# Scenarios and Technological Challenges for an LHC Luminosity Upgrade (3/5):

# *Scenarios for the LHC Luminosity Upgrade*

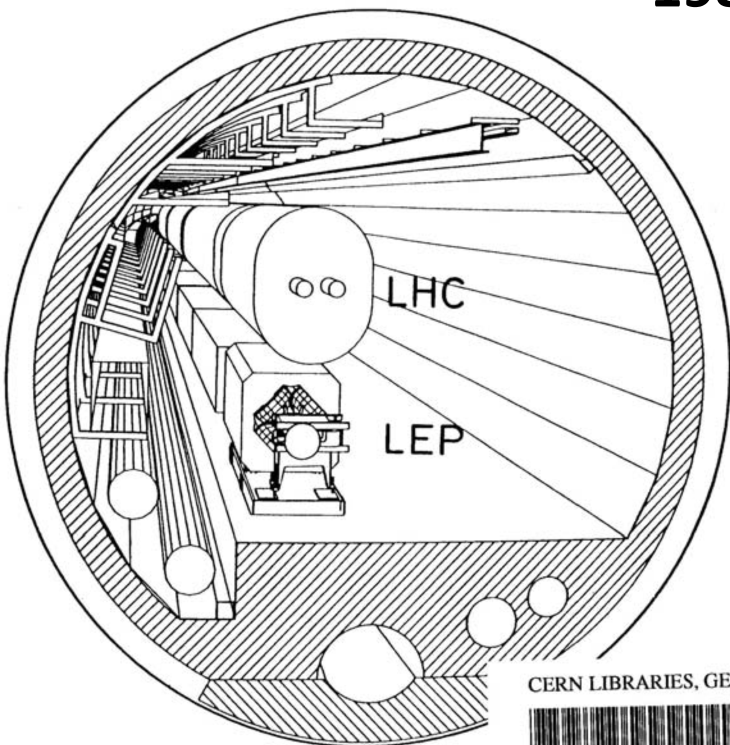
Frank Zimmermann

CERN Academic Training

10 June 2009

DIR-TECH/84-01
May 1984

**1984**






# LARGE HADRON COLLIDER IN THE LEP TUNNEL

A feasibility study of possible options

by

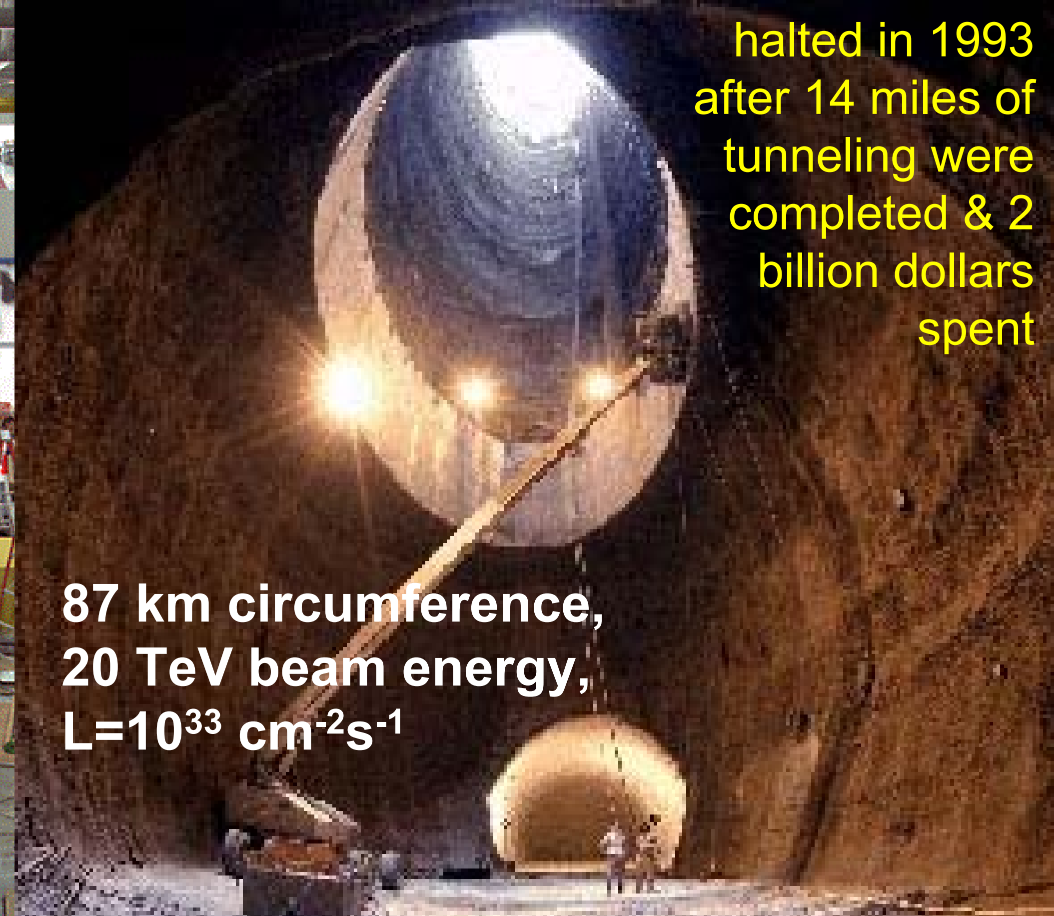
The CERN Machine Group

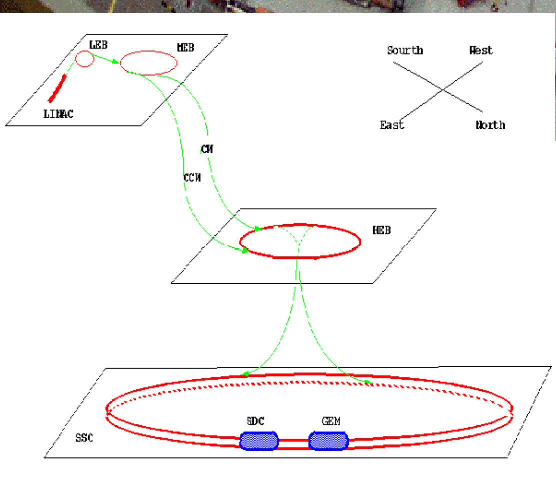
***"Although the machine operation would become more difficult, it is not unconceivable that the luminosity could eventually approach or even exceed $10^{33}$ $cm^{-2}$ $s^{-1}$ …"***

# *Superconducting SuperCollider*

halted in 1993 after 14 miles of tunneling were completed & 2 billion dollars spent

87 km circumference,
20 TeV beam energy,
$L=10^{33}$ $cm^{-2}s^{-1}$







AMERICAN INSTITUTE OF PHYSICS

Inside Science Research — Physics News Update

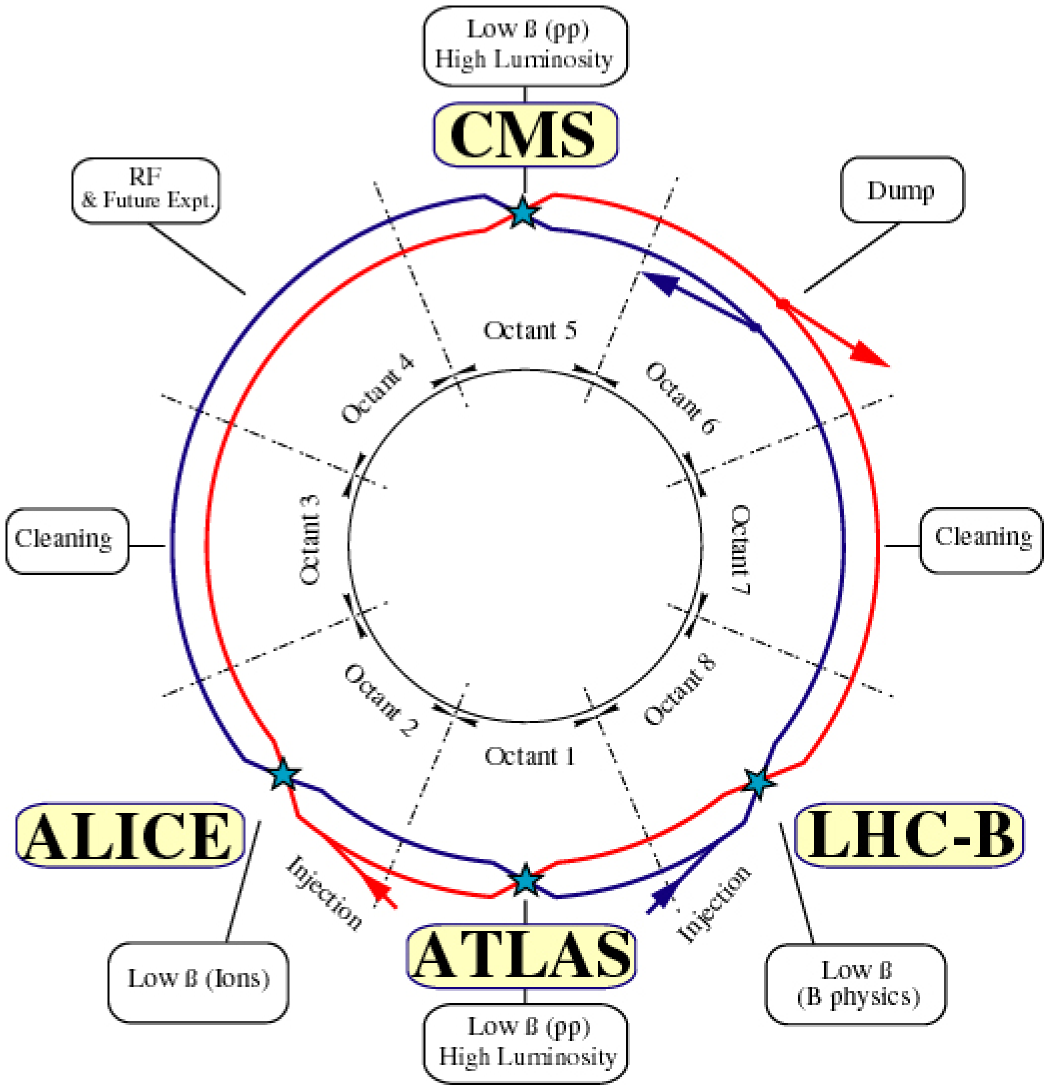
Number 47 (Story #3), September 13, 1991 by Phillip F. Schewe and Ben Stein

THE LARGE HADRON COLLIDER , Europe's version of the SSC, has not been officially approved …, but plans for the machine proceed... **LHC's maximum collision energy, …would be less than SSC's 40 TeV, but CERN's Director General Carlo Rubbia believes that their emphasis on high luminosity will enable them to harvest much of the new physics that may be waiting at TeV energies.**

***nominal LHC has 10x more luminosity than SSC design at 1/3 beam energy***

*(now LHC experiments are asking for 10x more still!)*

# nominal LHC 2009

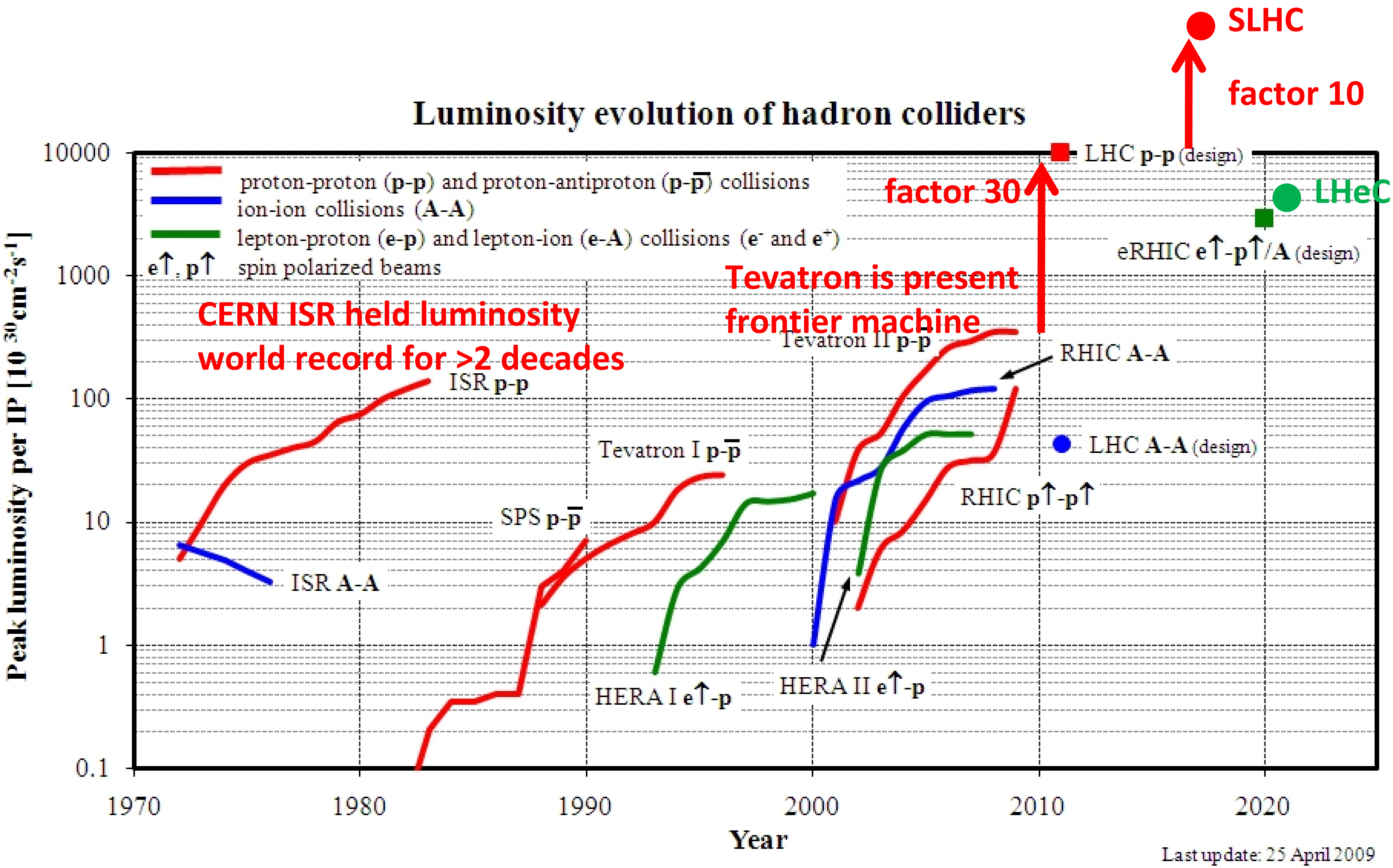



**c.m. energy 14 TeV (7x Tevatron)**

**design luminosity $10^{34}$ $cm^{-2}s^{-1}$ (~30x Tevatron)**

**beam commissioning started in 2008**

***LHC baseline luminosity was pushed in competition with SSC***




Courtesy W. Fischer

# physics reach, discovery potential, precision

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

Units are TeV (except $W_L W_L$ 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 |
| $W_L W_L$ | $2\sigma$ | $4\sigma$ | $4.5\sigma$ | $7\sigma$ | $18\sigma$ | $6\sigma$ | $90\sigma$ |
| Z' | 5 | 6 | 8 | 11 | 35 | 8† | 30† |
| Extra-dim ($\delta$=2) | 9 | 12 | 15 | 25 | 65 | 5-8.5† | 30-55† |
| q* | 6.5 | 7.5 | 9.5 | 13 | 75 | 0.8 | 5 |
| Lcompositeness | 30 | 40 | 40 | 50 | 100 | 100 | 400 |
| TGC ($\lambda_\gamma$) | 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 2001. e-Print: **hep-ex/0112004**

# *luminosity*

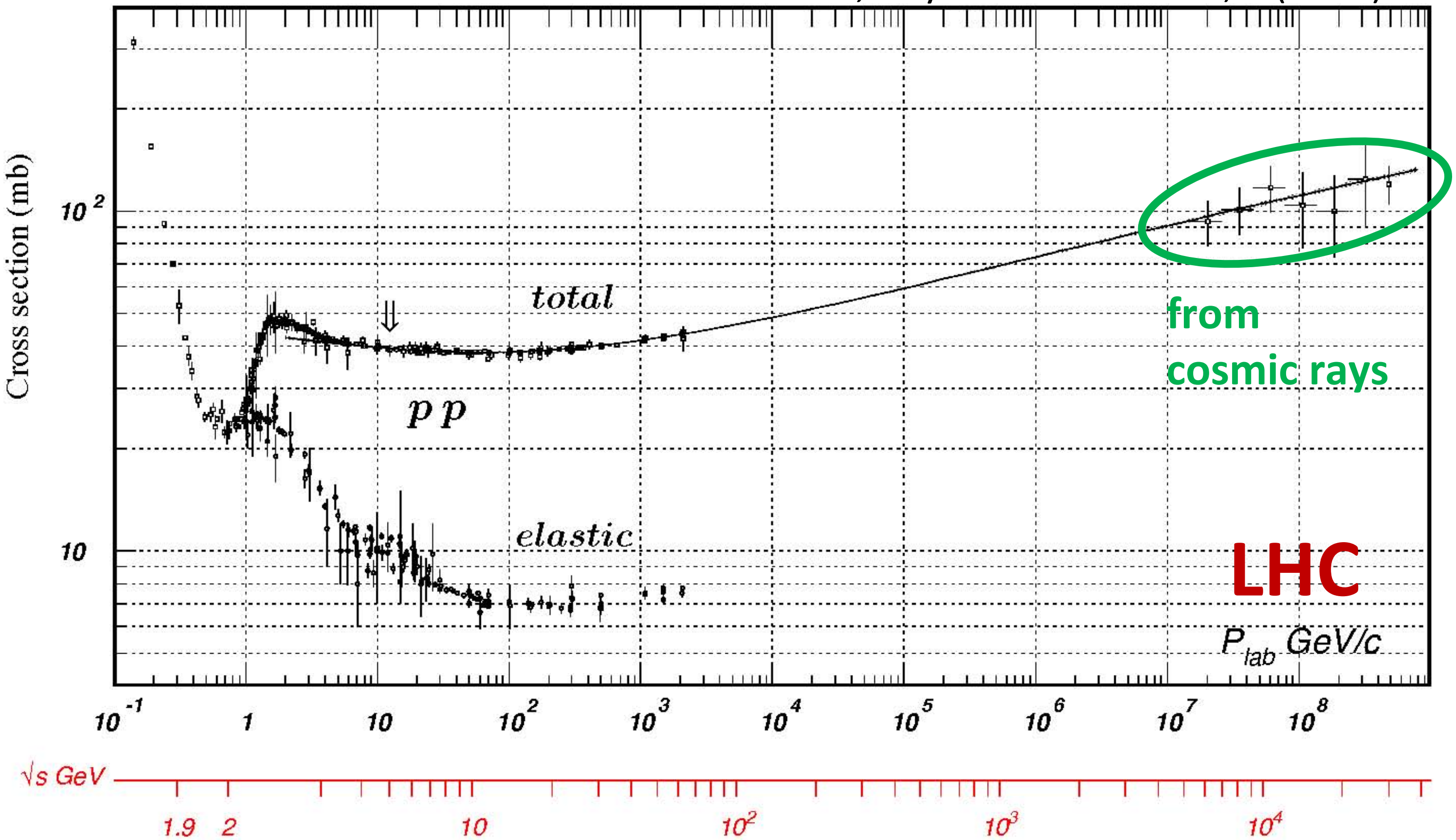
$$R = \sigma\, L$$

reaction rate

cross section

luminosity

C. Amsler *et al.*, Physics Letters **B667**, 1 (2008)




$\sigma_{tot}$~ 100 mbarn ~ $10^{-25}$ cm²

$\sigma_{inelastic}$~ 60 mbarn~ $6\times10^{-26}$ cm²

# *events / crossing*

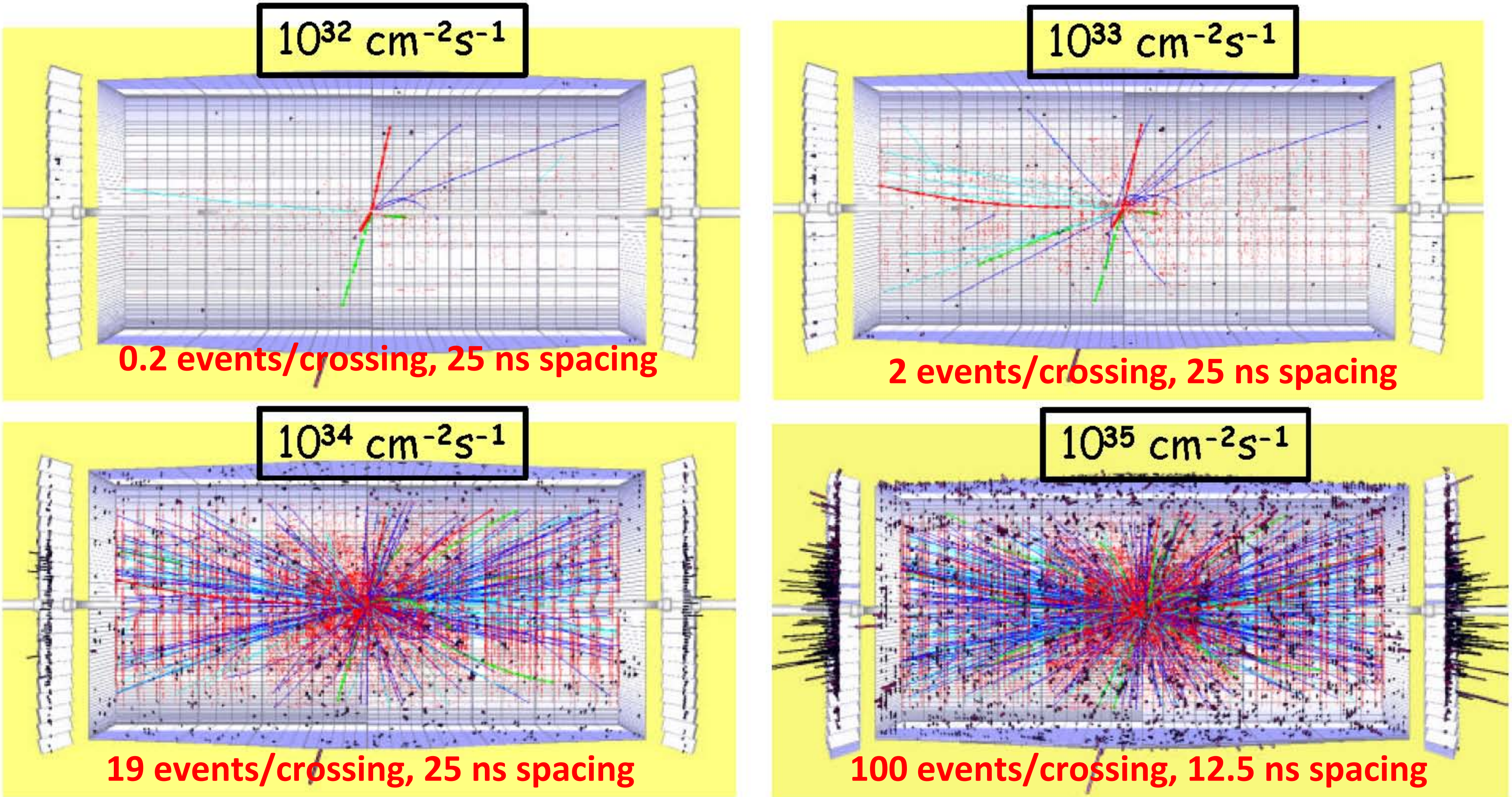
bunch collision rate
= #bunches/beam x revolution frequency

