Status of the Beam Gas Vertex (BGV) Monitor

WP 13.7

Bernadette Kolbinger on behalf of the BGV team (CERN SY-BI-XEI)

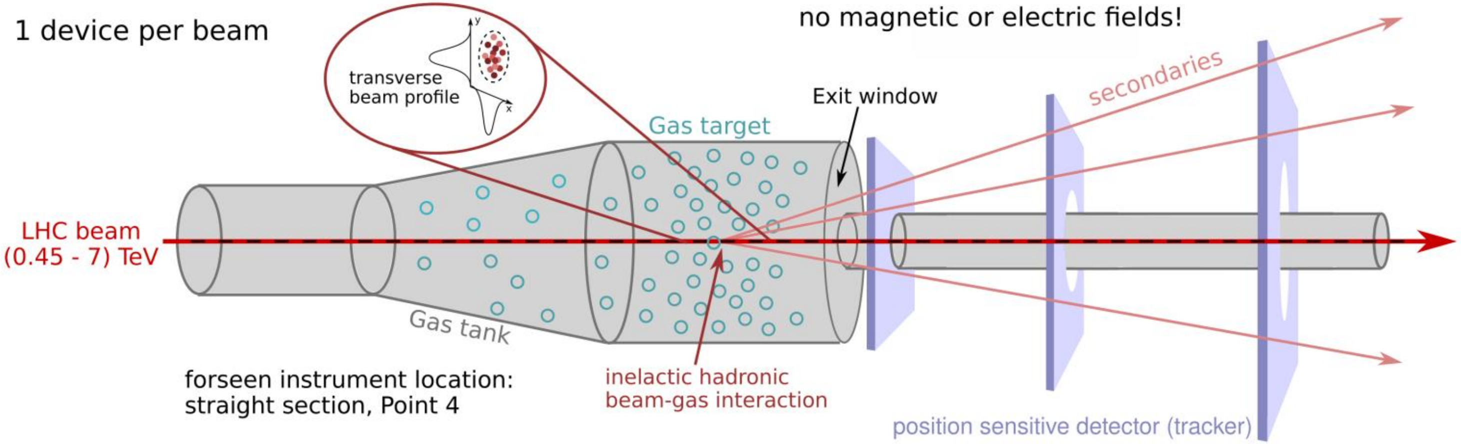
Acknowledgements:
BGV team: H. Guerin, J. Storey
With input from: G. Bregliozzi, A. Galloro, D. Hynds, R. Kersevan, R. De Maria, J. Oliveira, R. Plackett, D. Prelipcean, T. Ramos Garcia, B. Salvant, G. Schneider, T. Lefevre, B. Salvant, A. Salzburger, H. Sandberg, R. Veness

Outline

- **Introduction**
- **Simulations**
- **Status of the new design**
  - Gas target
  - Tracking detector
  - Integration
- **Expected performance**
- **Summary & outlook**

Introduction - principle

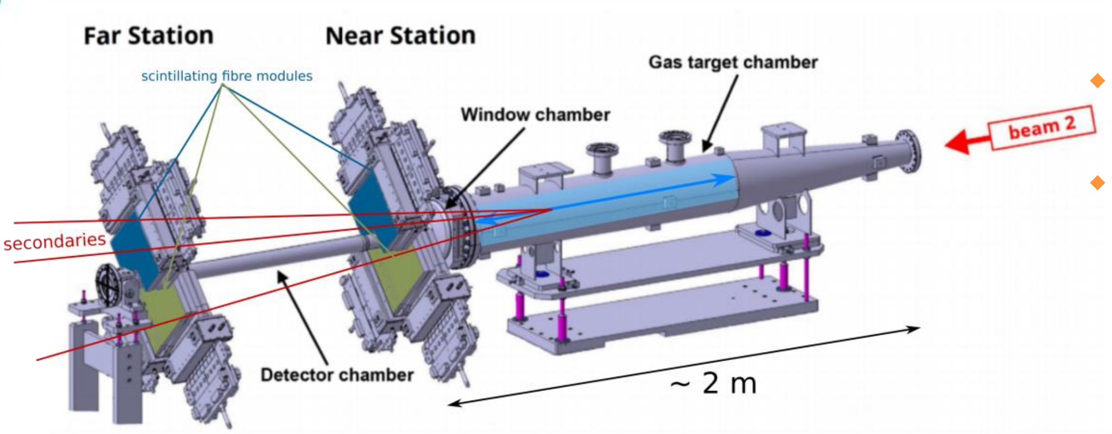
- **Noninvasive transverse beam profile monitor** based on the reconstruction of vertices of inelastic hadronic beam-gas interactions - **BGV (Beam Gas Vertex)** monitor.
- Provide **continuous emittance and beam profile measurement** throughout the LHC accelerator cycle (450 GeV to 7 TeV).



- Consists of: a gas target, a forward tracking detector and computing resources dedicated to event reconstruction.

History – BGV demonstrator

Installed, commissioned and operated in LHC Run 2 (PhysRevAB)



- **Tracking detector** based on **scintillating fibre** stations (LHCb SciFi).
- **Neon gas target** of ~1.8m length and 10-7 mbar (~200 kHz interaction rate).

- **Successful beam size measurements** (200 µm to 800 µm), throughout the LHC cycle with required precision. Bunch-by-bunch measurements.
- Coherent with other beam size measuring devices.
- Reconstruction of beam-gas interaction vertices not possible → **no beam profile measurement.**

Future BGV

- [Beam size review](#) after Run 2 Oct. 2019:

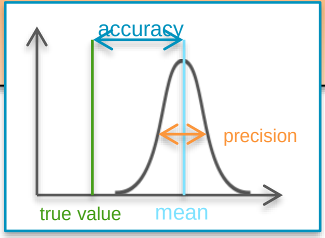
"None of the present instruments provide a bunch-by-bunch profile measurement for the physics beam along the whole cycle. An additional non-invasive measurement device complementary to the WS and BSRT devices is therefore required."

Case for a new device is solid.

- Work on **new design - conceptual design report** will be reviewed in **October 2022**.

Requirements for the future HL-LHC transverse beam profile monitor:

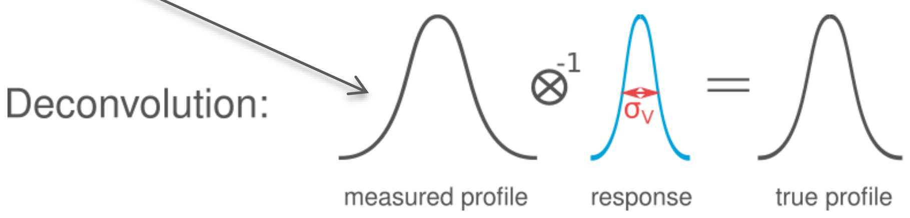
- Emittance measurement with **accuracy $\lesssim$ 10 %** (beam size $\lesssim$ 5%).
- **Bunch-by-bunch** measurements of **beam size with ~ 1 % precision after ~1 min** of accumulating data.
- Provide **transverse profile** measurements.



add. design goals: aim for simplicity, maintainable by small team, minimise R&D: robust technologies.

BGV performance - what's important?

- Method: deduce beam profile from spatial distribution of reconstructed vertices.



the better we know the response function, the better we know the profile!

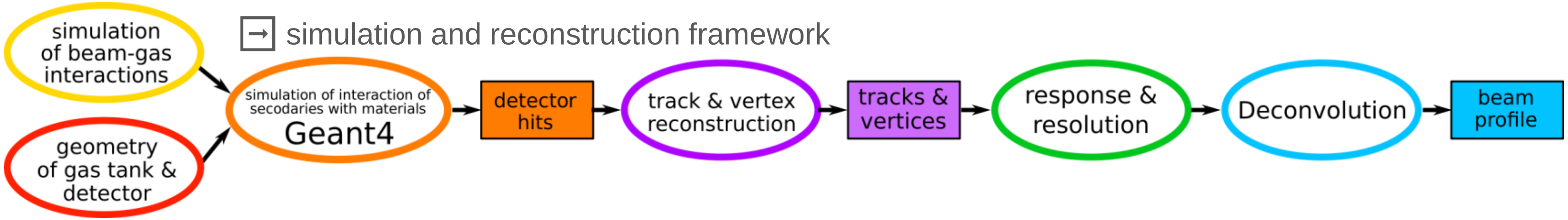
- Key performance measure = response function. Not easy to determine with high precision - keep its width (= vertex resolution $\boldsymbol{\sigma_v}$) small!

- **What σ_v do we need, to achieve a beam size measurement with accuracy of $\leq\ 5\ \%$?**
  - $\boxed{\rightarrow}$ **Depends on beam size!**
  - Minimum beam size at BGV locations is **235 µm (7 TeV)**. Assume knowledge of $\boldsymbol{\sigma_v}$ with 10 % accuracy $\boxed{\rightarrow}$ $\sigma_v \lesssim$ 166 µm (see calculation).

Performance study & optimisation

- **What impacts the vertex resolution σ_v?**
- **What are the requirements for BGV gas target and tracker**, to:
  - fulfilling performance specifications,
  - within the boundary conditions of: feasibility of integrating it into the LHC?

answer with complete simulation study!



Test important **design parameters and their impact on performance**:

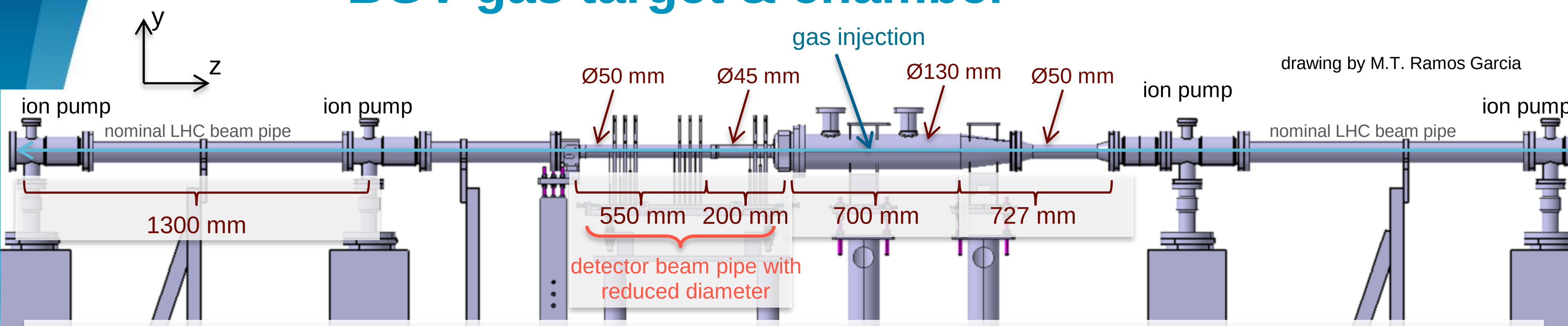
- Detector dimensions, material budget, position resolution etc.
- Gas target extension, pressure, gas species etc.

