Physics of future circular colliders

Séminaires du DPhP, CEA, Saclay
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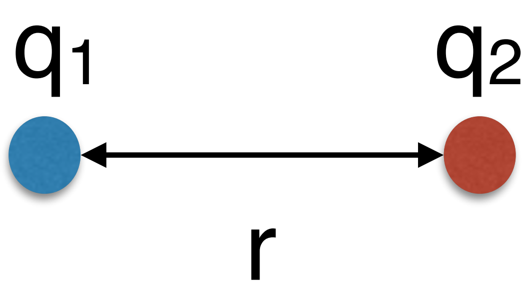
LHC → **Higgs**

what's next?

- 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)

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

Electromagnetic vs Higgs dynamics

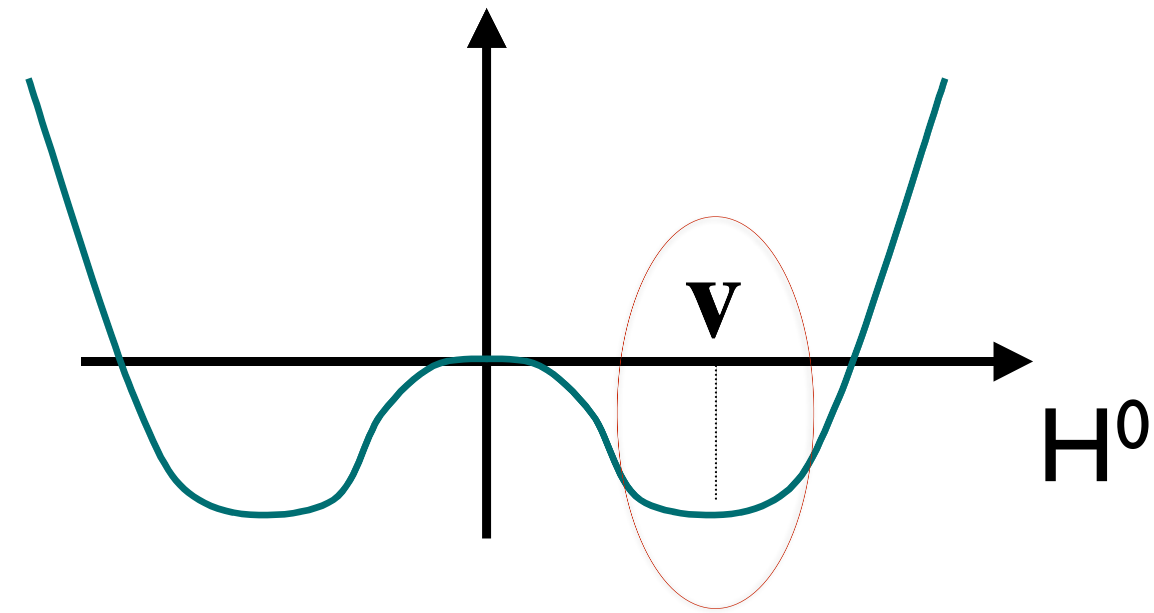


$$V(r) = + \frac{q_1 \times q_2}{r^1}$$

quantized, in units of fixed charge

sign fixed by photon spin

power determined by gauge invariance/charge conservation/Gauss theorem



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

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

both sign and value totally arbitrary

>0 to ensure stability, but otherwise arbitrary

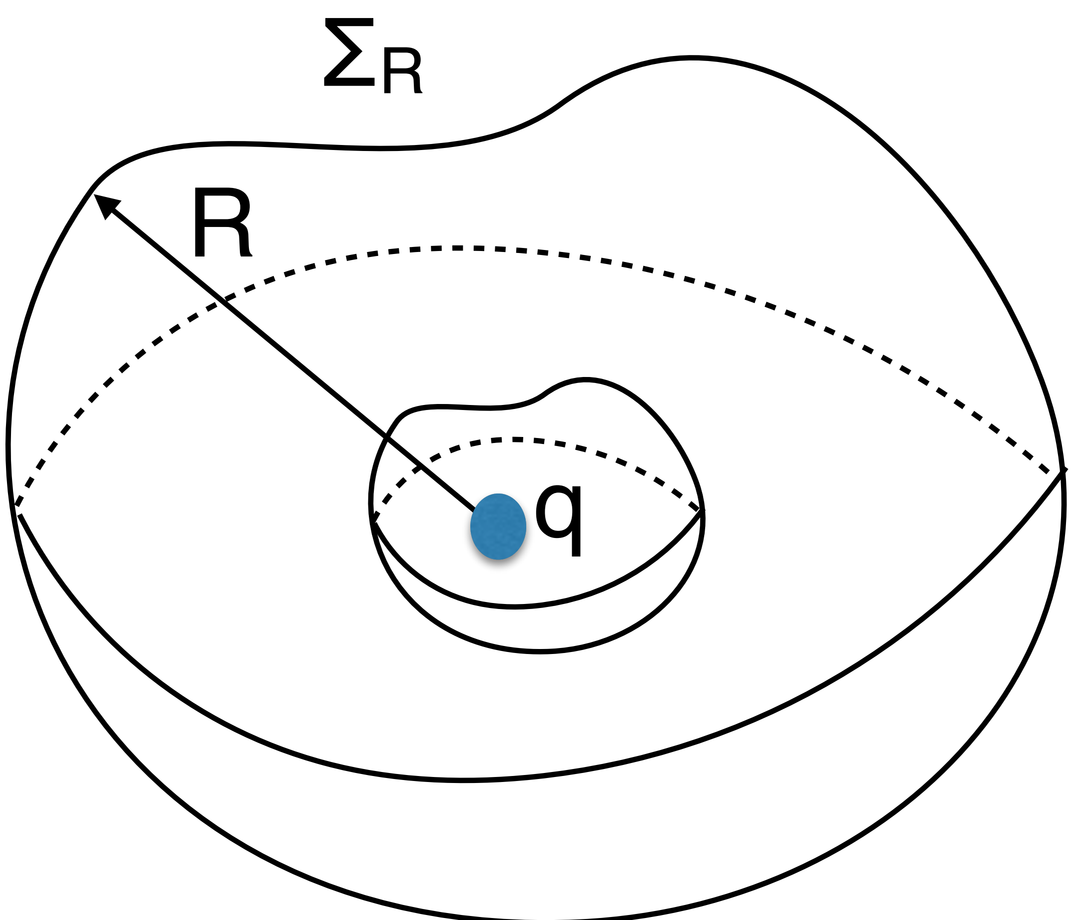
a historical example: superconductivity

- 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.

- 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

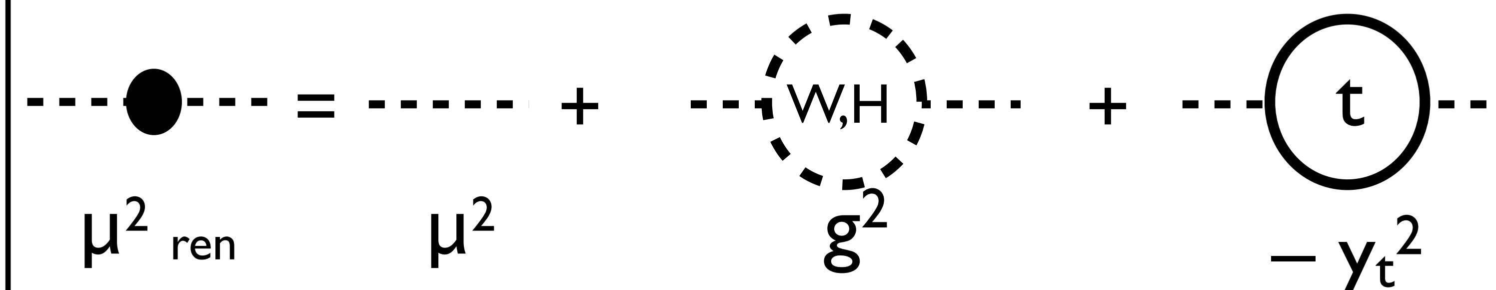
E&M



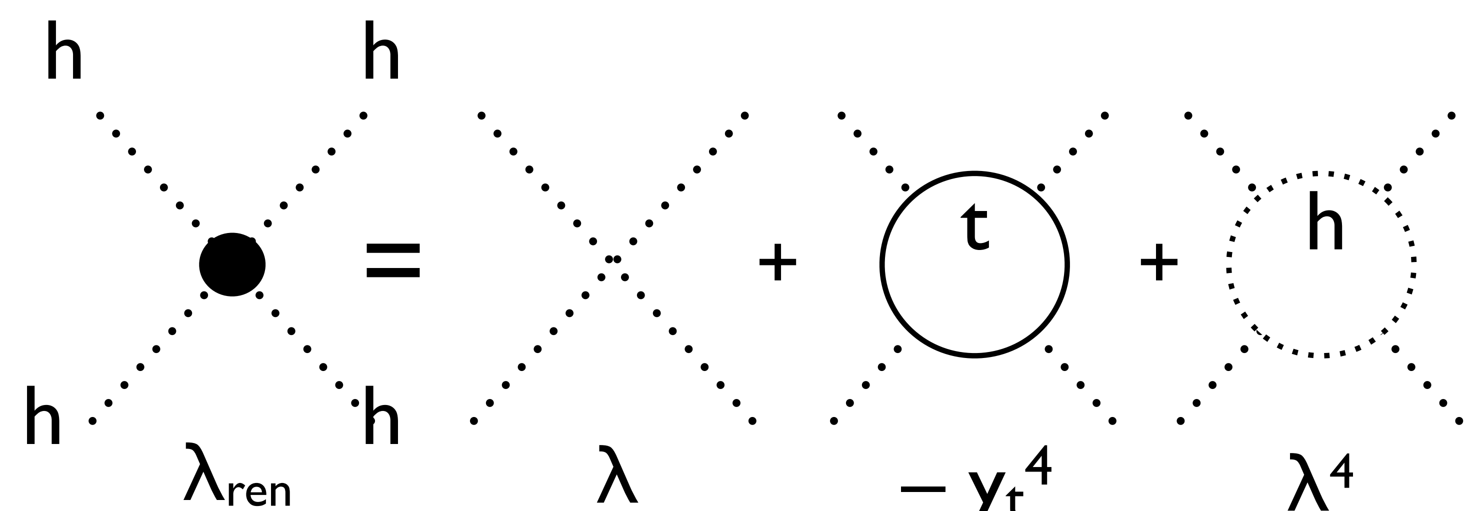
$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

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

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



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



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

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

bottom line

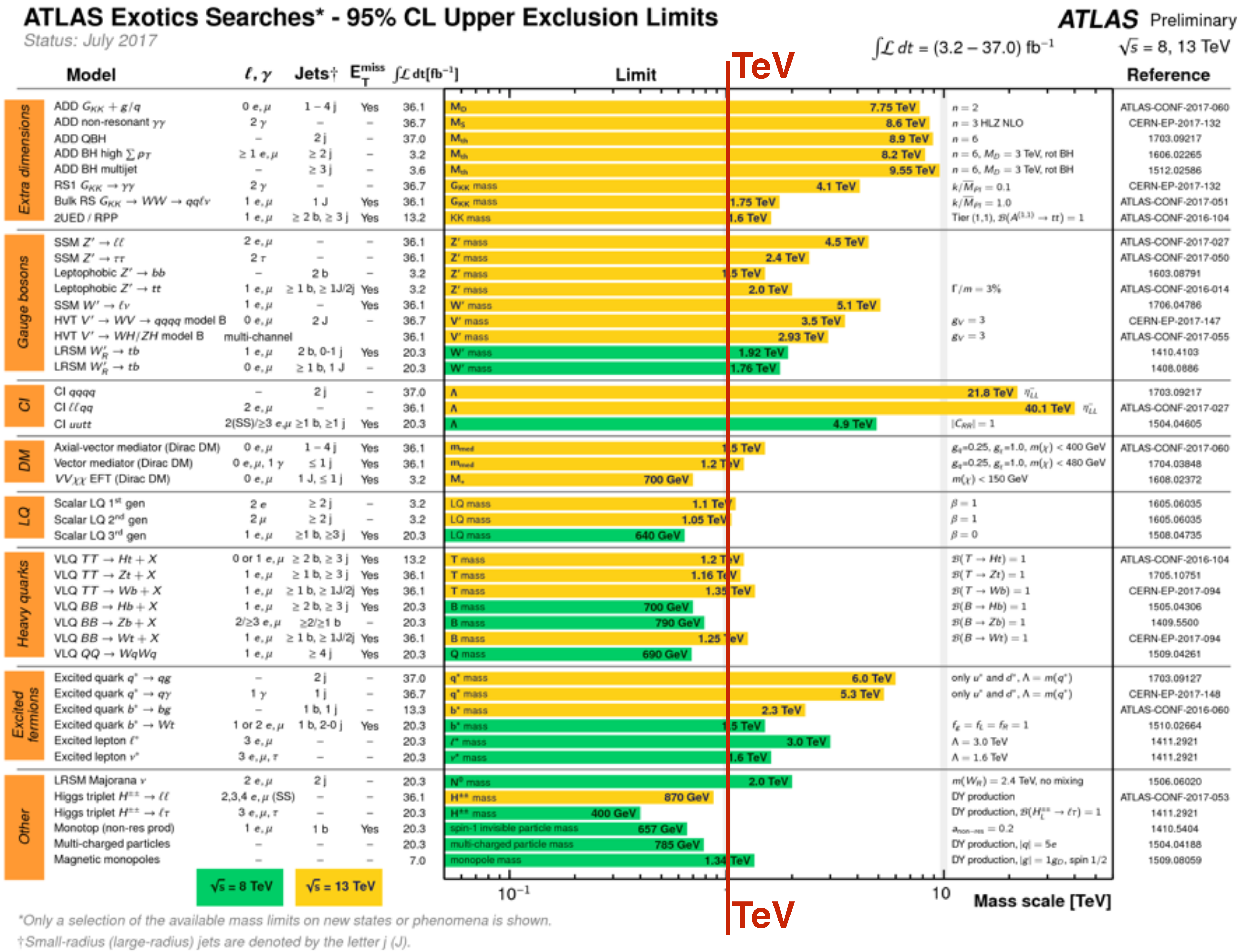
- To predict the properties of EM at large scales, we don't need to know what happens at short distance scales
- The Higgs dynamics is sensitive to all that happens at any distance scale shorter than the Higgs mass!!! A very unnatural **fine tuning** is required to protect the Higgs dynamics from the 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

  ⇒ **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?
- What protects the smallness of m_H / $m_{Plank,GUT}$ (hierarchy problem)?
- What's the origin of Dark matter / energy ?
- What's the origin of matter/antimatter asymmetry in the universe?
- What's the origin of neutrino masses?
- … *(flavour, inflation, cosmological constant, ….*

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



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

The physics potential (the "case") of a future facility for HEP should be weighed against criteria such as:

(1) the **guaranteed deliverables:**

- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(2) the **exploration potential:**

- target broad and well justified BSM scenarios .... *but guarantee sensitivity to more exotic options*
- exploit both direct (large Q^2) and indirect (precision) probes

(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

CLIC

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

CDR 2012+ <u>update</u> '16

CDR: Conceptual Design Report

FCC hh ee he

CDR (end '18)

