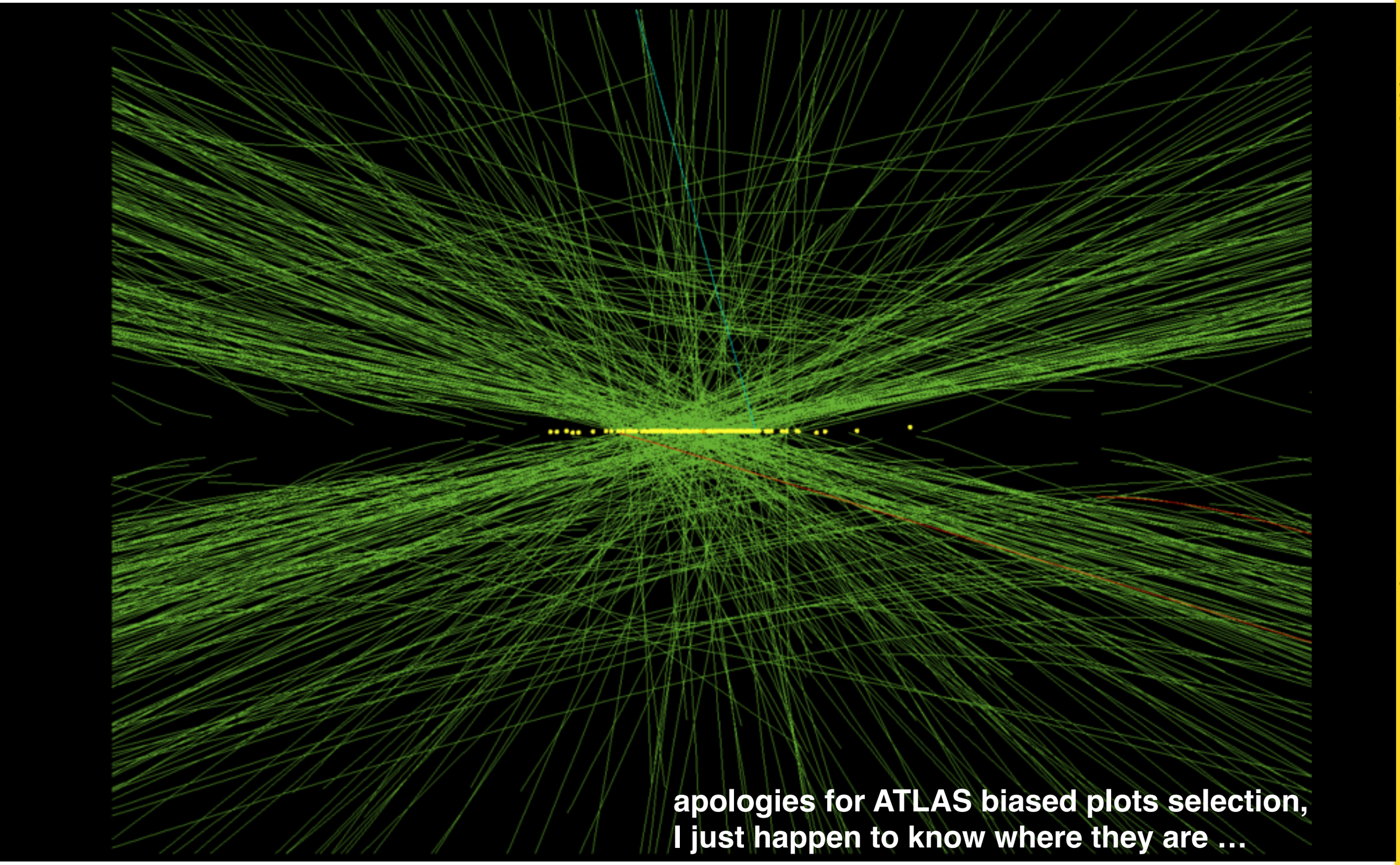
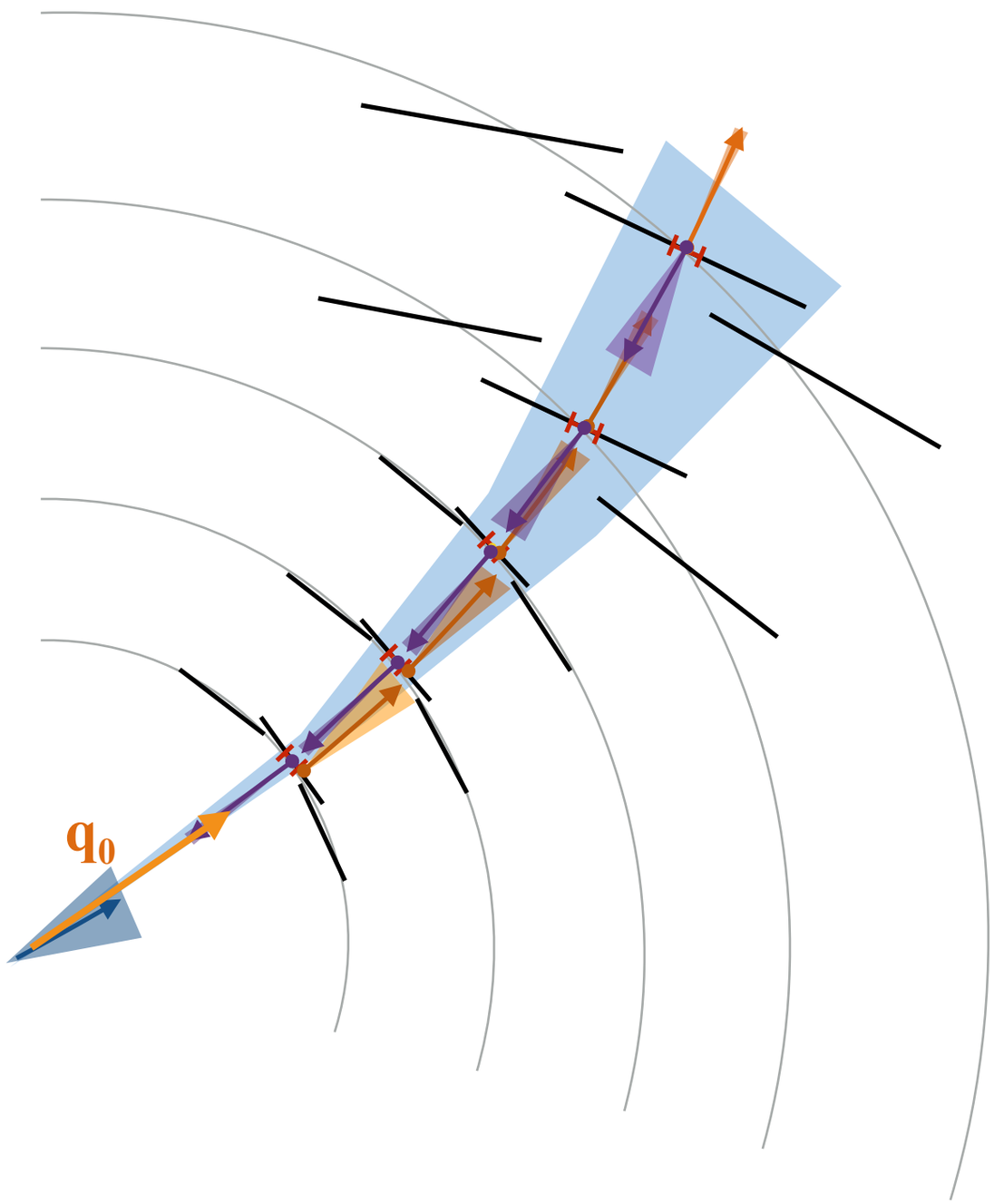
Part 3 - Vertex reconstruction, analysis & reality



http://cds.cern.ch/record/1479324/files/198609-56-3565522d.png?subformat=icon-1440

Recap of yesterday

- We've found tracks
  - global and local pattern recognition algorithms
- We've fitted those tracks
  - least squares estimator fit,
    e.g. global χ^2 minimazation, Kalman filter
- Discussed the fit output
- Touched upon "ghost tracks"
  - we will hear a bit more about that though
- Dedicated electron fitting



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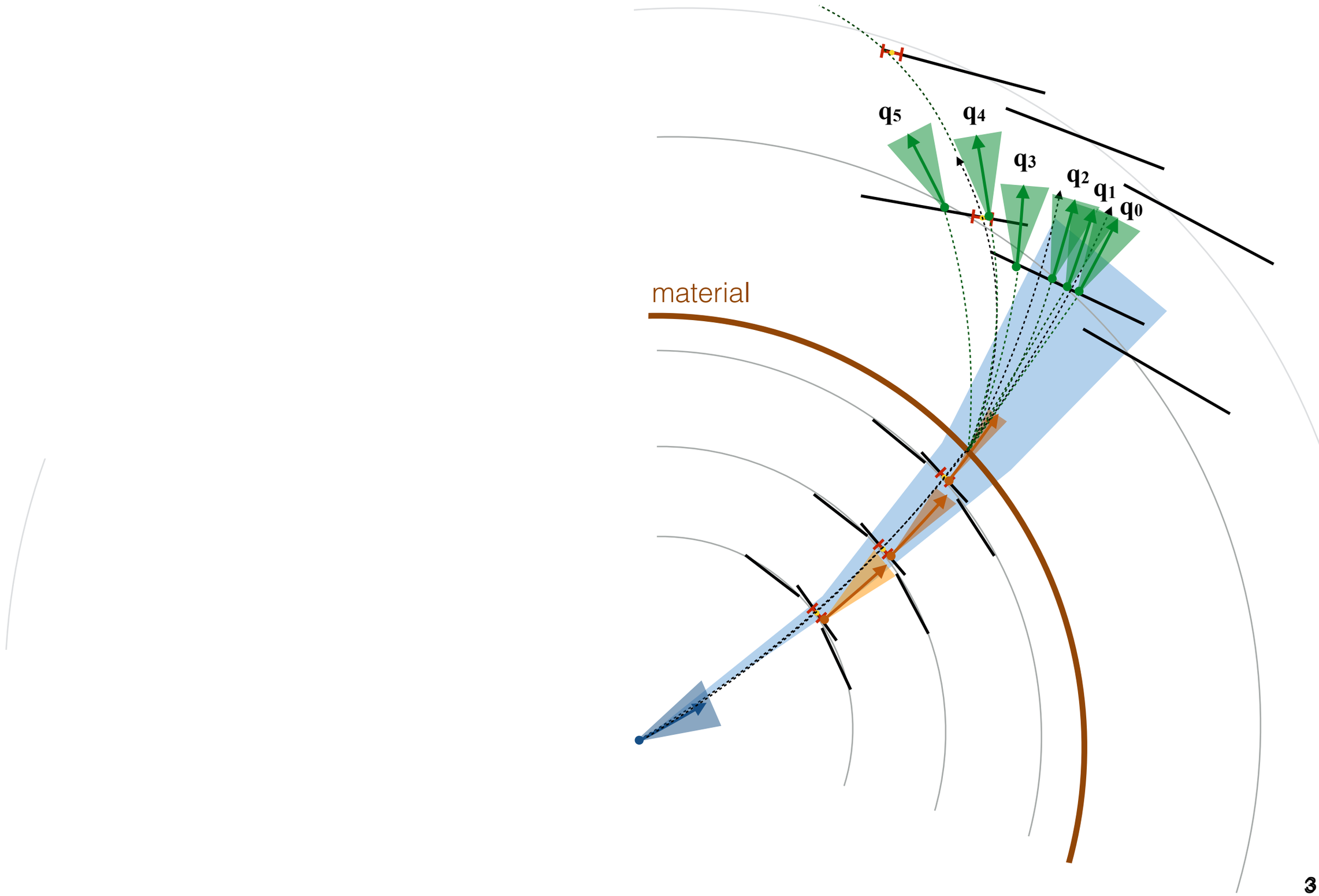
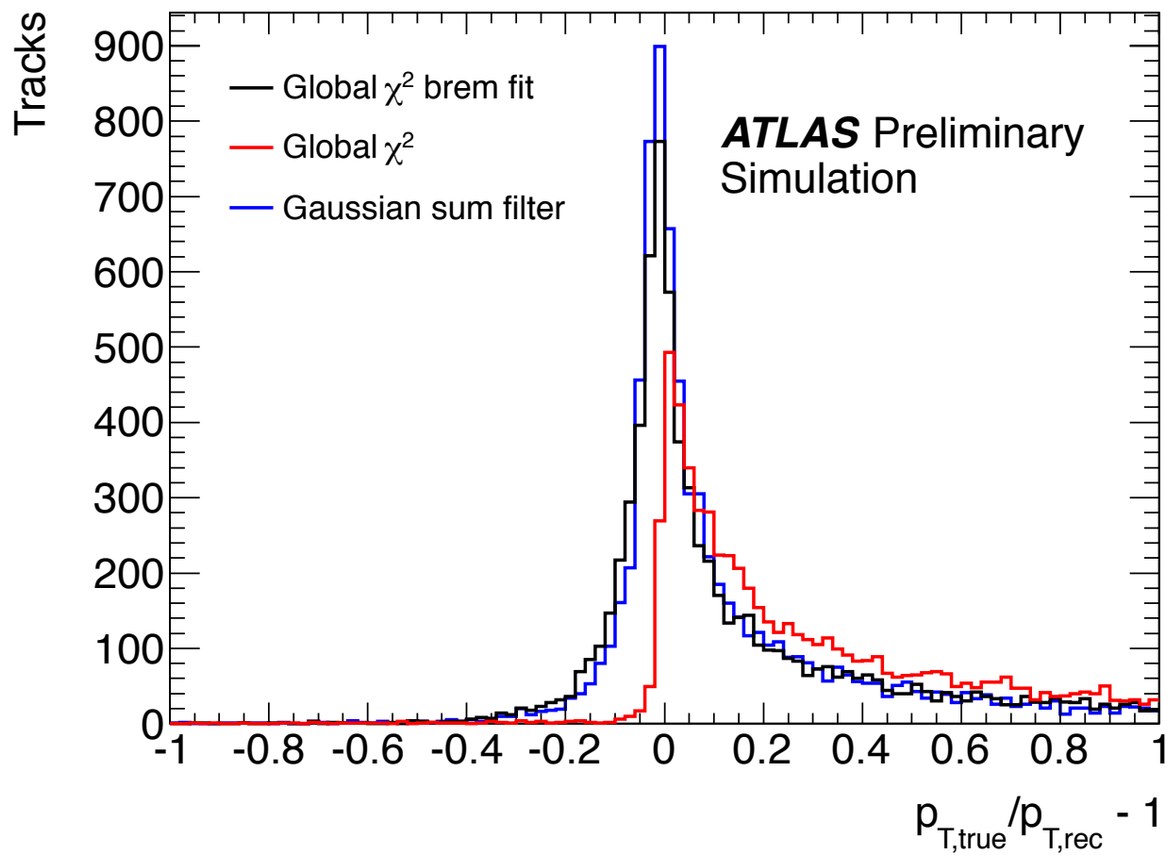
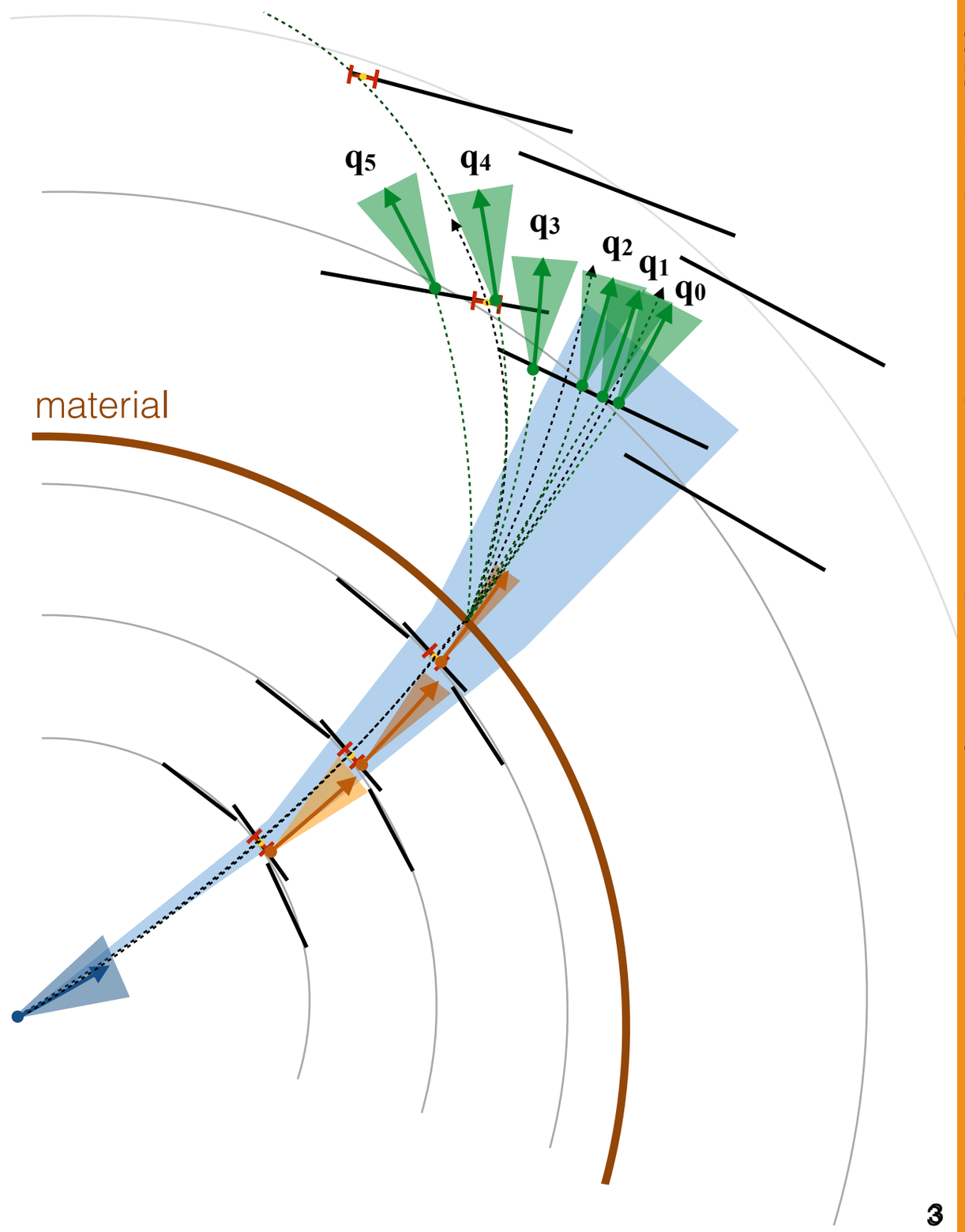


Dedicated electron fitting

- It works !





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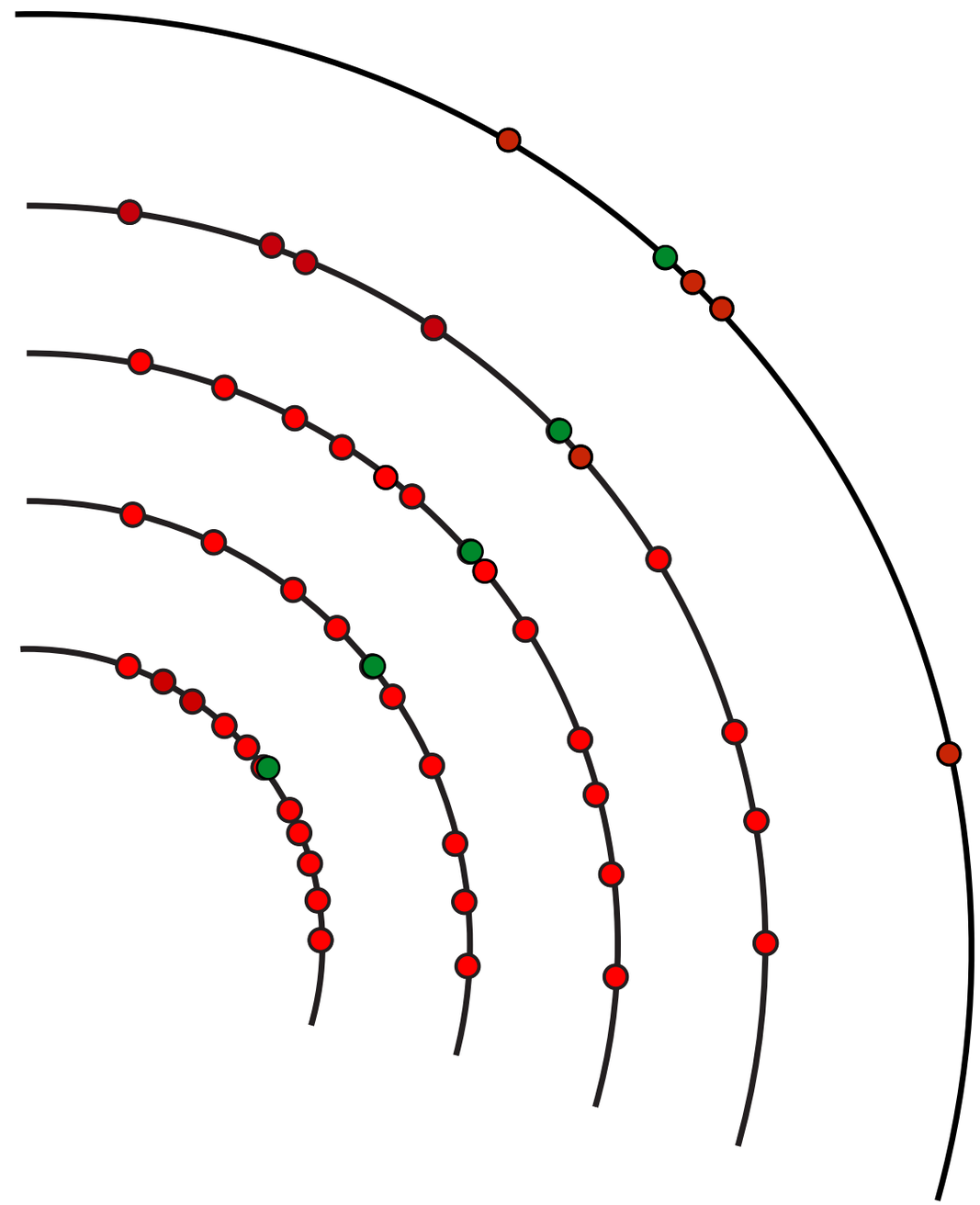

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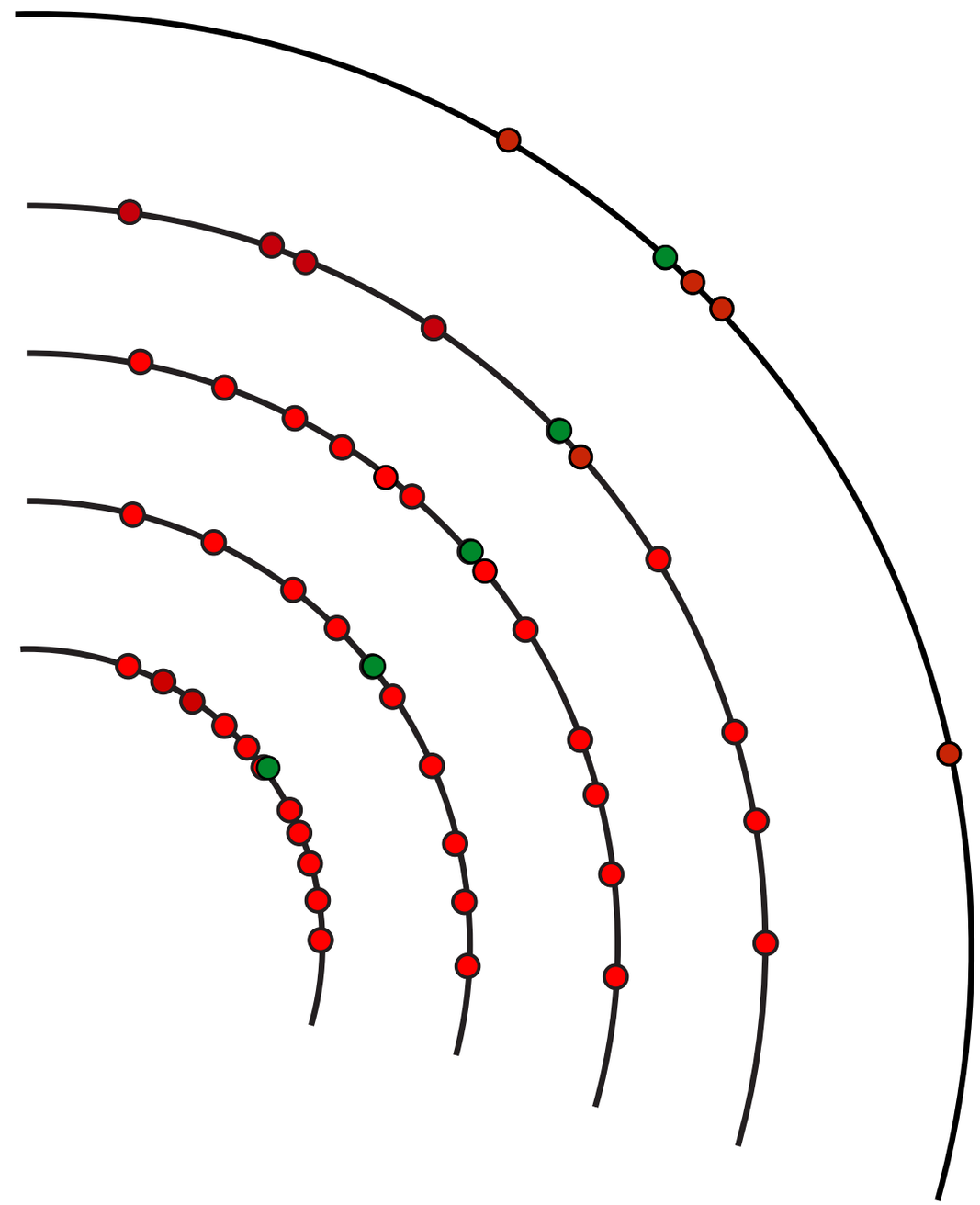

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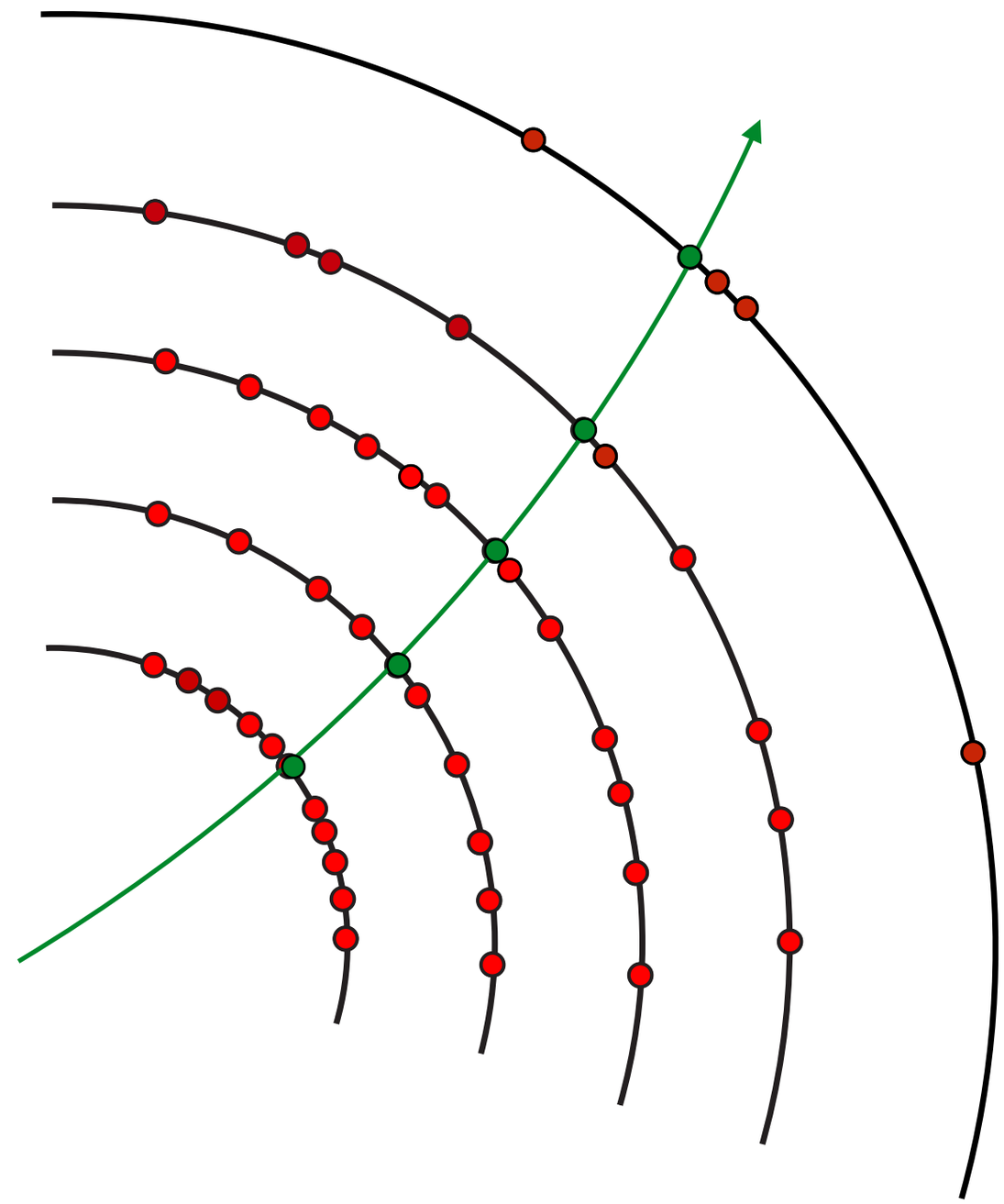

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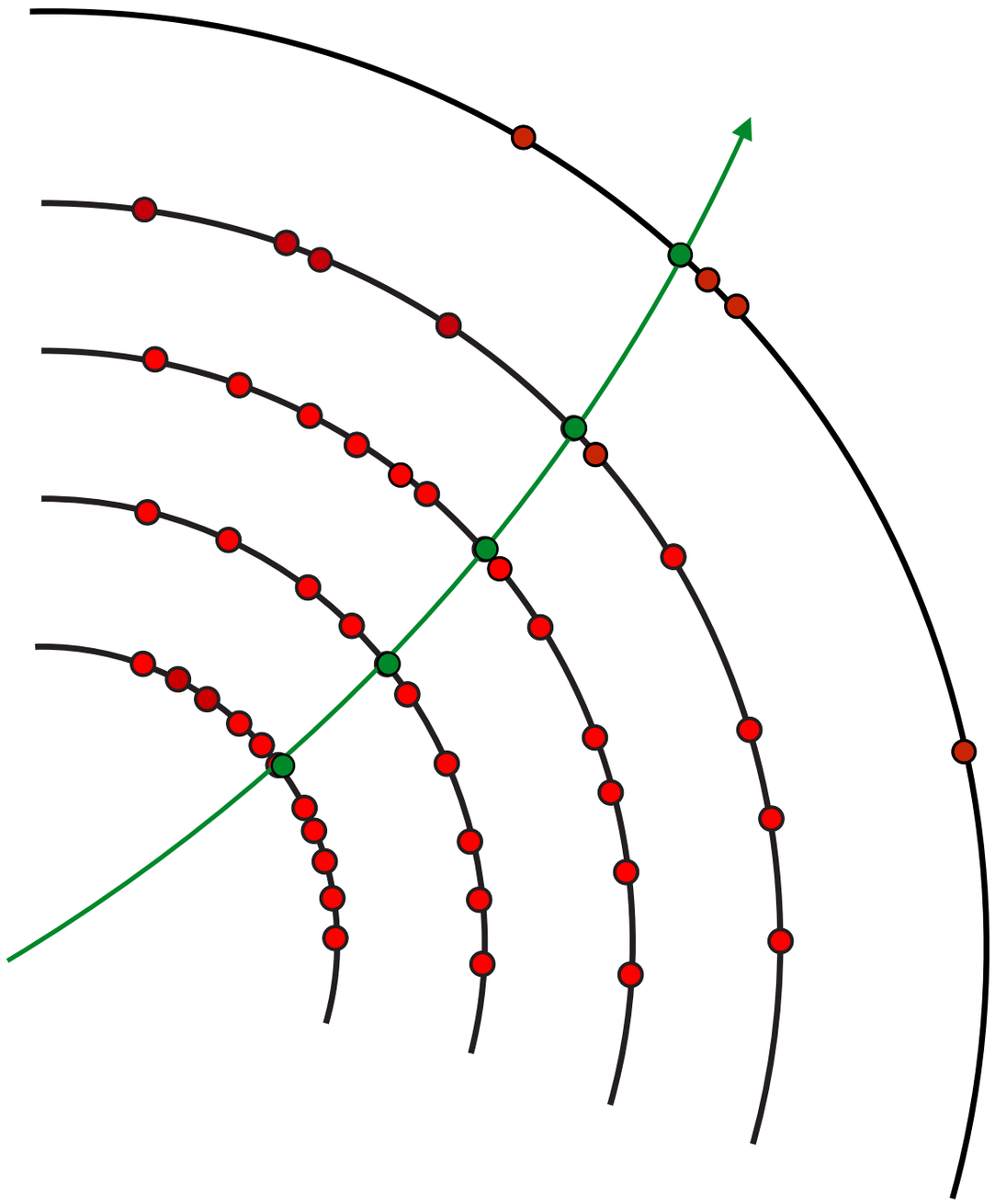

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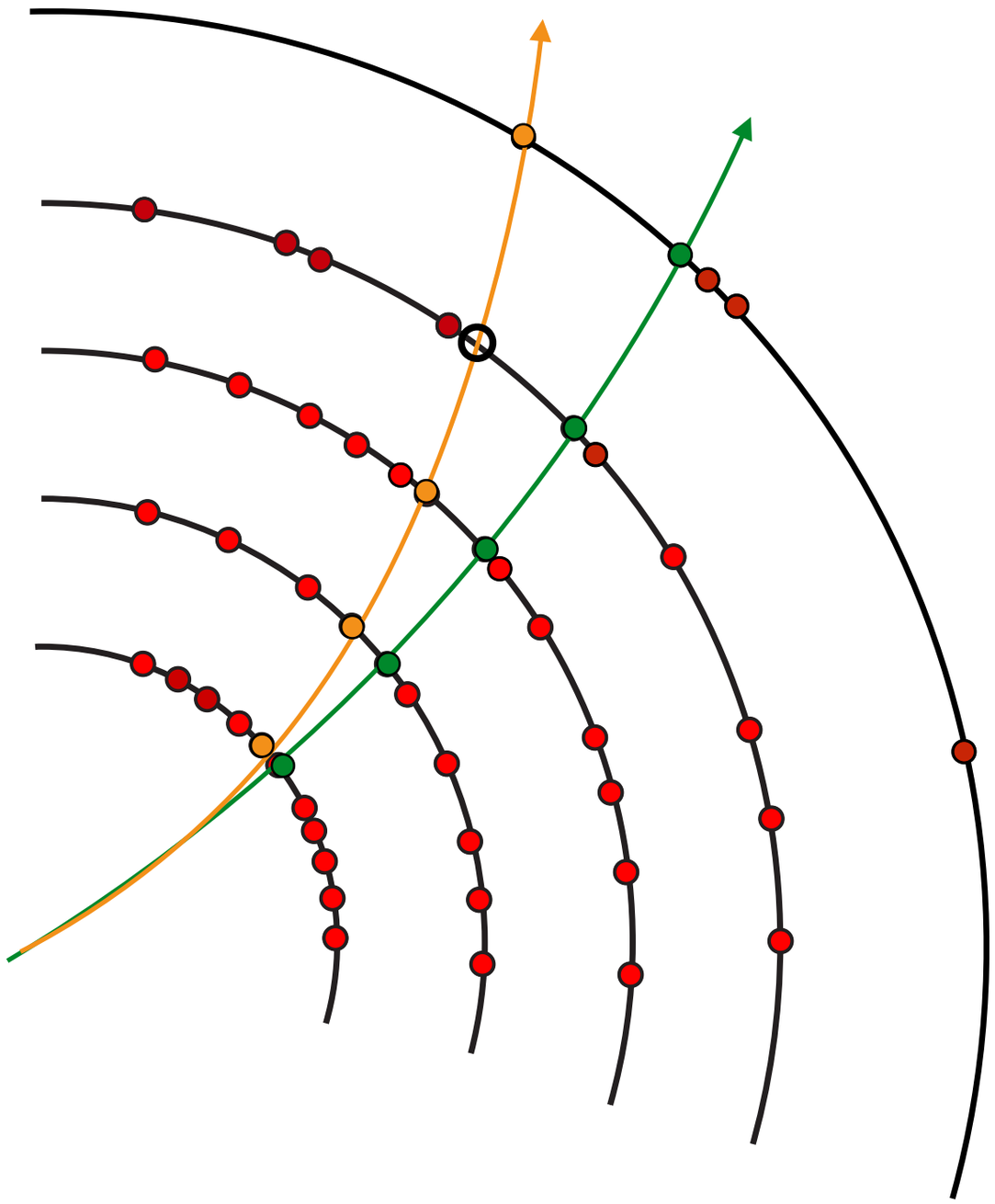

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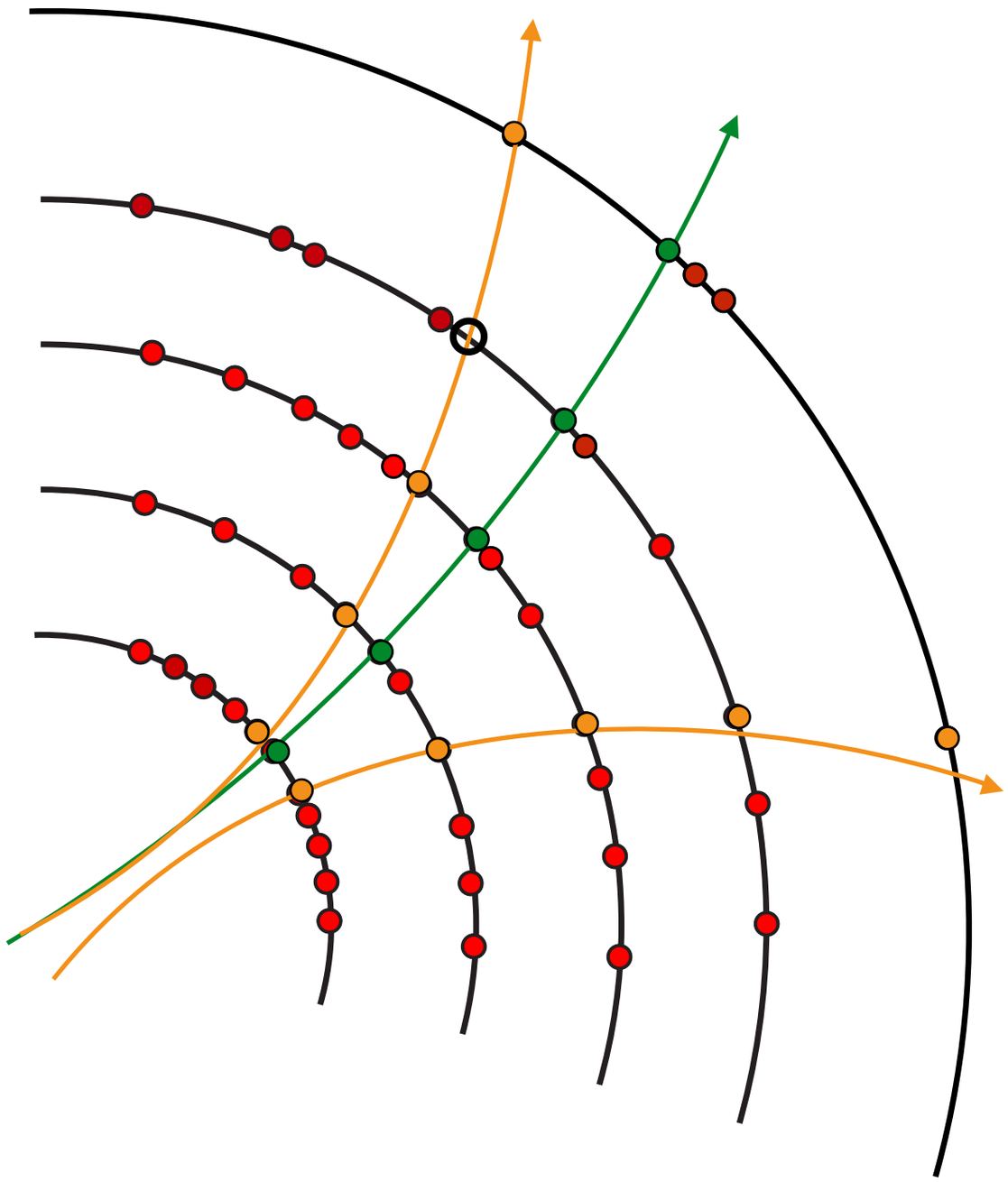

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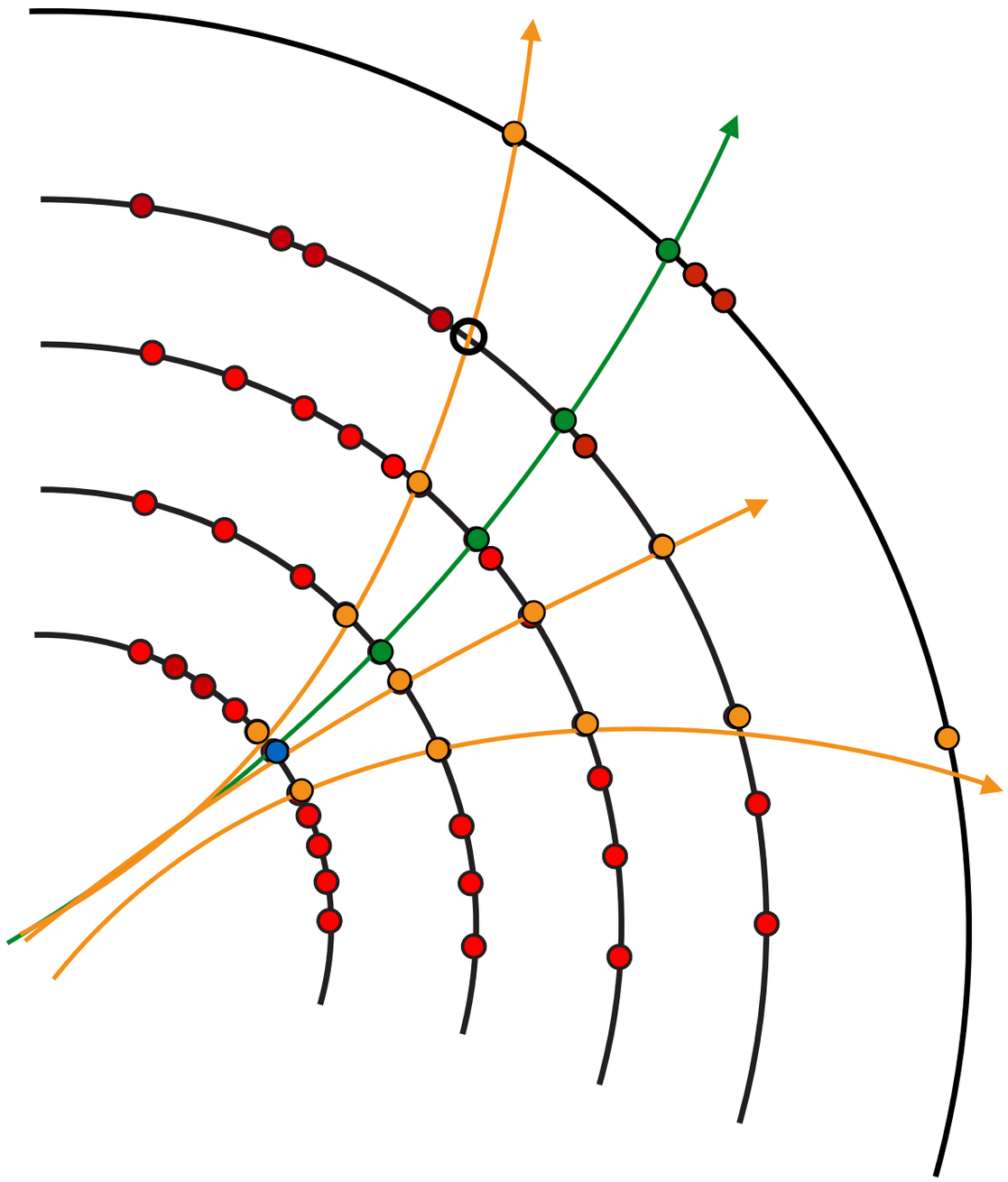

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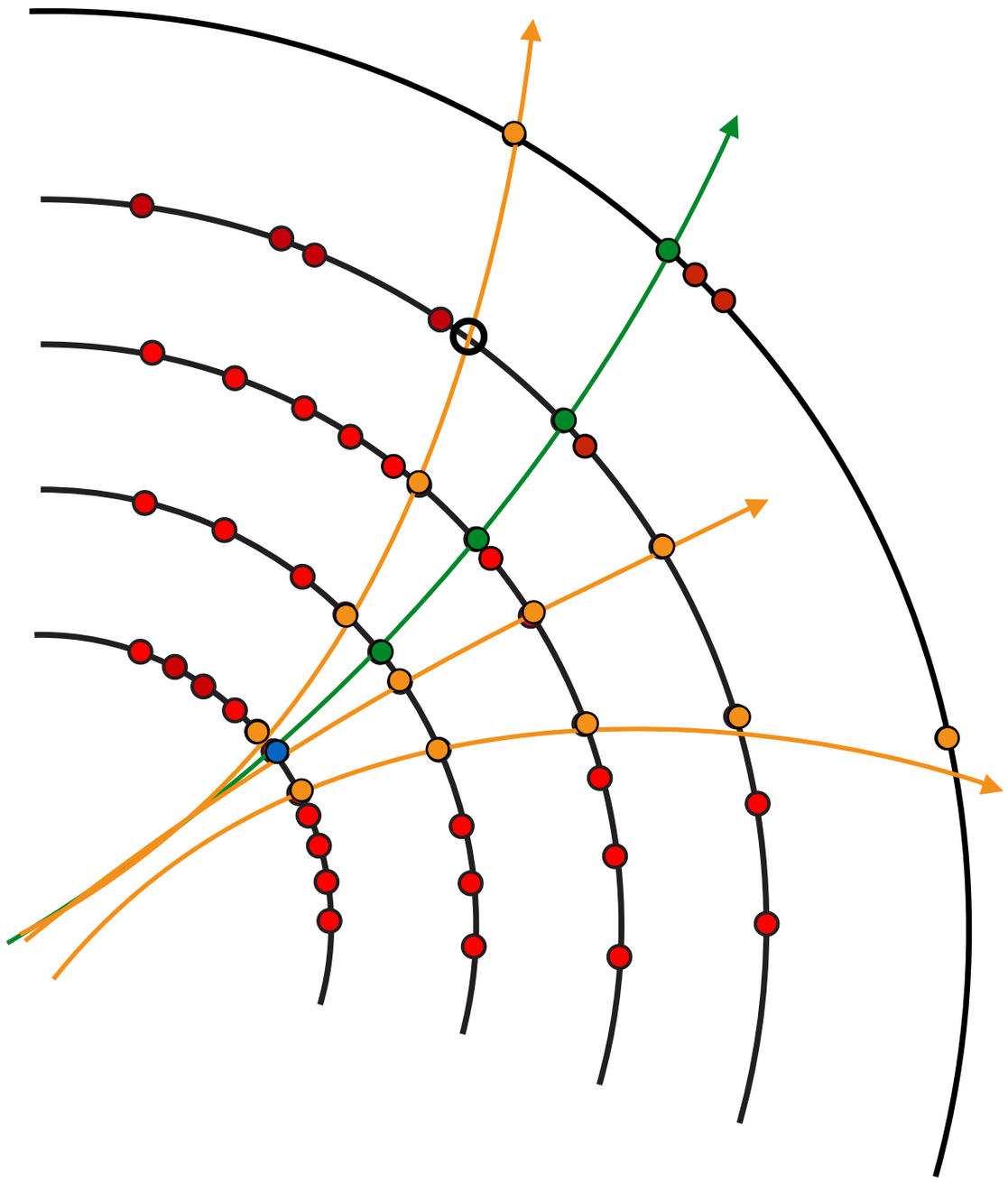

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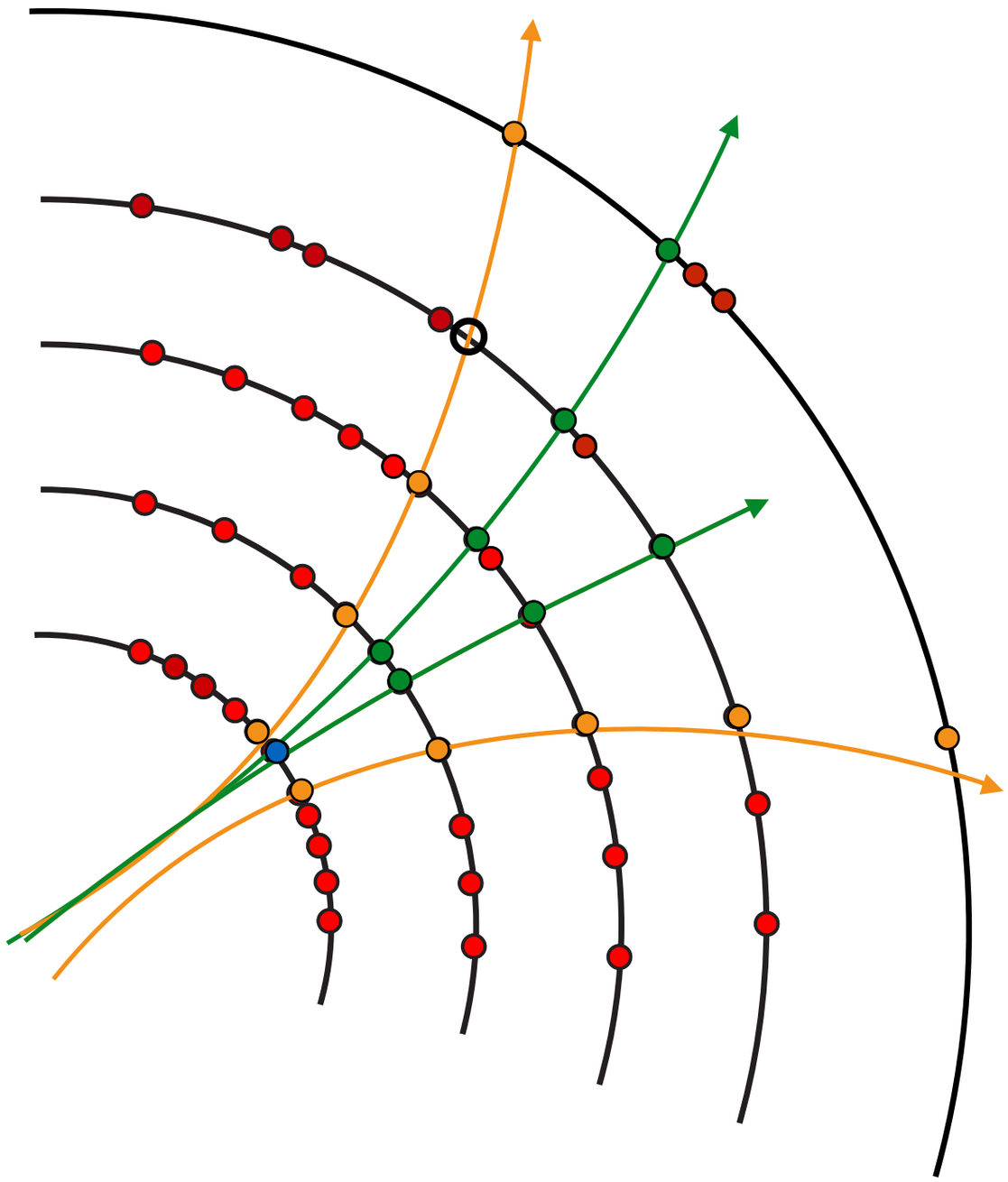

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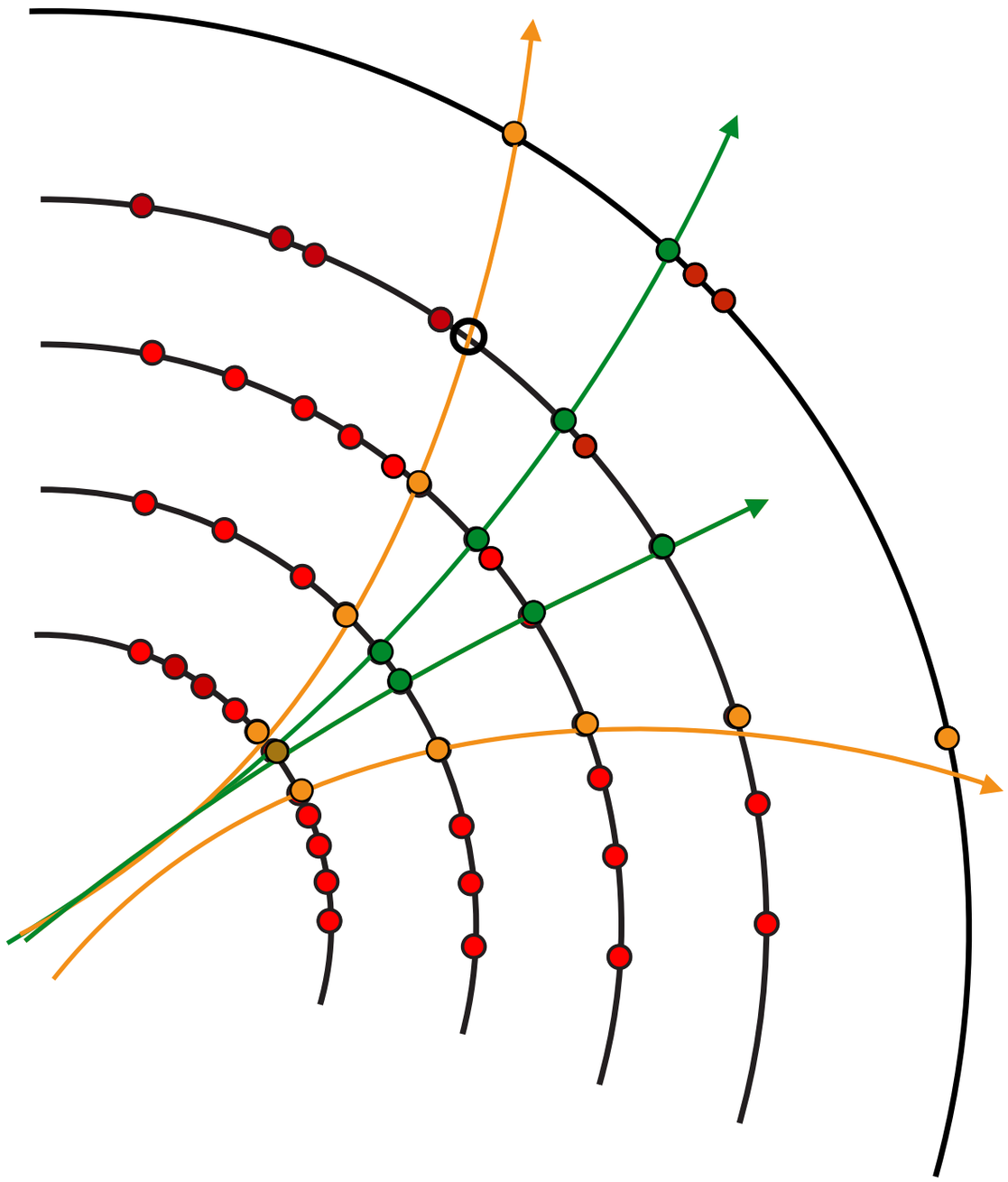

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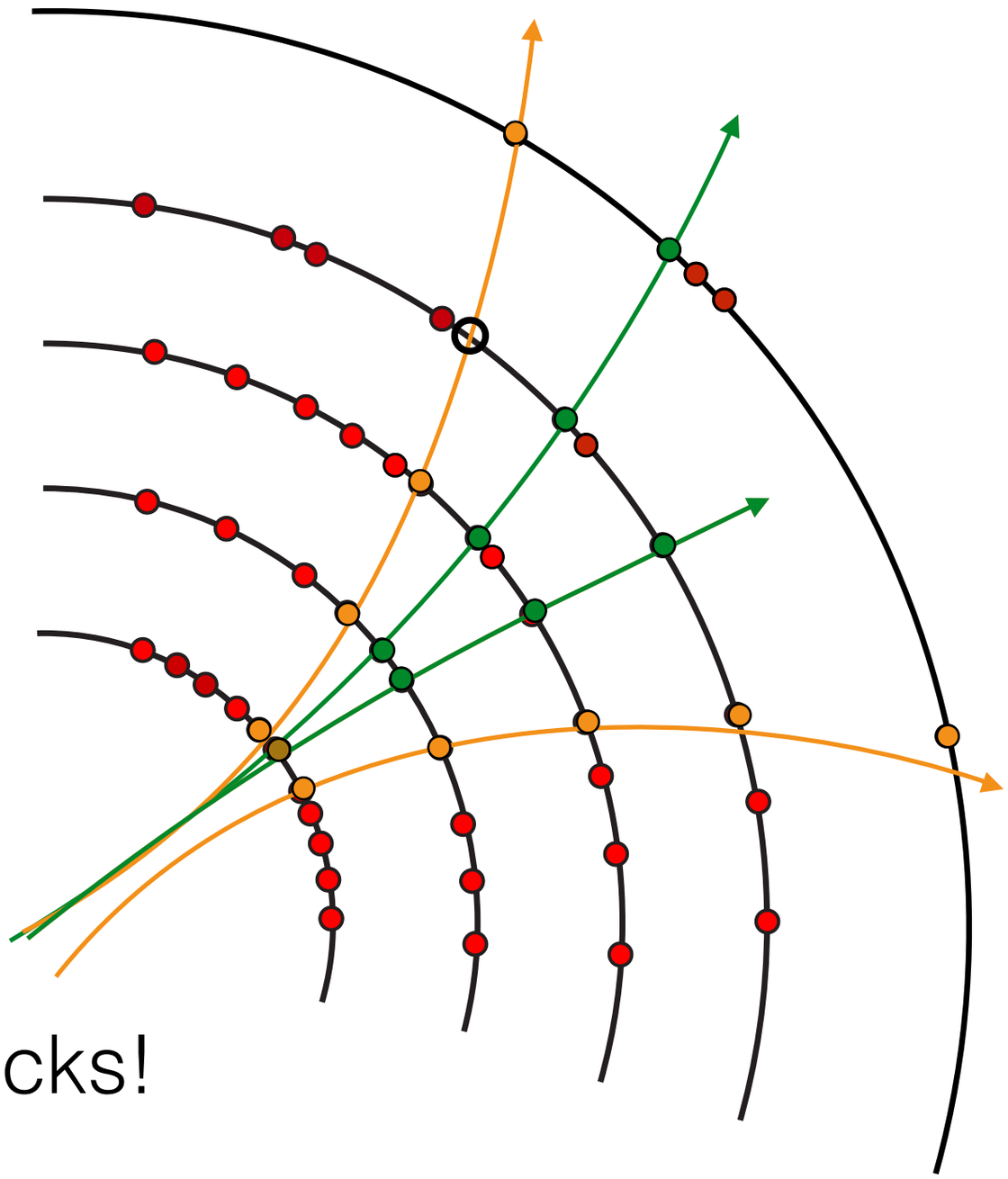

give scores and rank the tracks!

