LFC24
Fundamental Interactions
at Future Colliders

SISSA, 16-20 Sept 2024

Future colliders

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- As we approach the update of the European Strategy for Particle Physics, it's important to review the underlying criteria that motivate our future endeavors, our expectations, and the ultimate judgement of the most suitable directions (also in view of the practical reality emerging from the full context — technology, costs, sociology, etc)

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- Lack of a clear framework, analogous to the SM, does not just imply lack of no-lose theorems for discovery; it also implies a different approach to seeking answers to the important open questions, a different metric to assess the potential of different options, a different perspective on the role and value of measurements to explore the deep nature of physical laws, even those we already know

Preamble 2

- The ESPP 2025/26: a new ballgame wrt earlier editions, where definition of top priorities was relatively obvious:
  - **2006**: make sure the LHC works
  - **2013**: support the HL-LHC, and start looking at opportunities beyond
  - **2020**: further explore the feasibility of FCC and pursue advanced accelerator technology R&D

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  - **2020**: further explore the feasibility of FCC and pursue advanced accelerator technology R&D
- **2026** expectation:
  - move towards approval and construction of XXX

As a community, we never* faced such a challenge, towards a commitment that will impact our field for decades to come!

* community support for LEP or LHC was immediately unanimous and straightforward

Preamble 3

Conflict of interest statement:

being a strong and convinced advocate of the FCC and of the baseline definition of the project, as presented by the CERN management, I could profit of this opportunity to make proselytes, manipulating the information that’s been exposed in the last few days to bring home my own message … I will do my best to avoid that, trying to be as objective as possible…at the risk of making it the least informative talk of the Workshop…

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Nevertheless, at the end, I will present few slides on a recent development, which has not been exposed so far during the workshop (but see the following talk by Lucio Rossi), and which will play some role in the forthcoming ESPP discussions:

- possible scenarios, alternative to the baseline, for a future hadron collider, in the framework of the FCC

The Times They Are a-Changin’

a quick rewind on events passed, analogies and differences

50 years ago, 1974 signalled the greatest before/after discontinuity in particle physics since its birth

before:

<1973:

- GWS model — Glashow Weinberg Salam
- GIM — Glashow Iliopulos Maiani
- renormalizability of gauge interactions — ’t Hooft Veltman

1973:

- Discovery of neutral currents ⇒ SU(2)xU(1) gauge structure for weak interactions Gargamelle @ CERN
- Asymptotic freedom ⇒ SU(3) gauge structure for strong interactions Gross&Wilczek, Politzer
- Kobayashi-Maskawa CP violation with 3-generations ⇒ CKM flavour structure

1974:

- Discovery of charm ⇒ SU(2)xU(1) gauge structure for quarks and leptons Richter@SLAC, Ting@BNL

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In 1974 the SM gets firmly established as the framework to understand all known phenomena in particle physics … we just needed a few Nobel prizes to be distributed, and further experimental exploration to work out the details …

after:

1974:

- SU(5) and GUTs Georgi Glashow, Pati Salam
- Supersymmetry Wess Zumino

and the avalanche build-up ever since:

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- Naturalness and EWSB, composite Higgs, etc WIlson,
- Composite leptons and quarks Pati Slam, Glashow, Neeman, ’t Hooft, Harari …
- …

➡ explosion of BSM model building, phenomenology and exptl searches

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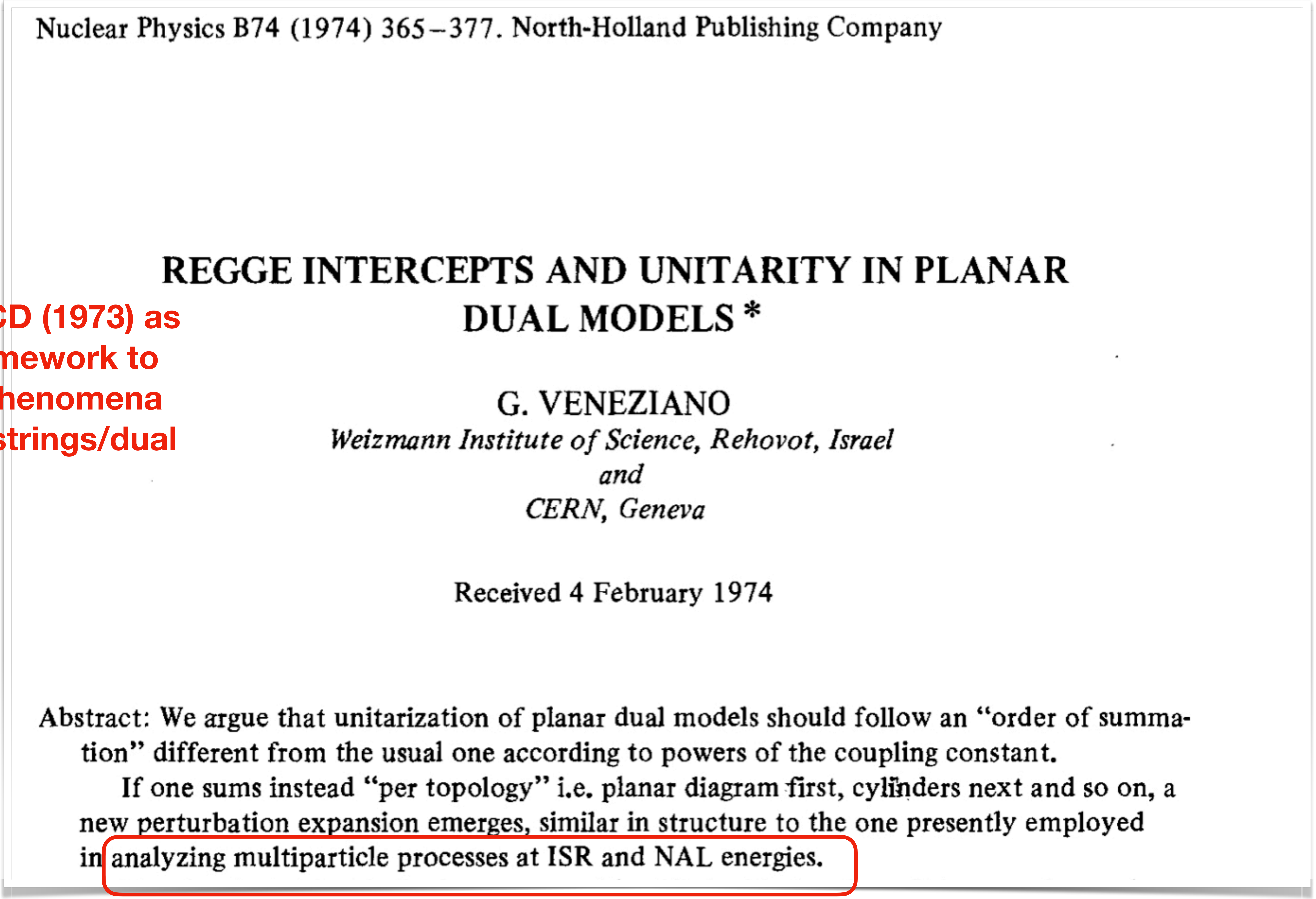
➡ explosion of BSM model building, phenomenology and exptl searches

By 1974 the SM is declared history, BSM searches become the new virgin territory of exploration, with theory providing guidance to experiments, rather than the opposite

A curiosity:

1974 was also a transition point for string theory

the “before”



Nuclear Physics B74 (1974) 365–377. North-Holland Publishing Company

REGGE INTERCEPTS AND UNITARITY IN PLANAR DUAL MODELS *

G. VENEZIANO

Weizmann Institute of Science, Rehovot, Israel

and

CERN, Geneva

Received 4 February 1974

Abstract: We argue that unitarization of planar dual models should follow an “order of summation” different from the usual one according to powers of the coupling constant.

If one sums instead “per topology” i.e. planar diagram first, cylinders next and so on, a new perturbation expansion emerges, similar in structure to the one presently employed in analyzing multiparticle processes at ISR and NAL energies.

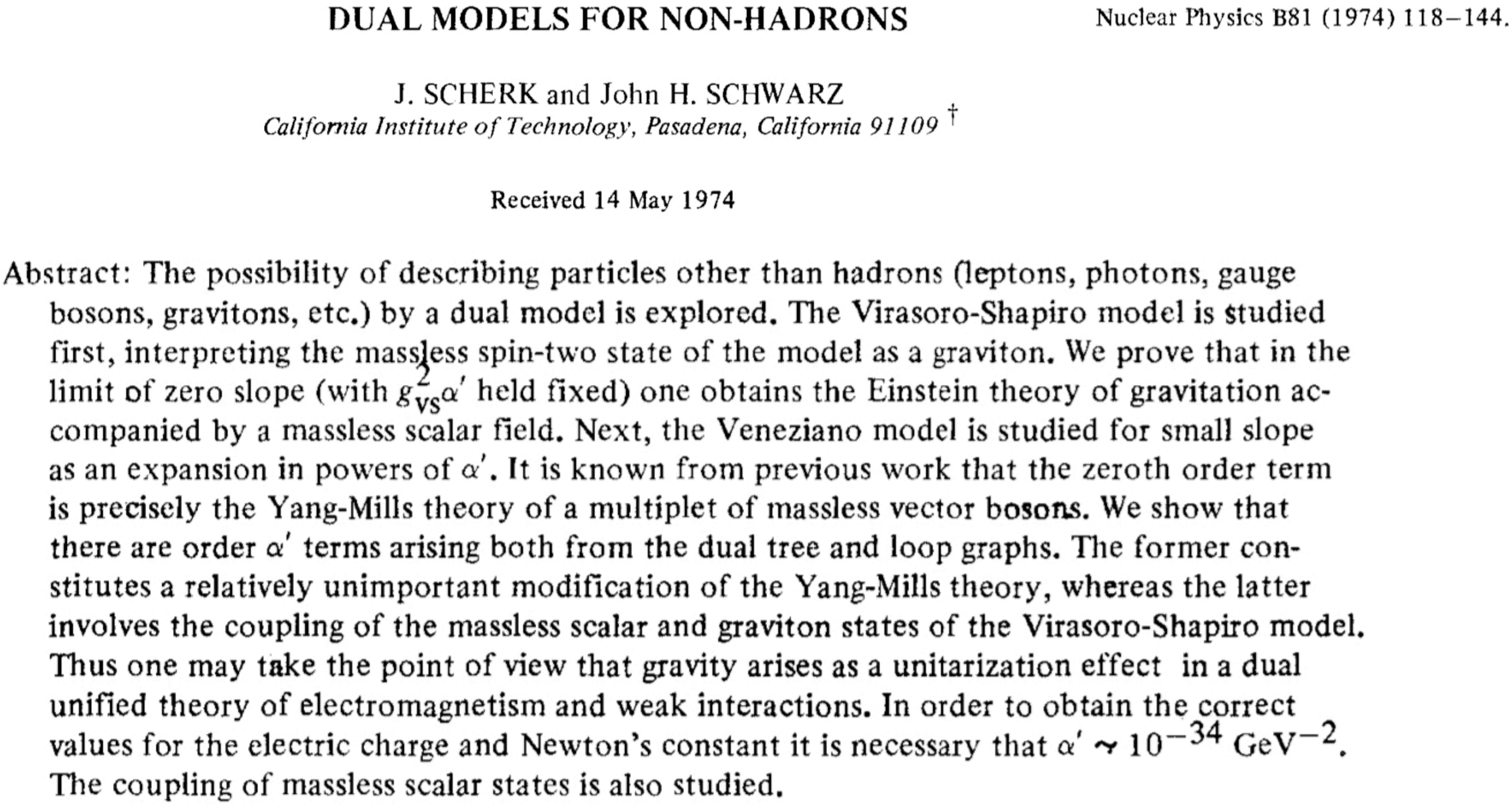
Yet no reference to QCD (1973) as the new possible framework to understand hadron phenomena and their relations to strings/dual models

