Beam Gas Vertex instruments for HL-LHC

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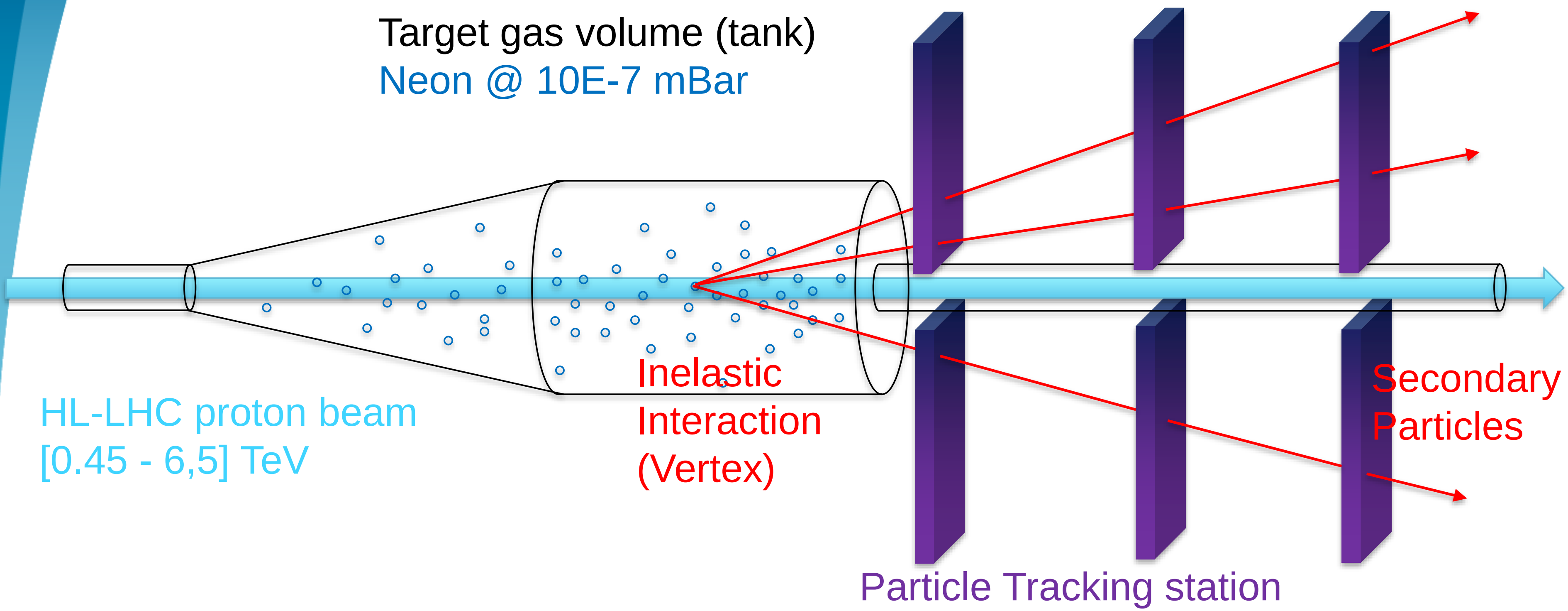
Overview

- (Re-)Introduction to the BGV
- From the BGV-demonstrator to HL-BGV
- New gas target design for the HL-BGV.
- Tracker development:
  - ➢ Geometry optimization and acceptance
  - ➢ Tracking sensor development
  - ➢ Readout acquisition system

Beam Gas Vertex profile monitoring



The BGV is nothing else than a small scale HEP fixed target experiment.

- Vacuum technology: Gas target development
- Tracking technology: Detector development and associated readout electronic chain.
- Reconstruction: Pattern recognition and global track fitting, to build vertexes.
- Real time processing: Like Level1 trigger in LHC experiments.

Motivation for the HL-BGV upgrade

- The **BGV prototype** is made of 4 bi-directional sensor planes arranged in two stations.
- The amount of fake reconstructed tracks is **above 30%** with **only 2 tracks** per event in average.
- Accurate **vertexing** is impossible in these conditions.

Hopefully these tracks are not completely random!

- The use of a **track correlation method** allowed us to use the **BGV prototype** to estimate the beam size without actually building a beam profile.
- We assumed a perfect Gaussian beam shape since no information on the shape and tilt of the beam can be accurately obtained with the correlation method.

Motivation for the HL-BGV upgrade

In order to move forward for HL-LHC with an operational BGV device a **complete redesign** is mandatory to **reach accurate vertexing**:

- Increase the number of sensor layers and coverage to allow **global tracking** methods.
- Reduce multiple scattering in reconstructed events by selecting **low material budget** technology for the sensors and exit window.
- Redesign the **gas target** to record all vertexes in a mm scale area along the beam (i.e. where vertexing resolution is optimum).

Constraint on beam size with new BGV design

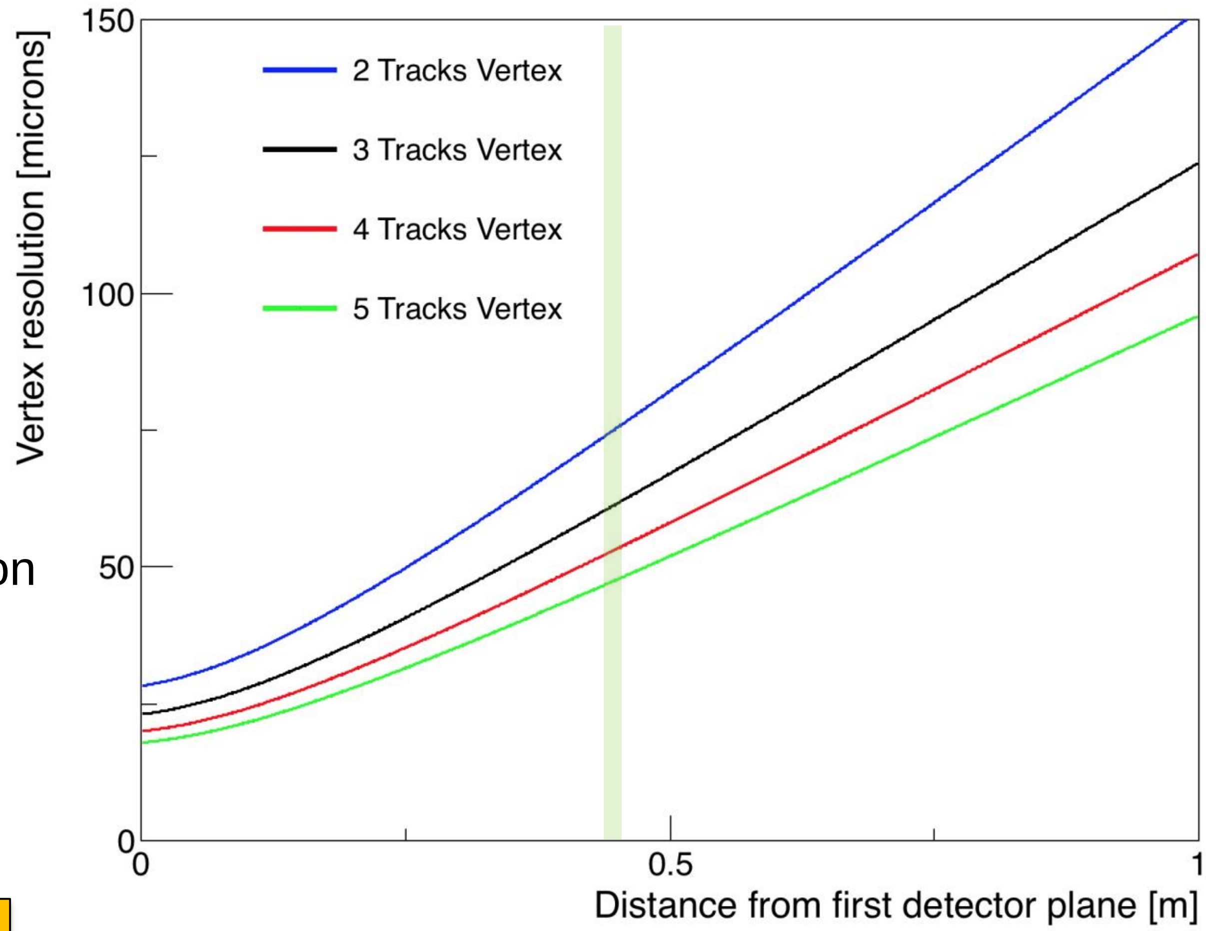
The distance aim to be around 450mm to optimize acceptance and using a localized gas jet target. Therefore the average vertex resolution is:

$$\sigma_{res} \approx 65\ \mu m$$

To reach <3% systematic uncertainty The constraint on beam size is: (see backp slides)

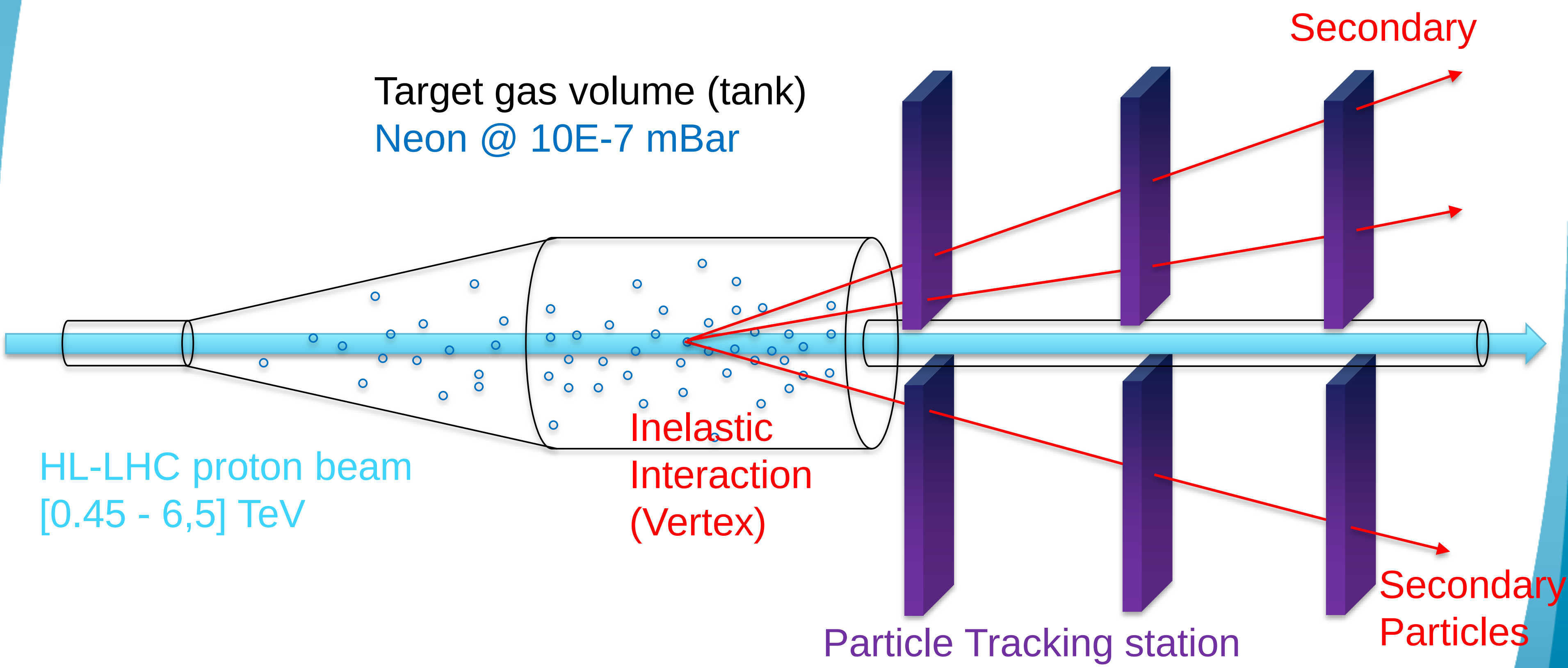
$$\frac{\sigma_{res}}{\sigma_{beam}} < 0.55$$

$$\boldsymbol{\sigma_{beam} > 120\ \mu m}$$



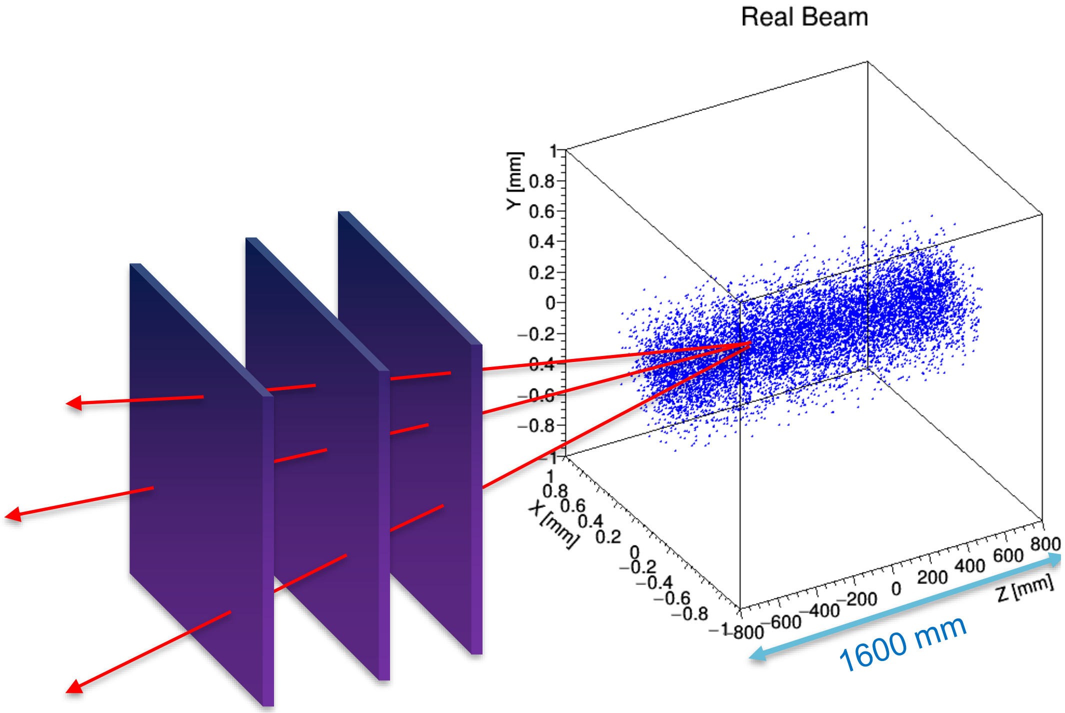
Gas target design for HL-BGV

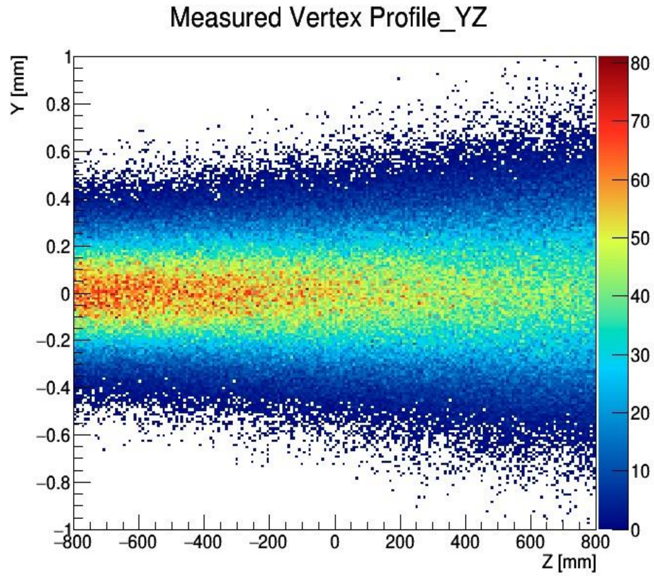
Extended homogeneous gas target case of the BGV prototype



Beam size error related to the gas target longitudinal extension

Simulated Gaussian **proton beam** $\sigma_{beam} = 0.2\ mm$
The **reconstructed interaction** include vertex resolution.



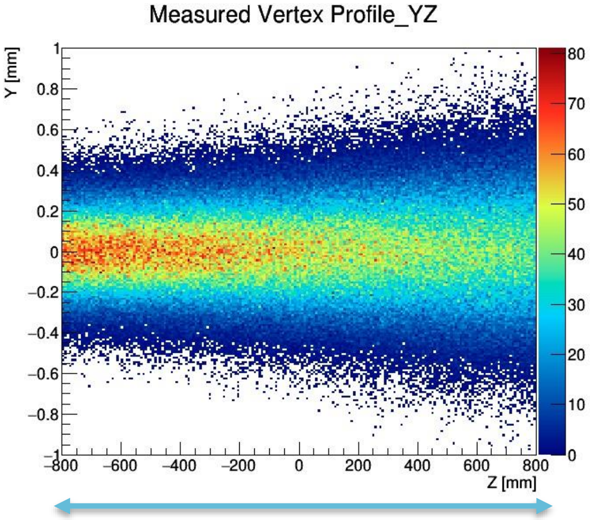


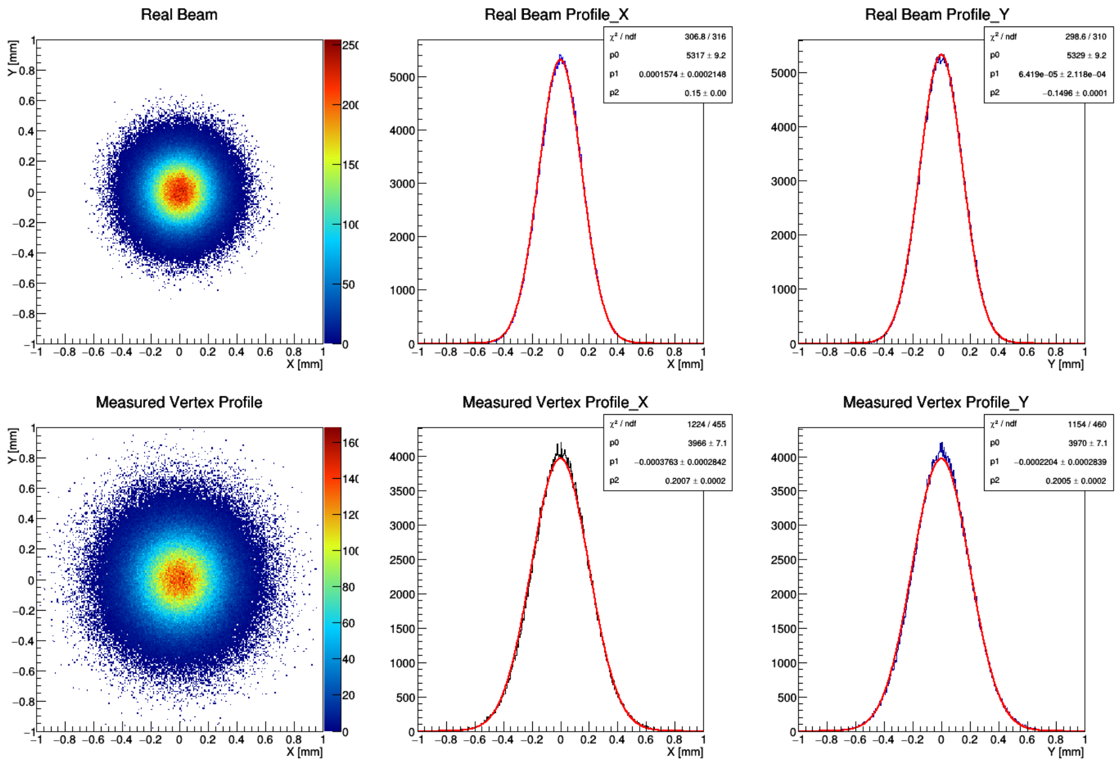
$$\sigma_{vertex} \approx \frac{\sigma_{ip}}{\sqrt{Ntracks}}$$