Vertex reconstruction

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- Similar problem to track reconstruction
  - consists of vertex finding and vertex fitting, (primary) input are tracks

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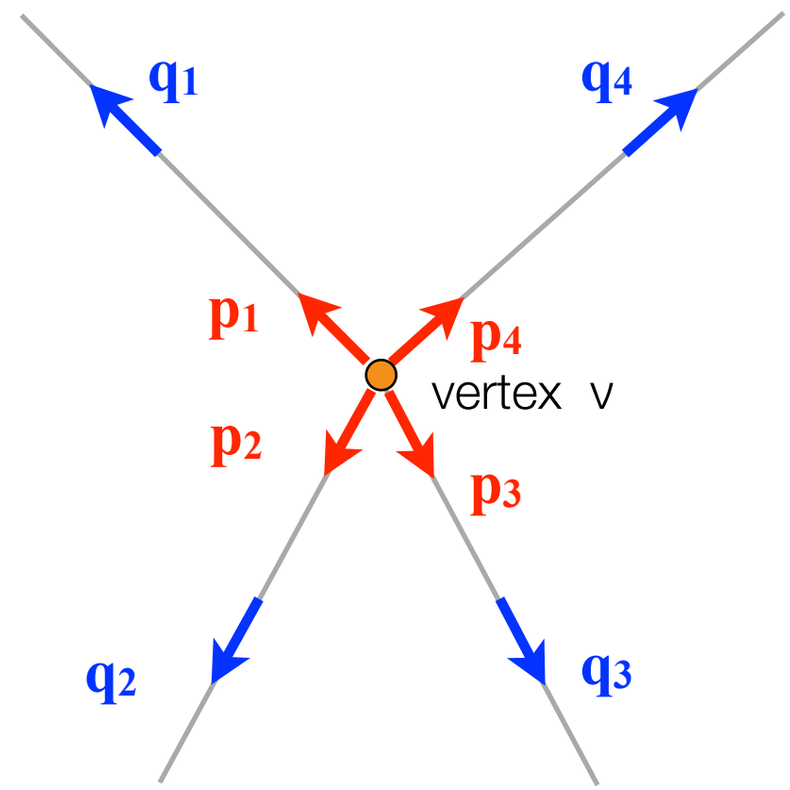
with: h_i = dependency of track parameters on vertex and parameters at vertex

ε_i = error of q_i

Jacobians: $A_i = \dfrac{\partial h_i(v, p_i)}{\partial v}$ $\quad B_i = \dfrac{\partial h_i(v, p_i)}{\partial p_i}$

$h_i = f \circ \tilde{q}(v, p_i)$ with: $v = (v_x, v_y, v_z)$, $p_i = (\theta_i, \phi_i, Q_i / P_i)$



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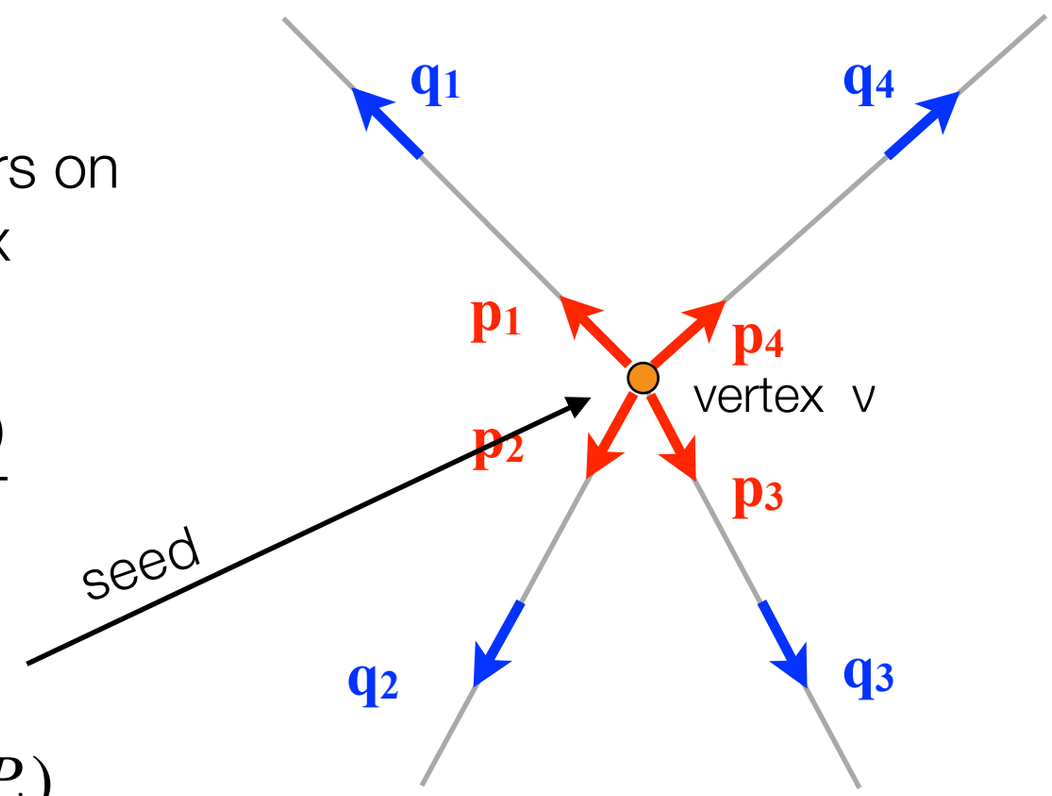


Vertex fitting

- And again, you can do a straight forward global χ^2 minimisation

$$\chi^2 = \sum_i \Delta q_i^T G_i \Delta q_i \quad \text{with:} \quad \Delta q_i = q_i - h_i(v, p_i)$$

$$V_i = G_i^{-1} \quad \text{covariance of the measured } q_i$$

linearize the problem: $v \rightarrow v_0 + \delta v$ and $p_i \rightarrow p_{i,0} + \delta p_i$

$$h_i(v, p_i) \cong h_i(v_0, p_{i,0}) + A_i \delta v + B_i \delta p_i \quad \text{+ higher terms}$$

this yields:

$$\chi^2 = \sum_i \left(h_i(v_0, p_{i,0}) + A_i \delta v + B_i \delta p_i \right)^T G_i \left(h_i(v_0, p_{i,0}) + A_i \delta v + B_i \delta p_i \right)$$

minimizing the linearized χ^2 gives the following set of equations:

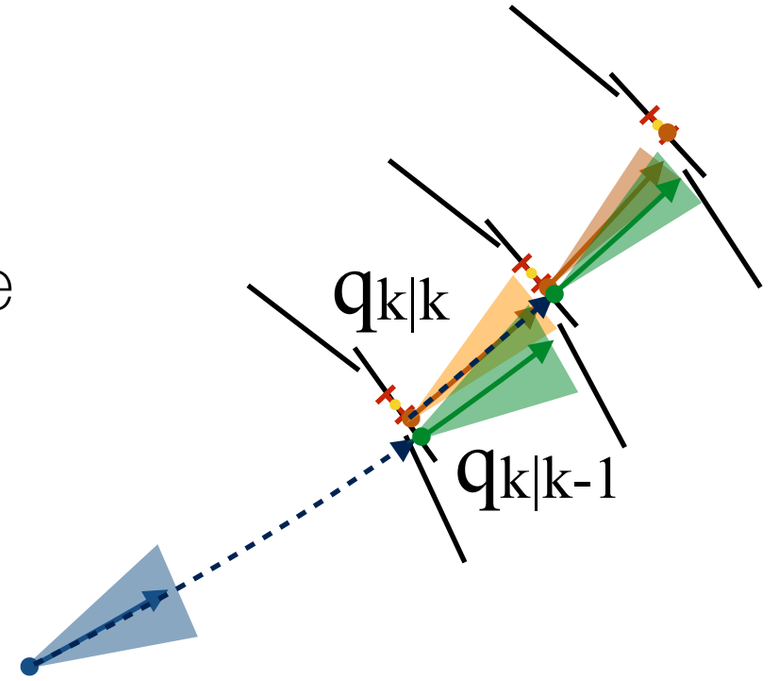
$$\frac{\partial \chi^2}{\partial v} = 0 \quad \Rightarrow \quad \left(\sum_i A_i^T G_i A_i \right) \cdot \delta v + \sum_i A_i^T G_i B_i \cdot \delta p_i = \sum_i A_i^T G_i \cdot \Delta q_{i,0}$$

$$\frac{\partial \chi^2}{\partial p_i} = 0 \quad \Rightarrow \quad B_i^T G_i A_i \cdot \delta v + B_i^T G_i B_i \cdot \delta p_i = B_i^T G_i \cdot \Delta q_{i,0}$$

with: $\Delta q_{i,0} = q_i - h_i(v_0, p_{i,0})$

Vertex fitting

- Or, you apply a Kalman filter technique

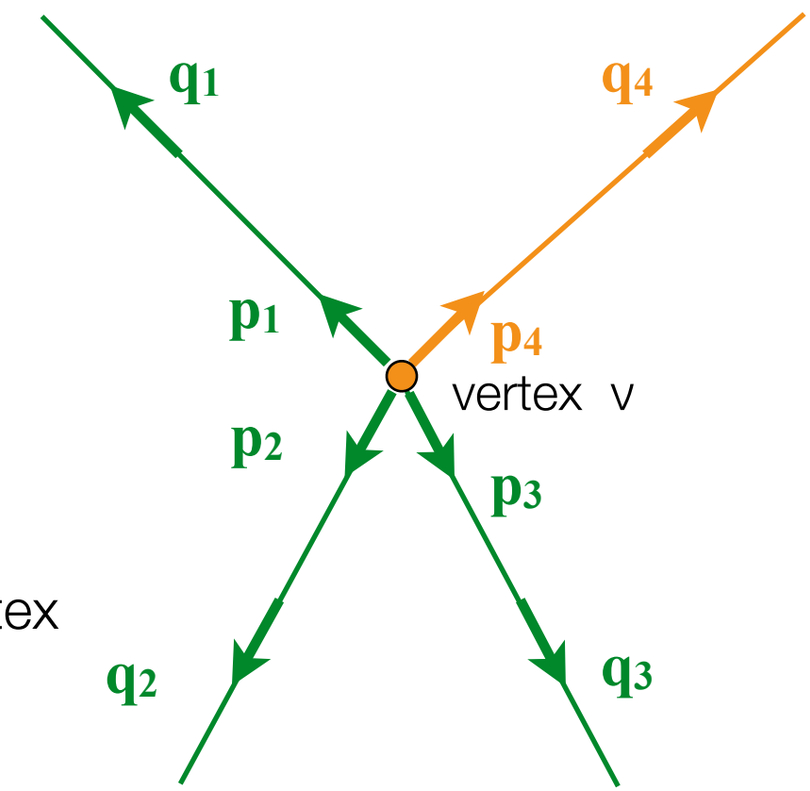


$$\delta v_i = C_i^{-1} \cdot \left[C_{i-1} \delta v_{i-1} + A_i^T G_i^B \cdot \Delta q_{i,i-1} \right]$$

$$C_i = \left(C_{i-1}^{-1} + A_i^T G_i^B A_i \right)^{-1}$$

$$\delta p_{i,i} = W_i B_i^T G_i \cdot \left(\Delta q_{i,i-1} - A_i \delta v_i \right)$$

$$D_i = W_i + W_i B_i^T G_i A_i C_i A_i^T G_i B_i W_i$$



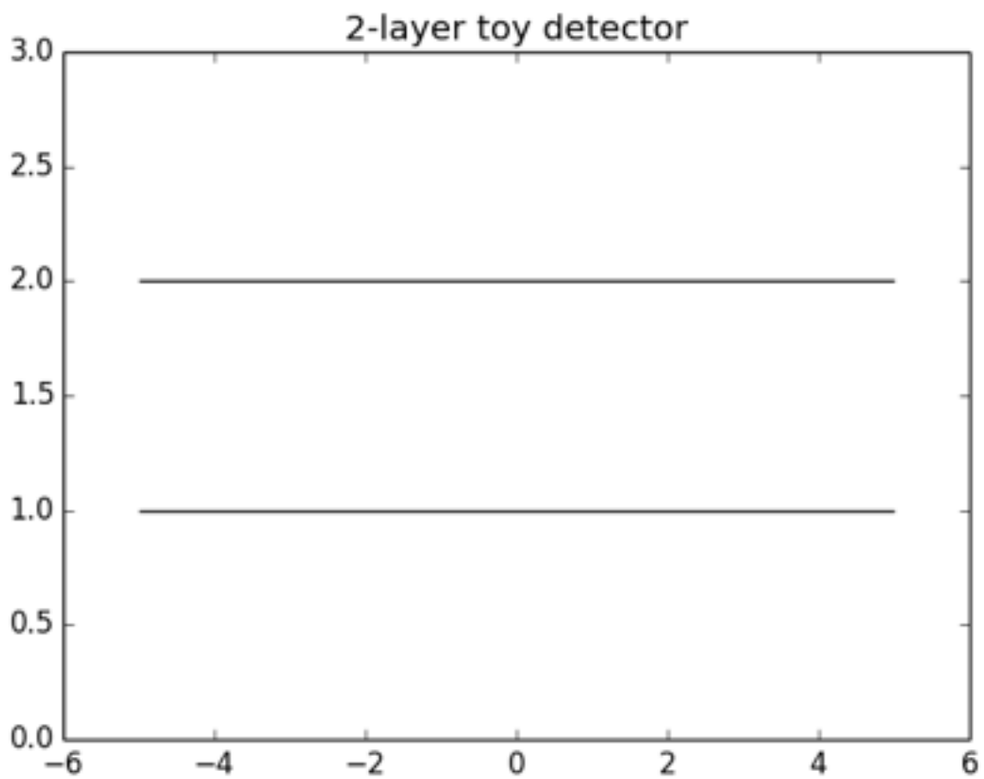
and the smoother becoming the re-evaluation of the parameters $q_{i,n}$ depending on the fitted vertex after inclusion of n tracks

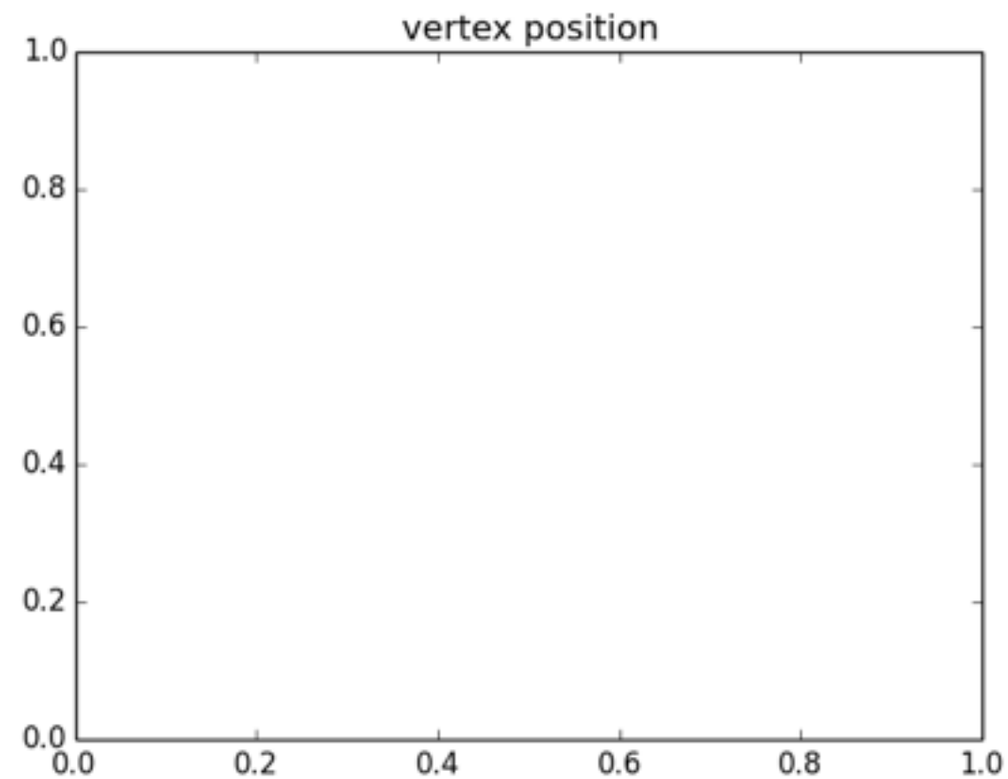
$$q_{i,n} = h_i(v_0 + \delta v_n, p_{i,0} + \delta p_{i,n})$$

with: $\mathrm{cov}(q_{i,n}) = B_i W_i B_i^T + V_i^B G_i A_i C_n A_i^T G_i V_i^B$ and $V_i^B = V_i - B_i W_i B_i^T$

MC Toy: vertex seed finding

- What about the initial seed ?



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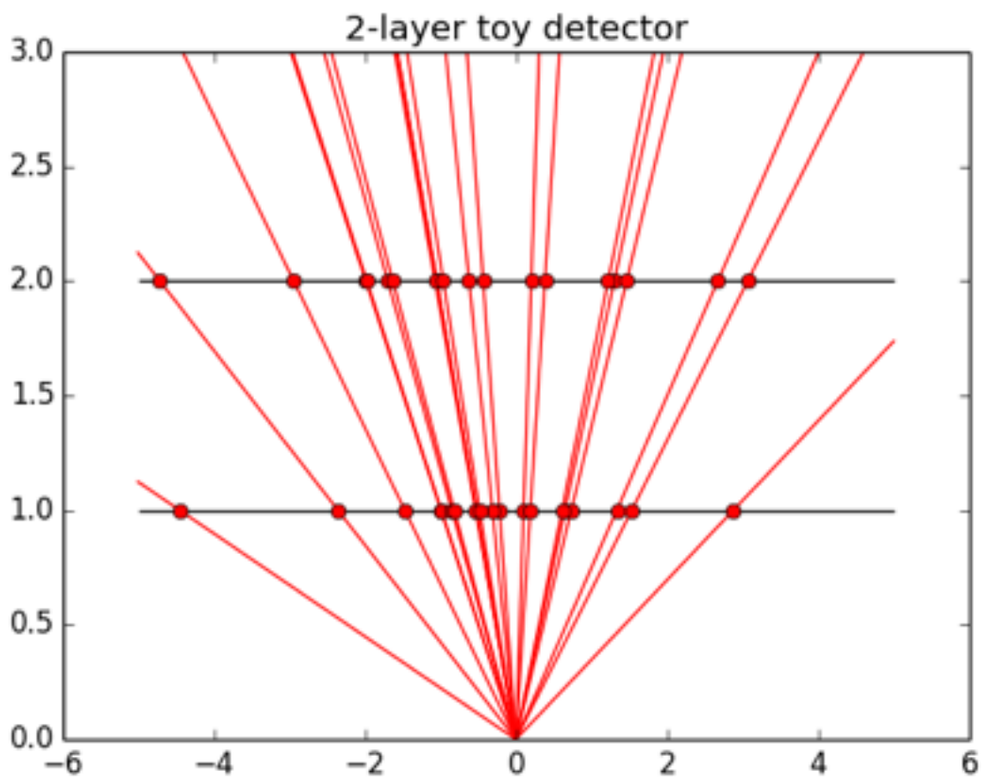

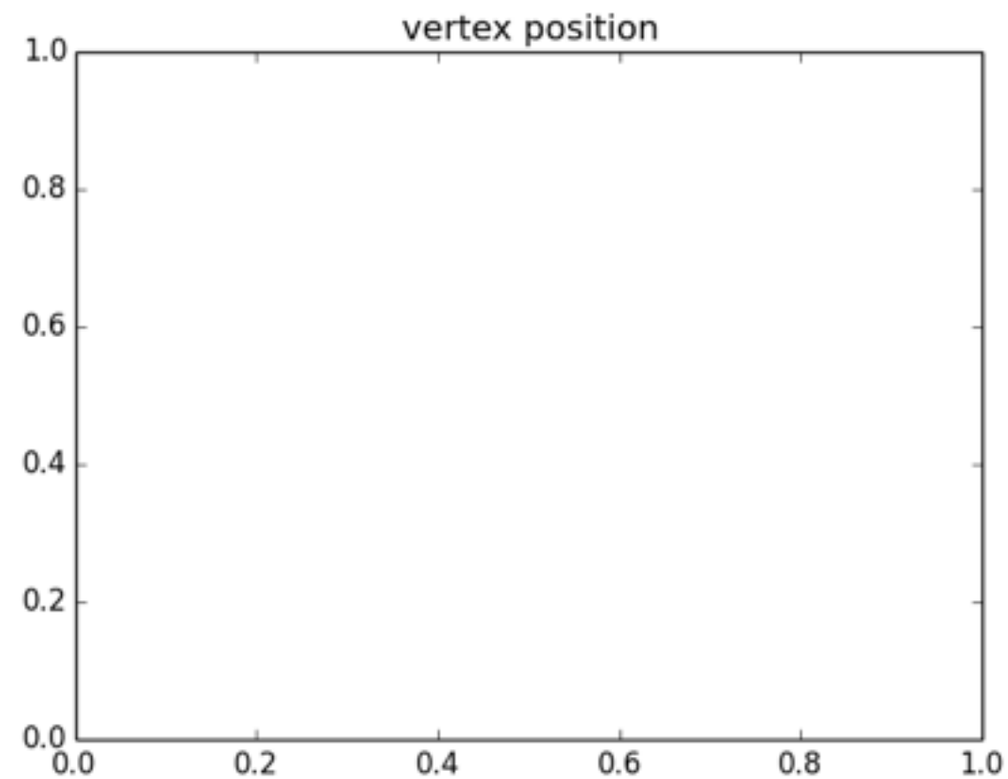


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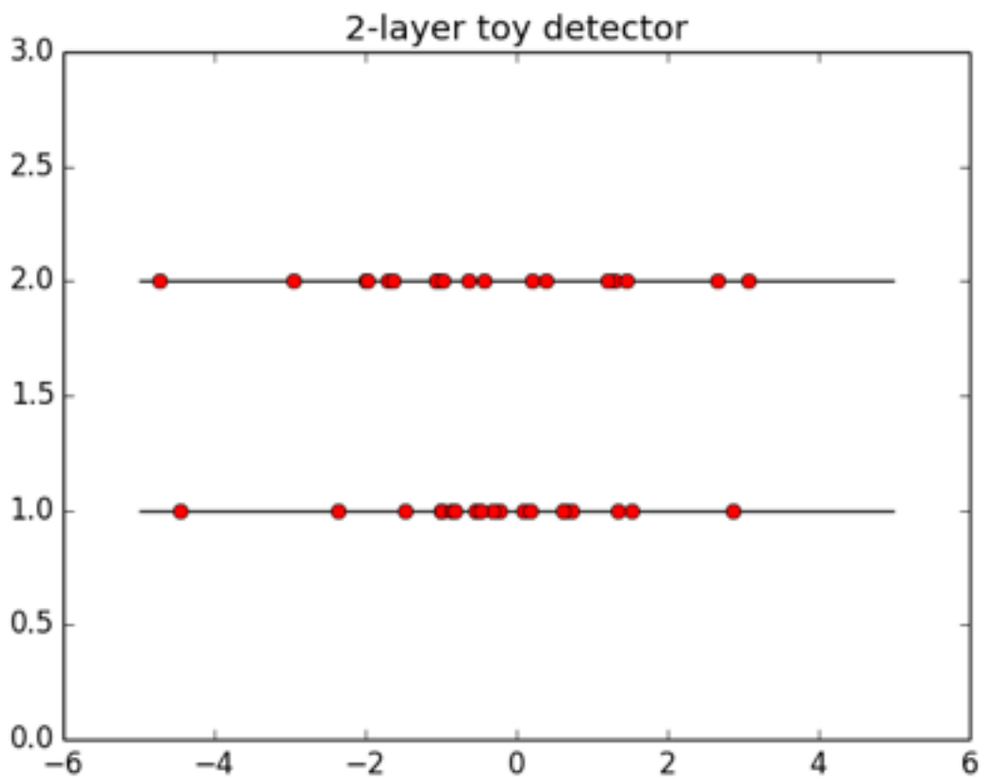

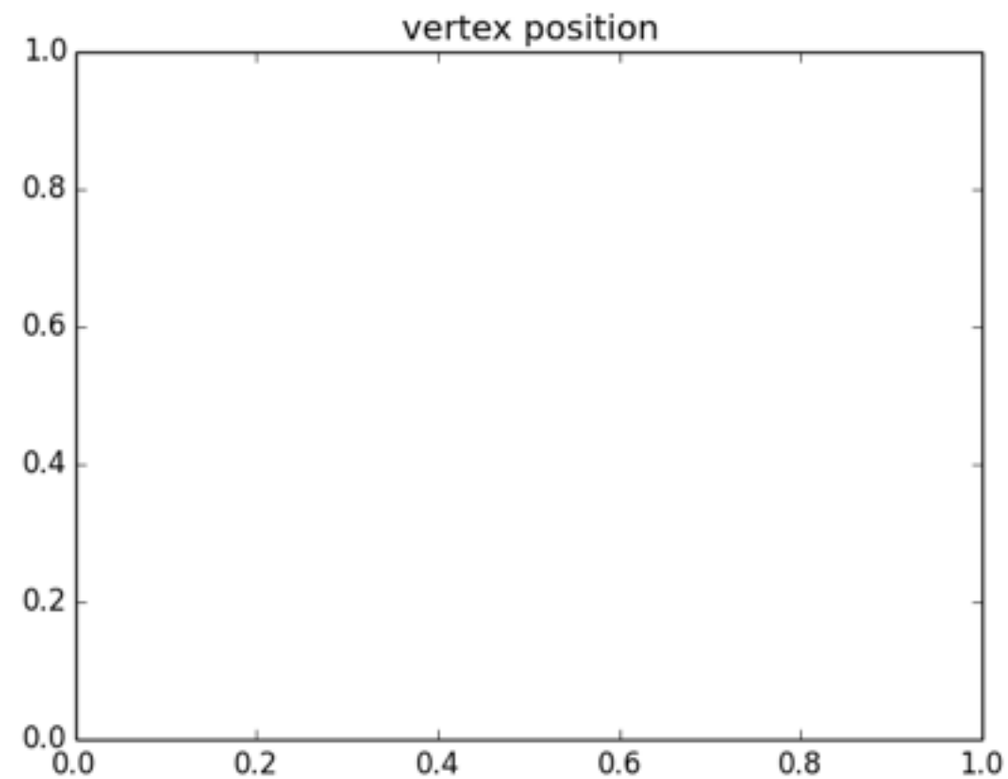


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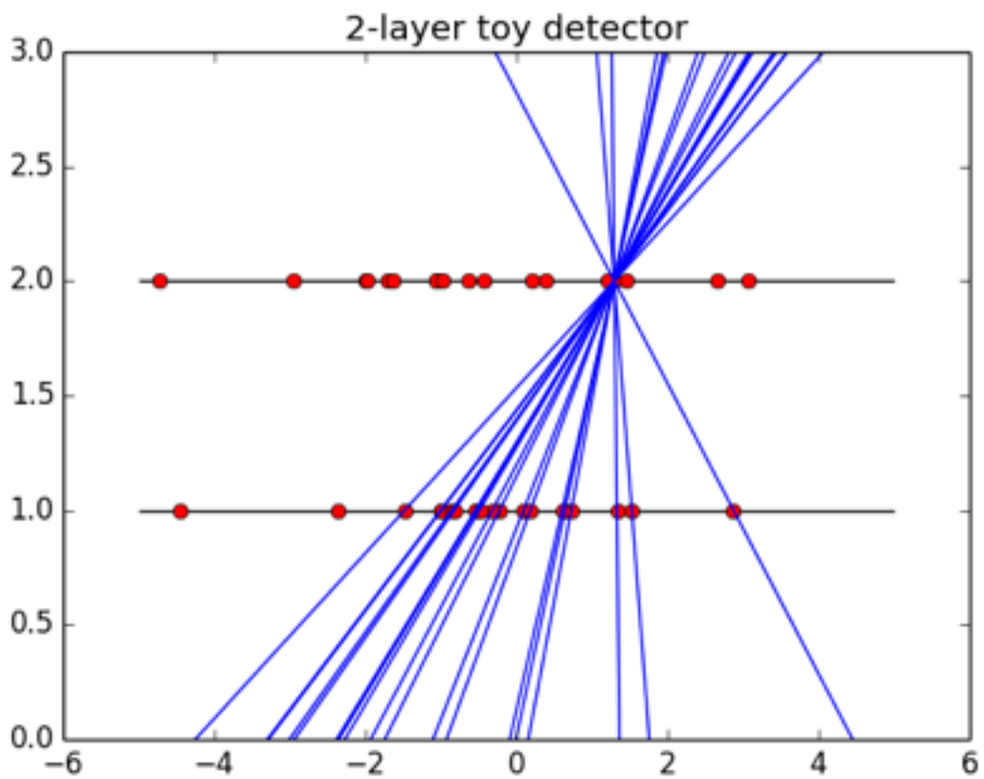

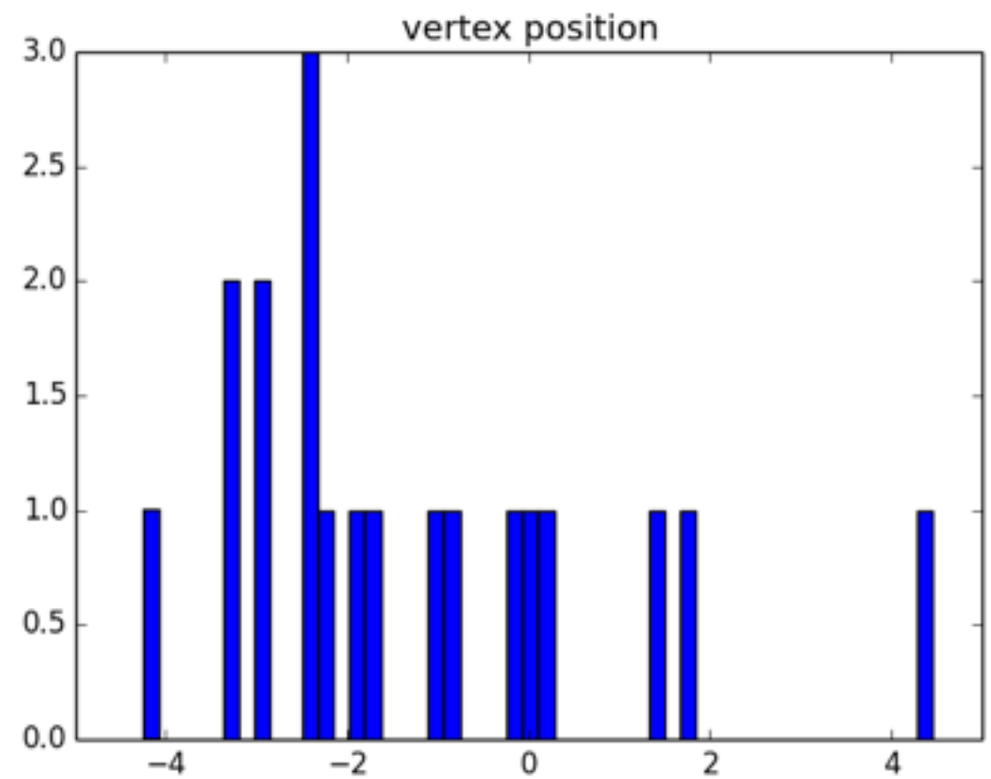


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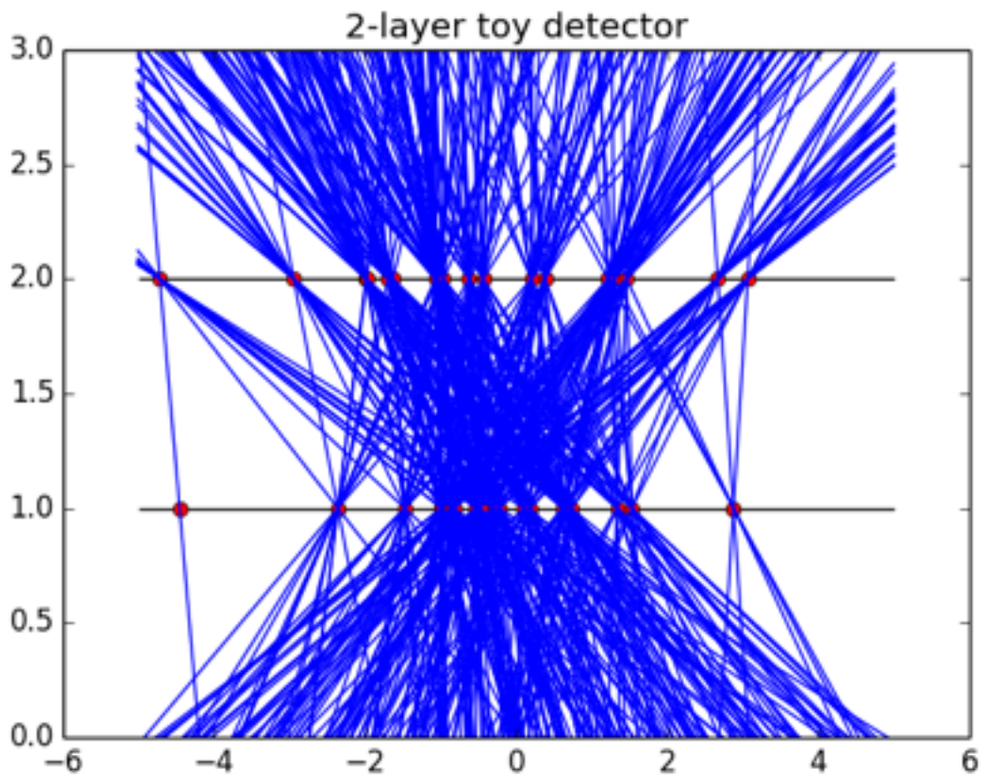

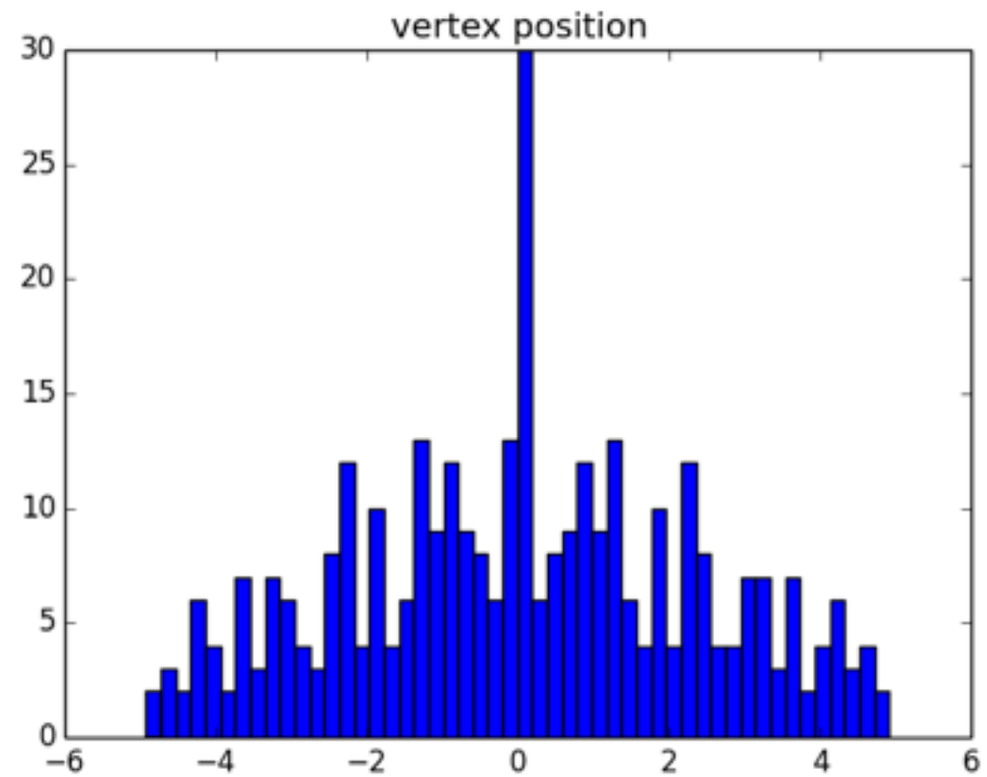


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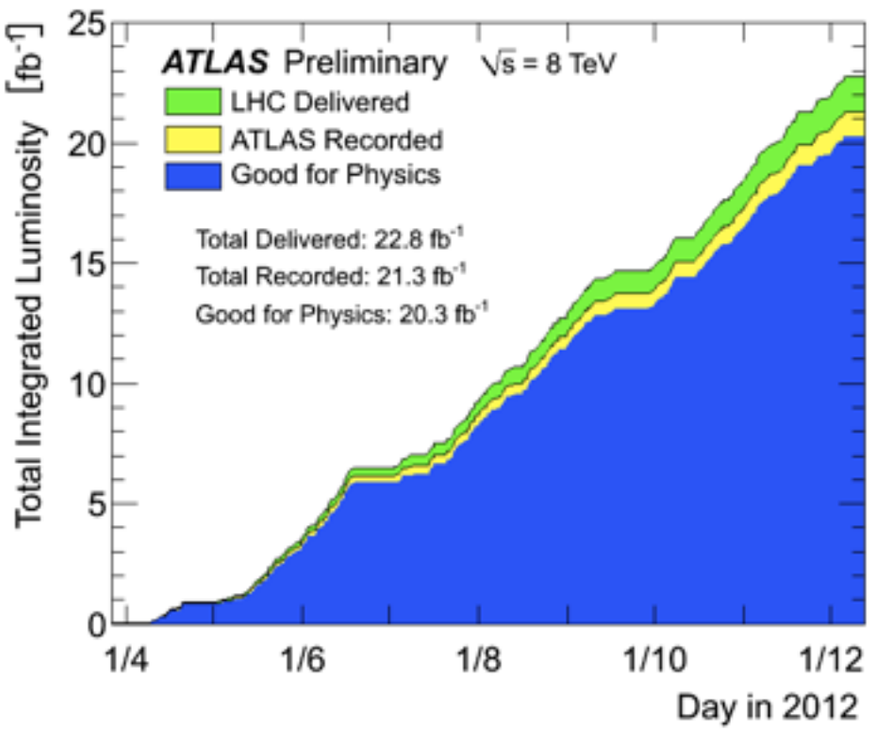

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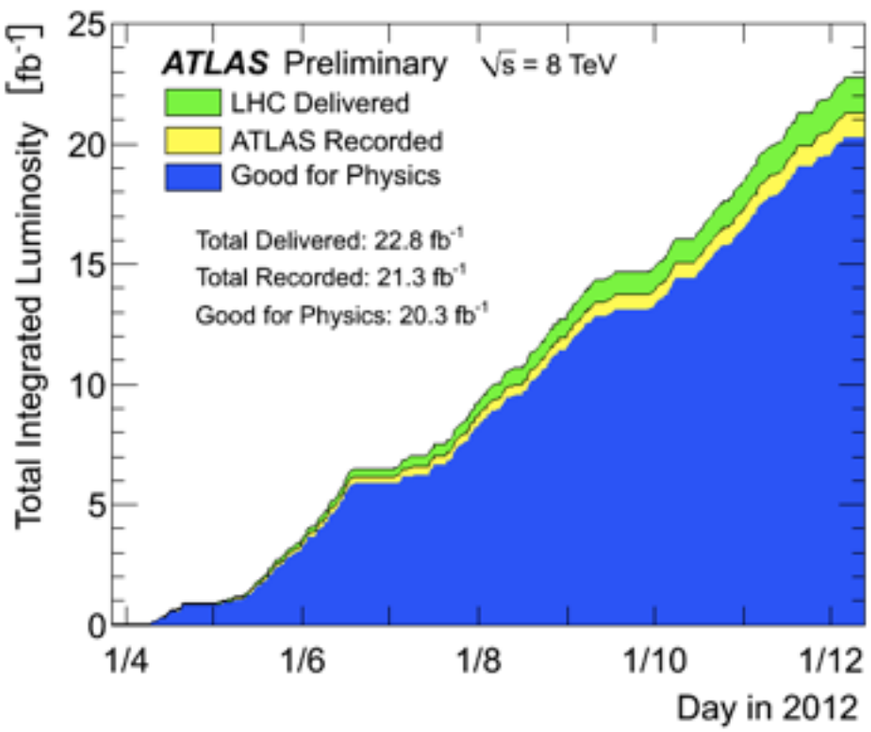

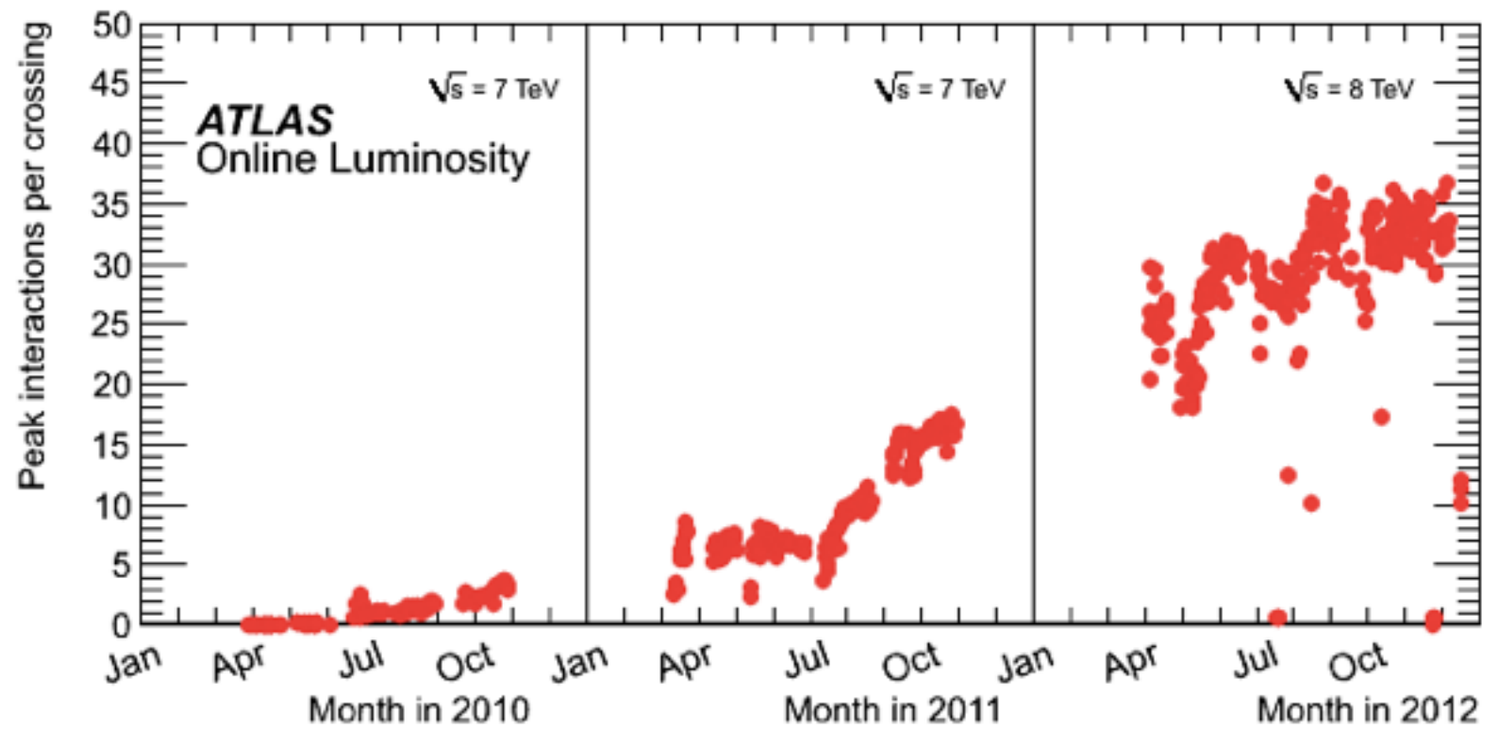

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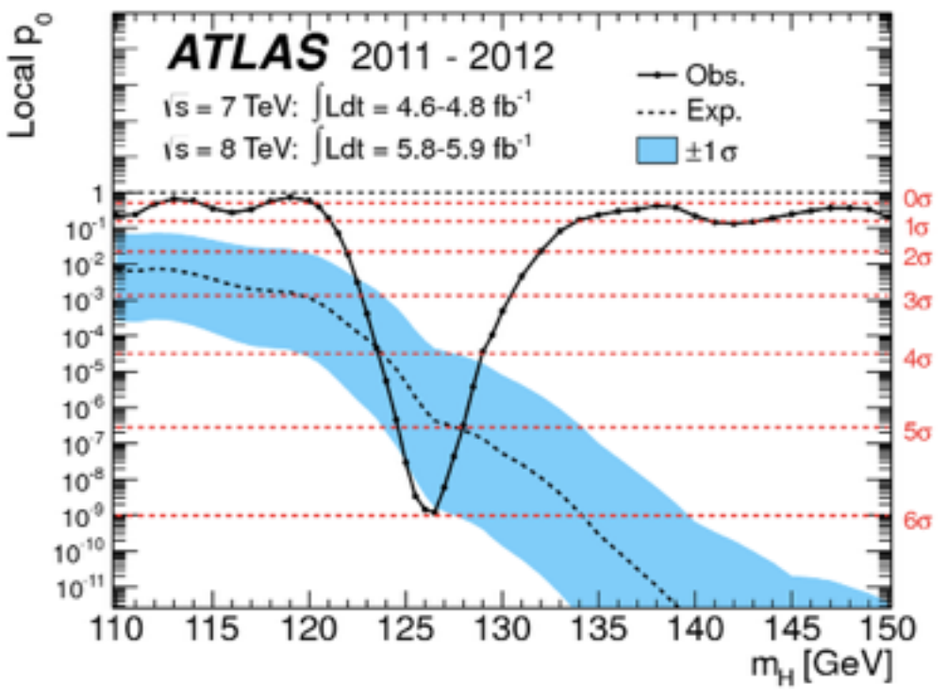

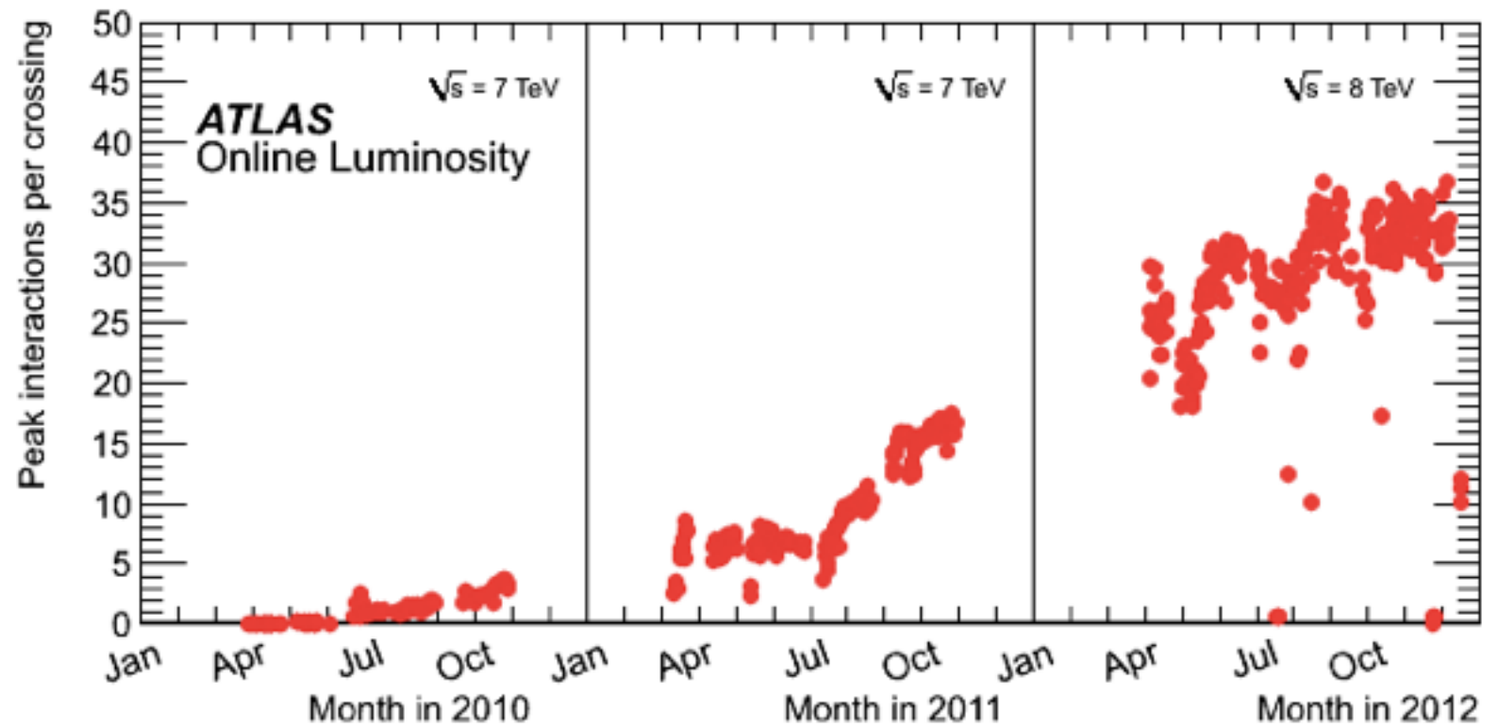

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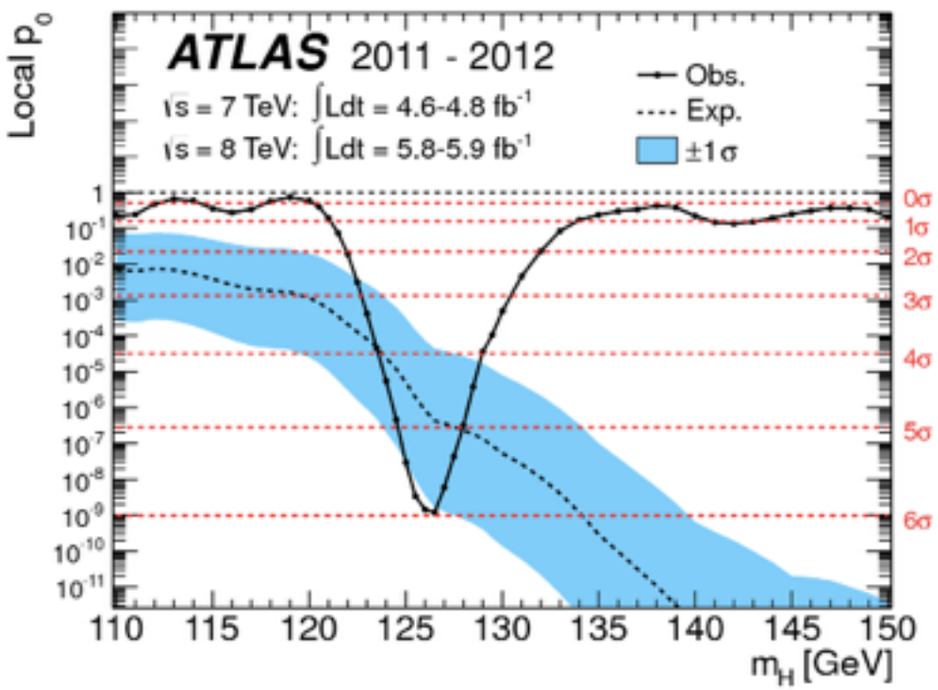

