Fast pattern recognition for ATLAS track triggers in HL-LHC

22.04.20

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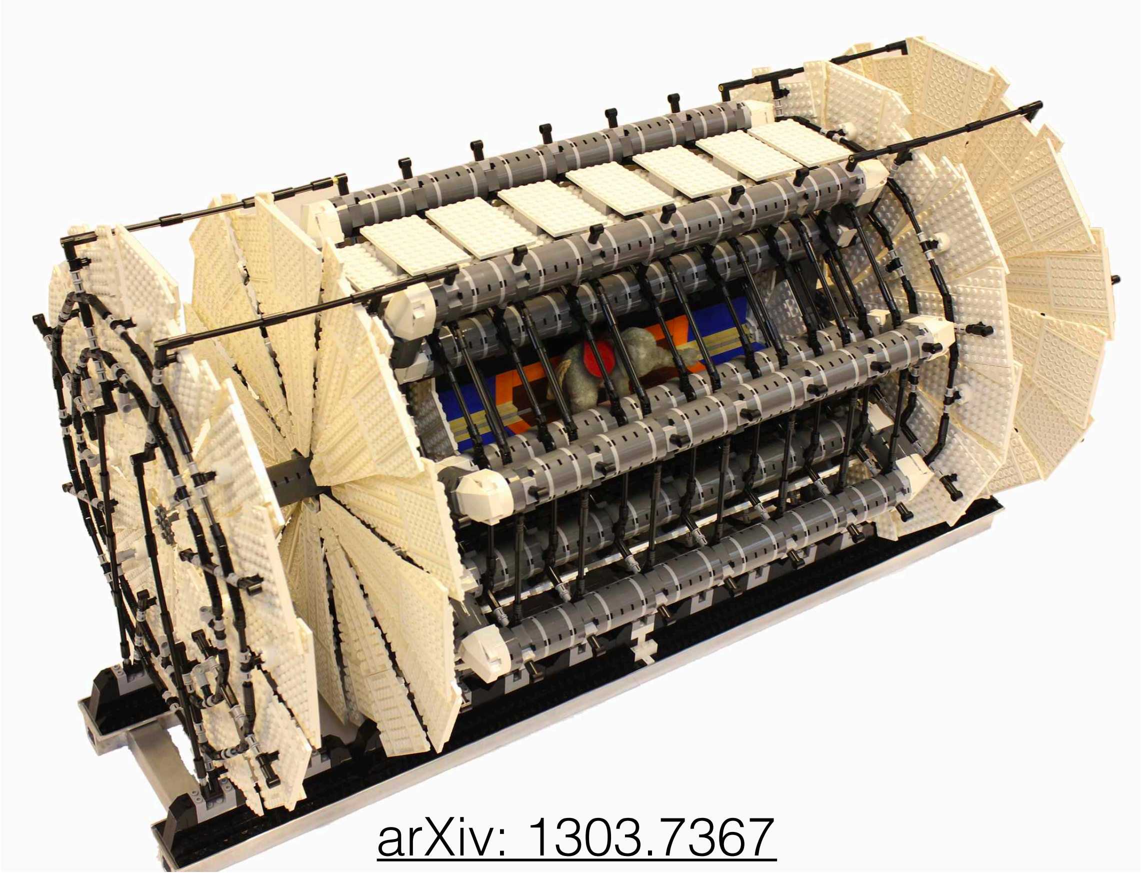
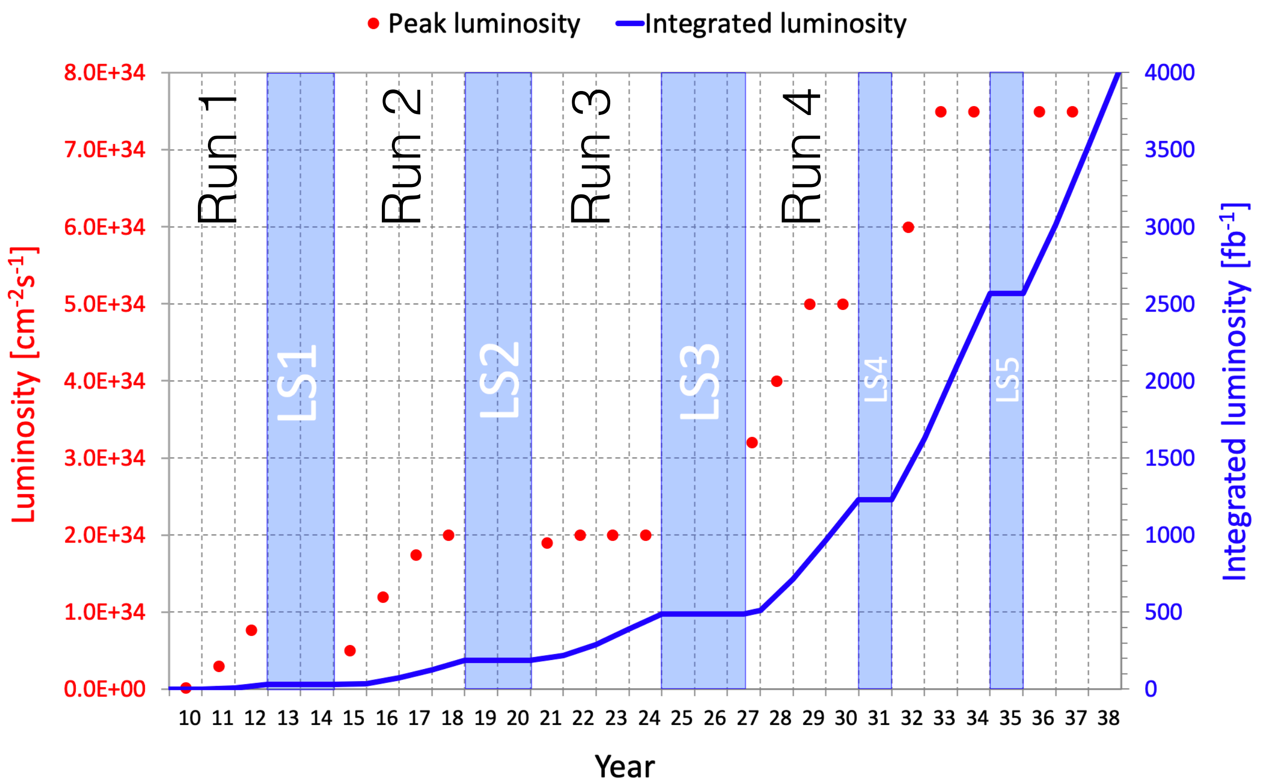
on behalf of the ATLAS Collaboration



arXiv: 1303.7367

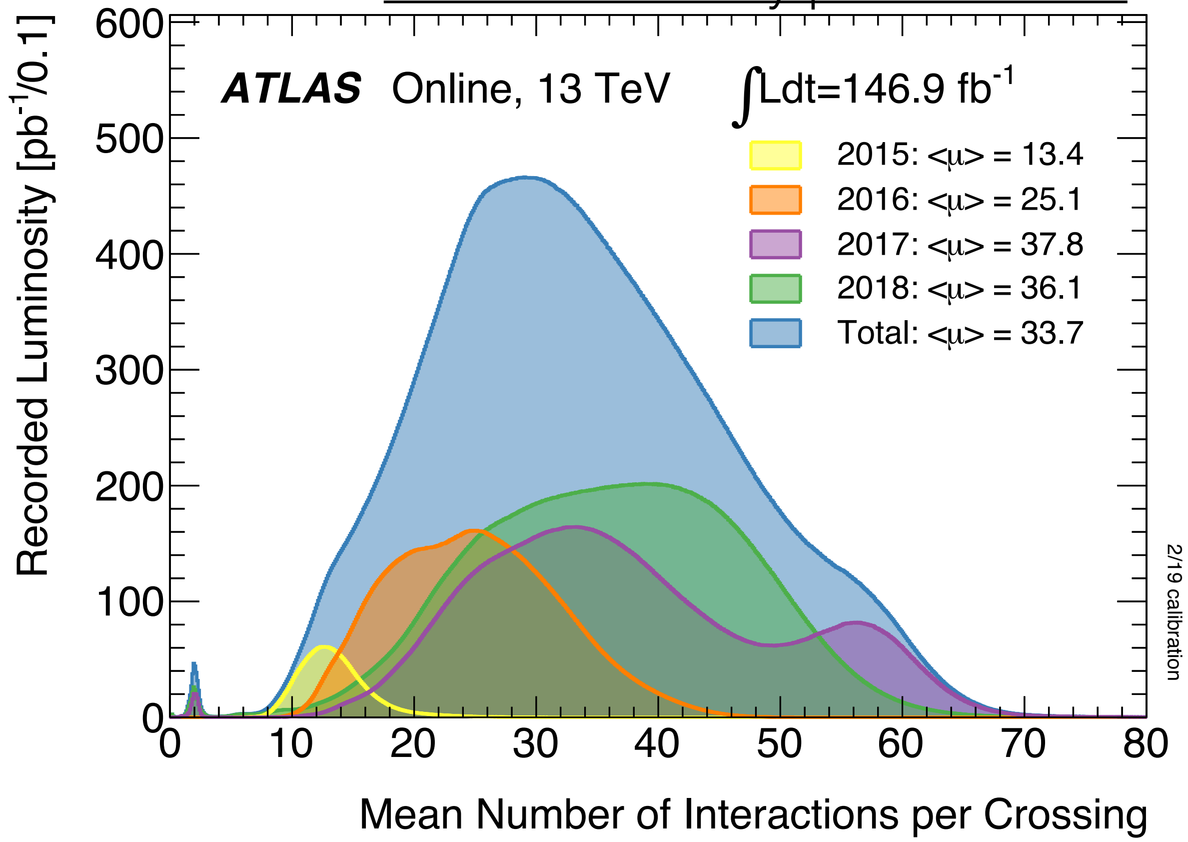


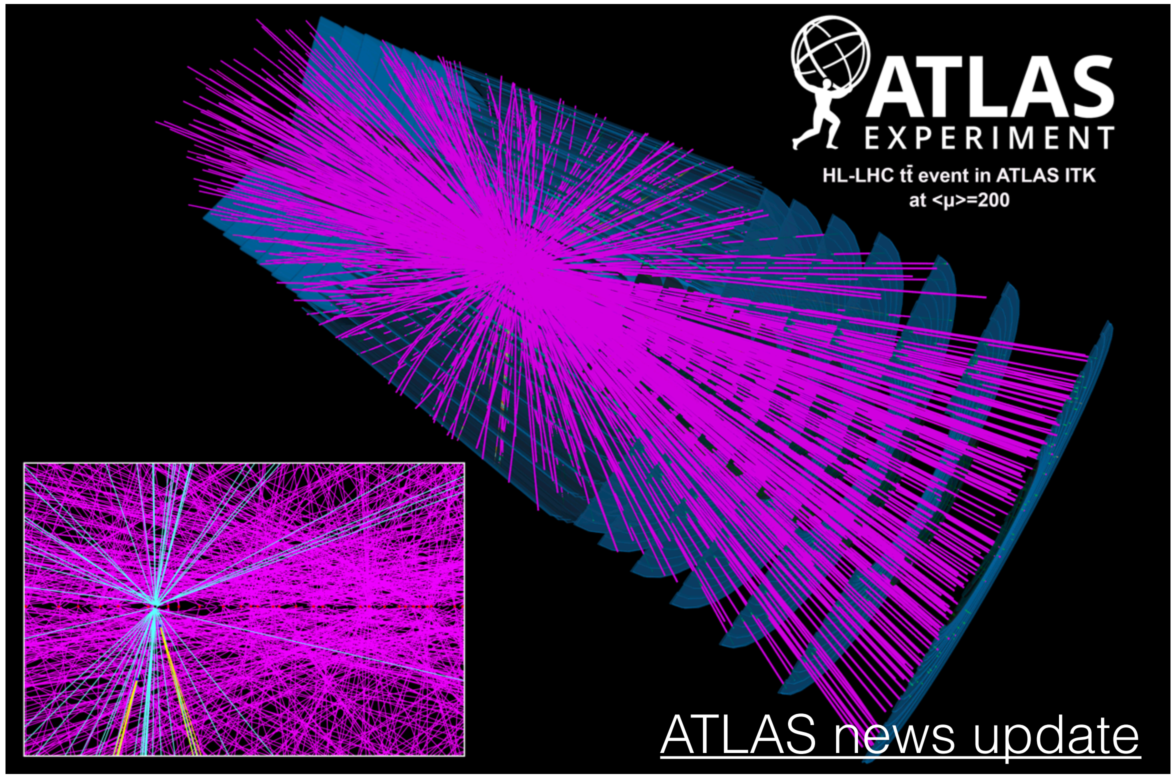
LHC commissioning

- ATLAS: large general-purpose LHC experiment
- To keep pushing research program, need an ever-increasing flow of data
  - Leaving rate constant would render each year increasingly less useful statistically
- High-Luminosity LHC: large increase in instantaneous luminosity -> more p-p collisions per second

- More p-p collisions but same bunch spacing -> more collisions per bunch crossing
- Peaked around 70 in Run 2, Run 4 may start around 140 and increase to 200
- Need much more capable tracking hardware: will replace entire inner detector with a new “inner tracker” (ITk)

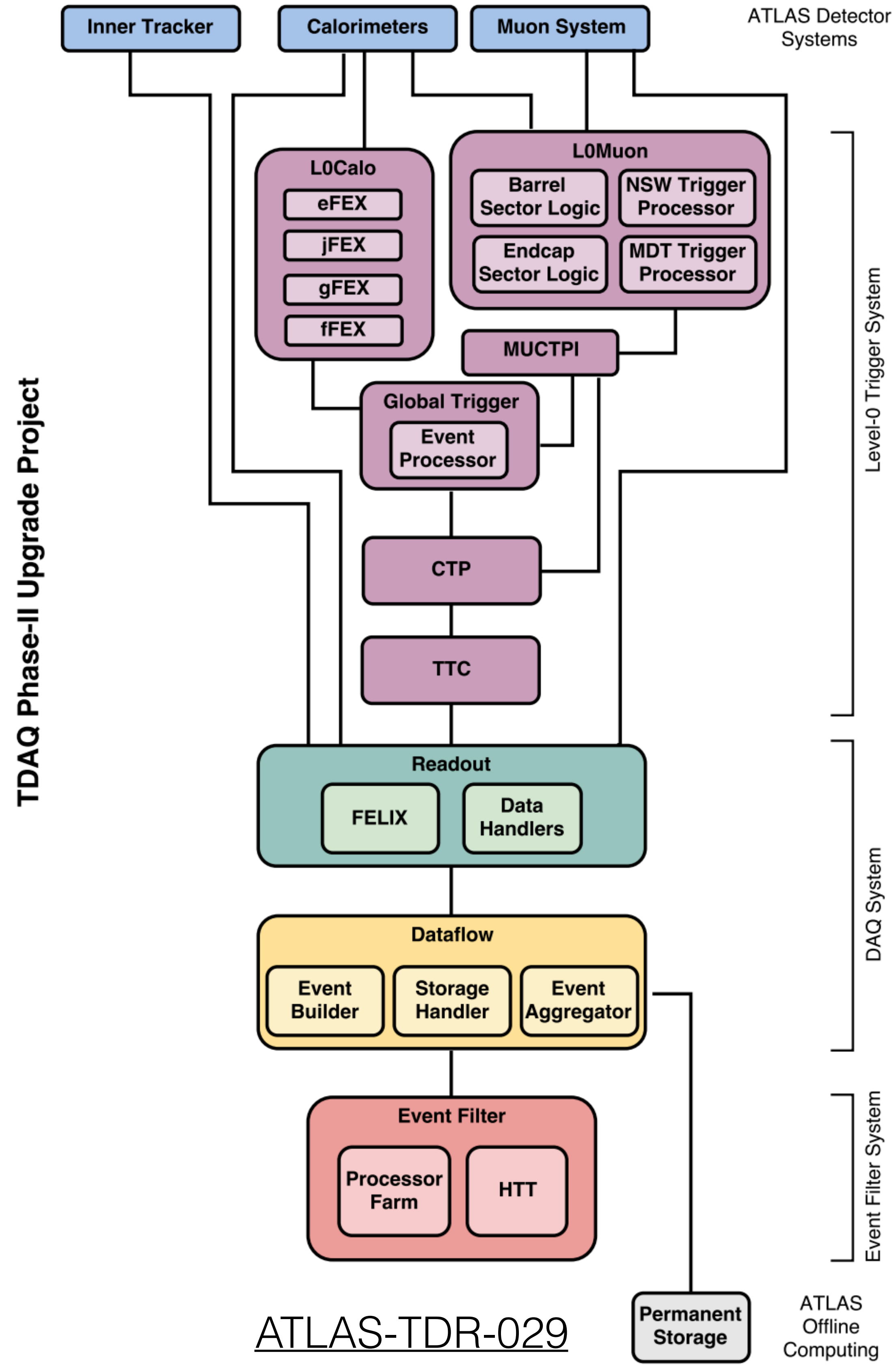
ATLAS luminosity public results





ATLAS news update

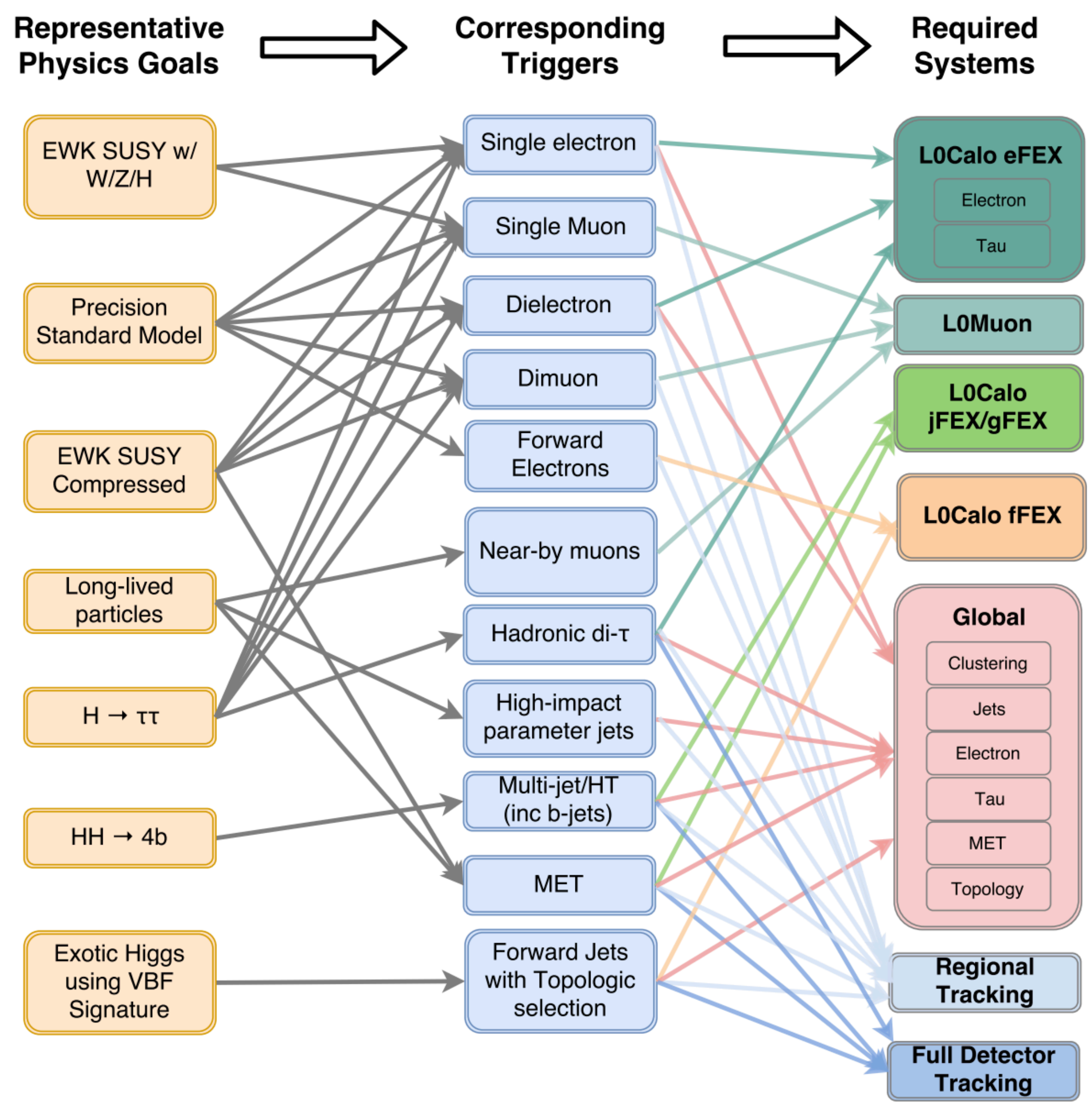
- Huge p-p collision rate is only useful if we can record the information we want
- Planned upgrades to trigger system: ATLAS-TDR-029
- Multi-stage system, progressively more detailed information and more time to make decision
  - 40 MHz input rate
  - Level-0: 1 MHz output, 10 μs latency
  - Event Filter: 10 kHz output (full events)



