Options and preferences for proton running in 2009

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Objectives for LHC running in 2009

- Deliver significant luminosity to experiments
- Understand limitations and behaviour of machine and beams
- Establish/improve procedures for operation and optimization
- Minimum risk operation

Key parameters for LHC performance

- **Energy**
- **Number of bunches**
- β^*
- **Bunch and beam intensity**

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- **Availability and performance of hardware**
- **Beam dynamics**

Key parameters for LHC performance

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→ **Strongly correlated, depend on:**

- **Expected performance**
- **Availability and performance of hardware**
- **Beam dynamics**

→ **Try to give a "cook book"**

Energy for LHC running

- **Determined by:**
  - **Experiments desiderata**
  - **Machine protection**
  - **Ultimately: machine hardware**
- **Consequences for:**
  - **Crossing angle (if required)**
  - **Number of bunches**
  - β^*

Energy for LHC running

- **Experiments desiderata**
  - **450 GeV**
  - **2.75 TeV (ion comparison)**
  - **5 TeV**
  - **(7 TeV)**

β^* for LHC running

- **Key for significant luminosity, determined by:**
  - **Machine protection (aperture)**
  - **Machine energy**
  - **Beam dynamics**
- **Consequences for:**
  - **Number of bunches**
  - **Crossing angle (if required)**

Number of bunches for LHC running

- **Determined by:**
  - **Machine protection (total beam intensity)**
  - **Experiments desiderata (luminosity, pile up, ..)**
  - **Energy (crossing angle !)**
- **Implications for:**
  - **Crossing angle (for large number of bunches)**
  - β^*
  - **Luminosity sharing between experiments**

Number of bunches for LHC running

- **Without** crossing angle (spacing larger than shared beam pipe length):
  - 43, 156 bunches per beam (or less)
- **With** crossing angle (spacing smaller than shared beam pipe length):
  - 25, 50, 75 ns bunch spacing (within a train of 72, 36 or 24 bunches)
  - Total beam intensity depends on number of injected trains (max. 39, see later)

Minimum number of bunches

- **For colliding pairs in all experiments:**
  - **Minimum is 2 bunches per beam, but not symmetric, one pair colliding in each IP**
  - **Making it symmetric requires 3 bunches per beam: 3 collisions in IP1/5, 1 collision in IP2/8**

Without crossing angle

- (Almost) Equally spaced bunches (either 43 or 156)
- Requires shifting some bunches to allow for collisions in LHCb
  - Shift done by adjusting timing of SPS to LHC transfer
  - Determines possible filling schemes
  - Filling schemes can be adjusted to meet requirements from experiments
- Nota bene: TOTEM with $\beta^* = 90$ m must run without crossing angle

Filling schemes with 43 bunches per beam

displaced	0	4	11	19
IP1	43	43	43	43
IP2	42	34	21	4
IP5	43	43	43	43
IP8	0	4	11	19

- **Numbers give number of colliding bunches per interaction point**
- **See LHC Project Note for details**

Filling schemes with 156 bunches per beam

	no bunches displaced	option 1	option 2
IP1	156	156	156
IP2	152	76	16
IP5	156	156	156
IP8	0	36	68

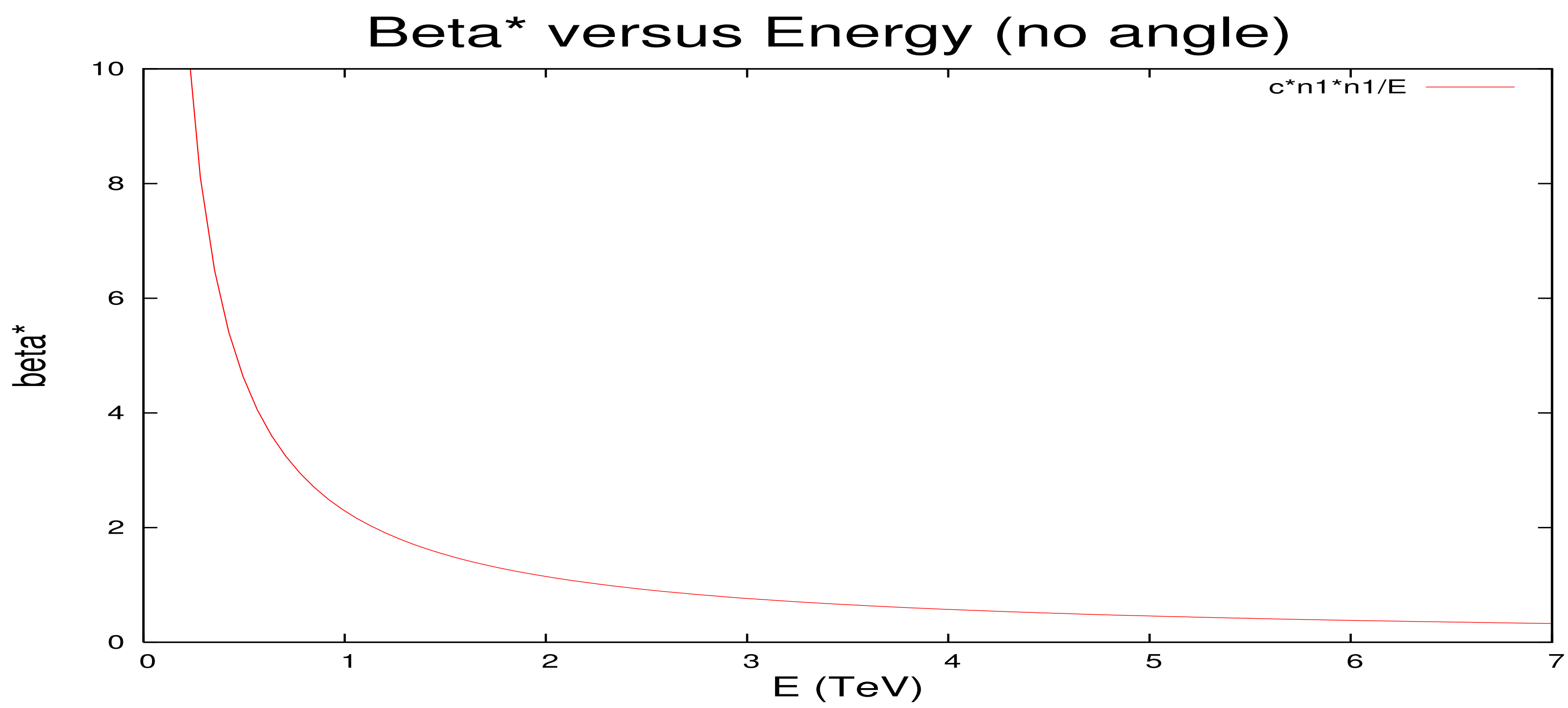
- Numbers give number of colliding bunches per interaction point