**#events per bunch crossing**
**= cross section x luminosity / bunch collision rate**

**nominal #events/crossing in the detector**
= $6\text{x}10^{-26}$ $\text{cm}^2$ $10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ / (32 $\text{x}10^6$ $\text{s}^{-1}$)
**= 19**

**10 times higher luminosity at same #bunches**
**→ ~200 events per crossing (*detector upgrade!*)**

# *event pile up in detector*

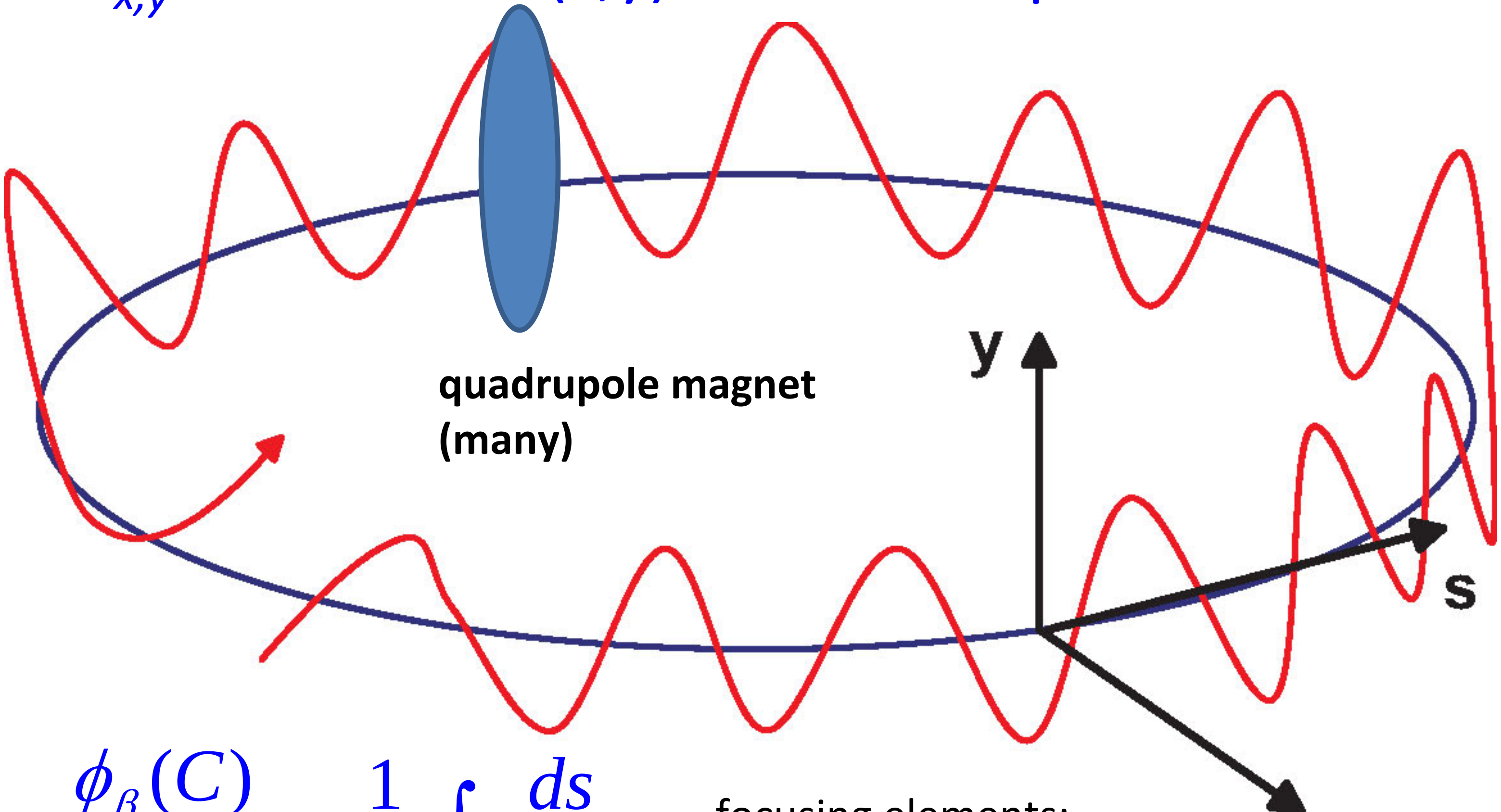



$p_t$ > 1 GeV/c cut, i.e. all soft tracks removed

I. Osborne

# schematic of betatron oscillation around storage ring

tune $Q_{x,y}$= number of (x,y) oscillations per turn

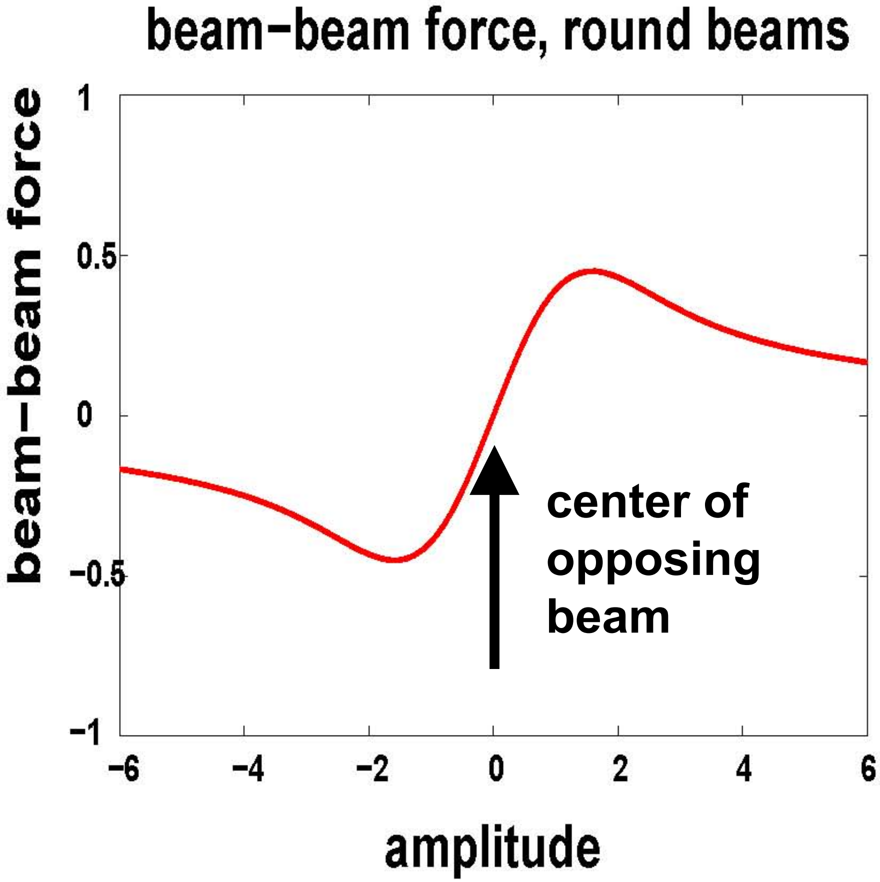



$$Q = \frac{\phi_\beta(C)}{2\pi} = \frac{1}{2\pi}\oint_C \frac{ds}{\beta(s)}$$

focusing elements:
quadrupole magnets

$$\sigma(s) = \sqrt{\frac{\beta(s)\varepsilon_N}{\gamma}}$$

# (nonlinear) beam-beam force




W. Herr

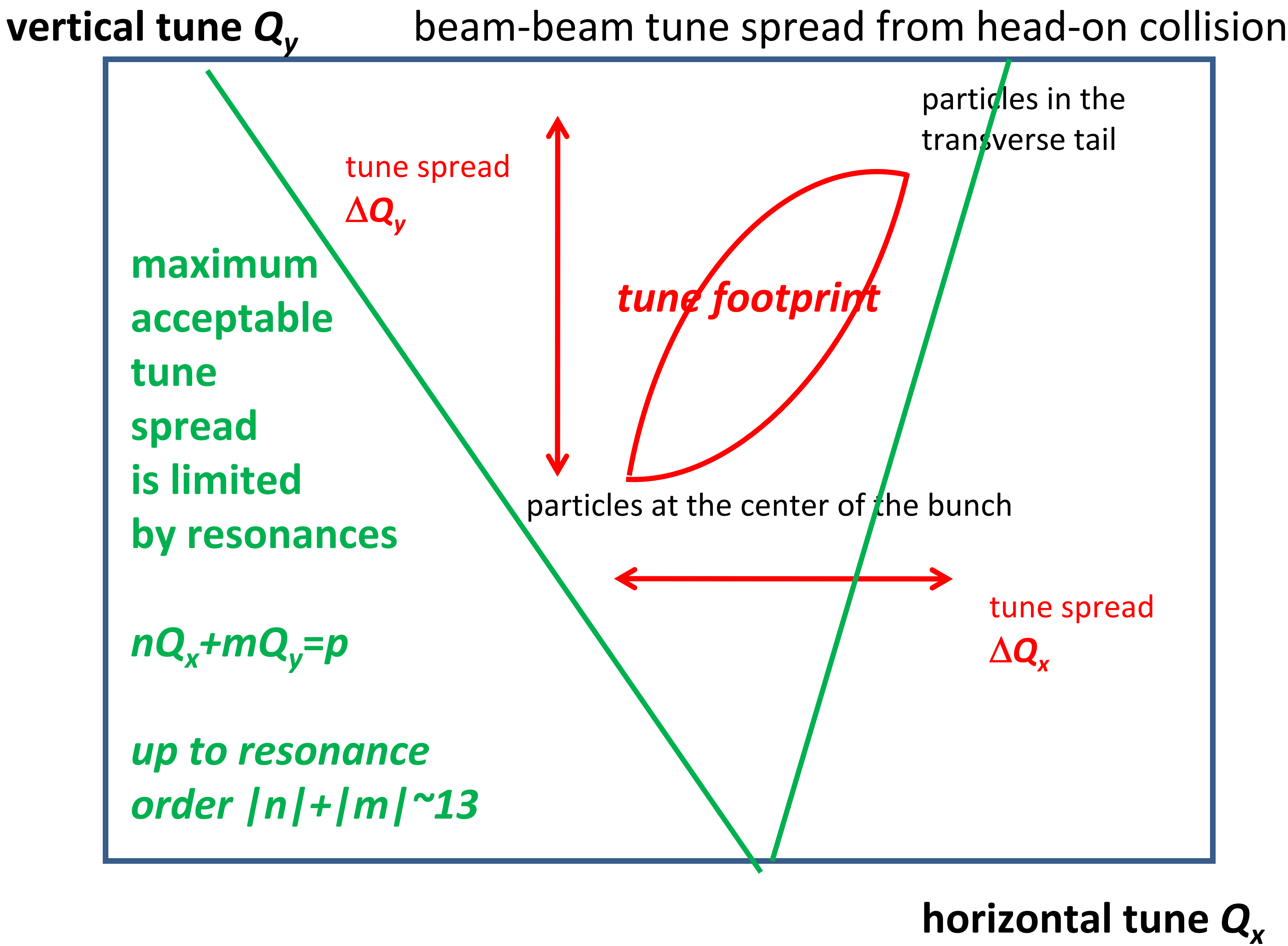
- Force varies strongly with amplitude
- Exponential function:
  - Contains many high order multipoles

at small amplitude similar to effect of defocusing quadrupole

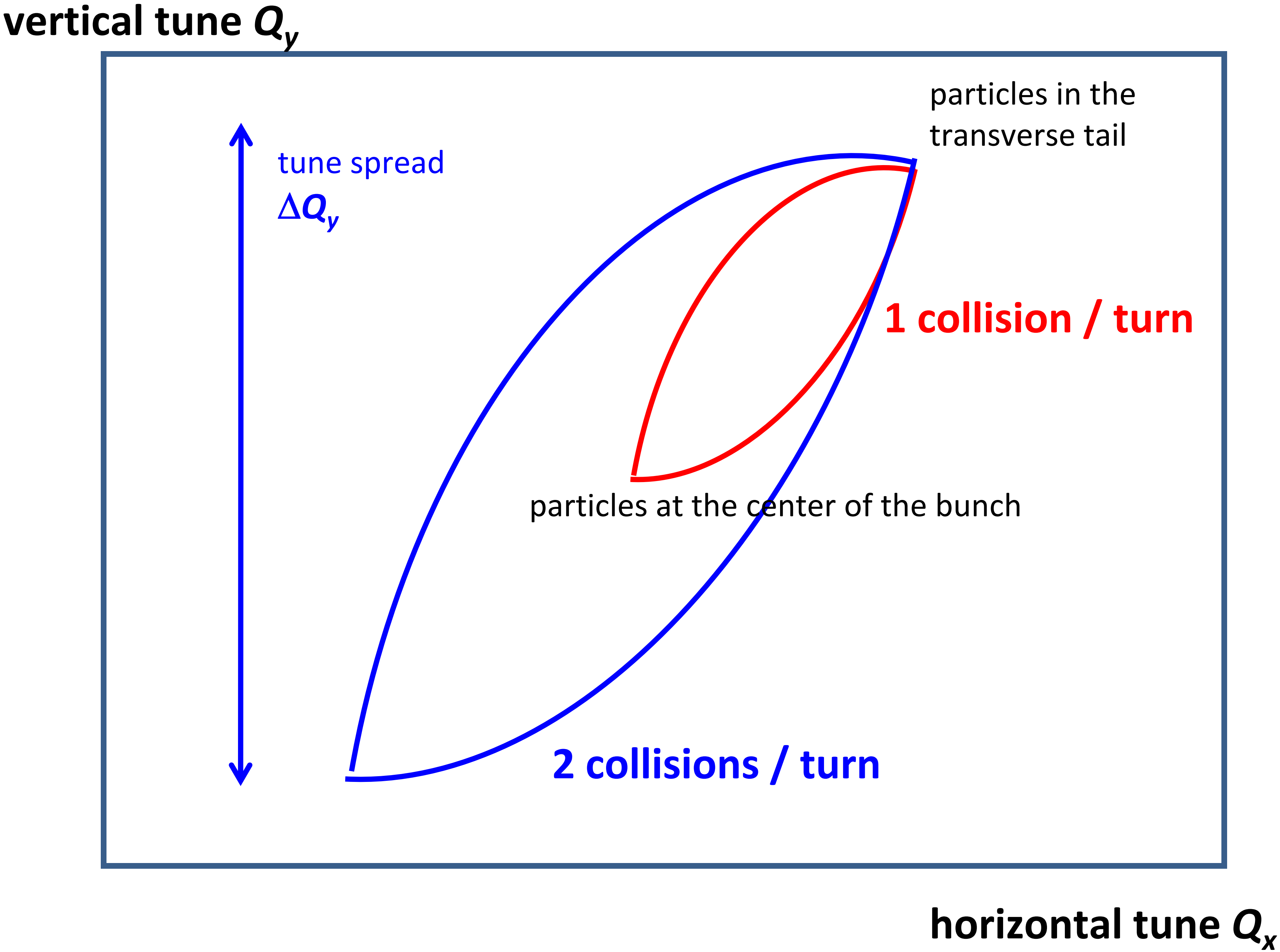
for pure head-on collision

$$\Delta Q_{x.y;\max} = \xi_{x,y} = \frac{2 N_b r_0 \beta^*}{4\pi\gamma\left(2\sigma^{*2}\right)} = \frac{N_b}{\varepsilon_N}\frac{r_0}{4\pi}$$

for single collision (nominal LHC ~0.0033)

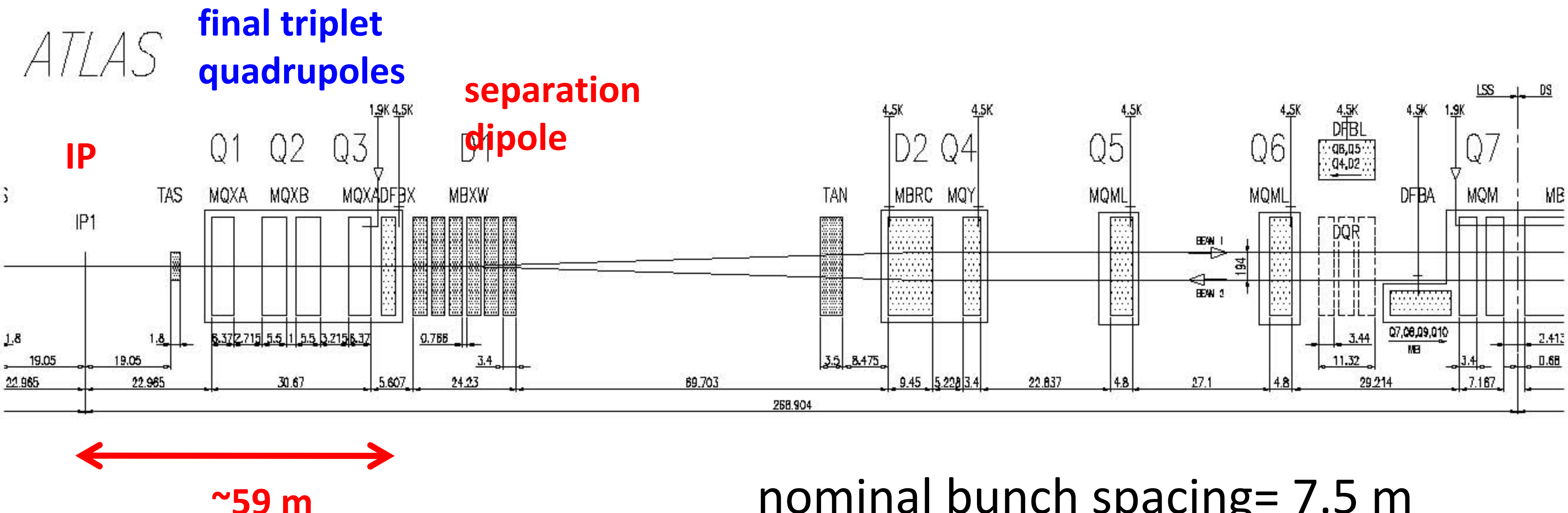


vertical tune $Q_y$
beam-beam tune spread from head-on collision
particles in the transverse tail
tune spread $\Delta Q_y$
maximum acceptable tune spread is limited by resonances
tune footprint
particles at the center of the bunch
tune spread $\Delta Q_x$
$nQ_x+mQ_y=p$
up to resonance order |n|+|m|~13
horizontal tune $Q_x$



vertical tune $Q_y$
tune spread
$\Delta Q_y$
particles in the transverse tail
1 collision / turn
particles at the center of the bunch
2 collisions / turn
horizontal tune $Q_x$