<u>100km tunnel</u>

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

<u>LHC tunnel: HE-LHC</u>

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

… 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

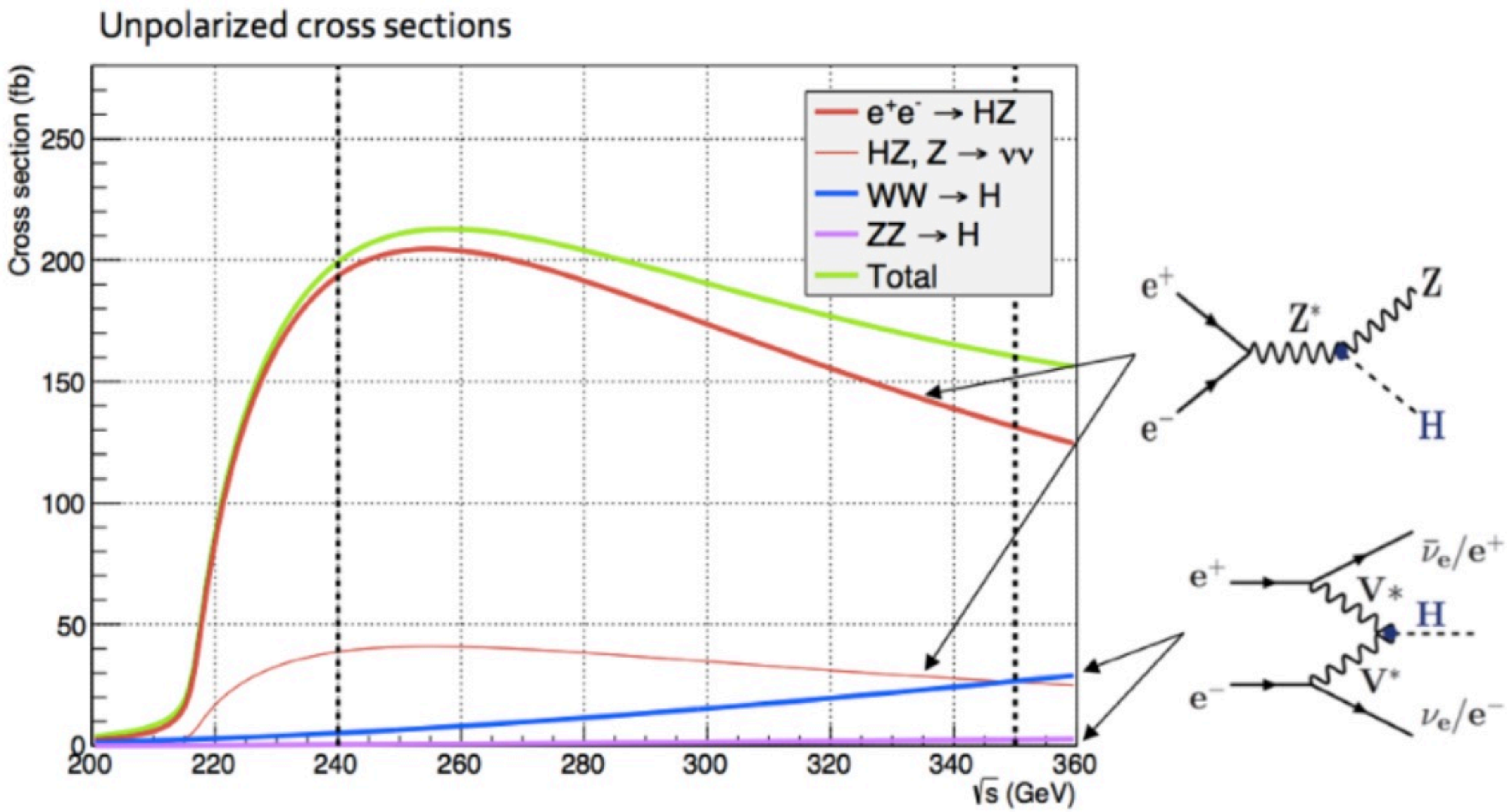
- e^+e^- @ 91, 240 GeV (but possibly 160 & 350)
- Future possible pp @ ~70 TeV and $e_{60GeV}\ p_{35TeV}$

The potential of a Future Circular Collider

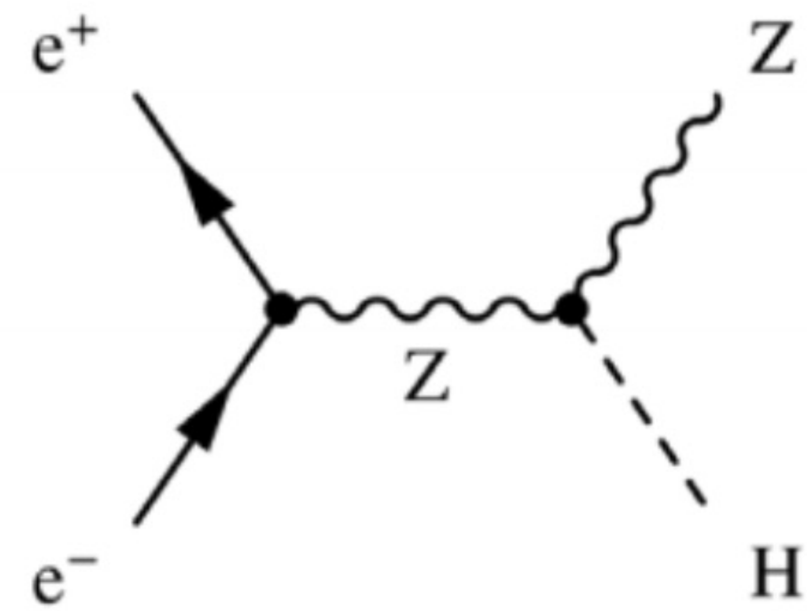
- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with unmatchable **precision and sensitivity**
- Exploration potential:
  - **mass reach enhanced** by factor ~ E / 14 TeV (will be 5–7 at 100 TeV, depending on integrated luminosity)
    - *statistics enhanced by several orders of magnitude for BSM phenomena brought to light by the LHC*
  - 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



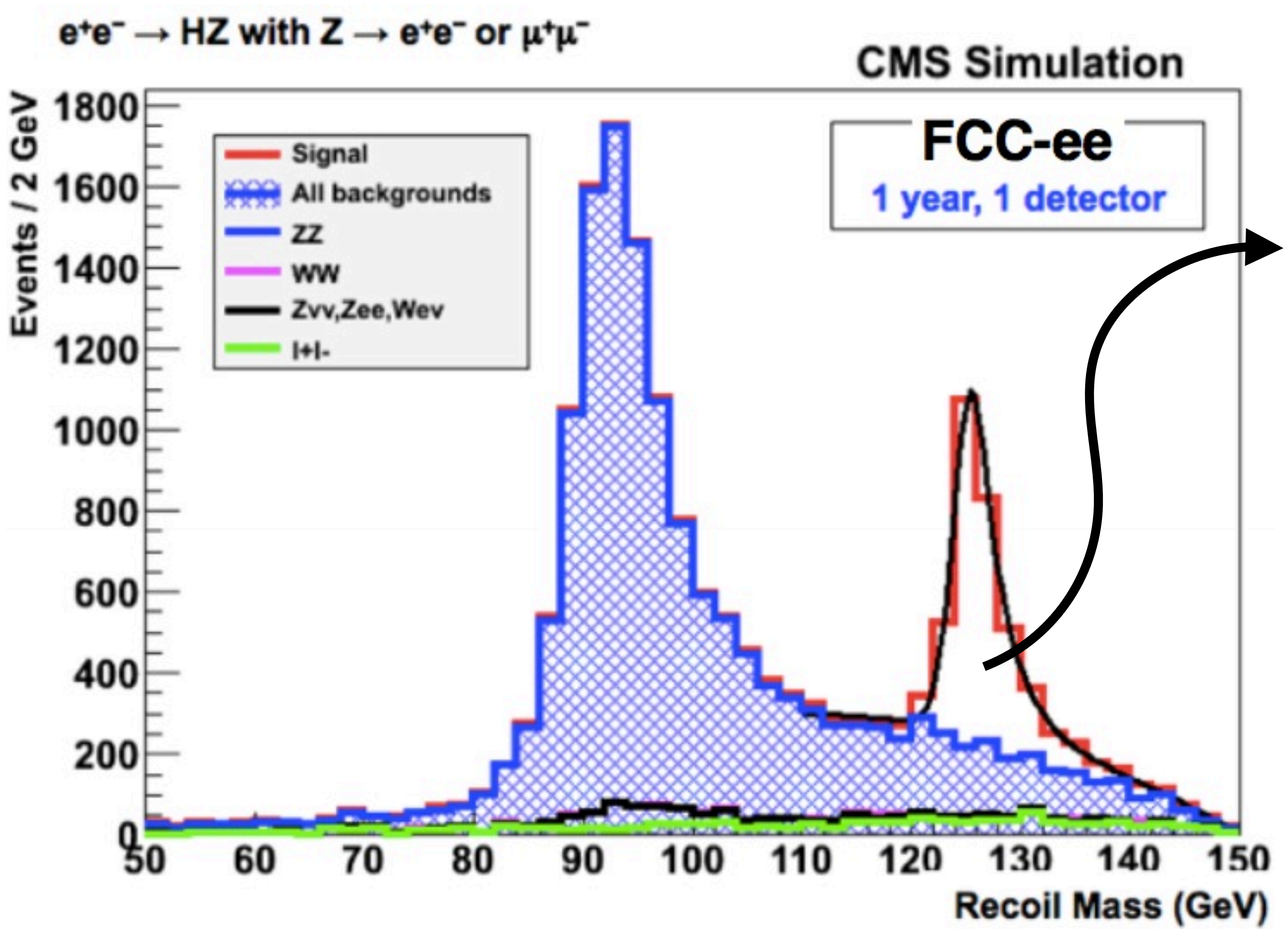
	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	5	1.5
# Higgs bosons from $e^+e^- \rightarrow HZ$	1,000,000	200,000
# Higgs bosons form fusion process	25,000	40,000



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) ∝ σ(ZH) ∝ g_{HZZ}^2

N(ZH[→ZZ]) ∝
σ(ZH) x BR(H→ZZ) ∝
g_{HZZ}^2 x g_{HZZ}^2 / **Γ(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

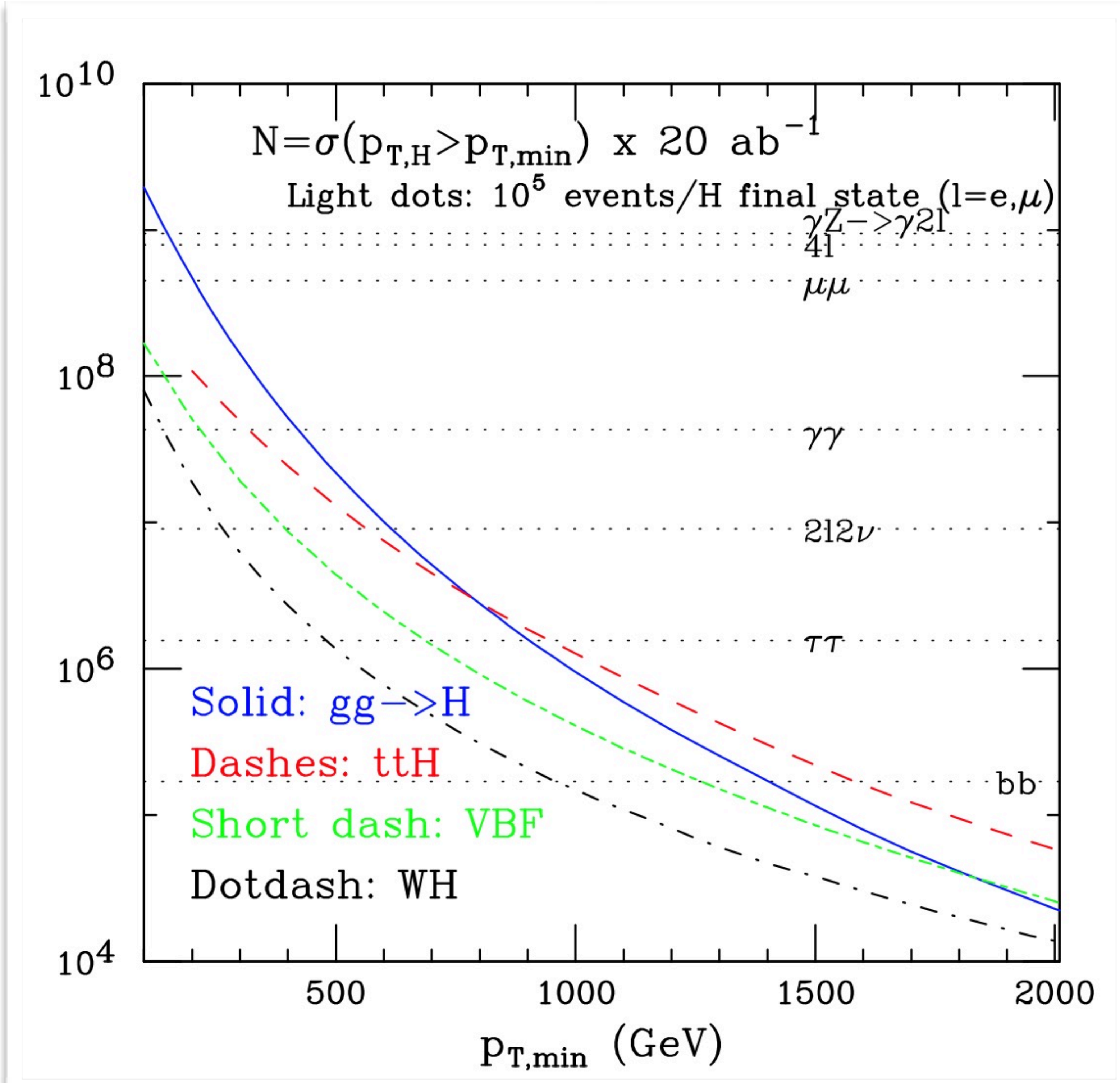
$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$

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

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

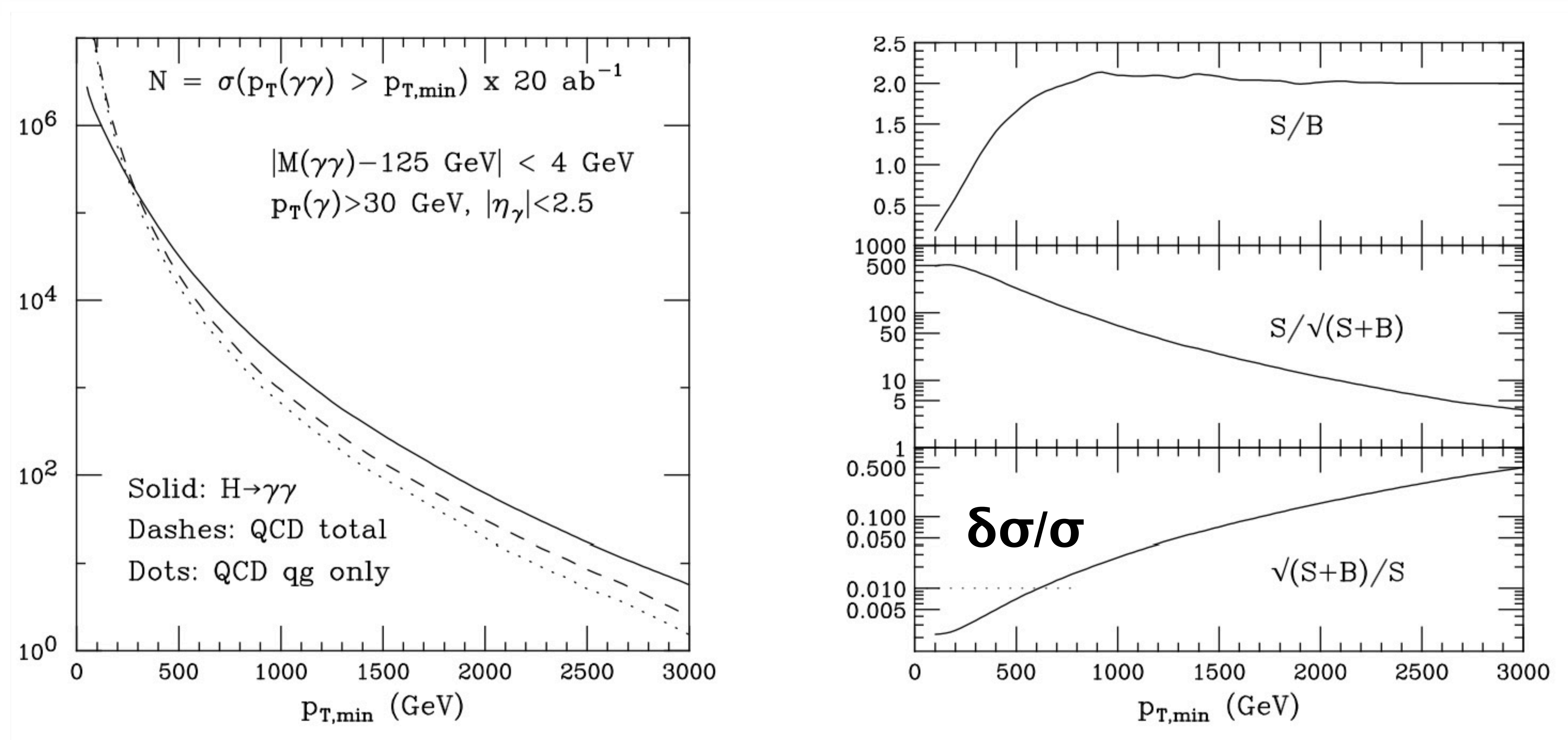
- Huge production rates imply:
  - can afford reducing statistics, with tighter kinematical cuts that reduce backgrounds and systematics
  - can explore new dynamical regimes, where new tests of the SM and EWSB can be done

