Luminosity measurement at LHCb, December 2009 run and future prospects

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on behalf of LHCb luminosity group

seminar at LAL, Orsay, Feb 02, 2010

- Introduction, recent news on future LHC operation from Charmonix workshop, brief summary of LHCb run in December.
- Four methods of absolute luminosity measurement at LHCb.
- Some preliminary results (no final number for December data yet).

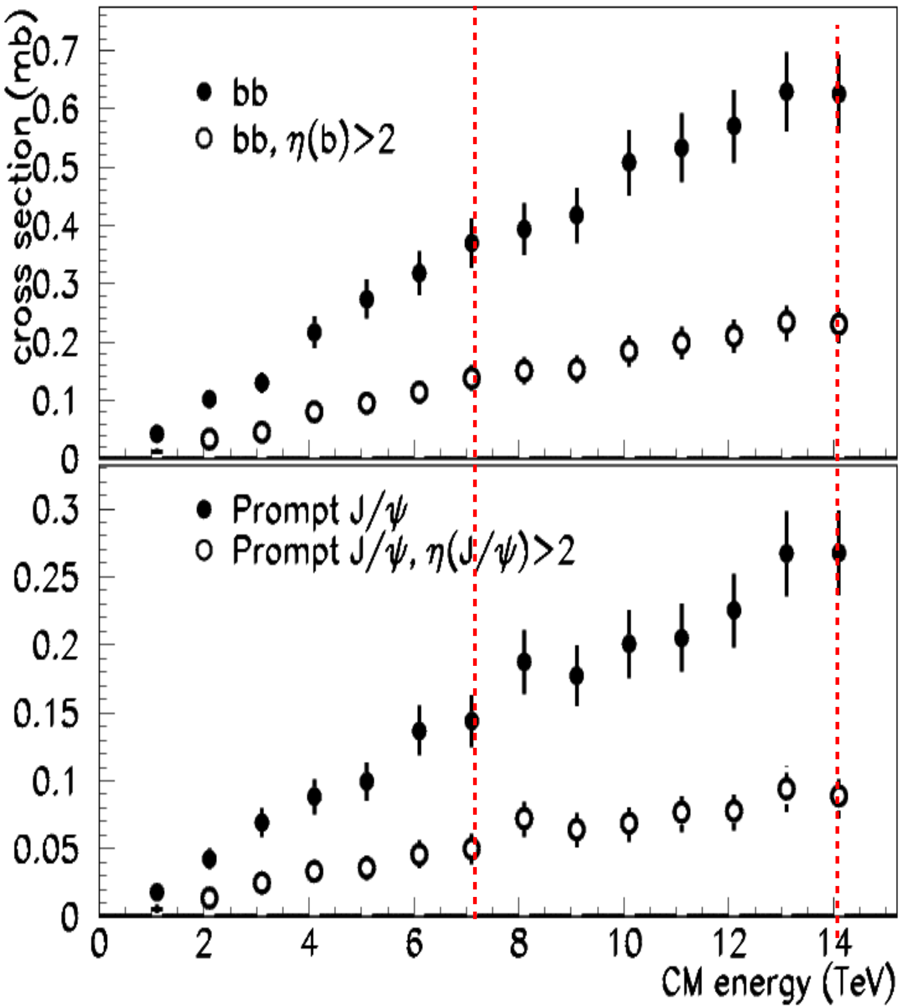
LHC Charmonix workshop, 25.01-29.01

1. Running at 5 TeV per beam is risky.
   Run at 3.5 TeV during 2 years, then upgrade shutdown.

2. Low luminosity in the beginning,
   close to nominal (for LHCb) only in 2011.

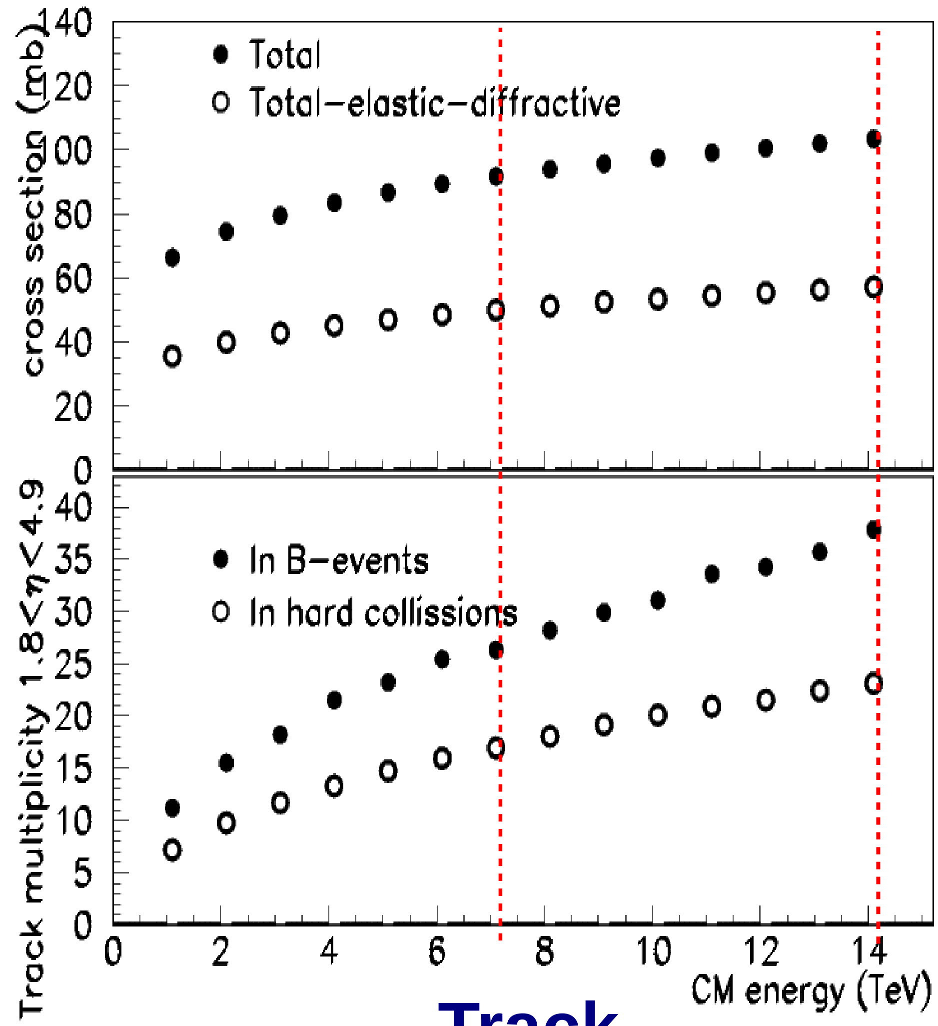
Cross sections versus energy

σ_{bb}



$\sigma_{J/\psi}$

σ_{mbias}



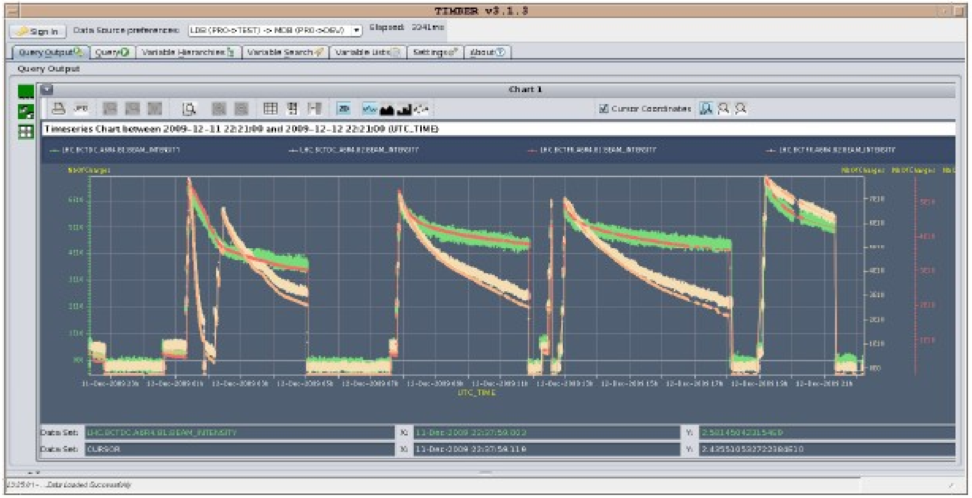
Track multiplicity

November – December LHC start up

Beam commissioning 2009

- 3 days - first collisions at 450 GeV
- 9 days - first ramp to 1.2 TeV
- 16 days - stable beams at 450 GeV
- 18 days - two beams to 1.2 GeV & first collisions

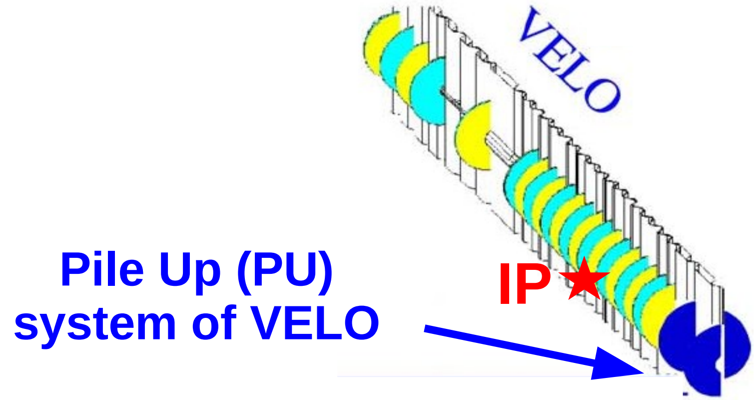
General agreement that this wasn't bad

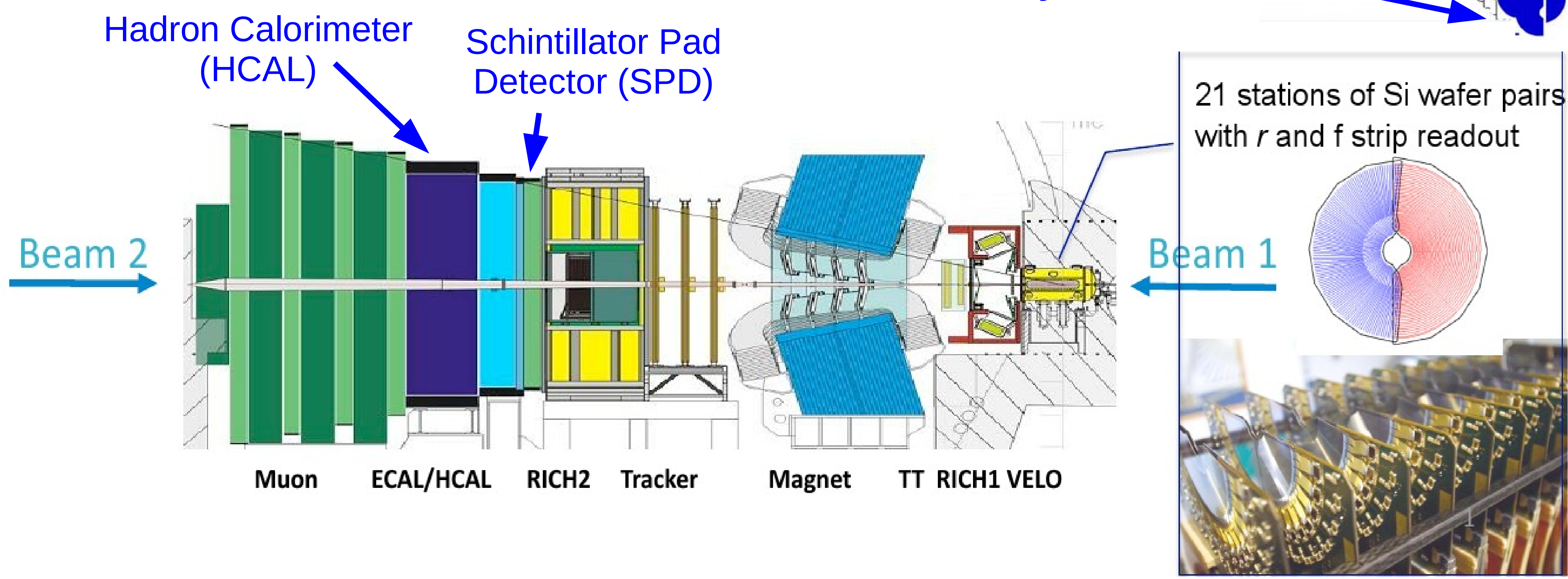


LHCb in December

Detector is fully operational

2009 trigger: loose minimum bias (SPD, HCAL, PU) accepting physics and beam1,2-gas, but discriminating cosmics.



