LHC Upgrade Scenarios

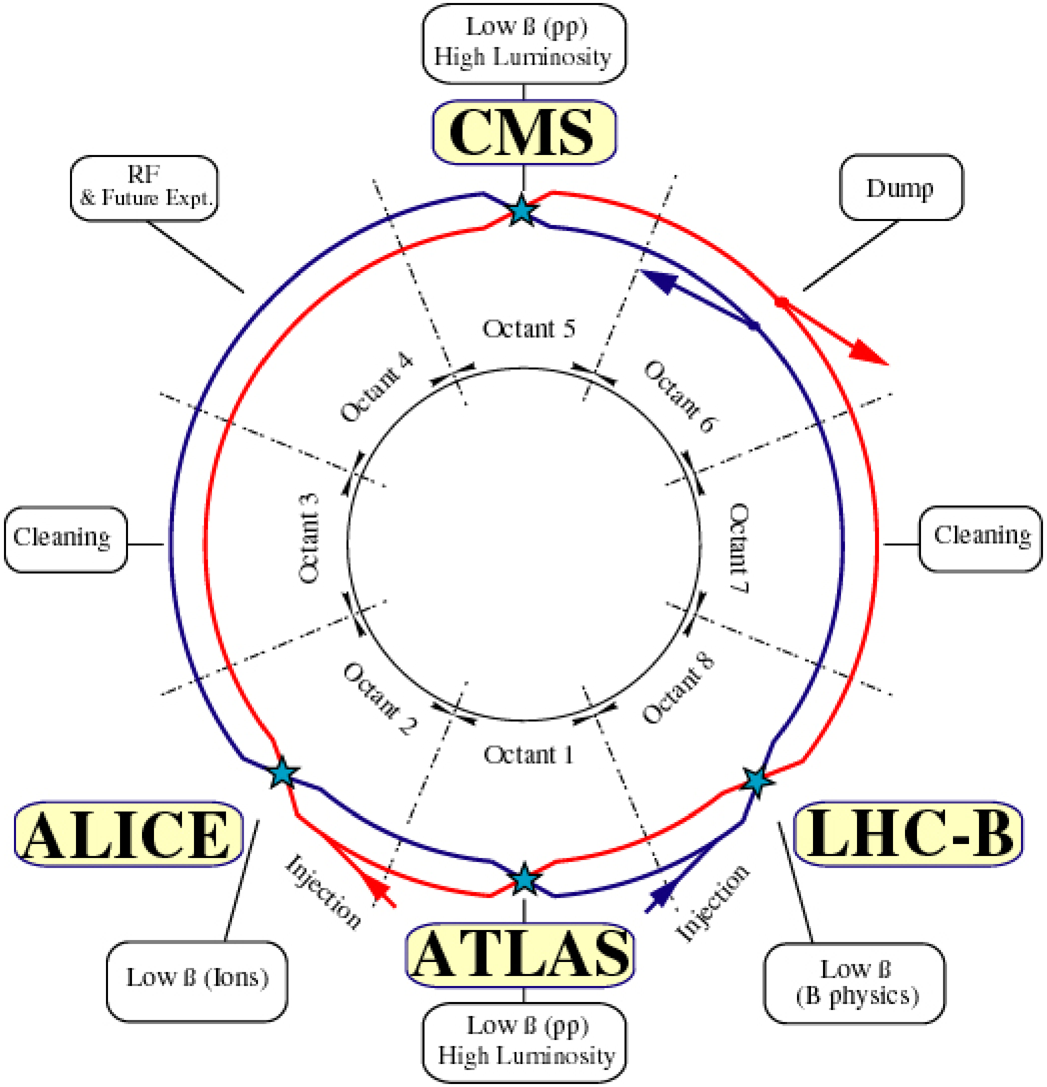
Frank Zimmermann

PAC 2007
Albuquerque

thanks to many colleagues from CERN and around the world, in particular to Walter Scandale and Jean-Pierre Koutchouk

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395)

Large Hadron Collider (LHC)



proton-proton collider

next energy-frontier discovery machine

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

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

start of beam commissioning in 2008

LHC baseline luminosity was pushed in competition with SSC

outline

performance challenges
players & schedule
two scenarios
- beam parameters; features; IR layouts
- merits and challenges;
- luminosity evolution

luminosity leveling
bunch-structure
injector upgrade
energy upgrade
conclusions

three LHC challenges

- **collimation & machine protection**

  - quenches, cleaning efficiency, impedance

    → LHC machine protection system: TUZAC03, R. Schmidt et al

    → performance reach of LHC phase-1 collimation system: TUPAN100, G. Robert-Demolaize et al

    → transverse collimator impedance: WEOAC03, E. Metral et al

    → LHC impedance reduction by nonlinear collimation TUPAN085, J. Resta Lopez et al

- **electron cloud**

  - heat load, instabilities, emittance growth

    → improved e-cloud simulations: THPAN066, W. Bruns et al

    → incoherent e-cloud: THPAN075, F. Zimmermann et al

    → e-cloud in wigglers: TUPAS067, L. Wang et al

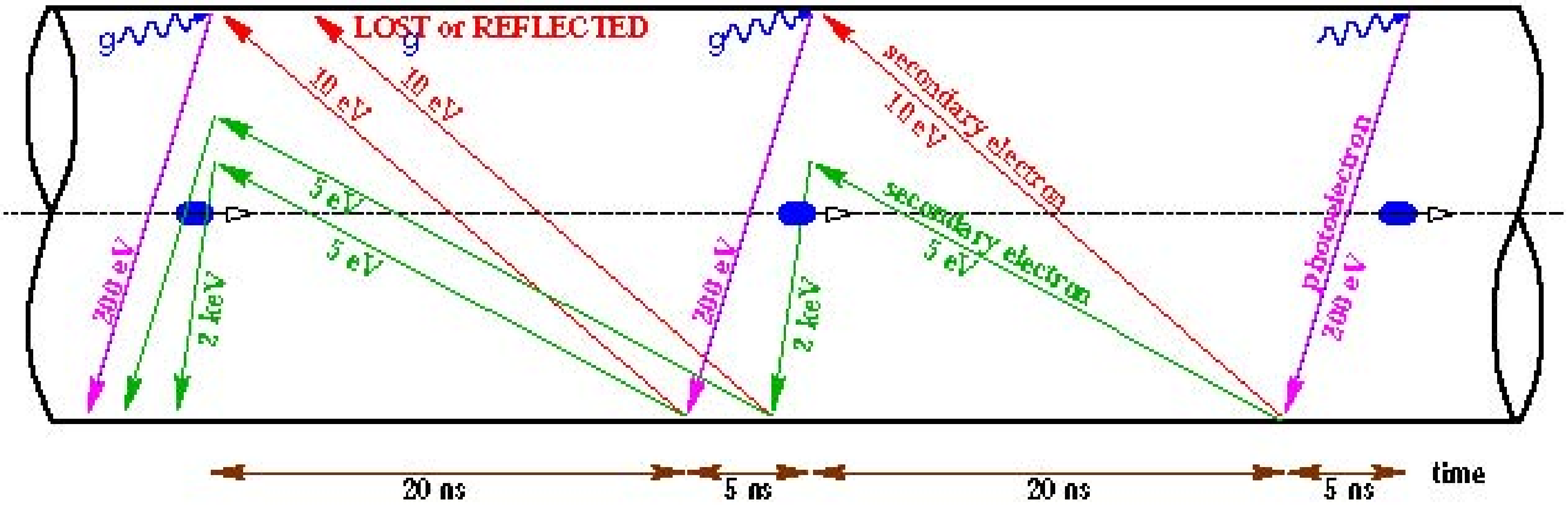
- **beam-beam interaction**

  - head-on, long-range, weak-strong, strong-strong

    → LHC beam-beam compensation: TUPAN091, U. Dorda et al

    → DC wire experiments in RHIC: TUPAS095, W. Fischer et al

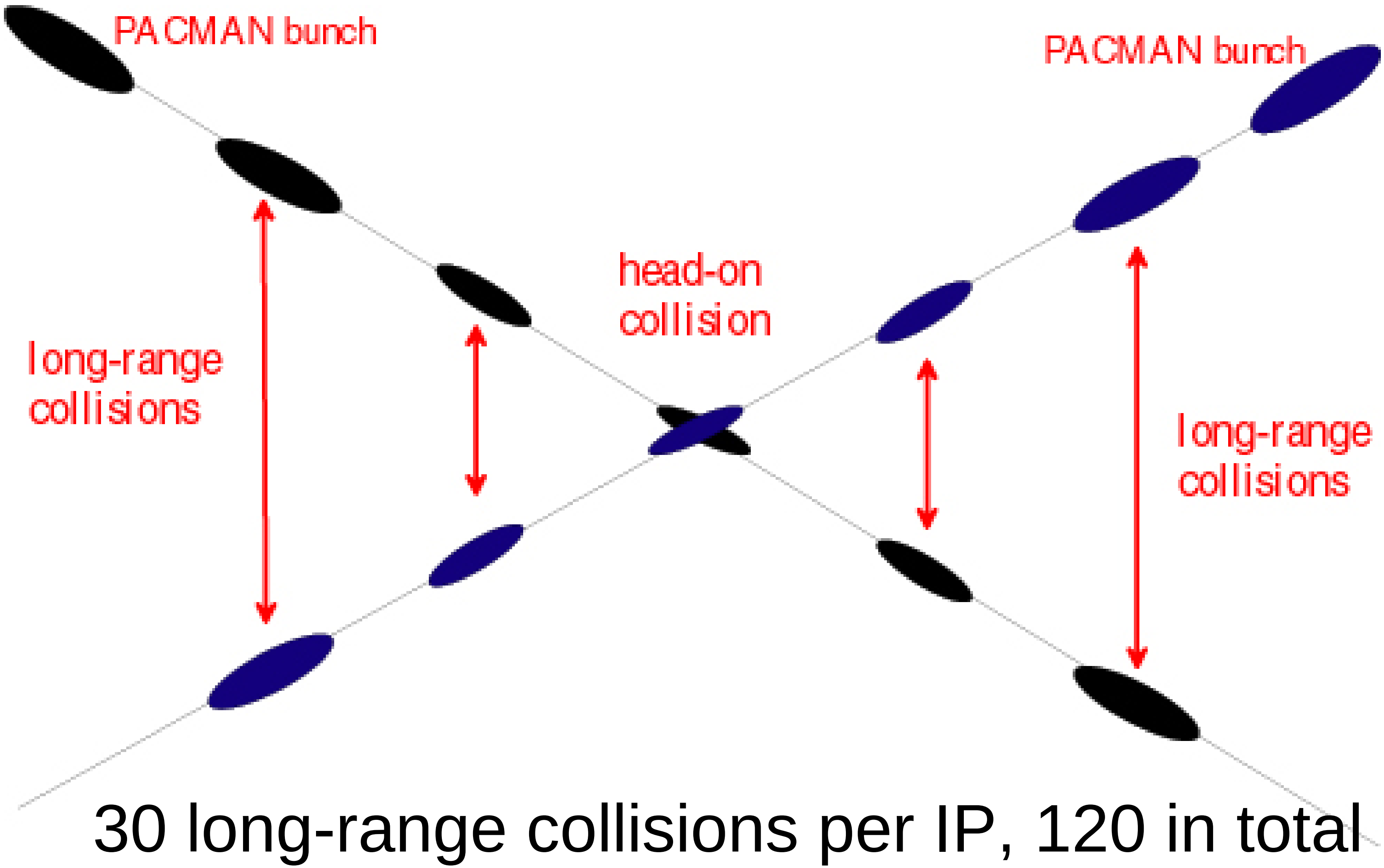
electron cloud in the LHC



schematic of e- cloud build up in the arc beam pipe, due to **photoemission** and **secondary emission**

[F. Ruggiero]

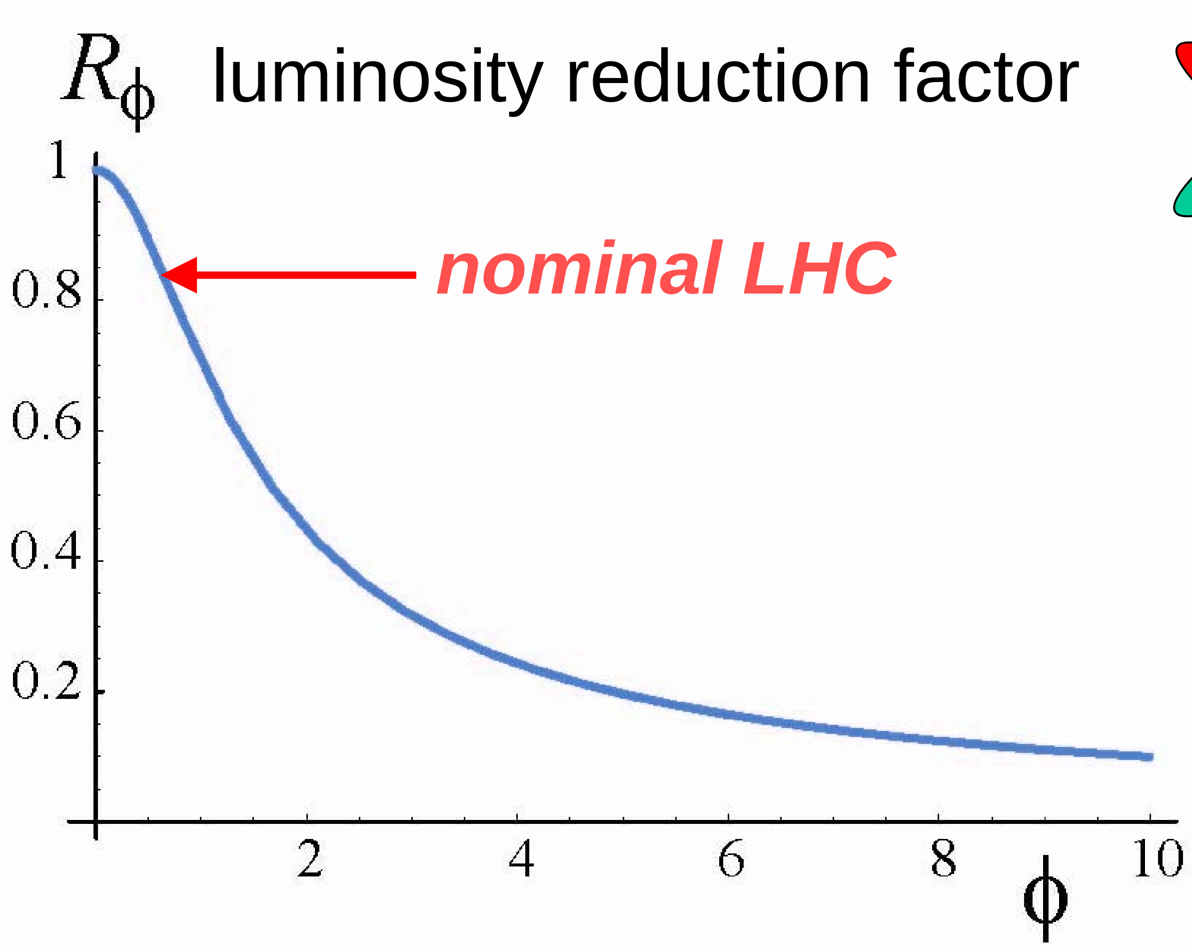
long-range beam-beam

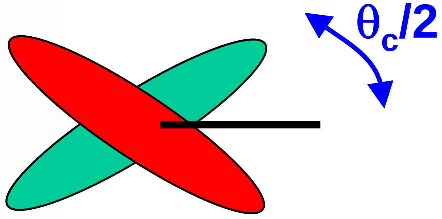


30 long-range collisions per IP, 120 in total

crossing angle

$$R_\phi = \frac{1}{\sqrt{1+\phi^2}}; \quad \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$ *"Piwinski angle"*





