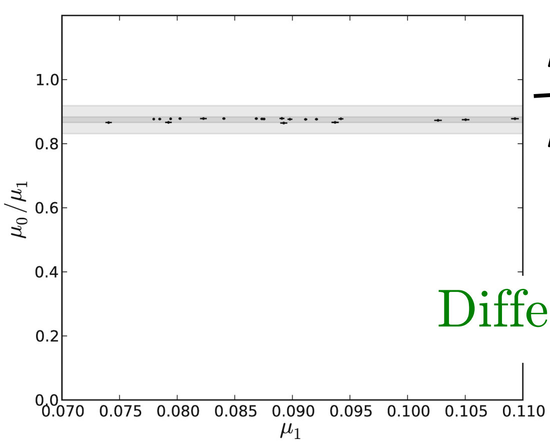
LHCb 2010 luminosity determination with van der Meer scans

Vladislav Balagura, CERN & ITEP, LHC Lumi Days, 13 Jan 2011

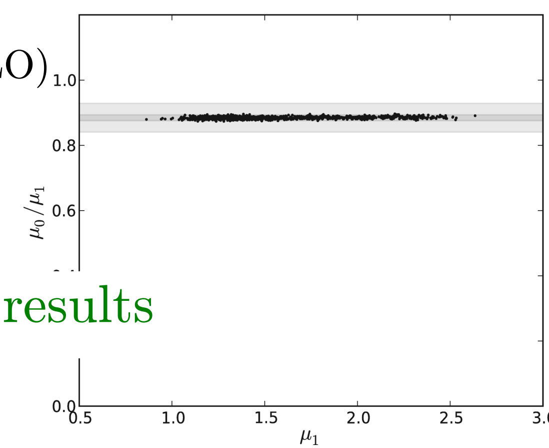
Continuous luminosity monitoring at LHCb: randomly triggered at 1 kHz "nano" events containing "luminosity counters"
(#vertexes, tracks, hits in vertex VELO detector, #hits in scintillator pad detector in front of CALO, transverse energy deposition in CALO)

Luminosity $\propto \mu = -\ln f_0$ (visible number of interactions),

where f_0 – fraction of empty events with #RZ VELO tracks < 2 (best counter)
Background visible in beam-empty, empty-beam BXs subtracted



$\frac{\mu(\text{\#PU VELO hits})}{\mu(\text{\#RZ VELO tracks})}$ vs. μ(#RZ VELO)



Different counters give consistent results

Nonlinearity for best counter $\ll$1% in full $0 \leq \mu \leq 2.5$ range

LHCb 2010 luminosity determination with van der Meer scans

Calibration of luminosity counters

1) using beam-gas imaging method in selected LHC physics fills (next talk) and

2) during dedicated van der Meer scans

Two LHC fills in April and October, each with two van der Meer scans

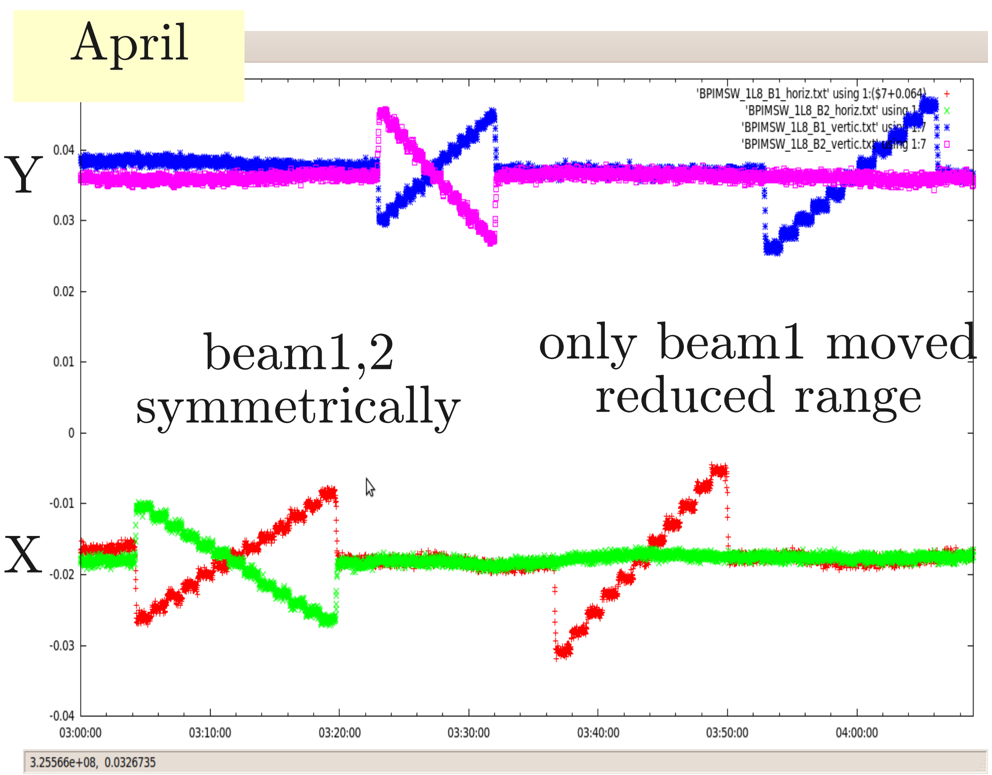
	p/bunch 1e10	β^*	# bunches colliding/all	μ_{max}	Trigger	τ(Lumi) hours	τ(I1*I2) hours
April	1	2	1/2	0.03	min.bias	30	950
October	7-8	3.5	12/16	1	- random at 22.5kHz, - 1kHz limited min.bias, - beam-gas	45.9	700

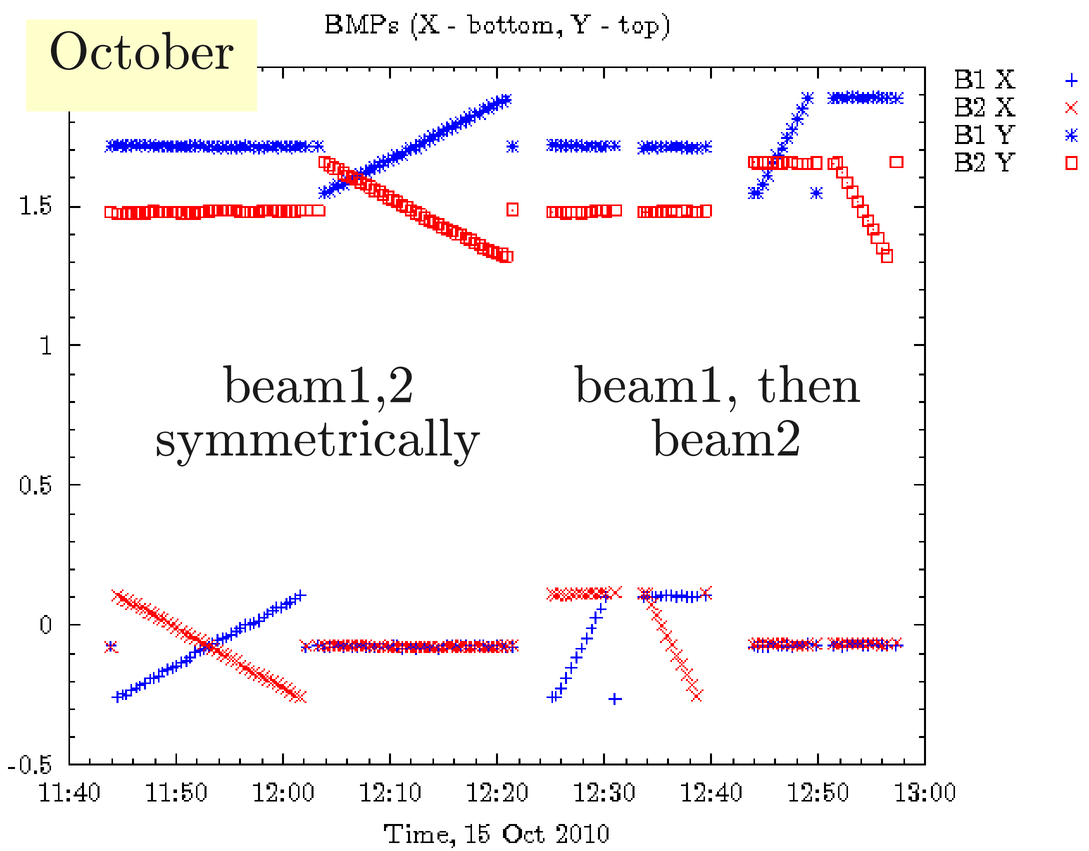
Beam movements

1) Detailed scan in X/Y, both beams moved symmetrically

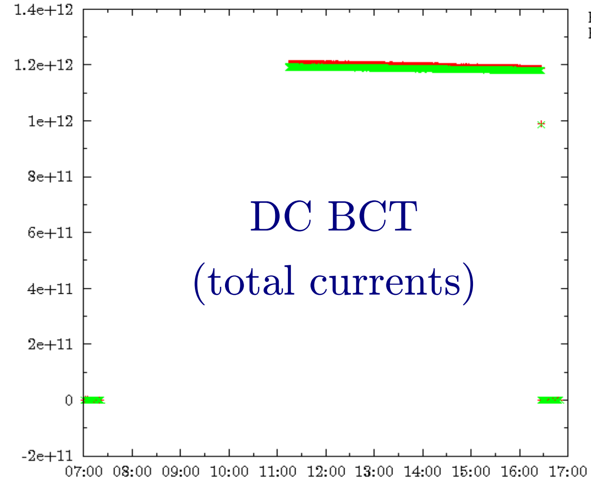
2) Either smaller range or bigger step, one beam moved

LHC Beam Position Monitors

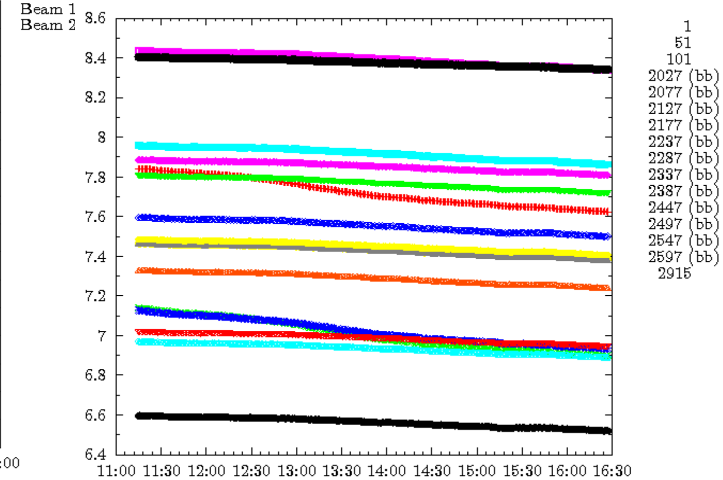




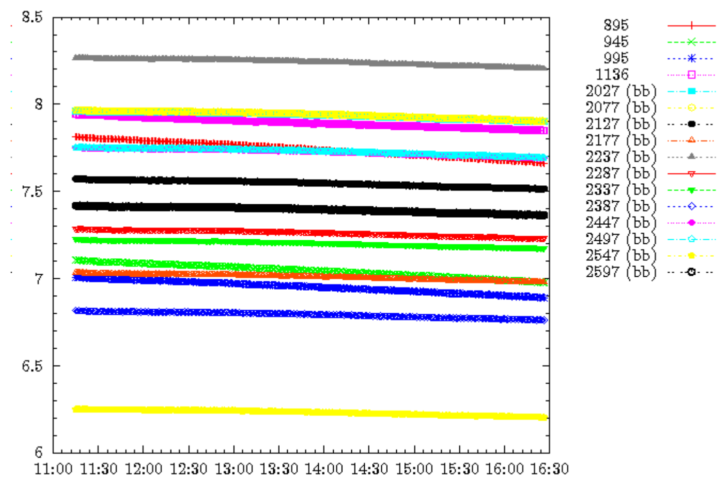
LHC currents in October (16 bunches)



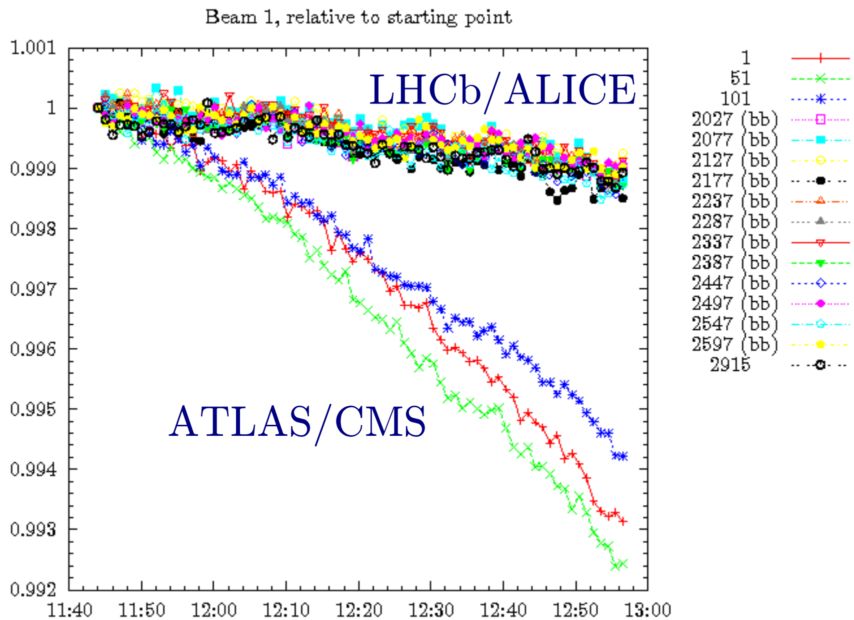
beam 1

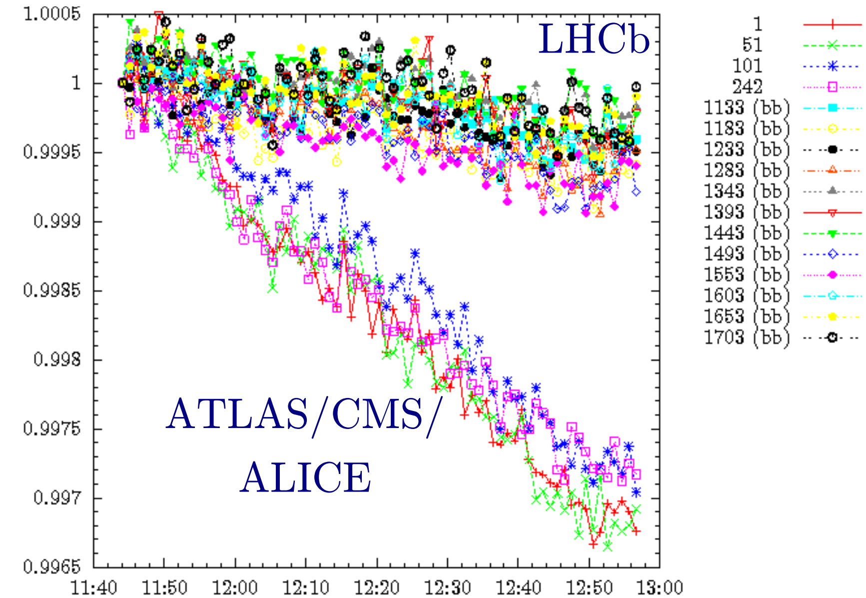


beam 2



Fast BCT (per bunch)

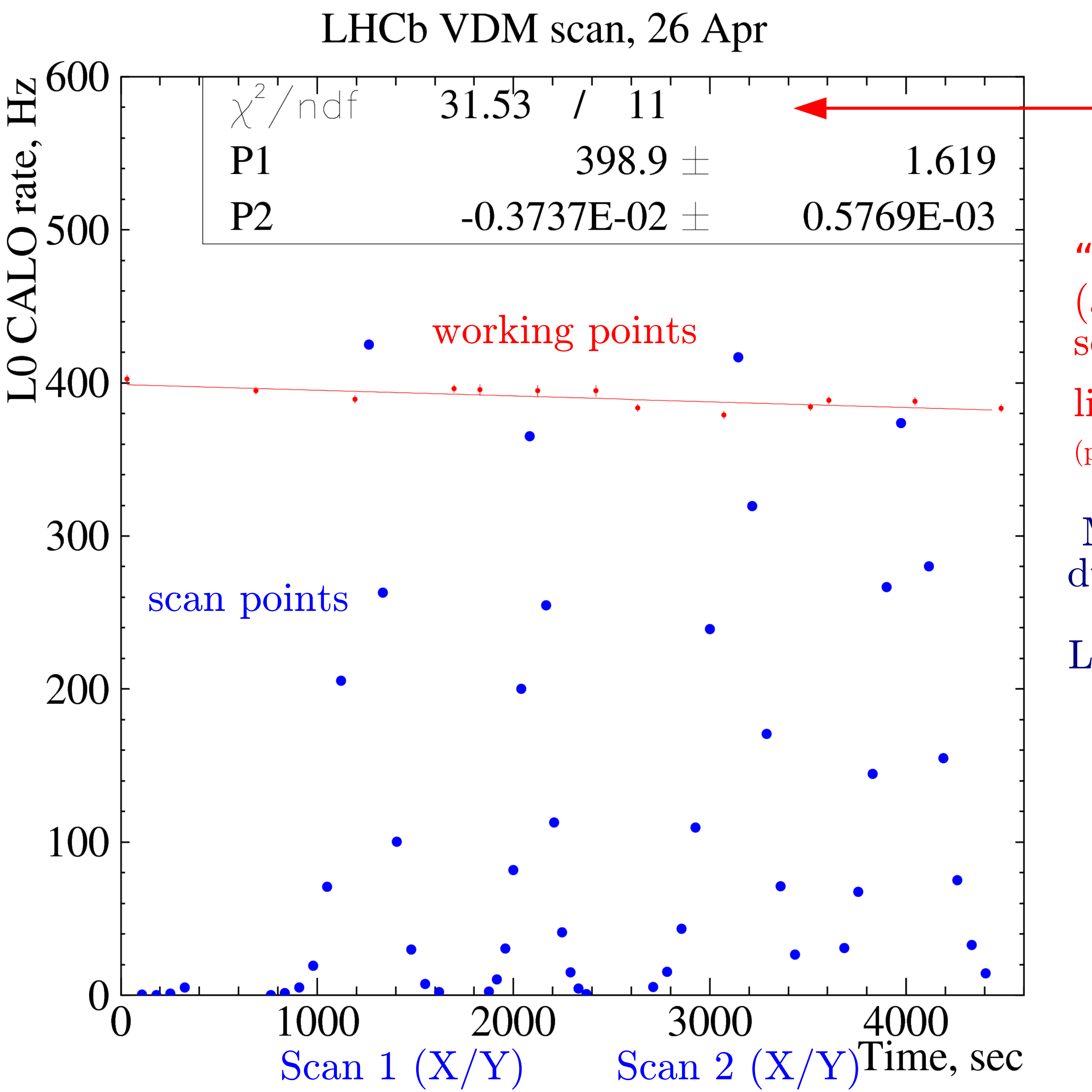




LHCb currents are stable within ~1e-3 (same in April).

