CERN accelerator school on
Beam Dynamics and Technologies for Future Colliders
Zurich, Febr 21 - Mar 6, 2018

High energy physics at future colliders

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HiLumi HL-LHC PROJECT

pp @ 14 TeV, $3ab^{-1}$

✓Approved 2026-37

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e^+e^- @ 380 GeV, 1.5 & ~3 TeV

CDR 2012+
update '16

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HiLumi — HL-LHC PROJECT

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✓Approved 2026-37

CLIC

e^+e^- @ 380 GeV, 1.5 & ~3 TeV

CDR 2012+
update '16

FCC — hh ee he

CDR (end '18)

100km tunnel

- pp @ 100 TeV
- e^+e^- @ 91, 160, 240, 365 GeV
- e_{60GeV} p_{50TeV} @ 3.5 TeV

LHC tunnel: HE-LHC

- pp @ 27 TeV, $15ab^{-1}$

and in the rest of the world:

e^+e^- @ 250, 350, 500 GeV

TDR 2012

CDR (Spring ’18)

100km tunnel

- e^+e^- @ 91, 240 GeV (but possibly 160 & 350)
- Future possible pp @ ~70 TeV and e_{60GeV} p_{35TeV}

Regardless of what I'll discuss,
whatever project you're working on
(LHC, ILC, CLIC, FCC, X-FEL, PSI, superKEKB, …)
just be proud of it!!

Particle physicists can only be infinitely grateful to accelerator physicists:

without you, we'd be nowhere!

MLM, from talk given to Council, 2015, to justify HL-LHC ….

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A "real" story from the past ...

Barcelona, 15 March 1493 .....

CristofoRolf Columbus:

Your Majesty, the fleet needs an **upgrade**, we need to go back to the Indies with **10 times** more ships

King Ferdinand and Queen IsAgnieszka:

You discovered the Indies, your theory is right, why do you need more?

CristofoRolf Columbus:

Theorists* say these may not be the **standard Indies**. They calculated the Earth radius, and the standard Indies cannot be so close: these are likely to be ***beyond* the standard Indies** (*moving eastward ...*)

** If the King had listened to theorists to start with, he would have never authorized the mission: everyone would have died of starvation well before reaching the "standard" Indies ...*

3

the discovery of the Higgs was not the end,
it was just the beginning …

The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

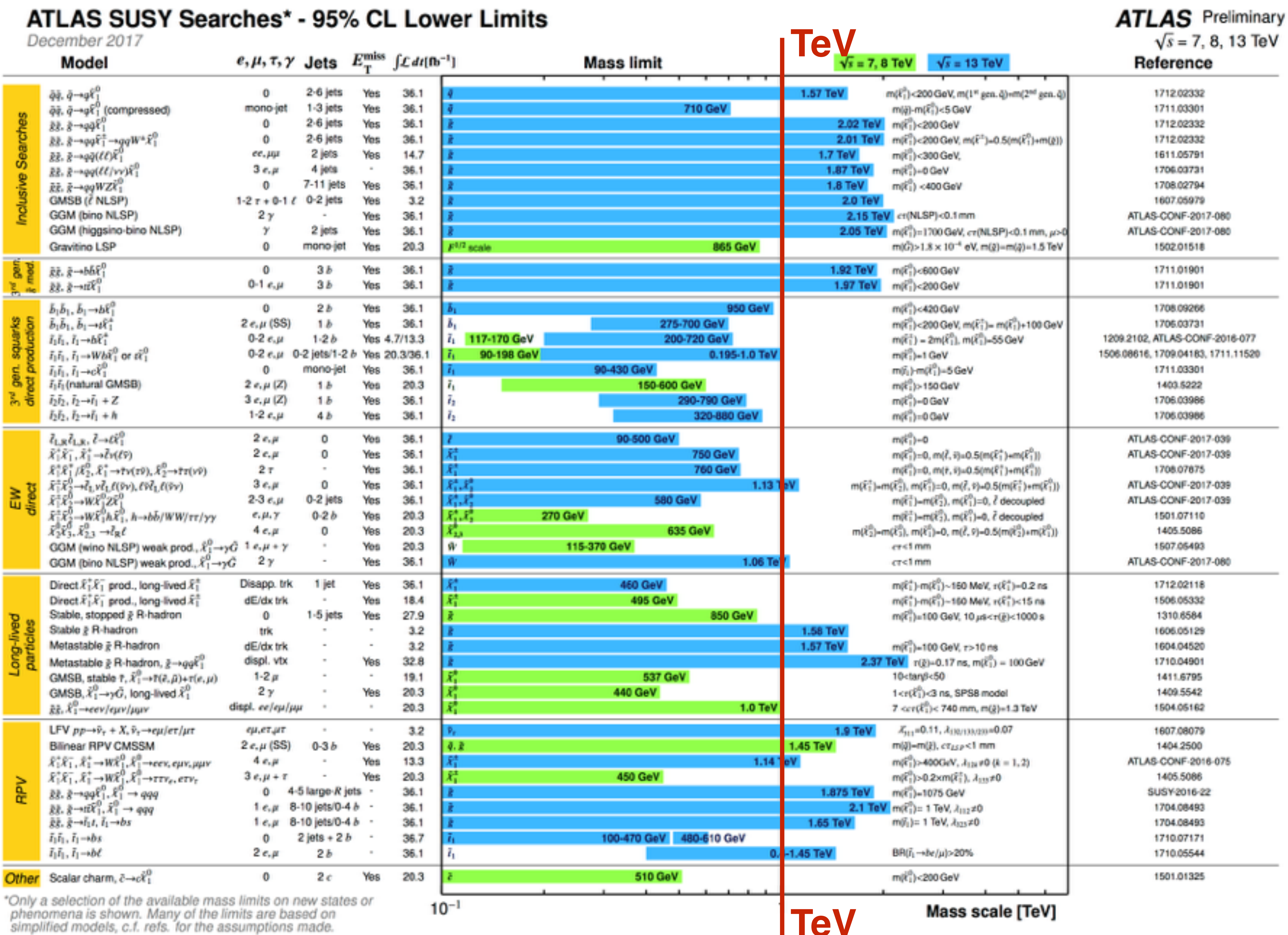
In search of the origin of known departures from the SM

- Dark matter, long lived particles
- Neutrino masses
- Matter/antimatter asymmetry of the universe

To explore alternative extensions of the SM

- New gauge interactions (Z', W') or extra Higgs bosons
- Additional fermionic partners of quarks and leptons, leptoquarks, …
- Composite nature of quarks and leptons
- Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, …)
- Extra dimensions
- New flavour phenomena
- unanticipated surprises …

So far, no *conclusive* signal of physics beyond the SM



however, notice the small print ….

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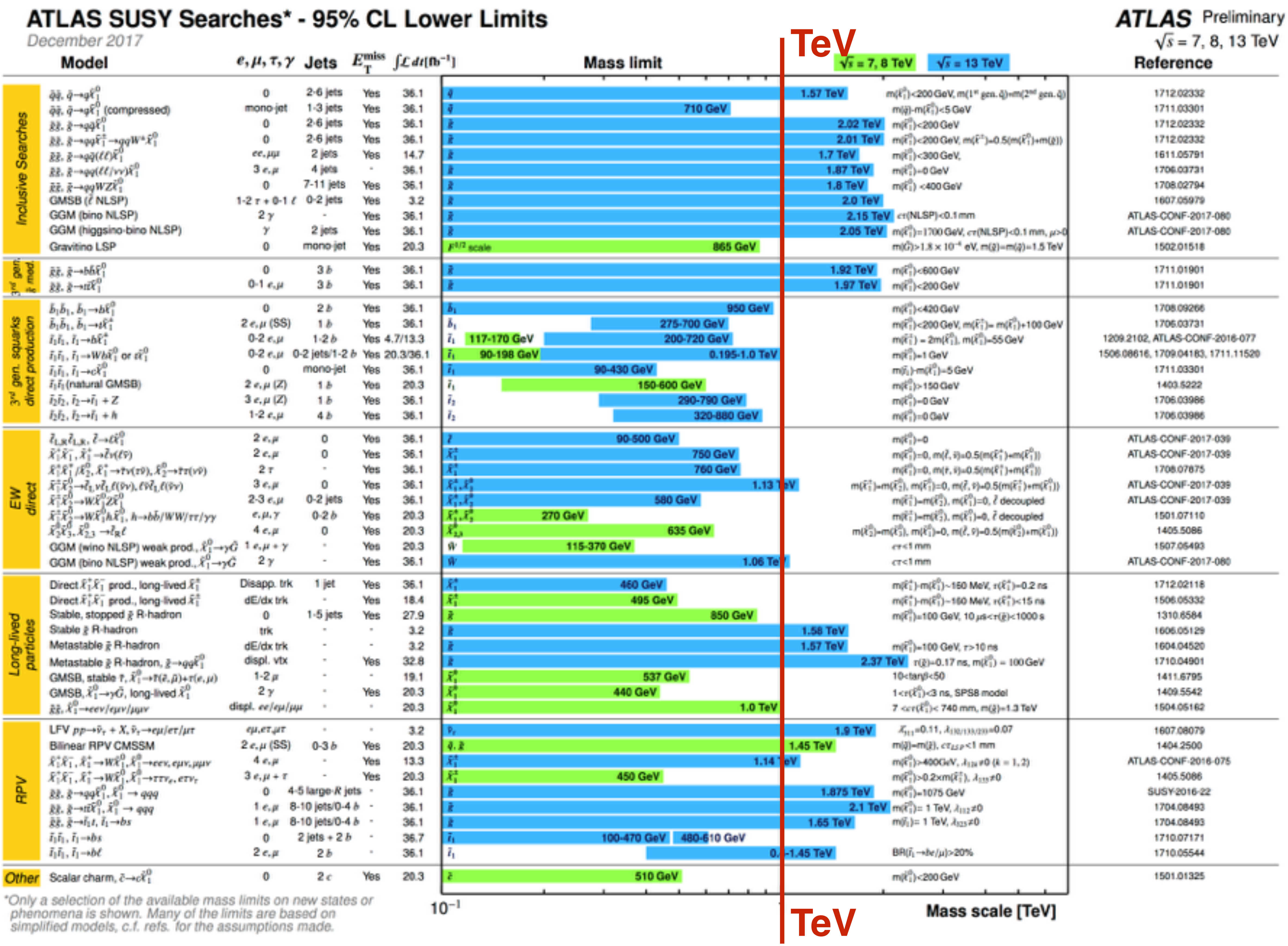

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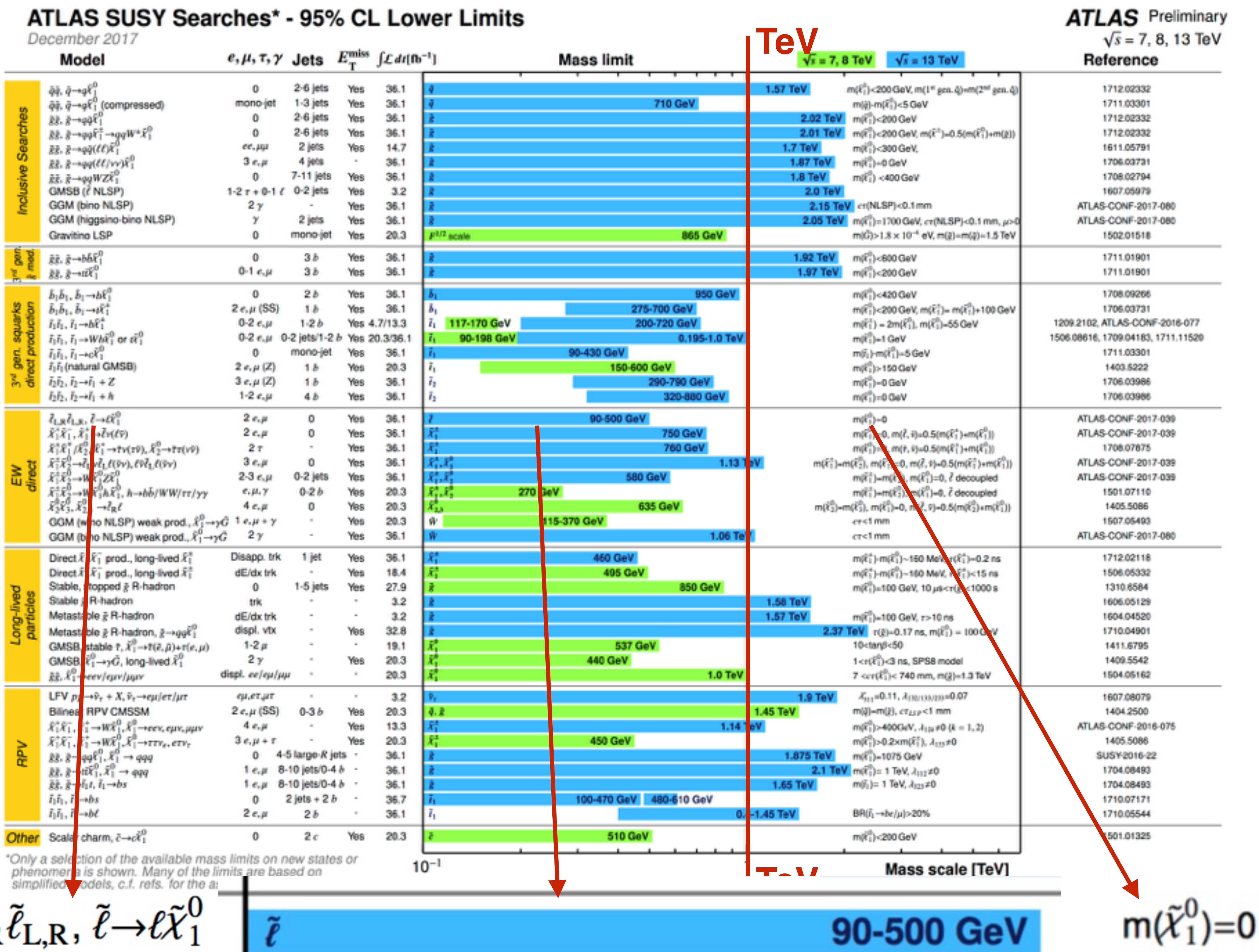
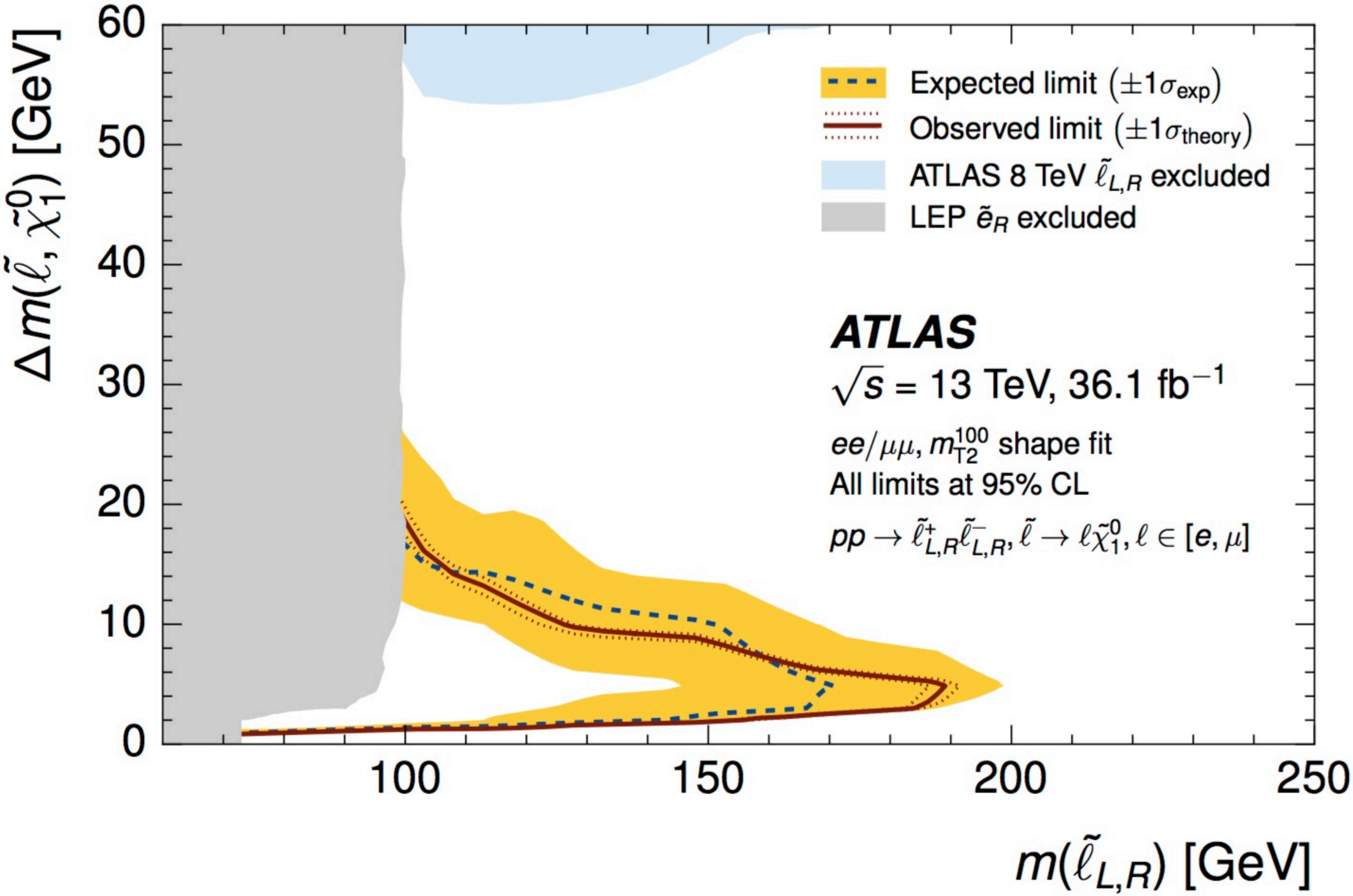


relaxing the $m(\chi^0)=0$ constraint …

… LHC has barely improved LEP2 limits …



=> in principle there is still room for discoveries at CLIC even at its lowest energies!

Key question for the future developments of HEP:

Why don't we see the new physics we expected to be present around the TeV scale ?

- **Is the mass scale beyond the LHC reach ?**
- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:

- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

Remark

the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field

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- exploit both direct (large Q^2) and indirect (precision) probes

(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions.

The guaranteed deliverable: relevance of a continued precision study of the Higgs boson

The Higgs and particles' masses

Light propagating in a medium is slowed down by its continuos interaction with the medium itself

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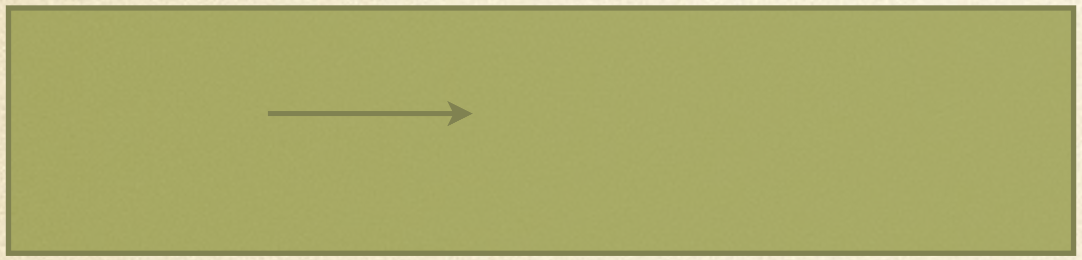

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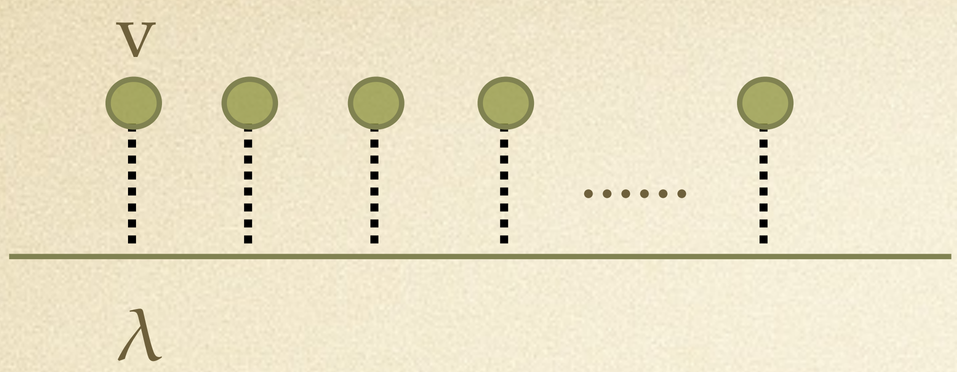
Think of the Higgs field as being a continuum medium embedding the whole Universe. Particles interacting with it will undergo a similar "slow-down" phenomenon. Rather than "slowing down", however, the interaction with the Higgs medium gives them "inertia" => mass



$m \propto \lambda v$

The number "v" is a universal property of the Higgs field background. The quantity "λ" is characteristic of the particle moving in the Higgs field. Particles which have large λ will have large mass, with $m \propto \lambda v$

Now the question of "why does a given particle has mass **m**" is replaced by the question "why does a given particle couple with the Higgs field with strength $\lambda \propto m / v$"

However at least now we have a model to understand **how** particles acquire a mass.

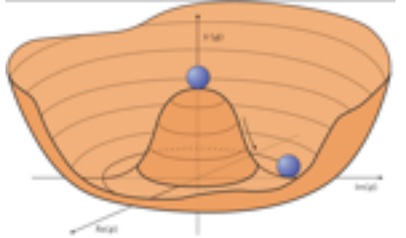
Detecting the Higgs boson

Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we "bang" on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate "Higgs waves". These waves manifest themselves as particles* , the so-called Higgs bosons

What is required is that the energy available be larger than the Higgs mass ⇒ LHC !!!