H at large p_T



- Hierarchy of production channels changes at large p_T(H):
  - σ(ttH) > σ(gg→H) above 800 GeV
  - σ(VBF) > σ(gg→H) above 1800 GeV

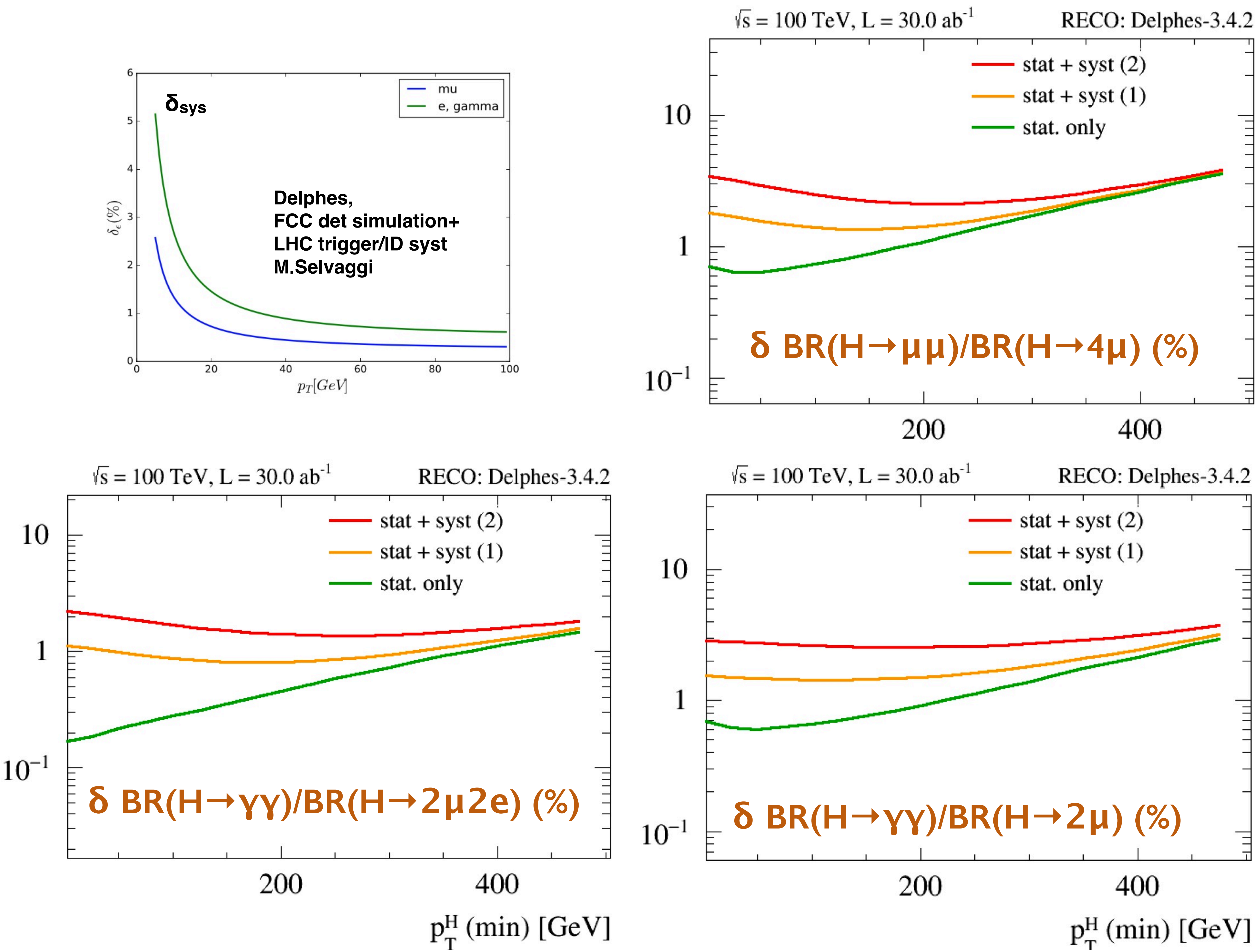
gg→H→γγ at large p_T



- At LHC, S/B in the H→γγ 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



δsys
mu
e, gamma
Delphes,
FCC det simulation+
LHC trigger/ID syst
M.Selvaggi
$\delta_\epsilon(\%)$
$p_T[GeV]$
√s = 100 TeV, L = 30.0 ab-1
RECO: Delphes-3.4.2
stat + syst (2)
stat + syst (1)
stat. only
δ BR(H→μμ)/BR(H→4μ) (%)
δ BR(H→γγ)/BR(H→2μ2e) (%)
δ BR(H→γγ)/BR(H→2μ) (%)
p_T^H (min) [GeV]

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

BR(H→inv)/BR(H→γγ)

tree-level neutral loop-level charged

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		
ss	H->φγ, under study		
BR_{inv}	< 0.45%	few 10^{-4}	
Γ_{tot}	1.5%		

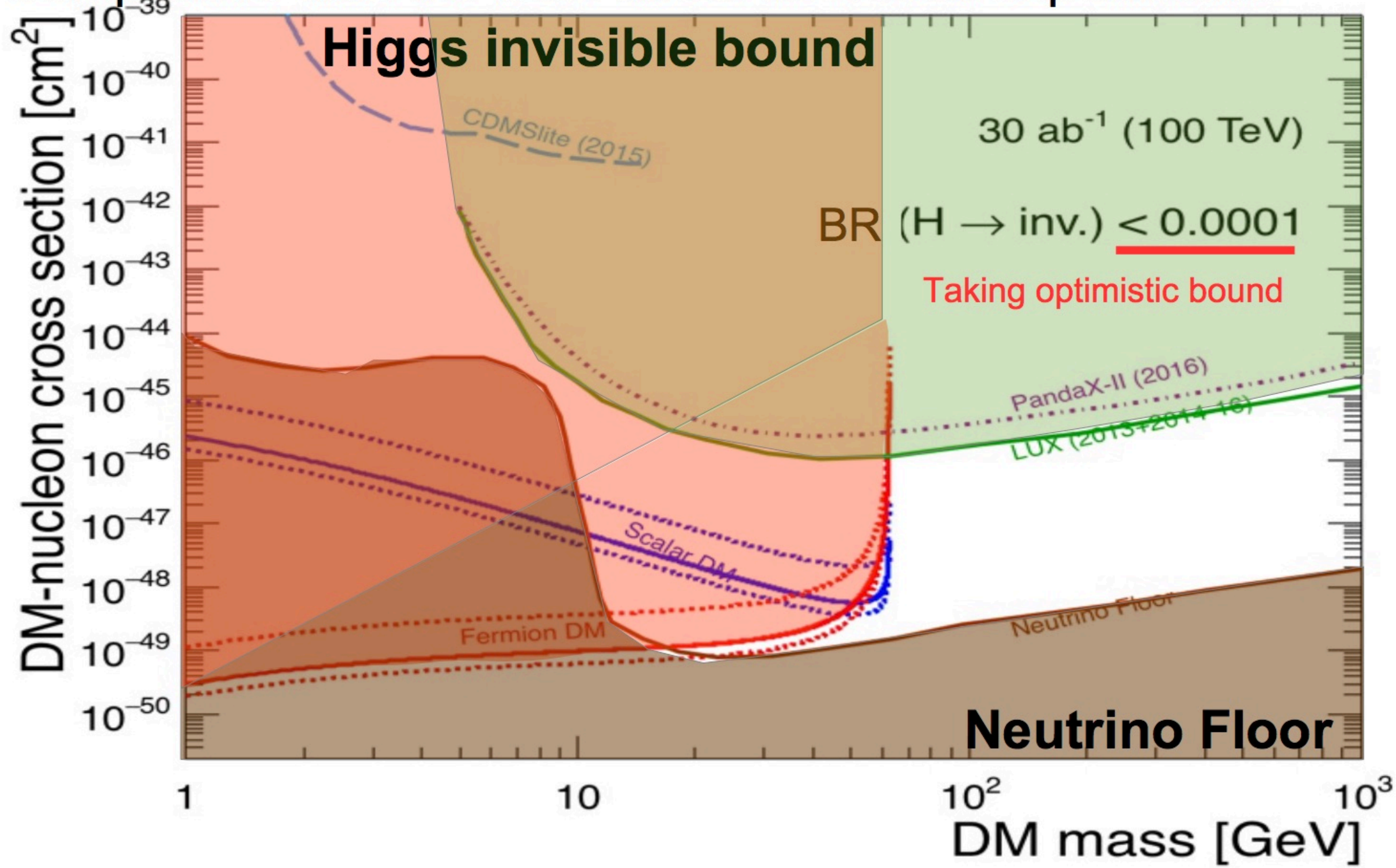
first probe of the Higgs potential beyond the 2-point function

sensitive to possible Higgs-to-DM decays

P.Harris & K.Hahn

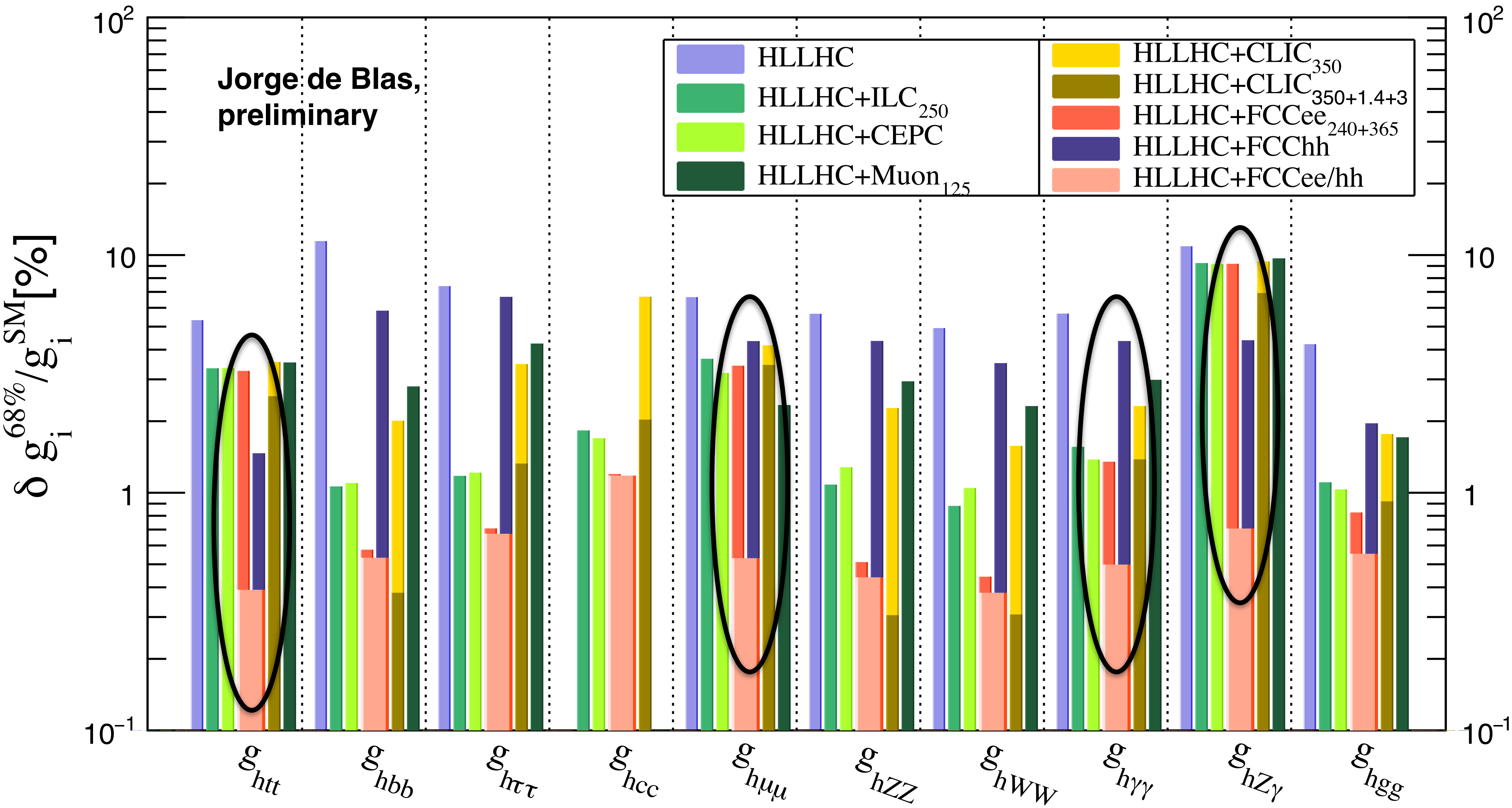
Impact on DM bounds

Competitive with the best direct detection experiments



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

Joint fit of Higgs couplings



High-Q^2 aspects

- We often talk about "**precise**" Higgs measurements. What we actually aim at is "**sensitive**" tests of the Higgs properties, where *sensitive* refers to the ability to reveal BSM behaviours.
- ***Sensitivity*** may not require extreme precision
    - Going after "sensitivity", rather than *just* precision, opens itself new opportunities …

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = |\,\langle f|L|i\rangle\,|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. δ*O*=1% ⇒ Λ ~ 2.5 TeV