# nominal interaction-region layout




nominal bunch spacing= 7.5 m

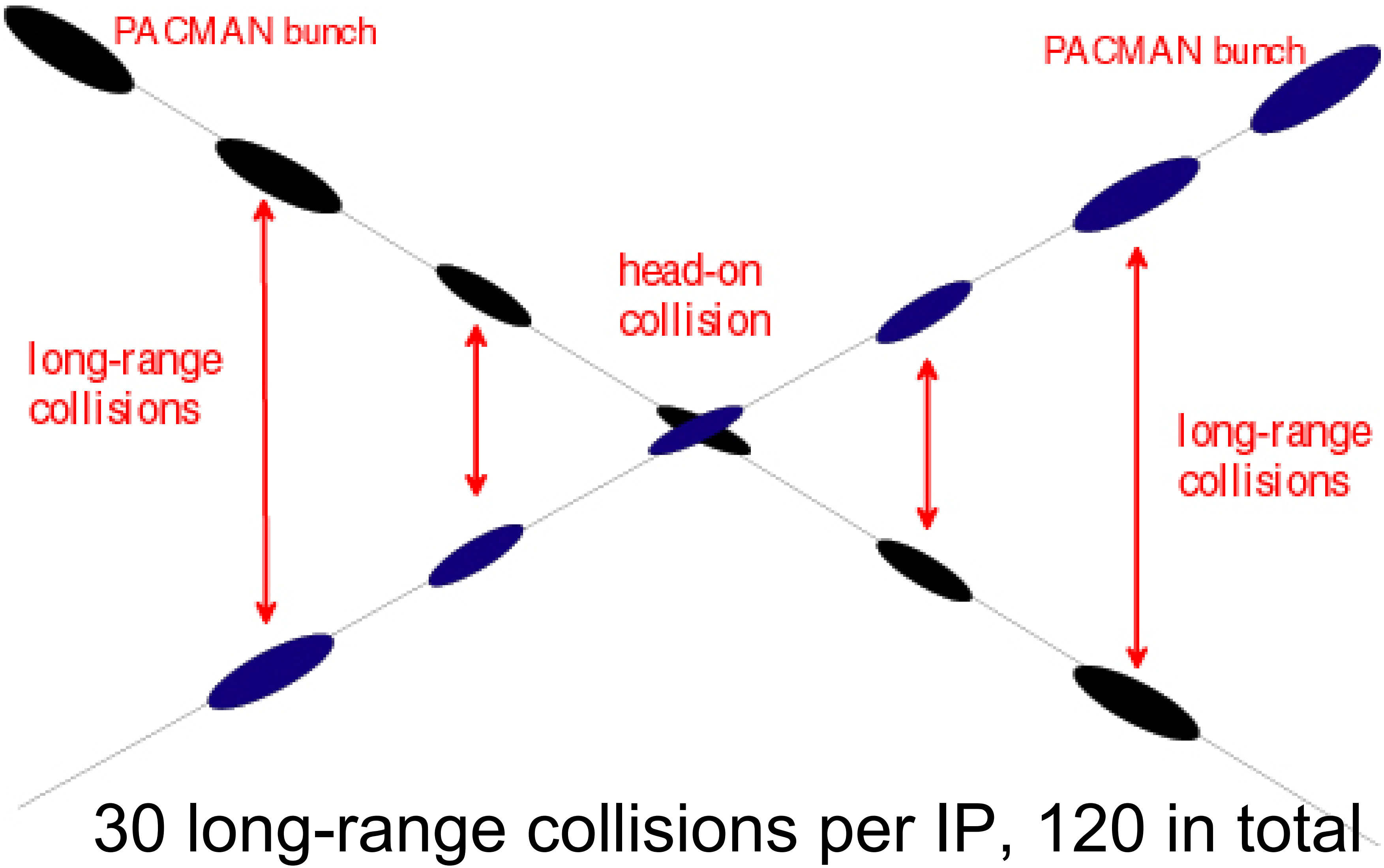
nominal collision spacing = 3.75 m

→ *about 2x15 collisions between IP and separation dipole!*

*tune shift would increase 30 times!*

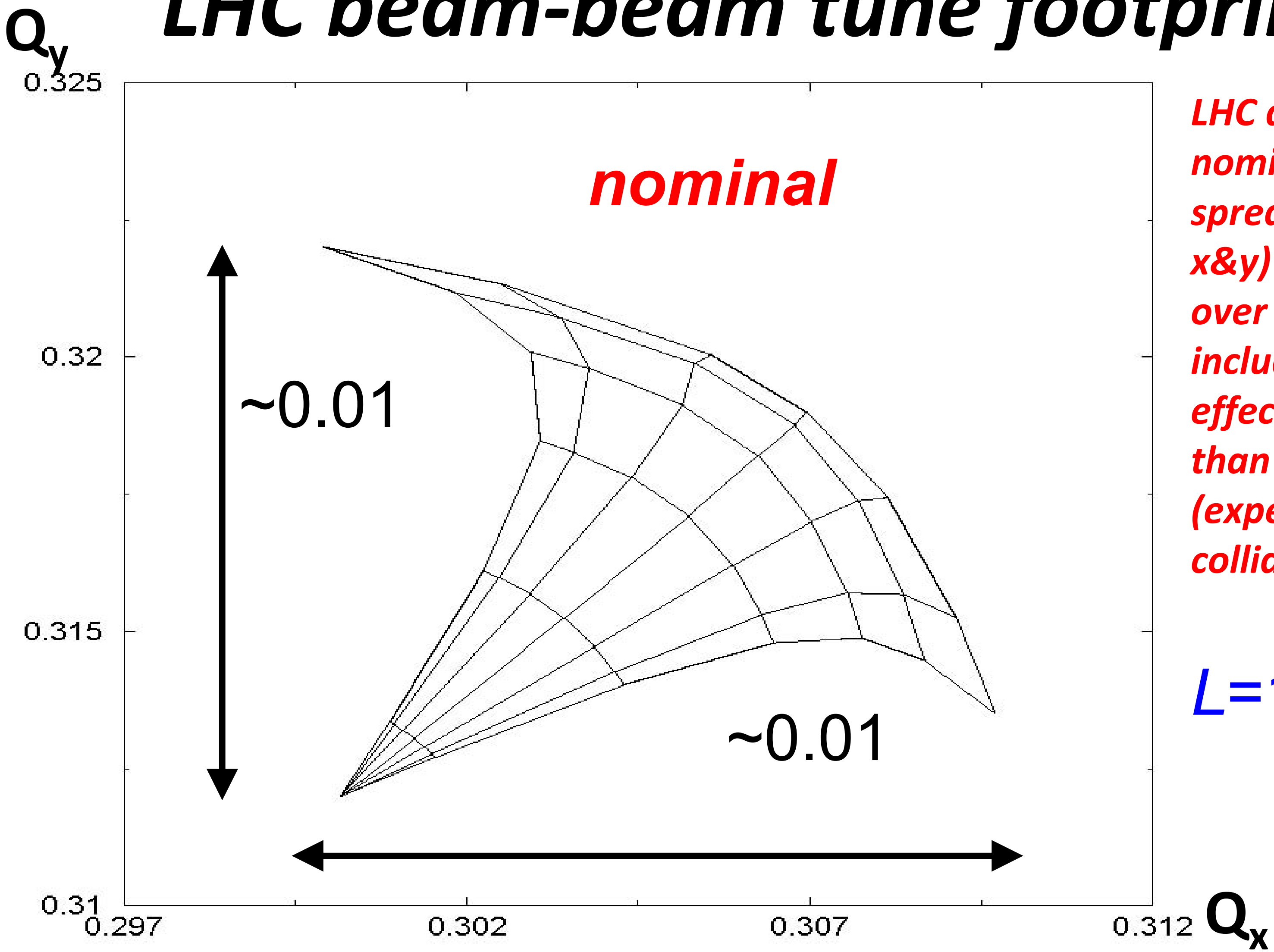
*solution: crossing angle*

# long-range beam-beam




30 long-range collisions per IP, 120 in total

# *LHC beam-beam tune footprint*



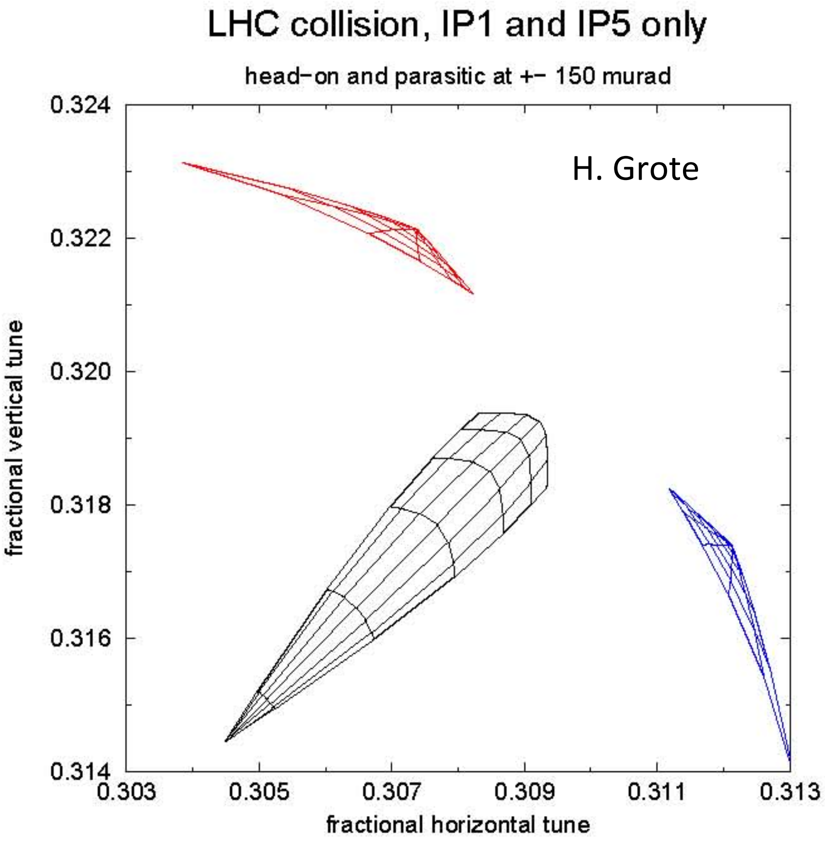

***LHC design criterion: nominal total tune spread (up to 6σ in x&y) from all IPs and over all bunches, including long-range effects, should be less than 0.01 (experience at SPS collider)***

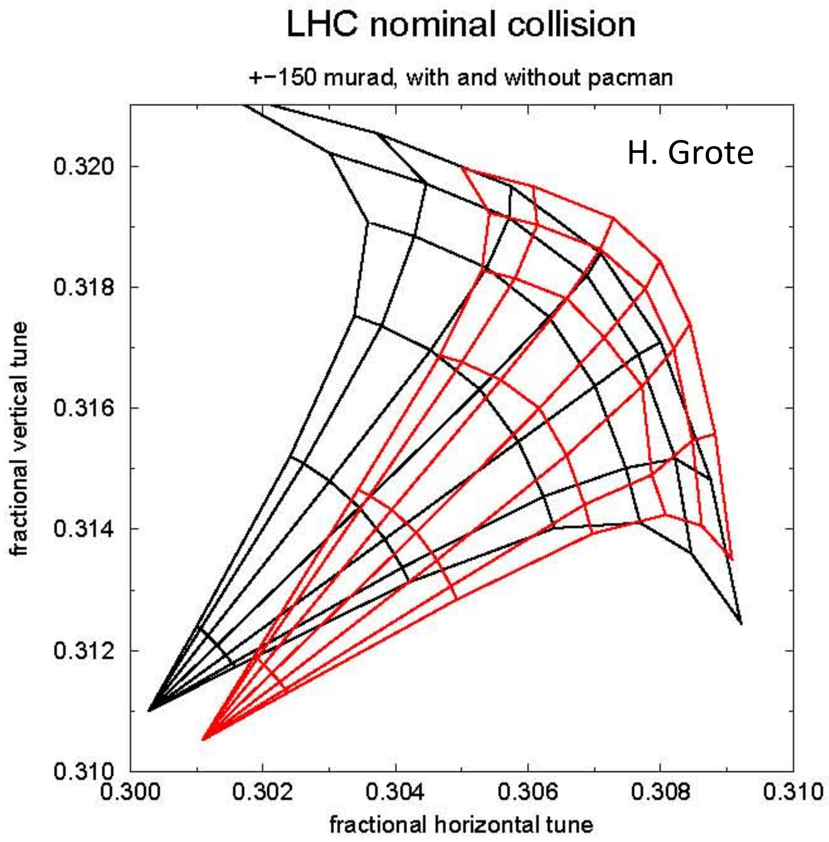
$L=10^{34}$ cm$^{-2}$s$^{-1}$

nominal tune footprint up to 6σ with

4 IPs & nom. intensity $N_b=1.15\text{x}10^{11}$

# *tune footprints & alternating crossing*



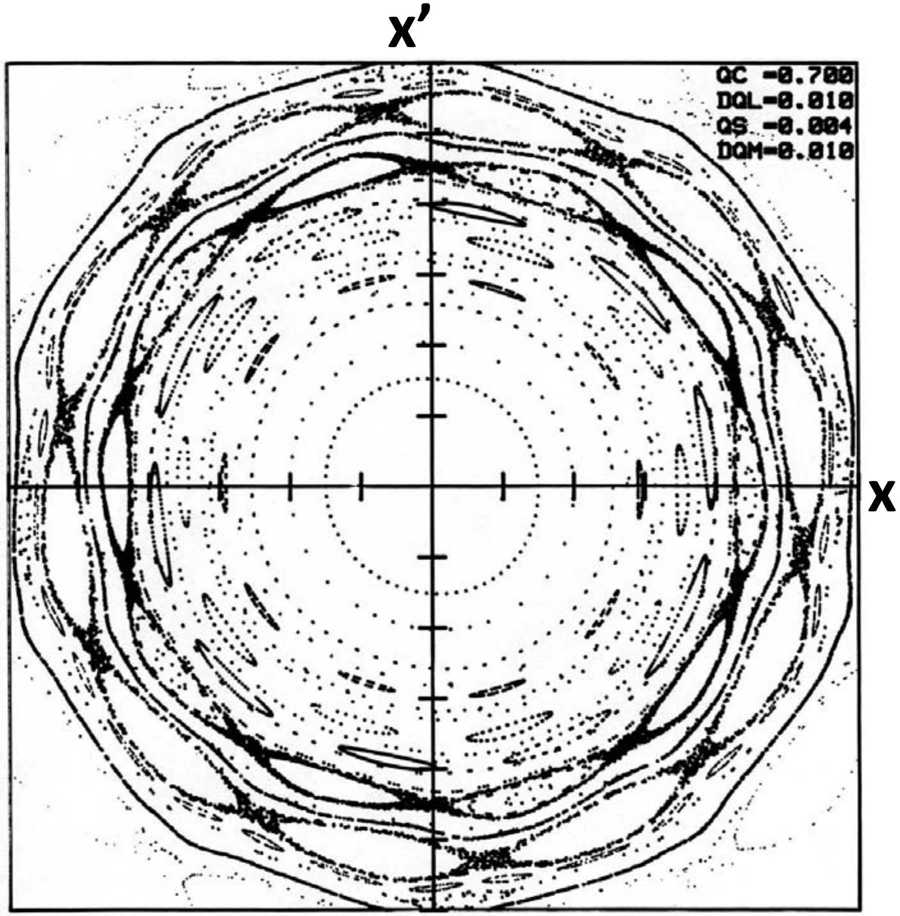



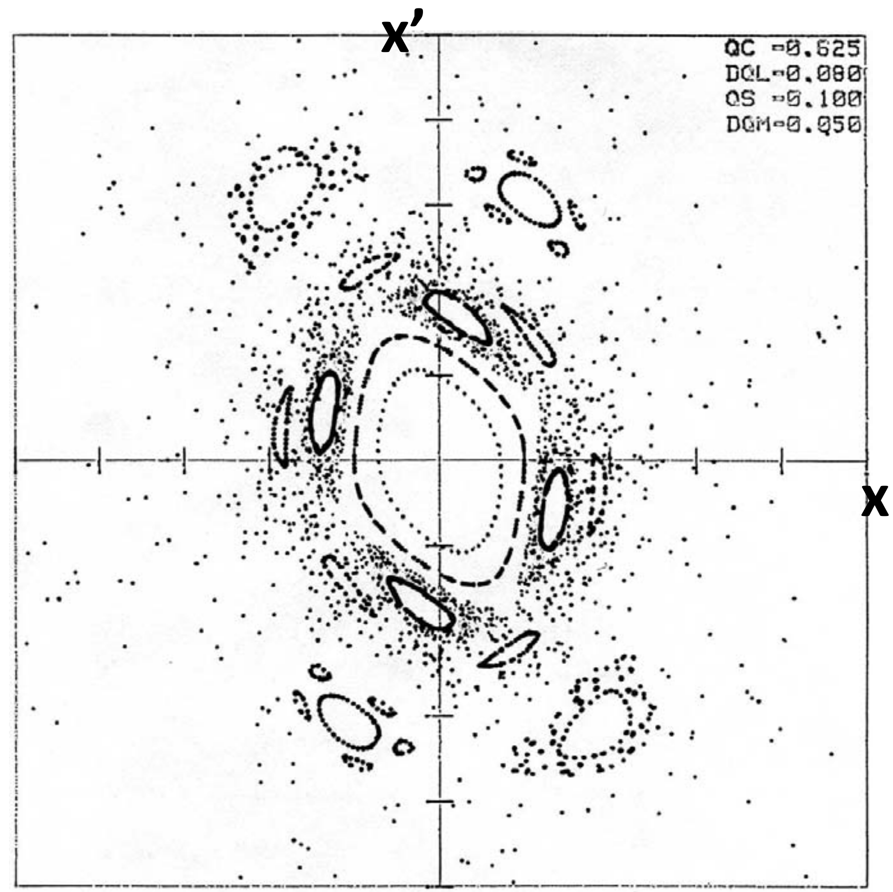

tune footprints due to head-on and long-range collisions in IP1 and IP5

total LHC tune footprint for regular and so-called PACMAN bunch

*ΔQ from LR collisions is approximately cancelled by* ***alternating horizontal and vertical crossing in two colision points*** *[D. Neuffer, S. Peggs, SSC-63 (1986)]*

# *dynamic aperture*



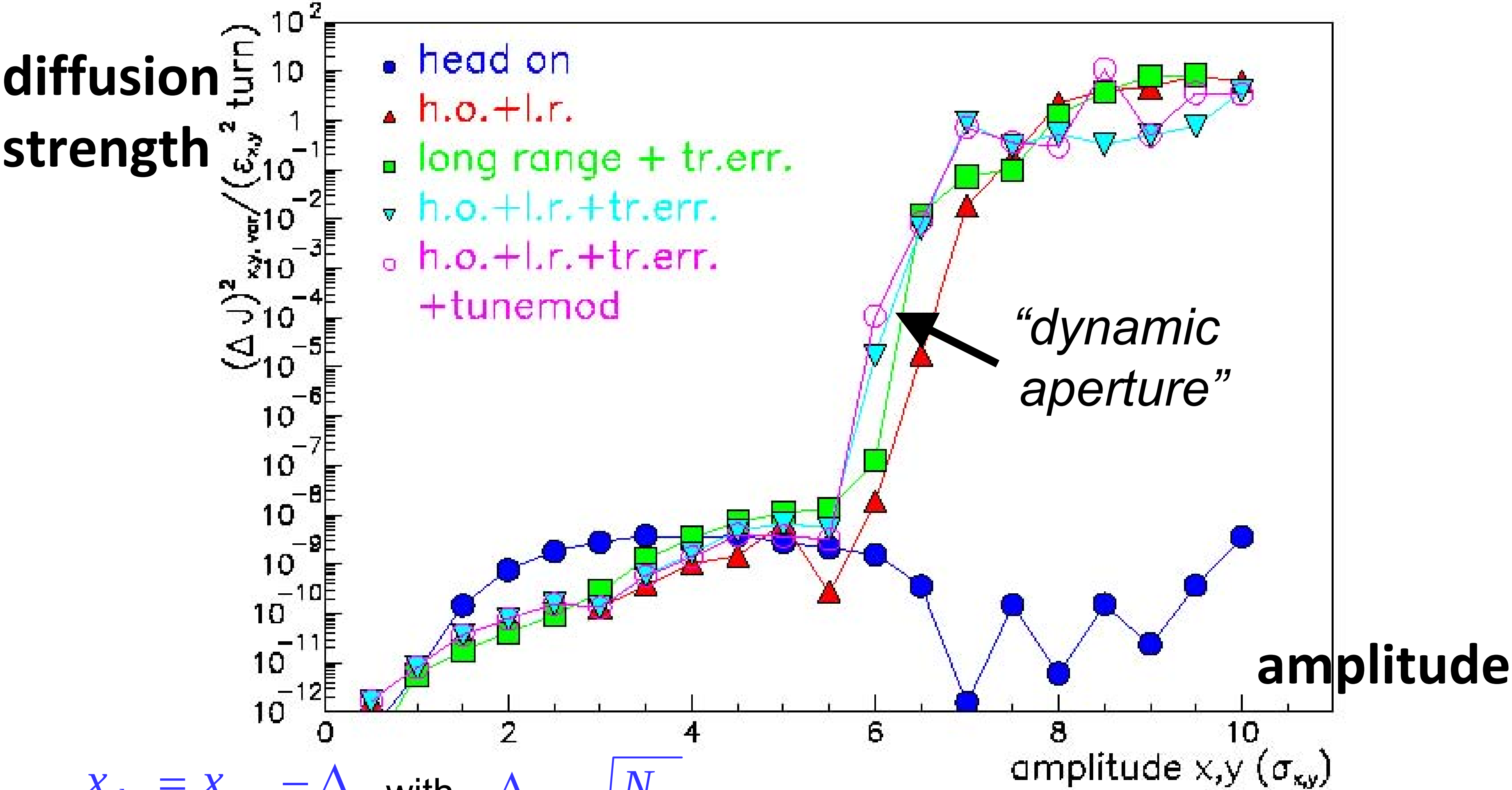




simulation by L. Evans

**= dynamically stable region in phase space**

**outside: global chaos, rapid diffusion, losses**

# dynamic aperture due to long-range collisions; determines minimum crossing angle




$$x_{da} = x_{sep} - \Delta$$ with $$\frac{\Delta}{\sigma} \propto \sqrt{\frac{N_b}{\varepsilon_N}}$$