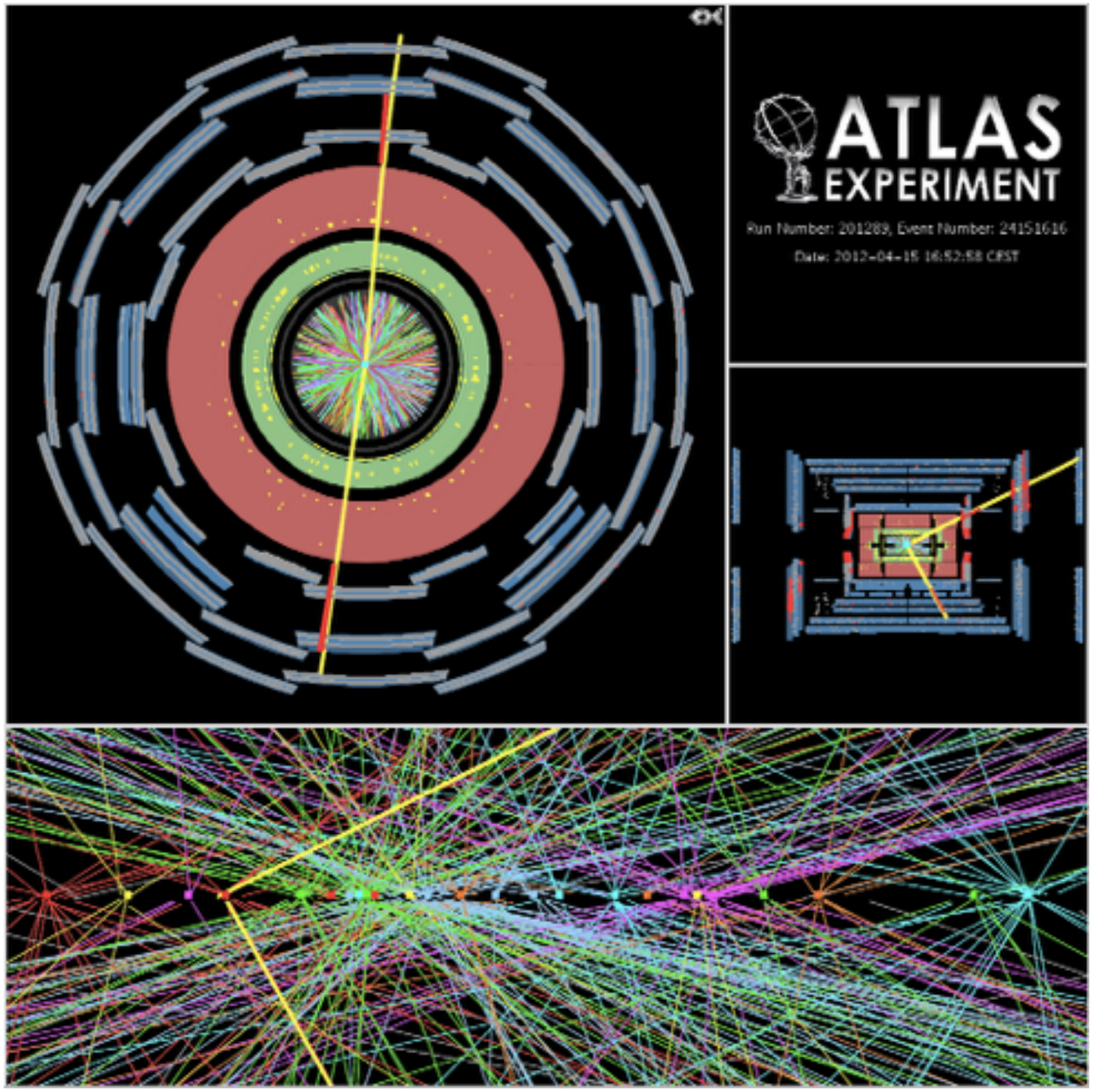

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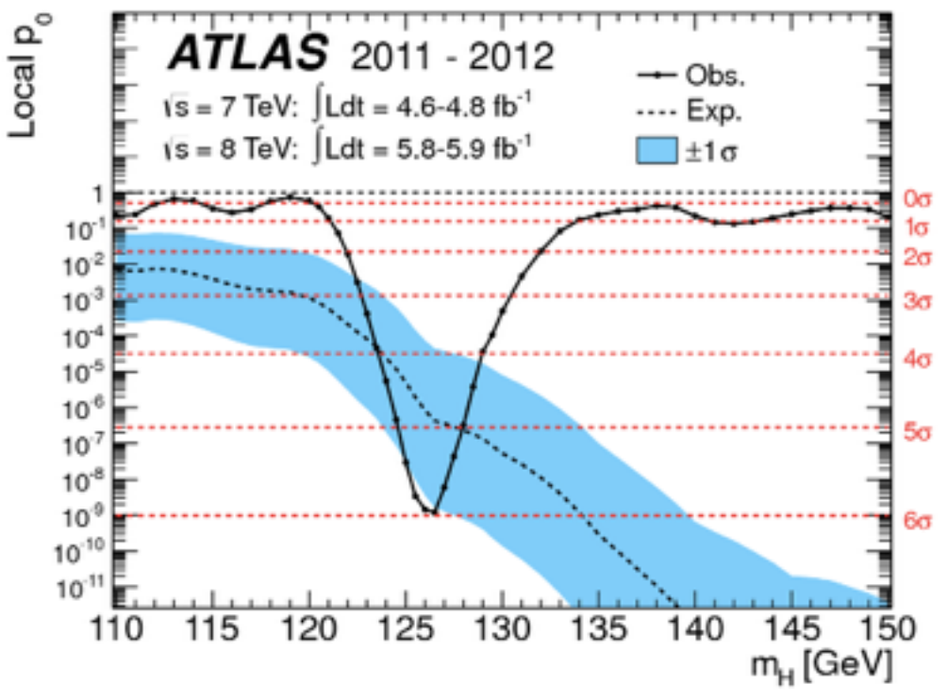

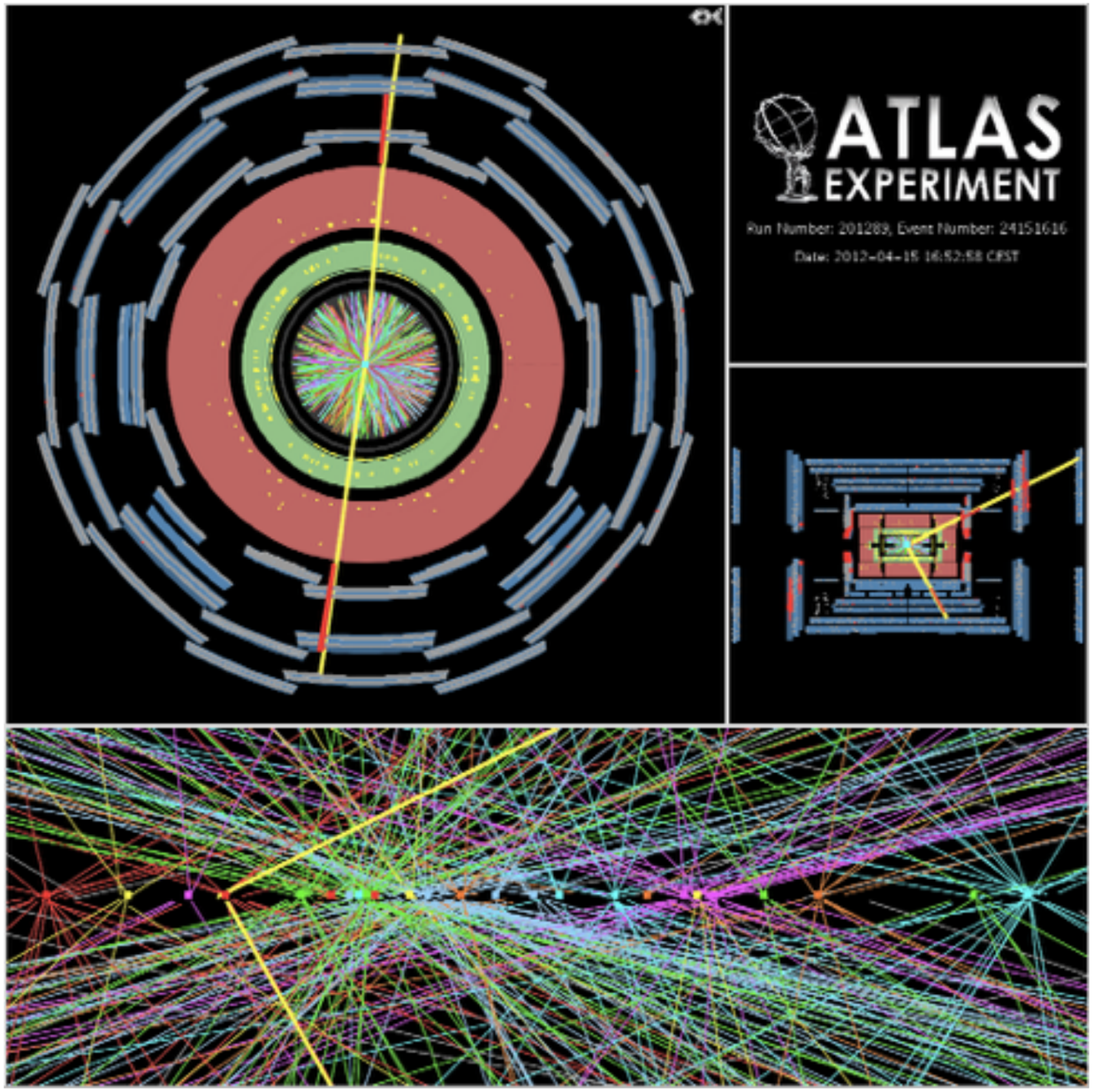

- More “fun” for track reconstruction

Enemy No. 3: **pile-up**

- Pile-up let's combinatorics explode

- This is bad from many angles:
  - CPU time explodes
  - low track fake rate is at risk
    (make more stringent requirements)
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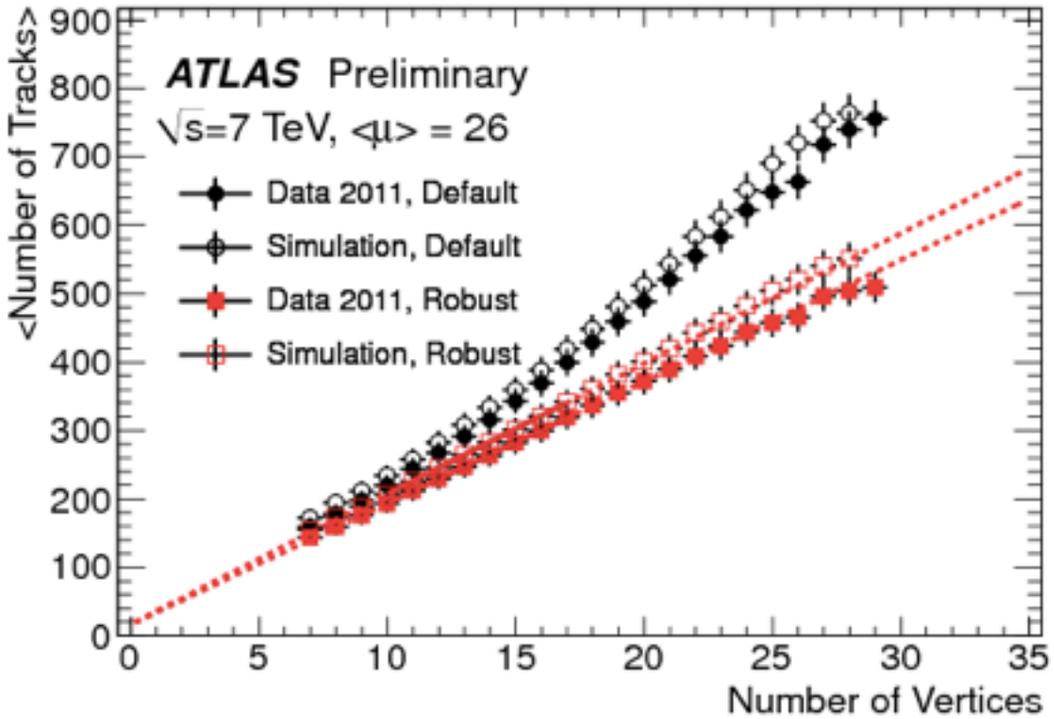

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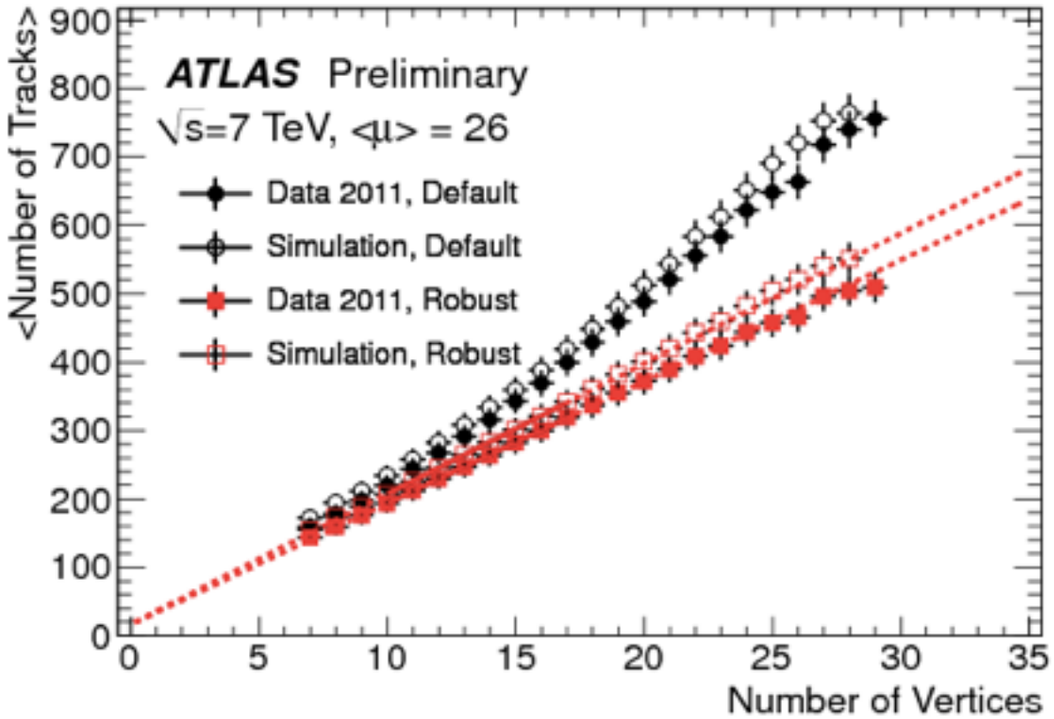

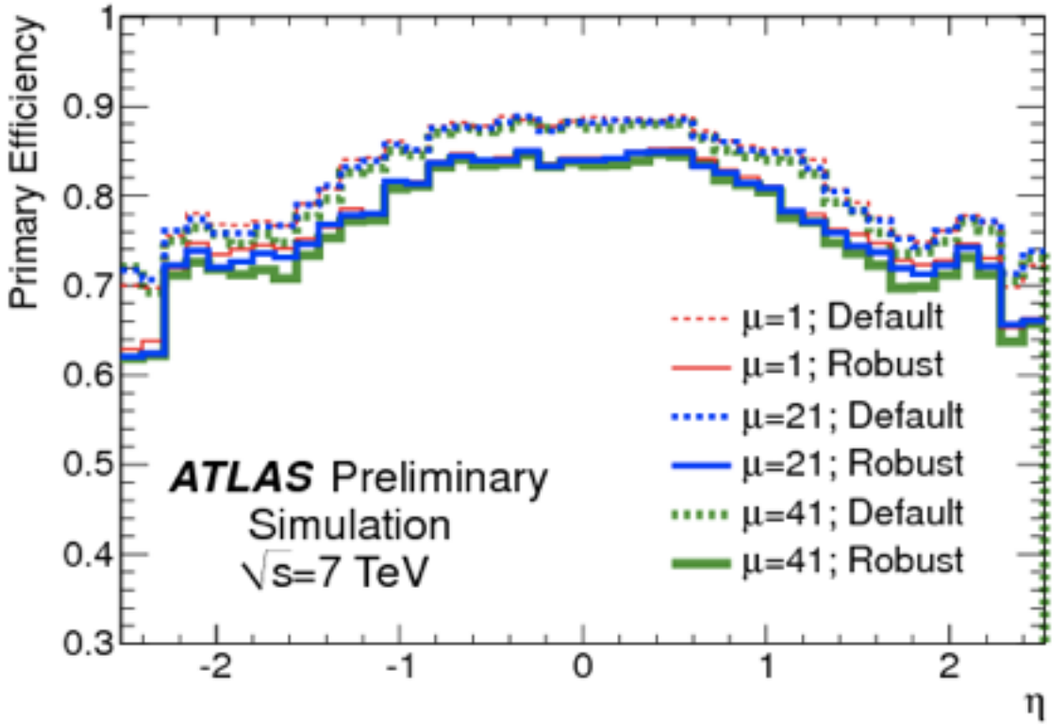

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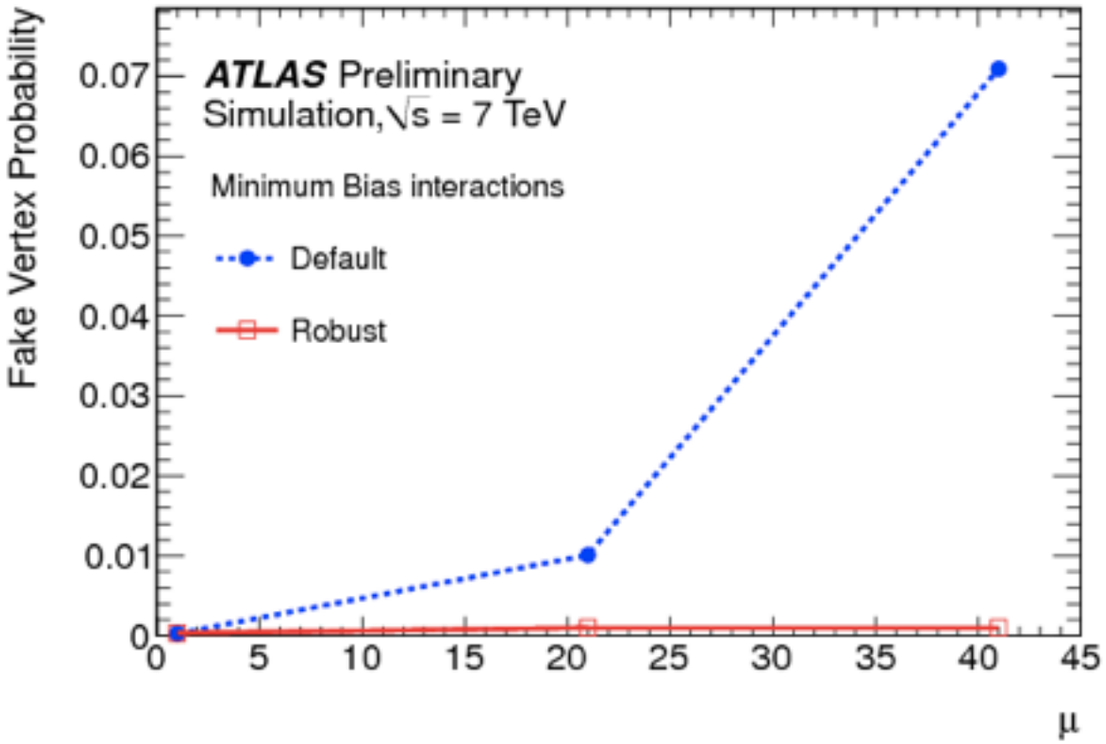

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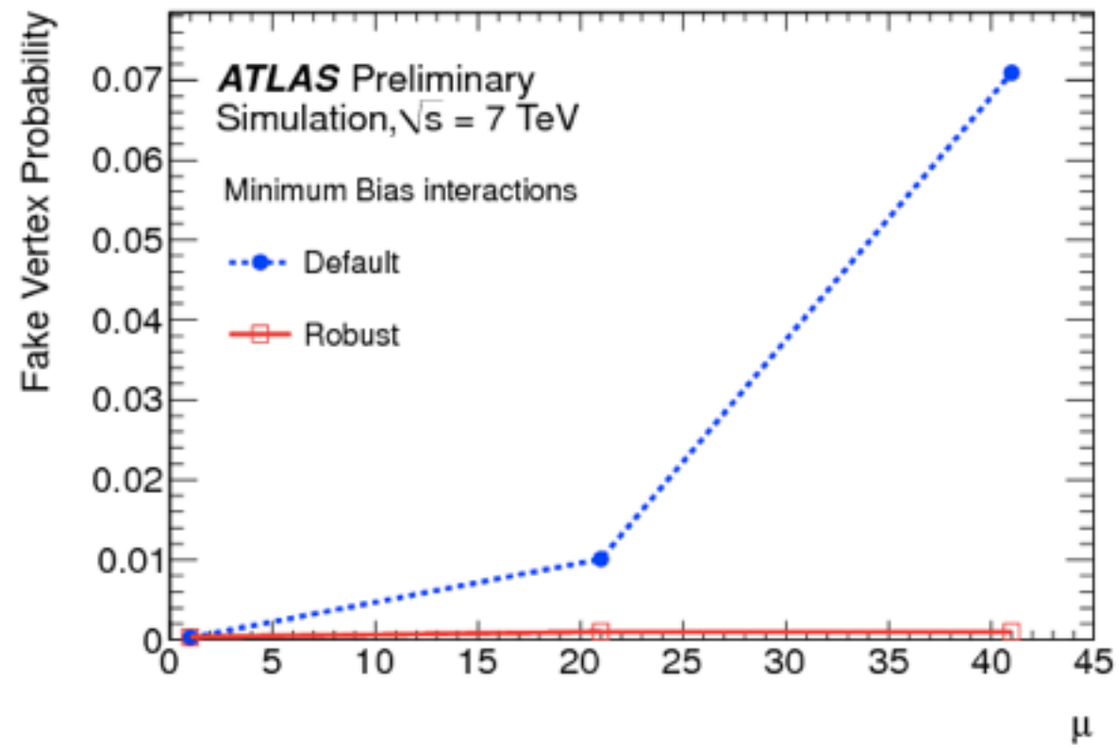
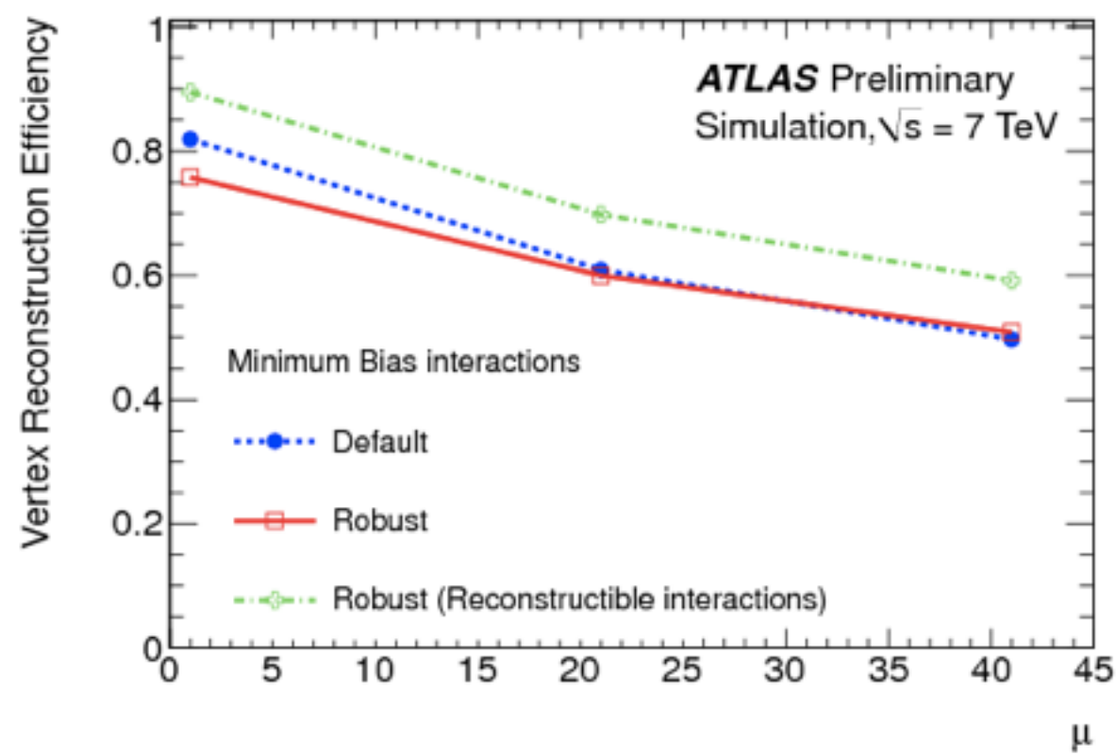
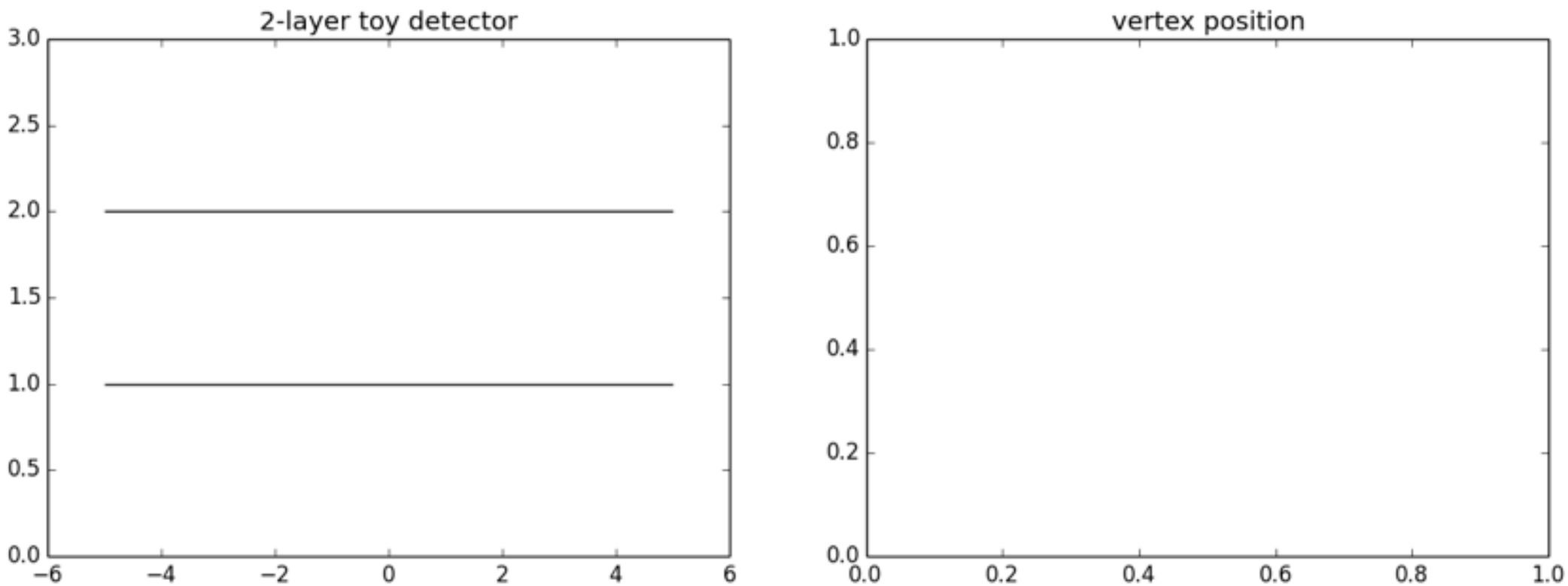




MC Toy: vertex seed finding with pile-up

- Our collider switched to pile-up mode

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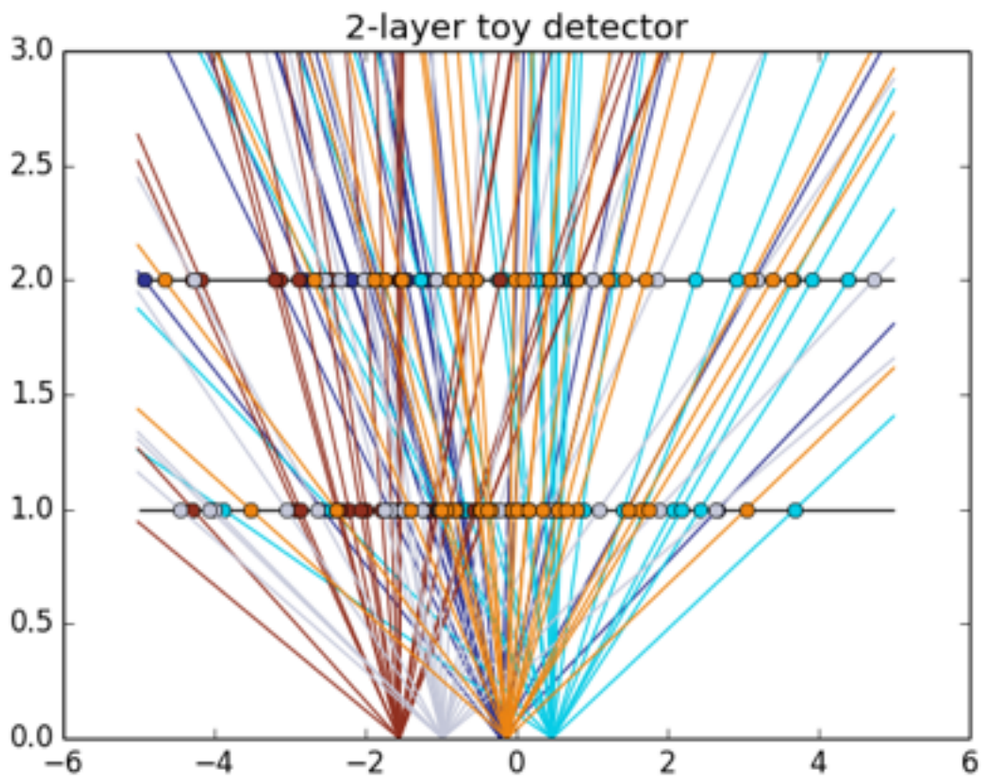

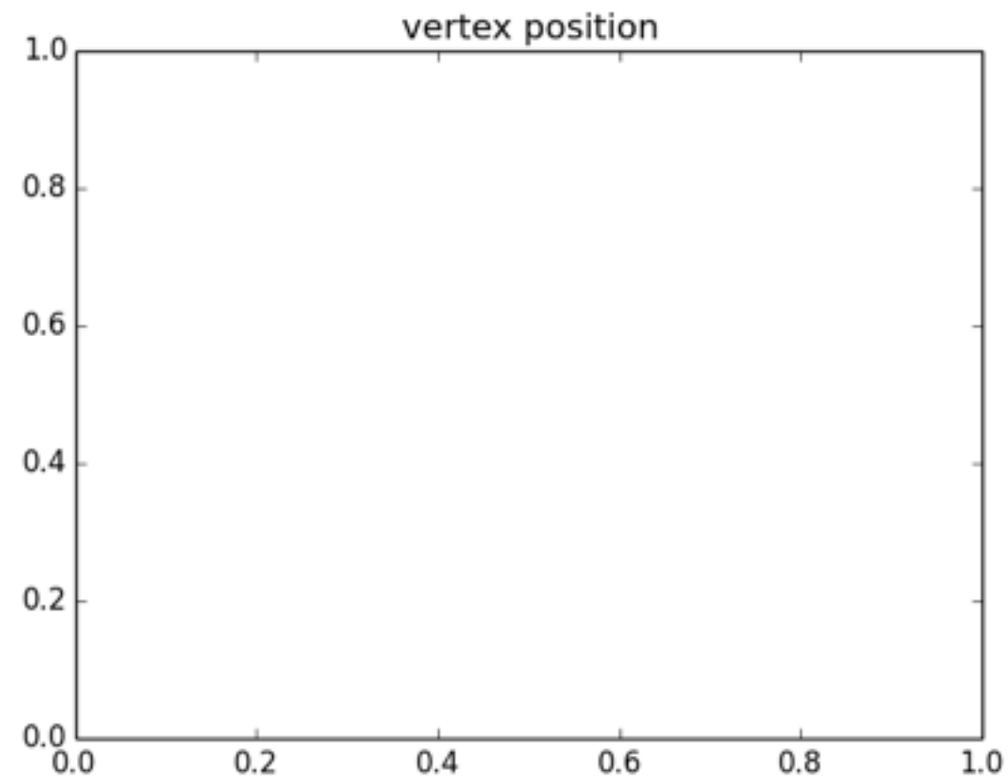


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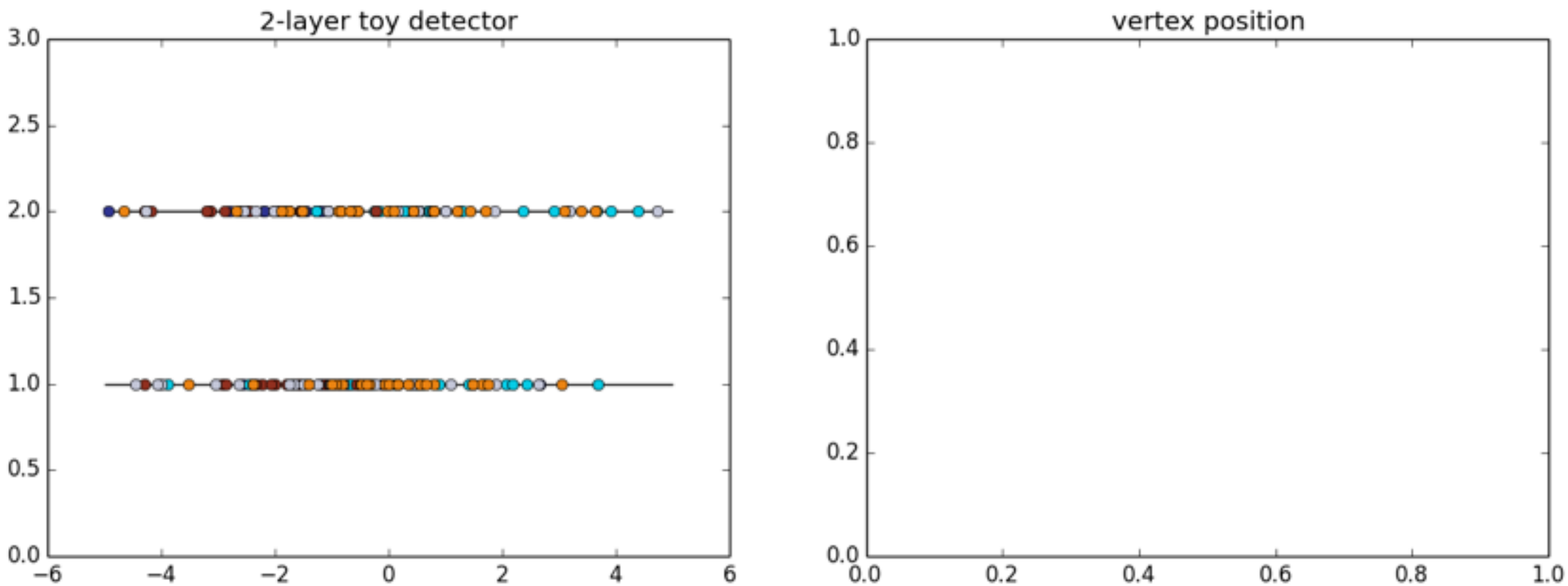


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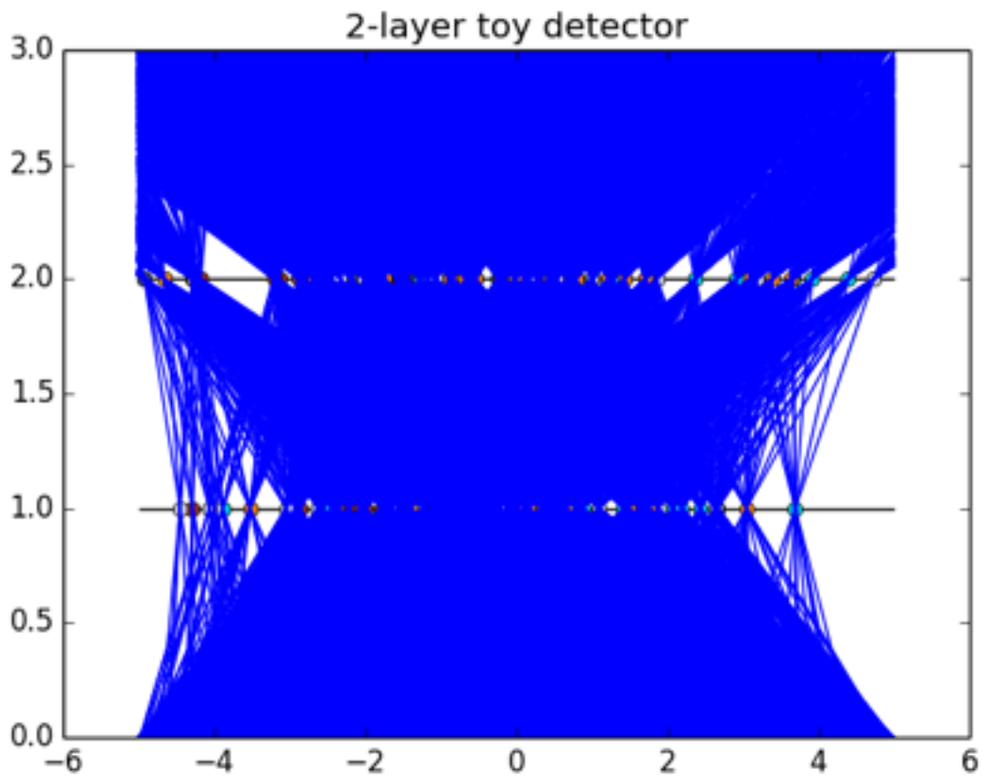

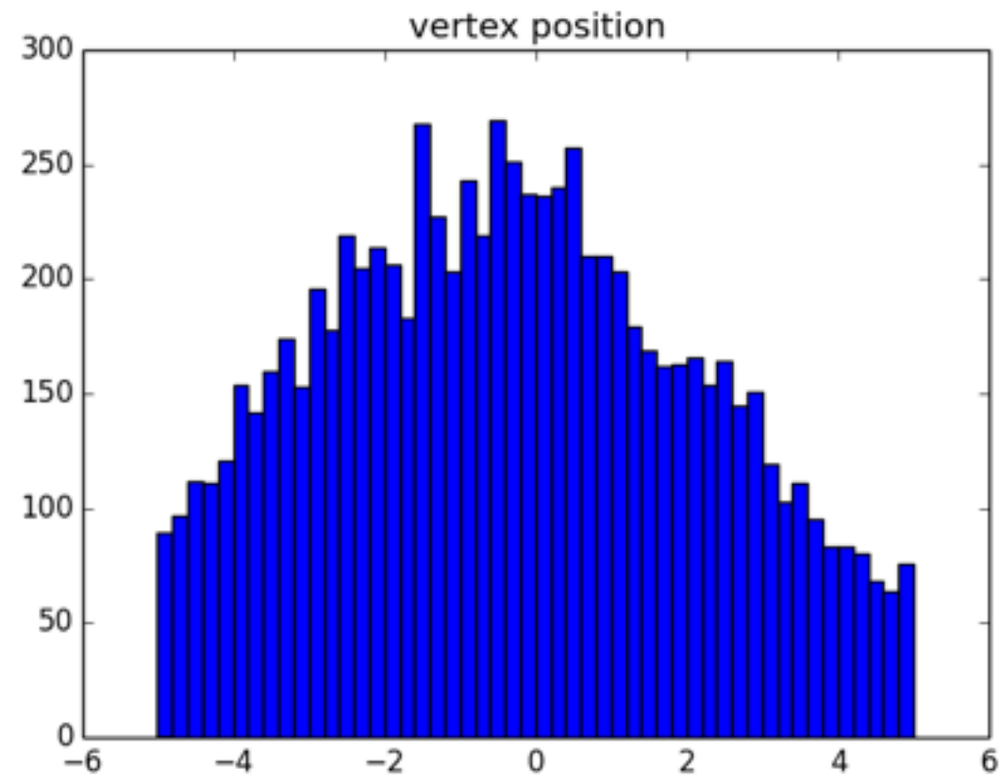


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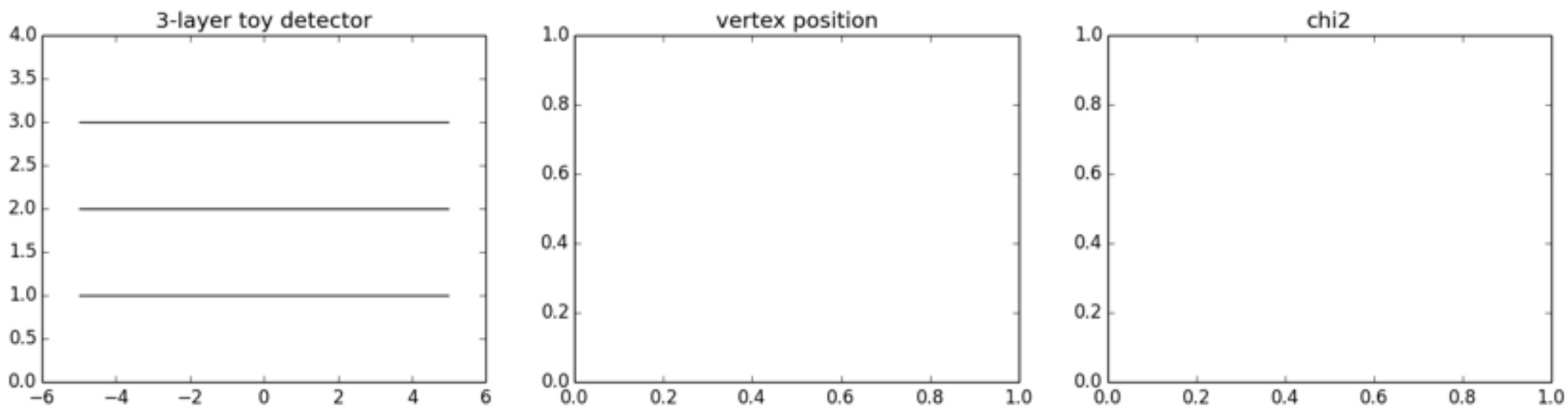


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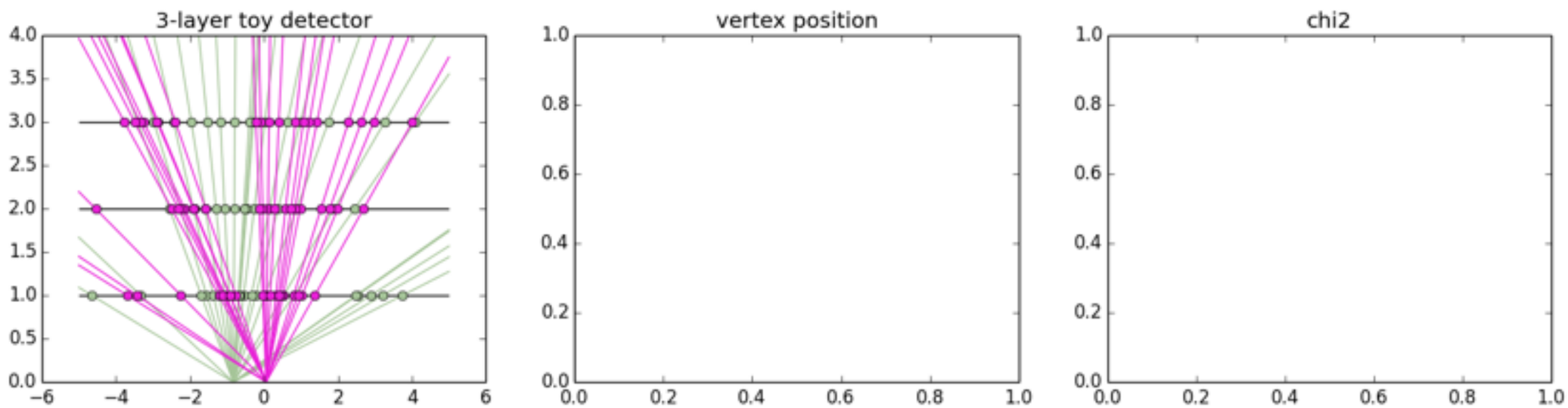


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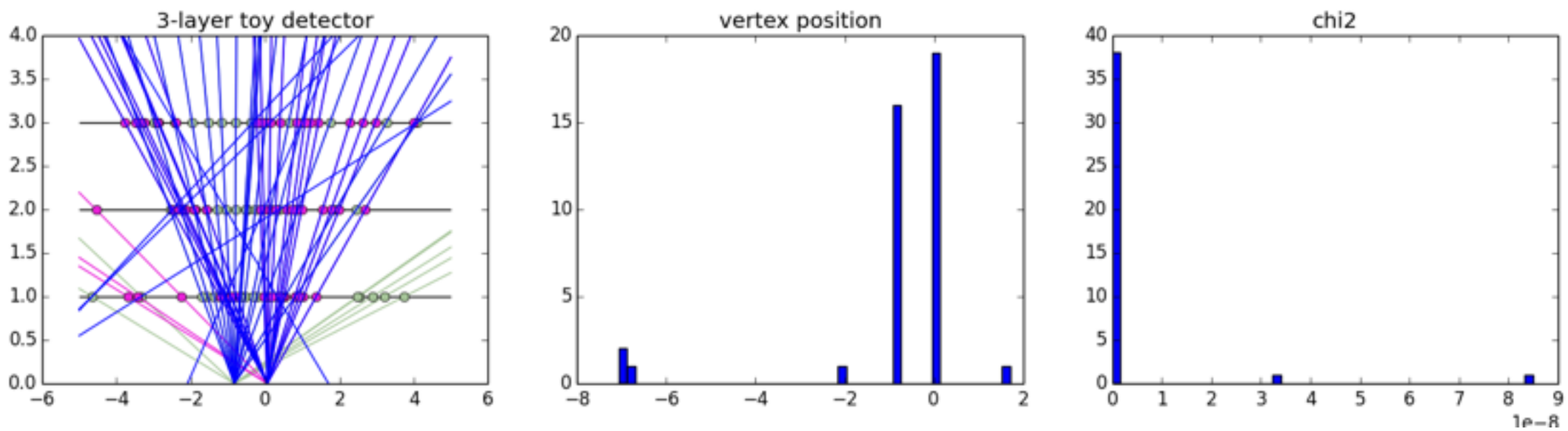


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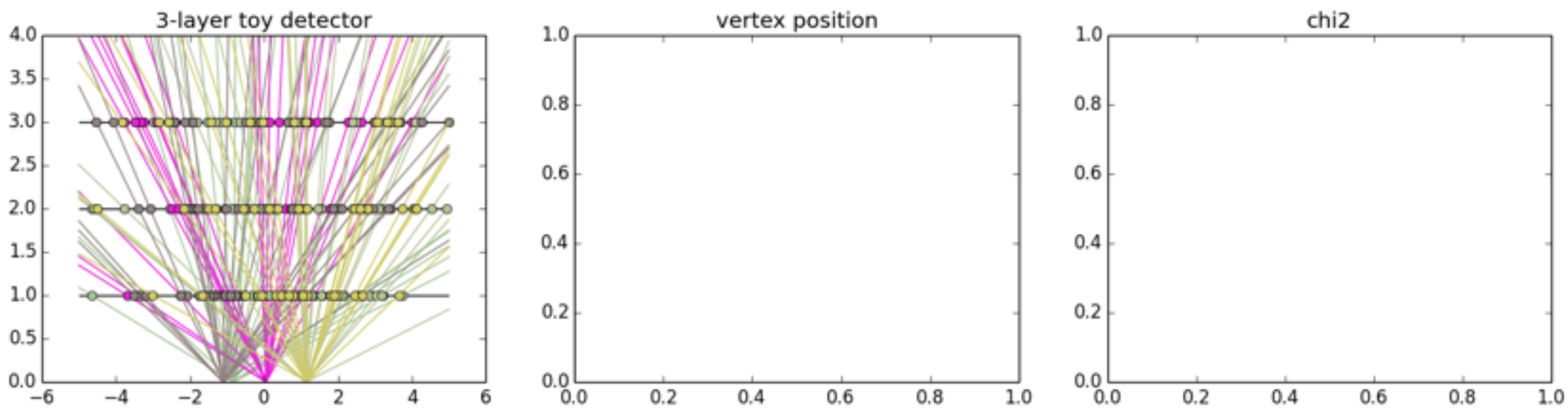


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vertex 0  - position is  -0.828622777212
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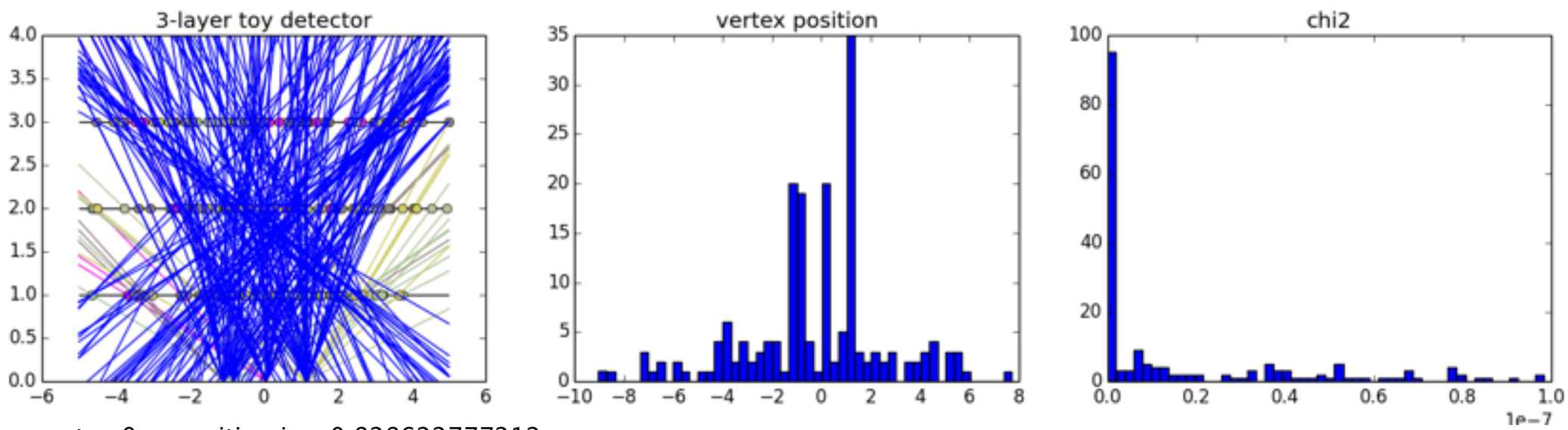


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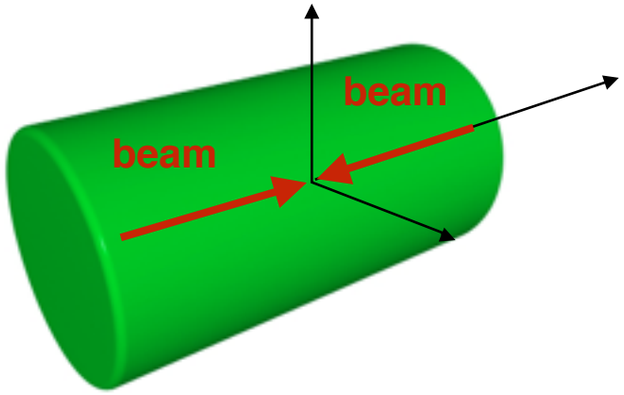
Track reconstruction in analysis

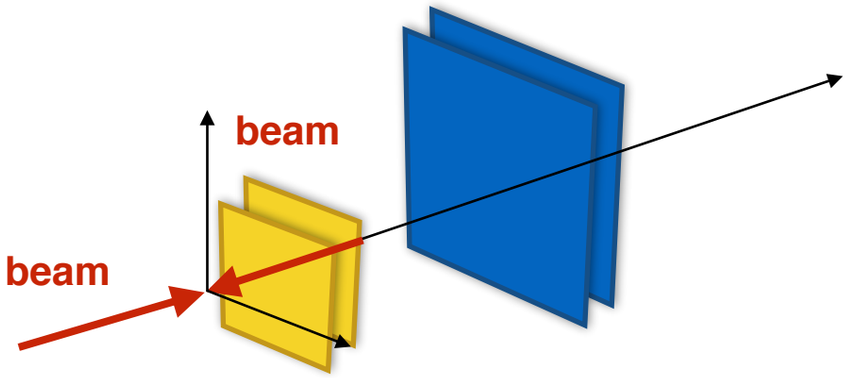
- The first published analyses of all LHC experiments were tracking based

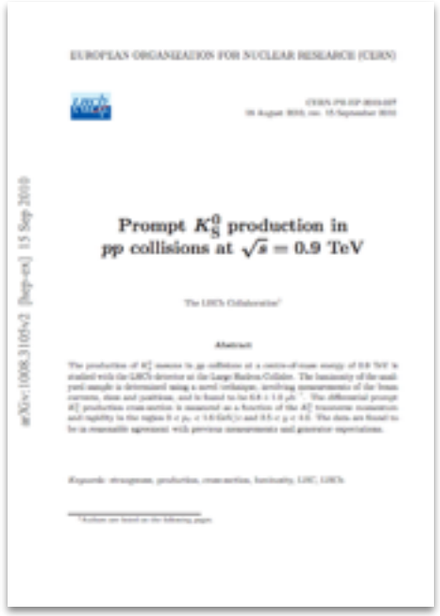
First proton–proton collisions at the LHC as observed with the ALICE detector: measurement of the charged-particle pseudorapidity density at √s=900 GeV

Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at √s= 0.9 and 2.36 TeV



Charged-particle multiplicities in pp interactions at √s = 900 measured with the ATLAS detector at the LHC





Prompt K_S^0 production in pp collisions at √s = 0.9 TeV

Example: charged particle multiplicity

- A three-step master plan to a Soft QCD paper :
  (might be “slightly" simplified)

1. take data from generic p-p collisions without bias towards some signature
   (“Minimum bias measurement”)

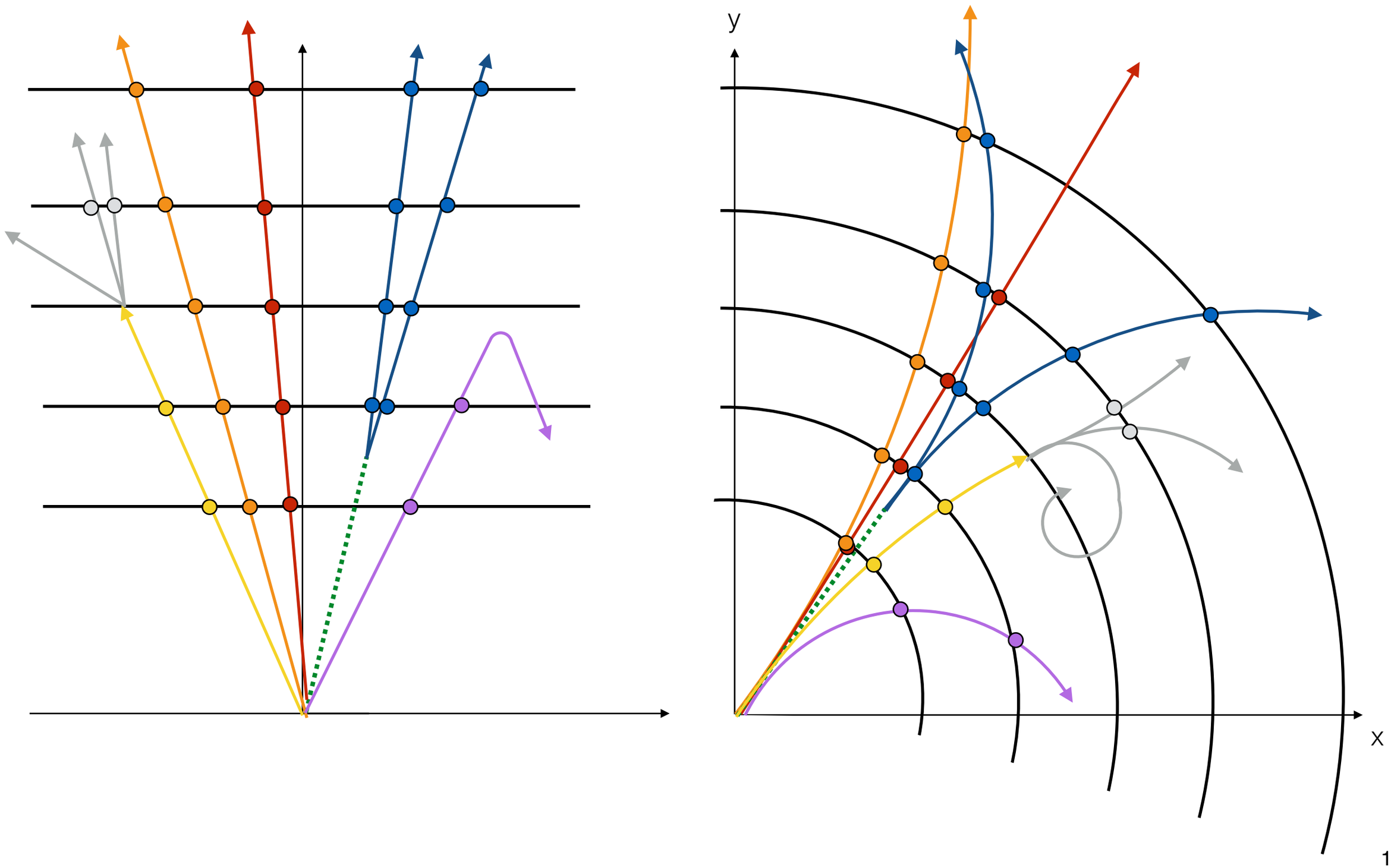
2. count how many primary tracks you find (e.g. vs η, vs p_T)

3. correct for tracks you have not found and publish

Let’s do it !