Rate not normalized to I1*I2 to reduce noise

"Working" point time evolution (April)



"working" point (at start/end of every scan and in middle)

lifetime = 30 hours

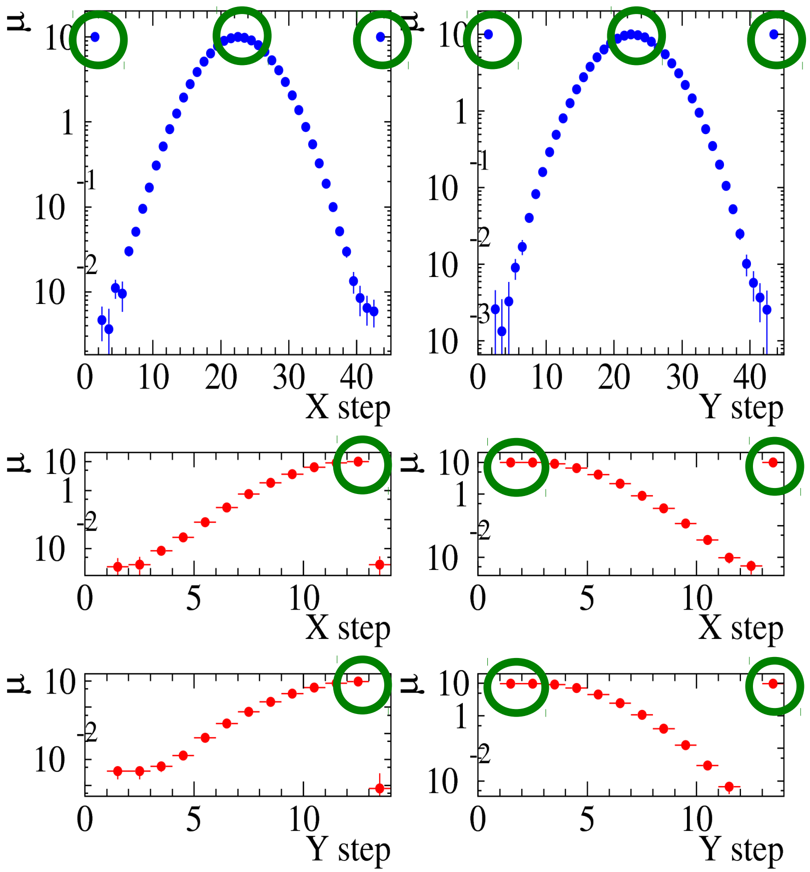
(probably due to beams blow up)

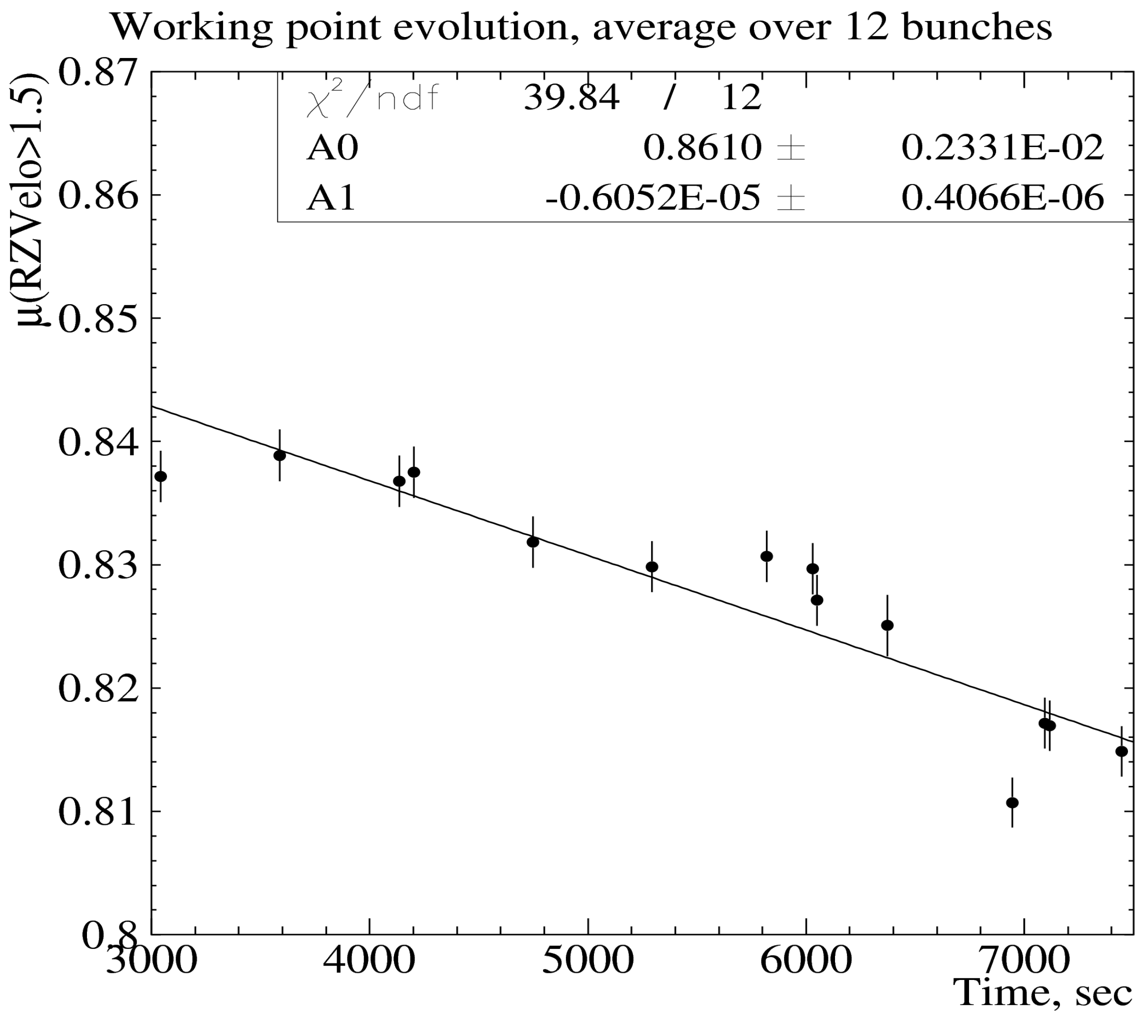
Max luminosity drop during one scan: 0.9%.

Left/right side of vdM shape is enhanced/ suppressed, compensation in integral in 1^{st} order, systematics $\ll 1\%$

(no correction)

Evolution of working point (October)

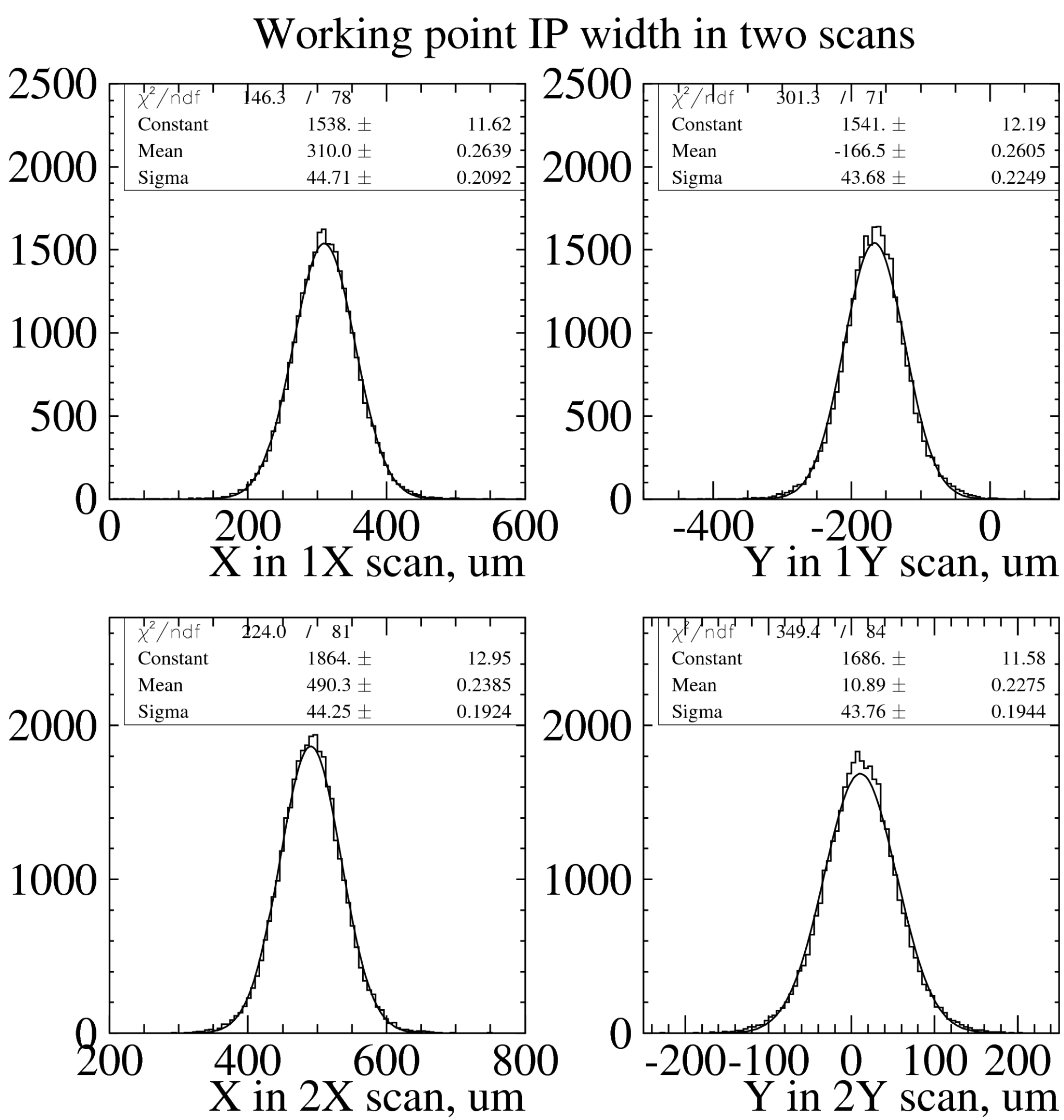




3+3+4+4 working points

Luminosity lifetime: 1/0.60516E-05 sec = 45.90 hours
Luminosity drop during 1st (longer) X or Y scan: 0.7%, compensation in 1st order,
no correction, systematics $\ll$ 1%

Comparison of IP widths in October



No visible beam blowing up during two scans: widths the same within 0.5% stat. errors, difference -0.46±0.28 um in X, 0.08±0.29 um in Y

Van der Meer method for collinear beams

Any rate: $R(\Delta x, \Delta y) = \sigma \cdot L = \sigma \cdot f N_1 N_2 \underbrace{\int \rho_1(x-\Delta x, y-\Delta y) \rho_2(x,y)\, dx\, dy}_{\text{overlap integral}}$

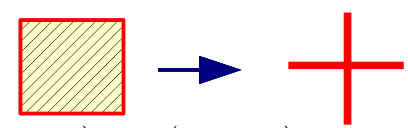
Key idea: $\int \{ \int \rho_1(x-\Delta x) \rho_2(x)\ dx \}\ d\Delta x\ =$

$$\iint \rho_1(x-\Delta x) \rho_2(x)\ dx\ d(x-\Delta x) = \int \rho_1(x')\, dx' \cdot \int \rho_2(x)\, dx = 1$$

Cross-section: $\sigma\ =\ \dfrac{1}{f N_1 N_2} \iint R(\Delta x, \Delta y)\ d\Delta x\ d\Delta y$

If X & Y independent, i.e. no X-Y coupling (the only requirement, $\rho_{x,y}$ are arbitrary):

$$\rho_{1,2}(x,y) = \rho_{1,2\,x}(x)\, \rho_{1,2\,y}(y), \quad R(\Delta x, \Delta y) = R_x(\Delta x)\, R_y(\Delta y)$$

2-D integral can be expressed via 1-D integrals along Δx, Δy: 

$$\iint R(\Delta x, \Delta y)\ d\Delta x\ d\Delta y\ =\ \int R_x(\Delta x)\ d\Delta x \cdot \int R_y(\Delta y)\ d\Delta y\ \frac{R_x(\Delta x_0) R_y(\Delta y_0)}{R(\Delta x_0, \Delta y_0)}\ =$$

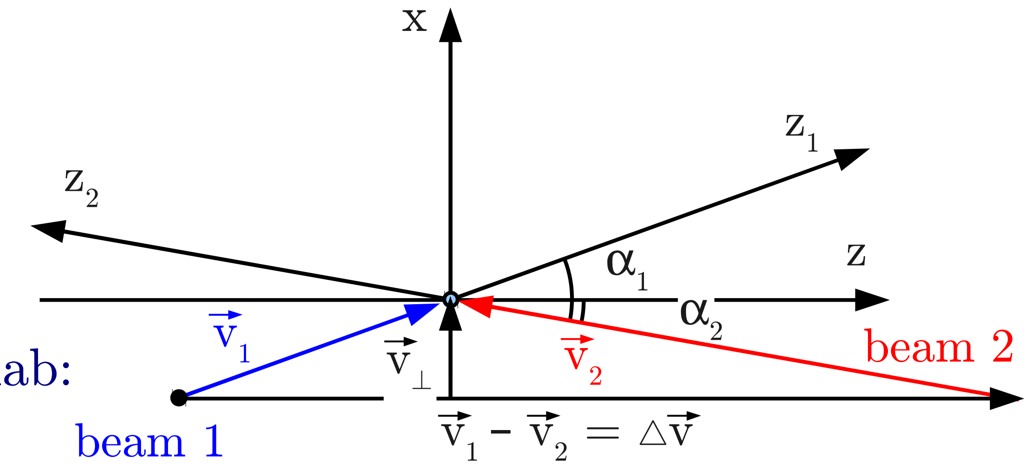
$$\frac{\int R(\Delta x, \Delta y_0)\ d\Delta x \times \int R(\Delta x_0, \Delta y)\ d\Delta y}{R(\Delta x_0, \Delta y_0)}$$ for any "working point" Δx_0, Δy_0 .