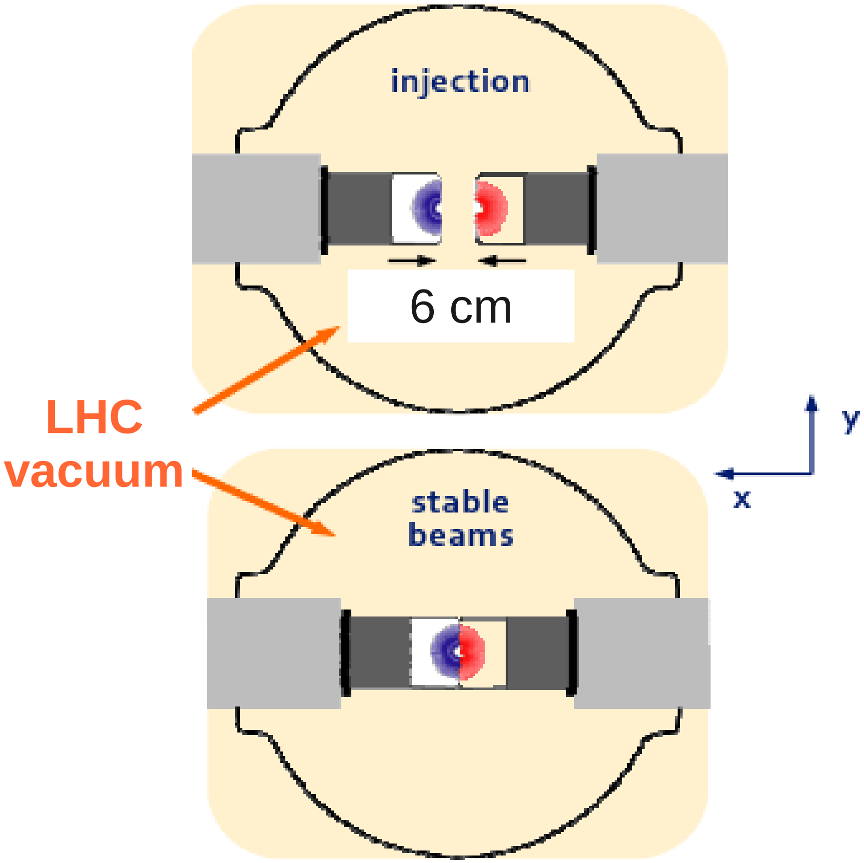


Vertex Locator in December

>2 TeV is required to move VELO fully in

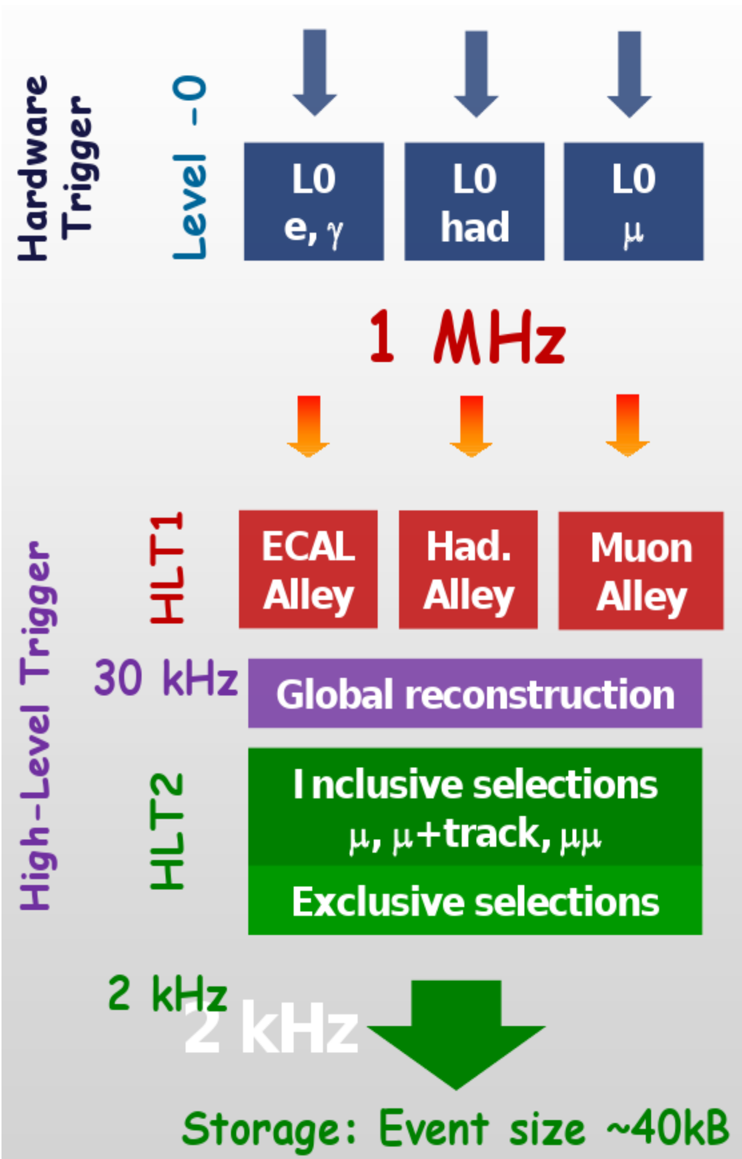
450 GeV: VELO fully powered but only moved to **+-15 mm from beam axis**

1.18 TeV: no Stable Beam → All detectors ON **except VELO**



LHCb trigger

Rates in December: up to 20 Hz
(probability of interaction per bunch crossing: ≈0.001, nominal ≈1
number of colliding bunches: 2, nominal: 2808)



High Level Trigger (C++ application)

Event Filter Farm with up to 1000 16-core nodes

HLT1: Check L0 candidate with more complete info (tracking), adding impact parameter

HLT2: global event reconstruction + selections.

	ε(L0)	ε(HLT)	ε(total)
Hadronic	50%	80%	40%
Electromagnetic	70 %	60%	40%
Muon	90%	80%	70%

Trigger is crucial as σ_{bb} is less than 1% of total inelastic cross section and B decays of interest typically have BR < 10^{-5}

LHCb data in December

Total of (320 ±40) 10^3 pp-collision events beam gas subtracted recorded

All detectors ON and VELO fully powered:

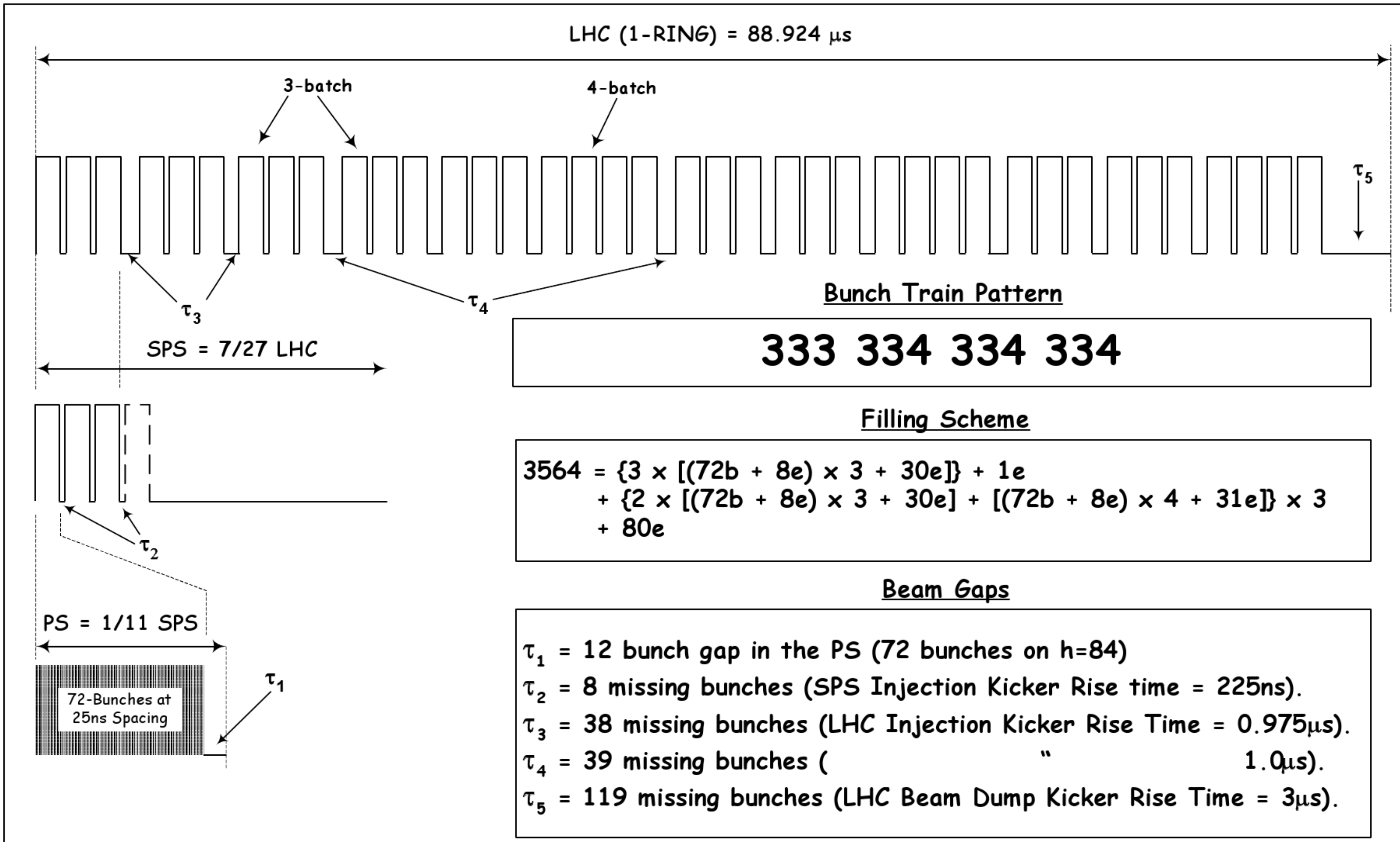
Fill	Date	Number of crossing on disk	Number of beam-beam crossing on disk	Number of beam1-gas crossing on disk	Number of beam2-gas crossing on disk	Estimated Number of pp interaction on disk	pp-interaction /(bb-crossing)	Estimated pp-interaction rate(t=0)[Hz]	L0 rate(t=0) beam1-gas crossing [Hz]	L0 rate (t=0) beam2-gas crossing [Hz]	Recorded luminosity $[\mu b^{-1}]$
901	Dec 6, 09	994	606	336		270	44.6%	0.5	0.4		0.01
902	Dec 6, 09	7 762	5 506	2 023		3 483	63.3%	0.8	0.5		0.09
903	Dec 8, 09	16 220	11 449	4 298		7 151	62.5%	0.8	0.5		0.18
904	Dec 9, 09	3 227	2 155	837		1 318	61.2%	0.5	0.2		0.03
907	Dec 11, 09	75 511	55 478	14 975	48	40 503	73.0%	5.1	1.6	0.01	1.01
907	Dec 11, 09	2 070	1 424	382	30	1 042	73.2%	2.0	0.8	0.06	0.03
910	Dec 12, 09	88 819	62 772	21 562	963	48 397	77.1%	6.6	2.1	0.11	1.21
911	Dec 12, 09	92 776	62 644	25 028	1 301	45 959	73.4%	5.6	2.2	0.14	1.15
912	Dec 12, 09	84 759	69 889	11 837	878	61 998	88.7%	13.1	2.2	0.17	1.55
919	Dec 15, 09	23 670	19 581	3 539	2	16 042	81.9%	22.6	5.0	0.01	0.40
919	Dec 15, 09	63 103	50 412	9 788	597	40 624	80.6%	20.8	4.8	0.28	1.02

After 1st MiniScan

After 2nd MiniScan

Nominal 25 nsec bunch filling scheme

During beam dump kicker rise time there should be no filled bunches → groups of empty bunches for PS, SPS, LHC



Nominal 25 nsec bunch filling scheme

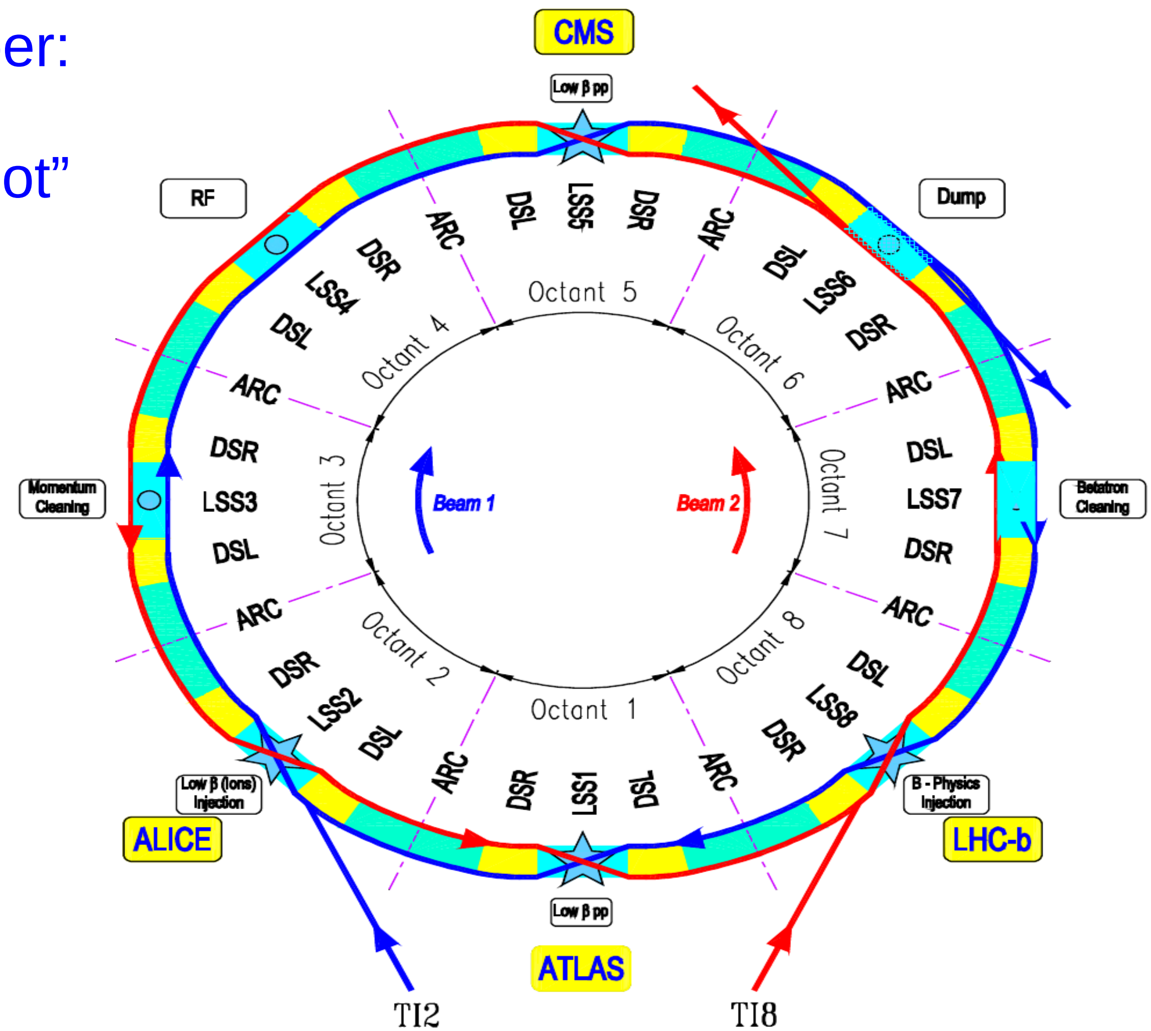
Since ATLAS and CMS are opposite to each other, the same pairs of bunches collide there.
LHCb and ALICE see collisions of different pairs.