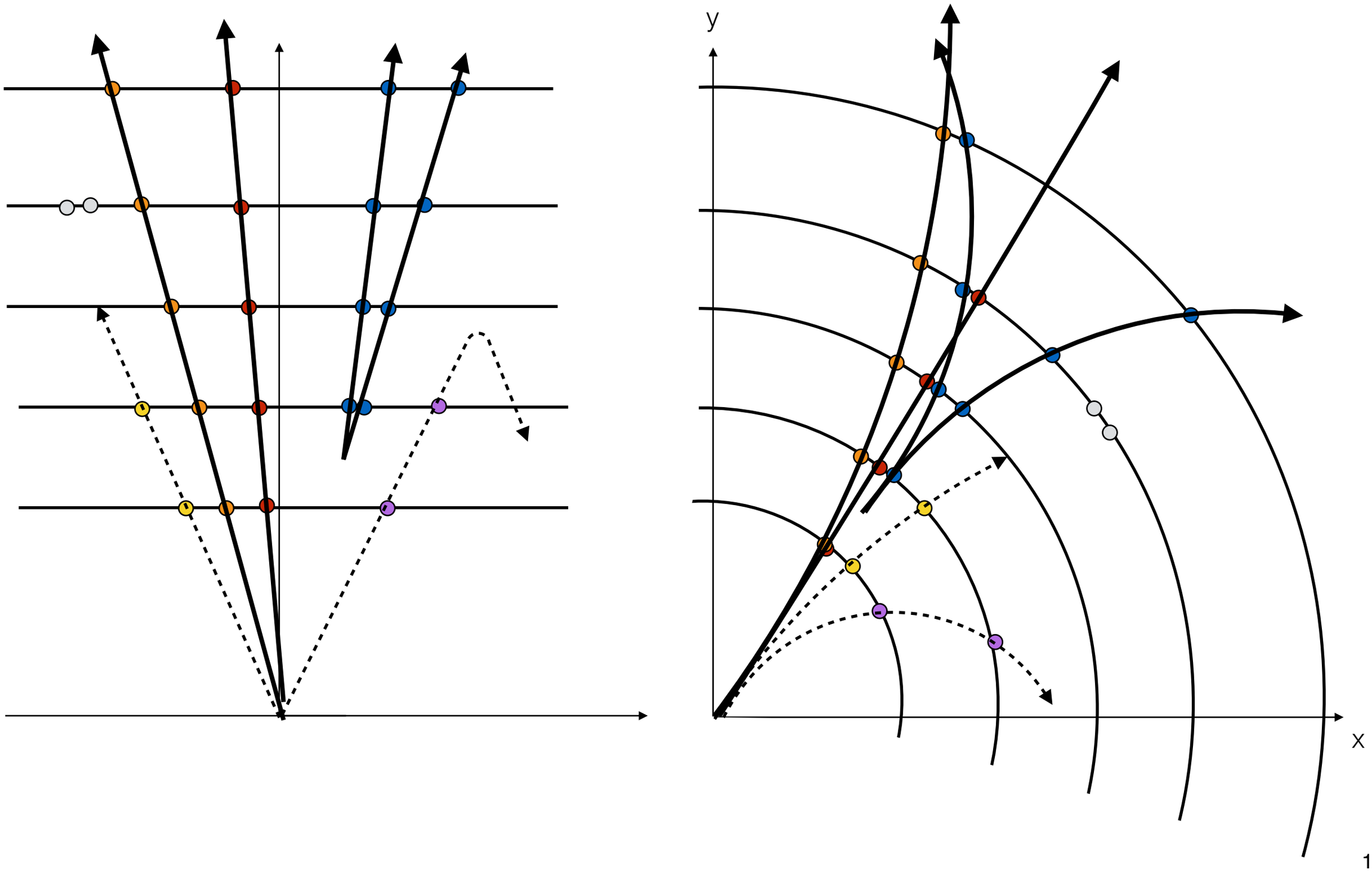
Example: charged particle multiplicity

- Let's roll the dice ourselves



Example: charged particle multiplicity

- And that's what the track reconstruction gives us



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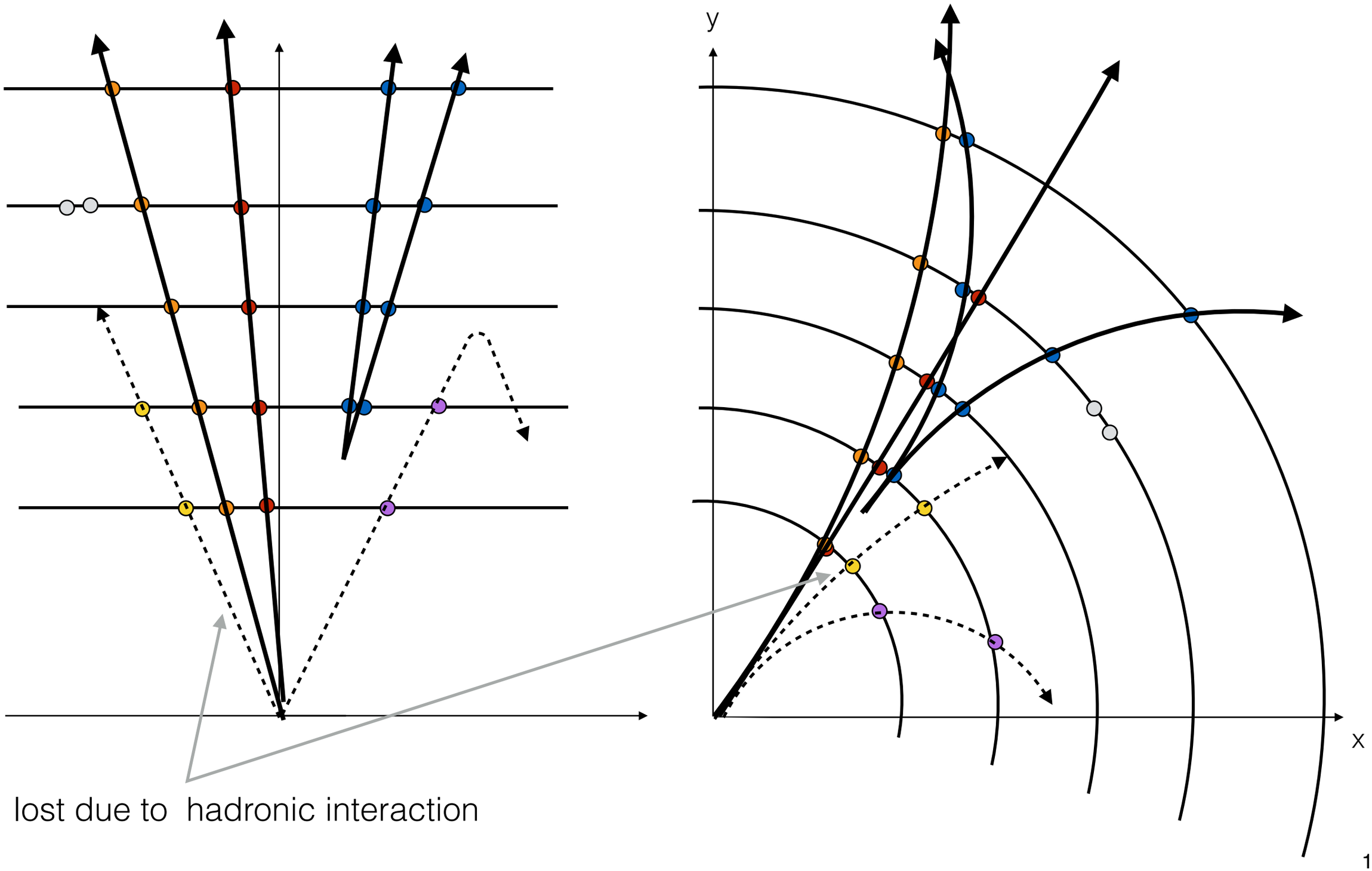

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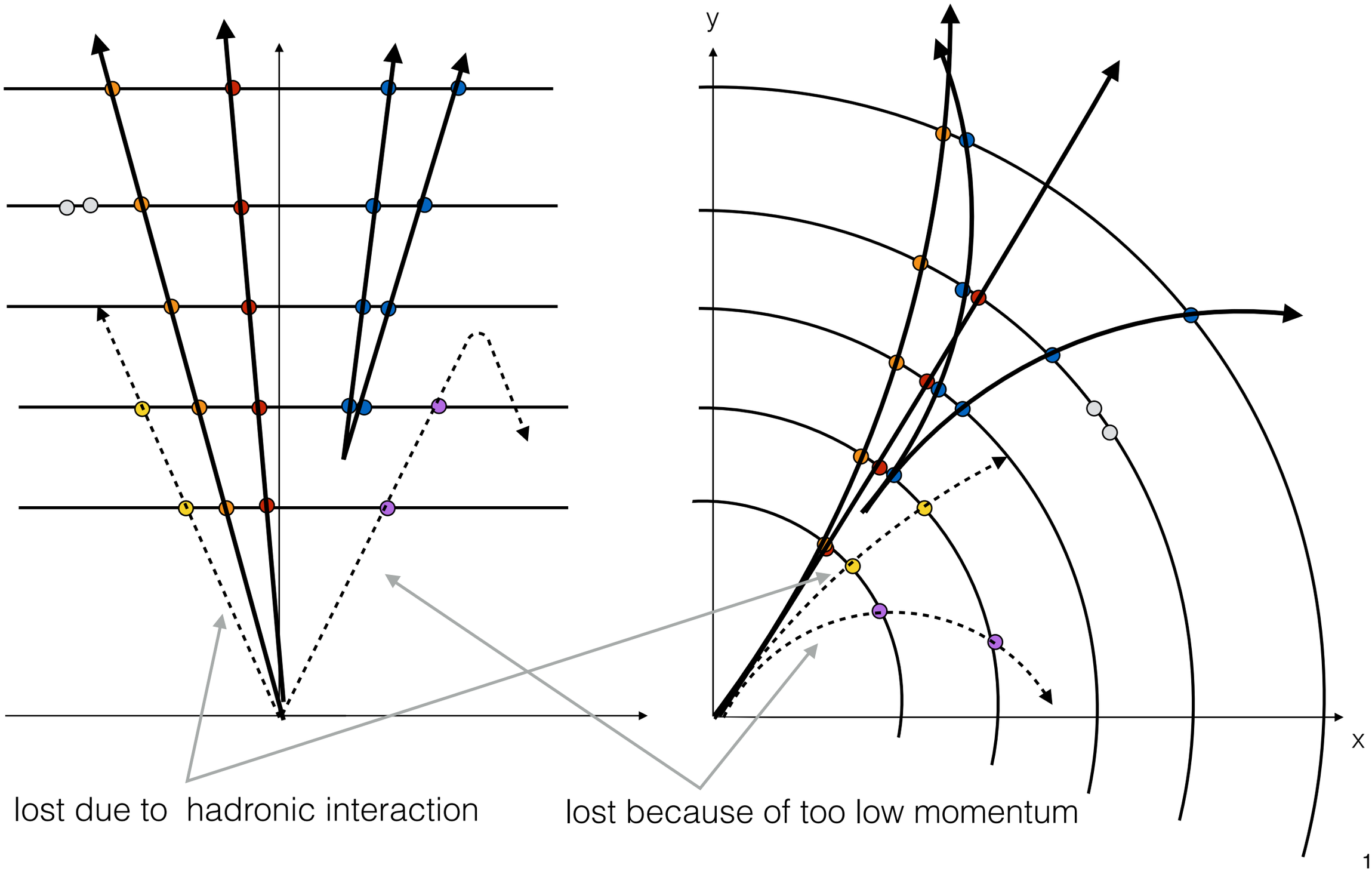
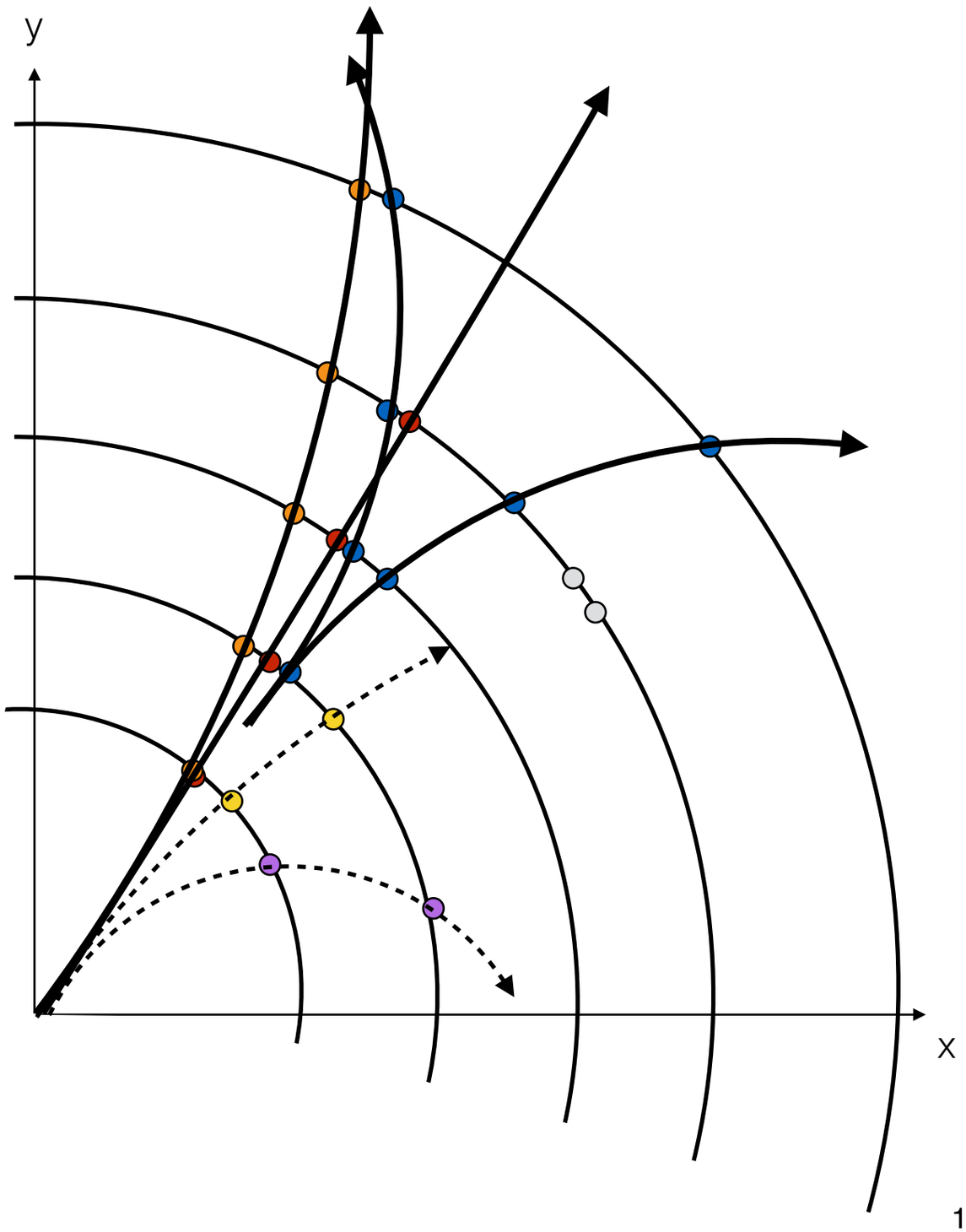


We need to define a tracking efficiency

- There is **no** such thing as a tracking efficiency
  - restricted to phase-space
  - restricted to your definitions of a track (requirements and cuts)
  - different for different particles
- For checking the algorithmic performance
  - define a “reconstructable track” in Monte Carlo and check how often you can find it
  - can we do that in data ?



Tracking efficiency

- Material is the main source of inefficiency in the tracker
  - majority of particles are hadrons: nuclear interaction dominates
  - for electrons also bremsstrahlung needs to be considered

- Tracking efficiency for hadrons is usually taken from Monte Carlo
  - defined by :

$$\varepsilon = \frac{\textit{Number of found tracks*and matched to a truth particle}}{\textit{Number of generated stable charged particles**}}$$

**satisfying my track cuts* ***satisfying my phase space*

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Perfect ! Now we can measure it …

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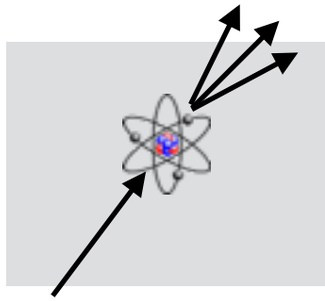

remember ?

" … rather constant in $\mathbf{p}$ …"

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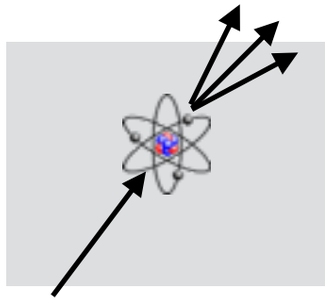

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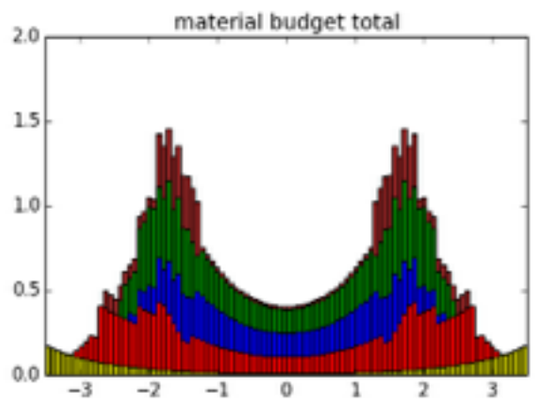

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our built-up material map …

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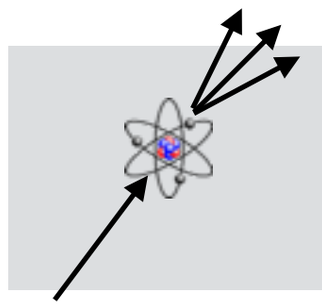

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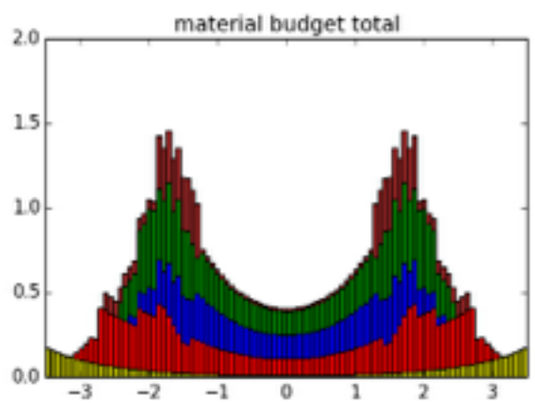

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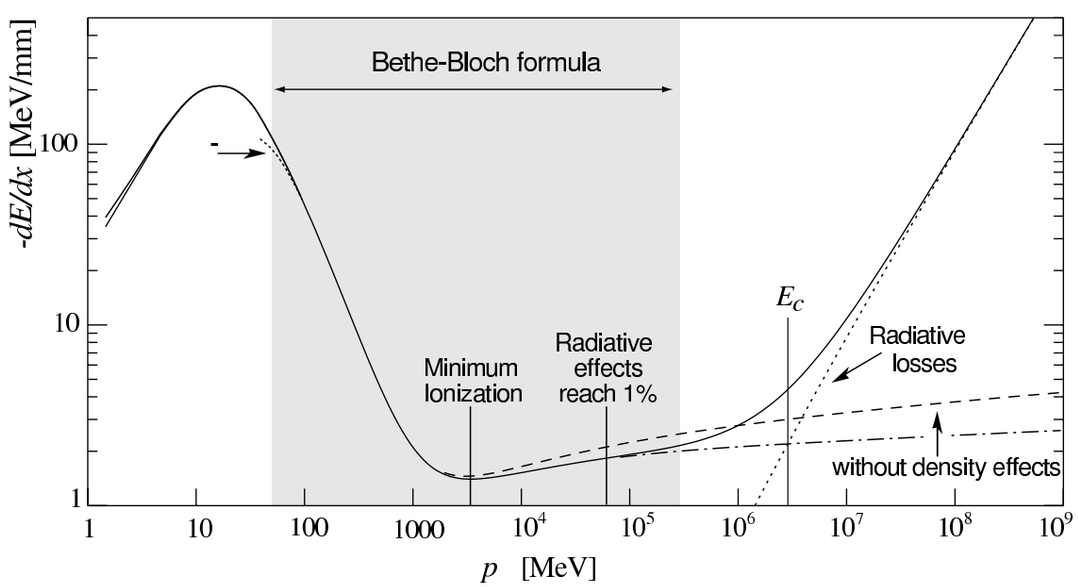

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both ionisation loss and multiple scattering act most at low $\mathbf{p_T}$ in the minimum bias regime

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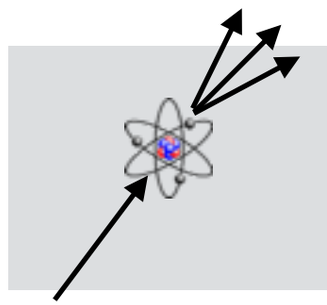

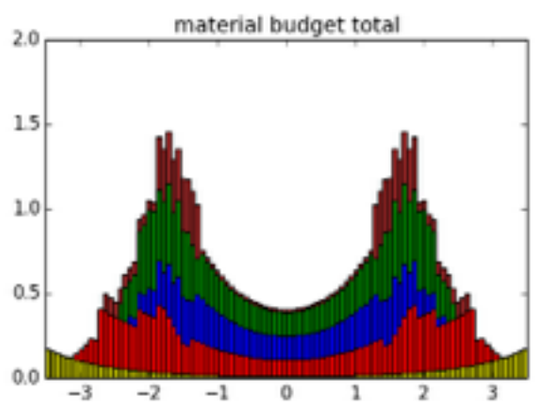

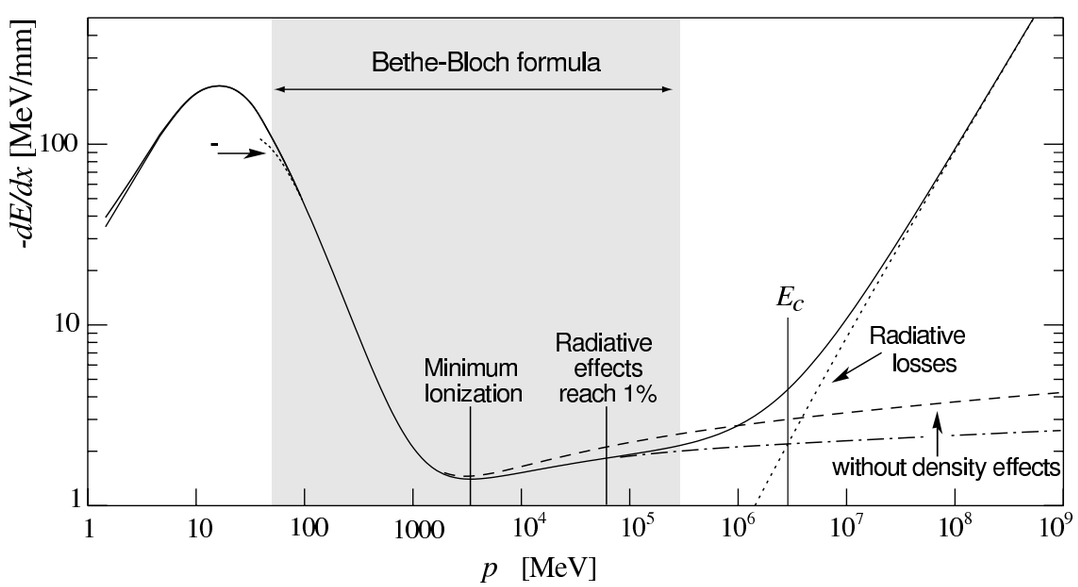

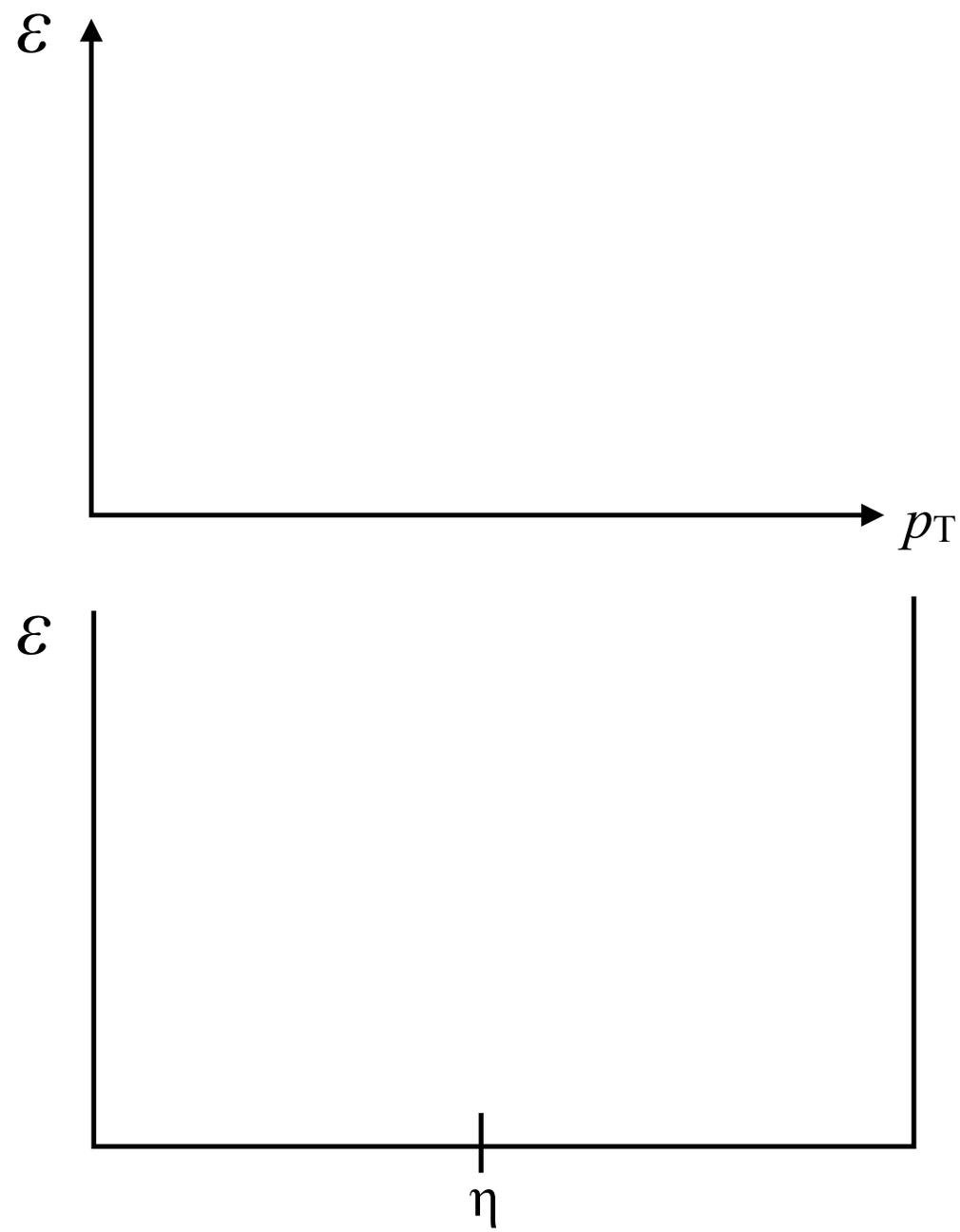

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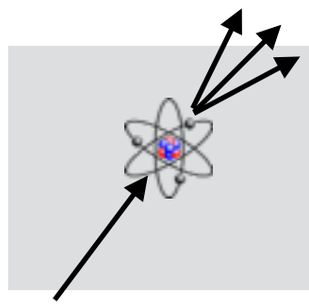

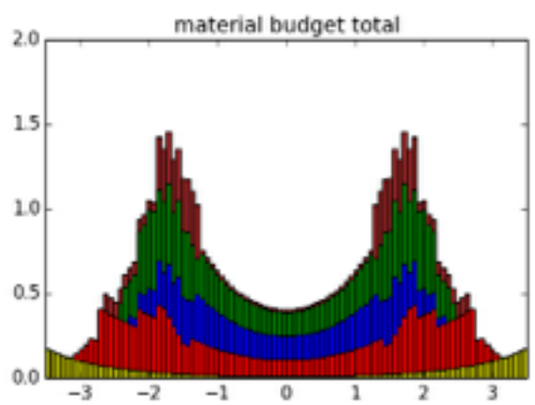

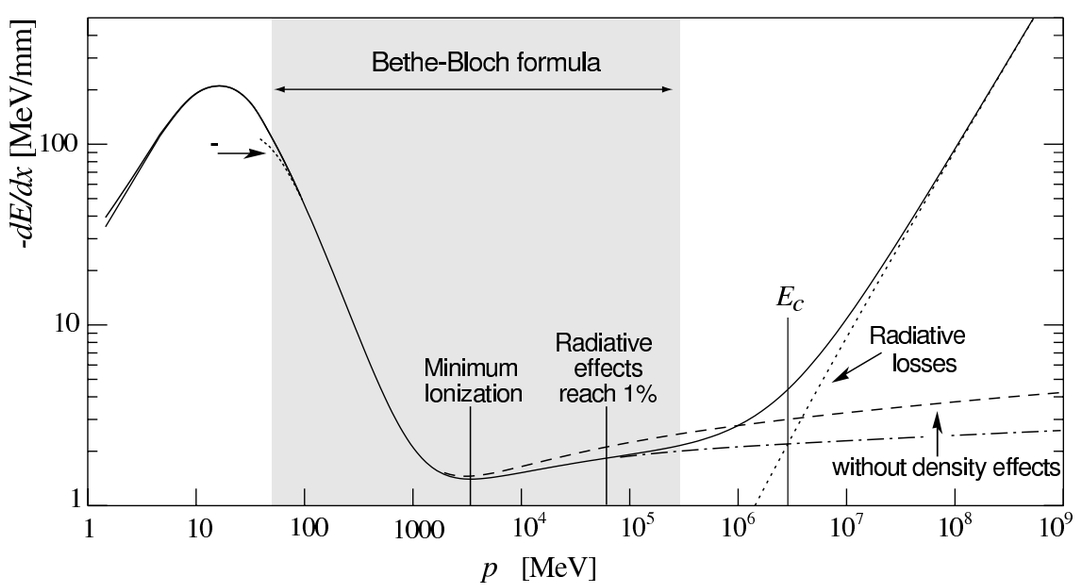

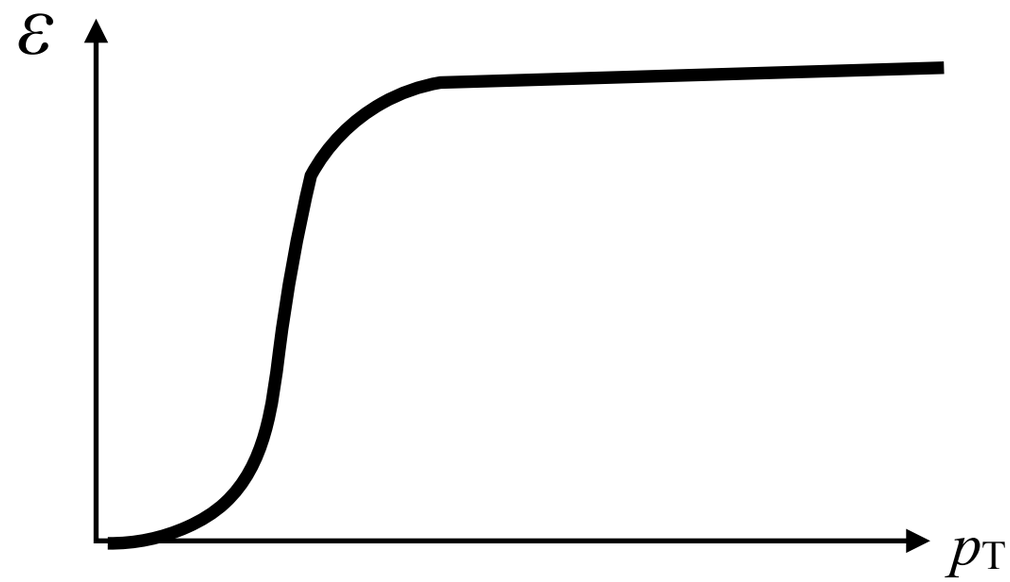

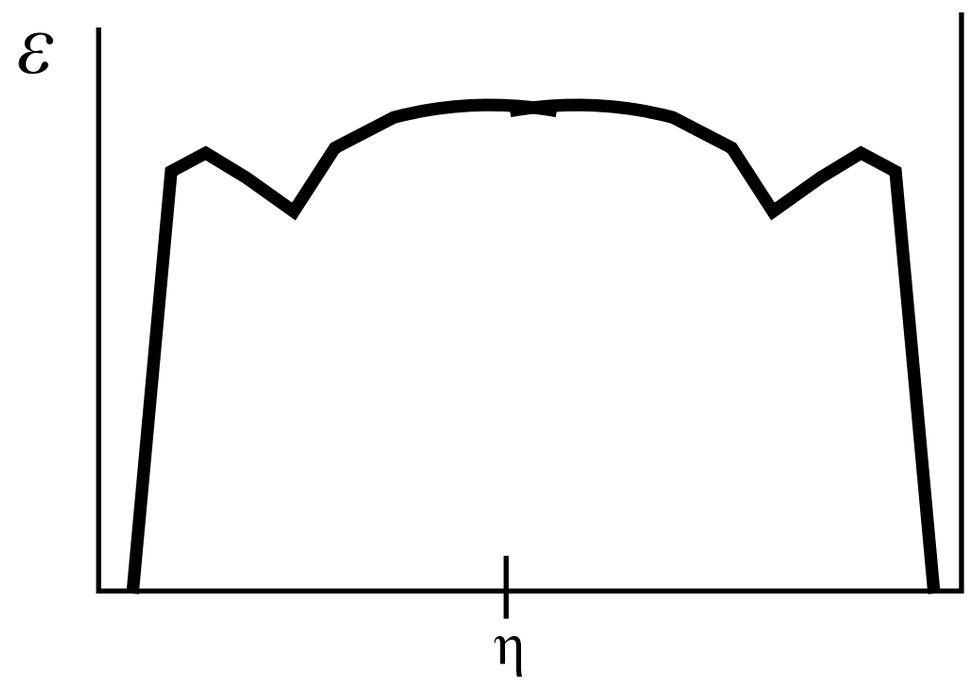

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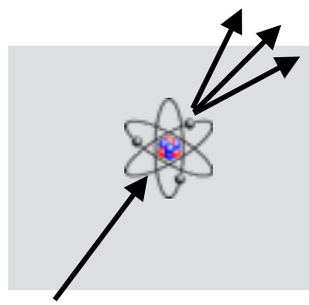

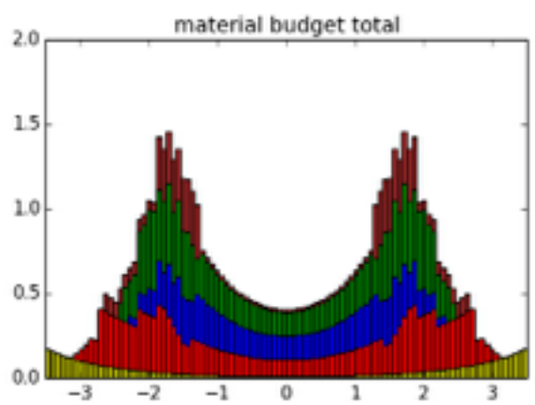

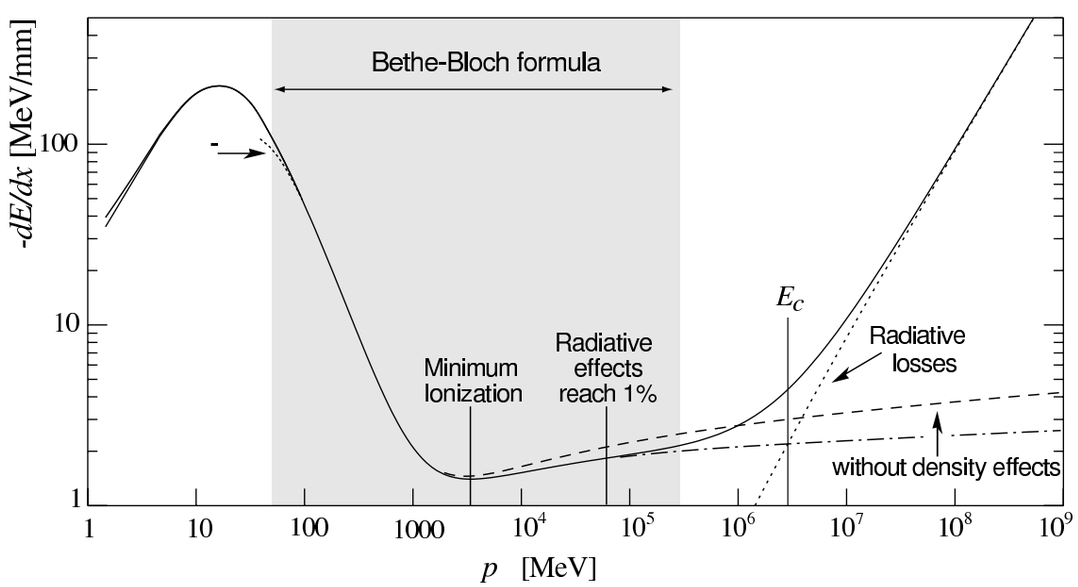

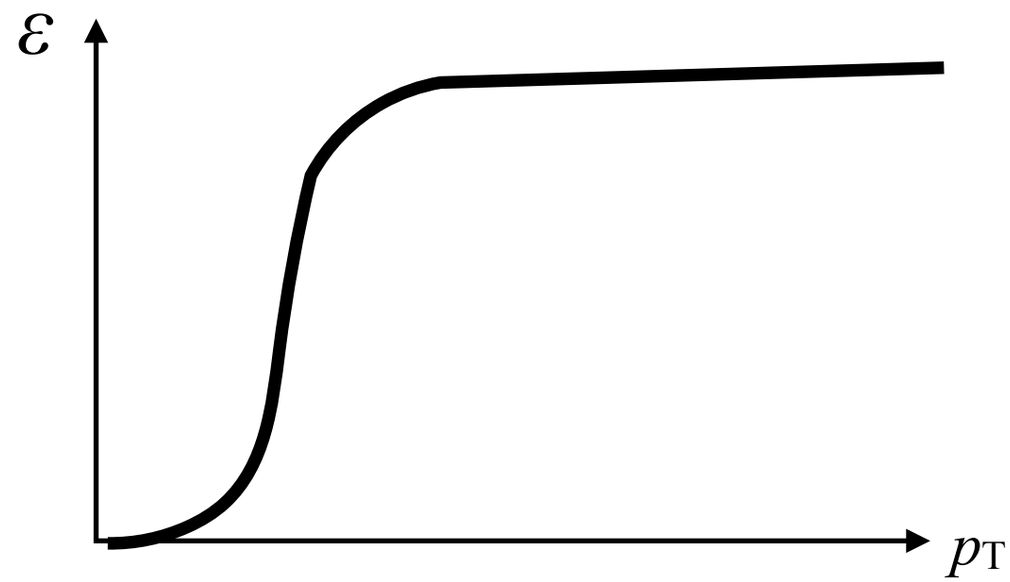

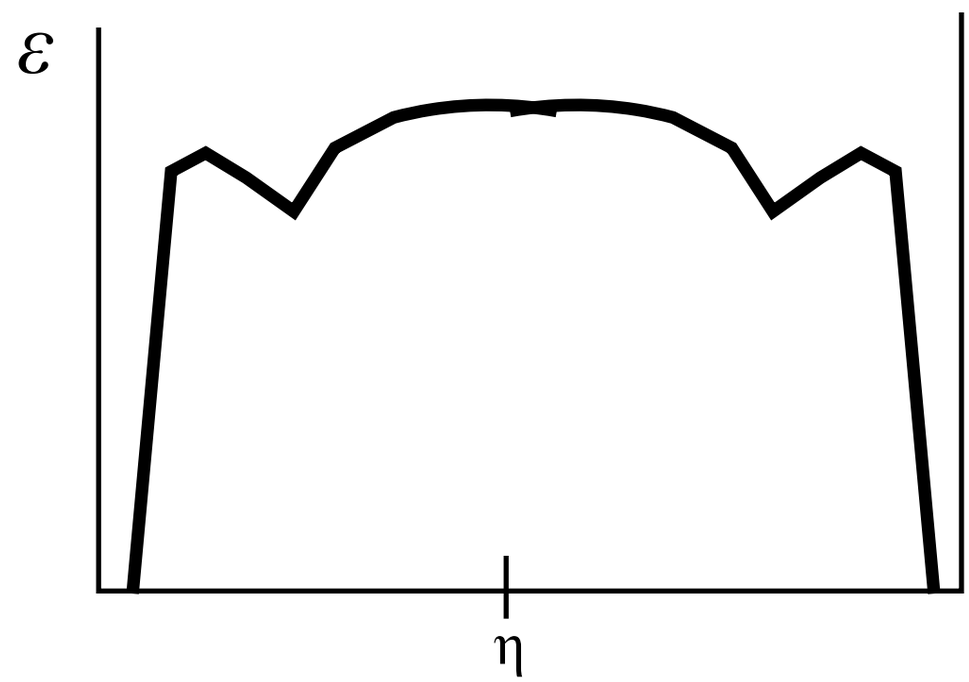

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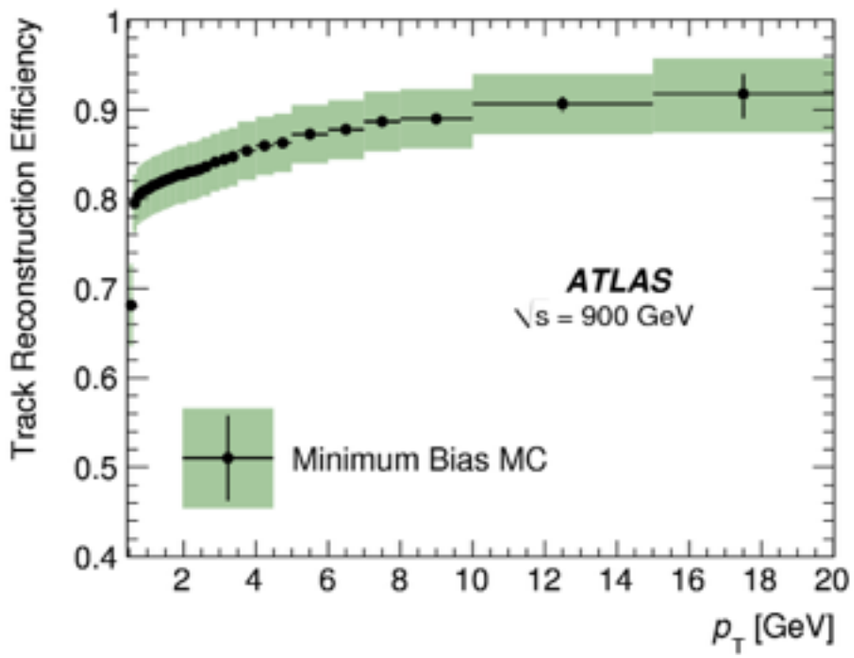

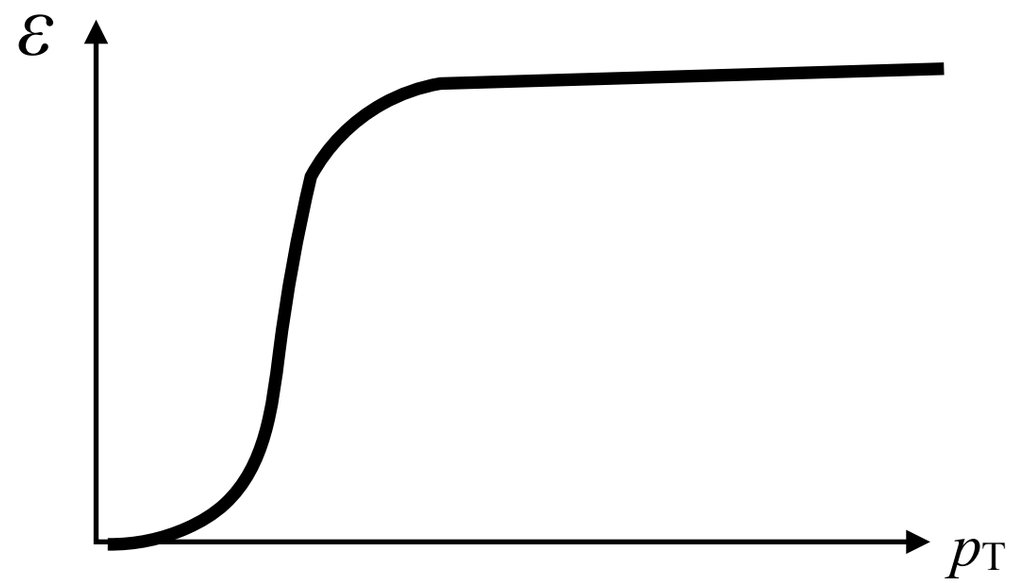

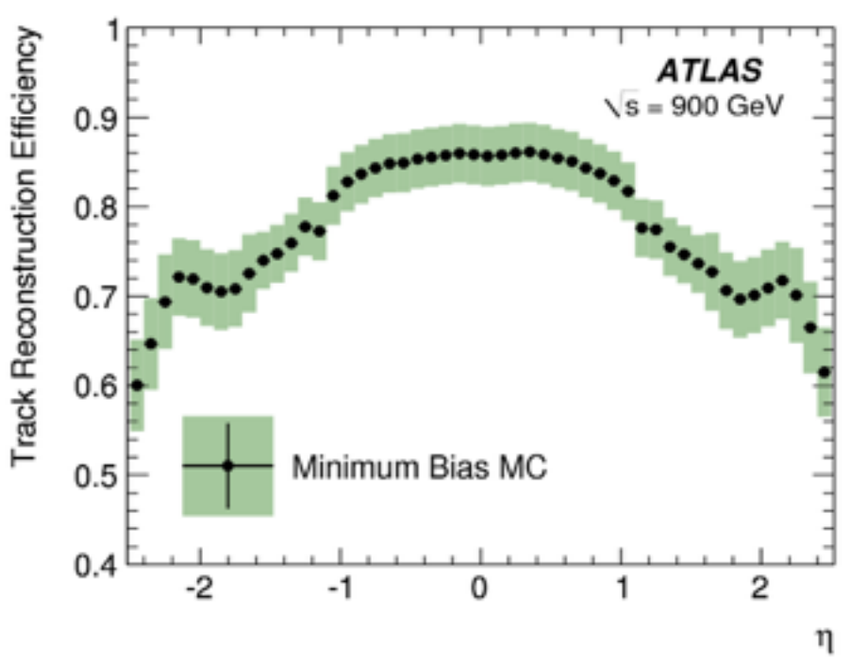

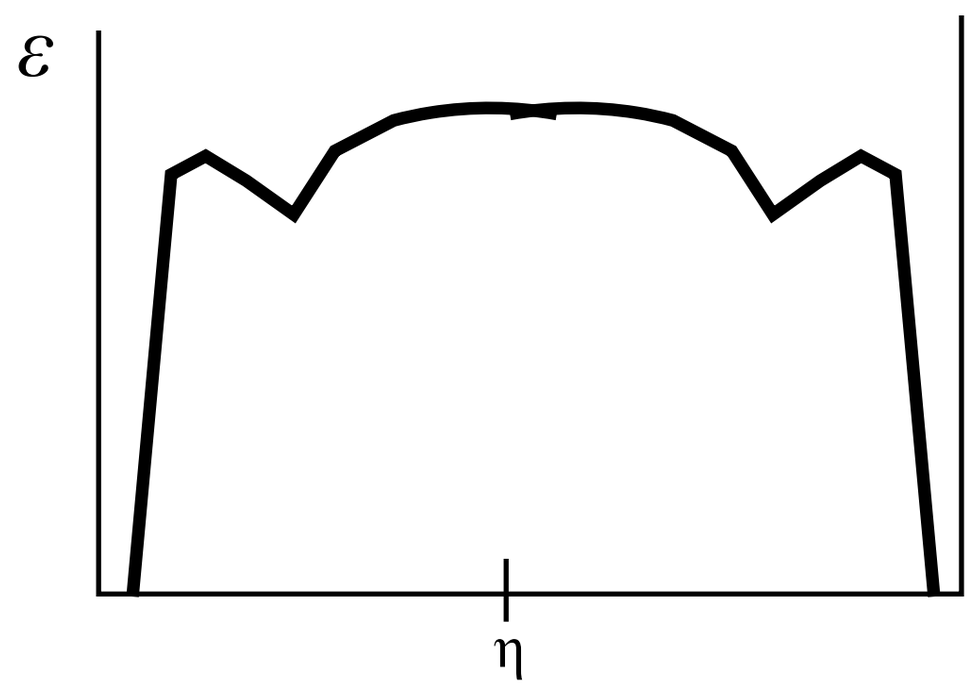

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where do
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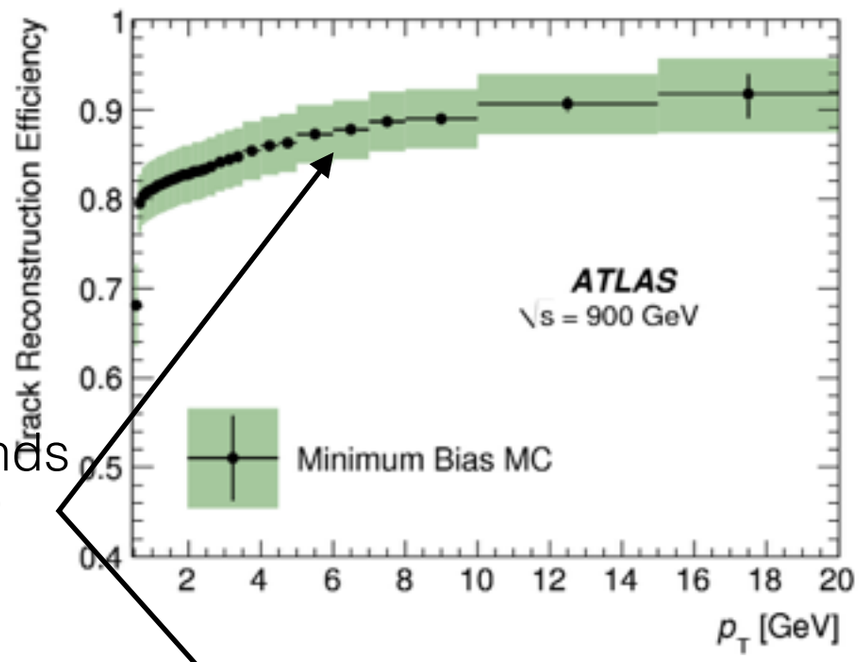