Operation without crossing angle

- **No long range interactions, i.e. no crossing angle**
  → **aperture limiting factor**
- **Required aperture determined by:**
  - β^***, since** $\hat{\beta} \propto 1/\beta^*$
  - **Energy, since** $\sigma_{max} \propto 1/\sqrt{\gamma}$
- **Apply standard definition for aperture and use** $n1$ **as criterion**
- **Defines a relation between energy and minimum** β^*

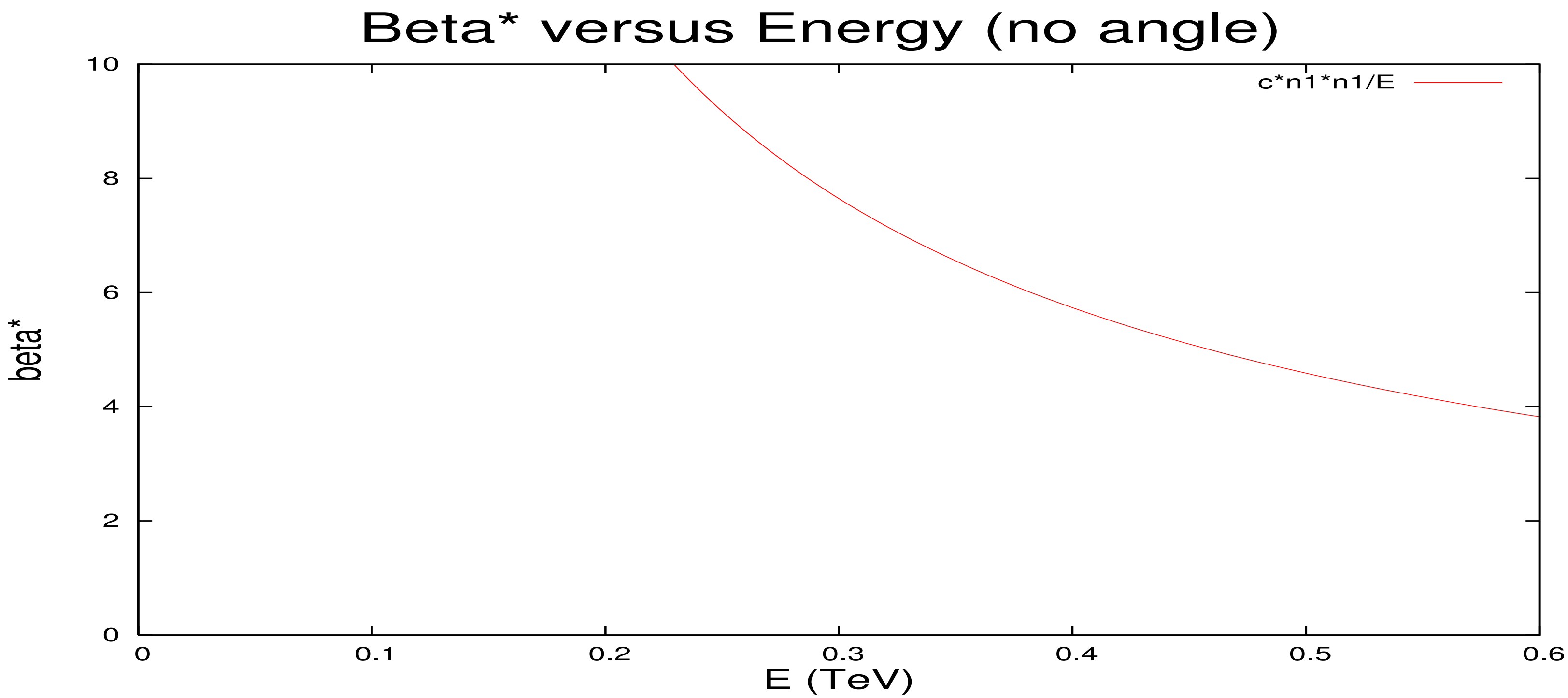
β^* versus energy

- **Requiring minimum $n1$ of 7.0**



β^* versus energy

- **Requiring minimum $n1$ of 7.0**



Collisions at 450 GeV

- **Operational scenarios are:**
  - **No crossing angle: 2, 3, 43, or 156 bunches per beam**
  - **If no crossing angle: only coupling left from solenoids**
  - β^* **limited to** $\beta^* \geq$ **6 m (may want to stay at injection** β^***)**
  - **Assuming N = 0.4** 10^{11}**,** ϵ_n **= 3.75** μ**m**
  - **Luminosity IP1/5 (43 bunches)** $\approx$ **1.3** $\cdot 10^{29}$ **cm**$^{-2}$**s**$^{-1}$
  - **Luminosity IP1/5 (156 bunches)** $\approx$ **4.7** $\cdot 10^{29}$ **cm**$^{-2}$**s**$^{-1}$
- **Luminosity in IP2 and IP8 smaller**

Beam-beam parameter and tune shifts

- **What about much smaller emittances ??**
- **Head-on collision may be a problem:**

$$\Delta Q \propto \xi = \frac{N \cdot r_o \cdot \beta^*}{4\pi\gamma\sigma^2} = \frac{N \cdot r_o}{4\pi\epsilon_n}$$

- **Head-on tune shift independent of β^* and γ**
- **For much smaller emittances ϵ_n ➡ head-on effects strongly increased !**
- **For $N = 0.4 \cdot 10^{11}$ can probably accept $\epsilon_n \approx$ 2 - 2.5 μm**
- **Alternative: transverse blow up of bunches**

Operation without crossing angle (IP1/5)

Energy (TeV)	β^* **(m)**	$\mathcal{L}_{43}$ $(\mathbf{cm^{-2}s^{-1}})$	$\mathcal{L}_{156}$ $(\mathbf{cm^{-2}s^{-1}})$
0.45	**6**	$\mathbf{0.13} \cdot 10^{30}$	$\mathbf{0.47} \cdot 10^{30}$
2.75	**1**	$\mathbf{4.30} \cdot 10^{30}$	$\mathbf{15.6} \cdot 10^{30}$
5.00	**0.6**	$\mathbf{13.0} \cdot 10^{30}$	$\mathbf{47.0} \cdot 10^{30}$
(5.00	**3.0**	$\mathbf{16.0} \cdot 10^{30}$	$\mathbf{60.0} \cdot 10^{30})$