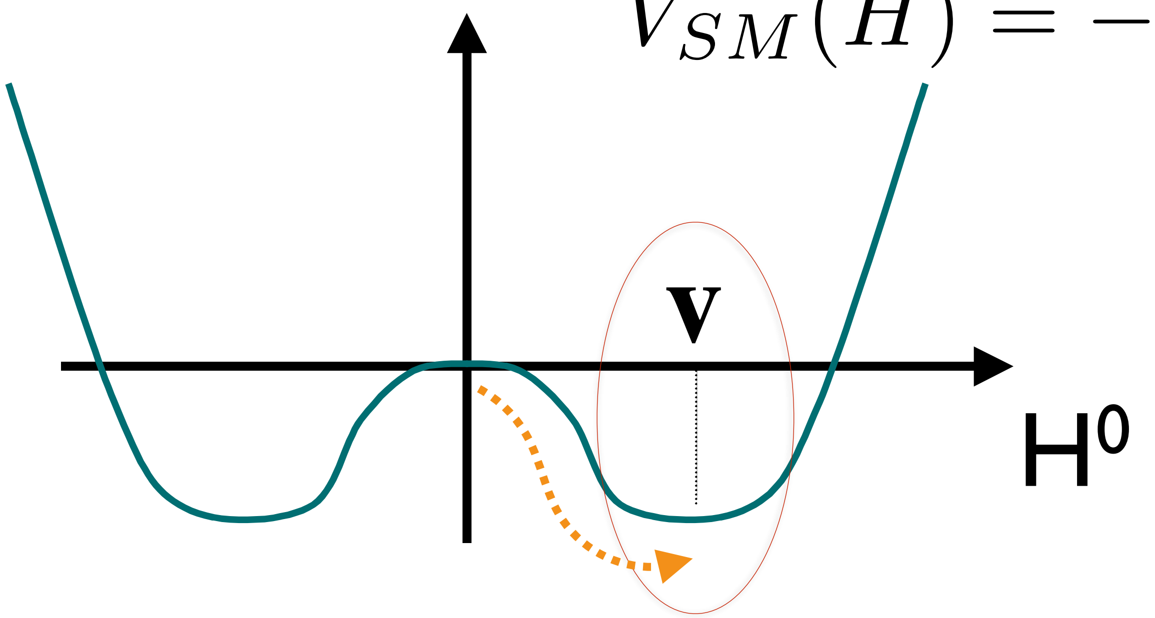
* Even the sound waves in a solid are sometimes identified with "quasi-particles", called "phonons"

What gives the Higgs field its background value?



$$V_{SM}(H) = -\mu^2 \, |H|^2 + \lambda \, |H|^4$$

$$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}$$



$$m \, \overline{\psi_L} \, \psi_R \rightarrow \lambda H \, \overline{\psi_L} \, \psi_R$$

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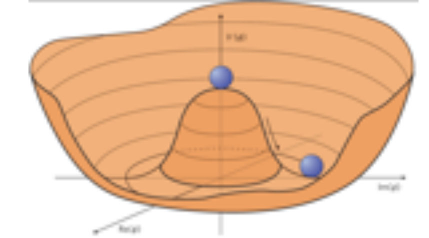

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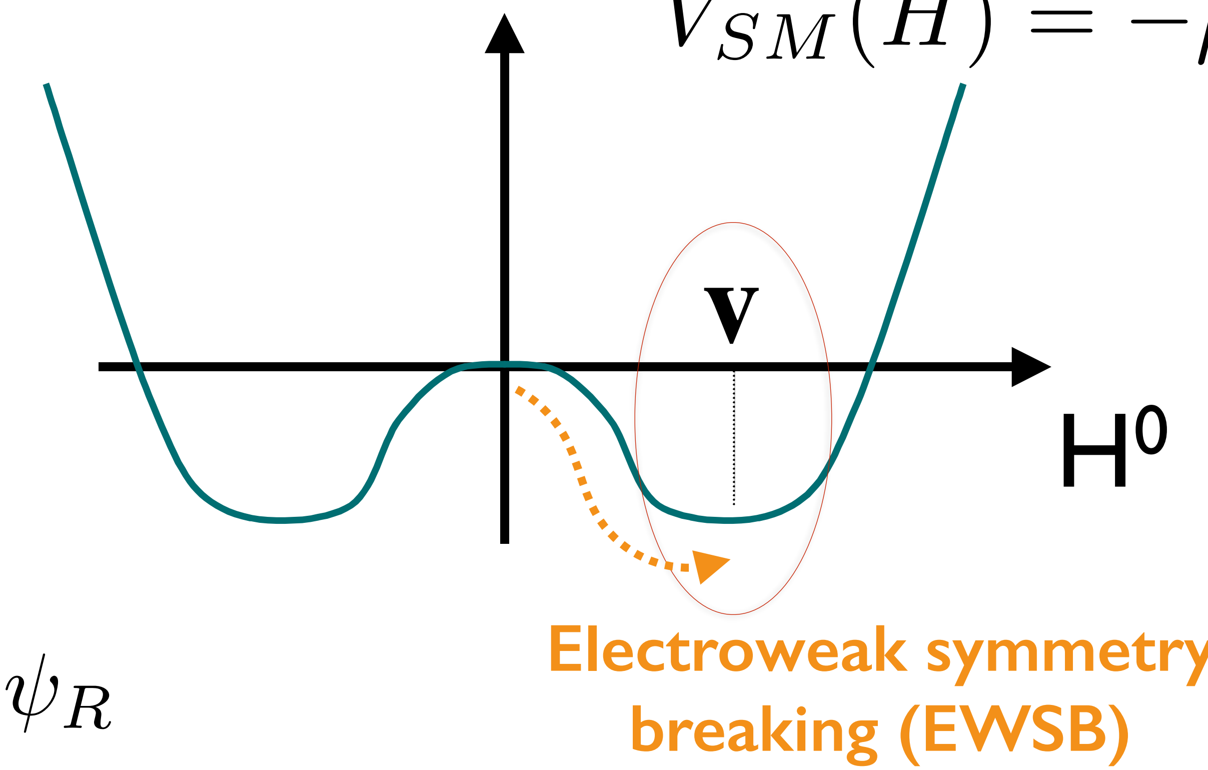

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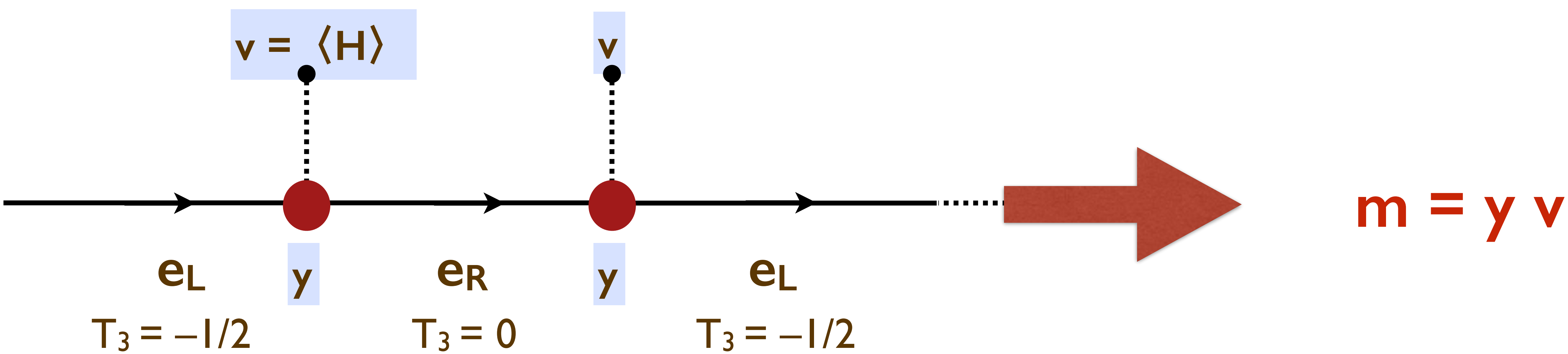


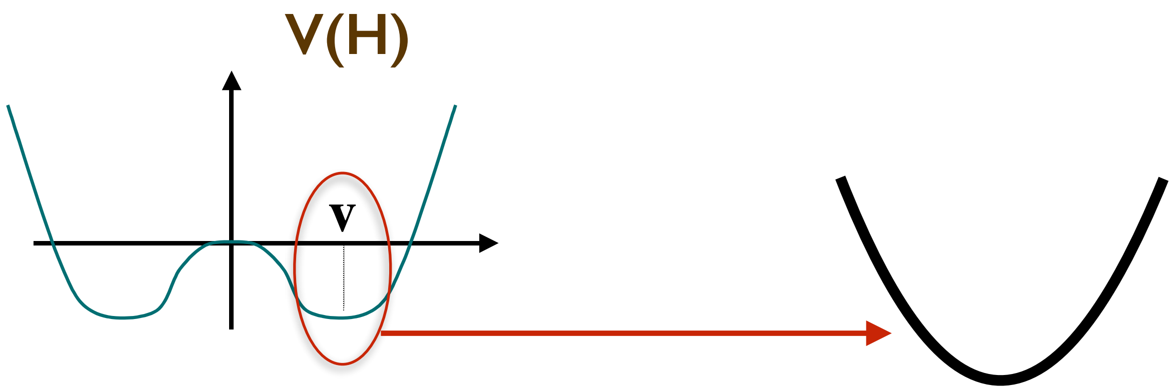
The transition between L and R states, and the absorption of the changes in weak charge, are ensured by the interaction with a background scalar field, **H**. Its "vacuum density" provides an infinite reservoir of weak charge.

First general consequences of this model

- Small oscillations around the minimum => a scalar particle (the "Higgs boson")
- Couplings of H to SM particles proportional to their mass
- 3 out of 4 components of complex doublet field provide longitudinal degrees of freedom to weak gauge bosons $W^{+/-}$ and Z^0

How far have we tested the Higgs mechanism?

parameters of the potential

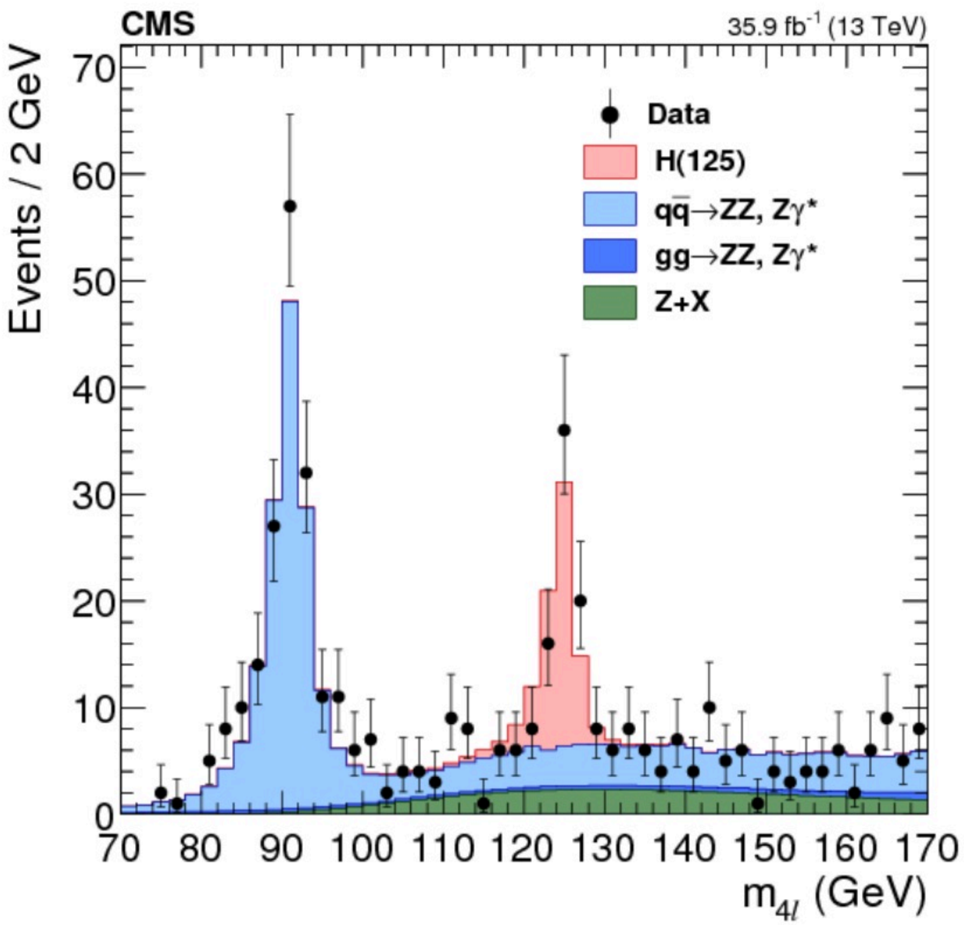


$V(H) \sim m_H^2\,(H-\mathbf{v})^2$

v=246 GeV, from weak decays

Higgs mass, 2017

CMS



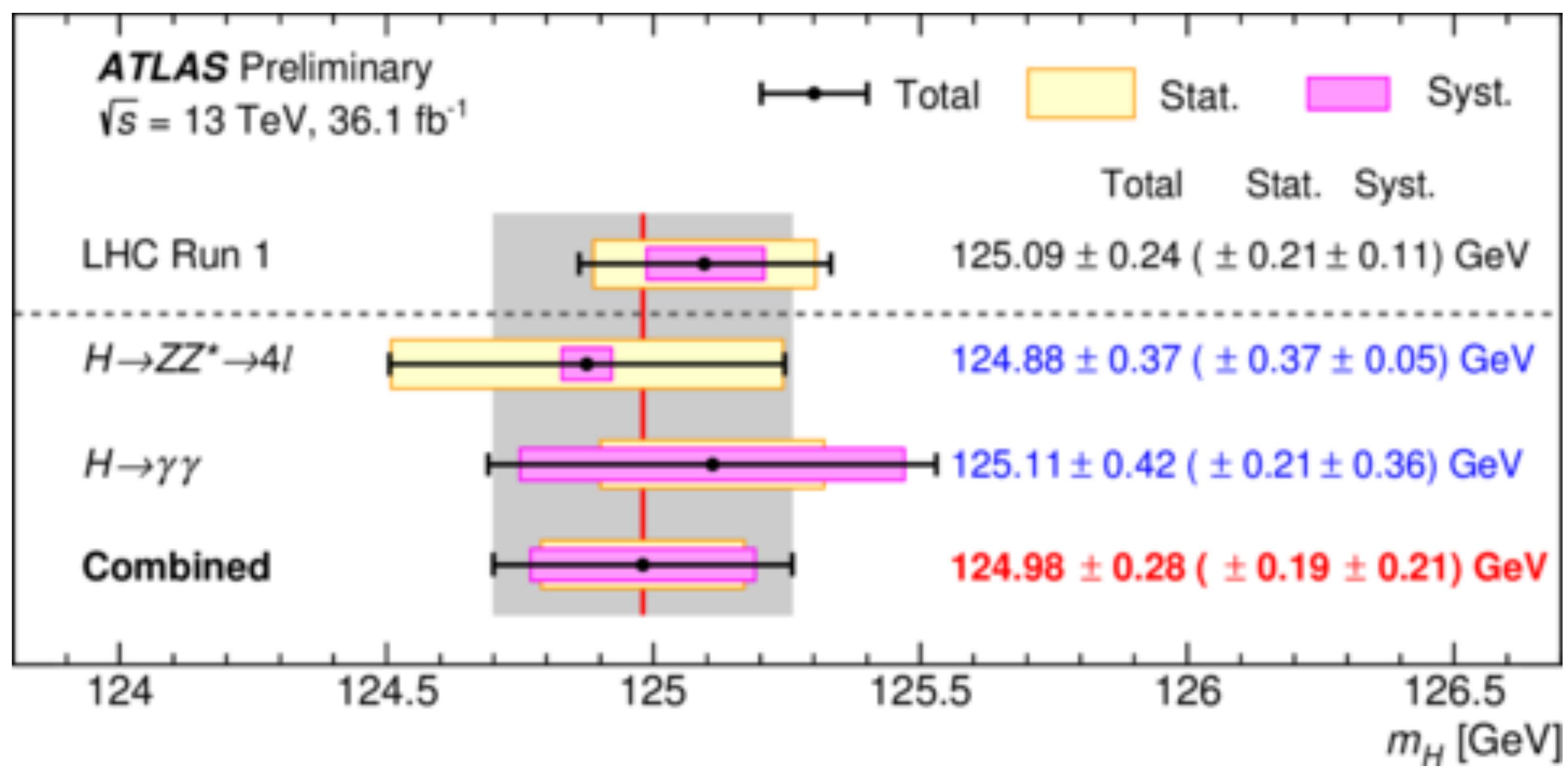
arXiv:1706.09936

3D likelihood fit (m_{4l}, ZZ bg, δm) ⇒

$m_H = 125.26 \pm 0.20_{stat} \pm 0.08_{syst}$ GeV

= 125.26 ± 0.22 GeV

ATLAS



ATLAS-CONF-2017-046

γγ and 4ℓ combination, run 1+2 ⇒

$m_H = 124.98 \pm 0.19_{stat} \pm 0.21_{syst}$ GeV

= 124.98 ± 0.26 GeV

⇒ 2 x 10^{-3} precision ….

it took over 6 years from 1983 discovery to get below 5 x 10^{-3} on m_Z (1989: CDF, SLC, LEP)

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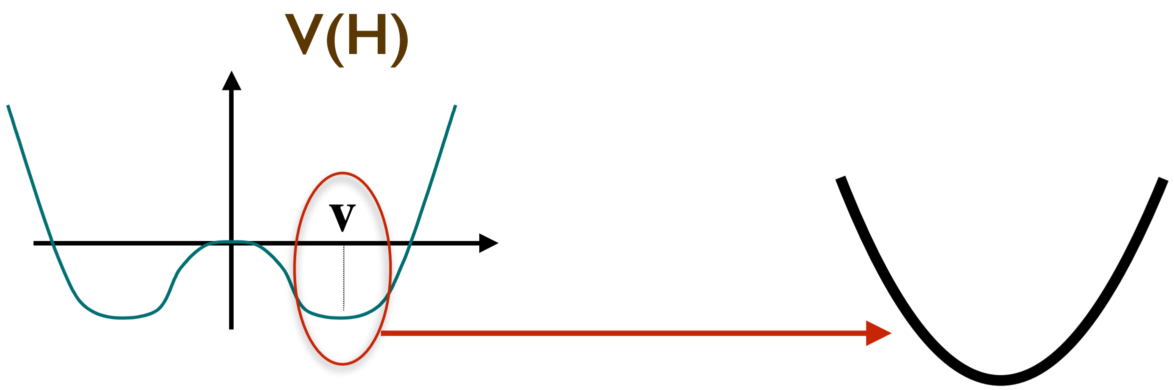

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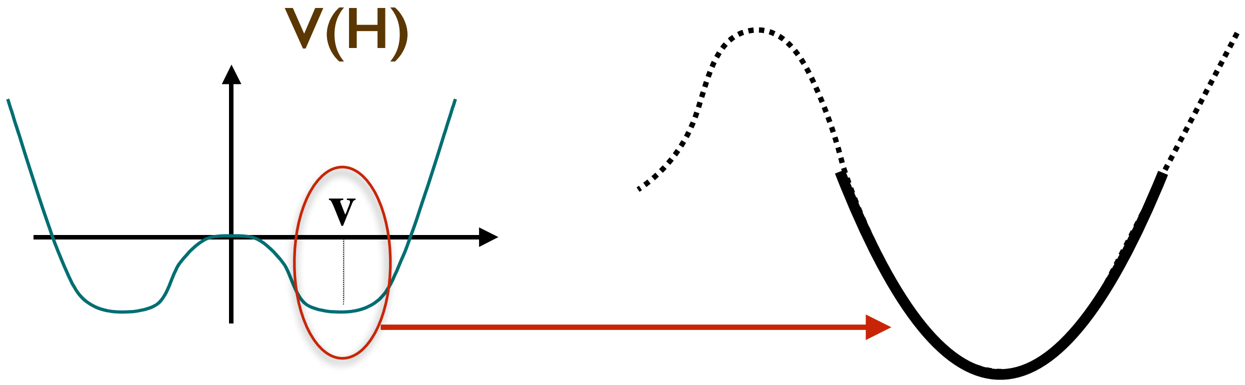

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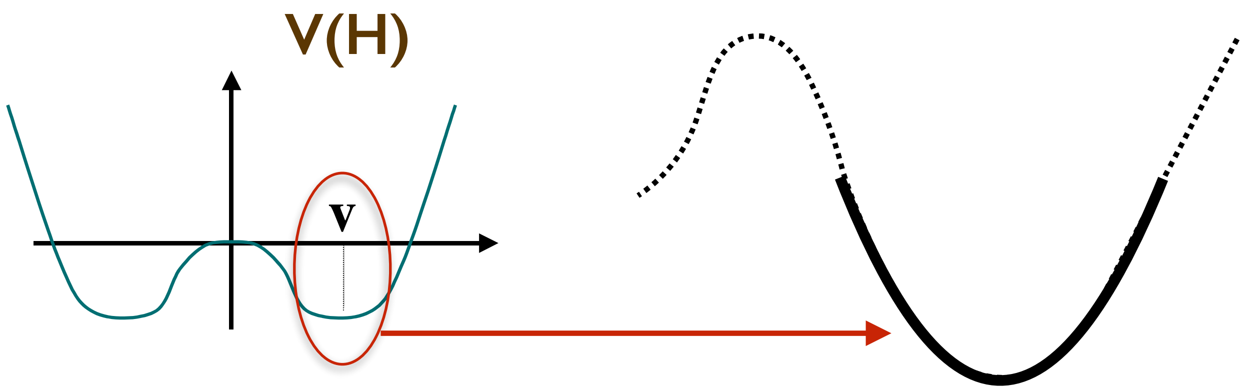

