BGV detector design studies

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Number of reconstructed tracks and stat. precision

- The requirement to have at least X tracks per reconstructed vertex has relation both to:
  - The statistical precision of the measured σ_{beam} / the gas pressure
  - The primary vertex (PV) resolution (and the related systematic error)

Rate of inelastic beam-gas interactions per bunch:

$$R_{\mathrm{inel}} = \int_{z=z_1}^{z=z_2} \rho(z)\,\mathrm{d}z \cdot \sigma_{\mathrm{pA}}(E) \cdot N \cdot f_{\mathrm{rev}}$$

- Not all inelastic events will be useful
- The vertex resolution will be sufficiently good only for events with at least N_{Tr} reconstructed tracks. The fraction of these events, F_{good}, depends on:
  - the geometrical distributions (η) of the beam-gas interaction products
  - the detector geometry
- $N_{\mathrm{good}} = R_{\mathrm{inel}}\,\Delta t\,F_{\mathrm{good}}$ determines the statistical precision of the measured σ_{beam}:
  $$\frac{\delta\sigma_{\mathrm{beam}}}{\sigma_{\mathrm{beam}}} = \frac{1}{\sqrt{2\,N_{\mathrm{good}}}}$$
- The knowledge of F_{good} is essential in the detector + gas-target design

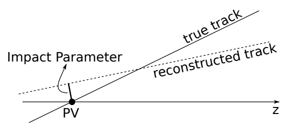
Number of reconstructed tracks and PV resolution

- As discussed previously, the primary vertex (PV) resolution in a given event depends on the number of measured tracks
- Assuming that all tracks in the event have the same impact parameter (IP) resolution σ_{IP}, the PV resolution scales approximately as $\sigma_{\mathrm{IP}}/\sqrt{N_{\mathrm{Tr}}}$
  - N_{Tr}: number of tracks making up the vertex
  - Many effects: different track p_T, different z_{vtx}, ...

Reminder of the IP definition and formulas:

The impact parameter resolution is determined by:

- σ_{MS} – IP induced by multiple scattering (MS)
- σ_{extrap} – IP induced by detector hit resolution



$$\sigma_{\mathrm{IP}}^2 = \sigma_{\mathrm{MS}}^2 + \sigma_{\mathrm{extrap}}^2$$

In each transverse coordinate:

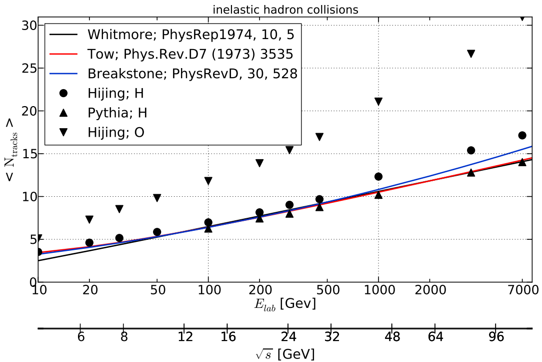
$$\sigma_{\mathrm{MS}} = r_1 \frac{13.6\ \mathrm{MeV}}{p_T} \sqrt{\frac{x}{X_0}} \left(1 + 0.038\ \log\frac{x}{X_0}\right) \approx r_1 \frac{13.6\ \mathrm{MeV}}{p_T} \sqrt{\frac{x}{X_0}}$$

$$\sigma_{\mathrm{extrap}} = \sqrt{\frac{z_2^2\,\sigma_1^2 + z_1^2\,\sigma_2^2}{(z_2 - z_1)^2}\ \cos^2\theta}$$

σ_1 and σ_2 are the detector hit resolutions, which in principle can depend on the radial position

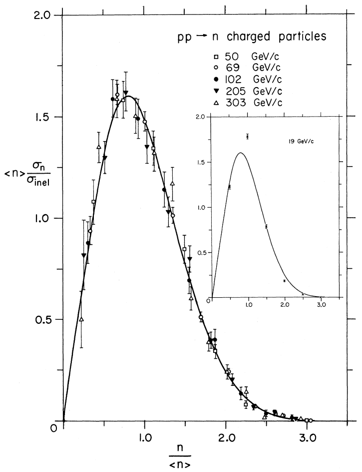
Average charged particle multiplicities

- The average number of charged particles produced in pp collisions have been measured by different experiments at different center-of-mass energy $\sqrt{s}$
  - Later I refer to this number as $< N_{\mathrm{Tr}} >$
  - Different parametrizations exist as $f(s)$. E.g.:
    - $< N_{\mathrm{Tr}} > (s) = A + B/\sqrt{s} + C \ln s$ [Tow; Phys.Rev.D7 (1973) 3535]
- To-do: make comparisons with experimental data of pA collisions
- Generated beam-gas interactions with PYTHIA (target = H) and HIJING (target = H, O or Xe), using the LHCb computing framework
  - Compare $< N_{\mathrm{Tr}} >$ in the simulated samples with the parametrizations based on experimental data



