Luminosity measurement at LHCb, December 2009 run and future prospects

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on behalf of LHCb luminosity group

seminar at LPC, Clermont-Ferrand, Mar 26, 2010

1. Introduction, first LHC run in December 2009, future plans
2. Four methods of absolute luminosity measurement at LHCb
3. December data
    a) Beam photos taken with beam-gas interactions, overlap integral
    b) Beam intensities
    c) Systematics
    d) Cross checks, van der Meer separation scan
4. Results and conclusions

November – December LHC start up

1. In 3 days: first collisions at 0.45 TeV
2. In 9 days: first ramp to 1.2 TeV
3. In 16 days: stable beams at 0.45 TeV
4. In 18 days: collisions at 1.2 TeV, <u>world record</u>

Very good progress of LHC.

LHC bunches

"Stable beams" only at 0.45 TeV.

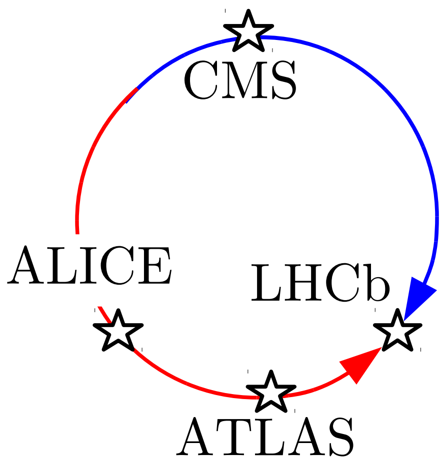
Every LHC beam contained 5 bunches, including one "pilot" bunch with lower intensity (in the end, last run with 17=16+1 bunches).

ATLAS and CMS are opposite to each other $\Rightarrow$ the same bunch pairs collide there.

LHCb and ALICE see collisions of other bunch pairs.

In 5x5 bunch filling scheme, 2 bunches out of 5 collided in LHCb, 3 – in other experiments. Thus:

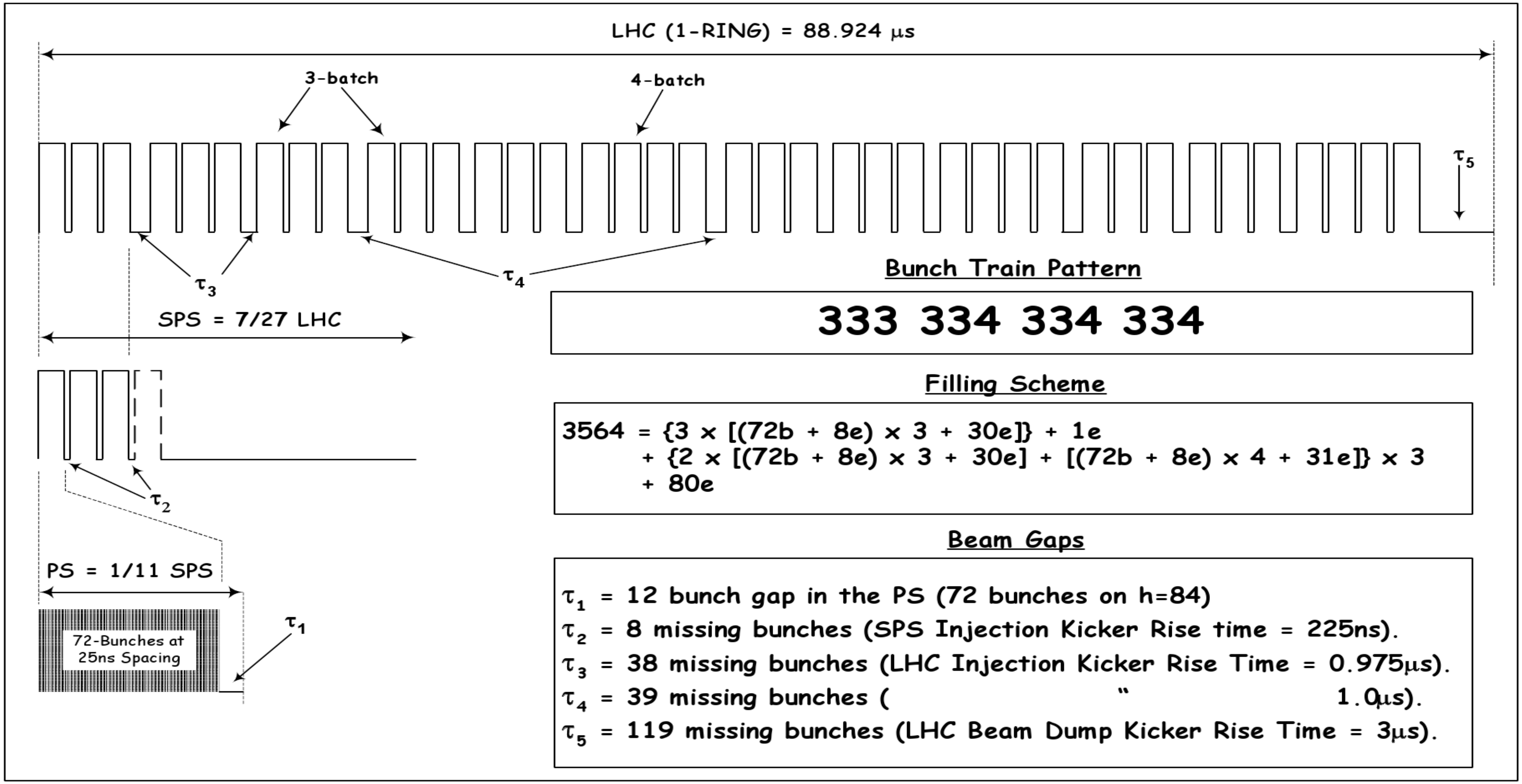
- 2 beam-beam crossings
- 3 beam-empty
- 3 empty-beam



(In last run with 17x17 bunches: 8 beam-beam crossings)

Beam intensities $\sim$1/10 lower than nominal, at 0.45 TeV luminous region is $\sim$10 broader than nominal $\Rightarrow$ probability of interaction per bunch crossing 0.001 instead of 1.

Nominal 25 nsec LHC bunch filling scheme



When beam dump kicker switches on, there should be no filled bunches
$\Rightarrow$ groups of empty bunches due to PS, SPS, LHC

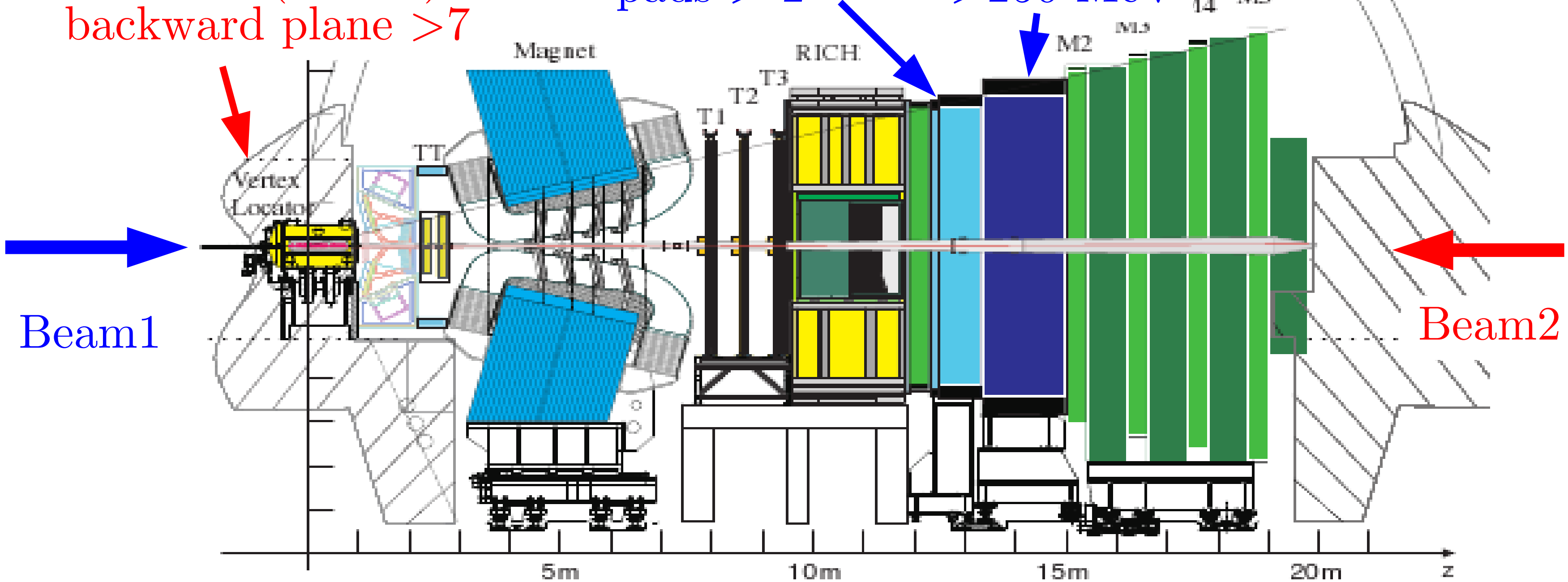
In total 2808 filled bunches out of 3564,
2622 collide in LHCb (2 in December).

Nominal event rate: 30 MHz, in December $\leq$ 20 Hz.

December 2009 run, trigger

LHCb detector is fully operational !

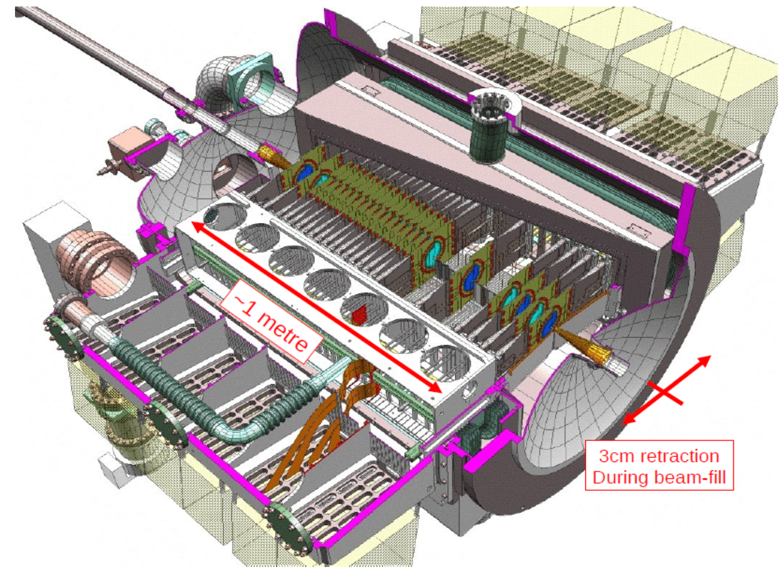
Loose min. bias trigger = # hits in Vertex Locator (VELO) backward plane >7 or # scintillator pads > 2 && HCAL >250 MeV



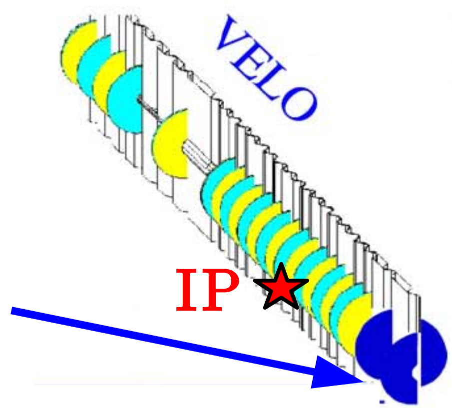
Trigger selected beam-beam and also beam1-gas, beam2-gas interactions

Vertex Locator (VELO) in December

VELO: 21 stations of Si wafer pairs with r and ϕ strip readout. One upstream station in the trigger



Trigger "Pile Up" system, designed to reject events with multiple interactions. Also triggers beam2-gas

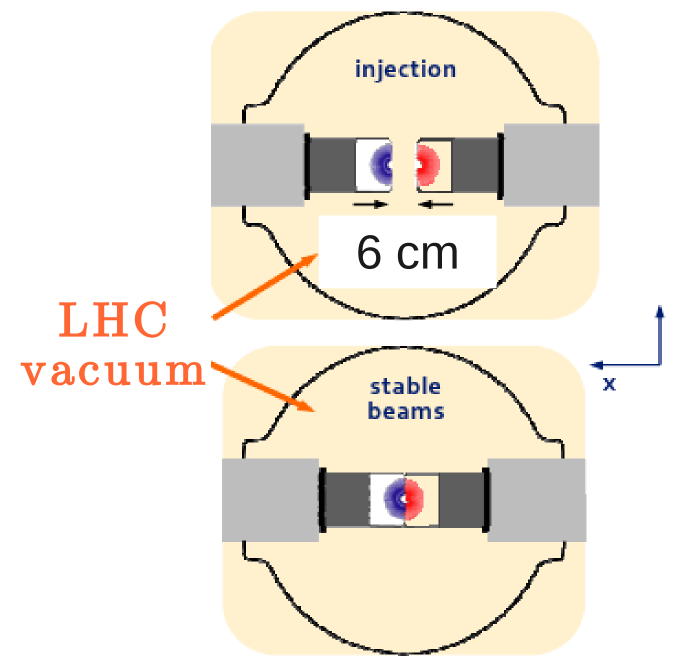


Broad beams at 450 GeV (beam area $\propto 1/E$)