For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

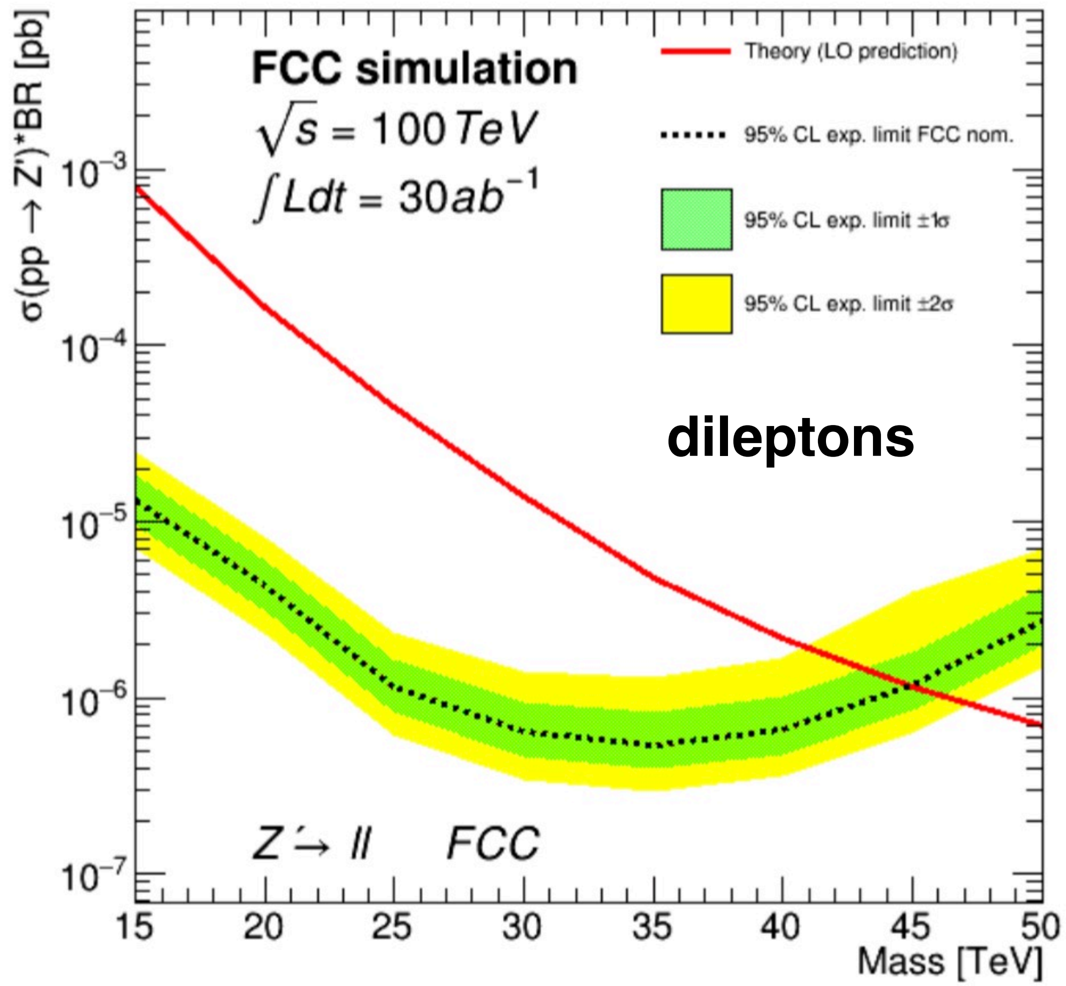
⇒ **kinematic reach** probes large Λ even if precision is "low"

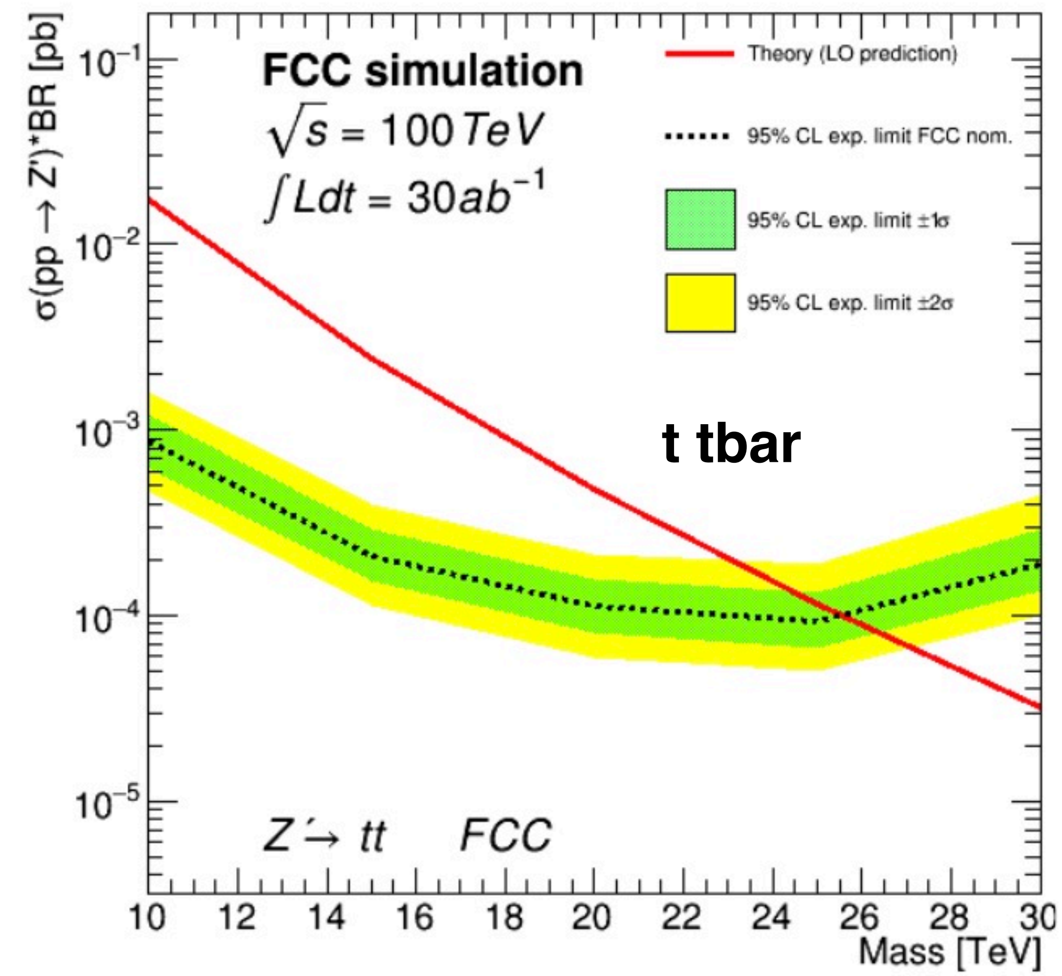
e.g. δ*O*=10% at Q=1.5 TeV ⇒ Λ~5 TeV

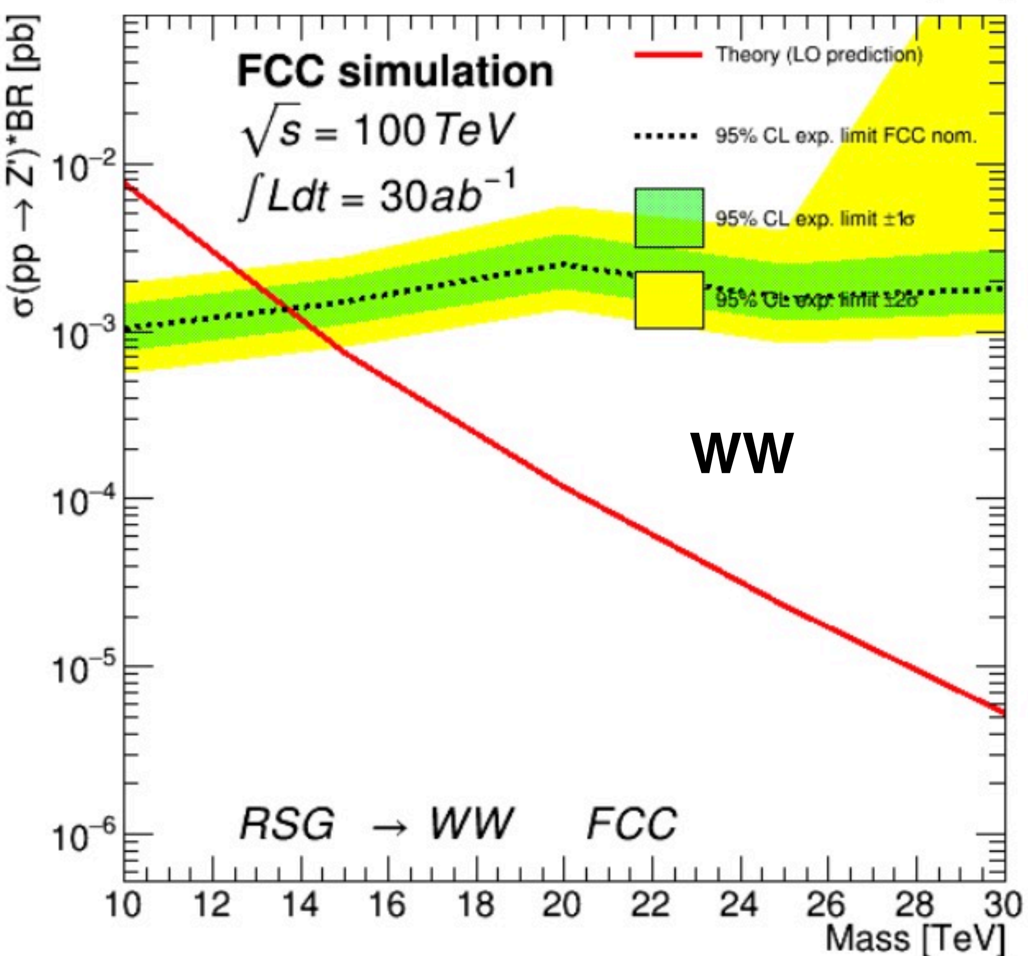
Complementarity between super-precise measurements at ee collider and large-Q studies at 100 TeV

Examples: direct discovery reach

Resonances: SSM Z'

