High Energy
High Intensity
Hadron Beams

APD
Accelerator Physics and synchrotron Design

Scenarios for the LHC Upgrade

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BEAM'2007
CERN

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outline

upgrade motivation & time frame

two scenarios

- beam parameters; features; IR layouts
- merits and challenges
- impact of β^*
- luminosity evolution

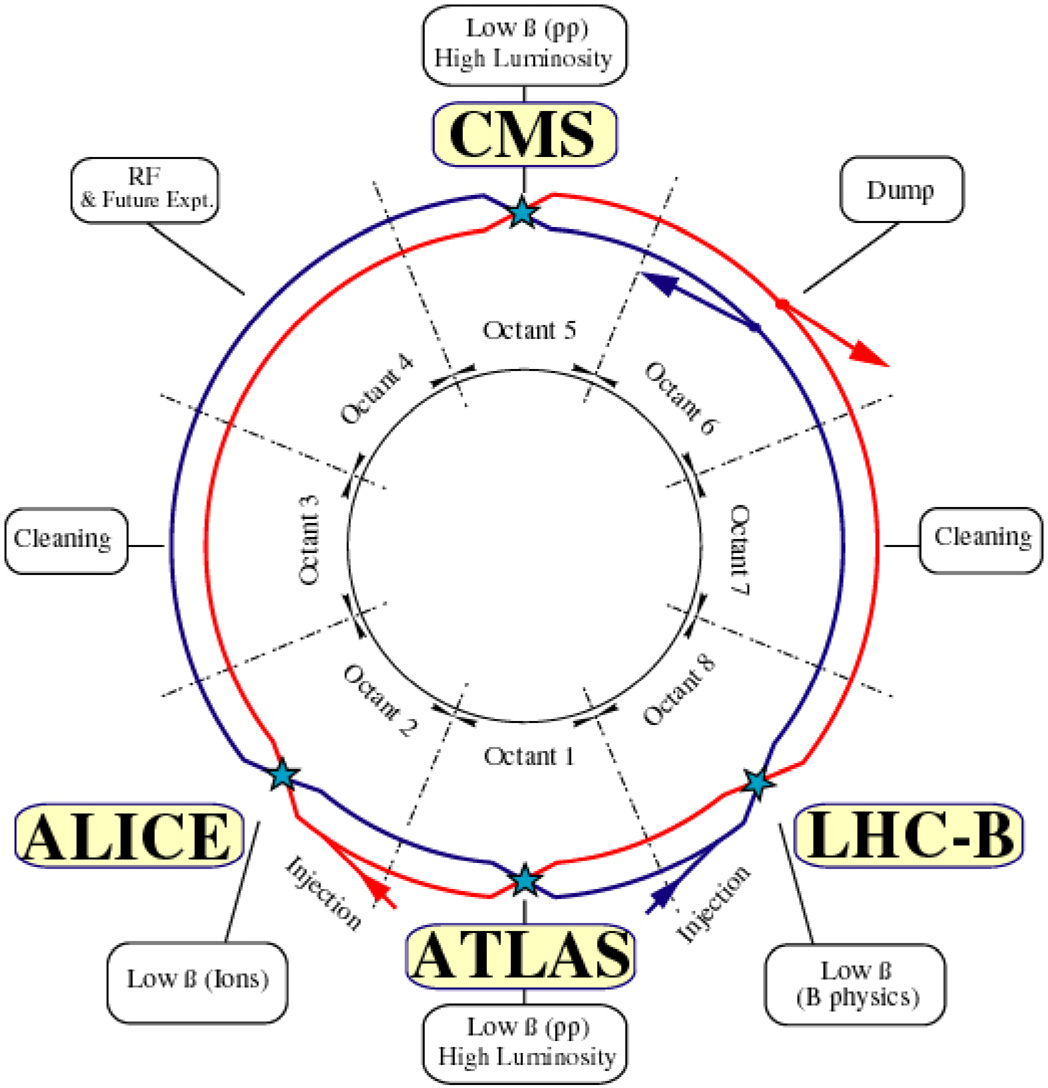
luminosity leveling (incl. β^* dependence)

bunch structures

injector upgrade

conclusion

Large Hadron Collider (LHC)



proton-proton collider

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

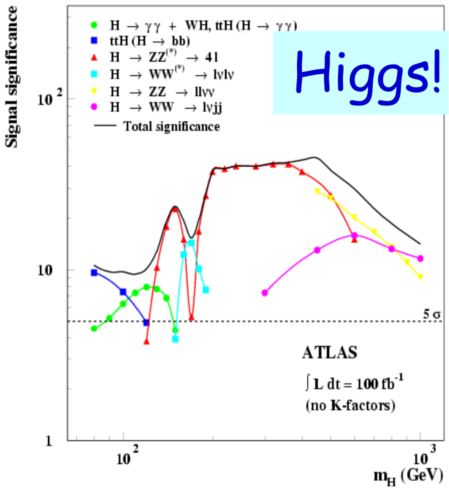
design luminosity
10^{34} cm^{-2}s^{-1}
(~100x Tevatron)

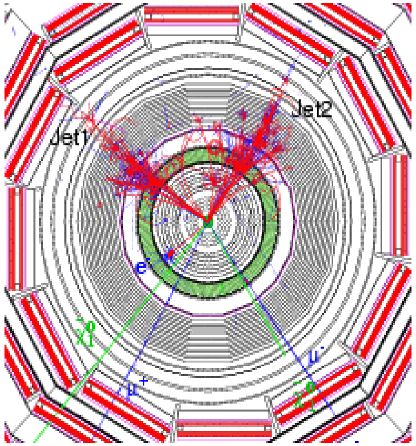
start of
beam commissioning
in 2008

LHC baseline luminosity was pushed in competition with SSC

Physics at the LHC: pp @ 14 TeV

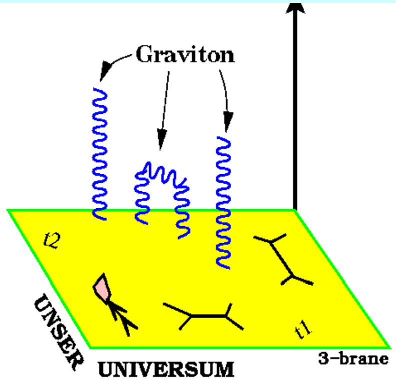
Higgs!



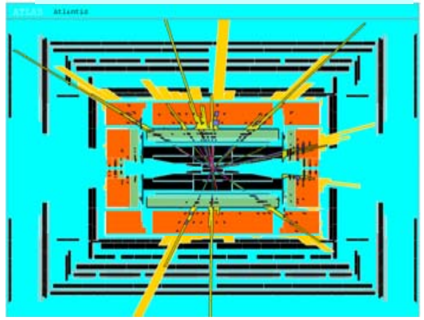


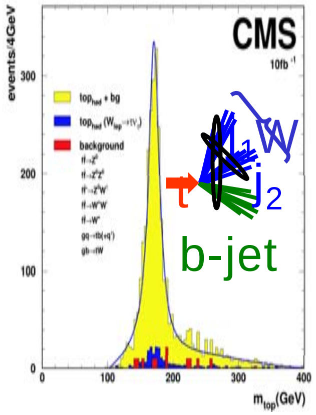
Supersymmetry?

Extra Dimensions?



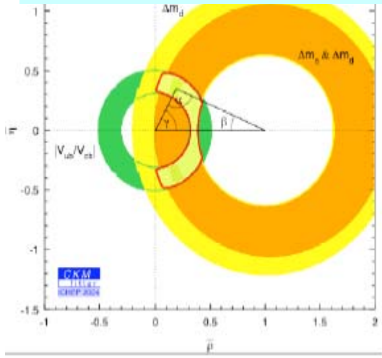
Black Holes???



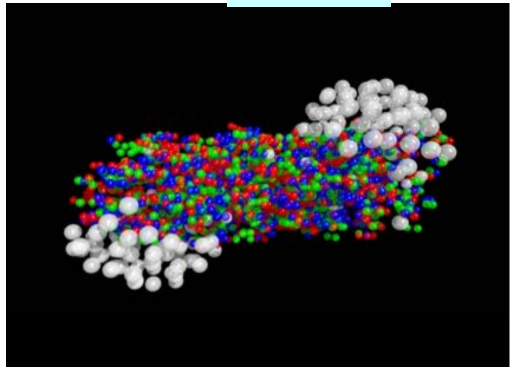


Precision measurements e.g top!

Unitarity triangle!



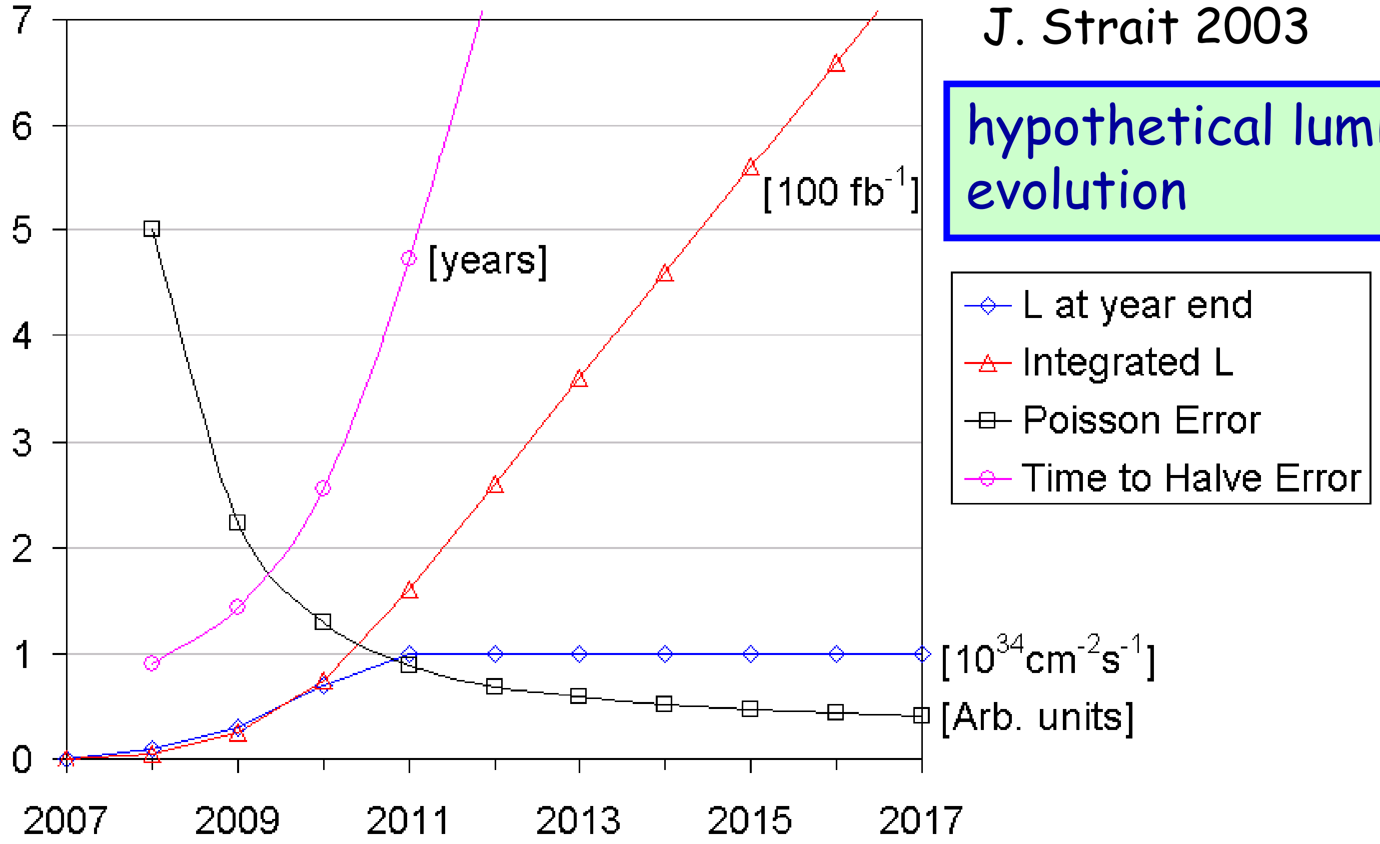
QGP?



