HL-LHC Accelerator

Frank Zimmermann, CERN/BE

"Higgs & Beyond" Conference

Tohoku University, Sendai

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thanks to Lucio Rossi, Oliver Brüning and Steve Myers

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LHC luminosity forecast

~30/fb at 3.5 & 4 TeV **2012 DONE**

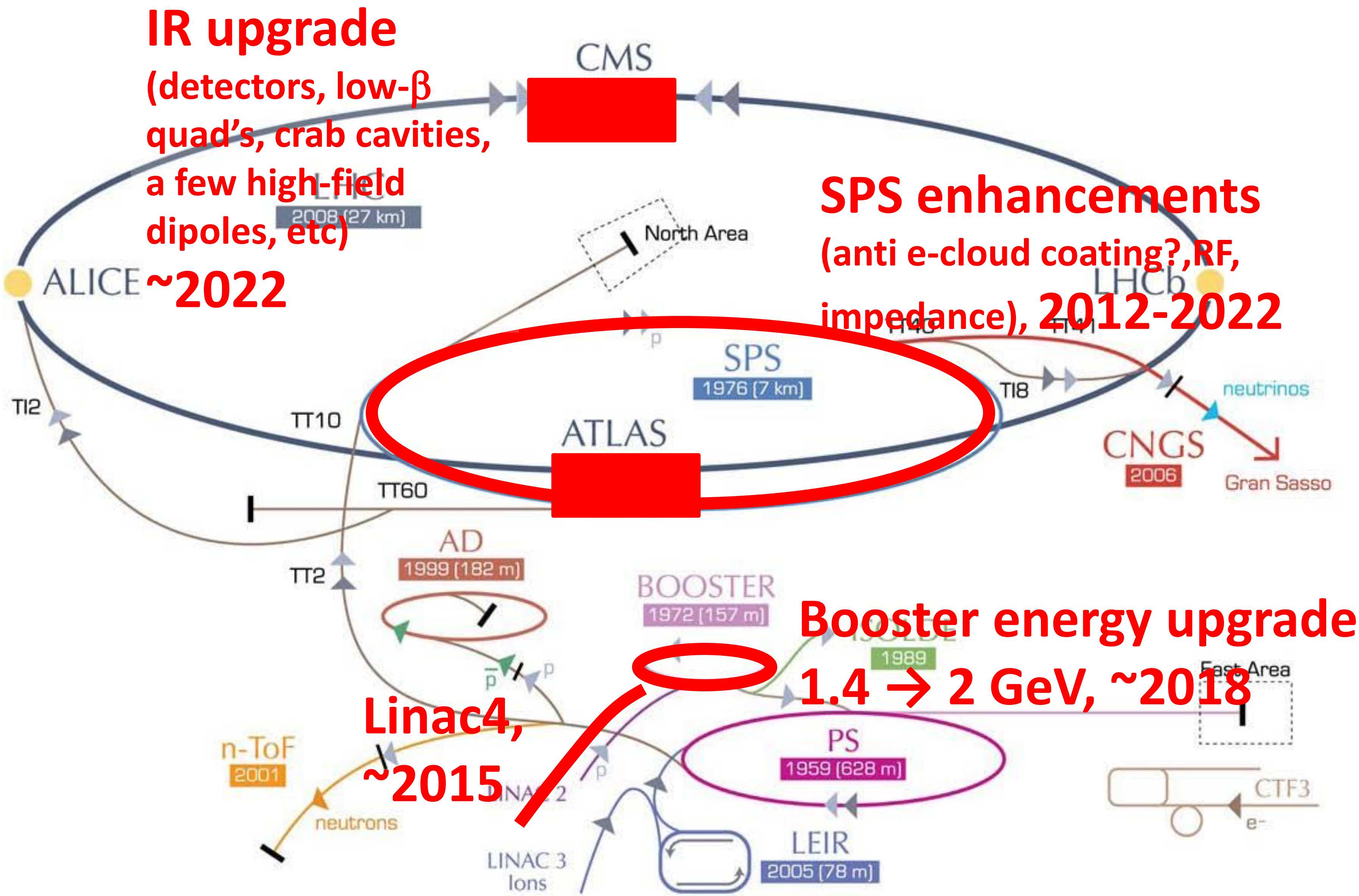
~400/fb at 6.5-7 TeV **2021 goal (?)**

~3000/fb at 7 TeV **2035 goal (??)**

*question: how do we get 3000/*fb *by 2035?*

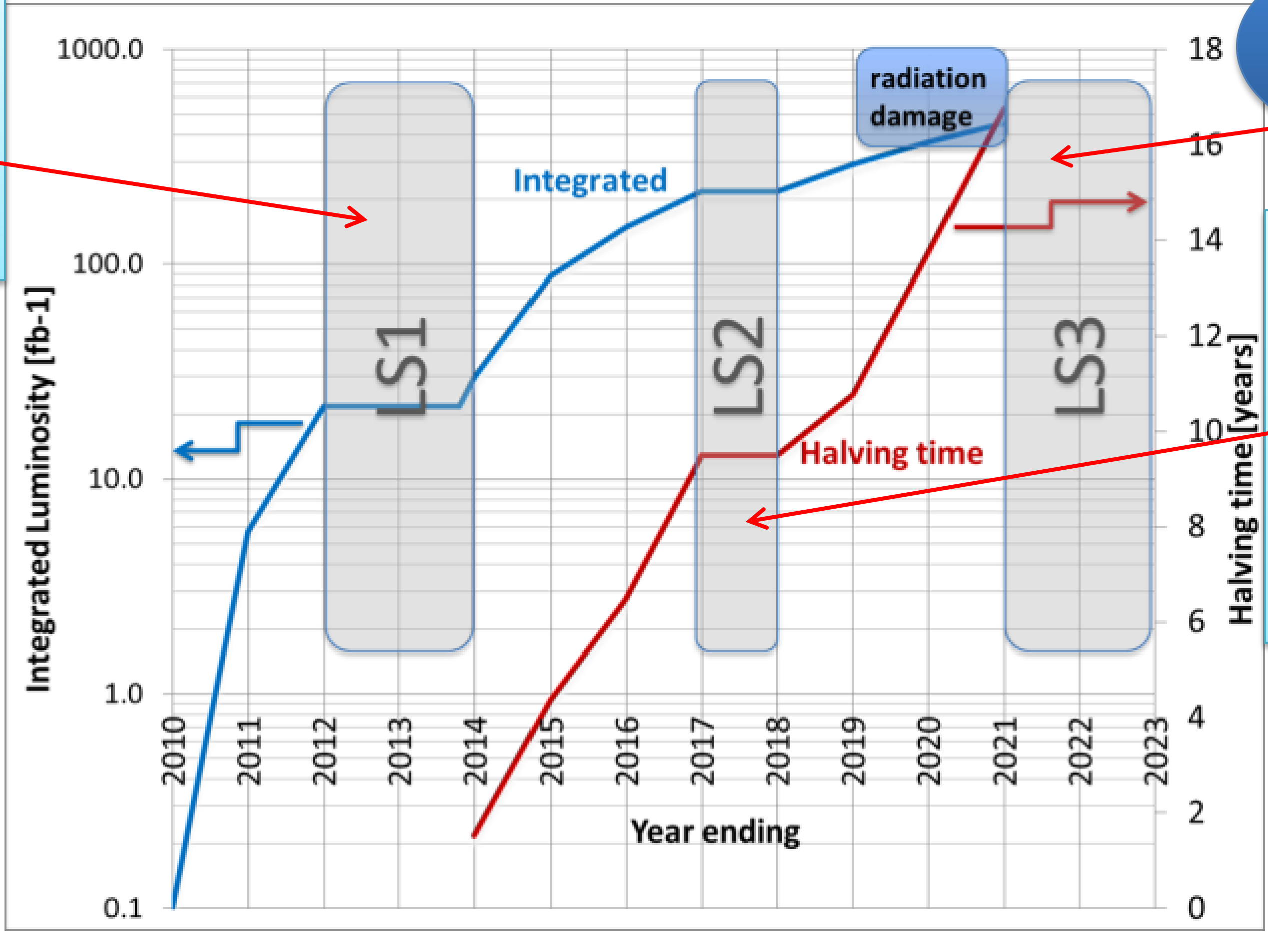
*answer: with **HL-LHC***

HL-LHC – modifications



(HL-)LHC Time Line

Shut down for interconnects to overcome energy limitation (LHC incident of Sept. 2008) and R2E

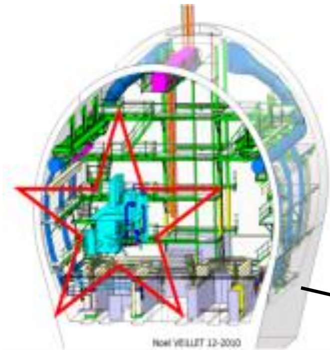


Full upgrade

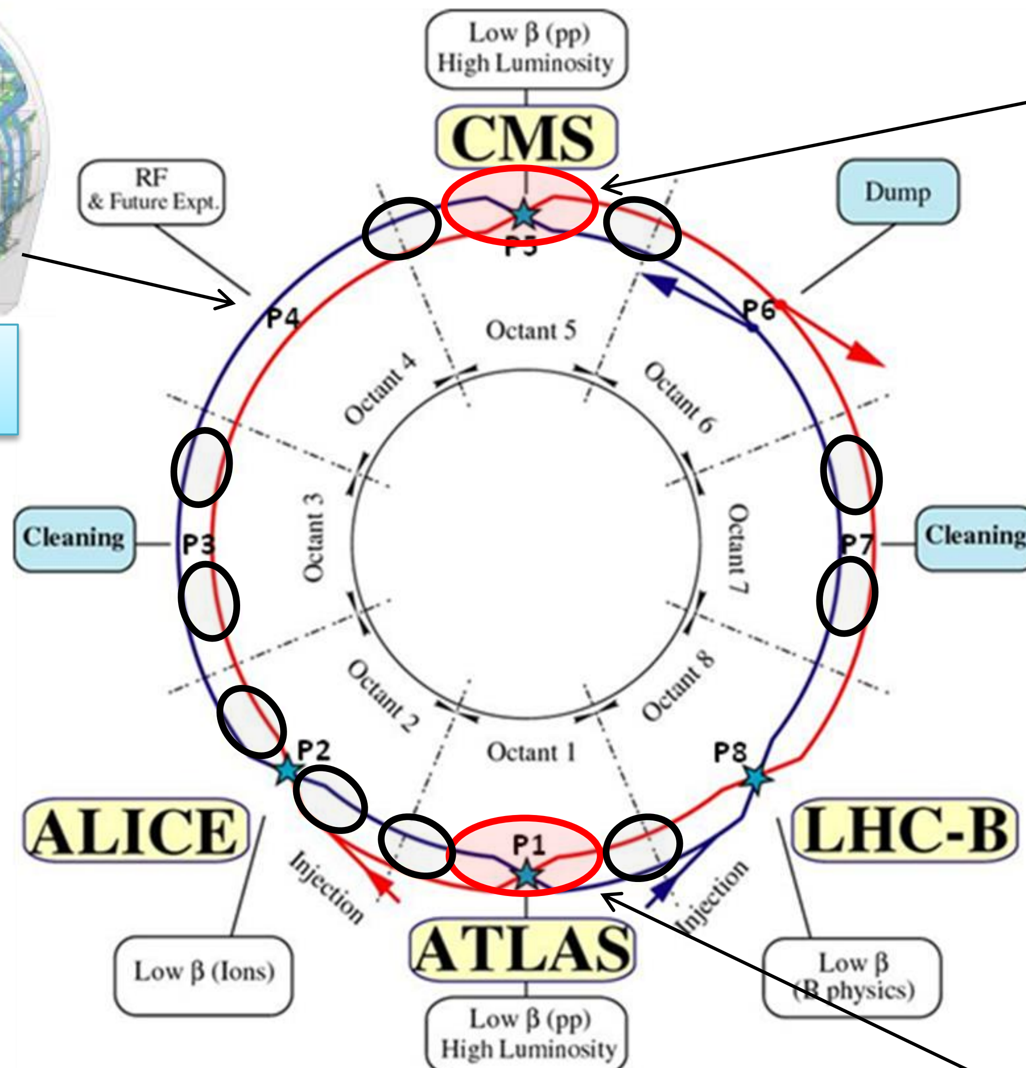
Shut down to overcome beam intensity limitation (Injectors, collimation and more…)