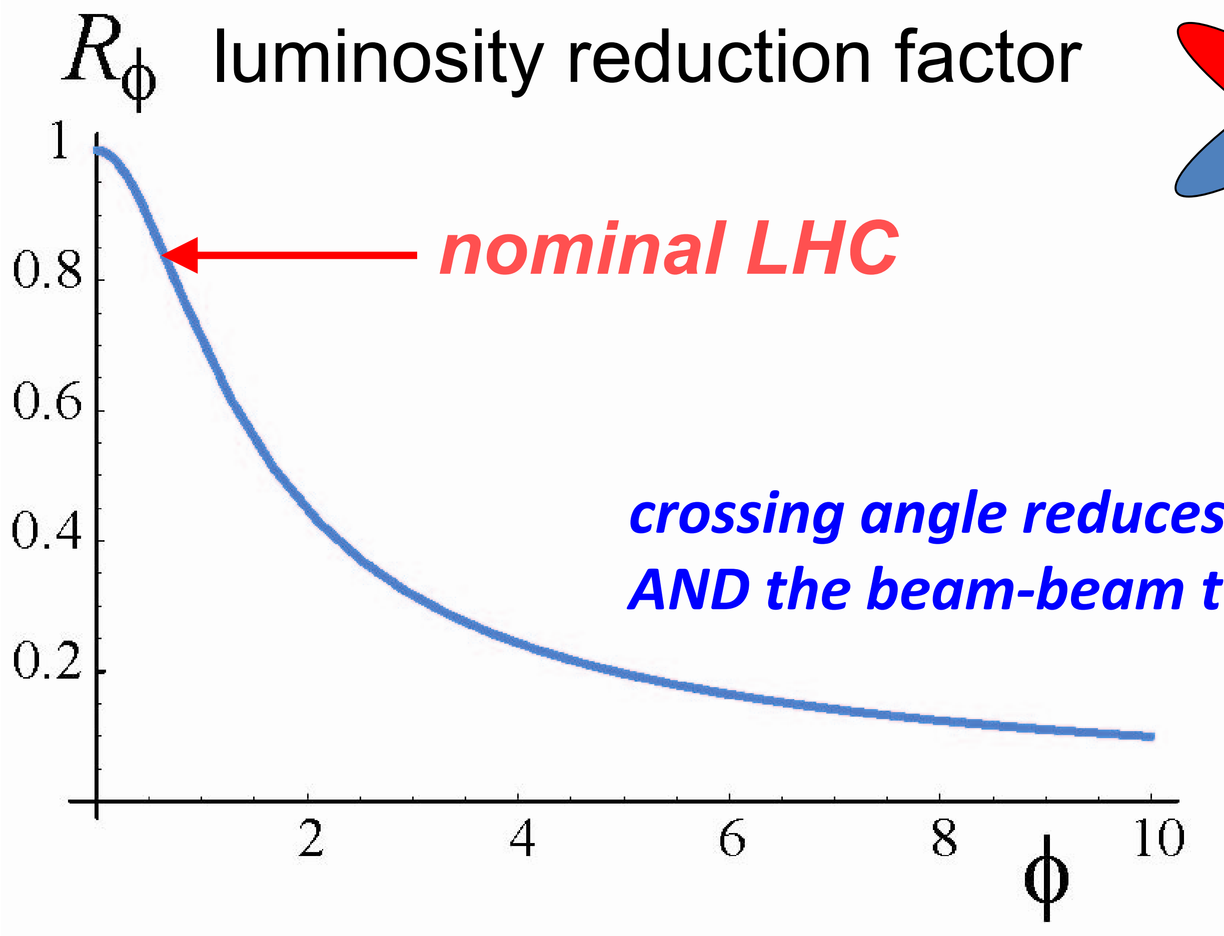
independent of β* and energy

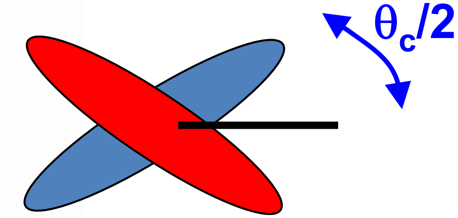
for nominal LHC: $x_{sep}$~9.5σ, $x_{da}$~6σ


J. Irwin, SSC-223 (1989)
Y. Papaphilippou & F.Z., PRST-AB 2, 104001 (1999)
Y. Papaphilippou & F.Z., PRST-AB 5, 074001 (2002)

# 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 $\sigma \rightarrow \sigma / R_\phi$**

***crossing angle reduces the luminosity AND the beam-beam tune shift***

# luminosity

$$L = \left(\frac{\gamma f_{rev}}{4\pi}\right)\frac{n_b N_b}{\beta^*}\left[\left(\frac{N_b}{\varepsilon_N}\right)R_\phi\right]$$

beam current

geometric factor

IP beta function

brightness

$$\sigma^* = \sqrt{\beta^* \frac{\varepsilon_N}{\gamma}}$$ rms IP beam size

$$d^* = \sqrt{\frac{1}{\beta^*}\frac{\varepsilon_N}{\gamma}}$$ rms IP divergence

normalized to nominal

$$\theta_c \approx a\, d^* \left(0.7 + 0.3 b \sqrt{\tilde{n}_b \tilde{N}_b / \tilde{\varepsilon}_N}\right)$$ minimum crossing angle for LR-BB

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

$$\Delta Q_{bb} \approx \frac{r_p}{2\pi}\left[\left(\frac{N_b}{\varepsilon_N}\right)R_\phi\right] < \Delta \hat{Q}_{bb}$$

for Gaussian bunch shape

geometric factor

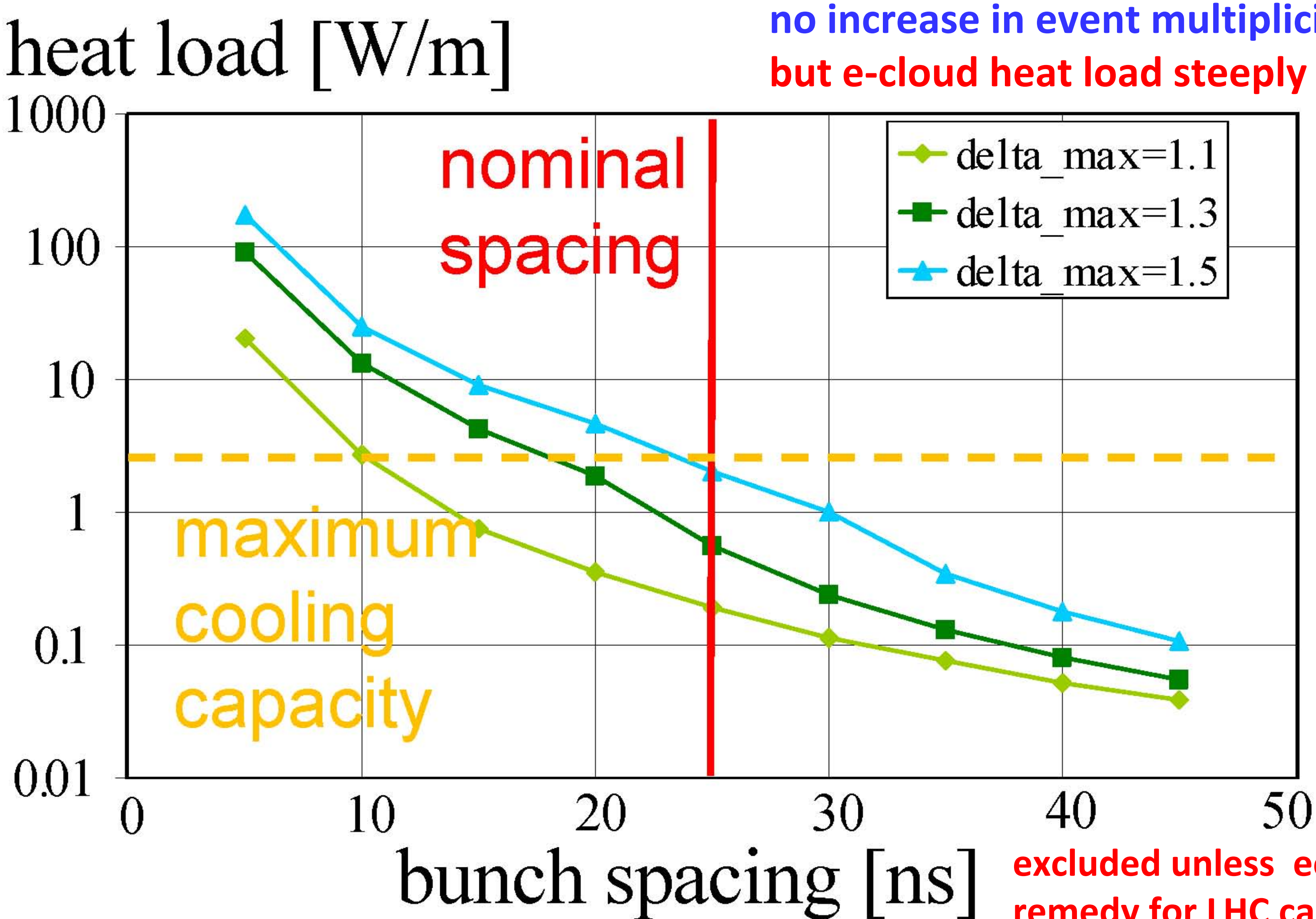
brightness

b-b tune shift also decreases with crossing angle feasibility & impact of modifying each parameter in the luminosity equation:

- $n_b$ - *# bunches*
- $N_b$ - *# protons / bunch*
- $\beta^*$ - *IP beta function*
- $\varepsilon$ – *transverse emittance*
- $R_\phi$ – *geometric reduction factor*

# # bunches $n_b$

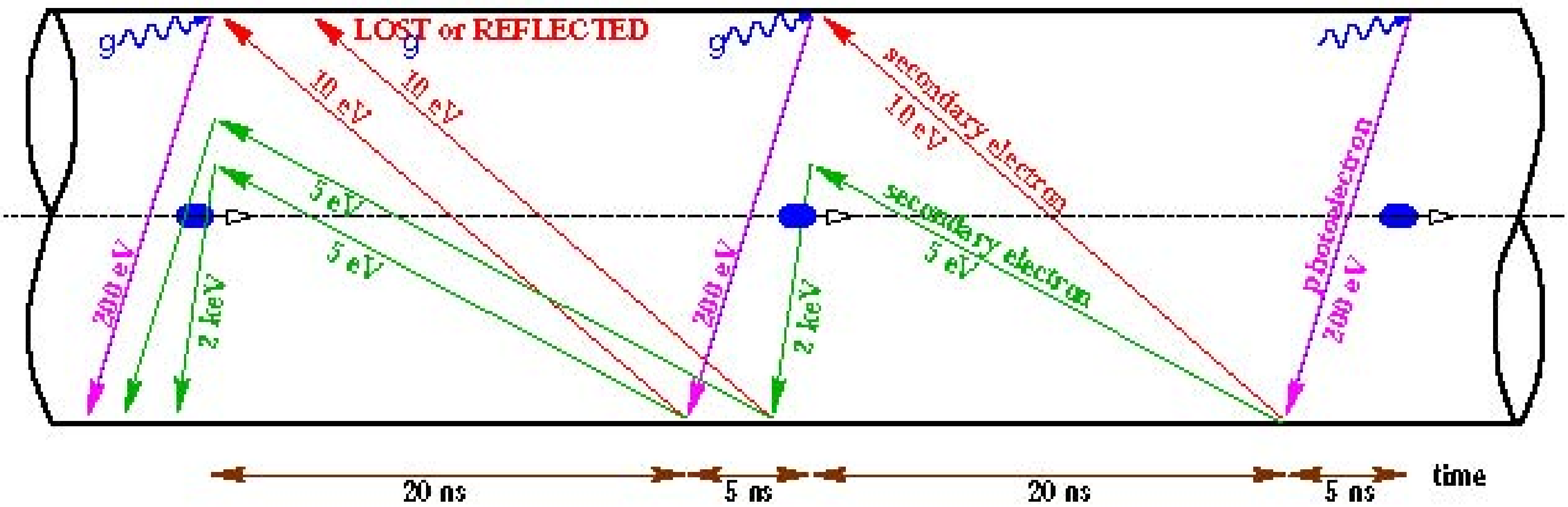
no increase in bb tune shift
no increase in event multiplicity
but e-cloud heat load steeply increases




excluded unless economical remedy for LHC can be found

# electron cloud

[F. Ruggiero]




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

→ ***heat load (→ quenches), instabilities, emittance growth, poor beam lifetime***

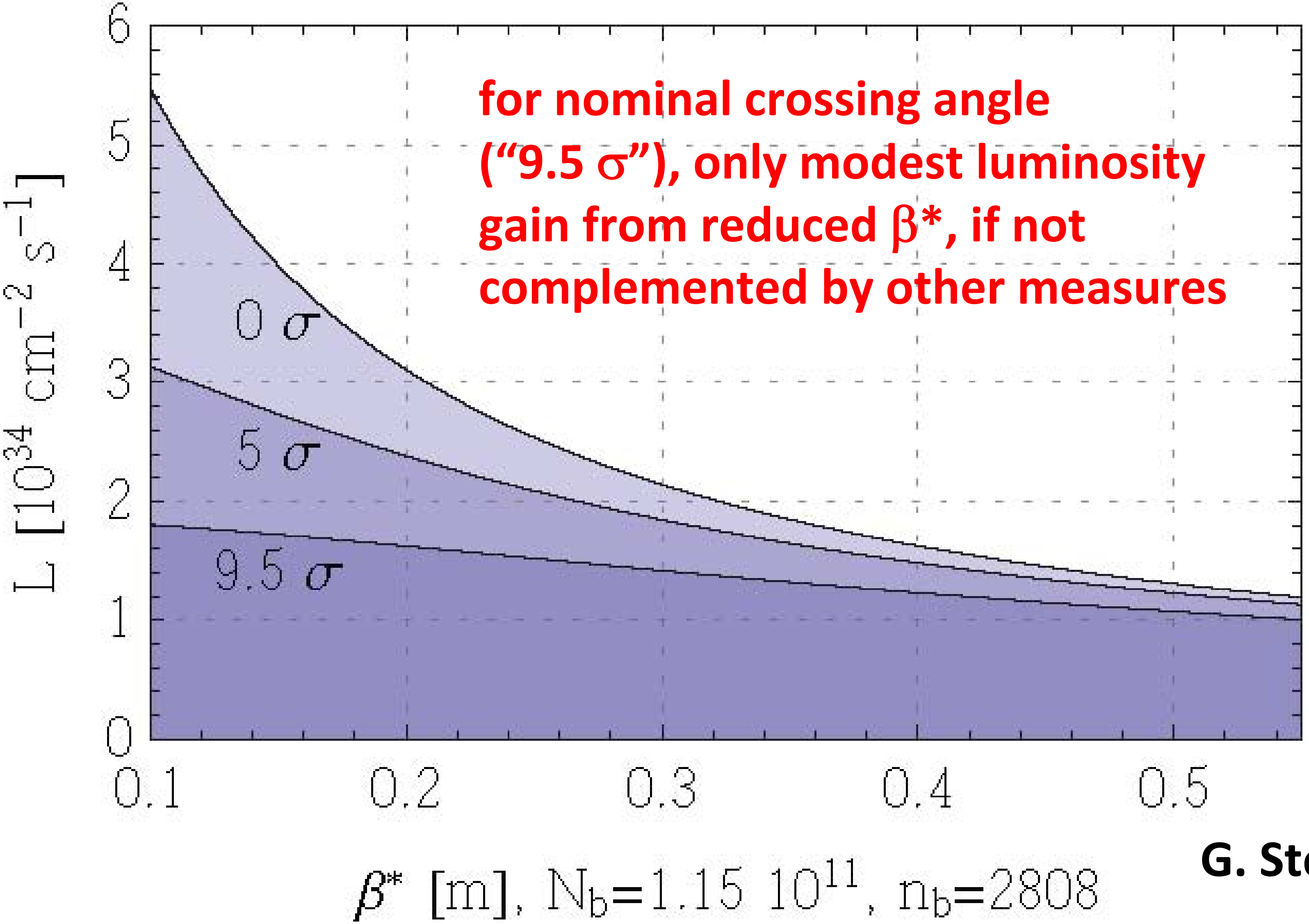
also synchrotron radiation & beam image currents add to heat load

# bunch charge $N_b$

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

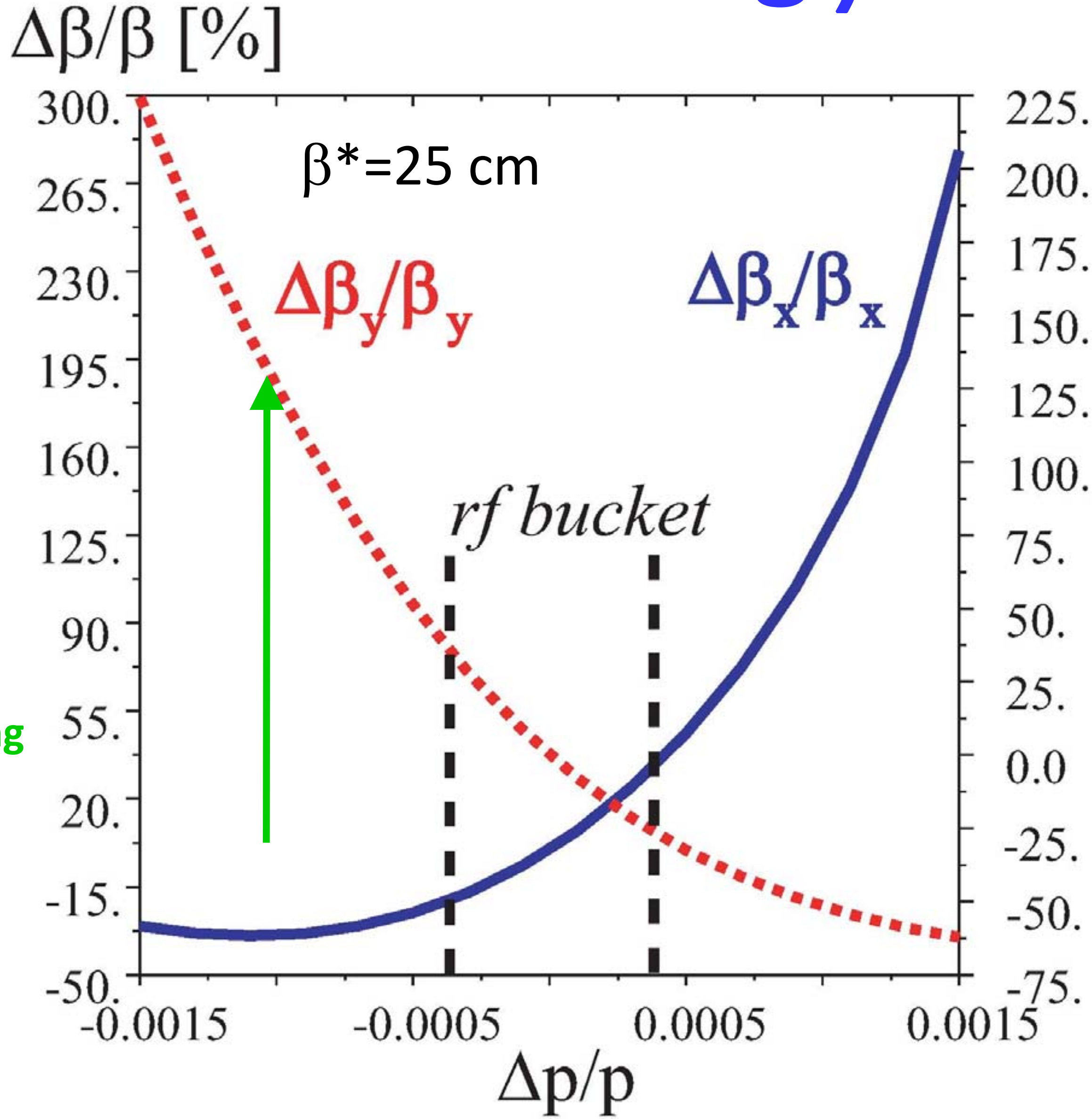
→ ***injector renewal***

# IP focusing *β* - 1*




G. Sterbini

# IP focusing $\beta^*$ - 2

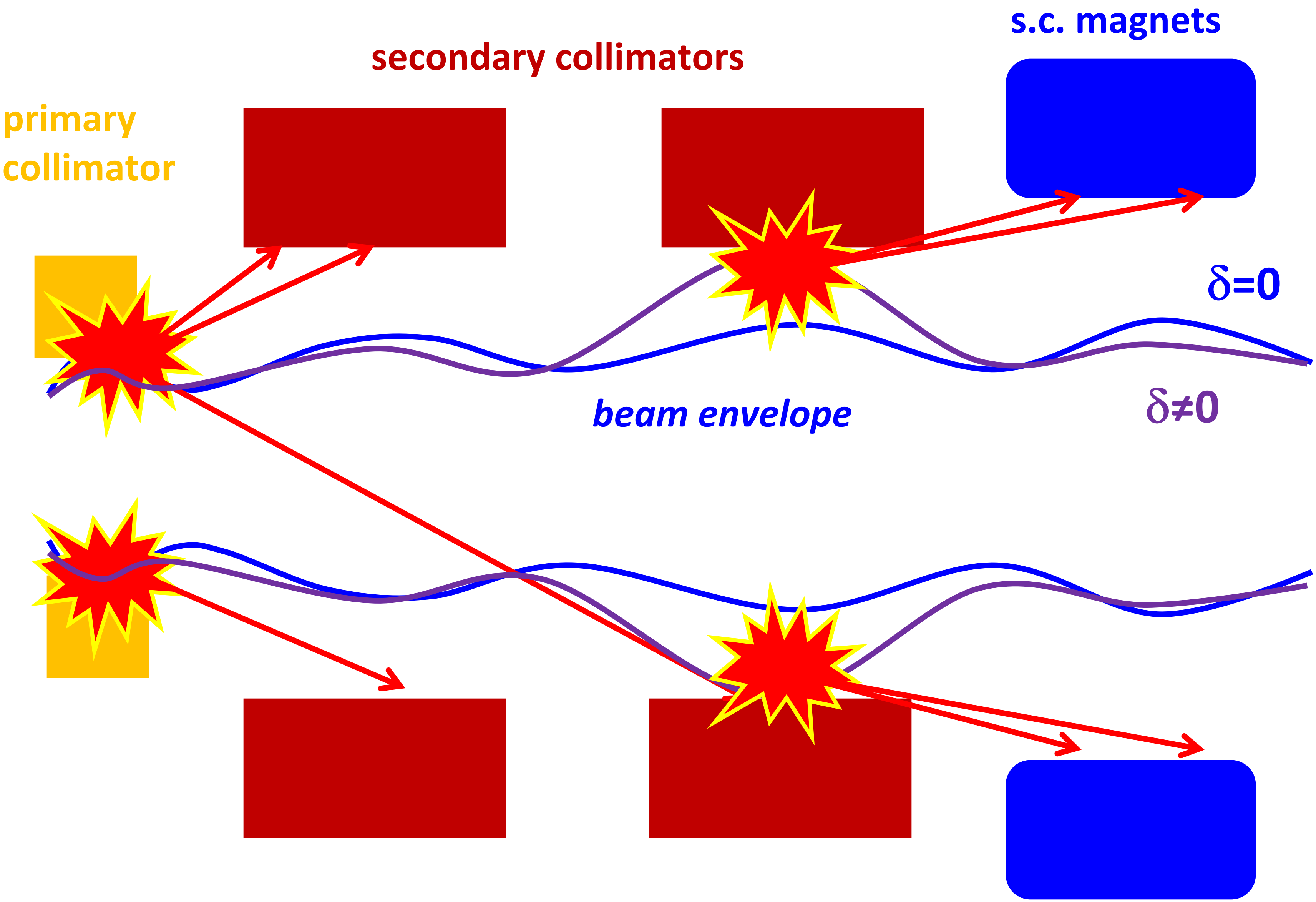



**at 9 σ**
**200%**
**β beating**

higher-order chromatic effects affect momentum collimation, by destroying hierarchy of primary, secondary, and tertiary etc. collimators

**S. Fartoukh**

# effect of off-momentum β beating on collimation



# IP focusing *β** - *3*

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

- **β* ~ 30 cm for *l** = +/- 23 m**

with *NbTi* magnet technology
limited by aperture and β beat correction

- **ultimate β* ~ 15 cm for *l** = +/- 23 m**
- **ultimate β* ~ 11 cm for *l** = +/- 13 m**

with *$Nb_3Sn$* magnet technology (higher field, more margin), limited by linear chromaticity correction

# emittance $\varepsilon$

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 $R_\phi$ 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.