effective beam size $\sigma \rightarrow \sigma/R_\phi$

upgrade players

CARE

NED

CMS

LARP

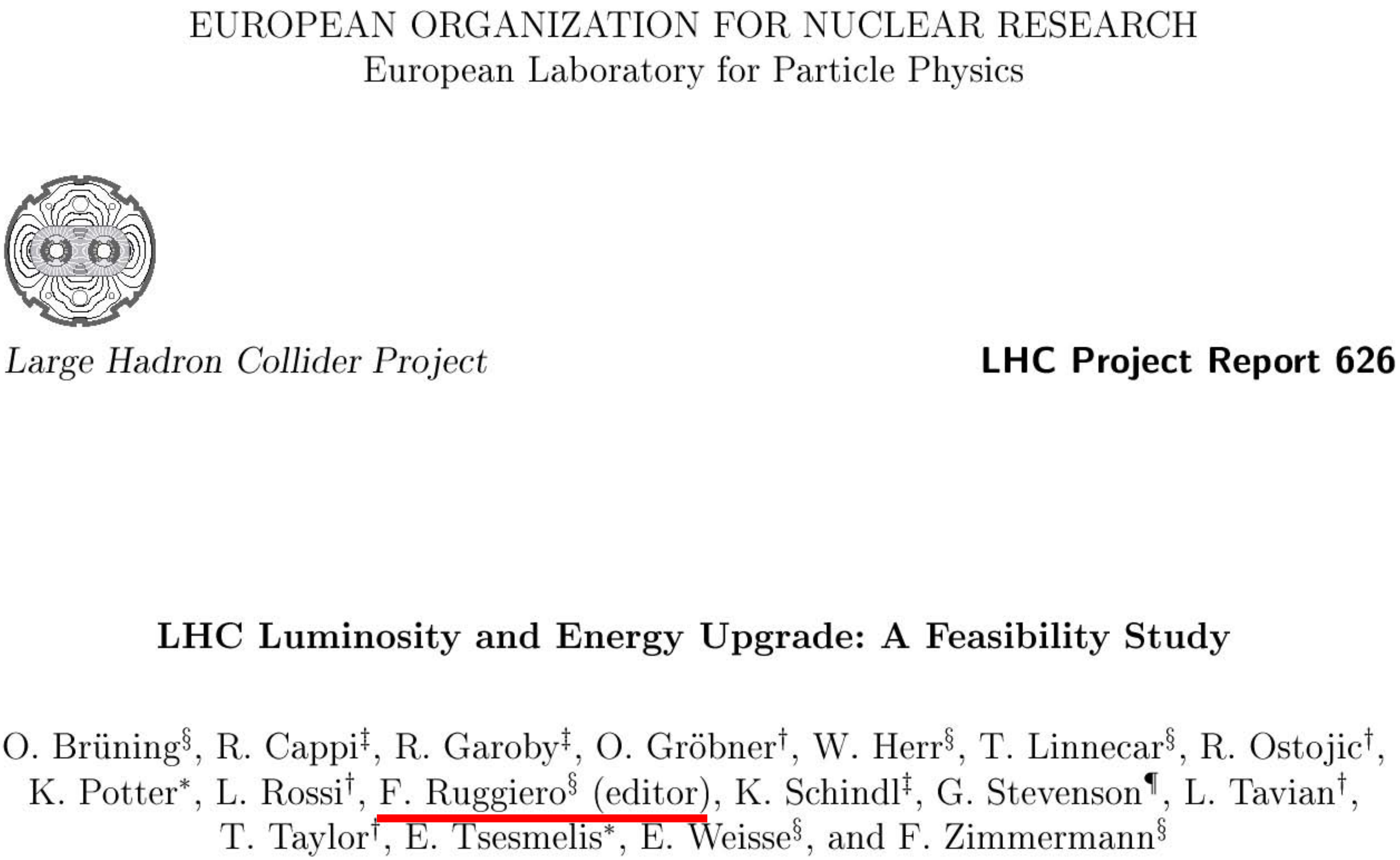
HHH

LHCb

ALICE

CERN Council Strategy Group

2001 upgrade feasibility study



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 626

LHC Luminosity and Energy Upgrade: A Feasibility Study

O. Brüning[§], R. Cappi[‡], R. Garoby[‡], O. Gröbner[†], W. Herr[§], T. Linnecar[§], R. Ostojic[†],
K. Potter[*], L. Rossi[†], F. Ruggiero[§] (editor), K. Schindl[‡], G. Stevenson[¶], L. Tavian[†],
T. Taylor[†], E. Tsesmelis[*], E. Weisse[§], and F. Zimmermann[§]

CARE-HHH workshops

ex. CARE-HHH APD workshop 'LUMI 06' (70 participants)

Towards a Roadmap for the Upgrade of the LHC and GSI Accelerator Complex

IFIC, Valencia (Spain), 16-20 October 2006

strong synergy with US-LARP mini collaboration meeting 25-27 Oct. 2006

IR scheme, beam parameters, injector upgrade

baseline upgrade parameters 2001-2005

parameter	symbol	nominal	ultimate	12.5 ns, short
transverse emittance	ε [μm]	3.75	3.75	~~3.75~~
protons per bunch	N_b [10^{11}]	1.15	1.7	~~1.7~~
bunch spacing	Δt [ns]	25	25	~~12.5~~
beam current	I [A]	0.58	0.86	~~1.72~~
longitudinal profile		Gauss	Gauss	~~Gauss~~
rms bunch length	σ_z [cm]	7.55	7.55	~~3.78~~
beta* at IP1&5	$\beta*$ [m]	0.55	0.5	~~0.25~~
full crossing angle	θ_c [μrad]	285	315	~~445~~
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.64	0.75	~~0.75~~
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	2.3	~~9.2~~
peak events per crossing		19	44	~~88~~
initial lumi lifetime	τ_L [h]	22	14	~~7.2~~
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.46	0.91	~~2.7~~
	$T_{run,opt}$ [h]	21.2	17.0	~~12.0~~
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.56	1.15	~~3.6~~
	$T_{run,opt}$ [h]	15.0	12.0	~~8.5~~
e-c heat SEY=1.4(1.3)	P [W/m]	1.07 (0.44)	1.04 (0.59)	~~13.34 (7.85)~~
SR heat load 4.6-20 K	P_{SR} [W/m]	0.17	0.25	~~0.5~~
image current heat	P_{IC} [W/m]	0.15	0.33	~~1.87~~
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.04 (0.38)	0.06 (0.56)	~~0.113 (1.13)~~
extent luminous region	σ_l [cm]	4.5	4.3	~~2.1~~
comment				~~partial wire c.~~

abandoned at LUMI'06

(SR and image current heat load well known)

total heat far exceeds max. local cooling capacity of 2.4 W/m

parameter	symbol	**Early Separation**	**Large Piwinski Angle**
transverse emittance	ε [μm]	3.75	3.75
protons per bunch	N_b [10^{11}]	1.7	4.9
bunch spacing	Δt [ns]	25	50
beam current	I [A]	0.86	1.22
longitudinal profile		Gauss	Flat
rms bunch length	σ_z [cm]	7.55	11.8
beta* at IP1&5	β* [m]	0.08	0.25
full crossing angle	θ_c [μrad]	0	381
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0	2.0
hourglass reduction		0.86	0.99
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	15.5	10.7
peak events per crossing		294	403
initial lumi lifetime	τ_L [h]	2.2	4.5
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	2.4	2.5
	$T_{run,opt}$ [h]	6.6	9.5
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	3.6	3.5
	$T_{run,opt}$ [h]	4.6	6.7
e-c heat SEY=1.4(1.3)	P [W/m]	1.04 (0.59)	0.36 (0.1)
SR heat load 4.6-20 K	P_{SR} [W/m]	0.25	0.36
image current heat	P_{IC} [W/m]	0.33	0.78
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.06 (0.56)	0.09 (0.9)
extent luminous region	σ_l [cm]	3.7	5.3
comment		**D0 + crab (+ Q0)**	**wire comp.**

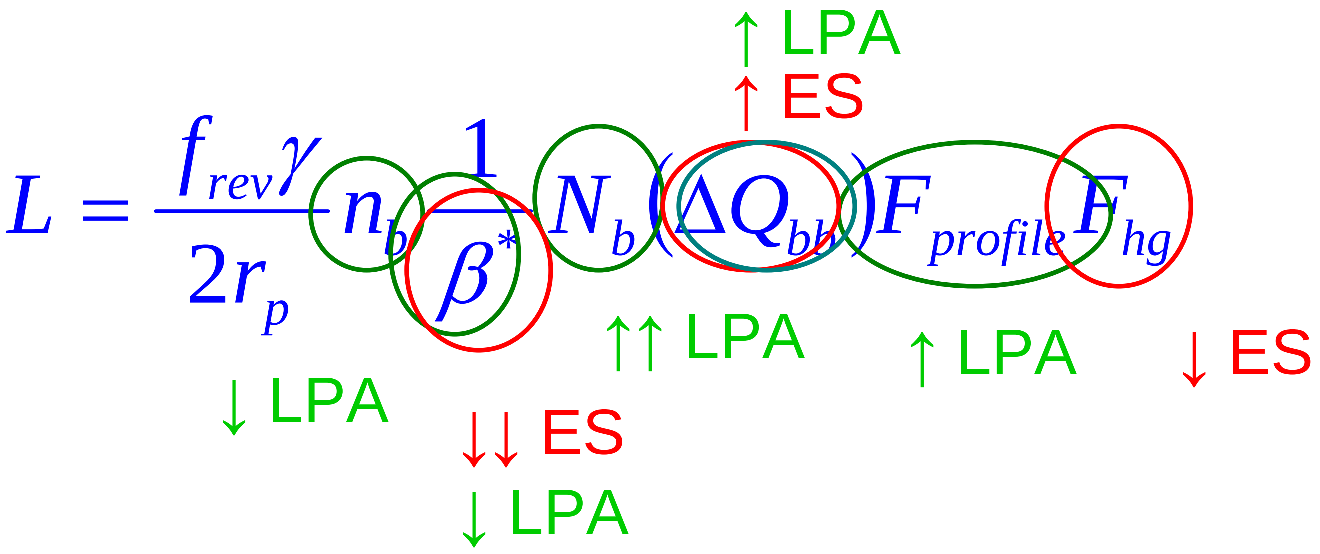
early separation (ES)

large Piwinski angle (LPA)

two new upgrade scenarios

compromises between heat load and # pile up events

for operation at beam-beam limit with alternating planes of crossing at two IPs



$$L = \frac{f_{rev}\gamma}{2r_p} n_b \frac{1}{\beta^*} N_b (\Delta Q_{bb}) F_{profile} F_{hg}$$

where (ΔQ_{bb}) = total beam-beam tune shift;

peak luminosity with respect to ultimate LHC:

ES: x 6 x 1.3 x 0.86 = 6.7

LPA: ½ x2 x2.9x1.3 x1.4 = 5.3

what matters is the integrated luminosity

early separation scenario

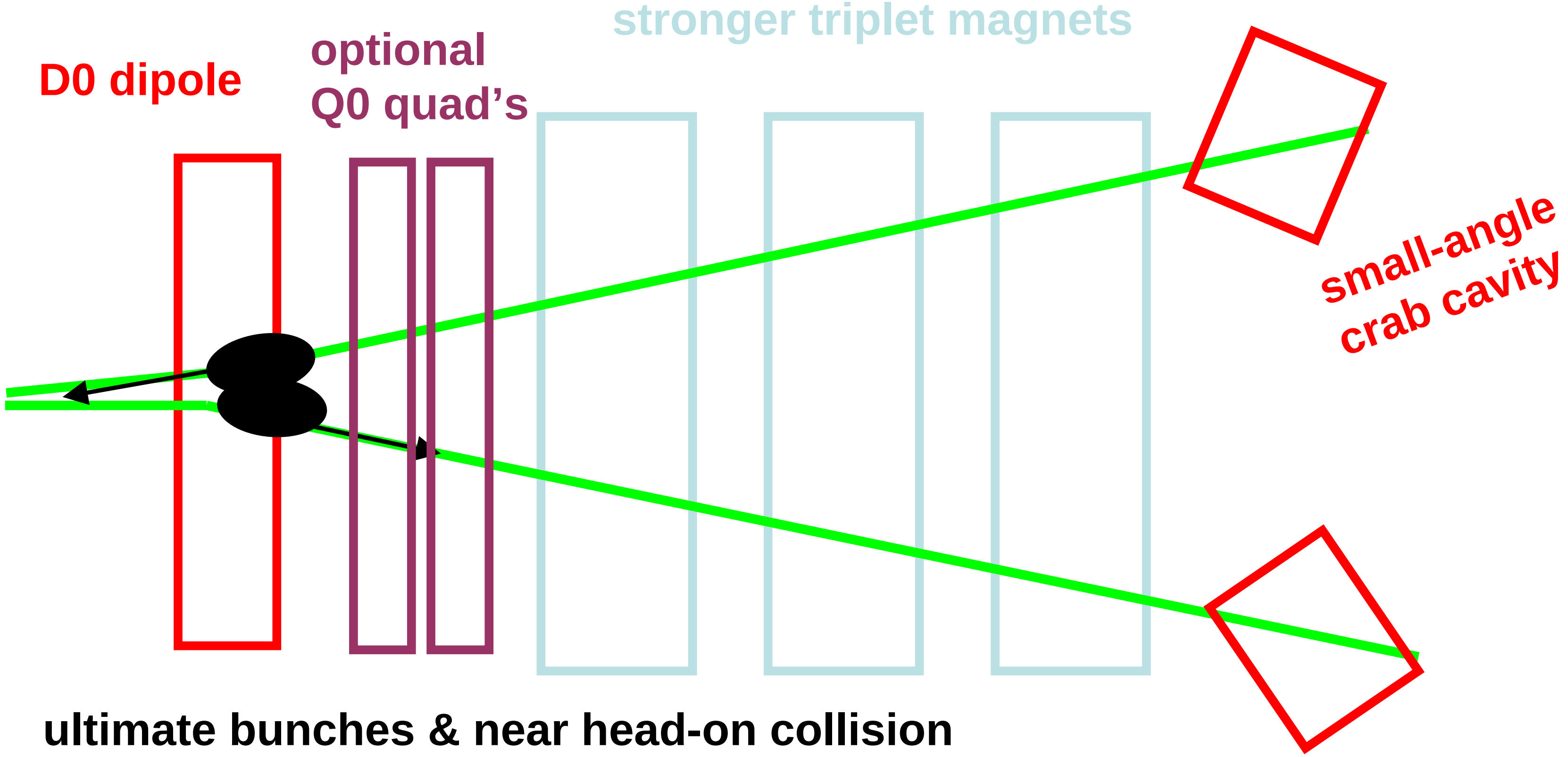
- stay with ultimate LHC beam (1.7×10^{11} protons/bunch, 25 spacing)
- squeeze β* to ~10 cm in ATLAS & CMS
- add early-separation dipoles in detectors starting at ~ 3 m from IP
- possibly also add quadrupole-doublet inside detector at ~13 m from IP
- and add crab cavities ($\phi_{\mathrm{Piwinski}} \sim 0$), and/or shorten bunches with massive addt'l rf

→ new hardware inside ATLAS & CMS detectors, first hadron-beam crab cavities

(J.-P. Koutchouk et al)

CMS & ATLAS IR layout for ES option

**→ ES scheme: THPAN072,
E. Todesco, J.-P. Koutchouk et al**


stronger triplet magnets

D0 dipole

**optional
Q0 quad's**

**small-angle
crab cavity**

ultimate bunches & near head-on collision

**→ Q0 doublet:
THPAN067 ,
E. Laface et al**

**→ LHC crab cavities;
TUPAN048, K. Ohmi et al
TUPAS089, R. Calaga et al**

ES scenario assessment

merits:

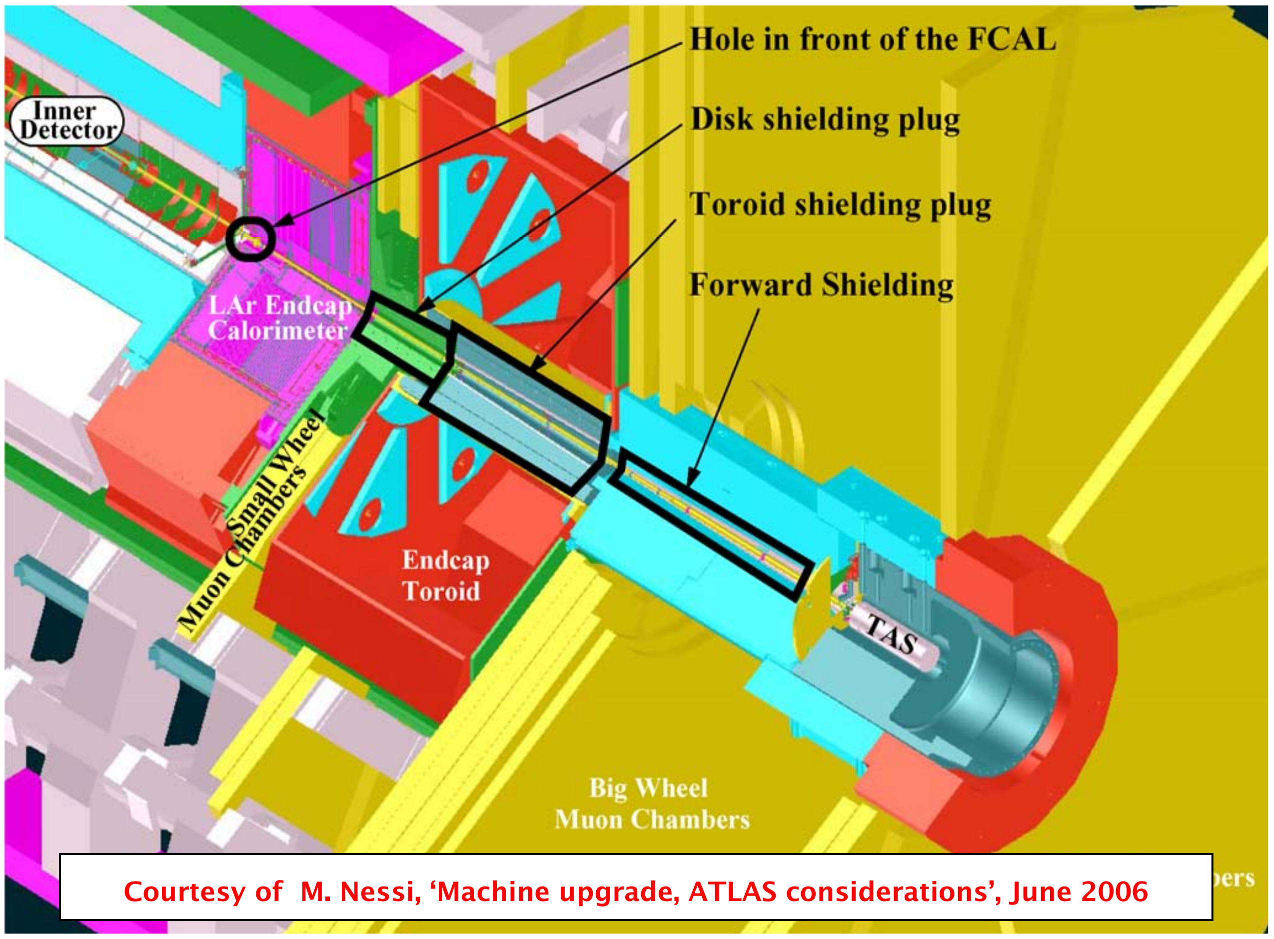
negligible long-range collisions,
no geometric luminosity loss,
no increase in beam current beyond ultimate,
could be adapted to crab waist collisions (LNF/FP7)

challenges:

D0 dipole deep inside detector (~3 m from IP),
optional Q0 doublet inside detector (~13 m from IP),
strong large-aperture quadrupoles (Nb_3Sn)
crab cavity for hadron beams (emittance growth),
or shorter bunches (requires much more RF)
4 parasitic collisions at 4-5σ separation,
off-momentum β beating 50% at δ=3x10^{-4} compromising
collimation efficiency,
low beam and luminosity lifetime ~β*

Are there slots for a “D0” dipole in ATLAS?

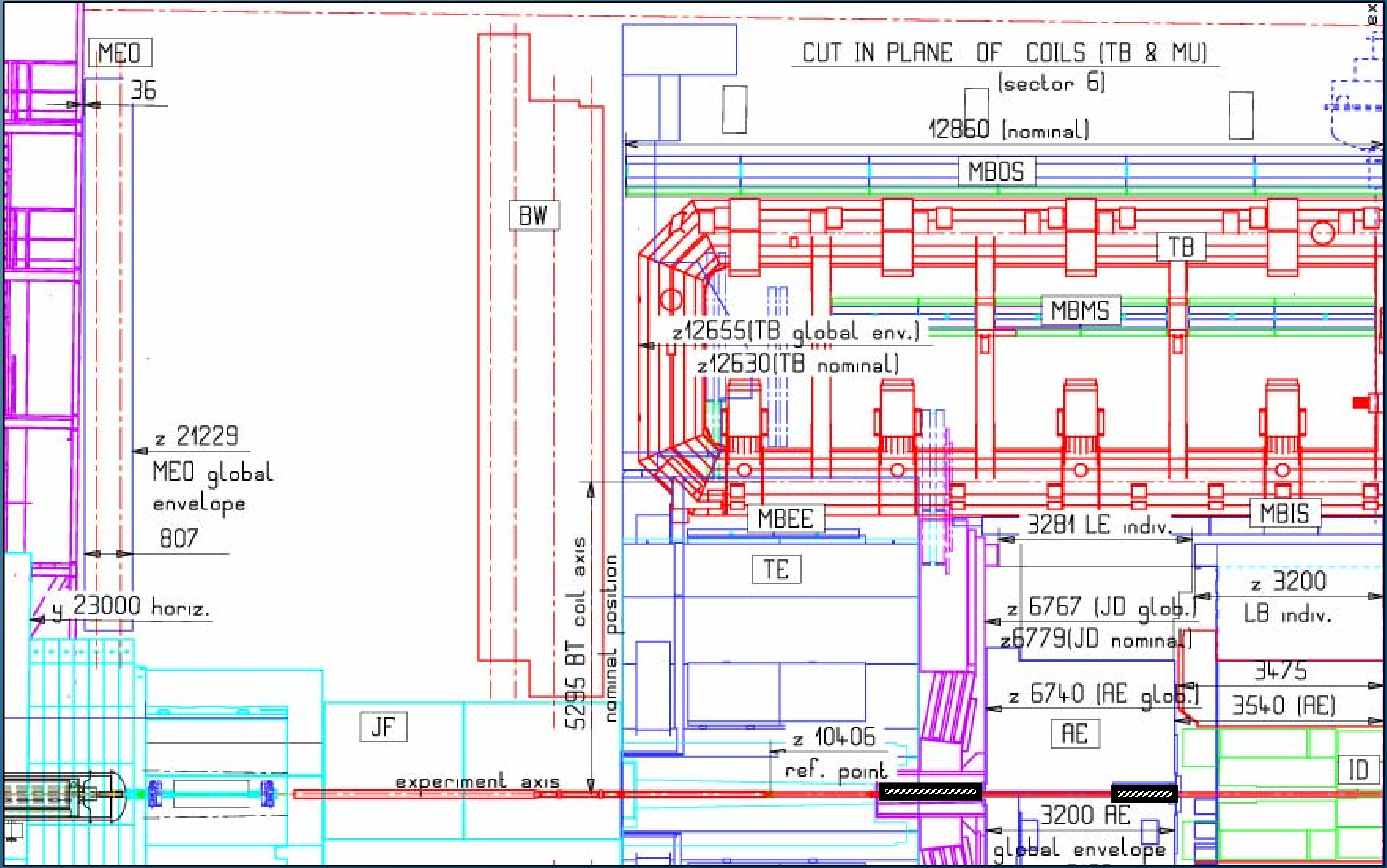
- We cannot put the D0 in the inner detector
- BUT there are potential slots starting at 3.5 m and 6.8 m (ATLAS)