The LHC will be the new collider energy frontier

Albert de Roeck, Bodrum 2007

Two Strong Reasons for LHC Upgrade



J. Strait 2003

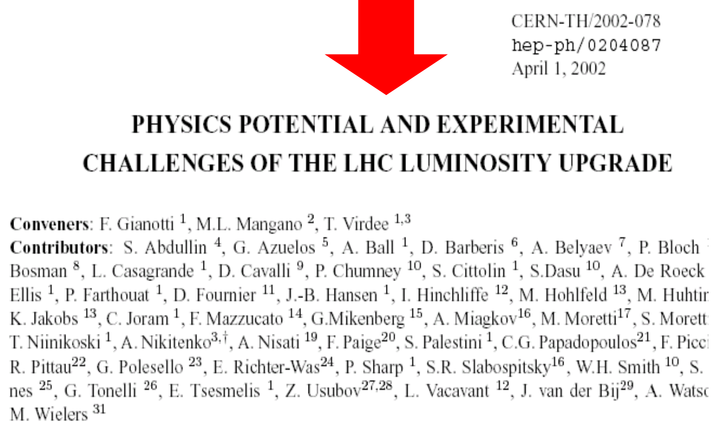
hypothetical luminosity evolution

1) After a few years, statistical error hardly decreases.
2) Radiation damage limit of IR quadrupoles (~700 fb^{-1}) reached by ~2016
$\Rightarrow$
Time for an upgrade!

A Third Reason: Extending the Physics Potential of LHC

⇒ 10x higher luminosity extends discovery range by ~ 25% in mass & precision by a factor of ~2

Examples studied in detail



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

PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

Conveners: F. Gianotti [1], M.L. Mangano [2], T. Virdee [1,3]
Contributors: S. Abdullin [4], G. Azuelos [5], A. Ball [1], D. Barberis [6], A. Belyaev [7], P. Bloch
Bosman [8], L. Casagrande [1], D. Cavalli [9], P. Chumney [10], S. Cittolin [1], S.Dasu [10], A. De Roeck
Ellis [1], P. Farthouat [1], D. Fournier [11], J.-B. Hansen [1], I. Hinchliffe [12], M. Hohlfeld [13], M. Huhtir
K. Jakobs [13], C. Joram [1], F. Mazzucato [14], G.Mikenberg [15], A. Miagkov[16], M. Moretti[17], S. Morett
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nes [25], G. Tonelli [26], E. Tsesmelis [1], Z. Usubov[27,28], L. Vacavant [12], J. van der Bij[29], A. Watsc
M. Wielers [31]

Include pile up, detector

- Electroweak Physics
  - Production of multiple gauge bosons ($n_V \geq 3$)
    - triple and quartic gauge boson couplings
  - Top quarks/rare decays
- Higgs physics
  - Rare decay modes
  - Higgs couplings to fermions and bosons
  - Higgs self-couplings
  - Heavy Higgs bosons of the MSSM
- Supersymmetry (up to masses of 3 TeV)
- 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, $W^+_L W^+_L$
- New Gauge Bosons

hep-ph/0204087

Albert de Roeck, Bodrum 2007

LHC Upgrade

- 10x higher luminosity ~$10^{35}cm^{-2}\,s^{-1}$ (SLHC)
  - Requires changes of the machine and particularly of the detectors

  ⇒ Upgrade to SLHC mode around 2014-2016

  ⇒ Collect ~3000 fb^{-1}/experiment in 3-4 years data taking.

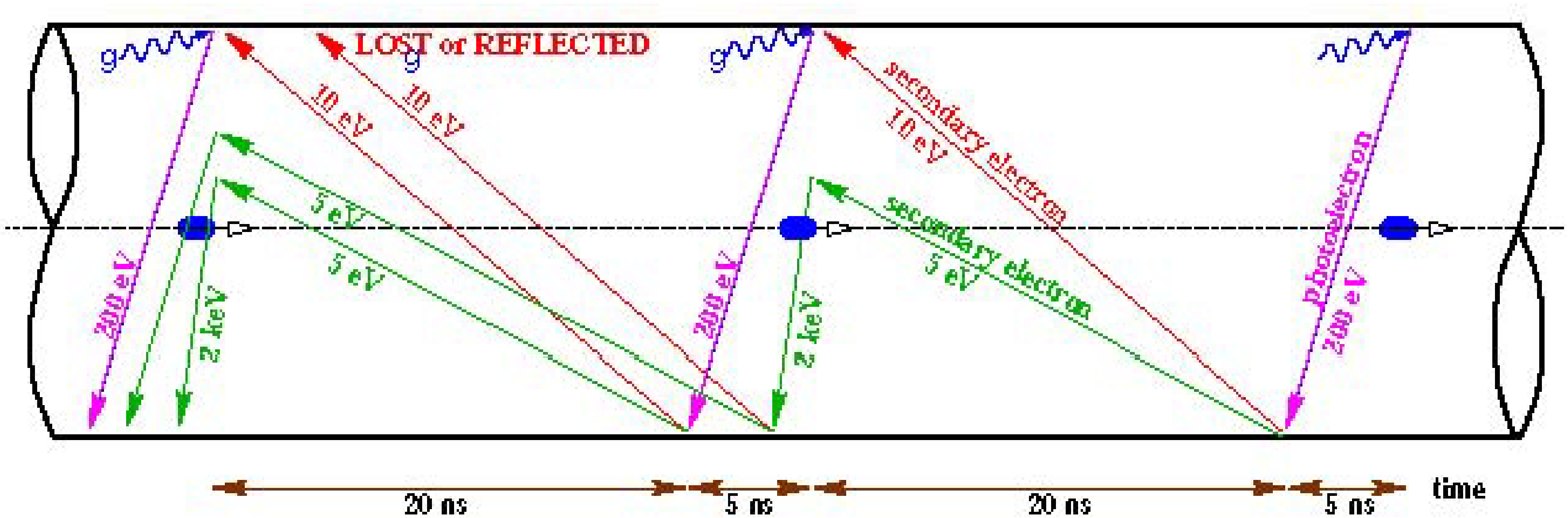
- much later: higher energy? (DLHC)
  - LHC can reach $\sqrt{s}$ = 15 TeV with present magnets (9T field)
  - $\sqrt{s}$ of 28 (25) TeV needs ~17 (15) T magnets ⇒ R&D needed!
  - Even some ideas on increasing the energy by factor 3 (P. McIntyre)

	Run I $\sqrt{s}$	Run II $\sqrt{s}$	Int Lumi (run I)	Int. Lumi (expected/runII)
Tevatron	1.8 TeV	1.96 TeV	100 pb^{-1}	~4-8 fb^{-1}
HERA	300 GeV	320 GeV	100 pb^{-1}	~500 pb^{-1}

three LHC challenges

- collimation & machine protection
  - damage, quenches, cleaning efficiency, impedance
- electron cloud
  - heat load, instabilities, emittance growth
- beam-beam interaction
  - head-on, long-range, weak-strong, strong-strong

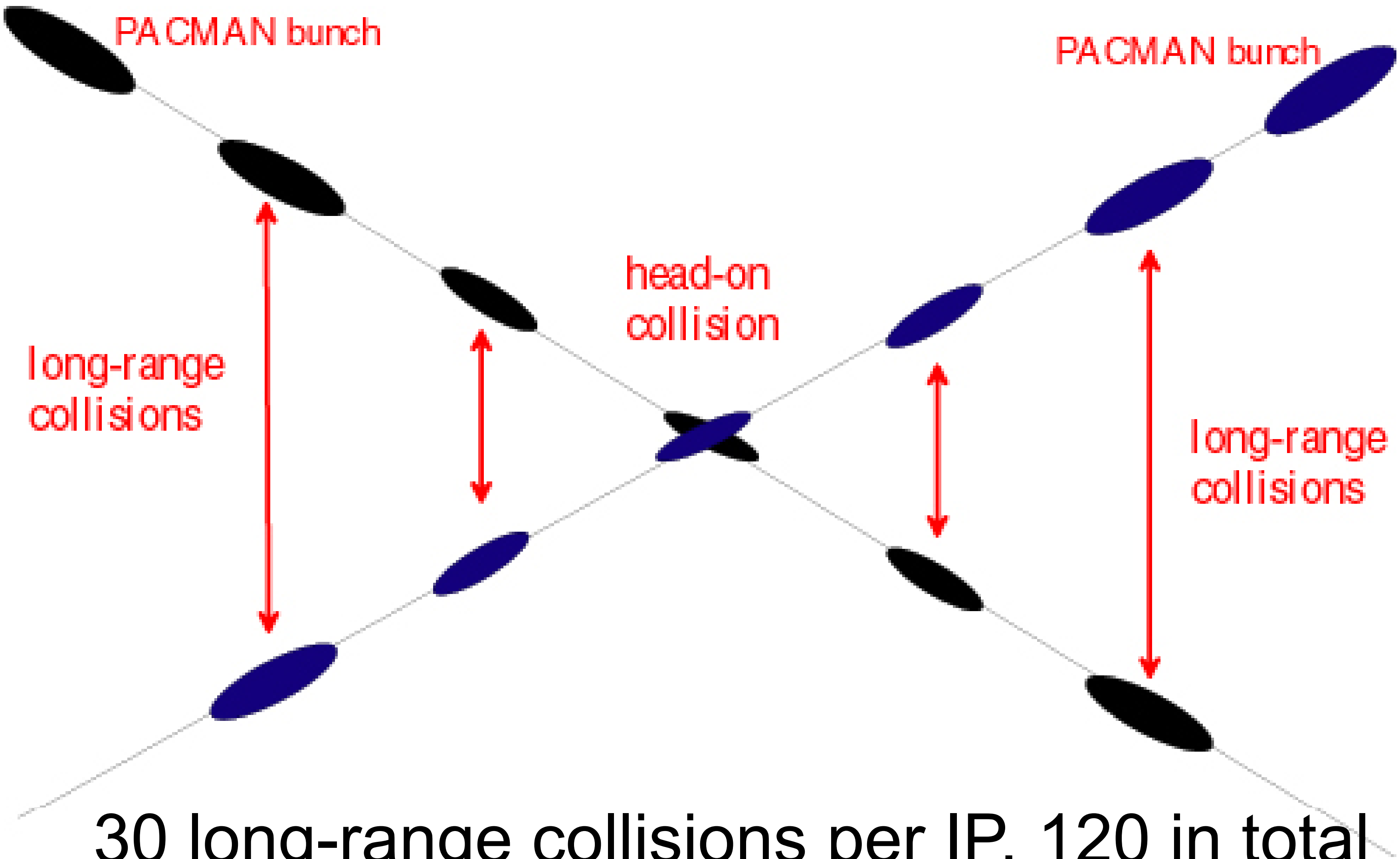
electron cloud in the LHC



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

[F. Ruggiero]