$\Rightarrow$ VELO halves not fully closed, at $\pm$15mm

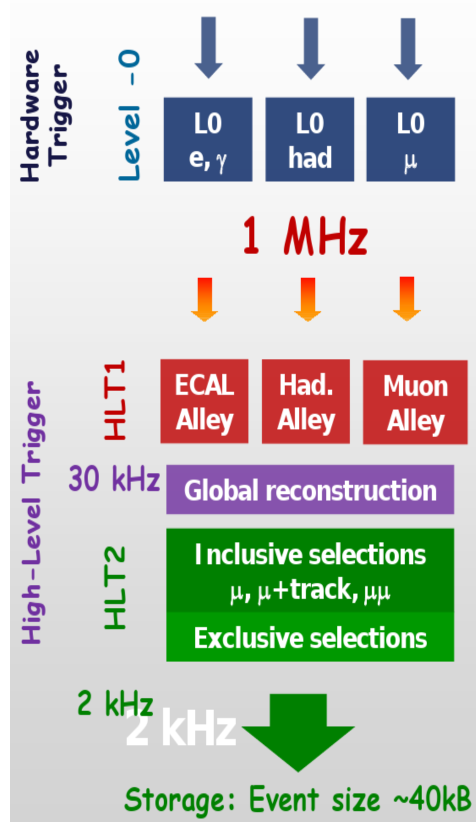
$>$2 TeV is required to move VELO fully in

At 1.18 TeV: no stable beams, all detectors ON, except VELO



LHCb trigger

LHCb has sophisticated trigger for B-physics



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}

Rate of events in December: $\leq$ 20 Hz (instead of nominal 30 MHz)

$\Rightarrow$ loose min. bias trigger:

Level 0: #hits in VELO Pile Up $>$ 7 $\|$ (SPD>2 && HCAL>250 MeV)

High Level Trigger: "pass through" mode

LHCb data in December

In total, $(320 \pm 40) \times 10^3$ pp-collisions recorded (beam-gas subtracted)

All detectors ON and VELO fully powered:

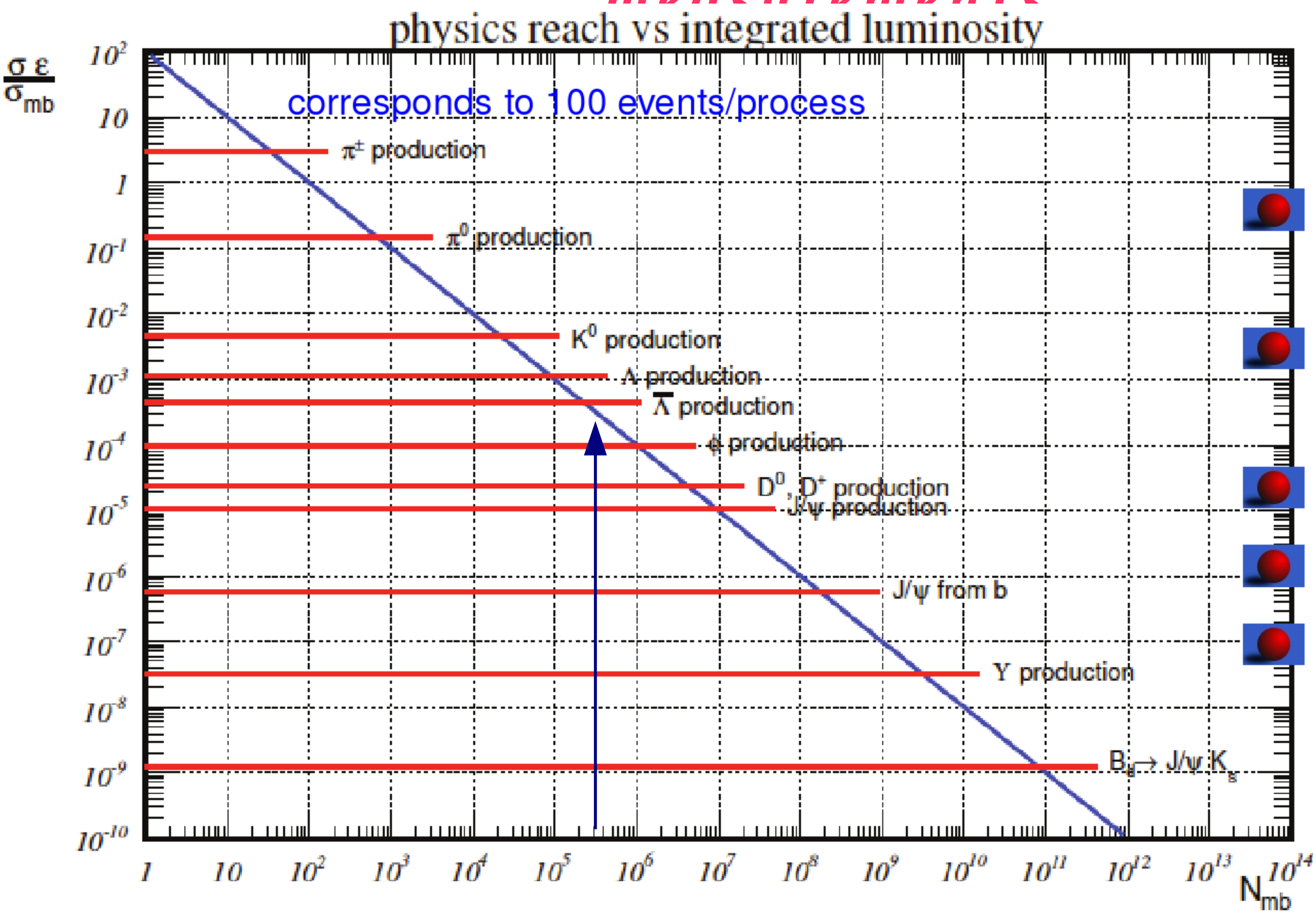
Fill	Date	Number of crossing on disk	Number of beam-beam crossing on disk	Number of beam1-gas crossing on disk	Number of beam2-gas crossing on disk	Estimated Number of pp interaction on disk	pp-interaction /(bb-crossing)	Estimated pp-interaction rate(t=0)[Hz]	L0 rate(t=0) beam1-gas crossing [Hz]	L0 rate (t=0) beam2-gas crossing [Hz]	Recorded luminosity [μb^{-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

First estimation from σ_{pp} = 40mb

Required LHCb statistics for various measurements

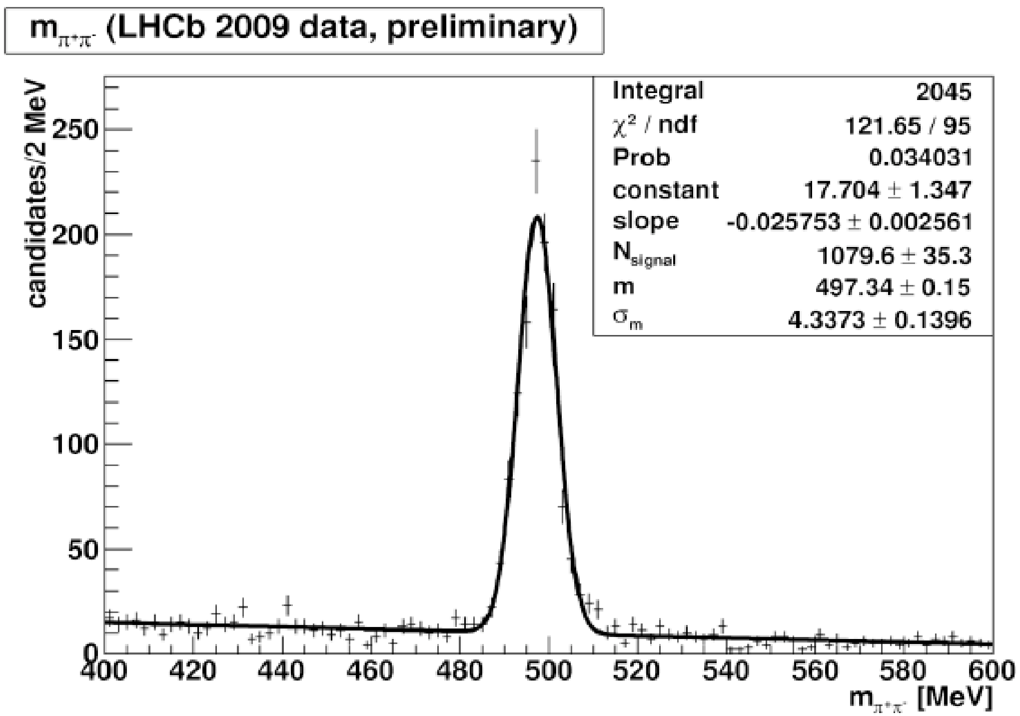


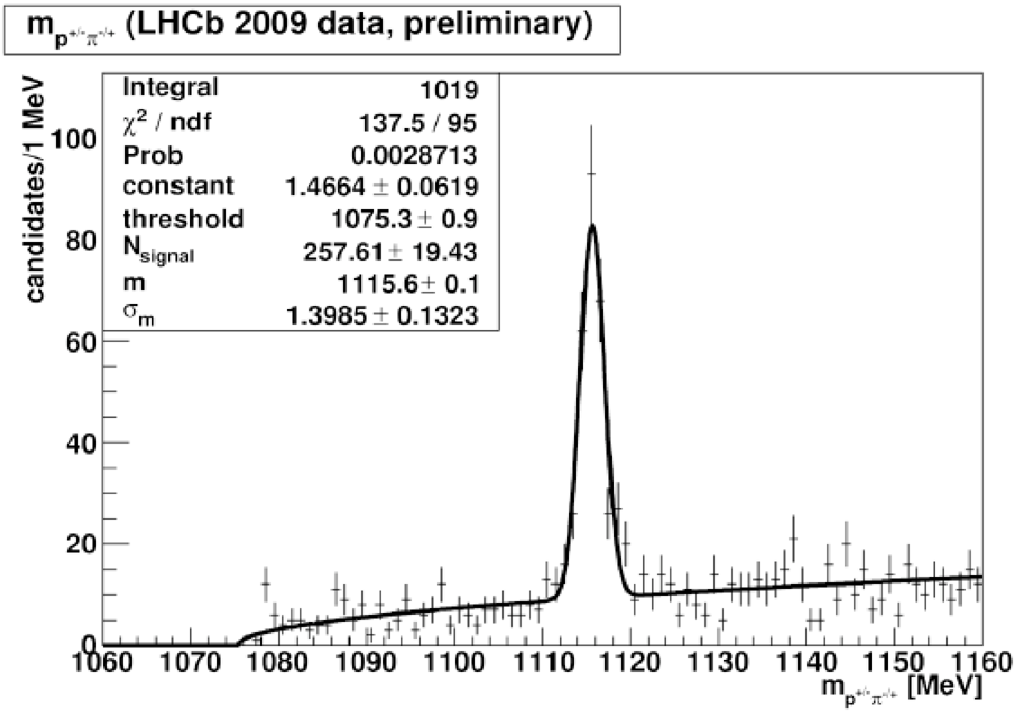
N min. bias events

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

First 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

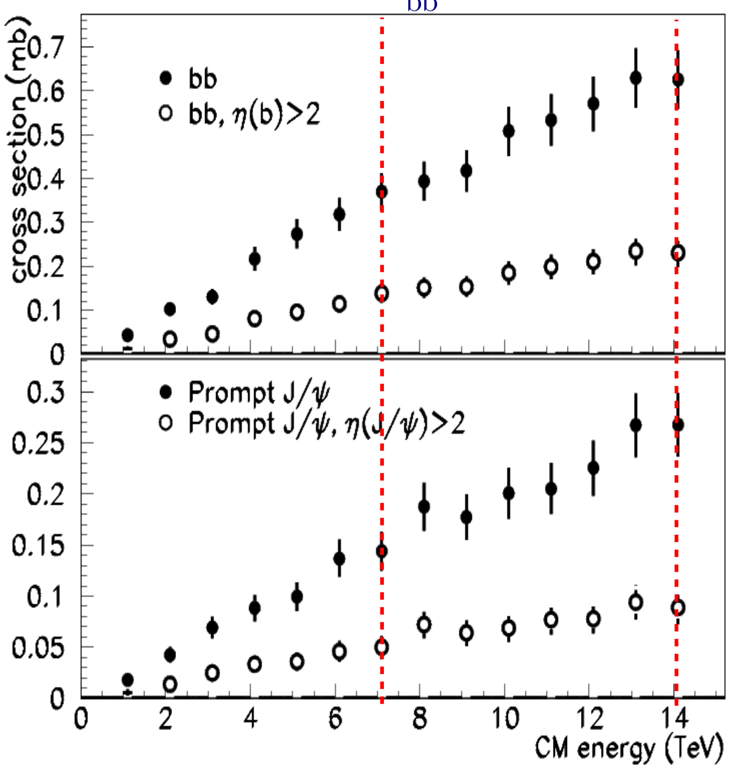
LHC plans (from Charmonix workshop)

1. 5 TeV per beam is risky. Run at 3.5 TeV during 2 years, then shutdown and upgrade for 7 TeV running.