Finally: $\sigma\ =\ \dfrac{\int R(\Delta x, \Delta y_0)\ d\Delta x \times \int R(\Delta x_0, \Delta y)\ d\Delta y}{N_1 N_2 f\, R(\Delta x_0, \Delta y_0)}$

Influence of beam crossing angle

Formula for collinear beams v1 ∥ v2 ∥ z: $\sigma = \frac{1}{f N_1 N_2} \iint R \, d^2 \Delta r_\perp^{coll}$

- σ is rel. invariant (in standard definition of Lumi with Moller rel. factor)
- R/f = #interactions per BX, rel. invariant
- $r_\perp^{coll}$ invariant only to boosts along z



General case:
boost with $-\vec{v}_\perp$ makes beams collinear,

from there: boost collinear formula back to lab:

$$\sigma = \frac{\gamma_\perp}{f N_1 N_2} \iint R \, d^2 \Delta r_\perp^{lab}$$

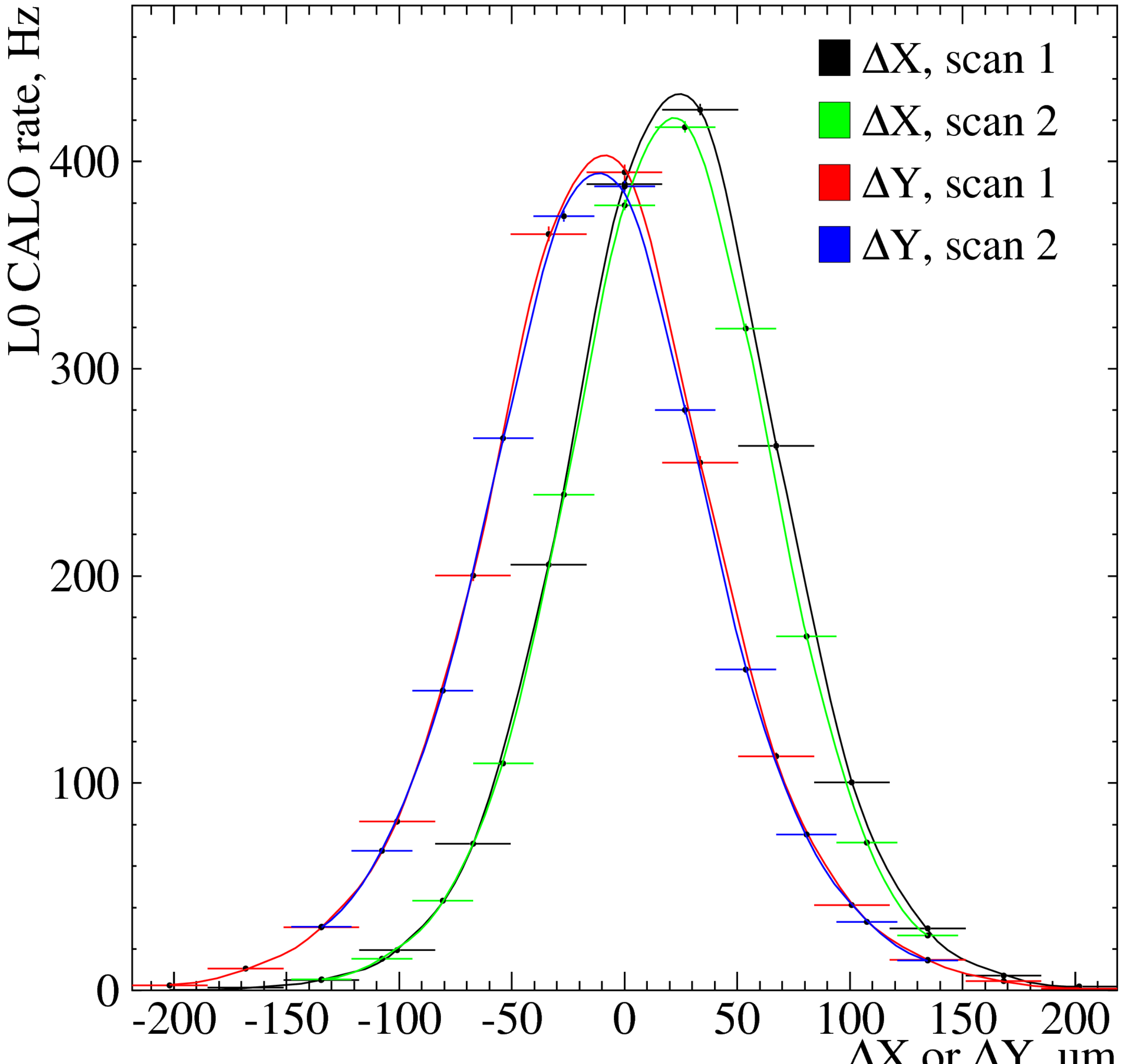
$$v_\perp = \frac{|\vec{v}_1 \times (\vec{v}_1 - \vec{v}_2)|}{|\vec{v}_1 - \vec{v}_2|} = \frac{|\vec{v}_1 \times \vec{v}|}{|\vec{v}_1 - \vec{v}_2|}, \qquad \gamma_\perp = 1 / \sqrt{1 - \frac{(\vec{v}_1 \times \vec{v})^2}{(\vec{v}_1 - \vec{v}_2)^2}}$$

At LHC: $\gamma_\perp = \cos^{-1} \frac{\alpha_1 + \alpha_2}{2} = \cos^{-1}((0.27,\ 0.17) \cdot 10^{-3}) = 1 + (4,\ 1.4) \cdot 10^{-8}$

VdM method works, correction $\gamma_\perp \simeq 1$

Van der Meer curves in April

1) both beams moved
2) only beam1 (×0.8 smaller step)



Visible (RZVelo) cross section (April)

First scan (both beams moved):

$$\sigma_{vis}(L0\,CALO) = \frac{\int F(y_0)\,d\Delta X \int F(x_0)\,d\Delta Y}{f\,N_1 N_2 F(x_{0,}\,y_0)} = \frac{5.11\,cm\cdot Hz \times 5.09\,cm\cdot Hz}{11.245\,kHz \times 1.050\text{e+}20 \times 392\,Hz} = 56.2\,mb$$

Second scan (only beam1 moved):

$$\sigma_{vis}(L0\,CALO) = \frac{4.87\,cm\cdot Hz \times 4.99\,cm\cdot Hz}{11.245\,kHz \times 1.050\text{e+}20 \times 383\,Hz} = 53.8\,mb$$

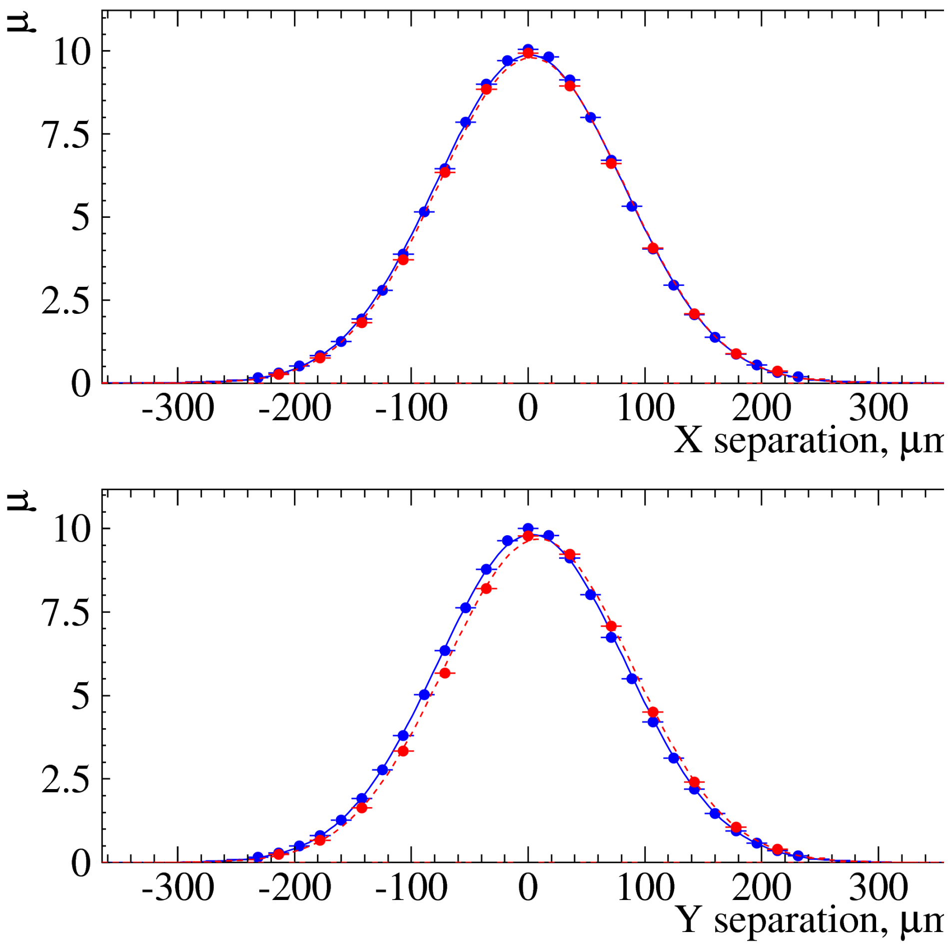
Difference between scans: 4.4 $\pm$ 1.2 (stat.)%

σ(RZVelo)/σ(L0 CALO) = 1.066

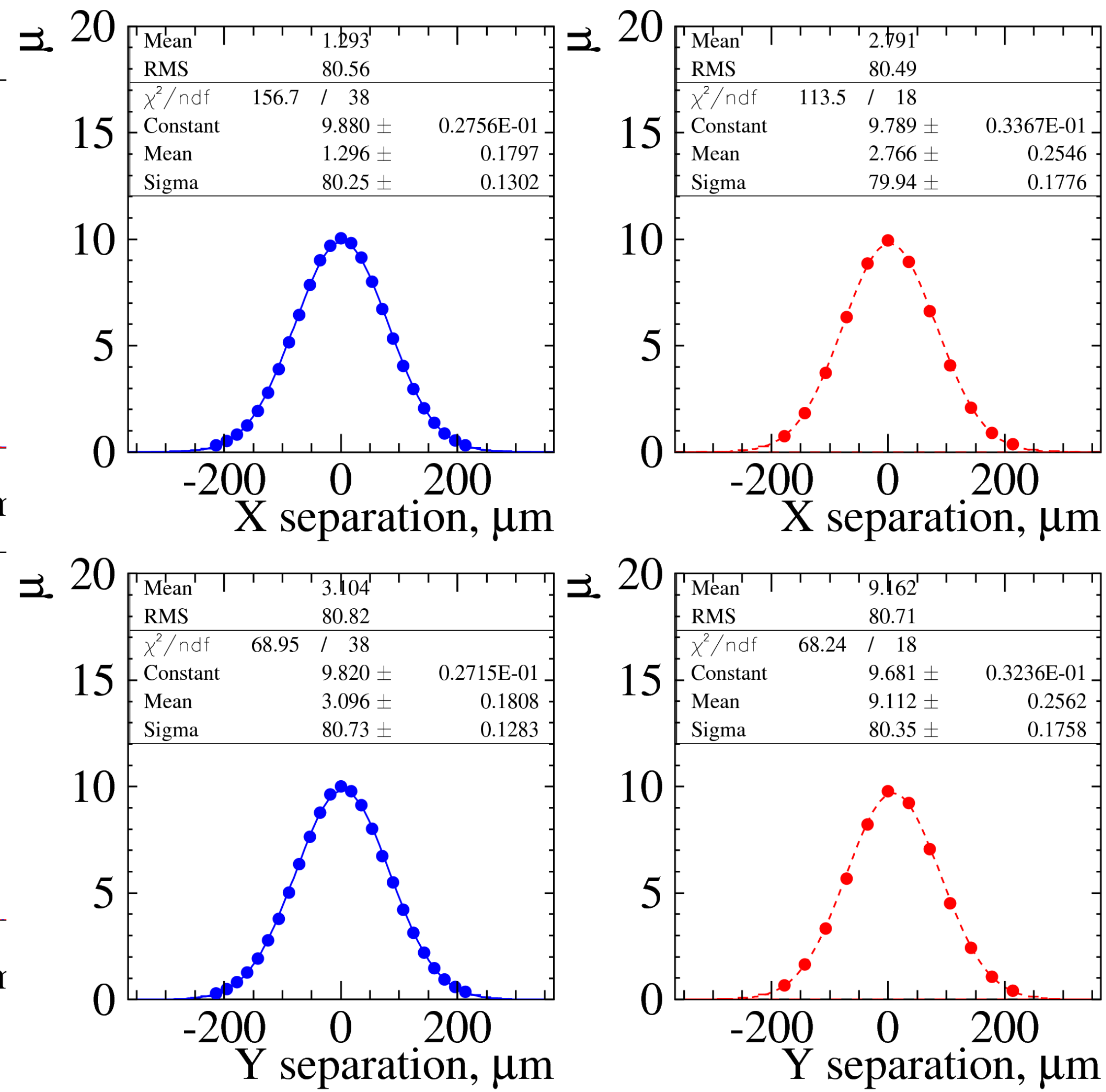
$$\boxed{\sigma(\text{RZVelo}) = (59.9+57.3)/2 = 58.6 \text{ mb}}$$

Van der Meer curves in October

Comparison of two scans, 12 bunches



Sum over 12 bunches

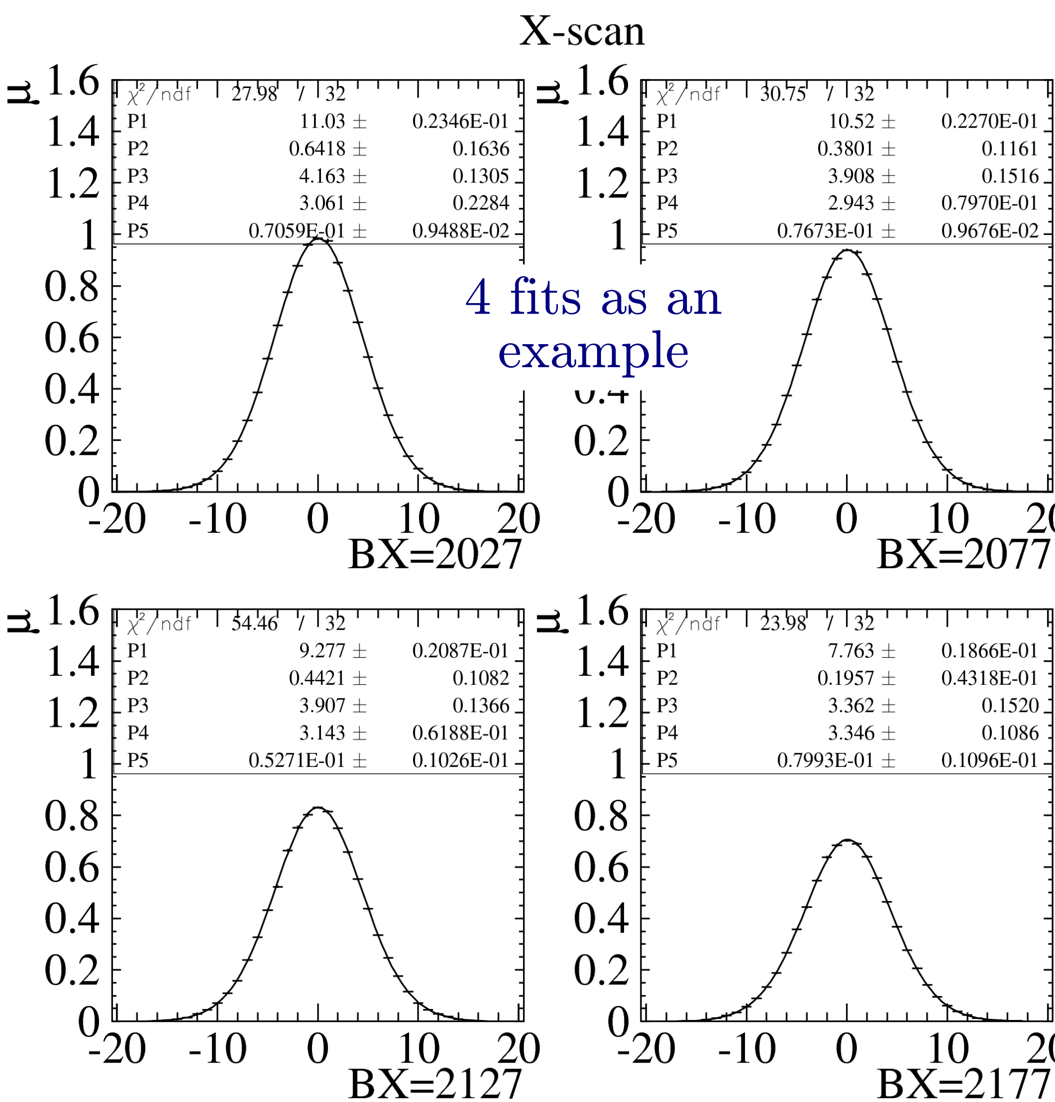


Y distribution is shifted by 7 um on left side and by 4 um on right

width in 2nd scan is smaller: RMS by 0.09-0.14%, sigma by 0.4-0.5% (stat. error 0.3%)

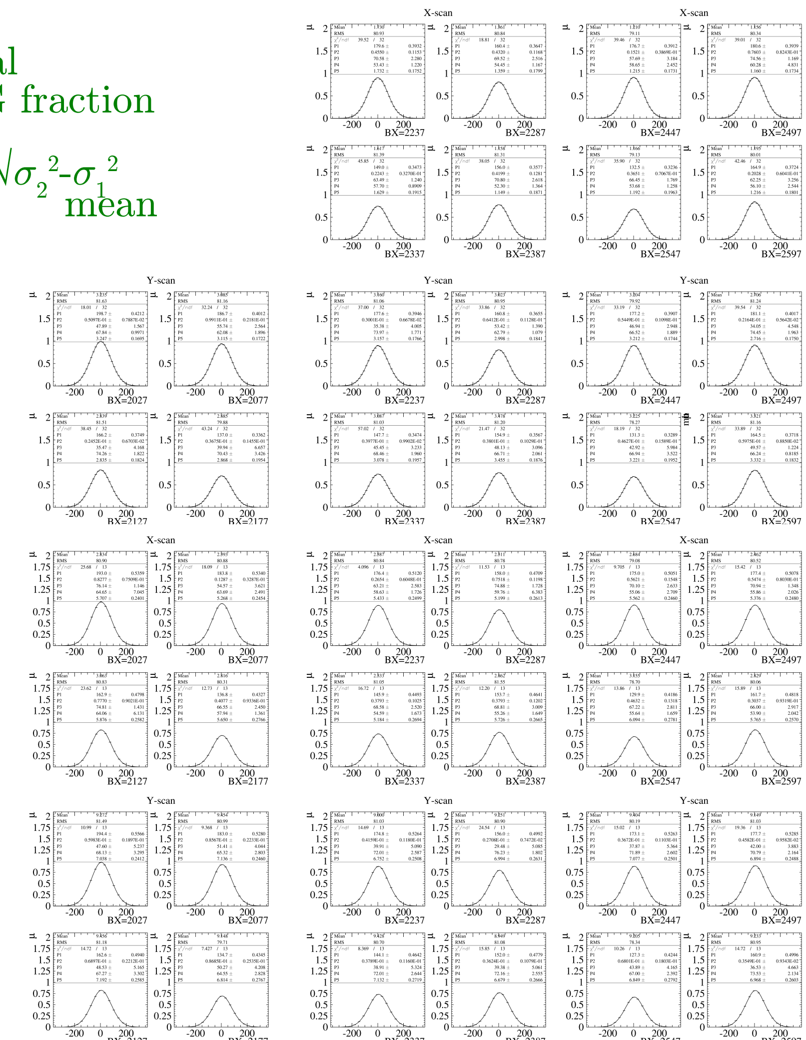
Analysis of individual bunches (October)

