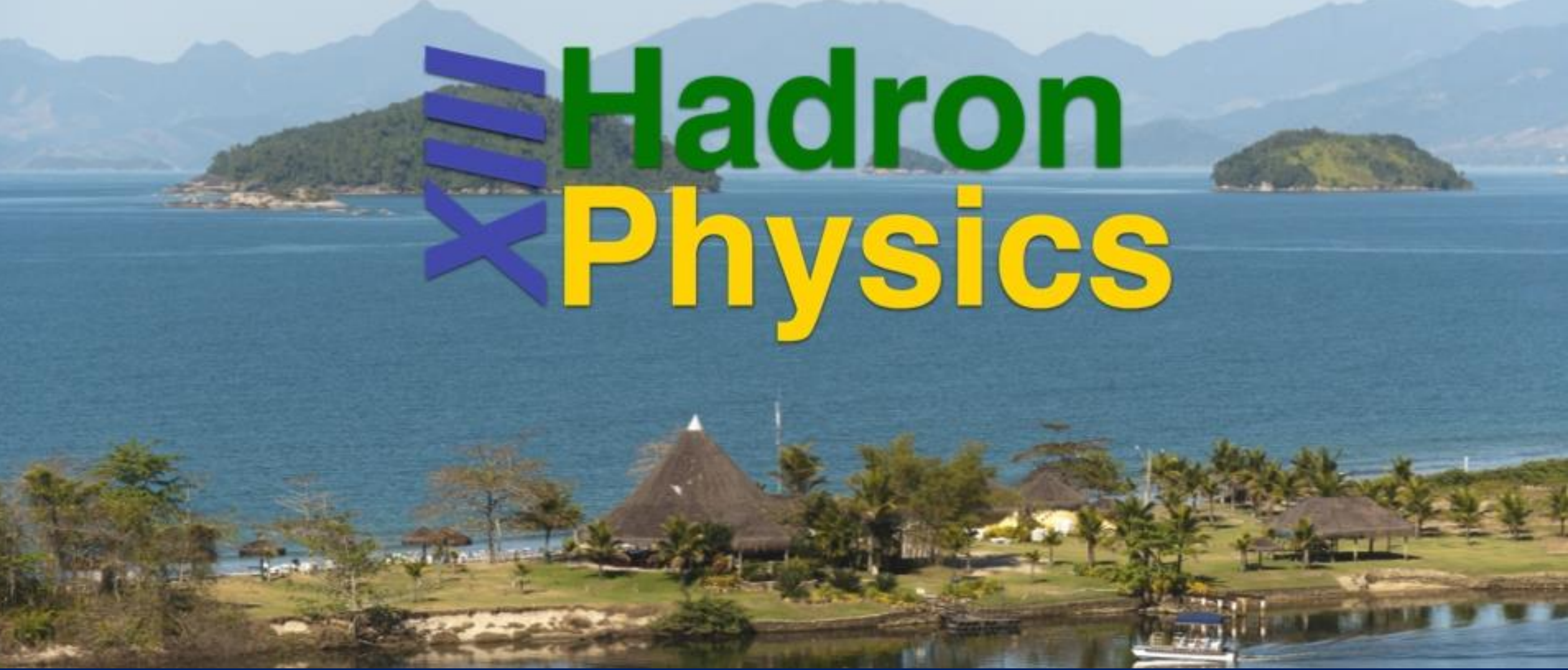


High-Luminosity upgrade of the LHC

Physics and Technology Challenges for the Accelerator and the Experiments

Burkhard Schmidt, CERN

Outline

- Lecture I
  - Physics Motivation for the HL-LHC
  - An overview of the High-Luminosity upgrade of the LHC

- Lecture II
  - Performance requirements for the experiments
  - An overview over the Detector upgrades

- Lecture III
  - Challenges and developments in detector technologies, electronics and computing

Acknowledgements

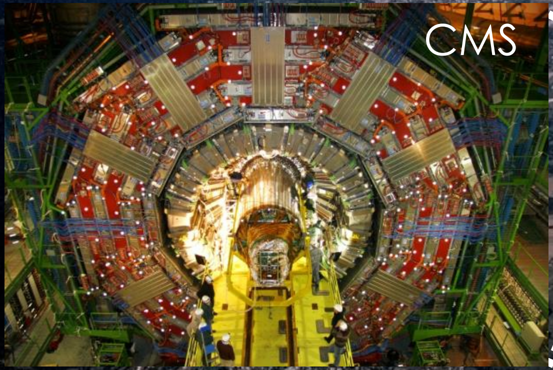
- Most of the material shown in these lectures has been shown at the two
  ECFA HL-LHC workshops
  Aix-les-Bains, France
  October 1-3, 2013,
  October 21-23, 2014
  and the RLIUP workshop,
  Archamps, France, October 2013.

- Sincere thanks to the many speakers who prepared the material for the above workshops !

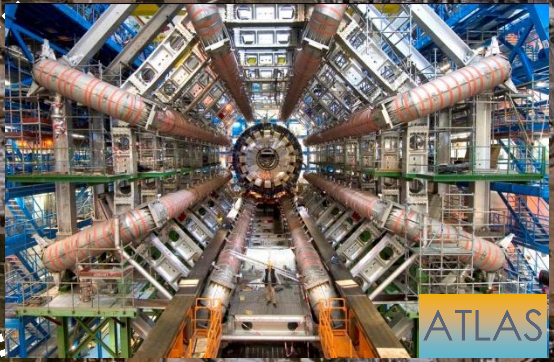
Jörg Wenninger

The LHC Accelerator Complex

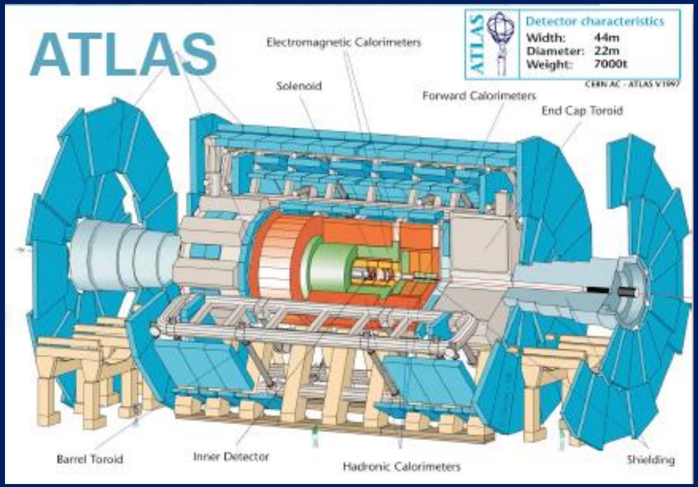
The Large Hadron Collider – LHC



Study of proton and lead collisions
at the TeV scale



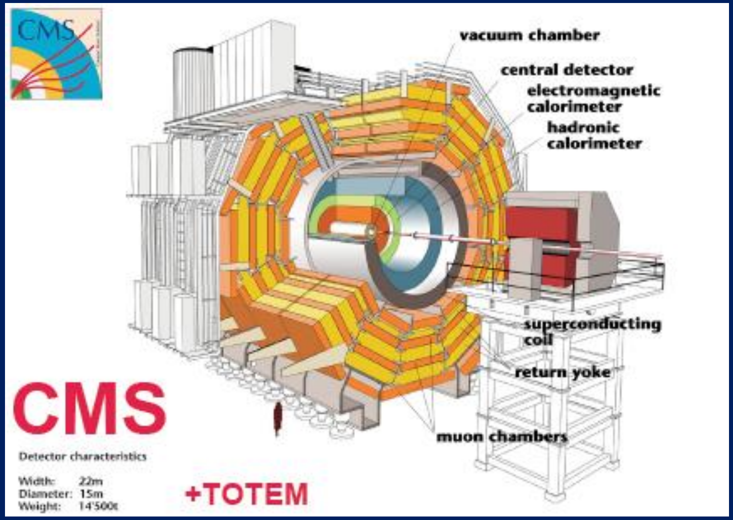
The LHC Detectors



ATLAS
7000 ton
l = 46m
D = 22m

ATLAS and CMS are General Purpose Detectors (GPD) for data-taking at high Luminosity.

LHCb is specialized on the study of particles containing b- and c- quarks



CMS
12500 ton
l = 22m
d = 15m

ALICE Detector is optimized for the Study of Heavy Ion physik.

Physics Motivation for the HL-LHC

- What did we accomplish so far with the LHC ?
- What are the outstanding questions ?
- How can the HL-LHC address them ?

Three main results from LHC Run-I

1. **We have consolidated the Standard Model (SM)**
   - The Standard Model works BEAUTIFULLY …

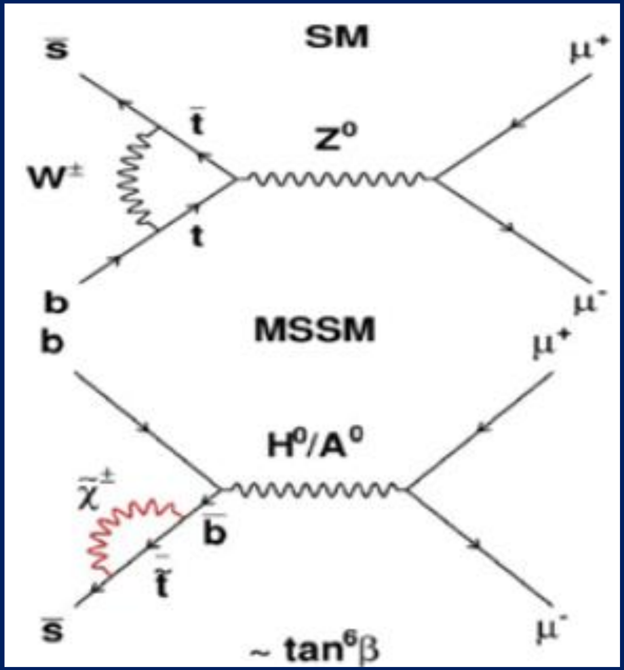
2. **We have completed the Standard Model:**
   - Higgs boson discovery

     Almost 100 years of theoretical and experimental efforts !

3. **We have NO evidence of new physics**

Consolidation of the Standard Model

- Wealth of measurements at 7-8 TeV at t LHC
  - They include the $B_{s,d} \rightarrow \mu\mu$ decay:
    - Very rare process: helicity suppressed FCNC
    - Small, but well predicted value in SM
    - Very sensitive probe to Higgs sector of New Physics models



- Standard Model expectations:
  - $B(B_s \rightarrow \mu^+ \mu^-) = (3.54 \pm 0.30) \times 10^{-9}$
  - $B(B_d \rightarrow \mu^+ \mu^-) = (1.0 \pm 0.1) \times 10^{-10}$

  [arXiv 1208.0934 and arXiv:1204.1737]

$B_{s,d} \rightarrow \mu^+\mu^-$ result

- Probability that the decay happens is measured to be

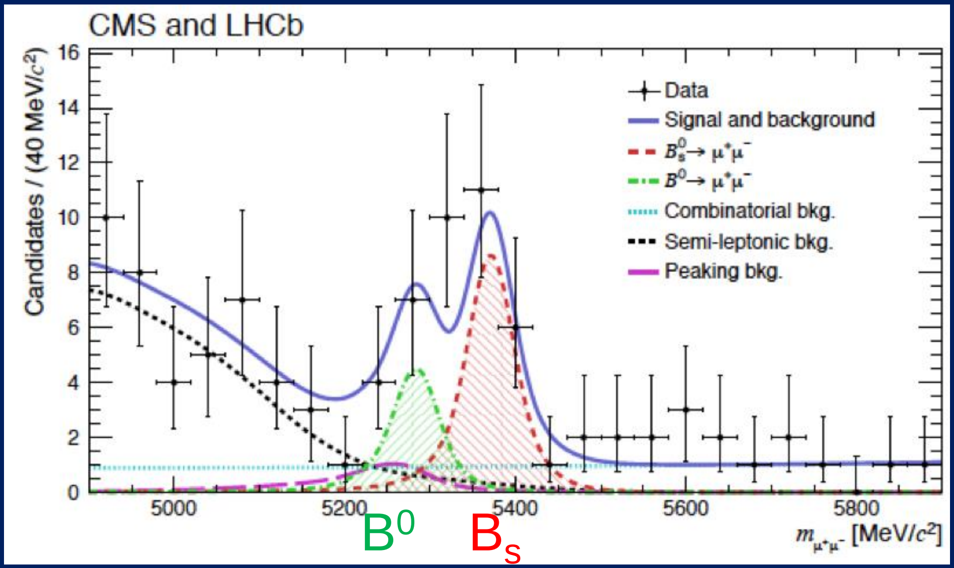
$$BR(B^o_s \rightarrow \mu^+ \mu^-) = 2.8\ ^{+0.7}_{-0.6} \times 10^{-9}$$

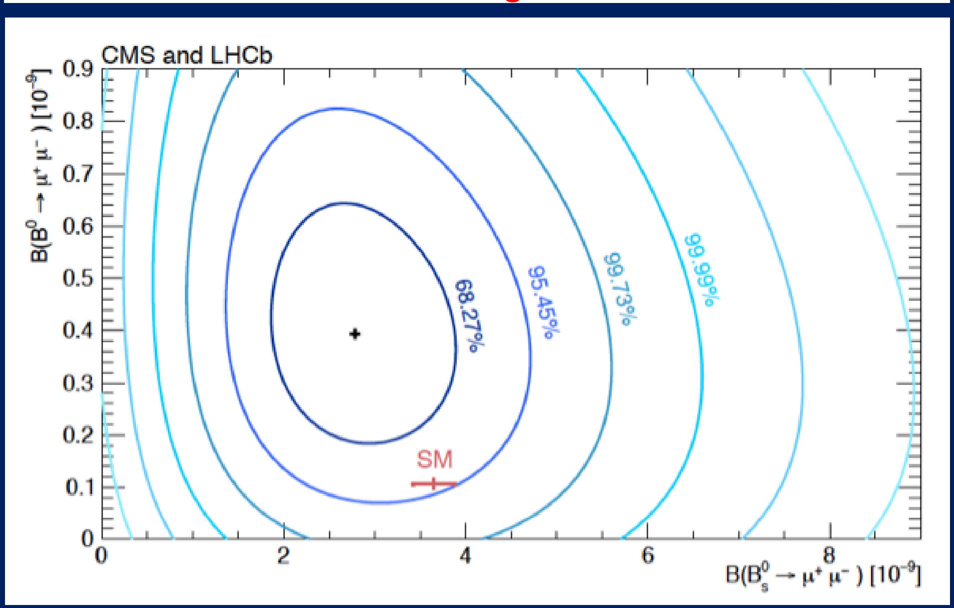
$$BR(B^o_d \rightarrow \mu^+ \mu^-) = 3.9\ ^{+1.6}_{-1.4} \times 10^{-10}$$

- Significance of $B^o_s \rightarrow \mu^+ \mu^-$ is 6.2 σ
- ➢ First observation of this decay!