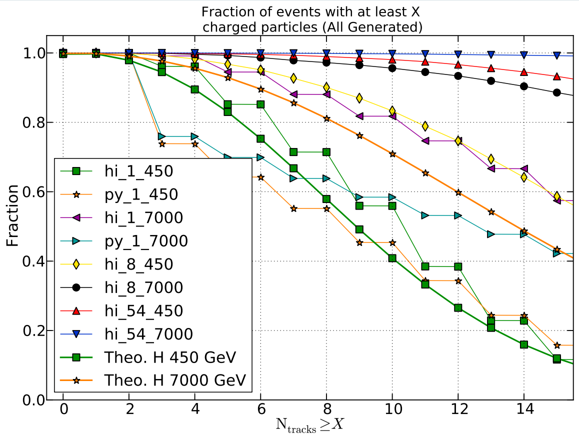
Distribution of N_{Tr}

[Slattery; Phys.Rev.Lett.29, 1624 (1972)]



- For different $\sqrt{s}$ the distributions of N_{Tr} are different (larger energy $\Rightarrow$ larger $< N_{\mathrm{Tr}} >$)
- However, it was found that the distribution of $< N_{\mathrm{Tr}} > \frac{\sigma_{\mathrm{n}}}{\sigma_{\mathrm{inel}}}$ vs $\frac{N_{\mathrm{Tr}}}{< N_{\mathrm{Tr}} >}$ does not depend on $\sqrt{s}$, at least in the $\sqrt{s}$ range we are interested in $(29 - 114$ GeV).
  - σ_{n} is the so-called "topological" cross-section: cross-section for an interaction to produce exactly n charged particles.
- For a fixed $\sqrt{s}$ we can use the parametrization of this distribution to determine the fraction of events producing at least n tracks
  - This is our expectation, which we compare with the results from the MC generated samples

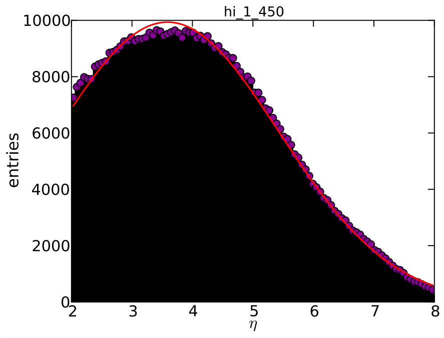
Fraction of events with at least X tracks

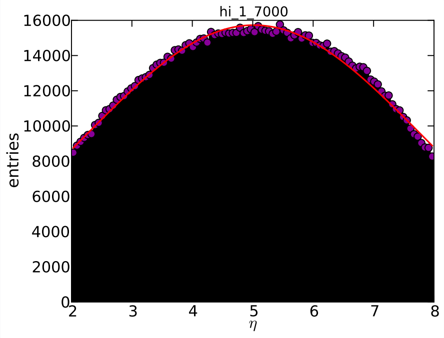


- hi/py : Hijing or Pythia MC generators
- 1/8/54: H or O or Xe target
- 450/7000: beam energy in GeV

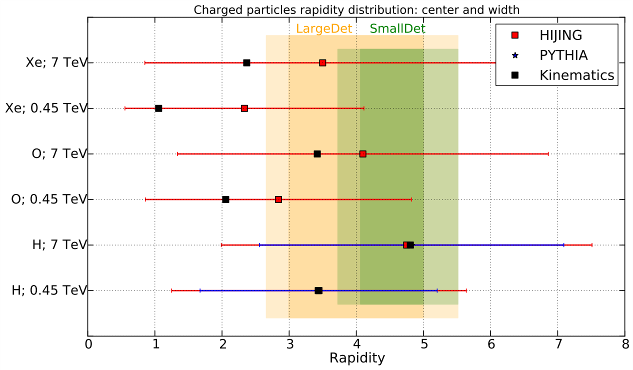
- The step-like behavior in the pH samples is attributed to el. charge conservation
- The agreement between PYTHIA and HIJING in not so good (elastic interactions!)
- The agreement between the expectation and the MC samples is not so bad
- Overall, acceptable agreement between MC simulation and parametrization based on real data

