The CERN Medium and Long Term Program

KRUGER 2014

December 1st, 2014
Sergio Bertolucci
CERN

From the Update of the European Strategy for Particle Physics (approved in May 2013)

The success of the LHC is proof of the effectiveness of the European organizational model for particle physics, founded on the sustained long-term commitment of the CERN Member States and of the national institutes, laboratories and universities closely collaborating with CERN.

Europe should preserve this model in order to keep its leading role, sustaining the success of particle physics and the benefits it brings to the wider society.

The scale of the facilities required by particle physics is **resulting in the globalization of the field**. The European Strategy takes into account the worldwide particle physics landscape and developments in related fields and should continue to do so.

European Strategy for Particle Physics

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.

***Europe's top priority** should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

Widening the horizon

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

2. Clarify the e-w symmetry breaking sector

SM has an unproven element: the generation of mass

Higgs mechanism ->? or other physics ?

Answer will be found at **LHC energies**

e.g. why $M_\gamma = 0$

M_W, $M_Z \sim 100{,}000$ MeV!

Transparency from the early 90's

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

Even if the Higgs boson is found all is not completely well with SM alone:

next question is "Why is (Higgs) mass so low"?

*If a new symmetry (Supersymmetry) is the answer, it must show up at O(***1TeV)**

5. Search for new physics at the TeV scale

SM is logically incomplete – does not incorporate gravity

Superstring theory ⇨dramatic concepts: supersymmetry , extra space-time dimensions ?

Widening the horizon

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

2. Clarify the e-w symmetry breaking sector

- **Use the Higgs boson as a new tool for discovery**

Answer will be found at **LHC energies**

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

- **Identify the new physics of dark matter**

*If a new symmetry (Supersymmetry) is the answer, it must show up at O(***1TeV***)*

5. Search for new physics at the TeV scale

- **Explore the unknown: new particles, interactions, and physical principles.**

Where is New Physics?

The question

- Is the mass scale beyond the LHC reach ?
- Is the mass scale within LHC's reach, but final states are elusive ?

We should be prepared to exploit both scenarios, through:

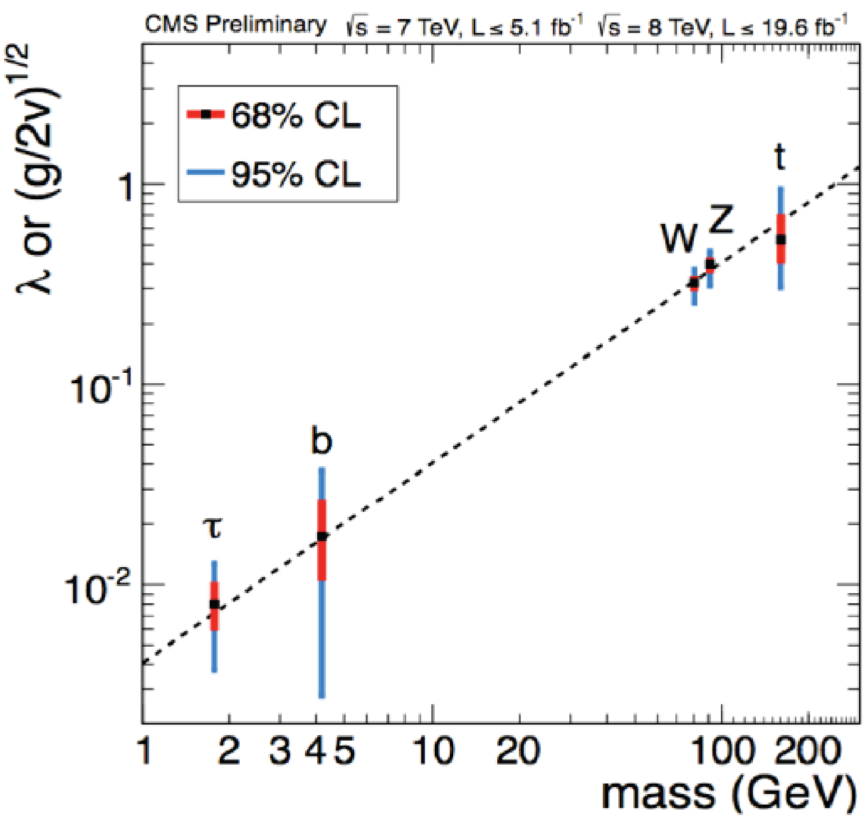
- Precision
- Sensitivity (to elusive signatures)
- Extended energy/mass reach

Mass and Couplings

CMS

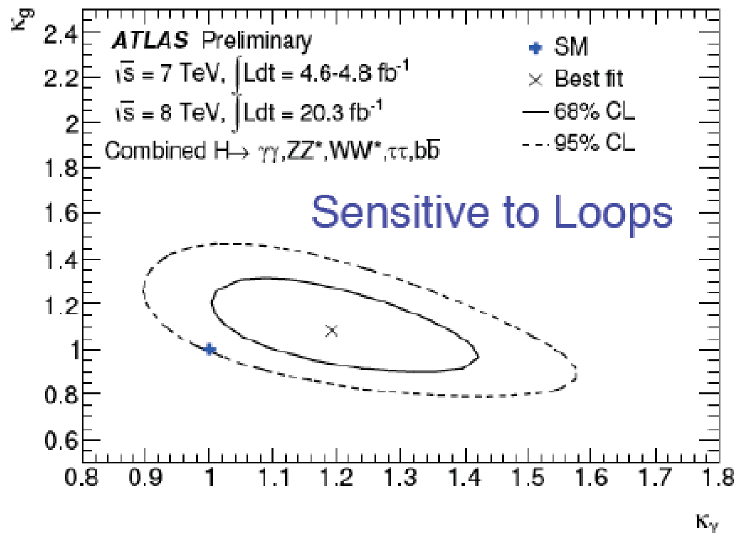
125.6 ± 0.4 (stat) ± 0.2 (syst) GeV

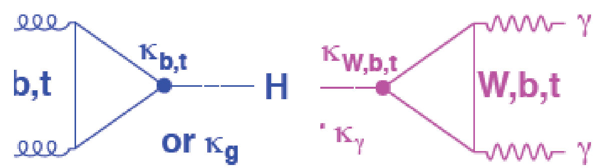
From $H \rightarrow ZZ^{(*)} \rightarrow 4l$



ATLAS

M_H= 125.5 $^{+0.5}_{-0.6}$ (stat) ± 0.2 (syst) GeV





CMS and LHCb $B^0_{s,d} \to \mu\mu$ combination

Fit to full run I data sets of both experiments, sharing parameters

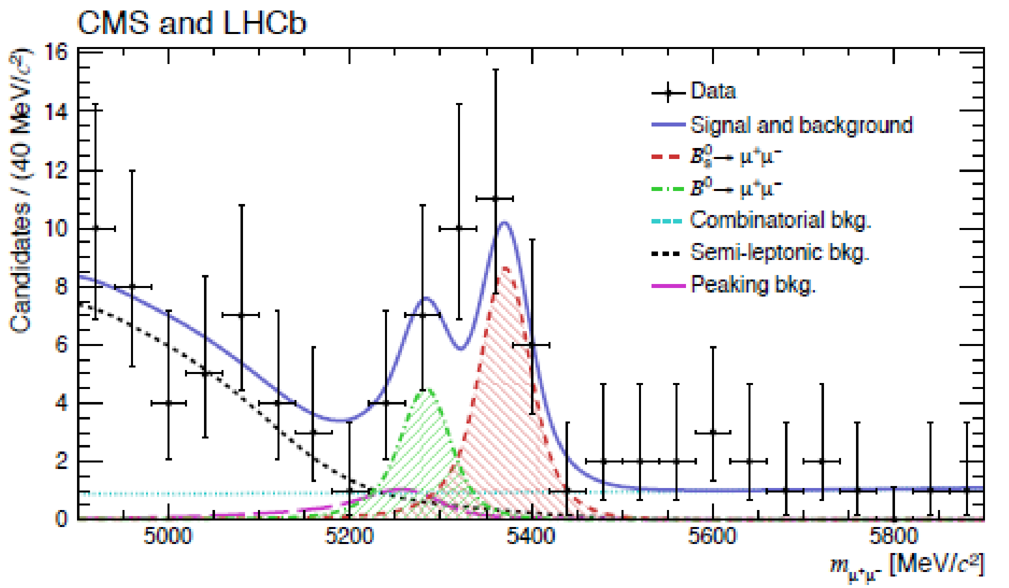
Result demonstrates power of combing data from >1 experiment (an LHC first!)
It was presented at CKM conference in Vienna, & will be submitted to Nature

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

6.2 σ for the $B^0{}_s \to \mu^+\mu^-$

(Expected SM 7.6 σ)