- **All compatible with aperture, consider as limit**
- **For IP2 and IP8, scale according to filling scheme**

Operation with many bunches (≥ 156)

- Requires crossing angle α to avoid parasitic interactions
- Long range interactions unavoidable, crossing angle must be large enough
- Too large crossing angle reduces luminosity (and aperture)
- Number of long range interactions increases with number of bunches per train
- Probably start with very few trains (see later)

Reminder:

Luminosity with crossing angle α in x-plane (round beams):

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \cdot S$$

S **is the reduction factor**

For small crossing angles and (Gaussian bunches) $\sigma_s \gg \sigma_{x,y}$

$$\Rightarrow S \approx \frac{1}{\sqrt{1 + (\frac{\alpha}{2}\frac{\sigma_s}{\sigma_x})^2}} = \frac{1}{\sqrt{1 + (\frac{\alpha^2}{4}\frac{\sigma_s^2}{\beta_x \epsilon})}}$$

Beam-beam parameter and tune shifts

Head-on (no crossing angle):

$$\Delta Q \;\approx\; \xi \;=\; \frac{N \cdot r_o \cdot \beta^*}{4\pi\gamma\sigma^2} \;=\; \frac{N \cdot r_o}{4\pi\epsilon_n}$$

Head-on (crossing angle α in x-plane):

$$\Delta Q_x \;\approx\; \xi \cdot S \;=\; \frac{N \cdot r_o \cdot \beta^*}{4\pi\gamma\sigma^2} \cdot S \;=\; \frac{N \cdot r_o}{4\pi\epsilon_n} \cdot S$$

$$\Rightarrow S \approx \frac{1}{\sqrt{1 + (\frac{\alpha}{2}\frac{\sigma_s}{\sigma_x})^2}} \;=\; \frac{1}{\sqrt{1 + (\frac{\alpha^2}{4}\frac{\sigma_s^2}{\beta_x \epsilon})}}$$

How many bunches should be aim at ?

Reminder:

$$\mathcal{L} \;\propto\; N \cdot N \cdot n_b \;=\; I_{tot} \cdot N \;=\; \frac{I_{tot} \cdot I_{tot}}{n_b}$$

$$\Delta Q \;\propto\; N \;=\; \frac{I_{tot}}{n_b}$$

- **If experiments not limited by pile up (we talk about** $\mathcal{L} \;\ll\; 10^{33}\; cm^{-2}s^{-1}$)
- **If** I_{tot} **limited (e.g. protection) and** N **not (yet) limited**
- **Smaller number of bunches** n_b **beneficial**

Filling schemes with crossing angle

Bunch spacing	Δs	# long range encounters (per IP)
25 ns	3.75 m	32
50 ns	7.50 m	16
75 ns	11.25 m	12

- Three different bunch spacings presently considered (for protons)
- Half bunch spacing Δs is position of first parasitic encounter

Filling schemes - colliding bunches per IP

Spacing	IP1	IP2	IP5	IP8
25 ns	2808	2736	2808	2622
50 ns	1404	1368	1404	0
75 ns	936	912	936	874

- **50 ns seem not attractive, but trains can be displaced**
- **Try 5 scenarios where different number of trains are shifted at transfer SPS/LHC**

Filling schemes - colliding bunches per IP

	a	b	c	d	e
IP1	1404	1404	1404	1404	1333
IP2	1368	684	0	72	2
IP5	1404	1404	1404	1404	1333
IP8	0	655	1311	1242	1173

- The 50 ns allow to adjust luminosity between experiments (not possible for 25 ns)

Long range beam-beam separation

- **Unavoidable parasitic interactions, number depends on bunch spacing**
- **Crossing angle required**
- **LHC: ($\frac{\alpha}{2} \approx$ 142.5 (!) μrad, $\beta^{*} \approx$ 0.55 m): S $\approx$ 0.80**
- **To small α: not enough separation**
- **To large α: little (or no) luminosity gain**
- **Smaller ϵ for given α, β^{*}: larger d_{sep}, but also reduced S**

Minimum required crossing angle versus β^*

- **Crossing angle as function of $\beta^*, \gamma, \epsilon_n, \Delta s$, valid for IP1 and IP5, (not for IP2 and IP8)**

$$\alpha = \frac{d_{sep} \cdot \sqrt{\frac{\epsilon_n}{\gamma}} \cdot \sqrt{\beta^* \left(1 + \frac{\Delta s^2}{\beta^{*2}}\right)}}{\Delta s}$$

where Δs is half the bunch spacing, and d_{sep} the minimum required separation in the drift between IP and Q1 (for nominal running $\approx$ 9.5)
For $\Delta s \gg \beta^*$ (and with parallel separation) we have simply:

$$\alpha = \frac{d_{sep} \cdot \sqrt{\frac{\epsilon_n}{\gamma}}}{\sqrt{\beta^*}}$$