ATLAS-TDR-029

Fast pattern recognition for ATLAS track triggers in HL-LHC

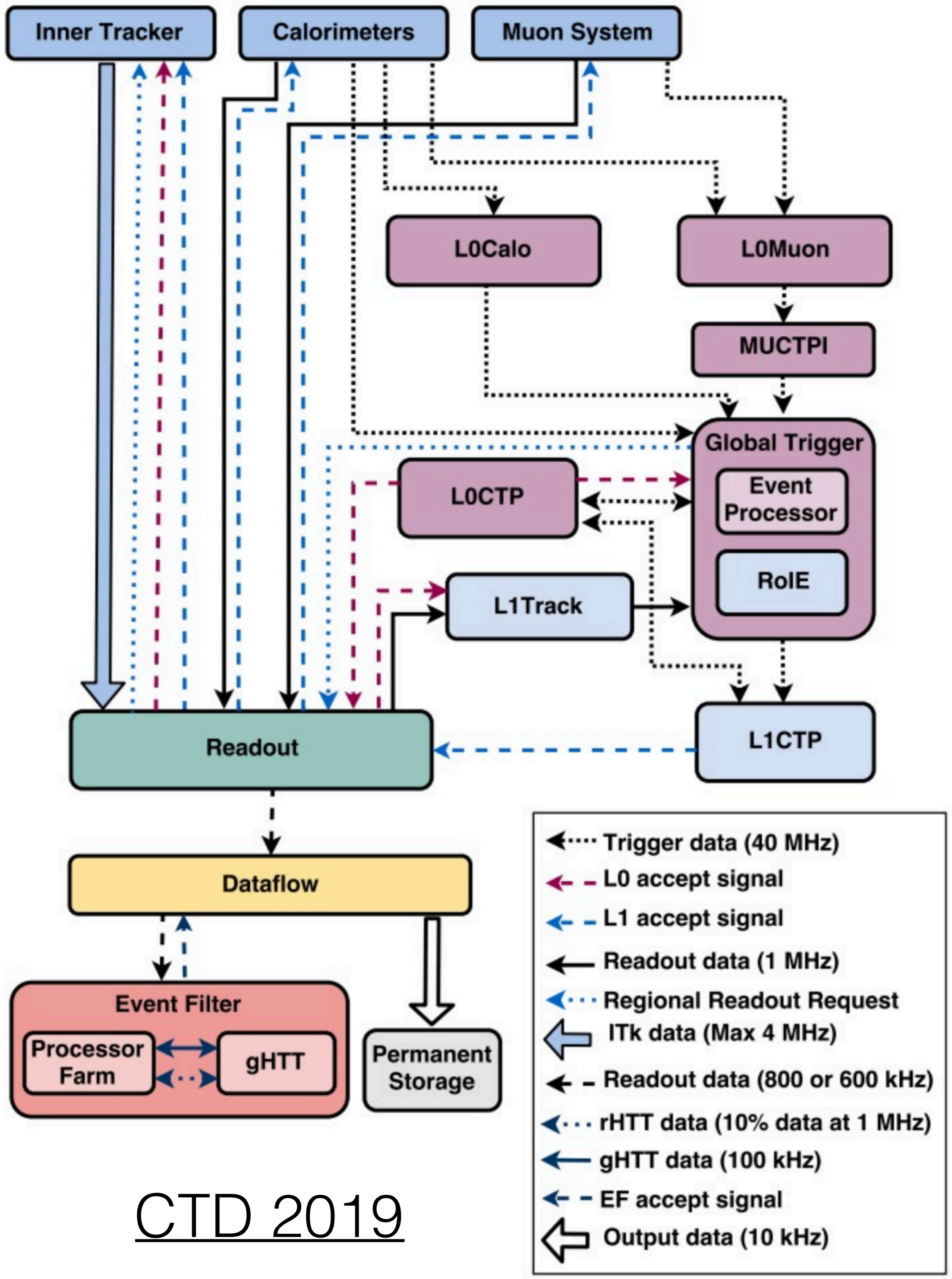
- Tracking is essential for Event Filter trigger performance
  - Particle flow identification
  - Missing transverse momentum
  - Jet tagging (b-jets, q/g, W/Z/h/top in large-R, …)
  - Tau identification
  - …
- Trigger system has limited latency and finite computing power: any tracking done has to be fast
  - The slower it is, the more limited it has to be: higher p_T, reduced regions in η / z / d_0



ATLAS-TDR-029

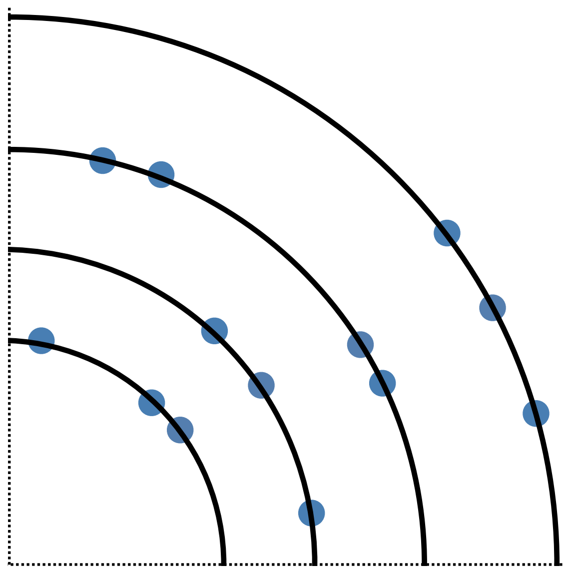
Hardware Track Trigger

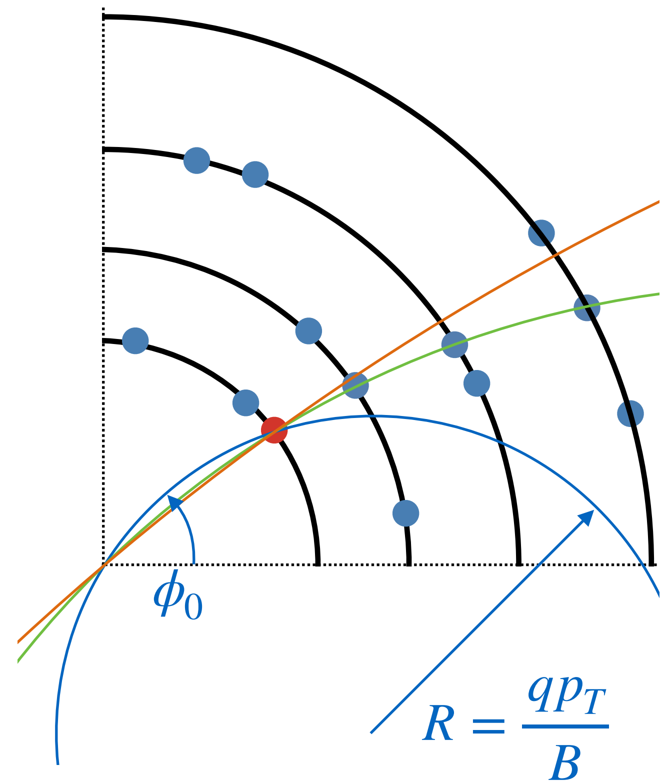
- Baseline ATLAS plan is to perform high-quality fast tracking with an associative-memory based Hardware Track Trigger processor
  - Regional: L0 RoIs
    - Event Filter, “rHTT”: 1 MHz, 2 GeV,
    - L1, “L1Track”, 4 MHz, 4 GeV
  - Global, “gHTT”: 100 kHz, 1 GeV
- ATLAS is investigating alternative approaches, such as fully software tracking [ATL-PHYS-PUB-2019-041], or CPU-FPGA or CPU-GPU hybrid architectures
- This talk: fairly simple algorithms to seed tracking, amenable to running on FPGAs
  - Not contingent on particular architecture
  - Proposed architectures not contingent on them



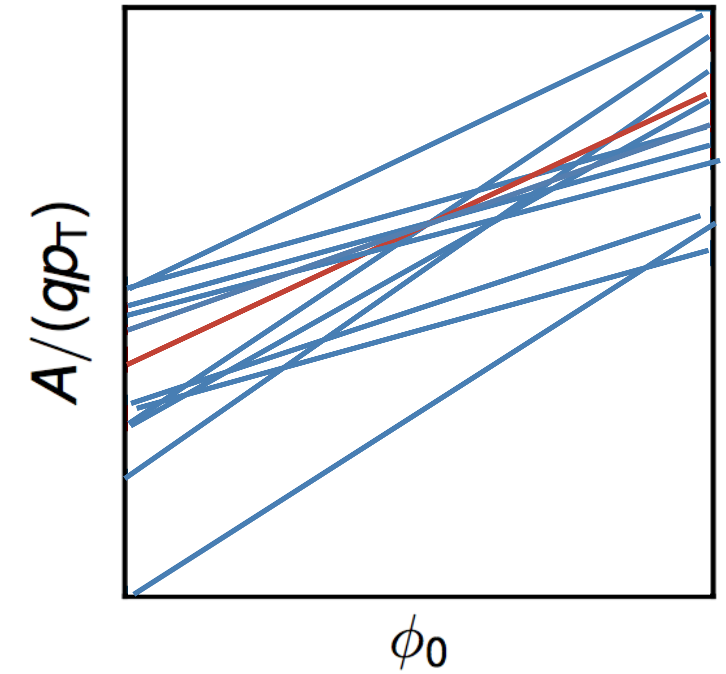
CTD 2019

Hough transform

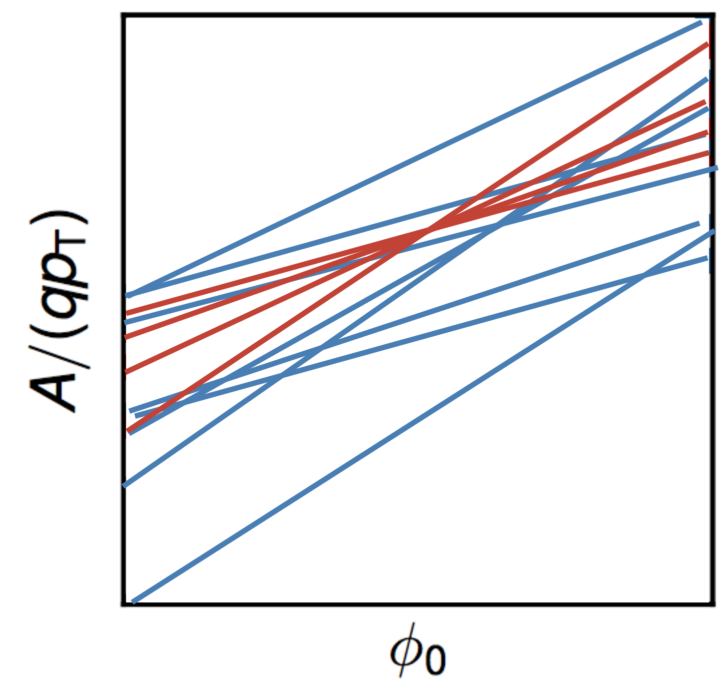




$$r = 2R\sin(\phi_0 - \phi)$$

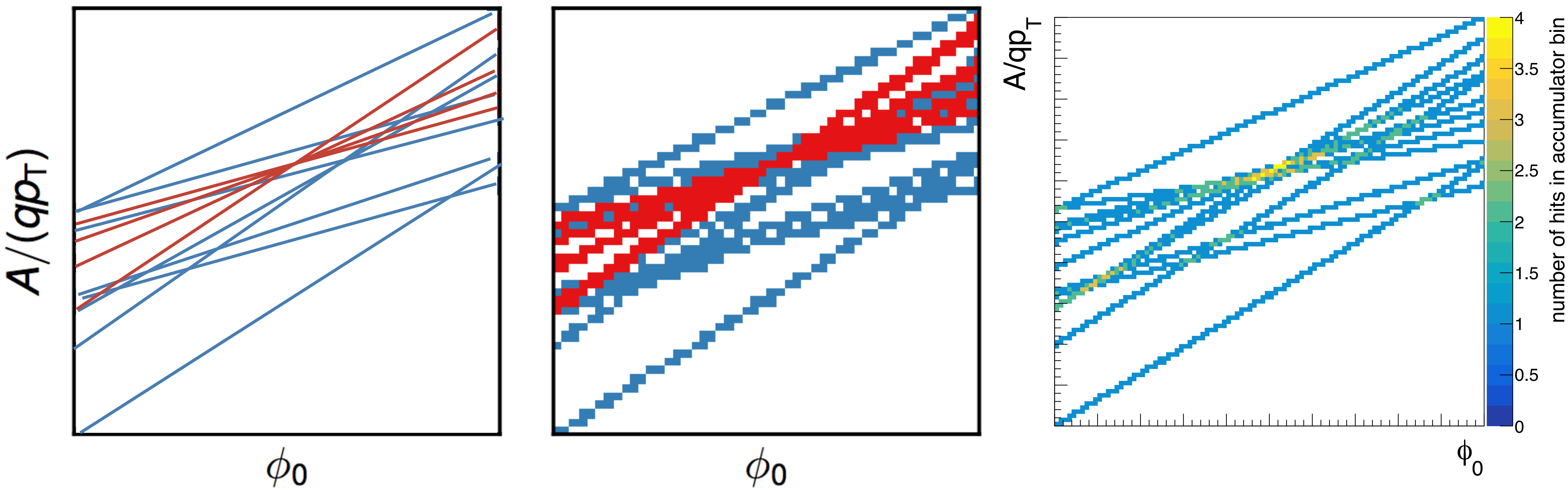


$$\frac{A}{qp_T} = \frac{1}{r}\sin(\phi_0 - \phi)$$

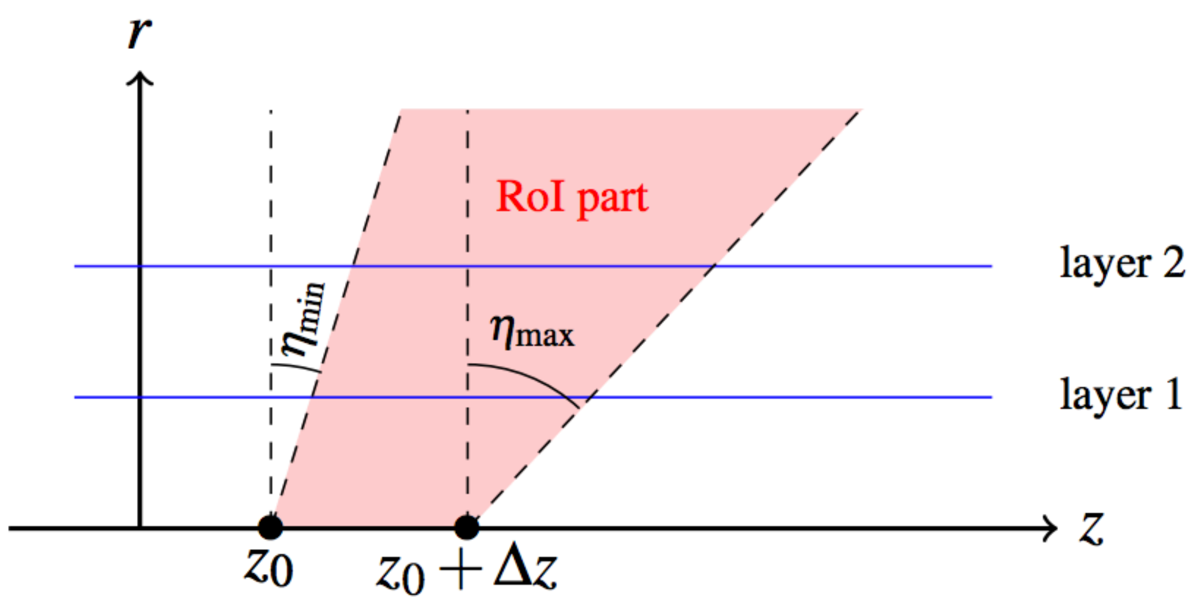


- Image-processing technique to find circles [Duda & Hart, J. Gradin et al 2018 JINST 13 P04019]
- Maps each hit to all circles through that point and the origin, straight lines for high-p_T tracks
- Intersection points of these lines = circles compatible with all hits

Hough transform, II

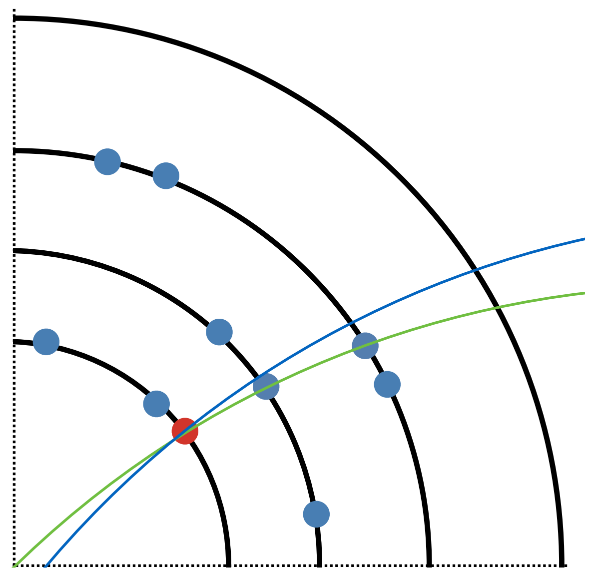


- Find intersections of lines using 2D "accumulator" histograms
- Split into multiple eta regions to reduce accumulator density
- Gives initial pass of track parameters and hits that seeded them

