THE BEAM GAS VERTEX DETECTOR

A non-invasive profile monitor for high energy accelerators

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On behalf of the BGV collaboration

Non-Invasive beam profile monitoring

Energy and luminosity independent

Beam Gas collisions

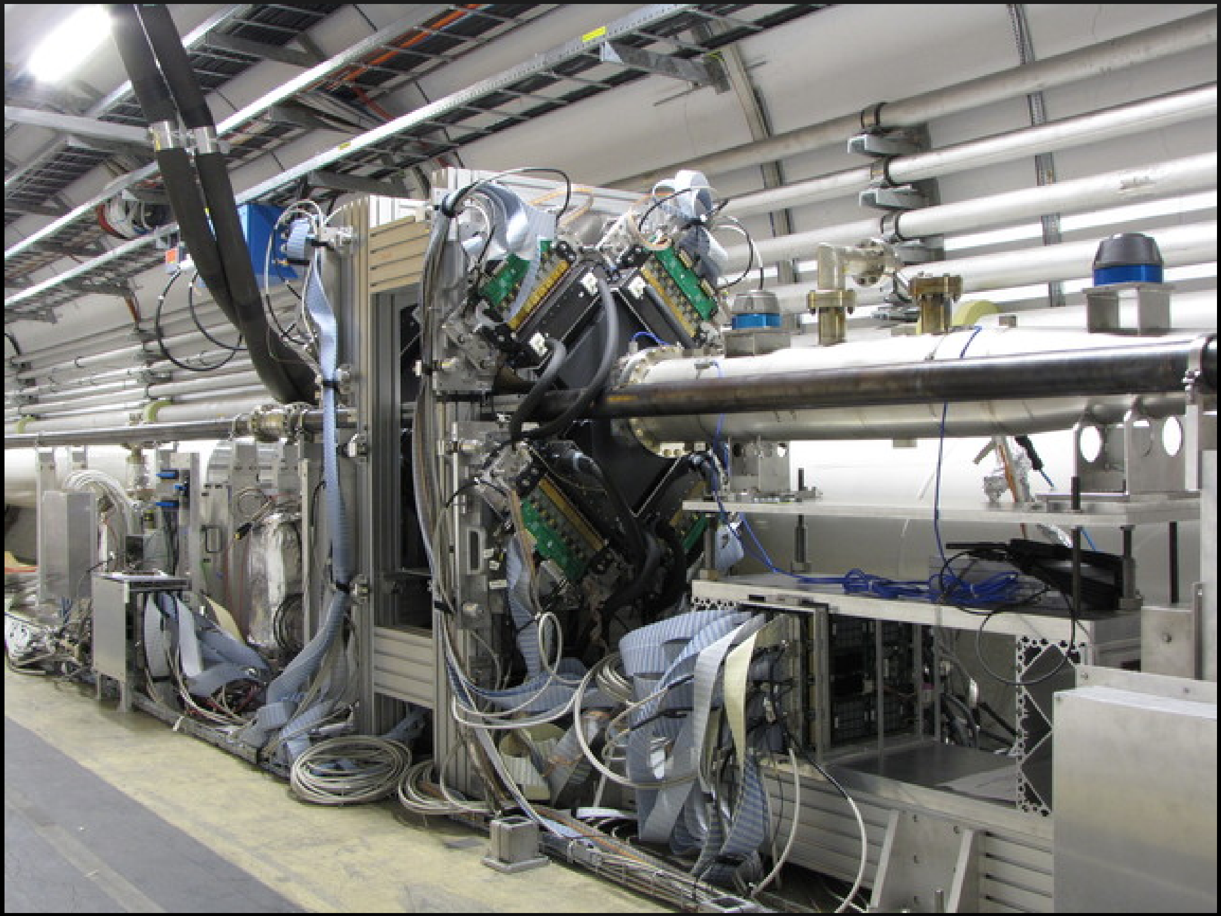
Inert gas	Local pressure bump

Reconstruction of collision points

Event selection	Precision tracker

BEAM GAS VERTEX (BGV) DETECTOR

Tracks from beam-gas interactions to reconstruct beam spot, Ne @ 10^{-7} mbar injected at interaction volume



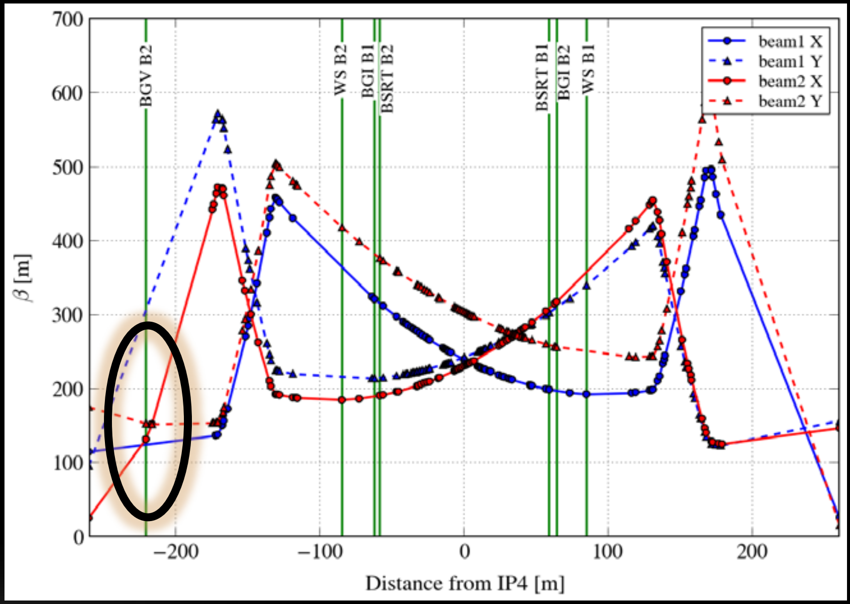
Expected beam spot size (and hence ε) measurements with precision <10% (5 minutes integration time)