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

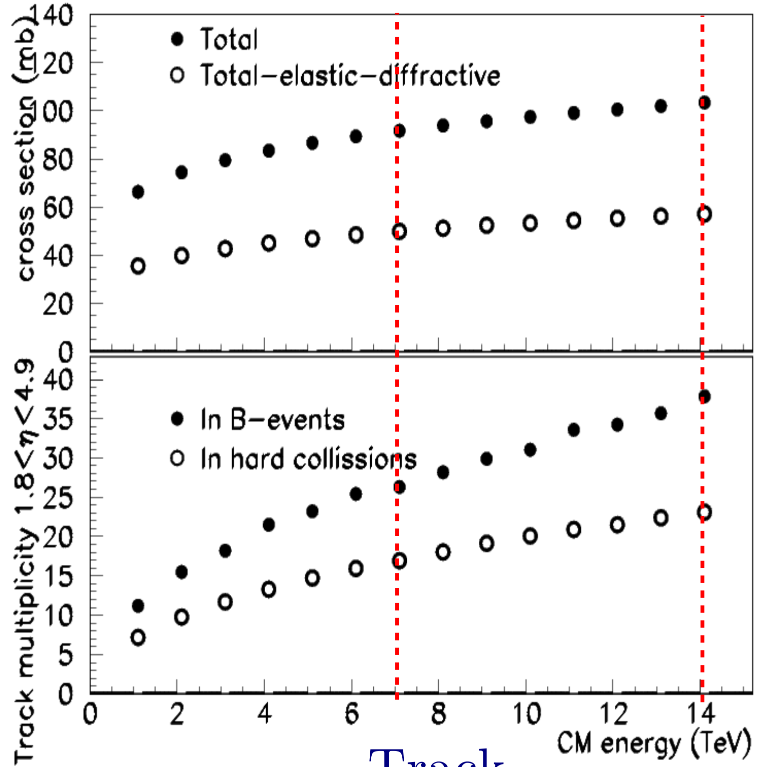
3. First collisions at 3.5 TeV on Mar 30, "media day"

σ_{bb}



$\sigma_{J/\Psi}$

$\sigma_{\mathrm{m.bias}}$



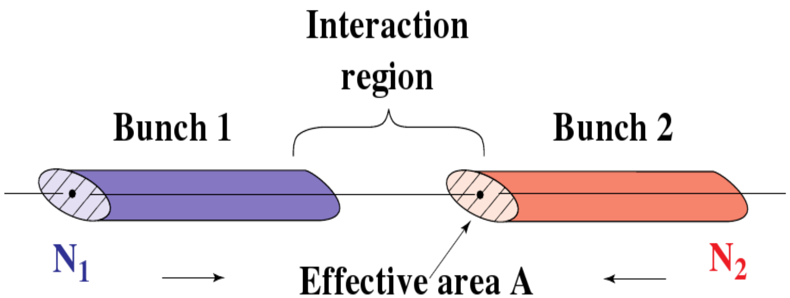
Track multiplicity

LHCb is in advantageous position compared to ATLAS and CMS

Luminosity measurement

Luminosity

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



$$\frac{1}{A_{\text{eff}}} = \underbrace{\int g_1(x,y)\, g_2(x,y)\; dx\, dy}_{\text{overlap integral}} \quad \Rightarrow \quad \text{Gaussian shape beams: } \mathcal{L} = \frac{N_1\, N_2\, f}{4\pi \sigma_x \sigma_y}$$

$N_{1,2}$ measured by LHC (ultimate precision 1-2%), f = 11 kHz * N collisions

overlap integral

1) photograph beams with beam-gas interactions (ultimate precision 5-10%)

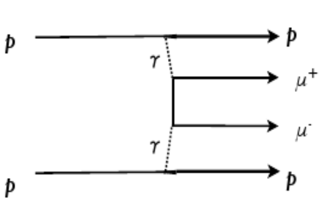
2) van der Meer: scan profiles by separating beams in transverse plane ($\simeq$10%)

Other methods

(unusable for small data sample in Dec 2009)

3) counting $pp \to ZX \to \mu^+\mu^- X$ events, depends on proton structure (PDF) $\Rightarrow$ cross section uncertainty $\simeq$5%

4) $pp \to pp\, \mu^+\mu^-$, calculable in QED but rare, with large statistics precision $\simeq$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), transverse energy deposition in calorimeter, number of tracks and vertexes in VELO, VELO Pile Up multiplicities, number of tracks in TT stations in front of the magnet.

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

The DAQ load is $< 1\%$ everywhere even at 1kHz event rate (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. 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 other counters.

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)**$(\text{lumi}/\text{lumi}_0)$. 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 and empty-beam bunch crossings

E.g. in the method of mean:

$$<bb> - <be> - <eb>$$

DAQ system is able to collect random triggers separately from bb, be, eb bunch crossings and with different probabilities which are selected to optimize precision of $<bb> - <be> - <eb>$

December data

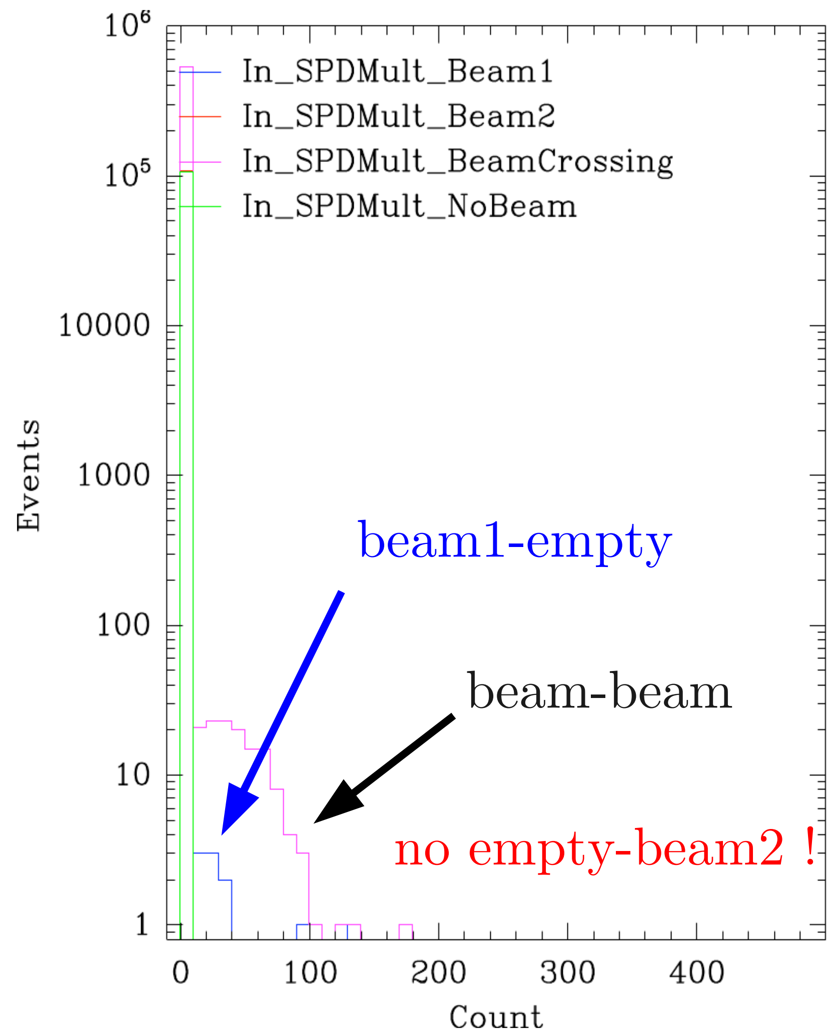
Statistics is not enough for luminosity measurement
with physics channels.

Due to low probability of interactions, random trigger selected mainly empty events, luminosity counter spectra are pedestal dominated
$\Rightarrow$ not useful

Measure luminosity with beam-gas events and
use van der Meer scan as a cross check

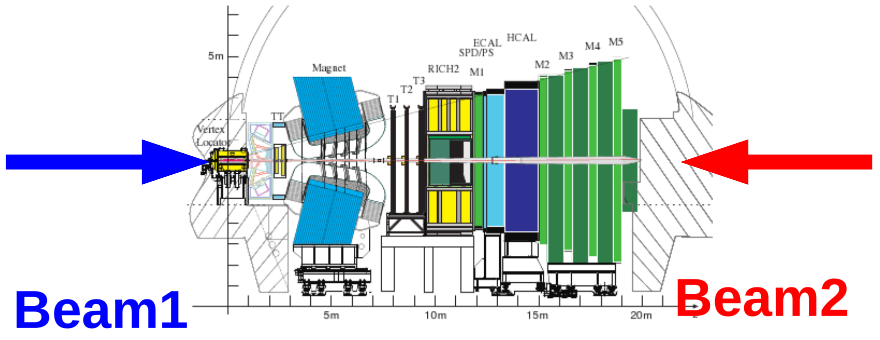
"Luminosity counters" in December

To see spectra of lumi counters above pedestal, in future we'll
1) increase random trigger rate and
2) use loose min. bias trigger (in parallel to random) to count #events above pedestal.



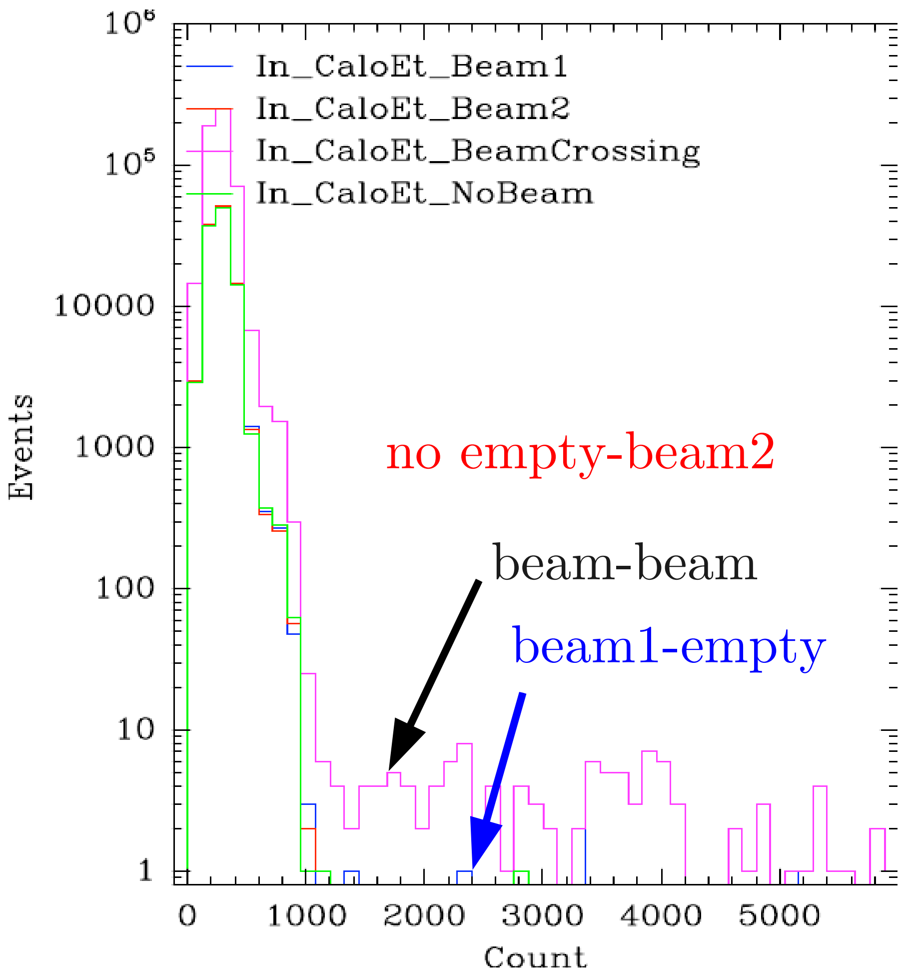
Particles produced in beam1-gas interactions to the left from calorimeters trigger them at the same time as if they were created in beam-beam IP at Z=0 (right timing).

