New Horizon in Particle Physics
Workshop for Future Particle Accelerators
4 ~ 19 July 2019 KAIST, Daejeon, Republic of Korea

www.future-colliders
why, what and which

Michelangelo L. Mangano
michelangelo.mangano@cern.ch
Theoretical Physics Department
CERN

WWW

- Why do we need future colliders?
- What should they do for us?
- Which one(s) to choose?

www

- Why do we need future colliders?
- What should they do for us?
- Which one(s) to choose?

- *a re-formulation of standard ideas and motivations, nothing new, but it helps to try formulate things in alternative ways*
- *no claim of providing an objective perspective, even though I believe it is objective…*

why

The next steps in HEP build on

The next steps in HEP build on

- having important questions to pursue

The next steps in HEP build on

- having important questions to pursue
- creating opportunities to answer them

The next steps in HEP build on

- having important questions to pursue
- creating opportunities to answer them
- being able to constantly add to our knowledge, while seeking those answers

The important questions

The important questions

- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …

The important questions

- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …
- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Quantum gravity
  - Origin of inflation
  - …

The opportunities

The opportunities

- For none of these questions, the path to an answer is unambiguously defined.

The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- Two examples:

The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- Two examples:
  - DM: could be anything from fuzzy 10^{-22} eV scalars, to O(TeV) WIMPs, to multi-$M_{\odot}$ primordial BHs, passing through axions and sub-GeV DM

The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- Two examples:
  - DM: could be anything from fuzzy 10^{-22} eV scalars, to O(TeV) WIMPs, to multi-$M_\odot$ primordial BHs, passing through axions and sub-GeV DM
    - ***a vast array of expts*** is needed, even though most of them will end up empty-handed…

The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- Two examples:
  - DM: could be anything from fuzzy 10^{-22} eV scalars, to O(TeV) WIMPs, to multi-$M_\odot$ primordial BHs, passing through axions and sub-GeV DM
    - ***a vast array of expts*** is needed, even though most of them will end up empty-handed…
  - Neutrino masses: could originate anywhere between the EW and the GUT scale

The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- Two examples:
  - DM: could be anything from fuzzy 10^{-22} eV scalars, to O(TeV) WIMPs, to multi-$M_\odot$ primordial BHs, passing through axions and sub-GeV DM
    - ***a vast array of expts*** is needed, even though most of them will end up empty-handed…
  - Neutrino masses: could originate anywhere between the EW and the GUT scale
    - we are still in the process of acquiring basic knowledge about the neutrino sector: mass hierarchy, majorana nature, sterile neutrinos, CP violation, correlation with mixing in the charged-lepton sector ($\mu \to e\gamma$, $H \to \mu\tau$, …): as for DM, ***a broad range of options***

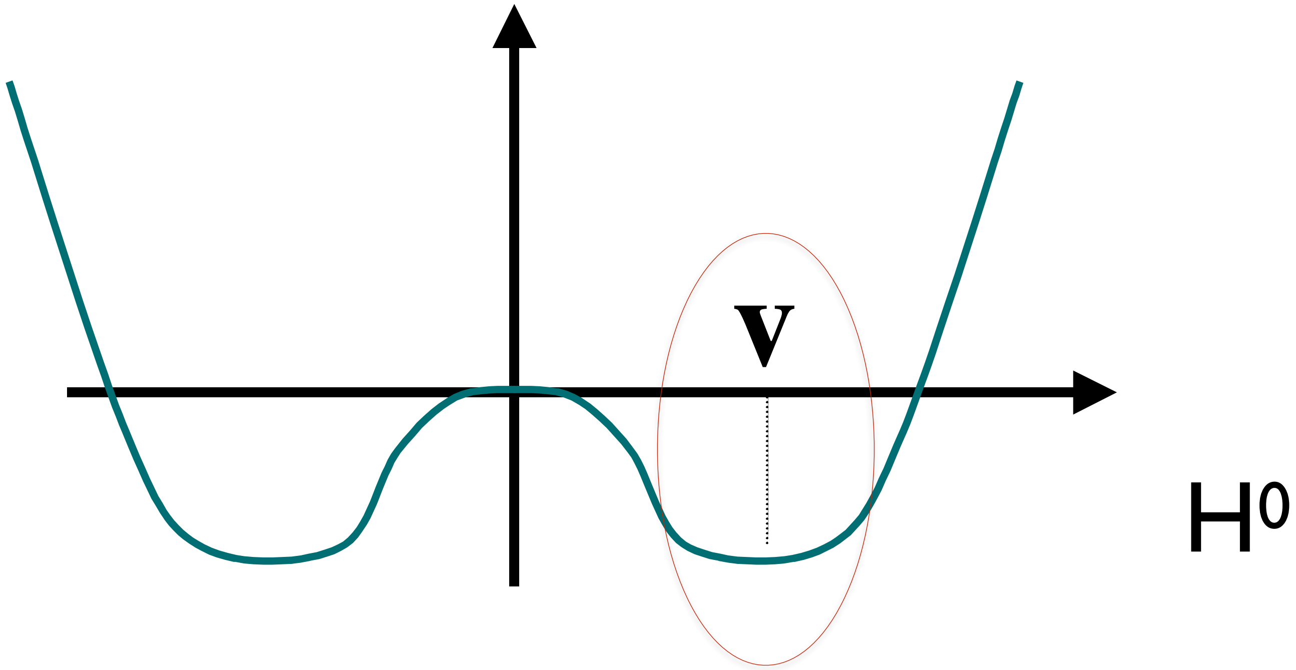
The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- Two examples:
  - DM: could be anything from fuzzy 10^{-22} eV scalars, to O(TeV) WIMPs, to multi-$M_\odot$ primordial BHs, passing through axions and sub-GeV DM
    - ***a vast array of expts*** is needed, even though most of them will end up empty-handed…
  - Neutrino masses: could originate anywhere between the EW and the GUT scale
    - we are still in the process of acquiring basic knowledge about the neutrino sector: mass hierarchy, majorana nature, sterile neutrinos, CP violation, correlation with mixing in the charged-lepton sector ($\mu \to e\gamma$, $H \to \mu\tau$, …): as for DM, ***a broad range of options***
- We cannot objectively establish a hierarchy of relevance among the fundamental questions. The hierarchy evolves with time (think of GUTs and proton decay searches!) and is likely subjective. It is also likely that several of the big questions are tied together and will find their answer in a common context (eg DM and hierarchy problem, flavour and nu masses, quantum gravity/inflation/dark energy, …)

The opportunities

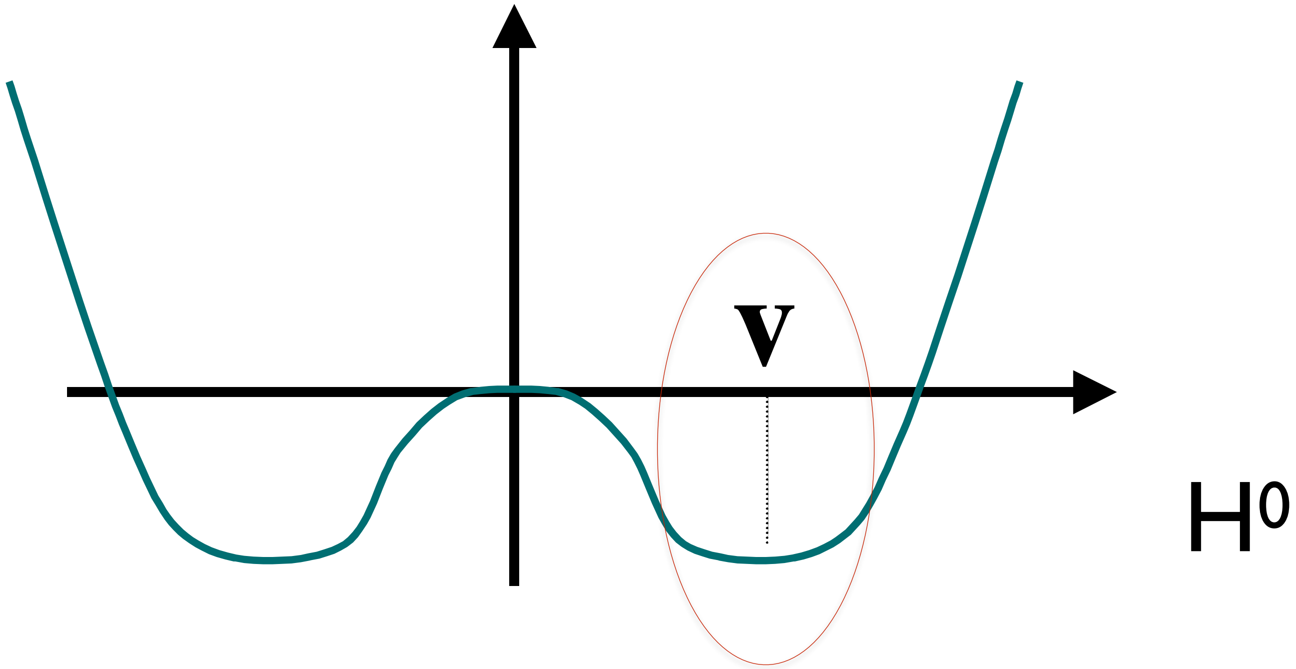
- For none of these questions, the path to an answer is unambiguously defined.
- Two examples:
  - DM: could be anything from fuzzy 10^{-22} eV scalars, to O(TeV) WIMPs, to multi-$M_\odot$ primordial BHs, passing through axions and sub-GeV DM
    - ***a vast array of expts*** is needed, even though most of them will end up empty-handed…
  - Neutrino masses: could originate anywhere between the EW and the GUT scale
    - we are still in the process of acquiring basic knowledge about the neutrino sector: mass hierarchy, majorana nature, sterile neutrinos, CP violation, correlation with mixing in the charged-lepton sector ($\mu \to e\gamma$, $H \to \mu\tau$, …): as for DM, ***a broad range of options***
- We cannot objectively establish a hierarchy of relevance among the fundamental questions. The hierarchy evolves with time (think of GUTs and proton decay searches!) and is likely subjective. It is also likely that several of the big questions are tied together and will find their answer in a common context (eg DM and hierarchy problem, flavour and nu masses, quantum gravity/inflation/dark energy, …)

One question, however, has emerged in stronger and stronger terms from the LHC, and appears to single out a unique well defined direction….



$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

Who ordered that ?

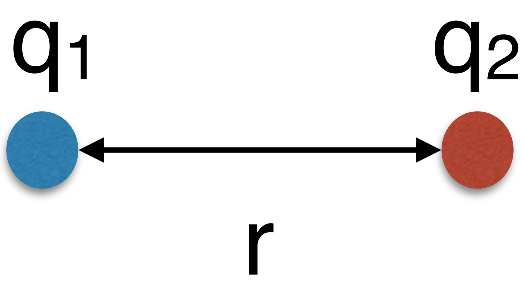


$$V(H) = -\mu^2 |H|^2 + \lambda\, |H|^4$$

Who ordered that ?

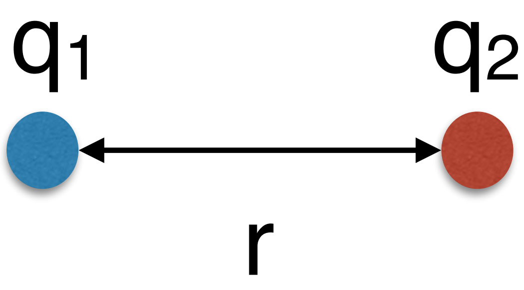
We must learn to appreciate the depth and the value of this question, which is set to define the future of collider physics

Electromagnetic vs Higgs dynamics



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

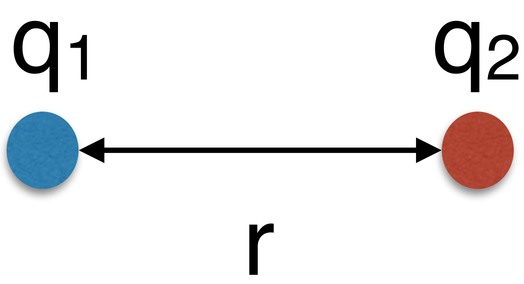
Electromagnetic vs Higgs dynamics



quantized,
in units of
fixed charge

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

Electromagnetic vs Higgs dynamics



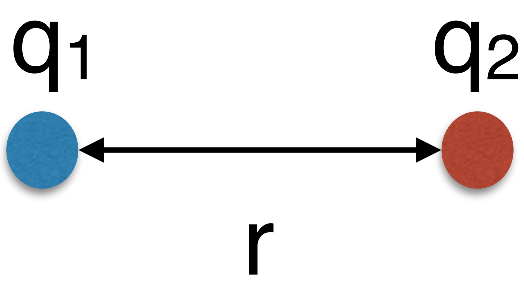
$$V(r) = \boxed{+}\,\frac{\boxed{q_1 \times q_2}}{r^{\boxed{1}}}$$

