Recent LHC Physics Results and their Impact on Future HEP Accelerator Programme

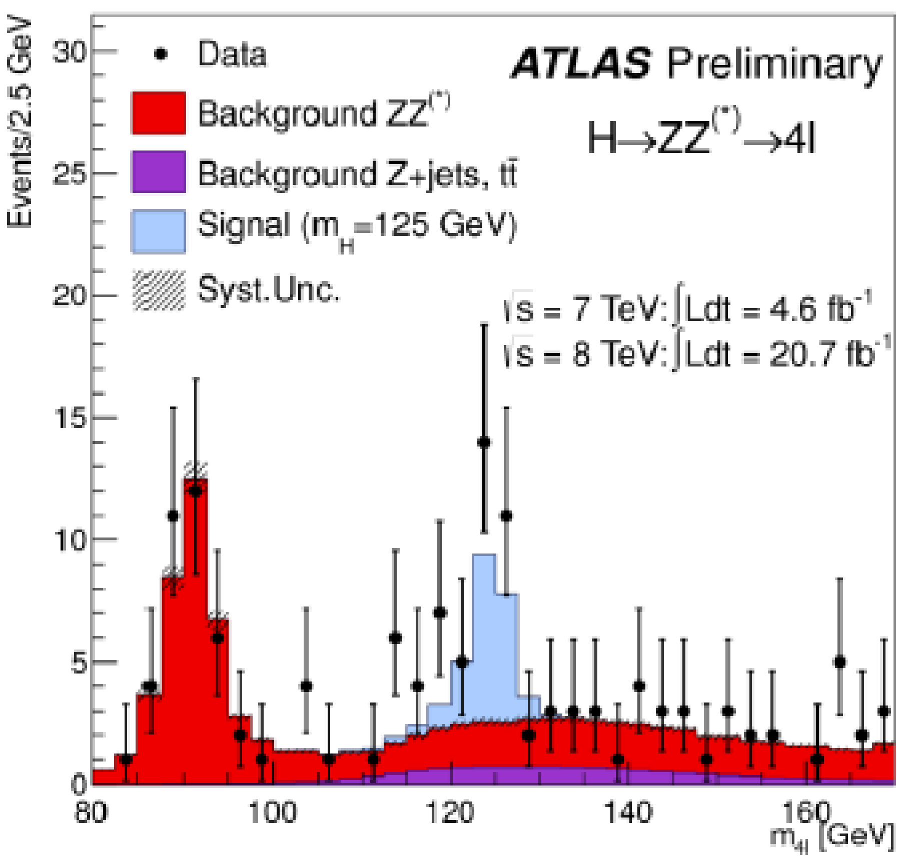
Sergio Bertolucci
CERN

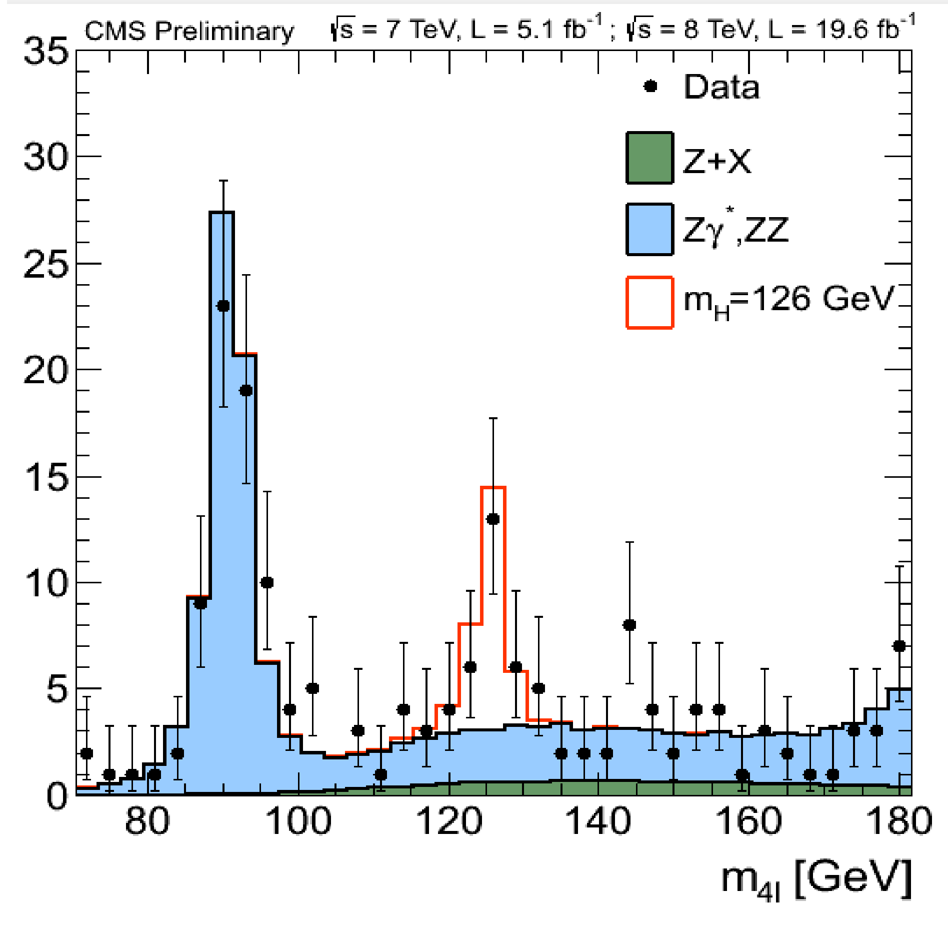
Where we stand

- ✓ **There is a new boson of mass ~125 GeV, with properties consistent with the SM Higgs, within the current uncertainties. More data needed to ascertain the nature of this object.**

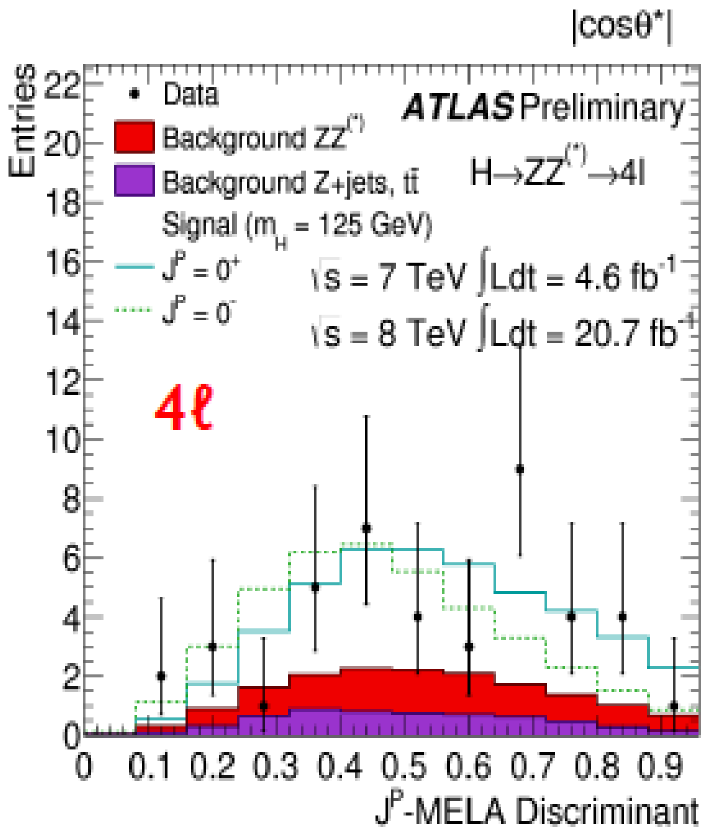
A new particle: no doubt that it is there…

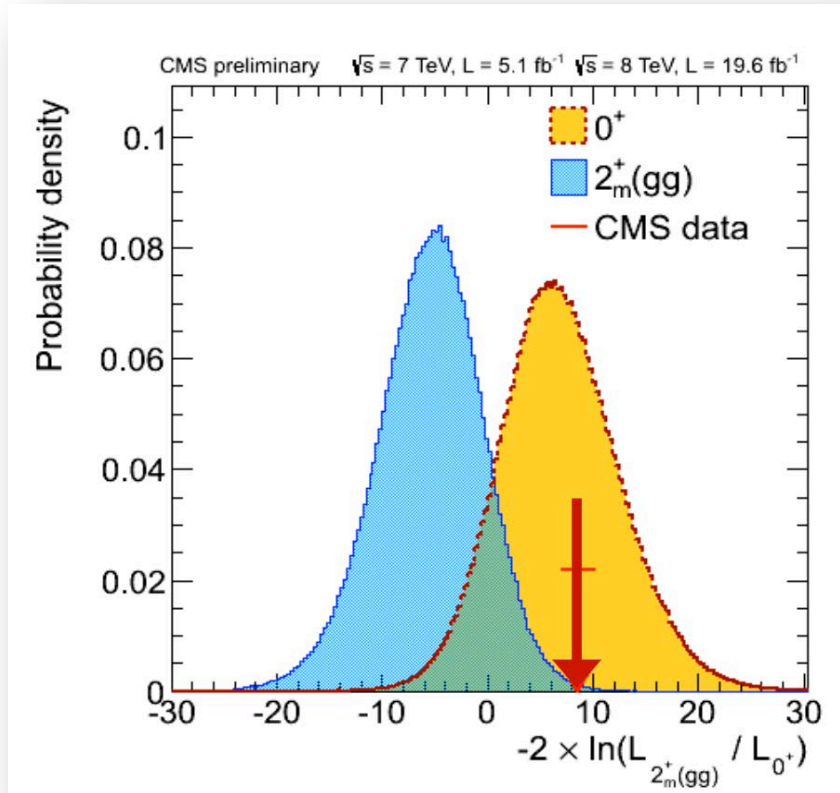
By now we can establish it with a single decay channel!
e.g. H → ZZ → 4l