BGV LOCATION

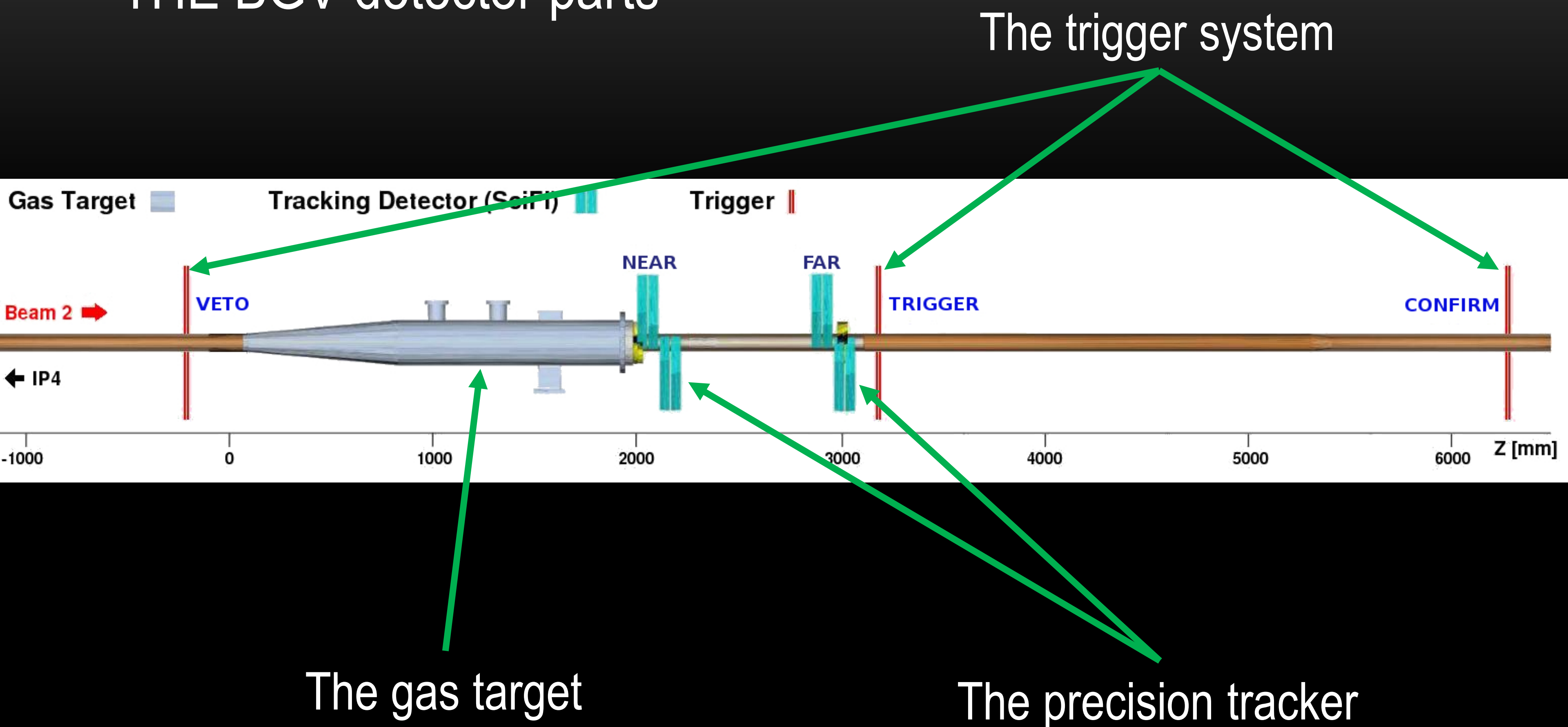
- Single beam demonstrator @ LHC, point 4, beam 2 ring

- at ~ -220m , beam 2 has $\beta_x \cong \beta_y \cong 150$ m
- at 7TeV and $\varepsilon_N \cong 2.5\mu m$, $\sigma_{beam} \cong 0.22$ mm

- $\beta_x \cong \beta_y$ allows beam pipe diameter reduction



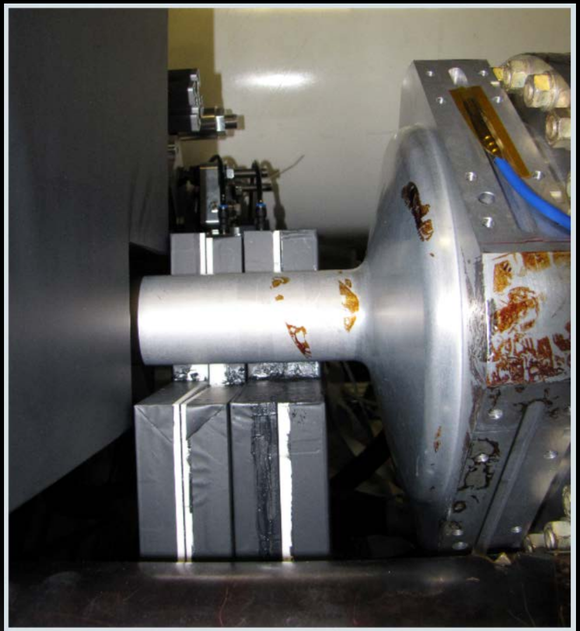
THE BGV detector parts



THE GAS TARGET

2m long gas volume:

- 0.75m conical tube (minimal beam impedance)
- 1.25m long cylinder (main interaction region)
- Thin (1 – 3 mm) exit window to reduce multiple scattering



Narrow beam pipe around BGV
(52 – 58 mm instead of nominal 80mm):

- Detector close to beam-gas interactions
  - Max. acceptance
  - Min extrapolation error
- Gas flow restriction : Increased gas pressure in target (10^{-7} mbar)

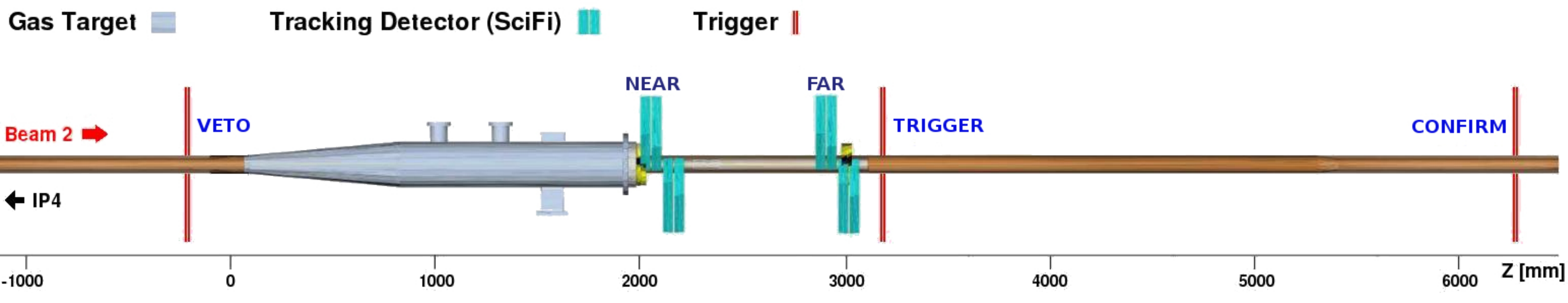
GAS TARGET OPERATING CONDITIONS

Expected beam-gas interaction rate:

$$R(Hz) = 2.5 \cdot 10^{-11}\, p(mbar)\, \Delta z(cm)\, \sigma_{pA}\, N\, f_{rev}(Hz)$$

- p the gas pressure (10^{-7} mbar)
- σ_{pA} the proton nucleus cross-section (295 mb for 7 TeV p on Ne target)
- N the number of protons per bunch (10^{11})
- f_{rev} the bunch revolution frequency (11.245 kHz)
- Δz the gas volume length along the beam axis (100 cm)

→ $\boldsymbol{R = 81\ Hz}$ **per bunch**



THE TRIGGER SYSTEM

Set of three scintillator planes (30x30 cm above and below beam line), not in particles' path between beam-gas collision and tracking measurements:

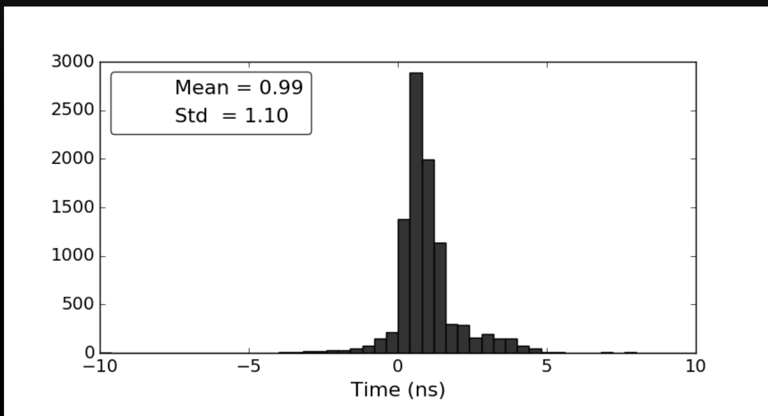
- VETO (upstream, before precision tracker)
- SIGNAL and CONFIRM (downstream, after tracker)

