Collider Physics - Chapter 6
Physics bSM – Future colliders

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last mod.
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6 – Physics bSM – Future colliders

i. Searches

1. Physics bSM
2. GUT's – SU(5)
3. SUSY
4. Dark Matter
5. Extra-dimensions
6. Axions
7. Bumps
8. Compositeness
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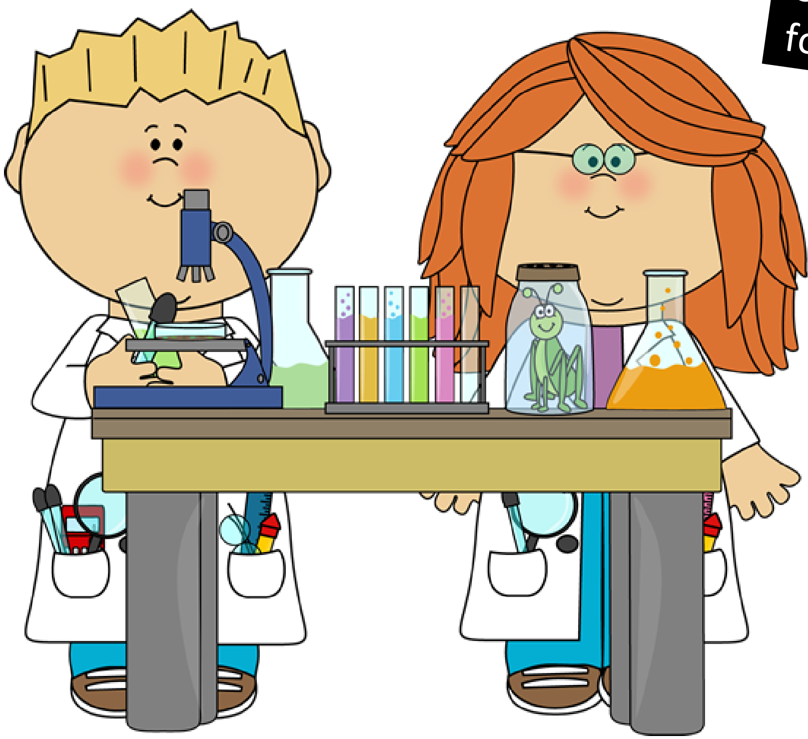
ii. Future tools

9. LHC next years
10. Future projects
11. Future performances

RAPHAEL, THE WORSHIP OF THE GOLDEN CALF (1519)
VATICAN, LOGGIAS

Huge amount of information, amateurish presentation (maybe unavoidable).

i. Searches



Some relevant searches for physics bSM not treated, either because they are elsewhere (extended Higgs sector) or because they have little connection with Collider Physics (e.g. astrophys. searches for DM).

Physics bSM: introduction

At the end of the "Particle Physics" lectures, some motivations for an extension of the SM are listed:

0. surprises/extensions from the Higgs sector [*not mentioned in PP*];
1. dark matter/energy;
2. excess of matter over anti-matter in the universe;
3. grand unification;
4. ν masses;
5. fermion mixing;
6. failure to include gravity;

x. any unexpected discovery.

This chapter deals with some of those subjects, the proposed solutions and on the investigations on present Particle Colliders, mainly LHC.

Two different type of searches:

1. a **new theory** ("***T***", e.g. SUSY, ED), which results in predictions for new observables (e.g. new particles);
2. a **new observable** ("***O***", e.g. a mass bump, not foreseen in SM);

A correspondence (many $\leftrightarrow$ many) exists among ***T***'s and ***O***'s; sometimes physicists prefer to work "top-down" (***T*** $\rightarrow$ ***O***'s) and sometimes "bottom-up" (***O*** $\rightarrow$ ***T***'s).

I personally think that the future will NOT be top-down but bottom-up, i.e. new-effect $\rightarrow$ confusion $\rightarrow$ explanation, as in Rutherford nucleus or q.m., but the majority disagrees.

The motivation of this chapter is to present a general view of the subjects. Too often (imho) the students are parachuted onto a target, without a clear view of the surrounding landscape.

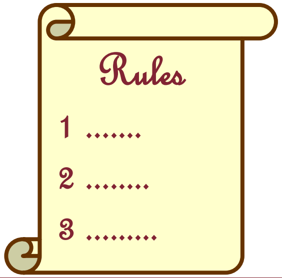
Physics bSM: a problem of communication

When looking for physics bSM, some problems occur:

- physics is an experimental science: the ultimate test resides on observation and comparisons of observables;
- experimentalists look for signatures, especially those rare in SM events (e.g. events with three high-p_T $\ell^\pm$);
- "theories" are basic principles (e.g. a new lagrangian, more dimensions);
- a source of problems:
  - sometimes, a "theory" (e.g. SUSY) may predict totally different observables, by varying its free parameters;
  - in this case both theo. and exp. tend to prefer the (regions of) parameters which are easily observable;
  - in case of success, the observation points to the signature(s), not to the underlying theory/ies: the selection of the correct theory is a longer story;
- other possible approaches:
  - start from a signature, not from a lagrangian [*"model independent", already discussed*];
  - start from an observable (e.g. dark matter) not foreseen in SM, and look for an explanation (the old way);
- a discussion on "physics bSM" is often incoherent and contains flaws [+ *the lack of successes, which is boooring*].

Physics bSM: rules of the game

- In this chapter call "SM" the minimal Standard Model (three generations, Dirac massive ν, CKM and PMNS mixings, H_{125});
- call "bSM" anything else (4^{th} generation, extended H-sector, theories non-SM);
- **you want to search for a process in a theory bSM (call it YP, "your process");**
- produce two (large) samples of mc events: one with SM and one with YP;
- do not forget to include detector- and software-failures in the "SM" sample;
- figure out a (set of) exp. signature(s), uncommon in the SM and likely to appear in YP: **high p_T jets**, **charged leptons**, **E_T^{miss}**, ...;
- produce and test on MC an algorithm which selects the events YP and rejects those SM: old-fashioned cuts, neural network, artificial intelligence, ...;
- the goal is NOT to confirm the novel theory, but to reject the SM-only hypothesis;
- to be more precise, you have to show:
  - the real data are NOT compatible with coming from SM only;
  - they are compatible with SM+YP;
  - (if the data agree with SM, produce a limit on some parameters of YP);
- in case of a discovery, the data could also be compatible with SM+obSM ("other processes bSM");
- the "confirmation" of YP is a longer path; it requires more tests of compatibility and the rejection of many other obSM's.



Physics bSM: another approach

The other approach is **model independent** [*less frequent, but I like it*]:

- produce a (set of) exp. signature(s), uncommon in the SM [*same as before*];
- produce a (large) sample of MC events, which obey to SM;
- do not forget to include detector- and reconstruction-failures;
- produce an algorithm which selects the signatures [*same as before*];
- show that the real data are NOT compatible with coming from SM only;
- of course, you do NOT know which theory bSM is consistent with the data;
- and, in case of compatibility with SM, it is difficult to produce a limit (on what ?);
- but the analysis is faster, you do not have to spend time on clumsy theories;
- in case of compatibility with SM, a full class of theories bSM is rejected (or limited), saving CPU and human time;
- the theoreticians have understood, and have produced (pseudo-)models, which do NOT insist on basic principles, but on the expected phenomenology (e.g. the "κ-*parameters*" [*previous* §] or the "*hidden valley*" seems a test case of it);
- [*these "tool models", created only for search purposes, combine the pros of both methods: I hope they will become the future standard*].

GUT's: Grand unified theories

In the present SM all the fundamental particles are accommodated in multiplets of the gauge groups SU(3)⊗SU(2)⊗U(1).

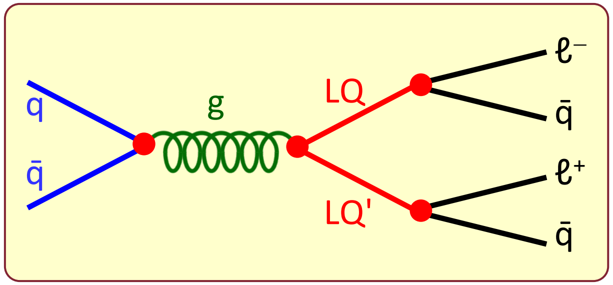
It looks conceivable that this breakdown represents the "low" energy effective behavior of a larger symmetry, which is acting at higher energy. The larger symmetry is represented by a gauge group, which contains SU(3), SU(2) and U(1). A group with these math requirements exists, namely **SU(5)** [*also other groups, like* SO(10) *satisfy the rule*].

Pros [*apart from aesthetics, which is not discussed here*]:

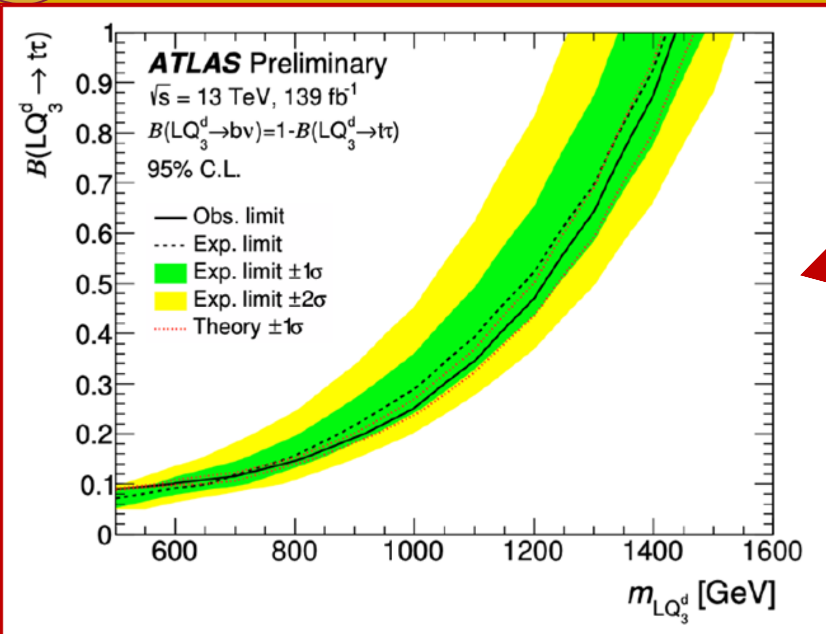
- less free parameters, i.e. relations among constants (e.g. a calculation of $\sin\theta_w$ at *some moment of the past* looked in fair agreement with the data);
- lots of new predictions (e.g. proton lifetime $\tau \approx 10^{29}$ y, *now excluded*)
- huge amount of new particles (e.g. leptoquarks, i.e. new states with both lepton- and baryon-number NOT 0).

Cons:

- the expected relations do not hold properly (lot of work to save them, but not really satisfactory)
- a well-constrained theory is severely damaged by a lack of exp. evidence [*next slide for an example*].

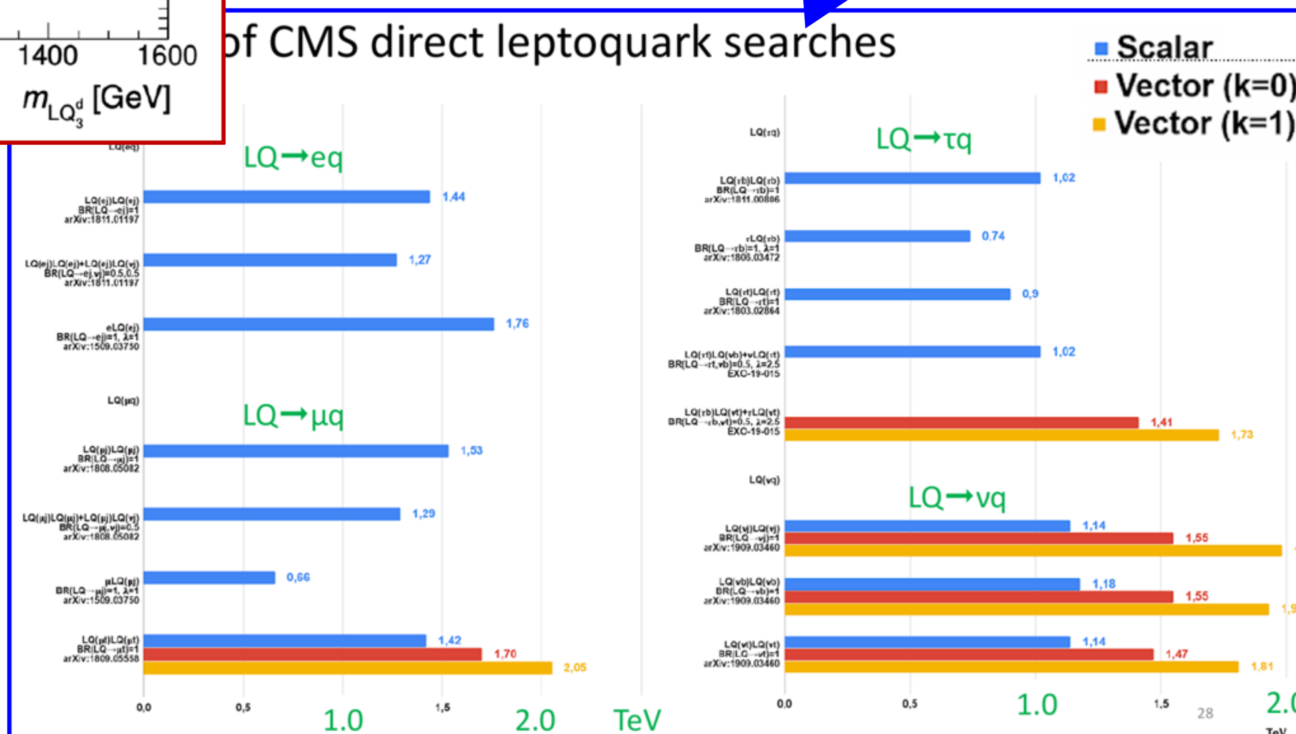


GUT's: leptoquark searches



ICHEP 2020 (Prague, July 2020)

- an analysis of ATLAS (V.Cavaliere)
- the CMS table of 95% CL limits (B.Kilminster)



As previously discussed, leptoquarks appear in many extensions of the SM. I use GUT to show some of the (more general) searches.

NB. "k" is a parameter in the LQ Lagrangian, see Dorsner et al., arXiv 1801.07641.

SUSY: symmetry fermions ↔ bosons

SuperSymmetry (SUSY) is an internal symmetry of the lagrangian, which relates each fermion/boson to a corresponding boson/fermion

Define new quantum number ("R-parity"):

- R = +1 for ordinary particles;
- R = –1 for s-particles;
- R multiplicatively conserved (*);

→ s-particles can only be created in pairs;

→ s-particles can only decay into 1/3/... s-particles + ordinary particles.

normal particle R = +1	spin	SUSY partner R = -1	spin
quark q	½	squark $\tilde{q}$	0
charged lepton $\ell^\pm$	½	charged slepton $\tilde{\ell}^\pm$	0
neutrino ν	½	sneutrino $\tilde{\nu}$	0
photon γ	1	photino $\tilde{\gamma}$	½
gluon g	1	gluino $\tilde{g}$	½
Z, $W^\pm$	1	Zino $\tilde{Z}$, Wino $\tilde{W}^\pm$	½
graviton	2	gravitino	3/2
Higgs $H^0, H^\pm, h^0, A^0$	0	Higgsino $\tilde{H}^0, \tilde{H}^\pm, \tilde{h}^0, \tilde{A}^0$	½

All the other qn (Q, baryon/lepton n., ...) but (spin and R) are the same for a particle and its s-partner.

All dynamics (non spin- or R-dependent) is equal.

For the actual observable particles, see next slide.

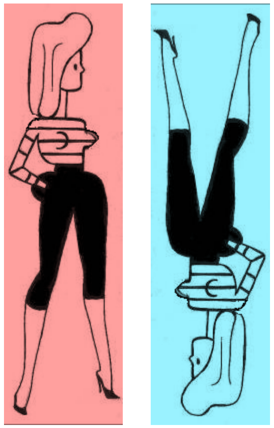
___

(*) In some models of SUSY, R is NOT conserved (models with ***R-parity violation***). *When not explicitly mentioned, in these slides R-conservation is assumed.*

SUSY: the particles

- [in R-cons. models] the ligthest s-particle (**LSP**) is stable:
  - not easily observable;
  - therefore neutral, not strongly-interacting (a sort of heavy ν);
  - LSP is a good candidate for **dark matter** [*see below*];
- the Higgs sector contains (+ s-partners):
  - h^0, H^0 : two neutral scalars, CP even (def. $m_h < m_H$);
  - A^0 : a neutral scalar, CP odd;
  - $H^\pm$: two charged scalars;
  - it can be shown $m_h < m_Z$ [before radiative corrections] ;
- the s-particles with equal Q, $\vec{s}$, CP mix into physical states [*remember* K^0]:
  - $\tilde{h}^0, \tilde{H}^0, \tilde{\gamma}, \tilde{Z} \rightarrow \tilde{\chi}^0_{1,2,3,4}$ (4 "neutralino");
  - $\tilde{W}^\pm, \tilde{H}^\pm \rightarrow \tilde{\chi}^\pm_{1,2}$ (2 "chargino");
- **mixing matrices** (4×4) and (2×2) are defined for $\tilde{\chi}^0$ and $\tilde{\chi}^\pm$ [*six/one angles + three/zero phases*(*)].
- the dynamics of the $\tilde{\chi}$'s varies according to the mixing (e.g. for small mixing $\tilde{\chi}^\pm_1 \approx \tilde{W}^\pm$ and $\tilde{\chi}^\pm_2 \approx \tilde{H}^\pm$);
- in most models LSP = $\tilde{\chi}^0_1$;
  - but in some model LSP = gravitino;
- many others rules [references];
- a nice theory, a plethora of new states, a well defined dynamics [*all the ingredients for a success story*].

(*) $n_{rot} = N(N-1)/2$;
$n_{ph} = (N-1)(N-2)/2$;
$n_{tot} = n_{rot} + n_{ph} = (N-1)^2$.



SUSY: the theory

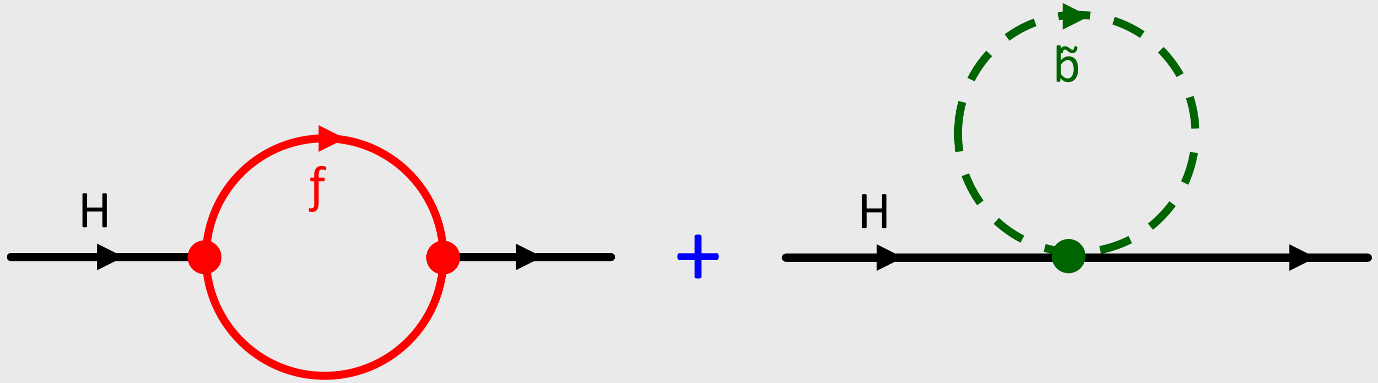
- ☹ if s-particles had the same mass and behavior as their partners, they would be known since ever; only possibility is **SUSY is broken, the mass of the s-partners is large**;
- ☺ the dynamical reasons used to justify SUSY (e.g. δm_H, see later) fix the mass scale to by smaller than **$\tilde{m} \sim$ O(TeV)**;
- 😐 O(100) free parameters (masses, mixings) → NO SUSY "theory", but "**SUSY models**", a mixture of theory, common sense, rules [*not simple to manage*]; most common "**MSSM**" (minimal SUSY model), "**SUGRA**" ("gra"=gravity), many others.
- ☹ these models have completely **different exp. predictions**;
- 😐 on the exp. side, many (thousands) possible searches, for particles with different mass and behavior (e.g. if a mixing 0 → 1, $\tilde{\chi}^0_1$ = from $\tilde{\gamma}$ to $\tilde{H}^0$);
- 😐 the majority of the models (= the larger part of the "parameter space") is excluded by existent data [*e.g. if small s-particle masses, if wrong dynamics*];
- ☹ for the rest of the parameter space, until now, **limits only** [*SUSY was "discovered" many times, but only mistakes / fluctuations*];
- ☹ because of its features, it is difficult to **falsify SUSY** (HL-LHC will exclude **almost all of the parameters' space**);
- ☺ [*physics is not a democracy, but at some point in the past, the majority of the theoreticians were true believers; now, not so much* ☺].

SUSY: a cure for the SM problems

In the SM the radiative correction to m_H are naturally large ($\delta m_H \to 10^{17}$ GeV): a miracle is required, in order to produce exact cancellations of the various terms order by order, i.e. to "fine tune" the loop corrections, by adjusting unrelated parameters to ~15 significant figures.

Instead, if superpartner exists, with $m \leq 1$ TeV, δm_H is under control, because, order by order, the loops with particles are (almost) cancelled by the s-particles, because bosons and fermions gives similar values with opposite sign.

similar arguments already used in PP when discussing α_s and GIM.



$\propto (m_b^2 - m_f^2)$ = small

SUSY: observable ?

If SUSY exists [*a big if*], is it observable ?

YES, because:

- dynamics similar to ordinary particles, so pp → $\tilde{g}\tilde{g}X$, $\tilde{q}\tilde{g}X$, $\tilde{q}\tilde{q}X$ is abundant;
- pp → $\tilde{W}$ / $\tilde{Z}$ / $\tilde{H}$ / $\tilde{h}$ similar to pp → W ...; (*popular wisdom: hadronic machines for hadronic s-particles, e^+e^- for e.w. ones*);
- $\tilde{\chi}$ production depends also on the mixings;
- LSP ($\tilde{\chi}^0$) must be there all the times, because all s-particles decay to it, but is not seen by detectors (but by E_T^{miss});
- signatures must be spectacular (see e.g. next slides);

but **DIFFICULT**, if:

- masses of s-particles too large (→ σ(SUSY) depressed by PDF's);
- it is customary to present the exclusion as a function of the mass of the searched particle: higher mass, less exclusion [*we are used to it, the same effect for the SM Higgs at LEP*];
- some particular combination of the parameters make SUSY difficult to observe (*e.g. a hadronic decay at threshold produces overlapped jets, similar to ordinary QCD*).

CONCLUSION:

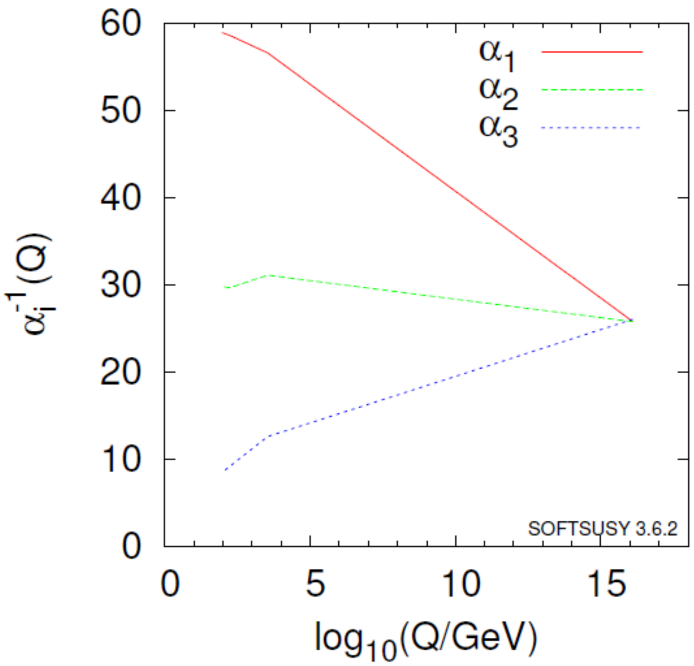
- probably evidence for SUSY is easy;
- the meas. of the parameters is difficult;
- if nothing seen, is a real mess: even if the remaining space of the parameters is tiny, no final conclusion is possible.

WELL, GIVEN THE MURPHY'S LAWS, ...

SUSY: a summary of pros

A summary of many arguments:

- the high-energy behaviour of the coupling constants [PP, § 6, see figure];
- the "natural" explanation of dark matter;
- the solution of the δm_H problem;
- the value of m_H, fairly compatible (within rad.corr.) with the limit $m_h < m_Z$;
- a possible explanation of the anomaly of the muon (g-2) [*just mentioned, not a collider argument*];
- a possible combination with GUT (SUSY-GUT), with very interesting features;
- a possible correlation with gravity (SUGRA), with the possibility of investigating "the last frontier", not yet conquered by quantum mechanics.



So, a done deal ?

ask LHC ...