quantized,
in units of
fixed charge

sign fixed
by photon
spin

power determined by gauge
invariance/charge
conservation/Gauss theorem

Electromagnetic vs Higgs dynamics

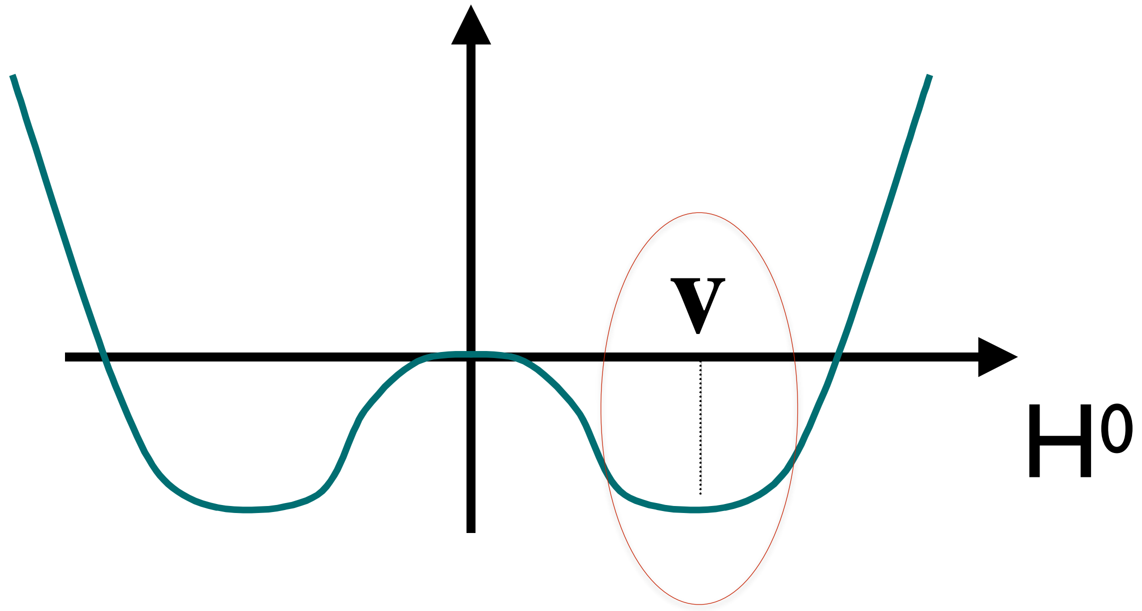


quantized,
in units of
fixed charge

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

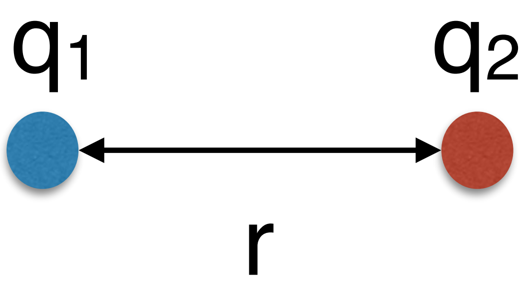
sign fixed
by photon
spin

power determined by gauge
invariance/charge
conservation/Gauss theorem



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

Electromagnetic vs Higgs dynamics

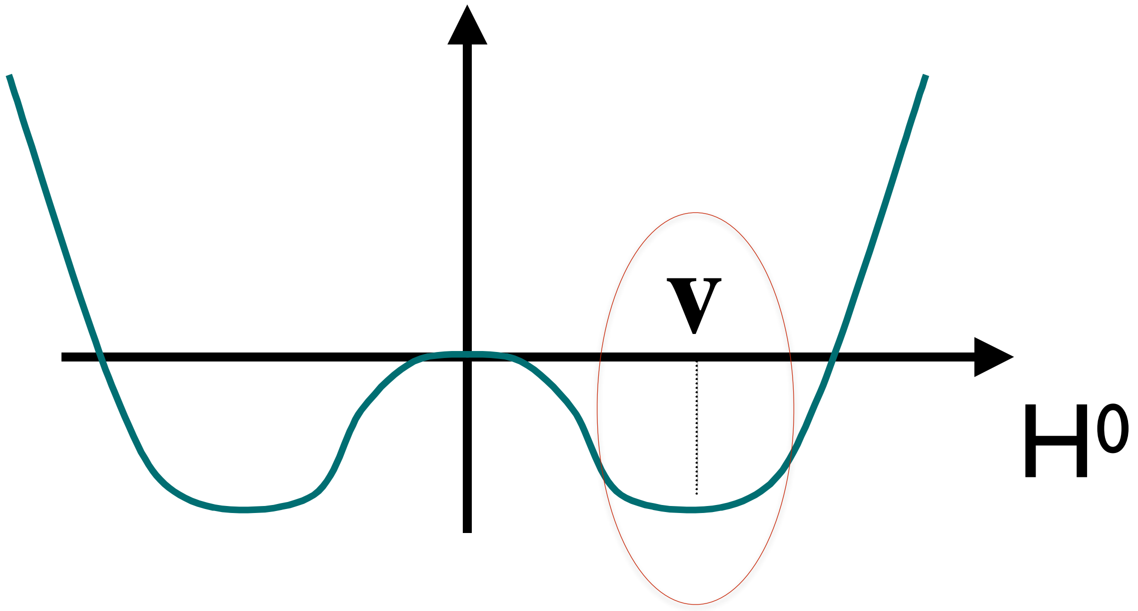


$$V(r) = + \frac{q_1 \times q_2}{r^1}$$

quantized,
in units of
fixed charge

sign fixed
by photon
spin

power determined by gauge
invariance/charge
conservation/Gauss theorem

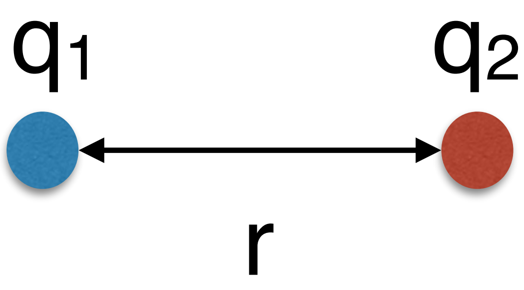


$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

both sign
and value
totally
arbitrary

>0 to ensure
stability, but
otherwise arbitrary

Electromagnetic vs Higgs dynamics

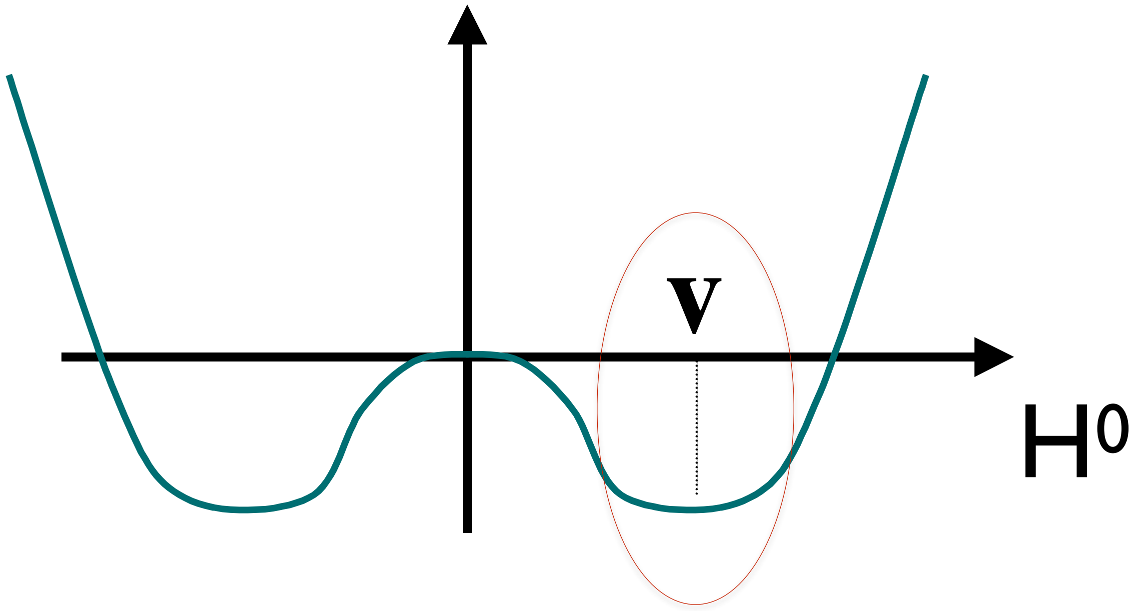


quantized, in units of fixed charge

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

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.

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.

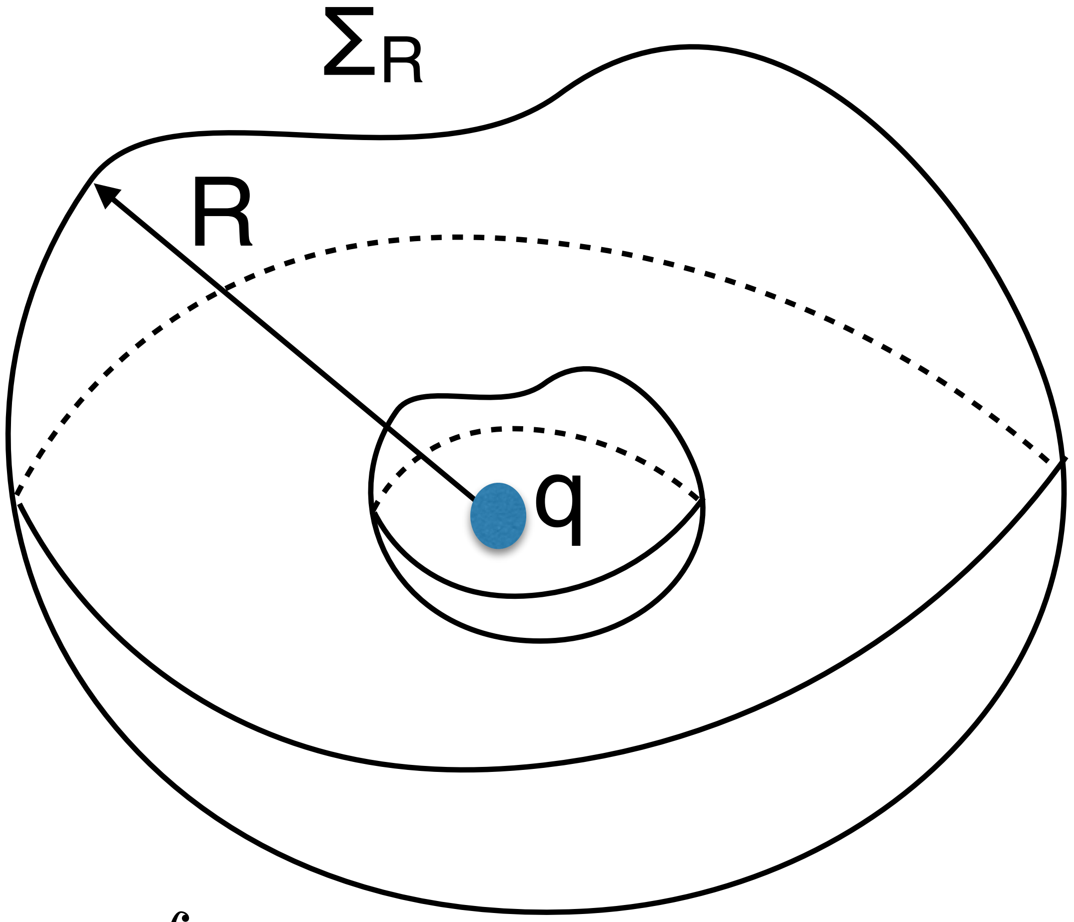
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in either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

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2+g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking
- …

Decoupling of high-frequency modes

E&M

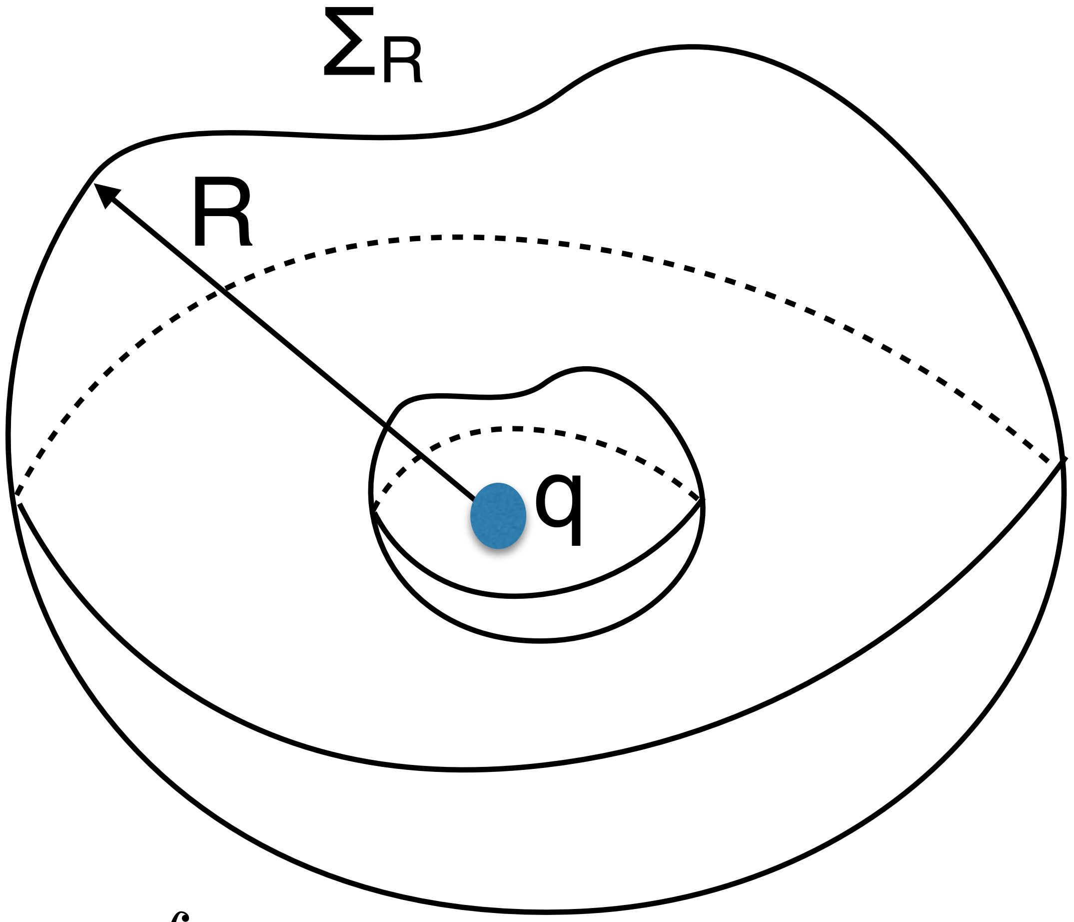


$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

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

Decoupling of high-frequency modes

E&M



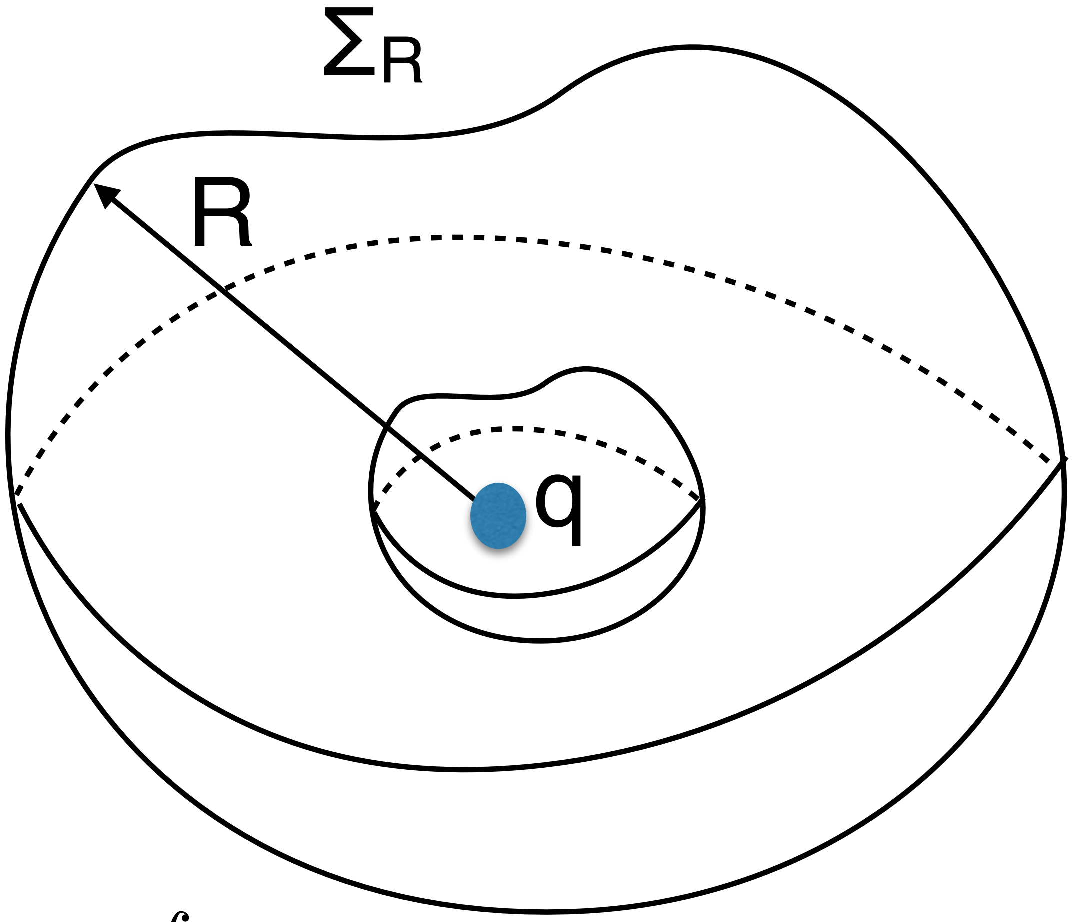
$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

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

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

Decoupling of high-frequency modes

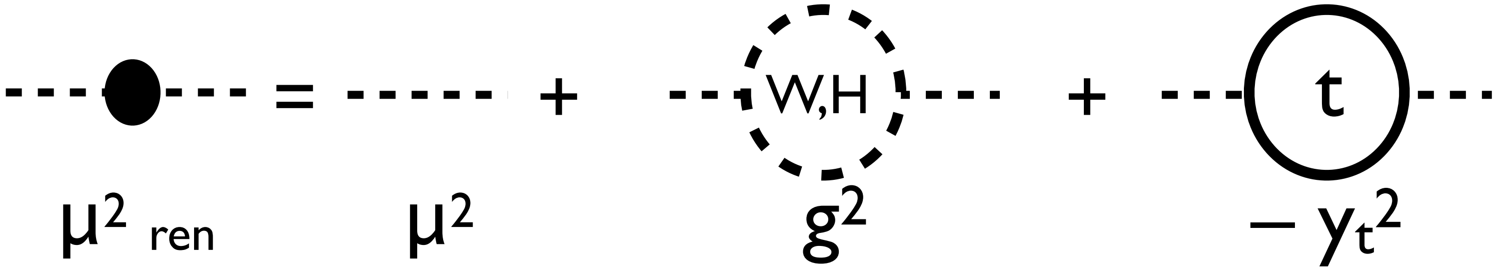
E&M



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

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

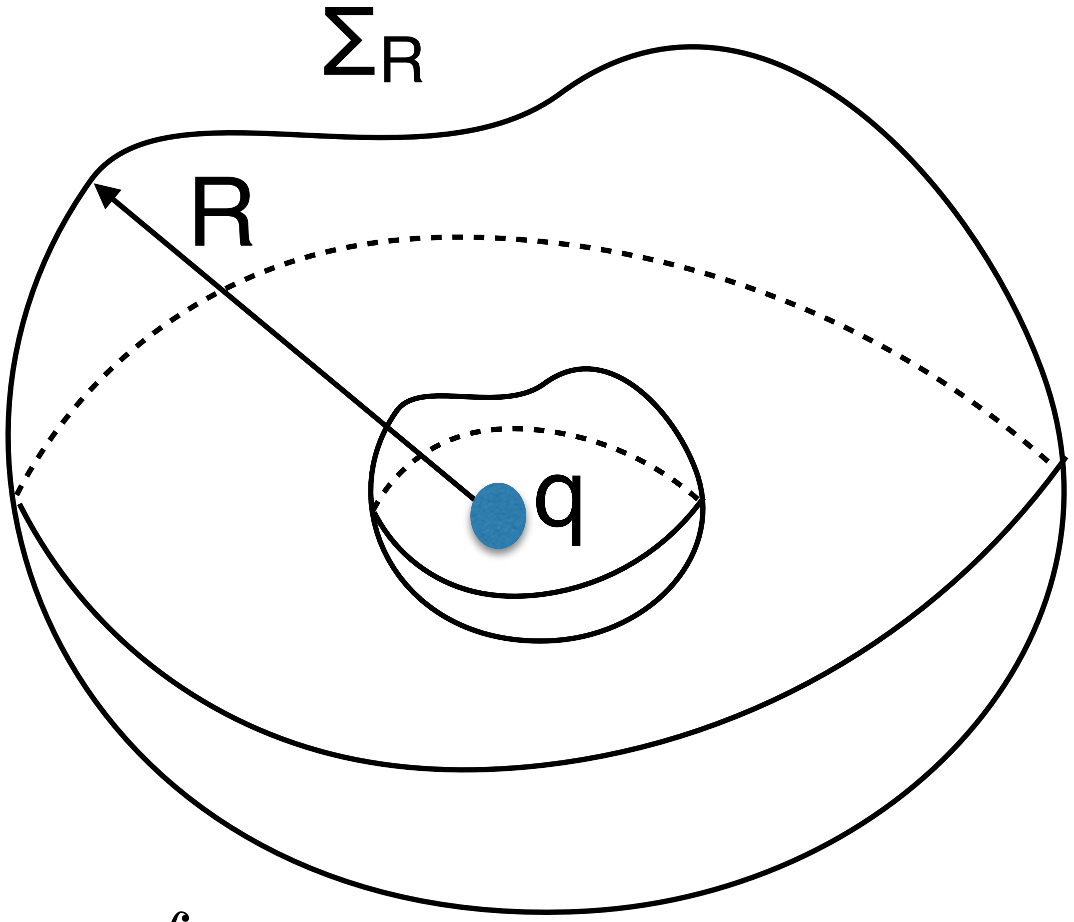
$$V_{SM}(H) = -\mu^2 \, |H|^2 + \lambda \, |H|^4$$



$$\Delta\mu^2 \sim (\, c_B \, m_B^2 - c_F \, m_F^2 \,) \times (\, \Lambda \,/\, v)^2$$