- ➢ Excess of events at the 3 σ level observed for $B^o_d \rightarrow \mu^+ \mu^-$ hypothesis with respect to bkg.
- ➢ Compatible with the SM at 2.2 σ

- ➢ Joint CMS-LHCb paper to Nature





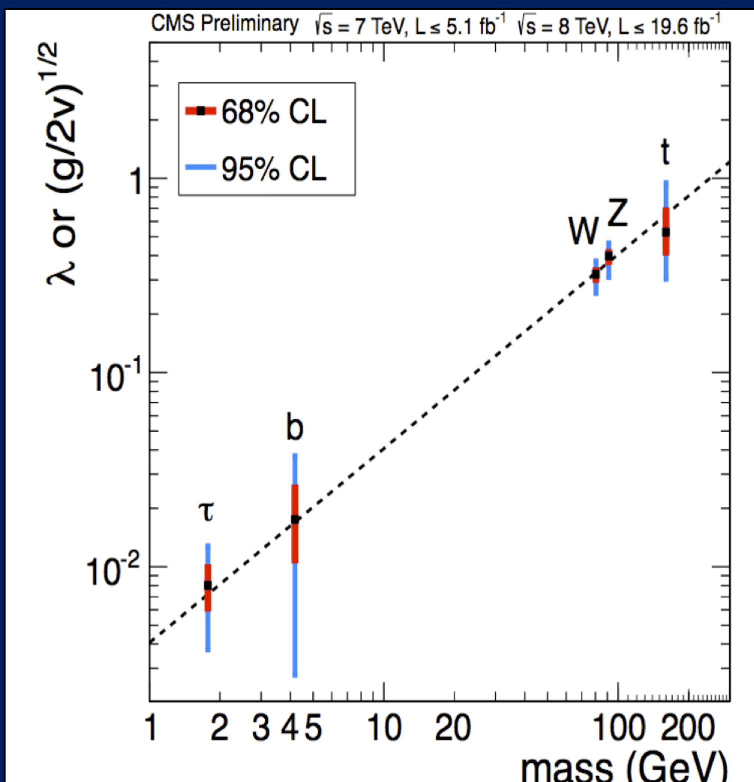
Higgs boson discovery

YES !

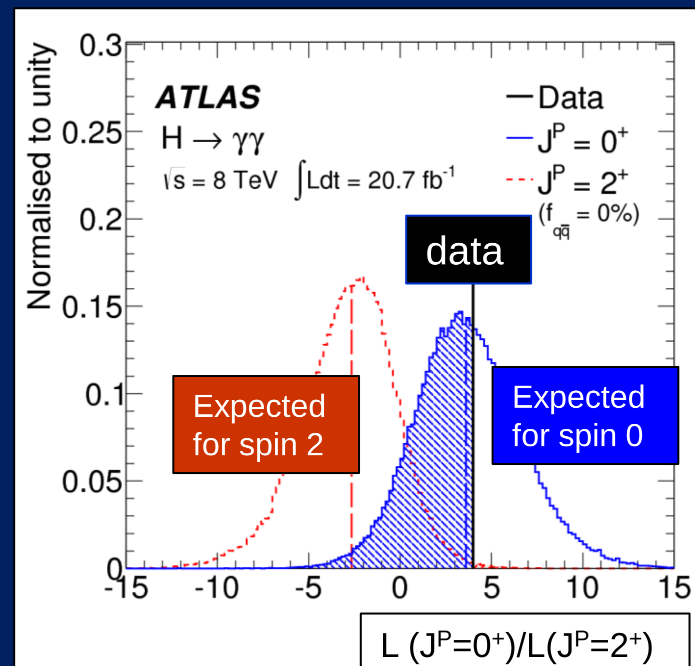
Is the new particle the SM Higgs boson ?

The two "Fingerprints" verified by ATLAS and CMS

1. **It interacts with other particles (in particular W, Z) with strength proportional to their masses**

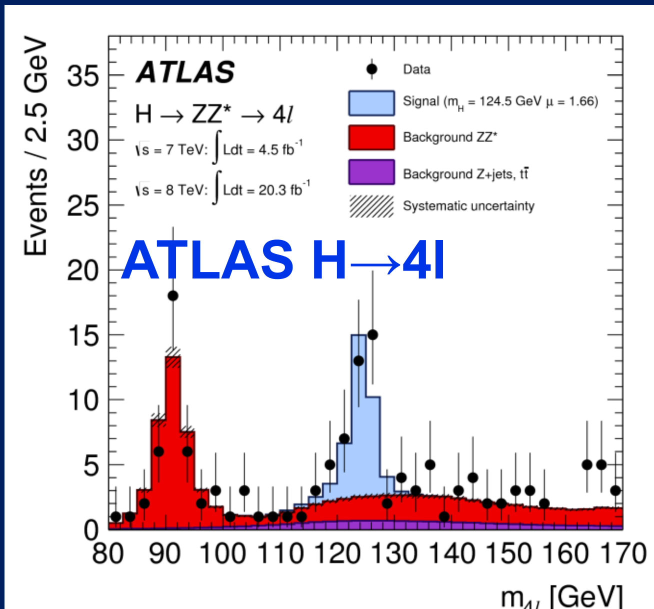


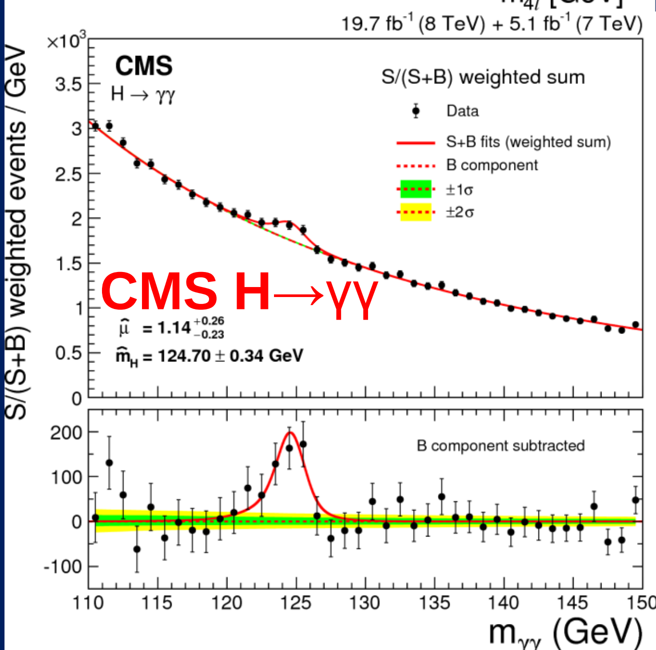
2. **It has spin zero (scalar)**



Hypothesis	Rejection (C.L.)
0^-	97.8%
1^+	99.97%
1^-	99.7%
2^+	99.9%

ATLAS+CMS Higgs mass combination

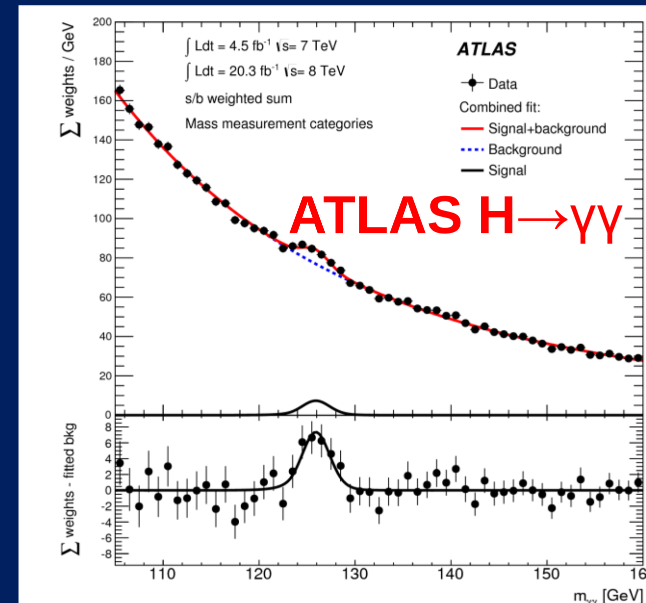


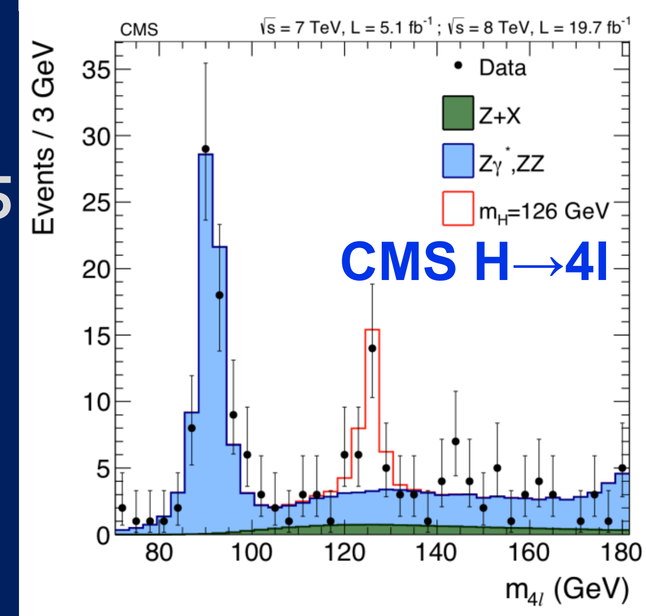


Combination of ATLAS+CMS mass measurements in

- $H \to \gamma\gamma$
- $H \to 4l$

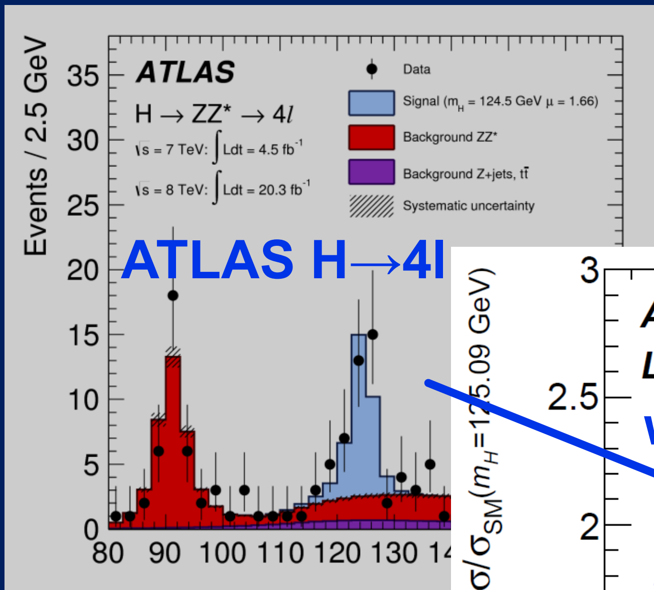
Shown for the first time at Moriond 2015 last week; result submitted to PRL

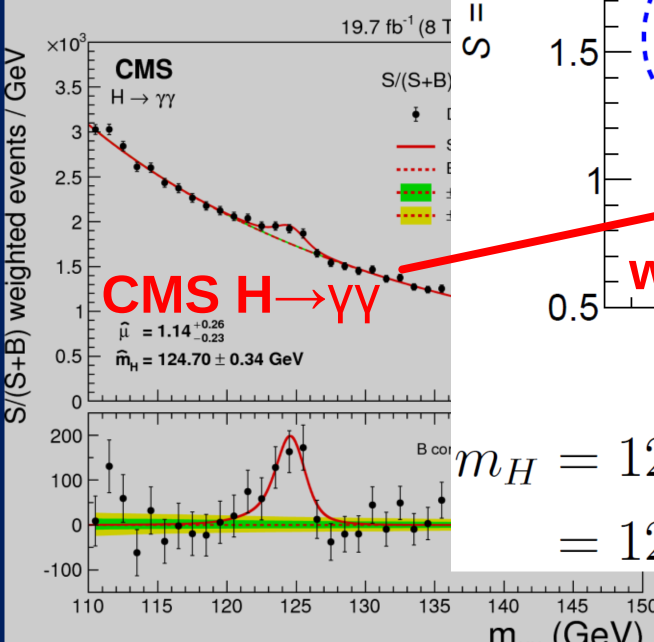


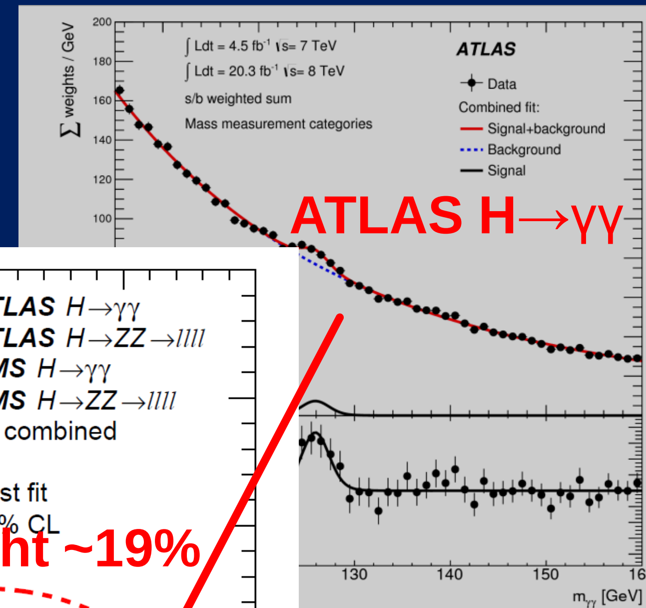


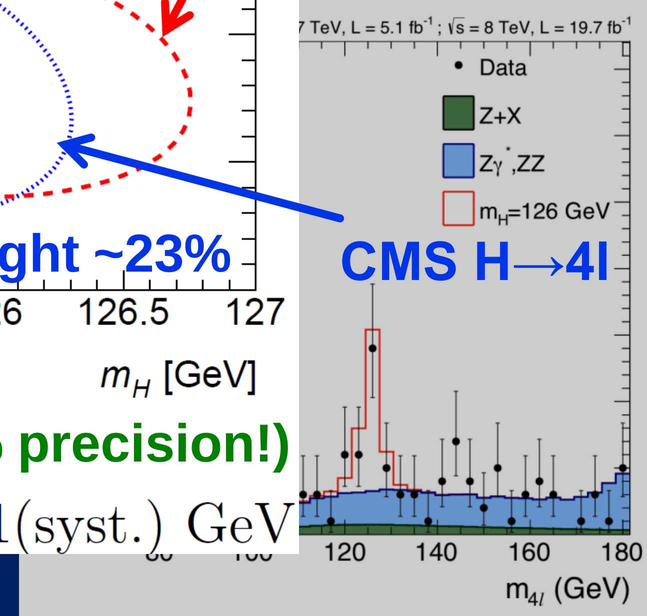
ATLAS+CMS Higgs mass combination

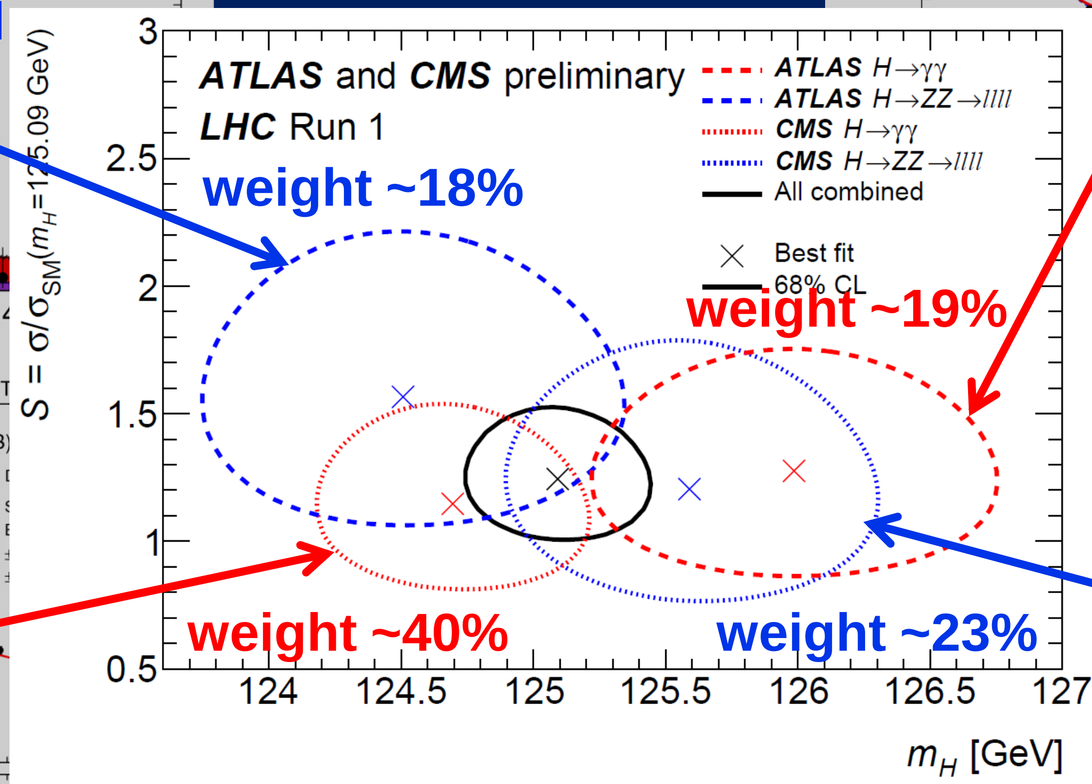
Combination of ATLAS+CMS mass measurements











$$m_H = 125.09 \pm 0.24 \text{ GeV}$$ **(0.19% precision!)**

$$= 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV}$$

NO evidence of new physics so far

This is VERY puzzling:

- **On one hand**: the LHC results imply that the SM technically works up to scales much higher than the TeV scale.
- Limits on new physics seriously challenge the simplest attempts (e.g. minimal SUSY) to fix its weaknesses

- **On the other hand**: there is strong evidence that the SM must be modified with the introduction of new particles and/or interactions at some energy scale to address fundamental outstanding questions, including the following:

1. Why is the Higgs boson so light (so-called “naturalness” or “hierarchy” problem) ?
2. What is the nature of the matter-antimatter asymmetry in the Universe ?
3. Why is Gravity so weak ?
4. And perhaps the most disturbing one …

The DARK Universe (96%):
73% Dark Energy
23% Dark Matter

Only 4% is ordinary (visible) matter

DARK …. MATTERS !

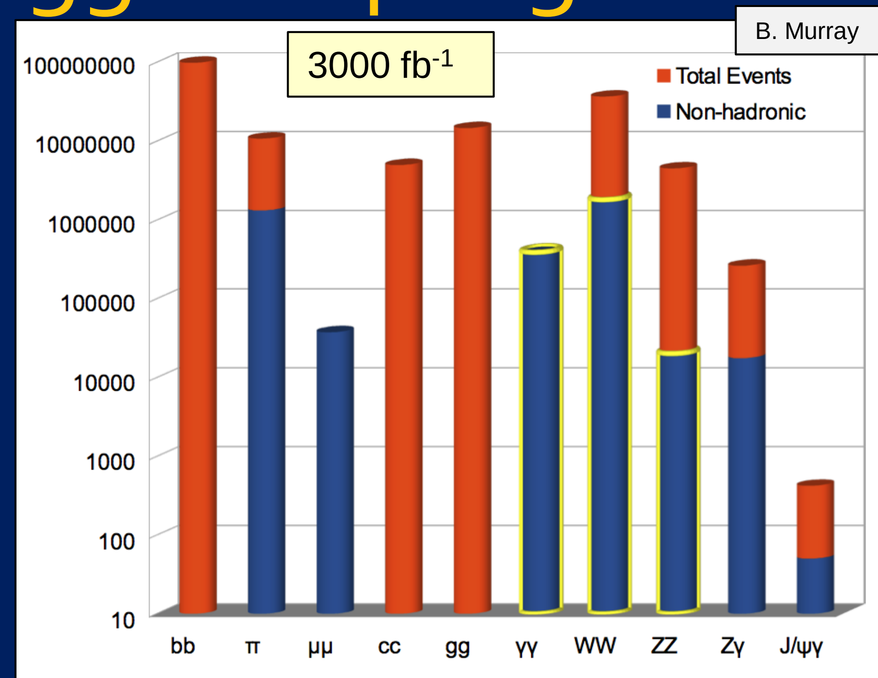
Some of the outstanding questions …

- Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?
- What is the nature of the matter-antimatter asymmetry in the Universe ?
- Why is Gravity so weak ?
  Are there additional (microscopic) dimensions responsible for its "dilution" ?
- What is the nature of Dark Matter and Dark Energy ?
- …. and the "unknown unknown" …
- In addition: The Higgs sector (and the Electroweak Symmetry Breaking mechanism): less known component (experimentally) of the Standard Model
  - A lot of work needed to e.g. understand if it is the minimal mechanism predicted by the SM or something more complex (e.g. more Higgs bosons)
- What can the HL-LHC do to address these (and other) questions ?
- A LOT: answers to some of the above questions expected at the TeV scale whose exploration JUST started … 3000 fb^{-1} are crucial in several cases

→ Here only a few examples …

Measurement of Higgs couplings

- ❑ Measure as many Higgs couplings to fermions and bosons as precisely as possible
- ❑ Measure Higgs self-couplings (give access to λ)
- ❑ Verify that the Higgs boson fixes the SM problems with W and Z scattering at high E

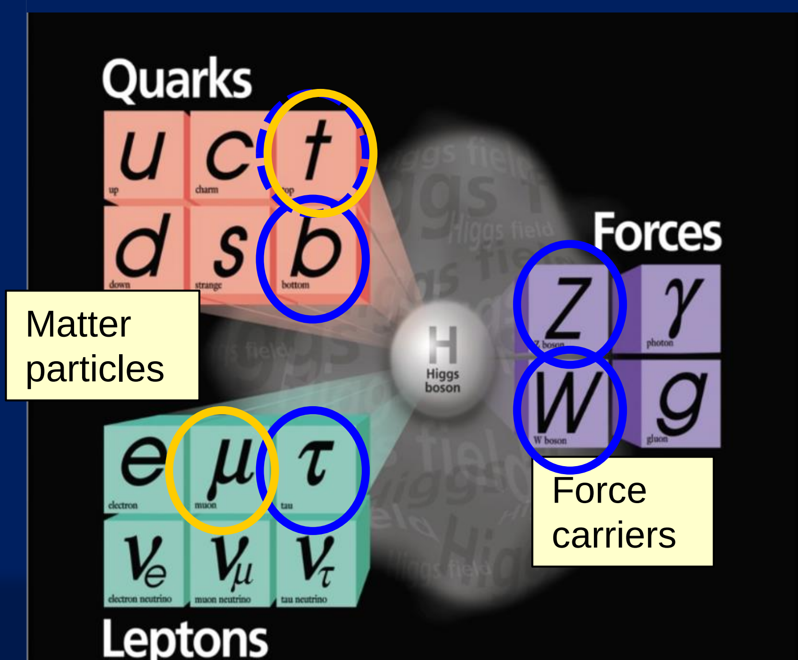


HL-LHC (3000 fb^{-1}): THE Higgs factory:

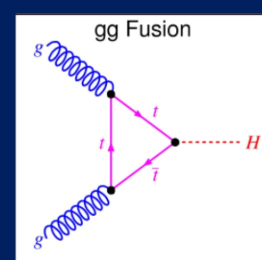
- ❑ > 170M Higgs events produced
- ❑ > 3M useful for precise measurements

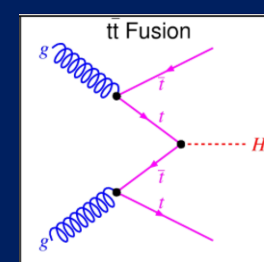
more than (or similar to) ILC/CLIC/TLEP

Today ATLAS+CMS have 1400 Higgs events



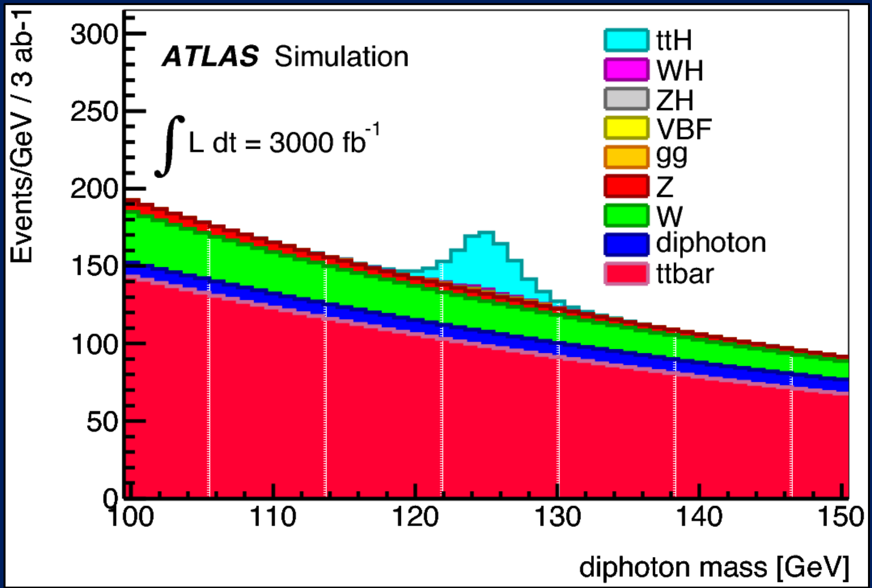
Observed/measured until now (note: top-Higgs coupling indirectly through gg-fusion production)

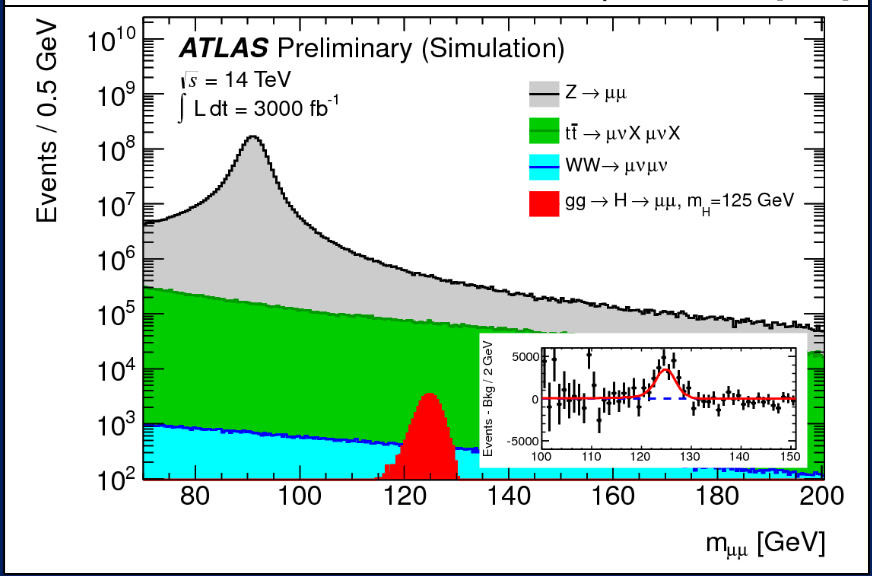




Become accessible with 3000 fb^{-1}: coupling to muons (H→ μμ) and direct coupling to top quark (mainly through ttH→ ttγγ)

Measurement of Higgs couplings





ttH production with H → γγ

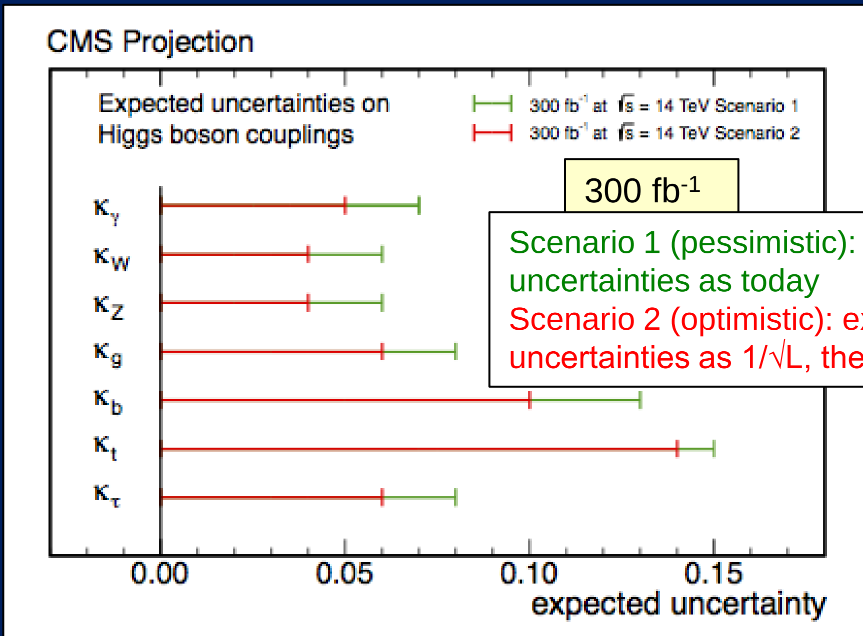
- ❑ Gives direct access to Higgs-top coupling (intriguing as top is heavy)
- ❑ Today's sensitivity: 6xSM cross-section
- ❑ With 3000 fb^{-1} expect 200 signal events (S/B ~ 0.2) and > 5σ
- ❑ Higgs-top coupling can be measured to about 10%

H → μμ

- ❑ Gives direct access to Higgs couplings to fermions of the second generation.
- ❑ Today's sensitivity: 8xSM cross-section
- ❑ With 3000 fb^{-1} expect 17000 signal events (but: S/B ~ 0.3%) and ~ 7σ significance
- ❑ Higgs-muon coupling can be measured to about 10%

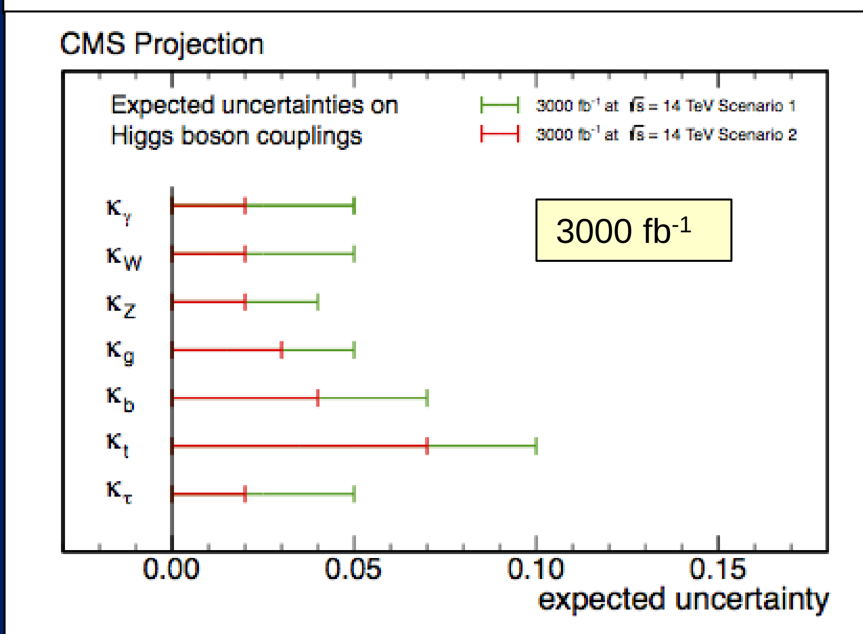
➢ Rare processes → sensitive studies only possible with 3000 fb^{-1}