✦ First **observation**



projection of invariant mass in most sensitive bins

Higgs 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

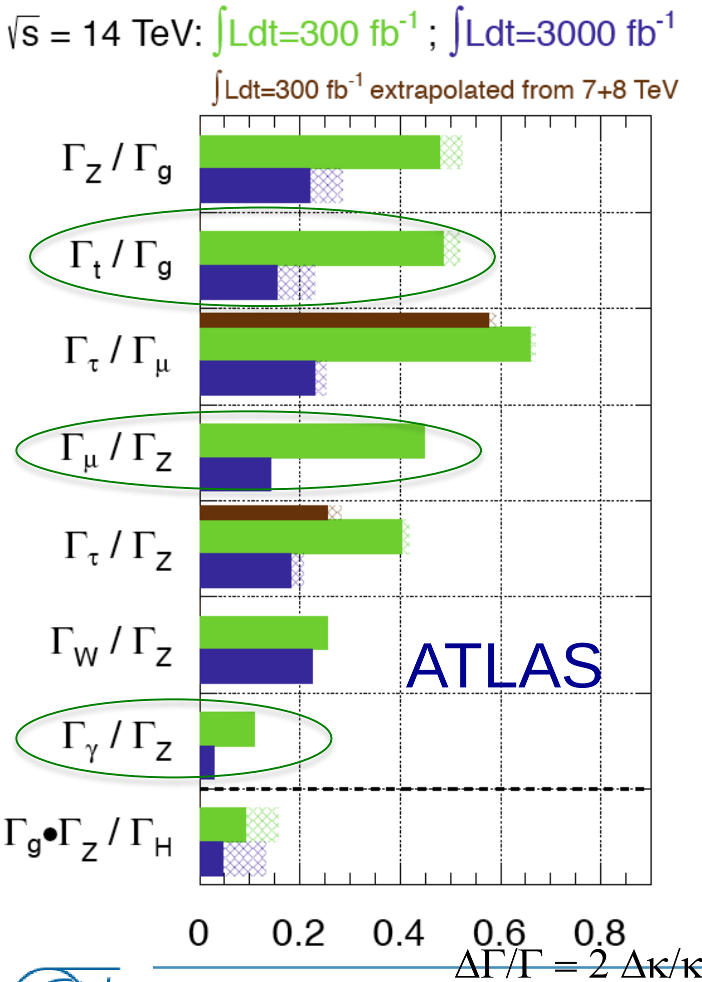
✓ γγ loop at 2-5% level

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

✓ direct top coupling at 4-8% level

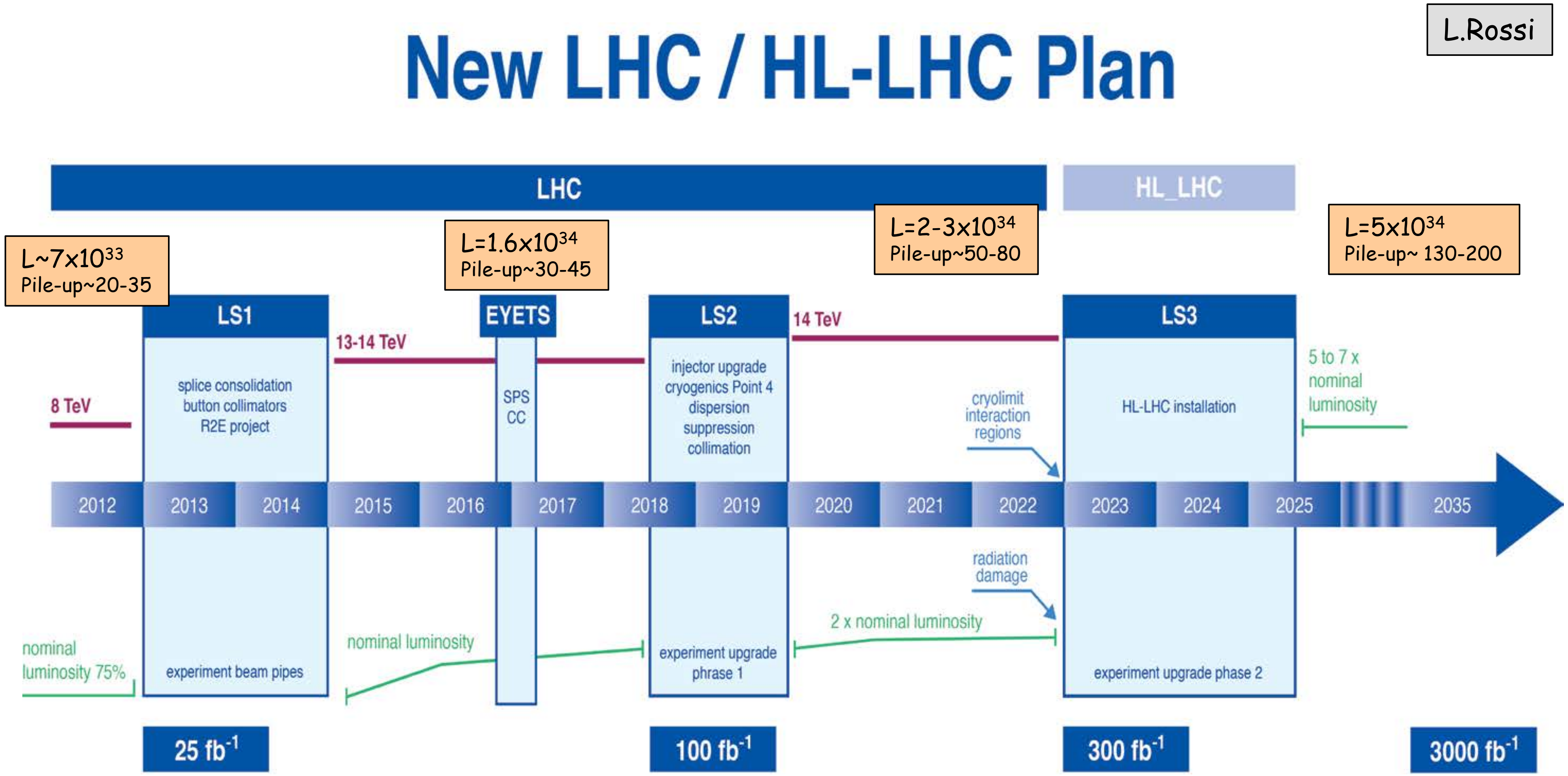
✓ gg loop at 3-8% level

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%

The LHC timeline



The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

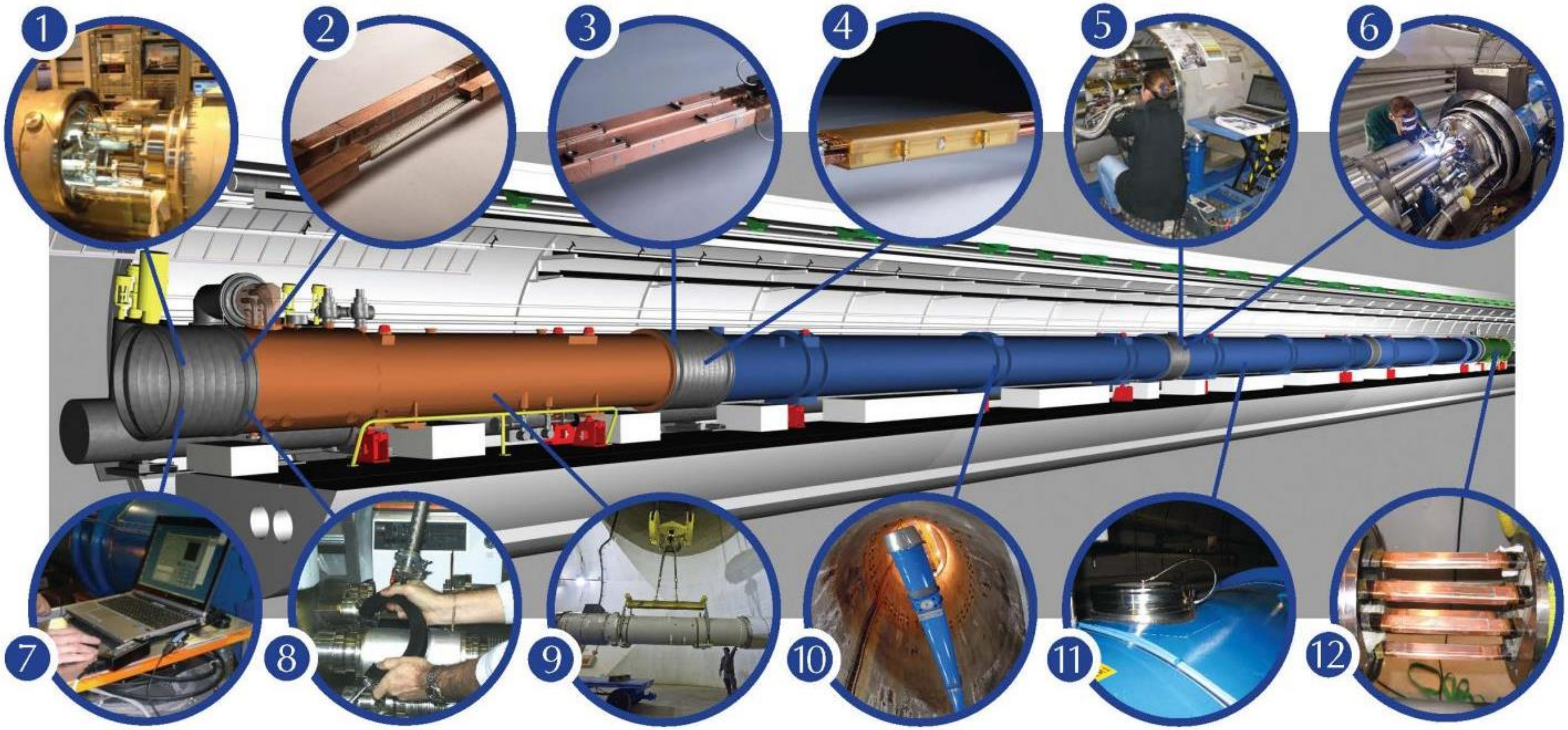
Complete reconstruction of 1500 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

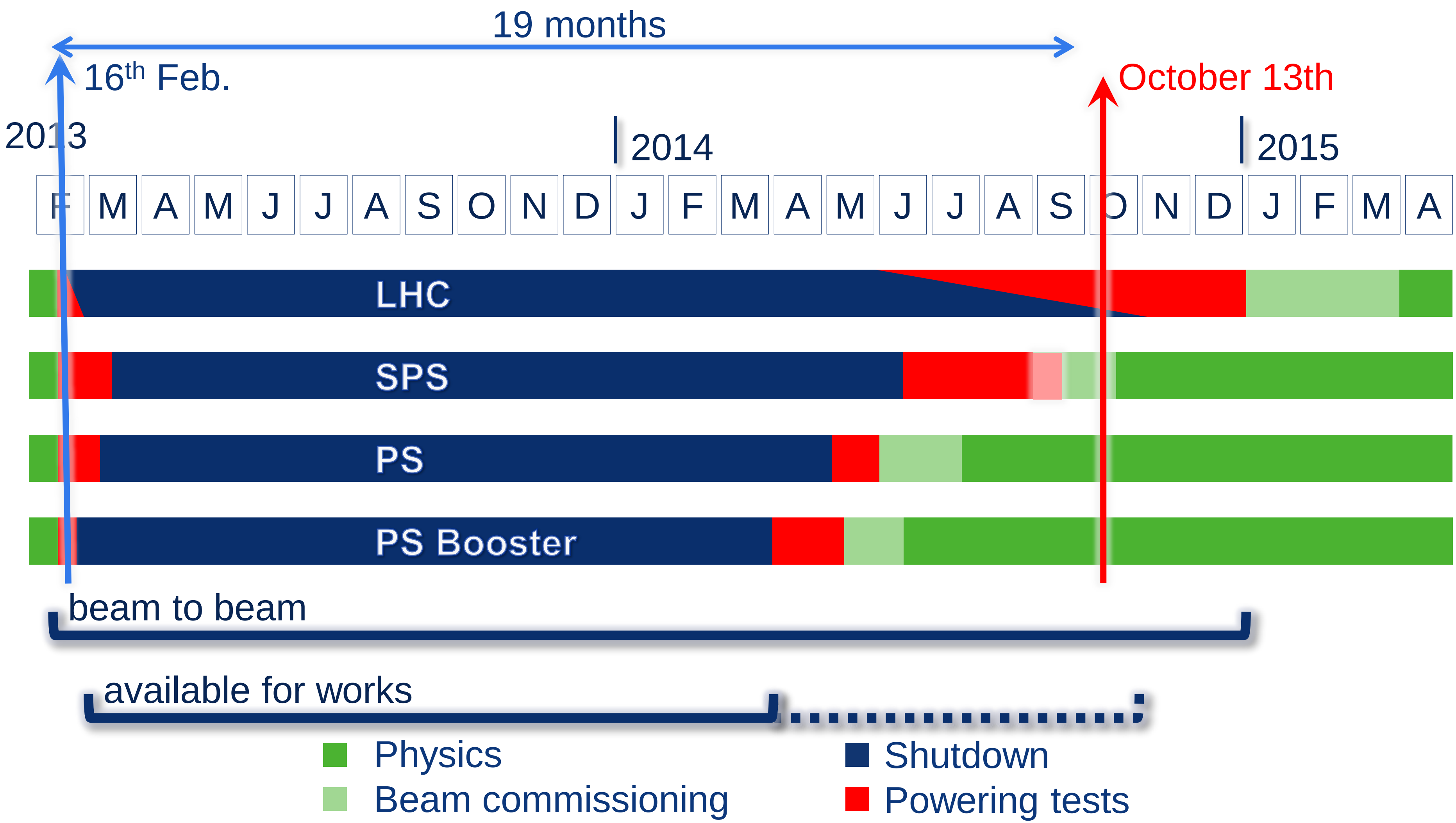
3 quadrupole magnets to be replaced

15 dipole magnets to be replaced

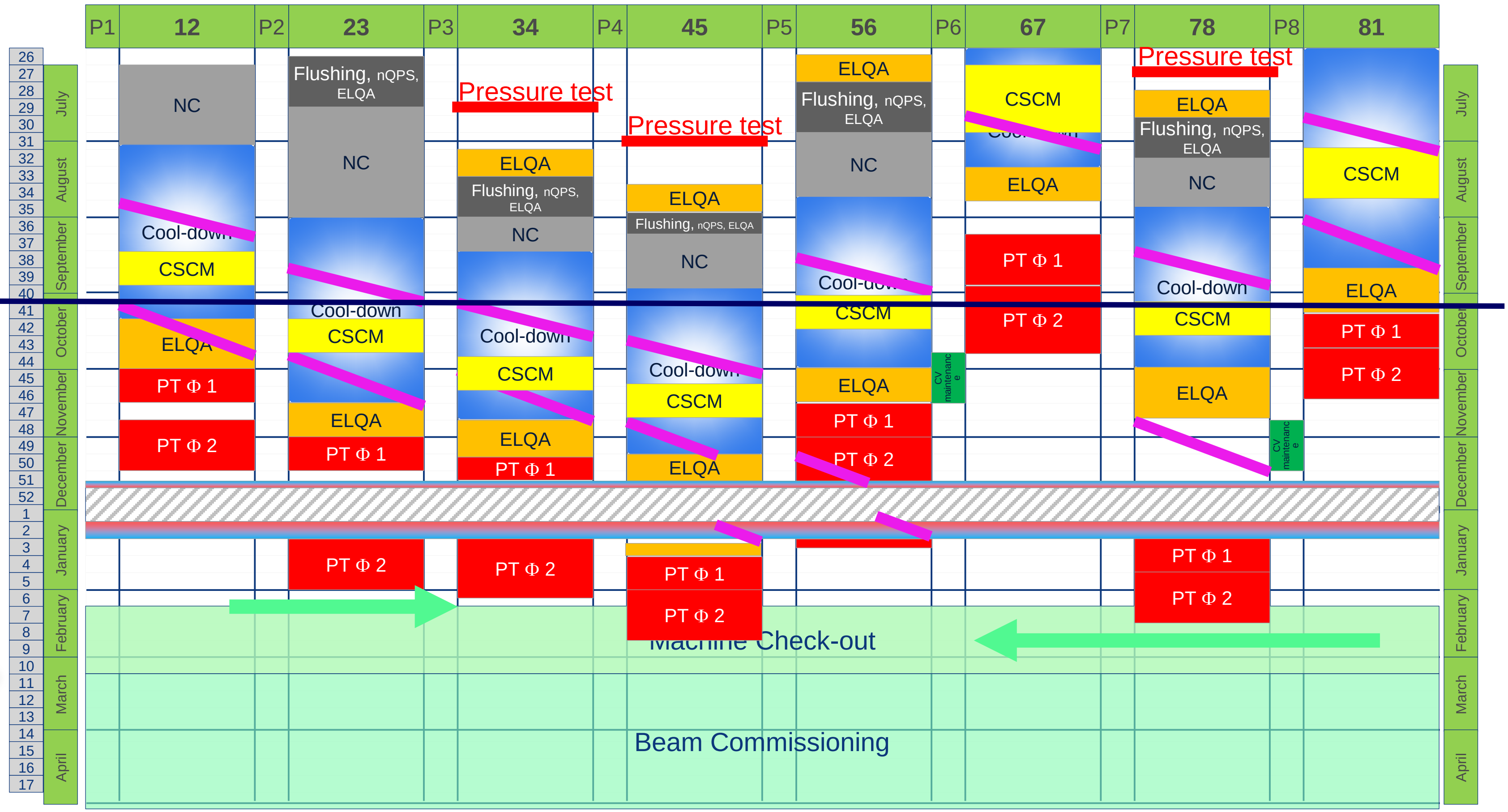
Installation of 612 pressure relief devices to bring the total to 1344

Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

LS 1 from 16th Feb. 2013 to Dec. 2014



LHC schedule V4.1



1st beam on week 11 (starting 9th March 2015)

Maximum beam energy : **13 TeV c.m. in 2015**

Decision to run at a **maximum** energy of 6.5 TeV per beam during the powering tests and during 2015.
(10 to 15 training quenches per sector are expected to be needed to reach that energy).

NO change of beam energy in 2015.

A decision regarding the possibility of increasing the energy will be taken later in 2015, based on the experience gained in all eight sectors at 6.5 TeV per beam during powering tests and operation with beams.

LHC goal for **2015 and for Run 2 and 3**

Priorities for the 2015 run :

- **Establish proton-proton collision at 13 TeV with 25ns and *low* β* to prepare production run in 2016.**
  Optimisation of physics-to-physics duration

- **Later in 2015: decision on special runs "when and duration" (90m optics): not in the 1st part of the year. Waiting LHCC recommendation**

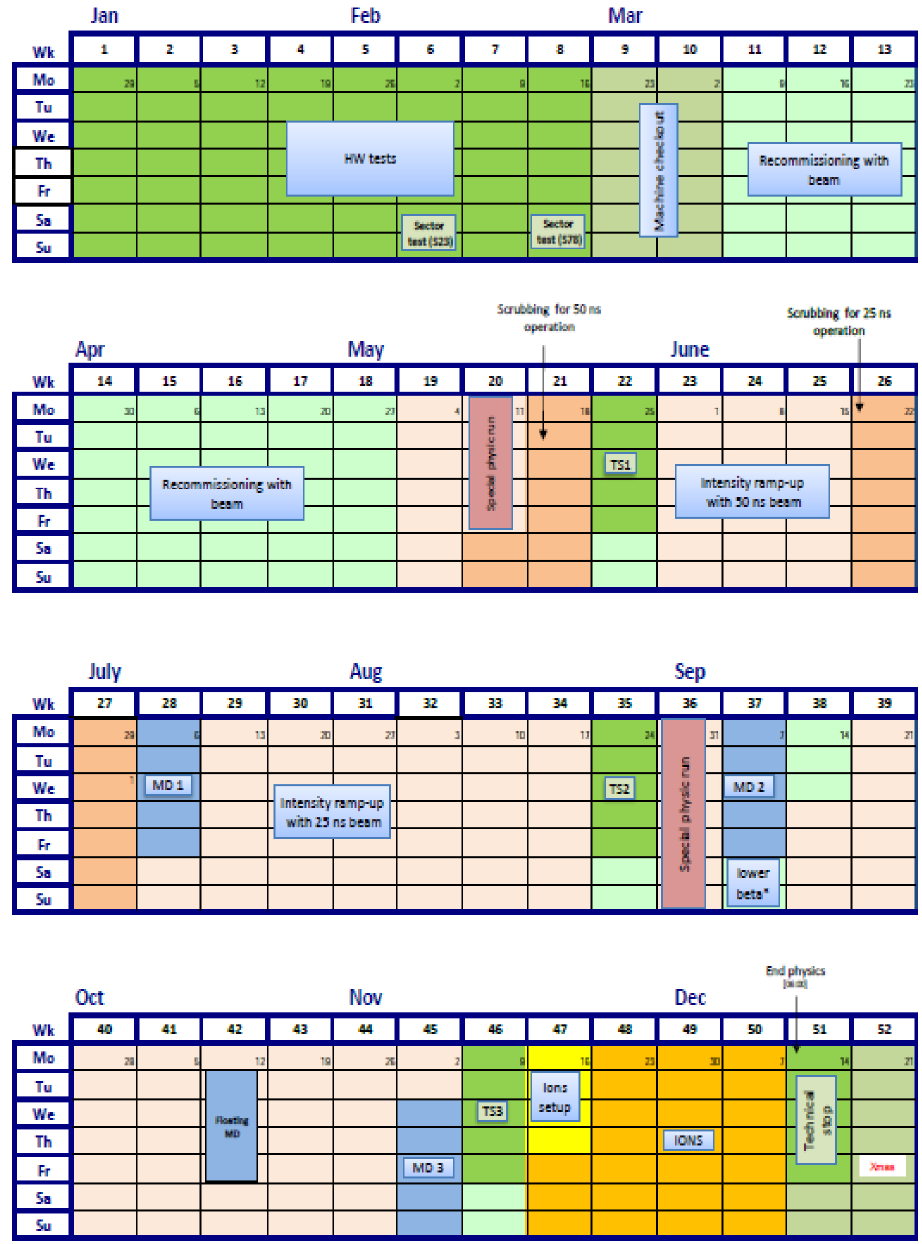
- **Pb-Pb run: one month at the end of 2015**

The goal for Run 2 luminosity is 1.3 x 10^{34} cm^{-2} s^{-1} and operation with 25 ns bunch spacing (2800 bunches), giving an estimated pile-up of 40 events per bunch crossing.