Conclusions

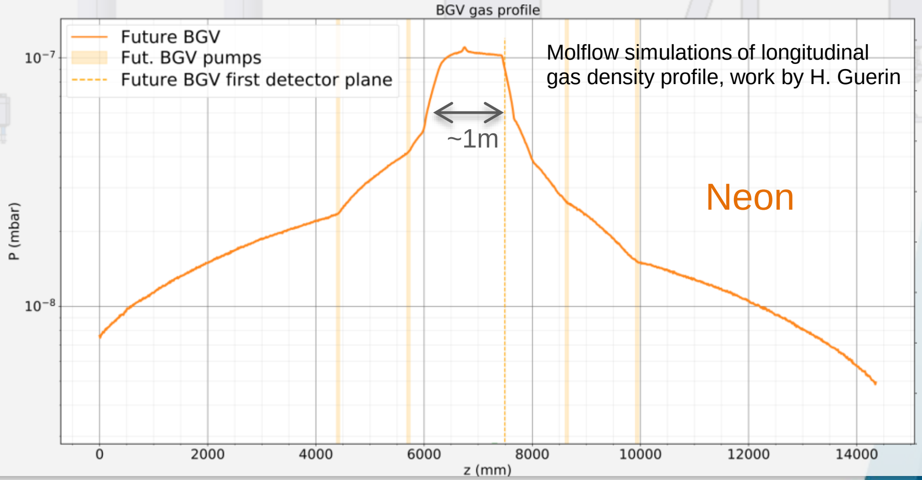
- Results point towards possibility of **compact tracker with a high spatial resolution.**
- **Extended gas target** not a show stopper - **~1 m neon, with ~10^{-7} mbar**.

→ see: BGV talk at 2021 Hilumi Collaboration Meeting, IBIC paper 2021, or back-up slides.

BGV gas target & chamber



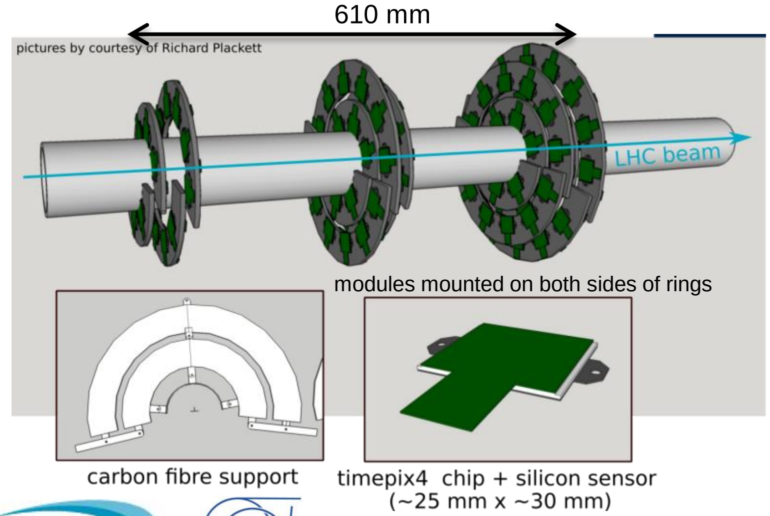
- Redesign of the demonstrator target - more compact.
- **Neon** gas injected on the tank via a capillary.
- **Distributed gas target**, with density plateau Δz ~ 1m.
- $\mathbf{10^{-7}}$ **mbar** at plateau ⇒ ~200 Hz inelastic collisions per bunch.
- **Gas tank design**: taking impedance, performance needs and mechanical stability into consideration.
- **Exit window** (0.9 mm to ~2 mm), aluminium alloy.
- **Potential future upgrade**: gas curtain target.

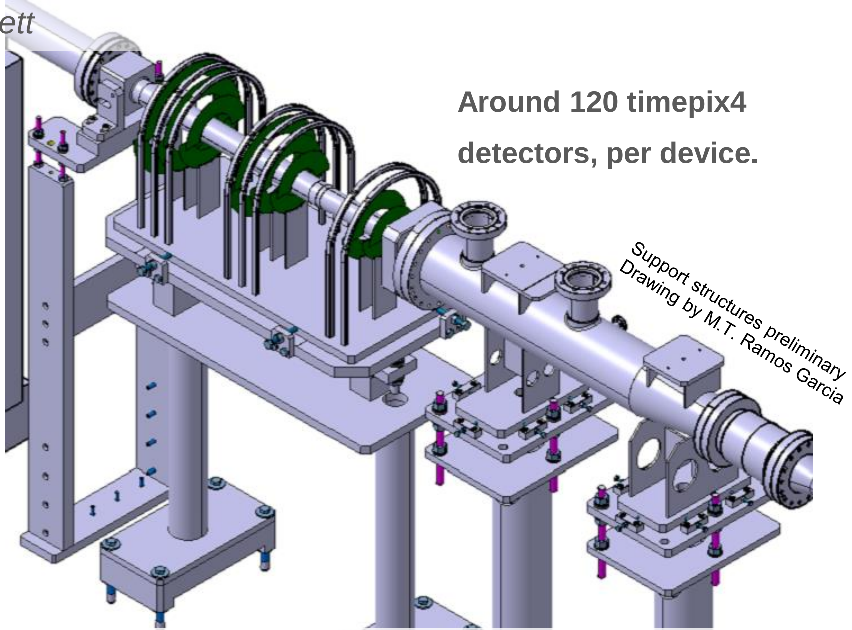


A BGV tracker based on silicon hybrid pixel detectors

Collaboration with Oxford University: D. Hynds and R. Plackett

- Design based on the **ATLAS ITk HiLumi upgrade**.
- **Timepix technology**: robust and widely used detectors. **XP within Beam Instrumentation** group.
- **DAQ:**
  - Read-out system based on BGI read-out.
  - CPU farm in service tunnel for event reconstruction.



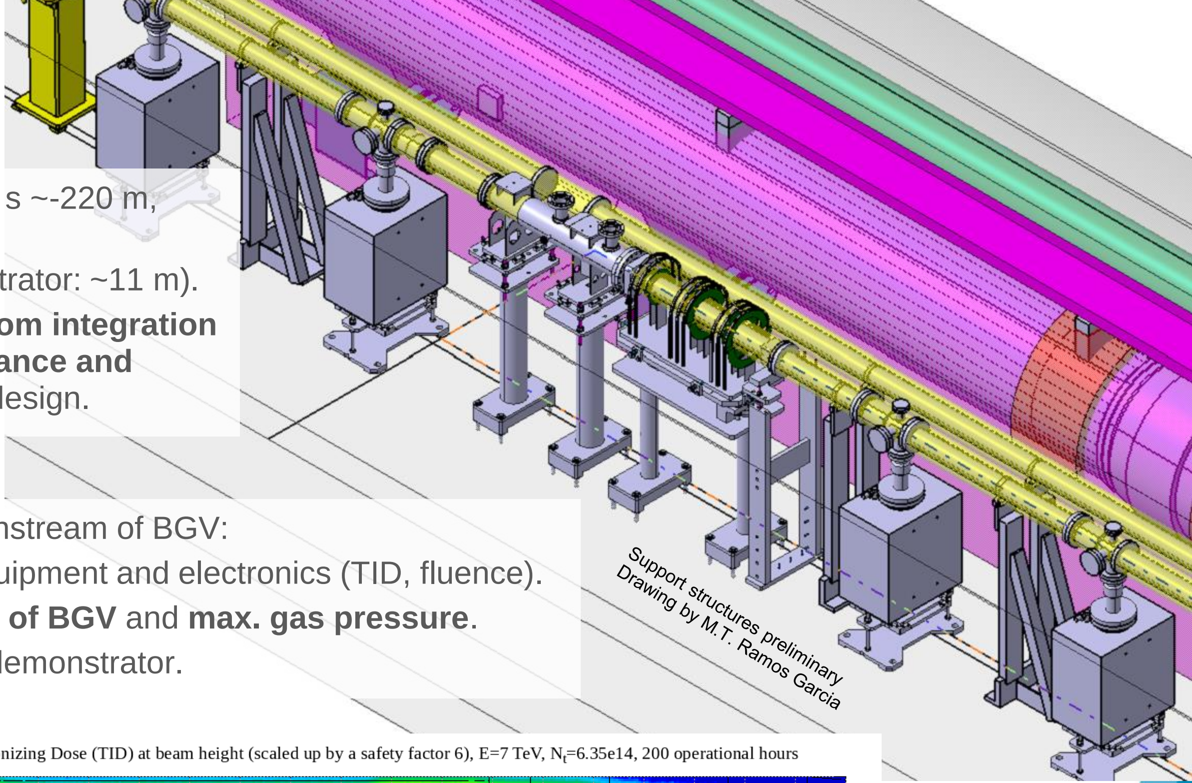


Around 120 timepix4 detectors, per device.

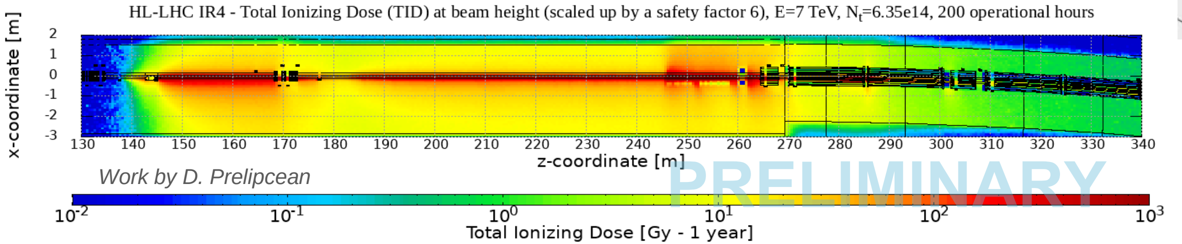
- **Project planning on-going**:
  - Module design & building, support structure @Oxford.
  - Read-out, reconstruction software, commissioning @CERN.
- Installation could be foreseen in 2028.

Integration aspects

- **Location: LSS of Point4**, beam 2 device at s ~-220 m, beam 1 device at s ~142 m.
  - Total instrument length ~6 m (demonstrator: ~11 m).
- Integration study on-going - taking **inputs from integration** (WP15), **ABP, survey & alignment, impedance and vacuum** teams into account for instrument design.

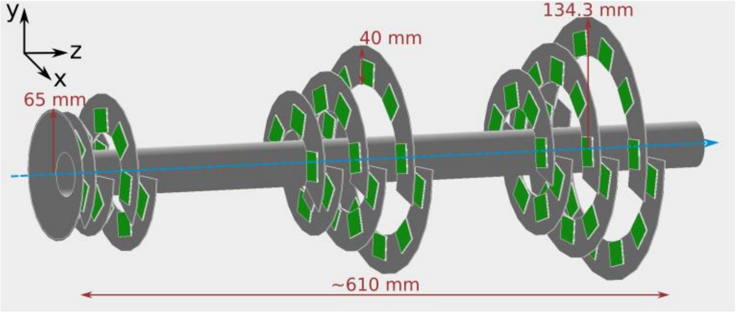


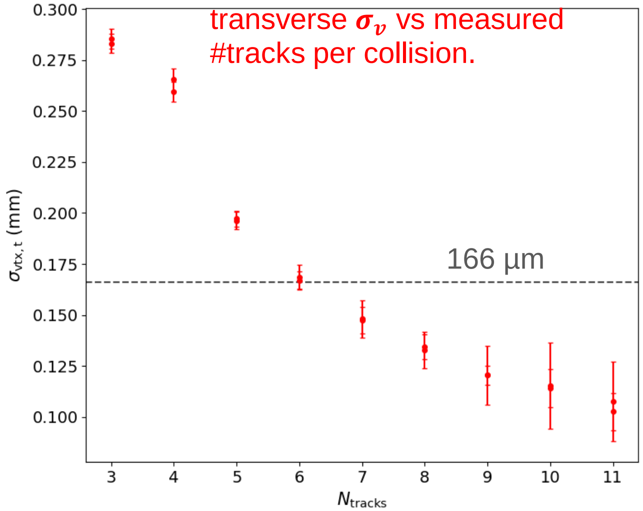
- FLUKA study of **radiation environment** downstream of BGV:
- Impact on magnets (heat loads) and other equipment and electronics (TID, fluence).
- Caused radiation impacts **total max. up-time of BGV** and **max. gas pressure**.
- Integrated pressure ~25% less compared to demonstrator.