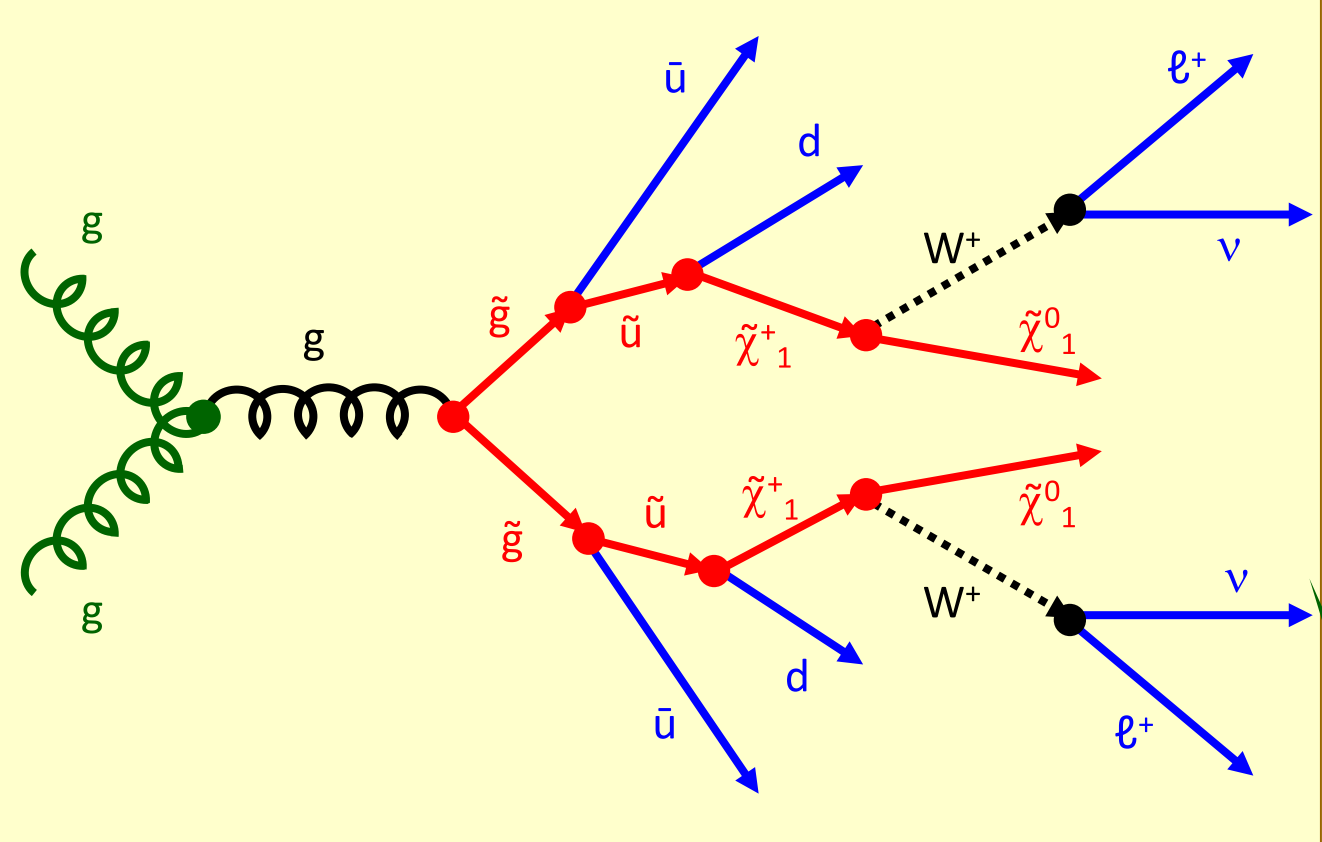
SUSY: pre-LHC

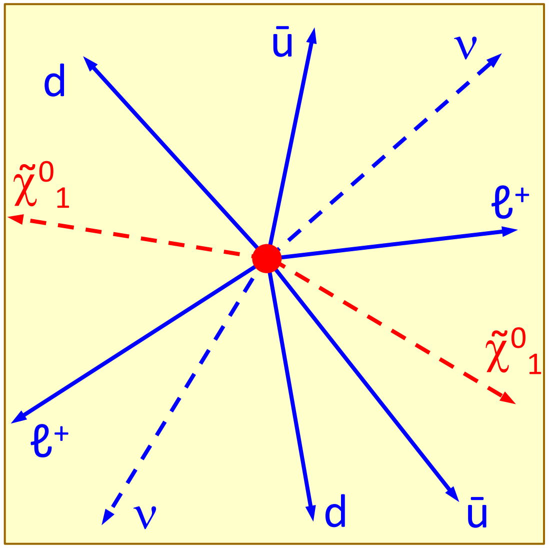
"... If SUSY exists at the electroweak scale, i.e., with squark and gluino masses less than 1-2 TeV, it should be straightforward to find signals for it at the LHC in the jets + E_T^{miss} channel and perhaps in many other channels. Discovery of a deviation from the Standard Model should be possible with an integrated luminosity of ***10 fb^{-1} or even less*** for masses below 1 TeV. In many cases, it should be possible to determine combinations of masses from features of kinematic distributions, giving precision measurements of these mass combinations. If the SUSY model turns out to be simple, it will also be possible to determine its parameters from such precision measurements. ***Shortly*** after the LHC starts operation, either SUSY will become a central part of particle physics (…), or it will be relegated to an obscure corner of mathematical physics.

The LHC will mainly produce ***gluinos***, ***squarks***, and their main decay products, the ***light gauginos***, $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, and $\chi^\pm_1$. The dominant backgrounds for SUSY signatures come not from Standard Model processes but from other SUSY processes. For some choices of the SUSY model, it will also be possible to detect other SUSY particles, including some or all of the sleptons and the heavier gauginos. However, it is generally not possible to detect the whole SUSY and heavy Higgs spectrum. Thus, some of the conclusions from any LHC SUSY analysis will probably be model dependent. (…)"

F.Paige, 1997 Lectures
[emphasis mine]

SUSY: example 1

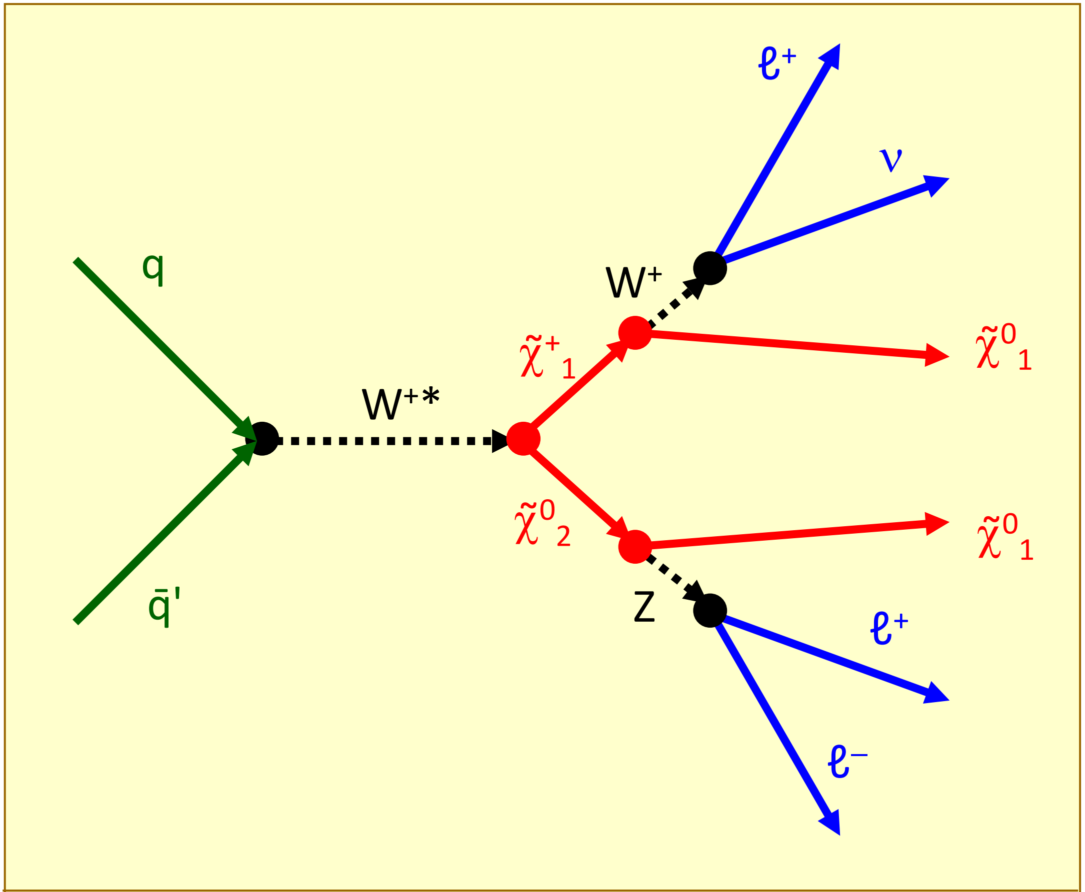




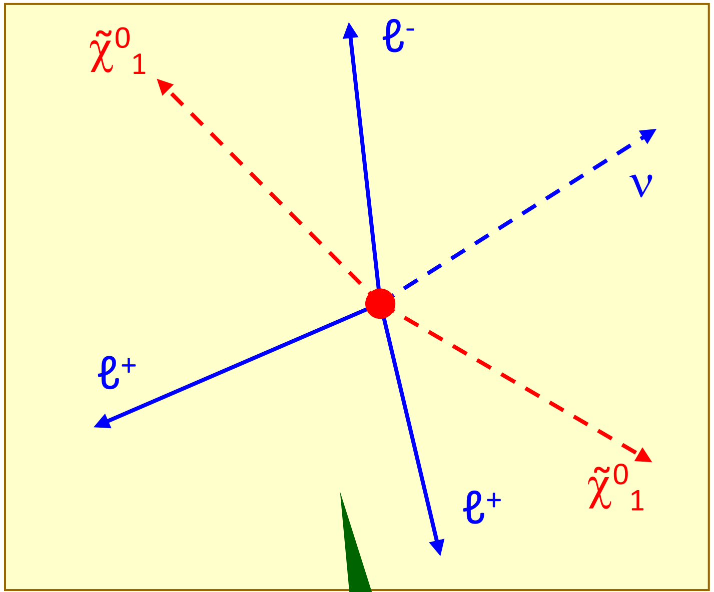
$gg \rightarrow \bar{u}\, d\, \bar{u}\, d\, \ell^+ \nu\, \ell^+ \nu\, \tilde{\chi}^0_1\, \tilde{\chi}^0_1 \rightarrow$ 4 jet, $2\ell^+$, E_T^{miss}

a "typical **mc** event" [from D. Green - High p_T physics at Hadron Colliders, Cambridge U.P. (2005); pag 209]: very rare, but bckgd free, spectacular signatures, easy identification [*in mc, life is always simpler*]

SUSY: example 2



$q\bar{q}' \rightarrow \ell^+ \ell^+ \ell^- \nu \, \tilde{\chi}^0{}_1 \, \tilde{\chi}^0{}_1 \rightarrow 2\ \ell^+, \ell^-, E_T^{miss}$



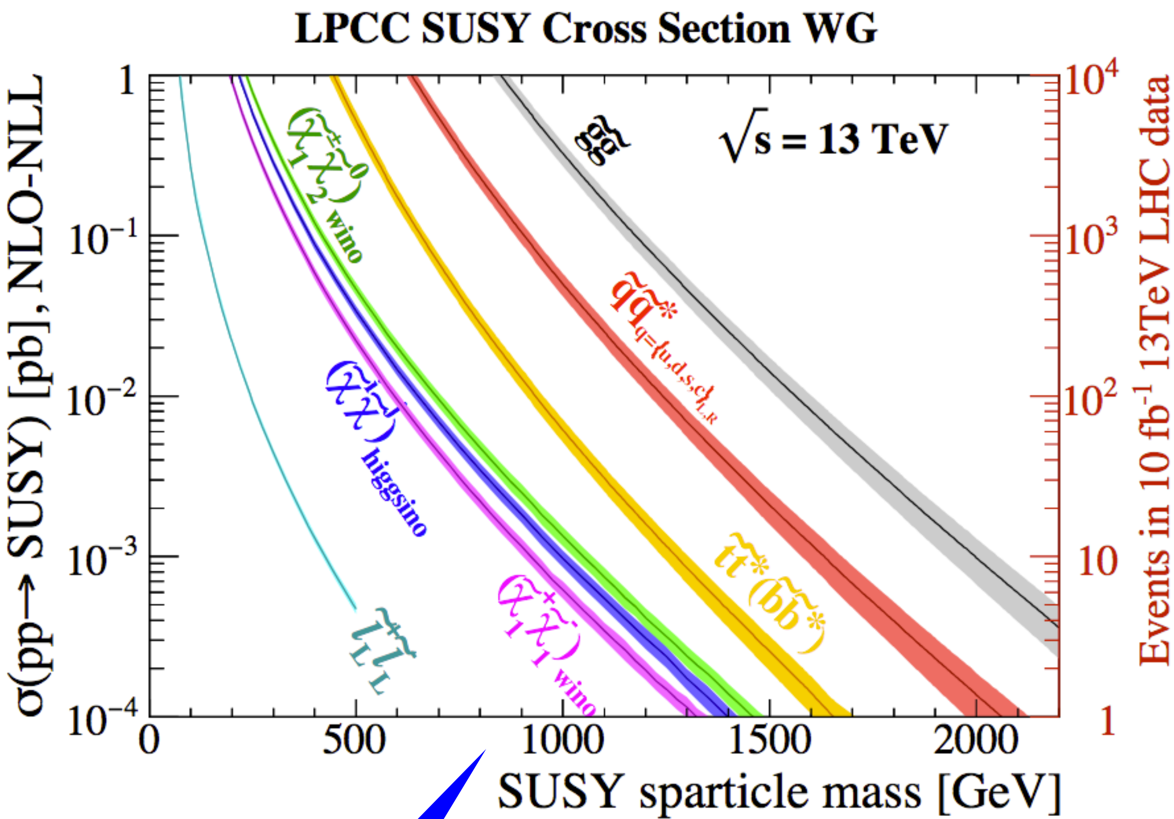
another "typical **mc** example" from Green, pag 209:

spectacular signatures, easy identification

[the 2nd generation W/Z can be real or virtual, but the 1st W is certainly virtual]

SUSY: LHC cross-sections

in 2020, after 20+ years and O(10^3) searches → $10^{2÷3}$ papers:



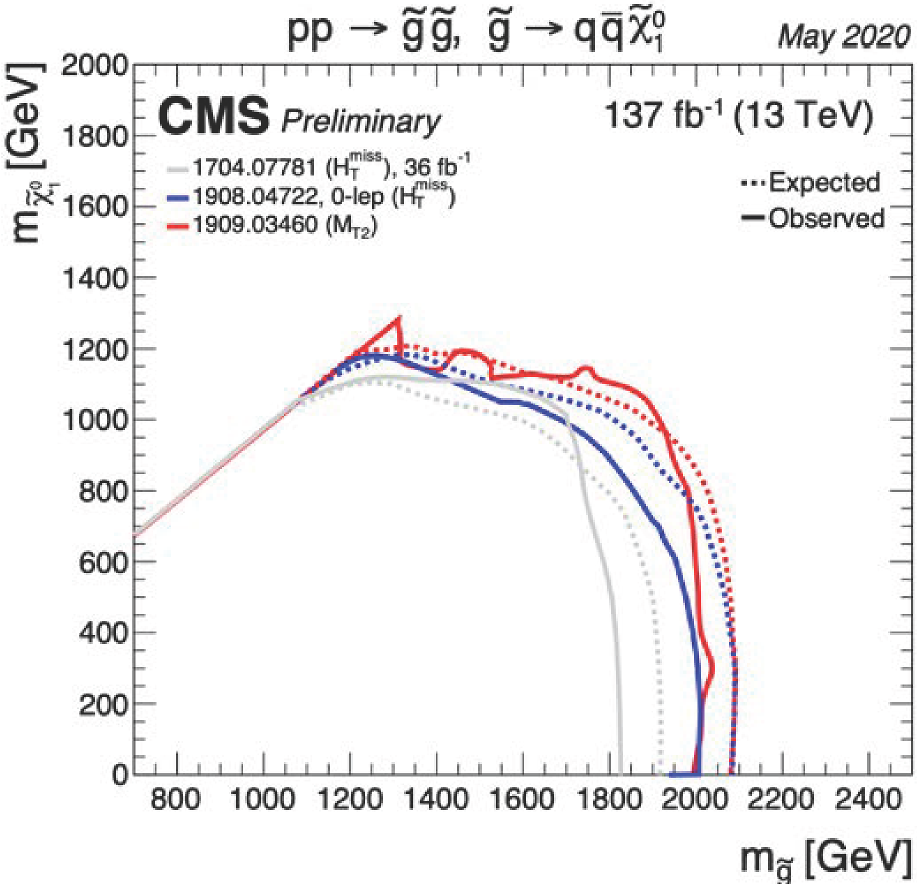
+ DAQ, trigger, acceptance, analysis ...

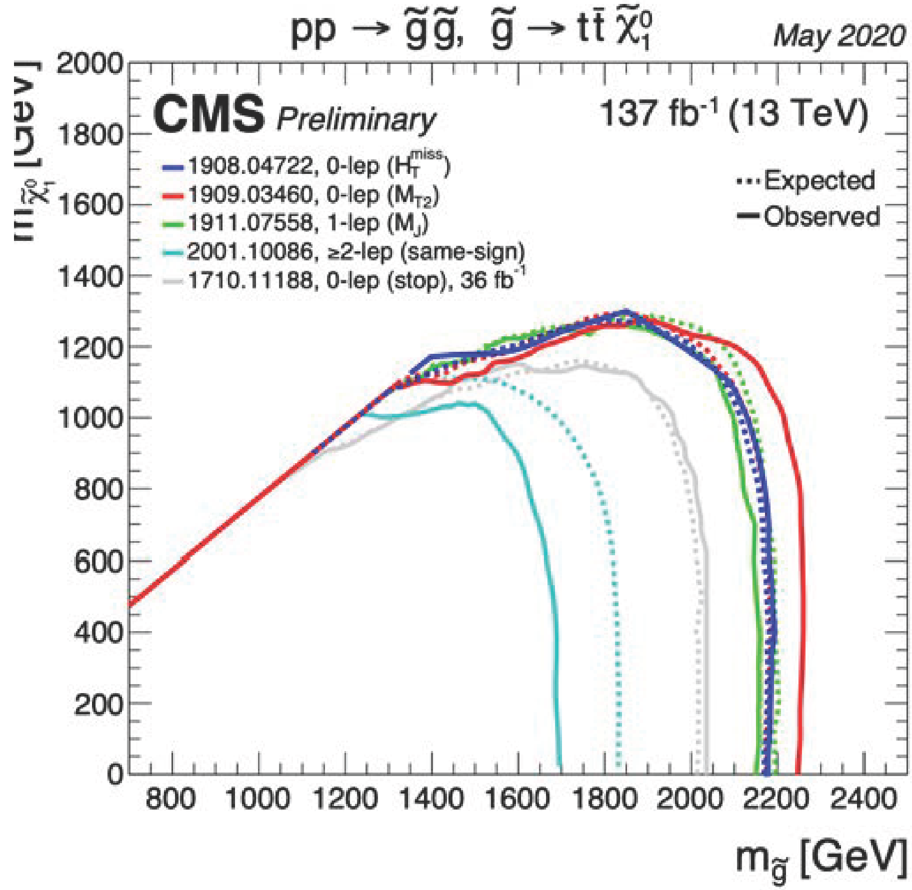
still very comfortable → no real exp. problem.

the usual game: σ_{SUSY} vs mass, at fixed $\sqrt{s}$, in qpm+pQCD+SUSY.

SUSY: LHC cross-sections

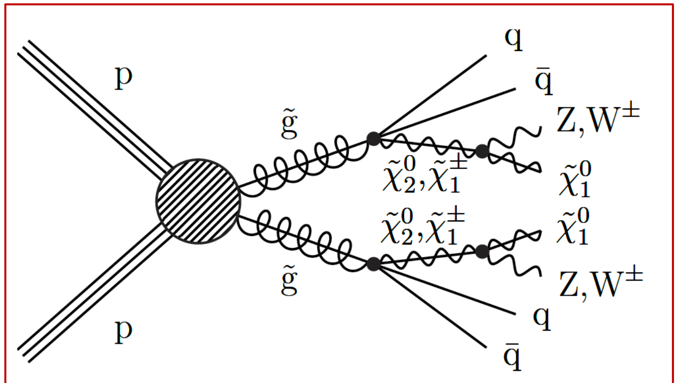
A nice example of two CMS analyses (C.Botta, Prague 2020): the exclusion in the plane $m(\tilde{g})/m(\tilde{\chi}^0{}_1)$ for two different searches:

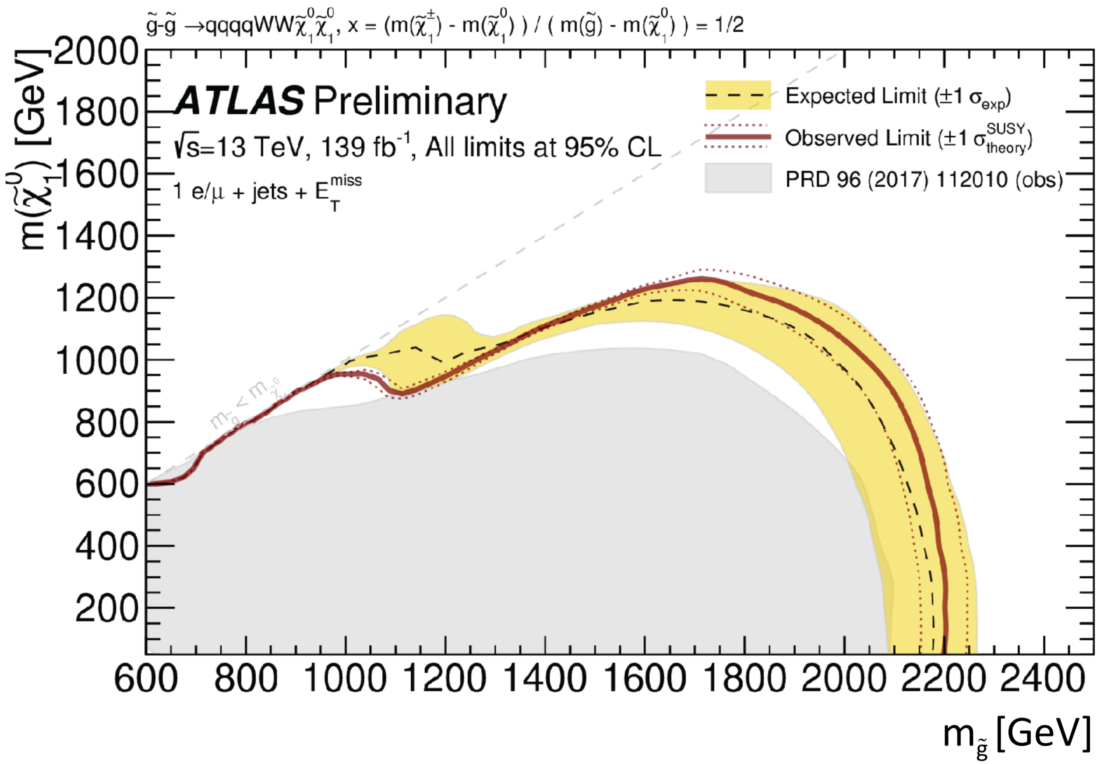




SUSY: LHC cross-sections

... and one from ATLAS, from the same talk (C.Botta, Prague 2020). The interested people can look to the (infinite) number of papers on SUSY searches.





