Beyond the LHC: future prospects for high-energy physics

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New Frontiers in Theoretical Physics 2018
CONVEGNO NAZIONALE DI FISICA TEORICA

LHC → **Higgs**

what’s next?

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- HEP has two priorities:
  - **explore the physics of electroweak symmetry breaking**:
    - experimentally, via the measurement of Higgs properties, Higgs interactions and selfinteractions, couplings of gauge bosons, flavour phenomena, etc
    - theoretically, to understand the nature of the hierarchy problem and identify possible natural solutions (to be subjected to exptl test)
  - **explore the origin of known departures from the SM** (DM, neutrino masses, baryon asymmetry of the universe)

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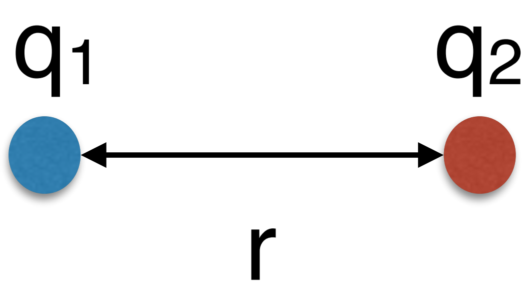
The programme builds on the belief that these two directions are deeply intertwined

Electromagnetic vs Higgs dynamics



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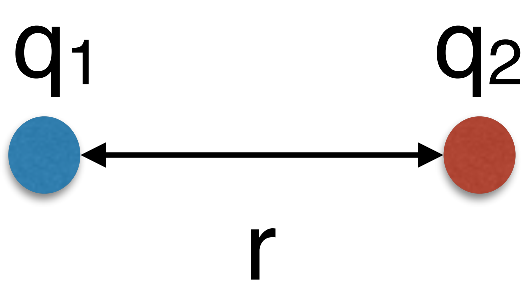

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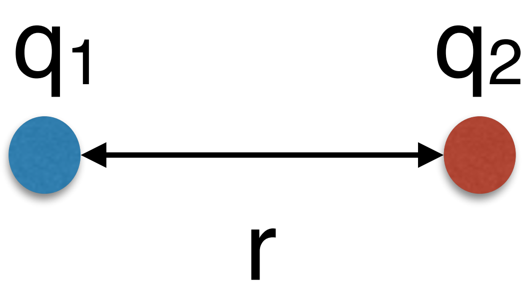

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power determined by gauge
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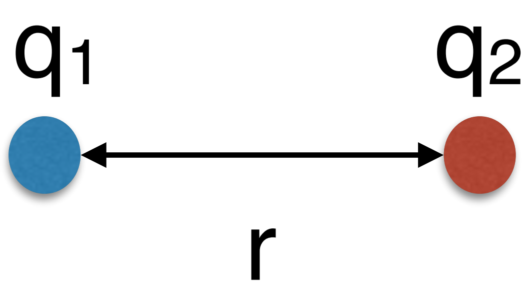

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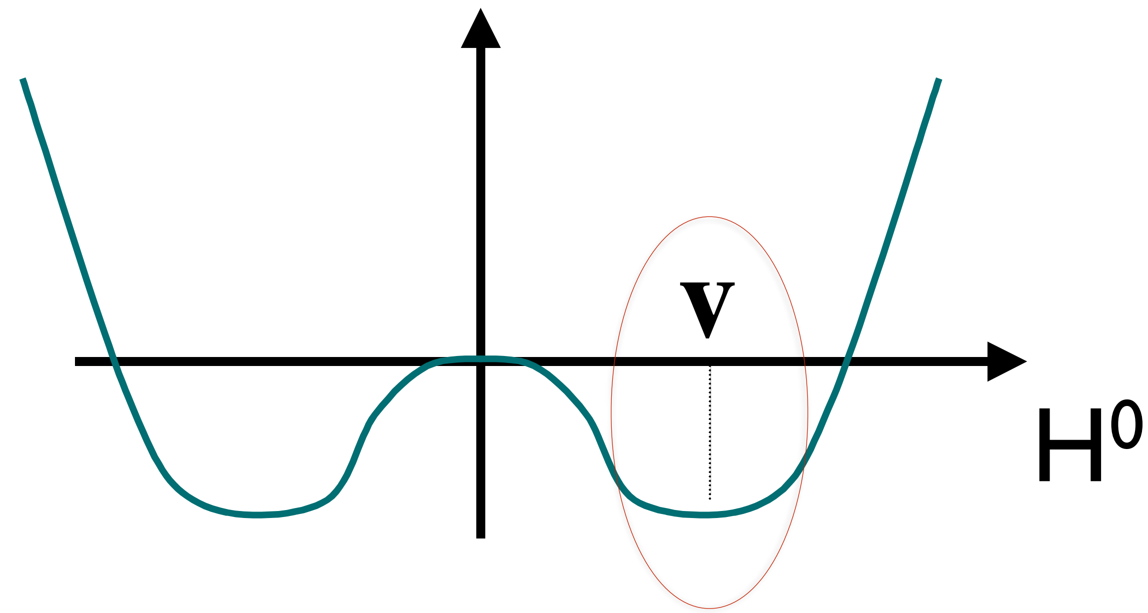

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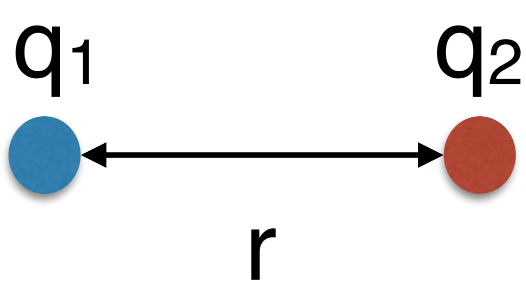

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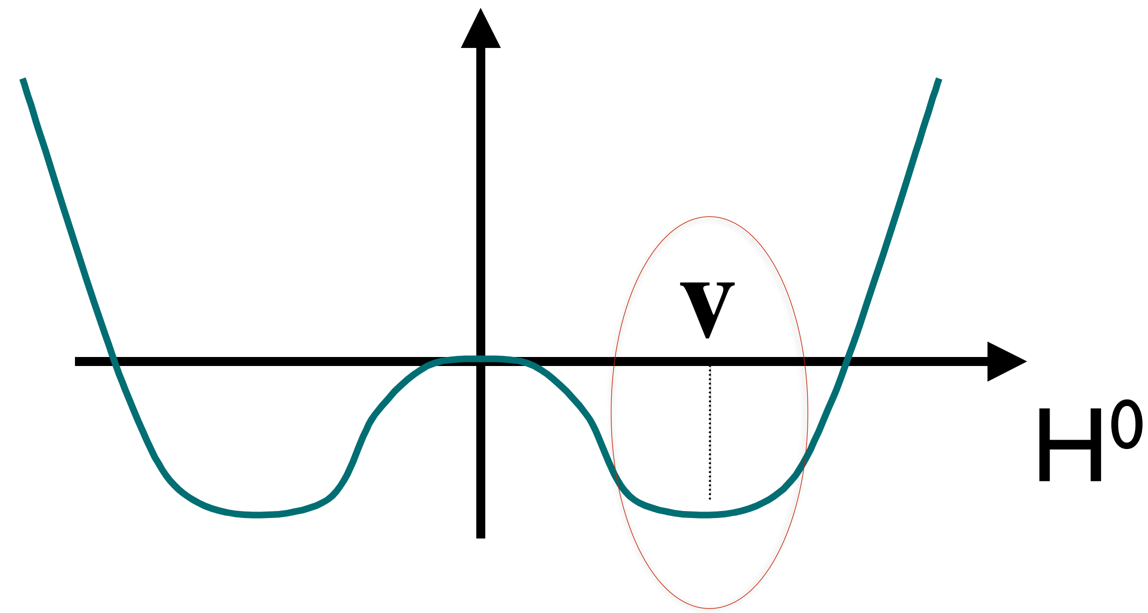

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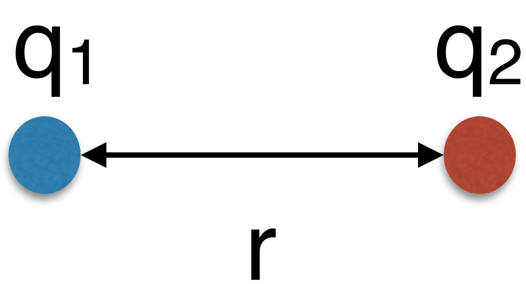

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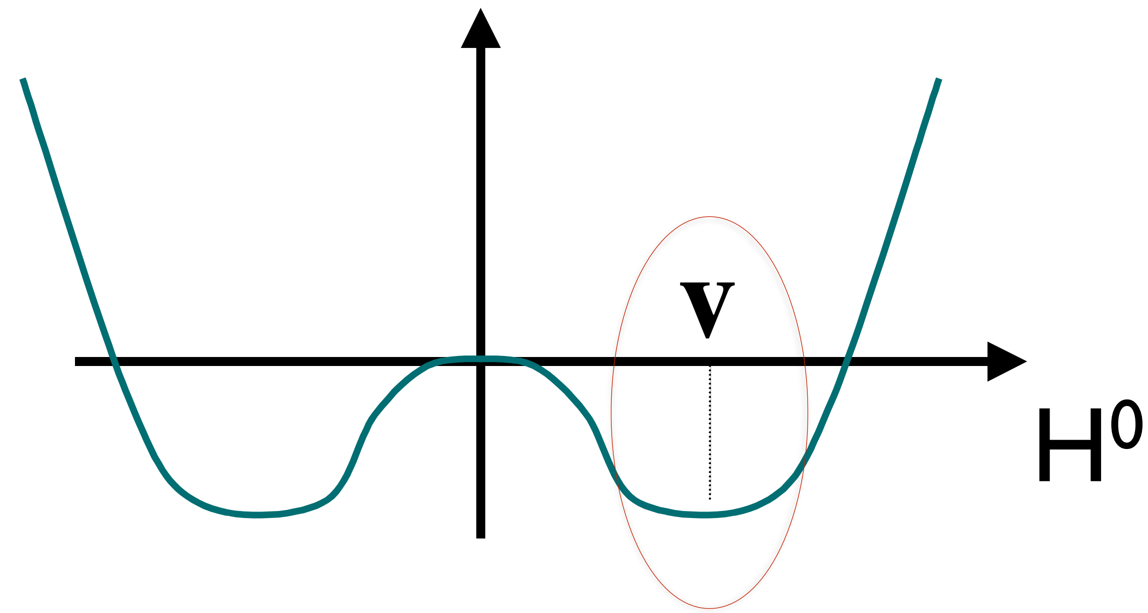

any function of $|H|^2$ would be ok wrt known symmetries

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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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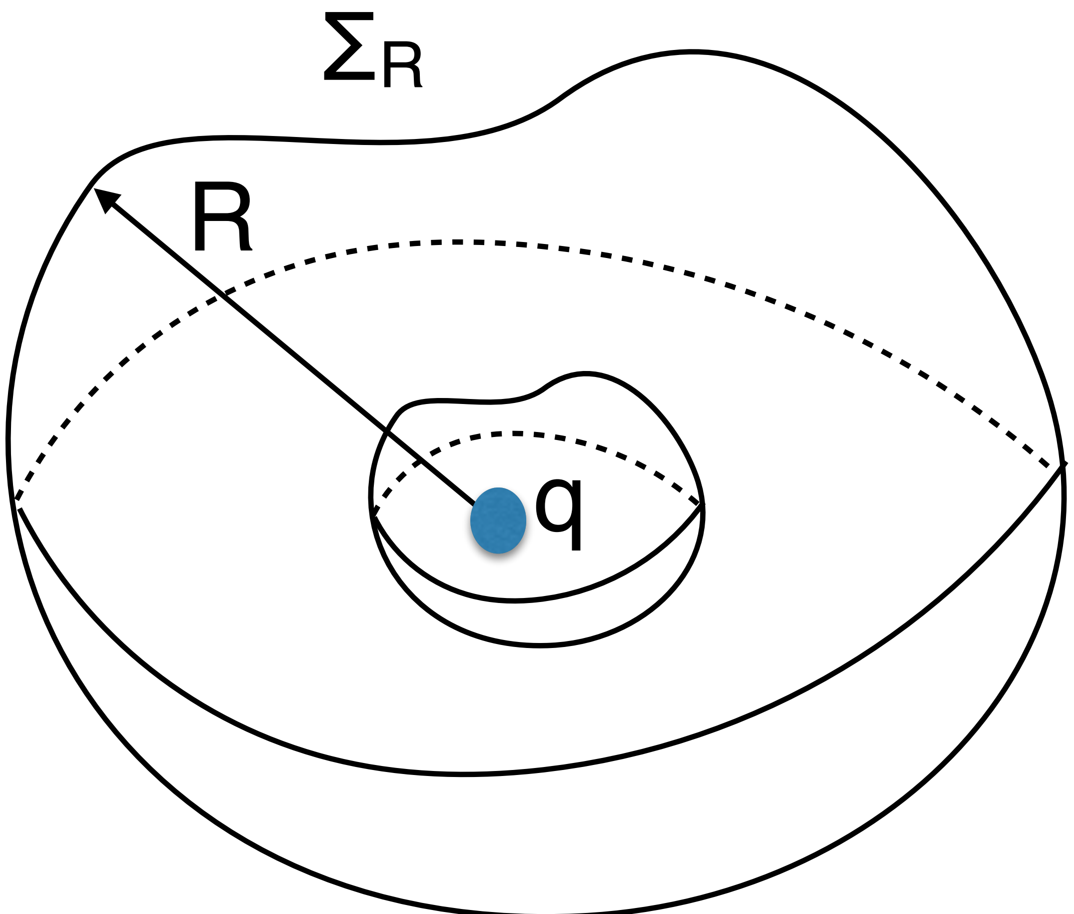
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases 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



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short-scale physics does not alter
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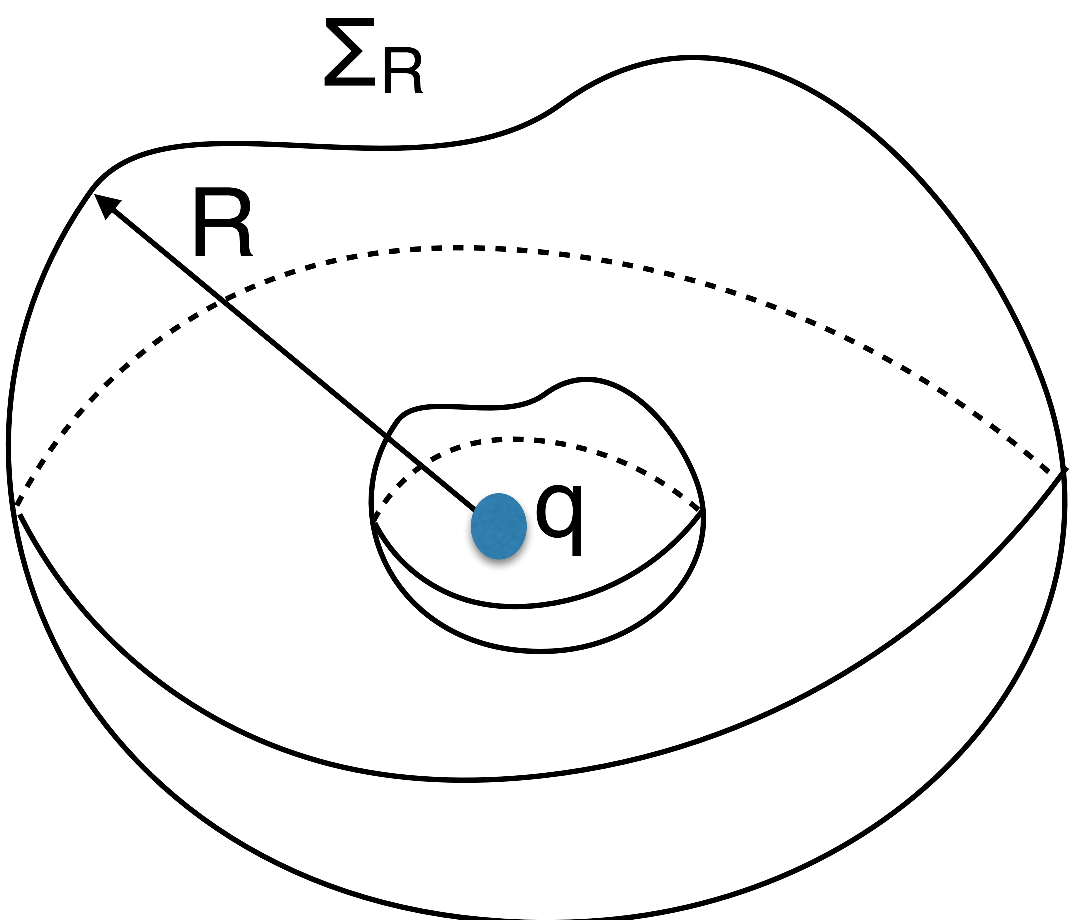

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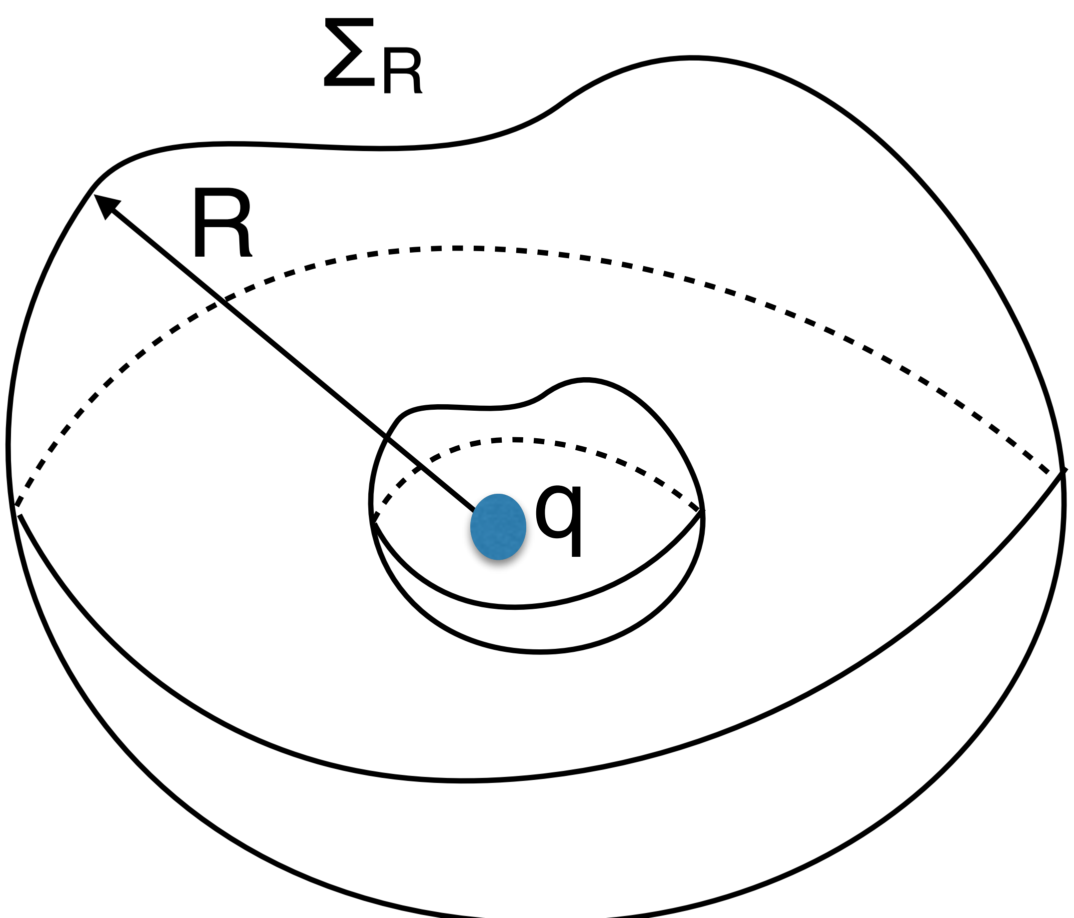

