Multiple Scattering of HE Muons in Geant4

A Summer Students Project

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Outline

Introduction

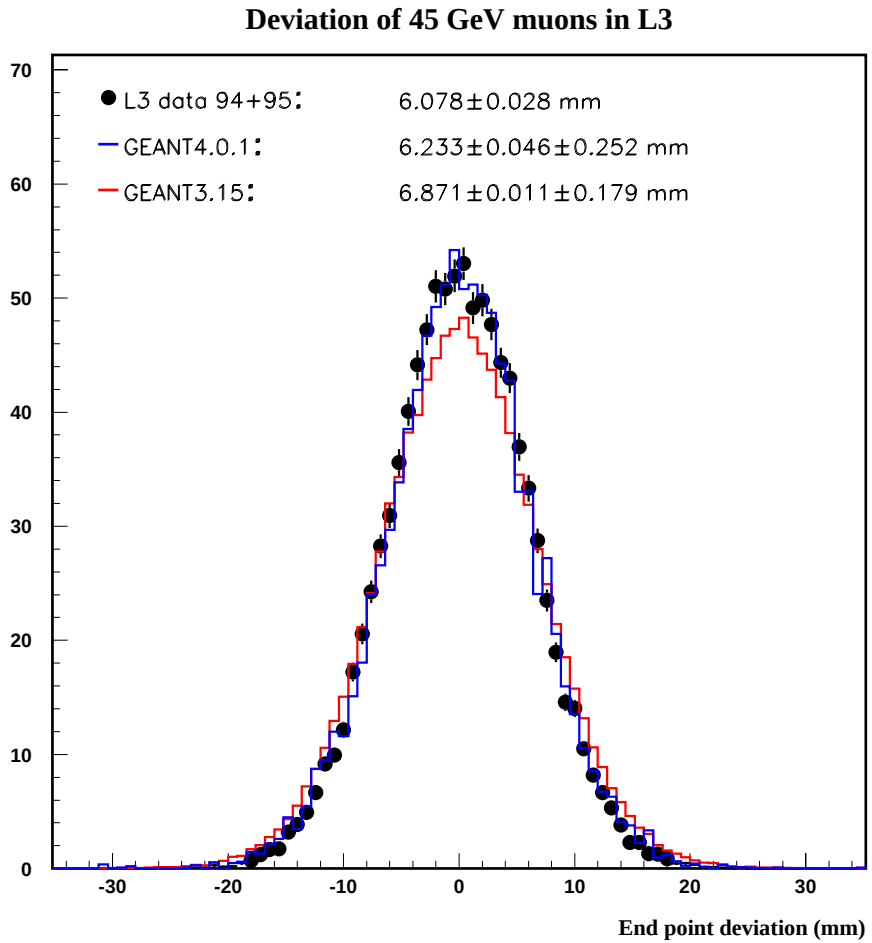
Objectives

1. Develop an **automated validation tool** for the simulation of **MSC of μ** resulting from $Z \rightarrow \mu^+\mu^-$ using a simplified representation of the former **L3 detector** at LEP, CERN.
2. Enable **comparisons between different MSC models** and **Geant4 releases** in order to uncover possible differences.
3. **Compare the latest MSC models** with results published by **P. Arce et al.** in

   Multiple Scattering in GEANT4. A Comparison with Molière Theory and L3 Detector Data. (October 2000)

Introduction

Paper by P. Arce et al.



P. Arce et al., *MSC in GEANT4*

Goal

Study the μ endpoint displacement from a straight-line trajectory in the $r\varphi$-plane of L3 caused by MSC.

Main results: distribution widths

- *Geant4.0.1:*
  $6.233 \pm 0.046_{\text{stat.}} \pm 0.252_{\text{sys.}}$ mm
- *L3 data:*
  $6.078 \pm 0.028_{\text{stat.}}$ mm

Simulation Setup

Overview

- Geant4.9.6 beta
- Simplified geometry to represent only a part of the L3 detector.
- Particle gun emitting μ with an angular distribution in θ (angle between initial μ direction and beamline)

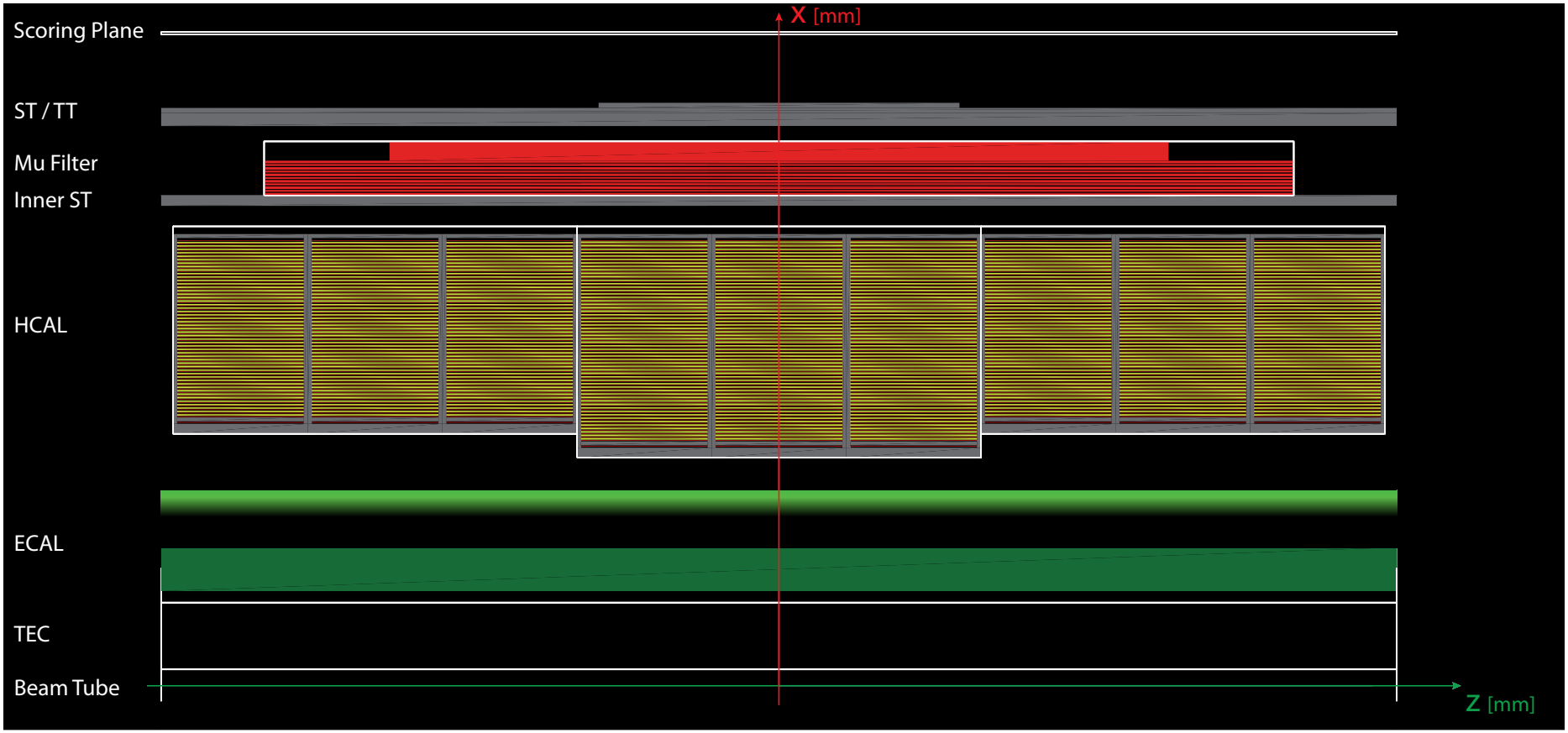
$$\frac{dF(\cos\theta)}{d\cos\theta} \propto \left(1 + \cos^2\theta\right)$$

- Angular distribution in φ is neglected due to simplified geometry.
- If not stated otherwise, the initial μ momentum distribution is neglected, i.e. $P_\mu = \frac{m_Z}{2} \approx 45.6\,\text{GeV}$ fix.
- MSC models in use are WentzelVI, Urban90, Urban93 and Urban95.