$N_{b,max}$ ~2.3x$10^{11}$ $\rightarrow$ **factor 3 gain in *L*;**

**larger aperture in final focus neede**d

# tune shift & (peak) luminosity

$$\Delta Q_{bb} = \frac{N_b}{\gamma\varepsilon}\frac{r_p}{2\pi}\frac{1}{\sqrt{1+\phi_{piw}^2}}\frac{1}{F_{profile}} \qquad \phi_{piw} \equiv \frac{\sigma_z \theta_c}{2\sigma_{x,y}^*}$$

Piwinski angle

total beam-beam tune shift at 2 IPs with alternating crossing;

**we increase charge $N_b$ until limit $\Delta Q_{bb}$ is reached; to go further we must increase $\phi_{piw}$, and/or $\varepsilon$ and/or $F_{profile}$ (~$2^{1/2}$ for flat bunches)**

$$L = \frac{1}{4\pi} f_{rev} n_b \gamma \frac{1}{\beta^*(\gamma\varepsilon)} N_b^2 \frac{1}{\sqrt{1+\phi_{piw}^2}}$$

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

$$= \frac{\pi}{r_p^2} f_{rev} n_b \gamma \frac{(\gamma\varepsilon)}{\beta^*} \Delta Q_{bb}^2 F_{profile}^2 \sqrt{1+\phi_{piw}^2}$$

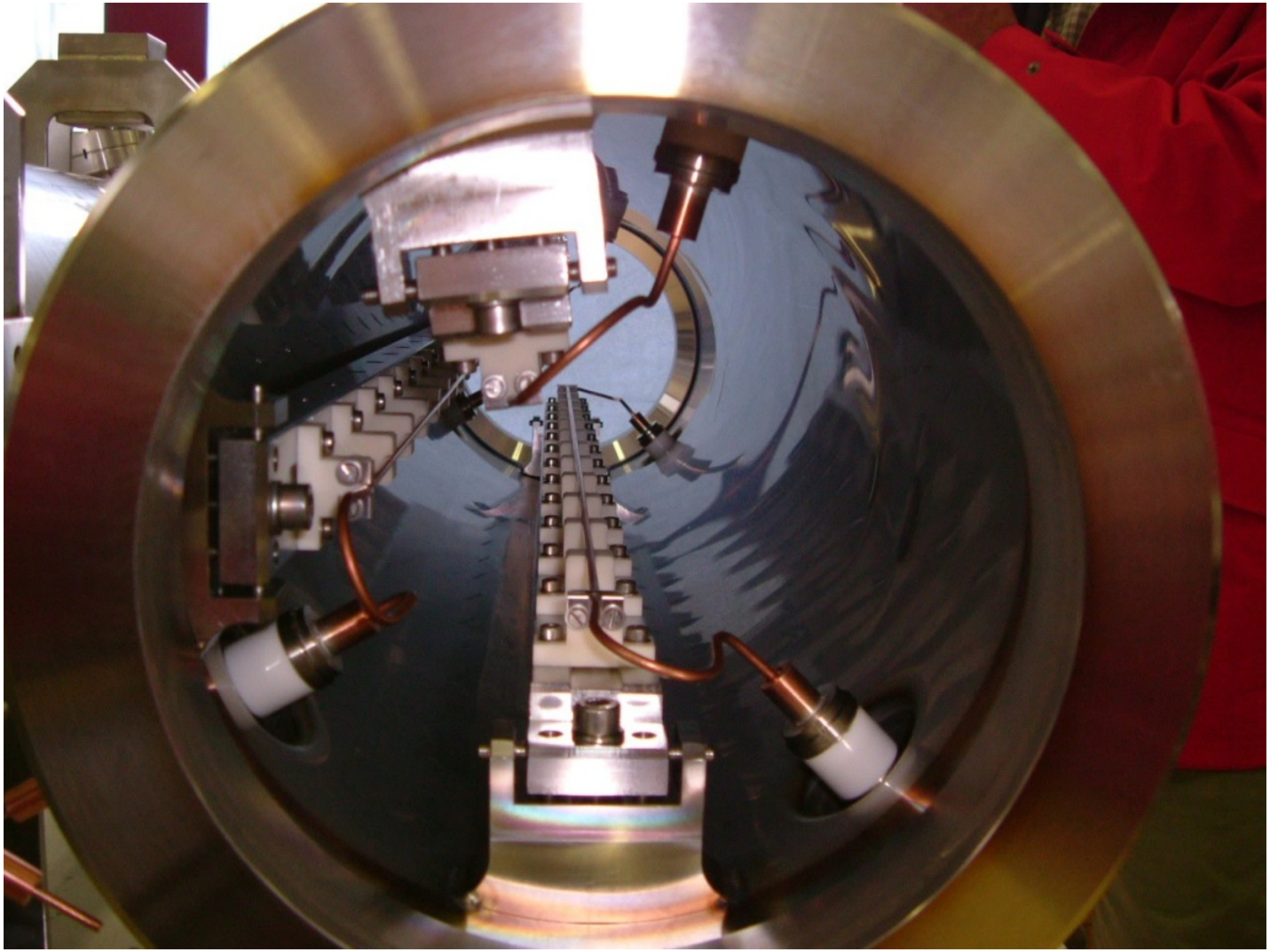
at the b-b limit, larger Piwinski angle &/or larger emittance increase luminosity

# collision schemes

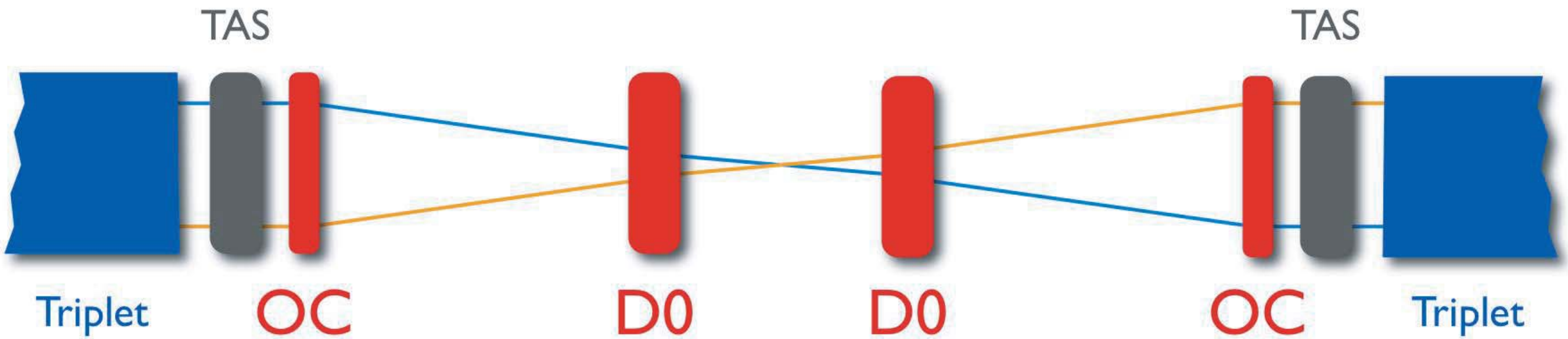
*address drop in geometric overlap for smaller $\beta^*$*

- **long-range beam-beam compensation** increase $R_\phi$
  - robust in simulations, effective in SPS beam experiments
  - allows for reduced crossing angle
- **"Early Separation (ES) scheme** further increase $R_\phi$
  - aims at decoupling IP crossing angle from beam-beam separation in common sections by installing dipoles inside the detectors; weak crab cavities further boost luminosity
  - dynamical control of crossing angle $\rightarrow$ simple leveling
- **Full Crab Crossing** maximum $R_\phi$
  - similar effect as ES, no magnets inside detector
  - under test at KEKB
- **"Large Piwinski Angle" (LPA) scheme** exploit $R_\phi \neq 0$
  - exploits concomitant drop in beam-beam tune shift to increase the bunch charge

# *prototype long-range beam-beam compensator in the SPS*

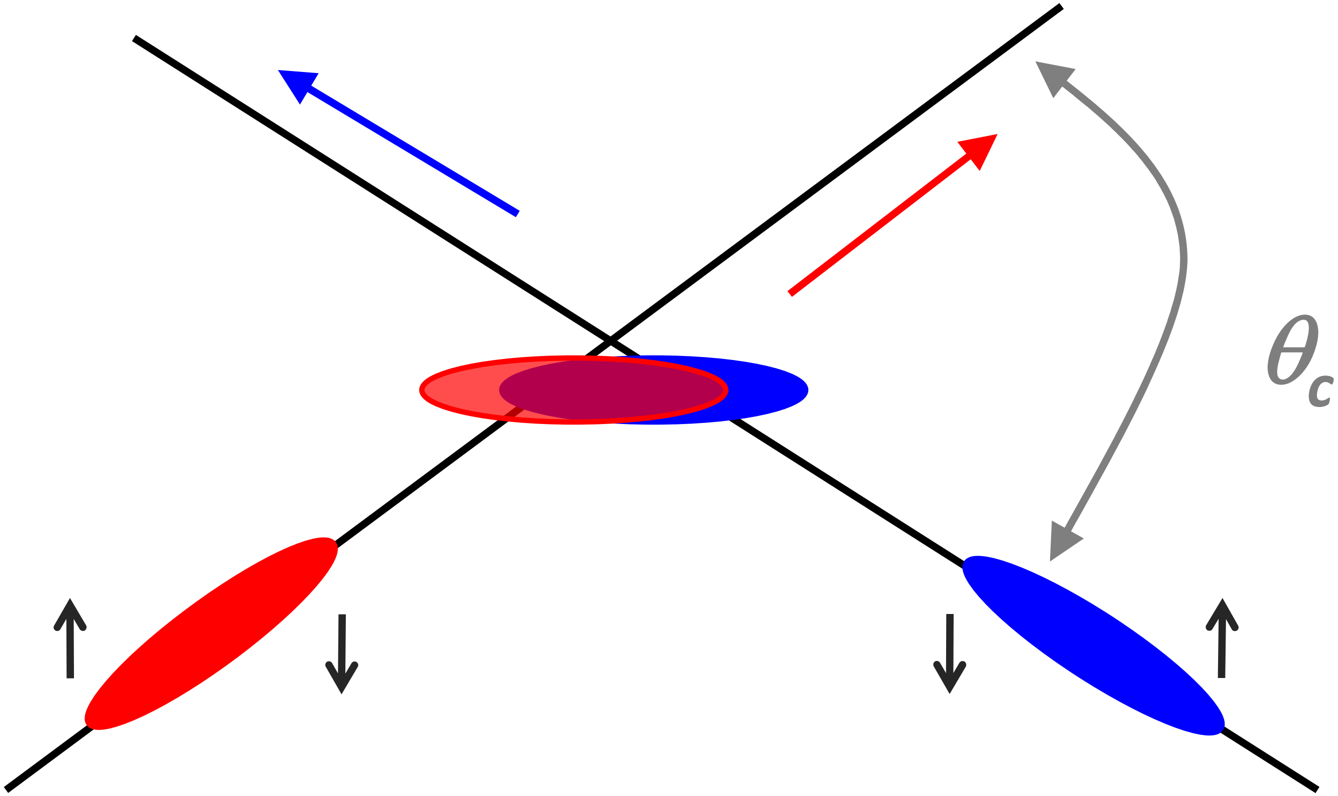


# layout of Early Separation scheme



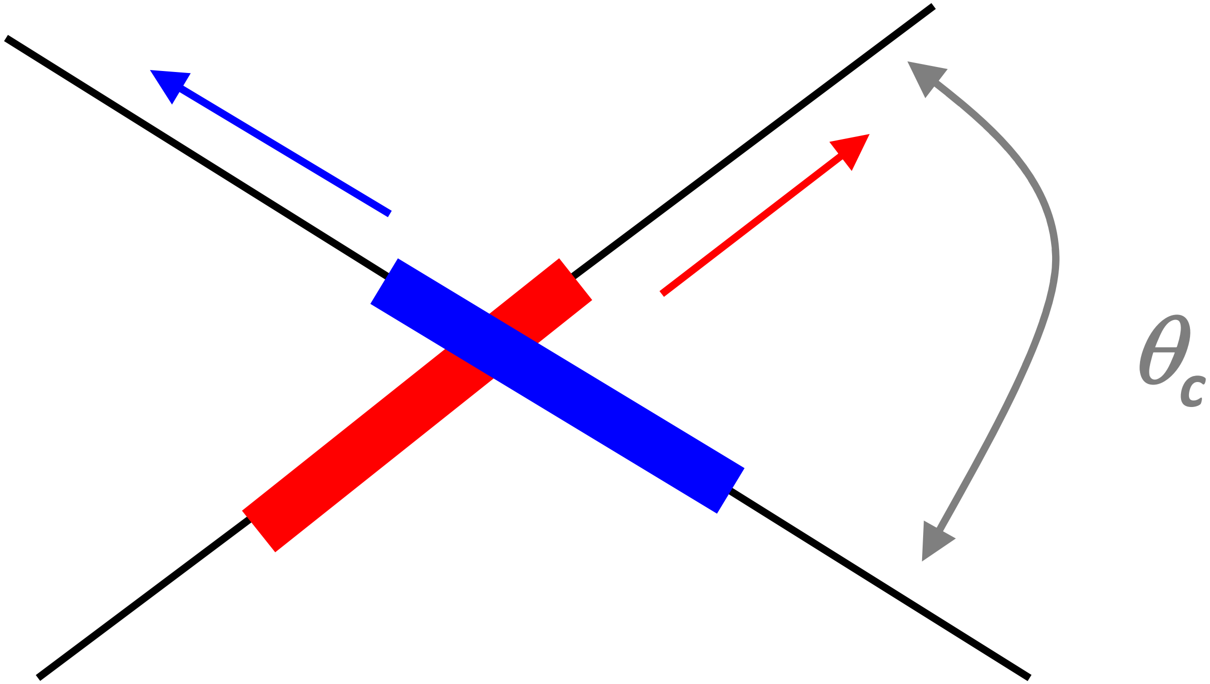

**G. Sterbini**

# 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, in operation at KEKB since 2007

# schematic of "LPA" collisions




1) large Piwinski angle $\theta_c \sigma_z >> 2\, \sigma_x^*$
2) longitudinally flat profile

$\rightarrow$ reduced tune shift, higher bunch charge

# heat load from collision debris

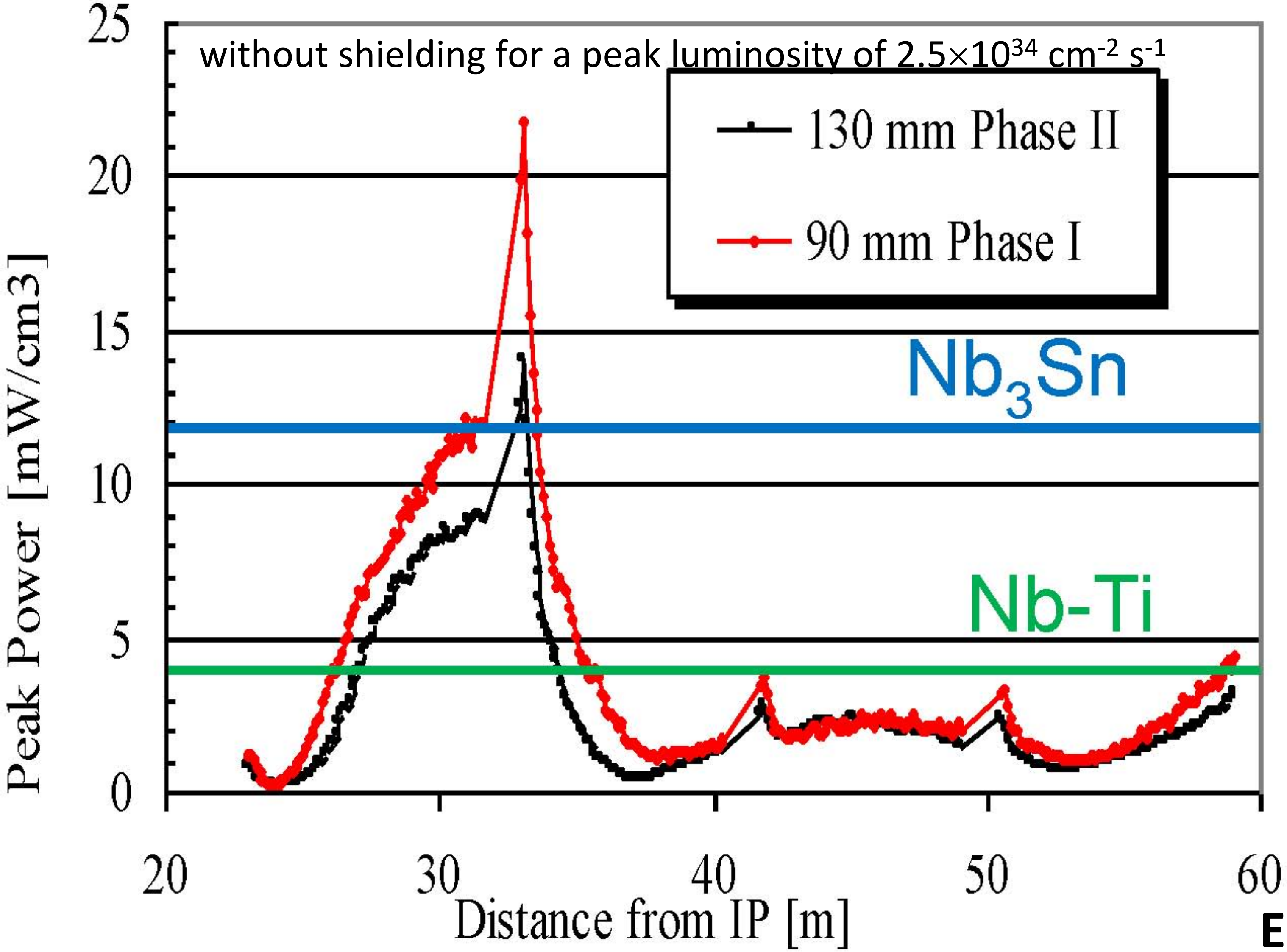
10-fold increase in luminosity would bring the nominal triplets well above their **quench limit** and reduce their **lifetimes** to below 1 year

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 coil of triplet quadrupoles compared with limit