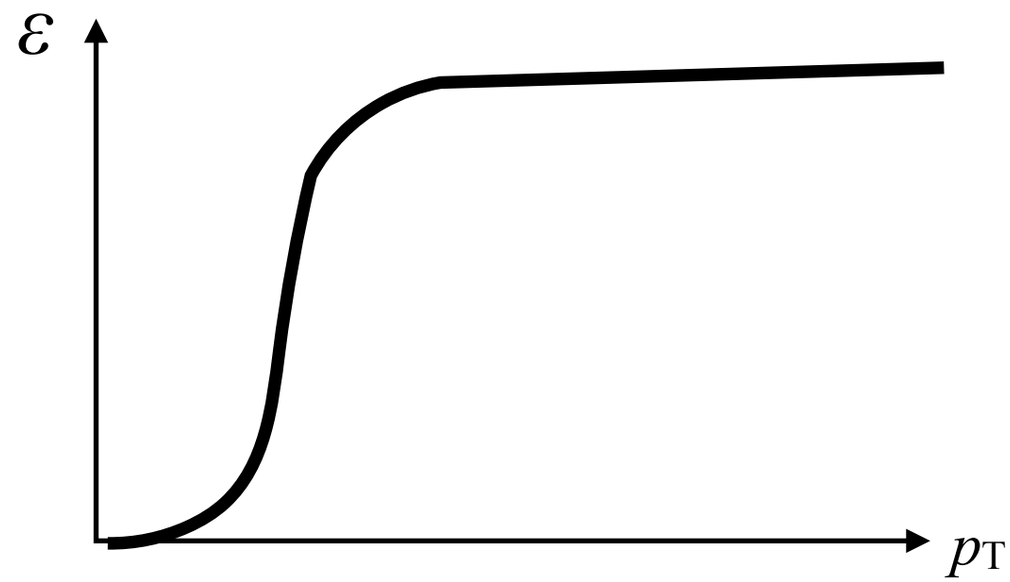

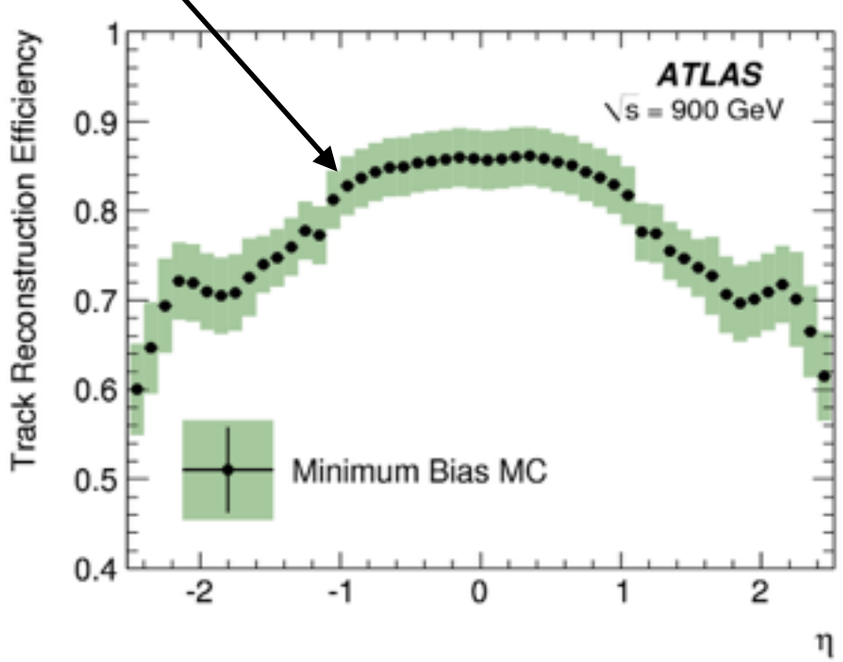

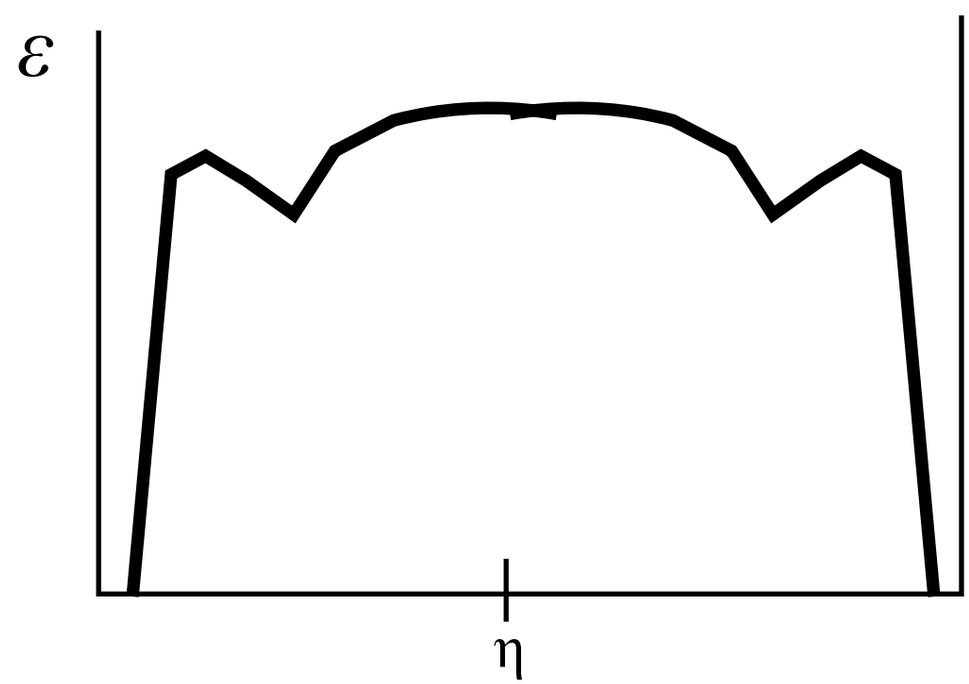

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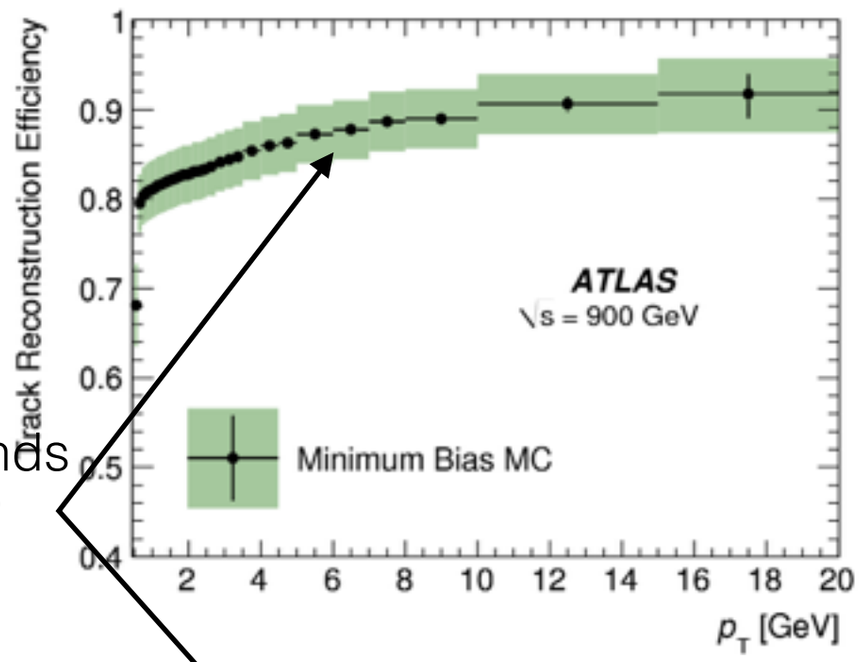
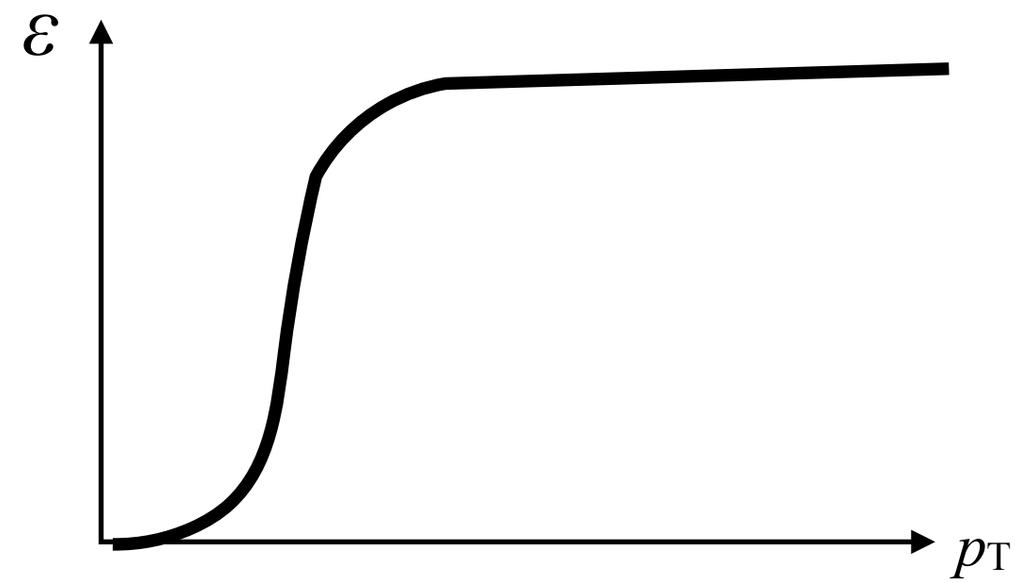
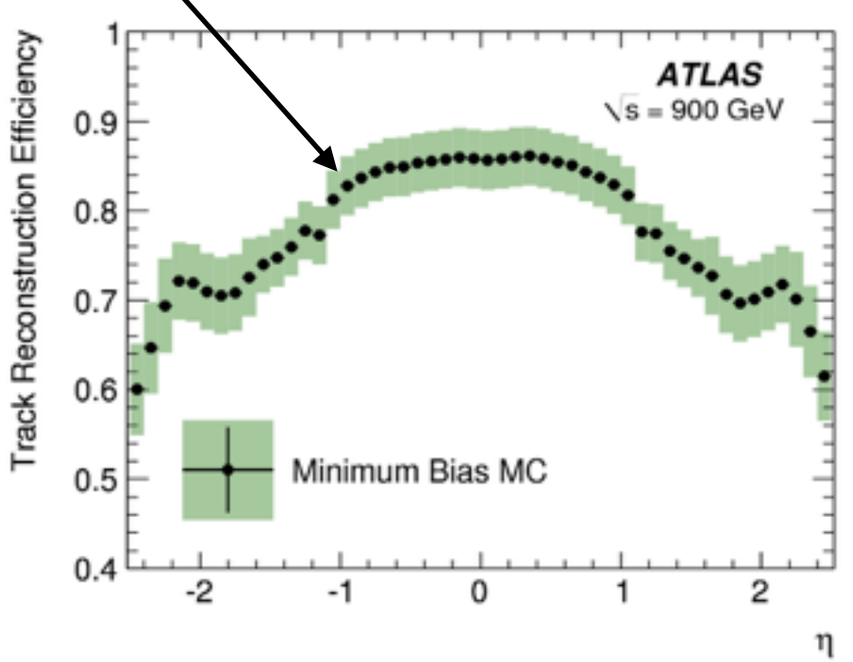
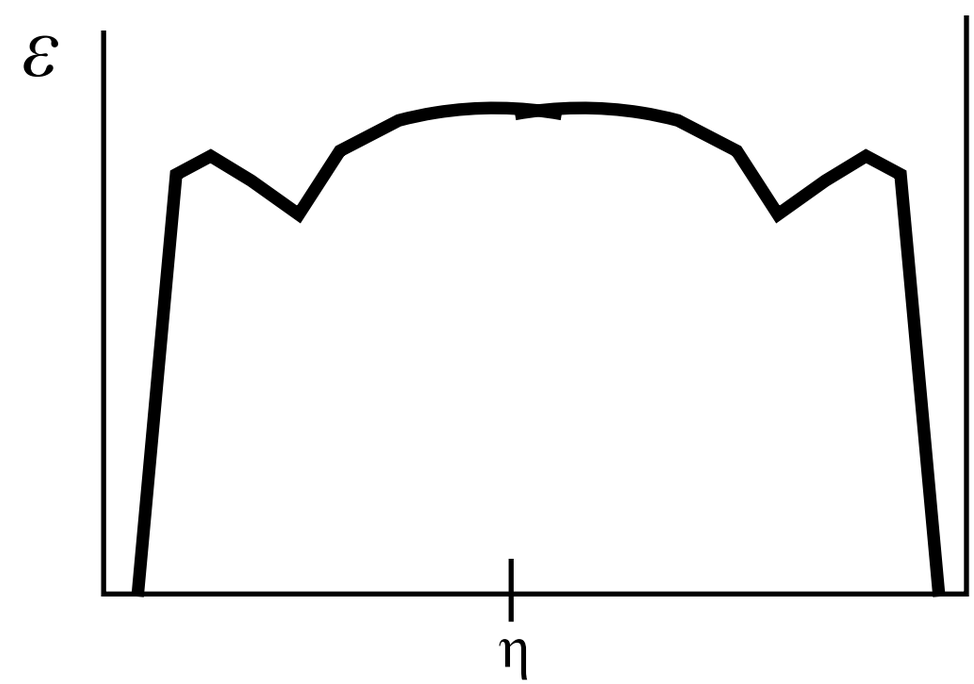




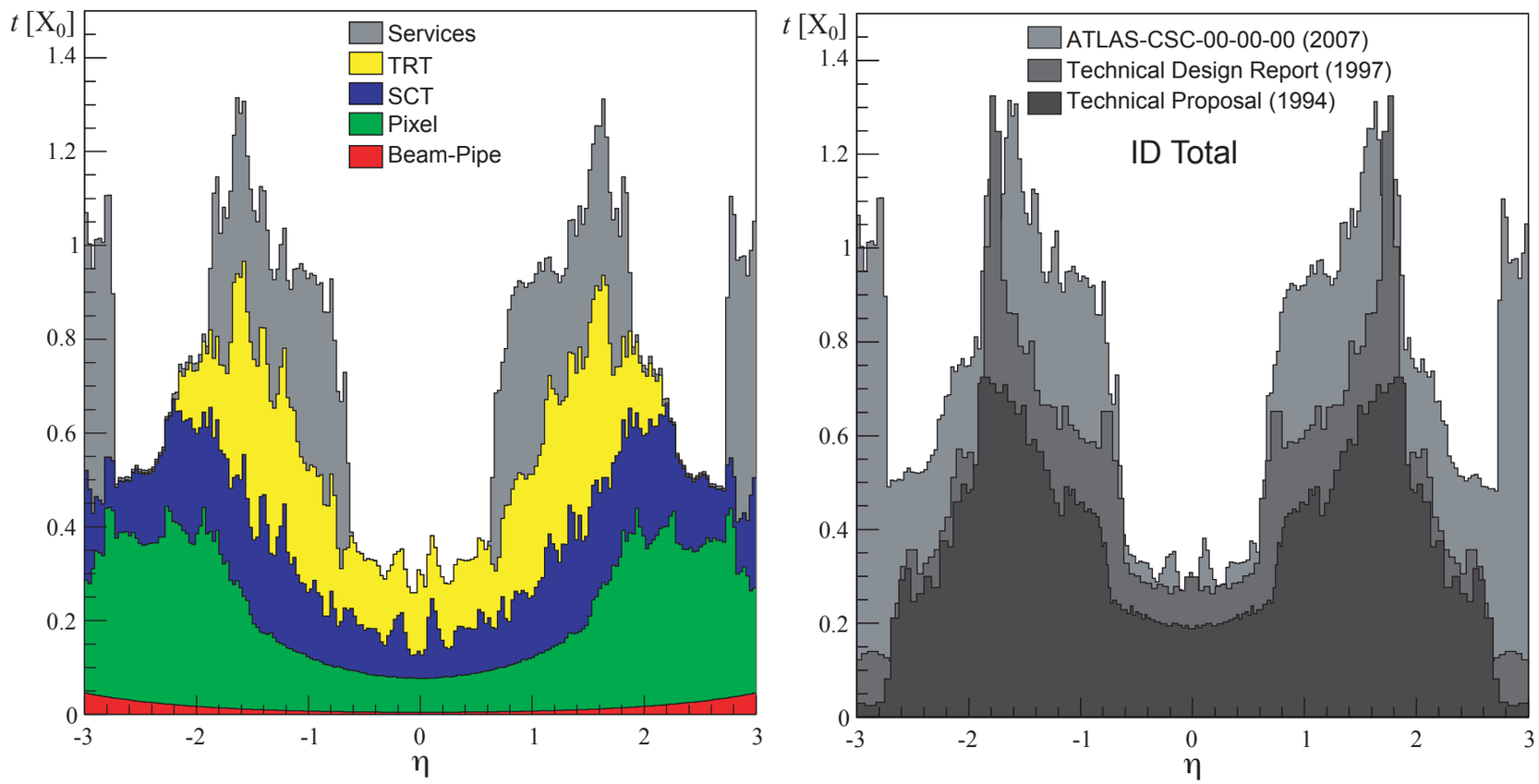
uncertainty of material modelling !





Measuring your detector material

- Hundreds of pages of TDRs and technical drawings before detector construction
  - still …

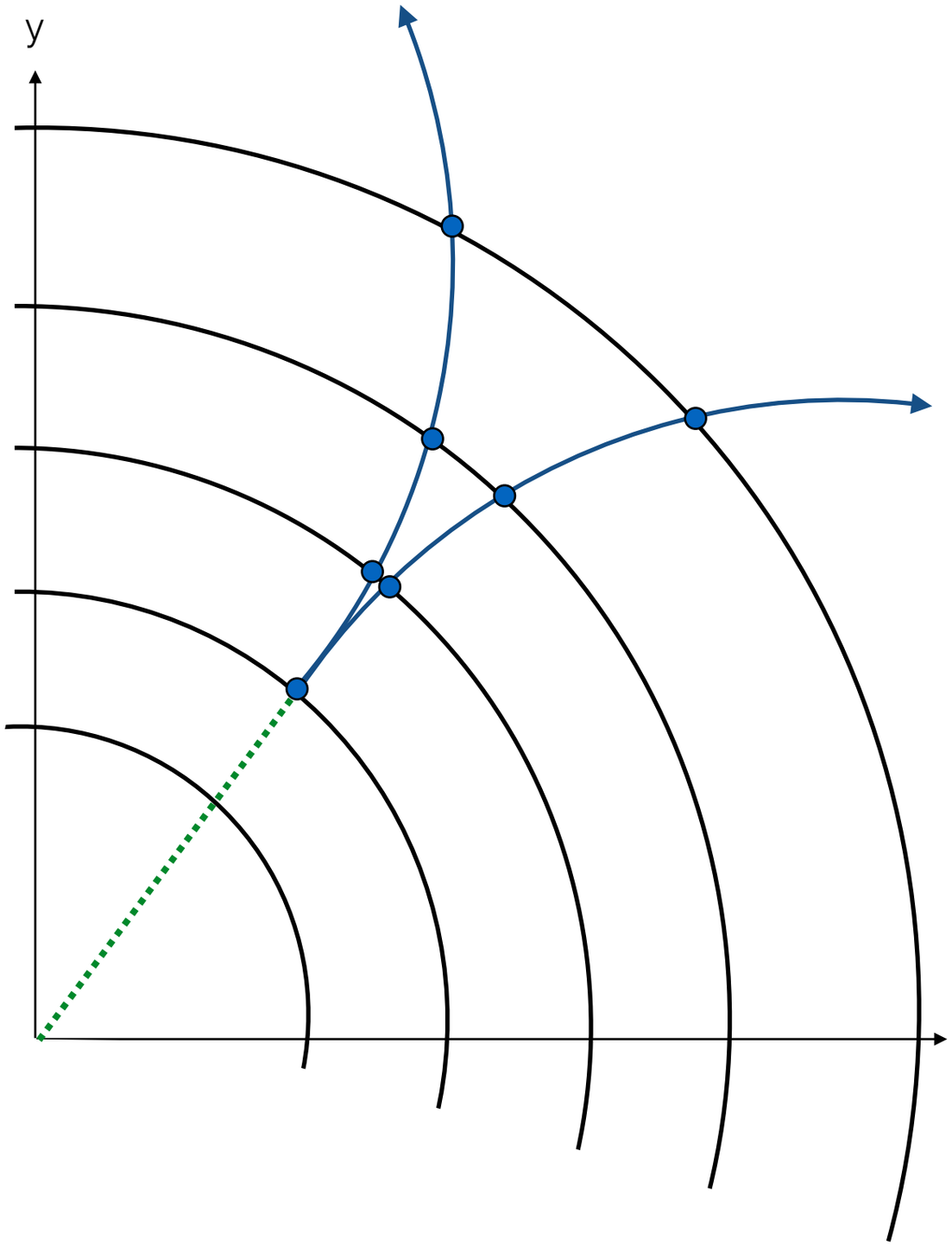


- ATLAS has actually weighted the detector before installing it and compared the weight to the one in simulation

- Best: measure the material in situ !

Using photon conversions

- Photons can convert into e^+e^- when hitting detector material
- 2-track vertices with electron PID
  - very clear signal
- Count conversion vertices in data and MC and compare
  - Is this really measuring the material ?
  - Are we just seeing an artefact of non-ideal simulation (cross-section …) ?



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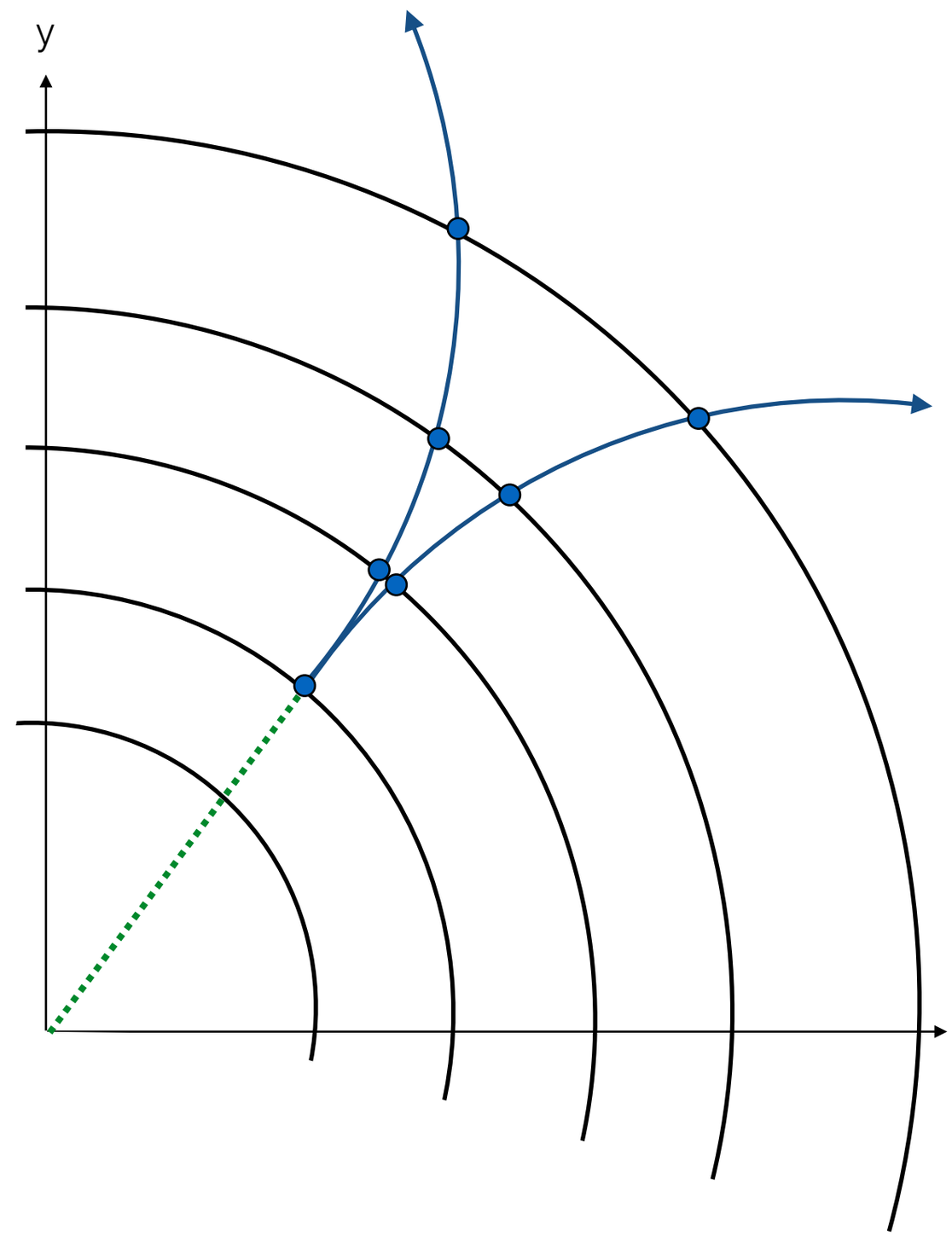

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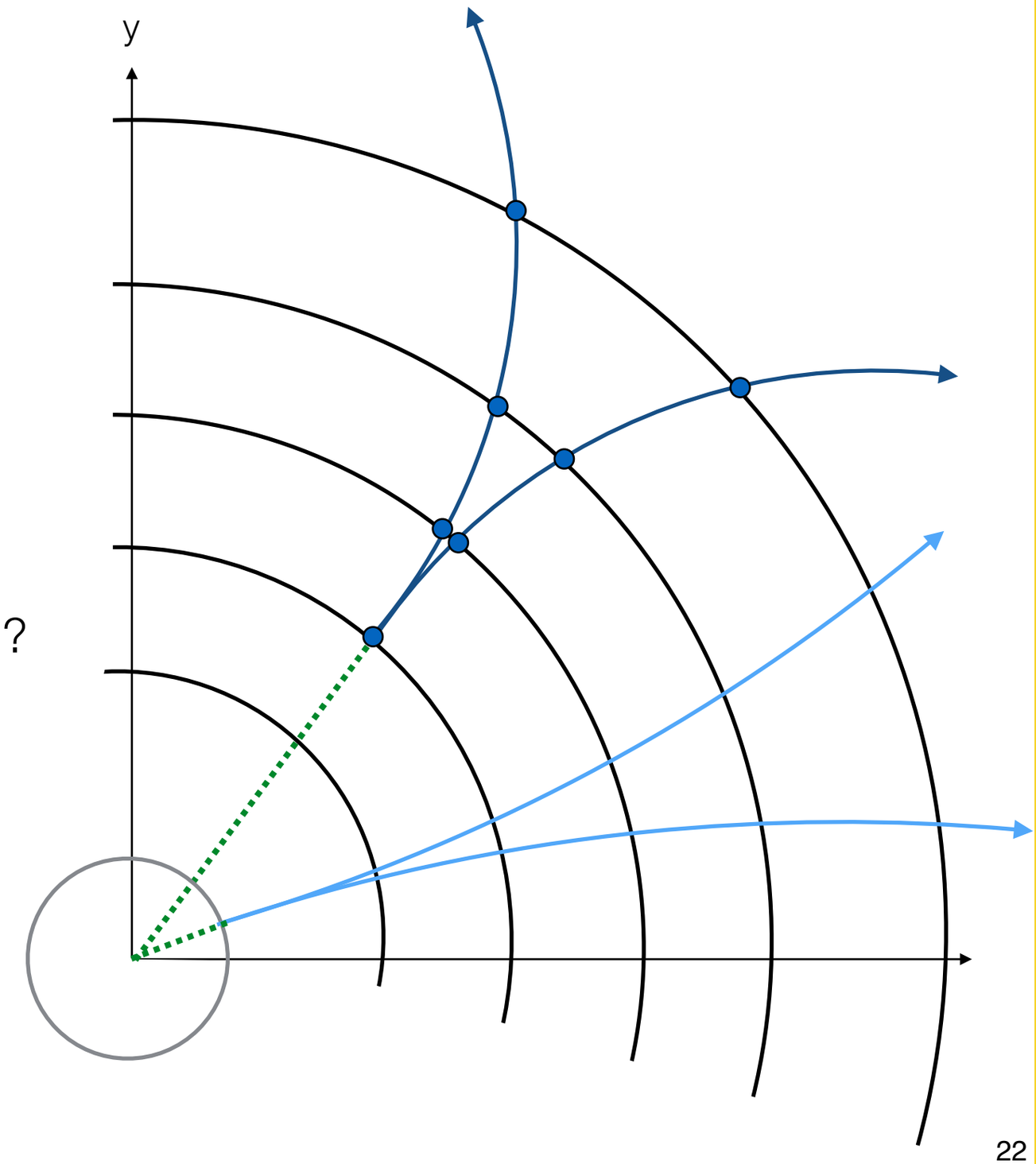

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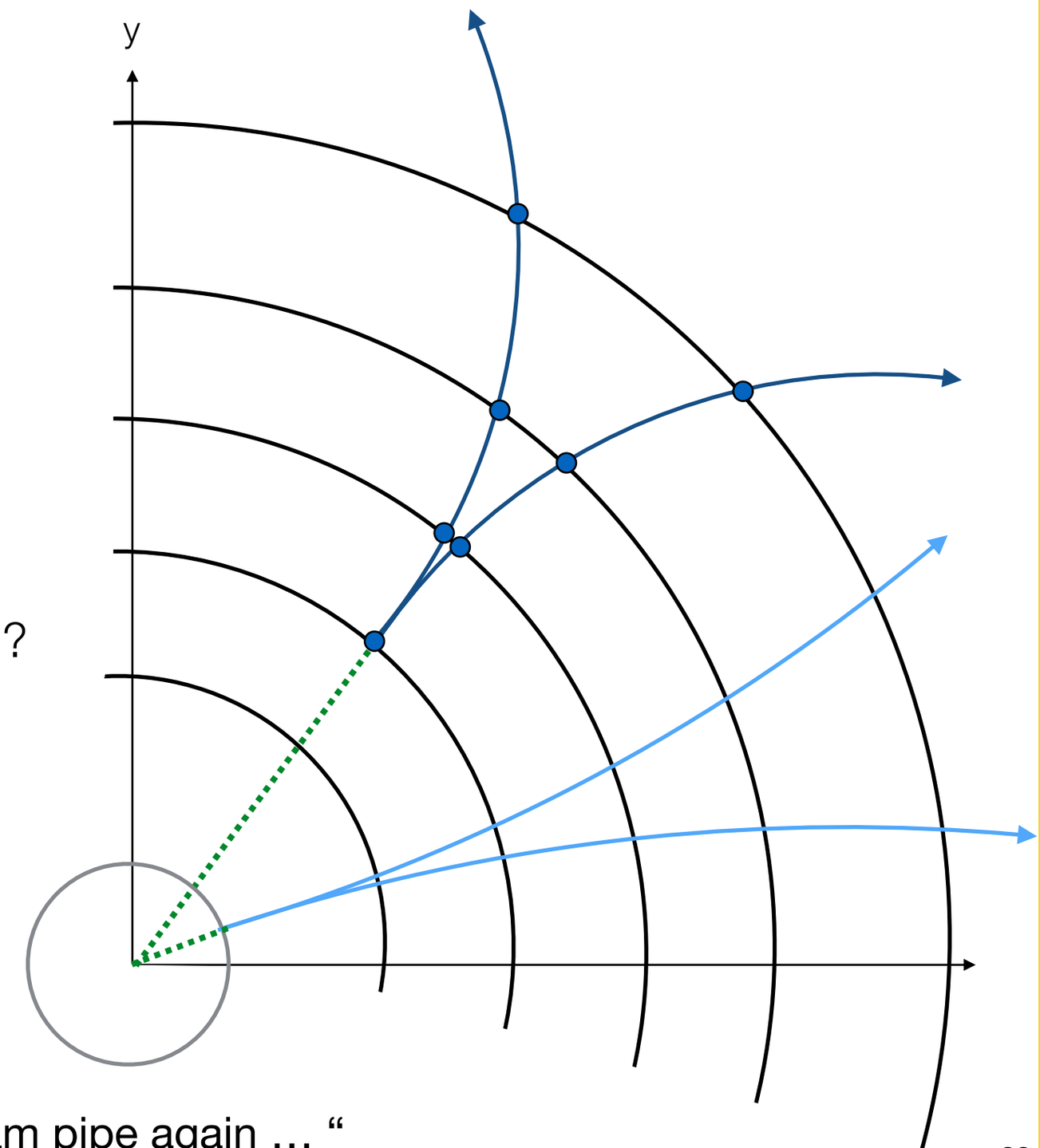
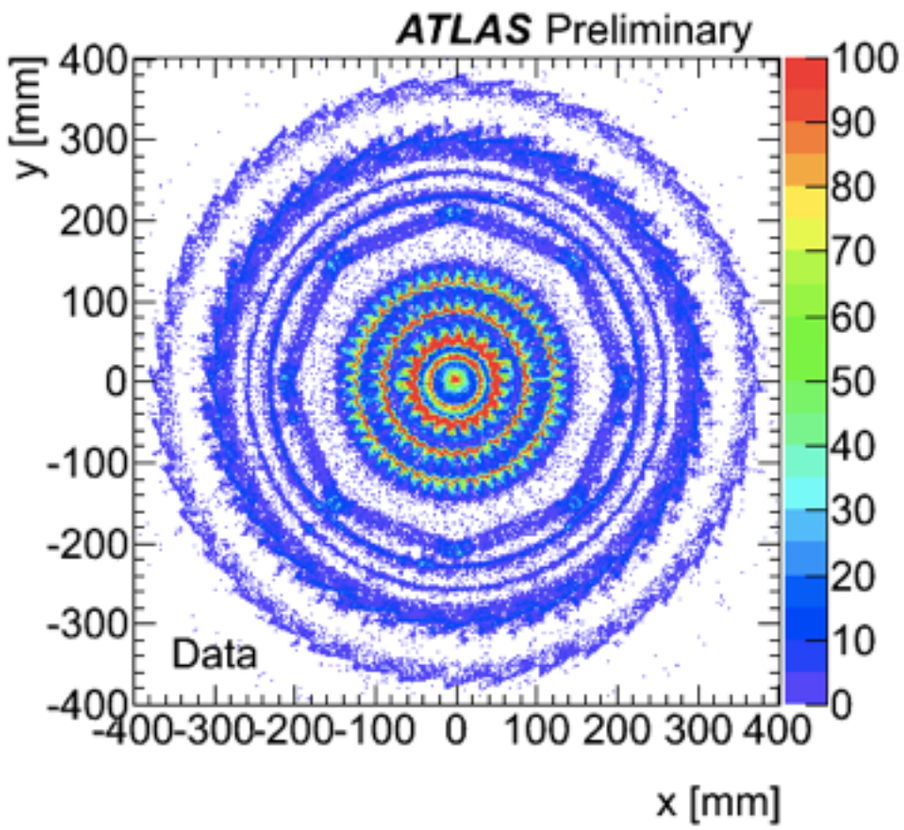
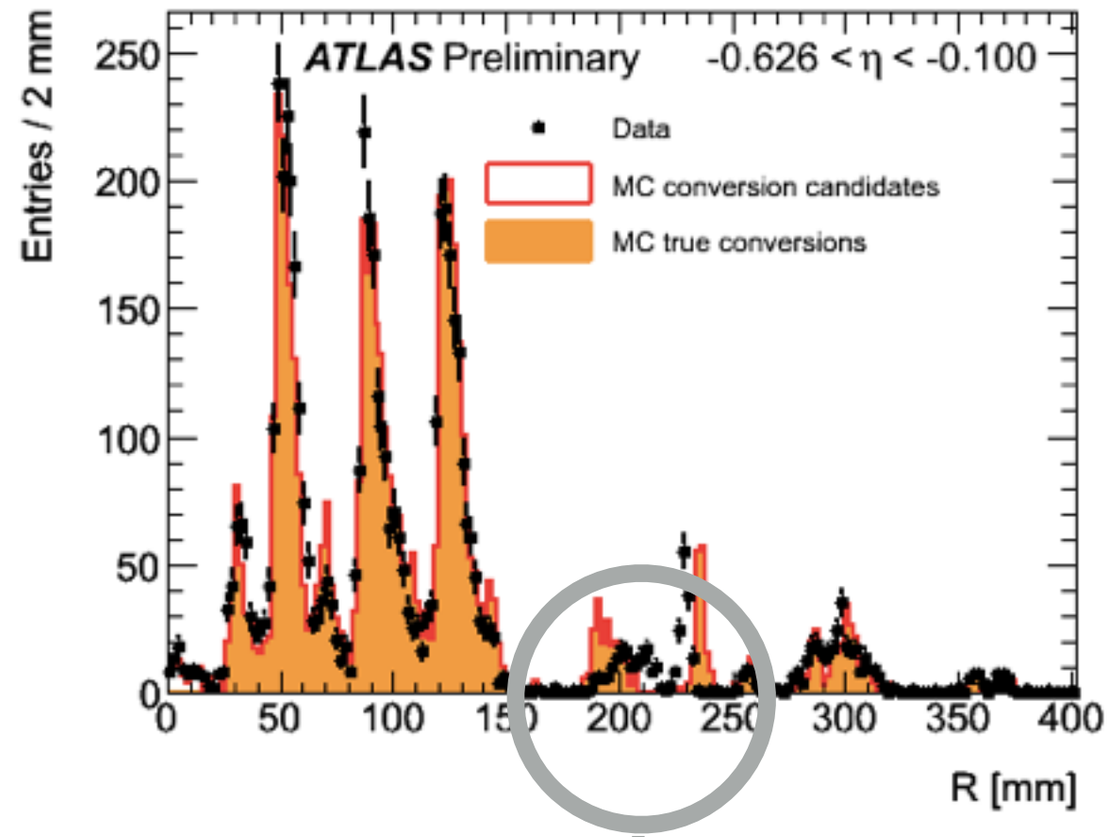


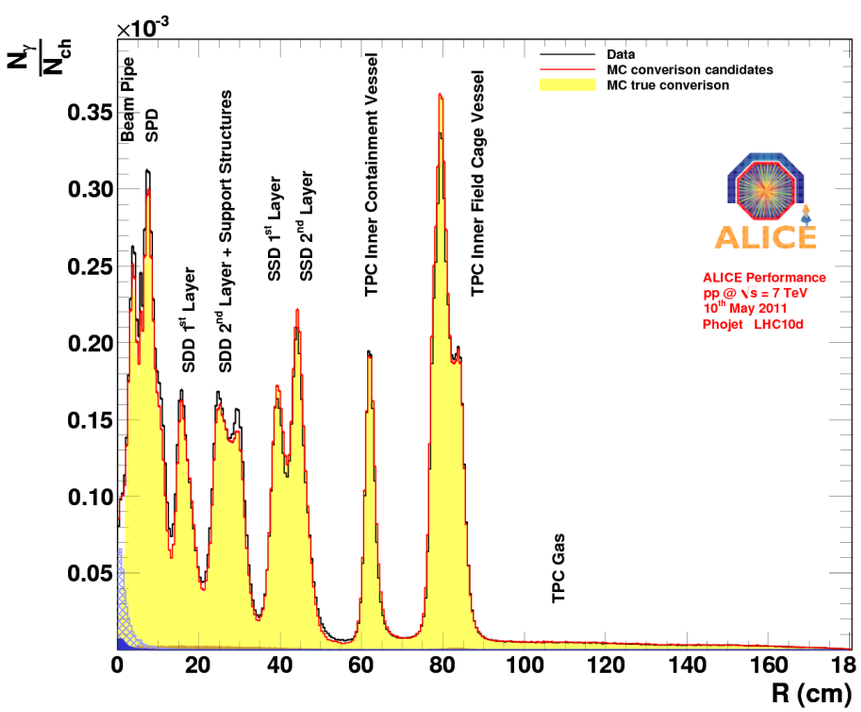
remember ?

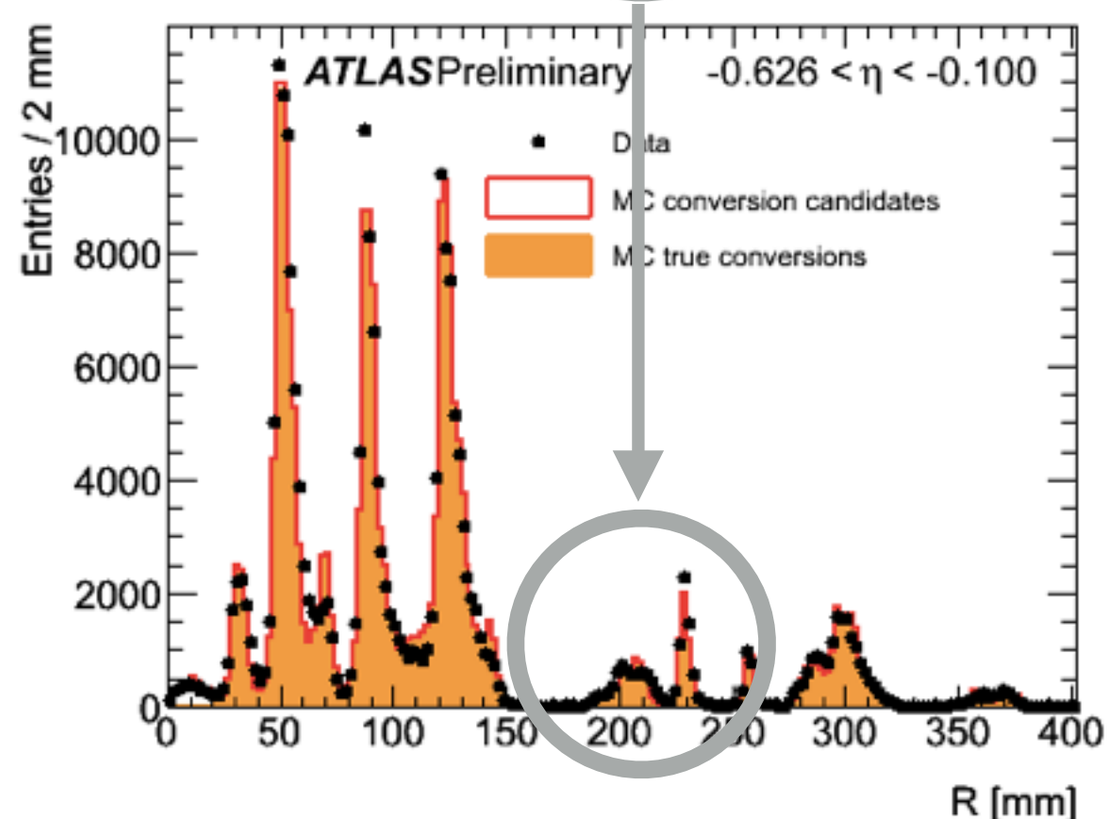
"… ATLAS is trying to measure the old beam pipe again … "

Using photon conversions



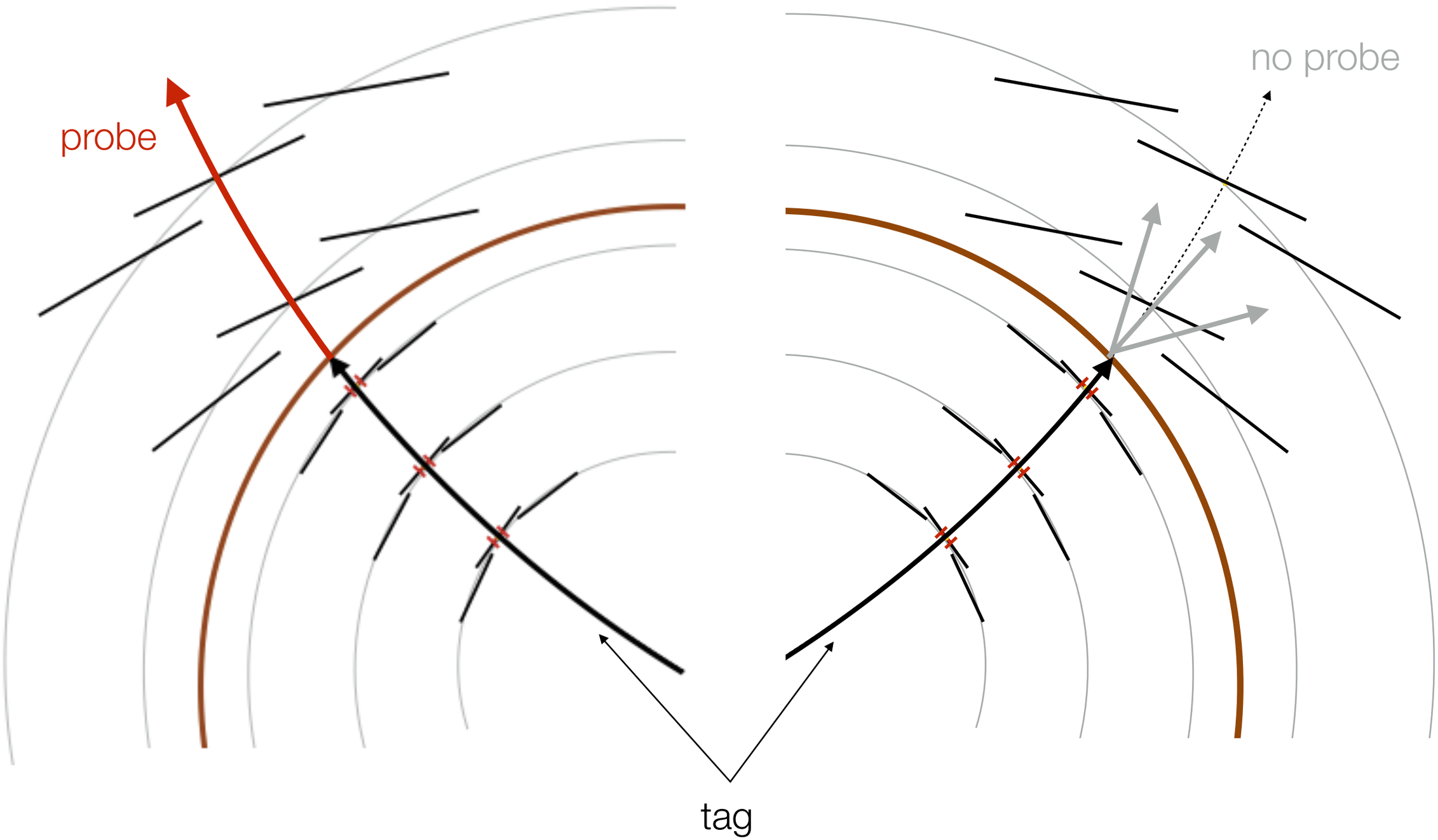






Using hadronic Interactions

- The straight-forward way
  - measure how often tracks “survive” when passing material



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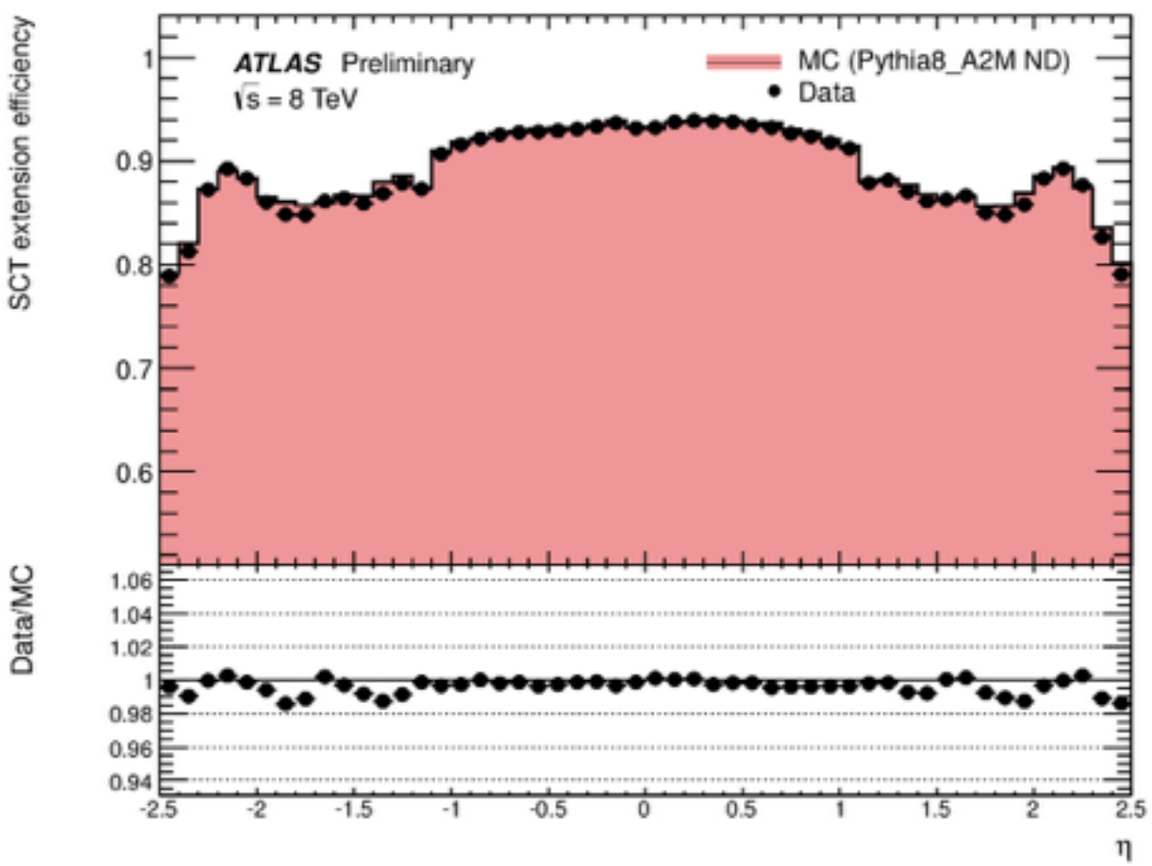
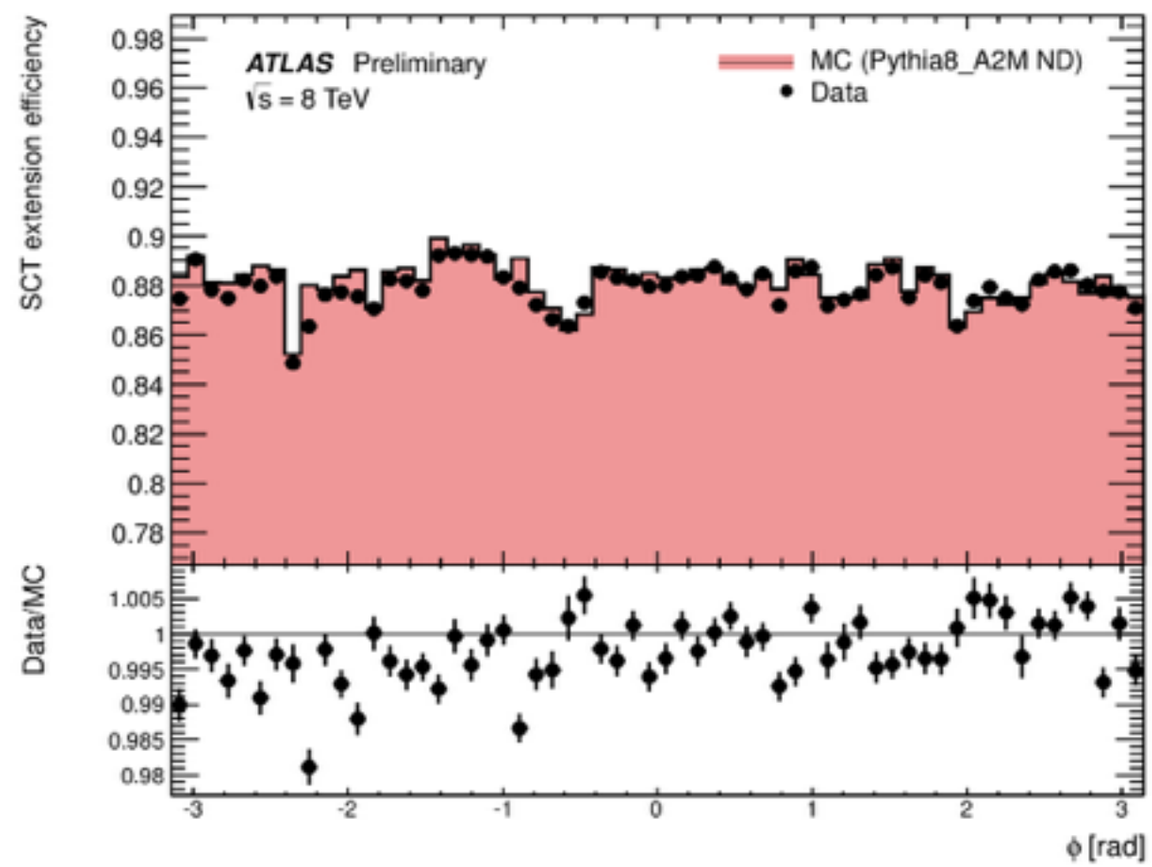
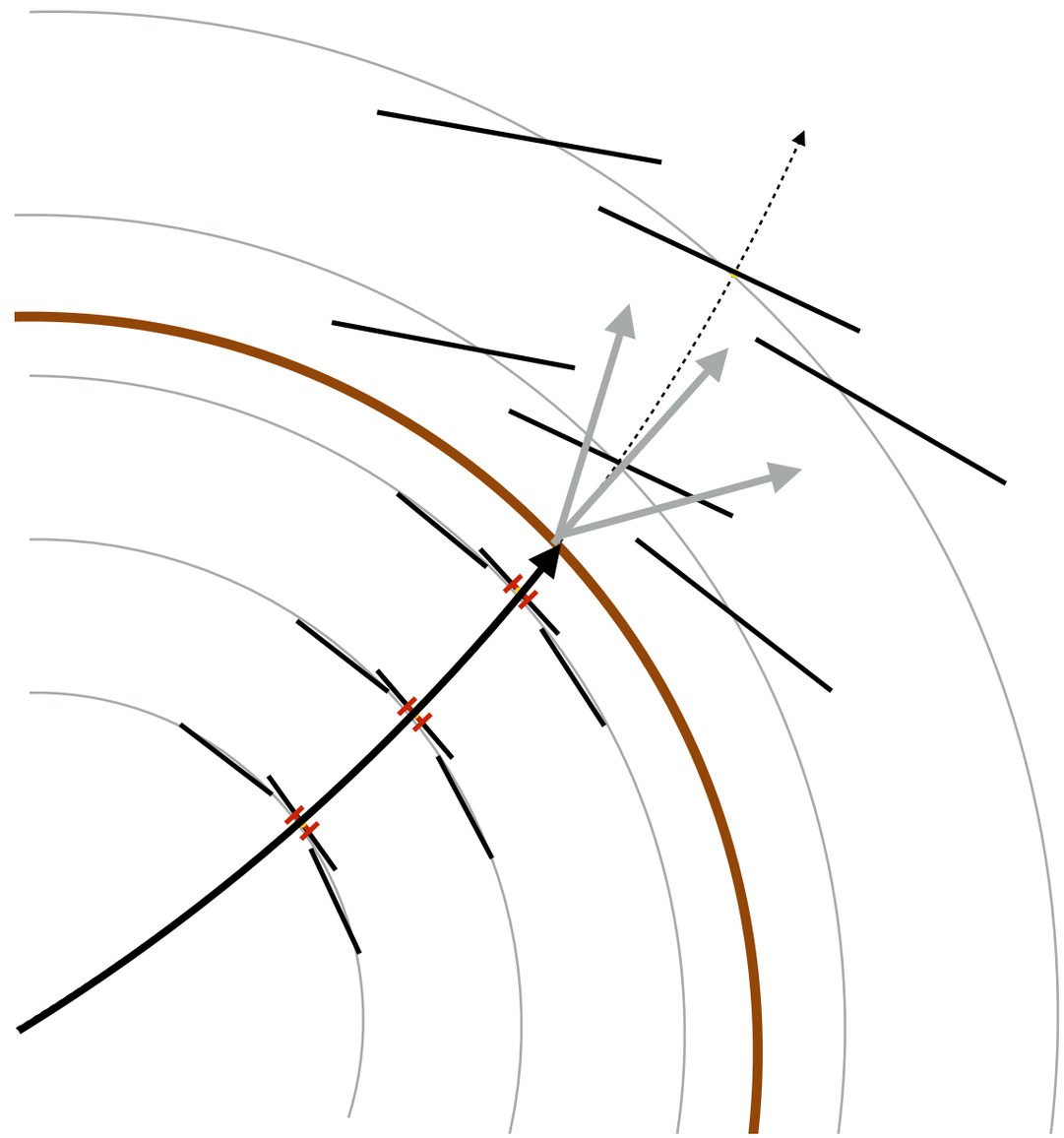




Using hadronic Interactions

- The more sophisticated way
  - assume we can configure our track reconstruction to also reconstruct the charged particles coming out of a hadronic interaction
  - let's try to use our vertex reconstruction skills and try to reconstruct the vertices from hadronic interactions



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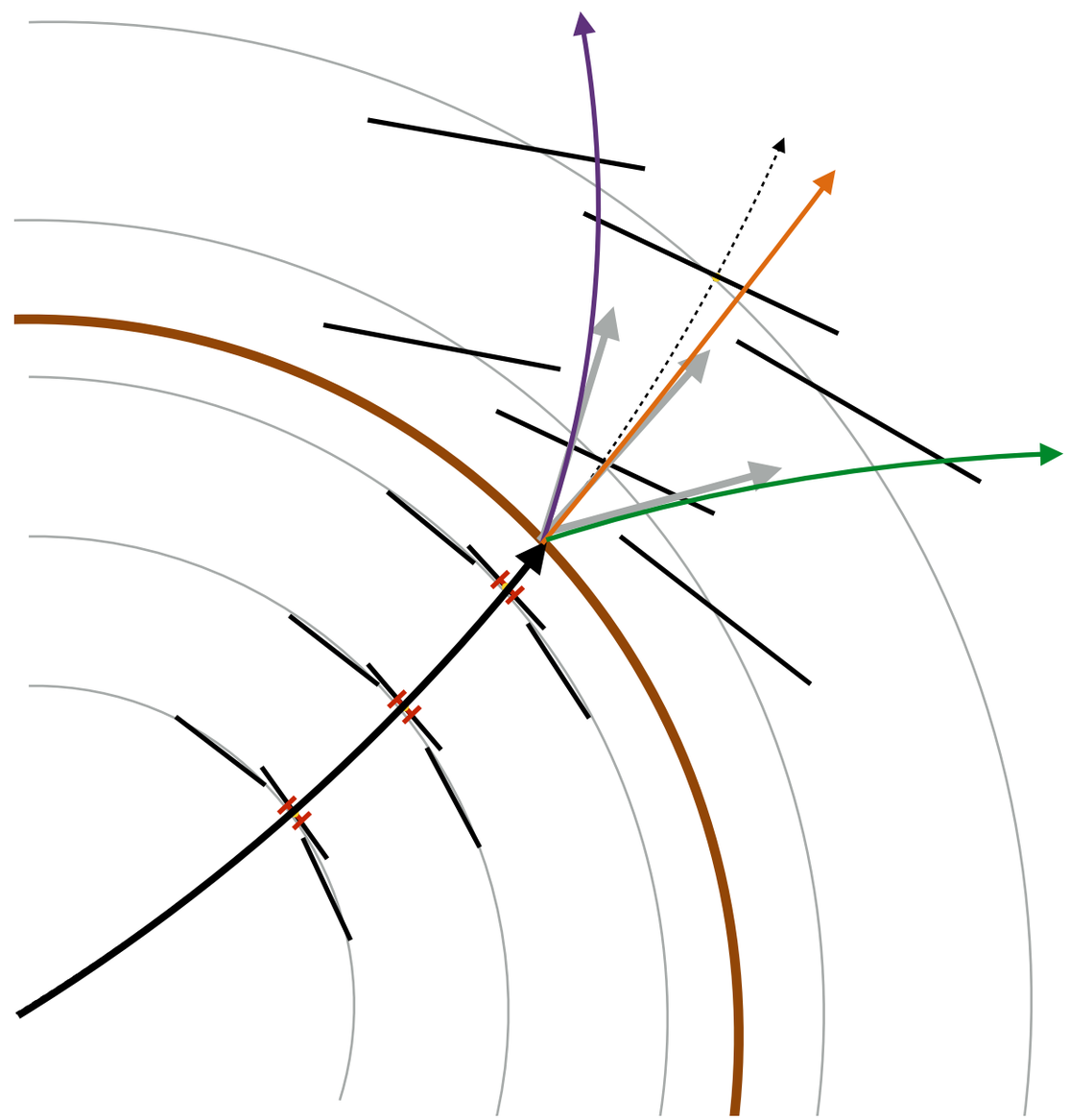

