Reconstructing charginos at the muon collider

Very high-p_T (short) tracks and displaced pions

Detector and Physics simulation meeting - 27/10/2020

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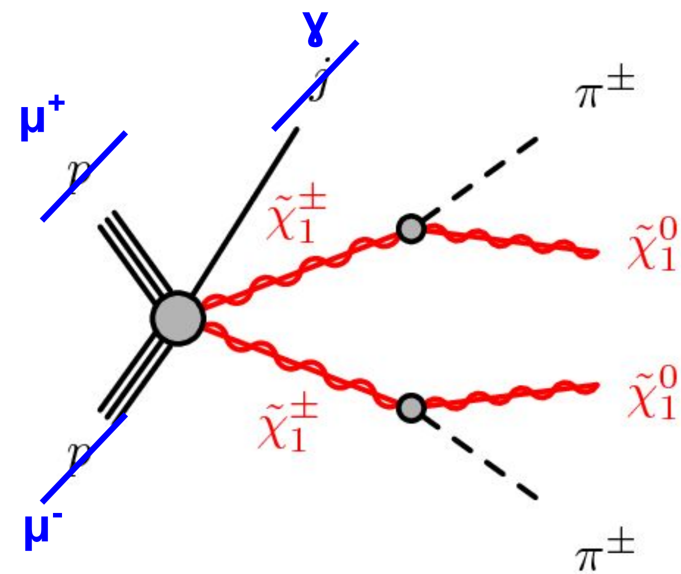
obo the "Electroweak multiplets at the Muon Collider" team

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Context of the study

Goal: evaluate the sensitivity of the muon collider in searches for electroweak multiplets using the disappearing tracks signature.

Detector signature: tracks (tracklets) that disappear (or connect to another track of significantly lower momentum)



Full simulation needed to properly assess:

- tracklet reconstruction efficiency vs p_T, η, decay position in the detector
- effect of disappearing condition (veto on tracker layer)
- tracklet momentum resolution
- combinatorial fakes and BIB tracks

The next slides show some *very preliminary/work-in-progress* results towards achieving this.

Signal generation and simulation

Focused on wino C1C1 production

Model: MSSM_SLHA2

- aMC@NLO 2.7.3 + Pythia 8.2

```
MG5_aMC > generate mu+ mu- > vm vm~ x1+ x1-
MG5_aMC > add process mu+ mu- > x1+ x1-
MG5_aMC > add process mu+ mu- > x1+ x1- mu+ mu-
```

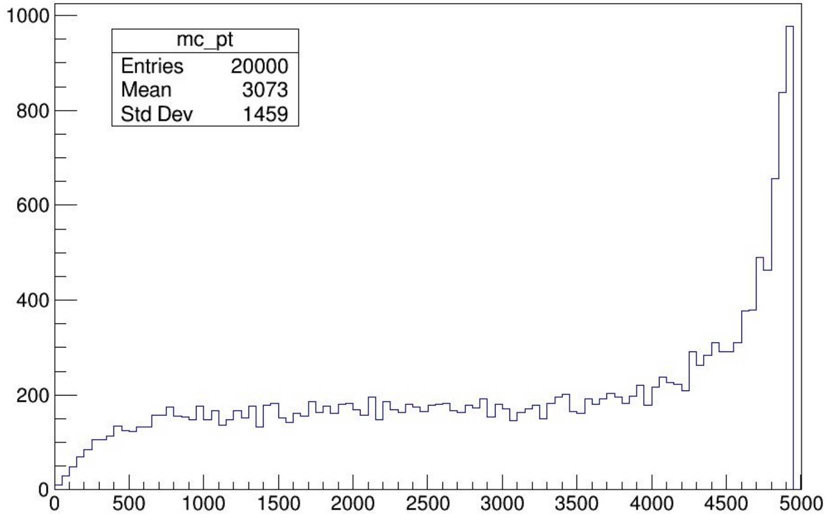
Simulation in dd4hep

- Good support for BSM particles
- GEANT physics list automatically generated from list of “extra particles”
- Need to make sure the masses are consistent with what was included in the MadGraph param_card
- Lifetimes are arbitrary (specified in mm)
  - C1 lifetime set to 100 mm

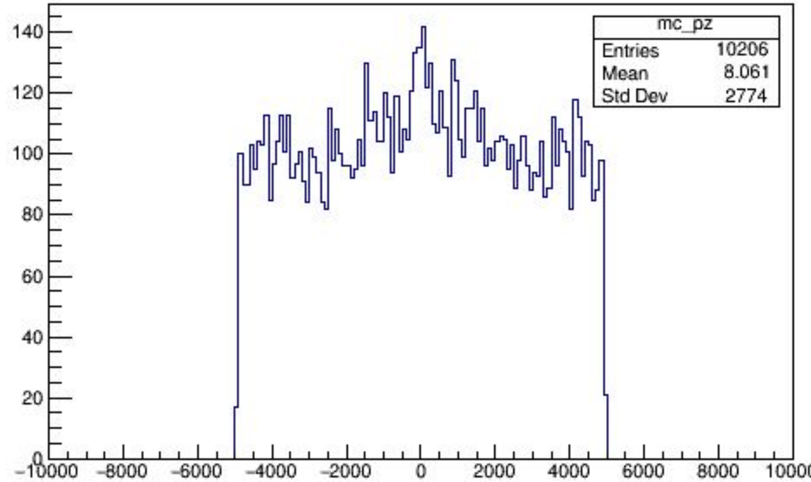
```
Block MASS   # Scalar and gaugino mass spectrum
#  PDG code   mass                particle
         5    4.80000000E+00   # b-quark pole ma
         6    1.72500000E+02   # t-quark pole ma
        15    1.77682000E+00   # tau pole mass
        23    9.11876000E+01   # Z pole mass (n
        24    8.04229965E+01   #  W^+
        25    1.17354164E+02   #  h^0
        35    6.99664014E+03   #  H^0
        36    6.95080322E+03   #  A^0
        37    6.99698096E+03   #  H^+
   1000001    7.43424219E+03   #  dnl
   1000002    7.43383691E+03   #  upl
   1000003    7.43424219E+03   #  stl
   1000004    7.43383691E+03   #  chl
   1000005    6.38580225E+03   #  b1
   1000006    5.10177637E+03   #  t1
   1000011    4.83639551E+03   #  el-
   1000012    4.83417090E+03   #  nuel
   1000013    4.83639551E+03   #  mul-
   1000014    4.83417090E+03   #  numl
   1000015    4.78479004E+03   #  tau1
   1000016    4.82647363E+03   #  nutl
   1000021    6.08901953E+03   #  glss
   1000022    8.99637451E+02   #  z1ss
   1000023    2.93977783E+03   #  z2ss
   1000024    8.99811523E+02   #  w1ss
   1000025   -4.83659033E+03   #  z3ss
   1000035    4.83768994E+03   #  z4ss
   1000037    4.84269434E+03   #  w2ss
   2000001    7.51731982E+03   #  dnr
   2000002    7.47251123E+03   #  upr
   2000003    7.51731982E+03   #  str
   2000004    7.47251123E+03   #  chr
   2000005    7.46611328E+03   #  b2
   2000006    6.42913818E+03   #  t2
   2000011    4.79959424E+03   #  er-
   2000013    4.79959424E+03   #  mur-
   2000015    4.82940039E+03   #  tau2
```

