LHC Upgrade Scenarios

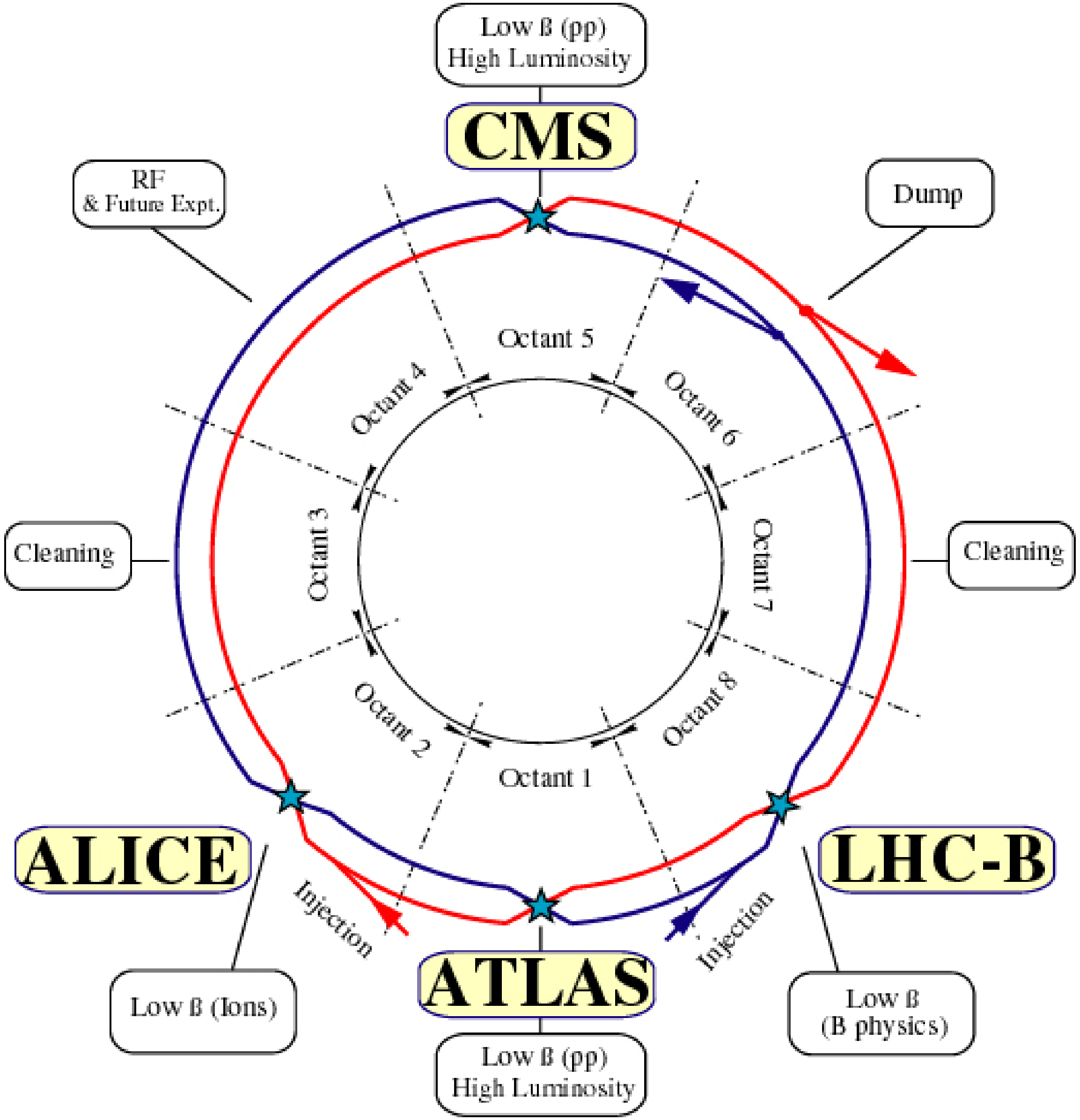
Jean-Pierre Koutchouk,

Frank Zimmermann

outline

1) motivation
2) performance limits & new approaches
3) luminosity leveling
4) upgrade scenarios
5) conclusions & perspective

Large Hadron Collider (LHC)



proton-proton
and heavy-ion collider

next energy-frontier
discovery machine

c.m. energy 14 TeV
(7x Tevatron)

design luminosity
10^{34} cm^{-2}s^{-1}
(~100x Tevatron)

LHC nominal luminosity was pushed in competition with SSC

motivation

The LHC is a significant public investment for pursuing the research in high-energy physics and the origin of the Universe.

Whatever can reasonably be done to extend its already ambitious physics reach needs to be prepared well in advance, keeping in mind the required development times for new concepts and/or technologies and the decision making process.

physics reach, discovery potential, precision

Ellis, Gianotti, ADR
hep-ex/0112004+ few updates

Units are TeV (except W_LW_L reach)
ILdt correspond to 1 year of running at nominal luminosity for 1 experiment

PROCESS	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	DLHC 28 TeV 100 fb^{-1}	VLHC 40 TeV 100 fb^{-1}	VLHC 200 TeV 100 fb^{-1}	ILC 0.8 TeV 500 fb^{-1}	CLIC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	4	5	20	0.4	2.5
W_LW_L	2σ	4σ	4.5σ	7σ	18σ	6σ	90σ
Z'	5	6	8	11	35	$8^{\dagger}$	$30^{\dagger}$
Extra-dim (δ=2)	9	12	15	25	65	$5\text{-}8.5^{\dagger}$	$30\text{-}55^{\dagger}$
q*	6.5	7.5	9.5	13	75	0.8	5
Lcompositeness	30	40	40	50	100	100	400
TGC (λ_{γ})	0.0014	0.0006	0.0008		0.0003	0.0004	0.00008

† indirect reach
(from precision measurements)

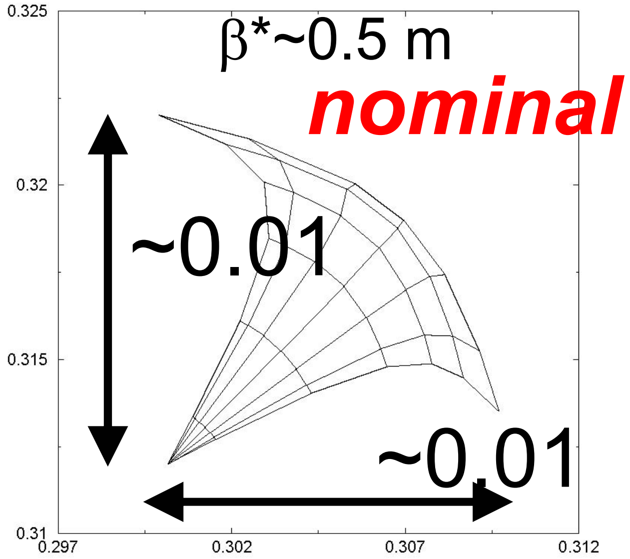
Approximate mass reach machines:

$\sqrt{s}$ = 14 TeV, L=10^{34} (LHC) : up to ≈ 6.5 TeV
$\sqrt{s}$ = 14 TeV, L=10^{35} (SLHC) : up to ≈ 8 TeV
$\sqrt{s}$ = 28 TeV, L=10^{34} : up to ≈ 10 TeV

Physics motivations for future CERN accelerators.
Albert De Roeck, John R. Ellis, Fabiola Gianotti. CERN-TH-2001-023, Dec 2001. 14pp. Prepared for the CERN Scientific Policy Committee in September 2001, and presented to the CERN Council in December

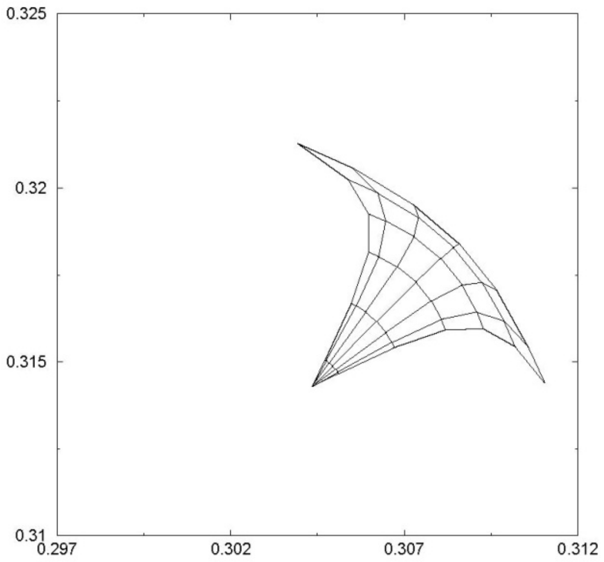
upgrade to ‘ultimate’ in original design

[from F. Ruggiero *et al*, 2001 upgrade feasibility study, LHC Project Report 626]

