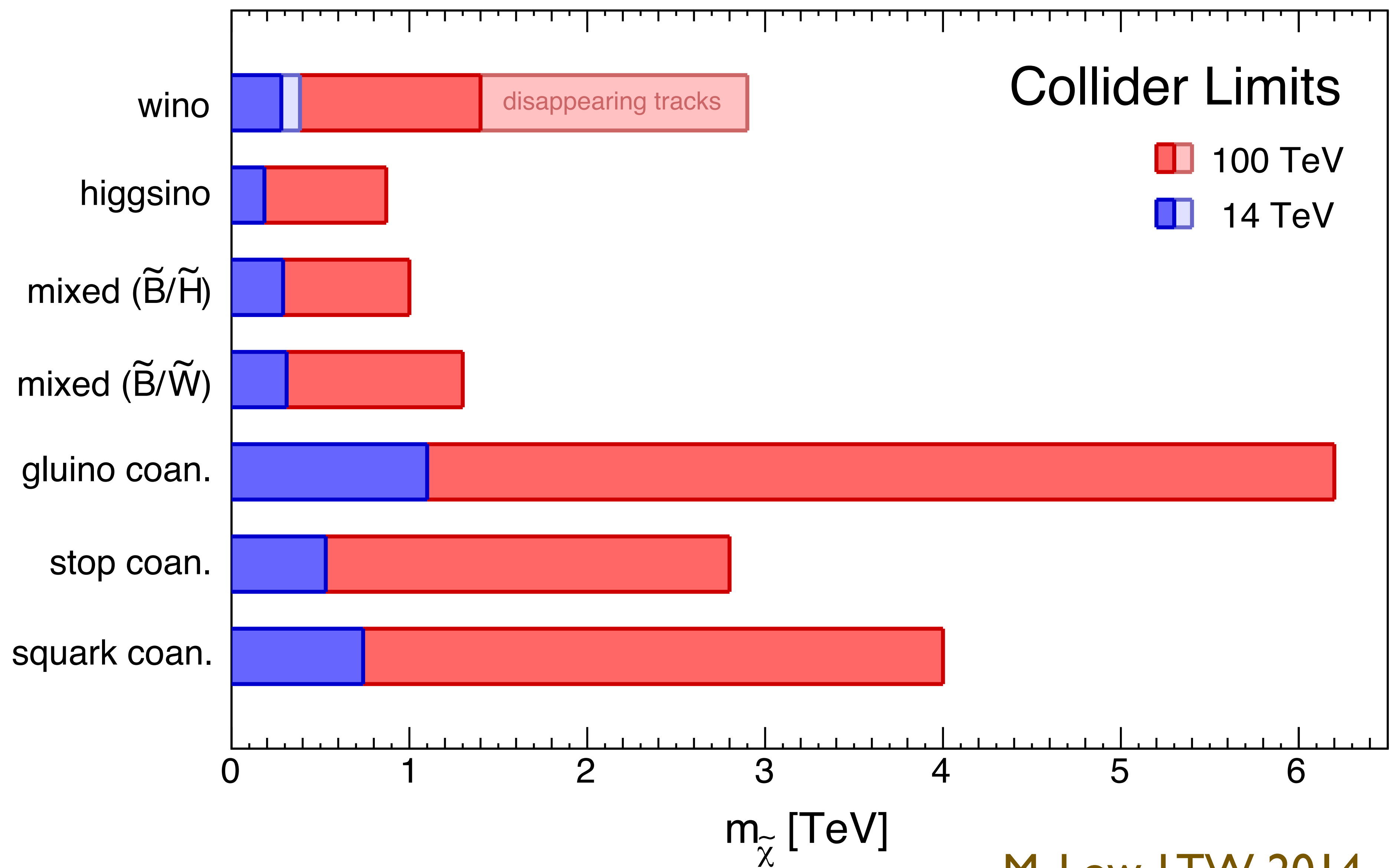
- Main decay mode $\chi^\pm \to \pi^\pm + \chi^0$.
- Charge track ≈ 10(s) cm
- Impressive limit at the LHC already.

Wino



– "Completely cover" the wino parameter space.

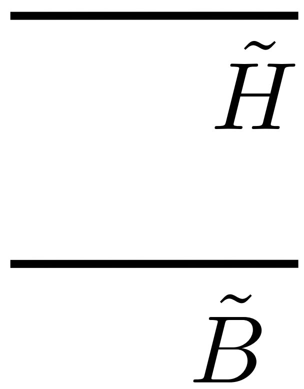
Mono-jet

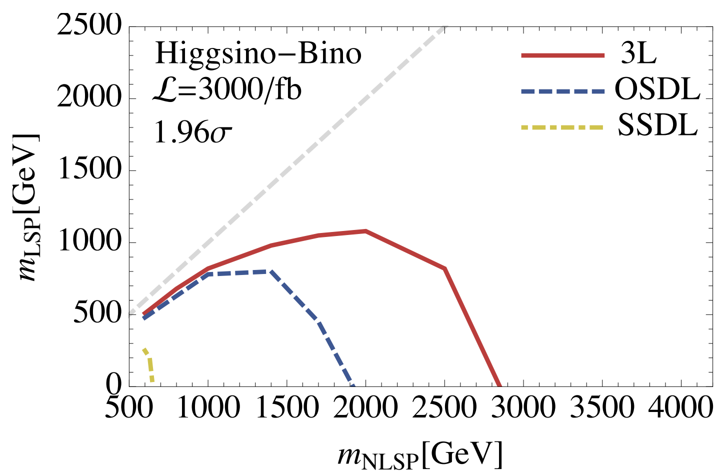


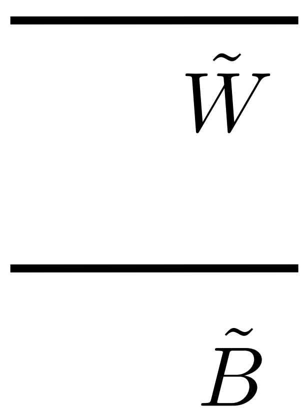
M. Low, LTW 2014

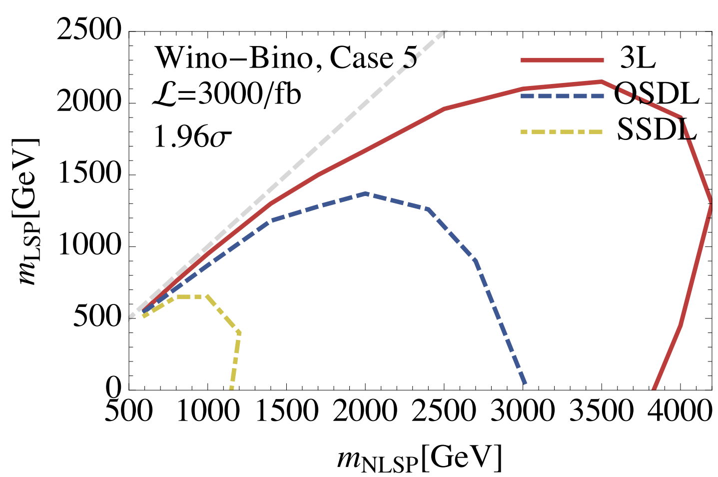
$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