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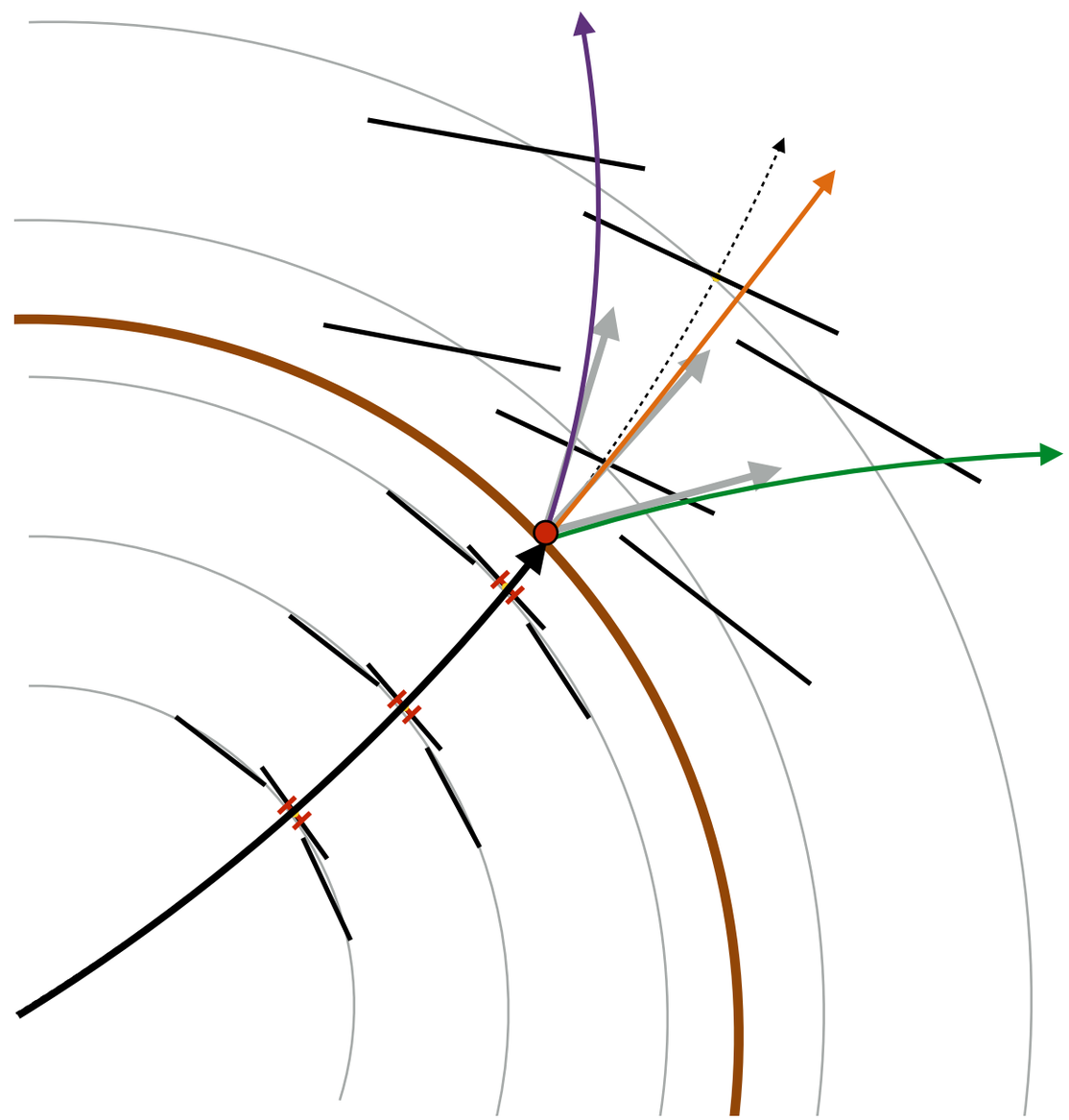

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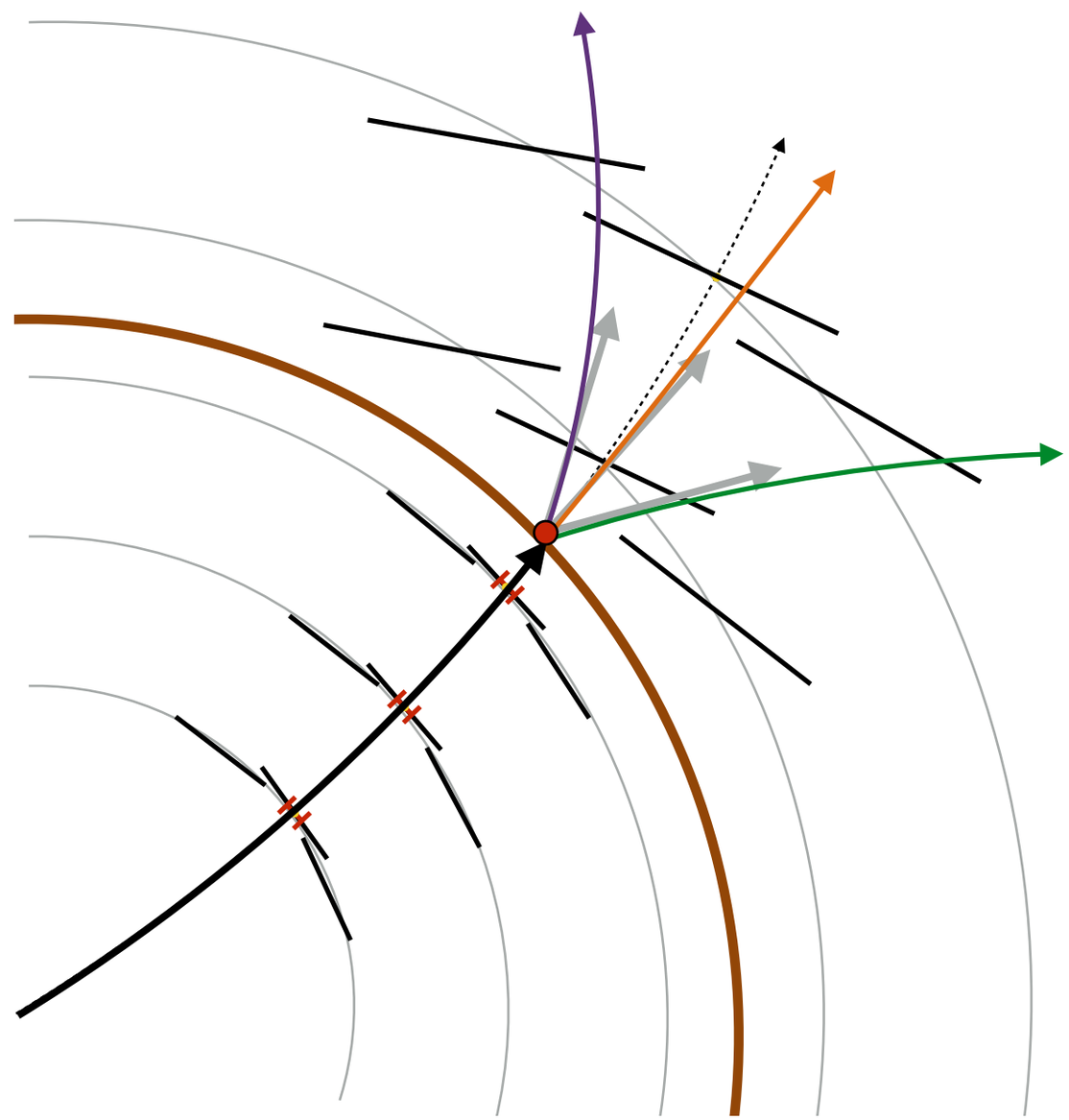
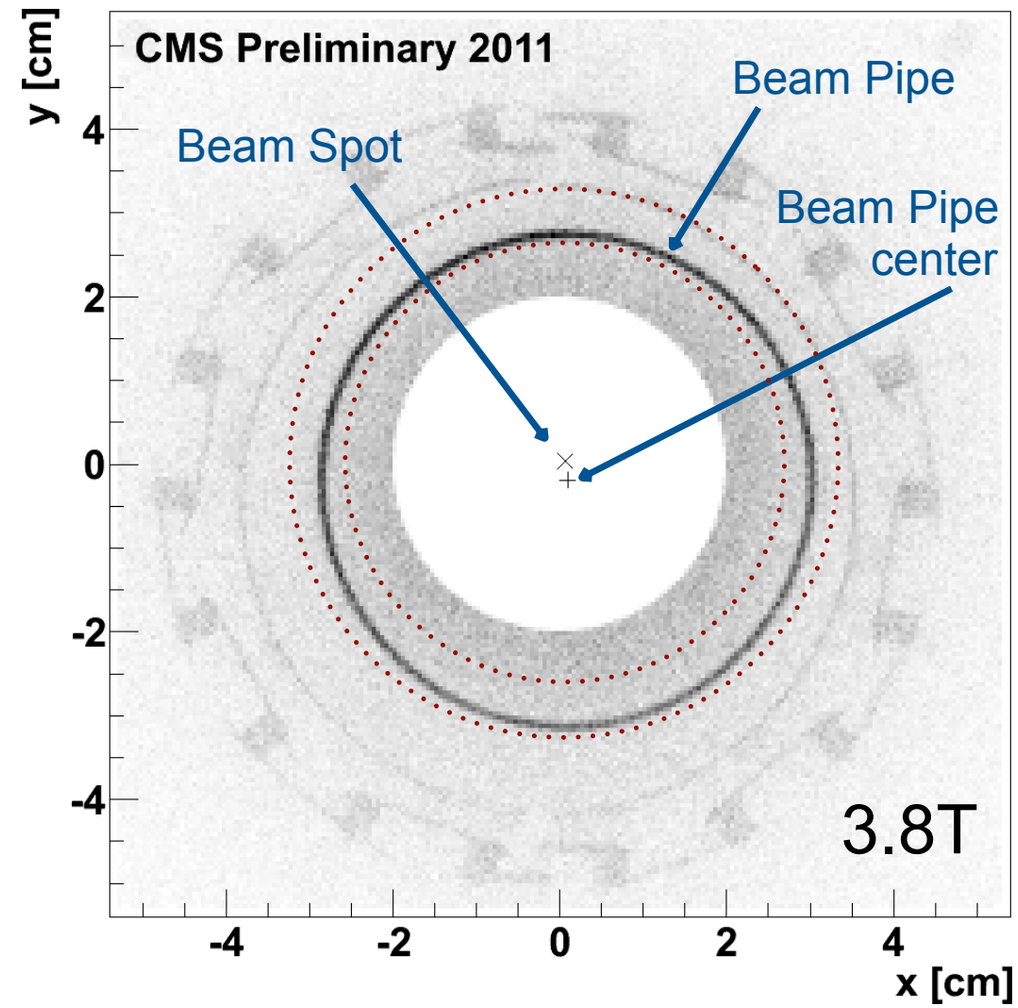
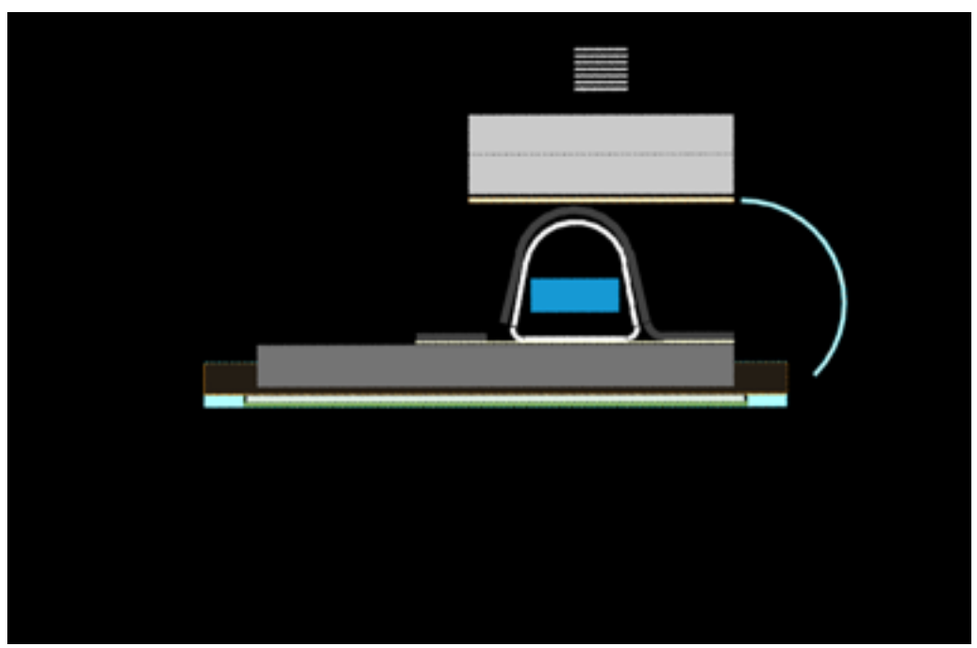
What do you need to be very careful about ?

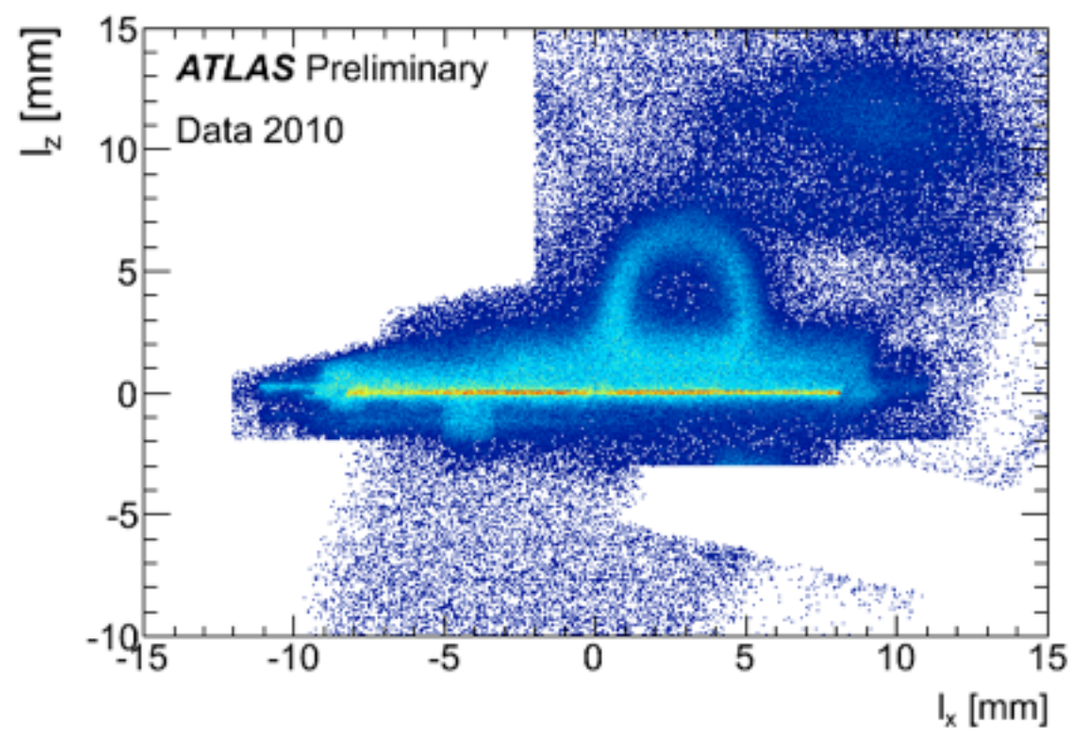


Using hadronic Interactions

- Both CMS & ATLAS have achieved astonishing results with this technique
  - offset of nominal beam pipe seen for both experiments
  - accuracy of material measurement for ATLAS ~8 %

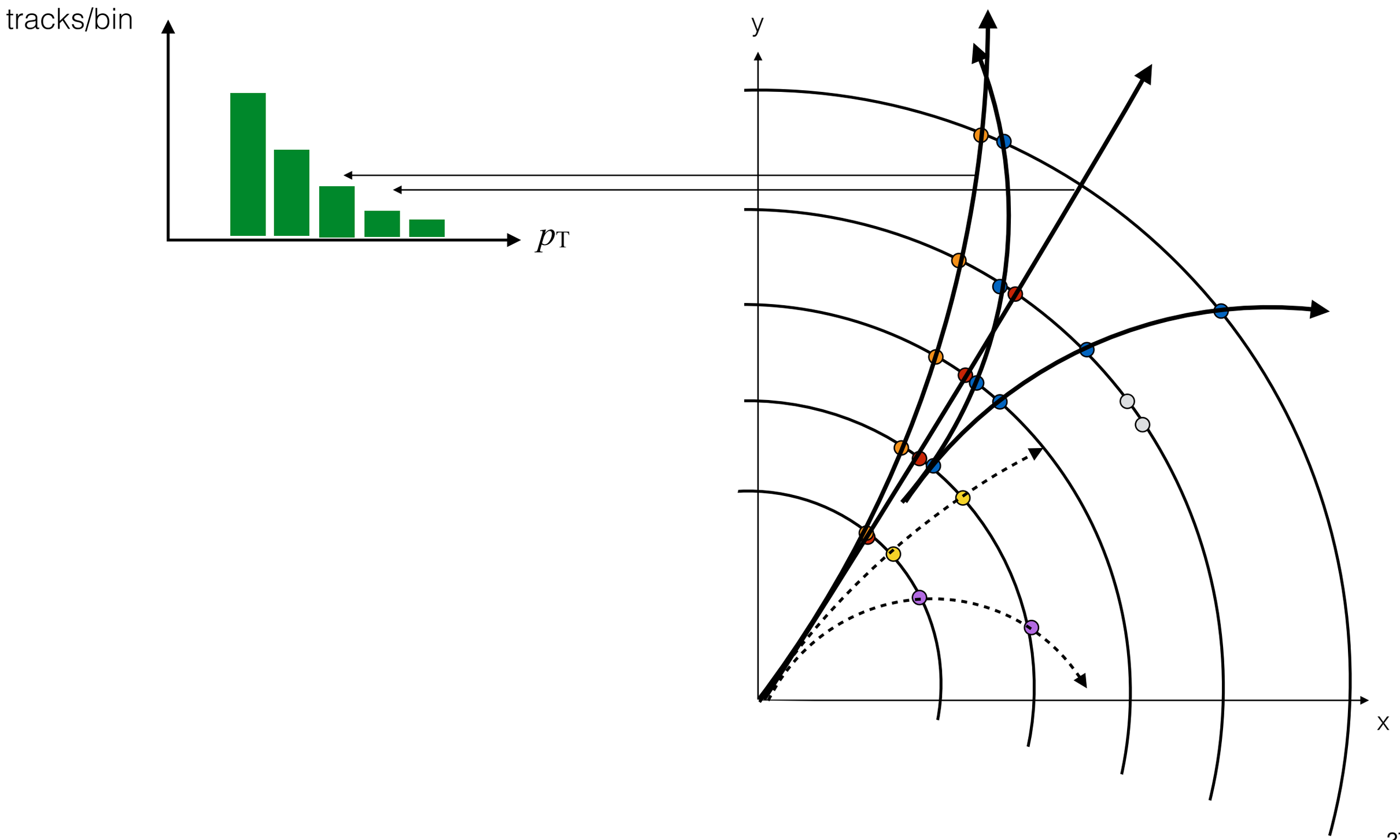






Example: charged particle multiplicity

- Let's finish the analysis



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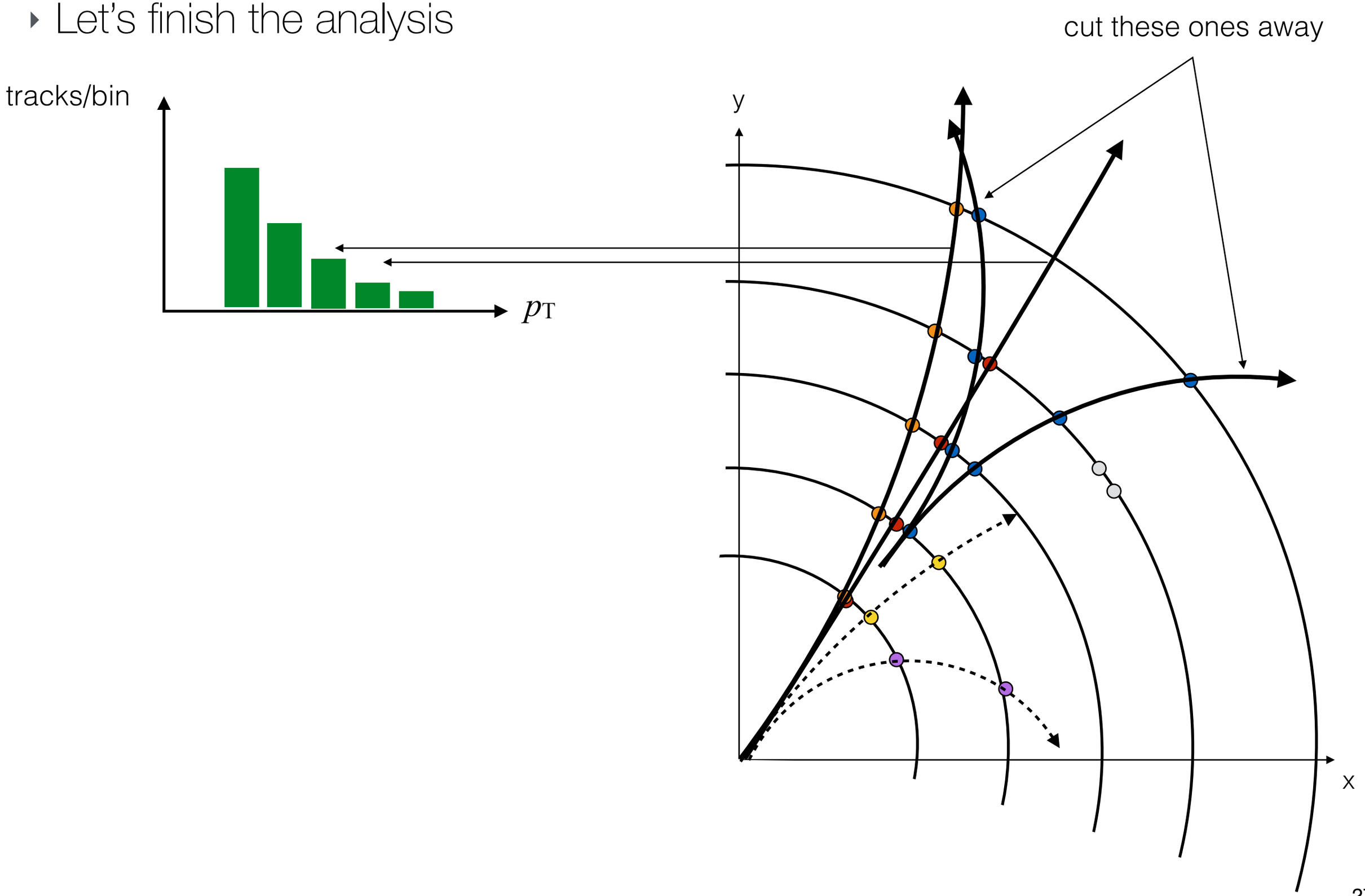

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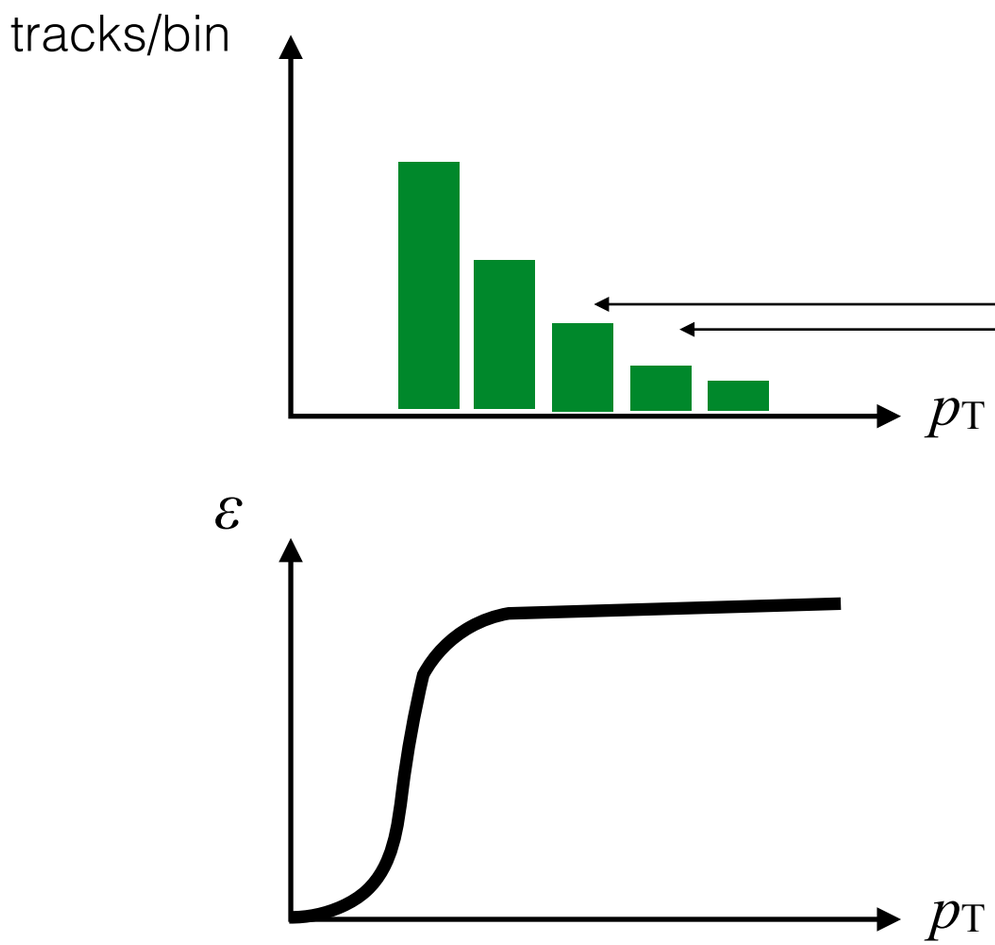

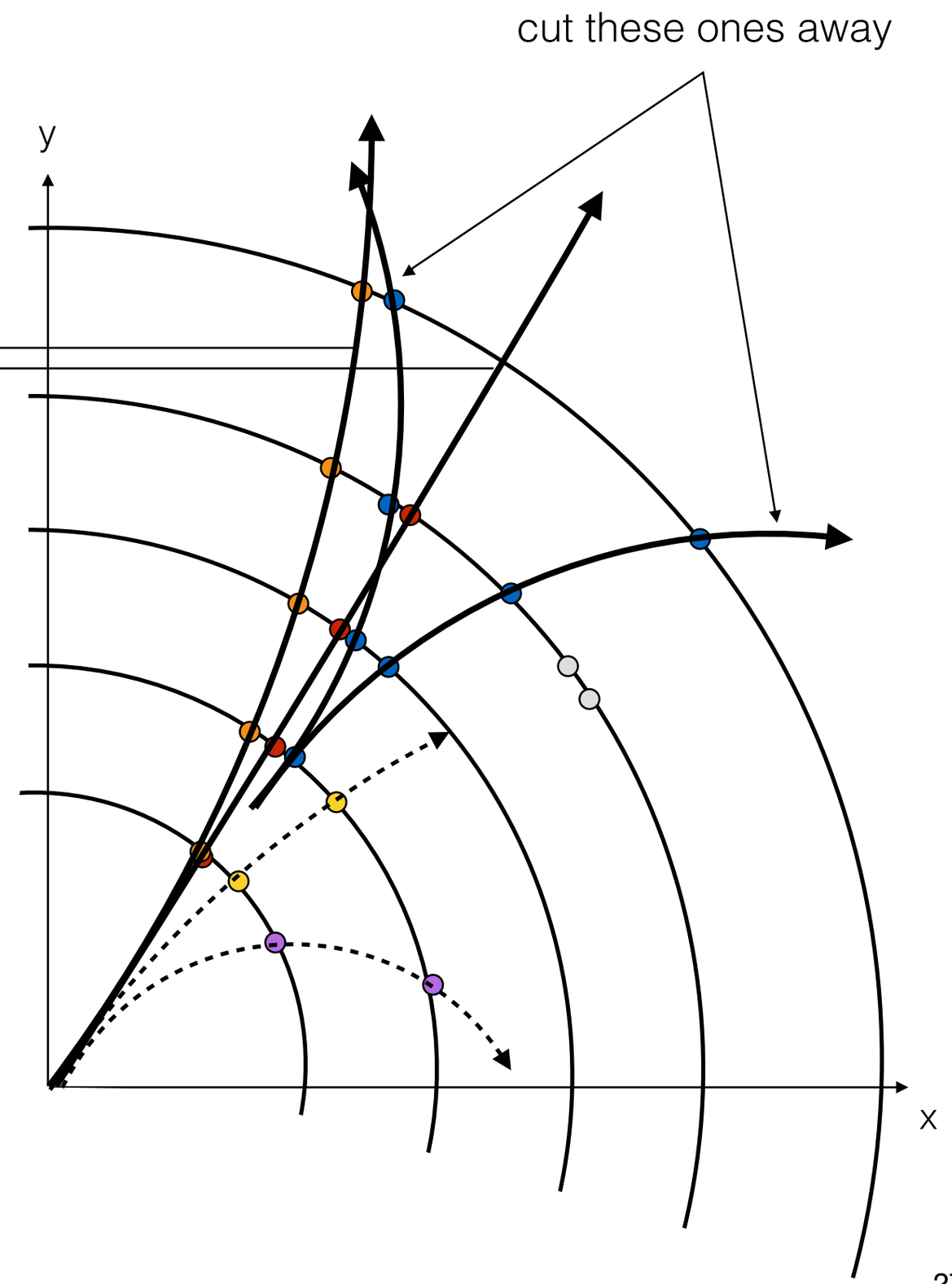

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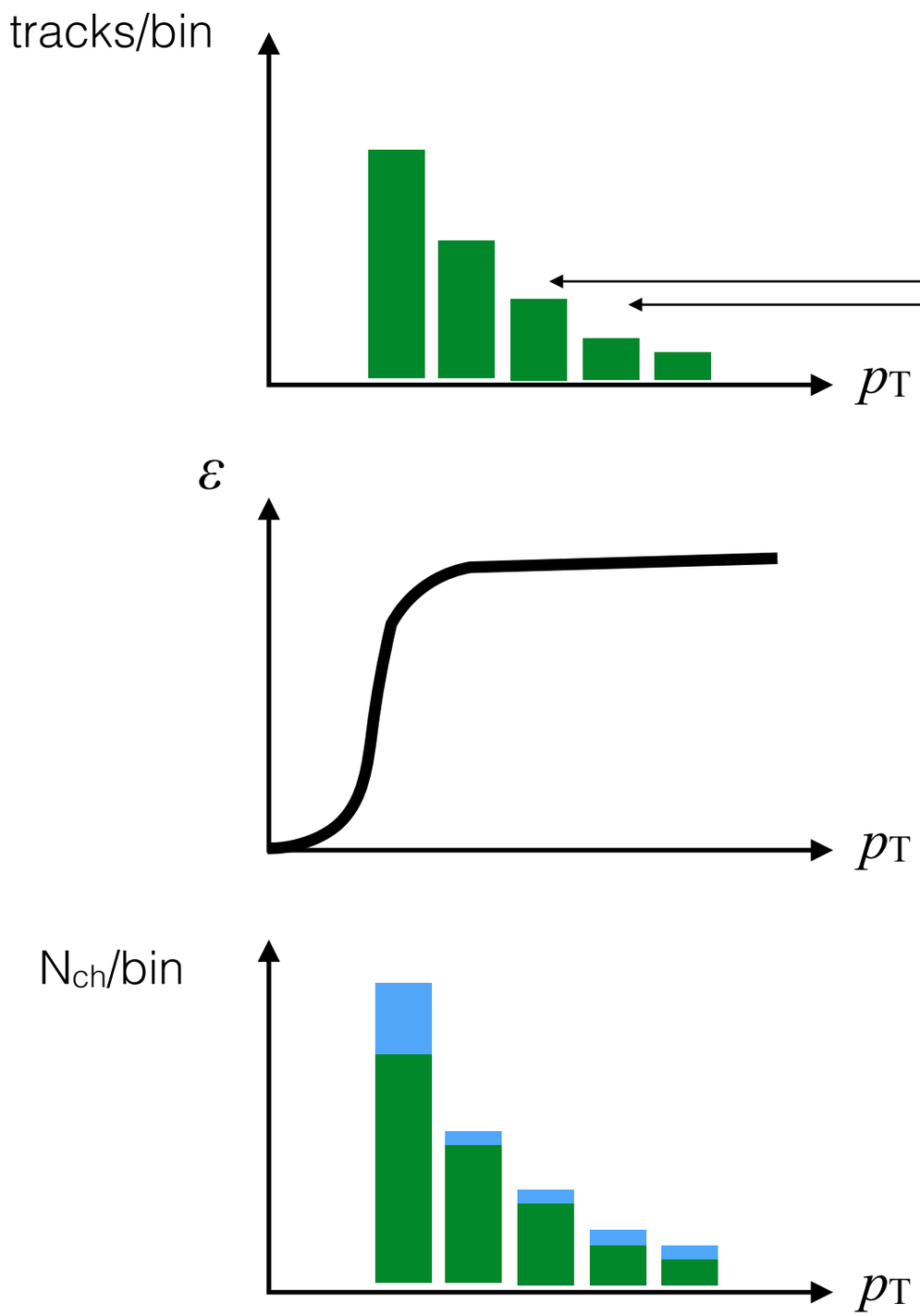

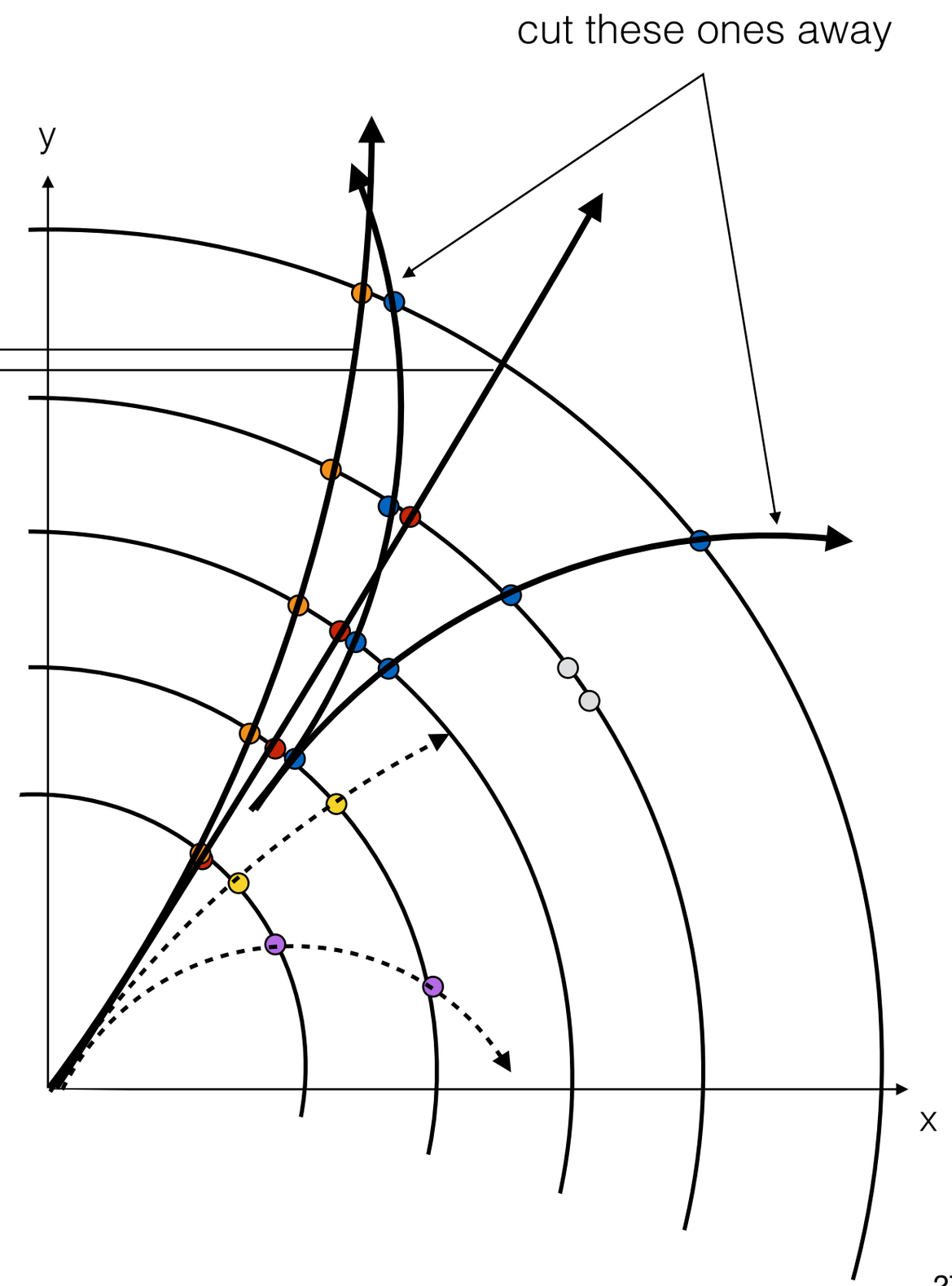

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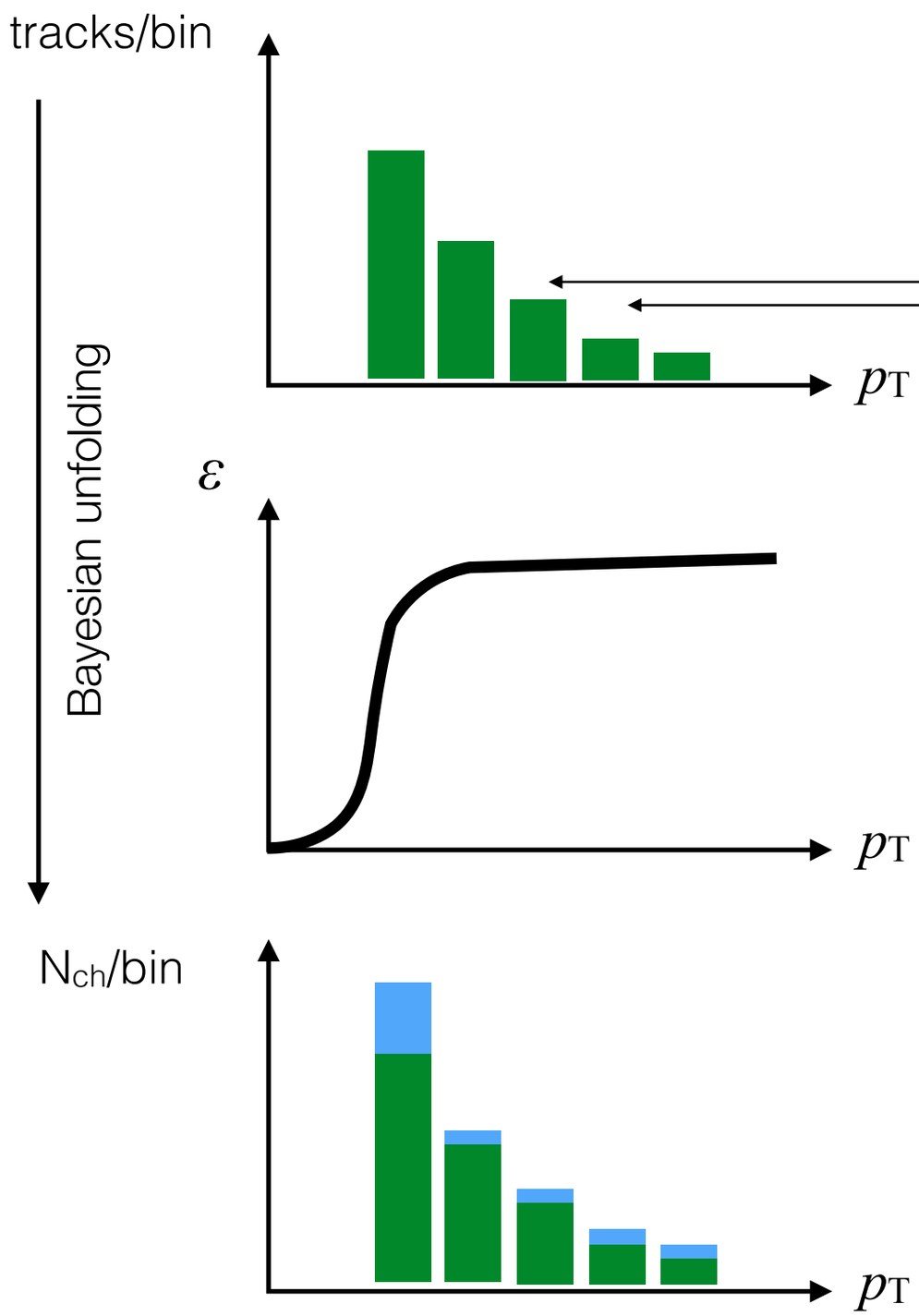
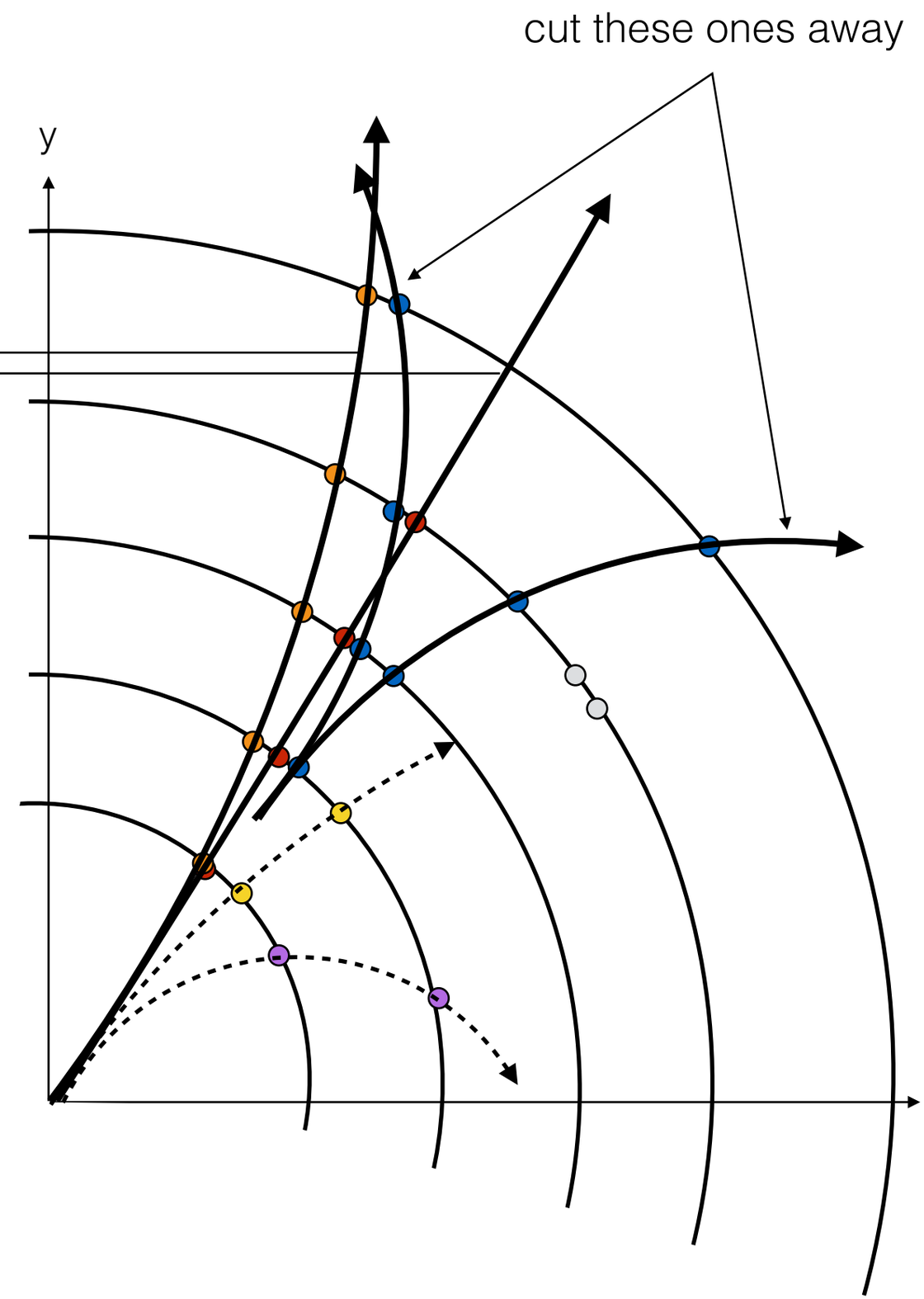
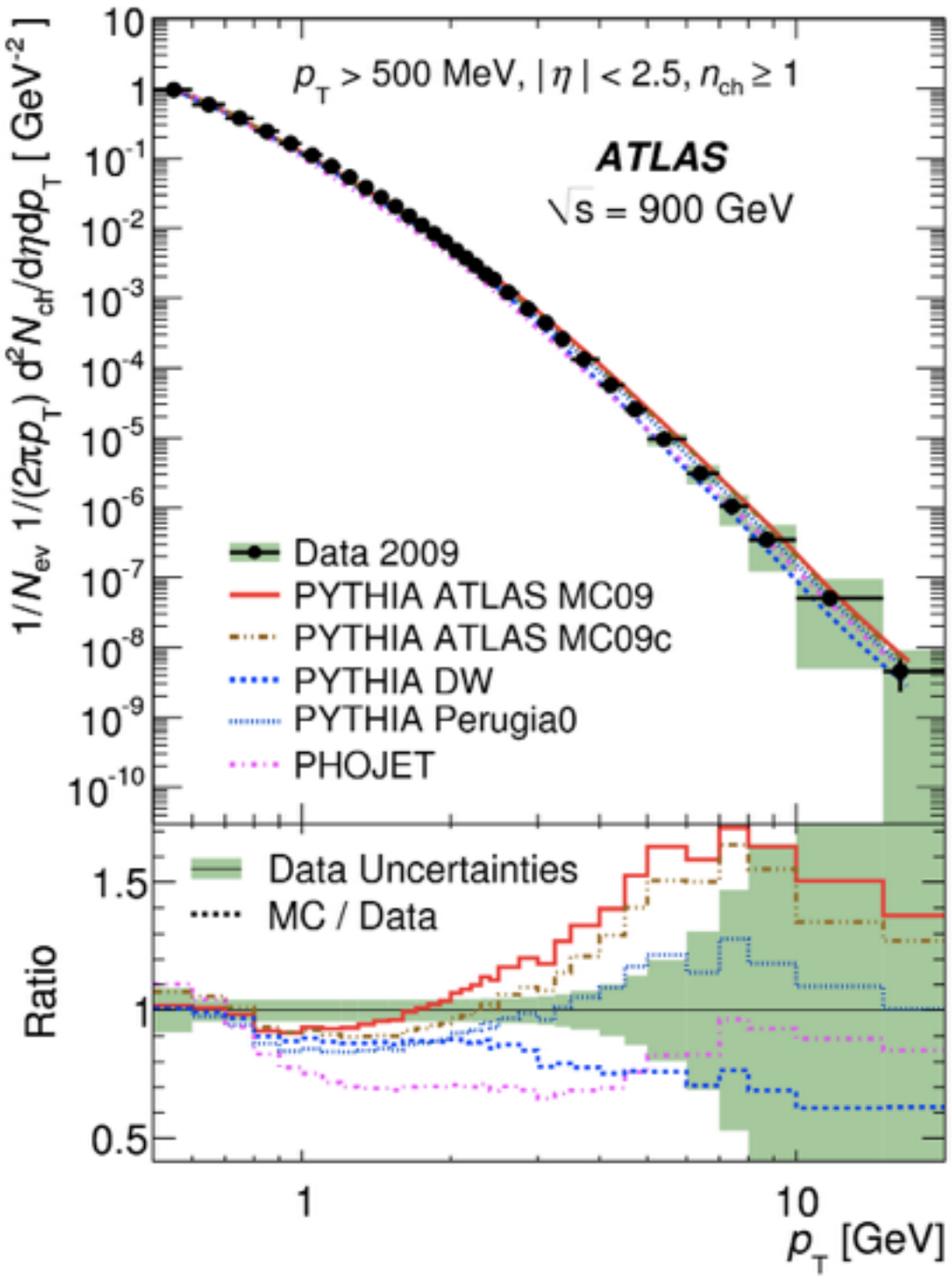
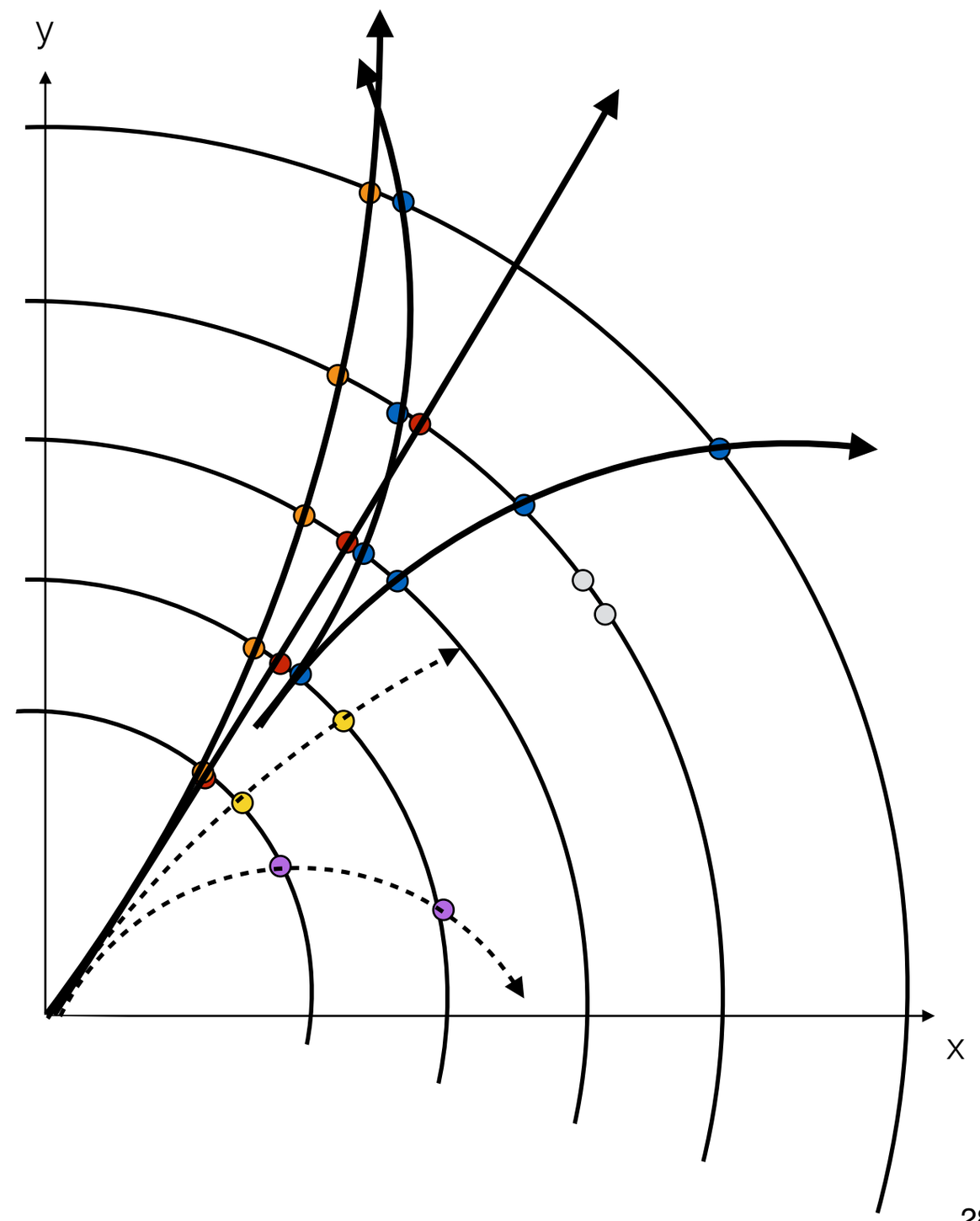




Example: charged particle multiplicity

- Let's finish the analysis: done.