If beam2-gas interaction occurres to the right from calorimeters, it fires them much earlier (wrong timing) ⇒ randomly selected event at the "right" moment relative to empty-beam crossing is always empty.

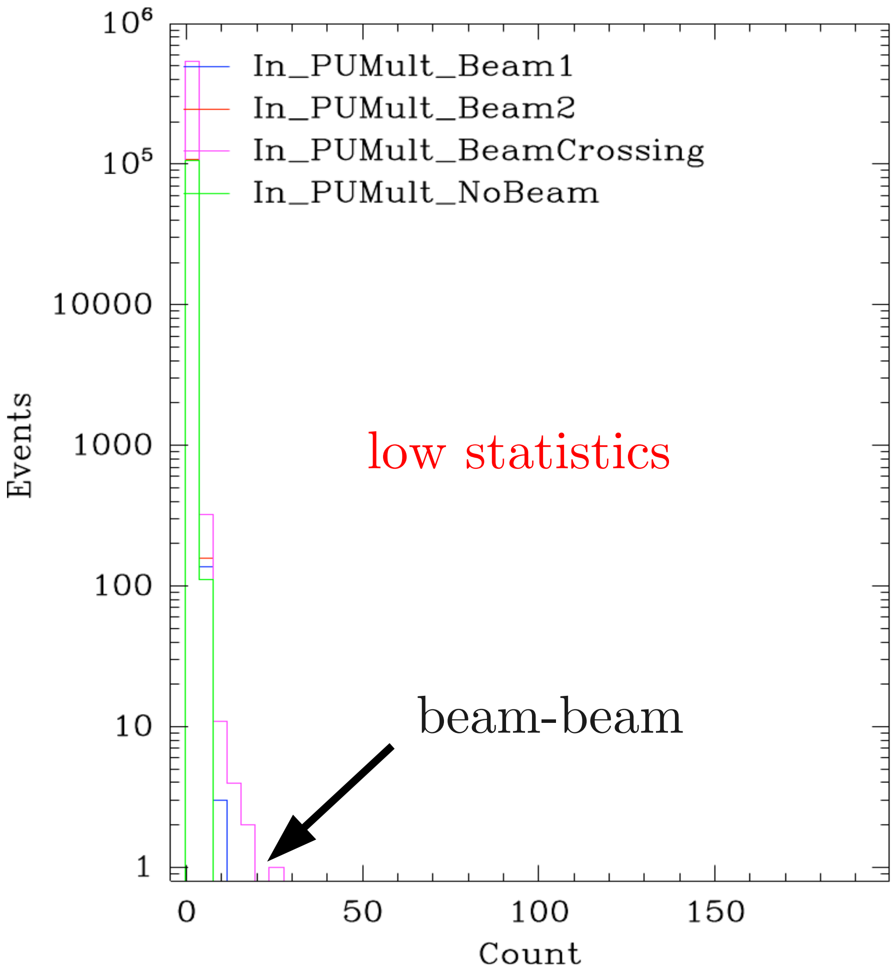


"Luminosity counters" in December

Transverse energy deposition in ECAL



Pile Up (in VELO) multiplicity



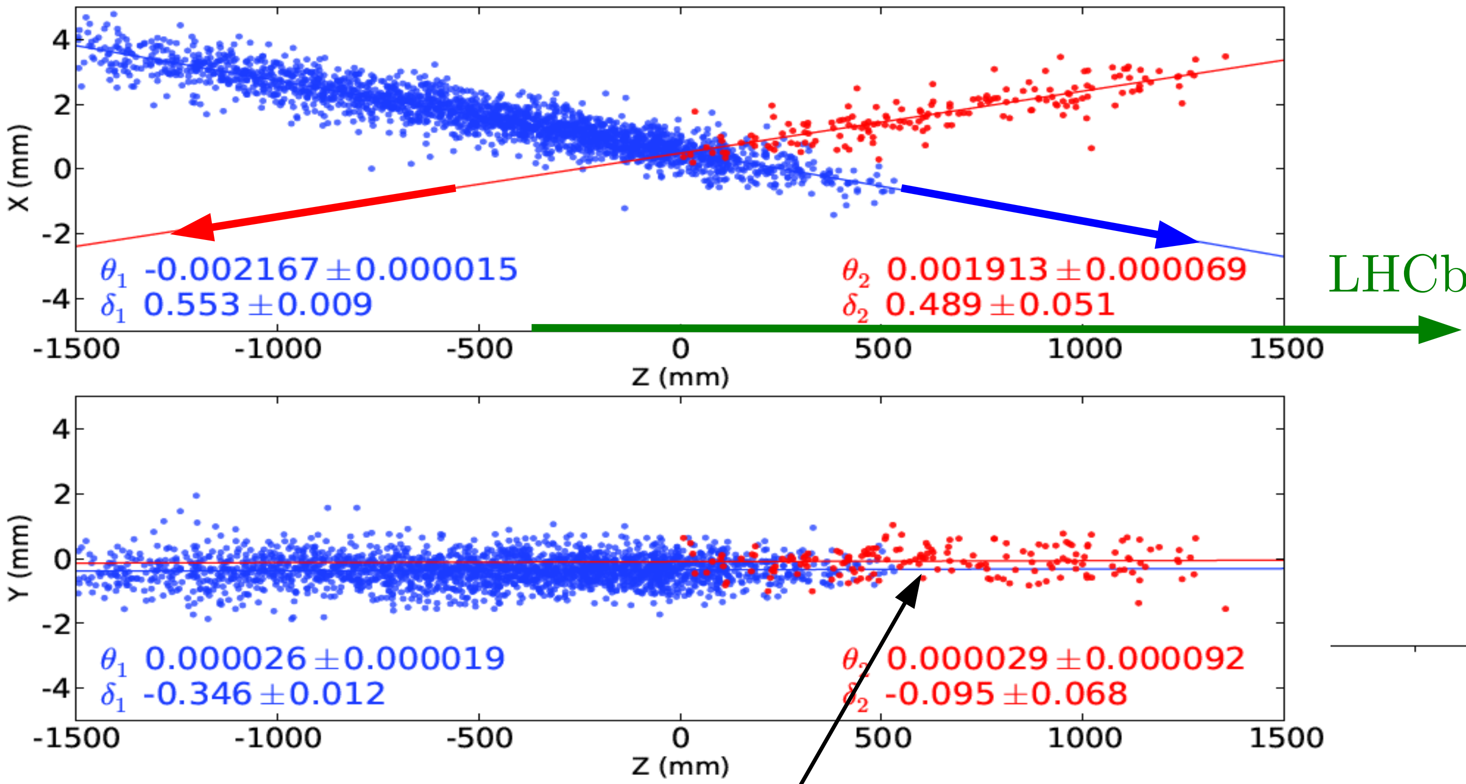
Beam-gas events in December

Proved to be very helpful, selected by loose min. bias trigger.

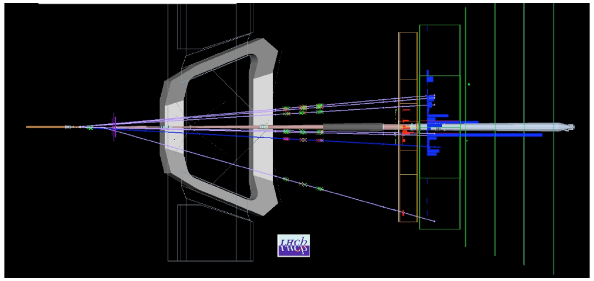
Beam1 - gas: calorimeter trigger (particles from beam1-gas arrive at SPD and HCAL at the same time as from beam-beam)

Beam2 - gas: VELO Pile Up trigger (commissioned in in the middle of December run)