"A maximum pileup of ~50 is considered to be acceptable for ATLAS and CMS"

LHC Strategy for **2015**

- **To restart with the similar 2012 parameters and a relaxed β* (80cm) (Alice 10m; LHCb 3m) to establish asap collisions at 13 TeV with 50 ns bunch spacing, no combined collide-squeeze, ramp-squeeze,…**
- **LHCf request and VdM with same optics**
- **To do a 1st scrubbing run (50ns+25ns; 7-9 days) and to accumulate up to 1fb^{-1} with 50 ns (around 20 days)**
- **To establish the running with 25 ns: enough time for the scrubbing (10-15 days and no pressure for production)**
- **To run at 25ns with β* (80cm) during 2 months (45 days) and to decrease the β* (60 cm- 40 cm?) to have around 45 days of operation to prepare 2016 and 2017**
- **One month for heavy ions.**



LHC goal for **2015 and for Run 2 and 3**

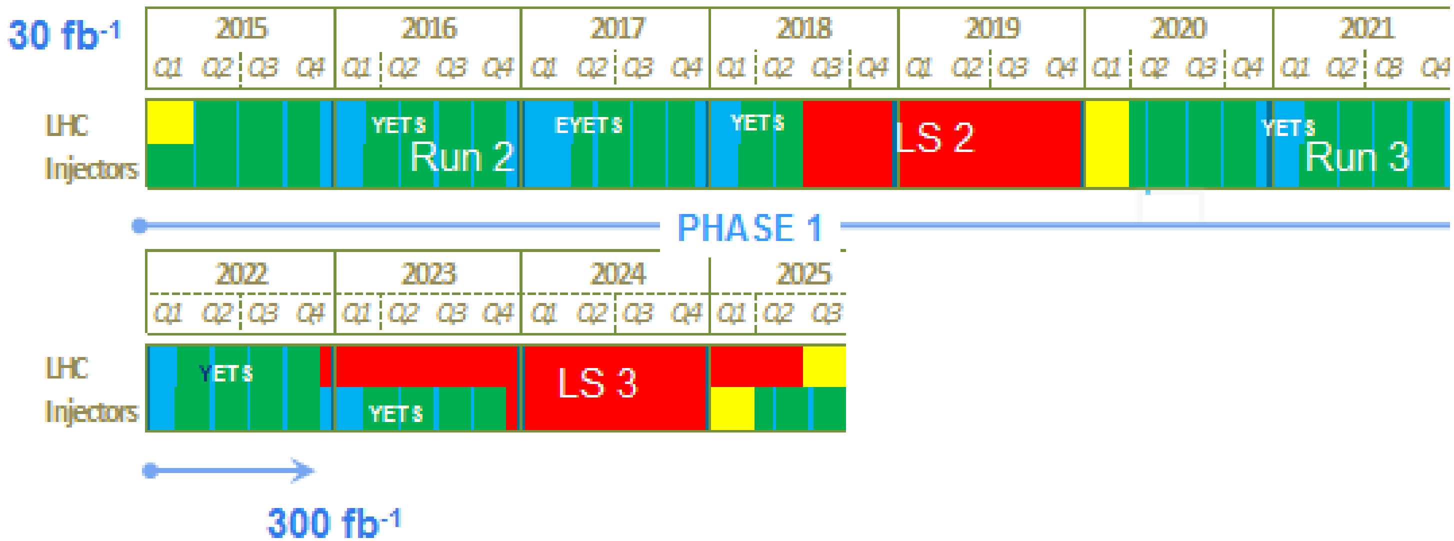
Integrated luminosity goal:

2015 : 10 fb^{-1}

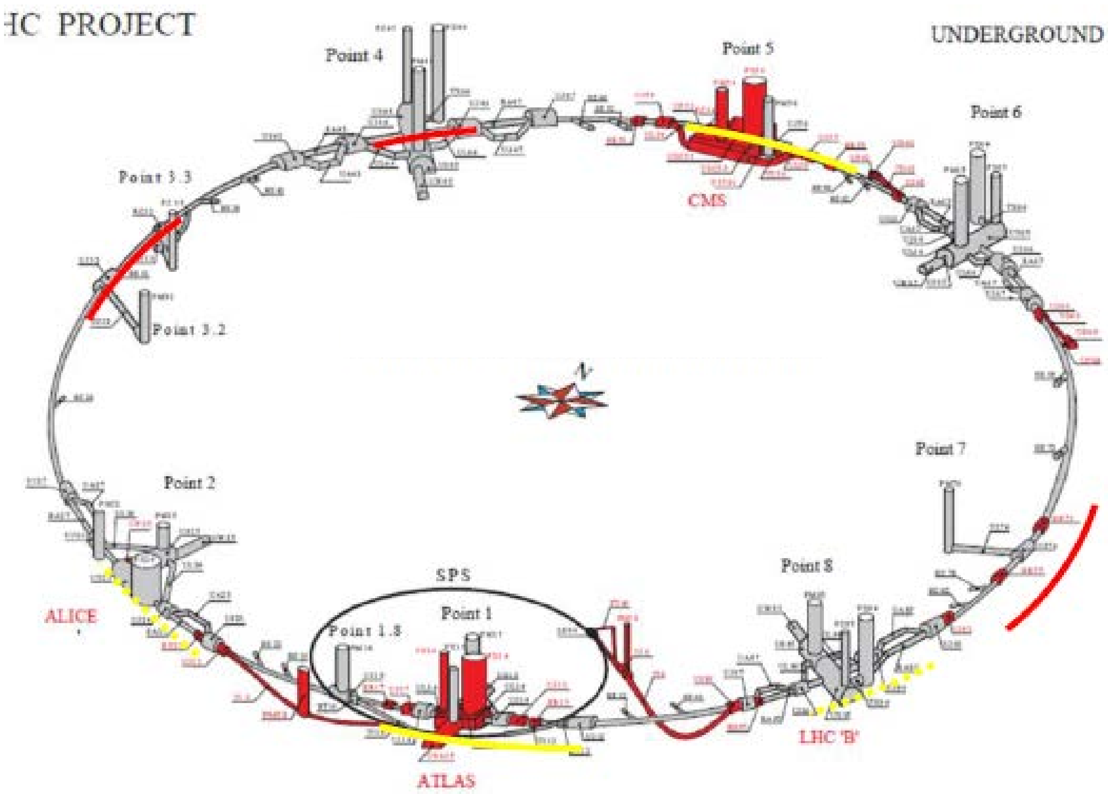
Run2: ~100-120 fb^{-1}

(better estimation by end of 2015)

300 fb^{-1} before LS3



The HL-LHC Project

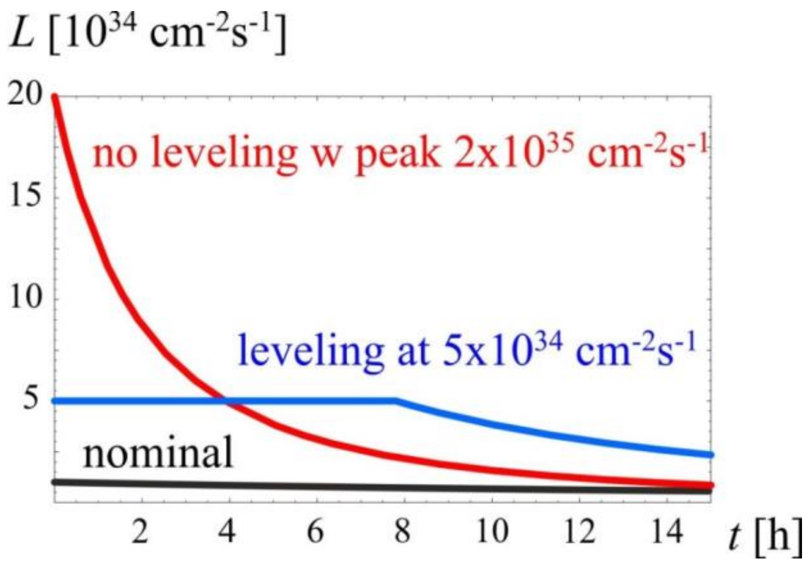


- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

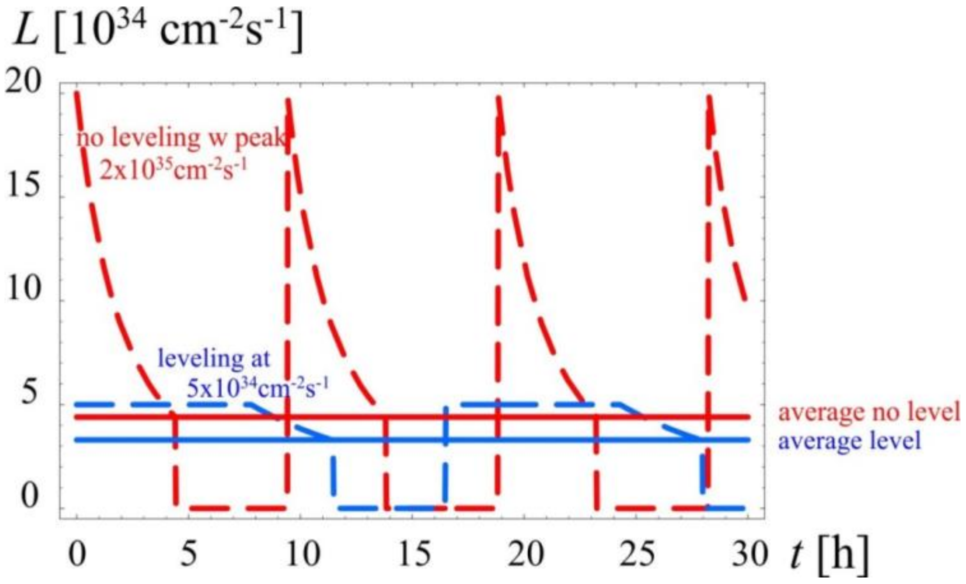
Project leadership: L. Rossi and O. Brüning

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



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

25 ns is the option

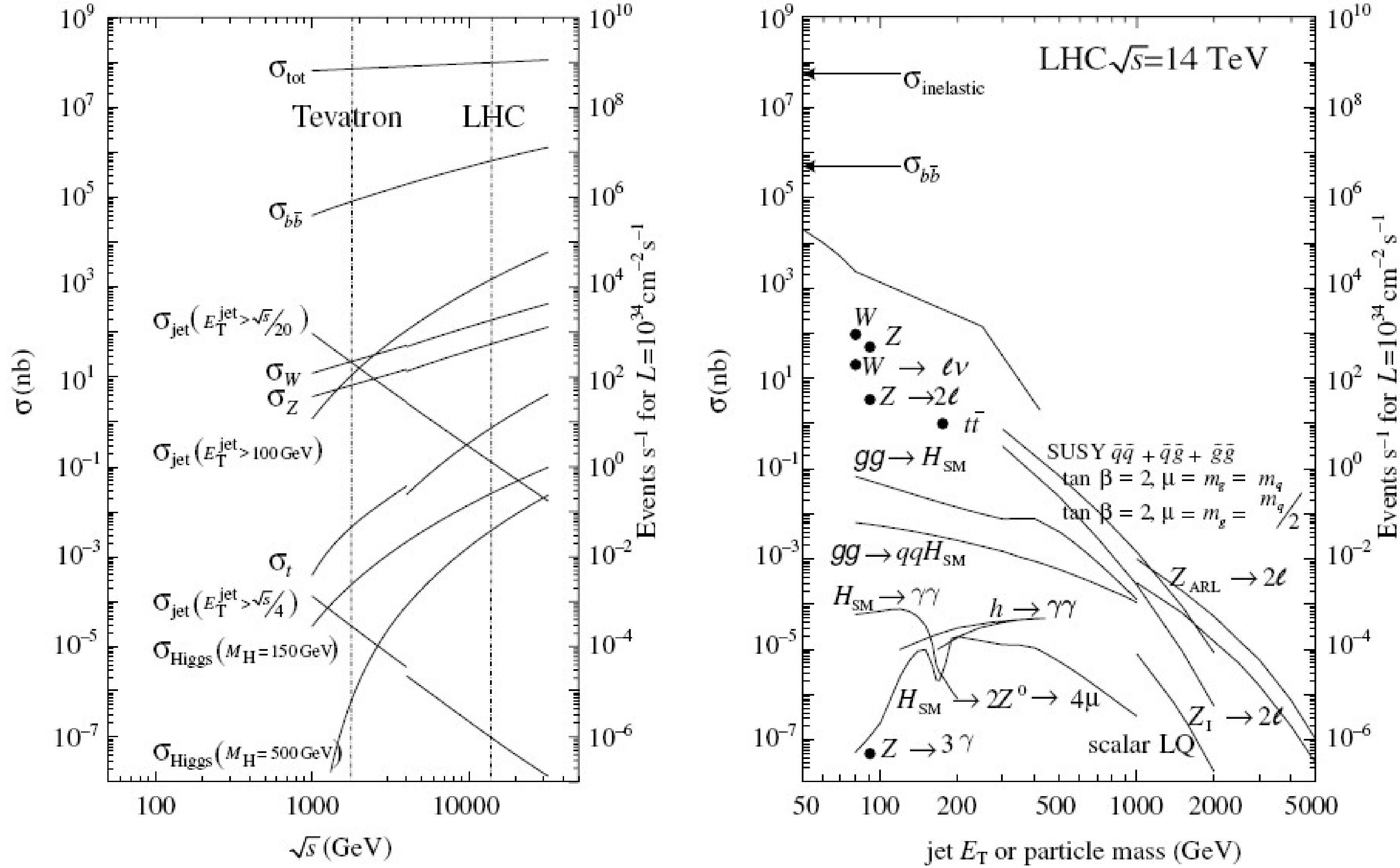
However:
50 ns should be kept as alive and possible because we DO NOT have enough experience on the actual limit *(e-clouds, I_{beam})*