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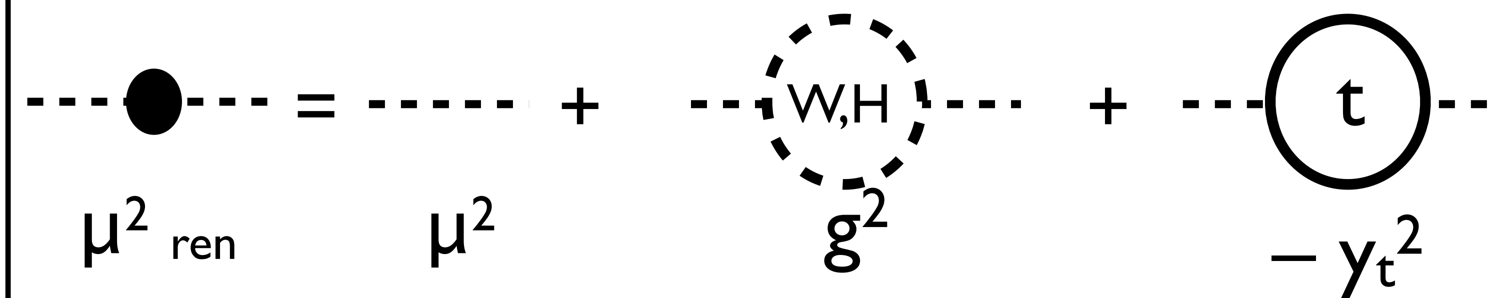

$\Delta\mu^2 \sim (c_W\, m_W^2 - c_t\, m_t^2) \times (\Lambda / v)^2$

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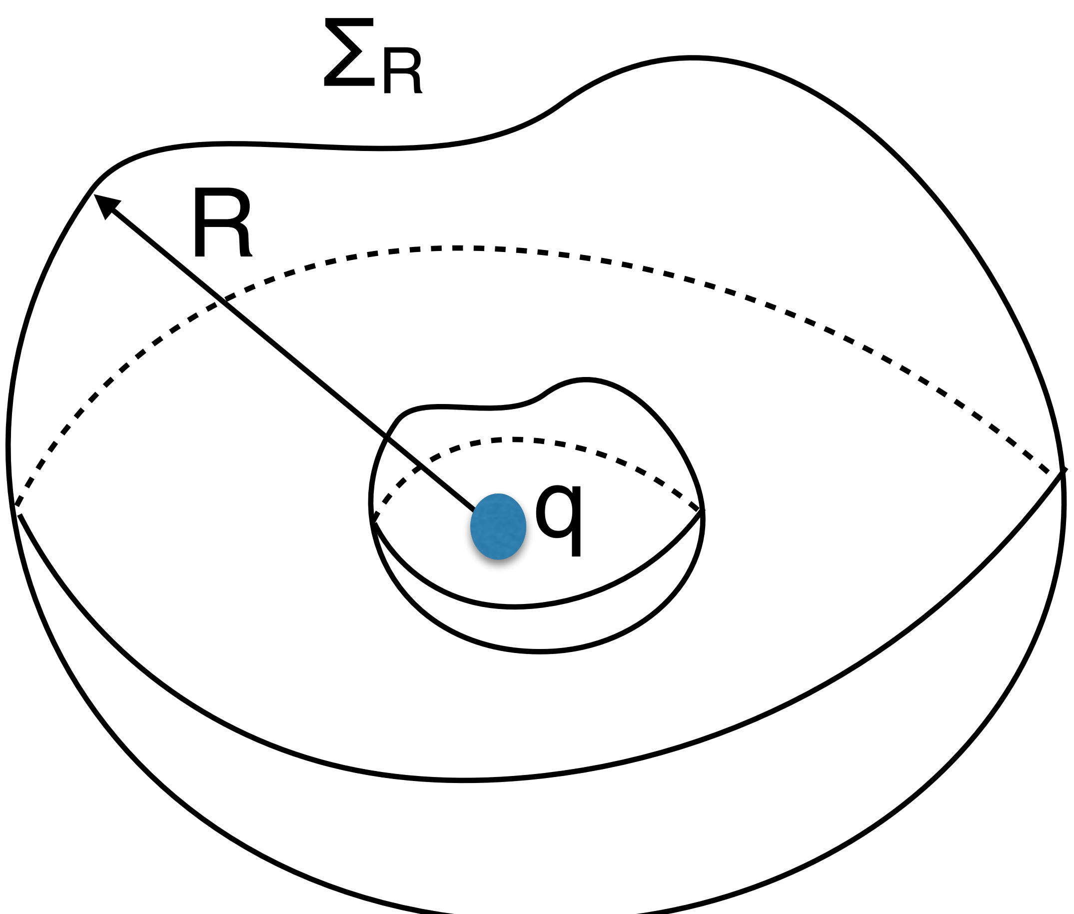

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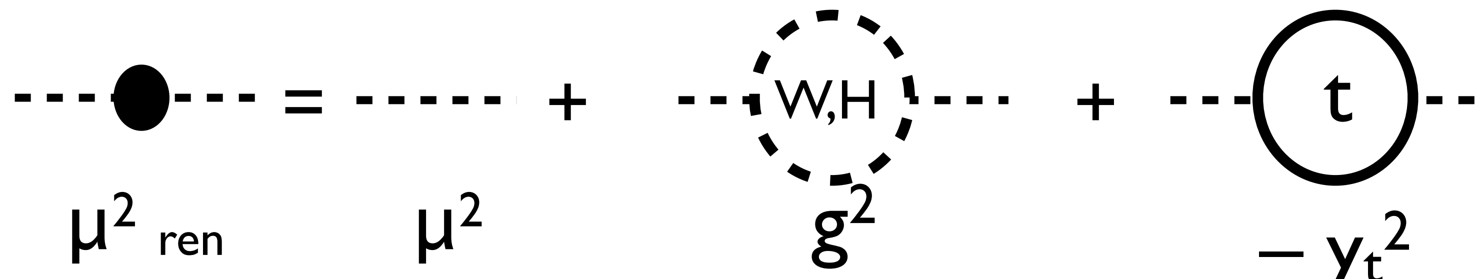

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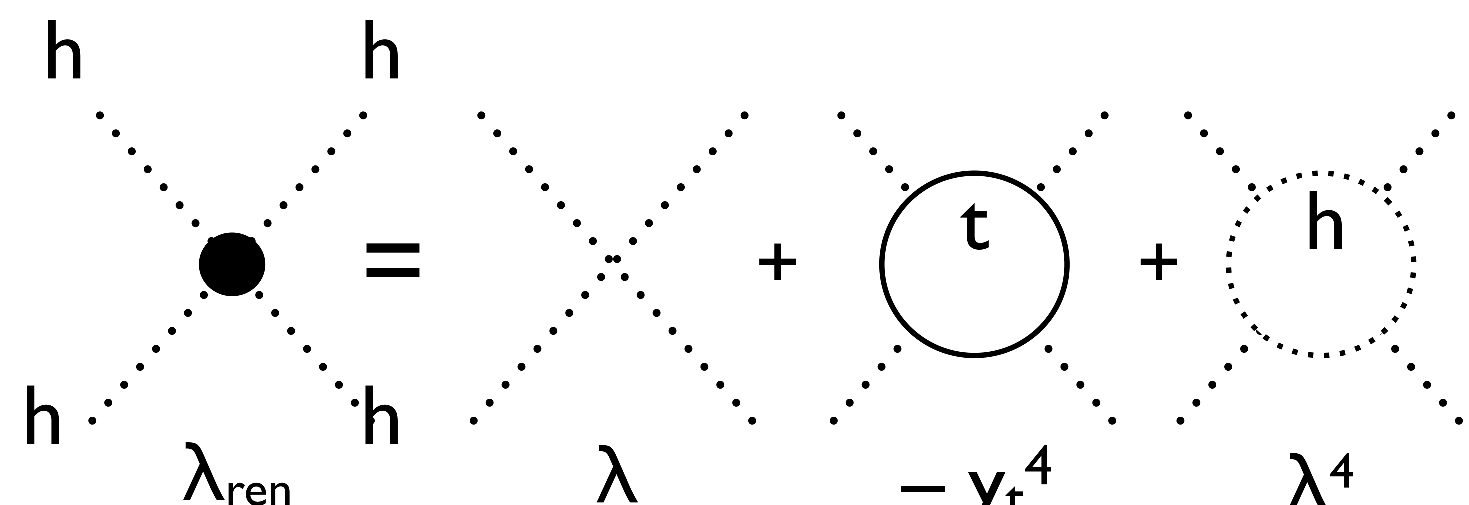

$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4 \quad \propto a \, m_H^4 - b \, m_t^4$$

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 distance scales
- The Higgs dynamics is sensitive to all that happens at any distance scale shorter 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

$\Rightarrow$ **naturalness**

The other *big* questions that press us to look *beyond* the Standard Model

- What's the real origin of EW symmetry breaking and particle's masses?
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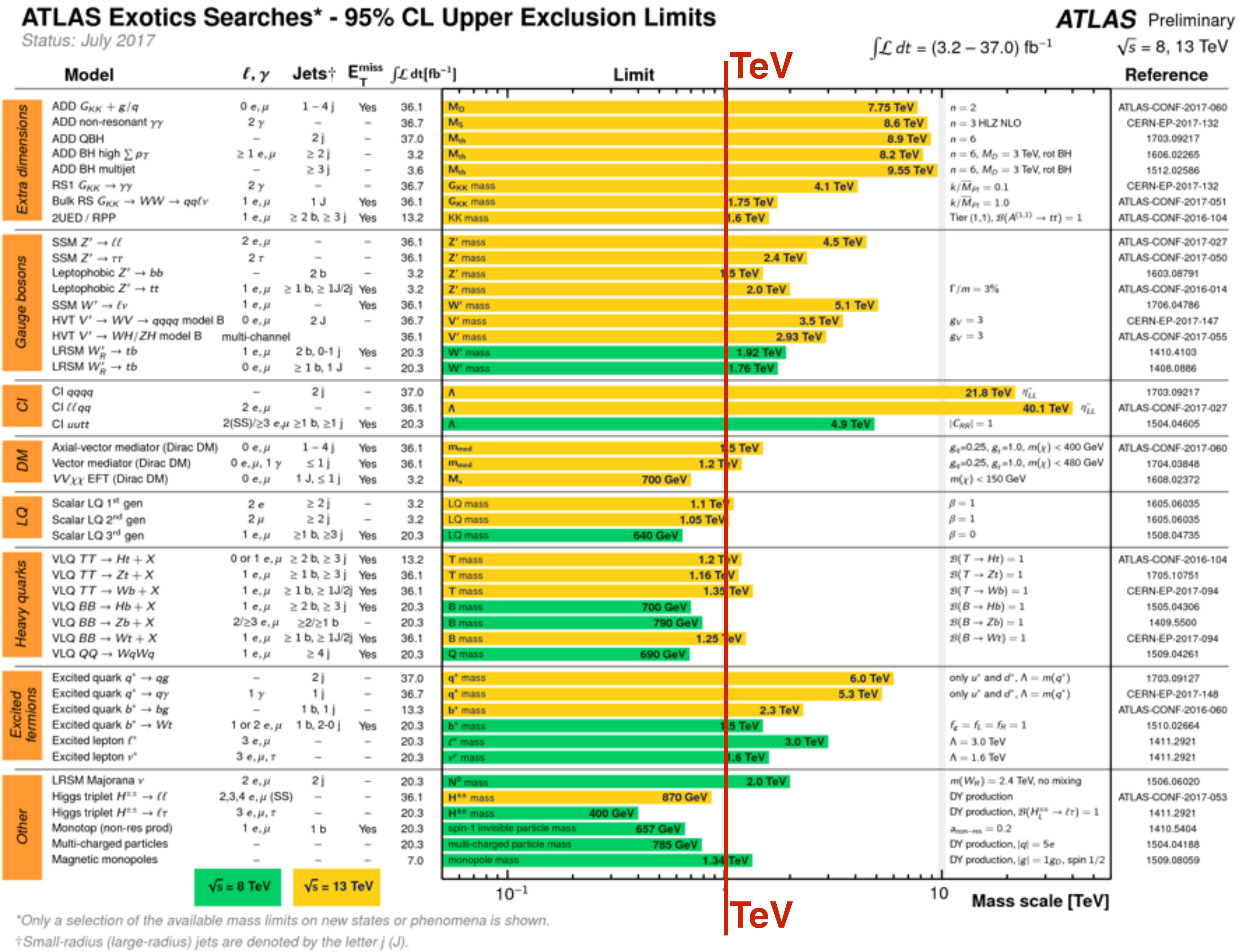
- What's the origin of neutrino masses?
- … *(flavour, inflation, cosmological constant, ….*

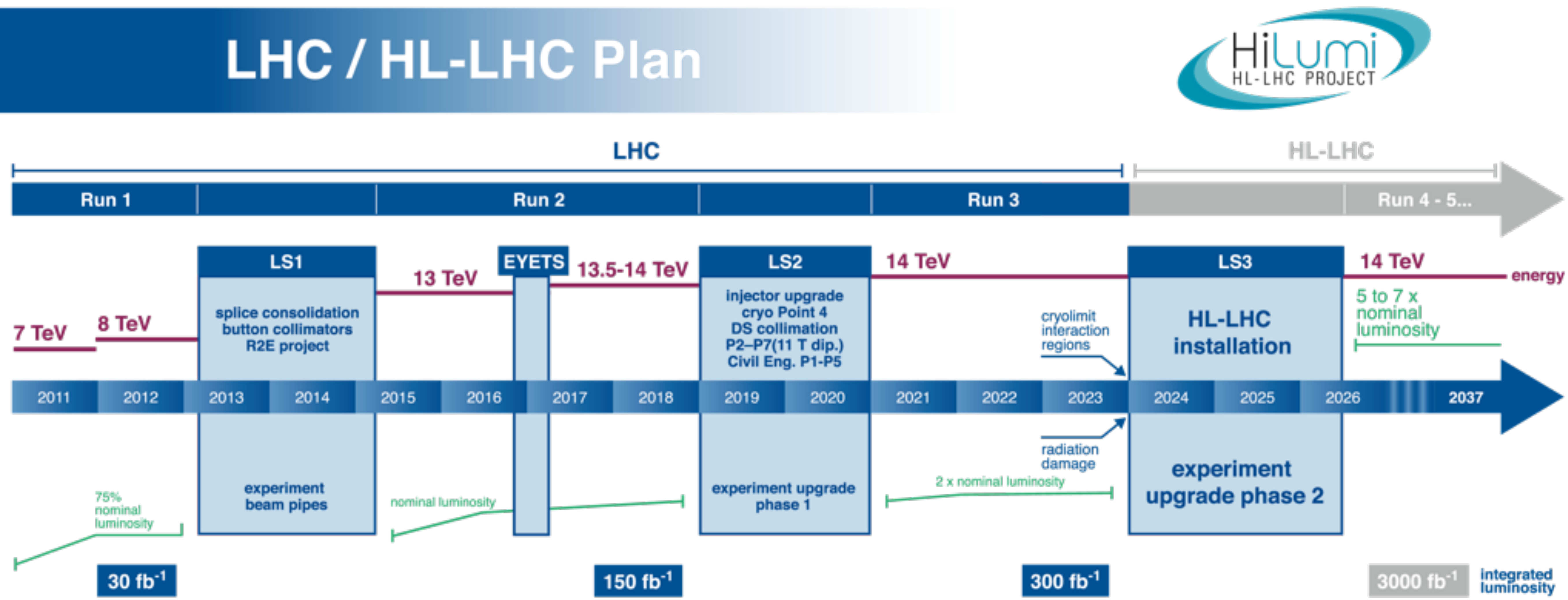
The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

- 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, …)
- Dark matter, long lived particles
- Extra dimensions
- New flavour phenomena
- unanticipated surprises …

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



Long-term LHC plan



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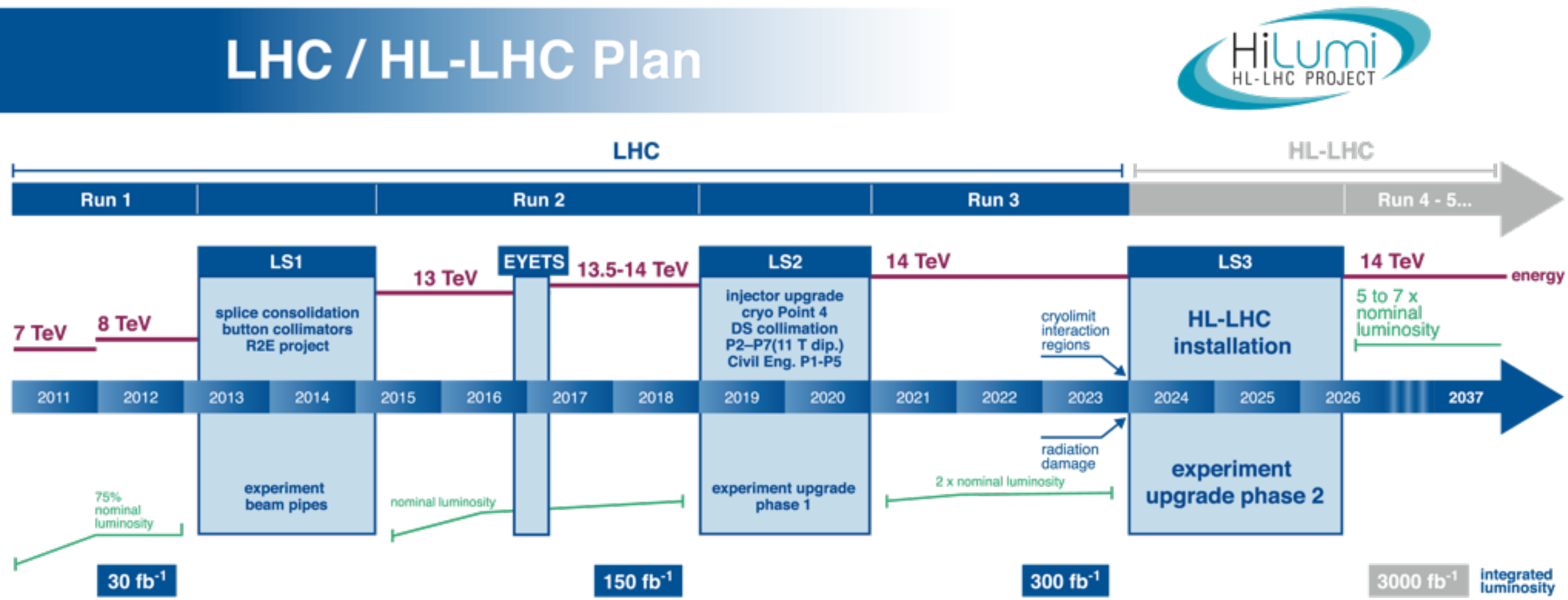