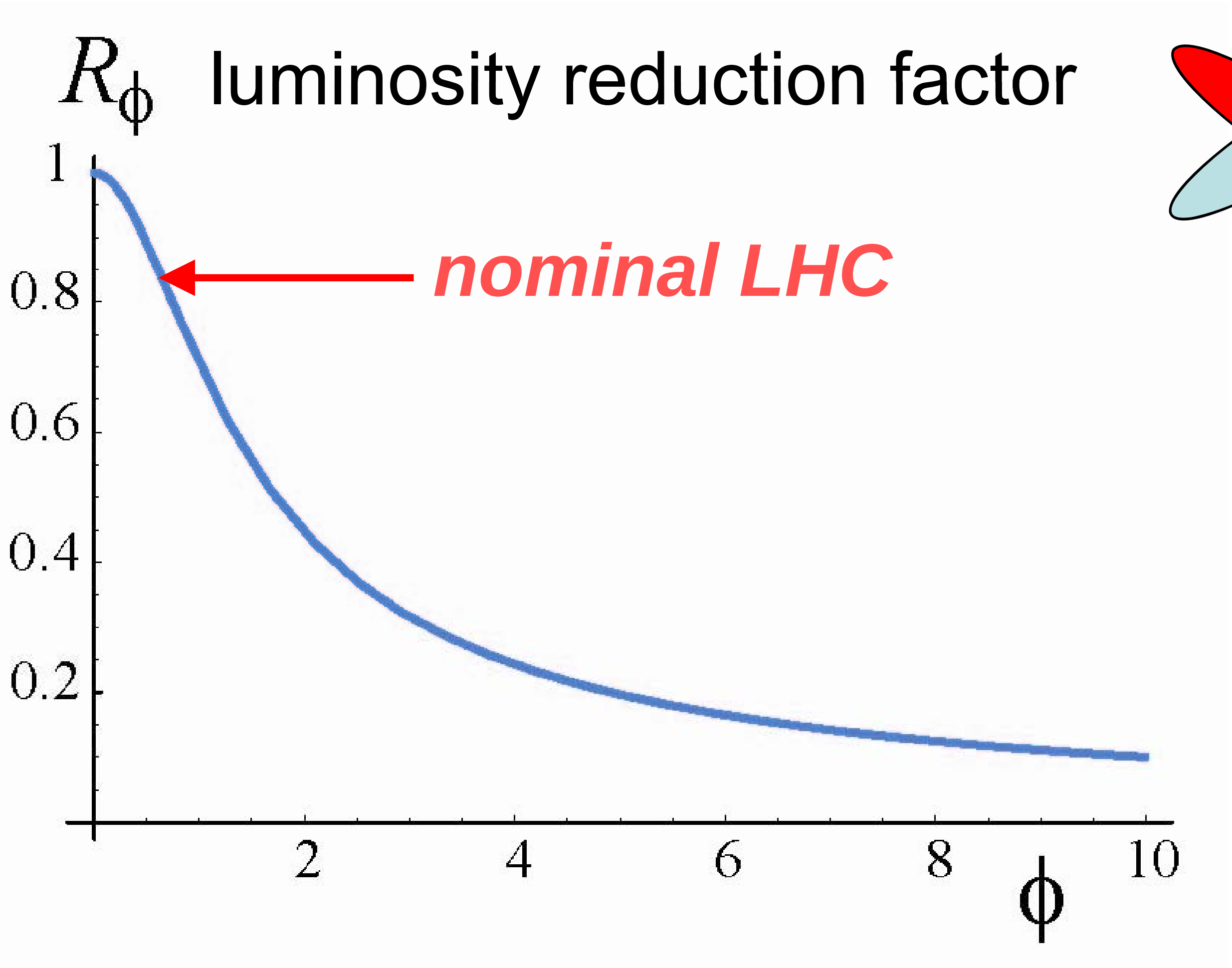
long-range beam-beam

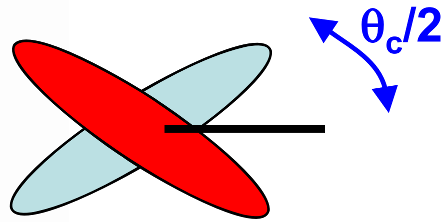


30 long-range collisions per IP, 120 in total

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 $\sigma \rightarrow \sigma / R_\phi$

CARE-HHH workshops

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

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	β^* [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.

baseline upgrade parameters 2001-2005

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	$\beta*$ [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 # pile up events and heat load

for operation at beam-beam limit with alternating planes of crossing <u>at two IPs</u>

↑ LPA
↑ ES

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

↓ LPA ↓↓ ES ↓ LPA ↑↑ LPA ↑ LPA ↓ ES

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

<u>peak luminosity</u> with respect to ultimate LHC (2.4 x nominal):

ES:		**x 6**	**x 1.3**		**x 0.86**	**=**	**6.7**
LPA:	**½**	**x2 x2.9**	**x1.3**	**x1.4**		**=**	**5.3**

what matters is the <u>integrated luminosity</u>

luminosity lifetime

$$\tau = \frac{1}{2}\frac{N_b}{\dot{N}_b} = \frac{n_b N_b}{L\sigma} = \frac{4\pi\varepsilon\beta^*}{f_{rev} N_b \sigma}$$

inversely proportional to luminosity (L ~10x up from nominal) and proportional to β^*

larger luminosity lifetime requires higher total beam current ~ $n_b N_b$

→ EITHER more bunches n_b (previous 12.5 ns scheme)
→ OR higher charge per bunch N_b (LPA scheme)

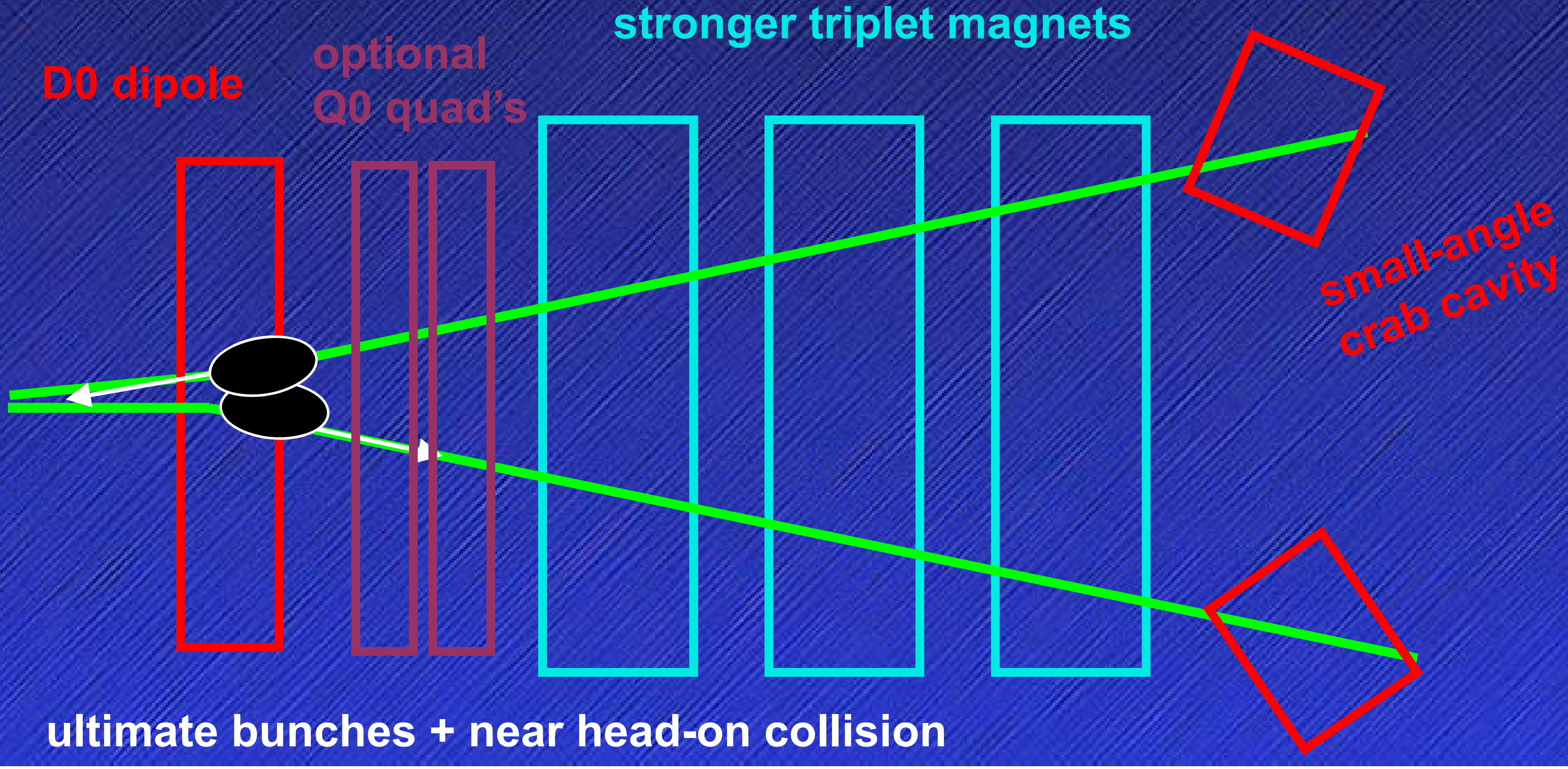
+ luminosity leveling (see later)

LHC upgrade path 1: early separation (ES)

J.-P. Koutchouk

- 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 ($\phi_{Piwinski}\sim 0$)

