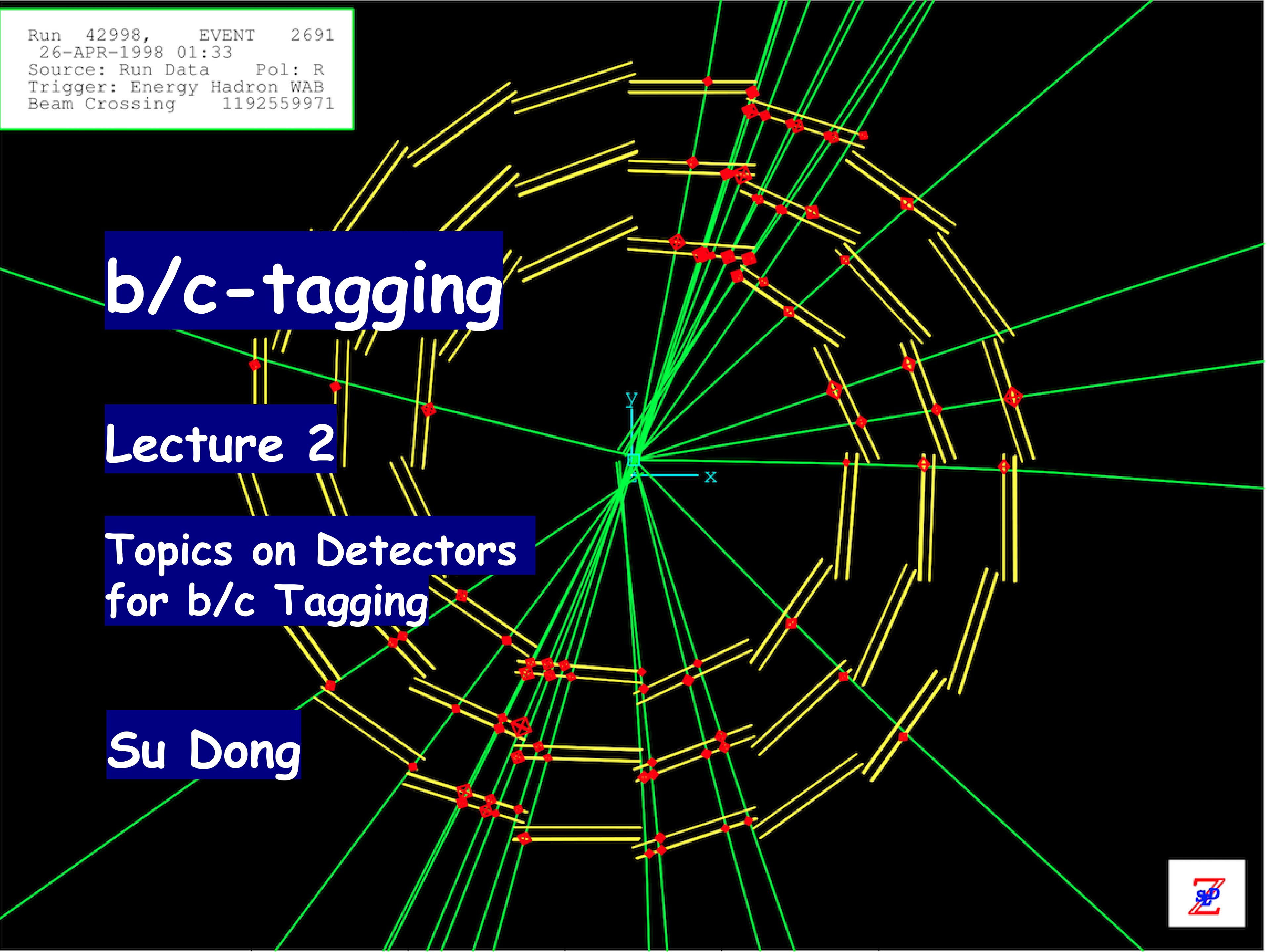


b/c-tagging

Lecture 2

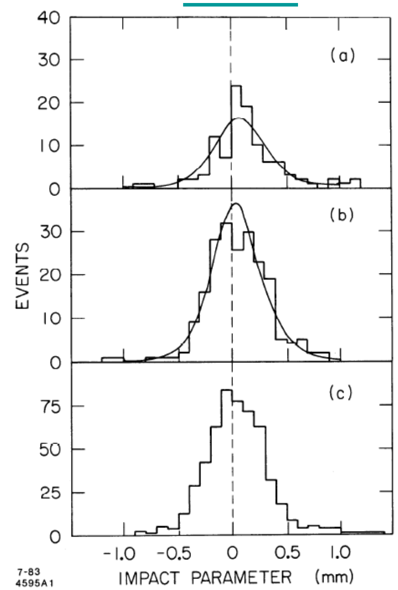
Topics on Detectors for b/c Tagging

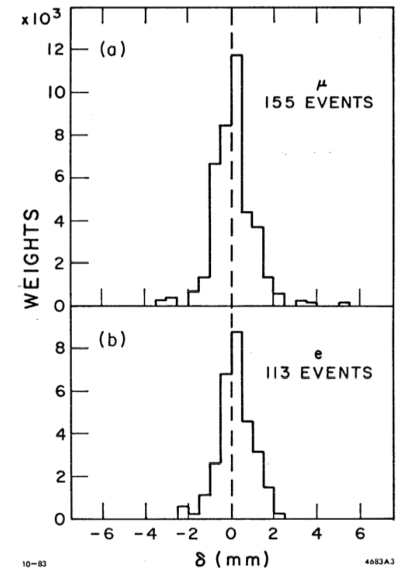
Su Dong

Vertex Detector Chronology: 80s

- Vertex drift chambers @ e^+e^- colliders
  - τ, charm, b lifetime: MK-II, MAC, HRS, DELCO @PEP, TASSO, JADE@PETRA, CLEO@CESR, ARGUS@DORIS
  - Lifetime b-tag: TASSO
- Various detector types @ fixed target
  - All aimed at charm lifetime measurements
  - Silicon strip: ACCMOR (+CCD)@CERN, E691@FNAL, …
  - Emulsion, Bubble chambers …