Courtesy of M. Nessi, ‘Machine upgrade, ATLAS considerations’, June 2006

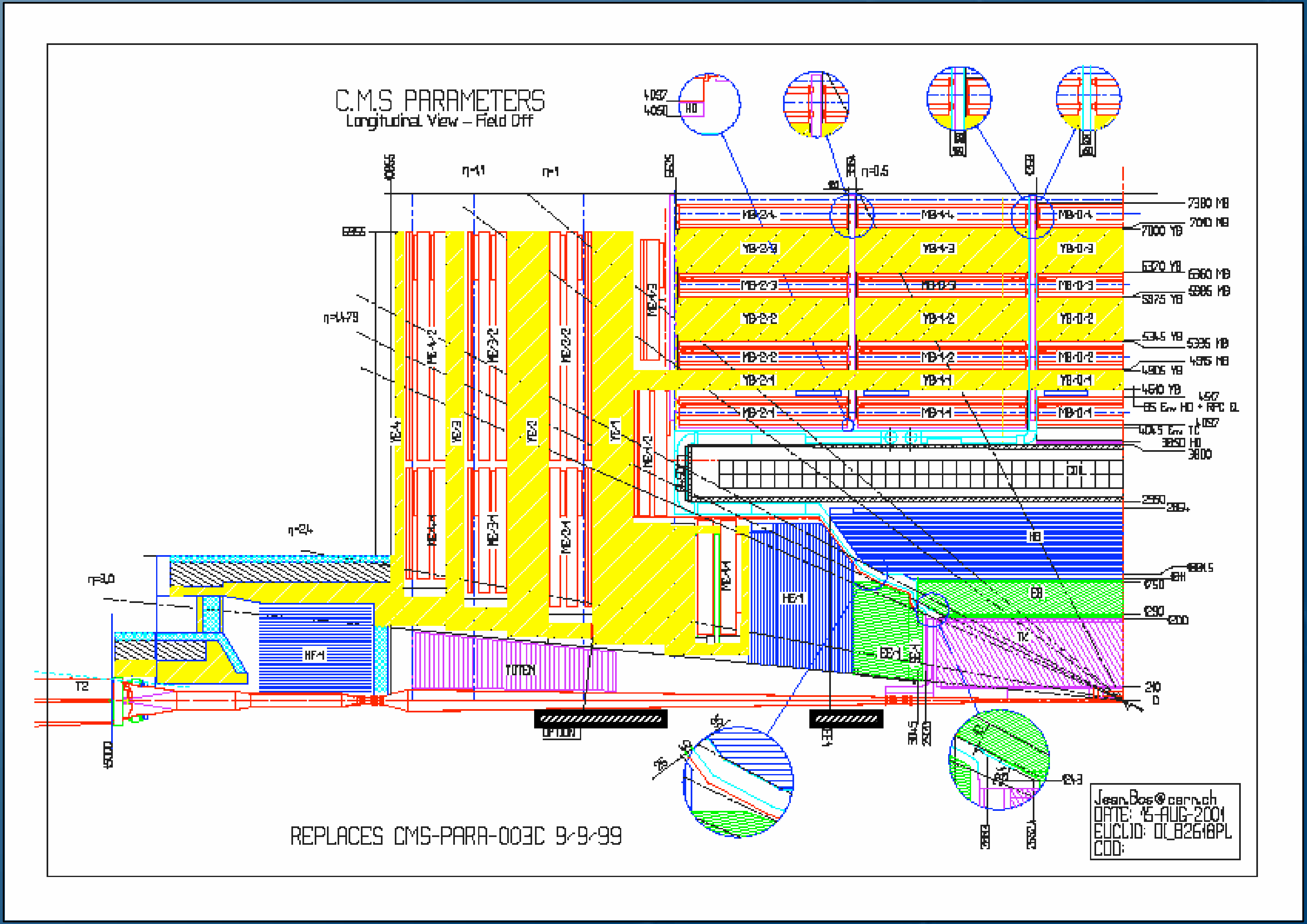
G. Sterbini,
J.-P. Koutchouk,
LUMI’06

Where would we put the D0 in ATLAS?



G. Sterbini, J.-P. Koutchouk, LUMI'06

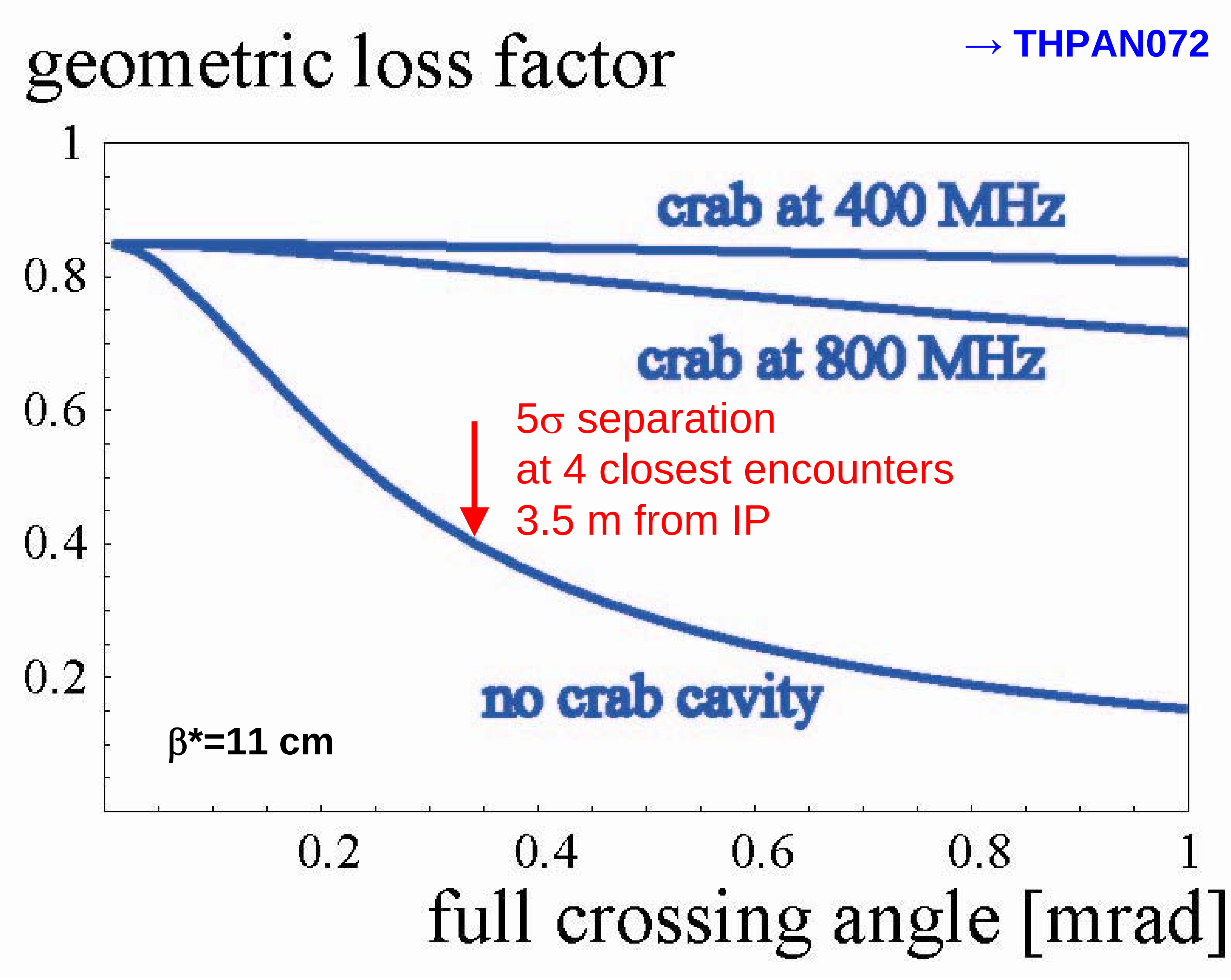
The same strategy in CMS



G. Sterbini, J.-P. Koutchouk, LUMI’06

ES scheme needs crab cavities

→ THPAN072



5σ separation
at 4 closest encounters
3.5 m from IP

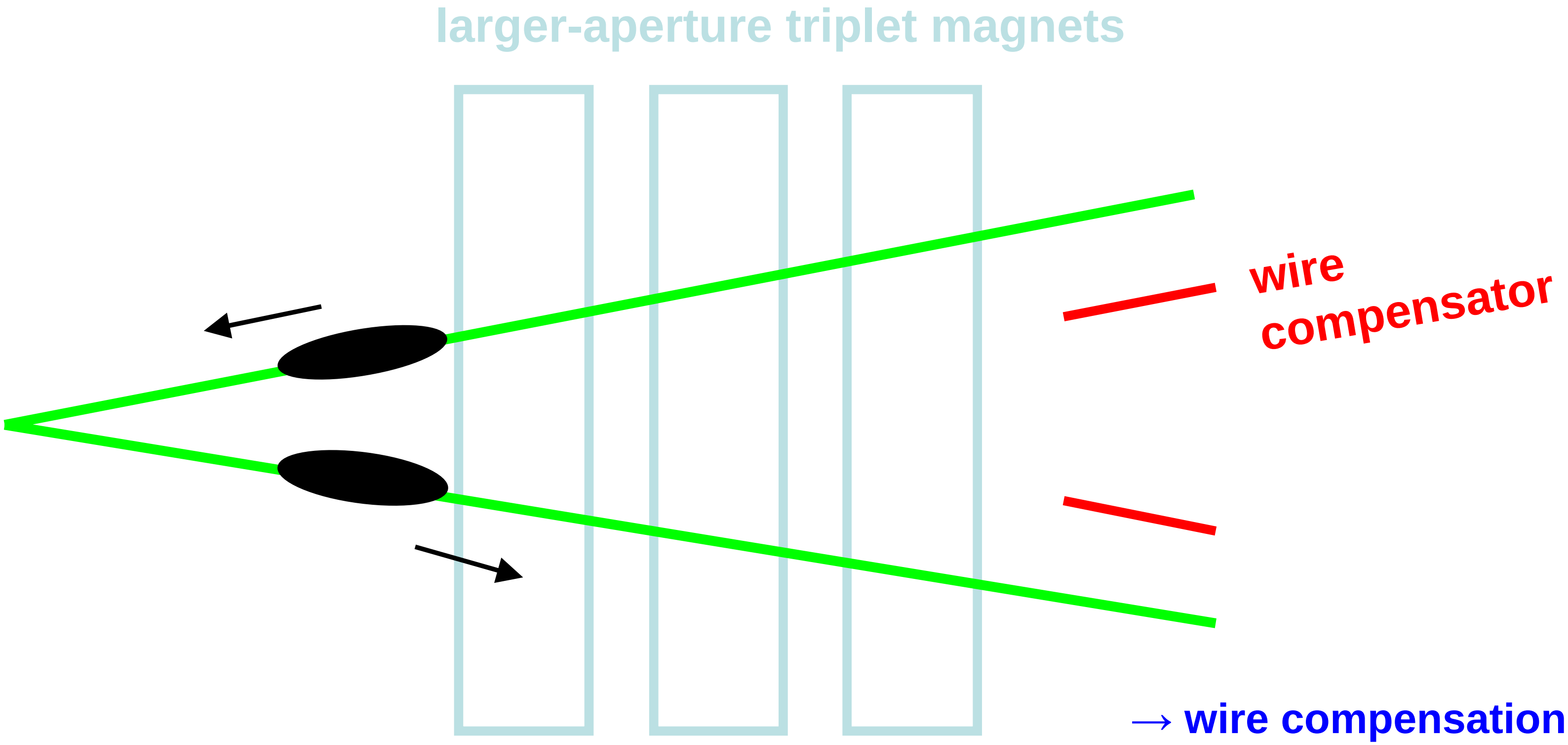
β*=11 cm

large Piwinski angle scenario

- **double bunch spacing**
- **longer & more intense bunches with $\phi_{\mathrm{Piwinski}} \sim 2$**
- **keep β*~25 cm** (achieved by larger-aperture low-β quads alone; numerous optics solutions, e.g. LHC Project Report 1008 by O. Bruning, R. De Maria, & R. Ostojic)
- **do not add any elements inside detectors**
- **long-range beam-beam wire compensation**

→ novel operating regime for hadron colliders

CMS & ATLAS IR layout for LPA option



→ **wire compensation:**
TUPAN091, U. Dorda et al
TUPAS095, W. Fischer et al

long bunches & nonzero crossing angle & wire compensation

LPA scenario assessment

merits:

**no elements in detector, no crab cavities,
lower chromaticity,
less demand on IR quadrupoles
(NbTi expected to be possible),
could be adapted to crab waist collisions (LNF/FP7)**

challenges:

**operation with large Piwinski parameter unproven for hadron beams (except for CERN ISR),
high bunch charge,
beam production and acceleration through SPS,
larger beam current,
wire compensation (almost etablished),
off-momentum β beating ~30% at $\delta=3\times10^{-4}$**

IR upgrade optics

“compact low-gradient” NbTi, $\beta^*=25$ cm

<75 T/m (Riccardo De Maria, Oliver Bruning)

“modular low gradient” NbTi, $\beta^*=25$ cm

<90 T/m (Riccardo De Maria, Oliver Bruning)

“low β_{max} low-gradient” NbTi, $\beta^*=25$ cm

<125 T/m (Riccardo De Maria, Oliver Bruning)

standard Nb$_3$Sn upgrade, $\beta^*=25$ cm

~200 T/m, 2 versions with different magnet parameters
(Tanaji Sen et al, Emmanuel Laface, Walter Scandale)