48 double Gaussian fits it total, bunch shapes are very similar



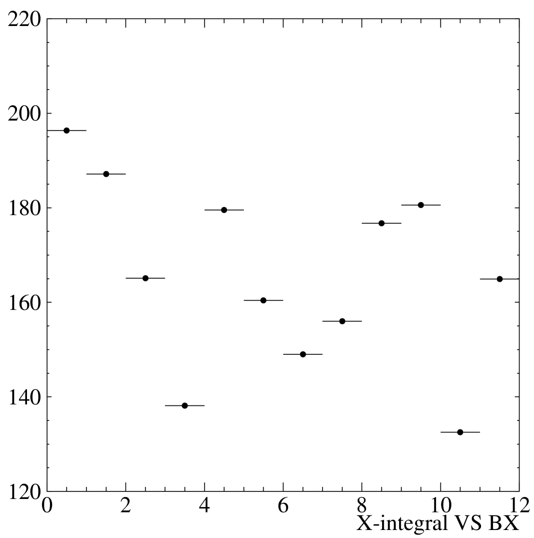
4 fits as an example

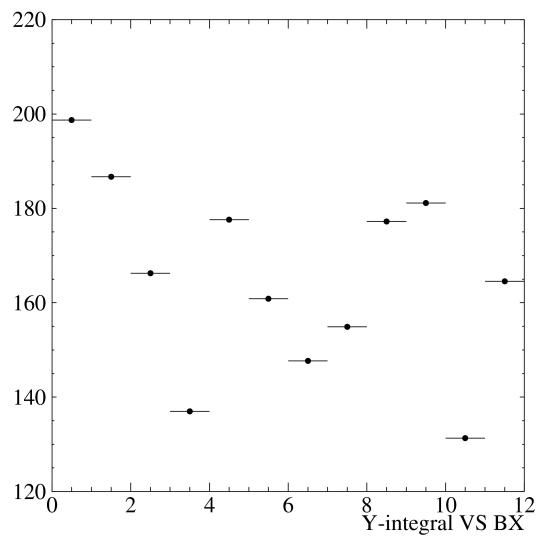
Integral
1st G fraction
σ_1
$\sqrt{\sigma_2^2-\sigma_1^2}$
mean



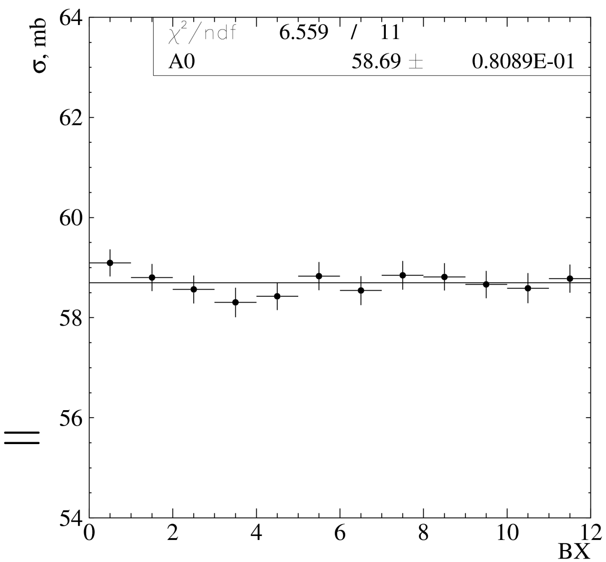
Cross section calculation for 1st scan in October

$$\sigma = \frac{\int \mu(\Delta x, \Delta y_0)\, d\Delta x \times \int \mu(\Delta x_0, \Delta y)\, d\Delta y}{N_1 N_2 \mu(\Delta x_0, \Delta y_0)}$$

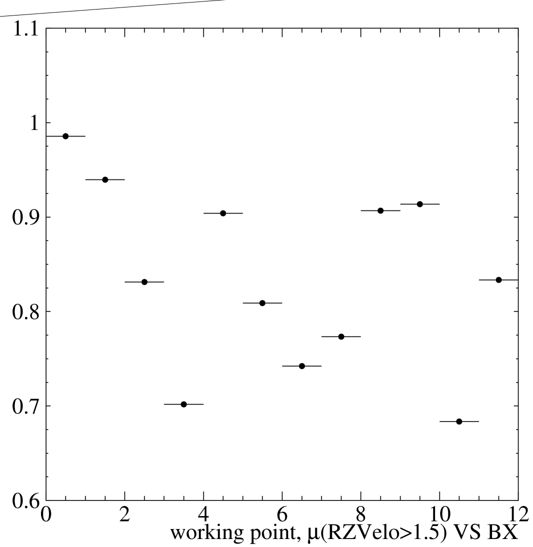


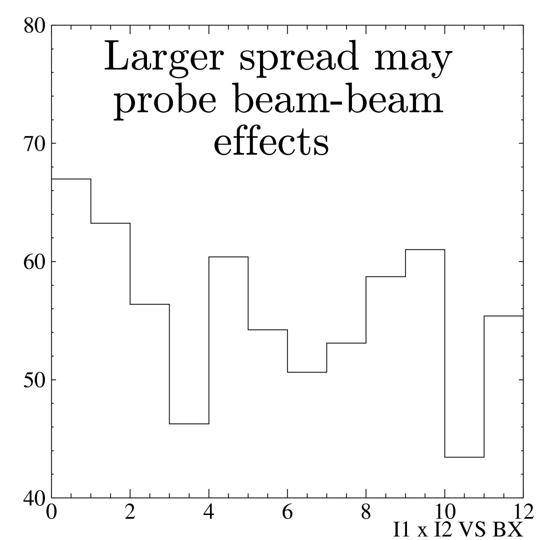


1st scan: 58.69±0.08 mb



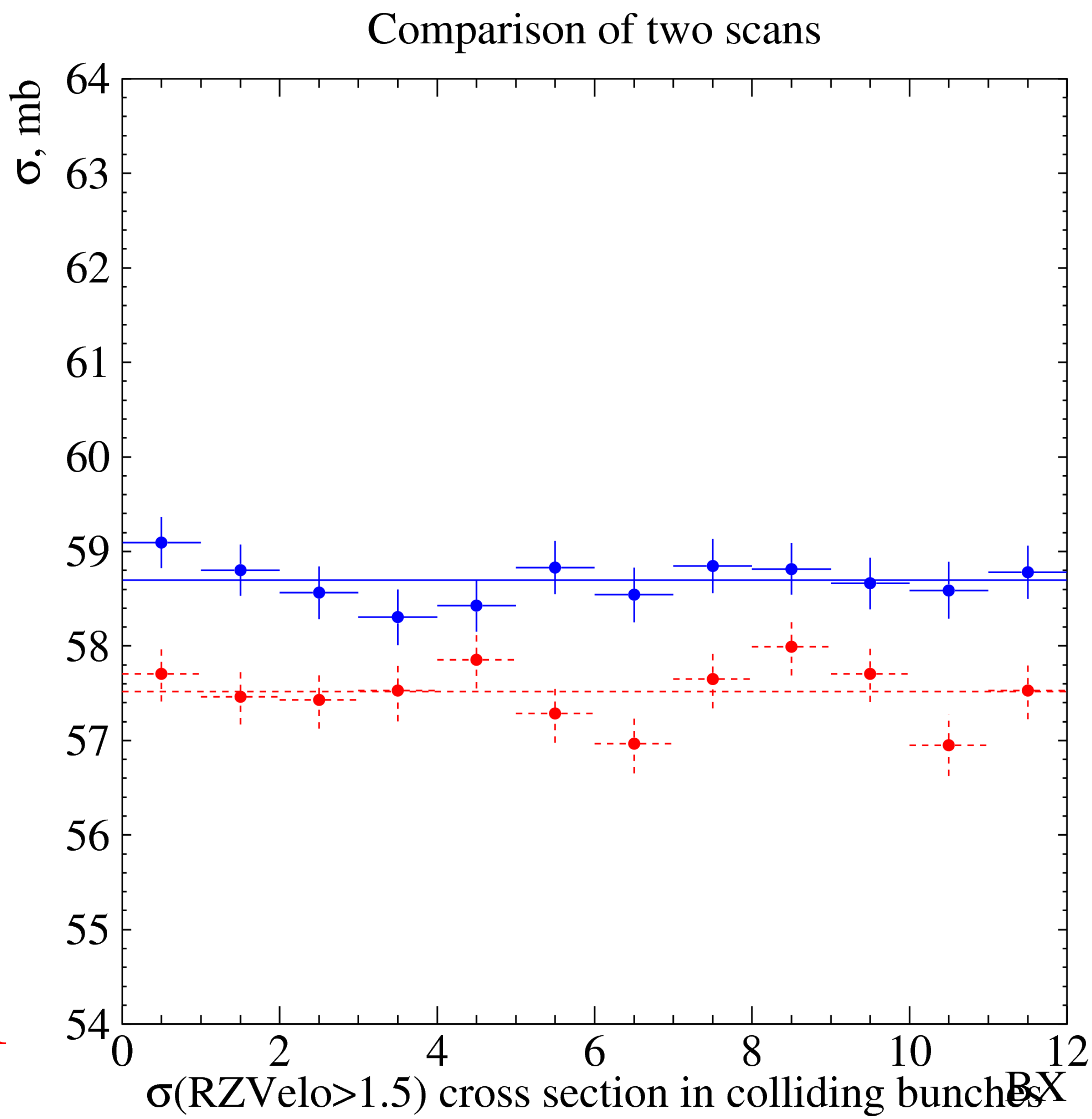
X 0.1 =





In spite of RMS/mean = 11-12% variations between bunches, cross-sections are same within 0.5% stat errors

Cross section results (October)



1st scan: 58.69±0.08 mb

2nd scan: 57.52±0.09 mb

Difference 2.0±0.2%

12 bunches give consistent results, $\chi^2/2 = 6.6/11$, $11.5/11$

April: $\sigma = (59.6+57.0)/2 = 58.3$ mb

New method to reconstruct individual bunch shapes

Luminous region profile with VELO resolution V, no crossing angle:

$$IP(x,\Delta) = \sigma N_1 N_2 \int \rho_1(x'-\Delta)\rho_2(x')V(x-x')\,dx'$$

In van der Meer method we integrate over x (to get rates) and over Δ (this removes ρ_1(x)):

$$\frac{1}{\sigma N_1 N_2}\int IP(x,\Delta)\,dx\,d\Delta = \int \rho_1(x'-\Delta)\,d(x'-\Delta)\cdot\int[\rho_2\circ V](x)\,dx = 1,$$

and use this constraint to get absolute normalization.

By dropping integration over x:

$$\frac{1}{\sigma N_1 N_2}\int IP(x,\Delta)\,d\Delta = \int \rho_1(x'-\Delta)\,d(x'-\Delta)\cdot[\rho_2\circ V](x) = [\rho_2\circ V](x),$$

and after deconvolution with V we can determine beam image ρ_2!

By doing same from 1st beam rest frame (beam 2 moves) one can reconstruct ρ_1 .

With crossing angle: beam transverse image = sum of all VX distributions transverse to beam and visible from its center during scan

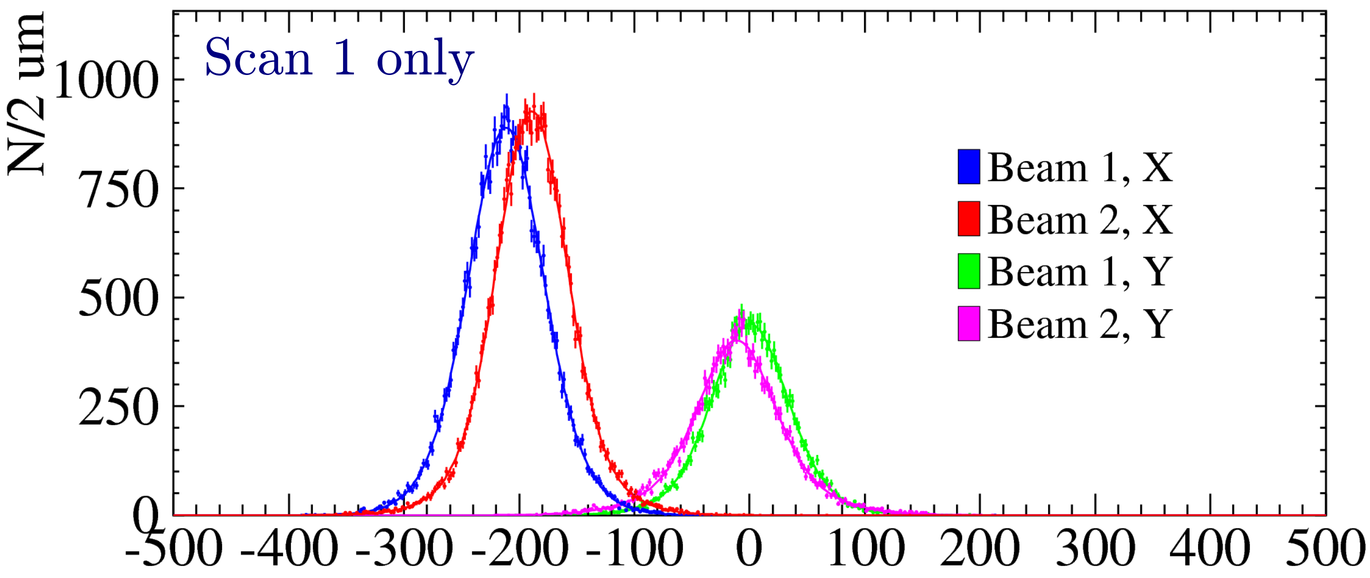
(note with proof prepared, to be published soon)

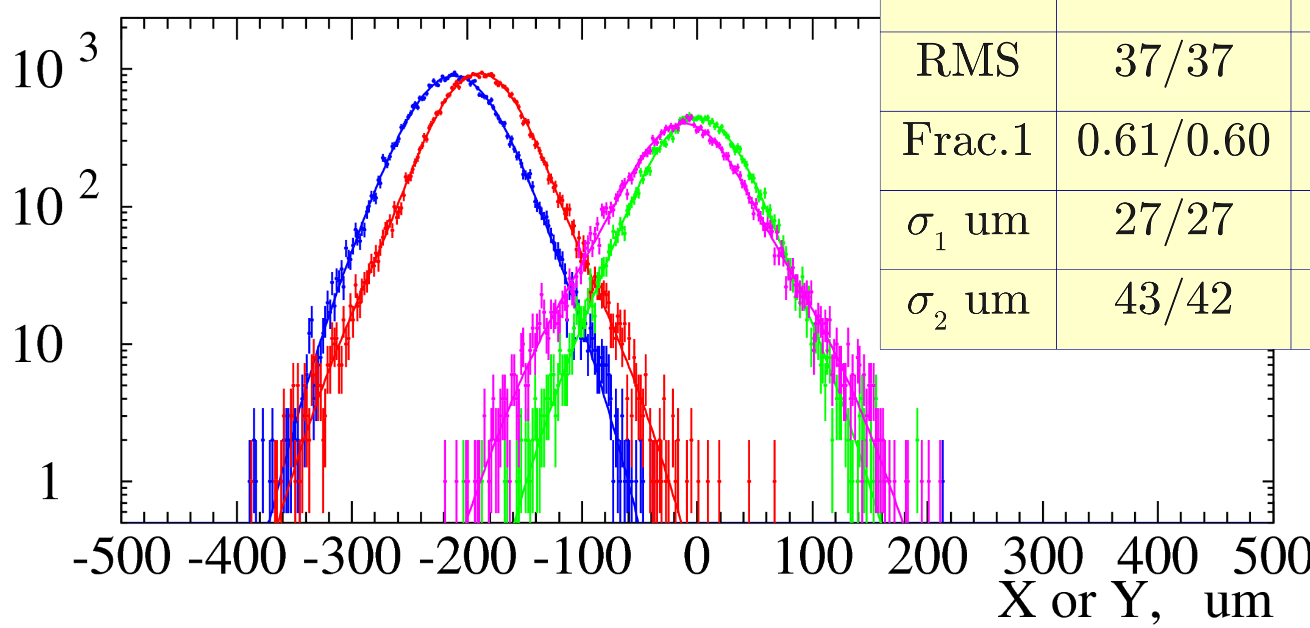
Same image as in beam-gas method

- big statistics,
- VELO resolution optimized for IP point (worse for far beam-gas interactions)

Very interesting to have both methods in one fill

Reconstructed bunch shapes *(folded with VELO res., April)*





Scan 1 / Scan 2

	x1	x2	y1	y2
RMS	37/37	37/36	38/37	45/43
Frac.1	0.61/0.60	0.73/0.70	0.68/0.69	0.57/0.42
σ_1 um	27/27	26/25	26/26	25/22
σ_2 um	43/42	50/46	46/45	55/48

VELO resolution

Variance (RMS squared) of convolution = sum of variances.