Expected performance – bunch width precision

simulation set-up including all important materials.

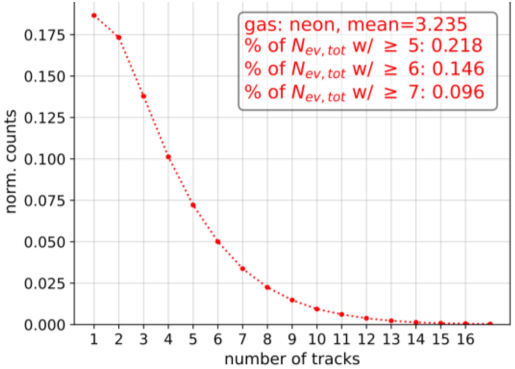




- 7 TeV protons (most stringent case).
- Accept events with $\mathbf{N_{tracks}} \geq$ **6** → **14.6 % of total number of collisions**.
  - Cut on $\mathbf{N_{tracks}}$ can be relaxed for larger beam sizes.

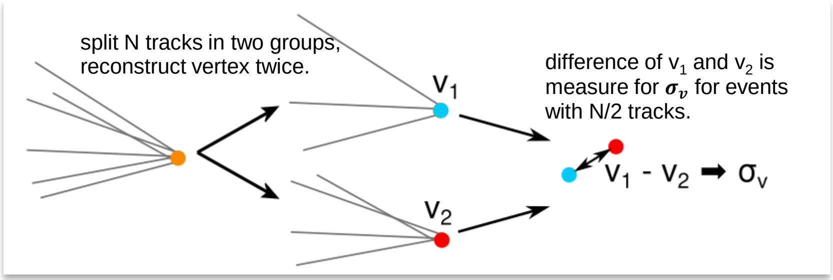
Precision on bunch width:

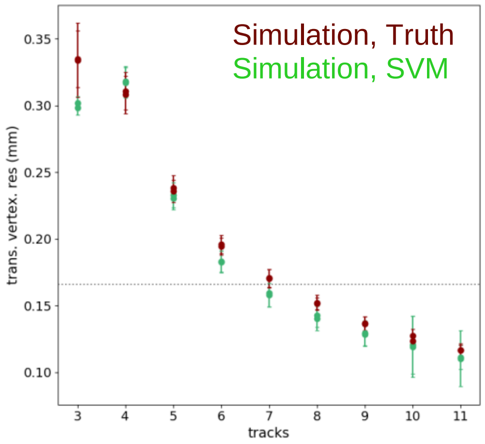
- Reminder: bunch-by-bunch measurements with ~1% precision in ~1 min.
- **How many interactions in 1 min with $\mathbf{N_{tracks}} \geq$ 6?**
- Assume a gas pressure of 10^{-7} mbar.
- 1740 recorded coll. in 1 min → **bunch width relative precision 1.7 %.**

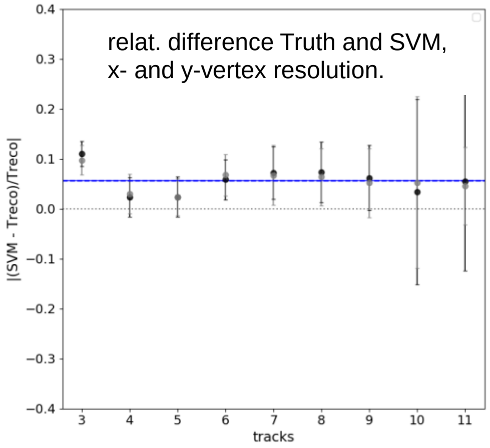


Vertex response and resolution for a profile measurement

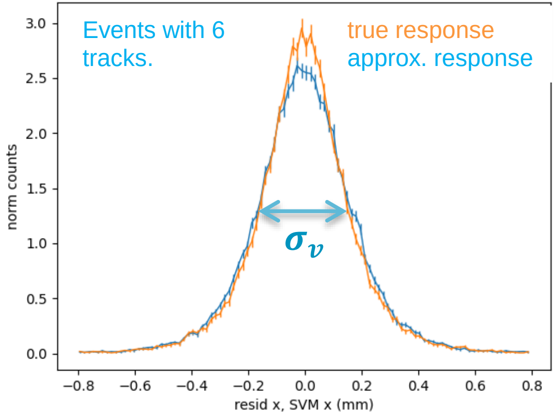
- During the measurements - need to determine response and vertex resolution.
- Common method of LHC experiments: **split vertex method (SVM)**.







- Applied to simulation data, SVM **shows agreement of ~ 6% with the true vertex resolution** (determined by comparison of reconstructed vertex to generator level).



- **Method to determine vertex response during BGV measurements**, no need to rely on simulations or additional measurement with known source!

Summary & outlook

- The BGV is currently being **optimised for the HL-LHC** – work on conceptual design report.
- **Design is based on extensive performance study** - based on established tools, support from experts.
- **Gas target baseline: extended neon gas target** with **~1m** density plateau of **10^{-7} mbar**, via injection of neon into gas chamber.
- **Compact tracker** based on silicon pixel detectors in collaboration with University of Oxford**.**
- **Integration constraints** are taken into account, no showstoppers identified.
- **Performance study shows promising results in accord with specifications** - bunch width precision 1.7 % in 1 min.
- **Method of measuring vertex response and resolution** for deconvolution of true profile.
- On-going: deconvolution, detector alignment, pattern recognition.

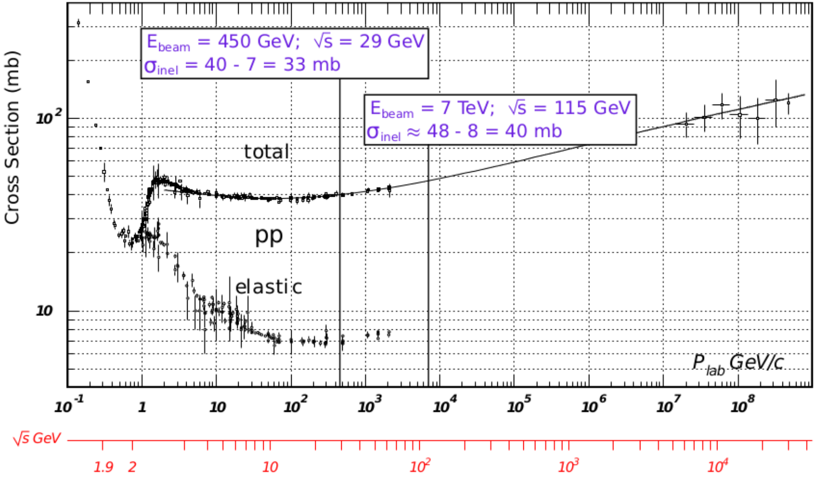
- **Next milestone - Review of BGV (& BGI) proposal on October 19th 2022.**

Thank you for your attention!

BACK UP

Inelastic collisions

- Inelastic proton-nucleus cross-section
  $\sigma_{pA}(E) \approx \sigma_{pp}(E) \cdot A^{2/3}$
  A – atomic mass
  In the case of ^{20}Ne:
  - $\sigma_{pNe}(450\,GeV) = 243\,mb$
  - $\sigma_{pNe}(7\,TeV) = 295\,mb$



Data from PDG, plot taken from Plamen Hopchev's presentation (13/11/2013)

- Rate of inelastic collisions per bunch:

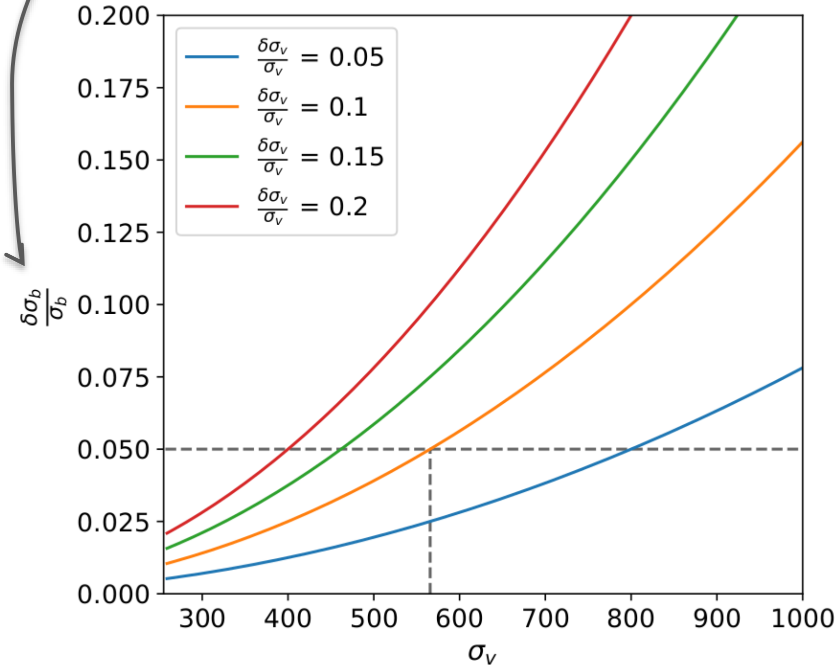
$$R_{\rm inel} = f_{\rm rev}\ N\ \sigma^{\rm inel}_{\rm p\text{-}gas}\ \rho_{\rm gas}\ \Delta z$$

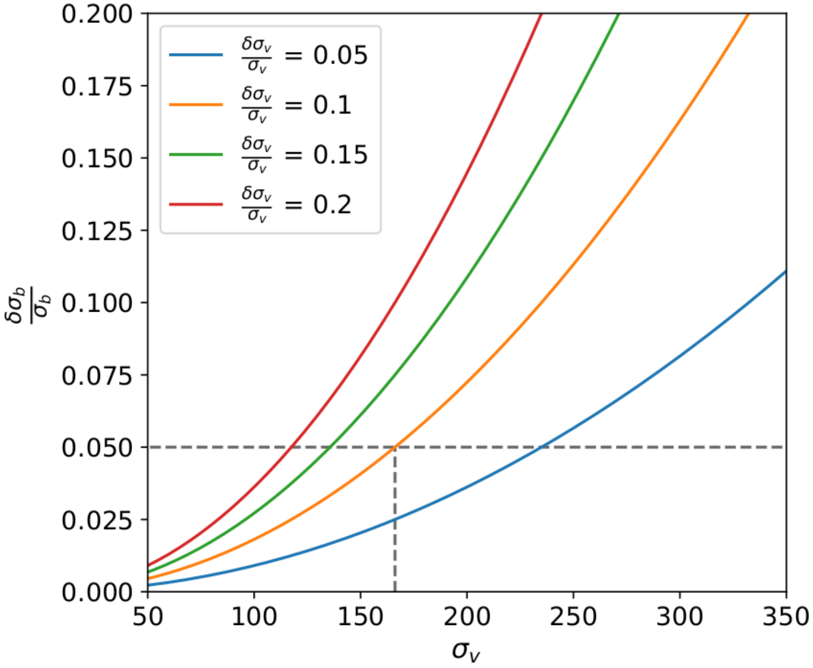
- with the revolution frequency (11245 Hz), the number of protons per bunch N (2.2 x 10^{11}), the gas density ρ and the gas width Δz.