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

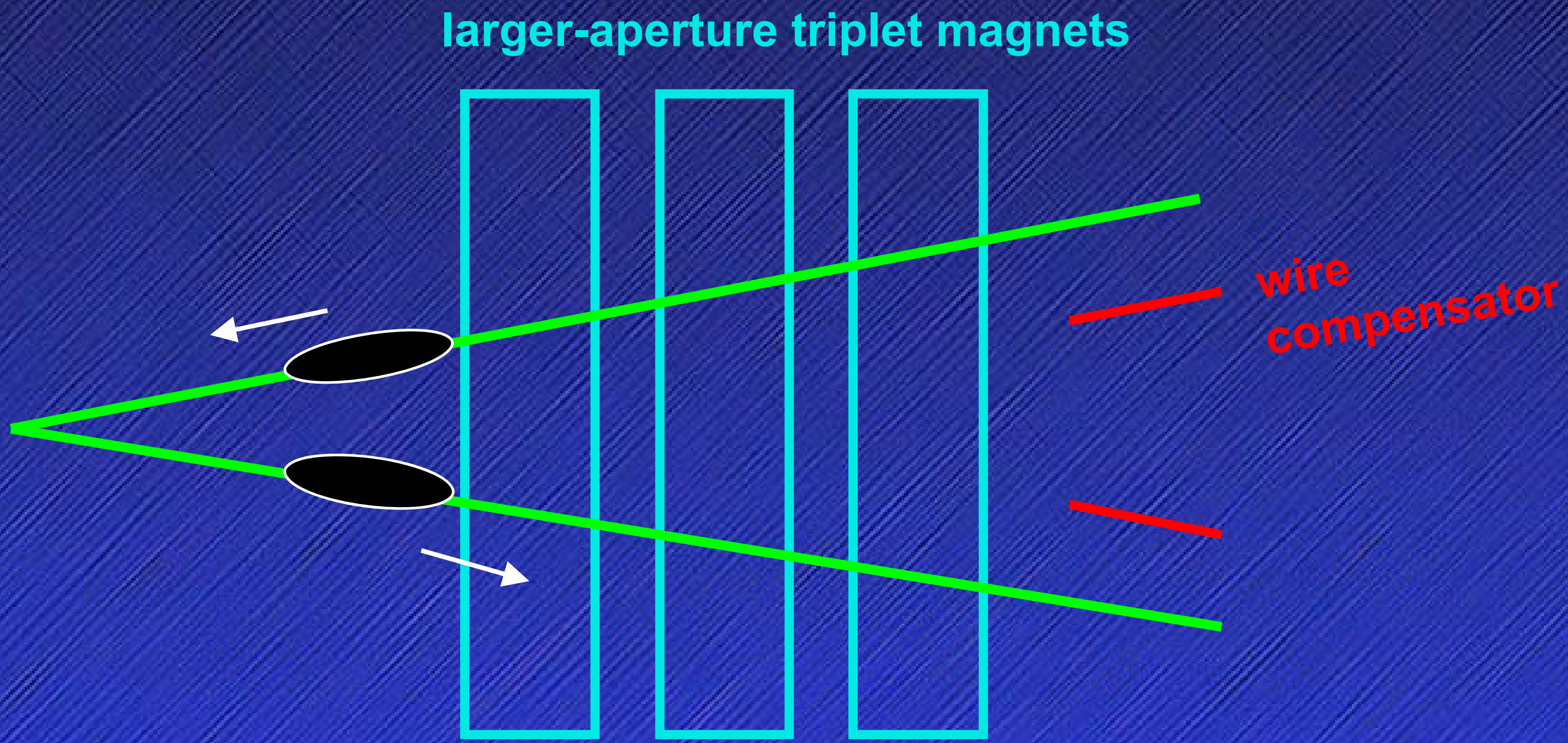


LHC upgrade path 2: large Piwinski angle (LPA)

- double bunch spacing to 50 ns, longer & more intense bunches with $\phi_{Piwinski}$~ 2
- β*~25 cm, do not add any elements inside detectors
- long-range beam-beam wire compensation

→ novel operating regime for hadron colliders

F. Ruggiero,
W. Scandale.
F. Zimmermann



fewer, long & intense bunches + nonzero crossing angle + wire compensation

ES scenario assessment

merits:

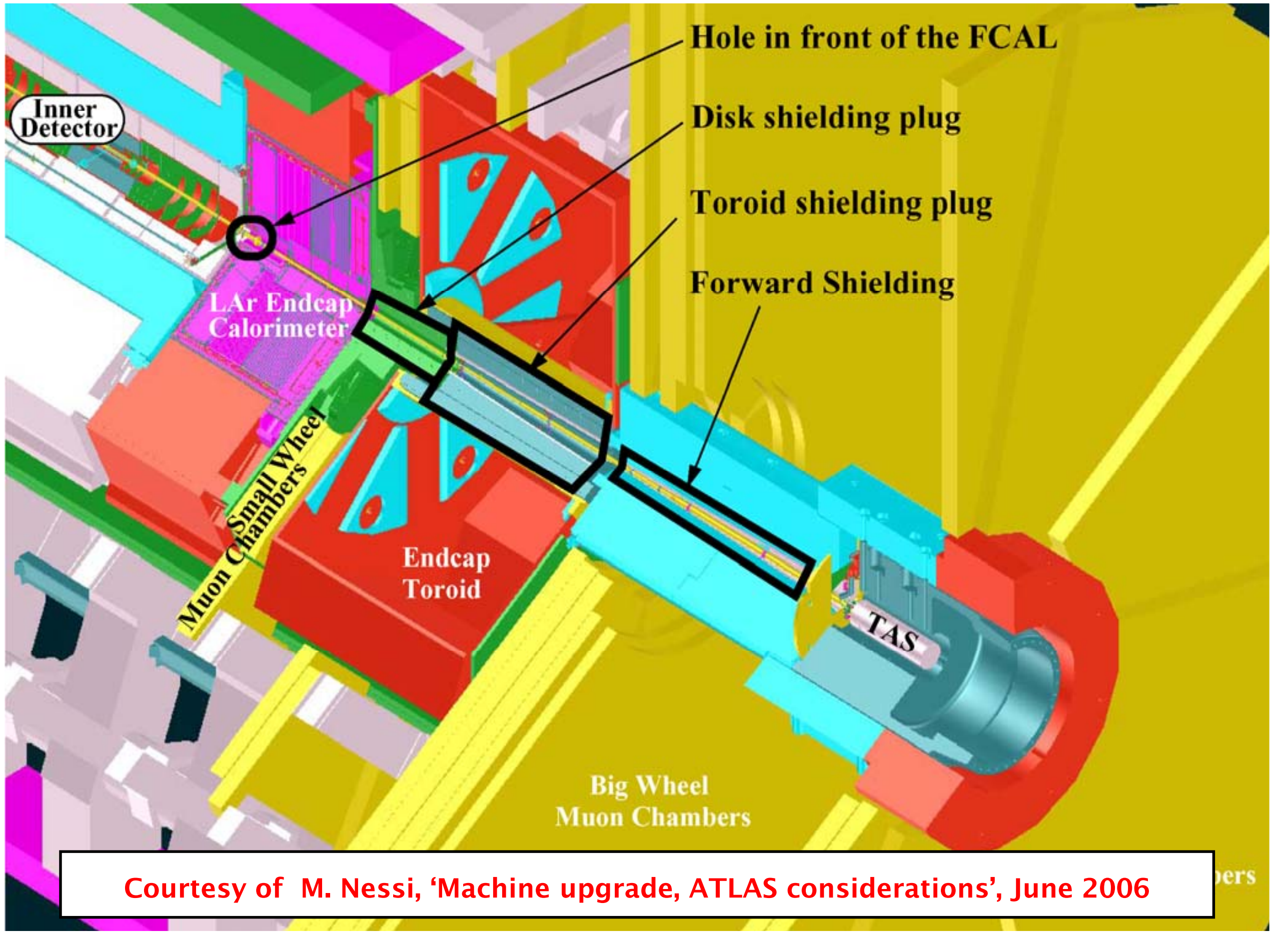
most long-range collisions negligible,
no geometric luminosity loss,
no increase in beam current beyond ultimate,
could be adapted to crab waist collisions (LNF/FP7)

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?

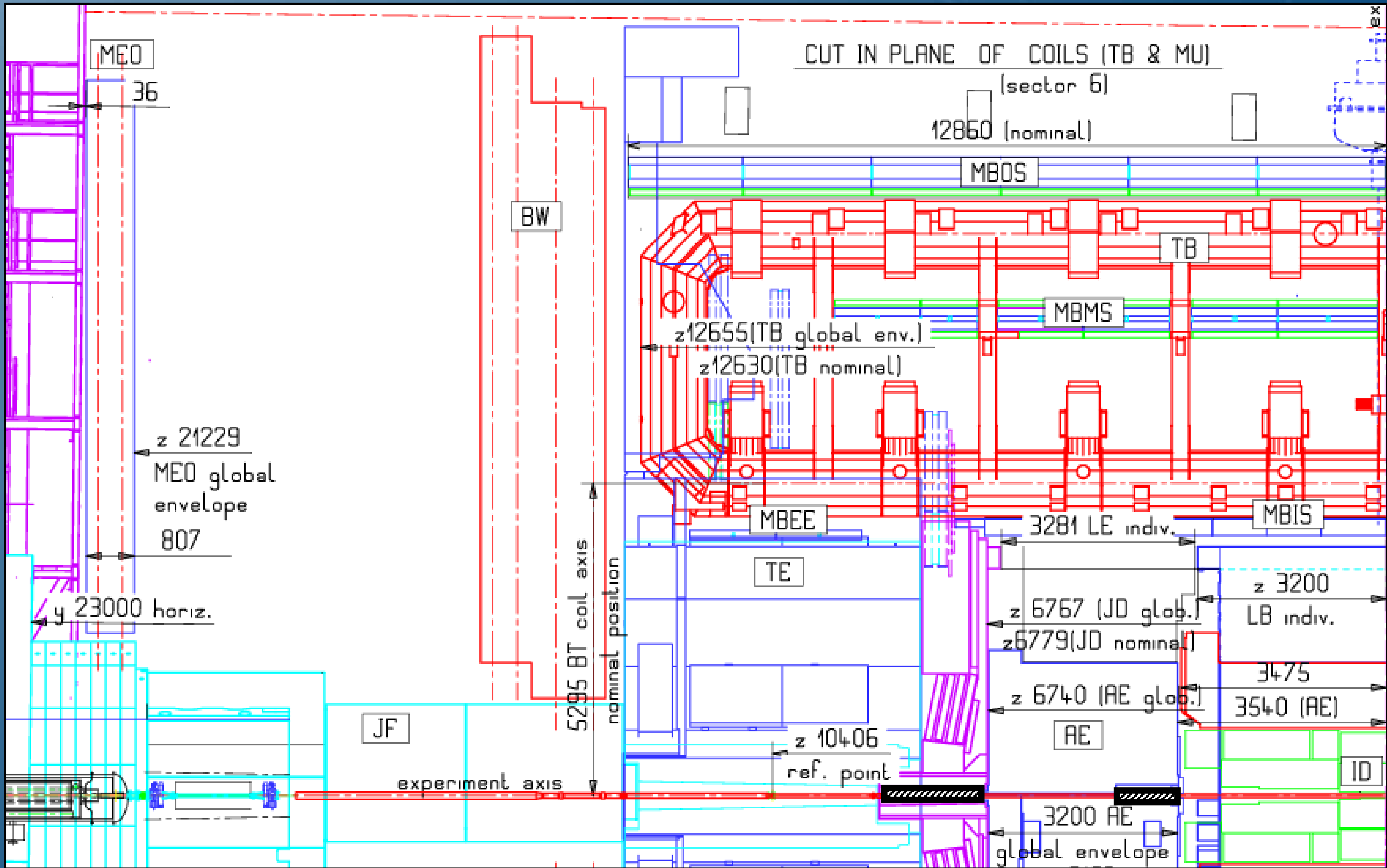
- We cannot put the D0 in the inner detector
- BUT there are potential slots starting at 3.5 m and 6.8 m (ATLAS)



