Tracking at the LHC

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Outline

- Momentum measurement
- Performance of CMS and ATLAS trackers
- Track fitting
- Track finding
- Alignment
- Vertex fitting

Momentum measurement

Momentum measurement

- Transverse momentum p_T measured from curvature in (r,ϕ) plane $\perp$ **B**- field
- Measure N points along trajectory
  - Precision in bending plane: $\sigma_{r\phi}$
  - Precision in z: σ_z
- Suppose B- field constant and // z- axis
- In plane transverse to B- field:
  - Lorentz force on charged particle:

$$\vec{F}_L = q\vec{v}_T \times \vec{B} = \frac{d\vec{p}_T}{dt}$$

  - Circular trajectory of radius R:

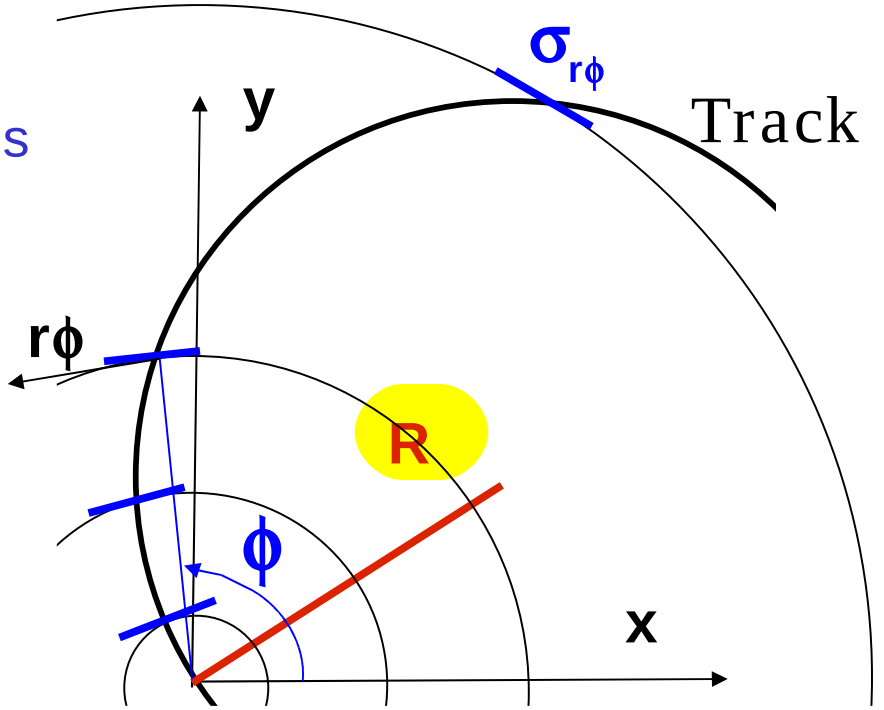
$$m\frac{v_T^2}{R} = q v_T B$$

$$p_T = qBR$$

- In convenient units:

$$p_T[GeV/c] = 0.3\, B[Tesla]\, R[m]$$

$$\vec{B} = B.\vec{1}_z$$



Momentum measurement (2)

- R measured through measurement of sagitta *s*:

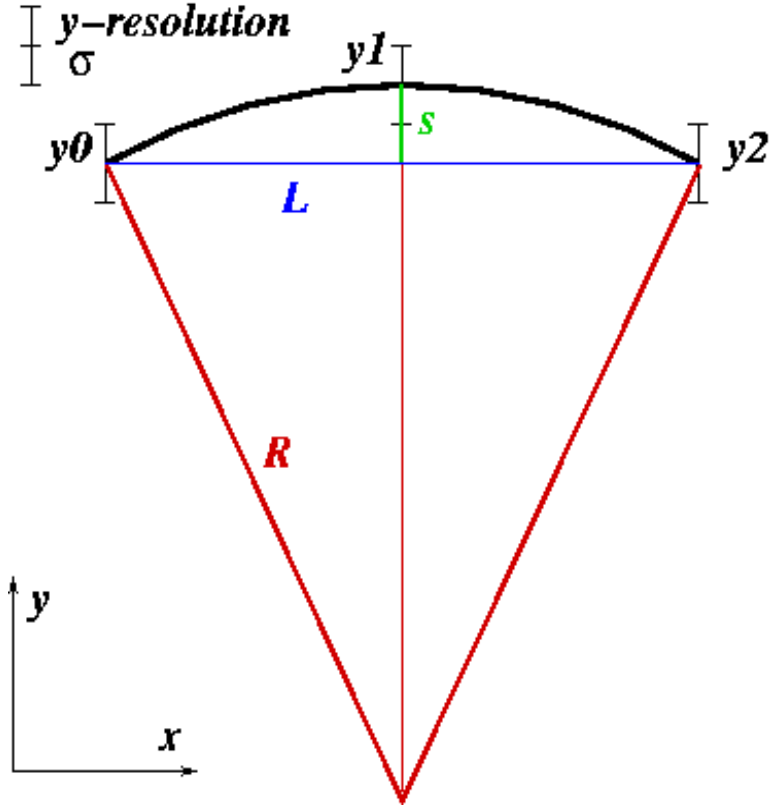
$$\left(\frac{L}{2}\right)^2+(R-s)^2=R^2$$

$$R=\frac{L^2}{8s}+s\approx\frac{L^2}{8s}$$

$$\frac{\Delta p_T}{p_T}=\frac{\Delta s}{s}=\Delta s\frac{8R}{L^2}=\Delta s\frac{8p_T}{0.3BL^2}$$