SUSY: LHC cross-sections

... and the full table of results (PDG 2020):

Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
Simplified model	$m_{\tilde{\chi}_1^0}= 0$, $m_{\tilde{q}} \approx m_{\tilde{g}}$	≈ 3000	≈ 3000
$\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0}= 0$, all $m_{\tilde{q}}$	-	≈ 2200
	$m_{\tilde{\chi}_1^0}= 0$, all $m_{\tilde{g}}$	≈ 2600	-
Simplified models $\tilde{g}\tilde{g}$			
$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} =0$	-	≈ 2300
	$m_{\tilde{\chi}_1^0} >\approx 1200$	-	no limit
$\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} =0$	-	≈ 2300
	$m_{\tilde{\chi}_1^0} >\approx 1500$	-	no limit
$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} =0$	-	≈ 2250
	$m_{\tilde{\chi}_1^0} >\approx 1300$	-	no limit

Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
Simplified models $\tilde{q}\tilde{q}$			
$\tilde{q} \to q\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} =0$	≈ 1900	-
	$m_{\tilde{\chi}_1^0} >\approx 800$	no limit	-
$\tilde{u}_L \to q\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} =0$	≈ 1300	-
	$m_{\tilde{\chi}_1^0} >\approx 600$	no limit	-
$\tilde{b} \to b\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} =0$	≈ 1250	-
	$m_{\tilde{\chi}_1^0} >\approx 700$	no limit	-
$\tilde{t} \to t\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} =0$	≈ 1200	-
	$m_{\tilde{\chi}_1^0} >\approx 600$	no limit	-
$\tilde{t} \to b\tilde{\chi}_1^\pm$	$m_{\tilde{\chi}_1^0} =0$	≈ 1150	-
$(m_{\tilde{\chi}_1^\pm} = (m_{\tilde{t}} - m_{\tilde{\chi}_1^0})/2)$	$m_{\tilde{\chi}_1^0} >\approx 550$	no limit	-
$\tilde{t} \to Wb\tilde{\chi}_1^0$ $(m_W < m_{\tilde{t}} - m_{\tilde{\chi}^0} < m_t)$	$m_{\tilde{\chi}_1^0} <\approx 570$	≈ 700	-
$\tilde{t} \to c\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} <\approx 450$	≈ 550	-
	$m_{\tilde{t}} \approx m_{\tilde{\chi}_1^0}$	≈ 550	-
$\tilde{t} \to bff'\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} <\approx 450$	≈ 550	-
$(m_{\tilde{t}} - m_{\tilde{\chi}^0} < m_W)$	$m_{\tilde{t}} \approx m_{\tilde{\chi}_1^0}$	≈ 550	-

The main message is that, the vast amount of work and the quality of the data had resulted in many **limits**. Current 95% CL limits range from 500 to 3,000 GeV for squarks and gluinos. Unfortunately, as anticipated, none of this limit is fully **model-independent**, i.e. they all depend on some assumption on the SUSY parameters.

[the table is nice, but VERY simplified: the devil is in the SUSY models used in the computation; an exhaustive explanation requires endless and VERY boring comments]

SUSY: now (PDG 2020)

"... The ***absence of any observation*** of new phenomena at the first run of the LHC at √s = 7/8 TeV, and after the second run at √s = 13 TeV, place ***significant constraints*** on SUSY parameter space. Today, inclusive searches probe production of gluinos at about 2.3 TeV, first and second generation squarks in the range of about 1 to 1.9 TeV, third generation squarks at scales around 600 GeV to 1.2 TeV, electroweak gauginos at scales around 400 − 1100 GeV, and sleptons around 700 GeV. However, depending on the ***assumptions*** made on the underlying SUSY spectrum, these limits can also weaken considerably.

With the LHC having reached almost its maximum energy of about √s = 14 TeV, future sensitivity improvement will have to originate from more data, the improvement of experimental analysis techniques and the focus of special signatures like the one arising in long-lived sparticle decays. Therefore, it is expected that the current landscape of SUSY searches and corresponding exclusion limits at the LHC [...] ***will not change*** as rapidly anymore as it did in the past, when the LHC underwent several successive increases of collision energy.

[... The] interpretations in simplified models do not come without a price [... Q]uoted limits in simplified models are only valid under the explicit assumptions made in these ***models***.

[...] The next LHC runs at √s = 13 or 14 TeV with significantly larger integrated luminosities (notably the High-Luminosity LHC), will provide a large data sample for future SUSY searches. [...] Although the sensitivity for colored sparticles will increase somewhat as well, the expanded data set will be particularly beneficial for electroweak gaugino searches, and for the more difficult final states presented by compressed particle spectra, stealth SUSY, long-lived sparticles, or R-parity violating scenarios. (…)"

O.Buchmuller (London) and P. de Jong (NIKHEF)

[emphasis mine]

Dark Matter

- DM is an important [*possibly the most important*] unexplained effect in physics;
- its evidence came from astrophysics, and is outside the boundary of this course;
- DM is supposed to be ~85% of the matter of the universe, with ordinary (baryon) matter at ~15% level;
- particle physics can help a lot in the solution of the problem, by finding the particle (?) responsible for the effect;
- [*an old alliance between the sciences of the small and the large: cosmic rays, nuclear reaction in the stars, ...*]
- the idea is to uncover a particle/effect, which, replicated on a gigantic scale, may account for the phenomenon;
- therefore it is impossible to develop a coherent discussion on "DM at Colliders"; although the search for DM is an important subject for today Collider Physics, it is somehow "ancillary" to the other searches;
- it is better, when discussing another search (or a model-independent one) to claim that "*the result of the search could also be a DM candidate*" (*);
- e.g., if SUSY were found to be correct, the LSP would be an obvious candidate for the DM.

———————

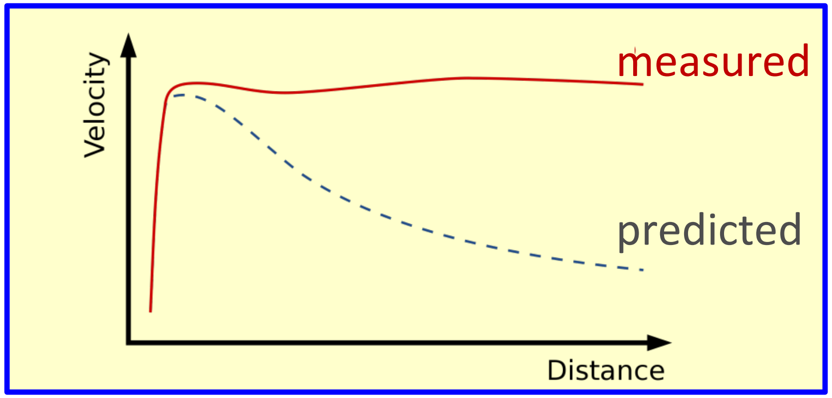
(*) Do NOT take the success for granted: one must show that there are enough particles, that they are properly distributed, etc. etc.; a *similar case happens for CP-violation, which creates an asymmetry matter-antimatter, but is unable to explain the size of the cosmological difference*.

Dark Matter: for dummies

Many converging evidences; here two:

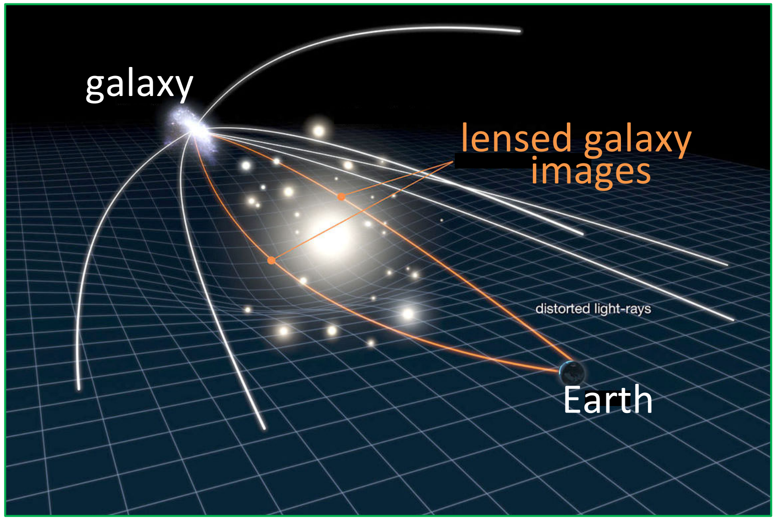
Tangential velocity:

- from classical mechanics the tangential velocity (v) of a star in a galaxy is given by $v^2/r = GM(r)/r^2$;
  r = distance from galaxy center;
  $M(r)$ = amount of matter within r;
- if M(r) is concentrated at small r:
  $v(r) \propto 1/\sqrt{r}$;
- the observations, using visible stars for M(r), disagree with predictions, showing the presence of "unseen" matter (= DM).



Gravitational lensing:

- in general relativity, a massive object "bends" the space around itself;
- the photons' paths near the object are subject to a lensing effect;
- the measure of the lensing gives the amount of matter of the object;
- it turns out NOT in agreement with the visible matter, but much larger.



Dark Matter: the question

The problem:

- **visible matter**: [*visible*: interacting with photons] objects, like baryons/charged-leptons, actually detected [different from "*observable in principle*", e.g. ν's];
- in galaxies the "visible matter" is too little and too concentrated at small r;
- the effects just described can be explained with another type of matter:
  - **NO e.m.** interactions (= *dark*);
  - **NOR strong** interactions;
  - only **gravitational** interactions;
  - ... and possibly **weak** ones;
  - more diffused (not only at small r);
- [*we (LHC guys) love DM, since it turns astro-physics into elementary-particle;*]

- but, just to be honest, we have to admit that a pure astro-physical solution could be envisaged;
- i.e., instead of postulating that the "frame" (general relativity + rqm) be correct, but part of the picture (the DM) be missing ...
- ... one could change the underlying theory, e.g. by modifying the general relativity, or by building a quantum theory of gravity ...
- ***who knows ?***

however, no weak interactions → no production in colliders.

Dark Matter: proposed solutions

A long list (see box):

- no justifications here (see other chapters);
- [*I admit that I have found the list on the web and I have crossed out the lines that I do not even understand*]
- some (e.g. 7) are not scientific statements, but just language (*a WIMP, without further explanation, is any particle like a* ν *or a LSP*);
- some (e.g. 9) are from cosmic-ray physics;
- none (but 1) is based on well-established particles;
- n. 1 is attracting, but it does NOT agree with data and known dynamics;
- I like n. 10 (and also S.Hossenfelder), but nobody knows how proceed with it;
- ... but I suspect that the truth is 11.

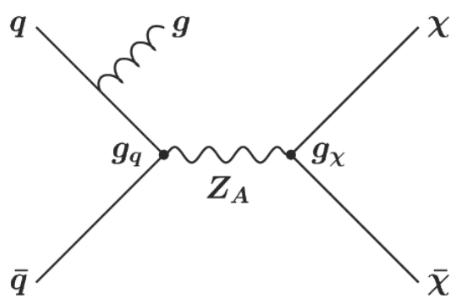
1. SM neutrinos (left-handed);
2. non-SM neutrinos (possibly r-h);
3. the LSP of SUSY;
4. axions or ALP's (axion-like particles);
5. extra dimensions particles;
6. non-MSM Higgs;
7. WIMPs (= Weakly interacting massive particles);
8. primordial black holes;
9. MaCHOs (= massive compact halo objects);
10. astro-physical dynamical explanations (= mods to general relativity);
11. something else ...

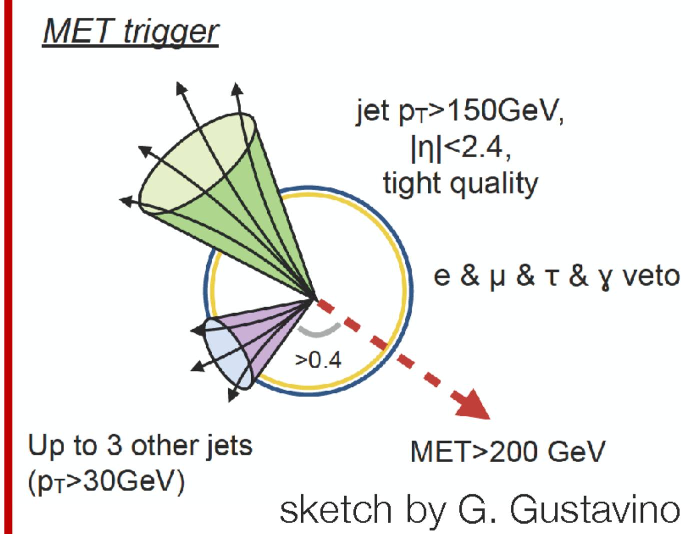
It is a riddle wrapped in a mystery inside an enigma (W. Churchill)

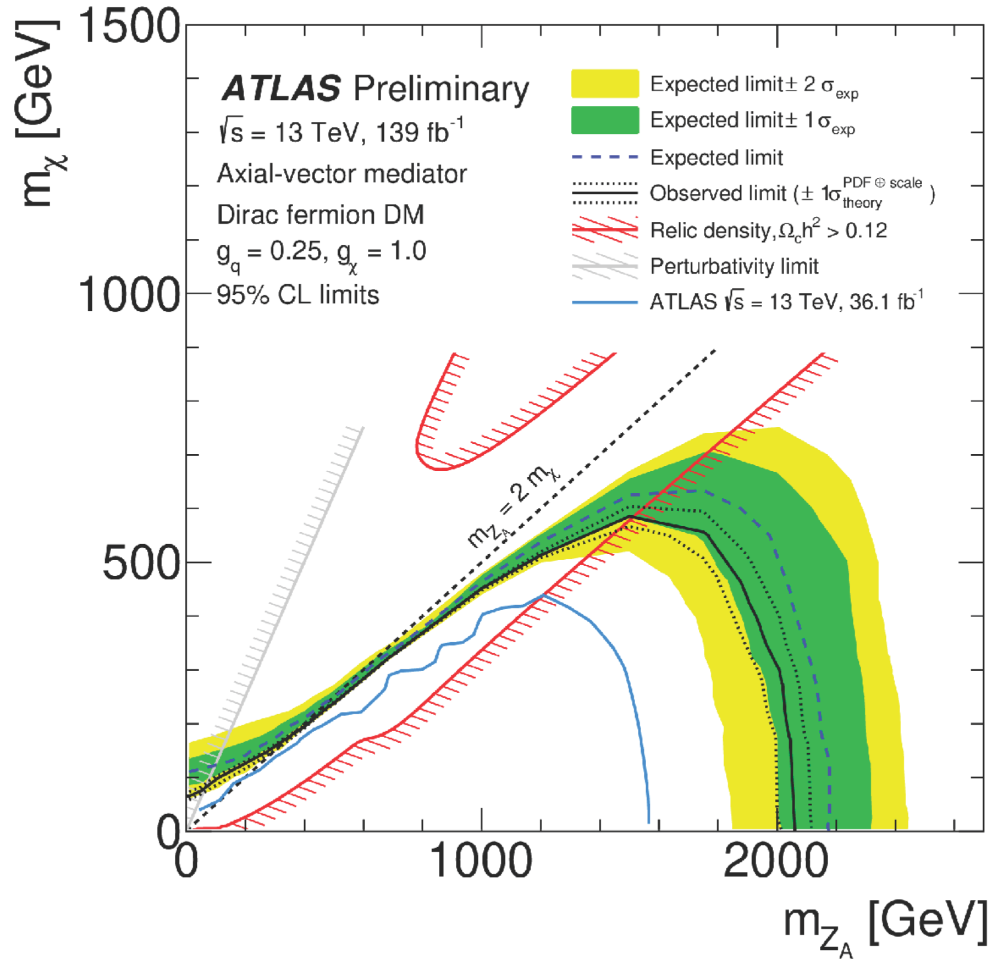
Dark Matter: a search

a dedicated search shown by (V. Cavaliere, Prague 2020).

A simplified model with a mediator Z_A (an ad-hoc model, don't judge the "theory", just appreciate the trigger and selection)







Extra-dimensions: a brane new world

In 1919-26 **Kaluza** and **Klein** tried to extend e.m. and relativity to five dimensions, but the attempt failed.

Many years after, the idea resurrected:

- in 1999 **Randall** and **Sundrum** proposed that our world is a 3-D "brane", immersed in a many-D world;
- all forces, but gravity, live in the brane;
- the other dimensions are small, $O(10^{-30}$ m), so they are hidden to us;
- the model solves the hierarchy problem (i.e. the mass scale of SM);
- ... and makes quantum gravity easier [*maybe*];
- ... and merges gracefully with the string model ($\rightarrow$ superstrings).

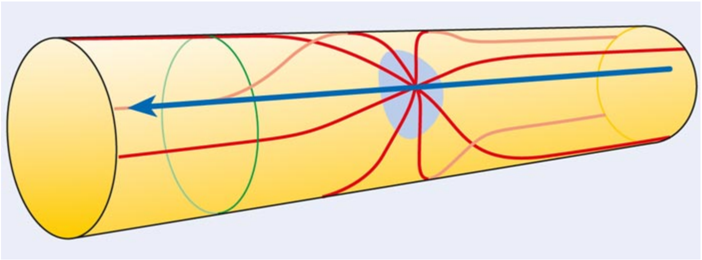
As SUSY, ED is not a closed theory, with a well defined set of observables, but more a general principle, which gives birth to a class of models, with different observables.

How to look for such a theory ?

- search particles traveling in many-D [?];
- detect them [??];
- understand their behavior [???];
- in practice, the search is closely related to other exotica;
- will see an example.

____

The only paper I dare to suggest you is L. Randall - Physics Today 60, 7, 80.



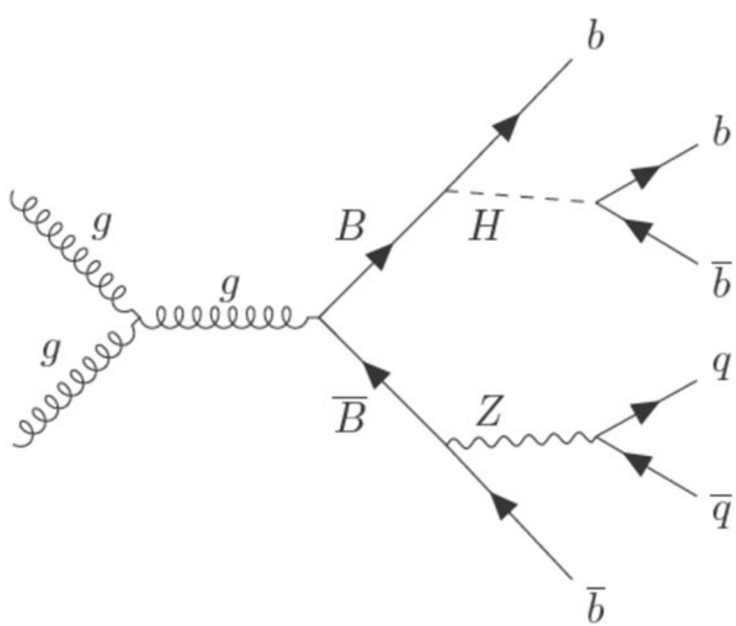
Extra-dimensions: a search

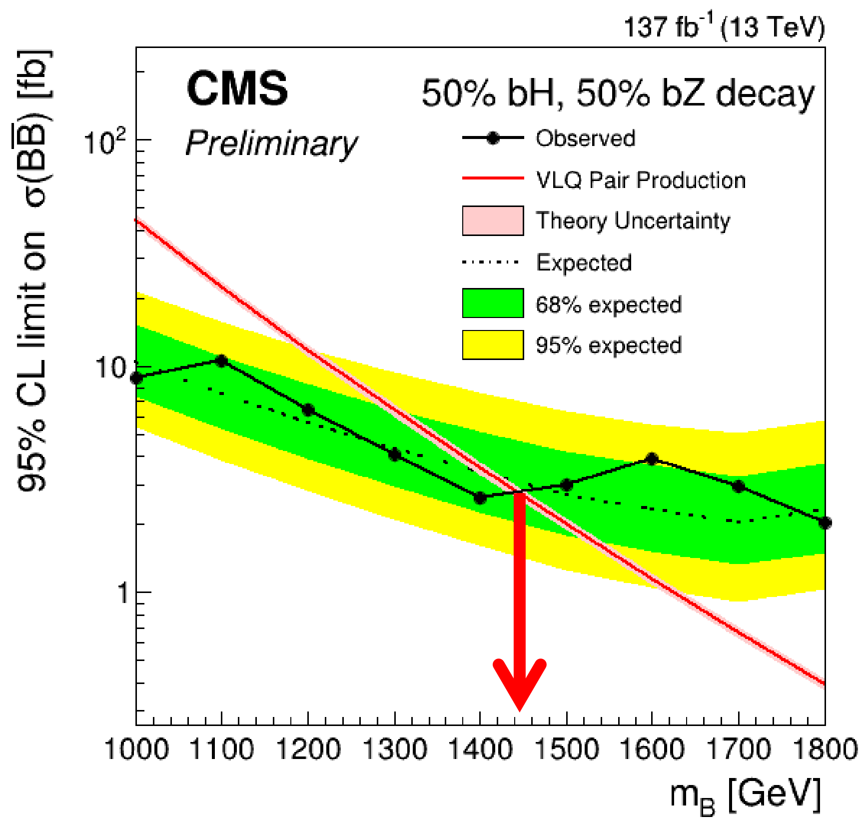
A dedicated search shown by (V. Cavaliere, Prague 2020).

"B" is supposed to be a vector-like quark (VLQ), proposed in some ED-models to solve the hierarchy problem. In the decay mode (50% B → bH, 50% B → BZ), they get:

m(B) > 1450 GeV @ 95% CL.

B is not specific to ED; it can appear in many other models bSM; I show it here just as an example.
Conclusion 1: apart from theories very "closed", signatures are more important than starting principles.
Conclusion 2: do not generalize; searches contain assumptions (50% ?); results are as good as these prejudices.





The axion: the QCD "θ" parameter

A problem of QCD: the ℂℙ violation in strong interactions:

- in the QCD part of the SM lagrangian ($\mathscr{L}_{QCD}$) an additional gauge-invariant term $\mathscr{L}_{CP}$ is allowed [PDG §9 + §91]:

$$\mathscr{L}'_{QCD} = \mathscr{L}_{QCD} + \mathscr{L}_{CP};$$

$$\mathscr{L}_{CP} = -\theta\,(\alpha_s/8\pi)\, G^{j\square}\ \tilde{G}^j_{\square}\ ;$$

$$G^j_{\square} = \partial_\alpha G^j_\beta - \partial_\beta G^j_\alpha - g_s f_{jkm} G^k_\alpha G^m_\beta;$$

[j : color index, $\tilde{G}^j_{\square}$: ½ $\varepsilon^{\square\square}$ $G^j_{\square}$,
G^j_α : gluon field, $\alpha_s = g^2_s/4\pi$];

- the parameter θ is free [□ ≤ θ ≤ π], not determined by the theory;
- the lagrangian $\mathscr{L}_{CP}$ is responsible of observables (e.g. the electric dipole moment of the neutron $\vec{d}_n$), which violate ℂℙ by an amount typical of strong interactions, multiplied by θ;
- such values are not observed; the only way-out is $\theta \approx 0$;
- actually:

$$|\vec{d}_n| < 0.18 \times 10^{-25}\ e\cdot cm\ @\ 90\%\ CL$$

$$\rightarrow \theta < 10^{-10};$$

- the SM lacks a "natural" explanation of this "non-natural" value for θ;
- **therefore, why ?**

at first sight, the SM looks perfect; however, there is quite some "dust swept under the carpet".