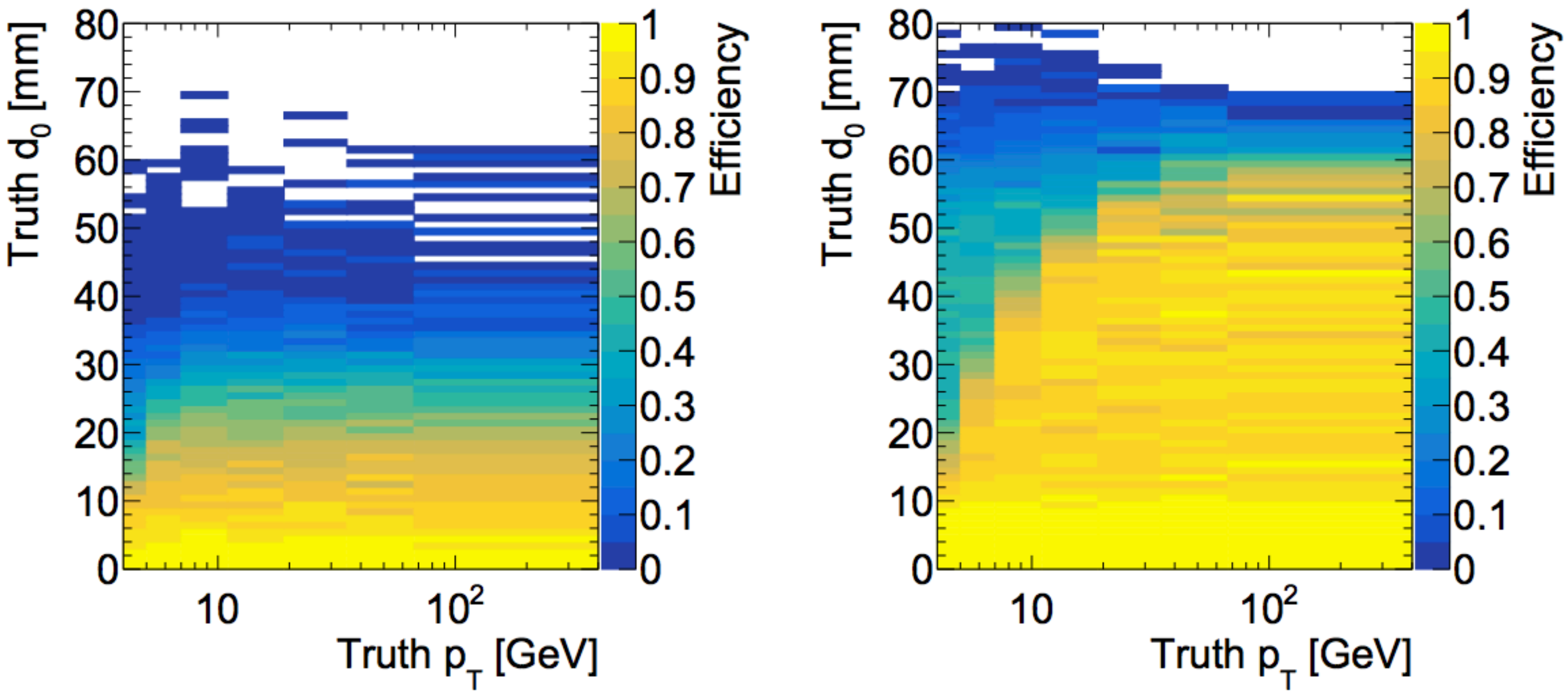


ATL-DAQ-PROC-2016-034

Hough transform, III



M. Mårtensson et al 2019 JINST 14 P11009

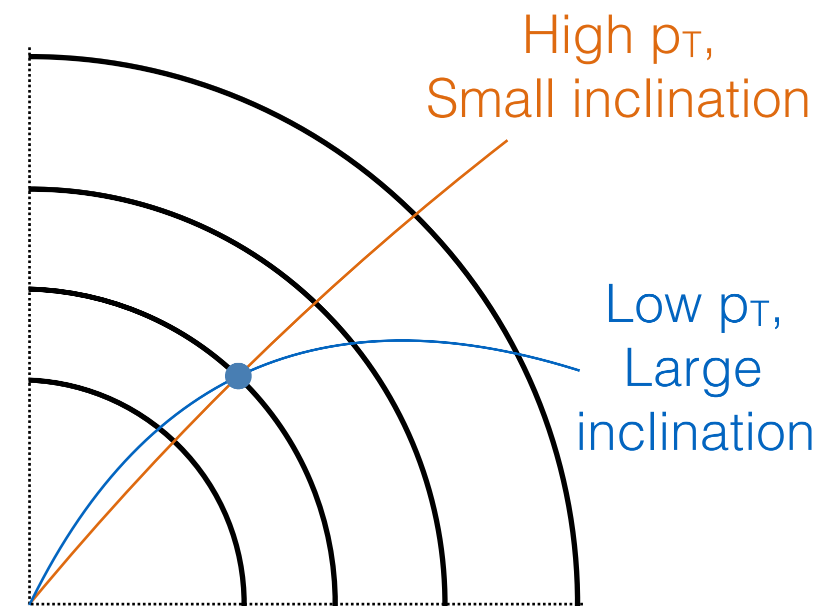


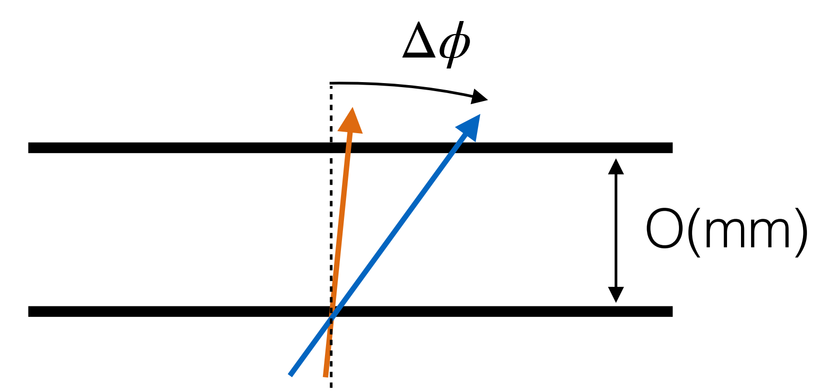
- Limitations on impact parameter: method designed for circles from known, fixed, origin
- Full treatment needs more complicated transform on pairs of hits, much more intensive -> slower and less feasible
- Can tune accumulator binning to mitigate impact (plot: efficiency to find at least 6 hits out of 8 in model tracker)
- Alternative tuning on ITk <μ>=200 simulation finds (6/8 hits) ~ 97% of 1 GeV and 2 GeV muons

ATLAS EXPERIMENT

Stub finding

- Lower p_T track will go through tracker layers at a higher inclination angle
- Large inclination -> large $\Delta\phi$ between layers
- CMS implements this starting with the design and readout of their phase-2 tracker
  - Mixed Pixel + Strip layers
  - Stub built on-detector
  - Require p_T > 2 GeV -> 90% reduction in hits



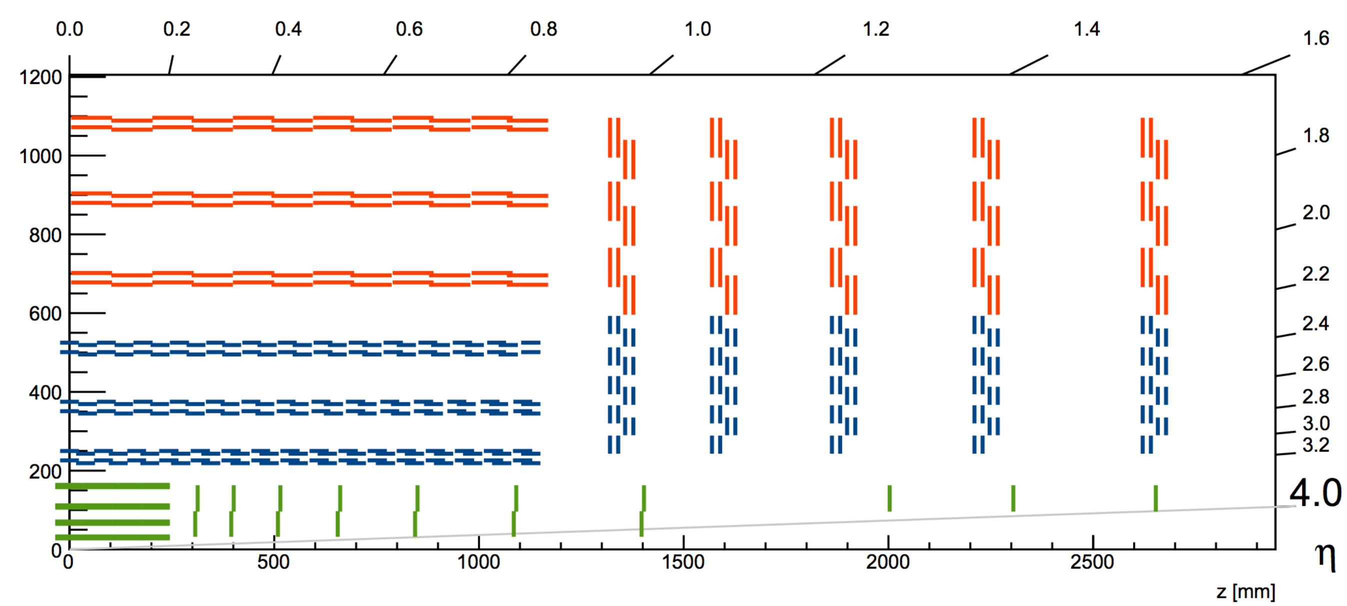


CMS Phase-II tracker: CMS-TDR-15-02

2S: Strip + Strip

PS: Pixel + Strip

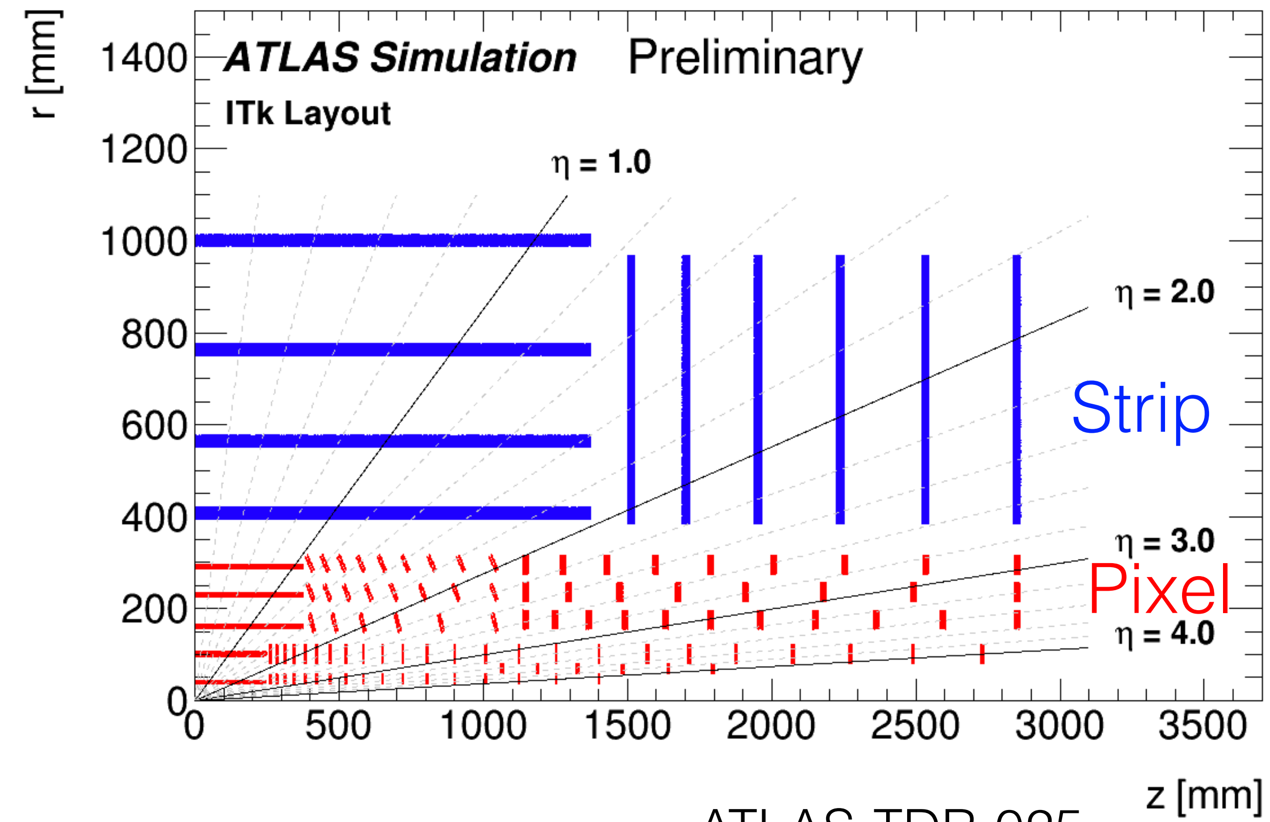
P: Pixel only



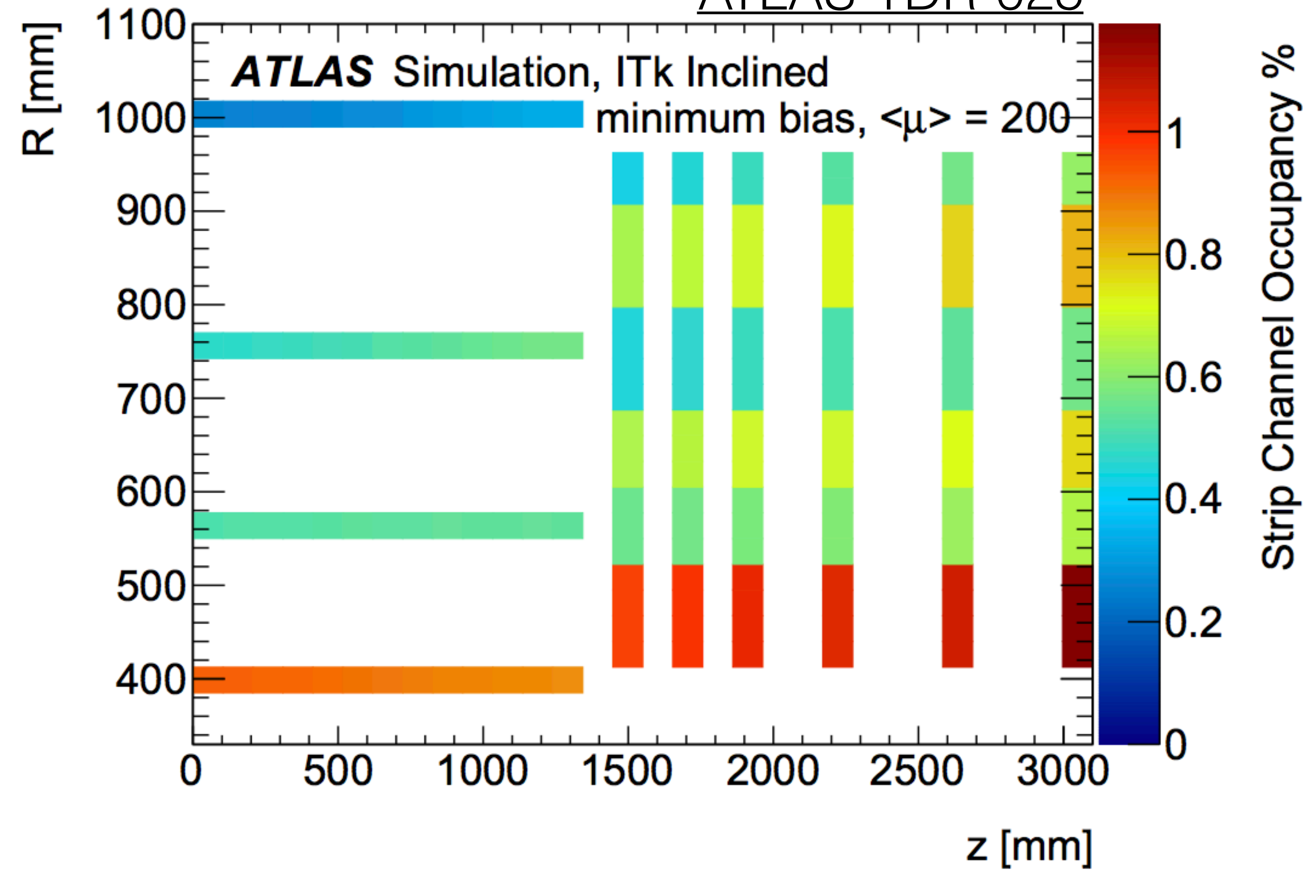
Stub finding: with ATLAS ITk

- ATLAS phase-II tracker different
  - Only strips are double-layered
  - Stub-finding only feasible within double layers
- ~ 0.5 - 1 % channel occupancy
- Barrel strips have 75.5 μm pitch, endcap 70-80 μm (wedge-shaped) -> $\Delta\phi$ from one strip to another is 0.1-0.2 mrad
- 100 strips = O(10) mrad between hits
  - Far too big for inter-layer stubs to be useful