Minimum required crossing angle versus β^*

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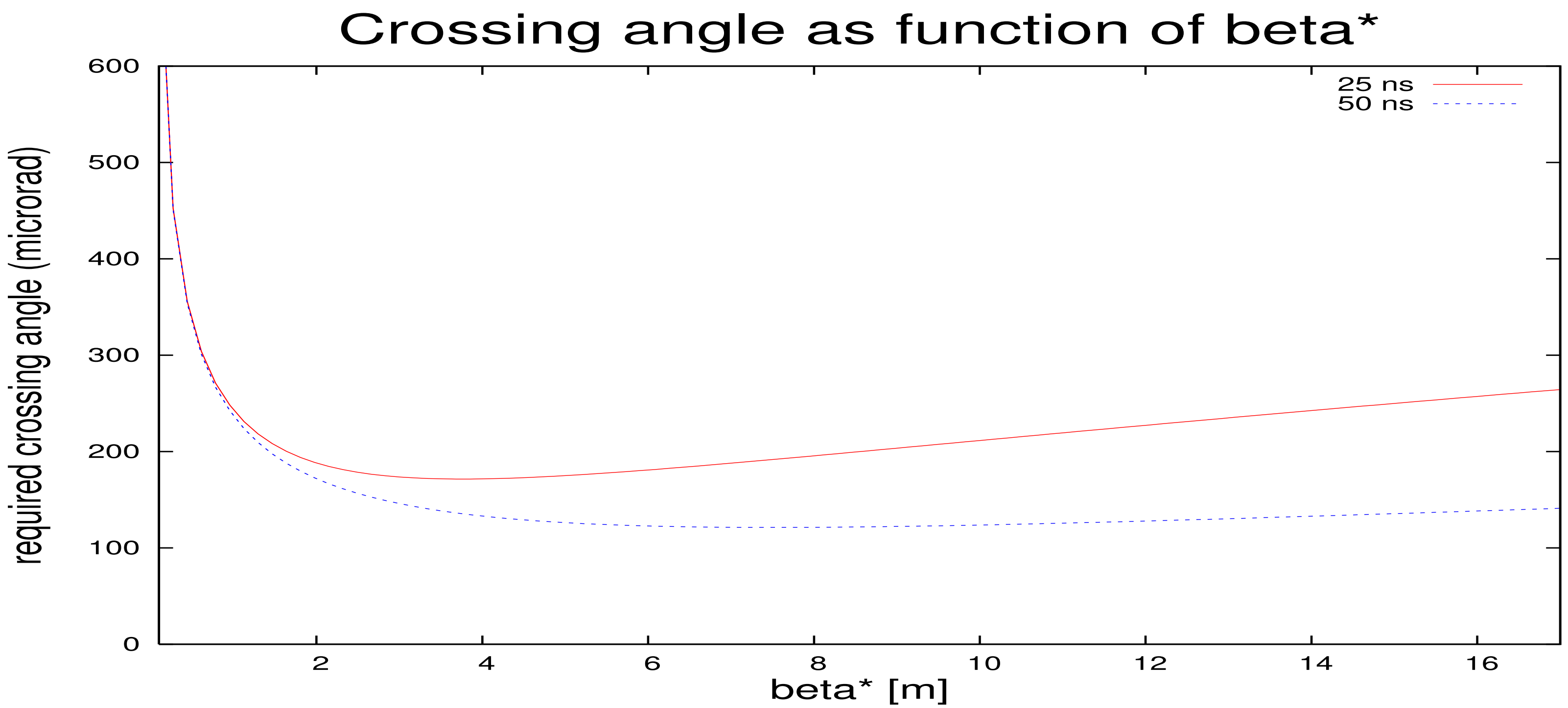
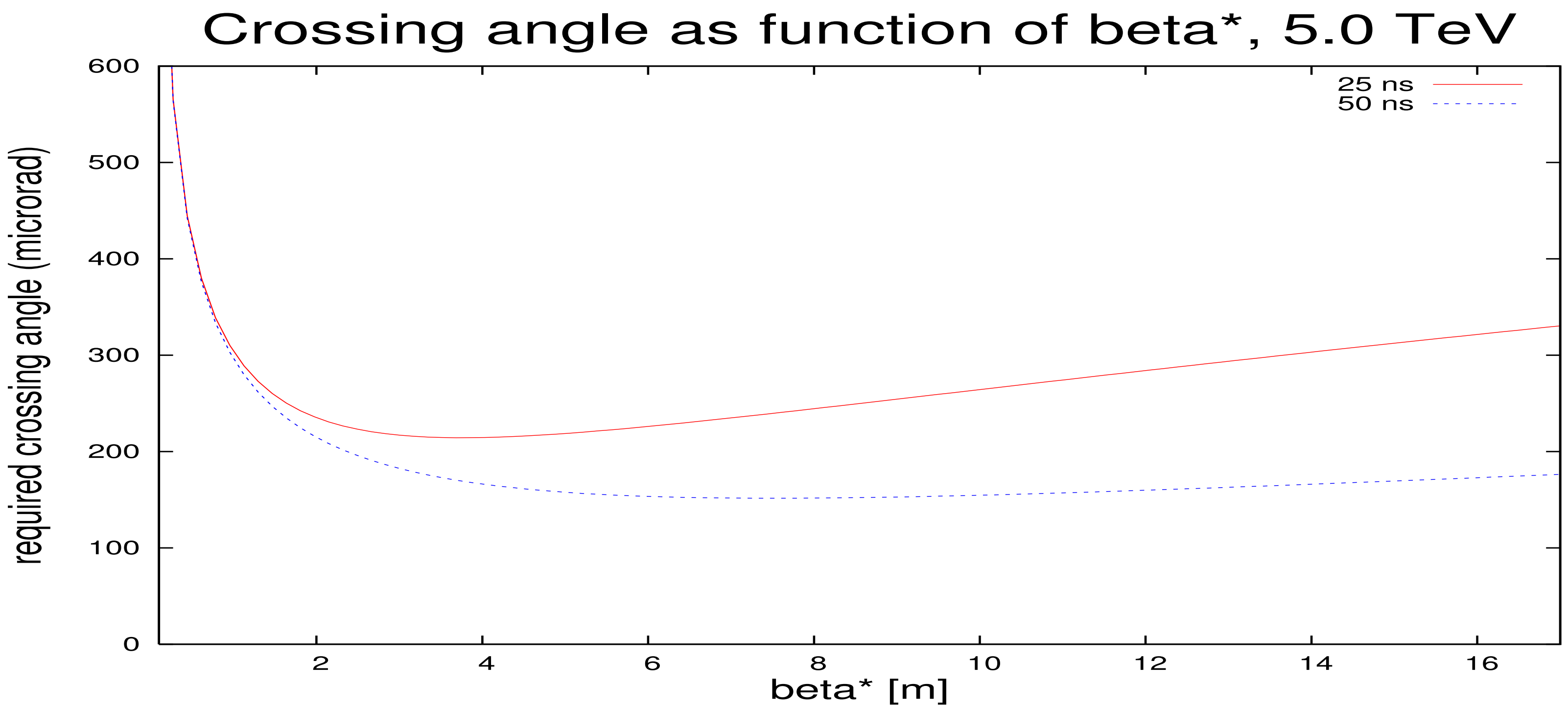
Minimum required crossing angle versus β^*

- **Required crossing angle for 7.0 TeV for minimum 10σ separation (scales $\approx 1/\sqrt{\gamma}$)**