Measurements of Higgs couplings



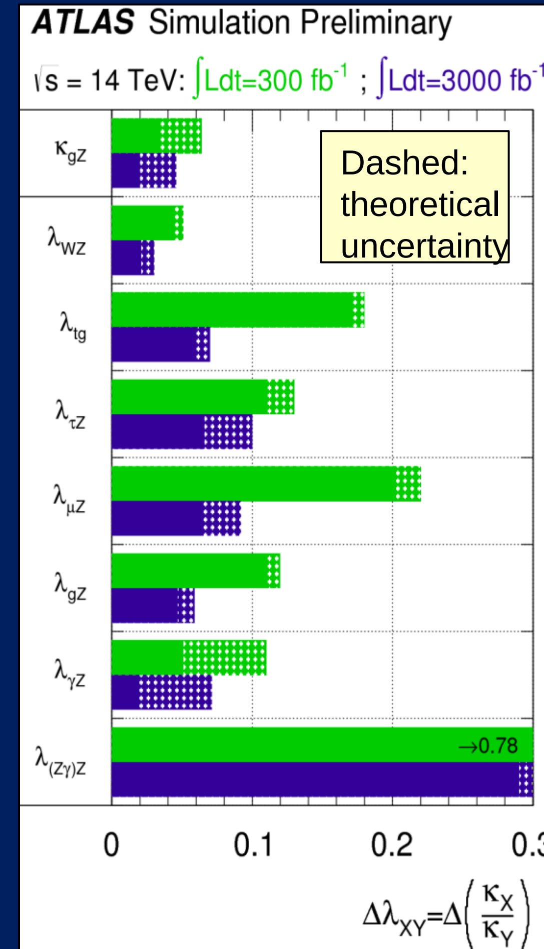
Scenario 1 (pessimistic): systematic uncertainties as today

Scenario 2 (optimistic): experimental uncertainties as $1/\sqrt{L}$, theory halved



k_i= measured coupling normalized to SM prediction

$\lambda_{ij}=k_i/k_j$



Main conclusions:

- 3000 fb^{-1}: typical precision 2-10% per experiment (except rare modes)
  → 1.5-2x better than with 300 fb^{-1}
- Crucial to also reduce theory uncertainties

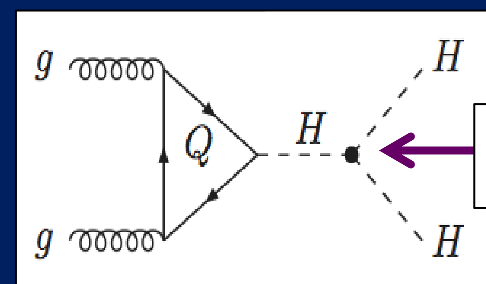
How well can the Higgs couplings be measured ?

Brock/Peskin, Snowmass 2013

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L} dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	10 – 13%	4 – 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

- HL-LHC: %-level → good sensitivity to BSM physics
- ILC/TLEP: sub-percent level

Note: hard to believe that New Physics will manifest itself through tiny effects on Higgs couplings and nothing else …unless very heavy (but then how to interpret the observed deviations ?)



$g_{HHH} \sim \lambda v$

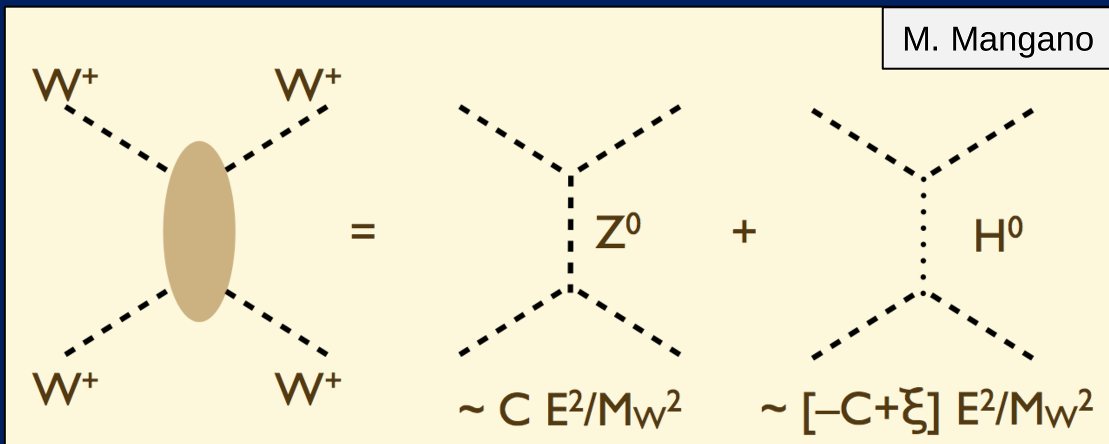
Higgs self-couplings: difficult to measure at any facility (energy is needed …)

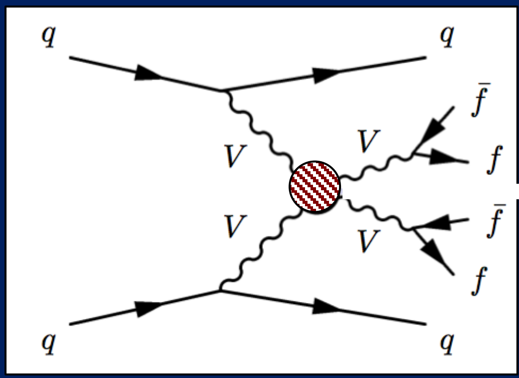
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L} dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	30%	83%	46%	21%	13%	21%	10%	20%	8%

HL-LHC studies not completed yet … ~30% precision expected, but need 3000 fb^{-1}

Vector-Boson Scattering

- W-, Z-Boson Scattering at large m_{VV} provides insight into EWSB dynamics





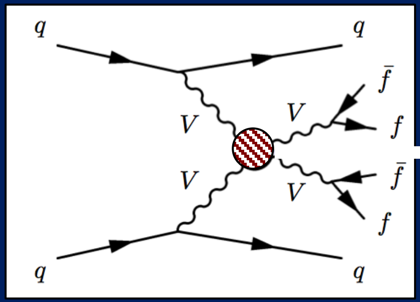
- First process (Z exchange) becomes unphysical ($\sigma \sim E^2$) at $m_{WW} \sim$ TeV if no Higgs, i.e. if second process (H exchange) does not exists. In the SM with Higgs: $\xi = 0$

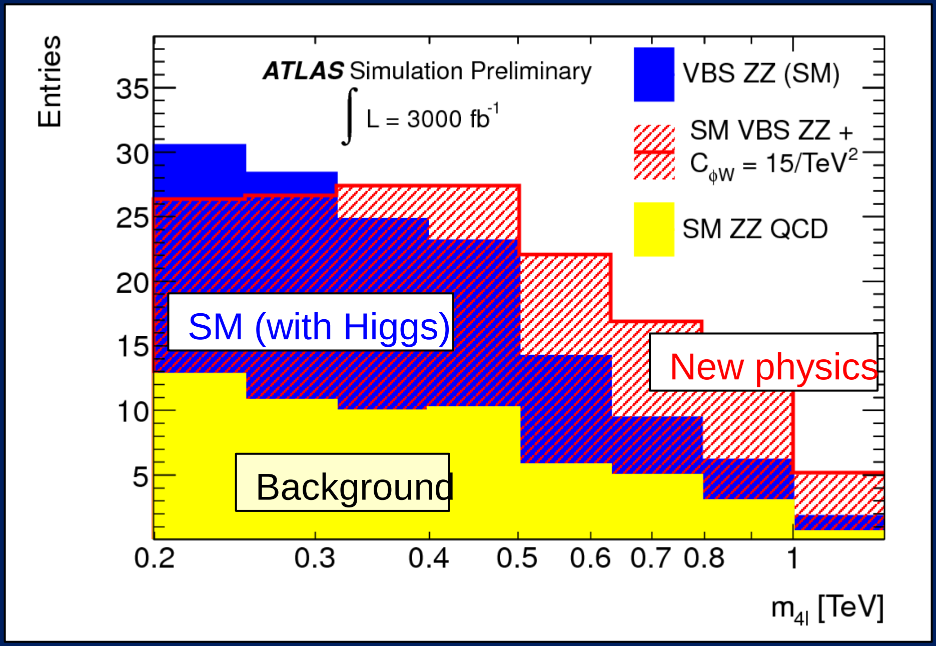
- **Crucial "closure test" of the SM:**
  - Verify that Higgs boson accomplishes the job of canceling the divergences
  - Does it accomplish it fully or partially ? I.e. is $\xi = 0$ or $\xi \neq 0$?
  - If $\xi \neq 0$ → new physics → important to study as many final states as possible (WW, WZ, ZZ) to constrain the new (strong) dynamics

- Requires energy and luminosity → first studies possible with design LHC
- HL-LHC 3000 fb^{-1} needed for sensitive measurements of SM cross section or else more complete understanding of new dynamics

Vector-Boson Scattering

VBS ZZ→ 4l





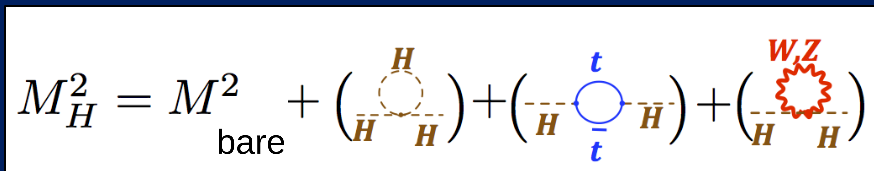
- If no new physics: good behaviour of SM cross section (i.e. no divergence thanks to Higgs contribution) can be measured to 30% (10%) with 300 (3000) fb^{-1}
- If new physics exists: sensitivity increases by factor of ~ 2 (in terms of scale and coupling reach) between 300 and 3000 fb^{-1})

➢ HI-LHC is crucial for a sensitive study of EWSB dynamics

Stability of the Higgs mass

(also known as "naturalness" problem)

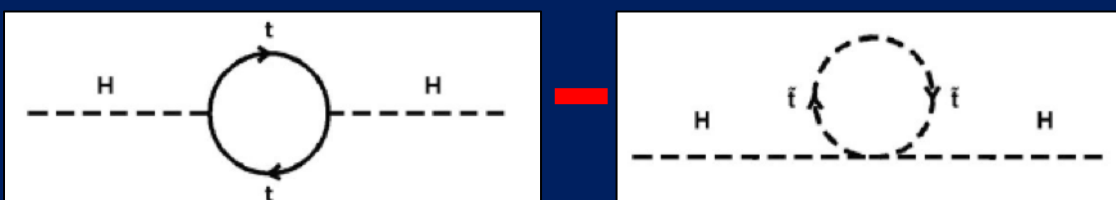
In quantum mechanics, the Higgs mass receives radiative corrections, as other particle



Mostly small, except top contribution: ~ $m_t^2\Lambda^2$
Λ^2 = energy scale up to which the SM is valid (or, equivalently, new physics sets in)

Two solutions:

1) "Naturalness": Higgs mass stabilized by new physics that cancel the divergences.
E.g. SUSY: the contribution of the super-symmetric partner of the top (stop) gives rise to the same contribution with opposite sign → cancellation



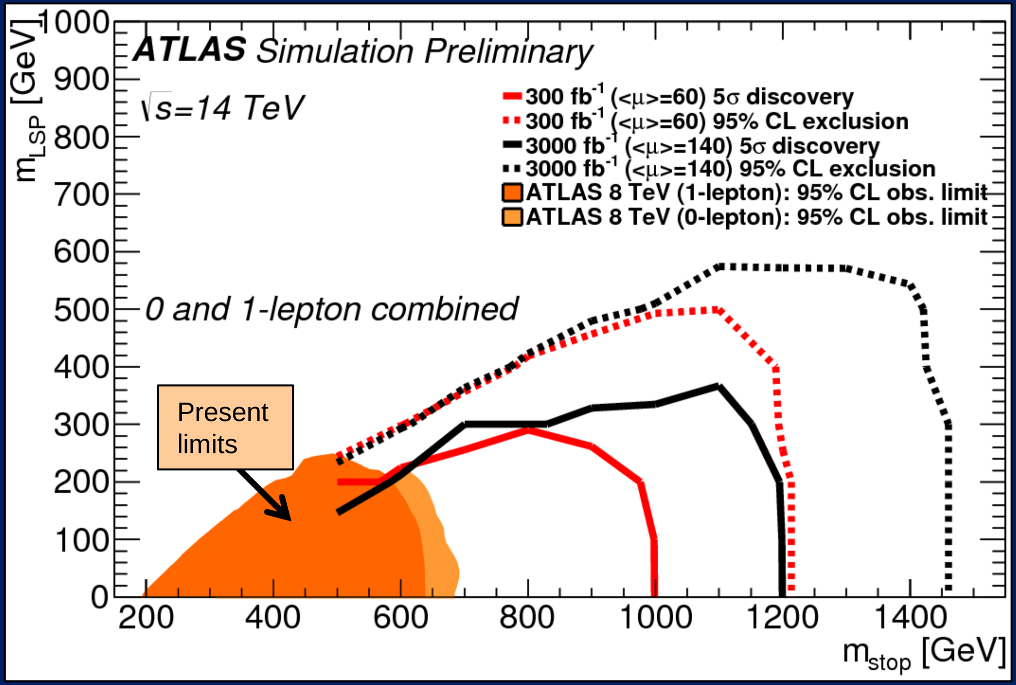
BUT: cancellation only works if stop mass not much larger than top mass
→ this is one of most compelling motivations for SUSY at the TeV scale

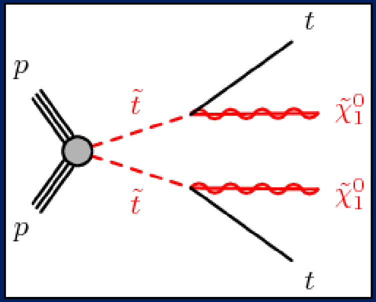
2) "Fine tuning": the bare mass cancels the radiative corrections → this becomes more and more tuned the higher the scale Λ up to which SM is valid (w/o NP)

E.g. Λ = 10 TeV → M^2 (rad. corr) = 8265625 GeV^2
→ need fine-tuned M_{bare}^2 = 8281250 GeV^2 to get M_H^2= (125 GeV)^2 = 15262 GeV^2
Λ= 10^{19} GeV → need fine tuning of M_{bare} to the 33rd digit !! → UNNATURAL

Search for New Physics at the TeV scale

- SUSY searches: to stabilize the Higgs mass, the stop should not be much heavier than ~ 1-1.5 TeV (note: the rest of the SUSY spectrum can be heavier)





Mass reach extends by ~ 200 GeV from 300 to 3000 fb^{-1}
→ most of interesting mass range will be covered !