(of course the relation of hadron physics and dual models remains today a hot topic … but the challenge is not to describe data, it’s to connect QCD and 4-d strings)

ISR: Intersecting storage ring, the first proton-proton collider in history (CERN)

NAL: National Accelerator Laboratory, to become FNAL/Fermilab shortly after

the “after”



DUAL MODELS FOR NON-HADRONS

Nuclear Physics B81 (1974) 118–144.

J. SCHERK and John H. SCHWARZ
California Institute of Technology, Pasadena, California 91109 †

Received 14 May 1974

Abstract: The possibility of describing particles other than hadrons (leptons, photons, gauge bosons, gravitons, etc.) by a dual model is explored. The Virasoro-Shapiro model is studied first, interpreting the massless spin-two state of the model as a graviton. We prove that in the limit of zero slope (with $g_{\mathrm{VS}}^2\alpha'$ held fixed) one obtains the Einstein theory of gravitation accompanied by a massless scalar field. Next, the Veneziano model is studied for small slope as an expansion in powers of α'. It is known from previous work that the zeroth order term is precisely the Yang-Mills theory of a multiplet of massless vector bosons. We show that there are order α' terms arising both from the dual tree and loop graphs. The former constitutes a relatively unimportant modification of the Yang-Mills theory, whereas the latter involves the coupling of the massless scalar and graviton states of the Virasoro-Shapiro model. Thus one may take the point of view that gravity arises as a unitarization effect in a dual unified theory of electromagnetism and weak interactions. In order to obtain the correct values for the electric charge and Newton’s constant it is necessary that $\alpha' \sim 10^{-34}$ GeV^{-2}. The coupling of massless scalar states is also studied.

back to:

By 1974 the SM is declared history, BSM searches become the new virgin territory of exploration, with theory providing guidance to experiments, rather than the opposite

None of these explorations has led anywhere as yet.

Open experimental puzzles remain open:

- what is dark matter?
- what is the origin of neutrino masses?
- what is the origin of CP violation?
- what is dark energy?

… as open as outstanding theoretical puzzles:

- what's the origin of EWSB (hierarchy problem, …)?
- what's the origin of flavour?
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Contrary to the times leading to 1974, **however**, today there is no dominant theoretical framework to be taken as obvious default or benchmark

Example 1: on the impact of precision measurements, when there is a framework

In the SM, the relation between M_W , M_Z and $\sin^2\theta_W$ is fixed at tree level. At the quantum level, the relation depends on input param's like m_{top} and m_H.

Precision measurements of M_W , M_Z and $\sin^2\theta_W$ at LEP/SLAC/Tevatron confirmed the deviation from tree level:

- ***is this BSM or a manifestation of radiative corrections to the SM prediction?***
  - ➡ ***calculate m_{top} and m_H that describe data, use/build a collider to search for top and Higgs with these mass values, and check if SM is ok***

The moral of the story:

the SM provided a framework to interpret the results of precision EW measurements, giving direct guidance as to how dedicated experiments (in this case Tevatron and LHC for top and Higgs resp) could confirm its consistency, or expose new phenomena

Example 2: on the impact of precision measurements, when there isn't a framework

In the SM, a prediction exists for the anomalous magnetic moment of the muon, $a_\mu = (g-2)_\mu$ … all SM parameters enter here via radiative corrections. All SM parameters are known today with sufficient precision to calculate a_μ with the accuracy required to challenge the SM with experimental data (FNAL, BNL).

Current data indicate that the SM prediction is off by 5.2σ … Options:

(A) the uncertainty of the SM result is underestimated (see eg recent lattice predictions)

(B) there is new physics

if (B), there is no BSM model, among the many considered, which can be singled out as a benchmark framework to interpret the origin of the a_μ anomaly, and plan for confirmation experiments/facilities

Example 3: on the impact of direct discoveries, when there is/isn't a framework

A jets+ missing ET signal is observed at the LHC

In the 90's this would have been immediately interpreted as a supersymmetric neutralino, calling for discovery of SUSY and DM

Today, many options could be on the table:

(A) SUSY

(B) invisible H decay (eg to axions, dark photons, etc)

(C) extra dimensions

(D) …

After the SM, interpreting discoveries and pinning down their origin is harder than just predicting possible manifestations of BSM models … even if we work with a specific class of BSM scenarios in mind

and things can get fuzzy even when a framework is there …
TH papers following the J/ψ discovery:

Are the New Particles Baryon-Antibaryon Nuclei?
Alfred S. Goldhaber and Maurice Goldhaber

Interpretation of a Narrow Resonance in e+ e- Annihilation
Julian Schwinger

Possible Explanation of the New Resonance in e+ e- Annihilation
S. Borchardt, V. S. Mathur, and S. Okubo

Model with Three Charmed Quarks R. Michael Barnett

Heavy Quarks and e+ e- Annihilation Thomas Appelquist and H. David Politzer

Is Bound Charm Found? A. De Rújula and S. L. Glashow

Possible Interactions of the J Particle
H. T. Nieh, Tai Tsun Wu, and Chen Ning Yang

Is the 3104-MeV Vector Meson the psi - Charm or the W0?
G. Altarelli, N. Cabibbo, R. Petronzio, L. Maiani, G. Parisi

Charm, EVDM and Narrow Resonances in e^+e^- Annihilation
C. A. Dominguez and M. Greco

Fig. 15. Immediate interpretations of the J/ψ, with their titles. PRL is Phys. Rev. Lett. **34**, Jan. 6th, 1975. The last two papers[88,89] are in Lett. Nuovo Cim.

Figure from A. de Rujula, https://arxiv.org/abs/1910.13891

New BSM search paradigms

- model-specific searches vs model-independent “object” searches
- direct probes (eg resonances) vs indirect probes (eg EFT)

- With the LHC approaching, it became clear that most possible discoveries were not going to single out at first a specific model, but at best to provide evidence for general properties (eg multijets or missing ET signatures). The task of identifying a specific model relied on the solution of the “inverse problem”, something more easily done with a structured model-independent approach, whereby many models at the same time could be tested against the features of the new data.

- This approach was particularly justified by the realization that the class of BSM scenarios discussed in the 90’s was too limited, followed by the explosion of new and phenomenologically diverse models to address naturalness (extra dimensions, Higgs-less theories, …)

- Simplified models and EFTs became the new paradigm.

    - the former to parametrize specific final state features, characteristic of BSM signatures, such as missing energy, high-pt leptons, heavy quarks, multijets, etc

    - the latter covering indirect signals, possibly manifest through precision measurements of slight deviations from predicted SM behaviours

A message:

- EFT is the best tool to analyze and document in a model-independent way the outcome of precision measurements. But its use to constrain high-mass phenomena and project sensitivity to new physics varies with concrete examples of new physics, and cannot set universal model-independent constraints on the scale of new physics
- In the discussion of the prospects of (LHC and) future colliders, EFT analyses and projections must always be accompanied by an assessment of the potential to decode the deep origin of possible SM deviations.
- Template of important questions to address:
  - say some Higgs BR or EW observable is found to deviate from the SM: what's the best way to discover the source of the discrepancy?
  - If the Higgs factory finds $H \rightarrow \gamma\gamma$ off by 3σ, what is the class of BSM models that could give rise to this? How to search for these models, what's the reach of a given future accelerator, how complete would the coverage of model and parameter space be?

A model-independent “sort-of-EFT” analysis of Mercury’s orbit anomaly

$$V_{eff}(M,R) = -\,G_N \frac{M}{R}\left[1 + \sum_{n\geq 1} v_n \left(\frac{R_S}{R}\right)^n\right]$$

with $R_S = 2G_N M/c^2$ and $R_S/R \sim (v/c)^2$

- This could have been done before Einstein’s **General Relativity**, as a GR EFT precursor
- The precise study of Mercury’s perihelion precession would have given values of v_n coefficients consistent with General Relativity results.
- However out of this exercise we would not have recovered the full “non-perturbative” version of the underlying theory, or even predicted the deflection of light by the gravitational field.
- Even Eddington’s experimental input may not have helped, as it’s not obvious (not to me at least!) how to connect the EFT coefficients above to light’s deflection in the gravitational field of the Sun
- Here the “new physics” is General Relativity, and uncovering the full theory required a quantum leap that seems to go beyond a basic model-independent approach to canonical observables and expansion parameters

➡ ***an intrinsic limitation of the power of EFTs or model-independent searches for new physics?***

- **NB** In the analysis of the Sun-Mercury 2-body problem, the expansion in powers of R_S/R is equivalent to an expansion in powers of $(v/c)^2 \sim GM/R$ ==> see today’s non-relativistic EFTs

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- The guaranteed deliverables
  - improved measurements of fundamental constants and parameters (eg H couplings)
  - deeper exploration of dynamics of SM interactions, eg
    - EW symmetry breaking and flavour phenomena
    - QCD non-perturbative dynamics
  - *push further the boundary between* ***established*** *facts (e.g. quarks are pointlike at the scale of (10 TeV)–1) and* ***conjectures*** *(e.g. quarks are pointlike)*

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- The exploration and discovery potential
  - higher and higher energy !!
- Conclusive answers to important questions, like
  - Is DM a thermal WIMP ?
  - What was the nature of the EW phase transition ?
  - Does the origin of neutrino masses lie at the TeV scale ?
  - Are the Higgs potential and mass defined by physics at the few-TeV scale ?
  - are there BSM sources of CPV below the few-TeV scale ?