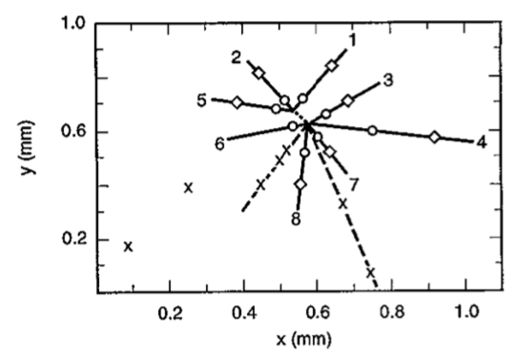
MK-II 1983 MAC





$\tau_B = 1.2 \pm 0.4 \pm 0.3$

$\tau_B = 1.8 \pm 0.6 \pm 0.4$



NA32 with CCD

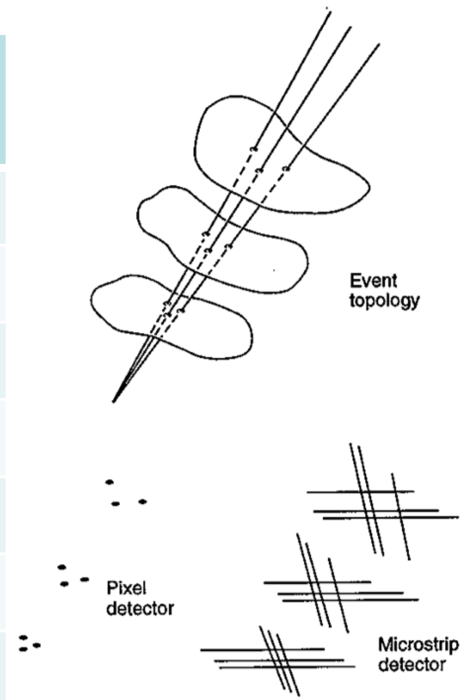
Vertex Detector Chronology: 90s

- e^+e^- @ SLC/LEP
  - Si strip: MK-II, ALEPH,DELPHI,L3,OPAL
  - CCD pixel: SLD
  - τ, b lifetime and B mixing
  - Lifetime b-tag: R_b, b asymmetry, QCD b jets, Higgs search…
  - Lifetime c-tag: R_c, c asymmetry (SLD only)
- $p\bar{p}$ @ Tevatron
  - Silicon strip detectors at CDF, D0
  - b lifetime and B mixing
  - Lifetime b-tag: top quark, Higgs search…
- Fixed target
  - Si strip: E791, FOCUS @FNAL… more charm lifetime

Vertex Detectors @ LHC

New pixel era: ATLAS/CMS instrumented with active hybrid pixels. Evolution compared to SLD.

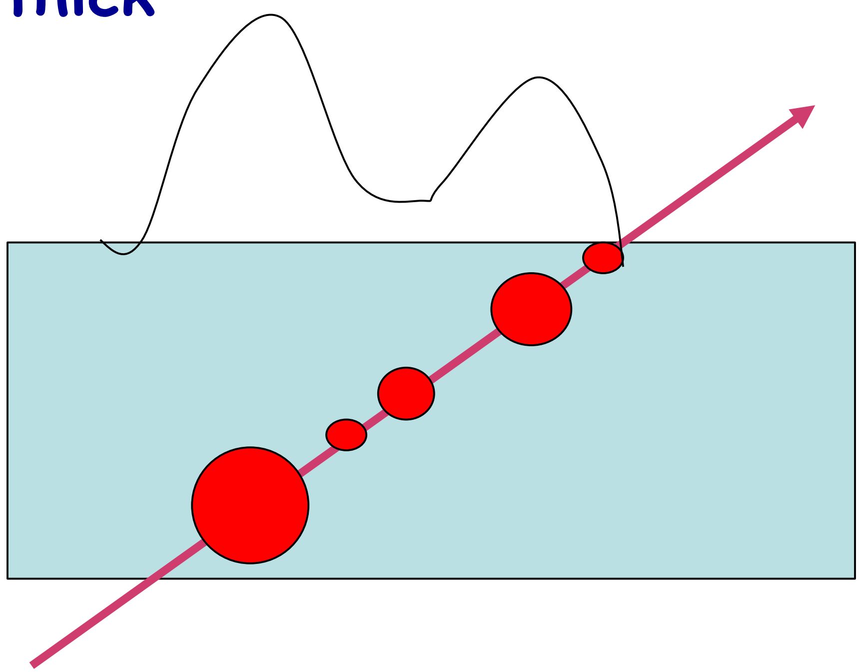
Experiment /detector	Pixel type	Year	#pixels	Pixel size (μm) (rϕ/ z /depth)
SLD VXD2	CCD	1992	120M	22 x 22 x 20
SLD VXD3	CCD	1996	307M	20 x 20 x 20
ATLAS Pixel	hybrid	2008	80M	50 x 400 x 250
CMS Pixel	hybrid	2008	66M	100 x150 x 285
ATLAS IBL	hybrid	2015	12M	50 x 250 x 200
CMS Phase1	hybrid	2017	124M	100 x150 x 200
ATLAS ITk	hybrid	2025	4886M	$\frac{50}{25}$ x $\frac{50}{100}$ x 100-200
CMS Phase2	hybrid	2025	1947M	$\frac{50}{25}$ x $\frac{50}{100}$ x 100-150