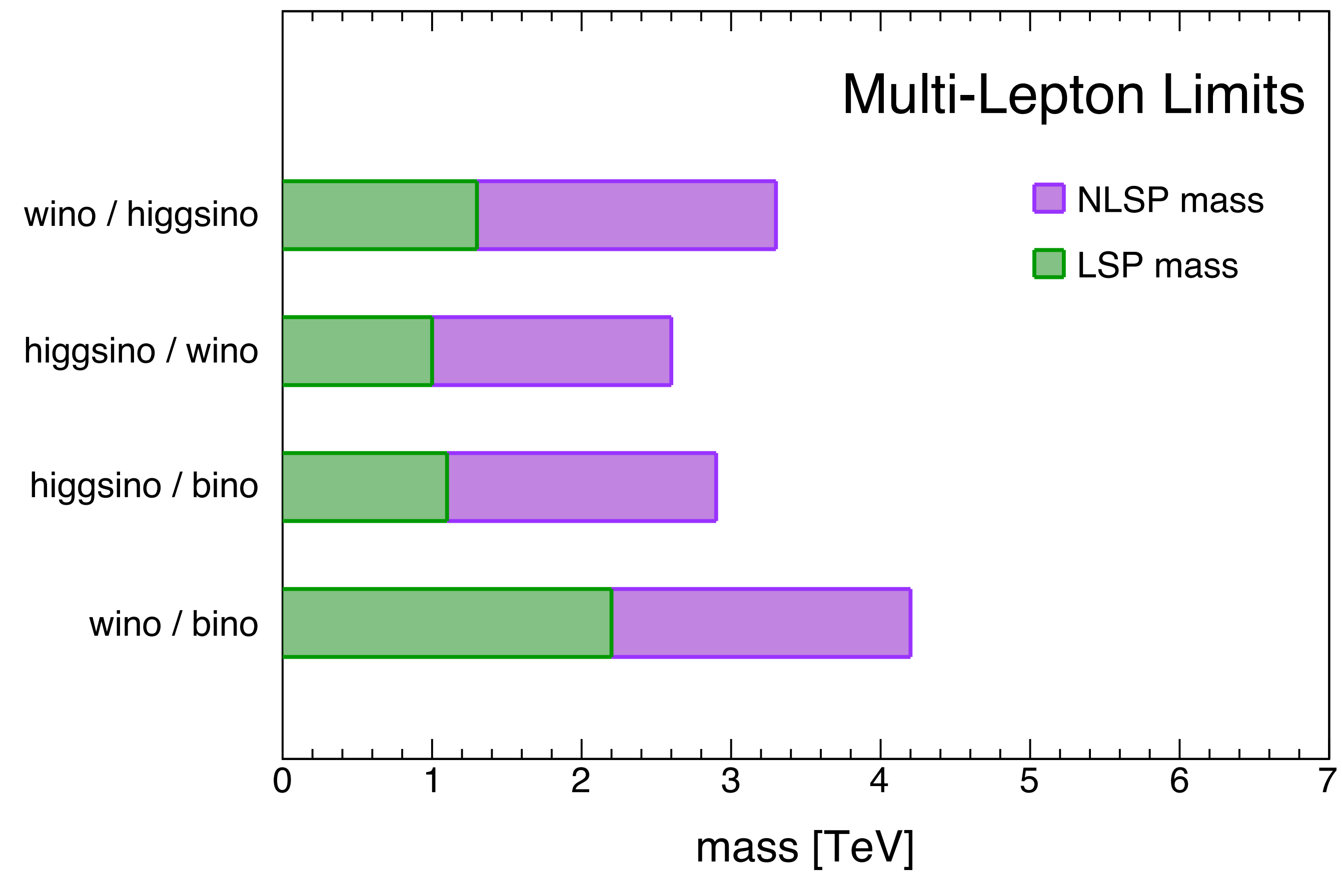
With cascade decays









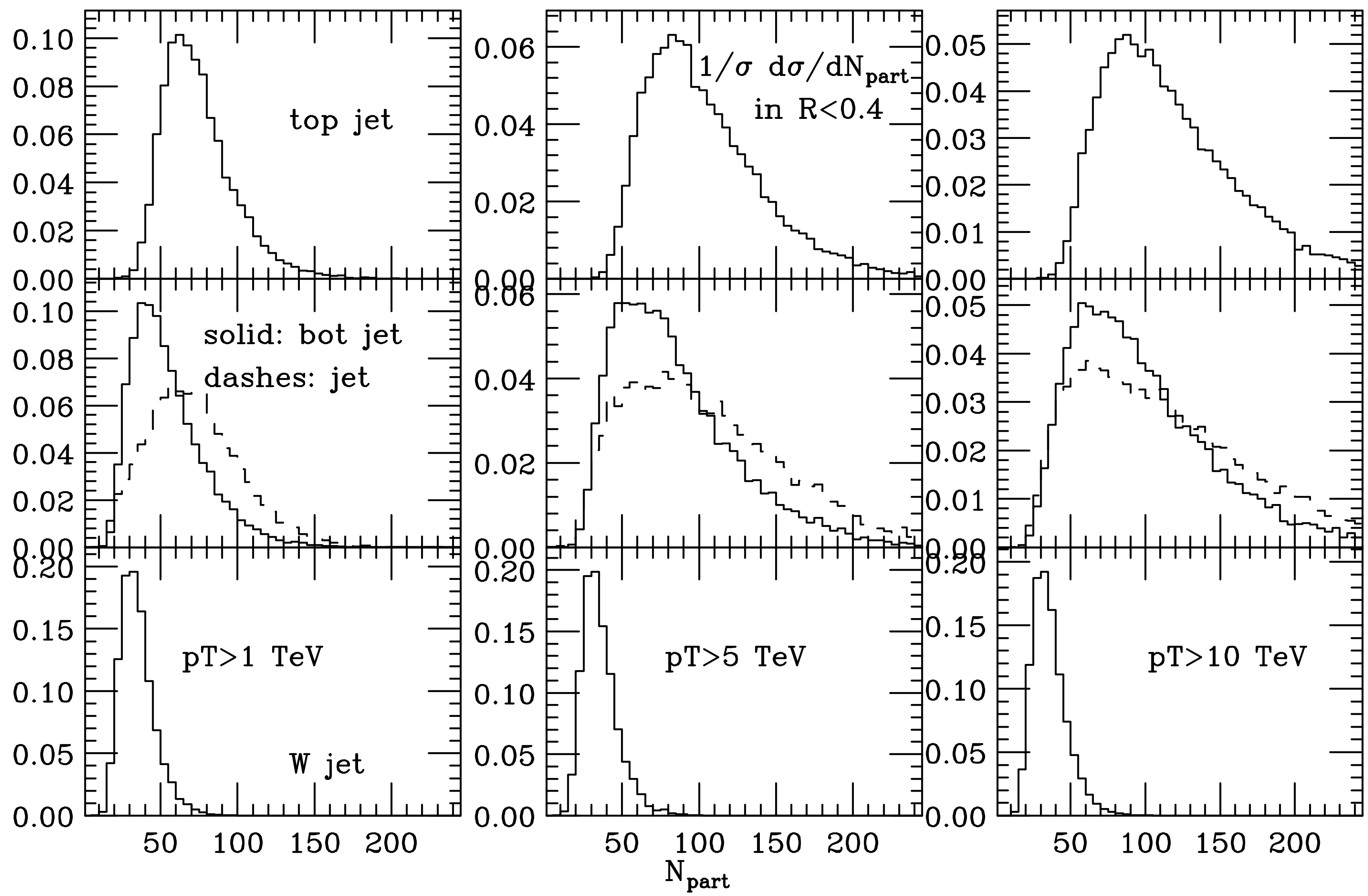


Gori, Jung, Wang, Wells, 2014

Decay ⇒ leptons ⇒ stronger limits

More novelties at a 100 TeV collider

- Bigger, messier jets.