The guaranteed deliverables and the value of diversity: example of the LHC scientific production

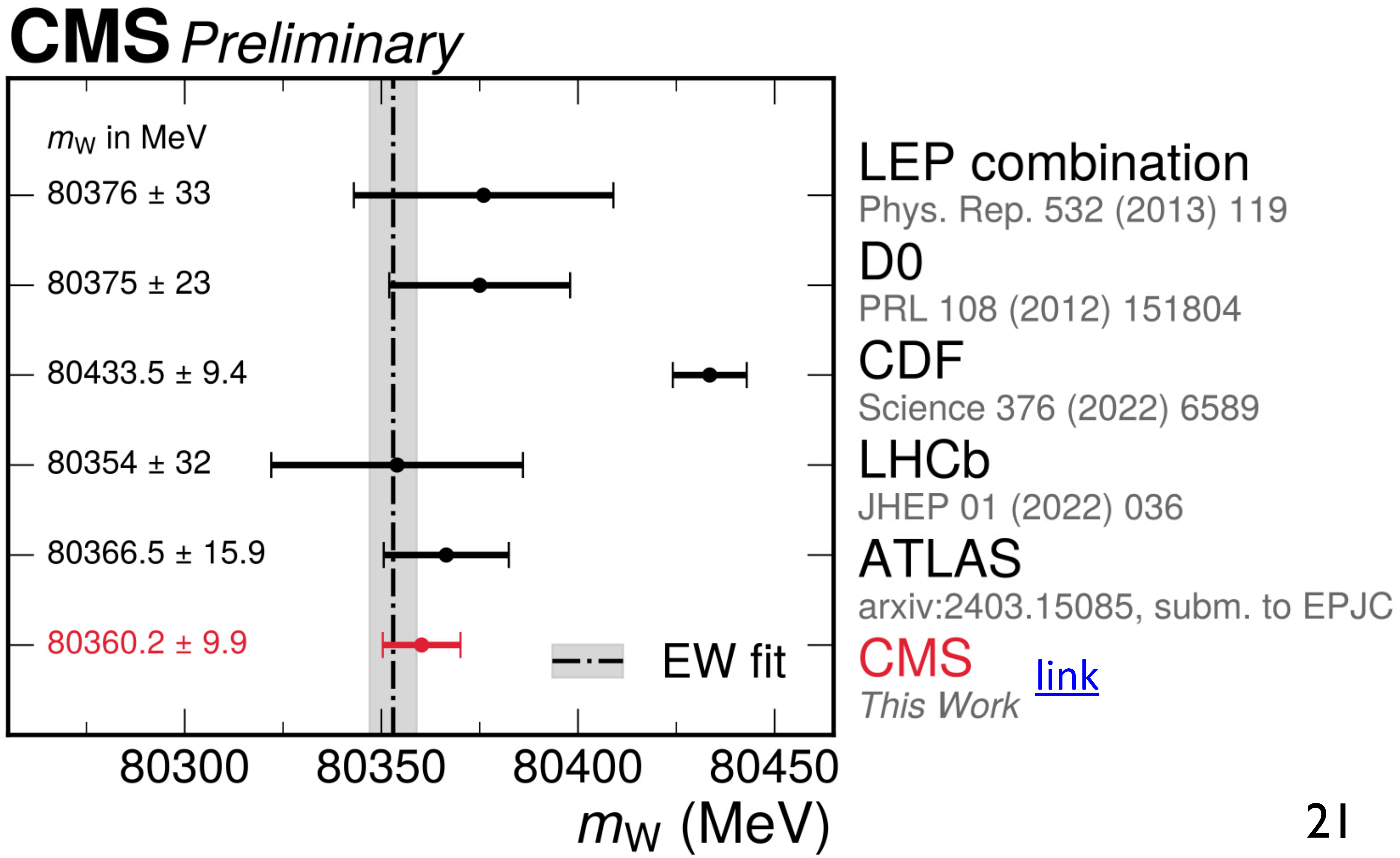
Over 3000 papers published/submitted to refereed journals by the 7 experiments that operated in Run 1 and 2 (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL)… and the first papers are appearing by the new experiments started in Run 3 (FASER, SND@LHC)

Of these:

~10% on Higgs (15% if ATLAS+CMS only)

~30% on searches for new physics (35% if ATLAS+CMS only)

~60% of the papers on SM measurements (jets, EW, top, b, HIs, …)



link

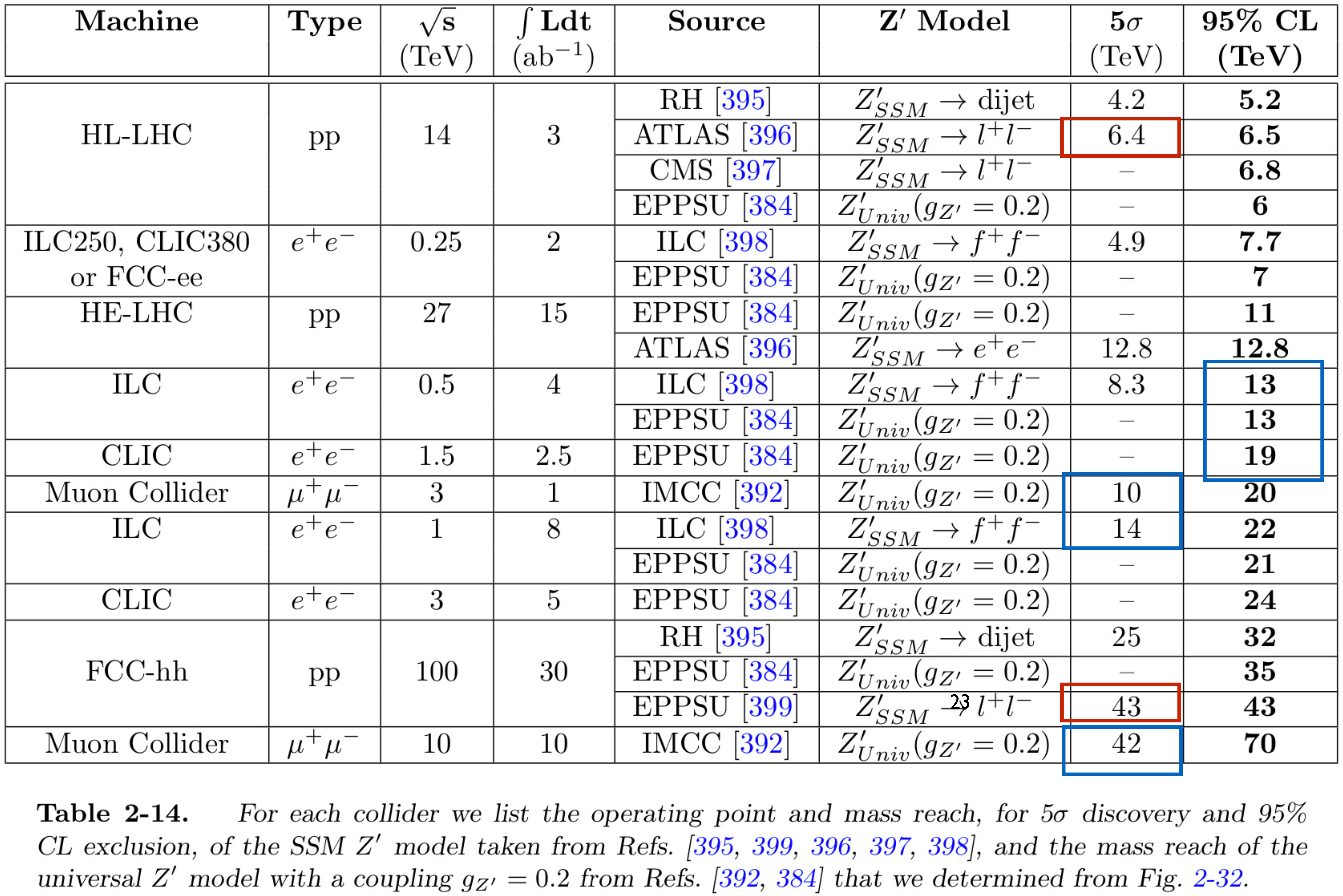
Remarks on colliders' cross comparisons

- Discovery-reach comparison among different colliders is by and large subjective
  - statements like *"collider A is more/less/as powerful as collider B"* are often of limited value and possibly misleading, unless they refer to the performance for specific new-physics scenarios and observables
- Studies/discovery prospects presented by the proponents of various colliders typically focus on new-physics scenarios best suited for discovery at their preferred collider … nothing wrong with that … but interpretation requires a grain of salt …
- An important criterion to evaluate is the extent to which a facility can, in the course of its full evolution, answer to questions it raises (eg directly discover the origin of indirect evidence for new physics)