ATL-PHYS-PUB-2019-014

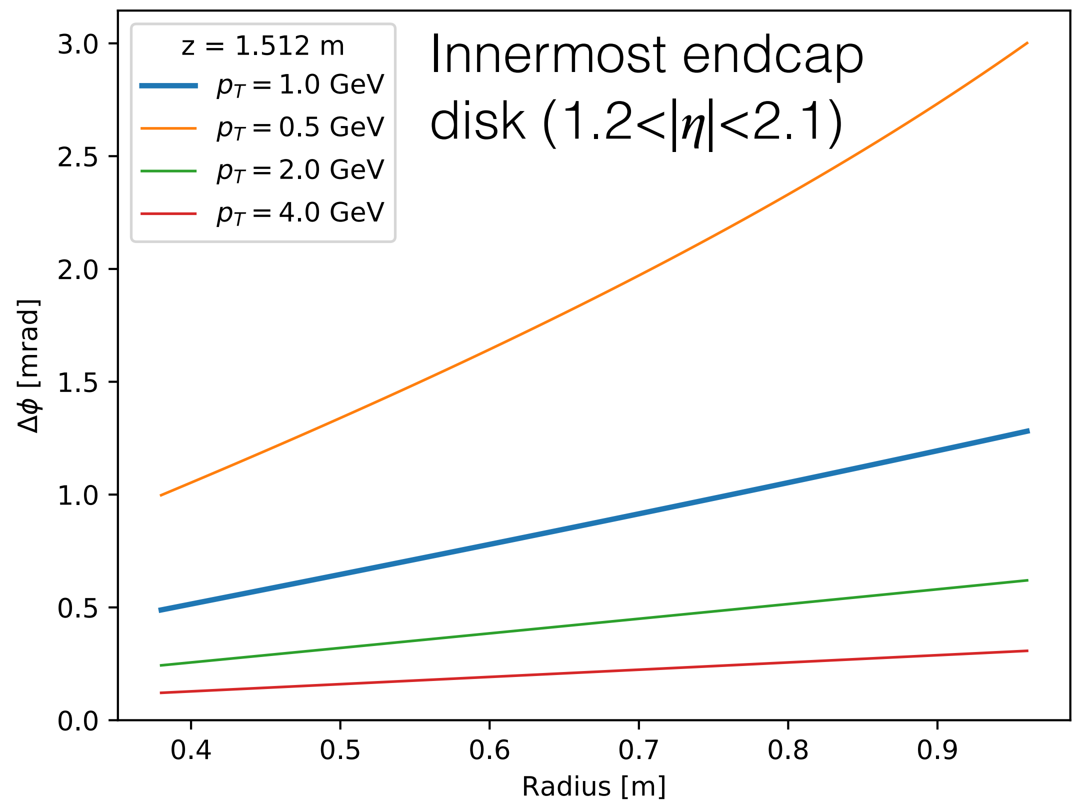


ATLAS-TDR-025

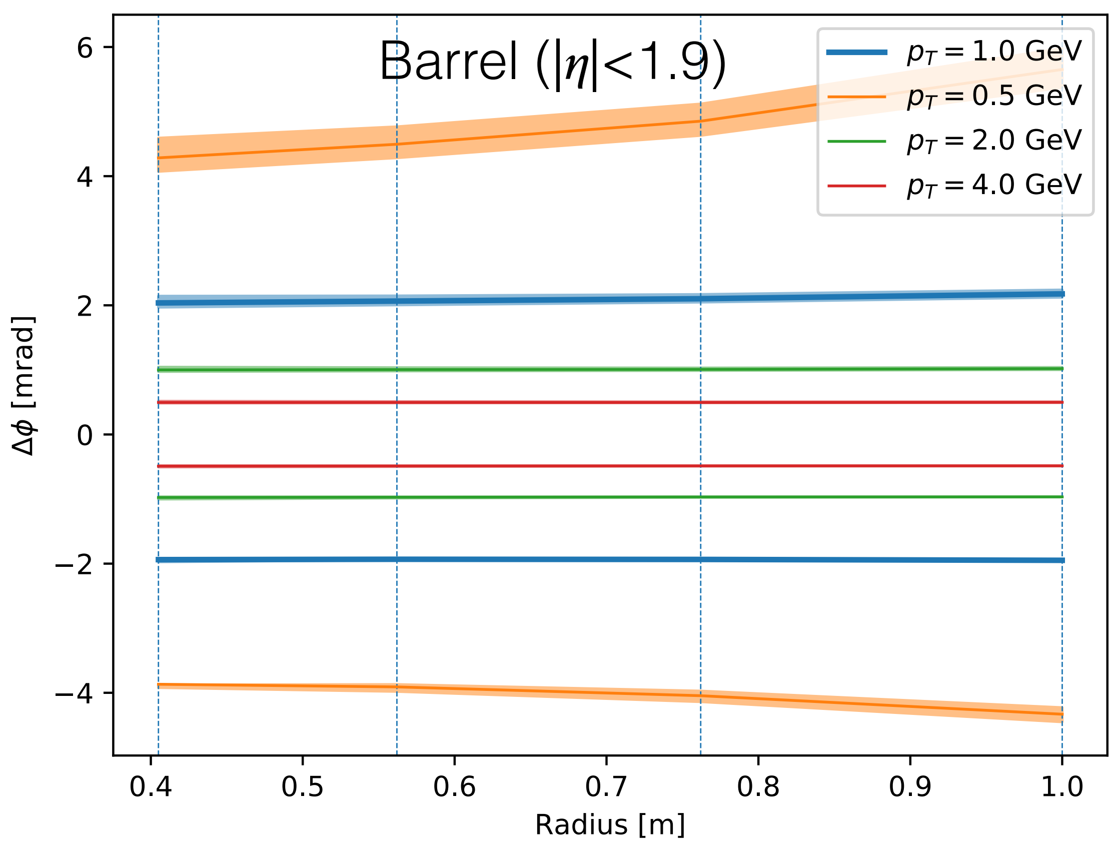


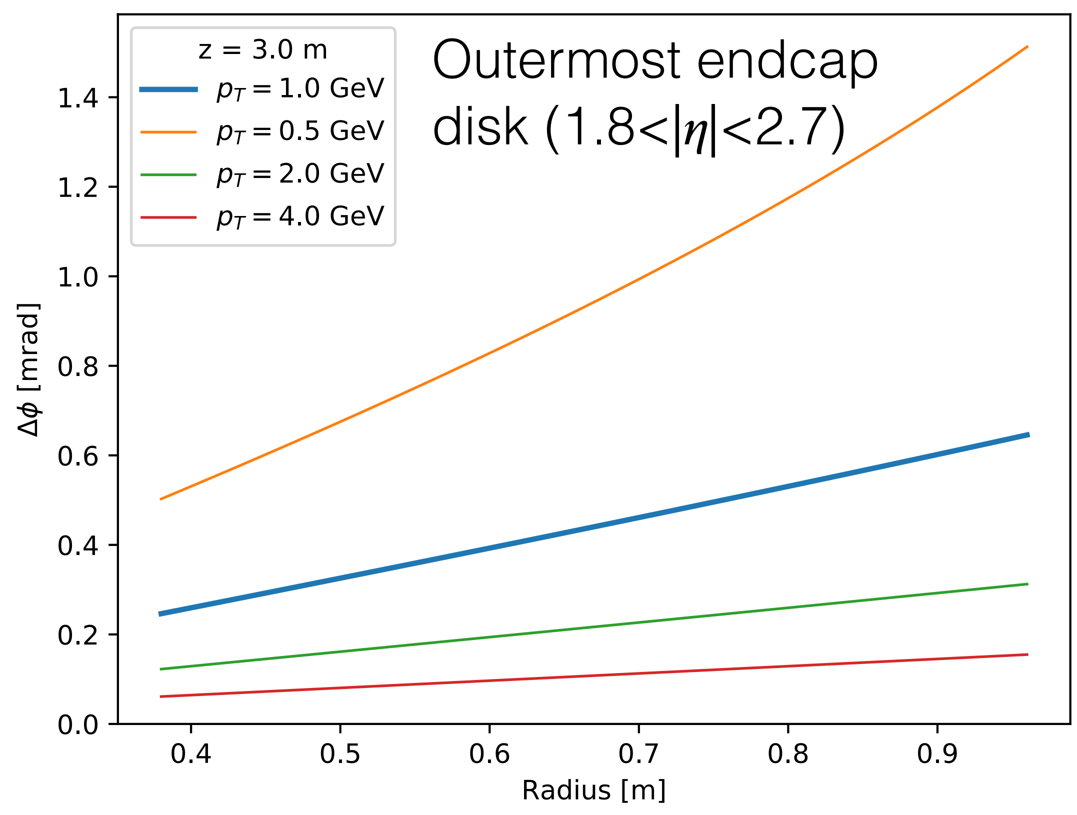
Stub finding: expectation

- Trigonometry from TDR numbers
- ~ Linear in track p_T
- 1 GeV track ~ 2 mrad in barrel, 0.2-1.0 mrad in endcap
- cf pileup occupancy ~ 10 mrad
  - Sadly this isn't the whole story…



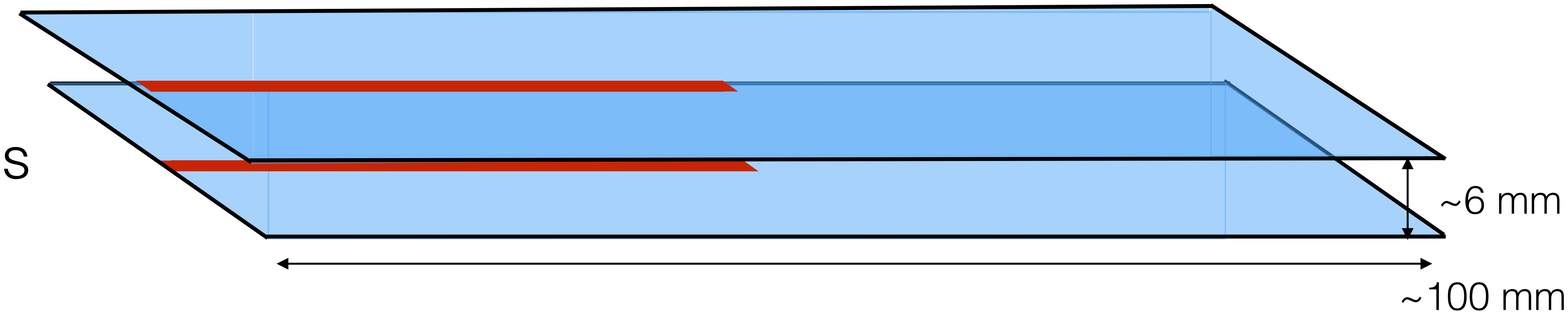
NB: not-quite-valid approximation for high η





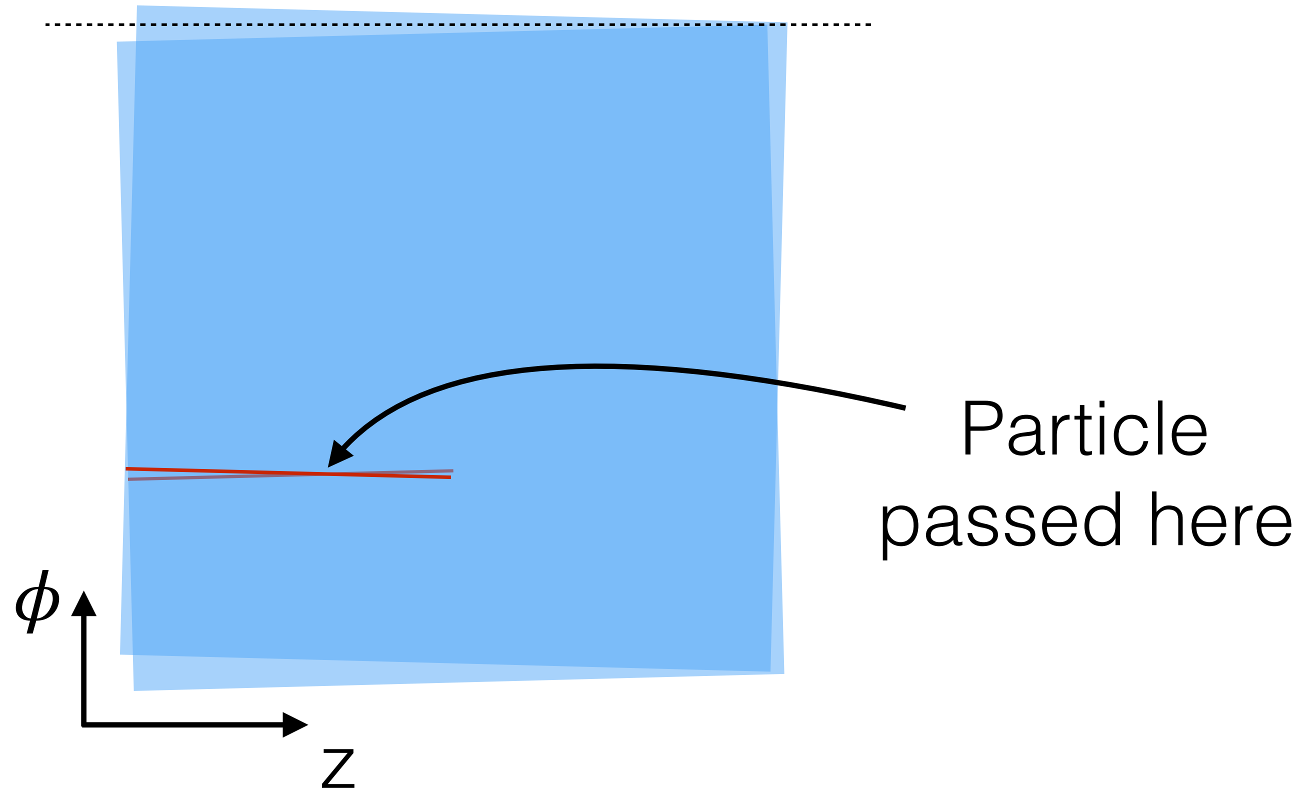
Stereo angle

Modules come in pairs



Each rotated 26 mrad = 1.5° from z axis
-> 52 mrad = 3° between them
Strips 18-60 mm long

Allows position information to be determined along strip direction



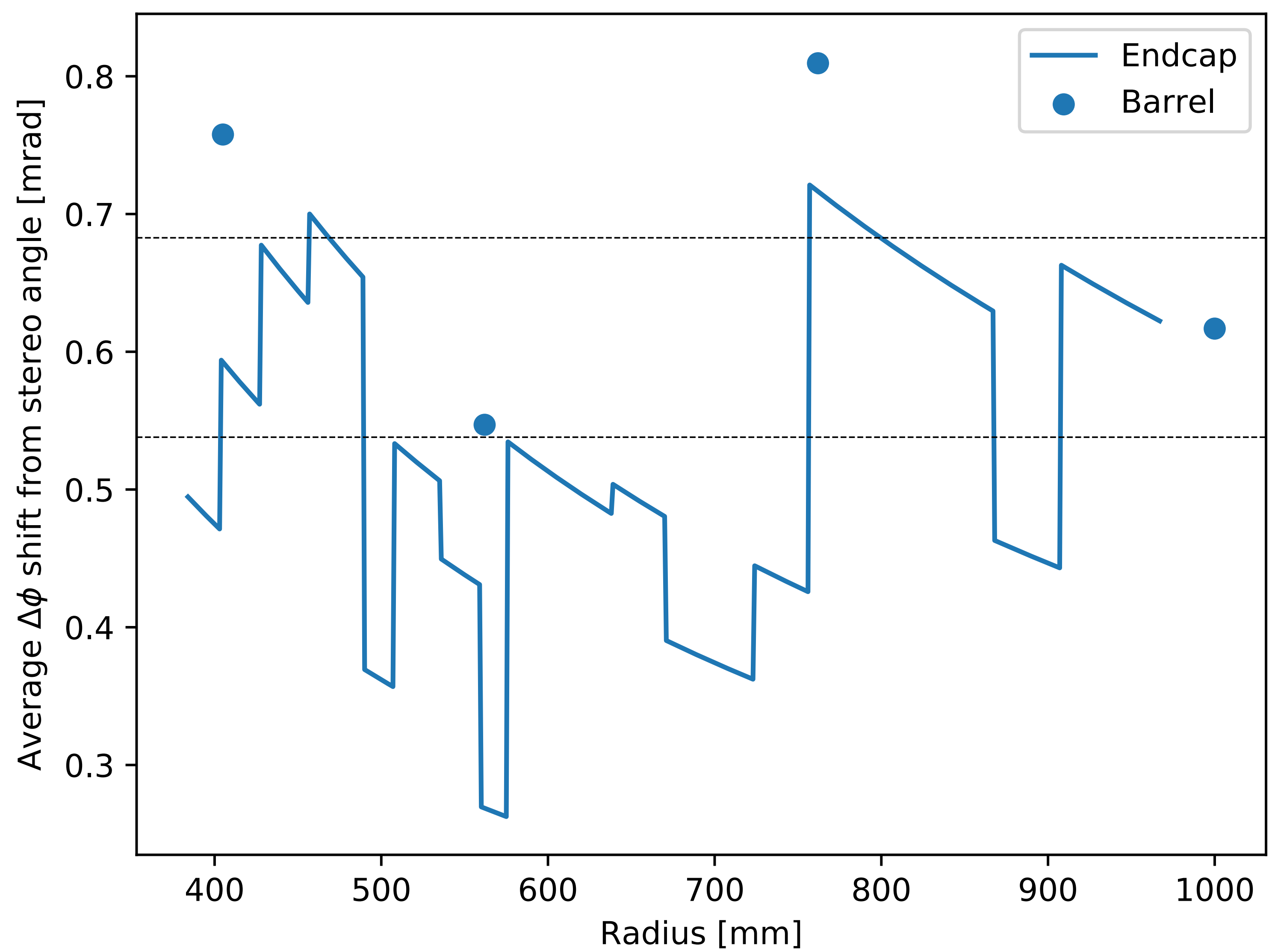
But means that strip 1 in layer A to strip 2 in layer B has an indeterminate $\Delta\phi$ depending on where along the strip it is

NB: not a problem for CMS pixel+strip modules, no need for stereo angle

Stereo angle

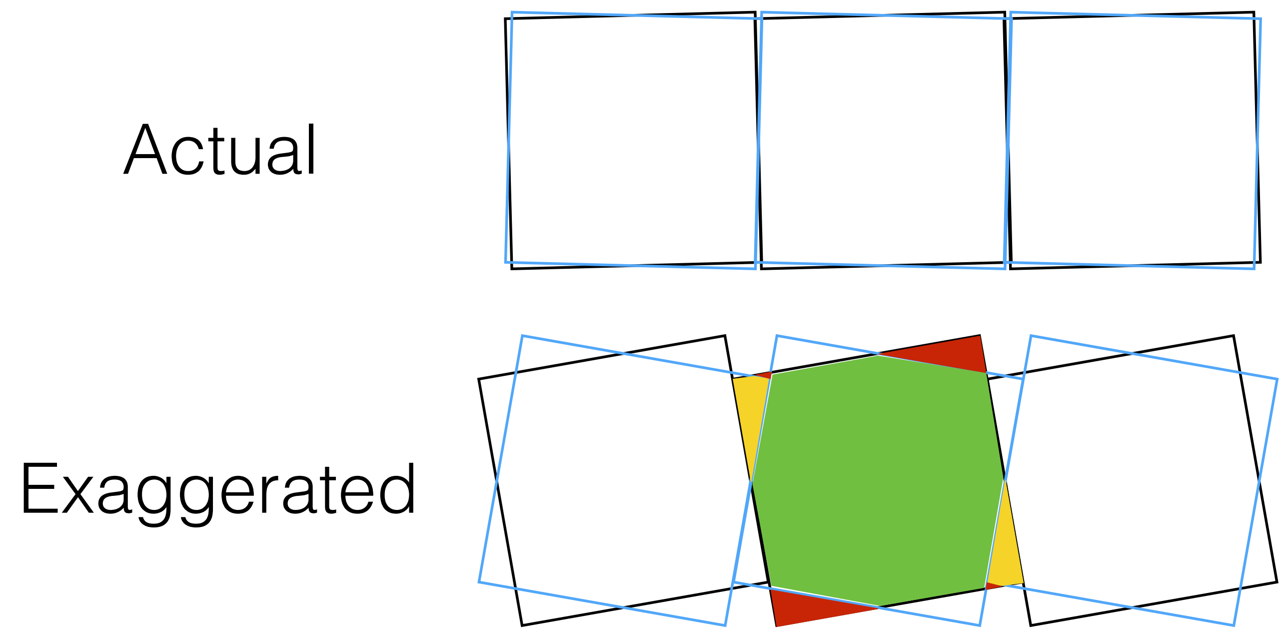
Barrel short strip to scale: 24.1 mm x 75.5 μm, 52 mrad angle = 3°

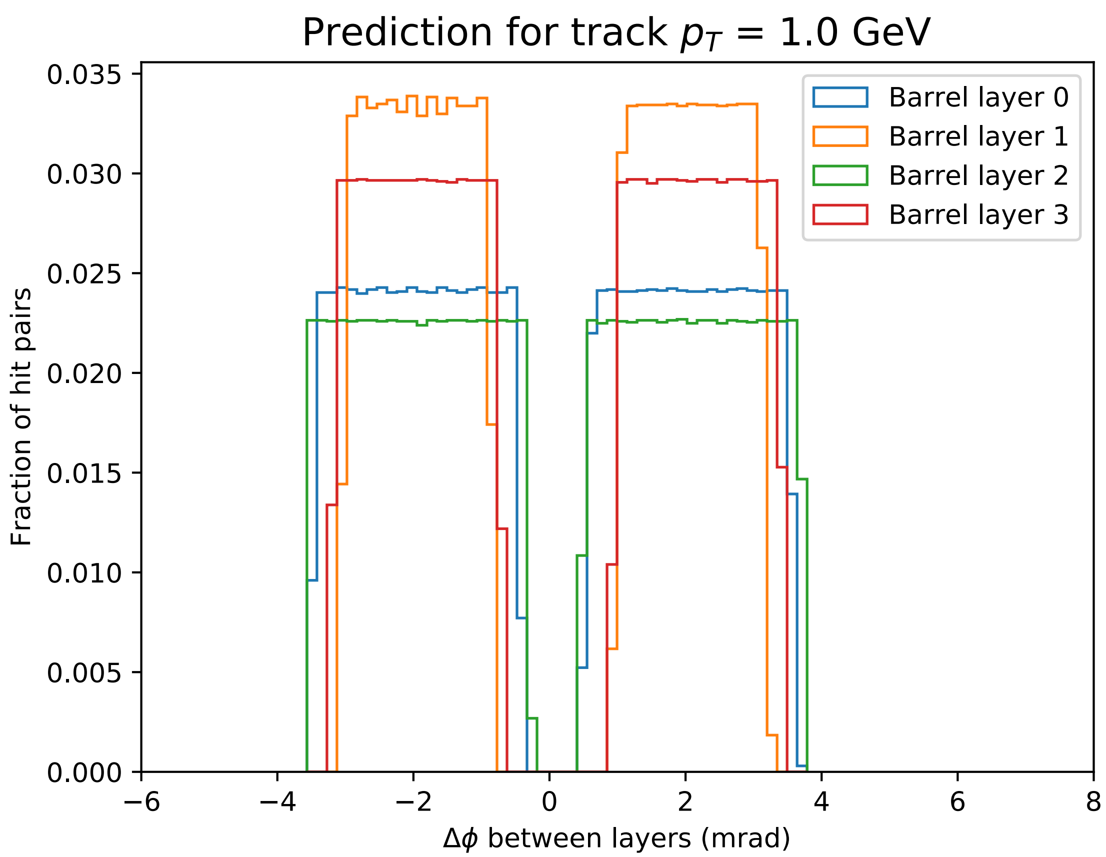
- Plot: average shift in $\Delta\phi$ from stereo angle (half maximum)
- $\Delta\left(\Delta\phi\right) \sim \frac{1}{r}$ for fixed strip length and stereo angle
- In reality, length varies (shorter at smaller radius for higher track density)
- ~0.69 mrad for barrel, ~0.54 mrad for endcaps