two reasons for HL-LHC: performance & consolidation

in LHC: 1.2 km of new equipment …

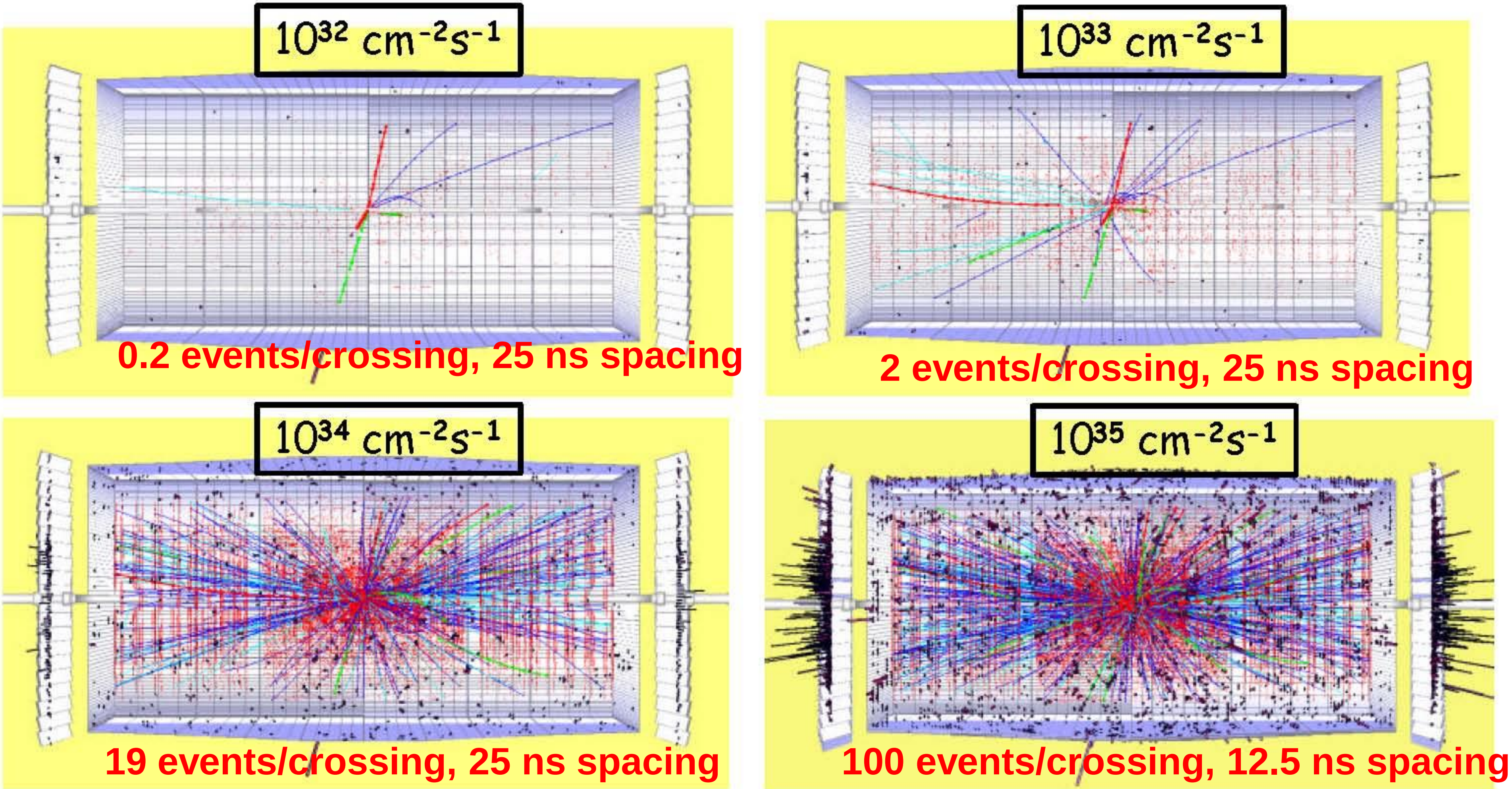


6.5 kW@4.5K cryoplant



2 x 18 kW @4.5K cryoplants for IRs

high luminosity → event pile up↑

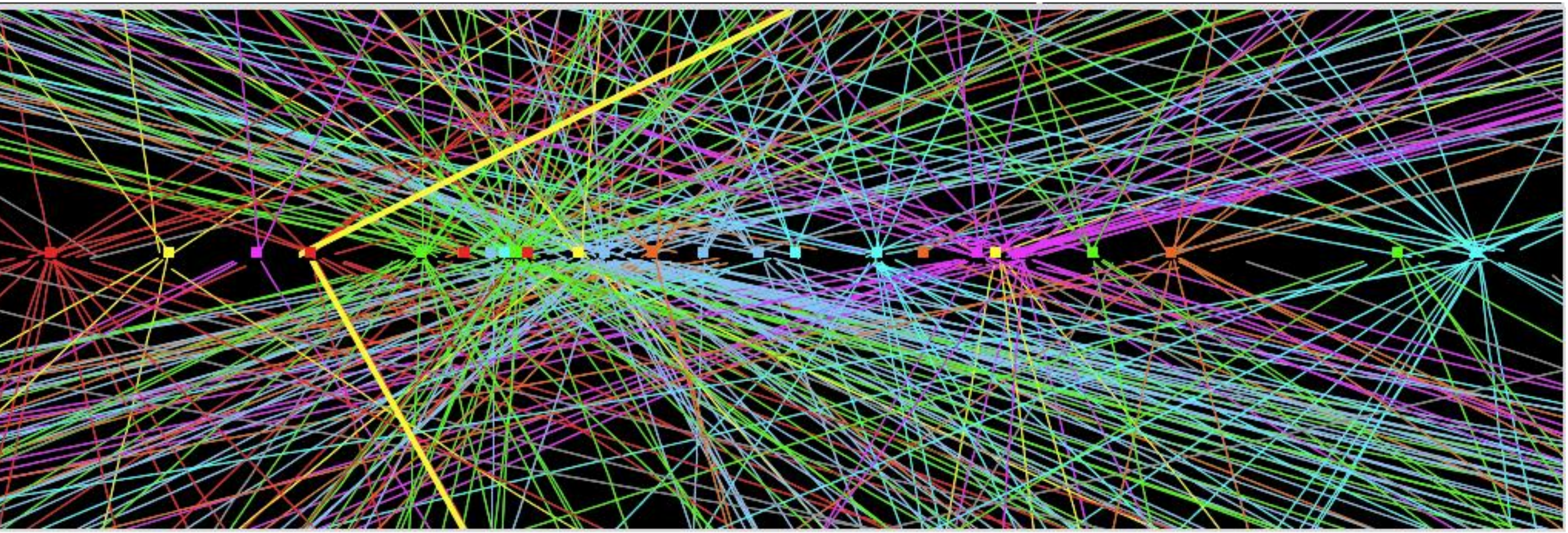


p_t > 1 GeV/c cut, i.e. all soft tracks removed

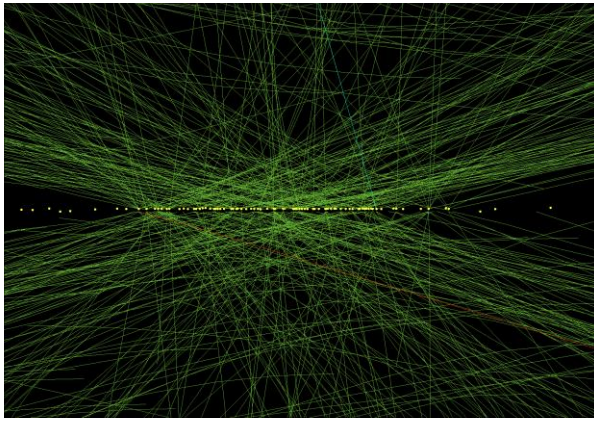
I. Osborne

historical simulation

$Z \rightarrow \mu\mu$ event from 2012 data with 25 reconstructed vertices (ATLAS)



actual data



78 reconstructed vertices in event from high-pileup run (CMS)

HL-LHC requires leveling for ATLAS & CMS

High-Luminosity LHC (HL-LHC)

luminosity goals:

leveled peak luminosity: $L = 5 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
(upgraded detector pile up limit ~140)

"virtual peak luminosity": $L \geq 20 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

integrated luminosity: 200 - 300 fb^{-1} / yr

total integrated luminosity: ca. 3000 fb^{-1} by ~2035

luminosity formula with leveling

$$L = \frac{f_{rev} n_b}{4\pi} \frac{N_b^2}{\beta^* \varepsilon} R(\theta_c, \sigma_z, \beta^*, \Delta x ...)$$

F: geometric reduction from crossing angle, profile, hourglass effect, offset,…

$$L_{lev} = f_{lev}(t) L_{\max}(t)$$

f_{lev}: time-dependent leveling factor, $f_{lev} \leq 1$

maximum value pushed up 10-25 times by HL-LHC

define “virtual peak luminosity”

$$\hat{L} \equiv L_{\max}(0) = \frac{L_{lev}}{f_{lev}(0)}$$

HL-LHC Official Beam Parameters

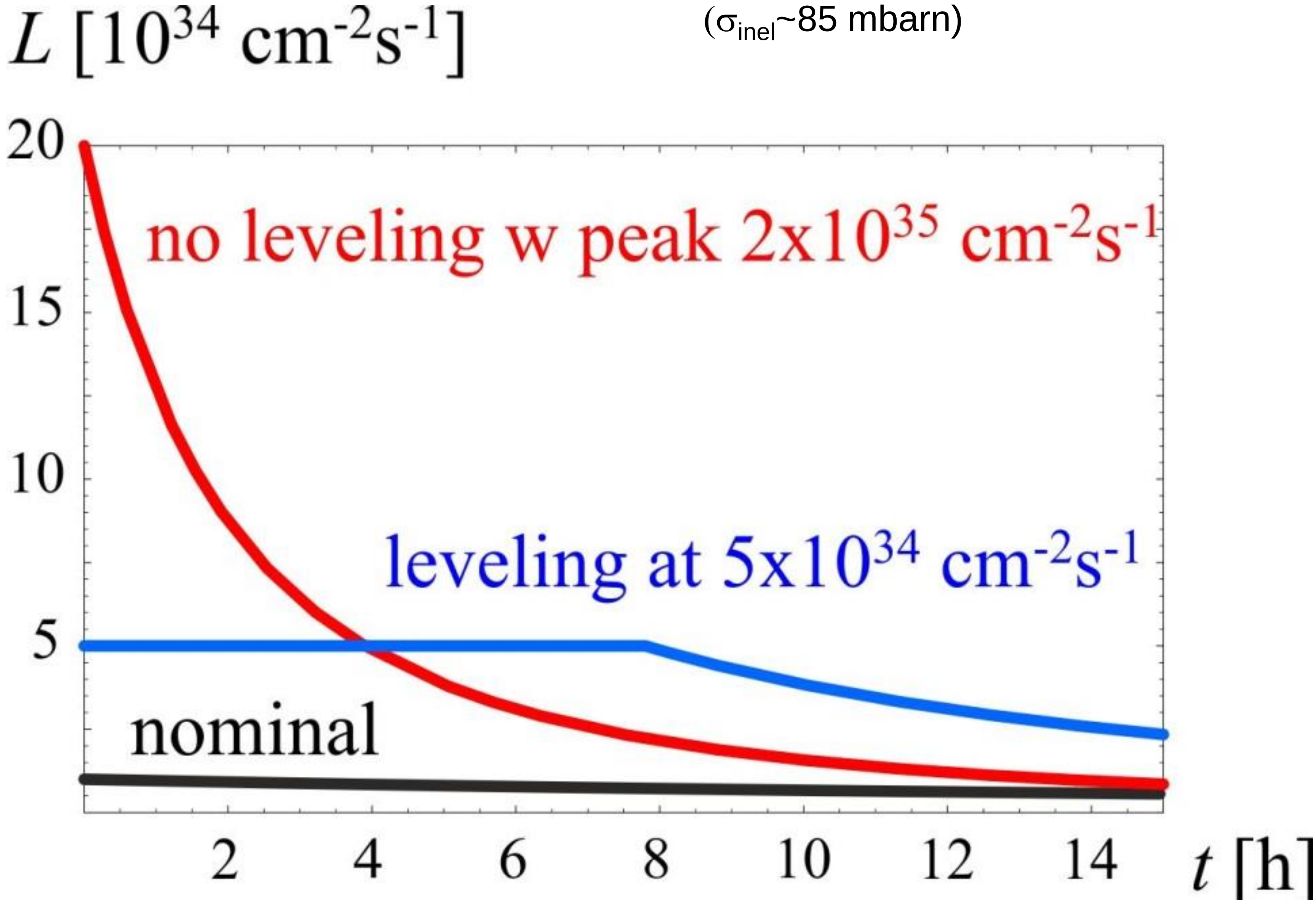
Parameter	nominal	25ns	50ns		
N	1.15E+11	**2.2E+11**	**3.5E+11**		
n_b	2808	2808	1404		
beam current [A]	0.58	**1.12**	**0.89**		
x-ing angle [μrad]	300	590	590		
beam separation [σ]	10	12.5	11.4		
β^* [m]	0.55	**0.15**	**0.15**		
ε_n [μm]	3.75	2.5	3.0		
ε_L [eVs]	2.51	2.5	2.5		
energy spread	1.20E-04	1.20E-04	1.20E-04		
bunch length [m]	7.50E-02	7.50E-02	7.50E-02		
IBS horizontal [h]	106	**20.0**	**20.7**		
IBS longitudinal [h]	60	**15.8**	**13.2**		
Piwinski parameter	0.68	**3.1**	**2.9**		
geom. reduction	0.83	**0.35**	**0.33**		
beam-beam / IP	3.10E-03	**3.9E-03**	**5.0E-03**		
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.5\ 10^{34}$**		
Virtual Luminosity	$1.2\ 10^{34}$	**$21\ 10^{34}$**	**$26\ 10^{34}$**		
Events / crossing (peak & leveled L	27	**210**	**475**	**140**	**140**