Sequential Z’ reach: comparison across colliders, direct vs indirect reach

🟦 **Indirect observation through EW precision observables**

🟥 **Direct observation**

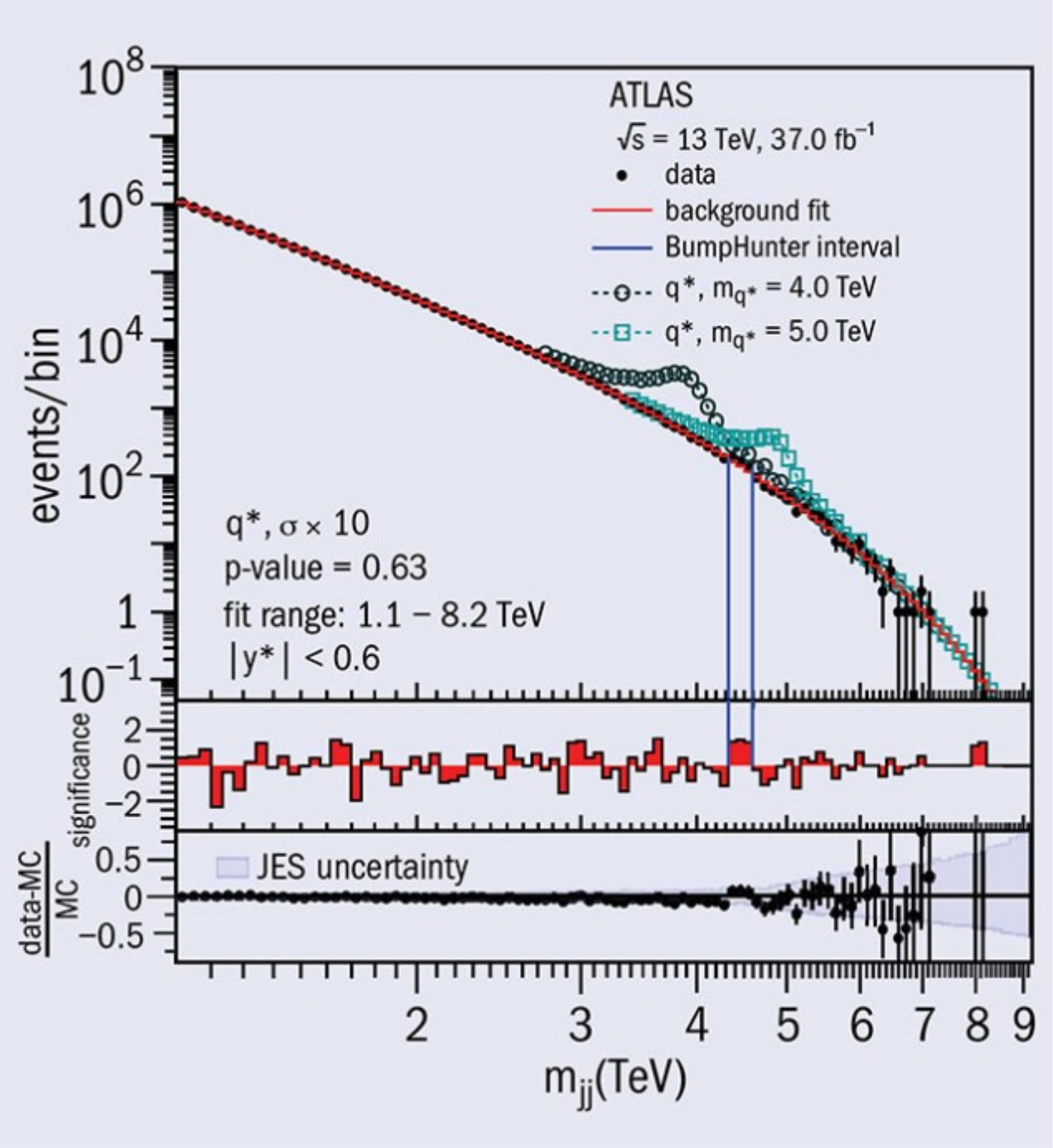


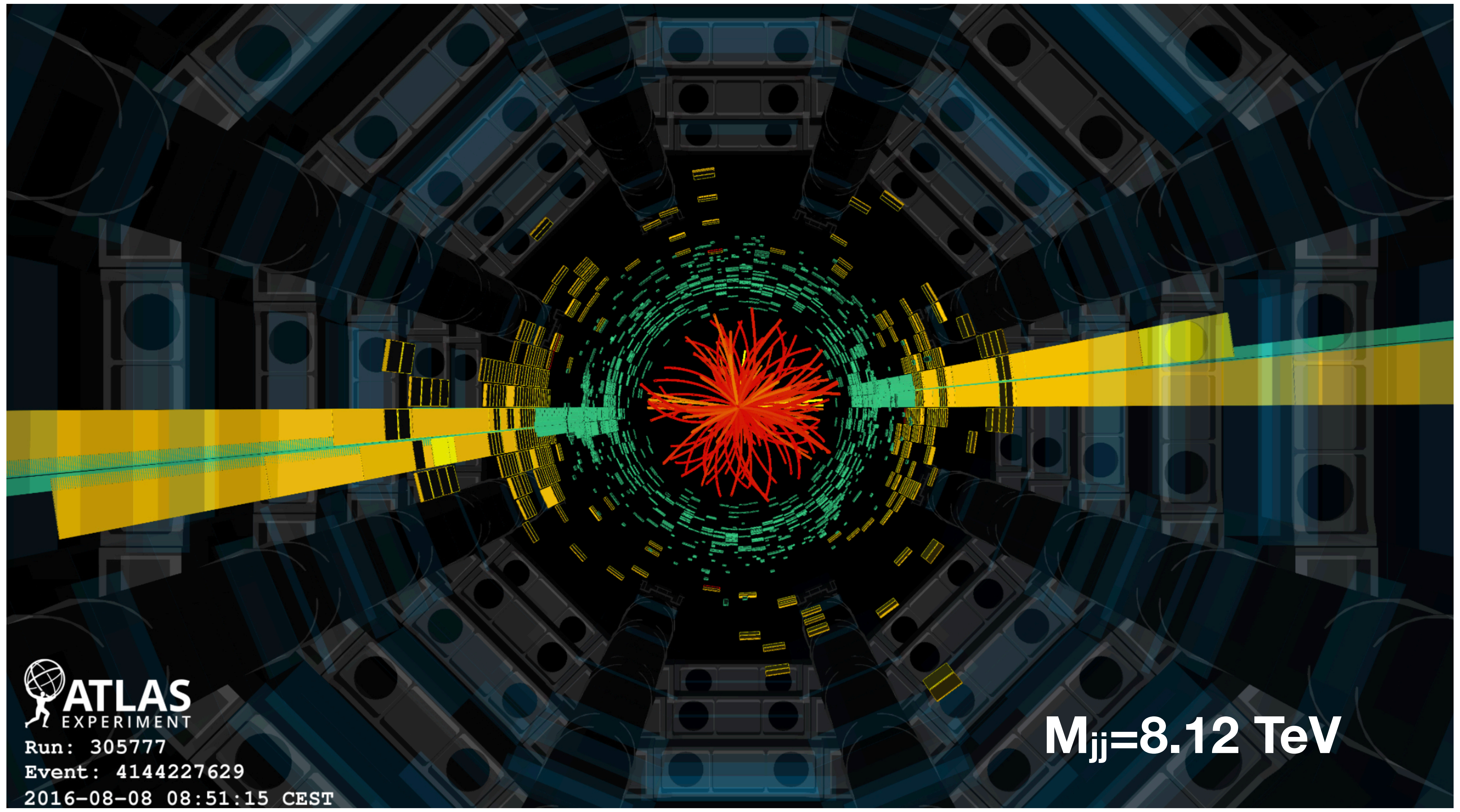
Machine	Type	$\sqrt{s}$ (TeV)	$\int$ Ldt (ab^{-1})	Source	Z' Model	5σ (TeV)	95% CL (TeV)
HL-LHC	pp	14	3	RH [395]	$Z'_{SSM} \to$ dijet	4.2	**5.2**
				ATLAS [396]	$Z'_{SSM} \to l^+l^-$	6.4	**6.5**
				CMS [397]	$Z'_{SSM} \to l^+l^-$	–	**6.8**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**6**
ILC250, CLIC380 or FCC-ee	e^+e^-	0.25	2	ILC [398]	$Z'_{SSM} \to f^+f^-$	4.9	**7.7**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**7**
HE-LHC	pp	27	15	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**11**
				ATLAS [396]	$Z'_{SSM} \to e^+e^-$	12.8	**12.8**
ILC	e^+e^-	0.5	4	ILC [398]	$Z'_{SSM} \to f^+f^-$	8.3	**13**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**13**
CLIC	e^+e^-	1.5	2.5	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**19**
Muon Collider	$\mu^+\mu^-$	3	1	IMCC [392]	$Z'_{Univ}(g_{Z'} = 0.2)$	10	**20**
ILC	e^+e^-	1	8	ILC [398]	$Z'_{SSM} \to f^+f^-$	14	**22**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**21**
CLIC	e^+e^-	3	5	EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**24**
FCC-hh	pp	100	30	RH [395]	$Z'_{SSM} \to$ dijet	25	**32**
				EPPSU [384]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**35**
				EPPSU [399]	$Z'_{SSM} \to l^+l^-$	43	**43**
Muon Collider	$\mu^+\mu^-$	10	10	IMCC [392]	$Z'_{Univ}(g_{Z'} = 0.2)$	42	**70**

Table 2-14. *For each collider we list the operating point and mass reach, for 5σ discovery and 95% CL exclusion, of the SSM Z' model taken from Refs. [395, 399, 396, 397, 398], and the mass reach of the universal Z' model with a coupling $g_{Z'} = 0.2$ from Refs. [392, 384] that we determined from Fig. 2-32.*

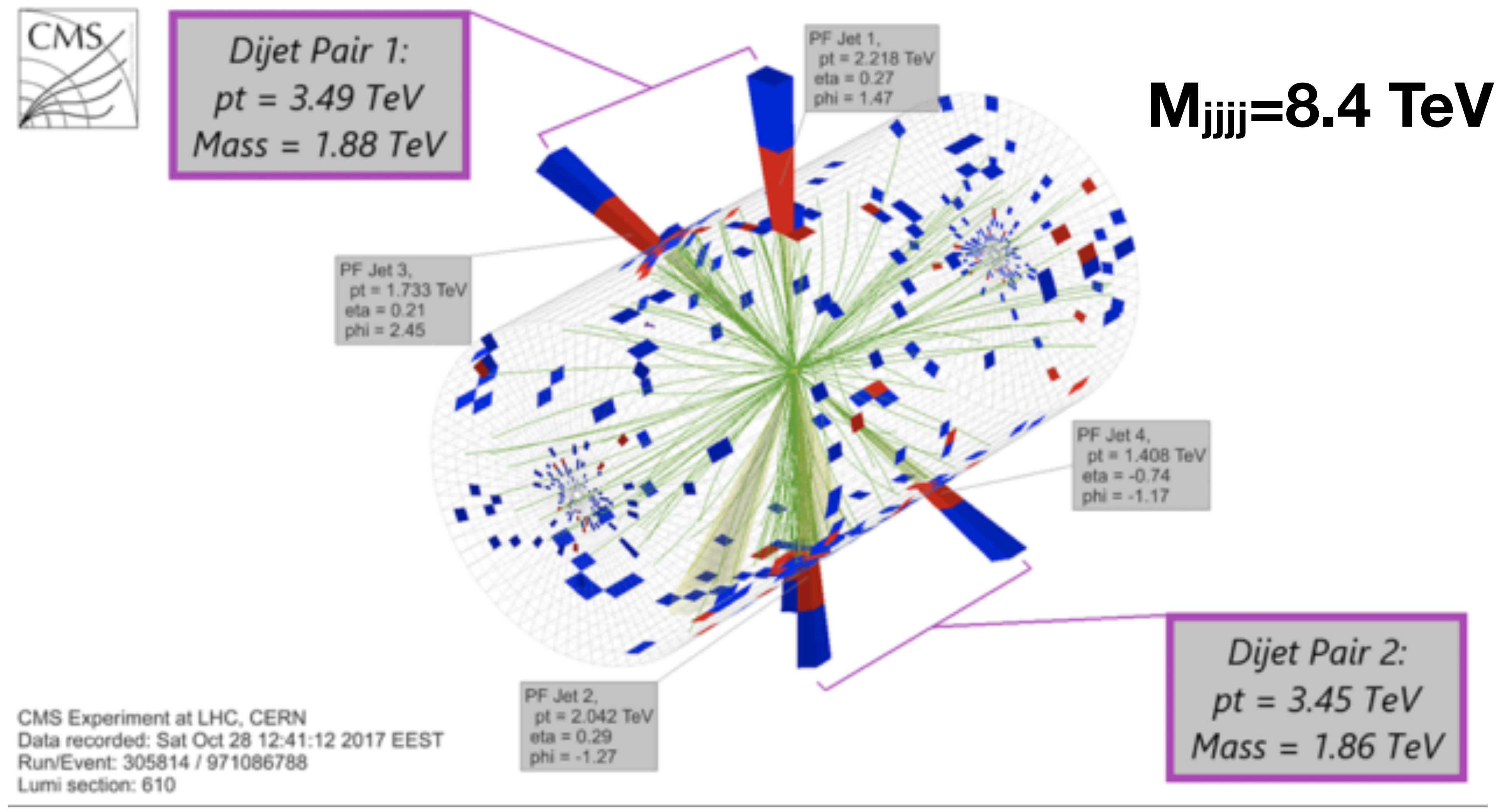
> ***“All options for a 10 TeV pCM collider are new technologies under development and R&D is required before we can embark on building a new collider”***
>
> *P5 Report (2023), p. 17*