TRIGGER = SIGNAL · CONFIRM · $\overline{VETO}$

Trigger rate $\simeq$ 300 Hz per LHC bunch

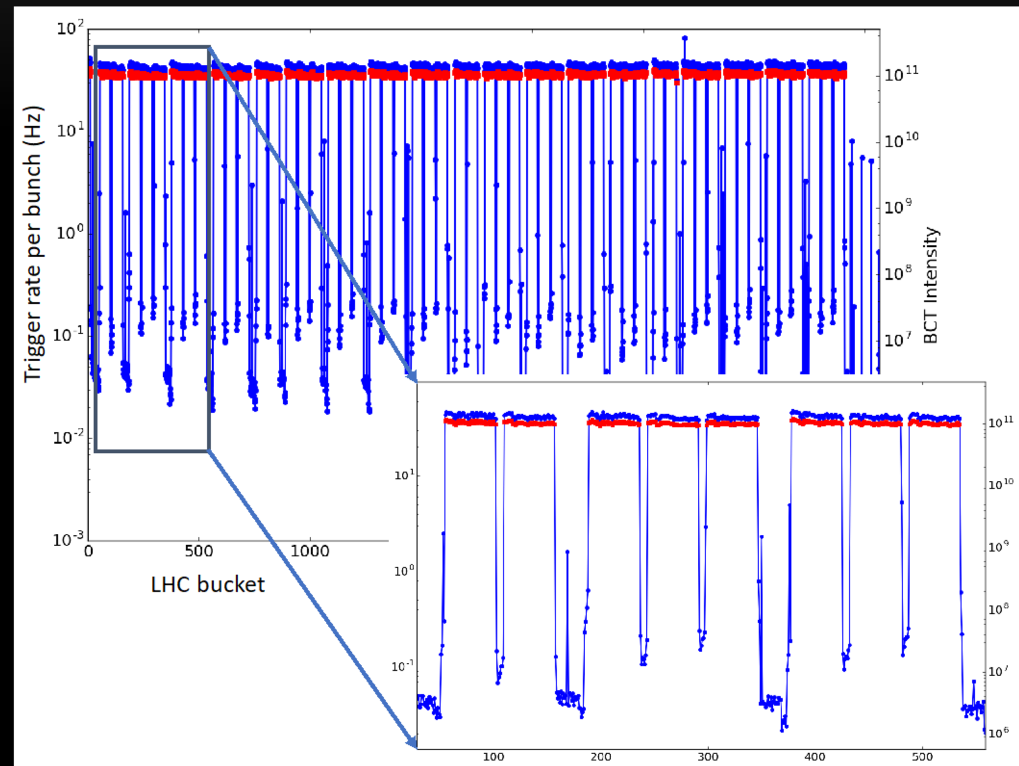
TRIGGER DETECTOR PERFORMANCE

- 1 ns resolution – easy beam bunch identification
- Background contamination < 10^{-4}



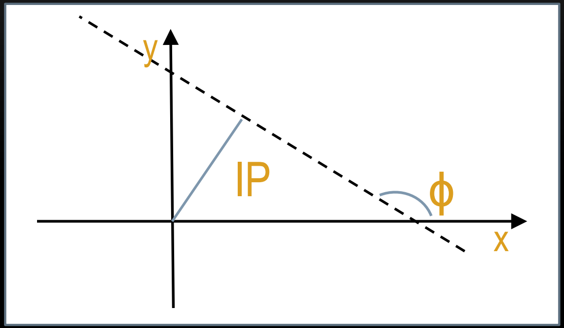
Adjusted time difference between SIGNAL and CONFIRM planes

LHC bunch structure as seen by BGV Trigger



Standalone measurement:
Ghost charge fraction = 0.29% ± 0.03%

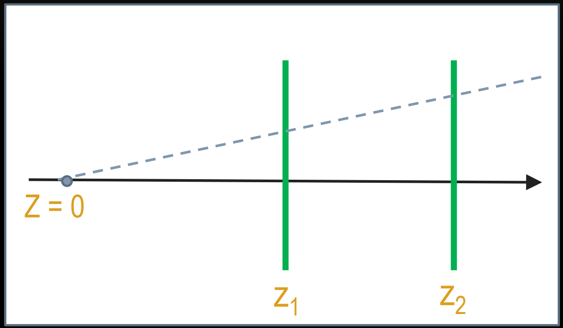
IMPACT PARAMETER (IP) MEASUREMENT



IP resolution depends on extrapolation error and multiple scattering (at 1st station):

- $\sigma_{IP}^2 = \sigma_{Extrap}^2 + \sigma_{MultScat}^2$
- $\sigma_{Extrap}^2 = \frac{z_1^2 + z_2^2}{(z_2 - z_1)^2}\ \sigma_{hit}^2$
- $\sigma_{Multscat} = z_1 \frac{13.6\ MeV}{p} \sqrt{\frac{x}{X_0}}$

Use two detectors along z

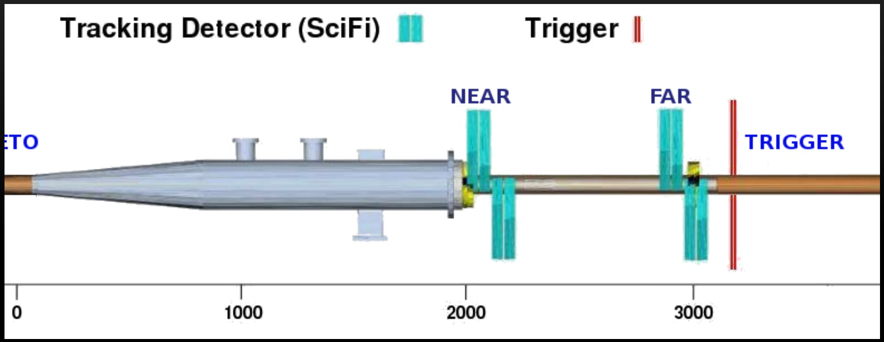


Optimization:

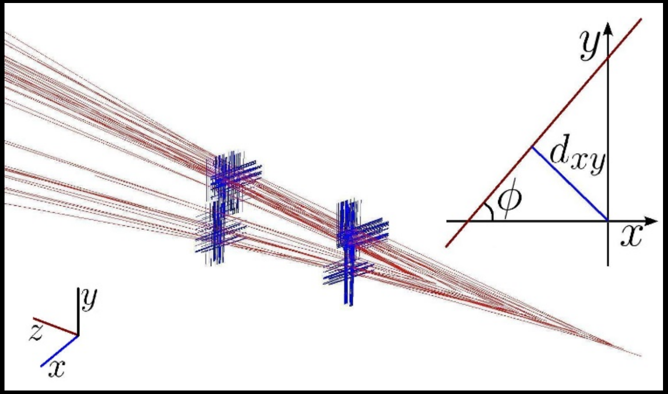
- Min z and max Δz
- Good Spatial resolution
- Thin detectors

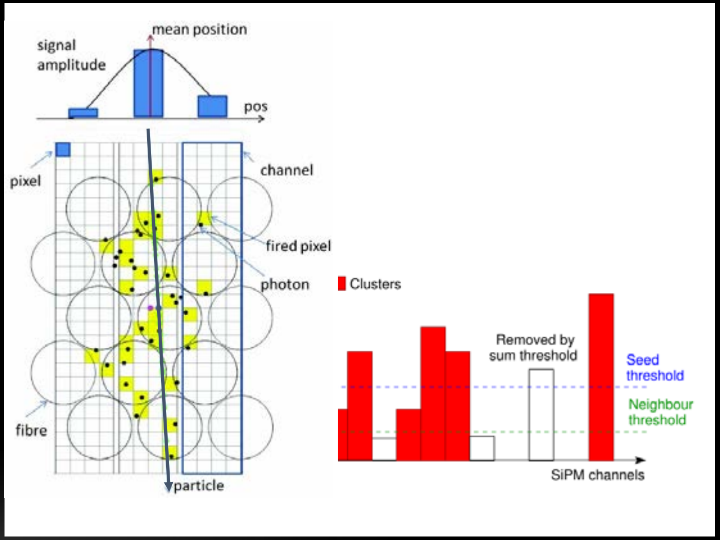
To get comparable values for both error contributions