$6.2\ 10^{14}$ and $4.9\ 10^{14}$ p/beam

(Leveled to $5\ 10^{34}$ $cm^{-2}\ s^{-1}$ and $2.5\ 10^{34}$ $cm^{-2}\ s^{-1}$)

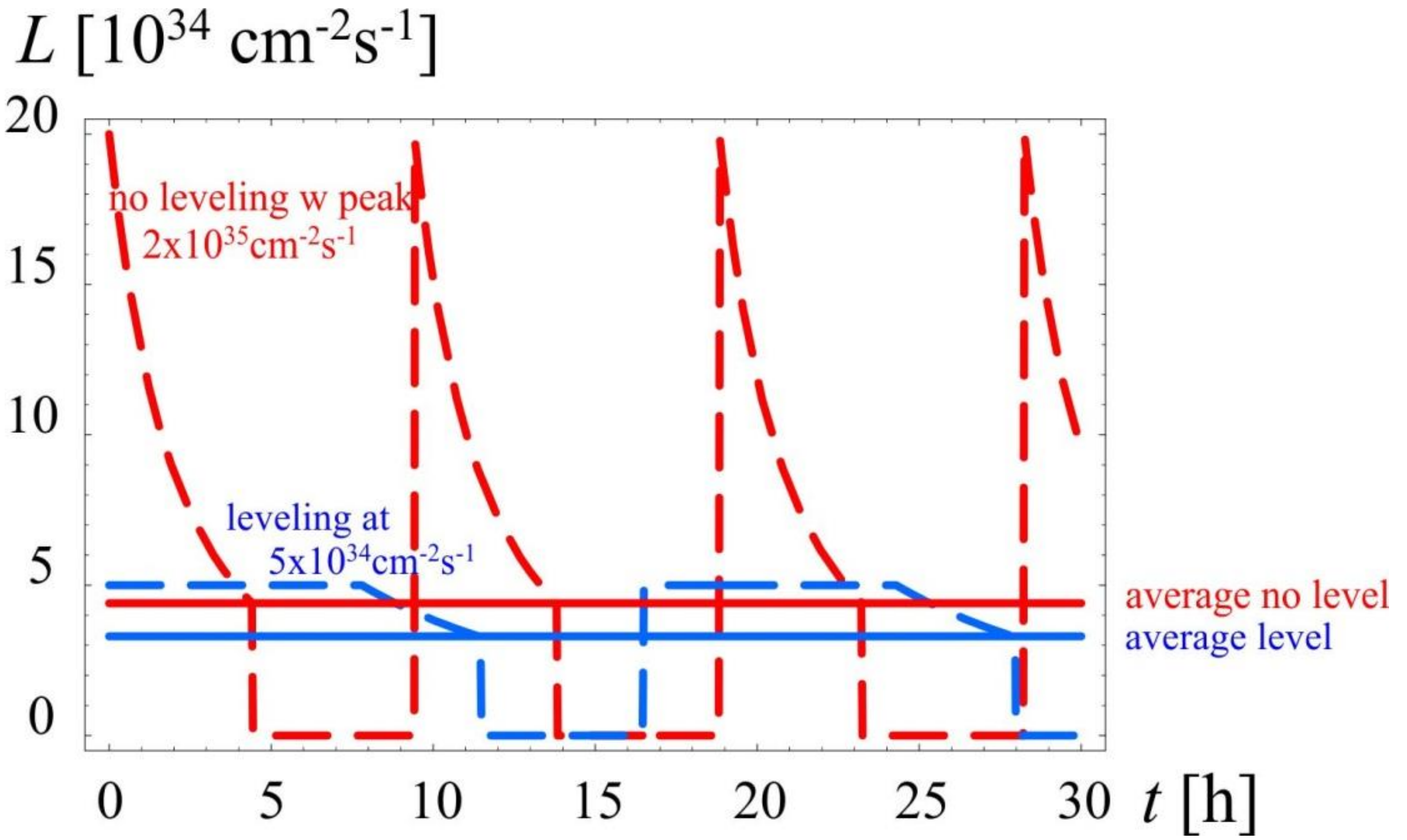
luminosity leveling at the HL-LHC

example: maximum pile up 140
(σ_{inel}~85 mbarn)



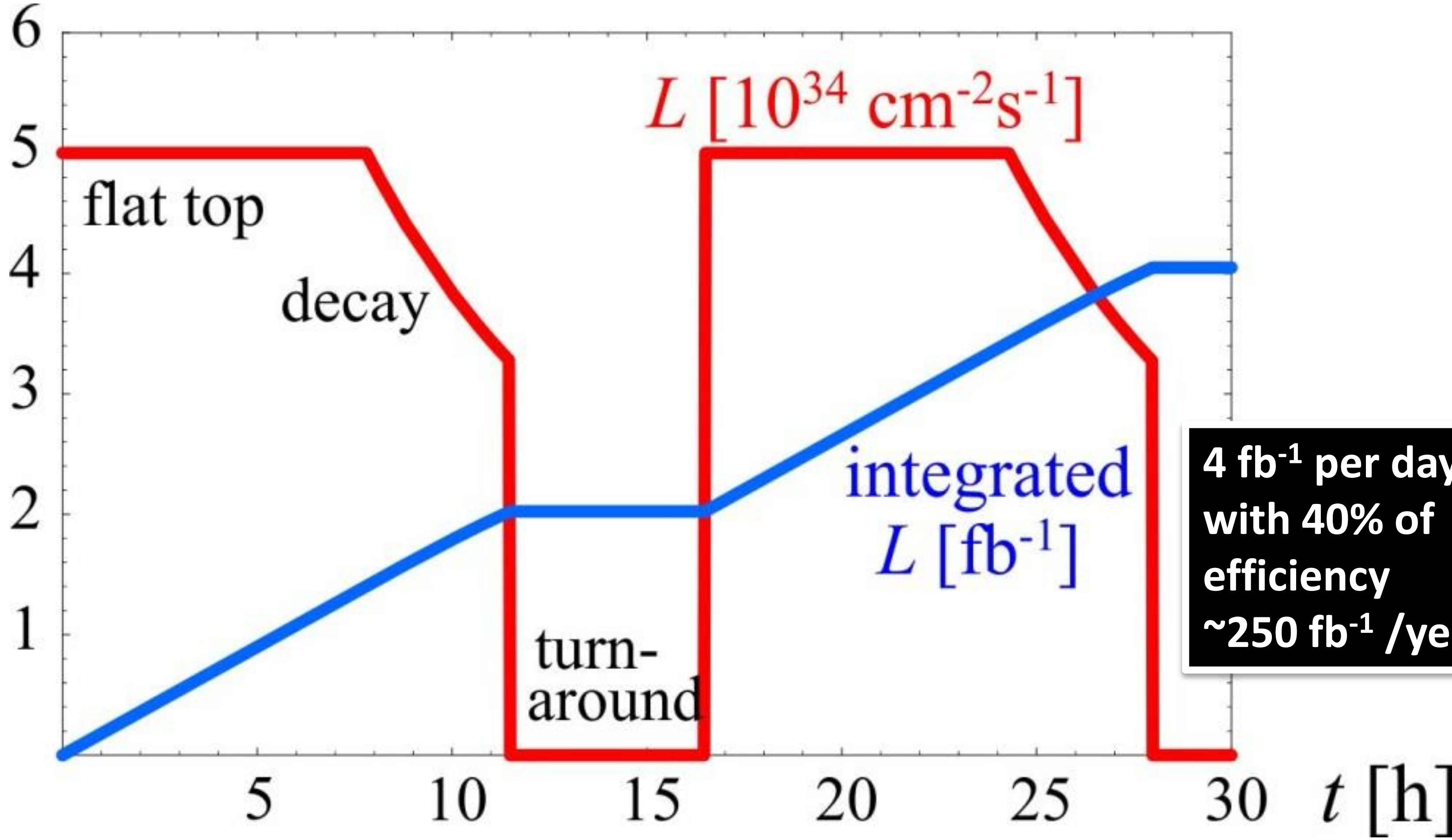
luminosity leveling at the HL-LHC

example: maximum pile up 140



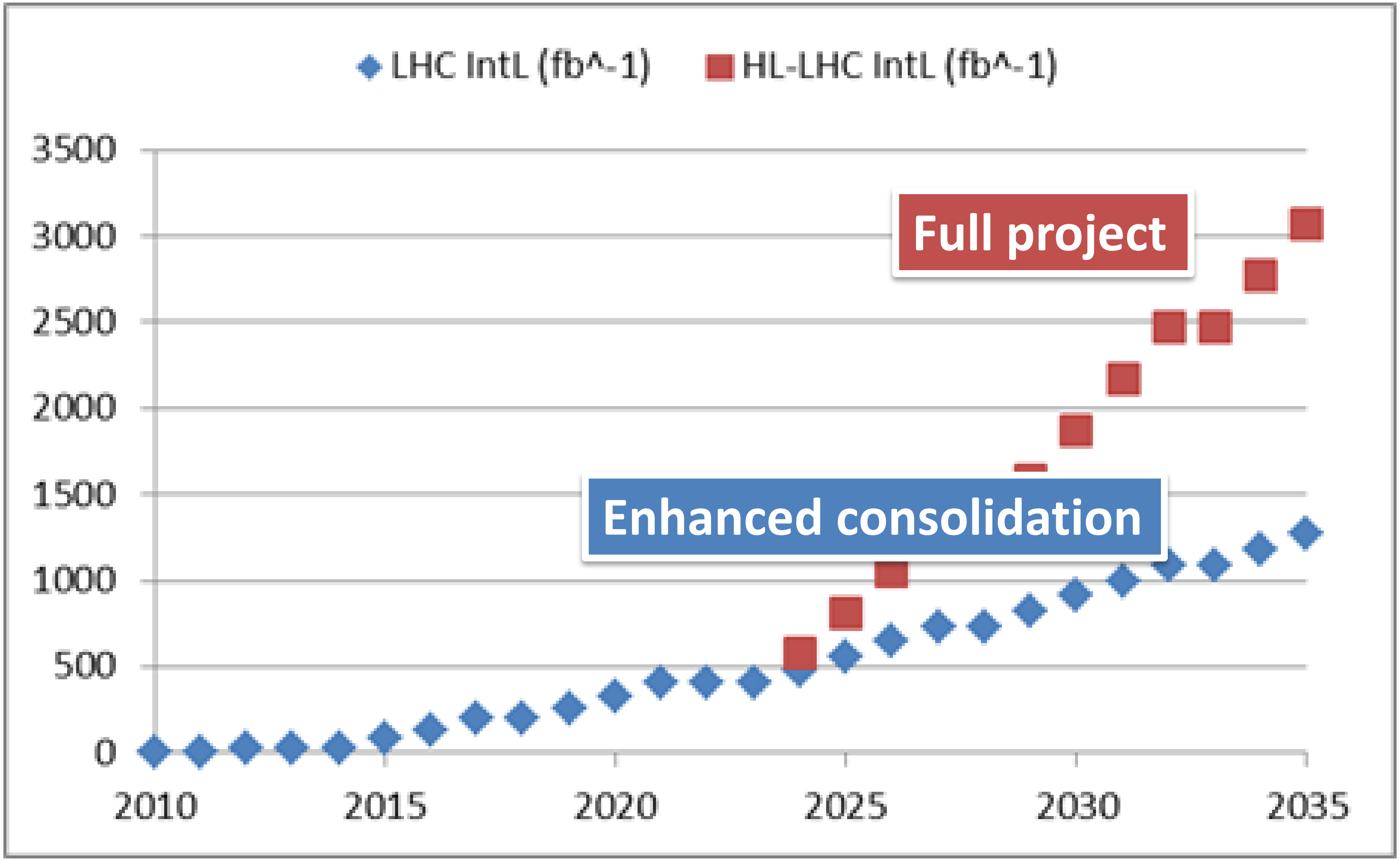
luminosity & integrated luminosity during 30 h at the HL-LHC