The 10 TeV pCM holy Grail: how far are we from it, really?
not much actually, already at the LHC



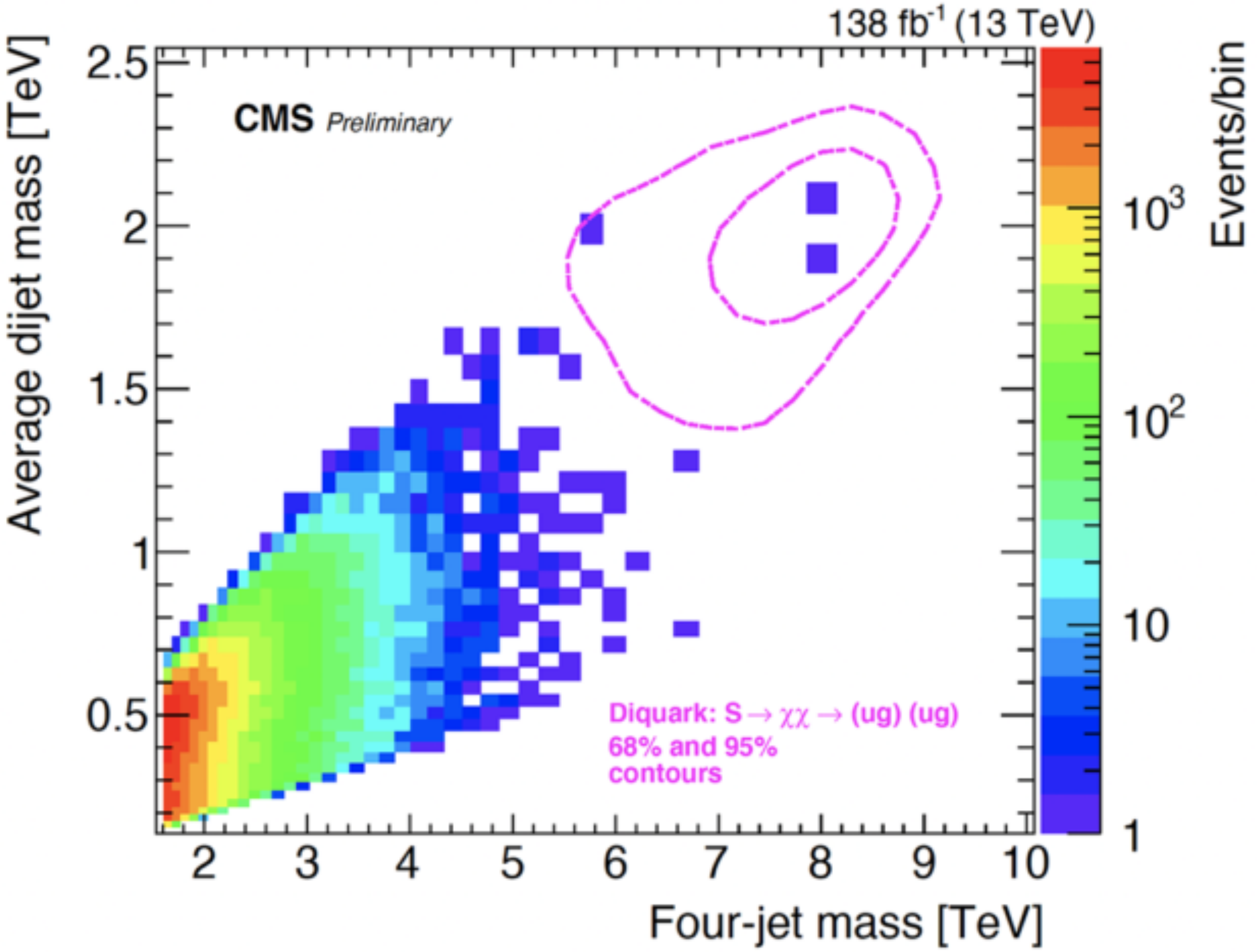


M_{jj}=8.12 TeV



M_{jjjj}=8.4 TeV

https://arxiv.org/abs/1911.03947

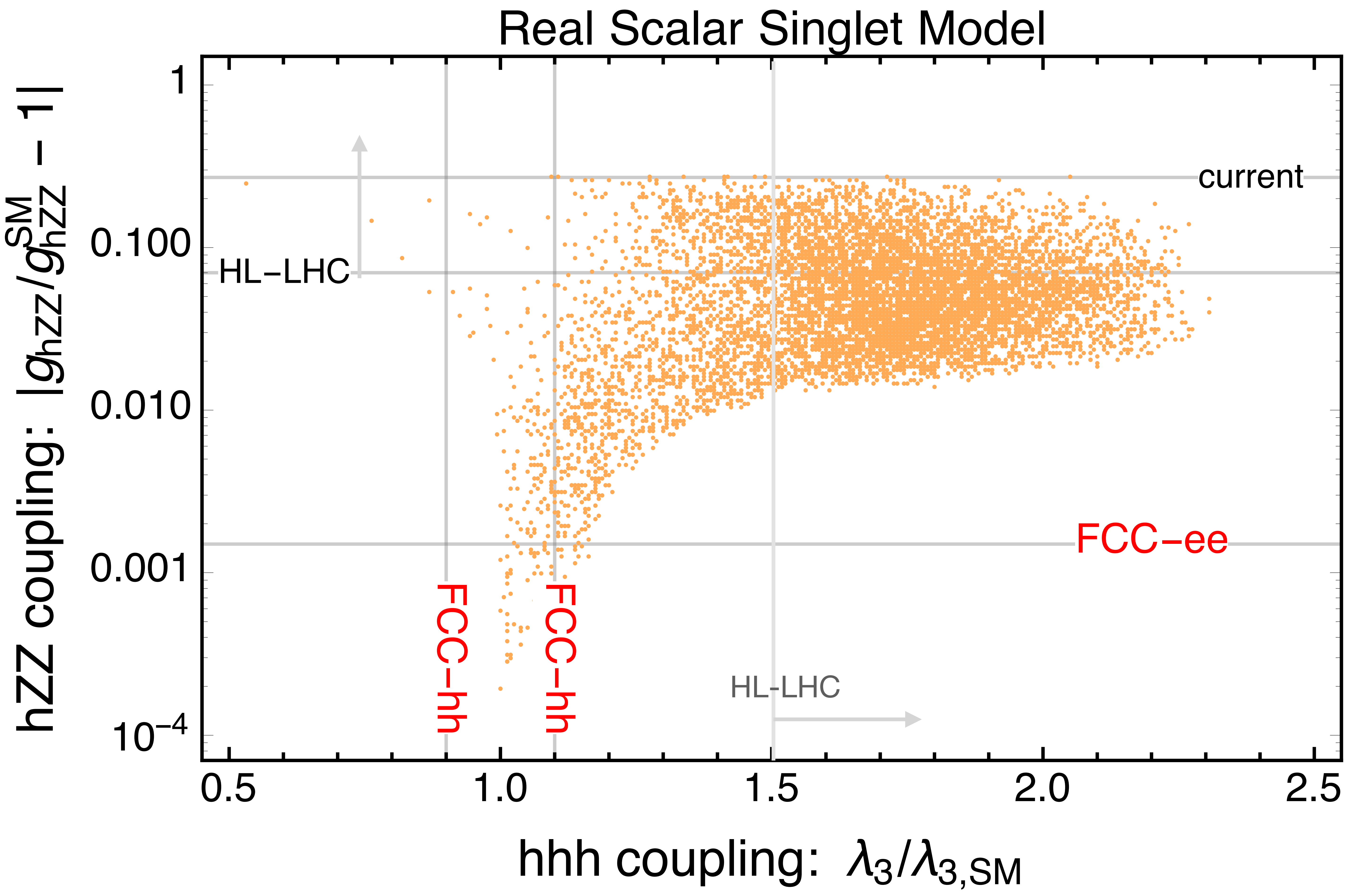


The value of redundancy, an example

Impact of extended Higgs sectors on nature of the EW phase transition

Extra-singlet models with potential strong 1st order phase transition

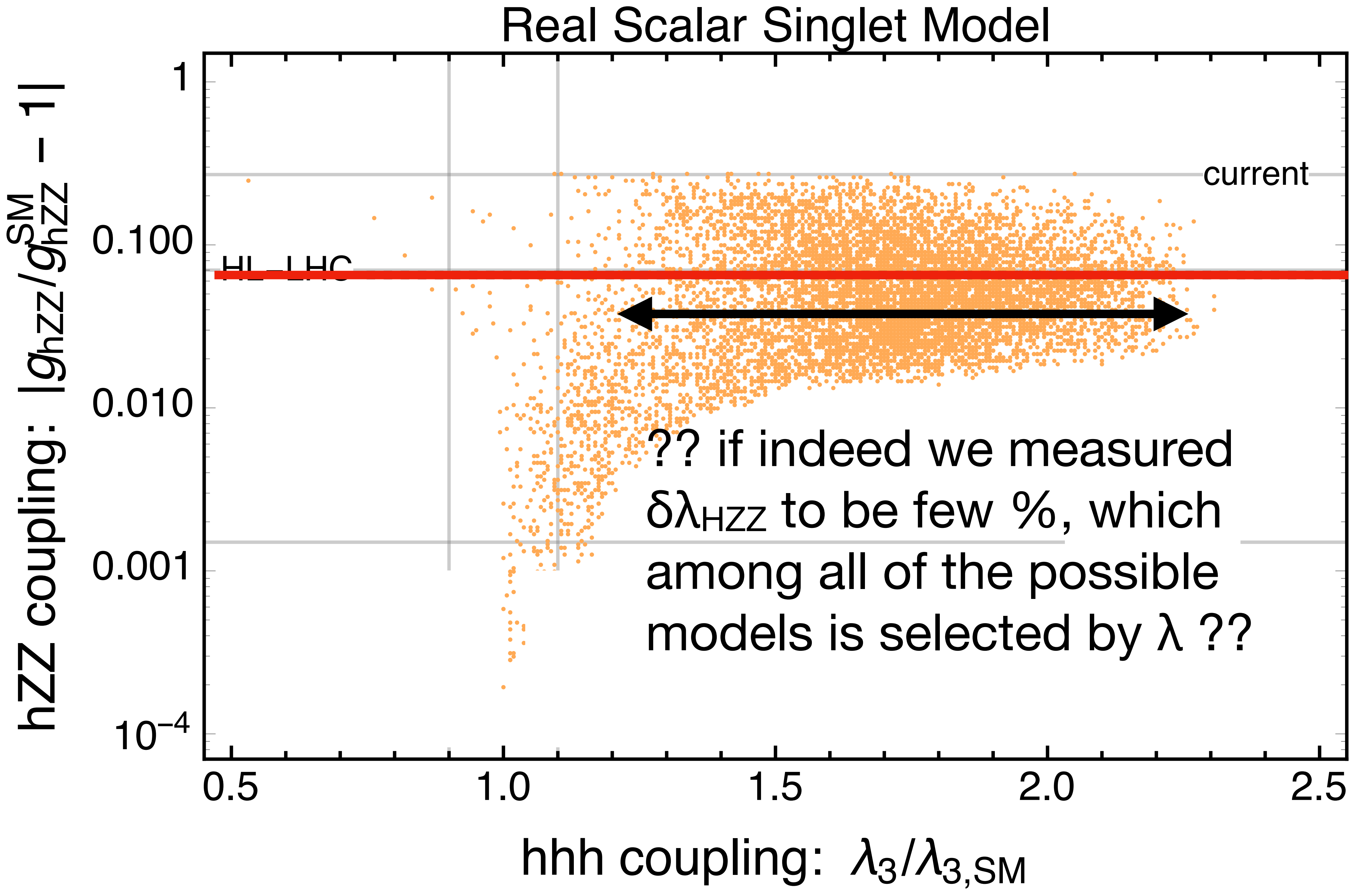
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$



<u>Experimental signature</u>:
deviation in the Higgs coupling to the Z (g_{hZZ}) and in the Higgs self-coupling λ_3

Scan of model parameters a_i and b_i , and impact on g_{hZZ} and λ_3 for parameter points with strong FOPT