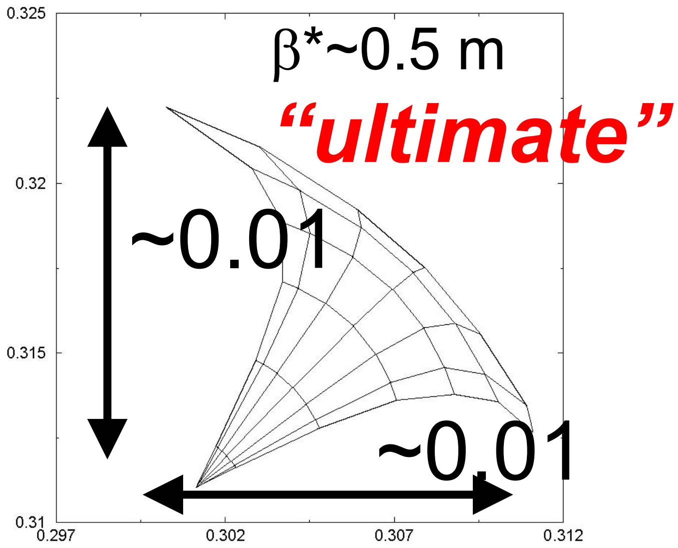


nominal tune footprint up to 6σ with 4 IPs & nom. intensity N_b=1.15x10^{11}

$L=10^{34}$ cm^{-2}s^{-1}



tune footprint up to 6σ with nominal intensity and 2 IPs



tune footprint up to 6σ with 2 IPs at ultimate intensity N_b=1.7x10^{11}

$L=2.3\times10^{34}$ cm^{-2}s^{-1}

note: beam-beam tune-shift limit $\Delta Q\sim0.01$ is conservative estimate from the SPS; for $\Delta Q\sim0.015$ “ultimate luminosity” may be reached with collisions in all 3 IPs

"To qualitatively modify the LHC physics reach, the integrated luminosity per year should be increased by a factor 10. Although this ambition would have been unconceivable at the time of the LHC design, the deeper theoretical understanding of the machine combined with experimental observations at existing hadron colliders seem to show that this ambition is not anymore purely speculative."

Jean-Pierre Koutchouk

luminosity

$$L=\left(\frac{\beta_r\gamma_r f_{rev}}{4\pi}\right)\frac{k_b N_p}{\beta^*}\left[\left(\frac{N_p}{\varepsilon_N}\right)F(\Phi_P)\right]$$

form factor

$$F(\Phi_P)\approx\frac{1}{\sqrt{1+(\Phi_p/2)^2}}$$

depends strongly on β* and ε_N

$$\sigma^*=\sqrt{\beta^*\frac{\varepsilon_N}{\beta_r\gamma_r}}$$

rms IP beam size

$$\Phi_P=\theta_c\left(\frac{\sigma_s}{\sigma^*}\right)$$

Piwinski angle

$$d^*=\sqrt{\frac{1}{\beta^*}\frac{\varepsilon_N}{\beta_r\gamma_r}}$$

rms IP divergence

normalized to nominal

$$\theta_c\approx a\,d^*\left(0.7+0.3b\sqrt{\tilde{k}_b\tilde{N}_p/\tilde{\varepsilon}_N}\right)$$

minimum crossing angle for LR-BB

total beam-beam tune shift for 2 IPs w x&y crossing

$$\Delta Q_{bb}\approx\frac{r_p}{2\pi}\left[\left(\frac{N_p}{\varepsilon_N}\right)F(\Phi_P)\right]<\Delta\hat{Q}_{bb}$$

b-b tune shift decreases with crossing angle

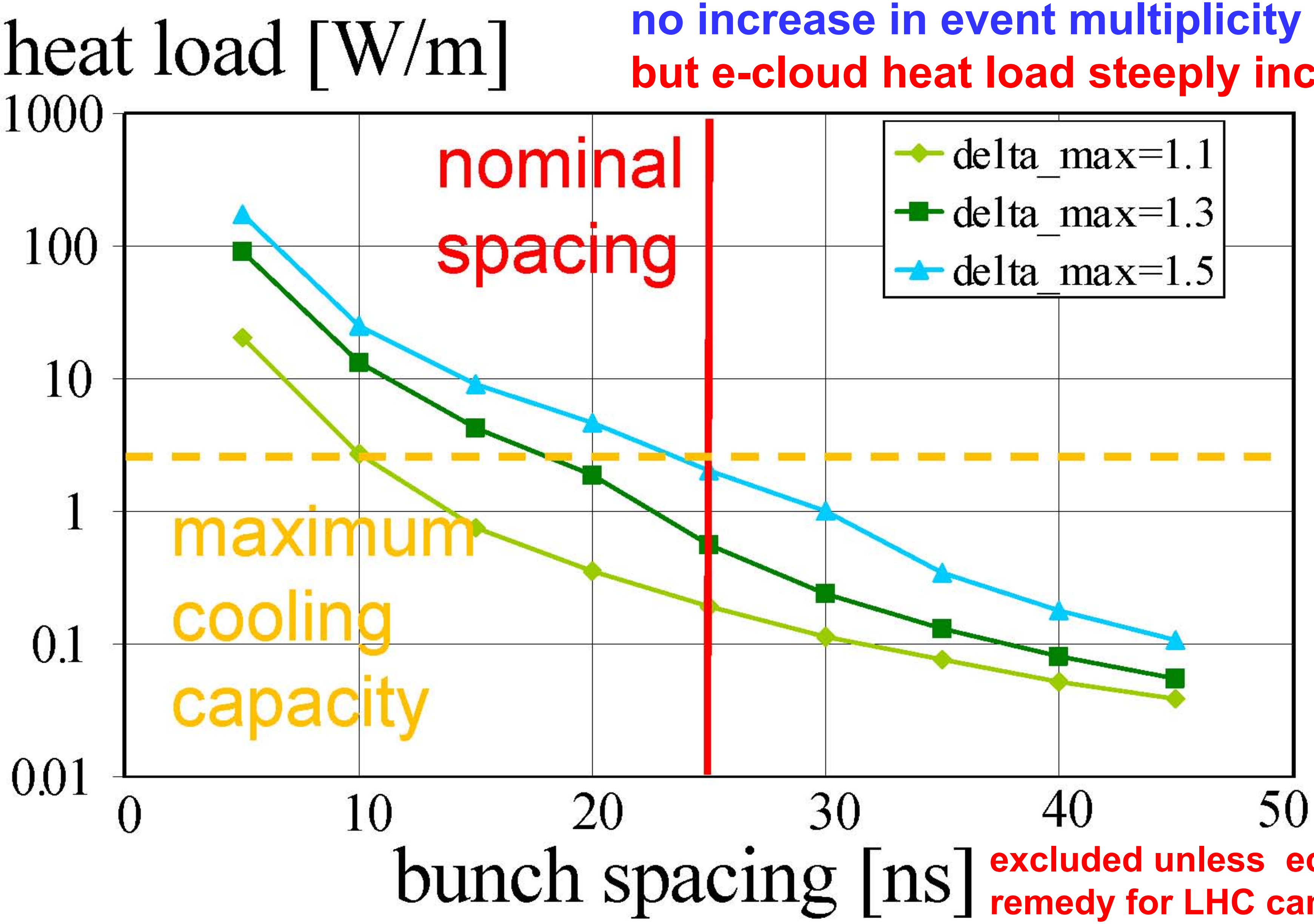
feasibility and impact of modifying each parameter in the luminosity equation while keeping the others at their nominal values