Decoupling of high-frequency modes

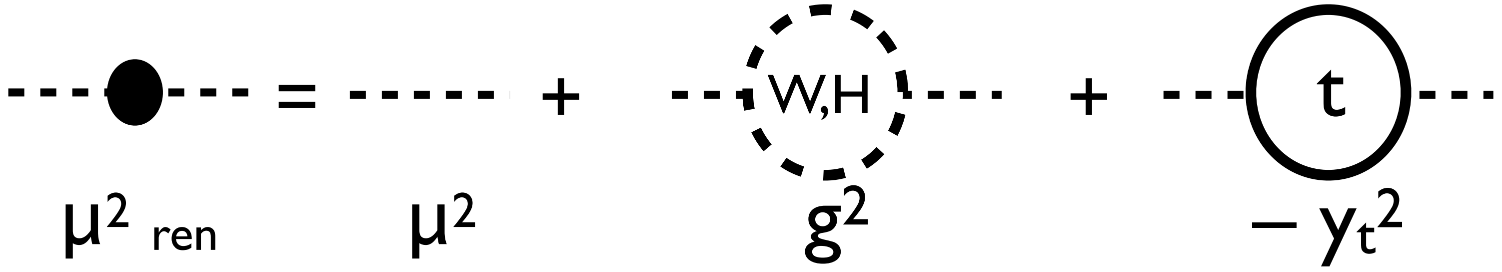
E&M



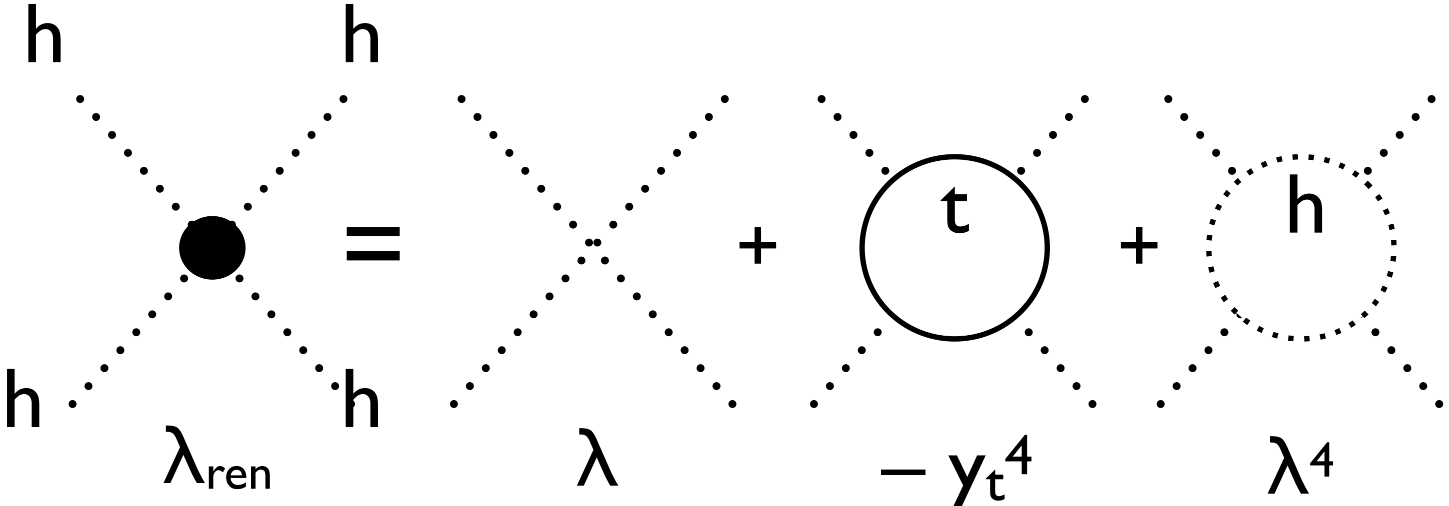
$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

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

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



$$\Delta\mu^2 \sim (\, c_B\, m_B^2 - c_F\, m_F^2 \,) \times (\, \Lambda / v)^2$$



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

high-energy modes can change size and sign of both μ² and λ, dramatically altering the stability and dynamics => **hierarchy problem**

The hierarchy problem

- The search for a **natural** solution to the hierarchy problem is likewise unavoidably tied to BSM physics, and has provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.

The hierarchy problem

- The search for a **natural** solution to the hierarchy problem is likewise unavoidably tied to BSM physics, and has provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.
- Lack of experimental evidence so far for a straightforward answer to naturalness, forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties

The hierarchy problem

- The search for a **natural** solution to the hierarchy problem is likewise unavoidably tied to BSM physics, and has provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.
- Lack of experimental evidence so far for a straightforward answer to naturalness, forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties
  - again, “who ordered that?”

The hierarchy problem

- The search for a **natural** solution to the hierarchy problem is likewise unavoidably tied to BSM physics, and has provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.
- Lack of experimental evidence so far for a straightforward answer to naturalness, forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties
  - again, "who ordered that?"
  - in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification, nothing of the Higgs boson can be given for granted

The hierarchy problem

- The search for a **natural** solution to the hierarchy problem is likewise unavoidably tied to BSM physics, and has provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.
- Lack of experimental evidence so far for a straightforward answer to naturalness, forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties
  - again, "who ordered that?"
  - in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification, nothing of the Higgs boson can be given for granted
  - what we've experimentally proven so far are basic properties, which, from the perspective of EFT and at the current level of precision of the measurements, could hold in a vast range of BSM EWSB scenarios

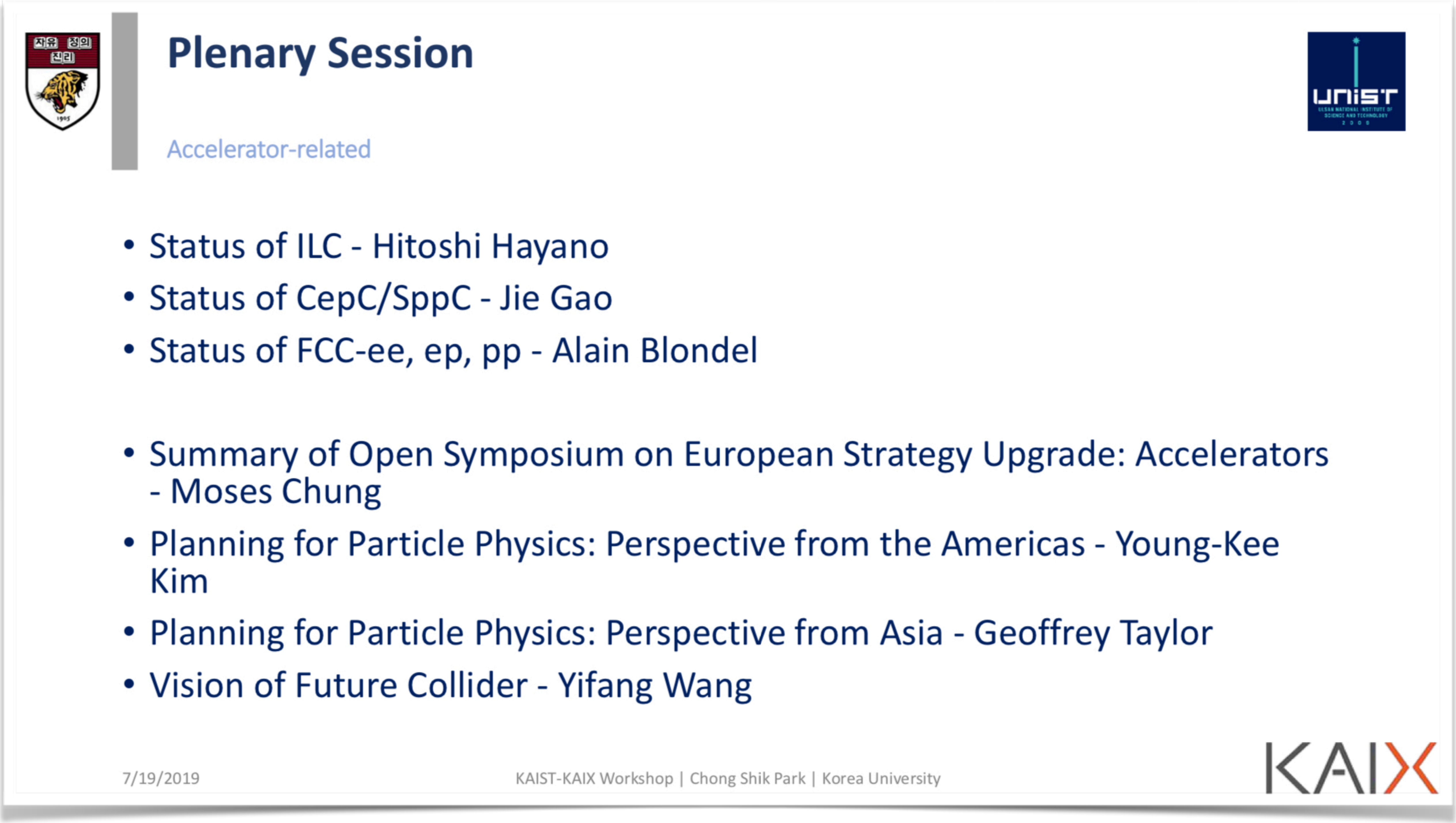
The hierarchy problem

- The search for a **natural** solution to the hierarchy problem is likewise unavoidably tied to BSM physics, and has provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.
- Lack of experimental evidence so far for a straightforward answer to naturalness, forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties
  - again, "who ordered that?"
  - in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification, nothing of the Higgs boson can be given for granted
  - what we've experimentally proven so far are basic properties, which, from the perspective of EFT and at the current level of precision of the measurements, could hold in a vast range of BSM EWSB scenarios

➡ *the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, which can* ***only*** *rely on a future generation of colliders*

which

=> Chong Shik Park's summary



Plenary Session

Accelerator-related

- Status of ILC - Hitoshi Hayano
- Status of CepC/SppC - Jie Gao
- Status of FCC-ee, ep, pp - Alain Blondel

- Summary of Open Symposium on European Strategy Upgrade: Accelerators - Moses Chung
- Planning for Particle Physics: Perspective from the Americas - Young-Kee Kim
- Planning for Particle Physics: Perspective from Asia - Geoffrey Taylor
- Vision of Future Collider - Yifang Wang

7/19/2019 KAIST-KAIX Workshop | Chong Shik Park | Korea University

what

Key issue

<u>Key question for the future developments of HEP:</u>
Why don’t we see the new physics we expected to be present around the TeV scale ?

Key issue

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 ?**

Key issue

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*

What we want from a future collider

What we want from a future collider

- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**

What we want from a future collider

- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**
- Exploration potential:
  - exploit both direct (large Q^2) and indirect (precision) probes
  - **enhanced mass reach** for direct exploration
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*

What we want from a future collider

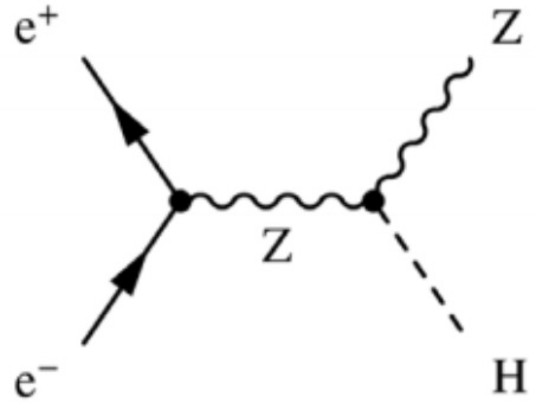
- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**

- Exploration potential:
  - exploit both direct (large Q^2) and indirect (precision) probes
  - **enhanced mass reach** for direct exploration
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*

- Provide firm Yes/No answers to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase transition have been 1st order?
  - could baryogenesis have taken place during the EW phase transition?
  - could neutrino masses have their origin at the TeV scale?
  - …

Higgs physics targets

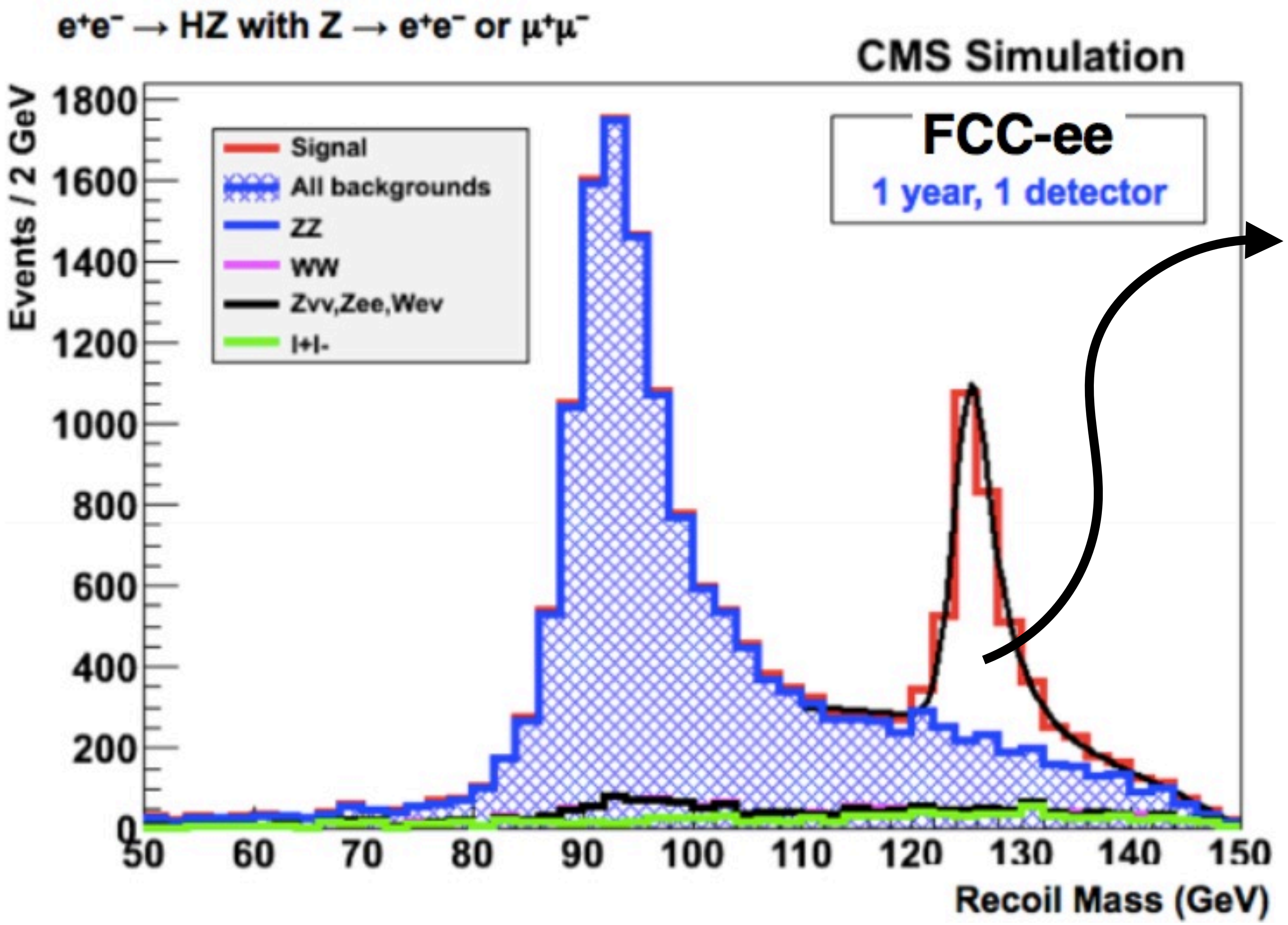
The necessity of $e^+e^- \rightarrow ZH$



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

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

reconstruct Higgs events independently of the Higgs decay mode!



