SLHC
THE LHC UPGRADE

Emmanuel Tsesmelis
Directorate Office, CERN

9th Corfu Summer Institute
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INTRODUCTION

Why Upgrade the LHC ?

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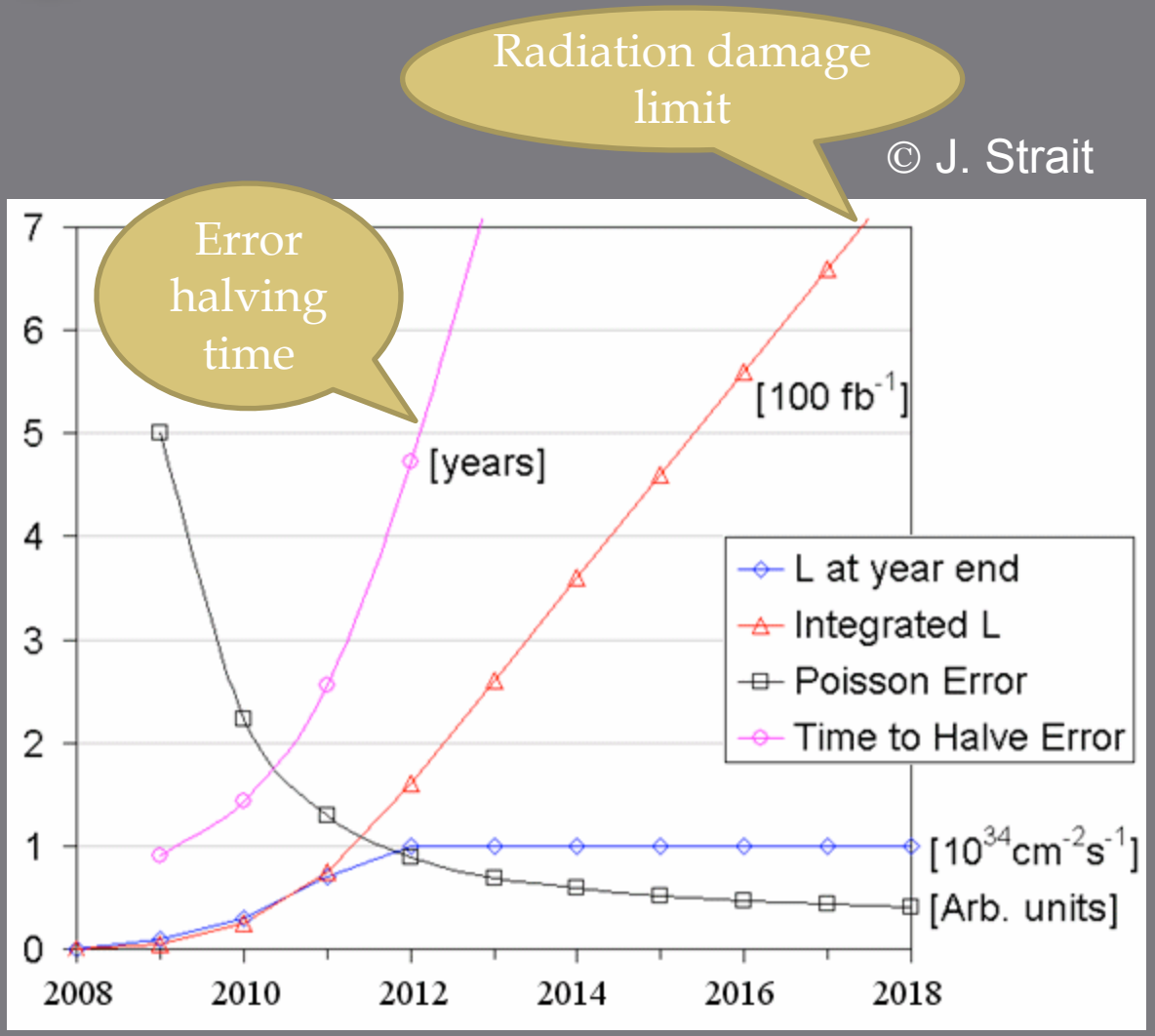
- Hardware ageing



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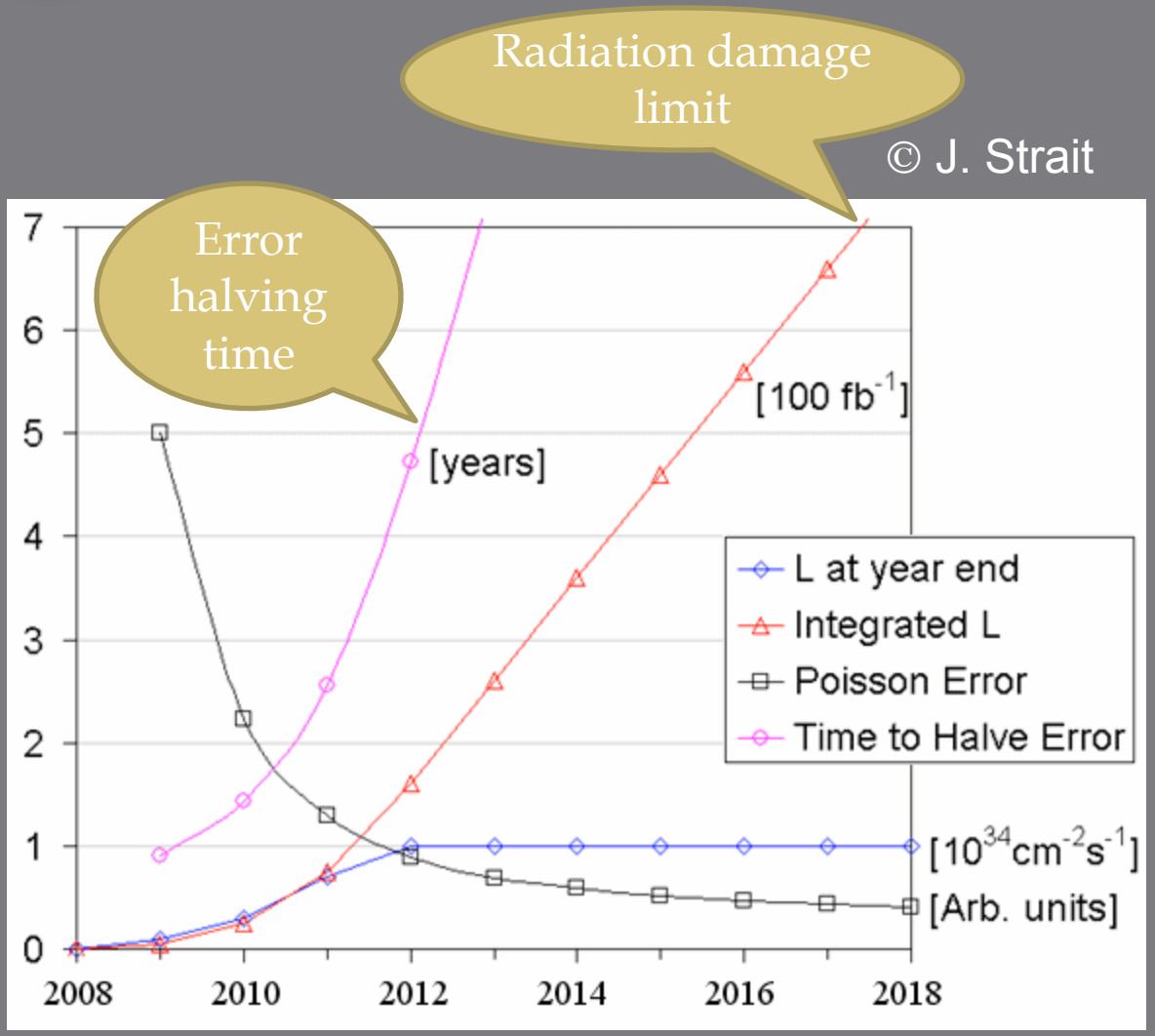

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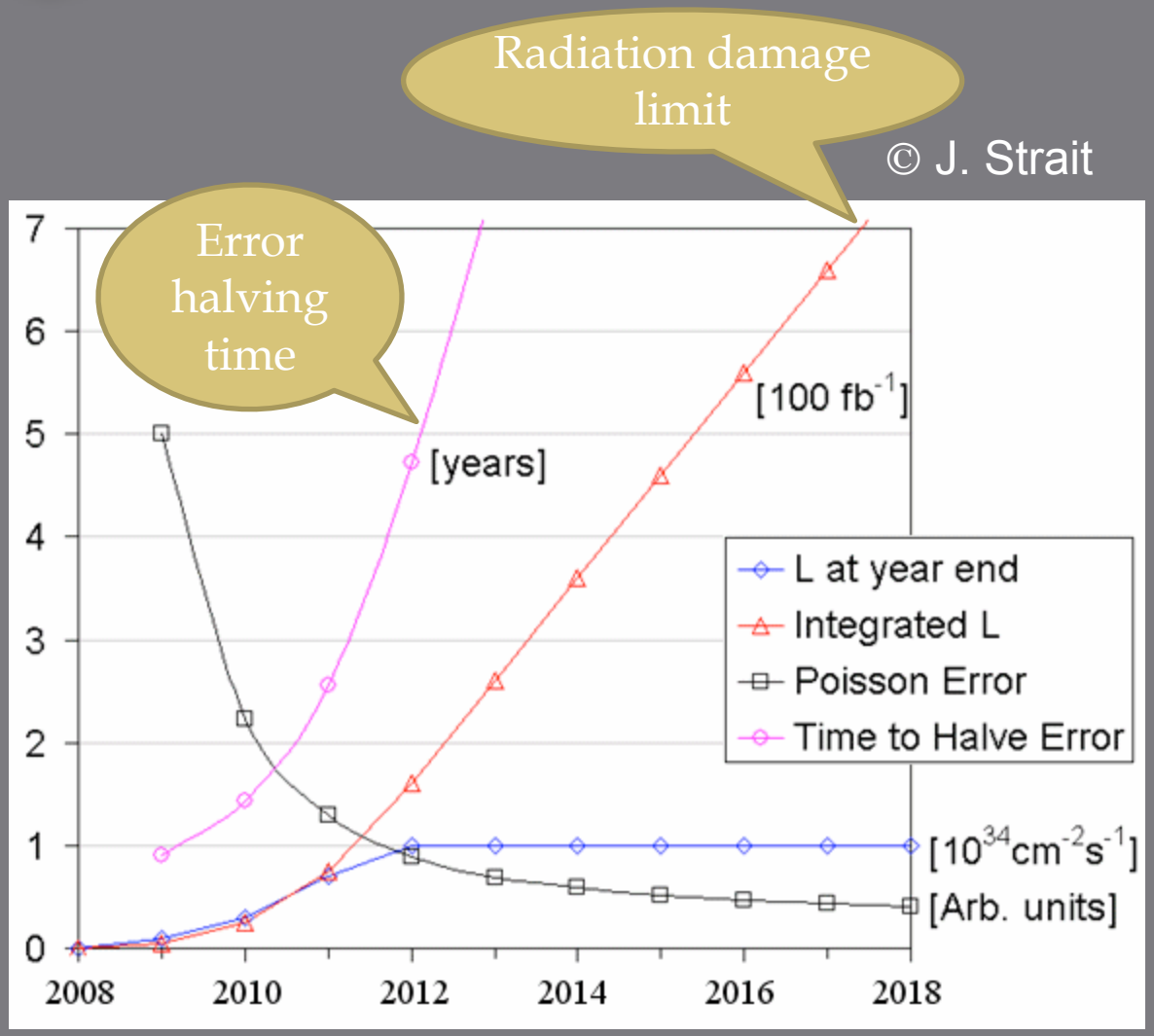
- Foreseeable luminosity evolution