bunches k_b

no increase in bb tune shift

no increase in event multiplicity

but e-cloud heat load steeply increases

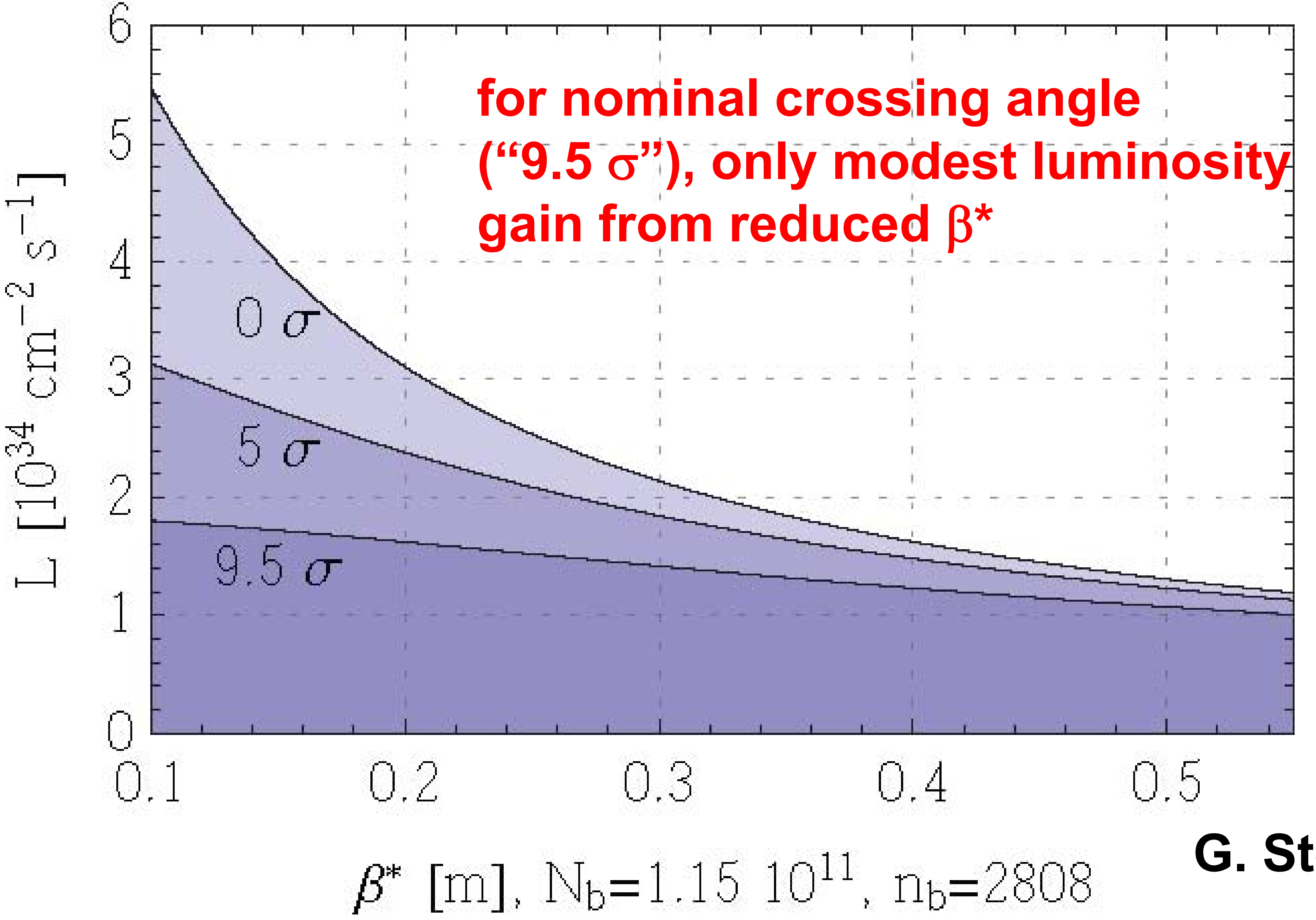


excluded unless economical remedy for LHC can be found

bunch charge N_b

- limited by LHC injectors (PS Booster, PS, SPS)
  - space charge, electron cloud
- present injectors deliver nominal 1.15×10^{11} ppb, upgrade scenarios assume up to 4.9×10^{11}
- LHC luminosity lifetime dominated by consumption in *pp* collisions
- **it is essential to reach maximum bunch charge allowed by LHC without being constrained by the injectors**

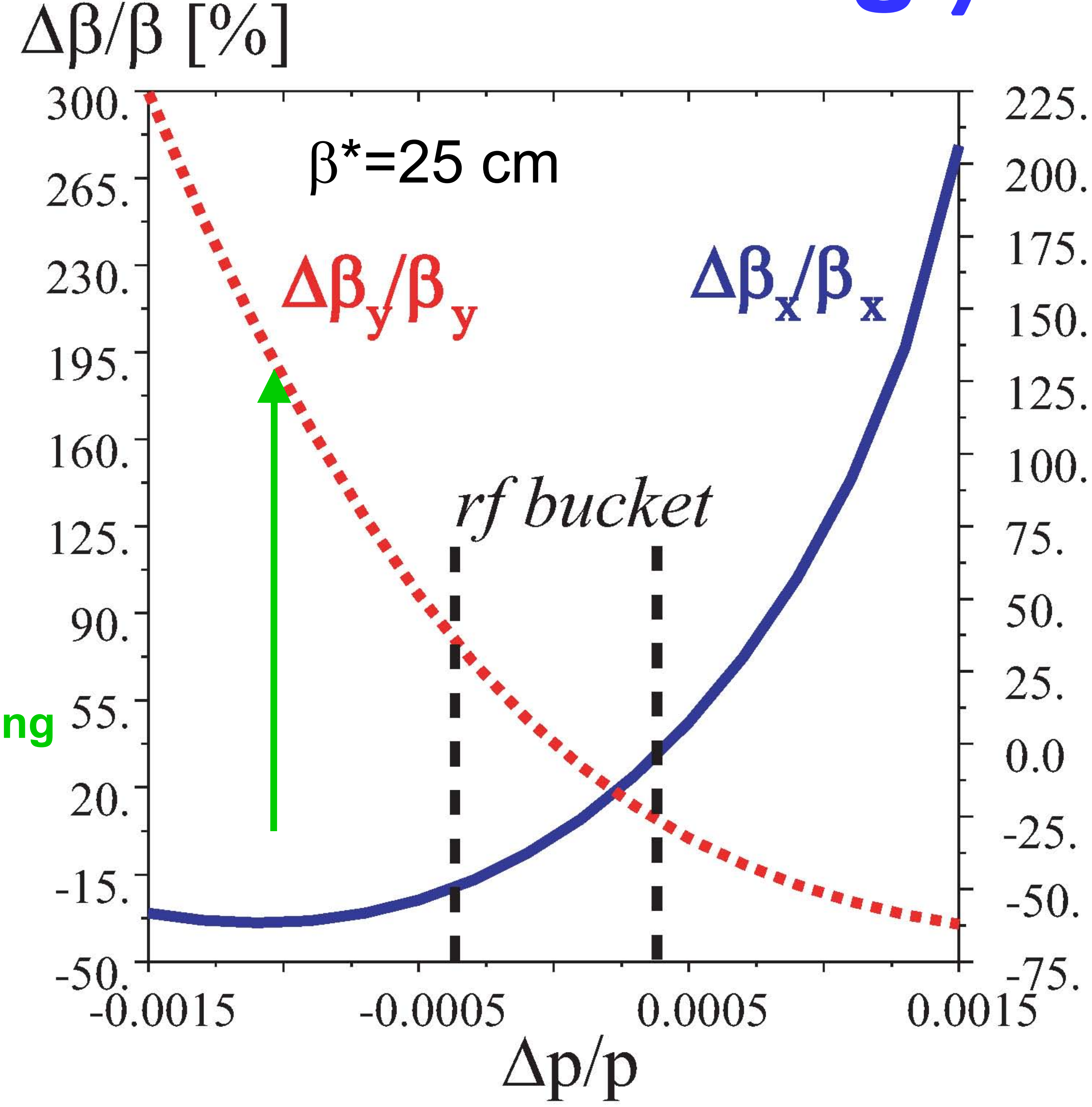
IP focusing β^* - 1



for nominal crossing angle ("9.5 σ"), only modest luminosity gain from reduced β^*

G. Sterbini

IP focusing β^* - 2



at 9 σ
100%
β beating

higher-order chromatic effects affect momentum collimation

S. Fartoukh

IP focusing β^* - 3

if off-momentum beta beating can be corrected
or the collimation be made more robust:

- **ultimate β^* ~ 15 cm for l^* = +/- 23 m**

- **ultimate β^* ~ 11 cm for l^* = +/- 13 m**

with Nb_3Sn magnet technology

limited by linear chromaticity correction

emittance ε

initially considered as parameter only in conjunction with new higher-energy SPS ; recently two new proposals

(1) lowering the emittance **R. Garoby**

- leaves form factor *F* unchanged
- **gain proportional to emittance decrease**
- limited by beam-beam tune shift & IBS
- favorable at injection, robust collimation