Philosophical/metaphysical discussions (for the coffee break ...):

- Naturalness is maybe a good concept for us, but not for Nature

→ Anthropic principle: of all possible worlds, we live in a fine-tuned one as otherwise we could not exist

Conclusions part I

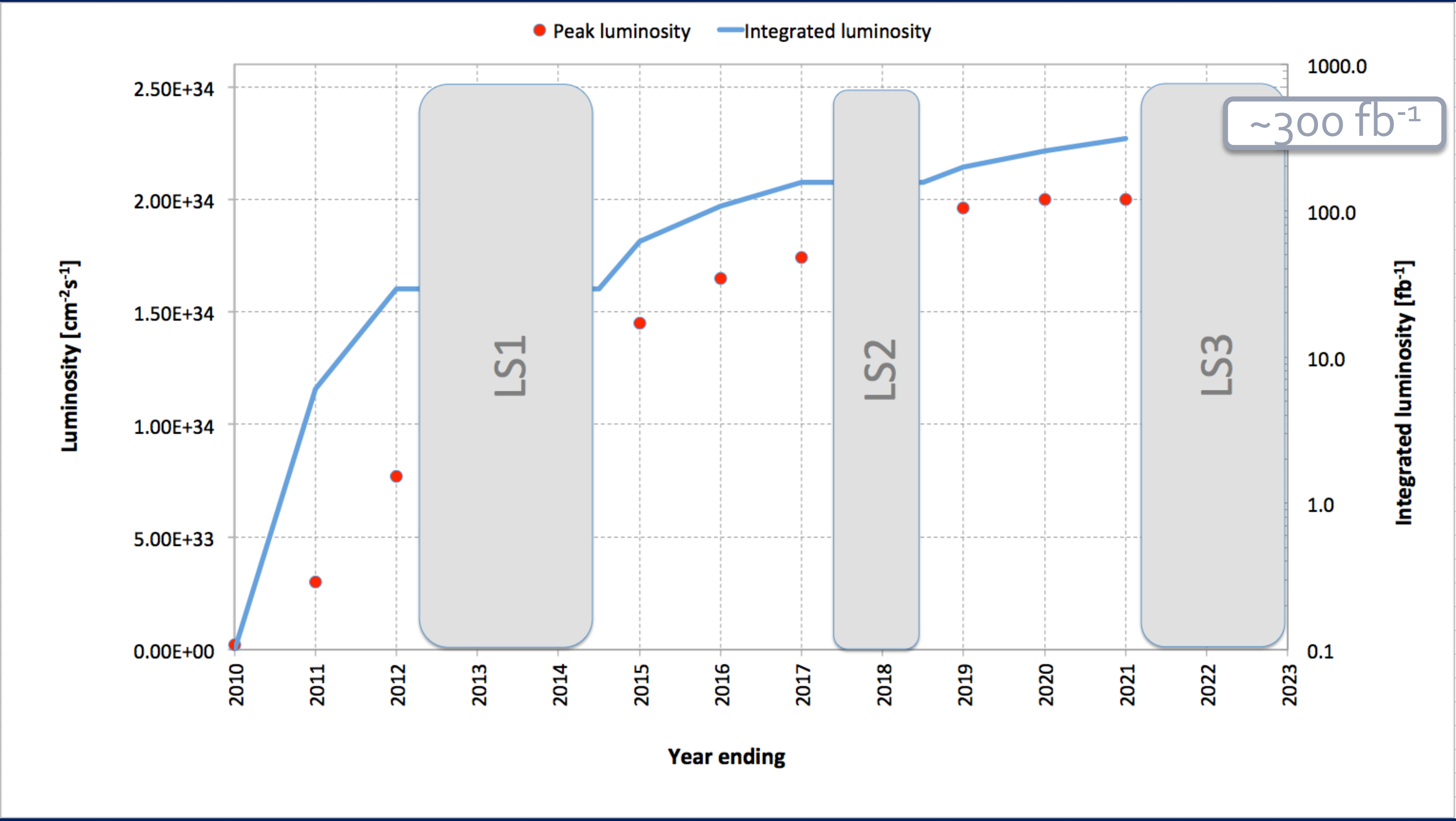
- The discovery of the Higgs boson is a giant leap in our understanding of fundamental physics and the structure and evolution of the universe.
- After almost 100 years of superb theoretical and experimental work, the Standard Model has been completed.
- However, there are many outstanding questions, including:
  - Why is the Higgs boson so light ("naturalness" problem) ?
  - What is the the nature of the dark part (96% !) of the universe ?
  - What is the origin of the matter-antimatter asymmetry ?
  - Why is gravity so weak ?
- The answers to some of the above questions could well lie at the TeV scale, whose exploration only started.

➢ The STRONG physics case for the HL-LHC with 3000 fb^{-1} comes from the importance of exploring this scale as much as we can with the highest-E facility we have today.

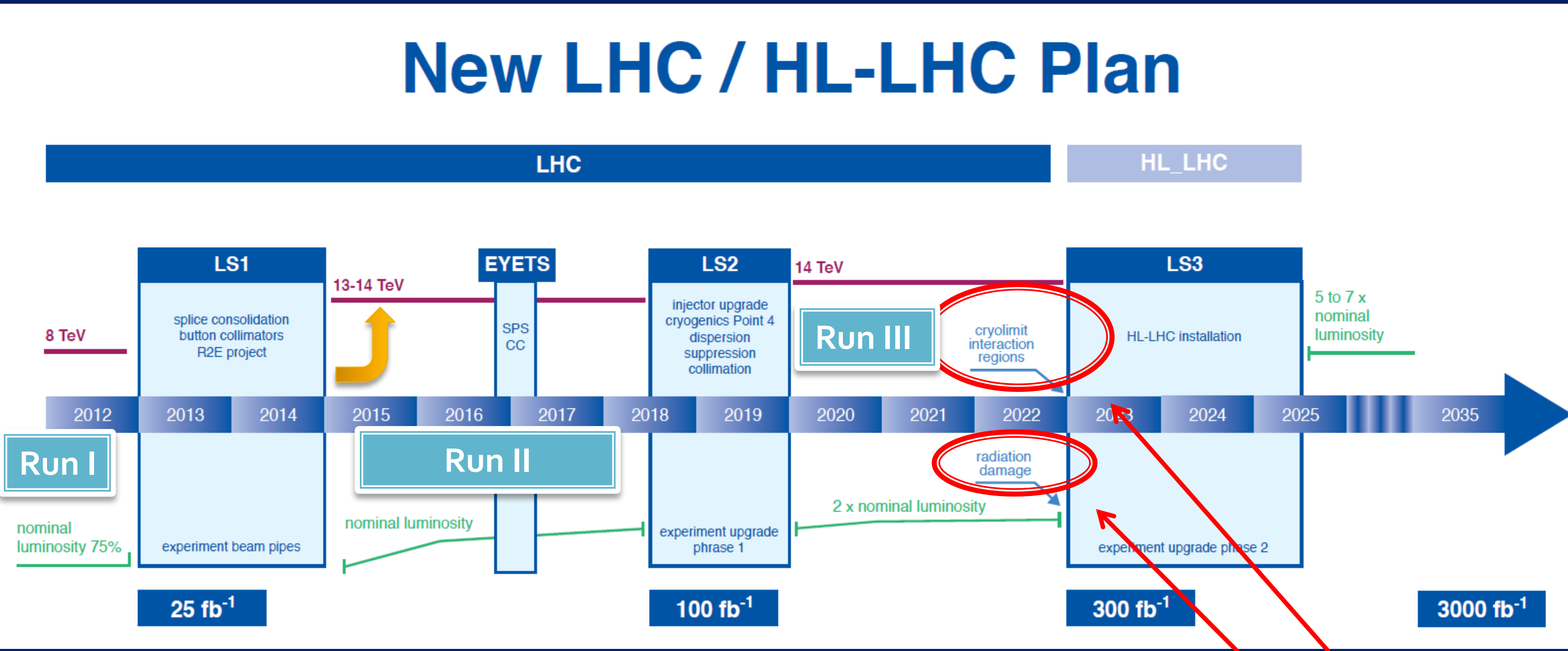
An overview of the High-Luminosity upgrade of the LHC

- Why High-luminosity LHC ?
- Technical limits and bottlenecks
- Challenges for performance improvement

LHC performance projection until 2021



LHC Performance Projection



0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

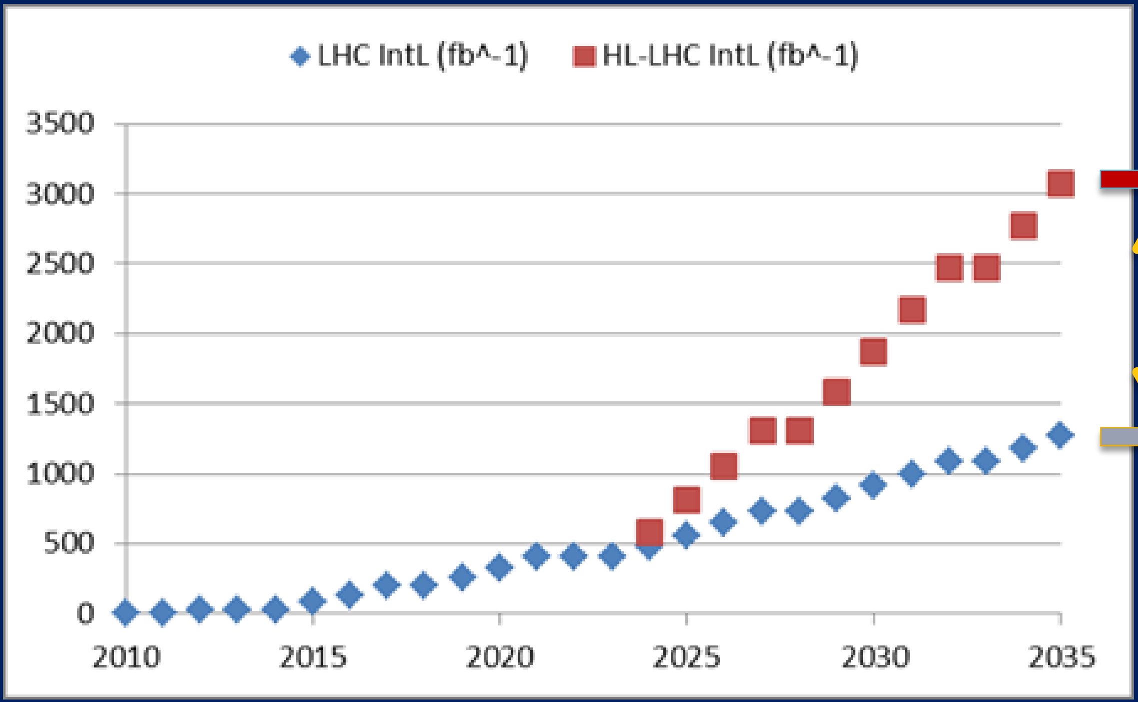
1.5 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~40

1.7-2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

Technical limits
(experiments too)
like :

50 ⇒ 25 ns

Why High-Luminosity LHC ?



By implementing HL-LHC

Almost a factor 3

By continuous performance improvement and consolidation

Goal of HL-LHC project:

- 250 – 300 fb^{-1} per year
- 3000 fb^{-1} in about 10 years

High Luminosity LHC

LHC performance optimization

Luminosity recipe (round beams):

$$L = \frac{n_b \times N_1 \times N_2 \times g \times f_{rev}}{4p \times b^* \times e_n} \times F(f, b^*, e, s_s)$$

1) maximize bunch intensities
2) minimize the beam emittance
3) minimize beam size
4) maximize number of bunches
5) compensate for 'F';
6) Improve machine 'Efficiency'

- Injector complex
  LHC Inj. Upgrade
- triplet aperture
- 25ns
- Crab Cavities
- minimize number of unscheduled beam aborts

HL-LHC Performance Goals

- **Design HL-LHC for Virtual luminosity:** **$L > 10 \times 10^{34}\ cm^{-2}\ s^{-1}$**

  Peak luminosity limitations:

  - Event Pileup in detectors
  - Debris leaving the experiments and impacting on the machine (magnet quench protection @ heat load)

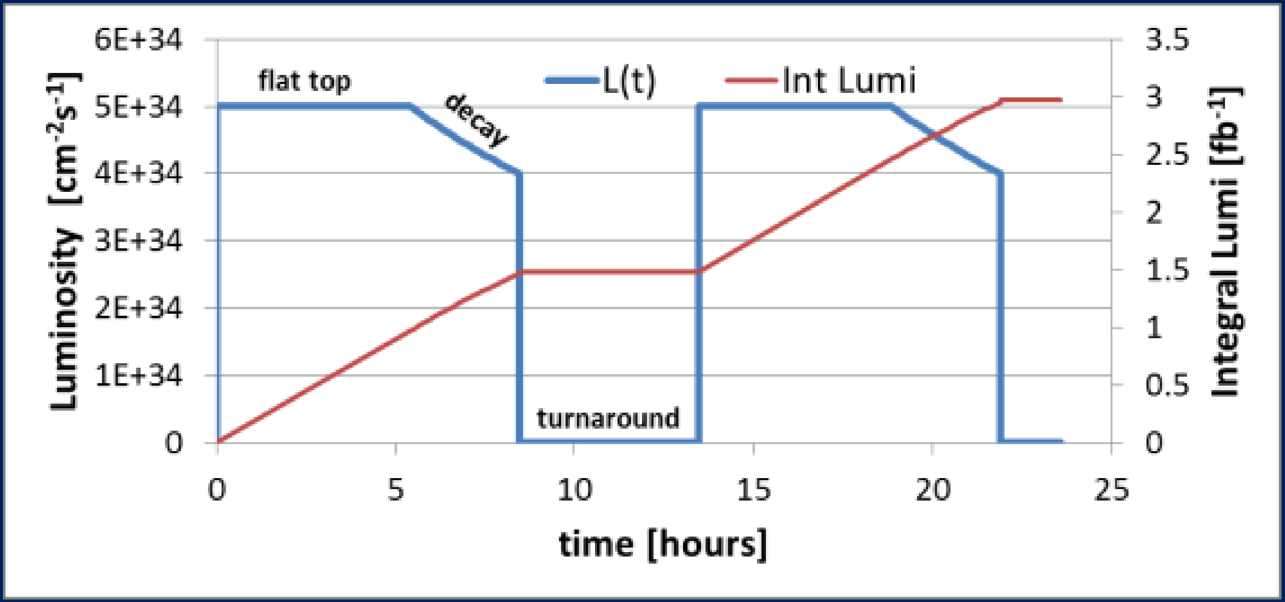
- **Operate with a leveled peak luminosity**: **$L = 5 \times 10^{34}\ cm^{-2}\ s^{-1}$**

  Maximize the time spend in physics production:

  - Machine efficiency
  - Scheduled physics time
  - Turnaround time

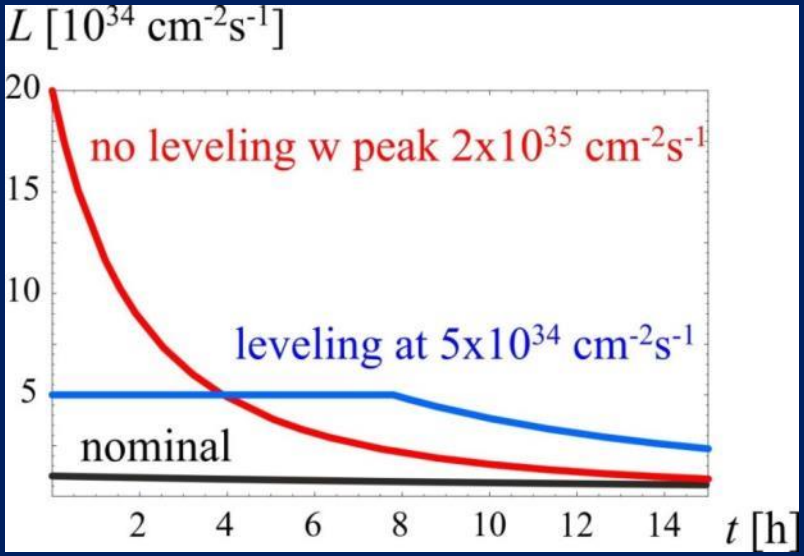
HL-LHC Performance optimization

- Luminosity levelling:

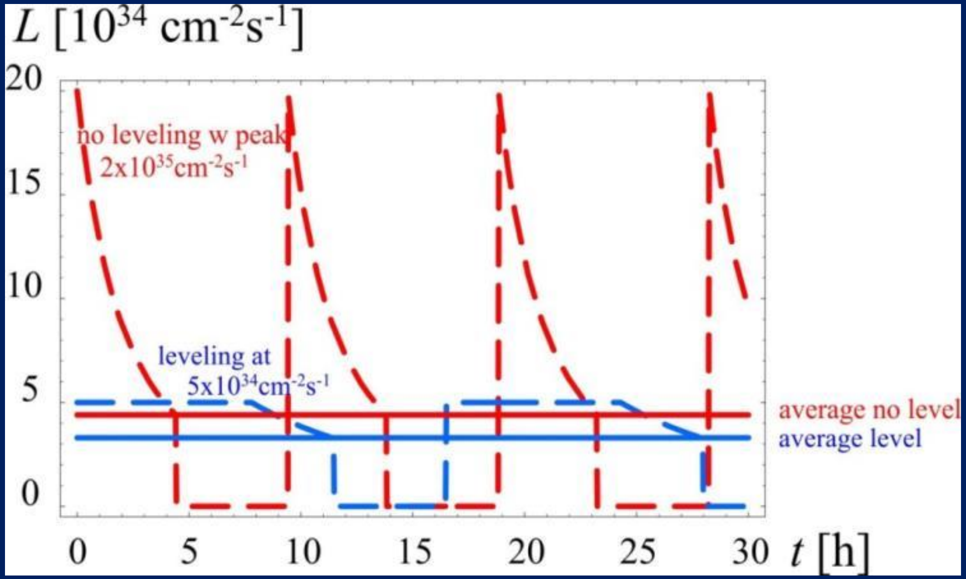


- Integrated Luminosity limitations:
  - Average Fill length must be larger then levelling time!
  - Average Turnaround time must be small wrt fill length
  - Number of operation days must be as large as possible
  - Overall machine efficiency fraction of physics over scheduled time

Luminosity Levelling, a key to success



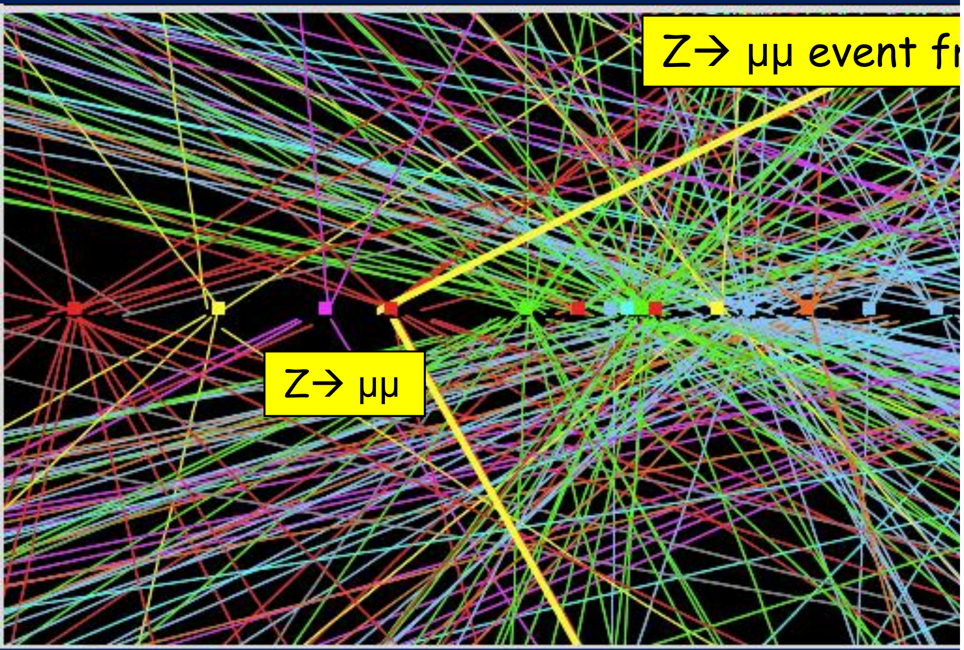
- High peak luminosity
- Minimize pile-up in experiments and provide “constant” luminosity

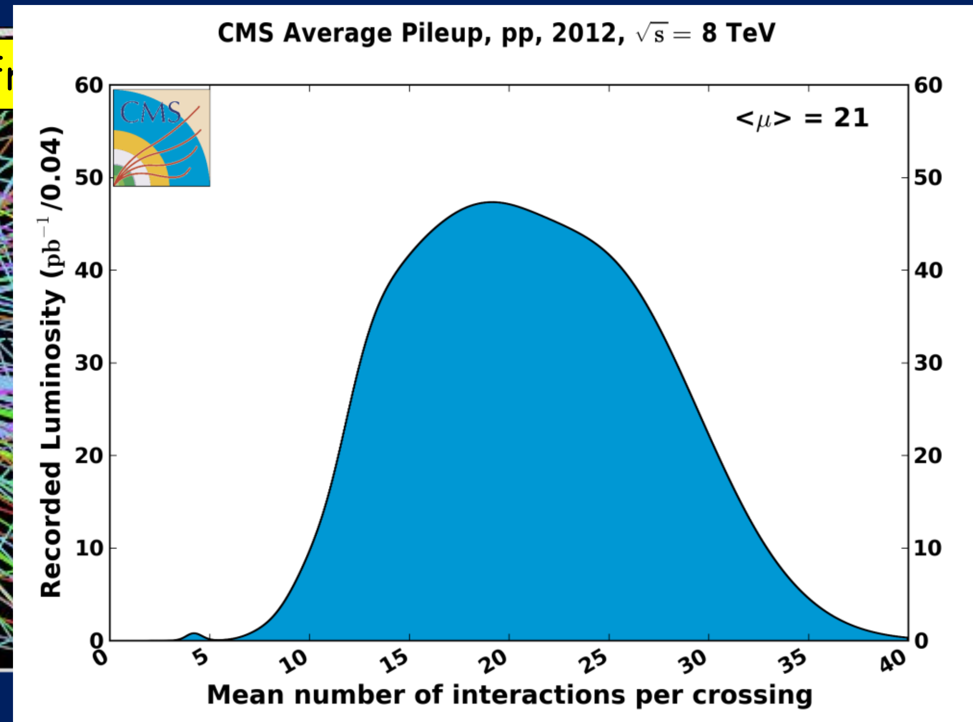


- Obtain about 3 - 4 fb^{-1}/day (40% stable beams)
- About 250 to 300 fb^{-1}/year

HL-LHC Challenge: Event Pileup Density

Vertex Reconstruction for 0.7 x 10^{34} cm^{-2} s^{-1} @ 50ns



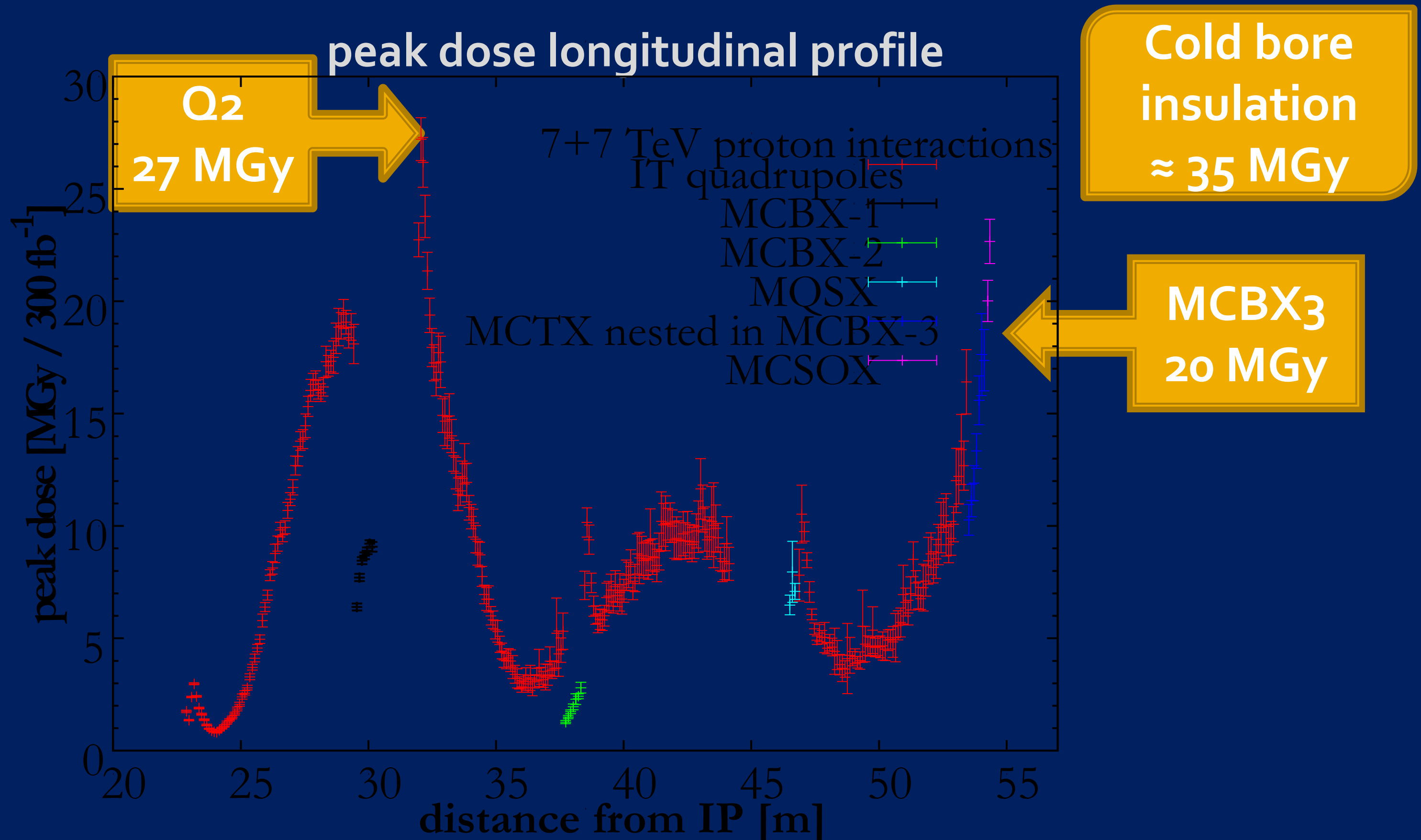


Extrapolating to 5 x 10^{34} cm^{-2} s^{-1} implies:

- $<\mu> = 280$; $\mu_{peak} > 500$ @ 50ns bunch spacing
- $<\mu> = 140$; $\mu_{peak} = 280$ @ 25ns bunch spacing

HL-LHC technical bottleneck:

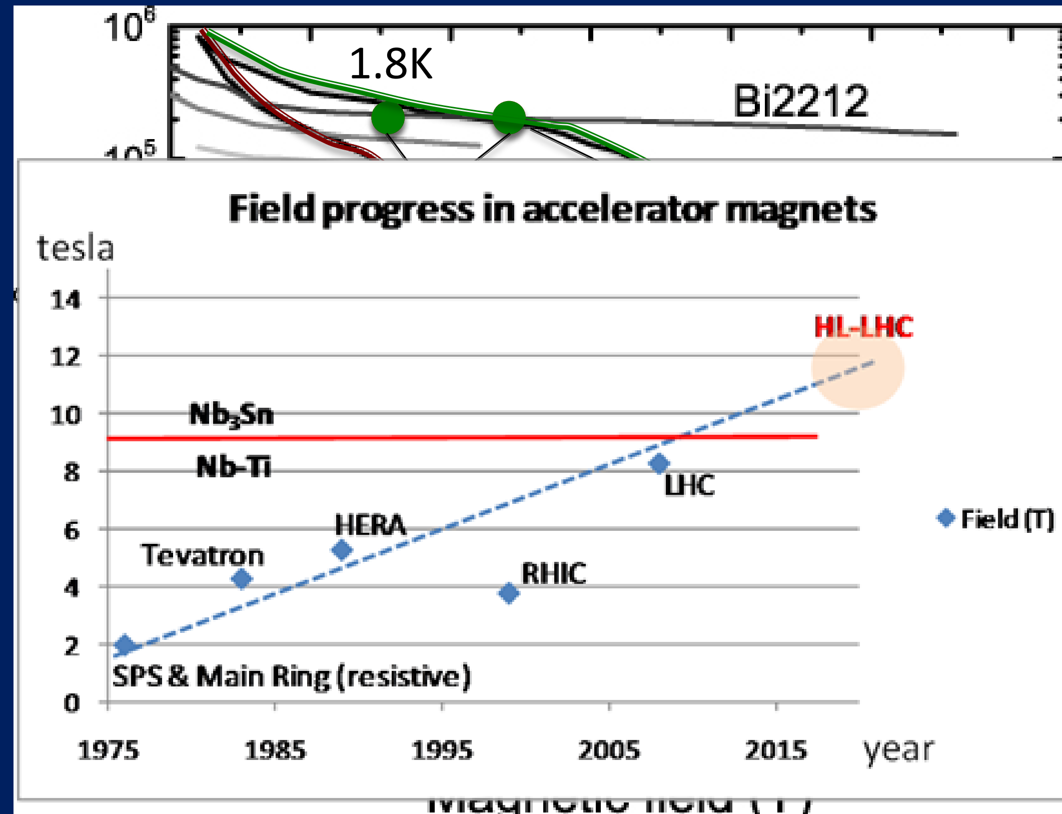
Radiation damage to triplet magnets at 300 fb^{-1}



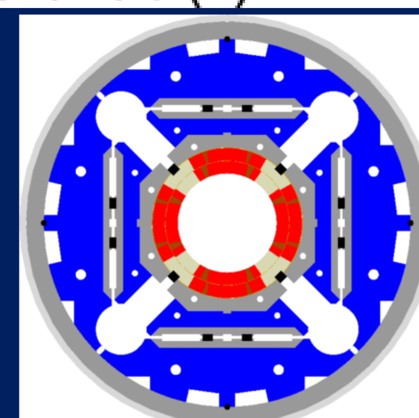
Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnets coils receive a similar radiation dose at 10 times higher integrated luminosity!