Beam size error related to the gas target longitudinal extension

Simulated Gaussian **proton beam** $\sigma_{beam} = 0.150\ mm$

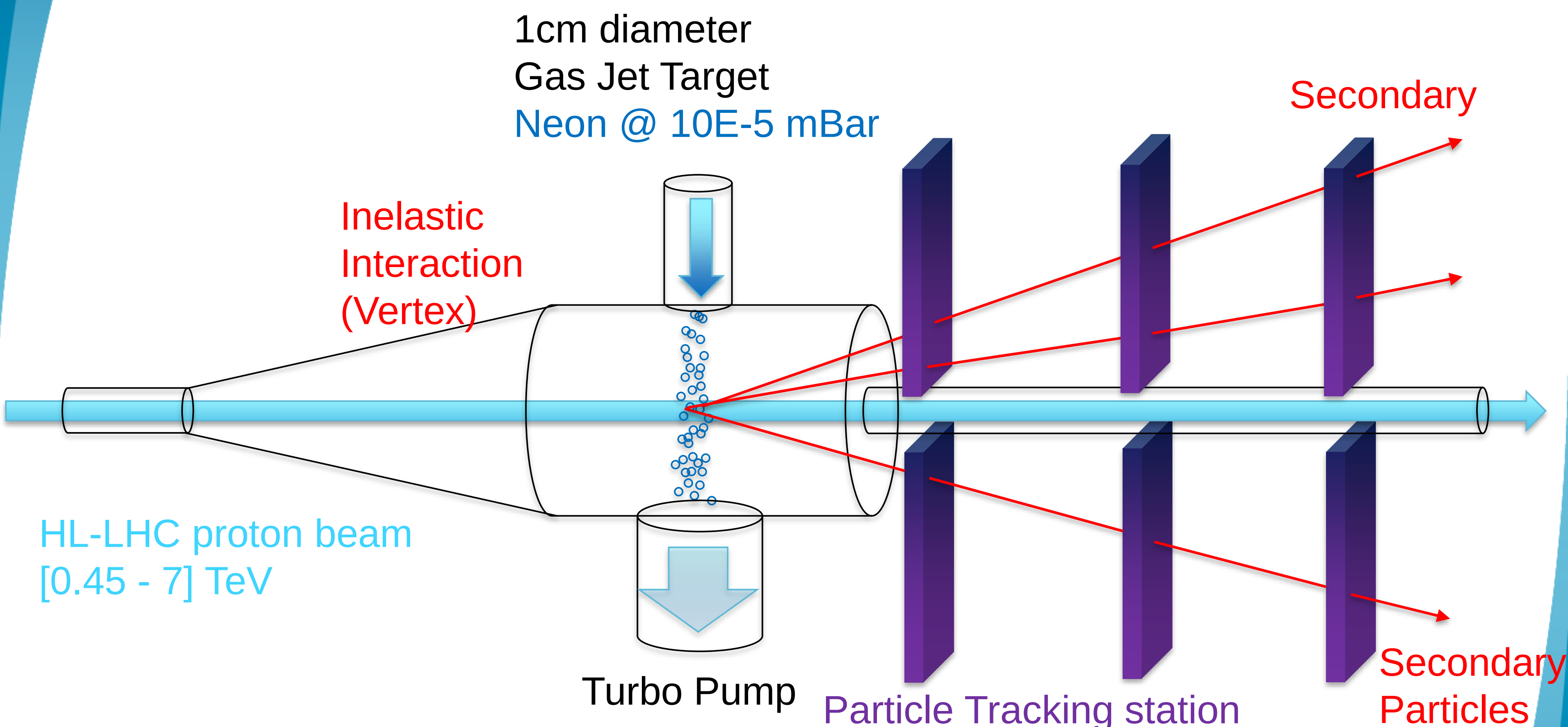
Measured Gaussian **vertex distribution** $\sigma_{meas} = 0.200\ mm$





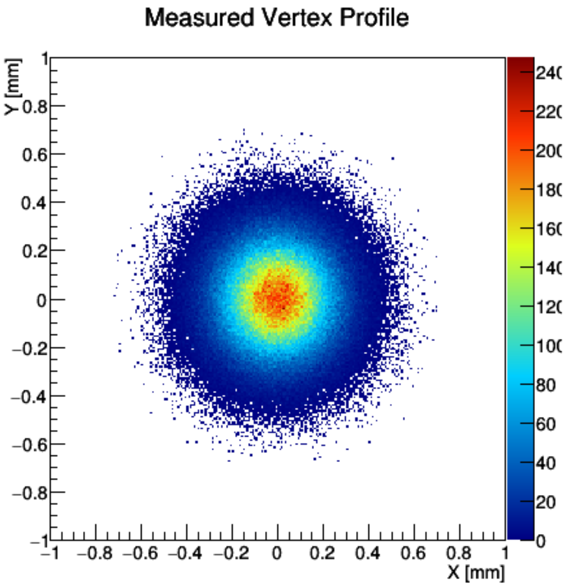
$$\sigma_{measured}{}^2 = \sigma_{beam}{}^2 + \int_{-800}^{800} A(z)\sigma_{vertex}(z)^2\, dz$$

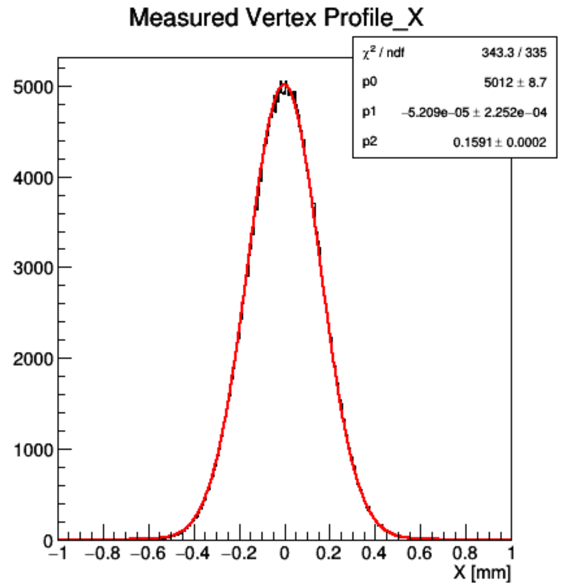
Beam Gas Vertex using Gas jet Target

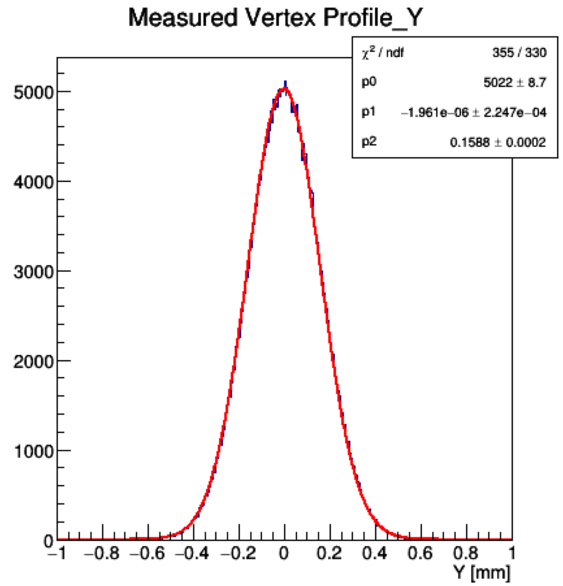


Monte Carlo simulation of a gas jet target

With 5mm thick gas jet, distance 450mm from first detector for best acceptance.







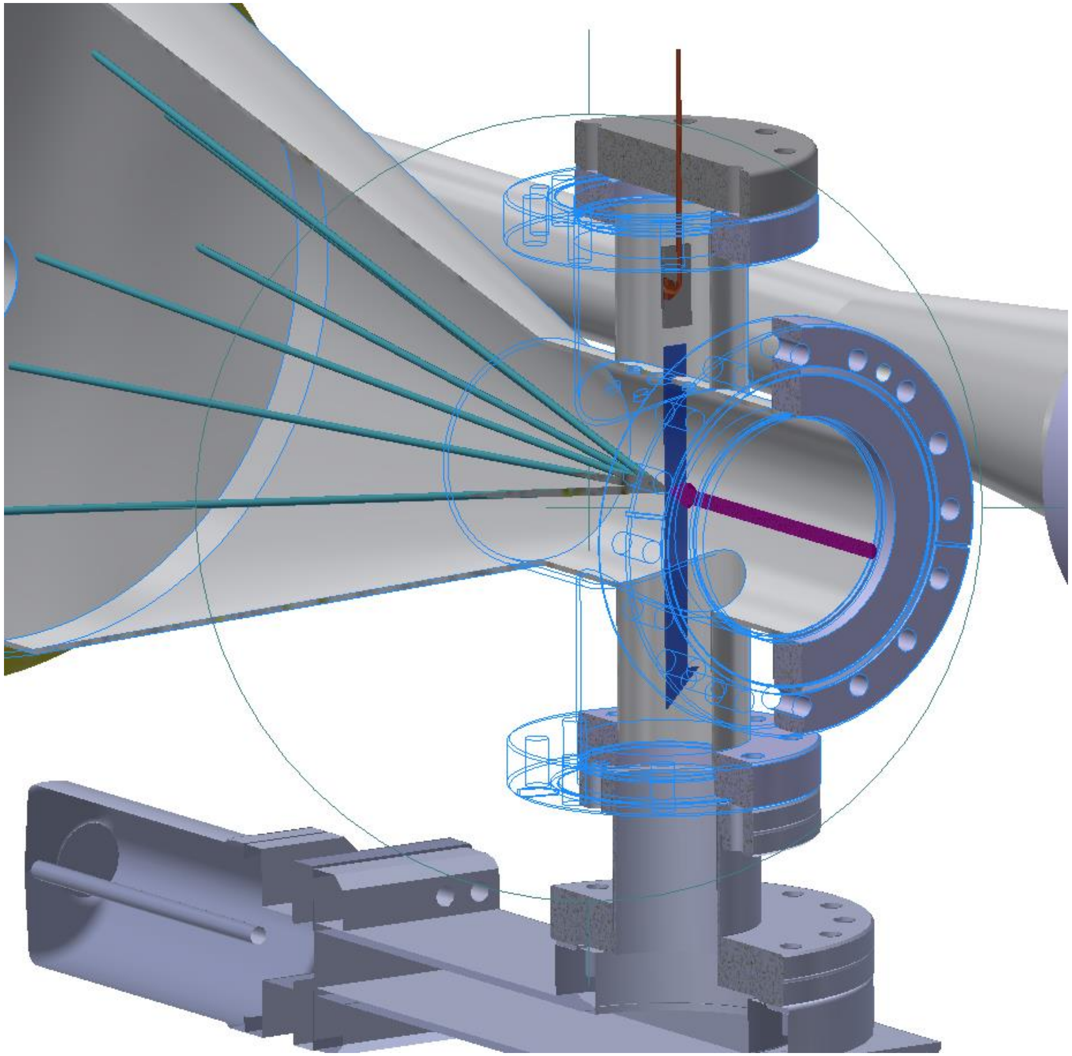
$$\frac{d\sigma_{vertex}}{dz} = 0.1um/mm$$

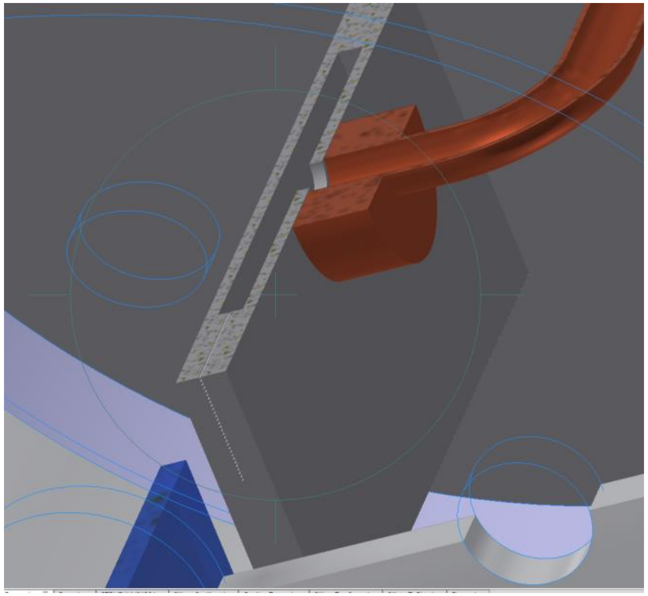
$$\boldsymbol{\sigma_{measured}}^{\mathbf{2}} = \boldsymbol{\sigma_{beam}}^{\mathbf{2}} + \boldsymbol{\sigma_{vertex}}^{\mathbf{2}}$$

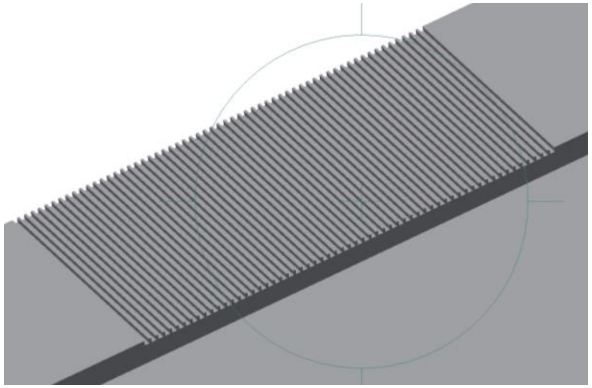
$$\sigma_{vertex} \approx 0.052\ mm$$

$$\sigma_{measured} = 0.159\ mm \qquad \sigma_{beam} = 0.150\ mm$$

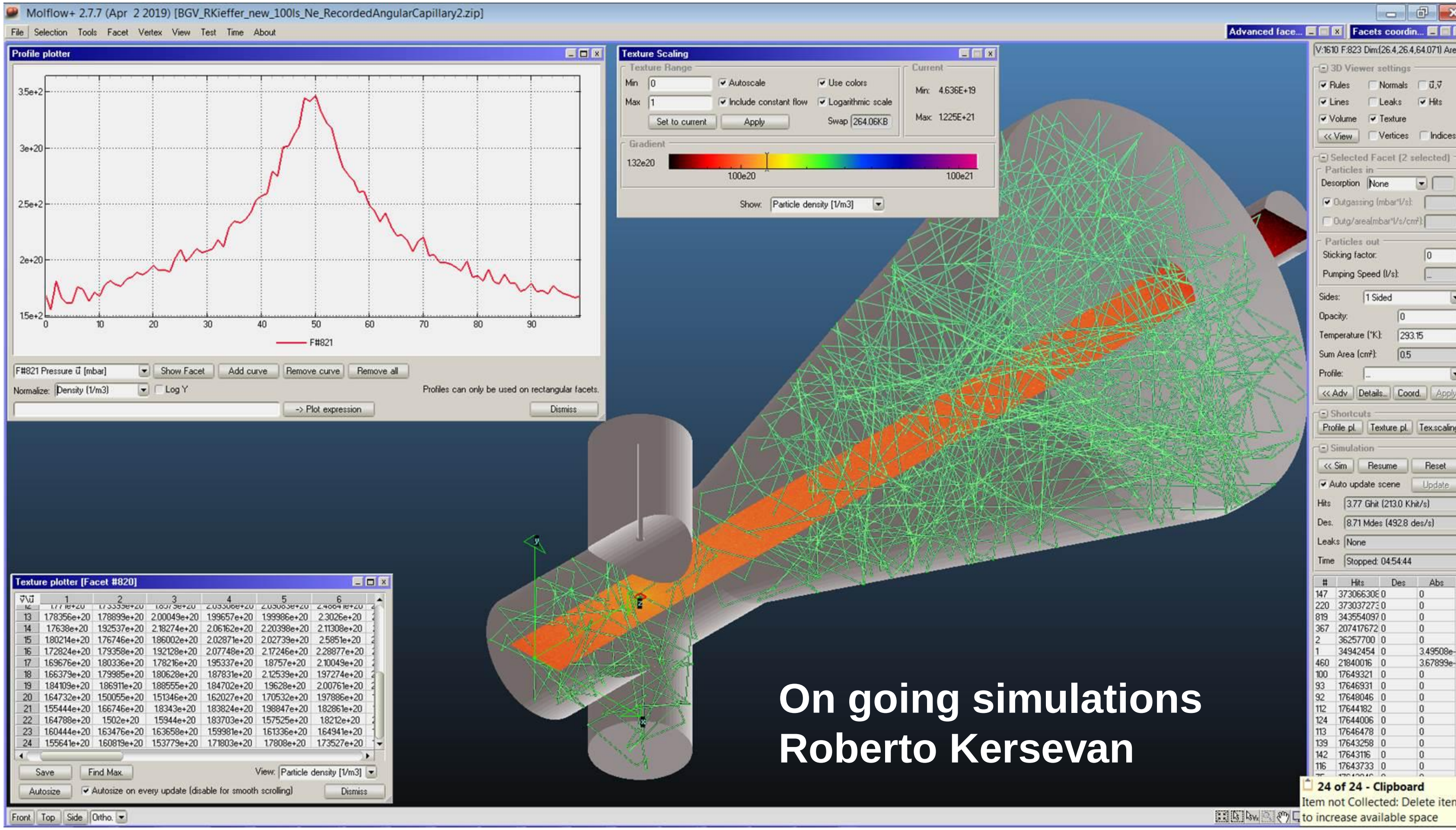
An optimized HL-BGV target







MOLFLOW simulations of capillary target

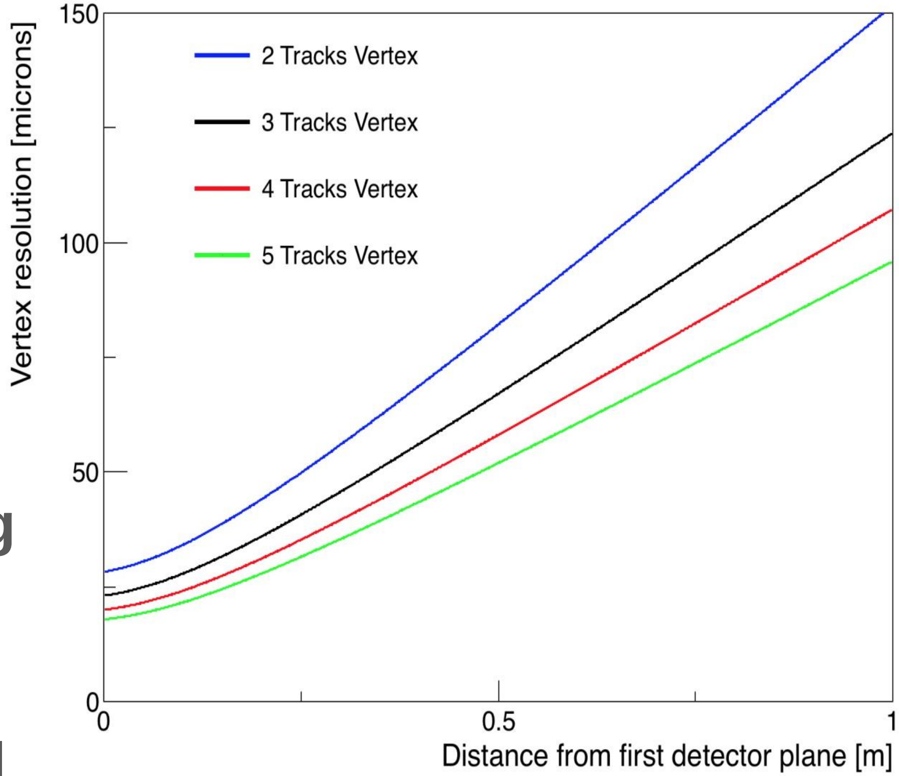


Ref: Cascaded collimator for atomic beams traveling in planar silicon devices, Chao Li1, Xiao Chai1, Bochao Wei1, Jeremy Yang2, Anosh Daruwalla2, Farrokh Ayazi2 & C. Raman1 , NATURE COMMUNICATIONS | https://doi.org/10.1038/s41467-019-09647-3