If VELO resolution V depends on number of vertex tracks as $A/\sqrt{N}$, variance of

$$IP(x,\Delta) \propto \int \rho_1(x'-\Delta)\rho_2(x')V(x-x')\,dx' = [\rho_1\rho_2]\circ V$$

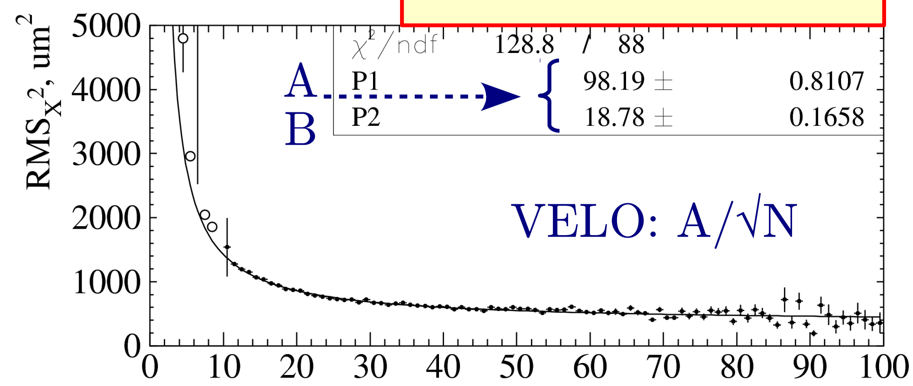
as function of x (for a fixed Δ):

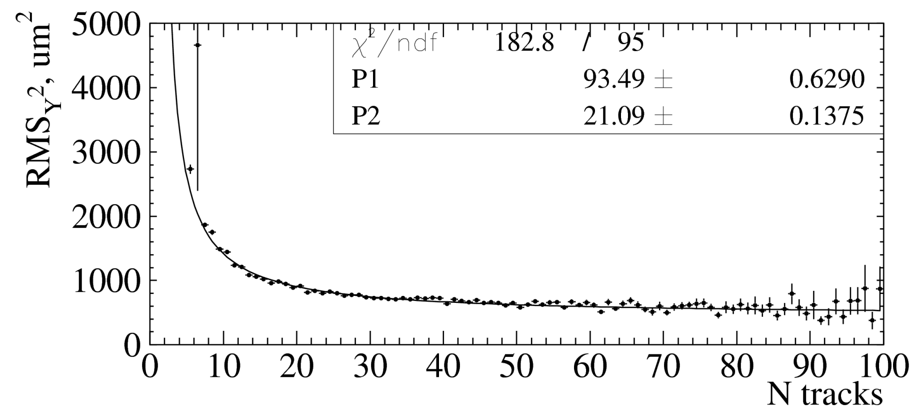
$$\boxed{(A/\sqrt{N})^2 + B^2}$$

B - constant RMS of $[\rho_1\rho_2]$

$\Rightarrow$ A and B can be distinguished in the fit.

RMS^2 vs. N tracks





Variance error: $\sqrt{\frac{1}{N_{ev}}\left(\mu_4 - \frac{N_{ev}-3}{N_{ev}-1}RMS^4\right)}$, μ_4 - 4th central moment.

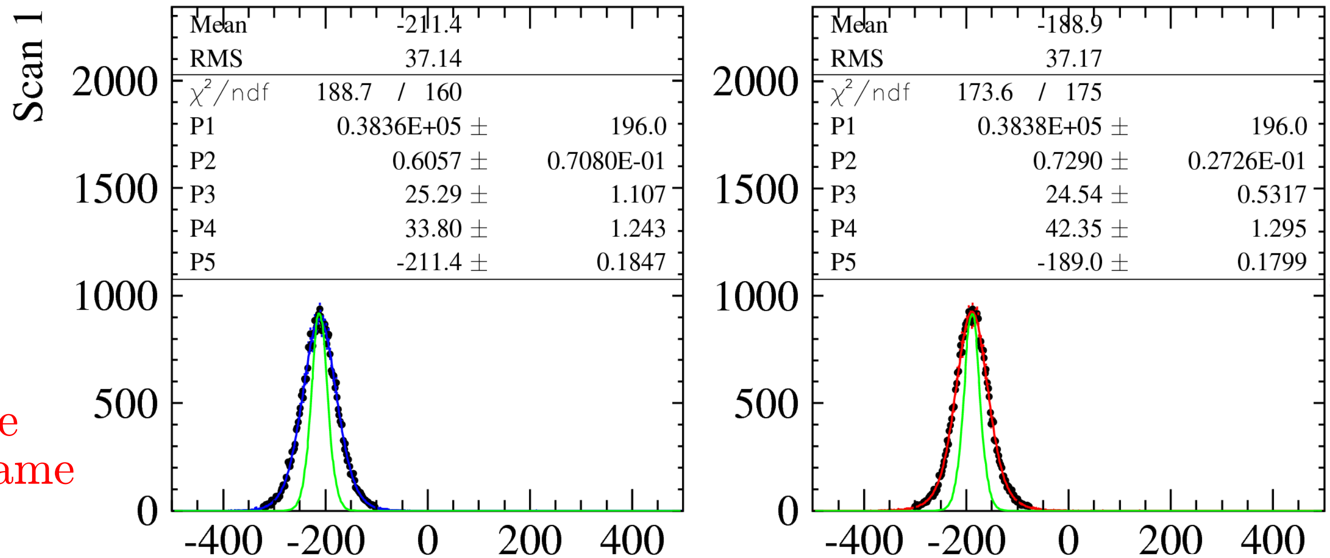
VELO unfolded bunch shapes, X projections (April)

Blue – beam 1

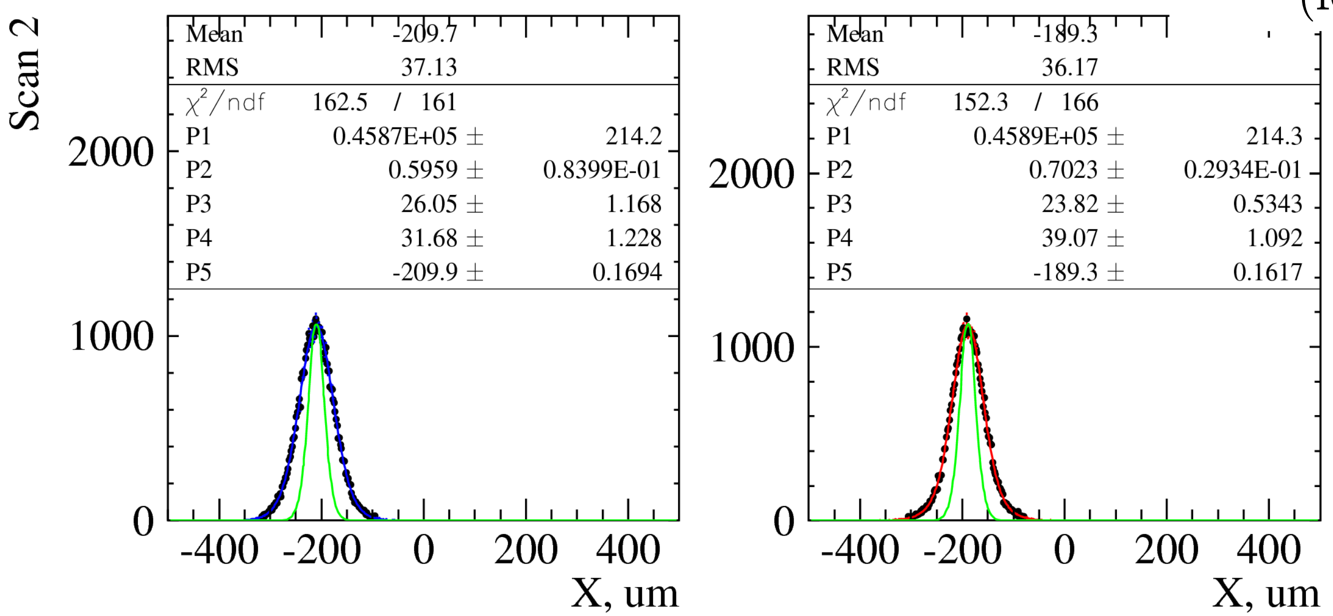
Red - beam 2 (folded with VELO)

Unfolded parameters

Profiles visible from moving frame

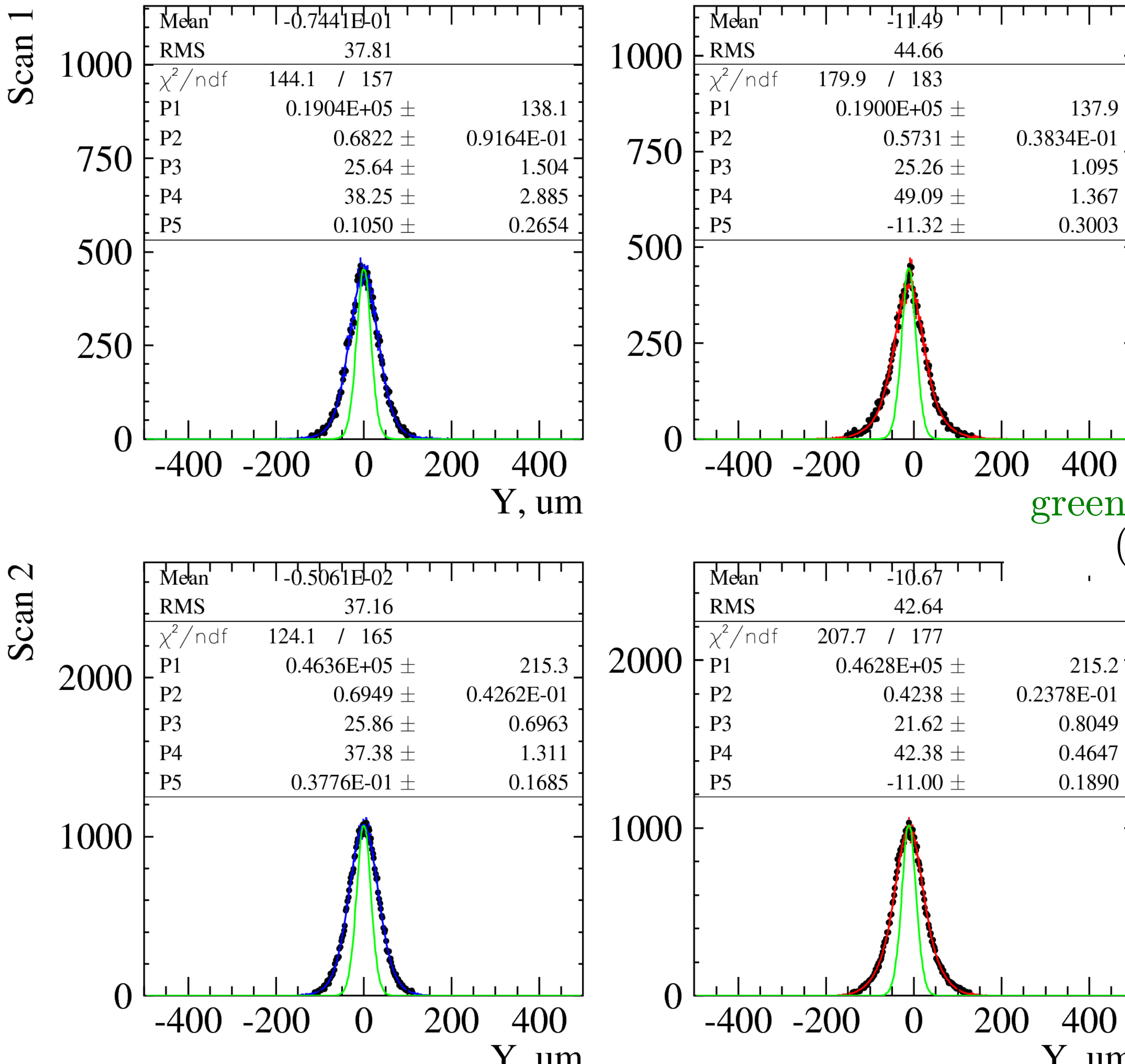


green – VELO resolution (for comparison)



VELO unfolded bunch shapes, Y projections (April)

Blue – beam 1 Red - beam 2 (folded with VELO)

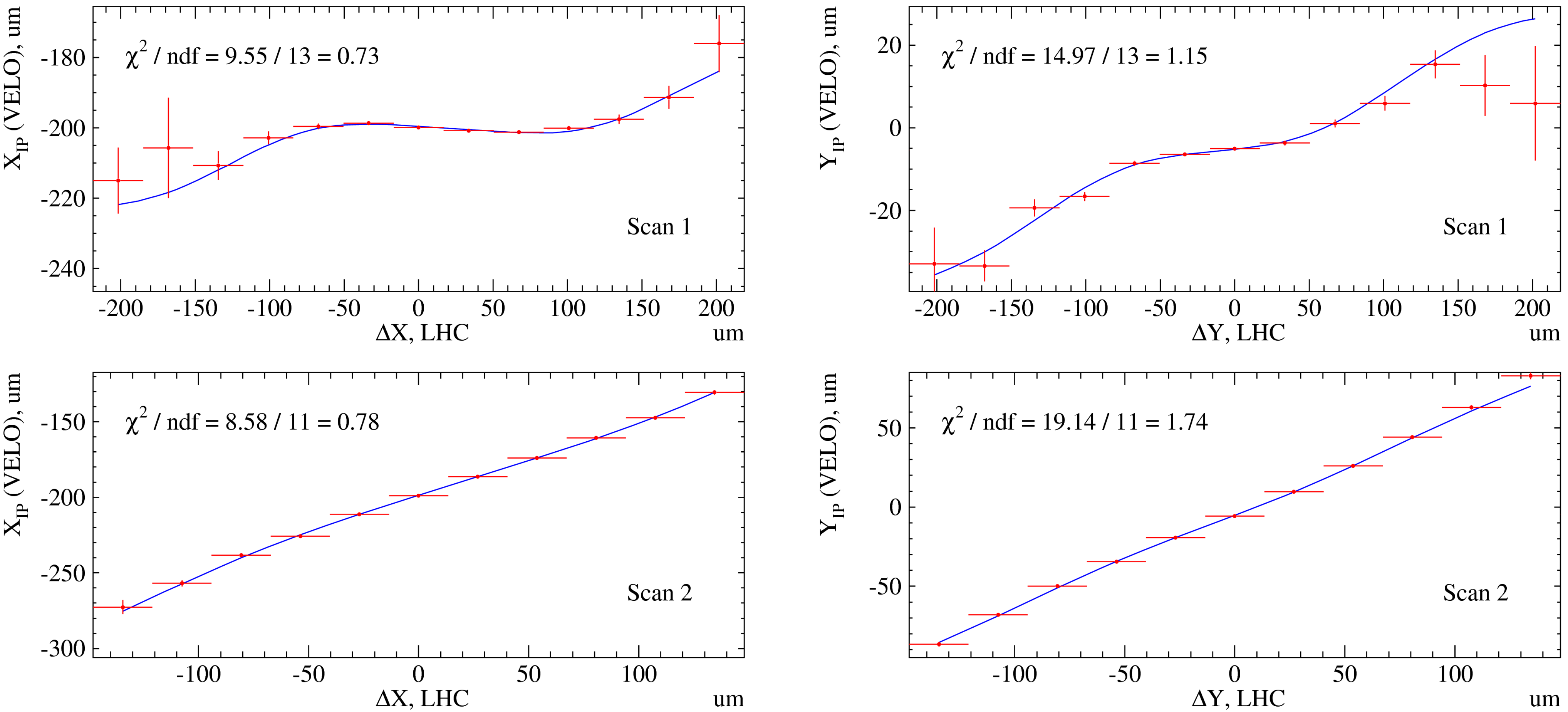


Unfolded parameters

green – VELO resolution (for comparison)

IP position from beam images (April)

Blue lines - center of luminous region from reconstructed beam shapes
Red - data points $\Rightarrow$ good agreement



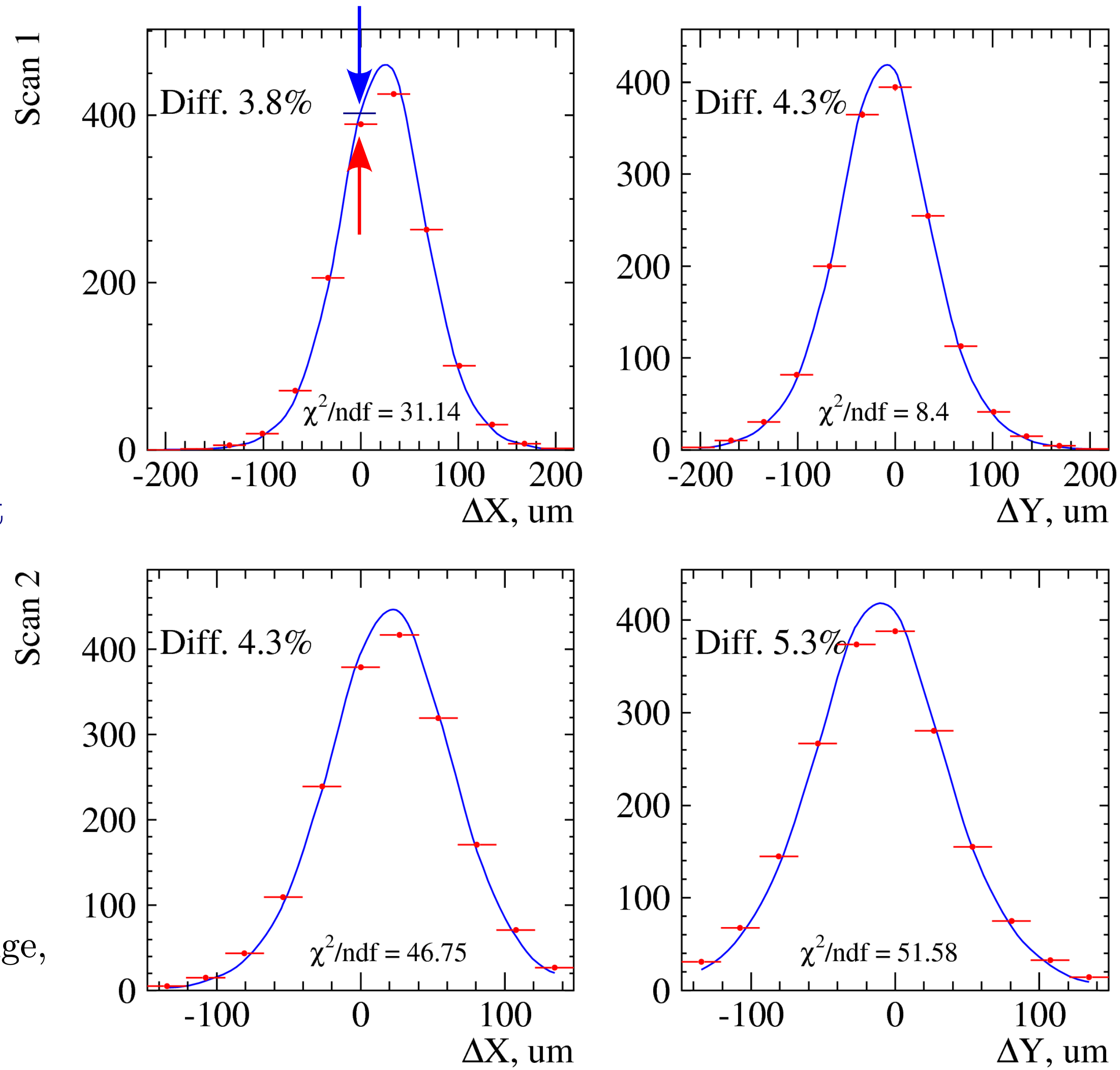
Rates from reconstructed beam images (April)