	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

Continuous global optimisation with LIU

Courtesy Oliver Brüning

The detectors challenge



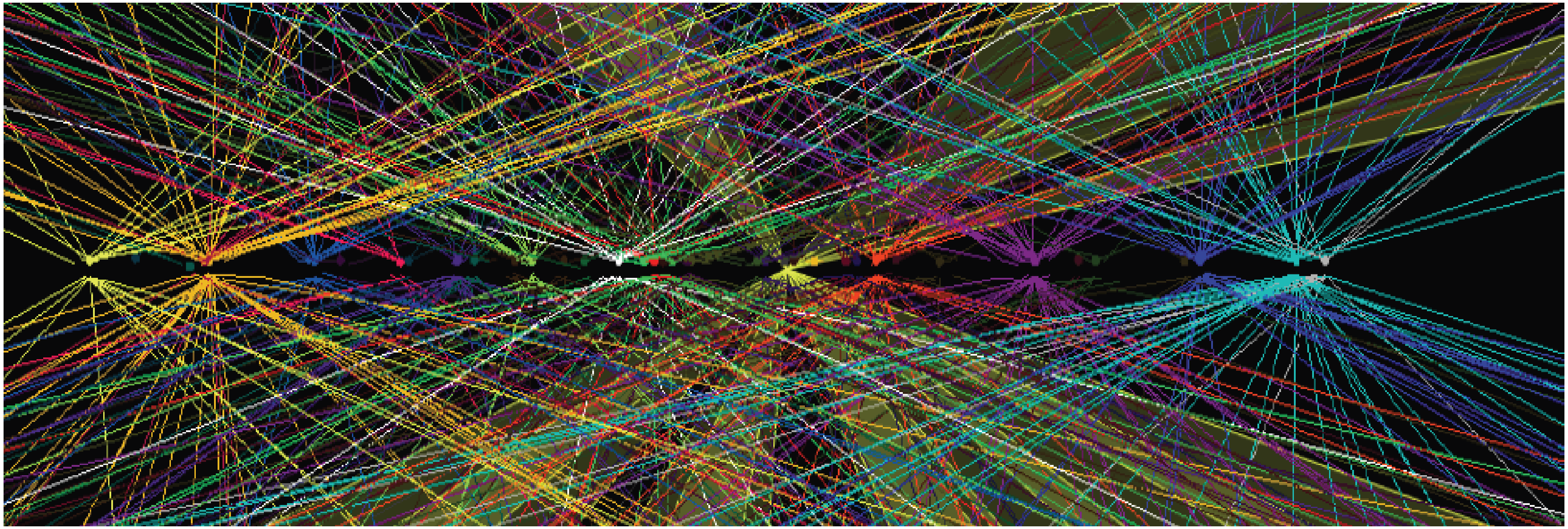
7 – 11 orders of magnitude between inelastic and "interesting" - "discovery" physics event rate

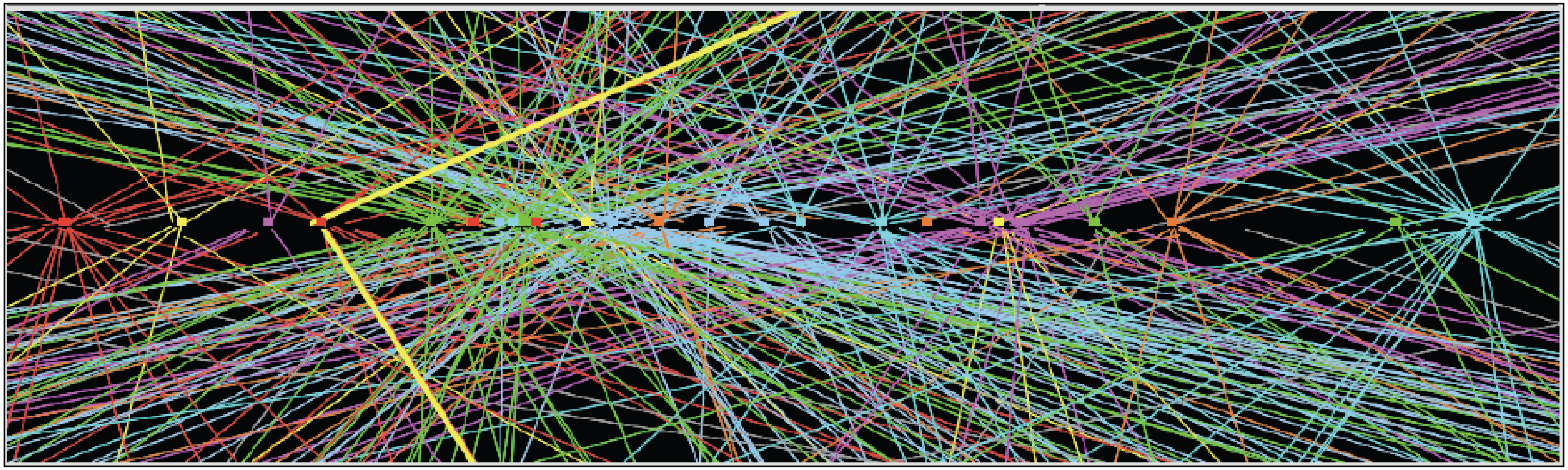
The detectors challenge

In order to exploit the LHC potential, experiments have to maintain full sensitivity for discovery, while keeping their capabilities to perform precision measurements at low p_T, in the presence of:

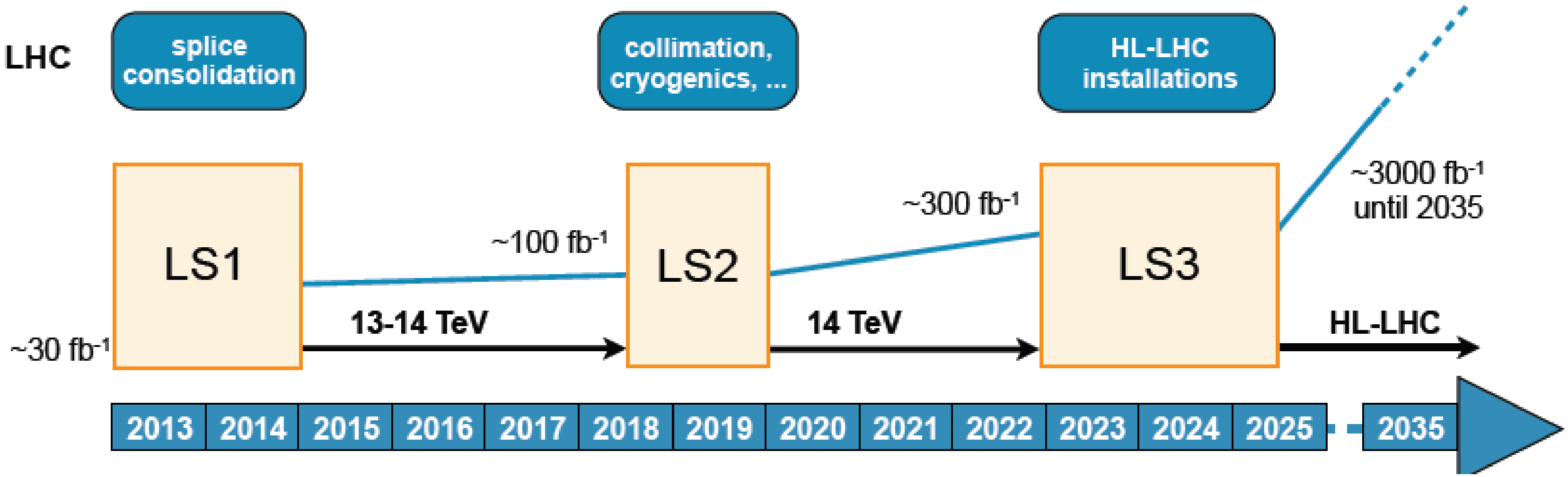
- Pileup
  - <PU> ≈ 50 events per crossing by LS2
  - <PU> ≈ 60 events per crossing by LS3
  - <PU> ≈ 140 events per crossing by HL-LHC
- Radiation damage
  - Requires work to maintain calibration
  - Limits performance-lifetime of the detectors
    - Light loss (calorimeters)
    - Increased leakage current (silicon detectors)

Try to visualize x5!





ATLAS Upgrade Roadmap



ATLAS Phase-0

New inner pixel layer
Detector consolidation
2015: FTK deployment

ATLAS Phase-1

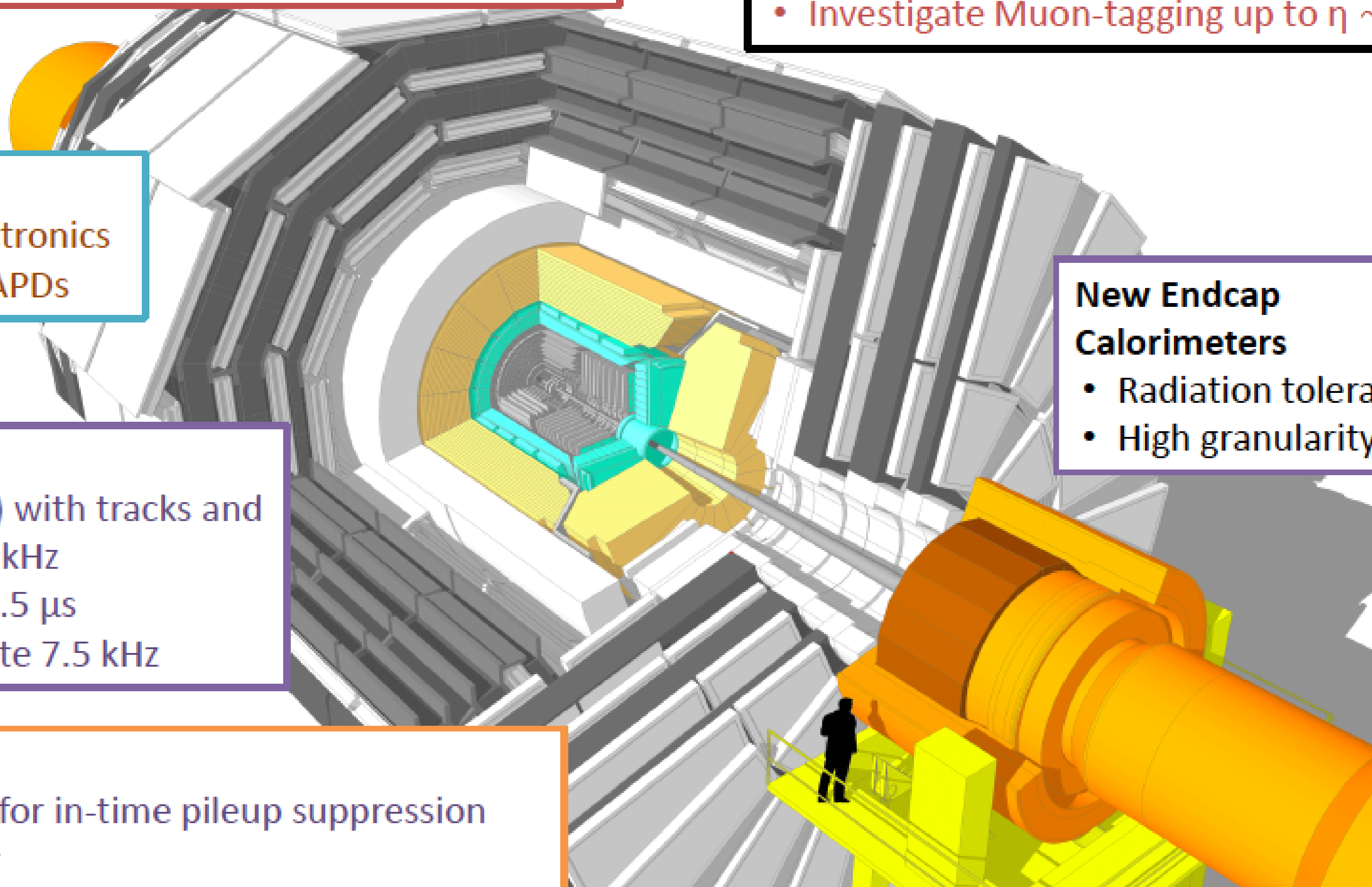
Improve L1 Trigger, NSW and LAr electronics to cope with higher rates

ATLAS Phase-2

Prepare for 140-200 pile-up events
Replace Inner Tracker
New L0/L1 trigger scheme
Upgrade muon/calorimeter electronics
Upgrade of DAQ detector readout

A long and exciting road ahead !

CMS Phase II Upgrade



New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 3

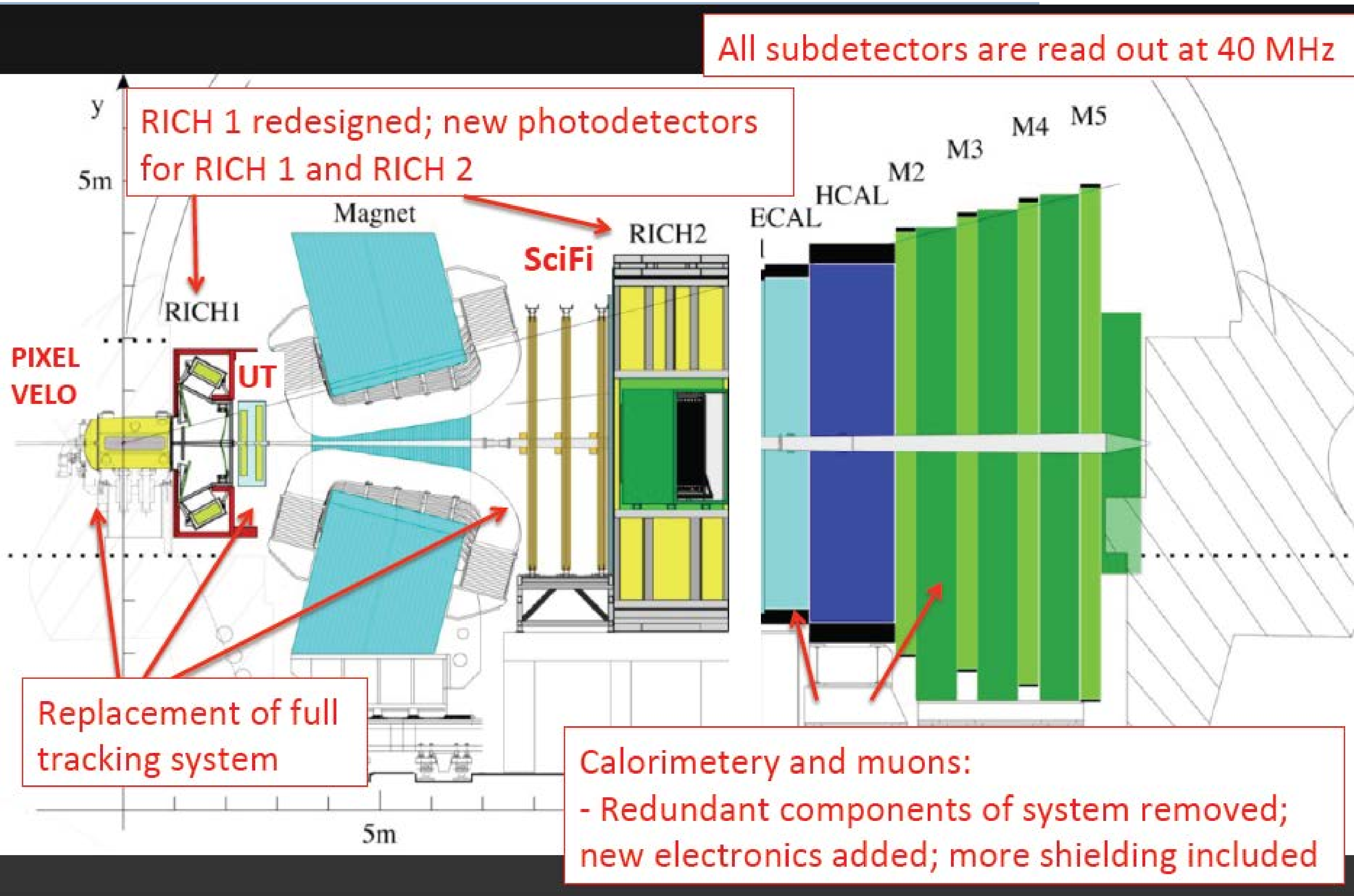
Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