THE PRECISION TRACKER



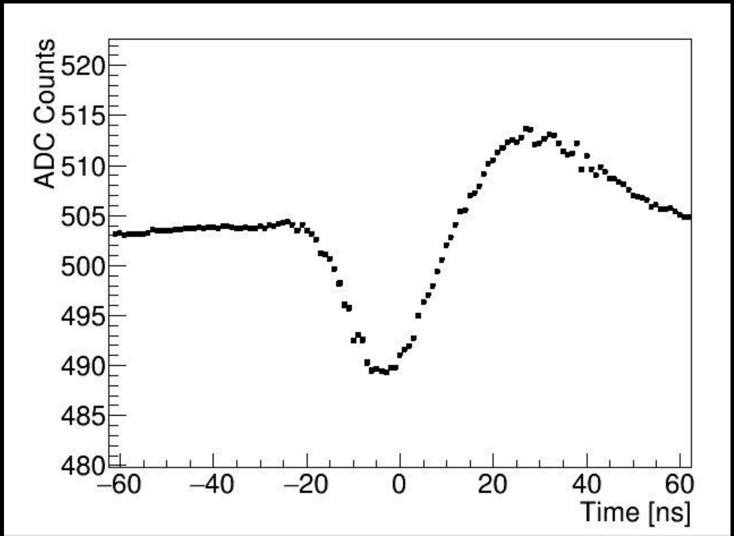
- 4 Scintillating fibre (SciFi) (250 μm) modules (x, x', y, y') per (NEAR/FAR) station
- 4 (NEAR), 5 (FAR) SciFi planes per module
- $\Delta z = 1$ m
- $\sigma_{hit} \simeq 50$ μm





FIBRES READ OUT WITH SI PM

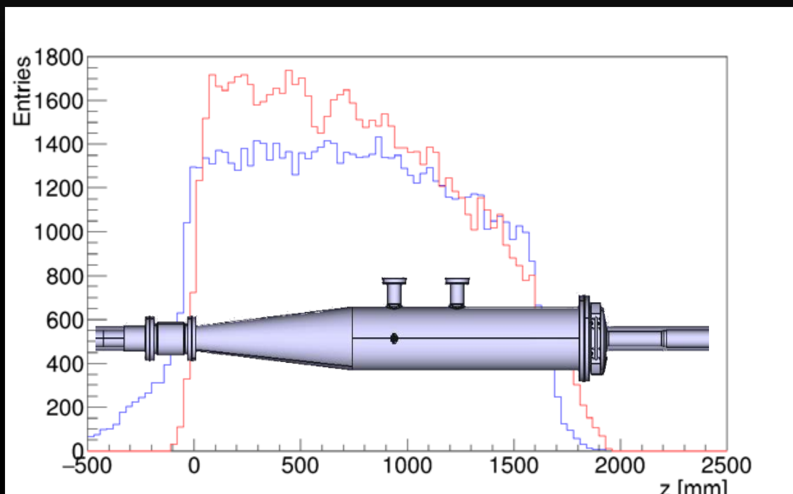
Analogue Si PM signals are send to service tunnel (low radiation) for digitization and recording



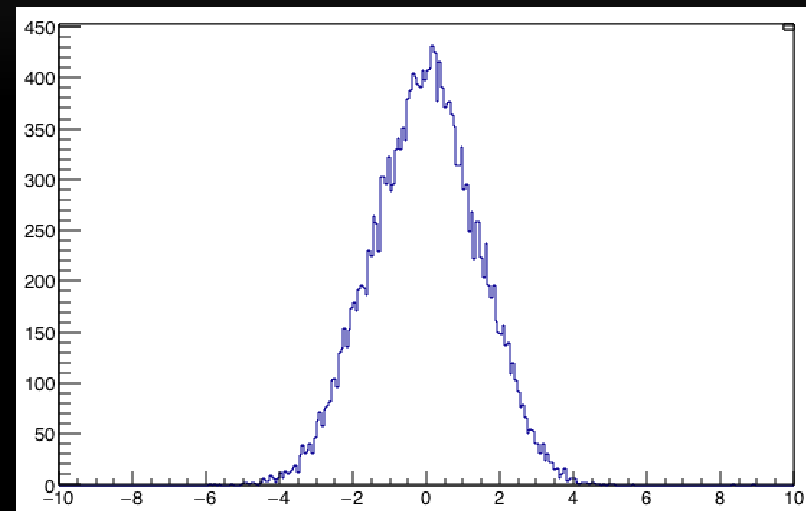
SiPM pulse shape

Fix ADC sampling point wrt the trigger BCID
In order to digitize the negative peak of the distribution

FIRST LOOK AT REAL DATA



IP vs Z : Real data (blue) and Simulation (red)

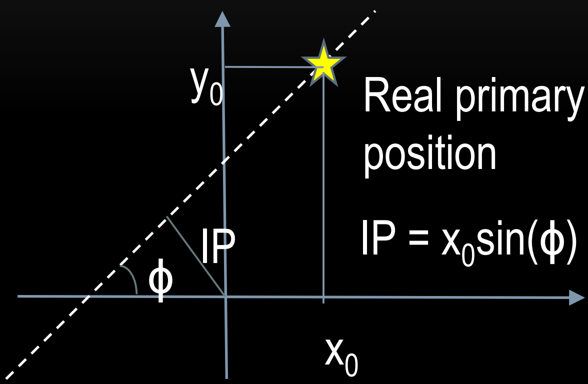


IP distribution

Cannot be used directly for beam profile:

- Convolution of beam width and σ_{IP}
- σ_{IP} depends heavily on z

BEAM POSITION MEASUREMENT

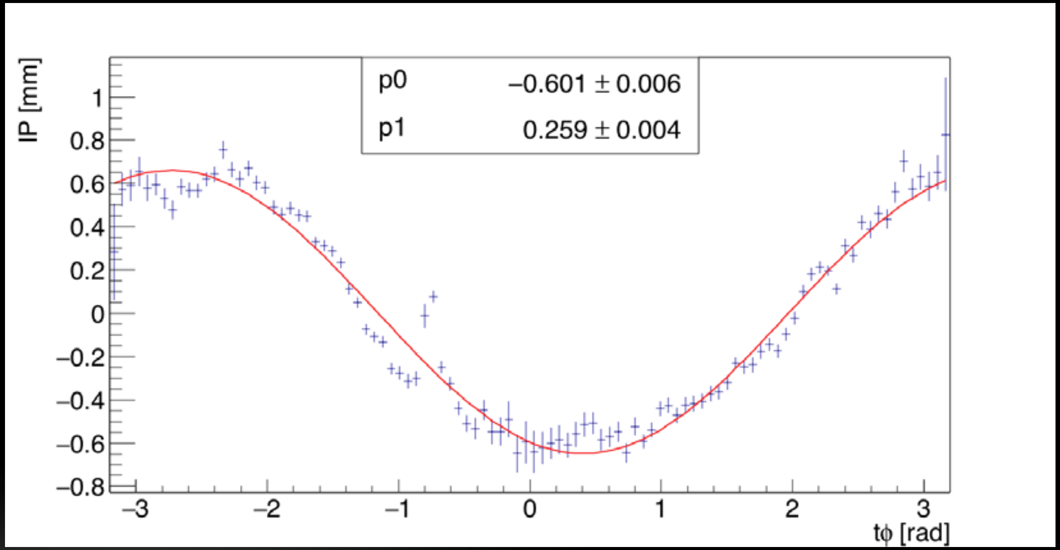


Real primary vertex position

$IP = x_0 \sin(\phi) - y_0 \cos(\phi)$

LHC fill 6082, beam 2 position measured:

(x, y) = (-0.6 mm, 0.26 mm)



BEAM WIDTH MEASUREMENT

IP and ϕ of particles from the same primary vertex are correlated.
This correlation for pairs of tracks (1,2 from the same event) is given by:

$$\langle IP_1\ IP_2 \rangle = \frac{\sigma_x^2 + \sigma_y^2}{2} \cos(\phi_1 - \phi_2) + \frac{\sigma_y^2 - \sigma_x^2}{2} \cos(\phi_1 + \phi_2)$$

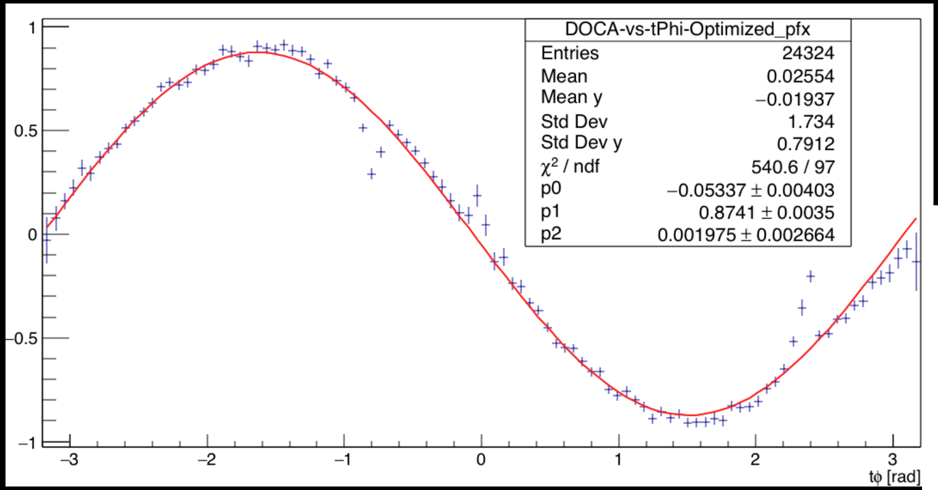
σ_x^2 (σ_y^2) being the beam spot variance along x (y)

If $\sigma_x^2 = \sigma_y^2 = \sigma_{beam}^2 \rightarrow \langle IP_1\ IP_2 \rangle = \sigma_{beam}^2 \cos(\phi_1 - \phi_2)$

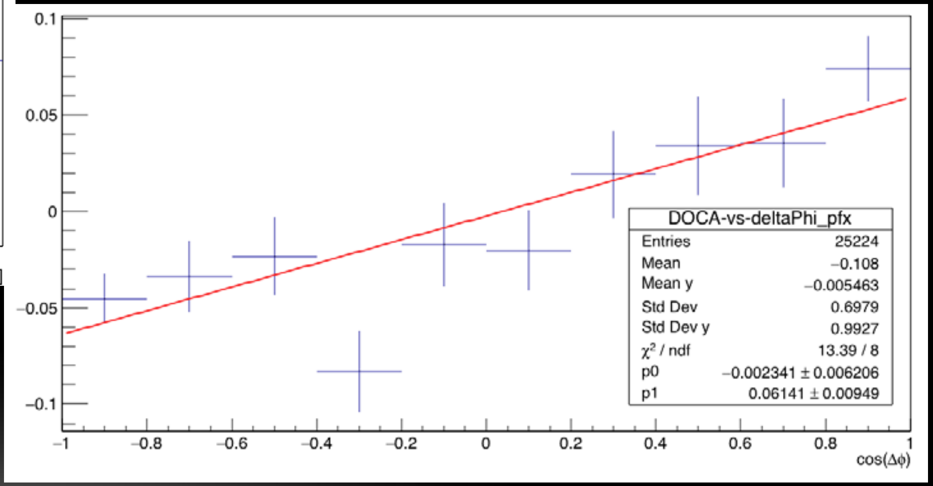
This correlation does not depend on σ_{IP}

MC STUDY OF ANALYSIS METHOD

Simulated p-Ne interactions @ (x,y) = (1 mm, 0 mm) all along the BGV z acceptance.
Simulated beam width σ_{beam} = 0.3 mm
Reconstruction and analysis with full BGV simulation

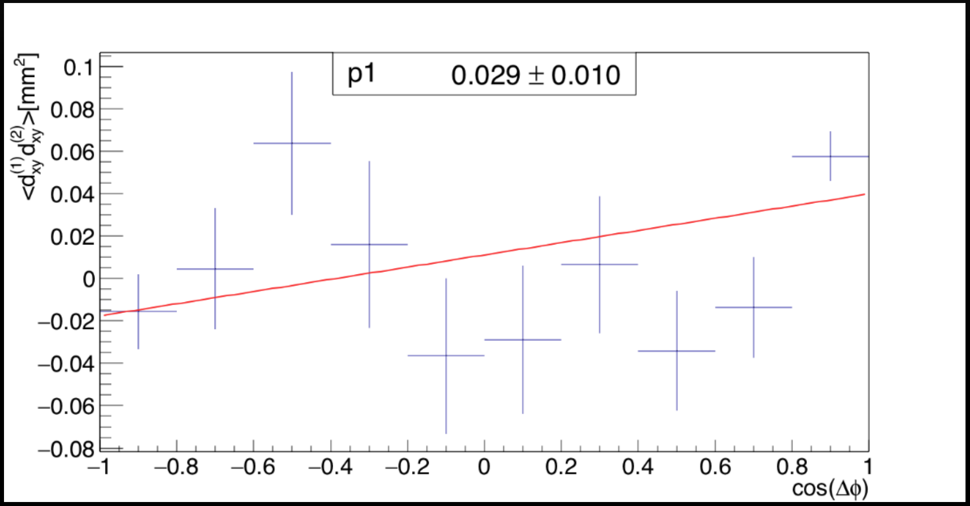


Reconstructed:
(x, y) = (-0.87 mm, 0.0 mm)
σ_{beam} = 0.25 mm ± 0.01 mm



Analysis introduced bias to be understood and corrected

IP CORRELATION → σ_{beam}



σ_{beam} = 0.17 ± 0.10 (stat) mm

Preliminary results, no estimation of systematic errors given
Spread of points indicate issues with the current tracking algorithm

BGV UPGRADES

- Move from Ne to Ar ($\sigma_{pA}(E) \sim \sigma_{pp}(E) a^{2/3}$), expect 50% increase in rate and track multiplicity per event
- Make thinner gas target exit window (max. 1mm) and evaluate Be option
- Use Si-strip or MicroMegas detectors for improved resolution and reduced material (100 – 200 µm thick detectors)
- Study installation of a fast tracker (50ps resolution) for longitudinal beam profile measurement

SUMMARY

- BGV demonstrator operational @ LHC point 4, beam 2
- Ne @ 10^{-7} mbar
- Excellent trigger and SciFi performance (10^{-4} background contamination, 99.7% of channels operational)

- First results: beam width estimation with 0.10mm error. Statistics and reconstruction method will improve this number significantly