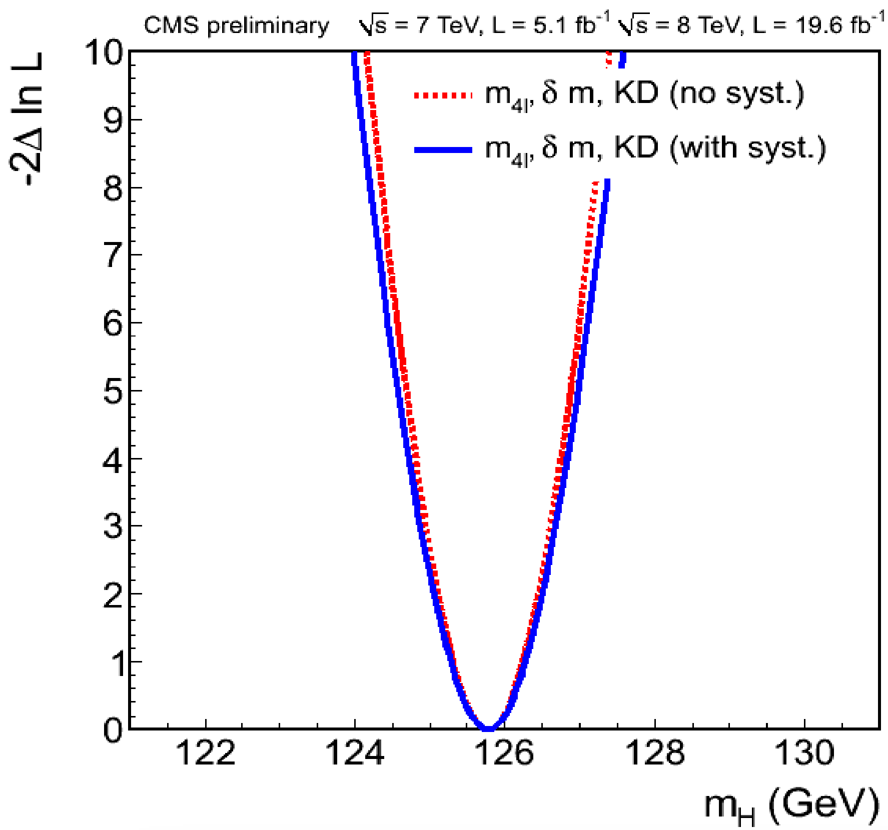


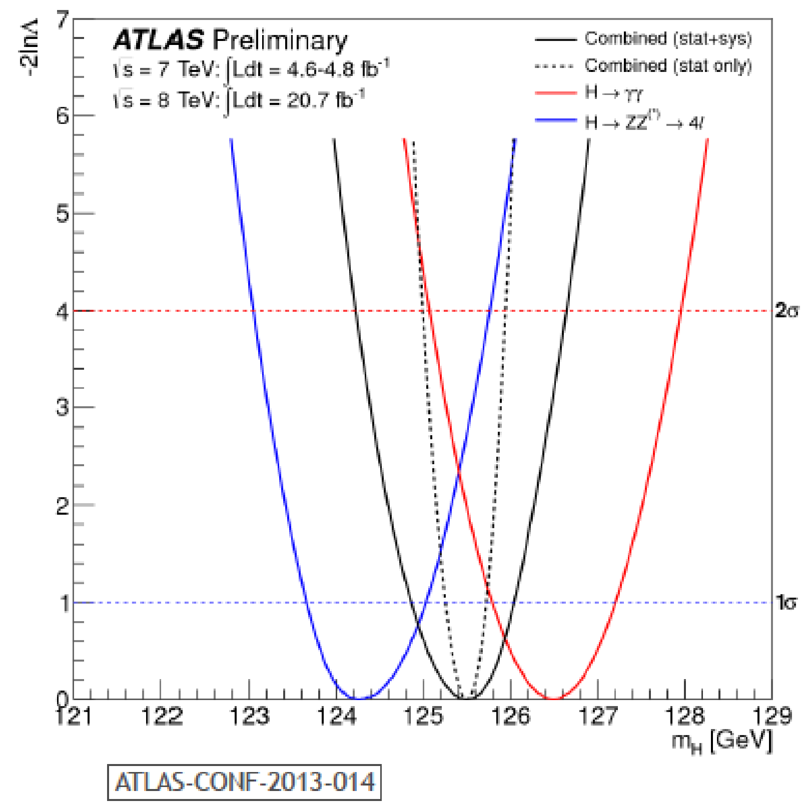
…it prefers 0+ quantum numbers





…its mass is measured to .5%

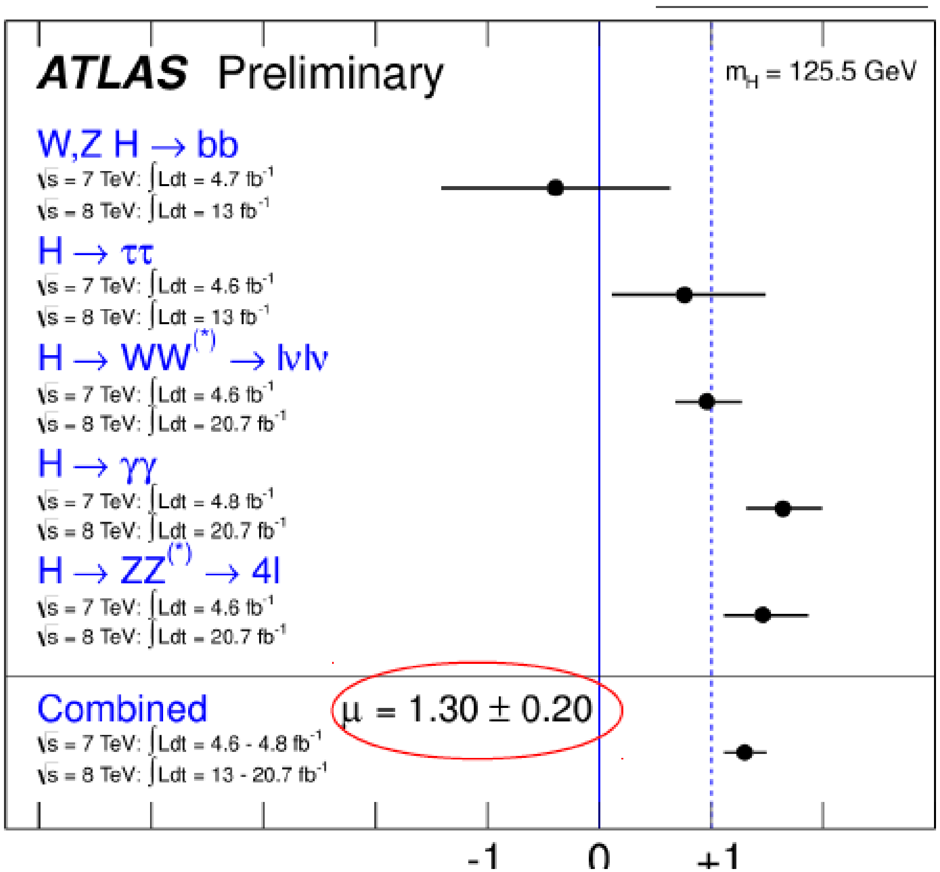


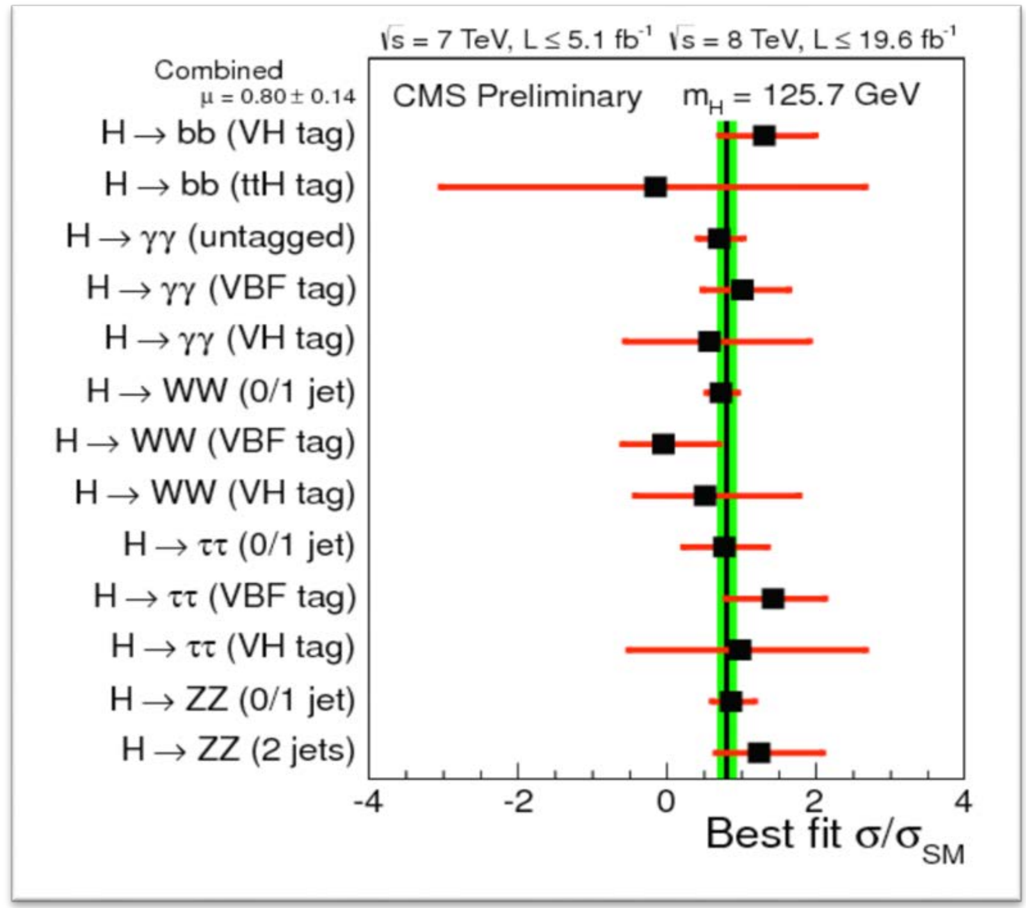


$$125.8 \pm 0.5(stat.) \pm 0.2(syst.)$$

$$m_H = 125.5 \pm 0.2 \pm ^{0.5}_{0.6} \text{ GeV}$$

…and the signal strength is compatible with a SM Higgs





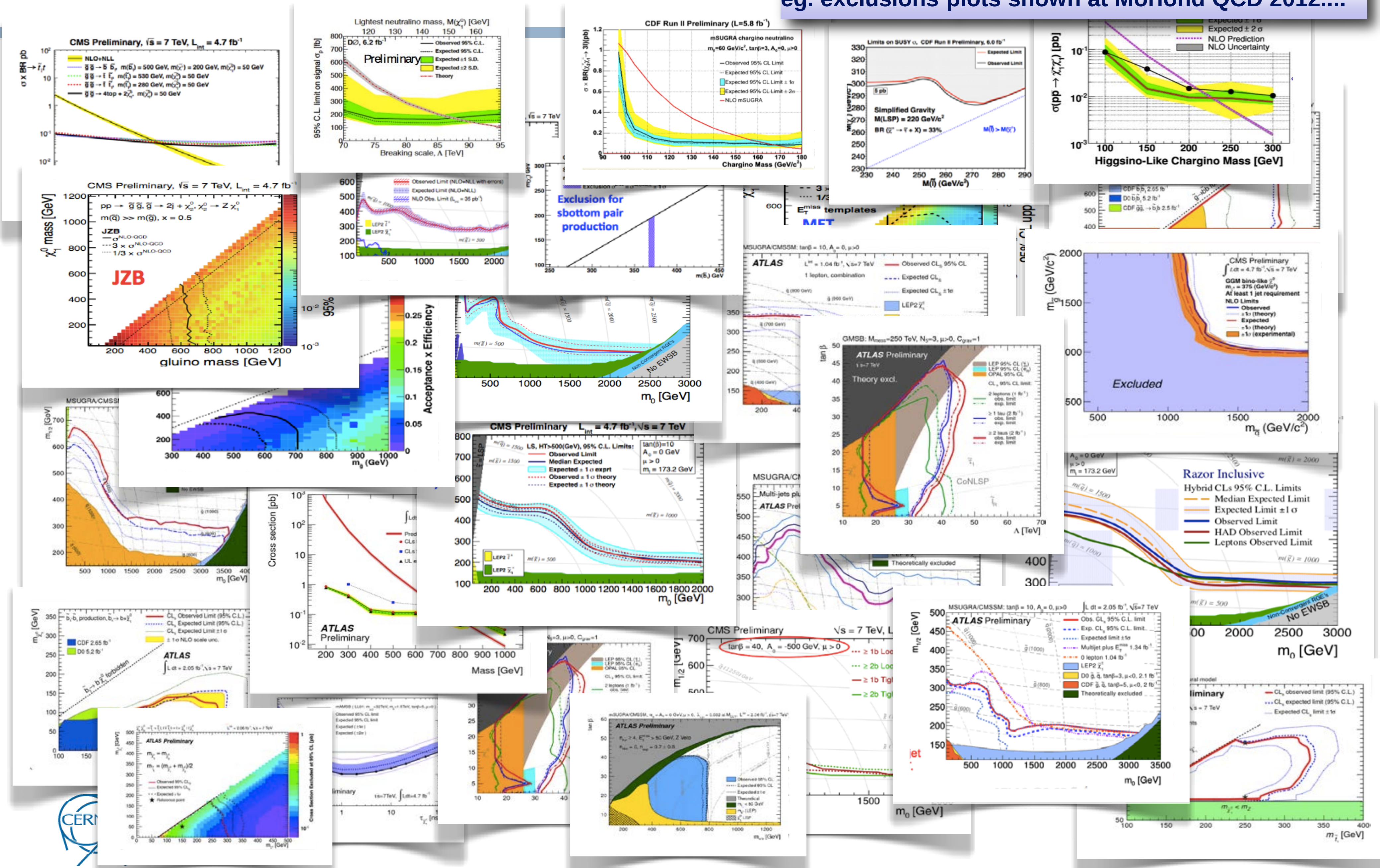
Where we stand

- **There is a new boson of mass ~125 GeV, with properties consistent with the SM Higgs, within the current uncertainties. More data needed to ascertain the nature of this object**.