Blue lines – rate versus beam separation from beam shapes

Red – data points

(same normalization = area)

Data points are wider,
4-5% difference at working point



Second scan not covered whole range,
bunch tails not fully reproduced

Systematics of vdM cross section

$$\sigma = \frac{\int \mu(\Delta x, \Delta y_0)\, d\Delta x \times \int \mu(\Delta x_0, \Delta y)\, d\Delta y}{N_1 N_2 \mu(\Delta x_0, \Delta y_0)}$$

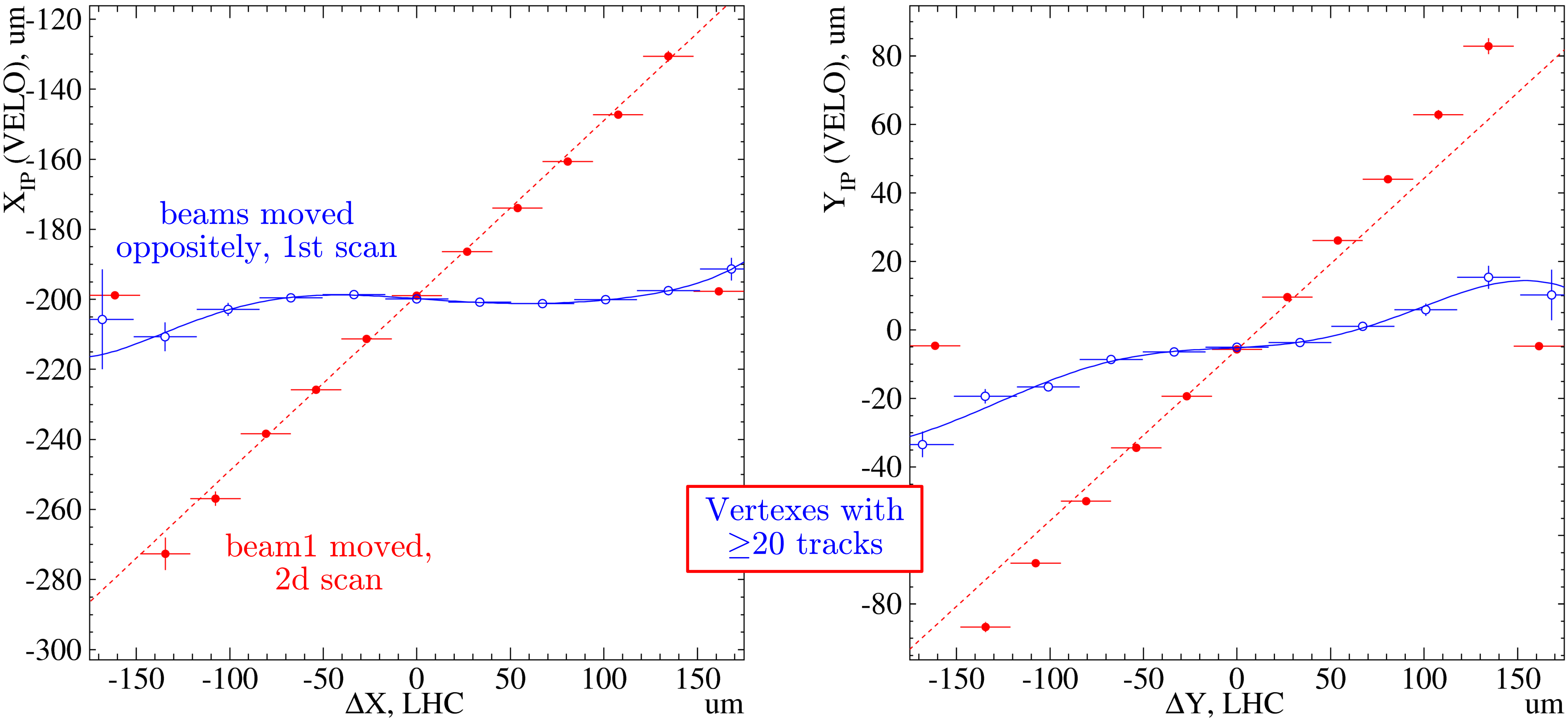
1. Proportionality of μ and luminosity – already shown
2. X-Y length scale
3. No X-Y coupling
4. LHC currents, ghost charges

Length scale calibration

1. From VELO IP position when 1st, 2nd or both beams moved during scans

2. From dedicated length calibration scan (only in October)

1. Luminous region movement in first / second scan (April)

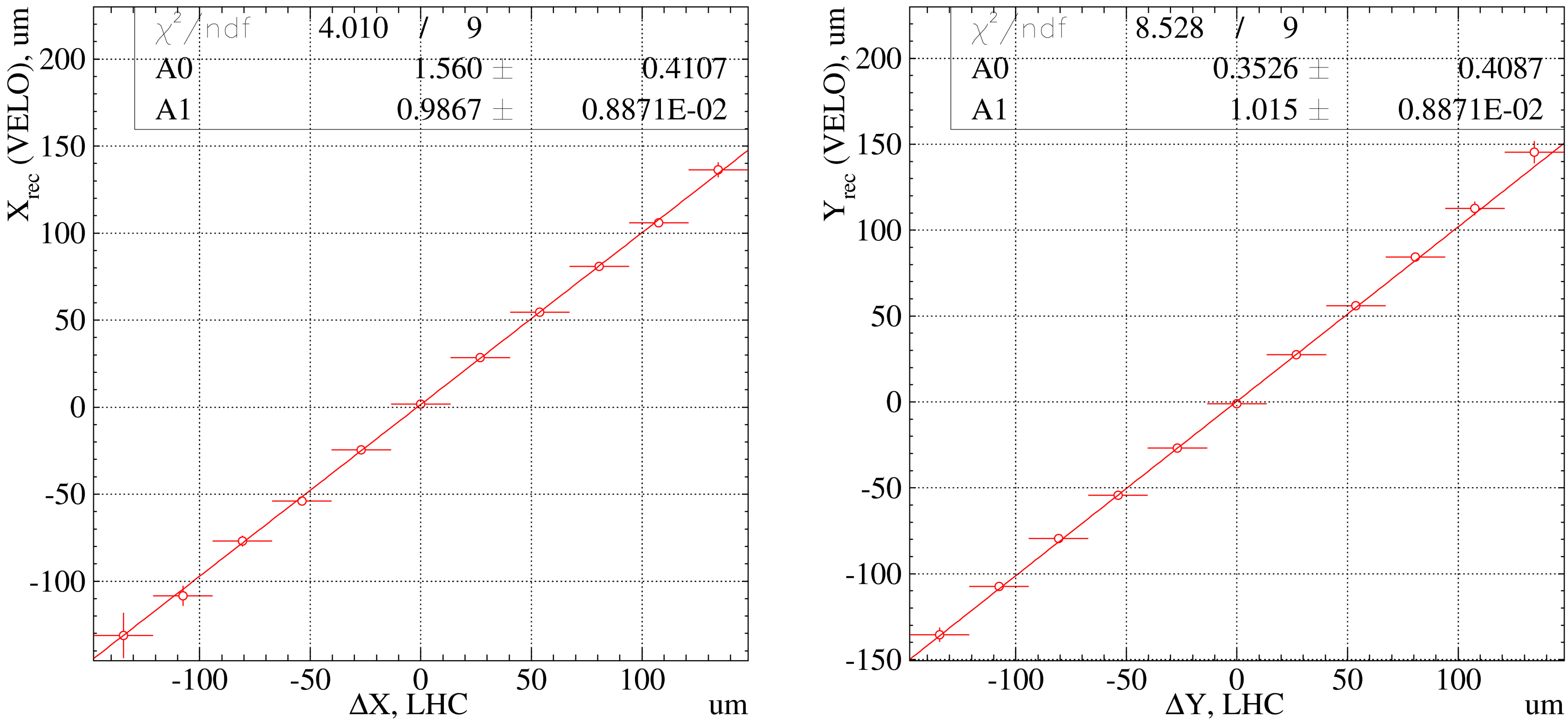


When beams moved oppositely (scan1), luminous region follows narrower beam, ⇒*beam 2 has broader tails*, *nonlinearity* due to *non-Gaussian* shapes.

IP distance from beams middle point: $\overrightarrow{\Delta r}_{IP}(\Delta X, \Delta Y) = \overrightarrow{R}^{I}_{IP} = \overrightarrow{R}^{IIa}_{IP} - \frac{\overrightarrow{R}^{IIa}_{b1}}{2} = \overrightarrow{R}^{IIb}_{IP} - \frac{\overrightarrow{R}^{IIb}_{b2}}{2}$

$\Rightarrow \quad \frac{\overrightarrow{R}^{IIa}_{b1}}{2} = \overrightarrow{R}^{IIa}_{IP} - \overrightarrow{R}^{I}_{IP} \;, \quad \frac{\overrightarrow{R}^{IIb}_{b2}}{2} = \overrightarrow{R}^{IIb}_{IP} - \overrightarrow{R}^{I}_{IP}$ $\quad \Rightarrow$ *allows to check scale* with VELO

Cross-check LHC scale with VELO (April)



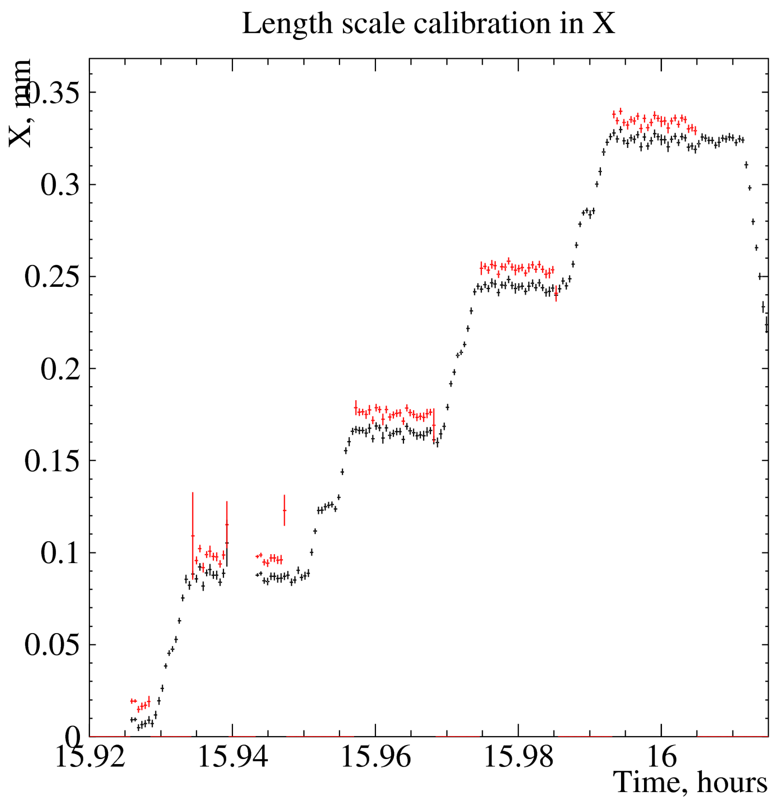
Agreement within ±1.5%

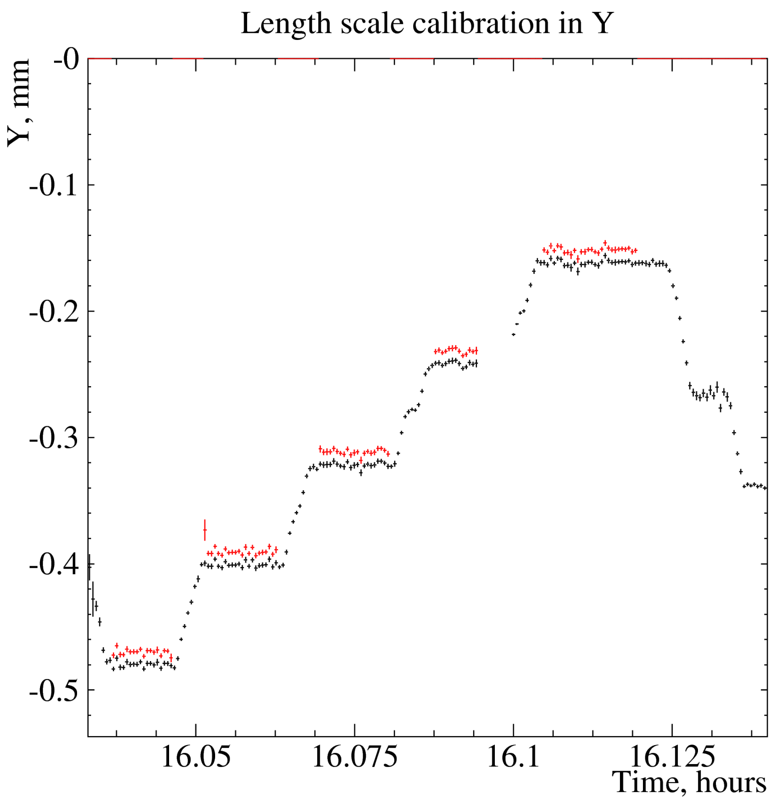
X changed by 1.5 um in 2d scan

2. Dedicated length calibration scan (October)

Beams moved together from one end point to another.

During X scan, beam separation in (X, Y) was fixed at (80 um, 0) where 80 um$\simeq$1σ of vdM shape to enhance derivative dL/dΔx, i.e. luminosity sensitivity to possible difference in beam1,2 scales. Similar in Y scan.





B1 B2, um: -220 -140 / -140 -60 / -60 +20 / +20 +100 / +100 +180 / -40 -60, in X,Y

2. Luminosity behavior

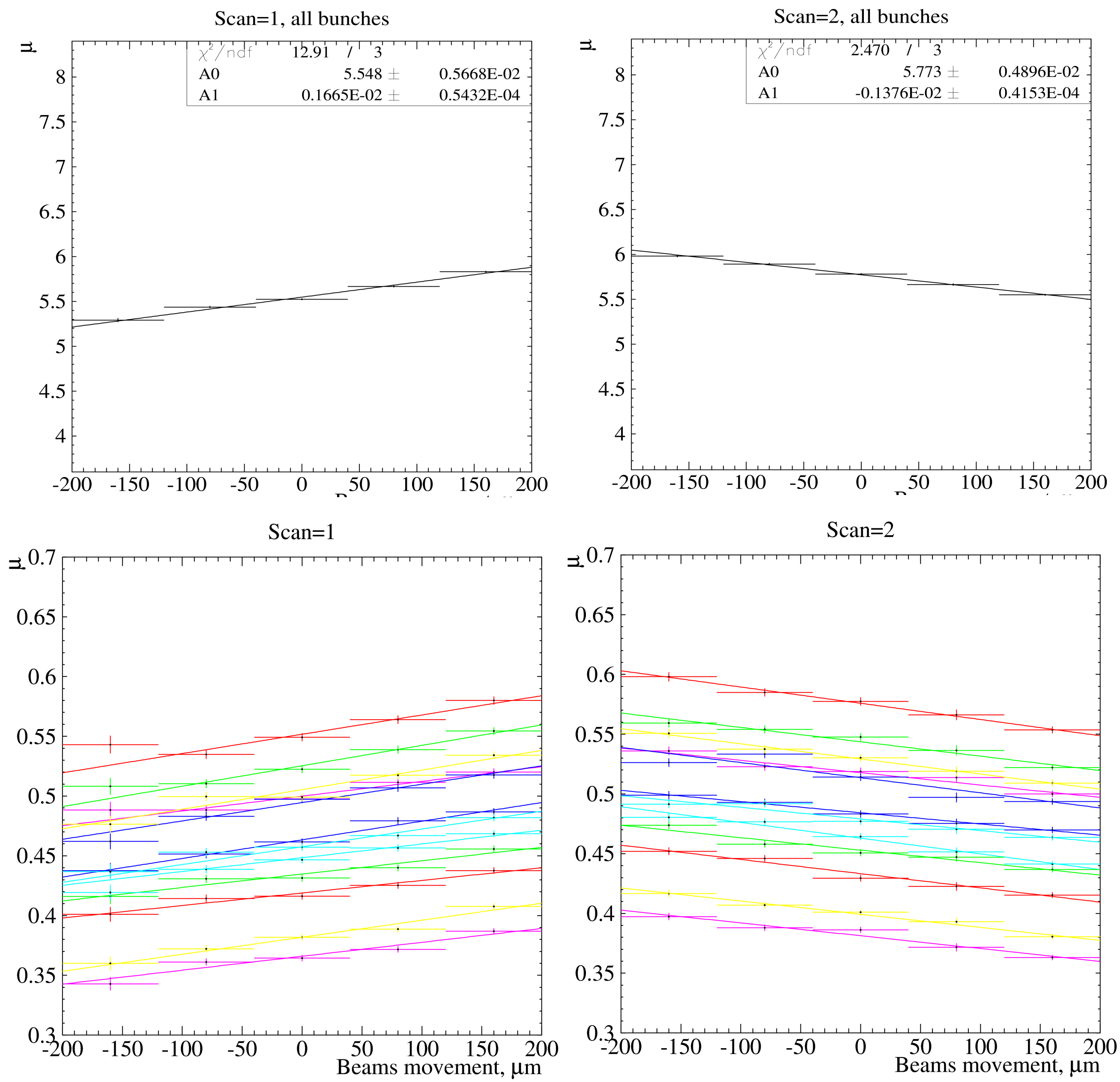
Ideally, luminosity should be constant.