- These were results for **all** charged particles (indep. of detector acceptance)
  - In practice we care about the number of charged particles **in detector acceptance**
- The pseudorapidity distributions are close to Gaussian; Examples with Hijing, H, 450/7000 GeV:





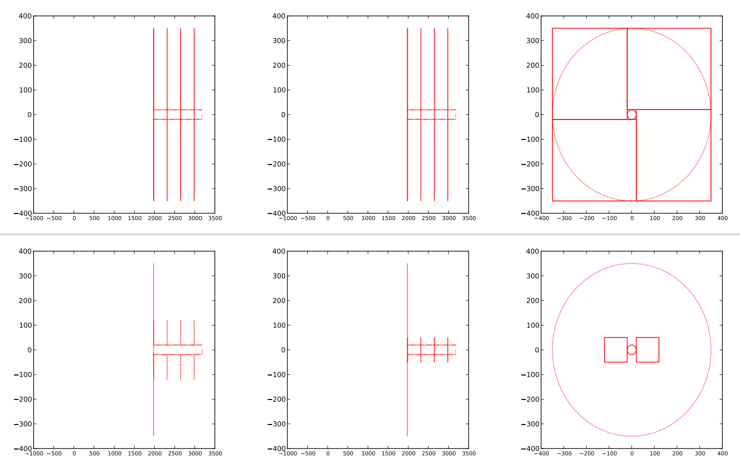
- Next, compare the fitted Gaussians mean and width for different targets and energy



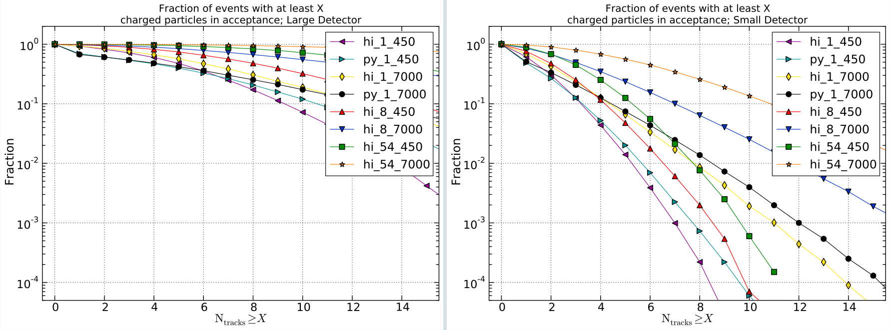
- The rectangles represent the η coverage of the *Large* and *Small* detectors.
  - For each detector type, two rectangles show the coverage for z_{min} (-0.5 m) and z_{max} (0.5 m)
- "Kinematics": Calculate boost assuming a **rigid** target. The velocity of the center-of-mass in the lab frame is: $\beta_{cm} = p_1^{lab}/(E_1^{lab} + m_2)$. Under a boost in the z-direction to a frame with velocity β: $y \rightarrow y - tanh^{-1}\beta$
  - Good agreement for Hydrogen; For heavier targets, the MC simulation results are somewhere between a rigid target and a single-nucleon target

Detector geometries used in toy MC simulations

- Both detectors:
  - 4 $x+y$ measuring layers, located at $z = 1984.0, 2317.3, 2650.7,$ and 2984.0 mm ($z=0$ is the center of the gas target)
  - 1 mm thick exit window
  - beam pipe with inner/outer radius of 19/20 mm
- *Large* detector: covers $20 \leq r \leq 350$ mm
- *Small* detector: made of 100×100 mm sensors on the left/right of the beam pipe