example: maximum pile up 140



4 fb^{-1} per day, with 40% of efficiency ~250 fb^{-1} /year

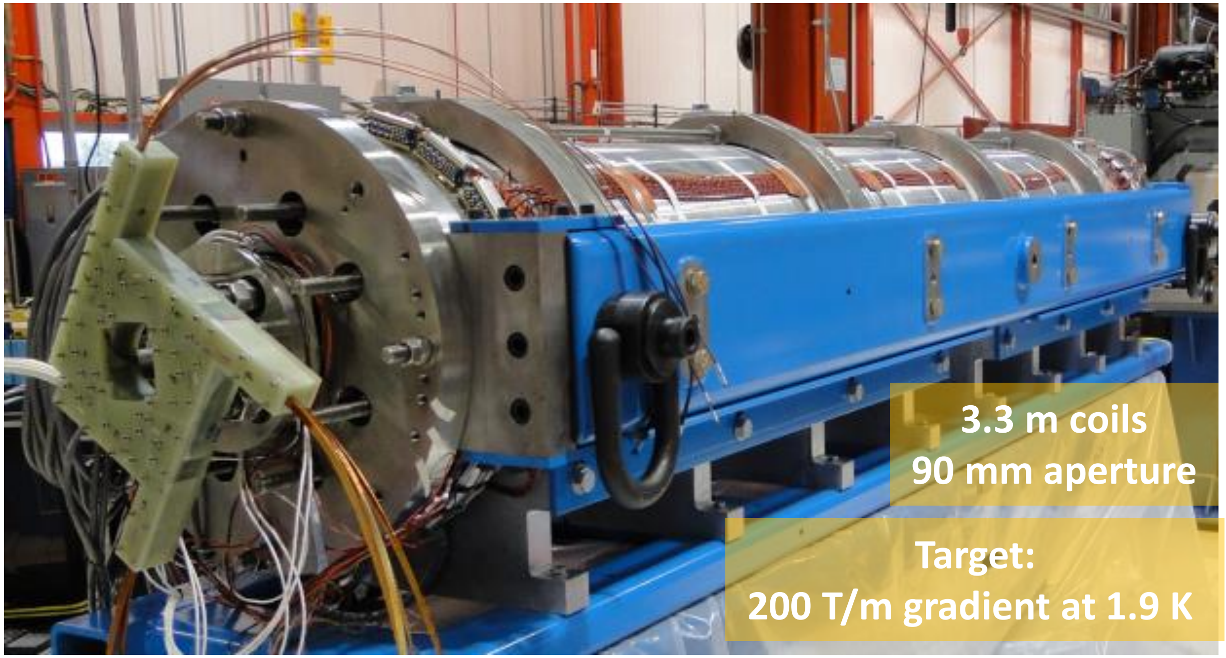
final goal : 3000 fb^{-1} by 2030's…



new triplet quadrupoles

- LARP: HQ (1 m, 120 mm) and LQ3 (3.6 m, 90 mm), *Nb_3Sn* quadrupoles, very positive test results
- New goal: **aperture 150 mm, 4.5+4.5 m long**, *W*-shielded, more limited by radiation damage than by heat deposition

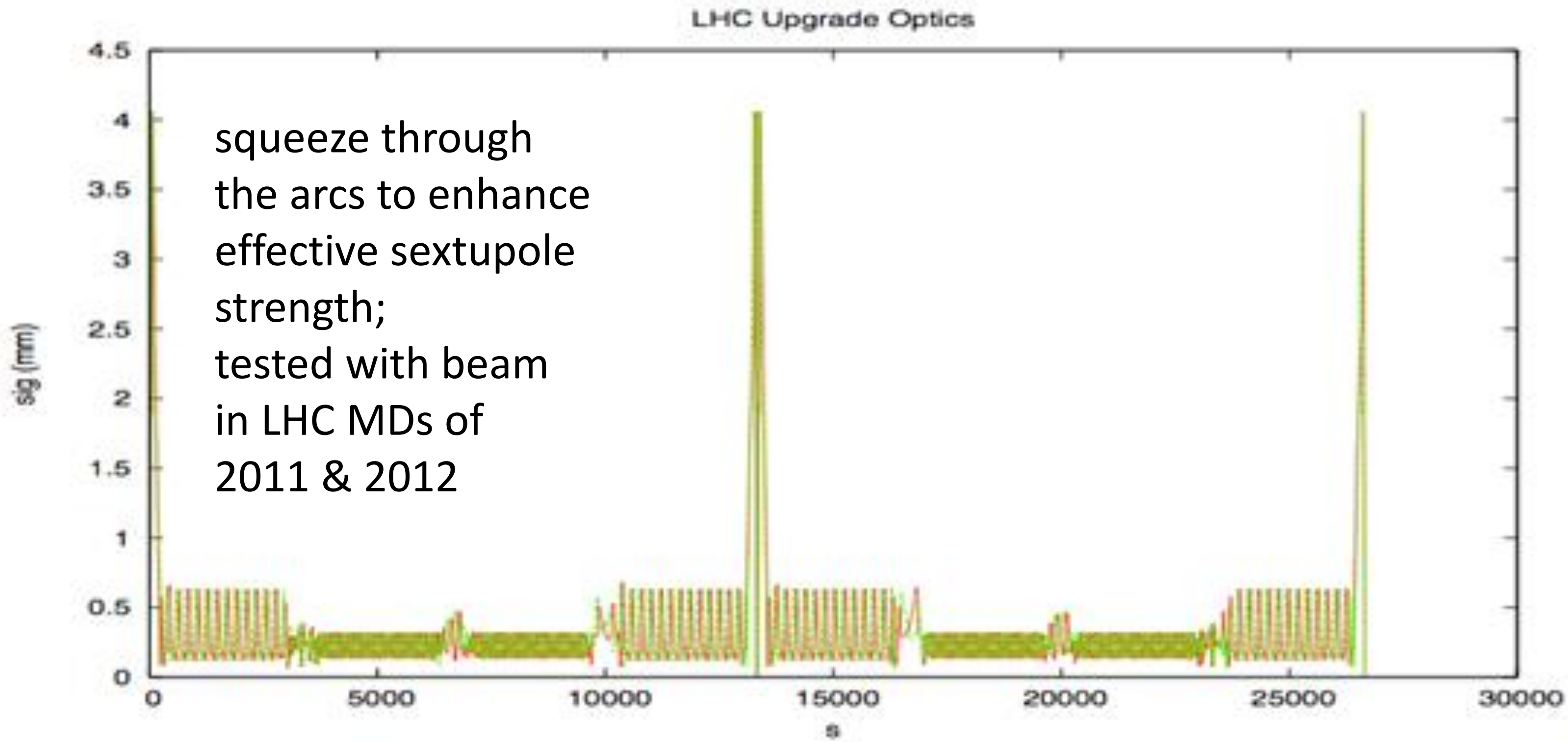
LQS03: **208 T/m** at 4.6 K
210 T/m at 1.9 K
1st quench: 86% s.s. limit



HL-LHC optics

S. Fartoukh

Achromatic Telescopic Squeeze (ATS) is fully proven
(β^* = 15 cm «easy», room for 10-12 cm); optics layout (many magnets to change); field errors (also CC)…



typical ATS collision optics with IR1 and IR5 squeezed down to β^*=10 cm

11 T dipole for dispersion suppressors

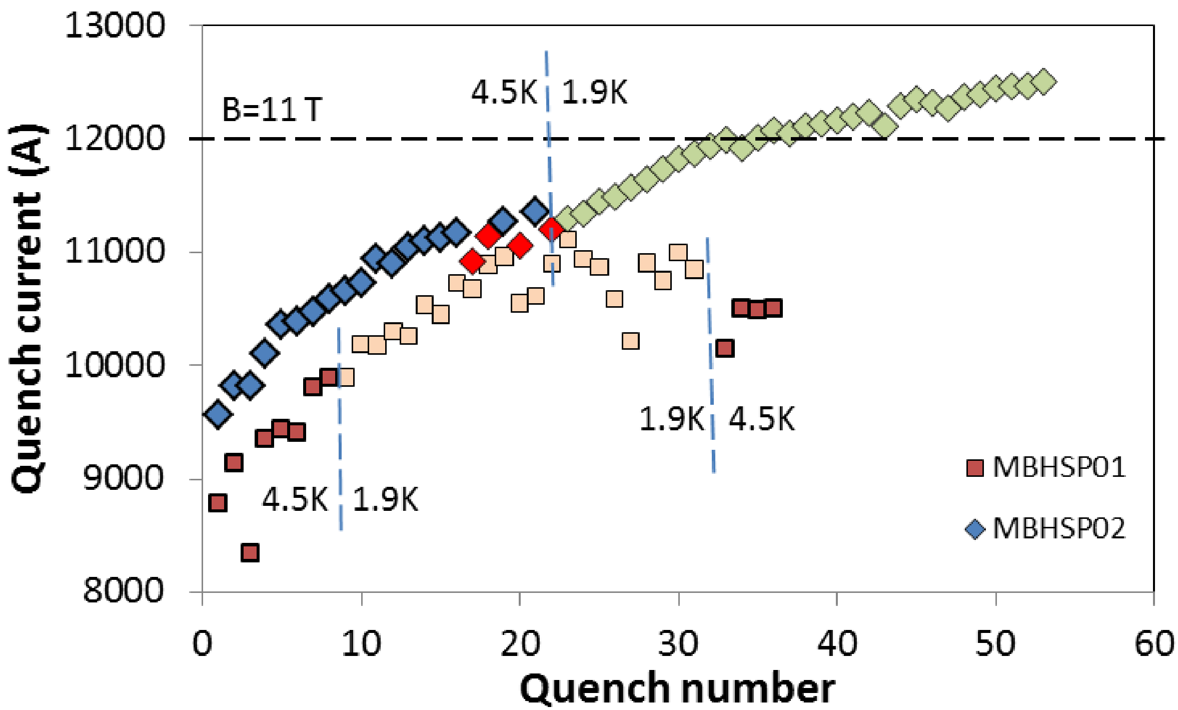
1st single-aperture 2 m long 11 T demonstrator dipole fabricated in record time (<18 months), tested in June 2012

1 m dipole model with R&D strand tested in April 2014,

B_{nom}=11 T was achieved

Next: one 2 m single bore and then 2-in-1

LARP



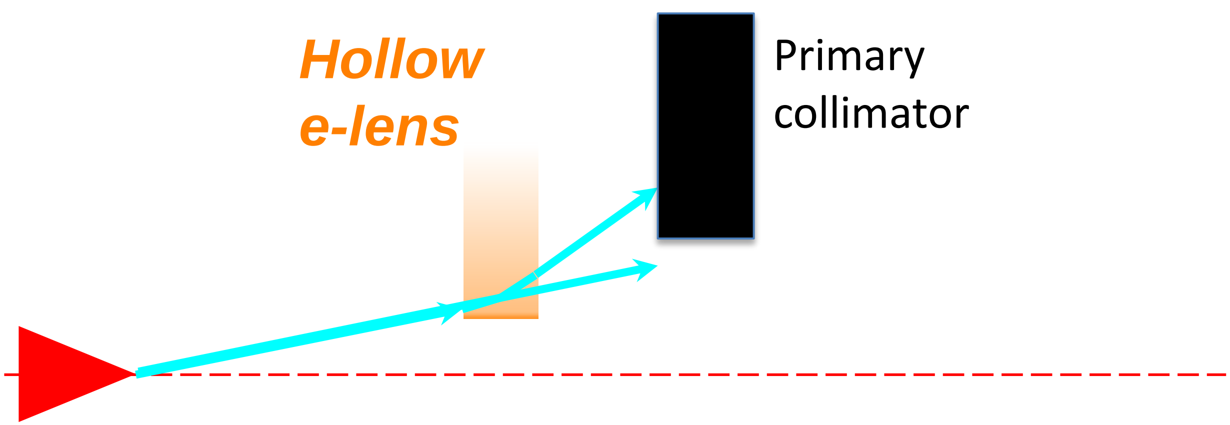
collimation

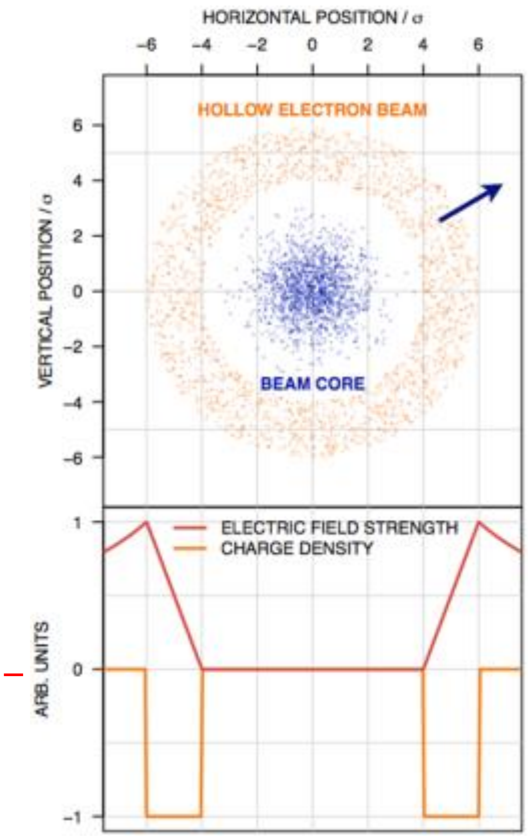
collimators in dispersion suppressors installed from LS2

cryo-collimators?