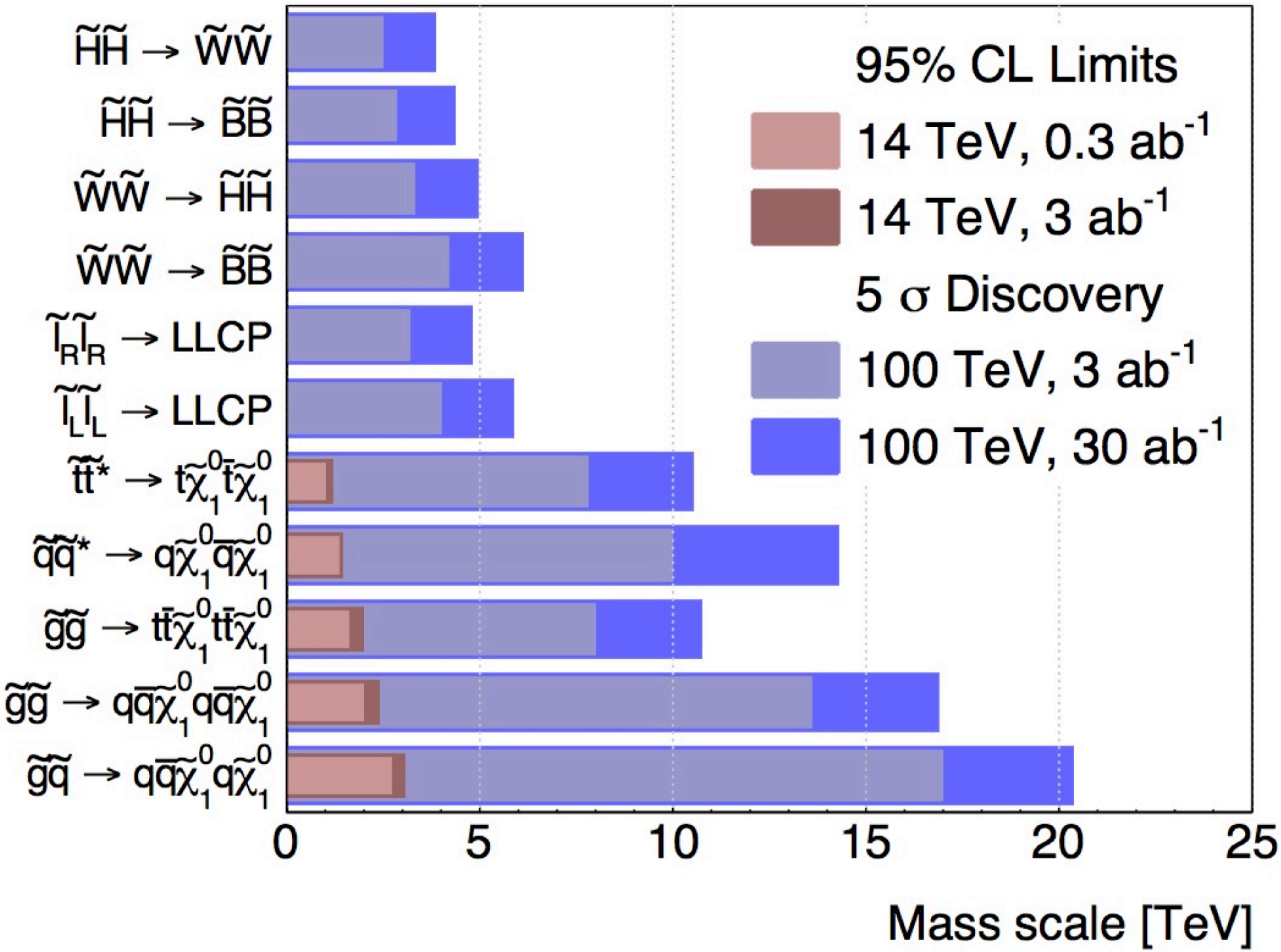




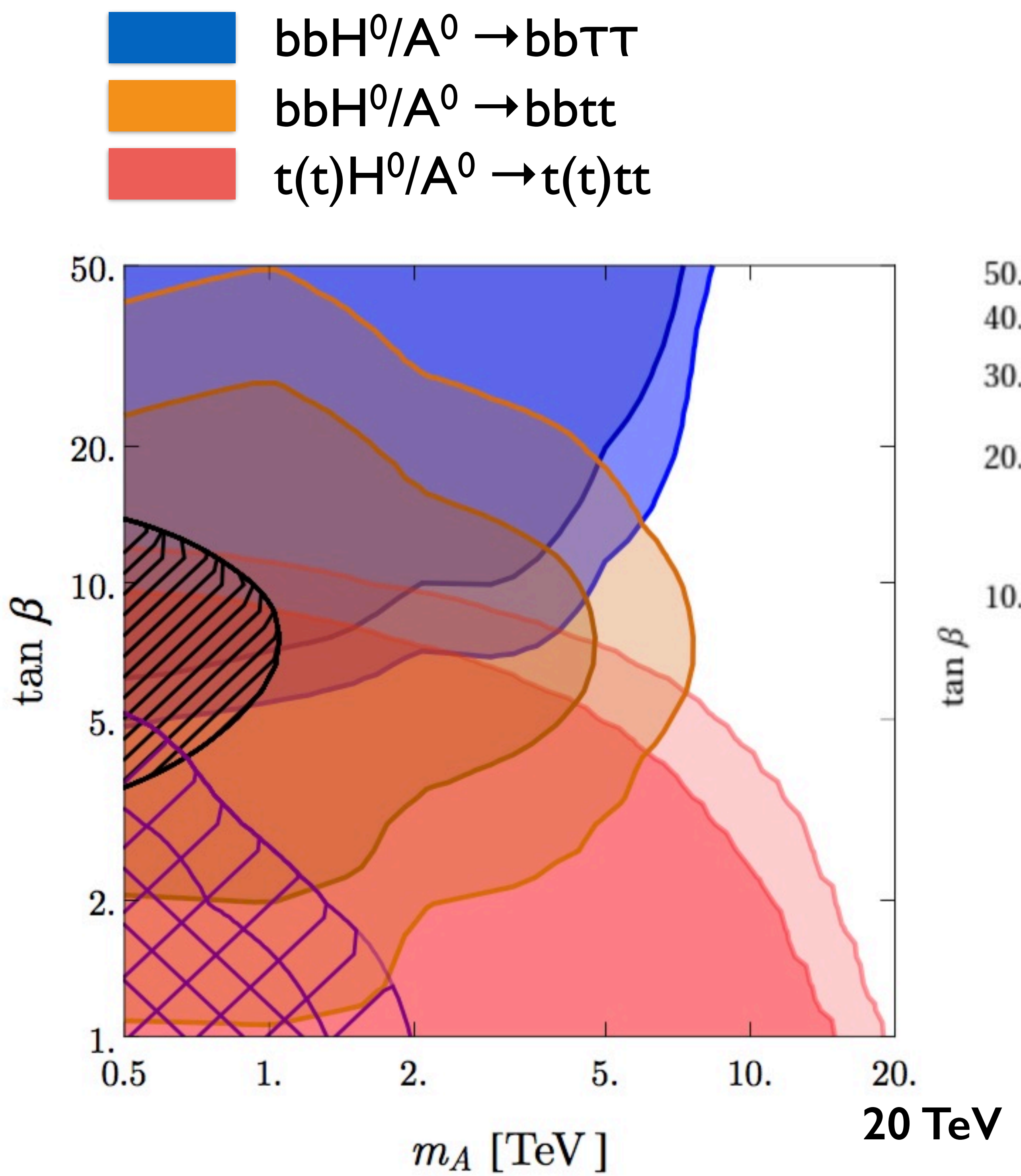


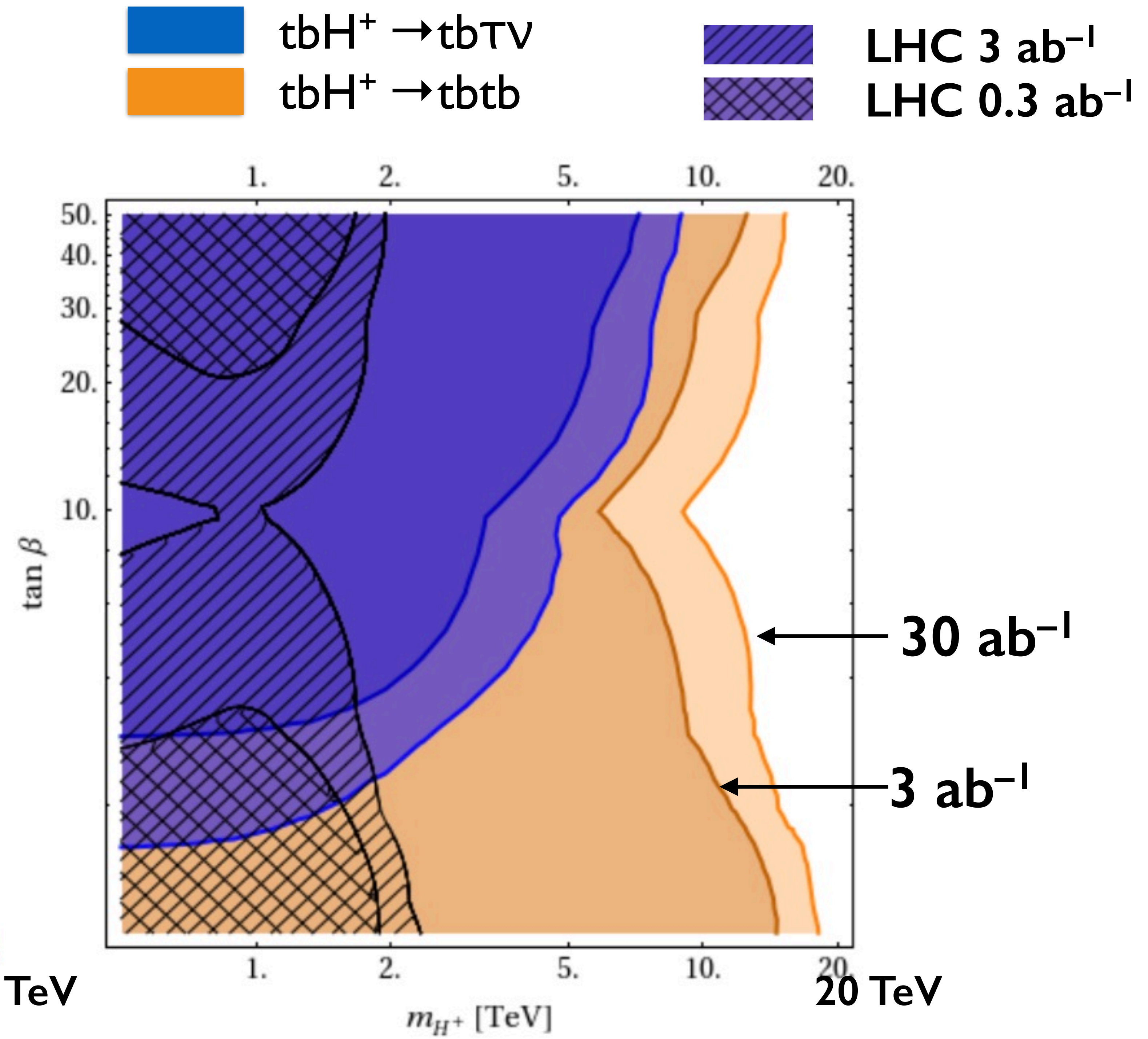
C. Helsens & M. Selvaggi + Summer students
Rachel Smith UIUC and Ine Arts UA

SUSY reach at 100 TeV



MSSM Higgs @ 100 TeV





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

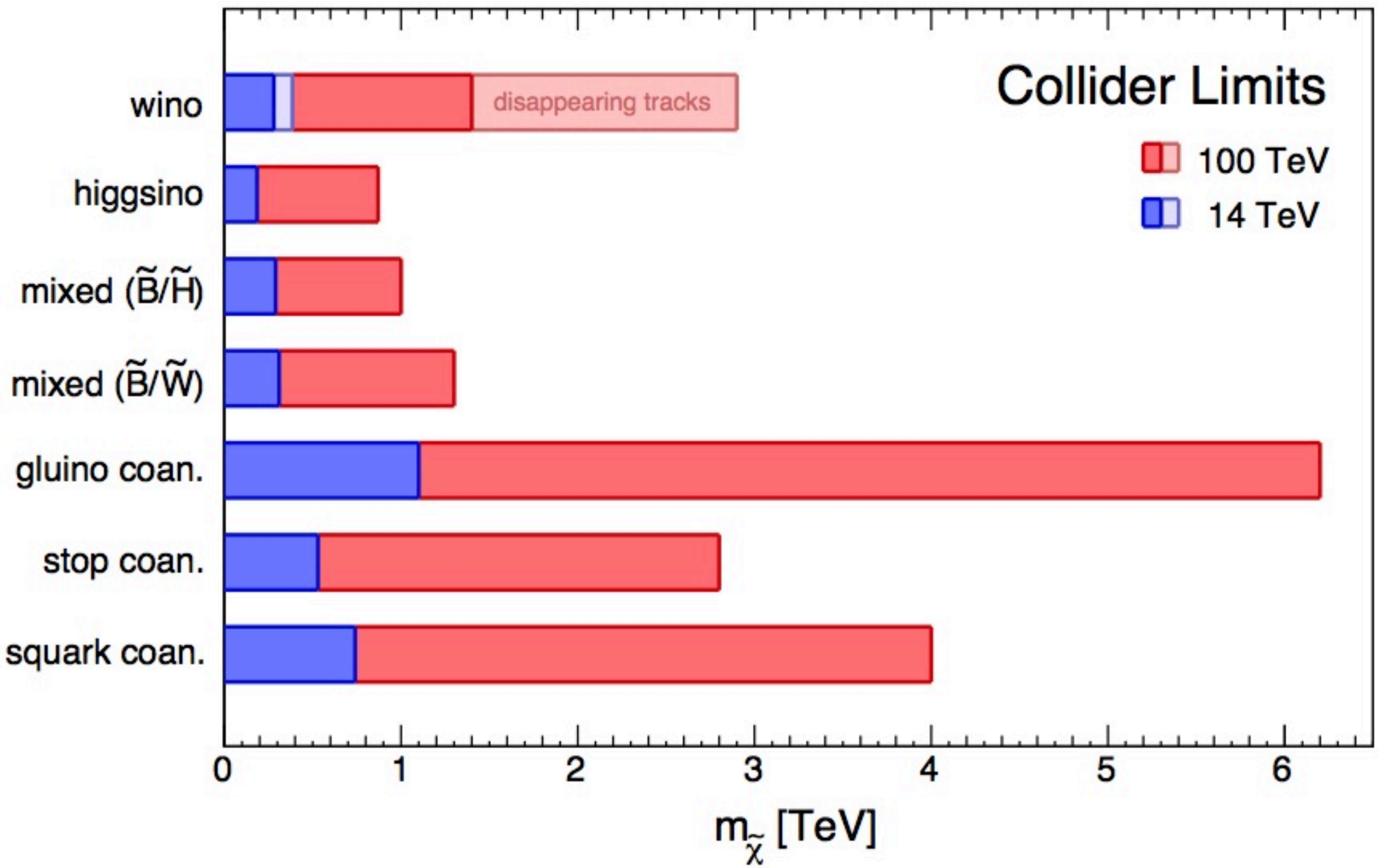
J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

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, ...)?

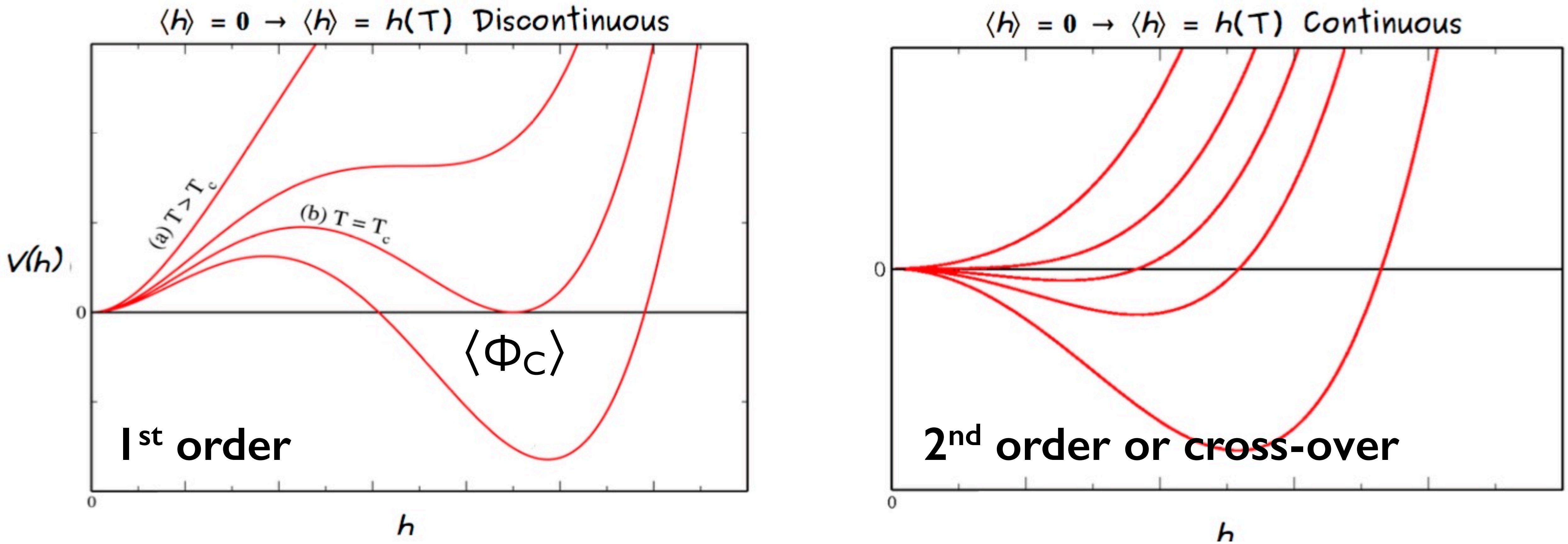
DM reach at 100 TeV



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

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

The nature of the EW phase transition



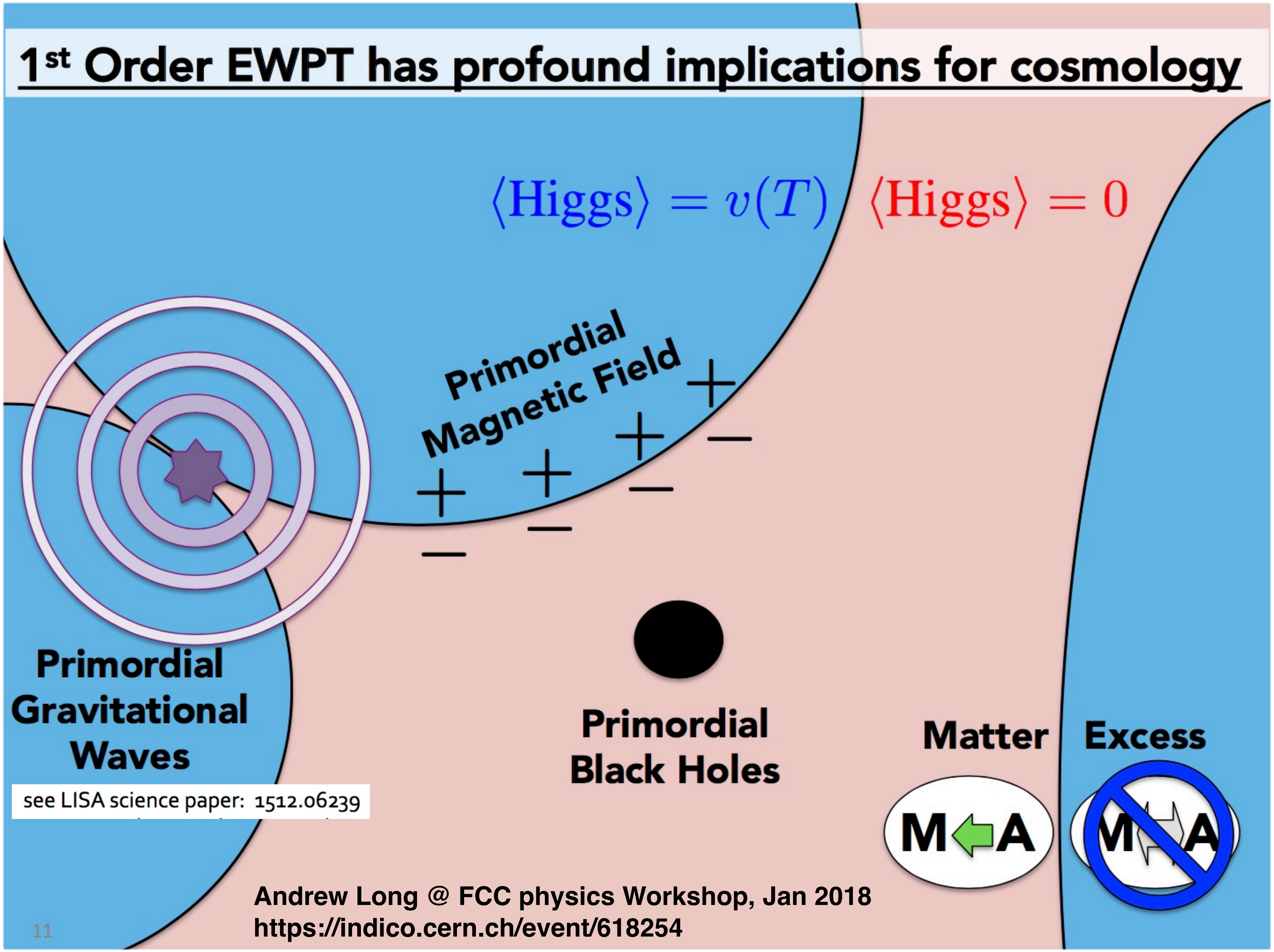
Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

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

In the SM this requires $m_H \lesssim 80$ GeV, else transition is a smooth crossover.