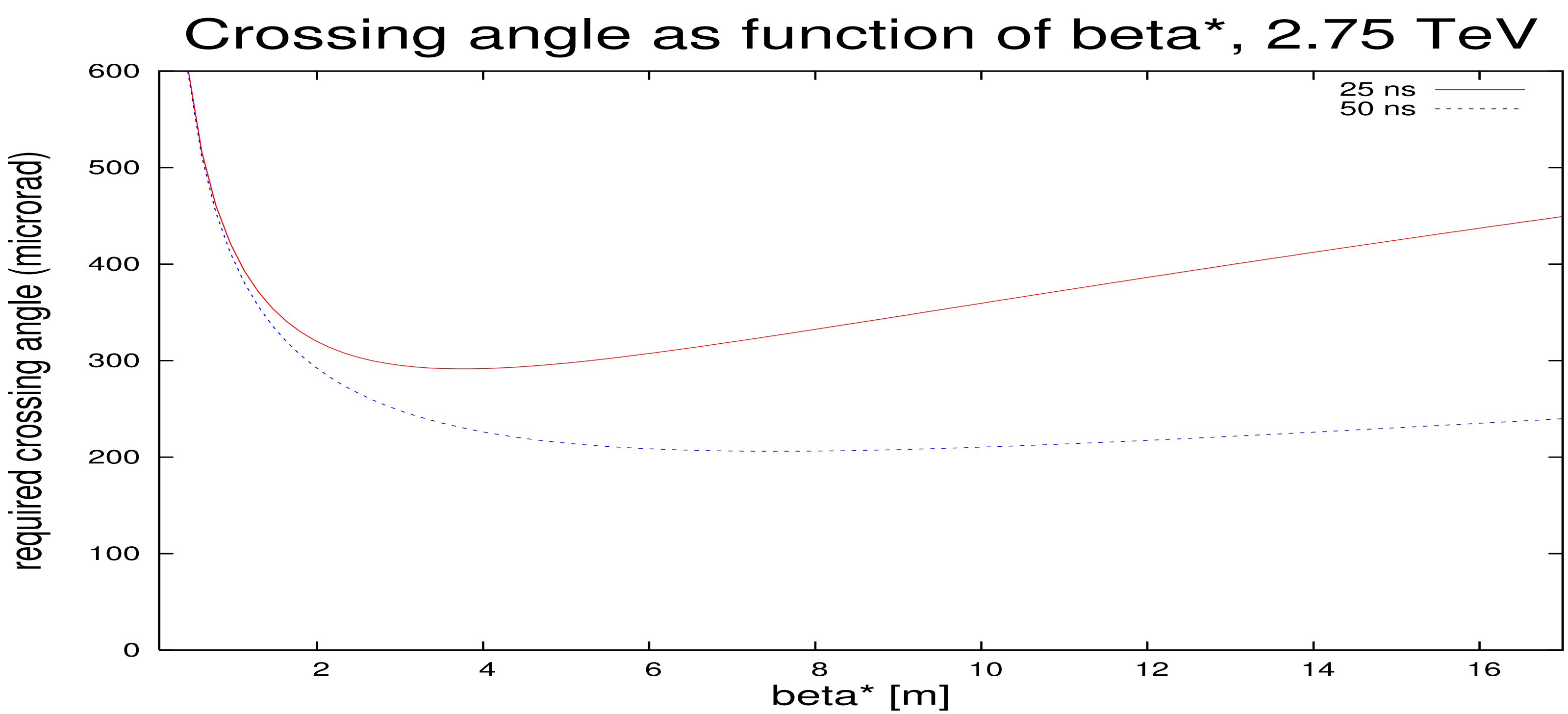
Minimum required crossing angle versus β^*

- **Required crossing angle for 5.0 TeV for minimum 10σ separation (scales $\approx 1/\sqrt{\gamma}$)**



Minimum required crossing angle versus β^*

- **Required crossing angle for 2.75 TeV for minimum 10σ separation (scales $\approx 1/\sqrt{\gamma}$)**



Operation with crossing angle

- **Operation with β^* between 1 m and 4 m very promising**
- **Get large enough crossing angle (within aperture) to avoid any significant long range effects**
  - **Over large range crossing angle can be kept $\approx$ constant (in particular for 50 ns spacing)**
  - **Initially, take e.g. 50% larger angle than necessary**
    → long range tune spread less than half !

Operation with crossing angle

- **Assume 0.5 10^{11} per bunch, and crossing angle $\approx$ 300 μrad**
- **Luminosity (in IP1 and IP5) in units of 10^{32} cm^{-2}s^{-1}**

Energy (TeV)	β^* (m)	$\mathcal{L}_{936}$ (cm^{-2}s^{-1})	$\mathcal{L}_{1404}$ (cm^{-2}s^{-1})	$\mathcal{L}_{2808}$ (cm^{-2}s^{-1})
5.0	3.0	0.9	1.4	2.8
5.0	2.0	1.4	2.1	4.2
5.0	1.0	2.6	4.0	8.0
7.0	3.0	1.3	2.00	4.0
7.0	2.0	2.0	3.00	6.0
7.0	1.0	4.0	6.00	12.0

Bunch spacing: 25 ns versus 50 ns

- **Dynamic aperture as function of Tune (courtesy D. Kaltchev, TRIUMF)**
- **For 50 ns spacing (half the number of long range interactions):**
  - **Loss of (maximum) luminosity, but:**
  - **Dynamic aperture strongly improved**
  - **Simplified operation**
  - **(same for 75 ns spacing)**

Collisions in IP2 and IP8

- Complication is internal crossing angle, produced by compensation of spectrometers (LHC Report 1009, LHC Note 419, "Chamonix" 2006)
- Without external angle (i.e. 43 or 156 bunches) no constraint on spectrometer polarity and on strength (even at 450 GeV), i.e. no ramping required
- But: large internal angle may substantially reduce luminosity (in particular for lower energies)
- When an external angle is required: follow procedures described in reports

With external angle: case IP8

- For all details: see LHC Project Note 419
- Crossing angle is in horizontal plane !
- Requires shifted trains (see later)
- With external crossing angle ramping of spectrometer is required for (at least) one of the polarities
- At 5.0 TeV: $\beta^* \geq$ 3 m (better: 4 m) possible (both polarities), if permitted by collimation system

How to increase the total intensity in the LHC ?

- **Basically two options:**
  - **All bunches and in steps increase intensity per bunch**
  - **Large (maximum) intensity per bunch and in steps increase number of bunches (i.e. trains)**