This setup does not aim to exactly reproduce the L3 result! The idea is to get as close to it as possible by simple means.

Simulation Setup

Detector Geometry



Scoring Plane Position

Problem

- **Inconsistency** between paper by P. Arce et al. and geometry descriptions of L3 concerning the **scoring plane position**:
  - **P. Arce et al.:** *'From its creation at the L3 interaction vertex until they hit the first muon chamber, these muons travel* 213 *cm.'*
  - **L3 descriptions:** The first muon chamber is located at a distance of 253 cm from the μ creation vertex.
- Scoring plane position is an **extremely sensitive parameter!**

$\Rightarrow$ Is scoring done at 213 cm or at 253 cm from the μ production vertex?

Scoring Plane Position

Additional information provided by Arce et al.

'MSC in GEANT4' (CMS Note 2000/016, January 2000)

1. **Magnetic field influence**

   0.5 T uniform magnetic field along the Z-axis causes a shift of the muons of around 12.5 mm in the $r\varphi$-plane at the scoring plane.

   - Mainly depends on scoring plane position (and P_μ distribution).
   - Minor dependence on geometry and MSC model.

   $\Rightarrow$ **Robust test**

2. **3D radius**

   Histogram given in the CMS note illustrates the distance travelled by the muons from their creation vertex to the scoring plane.

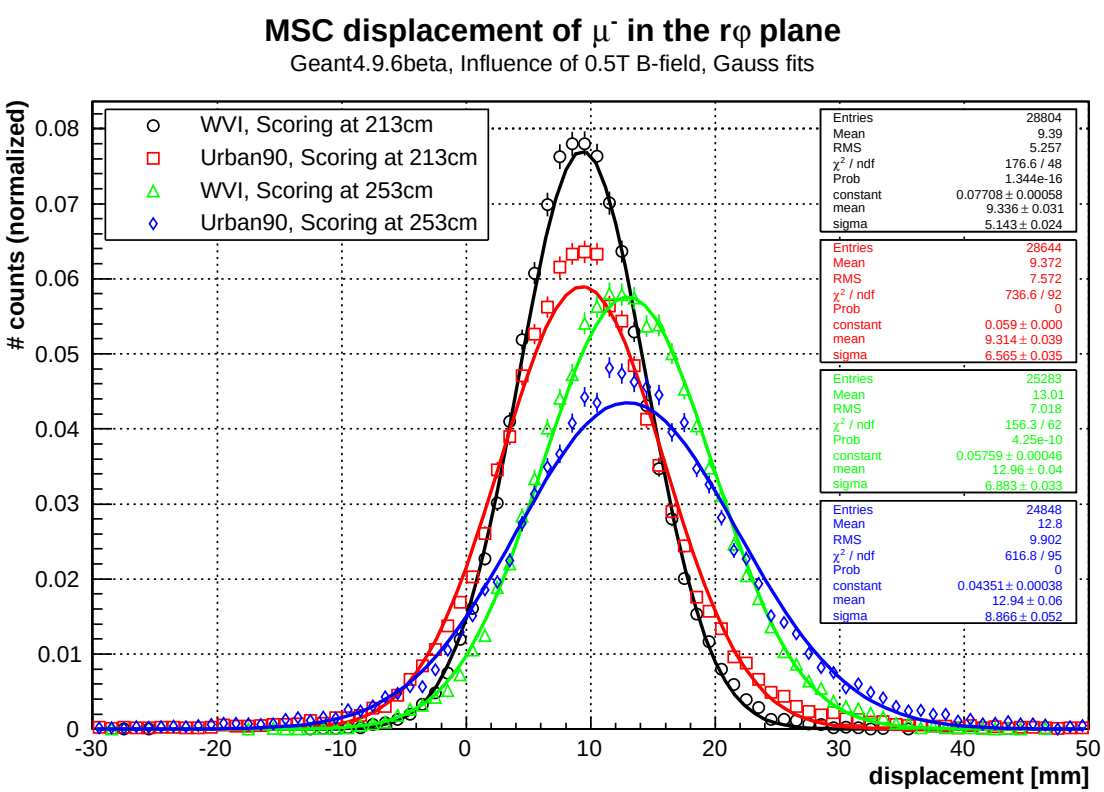
Scoring Plane Position

Simulation Setup for Scoring Plane Position Analysis

- **Simulation setup** is based on a description given by Arce et al. in *'MSC in GEANT4'* (CMS note 2000/016, January 2000)
  - 0.5 T homogeneous magnetic field along the Z-axis.
  - Same cuts are applied, $\theta \in [40^\circ, 80^\circ]$.
  - 50'000 μ with P_μ uniformly in $[40, 45.625]$ GeV combined with 10'000 μ with $P_\mu = 45.625$ GeV.
- **But:**
  - No reweighting of P_μ and 3D radius distributions.
  - No φ distribution.
  - No switching off of deviations from matter interactions.

Scoring Plane Position

1. Influence of a Magnetic Field



Shifts for scoring at 213 cm

- **WVI:** 9.34 ± 0.04 mm
- **U90:** 9.31 ± 0.04 mm

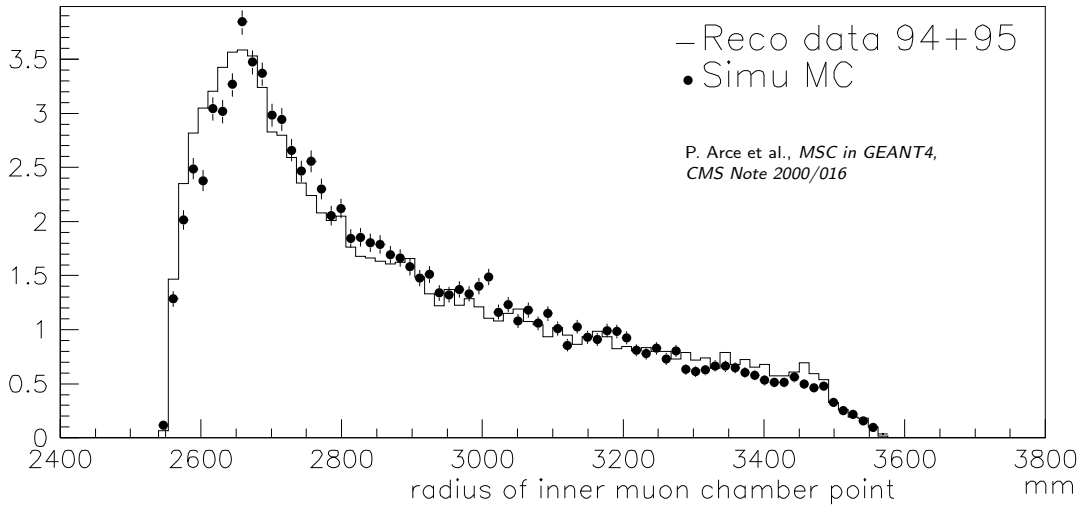
Shifts for scoring at 253 cm

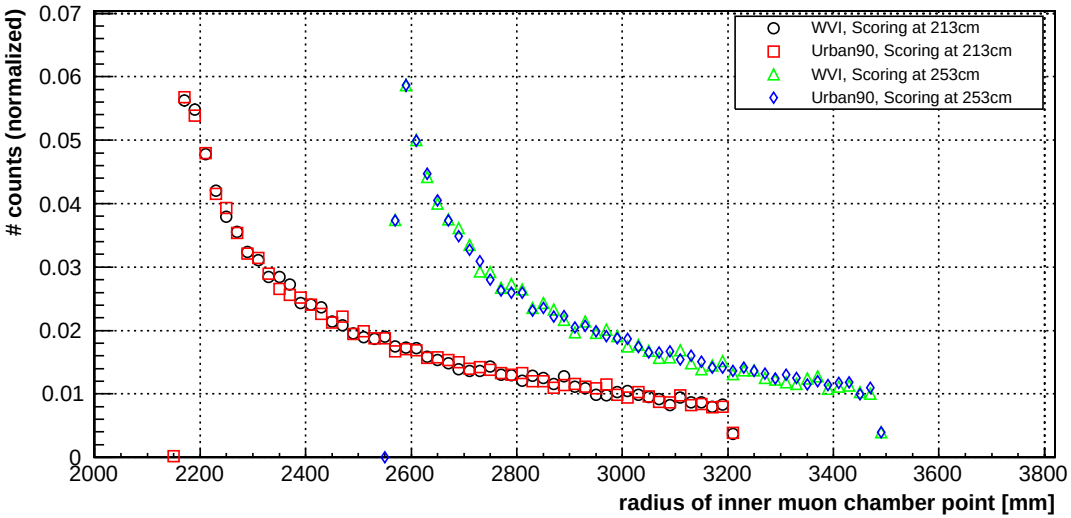
- **WVI:** 12.96 ± 0.04 mm
- **U90:** 12.94 ± 0.04 mm

A shift of 12.5 mm is observed when the scoring plane is positioned at 249 cm.