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==>> the LHC physics programme has barely started! <<==

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

Colliders beyond the LHC

What are we talking about when we're talking future colliders: at CERN…

HiLumi HL-LHC PROJECT

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

✓Approved 2026-37

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CDR: Conceptual Design Report

CDR (end '18)

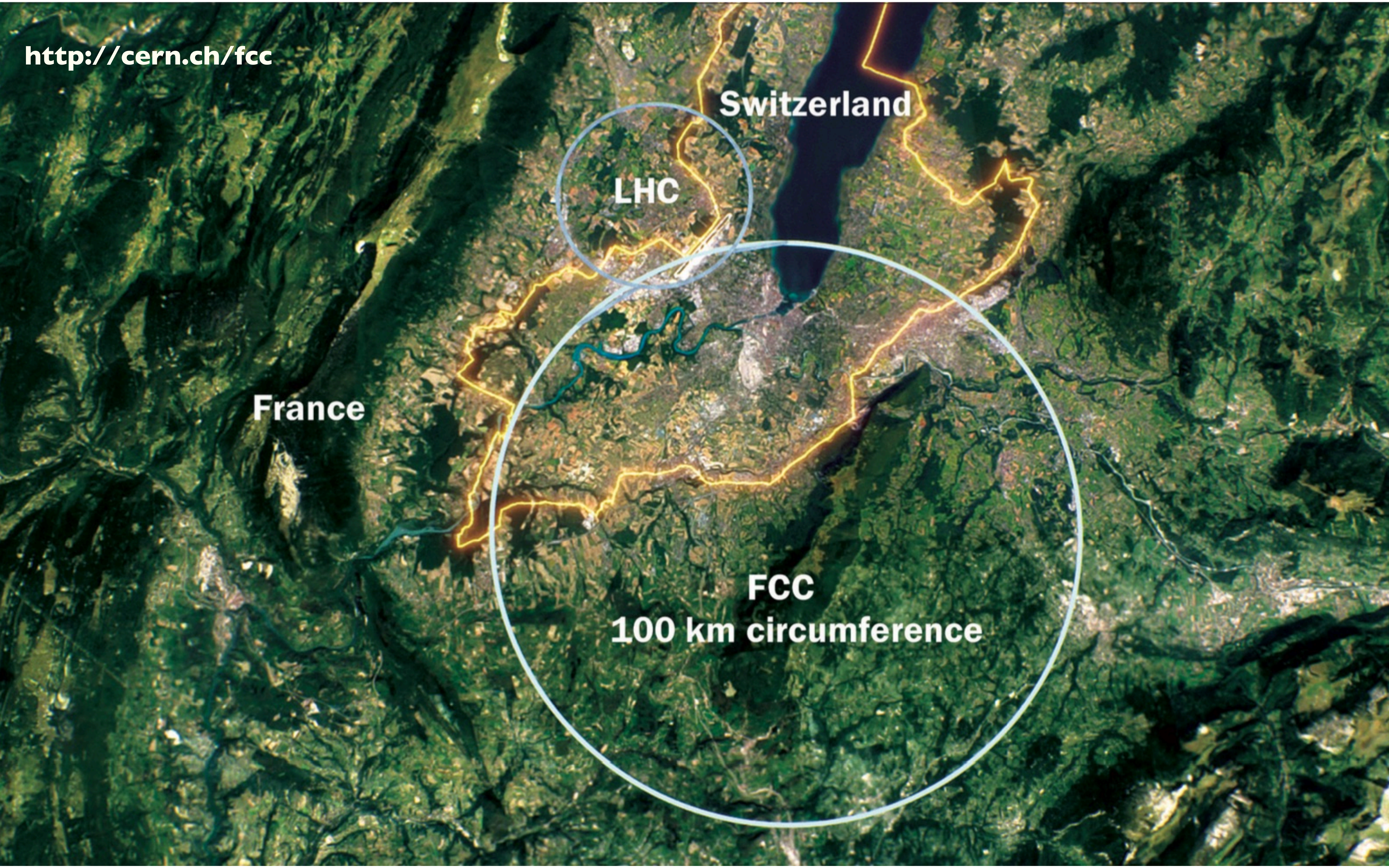
100km tunnel

- **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}**

Future Circular Collider



… and in the rest of the world:

ILC

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

TDR 2012,
decision by end 2018?

TDR: Technical Design Report

CEPC

CDR (Summer ’18)
decision by 2020?

100km tunnel

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

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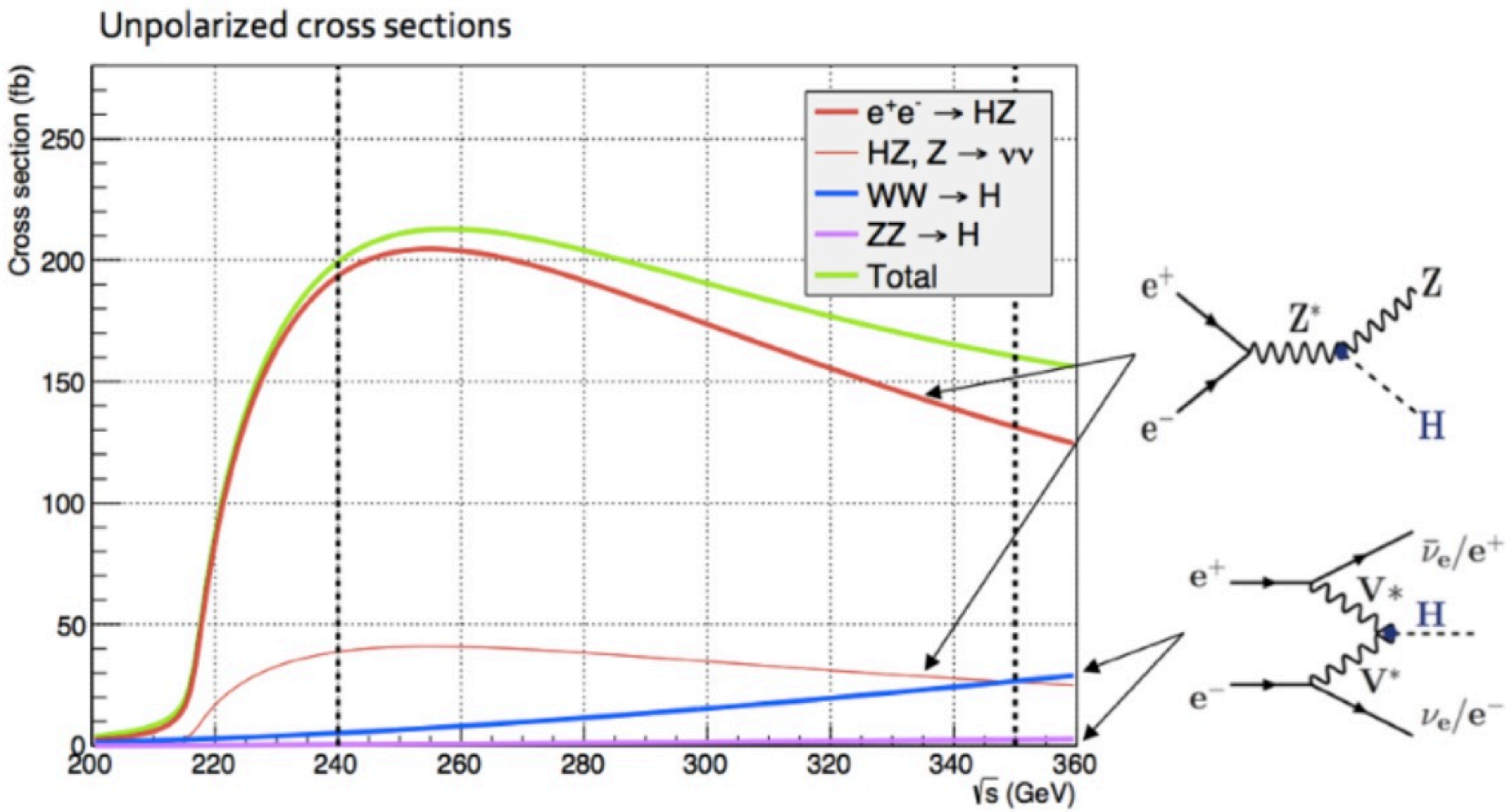
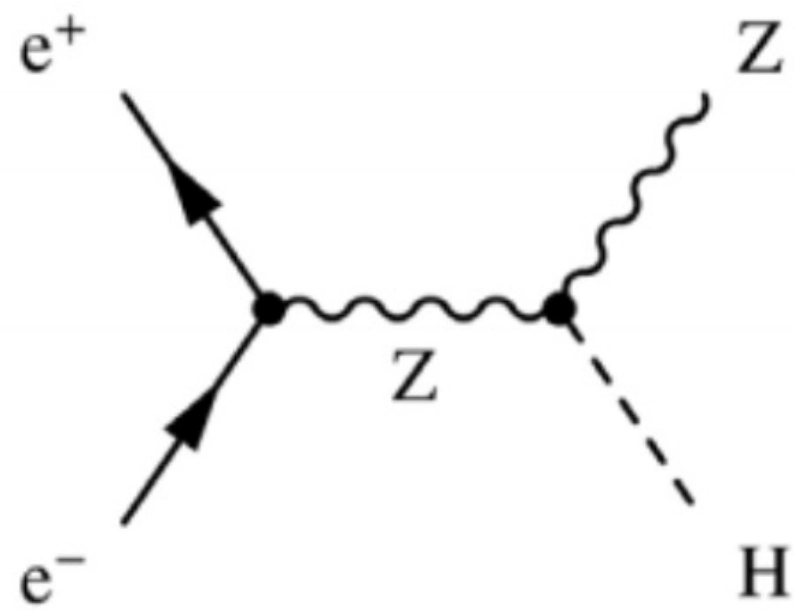
  - benefit from both direct (large Q^2) and indirect (precision) probes
- Provide firm Yes/No answers to questions like:
  - is the SM dynamics all there is at the TeV scale?
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - did baryogenesis take place during the EW phase transition?

Examples: precision Higgs physics

FCC-ee



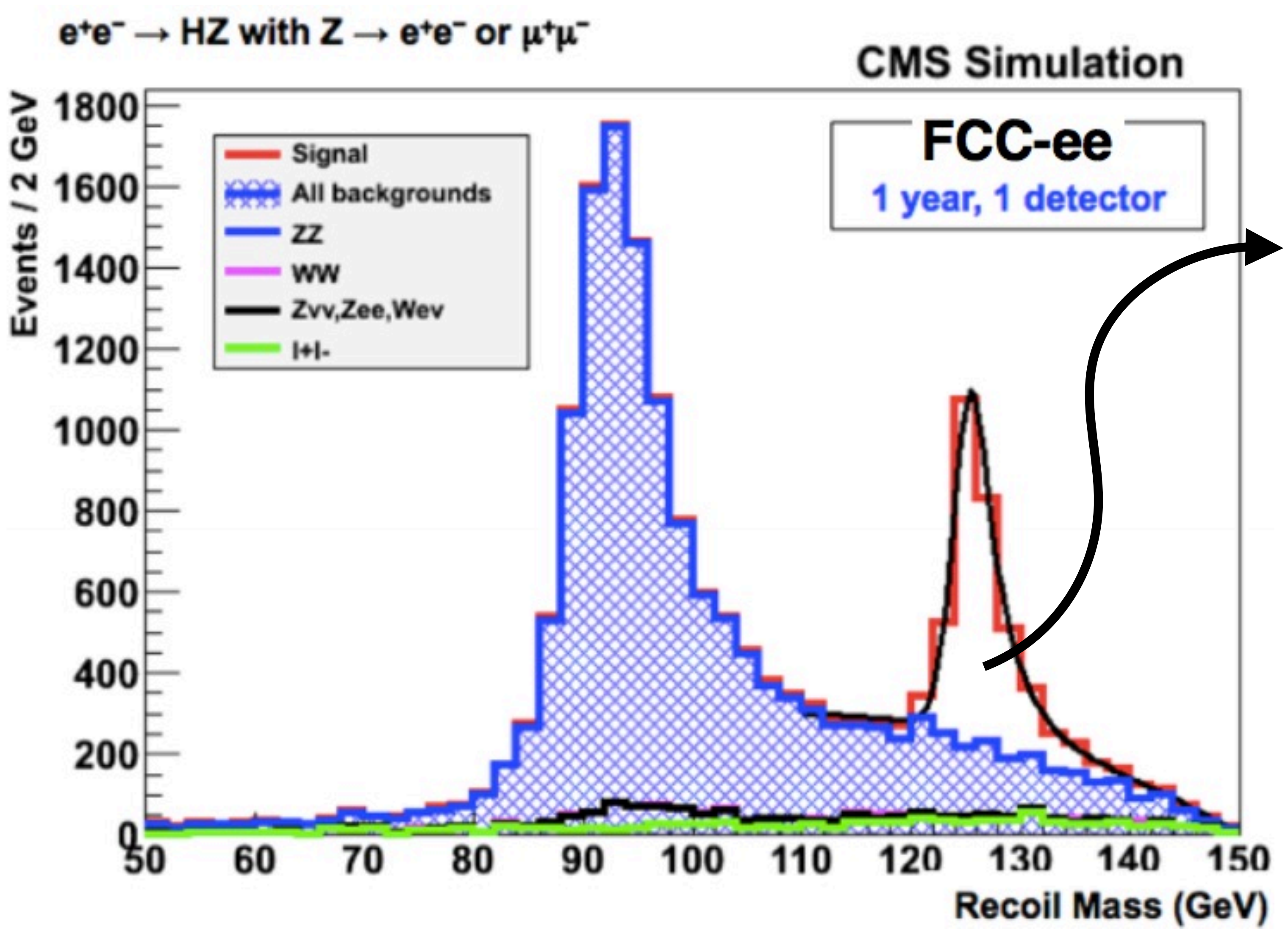
	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	5	1.5
# Higgs bosons from $e^+e^- \to HZ$	1,000,000	200,000
# Higgs bosons form fusion process	25,000	40,000



$p(H) = p(e^-e^+) - p(Z)$

=> $[\, p(e^-e^+) - p(Z)\,]^2$ peaks at $m^2(H)$

reconstruct Higgs events independently of the Higgs decay mode!



$N(ZH) \propto \sigma(ZH) \propto g_{HZZ}^2$

$N(ZH[\to ZZ]) \propto$
$\sigma(ZH) \times BR(H \to ZZ) \propto$
$g_{HZZ}^2 \times g_{HZZ}^2 / \mathbf{\Gamma(H)}$

=> absolute measurement of width and couplings

$m_{recoil} = \sqrt{[\, p(e^-e^+) - p(Z)\,]^2}$

Higgs couplings @ FCC-ee

measurement precision:

g_{HXY}	ee [240+350 (2IP)]
ZZ	0.21%
WW	0.43%
bb	0.64%
cc	1.04%
gg	1.18%
ττ	0.81%
μμ	8.8%
γγ	2.12%
Zγ	
tt	~13%
HH	~30%
uu,dd	H->ργ, under study
ss	H->ϕγ, under study
BR_{inv}	< 0.45%
Γ_{tot}	1.5%

SM Higgs at 100 TeV

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

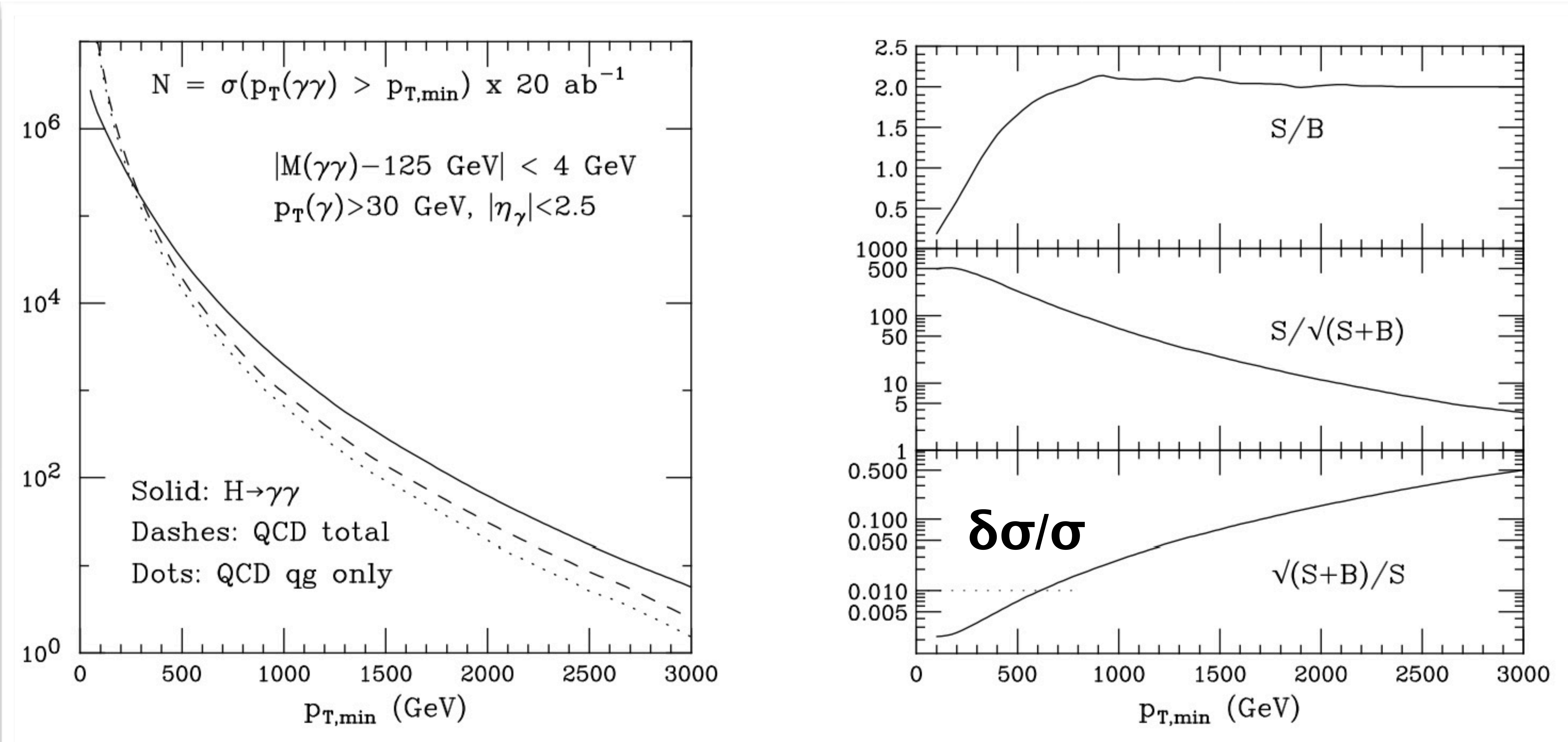
$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$