+ crab-waist sextupole insertions? (LNF/FP7)

probably compatible with LPA upgrade path

early separation with $\beta^*=8$ cm, Nb$_3$Sn

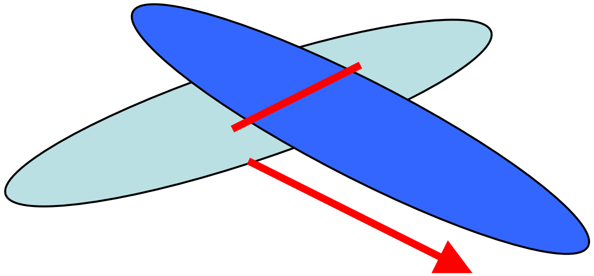
includes D0; triplet closer to IP or optional Q0;
(Jean-Pierre Koutchouk et al)

crab waist scheme

Hamiltonian $$H_I = -\frac{1}{4} p_y^2 \left(\frac{2x}{\theta_c} \right)$$

initiated and led by LNF in the frame of FP7; first beam tests at DAFNE later in 2007

minimizes β at $s=-x/\theta_c$

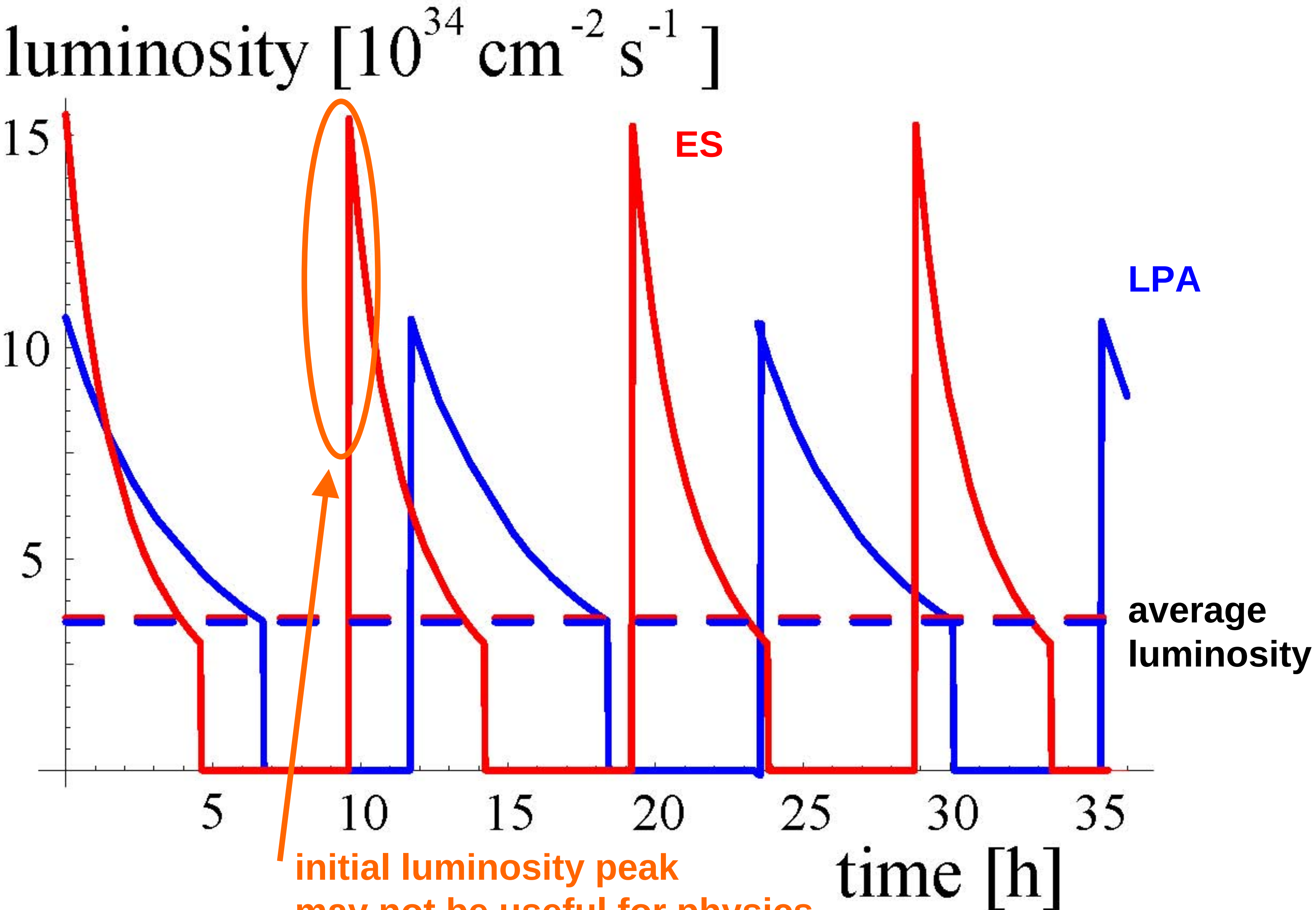


focal plane

implementation:

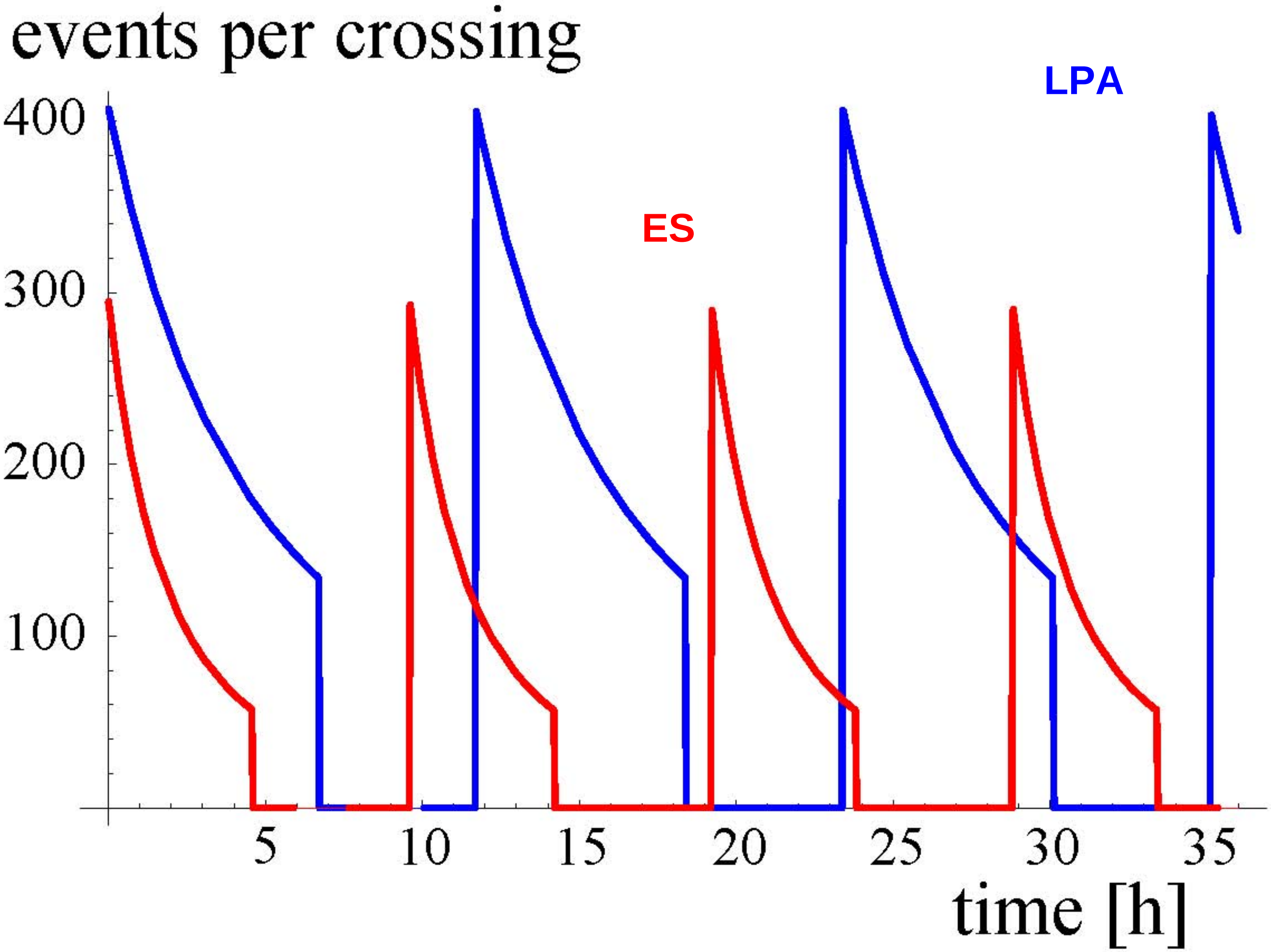
add sextupoles at right phase distance from IP

IP1& 5 luminosity evolution for ES and LPA scenario



initial luminosity peak may not be useful for physics (set up & tuning?)

IP1& 5 event pile up for ES and LPA scenario



experiments prefer more constant luminosity, less pile up at the start of run, higher luminosity at end

how could we achieve this?

luminosity leveling

ES:

dynamic β squeeze

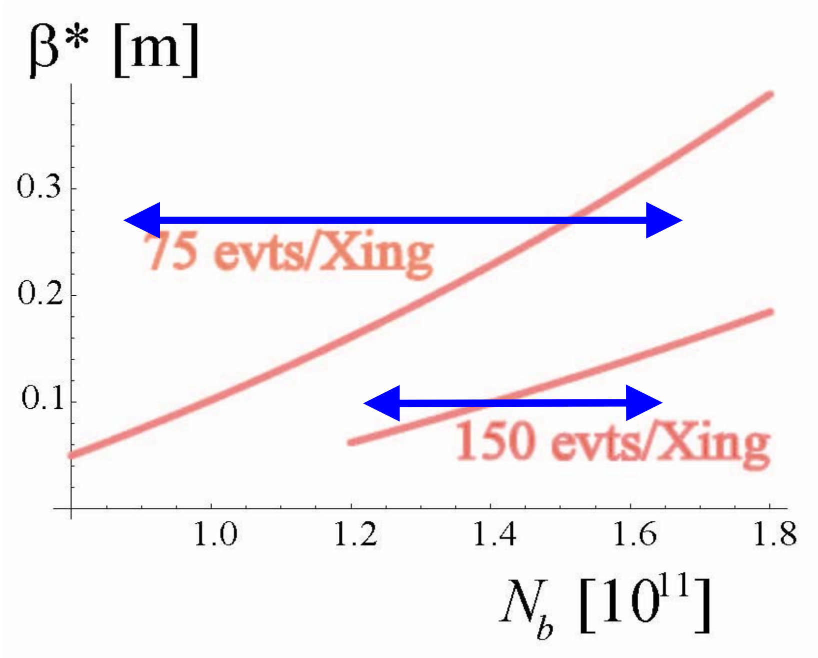
dynamic θ change (either IP angle bumps or varying crab voltage)

LPA:

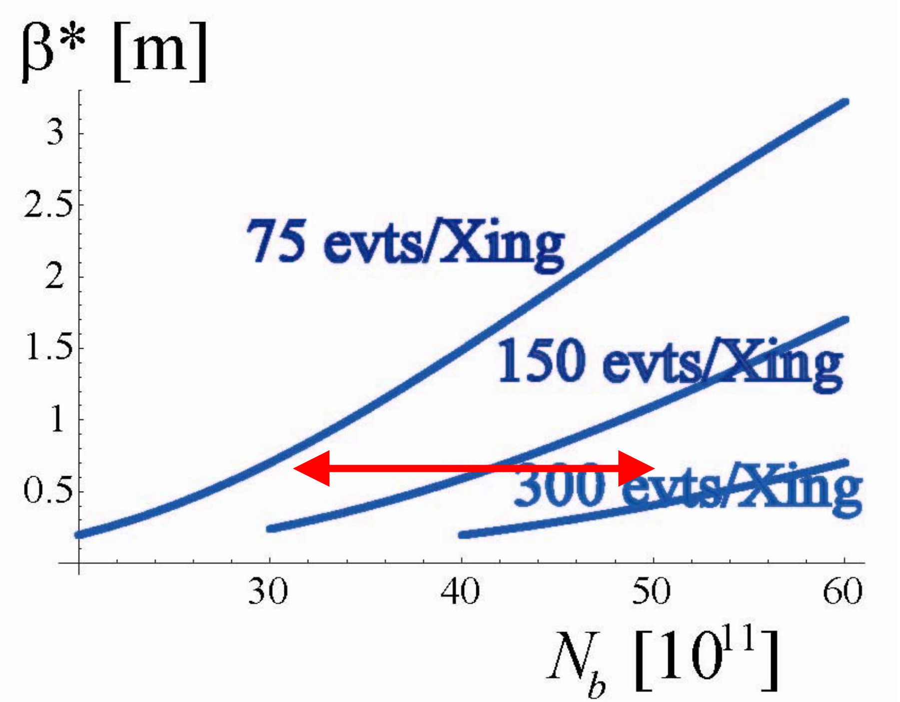
dynamic β squeeze, and/or

dynamic reduction in bunch length

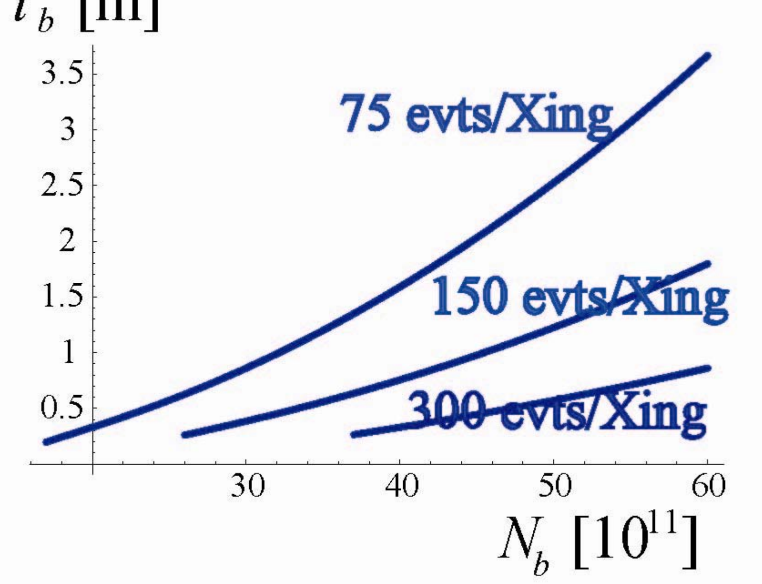
β squeeze for ES



β squeeze for LPA



bunch length change for LPA



run time & average luminosity

	w/o leveling	with leveling
luminosity evolution	$L(t) = \dfrac{\hat{L}}{\left(1 + t/\tau_{eff}\right)^2}$	$L = L_0 \approx const$
beam current evolution	$N(t) = \dfrac{N_0}{\left(1 + t/\tau_{eff}\right)}$	$N = N_0 - \dfrac{N_0}{\tau_{lev}} t$
optimum run time	$T_{run} = \sqrt{\tau_{eff} T_{turn-around}}$	$T_{run} = \dfrac{\Delta N_{\max} \tau_{lev}}{N_0}$
average luminosity	$L_{ave} = \hat{L} \dfrac{\tau_{eff}}{\left(\tau_{eff}^{1/2} + T_{turn-around}^{1/2}\right)^2}$	$L_{ave} = \dfrac{L_0}{1 + \dfrac{L_0 \sigma_{tot} n_{IP}}{\Delta N_{\max} n_b} T_{turn-around}}$