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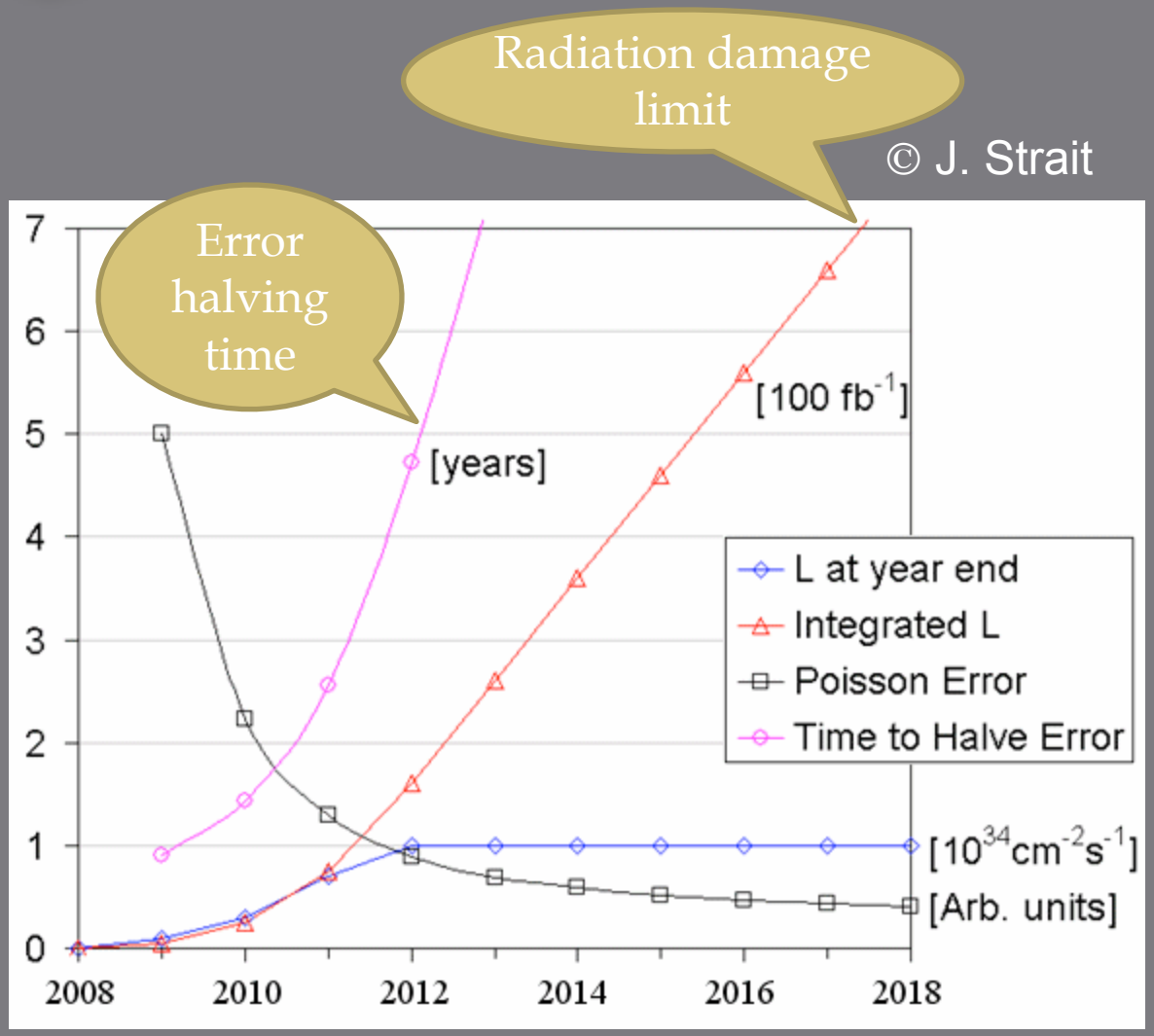

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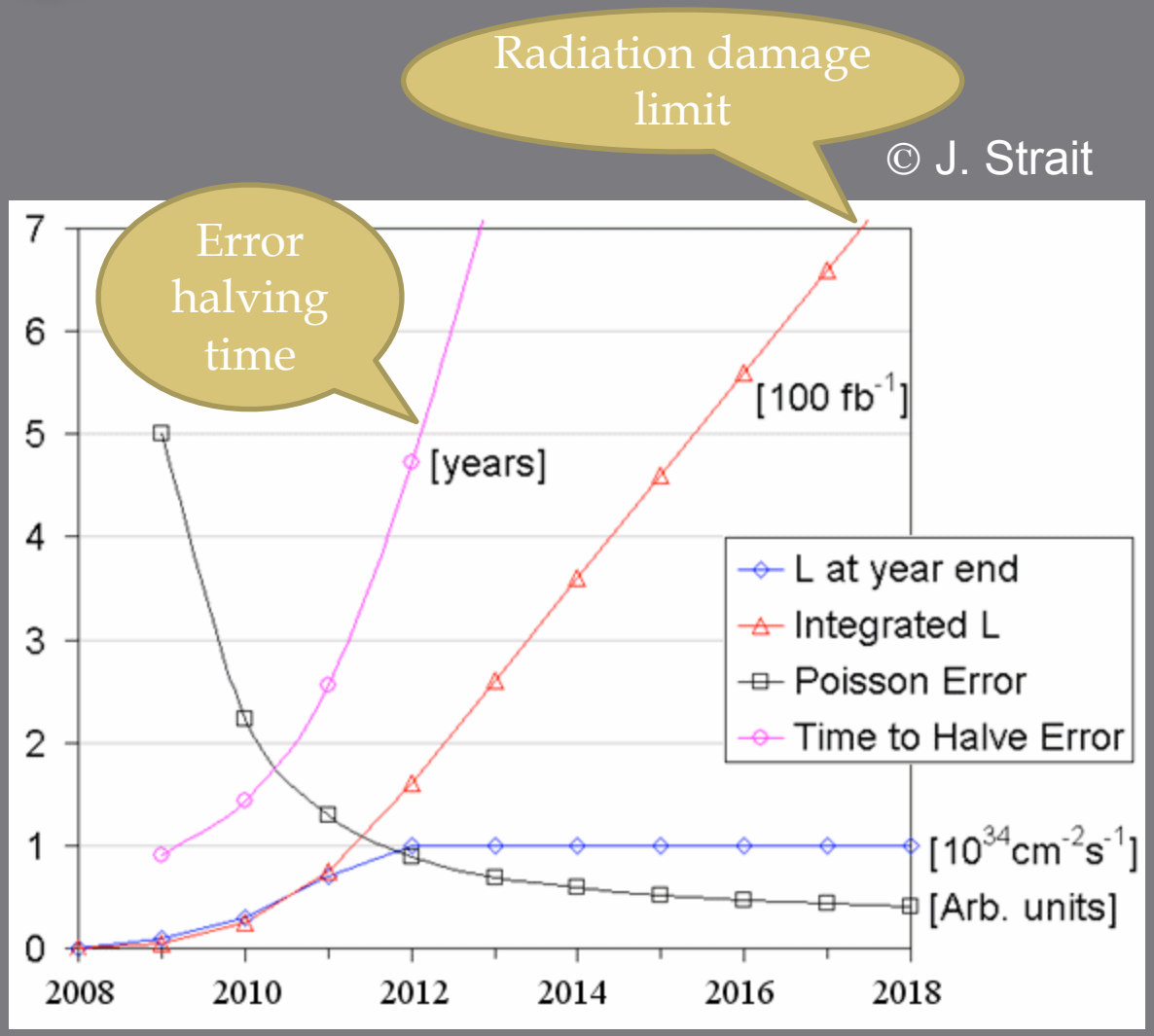
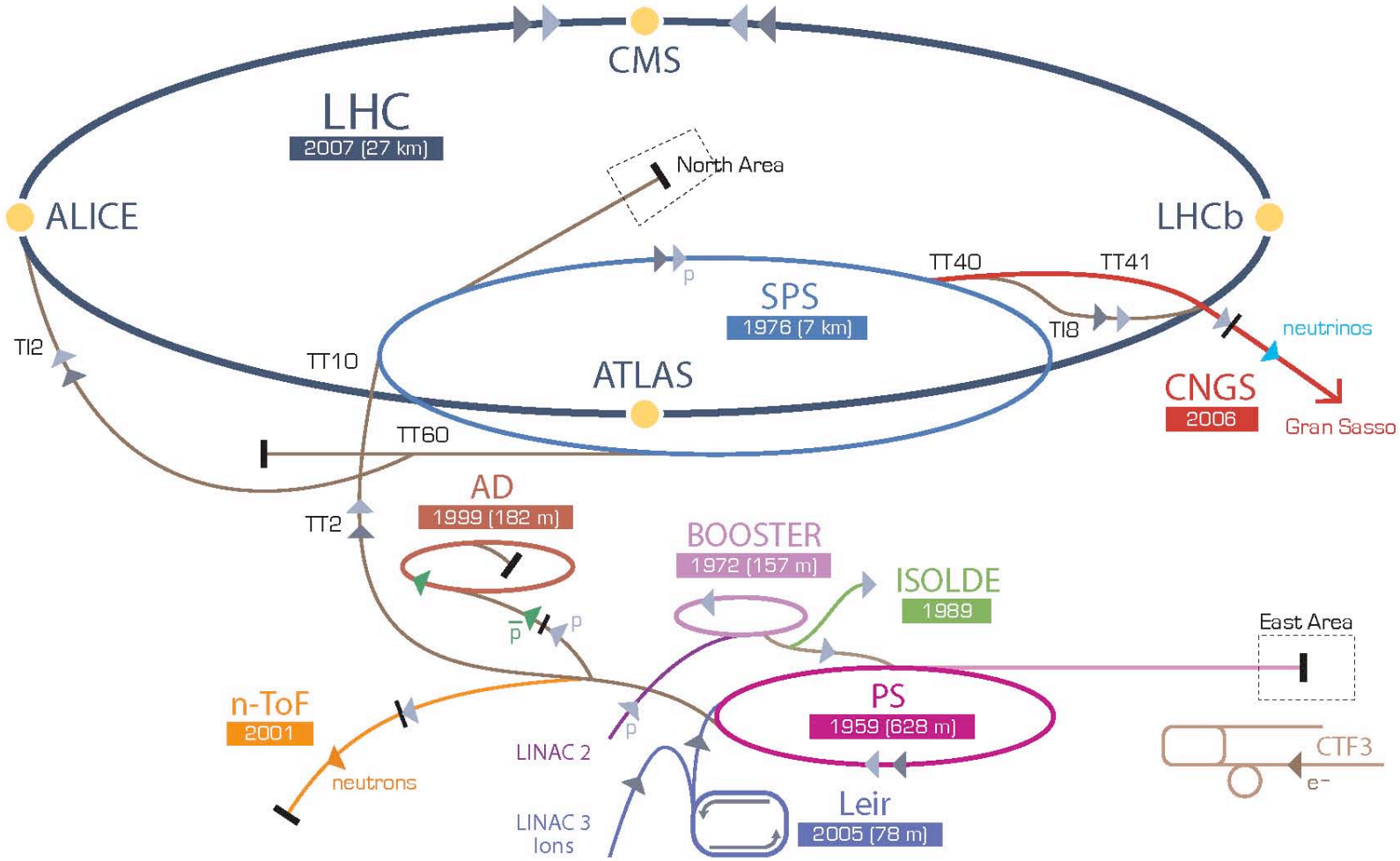
- Foreseeable luminosity evolution

⇒ **Need for a major luminosity upgrade in ~2017 (SLHC)**



CERN Accelerator Complex



p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

Why Upgrade the Injectors ?

- Need for reliability:
  - Accelerators are old [LINAC2 (1978), PSB (1975), PS (1959), SPS (1976)]
  - They operate far from their design parameters and close to hardware limits
  - The infrastructure has suffered from the concentration of resources on LHC during the past 10 years
- Need for better beam characteristics

INJECTORS

Upgrade Procedure

Upgrade Procedure

Main performance limitation:

Incoherent space charge tune spreads ΔQ_{SC} at injection in the PSB (50 MeV) and PS (1.4 GeV) because of the required beam brightness N/ε^*.

$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \times \frac{R}{\beta\gamma^2}$$

⇒ need to increase the injection energy in the synchrotrons

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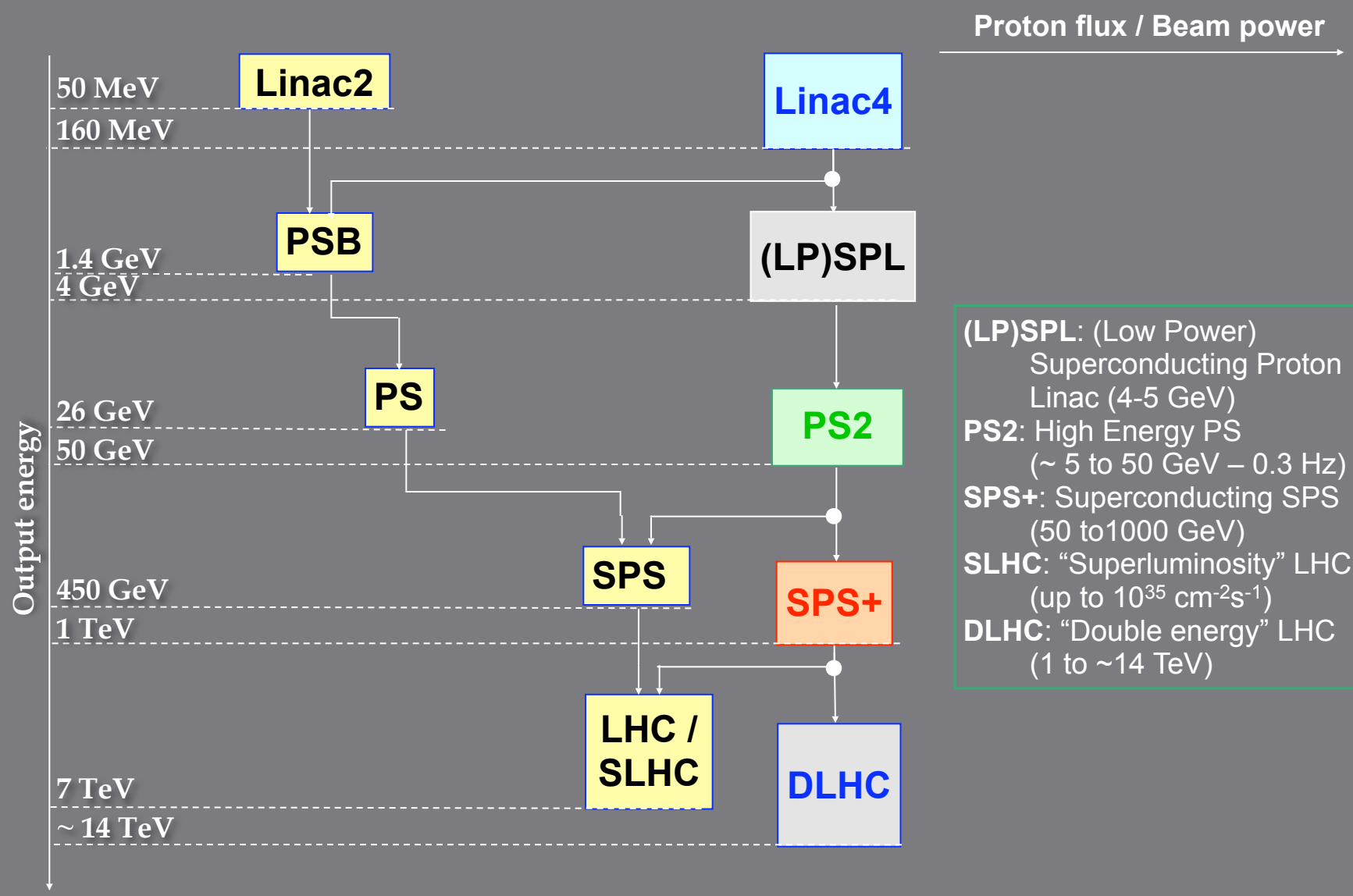
⇒ need to increase the injection energy in the synchrotrons