(2) increasing the emittance **S. Fartoukh**

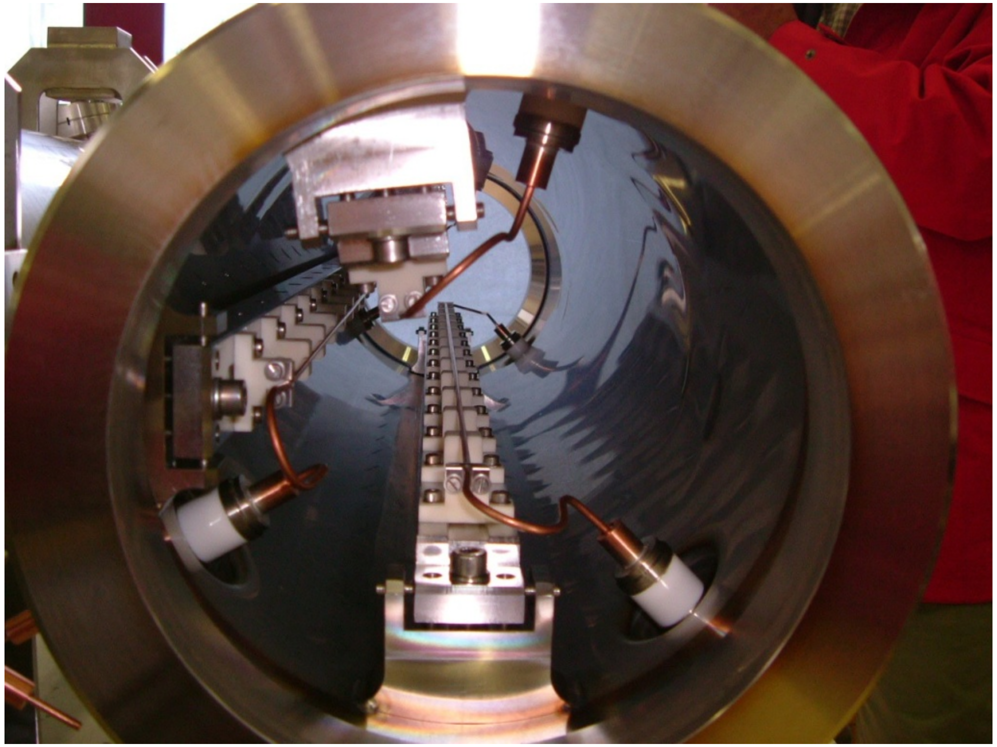
- 2x3 increase during LHC ramp (SPS example)
- inject max. charge permitted by heat&stabil.
  $N_{b,max}$ ~2.3×10^{11} → **factor 3 gain in *L*;**
  larger aperture in final focus needed

collision schemes

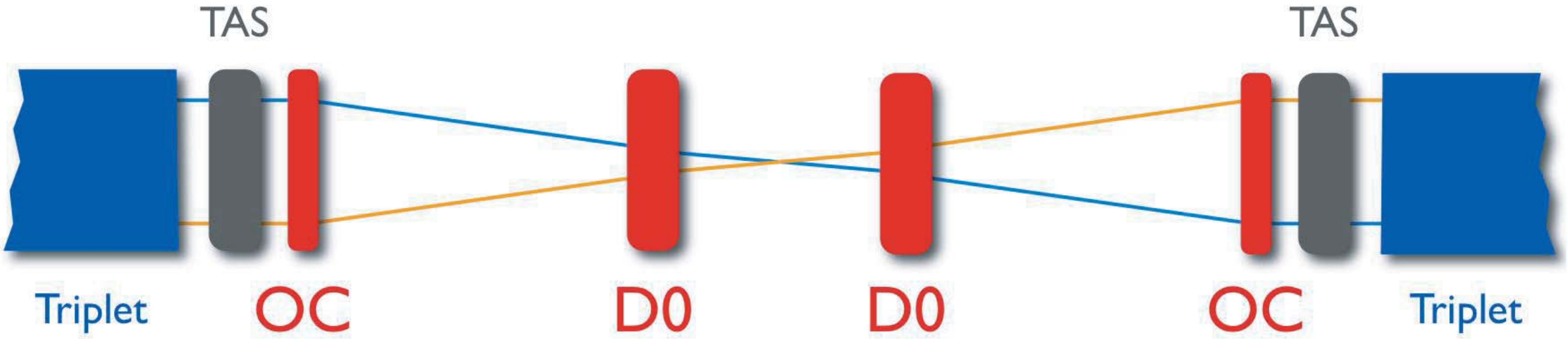
address drop in F for smaller β^*

- **long-range beam-beam compensation**
  - robust in simulations, effective in SPS beam experiments
  - allows for reduced crossing angle
- **"Large Piwinski Angle" (LPA) scheme**
  - exploits concomitant drop in beam-beam tune shift to increase the bunch charge
- **"Early Separation (ES) scheme**
  - aims at decoupling IP crossing angle from beam-beam separation in common sections by installing dipoles inside the detectors
  - dynamical control of crossing angle → simple leveling
- **crab crossing**
  - similar effect as ES, no magnets inside detector
  - under test at KEKB

photo of prototype LR beam-beam compensator in the SPS



layout of early separation scheme



G. Sterbini

heat load from collision debris

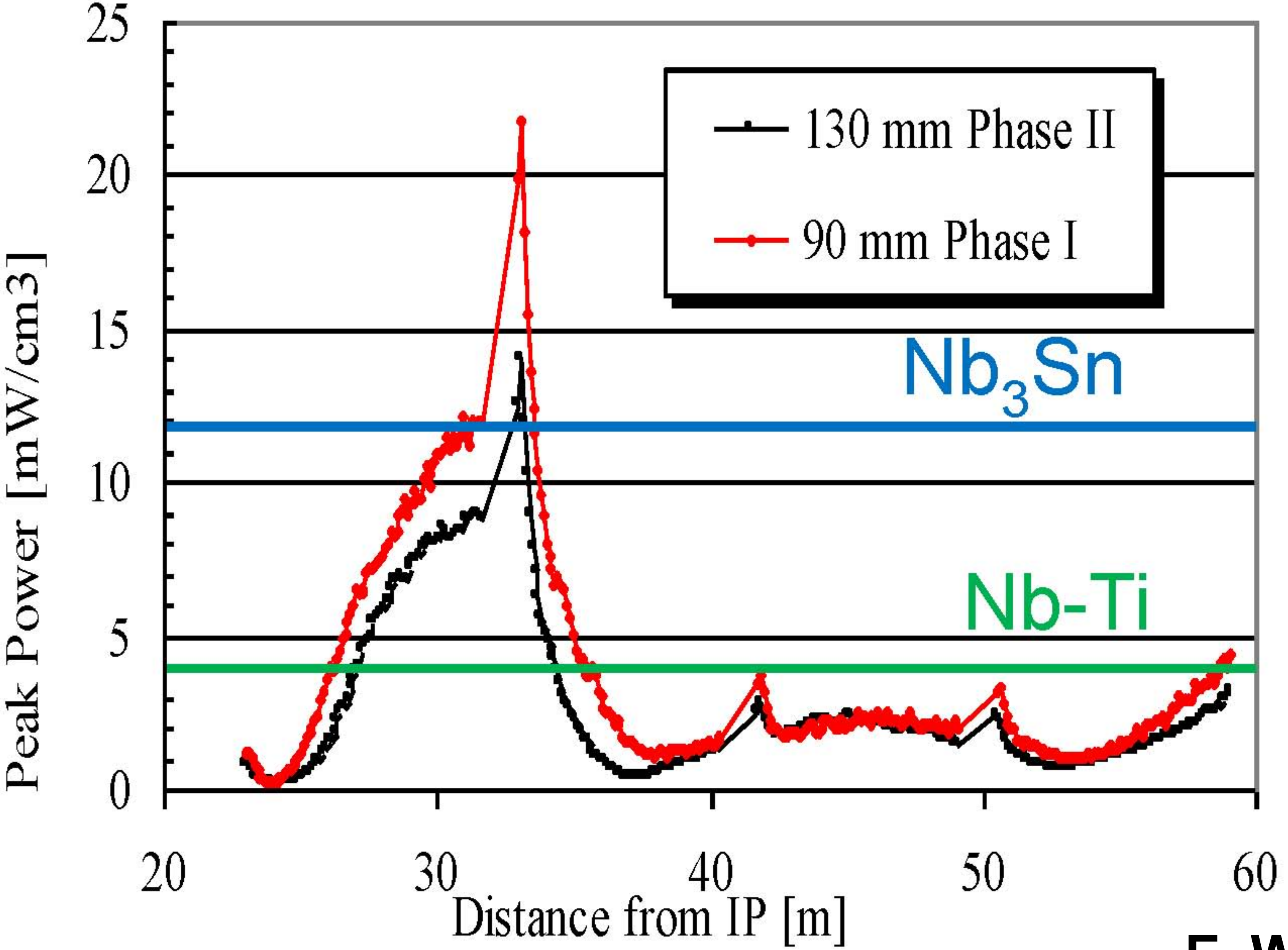
10-fold increase in luminosity would bring the nominal triplets well above their **quench limit** and reduce their **lifetimes** to below 1 year

LHC upgrade requires drastic actions

ongoing studies clarify importance of parameters like **quadrupole inner aperture and length**, and the efficiency of inner shielding from stainless steel or tungsten

larger aperture and shorter triplets made possible by **Nb_3Sn technology** are an advantage; Nb_3Sn can accept 3 times higher heat deposition than *NbTi*

peak power deposition in the coil



E. Wildner

machine protection

energy stored in each nominal LHC beam = 400 MJ
(100x Tevatron)

upgrade requires further increase by factor 2-3; appears moderate compared with step from Tevatron to nominal

tighter beam control required

irregular asynchronous beam dump requires provisions to be included in **next collimation phase**

beam dump upgrade for higher intensity: reduced carbon density; increased sweep length of dilution system

no fundamental obstacle

K.-H. Mess, R. Assmann
B. Goddard, HHH-2004

luminosity leveling

expected very fast decay of luminosity (few hours) dominated by proton burn off in collisions