Example: Higgs mass from $\mathbf{H \rightarrow ZZ^* \rightarrow 4\mu}$

- A three-step master plan to a Higgs mass paper :
  (might be even more “slightly" simplified)

1. take data with some sort of muon trigger and find events with 4 muons in the final state (2 oppositely charged muon pairs)

2. use their track momentum measurement and combine them to a common Higgs mass

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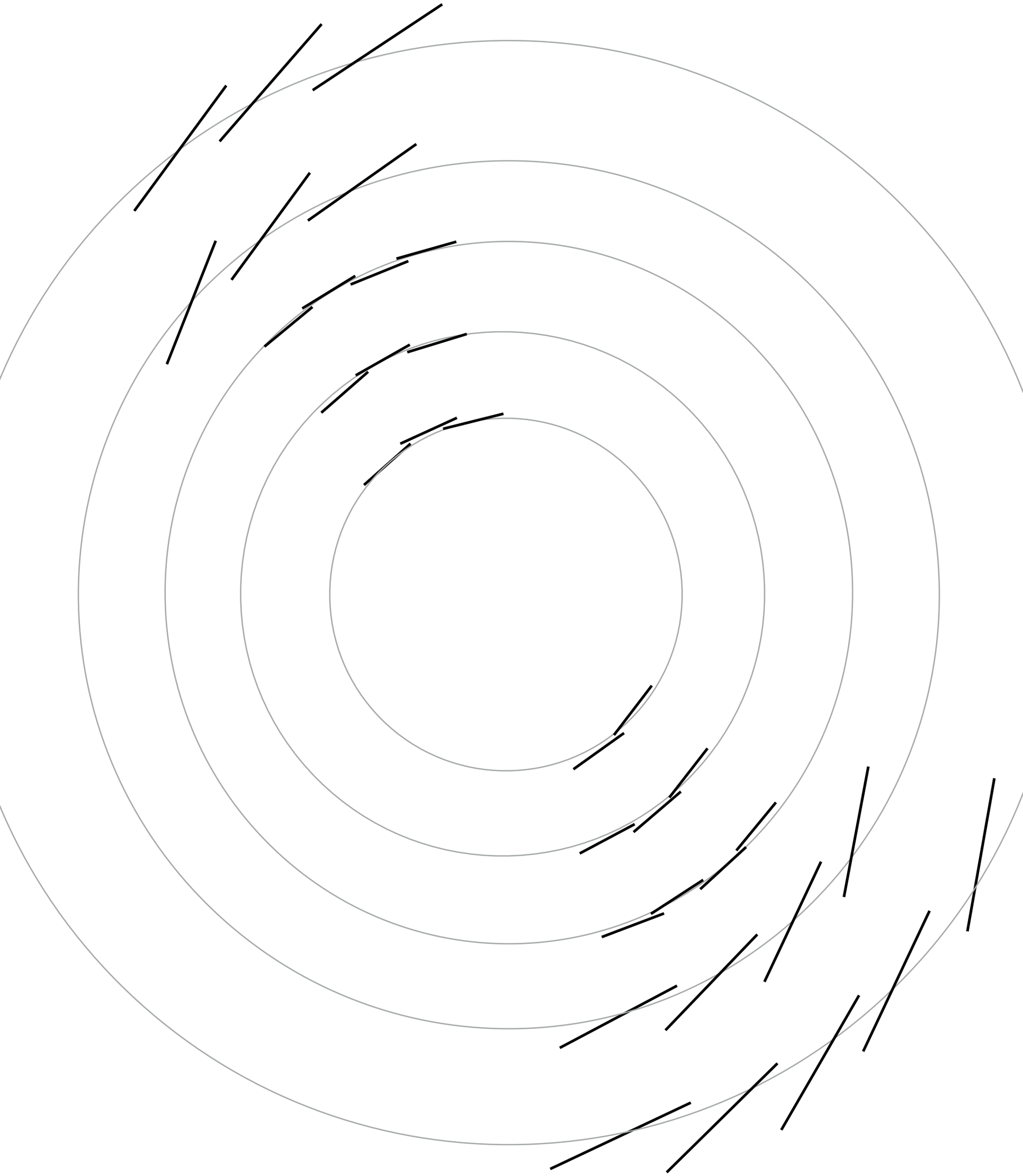
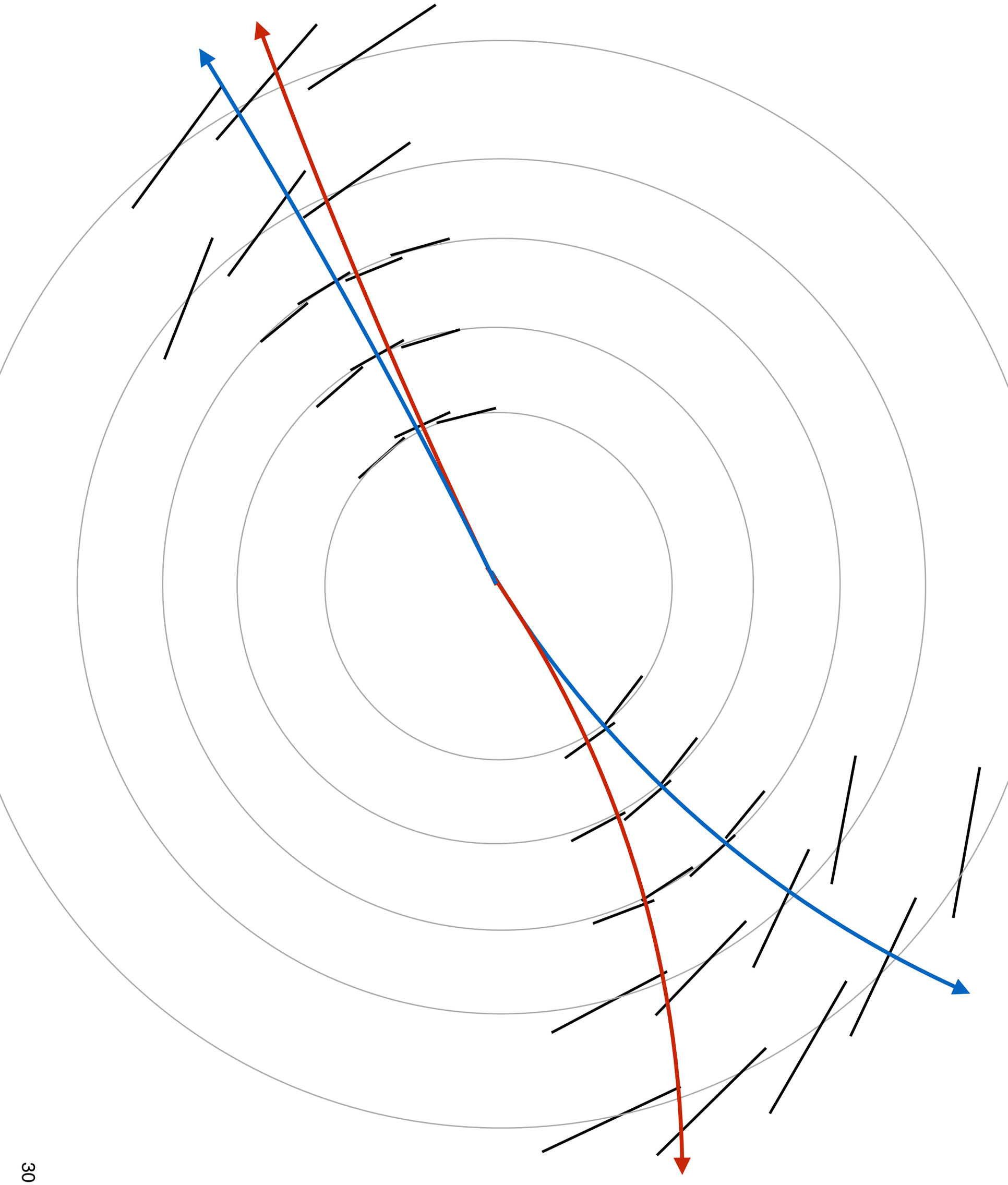
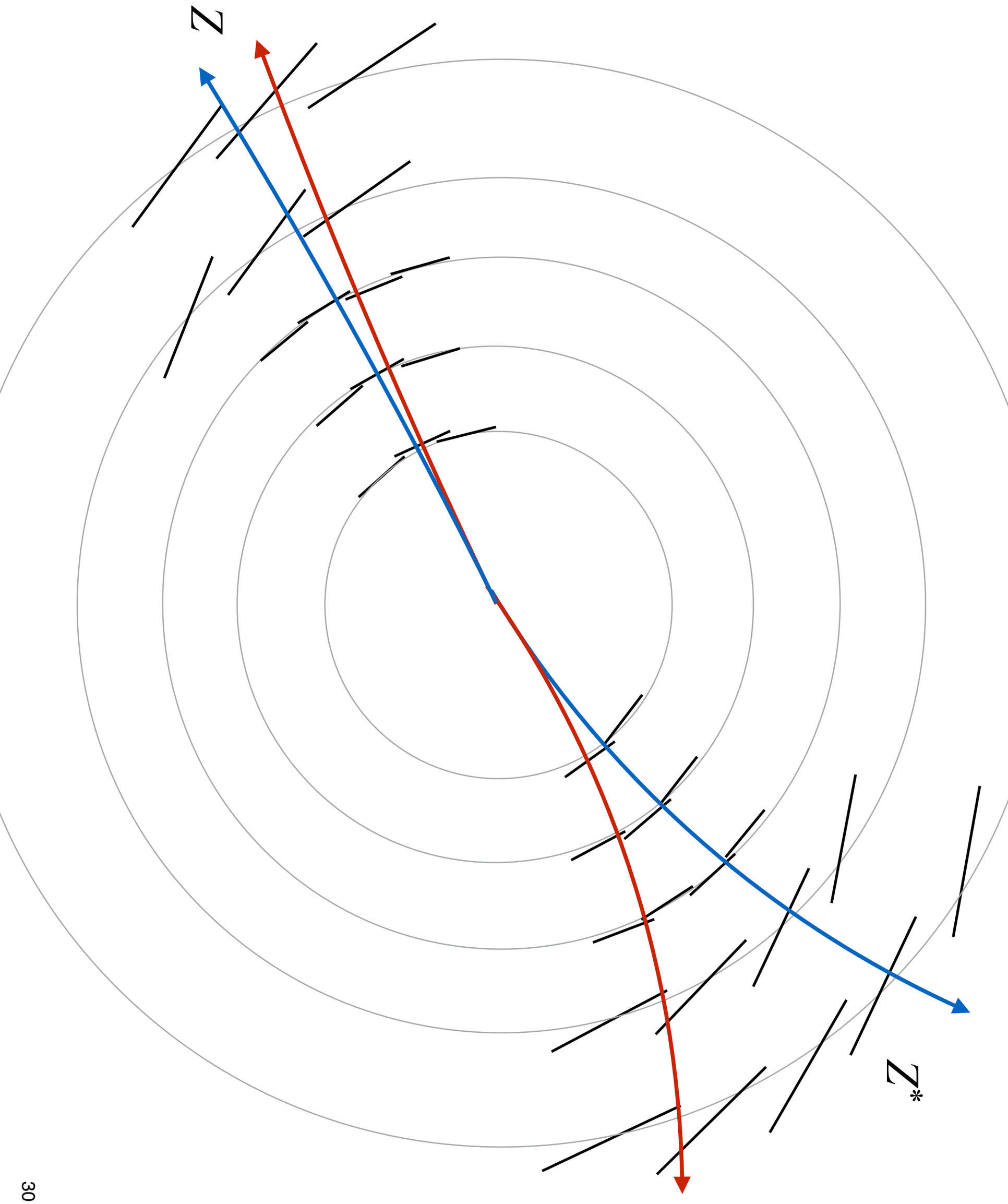
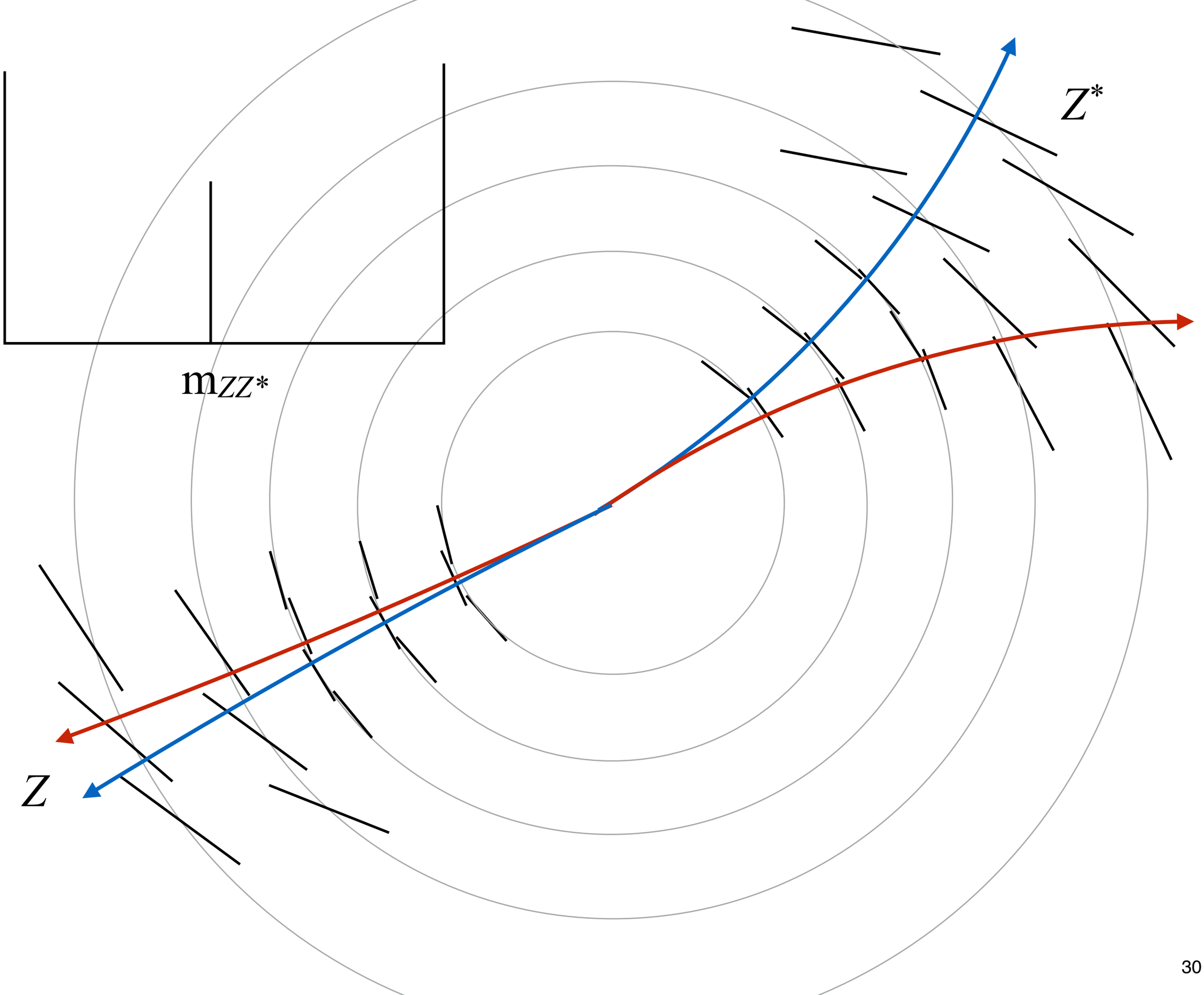
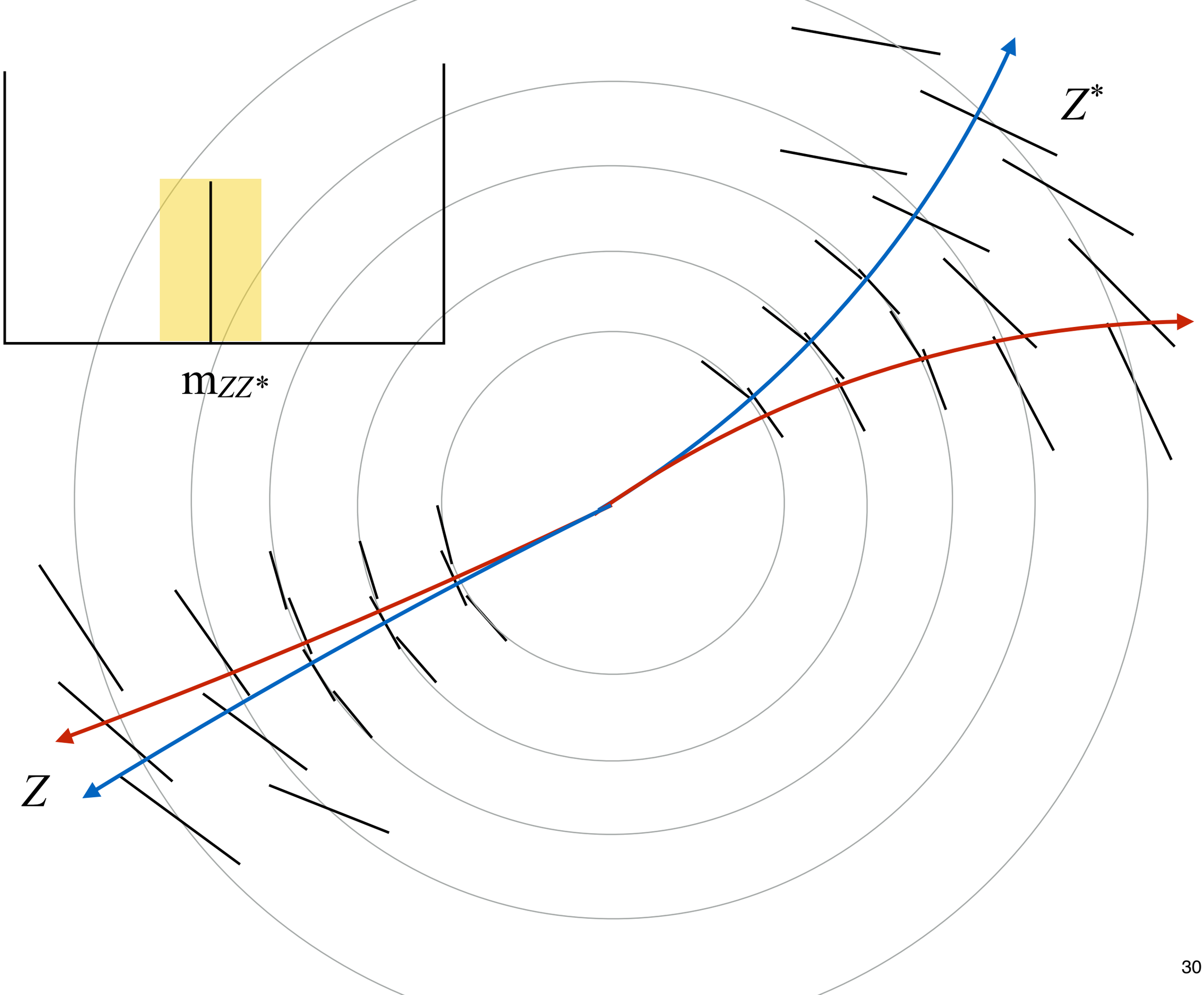
Let’s do it !






Z*
Z


m_{ZZ^*}
Z^*
Z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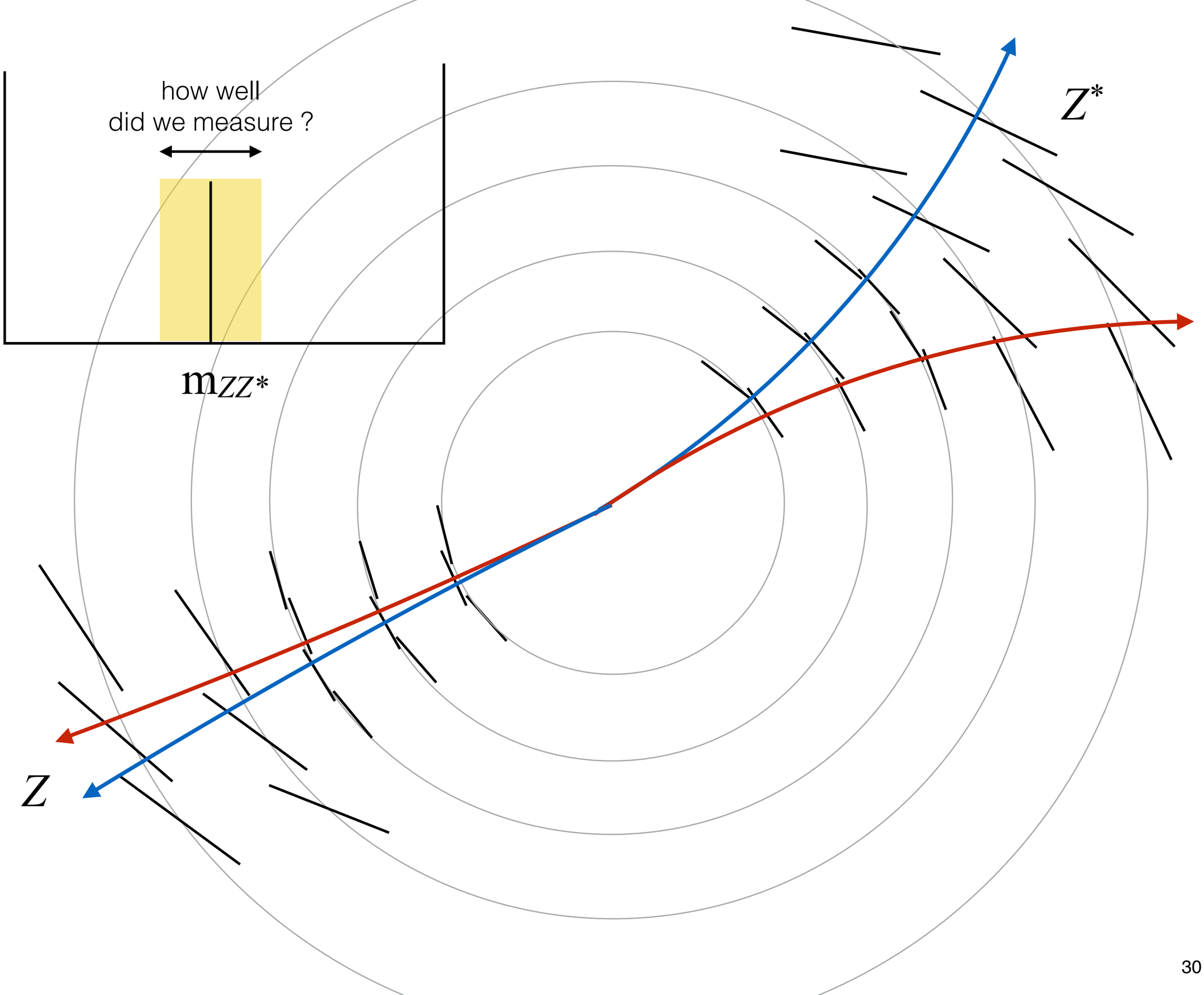
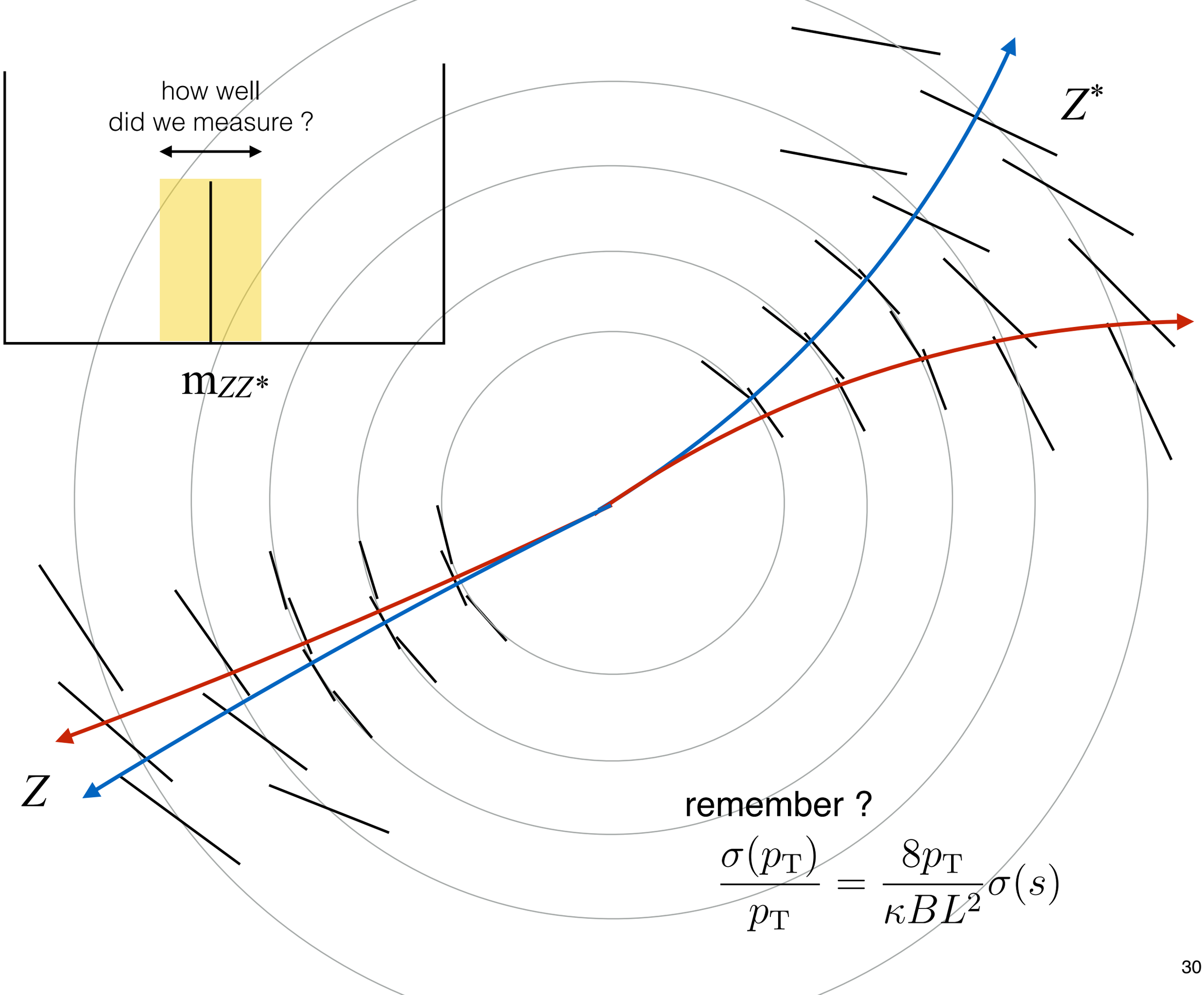
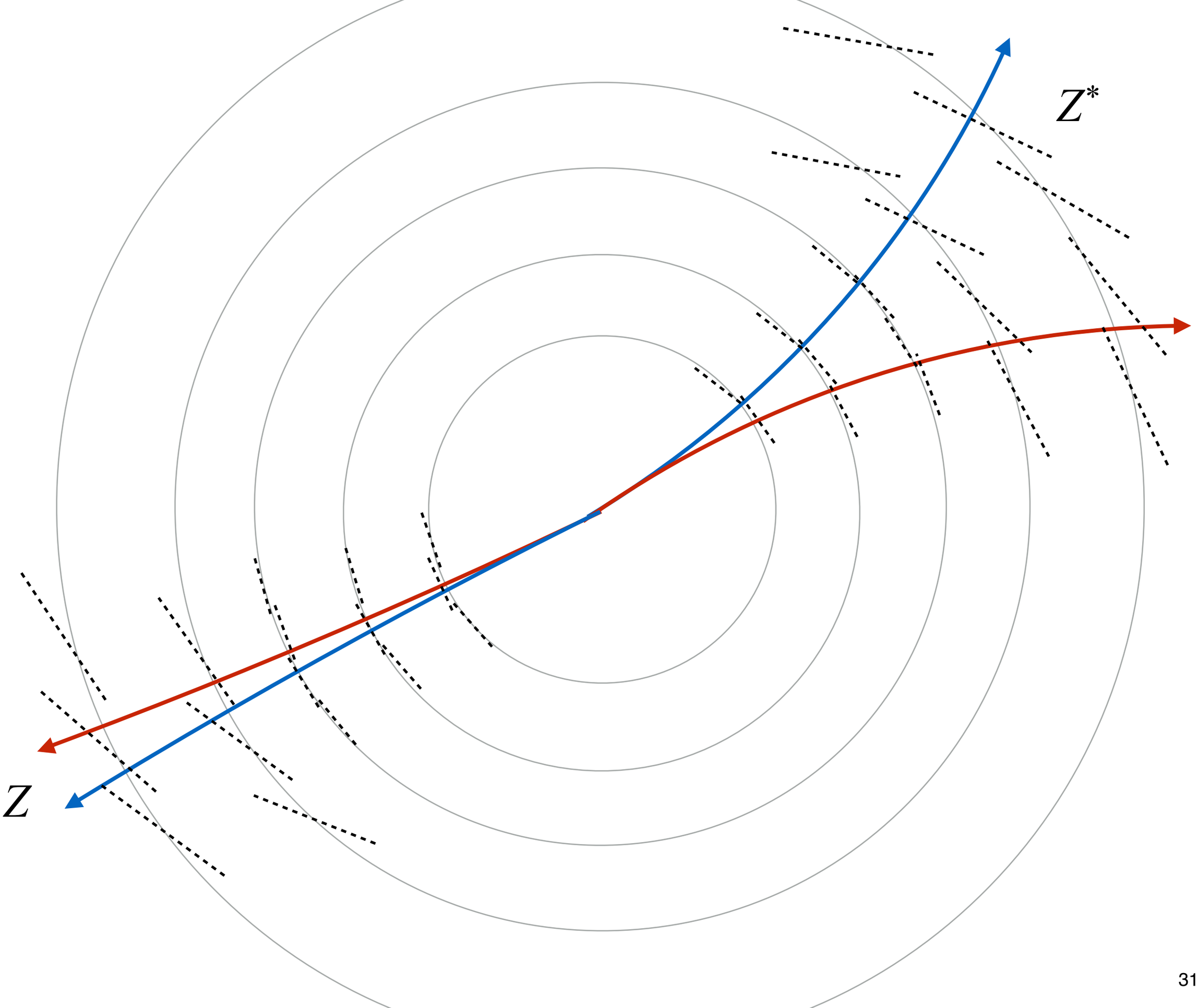
Z^*
Z

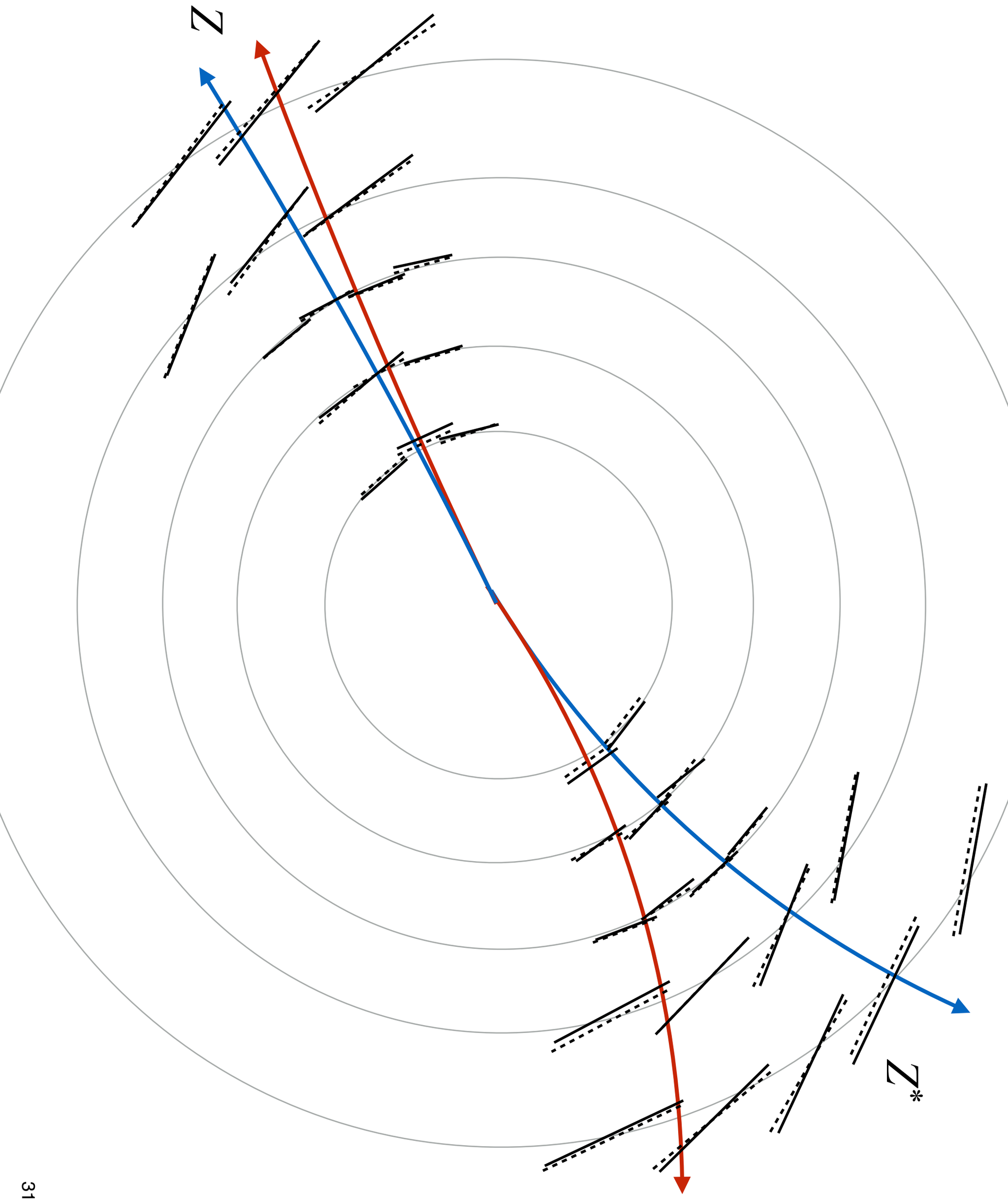

how well
did we measure ?
m_{ZZ^*}
Z^*
Z



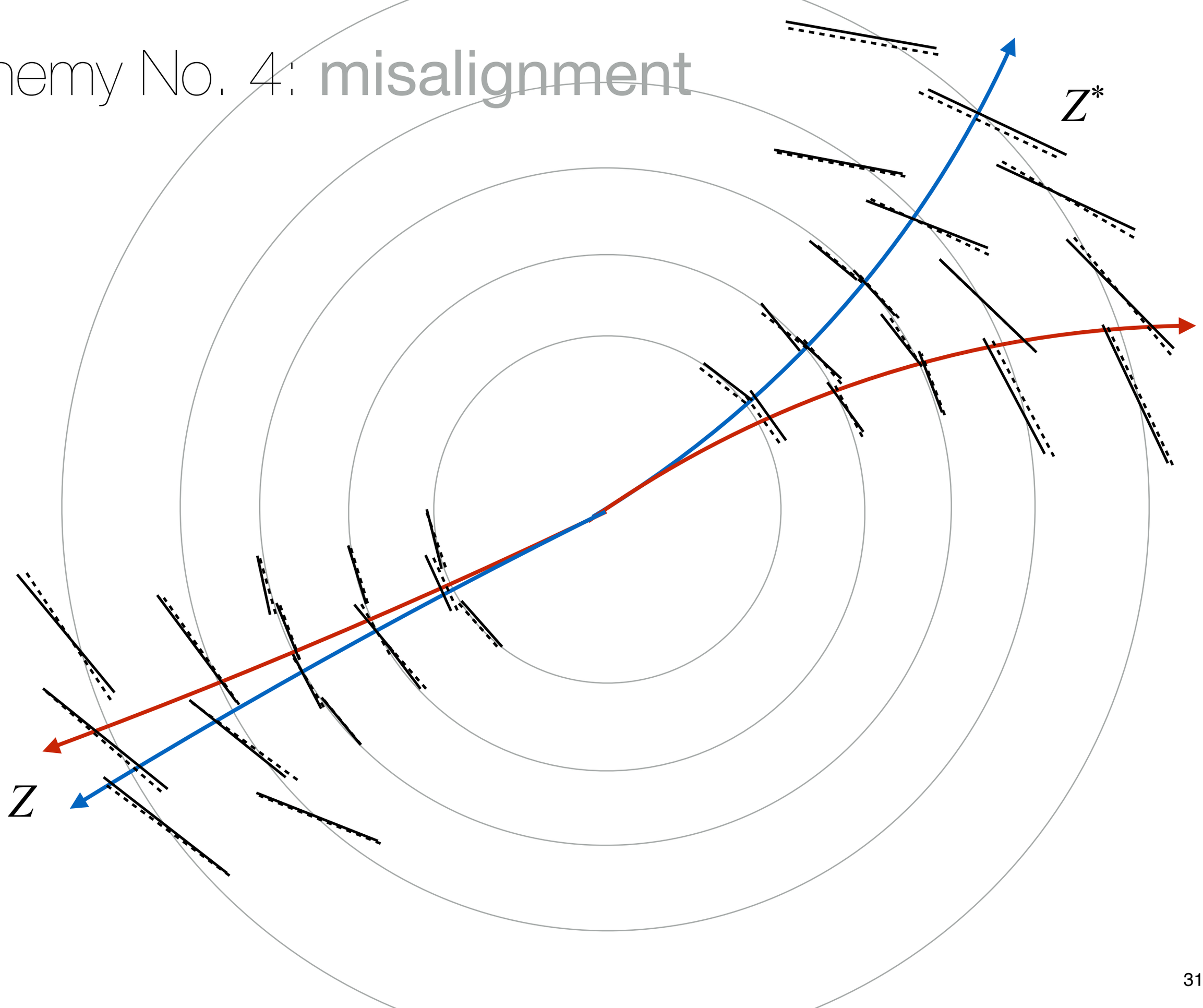
remember ?

$$\frac{\sigma(p_{\mathrm{T}})}{p_{\mathrm{T}}} = \frac{8p_{\mathrm{T}}}{\kappa B L^2}\sigma(s)$$

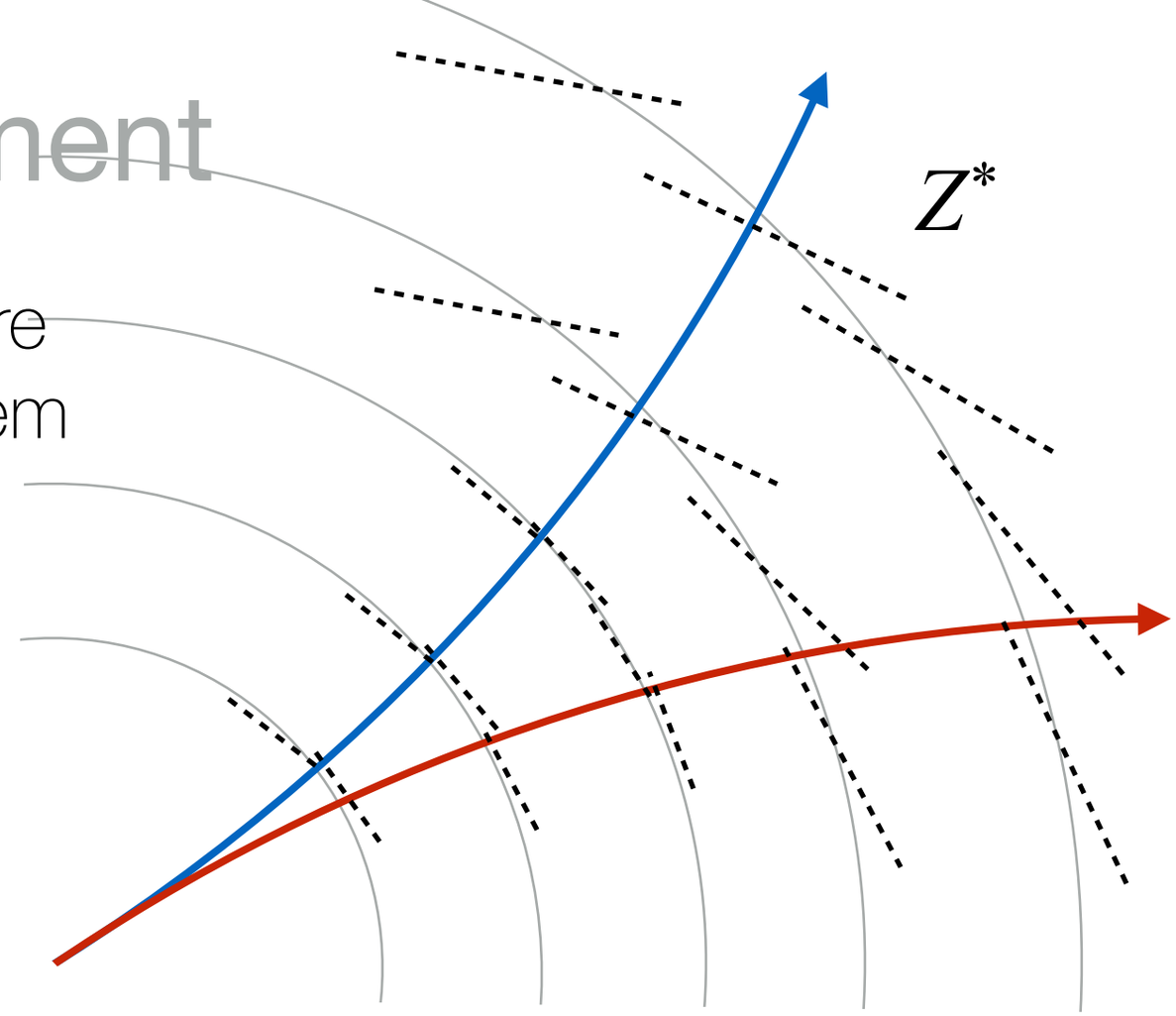

Z^*
Z


Z*
Z

Enemy No. 4: misalignment

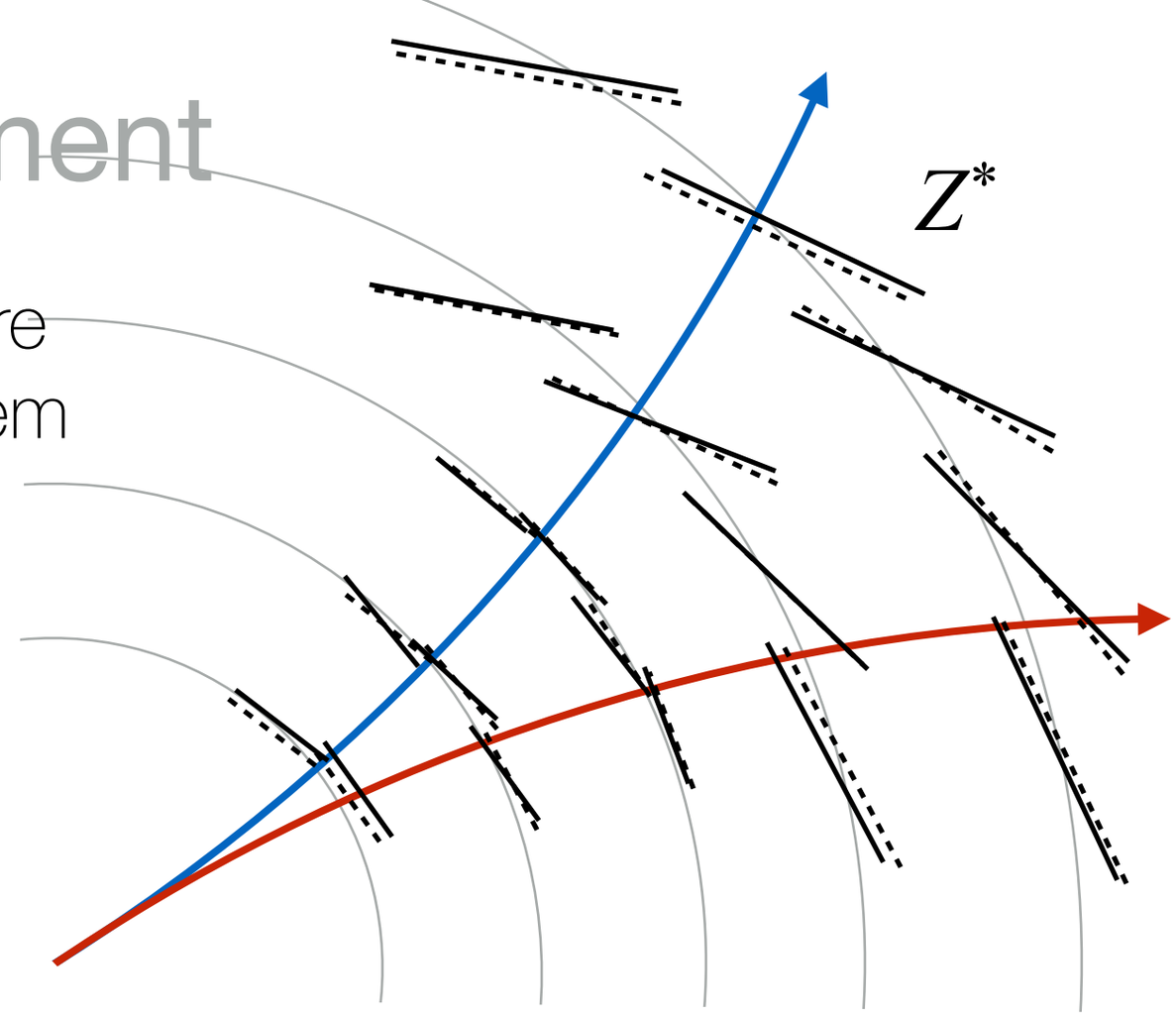


Enemy No. 4: misalignment



- No one said the detector elements are actually exactly where you expect them
  - you need to find out where they are !
- Major feature: random module misalignment
  - can be corrected for using alignment algorithms
  - most commonly used:
    a global χ^2 minimisation using tracks and varying the module positions
  - many many degrees of freedom (ATLAS: 36 k matrix inversion, CMS even more)
- It works !

Enemy No. 4: misalignment



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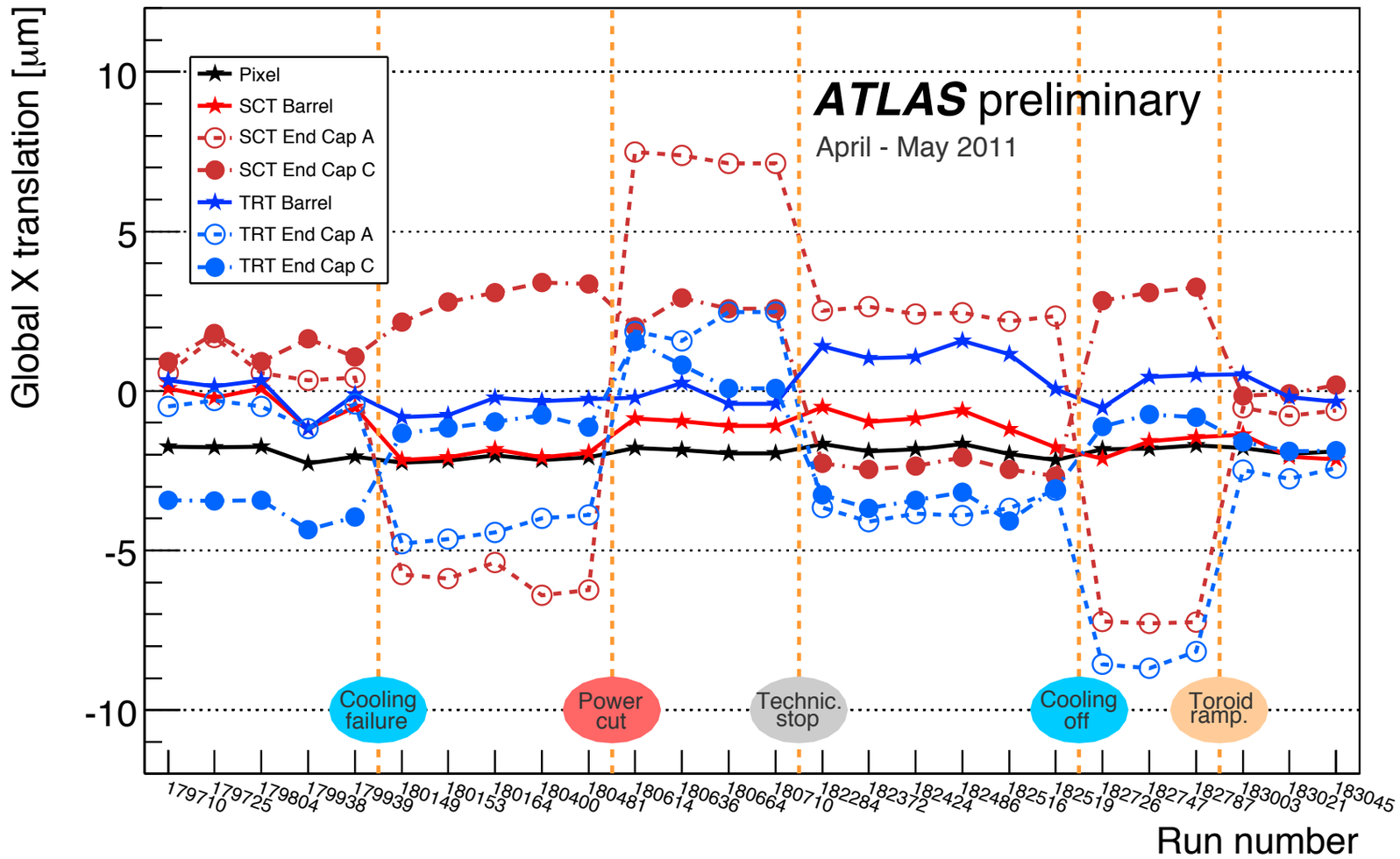
Enemy No. 4: misalignment

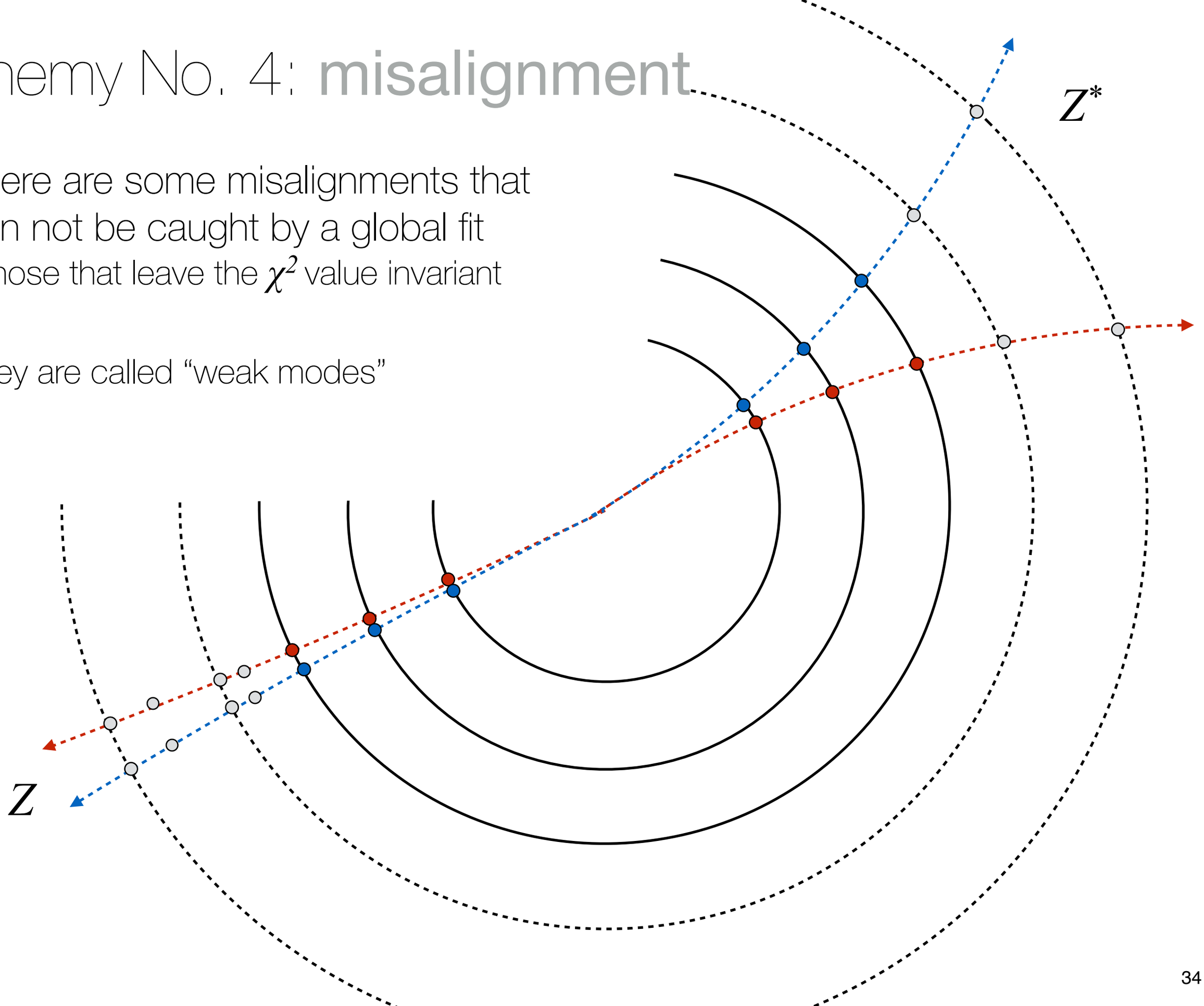
Level 1 alignment



Enemy No. 4: misalignment

- There are some misalignments that can not be caught by a global fit
  - those that leave the χ^2 value invariant

- They are called “weak modes”



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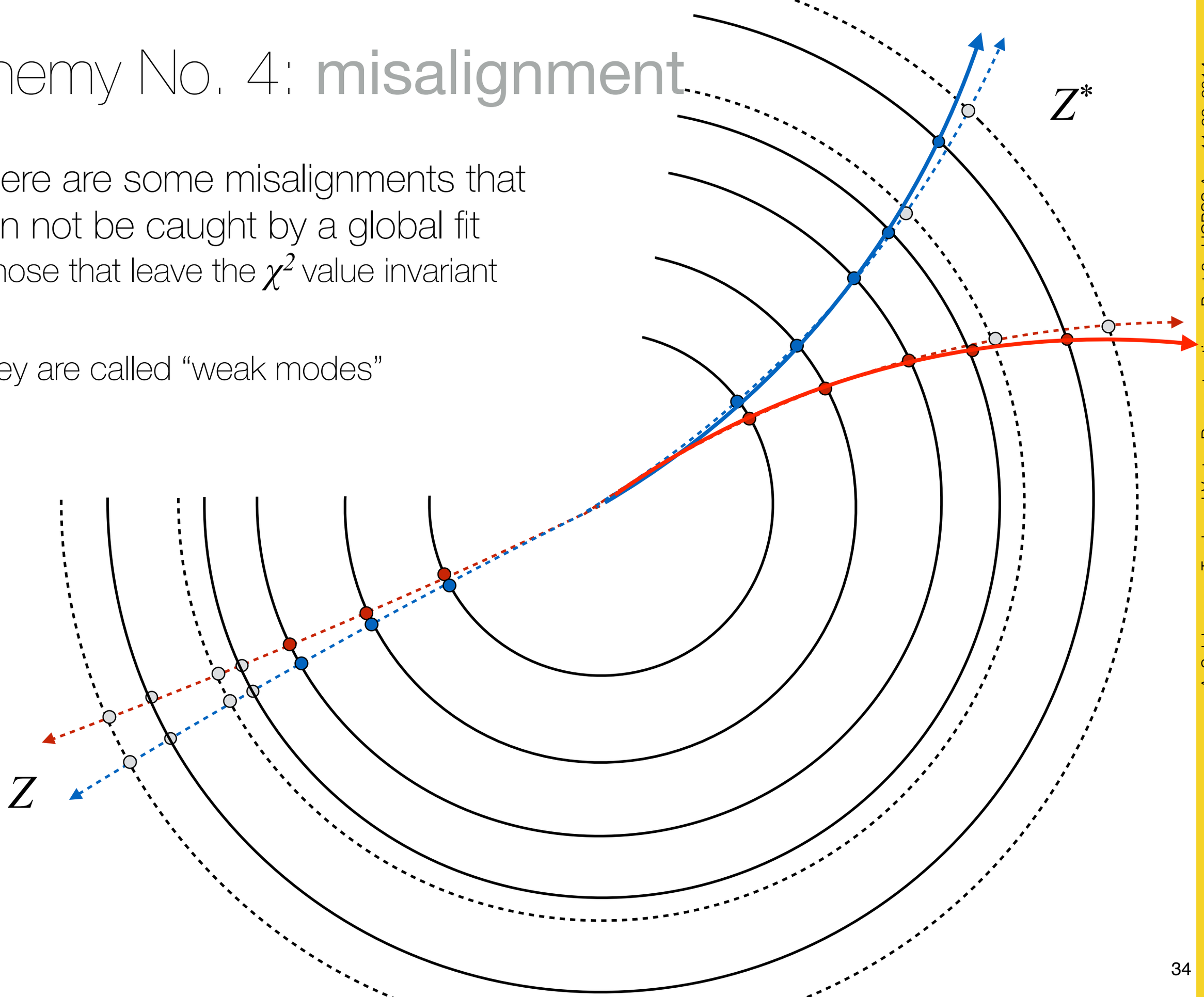
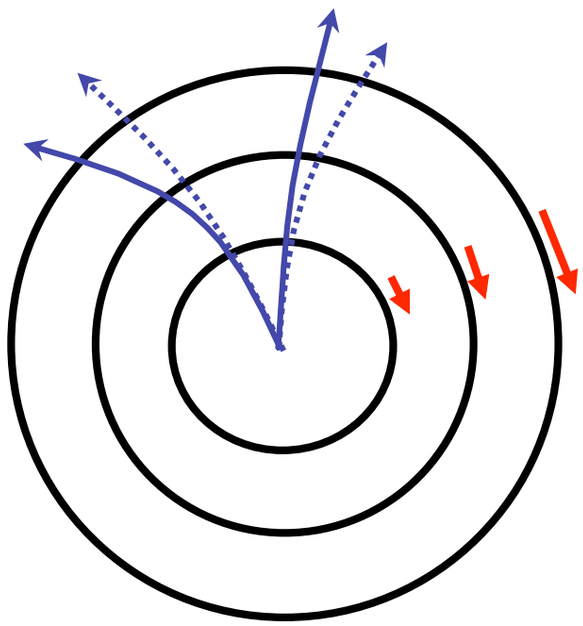
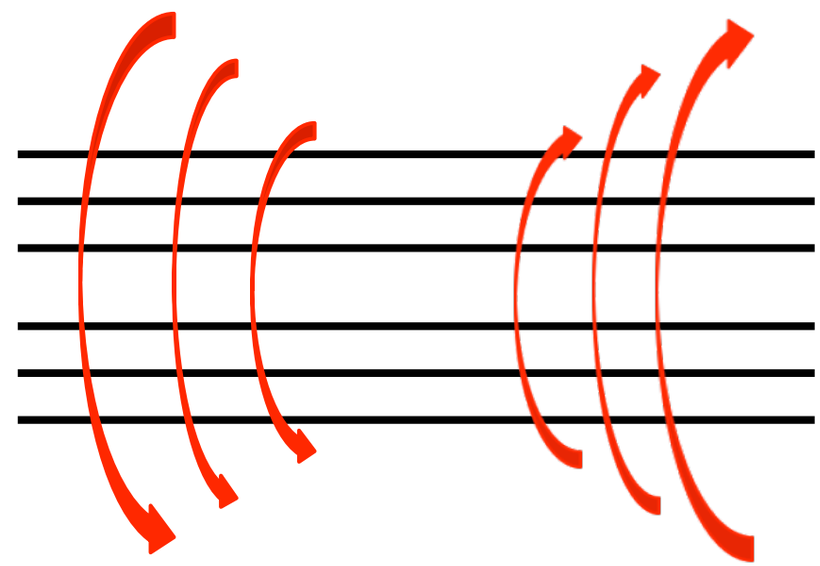