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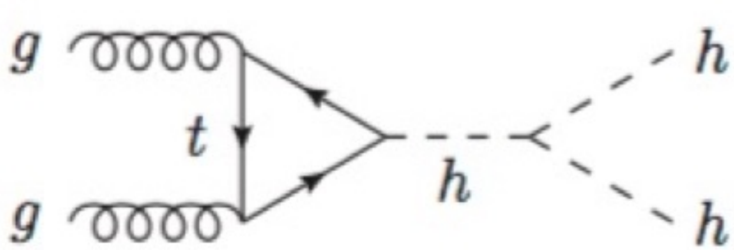
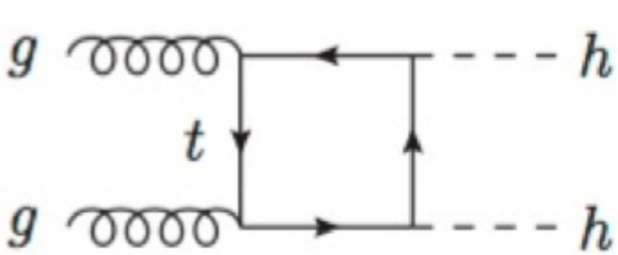
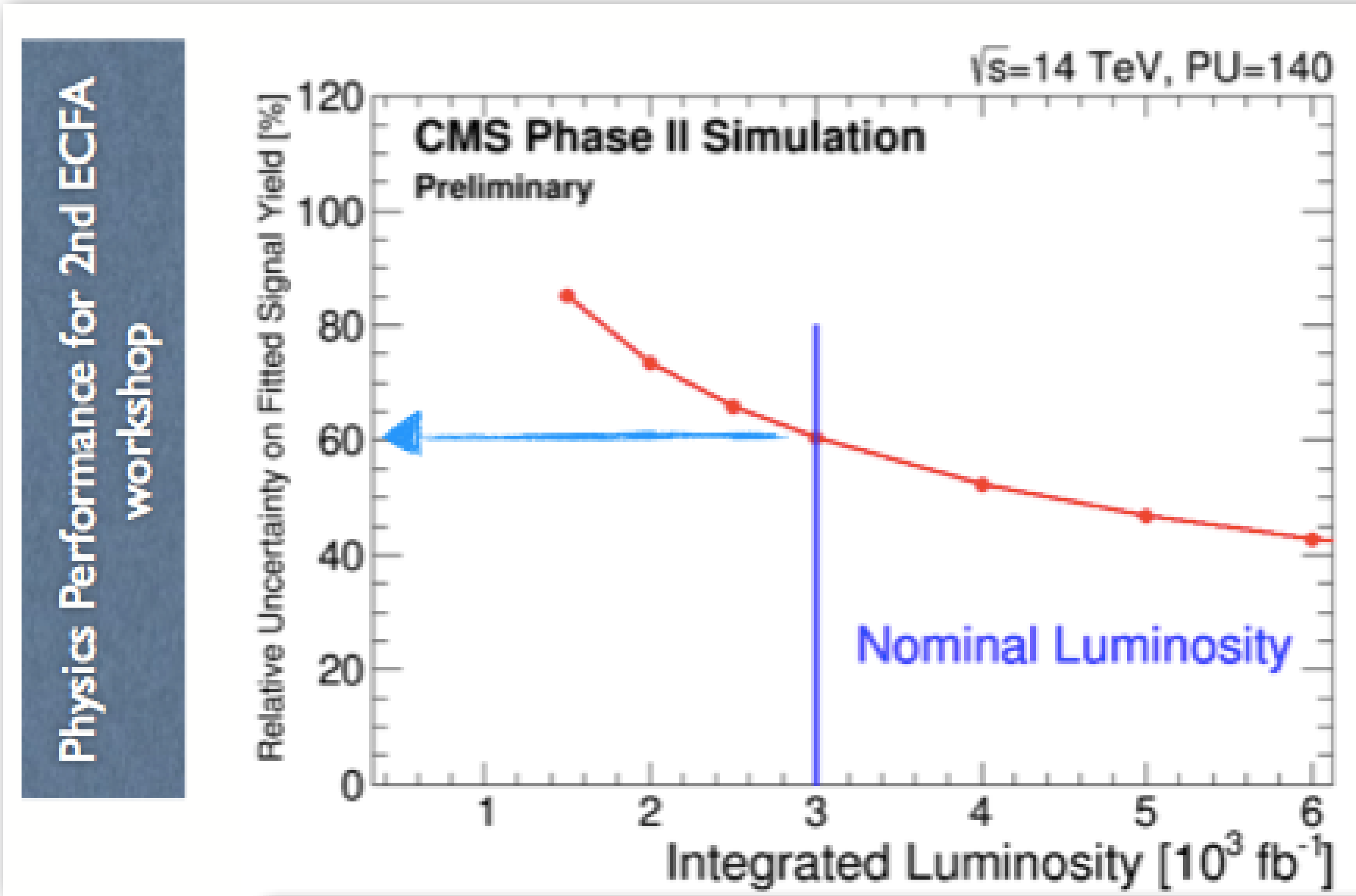
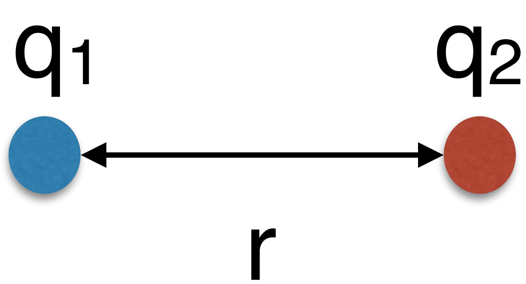
Probing the cubic term of the Higgs potential will require at least 100 x the current LHC statistics, and possibly more







Electromagnetic vs Higgs dynamics



$$V(r) = + \frac{q_1 \times q_2}{r^{1}}$$

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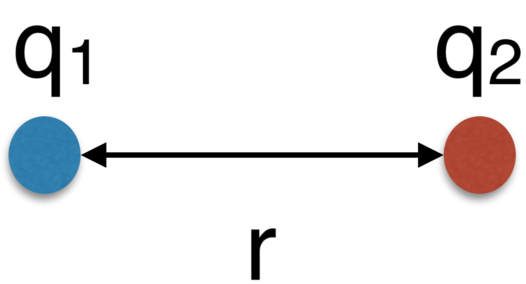

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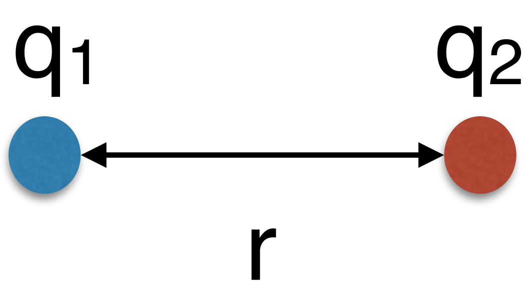

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sign fixed by photon spin

power determined by gauge invariance/charge conservation/Gauss theorem

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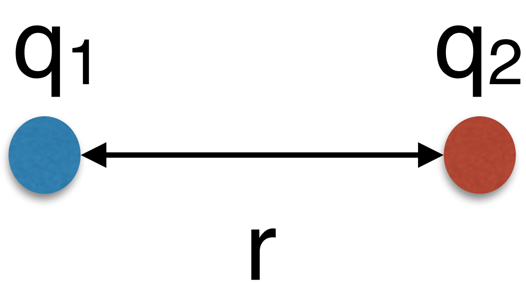

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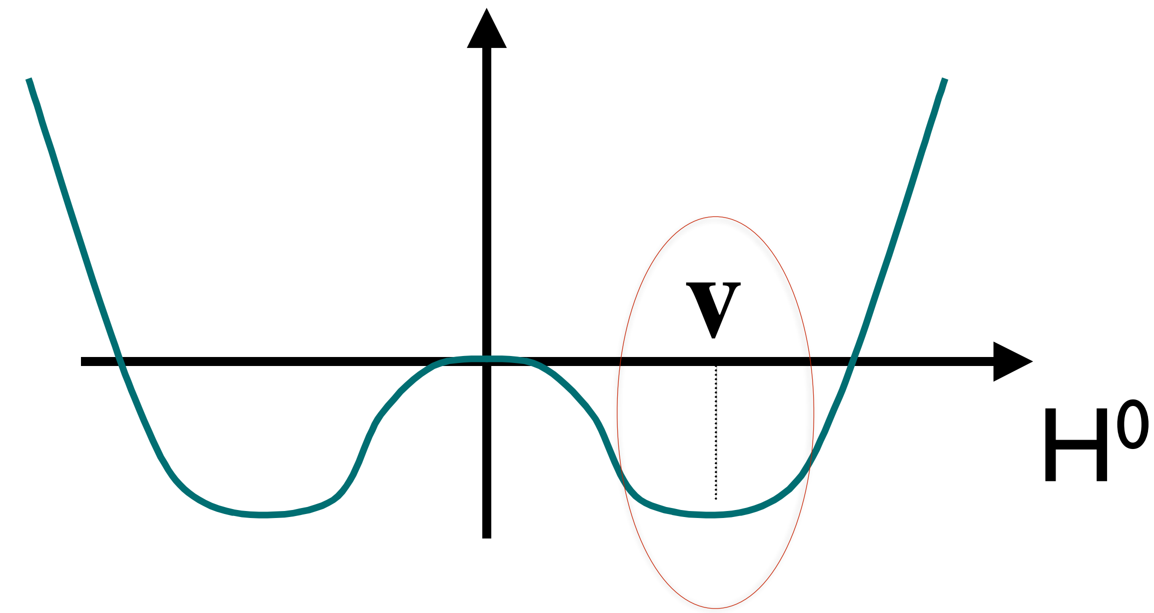

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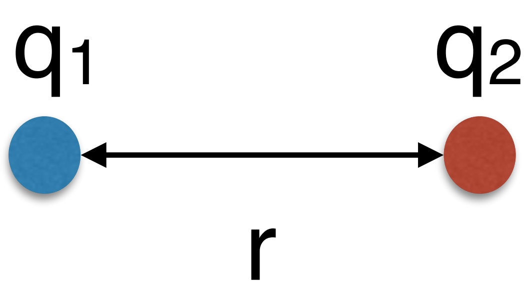

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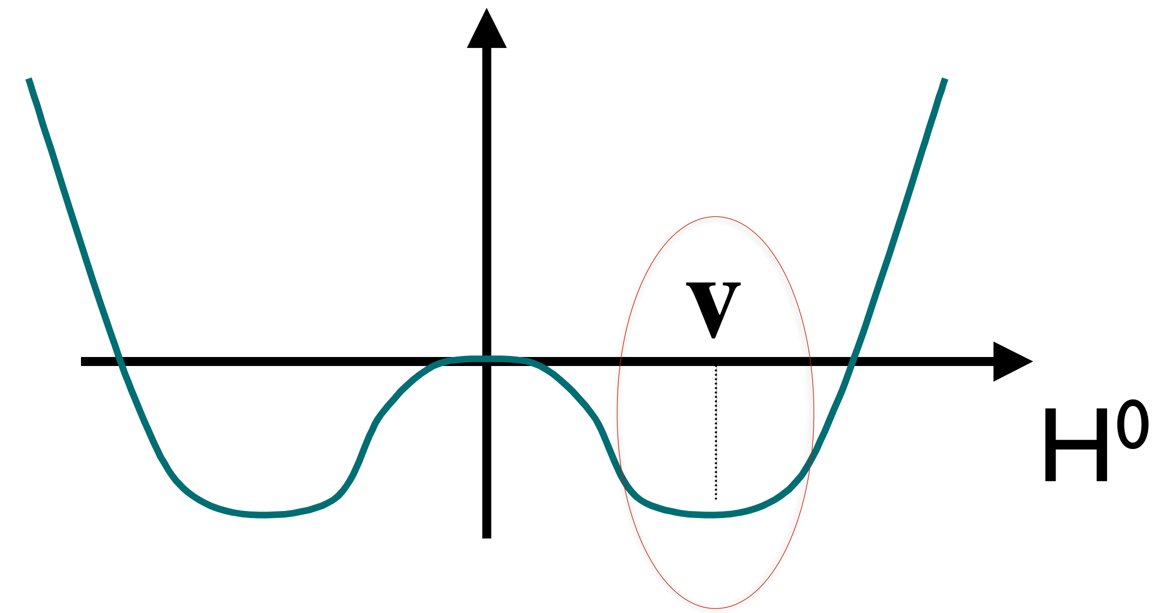

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both sign and value totally arbitrary

>0 to ensure stability, but otherwise arbitrary

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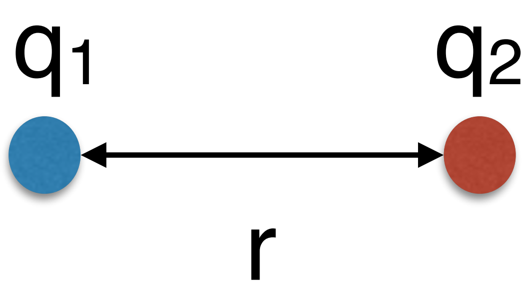

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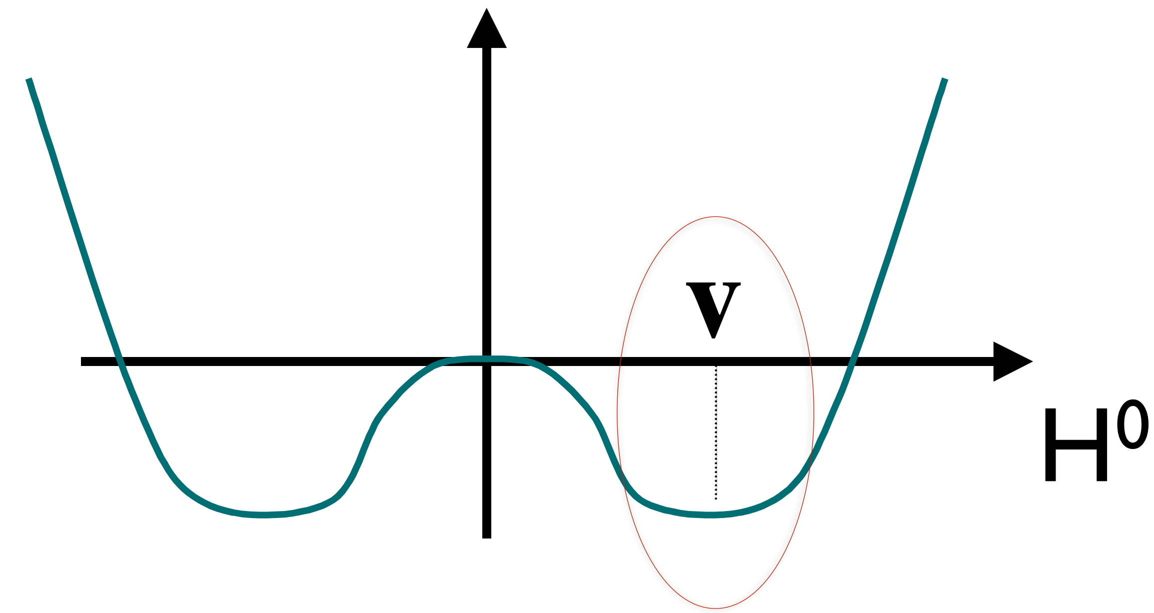

any function of $|H|^2$ would be ok wrt known symmetries

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a historical example: superconductivity

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- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

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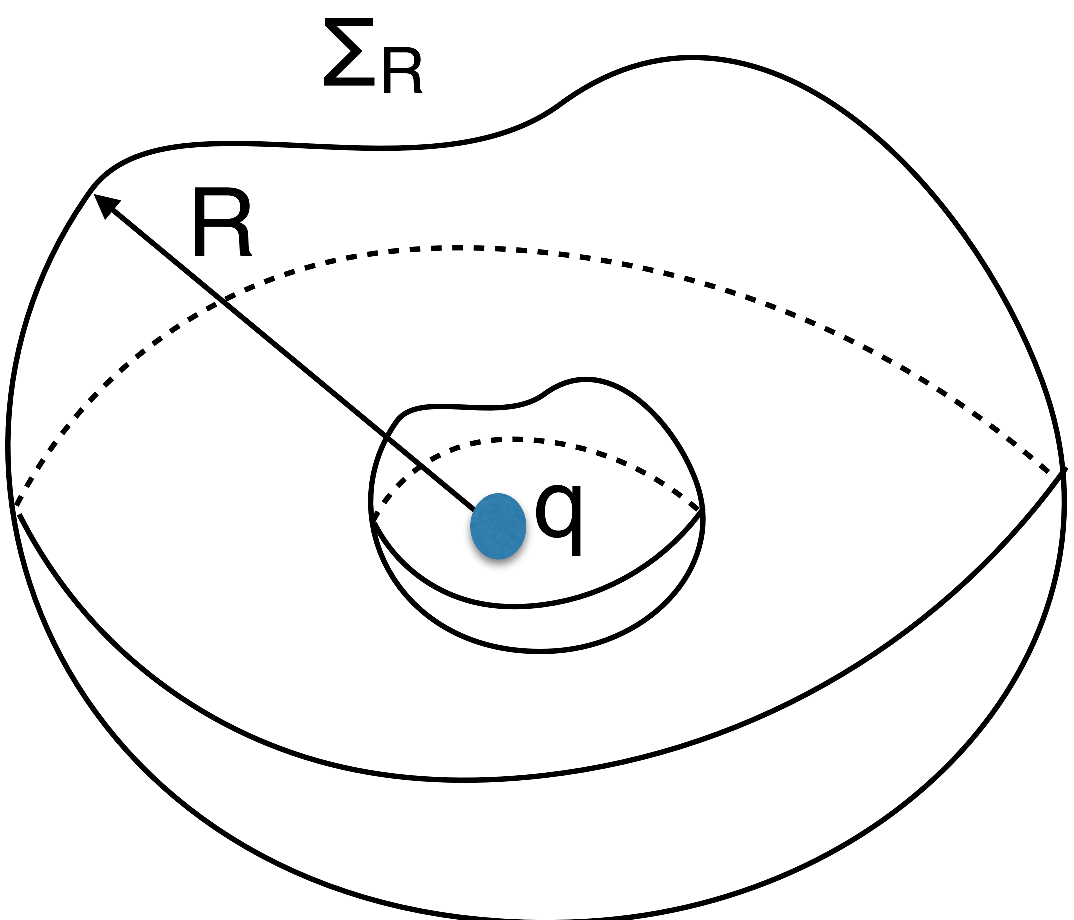
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

Decoupling of high-frequency modes

E&M



$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

short-scale physics does not alter the charge seen at large scales

Decoupling of high-frequency modes

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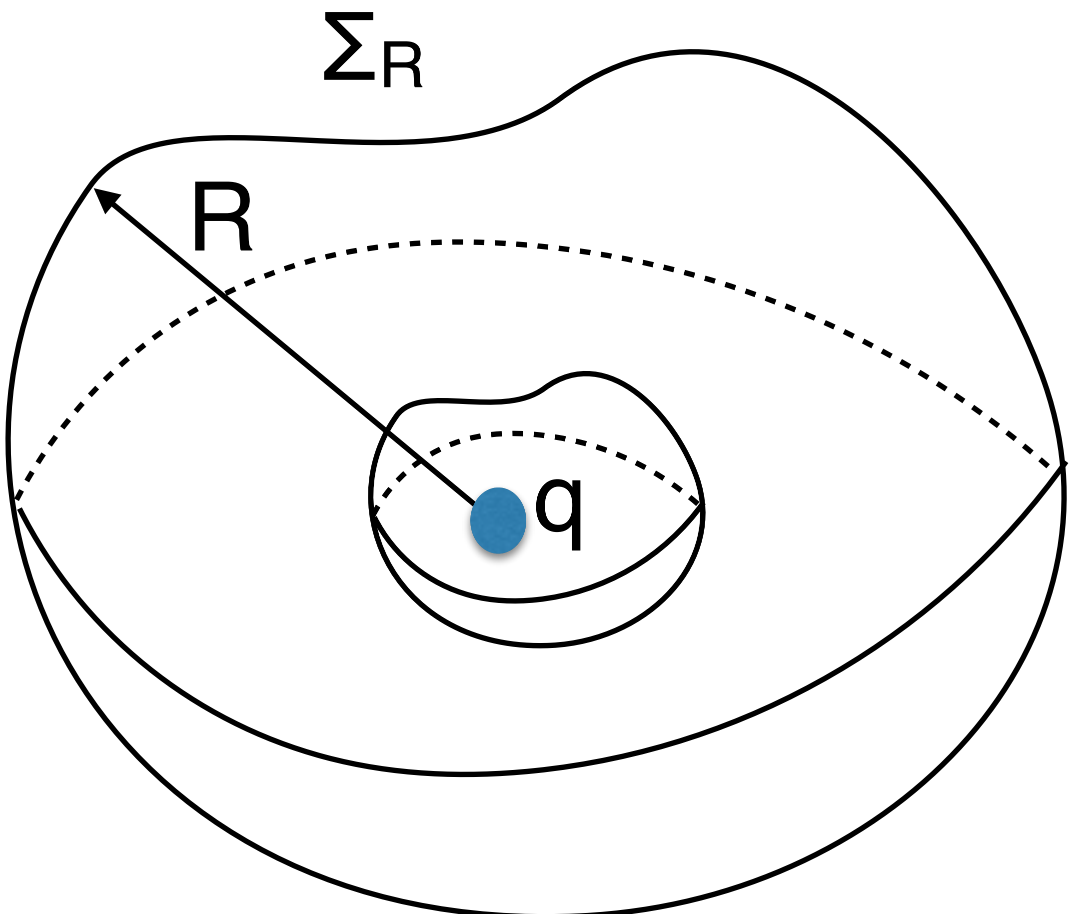

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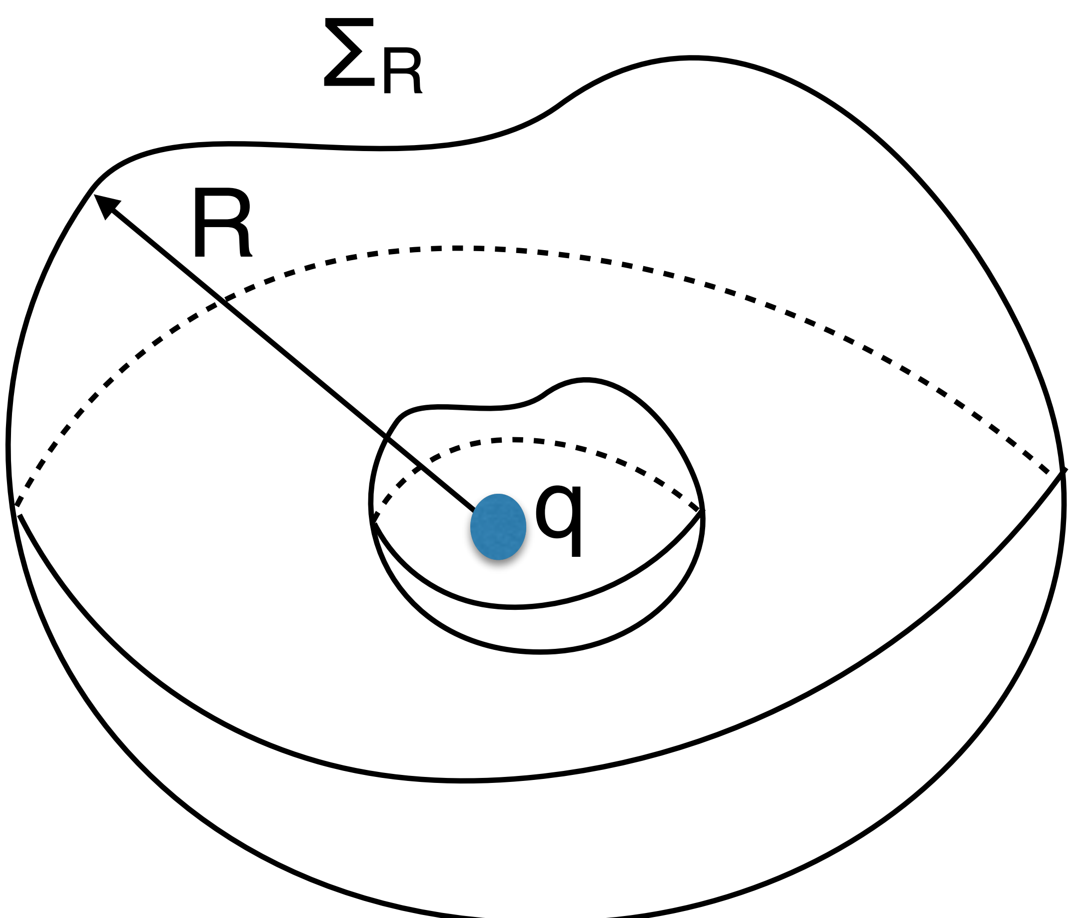