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

$N(ZH[\rightarrow ZZ]) \propto$

$\sigma(ZH) \times BR(H \rightarrow ZZ) \propto$

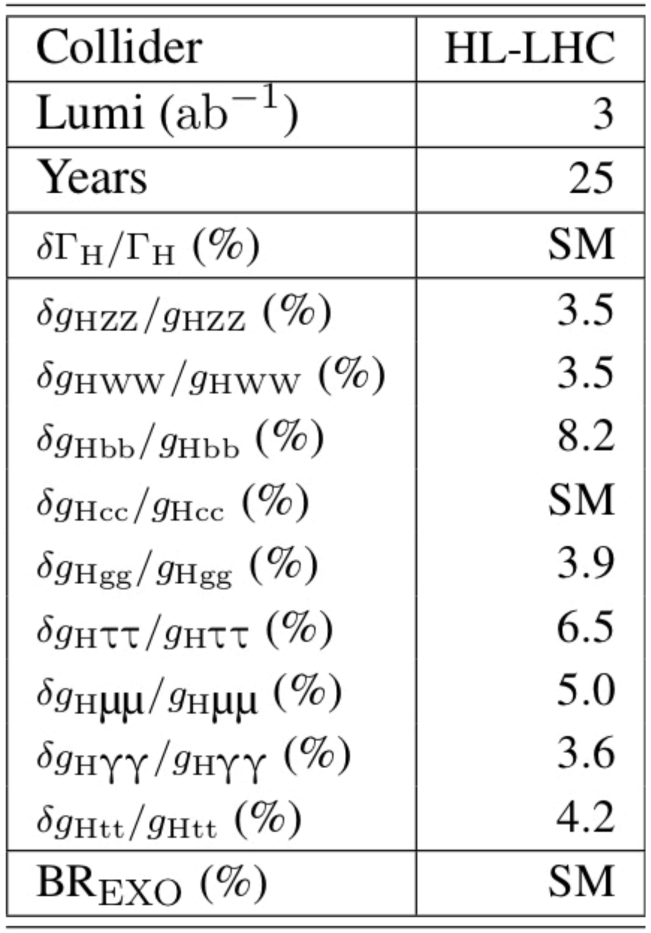
$g_{HZZ}^2 \times g_{HZZ}^2 / \Gamma(H)$

$\Rightarrow$ absolute measurement of width and couplings

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

Higgs couplings: beyond the HL-LHC

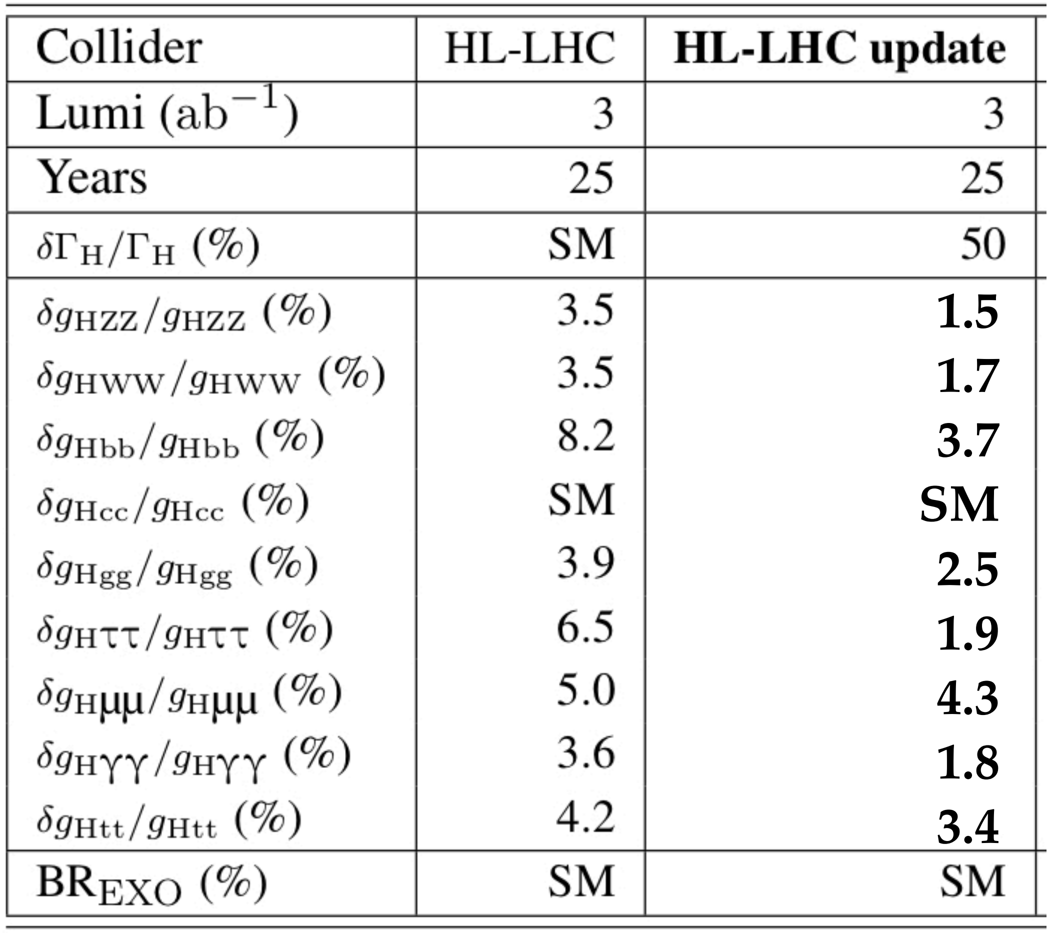
=> Zhen's summary



Collider	HL-LHC
Lumi (ab^{-1})	3
Years	25
$\delta\Gamma_{\mathrm{H}}/\Gamma_{\mathrm{H}}$ (%)	SM
$\delta g_{\mathrm{HZZ}}/g_{\mathrm{HZZ}}$ (%)	3.5
$\delta g_{\mathrm{HWW}}/g_{\mathrm{HWW}}$ (%)	3.5
$\delta g_{\mathrm{Hbb}}/g_{\mathrm{Hbb}}$ (%)	8.2
$\delta g_{\mathrm{Hcc}}/g_{\mathrm{Hcc}}$ (%)	SM
$\delta g_{\mathrm{Hgg}}/g_{\mathrm{Hgg}}$ (%)	3.9
$\delta g_{\mathrm{H}\tau\tau}/g_{\mathrm{H}\tau\tau}$ (%)	6.5
$\delta g_{\mathrm{H}\mu\mu}/g_{\mathrm{H}\mu\mu}$ (%)	5.0
$\delta g_{\mathrm{H}\gamma\gamma}/g_{\mathrm{H}\gamma\gamma}$ (%)	3.6
$\delta g_{\mathrm{Htt}}/g_{\mathrm{Htt}}$ (%)	4.2
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM

Higgs couplings: beyond the HL-LHC

=> Zhen's summary

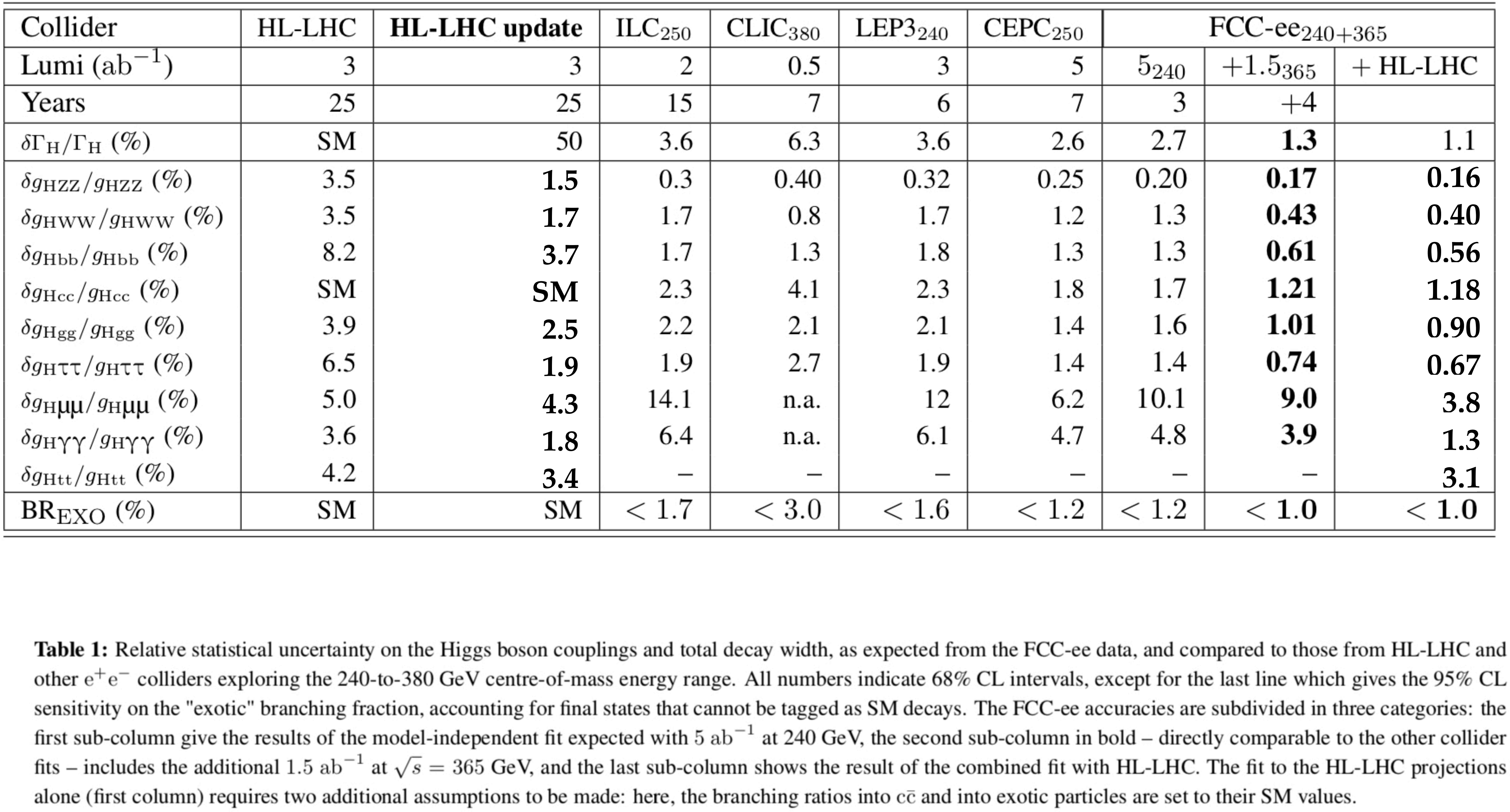


Collider	HL-LHC	**HL-LHC update**
Lumi (ab^{-1})	3	3
Years	25	25
$\delta\Gamma_H/\Gamma_H$ (%)	SM	50
$\delta g_{HZZ}/g_{HZZ}$ (%)	3.5	**1.5**
$\delta g_{HWW}/g_{HWW}$ (%)	3.5	**1.7**
$\delta g_{Hbb}/g_{Hbb}$ (%)	8.2	**3.7**
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	**SM**
$\delta g_{Hgg}/g_{Hgg}$ (%)	3.9	**2.5**
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	6.5	**1.9**
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	5.0	**4.3**
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	3.6	**1.8**
$\delta g_{Htt}/g_{Htt}$ (%)	4.2	**3.4**
BR_{EXO} (%)	SM	SM

* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, https://cds.cern.ch/record/2650162.

Higgs couplings: beyond the HL-LHC

=> Zhen's summary



Collider	HL-LHC	**HL-LHC update**	ILC_{250}	CLIC_{380}	$\mathrm{LEP3}_{240}$	CEPC_{250}	$\mathrm{FCC\text{-}ee}_{240+365}$		
Lumi (ab^{-1})	3	3	2	0.5	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	25	15	7	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	50	3.6	6.3	3.6	2.6	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	3.5	**1.5**	0.3	0.40	0.32	0.25	0.20	**0.17**	**0.16**
$\delta g_{HWW}/g_{HWW}$ (%)	3.5	**1.7**	1.7	0.8	1.7	1.2	1.3	**0.43**	**0.40**
$\delta g_{Hbb}/g_{Hbb}$ (%)	8.2	**3.7**	1.7	1.3	1.8	1.3	1.3	**0.61**	**0.56**
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	**SM**	2.3	4.1	2.3	1.8	1.7	**1.21**	**1.18**
$\delta g_{Hgg}/g_{Hgg}$ (%)	3.9	**2.5**	2.2	2.1	2.1	1.4	1.6	**1.01**	**0.90**
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	6.5	**1.9**	1.9	2.7	1.9	1.4	1.4	**0.74**	**0.67**
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	5.0	**4.3**	14.1	n.a.	12	6.2	10.1	**9.0**	**3.8**
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	3.6	**1.8**	6.4	n.a.	6.1	4.7	4.8	**3.9**	**1.3**
$\delta g_{Htt}/g_{Htt}$ (%)	4.2	**3.4**	–	–	–	–	–	–	**3.1**
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM	SM	< 1.7	< 3.0	< 1.6	< 1.2	< 1.2	$< \mathbf{1.0}$	$< \mathbf{1.0}$

Table 1: Relative statistical uncertainty on the Higgs boson couplings and total decay width, as expected from the FCC-ee data, and compared to those from HL-LHC and other e^+e^- colliders exploring the 240-to-380 GeV centre-of-mass energy range. All numbers indicate 68% CL intervals, except for the last line which gives the 95% CL sensitivity on the "exotic" branching fraction, accounting for final states that cannot be tagged as SM decays. The FCC-ee accuracies are subdivided in three categories: the first sub-column give the results of the model-independent fit expected with $5\ \mathrm{ab}^{-1}$ at 240 GeV, the second sub-column in bold – directly comparable to the other collider fits – includes the additional $1.5\ \mathrm{ab}^{-1}$ at $\sqrt{s} = 365$ GeV, and the last sub-column shows the result of the combined fit with HL-LHC. The fit to the HL-LHC projections alone (first column) requires two additional assumptions to be made: here, the branching ratios into $c\bar{c}$ and into exotic particles are set to their SM values.

* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, https://cds.cern.ch/record/2650162.

Remarks and key messages

- Updated HL-LHC projections bring the coupling sensitivity to the few-% level. They are obtained by extrapolating **current** analysis strategies, and are informed by current experience plus robust assumptions about the performance of the phase-2 upgraded detectors in the high pile-up environment
    - Projections will improve as **new** analyses, allowed by higher statistics, will be considered

Remarks and key messages

- Updated HL-LHC projections bring the coupling sensitivity to the few-% level. They are obtained by extrapolating **current** analysis strategies, and are informed by current experience plus robust assumptions about the performance of the phase-2 upgraded detectors in the high pile-up environment
  - Projections will improve as **new** analyses, allowed by higher statistics, will be considered

1. To significantly improve the expected HL-LHC results, future facilities must push Higgs couplings' precision to the sub-% level

Remarks and key messages

- Updated HL-LHC projections bring the coupling sensitivity to the few-% level. They are obtained by extrapolating **current** analysis strategies, and are informed by current experience plus robust assumptions about the performance of the phase-2 upgraded detectors in the high pile-up environment
  - Projections will improve as **new** analyses, allowed by higher statistics, will be considered

1. To significantly improve the expected HL-LHC results, future facilities must push Higgs couplings' precision to the sub-% level
2. Event rates higher than what ee colliders can provide are needed to reach sub-% measurements of couplings such as Hγγ, Hμμ, HZγ, Htt

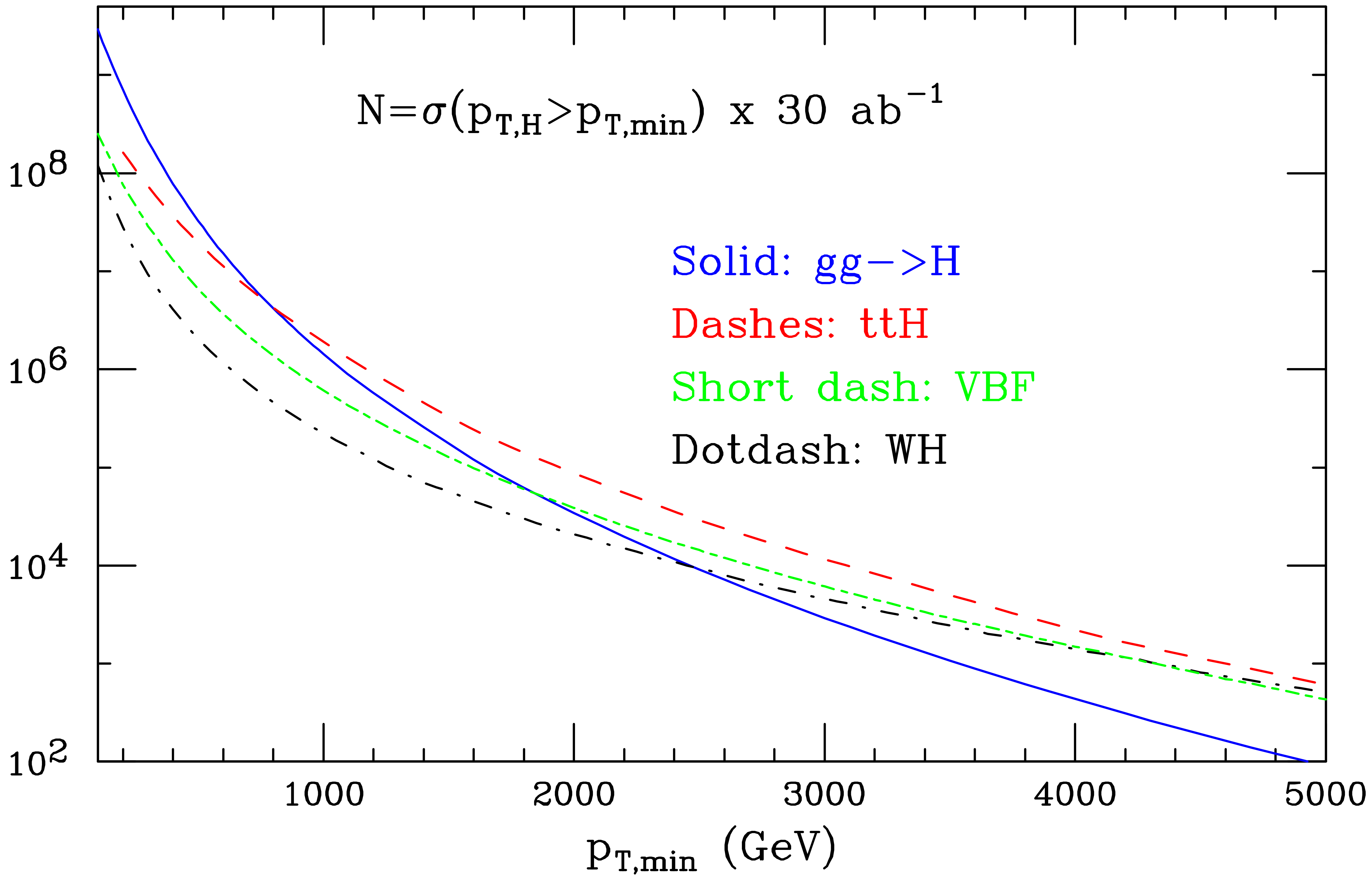
SM Higgs: event rates in pp@100 TeV

	gg→H	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 30\ \mathrm{ab}^{-1}$

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

H at large p_T



- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \rightarrow H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \rightarrow H)$ above 1800 GeV

Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65** $^{(*)}$
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4** $^{(*)}$
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	**0.95** $^{(**)}$
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9** $^{(*)}$
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	**6.5**
BR_{exo} (95%CL)	$\mathrm{BR}_{inv} < 2.5\%$	**< 1%**	**$\mathrm{BR}_{inv} < 0.025\%$**

* From BR ratios wrt B(H→4lept) @ FCC-ee

** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

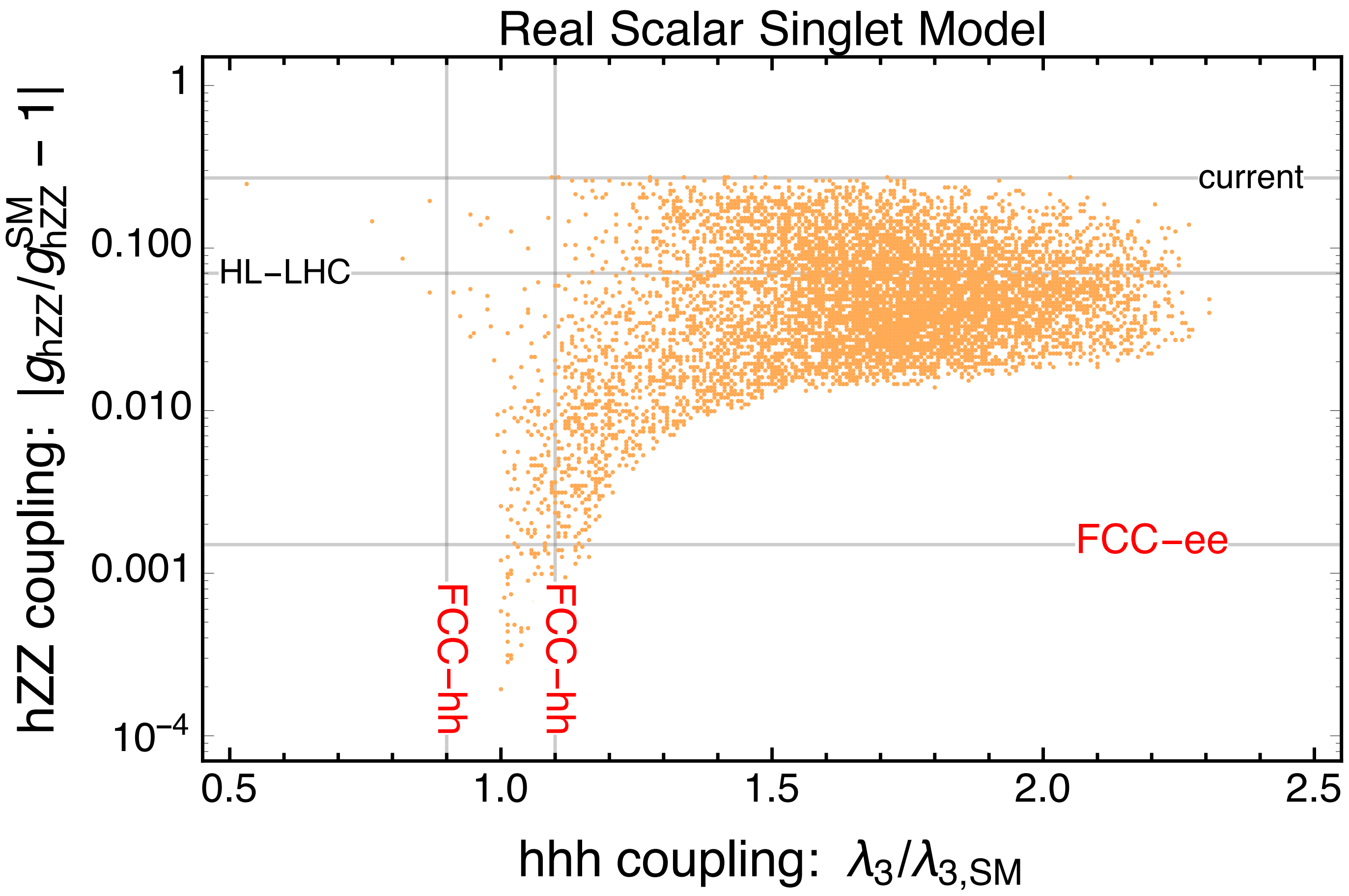
Example of precision targets:
constraints on models with 1st order phase transition

$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 .$$

Example of precision targets: constraints on models with 1st order phase transition

$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh

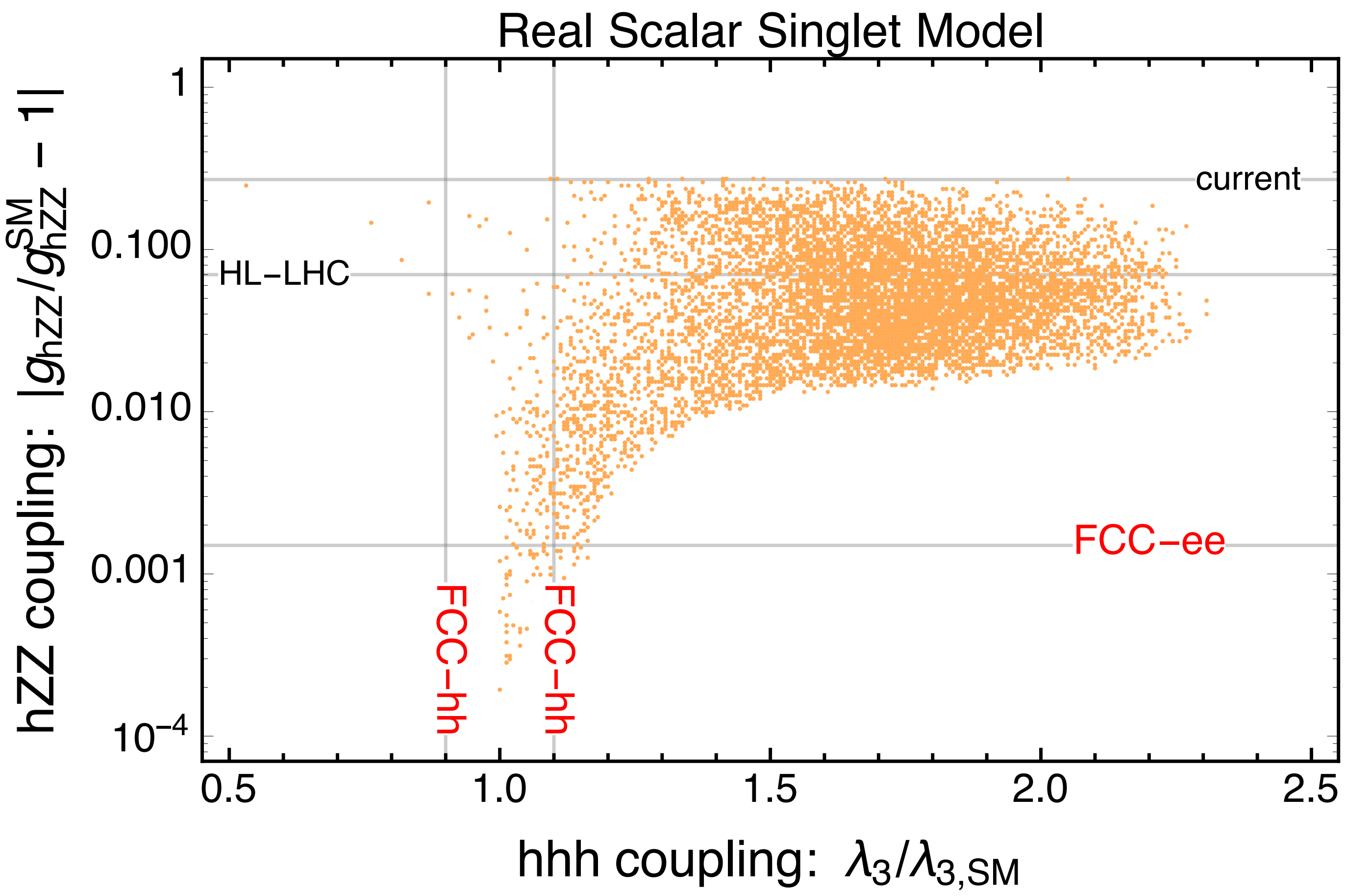


Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

Example of precision targets: constraints on models with 1st order phase transition

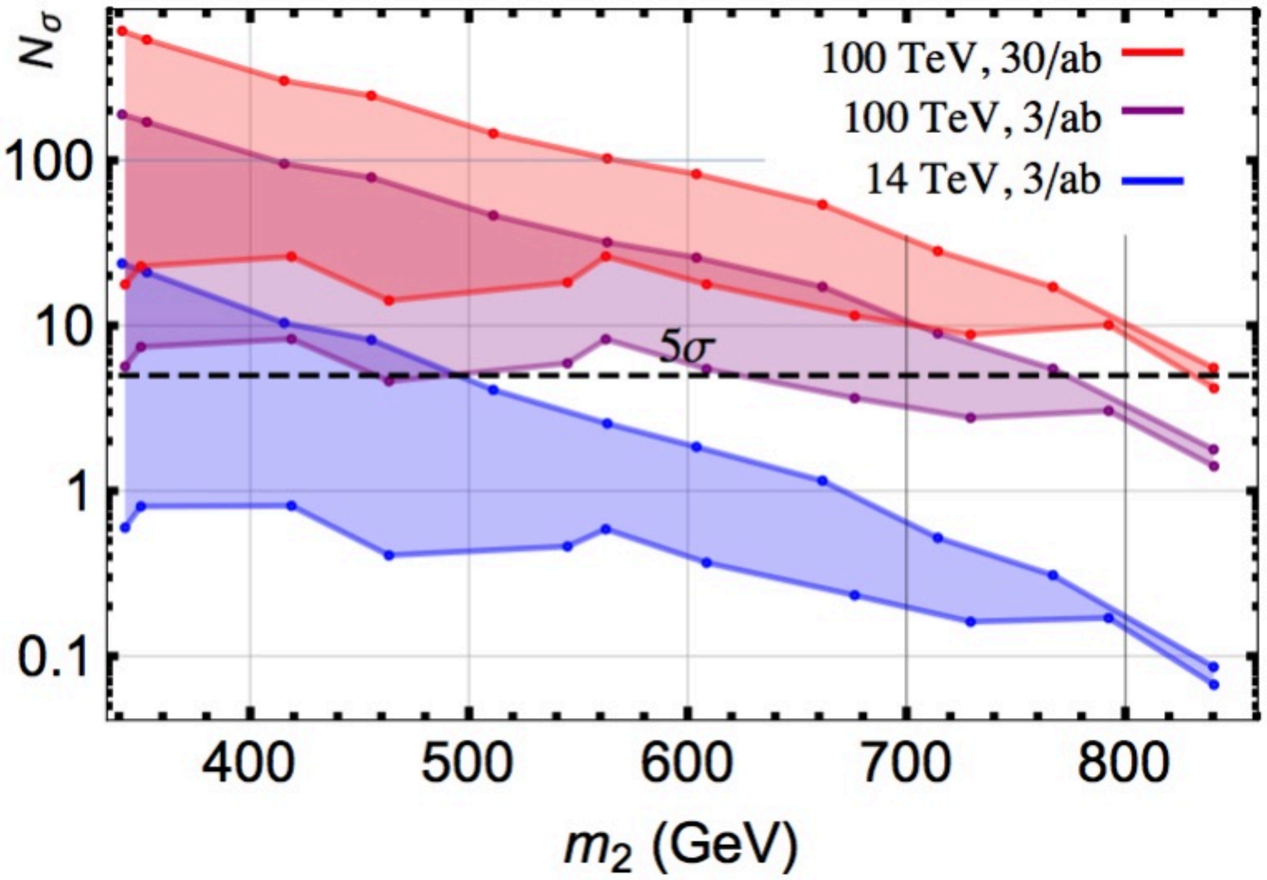
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S$$
$$+\frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

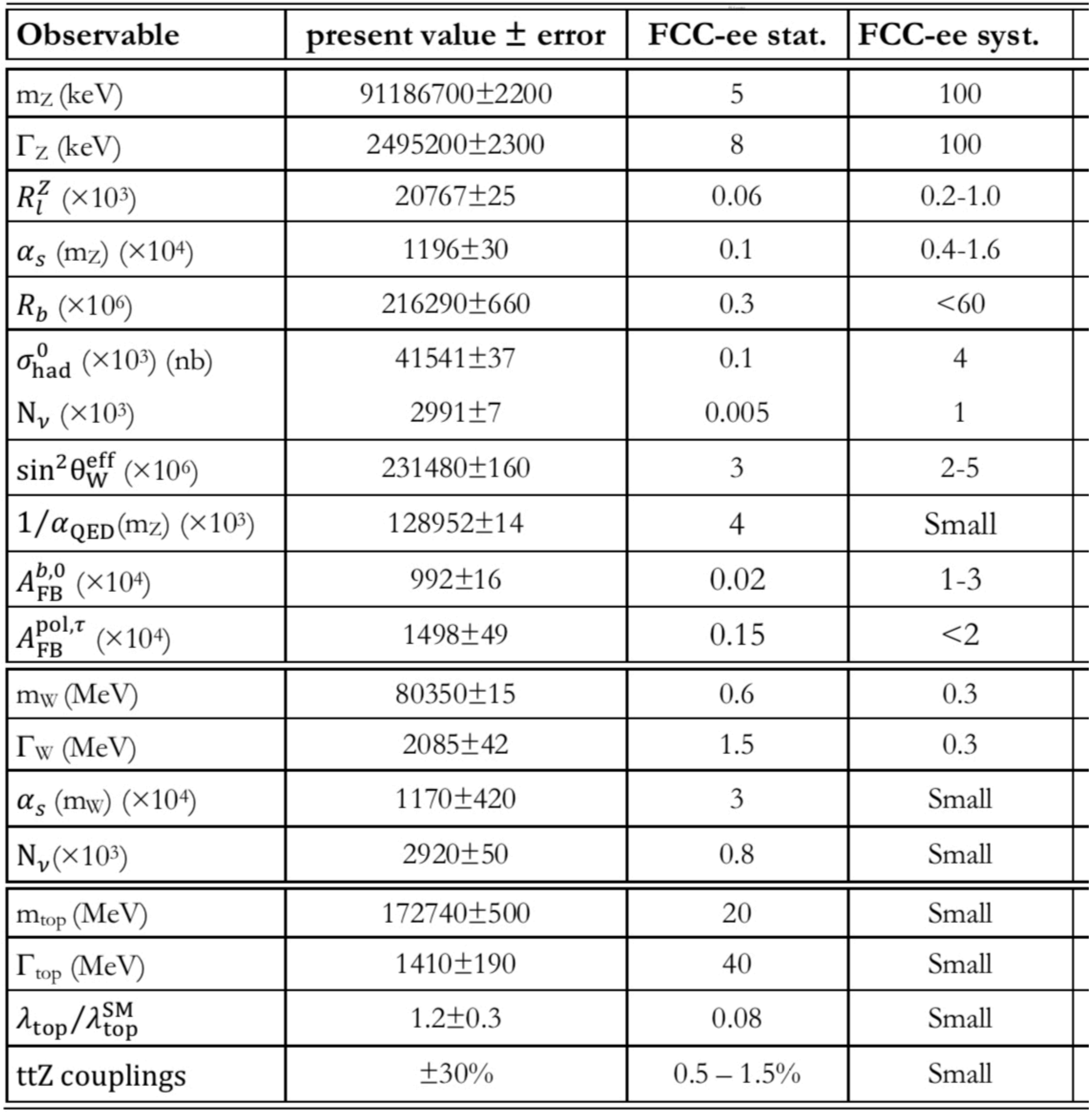
Direct detection of extra Higgs states at FCC-hh