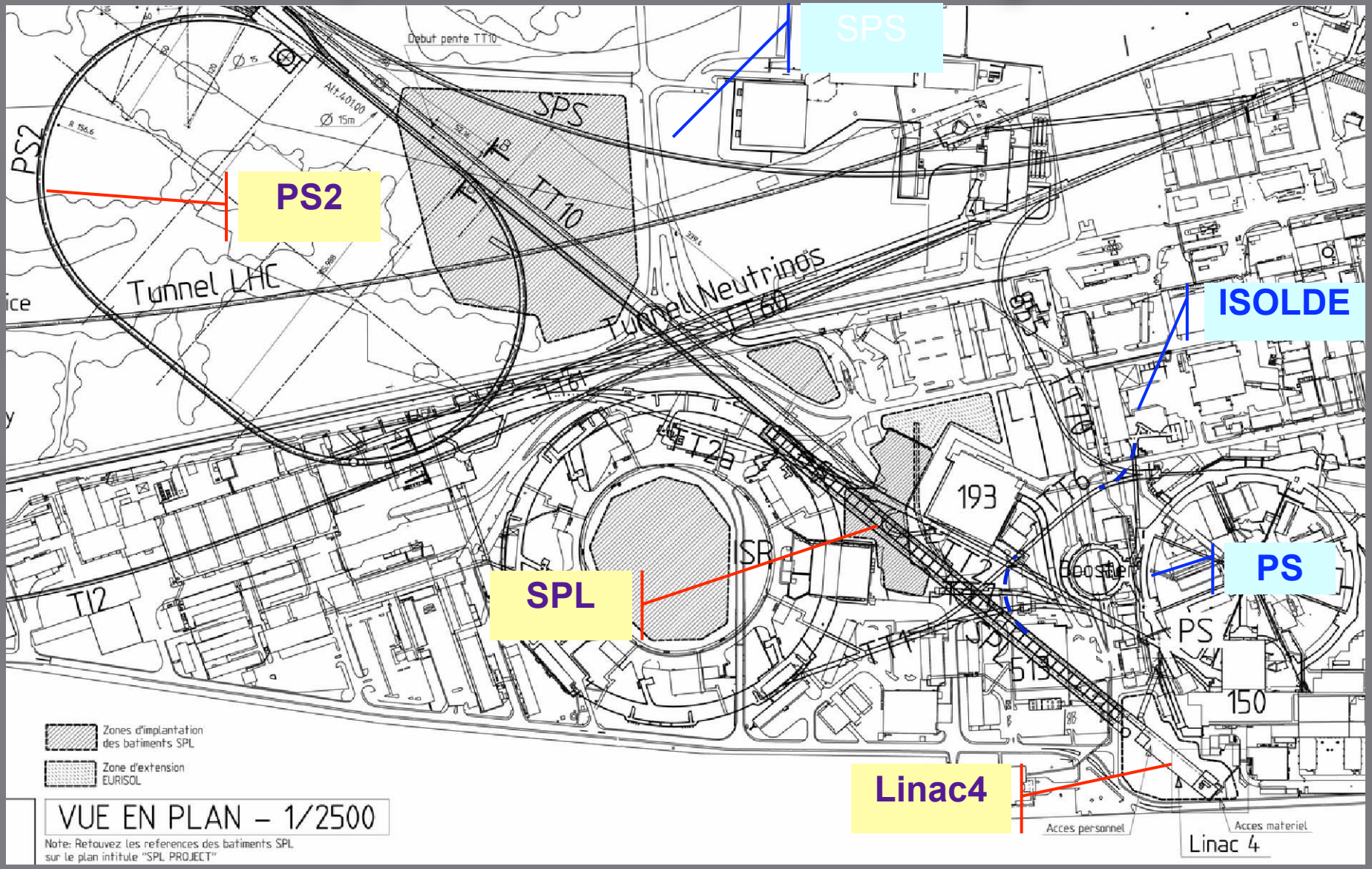
- Increase injection energy in the PSB from 50 to 160 MeV kinetic
- Increase injection energy in the SPS from 25 to 50 GeV kinetic
- Design the PS successor (PS2) with an acceptable space charge effect for the maximum beam envisaged for SLHC: => injection energy of 4 GeV

Present and Future Injectors



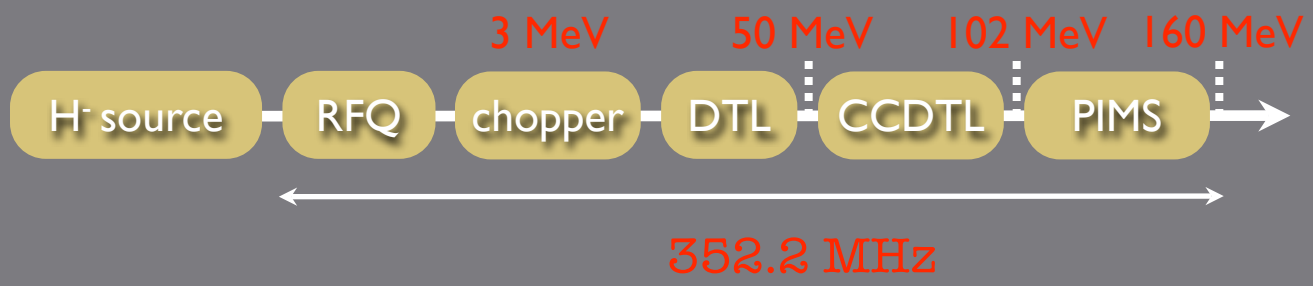
(LP)SPL: (Low Power) Superconducting Proton Linac (4-5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (1 to ~14 TeV)

Layout of the New Injectors



Stage 1: Linac4

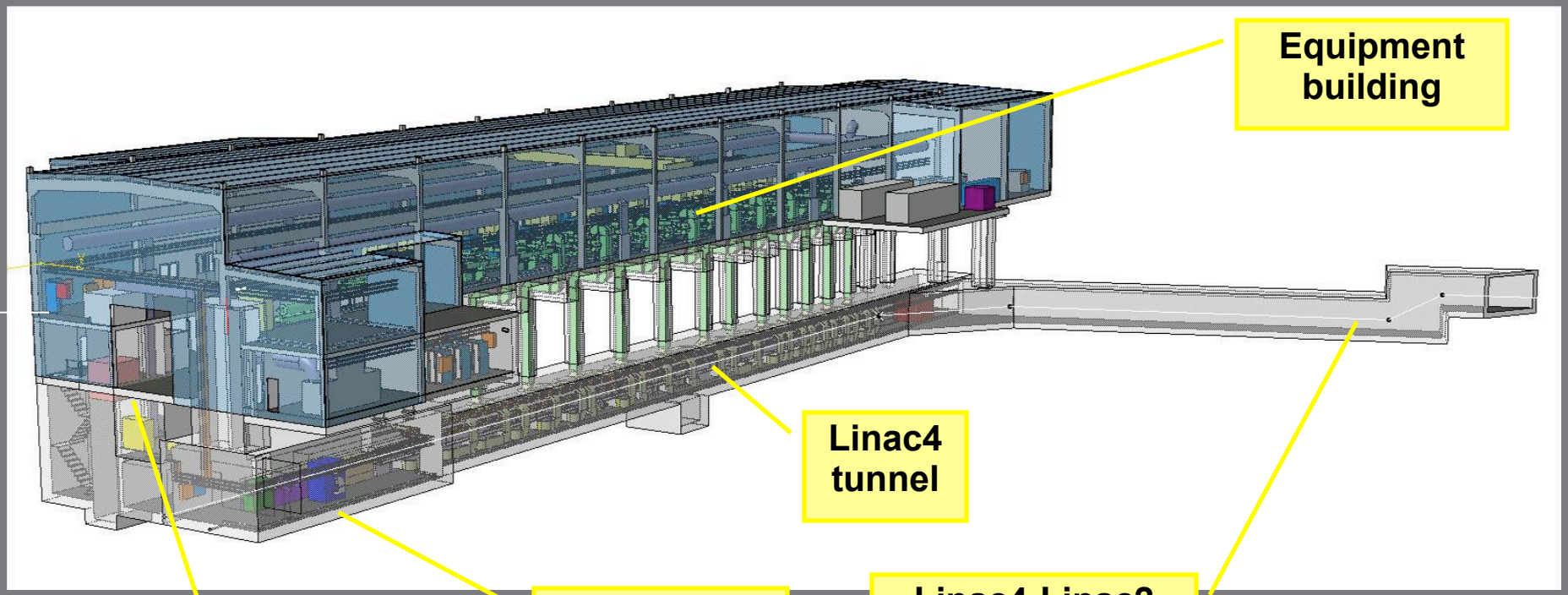
Enabled by additional resources for "New Initiatives"



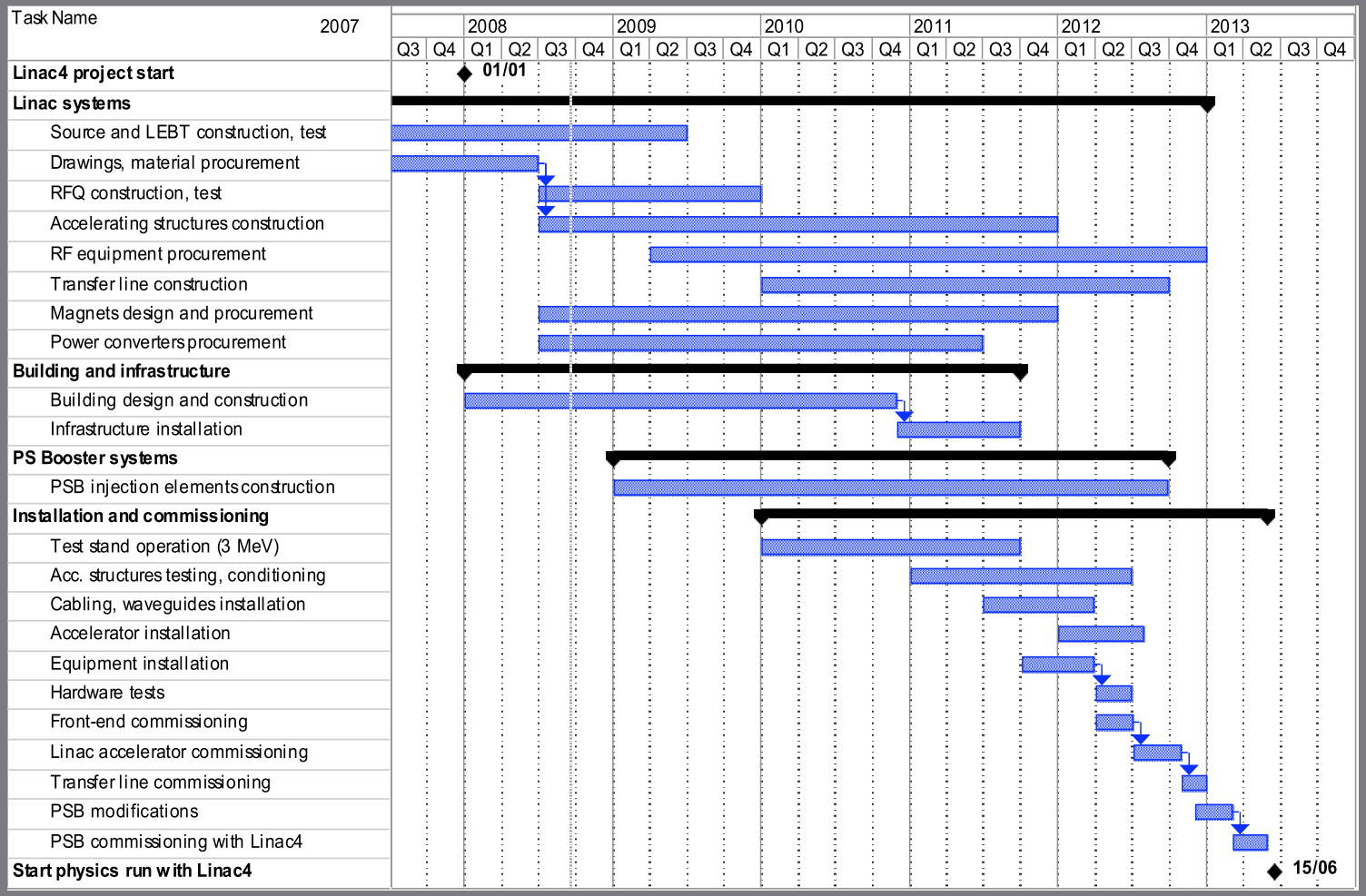
Linac4 beam characteristics

Ion species	H^-
Output kinetic energy	160 MeV
Bunch frequency	352.2 MHz
Max. repetition rate	1.1 (2) Hz
Beam pulse duration	0.4 (1.2) ms
Chopping factor (beam on)	62%
Source current	80 mA
RFQ output current	70 mA
Linac current	64 mA
Average current during beam pulse	40 mA
Beam power	5.1 kW
Particles / pulse	$1.0\ 10^{14}$
Transverse emittance (source)	0.2 mm mrad
Transverse emittance (linac)	0.4 mm mrad

