Beam-beam issues for a lepton-proton collider

(LHeC)

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Main beam-beam issues in colliders

- **Hadron colliders:**
  - **Beam loss (dynamic aperture)**
  - **Beam lifetime**
  - **...**
- **Lepton colliders:**
  - **Emittance growth**
  - **Background in experiments**
  - **...**

→ **In lepton-hadron colliders: have to expect many effects**

General considerations

- Large number of bunches in both beams
- Simultaneous collision of e-p and pp (one beam)
  - pp collisions in IR1 and IR5
  - ep collisions in IR8
  - Collisions with opposite focusing properties
- Stability of (both) p beams
- Stability of lepton beam

Assumed parameters (e.g. ring-ring)

	Protons	Leptons
Number of bunches	**2808**	**2808**
Intensity N	**$11.0 \cdot 10^{10}$/bunch**	**$1.40 \cdot 10^{10}$/bunch**
Energy	**7000 GeV**	**50 - 70 GeV**
β_x^*	**1.80 m**	**0.12 m**
β_y^*	**0.50 m**	**0.07 m**
ϵ_x^*	**0.5 nm**	**7.6 nm**
ϵ_y^*	**0.5 nm**	**3.8 nm**

Luminosity for e-p collisions

- **Simple formula for head-on collisions:**

$$\Longrightarrow \quad \mathcal{L} = \frac{N_e N_p f n_b}{2\pi \sqrt{\sigma_{ex}^2 + \sigma_{px}^2}\sqrt{\sigma_{ey}^2 + \sigma_{py}^2}}$$

aim: get luminosity in order of 10^{33} cm^{-2} s^{-1}

Beam-beam parameters for e-p collisions

- **Beam-beam parameter for electrons:**

$$\Longrightarrow \quad \boxed{\xi^{e}_{x,y} = \left(\frac{r_e}{2\pi}\right) \frac{N_p \beta^{*e}_{x,y}}{\gamma_e \sigma^{p}_{x,y}(\sigma^{p}_{x} + \sigma^{p}_{y})}}$$

- **Equivalent for protons**
- **Lepton tuneshift can be kept small when $\beta^{*e}_{x,y}$ small, but:**

Known performance issues

- **Optical matching (SPS, HERA experience) required:**
  - $\sigma_x^e = \sigma_x^p$
  - $\sigma_y^e = \sigma_y^p$
- **Since** $\epsilon_e \neq \epsilon_p \rightarrow \beta_e \neq \beta_p$
  - **Restricts the choice of** β_e
- **Bunch lengths probably also very different**

Assumed parameters (e.g. ring-ring)

- **With matched transverse beam sizes:**

	Protons	**Leptons**
σ_x^*	**30 μm**	**30 μm**
σ_y^*	**16 μm**	**16 μm**
ξ_x^*	**0.00055**	**0.048**
ξ_y^*	**0.00030**	**0.051**
$\mathcal{L}(cm^{-2}s^{-1})$	**8 10^{32}**	**8 10^{32}**

- **For protons: tune shift from ep small compared to pp collisions ($\approx$ 0.003 - 0.004)**
- **For leptons: tune shift similar to values reached at LEP**

Luminosity for e-p collisions

- **Large number of bunches requires crossing angle**
  - **2808 per beam, spaced by 25 ns**
  - **Parasitic encounters every 3.75 m**
- **Crossing angle between beams needed to avoid parasitic encounters**
  - **Large enough to control long range beam-beam effects**
  - **Lepton beam may not like it, challenge for the layout**

Luminosity for e-p collisions

$$\Longrightarrow \quad \mathcal{L} = \frac{N_e N_p f n_b}{2\pi \sqrt{\sigma_{ex}^2 + \sigma_{px}^2}\sqrt{\sigma_{ey}^2 + \sigma_{py}^2}}$$

- Large number of bunches requires crossing angle (... and it may be large)
- Correction factors for luminosity needed, depend on bunch lengths
  - Geometrical loss due to crossing angle
  - Hour glass effect

Luminosity for e-p collisions

Luminosity:

$$\mathcal{L} = 2 \cdot N_1 N_2 \cdot f \cdot n_b \cdot \int\int\int\int_{-\infty}^{+\infty} dx dy ds ds_0$$
$$\rho_x^e(x)\rho_y^e(y)\rho_s^e(s-s_0) \cdot \rho_x^p(x)\rho_y^p(y)\rho_s^p(s+s_0)$$

- **Needs modification for crossing angle**
- **Loss factor for equal bunch length:**

$$\Rightarrow S = \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2})^2}} \approx \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2}}$$