$N_8 = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

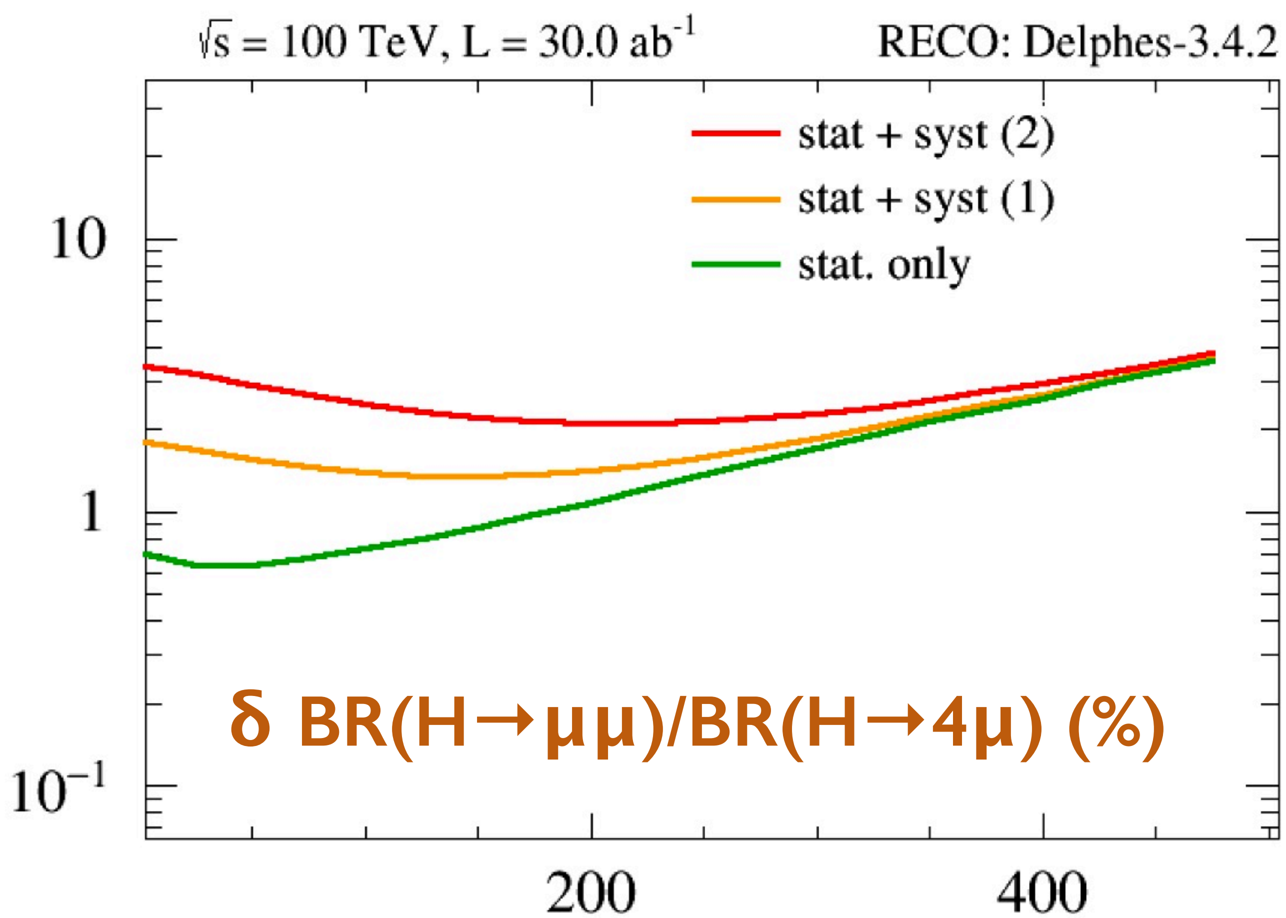
- Huge production rates imply:
  - can afford reducing statistics, with tighter kinematical cuts that reduce backgrounds and systematics
  - can explore new dynamical regimes, where new tests of the SM and EWSB can be done

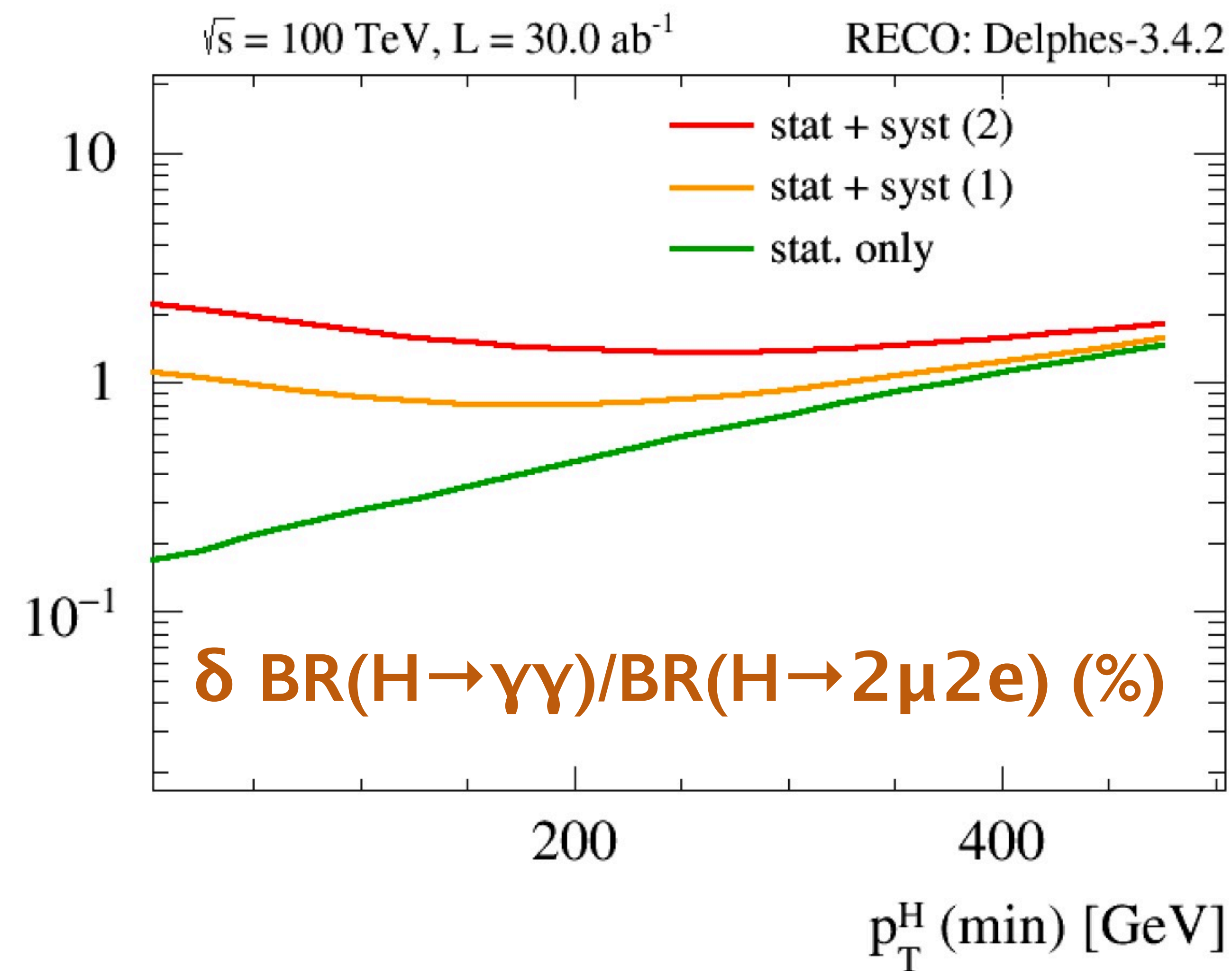
$gg \rightarrow H \rightarrow \gamma\gamma$ at large p_T

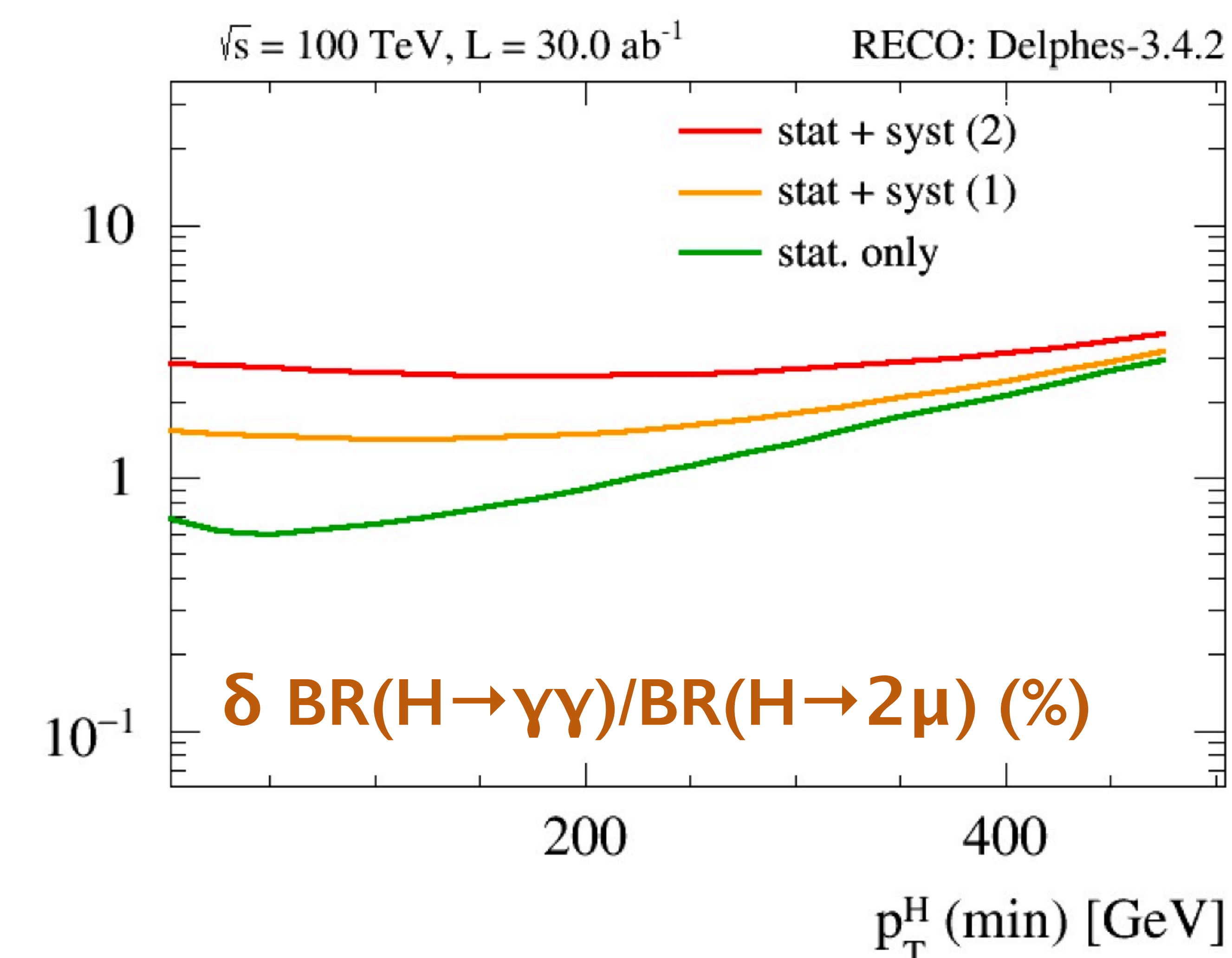


- At LHC, S/B in the $H \rightarrow \gamma\gamma$ channel is O(few %)
- At FCC, for $p_T(H)>300$ GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%







Normalize to BR(4l) from ee at 1% level => absolute sub-% for couplings

M.Selvaggi

One should not underestimate the value of FCC-hh standalone precise "ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

BR(H→γγ)/BR(H→ZZ*)

loop-level tree-level

BR(H→μμ)/BR(H→ZZ*)

2nd gen'n Yukawa gauge coupling

BR(H→γγ)/BR(H→Zγ)

different EW charges in the loops of the two procs

Higgs couplings @ FCC

g_{HXY}	ee [240+350 (2IP)]	pp [100 TeV] 30ab^{-1}	ep [60GeV/50TeV], 1ab^{-1}
ZZ	0.21%	<1%	0.43%
WW	0.43%		0.26%
bb	0.64%		0.74%
cc	1.04%		1.35%
gg	1.18%		1.17%
ττ	0.81%		1.10%
μμ	8.8%	<1%	
γγ	2.12%	<0.5%	2.35%
Zγ		<1%	
tt	~13%	1%	
HH	~30%	3.5%	under study
uu,dd	H->ργ, under study		
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BR_{inv}	< 0.45%	few 10^{-4}	
Γ_{tot}	1.5%		

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bb	0.64%		0.74%
cc	1.04%		1.35%
gg	1.18%		1.17%
ττ	0.81%		1.10%
μμ	8.8%	<1%	
γγ	2.12%	<0.5%	2.35%
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}	1.5%		

first probe of the Higgs potential beyond the 2-point function

Higgs couplings @ FCC

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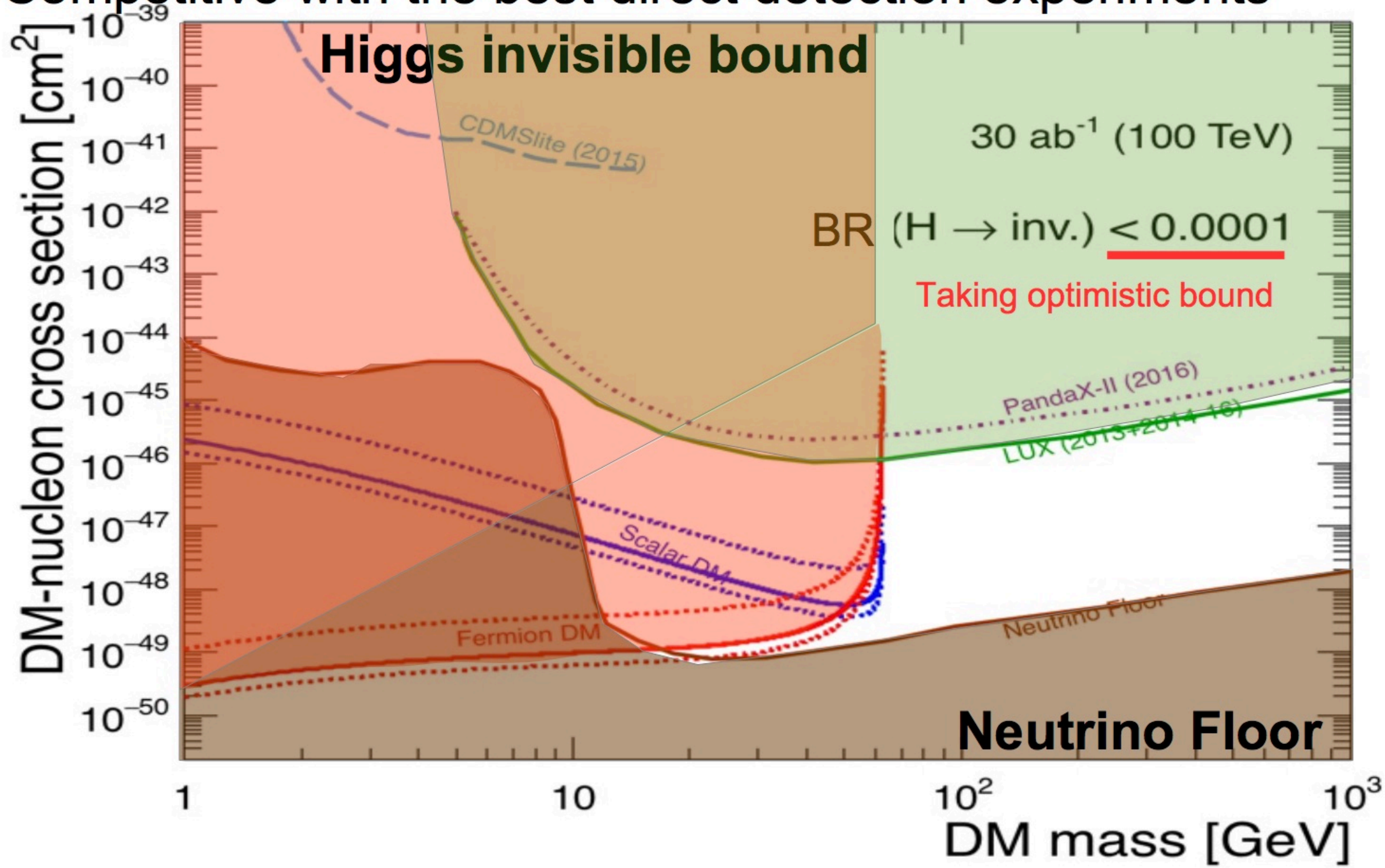
first probe of the Higgs potential beyond the 2-point function

sensitive to possible Higgs-to-DM decays

P.Harris & K.Hahn

Impact on DM bounds

Competitive with the best direct detection experiments



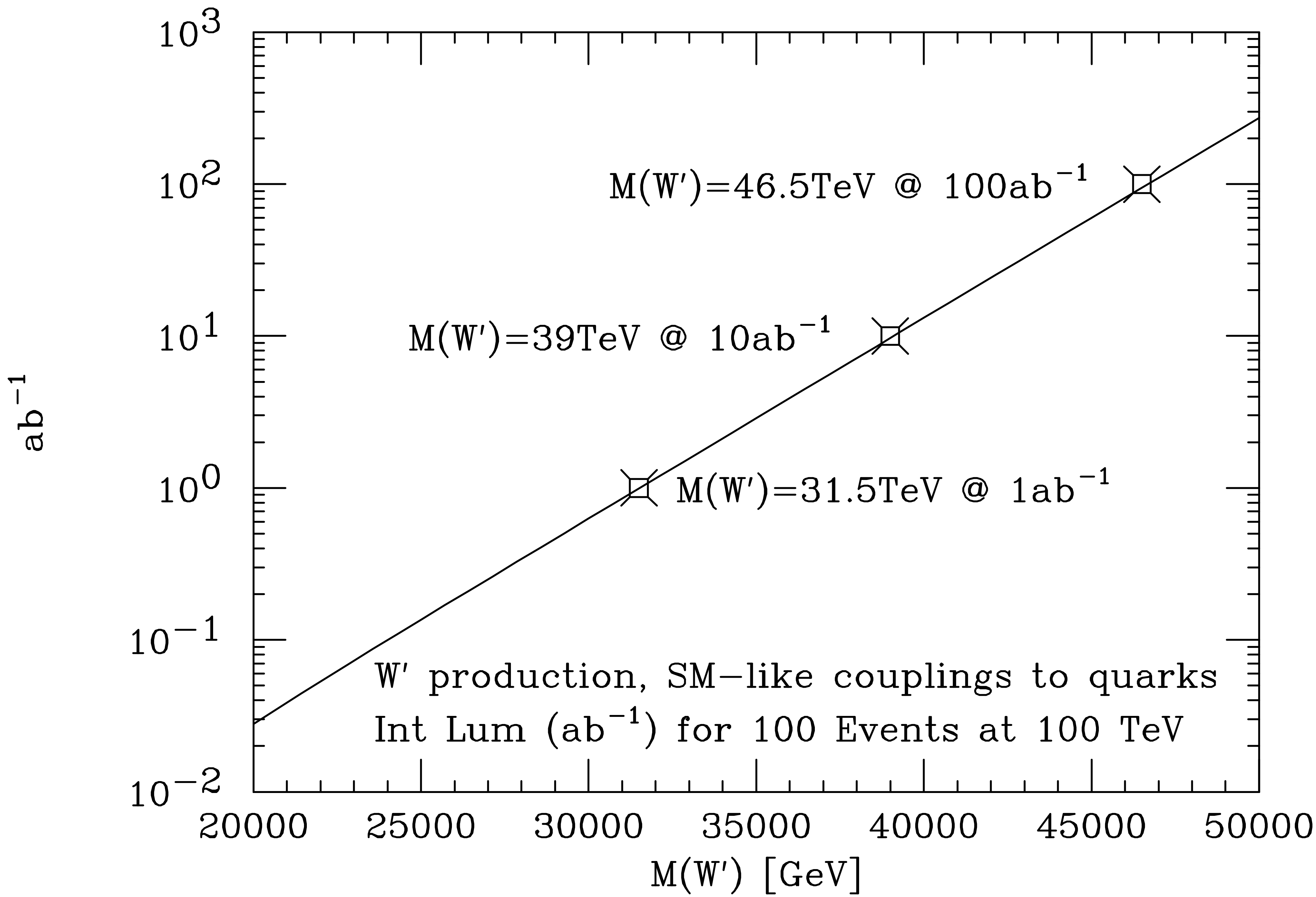
Higgs invisible of 10^{-4} corresponds to g_{SM} from 10^{-3} to 10^{-2}