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**


1st Order EWPT has profound implications for cosmology
⟨Higgs⟩ = v(T)
⟨Higgs⟩ = 0
Primordial Magnetic Field
Primordial Gravitational Waves
see LISA science paper: 1512.06239
Primordial Black Holes
Matter
Excess
M A
M A
Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254
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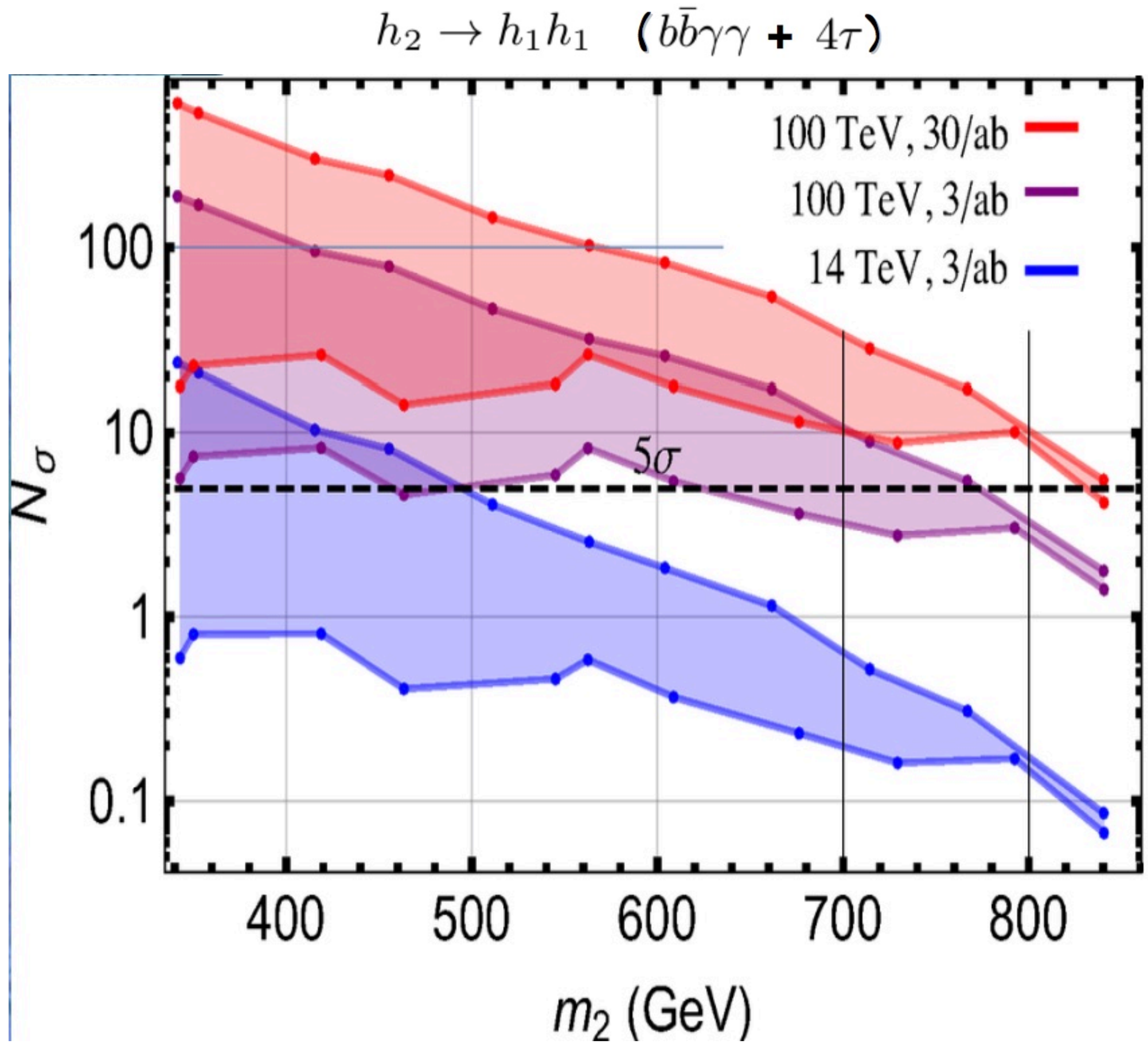
What will FCC tell us about the existence of extra Higgs bosons enabling a 1st order EWPT?



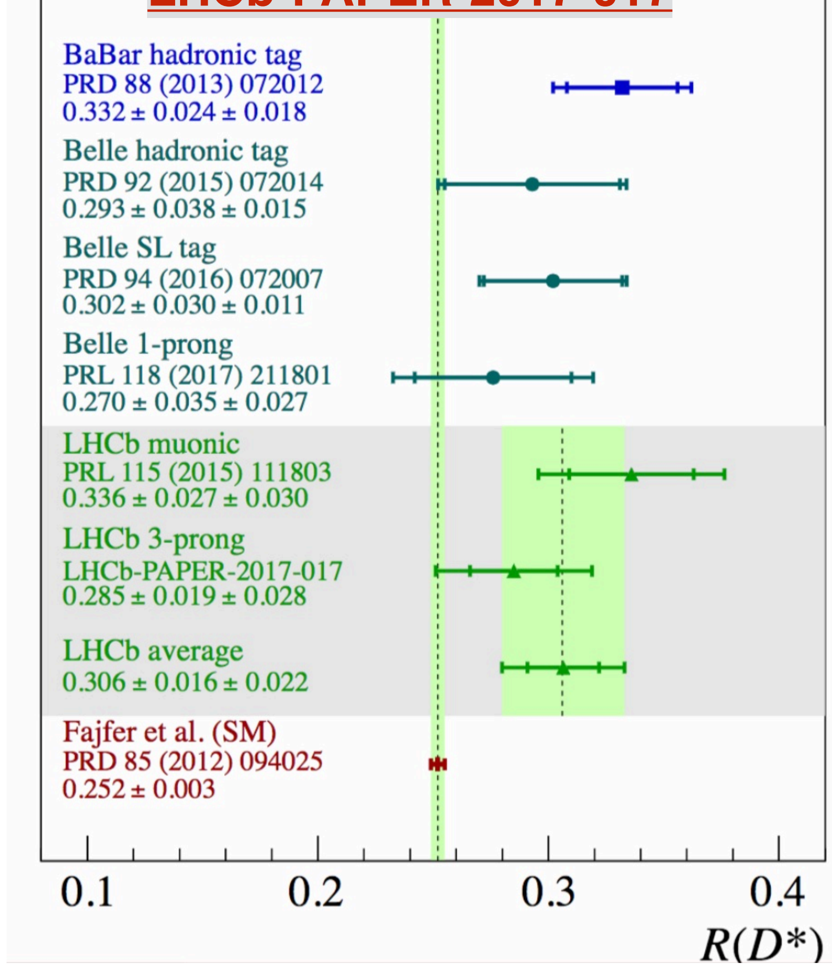
[Kotwal, No, Ramsey-Musolf, Winslow, arXiv:1605.06123](https://arxiv.org/abs/1605.06123)

Flavour anomalies at LHC & Bfact's

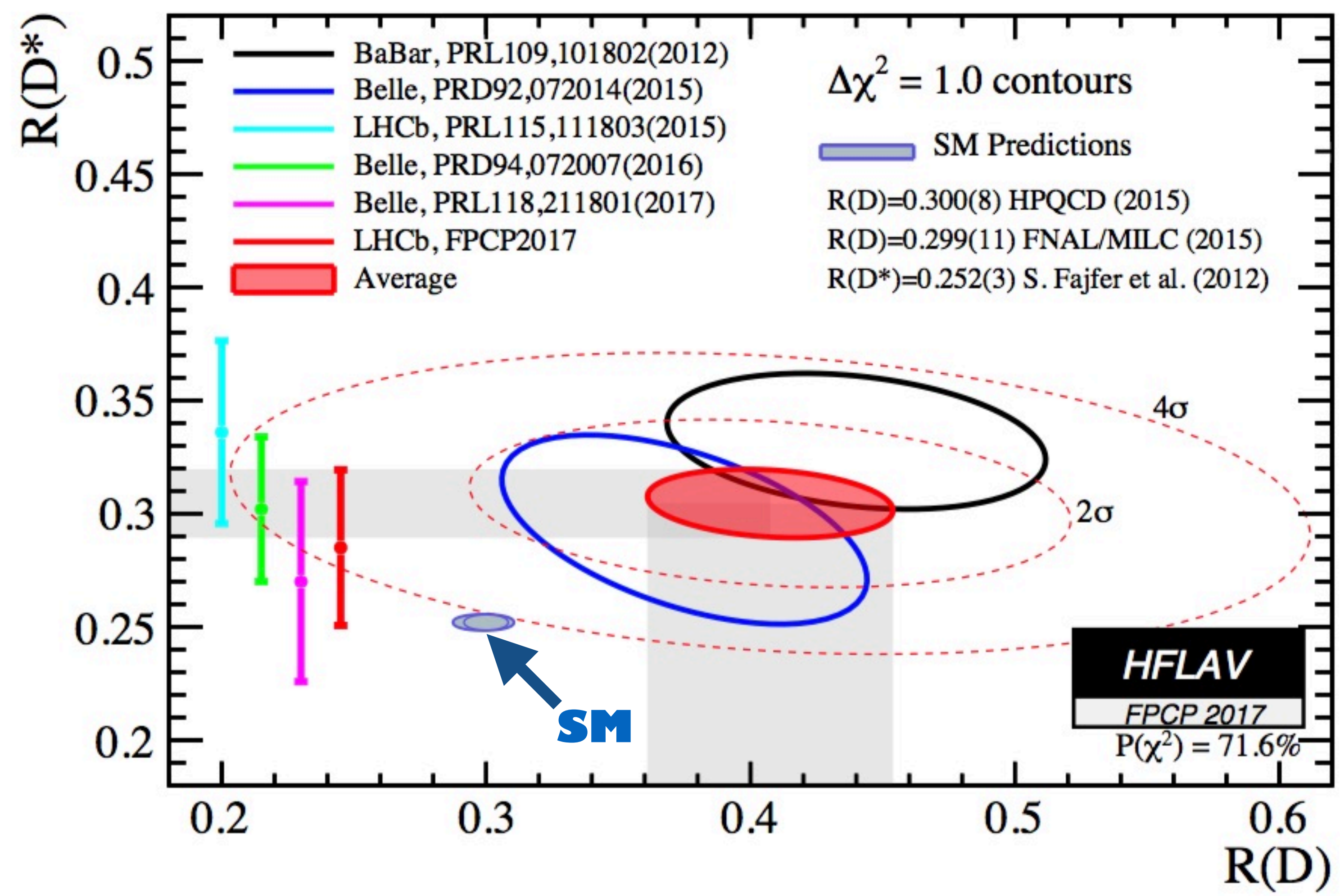
b→cℓν

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

LHCb-PAPER-2017-017



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



b→sℓℓ

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

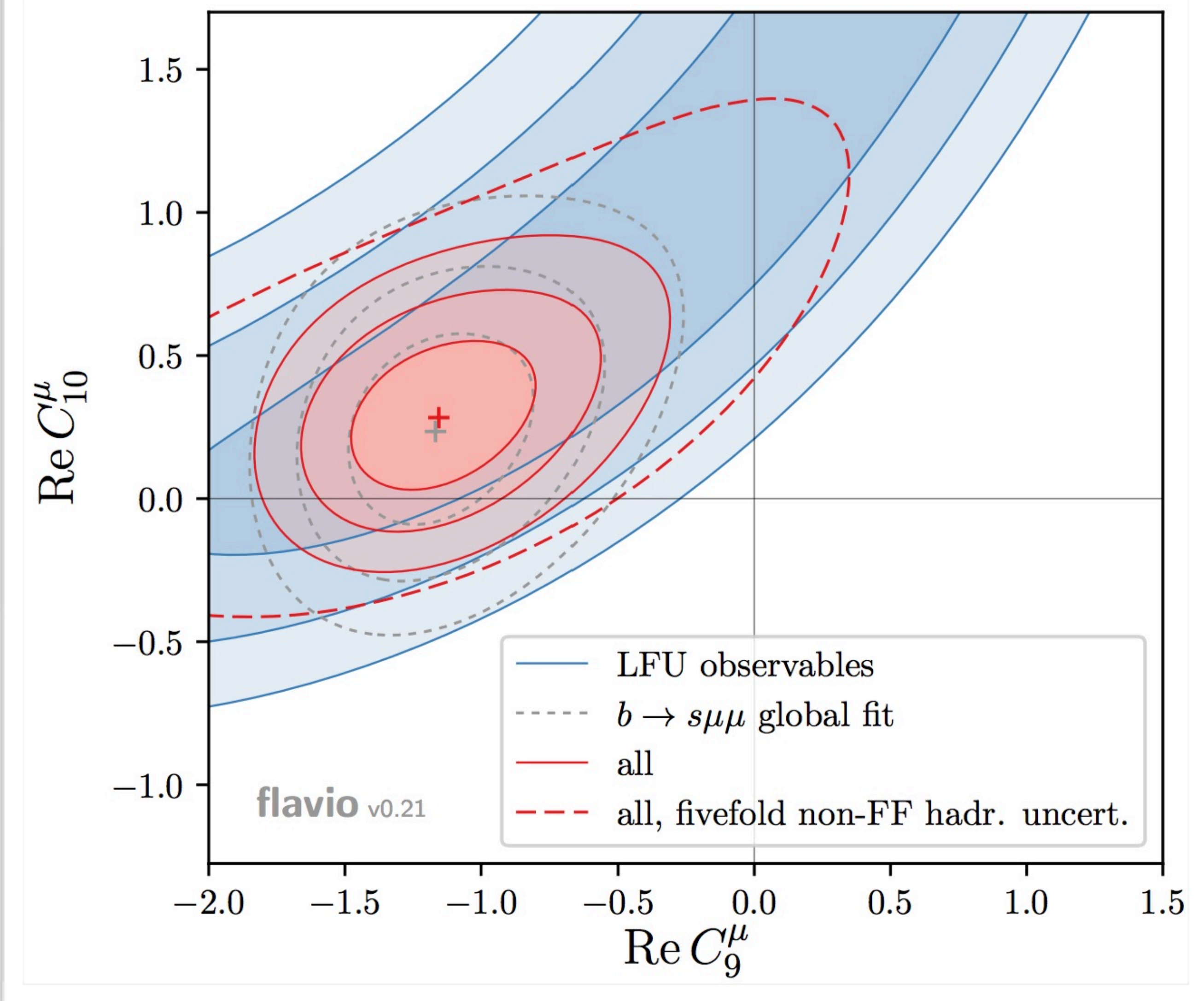
m_{ll} [mass range]	SM	Exp.
$R_K^{[1-6]}$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^*}^{[1.1-6]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.069} \pm 0.047$
$R_{K^*}^{[0.045,1.1]}$	0.91 ± 0.03	$0.660^{+0.110}_{-0.070} \pm 0.024$