New Endcap Calorimeters
- Radiation tolerant
- High granularity

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 μs
- HLT output rate 7.5 kHz

Other R&D
- Fast-timing for in-time pileup suppression
- Pixel trigger

LHCb Upgrade



ALICE Upgrade

New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

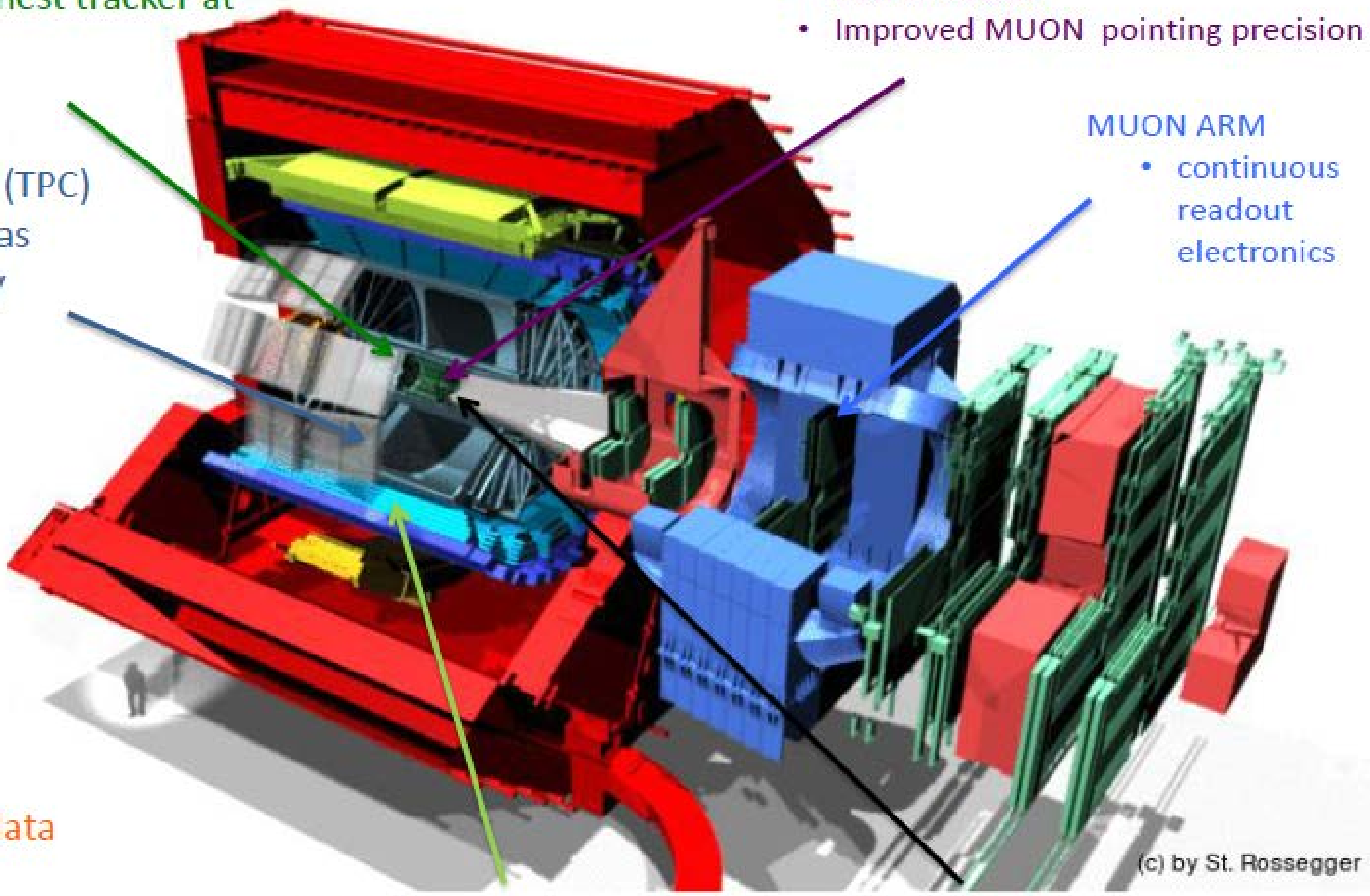
Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

Time Projection Chamber (TPC)
- New Micropattern gas detector technology
- continuous readout

MUON ARM
- continuous readout electronics

New Central Trigger Processor (CTP)

Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate



TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

LHC Experiments Phase II Upgrades

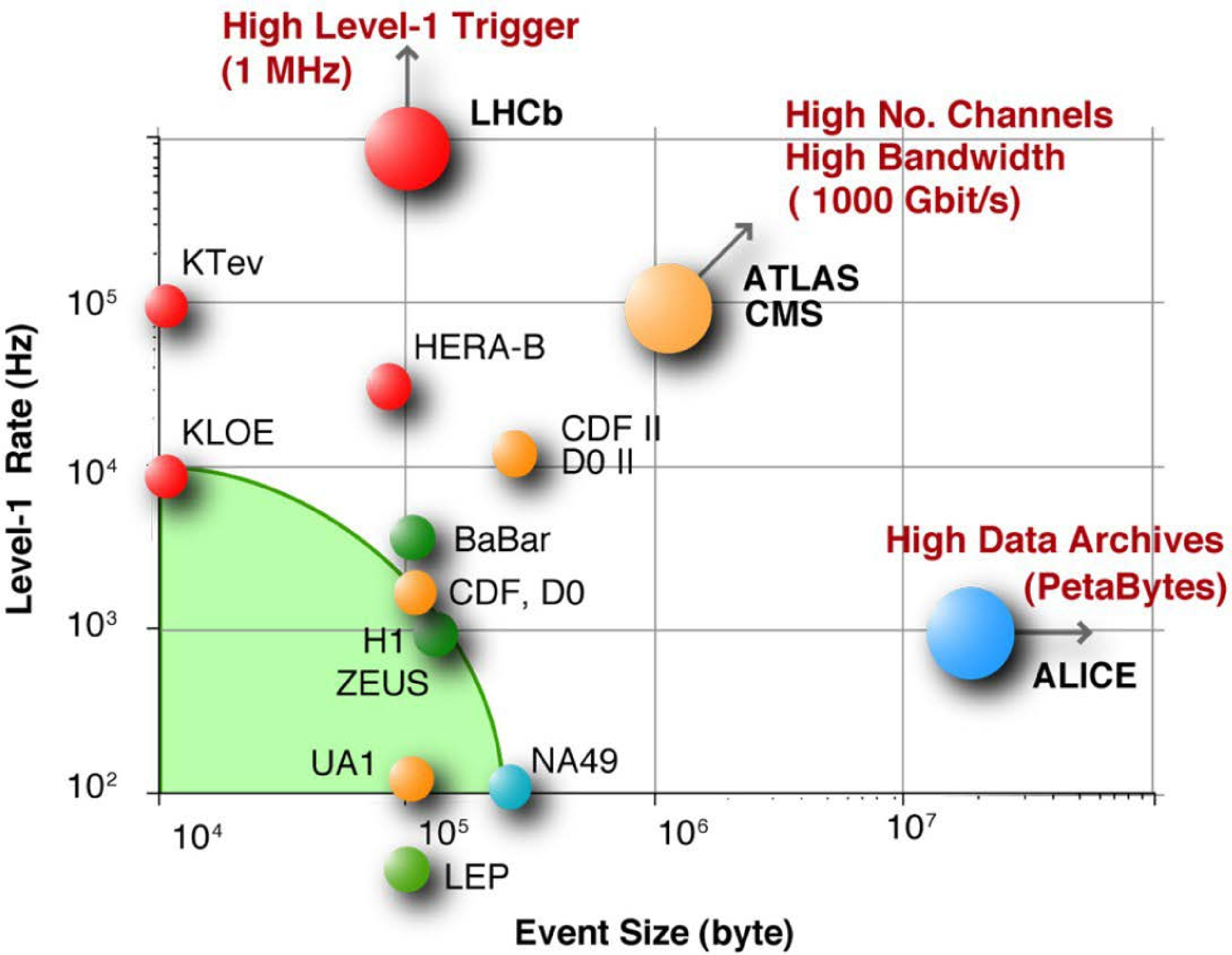
The scenario:

- By the year 2023, LHC will have delivered an integral luminosity ~ 300/fb to each of the two general purpose experiments.
- At that time, both the LHC low-beta insertions and many critical components of the experiments will have reached the end of their life-cycle, due to radiation damage. This aging model has by now been validated by the data collected in Run I.
- It is inconceivable under any reasonable scenario to stop the LHC program at that point, as it is also indicated as the top priority in the Update of European Strategy on Particle Physics → **ATLAS AND CMS PHASE II UPGRADES ARE MANDATORY**.
- The goal of the upgrades, clearly stated by both experiments, is **to retain the same performances as in Run I** in a much more challenging environment

The Experiments

- Long term schedule stabilized at the end of 2013
- Phase-I upgrades figures and timelines pretty consolidated
- Phase-II figures and timelines still based on LOI and subject to R&D results
- HL-LHC studies continuing (2nd ECFA HL-LHC Experiments Workshop https://indico.cern.ch/event/315626/)

The data challenge

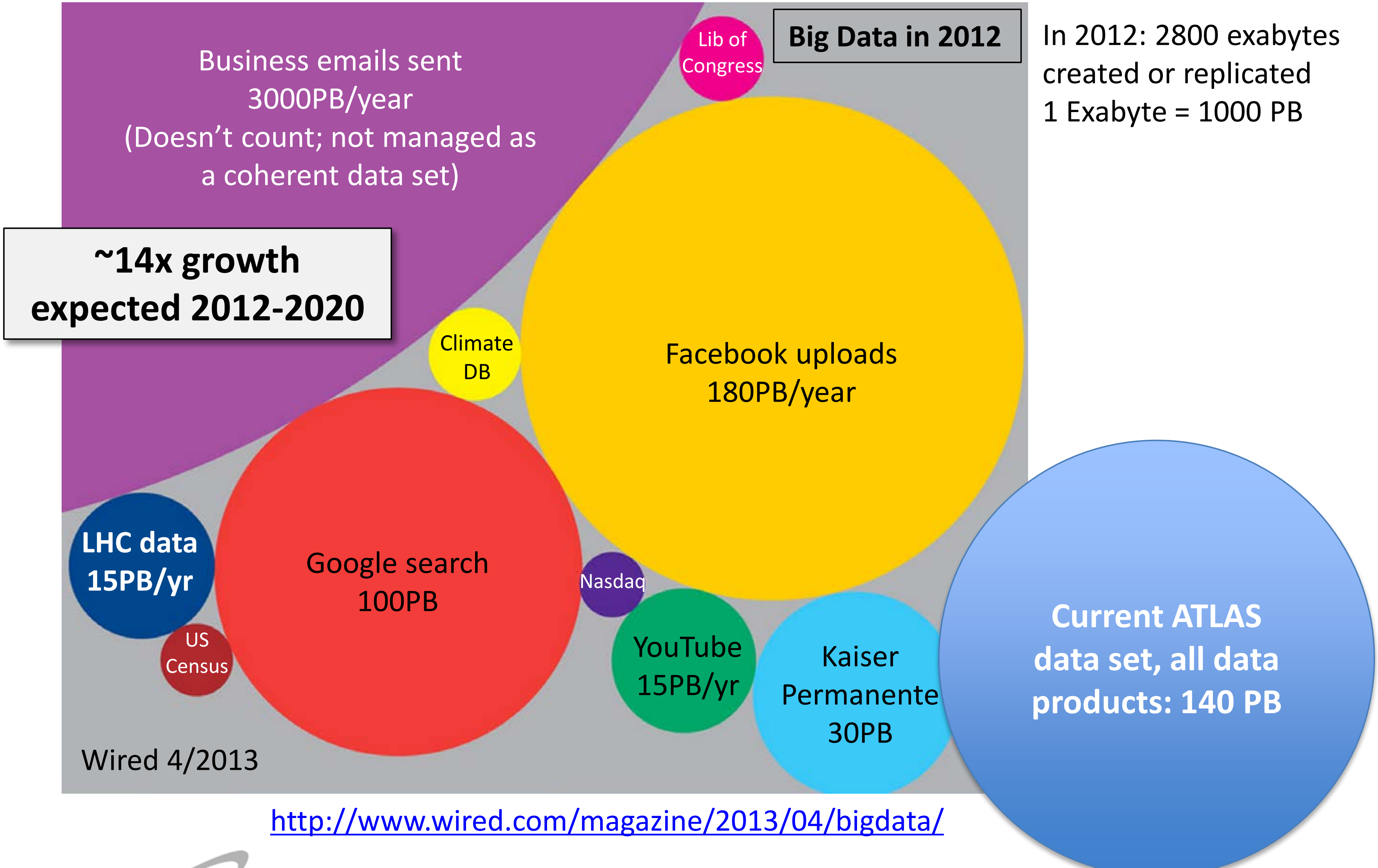


From: Torre Wenaus, CHEP 2013

Data Management

Where is LHC in Big Data Terms?