The axion: the "strong CP violation"

More specifically:

$$\mathcal{L}_{CP} = -\theta \frac{\alpha_s}{8\pi} G_i^{\mu\nu} \tilde{G}^i_{\mu\nu}$$

colour field force tensor
(i = colour index)

$$G^i_{\mu\nu} = \frac{\partial G^i_\nu}{\partial x_\mu} - \frac{\partial G^i_\mu}{\partial x_\nu};$$

$$\tilde{G}^i_{\mu\nu} = \tfrac{1}{2}\varepsilon_{\mu\nu\rho\sigma} G_i^{\rho\sigma}$$

(similar to $\vec{E}\cdot\vec{B}$ in electromagnetism)

$\theta = \theta_v + \arg\det M_q$

θ_v: parameter describing the QCD vacuum ($\neq 0$ only in non-Abelian theories)

M_q: quark mass matrix

Prediction of an electric dipole moment for the neutron:

$$|d_n| = A|\theta| \times 10^{-15}\ e \times cm$$

A = 0.04 - 2.0

$\square \quad \leq \theta \leq \pi$

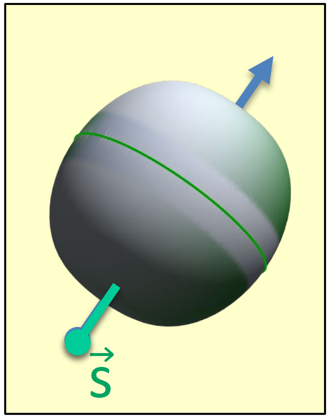
Present experimental limit: $|\vec{d}_n| < 0.18 \times 10^{-25}$ e × cm

$|\theta| < 10^{-10}$ WHY SO SMALL?

from L.DiLella

The axion: neutron electric dipole moment

Evidence for violation of $\mathbb{T}$ (and $\mathbb{CP}$) invariance



In the neutron rest frame :
(ρ_n: electric charge distribution)

$$\vec{d}_n = \int \vec{r}\rho_n(\vec{r})d^3r$$

Under $\mathbb{T}$ transformation ($t \to -t$) : $\vec{d}_n \to \vec{d}_n$

However: $\vec{d}_n = \pm|\vec{d}_n|\hat{s}_n$

neutron spin direction:
the only way to define a direction in the neutron rest frame

Under $\mathbb{T}$ transformation: $\hat{s}_n \to -\hat{s}_n \Rightarrow \vec{d}_n = -\vec{d}_n$

So, $\mathbb{T}$ invariance requires simultaneously

$\boxed{\vec{d}_n \to \vec{d}_n}$ and $\boxed{\vec{d}_n = -\vec{d}_n}$ $\Rightarrow$ $\boxed{\vec{d}_n = 0}$

from L.DiLella

The axion: the Peccei-Quinn solution (1977)

Existence of a new, massless pseudoscalar field a(x) (**the axion**), which interacts with the gluon field;

Add two new terms to $\mathscr{L}_{CP}$:

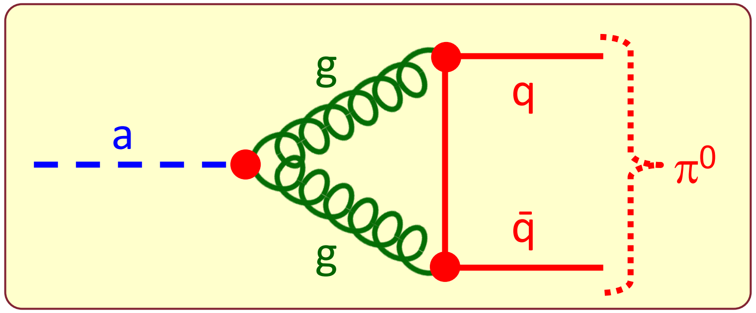
$$\mathscr{L}_{CP} = \frac{1}{2}(\partial_\mu a)^2 + \frac{\alpha_s}{8\pi}\left(\theta - \frac{a}{f_a}\right) G_i^{\mu\nu} \tilde{G}^i_{\mu\nu}$$

Kinetic term — Peccei-Quinn scale

If axion mass $\mathbf{m_a}$ = 0, $\mathscr{L}_{CP}$ is invariant for **$a \to a$ + constant**

$\to$ θ is "absorbed" in the definition of **a : $a \to a + f_a\theta$**

$\to$ θ disappears from $\mathscr{L}_{CP}$ which becomes $\mathbb{CP}$-invariant



Axion-gluon vertex induces axion – π^0 transitions

$\to$ axion – π^0 mixing

$\to$ axion acquires a mass and a coupling to hadrons and photons

The axion: exp. results

In the 1977 model :
(Peccei & Quinn, Weinberg, Wilczek)

$$m_a \approx 25 \text{ KeV}; \quad g_{a\gamma\gamma} \approx 3.5\times10^{-6} \text{ GeV}^{-1};$$

$$\tau_a[s] = \frac{3.3\times10^4}{g^2_{a\gamma\gamma}[\text{GeV}^2]\, m_a^3[\text{eV}^3]} \approx 150 \text{ s.}$$

→ **inconsistent with direct searches (e.g. : $K^+ \to \pi^+ + $ "invisible").**

modified models : many searches (both astro-physical and at colliders), some initial evidence, scarce evidence for anomalies;

→ **as of today, no real understanding.**

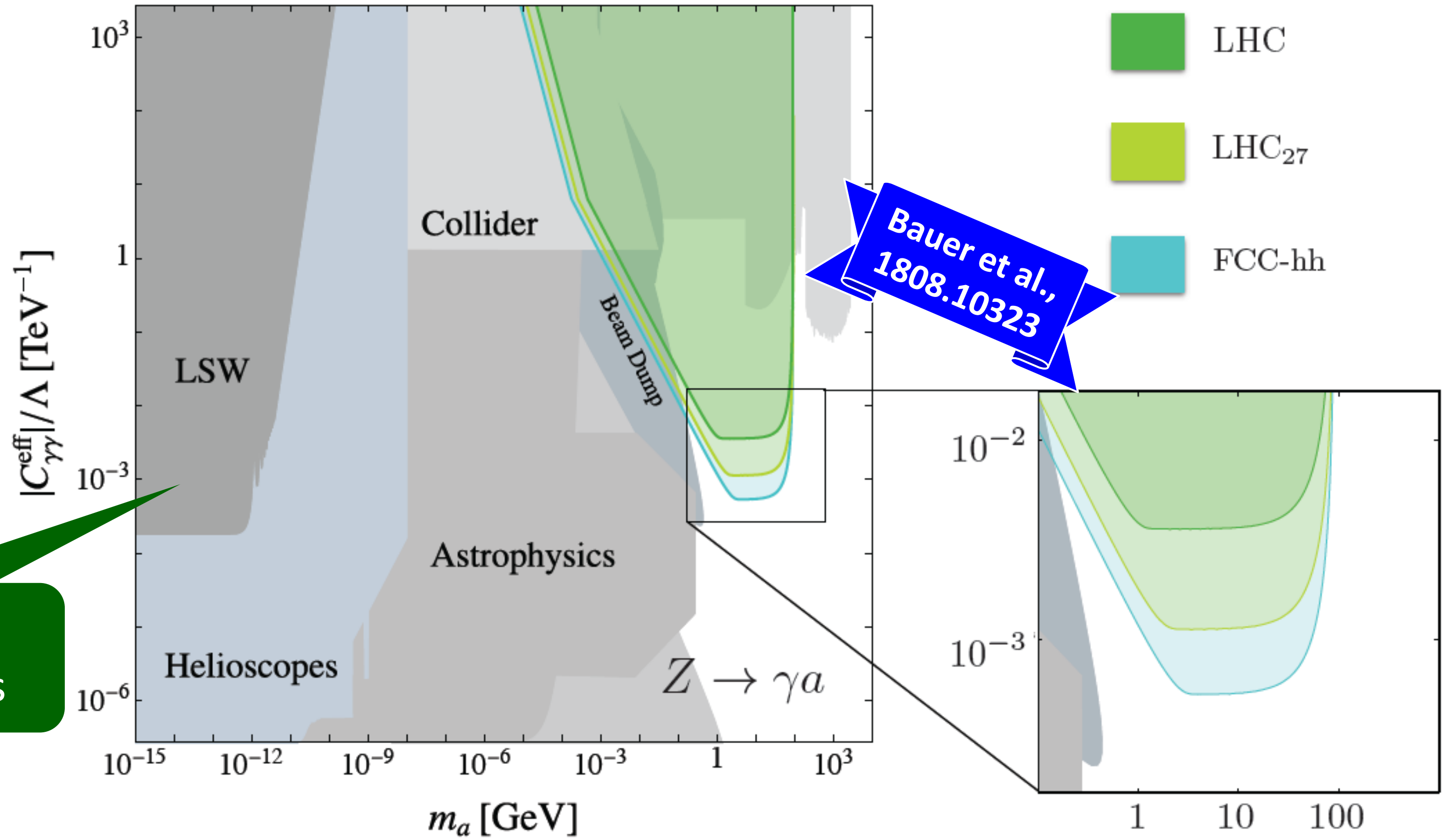
Conclusions (PDG 2020)

There is a strengthening physics case for very weakly coupled light particles beyond the Standard Model. The elegant solution of the strong CP problem proposed by Peccei and Quinn yields a particularly strong motivation for the axion. In many theoretically appealing ultraviolet completions of the Standard Model axions and ALPs [*axion-like particles*] occur automatically. Moreover, they are natural CDM [*cold dark matter*] candidates. Perhaps the first hints of their existence have already been seen in the anomalous excessive cooling of stars and the anomalous transparency of the Universe for VHE gamma rays. Interestingly, a significant portion of previously unexplored, but phenomenologically very interesting and theoretically very well motivated axion and ALP parameter space can be tackled in the foreseeable future by a number of terrestrial experiments searching for axion/ALP DM, for solar axions/ALPs, and for light apparently shining through a wall.

The axion: experimental searches (1)

Regions of search for "ALP"s in present and future accelerators in the plane m_a vs $(g_{a\square}/\Lambda)$, where Λ (as usual) is the "new physics scale" [LHC_{27} is a possible LHC @ 27 TeV and FCC-hh is discussed in this chapter].

The process is **$Z \to \gamma a$**. Different searches (LSW, solar- and astro-searches, colliders) are complementary. However, neither theory nor other exp. gives any hint on the scale of the (possible) discovery.



LSW:Light-Shining-through-Walls

The axion: experimental searches (2)

Similar plots for

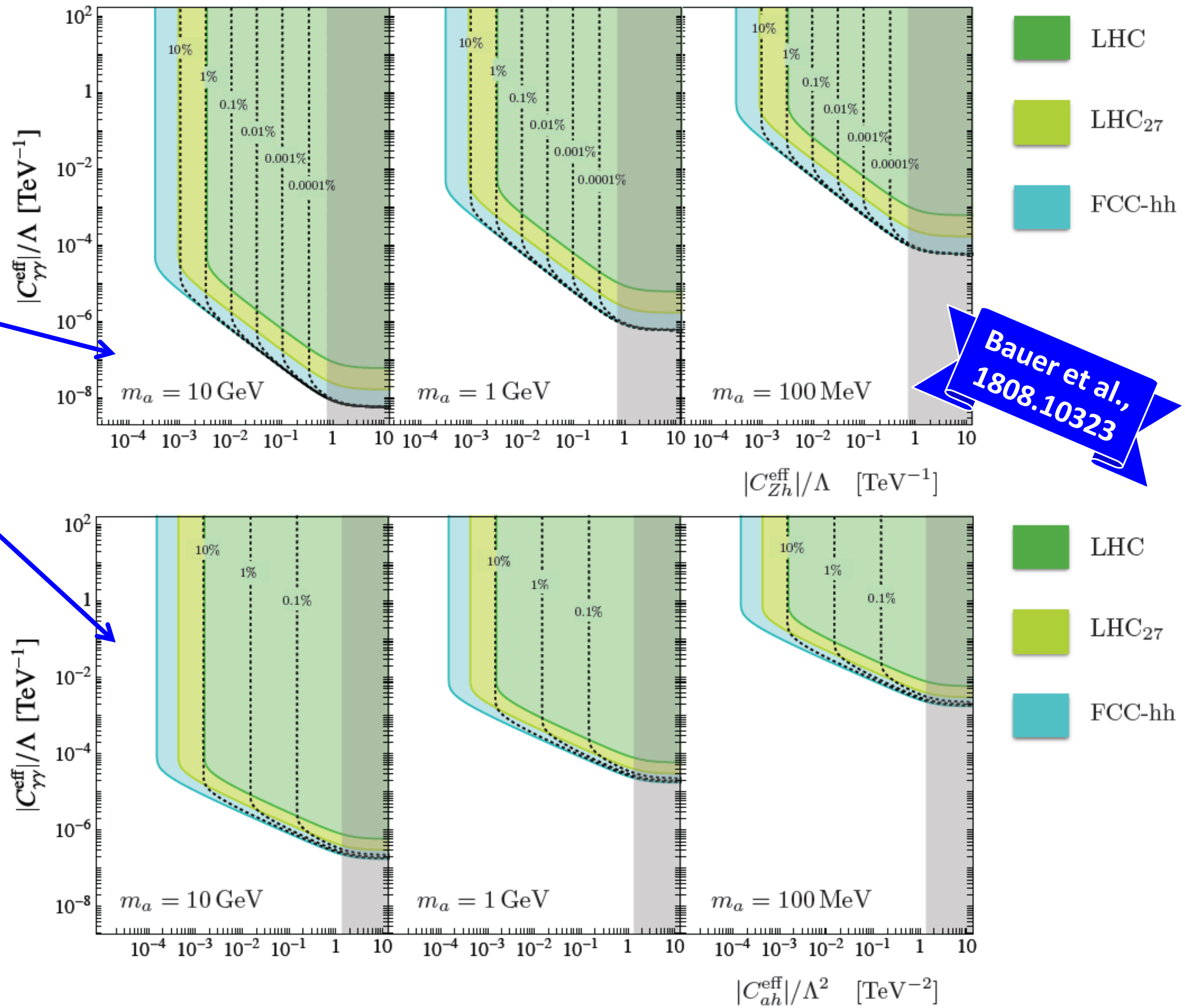
$h \to Za \to \ell^+\ell^-$□

and

$h \to aa \to$ □□

The plots assume BR(a□ γ)=1.

The dotted lines show the results for other values of the BR.



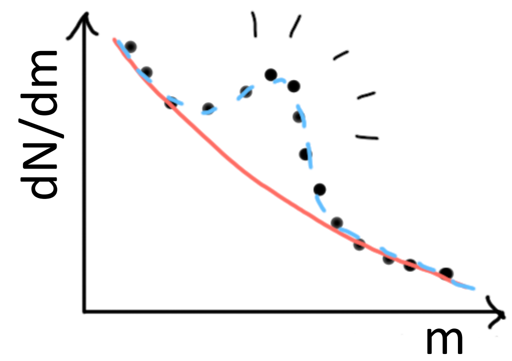
Bumps: the "signature"

The most typical signature in particle physics is a spike in the mass of some final state particles:

- the searches for J/ψ (Brookhaven), Υ (Fermilab), Z ($Sp\bar{p}S$), H (LEP/LHC) belong to this category;
- $W^{\pm}$ ($Sp\bar{p}S$), J/ψ (Spear), top (Fermilab), Z (LEP) are a modification of this method;
- any new data sample at LHC is always searched for a bump in $m(p_1\ p_2\ ...)$, where p_j are (some) final state particles;
- the "models" modify the selection: theoretical prejudices on a specific process decide the entry in the plot;
- E_T^{miss} is considered a (sum of) particle(s);
- jets are treated as the hadronization of quarks/gluons: after an attempt by UA2 and their use at LEP in the clean e^+e^- environment, at LHC they are used freely.

In the following, some examples (others shown before):

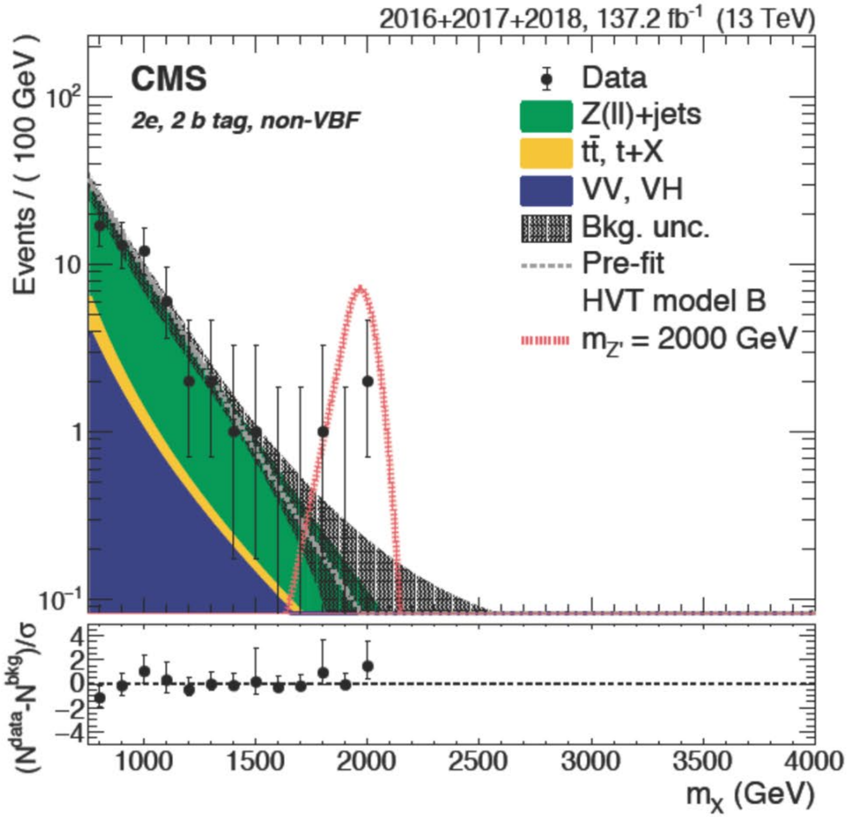
- a short lived particle shows up as a bump in the mass of its decay products;
- lots of limits, but no discovery (yet);
- the yield of a hypothetical particle is strongly correlated to $\hat{s}$ (therefore to s) and $\mathcal{L} \rightarrow$ analyses frequently improved;
- [*therefore many papers are repetitive, a simple update of previous ones*].

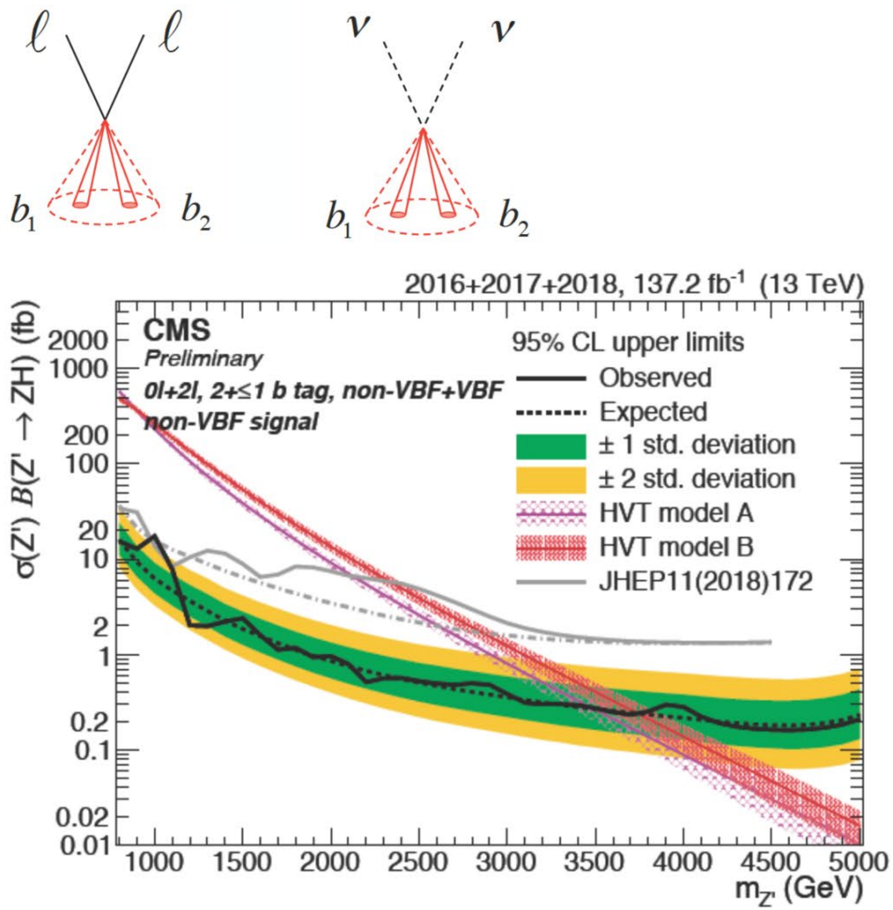


Bumps: the quest for Z' (1)

CMS looking for $Z' \to ZH$ using HVT (Heavy Vector Triplet) models [*your opinion on the "bump" at 2 TeV ?*]

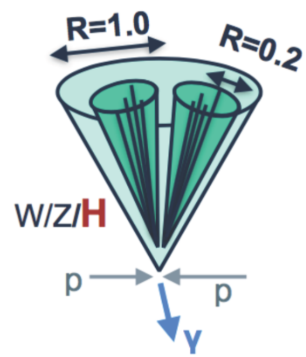
(V. Cavaliere, Prague 2020).

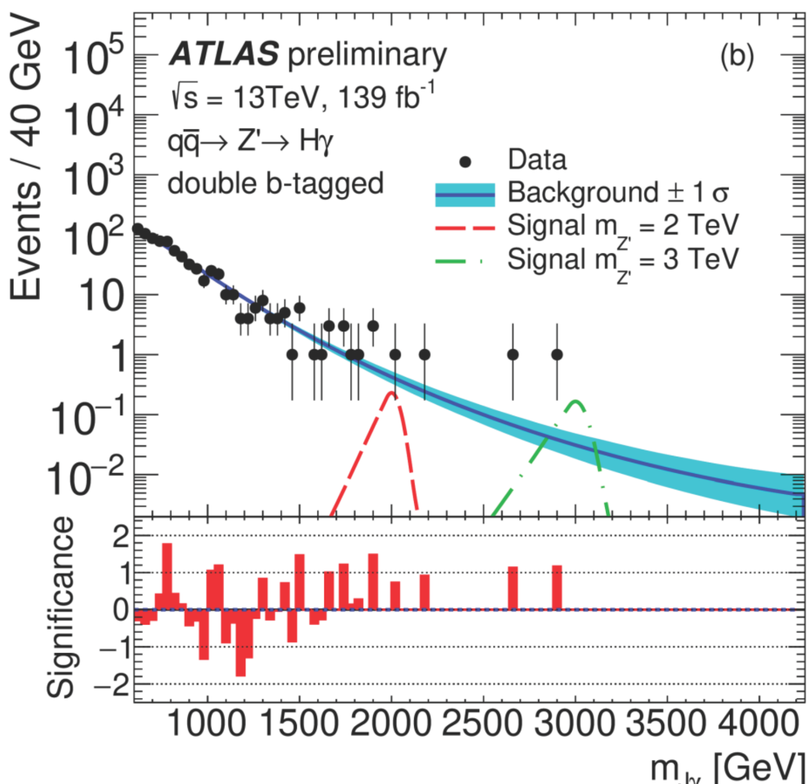


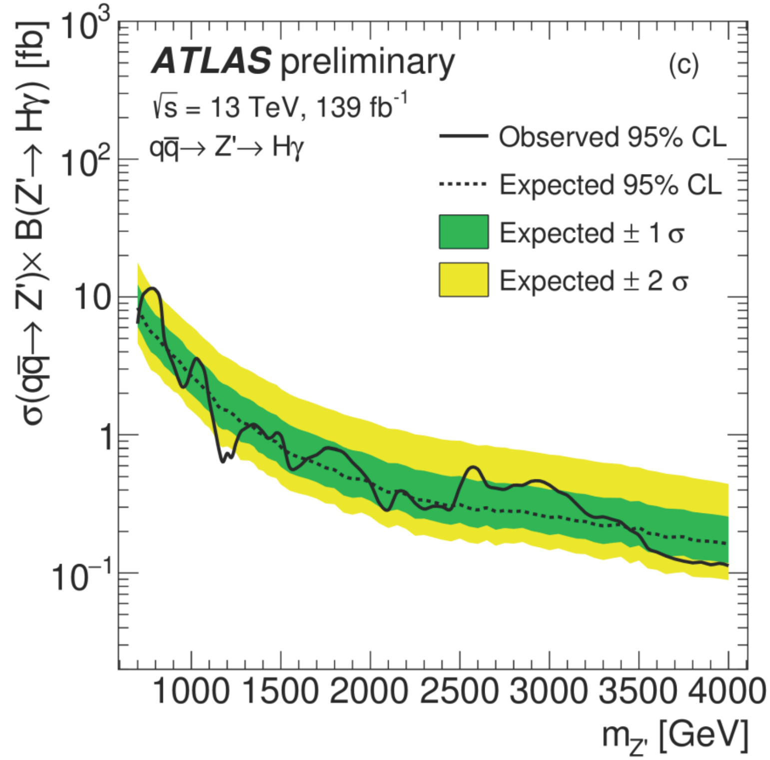


Bumps: the quest for Z' (2)

... and ATLAS looking for Z' → Hγ
(V. Cavaliere, Prague 2020).





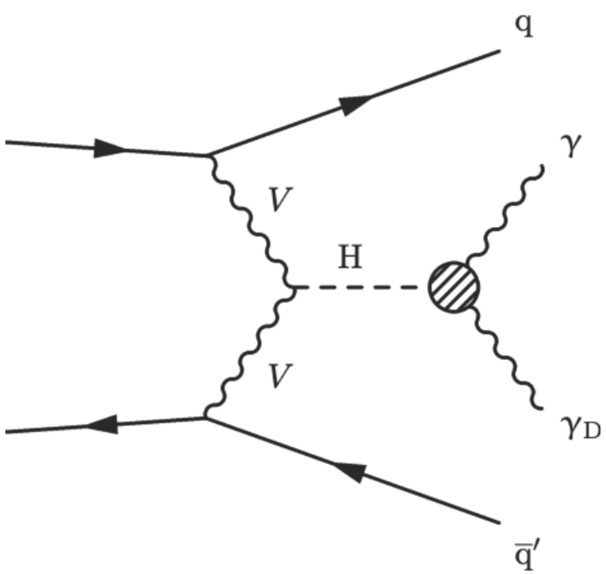


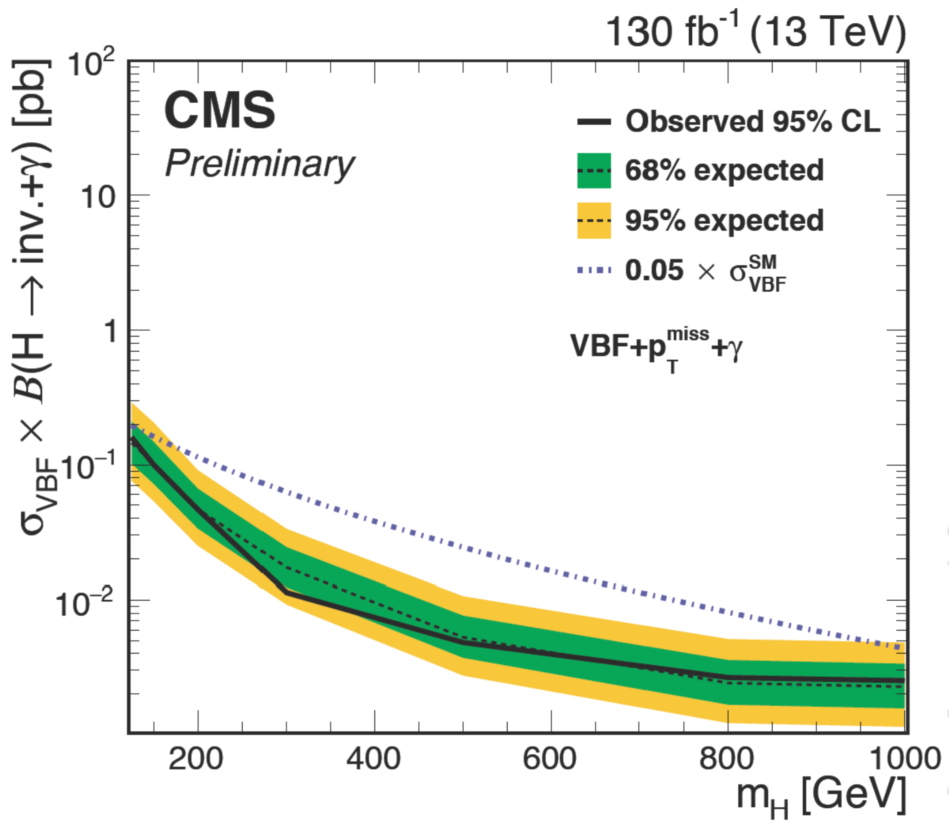
Bumps: a dark Higgs decay

CMS looking for extended Higgs sector in events with $\gamma_{visible}$ + E_t^{miss} ("γ_D" is a "dark photon", also a candidate for DM).