HL-BGV tracker geometry

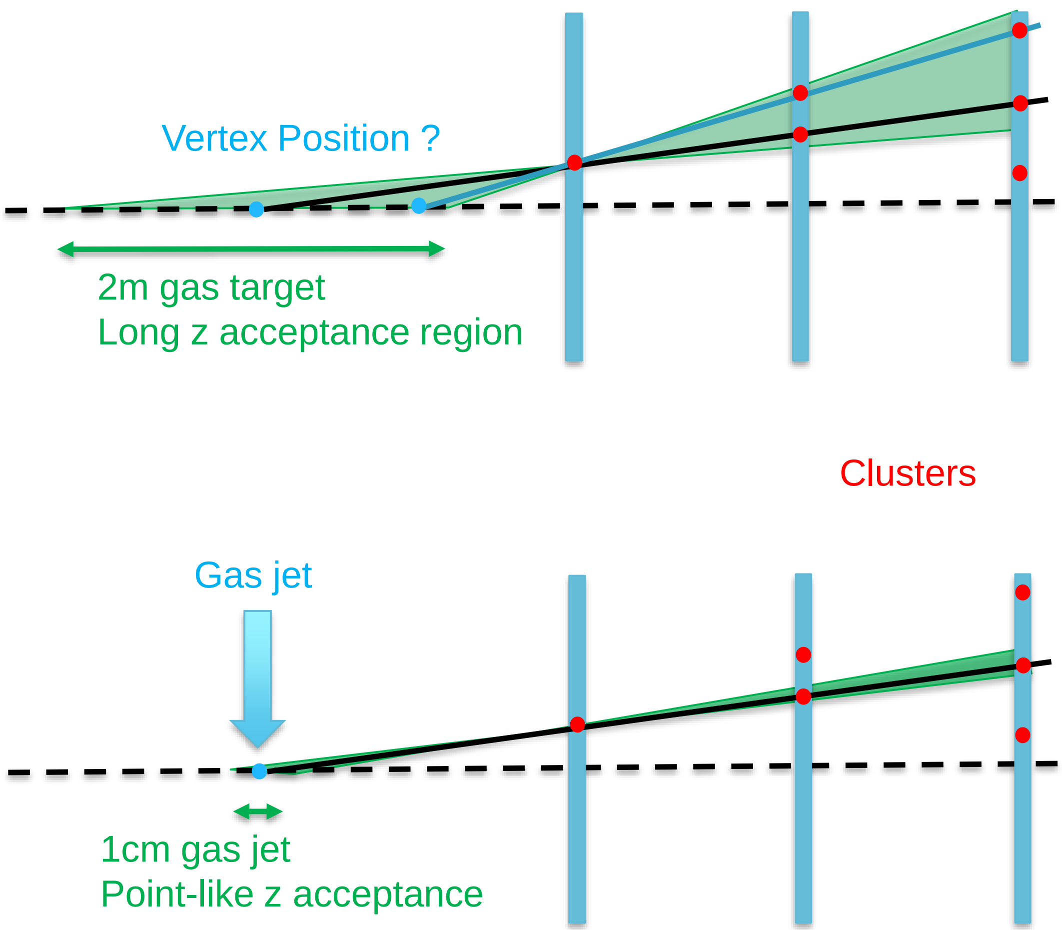
Driving factors for the BGV tracker geometry

In order to obtain a **improved vertex resolution** we need vertexes with a mean value of **4 reconstructed tracks** (instead of 2 per vertex with the prototype)



- Better hit association from geometrical constraints: the **gas jet target** will help greatly.
- Faster and more efficient track identification using **Global fitting algorithms**: need **more sensor layers** to be applied.
- Reducing multiple scattering for better track quality: **low material budget sensor** technology.

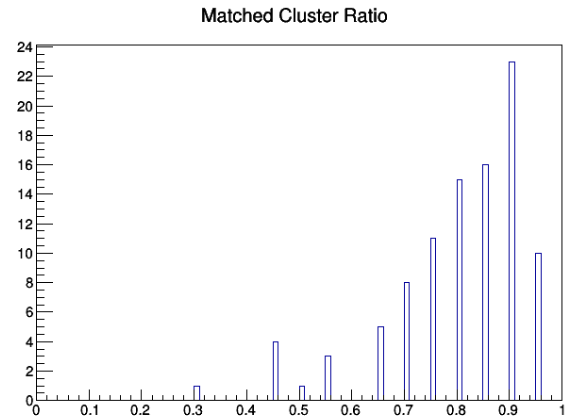
Gas jet benefits for the cluster association

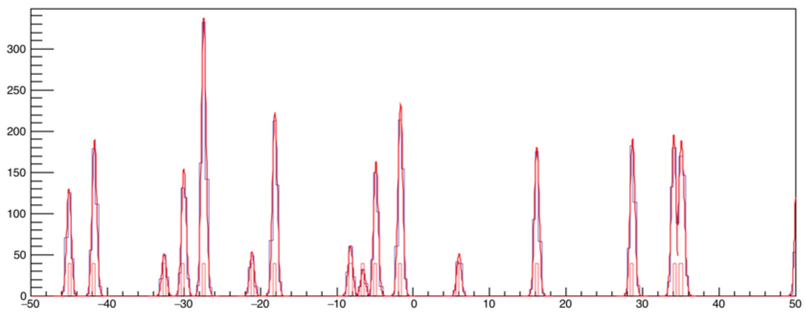


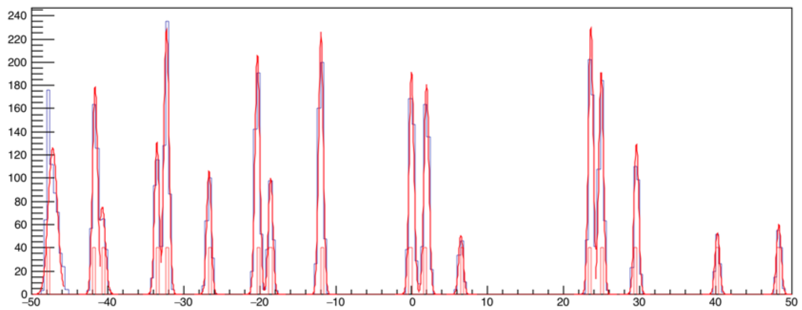
Strip sensor : The identification challenge

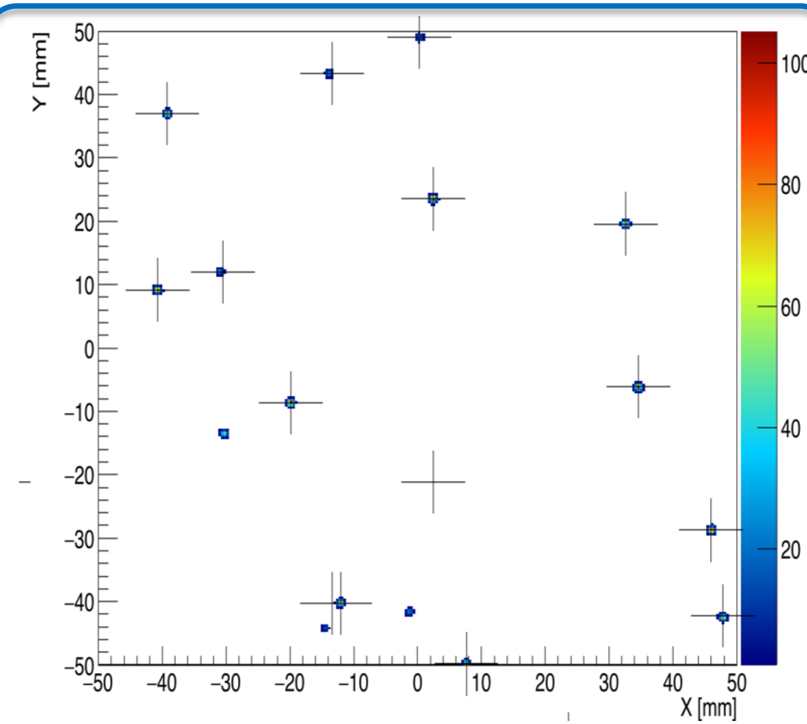
From **X and Y strip sensor data**, up to 25 cluster per plane need to be identified in the HL-BGV.

Signal overlap is the main difficulty to overcome, **cluster fitting** and **amplitude correlation** are used to **match X and Y clusters**.




Strip sensor data X axis


Strip sensor data Y axis

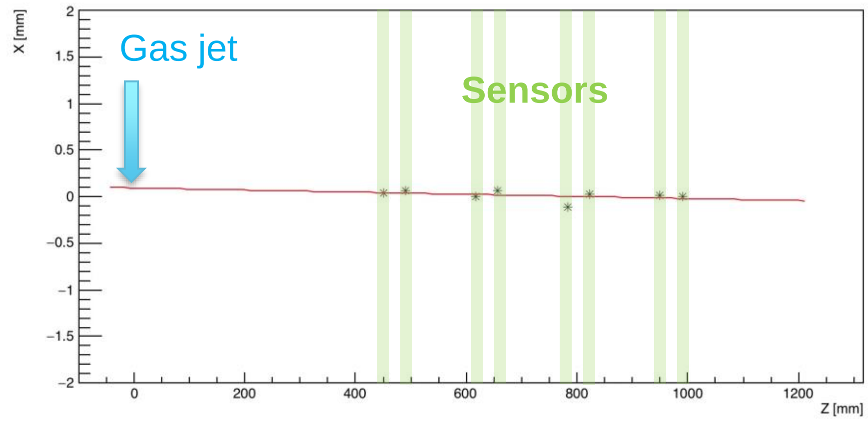


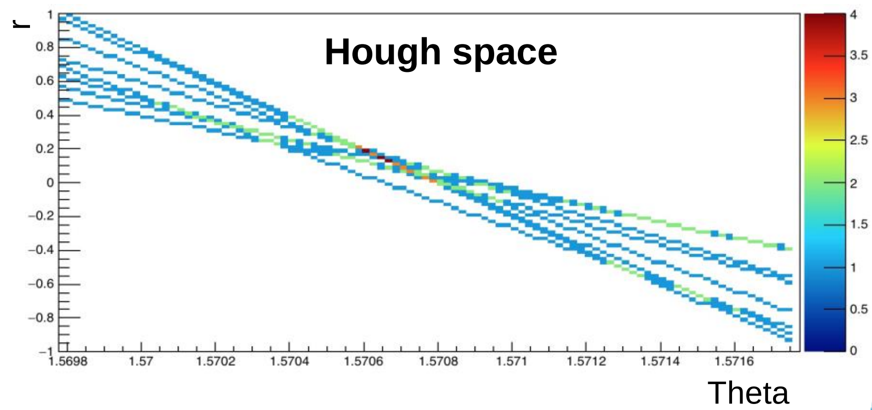
Track finding algorithms

Combinatorial cluster association based on geometry lead to high fake track identification, produce bias, and is highly demanding in terms of HLT computing resources (BGV prototype) .

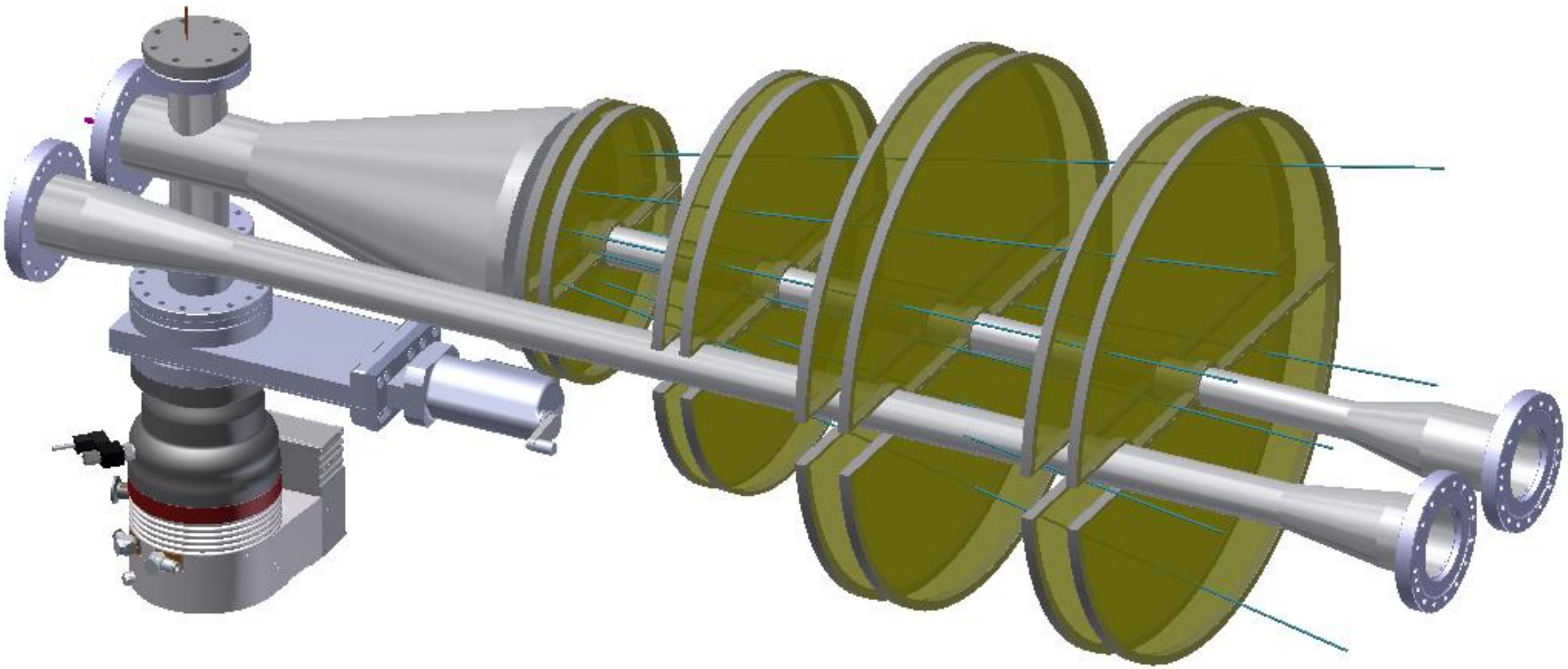
Global tracking algorithms can significantly speedup the HLT reconstruction rate and improve track identification:

- ➢ Hough transform
- ➢ Legendre transform
- ➢ Need a minimum of 8 sensor layers to be applied successfully.





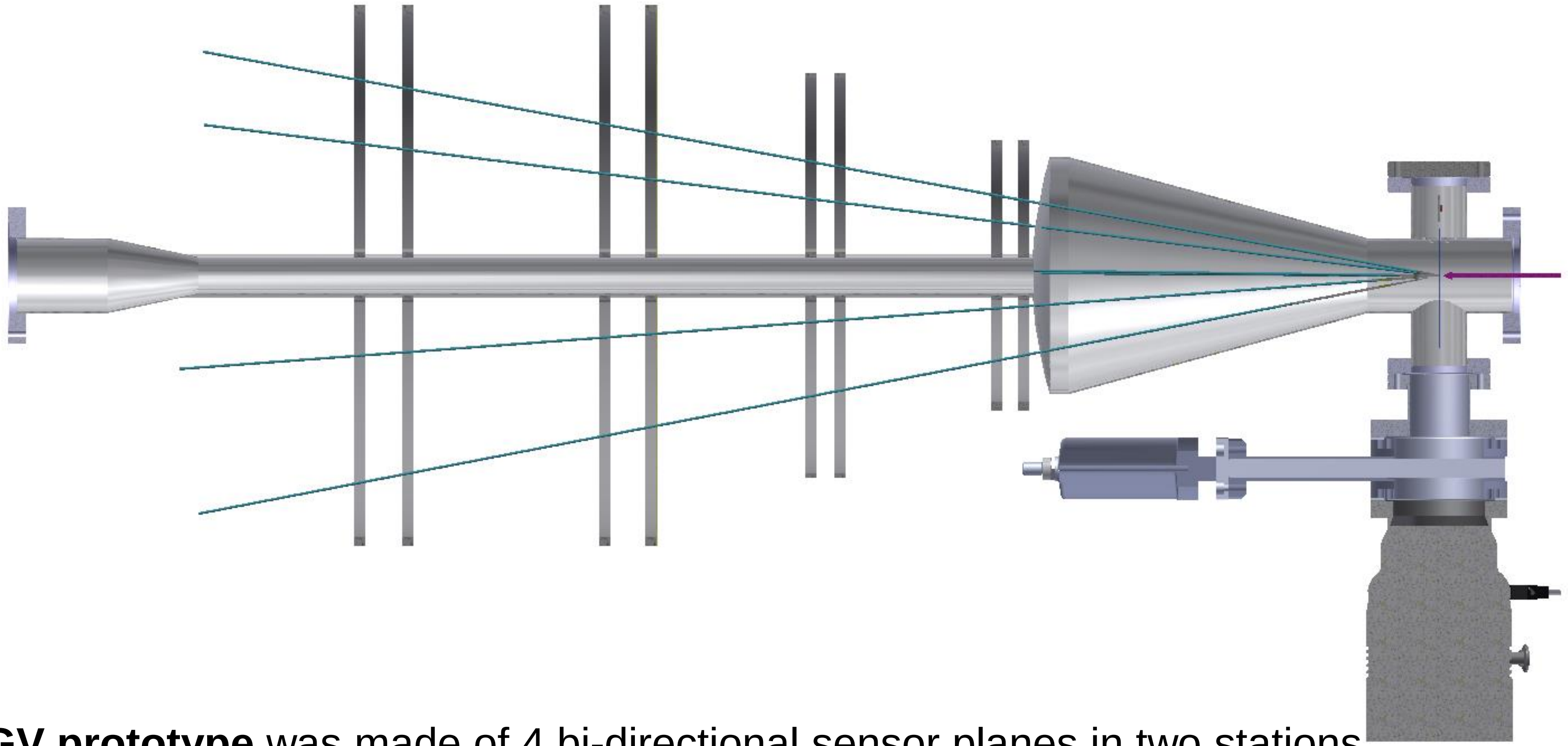
An optimized HL-BGV design for Global Tracking



BGV prototype was made of 4 bi-directional sensor planes in two stations.