Bunch filling scheme in December:

a) **4+4** bunches in total (plus “pilot” bunches),
2 colliding pairs in LHCb (and in ALICE) → max data sample

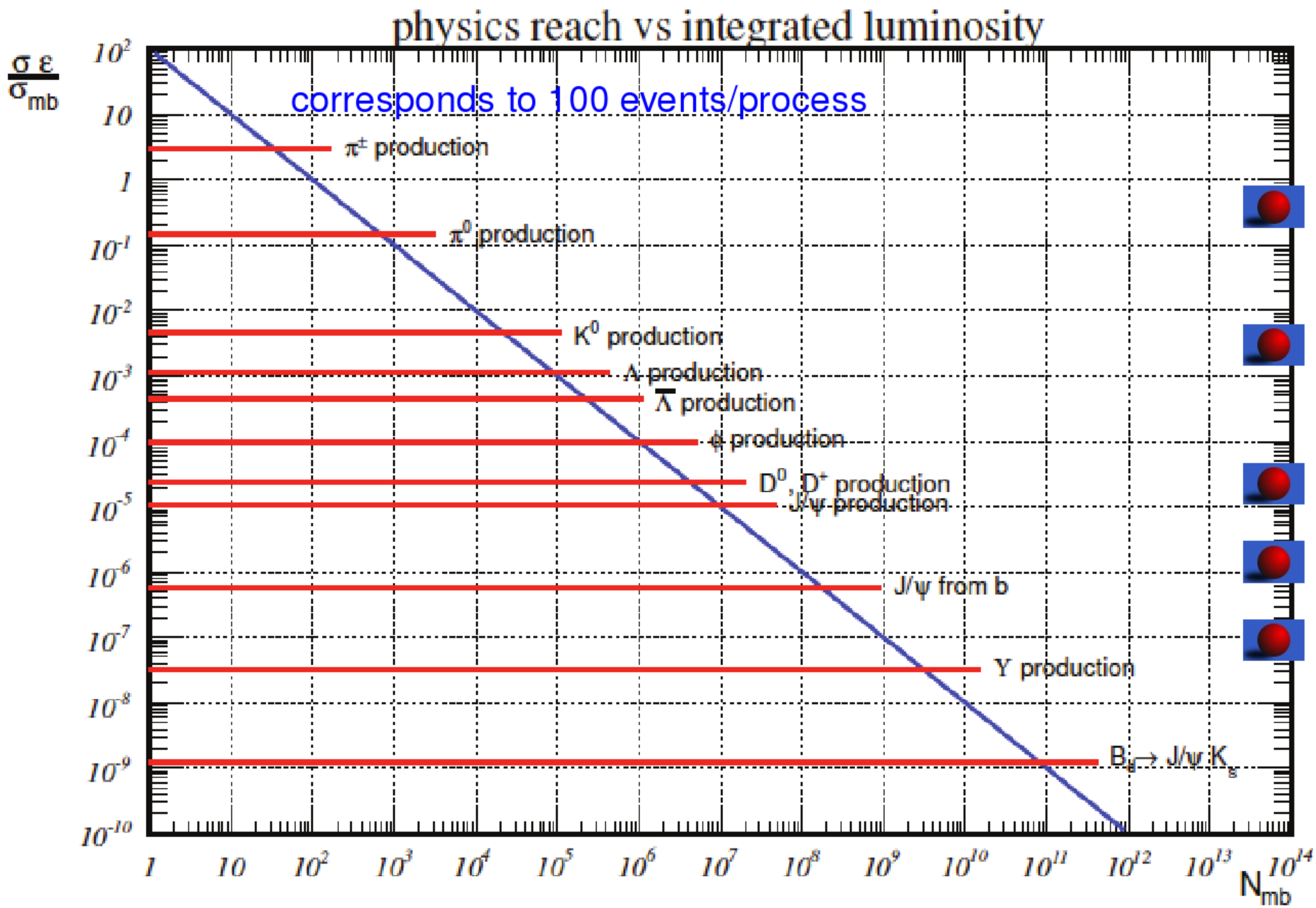
b) **8+8** in total,
4 colliding pairs.

Thus, for 4+4 case LHCb saw
two beam-beam crossings,
two beam-empty and
two empty-beam.



Beam intensities were lower than nominal by ≈1/10.

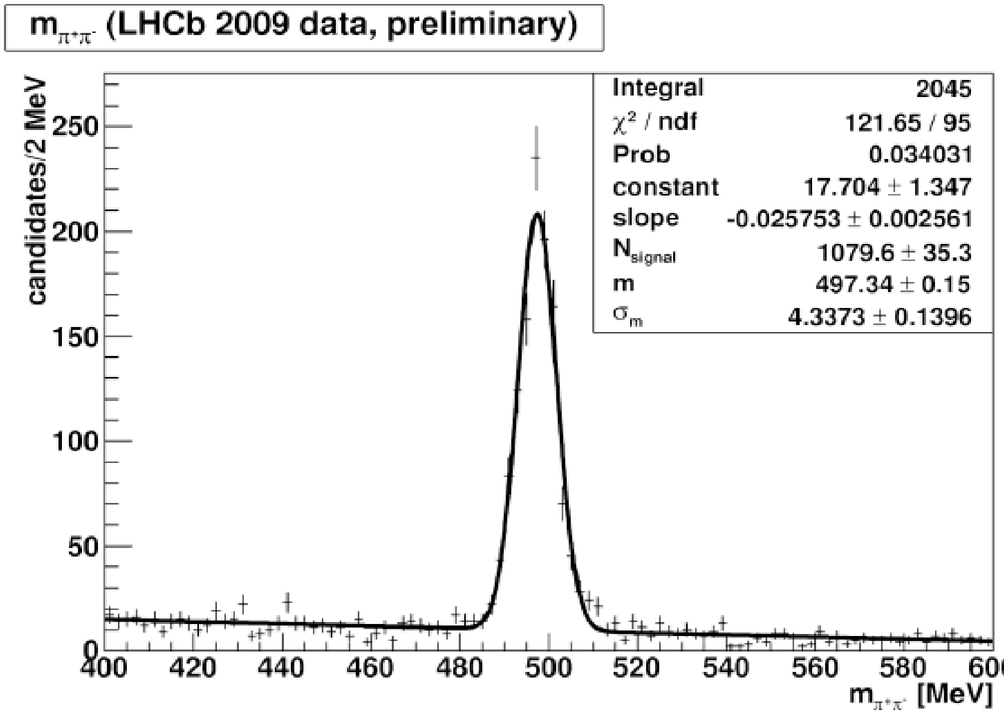
Required LHCb statistics for various measurements

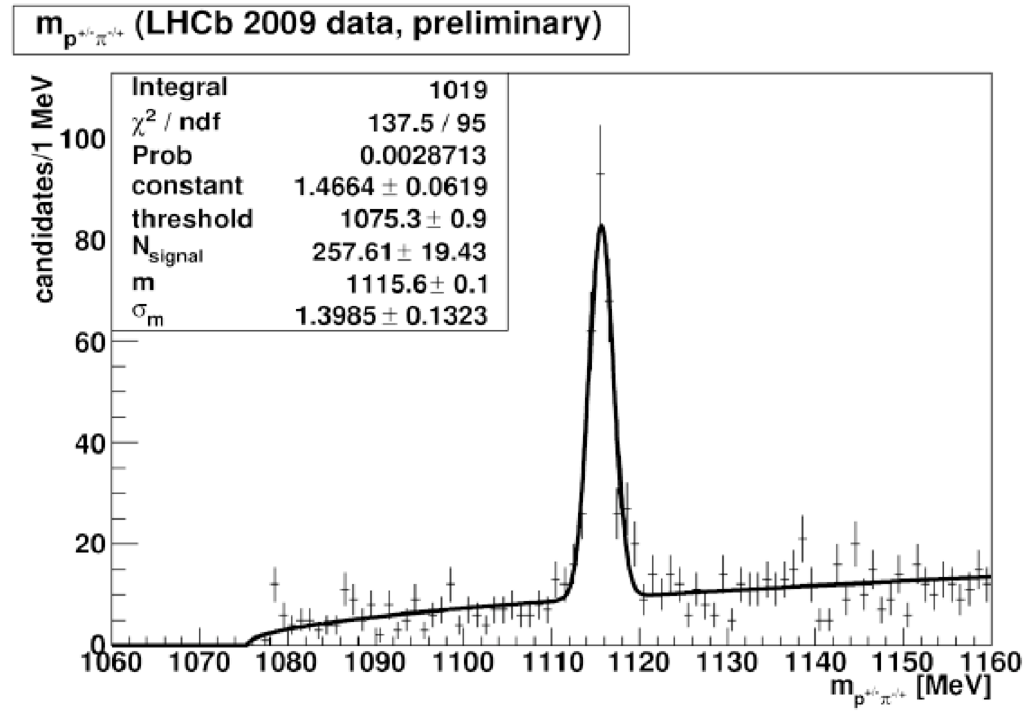


- Inclusive distributions
- Strangeness production
- Charm signals
- J/ψ production
- ....

V0 signals

Using full tracking power, including VELO





$M(K_S) = 497.3 \pm 0.2\ MeV/c^2$
$\sigma = 4.3 \pm 0.1\ MeV/c^2$

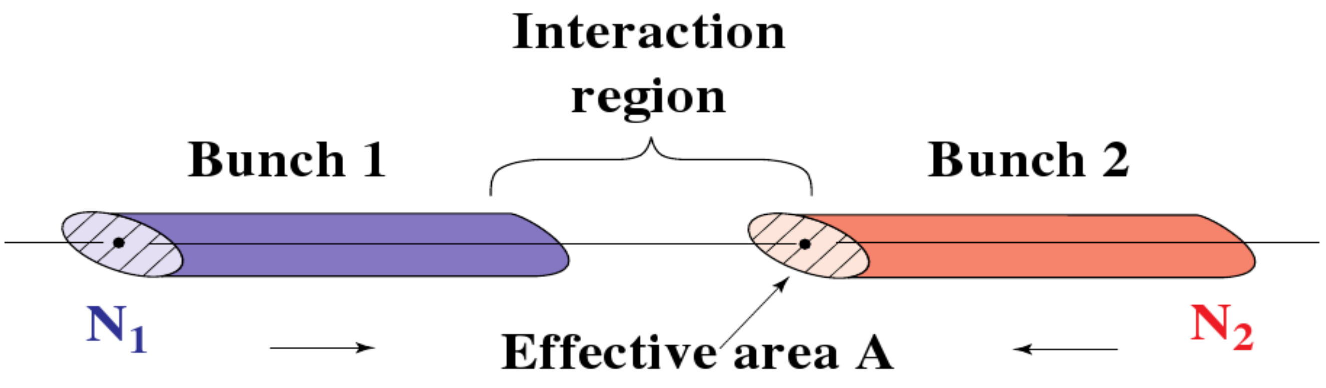
$M(K_S^{PDG}) = 497.7\ MeV/c^2$

$M(\Lambda) = 1115.6 \pm 0.1\ MeV/c^2$
$\sigma = 1.4 \pm 0.1\ MeV/c^2$

$M(\Lambda^{PDG}) = 1115.7\ MeV/c^2$

Accuracy will be further improved after complete alignment

Luminosity



$$\mathcal{L} = \frac{N_1 \, N_2 \, f}{A_{\text{eff}}}$$

A_{eff} is the effective transverse area.

If $g_{1,2}$ (x,y) are particle densities in beam1,2:

$$\frac{1}{A_{\text{eff}}} = \int g_1(x,y)\, g_2(x,y)\, dx\, dy$$

for beams with Gaussian shapes: $\mathcal{L} = \frac{N_1 \, N_2 \, f}{4\pi\sigma_x\sigma_y}$

Luminosity

“Direct” measurements:

1) Revolution frequency ***f*** and number of colliding bunches are known.
2) Number of protons per bunch should be monitored by LHC with ultimate precision ≈1%

3) Overlap integral:

a) via beam profile visible in **beam-gas interactions,** 3-5% precision

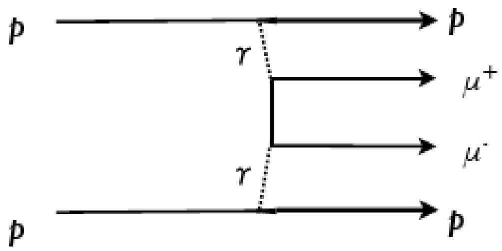
b) **van der Meer scan,** when beams are collided not head-on but are shifted in transverse direction (X and/or Y), ≈10% accuracy.

Luminosity

One can also calibrate the luminosity of the data sample using processes with known cross section:

c) **pp → Z^0 X → $\mu^+\mu^-$ X,** high statistics, depends on internal proton structure (parton distribution functions, PDFs), not precisely known → ≈5% accuracy;

d) **Two photon reaction pp → $\mu^+\mu^-$ pp,** proton acts as elementary particle, calculable in QED, but rare process → requires statistics, precision 1-2%.



Relative luminosity, monitoring

To continuously monitor luminosity, LHCb uses special, so called nano-events.

They are collected with random trigger to avoid any bias.

In time windows opened by this trigger, the quantities proportional to luminosity (“lumi counters”) are monitored, like Scintillator Pad Detector (SPD) and Pile Up (PU in VELO) multiplicities, transverse energy deposition in calorimeter, number of tracks and vertexes in VELO, number of tracks in TT stations in front of the magnet.

In nano-events only luminosity information is kept, event size is ≈130 bytes (to be compared with ≈35 kB for physics).

The DAQ load is <1% everywhere even at 1kHz (trigger rate, HLT CPU time, data transmission, data storage).

Nano-events are stored as a separate data stream.

Relative luminosity, monitoring

Continuous monitoring is important **online,** and also **offline:**
a) to cross check all other methods and
b) to "extrapolate" measurements available in limited time periods to the whole data sample (e.g. for van der Meer scans).

Since there are many Lumi counters, they can be cross-calibrated: if e.g. SPD thresholds change, SPD multiplicity can be recalibrated using PU multiplicity etc.

Two basic methods of luminosity monitoring:
1) calculate **mean value** of lumi counter (since, e.g. average SPD multiplicity is proportional to instantaneous luminosity)

2) calculate the fraction of "empty" events N_0/N and take **$-\ln(N_0/N)$.** This value is proportional to luminosity, since probability to have zero interactions changes with luminosity as (p_0)**(lumi/lumi0). E.g. fraction of empty events squares when luminosity doubles.

First method relies on lumi counter linearity, second – on proper definition of "empty" event.

Luminosity backgrounds

In both methods one should subtract backgrounds.

They can be determined from
beam-empty, empty-beam bunch crossings (beam related backgrounds)
and empty-empty (noise etc.)