- Apparently, adding the self-coupling constraint does not add much in terms of exclusion power, wrt the HZZ coupling measurement …
- … BUT, should HZZ deviate from the SM, λ_{HHH} is necessary to break the degeneracy among all parameter sets leading to the same HZZ prediction



?? if indeed we measured $\delta\lambda_{HZZ}$ to be few %, which among all of the possible models is selected by λ ??

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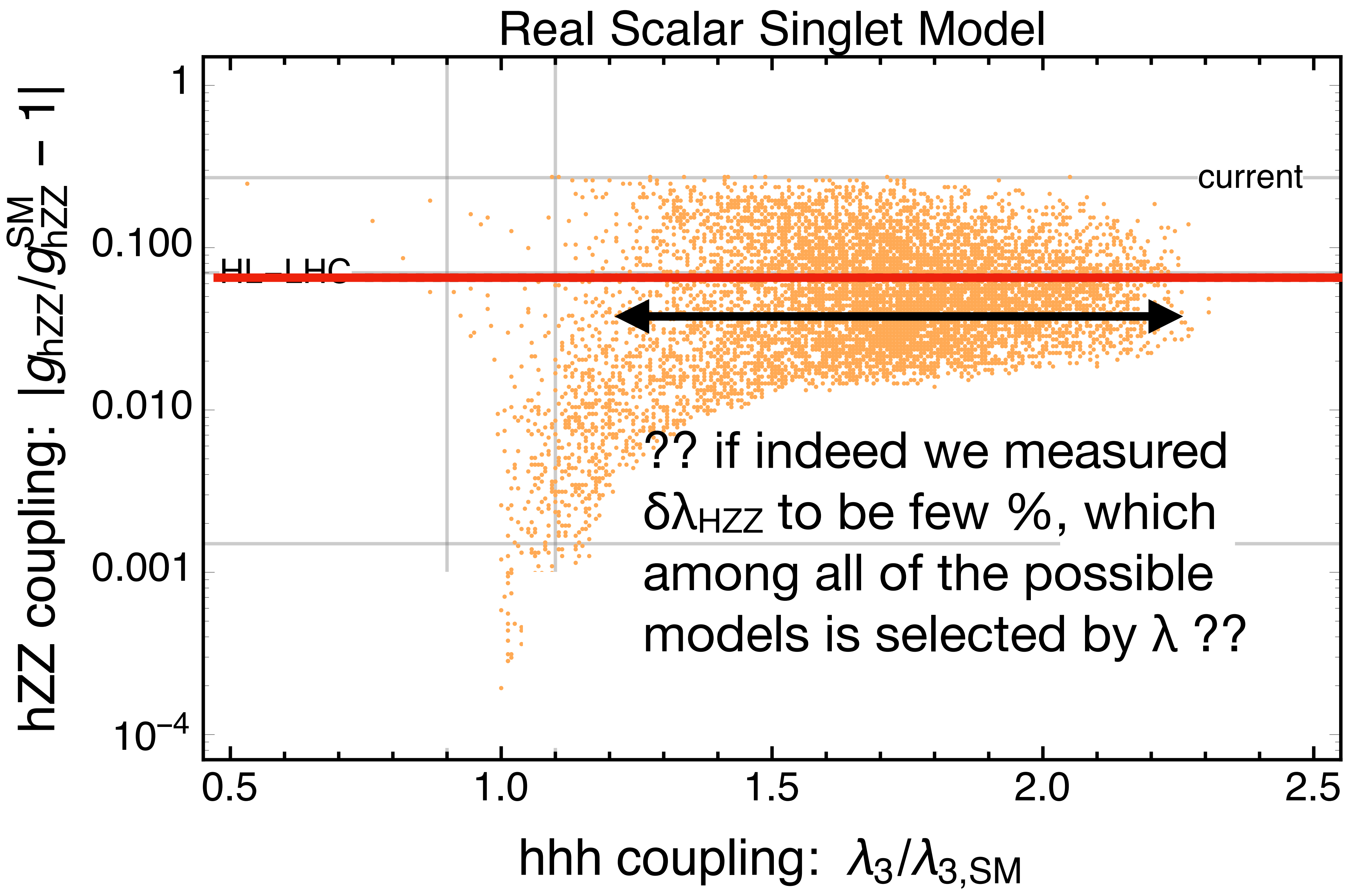

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- The concept of *"which experiment sets a better constraint on a given parameter"* is a very limited comparison criterion, which looses value as we move from *"setting limits"* to *"diagnosing observed discrepancies"*

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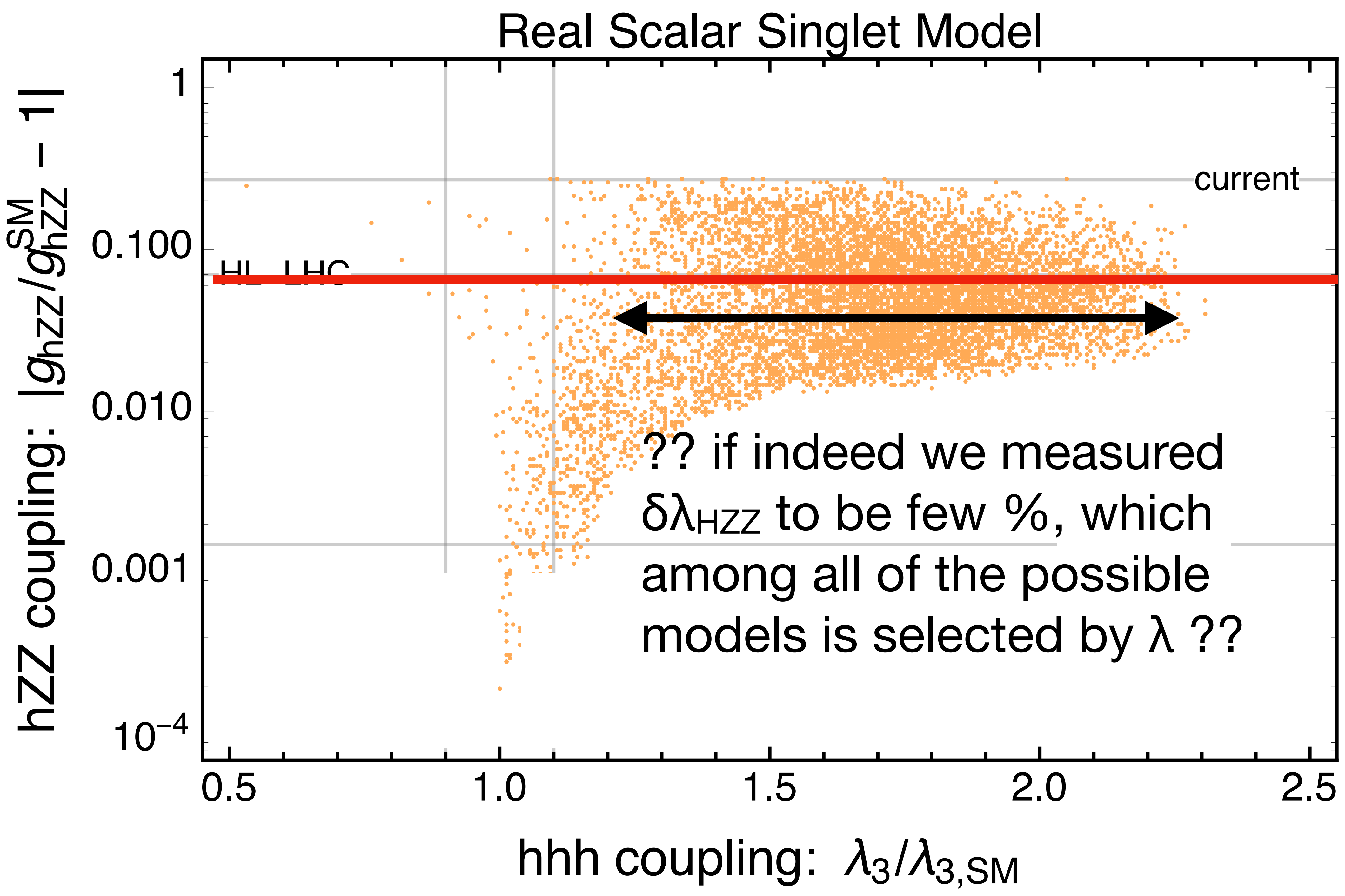