Some (ugly) truth-level validation plots

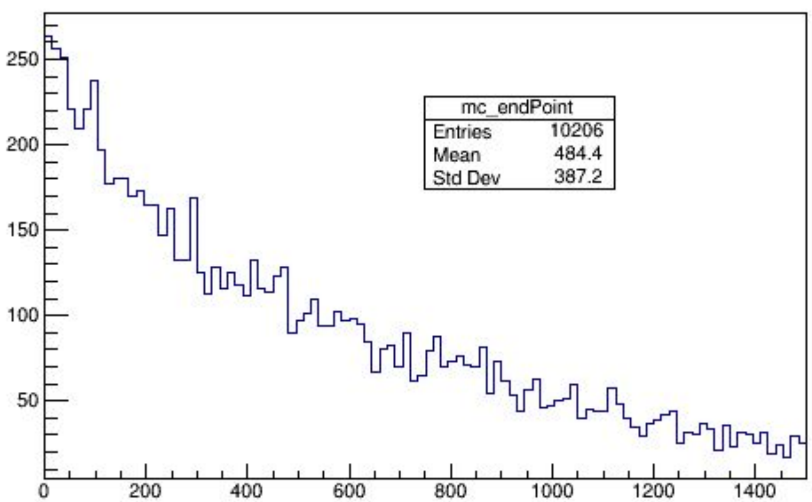
Everything seems ok



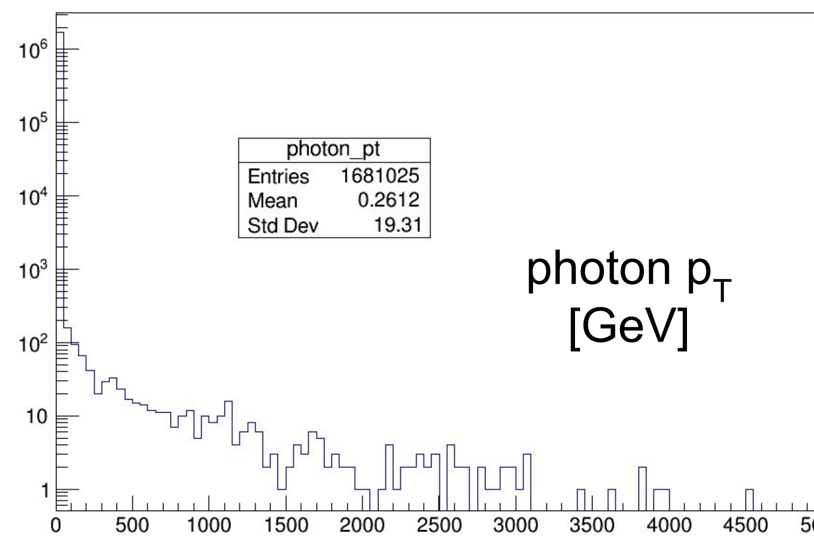
C1 p_T [GeV]



C1 p_z [GeV]



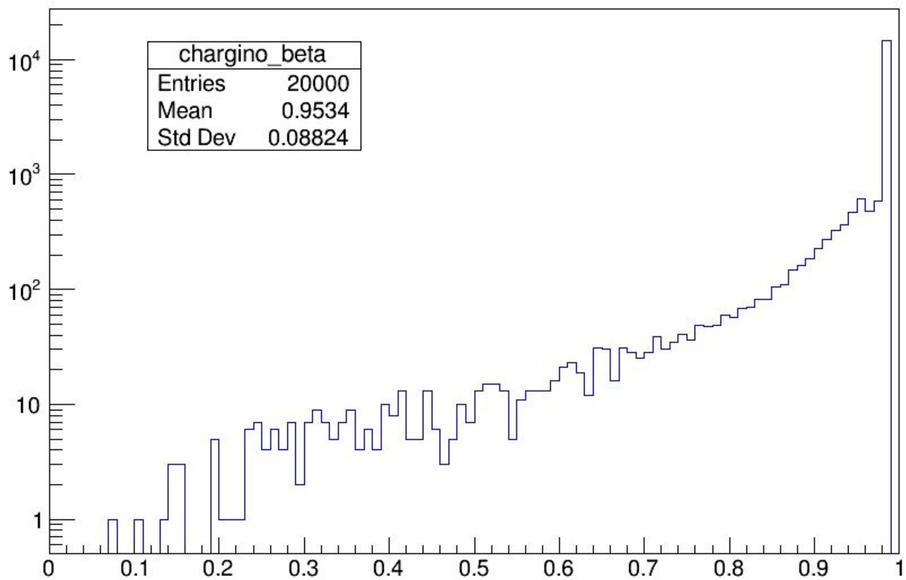
C1 decay r [mm]



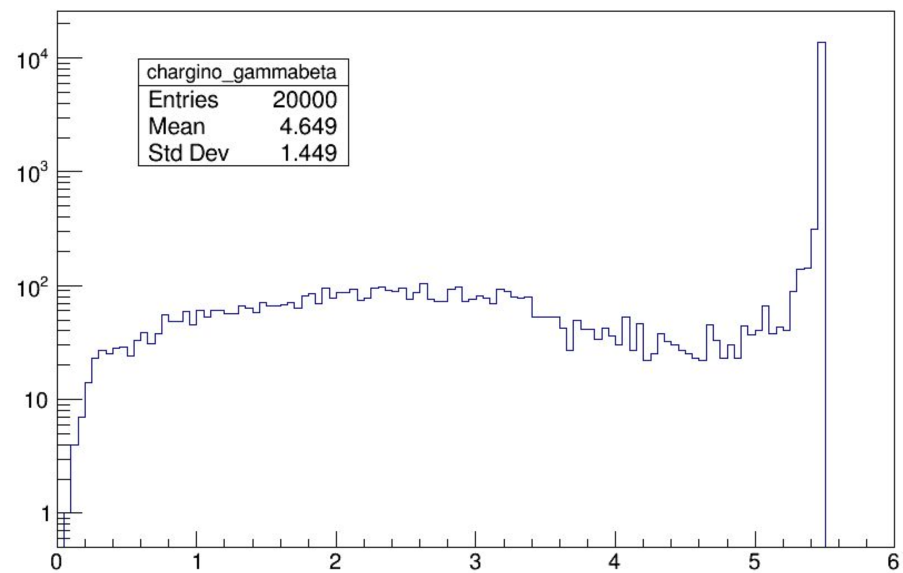
photon p_T [GeV]

