Tracking, vertexing and

Luminosity monitor at LHCb

VERTEX 2006 - Perugia

15th International workshop on vertex detectors

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- *Overview in a nutshell*: The LHCb experiment does not have a system devoted to measure the absolute luminosity, we investigate an option to use our precise vertex detector to measure profiles of the LHC beams directly.

❶ LHCb experiment and its Vertex Locator
see talks of Themis Bowcock and Sebastien Viret for more details

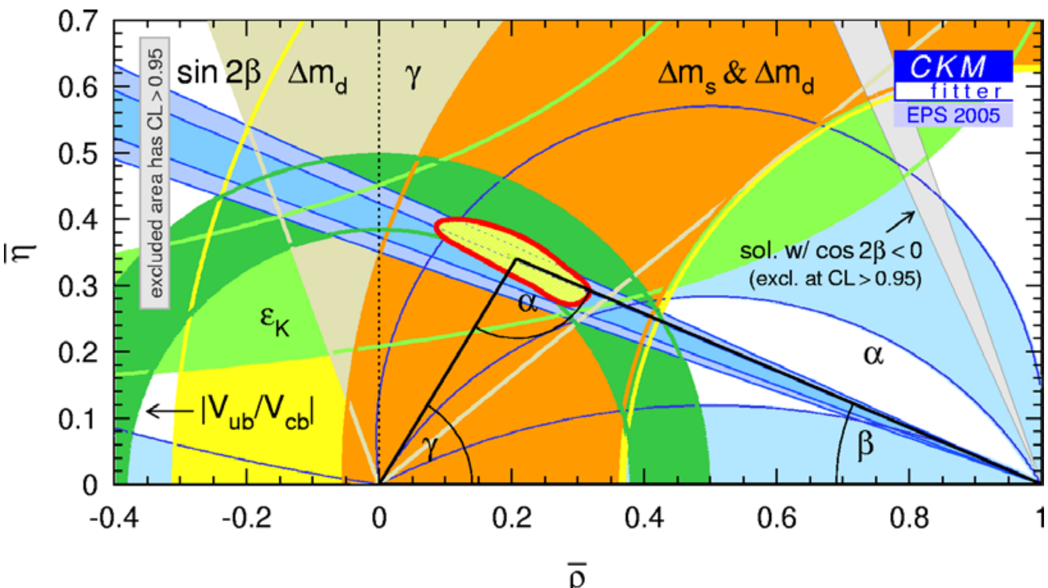
❷ A novel method to measure luminosity

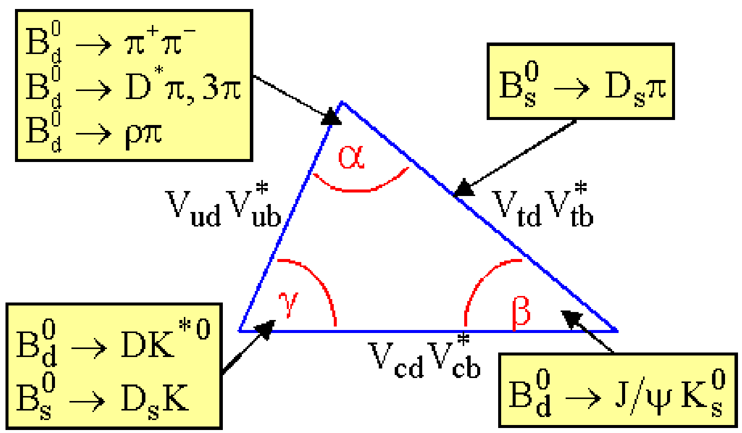
❸ An example of application

❹ Summary

❶ LHCb experiment

- Precise CP measurements and rare physics studies in b decays
- Main detector requirements
  - Efficient trigger
  - Excellent vertex finding and tracking efficiency
  - Particle identification