- **So far, no indications of BSM physics from direct searches at the High E Frontier:**
  - colored SUSY particles (first generations) ruled out up to O(1 TeV), for a light LSP;
  - "natural" SUSY probed at level of a few hundred GeV of 3rd generation spartners;
  - exotica: heavy objects probed up to masses of 2-3 TeV;
  - a lot of room still to be explored, **14 TeV will be essential**!

BSM: we have searched....

eg. exclusions plots shown at Moriond QCD 2012....



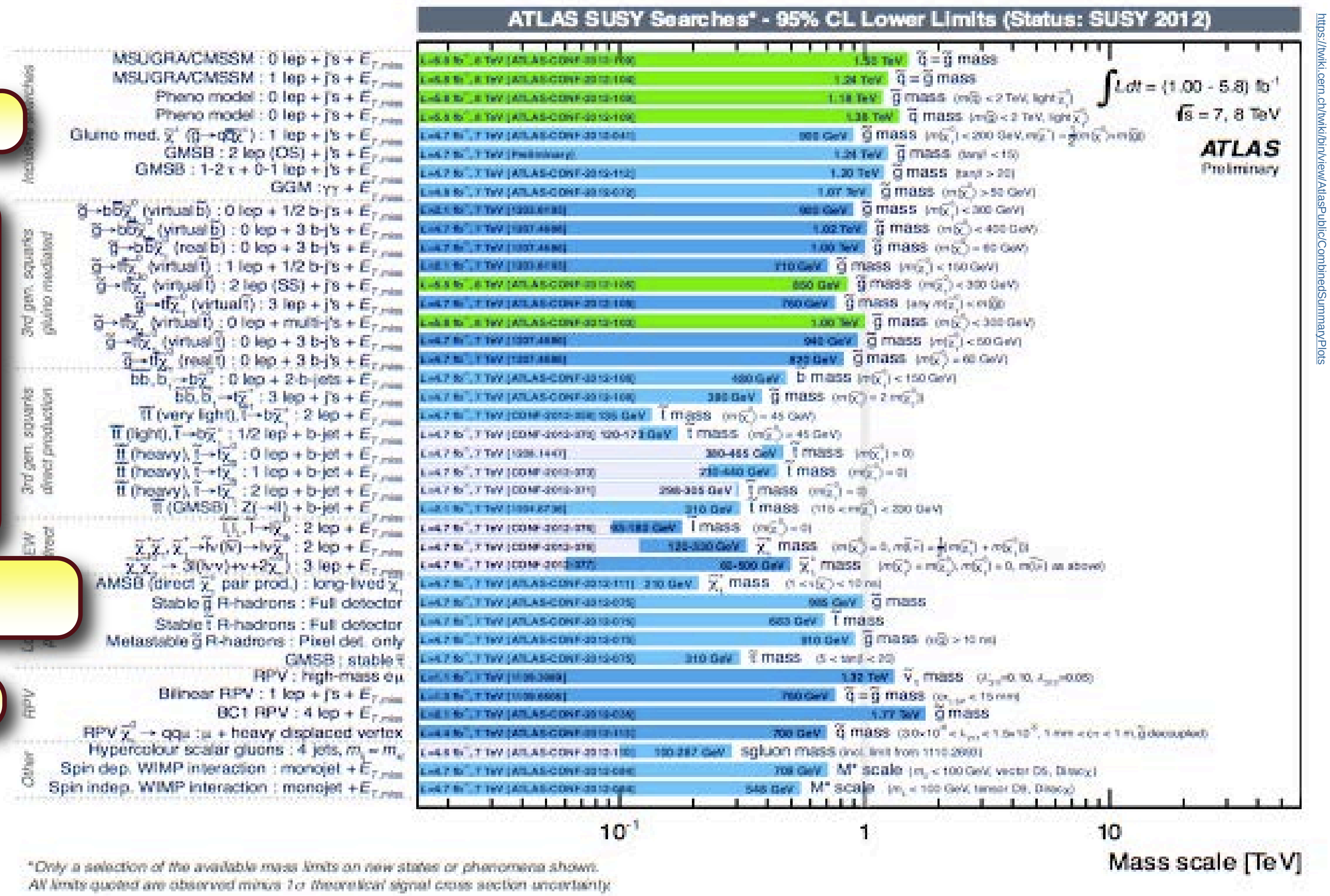
The big picture

inclusive searches

Natural SUSY

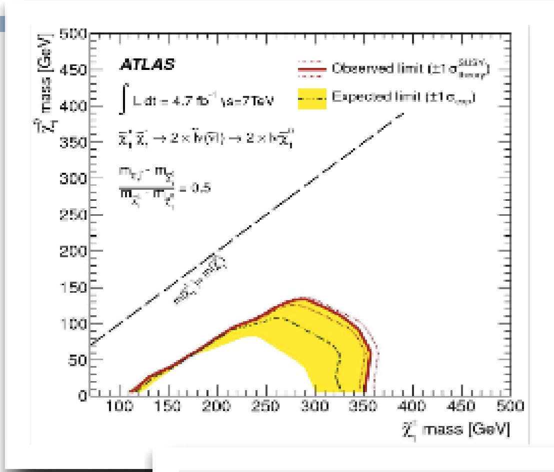
long-lived particles,
eg. split SUSY

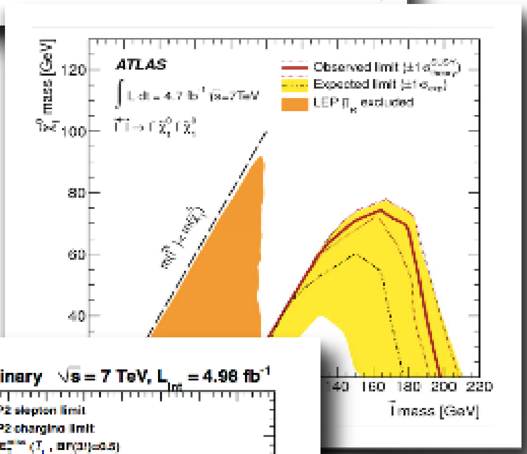
RPV

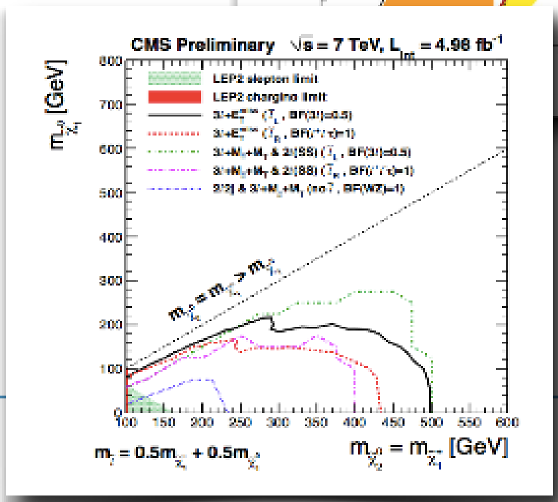


SUSY health

- The experiments have already explored a very vast range of masses and parameters
- Though, too early to declare SUSY’s death, since there remain important parameter regions to be explored, and because
  - Difficult or impossible to give “absolute” limits, since basically always assumptions involved
  - limits quickly degrade or disappear when raising m(LSP) beyond several hundreds of GeV
  - inclusive searches often assume degenerate 1st and 2nd generation squarks. Limits decrease (by several hundreds of GeV) if this is given up
  - simplified models make strong assumptions on branching ratios, masses of intermediate states
  - theory uncertainties (cross sections/scales/pdfs, initial state radiation)







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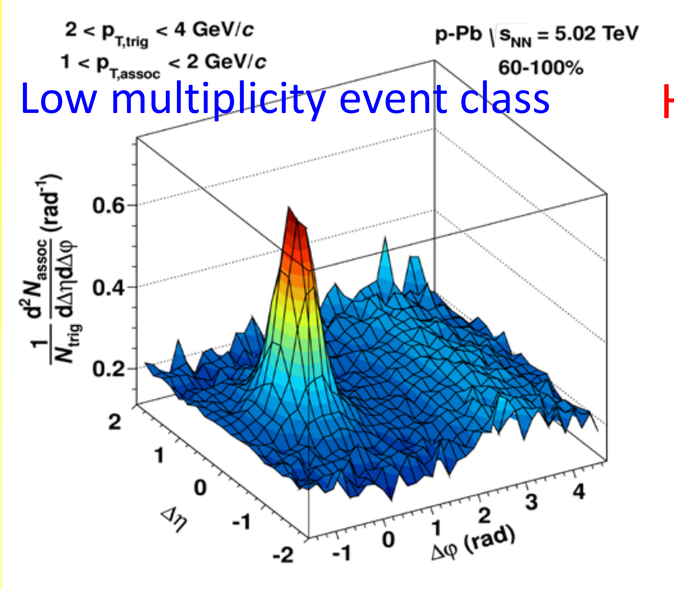
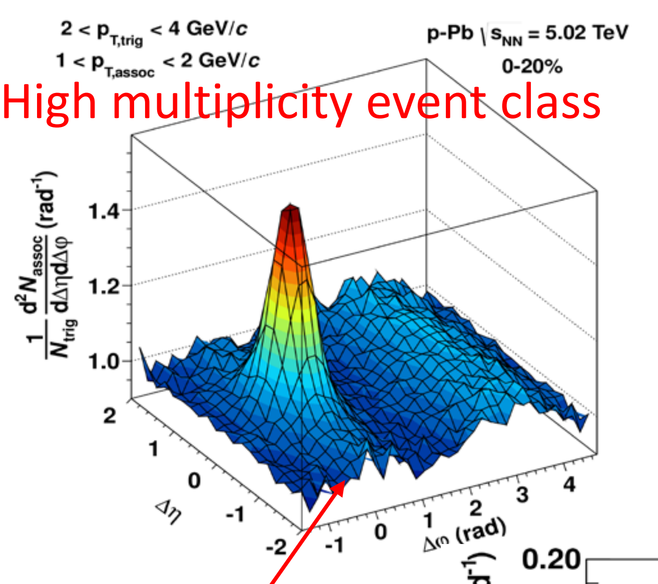
- **Very rich harvest coming from LHC PbPb and pPb runs**