- Measurements to be sent to LHC Control room before end of 2017

- Upgraded BGV design to be installed at HL-LHC

BACK UP SLIDES

MORE INFORMATION

All BGV-related information can be found in the dedicated twiki page :

https://twiki.cern.ch/twiki/bin/view/BGV/WebHome

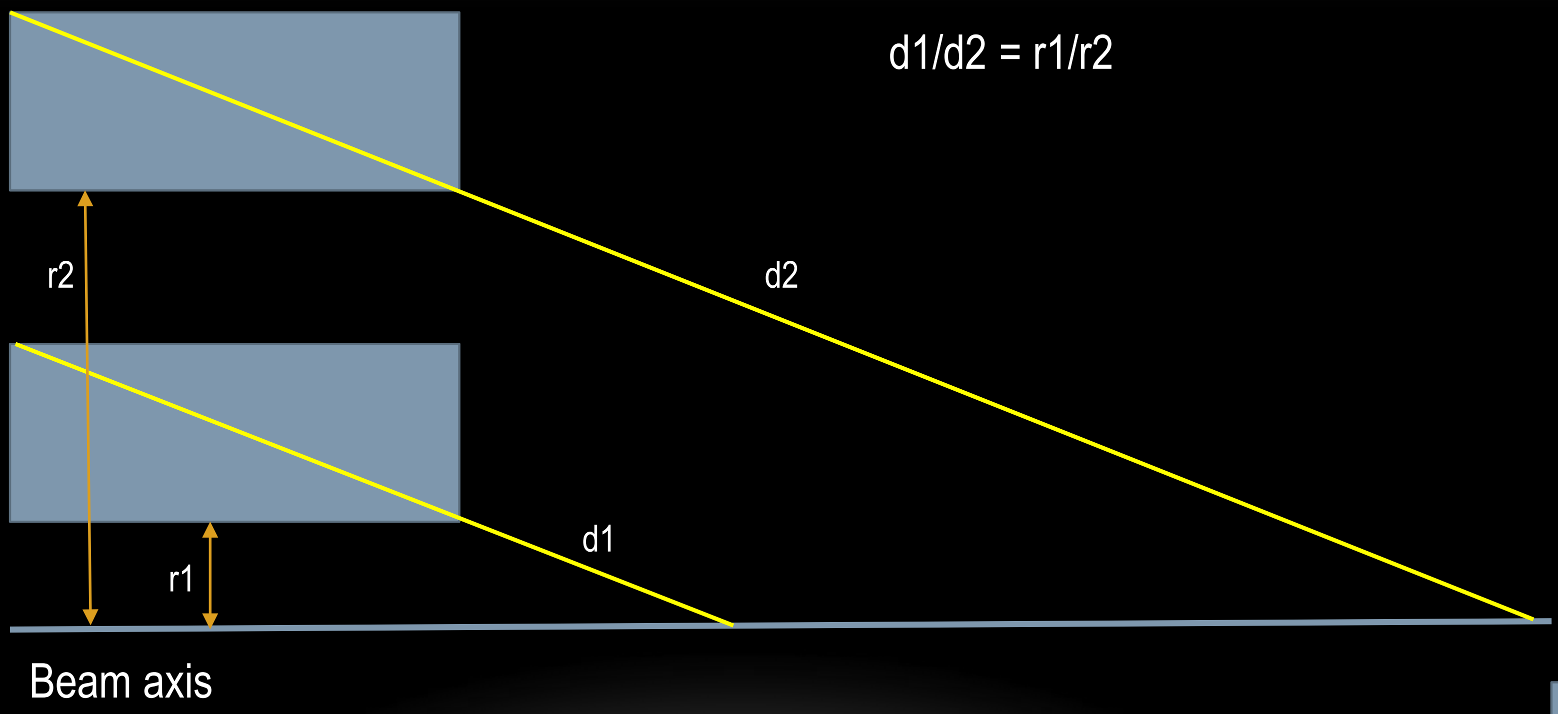
EVENT RATE ESTIMATION

$$R = \int_{z_a}^{z_b} \rho(z)dz\ \sigma_{pA}(E)N\ f_{rev}$$

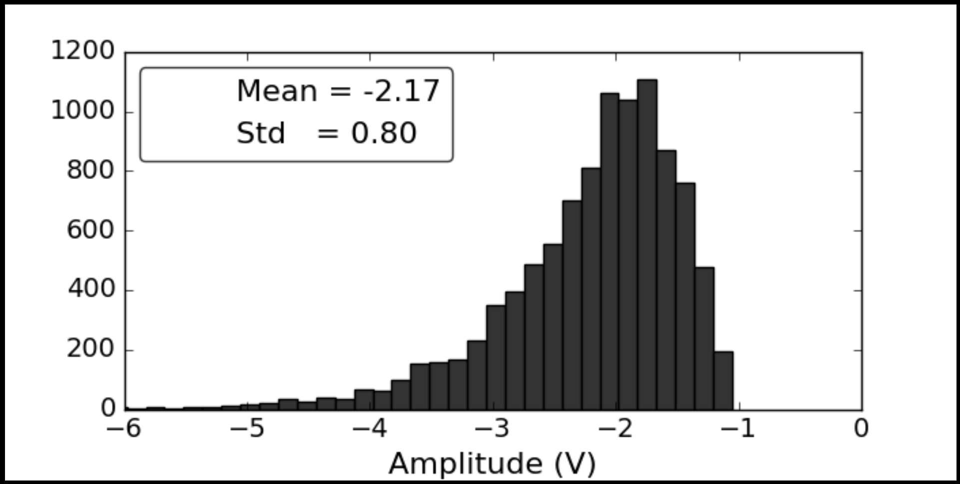
where

- $\rho(z)$ the gas density
- $\sigma_{pA}(E)$ the proton nucleus cross-section
- N the number of protons per bunch
- f_{rev} the bunch revolution frequency
- $z_a$and z_b the detector acceptance limits along the beam xis