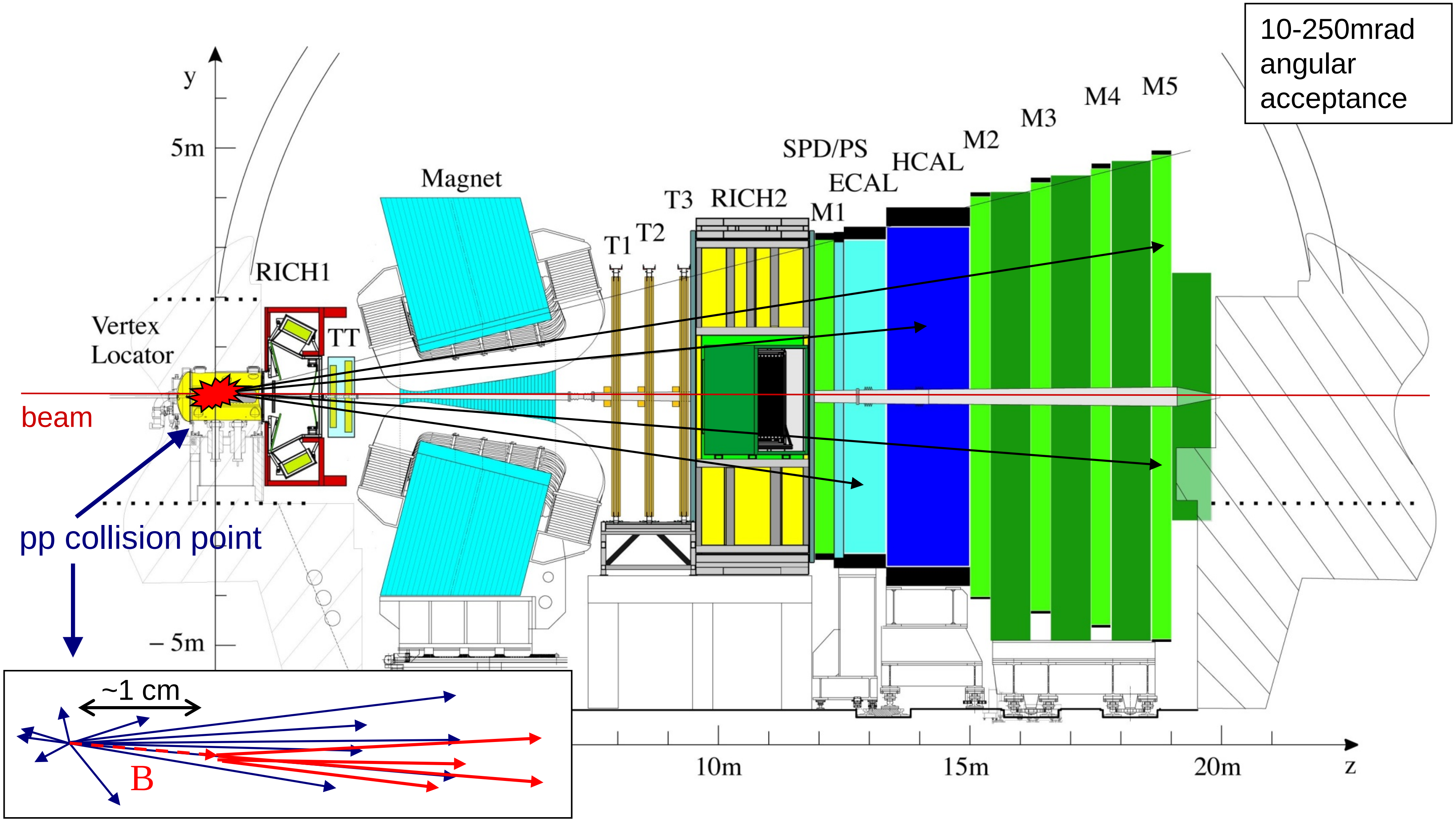




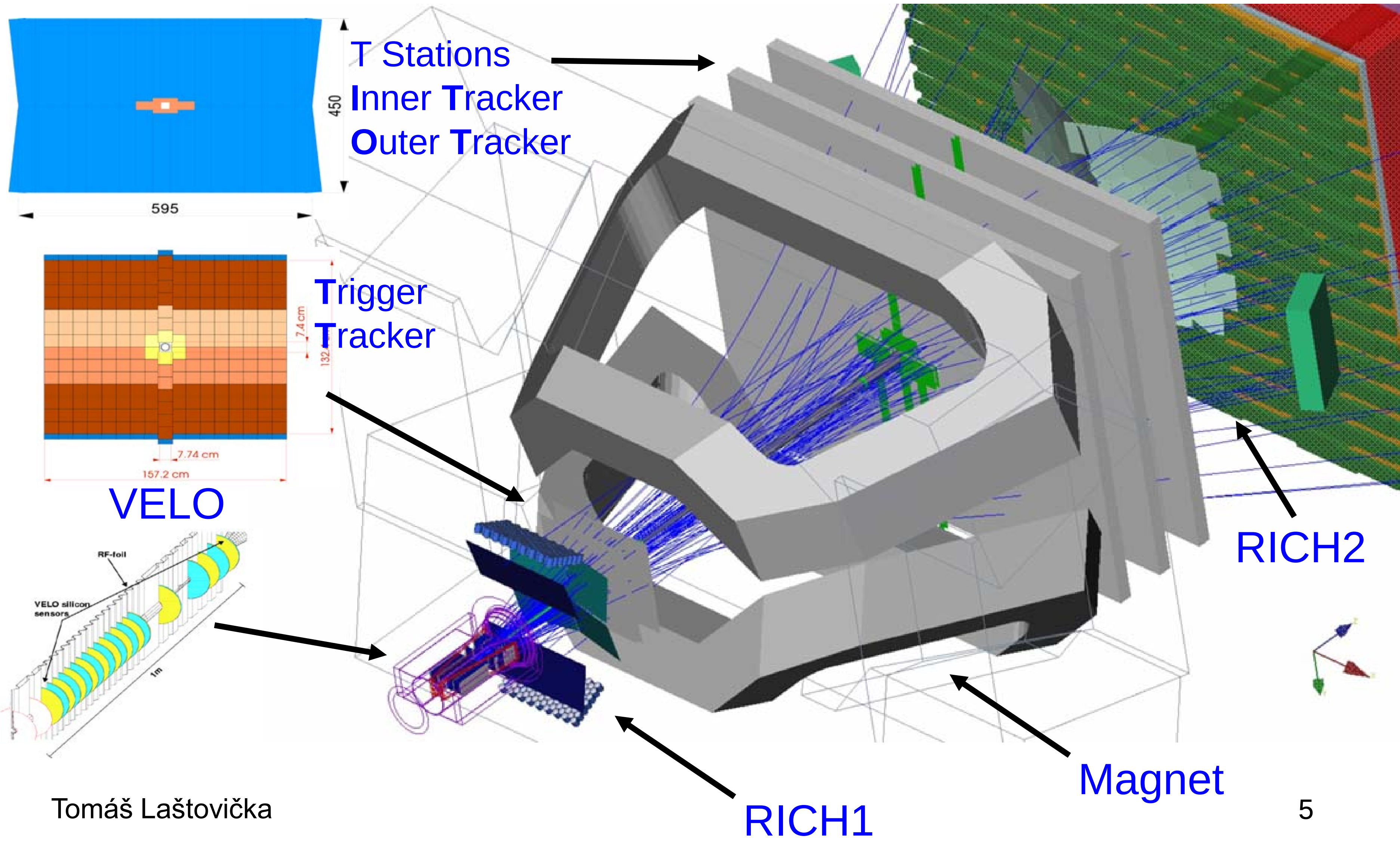
$$\overline{\varrho} = \varrho(1 - \frac{\lambda^2}{2}) \qquad \overline{\eta} = \eta(1 - \frac{\lambda^2}{2})$$

LHCb experiment

Vertex Locator: VELO [around IP]
TT, T1, T2, T3: Tracking stations
RICH1-2: Ring Imaging Cherenkov detectors
ECAL, HCAL: Calorimeters
M1–M5: Muon stations

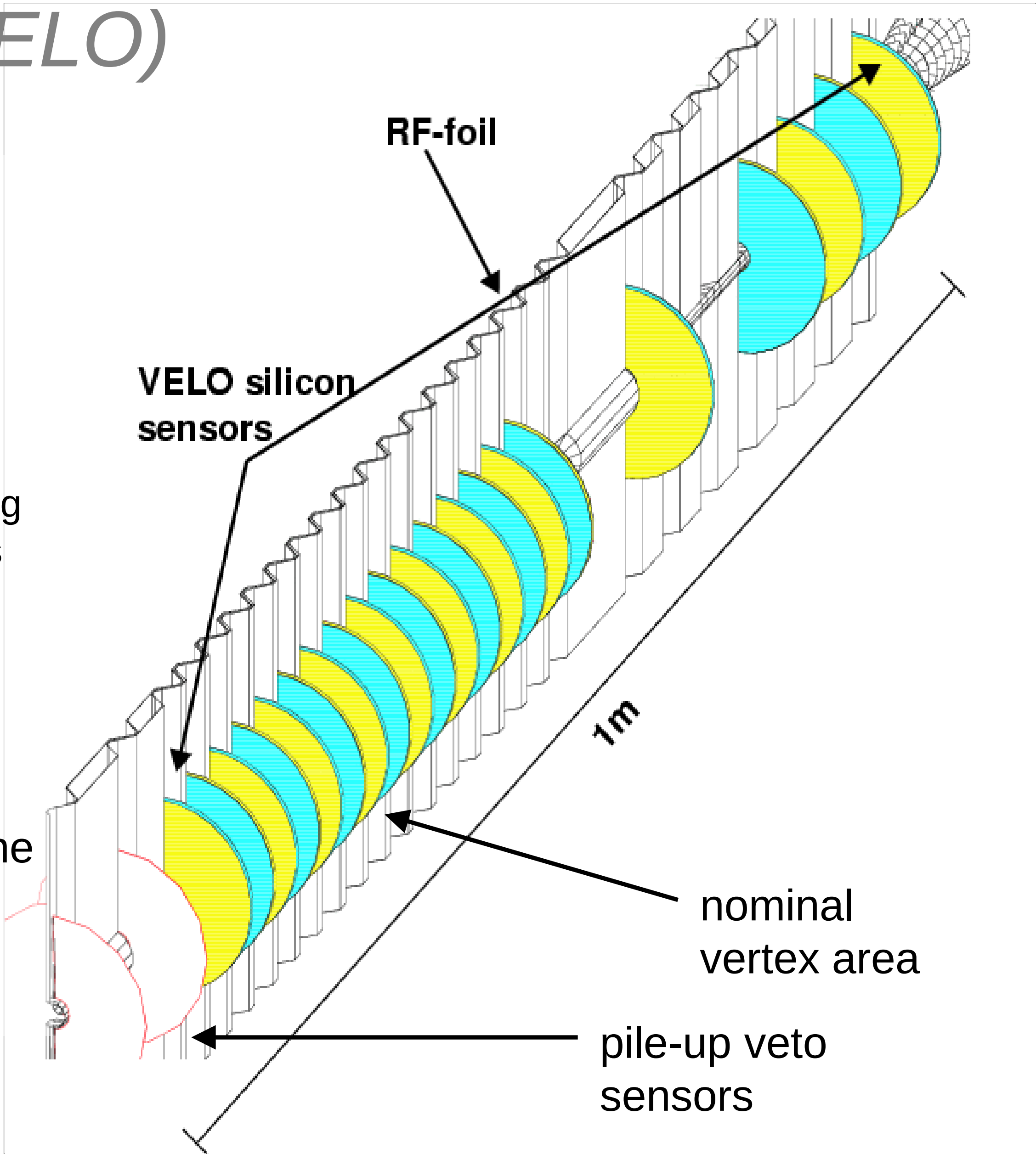


LHCb experiment 3D



Vertex Locator (VELO)