In 2012: 2800 exabytes created or replicated
1 Exabyte = 1000 PB



http://www.wired.com/magazine/2013/04/bigdata/

Software

- Moore's law only helps us if we can make use of the new multi-core CPUs with specialised accelerators etc. (Vectorisation, GPUs, …)
  - No longer benefit from simple increases in clock speed
- Ultimately this requires HEP software to be re-engineered to make use of parallelism at all levels
  - Vectors, instruction pipelining, instruction level pipelining, hardware threading, multi-core, multi-socket.
- Need to focus on commonalities:
  - GEANT, ROOT, build up common libraries
- This requires significant effort and investment in the HEP community
  - Concurrency forum already initiated
  - Ideas to strengthen this as a collaboration to provide roadmap and incorporate & credit additional effort

European Strategy for Particle Physics

High-priority large-scale scientific activities

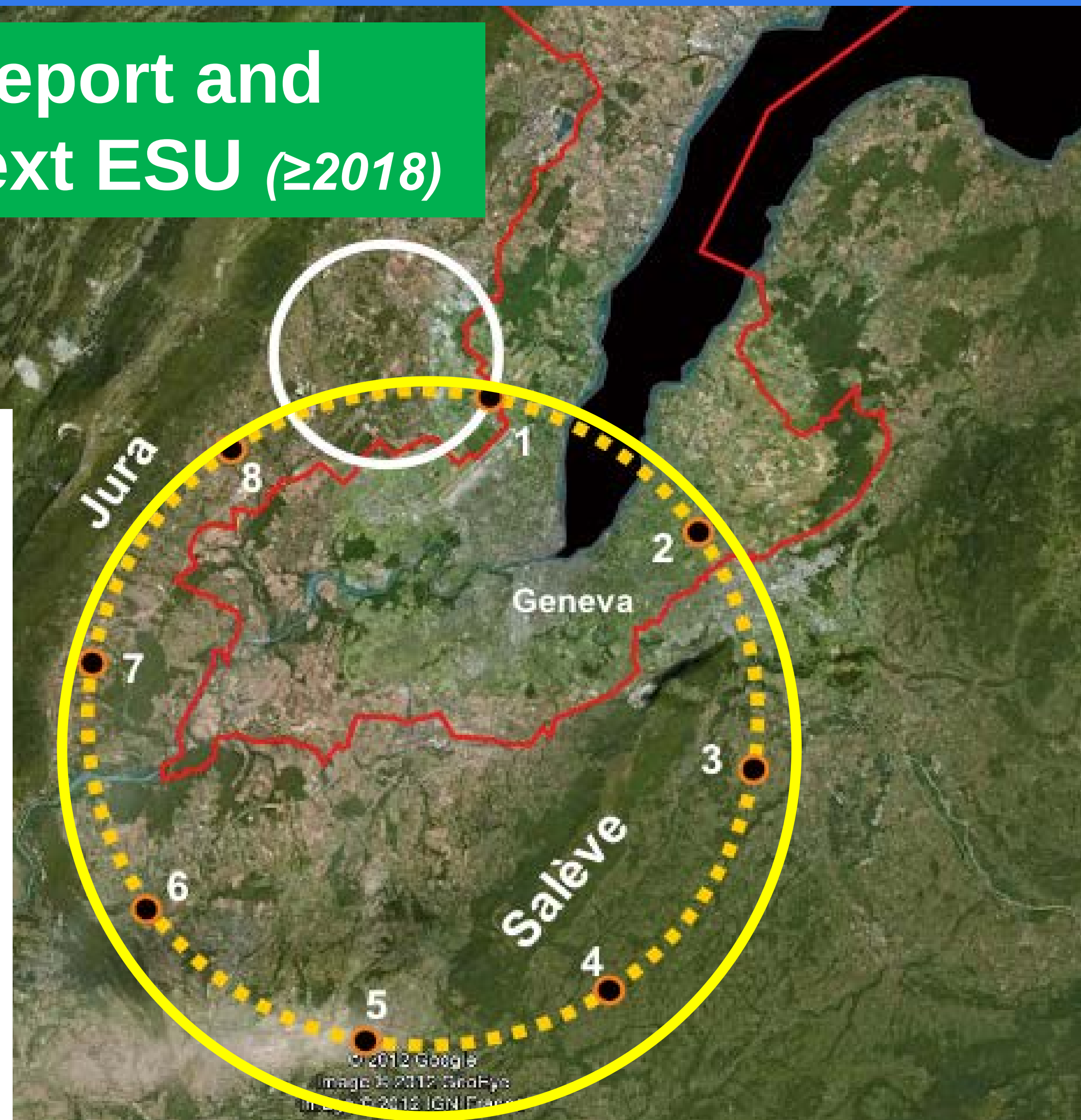
After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. ***CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.***

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements

with possibility of e+-e- (TLEP) and p-e (VLHeC)

Conceptual Design Report and cost review for the next ESU *(≥2018)*

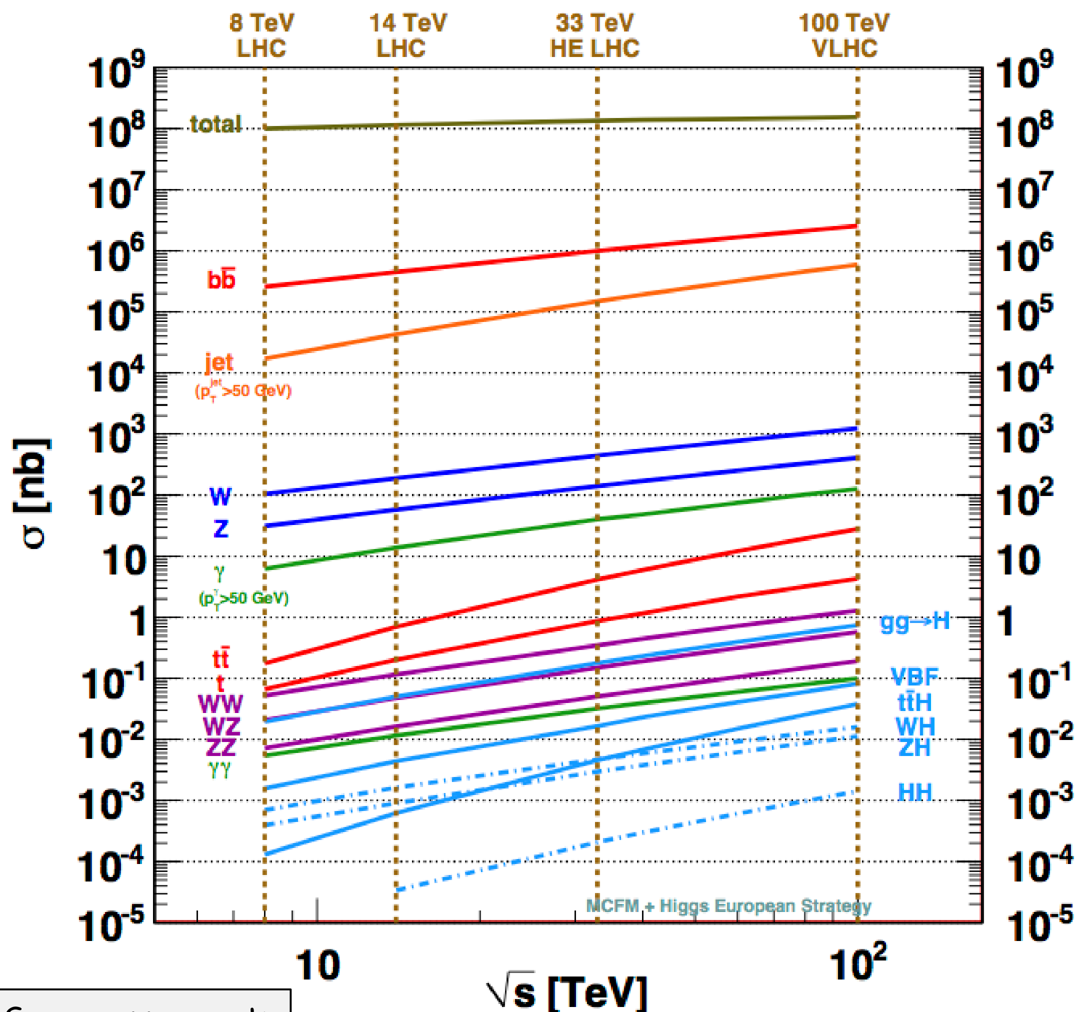


FCC Design Study Kick-off Meeting: 12-14. February 2014 in Geneva

Establishing international collaborations

- ***Set-up study groups and committees***

Cross sections vs √s



Snowmass report: arXiv:1310.5189

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

→ With 10000/fb at √s=100 TeV expect: 10^{12} top, 10^{10} Higgs bosons, 10^8 m=1 TeV stop pairs, …

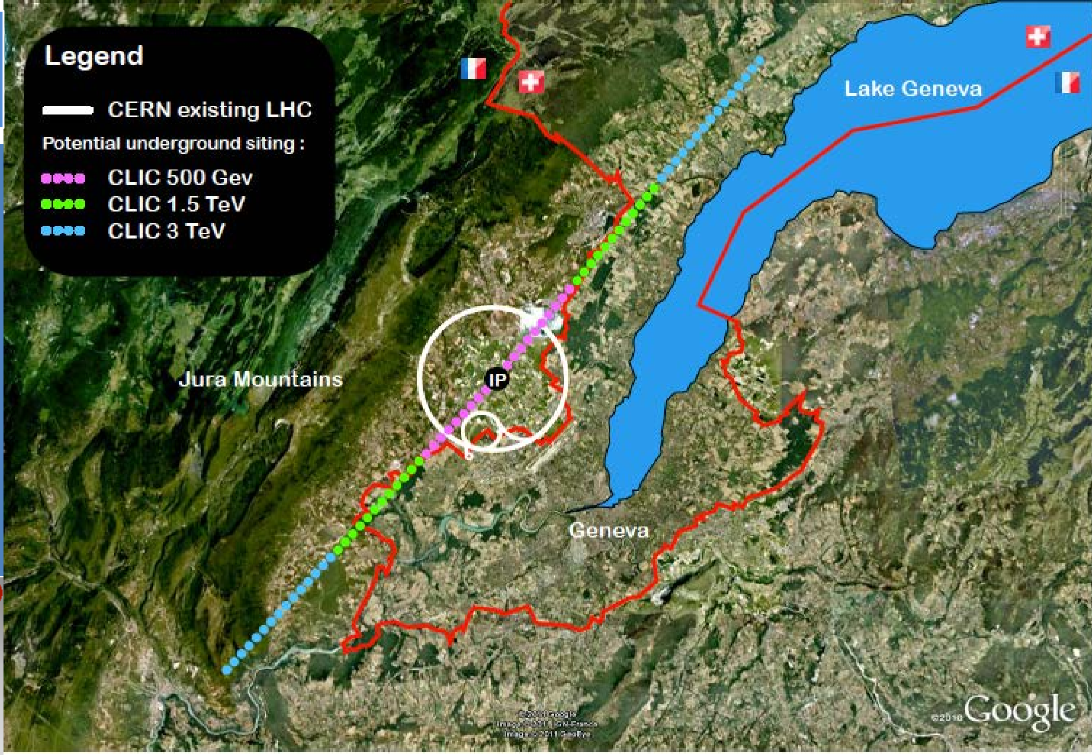
F. Gianotti, LHCP 2014, 6/6/2014

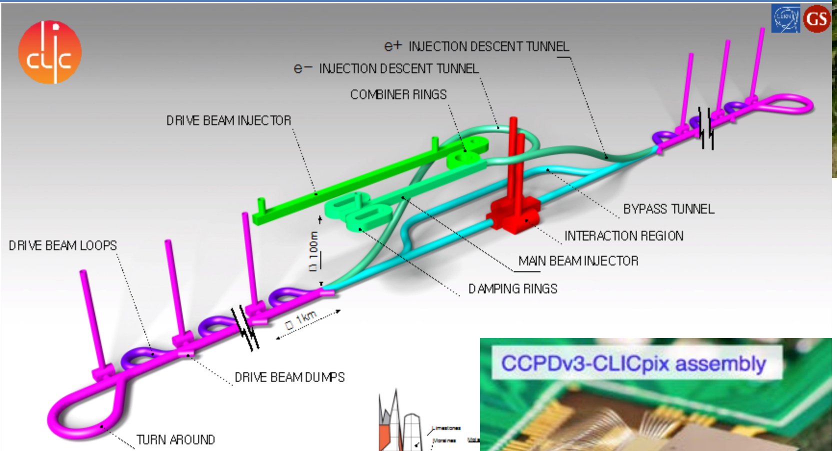
The CLIC project

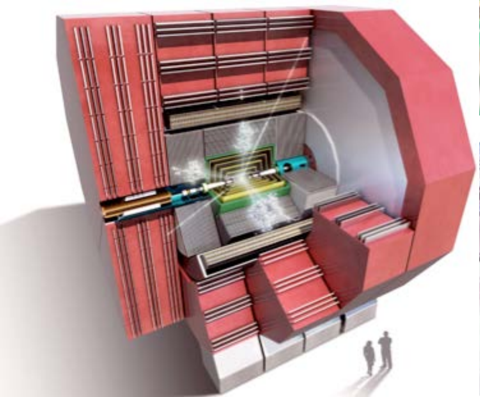
e+e- linear collider, can be built in stages covering from a few hundred GeV to 3 TeV, operated at luminosities ~1-5 10^{34} cm^{-2} s^{-1}

Key challenges:

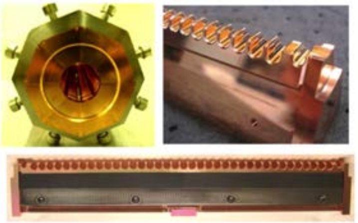
- High gradient (energy/length)
- Small beams (luminosity)
- Repetition rates and bunch spacing (experimental conditions)

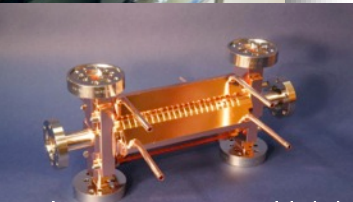






CALICE tungsten-DHCAL





Complete module, PETs (above), Acc. Structure (right)

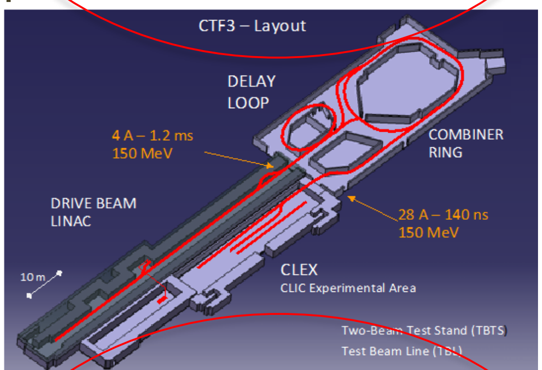
LINEAR COLLIDER COLLABORATION

New institutes are joining:
In 2014 SINAP Shanghai and IPM Tehran

Detector collaboration operative with 23 institutes

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

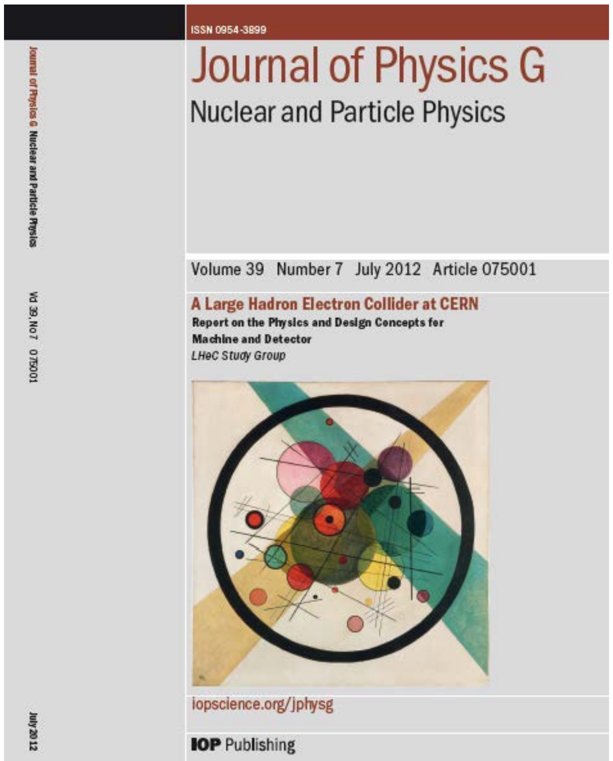


2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects as FCC), take decisions about next project(s) at the Energy Frontier.