More (ugly) truth-level validation plots

m(C1) = 899.8 GeV



C1 β

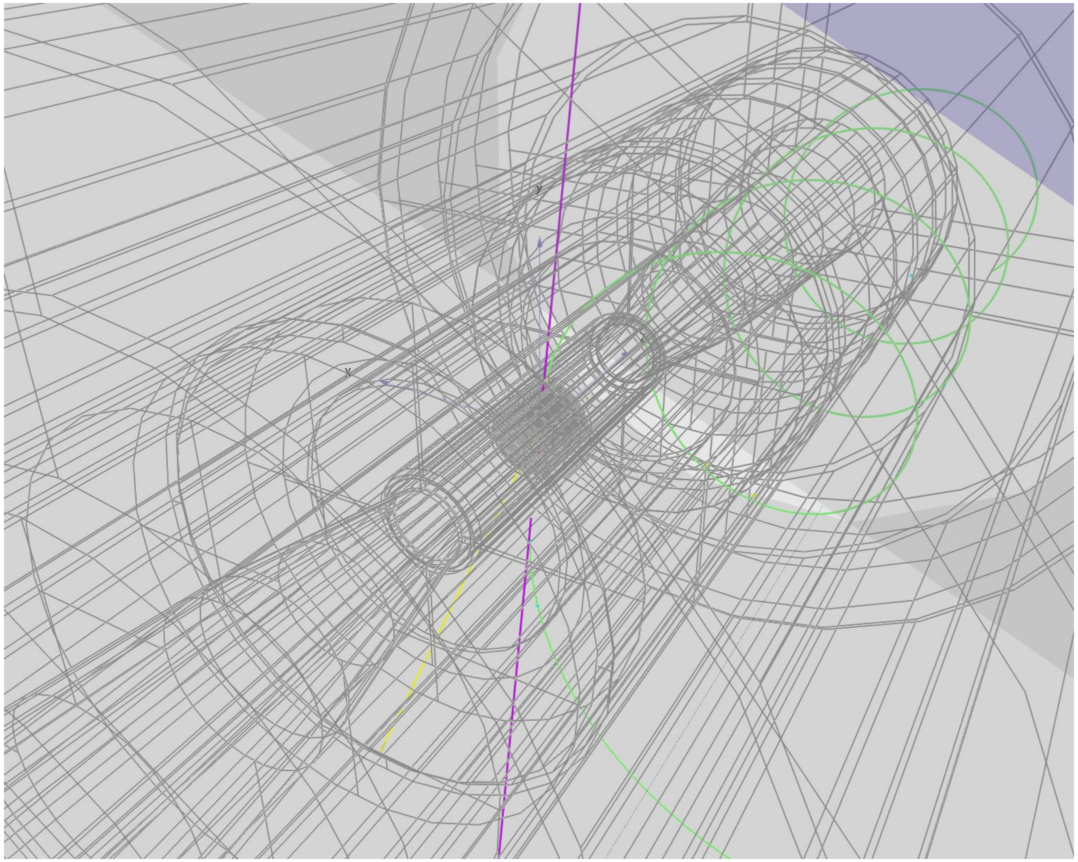


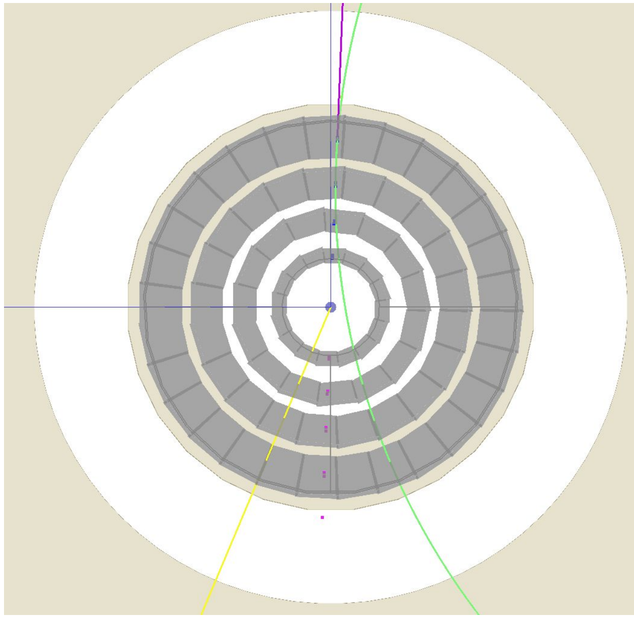
C1 γβ

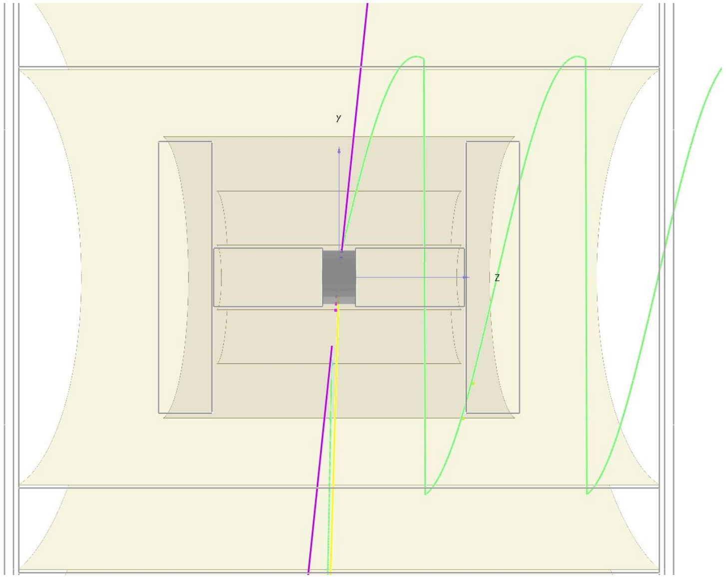
- Few slow charginos
- Need to keep this in mind when applying the timing cuts for BIB looking for slow particles