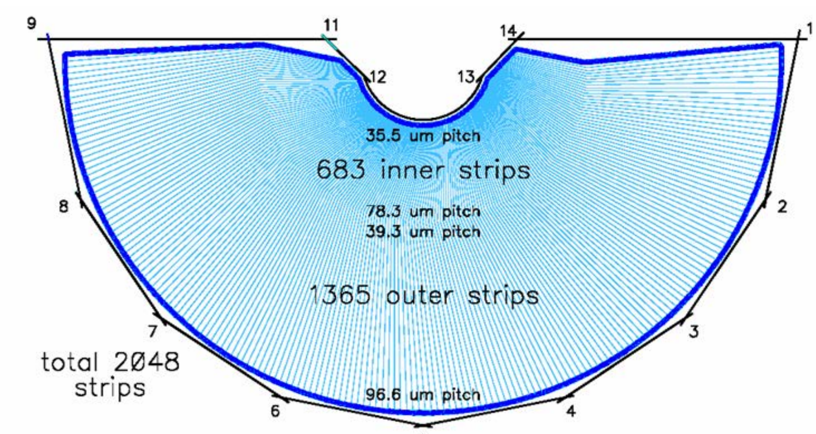
- 21 tracking stations on two sides
  - 42 modules, 84 sensors
  - plus pile-up sensors
- Optimised for
  - tracking of particles originating from beam-beam interactions
  - fast online 2D (R-z) tracking
  - fast offline 3D tracking in two steps (R-z then phi)
- Velo halves move from the LHC beam (by 30mm) during the beam injection and tuning



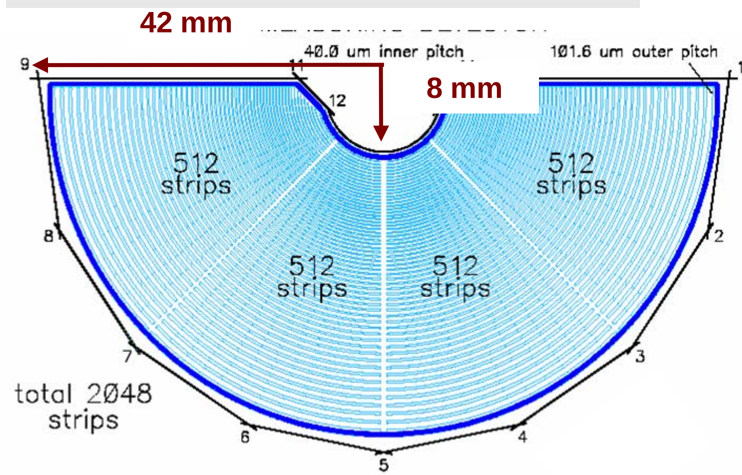
Vertex Locator (VELO)

- Each module consists of 2 sensors: R and φ type (Δz ~ 2mm)
- Each sensor contains 2048 strips in total distributed in 4 (R) and 2 (φ) zones with pitch varying from ~40um (inner region) to ~100um (outer region).
- Primary vertex reconstruction resolution <10um in x-y plane, ~50um in z-coordinate, IP~14+35/p_T um

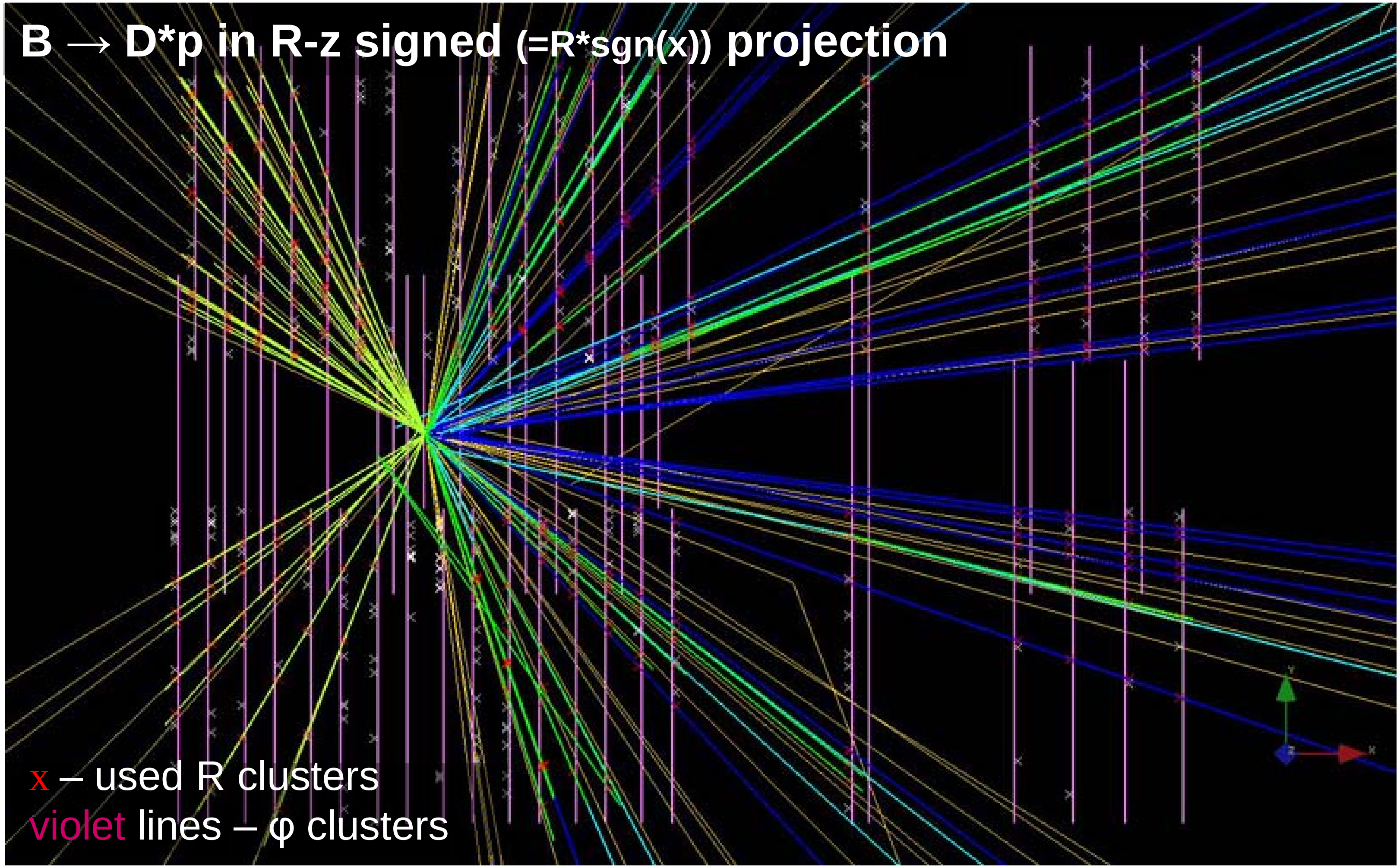
φ-sensors
2048 strip in inner and outer regions
strip pitch increase with R : 36um→97um