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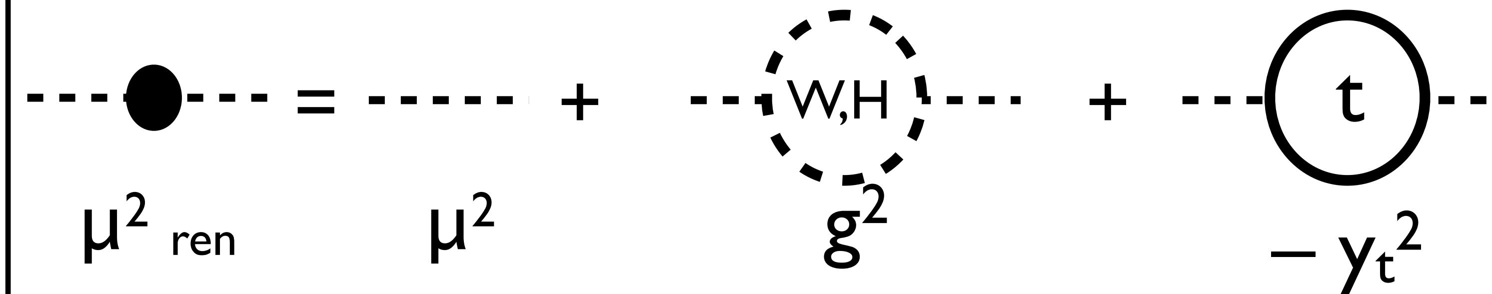

$\Delta\mu^2 \sim (c_W\, m_W^2 - c_t\, m_t^2) \times (\Lambda / v)^2$

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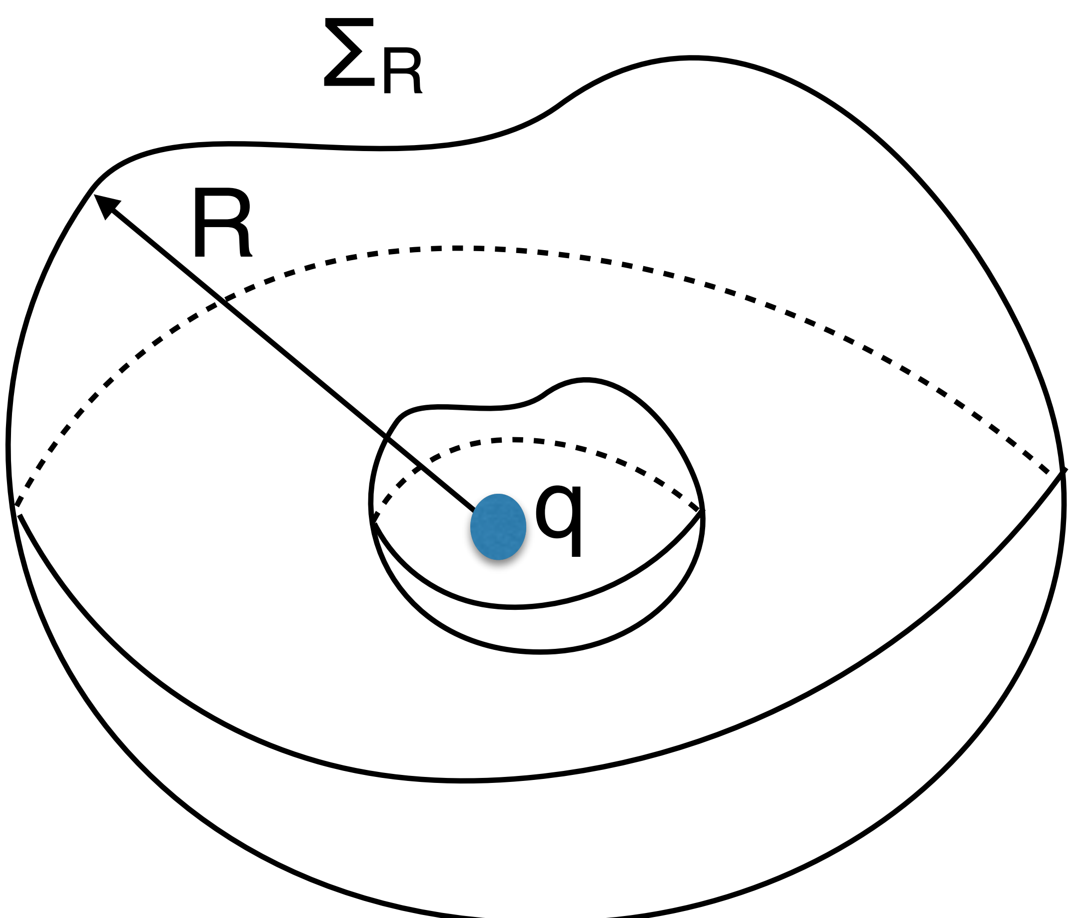

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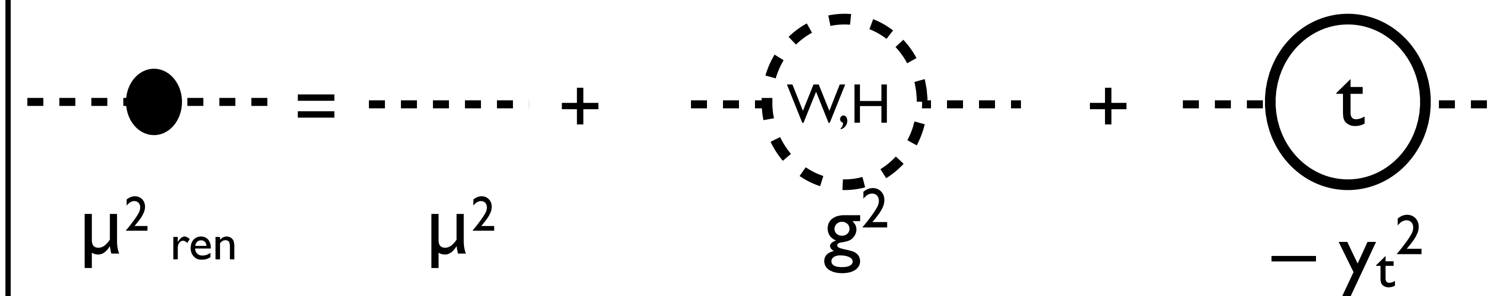

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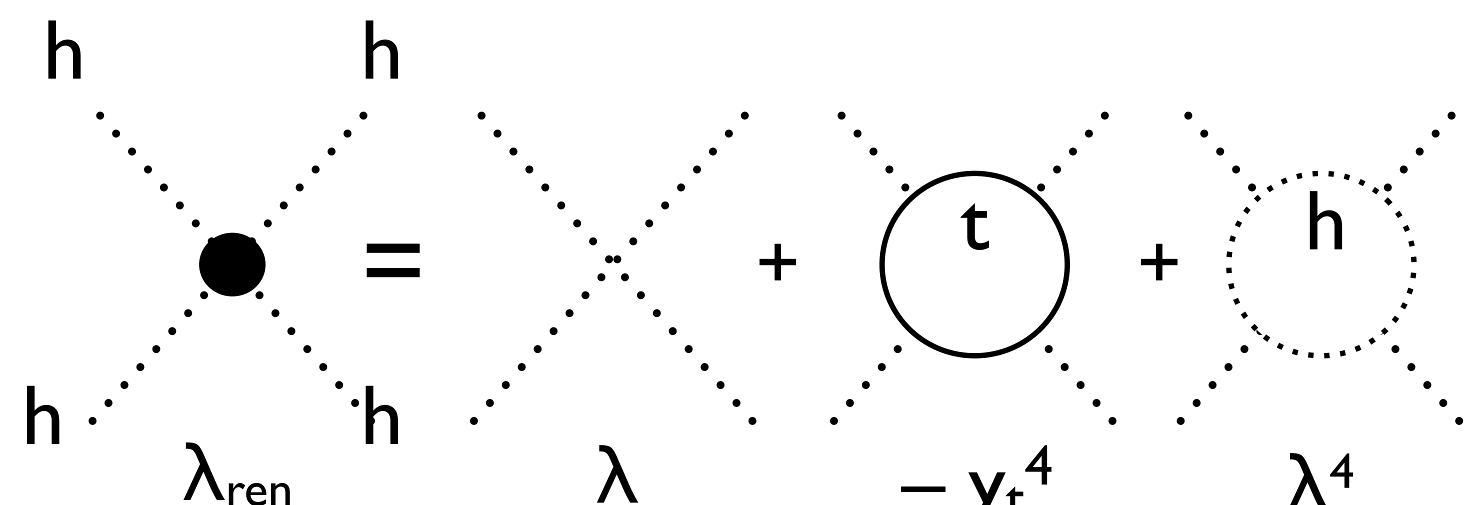

$\Rightarrow \dfrac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4 \quad \propto a\, m_H^4 - b\, m_t^4$

high-energy modes can change size and sign of both μ^2 and λ, dramatically altering the stability and dynamics

bottom line

- To predict the properties of EM at large scales, we don't need to know what happens at short scales
- The Higgs dynamics is sensitive to all that happens at any scale larger than the Higgs mass !!! A very unnatural **fine tuning** is required to protect the Higgs dynamics from the dynamics at high energy
- This issue goes under the name of **hierarchy problem**
- Solutions to the hierarchy problem require the introduction of new symmetries (typically leading to the existence of new particles), which decouple the high-energy modes and allow the Higgs and its dynamics to be defined at the "natural" scale defined by the measured parameters v and m_H

⇒ **naturalness**

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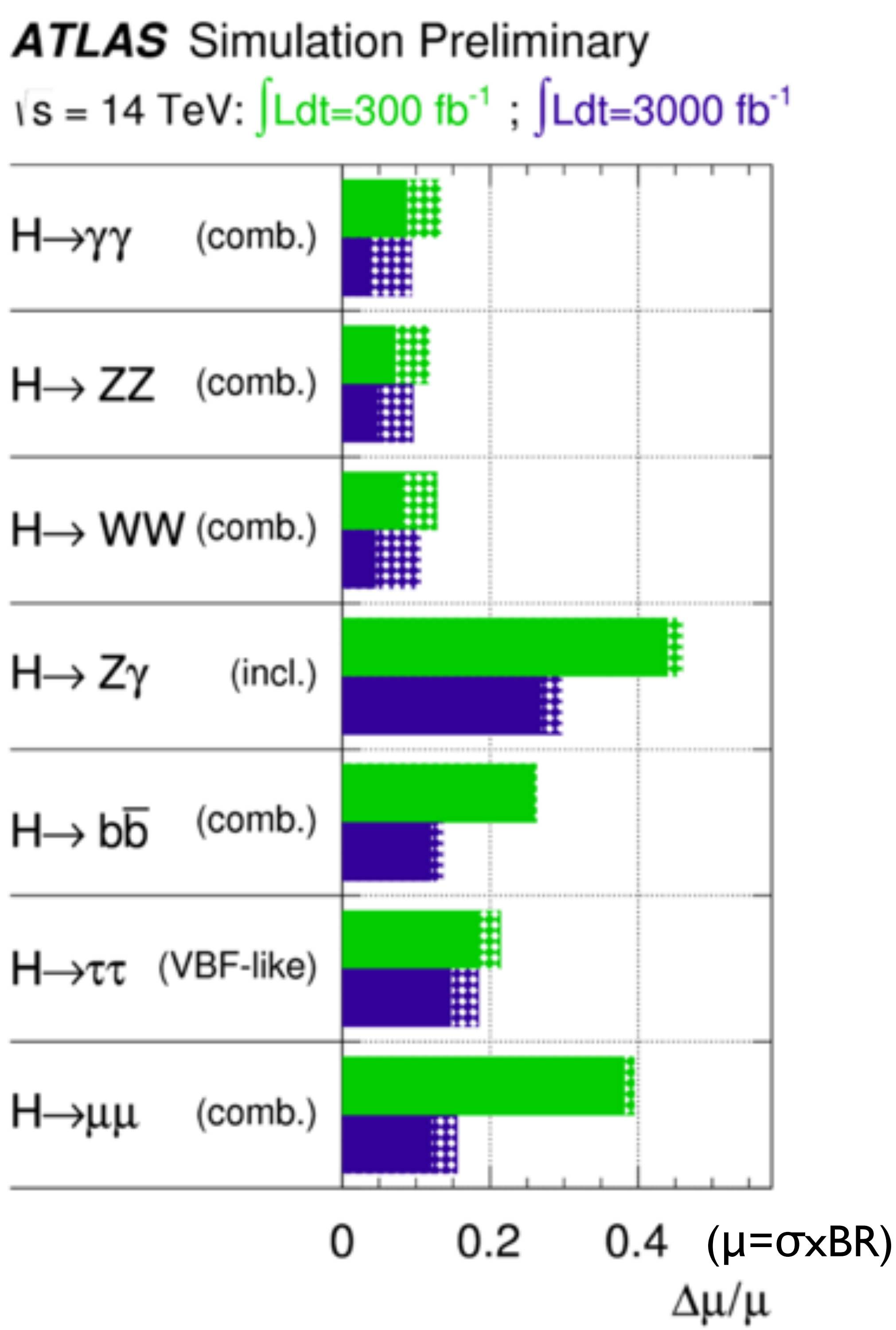
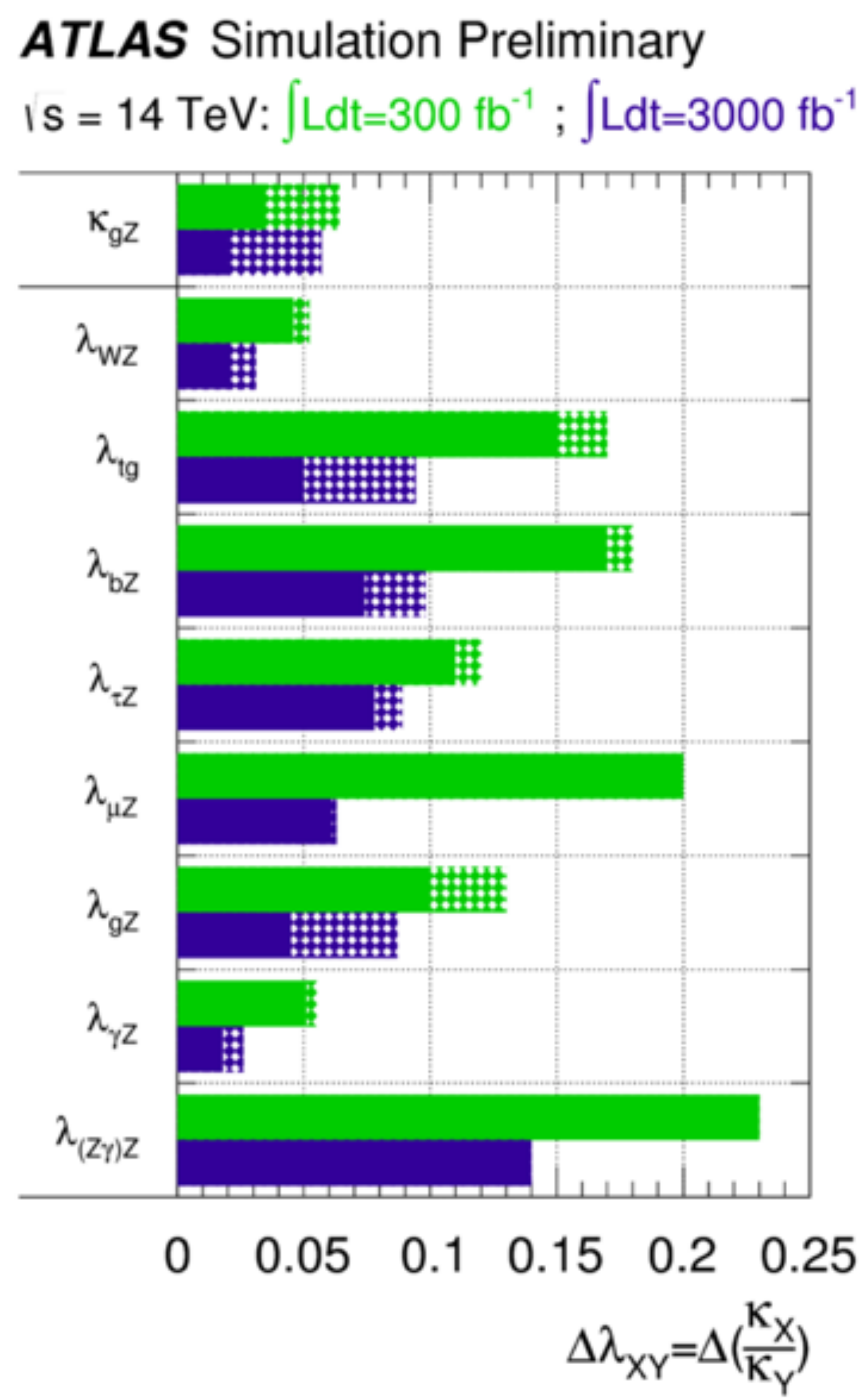
=> all this justifies the focus on the program of precision Higgs physics measurements