ALICE: Correlations

Low multiplicity event class



High multiplicity event class

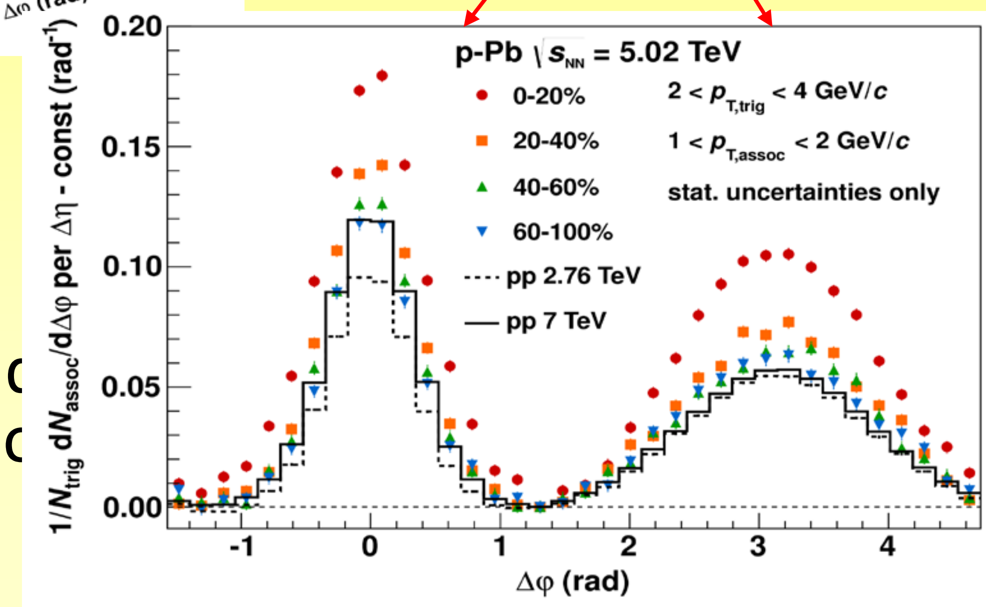


Phys.Lett. B719 (2013) 29-41

Excess on both near-side (NS) and away-side (AS) going from p-p/low multiplicity -> high multiplicity events

Qualitatively similar to CMS ridge

- Correlations for pairs of trigger and associated particles, p_T,trig>p_T,assoc as f(Δϕ,Δη), defined as associated yield per trigger particle



Projection on Δϕ – pPb and pp data

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- ✓ **Very few anomalies in the world-wide HEF data, no strongly smoking gun**

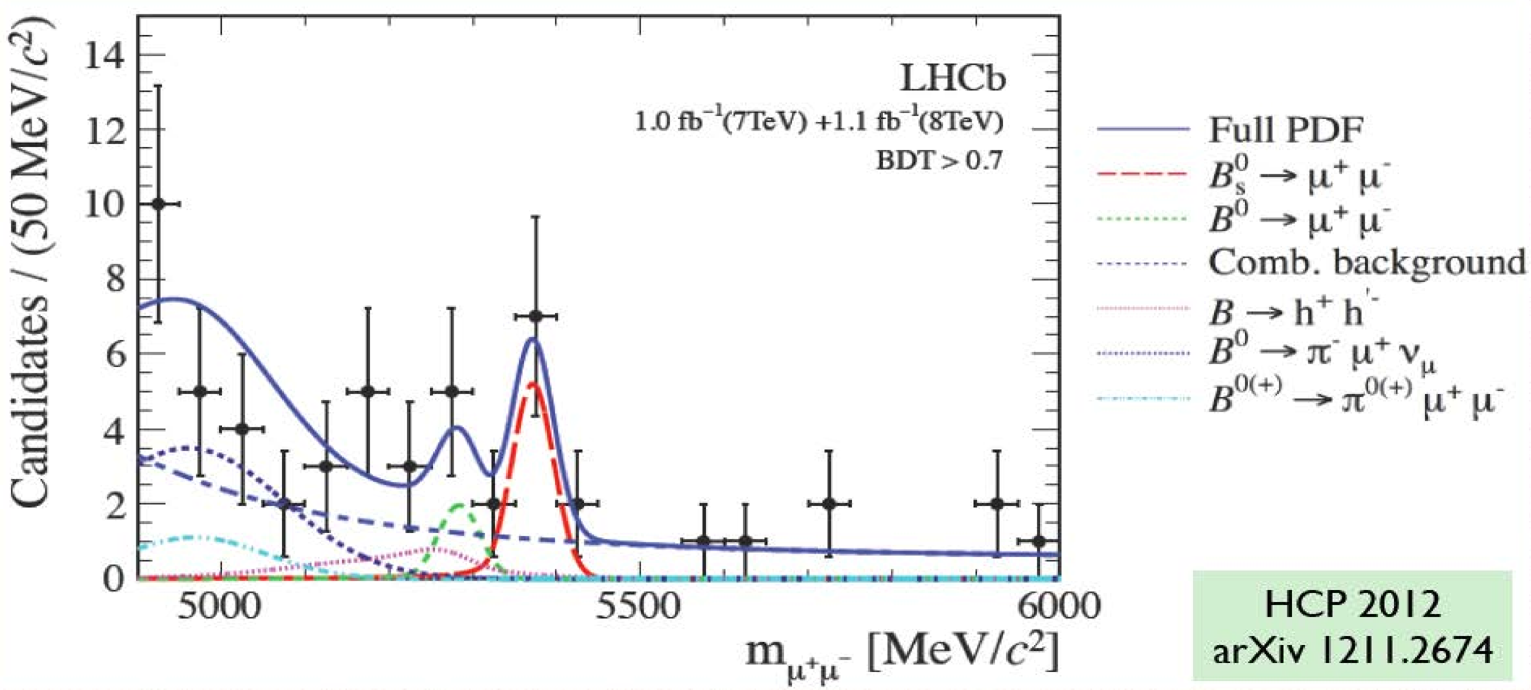
LHCb rare decay $B_s \to \mu\mu$

The search for $B_{s\,(d)} \to \mu\,\mu$

Branching fractions extracted from unbinned maximum likelihood fit to the mass spectra in 8 (7 TeV) and 7 (8 TeV) bins in BDT

$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$

SM: $BR(B_s \to \mu\,\mu) = 3.5 \pm 0.2\ 10^{-9}$



HCP 2012
arXiv 1211.2674

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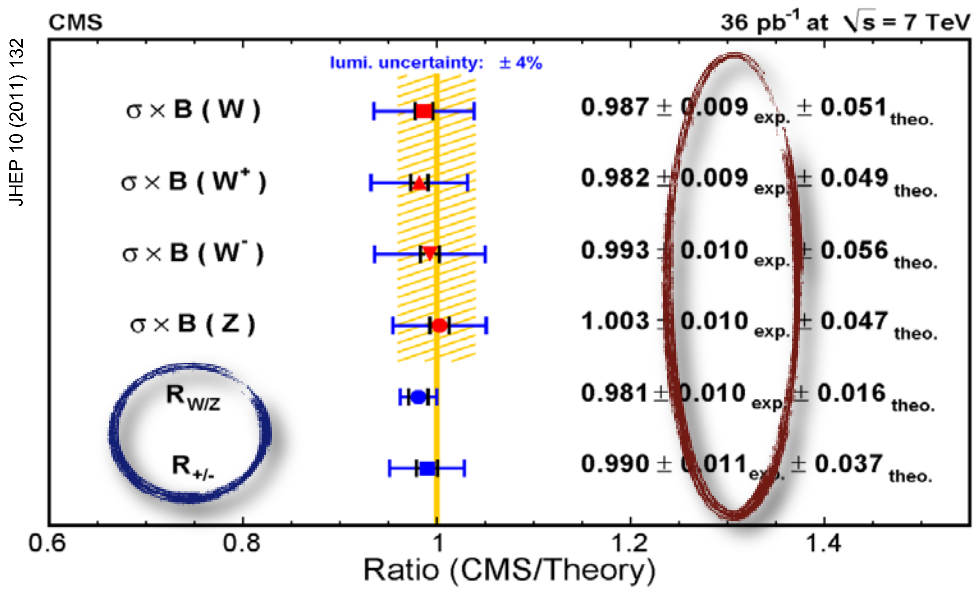
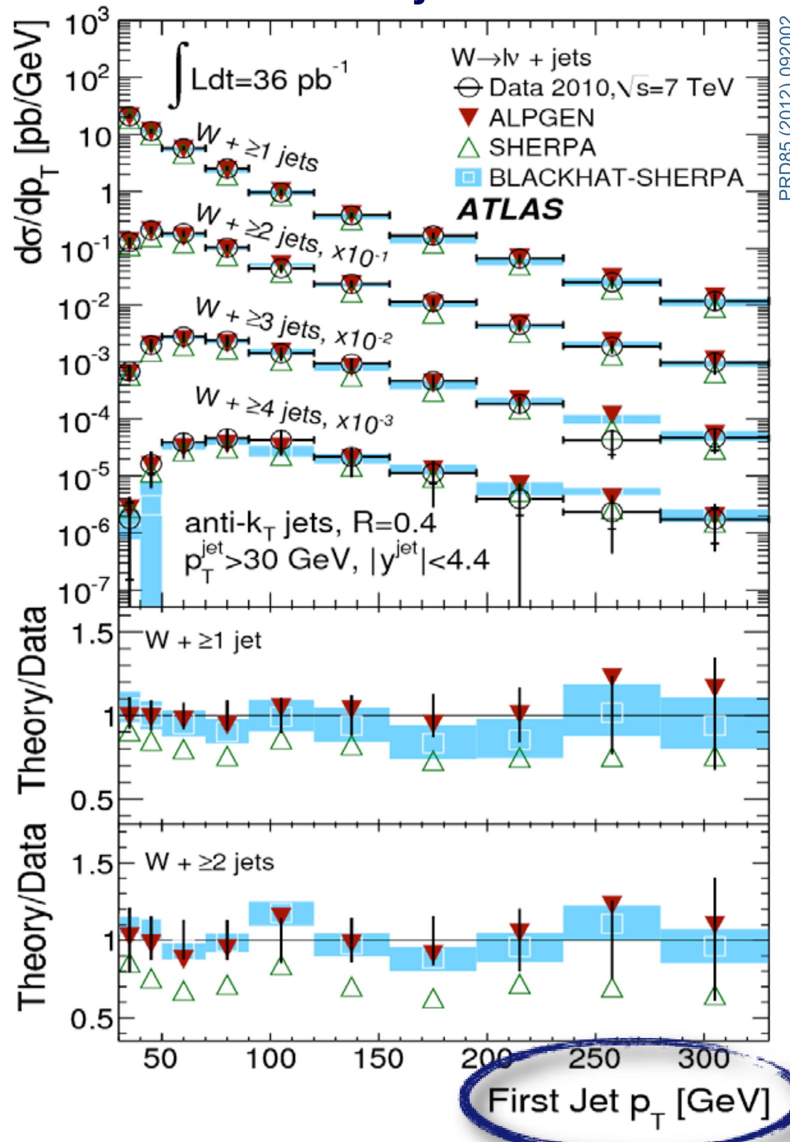
- ✓ **The SM (in terms of its QCD and EWK parts) works perfectly well, up to the % level, at the highest energies probed so far (7 and 8 TeV)**.