Fraction of events with at least X tracks in Acceptance

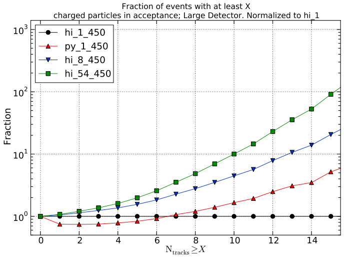


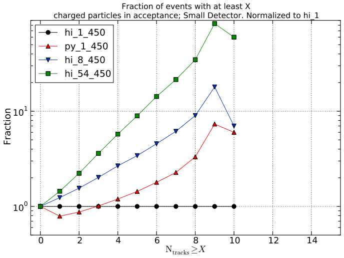
- Reminder: F_{good} and the gas pressure determine the time needed to achieve certain statistical precision on the measured σ_{beam}
- F_{good} itself depends on several parameters, including detector geometry and cut on N_{Tr}

Fraction of events with at least X tracks in Acceptance

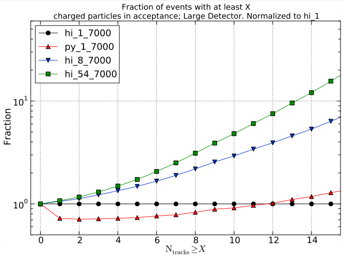
- Check the effect on F_{good} from using heavier targets

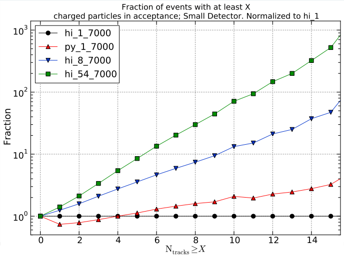
LargeDet $E_{beam} = 450\ GeV$ SmallDet





LargeDet $E_{beam} = 7\ TeV$ SmallDet

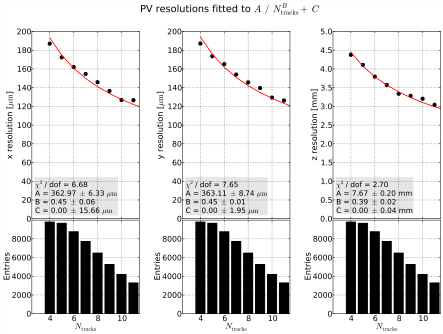




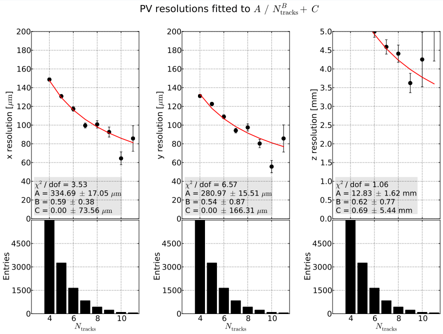
PV resolution

- Determine PV resolution as function of the cut on N_{Tr}, using the toy MC detector simulation tool

LargeDet

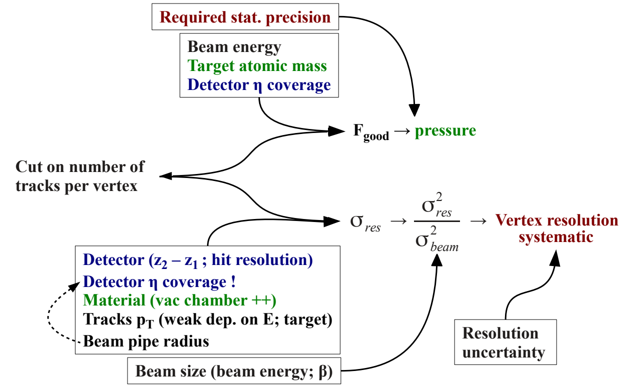


SmallDet



- These are 7 TeV H collisions. The results at 450 GeV are very similar
- However, we see a significant difference with the two detectors: the small one is more precise in x and y, and less precise in z
  - We attribute this difference to the different average η of the measured tracks: lower η tracks provide better constraint on the transverse coordinates. A calculation is needed for confirmation

Design scheme



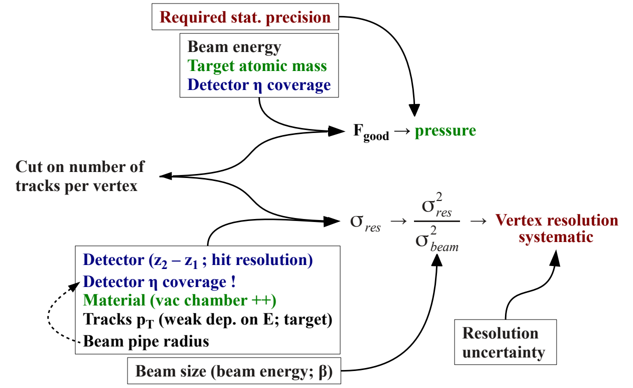
Fix stat. precision (5 % per bunch) and time (3 min) $\rightarrow$ need ~ 1 Hz per bunch. Determine needed pressure, given certain F_{good}
$\rightarrow$ see Massi's talk