new materials

new concepts: crystals, electron lens





SC link

first prototype, 20 m – 20 kA, under test at CERN!

tests of novel *MgB_2* and *HTS* (YBCO and BSCCO) cables

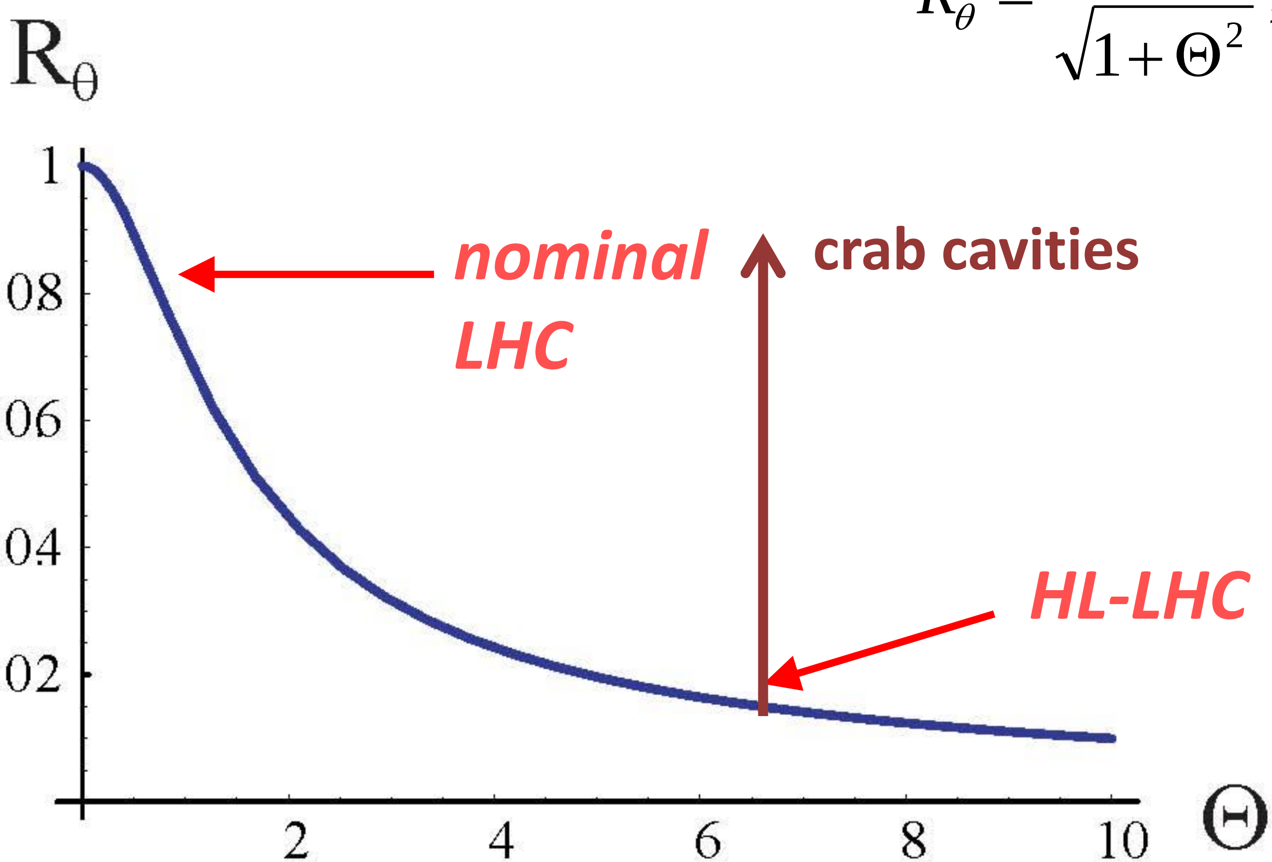
luminosity reduction due to crossing angle

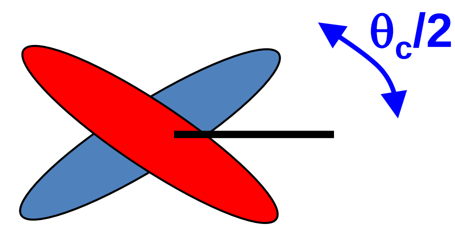
more pronounced at smaller β*

"Piwinski angle"

luminosity reduction factor

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

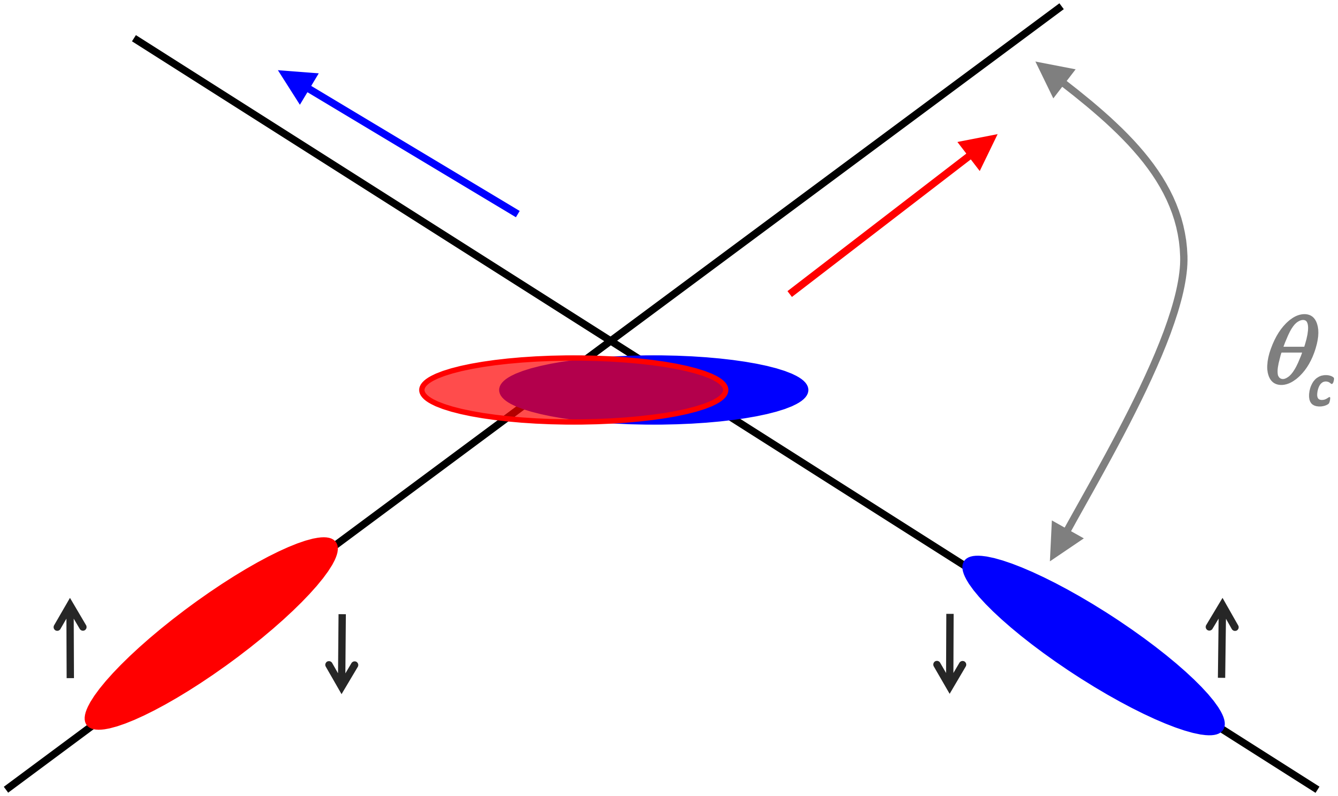




eff. beam size:

$\sigma^*_{x,eff} \approx \sigma_x^* / R_\theta$

schematic of crab crossing

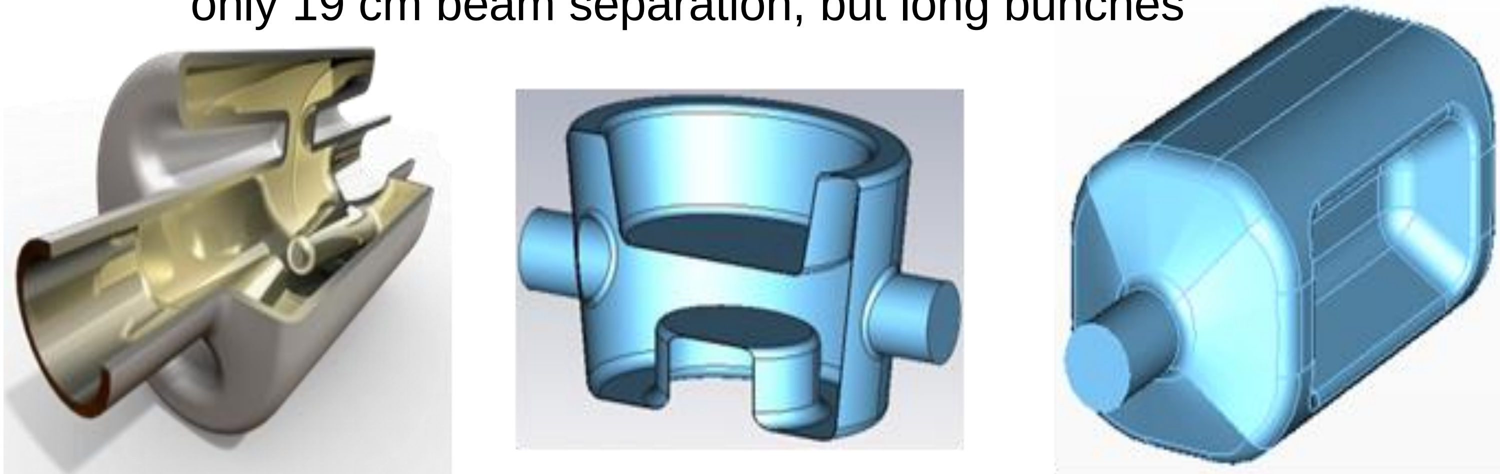


- RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" for luminosity and tune shift
- bunch centroids still cross at an angle (easy separation)
- 1st proposed in 1988, used in operation at KEKB since 2007

until recently plan was to vary crab cavity voltage for leveling, but this would change size of luminous region & is disliked by experiments (instead leveling by β* or offset?)

HL-LHC needs compact crab cavities

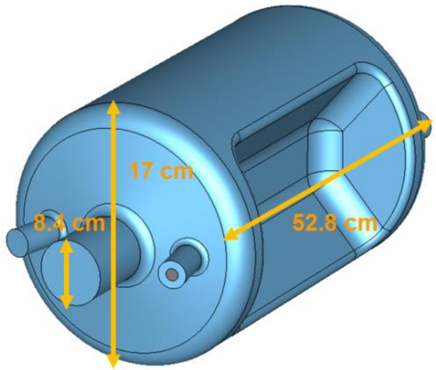
only 19 cm beam separation, but long bunches



Final down-selected compact cavity designs for the LHC upgrade: 4-rod cavity design by Cockcroft I. & JLAB (left), $\lambda/4$ TEM cavity by BNL (centre), and double-ridge $\lambda/2$ TEM cavity by SLAC & ODU (right).