Examples: direct discovery reach

New gauge bosons discovery reach

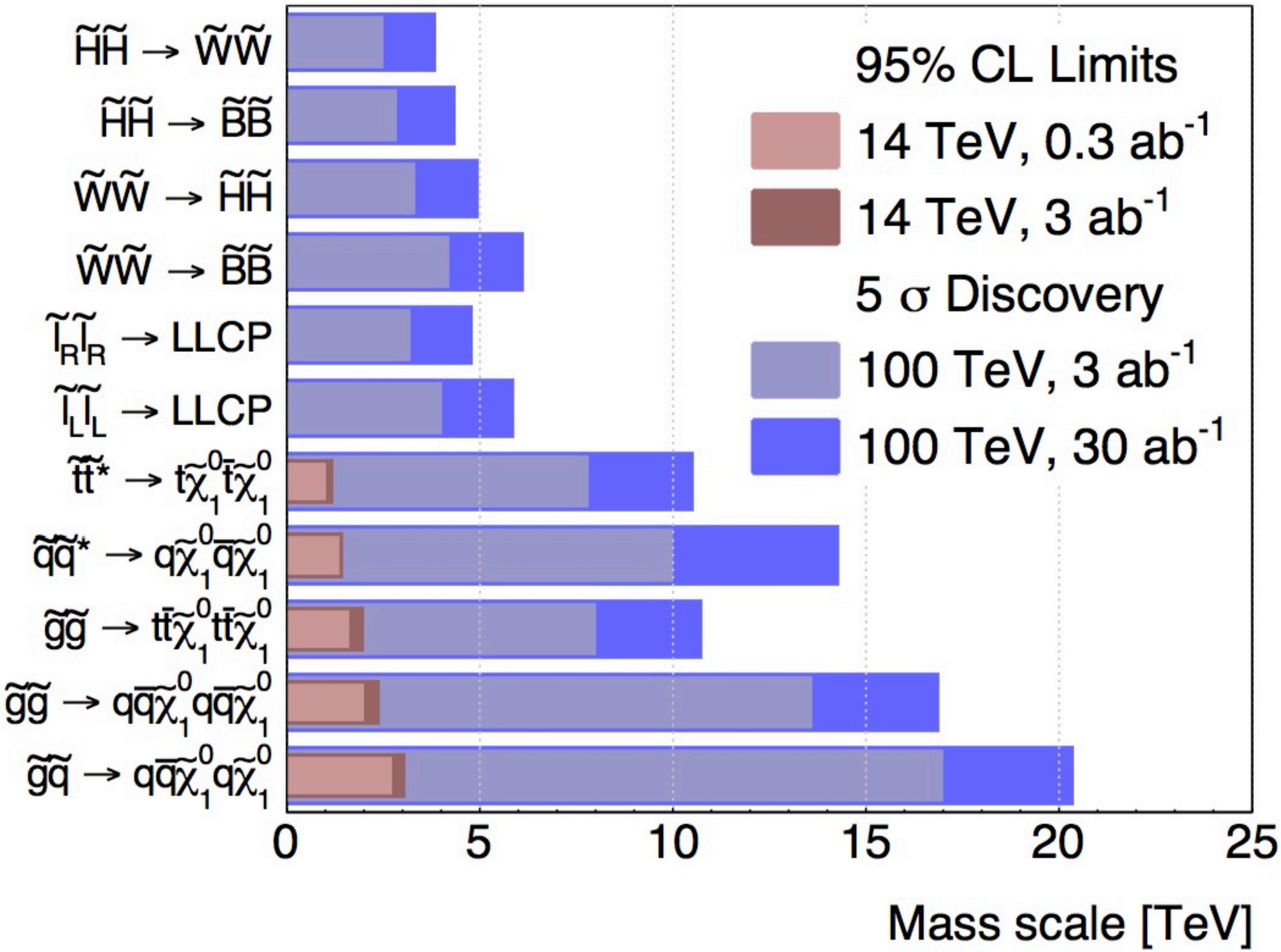
Example: **W' with SM-like couplings**

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



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

SUSY reach at 100 TeV

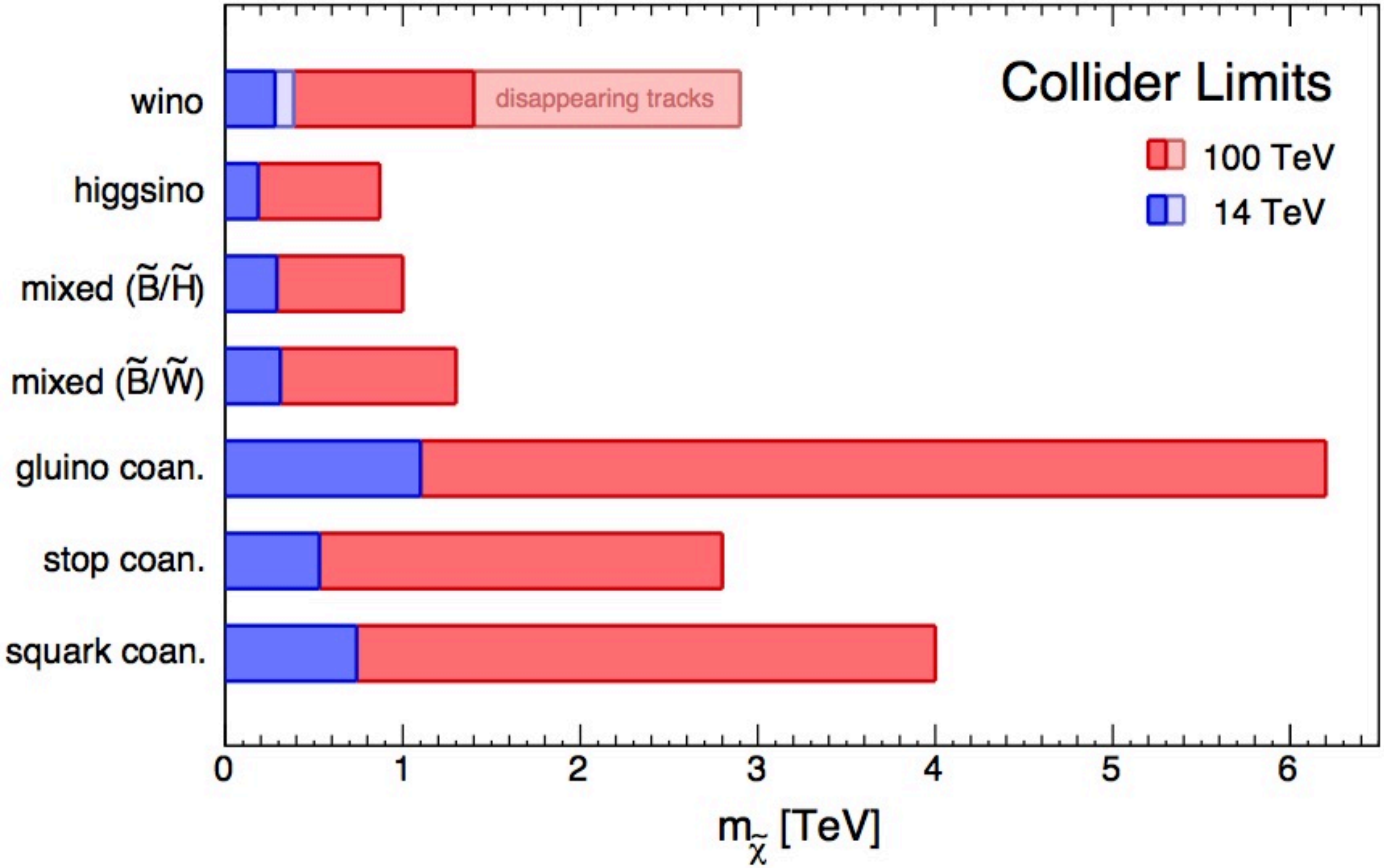


Examples: conclusive yes/no answers

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, ...)?

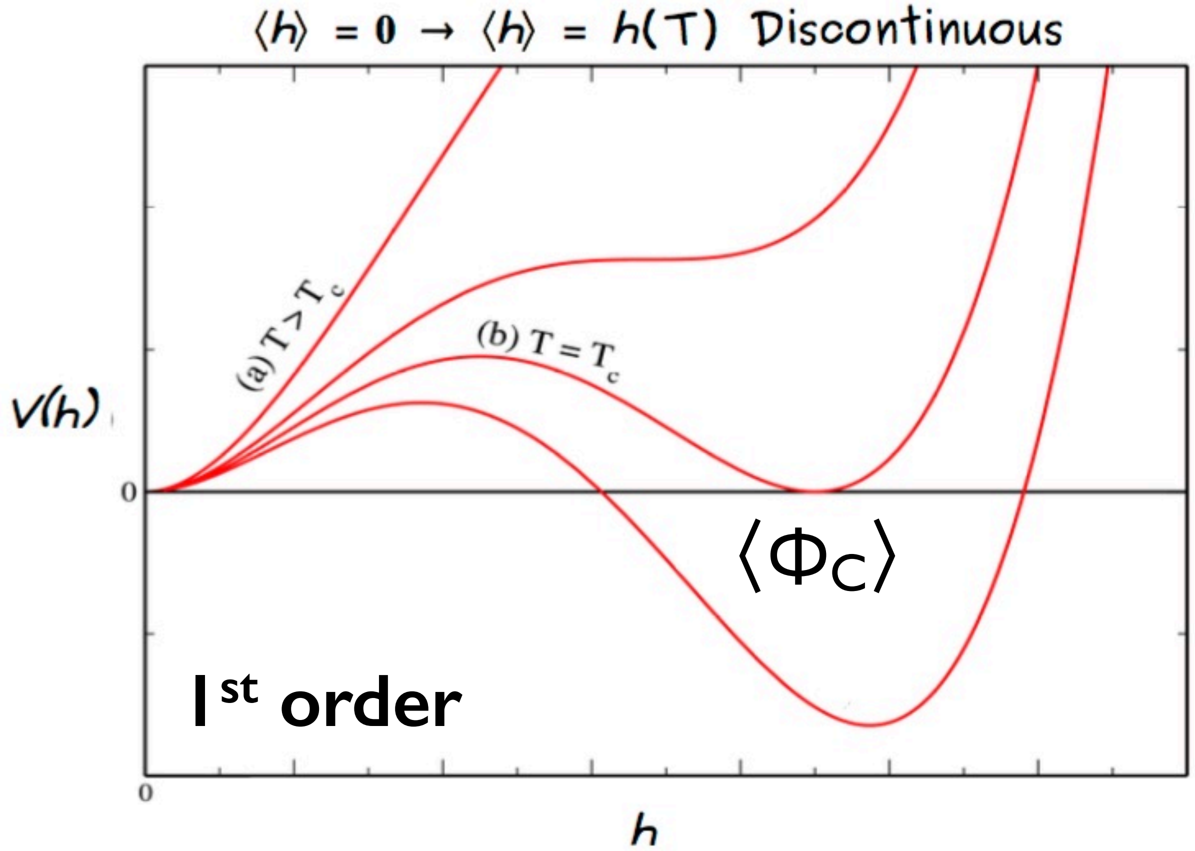
DM reach at 100 TeV

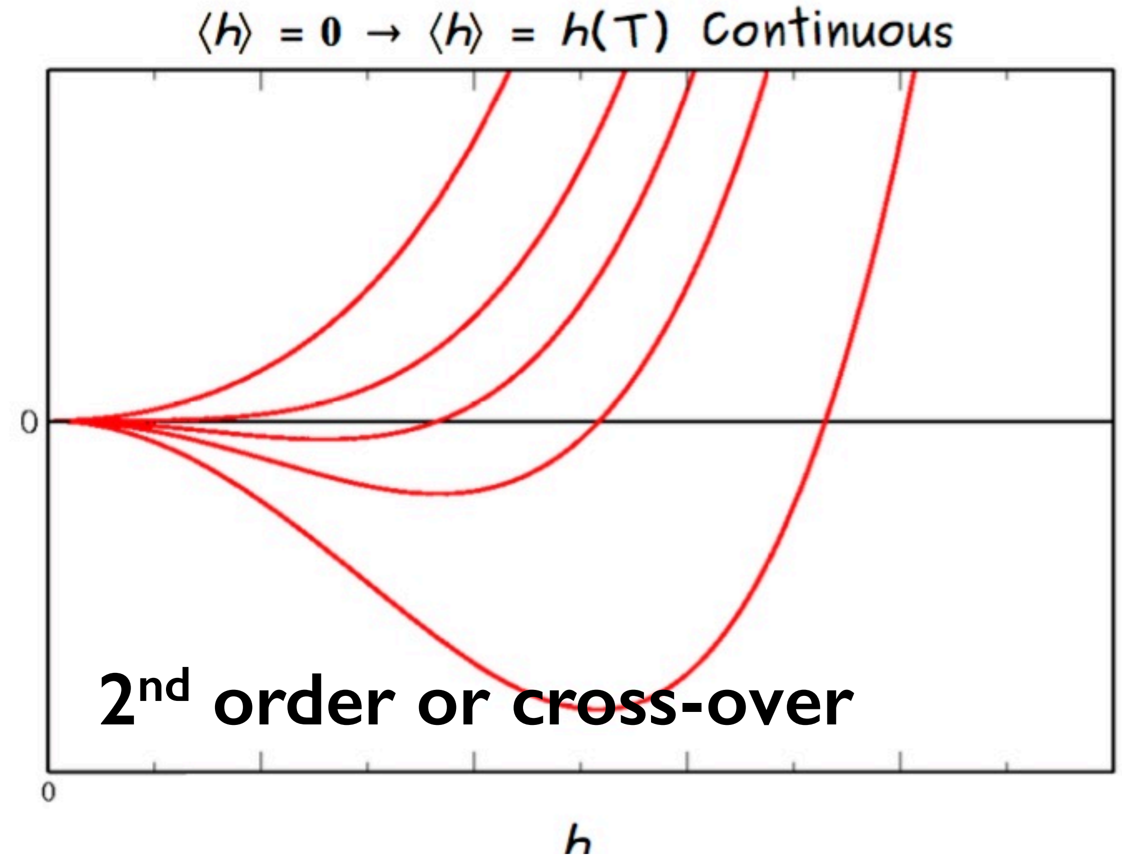


$$M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV}\left(\frac{g^2}{0.3}\right)$$

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

The nature of the EW phase transition





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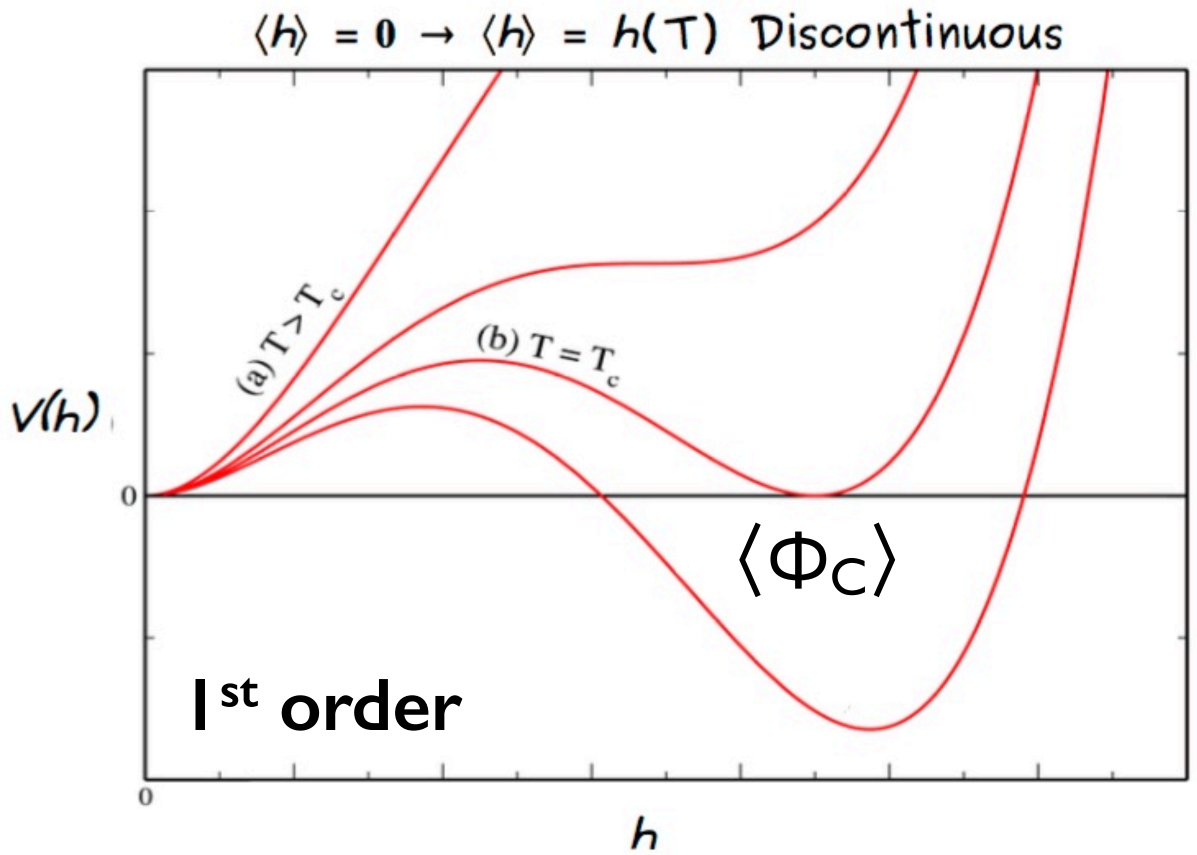