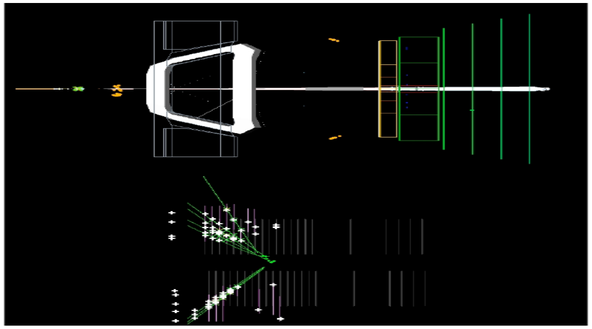
Beam-gas photos



Beam1-gas event

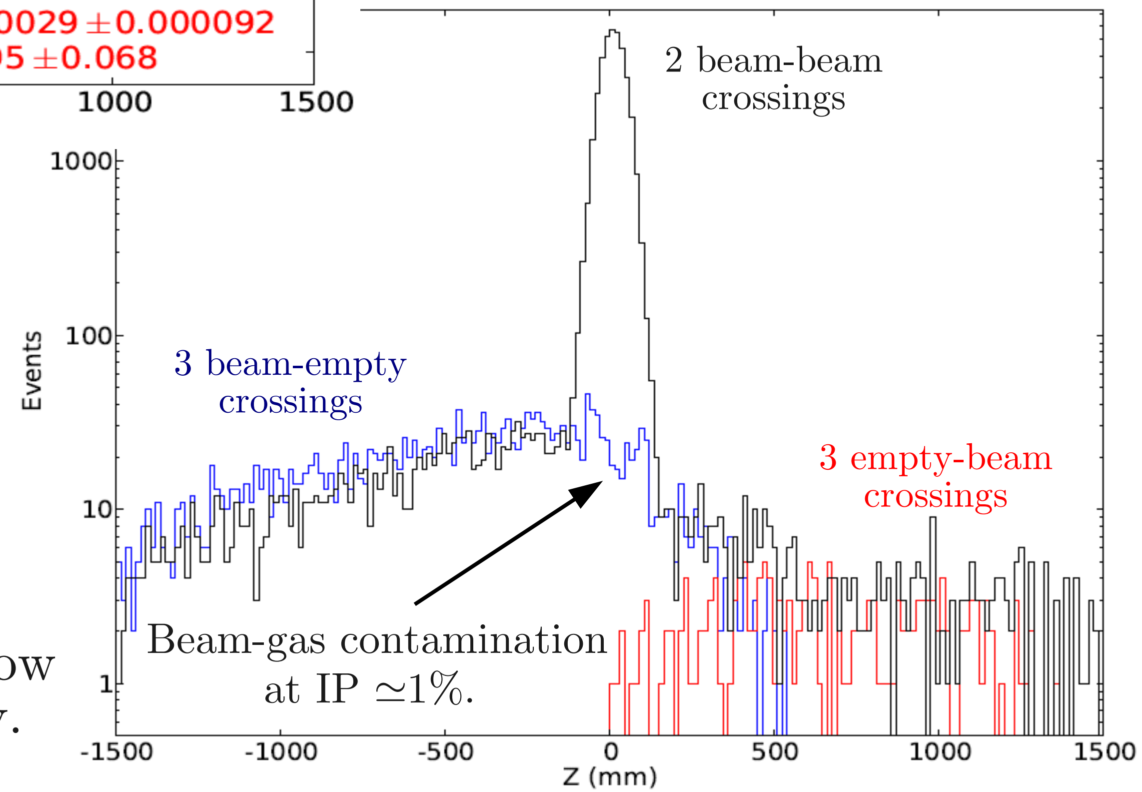


Beam2-gas event



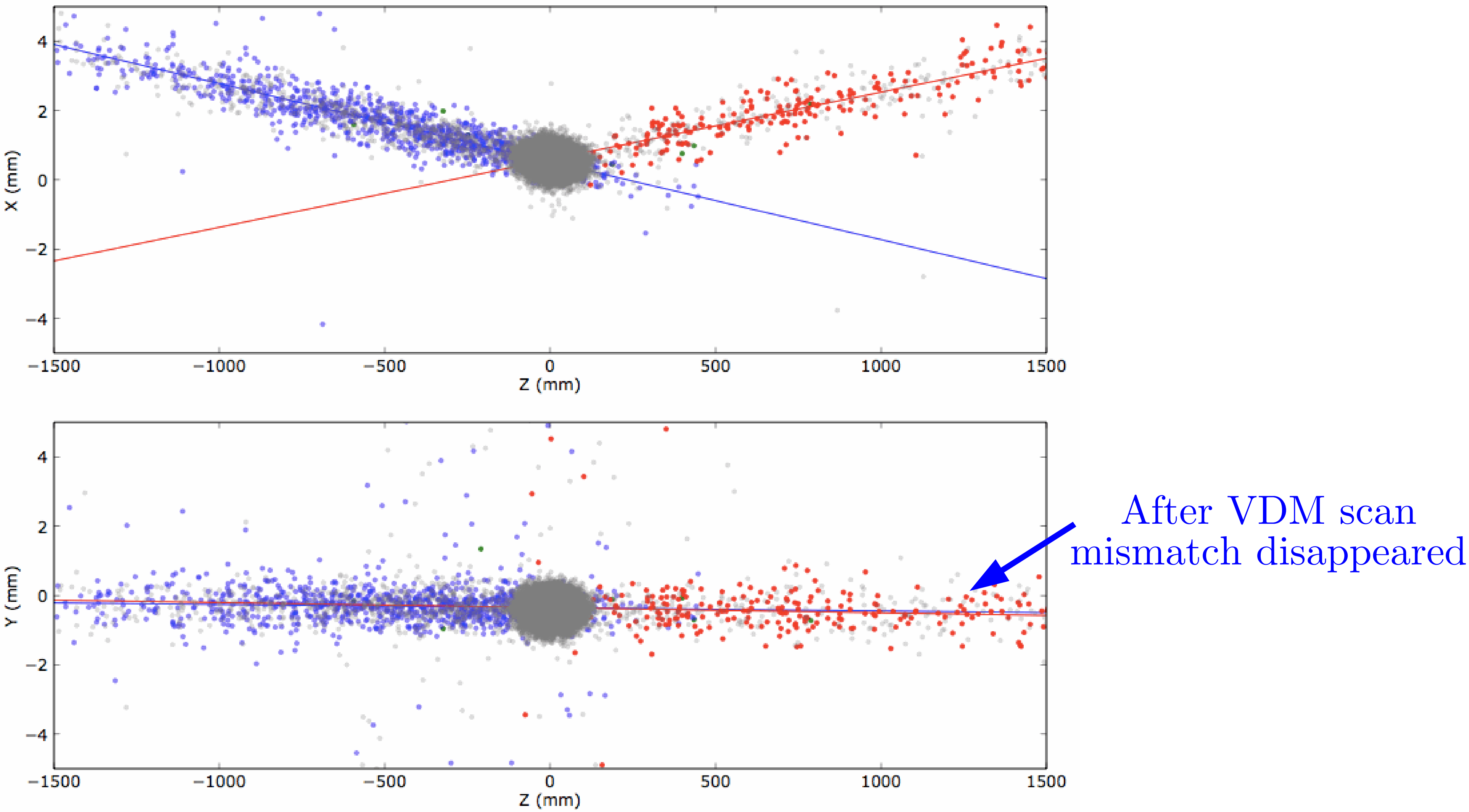
Before van der Meer beam alignment, mismatch visible

Crossing angle 2.1 mrad in X-Z due to LHCb dipole magnet



Note logarithmic scale. Beam2-gas low statistics due to detector asymmetry.

Beam-gas photos after van der Meer scan



Van der Meer luminosity optimization was performed online using L0 rate as a "luminosity counter" (with background subtraction).

VELO resolution

Needed in unfolding beam shapes
from beam-gas data

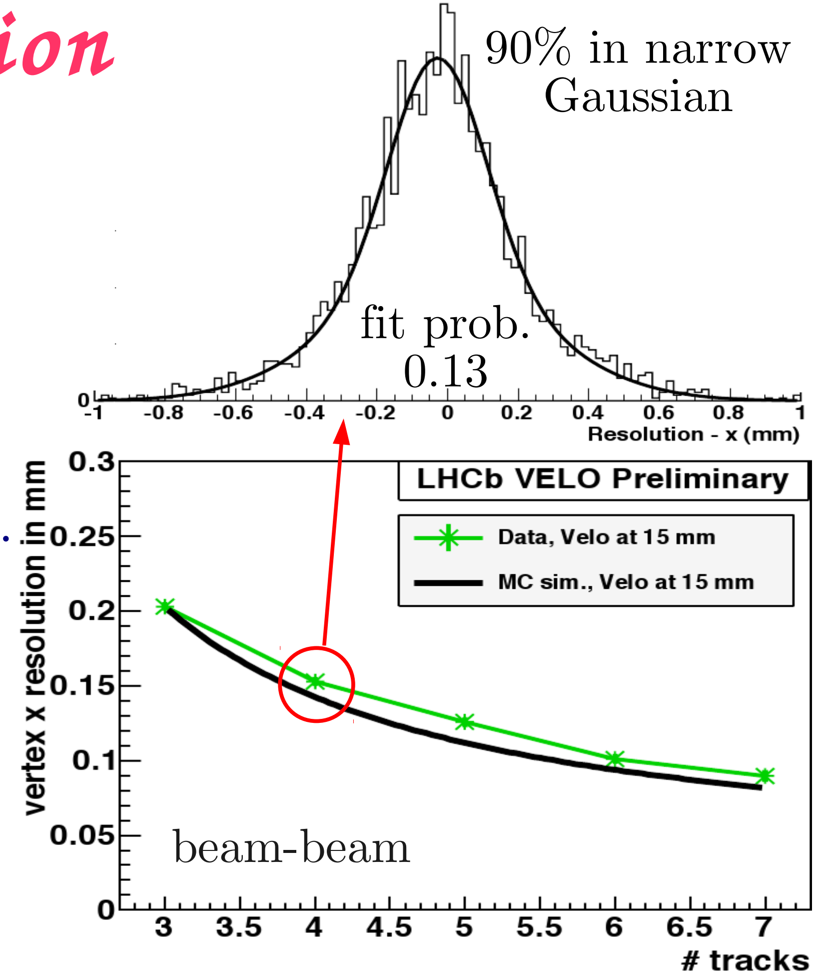
Randomly split N track vertex into two N/2 vertexes.

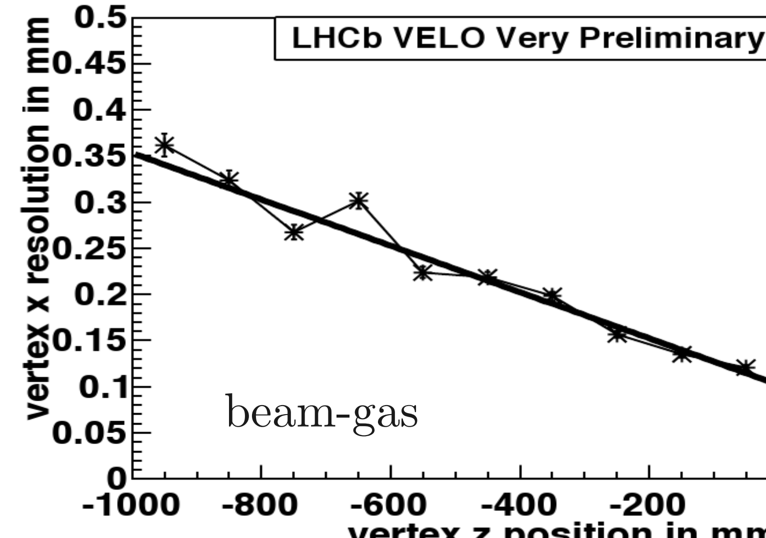
Resolution $_{N/2}$ = mismatch $/\sqrt{2}$

Parametrized as double Gaussian, linearly

depending on z and approximately as $1/\sqrt{N}$ on N:

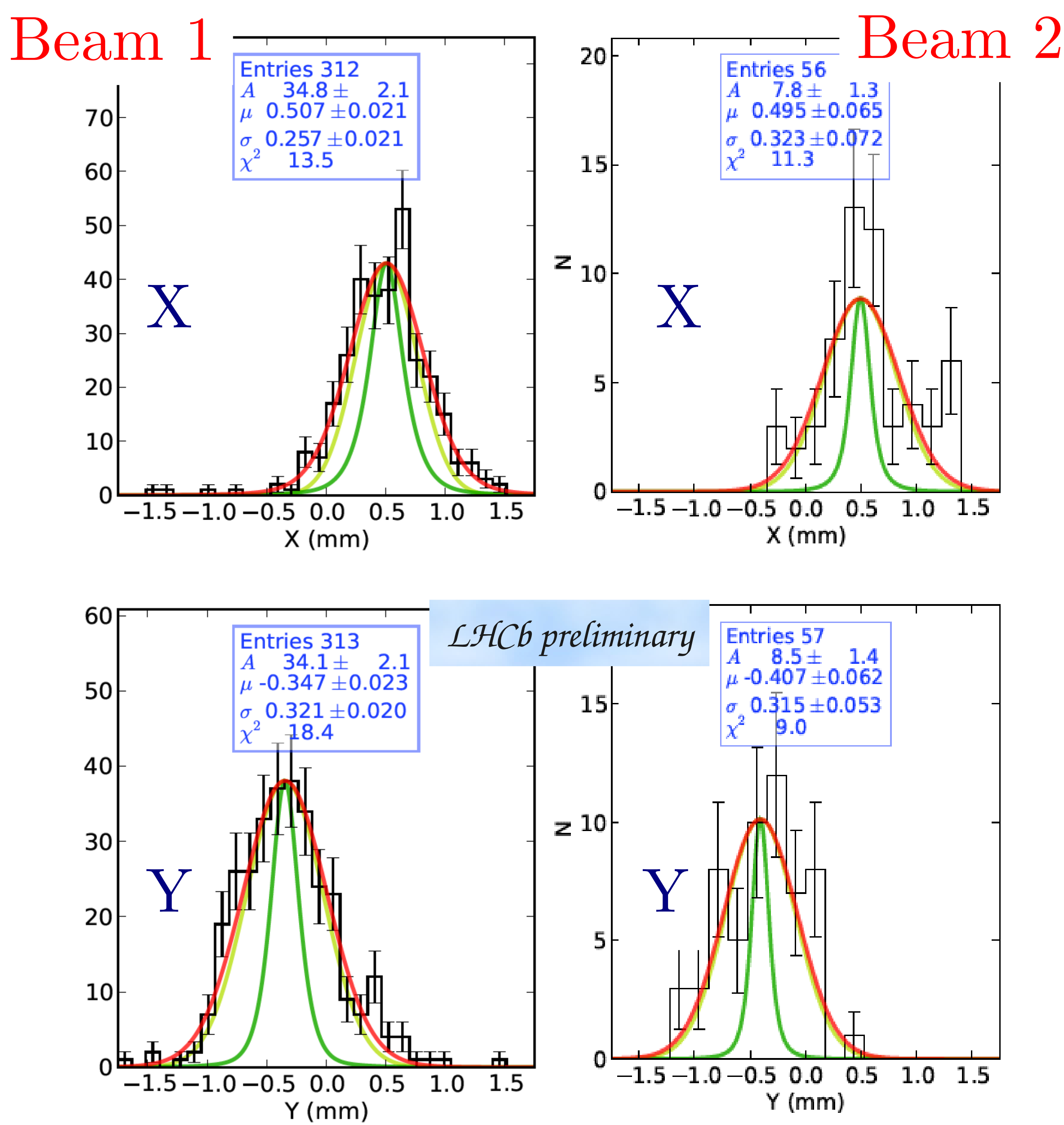
$$\sigma^{1,2}_{x,y}(N,z) = \frac{s^{1,2}_{x,y}(m_{x,y}z + b_{x,y})}{N^{0.5+\frac{\delta_{x,y}}{N^2}}}$$





Beam sizes measured in beam-gas (outside Z=0)

One beam-beam crossing outside luminous region at Z=0



Fit with VELO resolution added in quadrature for every bin in Z and #tracks

Green – overall VELO resolution

Yellow – unfolded beam profile

Size of luminous region (at Z=0)