Scoring Plane Position

2. 3D Radius of the Inner Muon Chamber Point





- Same simulation setup but without magnetic field.
- Curves show the distances travelled by μ.

$\Rightarrow$ **Lower edge closely represents the scoring plane position!**

- Curve shapes are different due to neglected φ angular distribution.

$\Leftrightarrow$ Negligible influence on location of lower edge.

Scoring Plane Position

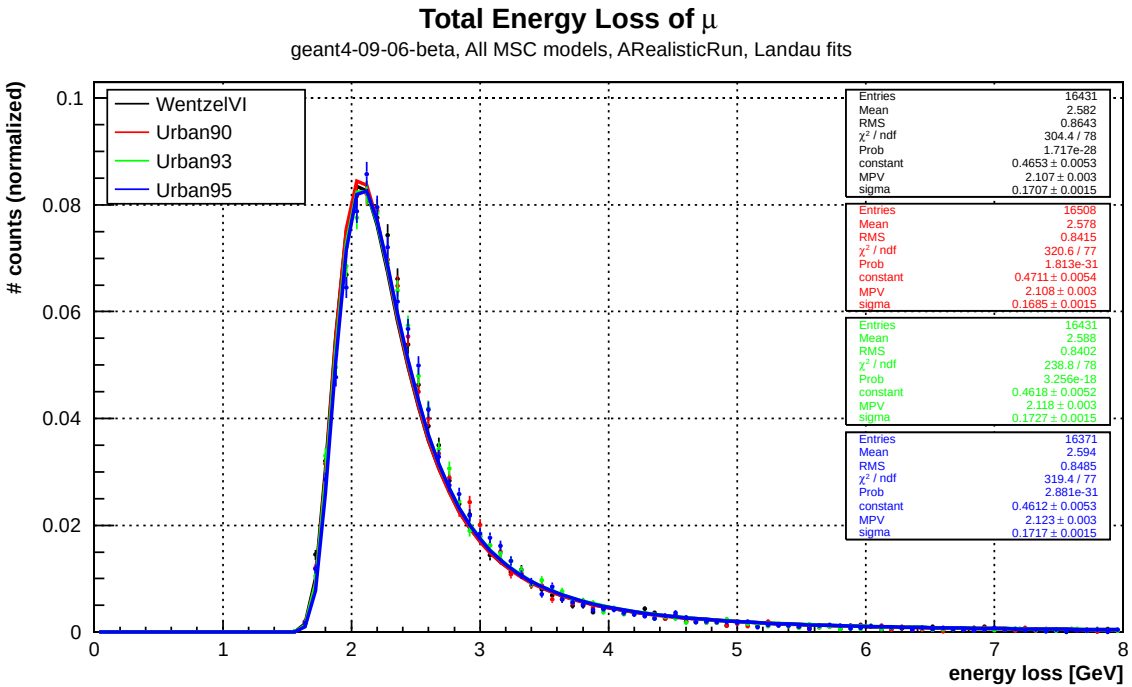
Conclusion

1. Results are much closer to 12.5 mm when the scoring plane is at 253 cm rather than 213 cm.
2. Radius of the inner muon chamber point strongly indicates a scoring plane position of 253 cm.

$\Rightarrow$ **Scoring plane is assumed to be located at 253 cm from the μ production vertex.**

Results

Total Energy Loss

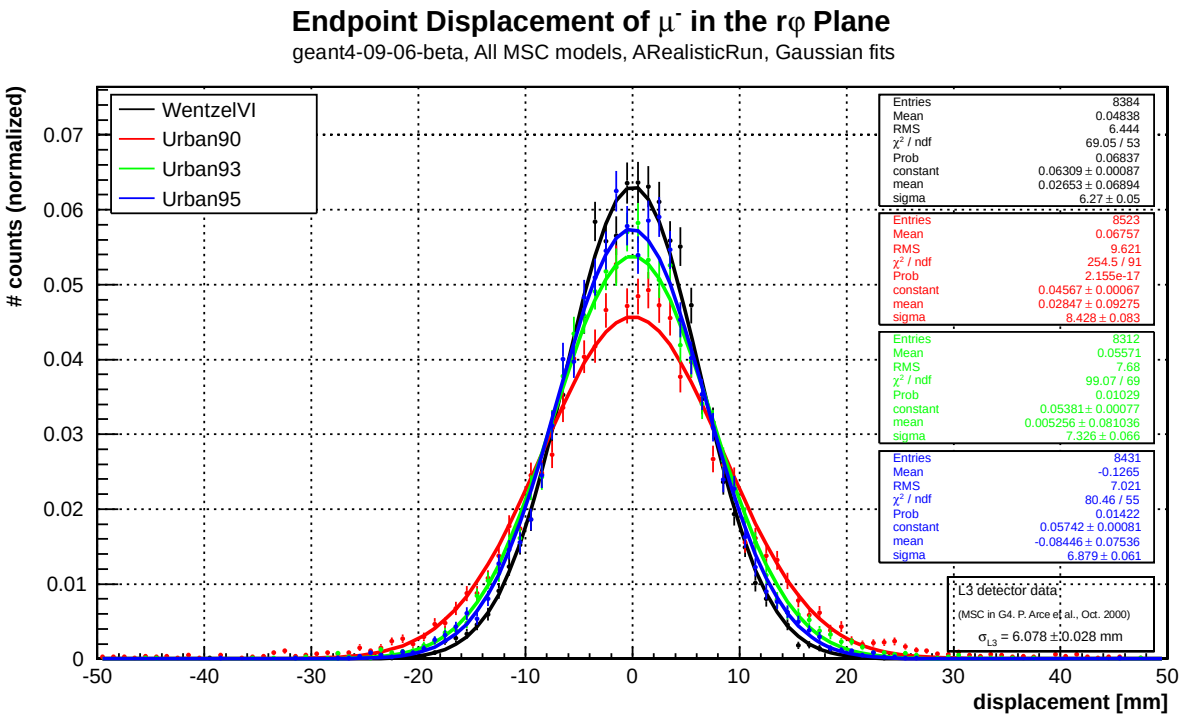


Mean energy loss

- P. Arce et al. mention a mean energy loss of about 2.5 GeV.
- The present simulation yields a value of about 2.6 GeV for all the MSC models.