If beam scales different $x_{1,2} = x_{1,2}{}^0\,(1 \pm \varepsilon/2)$ it changes, however:

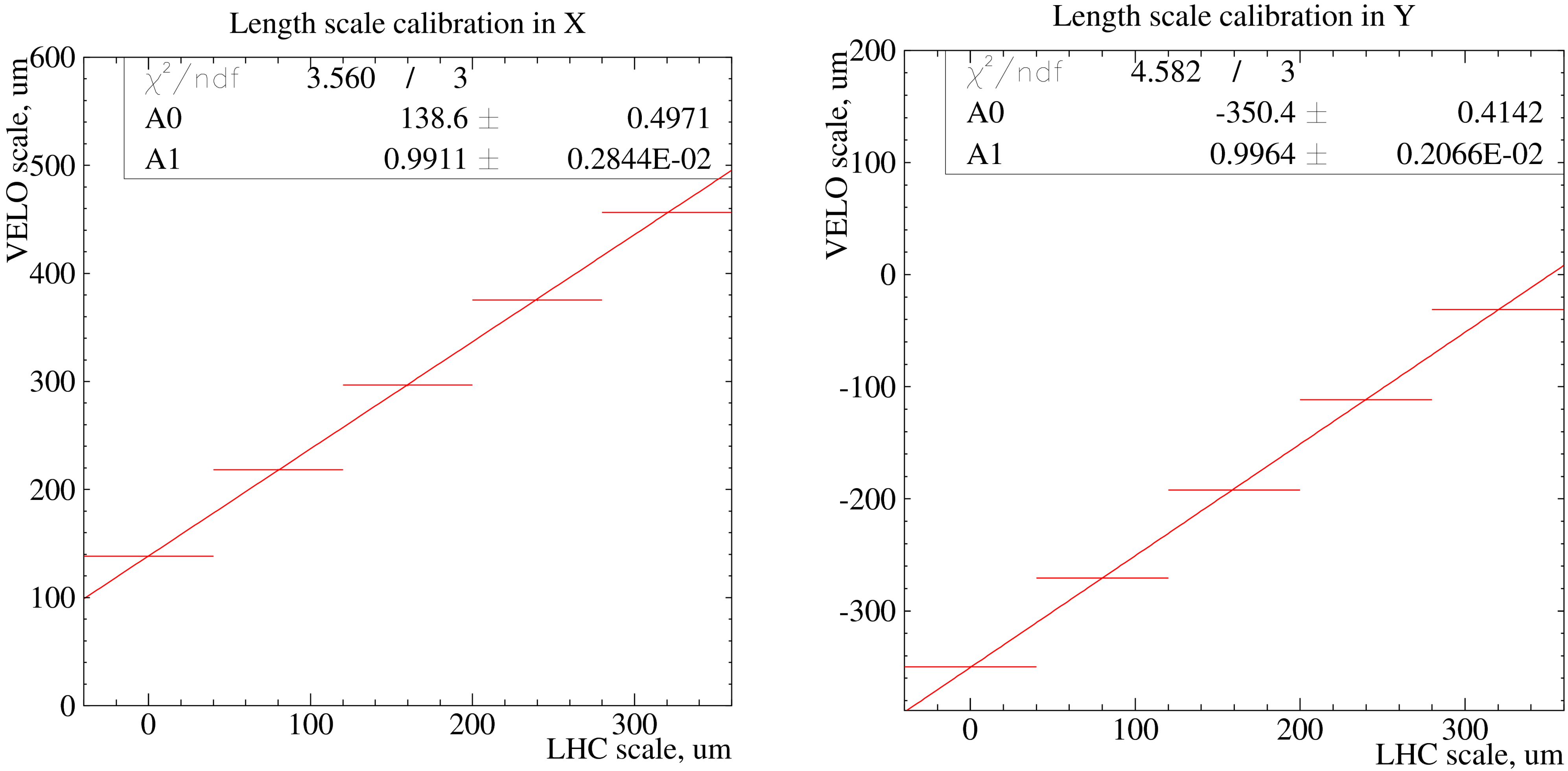
$$\frac{dL}{d\,(x_1^0 + x_2^0)/2} = -\epsilon\, L \frac{\Delta}{\sigma^2}$$

$\varepsilon_X = 2.4\%$
$\varepsilon_Y = -1.9\%$

Different bunches behave similarly



2. IP movement



Recall $x_{1,2} = x_{1,2}^{0}\,(1 \pm \varepsilon/2)$ from previous slide

VELO confirms middle point $(x_1+x_2)/2=(x_1^0+x_2^0)/2$ movement (average scale), corrections -0.89±0.28% in X, -0.36±0.21% in Y

Scale difference influence on cross-section (October)

$$x_{1,2} = x_{1,2}^{\,0}\,(1 \pm \varepsilon/2)$$

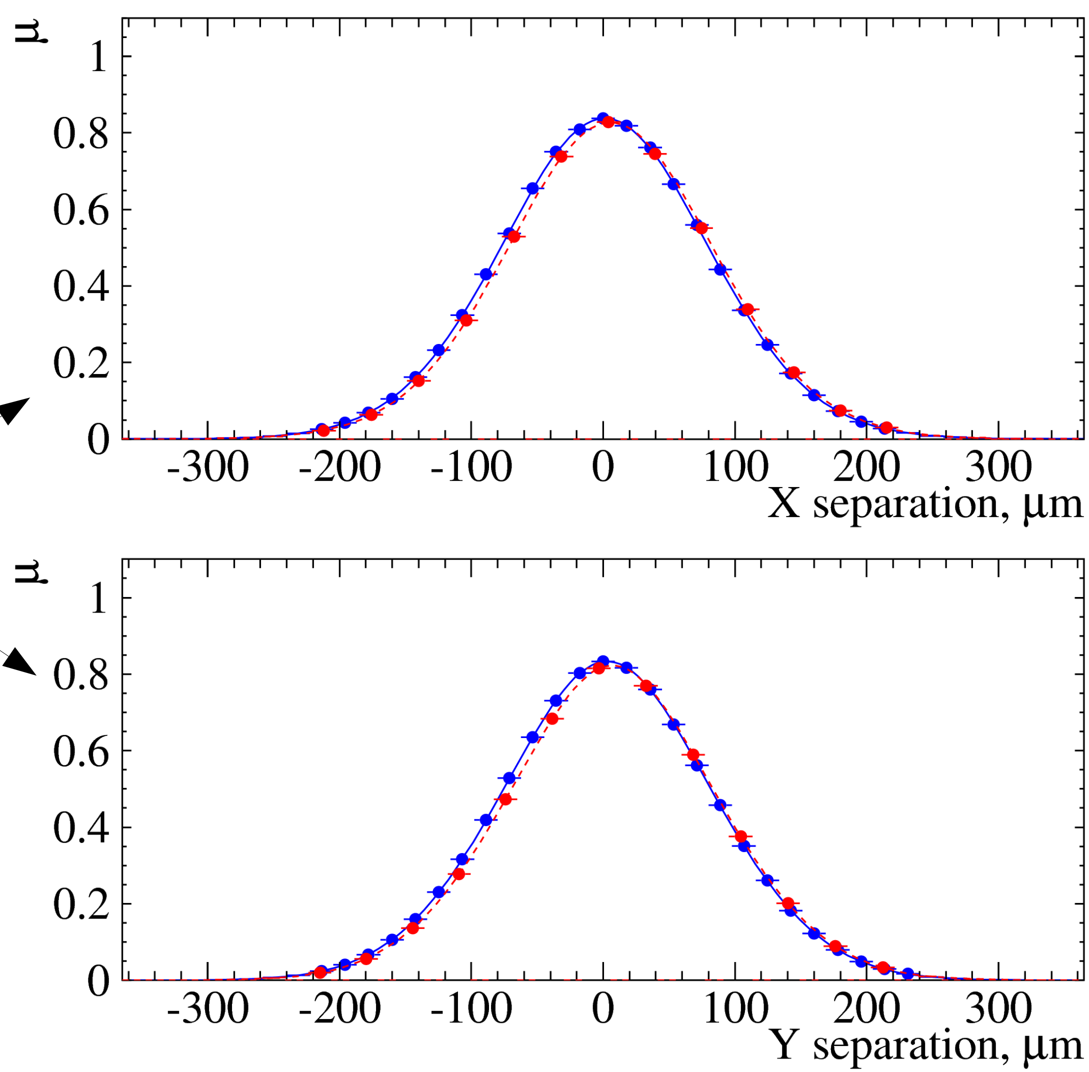
$$\Delta = x_1^{\,0} - x_2 = (x_1^{\,0} - x_2^{\,0}) + \varepsilon(x_1^{\,0} + x_2^{\,0})/2$$

- ε-correction depends on middle point $(x_1^{\,0}+x_2^{\,0})/2$ and affects 2nd scan

After correction shift is reduced in Y, but appears in X

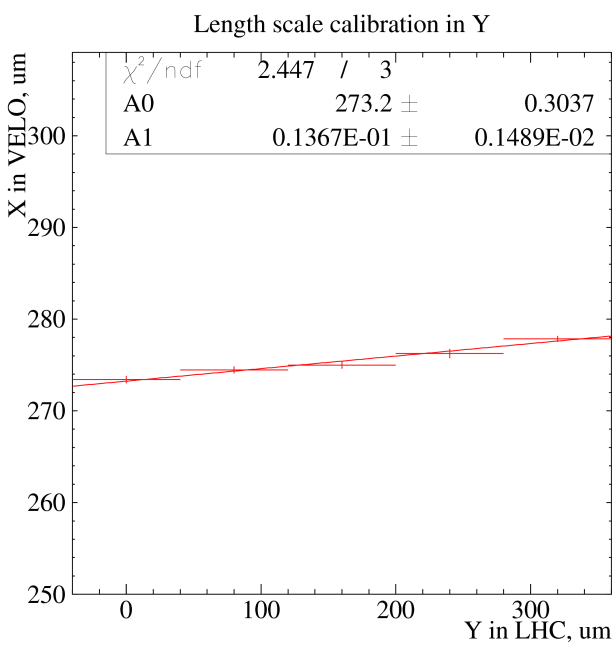
Cross section remains constant, however. On previous slide it was given already with correction. Without: lower by 0.10%

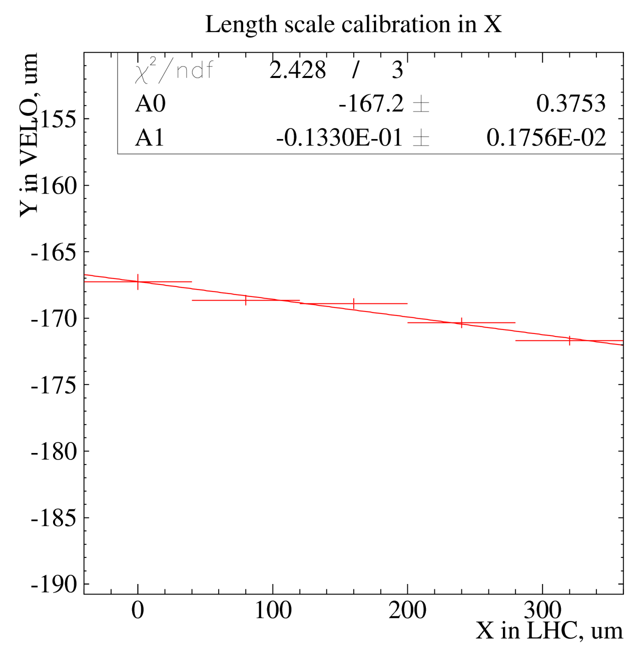
Two scans corrected for beams scale difference



X-Y coupling, rotation between LHC and VELO (Oct)

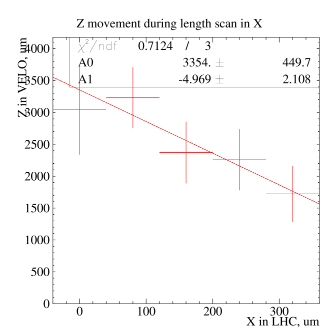
X(Y) IP movement measured in VELO during lengh calibration scan in Y(X).
Nice agreement with design 13 mrad (http://cdsweb.cern.ch/record/692072?ln=en)

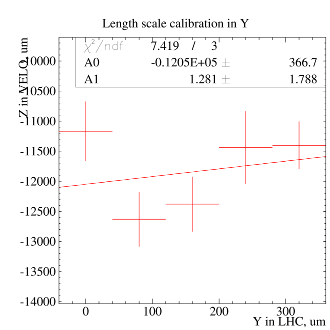




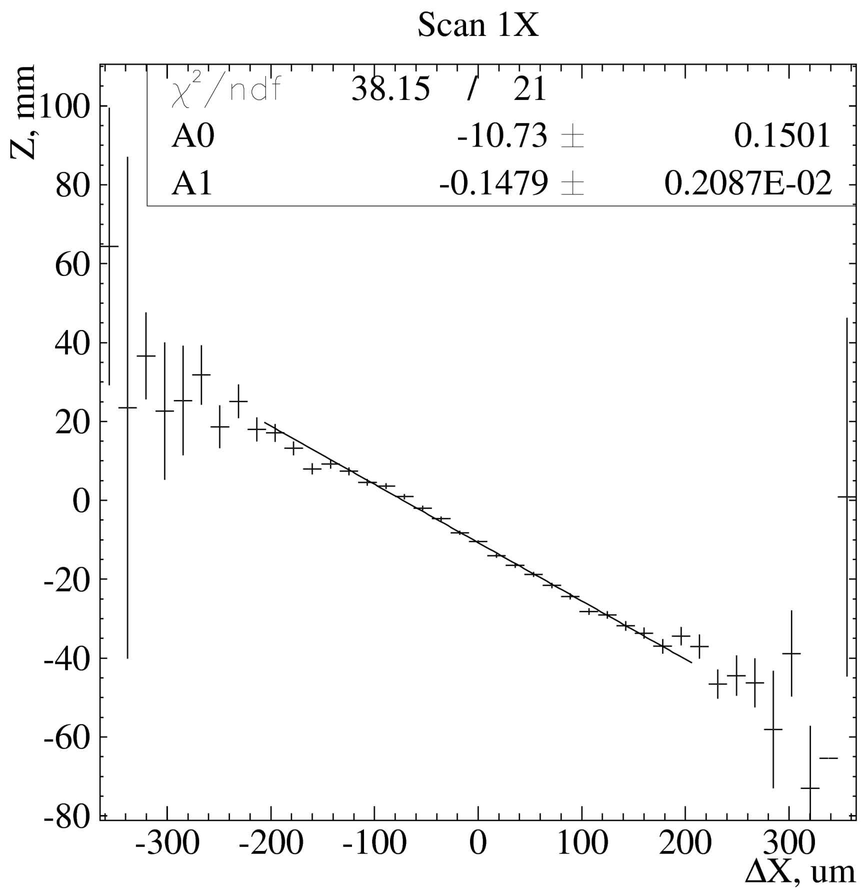
1 - cos(13 mrad) = 0.84e-04 invisible within errors (2.1-2.8 e-3)

Z moves (fluctuates?) in X, Y scans
within 2 mm:





Z_{IP} movement in vdM X scan due to crossing angle (Oct)



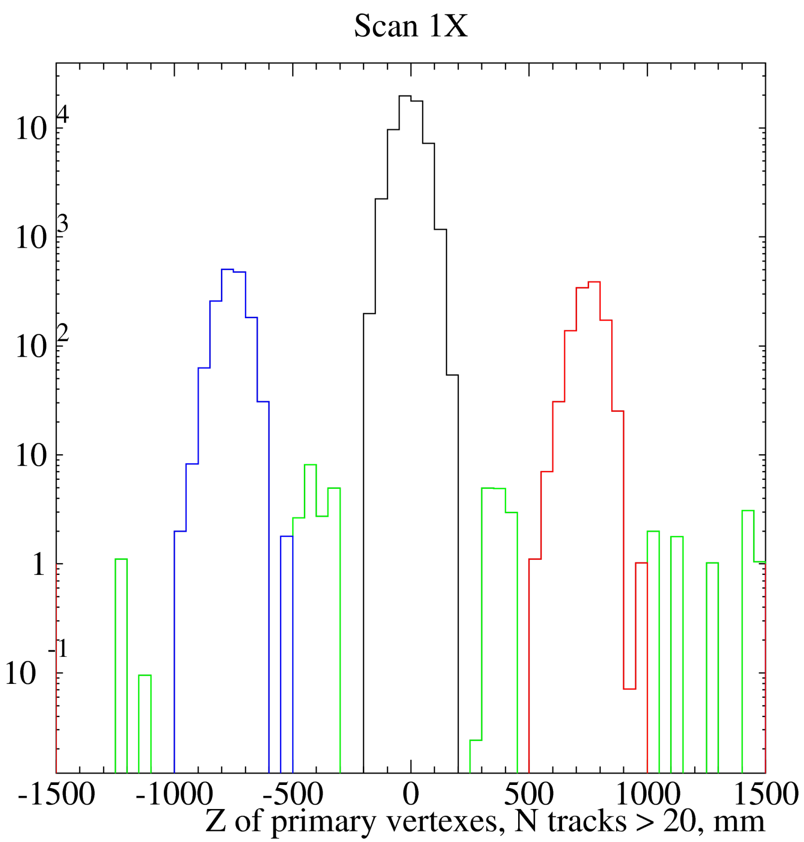
Beams separation in X moves Z due to crossing angle – noted by R.Jacobsson, calculated by M.Ferro-Luzzi for equal beams: $\delta Z/\delta\Delta X = \alpha/2/[(\sigma_X/\sigma_Z)^2+\alpha^2]$