Vertex resolution systematic:

$$\frac{\delta\sigma_{\mathrm{beam}}}{\sigma_{\mathrm{beam}}} = \frac{\sigma^2_{\mathrm{res}}}{\sigma^2_{\mathrm{beam}}} \cdot \frac{\delta\sigma_{\mathrm{res}}}{\sigma_{\mathrm{res}}}$$

- Note that certain properties (e.g. detector η coverage) have implications both on the stat. and syst. precisions
- It is a complex inter-connected system: fixing parameters like r_{pipe} and beam size (optics β) will facilitate greatly the identification of an optimal design

Design scheme



Fix stat. precision (5 % per bunch) and time (3 min) → need ~ 1 Hz per bunch. Determine needed pressure, given certain F_{good} → see Massi's talk

Vertex resolution systematic:

$$\frac{\delta\sigma_{\rm beam}}{\sigma_{\rm beam}} = \frac{\sigma^2_{\rm res}}{\sigma^2_{\rm beam}} \cdot \frac{\delta\sigma_{\rm res}}{\sigma_{\rm res}}$$

- **Why a measurement at 7 TeV is more challenging than at 0.45 TeV:**
- When we go from 7 TeV (where low $\boldsymbol{\sigma_{\rm res}}$ is the challenging requirement) to 450 GeV:
  - F_{good} decreases significantly, but if we choose lower $N_{\rm Tr}$ cut (3/4/5 ?) then:
  - F_{good} gets larger by about a factor of 10 (2.5) for small (large) detector, in comparison to 7 TeV → can operate at lower pressure
  - $\sigma_{\rm res}$ increases by about a factor of 1.5, but the ratio $(\sigma_{\rm res}/\sigma_{\rm beam})^2$ gets 7 times smaller!

Additional Slides

Definition of charged particles multiplicity

Default definition

- Count as charged particles all generated particles that:
  - 1. Have electric charge $= \pm 1$
  - 2. Are produced at most 5 mm away from the PV (distance in z)
  - 3. Have no decay vertices or have exactly 1 decay vertex, which is located at least 10 mm away from the PV (distance in z)

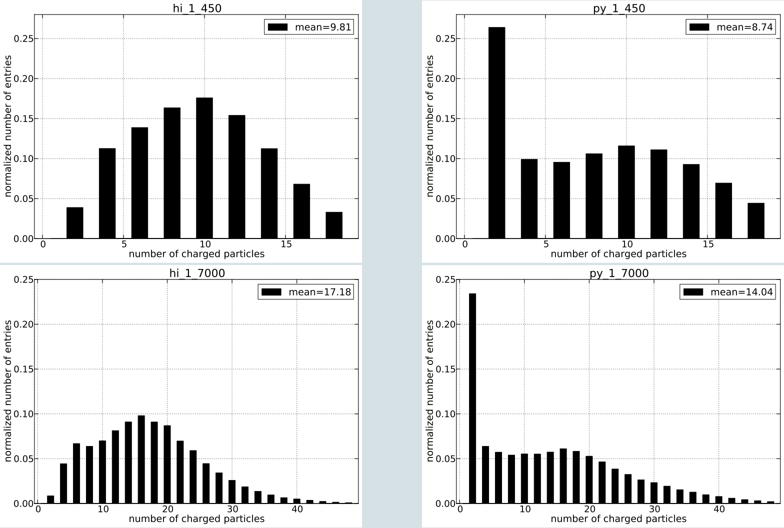
Alternative definition

- Count as charged particles all generated particles that:
  - 1. Same as above
  - 2. Same as above
  - 3. Have no decay vertices or have exactly 1 decay vertex, and the distance between the *end* and *origin* vertex is at least 2 m (distance in z)

- Both definitions give the same results within 1 %. The reason is that there are very few particles that have decay length between 10 mm and 2 m $(K_S, \Lambda, ?)$