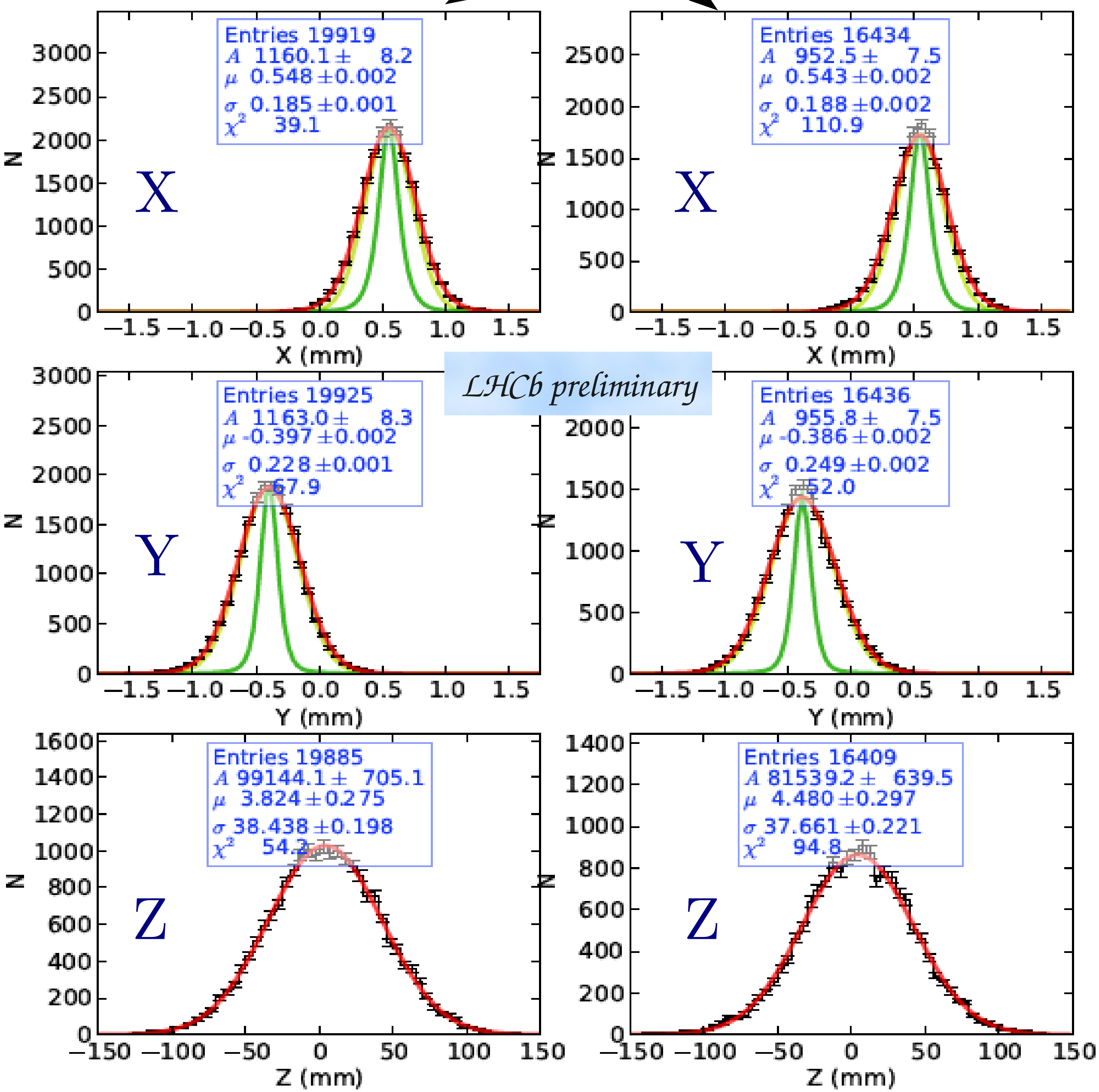
$$\sigma^2_{beam-beam} = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2} \quad for\ X, Y$$

correlated

$$Lumi \propto \frac{1}{2\pi\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}}$$

Strong constraint on overlap integral

Two colliding bunches



Cross check

$$\sigma^2_{beam-beam} = \frac{\sigma_1^2\sigma_2^2}{\sigma_1^2+\sigma_2^2}$$

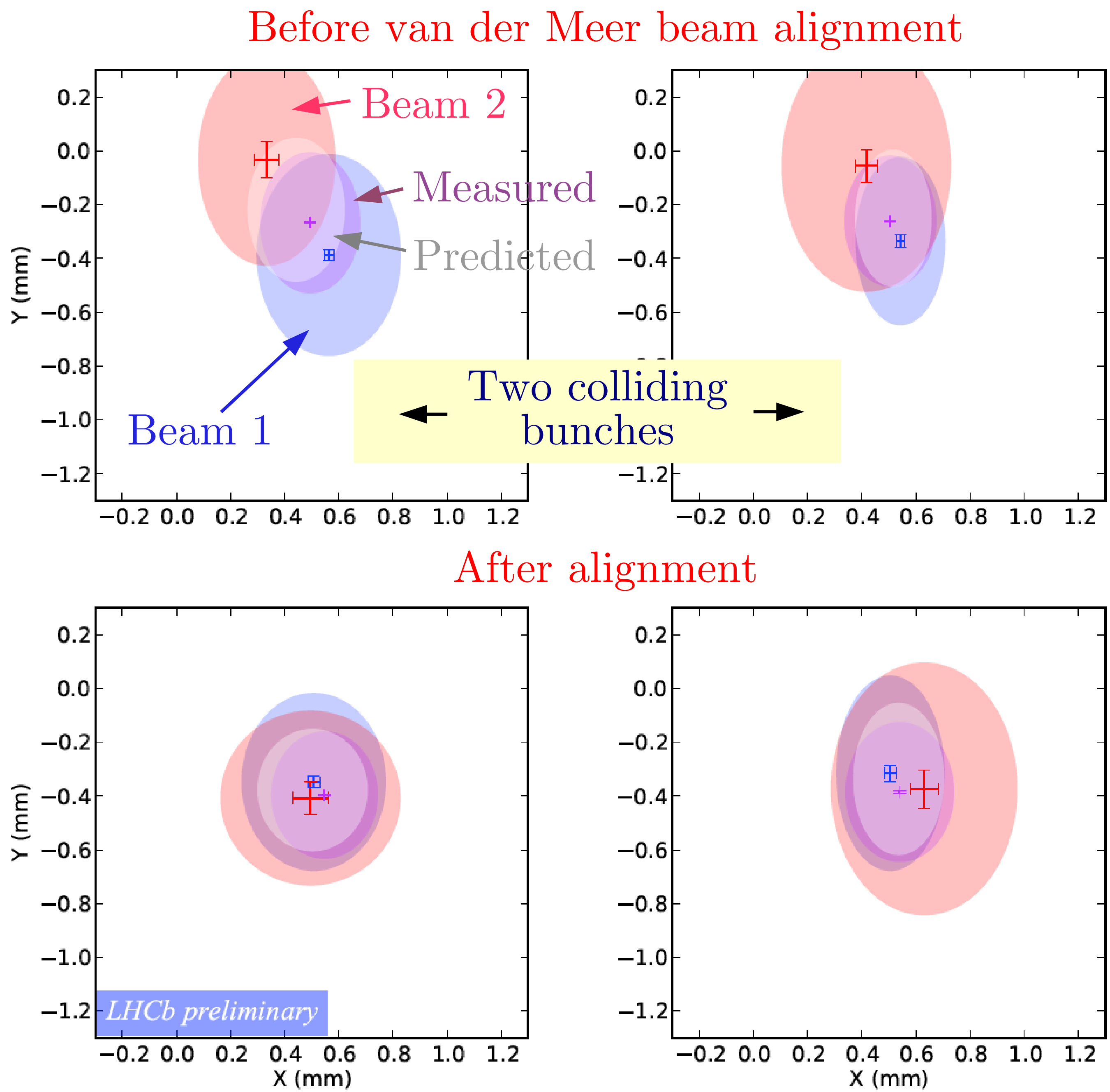
regardless of beam separation

One sigma ellipses:

Blue - beam 1
Red - beam 2

beam-beam:

Purple - measured
Light - predicted

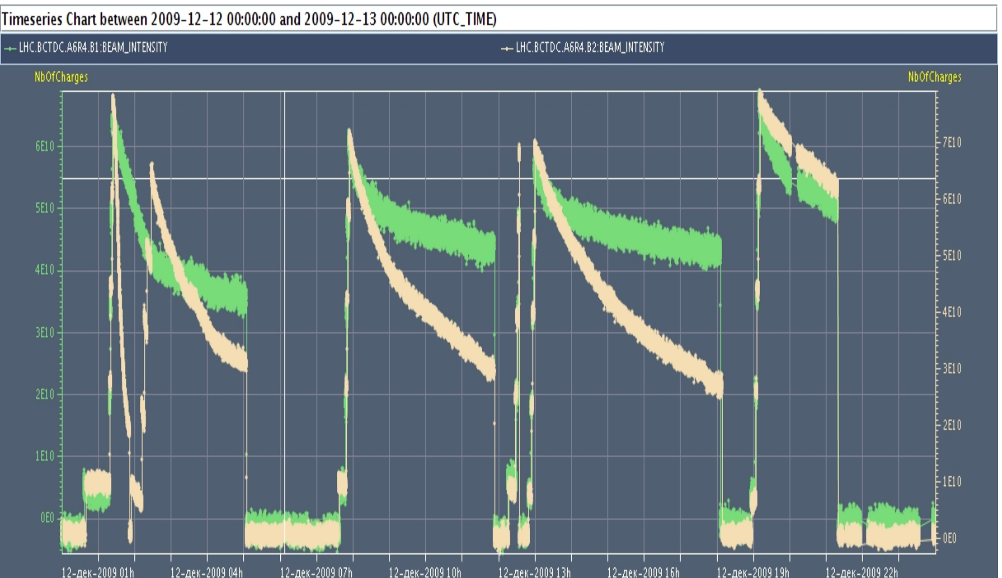


Beam intensities

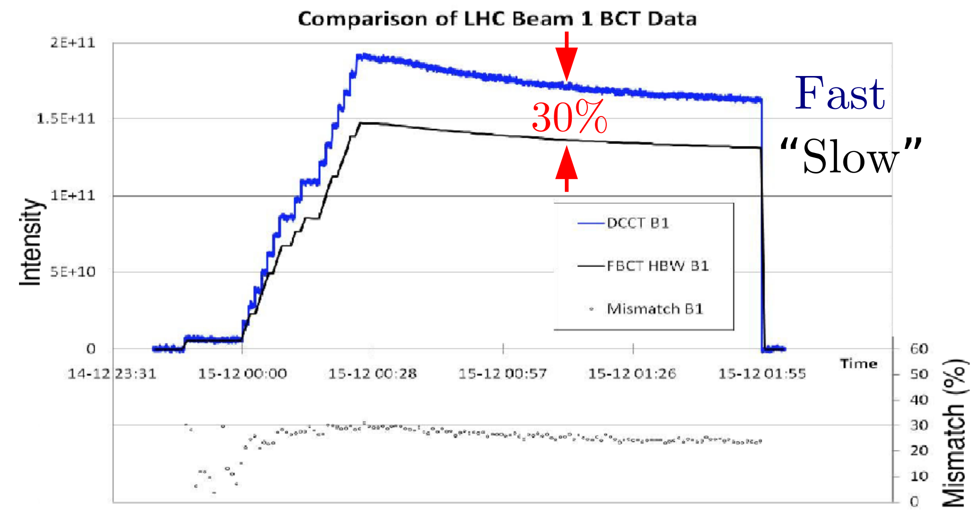
Measured by two LHC accelerator systems:

1) "slow": reliable absolute normalization

2) fast: charge sharing between bunches



One day of operation, "slow" system

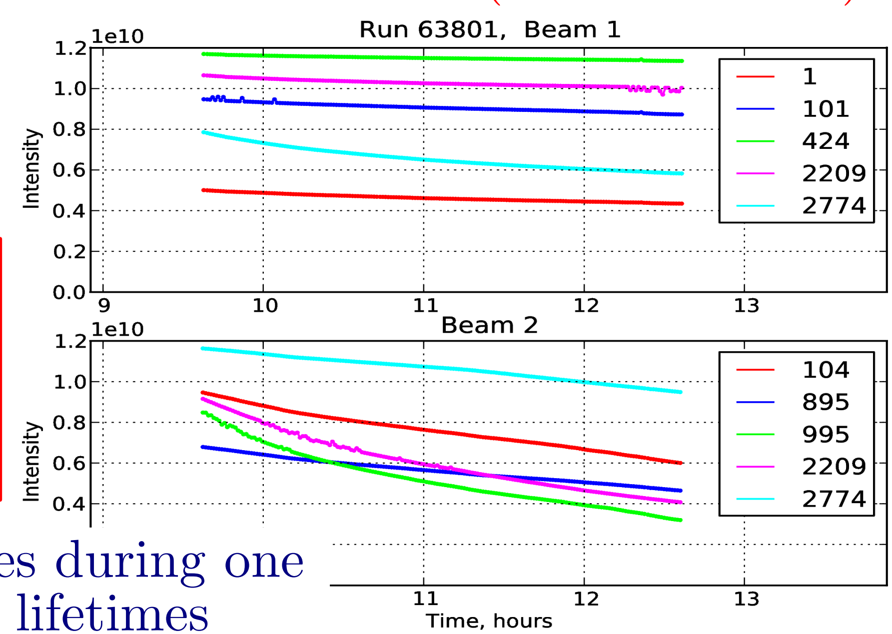


Fast - not calibrated (30% difference)

"Slow" system designed for higher currents than in December

Ultimate design accuracy $1 \oplus 1\%$ for two beams

Achieved in December (recalibration of fast system every minute) - 12%



Individual bunches during one run, different lifetimes

Putting results together

$$\int L\,dt = f \times \int N_1 N_2\,dt \times \sum_{bunches} A^{-1} \times \frac{1}{\epsilon_{crossing}} \times \frac{1}{\epsilon_{phase}} \times \frac{1}{\epsilon_{debunching}}$$

f = 11.25 kHz

$\int N_1 N_2\,dt$, integrated intensity product (±12%)