- Common work with ILC related to several acc. systems as part of the LC coll., also related to initial stage physics and detector developments
- Common physics benchmarking with FCC pp and common detect. challenges (ex: timing, granularity), as well as project implementation studies (costs, power, infrastructures …)

LHeC, not only PDFs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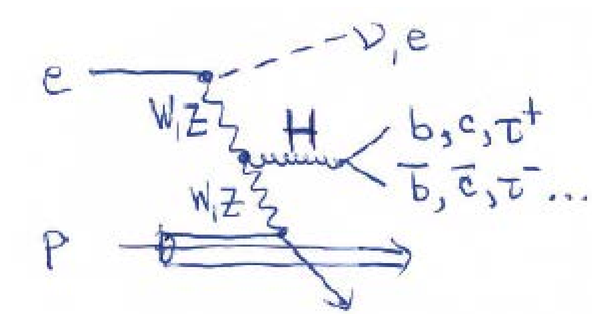
A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

iopscience.org/jphysg

IOP Publishing



Continuing activity on

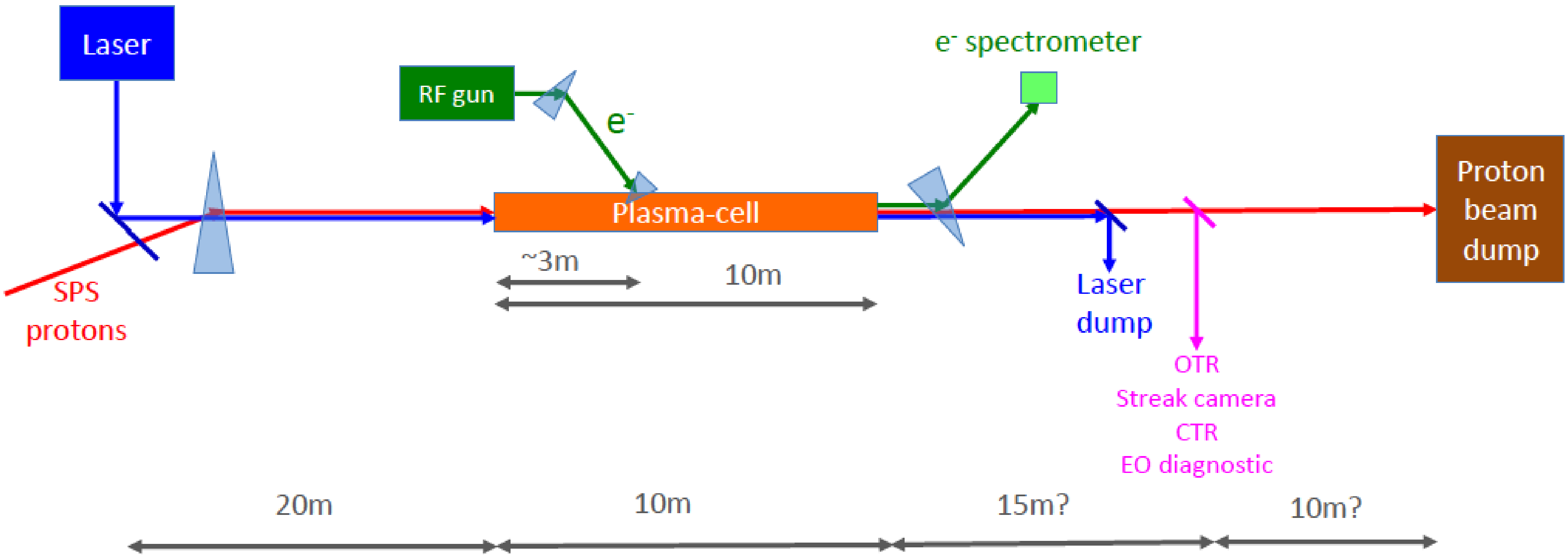
Physics

Detector

ERL

Goal: $L \sim 10^{34}\ cm^{-2}s^{-1}$

Experimental Layout



European Strategy for Particle Physics

High-priority large-scale scientific activities

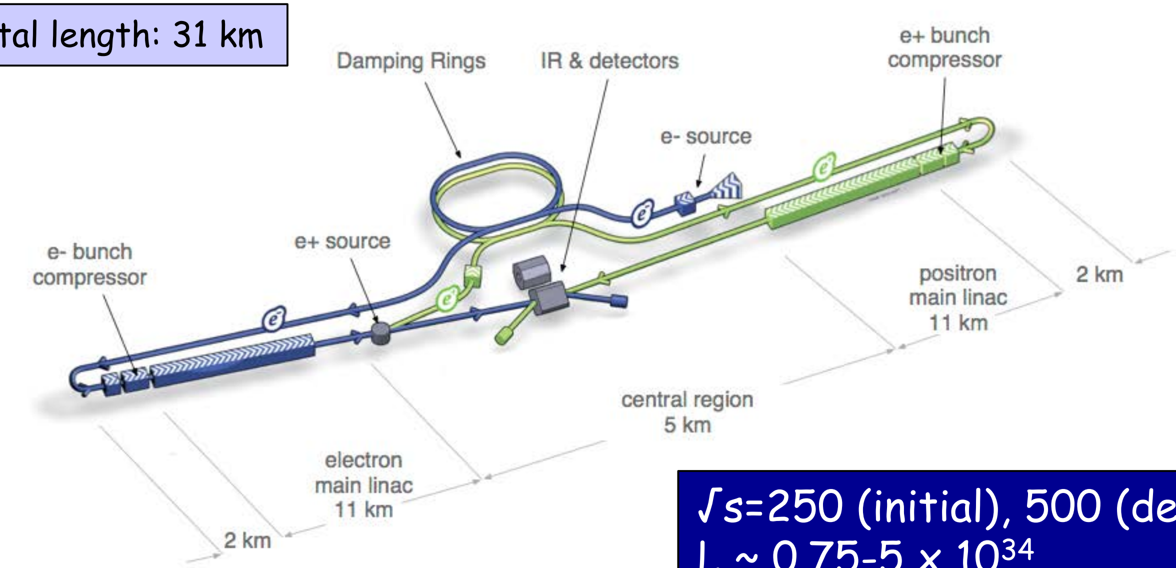
After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. ***Europe looks forward to a proposal from Japan to discuss a possible participation***

International Linear Collider (ILC)

Technical Design Report released in June 2013

Total length: 31 km



$\sqrt{s}$=250 (initial), 500 (design), 1000 (upgrade) GeV
L ~ 0.75-5 x 10^{34}
(running at $\sqrt{s}$=90, 160, 350 GeV also envisaged)

Main challenges:

- ❑ ~ 15000 SCRF cavities (1700 cryomodules), 31.5 MV/m gradient
- ❑ 1 TeV machine requires extension of main Linacs (50 km) and 45 MV/m
- ❑ Positron source; suppression of electron-cloud in positron damping ring
- ❑ Final focus: squeeze and collide nm-size beams

❑ Japan interested to host → decision ~2018 based also on ongoing international discussions
Mature technology: 20 years of R&D experience worldwide
(e.g. European xFEL at DESY is 5% of ILC, gradient 24 MV/m, some cavities achieved 29.6 MV/m)
→ Construction could technically start ~2019, duration ~10 years → physics could start ~2030

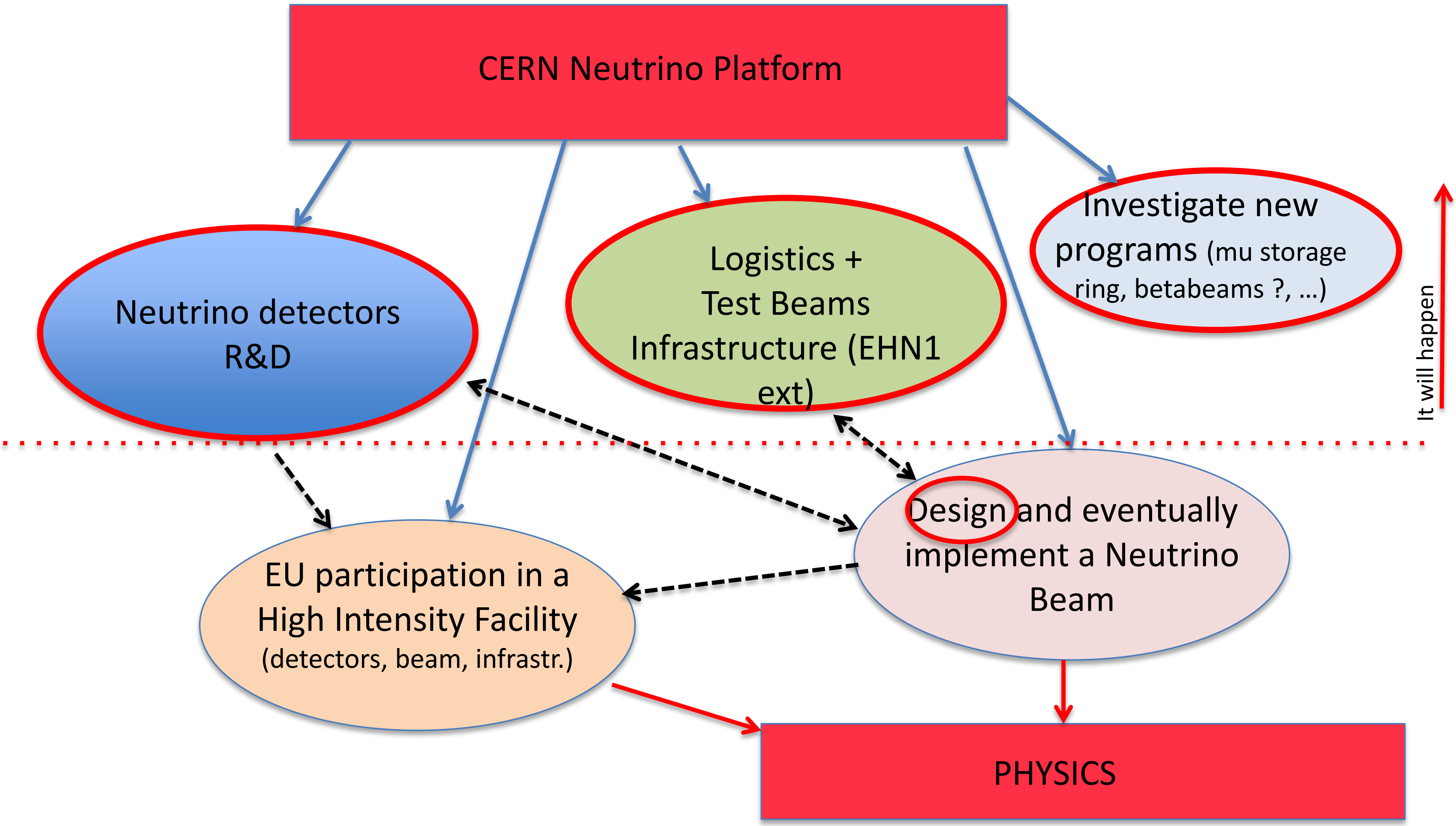
European Strategy for Particle Physics

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector.
CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

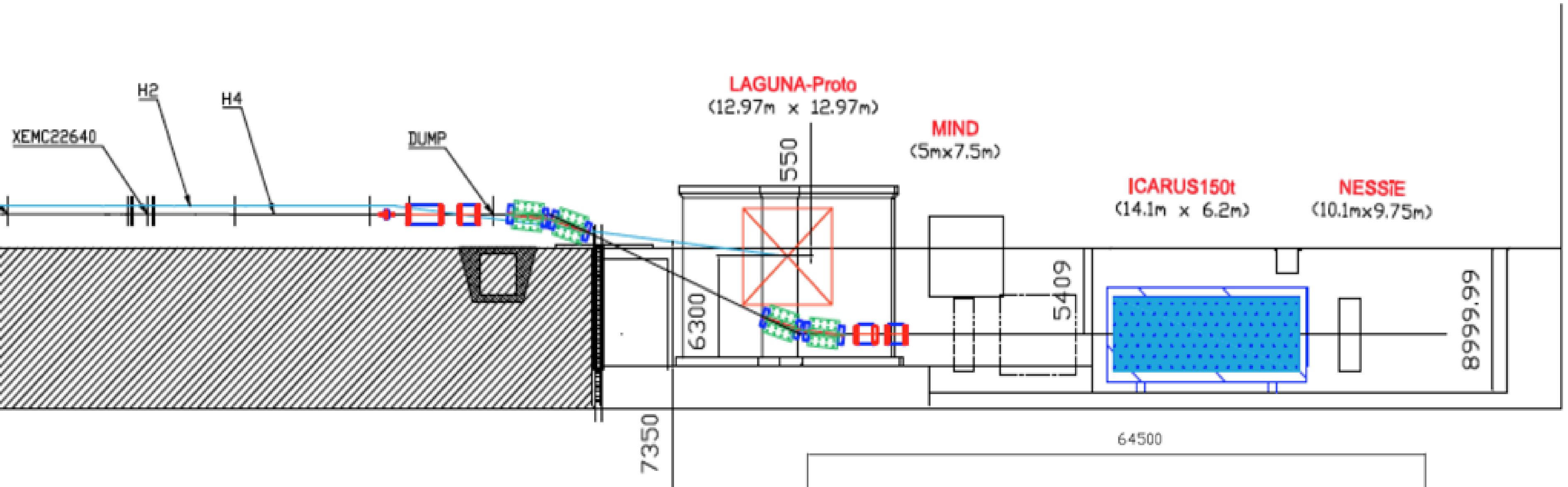
CERN Neutrino Platform



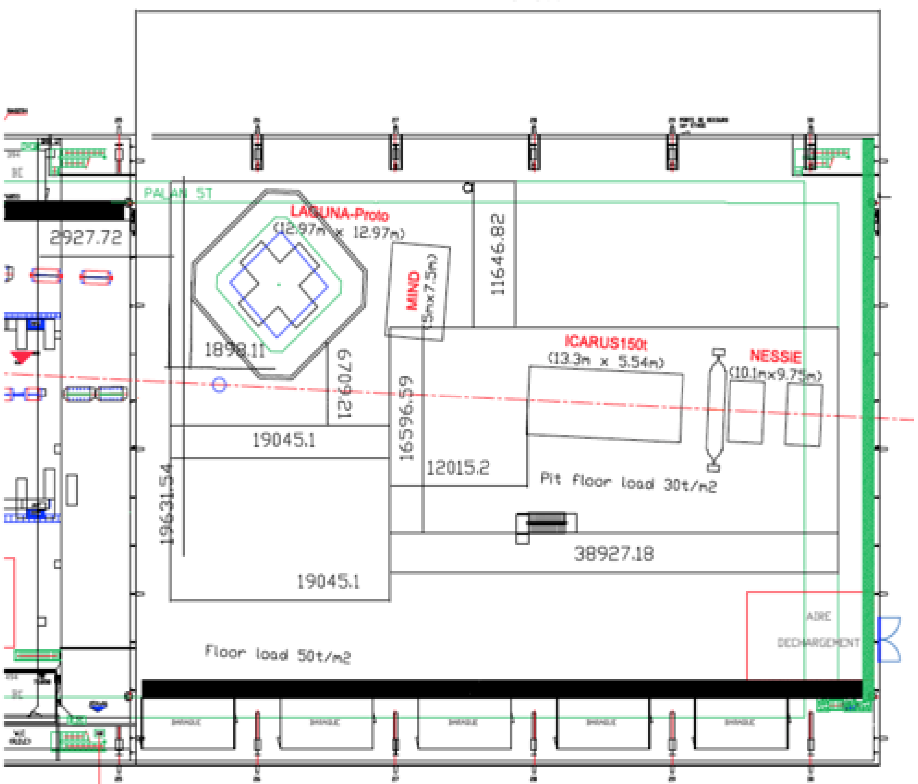
CERN Council in June 2014 has decided to implement the proposed Medium Term Plan (MTP) which for the first time (since years) contains an important allocation of resources in the next 5 years dedicated to the Neutrino CERN Platform