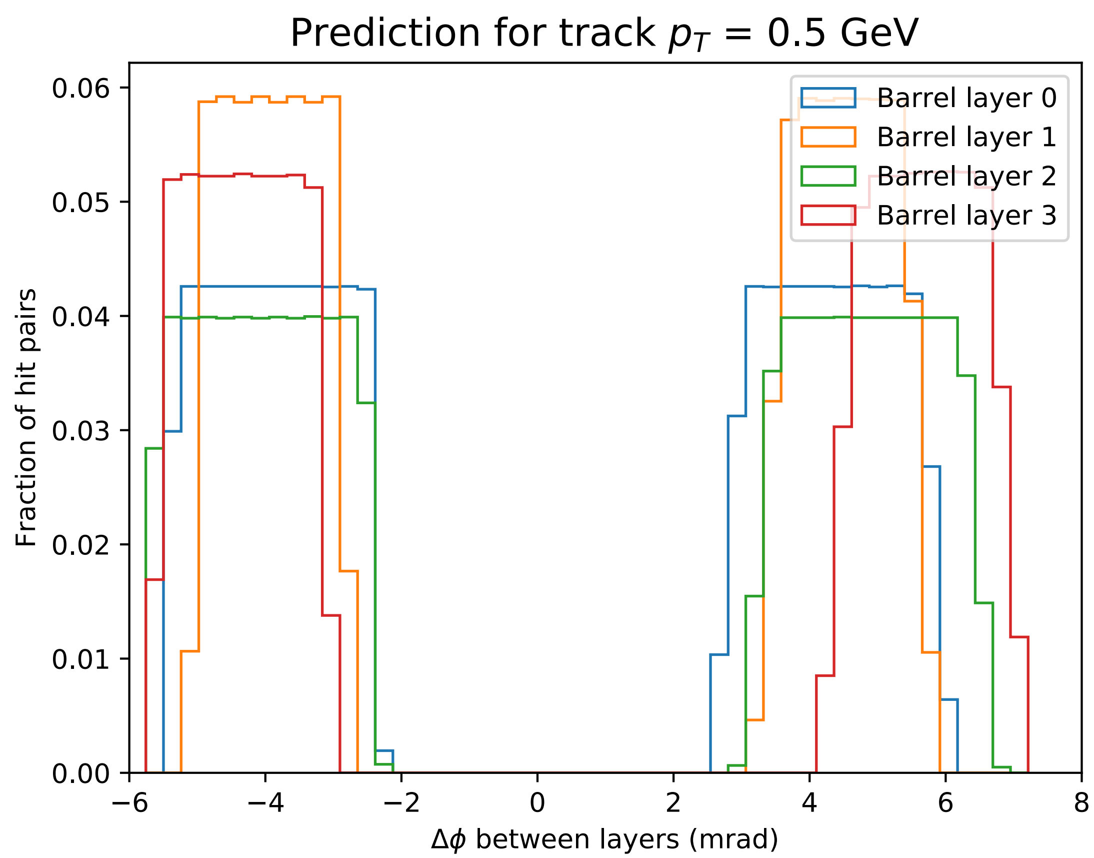


Expected distribution: barrel

- Geometry in 2 T uniform field predicts:
  - 1 GeV track bends ~2 mrad
  - Stereo angle shifts this by 0.7 mrad on average (both ways)
  - Shifts between + and - $\Delta\phi$ at low p_T thanks to module inclination
- Reasonable discrimination between tracks of 0.5 and 1 GeV (gHTT threshold)
  - Expect smearing from edge cases: 2.5% of module area is more complicated

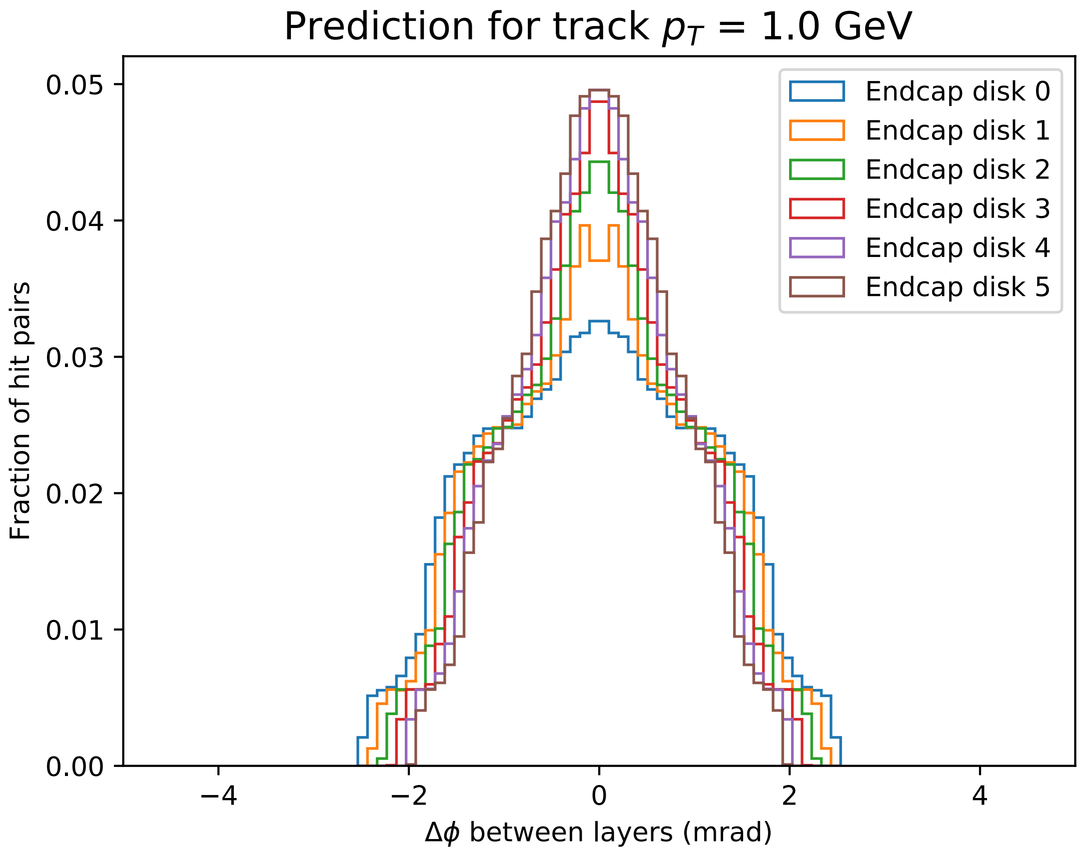


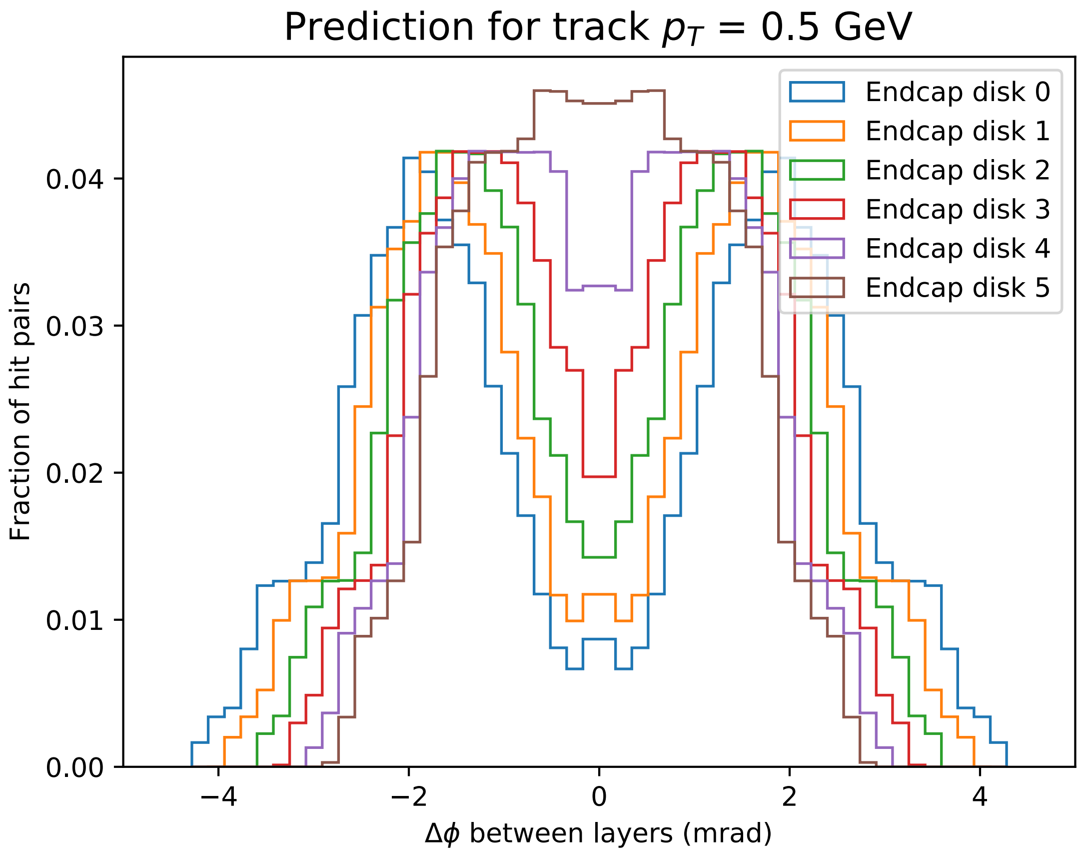




Expected distribution: endcap

- More complex shape for endcaps
- Retain some discrimination between tracks of 0.5 and 1 GeV





Observed separation

- In simulation, see similar distributions but with some extra smearing: if require 98% efficiency for 1 GeV hit pairs then reject ~ 20-30% of lower-p_T ones
    - More rejection at 2 GeV, but less than CMS thanks to less-optimal detector layout
- Studies ongoing to:
    - Translate hit pair efficiency to track efficiency
        - Not every track has 2 hits in a sublayer (between 1 and 4)
    - Evaluate speedup in downstream algorithms
        - Thanks to combinatorics, may be non-linear with rejection factor

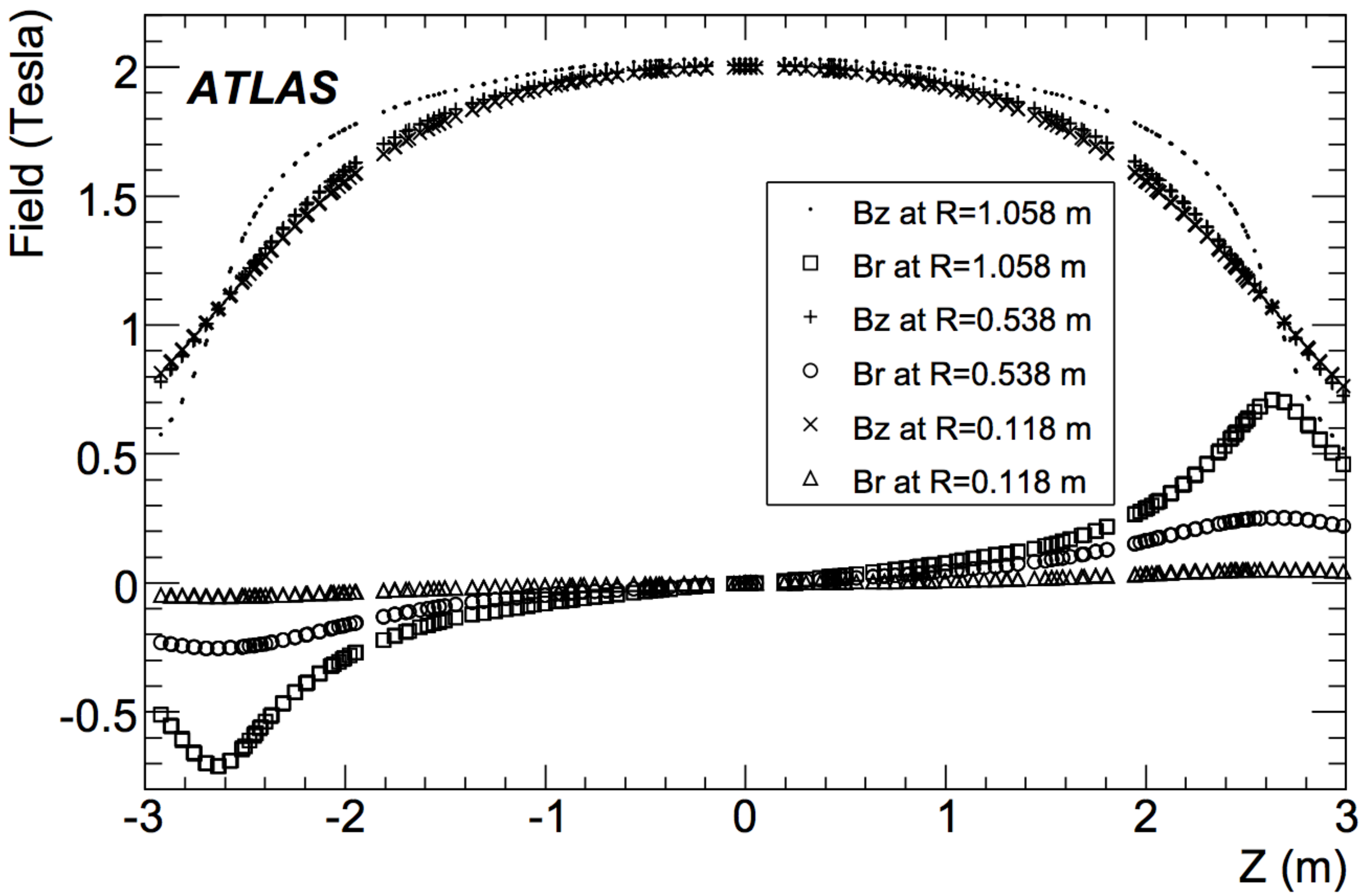
Summary

- HL-LHC will see significant upgrades to the LHC machine to provide many more p-p collisions per second
- This can only be exploited by the experiments with upgraded detectors, DAQ and trigger systems
- Having access to track information in the trigger, as early on in the decision-making process and with as few restrictions as possible, is critical for efficient and pure selection of the most interesting events
- Some methods to do some preliminary steps of track-finding in the trigger have been presented: Hough transform and stub finding, initially promising but further study needed for full cost and utility to be determined

Backup

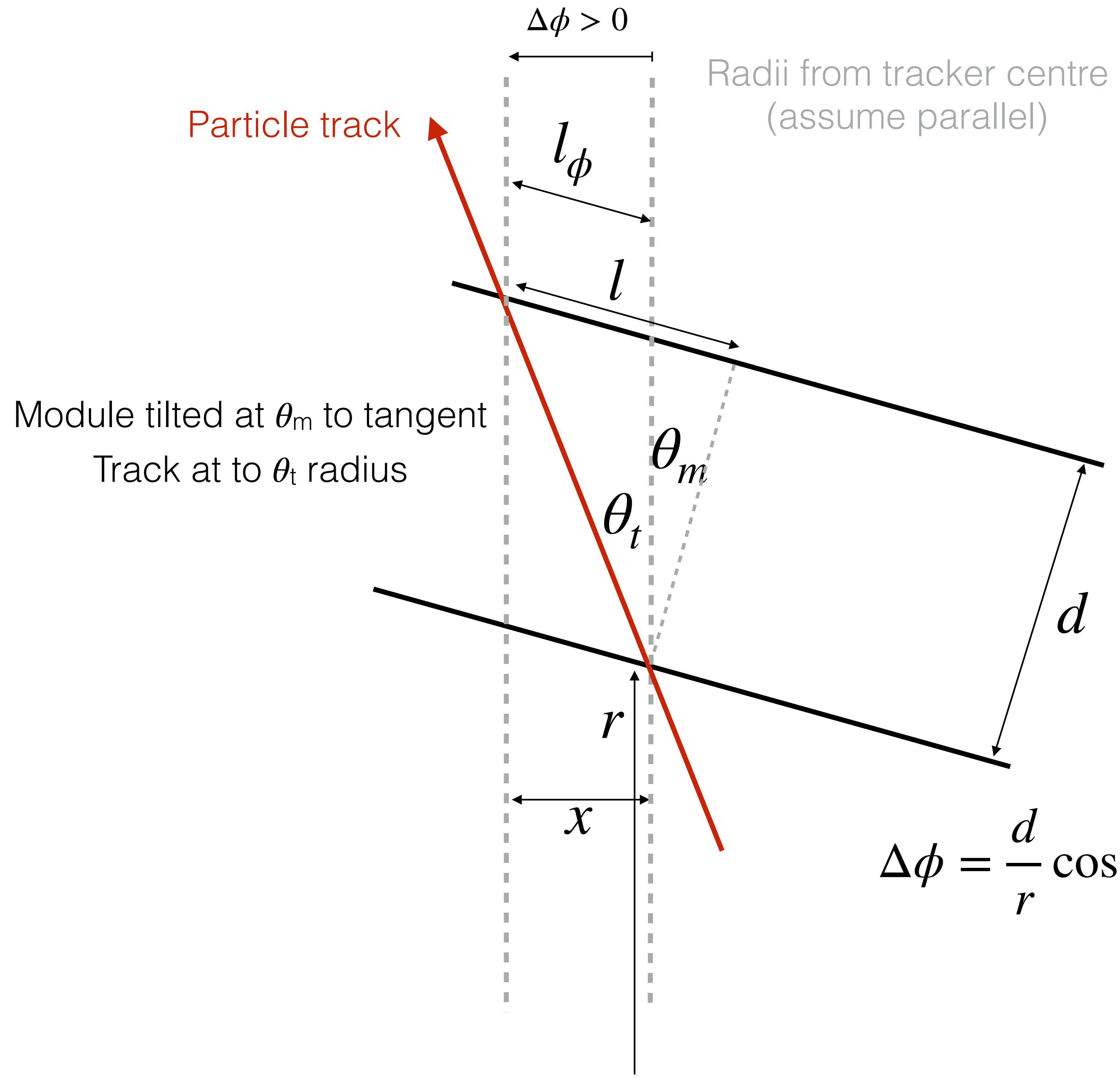
Magnetic field

- Here have used B_z = 2T, B_r = 0 everywhere
  - Constant curvature -> Circle
- $$R = \frac{p_T\ [GeV/c]}{B\ [T]} \times \frac{10^9}{c}$$
- $R \sim 1.67\ p_T$