W/Z (+Jet) Production

Inclusive



+jets



- incl. cross sections:
- experimental precision at the 1% level, especially for ratio-observables
- excellent agreement with NNLO QCD, both at 7 and 8 TeV
- many diff. distributions measured

- V+jets:
- “triumph” for MCs with matched matrix elements and parton showers
- also multi-leg NLO calculations available by now
- confidence in background predictions for many searches

But, despite its success…

…. we know that the Standard Model is not complete because:

- It doesn’t solve the hierarchy problem
- It has no explanation for dark matter/dark energy
- Its mechanisms of CPV are too small to explain matter/antimatter imbalance
- It cannot provide a QFT of gravitation
- ….etc

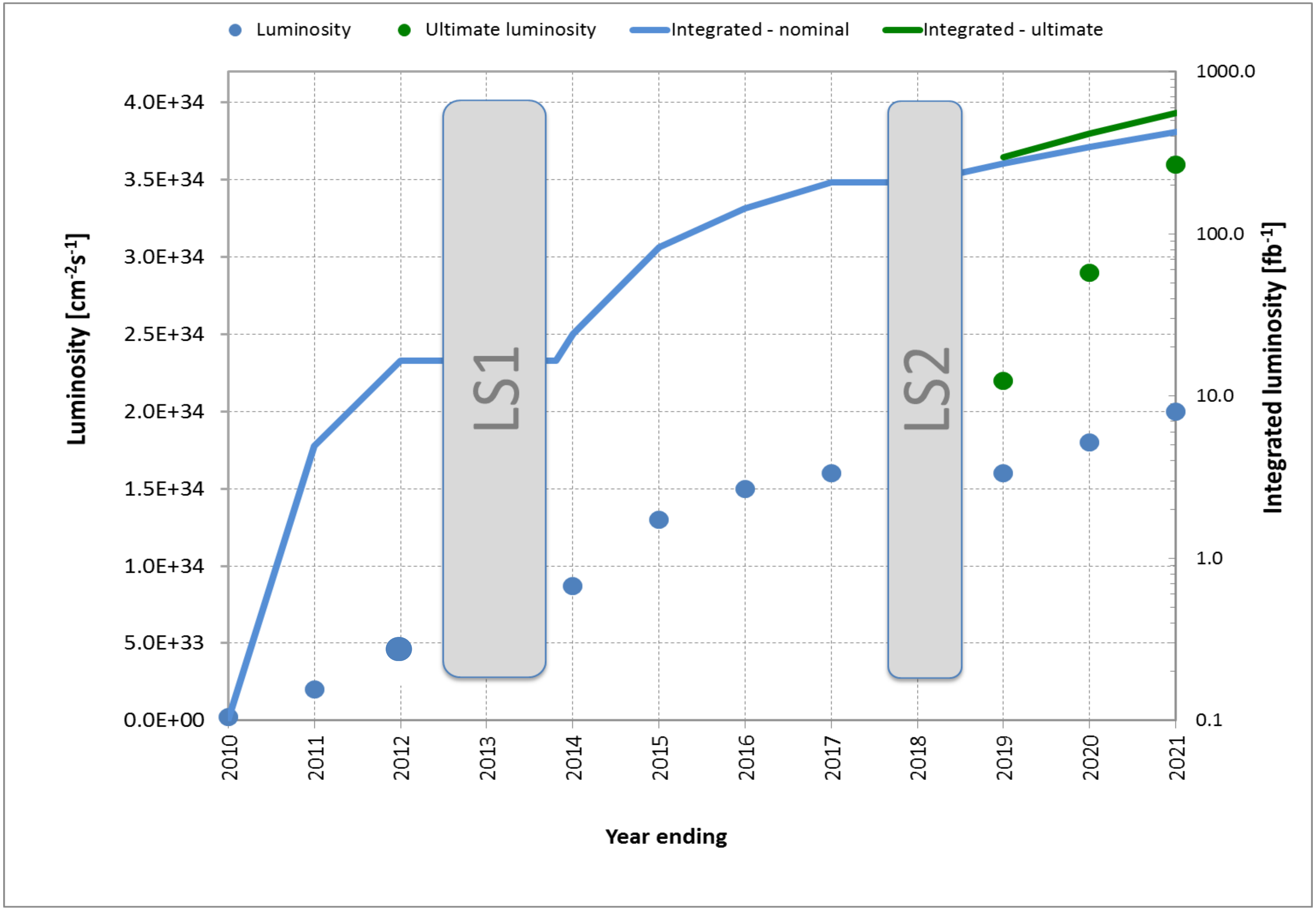
We have the tools to challenge it

- At the energy frontier
- At the intensity frontier
- At the precision frontier

LHC, the next 20 years

- 2009: ✧ LHC startup, $\sqrt{s}$ = 900 GeV
- 2010–2012: $\sqrt{s}$ =7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns — ~20-25 fb^{-1}
- 2013–2014 (LS1): Go to design energy, nominal luminosity
- 2015–2017: $\sqrt{s}$ =13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns — ~75-100 fb^{-1}
- 2018 (LS2): Injector and LHC Phase-1 upgrade to ultimate design luminosity
- 2019–2021: $\sqrt{s}$ =14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns — ~350 fb^{-1}
- 2022 (LS3): HL-LHC Phase-2 upgrade, IR, crab cavities?
- 2023 … 2030?: $\sqrt{s}$ =14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity levelling — ~3000 fb^{-1}

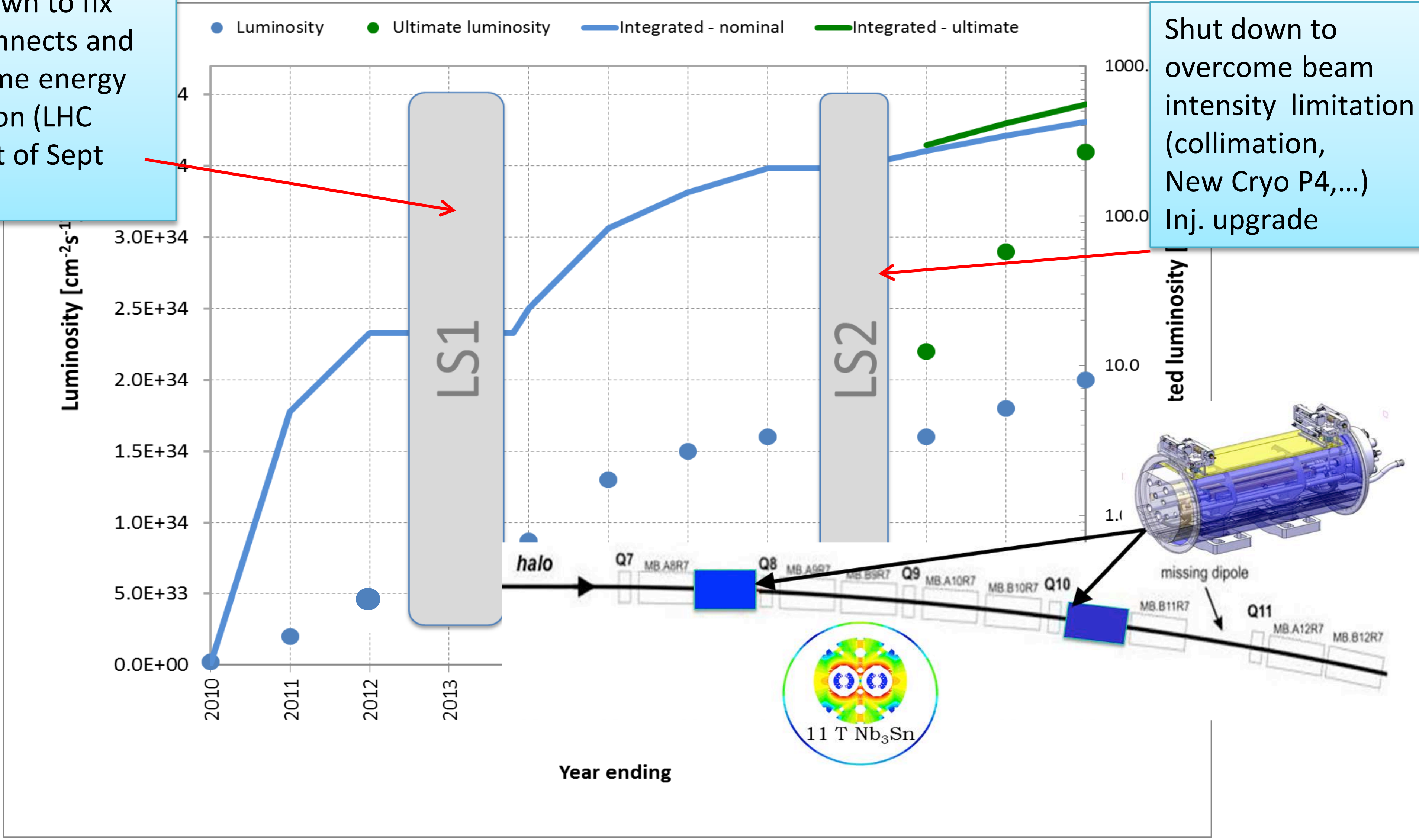
Luminosity: Best Guess for the next 10 years



Luminosity: Best Guess for the next 10 years

Shut down to fix interconnects and overcome energy limitation (LHC incident of Sept 2008)

Shut down to overcome beam intensity limitation (collimation, New Cryo P4,…) Inj. upgrade



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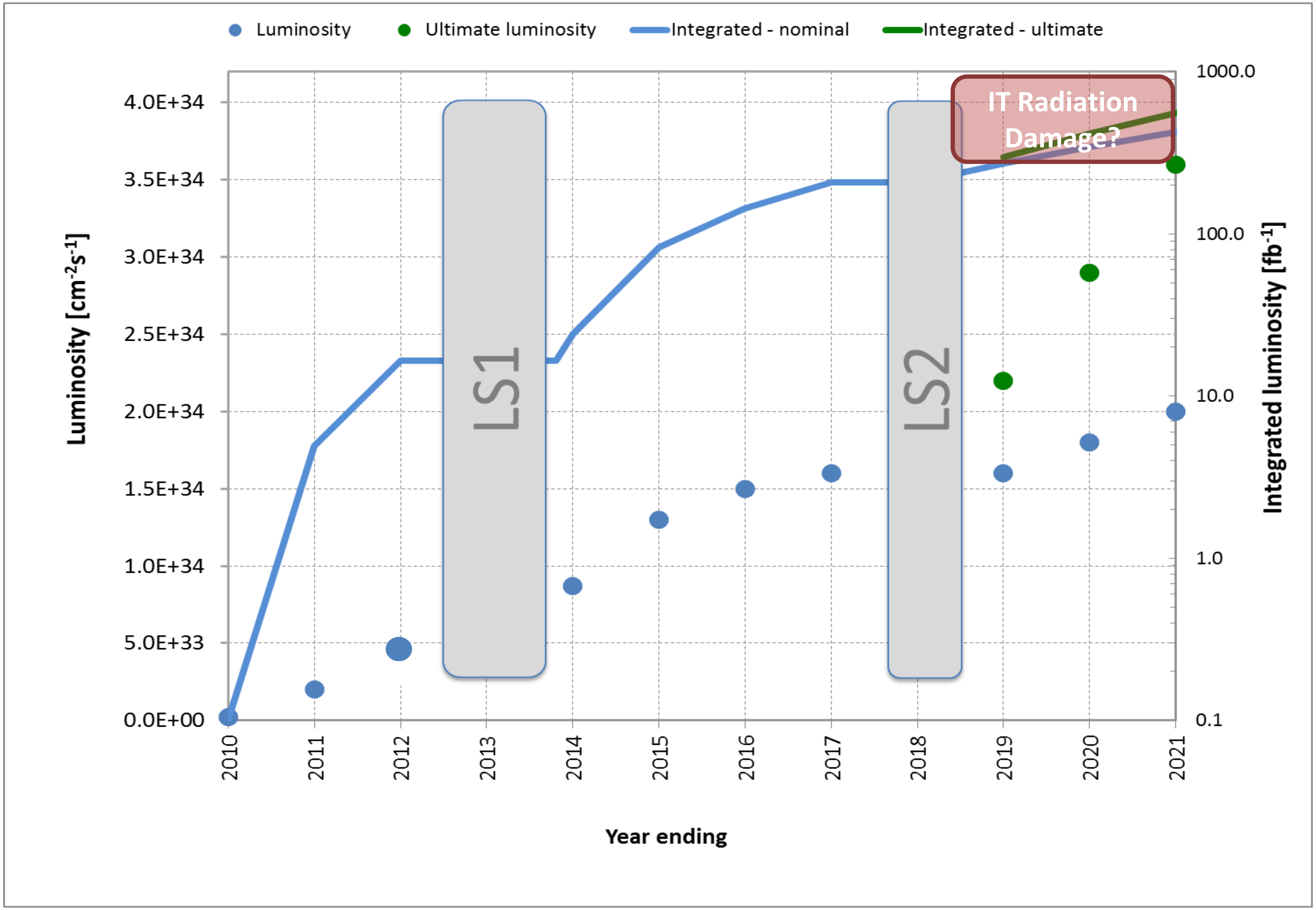
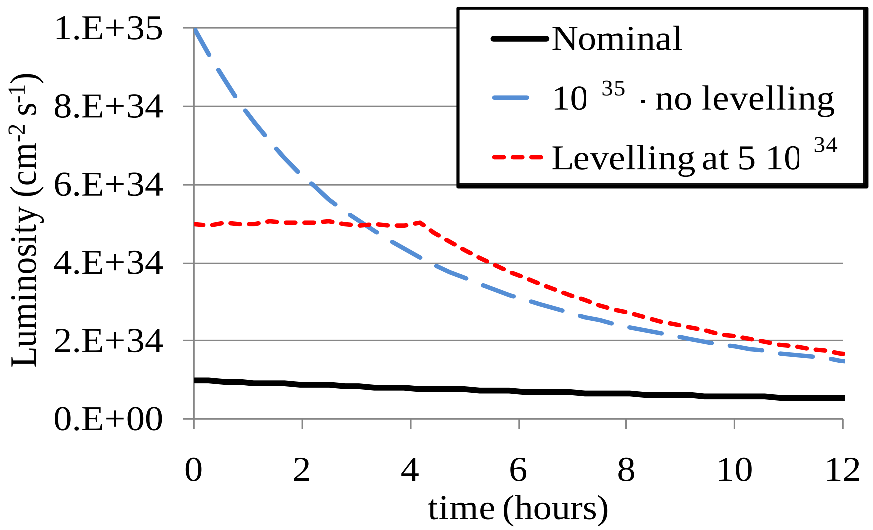