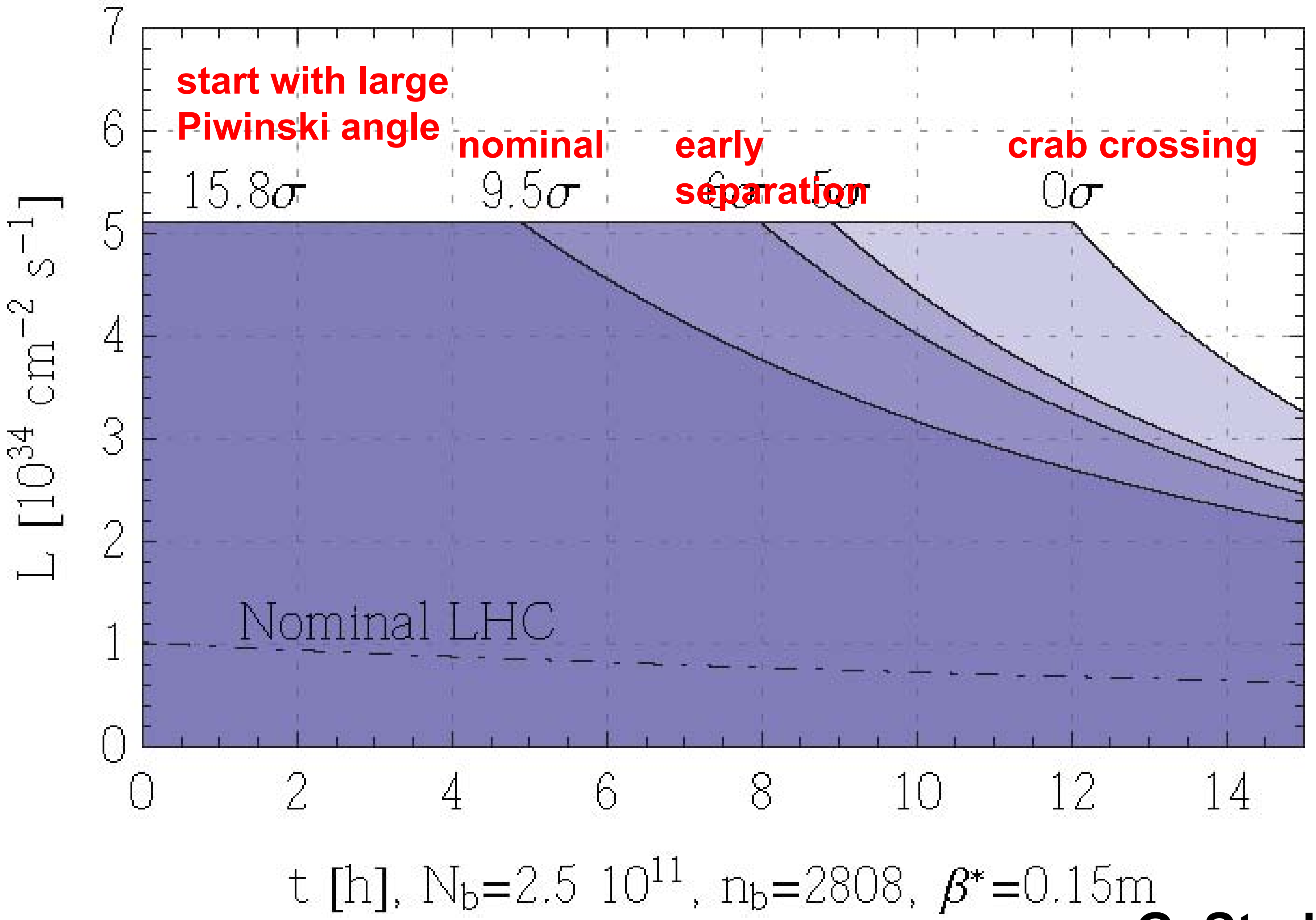
luminosity leveling become powerful strategy to reduce event pile up in the detector & peak power deposited in IR magnets

leveling with crossing angle has distinct advantages:

- increased average luminosity if beam current not limited
- operational simplicity

natural option for early separation or crab cavities

luminosity leveling with crossing angle



start with large Piwinski angle

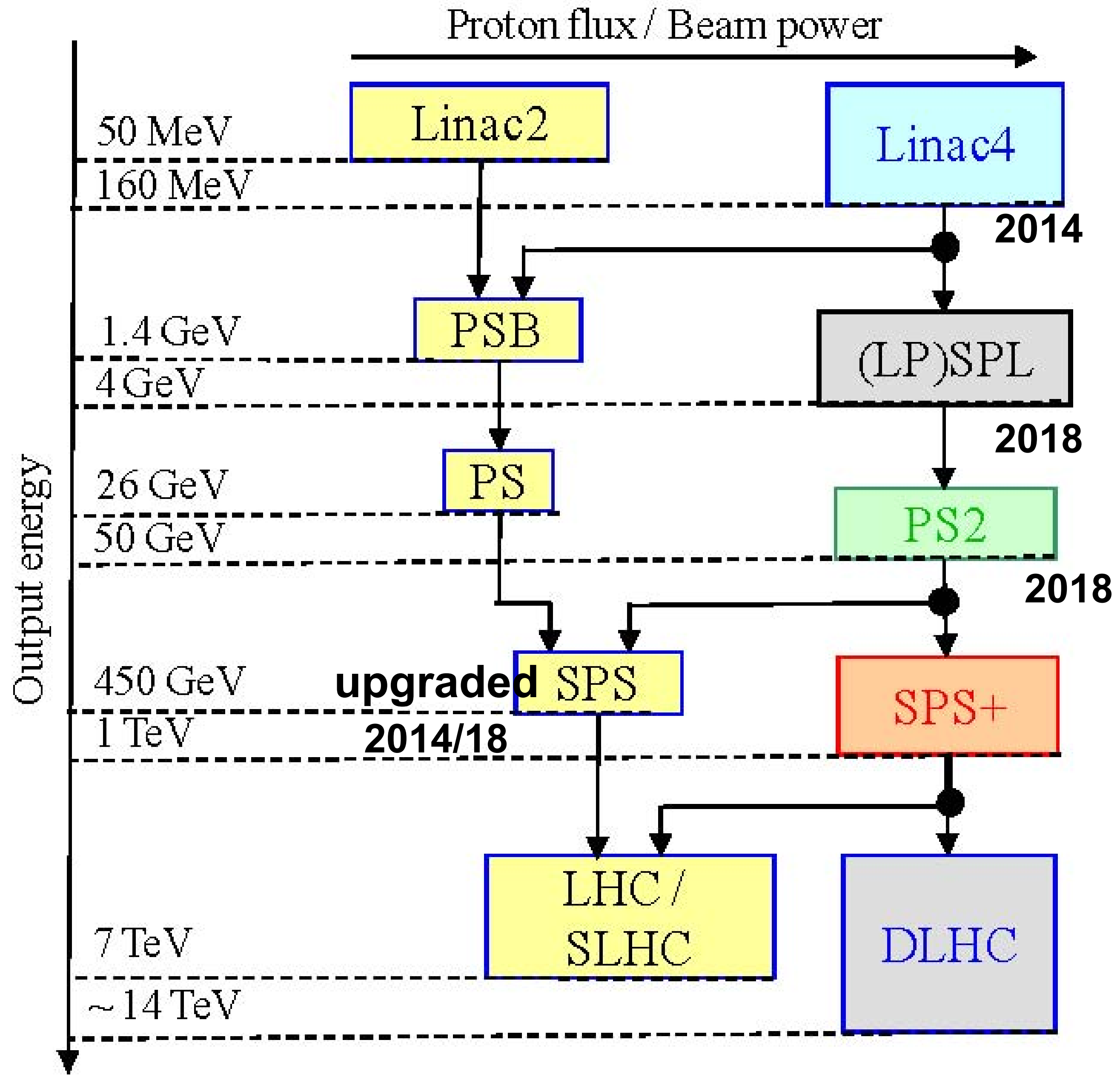
nominal

early separation

crab crossing

G. Sterbini

CERN complex upgrade strategy



new injectors:
increased reliability
&
superior beam parameters

synchronized with LHC IR upgrades:

phase I: 2014
phase II: 2018

R. Garoby

implementation plan for Upgrade Phase I

- **new Nb-Ti quadrupole triplets** with larger aperture, new separation dipoles, new front quadrupole absorber (TAS)
- may allow reaching **$\beta^* \sim 0.25$ m in IP1 and 5**
- beam from **new Linac4**, readily providing the **"ultimate" bunch charge $N_b \sim 1.7 \times 10^{11}$**
- should be completed by **2014**

implementation plan for Upgrade Phase II

- **two new injector accelerators: SPL and PS2**, providing 2x ultimate beam brightness at 25 ns bunch spacing
- new interaction region; promising option: **Nb_3Sn triplet** with larger aperture providing $\beta^*\sim15$ cm
- **complementary measures**: long-range beam-beam compensation, crab cavities?, dipoles inside detector?, “electron lenses”??
- realized around **2018**

example Phase-II scenarios

- early separation (ES)