This will cover:

- Generic ν detector R&D including large prototypes
- Design and generic R&D on ν beams
- The construction of a new experimental hall dedicated to neutrinos (Nord Area extension : EHN1) with charged test beams capabilities
- The reinforcement of various Technical/Scientific groups at CERN (cryogenics, physics, ….) which will support the activities of the platform
- The support with detectors and components of the Short Baseline/LBNF program at FNAL
- Support to various design/feasibility studies on this field (NUSTORM, ESS beam, …..)



charged beams layout (~0.5 – 20. GeV)



CERN Neutrino Platform

Neutrino detectors R&D

2014 -2018

WA104: rebuild ICARUS T600 in bldg 185 and make it ready for a FNAL beam

WA104: R&D on an AIR core muon detector (NESSiE) or eventually integrate a solenoid in the main TPC

WA105: R&D on 2 phases large LAr TPC prototypes

MIND : R&D on muon tracking detectors

LBNF : Test of a LBNE module inside the WA105 cryostat

In the pipeline : Argoncube-TPC, Hyper-Kamiokande EU prototypes, new 200t TPC,

The Particle Physics Landscape at CERN: The importance of diversity

High Energy Frontier

LHC

Hadronic Matter

deconfinement
non-perturbative QCD
hadron structure

Low Energy

heavy flavours / rare decays
neutrino oscillations
anti-matter

Non-accelerator

dark matter
astroparticles

Multidisciplinary

climate, medicine

Non-LHC Particle Physics = o(1000) physicists / o(20) experiments

In the past years

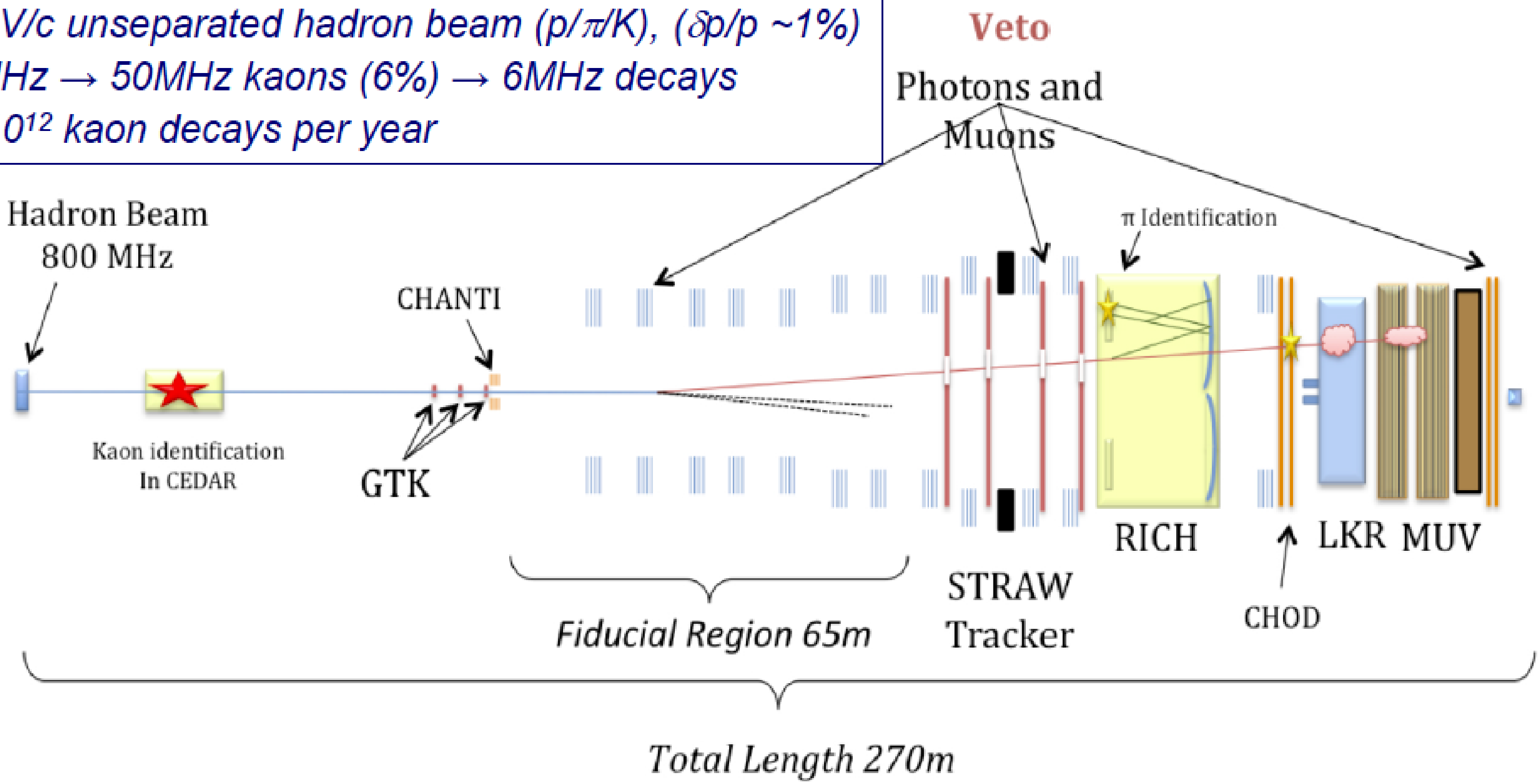
Several breakthroughs

Steady progress of other programs

New mid-term and long-term projects started or in discussion

The NA62 detector for $K^{\pm} \rightarrow \pi^{\pm}\nu\bar{\nu}$

- *SPS primary protons @ 400GeV/c*
- *75GeV/c unseparated hadron beam (p/π/K), (δp/p ~1%)*
- *750MHz → 50MHz kaons (6%) → 6MHz decays*
- *4.8×10^{12} kaon decays per year*



NA62 timeline:

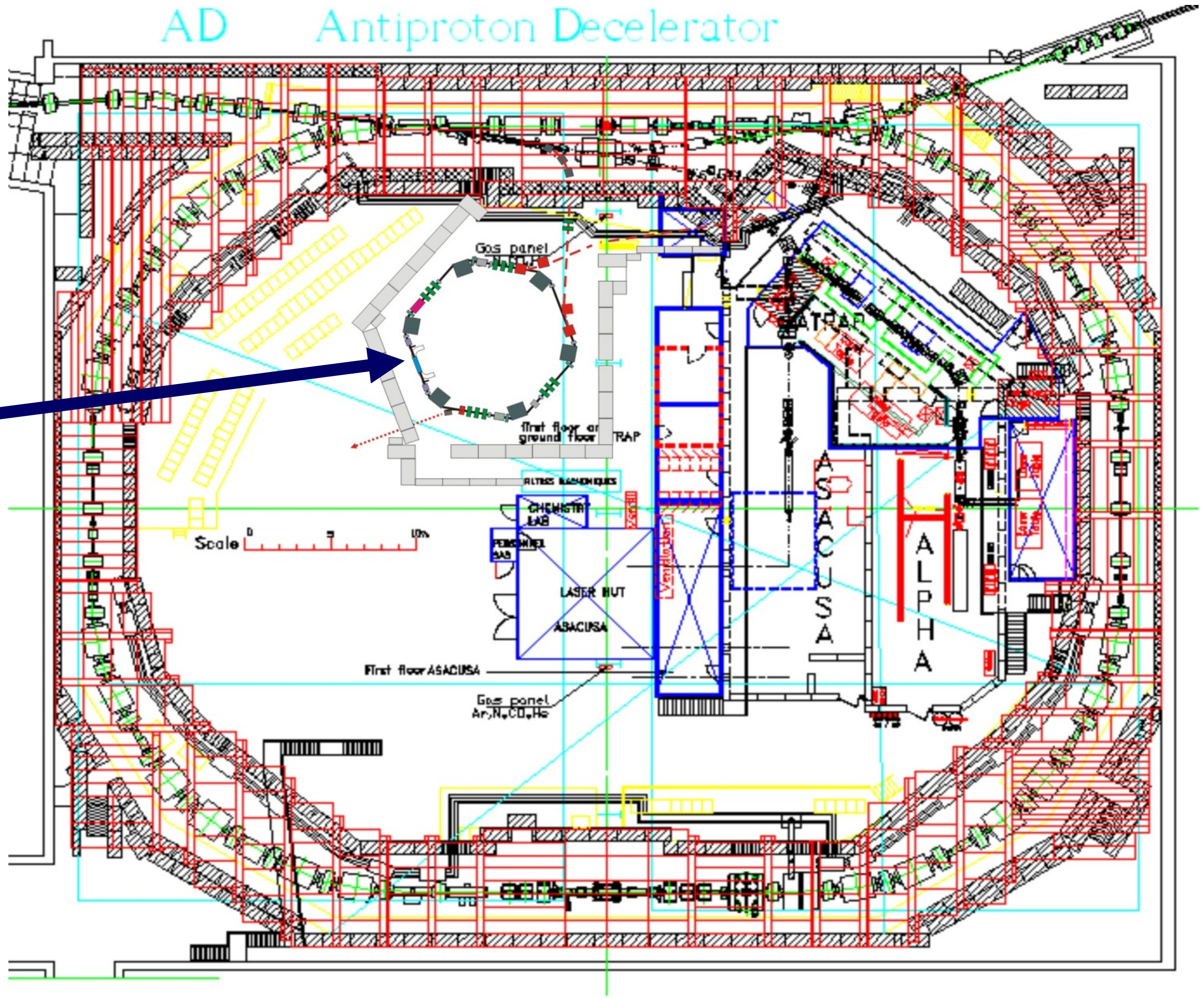
- *first technical run in autumn 2012 including many parts of the experiment*
- *2013: complete detector installation*
- *2014-?: data taking with full detector*

(driven by CERN accelerator schedule)

AD UPGRADE

Additional decelerating and cooling ring:

E_{kin} = 5 MeV → 100 KeV



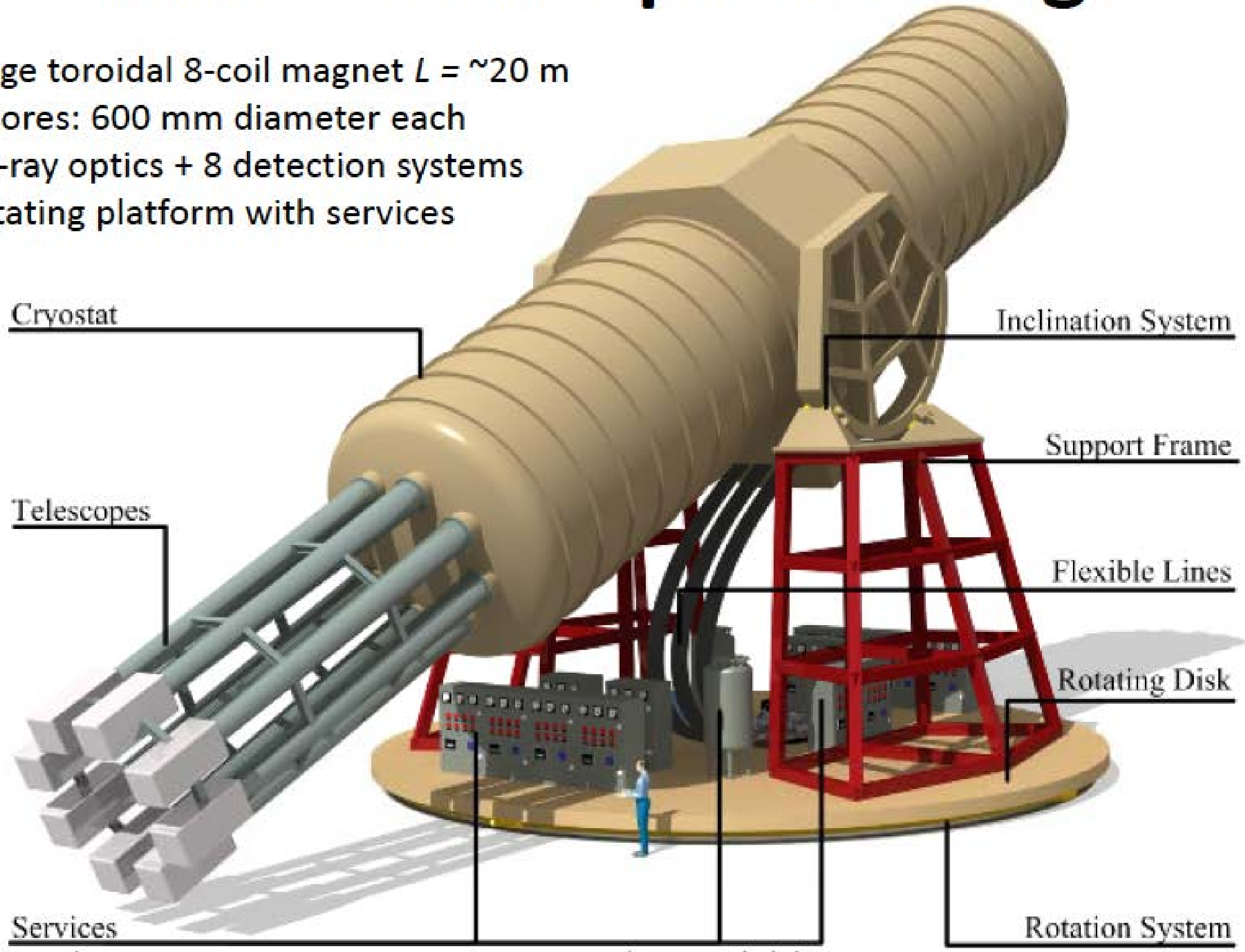
Expected gains :

- 1 to 2 orders of magnitude in trapping efficiencies
- Parallel running of all experiments
- Increased number of hosted experiments

Construction started, time scale ~2015-16

IAXO – Conceptual Design

- Large toroidal 8-coil magnet L = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray optics + 8 detection systems
- Rotating platform with services



Looking for “unknown unknowns”

Needs a synergic use of:

- High-Energy colliders
- neutrino experiments (solar, short/long baseline, reactors, 0{ ββ decays),
- cosmic surveys (CMB, Supernovae, BAO)
- dark matter direct and indirect detection
- precision measurements of rare decays and phenomena
- dedicated searches (WIMPS, axions, dark-sector particles)
- …..

In summary

An exciting period in front of us:

- We have finished the inventory of the “known unknown”…
- …but we have a vast space to explore, and tools to do it exhaustively.
- We have a solid physics program for the next 15 – 20 years
- In this time period we have to prepare for the next steps, both technologically and politically

In summary

Experimental results will be dictating the agenda of the field.

We will need:

- Flexibility
- Preparedness
- Visionary global policies

THANK YOU