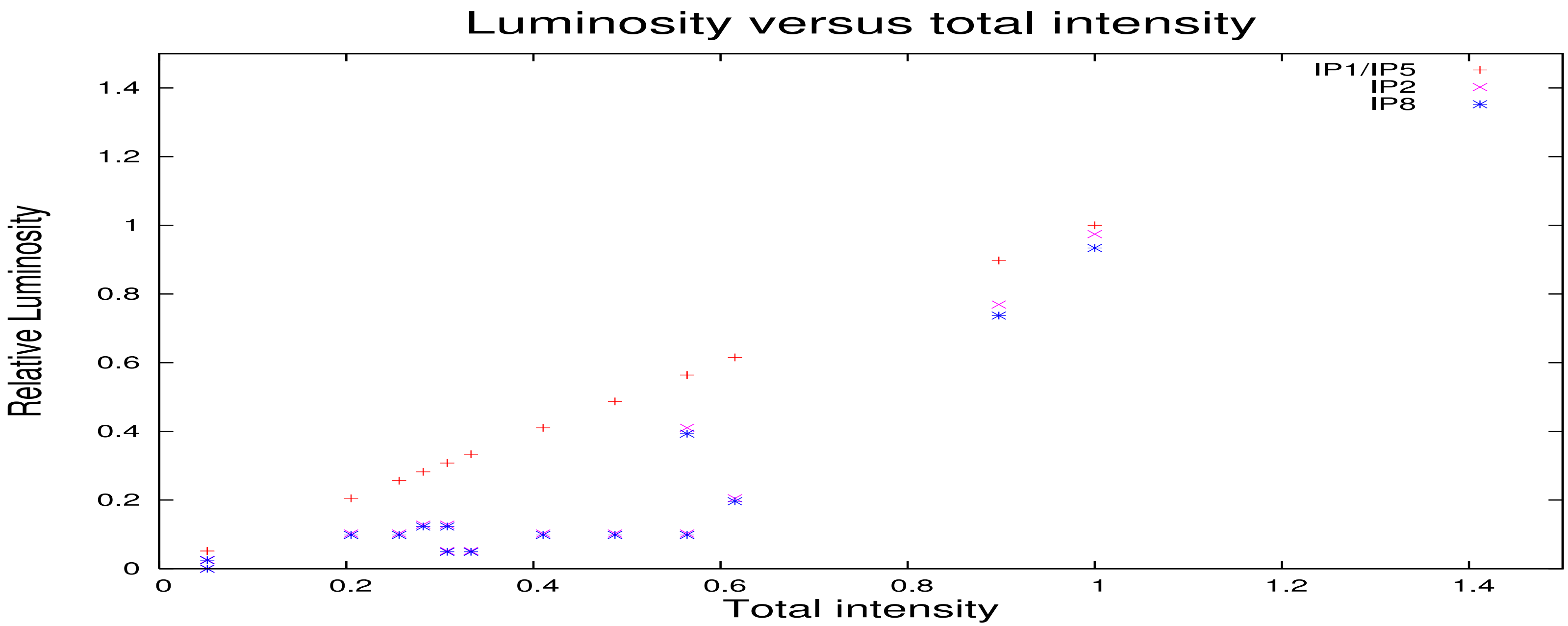
- **Consequences for:**
  - **Beam-beam effects**
  - **Luminosity control in experiments**
  - **Collimation**
  - **Operation**

Reminder: experimental luminosities

- **IP1 and IP5: largest possible luminosity for any configuration**
- **IP8: high luminosity, but 1 - 5 $\cdot$ 10^{32} cm^{-2} s^{-1} for any configuration**
- **IP2: low luminosity, if possible for any configuration**
- **Try strategy to increase total intensity fulfilling these requirements**
- **Start with very few trains and slowly increase their number**

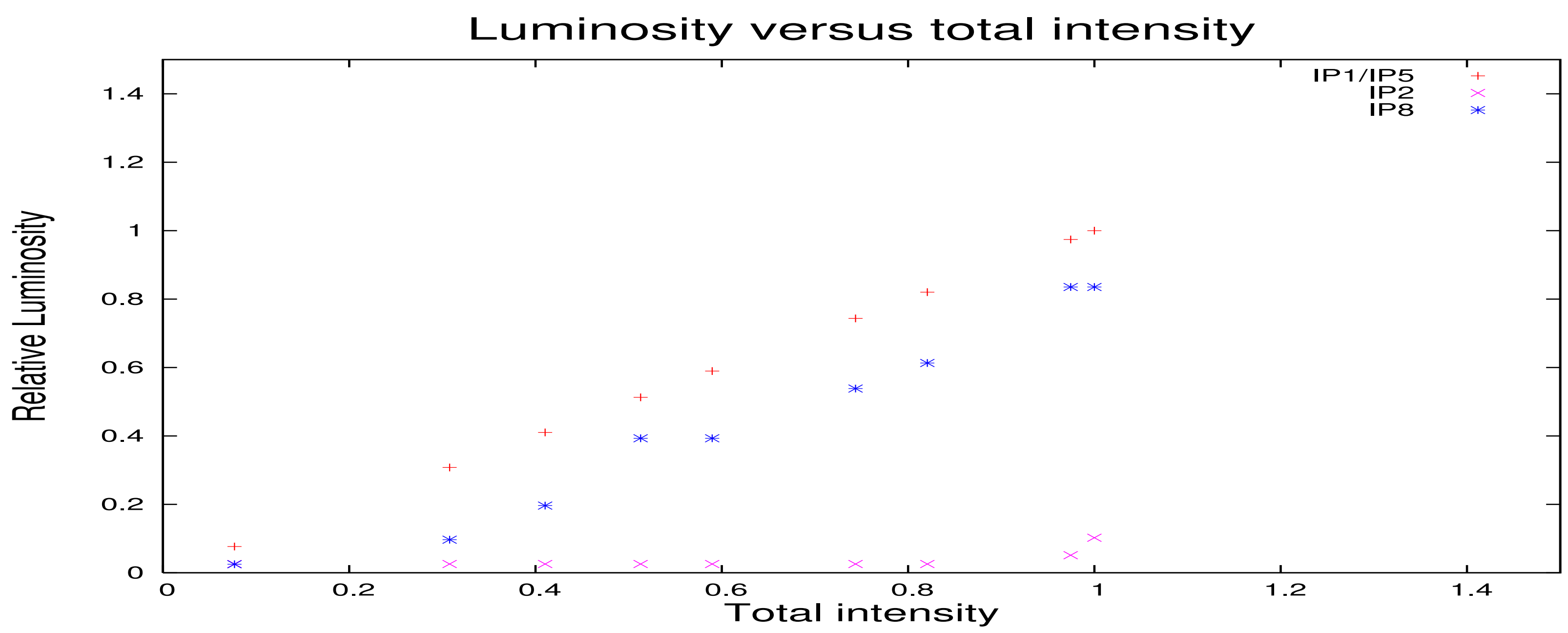
Relative luminosity as function of total intensity

- **Increase of I_{tot} by additional SPS-LHC injections**
- **Spacing 25/75 ns, selected LHC transfers shifted**