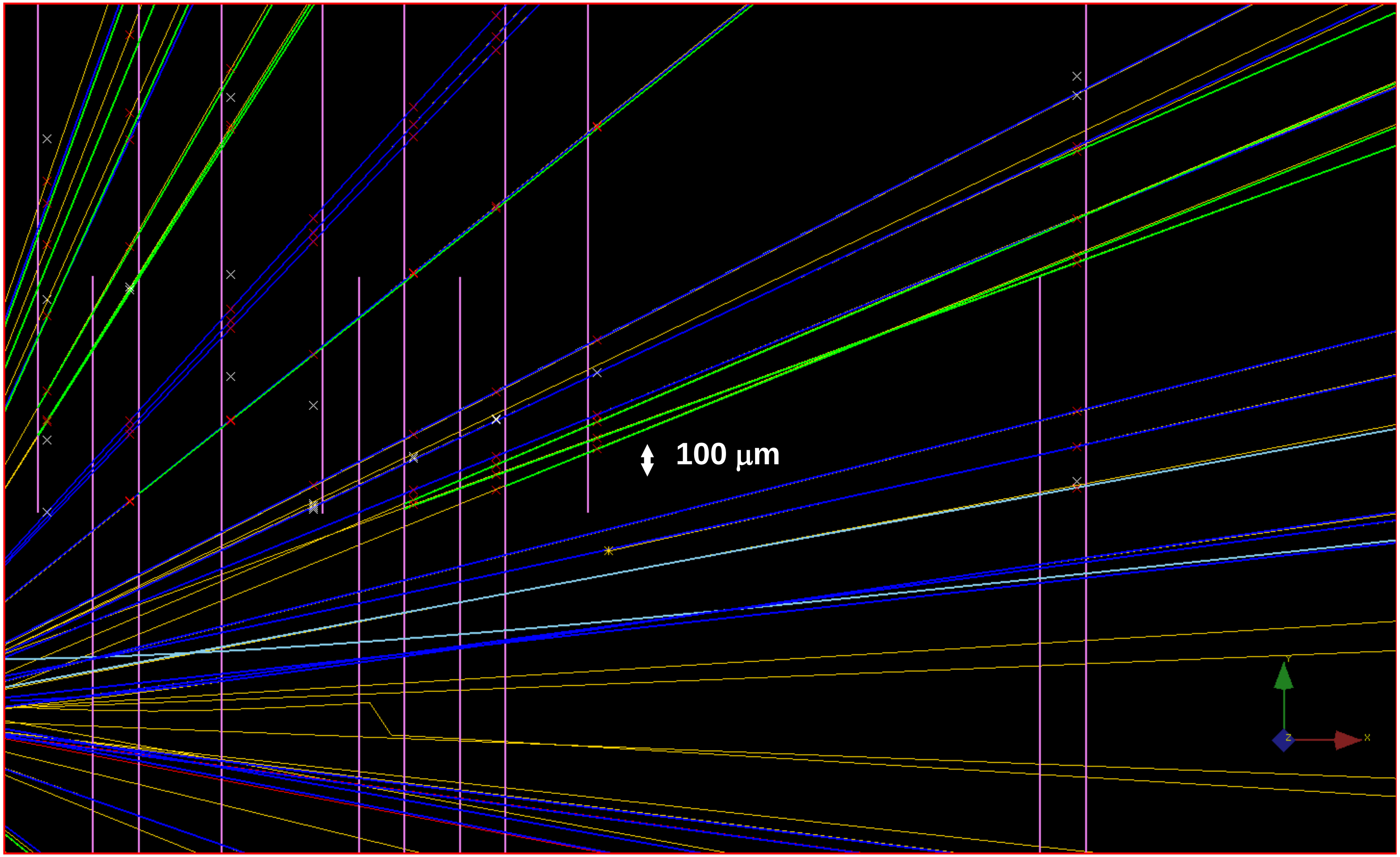
R-sensors
2048 strip in 45º sectors
strip pitch increase with R : 40um→100um



Vertex Locator (VELO)



Precise VELO tracking

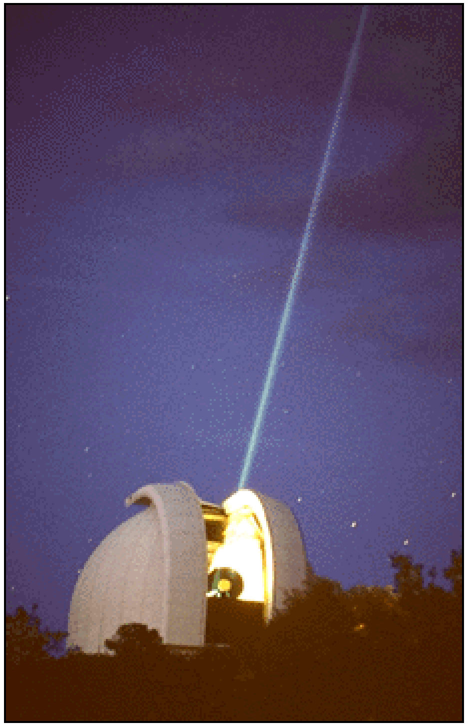


VELO in 2007

- Velo is an essential component of LHCb
  - the whole event reconstruction starts and ends at Velo
  - major disaster if destroyed or damaged → ☠
- Pilot runs at the end of 2007
  - crucial for Velo commissioning
  - will start with Velo in the open position, very carefully monitoring LHC beams
  - the first events to be seen are certainly beam-gas interactions

❷ *Luminosity measurements at LHCb*

- LHCb does not have a devoted system to measure absolute luminosity
  - not needed for majority of intended measurements
  - however, if it comes 'for free' there are interesting applications
- A novel method proposed: use high precision vertex locator (VELO) to measure parameters of both beams
- To actually 'see' the beams we employ beam-gas interactions
- It is just like to light a laser beam (LHC beam) in fog (gas)



A novel method to measure luminosity

- Reminder of general formula for two counter-rotating bunches:
  - all particles in bunch **i** move with velocity $\mathbf{v}_i$ in the lab frame
  - position and time dependent density functions $\rho_i(\mathbf{x},t)$ normalized to 1
  - the bunch populations N_i
  - revolution frequency **f**

see e.g. in Napoly, Particle Acc., **40** (1993) 181.

$$L = f\, N_1\, N_2 \sqrt{(\mathbf{v}_1 - \mathbf{v}_2)^2 - \frac{(\mathbf{v}_1 \times \mathbf{v}_2)^2}{c^2}} \int_{4\text{-fold}} \rho_1(\mathbf{x},t)\, \rho_2(\mathbf{x},t)\, d^3x\, dt$$

bunch populations — crossing angle — beam overlap integral

- Velocity term taken out of integral if negligible angular spread

Luminosity via the beam profiles

- Set $v_1 = v_2 = c$ and crossing angle ϕ :

$$L = f\, N_1\, N_2\; 2c\, \cos^2(\phi/2) \int_{4-\mathrm{fold}} \rho_1(\mathbf{x},t)\, \rho_2(\mathbf{x},t)\, d^3x\, dt$$

Measured by AB-BI ($N_1\, N_2$, ϕ)

Measured by the experiments (ϕ, $\rho_1(\mathbf{x},t)$, $\rho_2(\mathbf{x},t)$)

- Proposed method:
  - Inject a tiny bit of gas (if needed at all) into the vertex detector region
  - Reconstruct bunch-gas interaction vertices
    - get beam angles, profiles & relative positions (note $\sigma_{x,y}$ ~ 70um)
    - calculate overlap integral
  - Simultaneously reconstruct bunch-bunch interaction vertices
    - calibrate 'reference' cross-section

Beam-gas method: main requirements

- Reconstruction and discrimination of beam1-gas, beam2-gas and beam1-beam2 events
- Vertex resolution in x and y < beam transverse sizes and well understood
- Any dependence on x and y (gas density, efficiency, ...) must be small (or known to some precision)
- Bunch charge normalization measured by accelerator group

- For more info, see:
  - "Proposal for an absolute luminosity determination in colliding beam experiments using vertex detection of beam-gas interactions", MFL, CERN-PH-EP-2005-023
  - MFL, *Nucl. Instrum. Methods Phys. Res., A 553 (2005) 388-399*
  - CERN EP Seminar, MFL, 29.aug.2005
  - CERN AB Seminar, MFL, 30.mar.2006

❸ *Beam-gas method at LHCb I*

- Where are we compared to usual beam-beam events?
  - much less tracks (~8 for ^{1}H) → worse resolution
  - only VELO information → worse resolution (no charge and momentum info)
  - vertex reconstruction resolution for beam-beam B-events is better than 10um using information from the whole LHCb, we can't beat that
  - however, we still should be able to reconstruct beam profiles with high precision as long as we can control the resolutions
- First study done with beam1 - ^{1}H, full LHCb simulation software:
  - in the following transverse resolution $\sigma_{vtx\_x,y} \sim \sigma_0 / \mathrm{sqrt}(N_{tr})$ with σ_0 ~ 100 um in VELO region (-30 cm $< z_{vtx} <$ 80 cm)
  - luminosity varies with beam variance $\sigma_{x,y}$ → as well as we can measure $\sigma_{x,y}$ we can determine the overlap integral → needs to be known better than 1%.
  - we use 'generic' pattern recognition rather than 'standard' pattern recognition (which includes various assumptions about event topology)

What is generic and what is standard?