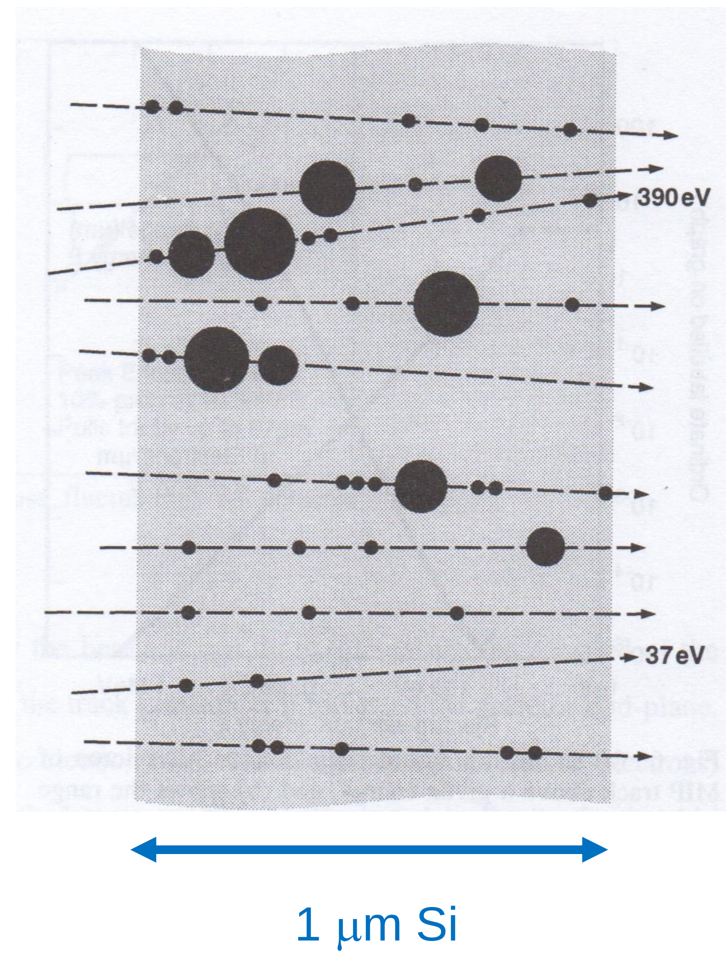


Charged Particle Ionization in Silicon

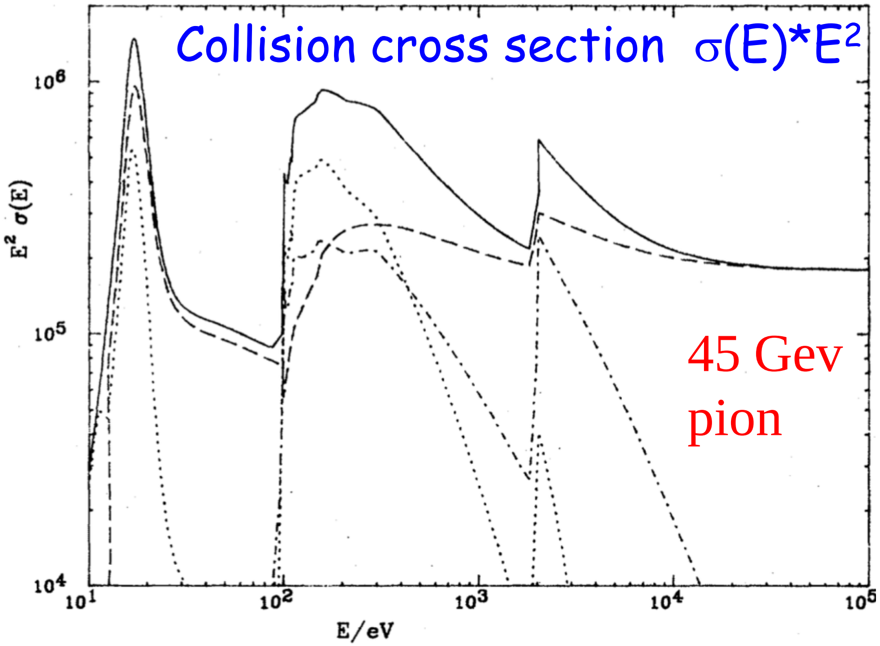
Charged Particle Ionization

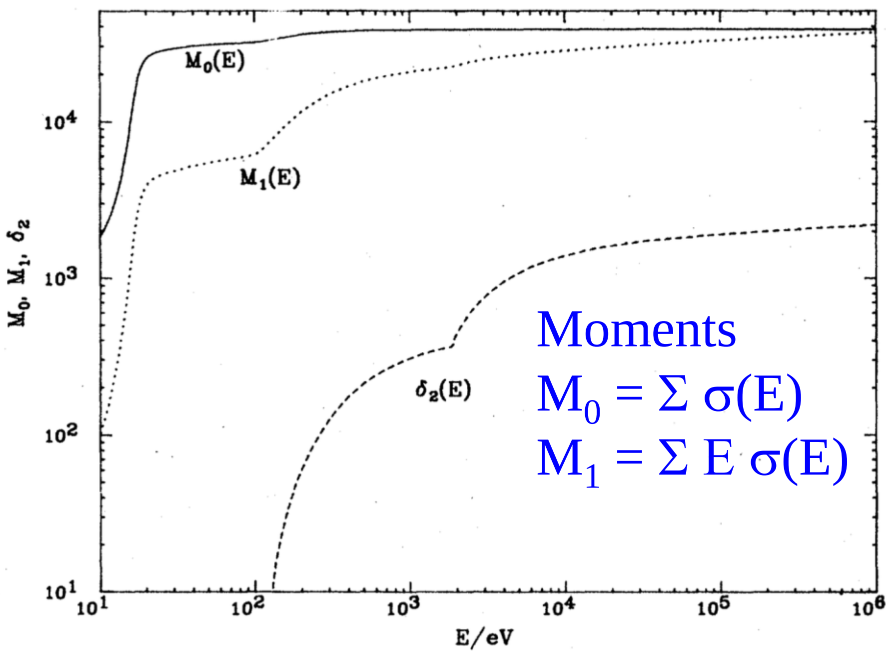
Ionization fluctuation is the main culprit of resolution degradation at inclined angle, especially when Si is thick