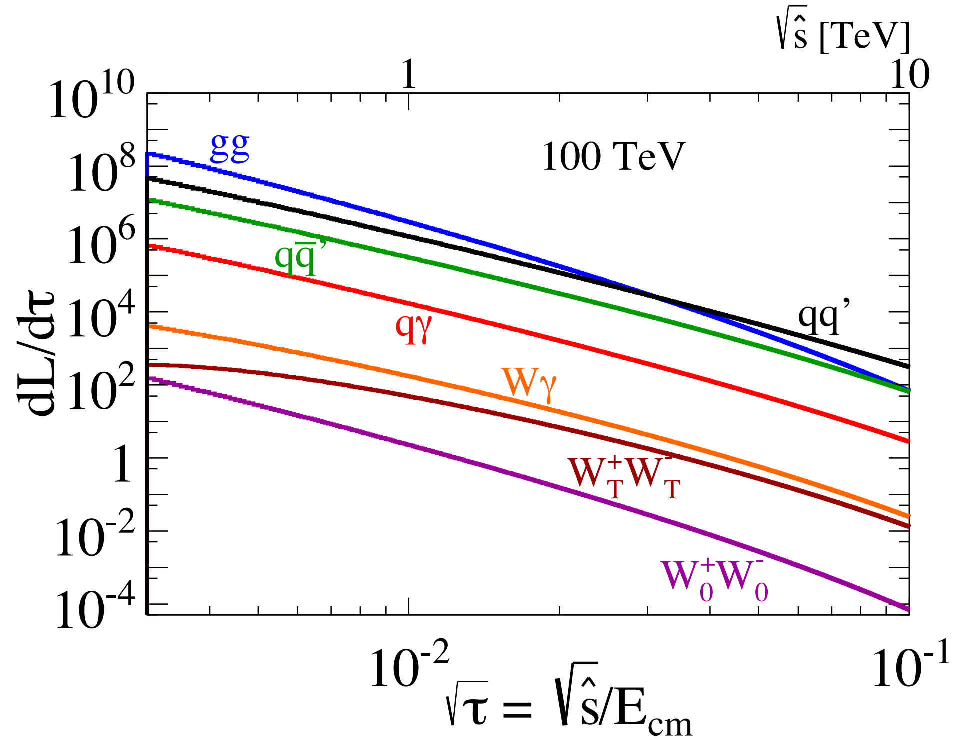


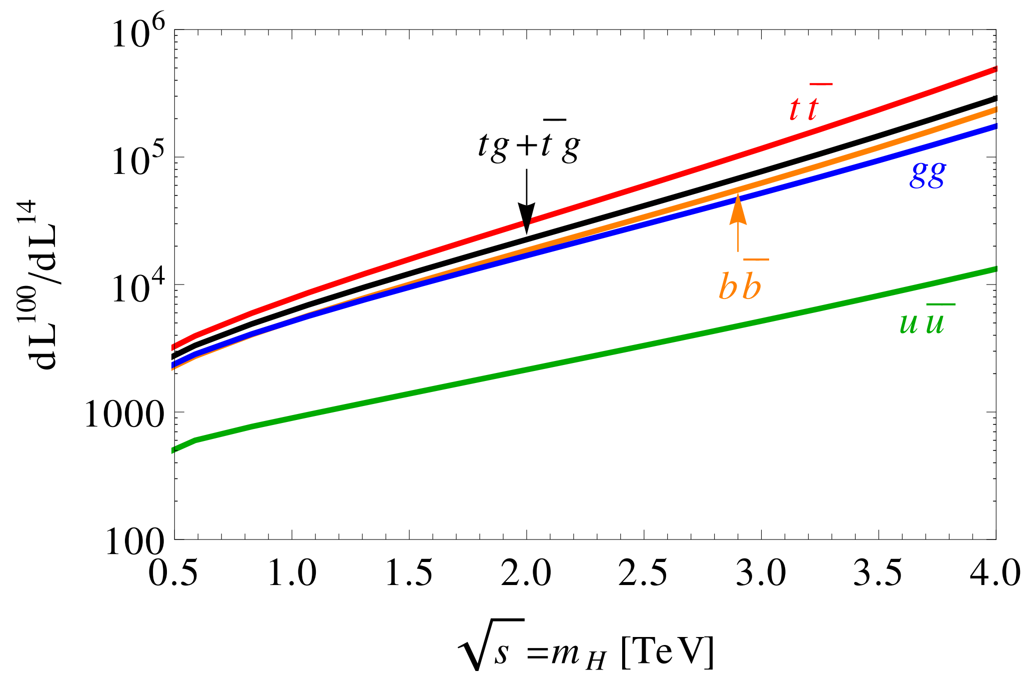
LHC triggered a revolution in jet technology.

100 TeV pp collider demands more!

More novelties at a 100 TeV collider

- SM EW scale particles become very light.
- W/Z/t/h
  - Treating them as part of the "PDF".