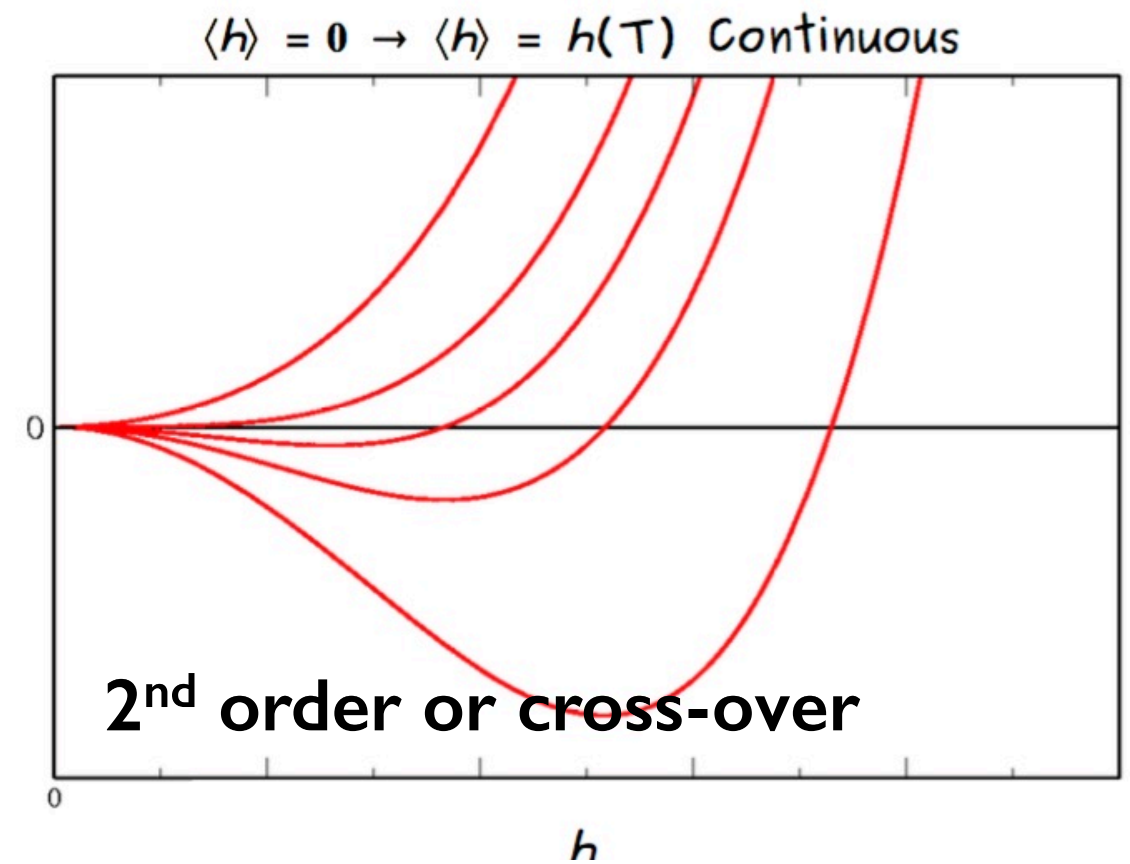

Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

Strong 1st order phase transition $\Rightarrow$ $\langle \Phi_C \rangle > T_C$

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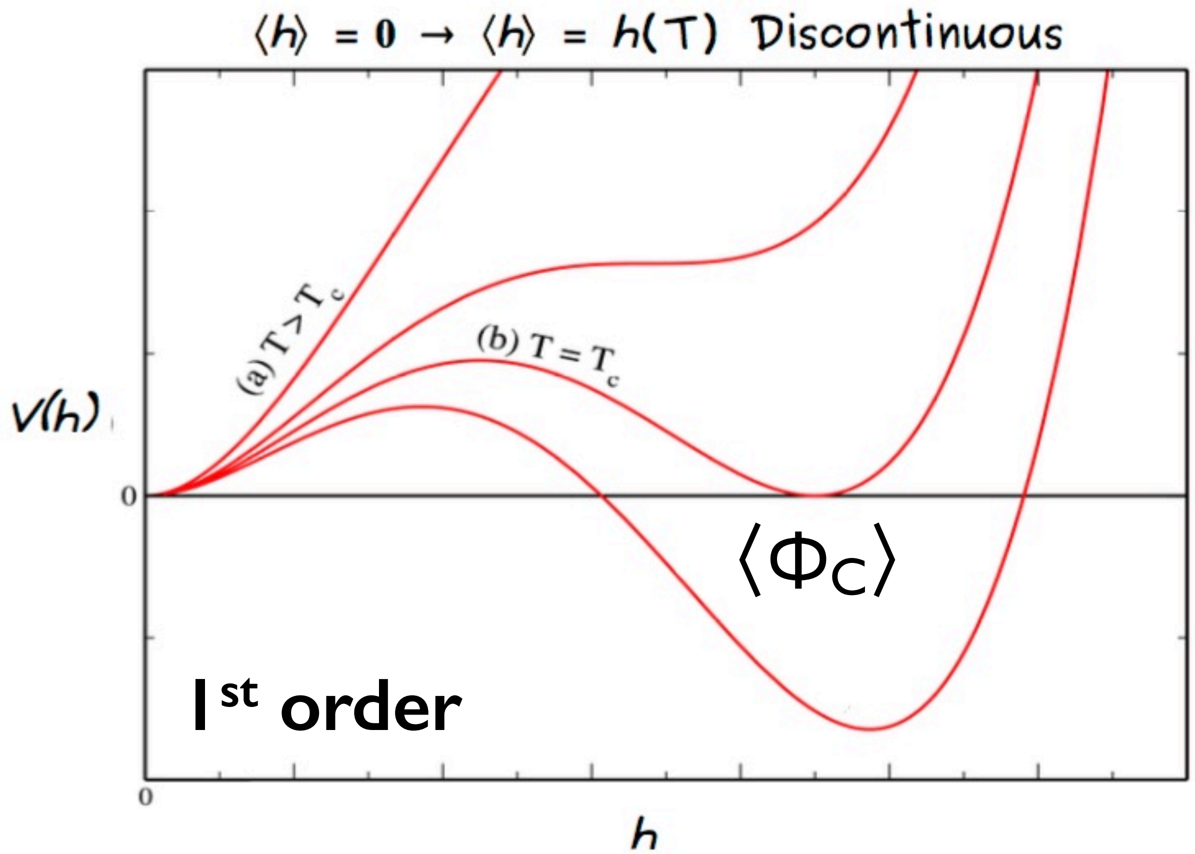

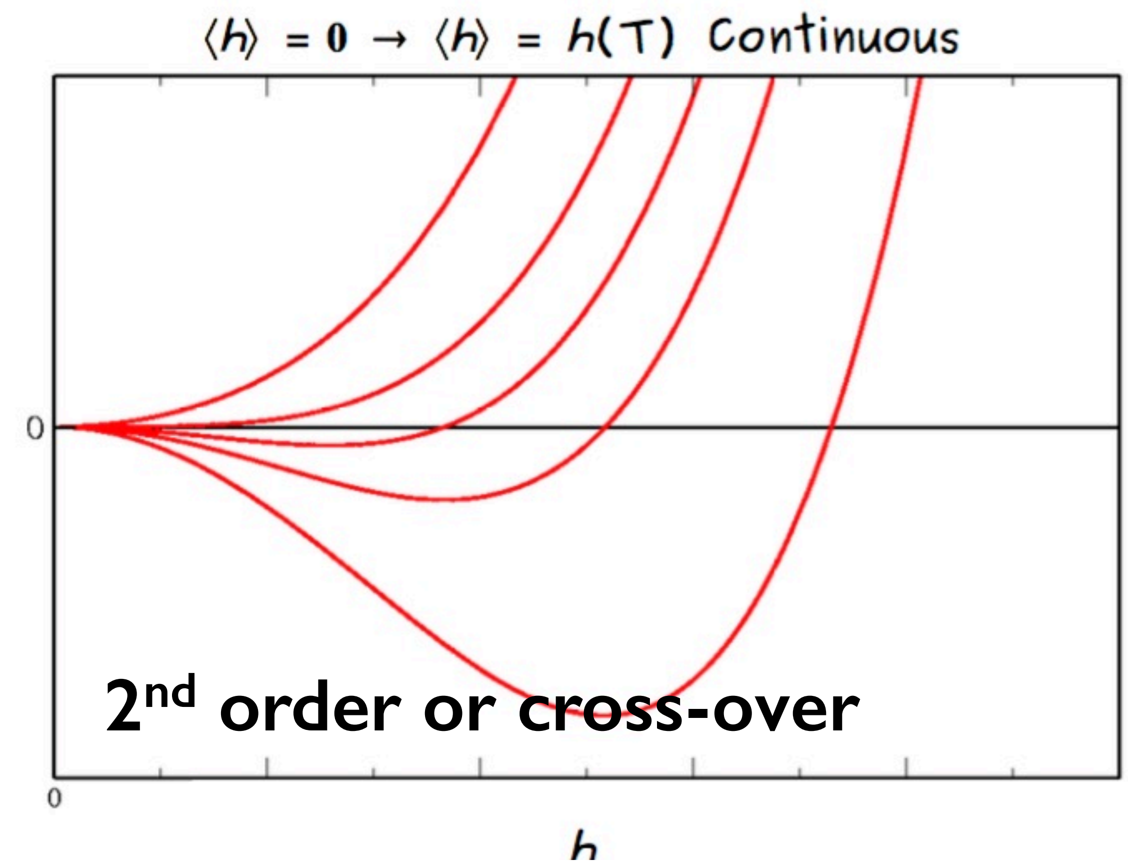

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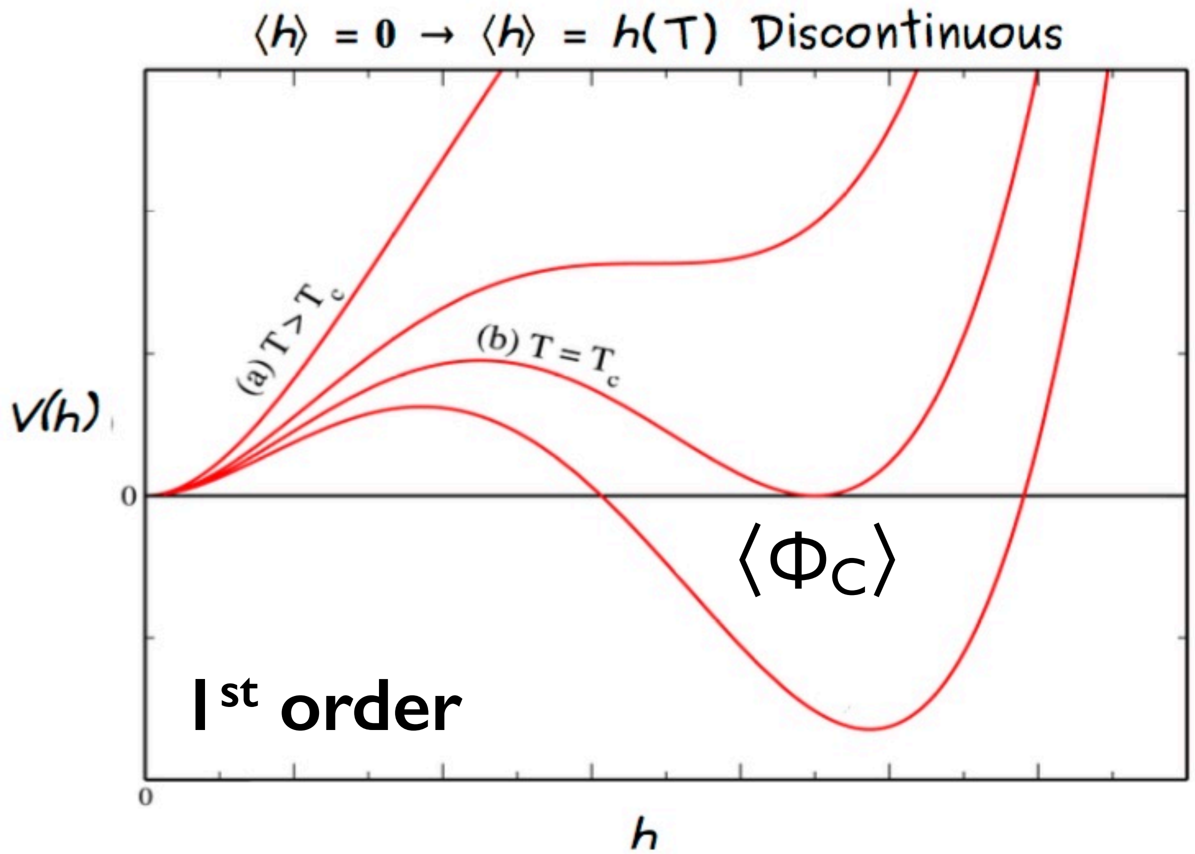