HL-BGV will be made of 8 bi-directional sensor planes arranged in four stations.

An optimized HL-BGV design for Global Tracking



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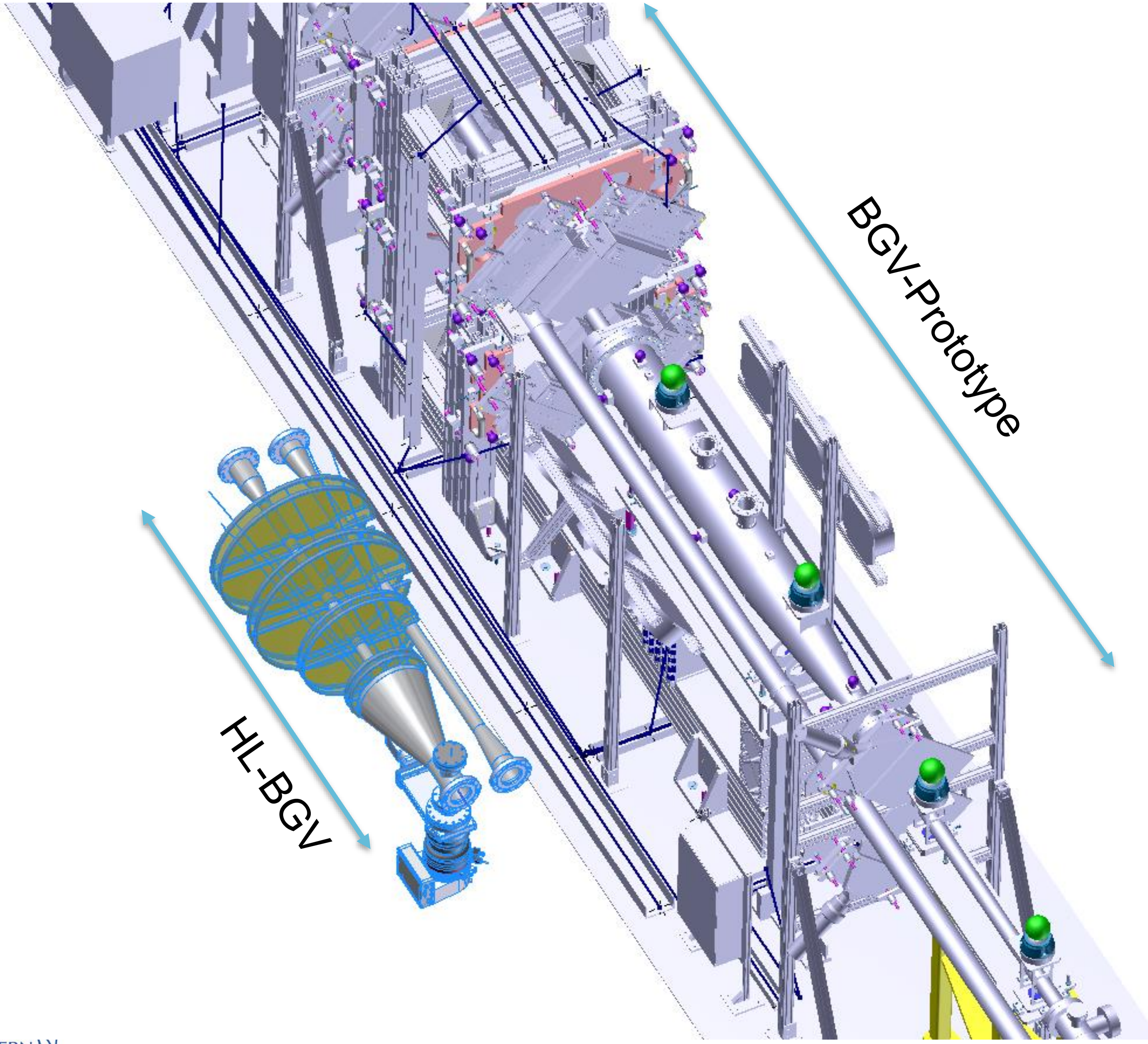
HL-BGV will be made of 8 bi-directional sensor planes arranged in four stations.

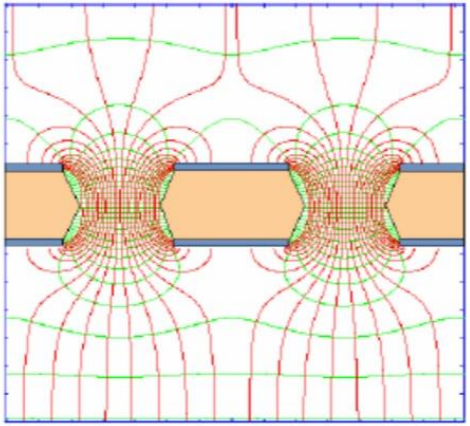
Space Occupancy along the LHC beamline



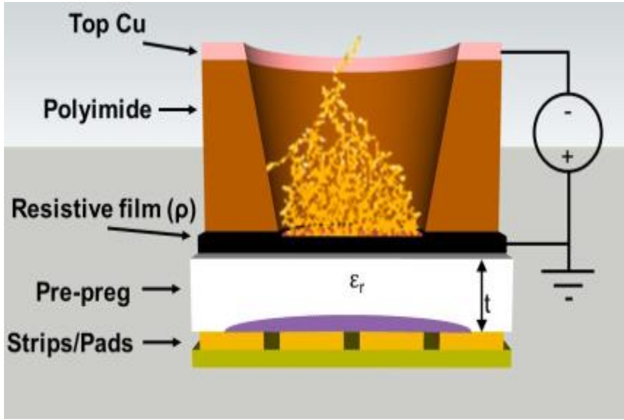
Low material budget
Tracking sensor Technology

Low material budget sensor technology

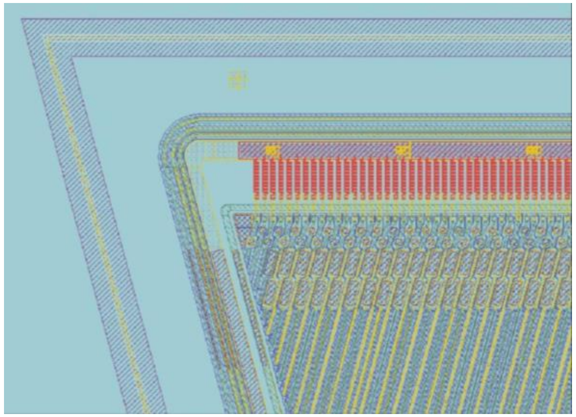
GEM



Micro Rwell



Silicon strip

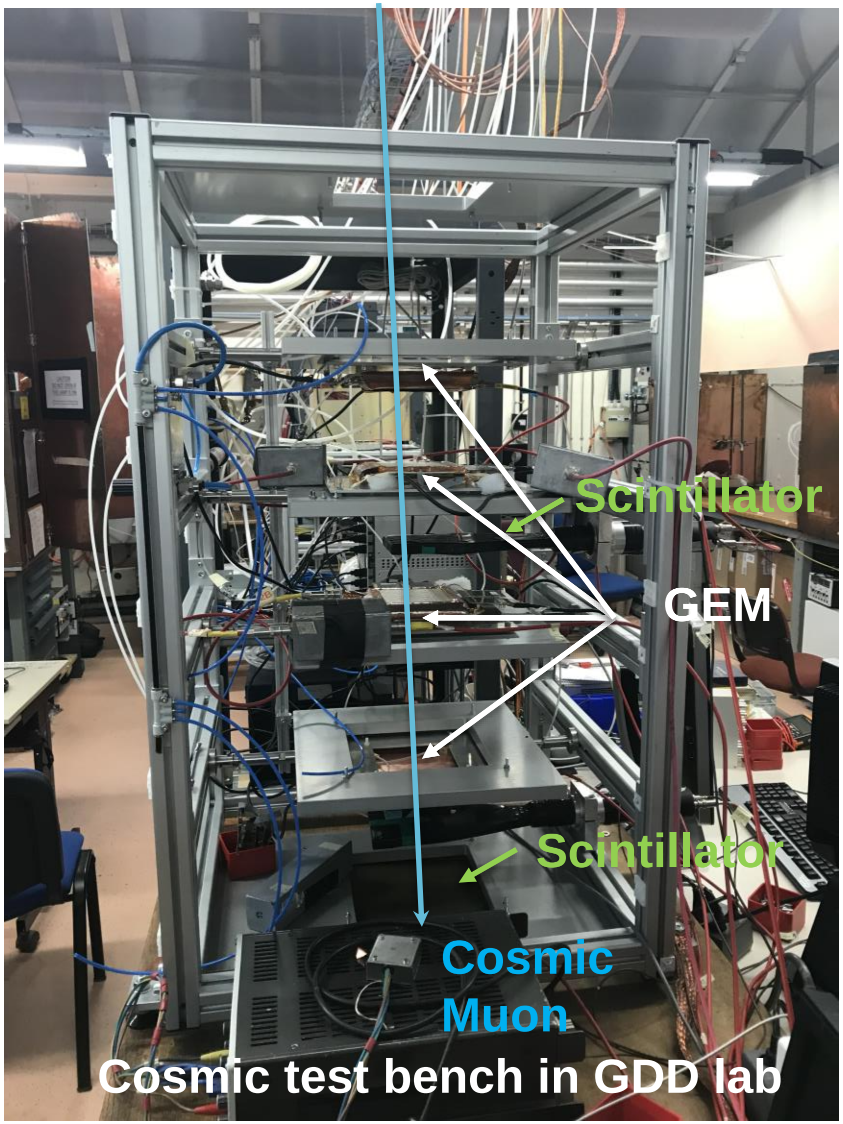


Sensor	**Triple GEM**	**Micro Rwell**	**SiFi (Fibers)**	**Silicon**
Spatial resolution **[um]**	**70**	**70**	**70**	**65**
Pitch **[um]**	**400**	**400**	**250**	**200**
Material budget **[% of X_0]**	**0.18**	**0.15**	**1.2**	**0.32**
MIP Signal (mean) **[fC]**	**30-50 (Gain:10^4)**	**20-25 (Gain:10^3)**	**1800**	**5**
Sensor cost				

Ref: **The gas electron multiplier (GEM): Operating principles and applications** Fabio Sauli, NIMA 805 1 (2016),
Ref: **The Resistive-WELL detector: a compact spark-protected single amplification-stage MPGD** 2014 JINST.
Ref: ***BGV fibre module: Test beam report*** LPHE Note 2016-04
Ref: ***LHCb Inner Tracker Technical Design Report*** CERN/LHCC 2002-029 LHCb TDR 008 November 8, 2002

GEM Detector performances evaluation

- Thanks to the CERN Gas Detector Group (EP-DT) hosting and supporting us we can evaluate gas detector technology for the HL-BGV.
- A setup of 4 GEM detectors is being used to evaluate its track spatial resolution with cosmic rays.
- Starting from a benchmarked APV electronic readout, the goal is to test a new ASIC namely the VMM3 to be used as front-end for the HL-BGV tracker.
- This is the work of Helen Guerin, PhD on the HL-BGV project.



Readout Scheme for the HL-BGV tracker

Readout Scheme for HL-LHC BGV

Front end Hybrid VMM

FPGA data concentrator

CPU network

The **VMM3a chip** is a good candidate for our readout scheme, it can read both **MPGD** and **silicon** sensors. Features: [ns] time stamp, 7bit ADC, auto-triggering.

The **FPGA data concentrator** system would be based on the BI standards (VFC) for better integration, and long term maintainability.

The **CPU network** can be scaled up in time to reach **higher online processing rate**. It is currently our limiting factor since we have only 5+1 computing nodes for the BGV demonstrator.

Conclusion

Thanks to the BGV demonstrator **precision requirements** of **1%** have been **meet**, with the DOCA correlation method.

To get to the accuracy **<3% vertexing capability** is needed. The main improvement levers have been identified for **HL-BGV**.

- The **gas jet target** is highly beneficial for **vertex resolution**.
- Tracking solutions based on **GEM** are **tested at CERN GDD**.
- **Global tracking** methods with **8 sensor layers** looks promising to overcome track identification limitations of the prototype.
- The readout scheme foreseen will be a solution based on **BI-standards (VFC)**, and using the **VMM ASIC frontend**.
- **High level trigger** processing framework and acquisition software are under design.

Backup slides

Long future for the HL-BGV

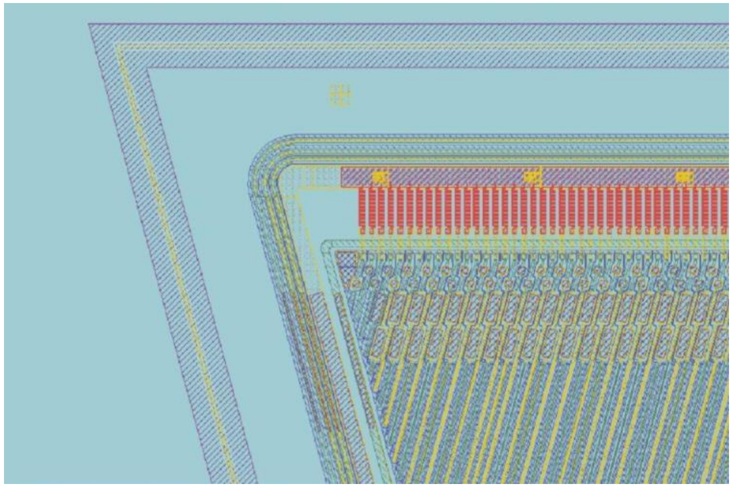
- Adding a picosecond timing sensor to allow longitudinal bunch profile measurement.
- The idea would be to add a rather small sensor able to tag the vertex in the pico-second range.
- No need for accurate tracking or precise position resolution.
- The only need is to get enough coverage to catch at least one track of the event and tag it accurately in time.

Silicon sensor Technology

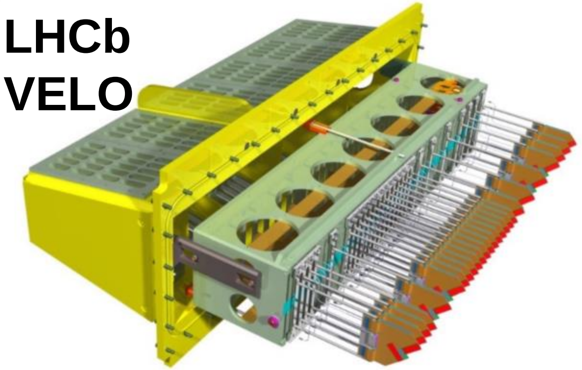
The **Silicon Strip Device (SSD)** standard is 300um.
Reducing this thickness is not obvious since:

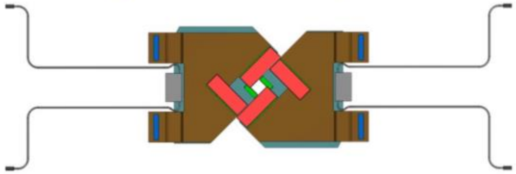
- The SSD device will be more fragile to manipulate if 100um thick.
- The charge deposition in depletion is proportional to Si thickness.
- The charge sharing between strips will be reduced and lead to a digital readout scheme instead of clustered analog. This have an effect on spatial resolution.

TOTAL for 300um wafer: 0.32 %X_0



LHCb VELO





Silicon pixel detector would be more adapted if used in vaccum at **very short distance** from the beam (<15mm).

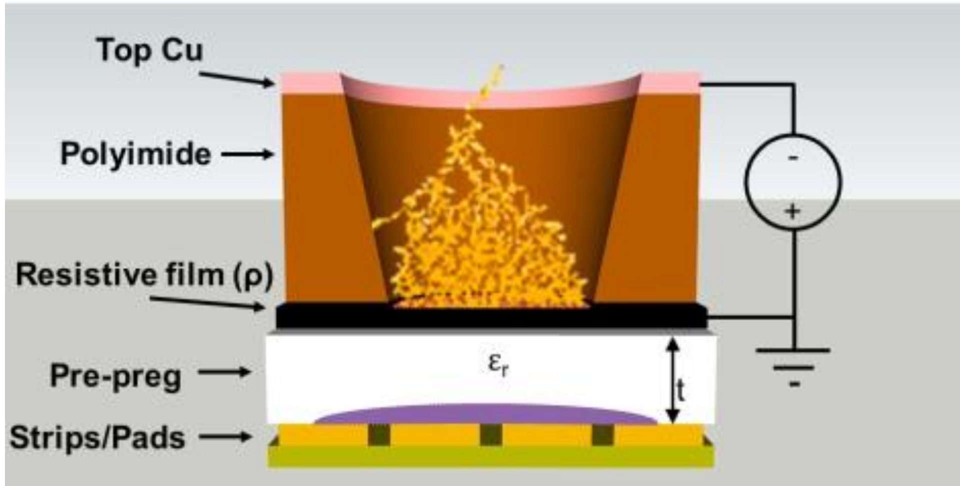
The best example is the LHCb VELO upgrade

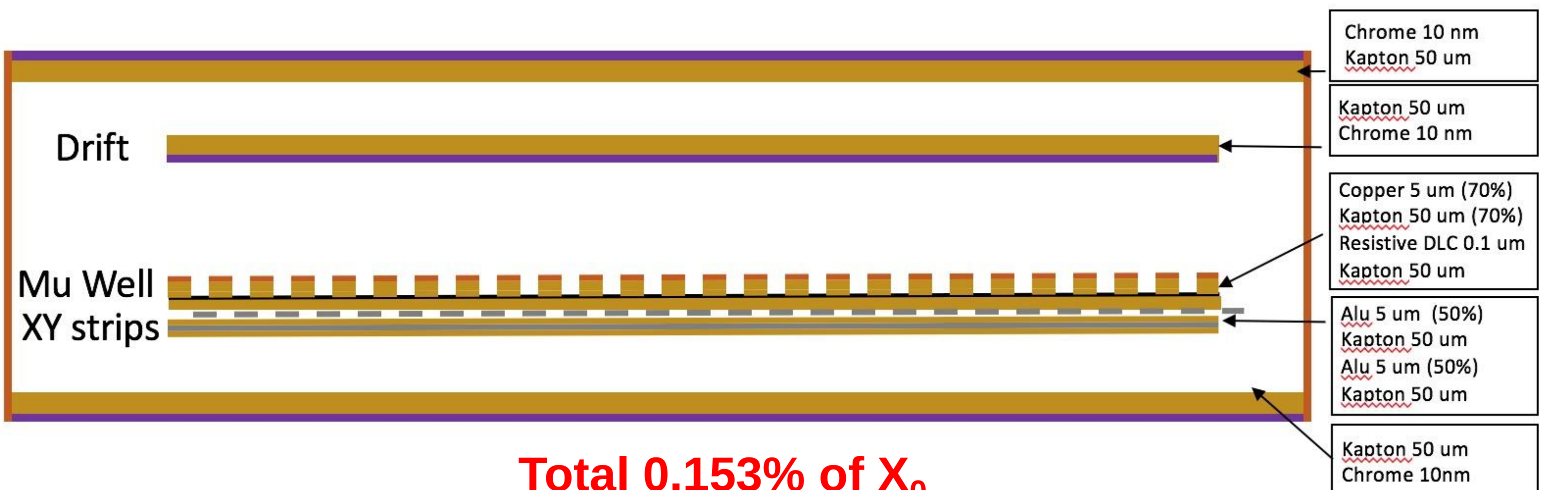
Not usable during ramp, since the devices need to be inserted close to the beam (VELO **wait for stable beams** to insert their trackers)

If used outside vacuum the sensor area to cover is very large (x100) and such technology is too expensive to be deployed.