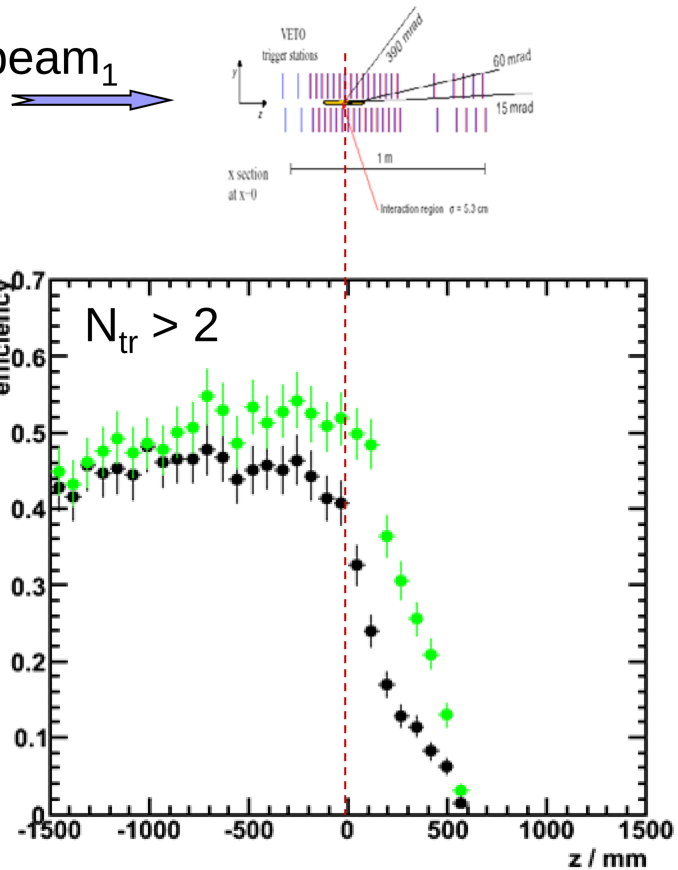
- Standard pattern recognition
  - designed for high performance PR of events originating from beam-beam interactions
  - assumes tracks are about constant in φ-z and linear in R-z projections
  - Velo is always 'closed', approximate correction of alignment (and full in track fitting)
- Generic pattern recognition
  - generally everything else:
    - reconstruction of beam halo for alignment purposes
    - open Velo tracking
    - test-beam studies
    - Ks', photon conversion and similar
    - luminosity measurements
    - …
  - fully accounts for misalignments and it is aware of Velo being 'opened'
  - it is full 3D (and non-linear, in general) and thus slower

Beam-gas method at LHCb II

- Ongoing studies with gas target
  - Hijing was implemented in the LHCb simulation software
  - Higher track multiplicity (4x for Xe) → better precision
- Ongoing studies for beam2 – gas
  - easier due to better acceptance of beam2 compared to beam1
    (due to spacing of VELO modules)
- LHCb software is continuously developing, the following few plots are not final results but rather an illustration of the current status.

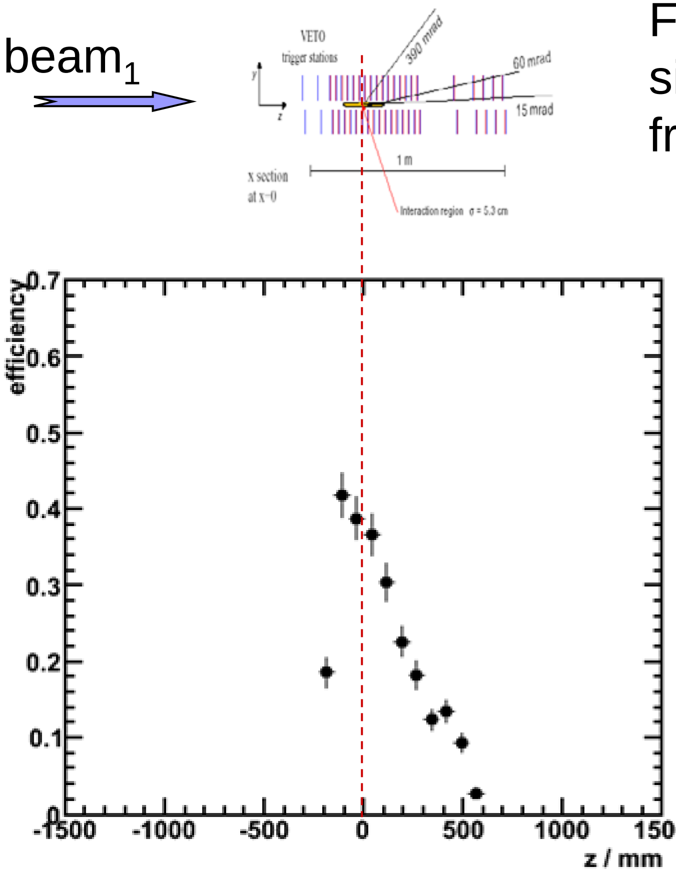
Acceptance for beam$_1$–^{1}H Pythia events

beam$_1$



Generic PatRec

beam$_1$



Full LHCb simulation framework!

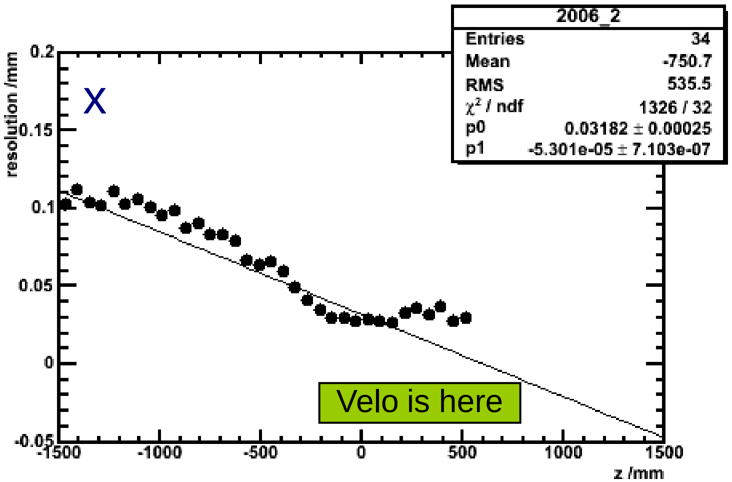
Standard PatRec
designed for *pp* collisions...

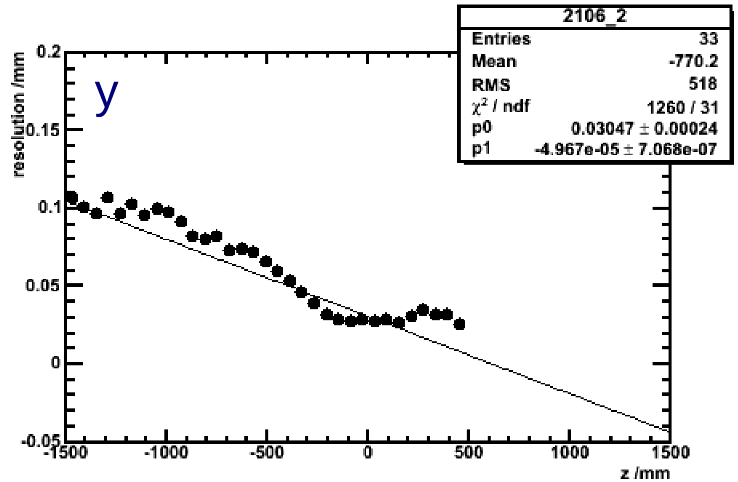
~30um for Ntr>5 around z=0
is it enough?
beam size > 100 um,beta* > 20 m