DETECTOR POSITION AND EXTRAPOLATION ERROR



TRIGGER SCINTILLATOR AMPLITUDE

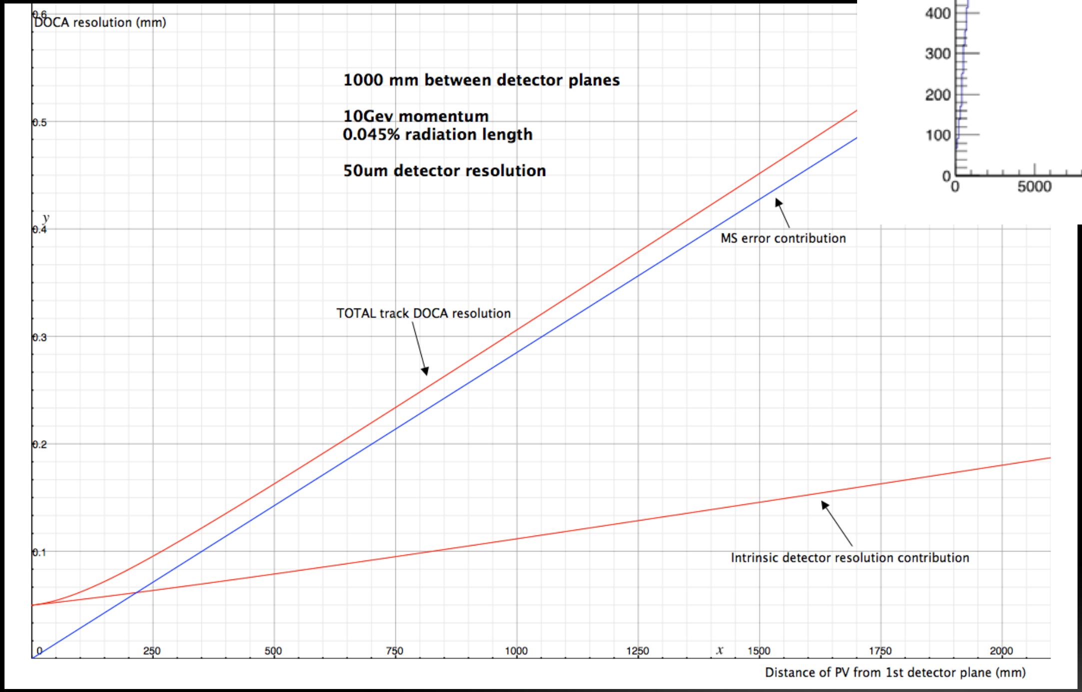


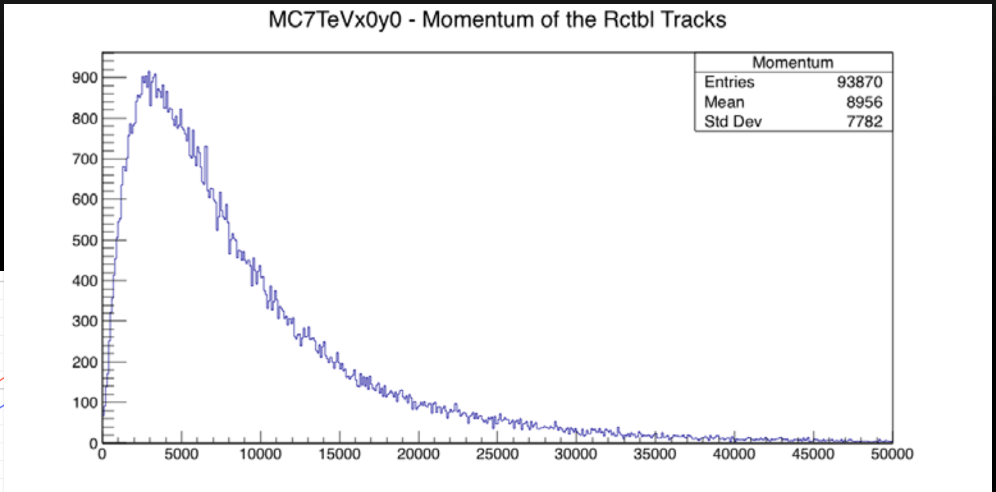
TRIGGER RATES

	SIGNAL	SIGNAL - VETO	SIGNAL + CONFIRM – VETO
Full LHC buckets	426	306	273
Empty LHC buckets	1.27	1.26	0.14

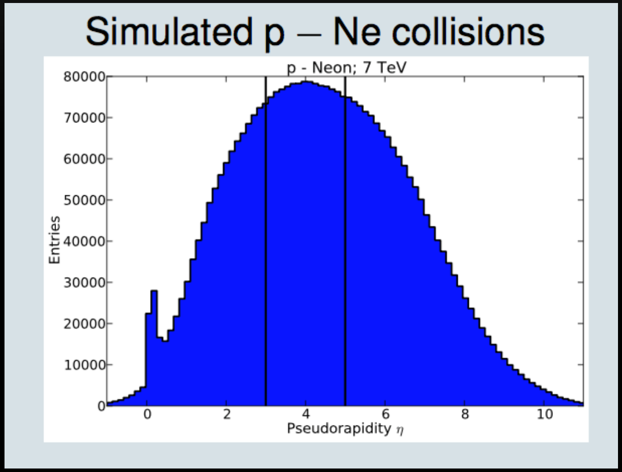
In Hz/bucket, with full gas in BGV

MULTIPLE SCATTERING AND EXTRAPOLATION ERROR

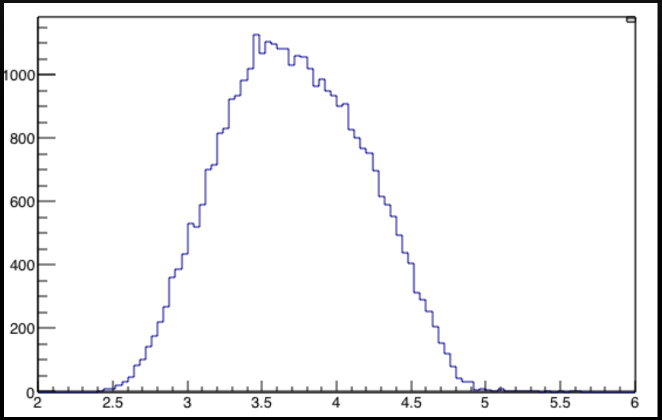




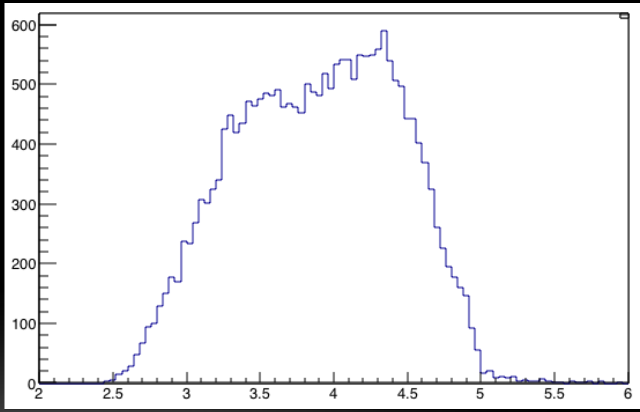
DETECTOR PSEUDO-RAPIDITY COVERAGE



Simulation of beam gas collisions



BGV Simulation

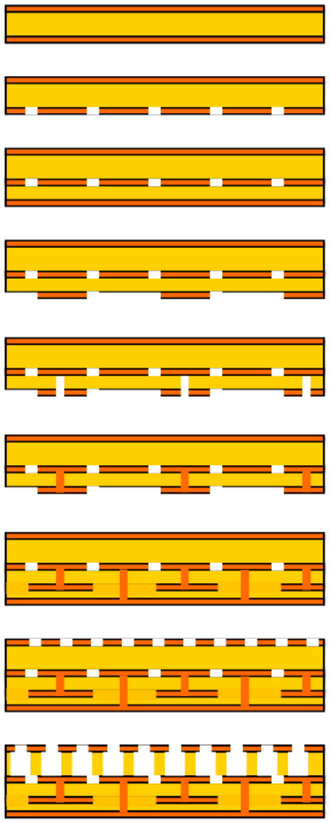


BGV Real Data

MICROBULK MICROMEGAS

Building a Microbulk

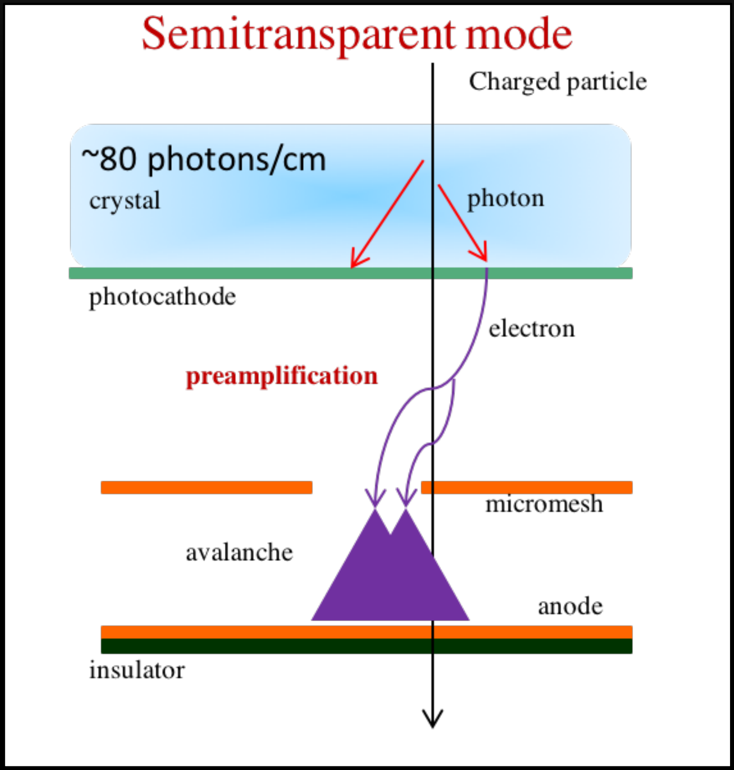
- Kapton foil (50 μm), both side Cu-coated (5 μm)
- Construction of readout strips/pads (photolithography)
- Attachment of a single-side Cu-coated kapton foil (25/5 μm)
- Construction of readout lines
- Etching of kapton
- Vias construction
- 2nd Layer of Cu-coated kapton
- Photochemical production of mesh holes
- Kapton etching
- Cleaning