Note the presence of 26 detector layers in the VELO (8 in HL-BGV).

Micro R-well structure with XY strip readout

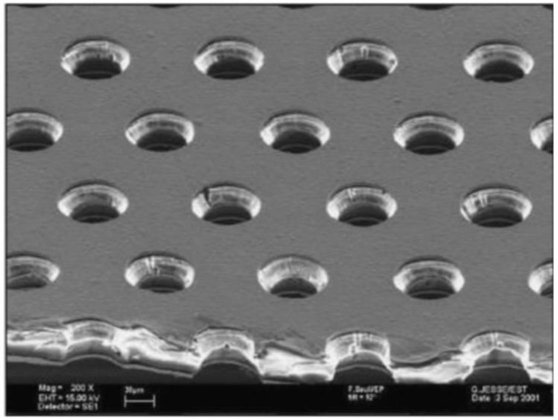


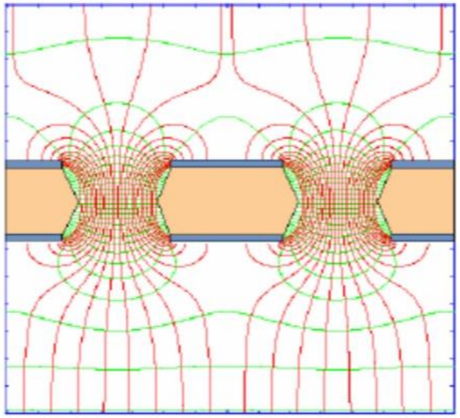


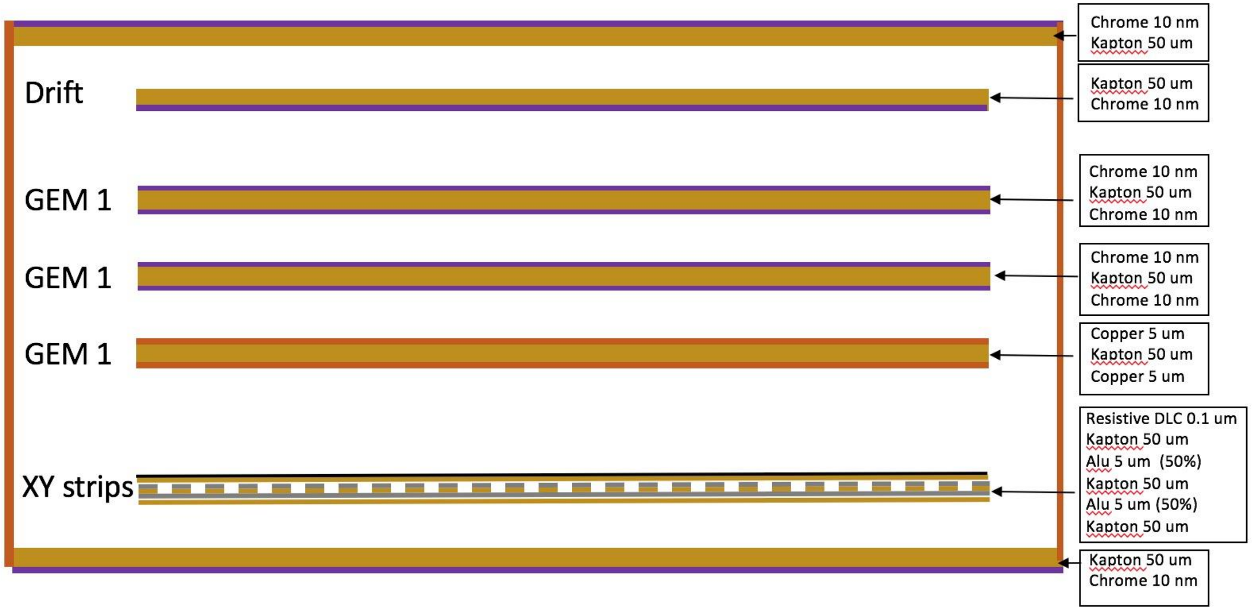
Total 0.153% of X_0

Ref: The Resistive-WELL detector: a compact spark-protected single amplification-stage MPGD November 2014 Journal of Instrumentation 10(02). DOI:10.1088/1748-0221/10/02/P02008

Tripple GEM structure with XY strip readout

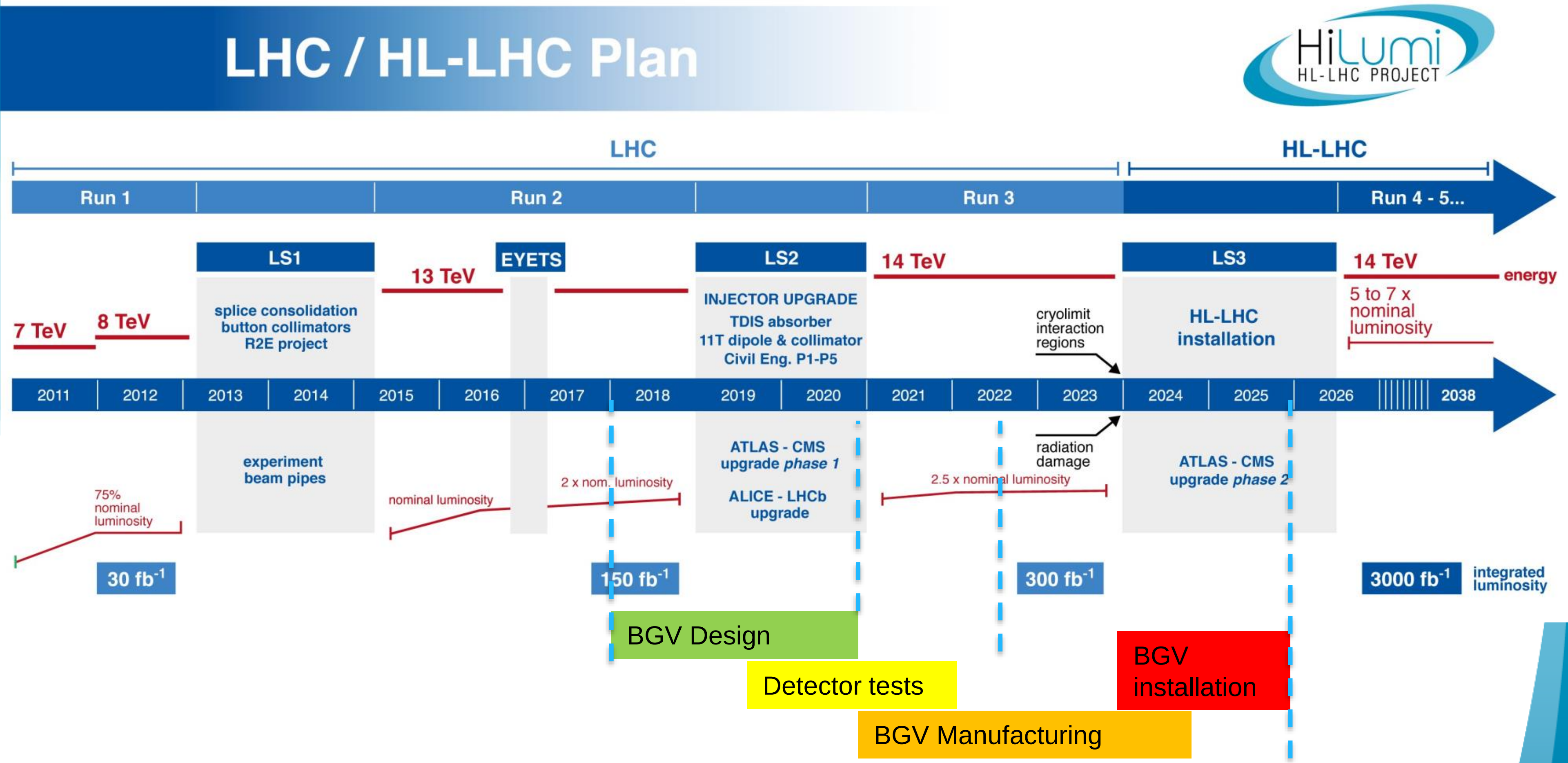






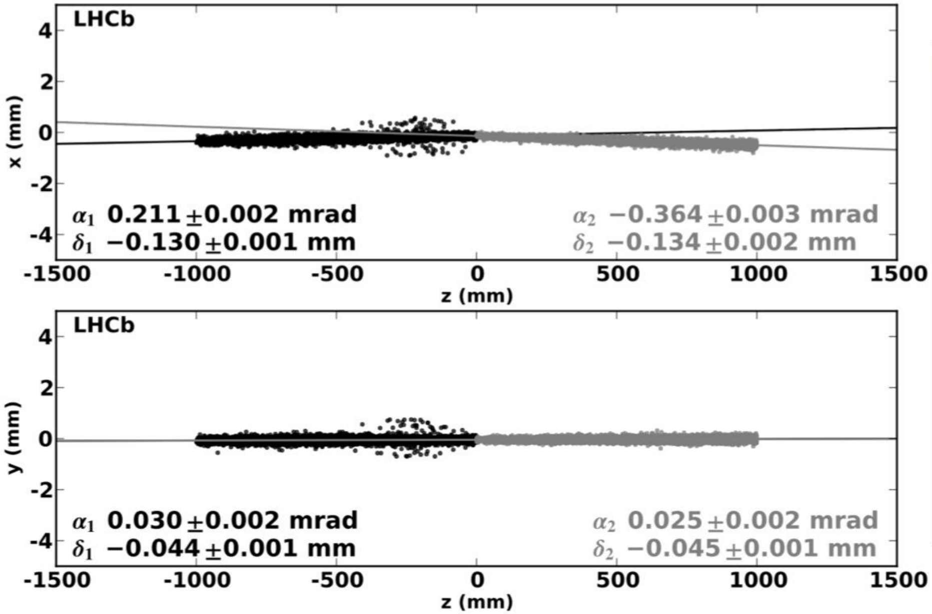
Total 0.18% of X_0

Timeline for HL-BGVs



LHCb beam gas vertex profile monitoring

Ref: **Absolute luminosity measurements with the LHCb detector at the LHC**
The LHCb Collaboration
Published 10 January 2012 • Journal of Instrumentation, Volume 7, January 2012



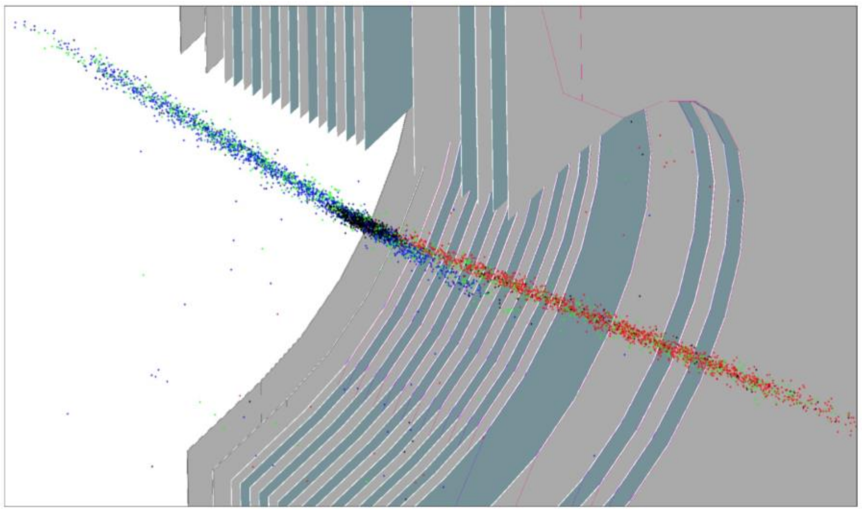
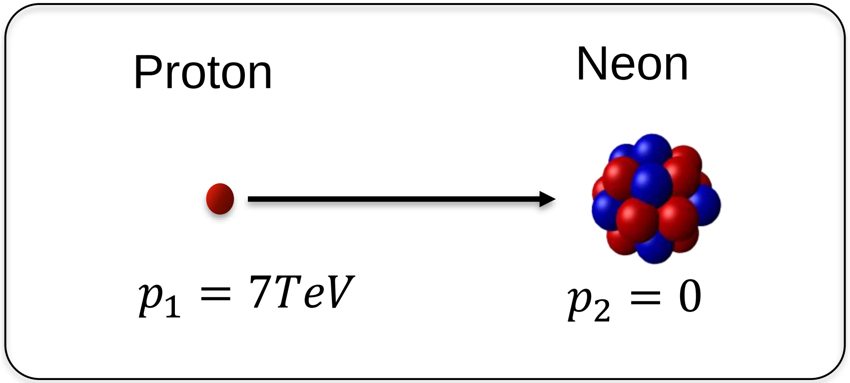


Figure 13. Positions of reconstructed beam-gas interaction vertices for be (black points) and eb (grey points) crossings during Fill 1104. The measured beam angles $\alpha_{1,2}$ and offsets $\delta_{1,2}$ at $z = 0$ in the horizontal (top) and vertical (bottom) planes are shown in the figure.

Beam Gas Collision Physics

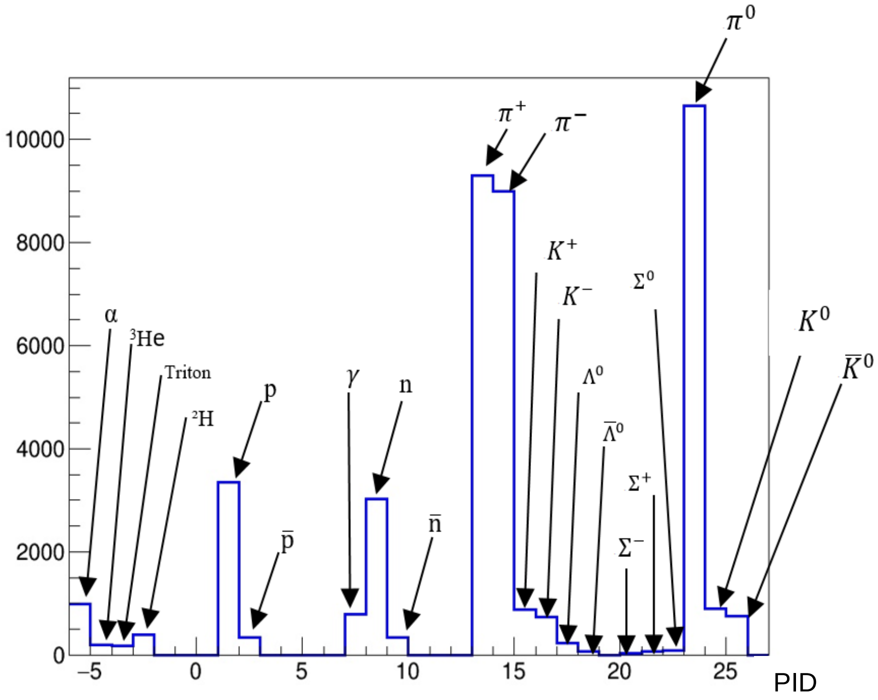


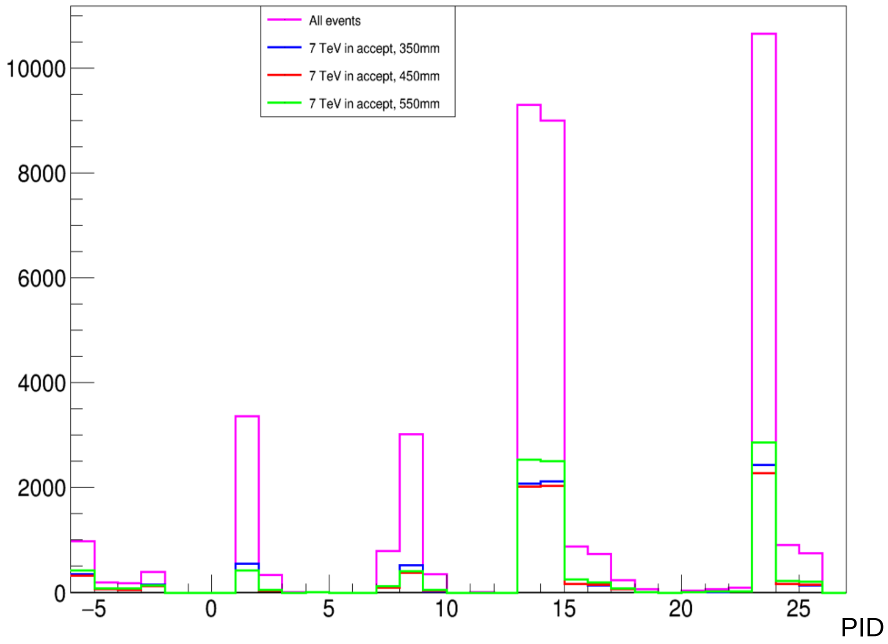
Fixed target scheme

- Proton rest mass : $m_1 = 0.93\ GeV$
- Neon rest mass : $m_2 = 19\ GeV$
- Proton kinetic energy: $E_1 = 7\ TeV$
- Collision energy $\sqrt{s} = 516\ GeV$

$$\sqrt{s} = \sqrt{{m_1}^2 + {m_2}^2 + 2E_1\, m_2}$$

FLUKA Particle ID Histograms





Beam Gas Collision Physics

Cross section of the Neon (A=10) for 7TeV protons

$$\sigma_{p+A} \approx \sigma_{p+p} \cdot A^{0.7}$$

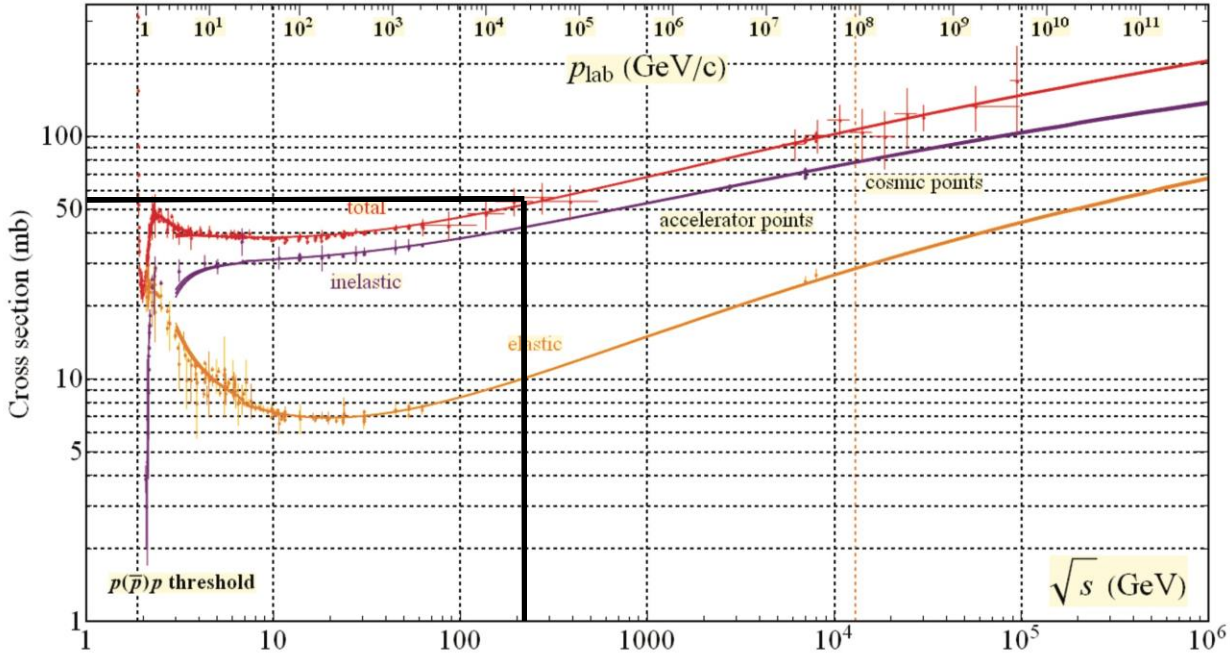
$$\sigma_{p+A} \approx 275mb$$

Mainly inelastic collisions (hadronic process)