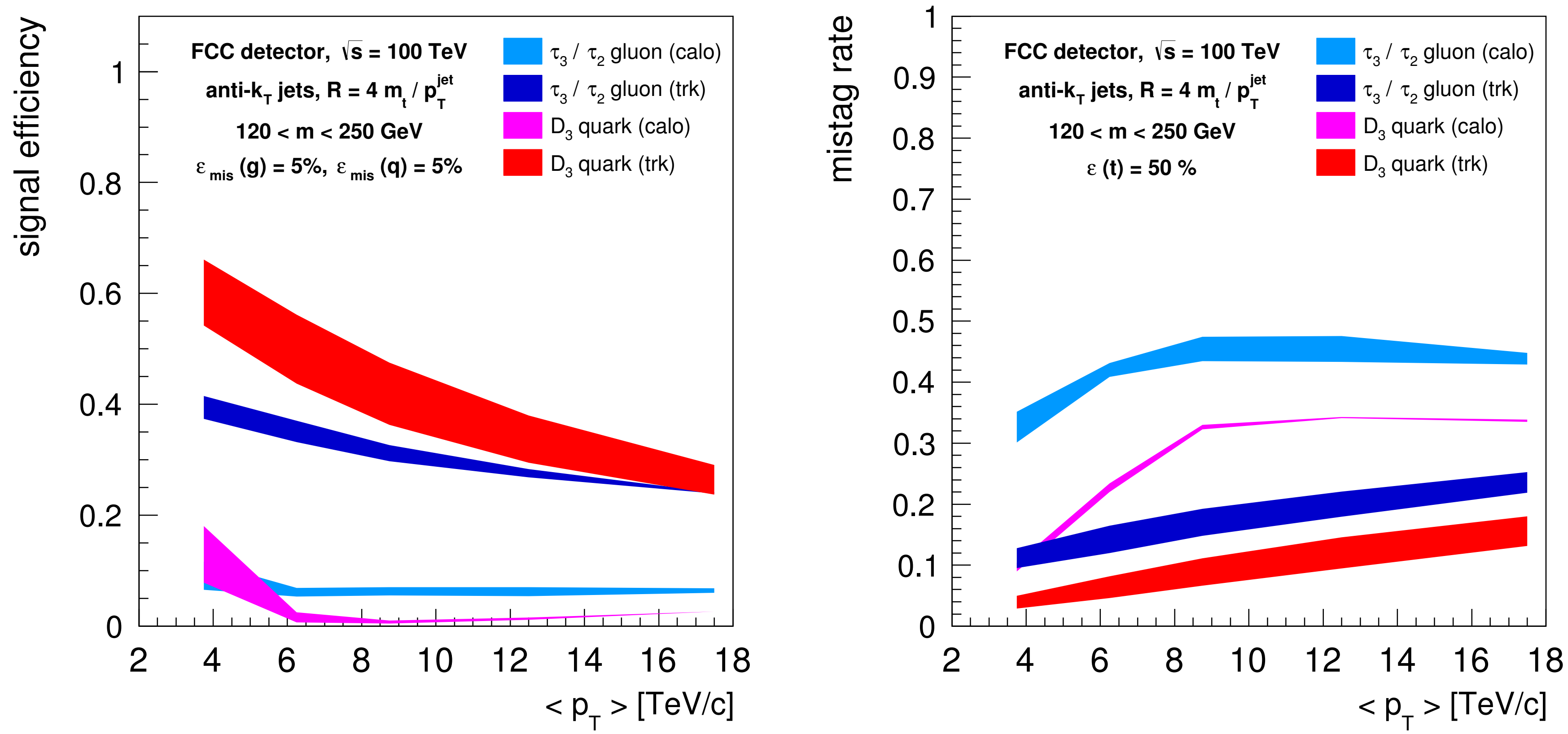
We learned a lot about going from 4 ➜ 5 flavors (doing bottom quark properly).

Similar strategy here (?)

More novelties at a 100 TeV collider

- SM EW scale particles become very like.
- Tagging W/Z/t/h as “fat” jets
  - Not so fat any more, using tracks.

Larkoski, Maltoni, Selvaggi, 2015



New strategies?

Why 100 TeV?

- A benchmark used in the studies.
- Of course, higher is better!
- However, technological + cost constraints
- 100-ish seems to be the best we can do at the moment.
- With further design and physics studies, the number can change.
- A discovery at the LHC can dramatic change the plan.

Comments

- Physics case of next generation high energy pp collider "obvious".

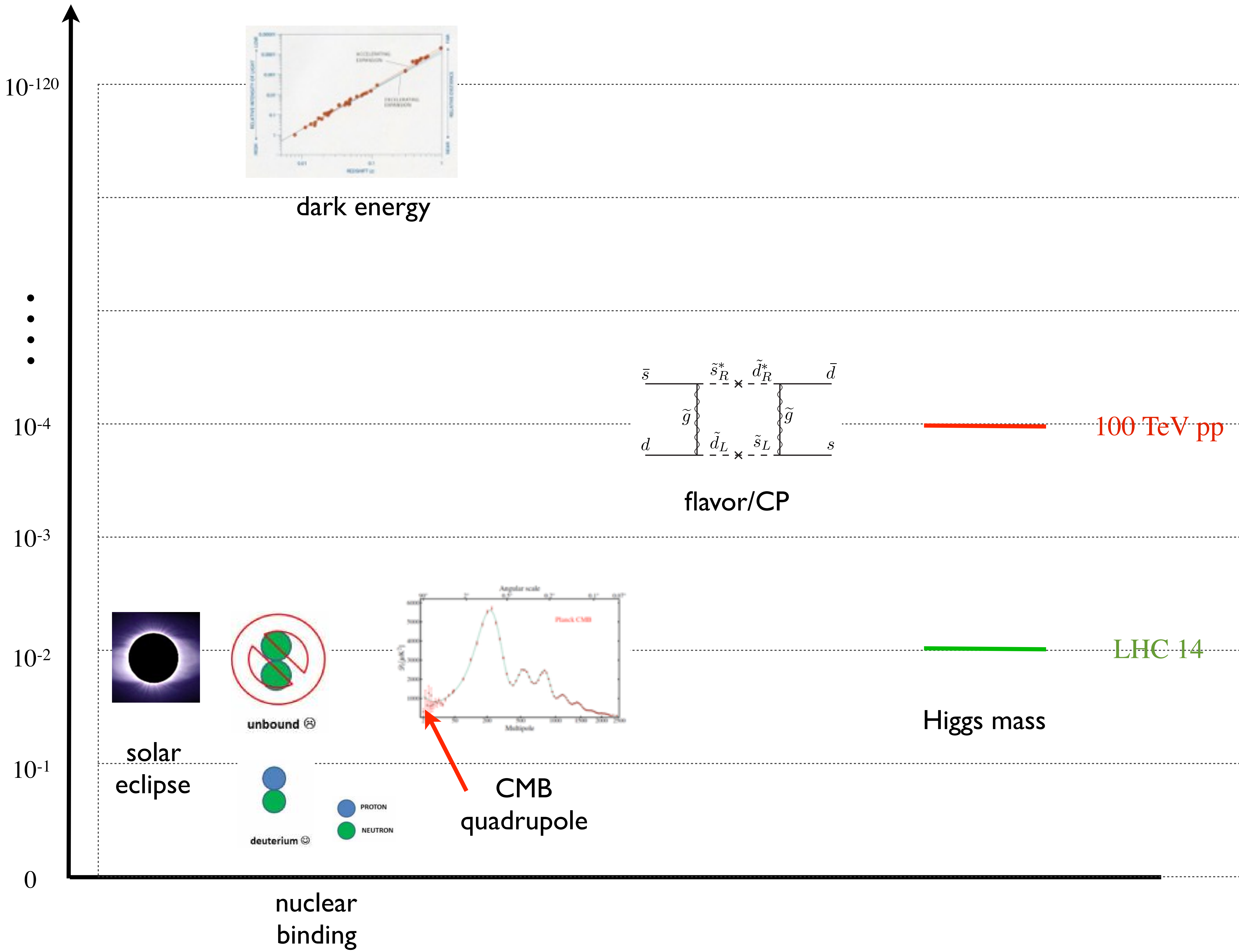
- Without LHC discovery.
  - Physics case for a 100 TeV pp collider stronger than HE-LHC at 28 TeV. Need a big step.
  - Cost+technological challenge. Perhaps easier to "sell" only as a second step of a circular Higgs factory in longer term.

More opportunities and challenges

- Better SM theory calculation needed for taking full advantage of energy and luminosity.
- Many more NP channels, e.g. flavor (violating) physics at 10s TeV?
- Full set of Higgs measurements at 100 TeV, more careful study.
- Physics driven (such as dark matter search) novel detector designs.
- We will do much better than we know now in a couple of decades. cf. LHC vs SppS.