They find: $Br(H \to \gamma X_{dark}) < 2.9\%$ @ 95% CL; and also look for a high mass Higgs;

(V. Cavaliere, Prague 2020).





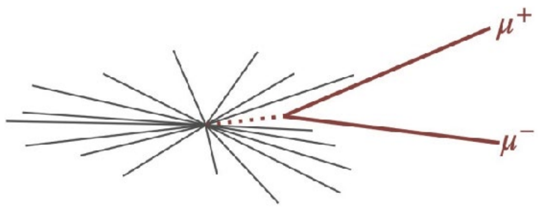
Bumps: the quest for a hidden valley

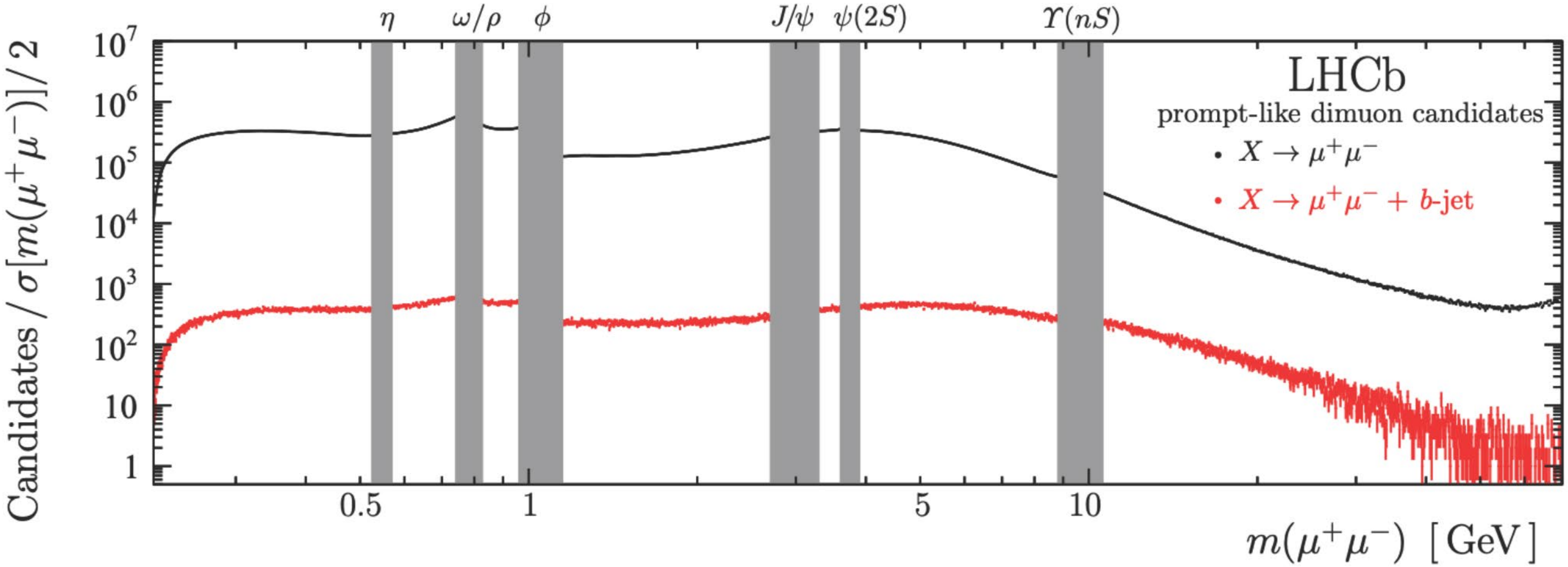
LHCb looking for $X \to \mu^+\mu^-$ and $X \to \mu^+\mu^- b$. (V. Cavaliere, Prague 2020).

Notice the normalization (σ = mass resolution, 0.6 MeV @ m = 200 MeV, 600 MeV @ m=60 GeV).

Regions with known particles are excluded.

They are looking for resonances from displaced pointing" (see sketch) in an "hidden valley" scenario.





Compositeness

[*my favourite subject, you know*]

In the XX century the progress of "elementary" particle physics has been driven by the discovery of the actual compositeness of a supposed pointlike state.

Why not look for that mechanism again ?

The discovery is model independent, experiment driven, energy dependent (better, p_T dependent).

The experiments are simple (at least in principle) and, if successful, tell us the truth: who is the "guilty" particle and which is the scale of compositeness.

Which is the "suspect" particle ?

[*composite Higgs models are important, but have nothing to do with the present discussion*]

If history is of any help, the **quarks**.

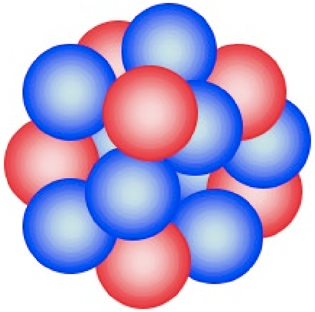
Which is the process to look for ?

- at fixed $\sqrt{\hat{s}}$, the two-jet angular cross-section should be "flatter" than QCD;
- at some large value of Λ (= 1/scale), the mass ($\sqrt{\hat{s}}$) distribution should deviate from QCD predictions.

The obvious kinematical variables are:

$$\chi = \frac{\hat{u}}{\hat{t}} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$ [the angular variable χ];

$$m_{jj} = \sqrt{\hat{s}}$$ [the two jet-mass in $2 \to 2$ processes];



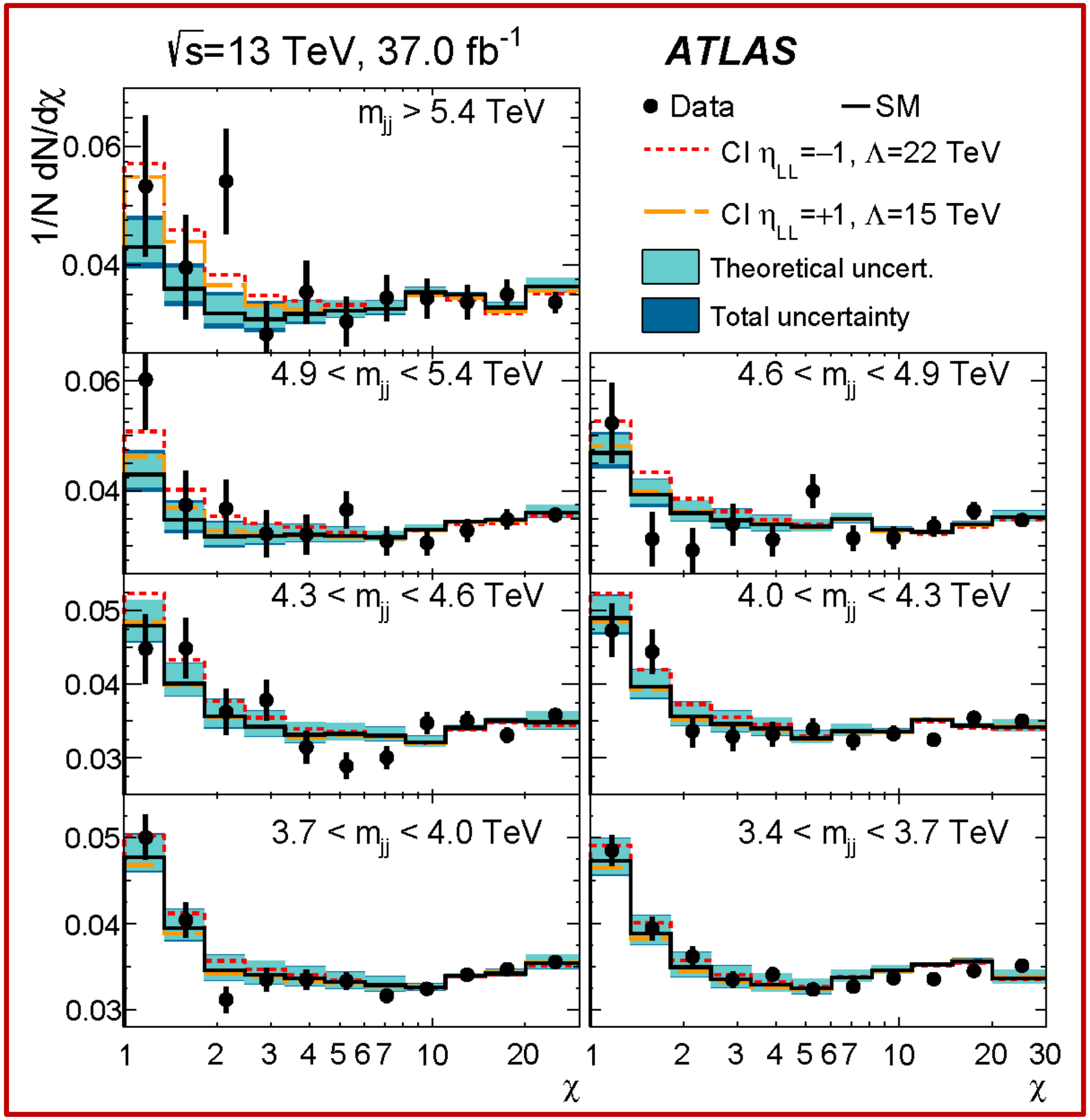
Compositeness: $d\sigma/d\chi$

$d\sigma/d\chi$ in bins of m_{jj} from ATLAS at $\sqrt{s}$ = 13 TeV [Phys. Rev. D 96, 052004 (2017), also PDG 2020].

- data compared with QCD for different values of scale Λ;
- clearly no discrepancy up to highest probed m_{jj} (= $\sqrt{\hat{s}}$);
- i.e. no deviation from point-like behavior;
- translate to limit on Λ $^{(*)}$;
- and → higher energy;
- ... which in qpm language, can also mean → higher $\mathscr{L}$ (!).

———

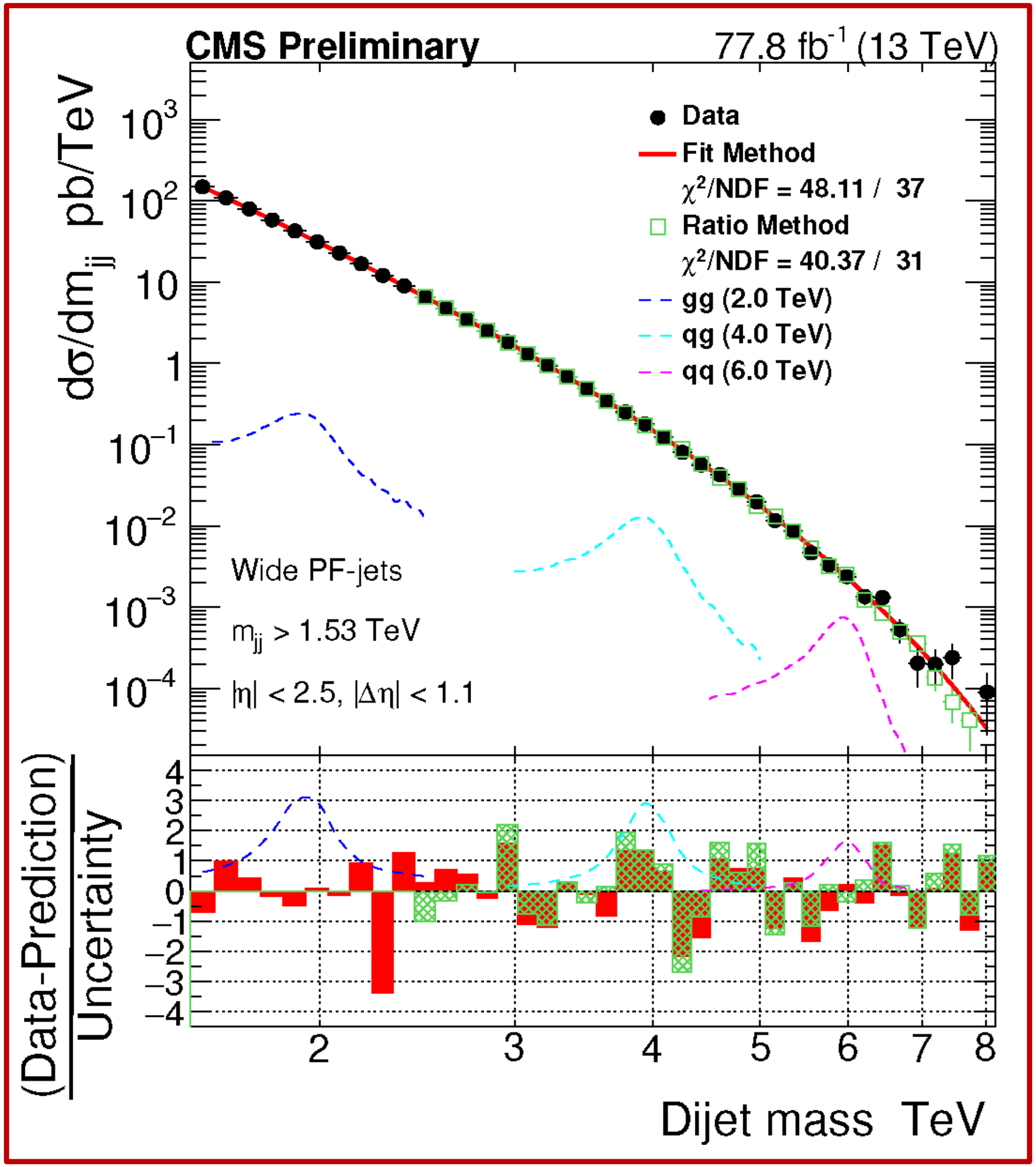
$^{(*)}$ the dynamics of the components is obviously unknown; so more than one model is used to parametrize them (the "CI").



Compositeness: $d\sigma/dm_{jj}$

$d\sigma/dm_{jj}$ from CMS at $\sqrt{s}$ = 13 TeV [CMS-PAS-EXO-17-026 (2018), also PDG 2020].

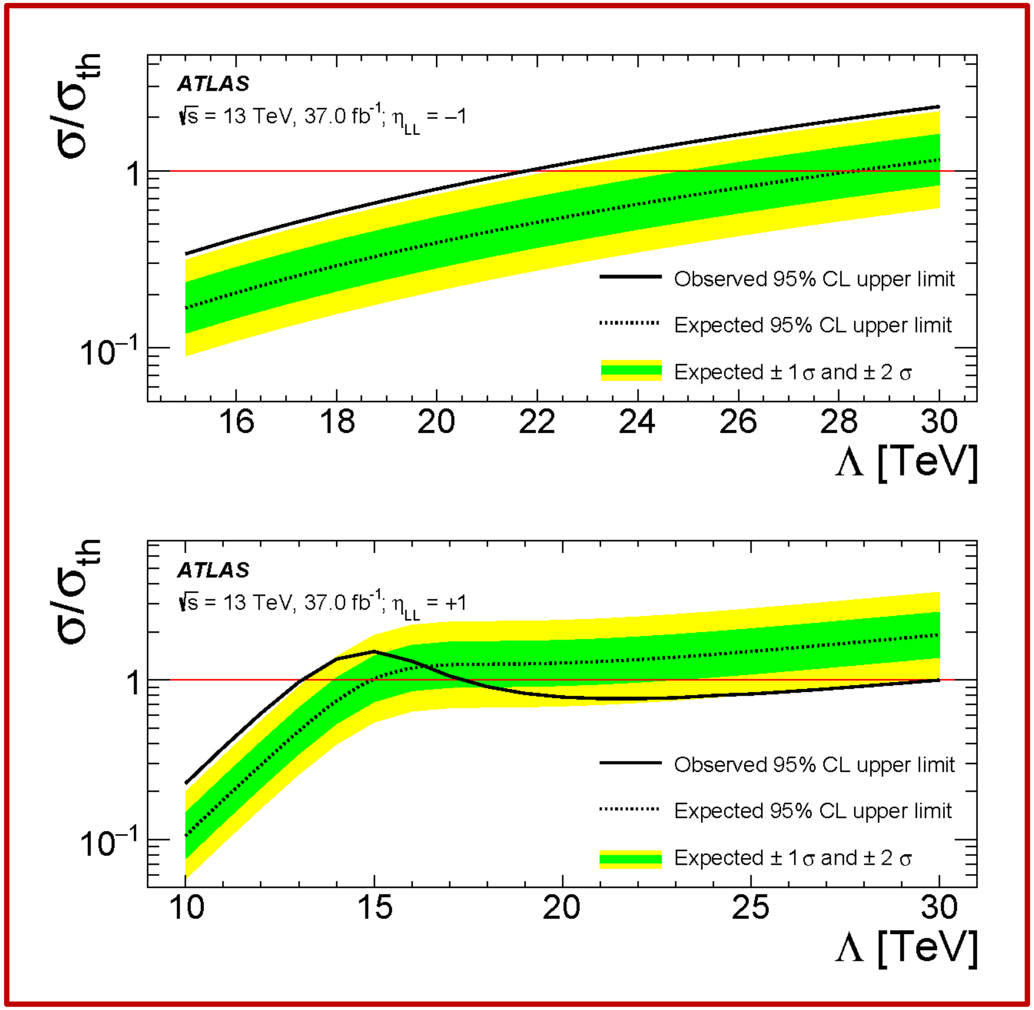
- data compared with QCD and resonances (e.g. $q^* \to qg$) in some bSM models;
- ... same comments as in the ATLAS case



Compositeness: limits on Λ

Computation of limits on Λ from ATLAS [op. cit.].

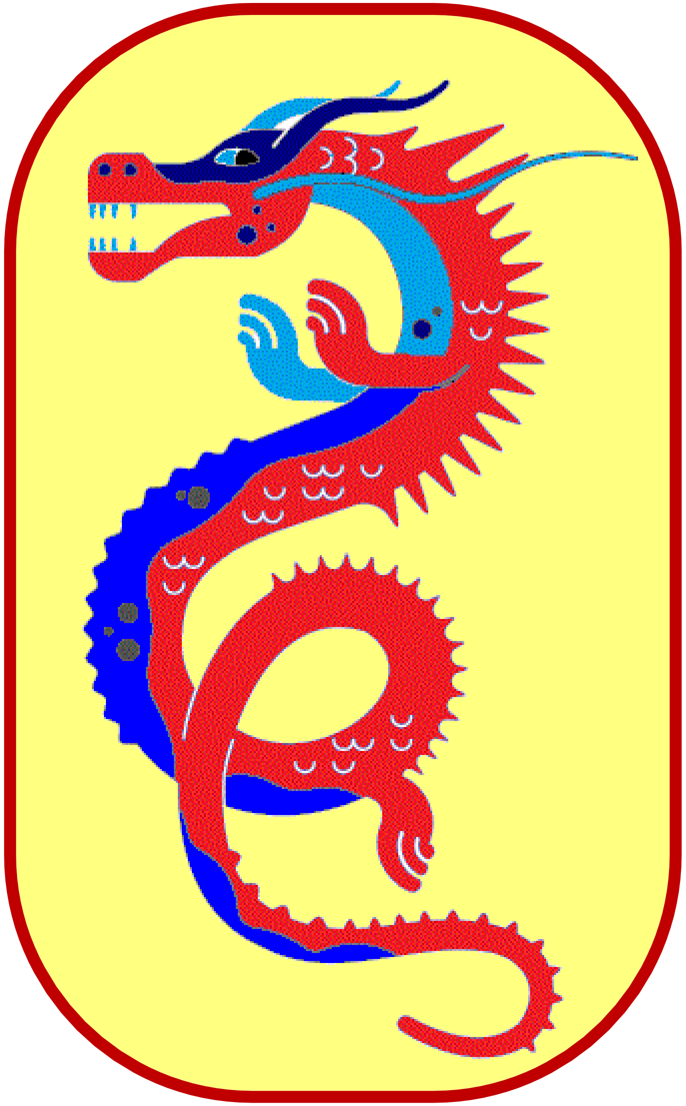
- σ/σ_{theory} is the parameter "μ", already defined;
- when the "observed" line is below μ=1 (red line), the theory (= this value of Λ) is excluded at 95% CL;
- i.e. Λ < 13 TeV is excluded in a wide range of models;
- notice that a value of Λ can be tested at $\sqrt{s} < \Lambda$ (and the typical value of $\sqrt{\hat{s}}$ is much lower);
- exclusion improves with $\sqrt{s}$ and $\mathscr{L}$ [*find a simple law*], so usual comment: → higher energy / luminosity.



Summary

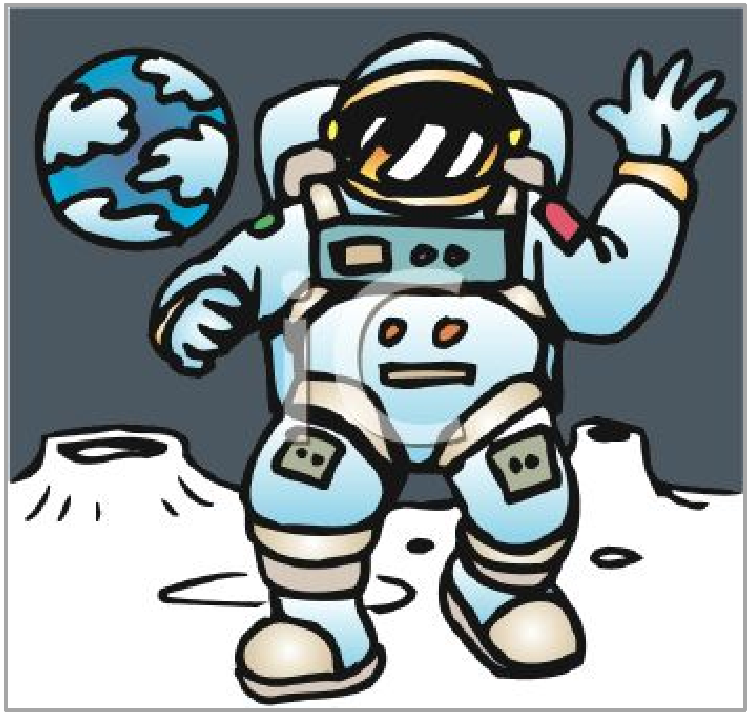
Imho the best summary of the present searches is from **J.Iliopoulos** & **T.Tomaras** at the end of their book:

This chapter does not present a generally accepted doctrine. It contains exploratory ideas and research which is still in progress. The reader should be particularly critical. It is true that no model among those we have studied so far imposes itself on the grounds of experimental support or aesthetic beauty, which means that, most probably, none is the right one. So far, they offer at best only partial answers to the questions we formulated in section 23.1. However, they all contain interesting and intriguing ideas and we believe that, embedded in a future scheme, they may be part of the actual theory beyond the Standard Model. The really puzzling fact is that LHC sees no sign of new physics, despite the fact that all the arguments we have presented indicate that such signs should already have been visible.



Conclusions

- This chapter is not exhaustive;
- its objective is to give a (preliminary and rough) idea of the analyses performed at LHC;
- just to give some statistics, my exp. (ATLAS) has published >1000 papers,
- … > ⅓ of them in physics bSM:
  - including non-MSM Higgs-es;
  - … and also the majority of SM papers was actually on bSM searches (e.g. the κ-modifiers determination);
  - [*I did not check CMS, but must be similar*];
- in future, the fraction of papers bSM will likely increase, because those subjects benefit more by the increase in energy/luminosity;
- the fraction of people which works on physics bSM will also increase (I mean YOU).



ii. Future tools

New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained.