Results

Comparison of WentzelVI and Urban MSC Models

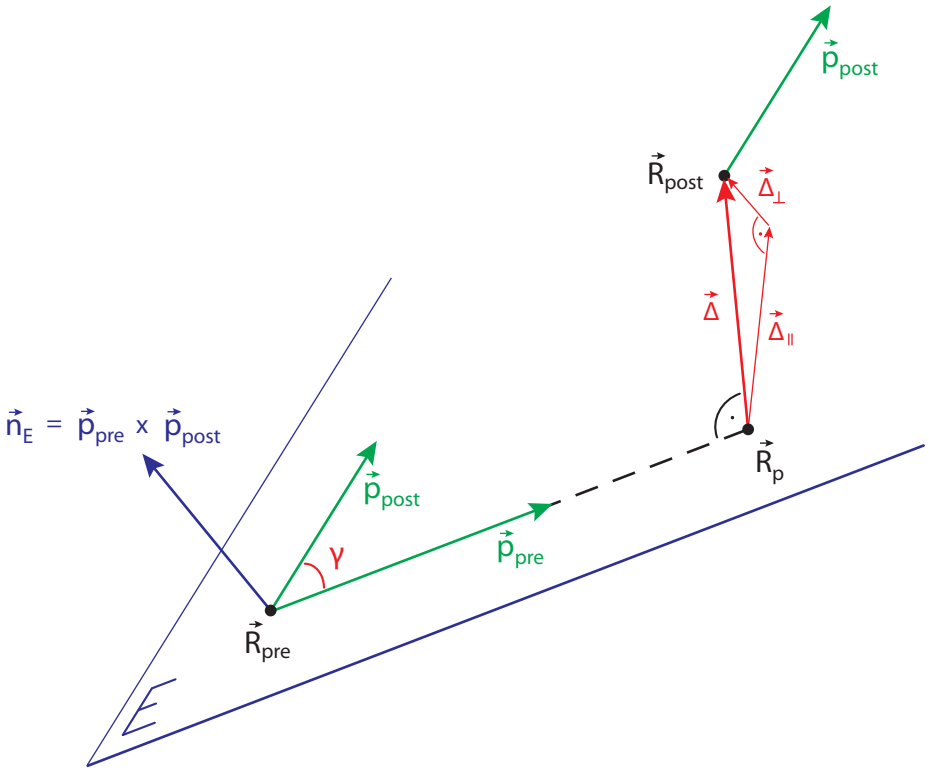


Distribution widths

- **WVI:** 6.27 ± 0.05 mm
- **U90:** 8.43 ± 0.09 mm
- **U93:** 7.33 ± 0.07 mm
- **U95:** 6.88 ± 0.07 mm
- **L3 data:** $\mathbf{6.08 \pm 0.03}$ **mm**

Stepwise Comparison of MSC Models

Definitions

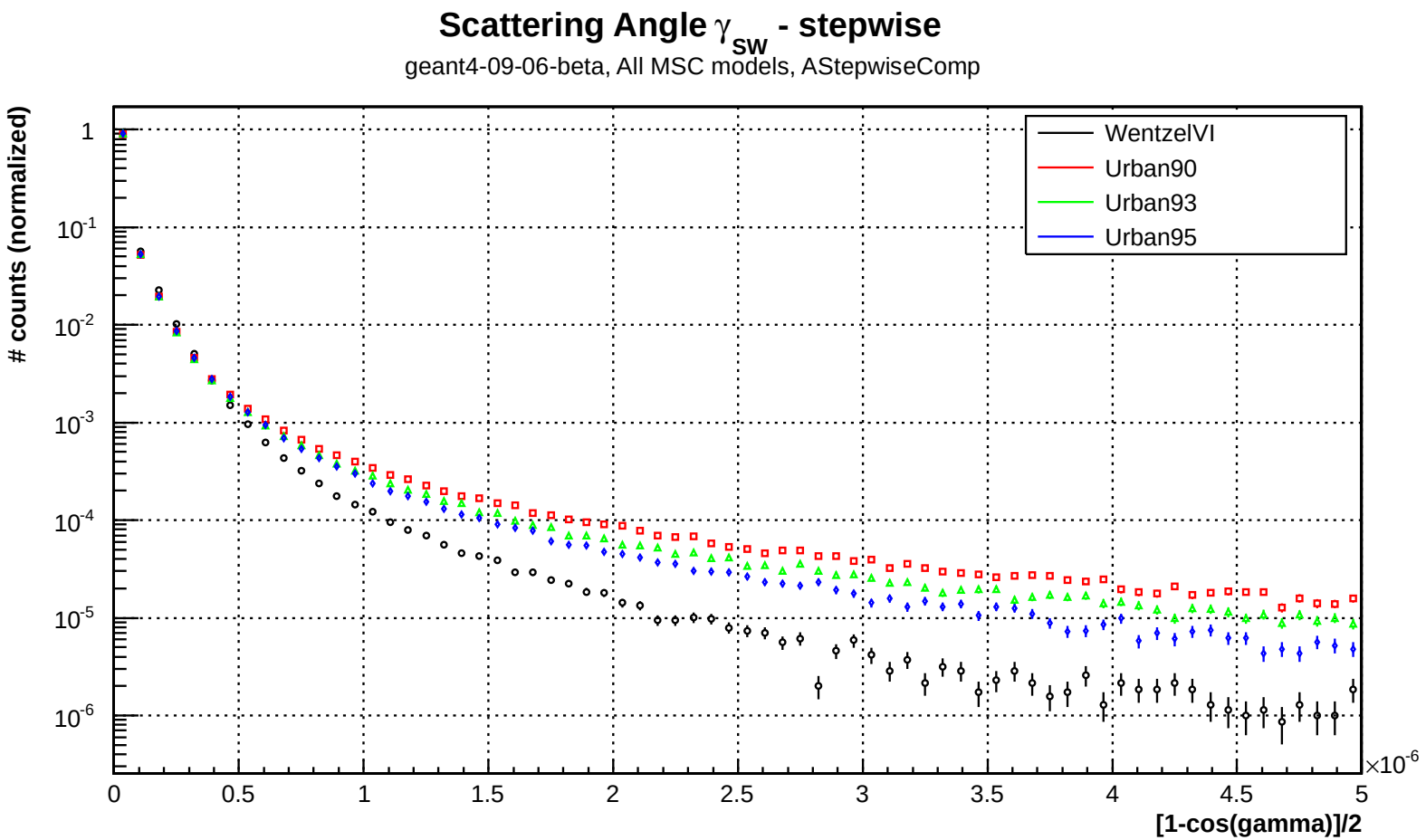


Definitions

- $\vec{R}_{pre}$ and $\vec{R}_{post}$ are the pre- and post step points respectively.
- The plane E is defined by the momentum vectors $\vec{p}_{pre}$ and $\vec{p}_{post}$.
- γ is the spatial scattering angle.
- $\vec{\Delta}$ denotes the displacement vector
  - $\vec{\Delta}_\perp$ normal component
  - $\vec{\Delta}_\parallel$ parallel component