  β^*~0.1 m, 25 ns, N_b=1.7x10^{11},
  detector embedded dipoles
- full crab crossing (FCC)

  β^*~0.1 m, 25 ns, N_b=1.7x10^{11},
  local and/or global crab cavities
- large Piwinski angle (LPA)

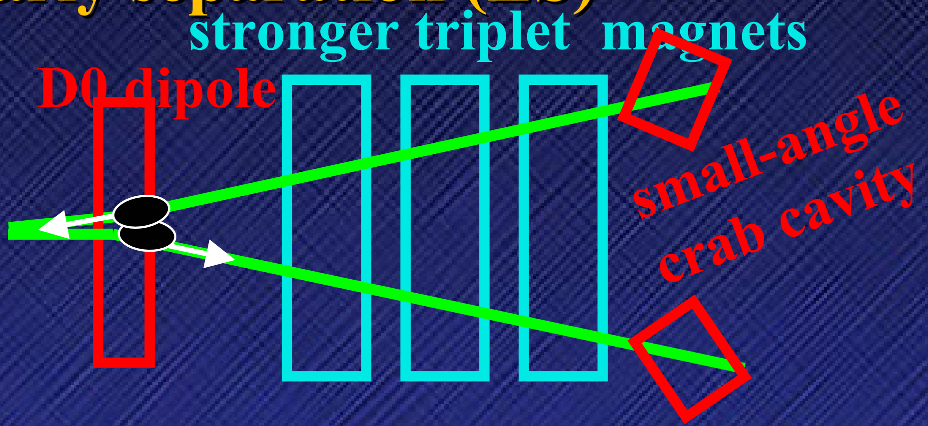
  β^*~0.25 m, 50 ns, N_b=4.9x10^{11},
  "flat" intense bunches
- low emittance (LE)

  β^*~0.1 m, 25 ns, $\gamma\varepsilon$~1-2 μm, N_b=1.7x10^{11}

example phase-II IR layouts

early separation (ES)

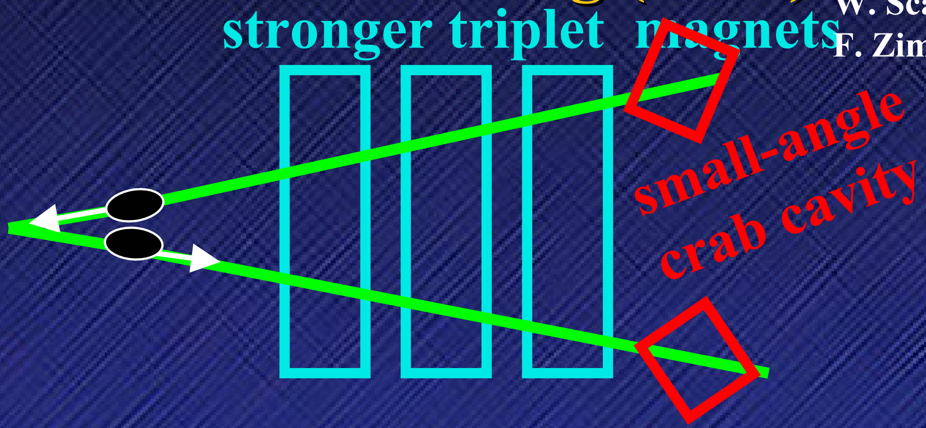
J.-P. Koutchouk



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

full crab crossing (FCC)

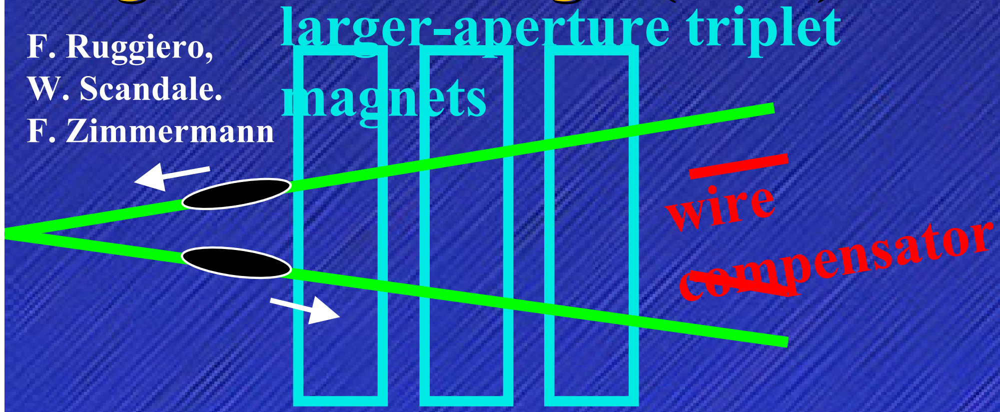
L. Evans,
W. Scandale,
F. Zimmermann



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

large Piwinski angle (LPA)

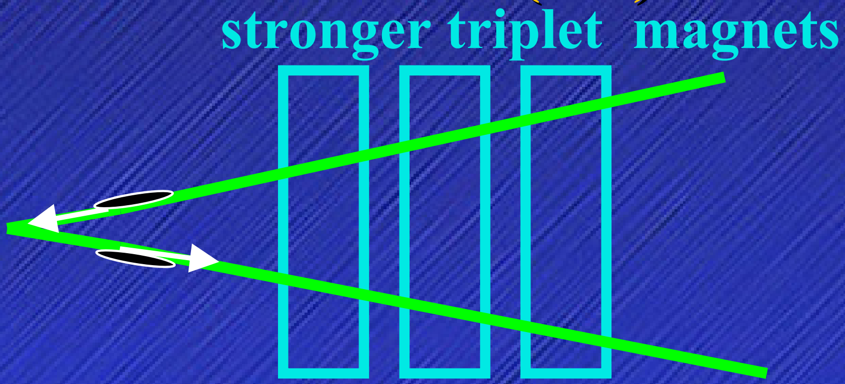
F. Ruggiero,
W. Scandale.
F. Zimmermann



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

low emittance (LE)

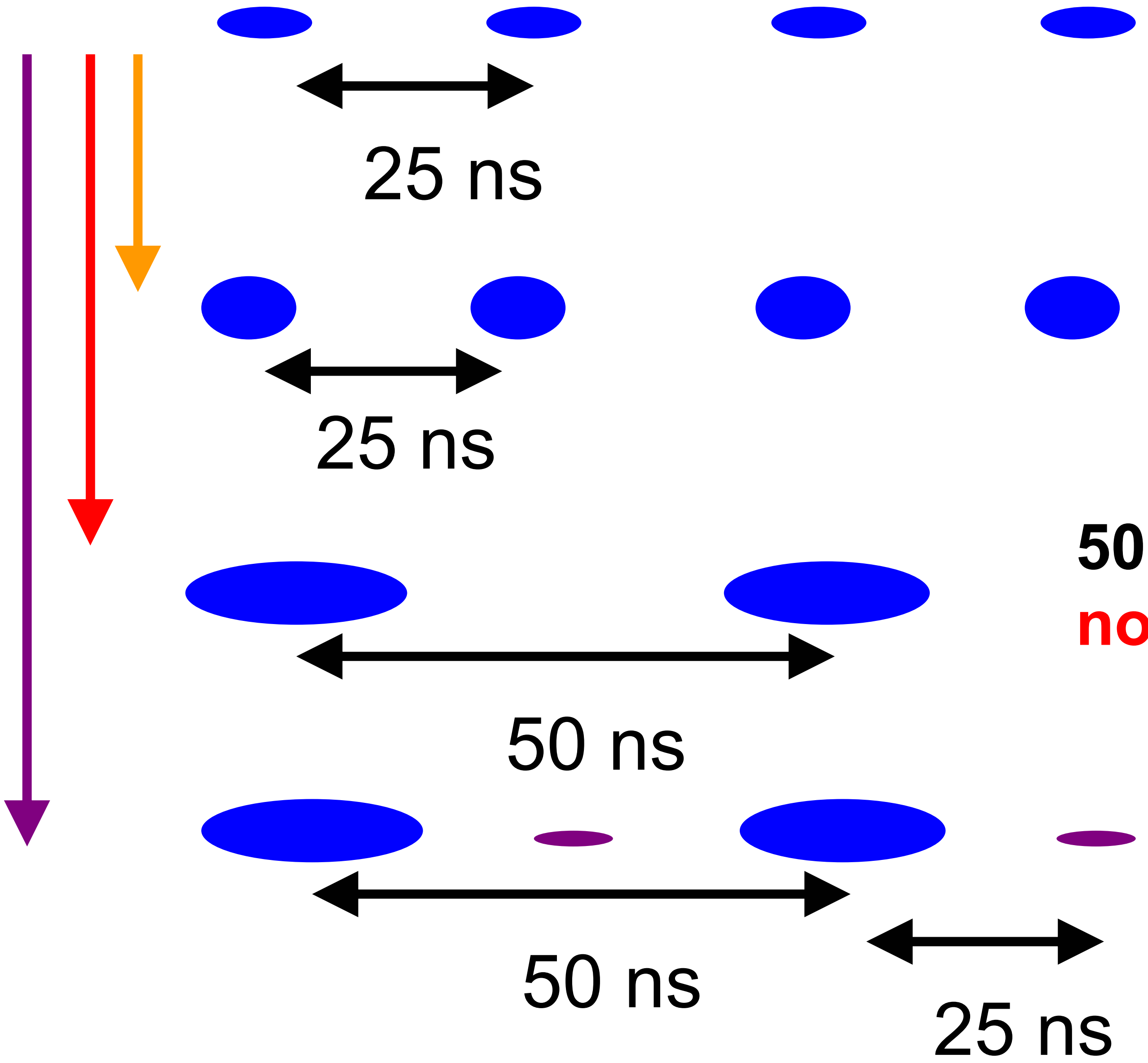
R. Garoby



- 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)
extent luminous region	σ_l [cm]	4.5	4.3	3.7	3.7	1.6	5.3
comment		nominal	ultimate	D0 + crab	crab		wire comp.