Freeman Dyson

The searches bSM require new ideas, but also new experimental tools, both detectors and colliders. The physics community is facing the problem …

Introduction

- Today we have a consistent picture of the physics landscape, (almost) all the observables fitting in the SM framework.
- Both the precision measurements and (more important) the developments in detectors and accelerators have the physics bSM as their real objective.
- It is appropriate to end the chapter with a quick review of the developments in these fields and a brief discussion of next years' operations.
- HL-LHC is a special case: already approved and financed, a "modest" upgrade of the present LHC; it will be treated in the "next years" section.
- For long term projects, the major laboratories used to have a detailed and "iron-made" schedule [*but SSC* ?], a necessary bridge among money (from politics), civil engineering, detector construction, people planning, ...
- ... however the pandemics has provided a dramatic perturbation.
- The present plans are far from being frozen, even though the high-energy planning could be used as an example for long-term schedules in other fields.
- The slides are written in mixed-mode [*sorry*]: sometimes I give the "pre-covid" schedule and sometimes a plausible hypothesis of the current evolution ...
- ... not in the mood of "*how good the ole time was*", but to give a reasonable time scale of the future projects ...
- **... and to help you programming your future.**

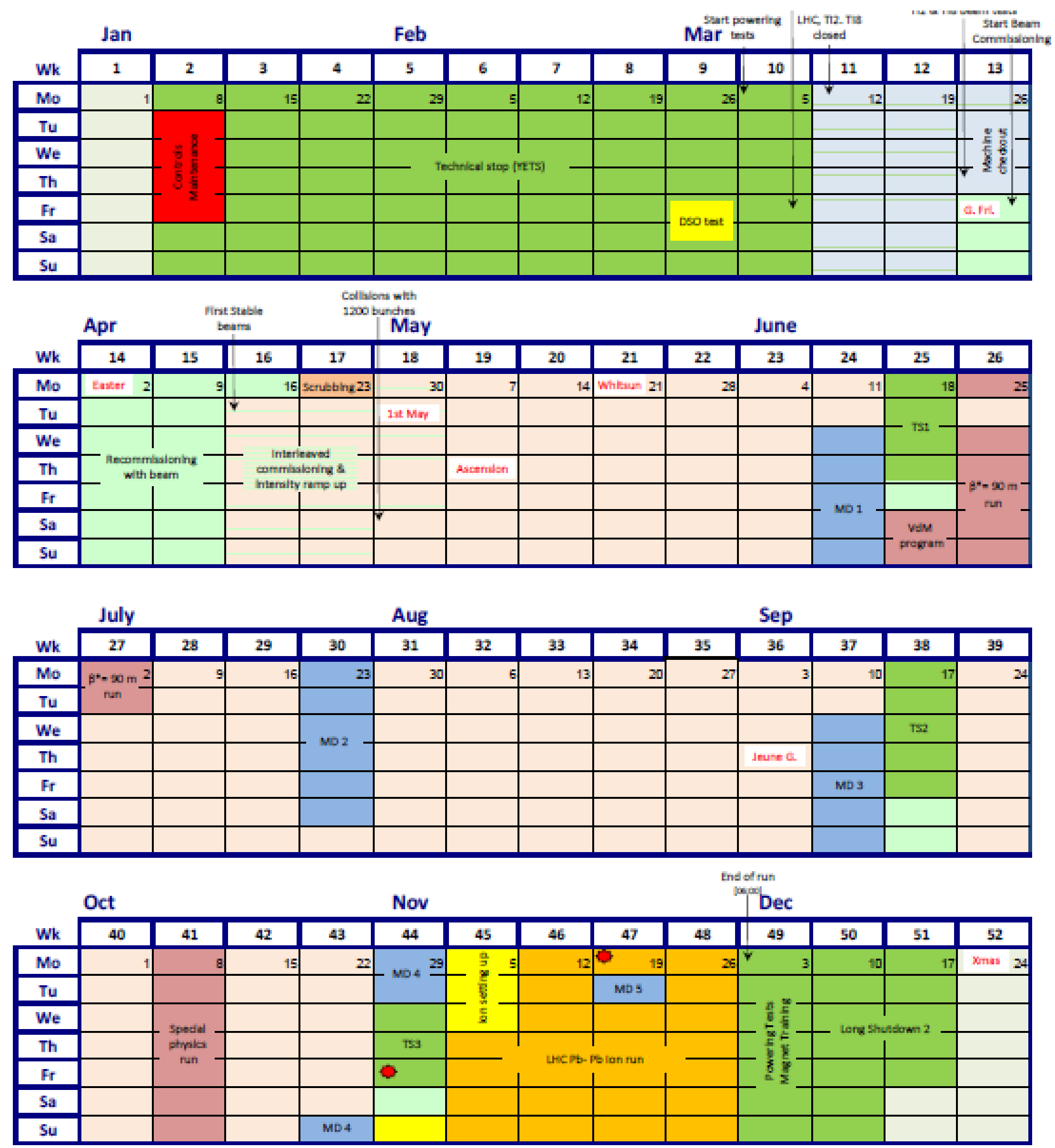
LHC next years: a standard year (2018)

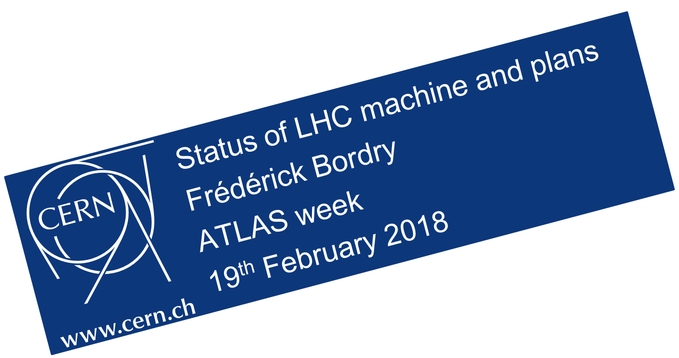
LHC schedule 2018

(the last year of operations before LS2, see later)

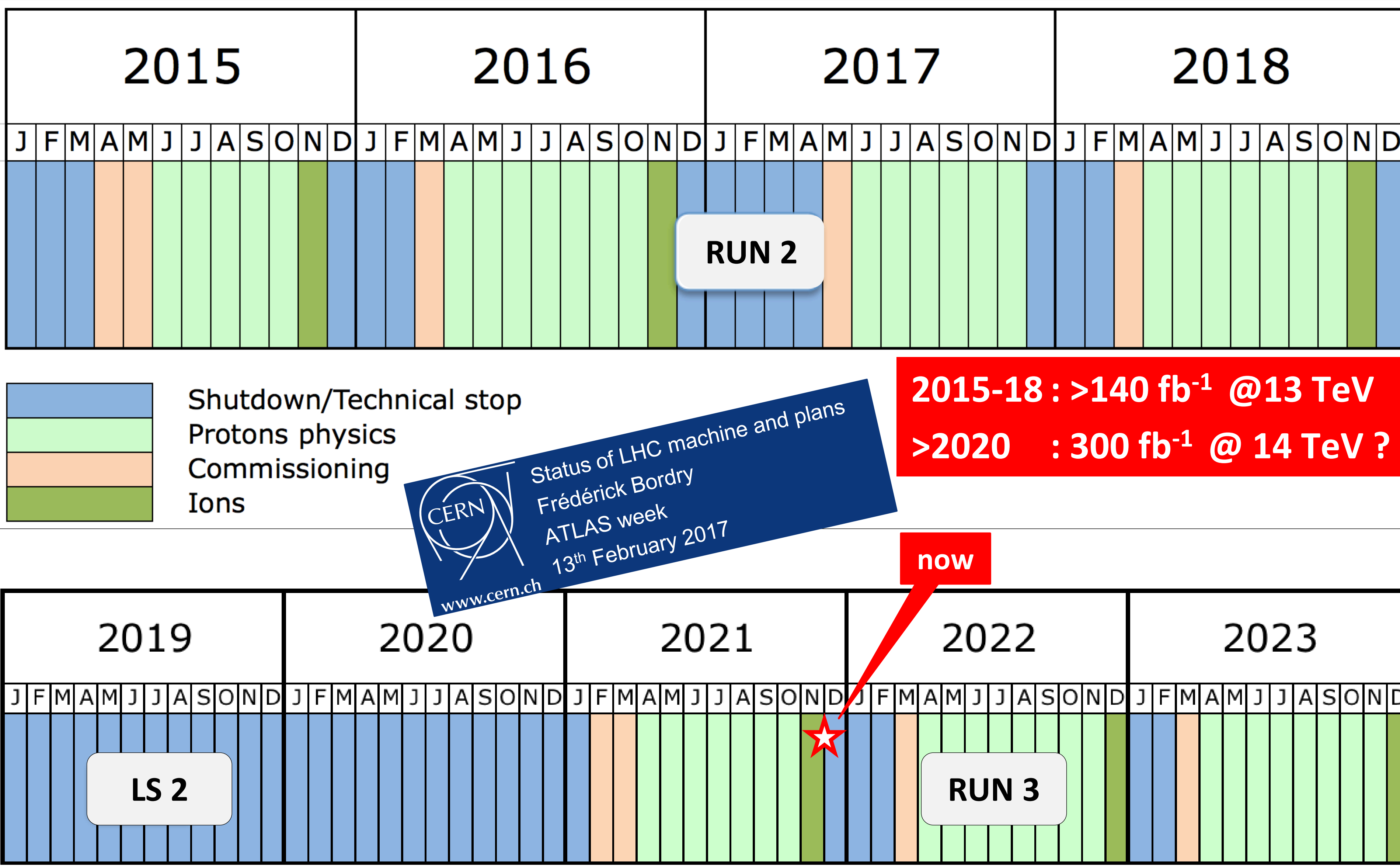
$> 65\ fb^{-1}$

keeping the LHC availability close to 50% (stable beams)





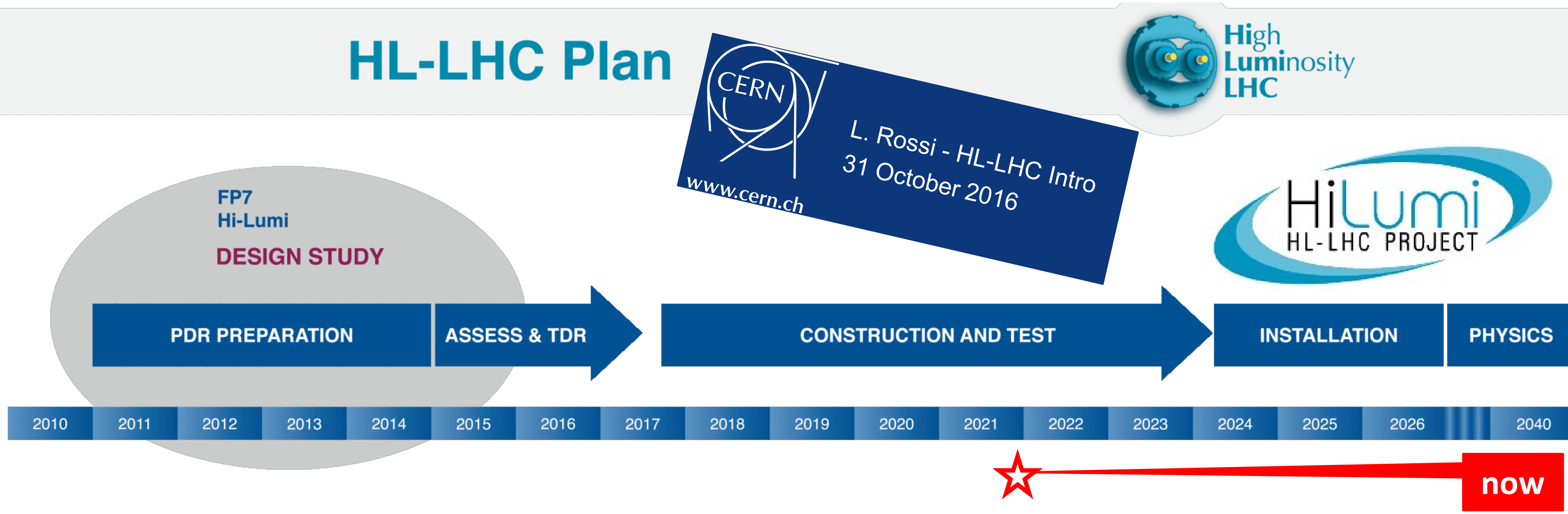
LHC next years: pre-covid schedule 2015-2023



2015-18 : >140 fb^{-1} @13 TeV

>2020 : 300 fb^{-1} @ 14 TeV ?

LHC next years: pre-covid HL-LHC - 1



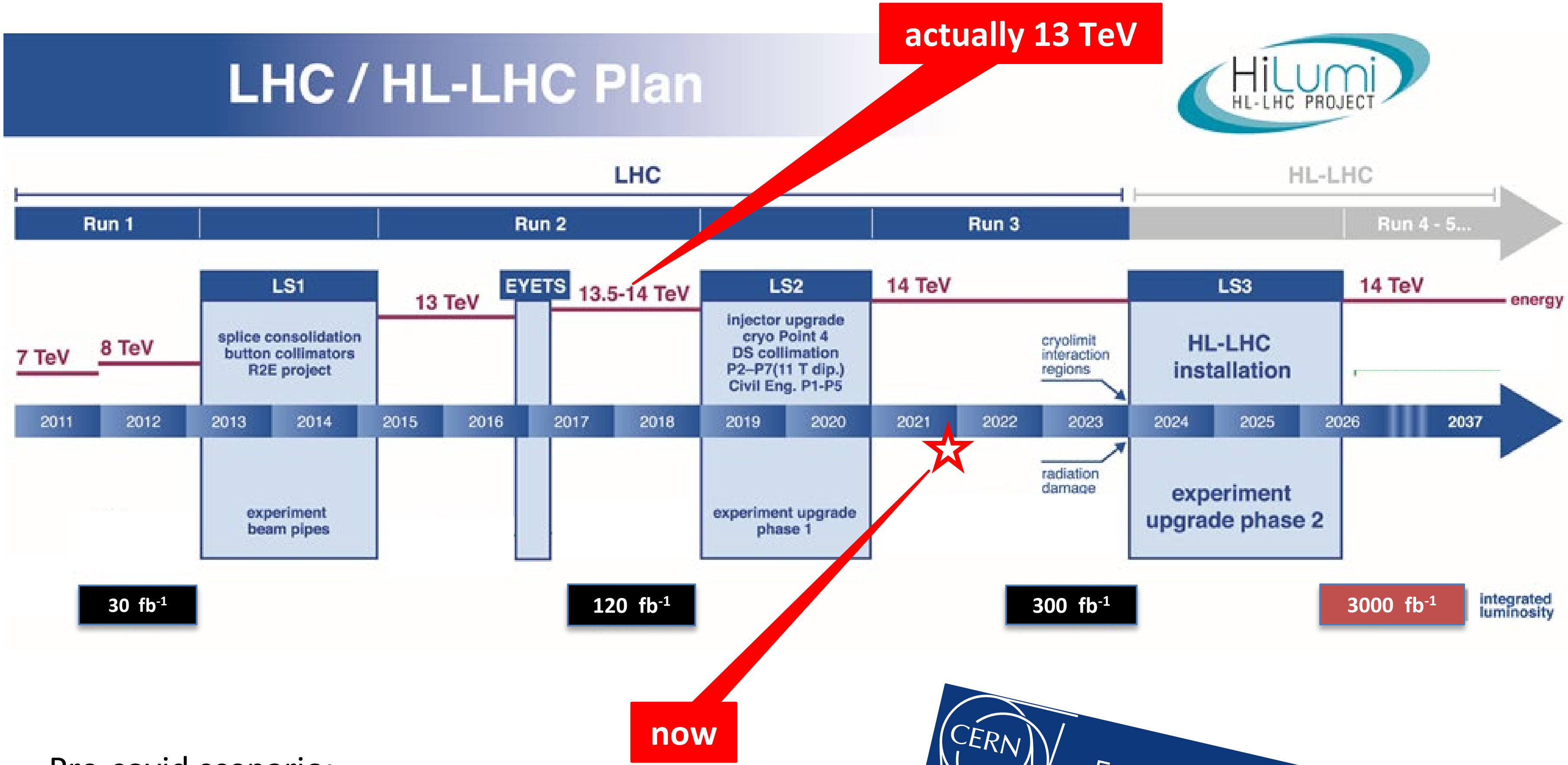
- March 2016: HL-LHC included in the ESFRI (European Strategy Forum on Research Infrastructures) roadmap as "landmark project" in March 2016.
- June 2016: HL-LHC project formally approved by CERN's Council.

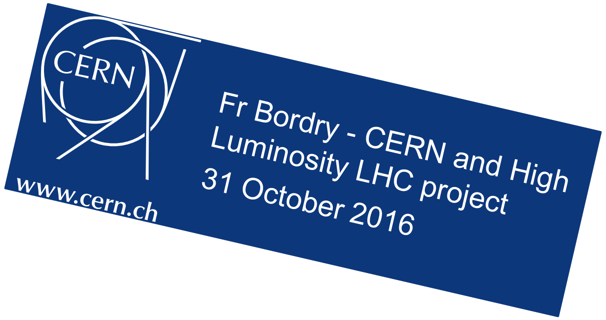
- "Full exploitation of the LHC physics potential with the HL-LHC phase is the top priority of the ESPP [*European Strategy for Particle Physics*] and the highest near-term large-project priority of the US P5 roadmap."

  "LHC/HL-LHC is CERN's flagship project for the next 20 years."

  [Fabiola Gianotti, CERN's Scientific Strategy, ECFA HL-LHC Experiments Workshop, Aix-Les-Bains, 3/10/2016].

LHC next years: pre-covid HL-LHC - 2



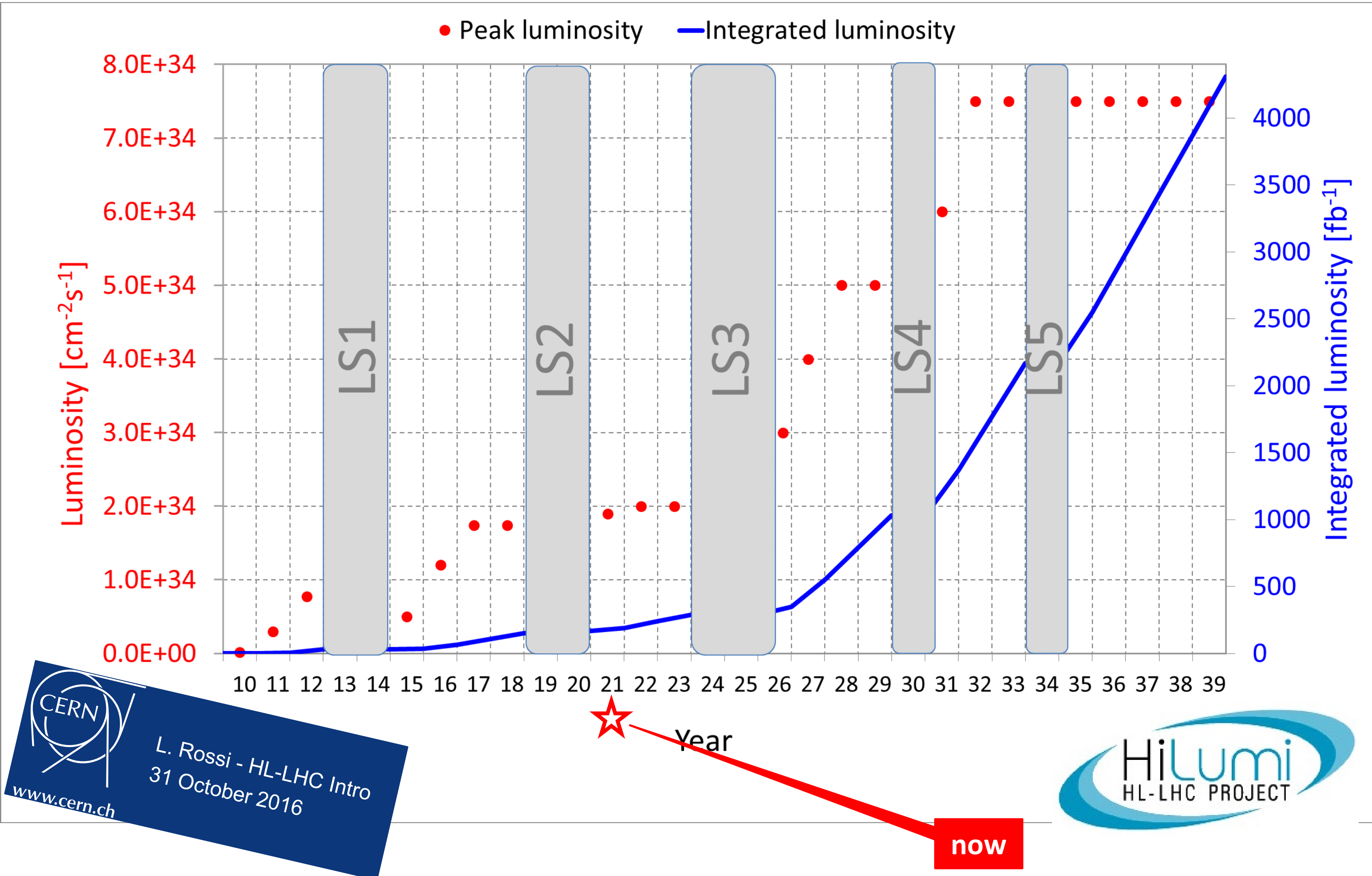


Pre-covid scenario:

- 2021-2023 run @ 14 TeV, $\mathscr{L}_{int} \approx 300$ fb^{-1};
- 2024-2026 install HL-LHC;
- 2026-2040 (?) run @ 14 TeV, $\mathscr{L}_{int} \approx 3000$ fb^{-1};

["EYETS" = Extended Year End Technical Stop, i.e. a lot of refurbishments/upgrade during winter time]

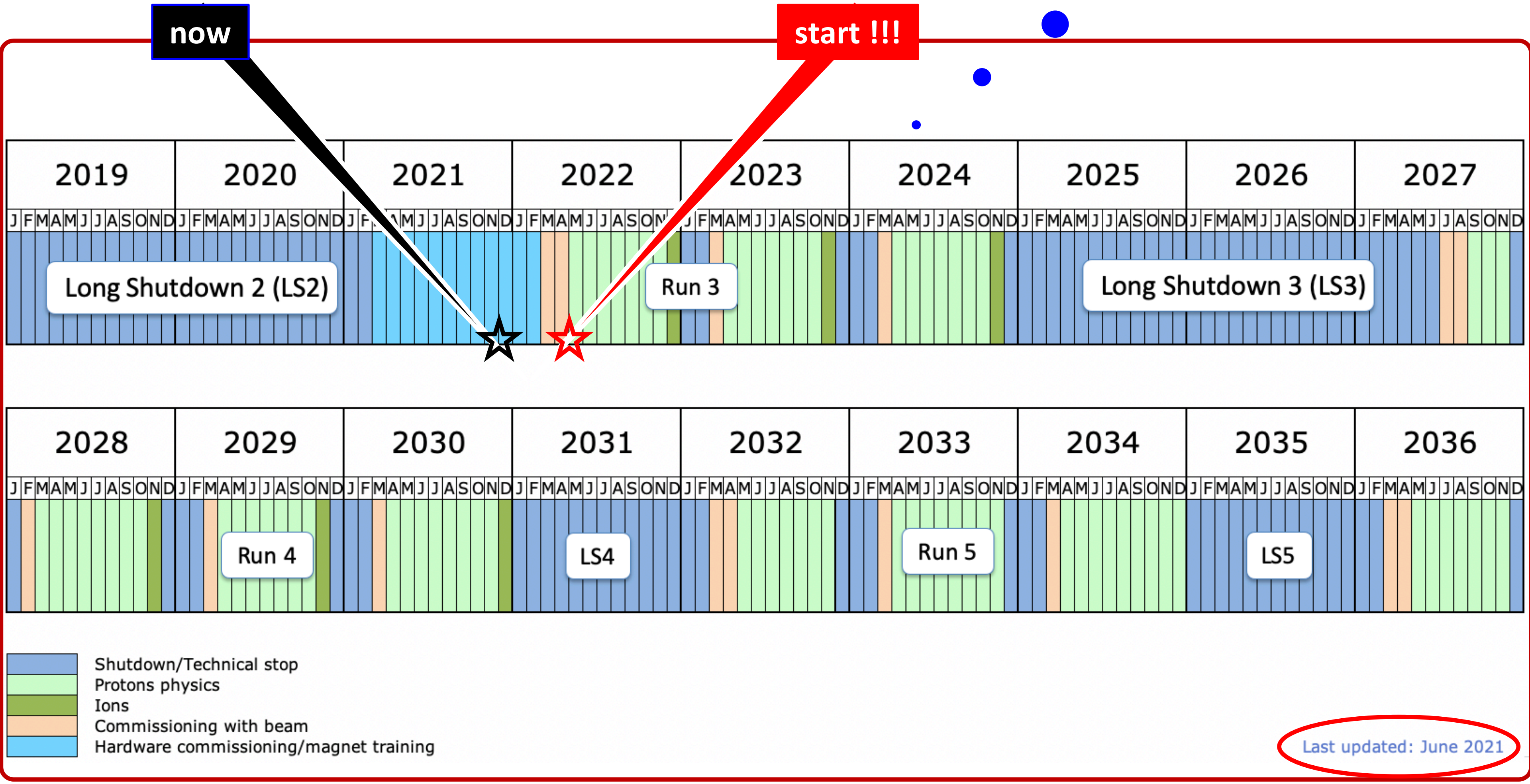
LHC next years: pre-covid HL-LHC - 3



LHC next years: the present schedule

the pandemics produced unavoidable delays, but no major problem – eventually the delays are attributed to it, but, frankly speaking …