Atomic Collisions in Silicon

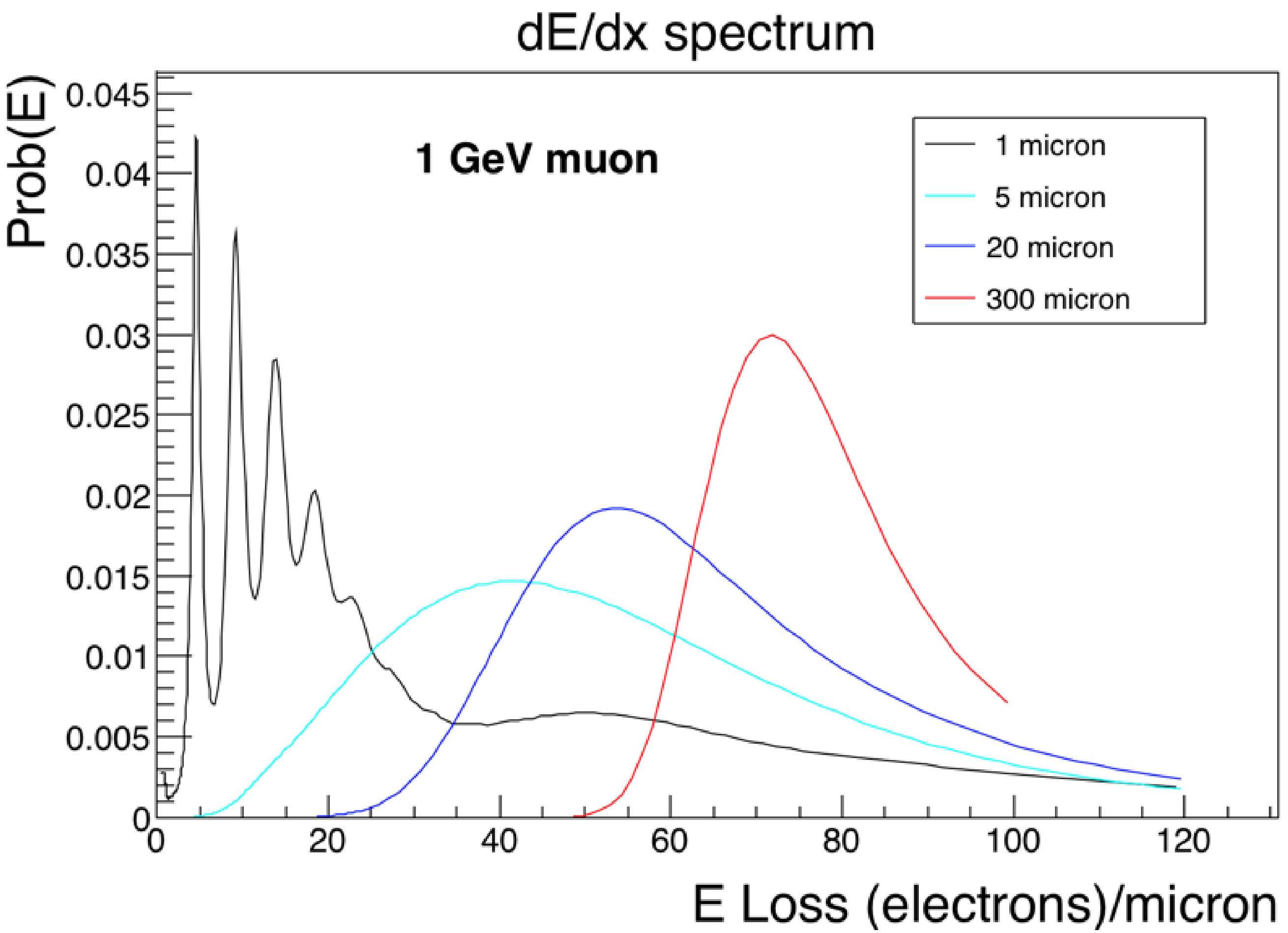




- **~4 collisions per μm but mostly very low loss (~17eV)**
- **Total E loss and fluctuation driven by the sporadic large E loss collisions.**

Han Bichsel Rev. Mod. Phys. 60, 663 (1988)

dE/dx is a misleading concept



Ionization loss spectrum is far from being scalable to different thicknesses as the naïve term dE/dx might suggest.

For thin Si, it is not Landau

Bichsel Model in ATLAS Simulation

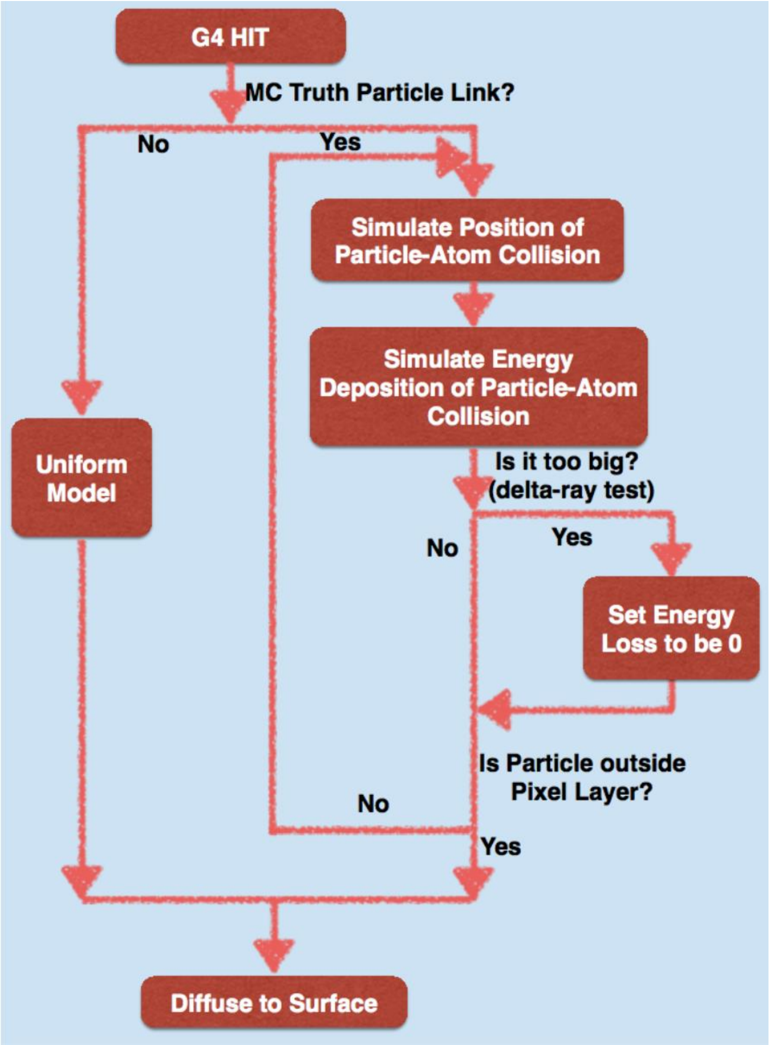
Implementation in ATLAS G4 simulation based on single atomic collision spectrum in Bichsel's COV program.