Projected precision on H couplings at HL-LHC

ATL-PHYS-PUB-2014-016

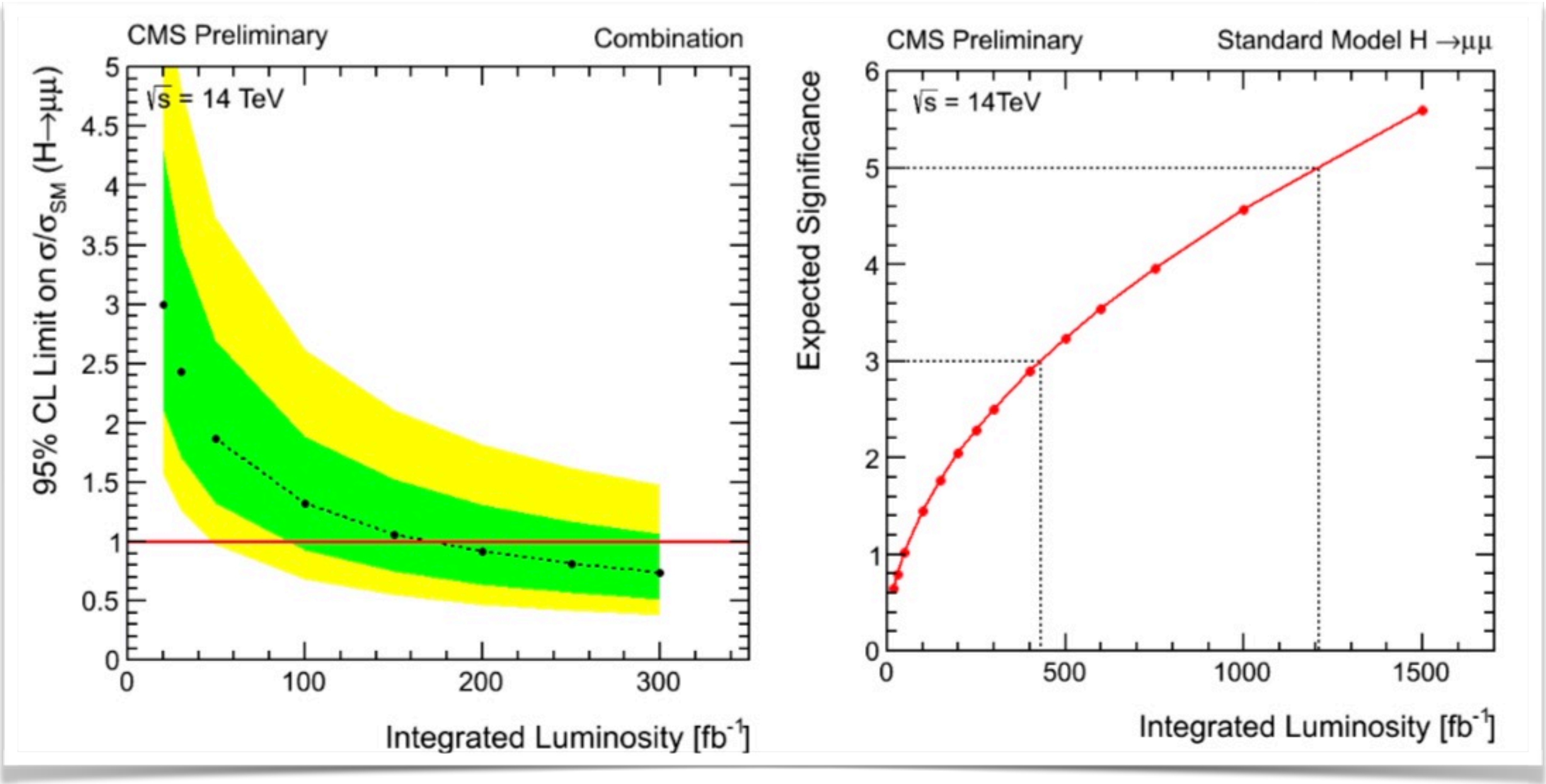




solid areas: no TH systematics

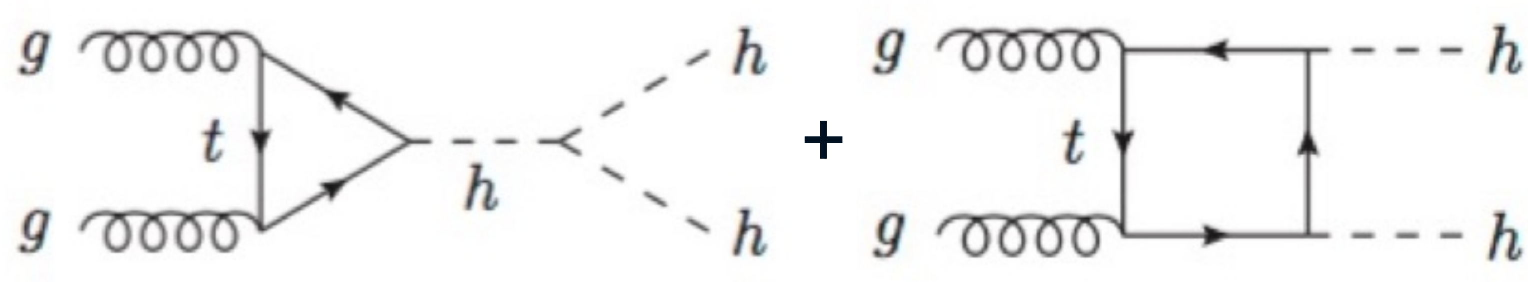
shaded areas: with TH systematics

H couplings to 2nd generation: the role of HL-LHC

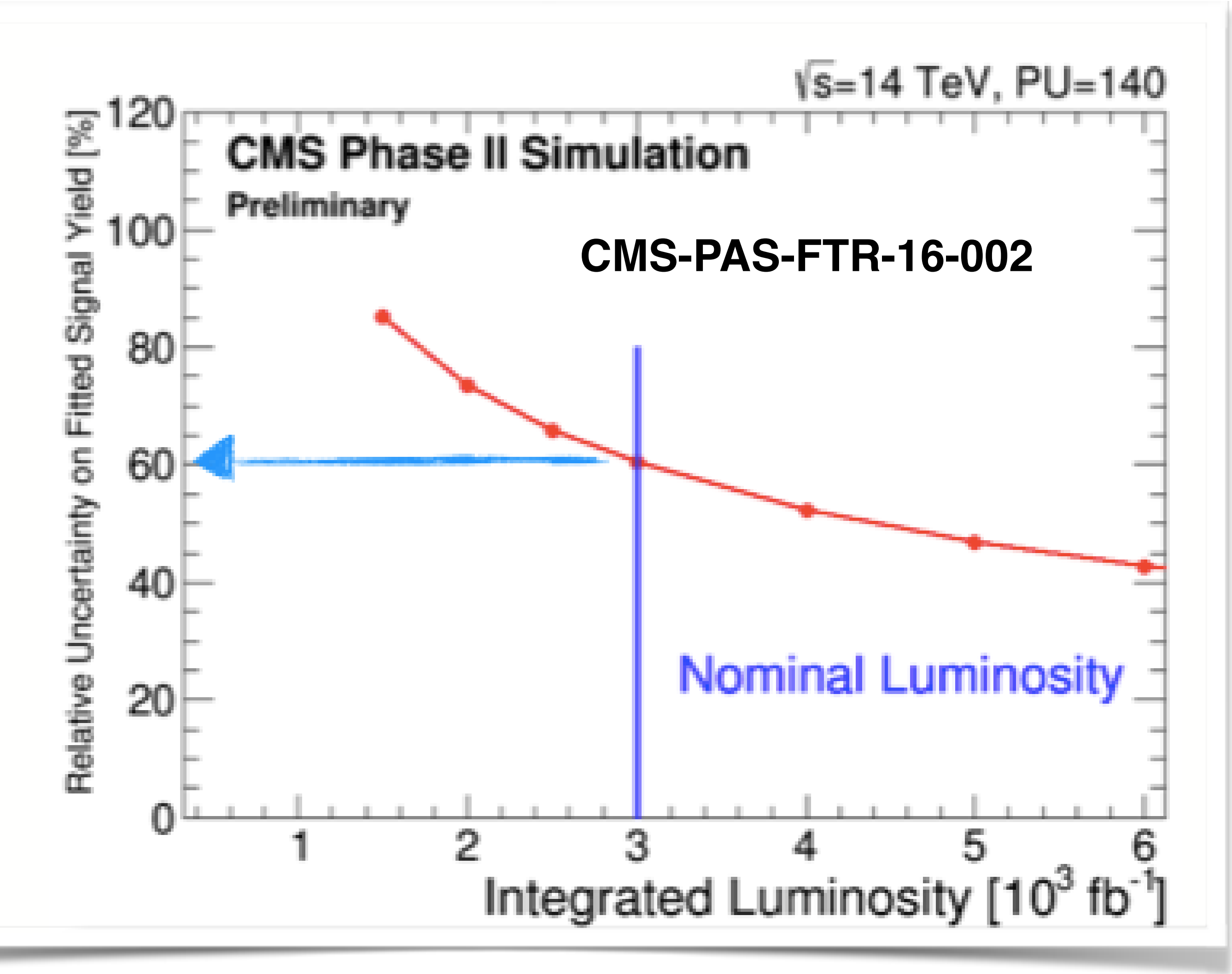


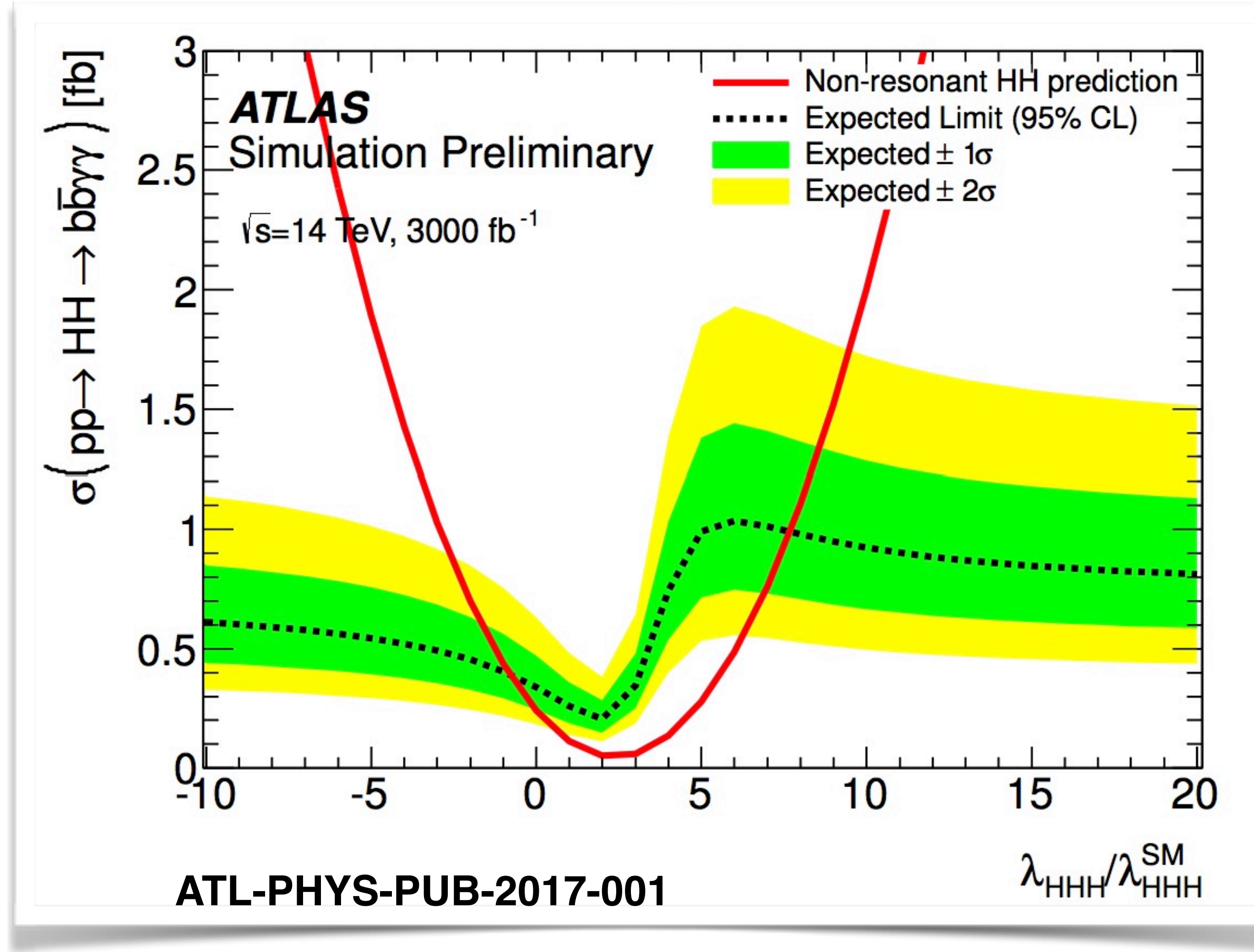
Projections from CMS-HIG-13-007

What will HL-LHC tells us about the Higgs potential?



- Strong negative interference between the two diagrams near threshold
- Selfcoupling diagram suppressed well above threshold, due to 1/S behaviour
- => it's hard!!





Barely 1-2σ evidence for Higgs pair production, but no quantitatively significant determination of λ: **$-0.8 < \lambda/\lambda_{SM} < 7.7$ @95%CL**

$-0.2 < \lambda/\lambda_{SM} < 2.6$
w. kinematical analysis

Higgs couplings @ FCC

g_{HXY}	ee [240+350 (4IP)]	pp [100 TeV] 30ab^{-1}	ep [60GeV/50TeV], 1ab^{-1}
ZZ	0.15%	<1%	
WW	0.19%		
bb	0.42%		0.2%
cc	0.71%		1.8%
gg	0.80%		
ττ	0.54%		
μμ	6.2%	<1%	
γγ	1.5%	<0.5%	
Zγ		<1%	
tt	~13%	1%	
HH	~30%	3.5%	under study
uu,dd	H->ργ, under study		
ss	H->φγ, under study		
BR_{inv}	< 0.45%	few 10^{-4}	
Γ_{tot}	1%		

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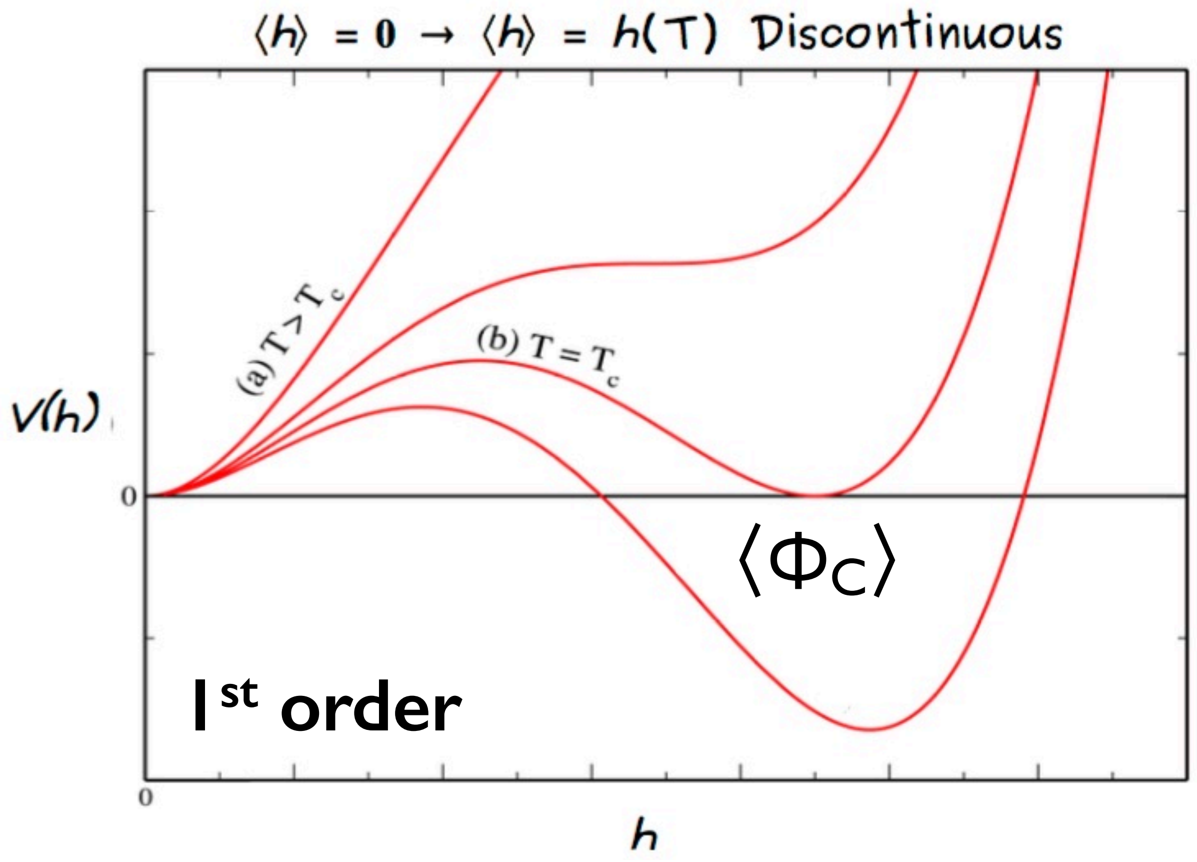
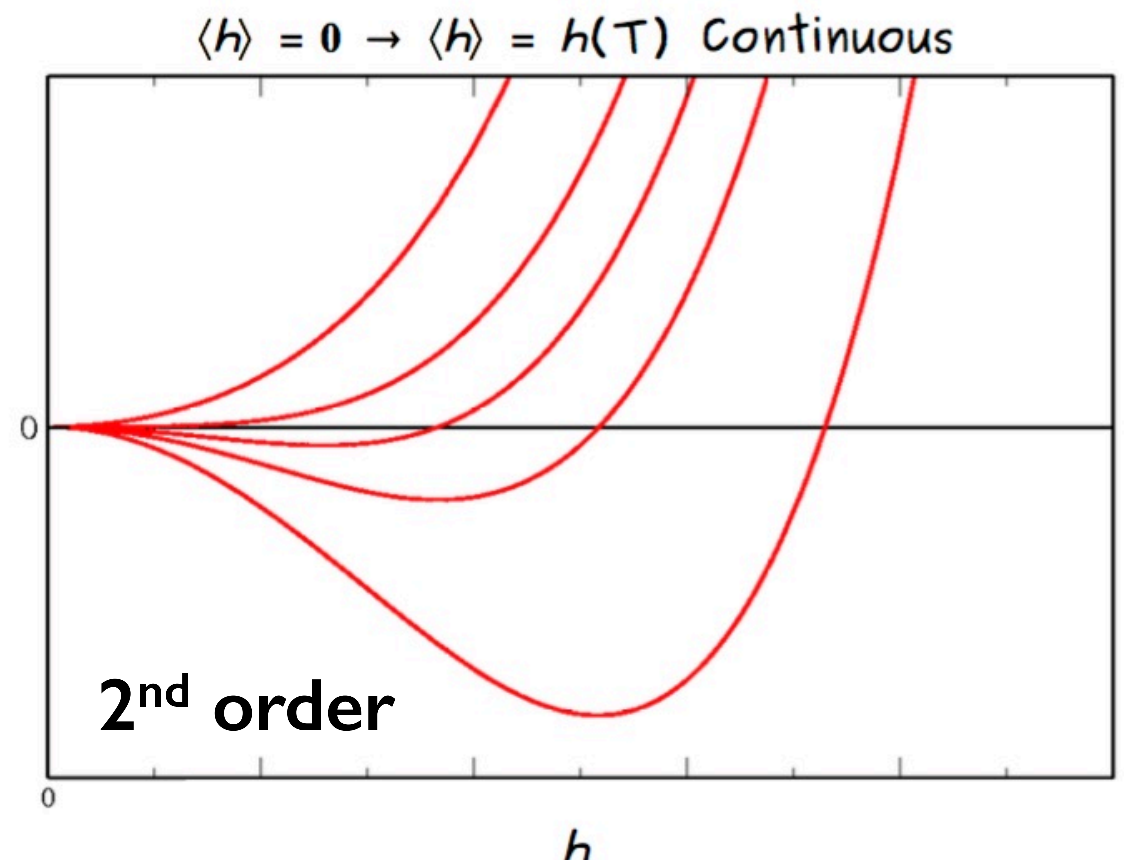
- Is there a deep reason for the apparent metastability of the Higgs vacuum?

The nature of the EW phase transition





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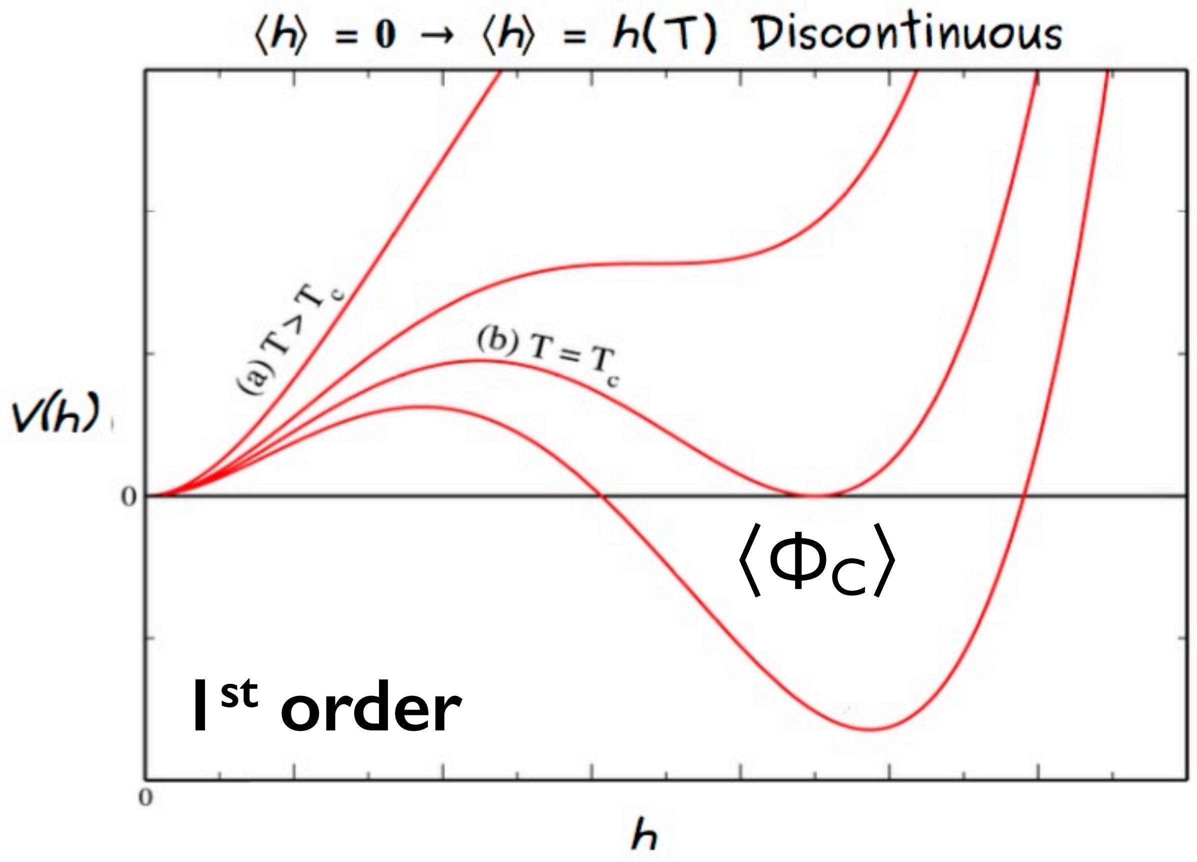