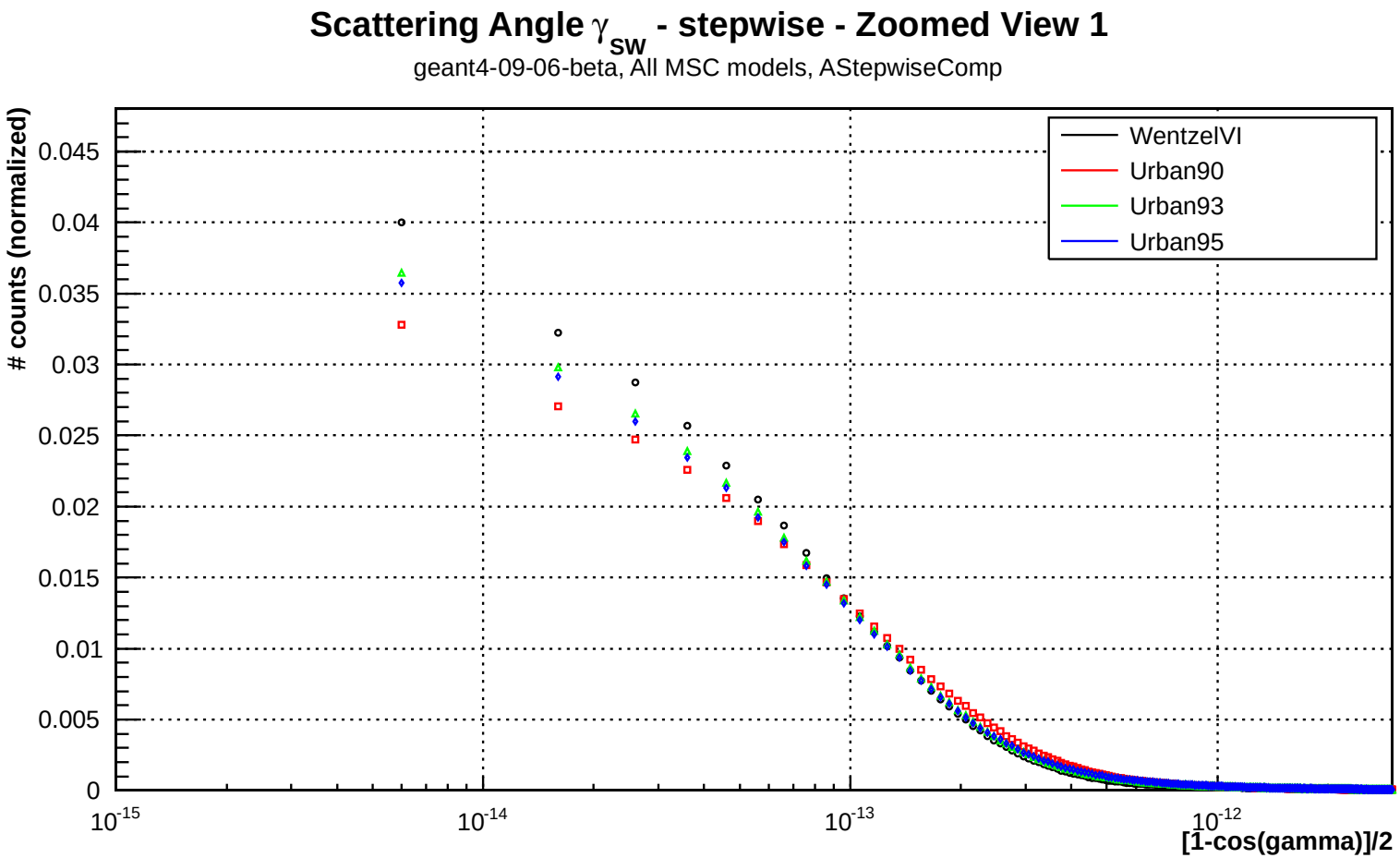
Stepwise Comparison of MSC Models

Scattering Angle I



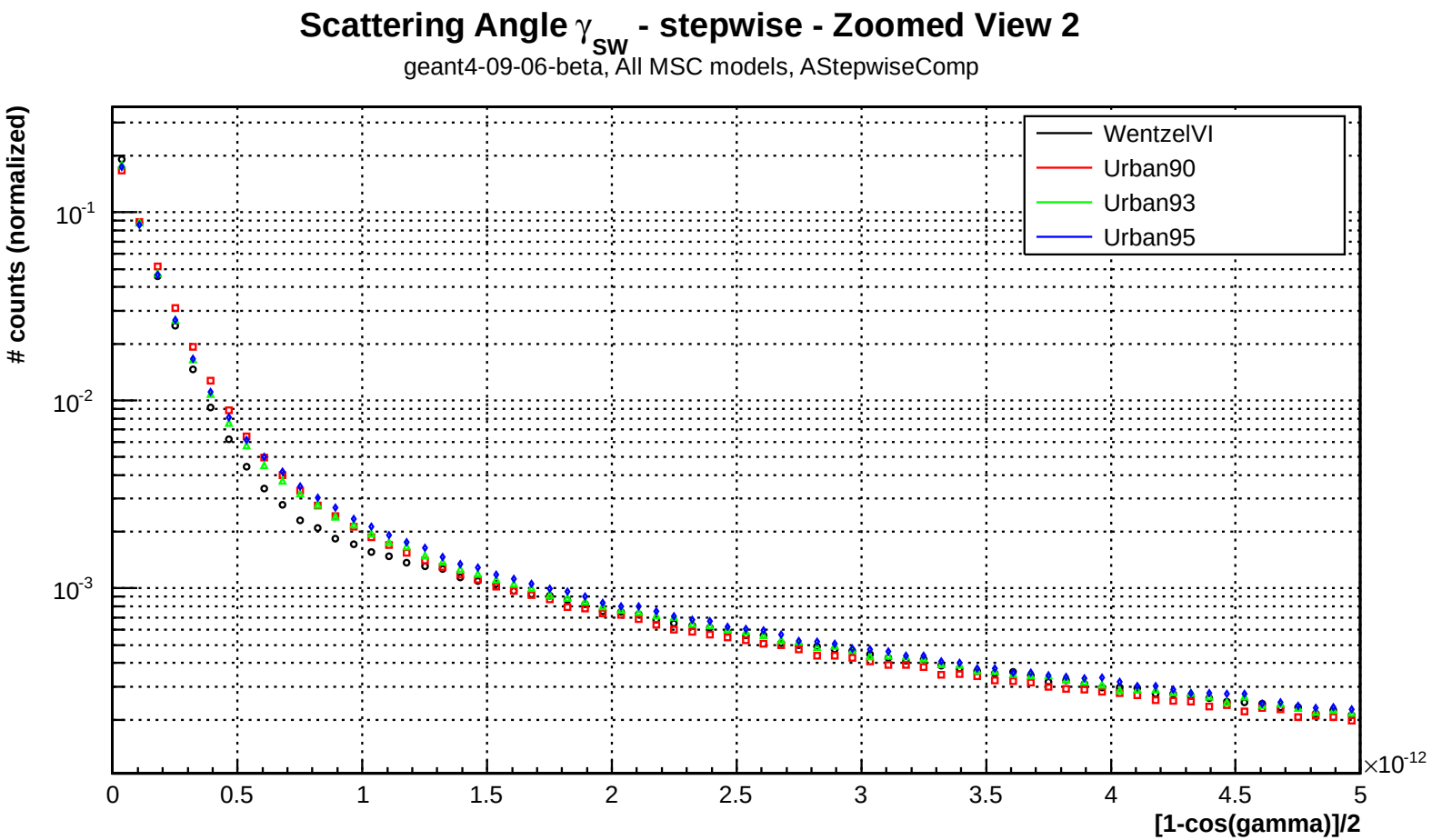
Stepwise Comparison of MSC Models

Scattering Angle II



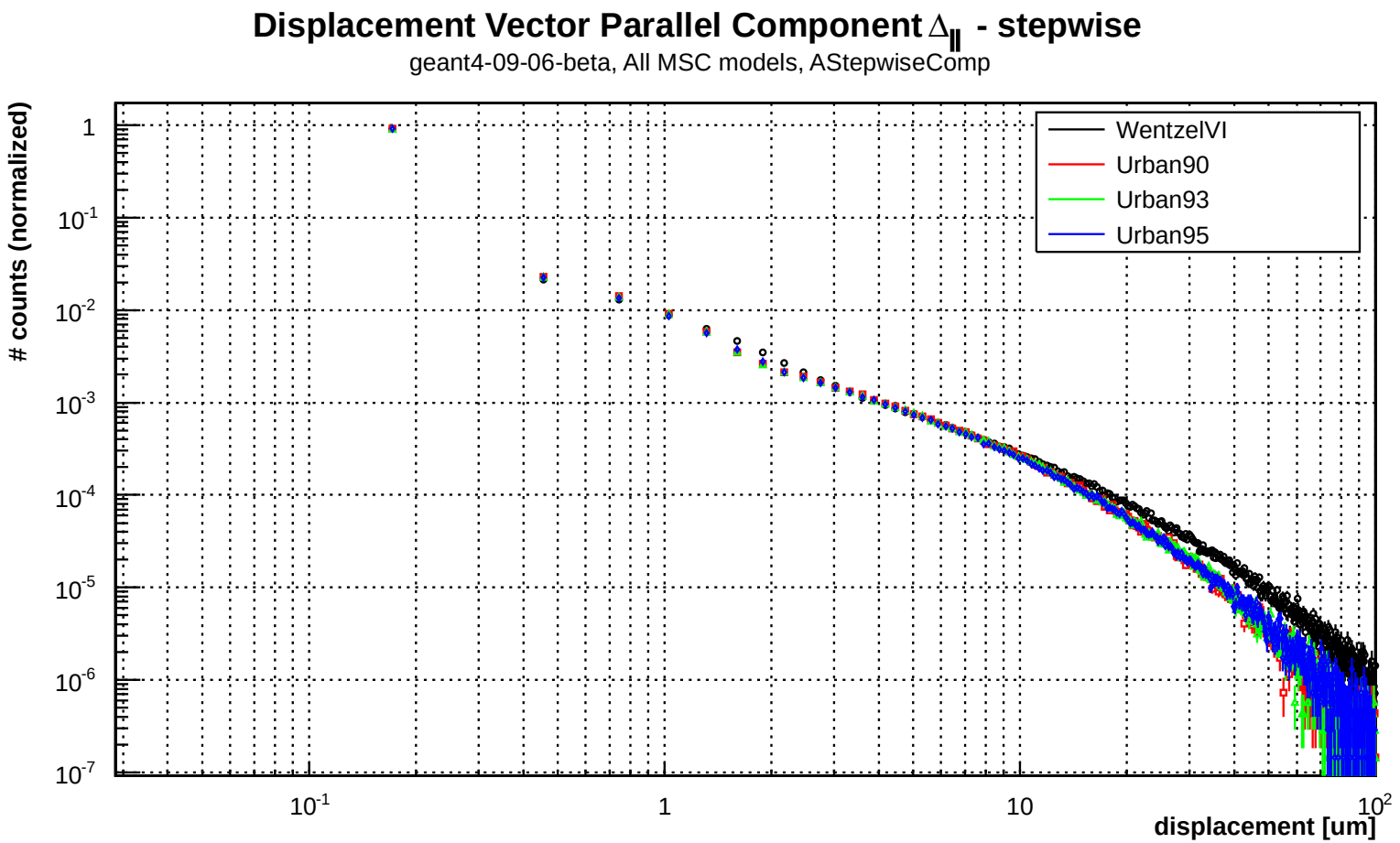
Stepwise Comparison of MSC Models

Scattering Angle III



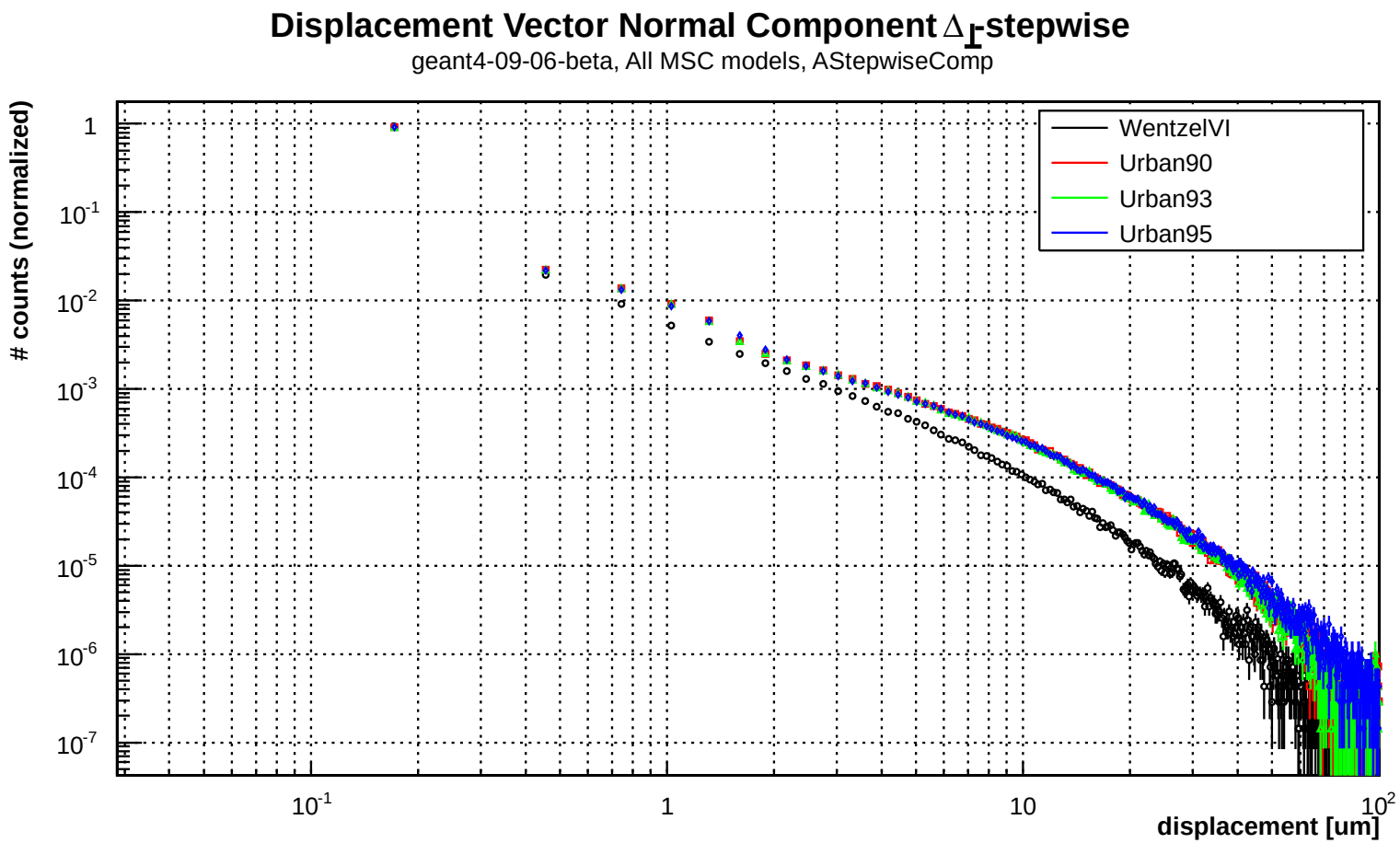
Stepwise Comparison of MSC Models

Displacement Vector I



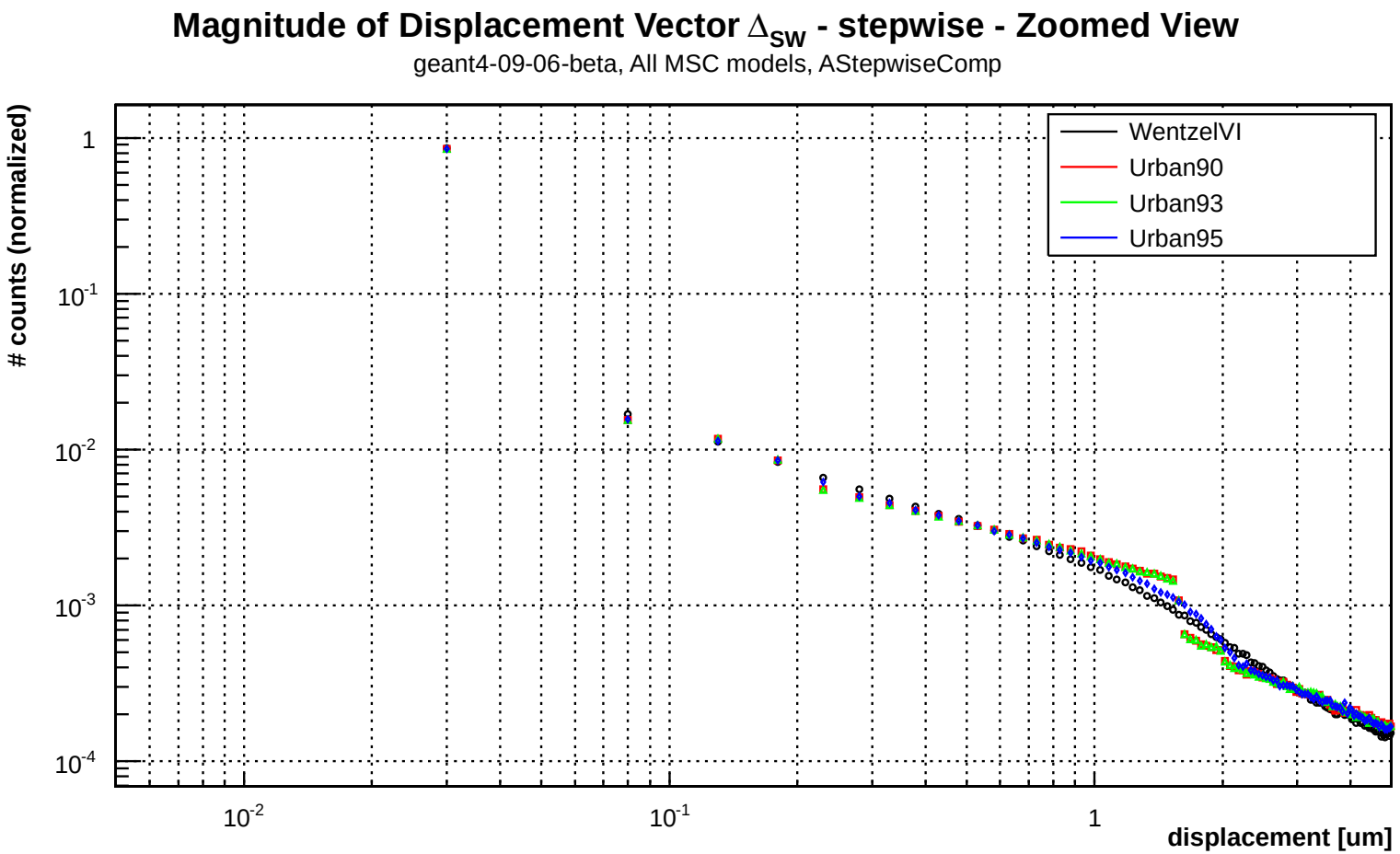
Stepwise Comparison of MSC Models

Displacement Vector II



Stepwise Comparison of MSC Models

Displacement Vector III



Conclusions

The present analysis shows that