Example event display

No BIB

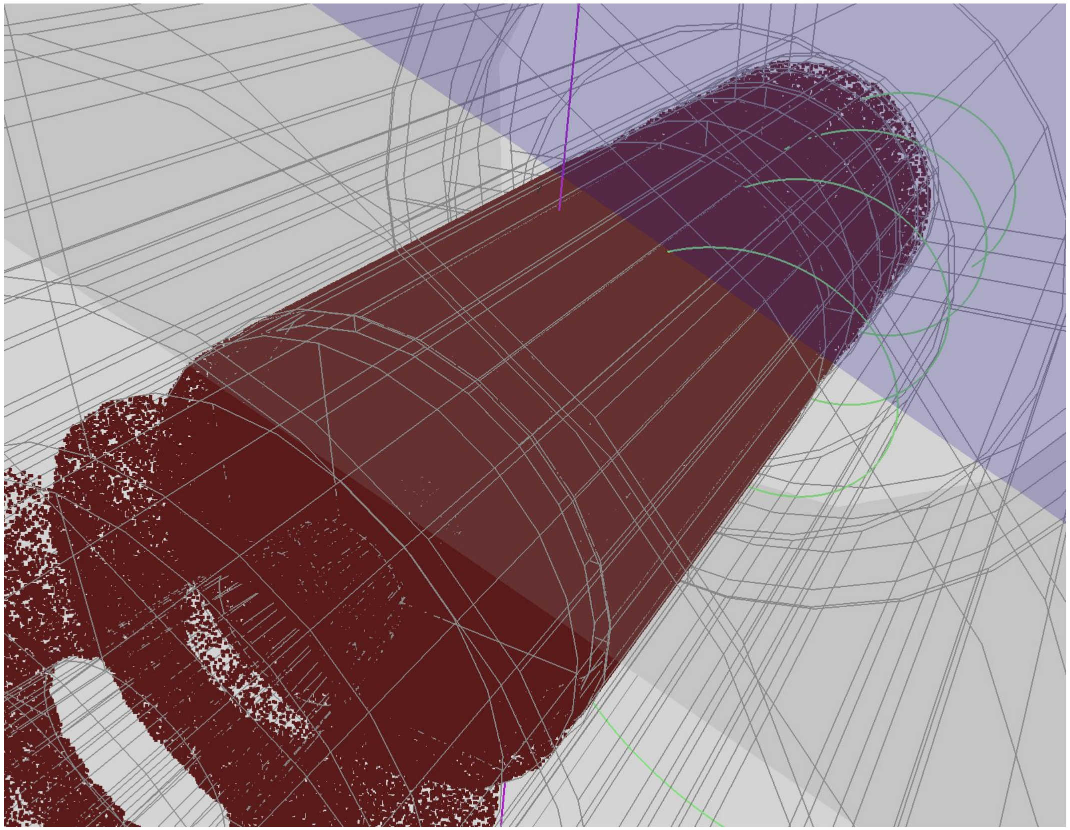






Example event display

Full BIB



Same event as before.

- Other views unavailable as the event display software became too unresponsive

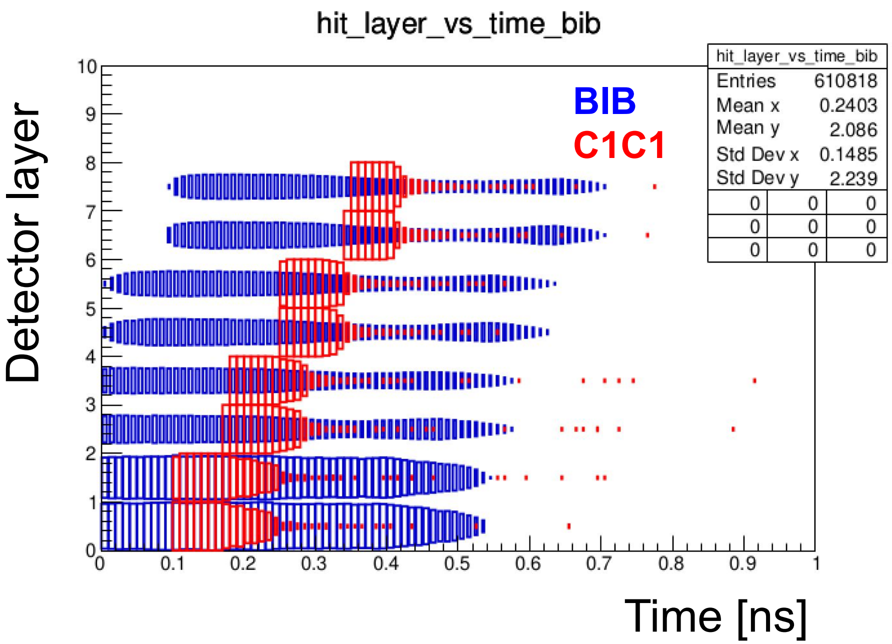
- In the following, BIB overlay done ONLY in Inner Tracker and Vertex Detectors
  - Truth particles dropped in overlay step

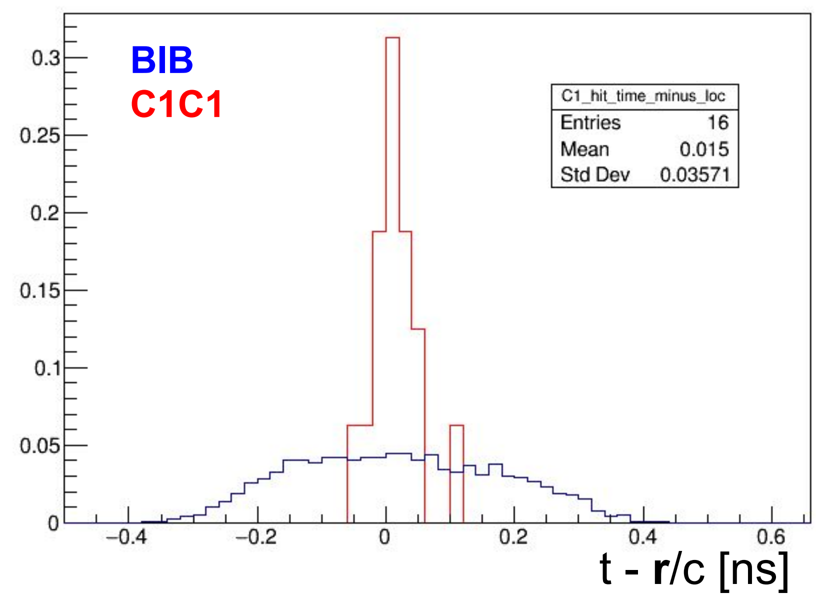
BIB rejection

With timing

Exploit particle arrival times to reduce BIB in custom Marlin module

- Found out this was already included in the hit smearing (50 ps resolution)
- Beware for low-beta particles!
- Timing cuts will kill hits from the displaced pion!





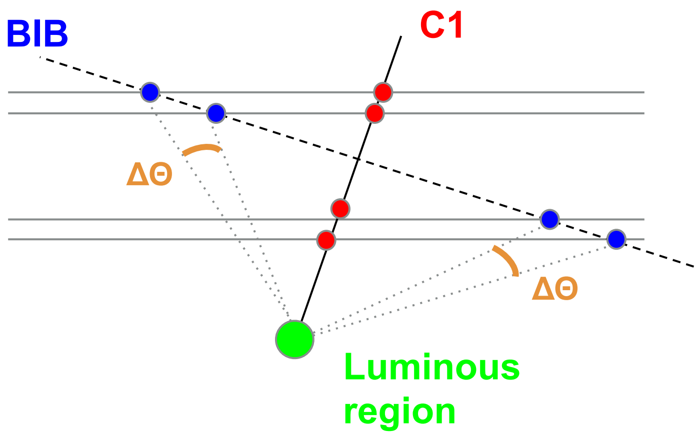
For now, assume another hard object in the event (e.g. ISR photons) can be timed