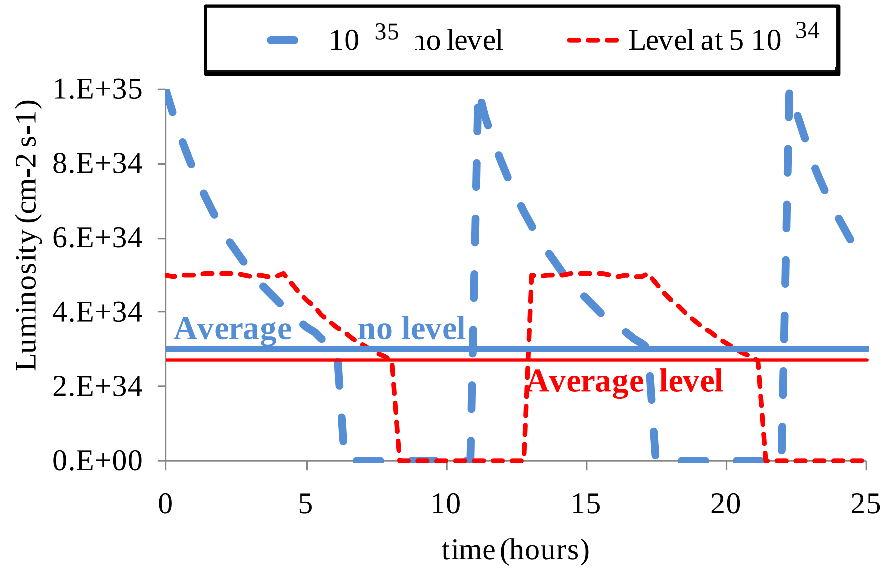
HL-LHC The Goal

The main objective of HL-LHC is to implement a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

- A luminosity of **5×10^{34} $cm^{-2}s^{-1}$ with leveling**
- Implies a "Virtual" peak luminosity of $>10^{+35}$ $cm^{-2}s^{-1}$
- An integrated luminosity of **250 fb^{-1}** per year, enabling the goal of **3000 fb^{-1}** twelve years after the upgrade.

Why Level?

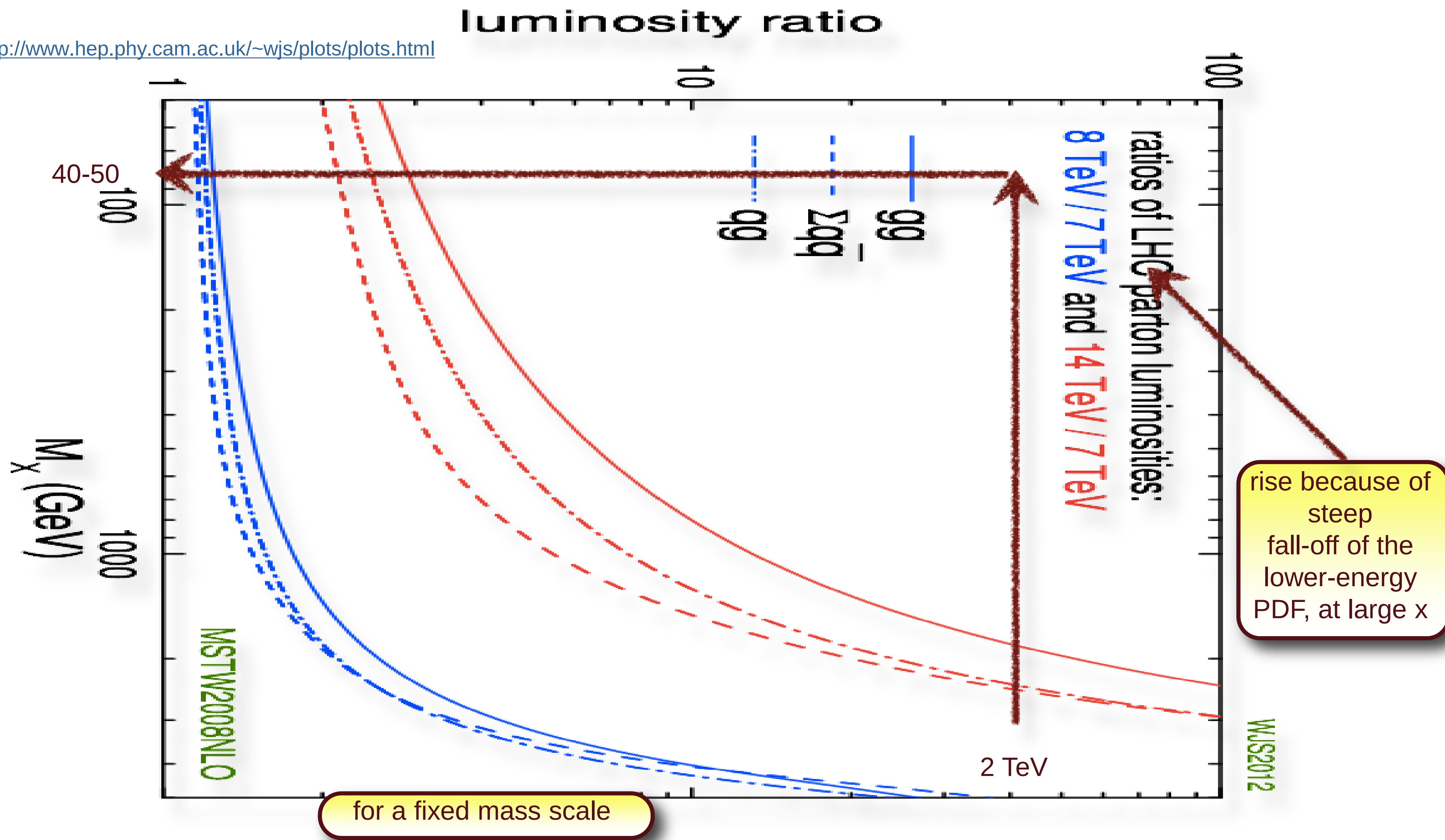




- ✓ *Allow design integrated Luminosity for a lower peak L, and less pile up for the experiments*
- ✓ *Lower peak heat deposition in the magnets*