Beam profile and vertex resolution

- **Assume**: bunches with Gaussian x- and y- distribution. Known vertex resolution i.e. Gaussian distribution with σ_{V}.
- The measured beam distribution is a **convolution** of the "true" beam distribution and the vertex response.
- De-convolution of the measured beam distribution (Gaussian with σ_{raw}) and **extract the true beam distribution** (Gaussian with σ_{beam}).
- σs of two convoluted Gaussians are related via: $\sigma_{\text{raw}}^2 = \sigma_{\text{beam}}^2 + \sigma_{\text{V}}^2 \rightarrow \sigma_{\text{beam}} = \sqrt{\sigma_{\text{raw}}^2 - \sigma_{\text{V}}^2}$.
- Using **error propagation**, arrive at: $\sigma_{\text{beam}}^2 \delta\sigma_{\text{beam}}^2 = \sigma_{\text{raw}}^2 \delta\sigma_{\text{raw}}^2 + \sigma_{\text{V}}^2 \delta\sigma_{\text{V}}^2$.
- Assuming a **negligible measurement uncertainty** i.e. $\delta\sigma_{\text{raw}} \rightarrow 0$.
- Arrive at: $\frac{\delta\sigma_{\text{beam}}}{\sigma_{\text{beam}}} = \frac{\sigma_{\text{V}}^2}{\sigma_{\text{beam}}^2} \frac{\delta\sigma_{\text{V}}}{\sigma_{\text{V}}}$
- **Estimate** required vertex resolution: $\frac{\delta\sigma_{\text{beam}}}{\sigma_{\text{beam}}} = \frac{\sigma_{\text{V}}^2}{\sigma_{\text{beam}}^2} \frac{\delta\sigma_{\text{V}}}{\sigma_{\text{V}}}$
- $\rightarrow$ **Small** σ_V **relative to beam size** σ_{beam}.
- $\rightarrow$ **Know** σ_V **precisely**.
- For $\frac{\delta\sigma_{\text{beam}}}{\sigma_{\text{beam}}} \lesssim 0.05$ and $\frac{\delta\sigma_{\text{V}}}{\sigma_{\text{V}}} \lesssim 0.1 \rightarrow$ for $\sigma_{\text{beam}} = 200\,\mu\text{m}$, get: $\sigma_V \lesssim 140\,\mu\text{m}$

$$\frac{\delta\sigma_{\text{beam}}}{\sigma_{\text{beam}}} = \frac{\sigma_{\text{v}}^2}{\sigma_{\text{beam}}^2}\frac{\delta\sigma_{\text{v}}}{\sigma_{\text{v}}}$$





Emittance growth (negligible)

- Consider beam particles scattered elastically within BGV gas target.
- Emittance growth budget should be below 10 to 15 %.
- Emittance growth per turn of gas target with length L [Ref]:
- $\Delta\varepsilon = \frac{1}{2} {q_p}^2 \left(\frac{13.6\ MeV}{p\beta_r}\right)^2 \overline{\beta_x} \frac{L}{L_{rad}}$
- q_p is the charge of the projectile, p the momentum, β_r the relat. velocity, $\overline{\beta_x}$ the average transverse beta-function along the gas targets length L. L_{rad} is the radiation length of neon.

Table 2: Elastic Scattering Emittance Growth.

Beam and Energy	$\Delta\epsilon$ (π **rad m**)	$\Delta\epsilon_n$ (**µm h**$^{-1}$)
Beam 1, 450 MeV	1.9×10^{-19}	3.2×10^{-3}
Beam 1, 7000 MeV	7.7×10^{-22}	2.0×10^{-4}
Beam 2, 450 MeV	9.3×10^{-20}	1.6×10^{-3}
Beam 2, 7000 MeV	3.8×10^{-22}	1.0×10^{-4}

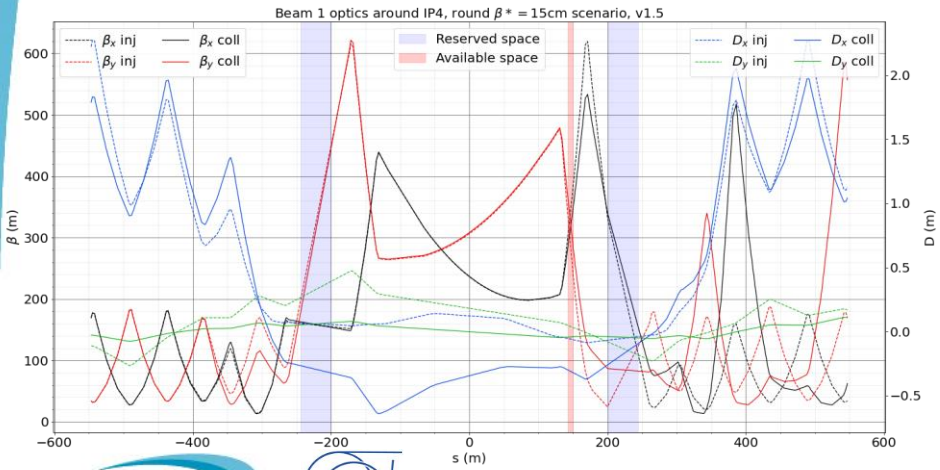
from latest IBIC paper by H. Guerin et al.

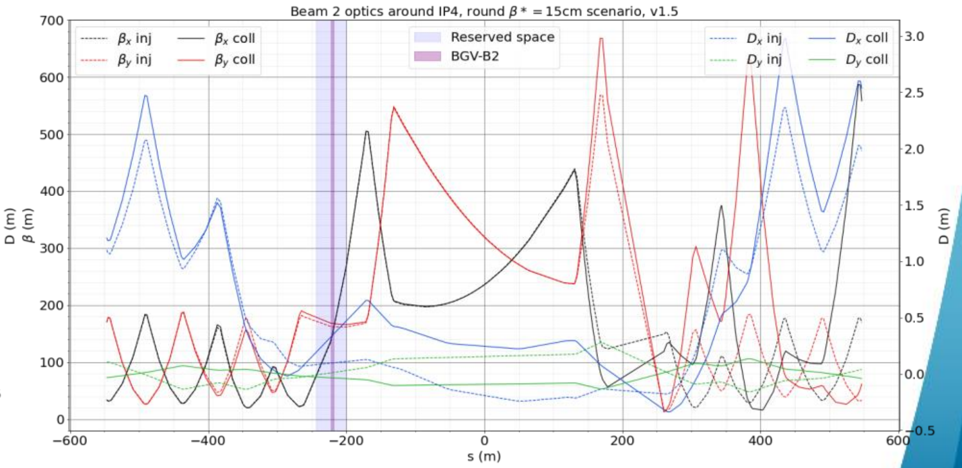
- For running the BGV 2h per fill: 0.16 % (beam 1) and 0.08 % (beam 2).

slide taken from HiLumi integration meeting 03/06/22:
https://indico.cern.ch/event/1165410/

Location and space reservations

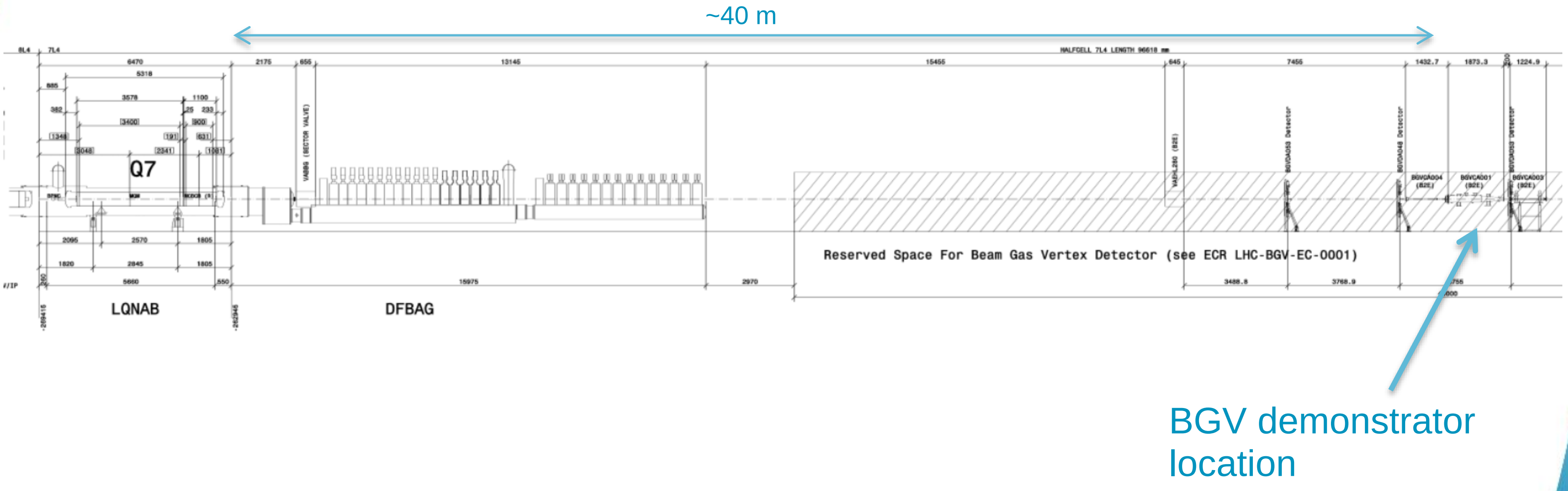
- Initial space reservation from LHC-BGV-EC-0001
- **B2-BGV** is foreseen to be installed where the demonstrator is on left of IP4, with space reservation **[-244, -200]m**
- ([9753.081, 9797.081]m DCUM) w.r.t IP4 centre
- The initially foreseen location for B1-BGV was symmetric to IP4 centre **[200, 244]m** but now shows too demanding beam optics for instrument vertex resolution.
- The new foreseen location is now **[141.052, 148.572]m** ([10138.133, 10145.653]m DCUM) w.r.t IP4 centre for **B1-BGV**.
- Possibly additional 1.2m on each side of this location, currently occupied by disconnected BQKH&V (confirmed by Thibaut).