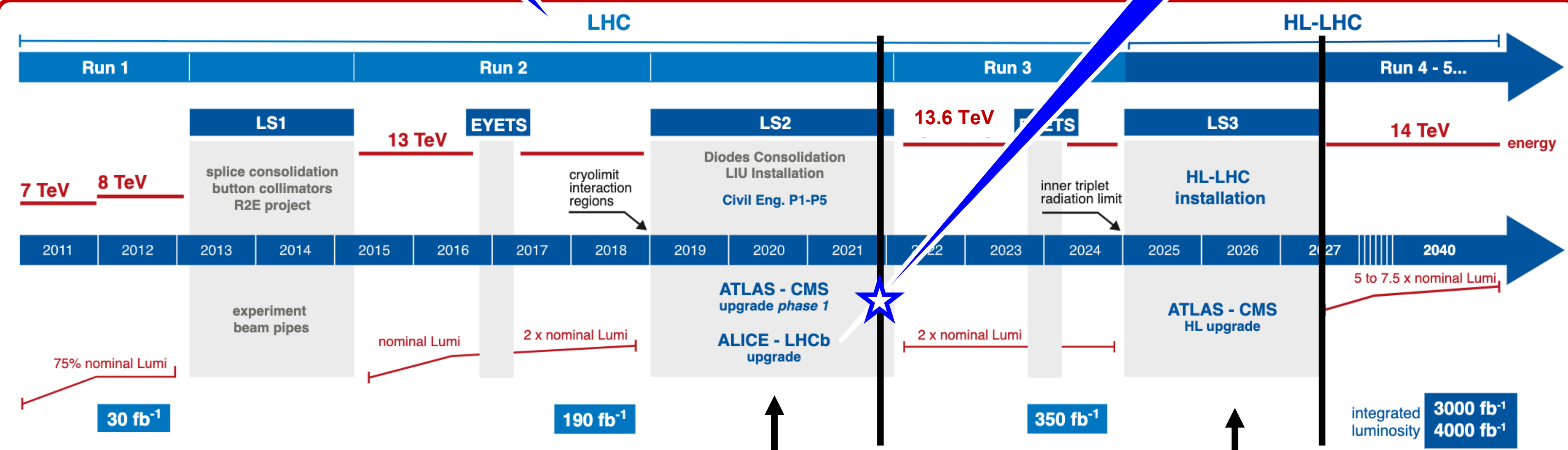
… not a dream , but a solid program



LHC next years: the present view

Fabiola Gianotti on 14/10/2021,

now



LS2

LHC Injectors Upgrade (LIU) completed

Excellent performance of upgraded injectors at restart

(HL-LHC parameters already achieved in some cases)

Phase-1 upgrades: major for LHCb and ALICE

(→ x 5 integrated luminosity in Run 3 than Run 2)

LS3

Installation of HL-LHC machine

Phase-2 upgrades of ATLAS and CMS

Start and duration will be re-assessed end of year

Future projects

The construction and commissioning of a state-of the-art collider is long and expensive (both 💰 and 🛠️):

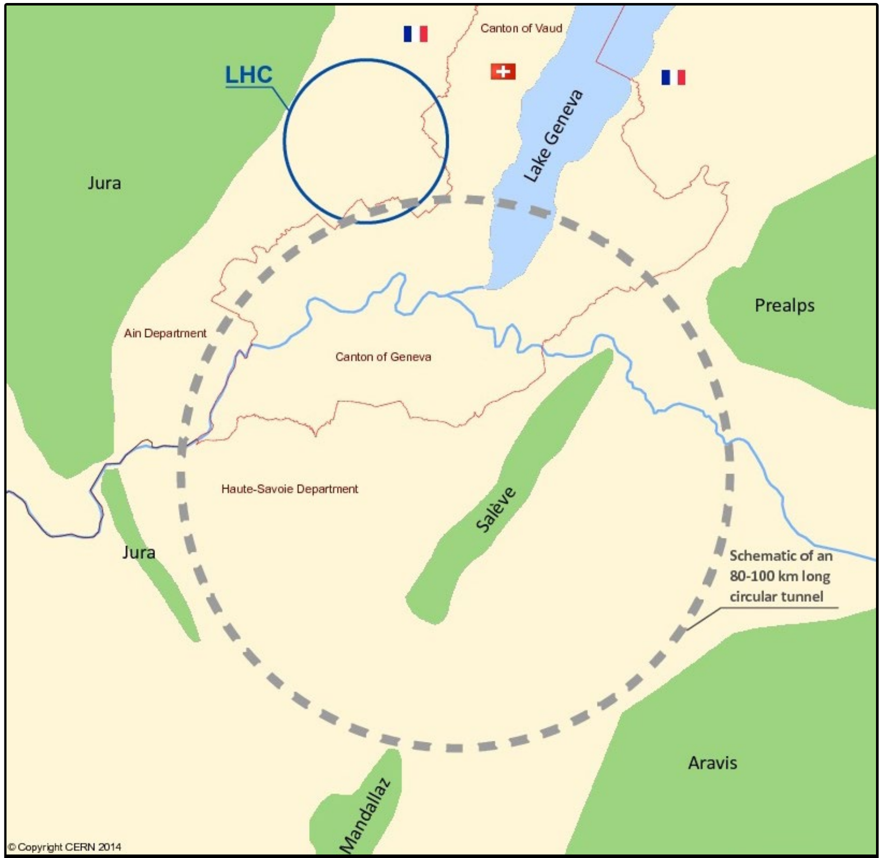
- The "European Strategy for Particle Physics" is a process for the decision ...
- ... together with a discussion worldwide, since everybody knows that the accelerator construction and exploitation must be a common effort.
- Proposals were sent in by the end of last year and selected presentations were given in Spring 2019.
- A summary document was prepared by September 2019 and has been approved by CERN council in May 2020.
- As of today, no project has been launched (= financed), but a decision is expected in the next few years ...
- ... since the construction effort will require O(10 year), and we [= *you*] want the new machine for the end of HL-LHC.
- In other words, between now and (say) 2025 the community will make the choices that will drive all the operations until (say) 2060.
- The choices are not strictly exclusive, but money and resources are scarce, so there is little margin for duplication (or mistakes).
- The slides present a fast and superficial review of the options; some are missing (sorry), refer to the references.

Future projects: FCC

FCC : **Future Circular Collider**, a CERN project of a circular ring 80-100 km;

… split (à la LEP/LHC) into several phases, obviously staged:

1. **FCC-ee**: e^+e^- at $\sqrt{s}$ = 90-350 GeV;
2. [lower energy versions of next phase;]
3. **FCC-hh**: pp at $\sqrt{s}$ = 100 TeV (+ ions);
   - dedicated to high-precision measurement of the Higgs parameters (similarly to the Z at LEP);
4. **FCC-he**: ep option, possible but not compulsory (LEP/LHC did not go through it, but there was HERA);
   - dedicated to model-(in)dependent searches for physics bSM;
5. … and then possibly restart the cycle in a new ring …

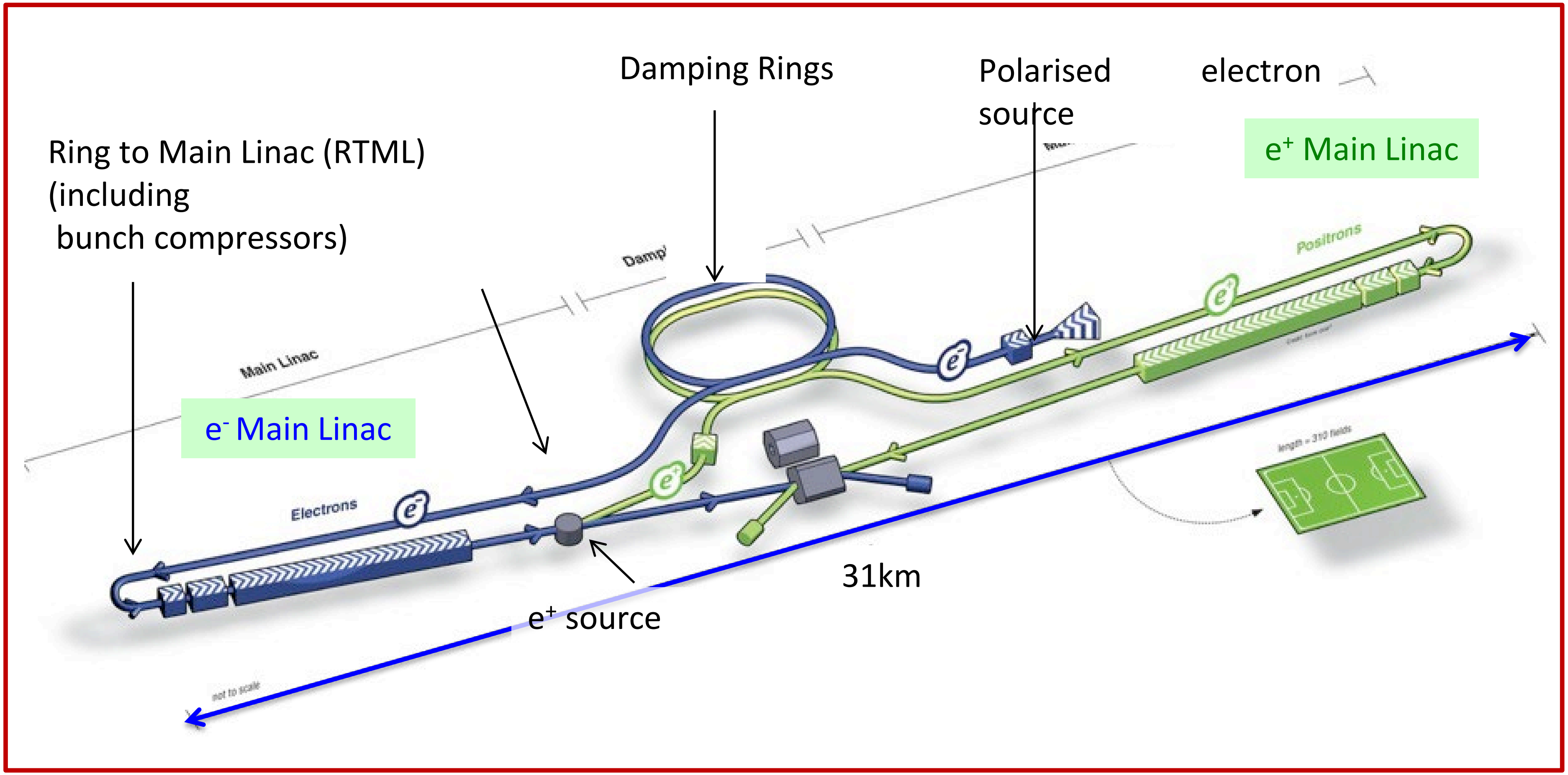


just a possibility: site still not defined

Future projects: ILC

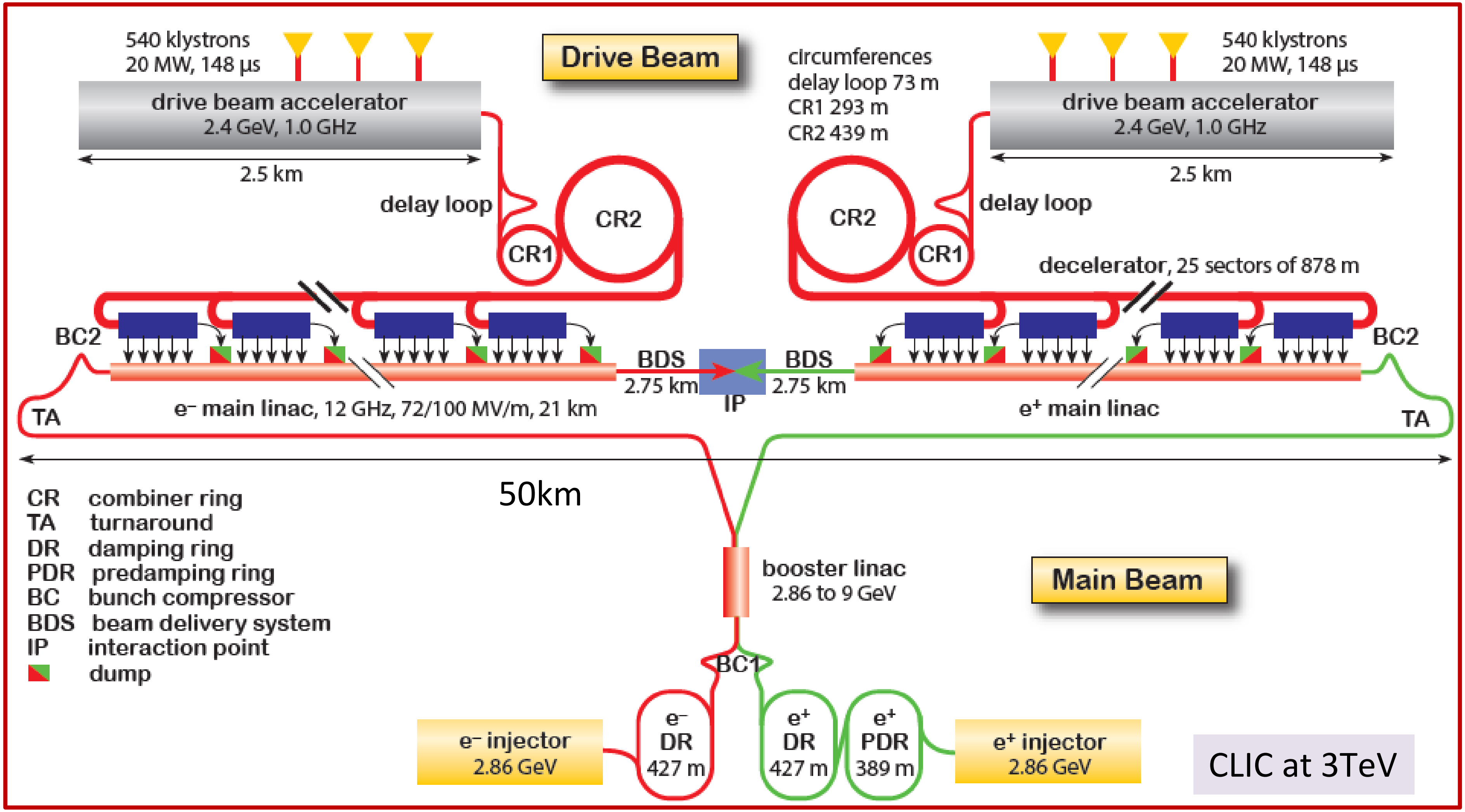
ILC: **International Linear Collider**, e^+e^- at $\sqrt{s} = 250$ GeV.

The project was developed at CERN by a large collaboration, Japan considers hosting it in Kitakami, Tohoku.



Future projects: CLIC

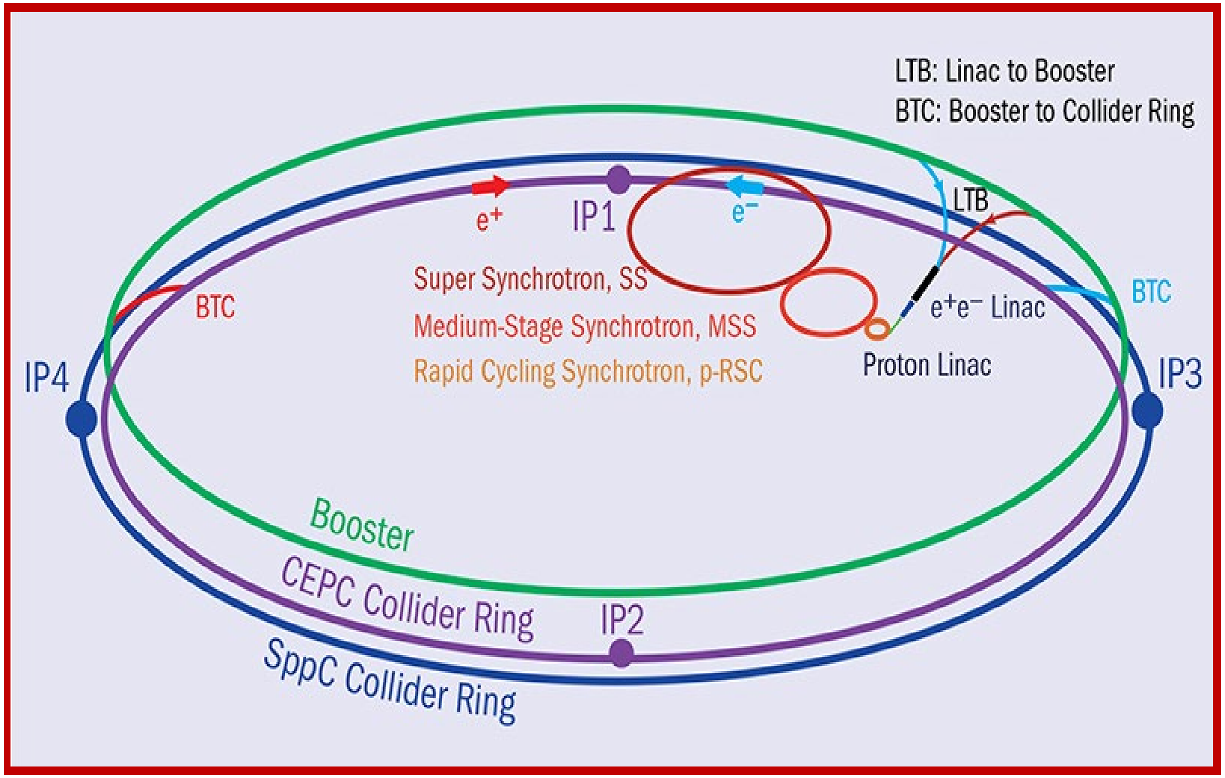
CLIC: **Compact Linear Collider**, e^+e^- at $\sqrt{s}$ = 380 GeV - 3 TeV (also lower $\sqrt{s}$ possible, the goal is the ultimate lepton frontier), CERN hosts the collaboration.



Future projects: CEPC

CEPC/SppC: **Circular Electron-Positron Collider/ Super Proton-Proton Collider**; the Chinese physics community is very willing to do it:

- CEPC : e^+e^- at $\sqrt{s}$ - 90 - 240 GeV;
- SppC : pp at $\sqrt{s}$ = 70 TeV.

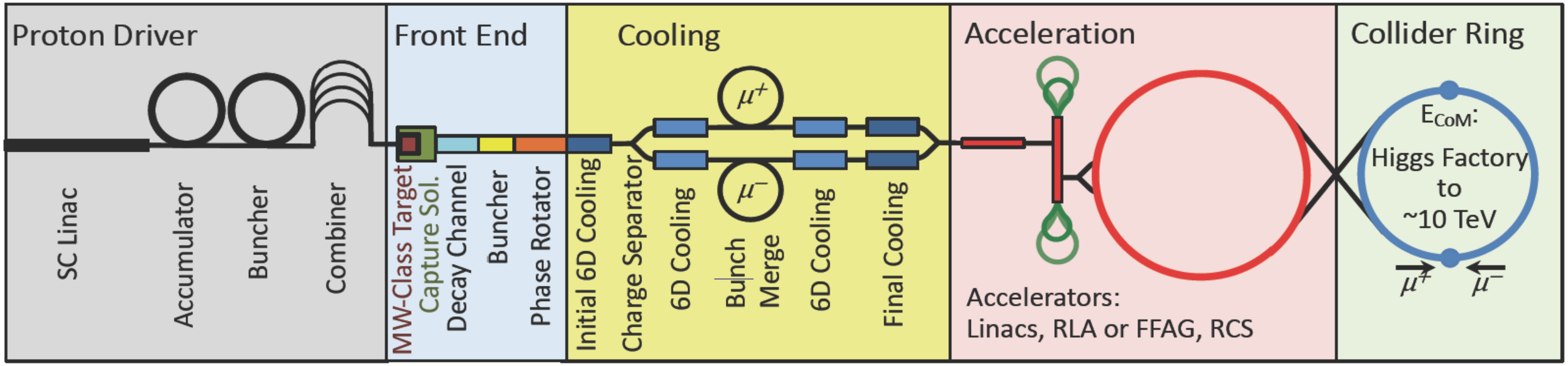


Future projects: μ-colliders + others

- SuperKEKB (Japan): e^+e^- at $\sqrt{s}$ = 10.5 GeV, $\mathscr{L}$ = 8 10^{35} $cm^{-2}s^{-1}$;
- EIC (BNL, USA): e-ion at $\sqrt{s}$ = 29-140 GeV;
- μ-colliders at $\sqrt{s}$ up to TeV [*imho the most ambitious and challenging option – <u>must follow</u>*];

present world record for $\mathscr{L}$; dedicated to Υ physics.

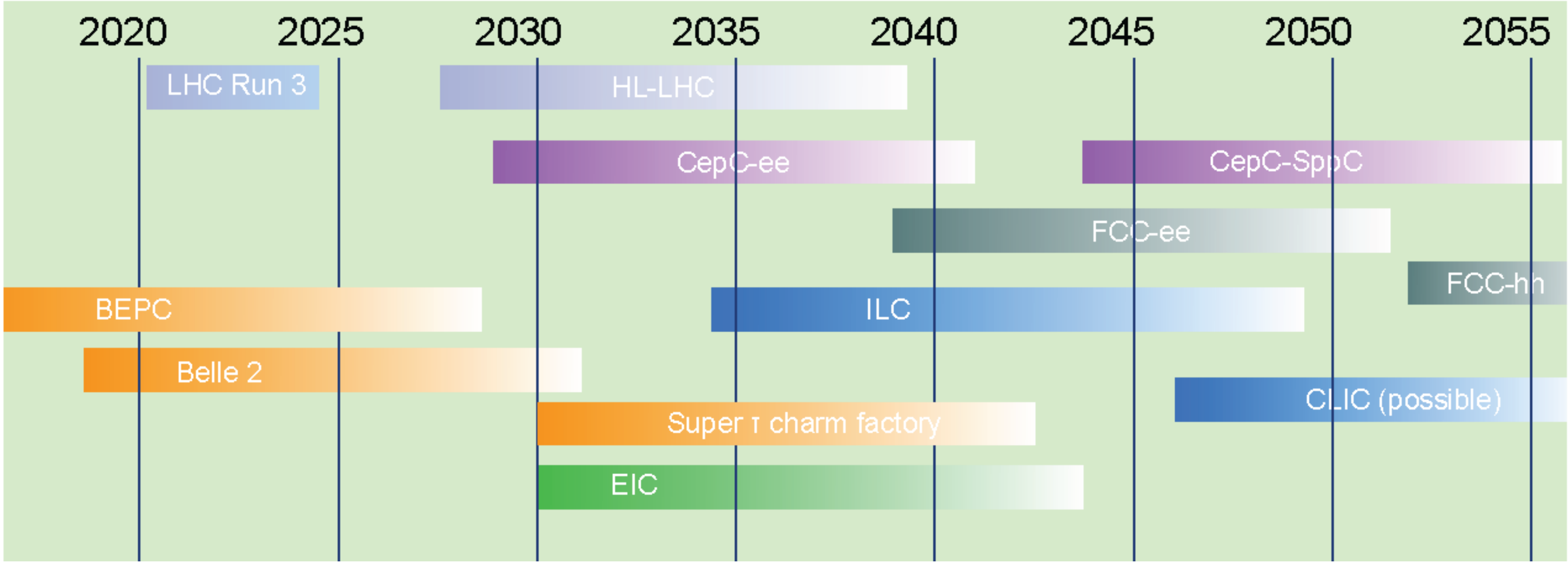
another option: create muons from e^+ (45 GeV) e^- (rest) $\rightarrow \mu^+\mu^-$ (collimated)



Future projects: a(n im)possible scenario

This figure comes from the summary of ICHEP 2020:

- each single line represents one machine;
- same color for same setup (e.g. FCC-ee/hh);
- each line is probably possible (at least plausible);
- but not enough "oxygen" for all the lines;
- *who will be the winner* ?