upgrade bunch patterns



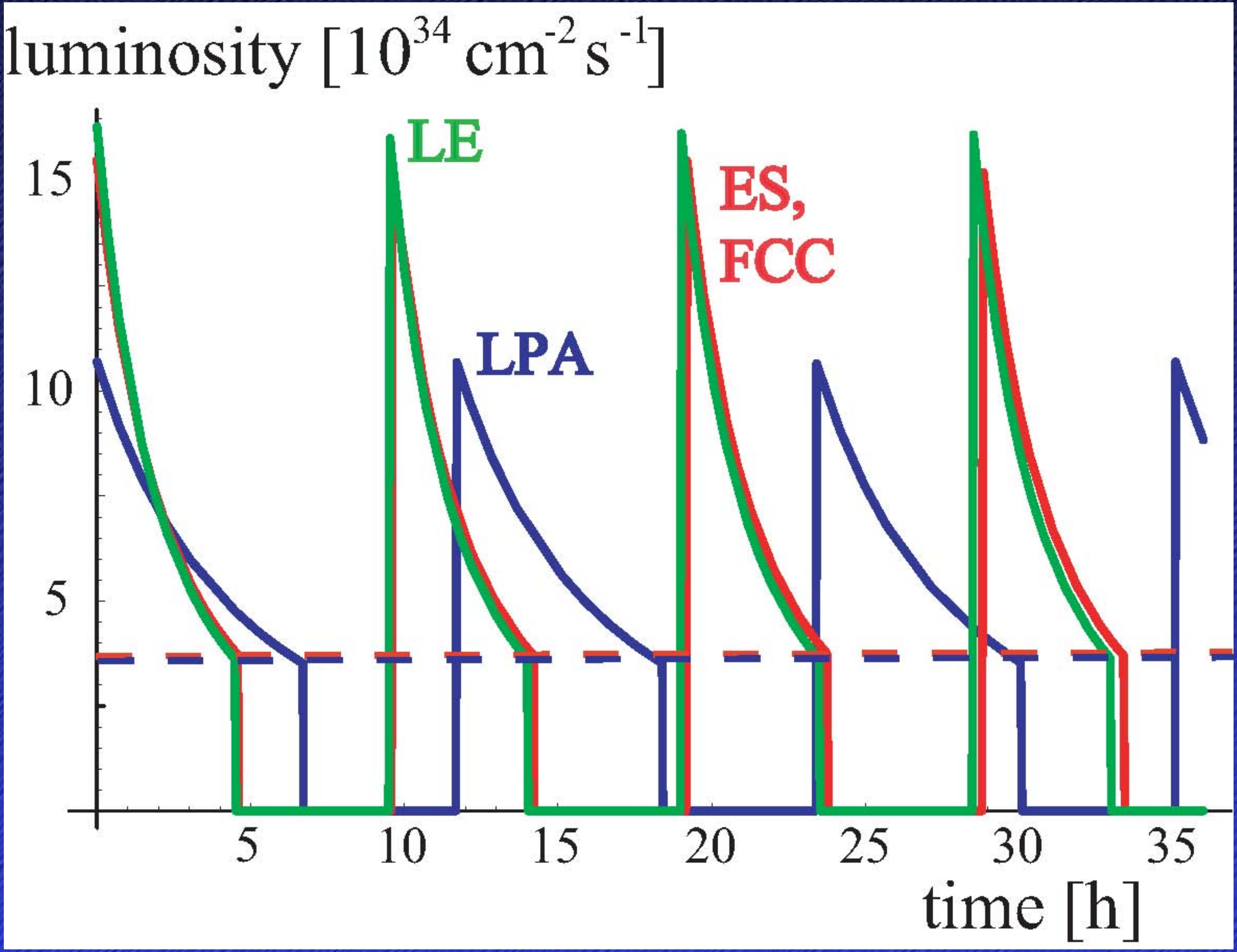
nominal

ultimate
& 25-ns upgrade
(ES, FCC, & LE)

50-ns upgrade (LPA),
no collisions in LHCb?

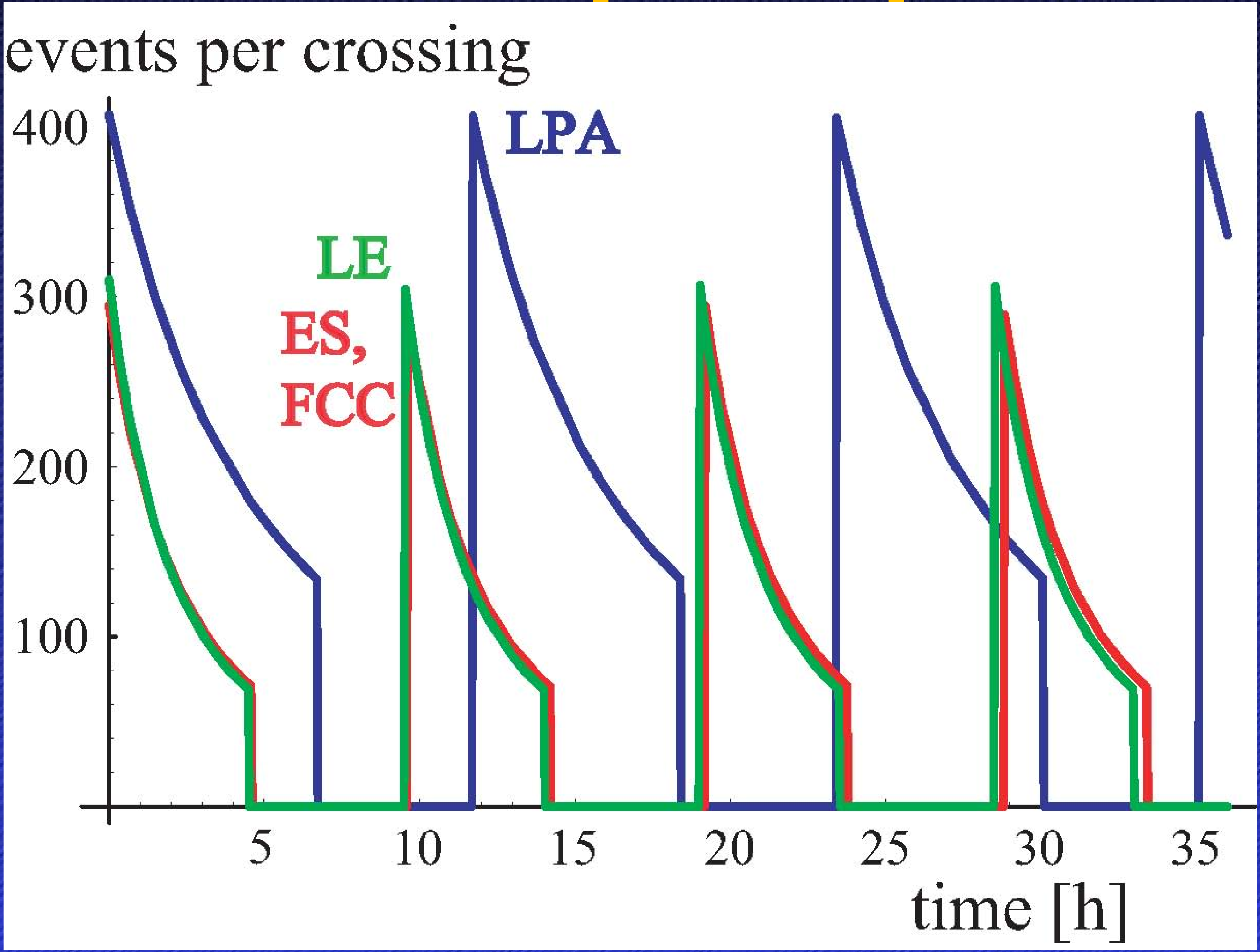
50-ns upgrade
with 25-ns
collisions
in LHCb