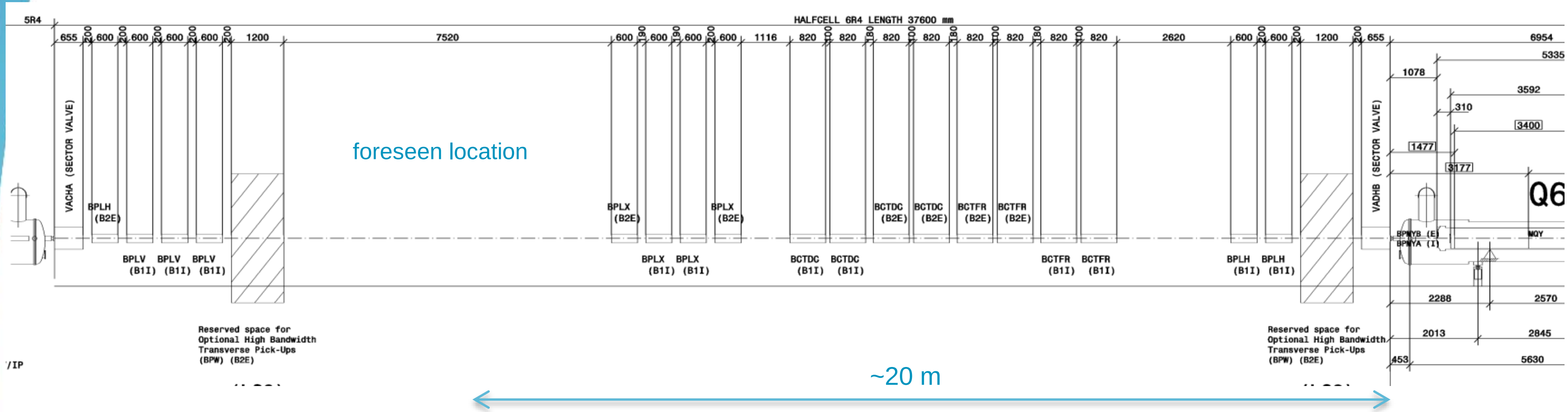
BGV2 foreseen location

https://edms.cern.ch/document/1395361/0

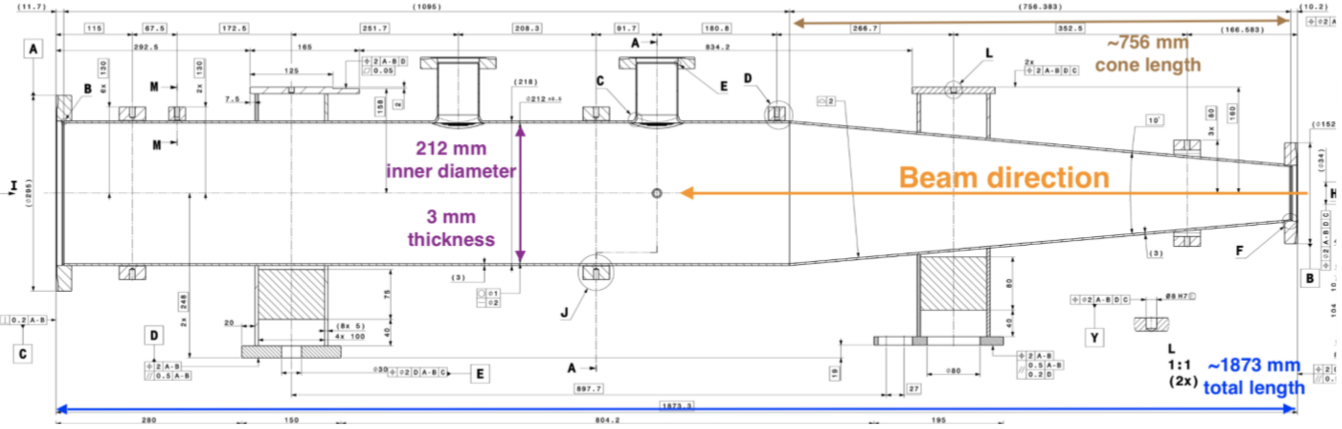


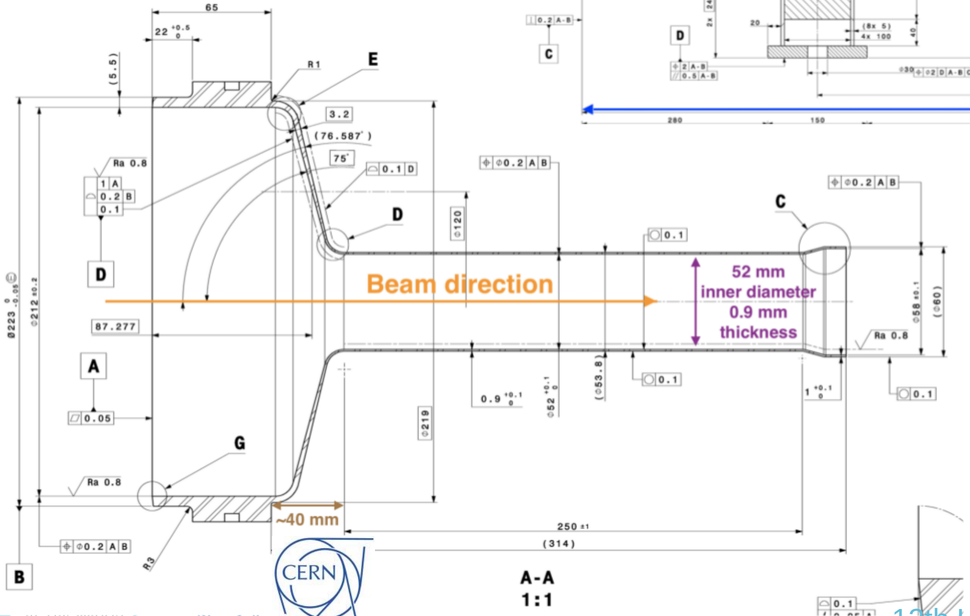
BGV1 foreseen location

https://edms.cern.ch/document/1395360/0



Demonstrator tank





Materials:
Steel, apart from:
exit window and reduced aperture beam pipe: Al alloy AA2219 (rad. length 89 mm, 5x higher compared to steel)

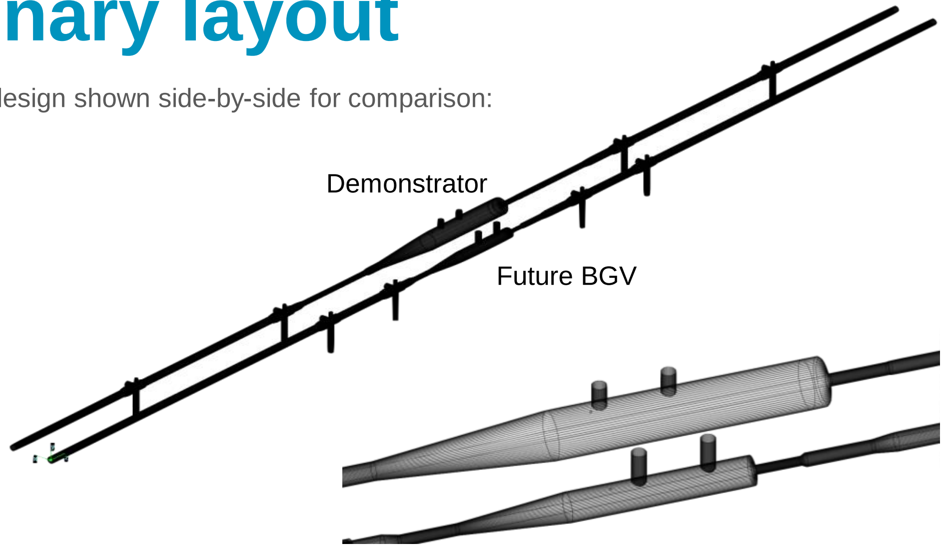
slide taken from HiLumi integration meeting 03/06/22:
https://indico.cern.ch/event/1165410/

Preliminary layout

The beam chamber layout has been modified compared to the demonstrator device:

- Smaller aperture of the downstream small radius beam pipe to maximise track acceptance
- Smaller gas tank diameter to reduce beam-coupling impedance
- Shorter total length (upstream taper, distance between pumps), to fit into the new B1-BGV location and reduce the radiations due to the longitudinal gas density profile tails.

Old and new design shown side-by-side for comparison:



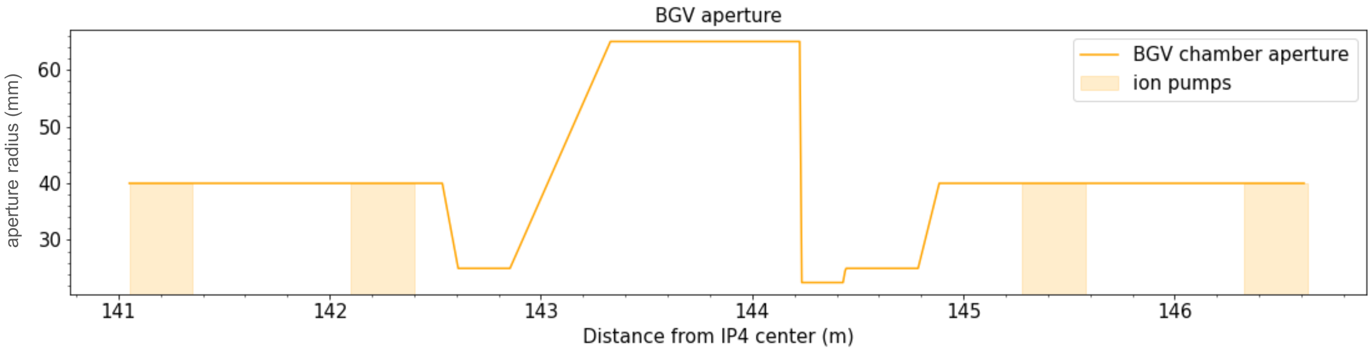
		Cone 1	Upstream chamber	Upstream taper	Tank cylinder	Exit window	Detectors beam pipe	Cone 2	Transition beam pipe	Cone 3
Demonstrator	ID (mm)		52		212		52		58	
	length (mm)	48	1108	815	1185	50	251	12	988	44
Future BGV	ID (mm)		50		**130**		**45**		50	
	length (mm)	50	**250**	**477**	700	11	**200**	12	**350**	100

+ 500mm beam pipes at each pump connection + **750mm** between pumps for the future instrument (vs. 2000mm demonstrator) -> total length ~**5.5m** (vs. ~10m total demonstrator length)

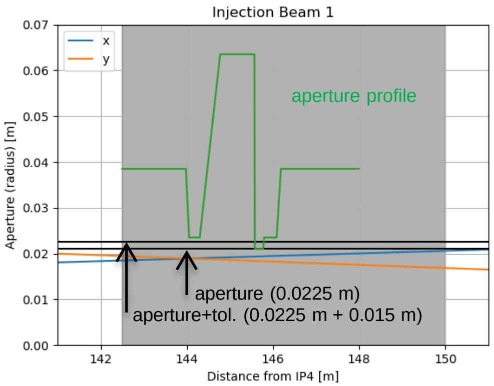
slide taken from HiLumi integration meeting 03/06/22:
https://indico.cern.ch/event/1165410/

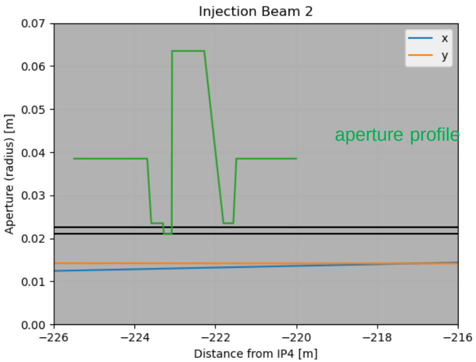
Aperture profile

- Preliminary aperture profile of B1-BGV (position can be shifted along z), total length ~6 m:



- Reduced-diameter beam pipe placement - as close to beta x/y crossing point as possible.