E.g. in the method of mean:

<bb> - <be> - <eb> + <ee>

(empty-empty is contained in be, eb, so it is subtracted twice and explicitely added once).

DAQ system is able to collect random triggers separately from bb, be, eb, ee bunch crossings and with different probabilities. Four probabilities are selected to optimize precision of **<bb> - <be> - <eb> + <ee>** (<ee> has the smallest probability).

Fit luminosity counter spectrum

More sophisticated approach, better than method of "mean" or -ln(N_0/N), as it uses all available information.

If we know SPD spectrum in events with one interaction, how to calculate it for two interactions? Or, if we know spectra separately for signal and background, what will be their "sum"?

It is not the sum of the spectra, since in more dense events the spectrum (and its mean) is shifted to the right.

Adding "horizontal" variables

Let's suppose that **spectrum** of some variable (e.g. SPD multiplicity) **receives contributions from** beam-beam interactions ("**signal**") and from some **background**. Separately they produce spectra $\mathbf{P_1}$ and $\mathbf{P_2}$. What will be their ***sum***?

Note: if there are n_1 signal and n_2 background hits in event, it is plotted in bin n_1+n_2. We sum abscissas (horizontal variables). If they were vertical, we would simply add two spectra P_1+P_2. But here this is wrong!

Let's consider one bin of P_1, or δ-function $P_1(x_0)\delta(x-x_0)$. It will be smeared by P_2 shape placed at x_0. I.e.

$$\delta(x-x_0) \quad \rightarrow \quad P_2(x-x_0)$$

$$P_1(x) = \int P_1(x_0)\delta(x-x_0)dx_0 \quad \rightarrow \quad P_{12}(x) = \int P_1(x_0)P_2(x-x_0)dx_0$$ ← ***convolution***

It is convinient to use **Fourier transforms**, where convolution is substituted by **multiplication**:

$$P_{12}^F = P_1^F \cdot P_2^F$$

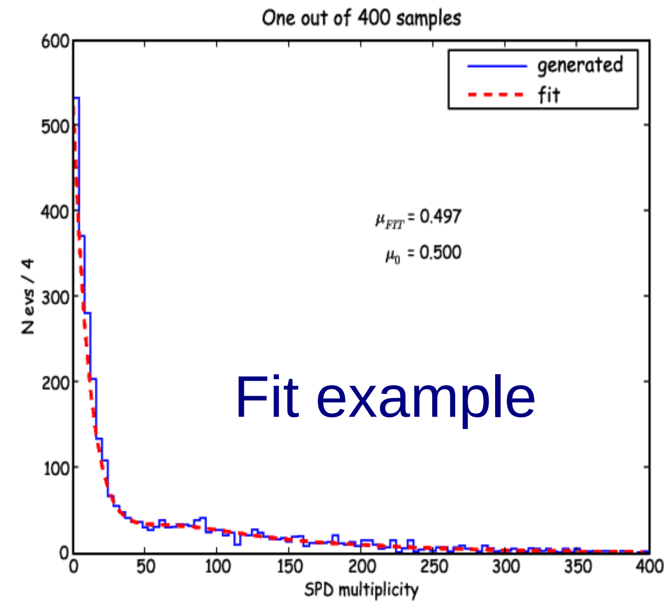
The same convolution law works when one event contains two interactions: if one interaction produces detector response I, two will give $I^F * I^F = (I^F)^2$.

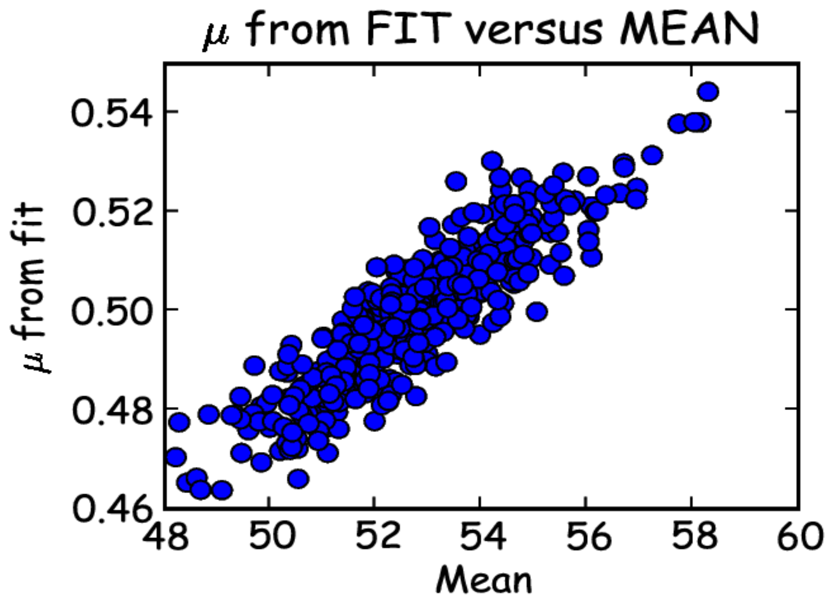
For Poisson distribution:

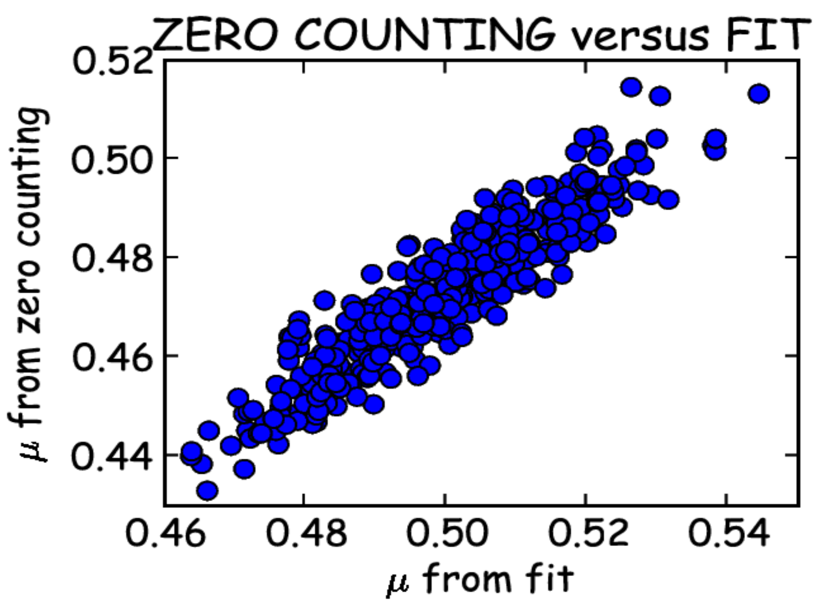
$$P^F = \sum_{n=0}^{\infty} \frac{e^{-\mu}\mu^n}{n!}(I^F)^n = \boxed{\exp\{\mu(I^F-1)\}}$$

Backgrounds can be estimated from be, eb, ee events: $P^F = P_{bb}{}^F\, P_{ee}{}^F / P_{be}{}^F / P_{eb}{}^F$

Comparion of fit and mean/logZero methods







Results are strongly correlated, fit gives ≈10% more accurate values

December data

Statistics is not enough for luminosity measurement with physics channels.

Plan:

1. ***"Monitoring" with lumi counters.***
2. ***"Direct" methods: van der Meer scan and beam-gas events***

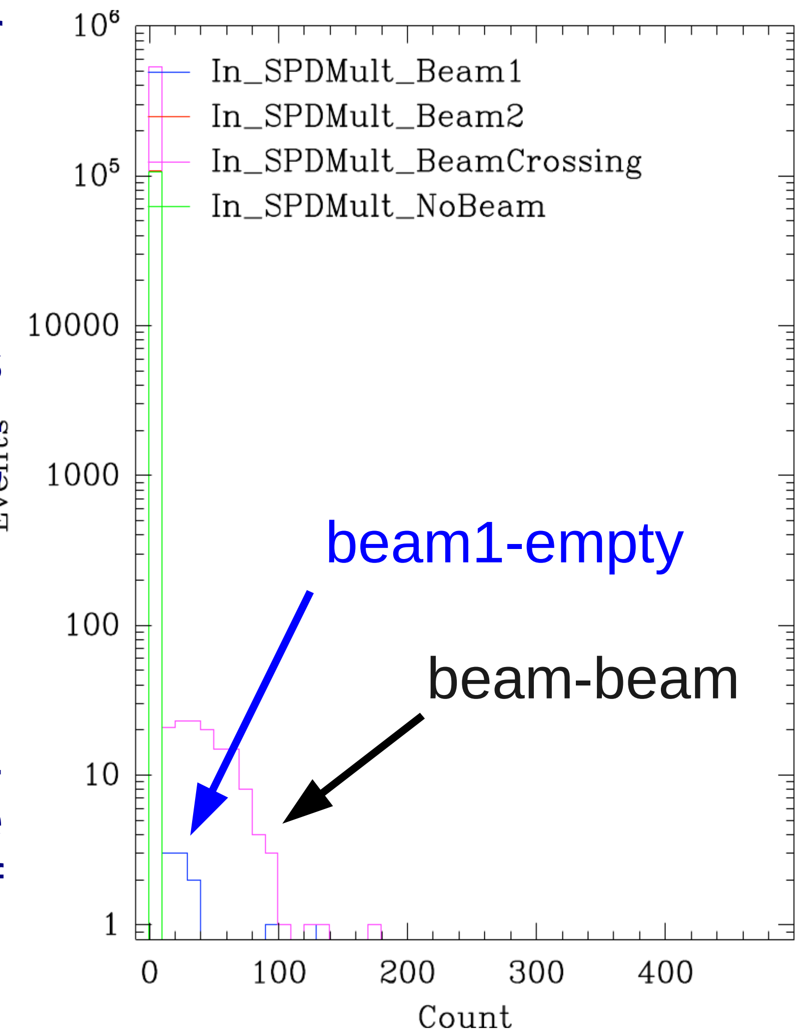
Luminosity counters in December

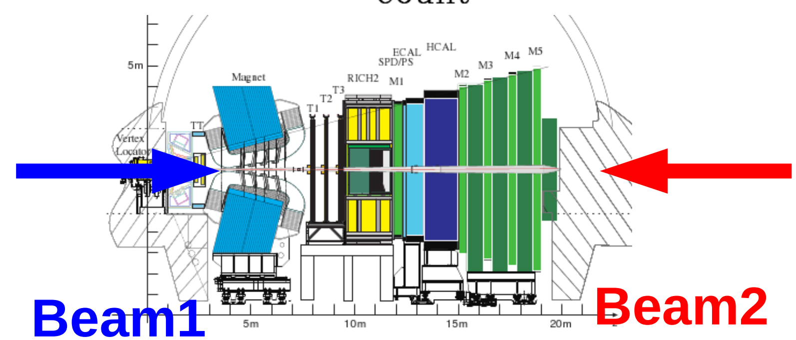
Due to **low probability of interaction** per bunch crossing (1e-4 .. 1e-3 in December), lumi counter spectra collected with random trigger are **pedestal dominated.**

We plan to use min. bias triggered physics events instead (bias is small due to loose trigger requirements in December), to “glue” different data samples.

Background particles produced by beam1 arrive at the same time as if they were created in beam-beam IP (regardless of Z of production).

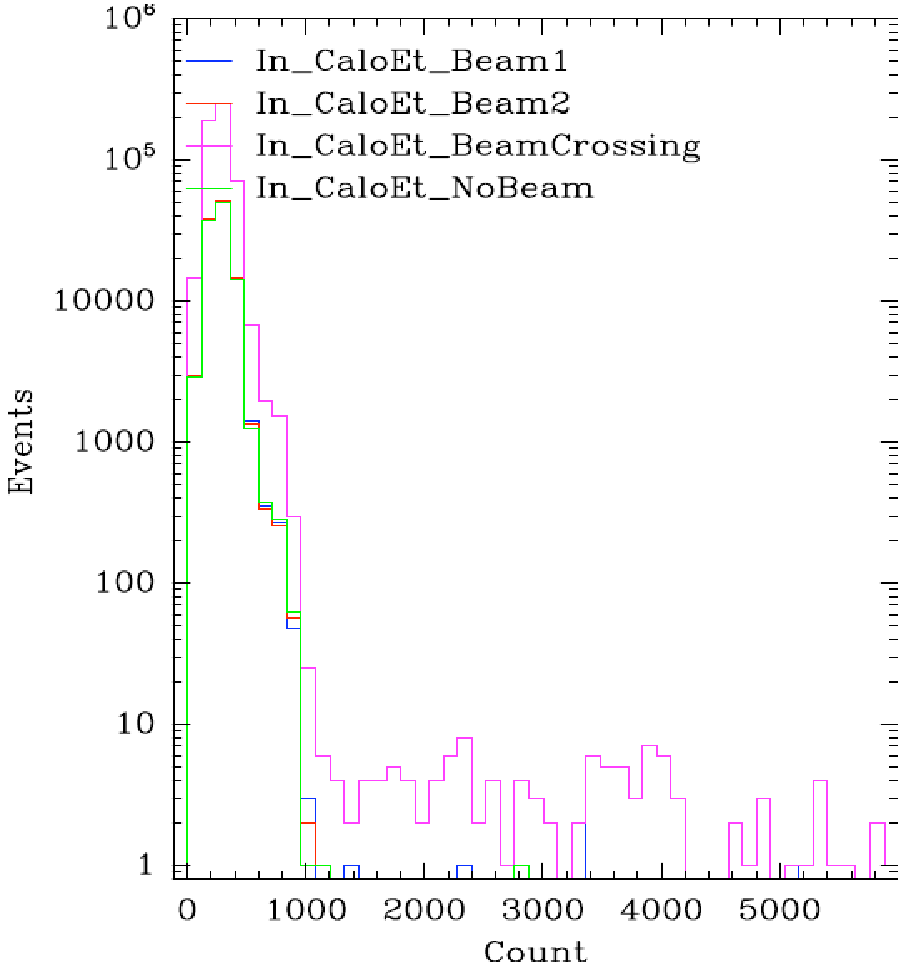
Timing of beam2 background is “wrong”, interactions in SPD, ECAL occur earlier than random trigger is fired in empty-beam event. Therefore there is beam1 above pedestal, and there is no beam2.