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

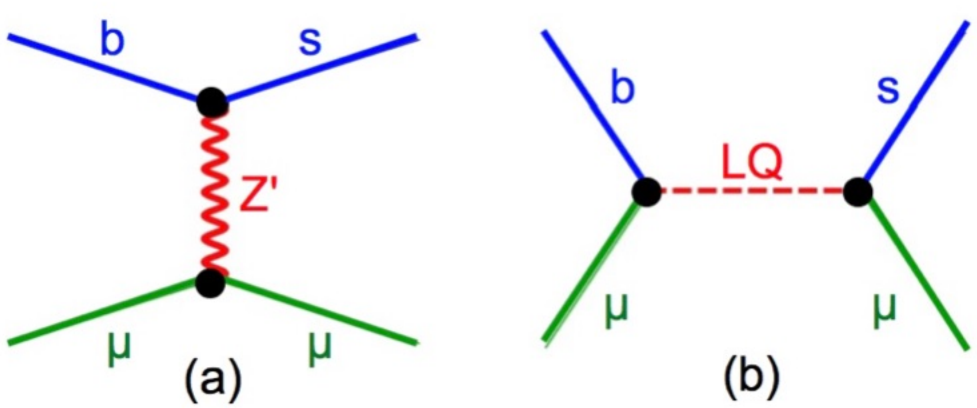
Example of EFT interpretation of R_K

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

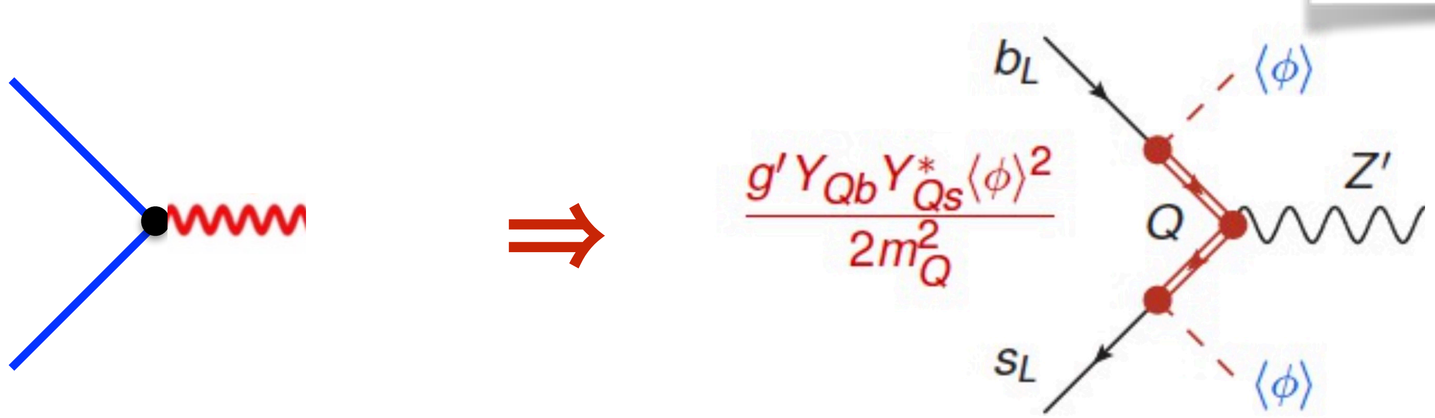
Altmannshoffer et al, arxiv:1704.05435



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 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

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 physics potential: domains to be evaluated

(1) extension of the LHC direct search for new particles (approximately doubling its mass reach);

(2) the Higgs self-coupling: establishing firm evidence for the structure of the symmetry-breaking Higgs potential;

(3) increased precision in the measurements made by the LHC, and the consequent increased sensitivity to new physics (indirectly to high mass scales, and, directly, to elusive final states such as dark matter);

(4) exploration of future LHC discoveries, confirmation of preliminary signs of discovery from the LHC, or the search for the underlying origin of new phenomena revealed indirectly **(e.g. the flavour anomalies under discussion nowadays)** or in experiments other than the LHC ones (e.g. dark matter or neutrino experiments).

(1) extension of mass reach for discovery: generic results

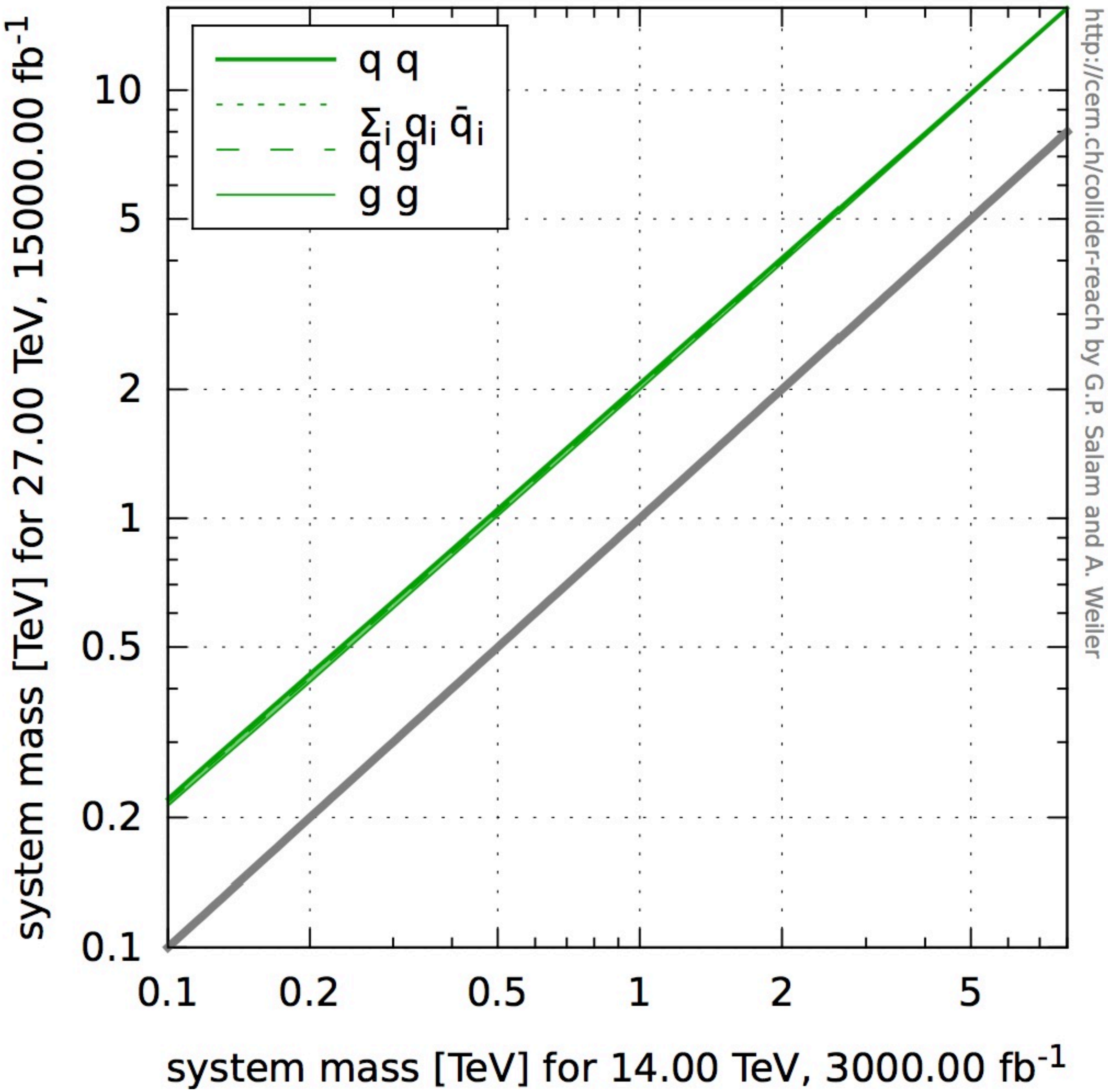


Figure 1.1: Estimate of the system mass (e.g. $m_{Z'}$ or $2m_{\tilde{g}}$) that can be probed in searches for new particles at HE-LHC, given an established system mass reach at HL-LHC.

G. Salam and A. Weiler, *Collider Reach*, `http://collider-reach.web.cern.ch/`.

(1) extension of mass reach for discovery: "natural" supersymmetry examples

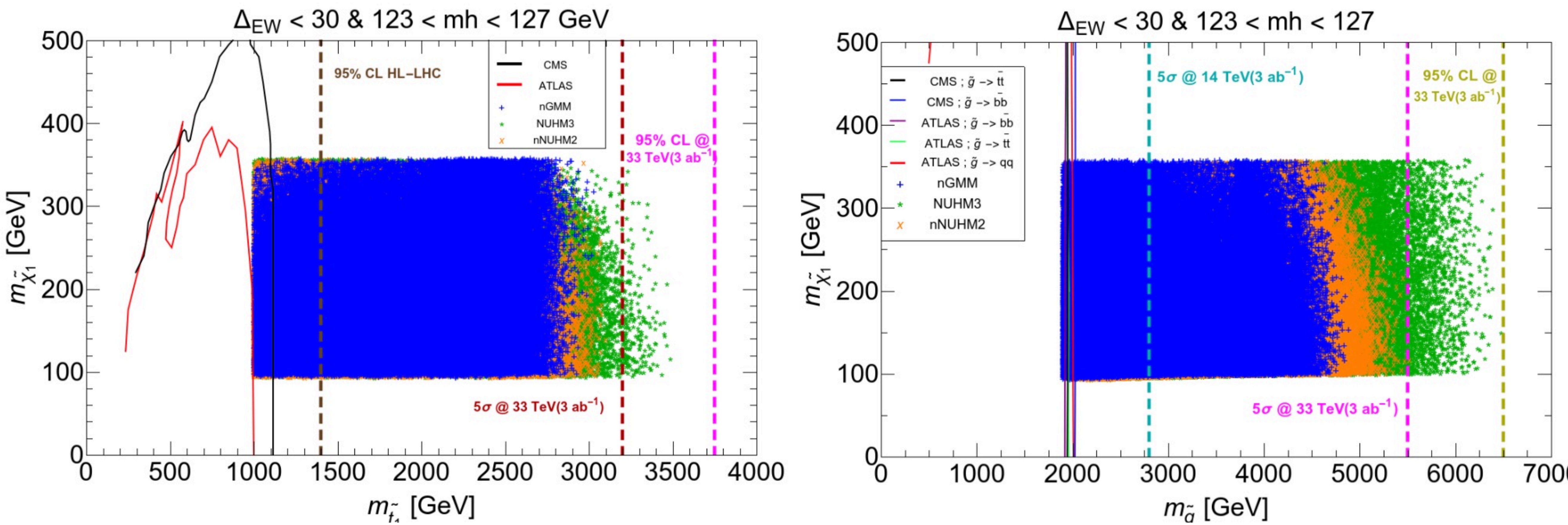


Figure 1.2: Discovery reach at the HE-LHC for gluinos and stops in various, compared to the HL-LHC reach and to the expectations of a several classes of natural supersymmetric models.

H. Baer, *talk at the Fermilab Workshop on HL-HE/LHC Physics, April 2-4 2018*, `https://indico.fnal.gov/event/16151/session/4/contribution/46/`.

For recent 27 TeV projections of DM WIMP searches:

T. Han, S. Mukhopadhyay, and X. Wang, *Electroweak Dark Matter at Future Hadron Colliders*, `arXiv:1805.00015 [hep-ph]`.

(II+III) precision measurements and EWSB probes: Higgs observables

Examples of goals in the Higgs sector:

(a) improve the sensitivity to the Higgs self-coupling

(b) reduce to the few percent level all major Higgs couplings

(c) improve the sensitivity to possible invisible Higgs decays

(d) measure the charm Yukawa coupling

	$gg \to H$	WH	ZH	ttH	HH
N_{27}	2.2×10^8	5.4×10^7	3.7×10^7	4×10^7	2.1×10^6
N_{27}/N_{14}	13	12	13	23	19

$N_{27} = \sigma(27\ \text{TeV}) * 15\ \text{ab}^{-1}$ $N_{14} = \sigma(14\ \text{TeV}) * 3\ \text{ab}^{-1}$

(II+III) precision measurements and EWSB probes: Higgs observables

- First results on Higgs selfcouplings measurement:

D. Gonçalves, T. Han, F. Kling, T. Plehn, and M. Takeuchi, *Higgs Pair Production at Future Hadron Colliders: From Kinematics to Dynamics*, arXiv:1802.04319 [hep-ph].

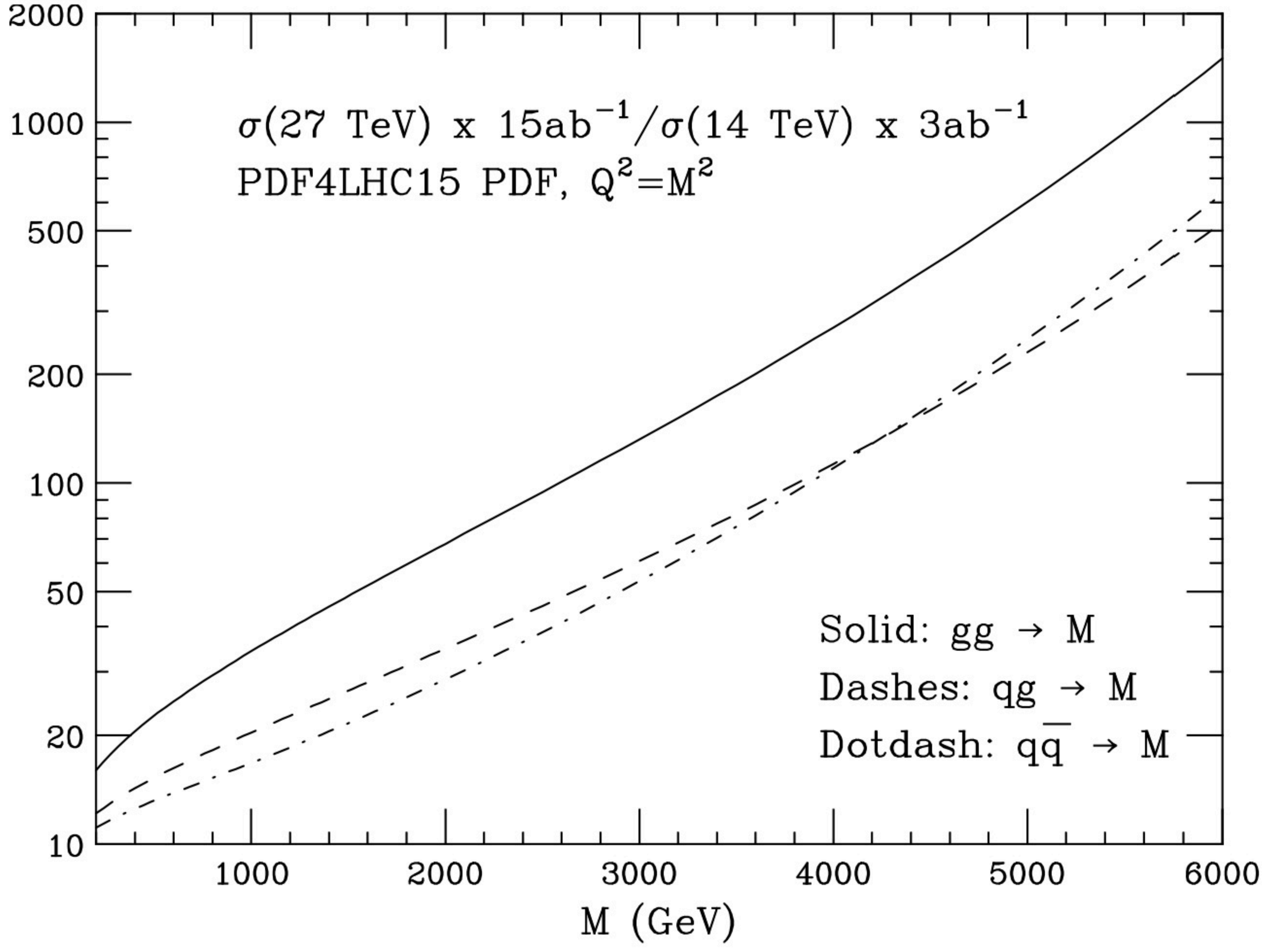
λ/λ_{SM} =1±0.3 at 95%CL (1±0.15 at 68%CL)

(compare to –0.2 < λ/λ_{SM} < 2.6 at HL-LHC)

F. Kling, T. Plehn, and P. Schichtel, *Maximizing the significance in Higgs boson pair analyses*, Phys. Rev. **D95** (2017) no. 3, 035026, arXiv:1607.07441 [hep-ph].