Linac4 Civil Engineering

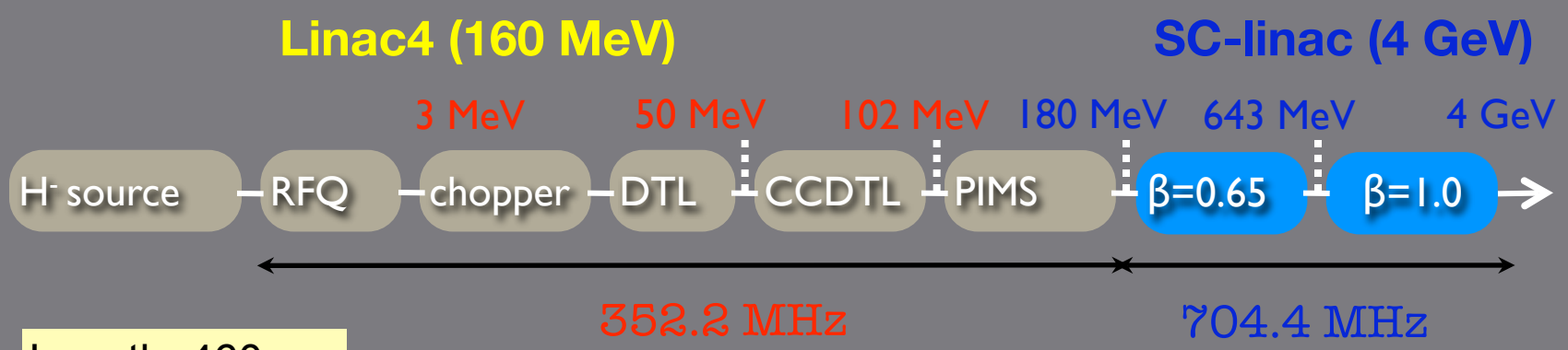


Linac4 Master Plan



- ✓ End CE works: December 2010
- ✓ Installation: 2011
- ✓ Linac commissioning: 2012
- ✓ Modifications PSB: shut-down 2012/13 (7.5 months), to be confirmed.
- ✓ Beam from PSB: June 2013

Stage 2: LP-SPL



Length: 460 m

LP-SPL beam characteristics

Kinetic energy (GeV)	4
Beam power at 4 GeV (MW)	0.16
Rep. period (s)	0.6
Protons/pulse (x 10^{14})	1.5
Average pulse current (mA)	20
Pulse duration (ms)	1.2

Stage 2: PS2

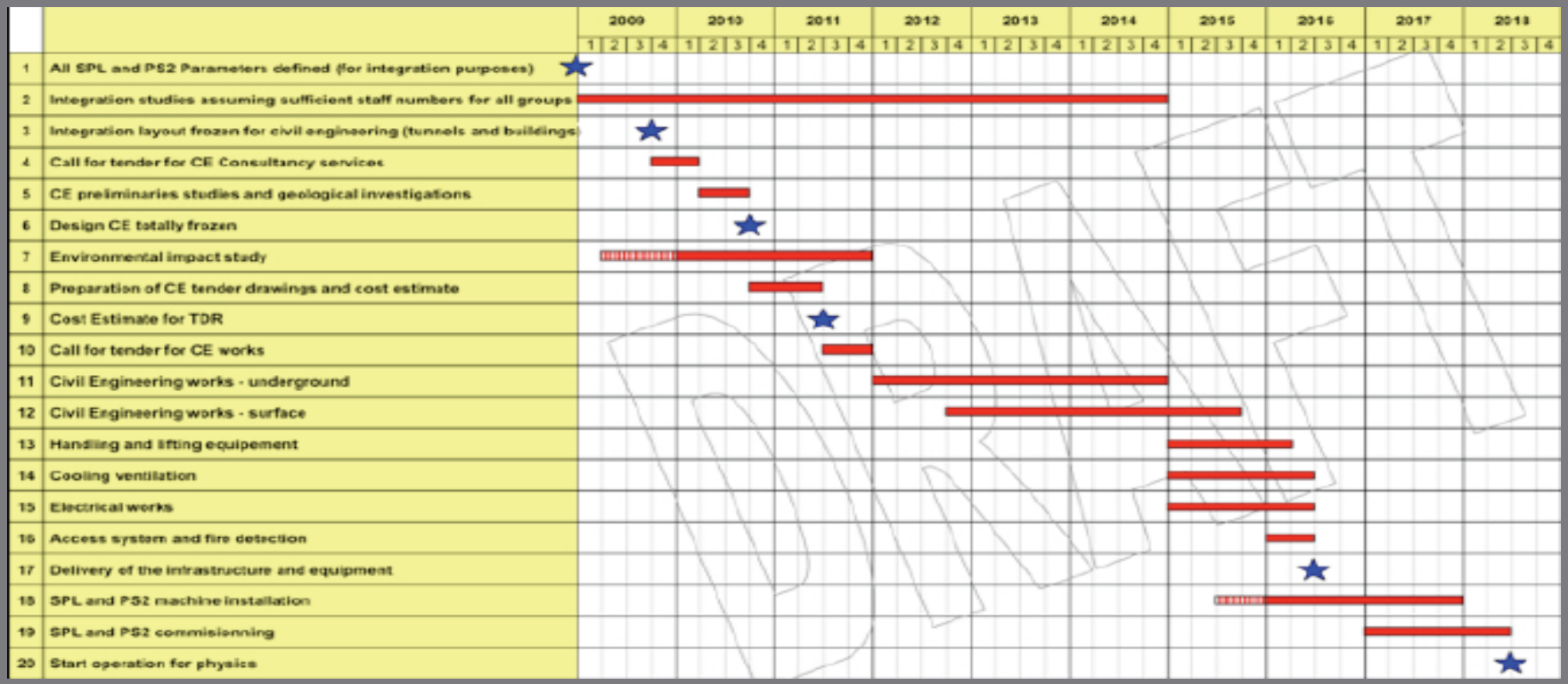
PS2 main characteristics compared to the present PS

	PS2	PS
Injection energy kinetic (GeV)	4.0	1.4
Extraction energy kinetic (GeV)	~ 50	13/25
Circumference (m)	1346	628
Maximum intensity LHC (25ns) (p/b)	4.0×10^{11}	$\sim 1.7 \times 10^{11}$
Maximum intensity for fixed target physics (p/p)	1.2×10^{14}	3.3×10^{13}
Maximum energy per beam pulse (kJ)	1000	70
Max ramp rate (T/s)	1.5	2.2
Cycle time at 50 GeV (s)	2.4	1.2/2.4
Max. effective beam power (kW)	400	60

Stage 2: Planning

- Construction of LP-SPL and PS2 will not interfere with the regular operation of Linac4 + PSB for physics.

- Similarly, beam commissioning of LP-SPL and PS2 will take place without interference with physics.



LHC

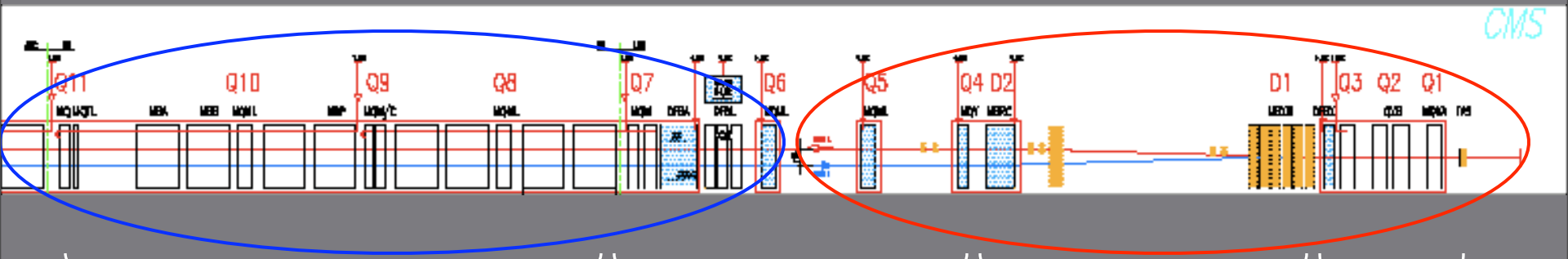
Preliminary Improvements

Enabled by additional resources for "New Initiatives" + Support of EC-FP7 & US-LARP

IR Upgrade Phase 1

- Goal: Enable focusing of the beams to β^*=0.25 m in IP1 and IP5, and reliable operation of the LHC at $2 - 3 \times 10^{34}$ $cm^{-2}s^{-1}$.
- Scope:
  - Upgrade of ATLAS and CMS IRs.
  - Replace present triplets with wide aperture quadrupoles based on LHC dipole cables (Nb-Ti) cooled at 1.9 K.
  - Upgrade D1 separation dipole, TAS and other beam-line equipment so as to be compatible with the inner triplet aperture.
  - Modify matching sections (D2-Q4, Q5, Q6) to improve optics flexibility. Introduction of other equipment to the extent of available resources.
- Planning: operational for physics in 2013

The ATLAS and CMS IRs



Dispersion suppressor | Matching section | Separation dipoles | Final focus

- Triplet position — L* = 23 m
- Triplet gradient — 205 T/m
- Triplet aperture
  - Coil 70 mm
  - Beam screen 60 mm → $\beta^* = 0.55$ m
  - → **L** = 10^{34}
- Power in triplet — ~ 200 W @ 1.9 K

The Low-β Triplet at IR1

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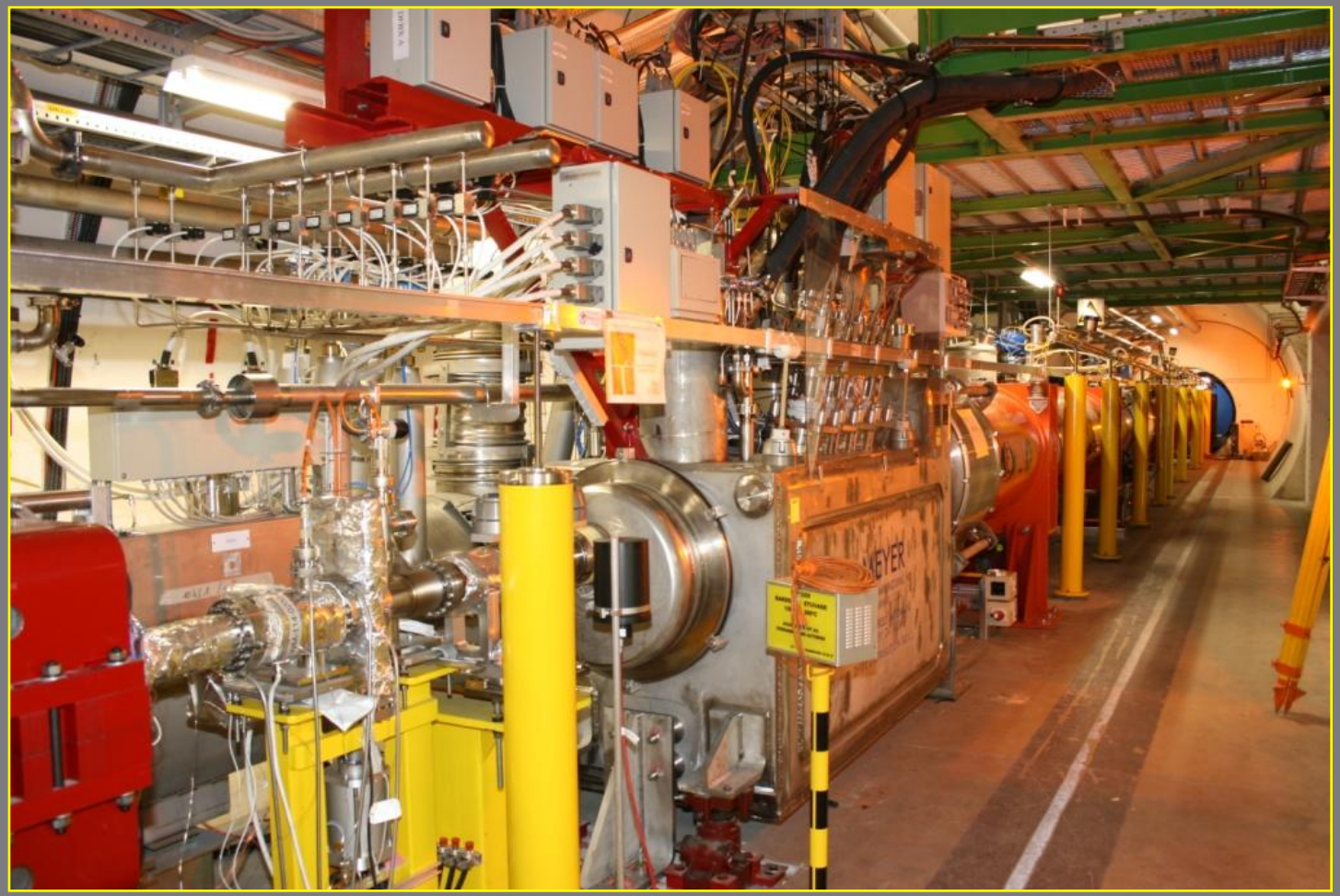