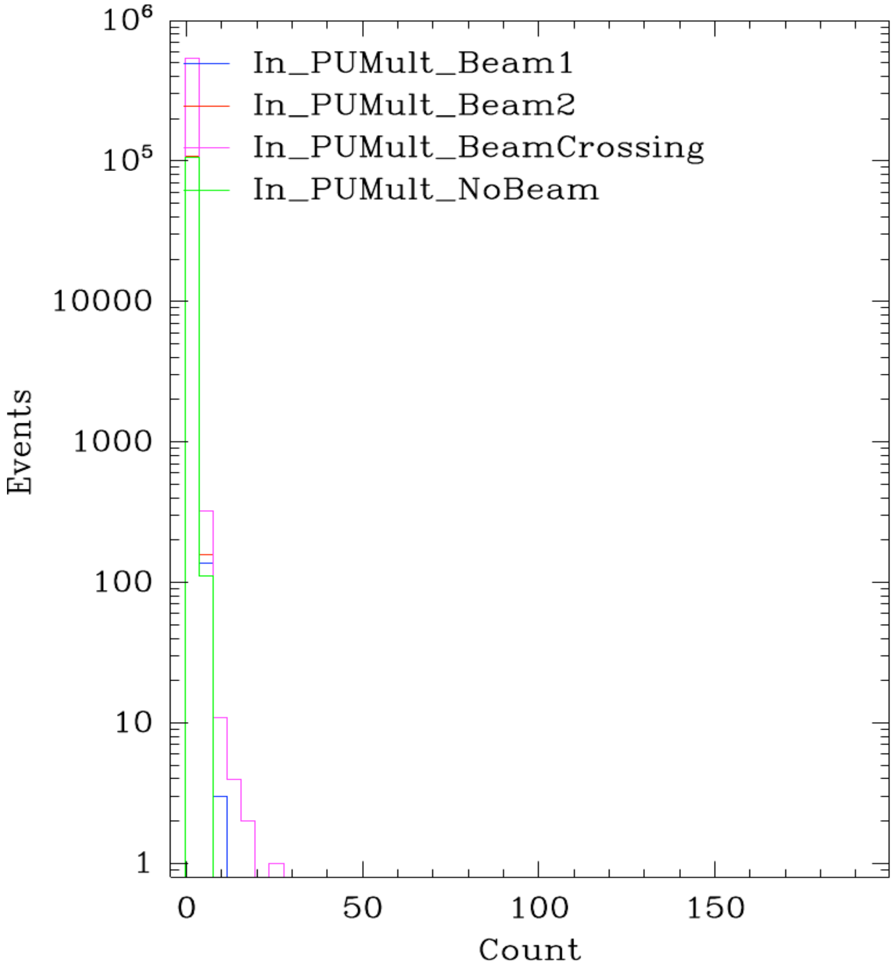


Luminosity counters in December

Transverse energy deposition in ECAL



Pile Up (in VELO) multiplicity



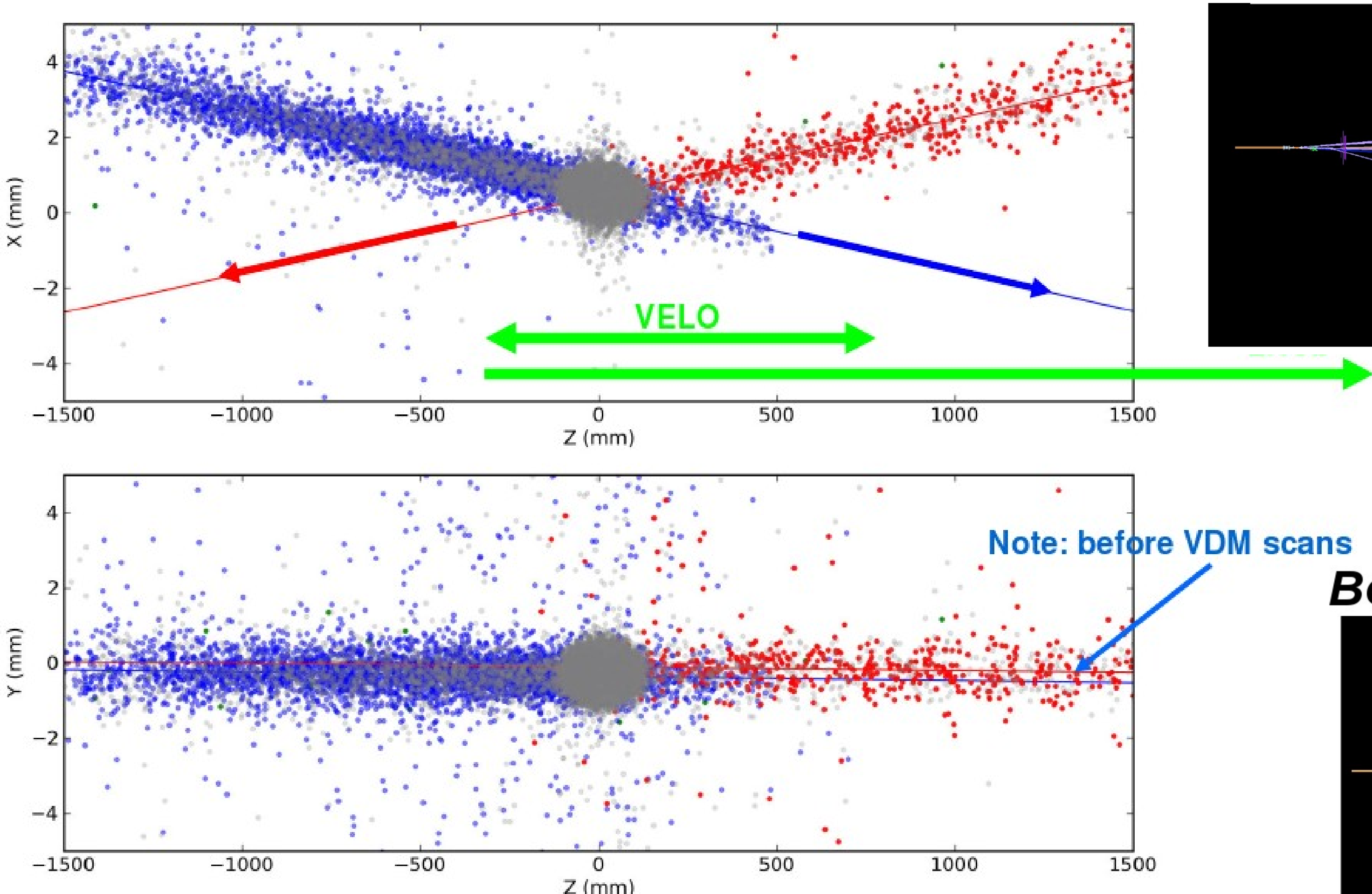
Beam-gas events in December

Proved to be very helpful

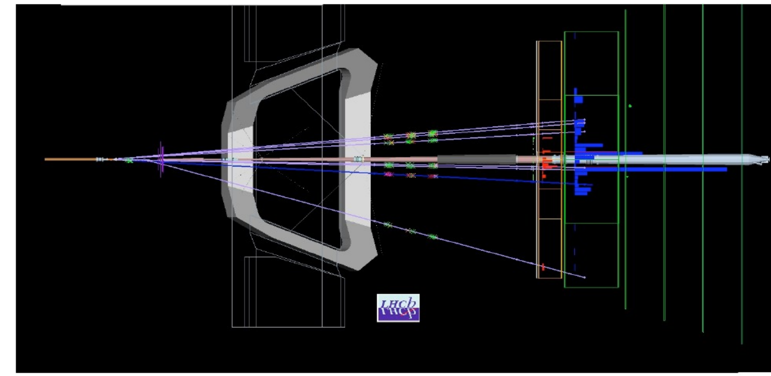
Beam1 – gas was taken with physics min. bias trigger (particles from beam1-gas arrive at SPD, HCAL at the same time as from beam-beam)

Beam2 – gas was triggered by PU (commissioned in December)