Relative luminosity as function of total intensity

- **Spacing 50 ns, selected SPS-LHC transfers shifted (see LPN 415)**



Relative luminosity as function of total intensity

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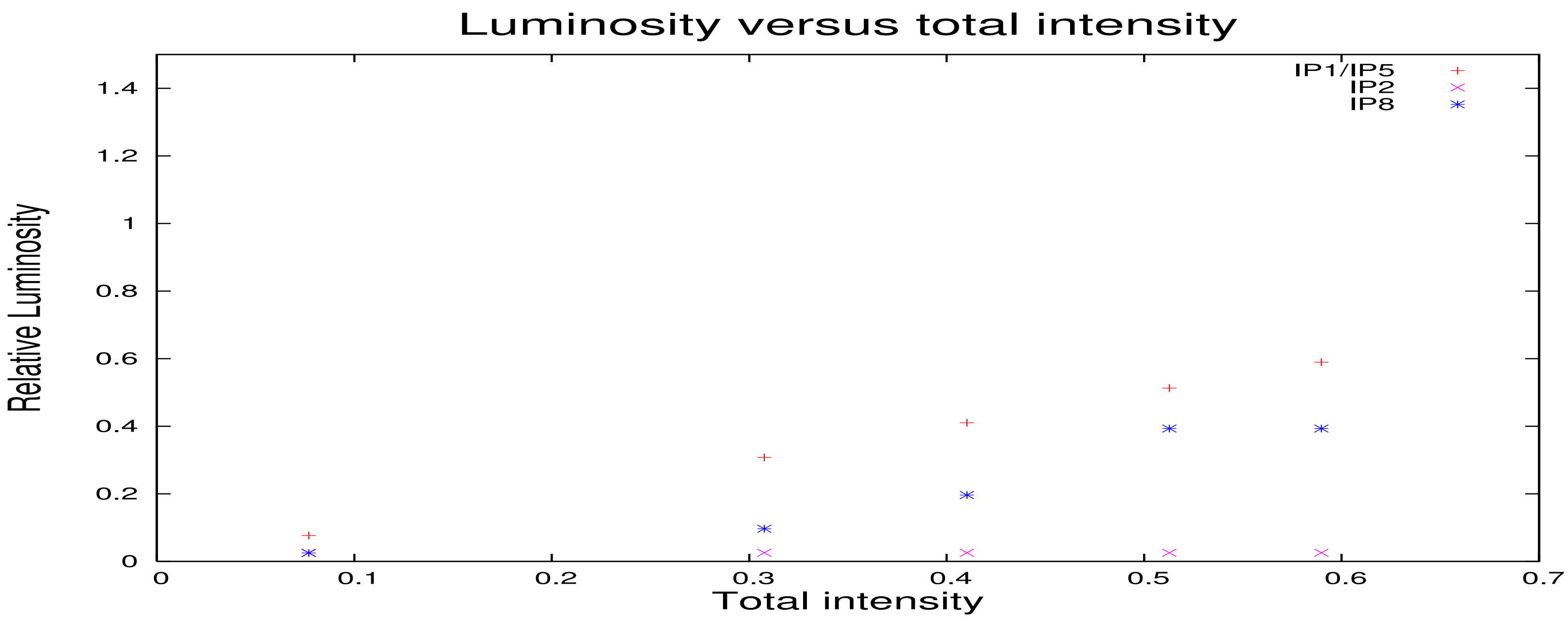
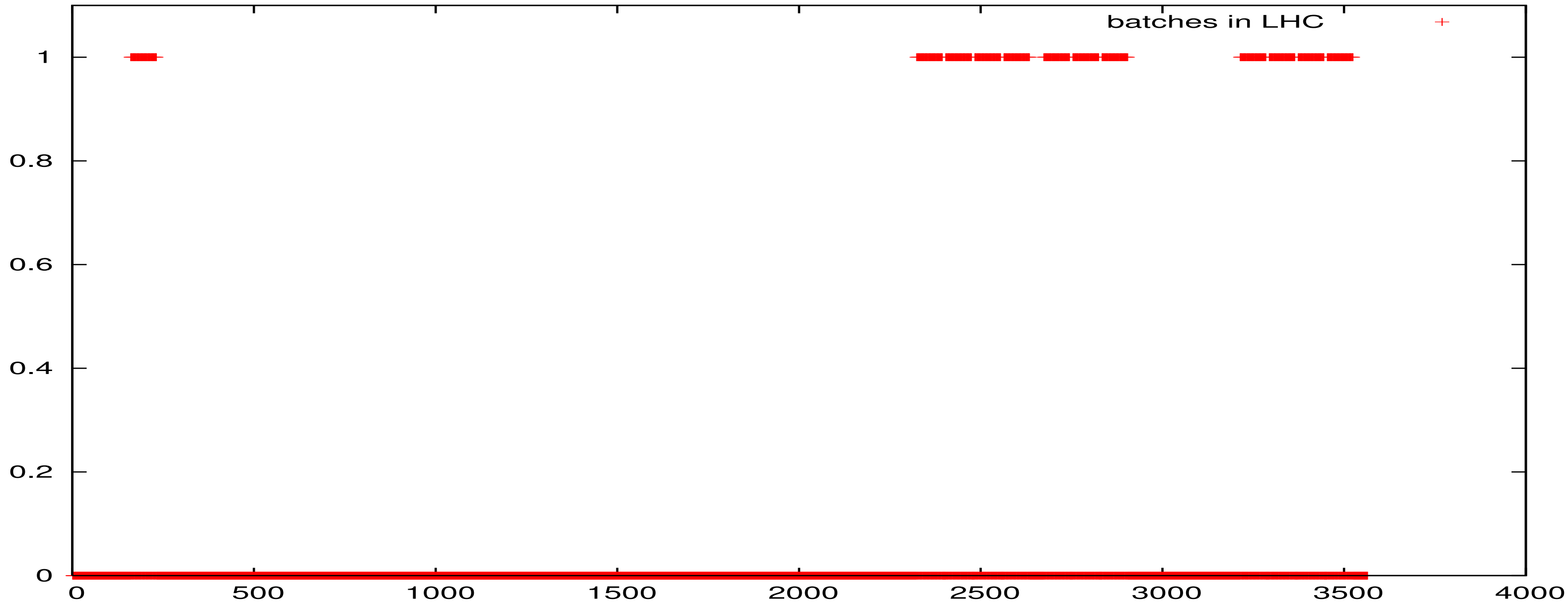