Vertex reconstruction resolution vs z

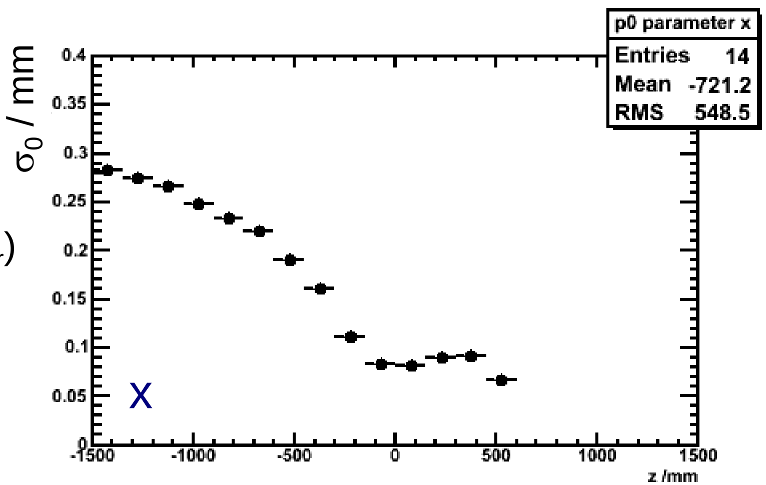
beam-^{1}H

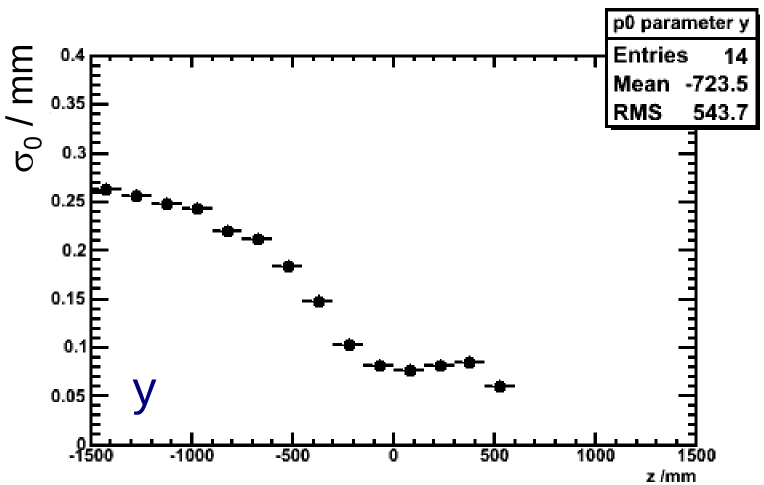
$N_{tr} > 5$





resol= $\sigma_0/\mathrm{sqrt}(N_{tr})$





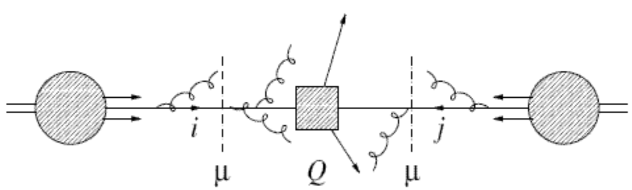
Beam-gas method: proposed strategy

- Try method early on with residual gas, if OK => pursue
  - LHC pilot runs at are the ideal playground
    - large beam, no magnetic field, …
    - may be very valuable experience for VELO in general
    - VELO is few mm from the beam → precaution needed
  - luminosity knowledge will be needed for the first physics (e.g. $J/\psi \rightarrow ee$)
- Dedicated run (few days, large β^*, 0 crossing angle):
  - inject gas (Xe), measure L and a reference cross section σ_{ref}
    - σ_{ref} is a large and "experimentally robust", not required to be theoretically interpretable, nor transferable to an other interaction point
- Then, during normal running:
  - measure $\sigma_{phys} = \sigma_{ref}\ R_{phys}\ / R_{ref}$ (R = rate) , any physics cross section
  - properly chosen σ_{phys} may allow comparison or cross-calibration between experiments (LHCb, CMS, ATLAS)
  - physics: heavy flavour production, inelastic cross section, PDFs, ...

Weak boson production at LHC

- See e.g. Dittmar, Pauss & Zürcher, PRD **56** (1997) 7284:

  ‘*Measure the x distributions of sea and valence quarks and the corresponding luminosities to within   1% … using the l pseudorapidity distributions from the decay of weak bosons.* ’



$$\frac{d\sigma}{dX} = \sum_{i,j}\sum_{\tilde{X}} \int dx_1 dx_2\, f_i(x_1,\mu^2) f_j(x_2,\mu^2) \times \hat{\sigma}_{ij}^{\tilde{X}}(\alpha_S(\mu^2), Q^2, \mu^2)\, F(\tilde{X} \to X, \mu^2)$$

K. Ellis, HCP2005

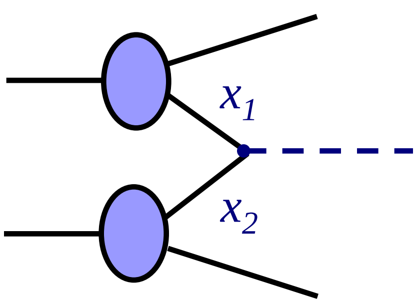
Here, we propose the opposite: to measure proton luminosities at LHCb and use weak boson production to constrain and check PDFs

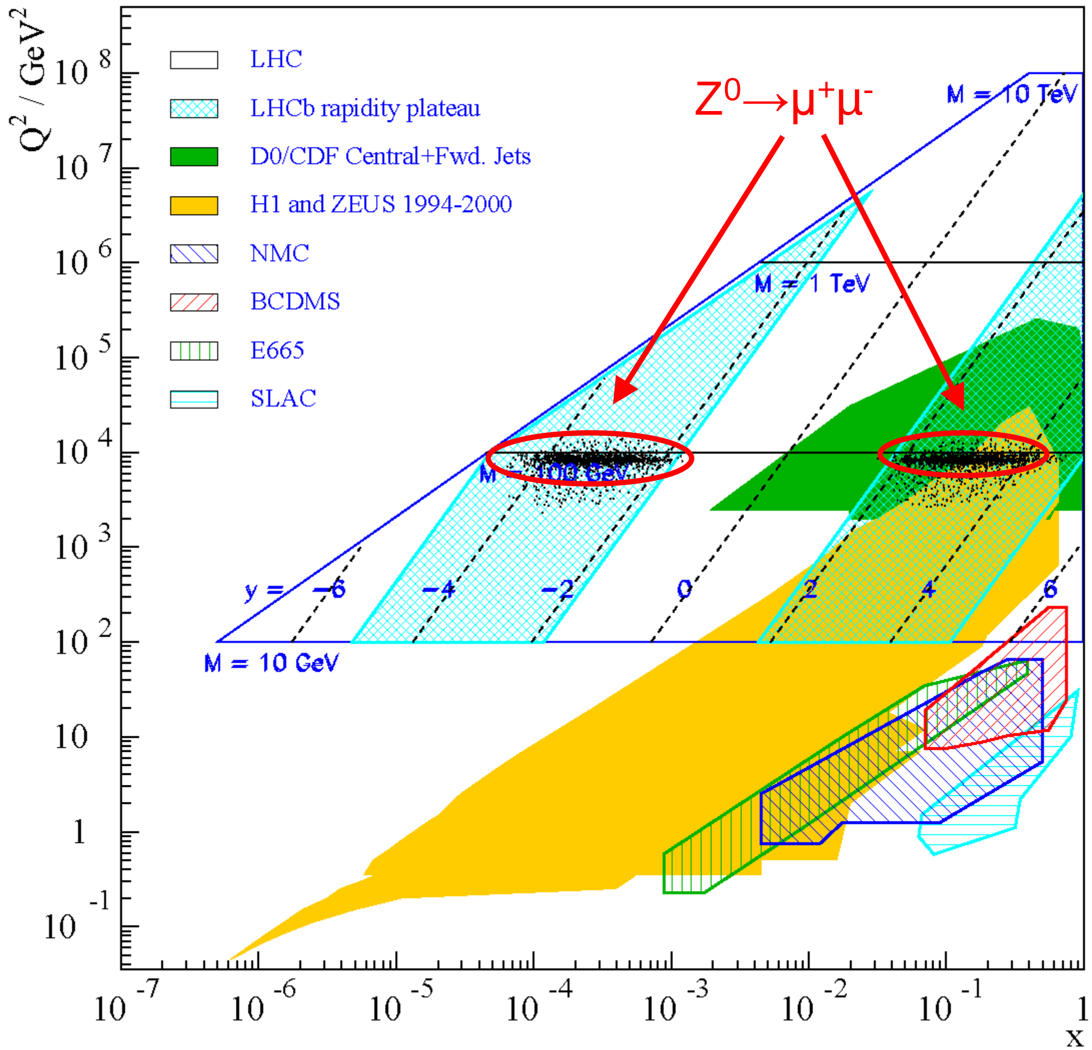
$Z^0 \to \mu^+\mu^-$ kinematic coverage

- At LHC center of mass energy is $\sqrt{s}$ = 14TeV
- LHCb acceptance in terms of rapidity:

  1.8 < y < 5
- Corresponds to a mixture of high/low x at high values of Q^2

$$x_{1,2} = \frac{M}{\sqrt{S}} \exp(\pm y)$$





Systematics of the method

- The proposed absolute luminosity measurement will be dominated by systematics, not statistics
- Bunch charges need to be known with absolute accuracy < 1%
  - effect of ghost charges to be investigated
- Beam overlap systematics due to
  - crossing angle effects
  - varying beta-function as a function of z (for small β^* only)
  - possible transverse inhomogeneity of gas density effects (small)
  - transverse dependence of reconstruction efficiency and/or resolution ?
  - longitudinal and transverse beam offsets

Future of the method

- Plan to organize a subgroup within one of physics working groups (Production and decay models WG)
- A number of people already involved (one PhD thesis to be written)
  - CERN, Bologna
- One of the first LHCb measurements in 2007!
  - use LHC pilot runs to practise and actually use the developed methods to measure luminosity
  - excellent opportunity to test the VELO detector itself in a real life, high precision measurement
- Further steps are
  - study events simulated with Hijing generator
  - develop methods to control the vertex reconstruction resolution from data itself
  - develop a suitable trigger and study event rates
  - test the method on simulations and determine systematic errors

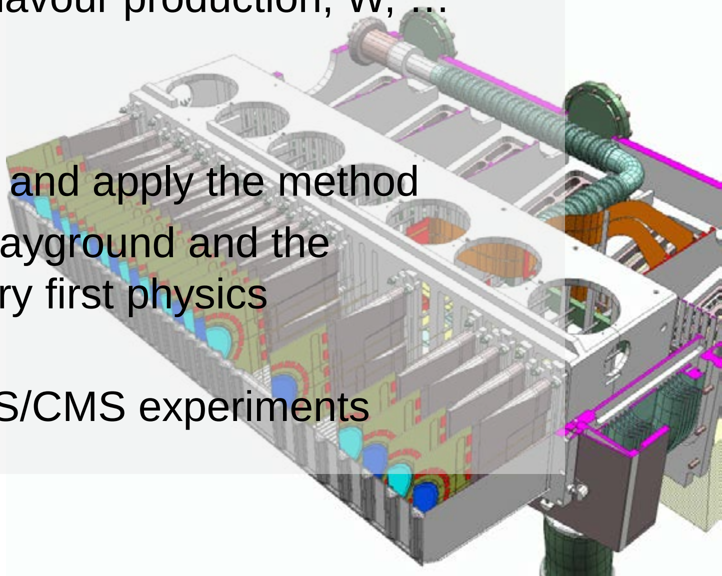
Other options

- Absolute luminosity measurement
  - wire method
    - no wires in beam….
  - Van der Meer's beam scans
    - requires 2D scans for the LHC case
    - will be tested, estimated to give 5% accuracy for 4um beam displacement control
  - reference reaction
    - as long as one believes in theoretically clean predictions
    - it is better to measure these reactions rather than to calibrate on them
    - mentioned $Z^0 \rightarrow \mu\mu$, QED processes such as $pp \rightarrow ppe^+e^-$,…
  - elastic and inelastic scattering – optical theorem (CMS/ATLAS)
- Relative luminosity measurement
  - use pile-up system built in Velo to detect collisions
  - very quick and implementable on trigger L0 level

Summary

- A novel method was proposed to measure <u>absolute</u> luminosity at the LHC(b) experiment(s) aiming for few % precision
  - note that LHCb does not have a luminosity measurement system, proposed method is entirely based on the vertex detector and tiny amount of gas injected inside the beam pipe
- Knowledge of luminosity would allow to e.g.
  - measure $Z^0 \rightarrow \mu^+\mu^-$ cross section in the rapidity region of $1.8 < y < 5$, access to PDFs at <u>low x</u> (+high x) and at high Q^2
  - measure inelastic cross section, heavy flavour production, W, ...

➲ Future:
  - we plan to set up a subgroup to develop and apply the method
  - LHC pilot runs in 2007 will be an ideal playground and the luminosity group will contribute to the very first physics measurements at LHCb
  - we are open for collaboration with ATLAS/CMS experiments



backups

Longitudinal and Transverse Offsets

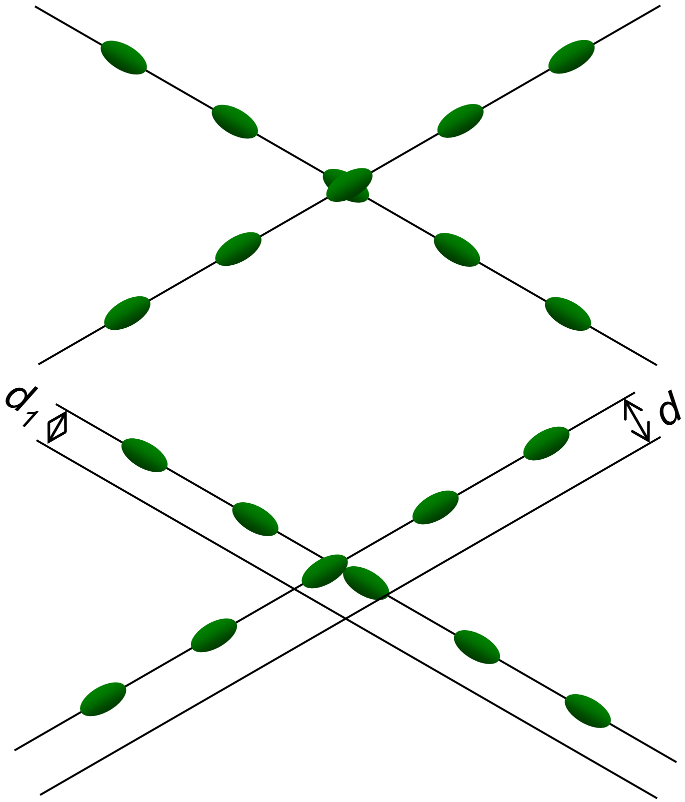
- In general, a crossing angle will mix transverse offsets and longitudinal offsets.
- Simple familiar case of Gaussian bunches:

$$L = f \frac{N_1 N_2}{4\pi \sigma_x \sigma_y} W e^{\frac{B^2}{A}} S(\phi)$$

$$W = e^{-\frac{(d_2-d_1)^2}{4\sigma_x^2}}$$

$$B = \frac{(d_2 - d_1)\sin(\phi/2)}{2\sigma_x^2}$$

$$A = \frac{\sin^2 \frac{\phi}{2}}{\sigma_x^2} + \frac{\cos^2 \frac{\phi}{2}}{\sigma_z^2}$$