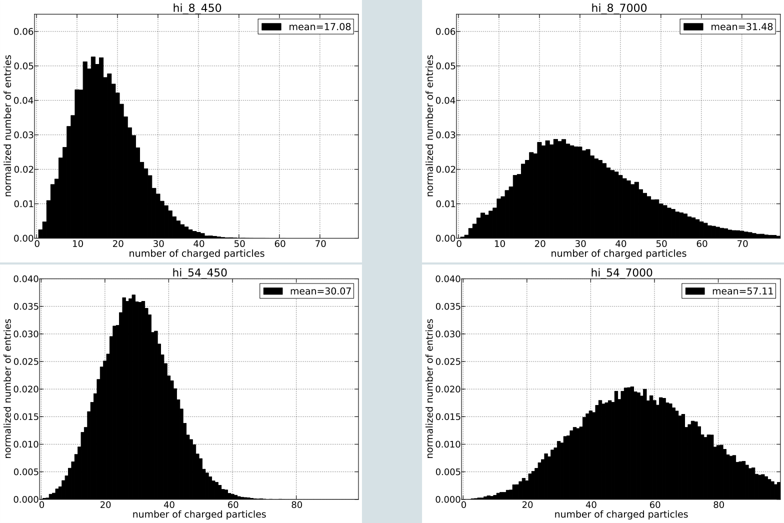
Distribution of charged particles multiplicity (1)

- 4 generated samples: Hijing/Pythia; Hydrogen; 450/7000 GeV
  - no selection cuts



Distribution of charged particles multiplicity (2)

- 4 generated samples: Hijing; Oxygen/Xenon; 450/7000 GeV
  - no selection cuts



Geometry definition: *Large* detector

- x and y hit resolution = 58 μm

```
# typ ODW    IDH     L       posx   posy   posz    X0
#  exit window (very short large diameter tube)
   1 700.0   40.0       1.0    0.0    0.0  1980.0  89.0
#  beam pipe (long small diameter tube)
   1  40.0    38.0  1200.0    0.0    0.0  2580.0  89.0
#  first plane of XY sensors (4 rectangles) covering 20 <= r <= 350 mm
   2 370.0   330.0      1.0  165.0  185.0  1984.0  93.0
   2 330.0   370.0      1.0  185.0 -165.0  1984.0  93.0
   2 370.0   330.0 1.0 -165.0 -185.0  1984.0  93.0
   2 330.0   370.0 1.0 -185.0  165.0  1984.0  93.0
#  second plane of XY sensors (4 rectangles) covering 20 <= r <= 350 mm
   2 370.0   330.0      1.0  165.0  185.0  2317.3  93.0
   2 330.0   370.0      1.0  185.0 -165.0  2317.3  93.0
   2 370.0   330.0 1.0 -165.0 -185.0  2317.3  93.0
   2 330.0   370.0 1.0 -185.0  165.0  2317.3  93.0
#  third plane of XY sensors (4 rectangles) covering 20 <= r <= 350 mm
   2 370.0   330.0      1.0  165.0  185.0  2650.7  93.0
   2 330.0   370.0      1.0  185.0 -165.0  2650.7  93.0
   2 370.0   330.0 1.0 -165.0 -185.0  2650.7  93.0
   2 330.0   370.0 1.0 -185.0  165.0  2650.7  93.0
#  fourth plane of XY sensors (4 rectangles) covering 20 <= r <= 350 mm
   2 370.0   330.0      1.0  165.0  185.0  2984.0  93.0
   2 330.0   370.0      1.0  185.0 -165.0  2984.0  93.0
   2 370.0   330.0 1.0 -165.0 -185.0  2984.0  93.0
   2 330.0   370.0 1.0 -185.0  165.0  2984.0  93.0
```