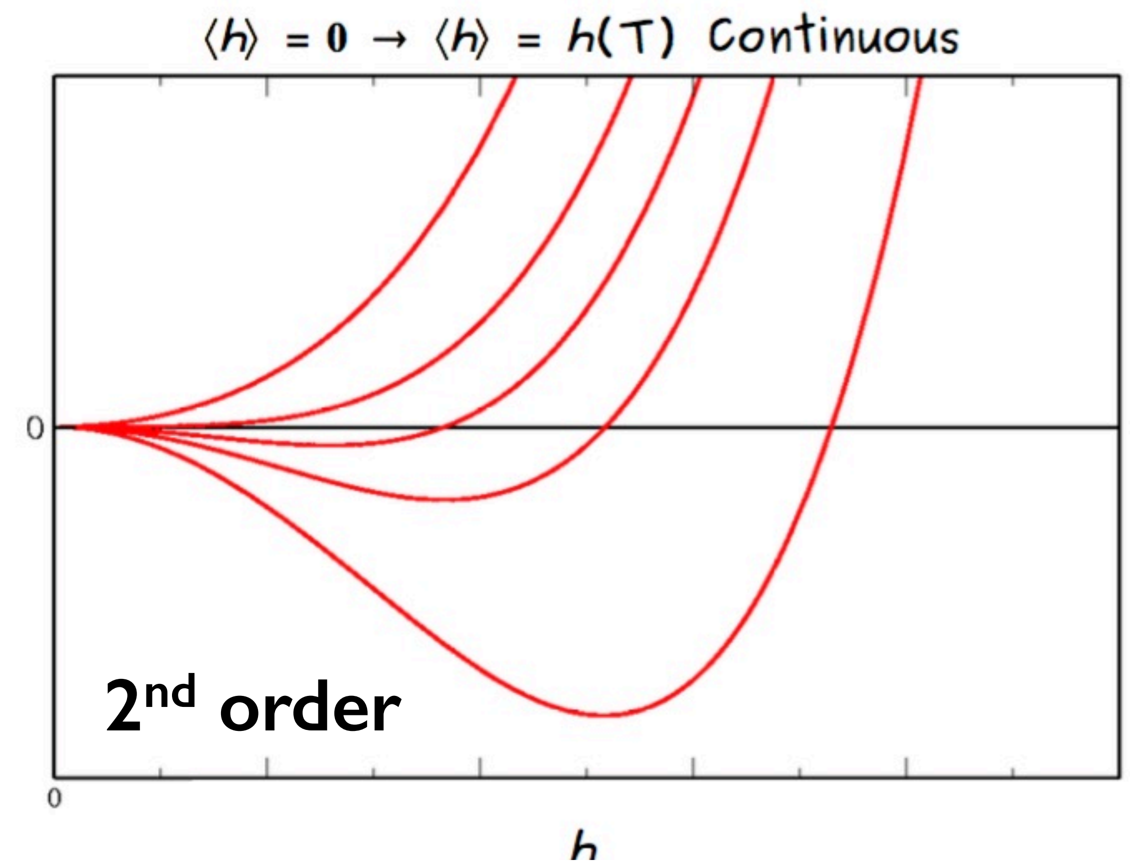

Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

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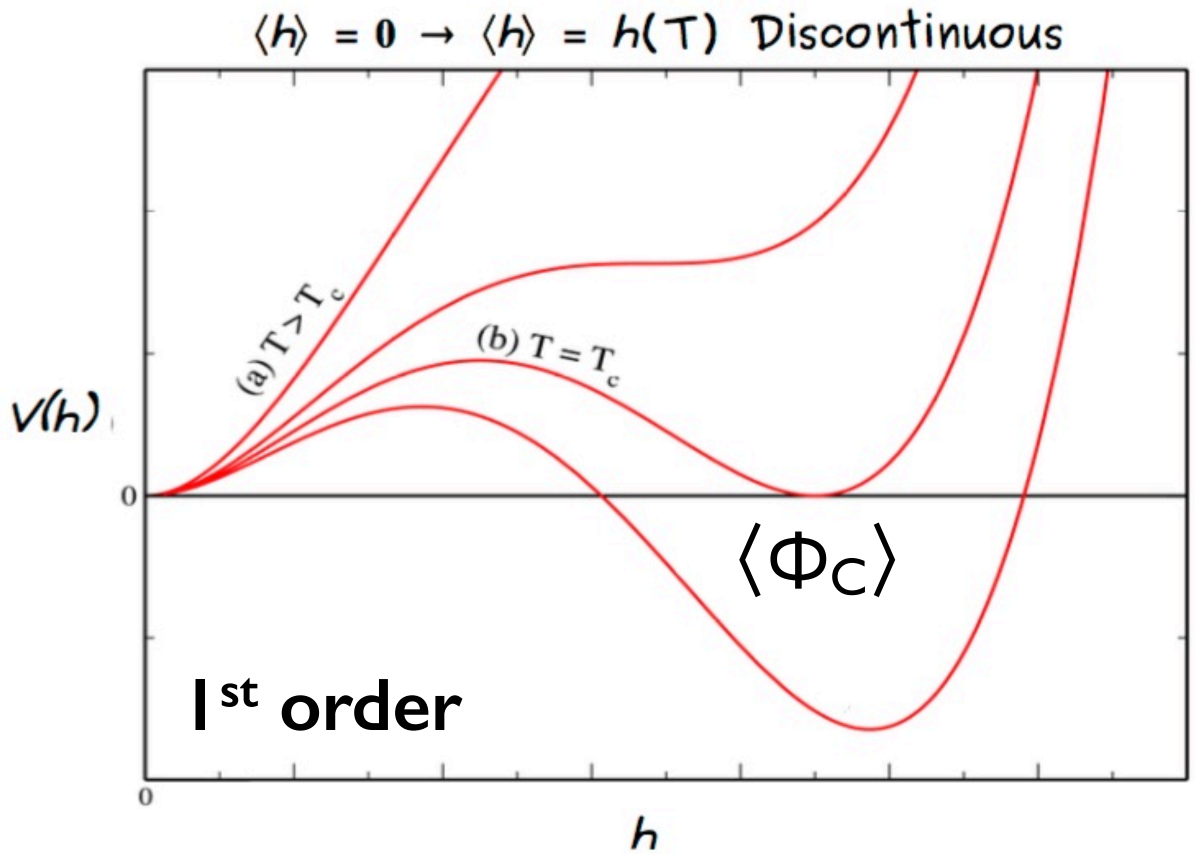

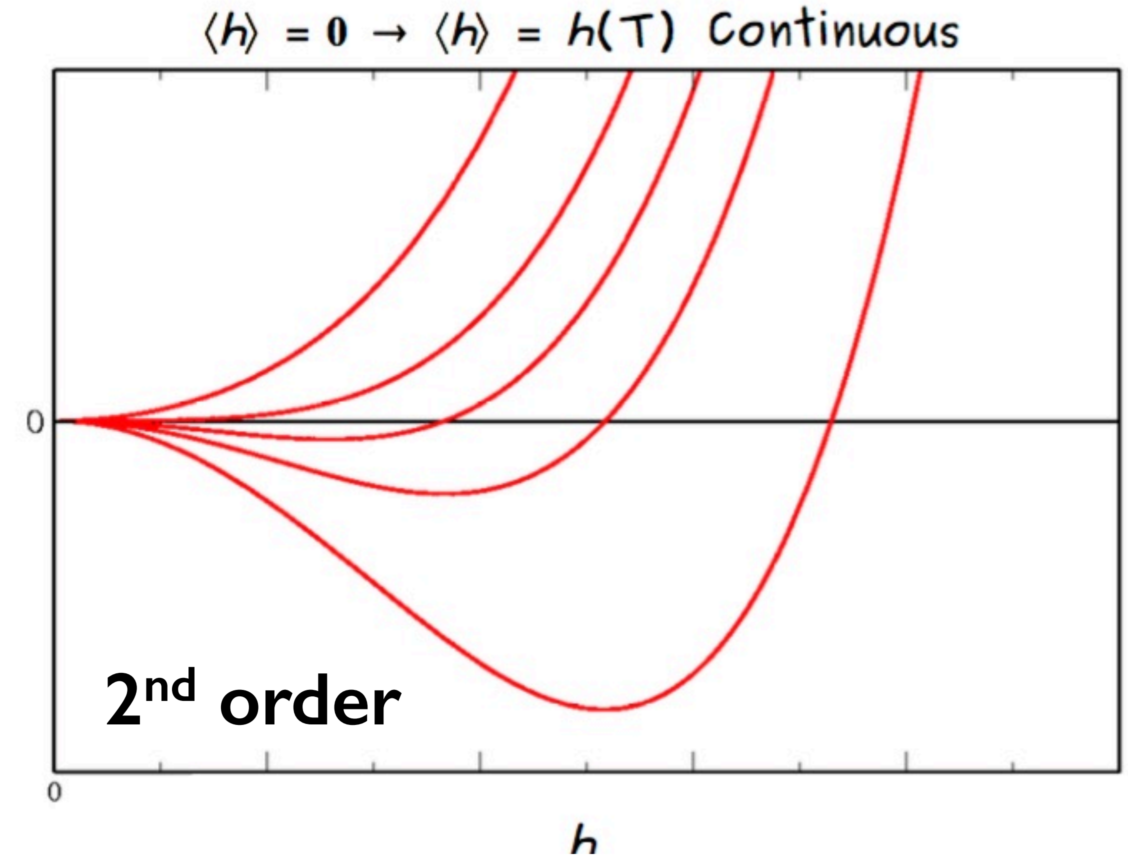

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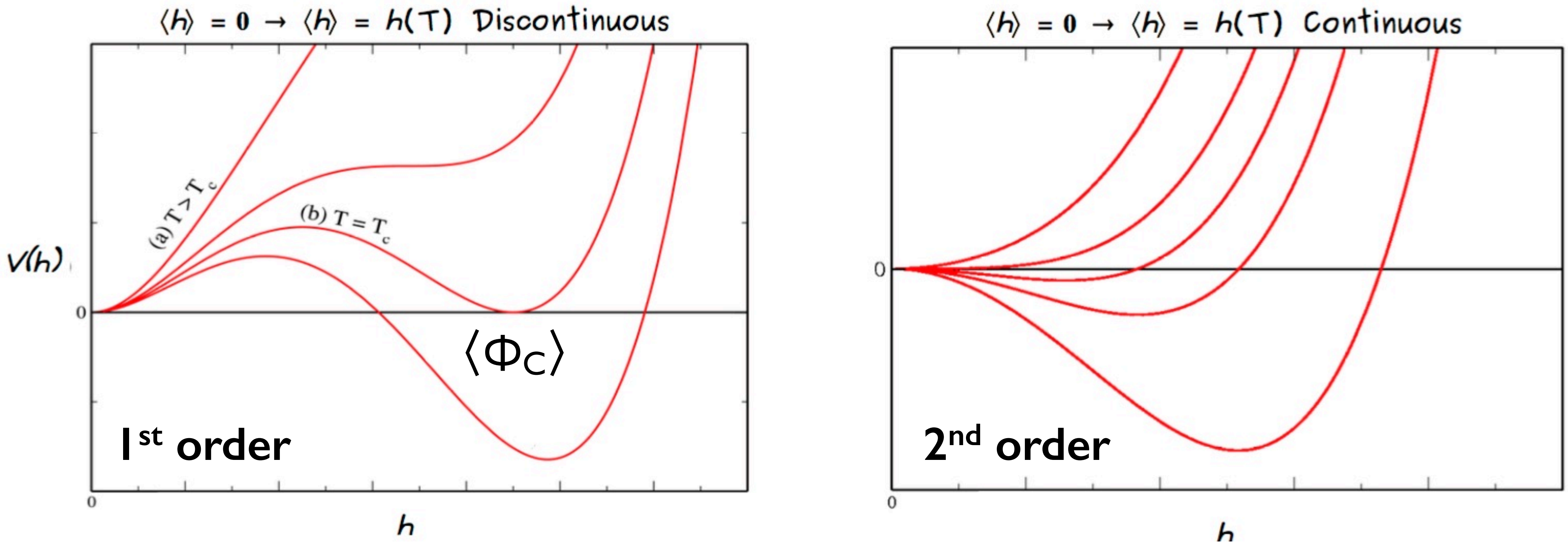

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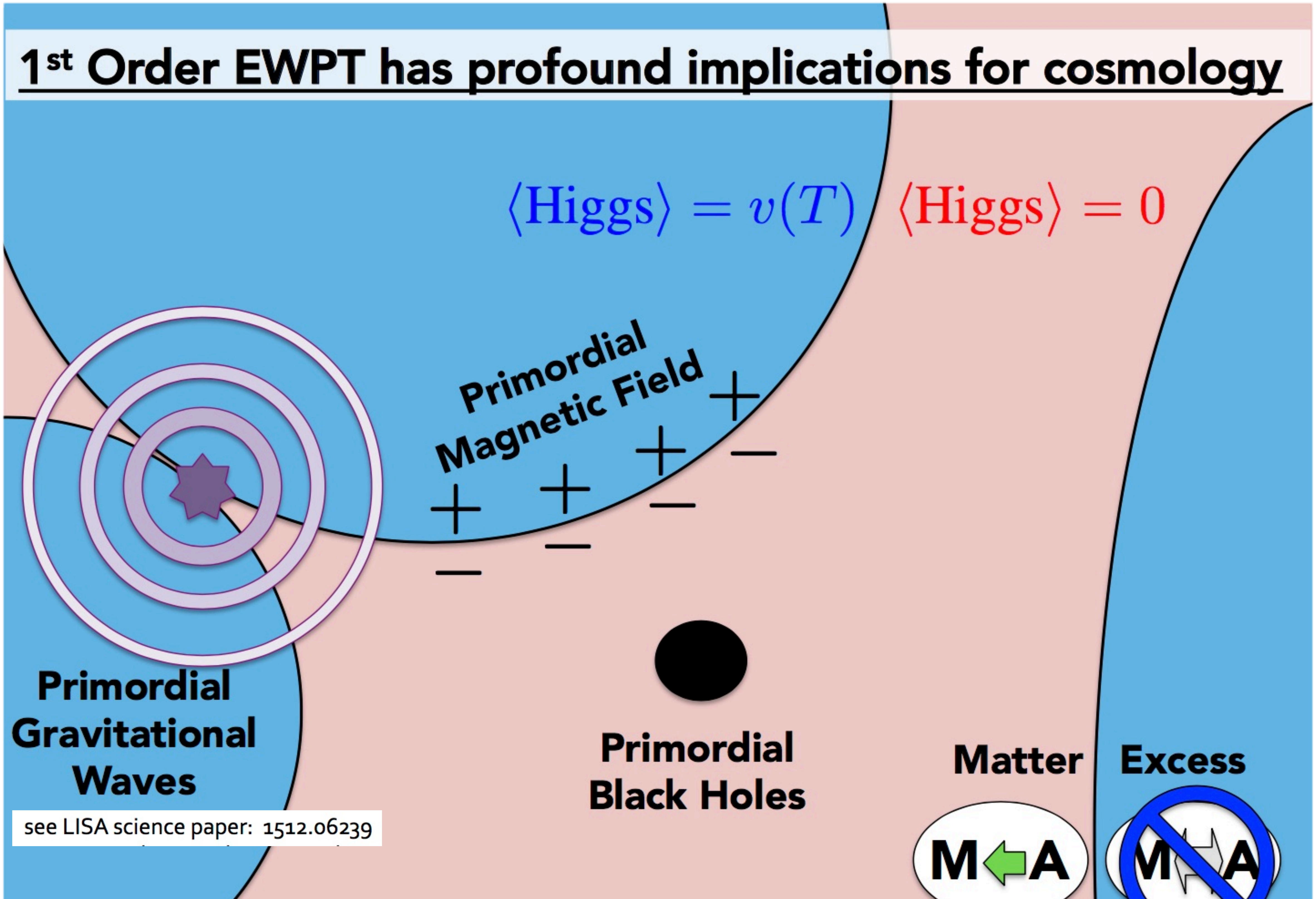
Since $m_H = 125$ GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

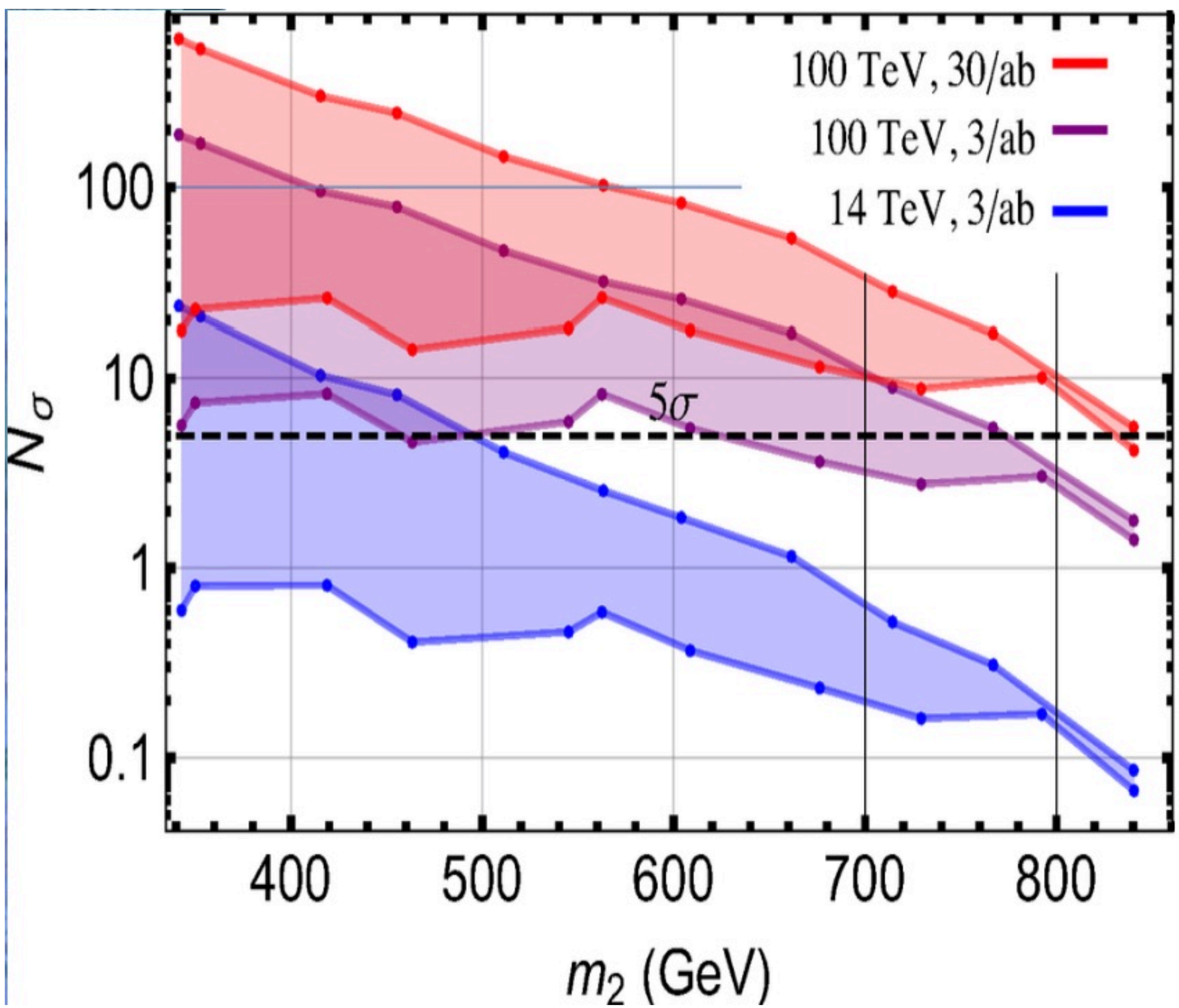
- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**



Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254

Sensitivity to extra Higgs bosons enabling a 1st order EWPT

$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$



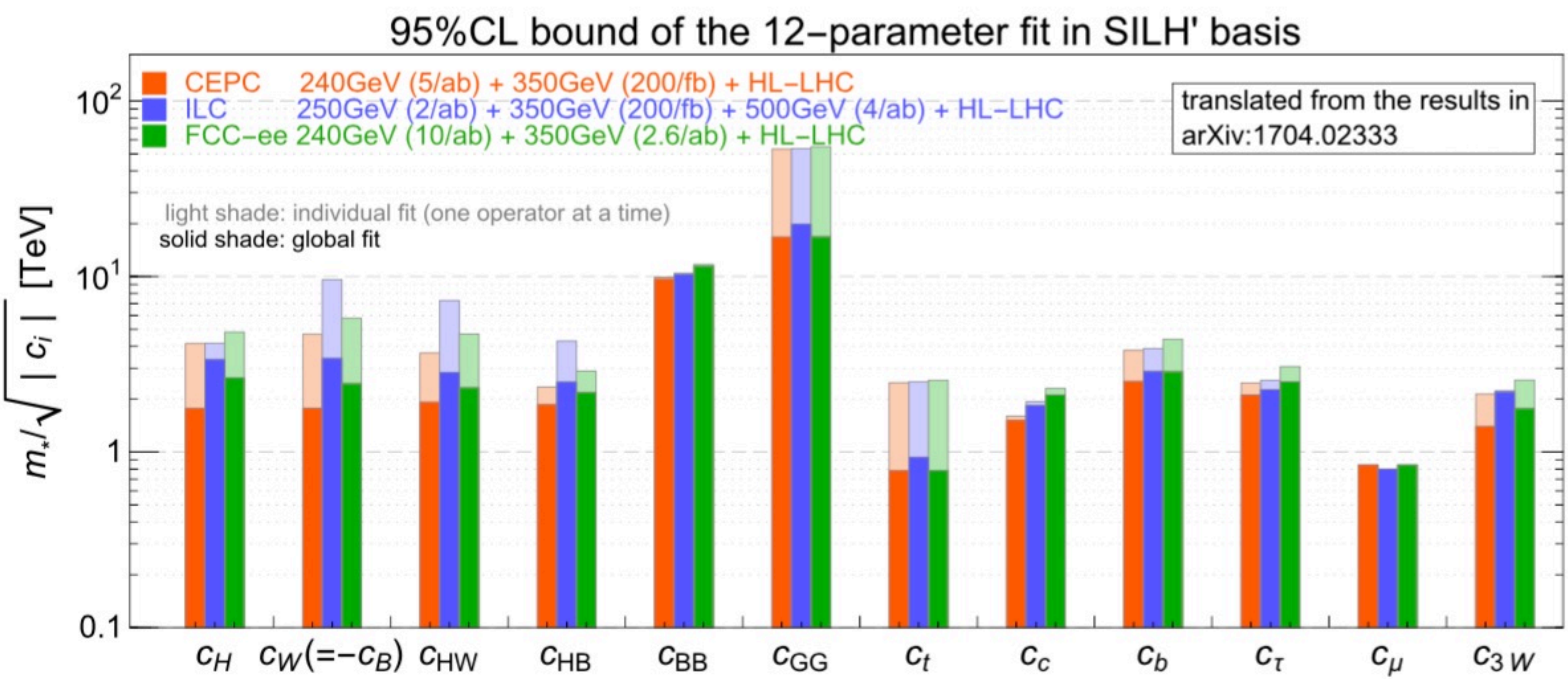
Notice role of energy and of luminosity

Kotwal, No, Ramsey-Musolf, Winslow, arXiv:1605.06123

Direct and indirect sensitivity to the largest mass scales: examples

Indirect sensitivity to new mass scales via Higgs and EW precision measurements in e^+e^-