- Plots by Riccardo de Maria (BE-ABP-LNO).
- **Tolerance budget**: **1.5 mm** (estimation from demonstrator page 6: LHC-BGV-EC-0002).
- Smallest aperture size: 22.5 mm (inner radius).
- Ok from ABP (if tol. can be guaranteed).
- See: initial discussion (2020), WP2 meeting (2022) and recent follow-up discussion.

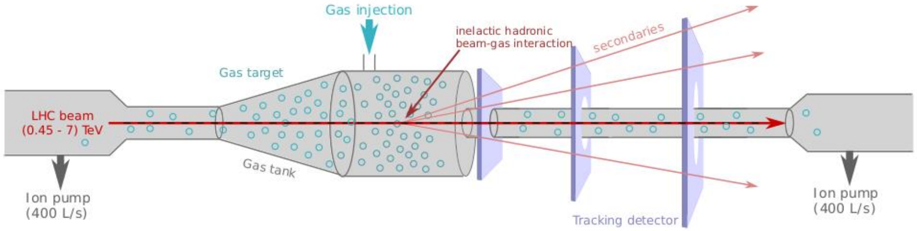
Gas target system

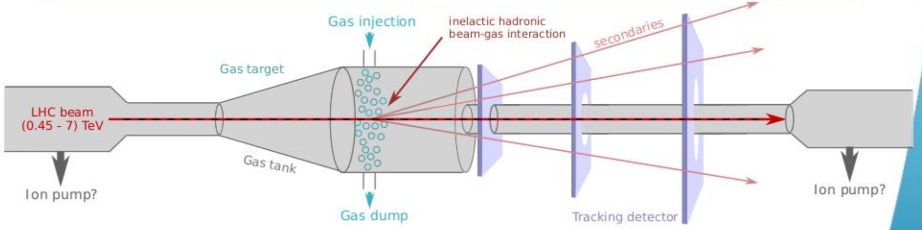
- Gas target requirement for an **unbiased beam profile measurement: Transverse gas density profile homogeneity**, over the time scale of $\approx 1\,\mathrm{min}$ (integration time).
- Gas target parameters impacting the performance:
  - Gas species $\Rightarrow$ number of tracks per interaction
  - Pressure $\Rightarrow$ interaction rate $\Rightarrow$ number of events with sufficient number of tracks in a given time interval

2 gas target options are considered:

Gas injection system: (demonstrator target [4])
extended pressure bump: $\Delta z \approx 1 - 2\,\mathrm{m}$
$10^{-7}\,\mathrm{mbar} \Rightarrow 200\,\mathrm{Hz}$ inelastic interaction rate per bunch
$\Rightarrow$ decrease instrument complexity

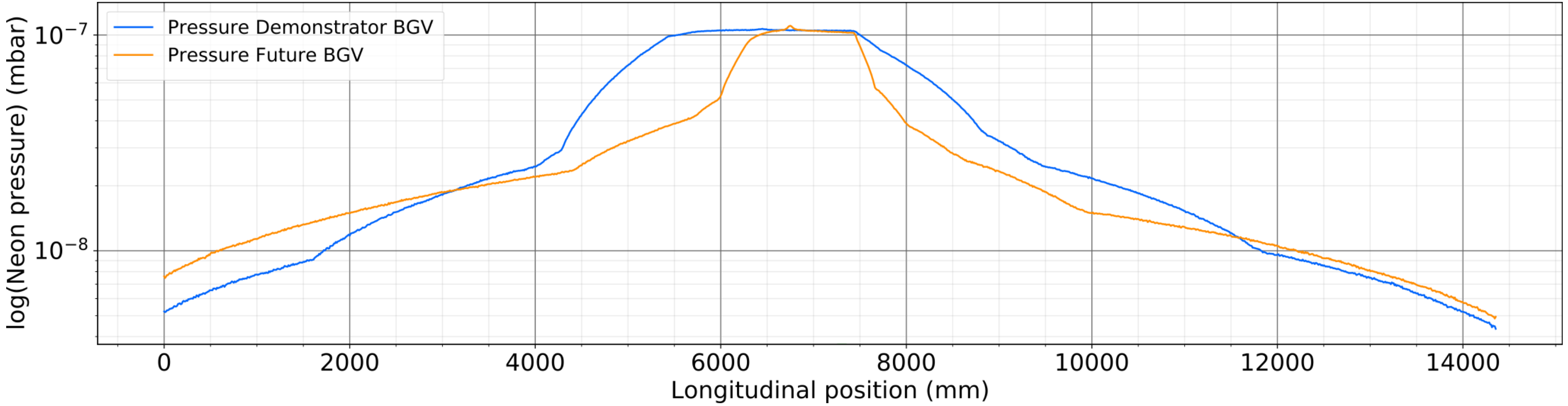
Gas curtain target: BGC target [5]
localised pressure bump: $\Delta z \approx$ few mm
$\Rightarrow$ similar interaction rate
$\Rightarrow$ easier identification of tracks from the interaction vertex.
$\Rightarrow$ improves vertex resolution due to z constraint.





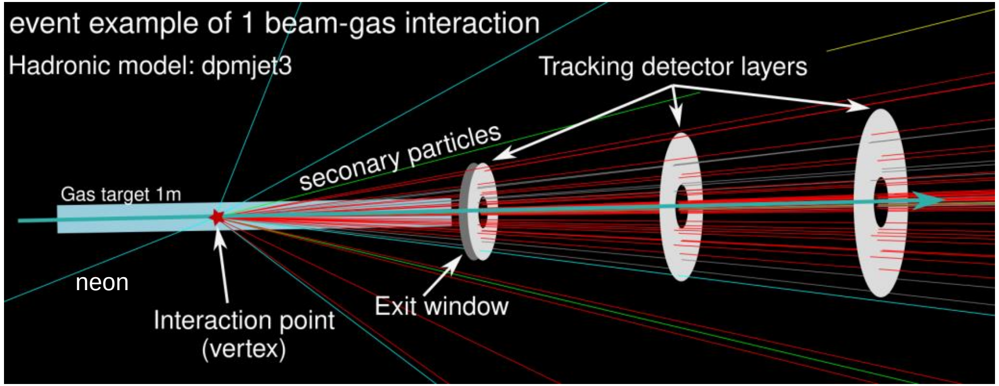
Longitudinal gas profile comparison

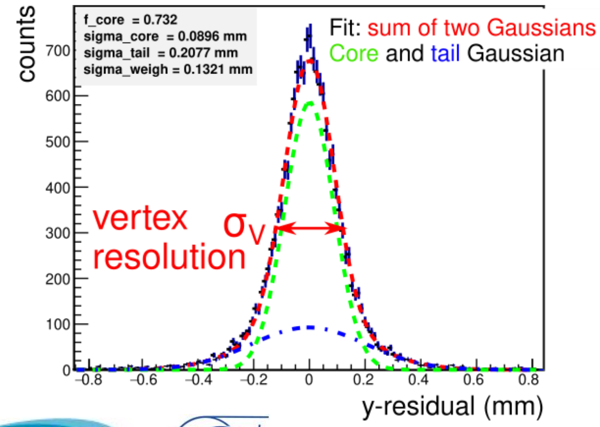
Molflow simulations by H. Guerin, with input from R. Kersevan



Performance study - overview

- **Initially: generic BGV** setup to ease navigation of extensive parameter space.
- **Goal**: efficiently identify impact of design parameters and provide first estimates of promising setup's dimensions etc.

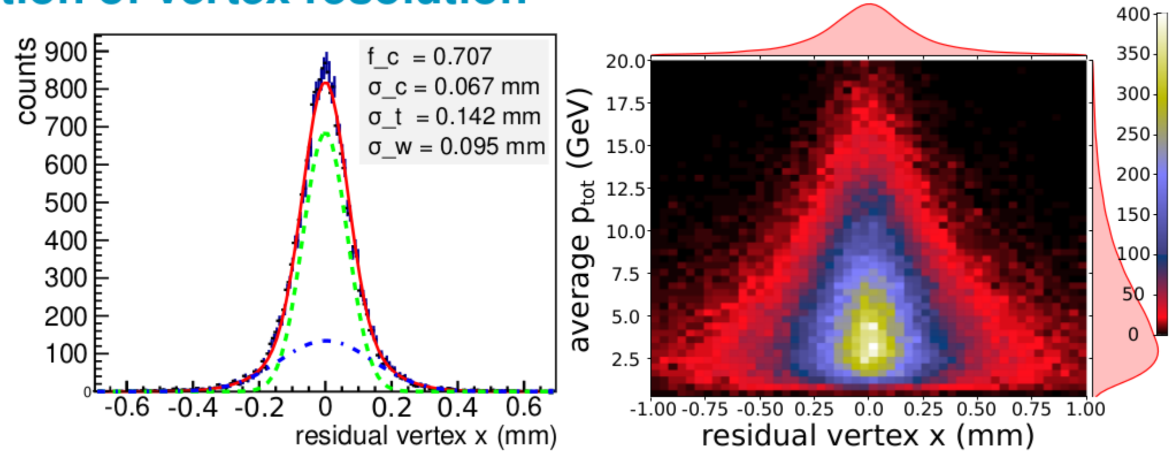




- detector parameters studied:
- material budget, size, separation, spatial resolution.
- extended gas target of 1 m in z.

- **Evaluation of performance**:
- compare reconstructed vertices to generator level vertices.
- determine response and vertex resolution.

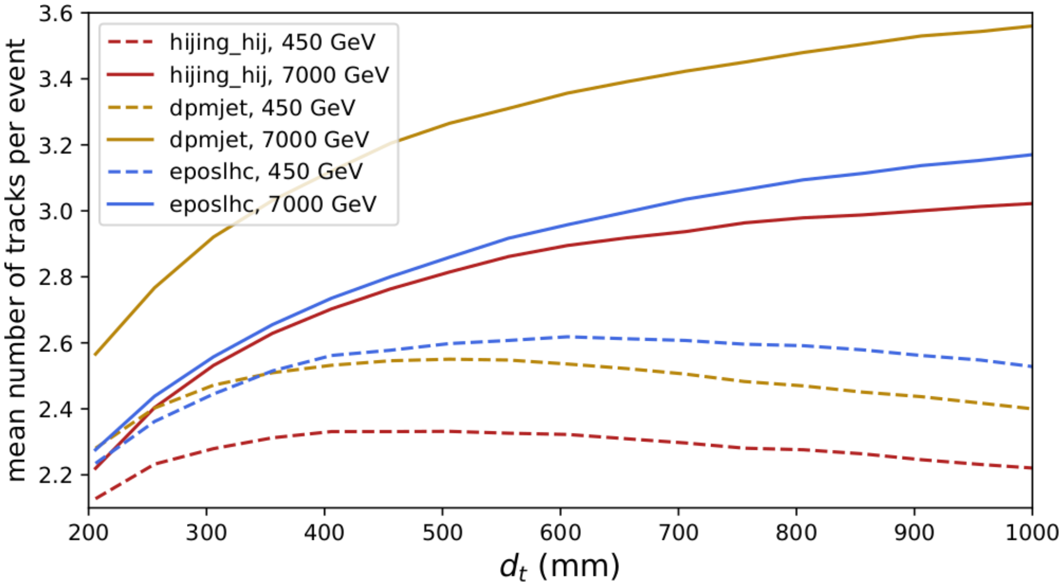
Determination of vertex resolution



Residual r_x ($N_{tr} = 5$). Red line: fit with sum of two Gaussians. Green and blue dashed lines: core and tail Gaussians. Right: two-dimensional histogram of the r_x ($N_{tr} \geq 2$) vs average total momentum of the tracks stemming from the vertex.