luminosity evolution

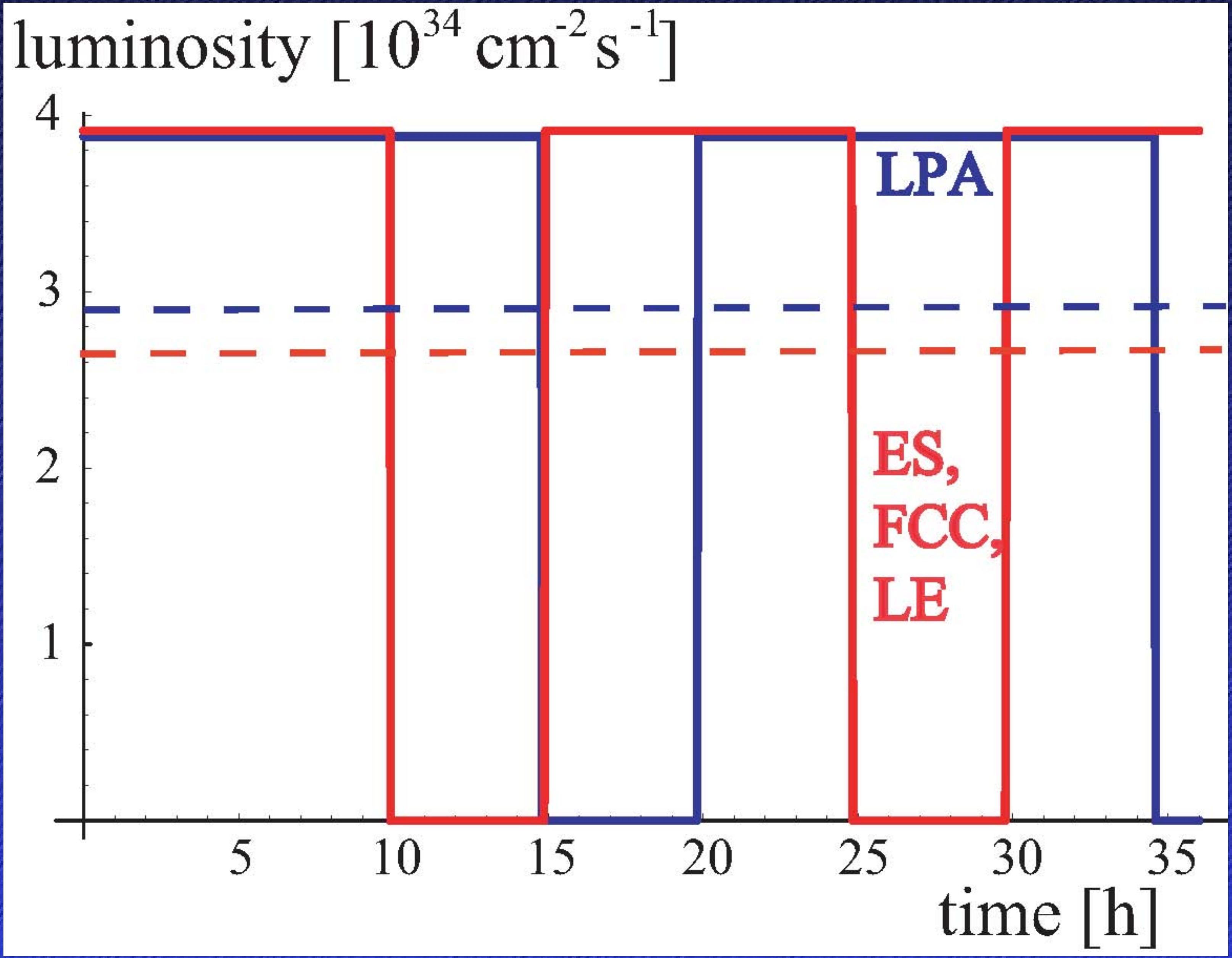


average luminosity

event pile up

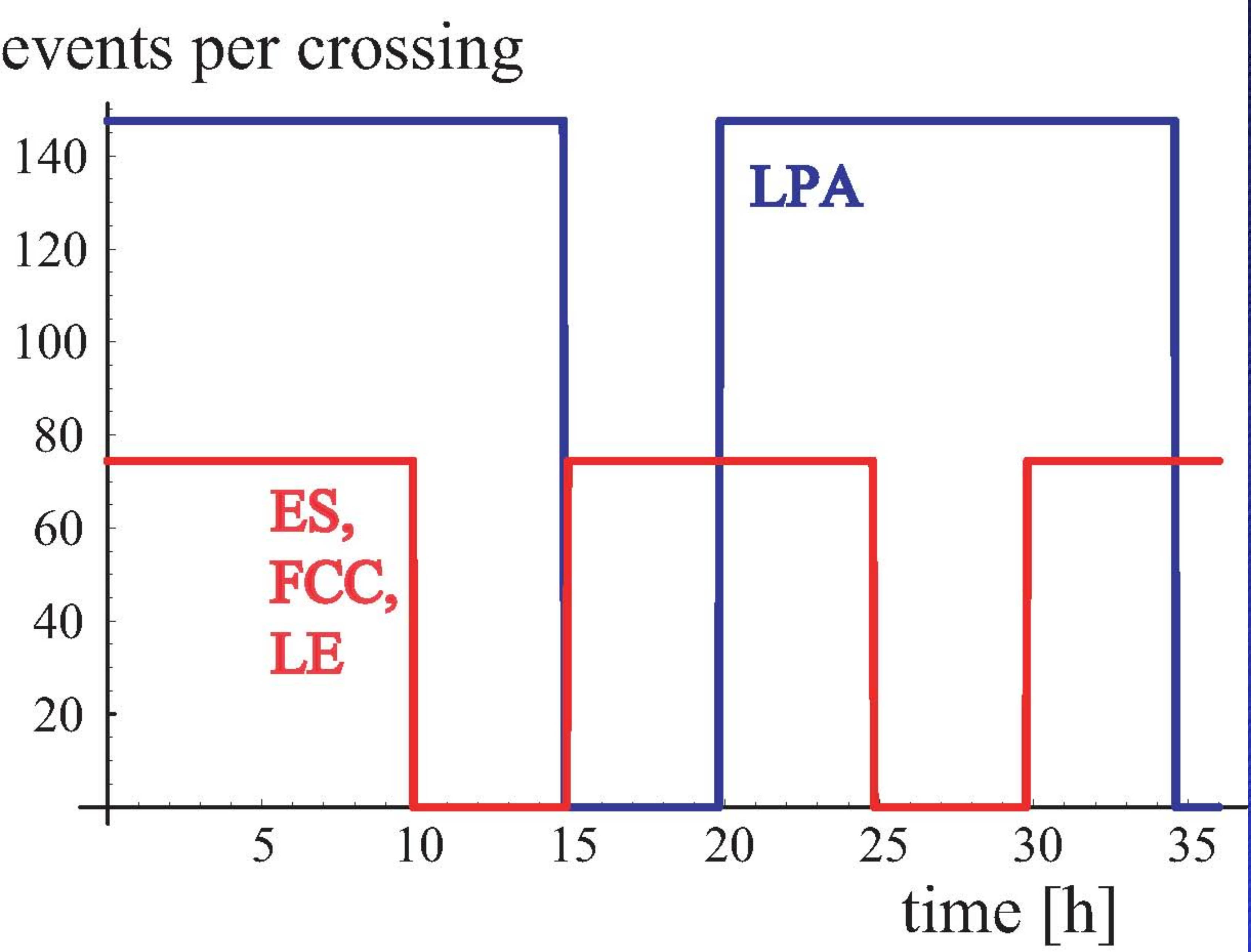


luminosity with leveling



average luminosity

event pile up with leveling



conclusions

several LHC upgrade schemes could raise peak & average **luminosity 10x beyond nominal**.

larger-aperture Nb_3Sn triplet quadrupoles benefit all options → risk mitigation & safe upgrade approach.

rejuvenation of CERN injector complex will lead to beams of **higher brightness**, improve overall **reliability**, **minimize turnaround** time, raise **integrated luminosity**, and increase **flexibility**.

concomitant upgrade of the LHC collimation system appears critical, whether for larger beam current or larger transverse density.

luminosity leveling becomes powerful strategy

acknowledgements

many accelerator physicists and engineers contributed to LHC upgrade studies since 2001

environment set by **CARE-HHH** and **US-LARP** was especially Profitable

special thanks to **R. Assmann, P. Chiggiato, S. Fartoukh, E. Métral, E. Shaposhnikova, G. Sterbini**, who helped putting together this summary

32 workshops
156 documents

CARE

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CARE – HHH 2004 - 2008
High energy High intensity Hadron beams