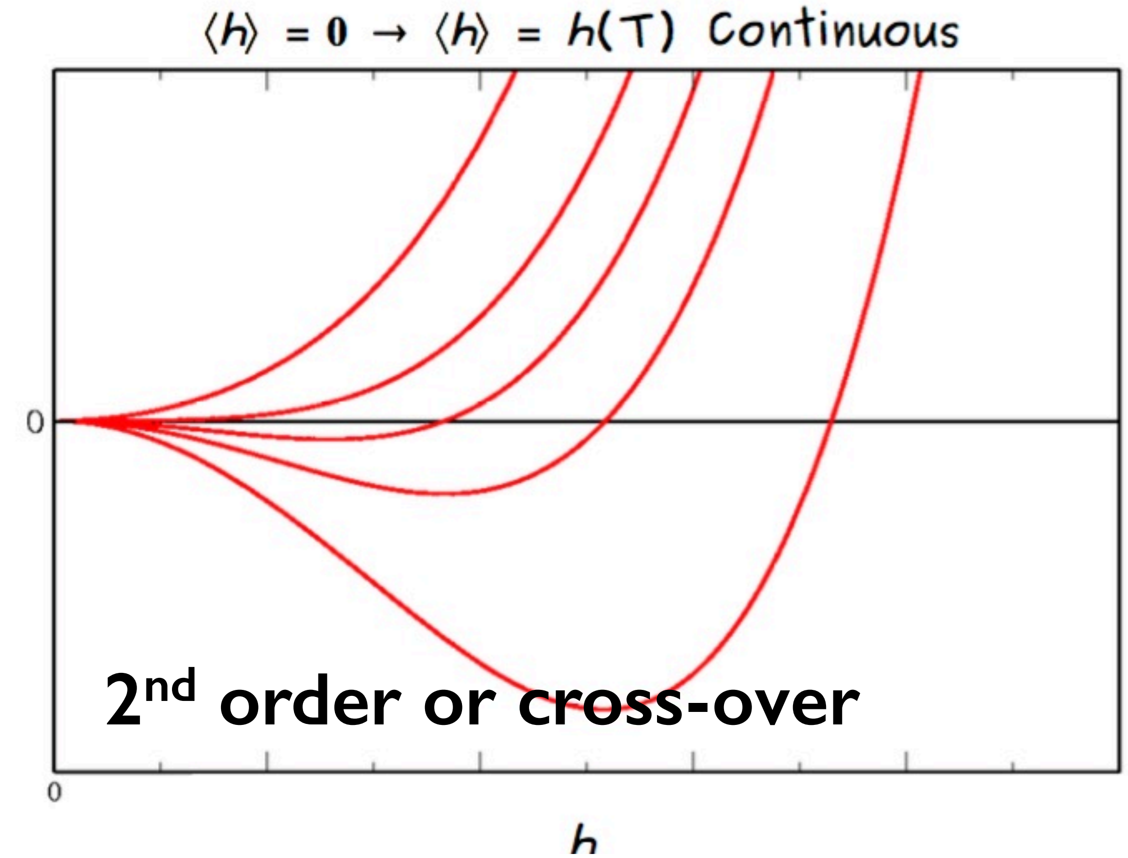

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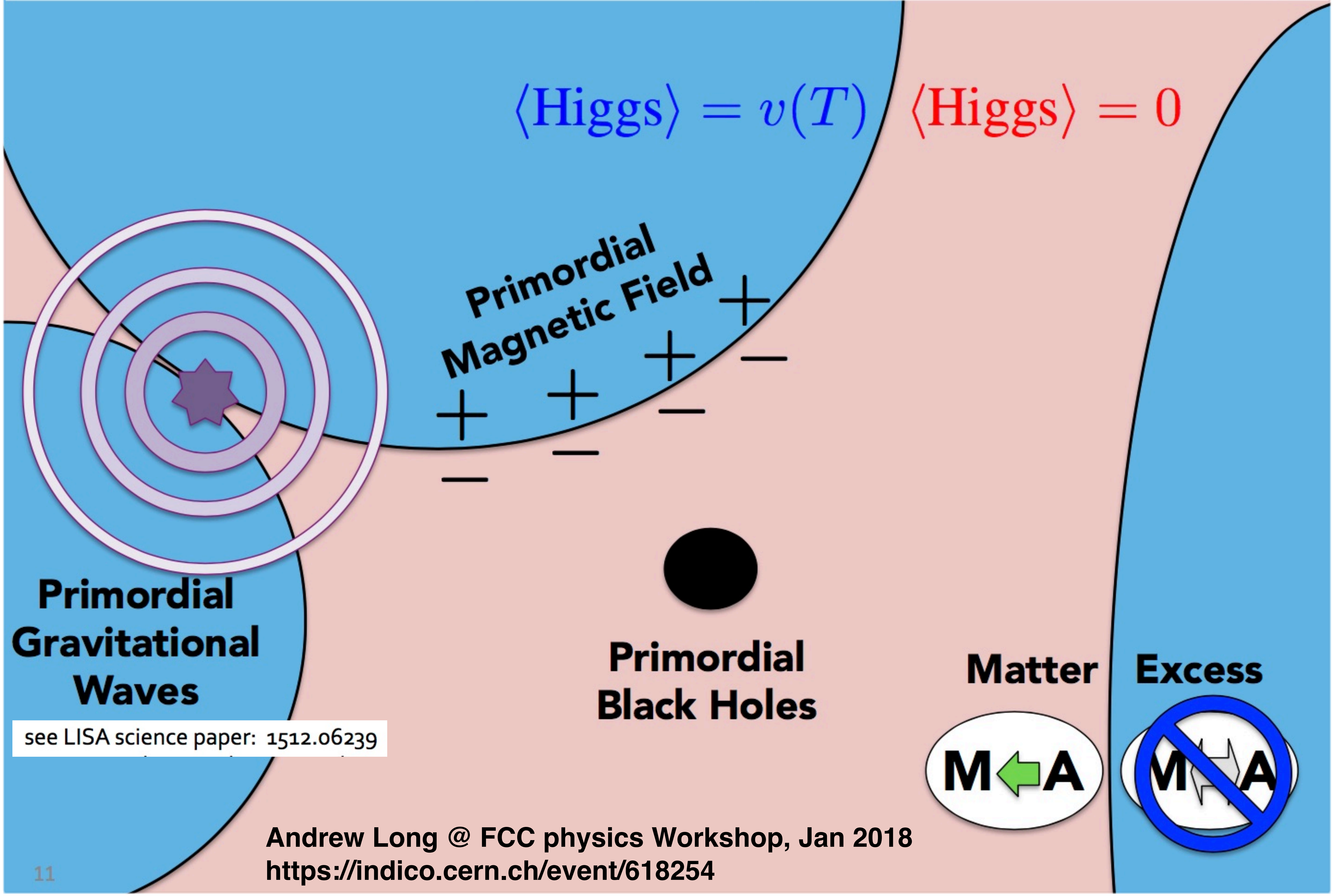
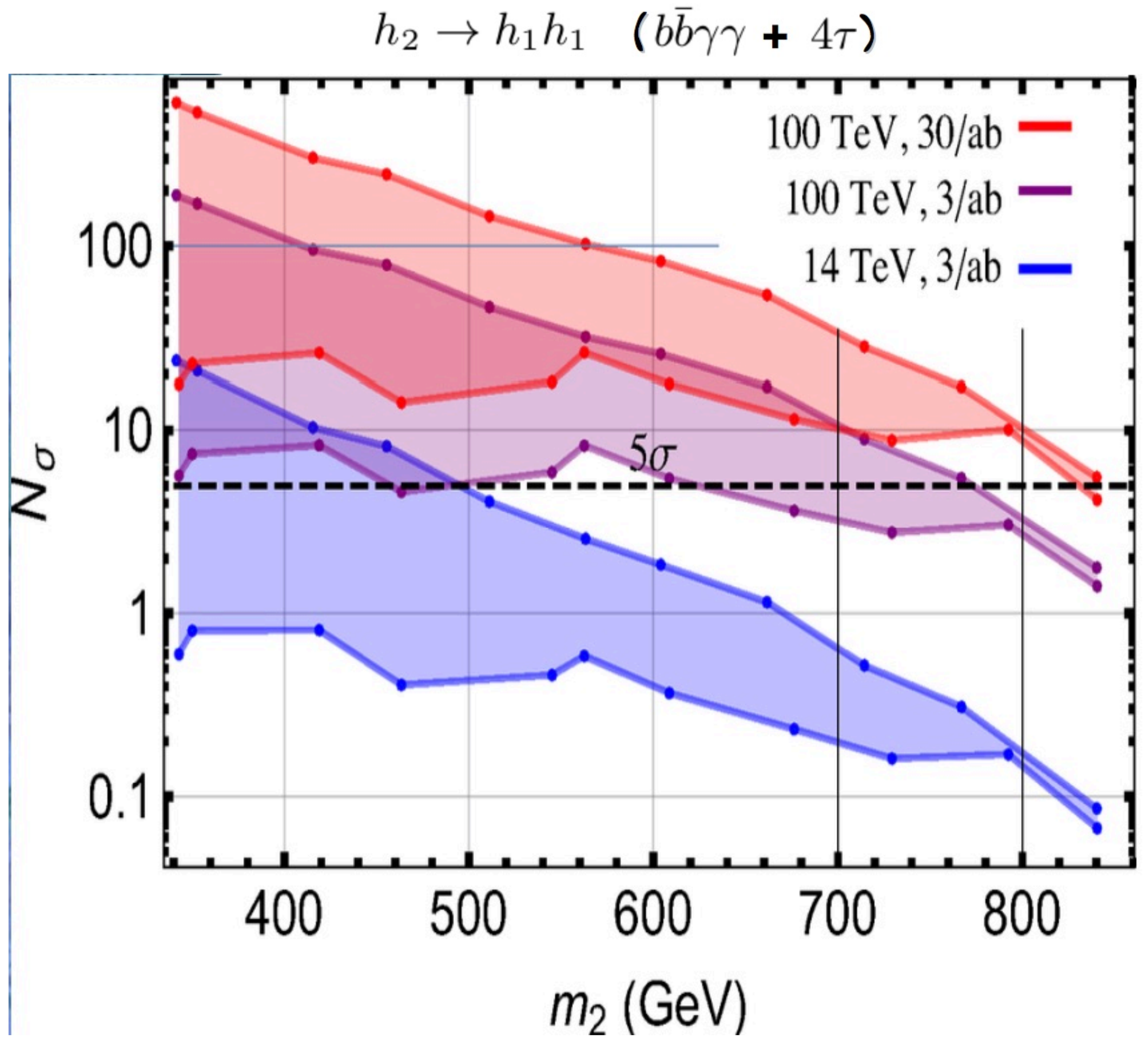
- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**

1st Order EWPT has profound implications for cosmology



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

What will FCC tell us about the existence of extra Higgs bosons enabling a 1st order EWPT?



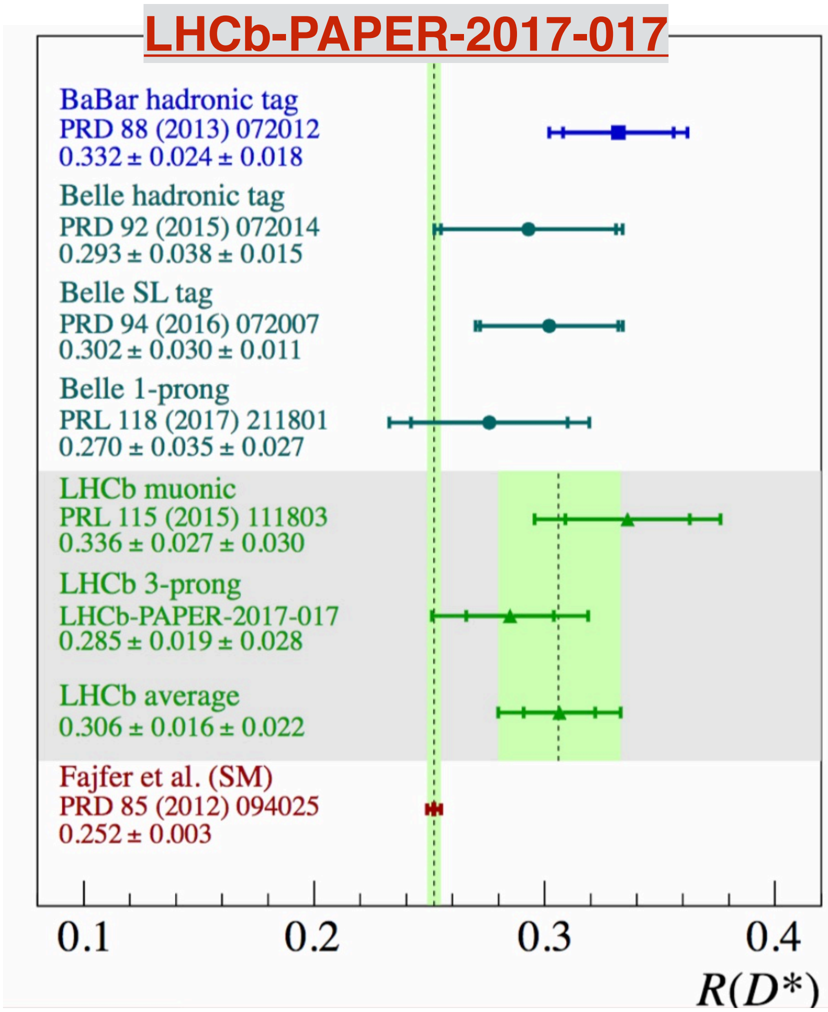
[Kotwal, No, Ramsey-Musolf, Winslow, arXiv:1605.06123](https://arxiv.org/abs/1605.06123)

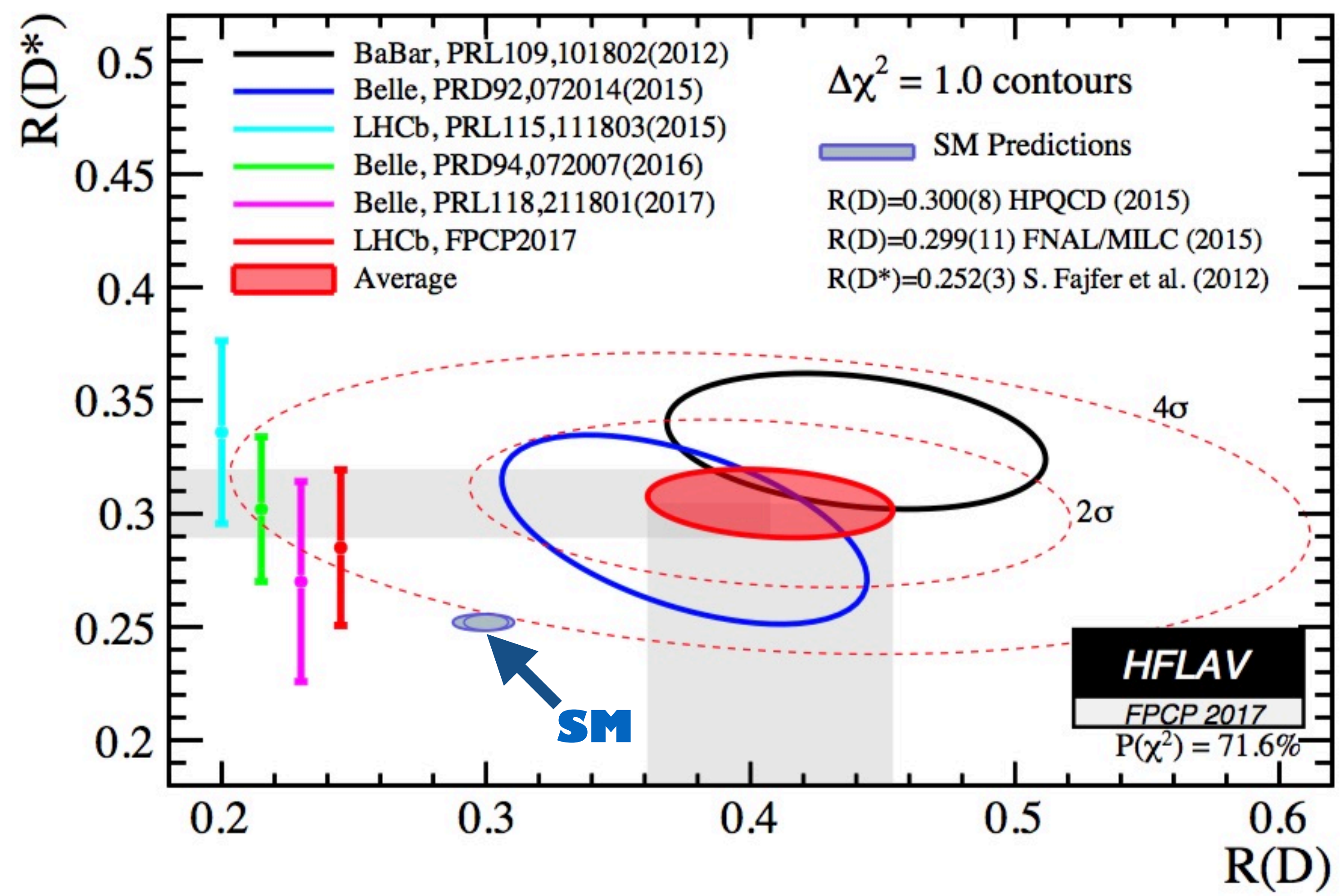
Flavour anomalies at LHC & Bfact's

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

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

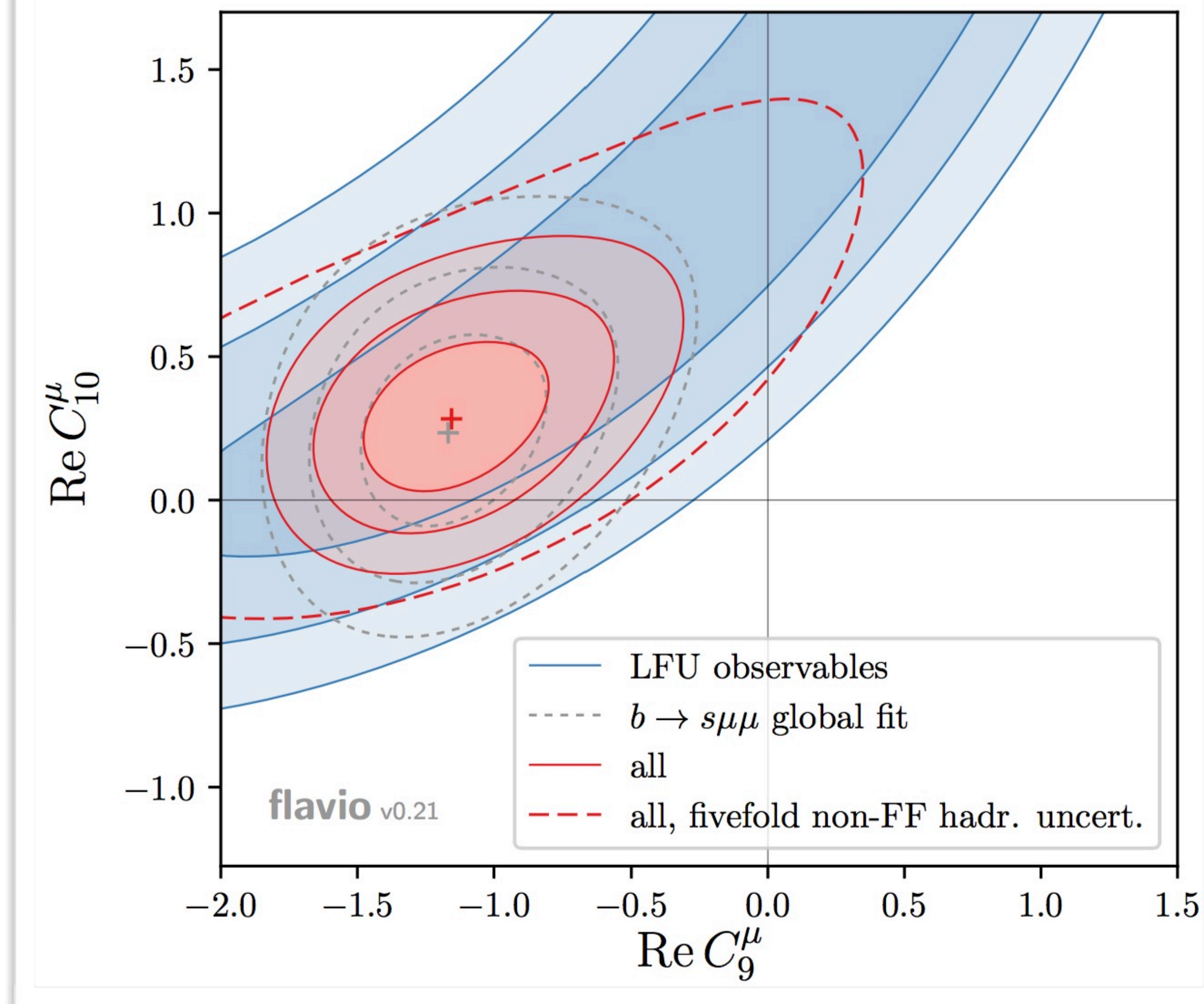
m_{ll} [mass range]	SM	Exp.
$R_K{}^{[1-6]}$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^*}{}^{[1.1-6]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.069} \pm 0.047$
$R_{K^*}{}^{[0.045,1.1]}$	0.91 ± 0.03	$0.660^{+0.110}_{-0.070} \pm 0.024$

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

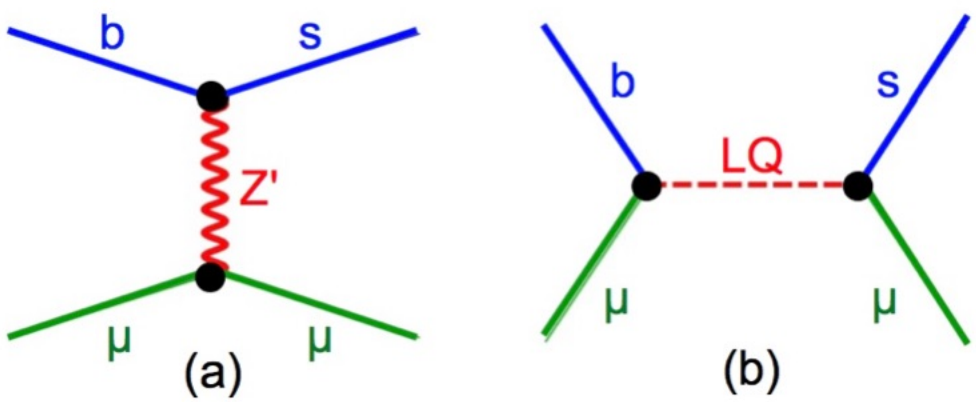
Example of EFT interpretation of R_K

Altmannshoffer et al, arxiv:1704.05435

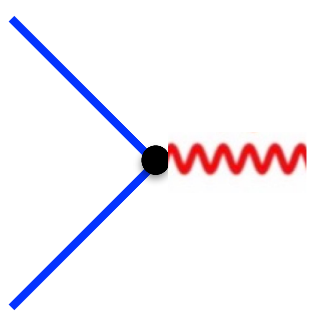
$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



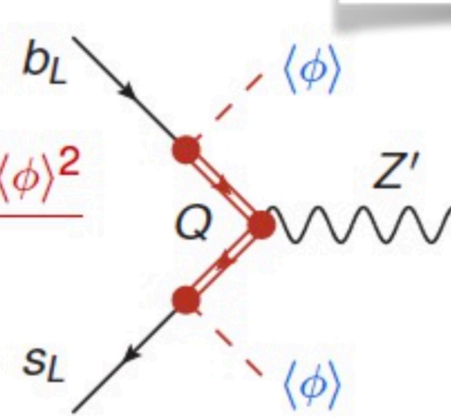
Possible explicit realizations:



where, e.g. ,



$\Rightarrow$ $\dfrac{g' Y_{Qb} Y^*_{Qs} \langle\phi\rangle^2}{2m_Q^2}$



Upper limits on Z' and Leptoquark masses are model-dependent, and constrained also by other low-energy flavour phenomenology, but the mass range is upper limited