A lot to look forward to!

extras



10^{-120}
dark energy
10^{-4}
10^{-3}
10^{-2}
10^{-1}
0
flavor/CP
100 TeV pp
LHC 14
Higgs mass
CMB
quadrupole
solar
eclipse
unbound ☹
deuterium ☺
PROTON
NEUTRON
nuclear
binding

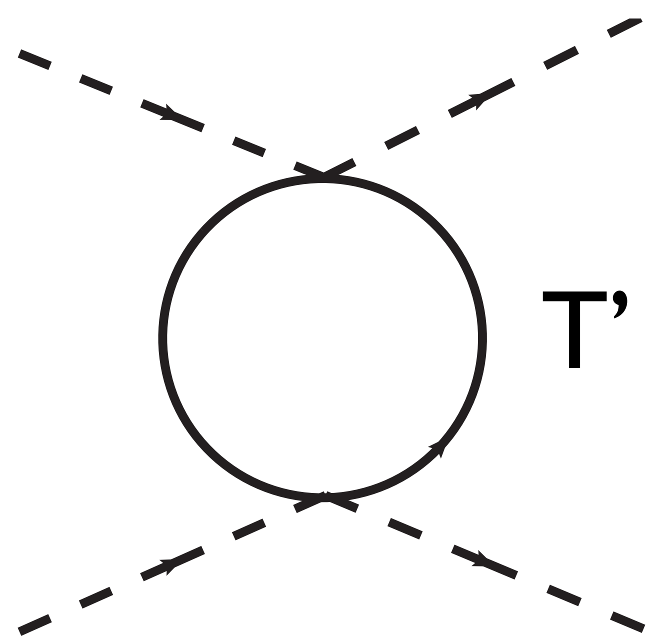
If we made a discovery at run 2

- Beginning of a new era. Seeing the first sign of a new layer of new physics.

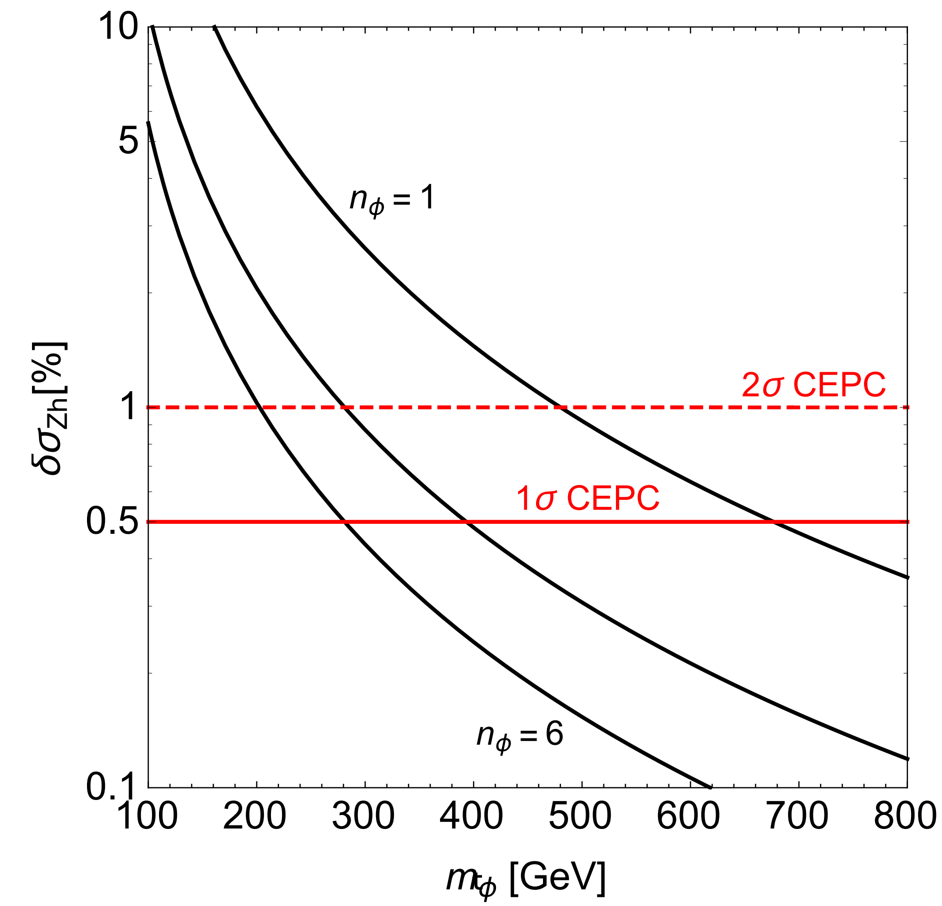
- However, it is unlikely to discover the full set of the particles, since we have not see anything yet.
- Typically, going from 8 TeV to 14 TeV increase the reach at most by a factor of 2.
- However, many models feature particles with masses spread at least factor of several apart.
- Won't be able to see everything.
- LHC discovery will set the stage for our next exploration, in particular at a 100 TeV pp collider.

Neutral naturalness

Twin Higgs. Chacko et al. Talk by Craig



Top partner only couple to Higgs.
Wavefunction renormalization
Induce shift in Higgs coupling.



Craig, Englert, McCullough, 2013

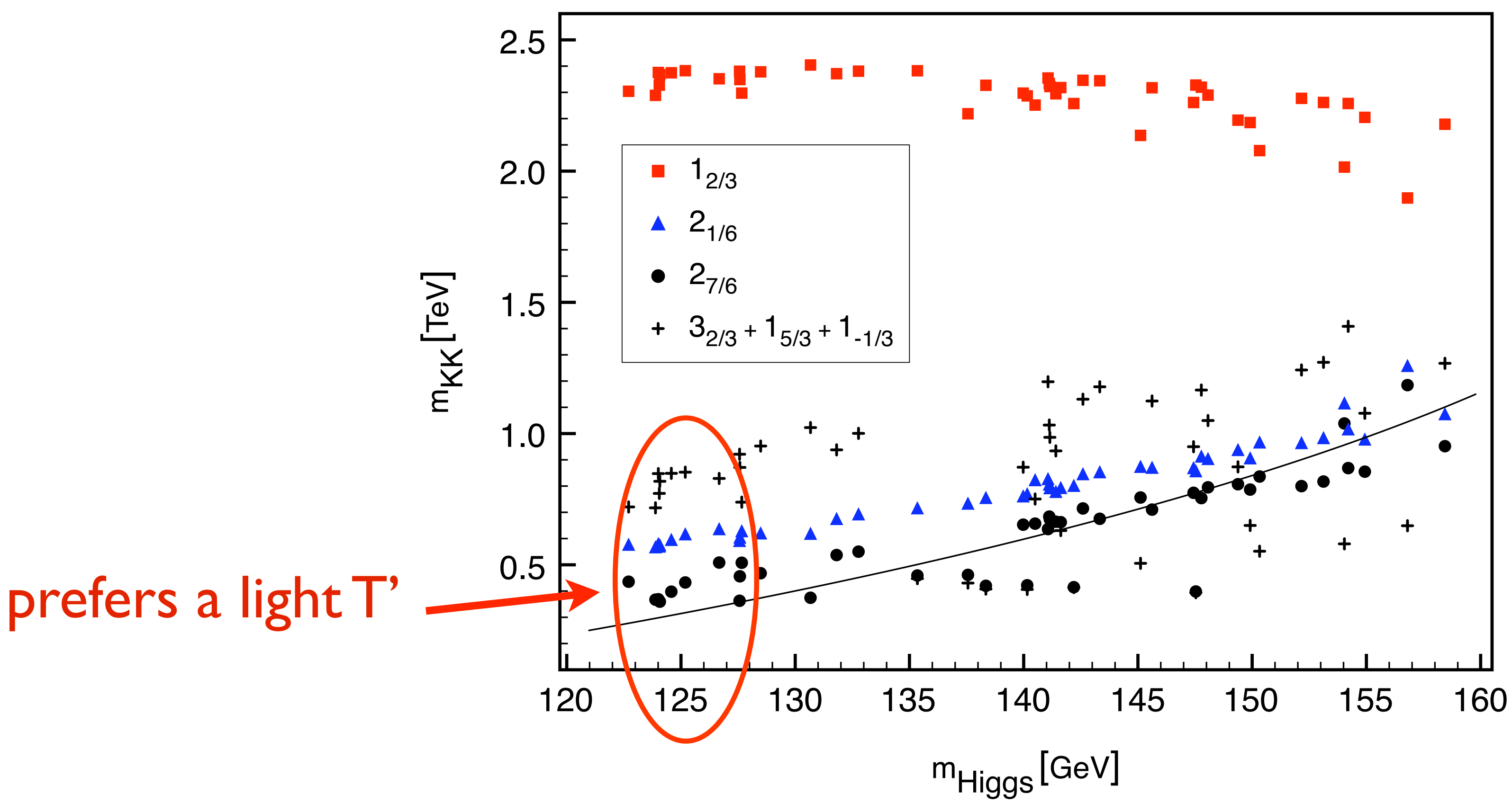
- LHC reach poor. Theory can be completely natural.
- Higgs factory can test this.