Equivalent cross section of p-p (from PDG data)

$$\sqrt{s_{p+p}} = 114GeV$$

$$\sigma_{p+p} = 55\, mb$$



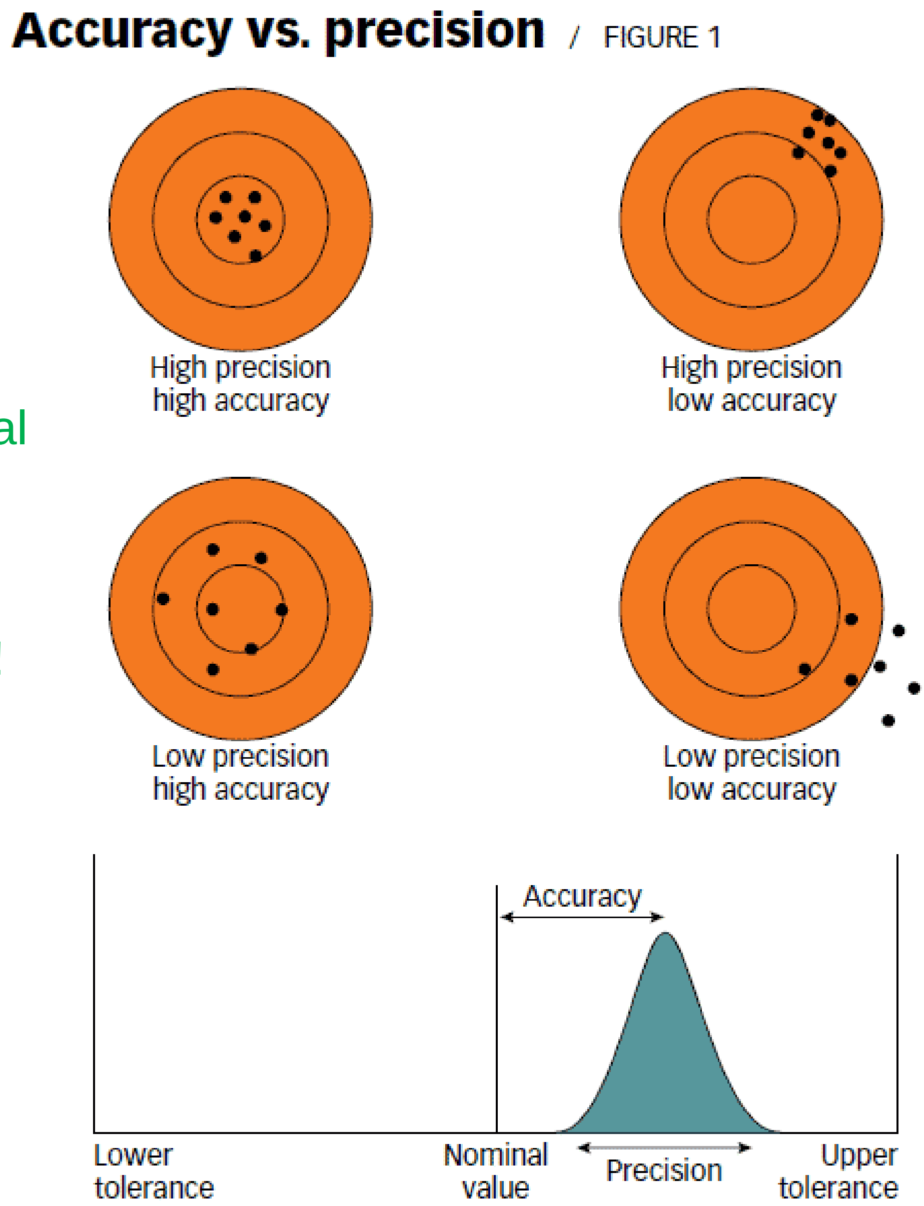
Ref: “Compilation of cross sections for proton-nucleus interactions at the HERA energy, J. Carvalho, Nuclear Physics A 725 (2003) 269-275. https://doi.org/10.1016/S0375-9474(03)01597-5.

Specification of beam size measurement

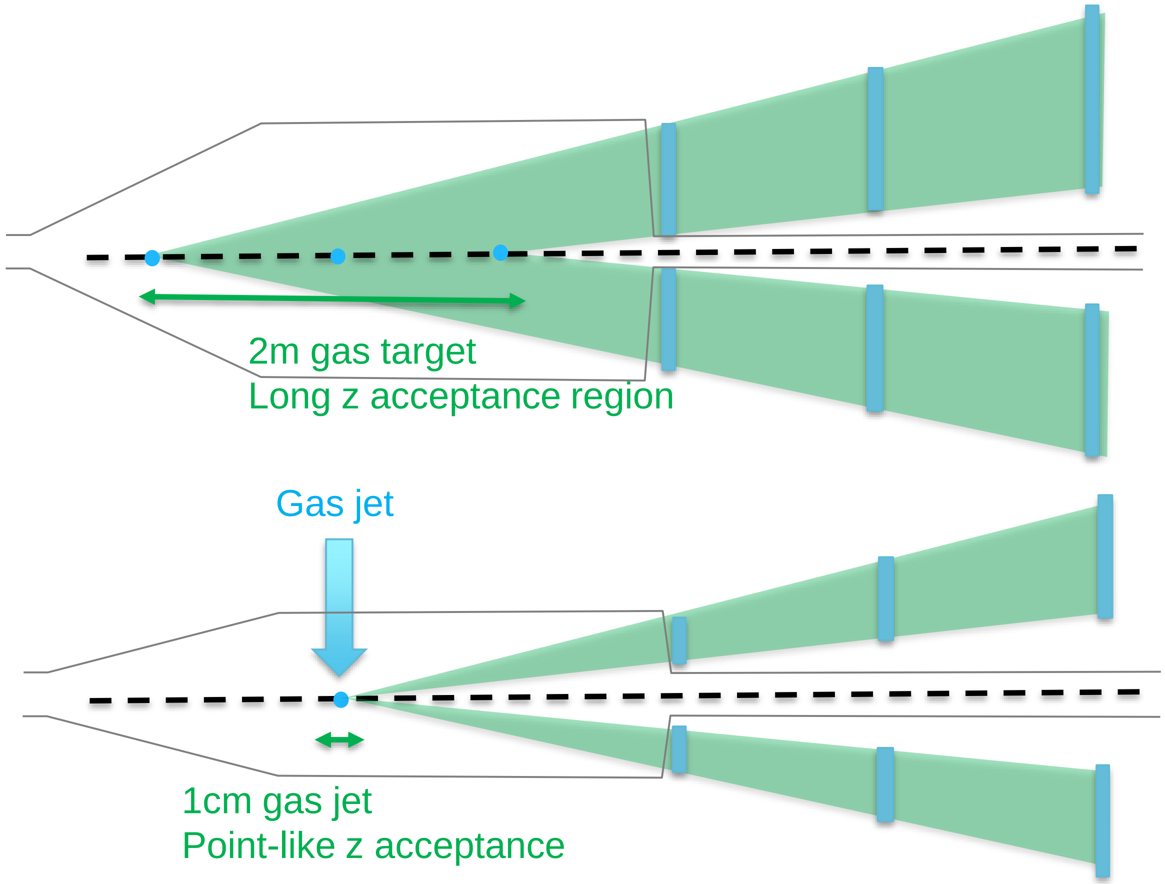
- **Precision**: Reproducibility of measurement taken many times

- **Accuracy:** is the mean offset of the measured value with respect to the real one.

- Resolution is different from precision !!
- **Resolution**: ratio of smallest variation measurable / maximum signal measured.
- (ex 12 bit ADC: 1ADU/1024ADU)

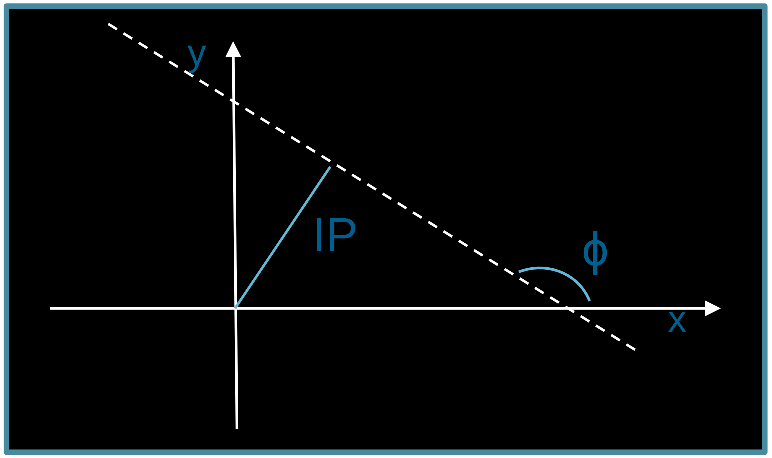


Gas jet reduces necessary tracker sensor surface and Exit window dimensions

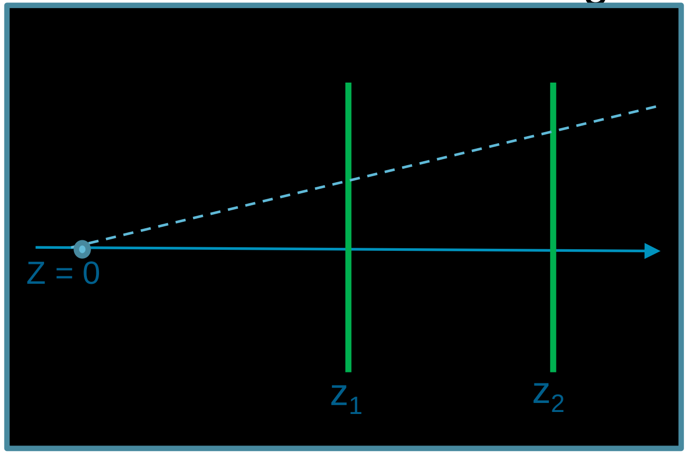


- Impact on Cost: **smaller sensor** dimensions and less electronic **channels**.
- Impact on Multiple scattering error if the **exit window can be made thinner**.

Impact Parameter (IP) Resolution



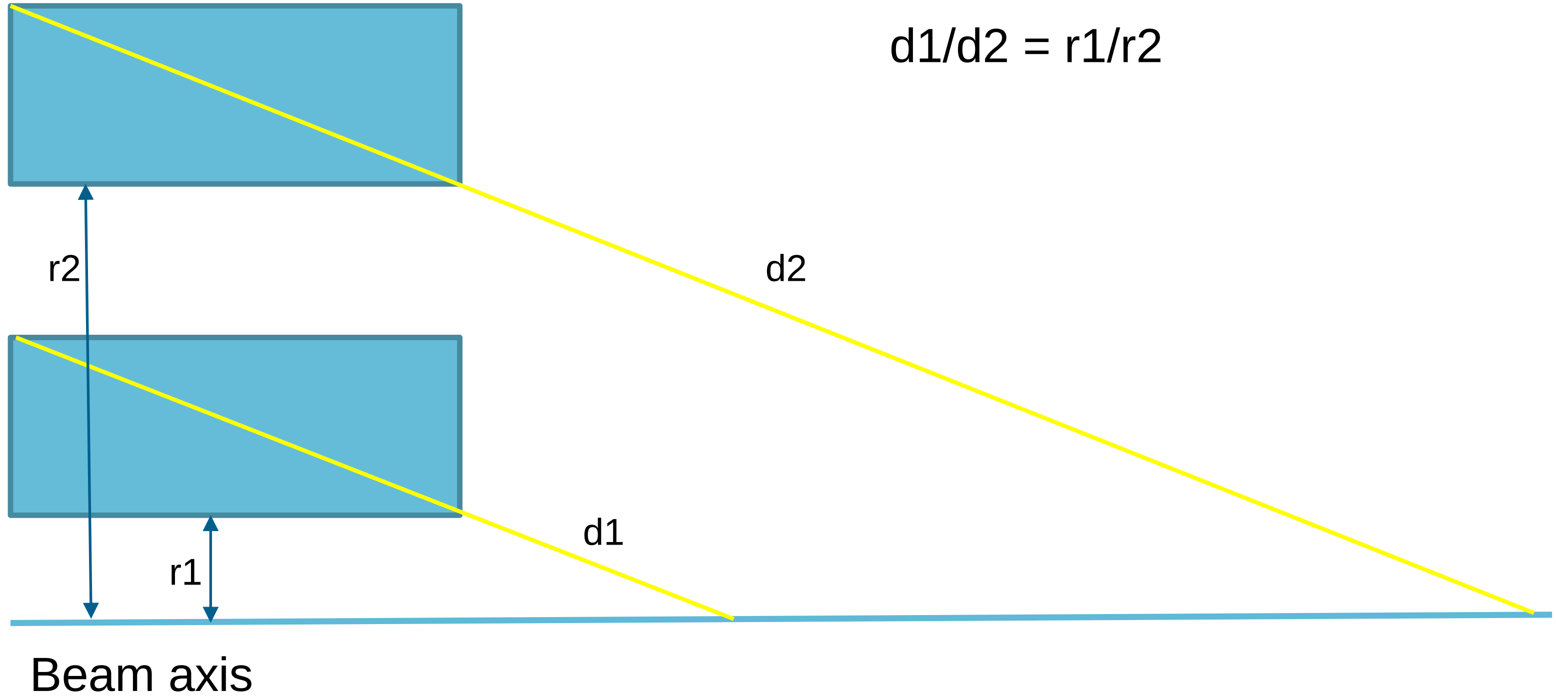
Use two detectors along z



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

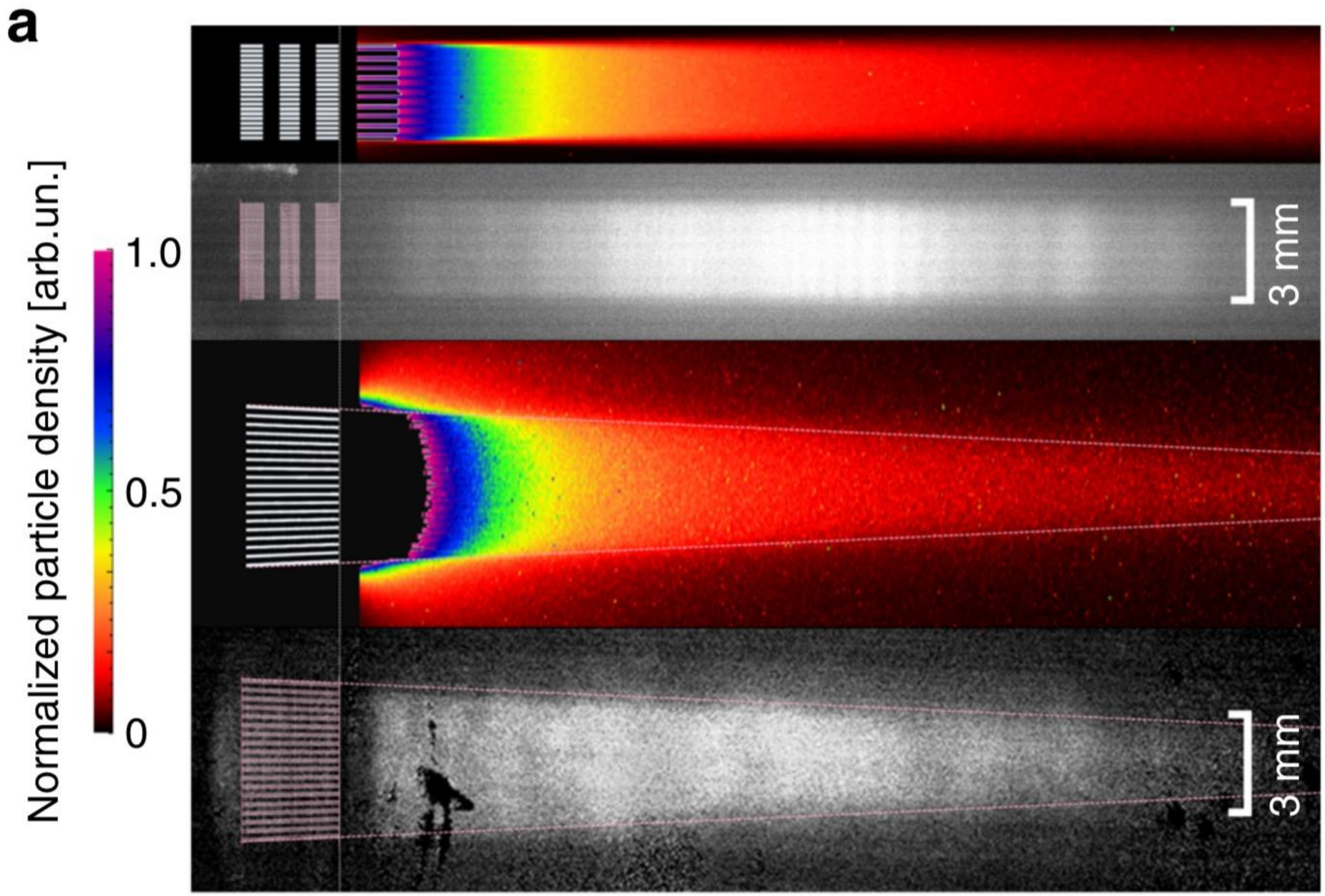
- $\sigma_{IP}^2 = \sigma_{Extrap}^2 + \sigma_{MultScat}^2$
- $\sigma_{Extrap}^2 = \frac{z_1^2 + z_2^2}{(z_2 - z_1)^2}\,\sigma_{hit}^2$
- $\sigma_{Multscat} = z_1 \frac{13.6\ MeV}{p} \sqrt{\frac{x}{X_0}}$