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

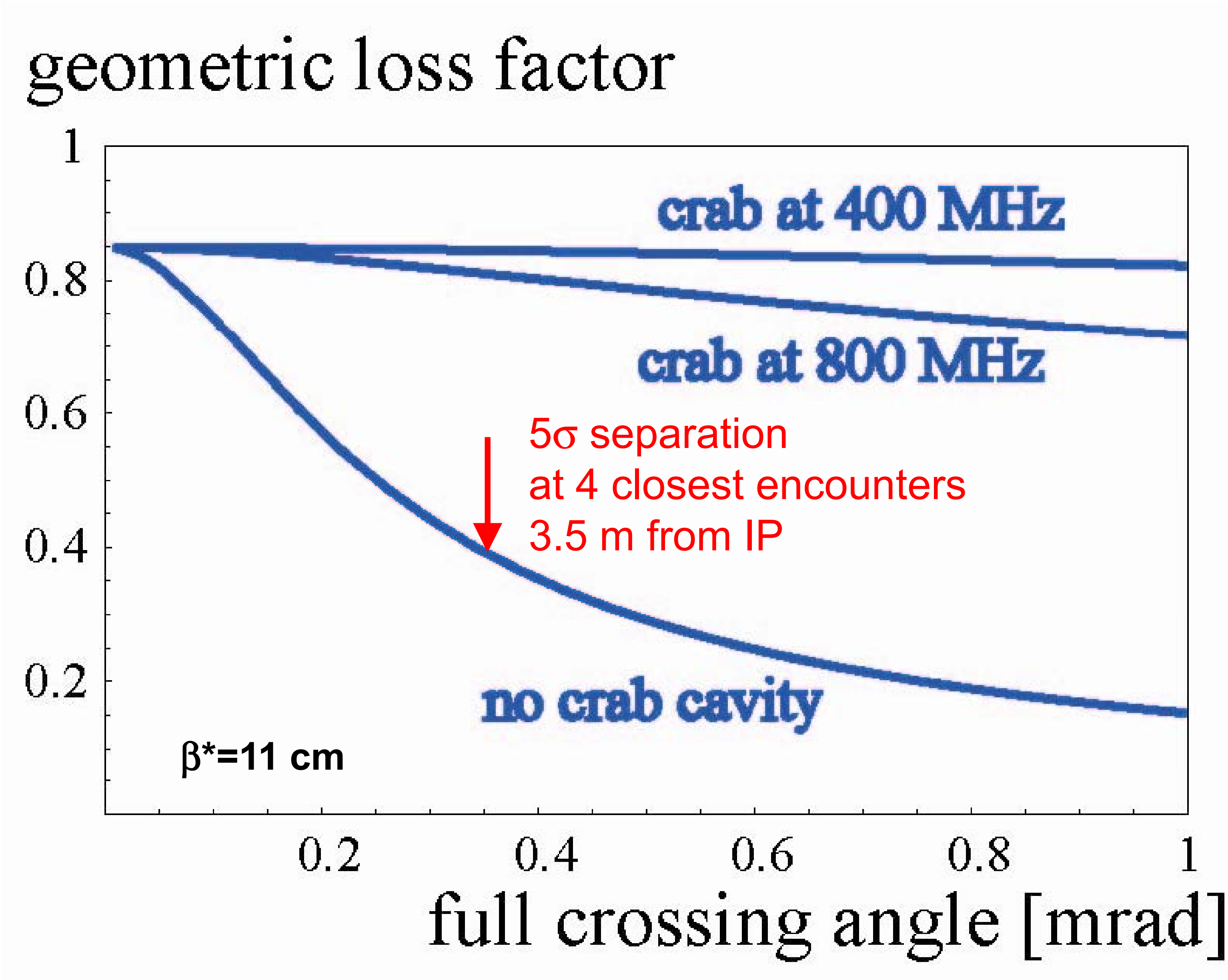
G. Sterbini, J.-P. Koutchouk, LUMI'06

Where would we put the D0 in ATLAS?



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

ES scheme needs crab cavities



crab rf vs bunch shortening rf

bunch shortening rf voltage:

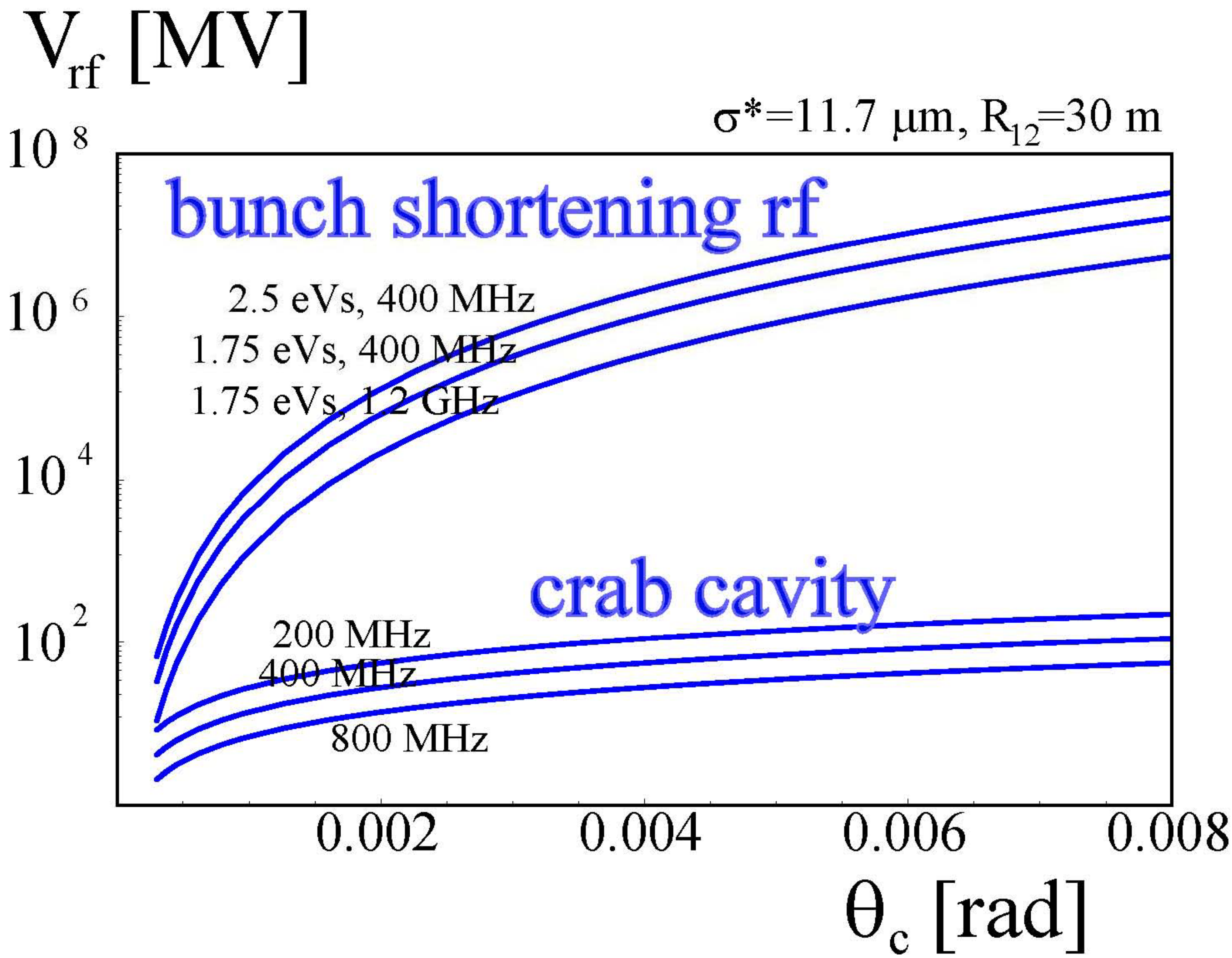
$$V_{rf} \approx \left[\frac{\varepsilon_{\|,rms}^{2} c^{3} C \eta}{E_0 \, 2\pi f_{rf}} \right] \frac{1}{\sigma_z^4} \approx \left[\frac{\varepsilon_{\|,rms}^{2} c^{3} C \eta}{E_0 \, 2\pi f_{rf}} \right] \frac{\theta_c^4}{0.7^4 \, 16 \sigma_x^{*4}}$$

unfavorable scaling as 4th power of crossing angle and inverse 4th power of IP beam size; can be decreased by reducing the longitudinal emittance; inversely proportional to rf frequency

crab cavity rf voltage:

$$V_{crab} = \frac{c E_0 \tan\left(\theta_c / 2\right)}{e 2\pi f_{rf} R_{12}} \approx \frac{c E_0}{e 4\pi f_{rf} R_{12}} \theta_c$$

proportional to crossing angle & independent of IP beam size; scales with $1/R_{12}$; also inversely proportional to rf frequency



F. Zimmermann, U. Dorda, LUMI'05

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 δ=3x10^{-4}

motivation for flat bunches & LPA

luminosity for Gaussian bunches

$$L^{Gauss} \approx \frac{1}{2} \frac{f_{coll}\gamma}{r_p \beta^*} \Delta Q_{tot} N_b$$

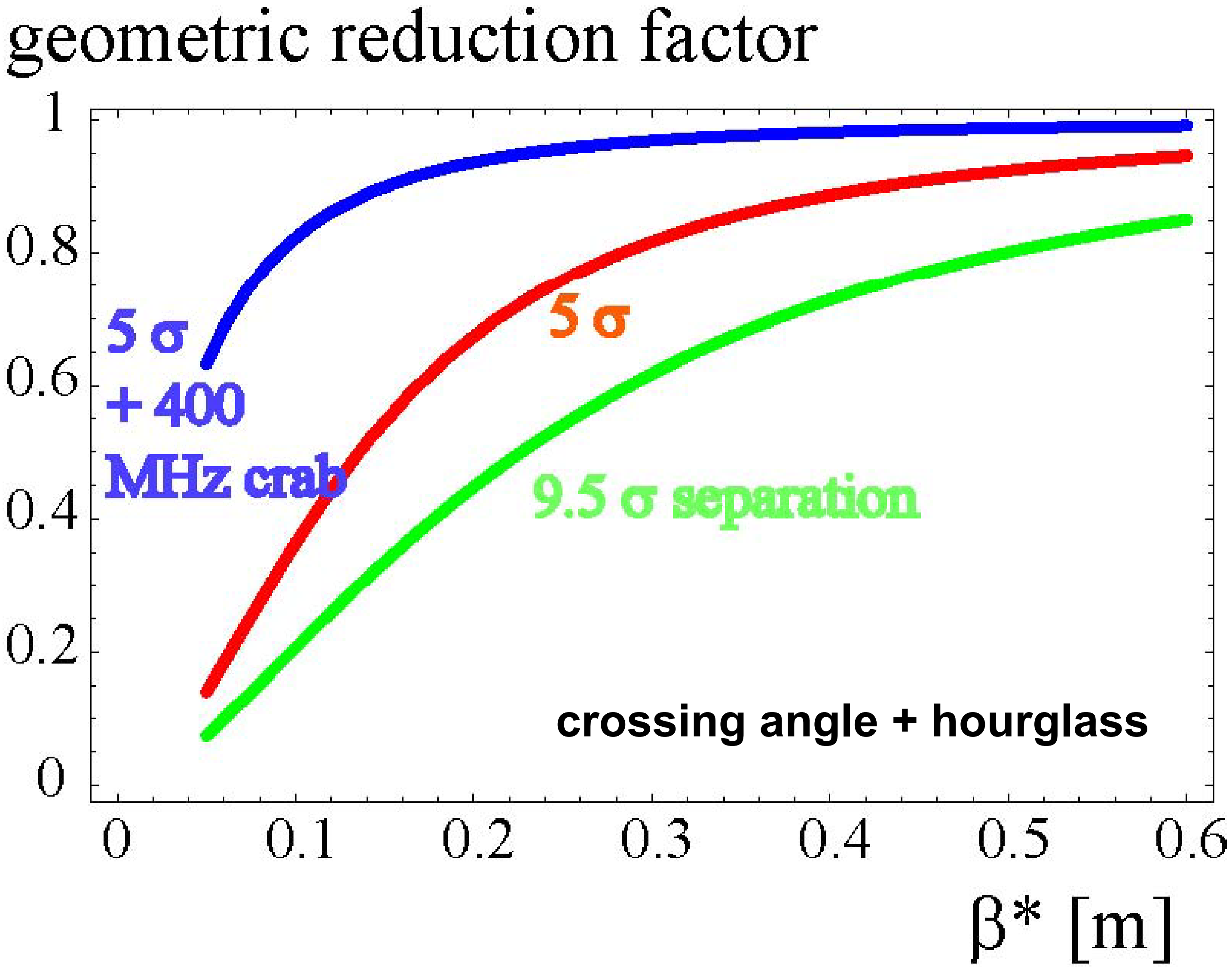
luminosity for "flat" bunches

$$L^{flat} \approx \frac{1}{\sqrt{2}} \frac{f_{coll}\gamma}{r_p \beta^*} \Delta Q_{tot} N_b$$