- the **WentzelVI model lies closer to the L3 data** than the Urban models. This is due to the **differences in the simulation of the tail.**
- **Urban95** is much **more similar to WentzelVI** than the former Urban models 90 and 93.
- Further analysis shows that differences between the MSC models are **visible on a stepwise scale** both for the **scattering angle** and especially for the **normal component** of the displacement vector.

Remarks

- With the present simulation setup all the above-mentioned MSC models seem to overestimate the endpoint displacement.
- It is expected that when including a distribution in φ and P_μ (i.e. lower momenta), the widths would become even larger (see backup slides)

Backup Slides

Influence of an Angular Distribution in φ

Simulation Setup

- Geant4.9.6 beta
- More advanced geometry to enable φ angular distribution.
- Particle gun emitting μ with an angular distribution in θ (angle between initial μ direction and beamline)

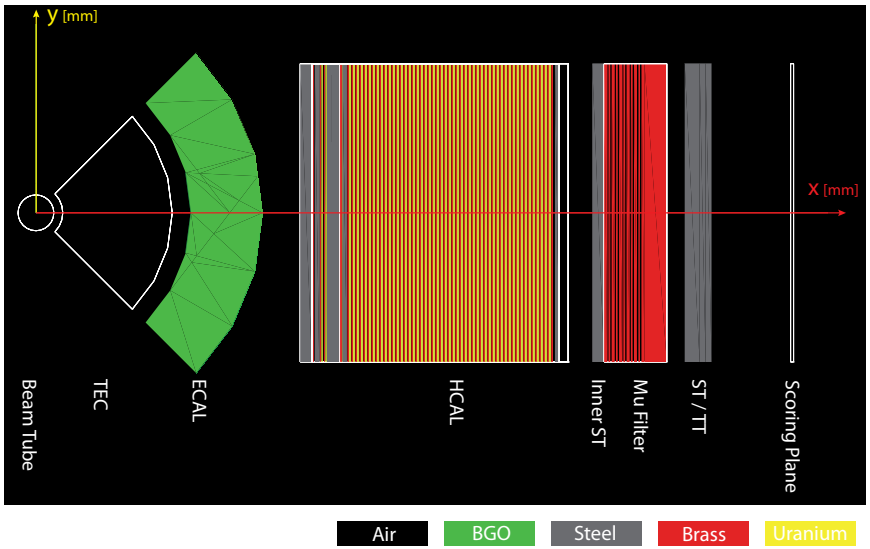
$$\frac{dF(\cos\theta)}{d\cos\theta} \propto \left(1 + \cos^2\theta\right)$$

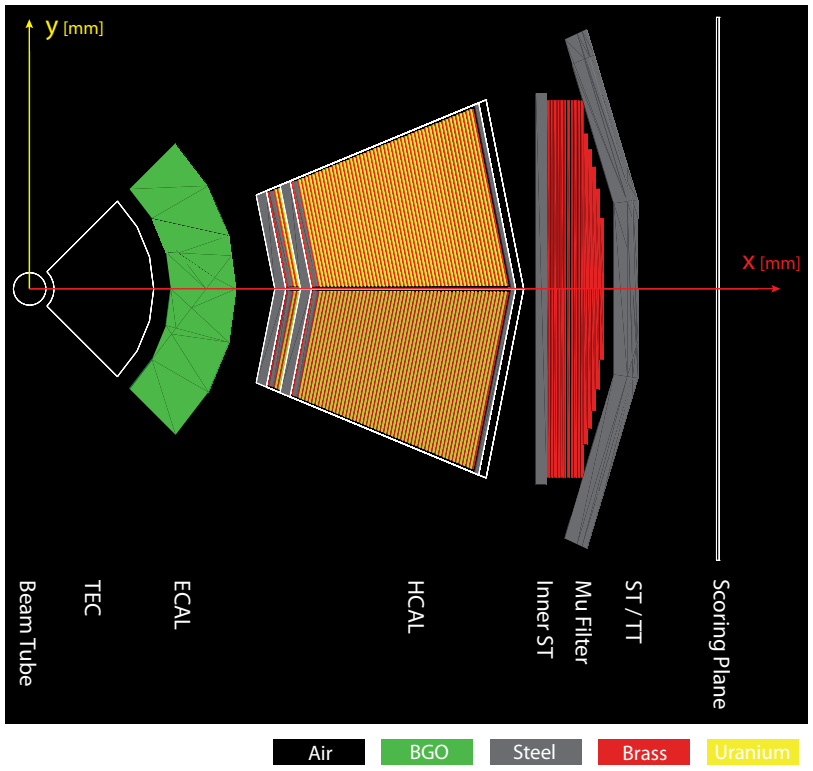
- The angle φ is uniformly distributed in $(-20°, -2.5°) \cup (2.5°, 20°)$.
- The initial μ momentum is fixed at $P_\mu = \frac{m_Z}{2} \approx 45.6\,\text{GeV}$.
- MSC models in use are WentzelVI, Urban90, Urban93 and Urban95.