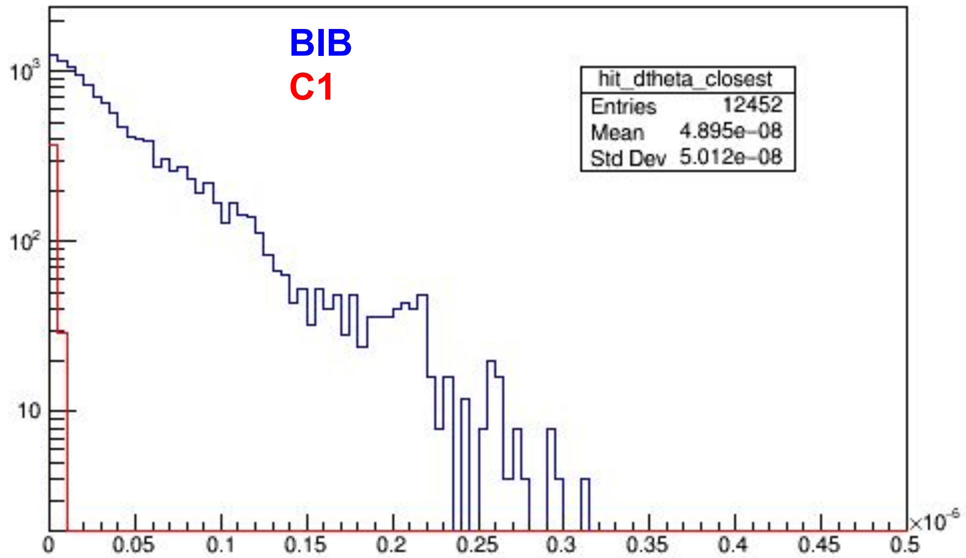
BIB rejection

With geometry

The current pattern recognition algorithms don't exploit in any way the double layer layout in the vertex detector.

- Can filter input hits based on whether there is another hit in the closeby layer with small ΔΘ.





ΔΘ with closest hit in nearmost layer

BIB rejection

Summary of selections

Timing:

- $-0.15\ \mathrm{ns} < t - \mathbf{r}/c < 0.15\ \mathrm{ns}$

Geometry:

- Reject all hits for which the closest hit in $\Delta R = \sqrt{(\Delta\varphi^2 + \Delta\Theta^2)}$ has $\Delta\Theta > 0.02$
- Could add a cut on $\Delta\varphi$ too

To reduce combinatorics and speed up tracking, the hits are split in subcollections in theta with this binning: [0, 30, 50, 70, 90, 110, 130, 150, 180]

- Only (50, 70, 90, 110, 130) considered in the following

Tracking setup

Vertex Tracker hits only

- Outside-in track reconstruction
- Tight cuts on cell creation (both in rφ and rz planes)

Minimum of 4 hits per track:

- Double layer layout means the minimal reconstructible decay length is 5.1 cm

Takes about 3.5h per event when overlaying the full BIB (and imposing cleaning cuts)

```
<parameter name="Steps" type="StringVec">
  [VXDBarrel7090]
  @Collections : VXDTrackerGoodSpaceTimeHits7090
  @Parameters : MaxCellAngle : 0.005; MaxCellAngleRZ : 0.005; Chi2Cut : 100;
  MinClustersOnTrack : 4; MaxDistance : 0.02; SlopeZRange: 10.0; HighPTCut: 10.0;
  @Flags : HighPTFit
  @Functions : CombineCollections, BuildNewTracks
  [VXDBarrelN7090]
  @Collections : VXDTrackerGoodSpaceTimeHitsN7090
  @Parameters : MaxCellAngle : 0.005; MaxCellAngleRZ : 0.005; Chi2Cut : 100;
  MinClustersOnTrack : 4; MaxDistance : 0.02; SlopeZRange: 10.0; HighPTCut: 10.0;
  @Flags : HighPTFit
  @Functions : CombineCollections, BuildNewTracks
  [VXDBarrel5070]
  @Collections : VXDTrackerGoodSpaceTimeHits5070
  @Parameters : MaxCellAngle : 0.005; MaxCellAngleRZ : 0.005; Chi2Cut : 100;
  MinClustersOnTrack : 4; MaxDistance : 0.02; SlopeZRange: 10.0; HighPTCut: 10.0;
  @Flags : HighPTFit
  @Functions : CombineCollections, BuildNewTracks
  [VXDBarrelN5070]
  @Collections : VXDTrackerGoodSpaceTimeHitsN5070
  @Parameters : MaxCellAngle : 0.005; MaxCellAngleRZ : 0.005; Chi2Cut : 100;
  MinClustersOnTrack : 4; MaxDistance : 0.02; SlopeZRange: 10.0; HighPTCut: 10.0;
  @Flags : HighPTFit
  @Functions : CombineCollections, BuildNewTracks
</parameter>
```

Split tracks

The conformal tracking algorithm (at least with these settings) has a tendency to reconstruct split tracks.

- Need decide which tracks to consider -> for now, implemented at analysis level.

```python
# Function to pick best of two tracks that contain several hits in common
def is_good_trk(track1, track2):

    decision = False

    nHitsInCommon = 0
    hits1 = track1.getTrackerHits()
    hits2 = track2.getTrackerHits()
    a_chi2 = track1.getChi2() / track1.getNdf()
    b_chi2 = track2.getChi2() / track2.getNdf()

    for hit in hits1:
        for jhit in hits2:
            if hit == jhit:
                nHitsInCommon = nHitsInCommon+1

    if nHitsInCommon == 0:
        decision = True
    else:
        if len(hits1) > len(hits2):
            decision = True
        elif len(hits1) == len(hits2):
            if a_chi2 <= b_chi2:
                decision = True
            else:
                decision = False
        else:
            decision = False

    return decision
```

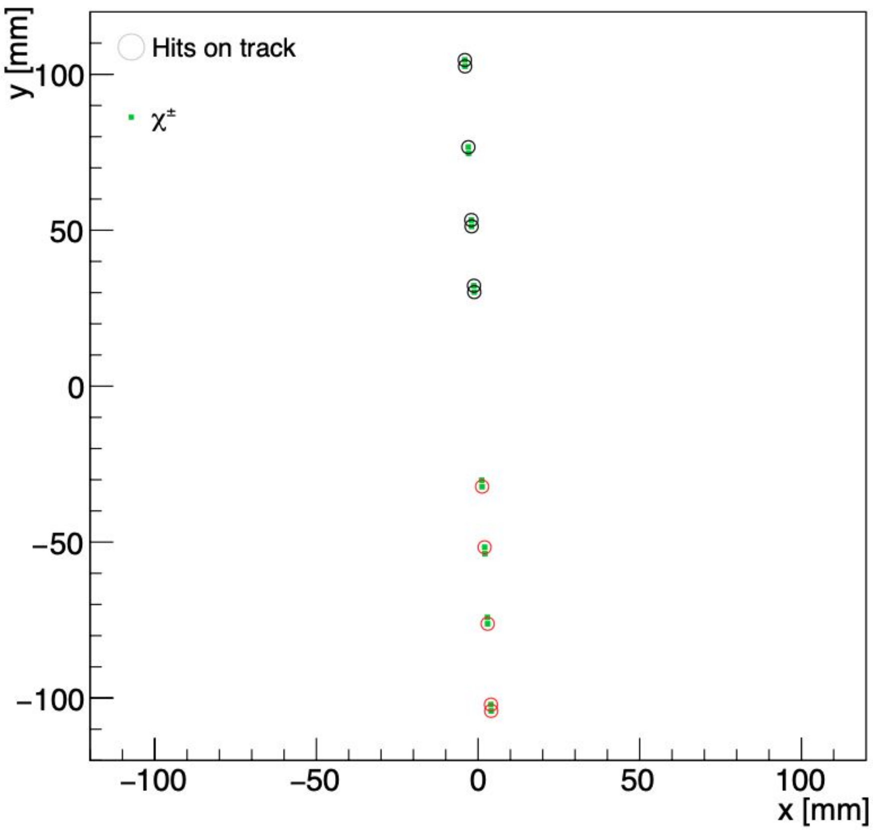
Strategy:

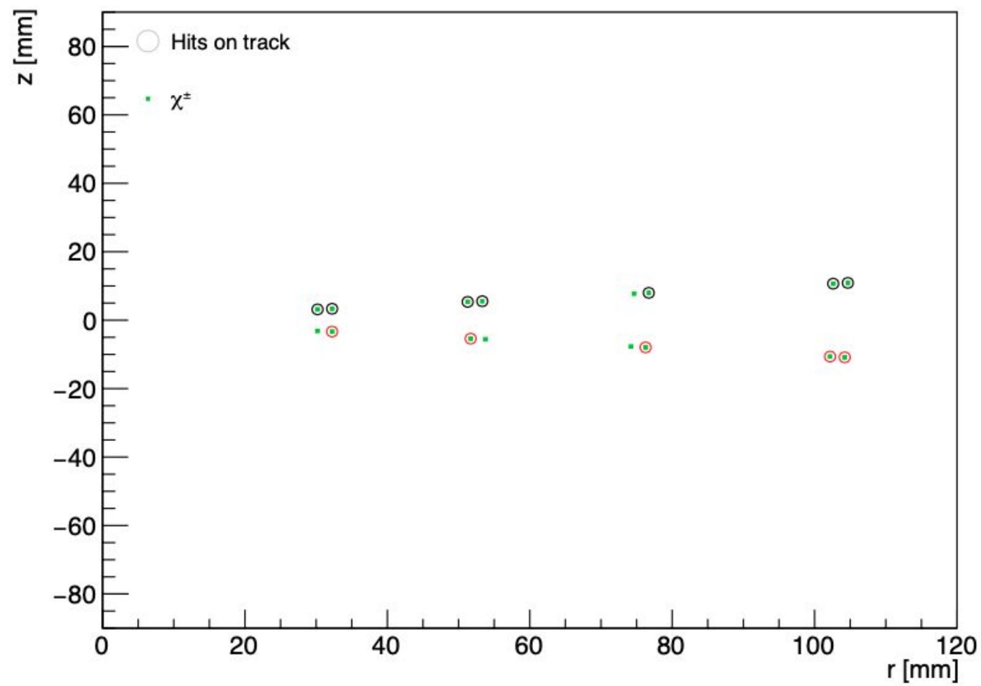
- Take longest track (in number of hits)
- If tracks have the same number of hits, take the one with the lowest chi2/ndf

Simplified event displays

Looking at hits and tracks

Same event as before (slide 6, 7)





- Signal hits are shown in green (they lie on the detector planes, which are not shown)
- Circles of the same color indicate hits associated to the same track
- Pattern recognition inefficiencies due to conformal tracking angular cell cuts

Reconstruction efficiencies

No BIB, but after BIB rejection cuts

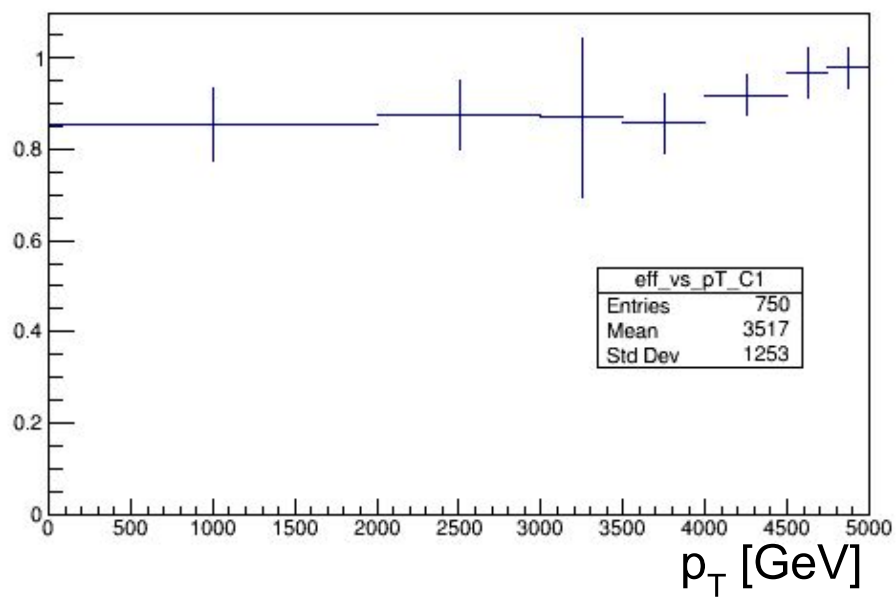
```
--- n_reconstructable_C1 = 3500
--- n_reconstructed_C1 = 3251
--- efficiency_C1 = 0.9288571428571428
```

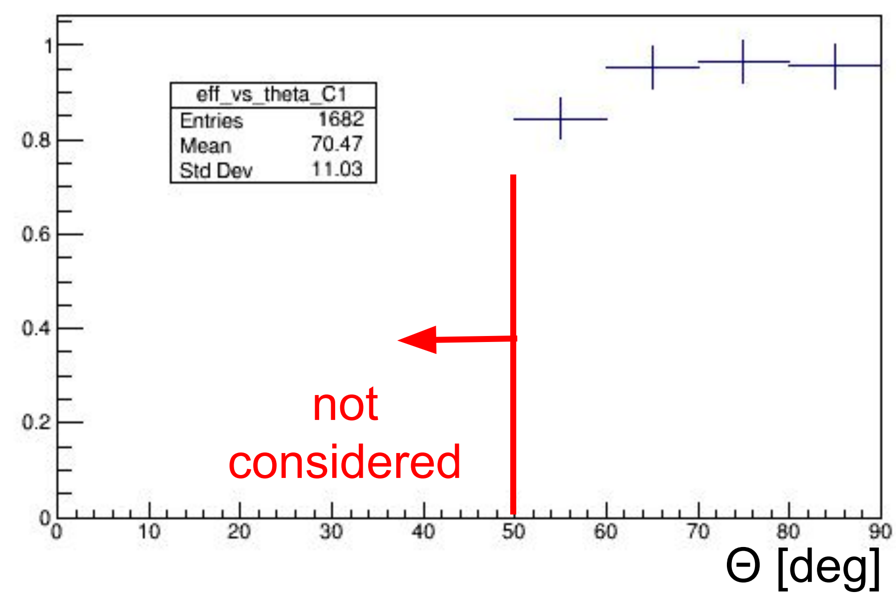
Efficiencies evaluated with truth matching to C1 particles.