  - Proportional to Δs thus to $\sigma_{r\phi}$
  - Proportional to p_T, $1/L^2$, $1/B$
  - $1/p_T \propto s \rightarrow 1/p_T$ gaussian, not p_T
- If N equally-spaced points [2]:

$$\frac{\Delta p_T}{p_T}=\frac{a_N\sigma_{r\phi}p_T}{0.3BL^2};\quad a_N\approx\sqrt{\frac{720}{N+4}}$$



$$s=y_1-\frac{y_0+y_2}{2}$$

$$\Delta s=\sqrt{\frac{3}{2}}\sigma_{r\phi}$$

NB: here $y \equiv r\phi$

Multiple scattering

- Charged particle of momentum *p* and charge *z* traversing a material thickness *x* undergoes deviation by multiple scattering (MS)
- RMS of deviation angle projected onto rϕ–plane:

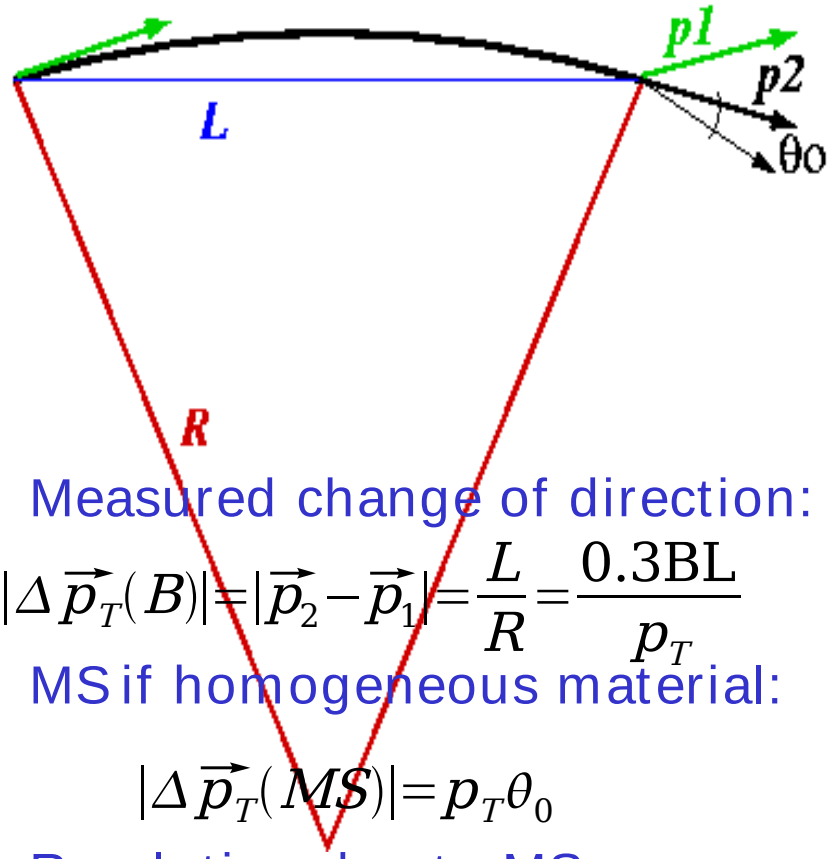
$$\theta_0 \approx \frac{13.6\,MeV}{\beta c p} z\sqrt{x/X_0}$$

- X_0 is material thickness characteristic of bremsstahlung and photon pair conversion in matter:

$$X_0 \approx \frac{716.4\,g cm^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- After 1 X_0 high-energy electrons (E> 50MeV) loose in average all but 1/ e*E by bremsstrahlung
- X_0 (Si / Cu / Be) = 9.4 / 1.4 / 35 cm

- Effect on p_T resolution:



- Measured change of direction:

$$|\Delta \vec{p}_T(B)| = |\vec{p}_2 - \vec{p}_1| = \frac{L}{R} = \frac{0.3\mathrm{BL}}{p_T}$$

- MS if homogeneous material:

$$|\Delta \vec{p}_T(MS)| = p_T \theta_0$$

- Resolution due to MS:

$$\frac{\Delta p_T}{p_T}(MS) = \frac{|\Delta \vec{p}_T(MS)|}{|\Delta \vec{p}_T(B)|} = \frac{p_T \theta_0}{0.3\,BL}$$

Summary on $\Delta p_T / p_T$

- Contribution from MS (cont.):

$$\frac{\Delta p_T}{p_T}(MS) = \frac{p_T \theta_0}{0.3 BL} = \left(\frac{0.06}{\beta B}\right)\sqrt{\frac{1}{X_0 L \sin\theta}}$$

$$\theta = polar\,angle$$

  - Note: independent of p_T !
- At LHC: tracker thickness typically $1X_0$
- Summary:

$$\left(\frac{\Delta p_T}{p_T}\right)^2 = \left(\frac{a_N \sigma_{r\phi} p_T}{0.3 BL^2}\right)^2 + \left(\frac{0.06}{\beta B}\right)^2 \frac{1}{X_0 L \sin\theta}$$