M Aleksa et al 2008 JINST 3 P04003

Strip barrel



$$l = d\tan(\theta_t + \theta_m)$$

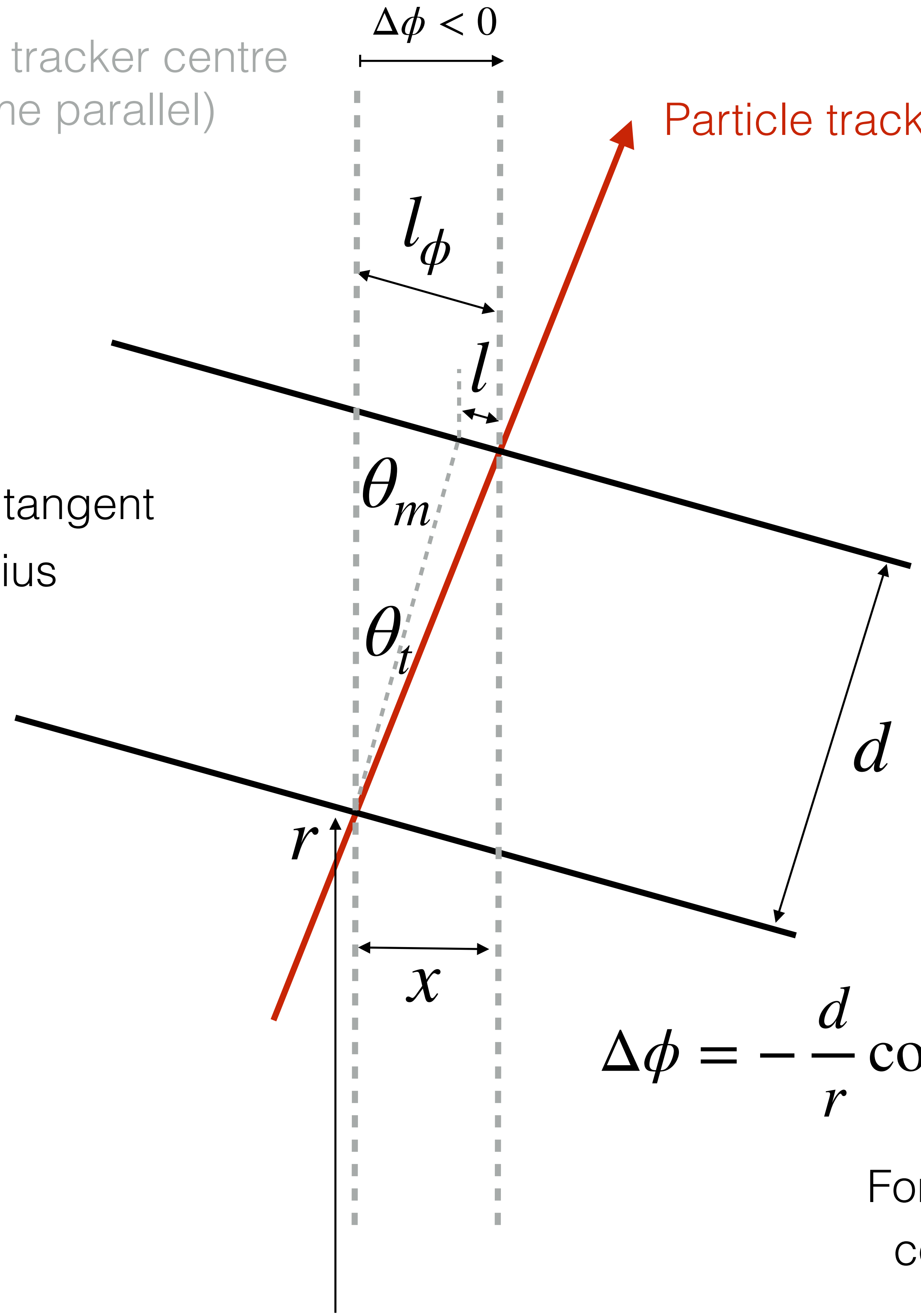
$$l_\phi = l - d\tan(\theta_m)$$

$$x = l_\phi \cos(\theta_m)$$

$$\Delta\phi = x/r_0$$

$$\Delta\phi = \frac{d}{r}\cos(\theta_m)\big(\tan(\theta_t + \theta_m) - \tan(\theta_m)\big)$$

Strip barrel



Module tilted at θ_m to tangent

Track at to θ_t radius

$$l = d\tan(\theta_t - \theta_m)$$

$$l_\phi = l + d\tan(\theta_m)$$

$$x = l_\phi \cos(\theta_m)$$

$$\Delta\phi = x/r_0$$

$$\Delta\phi = -\frac{d}{r}\cos(\theta_m)\big(\tan(\theta_t - \theta_m) + \tan(\theta_m)\big)$$

For a track the opposite charge, θ_m contributes in the other direction

Strip barrel

$$\Delta\phi = \frac{d}{r}\cos\theta_m\ (\tan(\theta_m + \theta_t) - \tan\theta_m)$$

$$\tan(A+B)) = \frac{\tan A + \tan B}{1 - \tan A \tan B}$$

$$\Delta\phi = \frac{d}{r}\cos\theta_m\ (\frac{\tan\theta_m + \tan\theta_t}{1 - \tan\theta_m \tan\theta_t} - \tan\theta_m)$$

$$\Delta\phi = \frac{d}{r}\cos\theta_m\ \frac{\tan\theta_t + \tan^2\theta_m \tan\theta_t}{1 - \tan\theta_m \tan\theta_t}$$

$$\Delta\phi = \frac{d}{r}\cos\theta_m\ \tan\theta_t \frac{\sec^2\theta_m}{1 - \tan\theta_m \tan\theta_t}$$

$$\Delta\phi = \frac{d}{r}\ \frac{1}{\cos\theta_m}\ \frac{\tan\theta_t}{1 - \tan\theta_m \tan\theta_t}$$

$$r = \frac{p_T}{0.3}\sin\theta_t$$

$$\Delta\phi = \frac{0.3d}{p_T}\ \frac{1}{\cos\theta_m}\ \frac{1}{cos\theta_t - \tan\theta_m \sin\theta_t}$$

$$cos\theta_t - \tan\theta_m \sin\theta_t = \sqrt{1 + tan^2\theta_m}\ \cos[\theta_t + \tan^{-1}(\tan\theta_m)] = \frac{1}{\cos\theta_m}\ \cos(\theta_t + \theta_m)$$

$$\Delta\phi = \frac{0.3d}{p_T}\ \frac{1}{cos(\theta_t + \theta_m)}$$

$$\Delta\phi = \pm\frac{0.3d}{p_T}\ \frac{1}{cos(\theta_t \pm \theta_m)}$$

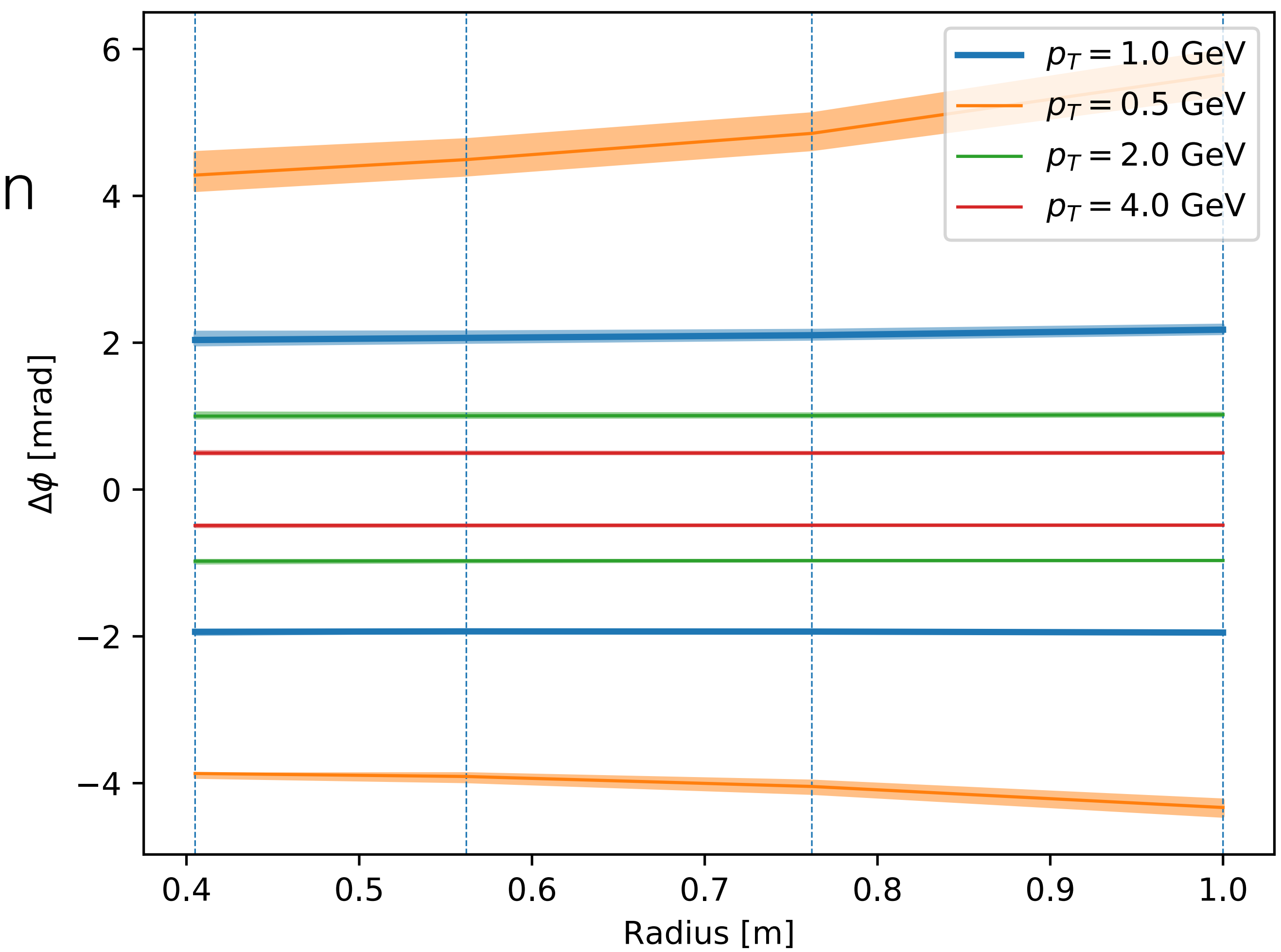
Strip barrel

$$\Delta\phi = \pm \frac{0.3d}{p_T} \frac{1}{cos(\theta_t \pm \theta_m)}$$

$$\sin\theta_t = \frac{0.3}{p_T} r \qquad d = 6.44 \text{ mm}$$

				positive				negative		
r	θ_t	**θ_t (deg)**		**$\Delta\phi$ (low)**	**$\Delta\phi$ (mid)**	**$\Delta\phi$ (high)**		**$\Delta\phi$ (low)**	**$\Delta\phi$ (mid)**	**$\Delta\phi$ (high)**
0.405	0.12	7.0		1.97	2.04	2.14		-1.93	-1.94	-1.97
0.562	0.17	9.7		2.01	2.07	2.15		-1.94	-1.93	-1.94
0.762	0.23	13.2		2.05	2.10	2.17		-1.95	-1.94	-1.93
1	0.30	17.5		2.12	2.18	2.24		-1.96	-1.95	-1.94

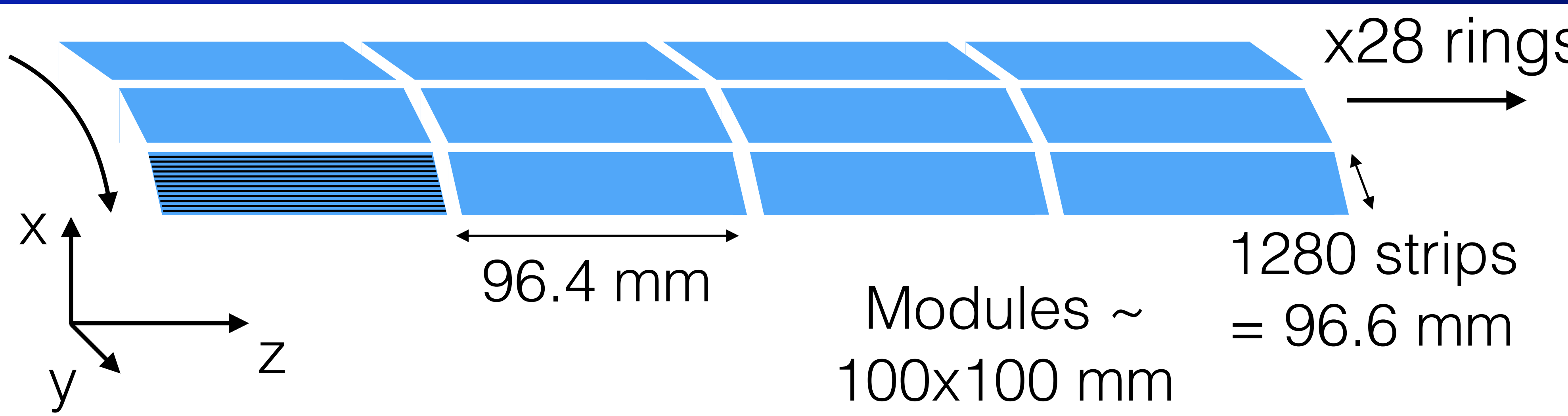
- ~ independent of radius
- ~ independent of module tilt, and variation from one end of a module to the other
- Barrel: 1 GeV particle, 6.4 mm spaced stereo-layers -> $\Delta\phi$ of **2 mrad**
- Lose small-angle approximations by 500 MeV: more, and non-linear, variation (incl with charge - smaller bending for $\Delta\phi$<0)

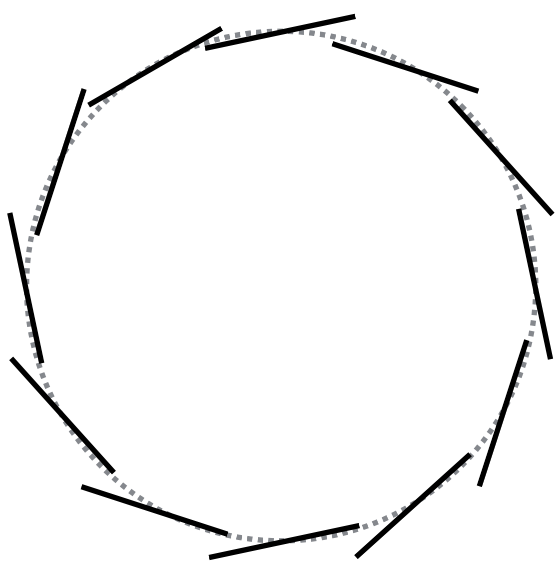


Strip barrel geometry (TDR)

x28, 40, 56, 72 modules per ring

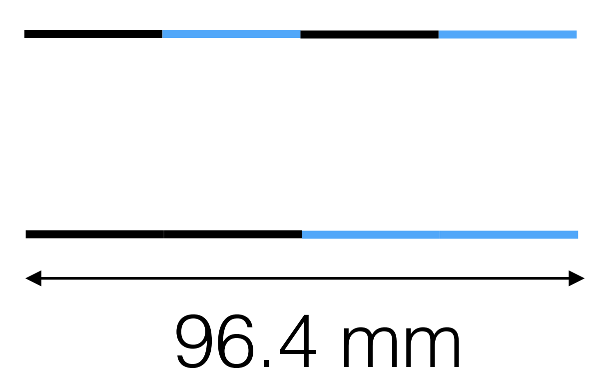
x2 since double-sided



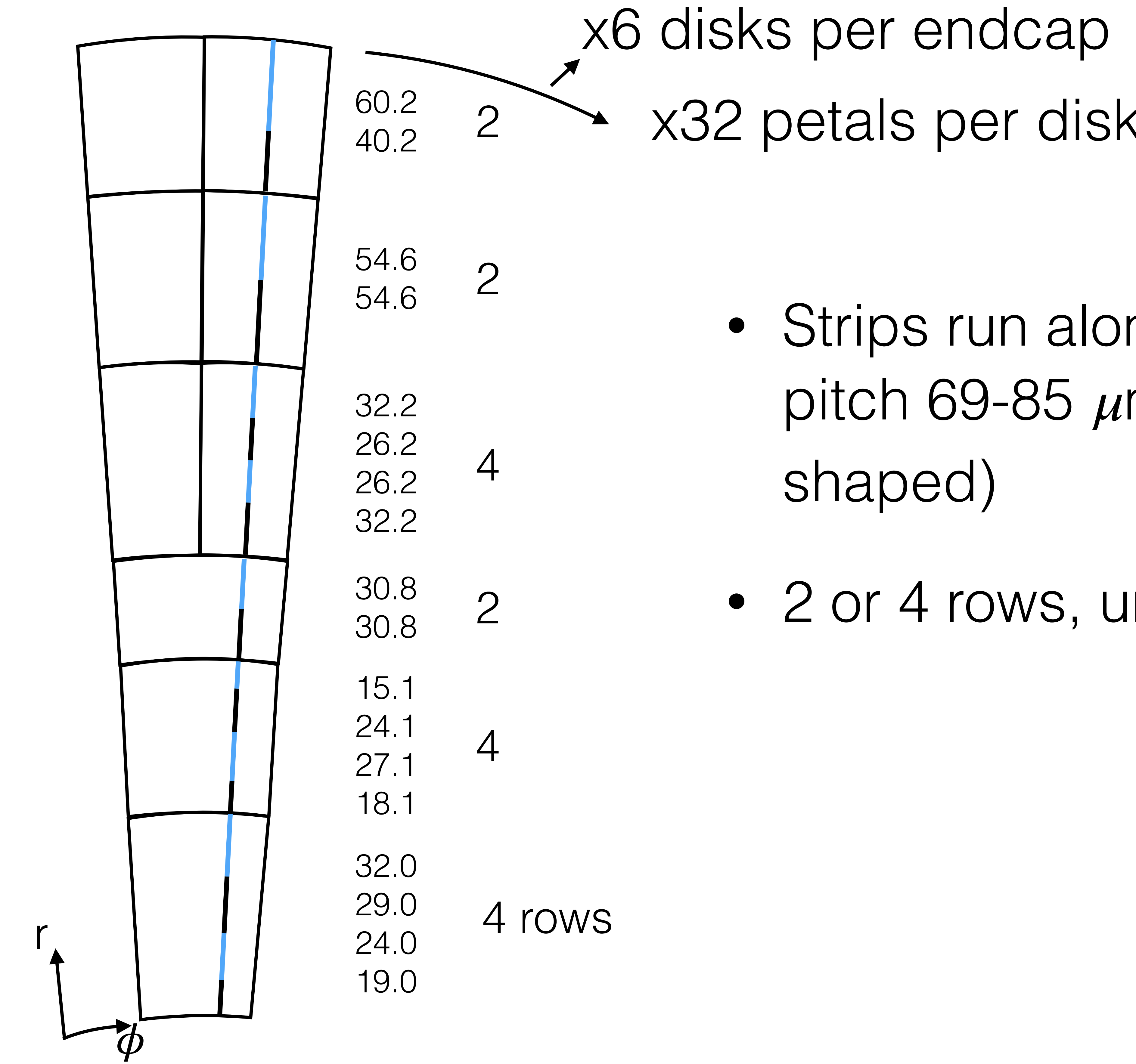


Sensors tilted in r-ϕ: hermeticity for tracks > 1 GeV (11.5°, 11.0°, 10.0°, 10.0° from tangent in layers 0-3)

- Strips run along z, pitch (ie strip width) 75.5 μm
- Inner: 4 rows of short strips 24.1 mm
- Outer: 2 rows of long strips, 48.2 mm