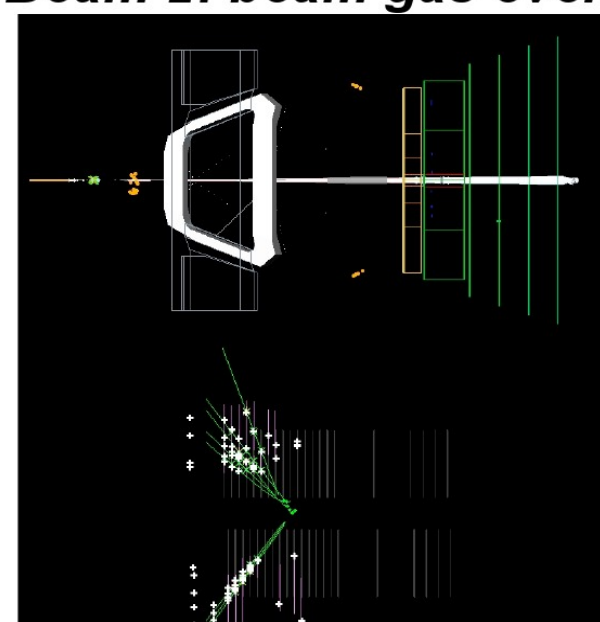
Beam-gas events in December



Beam 1: beam gas event

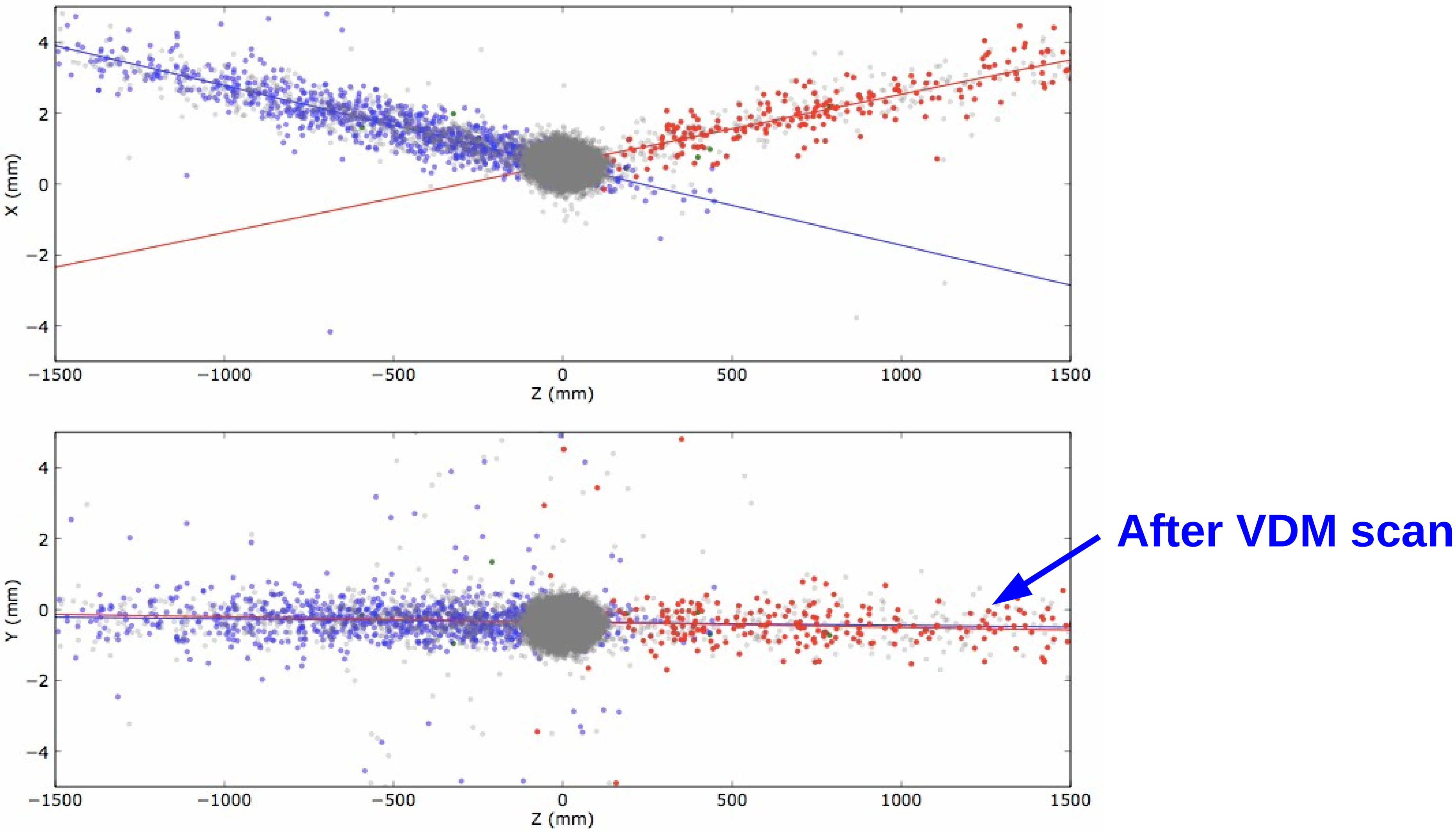


Beam 2: beam gas event



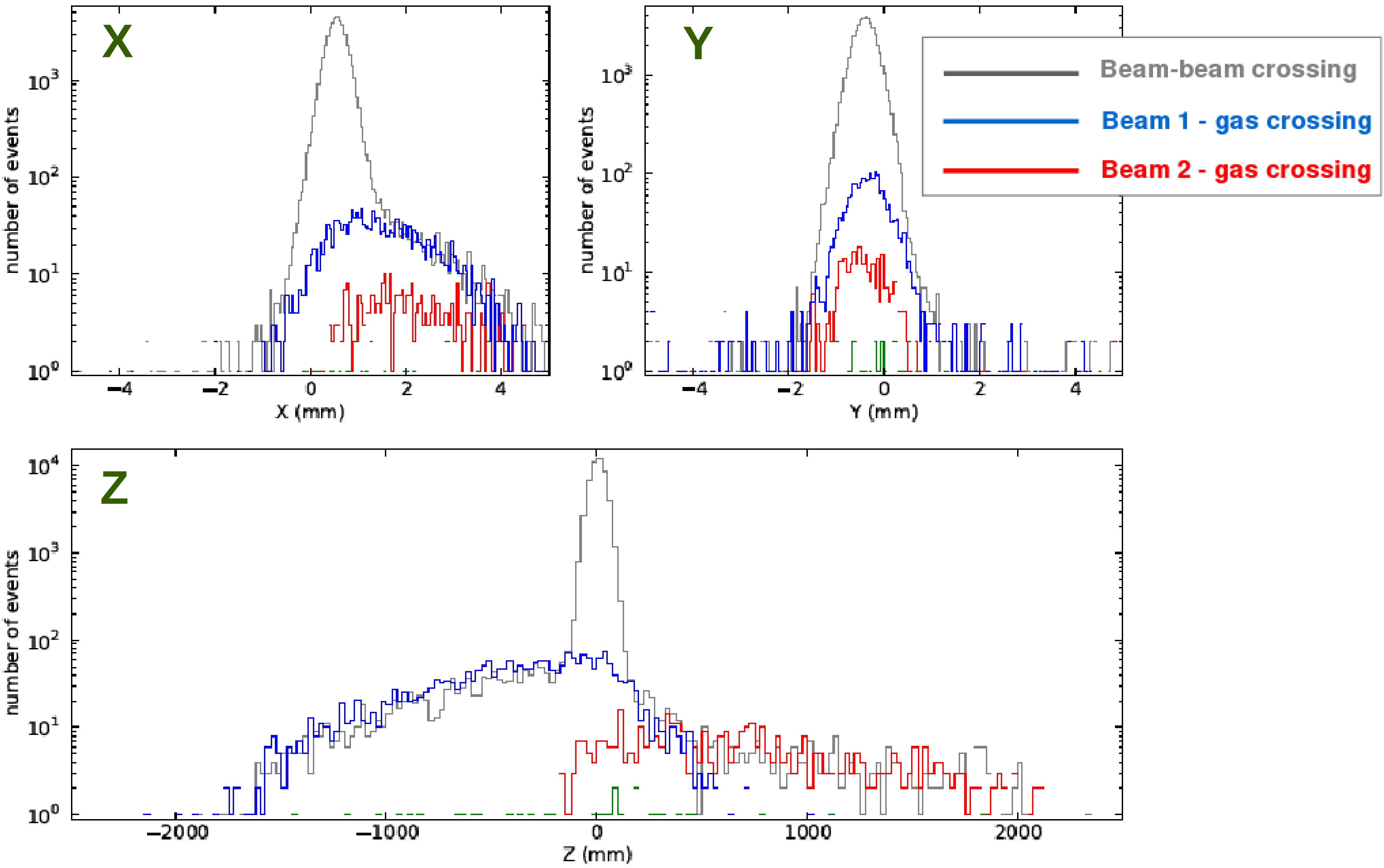
Crossing angle	X	Y
Beam1:	-2.099 +/- 0.020	-0.094 +/- 0.020
Beam2:	+2.041+/- 0.040	-0.070 +/- 0.040

Beam-gas events in December

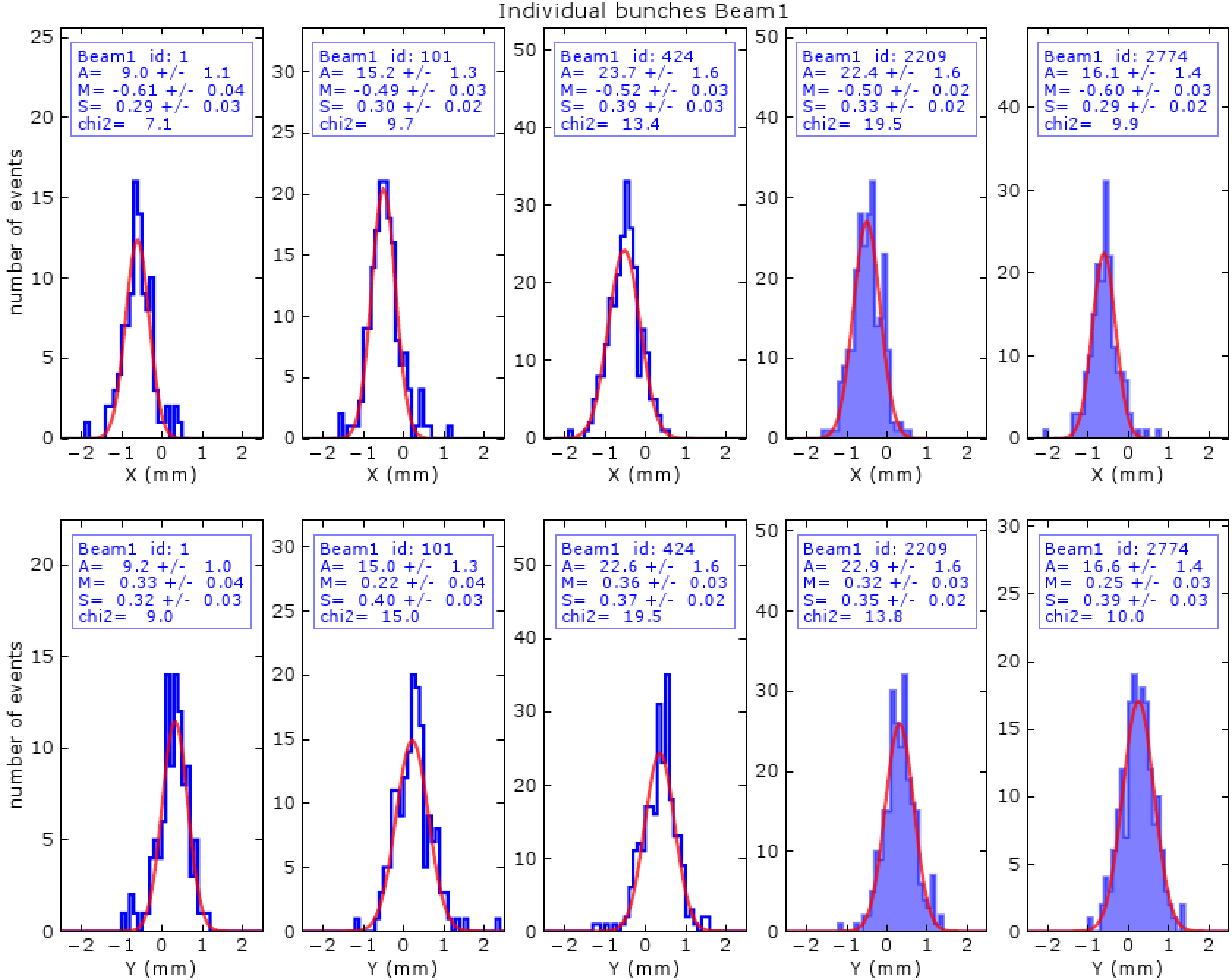


Van der Meer scan was performed with L0 rate as a luminosity counter (with background subtraction). Statistics of random triggers with normal lumi counters was not sufficient due to low rate of collisions.

Distribution of primary vertexes



Individual bunches



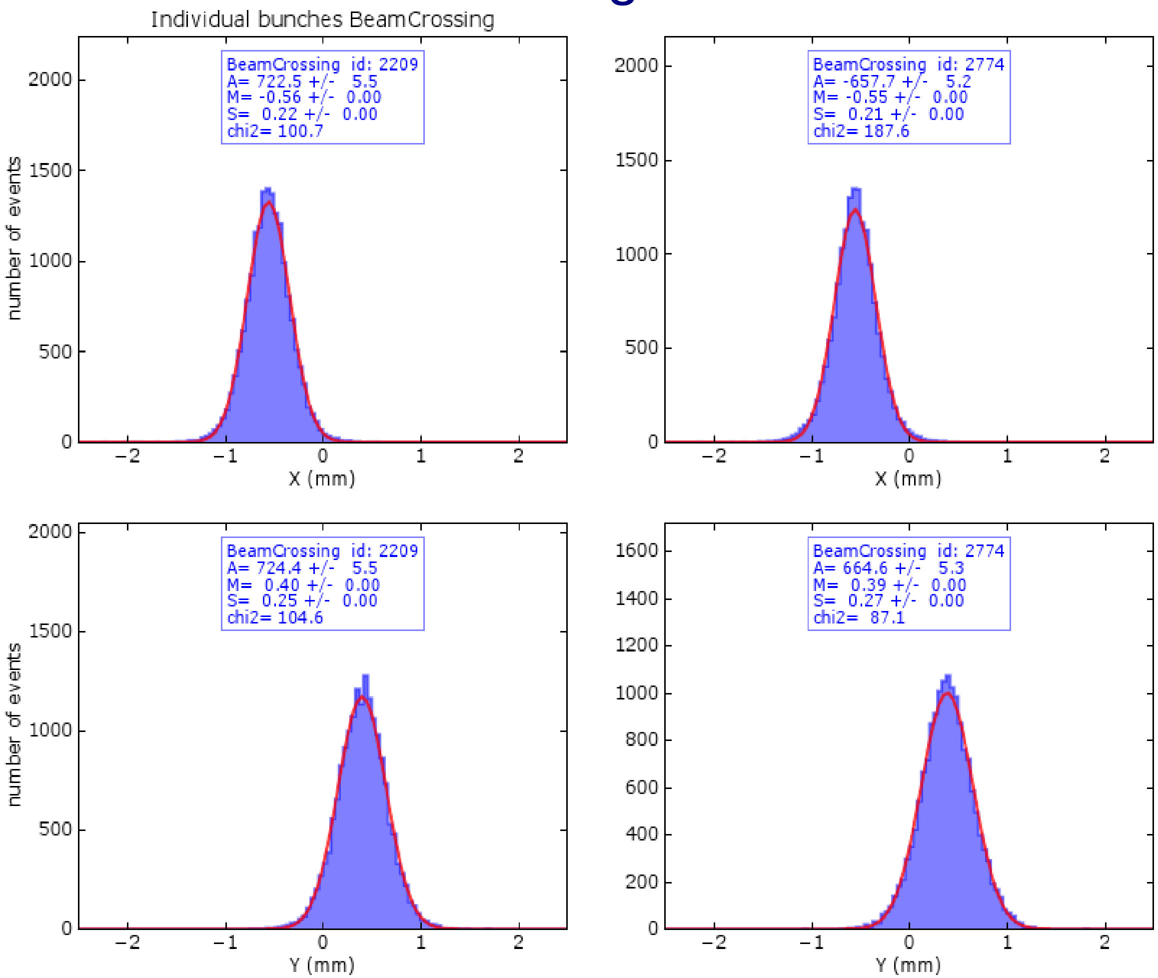
X

Y

Colliding bunches

Beam-beam luminous region

Two colliding bunches



X

Y

$$\mu_{\rm BB} = \frac{\mu_1 \sigma_2^2 + \mu_2 \sigma_1^2}{\sigma_1^2 + \sigma_2^2}$$

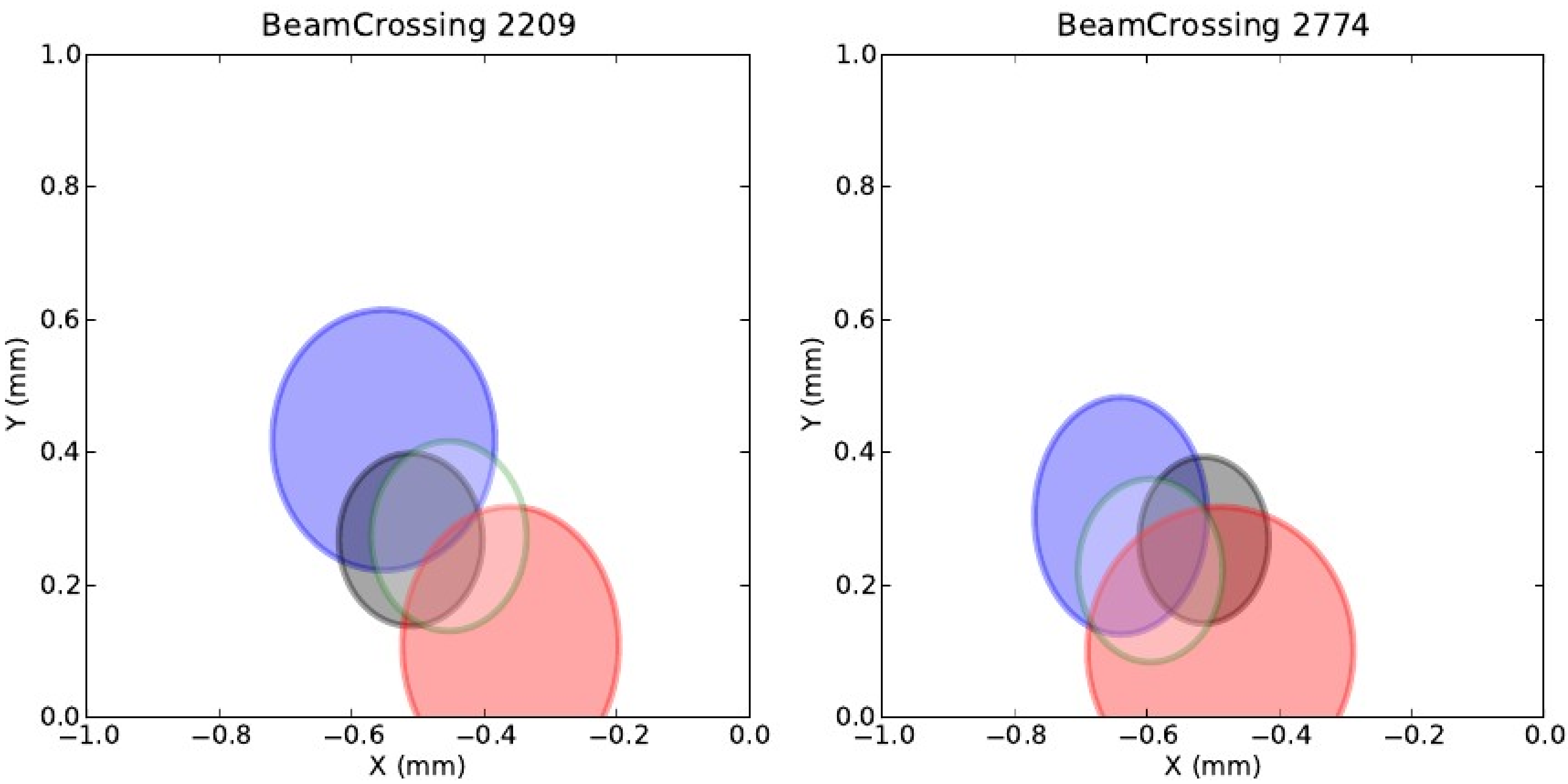
Without VELO resolutions:

$$\sigma_{\rm BB}^2 = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2}$$

One sigma beam spots

Before VDM scan

Blue: beam1, red: beam2, dark: measured beam-beam,
light: predicted without VELO resolutions:

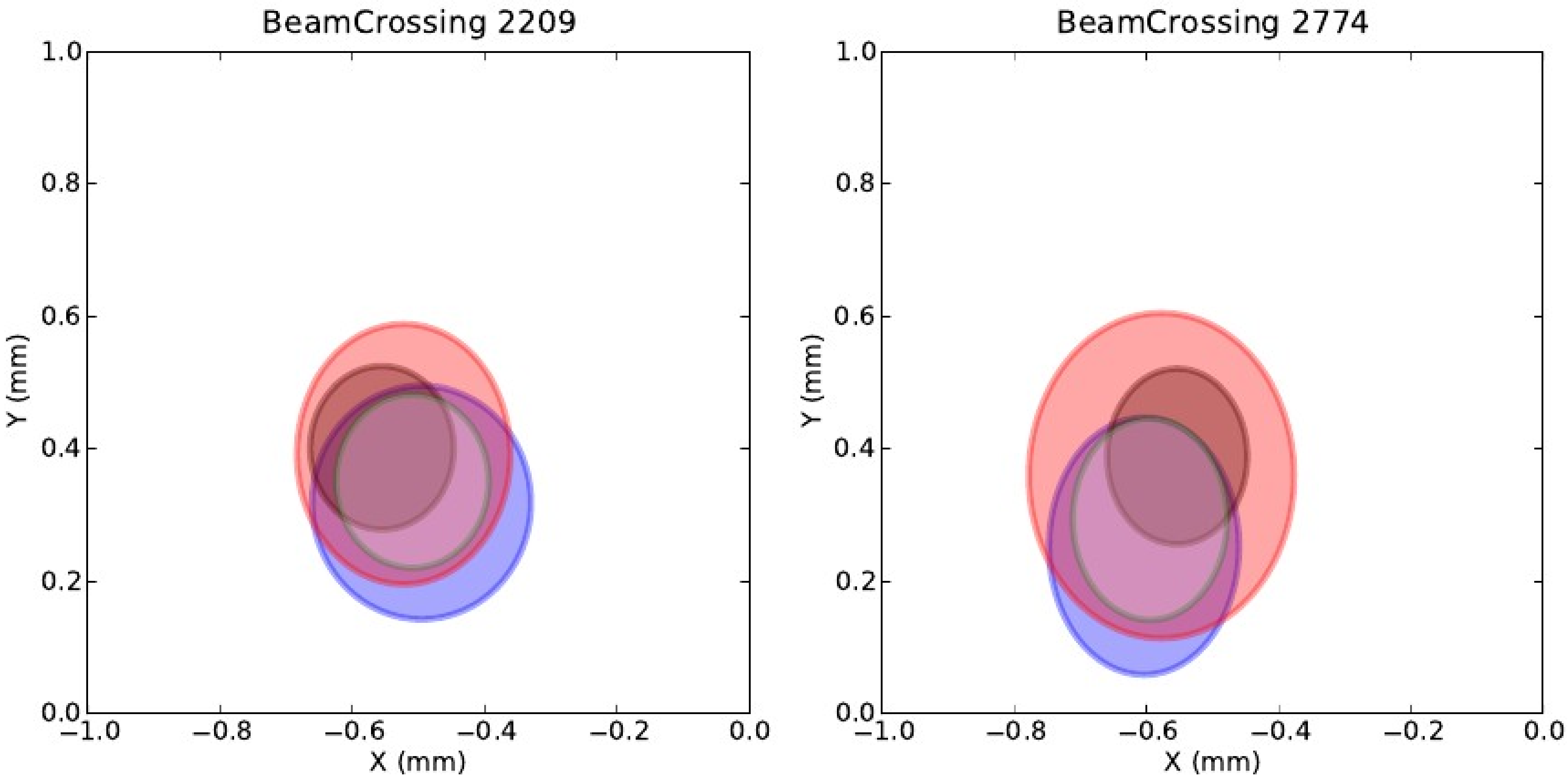


Predicted larger than observed: resolution?

One sigma beam spots

After VDM scan

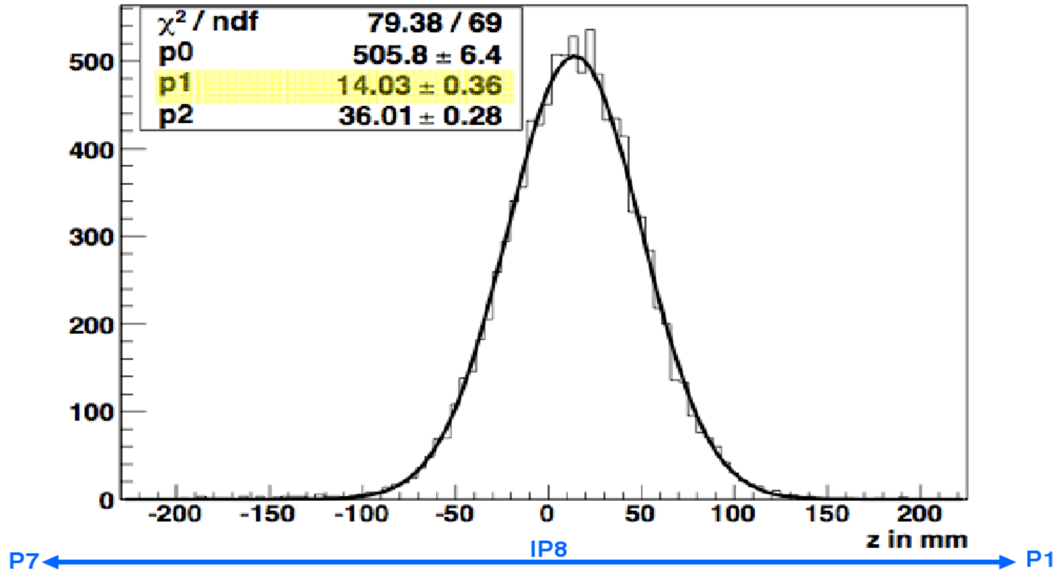
Blue: beam1, red: beam2, dark: measured beam-beam,
light: predicted without VELO resolutions:



Predicted larger than observed: resolution?

Luminous region

Z projection:



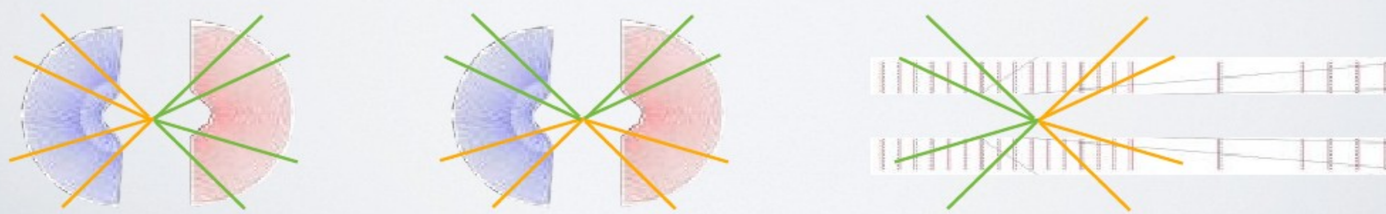
good X,Y stability

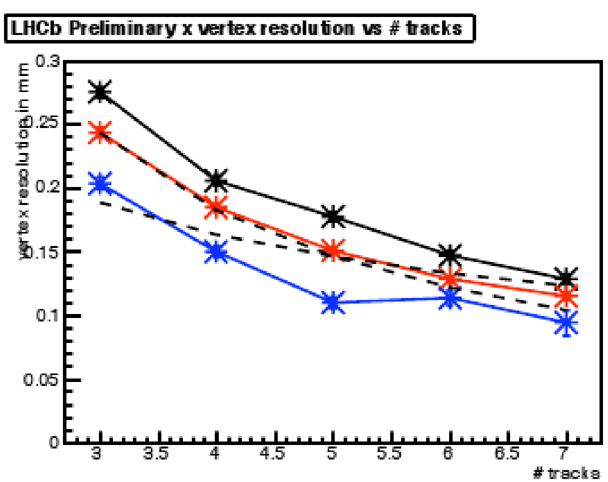
Long overnight run with stable beam, 11 Dec

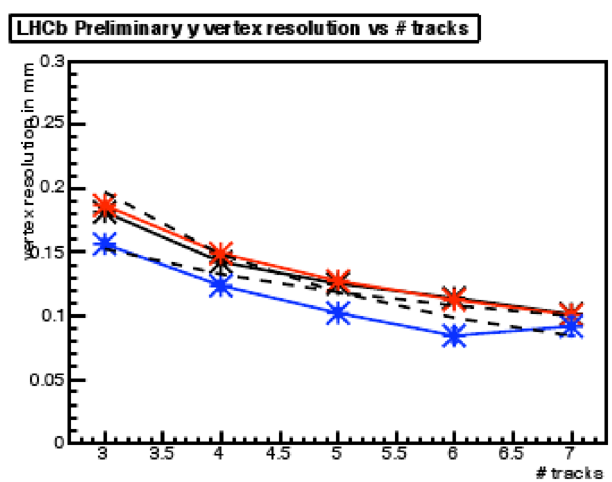
	PV_x		PV_y	
Run start	mean	σ	mean	σ
02:31	0.478	0.181	-0.269	0.256
03:30	0.481	0.186	-0.274	0.272
04:29	0.473	0.189	-0.273	0.295
	all numbers in mm with uncertainties of ~0.004 mm			

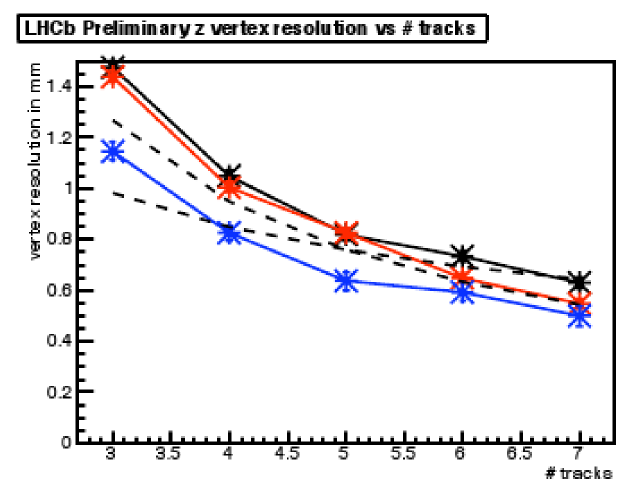
Vertex resolution

- Principle idea:
  Measure the same thing twice and compare
- Split track sample in two and reconstruct vertices with each sample:
  Difference is related to vertex resolution
- Obvious splits:
  left-right, up-down, forward-backward