Need to consider UV completions for neutral top partners

- Induce measurable shifts in Higgs couplings, precision observables.
- UV completions can be directly probed at 100 TeV.
- Combination of precision measurement and direct search at 100 TeV pp collider can test naturalness.

Compositeness and top partner

Wulzer's talk

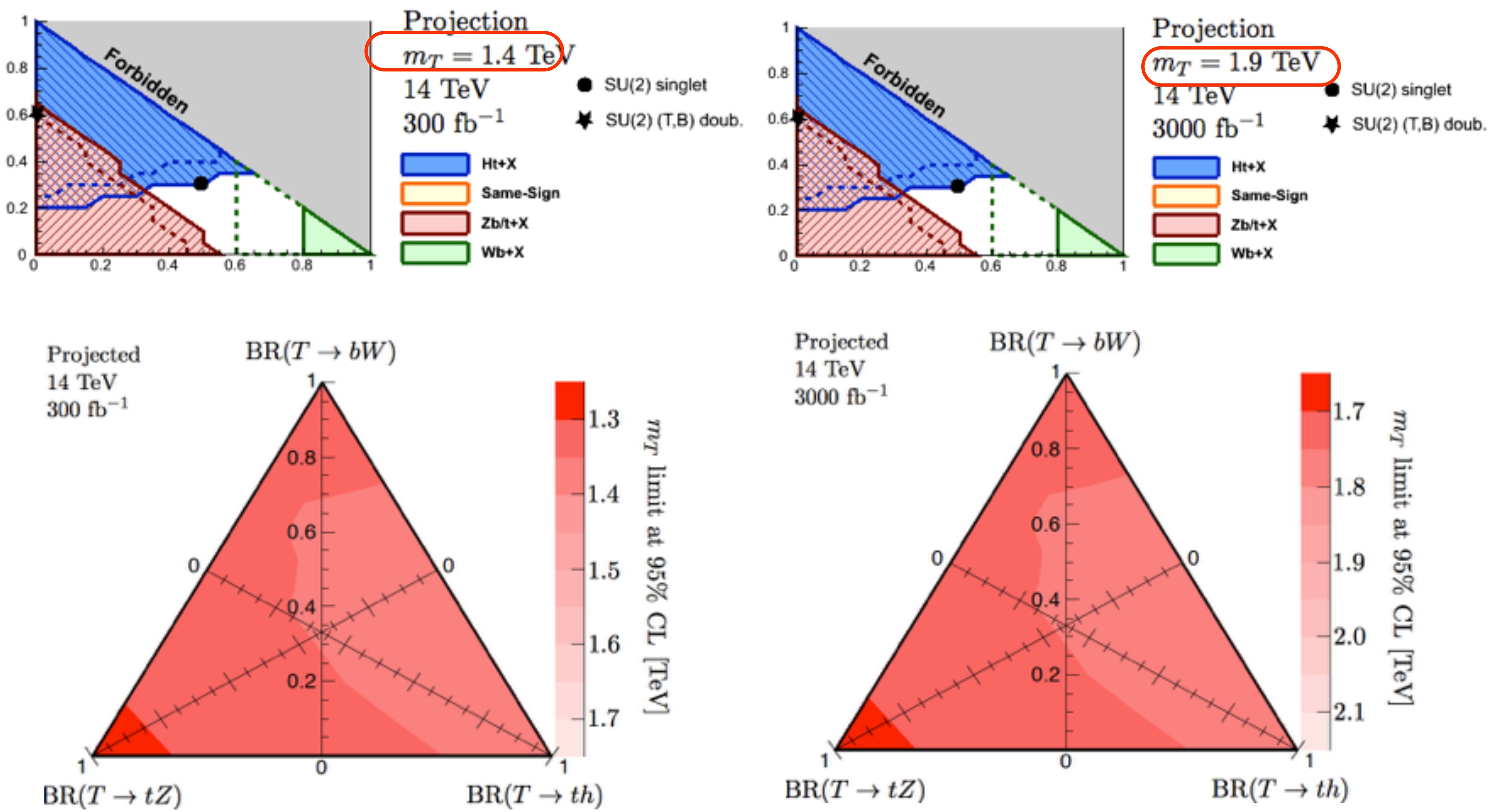


Contino, Da Rold, Pomarol, 2006

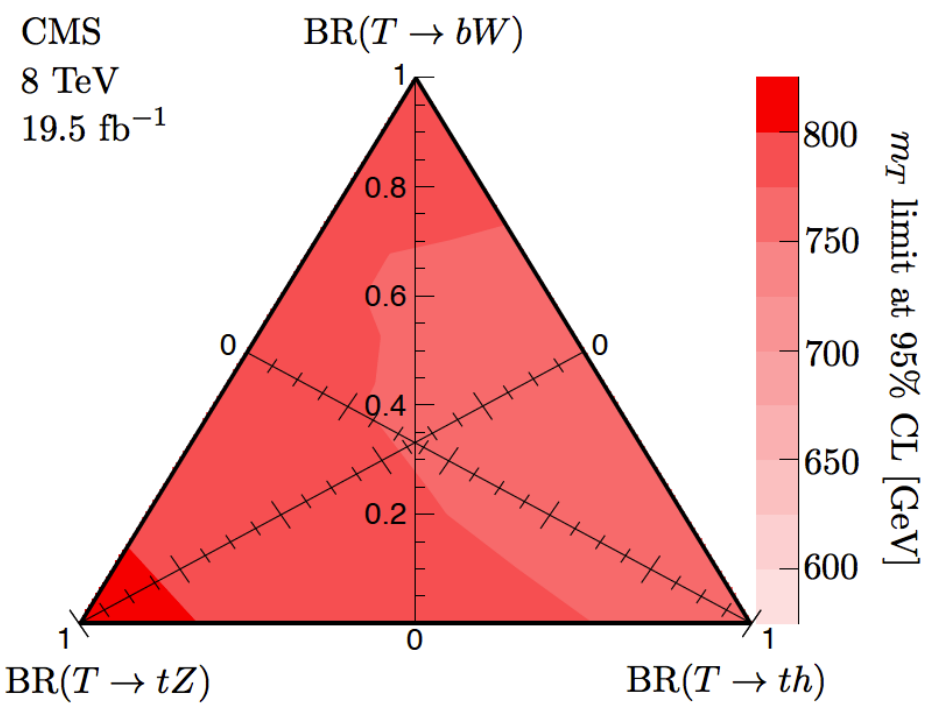
- Plays a crucial role in EWSB.

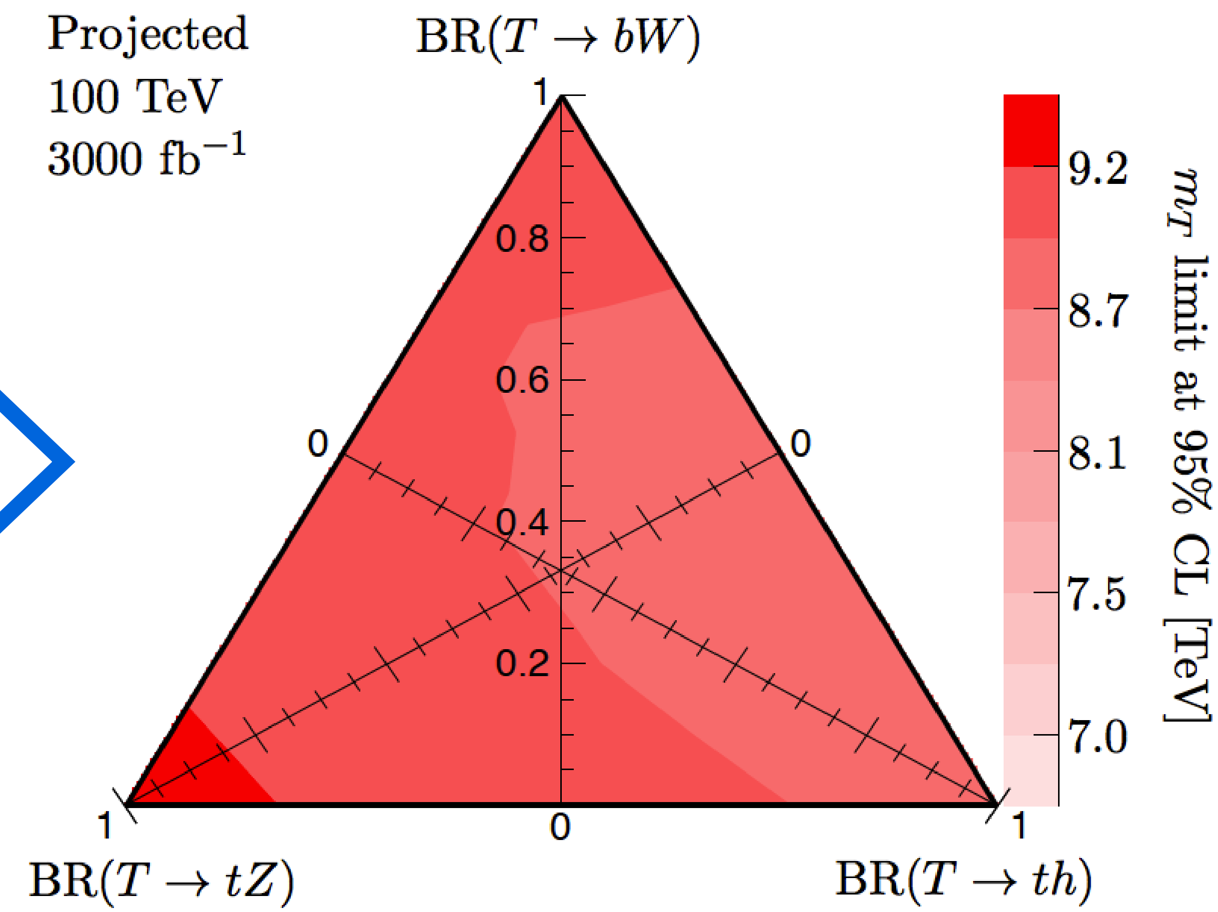
For a comprehensive discussion, see
De Simone, Matsedonskyi, Rattazzi, Wulzer, 1211.5663

LHC 14 should cover (most of) it.