- For couplings like Hγγ, HZγ, Hμμ, Htt, … , plan to repeat studies presented at 100 TeV

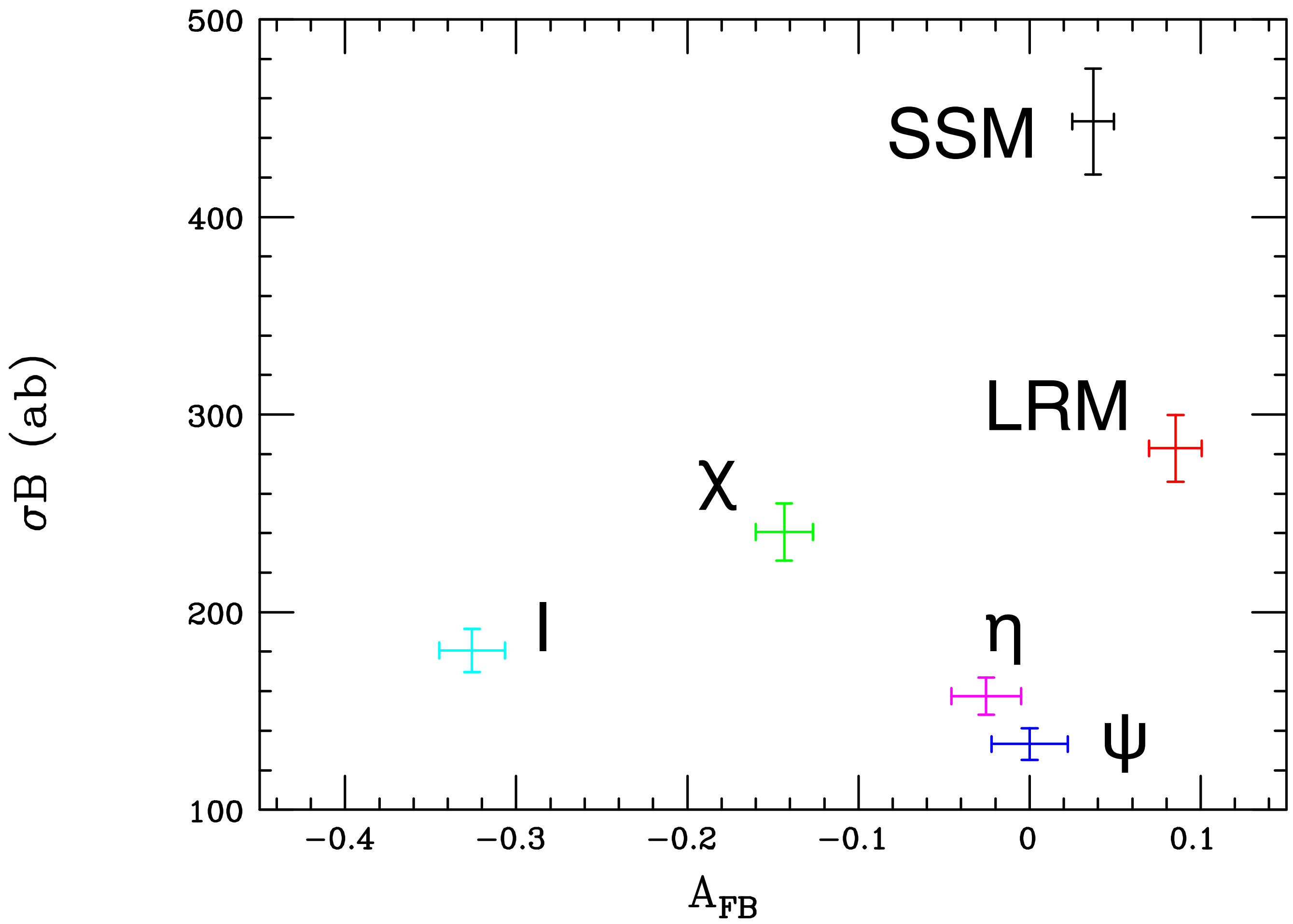
(IV) Exploration at 27 TeV of LHC discoveries: generic results

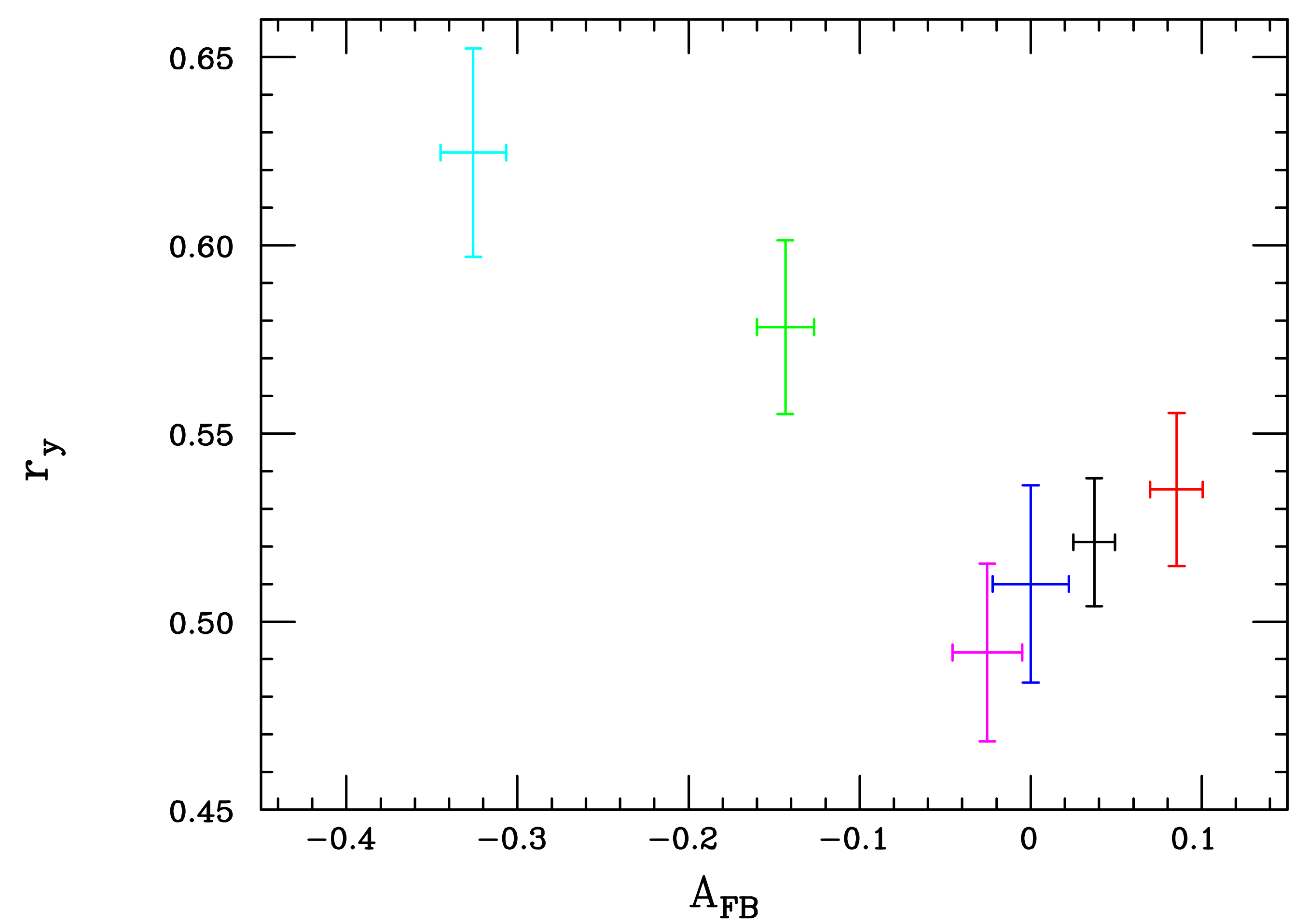


(IV) Exploration at 27 TeV of LHC discoveries: characterization of Z' models within reach of LHC observation

NB: uncertainty bars reflect very conservative syst assumptions

T. Rizzo, *work in progress,*

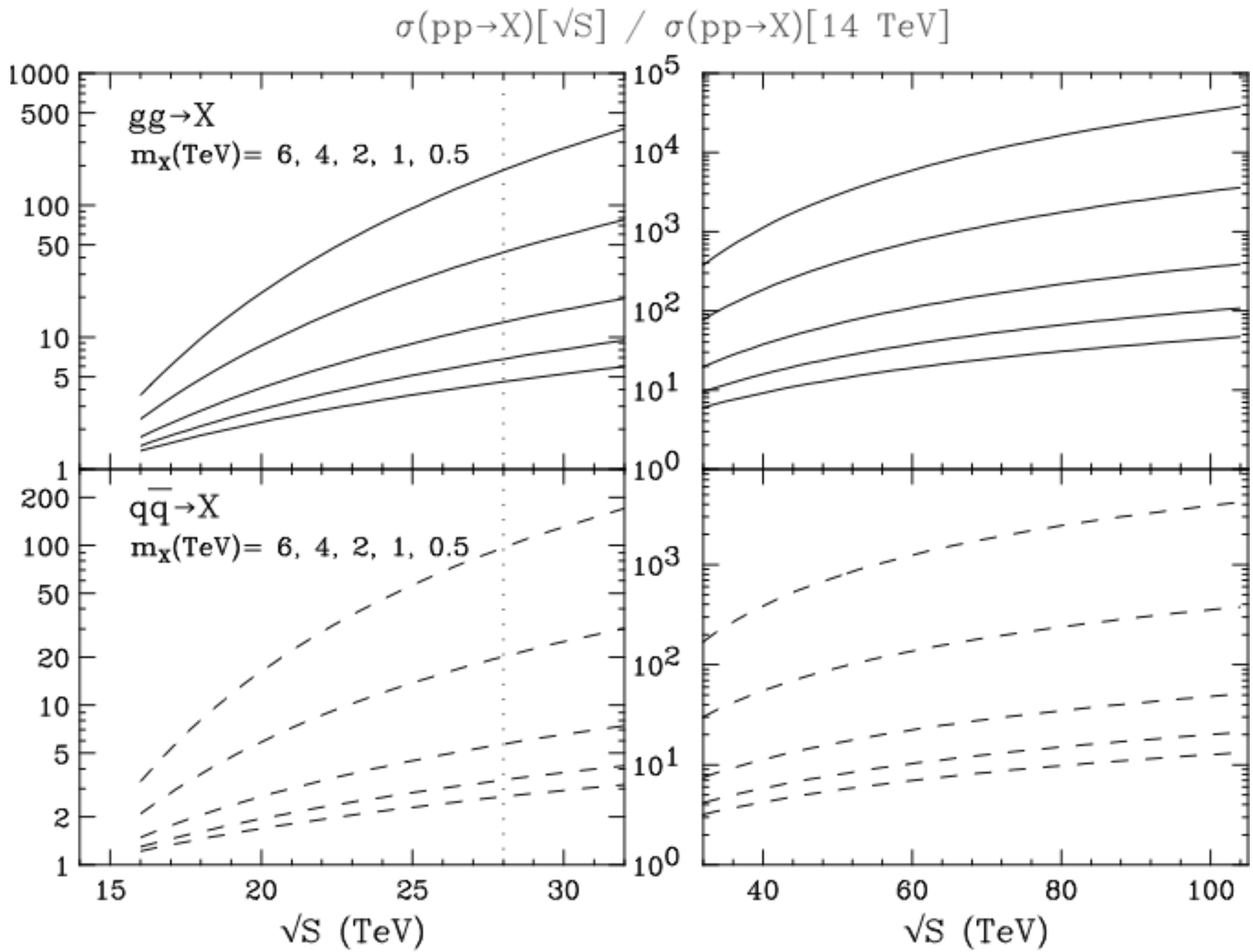




Colours: different Z' models, leading to observation at HL-LHC in Z'->dilepton decay for m(Z')=6 TeV

T. G. Rizzo, *Exploring new gauge bosons at a 100 TeV collider*, Phys. Rev. **D89** (2014) no. 9, 095022, arXiv:1403.5465 [hep-ph].

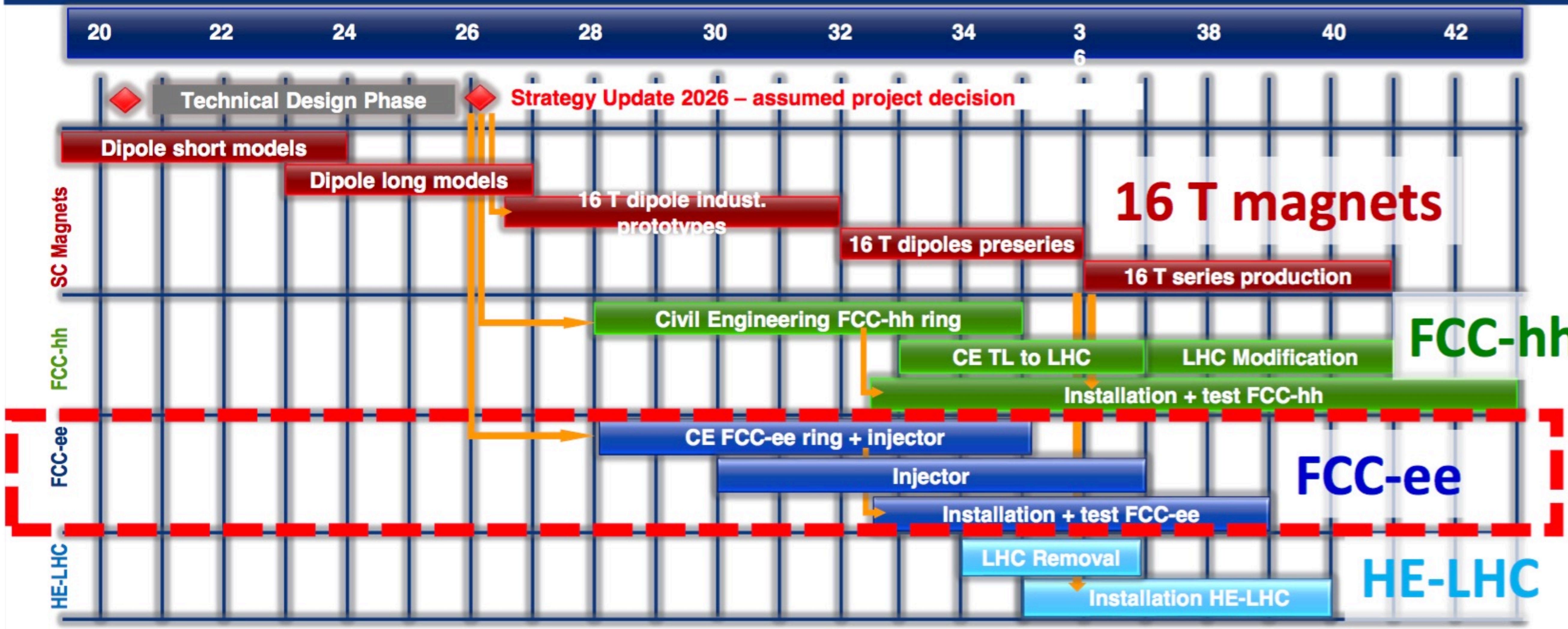
27 or 100? √S evolution of LHC discovery scenarios



Possible questions/options

- If m_X ~ 6 TeV in the gg channel, rate grows x 200 @28 TeV:
  - Do we wait to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$) ?
  - .... and the answers may depend on whether we expect partners of X at masses $\gtrsim 2m_X$ ($\Rightarrow$ *28 TeV would be insufficient ....*)
- If m_X ~ 0.5 TeV in the qqbar channel, rate grows x10 @100 TeV:
  - Do we go to 100 TeV, or push by x10 $\int L$ at LHC?
  - Do we build CLIC?
- 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

Final remarks

- The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
- As a possible complement to the mature ILC and CLIC projects, plans are underway to define the possible continuation of this programme after the LHC, with the same goals of thoroughness, precision and breadth that inspired the LEP/LHC era
- 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.