Detector position and extrapolation error



- The closest to the beam pipe, smaller are extrapolation errors
- Since the **gas target volume is long (2m),** the situation is quite different from LHC experiments with a **few mm long IP center.**

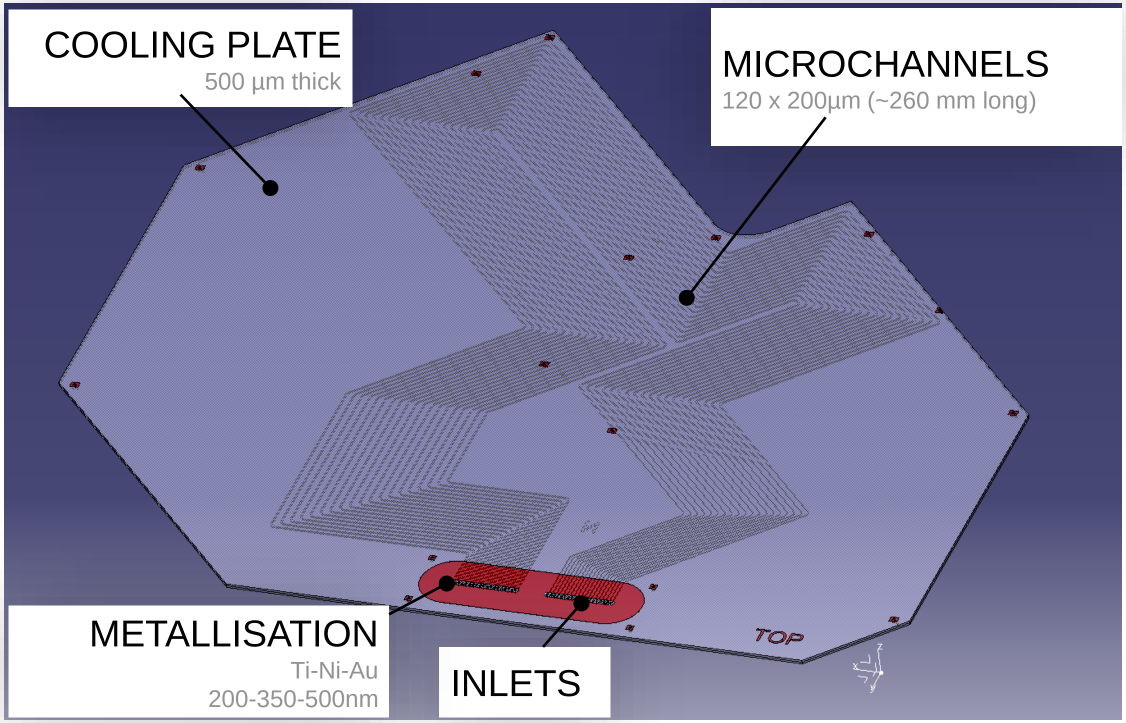
Example from literature on capillary target



Ref: Cascaded collimator for atomic beams traveling in planar silicon devices, Chao Li1, Xiao Chai1, Bochao Wei1, Jeremy Yang2, Anosh Daruwalla2, Farrokh Ayazi2 & C. Raman1 , NATURE COMMUNICATIONS | https://doi.org/10.1038/s41467-019-09647-3

Capillary gas jet target microfabrication

Similar example: microfabrication of cooling plates



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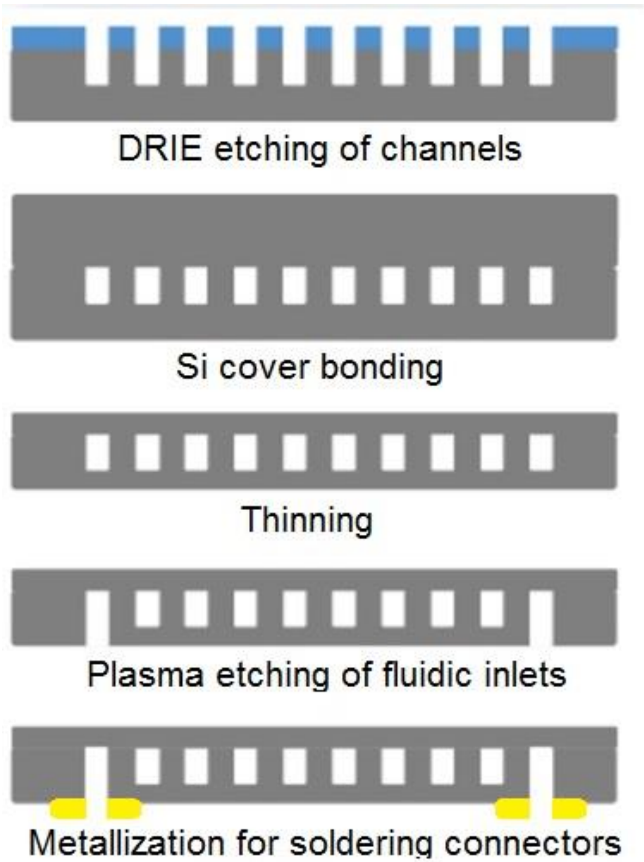
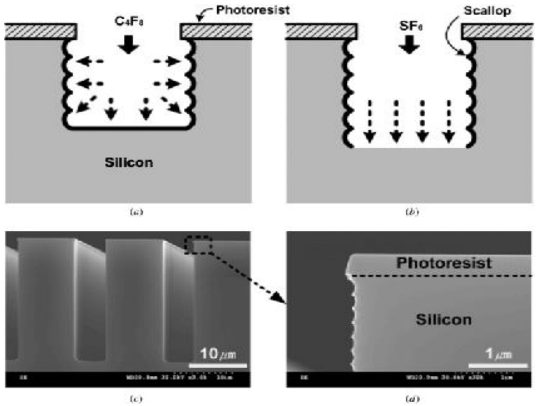
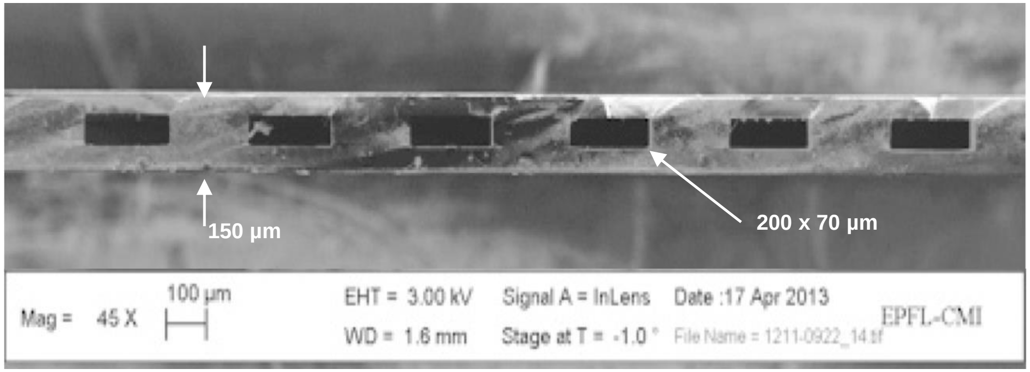


Plasma dicing by DRIE

Deep Reactive Ion Etching



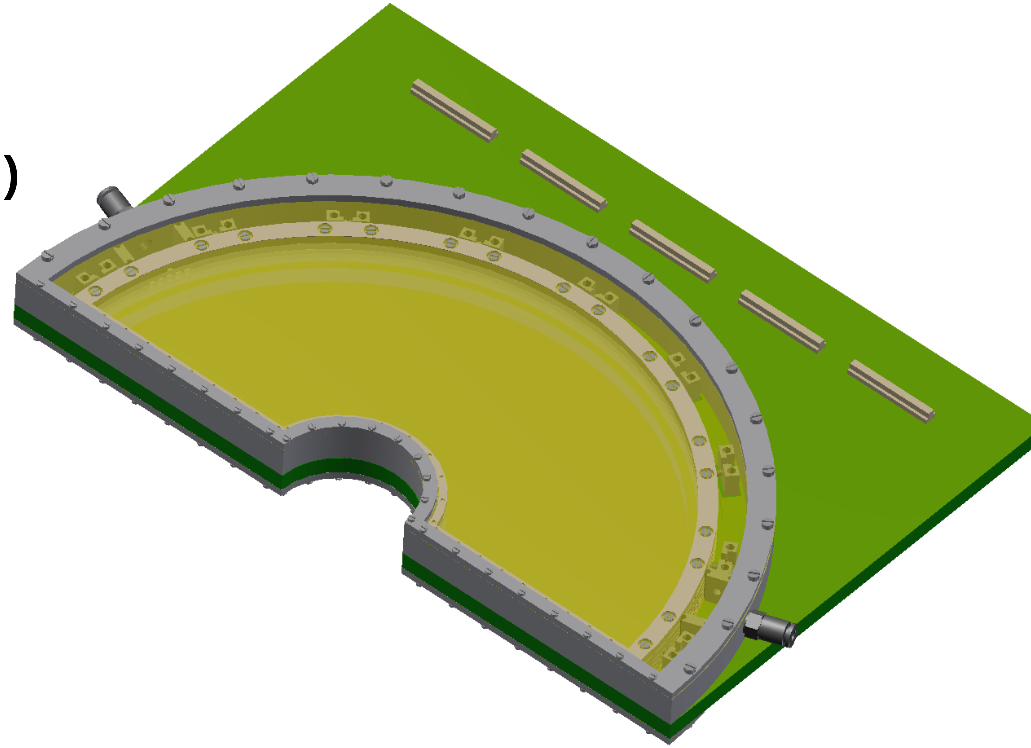
Chang Kun Kang *et al* 2008 *J. Micromech.Microeng.* **18** 075007

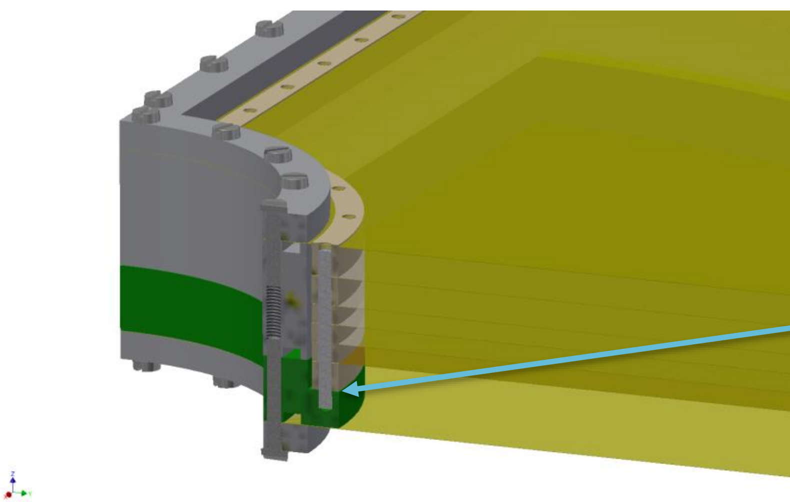


Low material budget triple GEM for the HL-BGV

<u>Small Detector **Half-moon design**</u>

- Triple GEM configuration
- Readout strips **stretched (New!)**
- Strip Pitch: **400 um**
- Goal: **50um** position resolution
- XY Strips: 640 x 2 = **1280 ch**
- Readout: **20 VMM** ASICs (64 channels)





- Minimization of the material used in between the beam pipe and first sensitive area of the GEM.
- The objective is to reduce the **multiple scattering in dead structural zones**.

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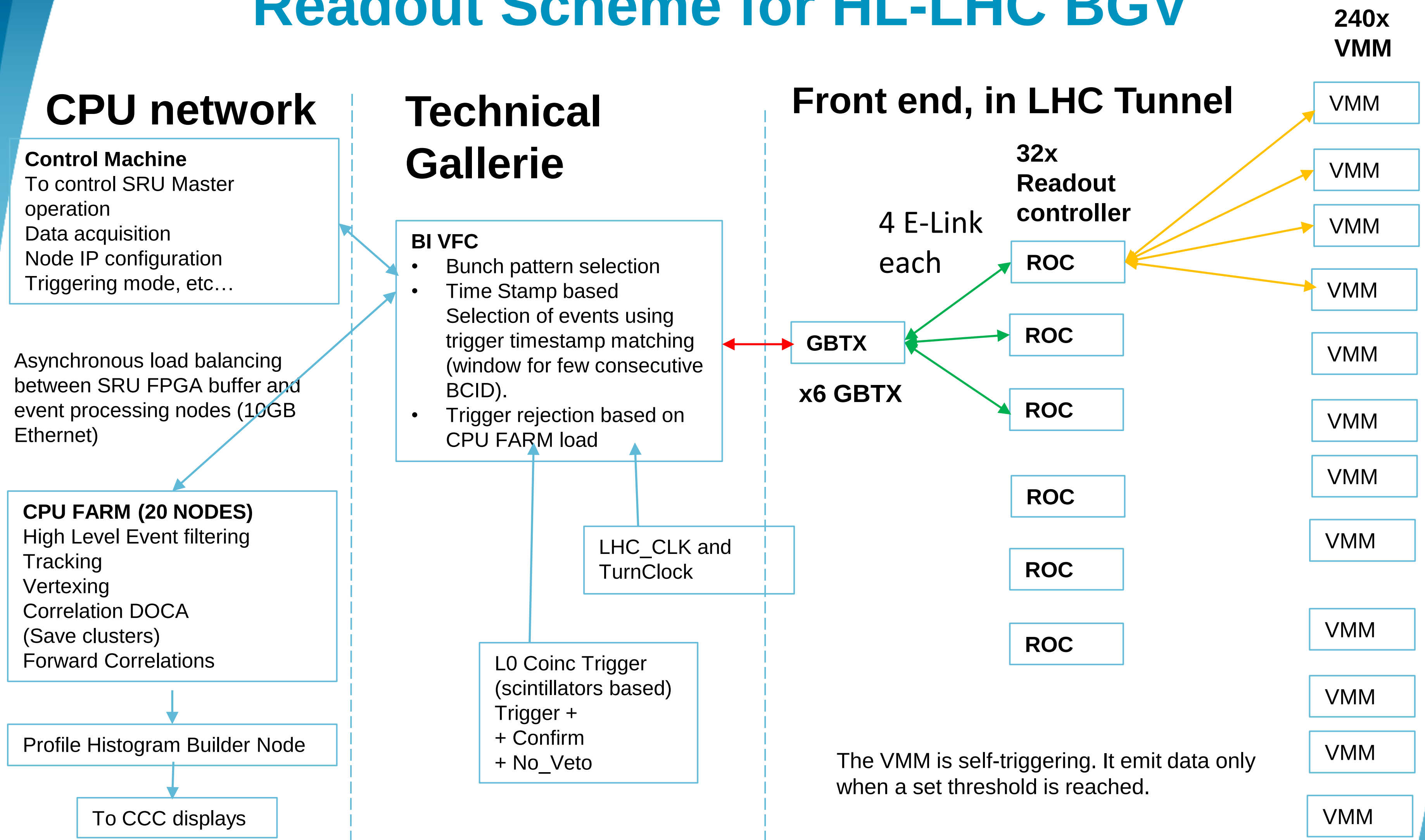
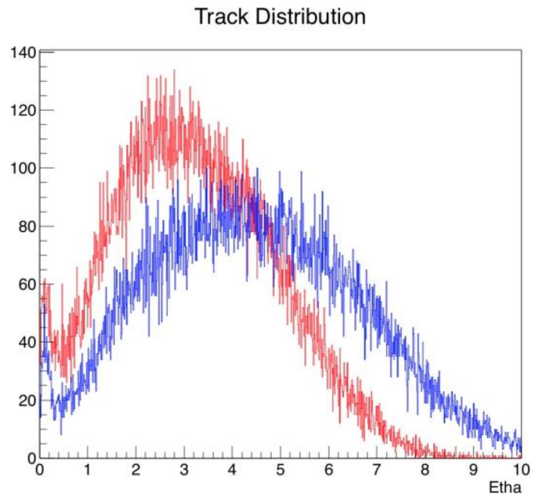
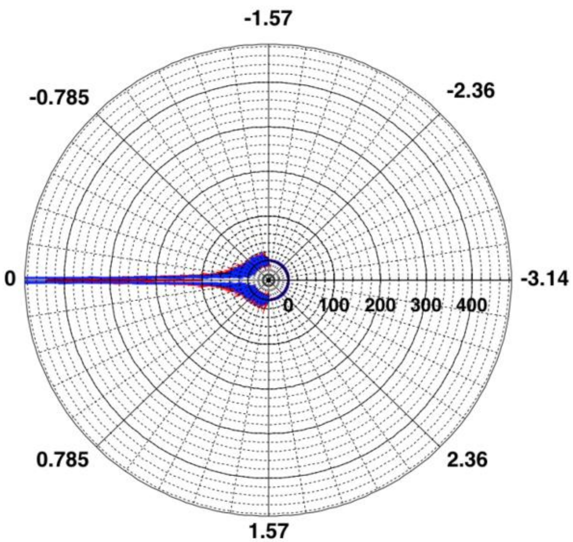
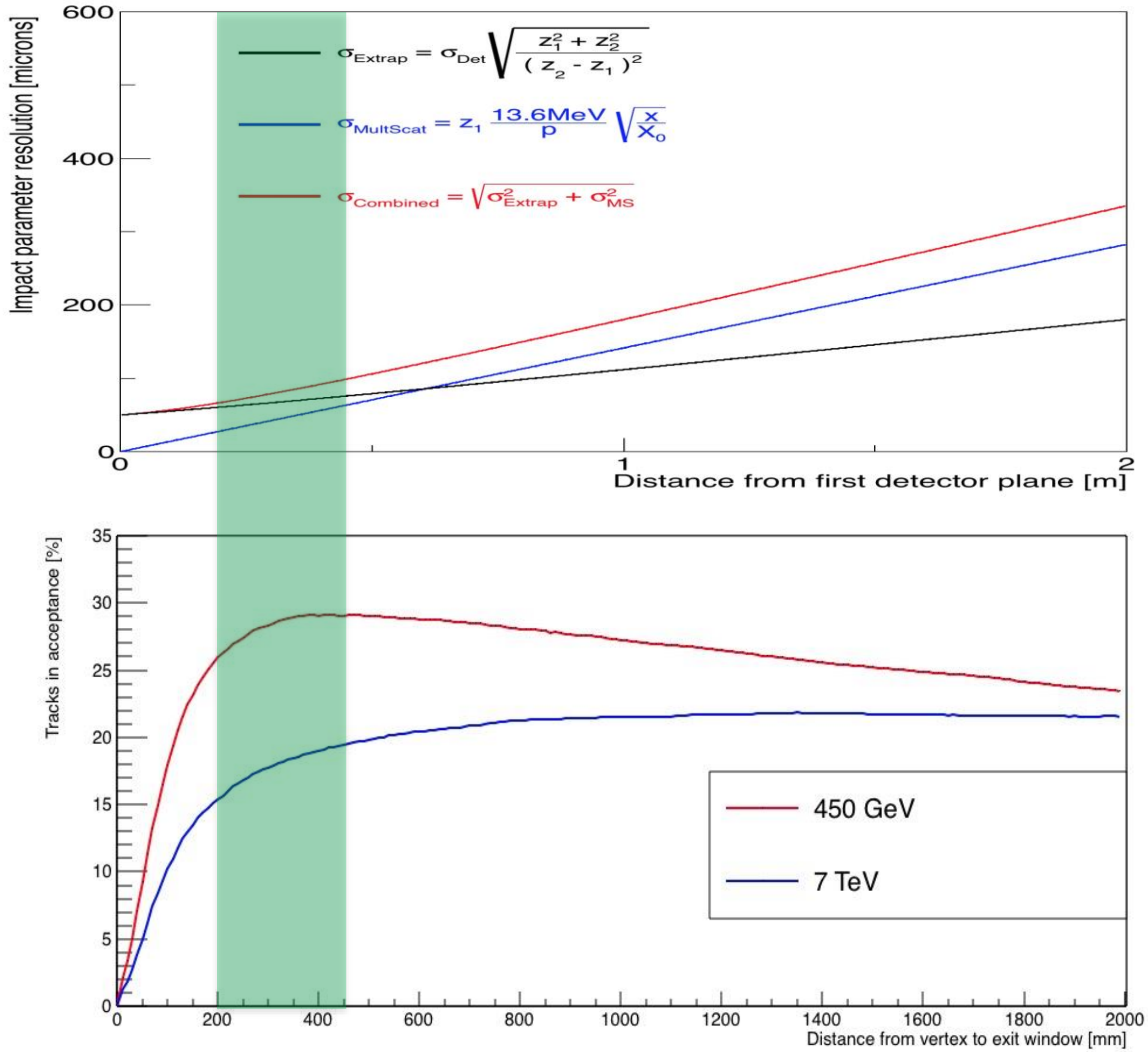
Readout Scheme for HL-LHC BGV