Prototype compact *Nb-Ti* crab cavities for the LHC: 4-rod cavity (left) and double-ridge cavity (right).

breaking news – PoP double-ridge cavity achieved 7 MV deflecting voltage cw

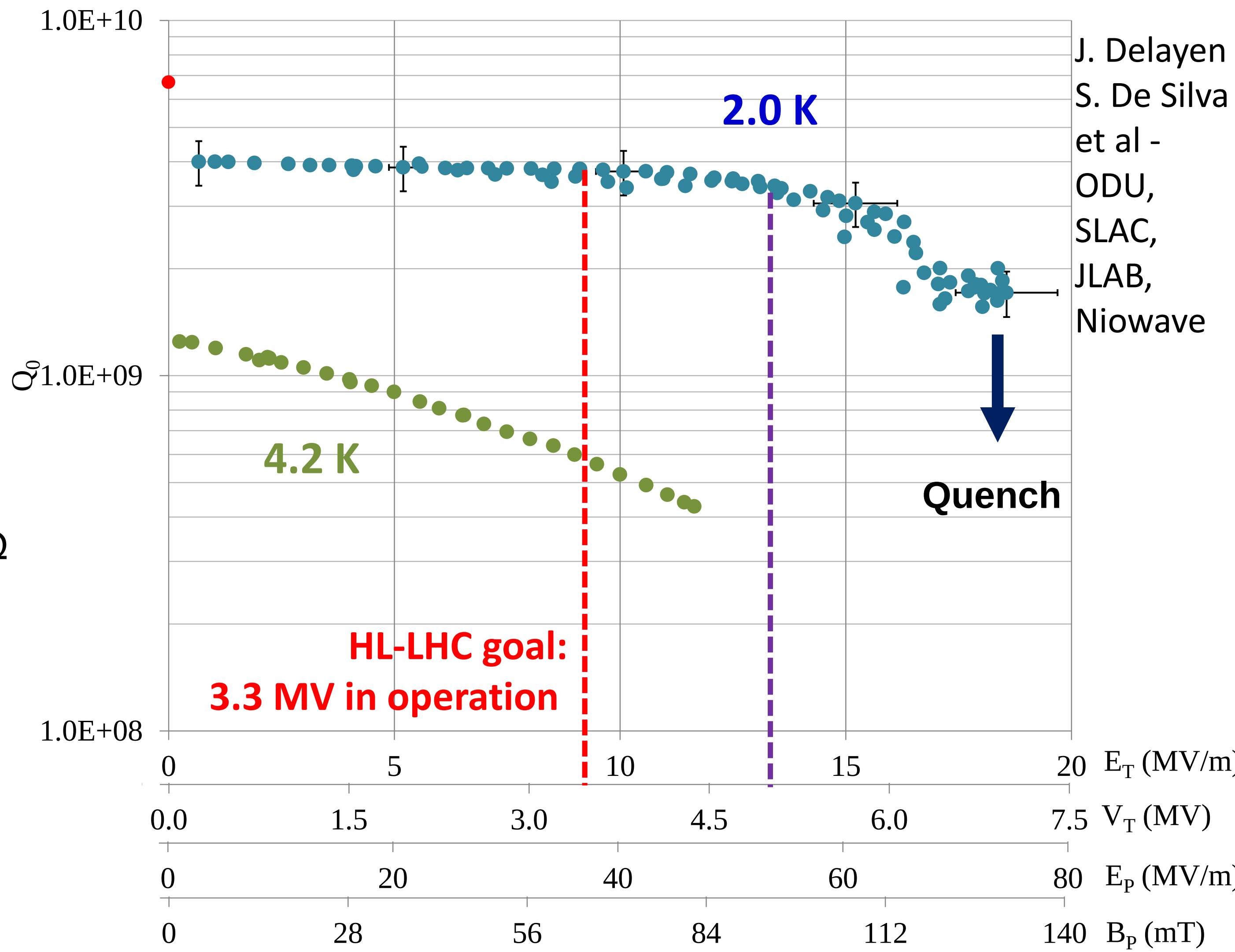


- Expected

  $Q_0 = 6.7\times10^9$

  - At R_S = 22 nΩ
  - And R_{res} = 20 nΩ
- Achieved

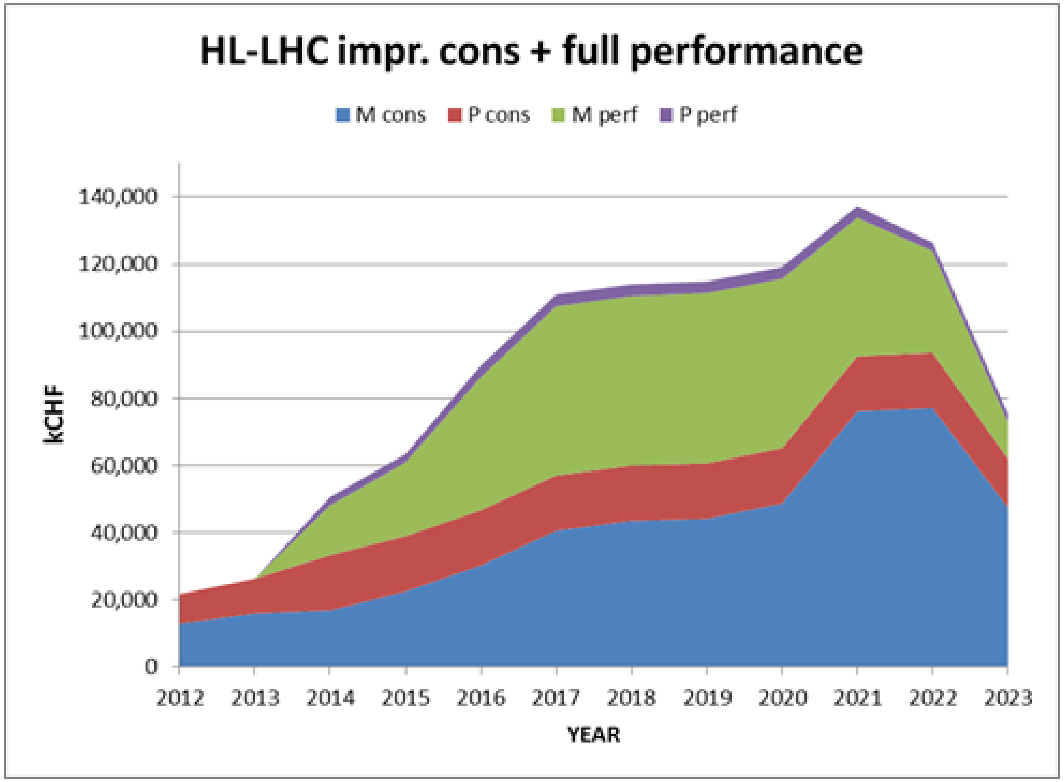
  $Q_0 = 4.0\times10^9$
- Achieved fields
  - E_T = 18.6 MV/m
  - V_T = 7.0 MV
  - E_P = 75 MV/m
  - B_P = 131 mT



better than required!

J. Delayen, LARP CM20

preliminary budget estimate



	Improving Consolidation	Full performance	Total HL-LHC
Mat. (MCHF)	476	360	836
Pers. (MCHF)	182	31	213
Pers. (FTE-y)	910	160	1070
TOT (MCHF)	658	391	1,049

RLIUP 2013

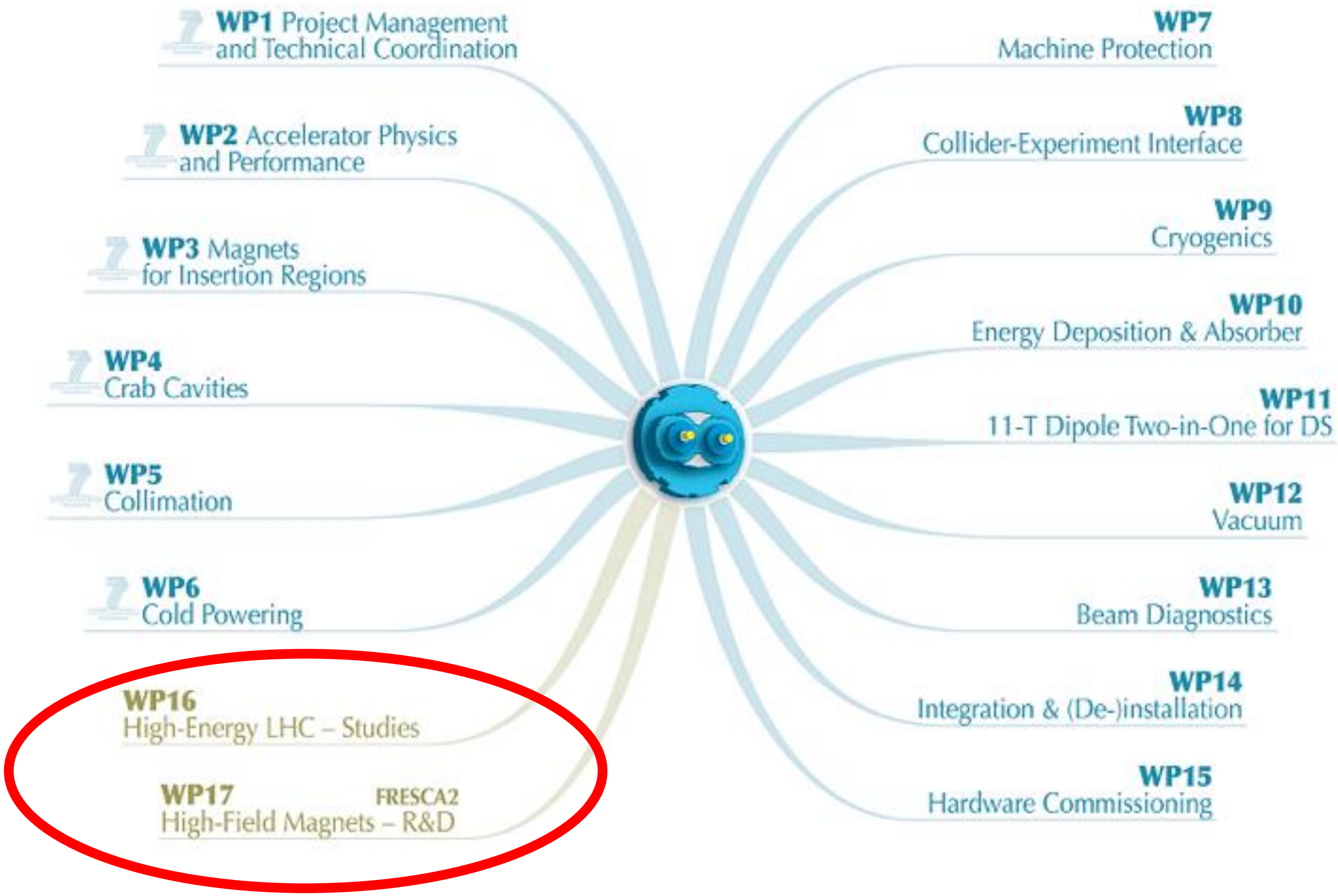
"Review of LHC and injector upgrade plans"

CERN, 8-10 October 2013

3 scenarios	PICs Performance Improving Consolidations	US1 Upgrade Scenario 1	US2 Upgrade Scenario 2
		+HHRF?+DS collimators?	+crab cavities, e-lens,…
integrated luminosity by 2035	**1000-1200/fb**	**2000/fb**	**3000/fb**

physics needs & motivation?; also, reasons to go >3000/fb?