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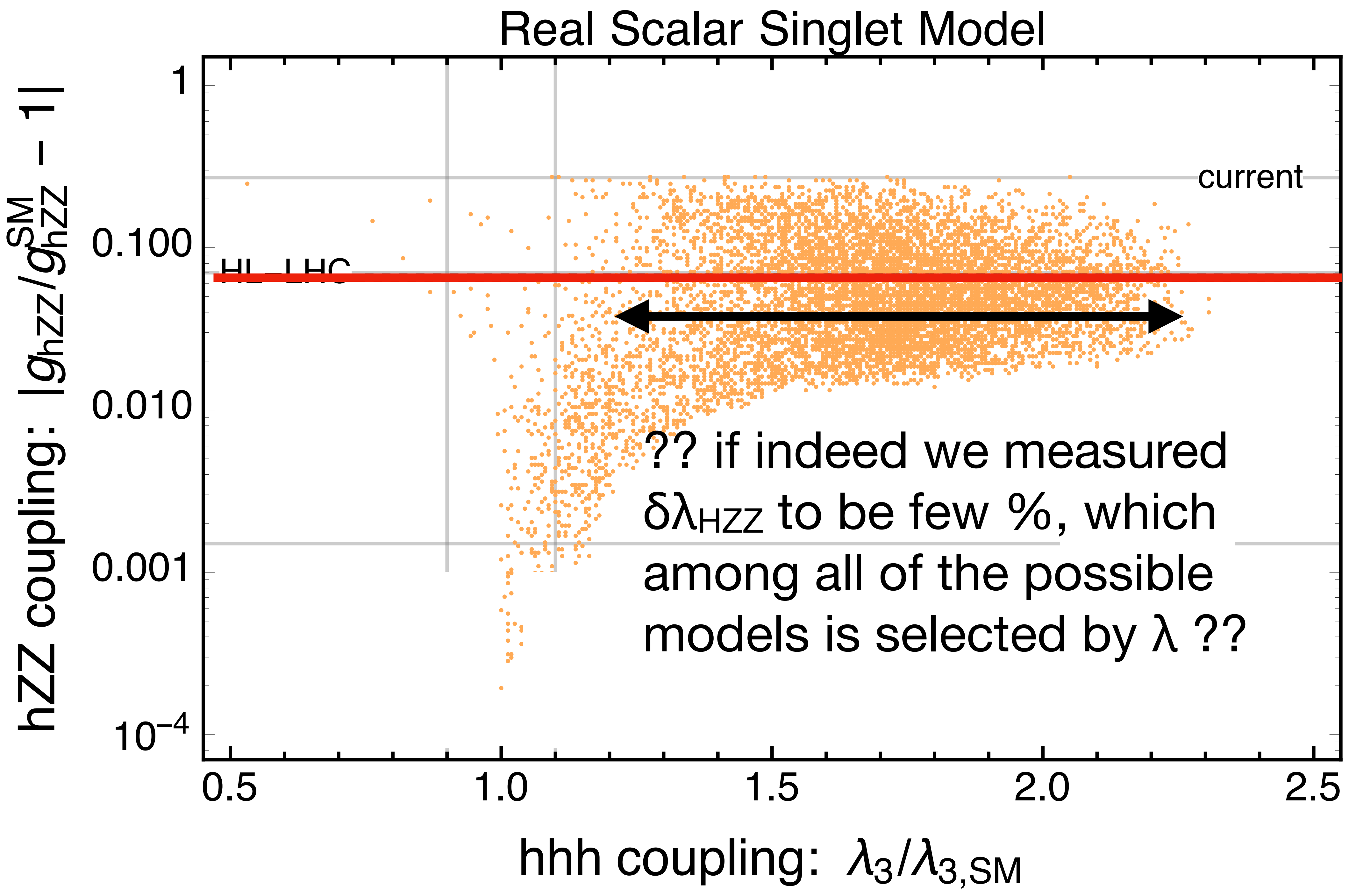

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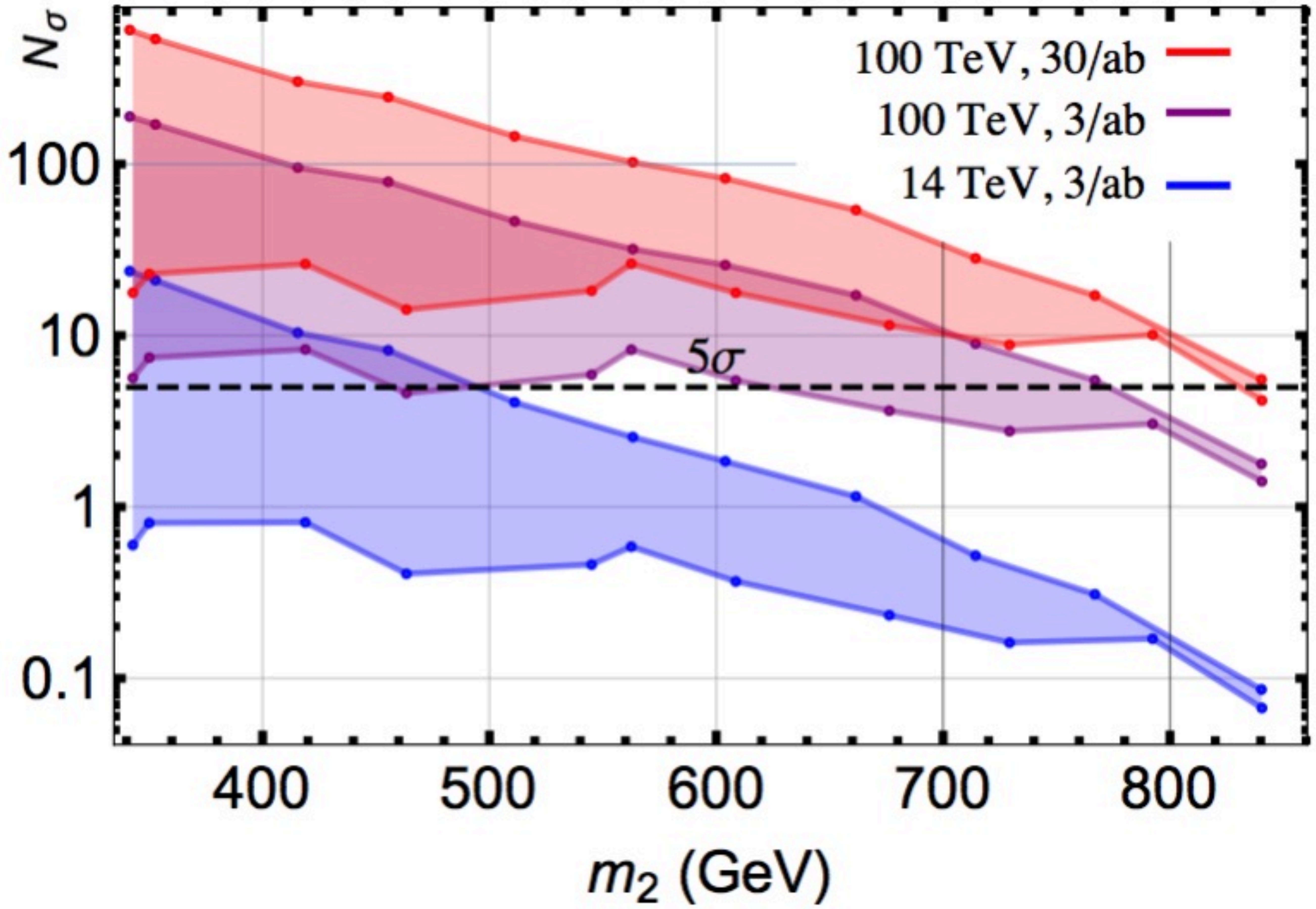
- Redundancy and complementarity of observables are of paramount importance

Direct detection of extra Higgs states compatible with strong 1st order EW phase transition at FCC-hh



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

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

New FCC-hh scenarios

- Driven by new accelerator layout (90.7 km ring vs 100 km, increased dipole filling factor)