- **e.g. for nominal LHC: S $\approx$ 0.80**

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Crossing angle

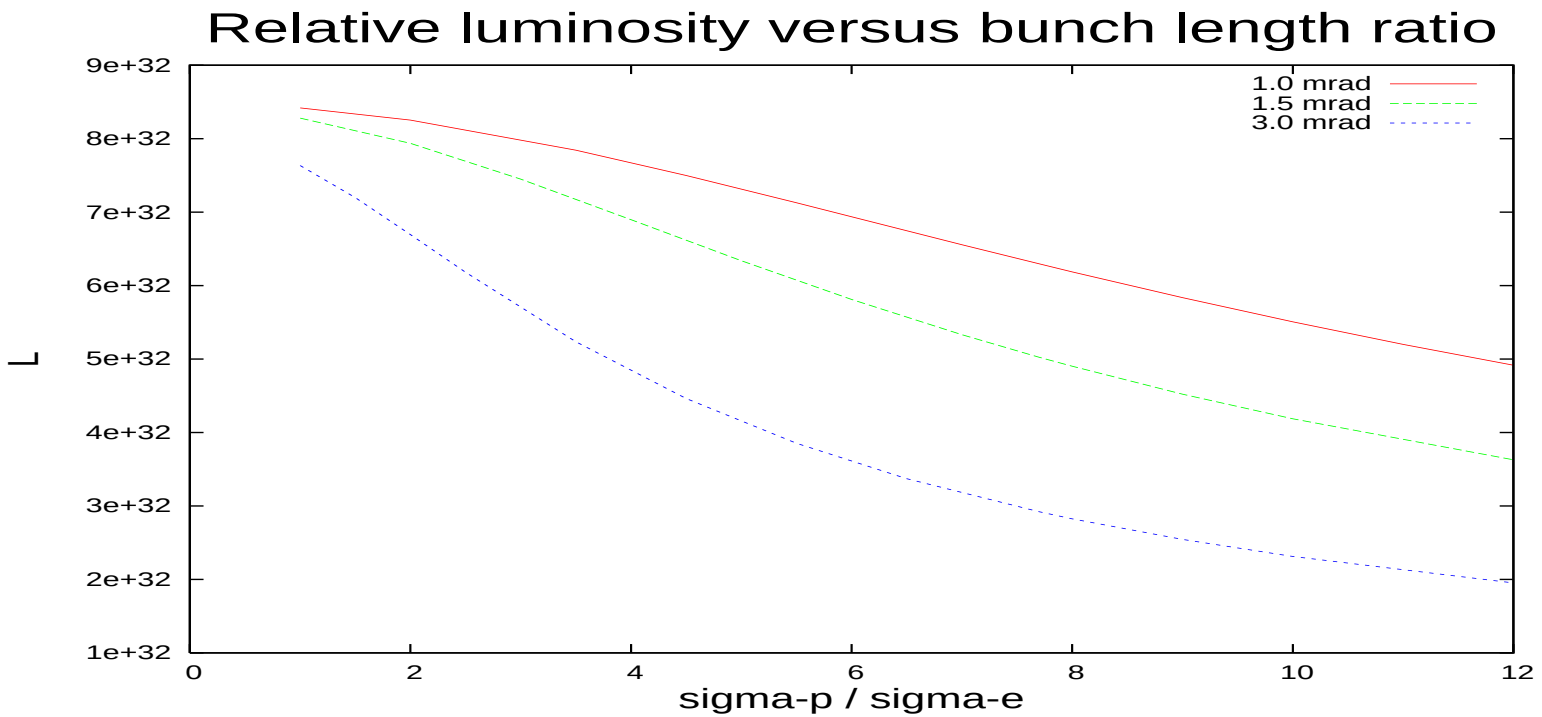
Assume crossing in horizontal (x, s)- plane.
Transform to new coordinates:

$$\begin{cases} x_1 = x\cos\frac{\phi}{2} - s\sin\frac{\phi}{2}, & s_1 = s\cos\frac{\phi}{2} + x\sin\frac{\phi}{2}, \\ x_2 = x\cos\frac{\phi}{2} + s\sin\frac{\phi}{2}, & s_2 = s\cos\frac{\phi}{2} - x\sin\frac{\phi}{2} \end{cases}$$

$$\mathcal{L} = 2\cos^2\tfrac{\phi}{2} N_1 N_2 f n_b \int\int\int\int_{-\infty}^{+\infty} dxdydsds_0$$
$$\rho_x^e(x_1)\rho_y^e(y_1)\rho_s^e(s_1 - s_0)\rho_x^p(x_2)\rho_y^p(y_2)\rho_s^p(s_2 + s_0)$$