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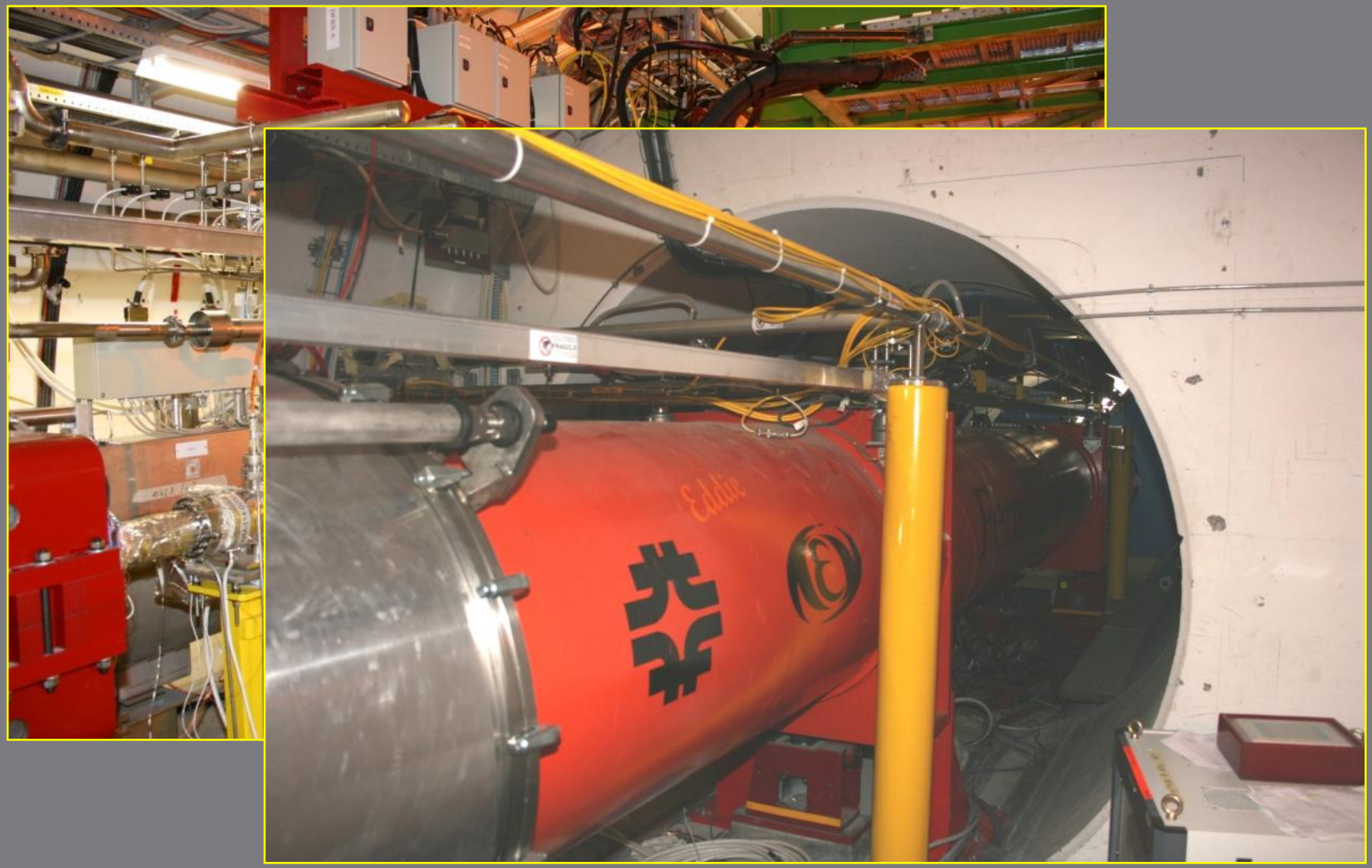


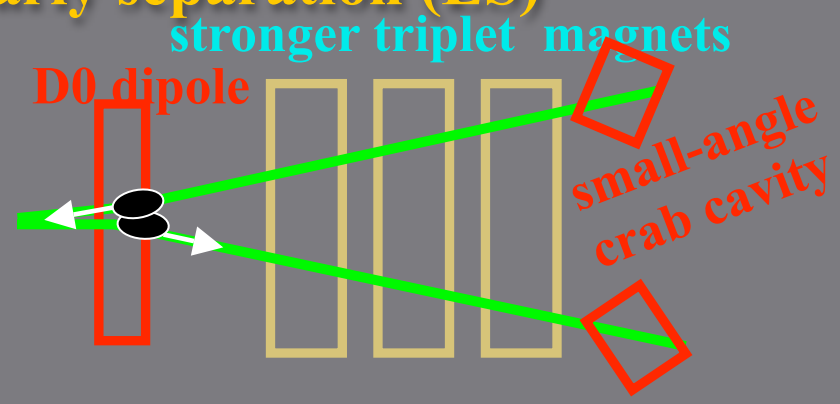
Project Milestones

Project Start	**Jan 2008**
CD Report	**Nov 2008**
TD Review	mid 2009
Model magnets	end 2009
Pre-series quadrupole	end 2010
String test	2012 -> 2013
Installation	shutdown 2013 -> 2014

“Phase-2” IR layouts

"Phase-2" IR layouts

early separation (ES) J.-P. Koutchouk



- early-separation dipoles in side detectors , crab cavities
  → hardware inside ATLAS & CMS detectors,
  first hadron crab cavities; off-δ β

"Phase-2" IR layouts

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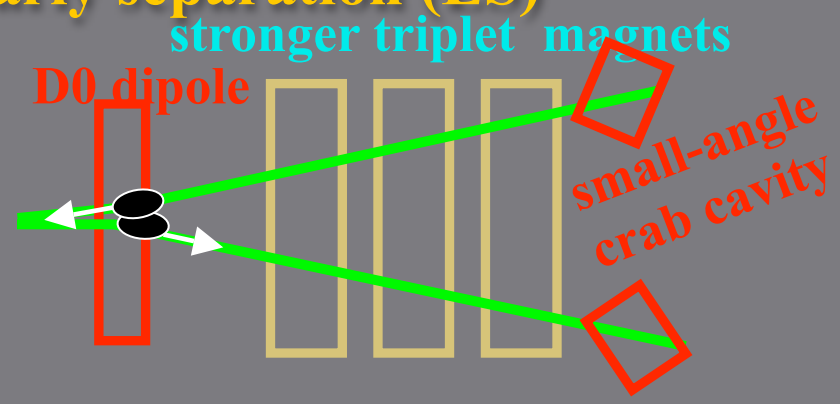

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full crab crossing (FCC)

L. Evans,
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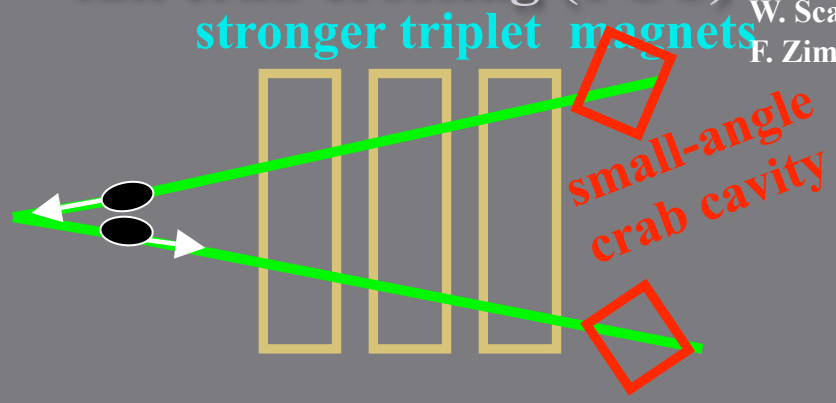

- crab cavities with 60% higher voltage
  → first hadron crab cavities, off-δ β-beat

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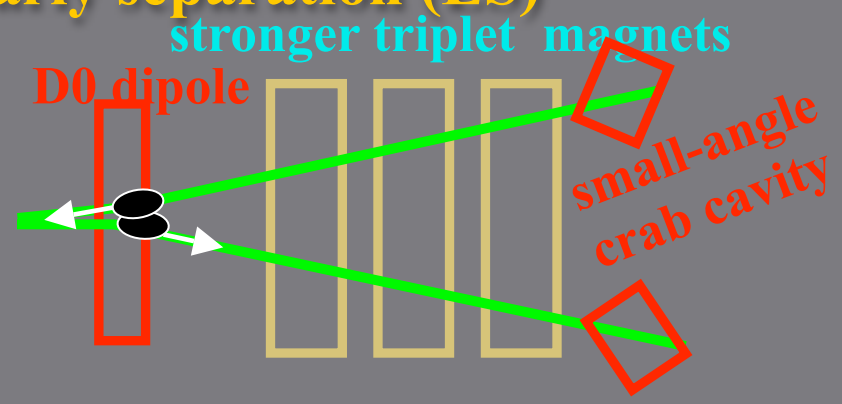

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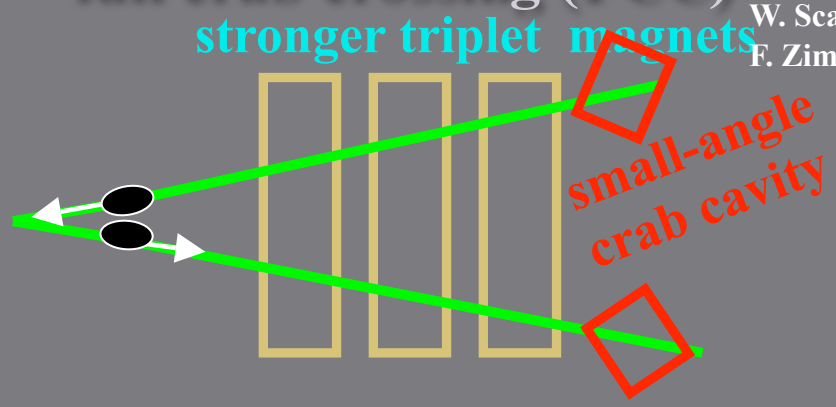

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large Piwinski angle (LPA)

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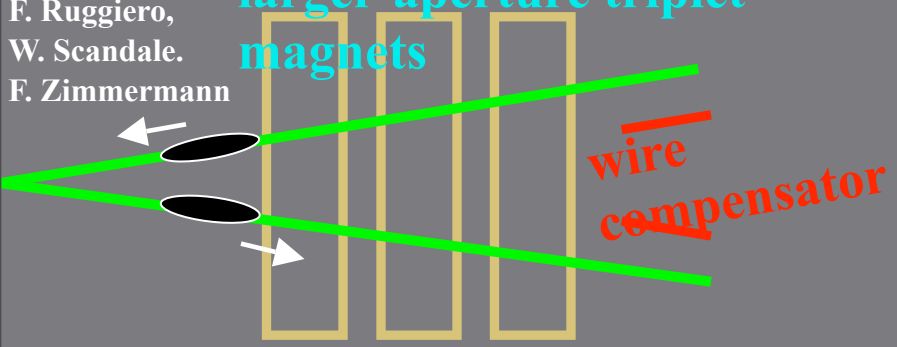

- long-range beam-beam wire compensation
  → novel operating regime for hadron colliders,
  beam generation