- Compute residuals $r_i = v_{i,\mathrm{fit}} - v_{i,\mathrm{true}}$ with $i = \{x, y, z\}$.
- **Fit residuals with a sum of two Gaussians** (core and tail Gaussian [9]) with widths σ_c and σ_t.
- The vertex resolution can then be calculated as the weighted average $\sigma_v = \sqrt{f_c\sigma_c^2 + f_t\sigma_t^2}$
- where f_c and f_t are core and tail fractions, calculated via: $f_t = \frac{p_t\sigma_c}{p_c\sigma_c + p_t\sigma_t}$, where p denotes the amplitudes and σ the widths of the Gaussians.

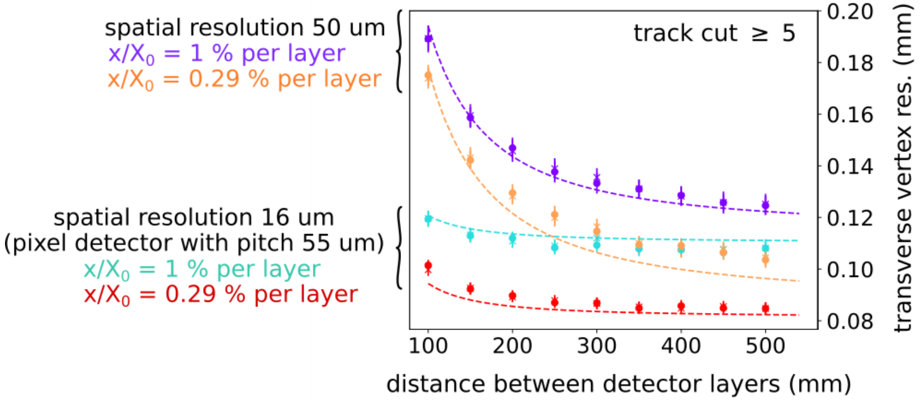
Distance source-detector vs mean #tracks per event



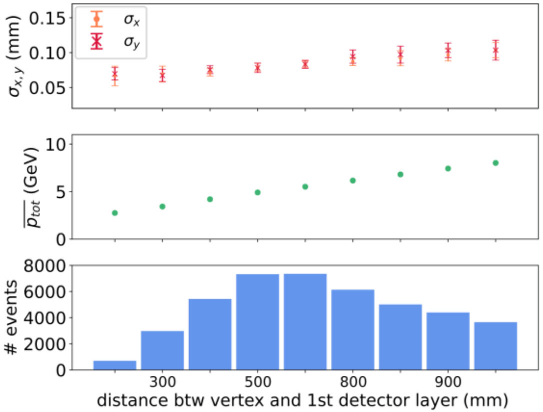
Results and conclusions of generic BGV study

- **Distance between vertices and first detector layer** that showed highest average number of tracks is **550 mm**.
- Extended gas target is no show stopper.
- Performance results point towards a **compact tracker with a high spatial resolution.**

vertex resolution vs distance between detector layers:



vertex resolution vs distance between interaction and detector:



- Eliminates any x/y hit association issues (demonstrator BGV).
- Promising candidate: compact Si pixel tracker with detector layer ~250 mm apart.
- Fits within space between the LHC beam pipes.

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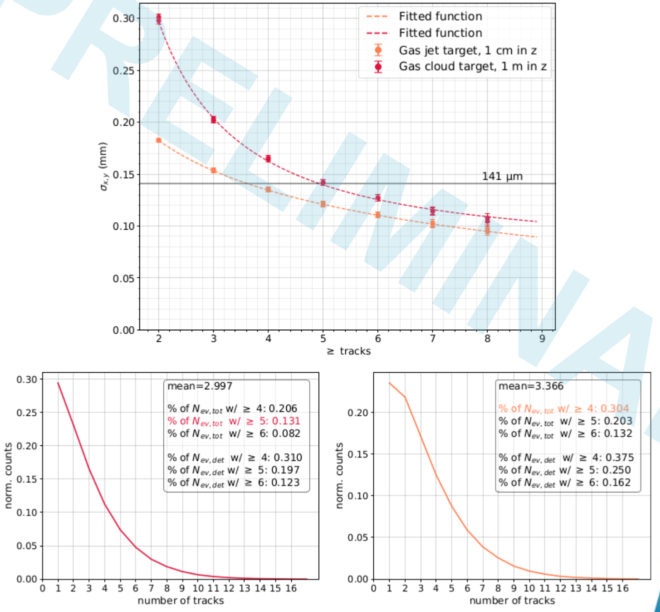
Gas curtain target - performance

slide from: BI/TB Meeting, March 2022

Performance results - gas injection and gas jet (7 TeV)

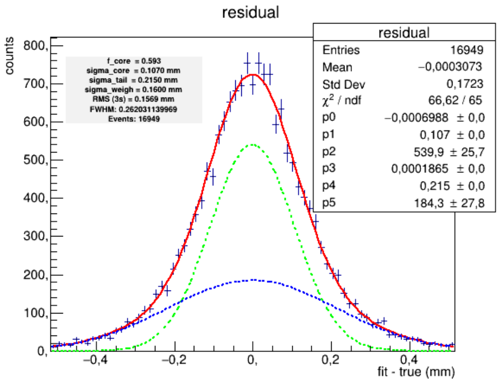
- 7 TeV, same number of initial beam-gas interactions.
- Vertex resolution vs registered number of tracks per event.
- Performance goal reached with:
  - Extended gas target: events with ≥ 5 tracks $\Rightarrow$ 13 % of total beam-gas collisions.
  - Gas jet: events with ≥ 4 tracks $\Rightarrow$ 30 % of total beam-gas collisions.
- Localised pressure bump $\rightarrow$ larger fraction of the total collisions can be accepted. Lower integrated pressure is necessary.
- Width < 1 cm no large impact on performance

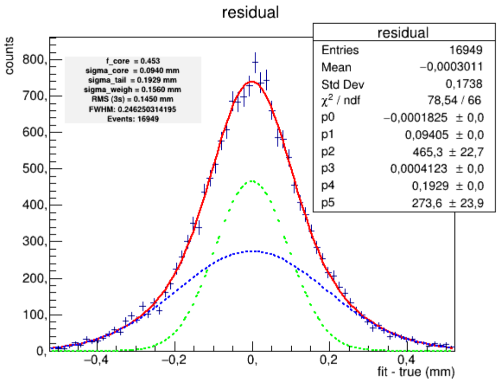
▸▸ back-up slide.

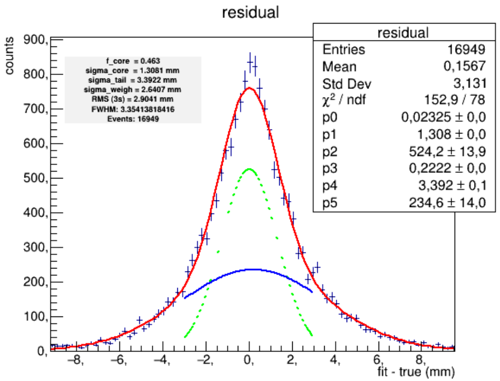


19 / 22

Vertex residuals examples (x, y, z)