Parton luminosities

from http://www.hep.phy.cam.ac.uk/~wjs/plots/plots.html



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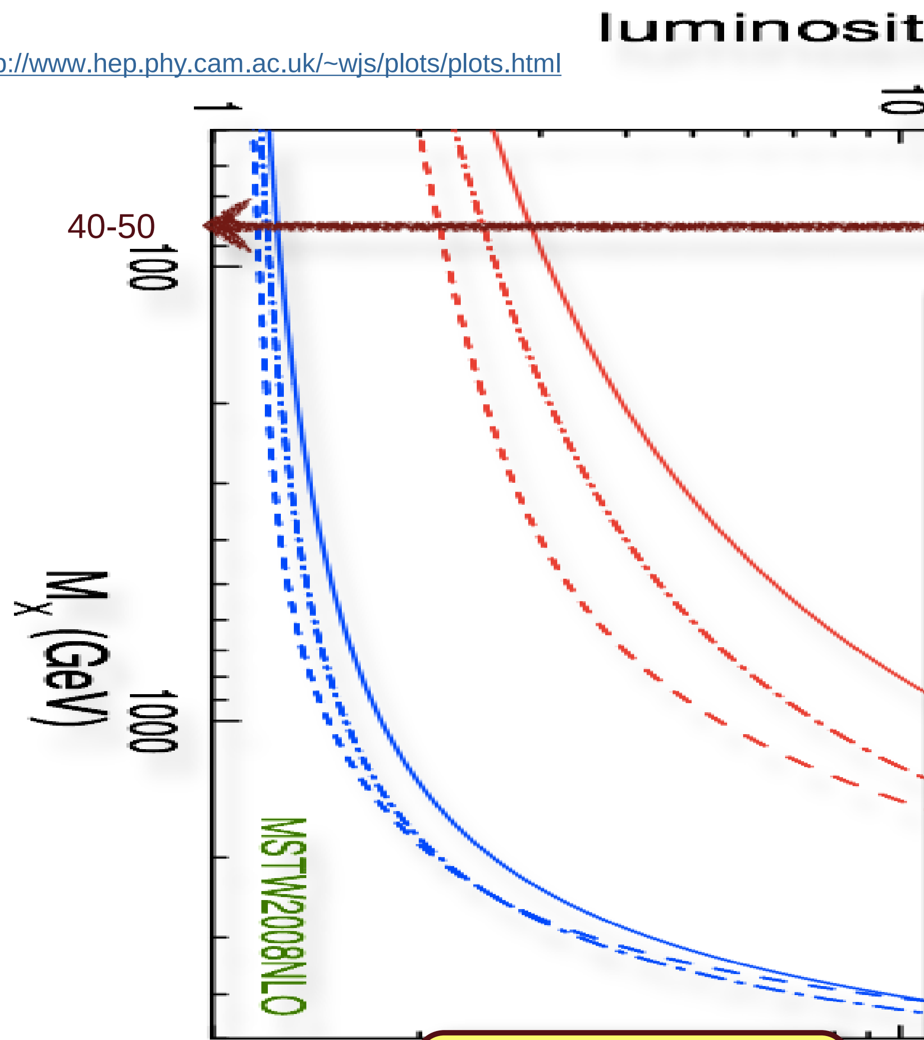
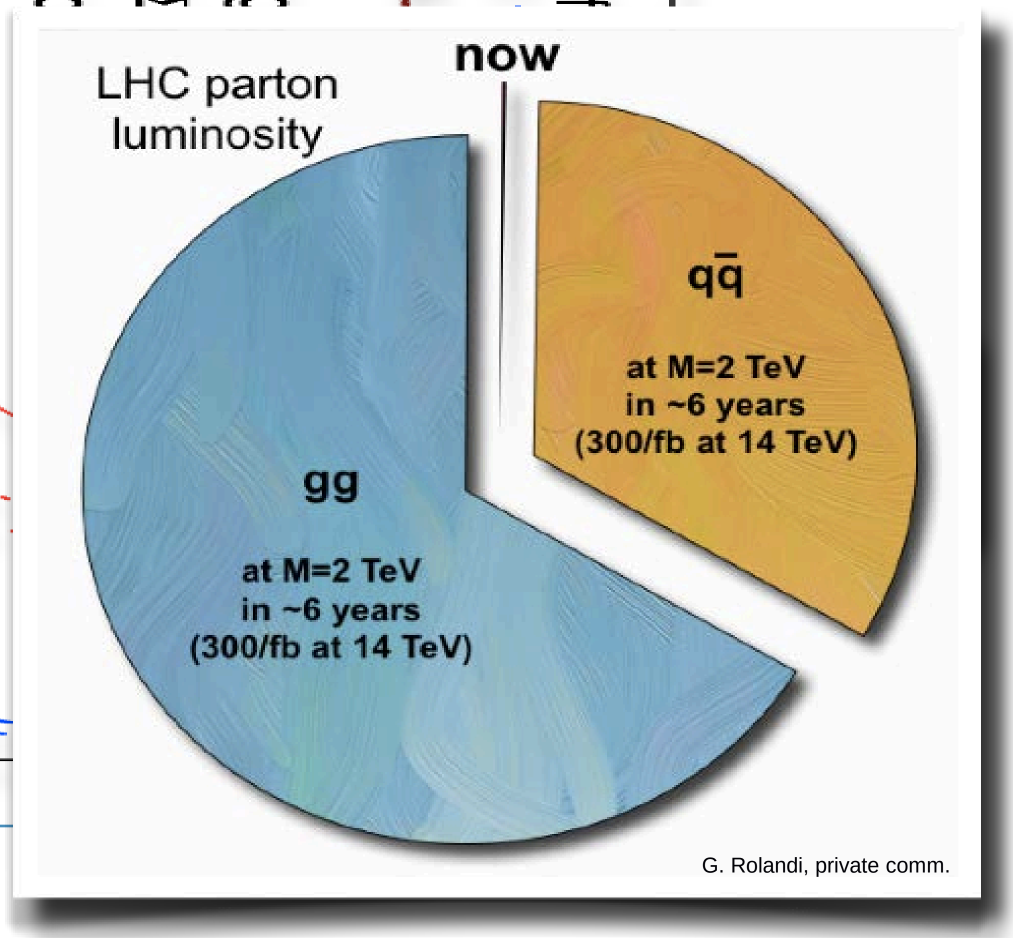


for a fixed mass scale



Extending the reach…

- Weak boson scattering
- Higgs properties
- Supersymmetry searches and measurements
- Exotics
- t properties
- Rare decays
- CPV
- ..etc

Couplings fit at HL-LHC

CMS

Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

CMS Projection

Assumption NO invisible/undetectable contribution to Γ_H:

- Scenario 1: system./Theory err. unchanged w.r.t. current analysis
- Scenario 2: systematics scaled by 1/sqrt(L), theory errors scaled by ½

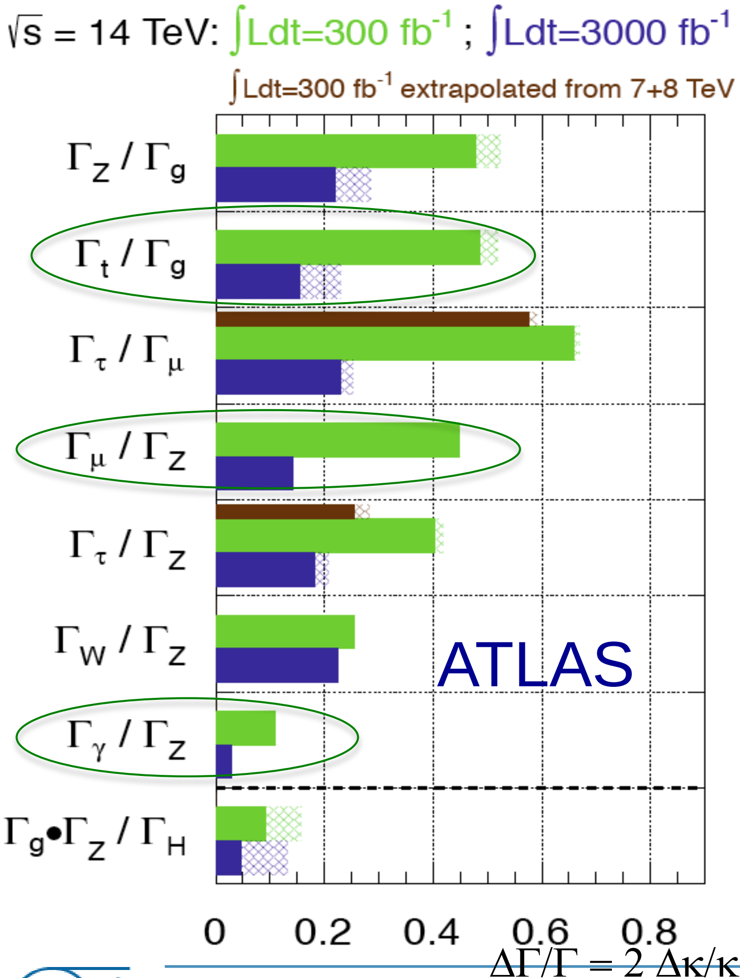
✓ γγ loop at 2-5% level

✓ down-type fermion couplings at 2-10% level

✓ direct top coupling at 4-8% level

✓ gg loop at 3-8% level

Coupling Ratios Fit at HL-LHC



- Fit to coupling ratios:
  - No assumption BSM contributions to Γ_H
  - Some theory systematics cancels in the ratios
- Loop-induced Couplings $\gamma\gamma$ and gg treated as independent parameter
  - κ_γ/κ_Z tested at 2%
  - gg loop (BSM) κ_t/κ_g at 7-12%
  - 2nd generation ferm. κ_μ/κ_Z at 8%

A lepton collider: a decisive asset…

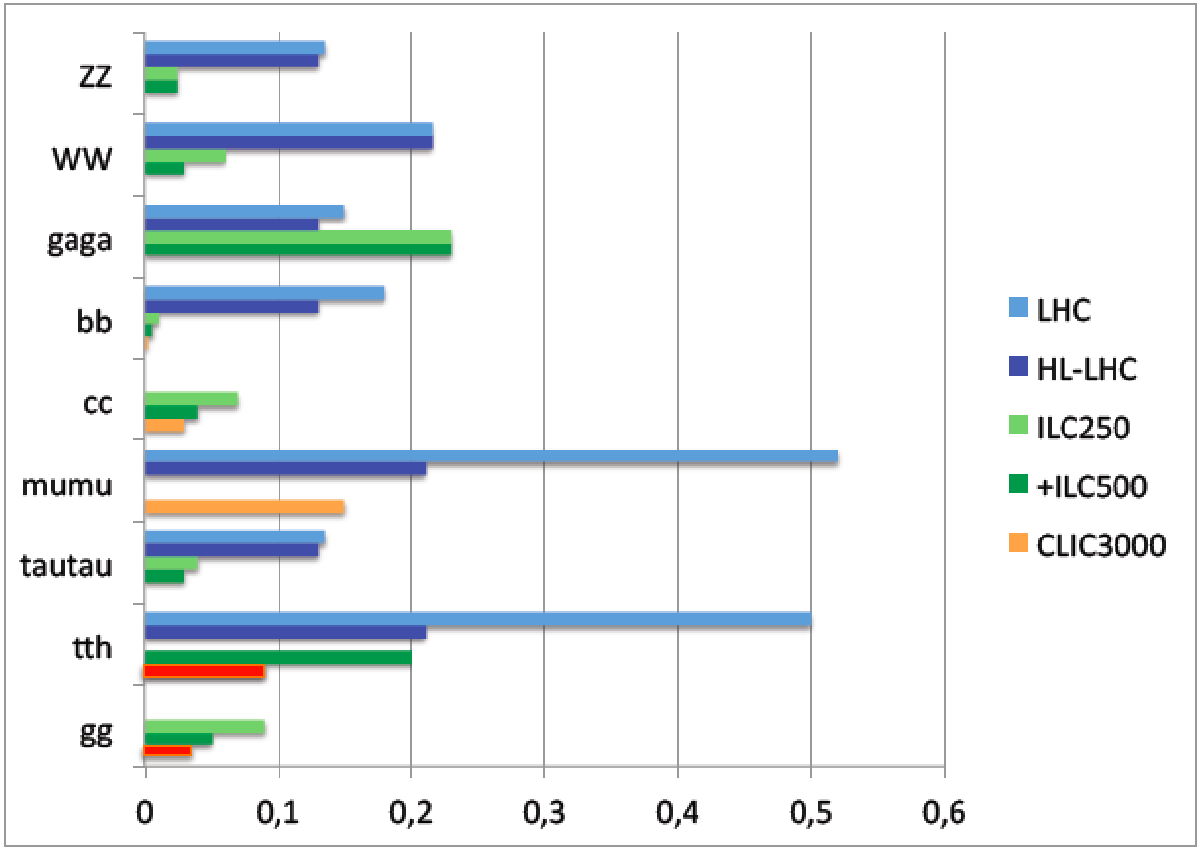
..if

- Can be decided/built soon
- It might start at 250 Gev, but it should be upgradable at 500 GeV, with a possible extension to 1 TeV c.m.

Best candidate: the International Linear Collider:

- Mature design
- TDR delivered
- Japanese community has submitted to the government a request to host it.

LHC vs LC: „signal strength“



KD attempt to compile available experimental studies.
(best estimates)

HANDLE WITH CARE

fineprint:

ATLAS/CMS from Krakow notes
(= preliminary!)

LHC = (ATLAS+CMS)/2 (300 fb^{-1})
HL-LHC = ATLAS (3000 fb^{-1})
ILC250 = 250 fb^{-1} at 250 GeV
+ILC500 = 500 fb^{-1} at 500 GeV + 250 fb^{-1} at 250 GeV
ILC1000 + CLIC3000 are only examples

1) prec. on σ_{HZ}(total)
2) prec. on $\sigma_{WW\text{-}Fusion}$(total)

LHC – mostly syst. limited
LC – mostly stat. limited

ILC1000/CLIC1400 further improves precision

ILC: not only a precision machine

- Great impact in exploring the EWK part of Supersimmetry, in a region which might be not accessible at the LHC, because the unfavorable S/B.
- A fundamental contribution in the precision studies of the W and Z bosons and the top quark.

The joint information coming from LHC and ILC will be a “conditio sine qua non” to enable the next particle accelerator at the energy frontier

The intensity/precision frontier

It is very important to continue to refine the search of New Physics, by exploiting the virtual loops:

a large set of fundamental measurements on LFV, rare $k \rightarrow \pi\nu\nu$ decays, flavor physics, CPT are underway/being planned at PSI, KEK, FERMILAB, JPARC, BINP, CabibboLab and at CERN.