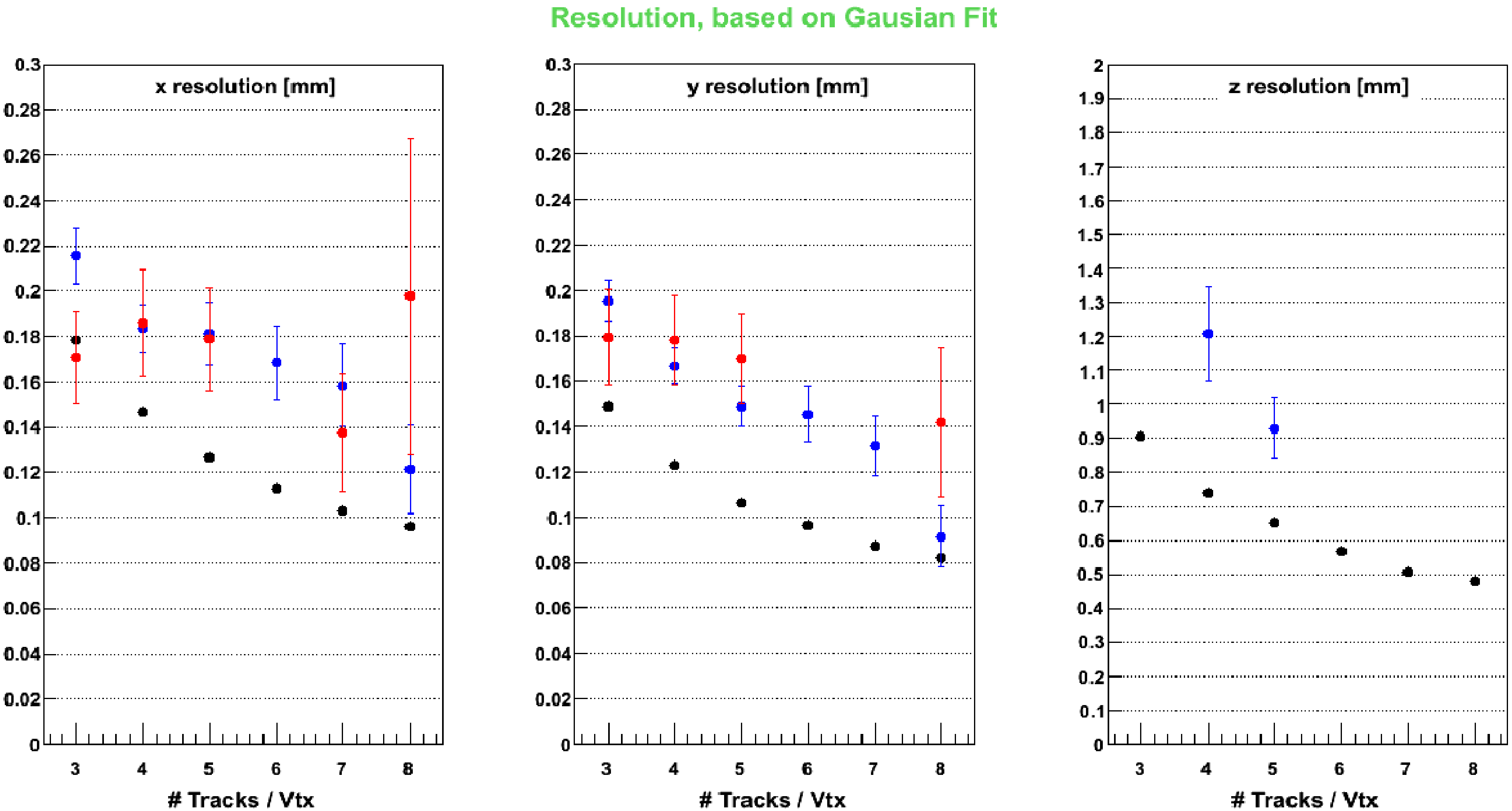






Vertex resolution

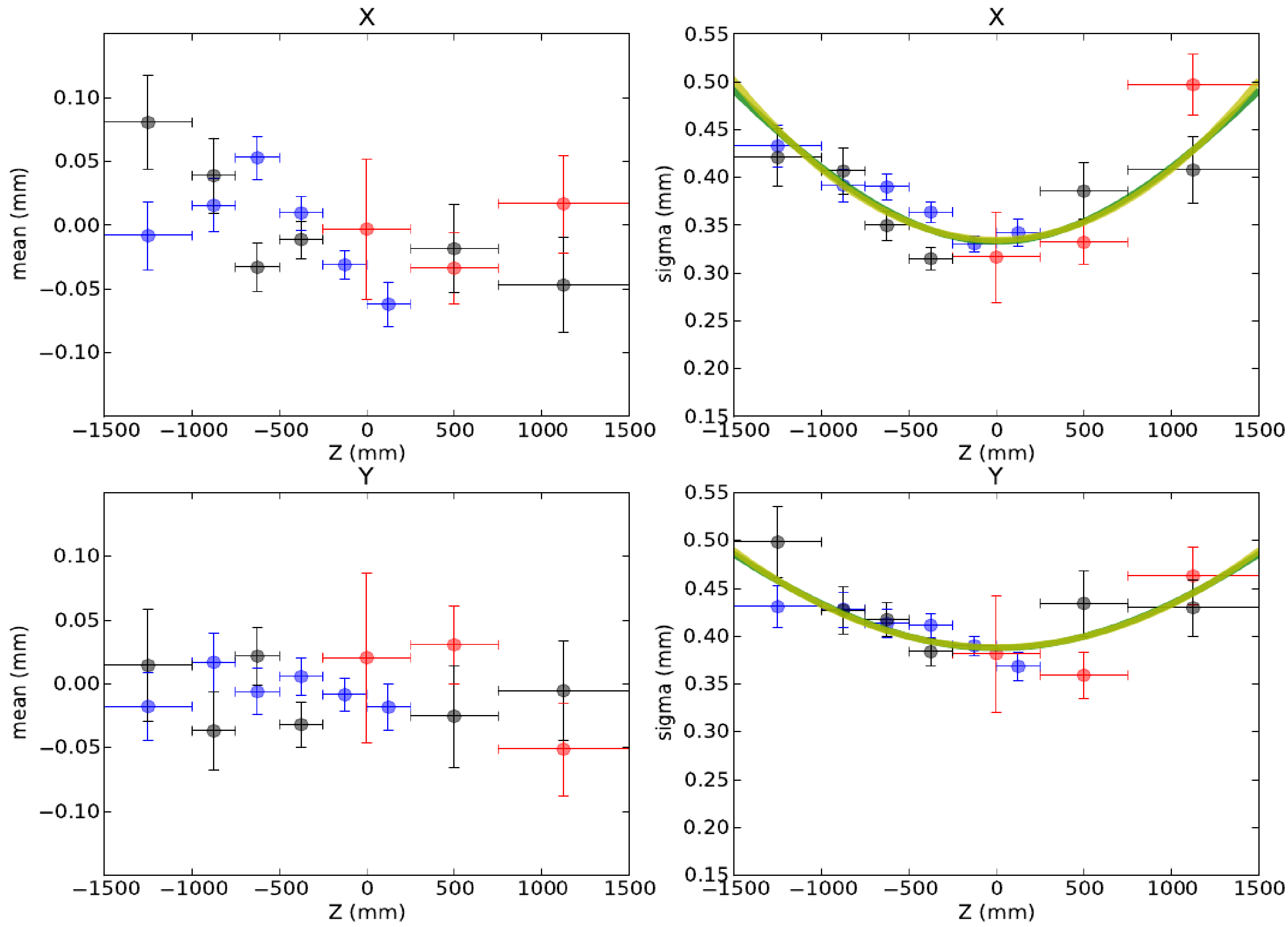
Second analysis, random splitting of tracks into two vertexes



- Draw only points with error < 0.2

Z dependence of beam-gas profile

Blue: beam1, red: beam2, black: beam-beam outside lumi region in Z

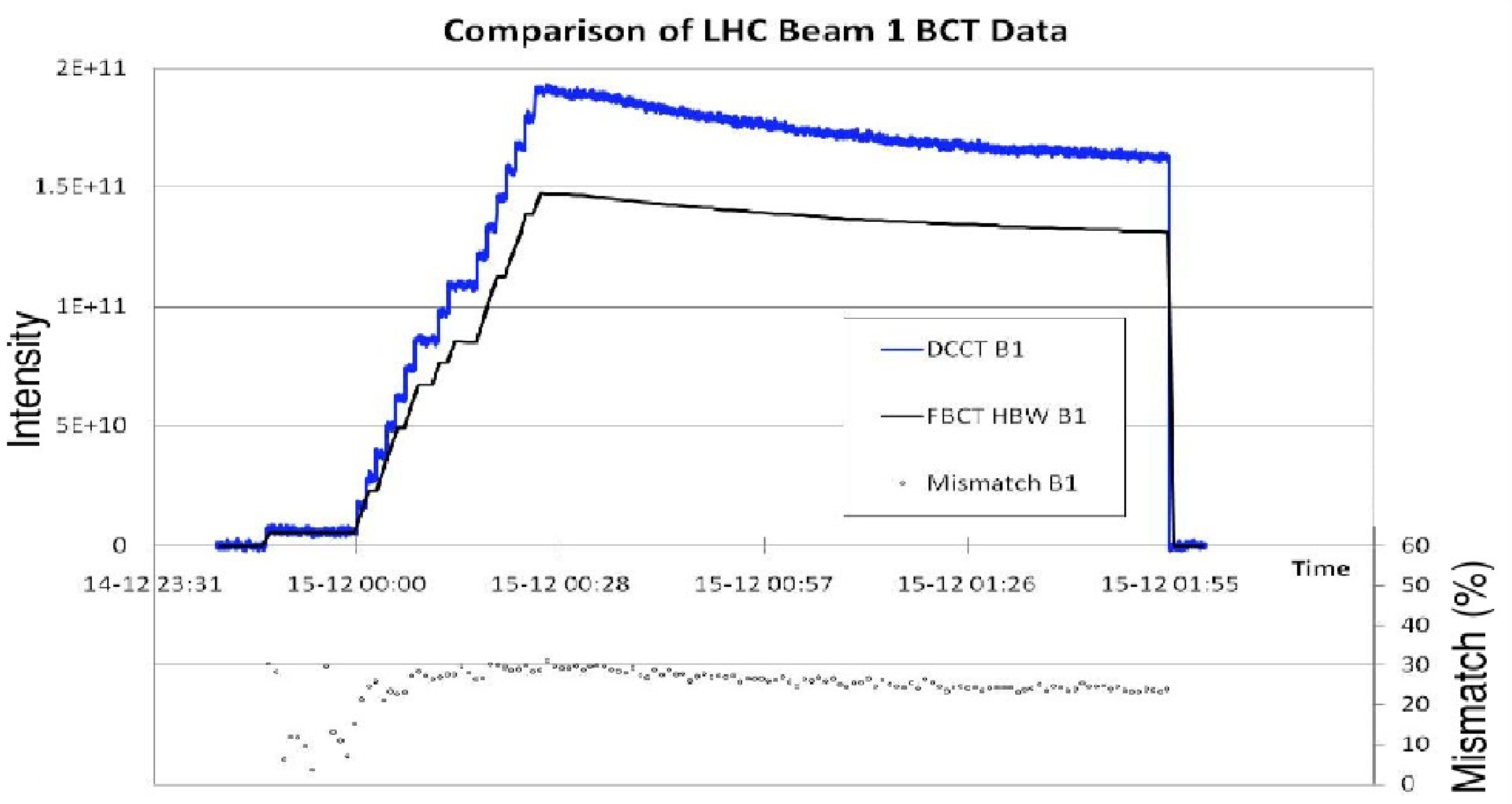


Hour-glass effect should be negligible, only resolution

LHC currents: not fully commissioned

Two systems for current measurement:

1. Fast BCT (total and per bunch intensities) – fast, but less precise
2. DC BCT (total intensity) – precise, but in December at the limit of sensitivity



Big (30%) difference, Fast BCT need to be calibrated

Status of the Fast BCT System

- Beam time in 2009 was extensively used for commissioning of the fast BCT system concentrating on
  - Total intensity for lifetime measurement
  - Detection of beam for beam presence flag
- Many issues
  - Instability of the front-end
    - Due to heavy load from multiple clients
      - Often led to loss of logging data
    - Improved by updates to the different controls communication layers
      - Much more stable towards the end of the 2009 run
  - Updates to the firmware
    - Loss of settings leading to incorrect data being logged
  - Calibration
    - Clearly an issue with the calibration
    - Tests ongoing to identify & correct the source
- Bunch by bunch measurements not looked into in great detail
  - Bunch Tagging – logging often does not reflect actual fill pattern
    - Nominally set for bunch 1 in bucket 1
      - Settings lost on reboot (fixed)
      - Problem with software for beam 2 did not allow easy phase-in (fixed)

LHC presentation "Beam Instrumentation", http://indico.cern.ch/conferenceDisplay.py?confId=77114

LHC currents

After Fast BCT value corrections, the LHC currents should be available (a few weeks)

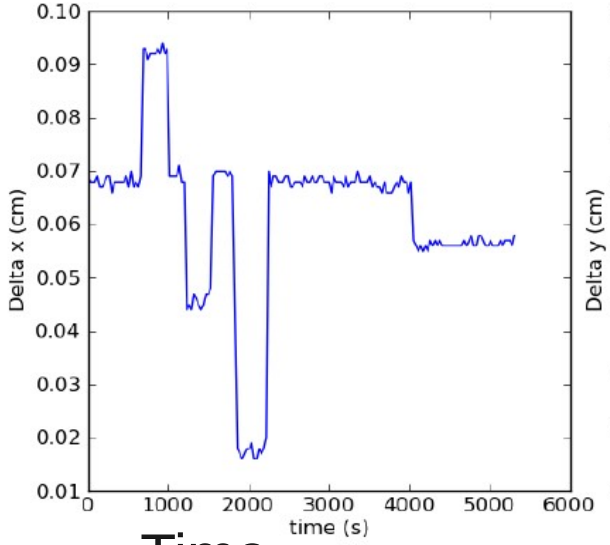
- Production of a coherent set of data for the 2009 Run
  - Requested by Massi for all stable beam periods
  - BI currently looking to produce such a set from the logging database
    - Correct for incorrect bunch tagging where necessary
    - Include cross-calibrated bunch by bunch data using DCCT information
      - Aim for absolute accuracy better than 10%
      - Relative accuracy between bunches should be at the few % level

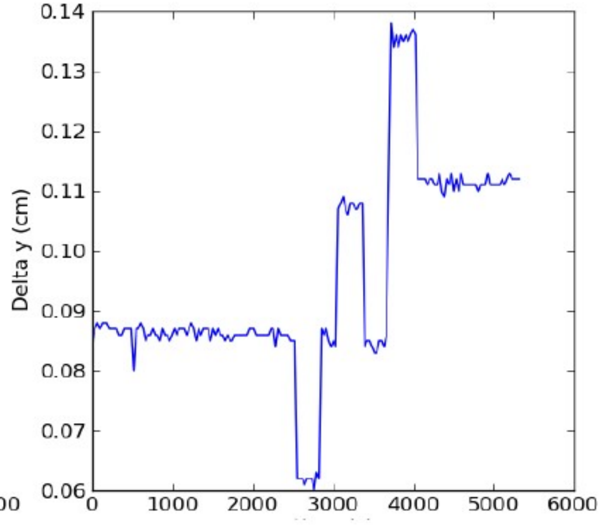
LHC presentation “Beam Instrumentation”, http://indico.cern.ch/conferenceDisplay.py?confId=77114

L0 rate during van der Meer scan

ΔX

ΔY

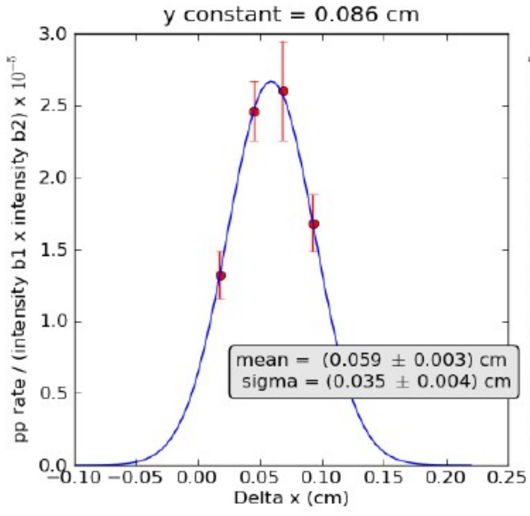


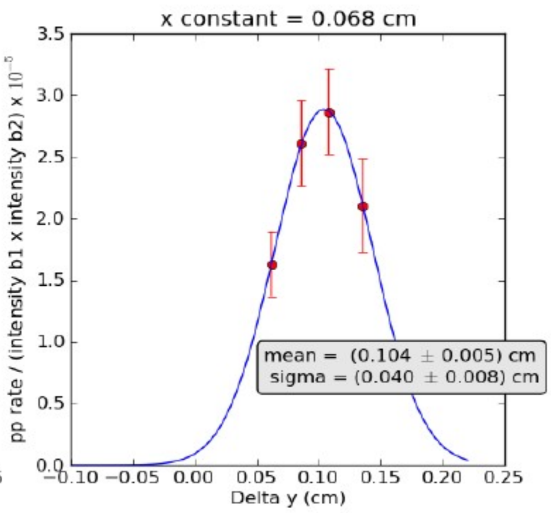


Time

Beam movement
(determined with BPM)

Change in luminosity





ΔX

ΔY

Note: VELO resolutions do not enter the widths,
half of the width should give sigma of luminous region

Conclusions

Luminosity measurement is in progress. All shown numbers are preliminary.

Required precision ≈20%

Necessary ingredients: $$\mathcal{L} = \frac{N_1 \, N_2 \, f}{4\pi\sigma_x\sigma_y}$$

1. **Currents**

2. **Beam widths**

   a) from **beam-gas** (requires resolutions)
   b) from **van der Meer scan**