- Reconstructable tracks are defined as tracks from C1 with at least 4 hits.
- Considering we are neglecting the hits in the endcaps, relatively ok

Will repeat the study asking additional quality cuts for additional BIB rejection:

- No holes in the first two double layers



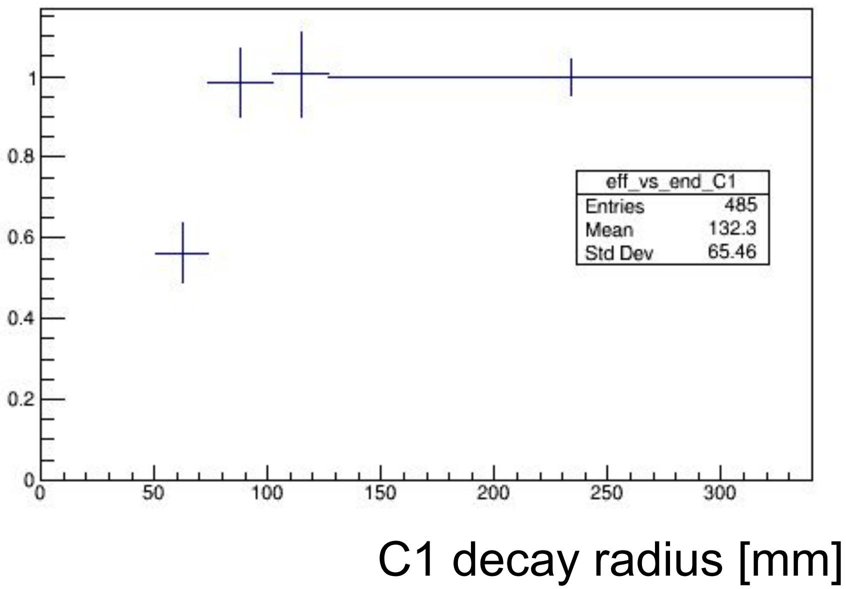


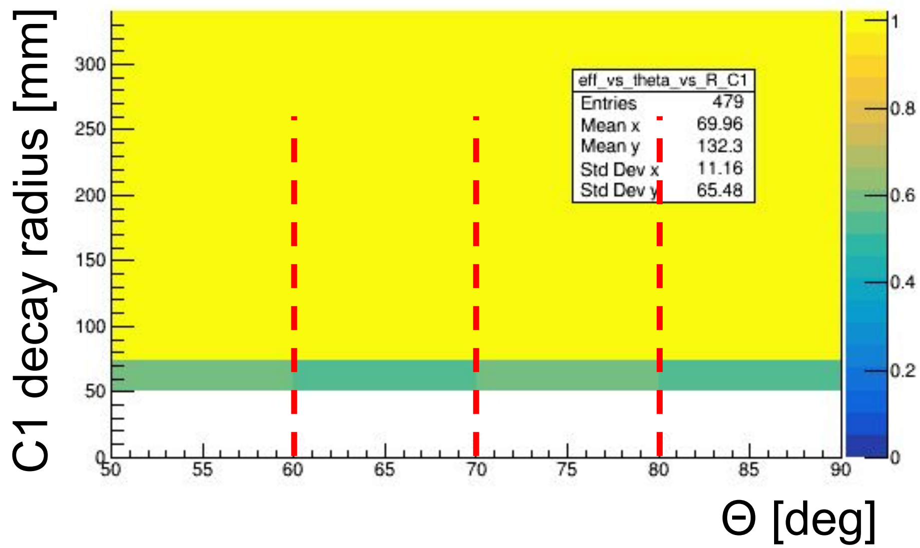
Reconstruction efficiencies

No BIB, but after BIB rejection cuts

Efficiencies evaluated with truth matching to C1 particles.

- Reconstructable tracks are defined as tracks from C1 with at least 4 hits.
- Evaluated vs the C1 decay radius R and vs (Θ, R)
    - Bin boundaries in R defined by position of tracking layers



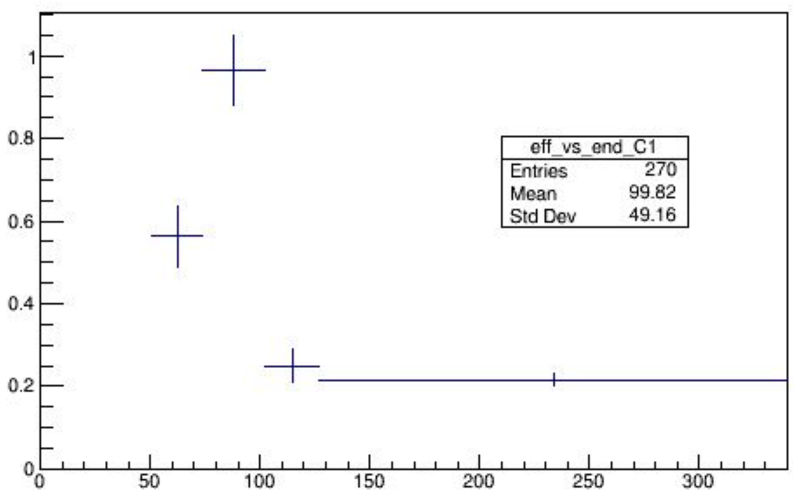


Effect of disappearing condition

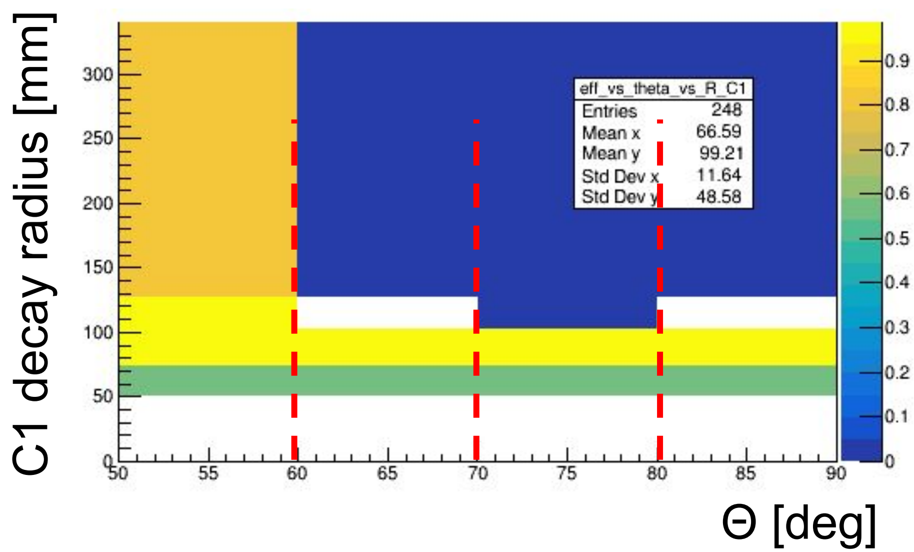
No BIB, but after BIB rejection cuts

Acceptance * efficiency evaluated with truth matching to C1 particles.