- Running COV at a few specific $\beta\gamma$ points to store spectra in numerical tables.
- Individual track hits interpolate to arbitrary $\beta\gamma$ to generate single atomic collision energy loss
- E-loss Spectrum cuts off at G4 δ-ray threshold. G4 simulates δ-ray explicitly as separate particle.
- Control options to group many collisions << detector resolution together for collective ionization electron diffusion and charge collection to save CPU time.

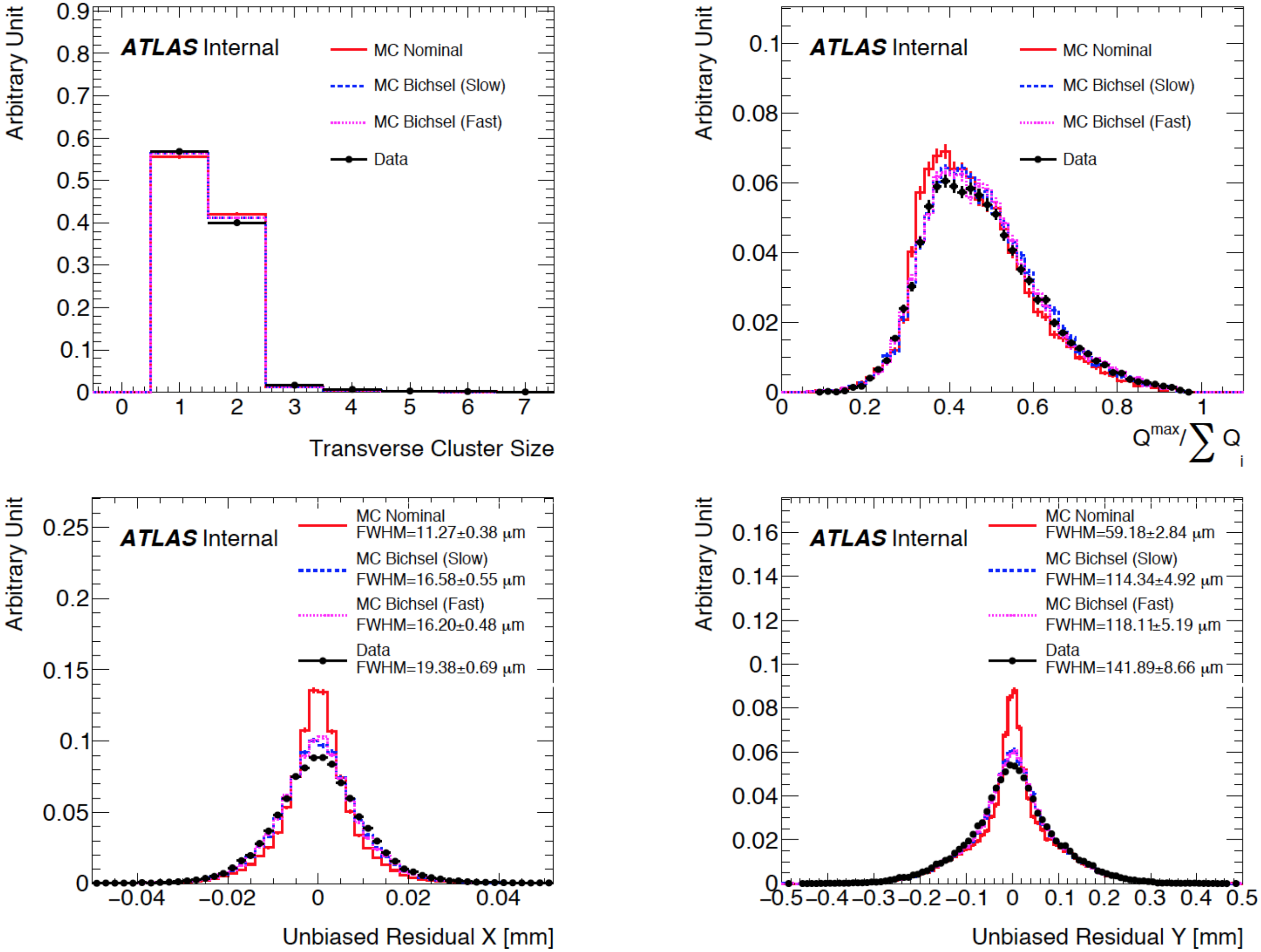
[Q.Zeng Stanford Ph.D thesis: CERN-thesis-2017-124 Appendix A]

Bichsel Model in ATLAS

- Default ATLAS implementation of Bichsel model only for $\beta\gamma > 0.7$
- Would have been easier to extend to low $\beta\gamma$ if grid was done in $dE/\beta\gamma$ – possible future improvements.
- ATLAS G4 δ-ray cut default = 117 KeV