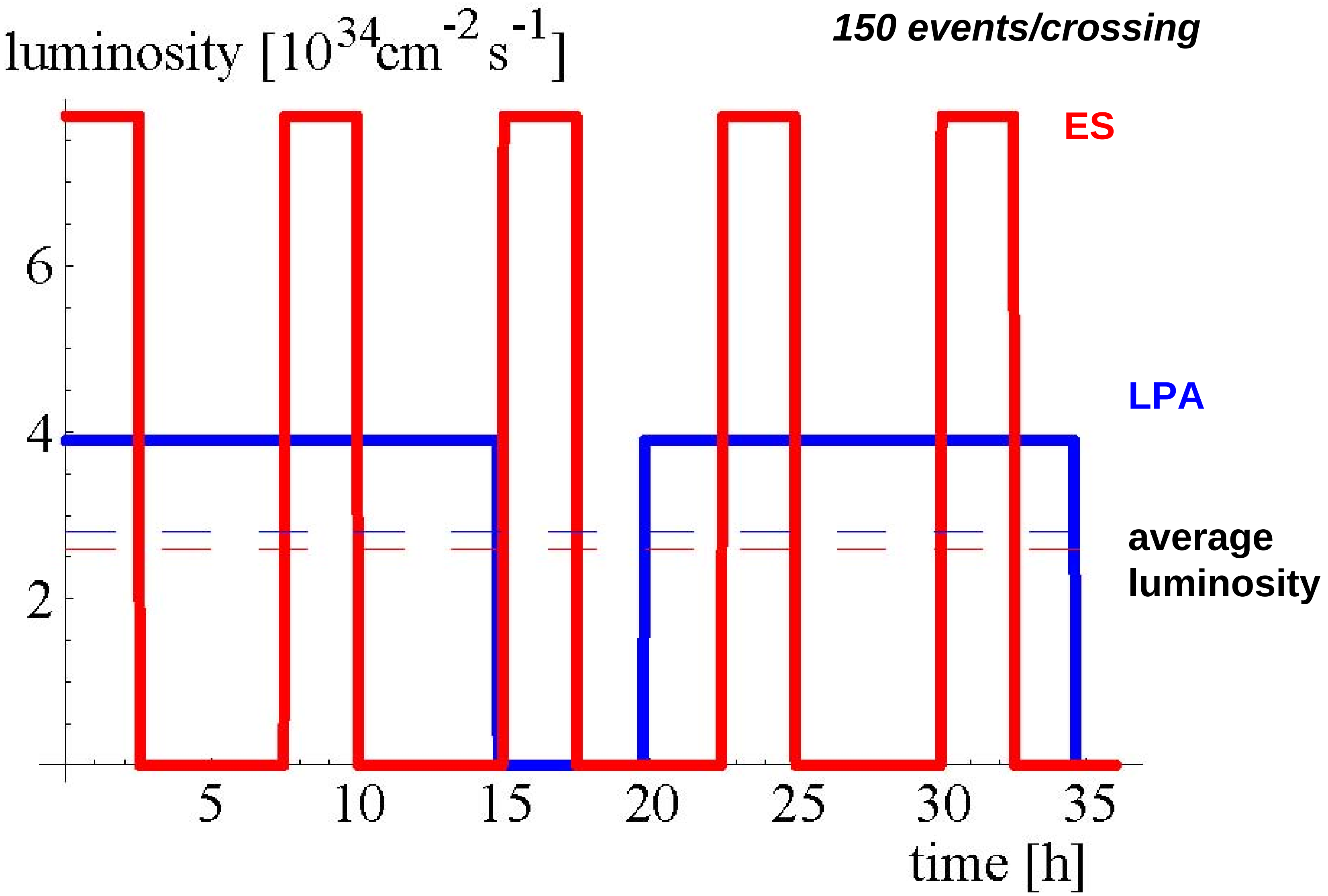
$$\tau_{eff} = \frac{N_0 n_b}{n_{IP} \hat{L} \sigma_{tot}} \qquad \tau_{lev} = \frac{N_0 n_b}{n_{IP} L_0 \sigma_{tot}}$$

Frank Zimmermann, LHC Upgrade Scenarios, PAC07, TUZAKI02

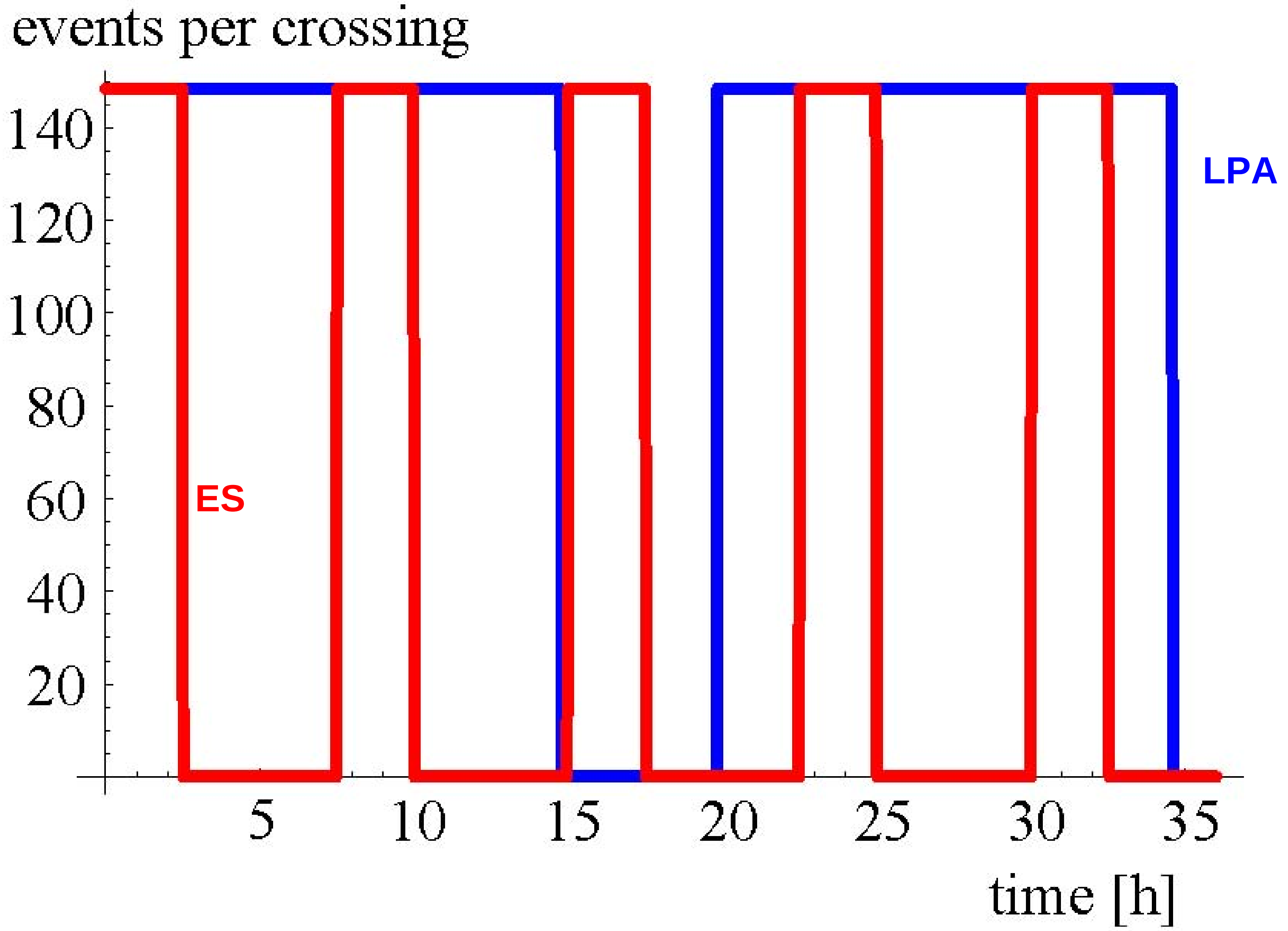
examples	ES, low β*, with leveling	LPA, long bunches, with leveling
events/crossing run time av. luminosity	300 N/A N/A	300 2.5 h $2.6\times10^{34}s^{-1}cm^{-2}$
events/crossing run time av. luminosity	150 2.5 h $2.6\times10^{34}s^{-1}cm^{-2}$	150 14.8 h $2.9\times10^{34}s^{-1}cm^{-2}$
events/crossing run time av. luminosity	75 9.9 h $2.6\times10^{34}s^{-1}cm^{-2}$	75 26.4 h $1.7\times10^{34}s^{-1}cm^{-2}$

assuming 5 h turn-around time

IP1& 5 luminosity evolution for ES and LPA with leveling

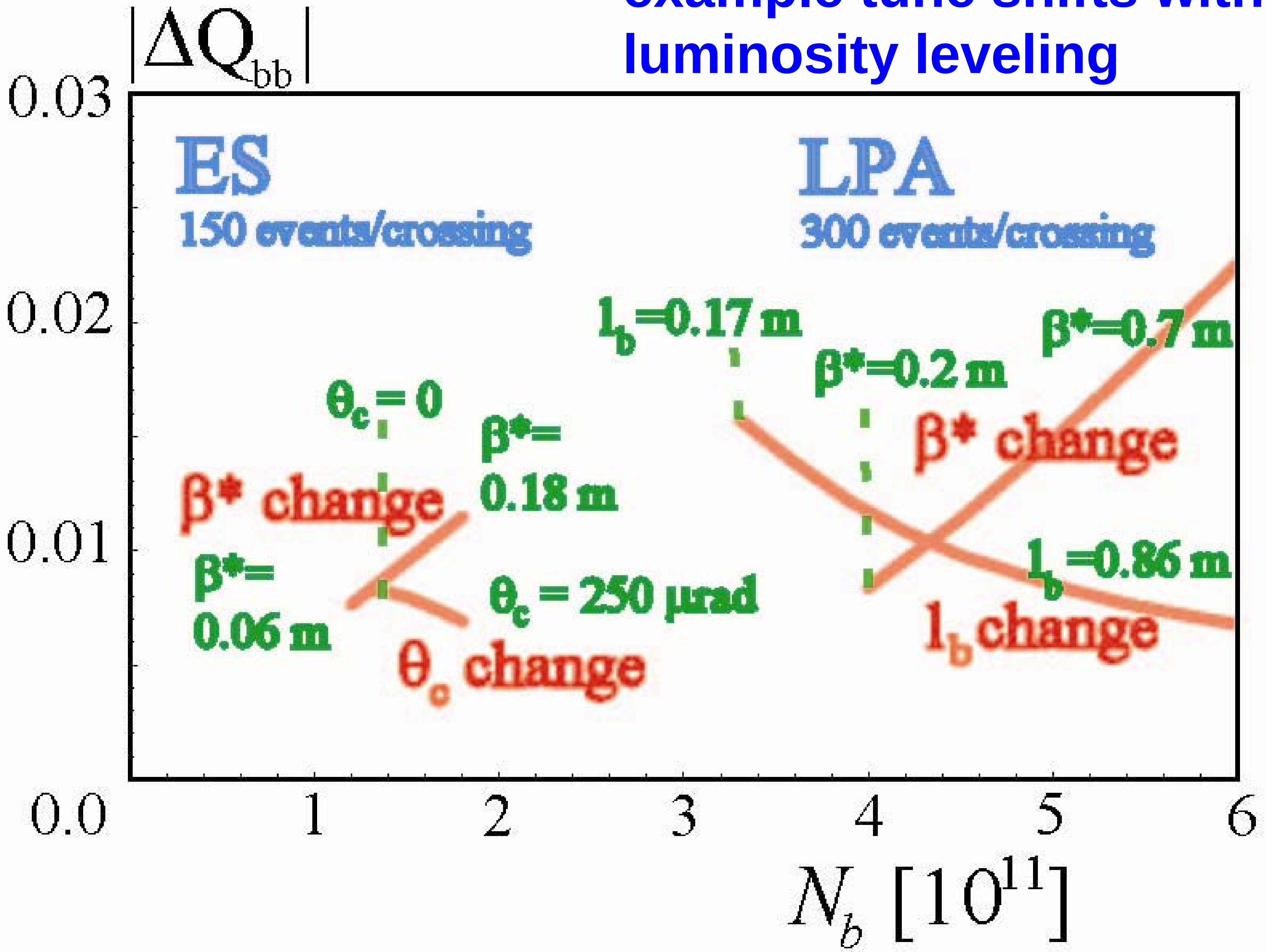


IP1& 5 event pile up for ES and LPA with leveling



Frank Zimmermann, LHC Upgrade Scenarios, PAC07, TUZAKI02

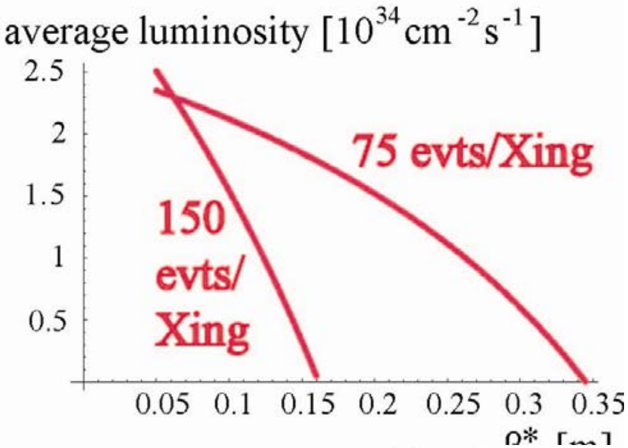
example tune shifts with luminosity leveling