A new generation of experiments trying to measure a nonzero EDM for protons, neutrons, atoms are also been planned in US, Europe and Asia

The success of most of this experiments relies on a robust development of the hosting accelerators

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beyond LHC ?

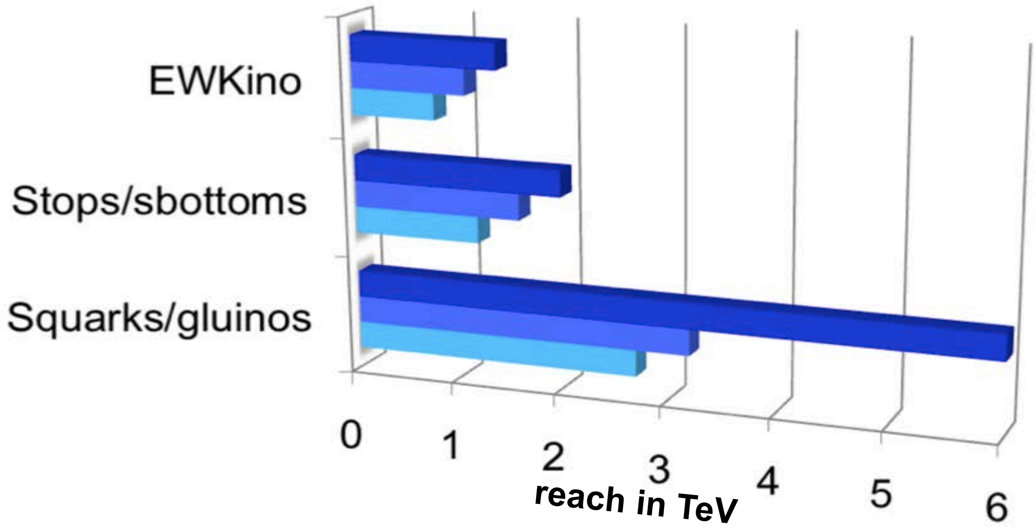
Not only luminosity: High Energy LHC

Preliminary HE-LHC - parameters

	nominal LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40-45
#bunches / beam	2808	1404
bunch population [10^{11}]	1.15	1.29
initial transverse normalized emittance [μm]	3.75	3.75 (x), 1.84 (y)
number of IPs contributing to tune shift	3	2
maximum total beam-beam tune shift	0.01	0.01
IP beta function [m]	0.55	1.0 (x), 0.43 (y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
stored beam energy [MJ]	362	479
SR power per ring [kW]	3.6	62.3
longitudinal SR emittance damping time [h]	12.9	0.98
events per crossing	19	76
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0
beam lifetime [h]	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

Prelim. Projections : direct searches

from the ATLAS/CMS input documents to the strategy process



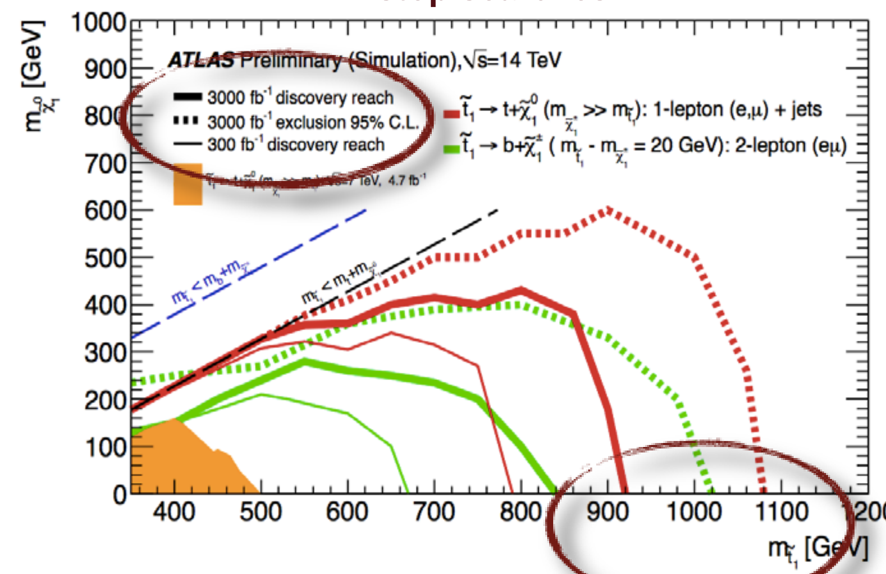
note: LHC projections based on well-tested simulations (validated with current data)

HE-LHC33
HL-LHC14
LHC14

LHC14 will be a new game!

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{\text{Topcolour}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)
$Z'_{SSM} \to ee$	6.5	7.2	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6

stop searches



- “large” masses, small couplings: HL-LHC
- “very large” masses: HE-LHC

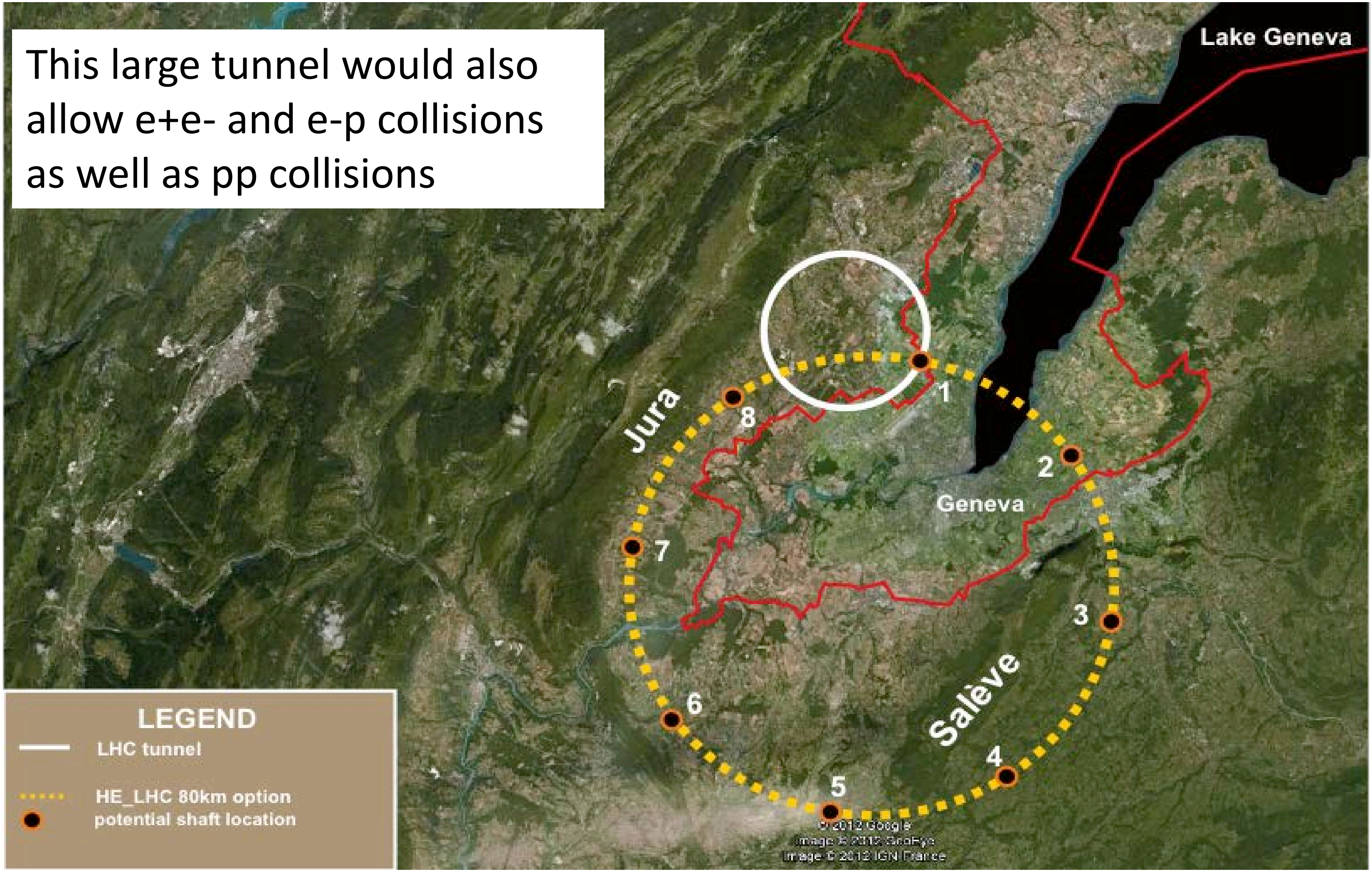
Thinking BIG

- HE-LHC dipole design will piggy back on the high gradient quadrupole R&D needed for HL-LHC
  - Would allow an increase in energy by factor of 2-2.5

- SHE-LHC (??SSC) needs a 80km tunnel
  - In conjunction with the high field magnets would allow a factor of (2-2.5)x(80/27) = 6-7.5 times LHC (42-52 TeV/beam)

Thinking BIG

This large tunnel would also allow e+e- and e-p collisions as well as pp collisions



From Choices *to* Choice

- Japan Roadmap published
- Roadmap discussion (US) in progress, completes next year
- Update of the European Strategy for Particle Physics in 2012/13 ≡ Strategy of Europe in a global context
  - Official approval in Bruxelles, 29-30 May 2013
- Use as 1st step to harmonize globally Particle Physics Strategy

Whatever the choice…

…we will need to be prepared: to this extent, not only generic R&D, but accelerator complex design studies play a fundamental role for the future of the field.

The size, cost and complexity of our projects requires a very careful period of studies, prototyping, industrialization.

A number of projects (CLIC,LHeC, ProjectX, Muon Collider, Tau-charm factory, TLEP, SHELHC, etc, are at different stages of this path:

we should find the resources to bring them all forward

In summary

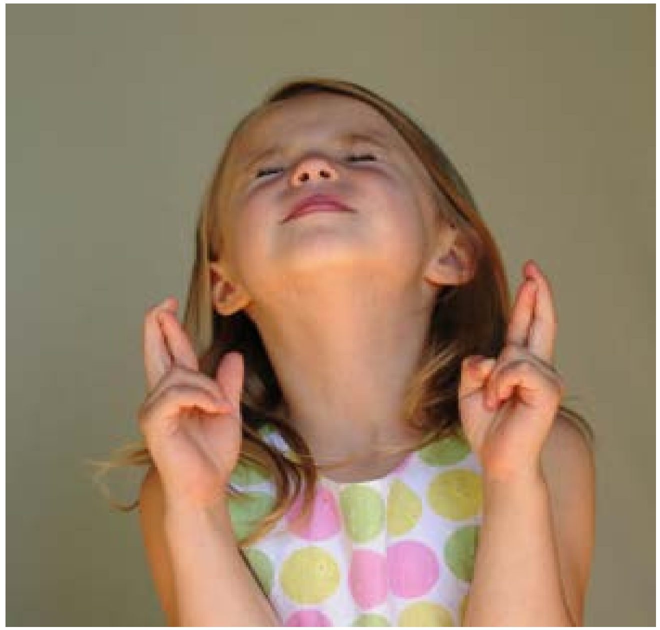
- 2010-2012: extraordinary years!
- But we are just at the beginning of a long journey.
- By now, **experimental results** are dictating the agenda of the field.
- We need to accelerate the reflection on **next steps**
- No time to idle: a lot of work has to be done

In summary

We will need

- Flexibility
- Preparedness
- Visionary global policies

- ...and a bit of luck!



Thank you!