Squeezing the beams: High Field SC Magnets

- **LHC triplet:**
  210 T/m, 70 mm bore aperture
  - ➢ 8 T @ coil (limit of NbTi tech.)
- **HL-LHC triplet:**
  140 T/m, 150 mm coil aperture
  - more focal strength: β^*
  - crossing angle, shielding
  - ➢ ca. 12 T @ coil ➔ 30% longer
  - ➢ Requires Nb_3Sn technology
    - ceramic type material (fragile)
      - ➢ ca. 25 year development for this new magnet technology!
    - US-LARP – CERN collaboration (**L**HC **Acc**. **R**esearch **P**rogram)



US-LARP MQXF magnet design Based on Nb_3Sn technology

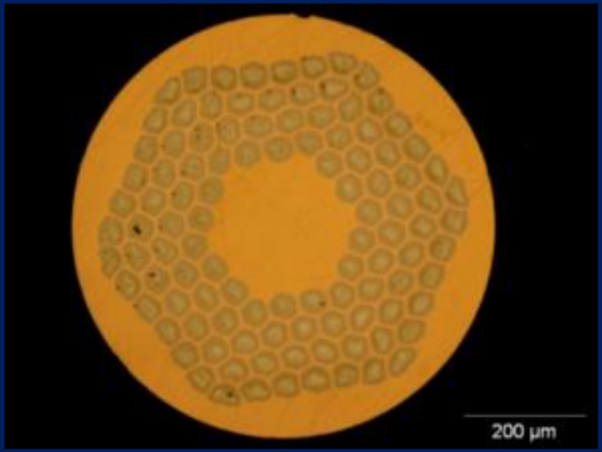


The « new » material : Nb_3Sn

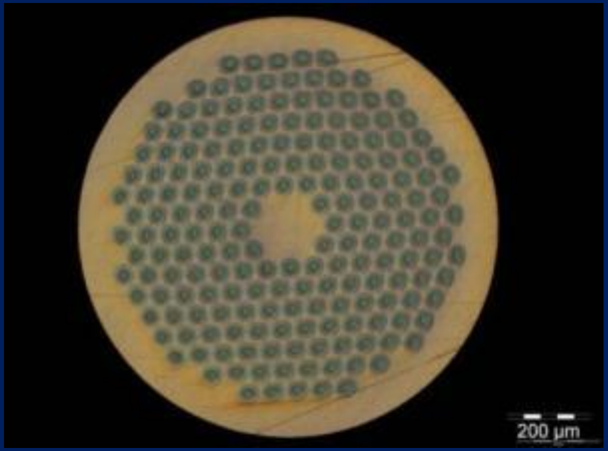
- Recent 23.4 T (1 GHz) NMR Magnet for spectroscopy in Nb_3Sn (and Nb-Ti).
- 15-20 tons/year for NMR and HF solenoids. Experimental MRI is taking off
- ITER: 500 tons in 2010-2015!

  It is comparable to LHC *(1200 tons of Nb-Ti but HL-LHC will require only 20 tons of Nb_3Sn)*

- HEP ITD (Internal Tin Diffusion):
  - High Jc., 3xJc ITER
  - Large filament (50 µm), large coupling current…
  - Cost is 5 times LHC Nb-Ti



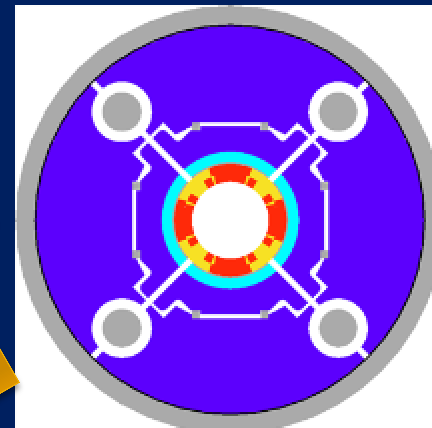
0.7 mm, 108/127 stack RRP from **Oxford OST**



1 mm, 192 tubes PIT from **Bruker EAS**

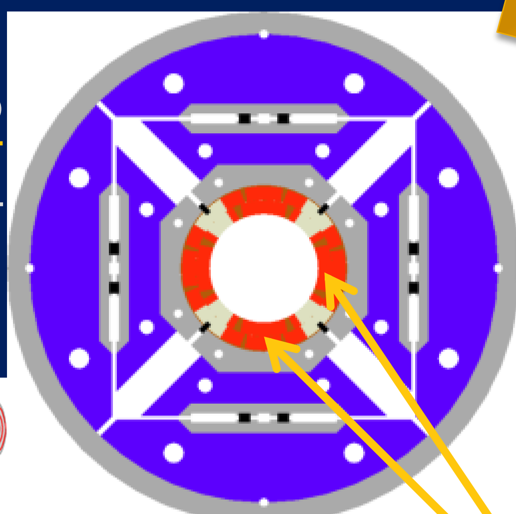
LHC low-β quads: steps in magnet technology from LHC toward HL-LHC

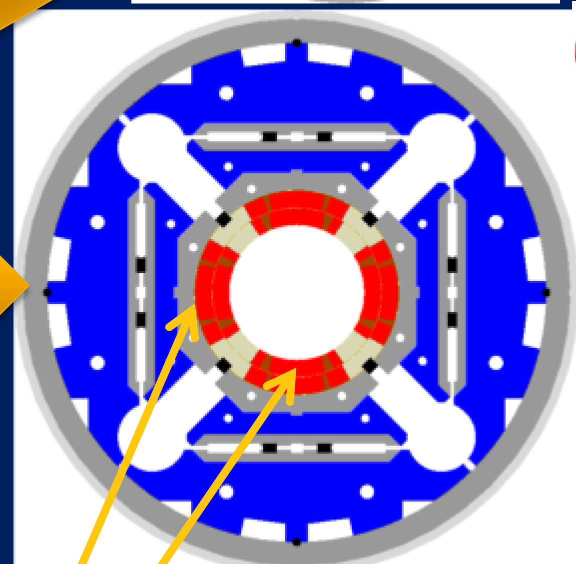
LHC (USA & JP, 5-6 m)
∅70 mm, B_{peak}~ 8 T
1992-2005



LARP TQS & LQ (4m)
∅90 mm, B_{peak}~ 11 T
2004-2010

LARP HQ
∅120 mm,B_{peak}~12T
2008-2014

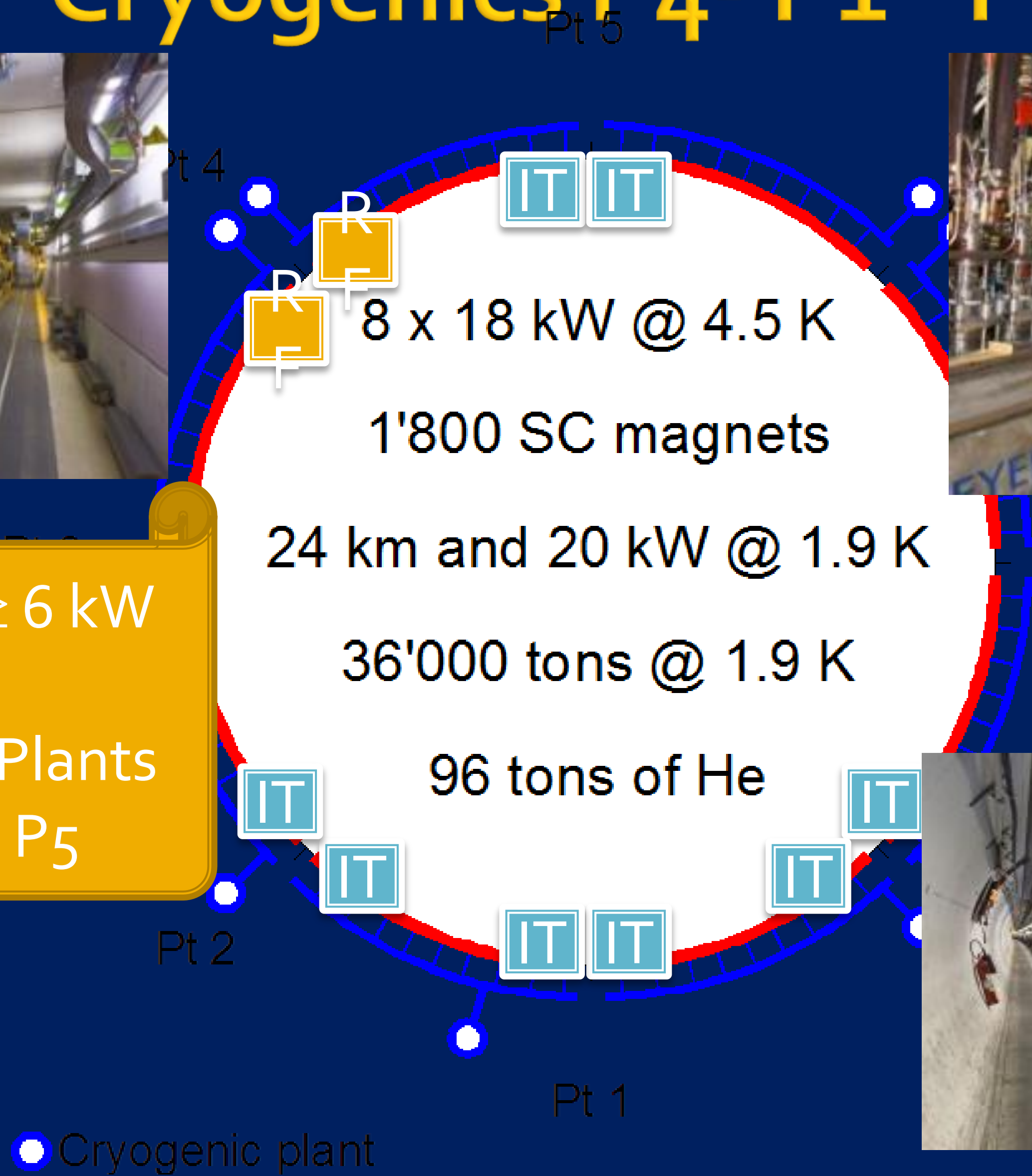




LARP & CERN MQXF
∅150 mm,
B_{peak}~ 12.1 T
2013-2020

Tungsten blocks for improved shielding

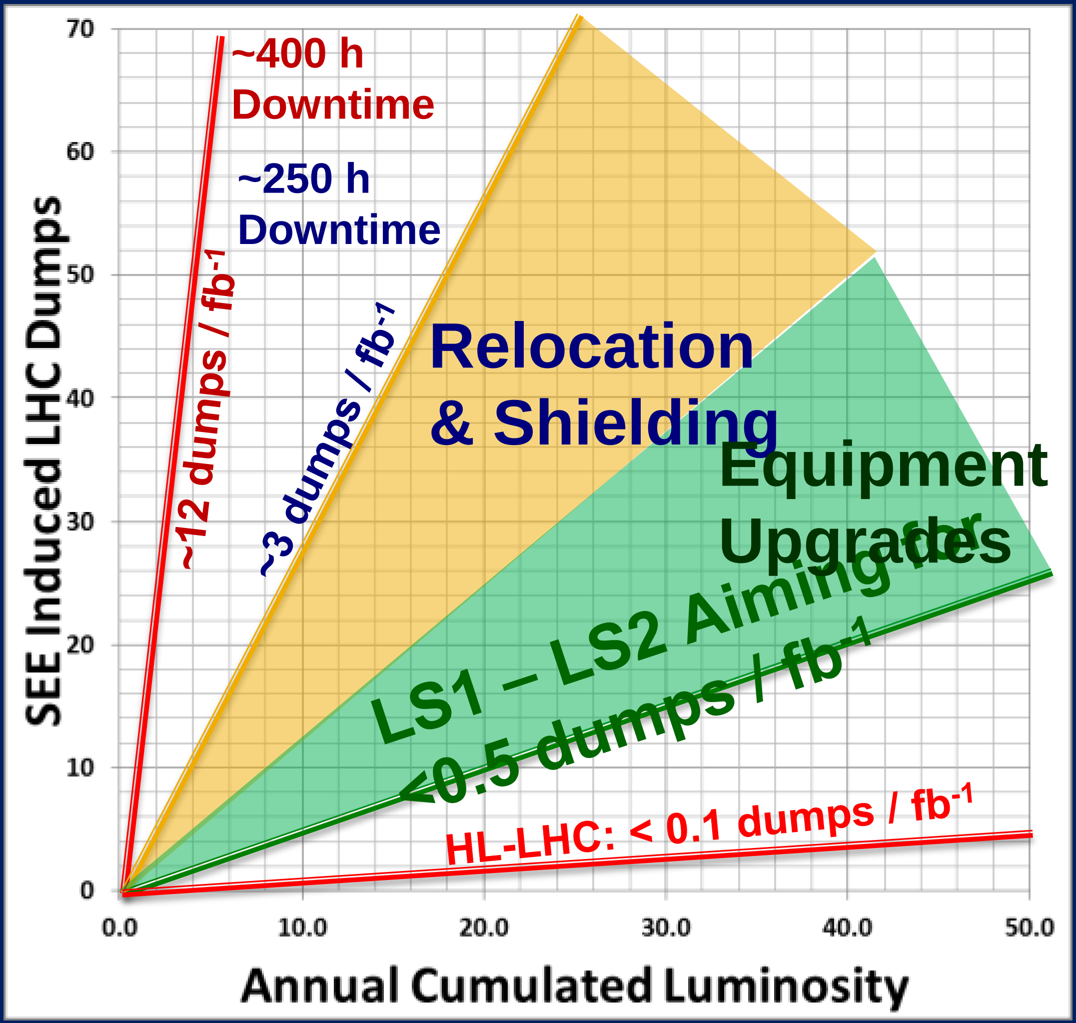
Eliminating Technical Bottlenecks
Cryogenics P4- P1 –P5



New Plant ≥ 6 kW
in P4
New 18 kW Plants
in P1 and P5

R2E SEU Failure Analysis – Actions

(R2E= Radiation to Electronics ; SEU = Single Event Upset)

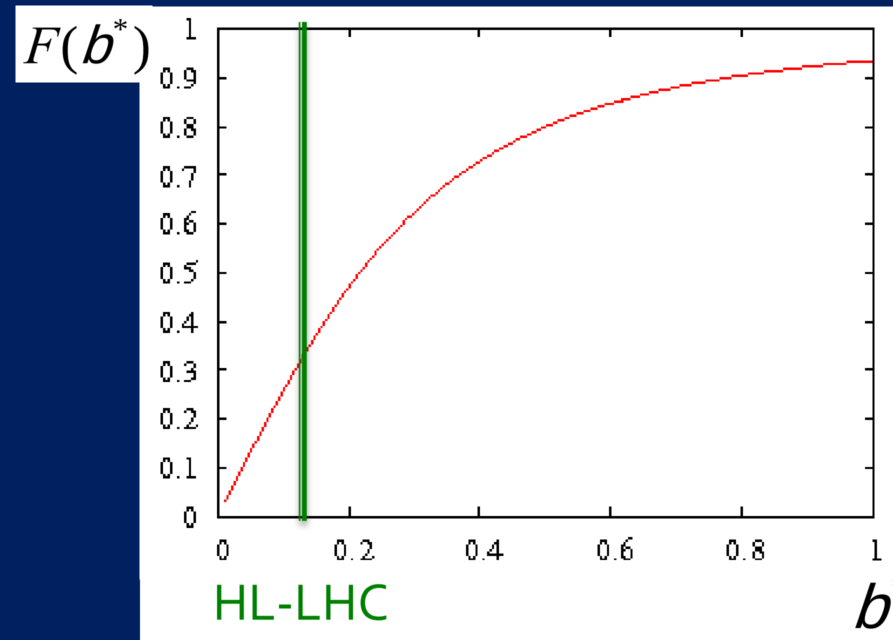


- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact
- **2011-2012**
  - Focus on equipment with long downtimes; provide shielding
- **LS1 (2013/2014)**
  - Relocation of power converters
- **LS1 – LS2:**
  - Equipment Upgrades
- **LS3 -> HL-LHC**
  - Remove all sensitive equipment from underground installations