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

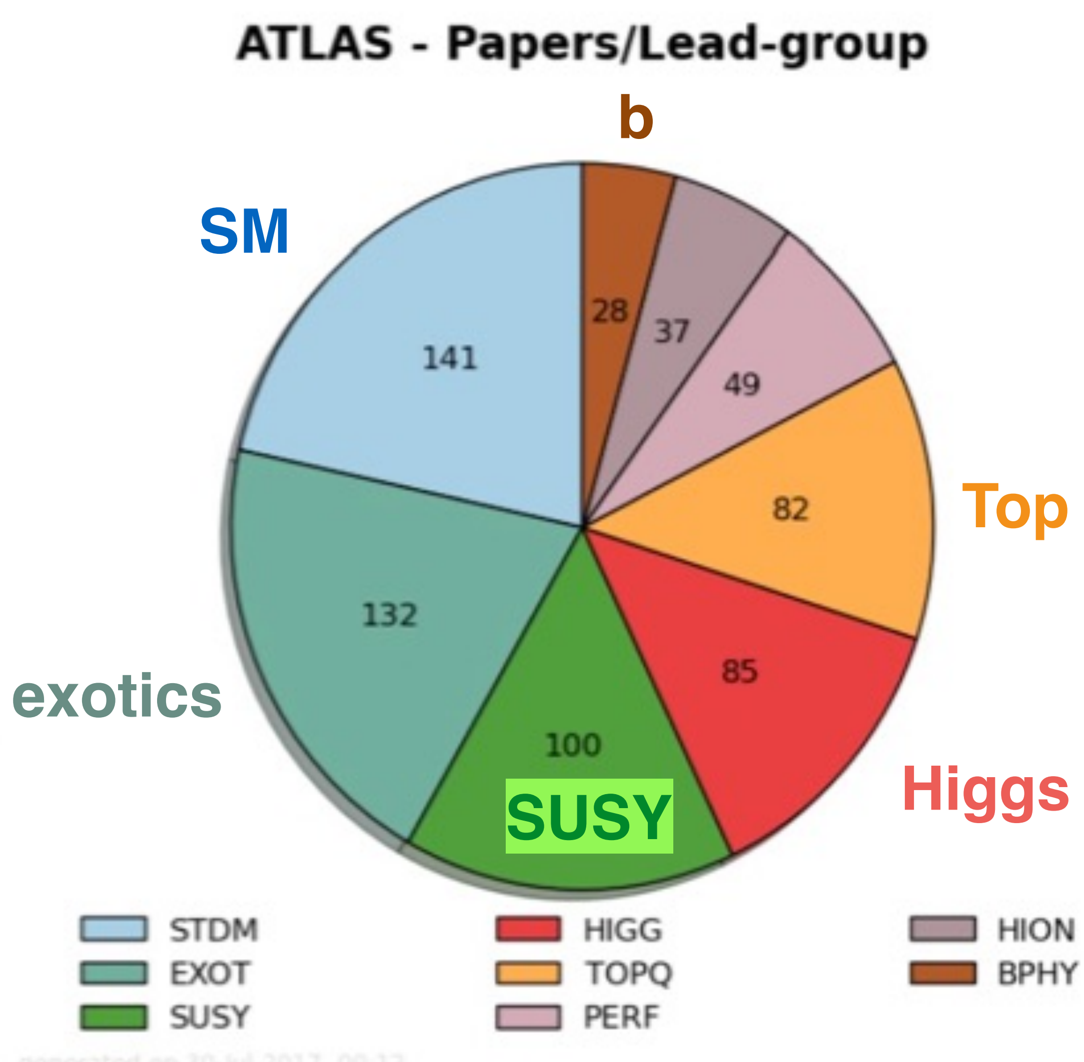
See eg Allanach, Gripaios & You, 1710.06363

LHC scientific production (ATLAS, CMS, LHCb)

Papers published/submitted to refereed journals

ATLAS	670
CMS	650
LHCb	396

Programme diversity (ATLAS example, similar stats for the others)



65% of the papers on measurements (ie on "the real world")

35% on searches

Remarks

- These 1700 papers reflect the underlying existence, at the LHC, of 100's of scientifically "independent" experiments, which historically would have required different detectors and facilities, built and operated by different communities

- On each of these topics the LHC expts are advancing the knowledge previously acquired by dedicated facilities

    - HERA→PDFs, B-factories→flavour, RHIC→HIs, LEP/SLC→EWPT, etc

- Even in the perspective of new dedicated facilities, LHC maintains a key role of complementarity (see eg $B_{(s)} \to \mu\mu$ etc)

This diversity, extended by the presence of the ee and ep, will represent a further a key virtue of the FCC physics programme

100 TeV ?

100 TeV ?

200 TeV ?

100 TeV ?

200 TeV ?

27 TeV in the LHC tunnel, replacing current magnets with those developed for FCC ?

=> High-Energy LHC (HE-LHC)

HE-LHC potential

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    - first estimates: **δλ~±30%** (https://arxiv.org/abs/1802.04319)
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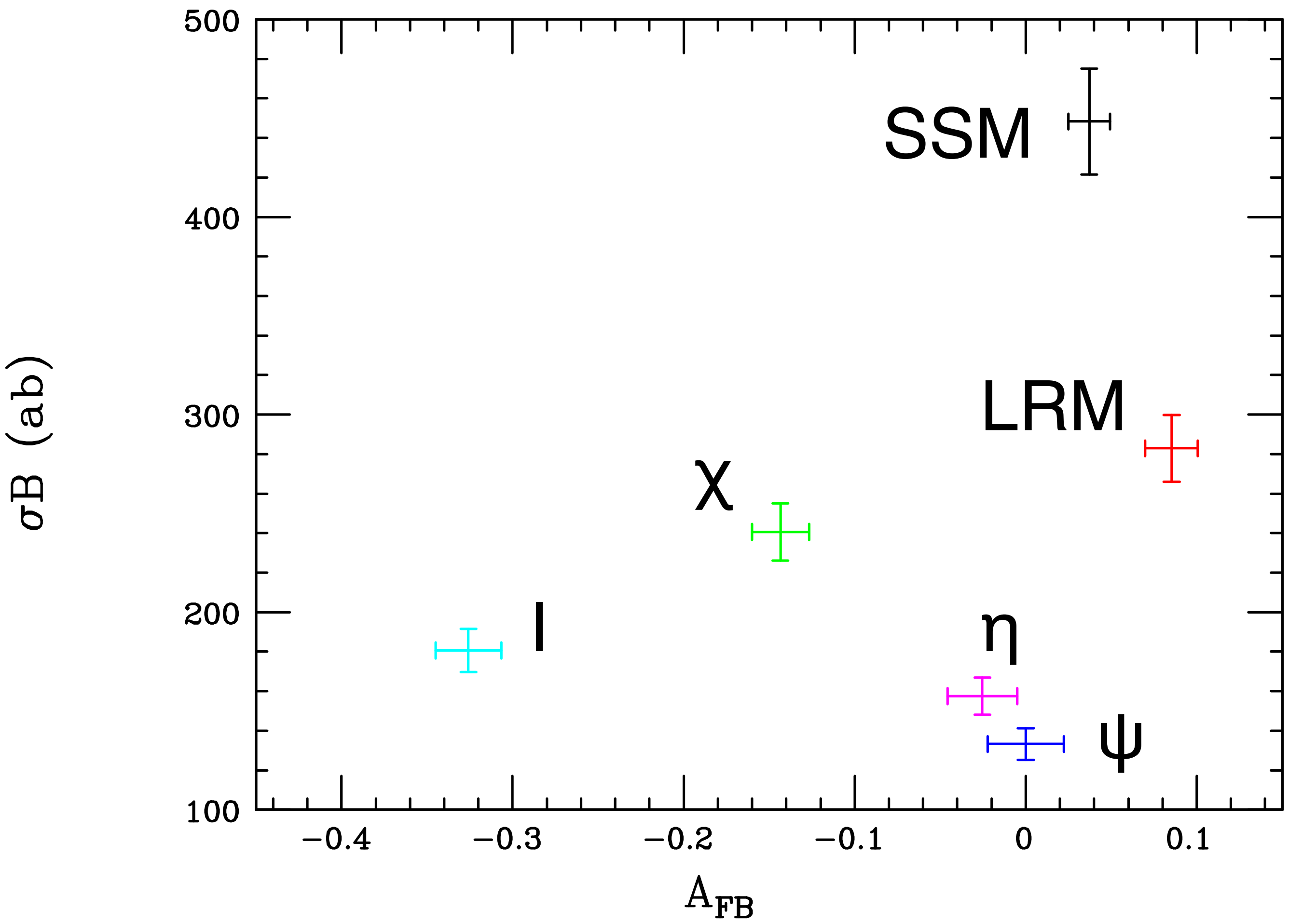
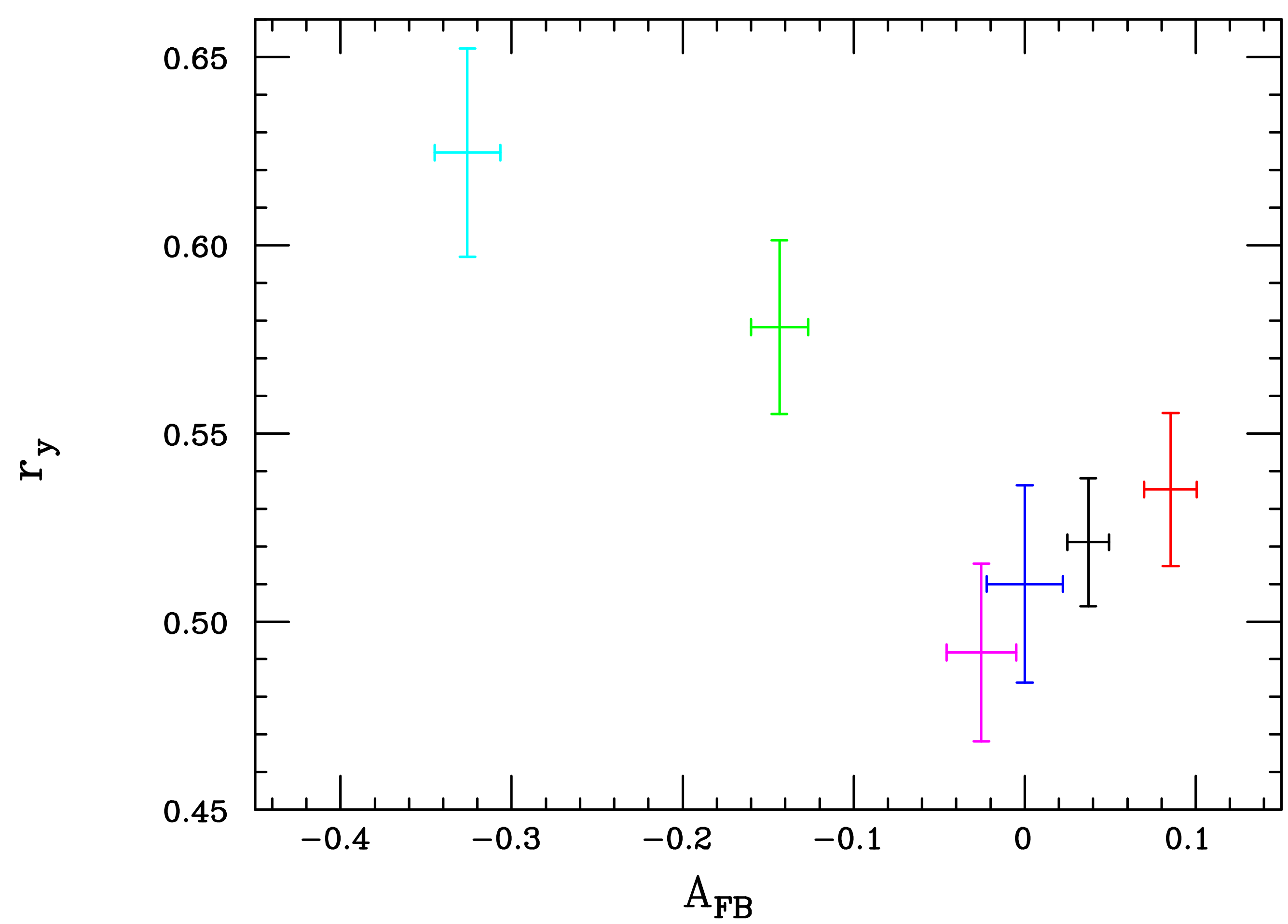
- **No-lose theorems:**
  - microscopic origin of current flavour anomalies?

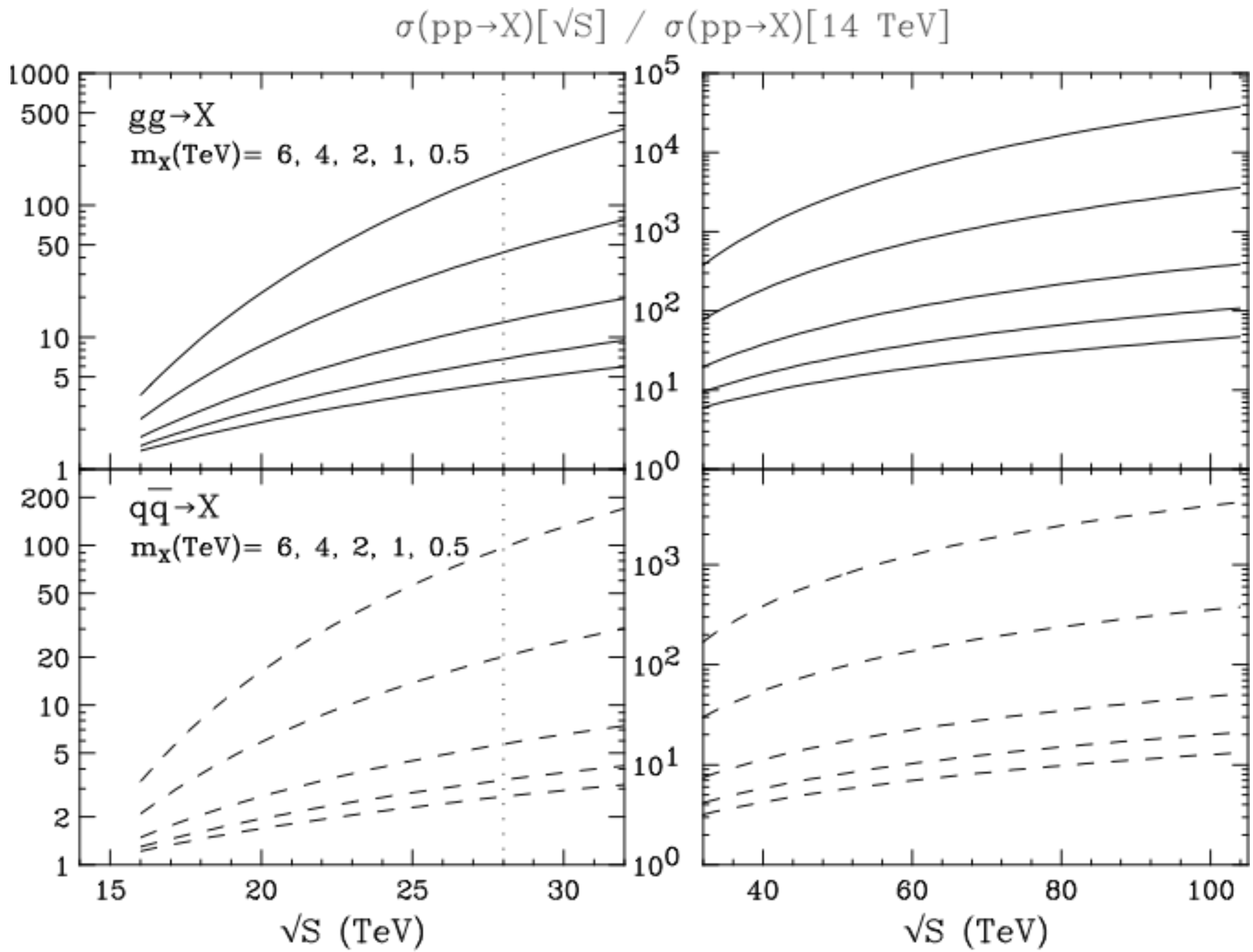
Characterization of Z' models within reach of LHC observation





Colours: different Z' models, leading to observation at HL-LHC in Z'->dilepton decay for m(Z')=6 TeV

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



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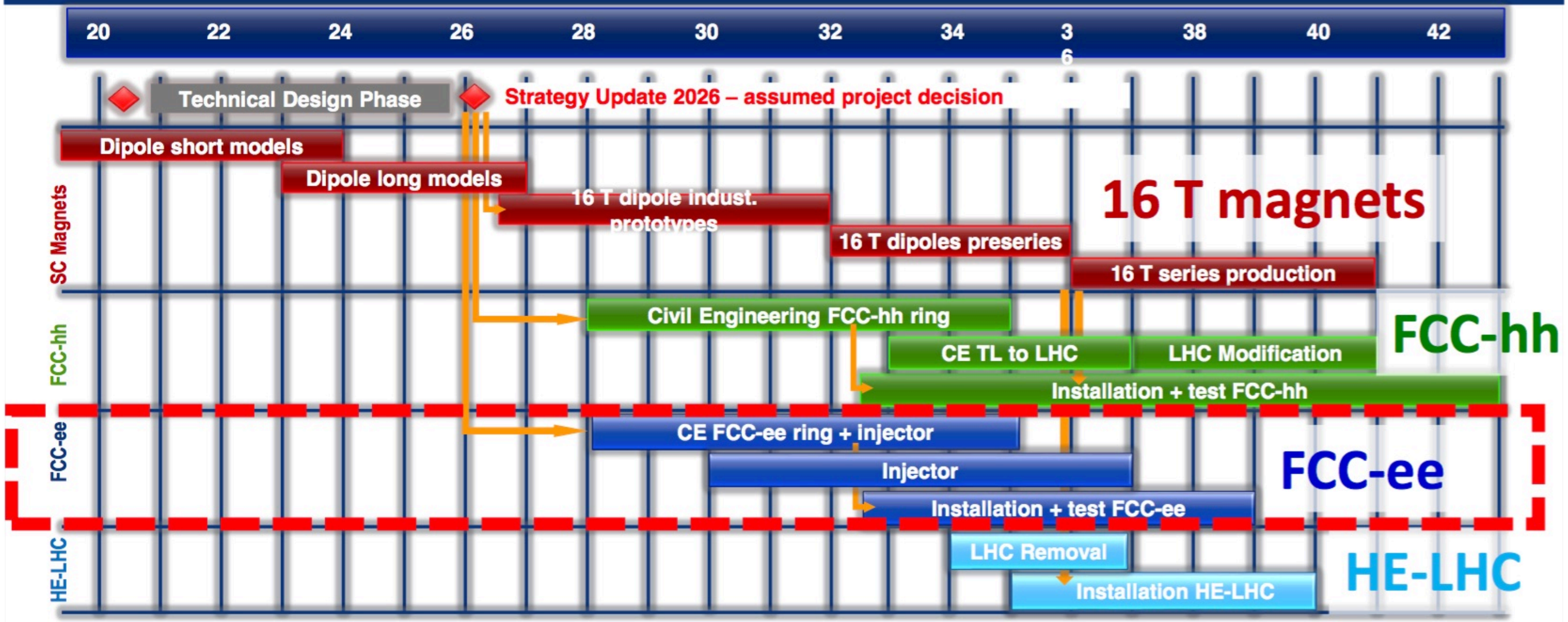
- etc.etc.

Technical Schedule for each the 3 Options



schedule constrained by 16 T magnets & CE
→ earliest possible physics starting dates

- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

M. Benedikt

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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 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.