HL-LHC project structure



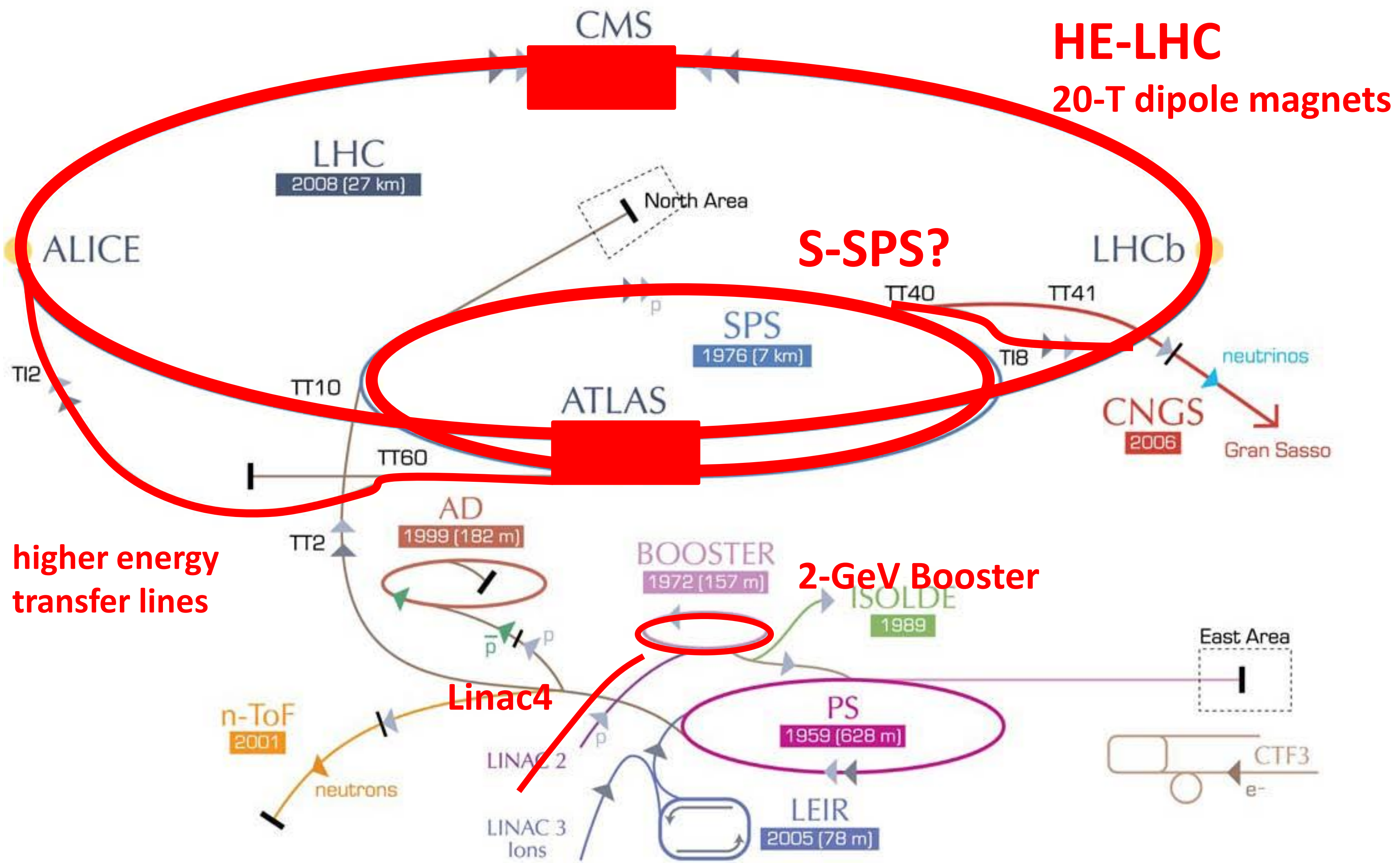
HL-LHC Structure and Management

	Description	Coordinator	Co-coordinator
WP1	Project Management and Technical Coordination	Lucio Rossi, CERN	Oliver Brüning, CERN
WP2	Accelerator Physics and Performance	Stéphane Fartoukh, CERN	Andy Wolski, UNILIV
WP3	Magnets for Insertion Regions	Ezio Todesco, CERN	GianLuca Sabbi, LBNL
WP4	Crab Cavities	Erk Jensen, CERN	Graeme Burt, UNILAN
WP5	Collimation Project	Stefano Redaelli, CERN	Grahame Blair, RHUL
WP6	Cold Powering	Amalia Ballarino, CERN	Francesco Broggi, INFN

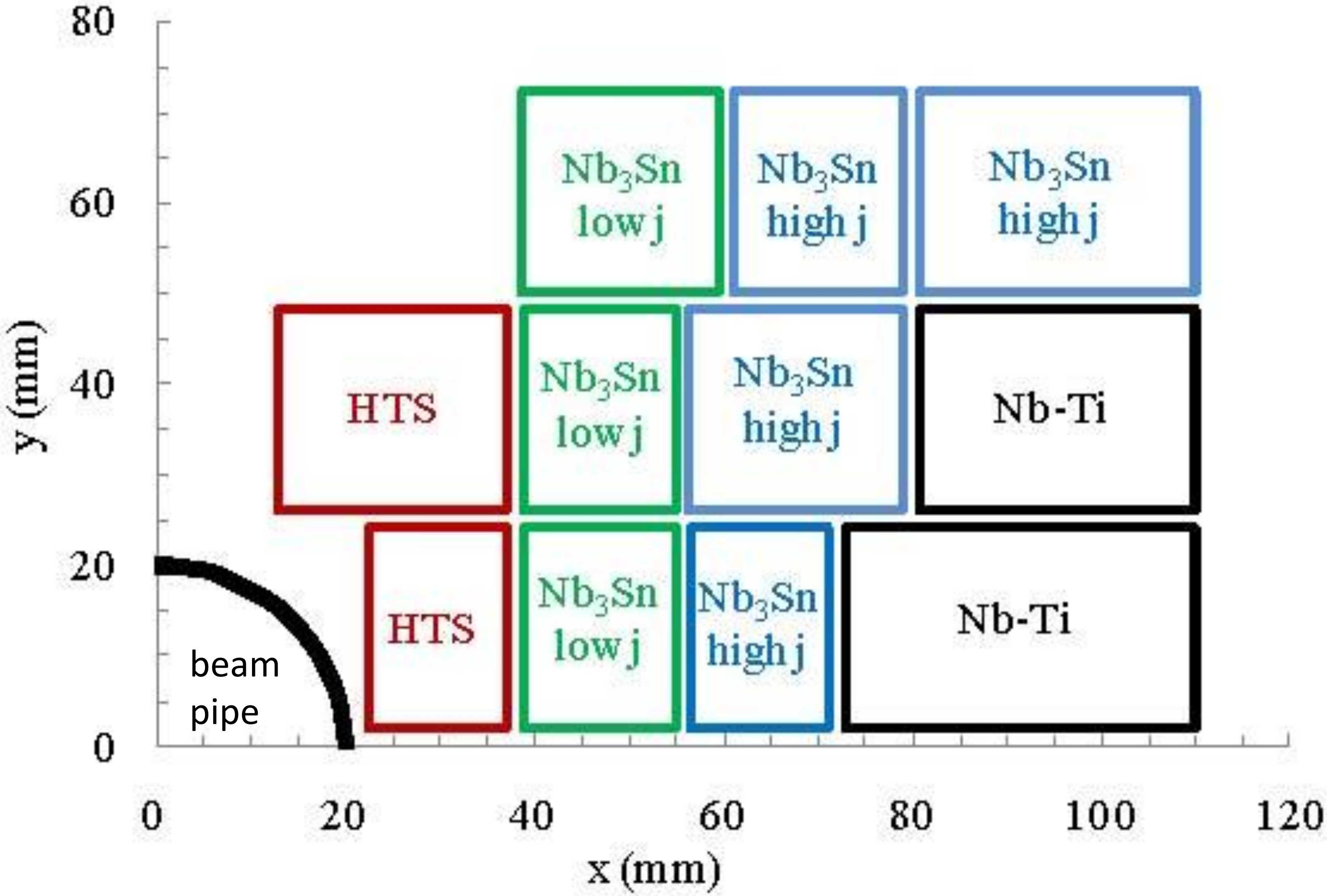
WP7	Machine Protection	Rudiger Schmidt, CERN	Jorg Wenninger, CERN
WP8	Collider-Experiment Interface	Helmut Burkhardt, CERN Austin Ball, CMS Marzio Nessi, ATLAS	Daniel Lacarrère, CERN
WP9	Cryogenics	Laurent Tavian, CERN	Rob Van Weelderen, CERN
WP10	Energy Deposition & Absorber	Francesco Cerutti, CERN	Nikolai Mokhov, FNAL
WP11	11 T Dipole Two-in-One for DS	Mikko Karppinen, CERN	Alexander Zlobin, INFN
WP12	Vacuum	Roberto Kersevan, CERN	Mark-Antony Gallilee, CERN
WP13	Beam Diagnostics	Rhodri Jones, CERN	
WP14	Integration & (De-)installation	Sylvain Weisz, CERN	
WP15	Hardware Commissioning	Mirko Pojer, CERN	
WP16	High-Energy LHC - Studies	Lucio Rossi, CERN	Frank Zimmermann, CERN
WP17	High-Field Magnets – R&D FRESCA2	Gijs de Rijk, CERN	François Kircher, CEA

Technical Coordinator	Herman Schmickler, CERN
Project Safety Officer	Thomas Otto, CERN
Deputy TC, QA and Risk Management	Isabel Bejar Alonso, CERN
FP7 HiLumi LHC Administrative Manager	Svetlomir Stavrev, CERN
Dissemination and Outreach	Agnes Szeberenyi, CERN
Administrative Support	Cécile Noels, CERN