Improvements for ATLAS



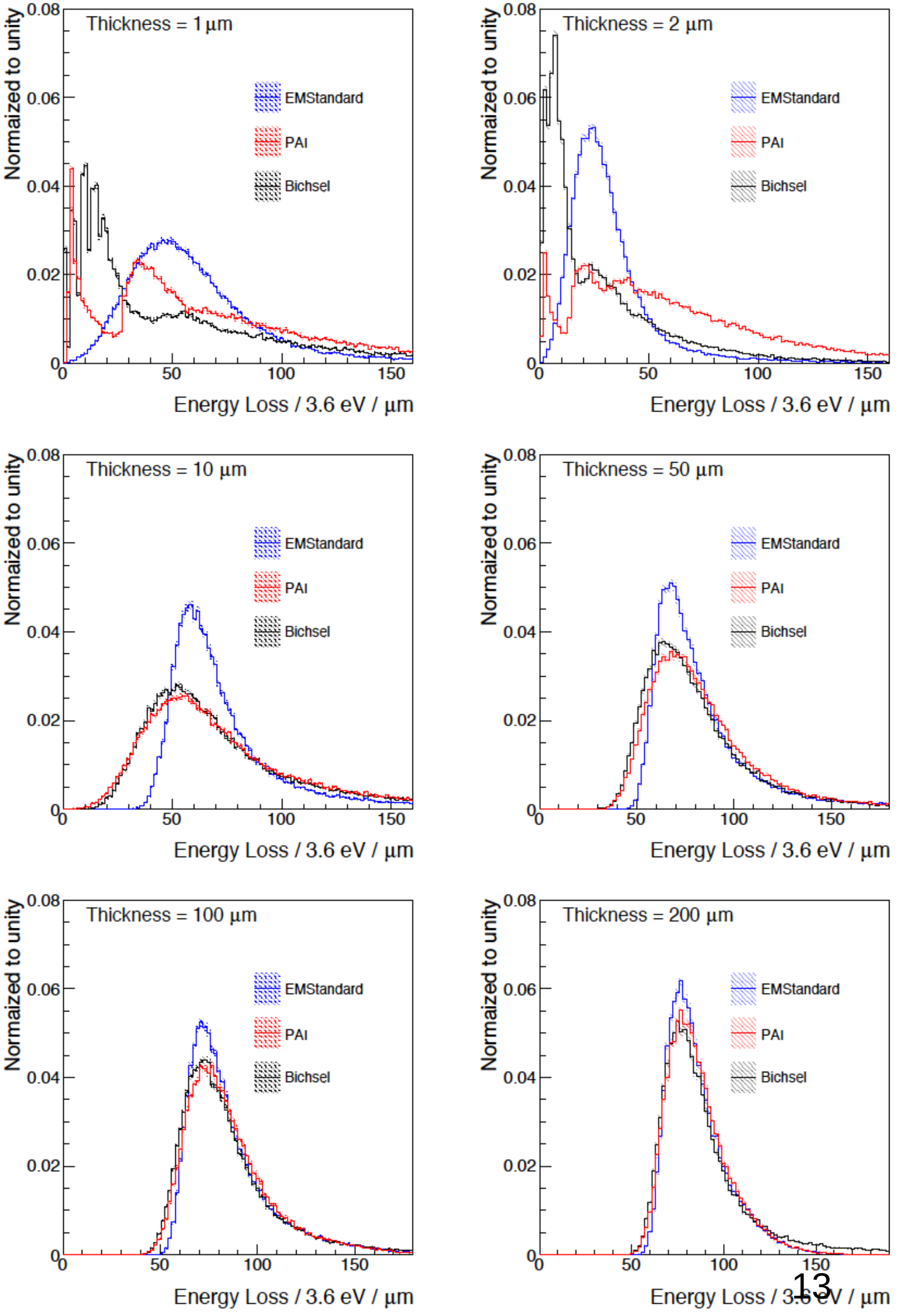
Bichel model became default digitization in release 21

Bichsel Model in Allpix

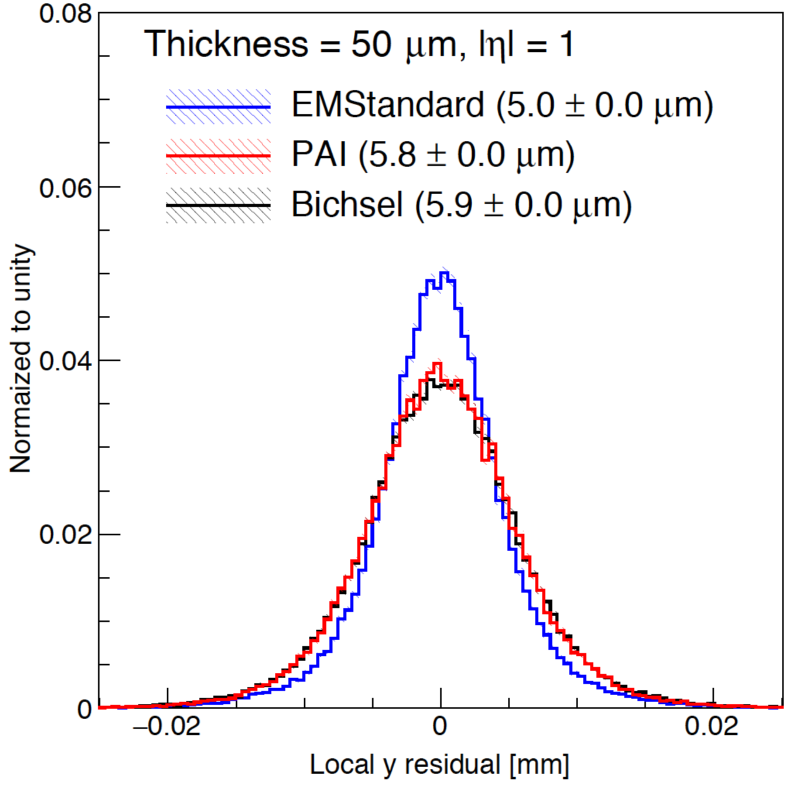
- Work done by Fuyue Wang, Ben Nachman, Maurice Garcia-Sciveres (LBNL)
- Converted COV (Fortran) to C++
- Embedded in Allpix simulation/reconstruction framework as a generic test beam utility [Temporary repository (contact Ben Nachman): https://github.com/bnachman/Bichsel]
- Some plotting routines to be converted to C++ still.
- Code to dump COV spectrum grid to be converted.
- Compared Bichsel model with G4 EMstandard and PAI models:
[illegible]