**E. Wildner**

**larger aperture & higher threshold for $Nb_3Sn$ help; peak power further reduced by shielding**

# 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

$$L(t) = \frac{\hat{L}}{\left(1 + t/\tau_{eff}\right)^2}$$

$$\tau_{eff} = \frac{N_b n_b}{n_{IP} \hat{L} \sigma_{tot}}$$

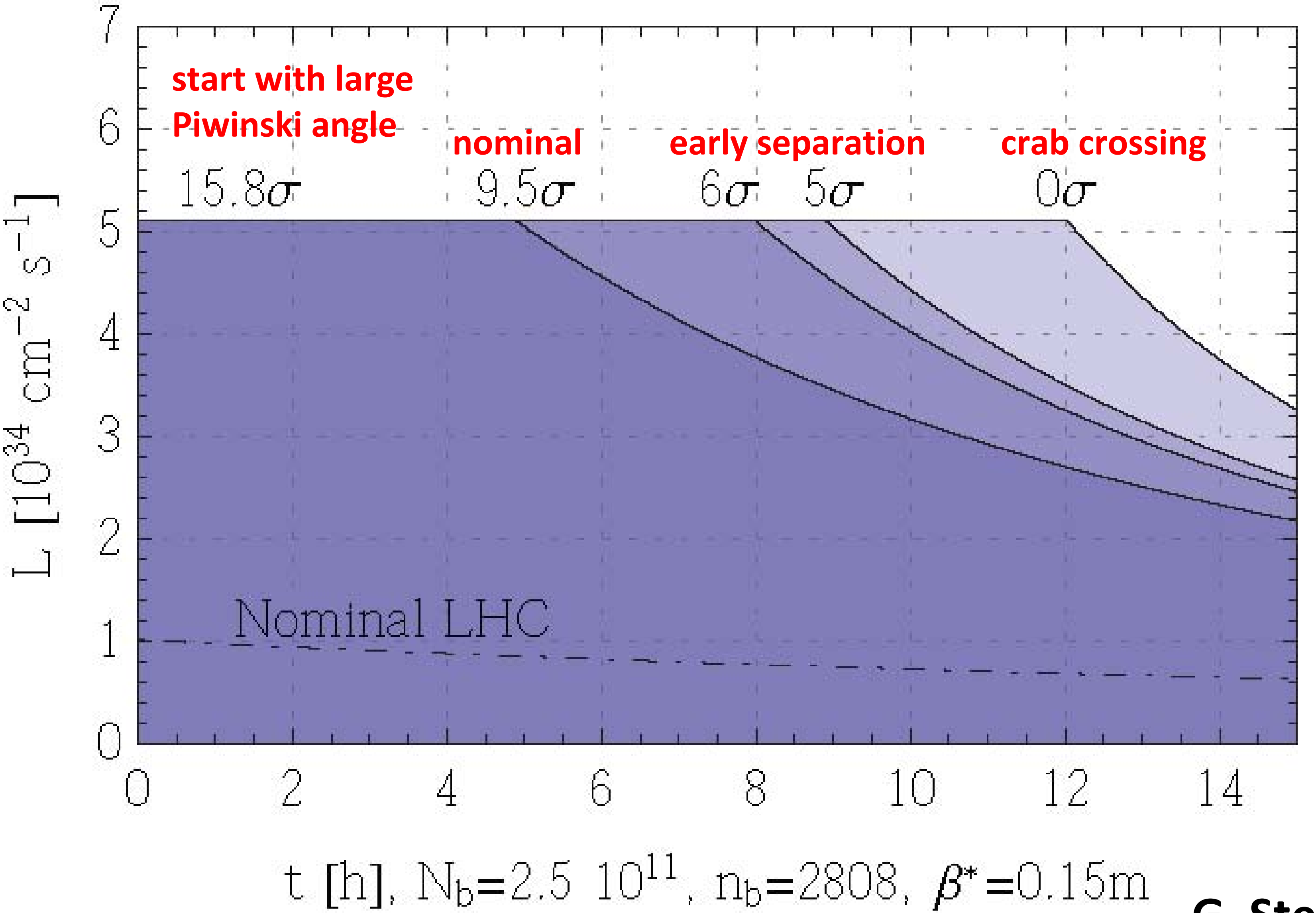
***luminosity leveling*** (changing $\theta_c$, $\beta^*$ or $\sigma_z$ in store to keep luminosity constant) becomes powerful strategy to reduce event pile up in the detector & peak power deposited in IR magnets

**leveling with crossing angle has distinct advantages:**

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

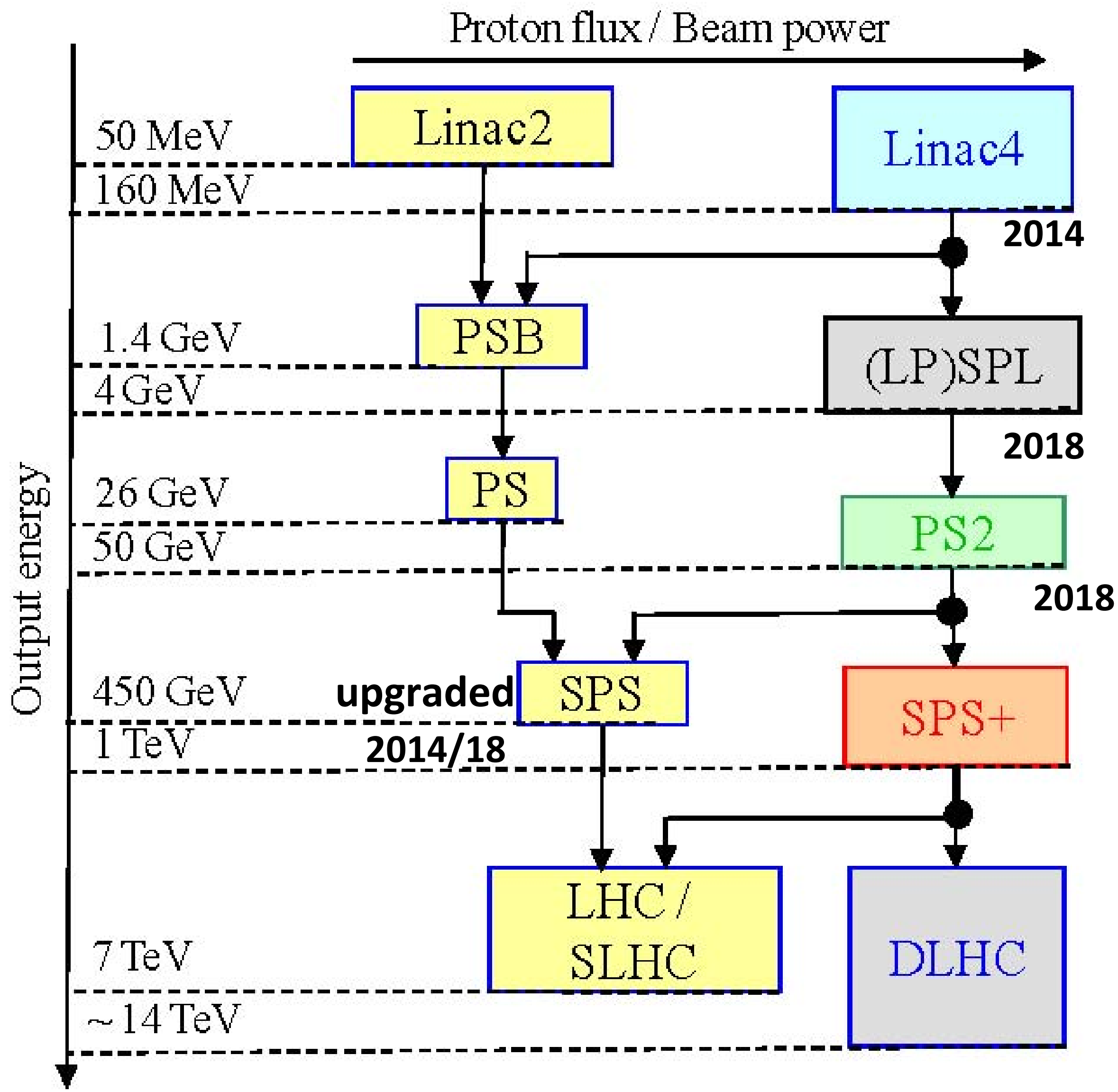
**natural option for early separation or crab cavities**

# luminosity leveling with crossing angle




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 **$\beta^*$ ~ 0.30 m in IP1 and 5**
- beam from **new Linac4**, readily providing the **"ultimate" bunch charge $N_b$~1.7x$10^{11}$**
- should be completed by **2014**

# implementation plan for Upgrade Phase II

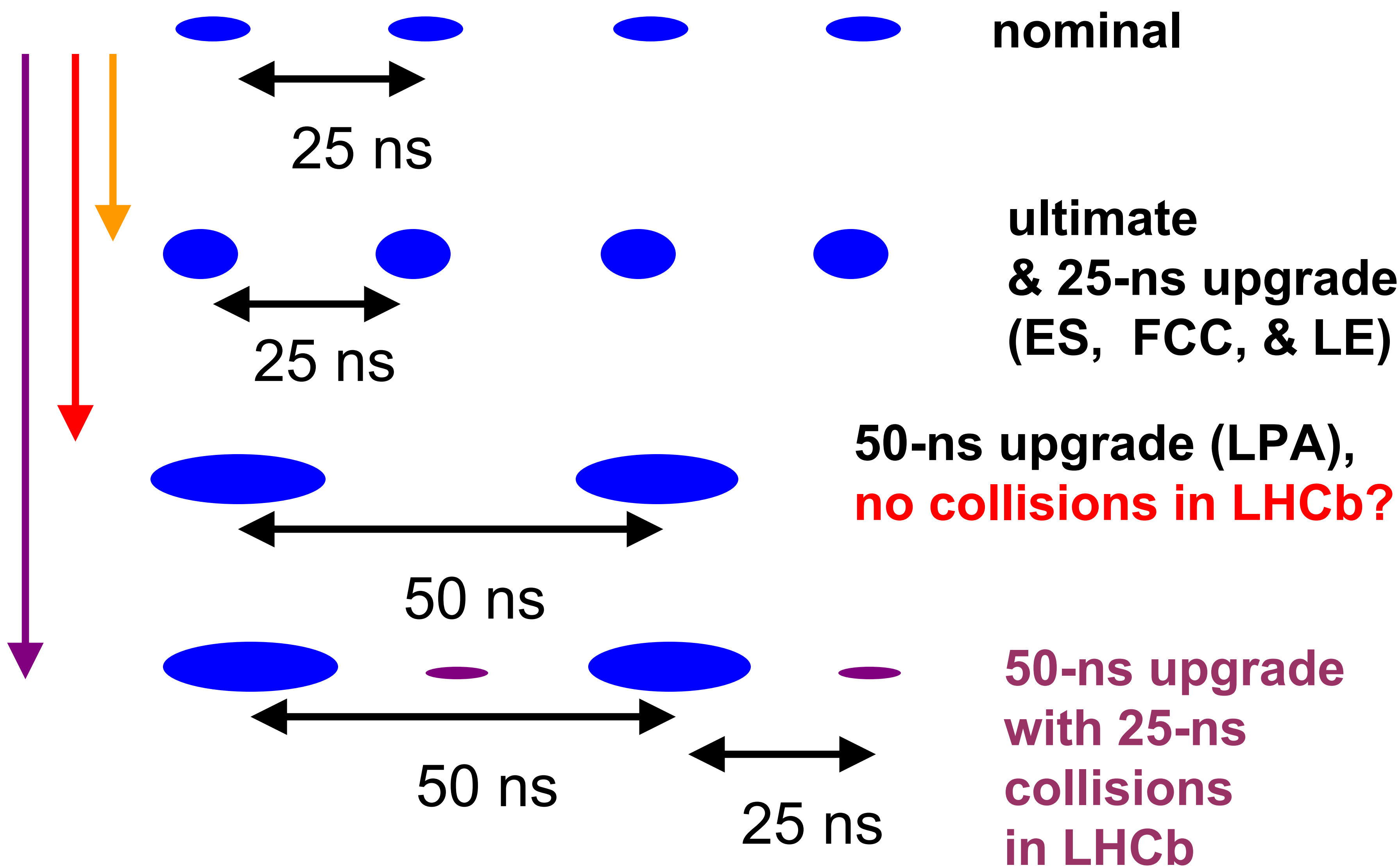
- **two new injector accelerators: SPL and PS2**, providing 2x ultimate beam brightness at 25 ns bunch spacing
- new interaction region; promising option: **$Nb_3Sn$ triplet** with larger aperture providing $\beta^*\sim 15$ cm
- **complementary measures**: long-range beam-beam compensation, crab cavities?, dipoles inside detector?, “electron lenses”??
- realized around **2018**

# phase-II scenarios

- early separation (ES)
  $\beta^*$~0.1 m, 25 ns, $N_b$=1.7x$10^{11}$,
  detector embedded dipoles
- full crab crossing (FCC)
  $\beta^*$~0.1 m, 25 ns, $N_b$=1.7x$10^{11}$,
  local and/or global crab cavities
- large Piwinski angle (LPA)
  $\beta^*$~0.25 m, 50 ns, $N_b$=4.9x$10^{11}$,
  "flat" intense bunches
- low emittance (LE)
  $\beta^*$~0.1 m, 25 ns, $\gamma\varepsilon$~1-2 $\mu m$, $N_b$=1.7x$10^{11}$

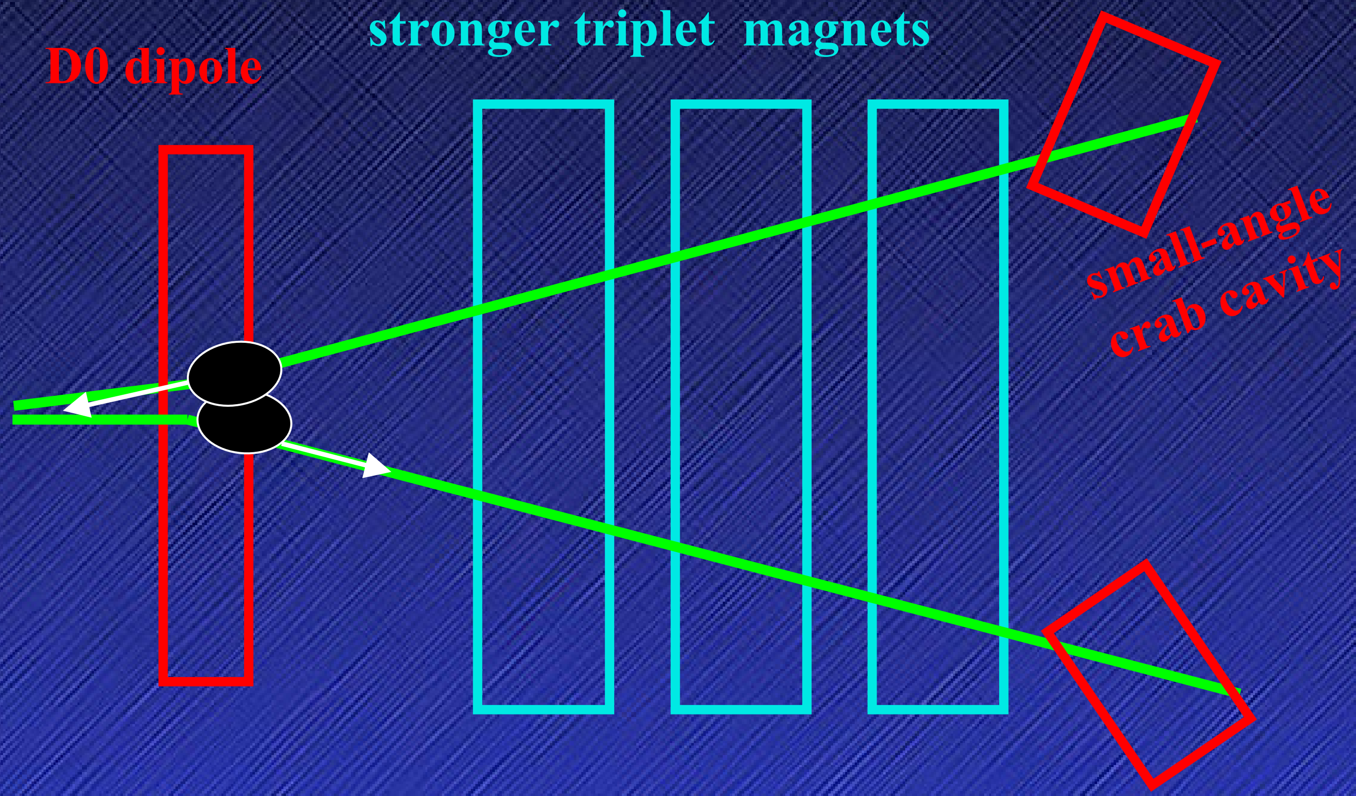
| parameter | symbol | nominal | ultimate | ES | FCC | LE | LPA |
|---|---|---|---|---|---|---|---|
| transverse emittance | $\varepsilon$ [$\mu$m] | 3.75 | 3.75 | **3.75** | **3.75** | **1.0** | **3.75** |
| protons per bunch | $N_b$ [$10^{11}$] | 1.15 | 1.7 | **1.7** | **1.7** | **1.7** | **4.9** |
| bunch spacing | $\Delta t$ [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 | $\sigma_z$ [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 | $\theta_c$ [$\mu$rad] | 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 | $\tau_L$ [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) $\tau_b$ | $P_{gas}$ [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 | $\sigma_l$ [cm] | 4.5 | 4.3 | **3.7** | **3.7** | **1.6** | **5.3** |
| comment | | nominal | ultimate | **D0 + crab** | **crab** | | **wire comp.** |

# upgrade bunch patterns



# early separation (ES)

J.-P. Koutchouk



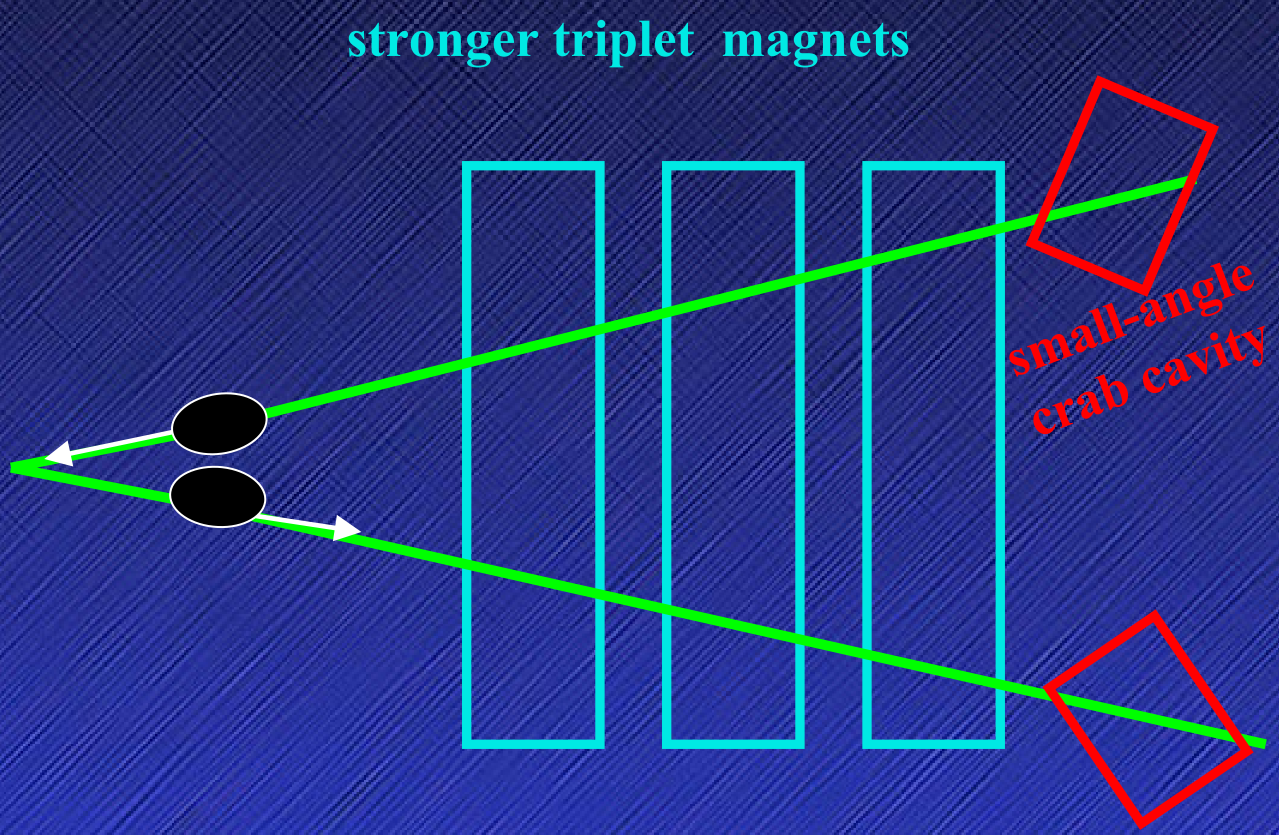

- early-separation dipoles in side detectors , crab cavities

  → hardware inside ATLAS & CMS detectors,

  first hadron crab cavities; off-δ β

# full crab crossing (FCC)

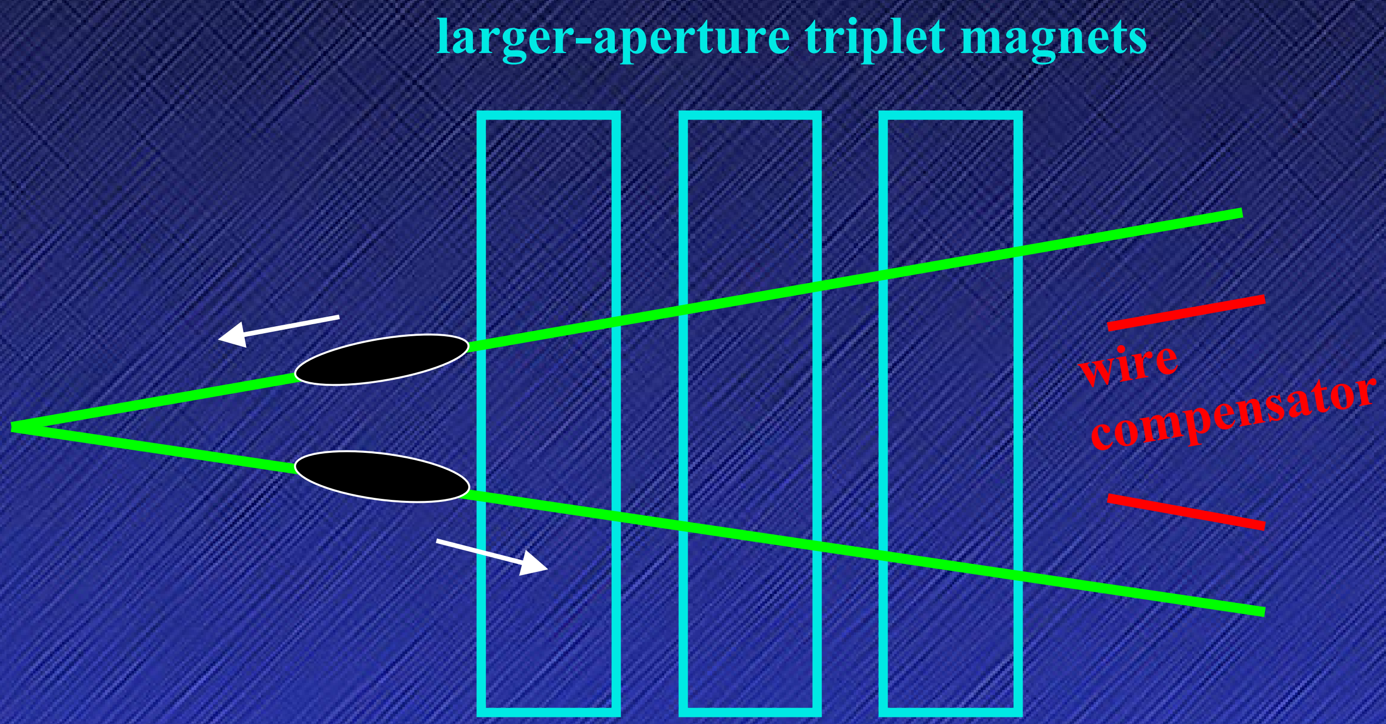
L. Evans,
W. Scandale,
F. Zimmermann




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

# large Piwinski angle (LPA)

F. Ruggiero,
W. Scandale.
F. Zimmermann



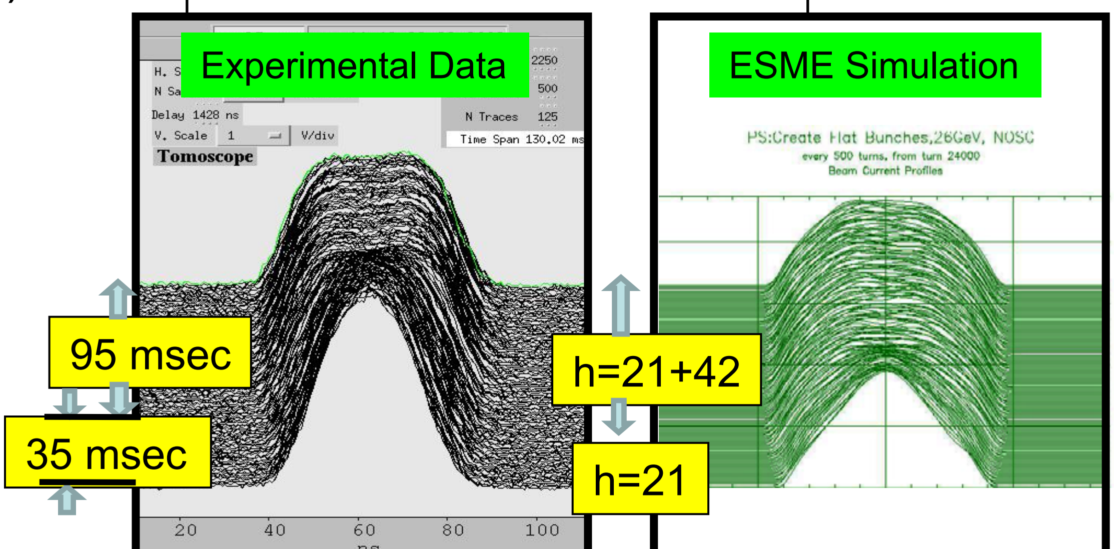

- long-range beam-beam wire compensation
  → novel operating regime for hadron colliders,
  beam generation