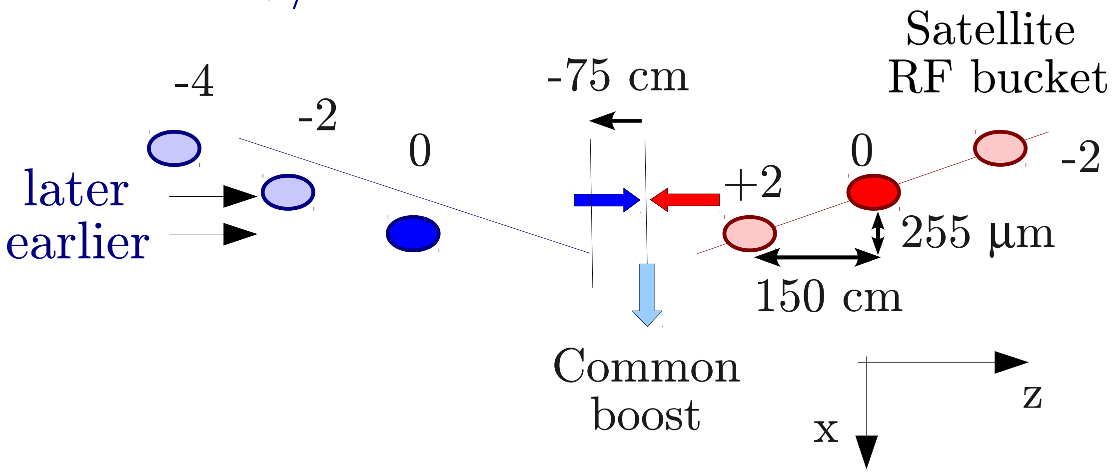
σ_Z=√2 σ_Z^{IP}=√2 (52.0±0.3) mm – VELO resolution negligible, α=170 urad

$\rightarrow \sigma_X^{VDM} = \sqrt{2}\ \sigma_X = 78$ um in agreement with measured 80 um

Ghost charge (October)

Parasitic vertexes at z = +/-75 cm due to collisions of main and non empty +/-2 RF buckets. Suppressed due to crossing angle but appear when beams are displaced. Blind to +/- 4 RF.





Events are taken with L0 CALO trigger (with arbitrary normalization in every scan step). At scan tails +/-75 cm VXs are enhanced by trigger

Ghost charge fraction: ~2%

Should be subtracted from both currents and X-integral => partial compensation. If satellites have same Y-shape – even zero effect.

⇨ Assign 2% syst. error to cross-section

Conclusions

σ(#RZVelo tracks>1) in mb

1. April vdM scans: 59.9 and 57.3, average 58.6 +/- 4.3
 - 5.5% BCT according to recent BCNWG note,
 - 4.4% difference between scans,
 - 2% length scale error

2. Beam-gas: 63.6 +/- 6.4 at ICHEP, to be updated with new N_1N_2 BCNWG knowledge

3. October vdM scan: 58.7 (and 2nd: 57.5) +/- 1.8 +/- (N_1N_2 error)

- 2.0% difference between scans, take first with less hysteresis effects
- 2% due to RF ghost charge
- 1% length scale

- $\ll$1% due to a) luminosity drop during the scan
  b) possible nonlinearity of μ(RZVelo) with luminosity
  c) difference of beam scales

- N_1N_2 error from BCT is not yet finalized

Conclusions

Observed problems:

1) non reproducibility, shifts between scans of the order of 5 um. All 12 bunches in October behave coherently.

2) non constant luminosity during length calibration scan in October, possible explanation – different by $\varepsilon_X = 2.4\%$, $\varepsilon_Y =$ -1.9% beam scales

3) parasitic collisions in October at z = +/-75 cm caused by +/-2 RF buckets, blindness to +/-4 RF (clean in April).

Note on

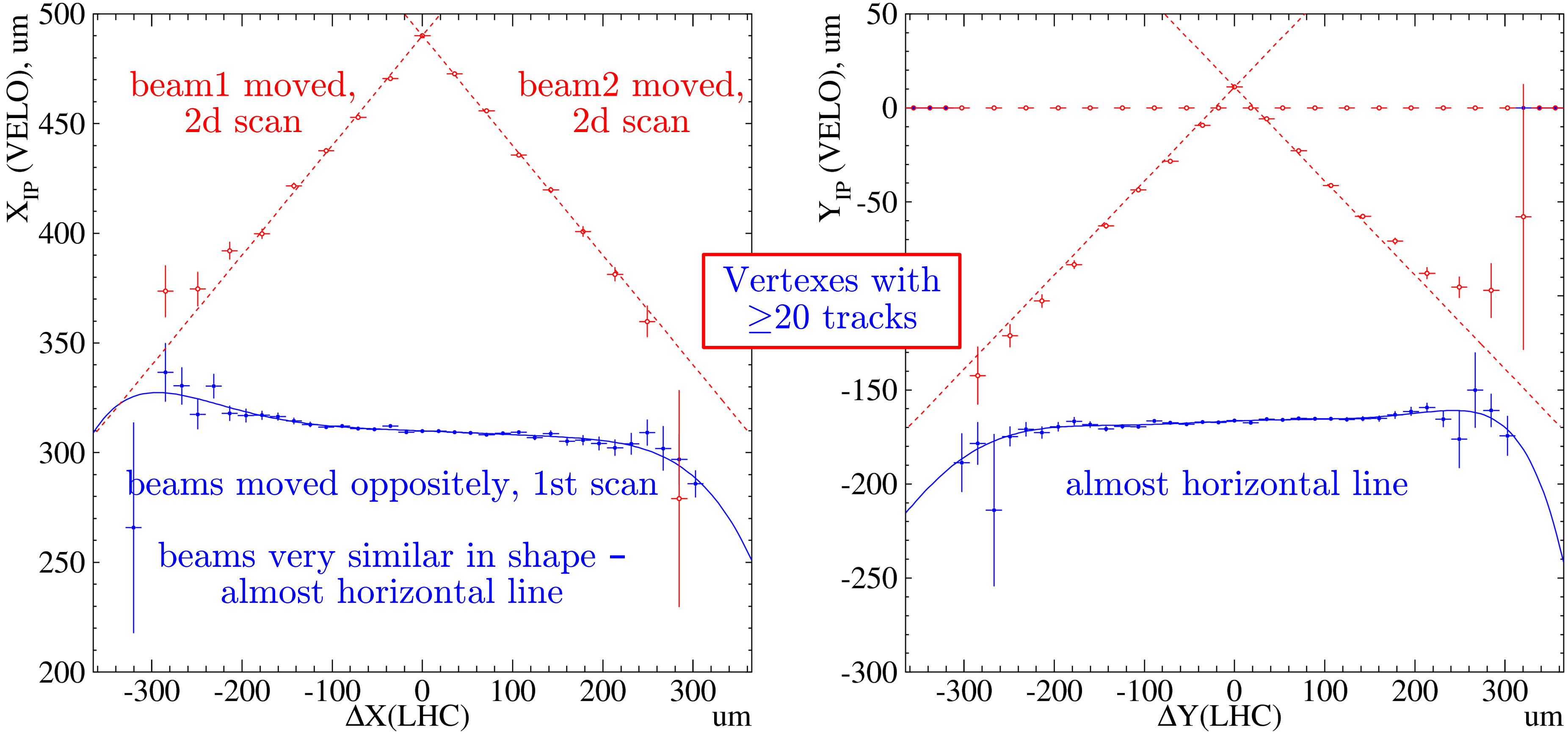
1) crossing angle correction ($\gamma_\perp$) and

2) beam image reconstruction during vdM scan

is ready, to be published soon.

Backup slides

1. *IP movement in first / second scan (October)*



When beams moved oppositely (scan1), luminous region follows narrower beam, *nonlinearity* due to *non-Gaussian* shapes.

IP distance from beams middle point: $\overrightarrow{\Delta r}_{IP}(\Delta X, \Delta Y) = \overrightarrow{R^{I}_{IP}} = \overrightarrow{R^{IIa}_{IP}} - \frac{\overrightarrow{R^{IIa}_{b1}}}{2} = \overrightarrow{R^{IIb}_{IP}} - \frac{\overrightarrow{R^{IIb}_{b2}}}{2}$

$\Rightarrow \quad \frac{\overrightarrow{R^{IIa}_{b1}}}{2} = \overrightarrow{R^{IIa}_{IP}} - \overrightarrow{R^{I}_{IP}} \;, \quad \frac{\overrightarrow{R^{IIb}_{b2}}}{2} = \overrightarrow{R^{IIb}_{IP}} - \overrightarrow{R^{I}_{IP}}$ $\Rightarrow$ *allows to check scale* with VELO

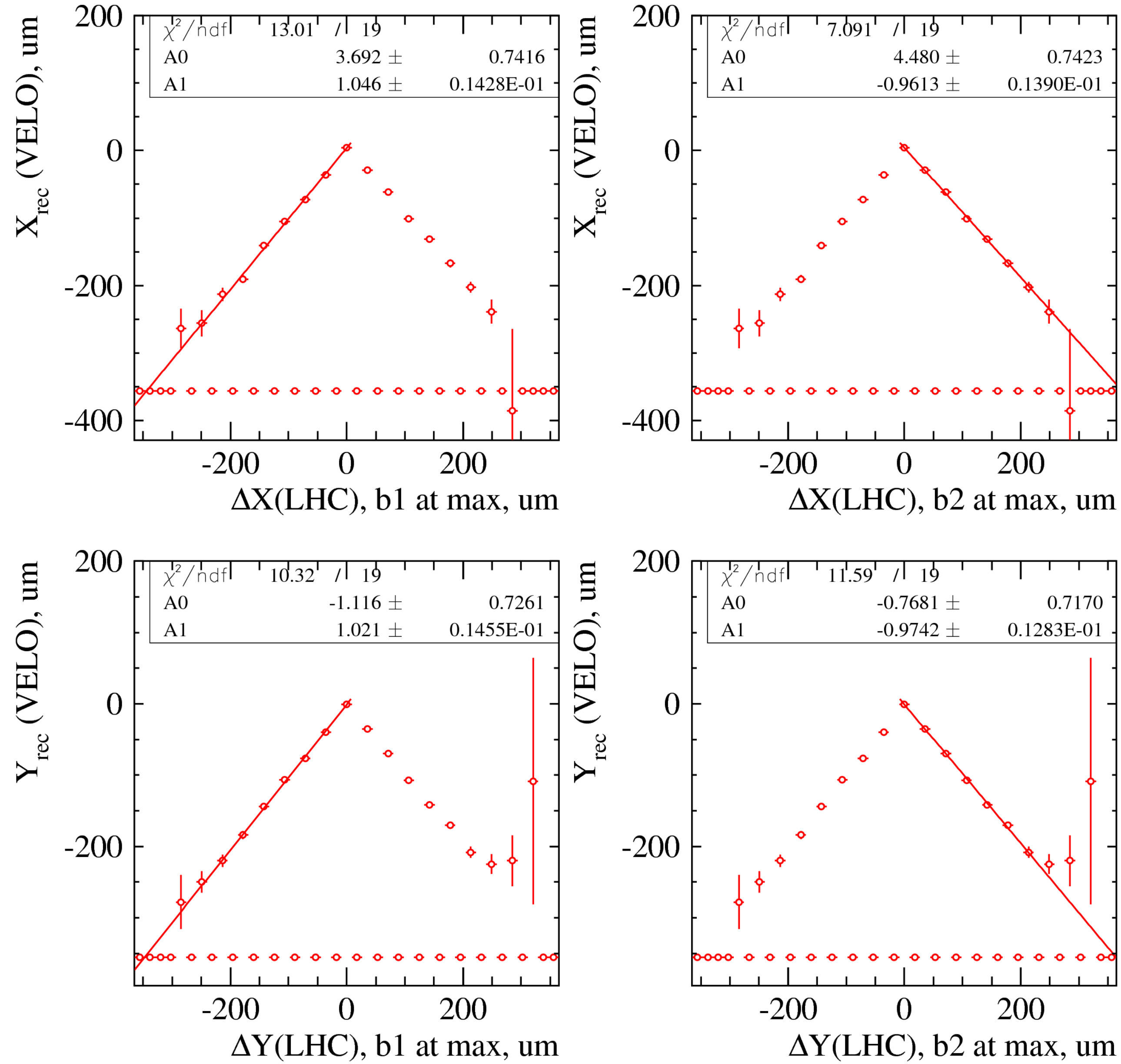
1. Length scale from IP movement during scans (October)

Difference between VELO and LHC scales, in %

	Beam 1	Beam 2
X	4.6±1.4	-3.9±1.4
Y	2.1±1.5	-2.6±1.3

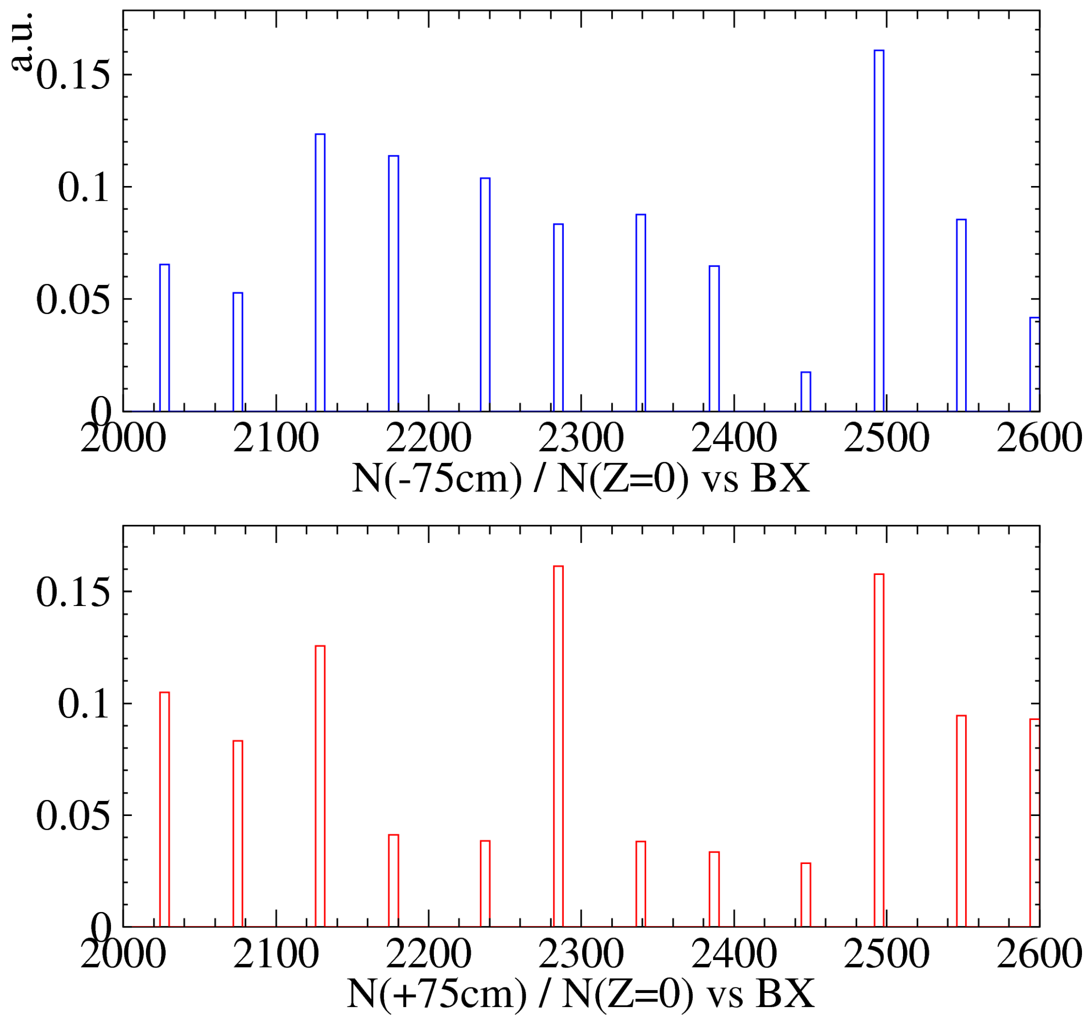
Zero in X moved by 3.7 ± 0.7, 4.5 ± 0.7 um in 2nd scan

Low statistics - lower than in Apr 26 vdM scan, actual rate of HLT 1 kHz L0 CALO was lower than expected



Ghost charge BX distribution (October)

+/- 2 RF population in 12 bunches colliding in LHCb



Fraction of events at +/- 75 cm relative to z=0 cm in different bunches (absolute scale is arbitrary)