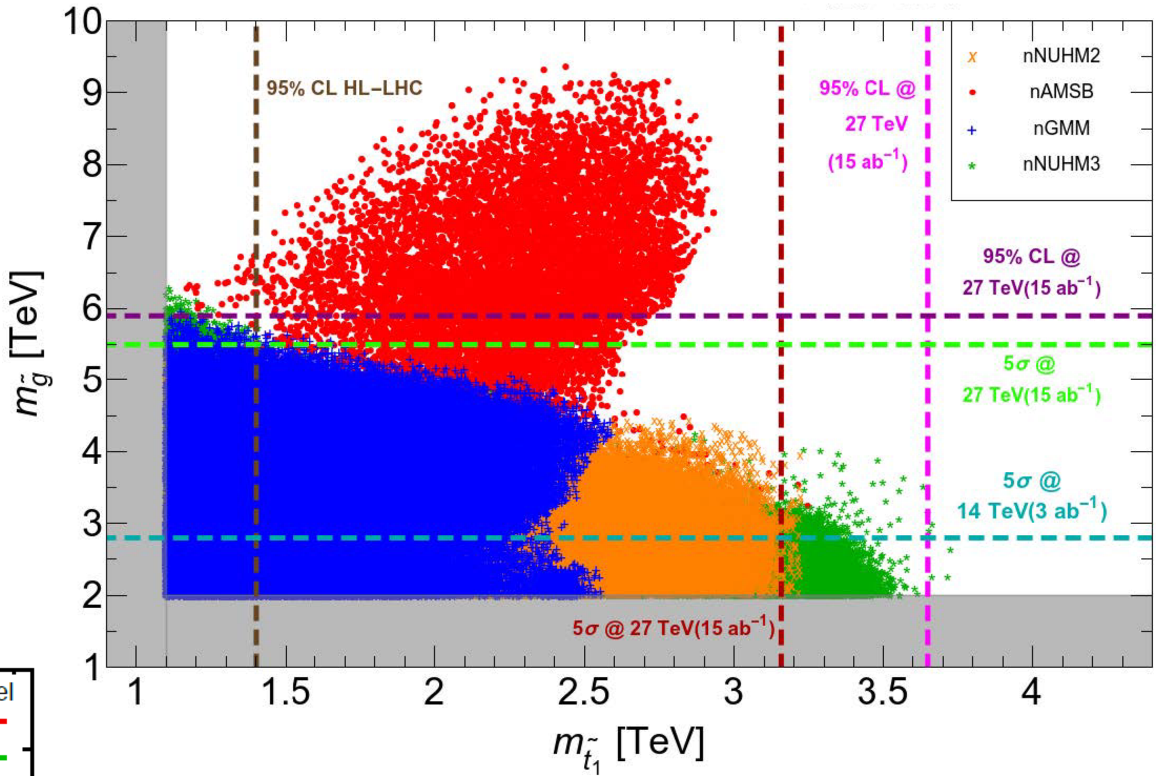
Future projects: summary table

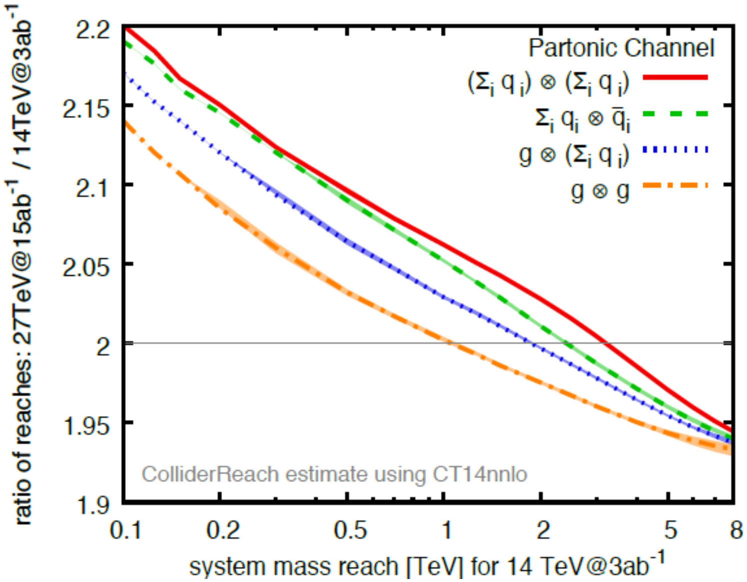
Project	Type	Energy [TeV]	$\mathcal{L}$ [10^{34} $cm^{-2}s^{-1}$]	$\mathcal{L}_{int}$ [ab^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	1.3	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5		4	10	163 (204)	7.8 GILCU
		1.0				300	?
CLIC	ee	0.38	1.5	1	8	168	5.9 GCHF
		1.5		2.5	7	(370)	+5.1 GCHF
		3	6	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	10.	16+2.6		149	5 G$
		0.24		5.6	7	266	
FCC-ee	ee	0.091+0.16	~200.	150+10	4+1	259	10.5 GCHF
		0.24	9	5	3	282	
		0.365 (+0.35)	2	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	8	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	5 (30)	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	25	20	20		7.2 GCHF

Future performances: HE-LHC

HE-LHC is a CERN project:

- replace present dipoles (8.3 T) with stronger ones (e.g. 16 T), so that $\sqrt{s}$ = 27 TeV;
- no new tunnel, no new detector, ...
- the devil is both in the realization of the dipoles and in the "details", like detector upgrades and beam controls.

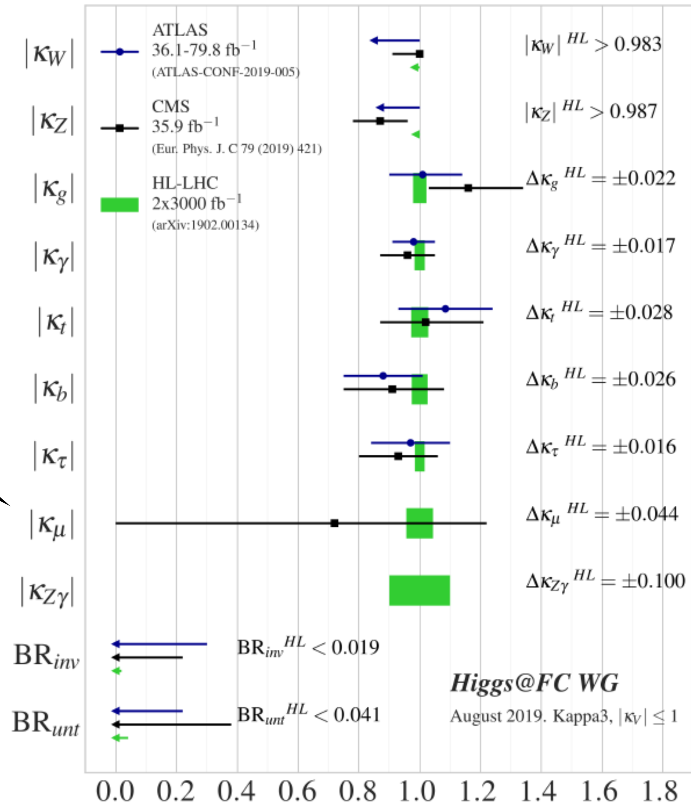


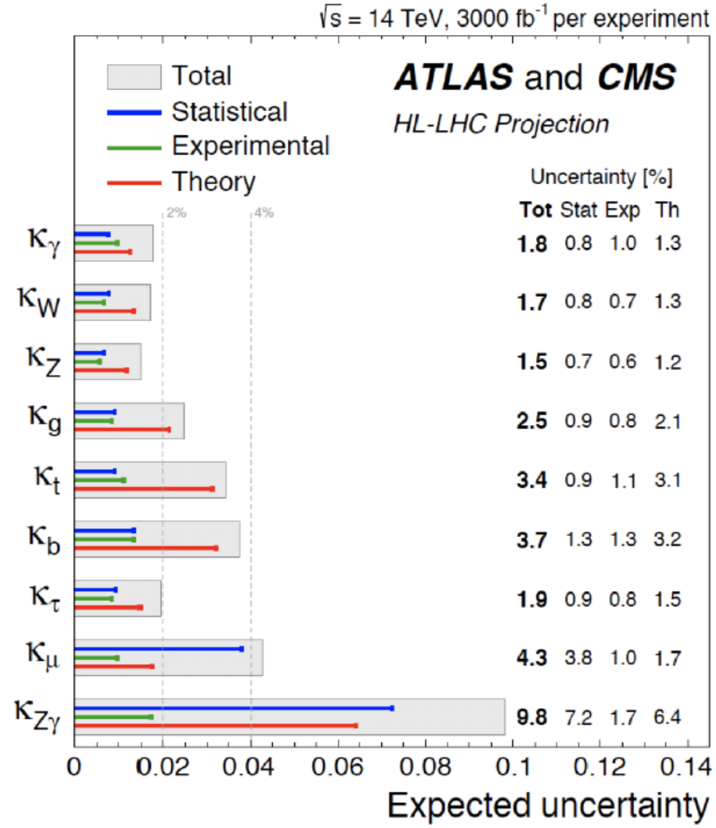


- a great machine: larger $\mathscr{L}$ [a = "atto" = 10^{-18} = femto × 10^{-3}] and larger $\sqrt{s}$ allow the PDF to reach much larger masses [LEFT];
- probably a SUSY killer [ABOVE];
- ... but no guaranteed physics bSM;
- *given the effort, time and cost, is it worth* ?

Future performances: κ-modifiers → HL-LHC

2019

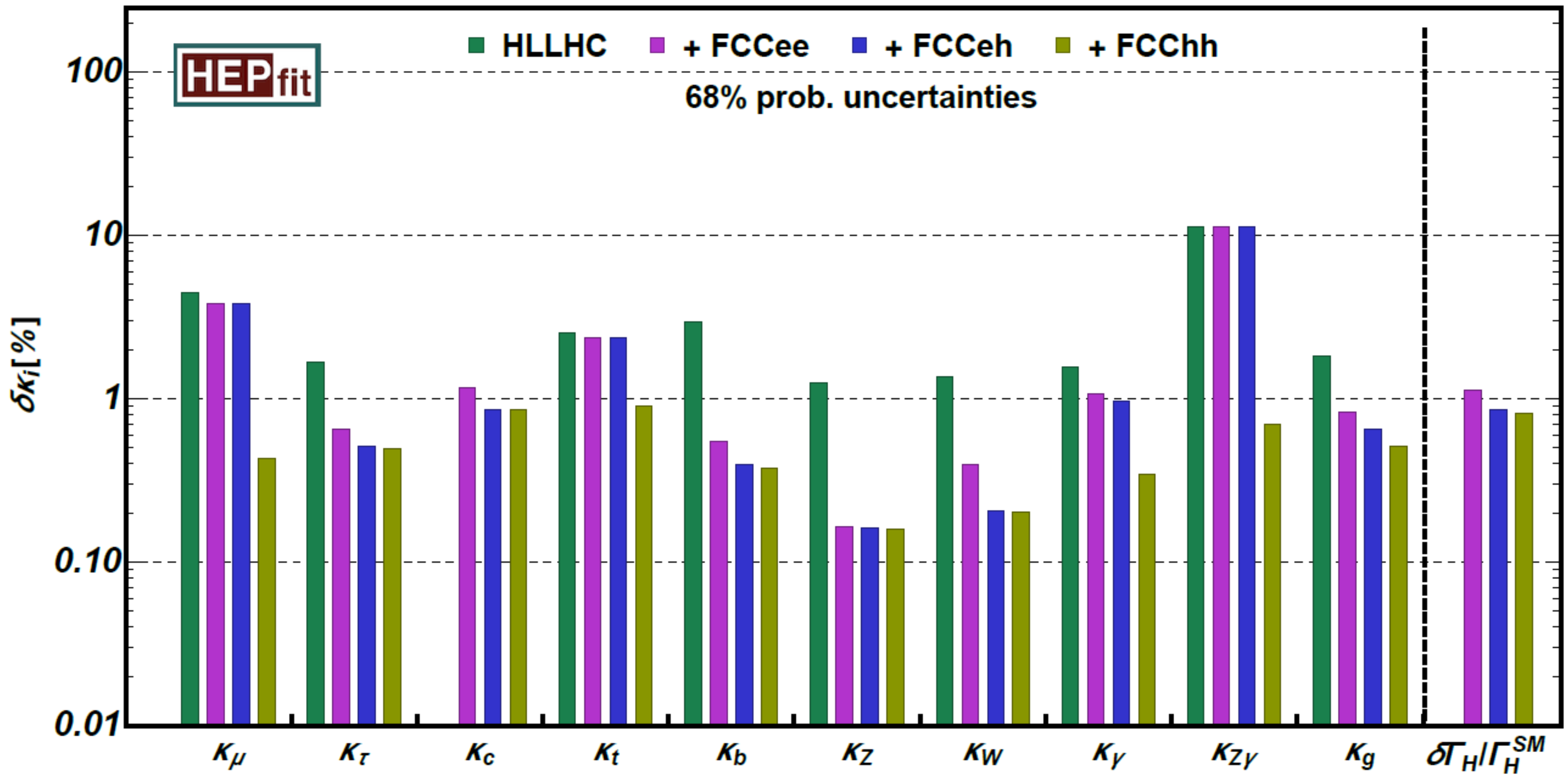




after HL-LHC

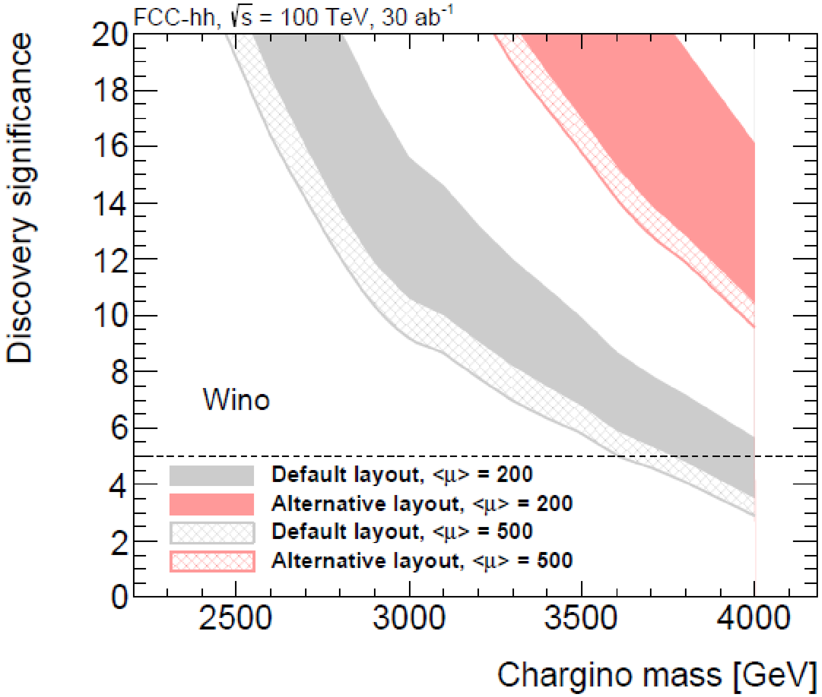
- the error on κ-modifiers (see in § LHC) are a benchmark of the quality of a machine;
- although defined in terms of SM, they are an indicator for physics bSM;
- after HL-LHC, they will improve a lot over present (LEFT: only error shown);
- their total error will be dominated by "theory" (= error in other parameters).

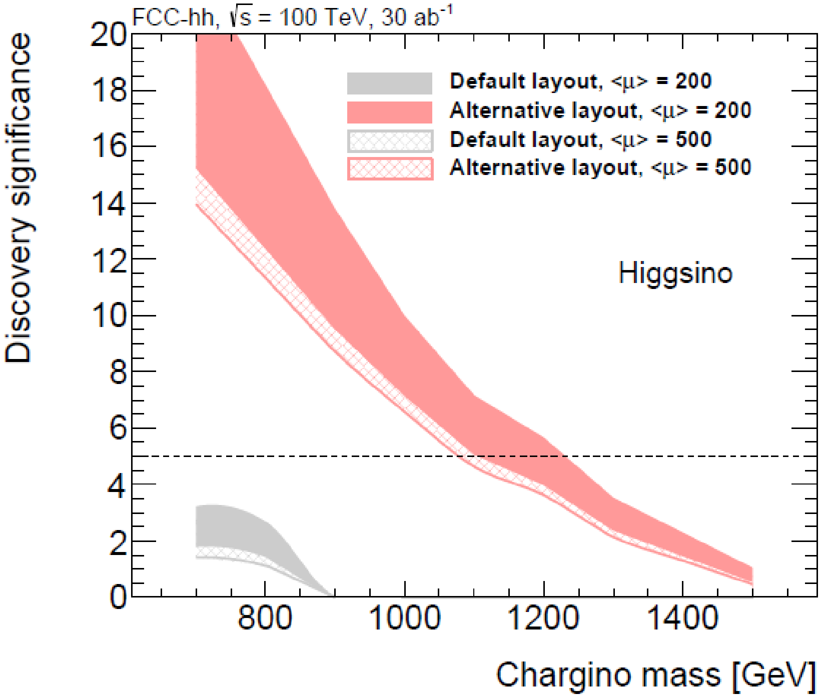
Future performances: κ-modifiers after FCC



- ... and after all the phases of FCC (at the quoted $\mathscr{L}_{int}$);
- all values better than 1%; some at 0.1%;
- probably the best model-independent test of the SM;
- [*imho the SM will not survive it, but if it will, probably will gain immortality*].

Future performances: W̃ and H̃ at FCC-hh

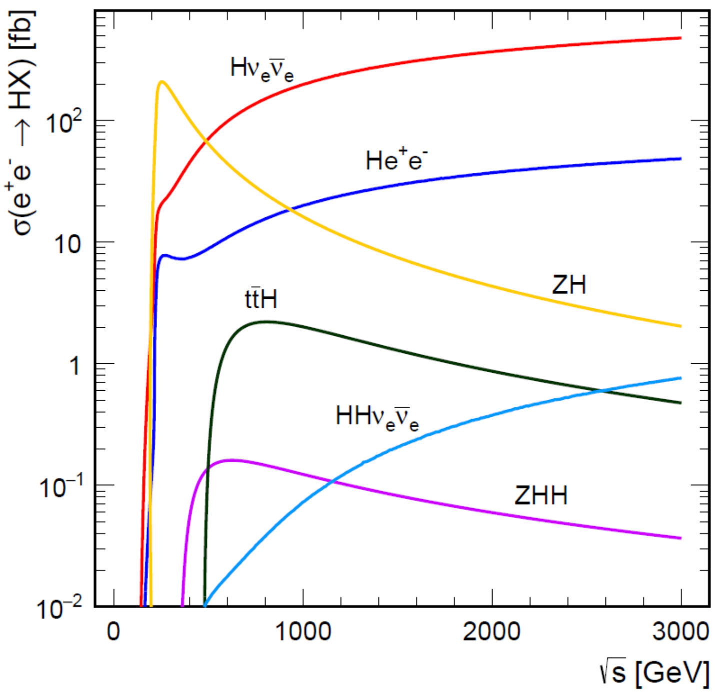


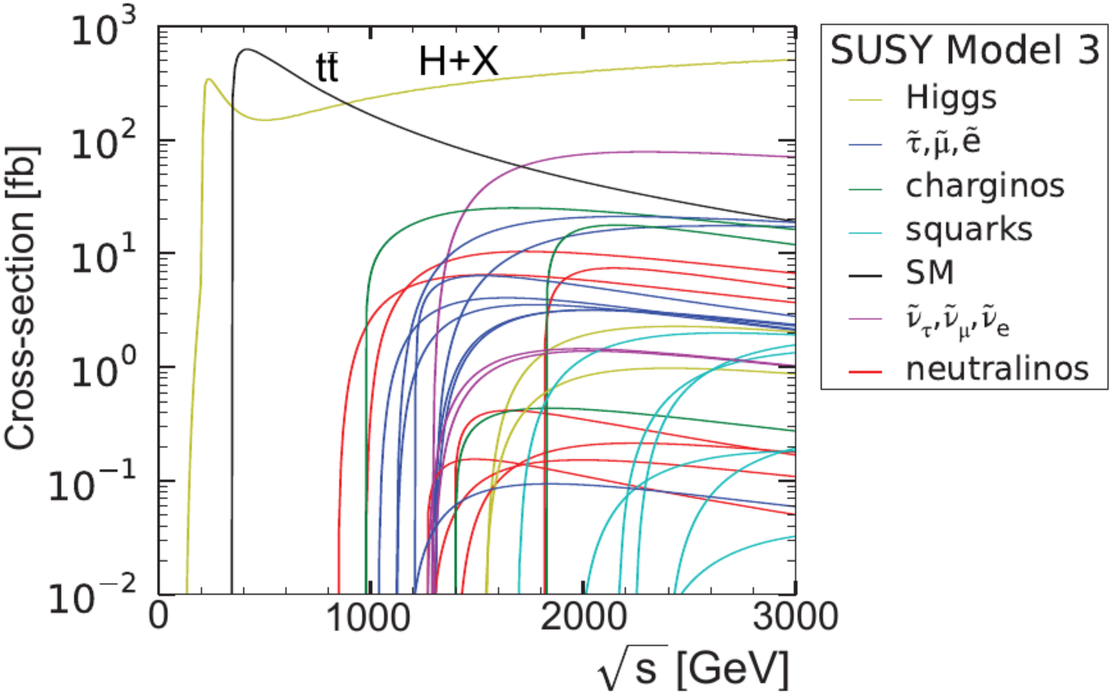


- an example of FCC-hh on SUSY;
- at 5σ, it will exclude W̃ of 3.5 TeV and H̃ of 1 TeV [*"layout" refers to the vtx detector and is outside the scope of these lectures*].

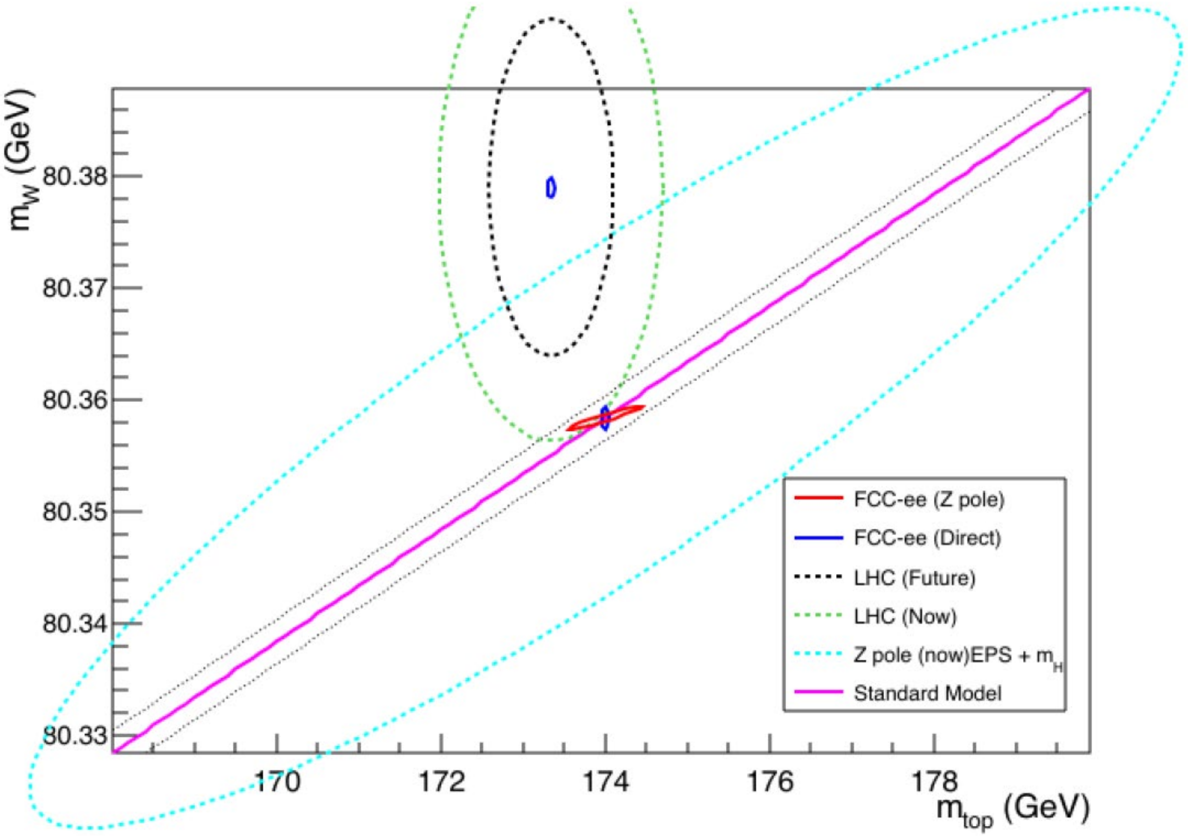
Future performances: why leptons ?

- with point-like particles, cross-sections show the usual threshold [*see LEFT for H in SM and RIGHT for a SUSY model*];
- lots of nice and very precise measurements [*know from LEP*];
- need high √s [*look at the thresholds, Lep was at* $\sqrt{s} \approx 200$ *GeV*].
- the dream of the analysis people (no bckgd, no dirty spectators);
- the nightmare of the accelerator people (and the politicians): the REAL devil is the brem.





Future performances: m_w vs m_t at FCC-ee



- an example of precision physics at FCC-ee: test of SM in the plane m_w vs m_t;
- "Z-pole" is at $\sqrt{s} = m_z$ (phase 1 of FCC-ee);
- "direct" is at $\sqrt{s} = 2\ m_w$ and $\sqrt{s} = 2\ m_t$;
- compared with LHC-2019 and HL-LHC;
- for future meas., position is irrelevant, only error (= ellipsis size) counts;
- [*impressive* !]

Thanks for attending

Best wishes !

P.B.

References

[*just impossible* !!! *only the papers used here*]

Theories and exps bSM:

- CERN summer student lectures and schools (from the 80's to 2019);
- CERN-ESU-004;
- CERN-ACC-2018-0056/57/58/59;
- CERN-ACC-2019-0003/5/6/7;
- AAVV – ICHEP 2020 (Prague).

Colliders:

- D. Schulte – CERN summer students 2019;
- J. D'Hondt – ICHEP 2020 (Prague);
- CERN report on HE-LHC.

[*the number of papers on both subjects is exponentially increasing – a true pandemics*]

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End of chapter 6