"Phase-2" IR layouts

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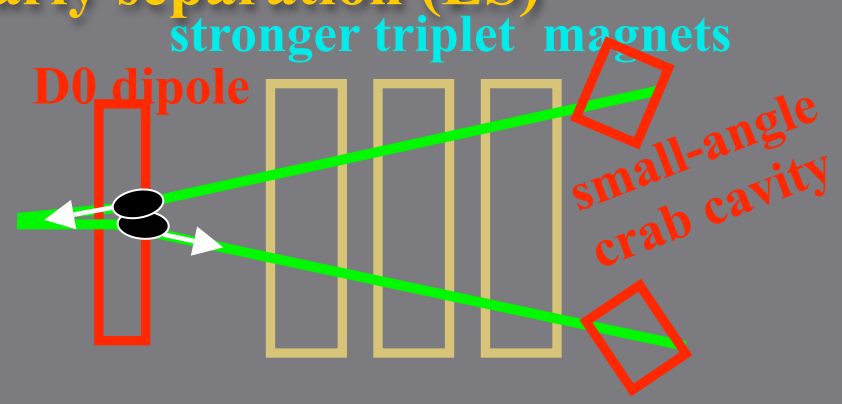

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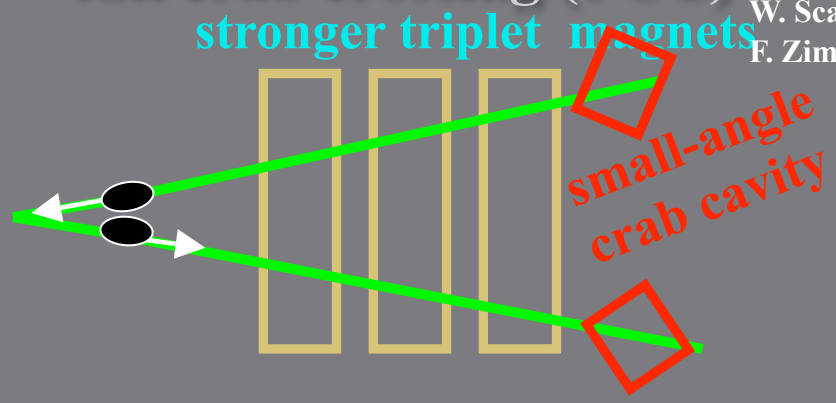

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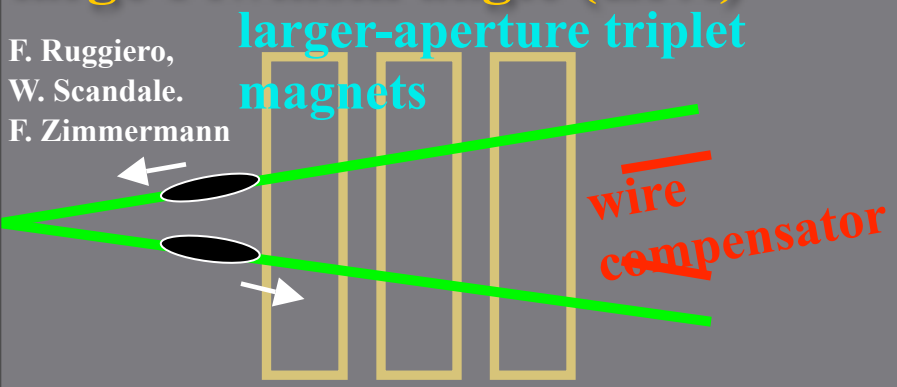

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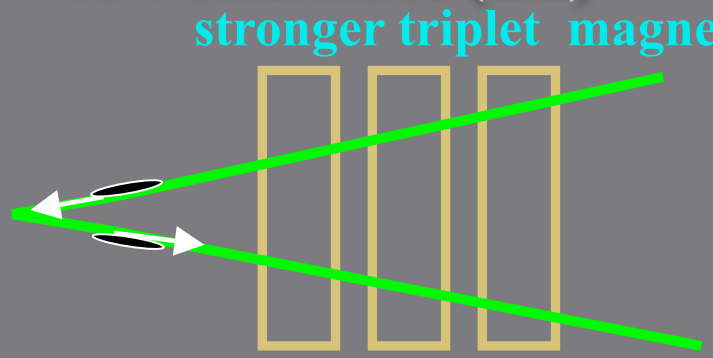
low emittance (LE)

R. Garoby

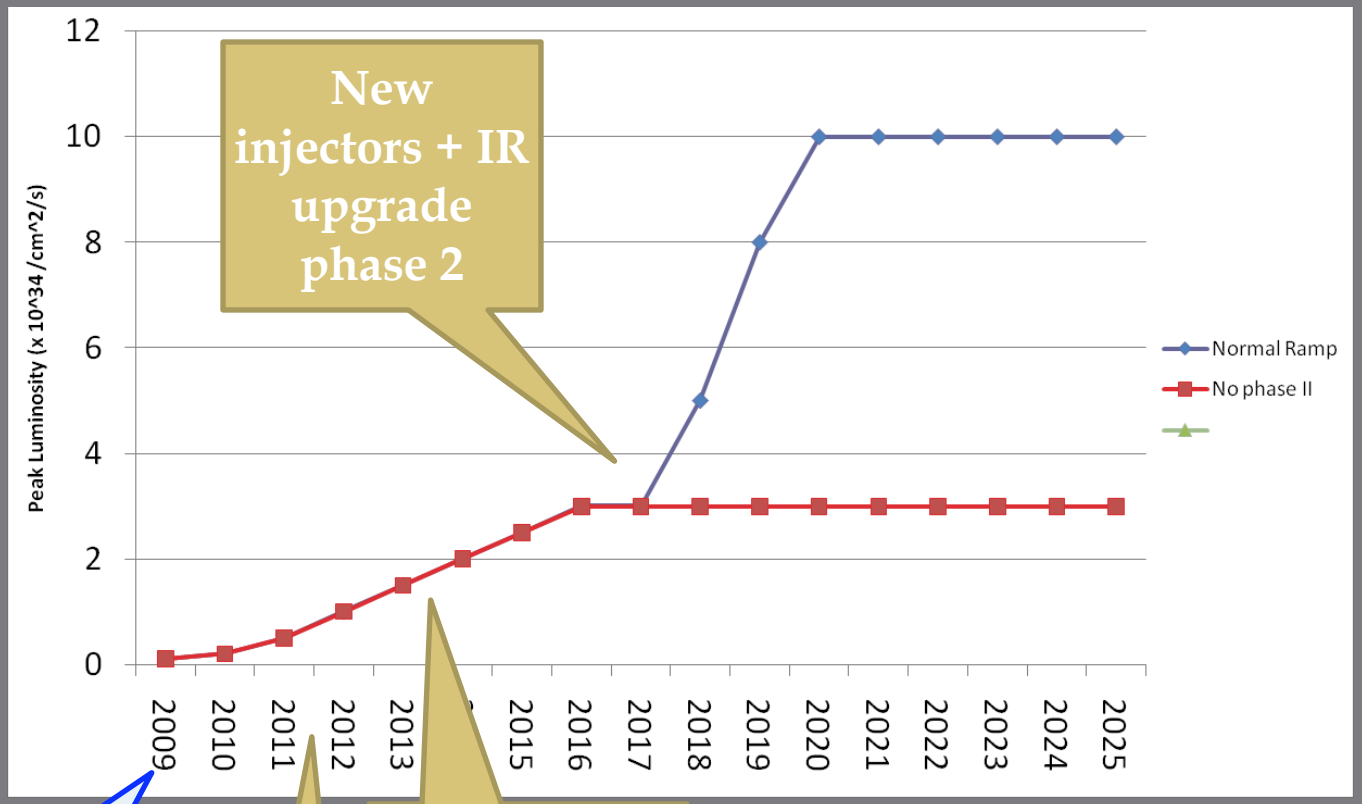


- smaller transverse emittance
  → constraint on new injectors, off-δ β-beat

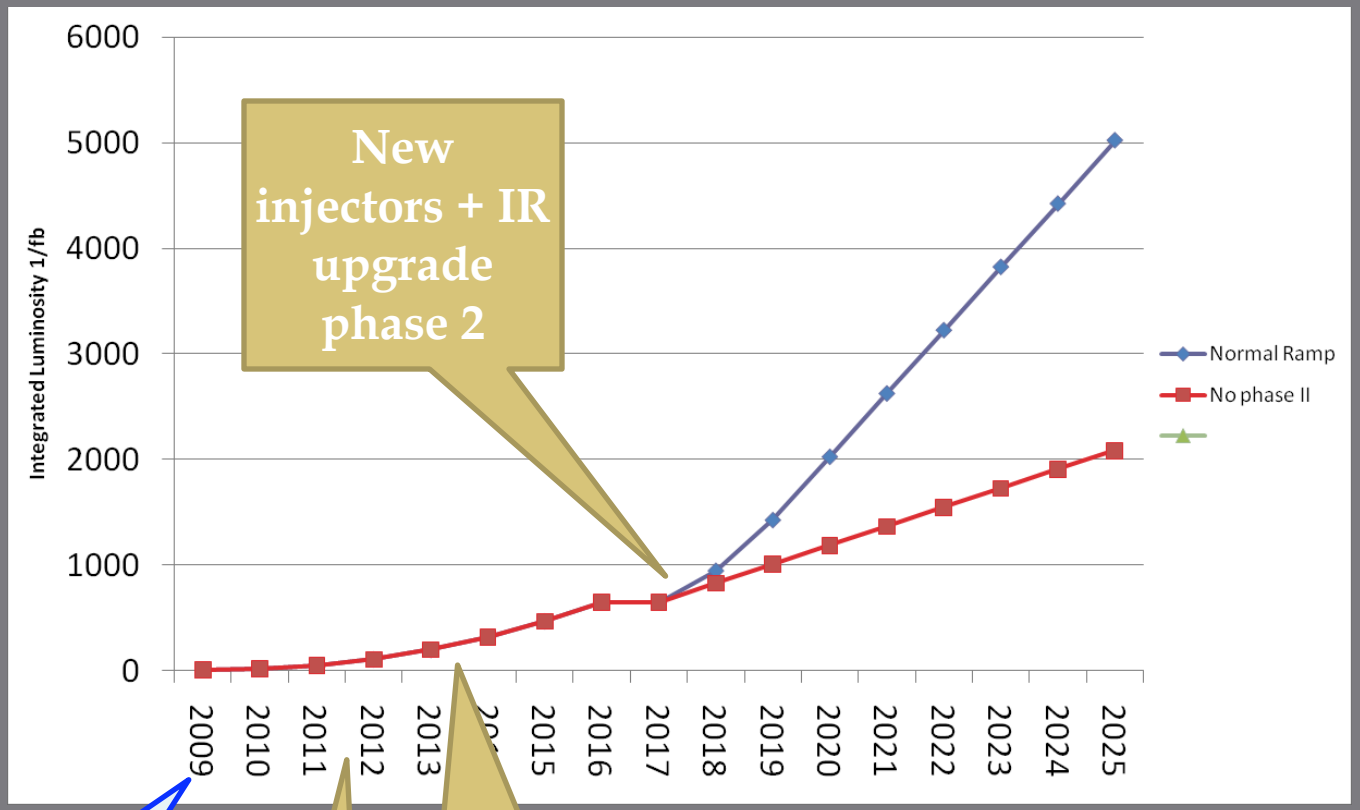
PARAMETER	SYMBOL	NOMINAL	ULTIMATE	ES	FCC	LE	LPA
transverse emittance	ε [μm]	3.75	3.75	3.75	3.75	1.0	3.75
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	1.7	1.7	4.9
bunch spacing	Δt [ns]	25	25	25	25	25	50
beam current	I [A]	0.58	0.86	0.86	0.86	0..86	1.22
longitudinal profile		Gauss	Gauss	Gauss	Gauss	Gauss	Flat
rms bunch length	σ_z [cm]	7.55	7.55	7.55	7.55	7.55	11.8
beta* at IP1&5	$\beta*$ [m]	0.55	0.5	0.08	0.08	0.1	0.25
full crossing angle	θ_c [μrad]	285	315	0	0	311	381
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.64	0.75	0	0	3.2	2.0
geometric reduction		1.0	1.0	0.86	0.86	0.30	0.99
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	2.3	15.5	15.5	16.3	10.7
peak events per #ing		19	44	294	294	309	403
initial lumi lifetime	τ_L [h]	22	14	2.2	2.2	2.0	4.5
effective luminosity ($T_{turnaround}$=10 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	0.46	0.91	2.4	2.4	2.5	2.5
	$T_{run,opt}$ [h]	21.2	17.0	6.6	6.6	6.4	9.5
effective luminosity ($T_{turnaround}$=5 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	0.56	1.15	3.6	3.6	3.7	3.5
	$T_{run,opt}$ [h]	15.0	12.0	4.6	4.6	4.5	6.7
e-c heat SEY=1.4(1.3)	P [W/m]	1.1 (0.4)	1.04(0.6)	1.0 (0.6)	1.0 (0.6)	1.0 (0.6)	0.4 (0.1)
SR heat load 4.6-20 K	P_{SR} [W/m]	0.17	0.25	0.25	0.25	0.25	0.36
image current heat	P_{IC} [W/m]	0.15	0.33	0.33	0.33	0.33	0.78
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.04 (0.4)	0.06 (0.6)	0.06 (0.56)	0.06 (0.56)	0.06 (0.56)	0.09 (0.9)