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

$(h_2 \sim S, \quad h_1 \sim H)$

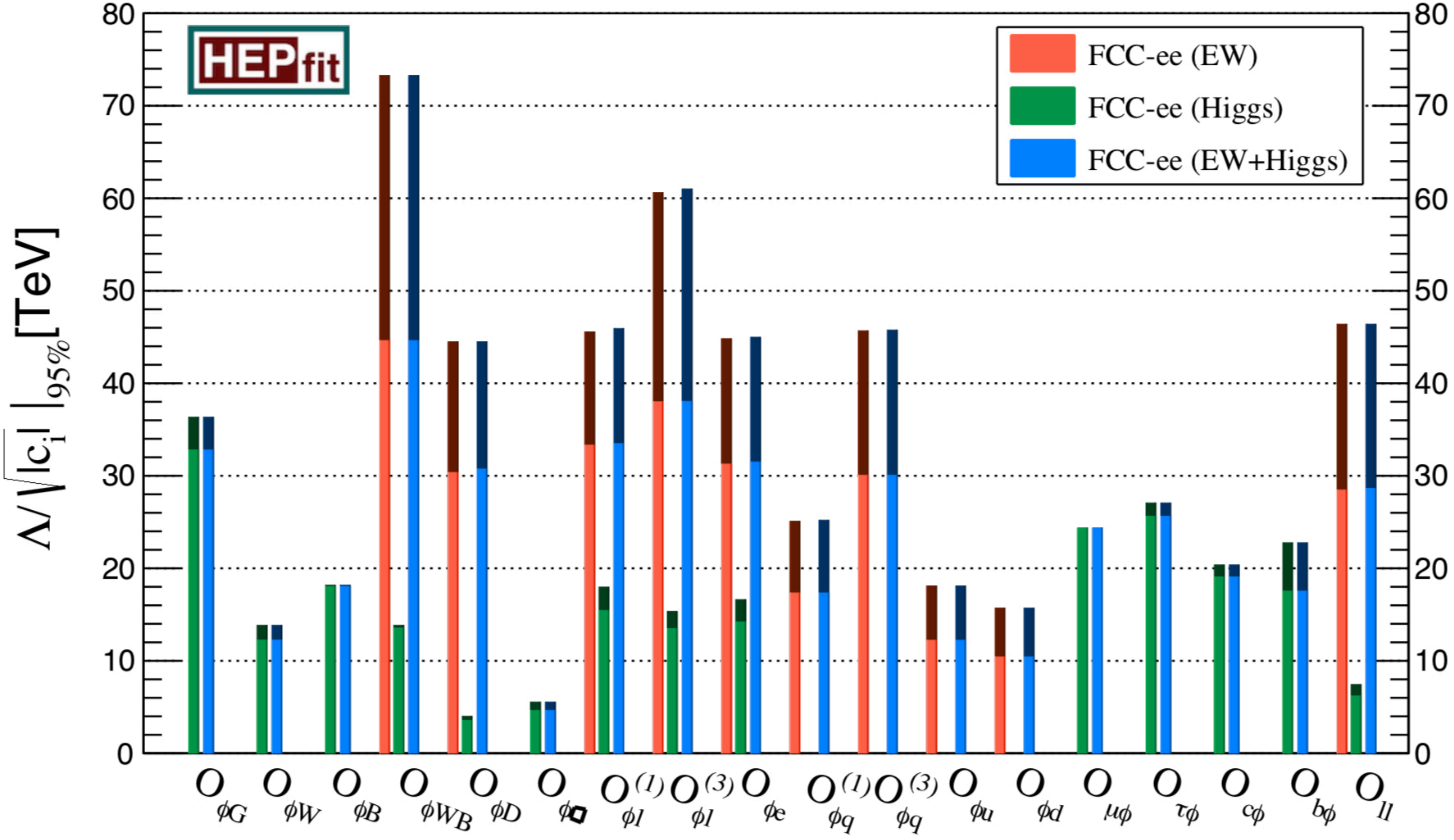
EW parameters @ FCC-ee



Observable	present value ± error	FCC-ee stat.	FCC-ee syst.
m_Z (keV)	91186700±2200	5	100
Γ_Z (keV)	2495200±2300	8	100
R_l^Z (×10³)	20767±25	0.06	0.2-1.0
α_s (m_Z) (×10⁴)	1196±30	0.1	0.4-1.6
R_b (×10⁶)	216290±660	0.3	<60
σ_{had}^0 (×10³) (nb)	41541±37	0.1	4
N_ν (×10³)	2991±7	0.005	1
$\sin^2\theta_W^{\text{eff}}$ (×10⁶)	231480±160	3	2-5
$1/\alpha_{\text{QED}}(m_Z)$ (×10³)	128952±14	4	Small
$A_{\text{FB}}^{b,0}$ (×10⁴)	992±16	0.02	1-3
$A_{\text{FB}}^{\text{pol},\tau}$ (×10⁴)	1498±49	0.15	<2
m_W (MeV)	80350±15	0.6	0.3
Γ_W (MeV)	2085±42	1.5	0.3
α_s (m_W) (×10⁴)	1170±420	3	Small
N_ν(×10³)	2920±50	0.8	Small
m_{top} (MeV)	172740±500	20	Small
Γ_{top} (MeV)	1410±190	40	Small
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2±0.3	0.08	Small
ttZ couplings	±30%	0.5 – 1.5%	Small

Global EFT fits to EW and H observables at FCC-ee

=> Jorge's summary



Constraints on the coefficients of various EFT op's from a global fit of (i) EW observables, (ii) Higgs couplings and (iii) EW+Higgs combined. Darker shades of each color indicate the results neglecting all SM theory uncertainties.

Remarks and key messages

Remarks and key messages

- Higgs and EW observables are greatly complementary in constraining EFT ops and possibly exposing SM deviations

Remarks and key messages

- Higgs and EW observables are greatly complementary in constraining EFT ops and possibly exposing SM deviations

1. An ee Higgs factory needs to operate at the Z pole and WW threshold to maximize the potential of precision measurements of the EW sector

Remarks and key messages

- Higgs and EW observables are greatly complementary in constraining EFT ops and possibly exposing SM deviations

1. An ee Higgs factory needs to operate at the Z pole and WW threshold to maximize the potential of precision measurements of the EW sector

- EW&Higgs precision measurements at future ee colliders could probe scales as large as several 10's of TeV ($c_i \sim 1 \div 4\pi$)

Remarks and key messages

- Higgs and EW observables are greatly complementary in constraining EFT ops and possibly exposing SM deviations

1. An ee Higgs factory needs to operate at the Z pole and WW threshold to maximize the potential of precision measurements of the EW sector

- EW&Higgs precision measurements at future ee colliders could probe scales as large as several 10's of TeV ($c_i \sim 1 \div 4\pi$)

2. To directly explore the origin of possible discrepancies, requires collisions in the several 10s of TeV region

Implications of Higgs/EWSB targets

Implications of Higgs/EWSB targets

- The goal of sub-% precision for Higgs couplings *(at least for couplings to gauge bosons and to 2nd & 3rd generation fermions)* demands both an ee and high-E/L pp collider

Implications of Higgs/EWSB targets

- The goal of sub-% precision for Higgs couplings *(at least for couplings to gauge bosons and to 2nd & 3rd generation fermions)* demands both an ee and high-E/L pp collider
- Should one not wait for the outcome of the ee program, before deciding whether pp@100 TeV is necessary? *(alternatives being eg CLIC@3TeV, muon collider or plasma collider at few-10 TeV)*

Implications of Higgs/EWSB targets

- The goal of sub-% precision for Higgs couplings *(at least for couplings to gauge bosons and to 2nd & 3rd generation fermions)* demands both an ee and high-E/L pp collider
- Should one not wait for the outcome of the ee program, before deciding whether pp@100 TeV is necessary? *(alternatives being eg CLIC@3TeV, muon collider or plasma collider at few-10 TeV)*
    - in presence of deviations in the Higgs/EW sector, the scale of new physics could extend to the few 10 TeV region, direct access requires the highest possible energy

Implications of Higgs/EWSB targets

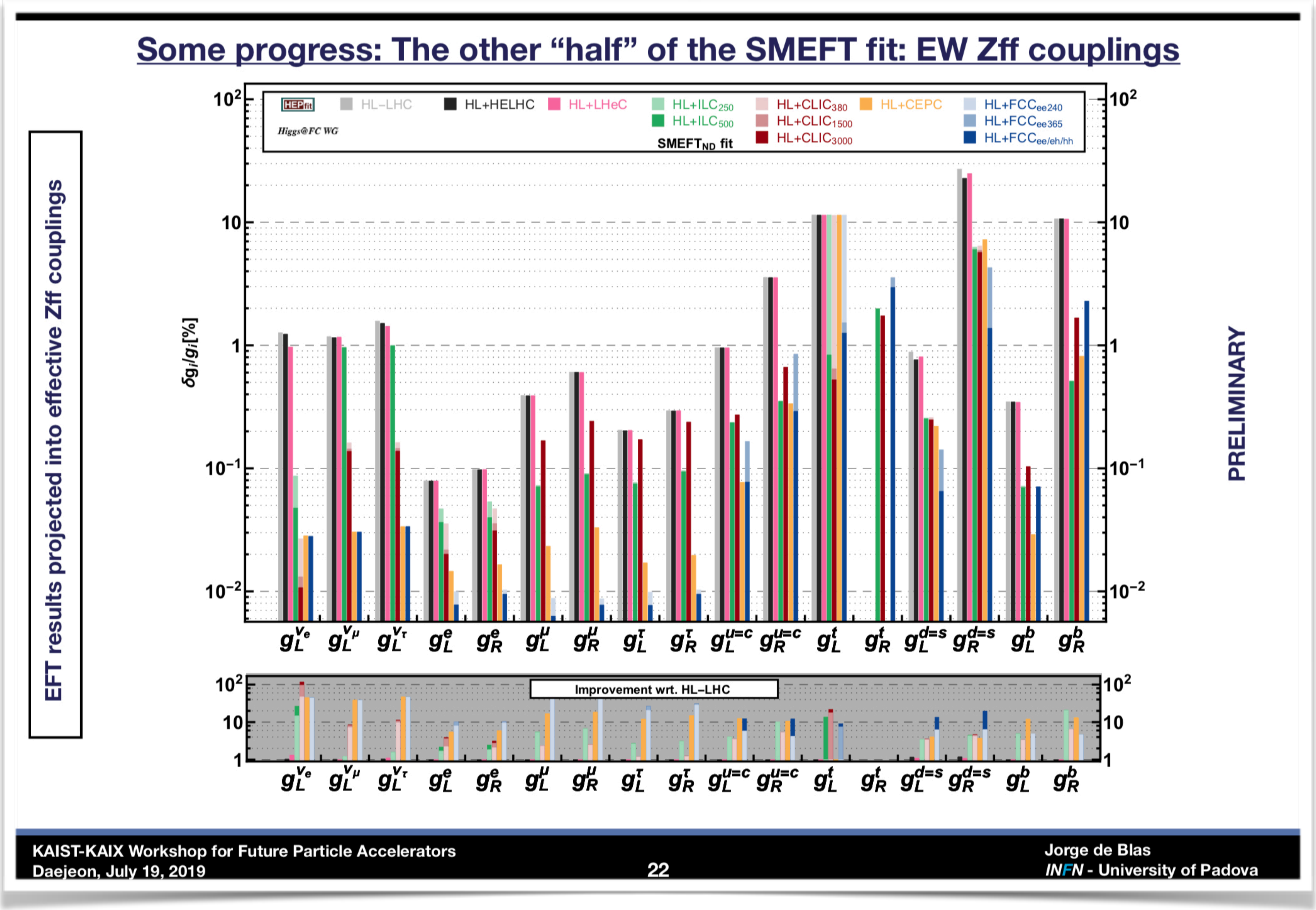
- The goal of sub-% precision for Higgs couplings *(at least for couplings to gauge bosons and to 2nd & 3rd generation fermions)* demands both an ee and high-E/L pp collider
- Should one not wait for the outcome of the ee program, before deciding whether pp@100 TeV is necessary? *(alternatives being eg CLIC@3TeV, muon collider or plasma collider at few-10 TeV)*
  - in presence of deviations in the Higgs/EW sector, the scale of new physics could extend to the few 10 TeV region, direct access requires the highest possible energy
  - absence of deviations does not imply no new physics up to 10's of TeV. Weakly coupled physics could be just beyond LHC reach, without leaving visible traces in the H/EWSB sectors

Implications of Higgs/EWSB targets

- The goal of sub-% precision for Higgs couplings *(at least for couplings to gauge bosons and to 2nd & 3rd generation fermions)* demands both an ee and high-E/L pp collider
- Should one not wait for the outcome of the ee program, before deciding whether pp@100 TeV is necessary? *(alternatives being eg CLIC@3TeV, muon collider or plasma collider at few-10 TeV)*
  - in presence of deviations in the Higgs/EW sector, the scale of new physics could extend to the few 10 TeV region, direct access requires the highest possible energy
  - absence of deviations does not imply no new physics up to 10's of TeV. Weakly coupled physics could be just beyond LHC reach, without leaving visible traces in the H/EWSB sectors

➡ the completion of the Higgs/EWSB programme, by itself, justifies the planning of a high-E/L pp collider following the ee phase

remark



Some progress: The other "half" of the SMEFT fit: EW Zff couplings

EFT results projected into effective Zff couplings

PRELIMINARY

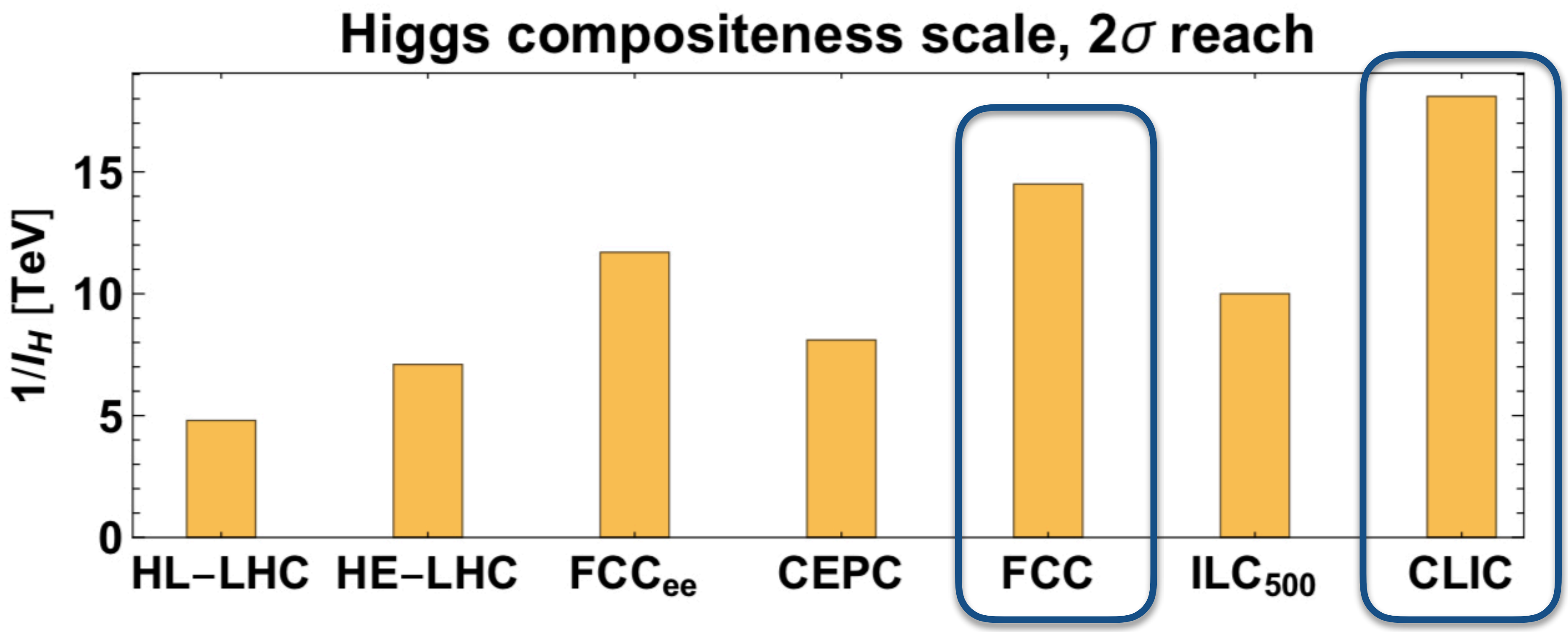
KAIST-KAIX Workshop for Future Particle Accelerators
Daejeon, July 19, 2019

22

Jorge de Blas
INFN - University of Padova

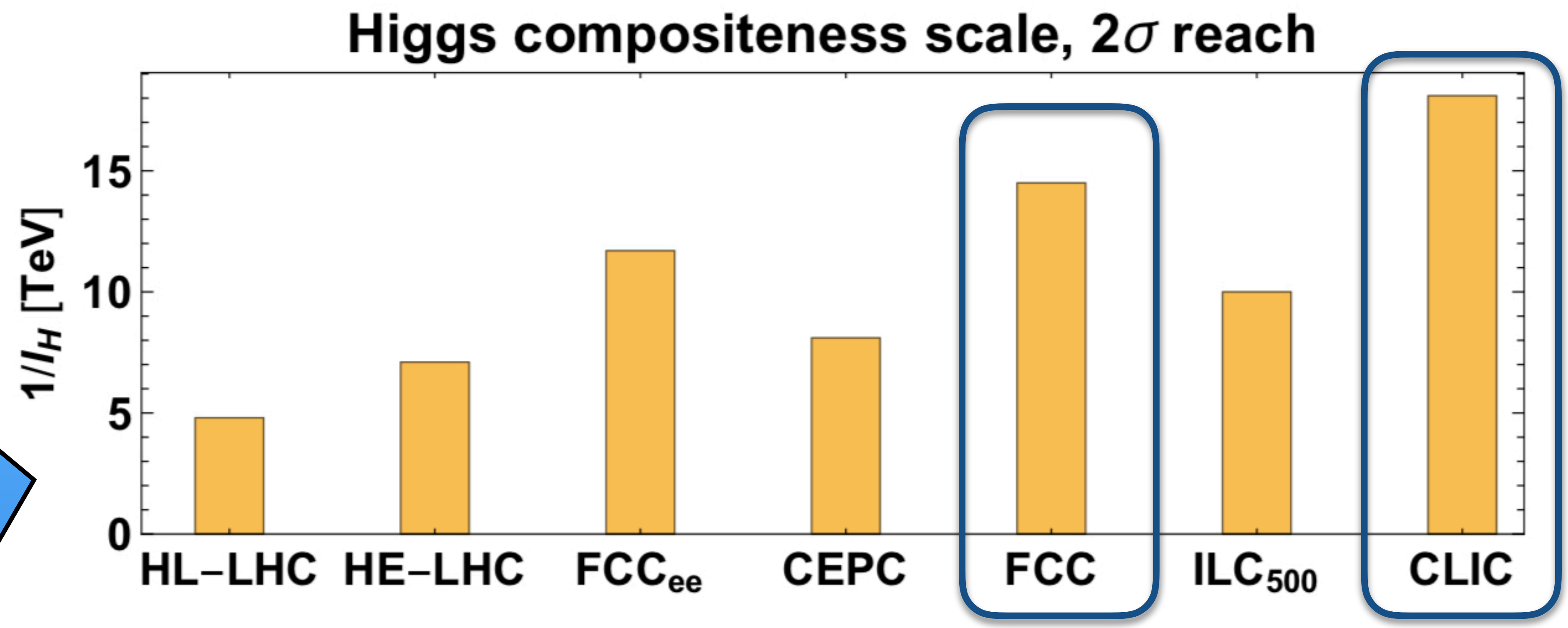
performance comparisons at the level of individual processes are very important, but one should not get hung on specific results: the assessment of the global value of a given project goes beyond single results

also, watch the fine print ...