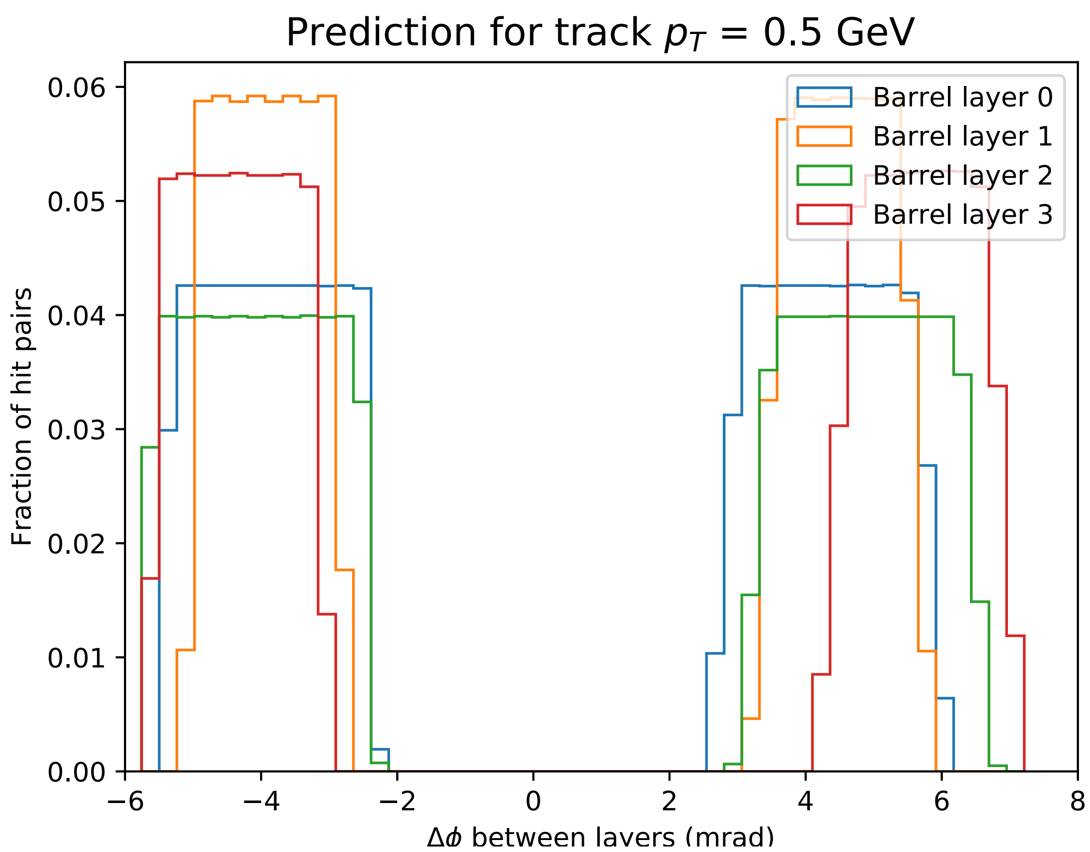


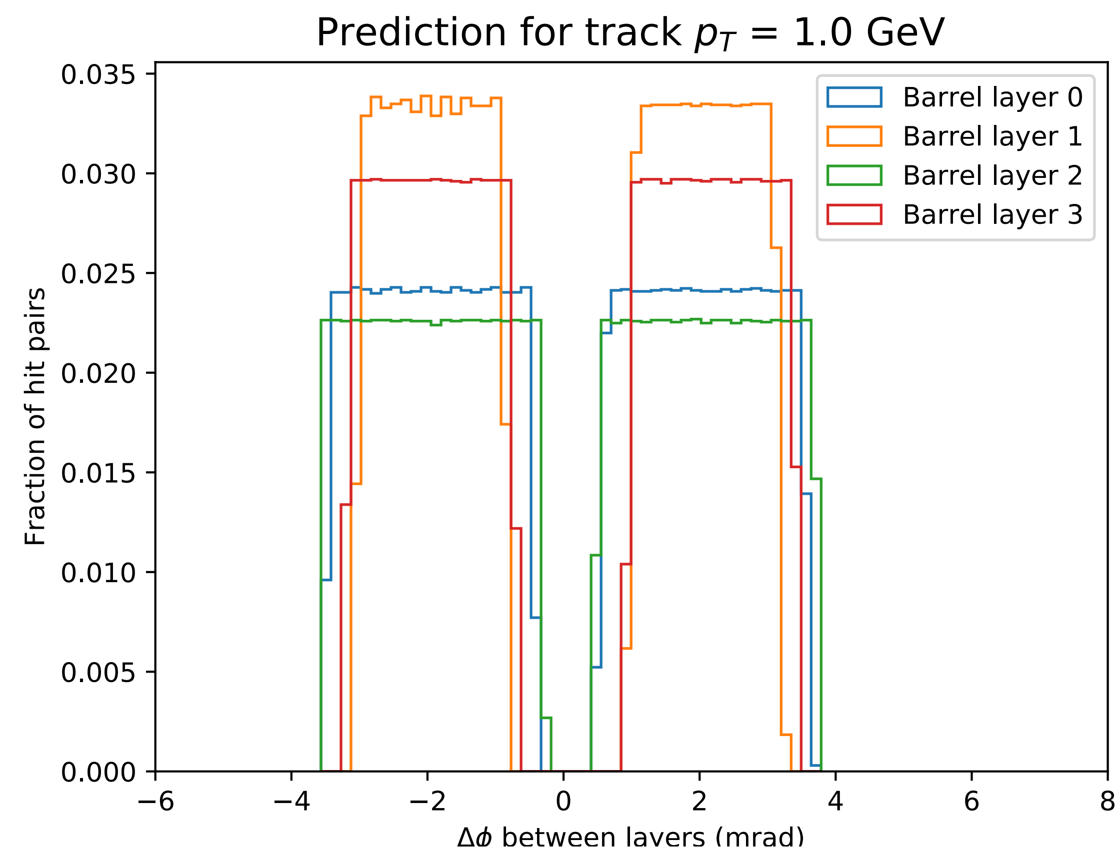
Strip endcap geometry

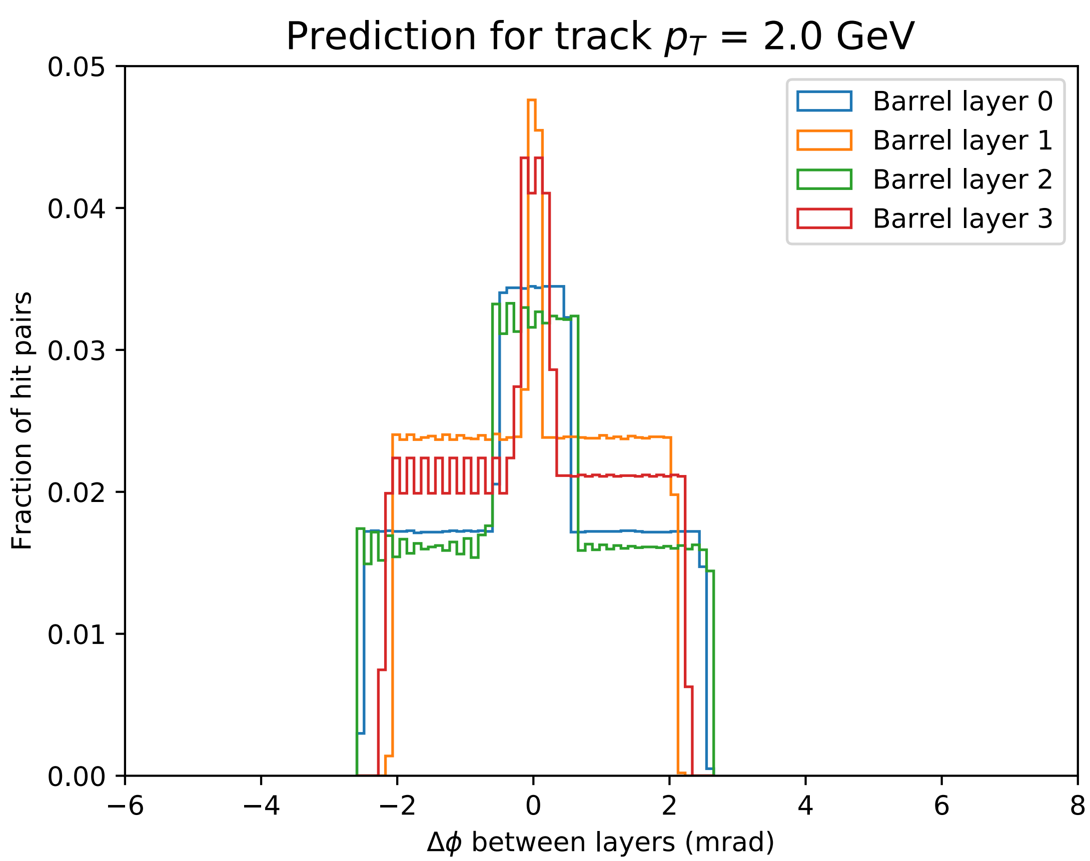


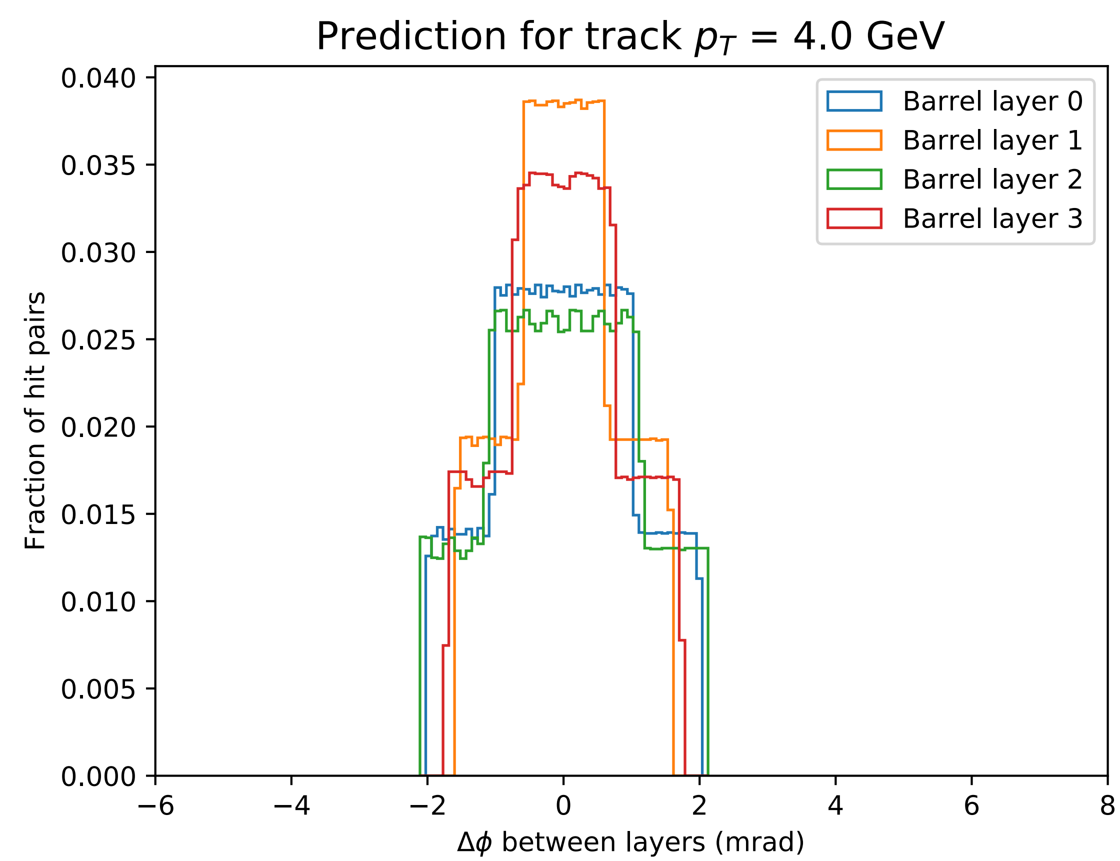
- Strips run along r, variable pitch 69-85 μm (wedge-shaped)
- 2 or 4 rows, uneven lengths