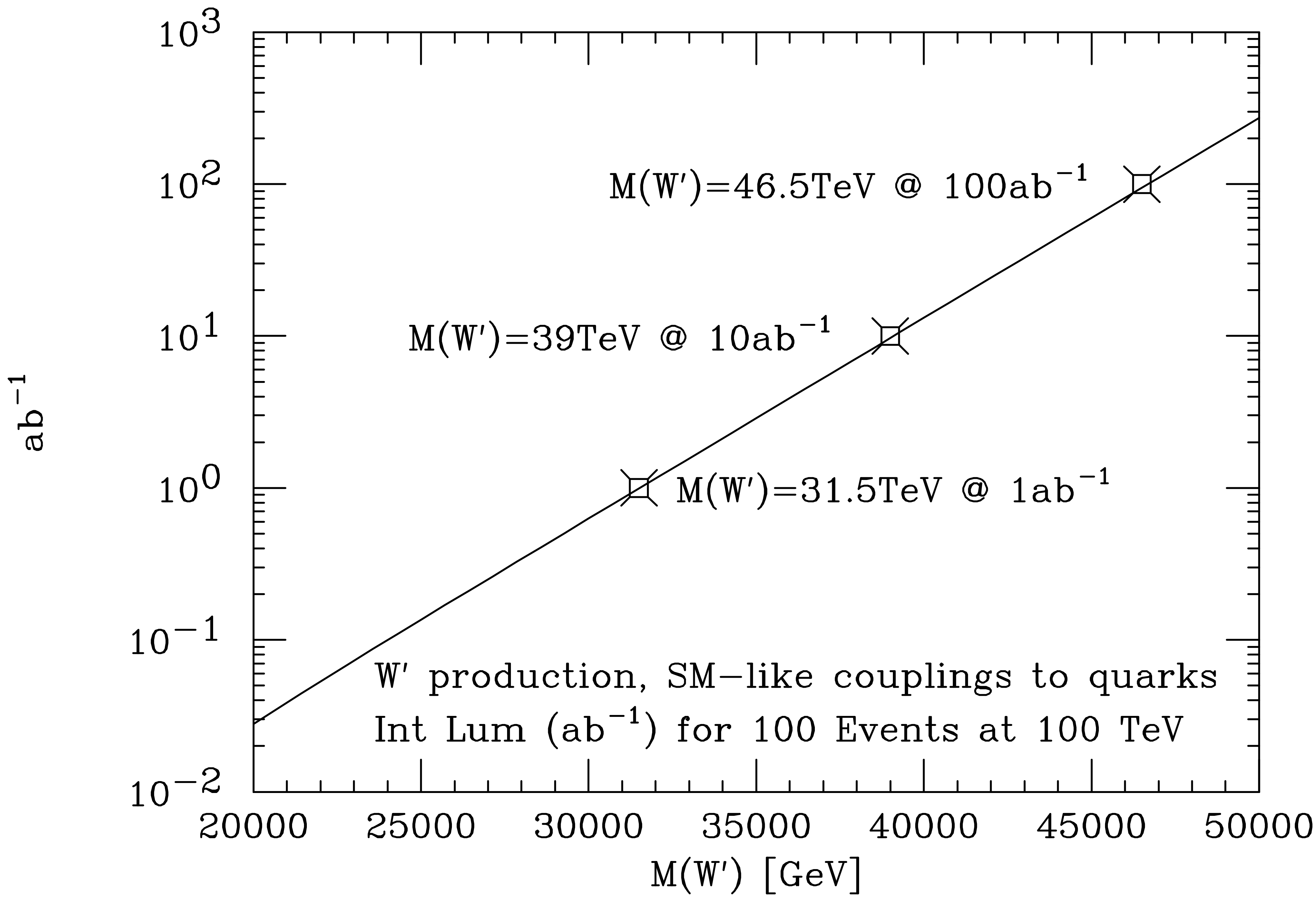
[arXiv:1709.06103] J. Gu, H. Li, Z. Liu, S. Su, W. Su



New gauge bosons discovery reach

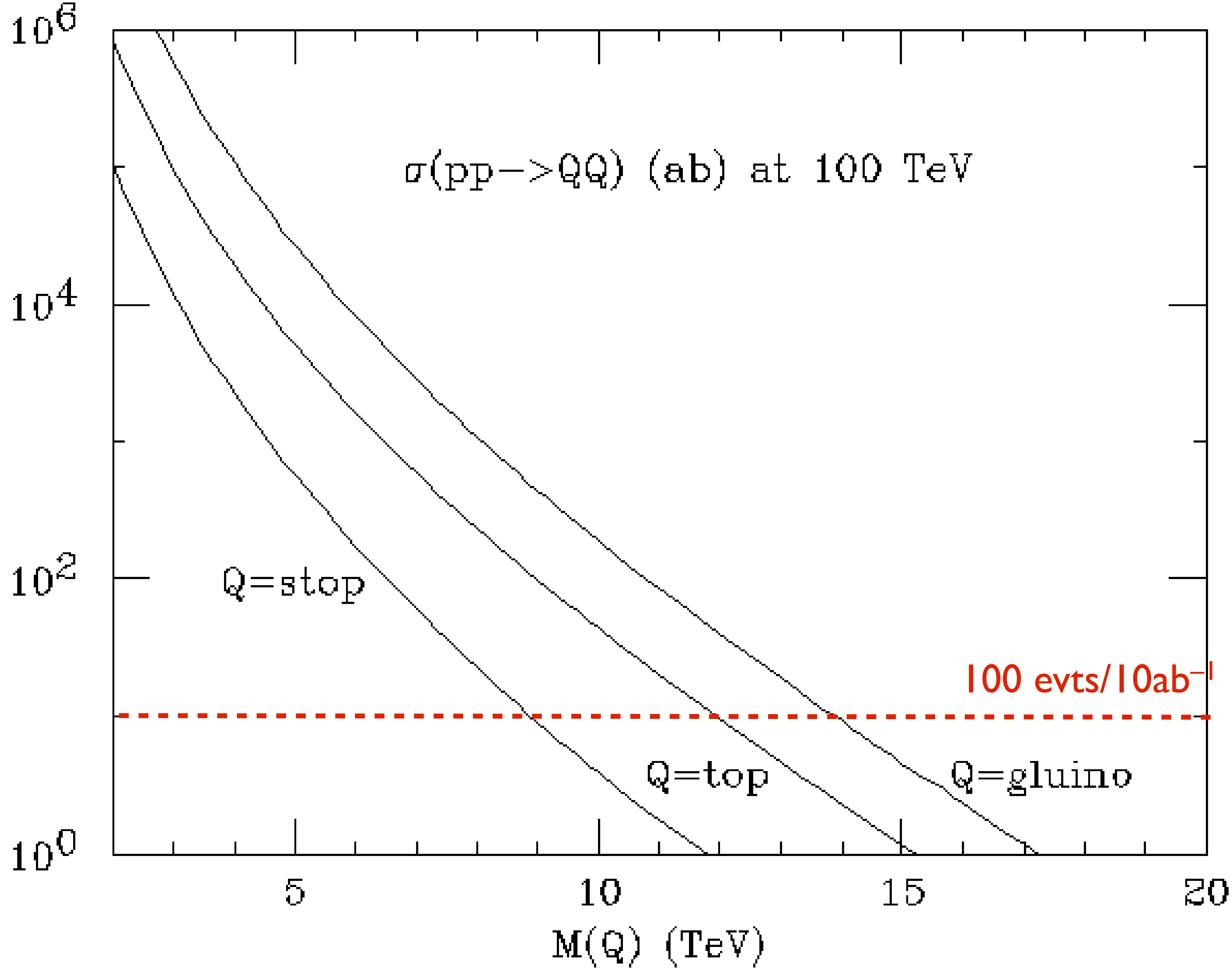
Example: **W' with SM-like couplings**

NB For SM-like Z', $\sigma_{Z'} BR_{lept} \sim 0.1 \times \sigma_{W'} BR_{lept}$, ⇒ rescale lum by ~ 10



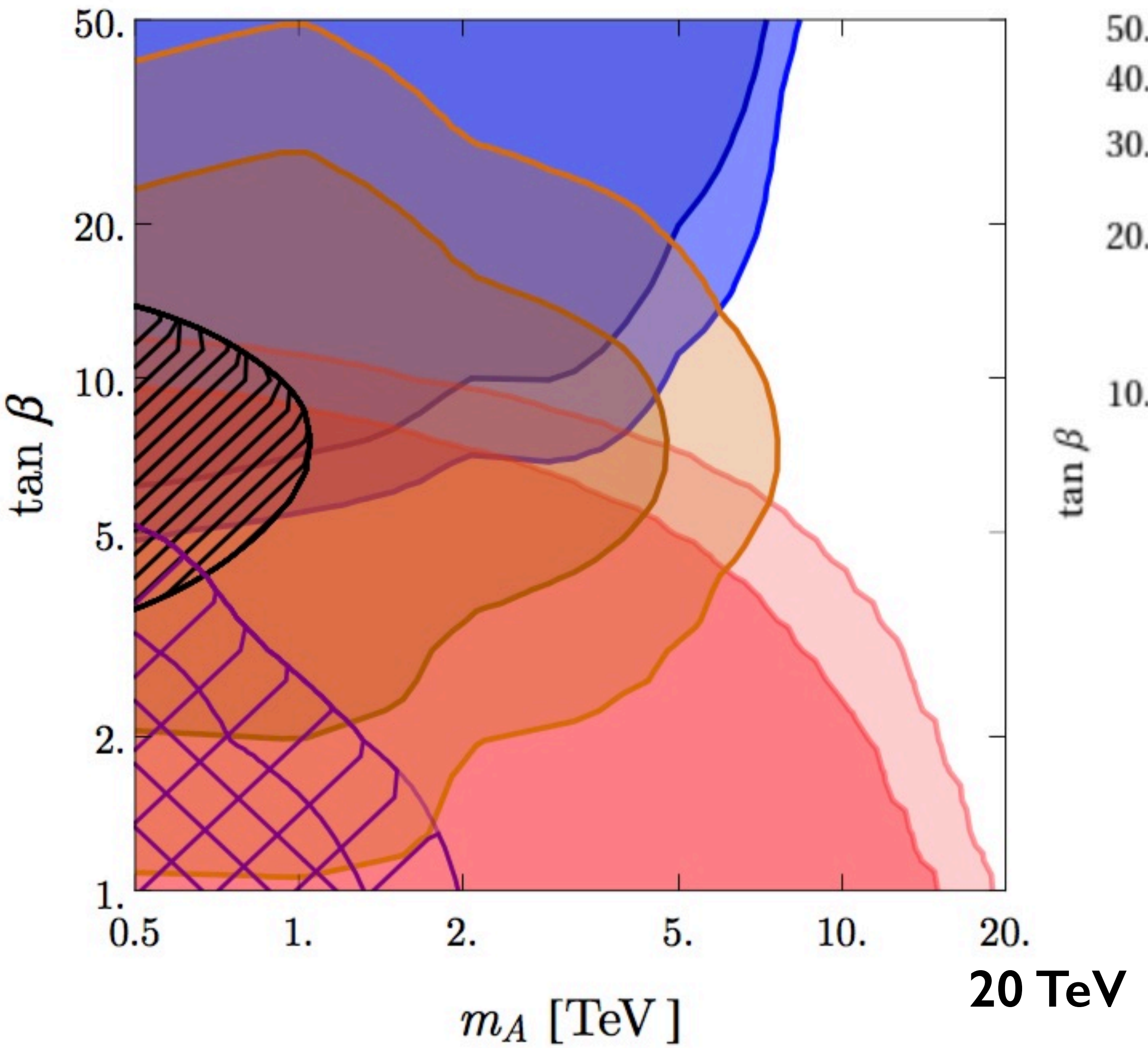
At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV

Discovery reach for pair production of strongly-interacting particles

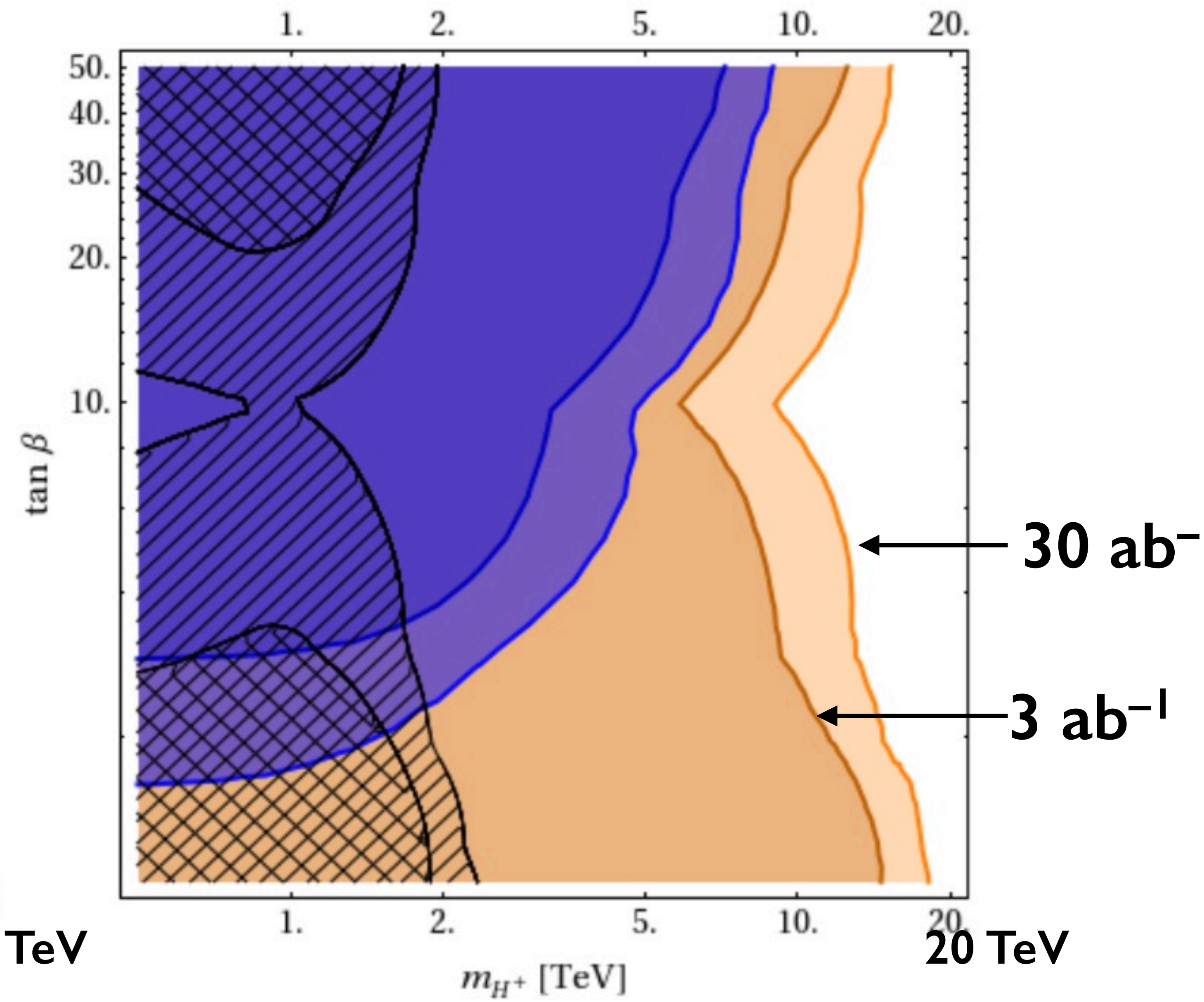


MSSM Higgs @ 100 TeV

- $bbH^0/A^0 \to bb\tau\tau$
- $bbH^0/A^0 \to bbtt$
- $t(t)H^0/A^0 \to t(t)tt$



- $tbH^+ \to tb\tau\nu$
- $tbH^+ \to tbtb$
- LHC 3 ab^{-1}
- LHC 0.3 ab^{-1}



N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang, arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

Bottom line

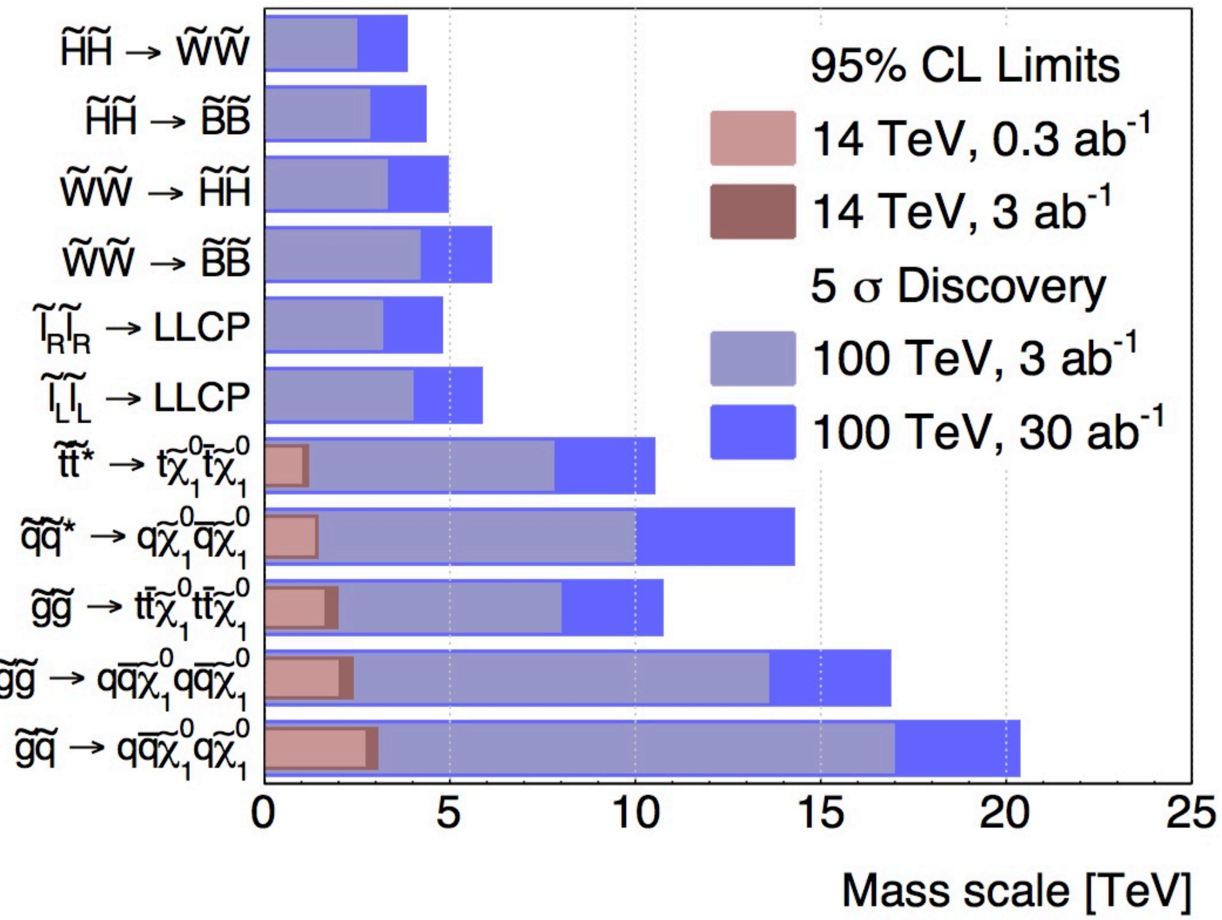
- energy and luminosities of the ee&pp components of the FCC programme are well matched, to synergistically cover similar mass scales in complementary ways

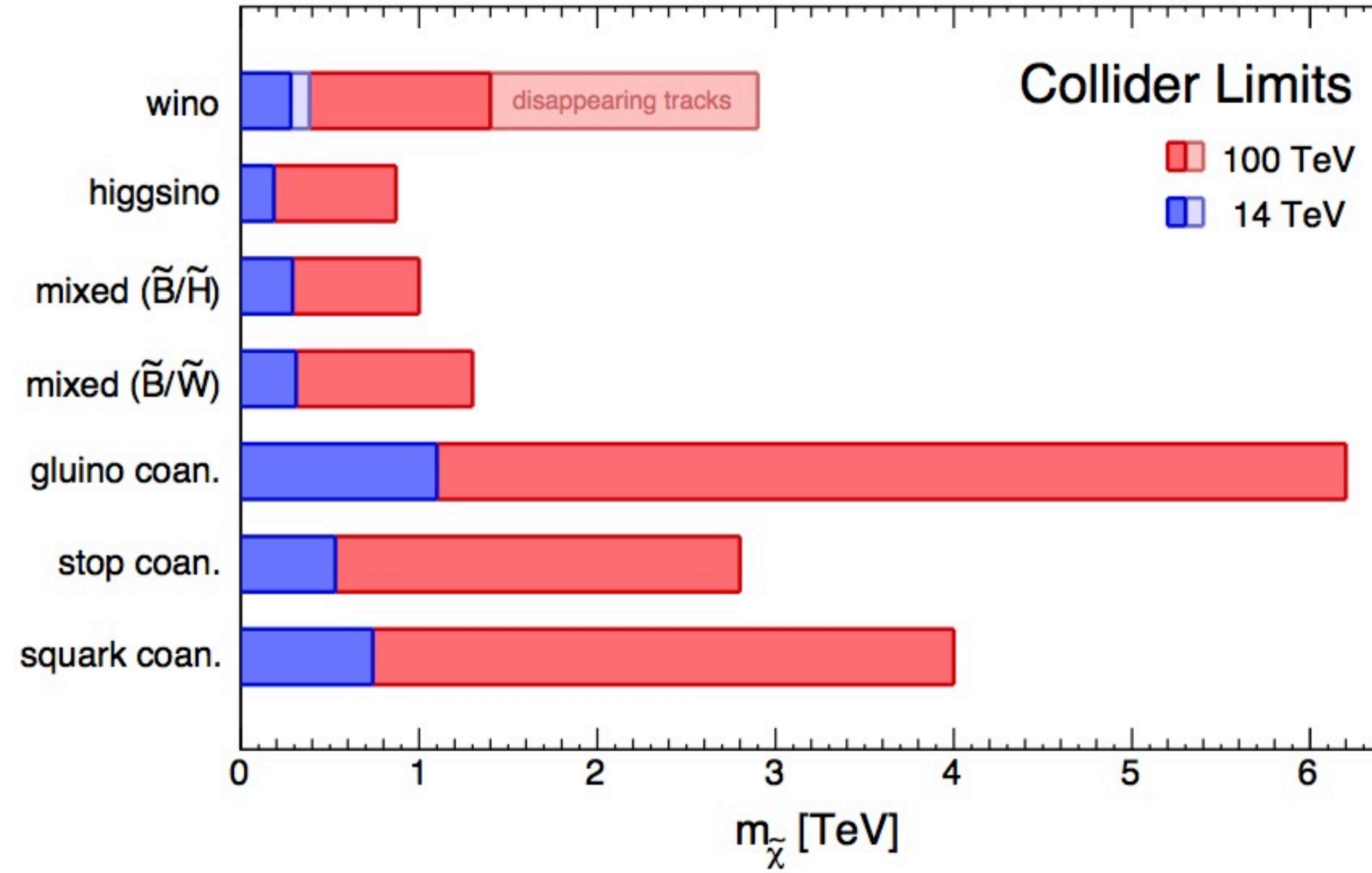
Examples: conclusive yes/no answers

Dark Matter

- DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).
- More in general, no experiment can guarantee an answer to the question ”what is DM?”
- Scenarios in which DM is a WIMP are however compelling and theoretically justified
- **We would like to understand whether a future collider can answer more specific questions, such as:**
  - do WIMPS contribute to DM?
  - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders? Is there sensitivity to the explicit detection of DM-SM mediators?
  - what are the opportunities w.r.t. new DM scenarios (e.g. interacting DM, asymmetric DM, ...)?