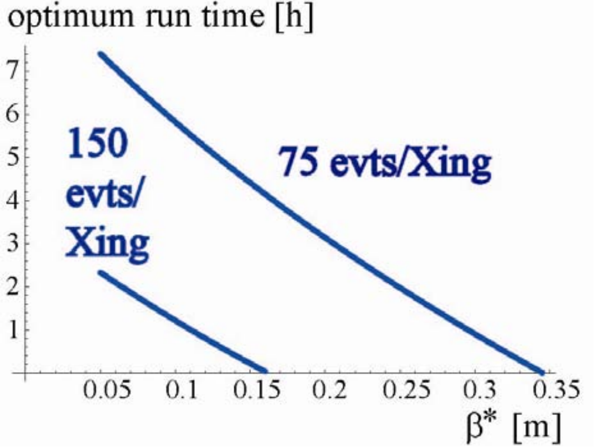


Frank Zimmermann, LHC Upgrade Scenarios, PAC07, TUZAKI02

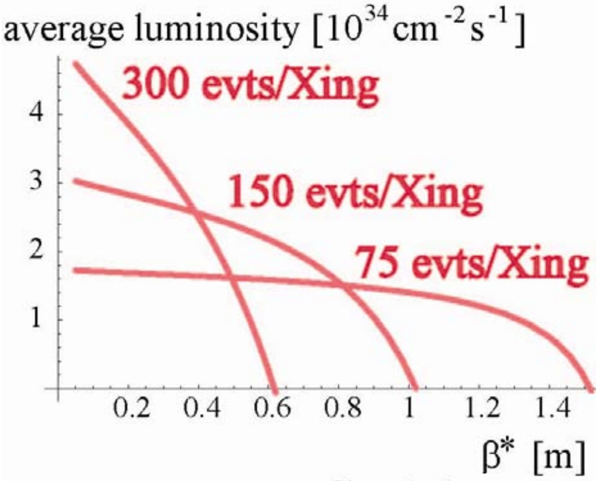
average luminosity & run time vs. final β∗, l_b

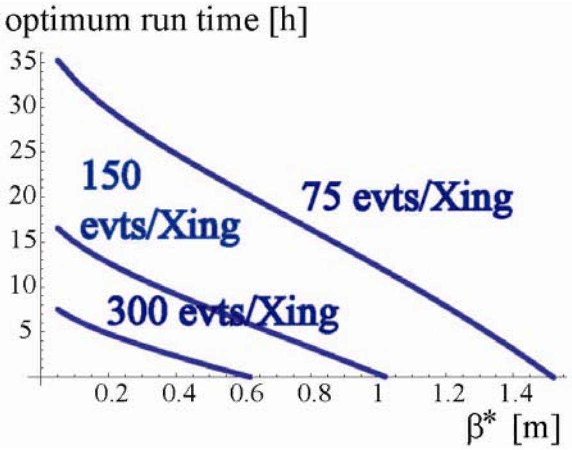
for ES with β* squeeze



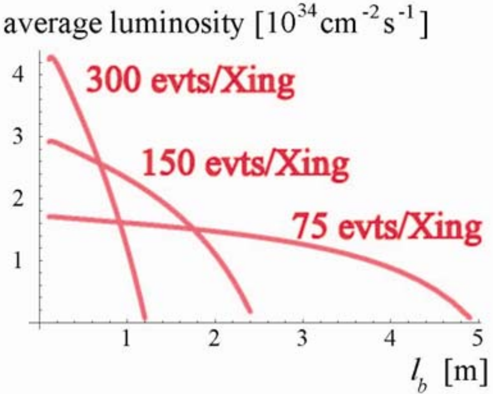


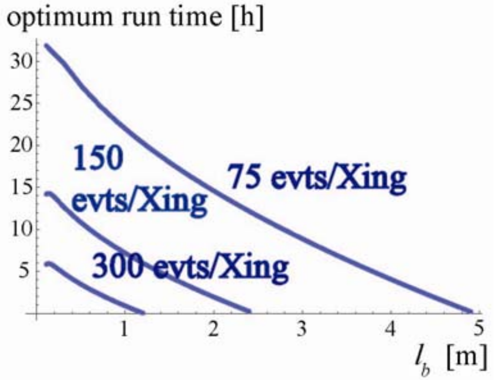
for LPA with β* squeeze



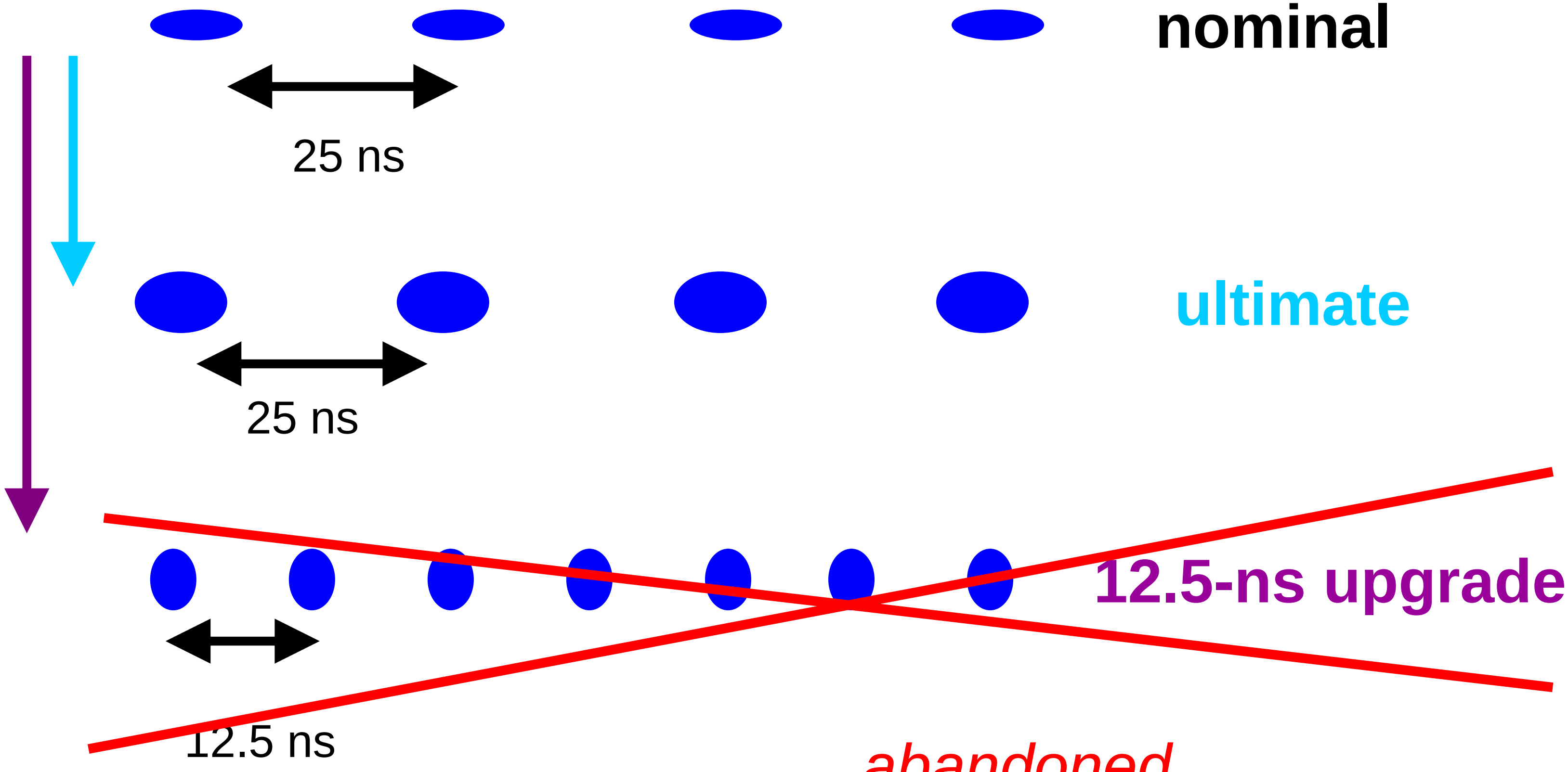


for LPA with l_b reduction





old upgrade bunch structure



nominal

25 ns

ultimate

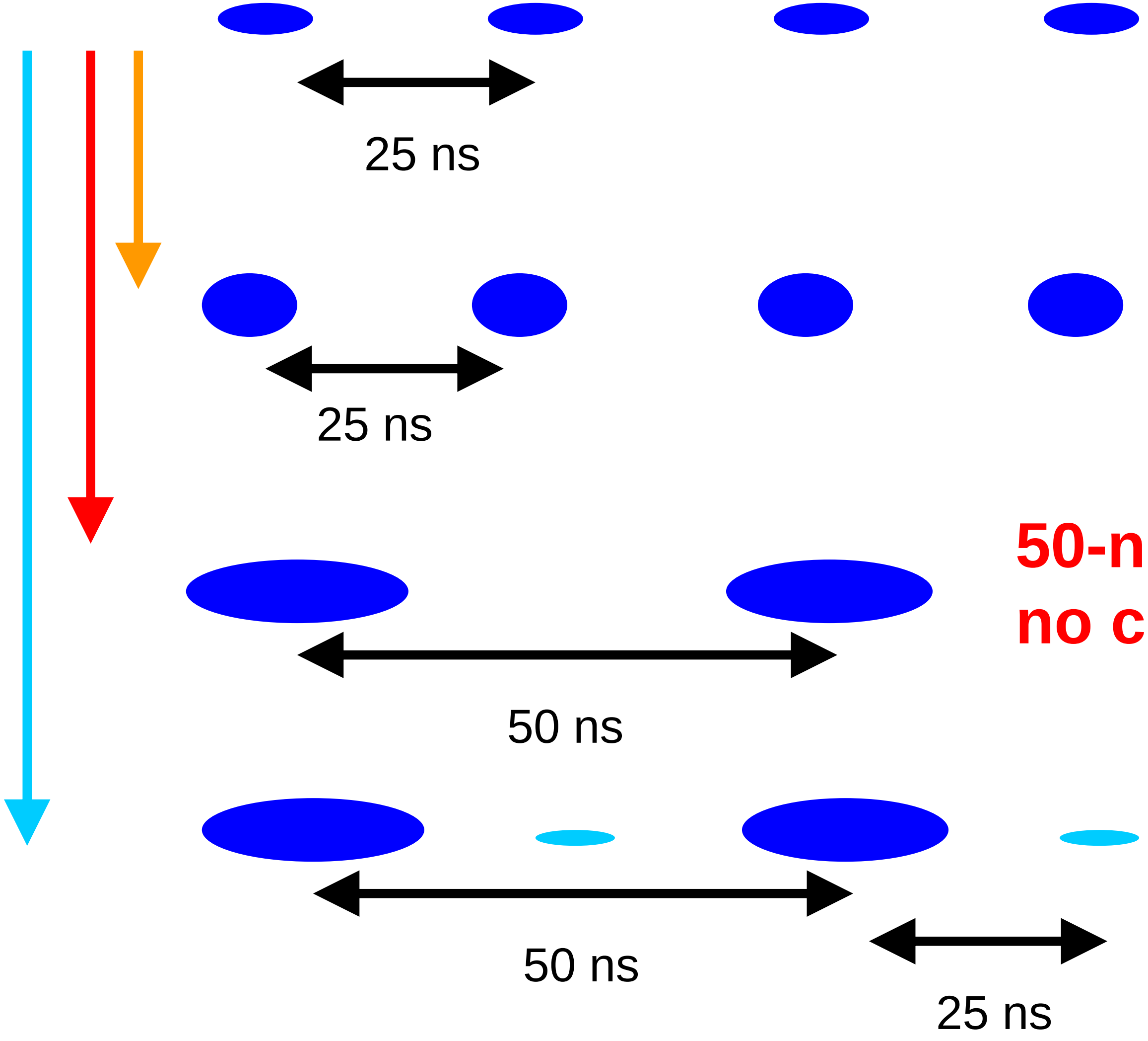
25 ns

12.5-ns upgrade

12.5 ns

abandoned
at LUMI’06

new upgrade bunch structures



nominal

new alternative!