# generation & stability of LPA bunches (50-ns spacing, long, flat, intense)

*R. Garoby*
*CARE-HHH*
*BEAM'07*

| | If SPS can accelerate $6\times10^{11}$ p/b ($\varepsilon_L$~0.7 eVs) | If SPS <u>cannot</u> accelerate $6\times10^{11}$ p/b ($\varepsilon_L$~0.7 eVs) |
|---|---|---|
| "Best" choice | **Generate beam in PS2 at capture [PS2/1]** | Slip stacking at high energy [SPS/4] ? |
| "Alternative" choice | Generate beam in PS2 by merging [PS2/2] | ? |
| Other (new) ideas | ? | ? |

***SPS may be bottleneck!***

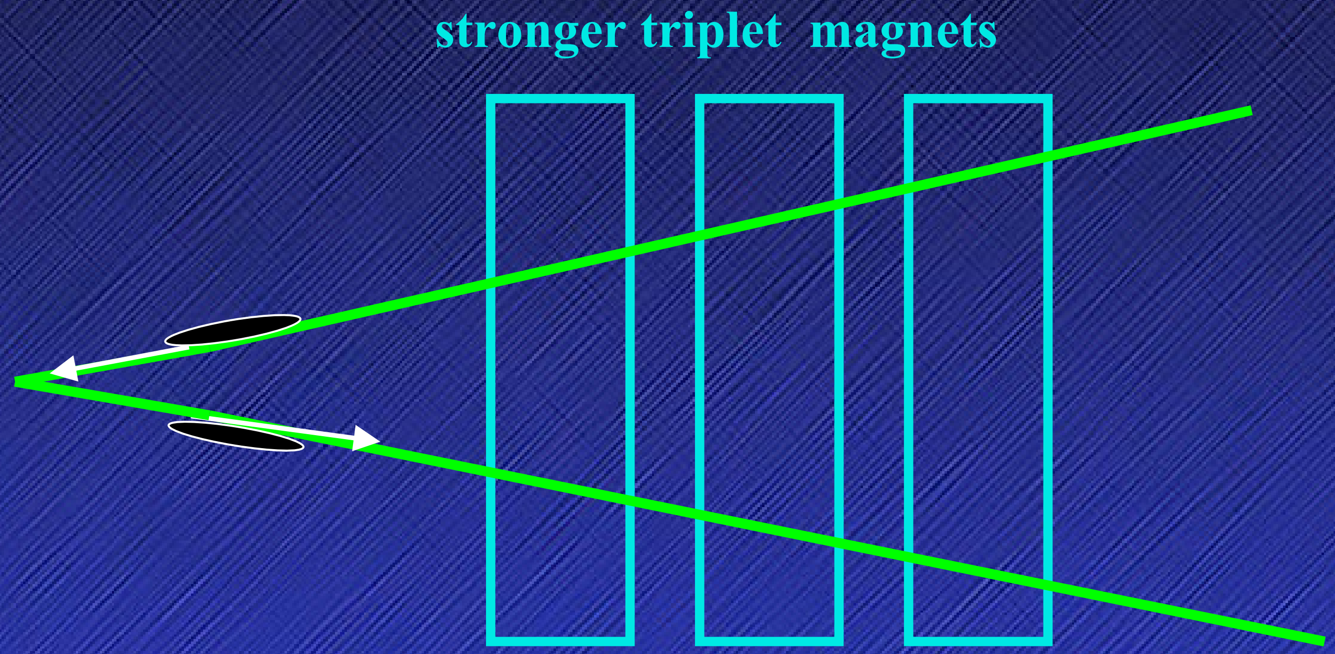



studies of flat-bunch generation in the CERN PS, C. Bhat (FNAL), 2008

*HHH-LARP collaboration*

# low emittance (LE)

R. Garoby




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

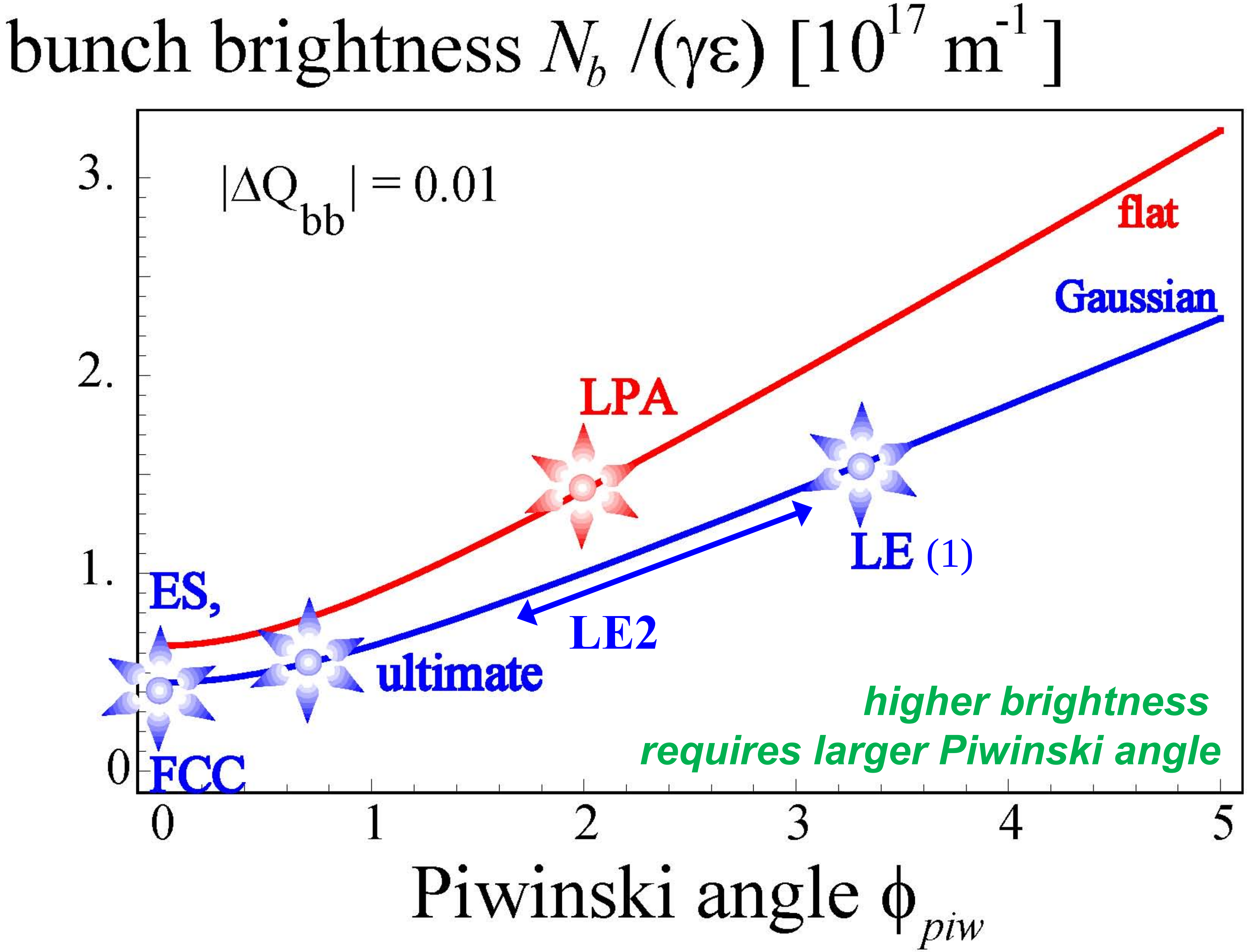
# LE parameter range

| parameter | symbol | LE 1 | LE 2 |
|---|---|---|---|
| transverse emittance | $\varepsilon$ [$\mu$m] | 1.0 | 2.6 |
| protons per bunch | $N_b$ [$10^{11}$] | 1.7 | 2.36 |
| beam current | I [A] | 0.86 | 1.19 |
| beta* at IP1&5 | $\beta*$ [m] | 0.1 | 0.15 |
| full crossing angle | $\theta_c$ [$\mu$rad] | 311 | 322 |
| Piwinski parameter | $\phi=\theta_c\sigma_z/(2*\sigma_x*)$ | 3.2 | 1.7 |
| geometric reduction | | 0.30 | 0.51 |
| peak luminosity | $L$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | 16.3 | 13.2 |
| peak events per #ing | | 309 | 250 |
| initial lumi lifetime | $\tau_L$ [h] | 2.0 | 2.5 |
| effective luminosity ($T_{turnaround}$=10 h) | $L_{eff}$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | 2.5 | 2.7 |
| | $T_{run,opt}$ [h] | 6.4 | 8.4 |
| effective luminosity ($T_{turnaround}$=5 h) | $L_{eff}$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | 3.7 | 3.9 |
| | $T_{run,opt}$ [h] | 4.5 | 5.9 |
| e-c heat SEY=1.4(1.3) | P [W/m] | 1.0 (0.6) | ~1.6 (1.1) |
| SR heat load 4.6-20 K | $P_{SR}$ [W/m] | 0.25 | 0.35 |
| image current heat | $P_{IC}$ [W/m] | 0.33 | 0.64 |
| gas-s. 100 h (10 h) $\tau_b$ | $P_{gas}$ [W/m] | 0.06 (0.6) | 0.08 (0.8) |
| extent luminous region | $\sigma_l$ [cm] | 1.5 | 2.8 |