To be used in high rate environments, a resistive strip plane has to be added (BGV ~ 1KHz/cm^2)

MICROMEGAS PS DETECTOR

For reconstructing the z profile of a beam bunch : need ~50ps resolution



MM: small amplification gap (50-150 μm)
- fast signals (~ 1 ns)
- short recovery time (~50 ns)
- high rate capabilities (> MHz/cm^2)
- high gain (up to 10^5 or more)

Time resolution already achieved: <50ps

Anode can be in the form of wide (~cm) strips to match the BGV geometry

To be placed possibly at the L0 confirm support frame

For more details see BE-BI seminar:
MicroMegas detector applications for beam diagnostics https://indico.cern.ch/event/540799/

BGV MODULE
TEST BEAM MEASUREMENTS

Hit resolution and detection efficiency of a BGV fibre (4-layer) module was measured at the SPS test beam facilities (north area). A fibre-based beam telescope developped at EPFL was used to provide the track ($\sigma_{track} \approx 40$ μm).

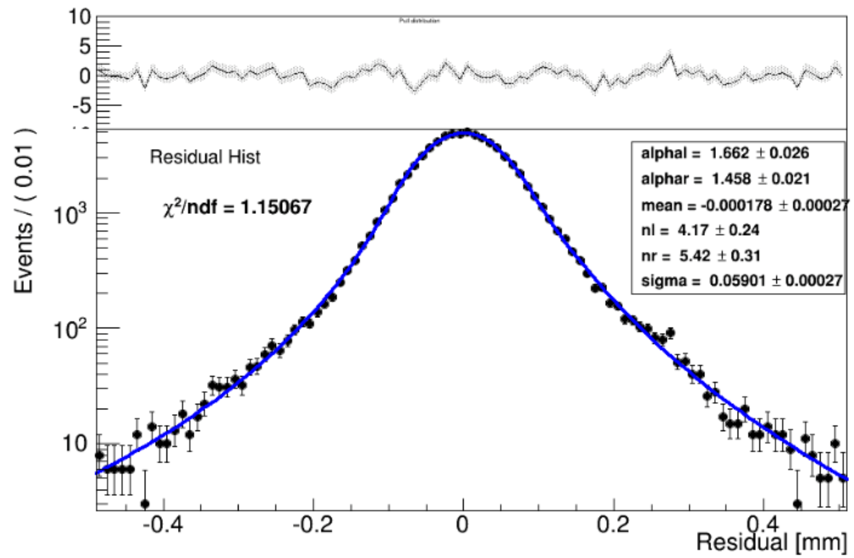
The hit resolution is:

$$\boldsymbol{\sigma_{hit} \approx 40\ \mu m}$$

And hit detection efficiency (with the signal thresholds currently forseen):

$$\boldsymbol{\varepsilon_{hit} = 98\%}$$

Example of residual distribtuion for one the BGV fibre plane



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Courtesy: O. Girard - EPFL

- DAQ installed in TS2 2015
- All systems functional
- A single chassis (HP ProLiant "Blade") hosts the control server and CPU boards
  - Thanks to BE-CO

- Racks layout
- Rack photos

LHC – HL-LHC

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)	LHC (CERN)		
Physics start date	1992	1987	2001	2009	2015	2024 (HL-LHC)
Physics end date	2007	2011	—	—		
Particles collided	ep	$p\bar{p}$	pp (polarized)	pp		
Maximum beam energy (TeV)	e: 0.030 p: 0.92	0.980	0.255 53% polarization	4.0	6.5	7.0
Maximum delivered integrated luminosity per exp. (fb^{-1})	0.8	12	0.38 at 100 GeV 0.75 at 250/255 GeV	23.3 at 4.0 TeV 6.1 at 3.5 TeV	4.2	250/y
Luminosity (10^{30} $cm^{-2}s^{-1}$)	75	431	245 (pk) 160 (avg)	7.7×10^3	5×10^3	5.0×10^4 (leveled)
Time between collisions (ns)	96	396	107	49.90	24.95	24.95
Full crossing angle (μ rad)	0	0	0	290	290	590
Energy spread (units 10^{-3})	e: 0.91 p: 0.2	0.14	0.15	0.1445	0.105	0.123
Bunch length (cm)	e: 0.83 p: 8.5	p: 50 $\bar{p}$: 45	60	9.4	9	9
Beam radius (10^{-6} m)	e: $110(H), 30(V)$ p: $111(H), 30(V)$	p: 28 $\bar{p}$: 16	85	18.8	21	7
Free space at interaction point (m)	±2	±6.5	16	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	10	6 (avg)	7.5	≈ 6	≈ 30	≈ 6 (leveled)
Turn-around time (min)	e: 75, p: 135	90	25	180	134	180
Injection energy (TeV)	e: 0.012 p: 0.040	0.15	0.023	0.450	0.450	0.450
Transverse emittance (10^{-9} m)	e: $20(H), 3.5(V)$ p: $5(H), 5(V)$	p: 3 $\bar{p}$: 1	13	0.59	0.5	0.34
β^*, ampl. function at interaction point (m)	e: $0.6(H), 0.26(V)$ p: $2.45(H), 0.18(V)$	0.28	0.65	0.6	0.8	0.15
Beam-beam tune shift per crossing (units 10^{-4})	e: $190(H), 450(V)$ p: $12(H), 9(V)$	p: 120 $\bar{p}$: 120	73	72	37	110
RF frequency (MHz)	e: 499.7 p: 208.2/52.05	53	accel: 9 store: 28	400.8	400.8	400.8
Particles per bunch (units 10^{10})	e: 3 p: 7	p: 26 $\bar{p}$: 9	18.5	16	12	22
Bunches per ring per species	e: 189 p: 180	36	111	1380	2244 2232 (i.r. $1/5^{\dagger}$)	2748 2736 (i.r. $1/5^{\dagger}$)
Average beam current per species (mA)	e: 40 p: 90	p: 70 $\bar{p}$: 24	257	400	467	1200
Circumference (km)	6.336	6.28	3.834	26.659		
Interaction regions	2 colliding beams 1 fixed target (e beam)	2 high $\mathscr{L}$	6 total, 2 high $\mathscr{L}$	4 total, 2 high $\mathscr{L}$		
Magnetic length of dipole (m)	e: 9.185 p: 8.82	6.12	9.45	14.3		
Length of standard cell (m)	e: 23.5 p: 47	59.5	29.7	106.90		
Phase advance per cell (deg)	e: 60 p: 90	67.8	84	90		
Dipoles in ring	e: 396 p: 416	774	192 per ring + 12 common	1232 main dipoles		
Quadrupoles in ring	e: 580 p: 280	216	246 per ring	482 2-in-1 24 1-in-1		
Magnet types	e: C-shaped p: s.c., collared, warm iron	s.c., $\cos\theta$ warm iron	s.c., $\cos\theta$ cold iron	s.c., 2 in 1 cold iron		
Peak magnetic field (T)	e: 0.274, p: 5	4.4	3.5	$8.3^{\ddagger}$		