Geometry definition: *Small* detector

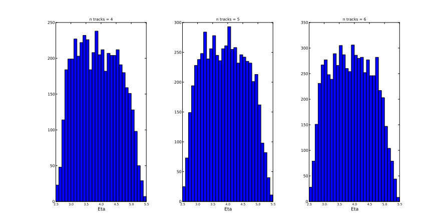
- x and y hit resolution = 58 μm

```
# typ ODW    IDH     L       posx   posy   posz    X0
#  exit window (very short large diameter tube)
   1 700.0   40.0       1.0    0.0    0.0  1980.0  89.0
#  beam pipe (long small diameter tube)
   1  40.0    38.0  1200.0    0.0    0.0  2580.0  89.0
#  first plane of XY sensors: one rectangle (10x10 cm) on the left/right of the beam
   2 100.0   100.0      1.0  70.0     0.0  1984.0  93.0
   2 100.0   100.0      1.0 -70.0     0.0  1984.0  93.0
#  second plane of XY sensors: one rectangle (10x10 cm) on the left/right of the bea
   2 100.0   100.0      1.0  70.0     0.0  2317.3  93.0
   2 100.0   100.0      1.0 -70.0     0.0  2317.3  93.0
#  third plane of XY sensors: one rectangle (10x10 cm) on the left/right of the beam
   2 100.0   100.0      1.0  70.0     0.0  2650.7  93.0
   2 100.0   100.0      1.0 -70.0     0.0  2650.7  93.0
#  fourth plane of XY sensors: one rectangle (10x10 cm) on the left/right of the bea
   2 100.0   100.0      1.0  70.0     0.0  2984.0  93.0
   2 100.0   100.0      1.0 -70.0     0.0  2984.0  93.0
```

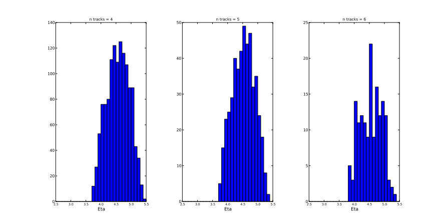
PV reconstruction: η distributions

- 0.45 TeV Hydrogen collision

LargeDet



SmallDet

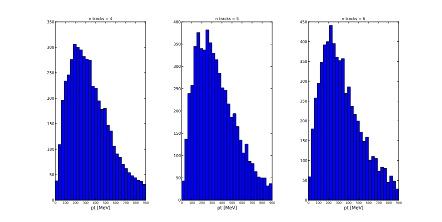


Detector Type	$N_{\mathrm{Tr}} > X$	$< \eta >$
Large	4	3.90
	5	3.92
	6	3.91
Small	4	4.57
	5	4.53
	6	4.56

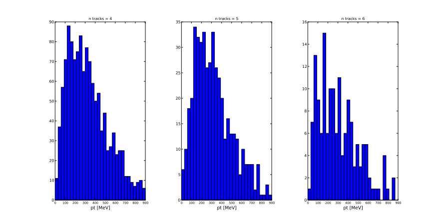
PV reconstruction: p_T distributions

- 0.45 TeV Hydrogen collision

LargeDet



SmallDet

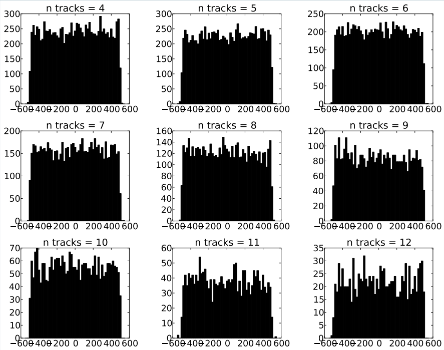


Detector Type	$N_{\mathrm{Tr}} > X$	$< p_T >$ [MeV]
Large	4	366.2
	5	365.4
	6	358.2
Small	4	345.6
	5	350.8
	6	324.8

PV reconstruction: z position of reconstructed vertices

- 450 GeV Hydrogen collision

LargeDet



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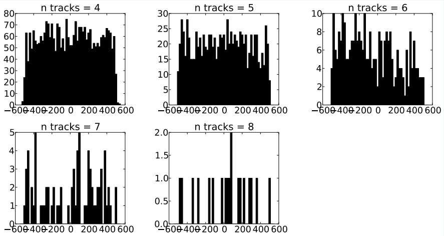
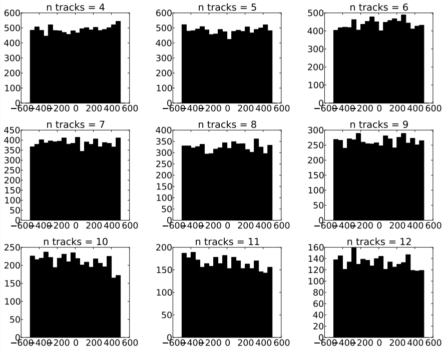


PV reconstruction: z position of reconstructed vertices

- 7 TeV Hydrogen collision

LargeDet



SmallDet