$\sum_{bunches} A^{-1}$, overlap integral: uncertainty due to width (±5% in best runs)

due to beam offset (not head-on) (±3% in best runs)

Corrections

$\epsilon_{crossing}$ - crossing angle: 0.90 – 0.92 (±1%)

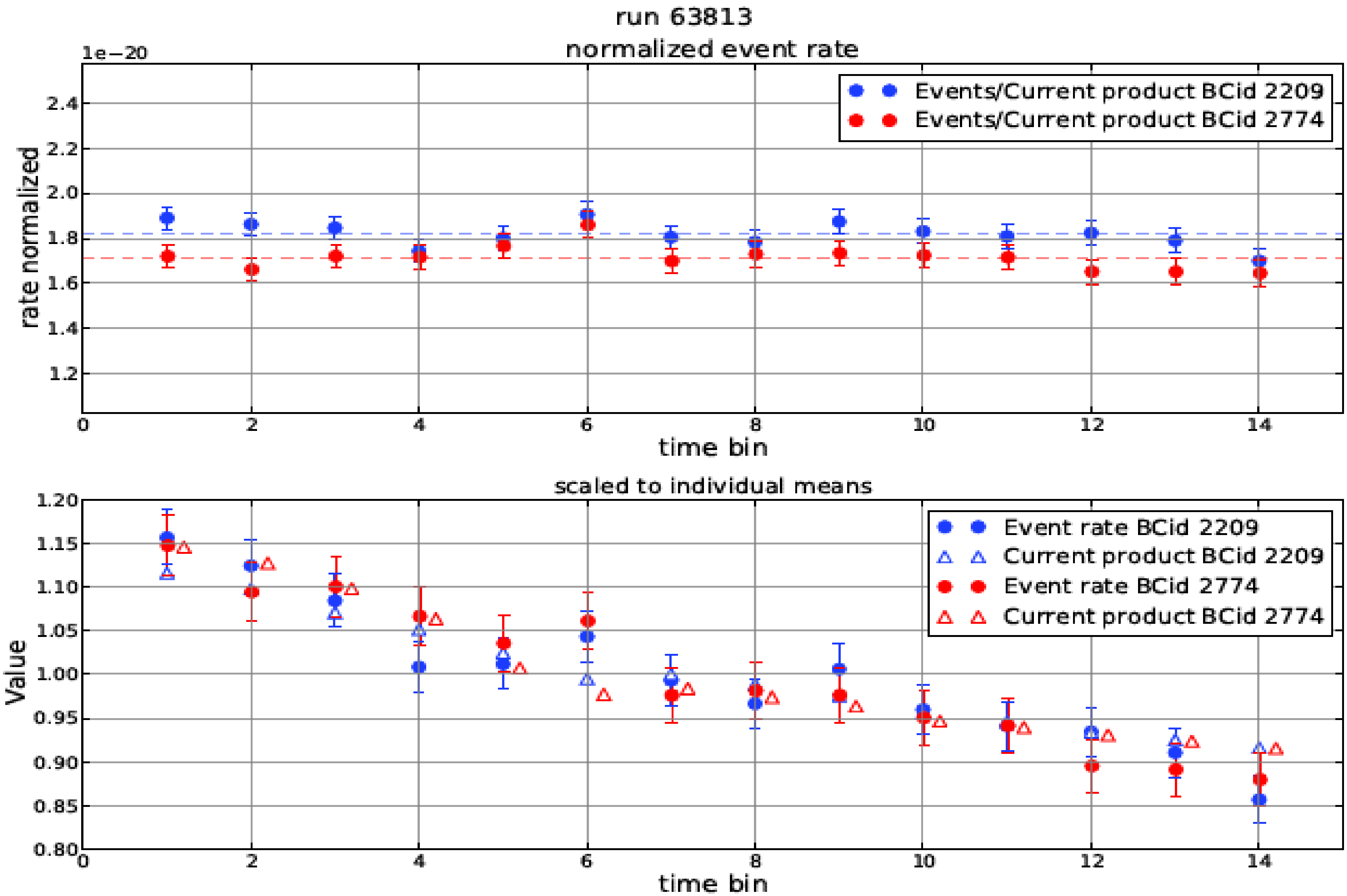
ϵ_{phase} - mismatch in beam phases: 0.95 only in one run (±5%)

$\epsilon_{debunching}$ - current outside bunches: 0.99 (±1%)

Total error ±15%

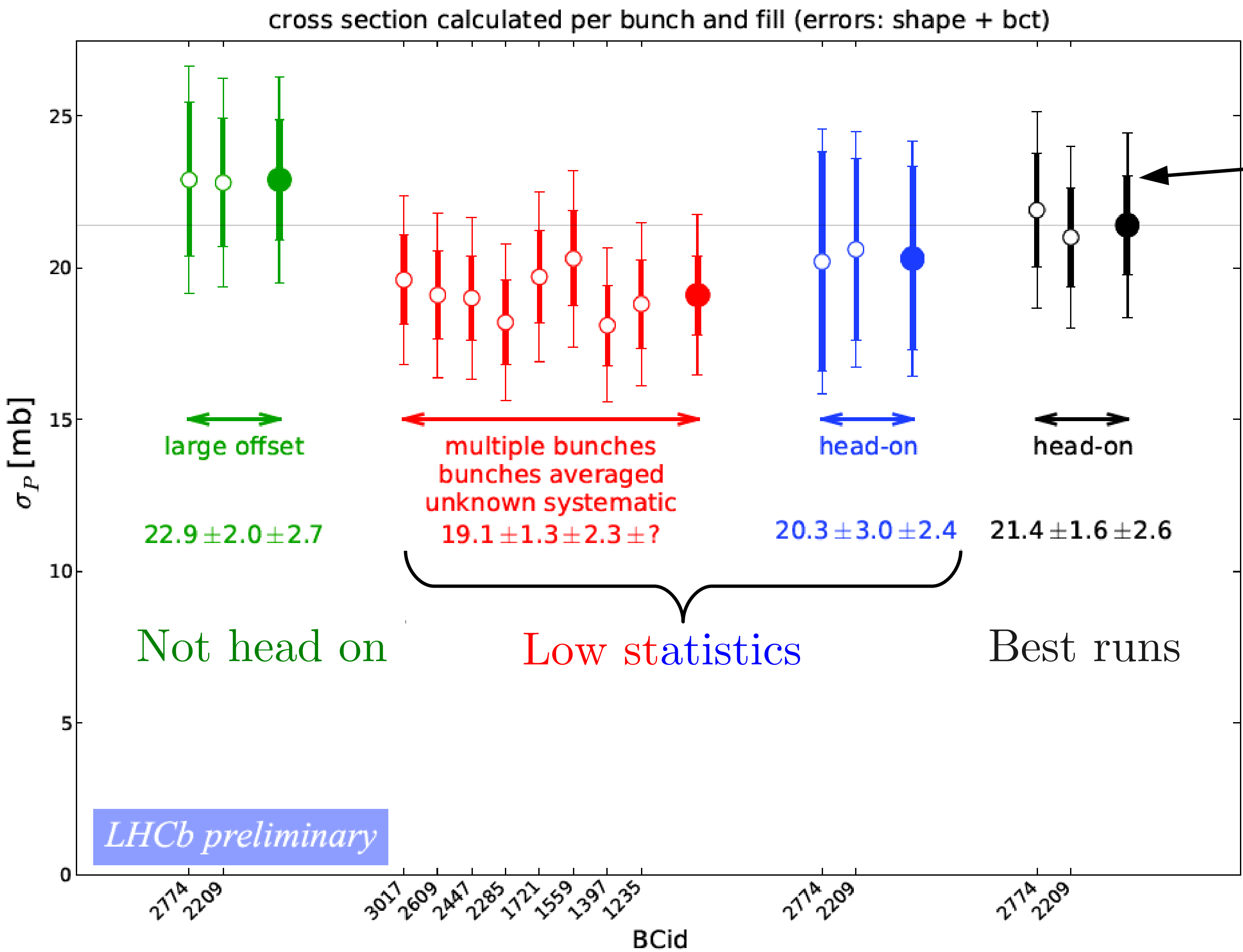
Time stability within one LHC fill

Event rate versus LHC beam intensity product in 5 min intervals for two bunch crossings (blue/red). No correction for overlap integral difference between bunches and its time dependence (low stat.)



Time stability between LHC fills

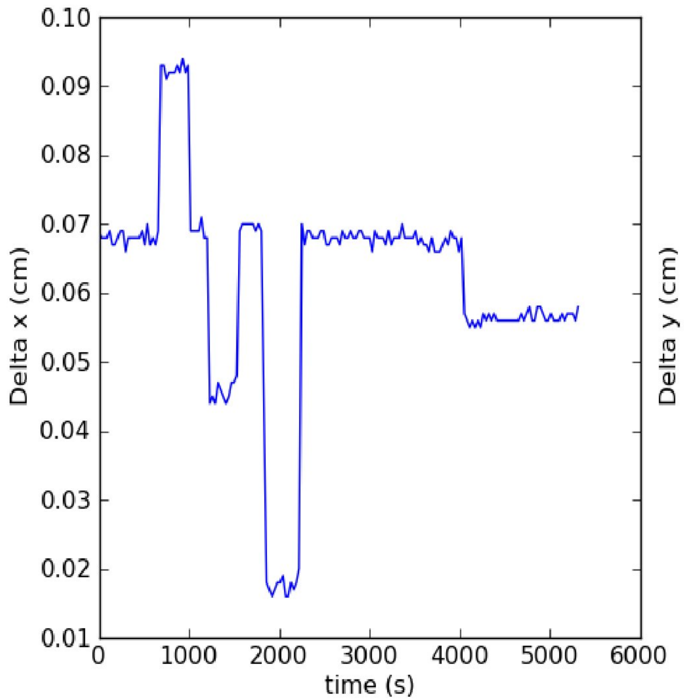
"Visible" cross section (after trigger and recon. eff. = 0.9*0.66):
before beam alignment, with 16+1 bunches, two LHC fills with VDM alignment

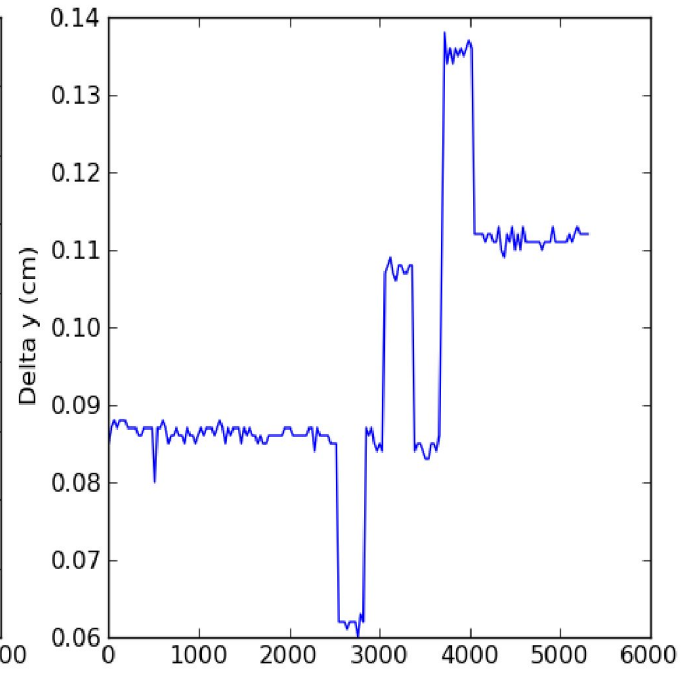


Without uncertainty in beam intensities

Measured pp inelastic cross section at 450 GeV:
(36±5) mb in agreement with 40 mb from PDG

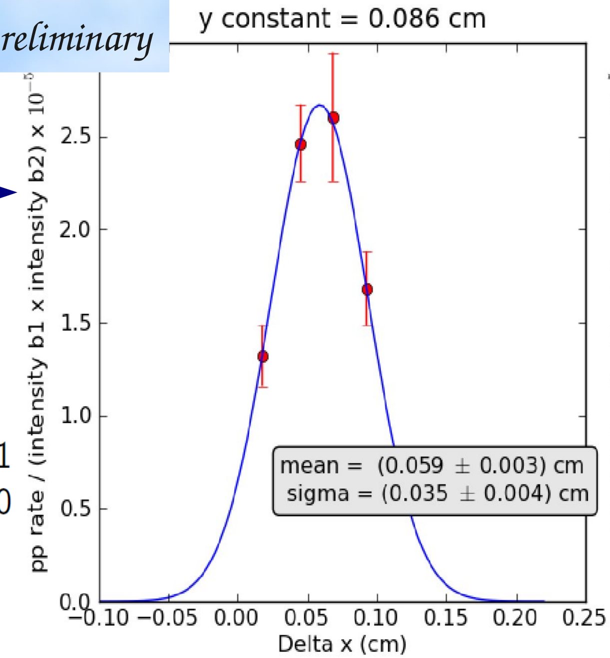
Cross check: van der Meer separation scan