Enemy No. 4: misalignment

- weak modes that leave the χ^2 of a track invariant

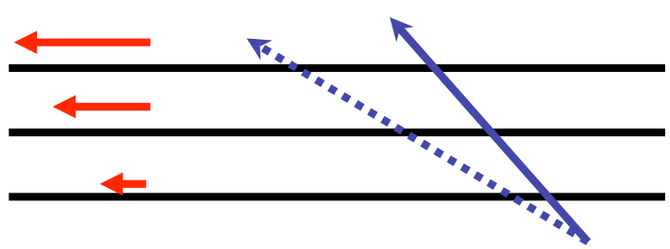
curl

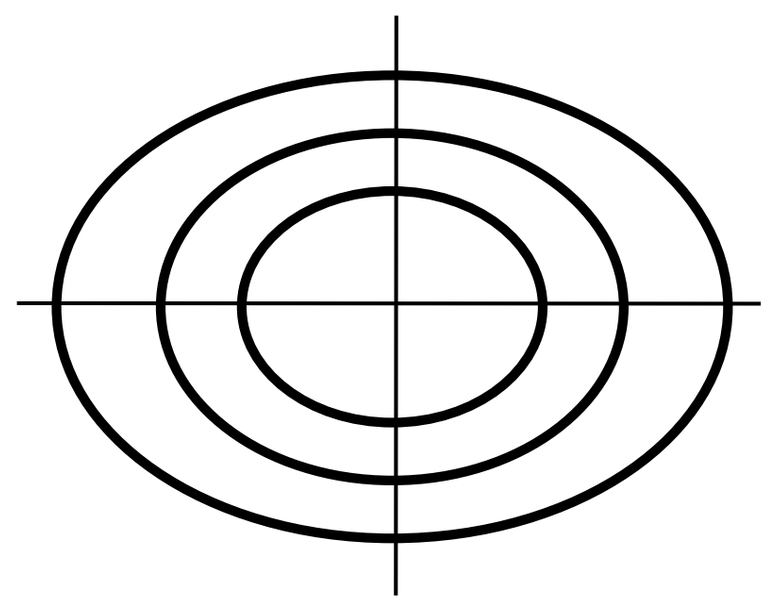




twist

telescope





elliptical

Enemy No. 4: misalignment

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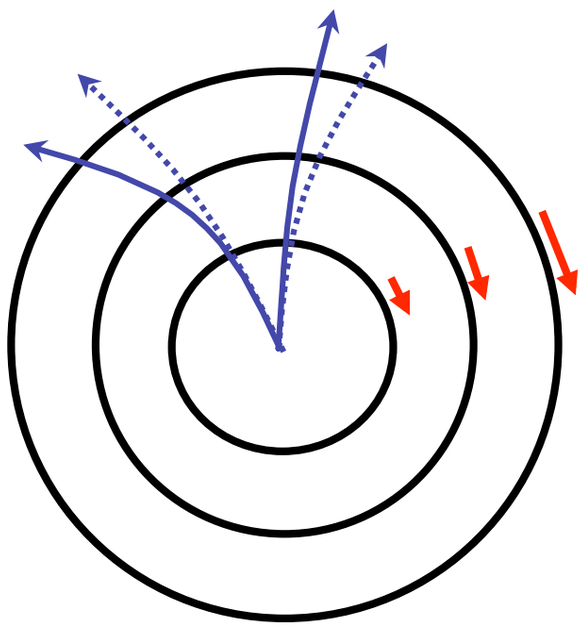
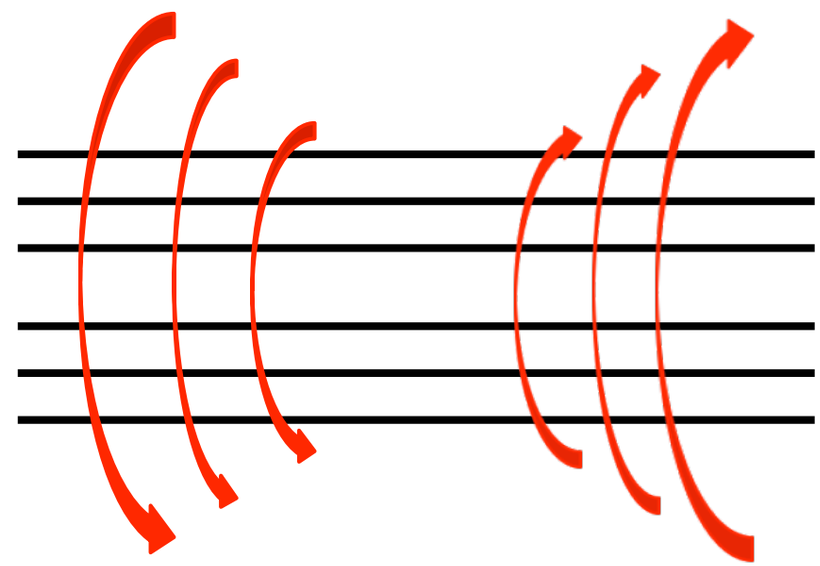
curl





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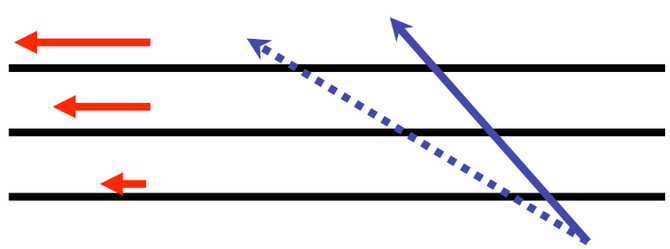
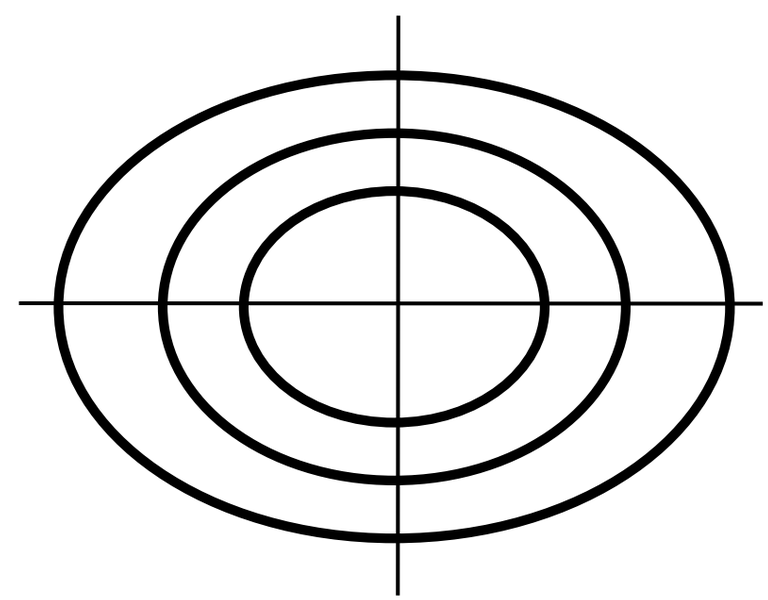




elliptical

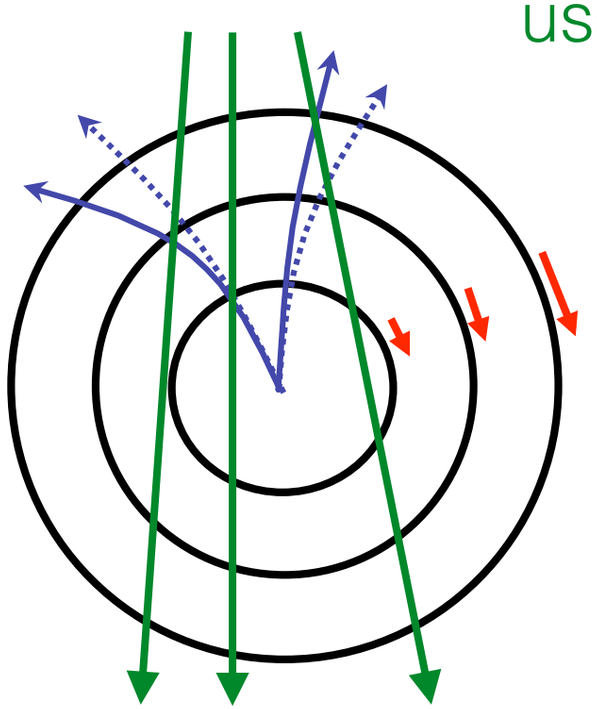
- What can we do ?

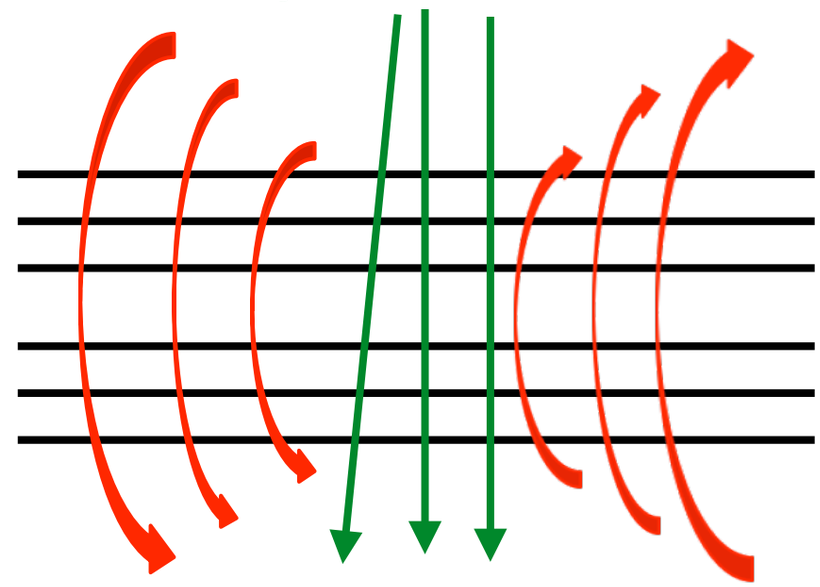
Enemy No. 4: misalignment

- weak modes that leave the χ^2 of a track invariant

use cosmic rays

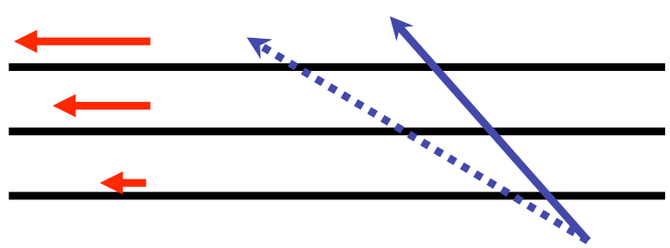
curl

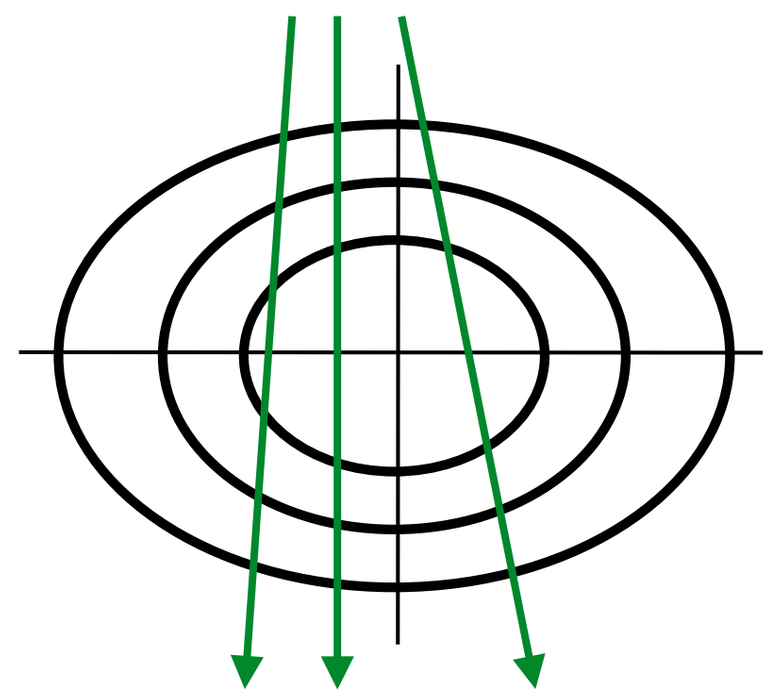




twist

telescope





elliptical

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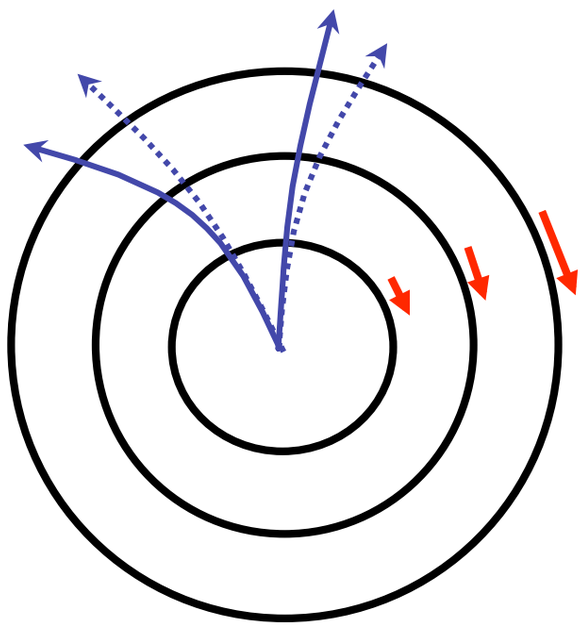

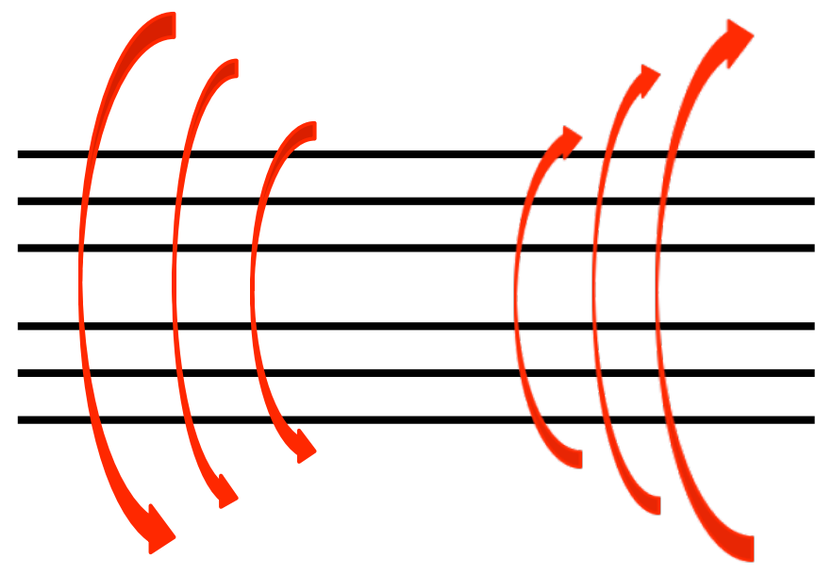

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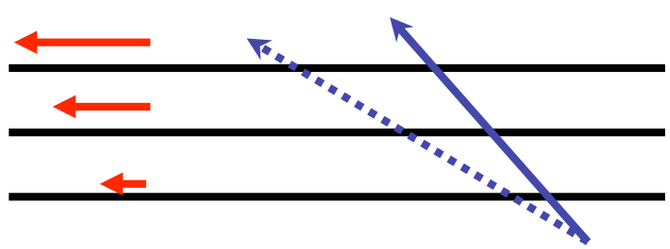

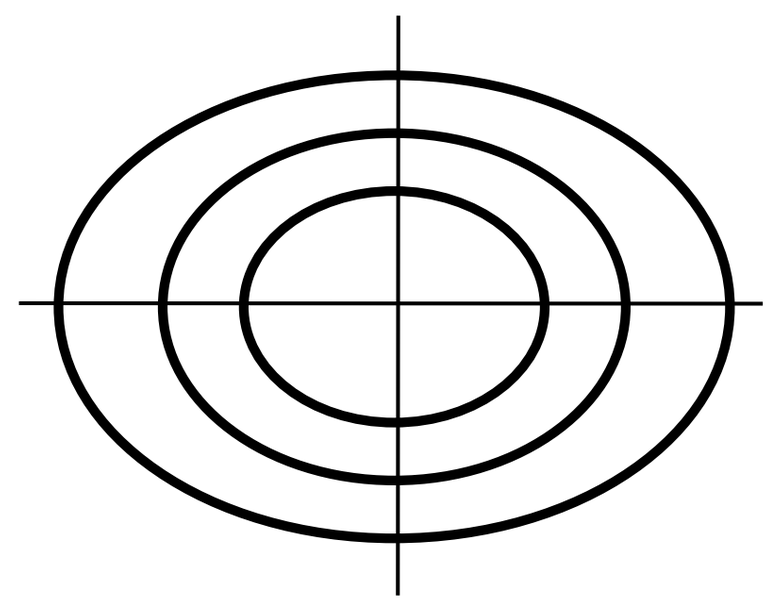

elliptical

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Enemy No. 4: misalignment

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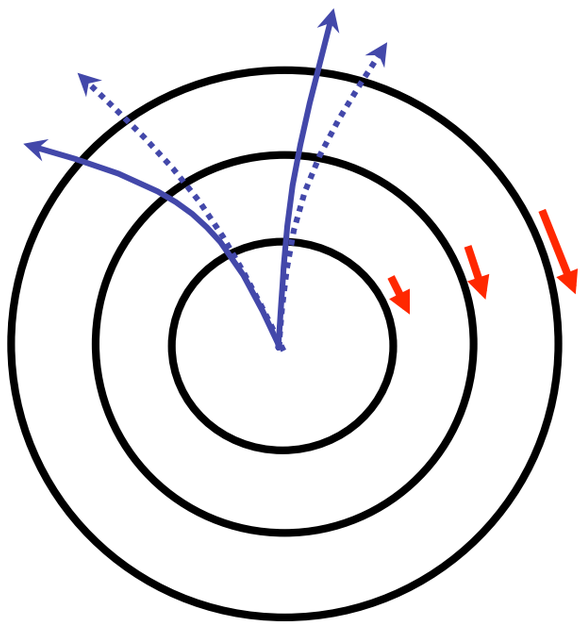

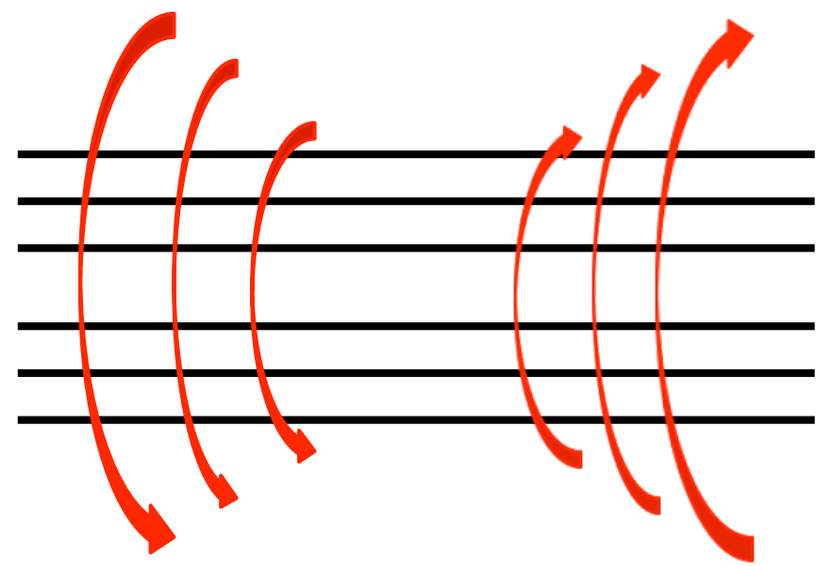

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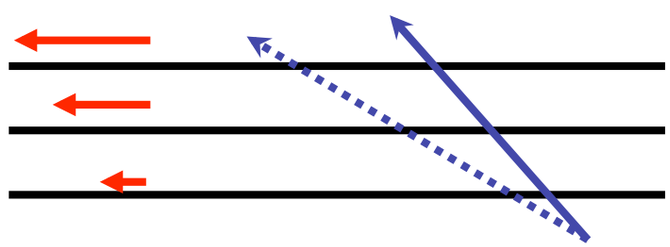
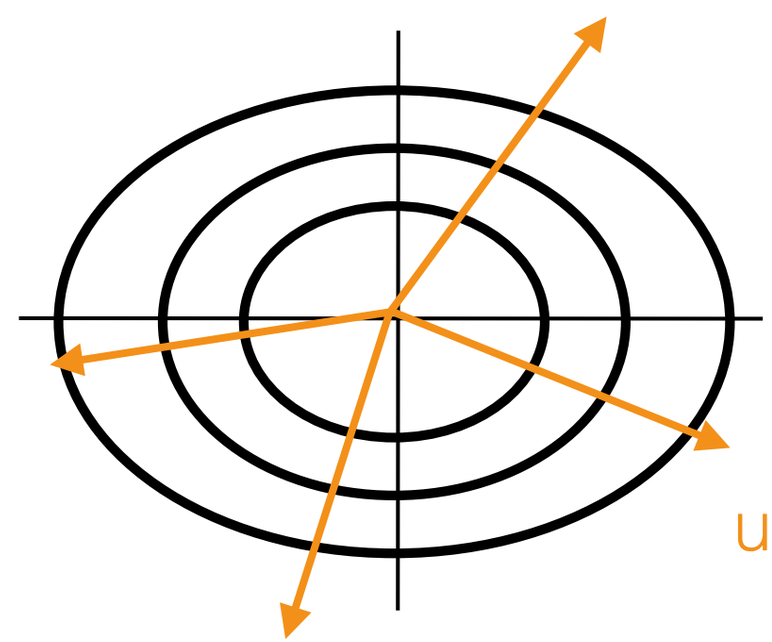




elliptical

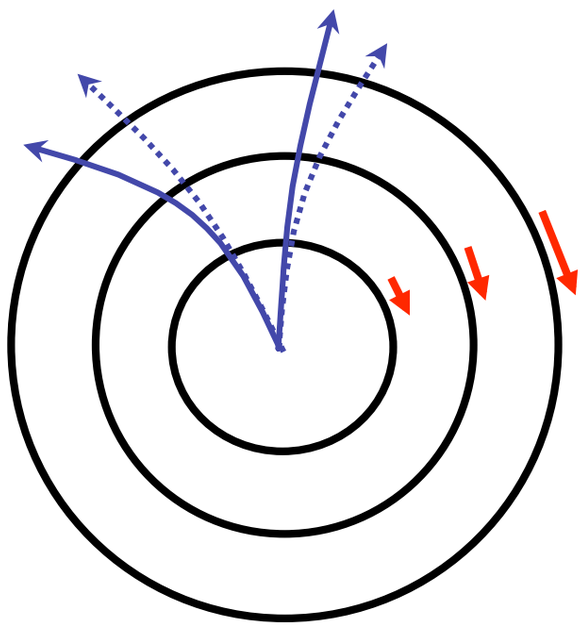
- What can we do ?

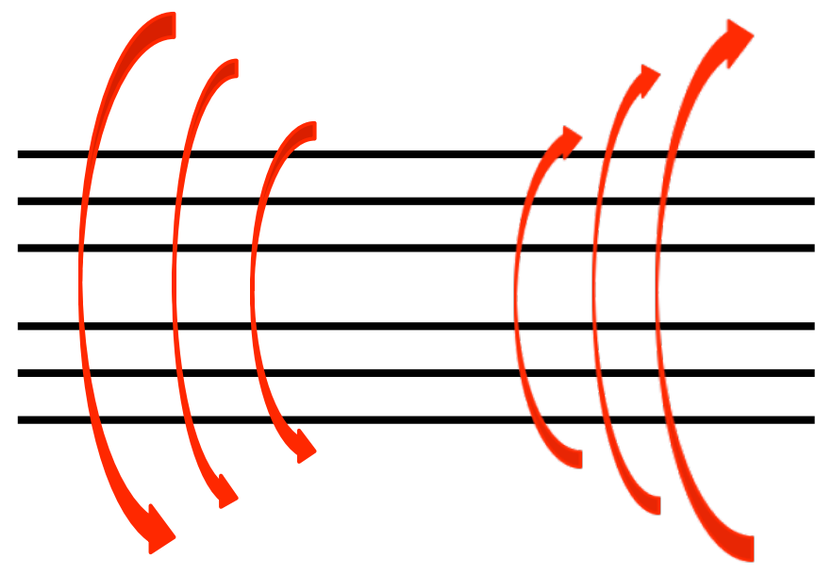
use field-off data

Enemy No. 4: misalignment

- weak modes that leave the χ^2 of a track invariant

curl





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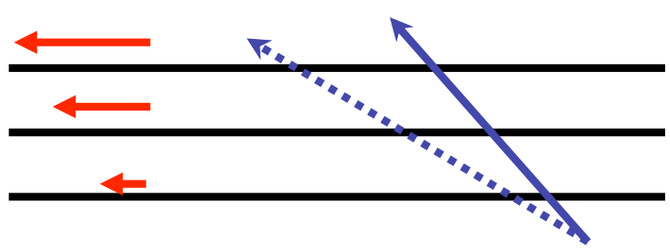

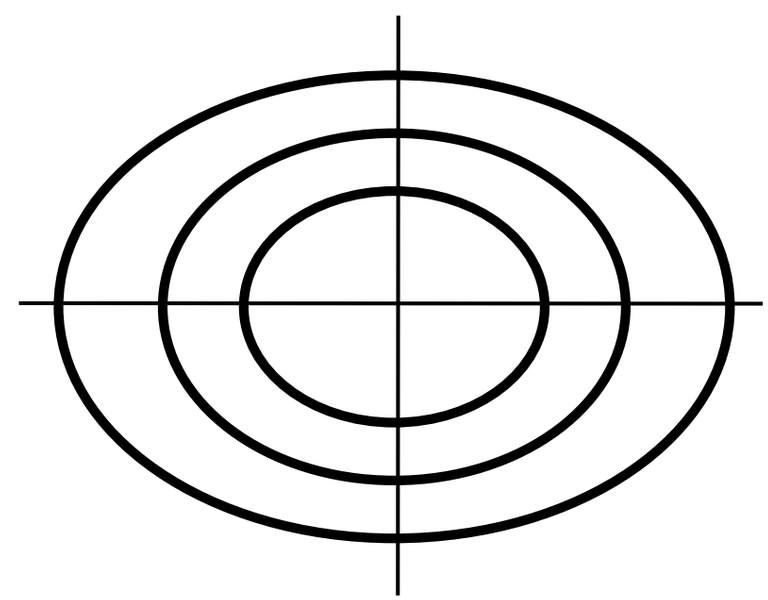

elliptical

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Enemy No. 4: misalignment

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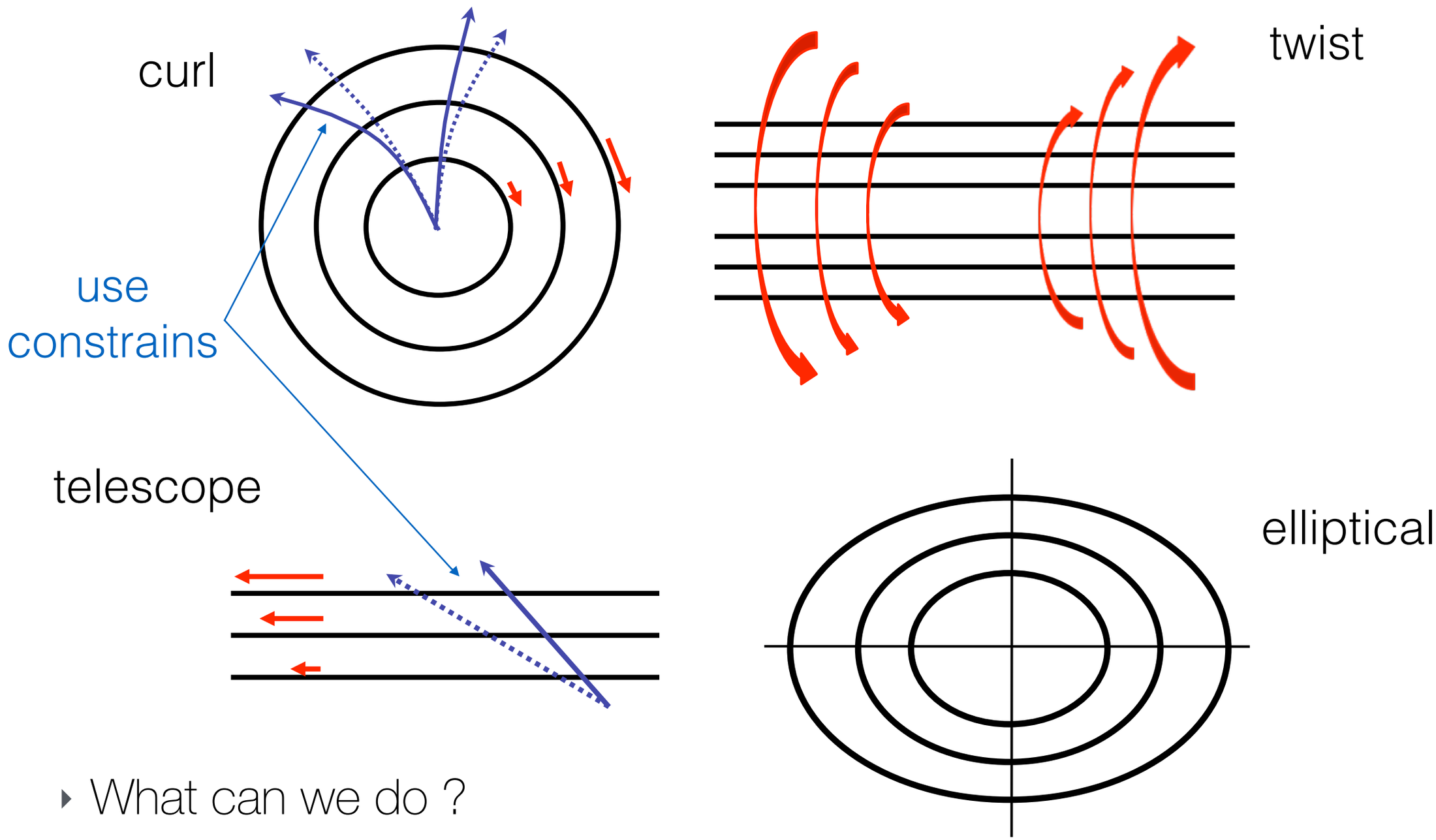

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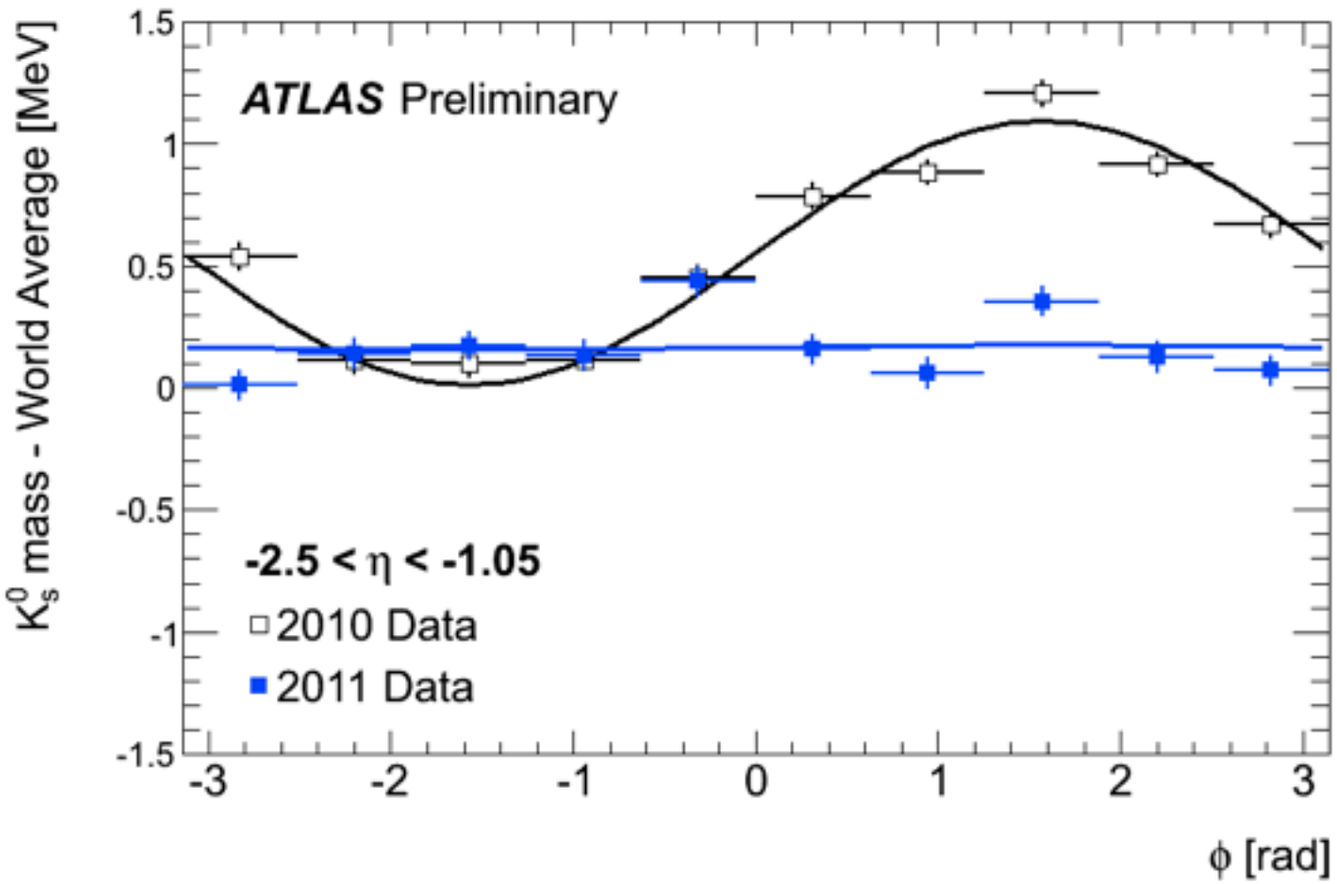
Calibrate your detector

- use known resonances to calibrate your detector



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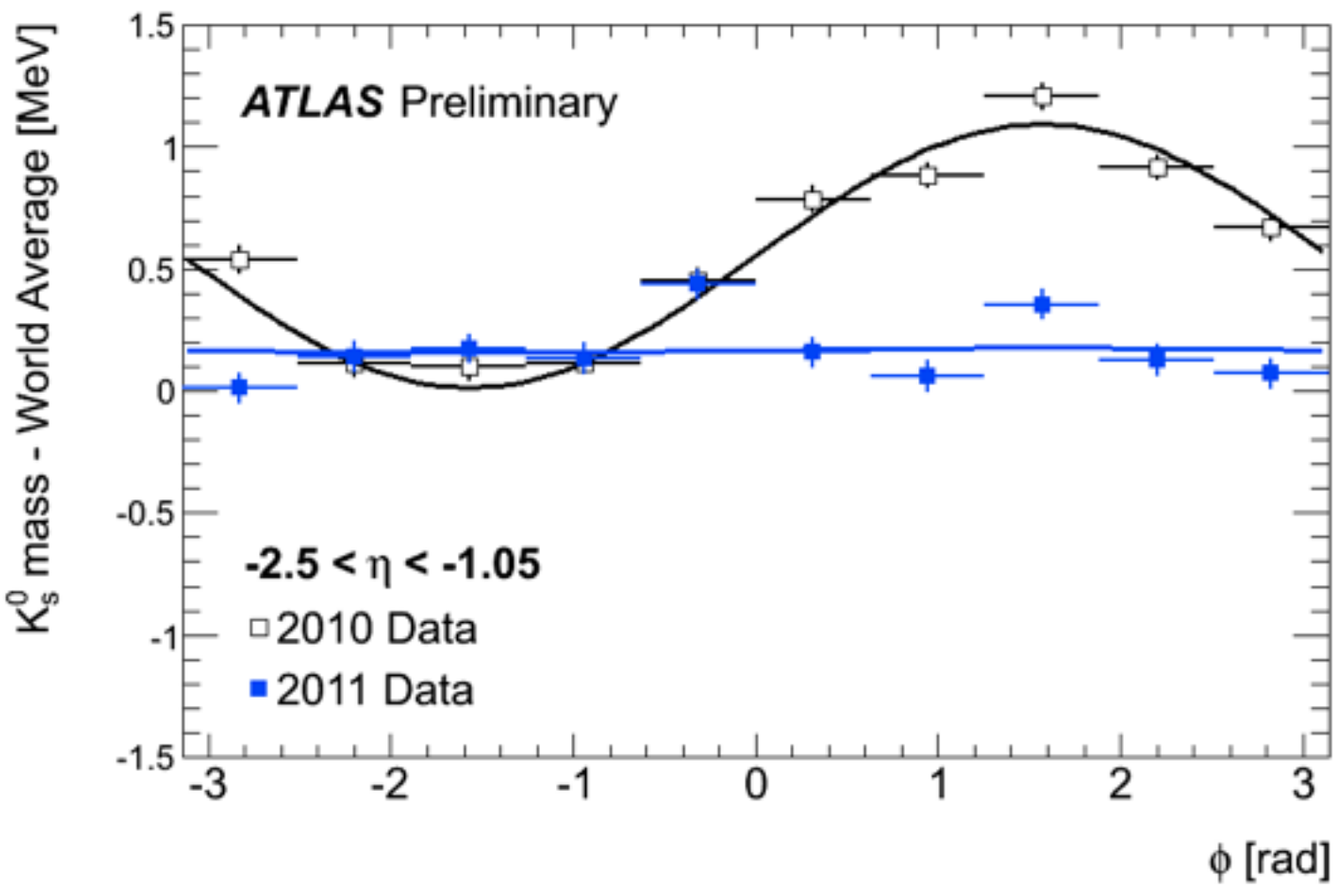

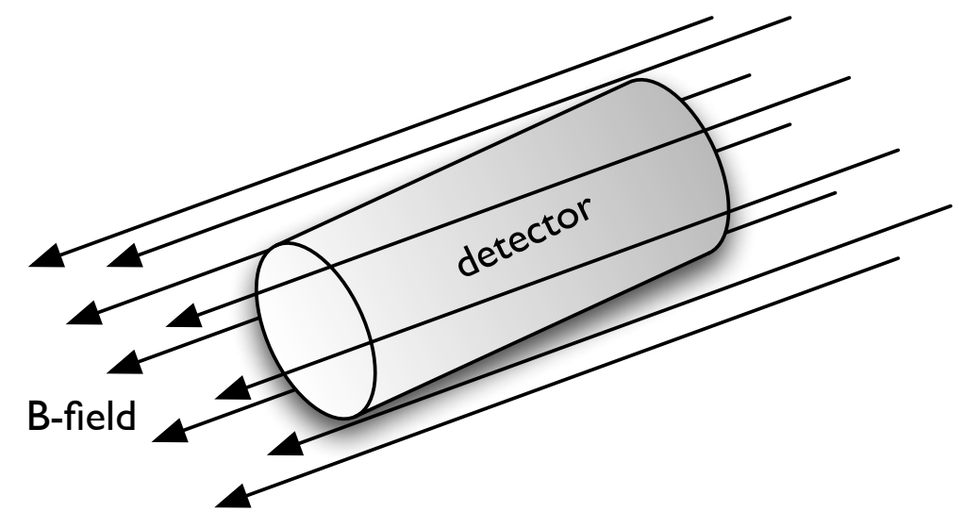

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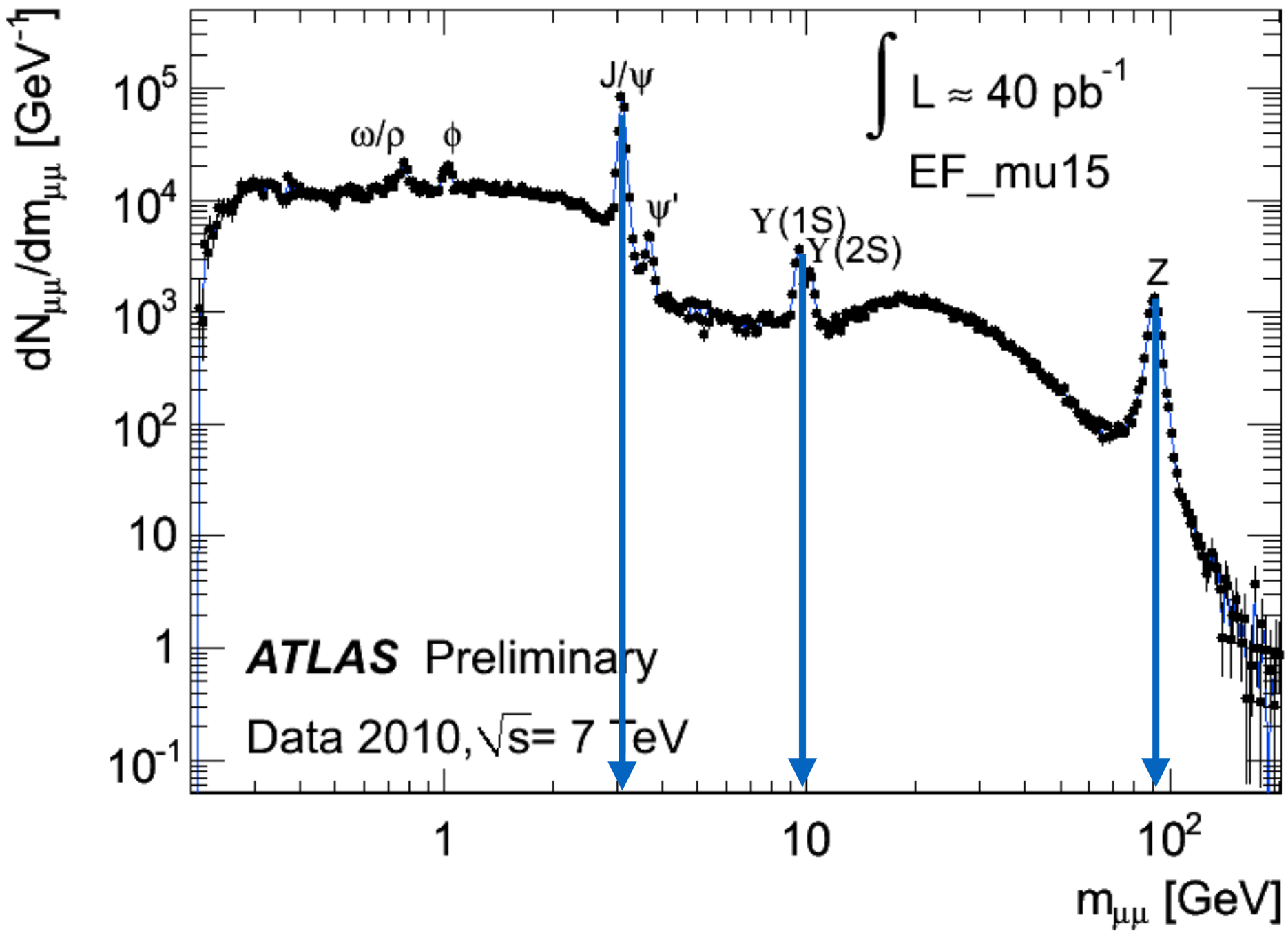
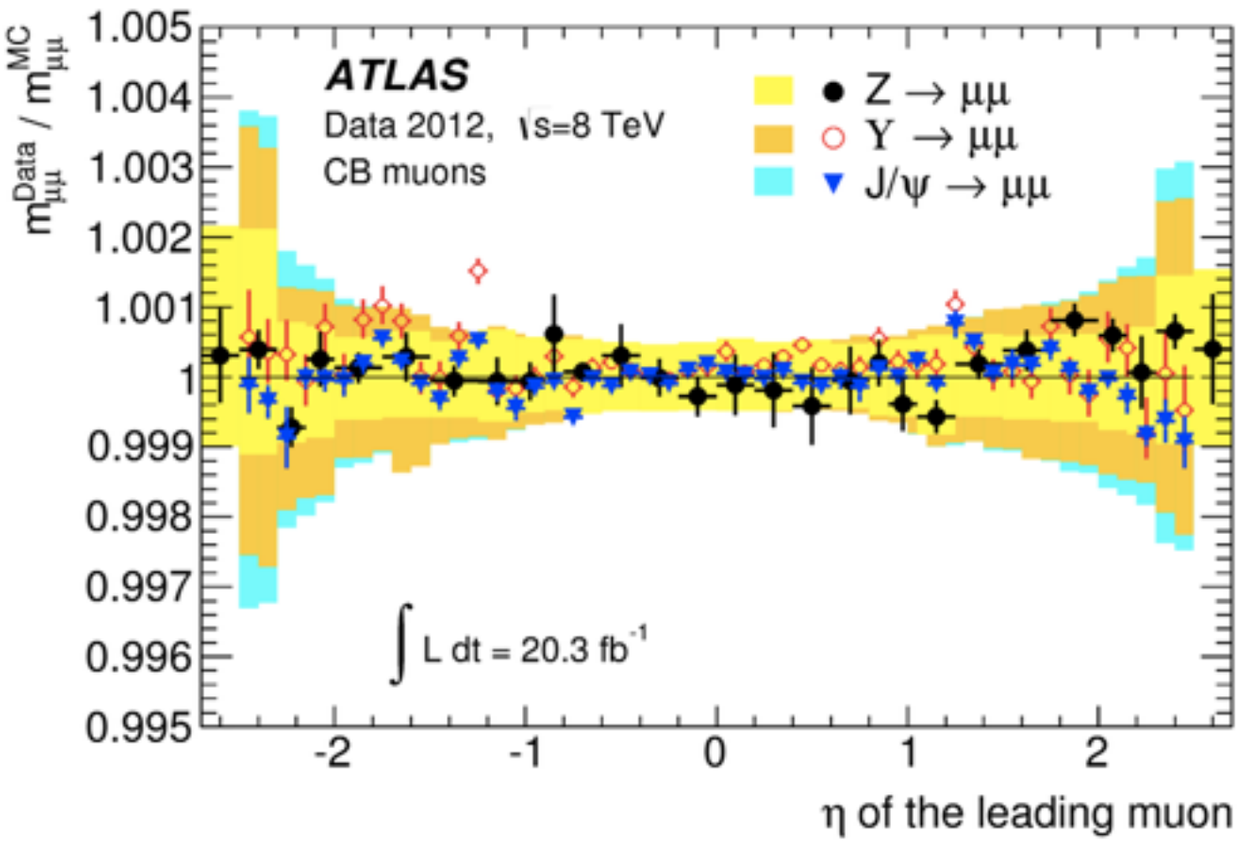


Example: Higgs mass from $\mathbf{H \to ZZ^* \to 4\mu}$

- Let's finish our analysis and get out of there …



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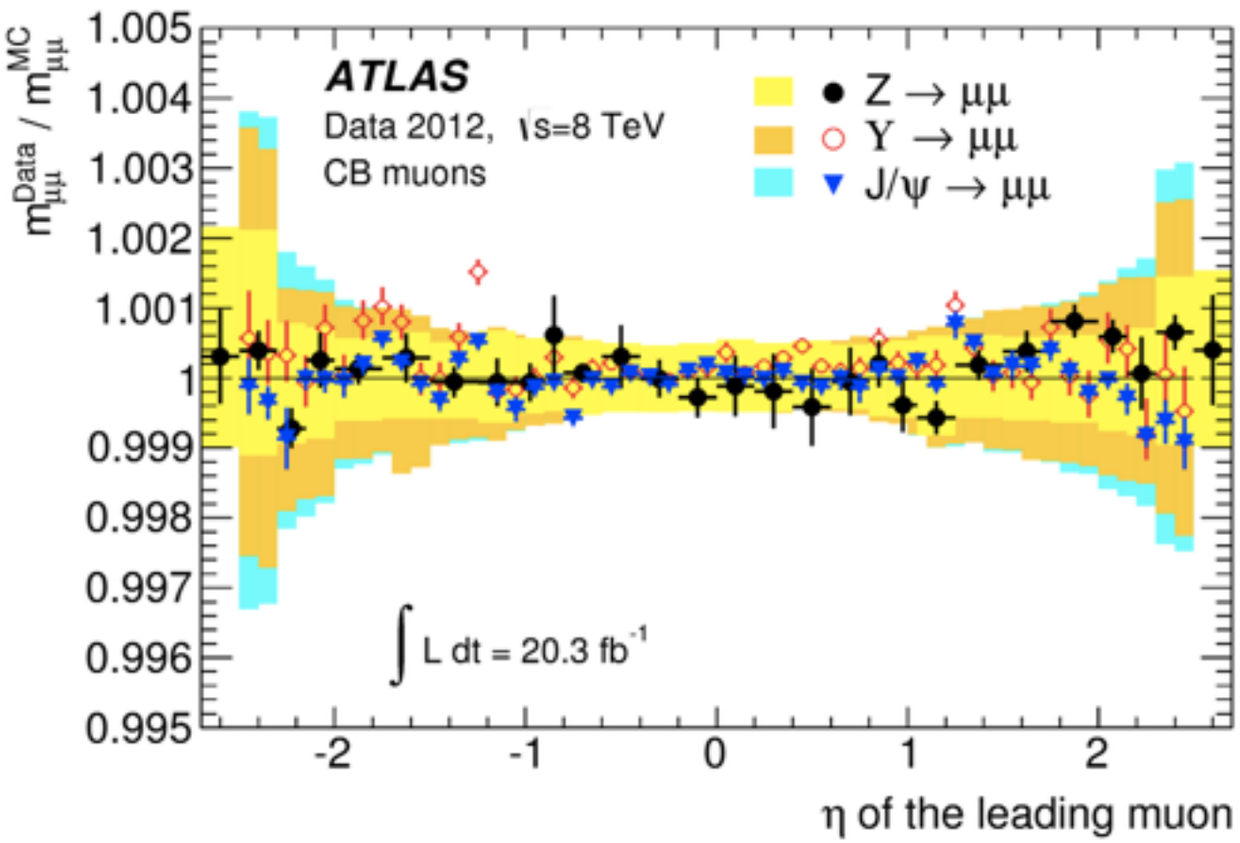

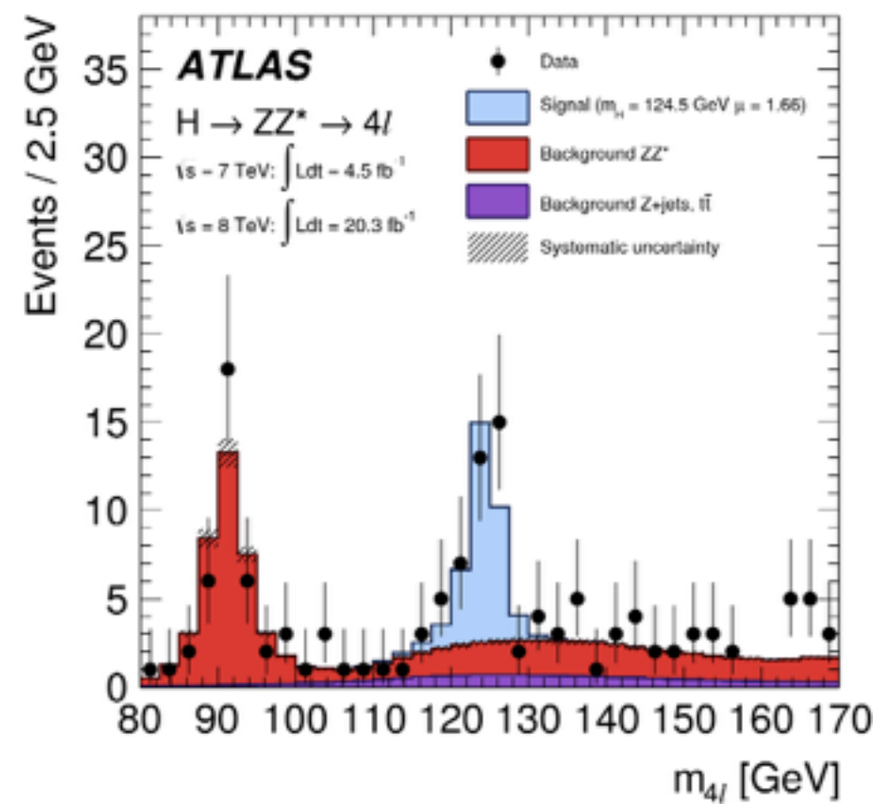

The take aways

- Actually, you should fill this page !

What I could not cover …

MISSED

- A lot …
- Track/vertex finding: there are way more methods
- Track fitting: there are way more methods
- Track reconstruction in very dense environments
  - e.g. in core of very dense jets
- Combined reconstruction
  - combined μ fitting, decay chain fitting, constraint fitting …
- Computing aspect
  - CPU time optimisation (very important for high pile-up)

… and much more

And finally

- Thanks to you for being such a great audience !
- To the school organisers and other lecturers to make this such a great school
- A special thank to Markus Elsing for some of the material.