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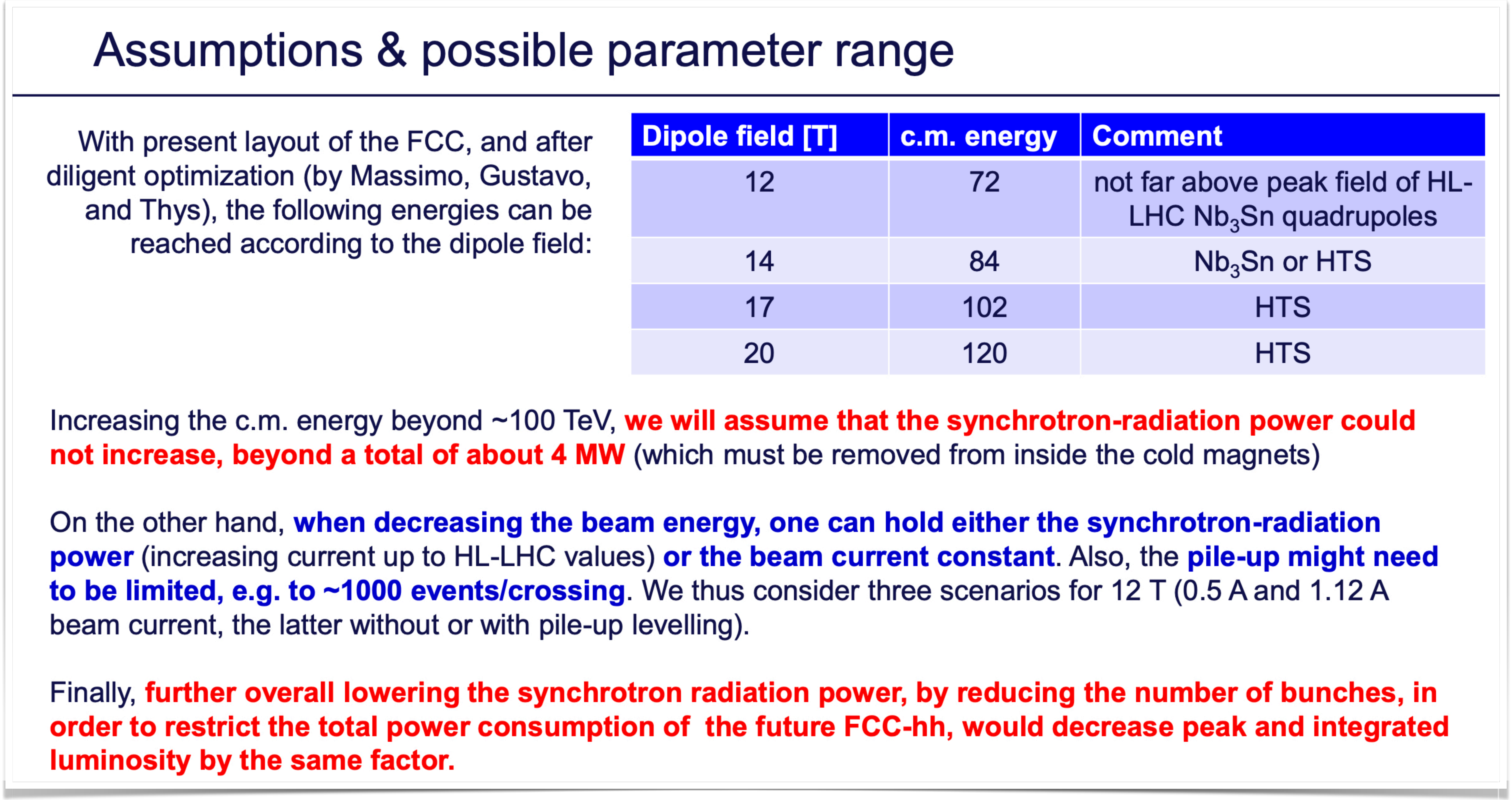
- Driven by assumptions about challenges/options in dipole technology (see L.Rossi next)
- Ongoing review of CDR physics potential projections, to assess impact of new scenarios:
  - See first discussion meeting (Sept 3) at https://indico.cern.ch/event/1439072/
  - (WG established, details in the introduction of the meeting)
  - Goal is NOT to push for an alternative “planA”, but to provide expert answers to questions that may be raised during the Strategy process, eg in the context of “plan-B” discussions

Slides from Frank Zimmermann (link), see also Frank's note



Assumptions & possible parameter range

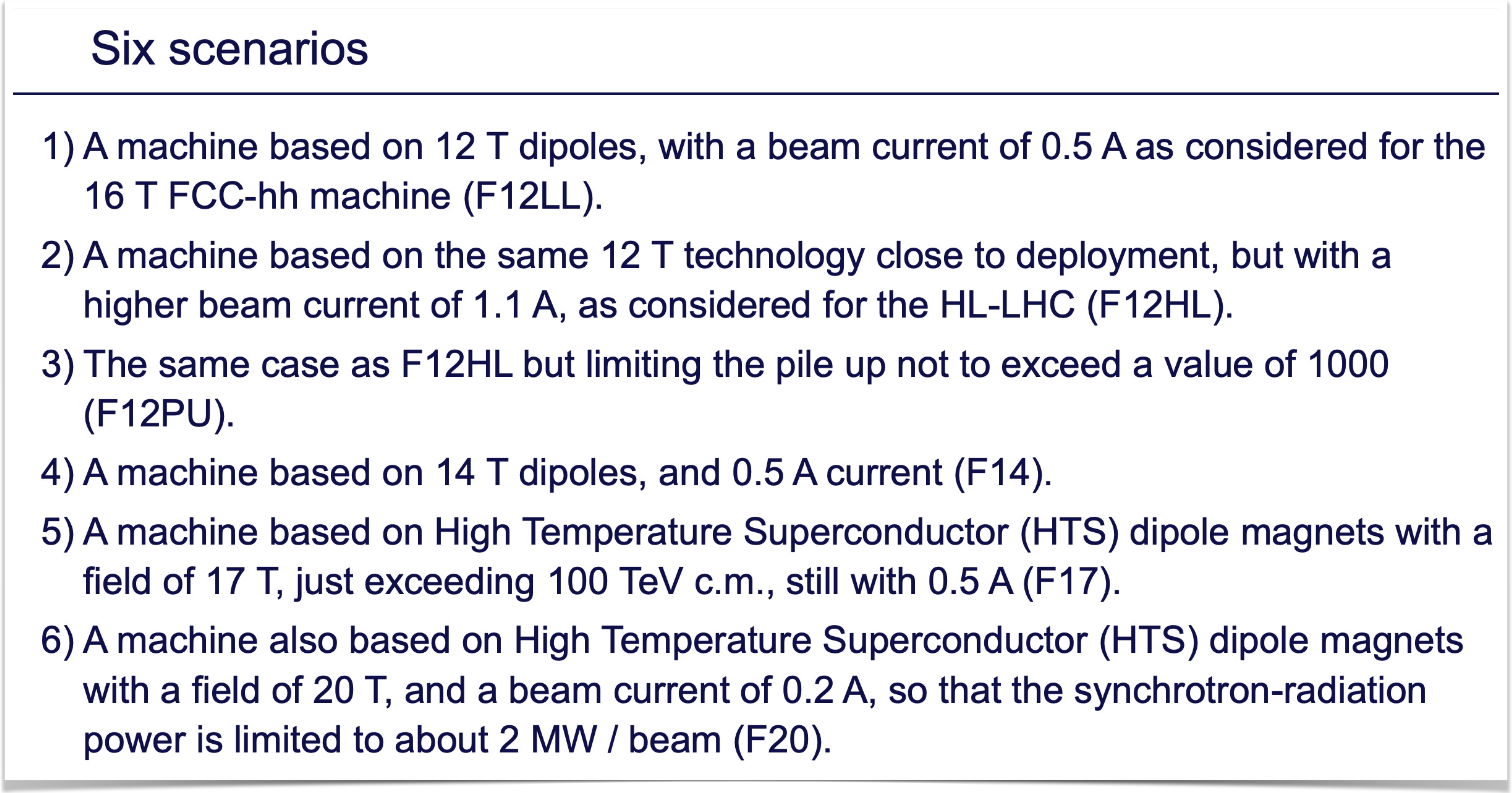
With present layout of the FCC, and after diligent optimization (by Massimo, Gustavo, and Thys), the following energies can be reached according to the dipole field:

Dipole field [T]	c.m. energy	Comment
12	72	not far above peak field of HL-LHC Nb_3Sn quadrupoles
14	84	Nb_3Sn or HTS
17	102	HTS
20	120	HTS

Increasing the c.m. energy beyond ~100 TeV, **we will assume that the synchrotron-radiation power could not increase, beyond a total of about 4 MW** (which must be removed from inside the cold magnets)

On the other hand, **when decreasing the beam energy, one can hold either the synchrotron-radiation power** (increasing current up to HL-LHC values) **or the beam current constant**. Also, the **pile-up might need to be limited, e.g. to ~1000 events/crossing**. We thus consider three scenarios for 12 T (0.5 A and 1.12 A beam current, the latter without or with pile-up levelling).

Finally, **further overall lowering the synchrotron radiation power, by reducing the number of bunches, in order to restrict the total power consumption of the future FCC-hh, would decrease peak and integrated luminosity by the same factor.**



Six scenarios

1) A machine based on 12 T dipoles, with a beam current of 0.5 A as considered for the 16 T FCC-hh machine (F12LL).
2) A machine based on the same 12 T technology close to deployment, but with a higher beam current of 1.1 A, as considered for the HL-LHC (F12HL).
3) The same case as F12HL but limiting the pile up not to exceed a value of 1000 (F12PU).
4) A machine based on 14 T dipoles, and 0.5 A current (F14).
5) A machine based on High Temperature Superconductor (HTS) dipole magnets with a field of 17 T, just exceeding 100 TeV c.m., still with 0.5 A (F17).
6) A machine also based on High Temperature Superconductor (HTS) dipole magnets with a field of 20 T, and a beam current of 0.2 A, so that the synchrotron-radiation power is limited to about 2 MW / beam (F20).

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Parameter	**Unit**	**F12LL**	**F12HL**	**F12PU**	**F14**	**F17**	**F20**	**(HL-)LHC**
initial *L*	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27
opt. run time	h	3.8	3.3	6.3	3.8	3.4	4.2	(18-13) ~10

Parameter	**Unit**	**F12LL**	**F12HL**	**F12PU**	**F14**	**F17**	**F20**	**(HL-)LHC**
ideal $\int L\,dt$ /day	fb^{-1}	7.9	17.1	10.8	7.7	7.7	3,1	(1.9) 0.4
$\int L\,dt$ / year	fb^{-1}	950	2000	1300	920	920	370	240 (55)

First assessment of $\sqrt{S}$-dependence of Higgs precision (MLM slides), see also M.Selvaggi's talk at Sep 3 mtg

Higgs couplings beyond precision reach of H factory

Coupling precision	100 TeV CDR baseline	80 TeV	120 TeV
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	0.4	0.4	0.4
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	0.65	0.7	0.6
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	0.9	1.0	0.8

NB: For the 3 energy scenarios studied here, we assume the same integrated lumi (30 ab^{-1}) and systematics

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Higgs self-coupling

Det performance/systematics scenarios

https://arxiv.org/abs/2004.03505

I. Target det performance: LHC Run 2 conditions
II. Intermediate performance
III. Conservative: extrapolated HL-LHC performance, with today's algo's (eg no timing, etc)

$$\frac{\sigma_{HH}(80\text{TeV})}{\sigma_{HH}(100\text{TeV})} \sim 0.72$$ => reduce δ_{stat} by 15%

$$\frac{\sigma_{HH}(120\text{TeV})}{\sigma_{HH}(100\text{TeV})} \sim 1.3$$ => increase δ_{stat} by 15%

$\delta\kappa_{HHH}(\ \%\ )$

100 TeV	s I	s II	s III
stat	3.0	4.1	5.6
syst	1.6	3.0	5.4
tot	**3.4**	**5.1**	**7.8**

80 TeV	s I	s II	s III
stat	3.5	4.7	6.4
syst	1.6	3.0	5.4
tot	**3.8**	**5.6**	**8.4**

120 TeV	s I	s II	s III
stat	2.6	3.6	4.9
syst	1.6	3.0	5.4
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Remarks:

- differences within the uncertainty range of detector performance. Run 2 performance keeps $\delta\kappa_{HHH}$ well below 5%
- detector performance (eg ability to cope with pileup, better PID/tagging, …) more critical here than beam energy

➡ worth comparing the challenges, physics gain, costs, etc of progress in magnet technology vs detector performance

Questions? Comments?