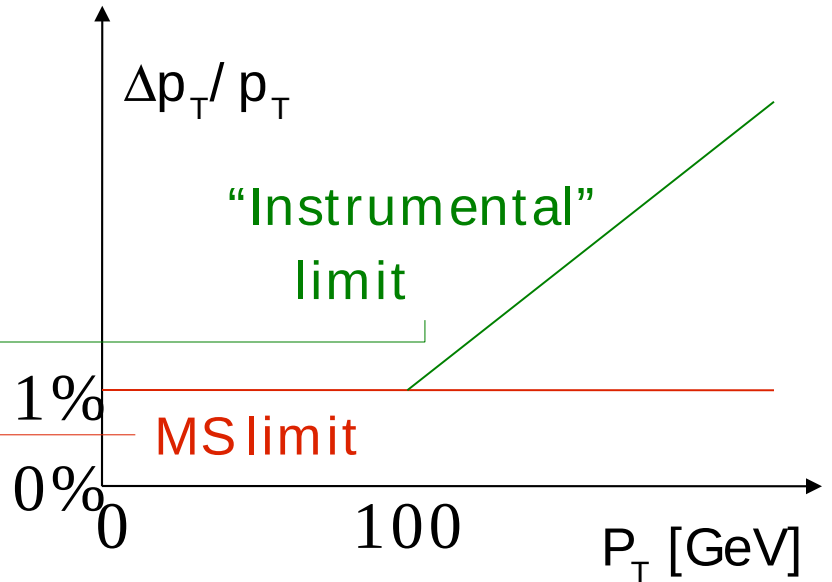
$$a_N \approx \sqrt{\frac{720}{N+4}}$$

- In order to achieve

$\Delta p_T / p_T \sim 1\%$ at $p_T = 100$ GeV/c

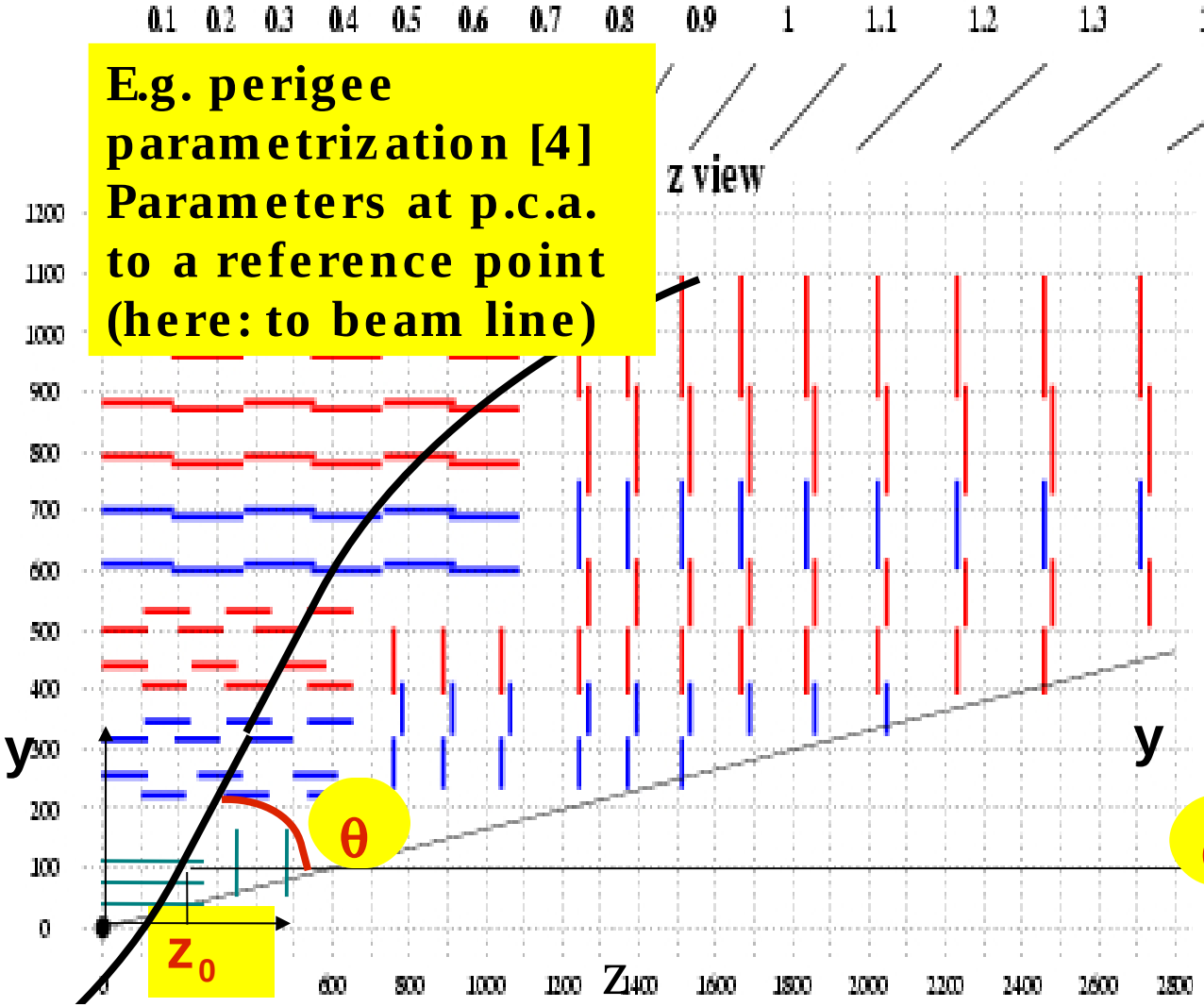
  - N= 10, L= 1m (radius of tracker), B= 4Tesla (CMS)
  - Need $\sigma_{r\phi} = 20\mu m$
- If material traversed = $1X_0$:

$(\Delta p_T / p_T)_{MS} \sim 1.5\%$

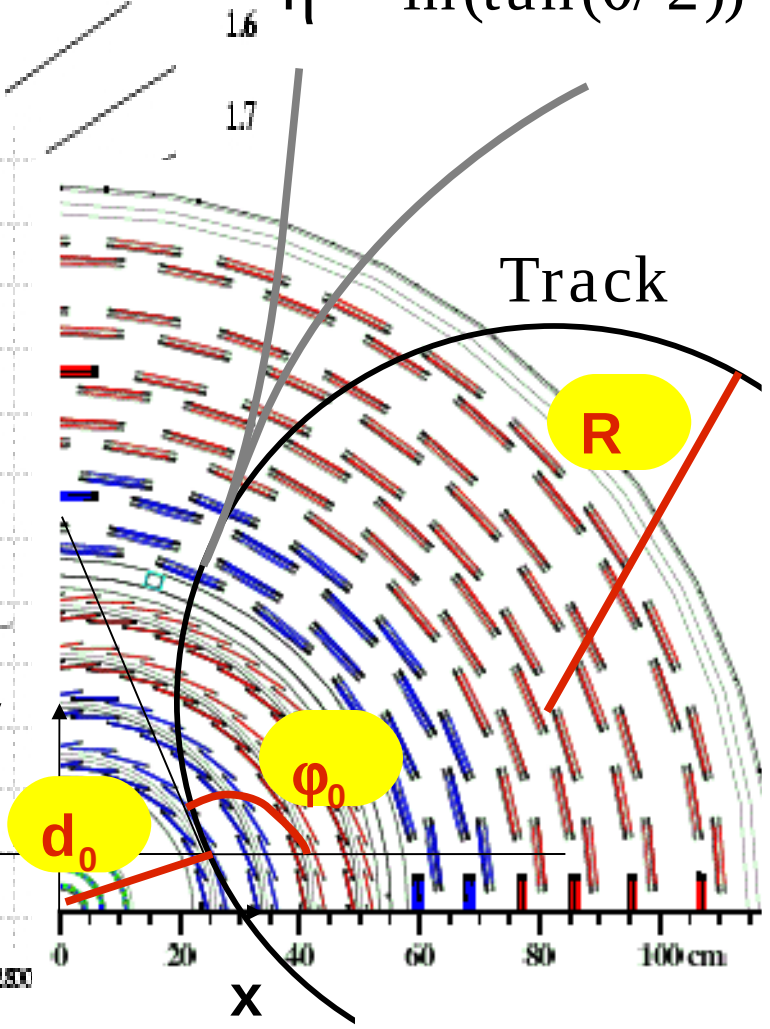


Five independent track parameters

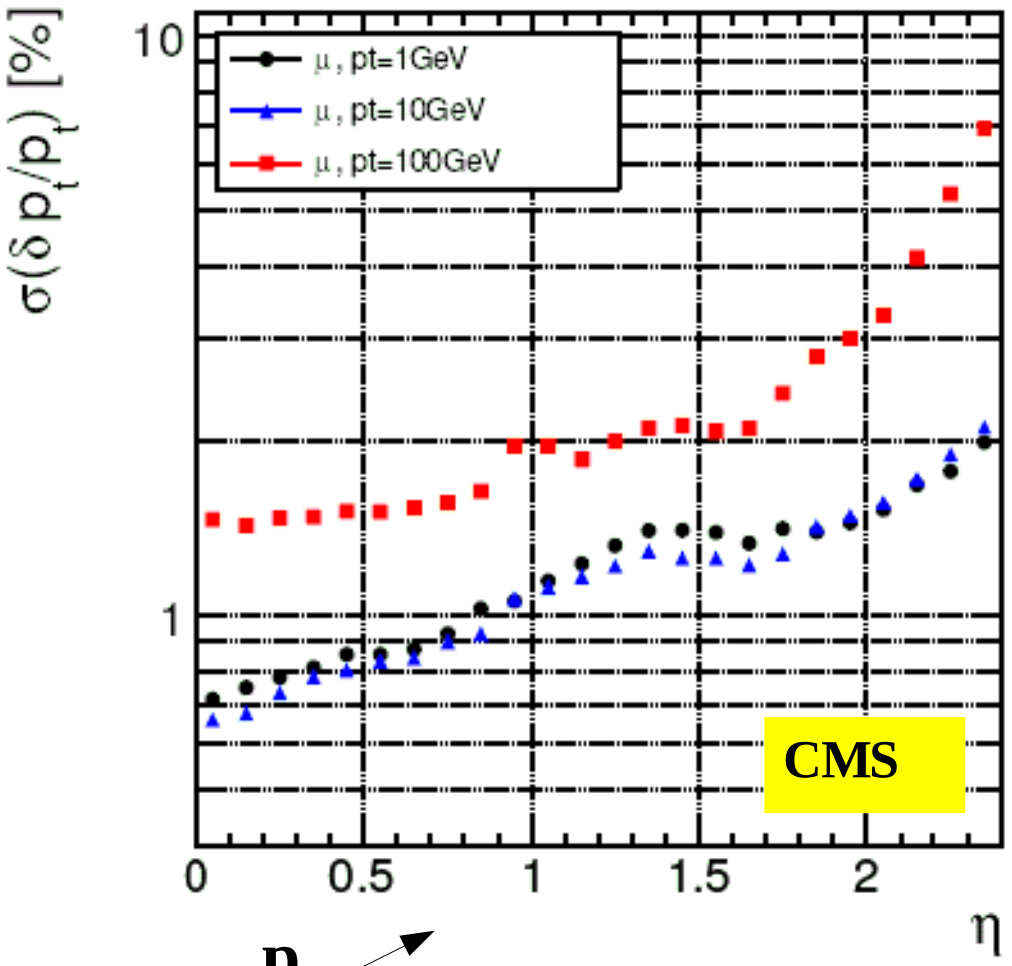
E.g. perigee parametrization [4]
Parameters at p.c.a. to a reference point (here: to beam line)