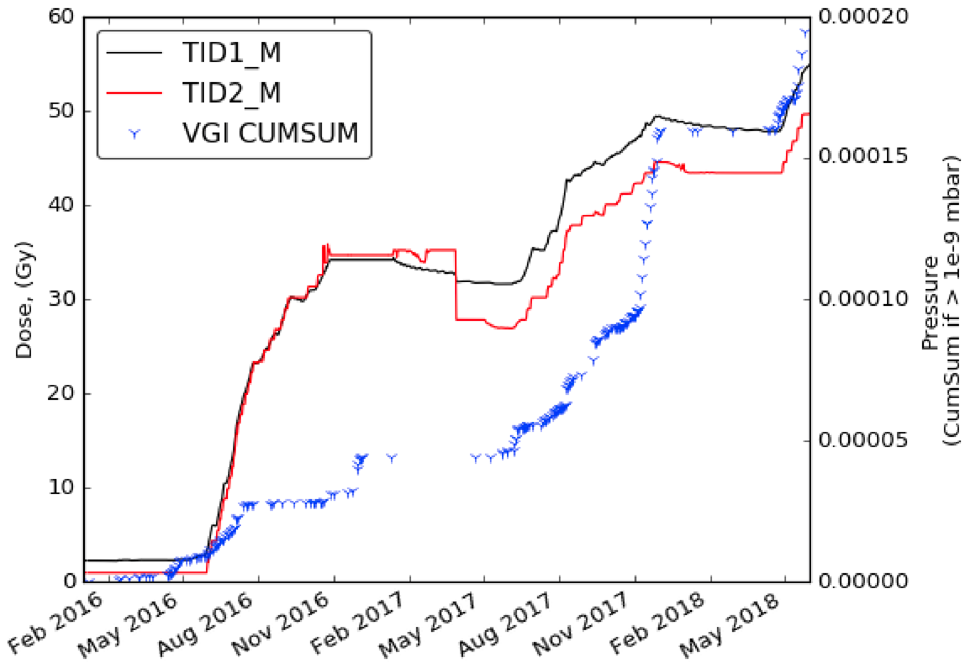
Gas jet open the path for vertexing capability





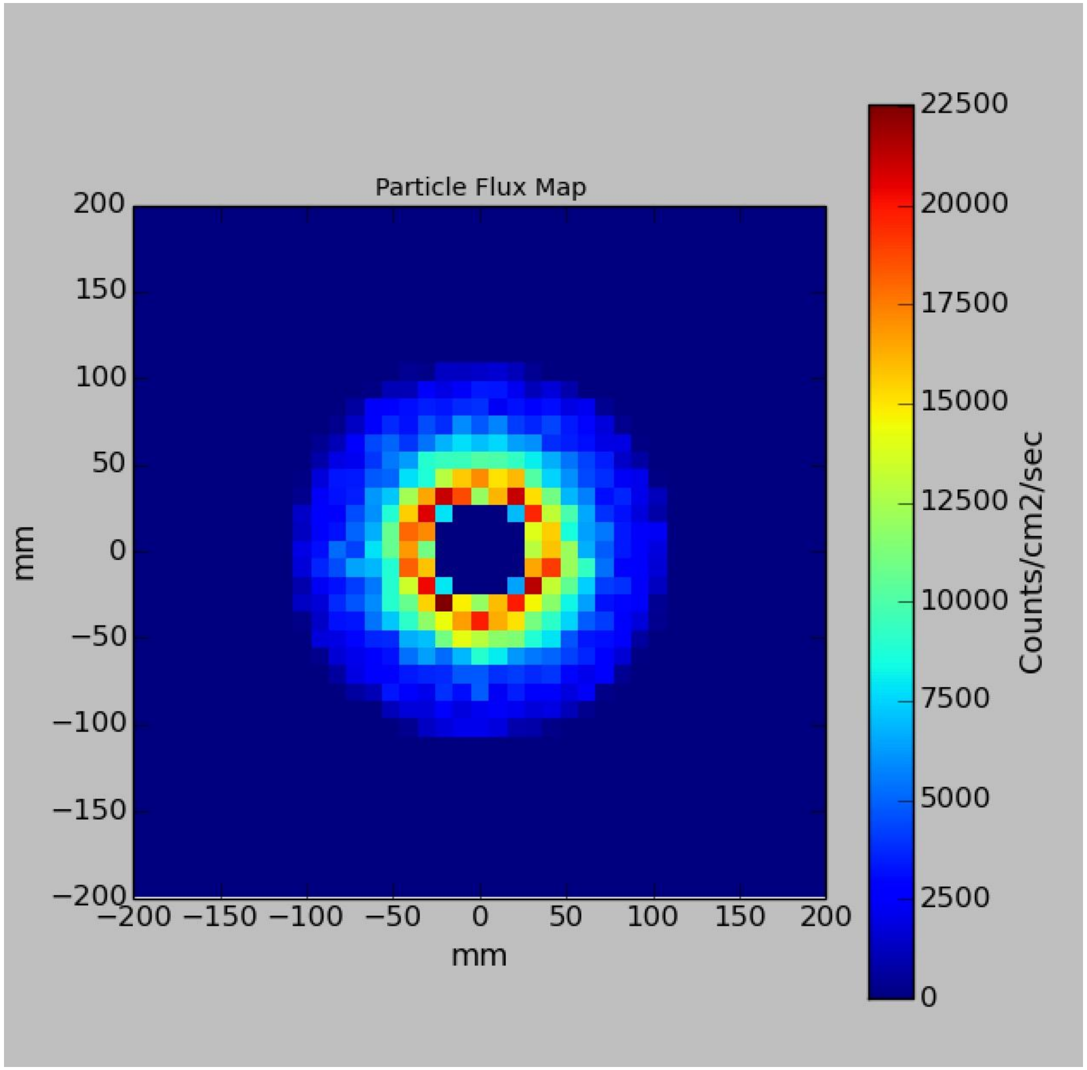


Expected radiation dose



- RadMon located 20 cm from beam axis (downstream from readout ASICs)
- Two years of BGV demonstrator operation accumulated a TID of 50 Gy.
- The annual TID is expected to be around 150Gy/year for full time operation.
- 150Gy/year -> need to confirm with the HL-LHC FLUKA model

Expected Rate in the first detector layer



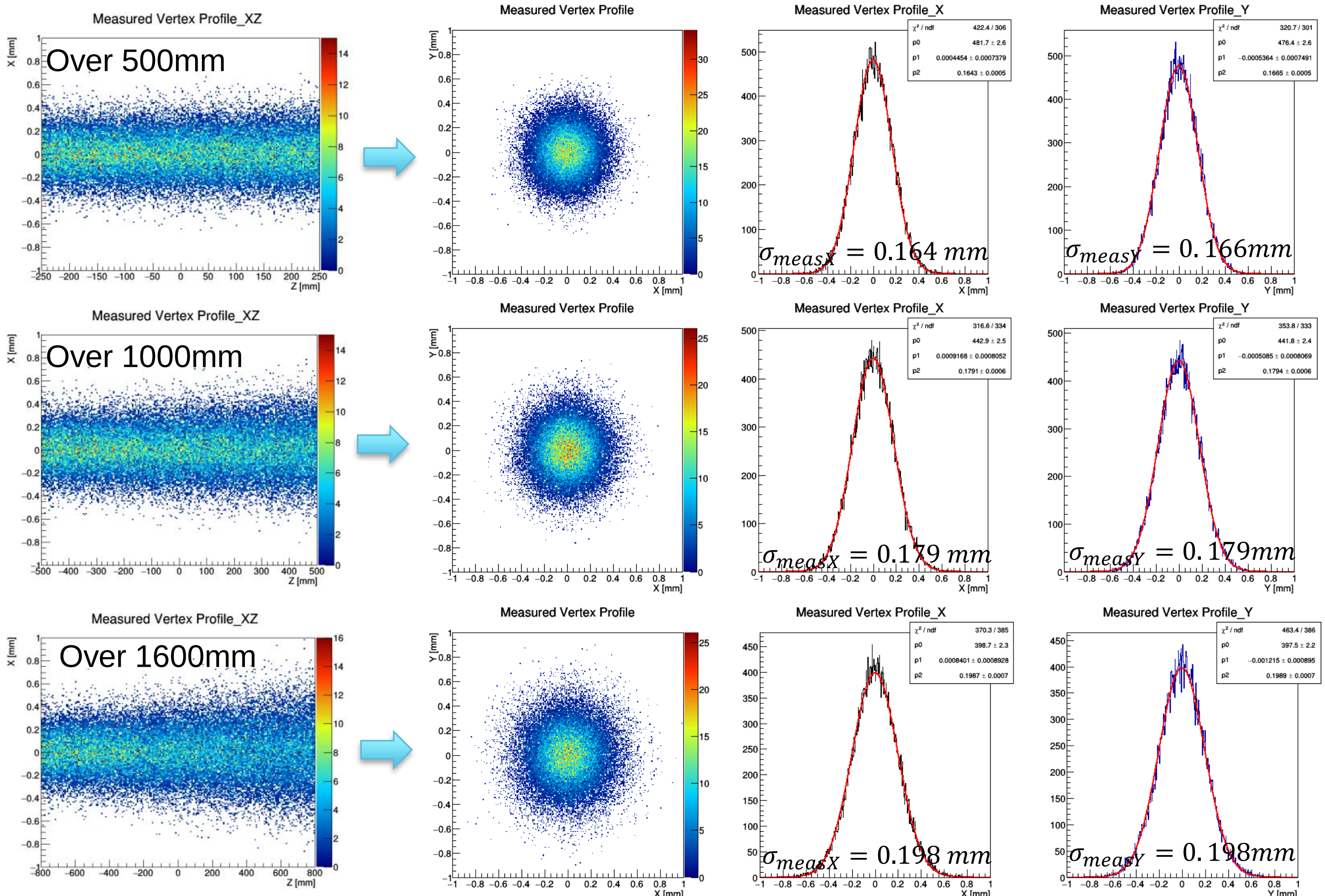
Full LHC train (2808 bunches) produce about 200kHz of beam-gas interactions in the gas target.

Collision rate of 80Hz/bunch

A maximum **secondary rate of 25kHz/cm^2** is expected in the first detector layer.

Advantage of a shorter gas target.

Simulated Gaussian **proton beam** : $\sigma_{beam} = 0.150\ mm$



Relation between beam size and BGV vertex resolution

The BGV aim is to obtain a beam size measurement with systematic uncertainty:

$$\frac{\delta\sigma_{beam}}{\sigma_{beam}} \leq 3\%$$

This beam size error is mainly driven by the vertex resolution of the BGV

$$\frac{\delta\sigma_{beam}}{\sigma_{beam}} = \frac{\sigma_{res.}^2}{\sigma_{beam}^2} \times \frac{\delta\sigma_{res.}}{\sigma_{res.}}$$

If we assume an accuracy of vertex resolution parametrization $\frac{\delta\sigma_{res}}{\sigma_{res}} \approx 10\%$

The constraint between beam size and vertex resolution is the following

$$\frac{\sigma_{res}}{\sigma_{beam}} < 0.55$$

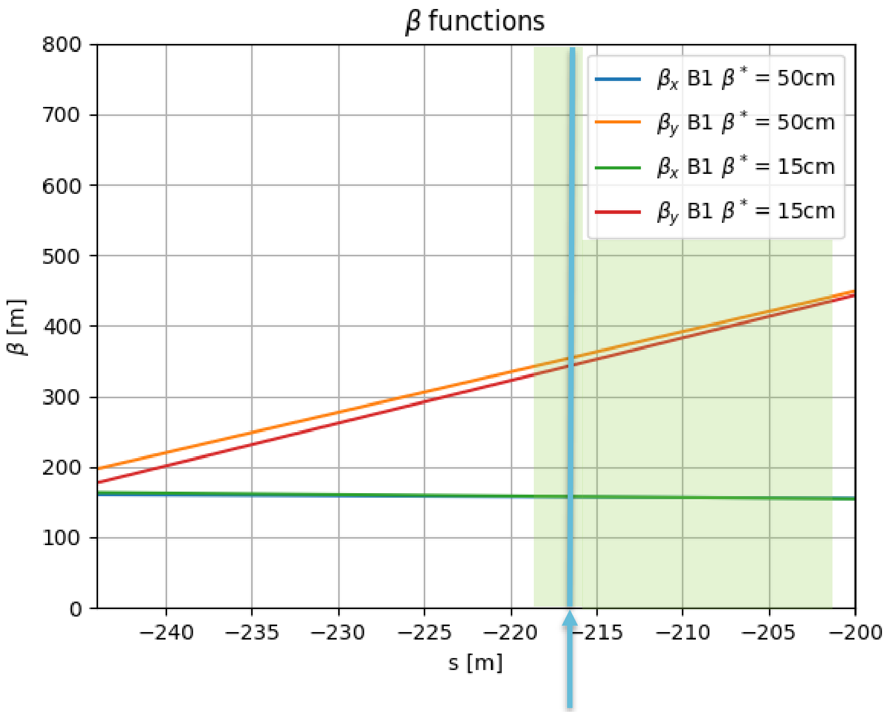
Location of the BGVs in point 4

- The BGV for beam 2 can use roughly the same position as the BGV prototype (after removal).

- The BGV for beam 1 have two options
  - SOLUTION1: Put BGV beam 1 just right after BGV beam 2 in the same (44m) reserved slot. s[-244,-200], **preferred** (stable Beta along ramp)!
  - SOLUTION2: Use another place on right side of PT4 (there is 7.5 meters of free space after BPLX(E) s[142,150], less preferable (Beta changes).

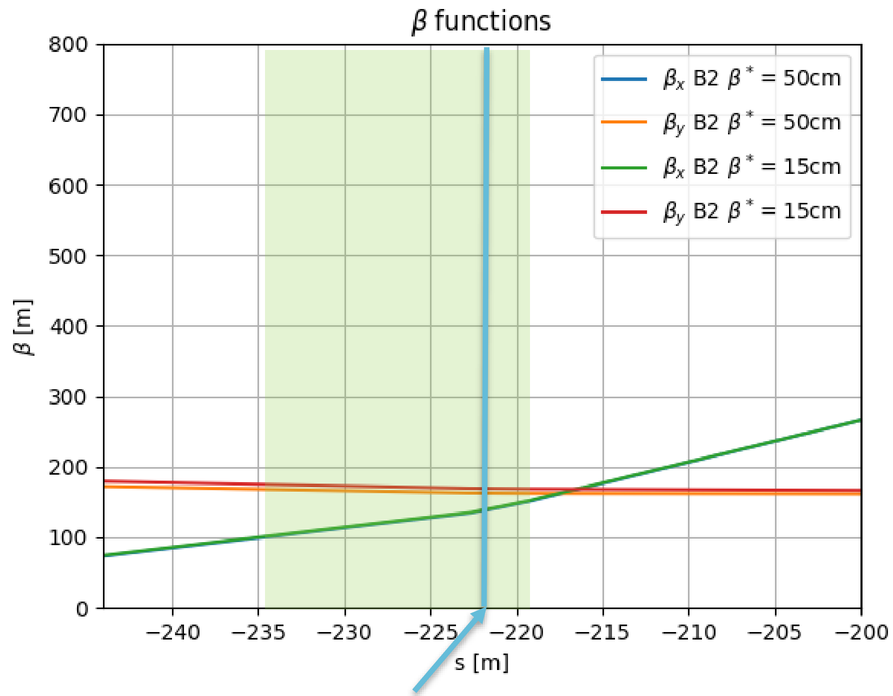
Solution1
BGV B1 s[-244 -200] same as BGV B2

BGV beam 1



BGV B1 IP

BGV beam 2



BGV B2 IP

The two BGVs are installed one after the other (each on its own beam)

Solution2
BGV B1 s[142.5 to 150] between Q5 and Q6