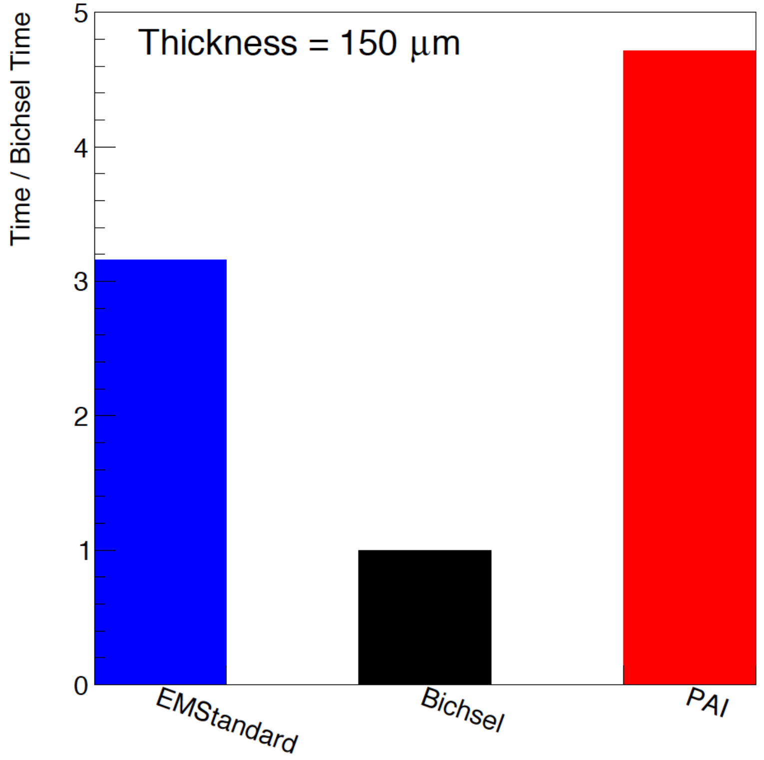
Comparison with G4

- EMstandard quite far off for thin silicon
- PAI came close but single shell approximation exposed for very thin silicon



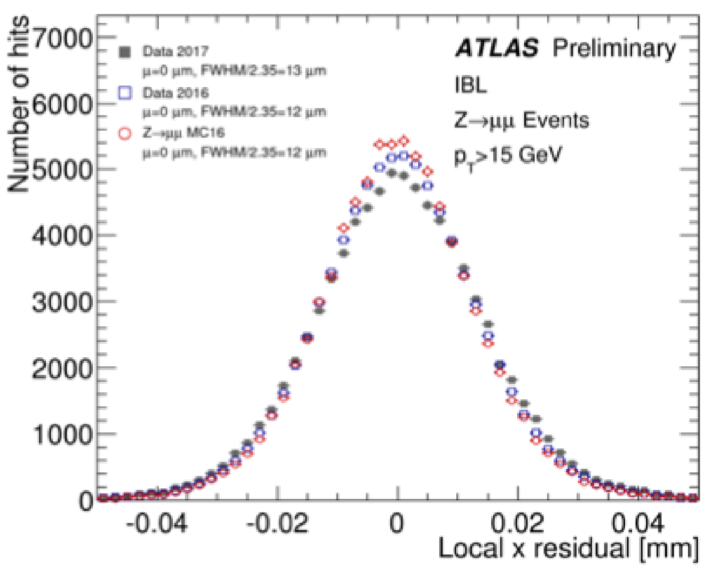
Comparison with G4

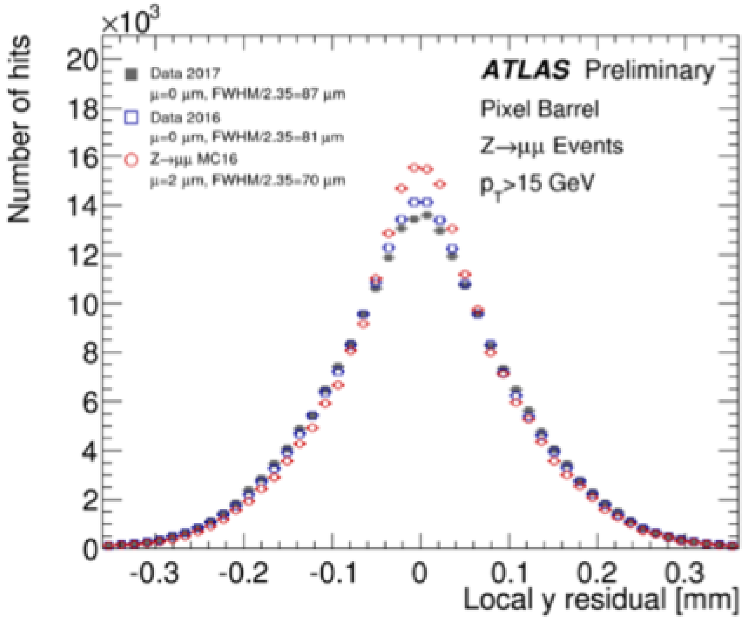




For all practical purposes PAI is good enough but slow

Spatial Resolution





rϕ: IBL = 13μm

Z: B-layer=87μm

General lesson for detector design:

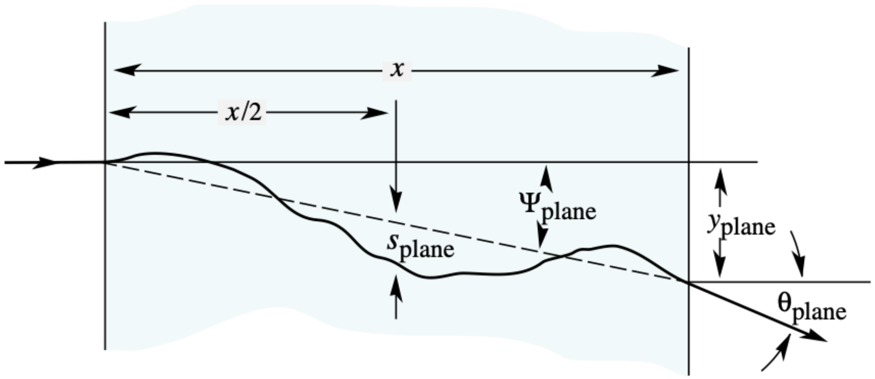
- ***Avoid large entrance angle geometry***
- **Use thin sensors if possible**