Expected distributions: barrel

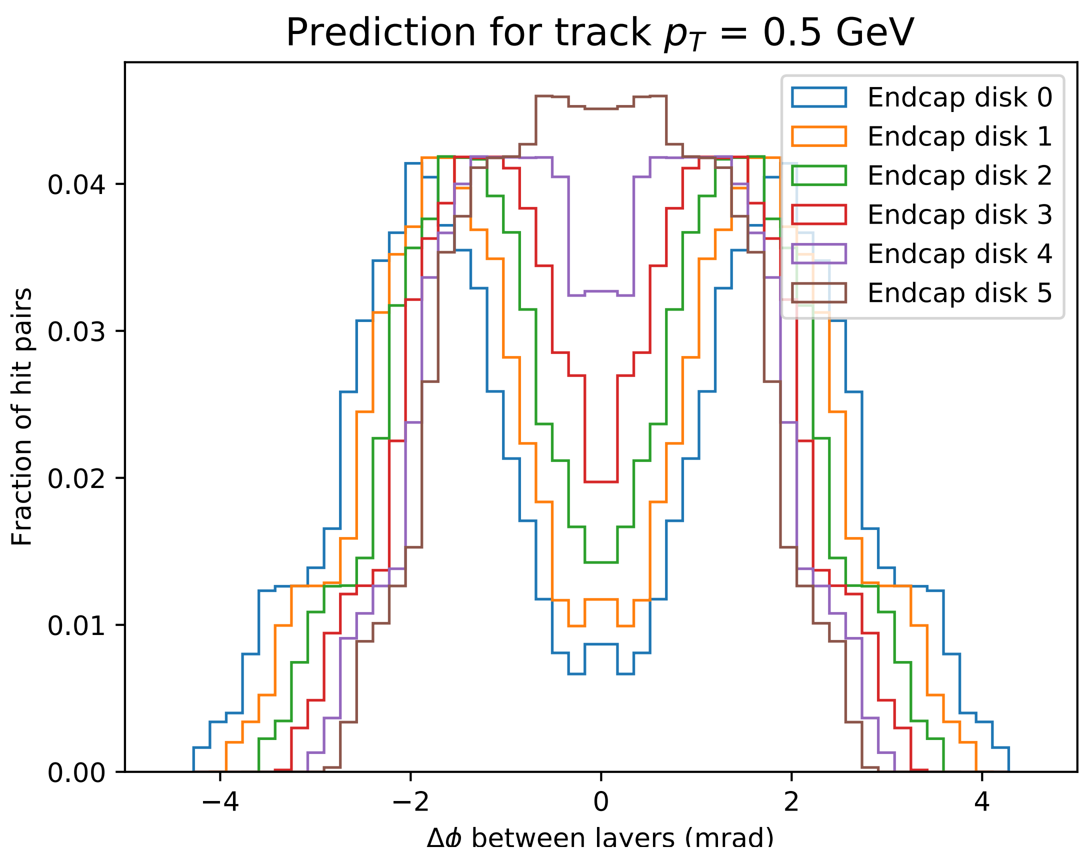


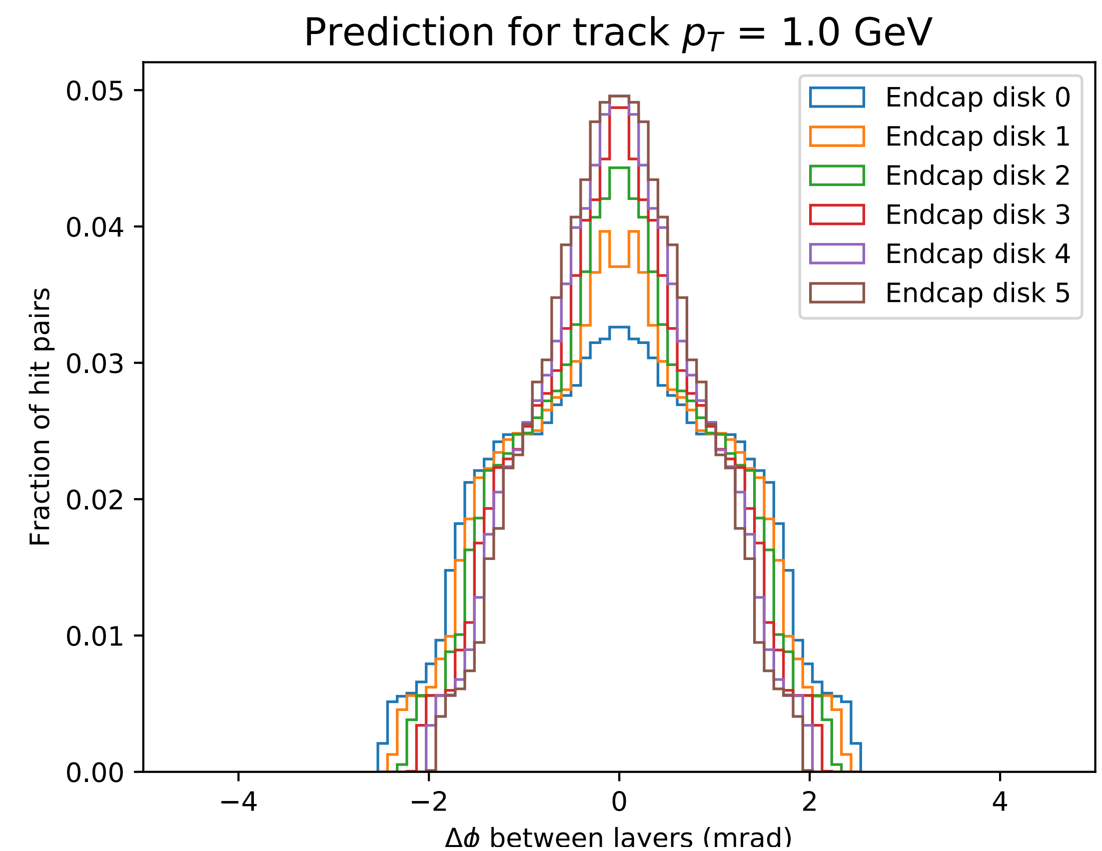


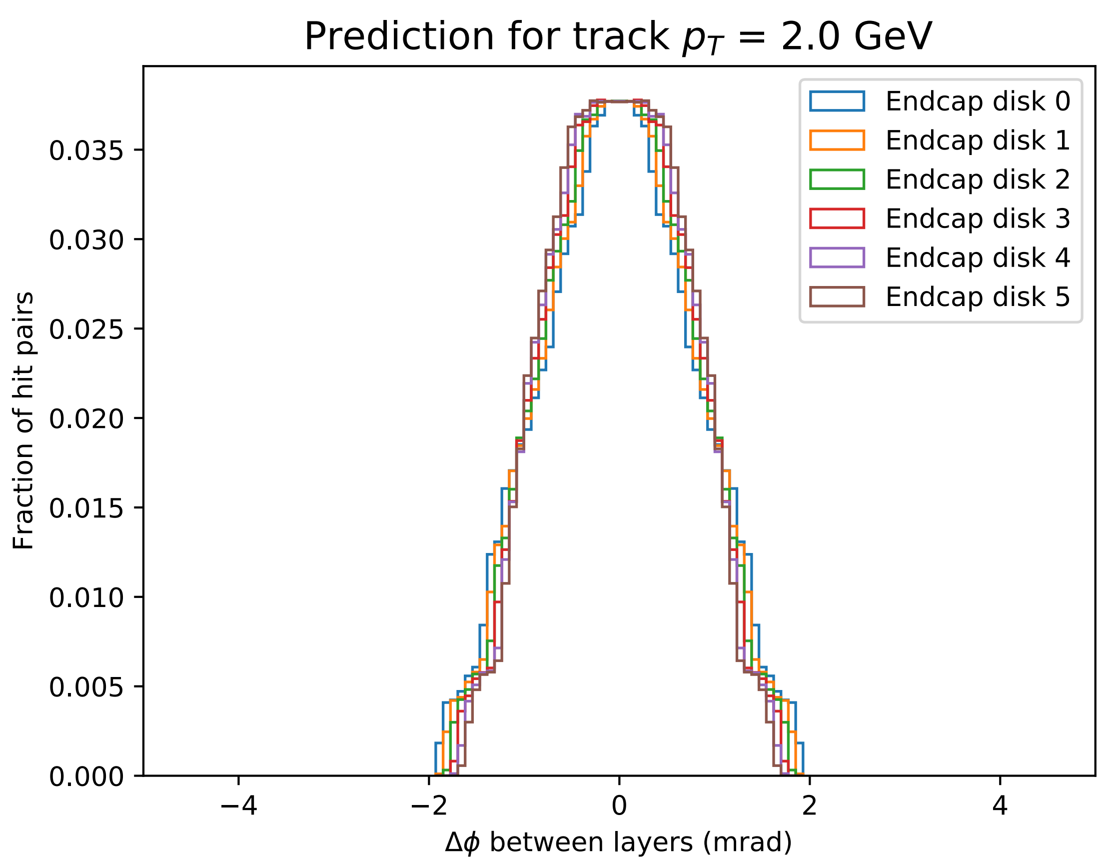


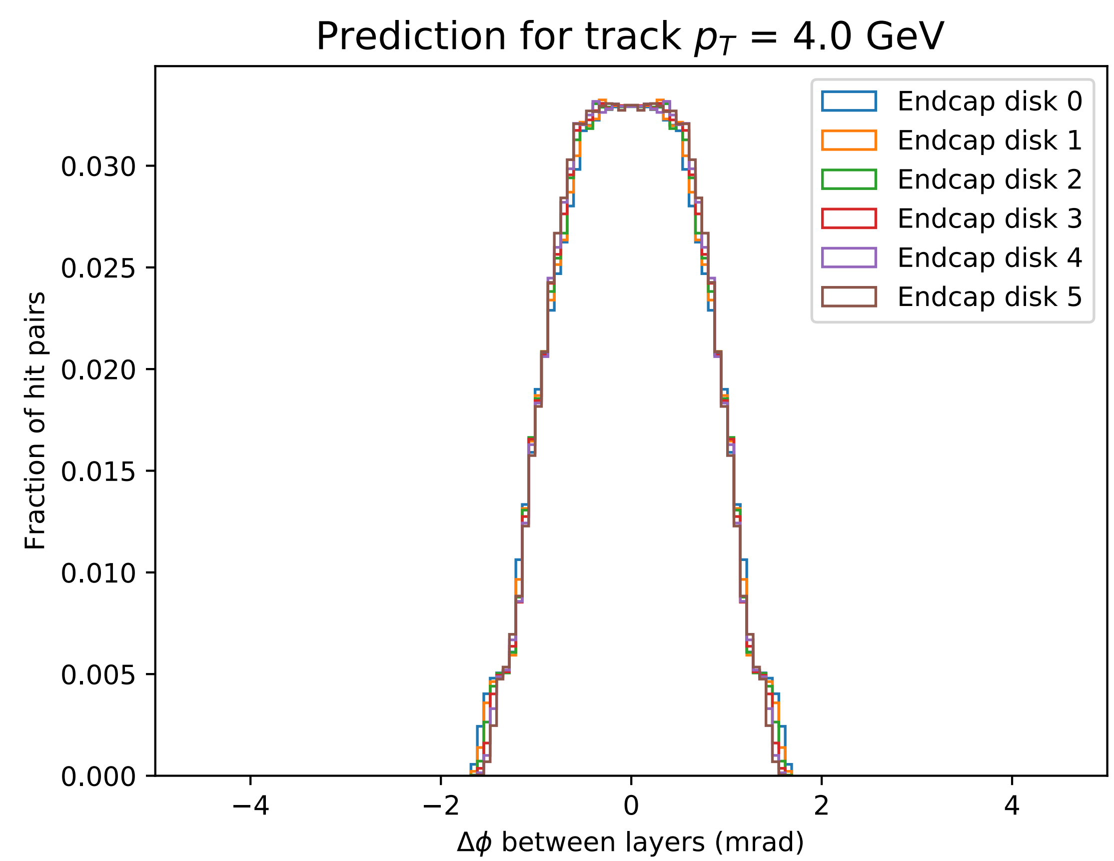


Expected distributions: endcap





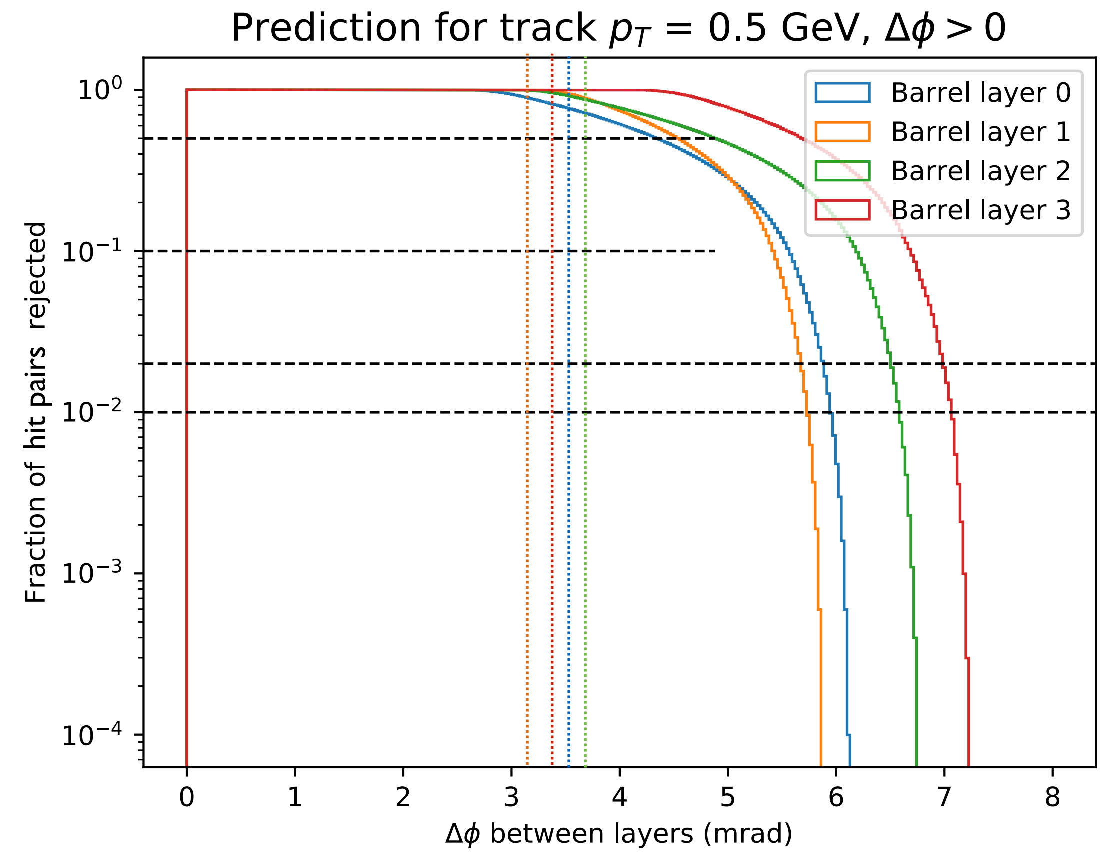


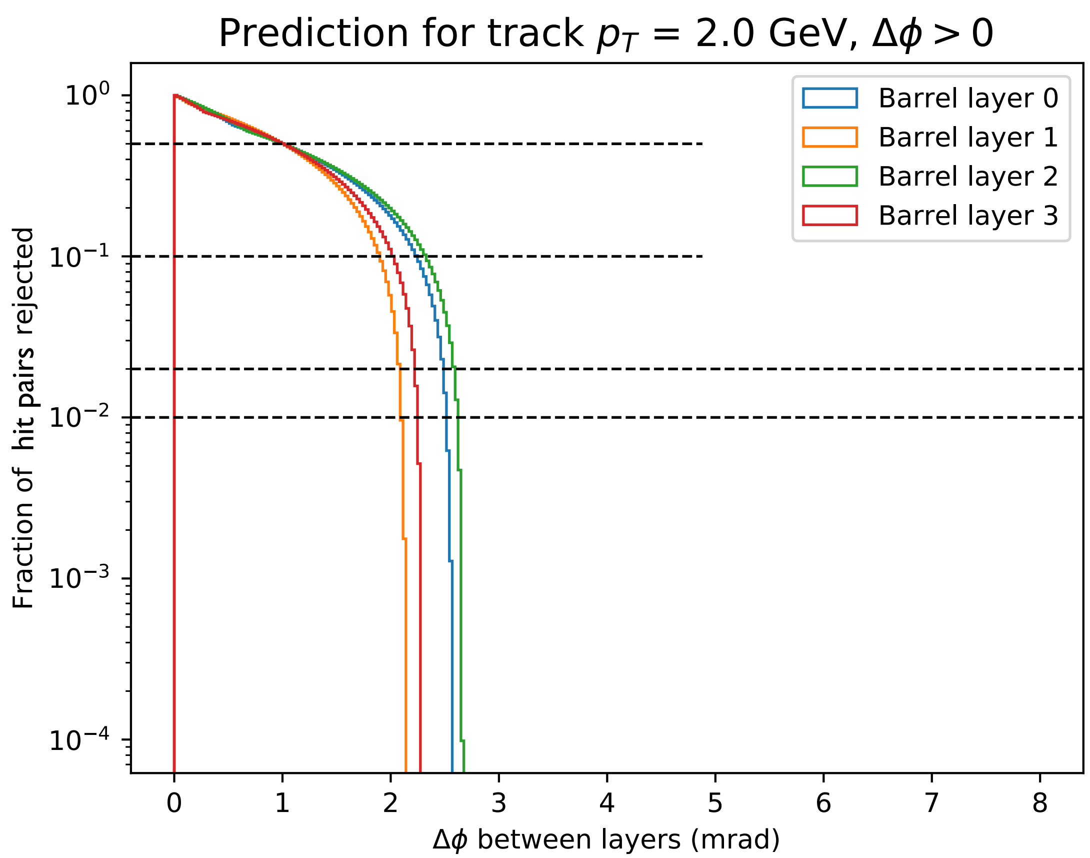


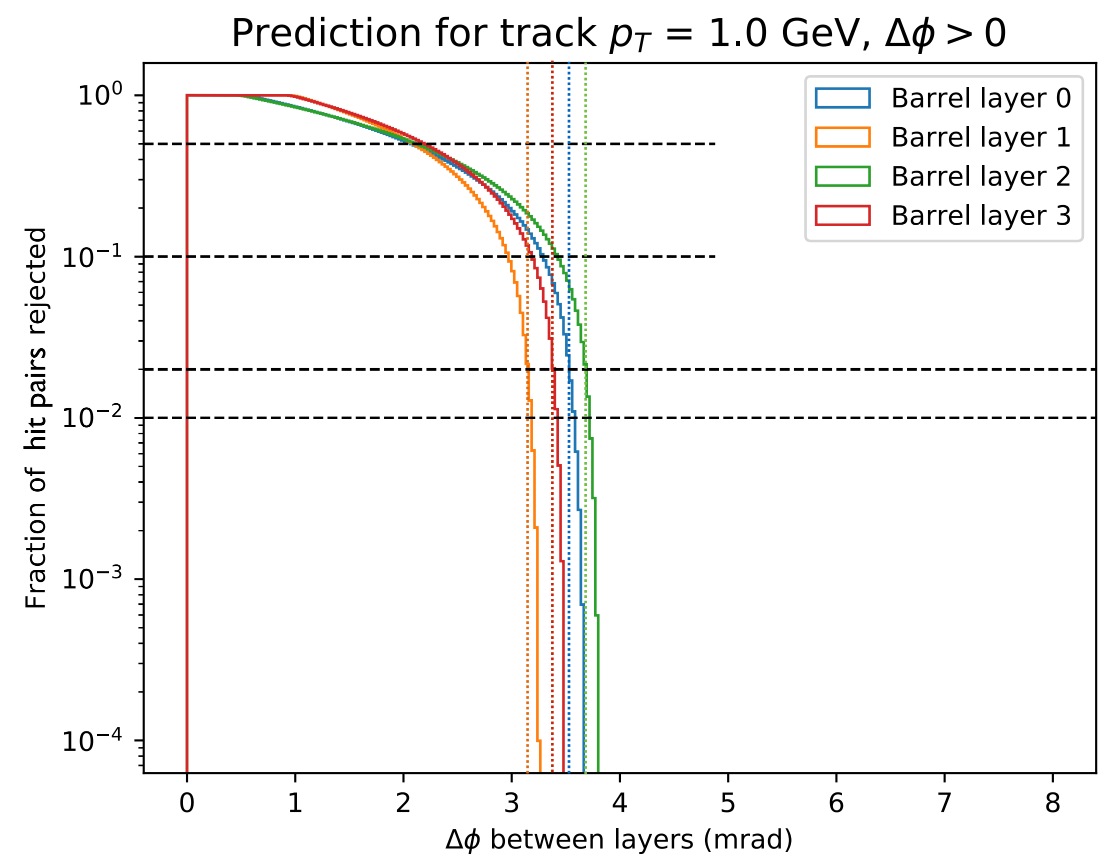
ATLAS EXPERIMENT

Expected separation: barrel

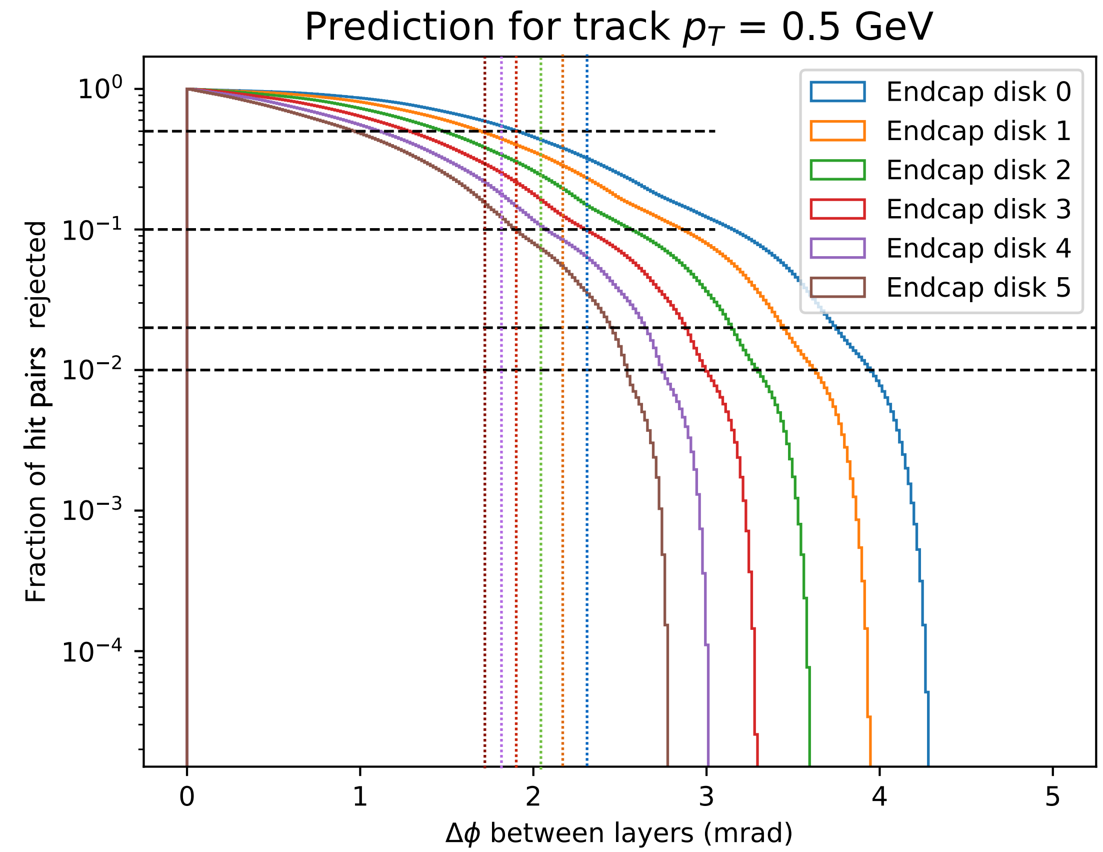
- 1 GeV: rejections of between 70 and 100% predicted in barrel
- 2 GeV: 100% rejection
- Extra smearing in reality will degrade this



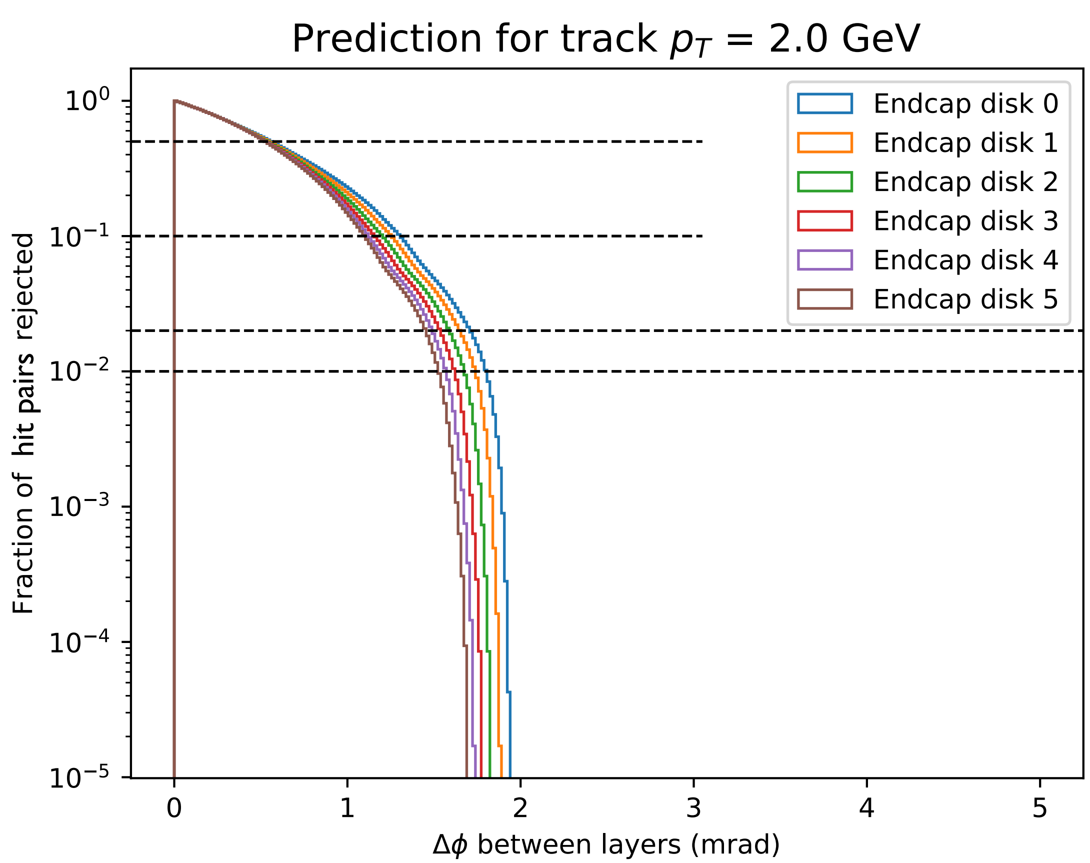


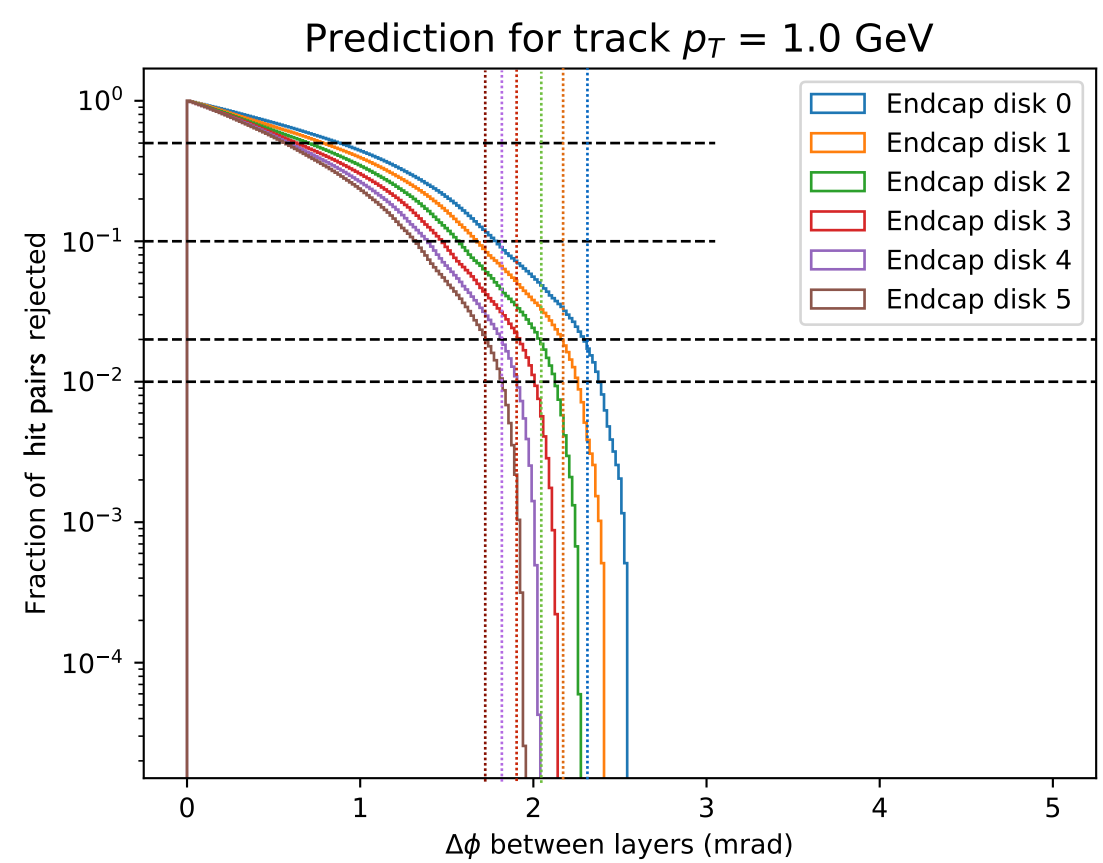


Expected separation: endcap



- 1 GeV: rejections of between 15 and 30% predicted in endcap
- 2 GeV: 20-60% rejection
- Extra smearing in reality will degrade this





Traversing modules