HL-LHC Challenges: Crossing Angle

geometric luminosity reduction factor:

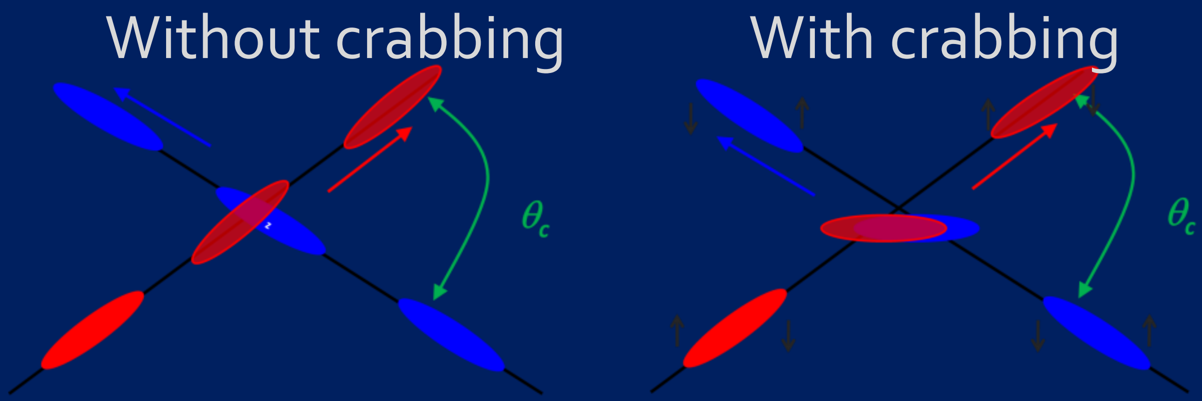
$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

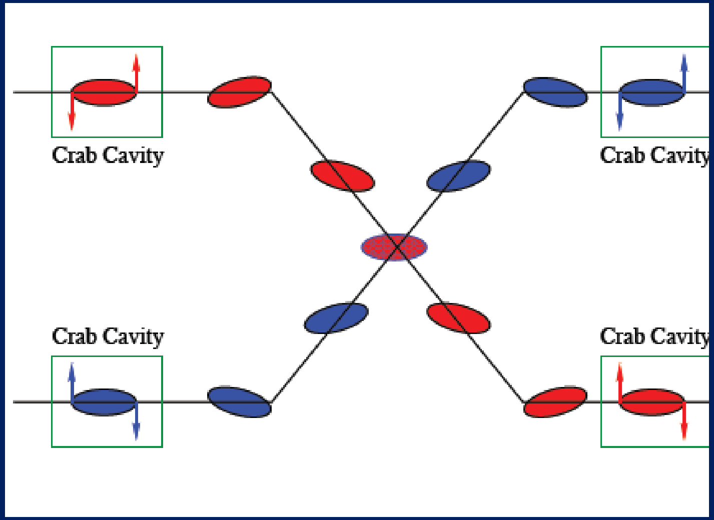


- large crossing angle:
  - + reduction of long range beam-beam interactions
  - + reduction of beam-beam tune spread and resonances
  - - reduction of the mechanical aperture
  - - increase of effective beam cross section at IP
  - - reduction of luminous region
  - - reduction of instantaneous luminosity
  - ➔ inefficient use of beam current!

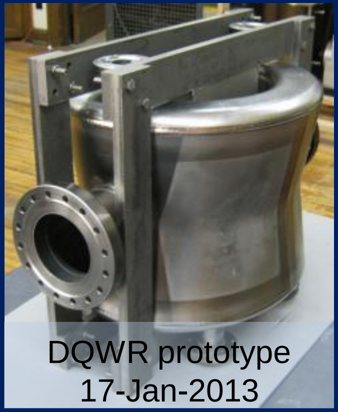
Crab Cavities, Increase "Head on"

Aim: reduce the effect of the crossing angle



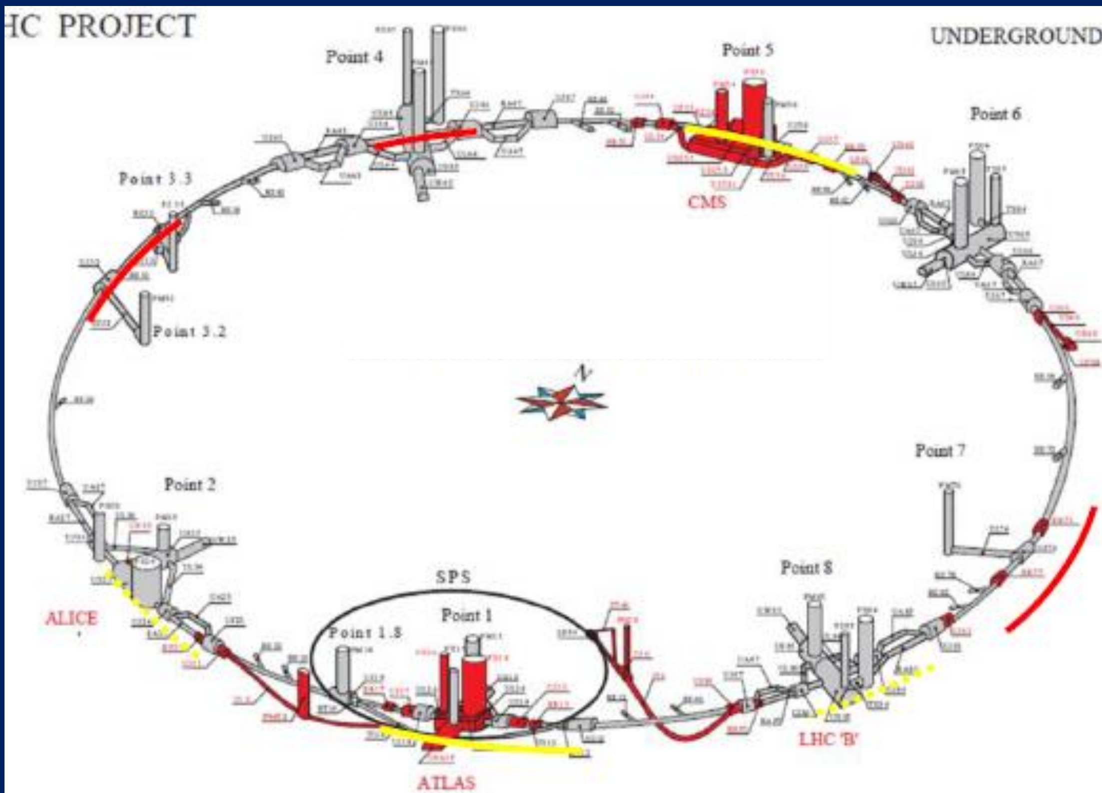


- 3 proto types available
- Cavity tests are on-going
- Test with beam in SPS foreseen in 2015-2016
- Beam test in LHC foreseen in 2017



Crossing strategy under study to soften pile-up density with interesting potential known as "crab-kissing"

The HL-LHC Project



- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

Project leadership: L. Rossi and O. Brüning

Baseline parameters of HL for reaching 250 -300 fb^{-1}/year

25 ns is the option

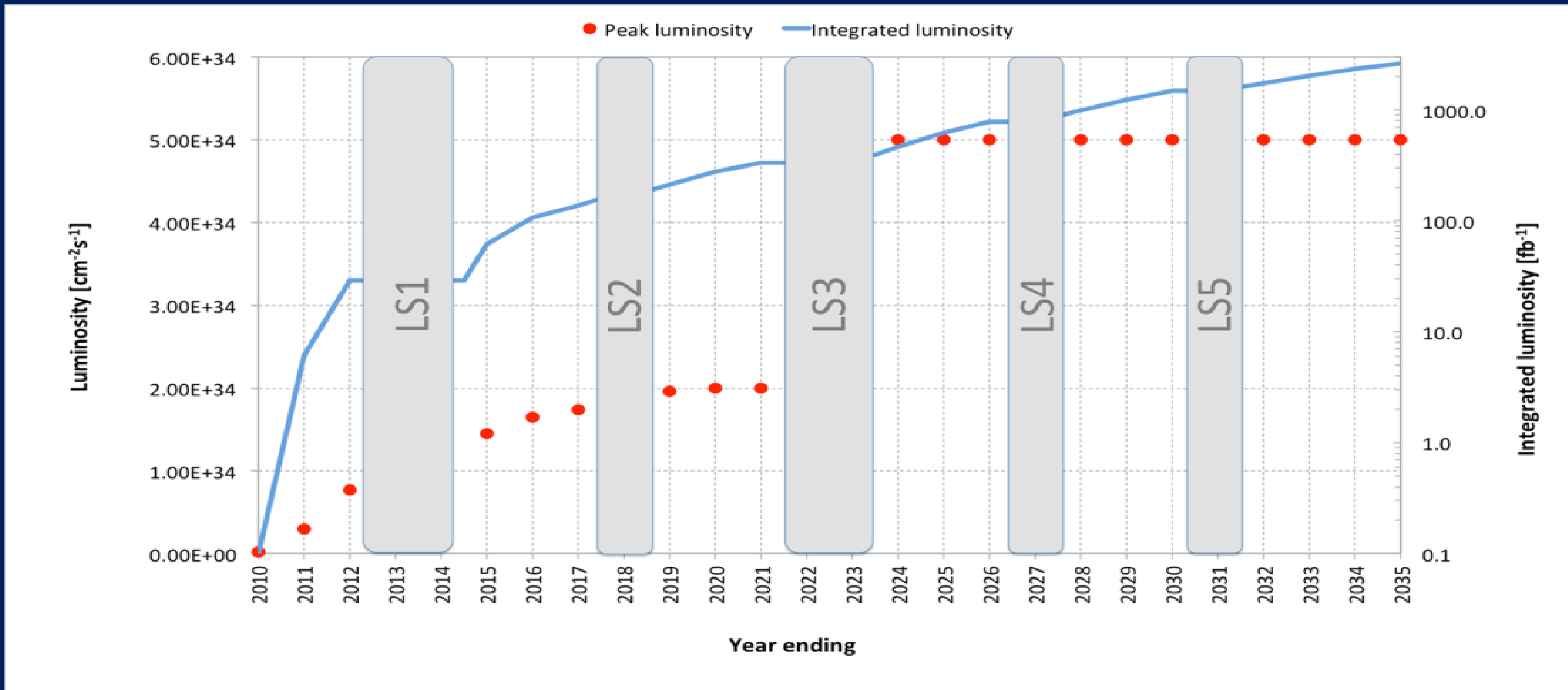
However:

50 ns should be kept as alive because we DO NOT have enough experience on the actual limit ***(e-clouds, I_{beam}).***

Continuous global optimisation with LIU

	25 ns	50 ns
# Bunches	2808	1404
p/bunch [10^{11}]	**2.0 (1.01 A)**	**3.3 (0.83 A)**
ε_L [eV.s]	2.5	2.5
σ_z [cm]	7.5	7.5
$\sigma_{\delta p/p}$ [10^{-3}]	0.1	0.1
$\gamma\varepsilon_{x,y}$ [μm]	**2.5**	**3.0**
β^* [cm] (baseline)	15	15
X-angle [μrad]	**590 (12.5 σ)**	**590 (11.4 σ)**
Loss factor	0.30	0.33
Peak lumi [10^{34}]	6.0	7.4
Virtual lumi [10^{34}]	20.0	22.7
$T_{leveling}$ [h] @ 5E34	**7.8**	**6.8**
#Pile up @5E34	123	247

The plan of HL-LHC (baseline)



Levelling at 5 10^{34} cm^{-2} s^{-1}: 140 events/crossing in average, at 25 ns; several scenarios under study to limit to 1.0 → 1.3 event/mm

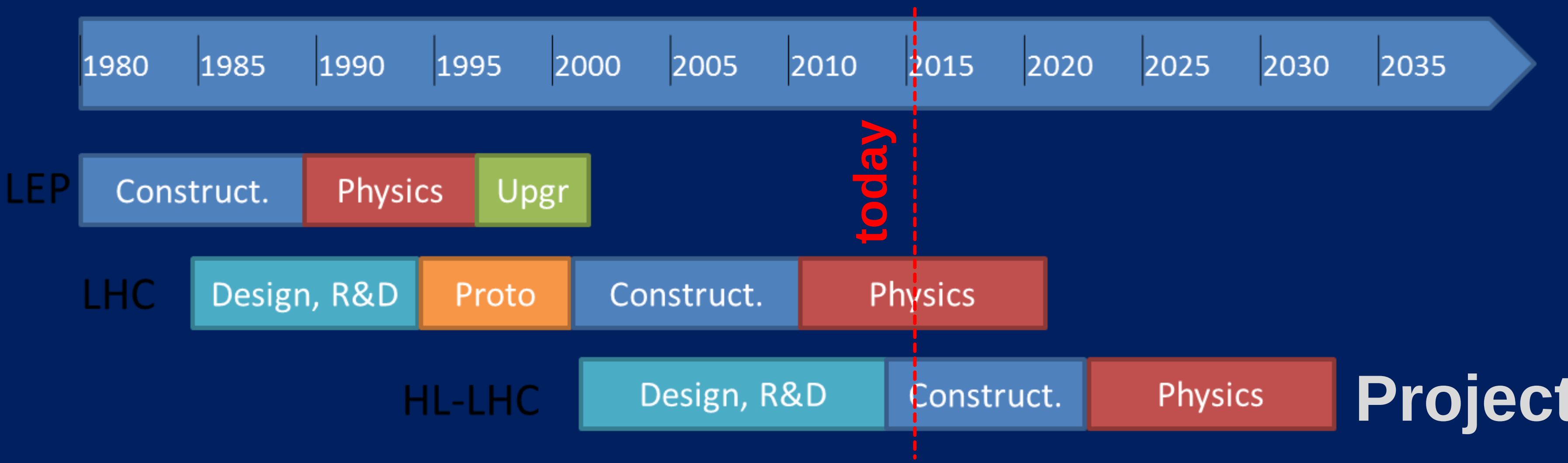
(“Pile-up at HL-LHC and possible mitigation” Stephane Fartoukh on Wed. 2nd Oct.)

Total integrated luminosity of 3000 fb^{-1} for p-p by 2035, with LSs taken into account and 1 month for ion physics per year.

European Strategy for Particle Physics

"…exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors…"

=> High Luminosity LHC project



http://cern.ch/hilumilhc

Conclusion part II

- The HL-LHC is an approved project

- A lot of technical and operation challenges :
  - Nb_3Sn magnets (accelerator field quality)
  - Collimators
  - Crab cavities
  - Increased availability (machine protection,…)
  - …

- Accelerator-experiment interface are central:
  - Bunch spacing, pile-up density, crossing schemes, background, forward detectors, collimation,…