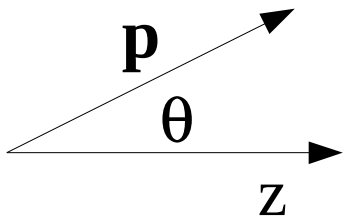


$\eta = -\ln(\tan(\theta/2))$

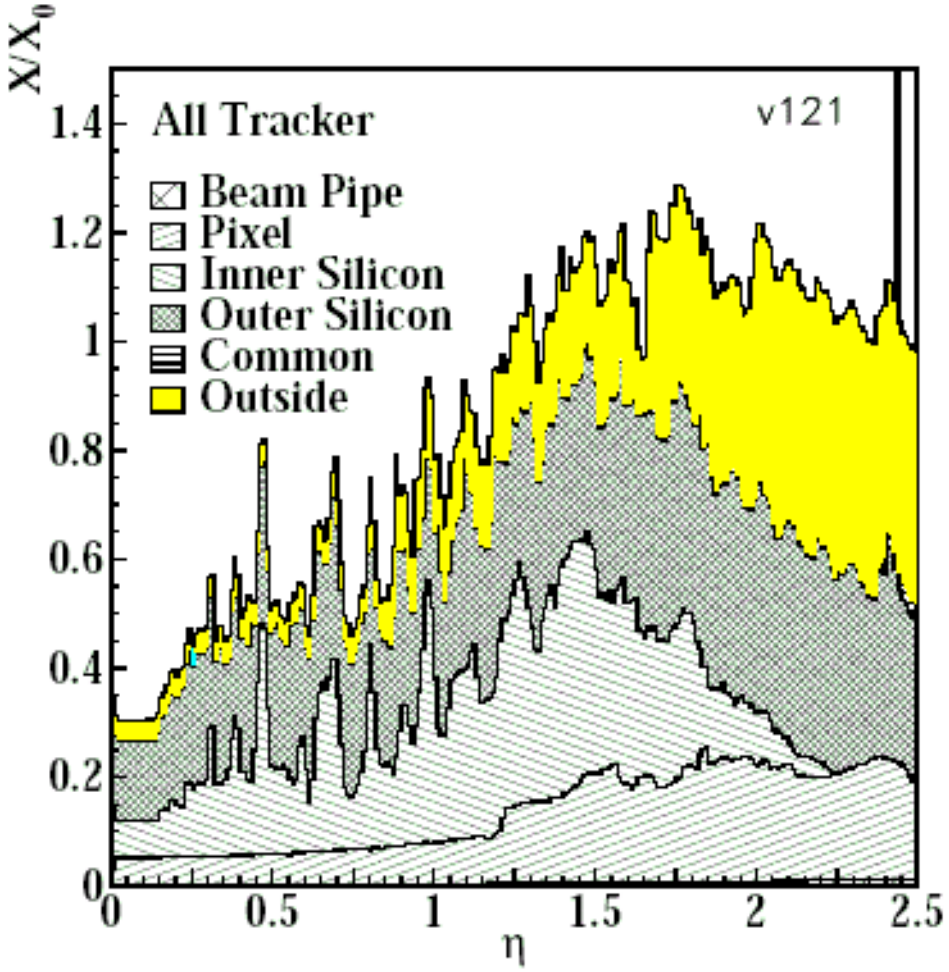


CMS momentum resolution

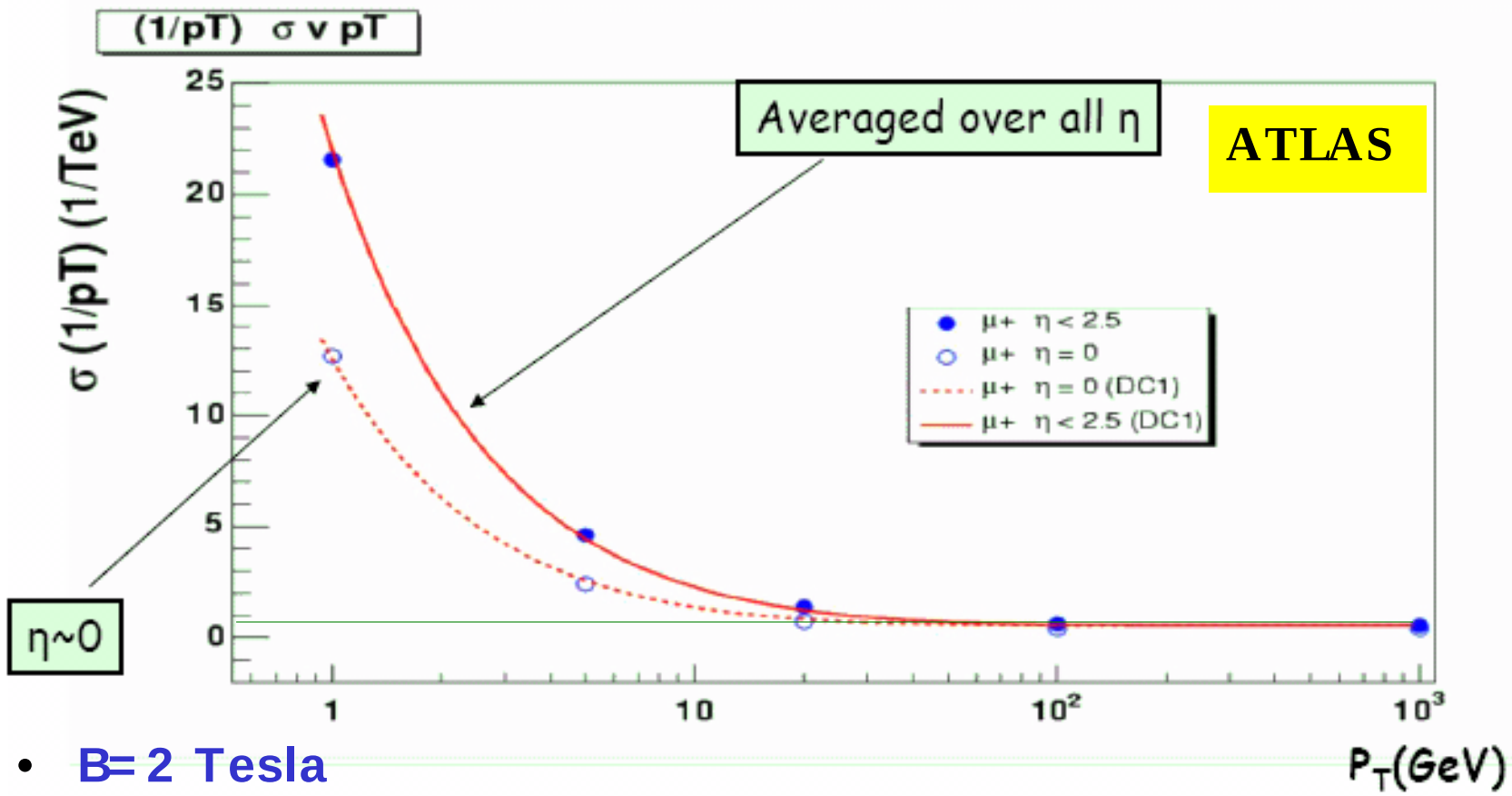