PRELIMINARY EXPECTATIONS

Peak Luminosity…



Integrated Luminosity…



Early operation

Collimation phase 2

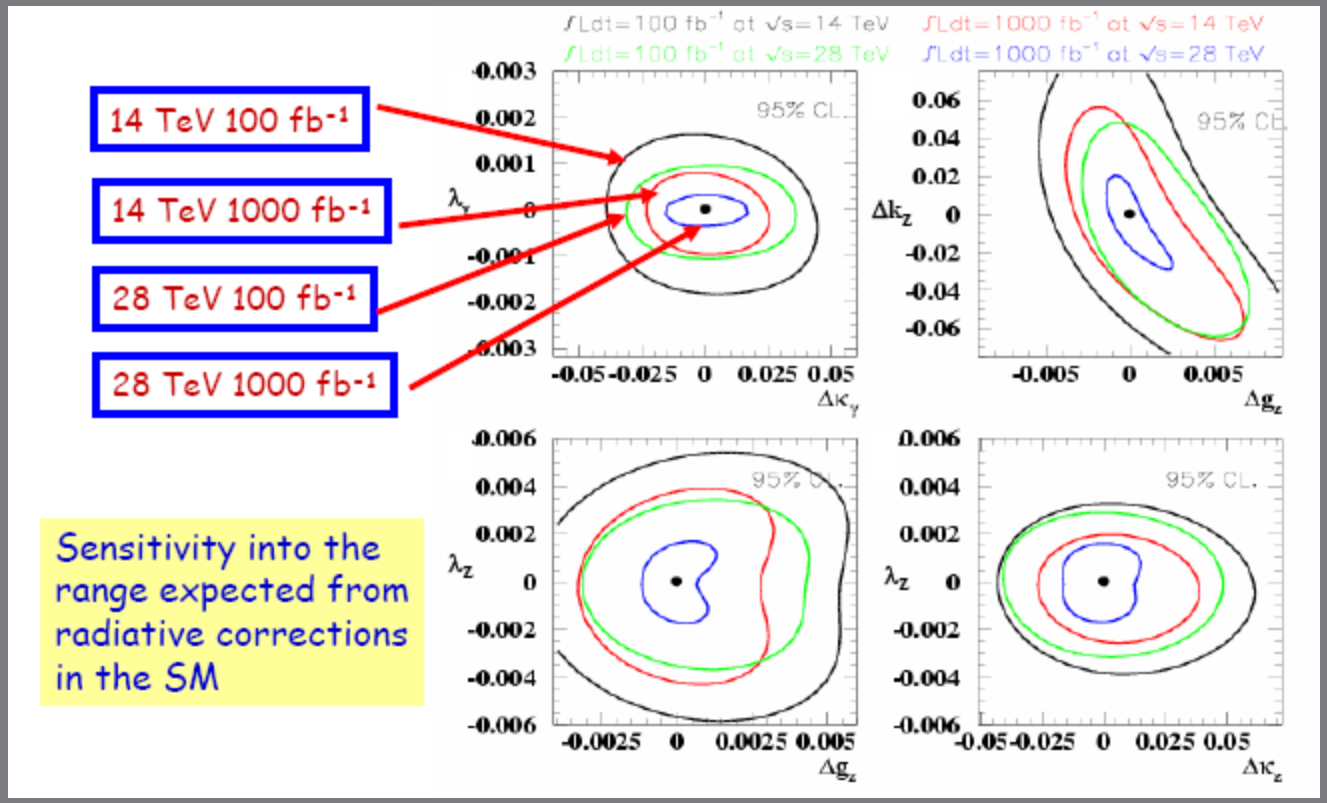
Linac4 + IR upgrade phase 1

sLHC
Extending the Physics Potential of

- Electroweak Physics
  - Production of multiple gauge bosons (nv3)
    - Triple & quartic gauge boson couplings
  - Top quarks / rare decays
- Higgs Physics
  - Rare decay modes
  - Higgs couplings to fermions & bosons
  - Higgs self-couplings
  - Heavy Higgs bosons of the MSSM
- Supersymmetry
- Extra Dimensions
  - Direct graviton production in ADD models
  - Resonance production in Randall-Sundrum models TeV-1 scale models
  - Black hole production
- Quark substructure
- Strongly-coupled vector boson system
  - $W_L Z_L g$, $W_L Z_L$, $Z_L Z_L$ scalar resonance, $W^+_L W^+_L$

see CERN-TH/2002-078
hep-ph/0204087
April 1, 2002

Triple Gauge Couplings

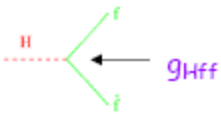


Sensitivity into the range expected from radiative corrections in the SM

Higgs Couplings

Higgs couplings!

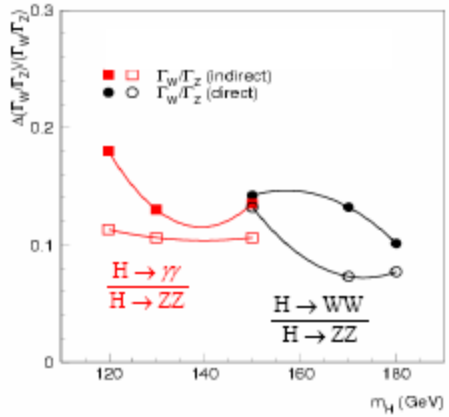
Couplings obtained from measured rate in a given production channel:



$$R_{ff} = \int L\,dt \bullet \sigma\,(e^+e^-, pp \to H + X) \bullet BR\,(H \to ff) \qquad BR\,(H \to ff) = \frac{\Gamma_f}{\Gamma_{tot}}$$

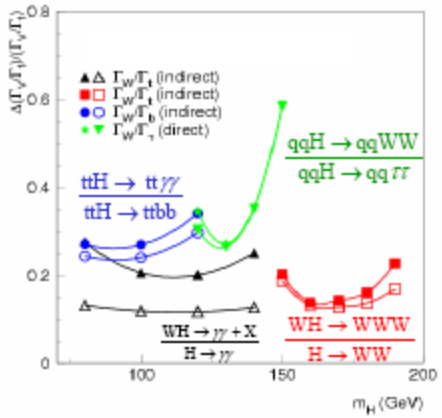
→ deduce $\Gamma_f \sim g^2_{Hff}$

- Hadron Colliders: Γ_{tot} and σ (pp → H+X) from theory → without theory inputs measure ratios of rates in various channels (Γ_{tot} and σ cancel) → $\Gamma_f/\Gamma_{f'}$



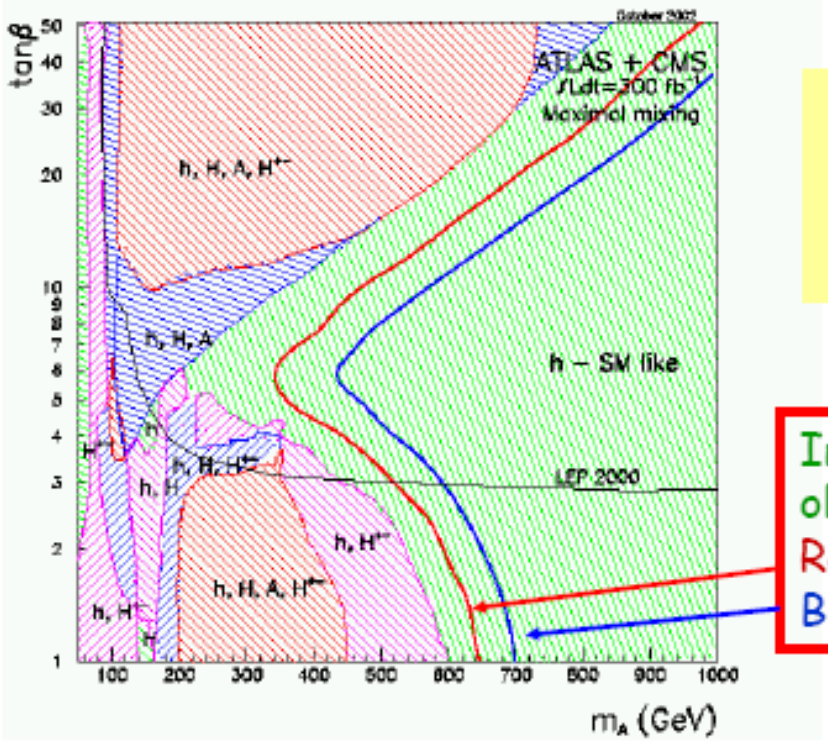
Closed symbols:
LHC 600 fb^{-1}

Open symbols:
SLHC 6000 fb^{-1}



SLHC could improve LHC precision by up to ~ 2

MSSM Higgs (h, H, A, H±)



Minimal supersymmetric model
Introduces two complex higgs doublets
→ 5 Higgs particles h,H,A,H±
H = CP even/ A = CP odd

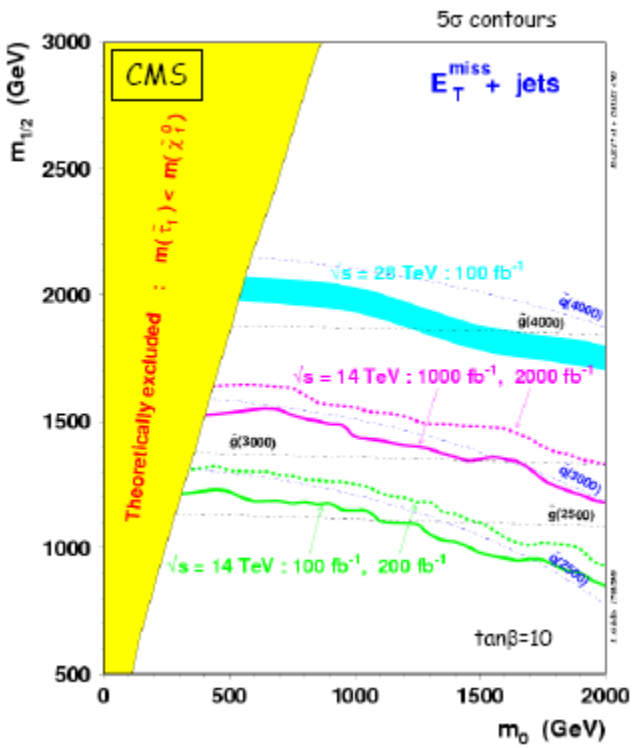
In the green region only SM-like h observable with 300 fb^{-1}/exp
Red line: extension with 3000 fb^{-1}/exp
Blue line: 95% excl. with 3000 fb^{-1}/exp

Heavy Higgs observable region extended by ~ 100 GeV

Supersymmetry

Impact of the SLHC
Extending the discovery region by roughly 0.5 TeV i.e. from
~2.5 TeV → 3 TeV

This extension involved high E_T jets/leptons and missing E_T
⇒ Not compromised by increased pile-up at SLHC



Indicative Physics Reach

Ellis, Gianotti, de Roeck
Hep-ex/0112004 + updates

Units : TeV (except $W_L W_L$ reach)

PROCESS	LHC 14 TeV 100 fb^{-1}	sLHC 14 TeV 1000 fb^{-1}	LC 0.8 TeV 500 fb^{-1}	LC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	0.4	2.5
$W_L W_L$	2σ	4σ	6σ	30σ
Z'	5	6	8†	30†
Extra-dim (δ=2)	9	12	5-8.5†	30-55†
q*	6.5	7.5	0.8	5
Λcompositeness	30	40	100	400
TGC (λ_γ)	0.0014	0.0006	0.0004	0.00008

† indirect search (from precision measurements)

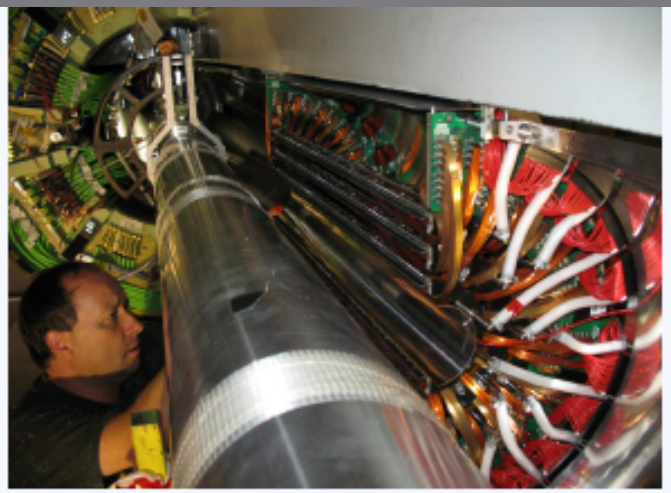
LHC Upgrade Goals

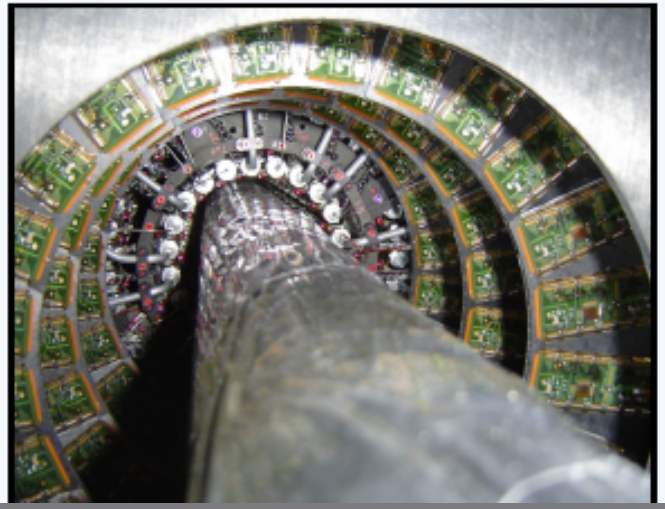
- Phase-I luminosity around $3x10^{34}$ cm^{-2} s^{-1} which means 75 events per BC at ATLAS and CMS; and 550 fb^{-1} delivered
- Phase-II luminosity $10x10^{34}$ cm^{-2} s^{-1} or more, and 300 – 400 collisions (or >~75 with luminosity levelling) per bunch crossing – very challenging to the detectors
- Independantly of machine upgrade, the inner trackers of both ATLAS and CMS will need replacing due to radiation damage
- LHCb does not use full LHC luminosity, and certainly not sLHC. But would like to increase luminosity from 2×10^{32} to 2×10^{33}, coupled with better efficiency for B-decay modes in order to get substantially larger data set

ALICE – increase PbPb luminosity by significant factor aiming at $5x10^{27}$ cm^{-2} s^{-1}, Requiring upgrades to the TPC and DAQ.