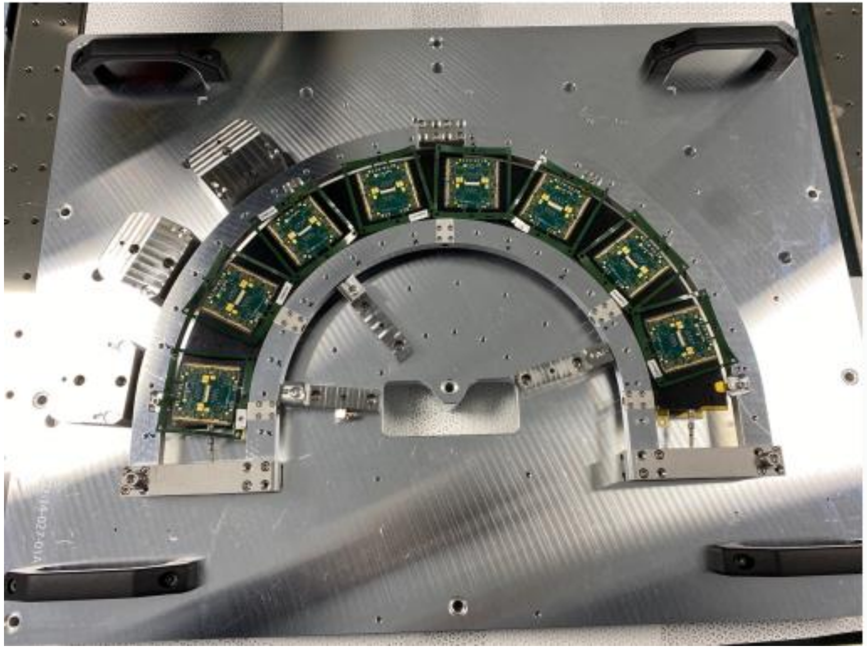


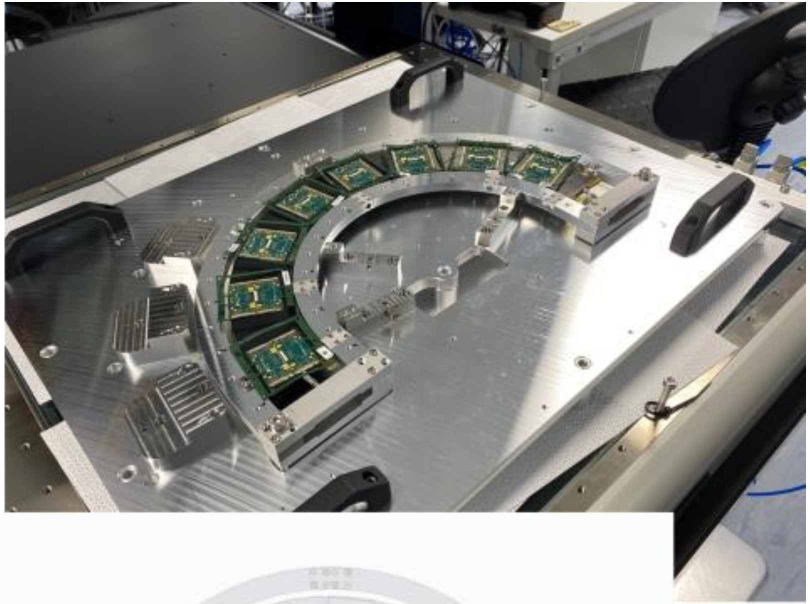


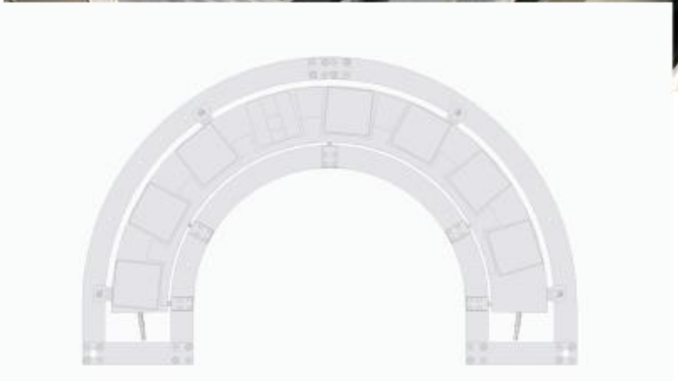


A glimpse in the future? - ATLAS iTk prototype

pictures by courtesy of D. Hynds

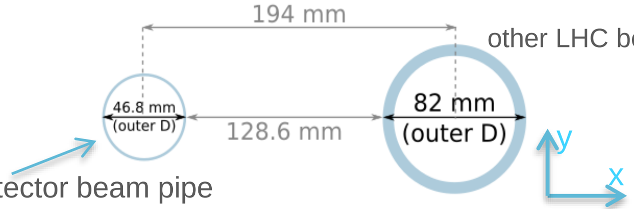


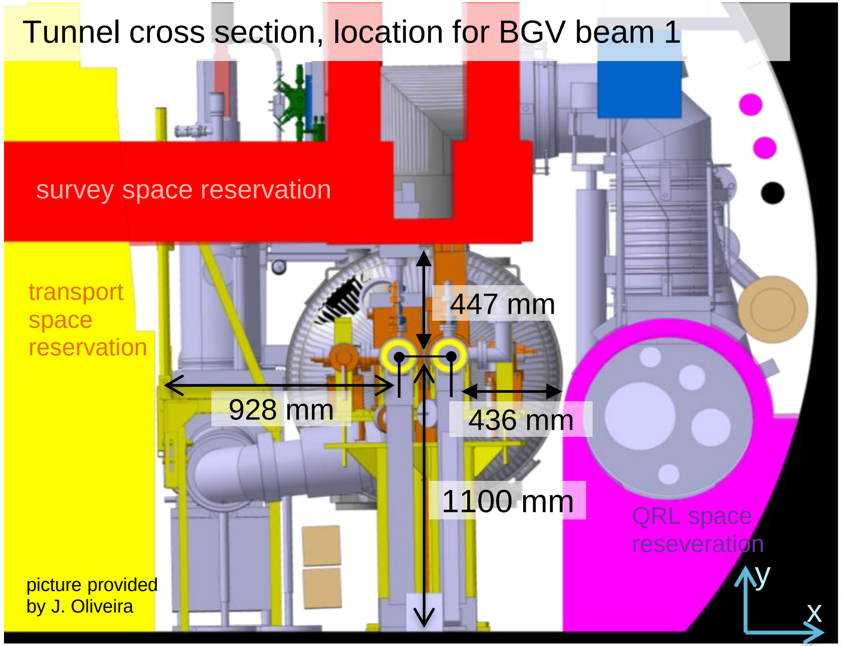


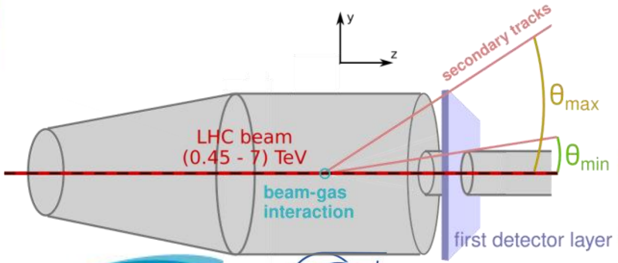


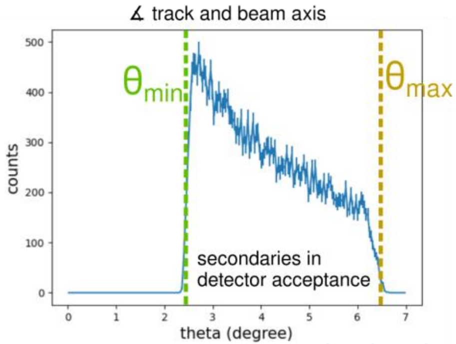
Detector space and placement

- Integrational space constraints (reserved areas in tunnel).
- **Allow access to beam pipes** for e.g. baking prior to runs. Take into account for detector support.
- **Space constraint transversally** due to **second beam pipe**:





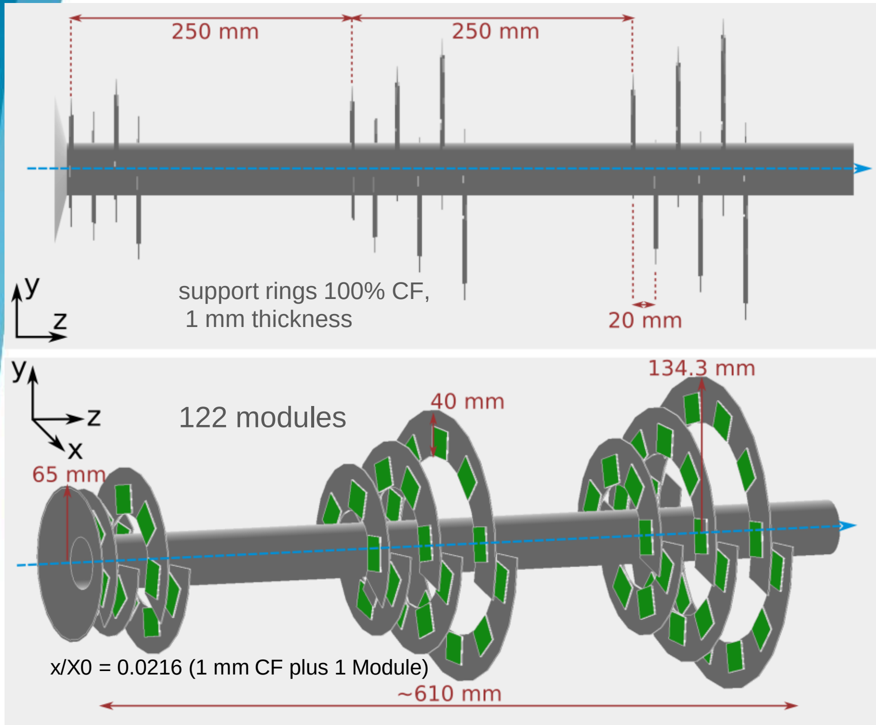




- Place detector layers **transversally as close to beam axis** as possible.
- Size of 1st detector layer is determined by diameter of gas tank.

Details of updated geometry

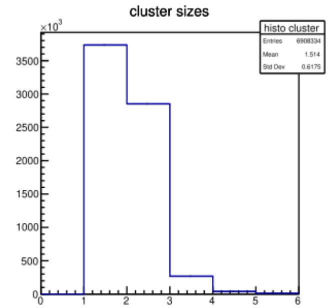
Tracker simulation geometry

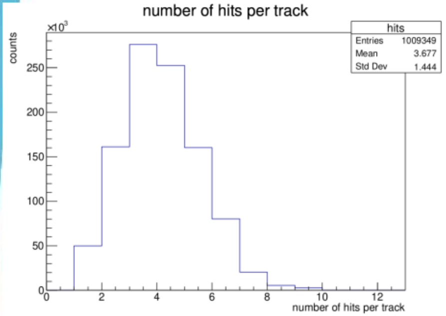


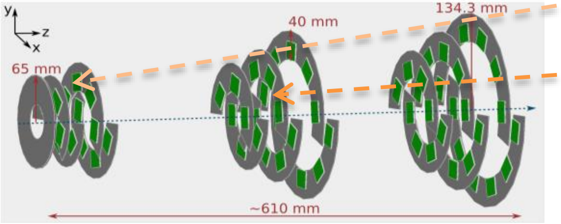
- Dimensions based on generic BGV dimensions.
- **Module**:
  - Material: Sensor 300 µm Si, Timepix 700 µm Si, Flex cable: 8 µm Cu, 170 µm Kapton, 300 µm C, Glue.
  - Transverse size: 24.7 mm x 29.96 mm.
- **Support half rings**: dz = 1 mm carbon fibre.
- **122 modules in total**.
- **Reconstruction analysis:**
  - Gaussian smearing $\sigma = 55\mu\mathrm{m}/\sqrt{12}$ of hits (spatial resolution).
  - Track and vertex fitting.
  - To be added: digitisation, clustering, track finding.
  - 3D track info of timepix4 not yet included in analysis.

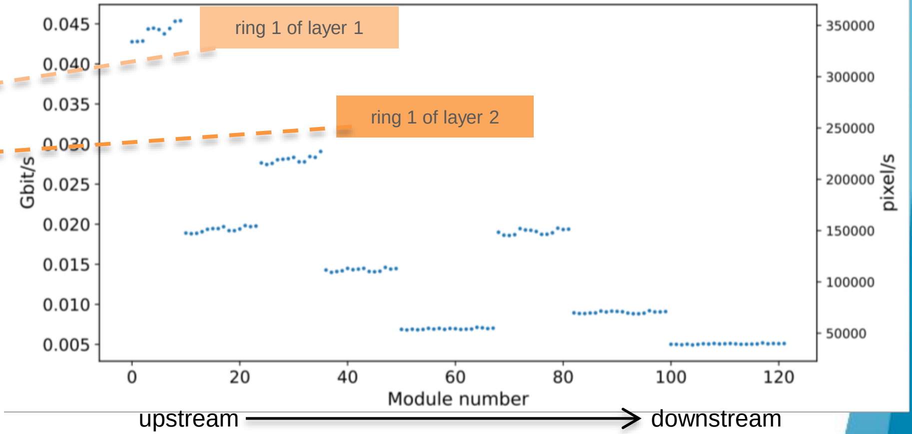
Hit and event rate estimation for DAQ via G4 simulations

- Collision rate 6 x 10^5 Hz, (7 TeV & gas pressure of 10^{-7} mbar).
- **Total number of secondaries traversing all detector modules**: 8.96 x 10^6 per sec.
- Geometric digitisation - average pixel cluster size is 1.5 pixels. **1.35 x 10^7 activated pixels/s**.
- Assume event size of 128 bit (64 bit plus padding). Total amount of **1.72 Gbit/s** data.
- Better estimation: Allpix2 and inclusion of background sources.









- **Data amount of "interesting" events ($N_{tracks} \geq 6$).**
- ~45 average activated pixels per event.
- Total event rate of $N_{tracks} \geq 6$: 53 kHz, 2.37 x 10^6 pixels/s.
- **0.3 Gbit/s**.

- **Processing time** for reconstruction per recorded collision: ~6 ms (rough conservative estimate).
- with 100 CPUs - 16.7 kHz.

Detector read-out

- **Read-out system mock-up** based on Beam Gas Ionisation monitor (BGI) by H. Sandberg.
- Around 120 timepix4 modules.
- **Frontend:** Low Power Giga Bit Transceiver (lpGBT) + an optical link module for data transmission (VTRx+) + DC/DC power supply.
- **Backend:** Based around a system-on-chip (SoC) from Xilinx: contains both programmable logic (FPGA) and processors.
- Flexibility to process data in both gateware and software on Zynq - **possibility to do some steps of the analysis on backend**.
- Analyse selected events with **reconstruction software on CPU farm** similar to demonstrator (~100 CPUs).