$$\eta = -\ln(\tan(\theta/2))$$

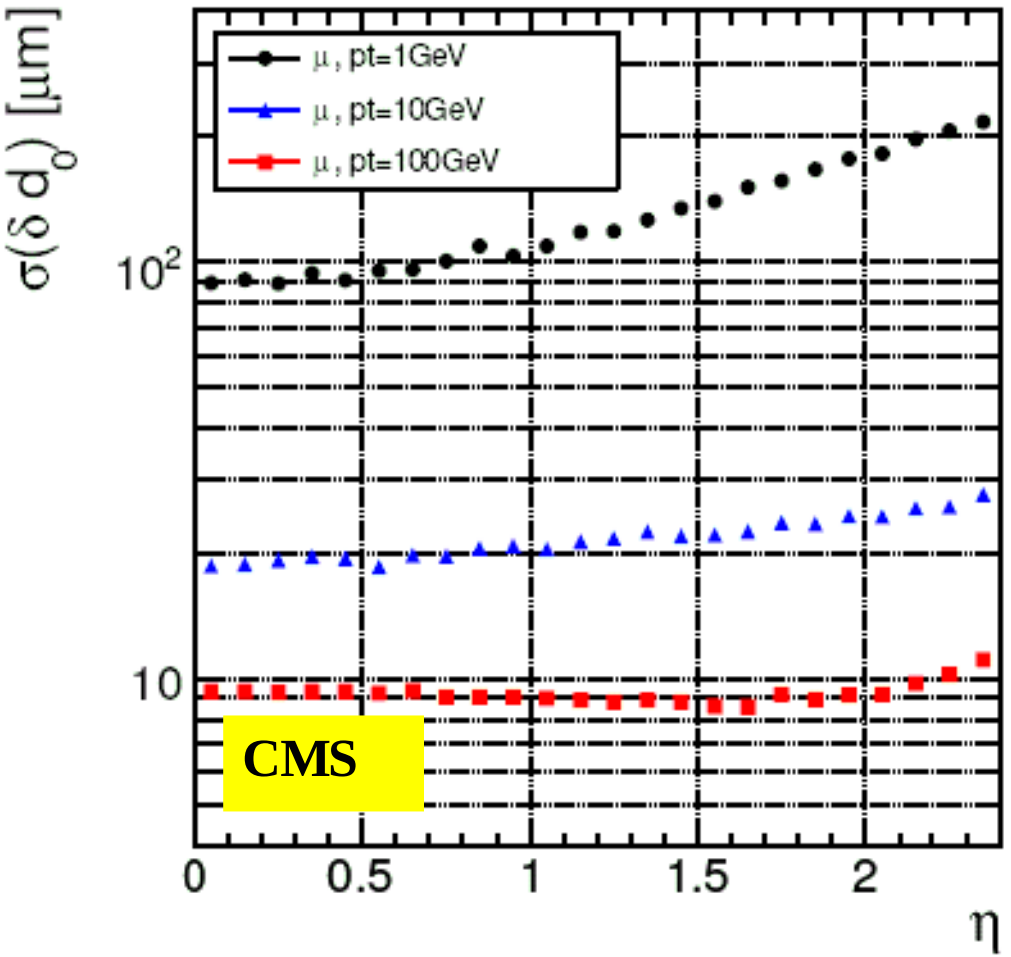


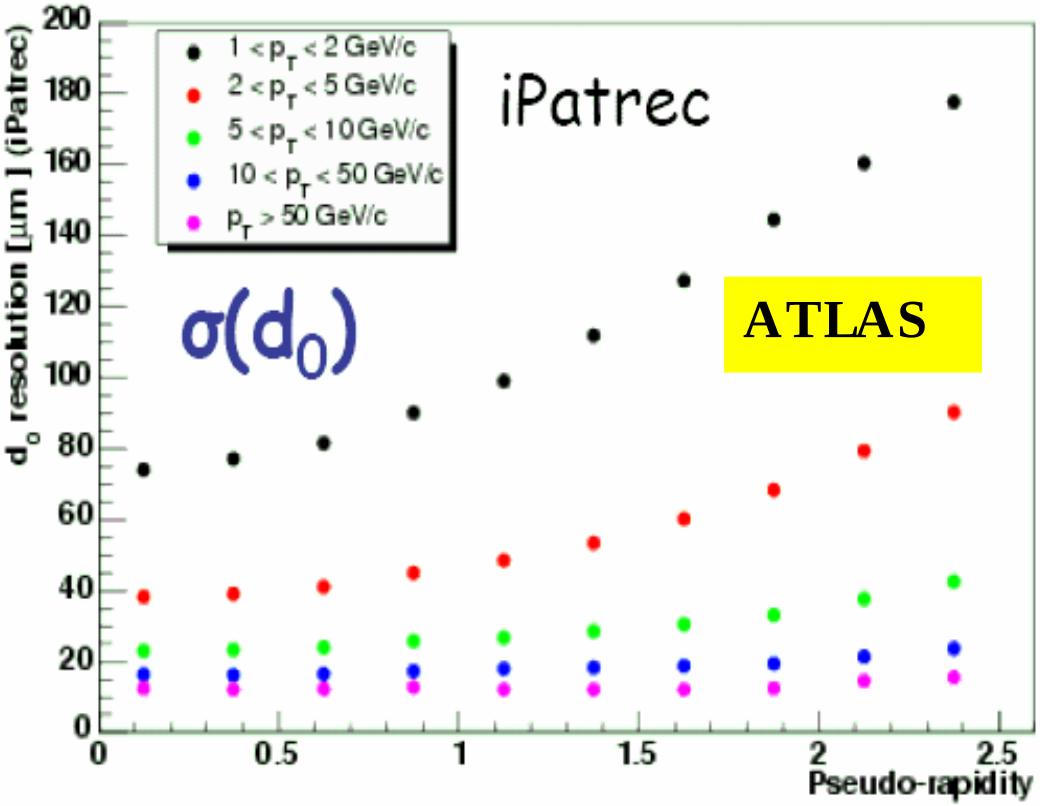
ATLAS momentum resolution



- **B= 2 Tesla**
- $\Delta p_T / p_T \sim 0.7\ p_T$ [TeV] in instrumental limit region
- $\Delta p_T / p_T = 7\%$ at $p_T = 100$ GeV; 1.3- 2.2% at $p_T = 1$ GeV
- Similar material thickness as CMS; decreased field for $\eta > 1.5$