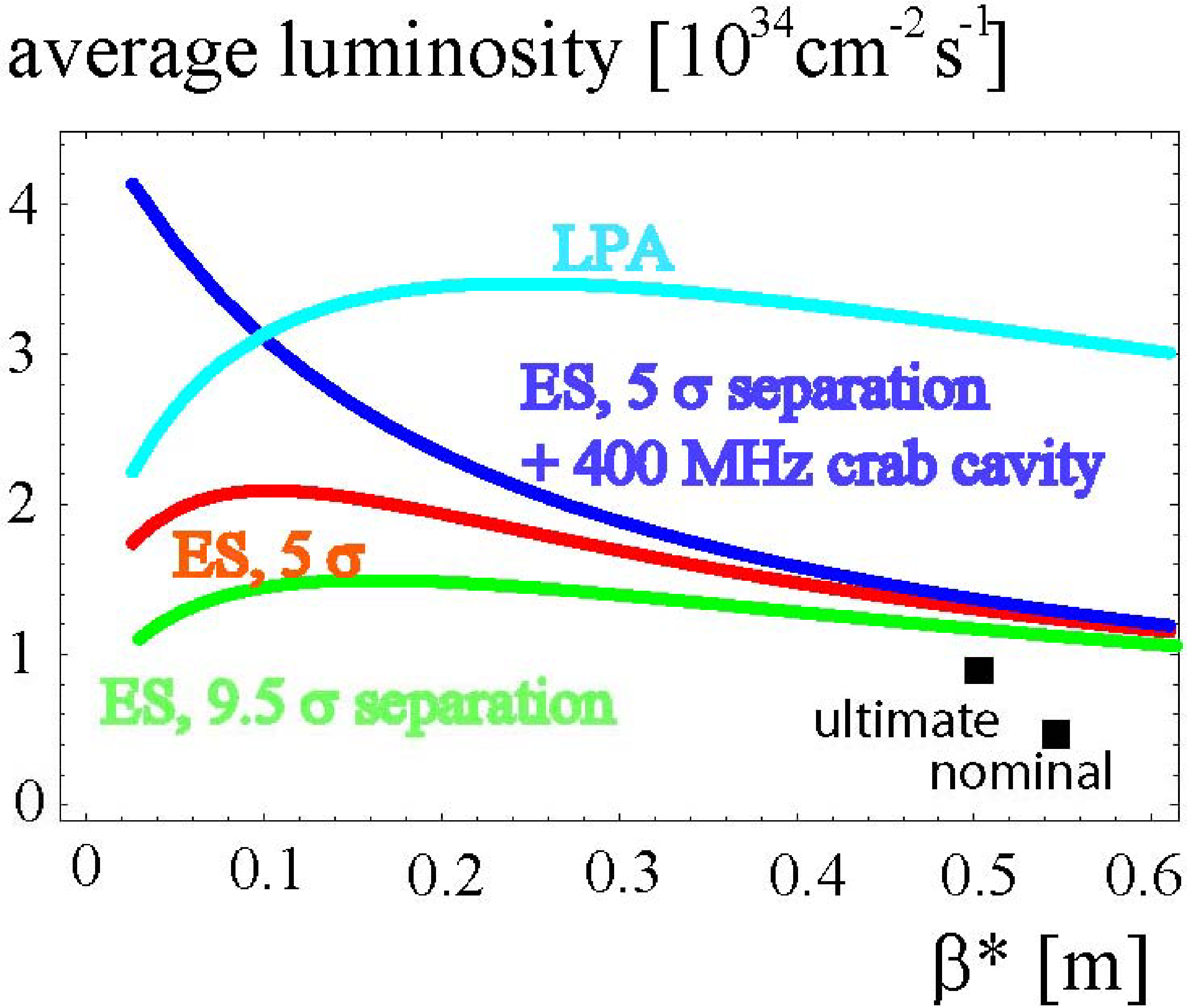
F. Ruggiero, G. Rumolo, F. Zimmermann, Y. Papaphilippou, RPIA2002

for the same total number of particles and the same total tune shift from two IPs the luminosity will be ~1.4x higher with a "flat" bunch distribution; also: the number of particles N_b can be increased independently of ΔQ_{tot} only in the regime of large Piwinski angle

geometric luminosity reduction vs β*



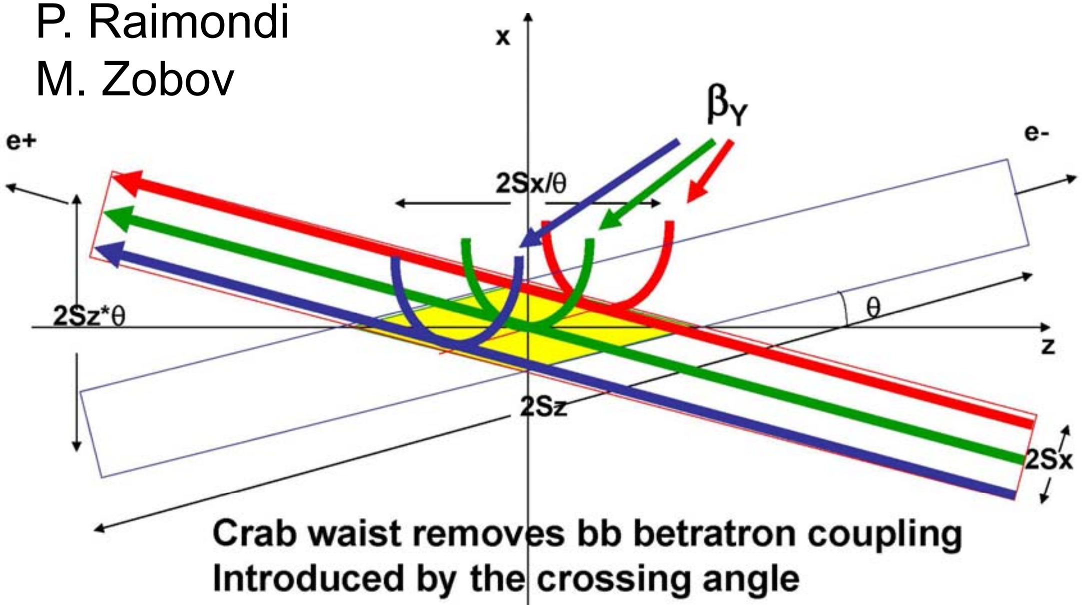
average luminosity vs β*



including crossing angle + hourglass, assuming optimum run time for 5 h turn-around

aside: “crab waist” scheme for LHC?

P. Raimondi
M. Zobov



Vertical waist has to be a function of x:

Z=0 for particles at $-\sigma_x$ ($-\sigma_x/2\theta$ at low current)

Z= σ_x/θ for particles at + σ_x ($\sigma_x/2\theta$ at low current)

Crab waist realized with 2 sextupoles in phase with the IP in X and at $\pi/2$ in Y

requires:

-flat beams ($\beta_y^* << \beta_x^*$)

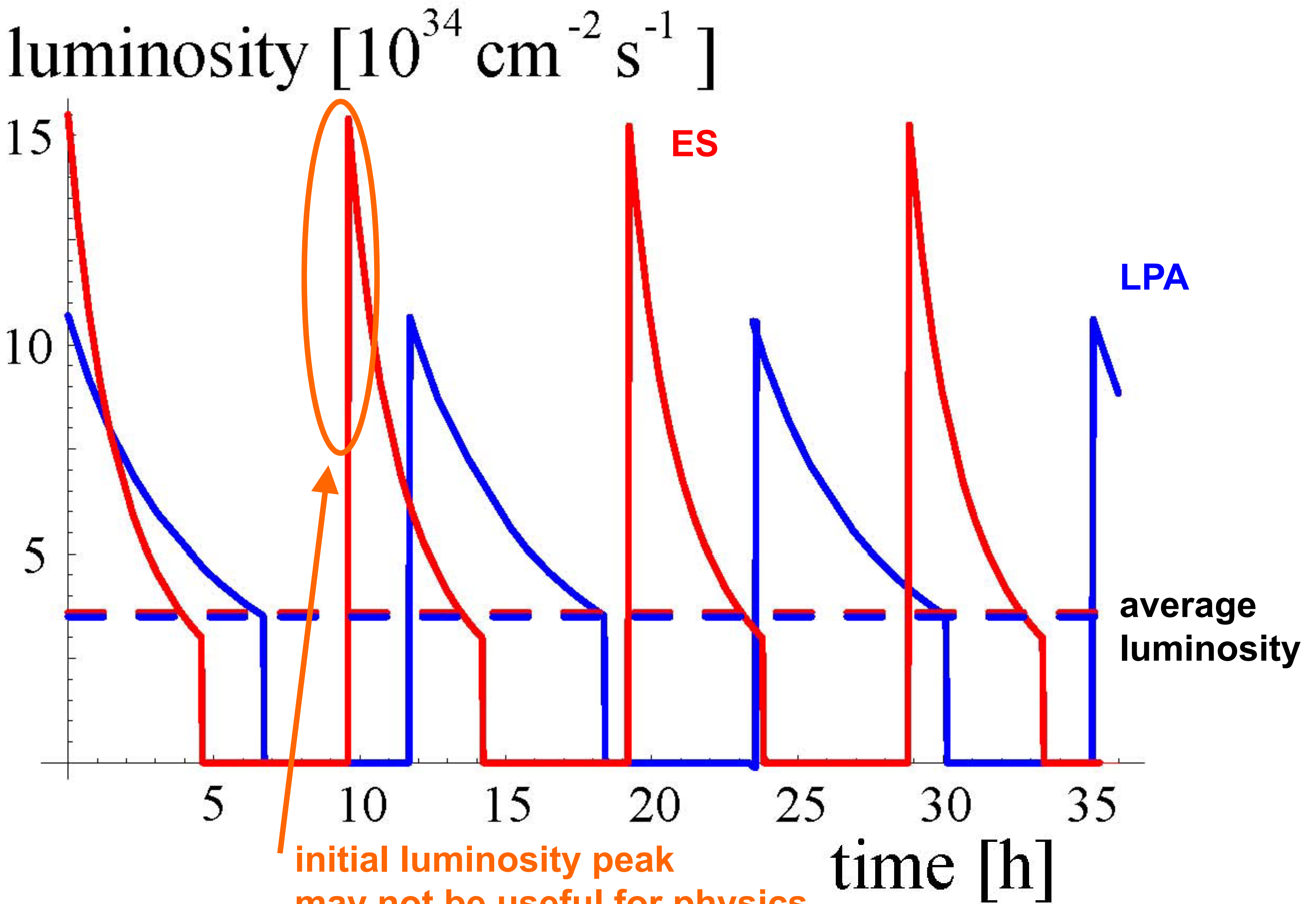
-large Piwinski angle (like LPA)