SUSY and DM reach at 100 TeV

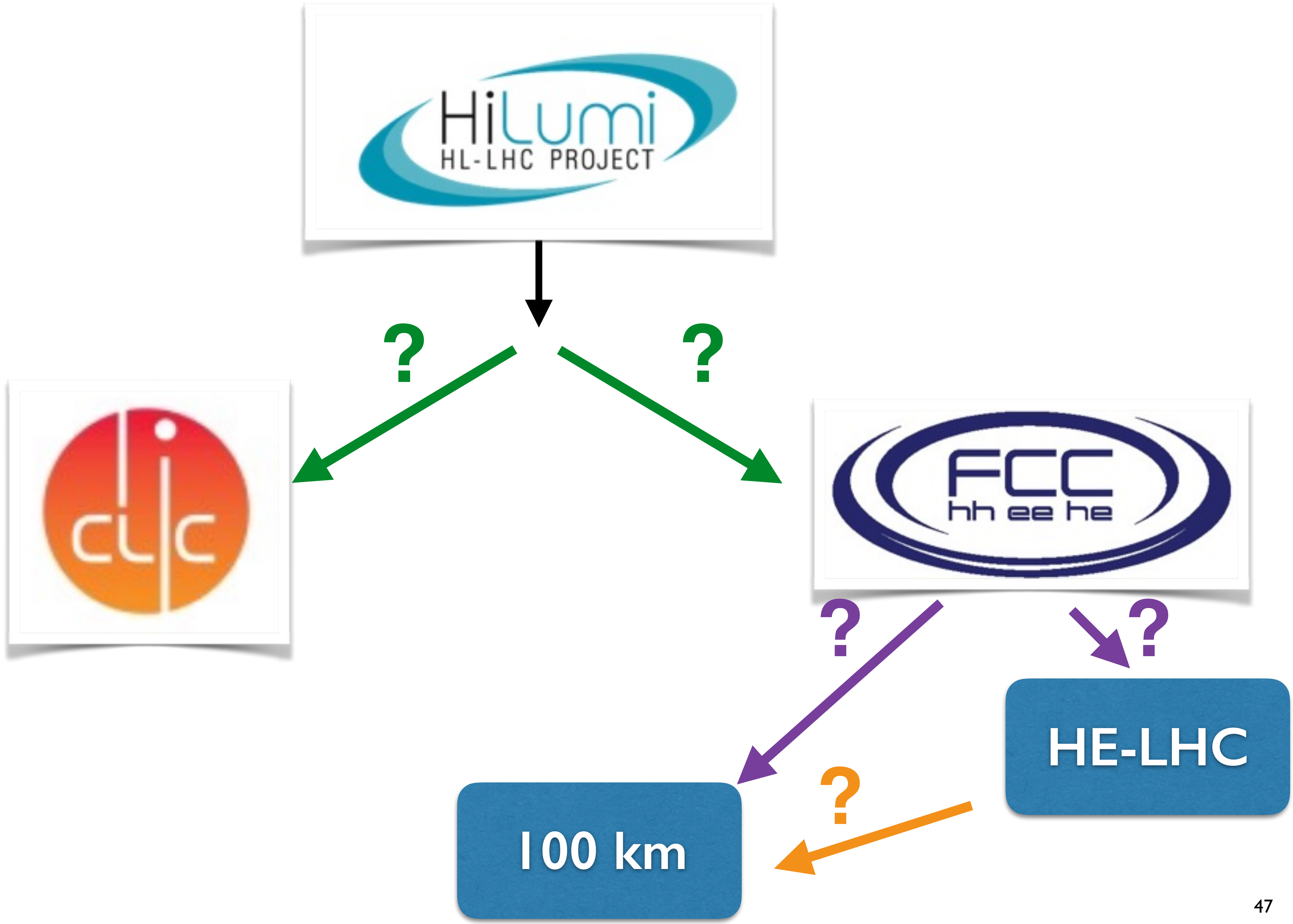




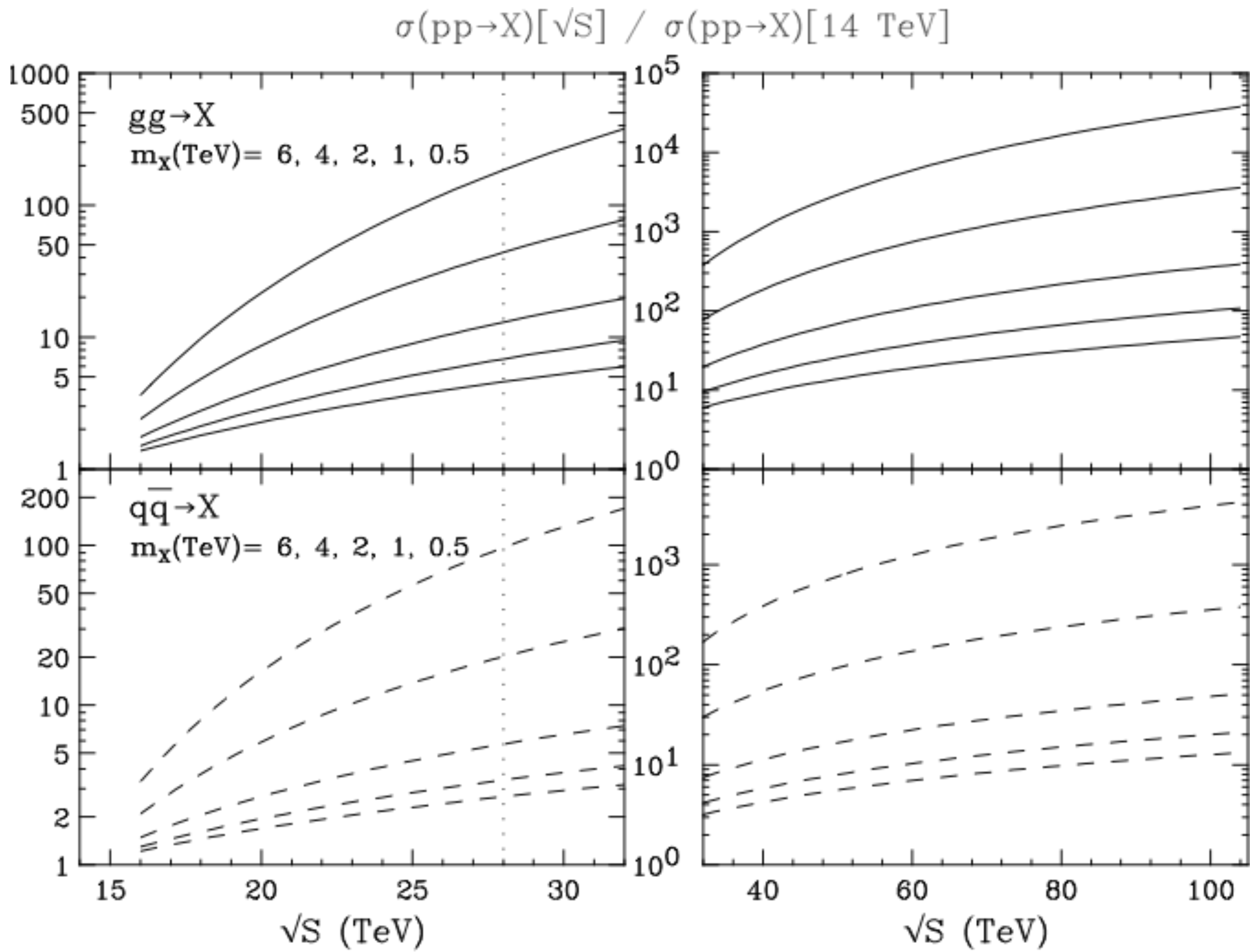
$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

possibility to find (or rule out) thermal WIMP DM candidates

Possible paths for CERN



Evolution, with beam energy, of scenarios with the discovery of a new particle at the LHC



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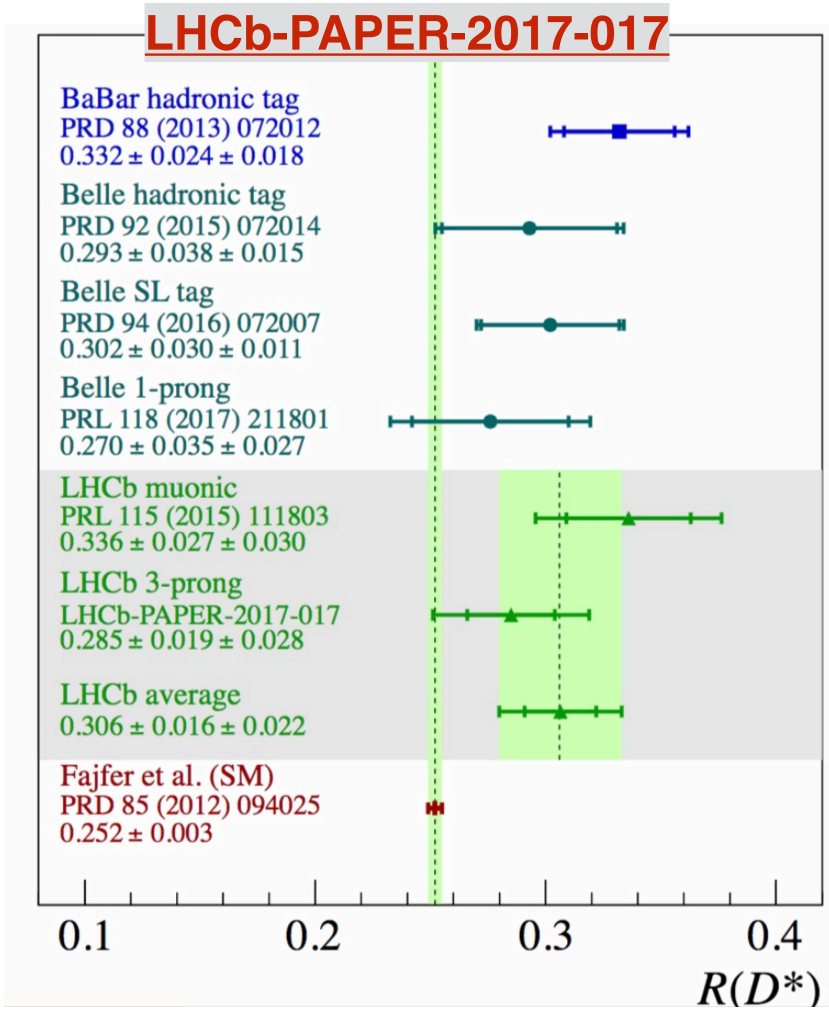
- etc.etc.

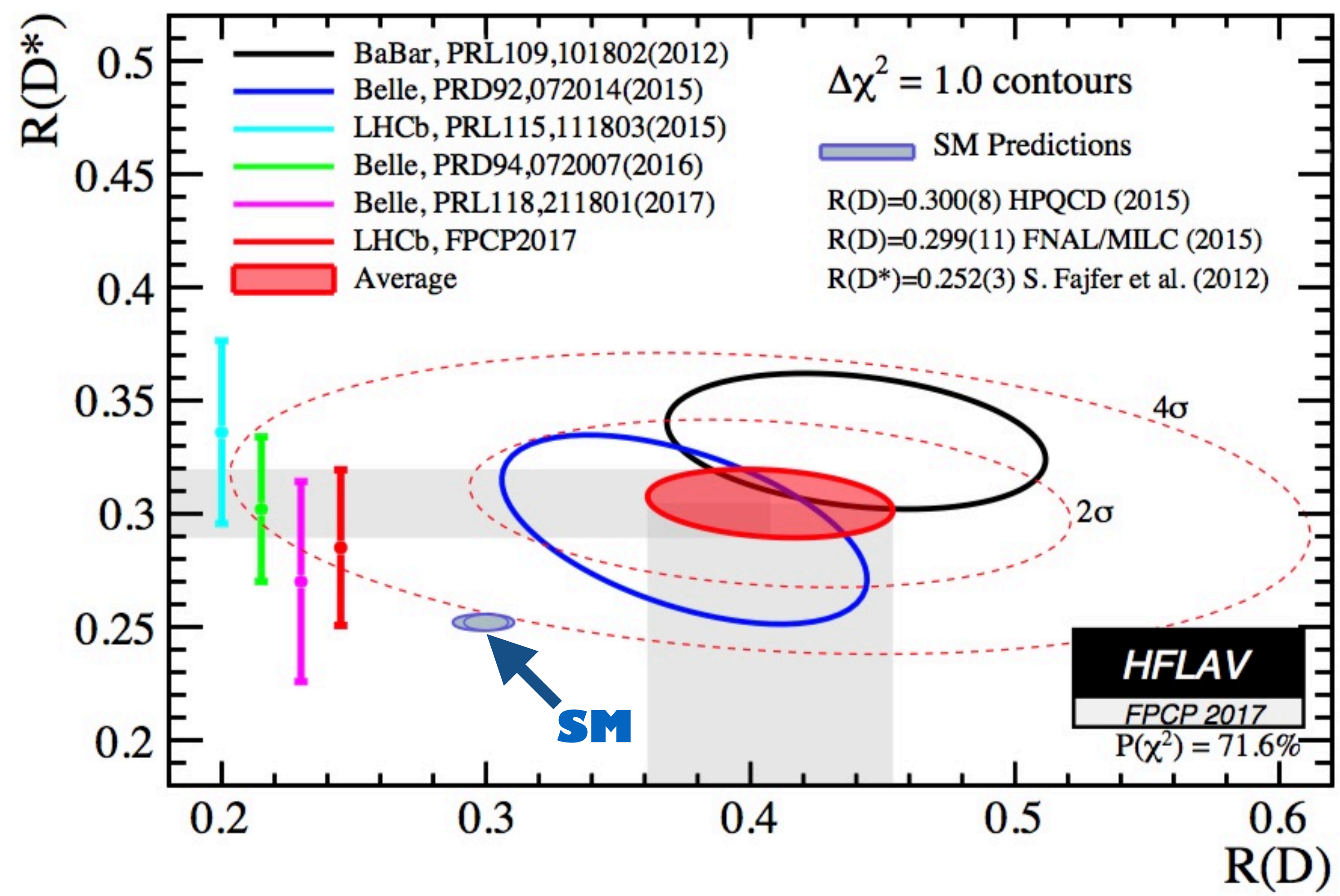
Flavour anomalies at LHC & Bfact's

b→cℓν

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\mu\nu)}$$

Overall combination of R(D) and R(D*) is 4.1σ from SM





b→sℓℓ

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

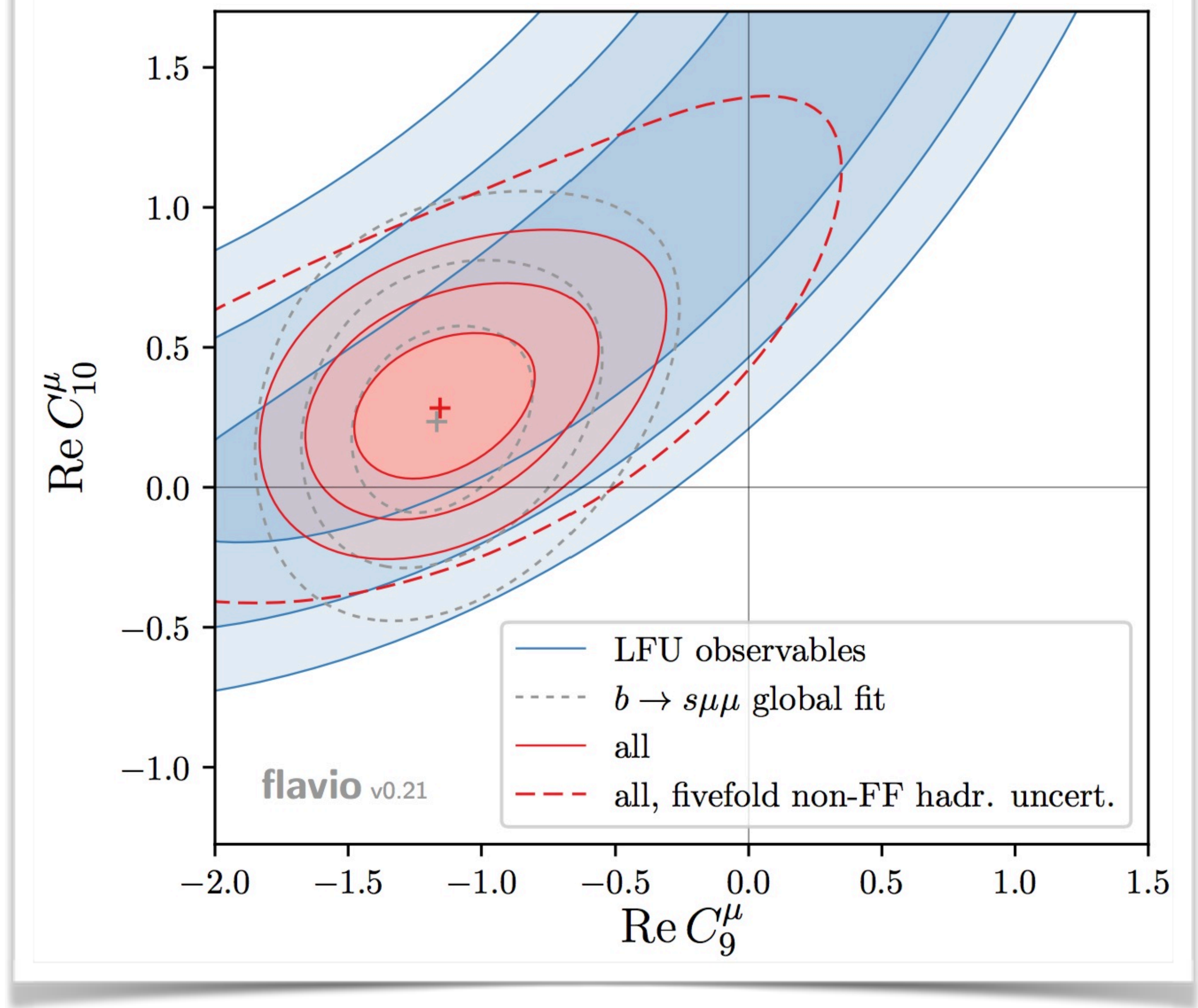
m_{ll} [mass range]	SM	Exp.
$R_K^{[1-6]}$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^*}^{[1.1-6]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.069} \pm 0.047$
$R_{K^*}^{[0.045,1.1]}$	0.91 ± 0.03	$0.660^{+0.110}_{-0.070} \pm 0.024$

LHCb, PRL 113 (2014) 151601 , arXiv:1705.05802

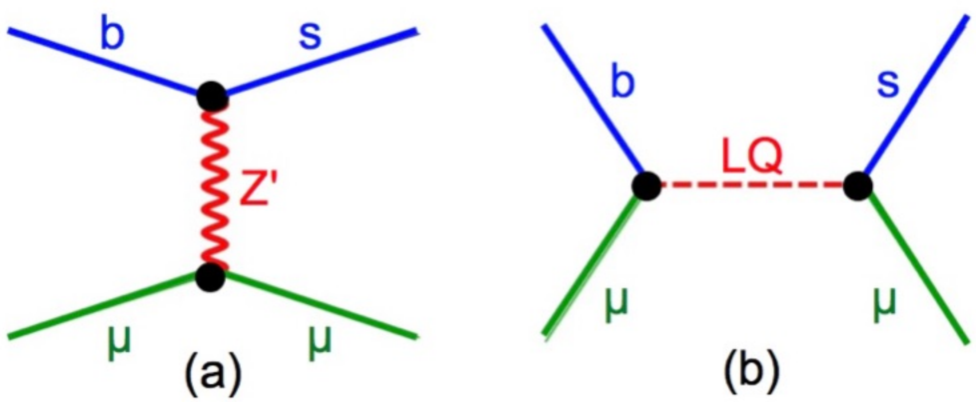
Example of EFT interpretation of R_K

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

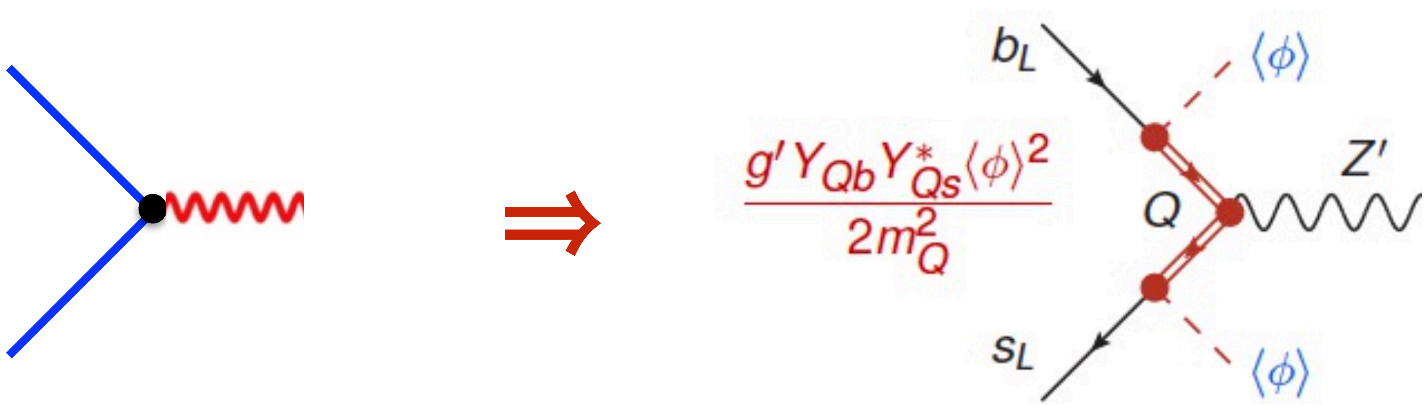
Altmannshoffer et al, arxiv:1704.05435



Possible explicit realizations:



where, e.g. ,



Upper limits on Z' and Leptoquark masses are model-dependent, and constrained also by other low-energy flavour phenomenology, but typically lie in the range of 1→O(10) TeV

⇒ if anomalies confirmed, we may want a no-lose theorem to identify the next facility!

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- The physics case of a 100 TeV collider is very clear as a long-term goal for the field, simply because no other proposed or foreseeable project can have direct sensitivity to such large mass scales.
- Nevertheless, the precise route followed to get there (via CLIC? via HE-LHC? via FCC-ee? …) must take account of the fuller picture, to emerge from the LHC as well as other current and future experiments in areas ranging from flavour physics to dark matter searches. The right time scale for this assessment is probably ~8-10 yrs from now