Going up to 100 TeV

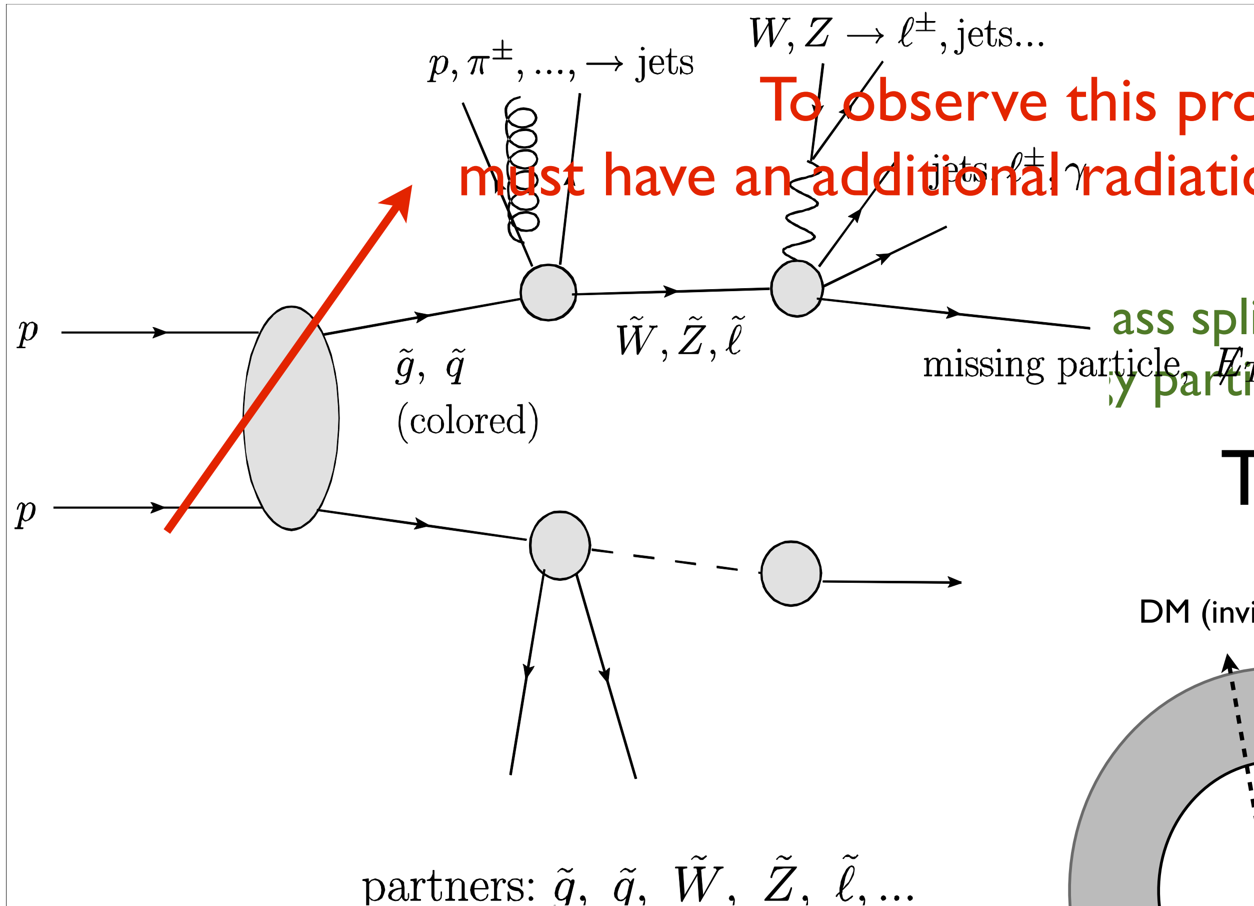




- Again, room for improvement by using single production, boosted technique, etc.

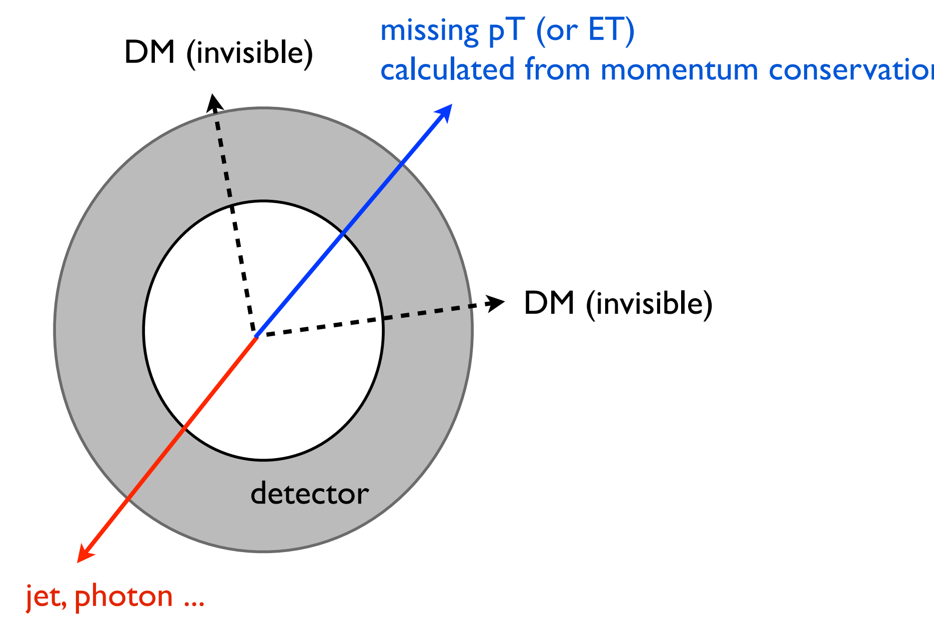
SUSY DM signal in the compressed case

To observe this process,
must have an additional radiation: jet, photon, ...



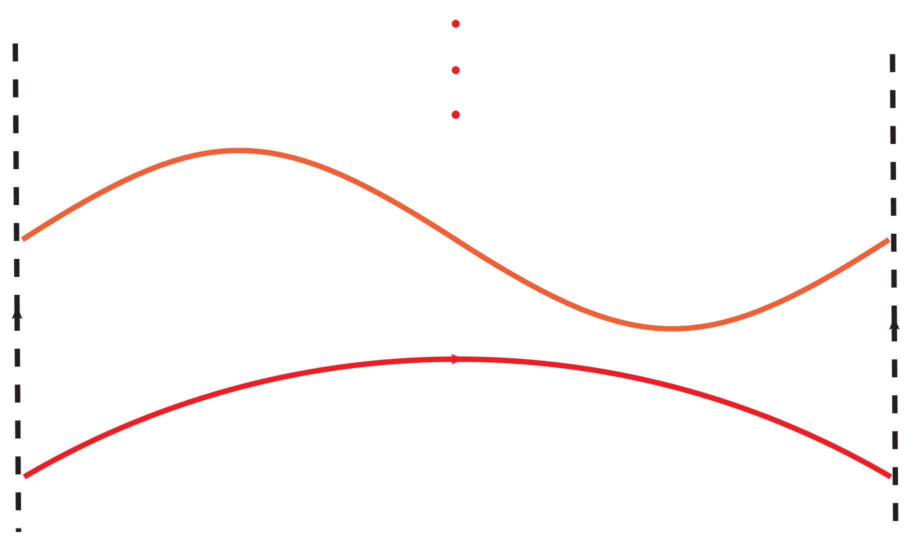
ass splitting, very
y particles, invisible

The “usual” story



– Back to the basic mono-jet, mono-photon...

Higgs mass in quantum theory.
Quantum fluctuation: Zero point energy



$$\mathcal{H}_{\text{quant}} = \sum_{\vec{p}} \frac{1}{2}\hbar\omega_{\vec{p}} \simeq \int^{|p|<\Lambda} \frac{d^3\vec{p}}{(2\pi)^3}\hbar\omega_{\vec{p}}$$

$$\omega_{\vec{p}} = \sqrt{\vec{p}^2 + m^2} \qquad (\hbar = 1)$$

Λ: a cut-off.
The energy scale of new physics.

Standard Model: include fluctuations of W boson, top quark, ...

$$m_{\mathrm{W}} = g_2 h, \quad m_{\mathrm{top}} = y_t h \qquad \mathcal{H}_{\text{quant}} \simeq \frac{9}{64\pi^2} g_2^2 \Lambda^2 h^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 h^2 + \cdots$$

- Renormalization: m_h^2(physical) = $m_0^2 + c\ \Lambda^2$
  - m_0^2 can always be adjusted to give correct m_h^2(physical).

Naturalness problem.

- m_h^2 (physical) = $m_0^2 + c\ \Lambda^2$, $c \approx O(0.01)$

- What is Λ? Or where is new physics?
  - Some fundamental scale beyond the Standard Model. $\Lambda \approx M_{Pl} = 10^{19}$ GeV, $M_{unification} = 10^{16}$ GeV...?

- $\Lambda^2 \approx M_{Pl}^2$, m_0^2 must be very close to M_{Pl}^2 . At the same time, they must cancel to the precision of 10^{-32} to have m_h^2 (physical) $\approx$ (100 GeV)^2, fine-tuning.

- No large cancellation $\Rightarrow$ m_h^2 (physical) $\approx c\Lambda^2$

Naturalness criterion leads to a prediction of the mass scale of new physics!!

Rate for double Higgs production.