– $\beta_y^* \sim \sigma_x^*/\theta$ (like ES)

– crab-waist sextupole transformation

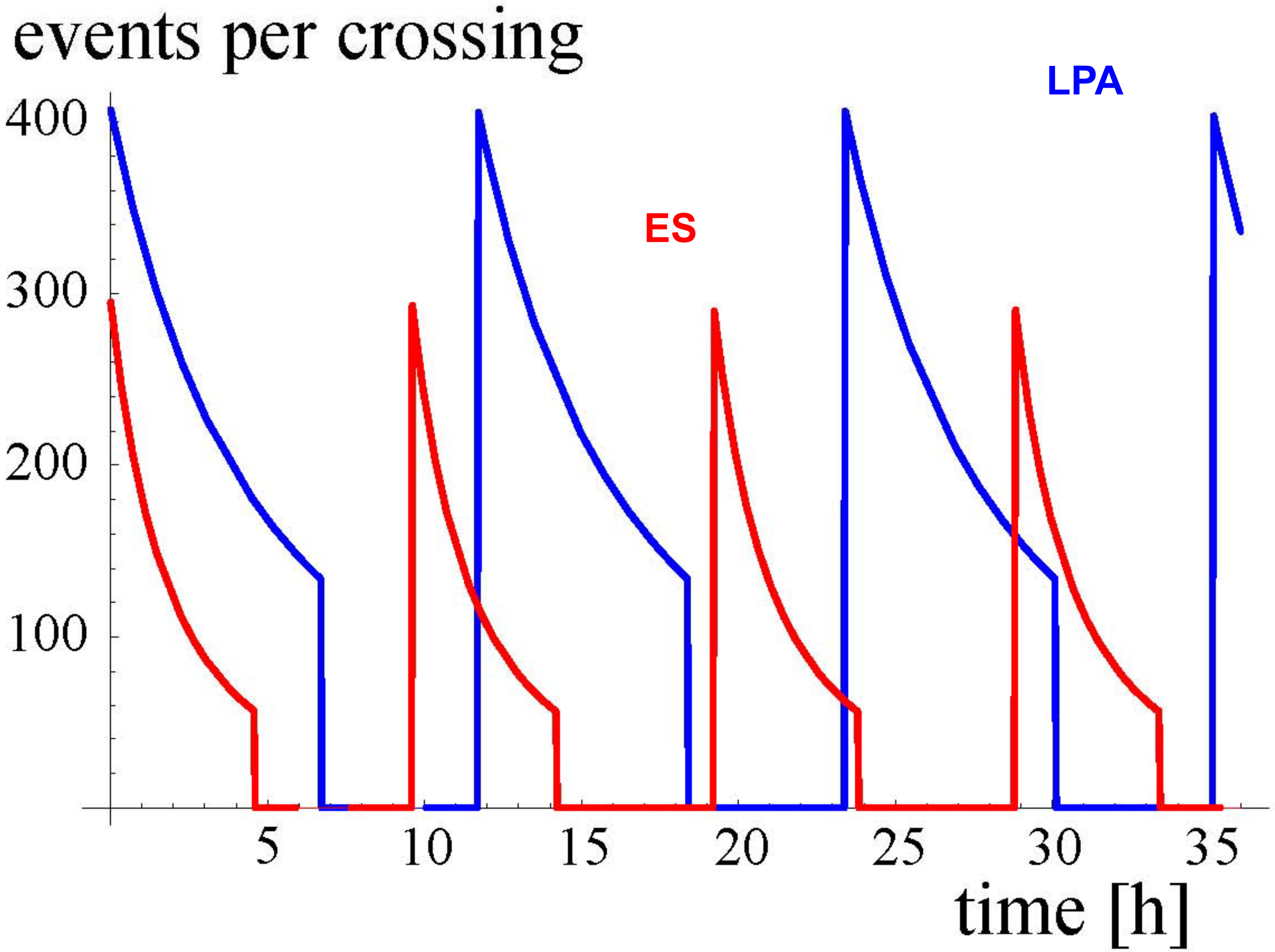
possible approach: go to flat beams, combine ingredients of LPA & ES schemes, add sextupoles

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

run time & average luminosity

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

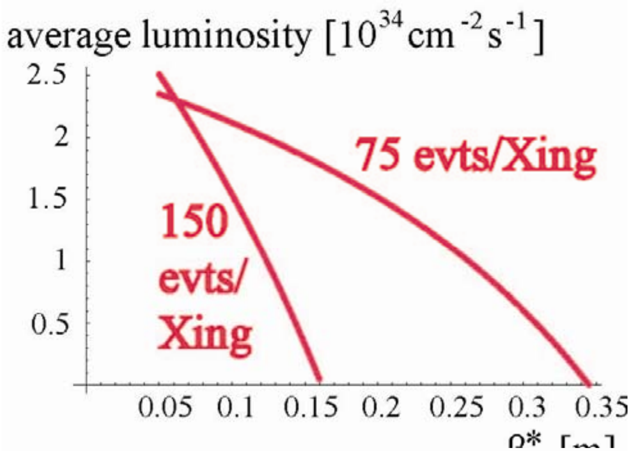
$$\tau_{eff}=\frac{N_0 n_b}{n_{IP}\hat{L}\sigma_{tot}} \qquad \tau_{lev}=\frac{N_0 n_b}{n_{IP}L_0\sigma_{tot}}$$

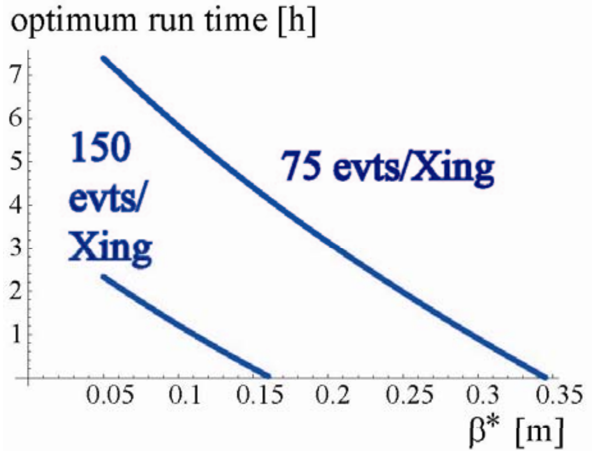
examples	ES, low β*, with leveling	LPA, long bunches, with leveling
events/crossing run time av. luminosity	300 N/A N/A	300 2.5 h $2.6\times10^{34}s^{-1}cm^{-2}$
events/crossing run time av. luminosity	150 2.5 h $2.6\times10^{34}s^{-1}cm^{-2}$	150 14.8 h $2.9\times10^{34}s^{-1}cm^{-2}$
events/crossing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

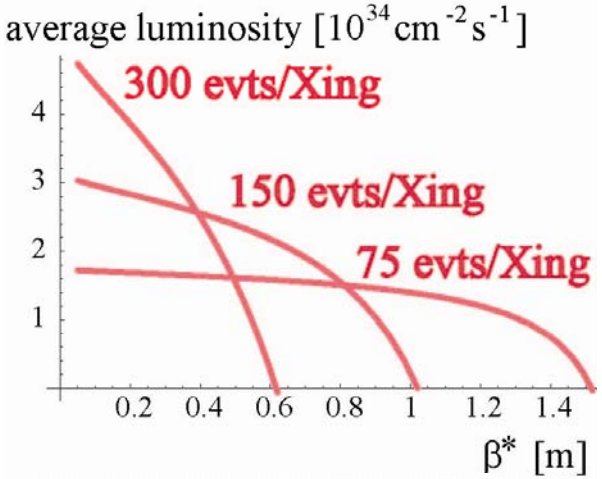
average luminosity & run time vs. final β*, l_b