ultimate
& 25-ns upgrade

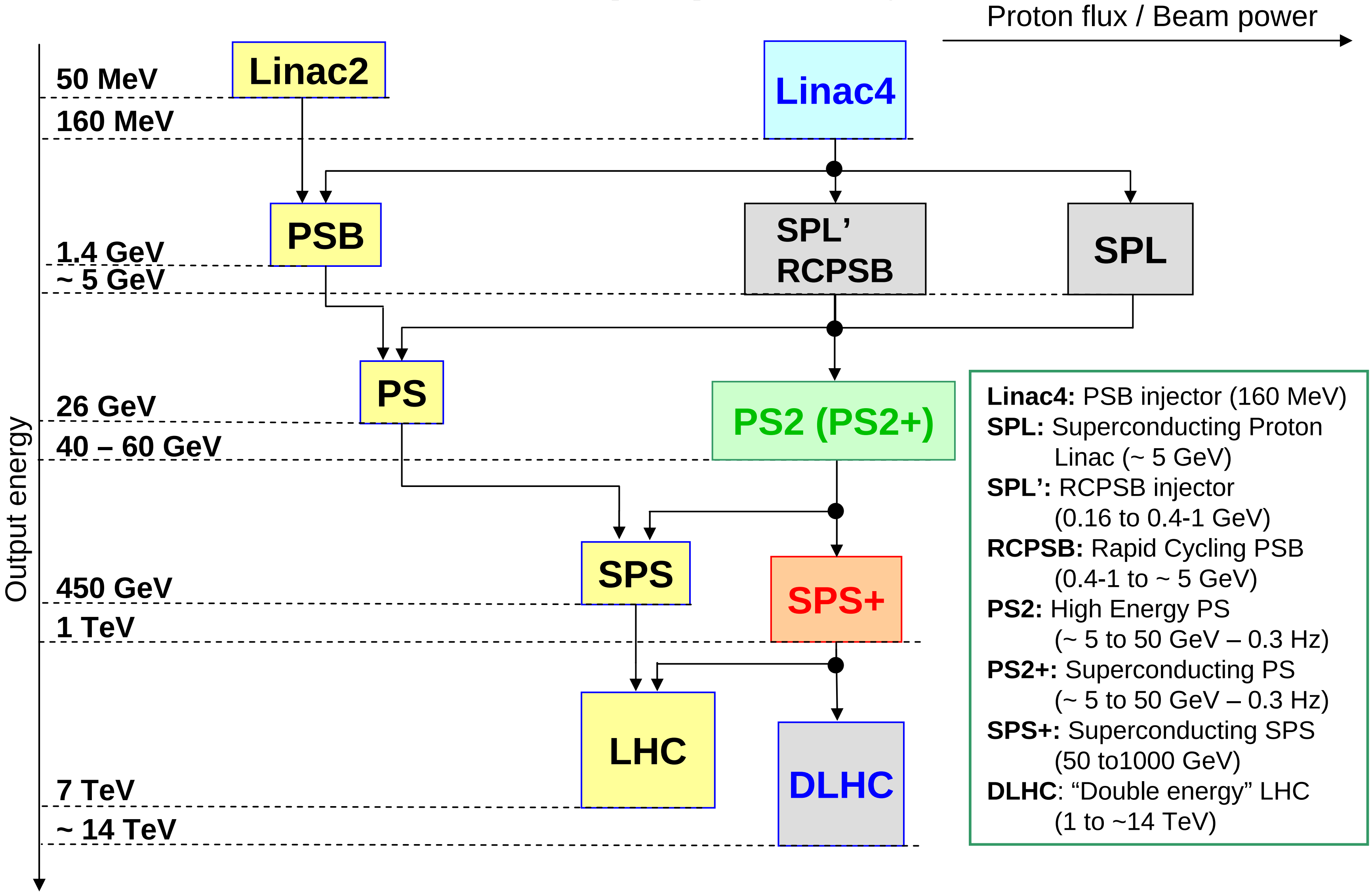
50-ns upgrade,
no collisions @S-LHCb!

new baseline!

50-ns upgrade
with 25-ns
collisions
in LHCb

Evolution of the CERN Accelerator Complex

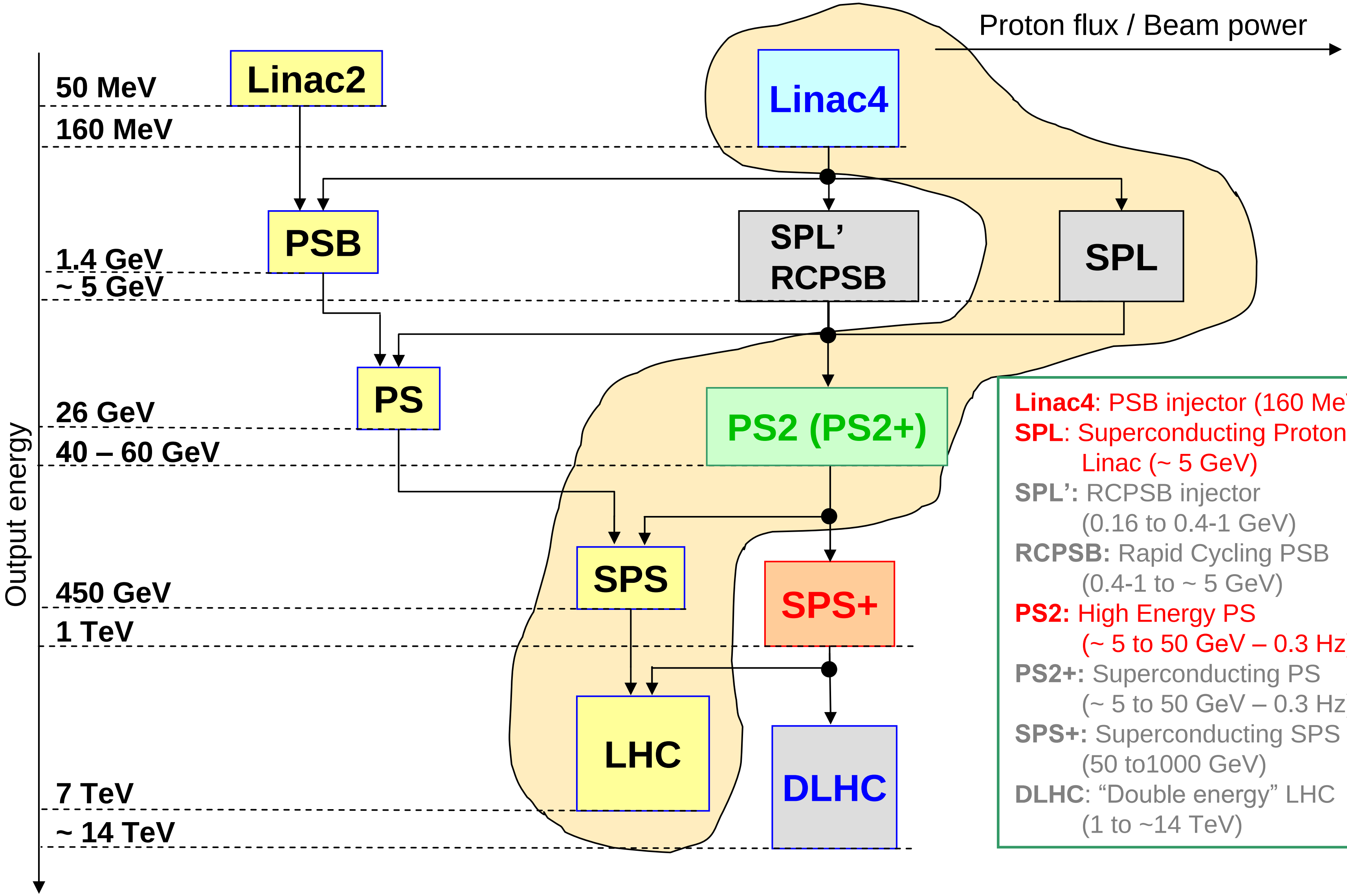
- Combinations proposed by PAF



Linac4: PSB injector (160 MeV)
SPL: Superconducting Proton Linac (~ 5 GeV)
SPL’: RCPSB injector (0.16 to 0.4-1 GeV)
RCPSB: Rapid Cycling PSB (0.4-1 to ~ 5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
PS2+: Superconducting PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
DLHC: “Double energy” LHC (1 to ~14 TeV)

M. Benedikt, R. Garoby

DG White Paper Injector Upgrade (Theme 2)



Linac4: PSB injector (160 MeV)
SPL: Superconducting Proton
Linac (~ 5 GeV)
SPL': RCPSB injector
(0.16 to 0.4-1 GeV)
RCPSB: Rapid Cycling PSB
(0.4-1 to ~ 5 GeV)
PS2: High Energy PS
(~ 5 to 50 GeV – 0.3 Hz)
PS2+: Superconducting PS
(~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS
(50 to1000 GeV)
DLHC: "Double energy" LHC
(1 to ~14 TeV)

M. Benedikt, R. Garoby, CERN DG

injector upgrade

- needed for ultimate LHC beam
- reduced turn around time & higher integrated luminosity
- $4x10^{11}$ protons spaced by 25 ns (now ~$1.5\ 10^{11}$)
- beam production:

  for ES straightforward
  for LPA e.g. omitting last double splitting in PS (or PS2)
- 3 techniques for bunch flattening available

→ **160-MeV injection in to PSB: TUPAN093, F. Gerigk; TUPAN109, W. Weterings,**
→ **Linac 4 rf structures, FROBC02, F. Gerikg et al**
→ **PS2 optics considerations: TUODKI02, C. Carli et al**
→ **PS2 Injection, Extraction and Beam Transfer: TUPAN094, T. Kramer et al**
→ **space-charge compensation in LHC injectors: THPAN074, M. Aiba et al**

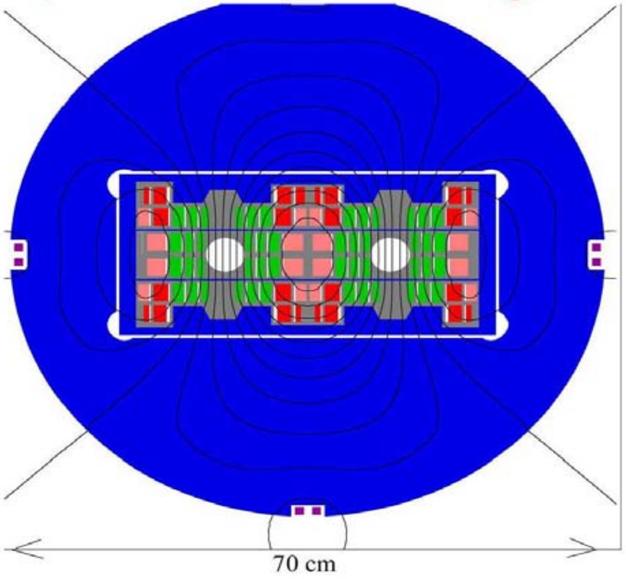
proposed design of 24-T block-coil dipole for "LHC energy tripler"

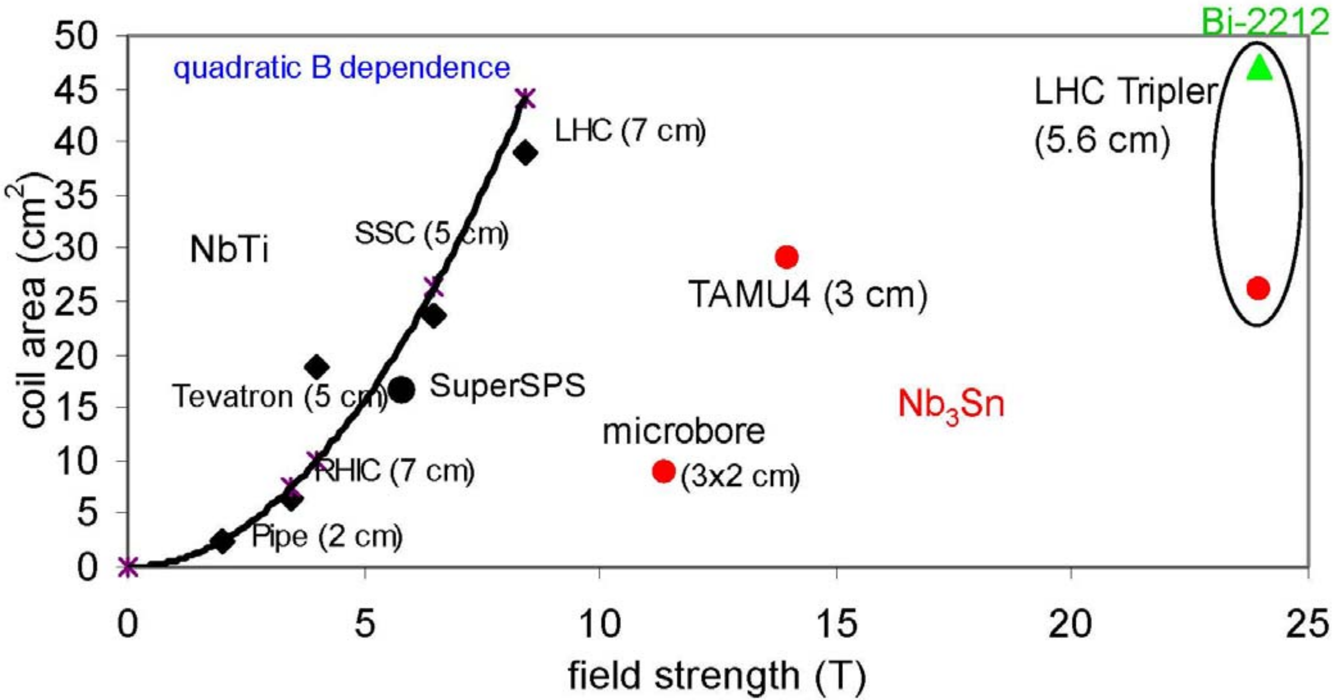
P. McIntyre et al,
Texas A&M, PAC'05

Bi-2212 in inner (high field) windings,
Nb_3Sn in outer (low field) windings

Dual dipole (ala LHC)

Bore field	**24 Tesla**
Max stress in superconductor	**130 MPa**
Superconductor x-section:	
Nb_3Sn	**26 cm²**
Bi-2212	**47 cm²**
Cable current	**25 kA**
Beam tube dia.	**50 mm**
Beam separation	**194 mm**





magnets are getting more efficient!

→Bi-2212 Coil Technology Development for an LHC Tripler Dipole: MOPAS034

summary - 1

- two scenarios of L~10^{35} $cm^{-2}s^{-1}$ for which heat load and #events/crossing are acceptable
- early separation: pushes β*; requires slim magnets inside detector, crab cavities, & Nb_3Sn quadrupoles and/or optional Q0 doublet; attractive if total beam current is limited; luminosity leveling via β* or θ_c (e.g. crab voltage)
- large Piwinski angle: fewer longer bunches of higher charge ; can probably be realized with NbTi IR technology if needed ; Q0 also an option here ; compatible with LHCb ; open issues are SPS & hadron beam-beam effects at large Piwinski angle; luminosity leveling via bunch length or via β*
- off-energy β beating common concern, worse at lower β*

summary - 2

- **first two or three years of LHC operation will clarify severity of electron cloud, long-range beam-beam collisions, impedance etc.**
- **first physics results will indicate whether or not magnetic elements can be installed inside the detectors**
- **these two experiences will decide the upgrade path**
- ***until then keep both options open!***

this talk is dedicated to the memory of Francesco Ruggiero (1957-2007)

who initiated and guided the LHC upgrade studies