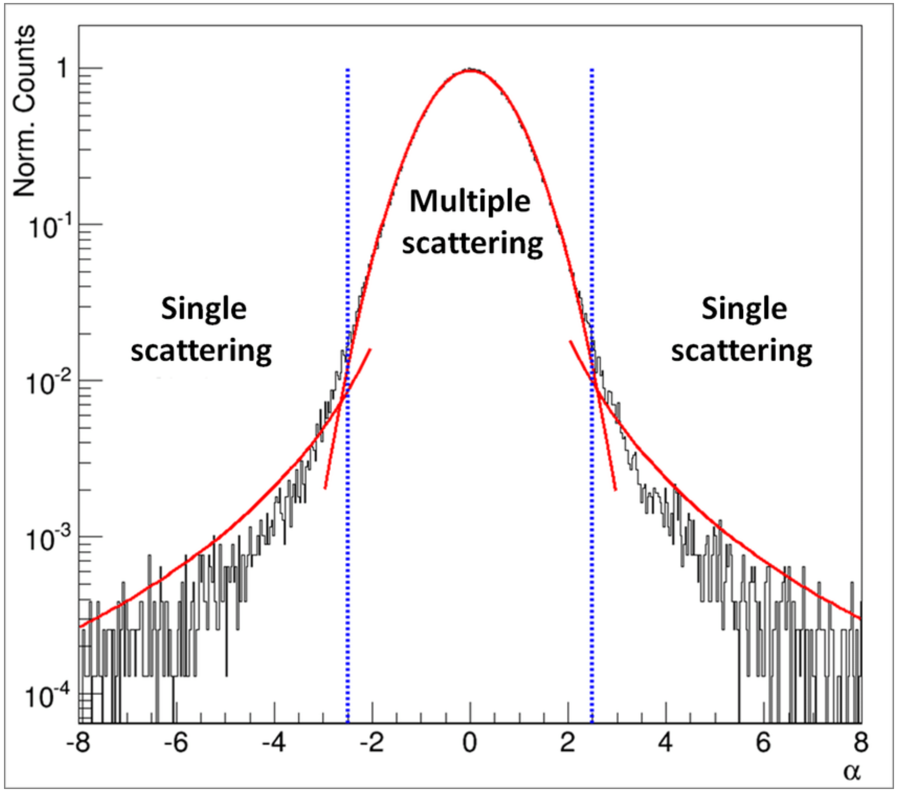
References

- References for more details on silicon detector principles
  - Chris Damerell: Lectures at SLAC Summer Institute (1995) "Vertex Detectors: the state of art and future prospects" RAL-P-95-008
  - Norbert Wermes: Lectures at SLAC Summer Institute (2016): "Tracking Detectors" [1][2]

Multiple Scattering and Material

Multiple Scattering

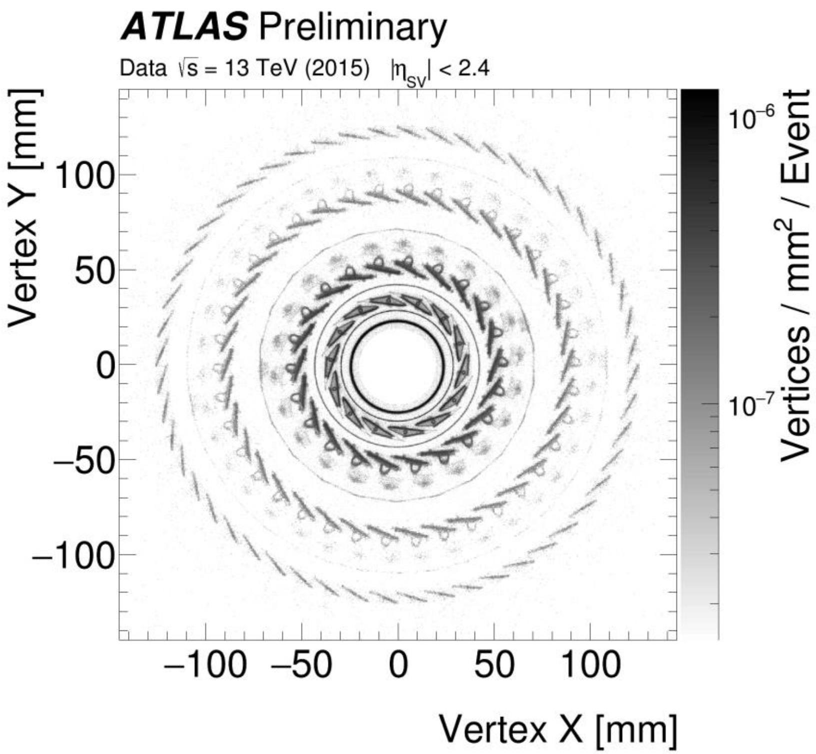


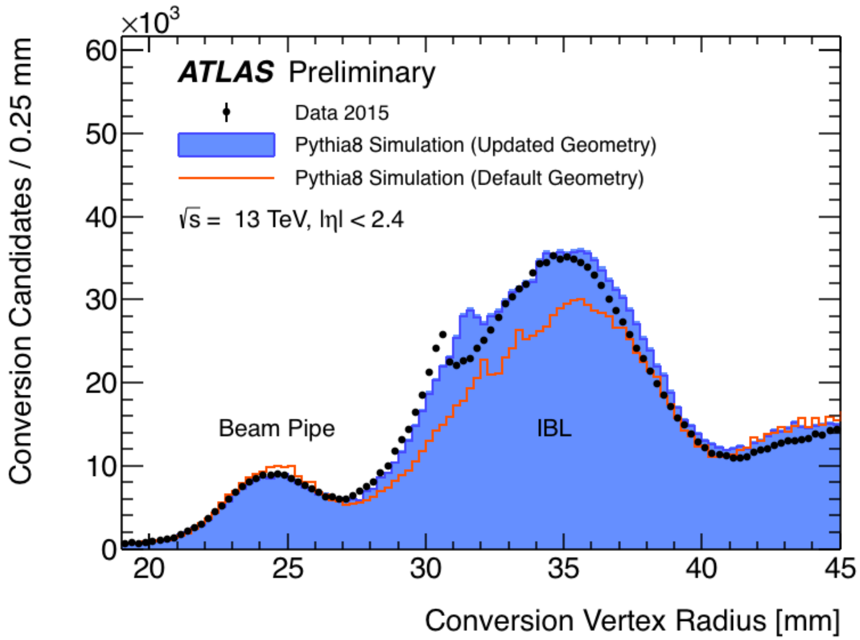


Be aware Gaussian approximations. Tails need to use Moliere scattering (G4)

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}}\left[1 + 0.088\log_{10}\left(\frac{x\, z^2}{X_0 \beta^2}\right)\right]$$

Material Mapping





Hadronic interactions

Material notes

- Try to avoid large entrance angle geometry if possible
- Same weight of material can have very different X/X_0 between different material – watch out for gold !