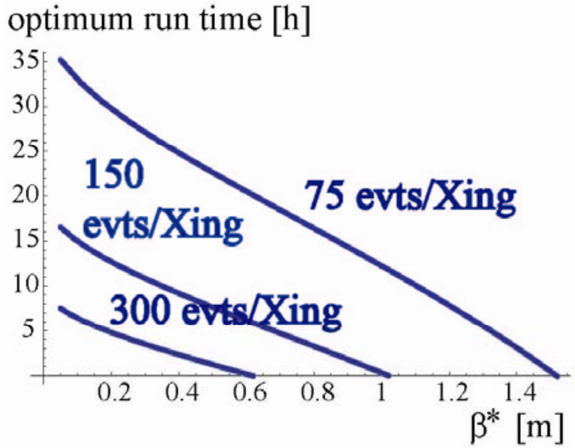
for ES with β* squeeze



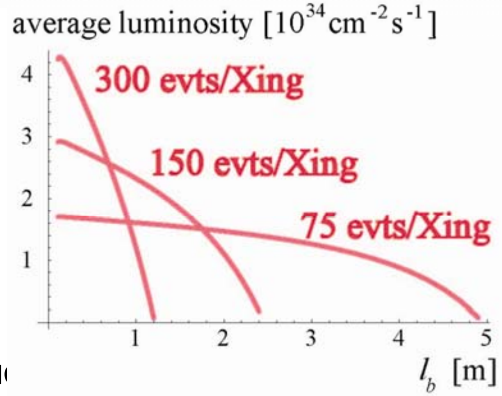


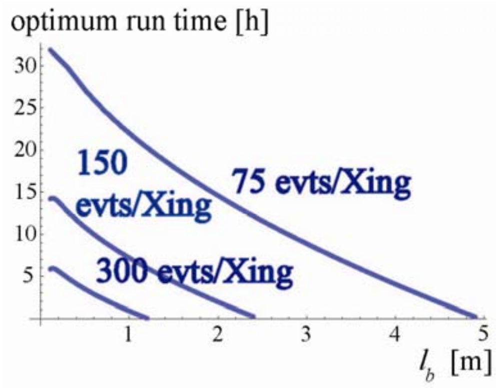
for LPA with β* squeeze



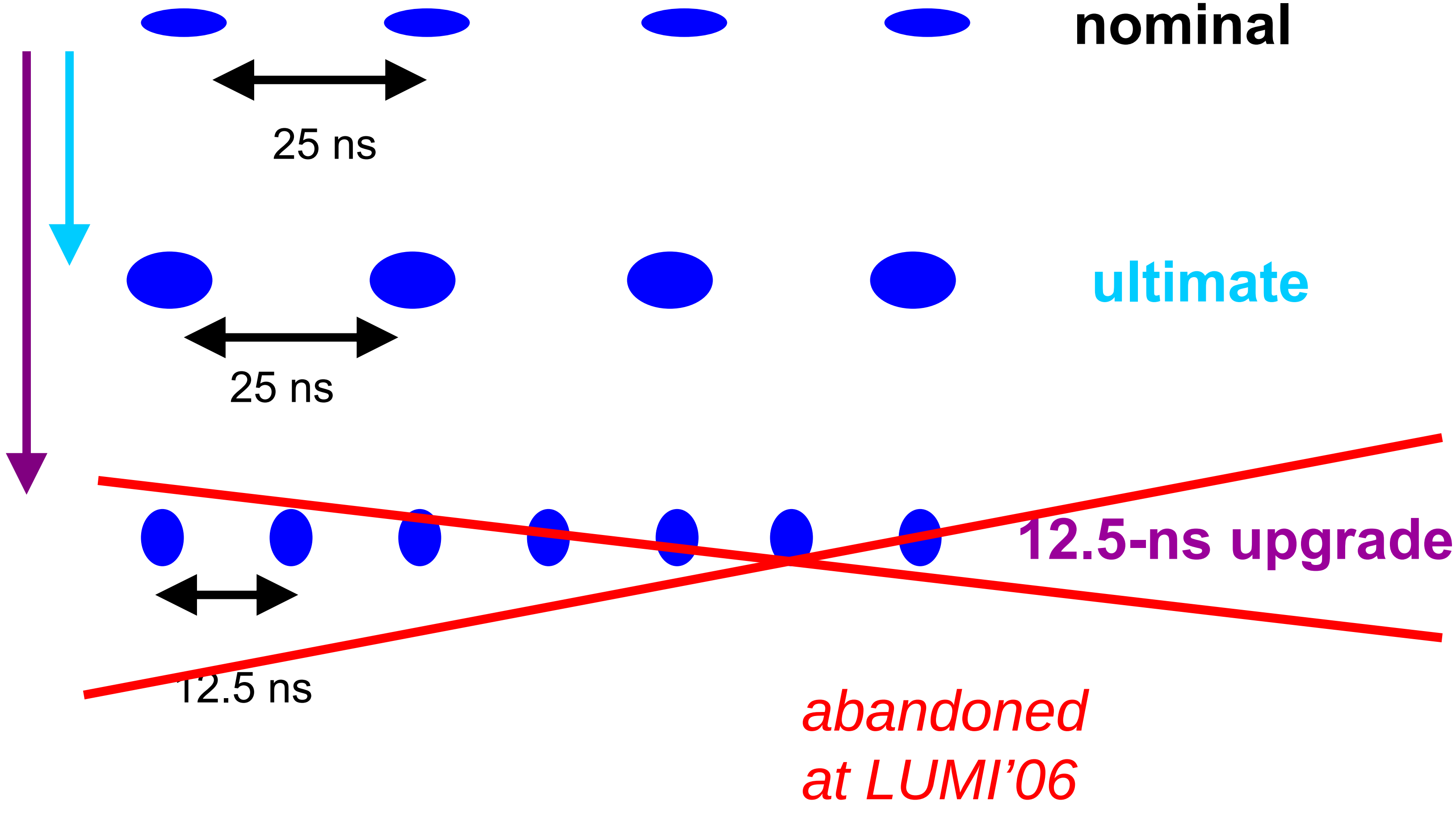


for LPA with l_b reduction

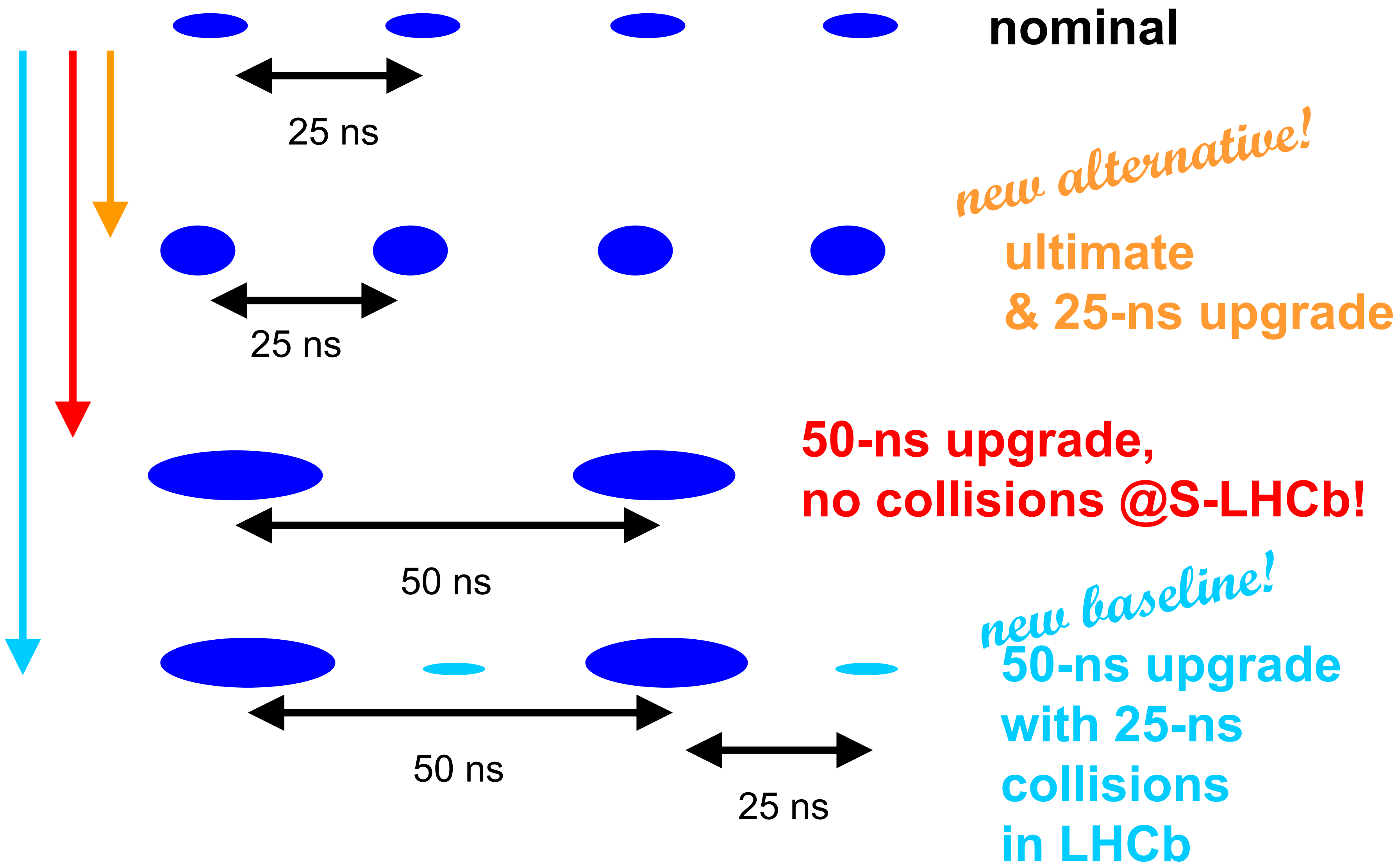




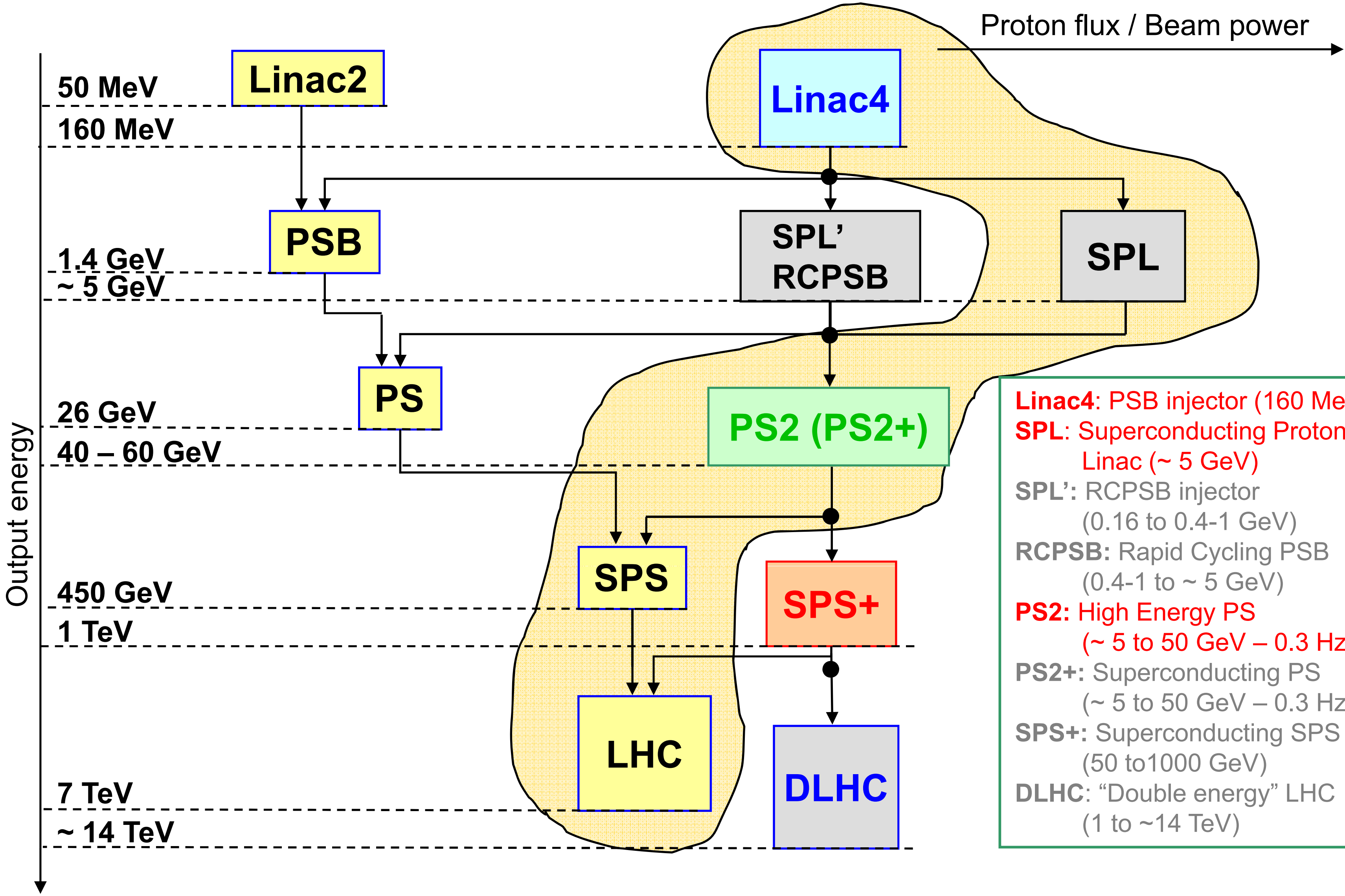
old upgrade bunch structure



new upgrade bunch structures



DG White Paper Injector Upgrade



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

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)
- numerous techniques for bunch flattening

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 may decide upgrade path**
- **crab waist option could be further explored**

BEAM'07 goals

- assess potential 'show-stoppers' for the two alternative upgrade paths (LPA and ES)
- compare their respective luminosity reach
- advance designs of LHC injector upgrade & GSI FAIR project