Influence of an Angular Distribution in φ

Detector Geometries

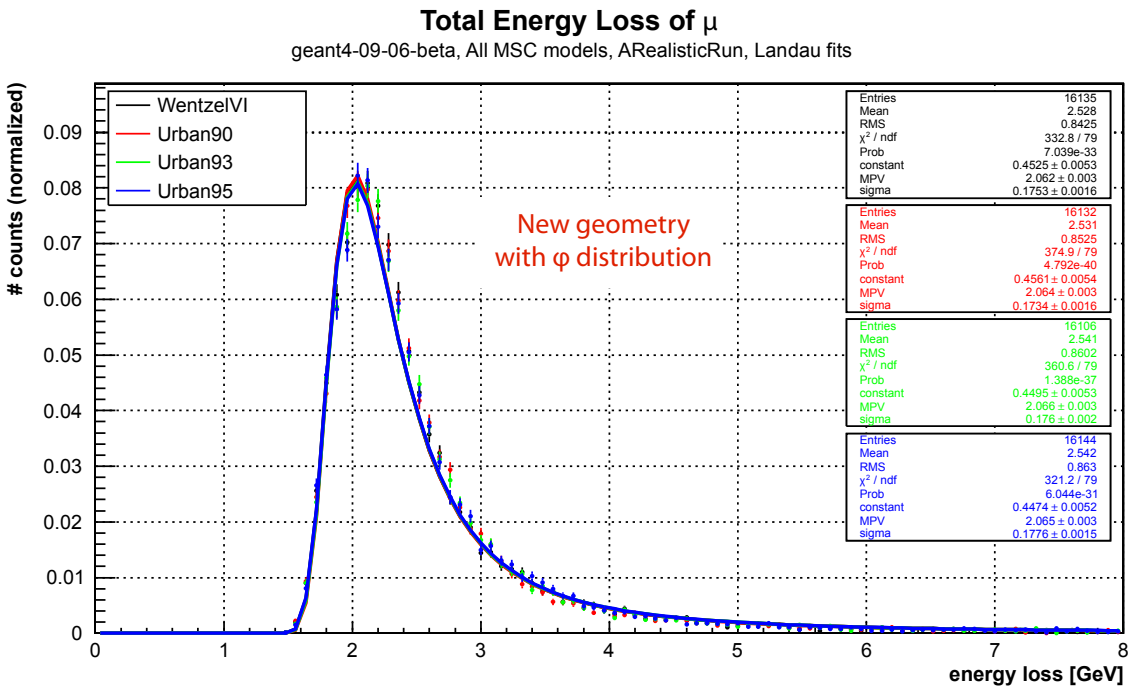
Simplified geometry $\Rightarrow$ **more accurate geometry**





Influence of an Angular Distribution in φ

Energy Loss

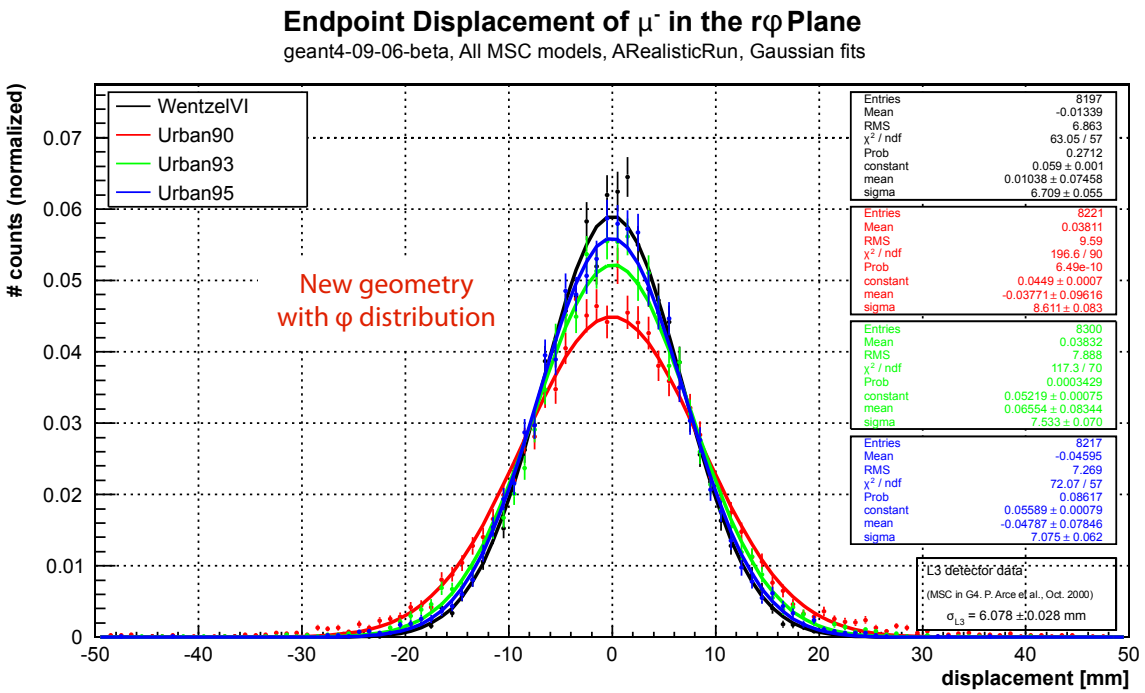


Mean energy loss

- P. Arce et al. mention a mean energy loss of about 2.5 GeV.
- Including a φ distribution, the present simulation yields a value of only slightly more than 2.5 GeV.

Influence of an Angular Distribution in φ

Endpoint Displacement



Distribution widths

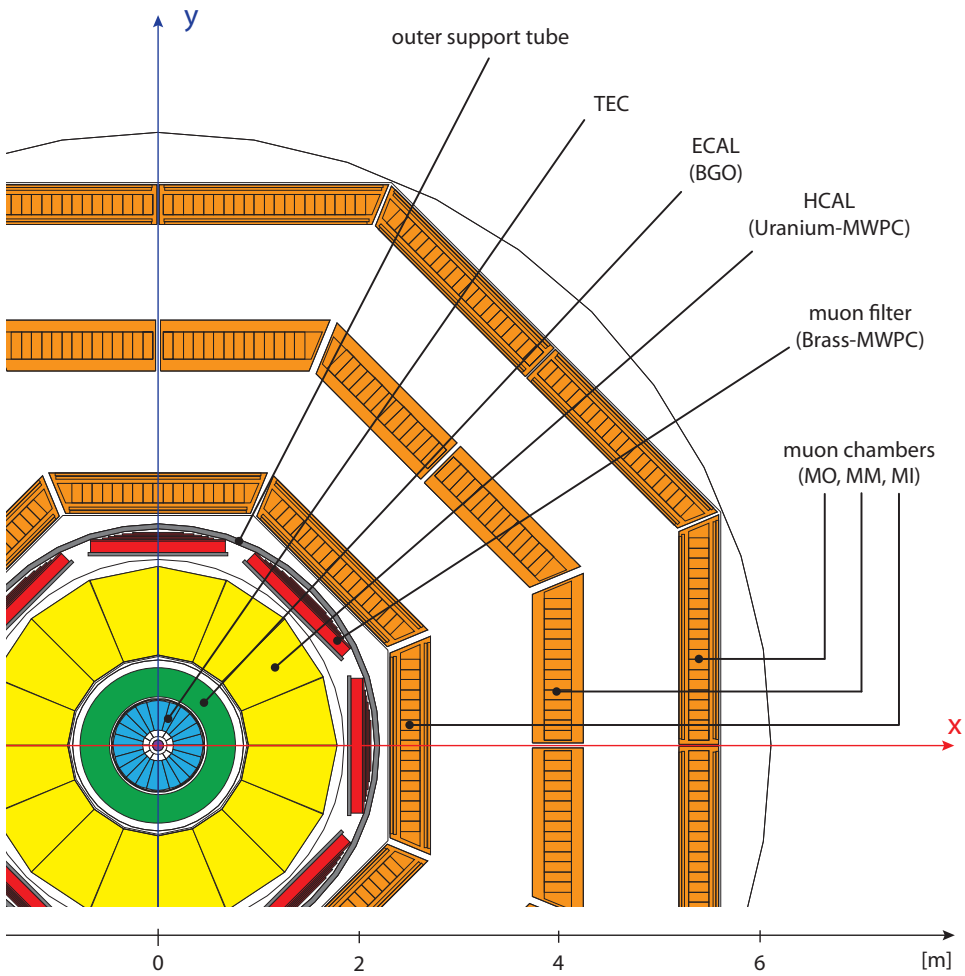
- **WVI:** 6.71 ± 0.06 mm
- **U90:** 8.61 ± 0.09 mm
- **U93:** 7.53 ± 0.07 mm
- **U95:** 7.08 ± 0.07 mm
- **L3 data:** $\mathbf{6.08 \pm 0.03}$ **mm**

Influence of an Angular Distribution in φ

Conclusions

- When including a φ distribution, the mean energy loss is even closer to the value mentioned by Arce et al.
- As expected, the widths of the endpoint displacement curves are slightly larger when including a φ distribution.
- Compared to the values without φ distribution, the widths are about 7% larger for WentzelVI and between 2% and 3% larger for the Urban models.

L3 Detector Geometry



http://l3.web.cern.ch/l3/