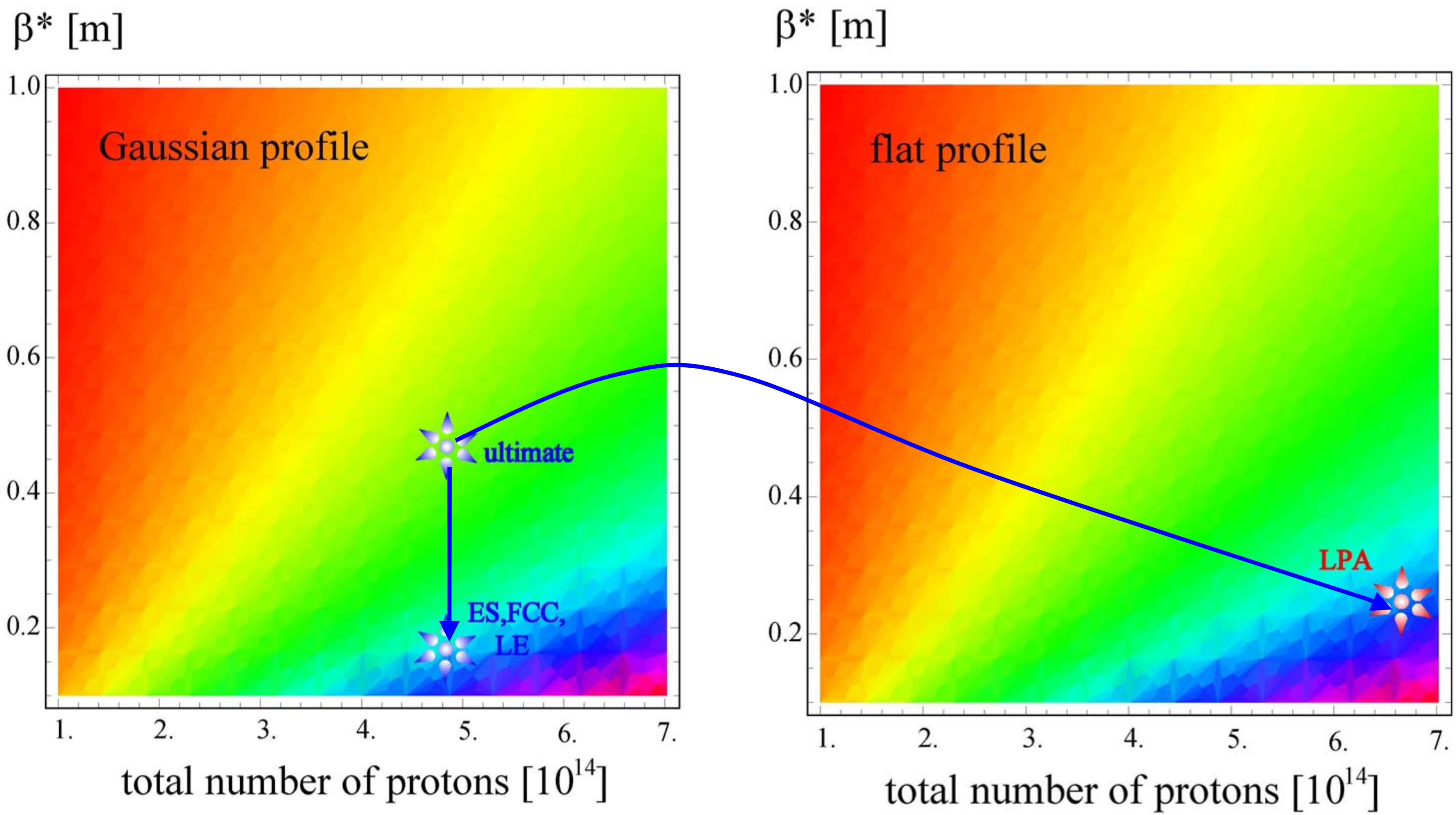
trade off
intensity vs. emittance

***smaller brightness is easier for injectors, but it comes together with higher bunch charge, higher heat load etc.***

# $N_b / (\gamma\varepsilon)$ vs $\phi_{piw}$ plane

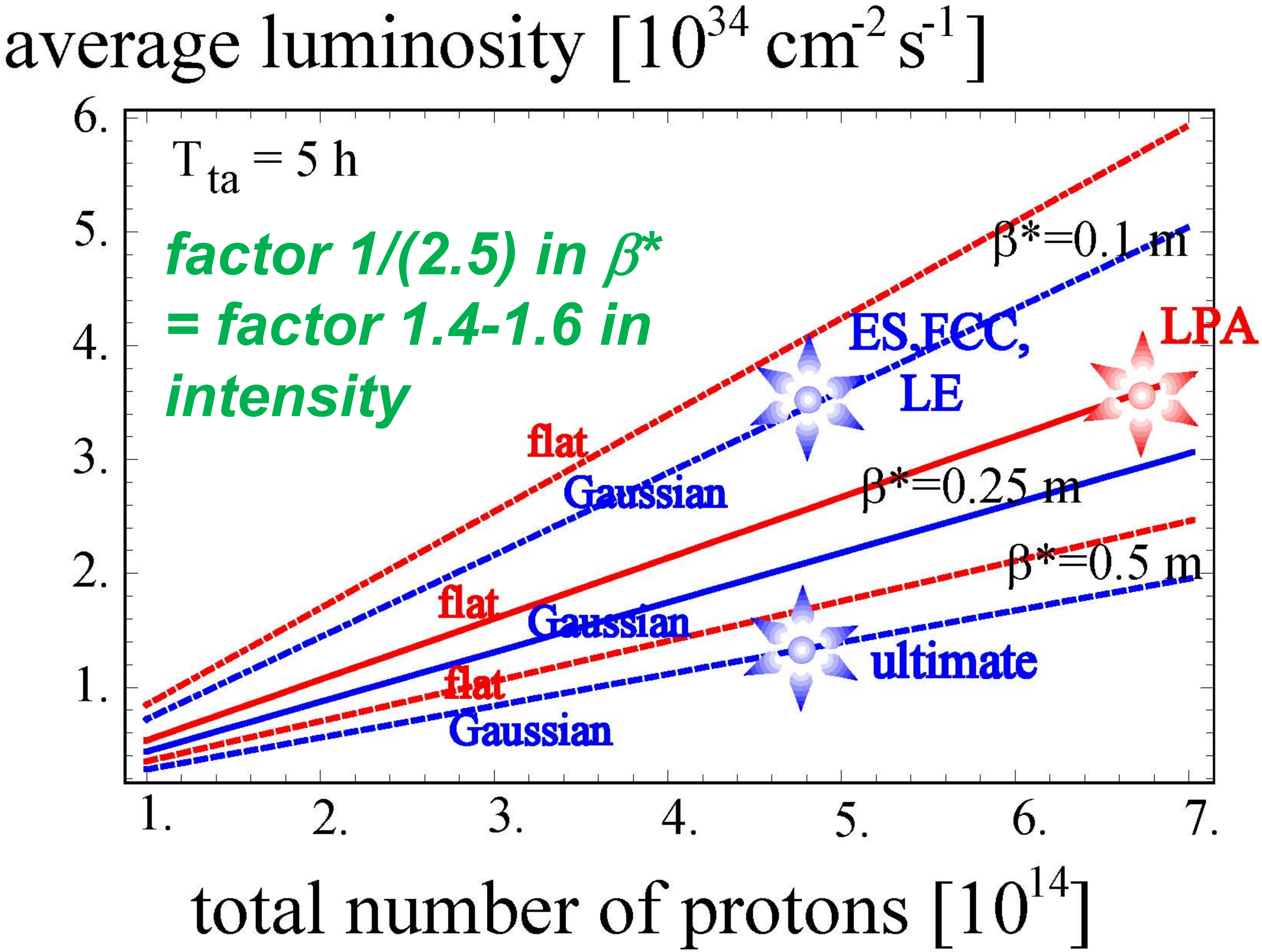


# av. luminosity vs #*p*'s & β*

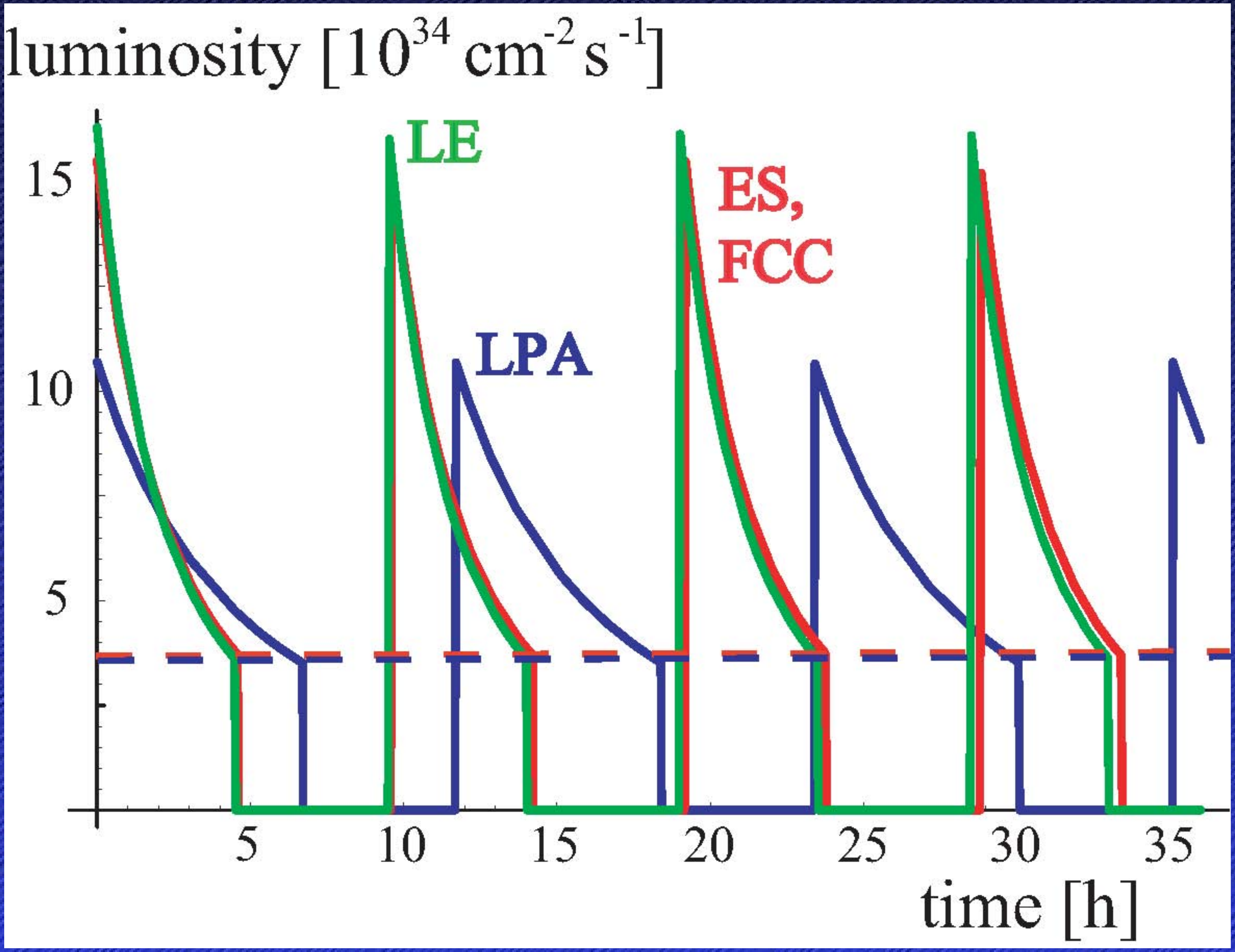



"linear" scale from $10^{33}$ to $2\times10^{35}$ $cm^{-2}s^{-1}$

# av. luminosity vs #*p*'s

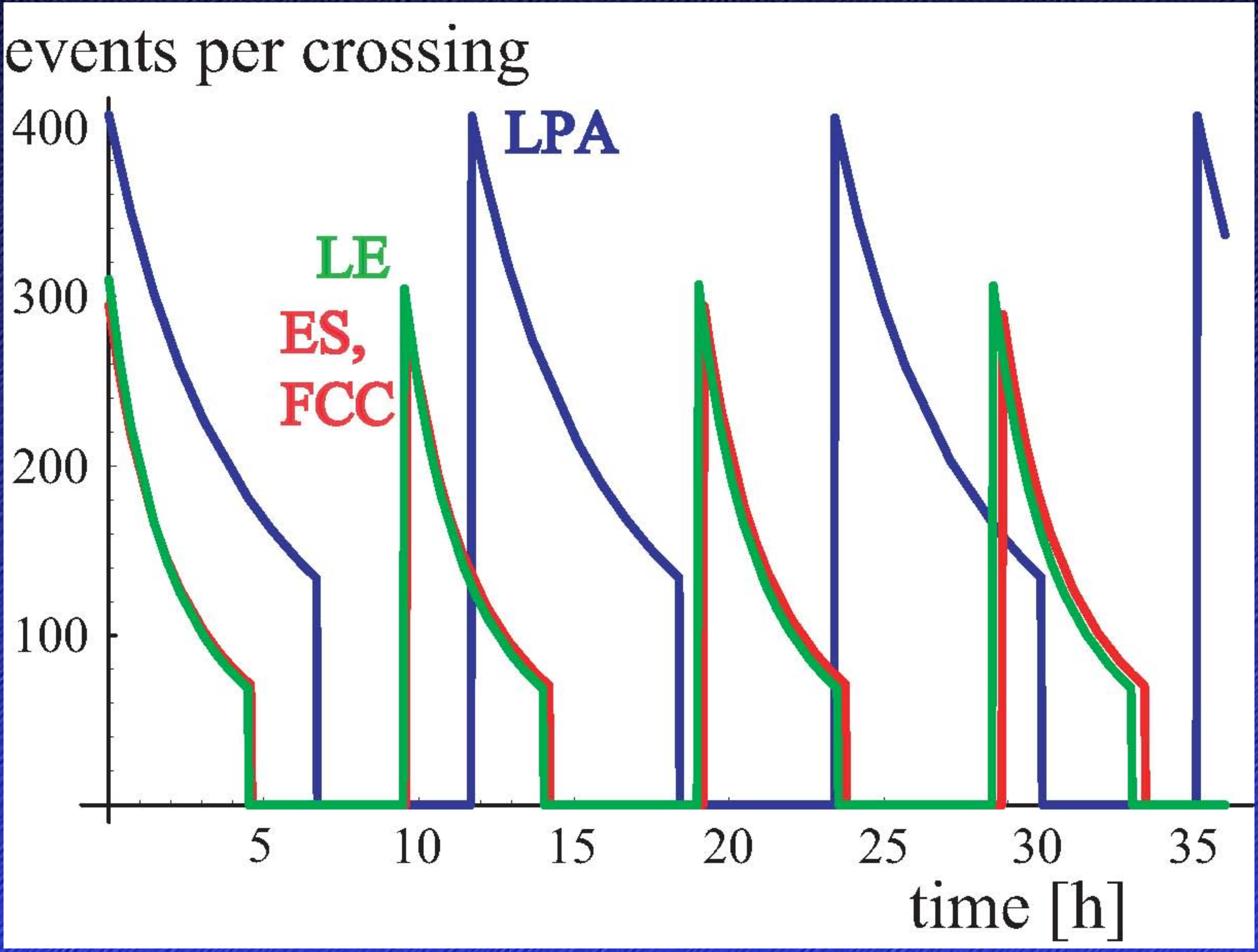


# luminosity evolution

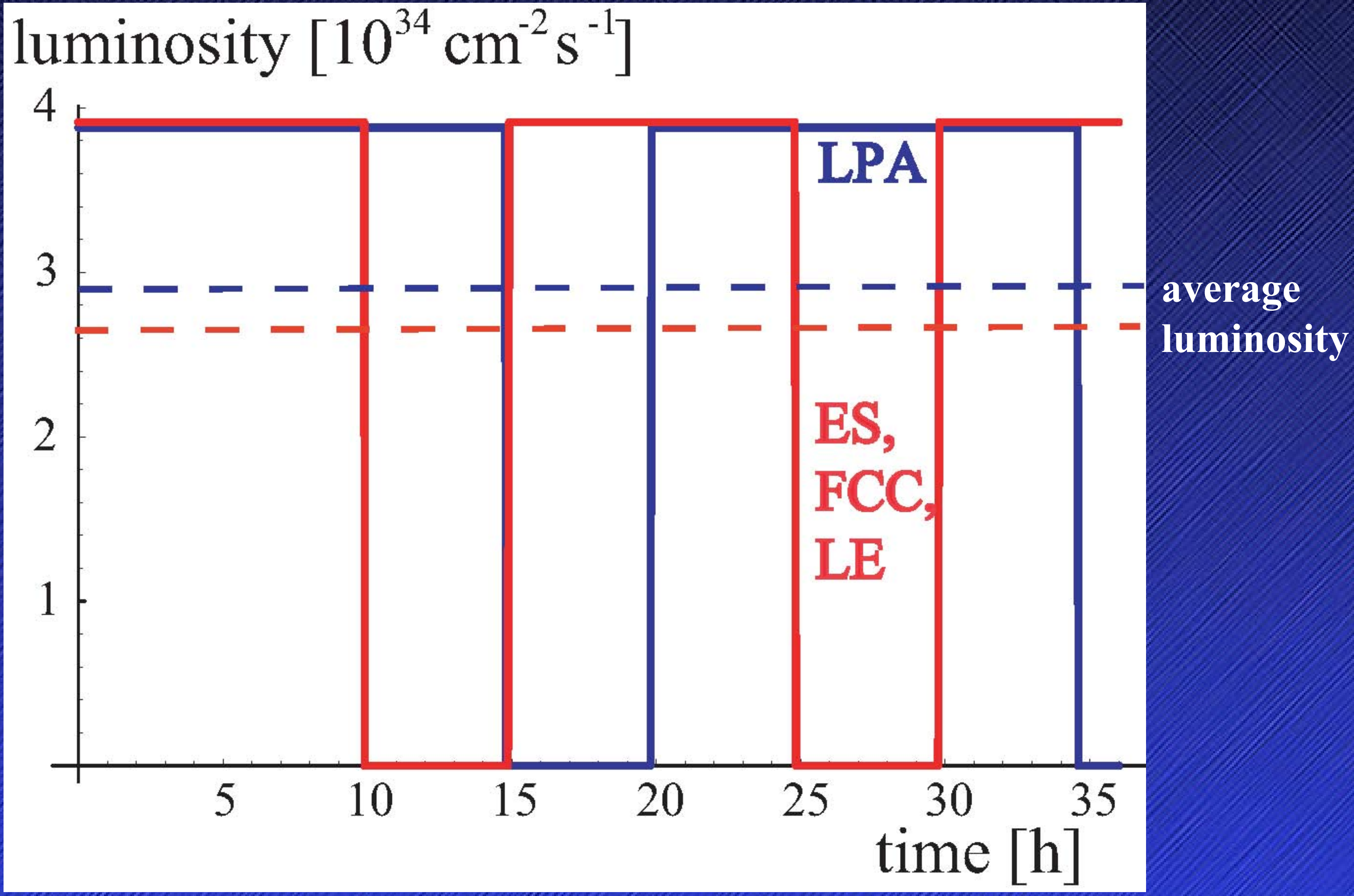



average luminosity

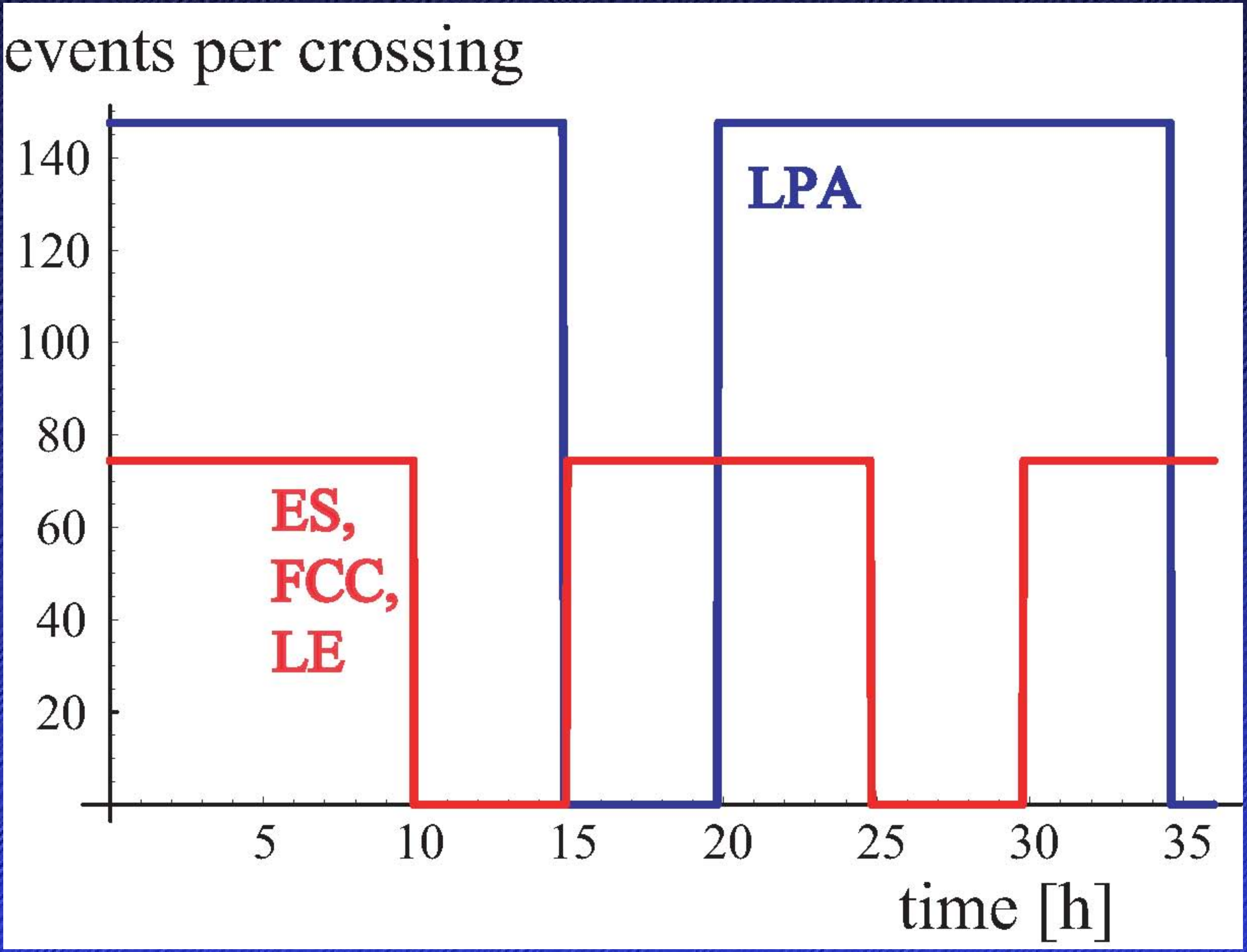
# event pile up



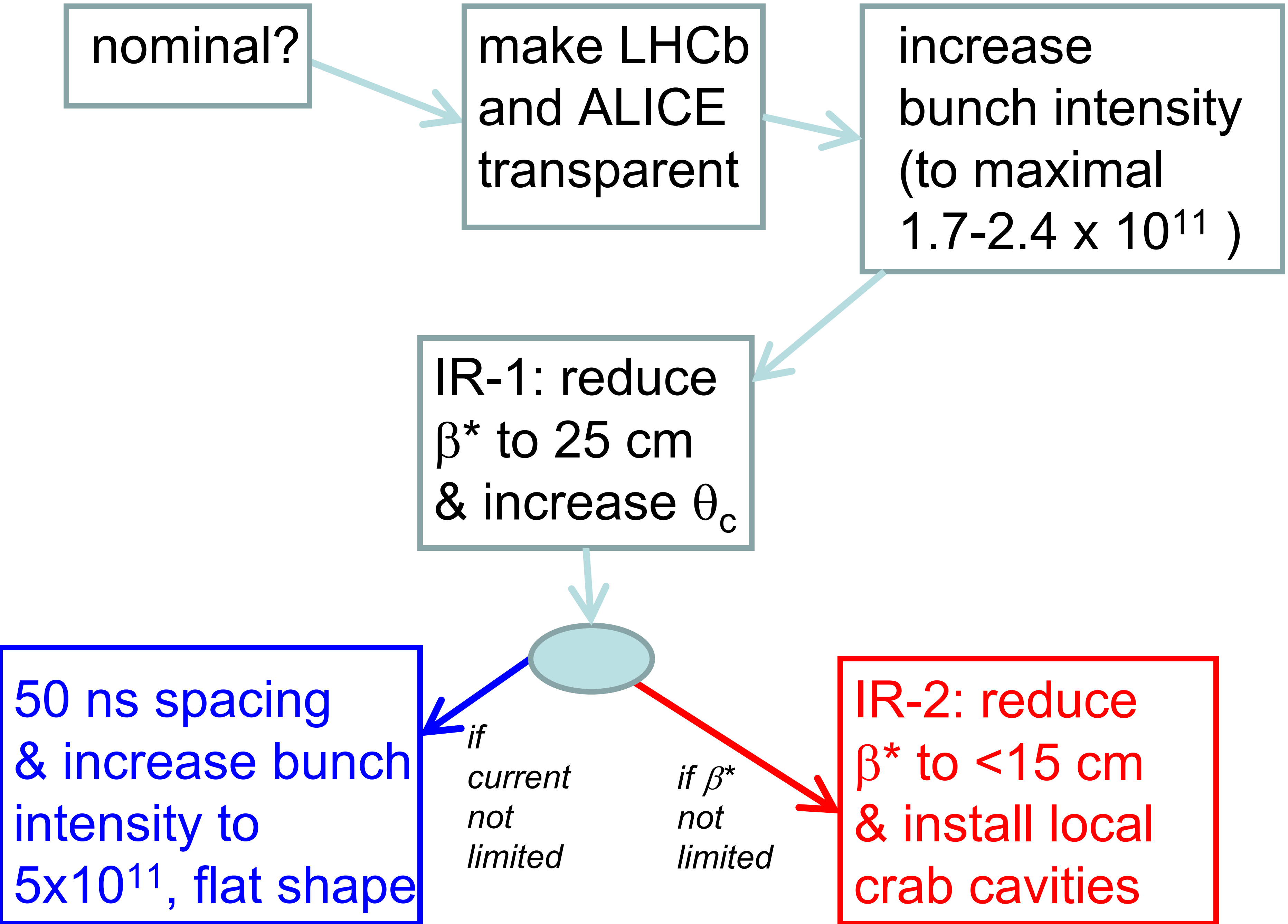
# luminosity with leveling



# event pile up with leveling



# possible
# LHC upgrade
# roadmap


nominal?
make LHCb and ALICE transparent
increase bunch intensity (to maximal 1.7-2.4 x $10^{11}$ )
IR-1: reduce β* to 25 cm & increase $\theta_c$
50 ns spacing & increase bunch intensity to $5x10^{11}$, flat shape
if current not limited
if β* not limited
IR-2: reduce β* to <15 cm & install local crab cavities

# 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

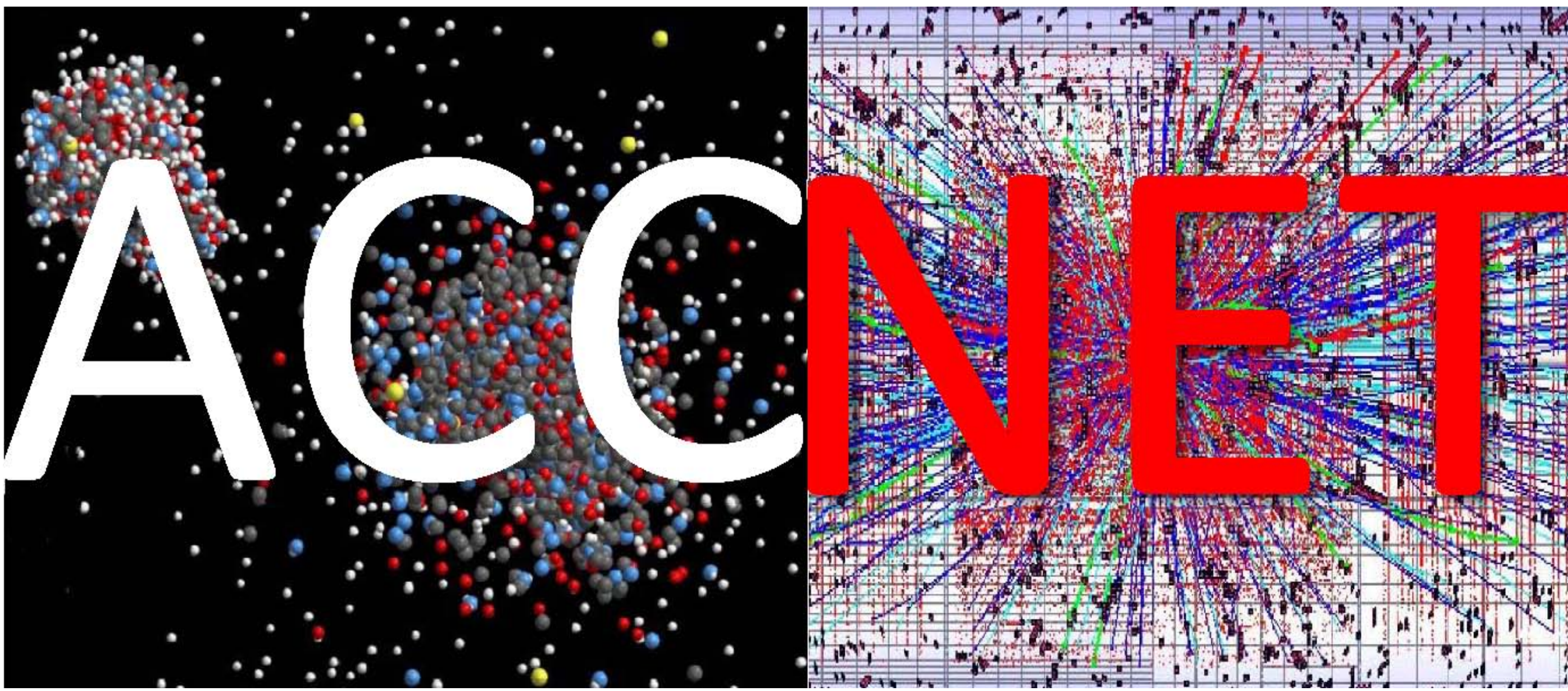
# acknowledgements

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

environment set by the EU's **FP6 CARE-HHH network and** and by **US-LARP** was especially profitable


special thanks to **R. Assmann, O. Brüning, R. Calaga, R. De Maria, L. Evans, S. Fartoukh, R. Garoby, J. Jowett, J.-P. Koutchouk, J. Nash, M. Nessi, K. Ohmi, L. Rossi, F. Ruggiero, W. Scandale, E. Shaposhnikova, G. Sterbini, T. Taylor, E. Todesco, E. Tsesmelis, J. Tückmantel, E. Wildner, …**

# future studies (2009-12)




**RFTECH** **EUROLUMI**