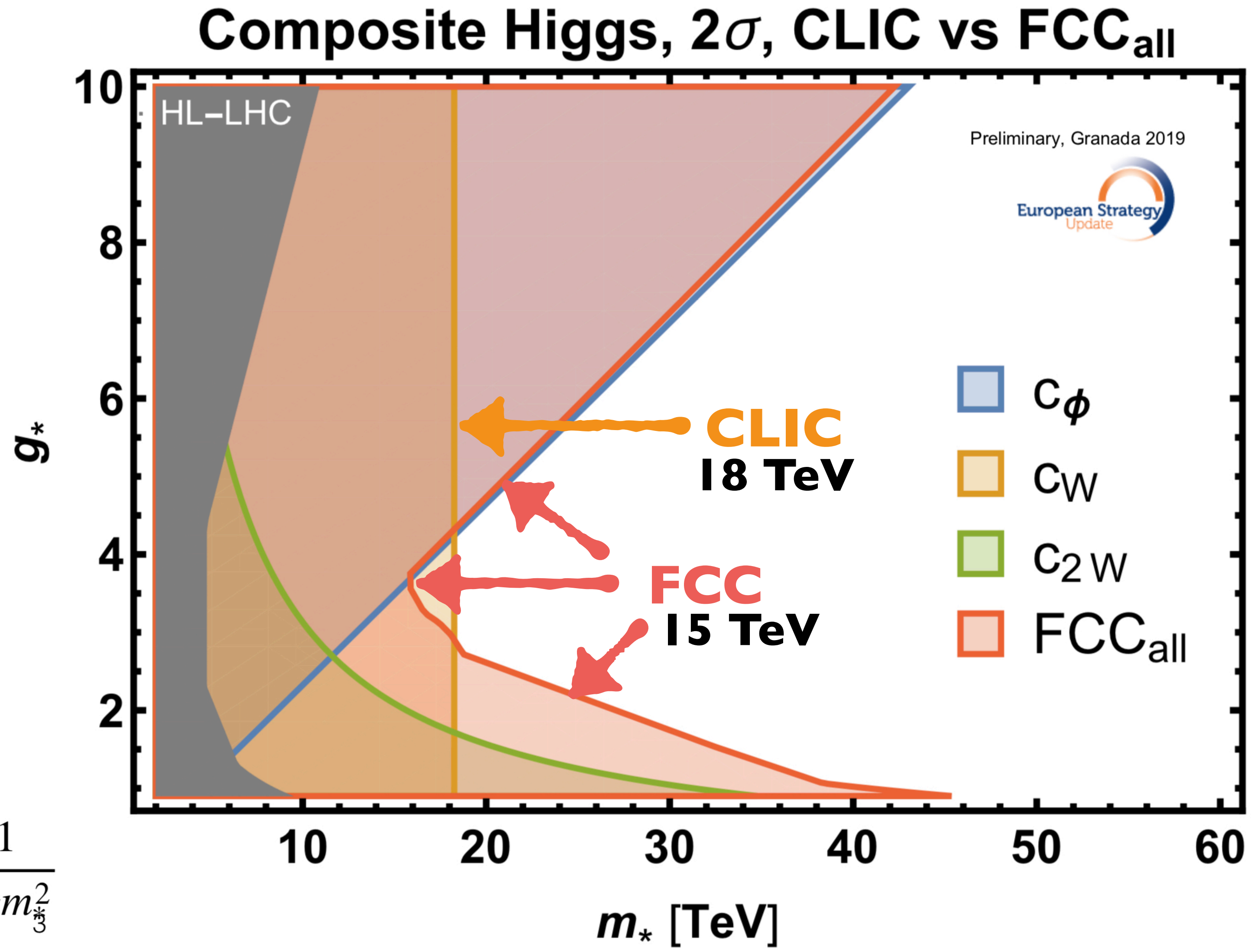


$$\frac{c_\phi}{\Lambda^2} = \frac{g_*^2}{m_*^2} \qquad \frac{c_W}{\Lambda^2} = \frac{1}{m_*^2} \qquad \frac{c_{2W}}{\Lambda^2} = \frac{1}{g_*^2 m_*^2}$$

also, watch the fine print …



Higgs compositeness scale, 2σ reach



Composite Higgs, 2σ, CLIC vs FCC$_{all}$

$$\frac{c_\phi}{\Lambda^2} = \frac{g_*^2}{m_*^2} \qquad \frac{c_W}{\Lambda^2} = \frac{1}{m_*^2} \qquad \frac{c_{2W}}{\Lambda^2} = \frac{1}{g_*^2 m_*^2}$$

What we want from a future collider

What we want from a future collider

- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**

What we want from a future collider

- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**

- Exploration potential:
  - exploit both direct (large Q^2) and indirect (precision) probes
  - **enhanced mass reach** for direct exploration
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*

What we want from a future collider

- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**

- Exploration potential:
  - exploit both direct (large Q^2) and indirect (precision) probes
  - **enhanced mass reach** for direct exploration
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*

- Provide firm Yes/No answers to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase transition have been 1st order?
  - could baryogenesis have taken place during the EW phase transition?
  - could neutrino masses have their origin at the TeV scale?
  - …

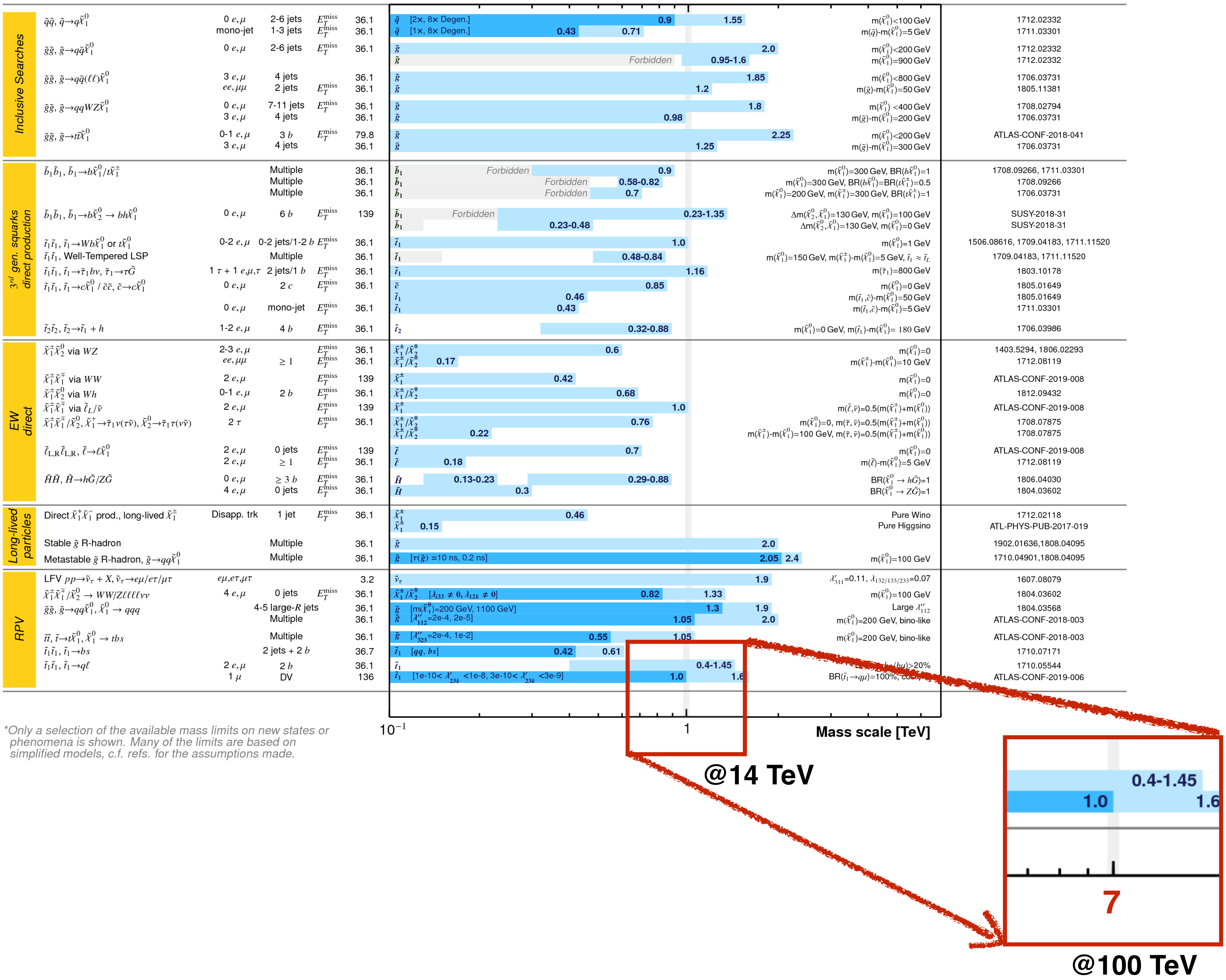
Direct discovery reach: the power of 100 TeV

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2019

ATLAS Preliminary

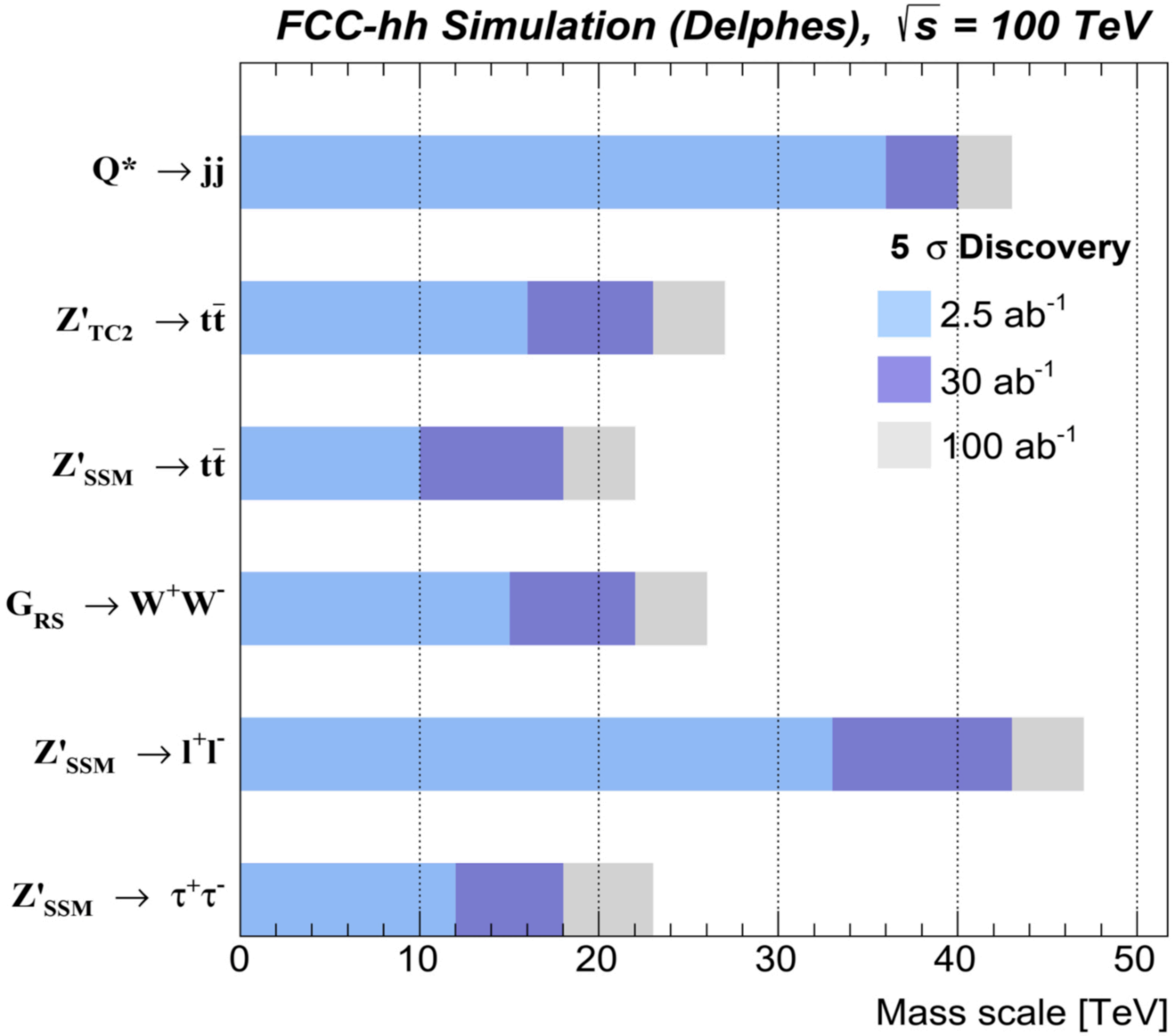
$\sqrt{s}$ = 13 TeV



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit				Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$	[2×, 8× Degen.]	0.9 1.55	m($\tilde{\chi}_1^0$)<100 GeV	1712.02332
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$	[1×, 8× Degen.]	0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$		2.0	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
						$\tilde{g}$	Forbidden	0.95-1.6	m($\tilde{\chi}_1^0$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets		36.1	$\tilde{g}$		1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$		1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$		1.8	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
		3 e,μ	4 jets		36.1	$\tilde{g}$		0.98	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$		2.25	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2018-041
		3 e,μ	4 jets		36.1	$\tilde{g}$		1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$	Forbidden	0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$	Forbidden	0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$	Forbidden	0.7	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden	0.23-1.35	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	SUSY-2018-31
						$\tilde{b}_1$		0.23-0.48	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	SUSY-2018-31
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$		1.0	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$		0.48-0.84	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$		1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$		0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$		0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$		0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_2$		0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ		$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$		0.6	m($\tilde{\chi}_1^0$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$		0.17	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=10 GeV	1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm$		0.42	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e,μ	2 b	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$		0.68	m($\tilde{\chi}_1^0$)=0	1812.09432
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}_1^\pm$		1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}_1\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}_1\tau(\nu\tilde{\nu})$	2 τ		$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$		0.76	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$		0.22	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=100 GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$		0.7	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	$E_T^{\rm miss}$	36.1	$\tilde{\ell}$		0.18	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$		0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{H}$		0.3	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm$		0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$		0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$		2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns, 0.2 ns]	2.05 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$			3.2	$\tilde{\nu}_\tau$		1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	[$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$]	0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$	[m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV]	1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$	[λ''_{112}=2e-4, 2e-5]	1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$	[λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$		0.4-1.45	[illegible]$b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, co[illegible]	ATLAS-CONF-2019-006