Relative luminosity correction

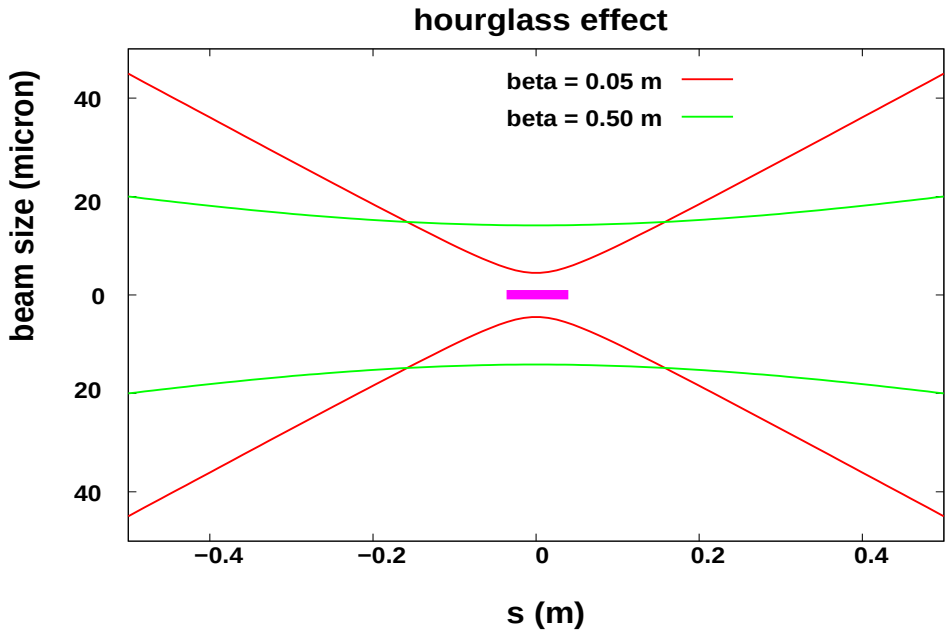
- **Result from numerical integration for $\sigma_s^p \neq \sigma_s^e$**
- **Vary proton/electron bunch length ratio**



Hour glass effect

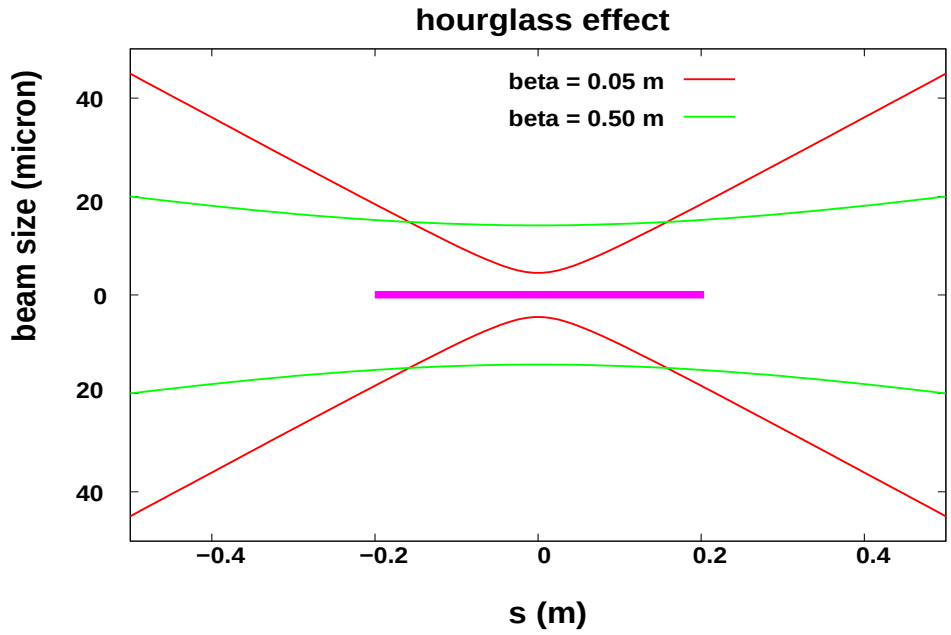
- **β-functions depends on position s**
- **Usually:** $\beta(s) = \beta^*(1 + \left(\frac{s}{\beta^*}\right)^2)$
  - **i.e.** $\sigma \implies \sigma(s) \neq$ **const.**
  - $\sigma(s) = \sigma^* \sqrt{(1 + \left(\frac{s}{\beta^*}\right)^2)}$
- **Important when β^* comparable to the r.m.s. bunch length σ_s (or smaller !)**

Hour glass effect - short bunches



- Small variation of beam size along bunch

Hour glass effect - long bunches



- Significant effect for long bunches and small β^*

Are the losses significant ?

- **For standard parameters:**
  - **Loss due to crossing angle acceptable**
  - **Hour glass reduction not significant for short bunches**
- **Parameters cannot be chosen independently: need to evaluate whenever parameters change**
- **Optimization of:** $\sigma^p, \sigma^e, \beta^p, \beta^e, ..$
- **Present parameter set a good basis for initial studies**

How to avoid the losses ?

- **Could make lepton bunches longer**
- **For small β^*, hour glass reduction may become important, but large β^* implies larger beam-beam tune shift**
- **Crab crossing scheme to avoid geometrical losses ?**

Beam-beam issues to be addressed

- Simultaneous collisions
- Crossing scheme
- Long range interactions
- Possibly: multi bunch effects
- → For any reliable study: draft interaction region layout needed (compatible with constraints from machine and experiments)