Impact parameter resolutions





CDF: $\sigma(d_0)$~ 6- 7 μm (asymptotic) / 25 μm at p_T= 2 GeV

- Similar module resolution but L0 at radius = 2.1/ 2.5 cm

A few remarks

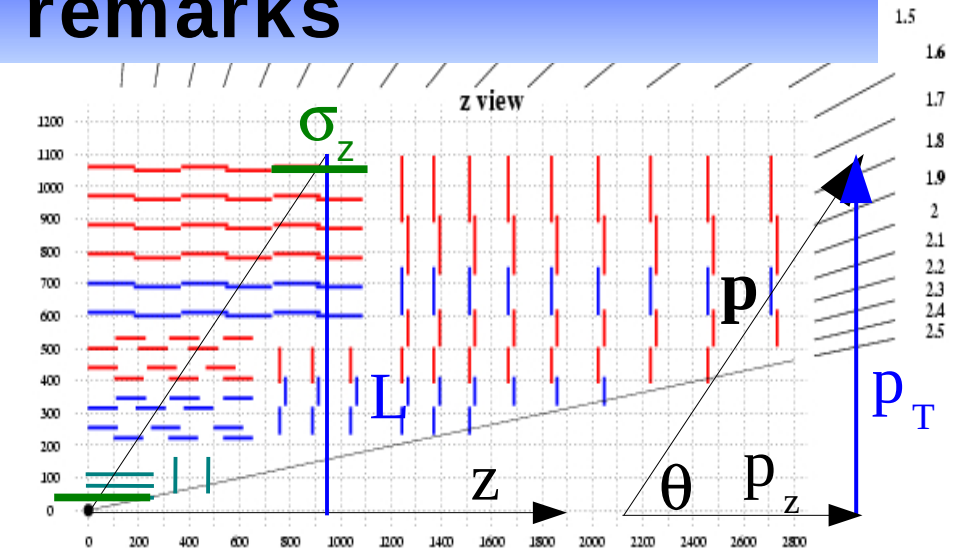
- Momentum P = pT / sin θ
- Contribution from error on θ:

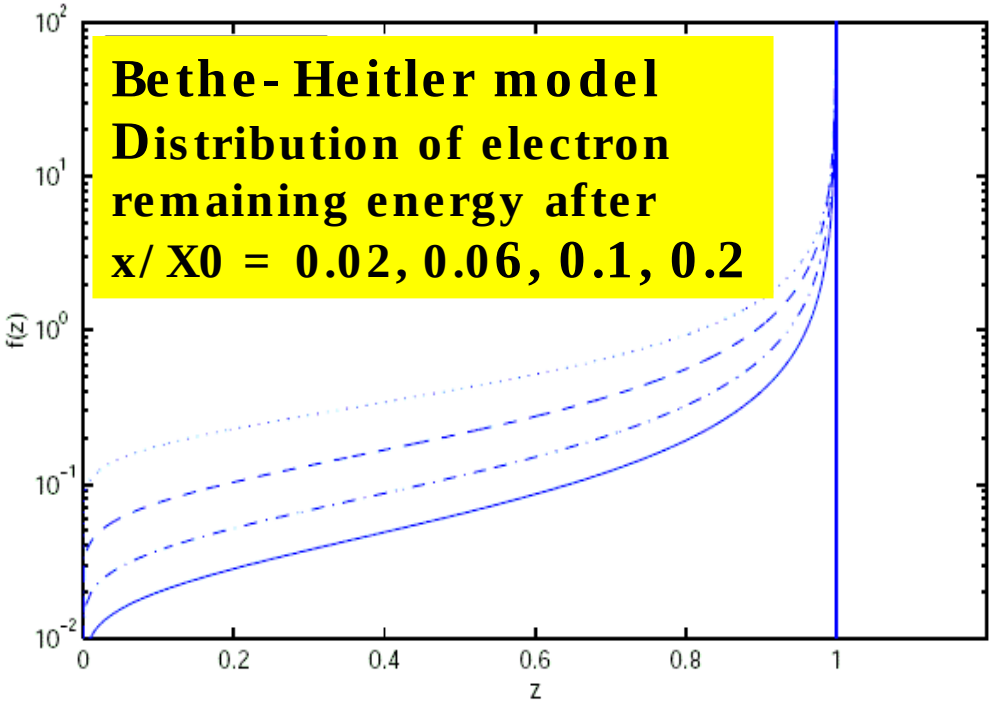
$$\left(\frac{\Delta p}{p}\right)_\theta = \frac{\cos\theta}{\sin\theta}\Delta\theta$$

$$\Delta\theta \approx O\left(\sigma_z / L\right) \approx \frac{O(1\,mm)}{1\,m} = 0.001$$

  - Negligible

- Energy loss
  - Bethe-Bloch model; Minimum-Ionizing Particle (MIP):
    - $-dE/dx \approx 2$ MeV $g^{-1}cm^2$
    - 1 cm Cu: ≈ 20 MeV
  - Electrons: Bethe-Heitler model
    - Much larger average loss by bremsstrahlung
    - Very large fluctuations





References

- [1] W.Blum, L.Rolandi, “Particle detection with Drift Chambers”, Springer-Verlag, 1993
- [2] R.L.Gluckstern, Nucl. Instr. and Meth. 24 (1963) 381
- [3] Particle Data Group reviews
- [4] P.Billoir, S.Qian, Nucl. Instr. and Meth. A311 (1992) 139
- [5] ATLAS, CMS Technical Design Reports
- [6] Hadron collider physics proceedings (update on TDR)