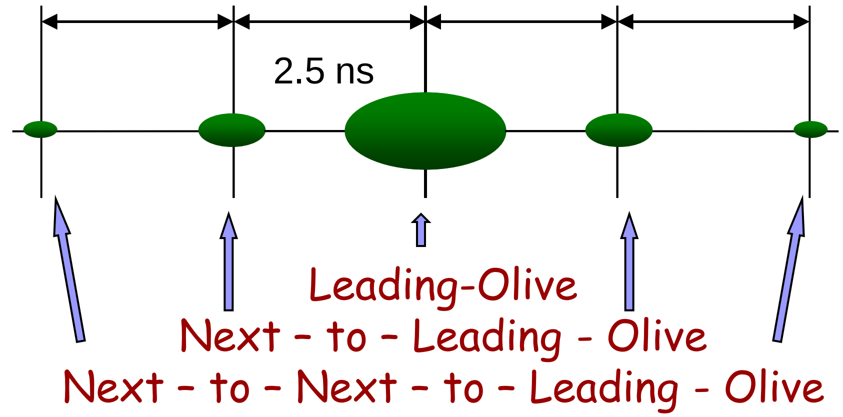


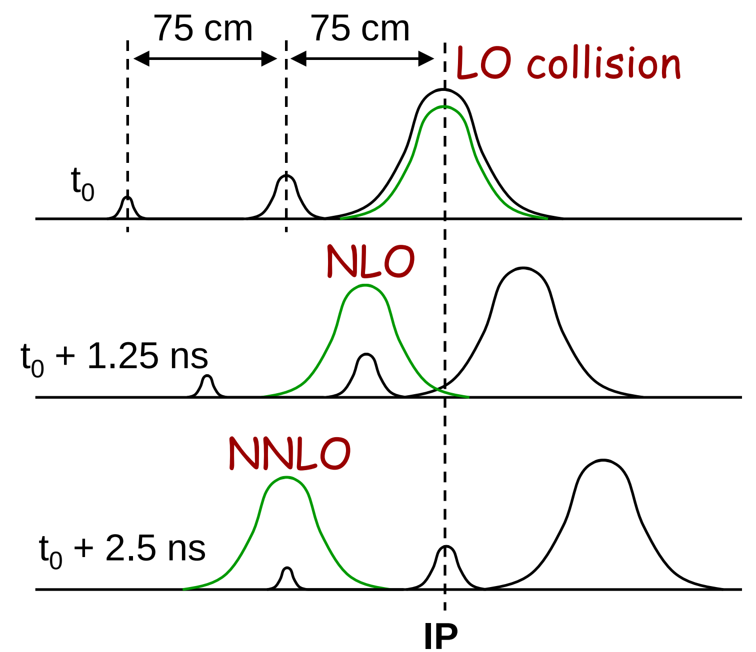
- Longitudinal offsets are not accessible with beam-gas vertex reconstruction (transverse offsets are)

  $\Rightarrow$ simpler to run at zero crossing angle (and angle is measured by beam-gas!)

Ghost charge

- SPS RF: 200 MHz, i.e. a 'bucket' every 5 ns
- LHC RF: 400 MHz, i.e. a 'bucket' every 2.5 ns
- Beams could contain satellite bunches
- Expect to be mostly in neighbour buckets
- They contribute to the total DC current
- Are they measurable by the fast AC current monitors ?
- Bunch charge normalisation problem…
- A challenge for AB group !!
  - LHC Design Report, vol 1, sec. 13.2.1 "Fast Beam Transformers": precision < 1% (5%) for nominal (pilot) bunch charges
- In fact, expect that NNLO > NLO
- Experiments can observe nearby satellites
- Extra luminous bumps at IP +/- n x 37.5 cm ?
- If observed, at least they aren't ghosts any more…



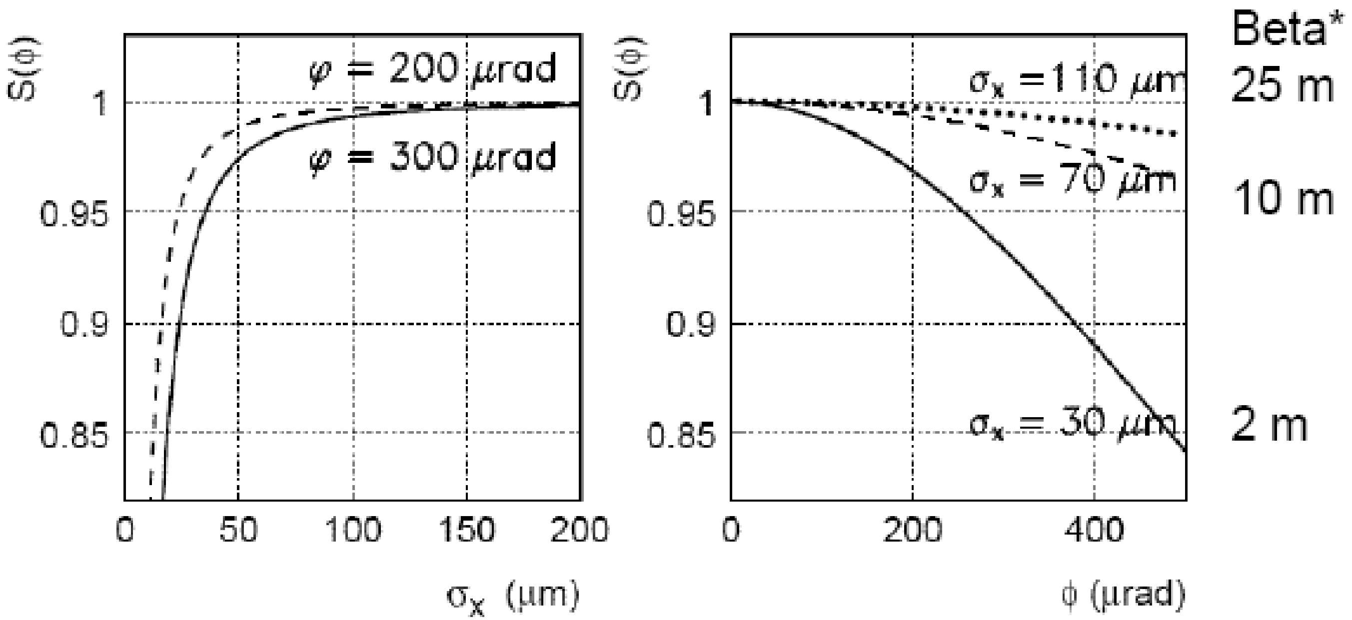


Ghost charge: remarks

- Ghost charge is expected to be smaller in the mode with single SPS bunches injected (no SPS trains)
  - to be understood and verified
- Possibility to rotate (the phase of) a beam relative to the other!
  - do this while monitoring beam-beam collisions
  - longitudinal scan of the charge distribution
  - could allow mapping or understanding the ghost charge
  - does the (transverse) beam-beam overlap change while making this longitudinal scan ?

Crossing angle phi

$$L = f \frac{N_1 N_2}{4\pi\, \sigma_x\, \sigma_y} S(\phi) \qquad \text{with } S(\phi) = \left(1 + \left(\frac{\sigma_z}{\sigma_x} \tan\frac{\phi}{2}\right)^2\right)^{-1/2}$$

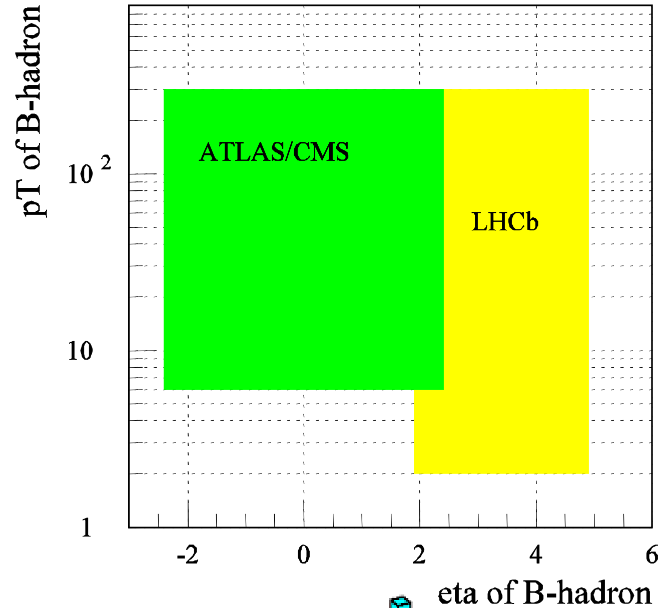


- Determine angle from beam-gas interactions
- Adjust angle and β* accordingly: for β* > 10 m the dependence on φ is already very small

B acceptance

- LHCb is designed to maximize B acceptance
  [within cost and space constraints]
- forward spectrometer, $1.9 < \eta < 4.9$
  - more b hadrons produced at low angles
  - single arm OK since bb pairs produced correlated in space
- rely on relatively soft higt p_T triggers, efficient also for purely hadronic B decays
- 1 year of running = ~2 fb^{-1}
  nominal luminosty: 2.10^{32} $cm^{-2}s^{-1}$

Pythia production cross section



$b\bar{b}$ correlation