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

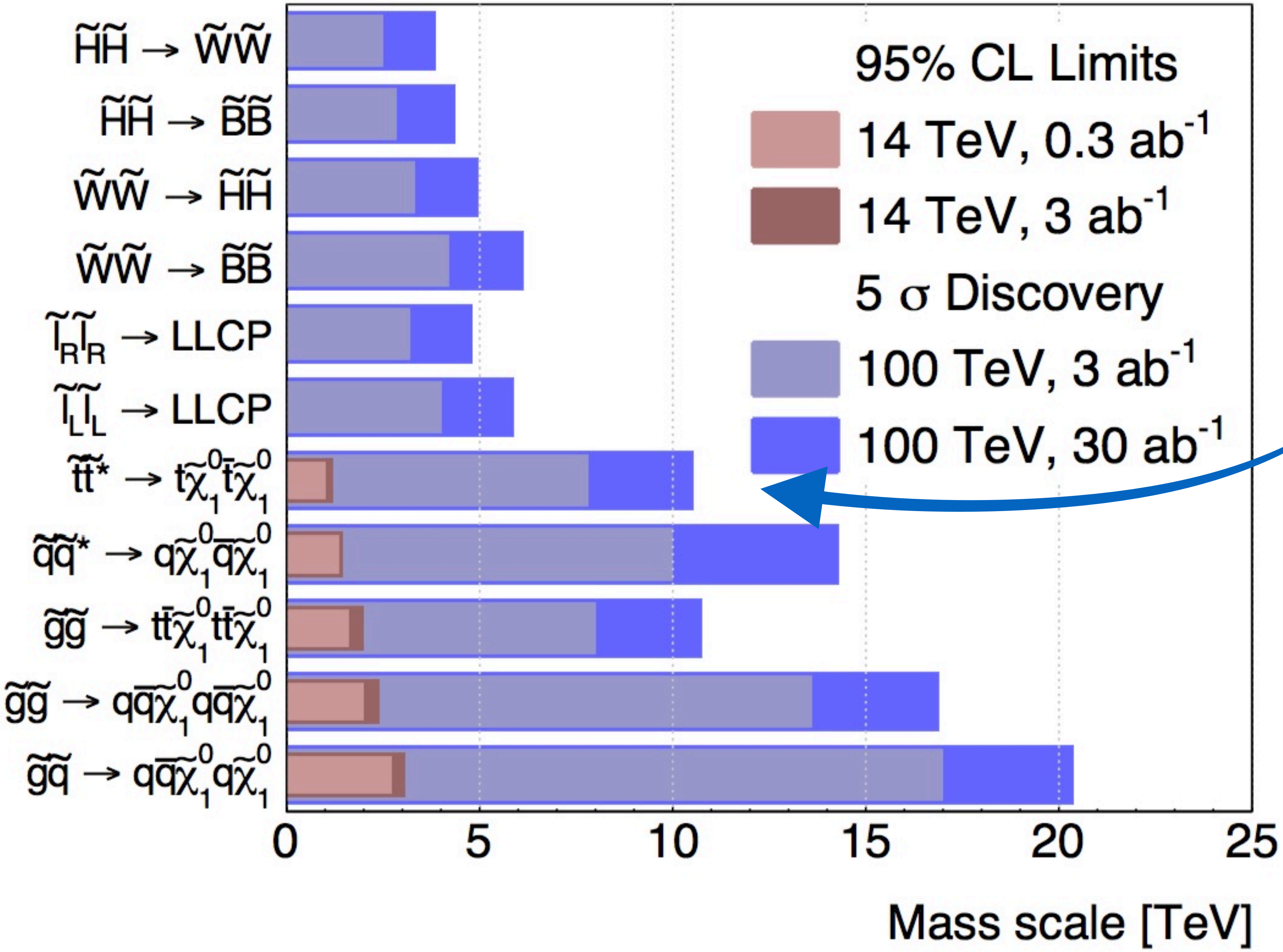
s-channel resonances



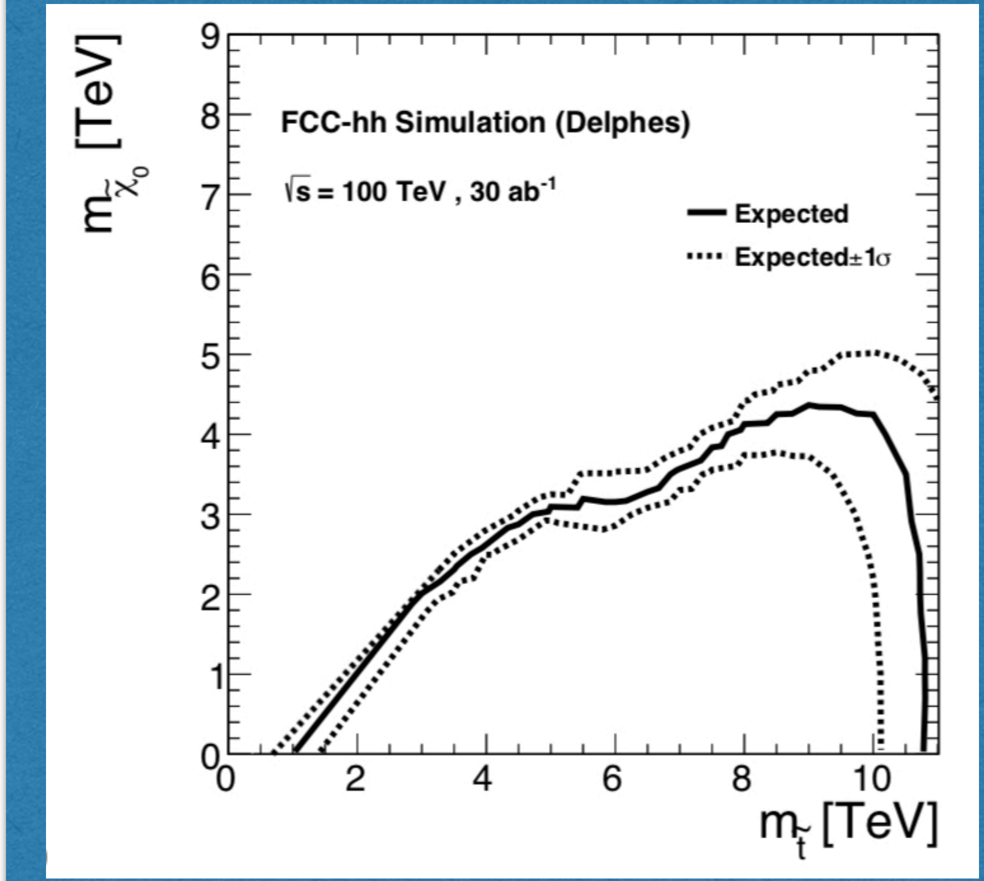
FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV

Early phenomenology studies

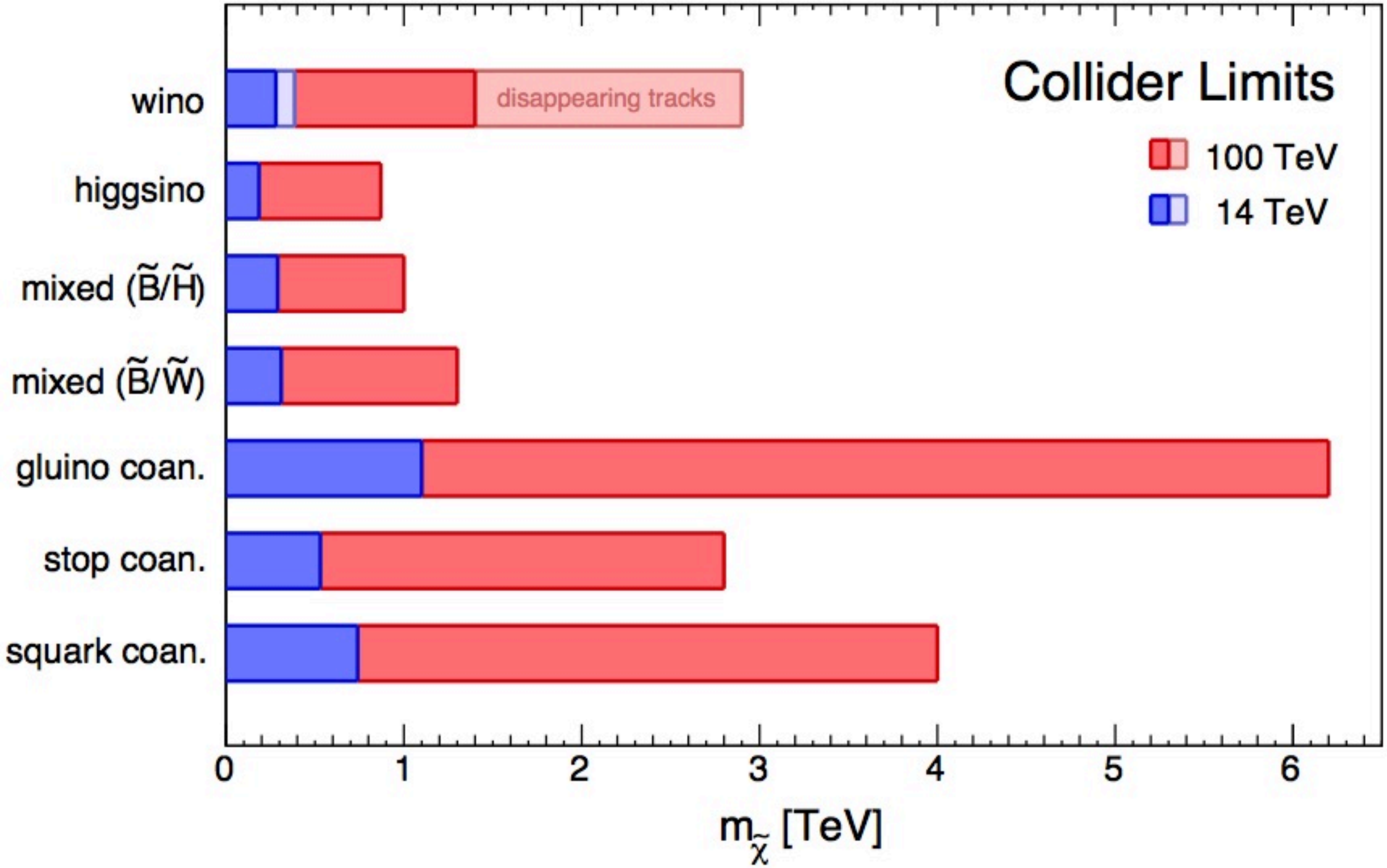


New detector performance studies



DM reach at 100 TeV

Early phenomenology studies

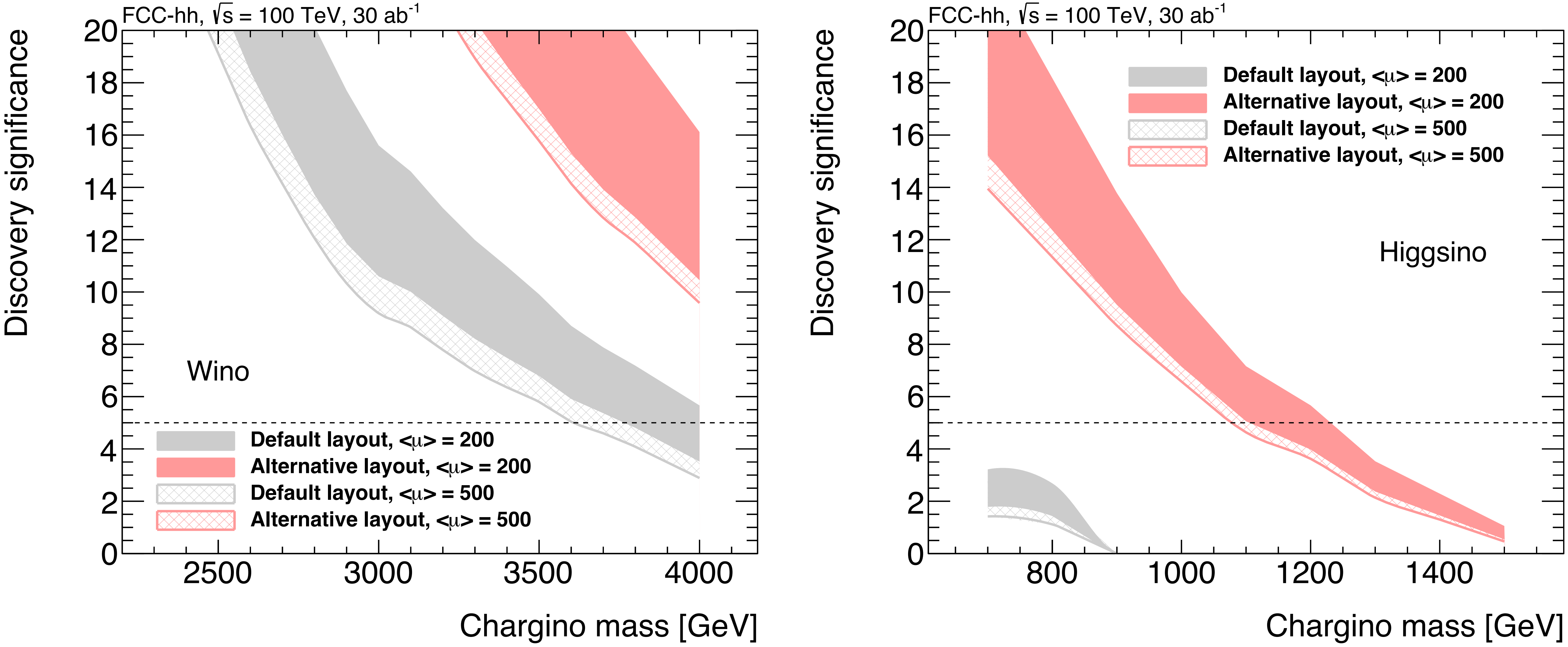


K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.

New detector performance studies

Disappearing charged track analyses

(at ~full pileup)



=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

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

further ingredients

further ingredients

- The huge cost and challenge of each of these future facilities calls for the maximal exploitation of the physics potential, and the inclusion of the broadest possible fraction of the scientific community.

further ingredients

- The huge cost and challenge of each of these future facilities calls for the maximal exploitation of the physics potential, and the inclusion of the broadest possible fraction of the scientific community.

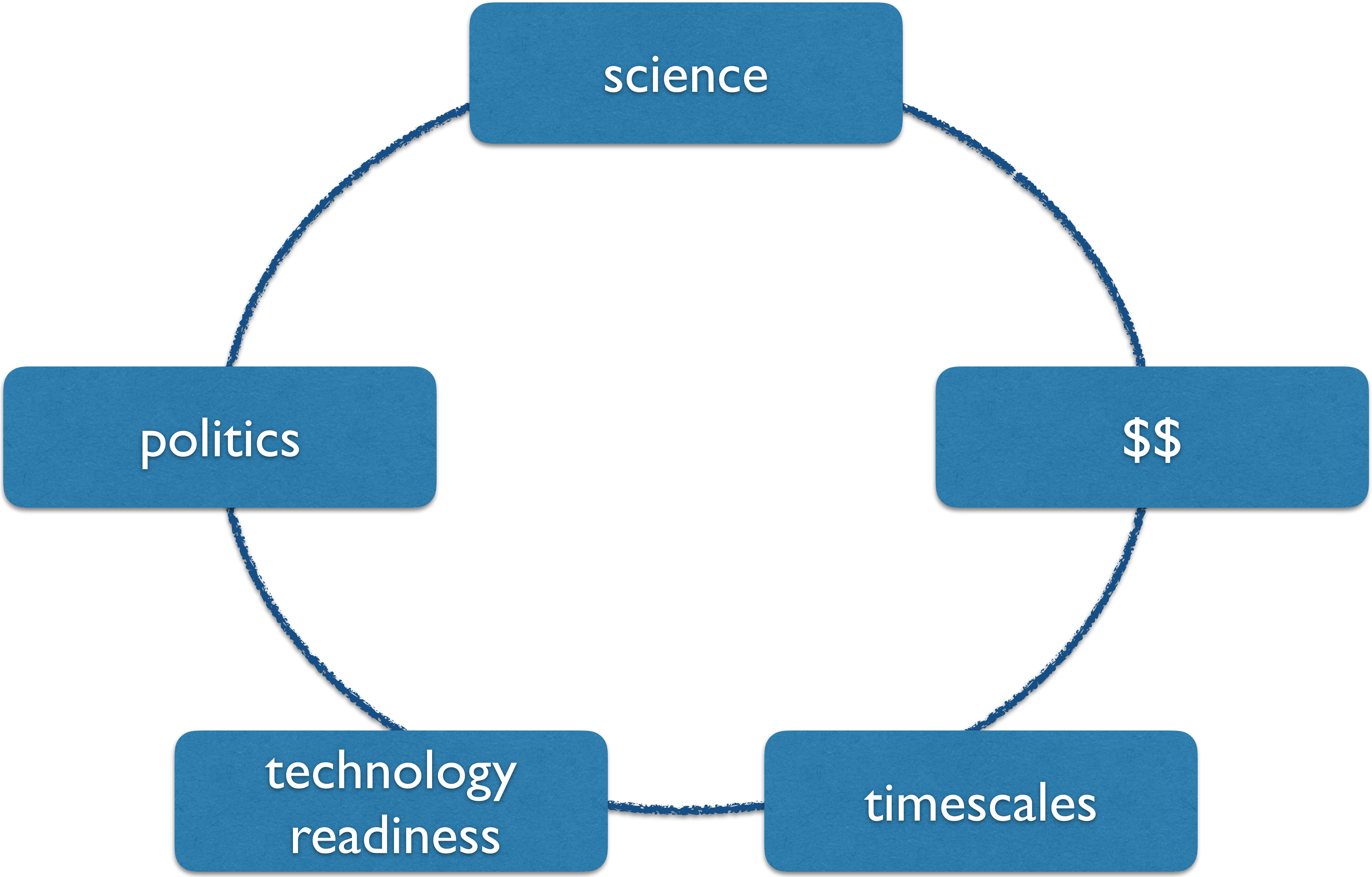
For example:

flavour

- b, c, τ: Tera-Z **=> Emmanuel's summary**
- top: pp
- neutrinos: Tera-Z and pp

QCD at high density and/or high T

- heavy ion collisions **=> In Kwon's summary**
- small-x physics, PDFs, at ep



science

$$

politics

technology readiness

timescales

the role of national strategies

- the scientific input to the worldwide discussion is as important as the readiness to engage financially
- developing a national strategy based on science priorities, even in absence of resources to implement them locally, can:
    - help the big players (CERN, Japan, China, USA) assess the potential international support, and can impact their choices
    - help the national communities reach out to their public and politicians, building support for future direct engagement