Phase-1 Detector Changes

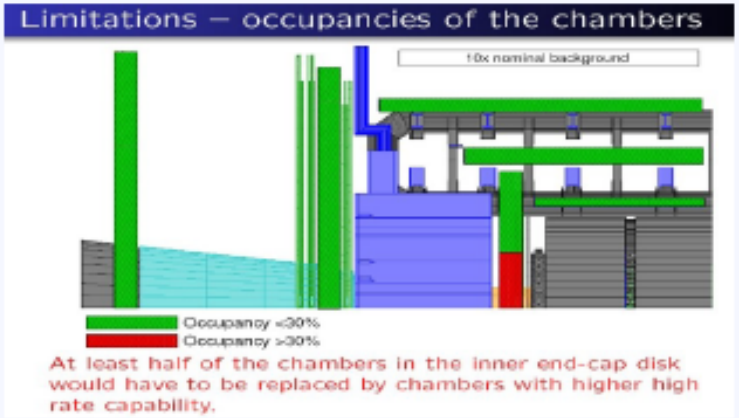
- CMS will replace the entire pixel detector with a new one (4 layers).
- ATLAS will insert one new pixel layer, inside the current pixel detector - "IBL Project"
  - These new detectors are needed because of radiation damage to the innermost layers, and to cope with the higher track rates
- Both experiments will complete staged muon chambers, necessary for the high rates at Phase-I
- Trigger-DAQ continuously evolves to cope with the data rate



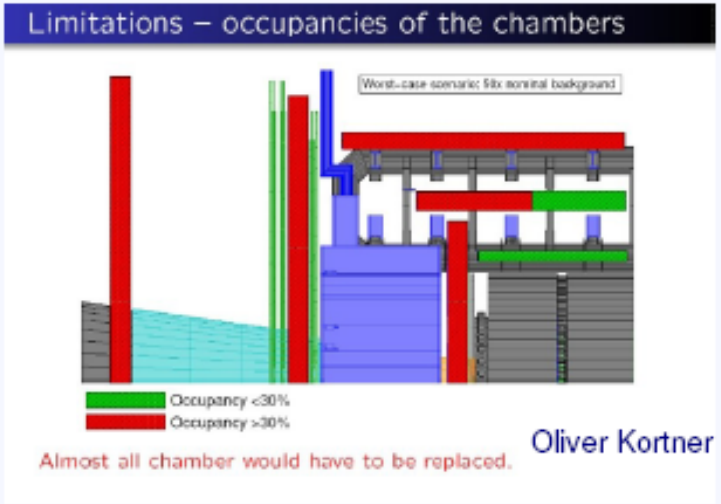


ATLAS Phase-2 Changes

- Muon System:
  - Large uncertainty factor 5 means we do not know how much of muon system needs replacing: Just forward region or nearly everthing?
  - R&D Projects on-going for the technology choice: New high-rate TGCs, micromegas, small-diameter MDT



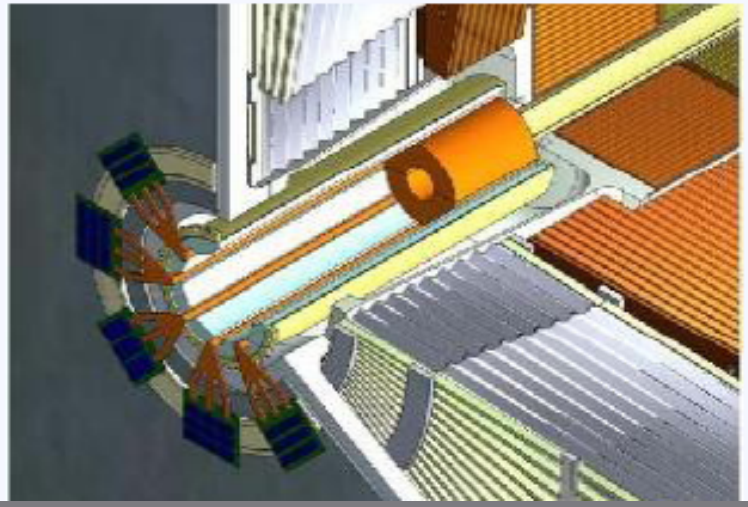
If safety factor not needed



...Worst case

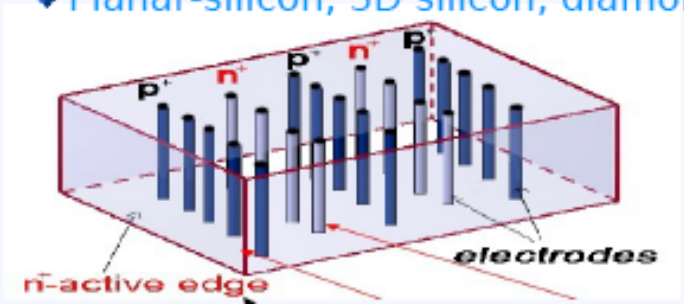
ATLAS Calorimeters

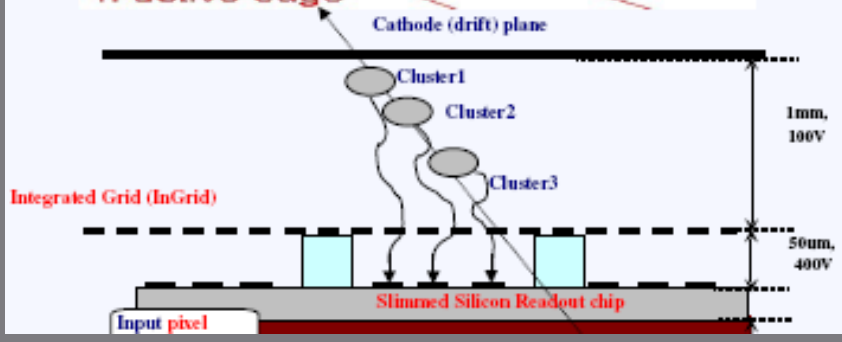
- Tiles and most of LAr calorimeter detectors perform well at sLHC
- But electronics and power supplies need replacing
  - New readout scheme, with all data moved to counting room at 40 MHZ
  - More flexibility in trigger
- Several possible problems of the small forward-most LAr known as FCAL, under study at Protvino testbeam:
  - (Fluctuating) HV drop
  - High Ion build up in gaps between electrodes
  - Heating causing boiling
- Two solutions considered:
  - Mini-FCAL in front
  - Replace FCAL
    - Major work in the pit
    - Can fit in the 18 month SD

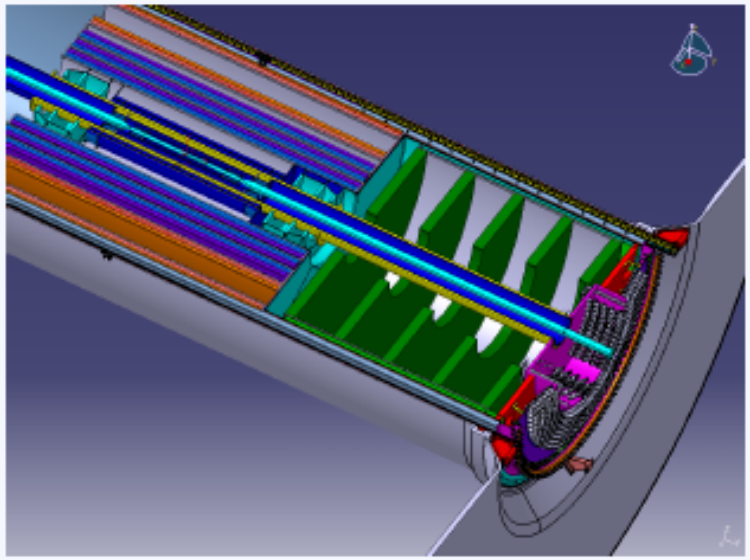


ATLAS Inner Detector

- All new; higher granularity to keep occupancy low at the very high rates of sLHC
  - All silicon (no more TRT)
  - Layout Task Force starting to accelerate convergence on working layout
- New technologies being investigated for inner-most layers, where the non-ionising dose can reach 2.5 x 10^{16} 1-MeV n_{eq}/cm^2
  - Planar-silicon, 3D silicon, diamond, and Gossip (gas pixel detector)





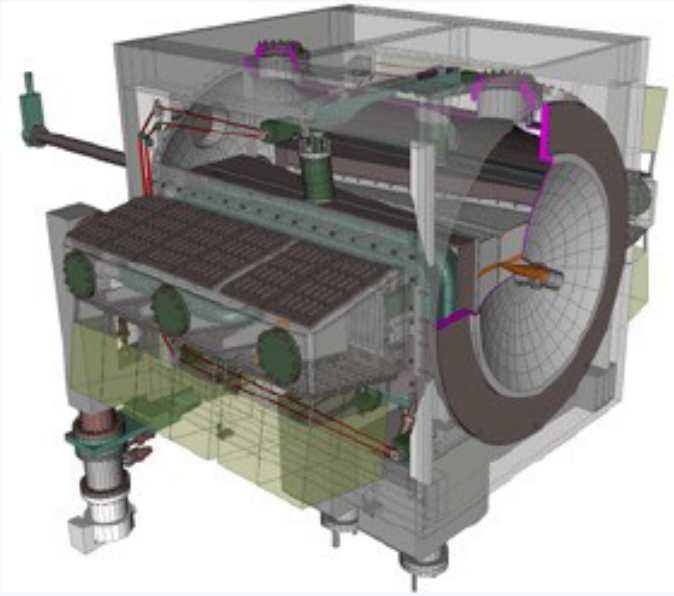


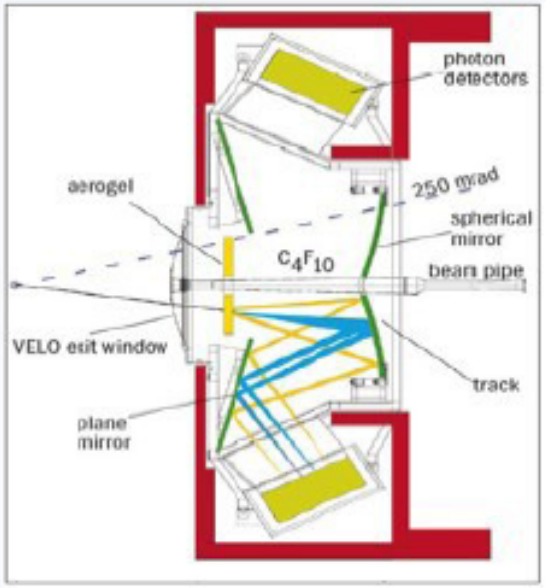
CMS Upgrade Summary

System	Phase 1	Phase 2
Pixel	New Pixel Detector (1 or 2 iterations?)	
Tracker	FEDs?	New Tracking System (incl Pixel)
HCAL	Electronics + PD replacement	HF/HE?
ECAL	TP (Off Detector Electronics) ?	EE?
Muons	ME4/2, ME1/1 ,RPC endcap, Minicrate spares, some CSC Electronics	Electronics replacement
Trigger	HCAL/RCT/GCT to μTCA	Complete replacement

LHCb Changes

- Read out all detectors at beam crossing rate of 40 MHz, in order to have all detector information available for trigger
- Upgrade Vertex Detector, trackers, RICH in order take into account higher rates and improve performance
- Increase event output rate from 2 kHz ⇒20 kHz





Conclusions

- Projects and scenarios for upgrading the LHC and its injection chain have been presented taking into account the physics motivation.
- Outlined the corresponding detector R&D priorities for the 4 large LHC experiments.
- It is very important to keep reviewing the physics drivers for CERN's future proton accelerator options.
  - In parallel, it would be necessary to compare physics opportunities offered by proton accelerators with those available at a linear e+e- collider.