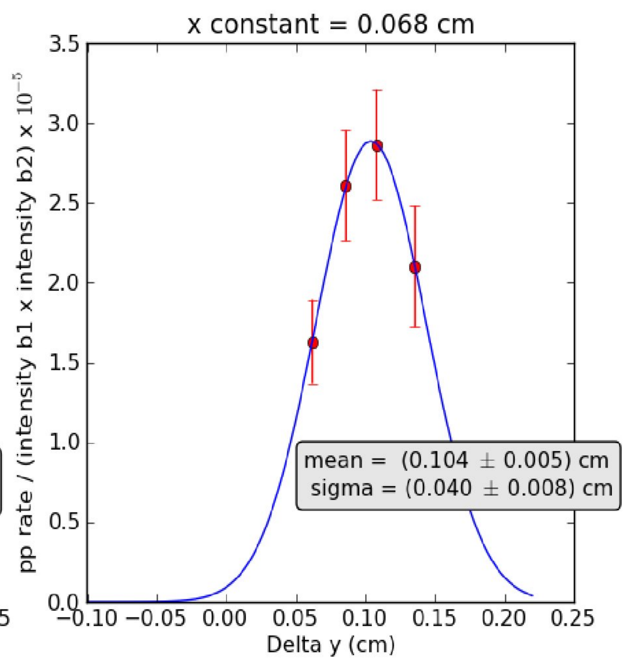




Beam separation in X, Y versus time

LHCb preliminary



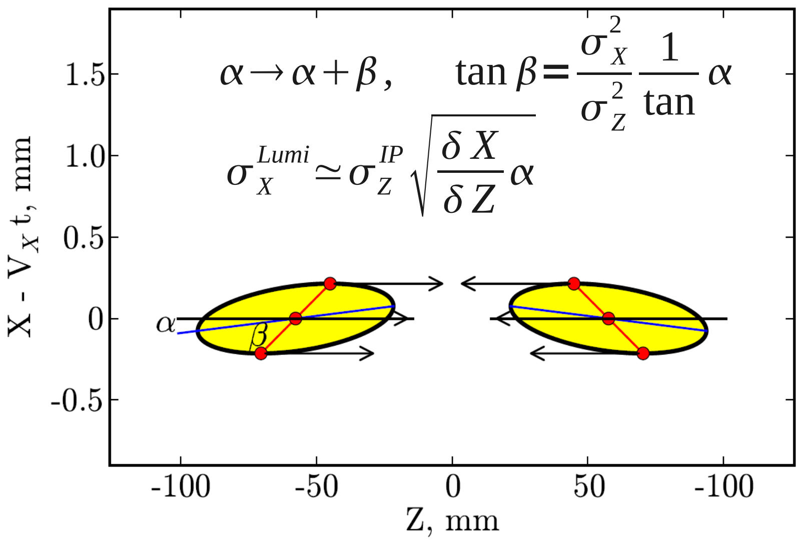


Luminosity change with sigma = $2^*\sigma_{IP}$, no contribution from VELO resolution

$\sigma_{X,Y}$ agree with fit results

fitted luminous region	0.186 ± 0.001	0.237 ± 0.001
from VDM scan	0.175 ± 0.020	0.200 ± 0.040

Cross check: van der Meer scan + crossing angle



In reference frame moving with beams along X: collision of two inclined ellipses.
Equivalent to collision of their centers = red lines.

Beam shift in X moves intersection in Z according to $\alpha+\beta$, dominated by β ($\beta/\alpha \simeq 5$).

$\Rightarrow \delta X/\delta Z$ measures β and $\sigma_x/\sigma_z \Rightarrow$ cross check σ_x

(VELO res. in Z $\simeq$1 mm $\ll \sigma_z$)

Agreement in σ_x from diff. methods

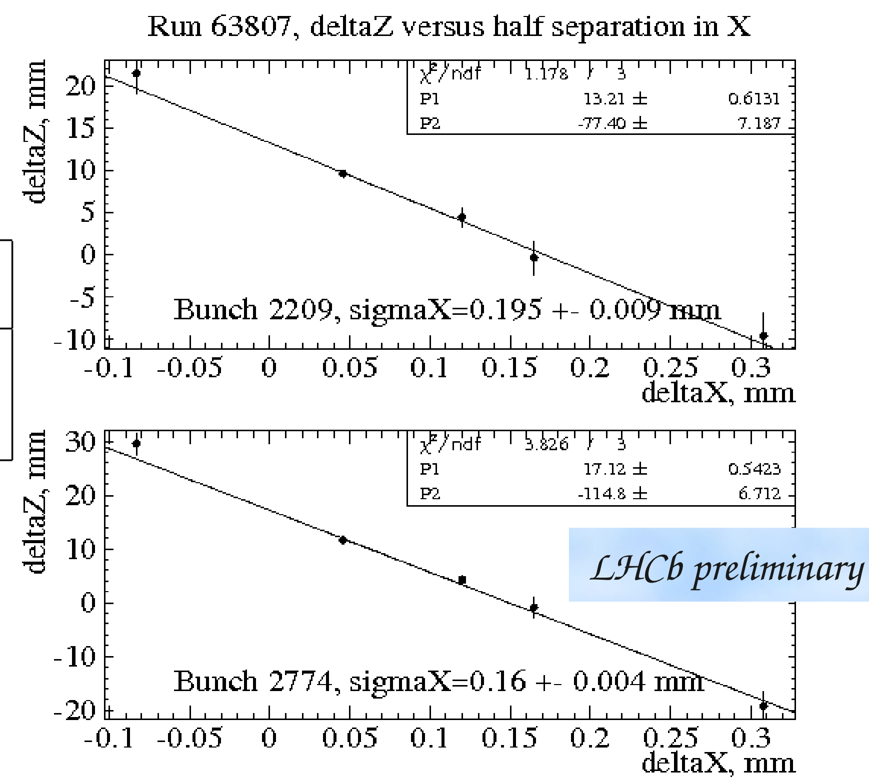
Fit results, change in time

BCid	σ_{BB} before VDM fit to vertices	during VDM from slope z/x	during VDM: VDM result	σ_{BB} after VDM fit to vertices
2209	0.198 $\pm$ 0.003	0.195 $\pm$ 0.009	0.175 $\pm$ 0.020	0.174 $\pm$ 0.006
2774	0.156 $\pm$ 0.003	0.160 $\pm$ 0.004		0.134 $\pm$ 0.004

LHCb preliminary

$\alpha+\beta$ slope

Luminosity change



Final results

Luminosity for all runs is calculated by counting beam-beam vertexes and by comparing to the "best running period".

Run	#Evs	#Vert.	Integrated Luminosity (cm^{-2})
63686	24391	8400	
63687	15642	5164	
63688	2169	730	
63690	20855	6448	
63691	2074	594	
63713	14295	4731	
63801	94112	29621	1.309e+30 ($\pm$15%)
63807	75285	22533	$\leftarrow$
63809	23465	6366	3.164e+29 ($\pm$19%)
63813	71429	29614	
63814	4629	1830	**1.696e+30** ($\pm$14%)
63815	11668	4504	
63949	64179	23668	1.252e+30
Sum		144203	**6.8$\pm$1.0** μb^{-1}

beam2-gas trigger not yet commissioned

before van der Meer scan

scan

beams aligned, first fill

Second fill, best precision, used for final result

16+1 bunches, low stat.

LHCb preliminary

Conclusions

1. Final result: $6.8 \pm 1.0\ \mu b^{-1}$

2. Open VELO precision was worse than nominal. In 2010 narrow 3.5 GeV beams will allow to close VELO and improve precision.

3. Current $\simeq$15% error is dominated by beam intensities. Expected precision in 2010: $\pm$5%

Backup slides

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.

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

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

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

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

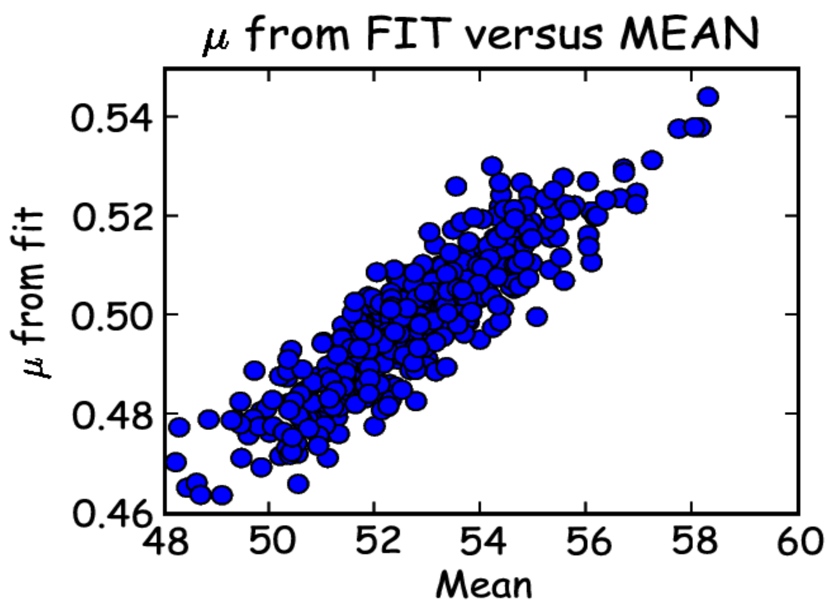
The same convolution law works when one event contains two interactions: if one interaction produces detector response I, two will give $I^F * I^F = (I^F)^2$.

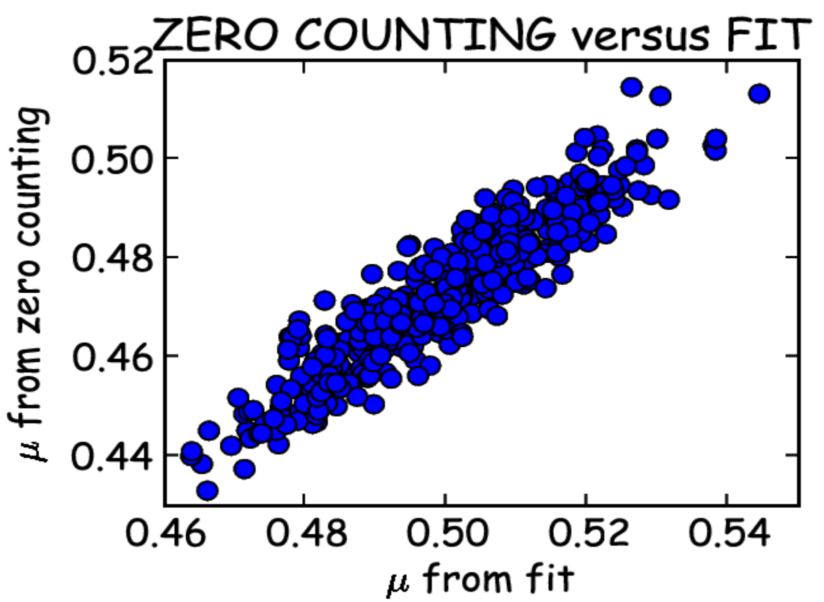
For Poisson distribution:

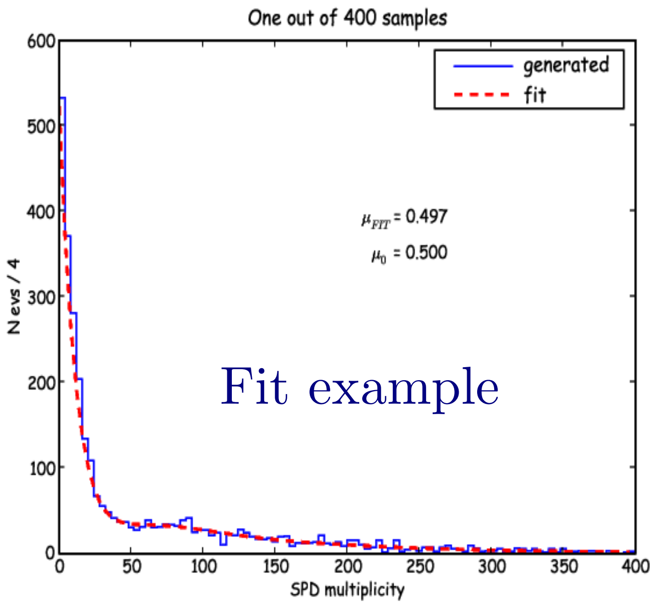
$$P^F = \sum_{n=0}^{\infty} \frac{e^{-\mu}\mu^n}{n!}(I^F)^n = \boxed{\exp\{\mu(I^F-1)\}}$$

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