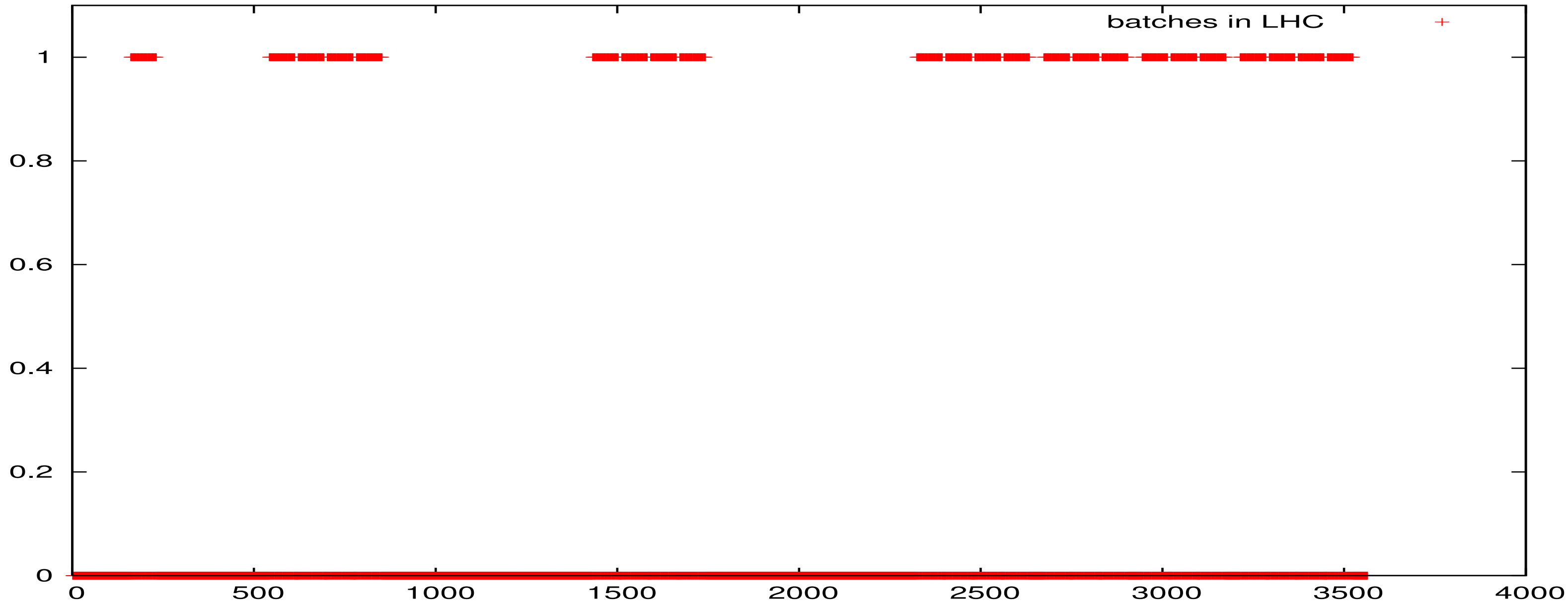
Filling scheme in LHC

- **Spacing 50 ns, ≈ 30% of maximum total current, bunch position versus bucket (slot) number**



Filling scheme in LHC

- **Spacing 50 ns, $\approx$ 60% of maximum total current, bunch position versus bucket (slot) number**

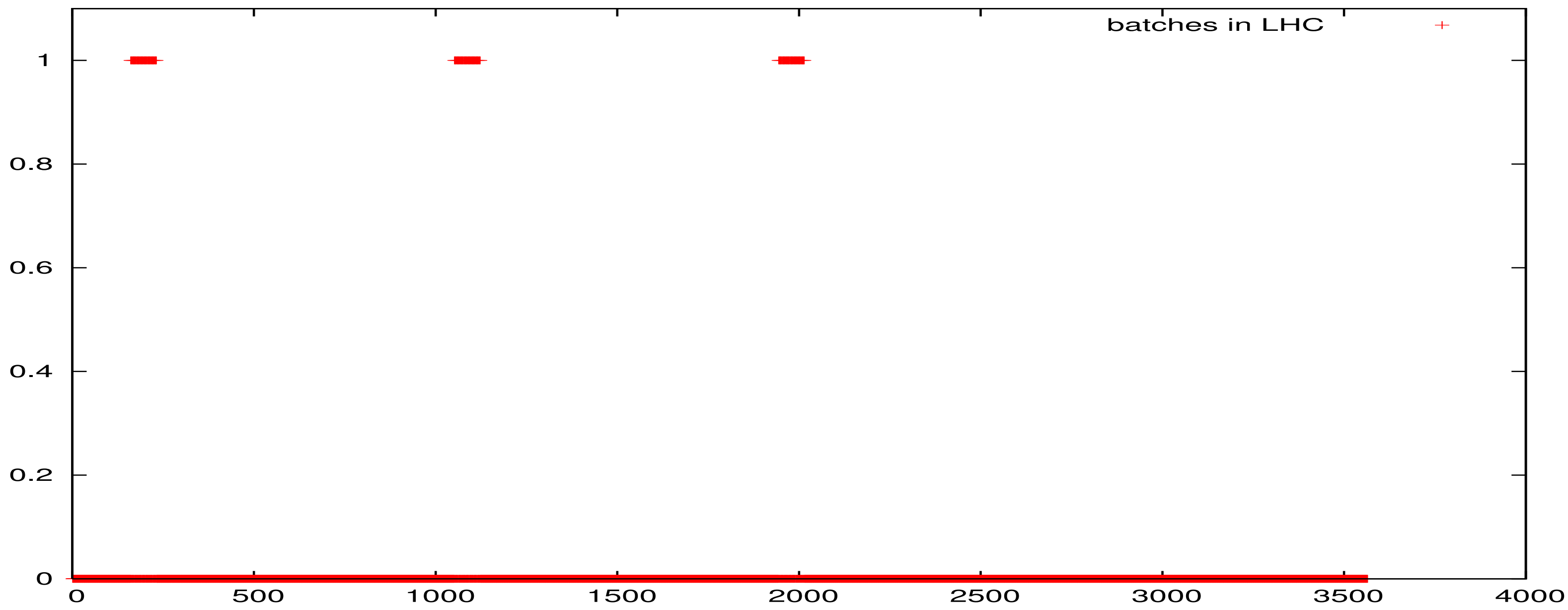


Summary

- **We have collision scenarios with/without crossing angle**
- **Possible options for different energies, including 450 GeV, requested performance seems reachable**
- **For less than nominal luminosity, 50 ns attractive:**
  - **Low total intensity**
  - **Together with larger β^* practically no long range effects expected**
  - **Can adjust luminosity between experiments**
  - **More flexible choice of parameters (β^*, α,..)**

Filling scheme in LHC

- **Minimum (train) filling scheme for collisions in 4 IPs**
- **IPs: 108 36 108 35**



Filling scheme in LHC

- Minimum (bunch) filling scheme for collisions in 4 IPs
- IPs: 3 1 3 1