High-Energy LHC

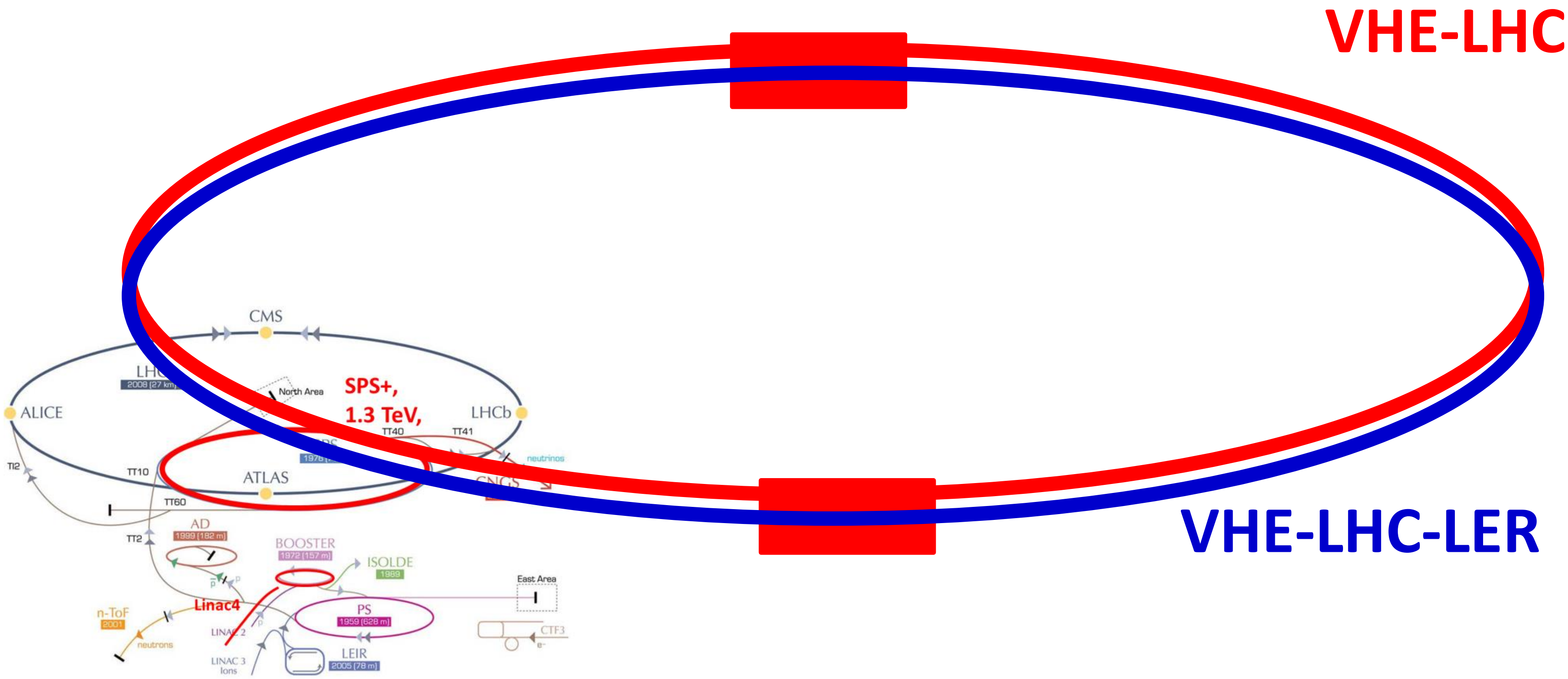


20-T dipole magnet



E. Todesco, L. Rossi, P.. McIntyre

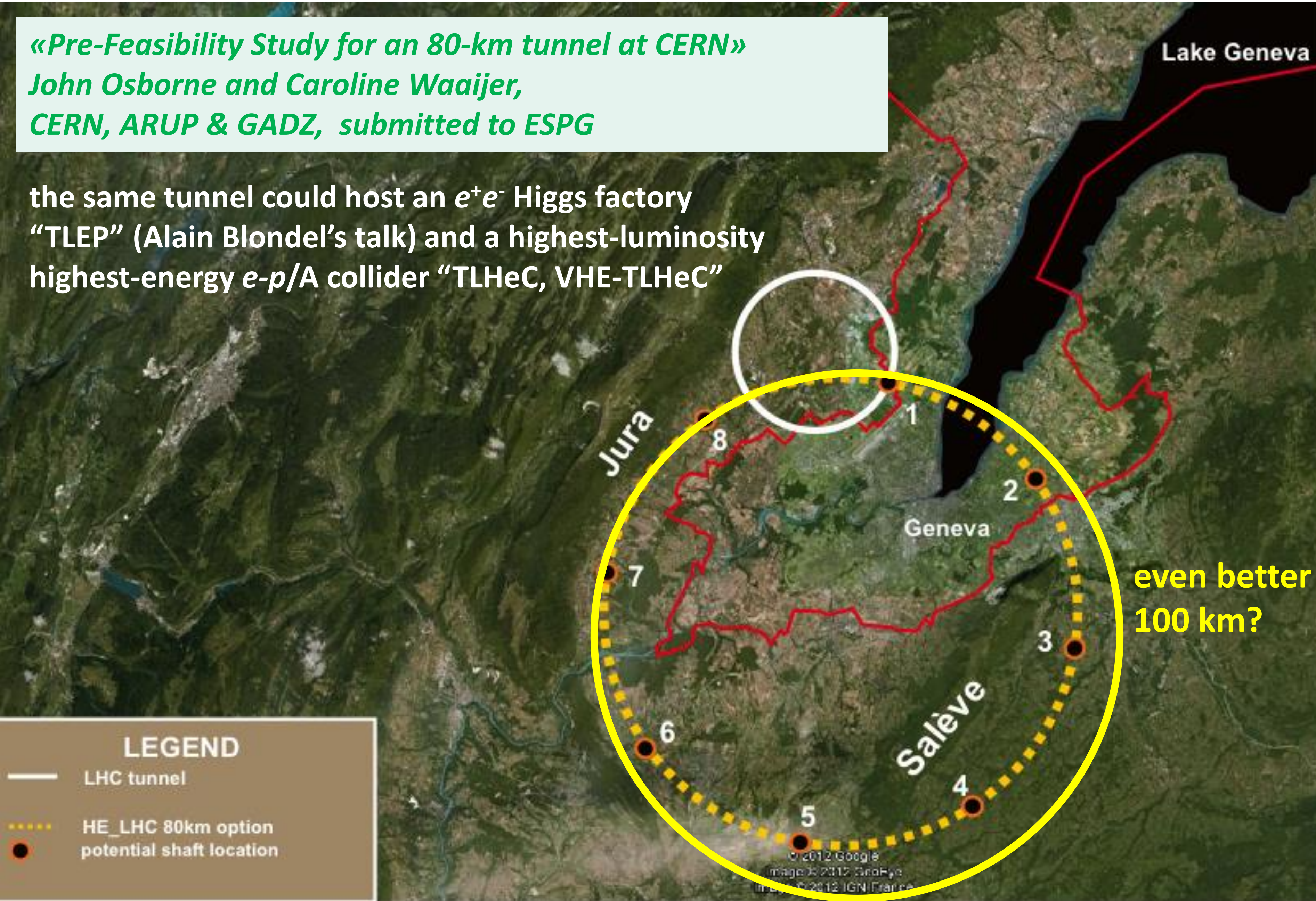
VHE-LHC


VHE-LHC
VHE-LHC-LER
SPS+,
1.3 TeV,
CMS
ALICE
LHCb
ATLAS
North Area
TT40
TT41
TT10
TT60
TI2
TT2
neutrinos
AD
1999 (182 m)
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
Linac4
n-ToF
2001
neutrons
PS
1959 (628 m)
LINAC 3
Ions
LEIR
2005 (78 m)
CTF3

80-km tunnel for VHE-LHC – “best” option

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG

the same tunnel could host an e^+e^- Higgs factory “TLEP” (Alain Blondel’s talk) and a highest-luminosity highest-energy *e-p*/A collider “TLHeC, VHE-TLHeC”



HE-LHC & VHE-LHC parameters – 1

	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14		33	100
circumference [km]	26.7			80
dipole field [T]	8.33		20	
dipole coil aperture [mm]	56		$\lesssim 40$	
beam half aperture [mm]	18 (x), 22 (y)		$\lesssim 13$ (x & y)	
no. bunches	2808			8420
av. bunch population [$\cdot 10^{11}$ ppb]	1.15	2.2	0.94	0.97
initial transverse norm. emittance [μm rad]	3.75	2.5	1.38	2.15
β_x^* [m]	0.55	0.15 (min.)	0.35	1.1
RF voltage [MV]	16			22
longitudinal emittance [eVs]	2.5		3.8	13.5
rms momentum spread [$\cdot 10^{-4}$]	1.13		0.74	0.85
no. IPs contributing to tune shift	3	2		
max. total beam-beam tune shift	0.01	0.015	0.01	
beam circulating current [A]	0.584	1.12	0.478	0.492
stored beam energy [GJ]	0.362	0.694	0.701	6.61

O. Dominguez, L. Rossi, F.Z.

HE-LHC & VHE-LHC parameters – 2

	LHC	HL-LHC	HE-LHC	VHE-LHC
SR power per ring [kW]	3.6	7.3	96.2	$2.9 \cdot 10^3$
arc heat load [W m^{-1}/aperture]	0.17	0.33	4.35	43.4
energy loss per turn [keV]	6.5		201.3	$5.9 \cdot 10^3$
critical photon energy [eV]	44		575	$5.5 \cdot 10^3$
longitudinal SR damping time [h]	12.9		1.01	0.32
transverse SR damping time [h]	25.8		2.02	0.64
initial horizontal IBS rise time [h]	103	20.4	20.1	157
initial longitudinal IBS rise time [h]	57	23.3	40.0	396
peak luminosity [$\cdot 10^{34} cm^{-2} s^{-1}$]	1.0	5.0 (leveled)	5.0	
crossing angle [μrad]	285	590	185	72
max. number of events per crossing	27	135	147	171
total/inelastic cross section [mb]	111 / 85		129 / 93	153 / 108
beam lifetime due to proton burn-off [h]	40.2	15.4	5.7	14.8
optimum run time [h]	16.9	10.2	5.8	10.7
integrated luminosity per day [fb^{-1}]	0.53	2.8	1.43	2.08

HE-LHC &VHE-LHC luminosities could much improve for bunch spacings < 25 ns, e.g. by factor 5 for 5 ns, and make better use of strong radiation damping!

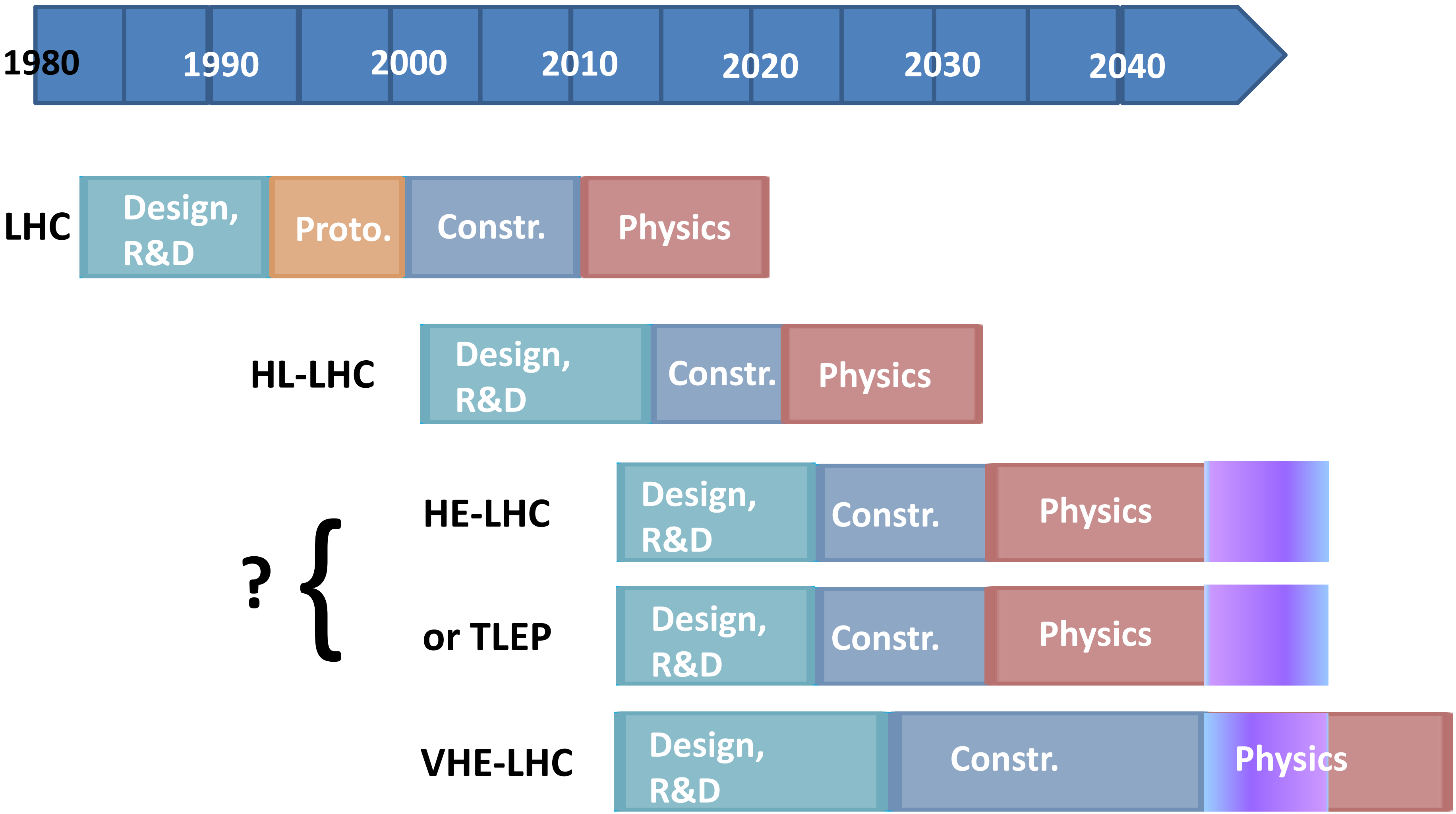
are 5 ns spacing & 2.5x10^{35}cm^{-2}s^{-1} acceptable for detectors?

O. Dominguez, L. Rossi, F.Z.

Conclusions

- **Well defined programme** for HL-LHC
- **Key prototypes successfully tested**
- **Plan & goals for HL-LHC under review**
  - budget considerations & LHC results
- HL-LHC develops the **technology** (*Nb_3Sn* magnets, 20-kA *HTS* cables) **for future higher energy *pp* collider**: HE-LHC (33 TeV c.m.) and/or VHE-LHC (100 TeV c.m.)

possible long-term time line



"reality is always changing, and it is always unpredictable"

Hideki Yukawa

Appendix

- example parameters for TLHeC & VHE-TLHeC

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 120 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	$e^{\pm}$	p	$e^{\pm}$	p
beam energy [GeV]	**120**	**7000**	**120**	**50000**
bunch spacing [μs]	3	3	3	3
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	24.3	51.0	24.3	51.0
rms bunch length [cm]	0.17	4	0.17	2
rms emittance [nm]	10,2	0.40	10,2	0.06
$\beta_{x,y}$*[cm]	2,1	60,5	0.5,0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	0.05, 0.09	**0.03,0.01**	0.07,0.10	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.8		4.9	
luminosity [10^{34}cm^{-2}s^{-1}]	**0.5**		**1.6**	

parameters for *TLHeC* & *VHE-TLHeC* (e^- at 60 GeV)

collider parameters	TLHeC		VHE-TLHeC	
species	$e^{\pm}$	p	$e^{\pm}$	p
beam energy [GeV]	**60**	**7000**	**60**	**50000**
bunch spacing [μs]	0.2	0.2	0.2	0.2
bunch intensity [10^{11}]	5	3.5	5	3.5
beam current [mA]	390	51.0	390	51.0
rms bunch length [cm]	0.18	4	0.18	2
rms emittance [nm]	10, 2	0.40	10, 2	0.06
$\beta_{x,y}$*[cm]	2, 1	60, 5	0.5, 0.25	60,5
$\sigma_{x,y}$* [μm]	15, 4		6, 2	
beam-beam parameter ξ	**0.10, 0.18**	**0.03,0.01**	**0.14, 0.20**	**0.03,0.007**
hourglass reduction	**0.63**		**0.42**	
CM energy [TeV]	1.3		3.5	
luminosity [10^{34}cm^{-2}s^{-1}]	**8.0**		**25.6**	