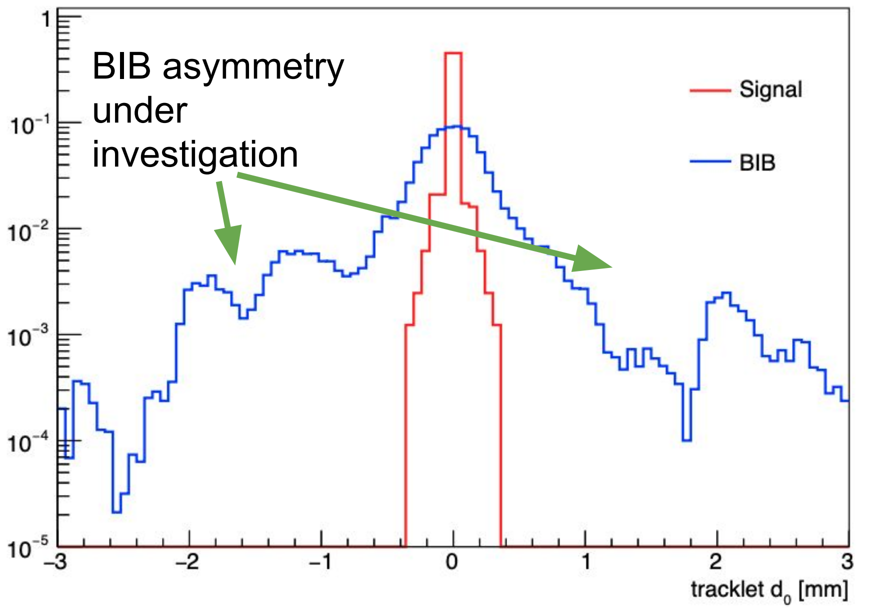
- Reconstructable tracks are defined as tracks from C1 with at least 4 hits.
- Disappearing condition - veto on last layer of Vertex detector (10.2 cm)
- Evaluated vs the C1 decay radius R and vs (Θ, R)
    - Bin boundaries in R defined by position of tracking layers
    - Plan to use this map to parameterise efficiencies

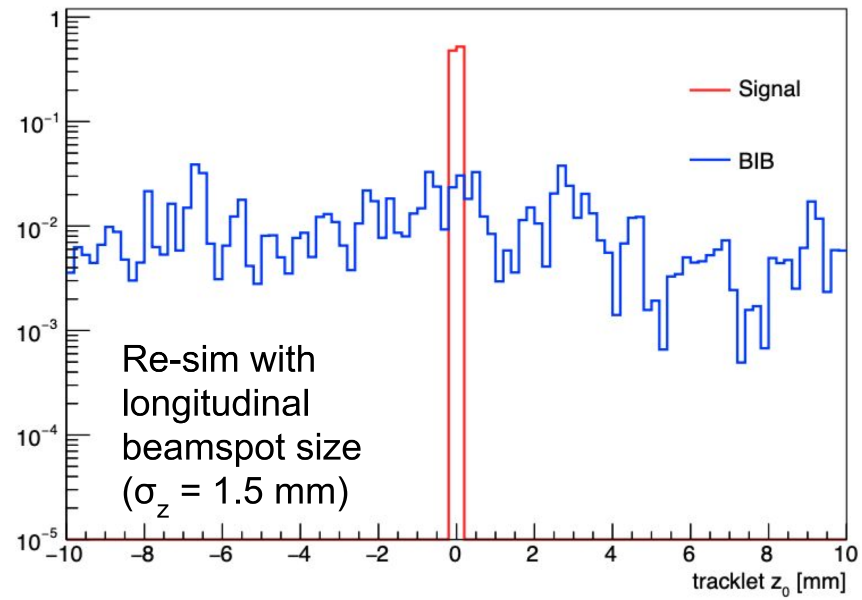


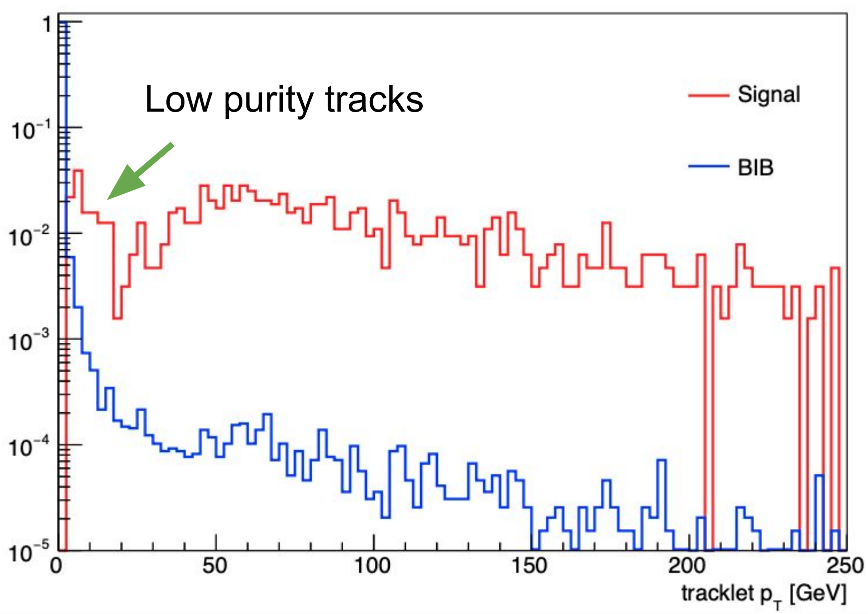
C1 decay radius [mm]

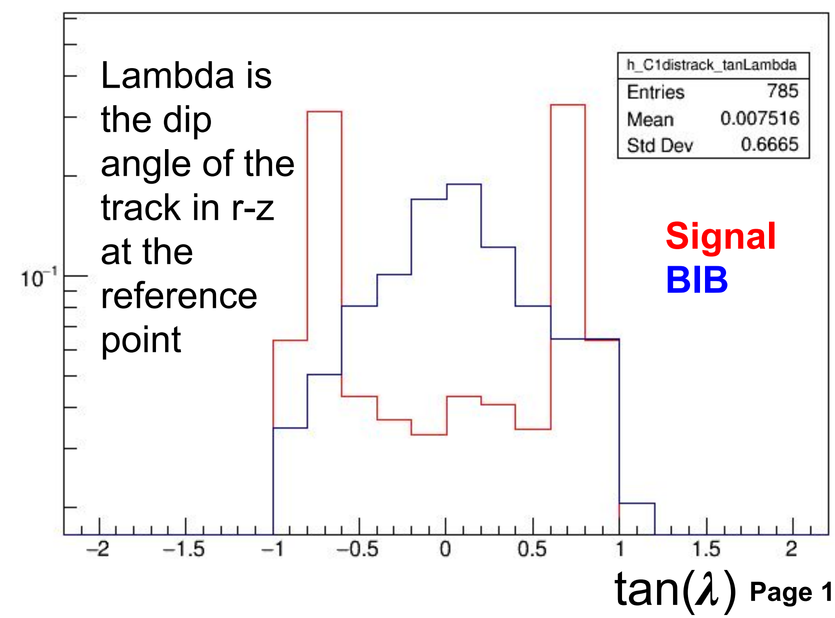


Disappearing tracks quantities









Future plans, questions and ideas

Repeat exercise at $\sqrt{s}$ = 3 TeV

For $\sqrt{s}$ = 10 TeV, the “soft pion” from the C1 decay is not too soft.

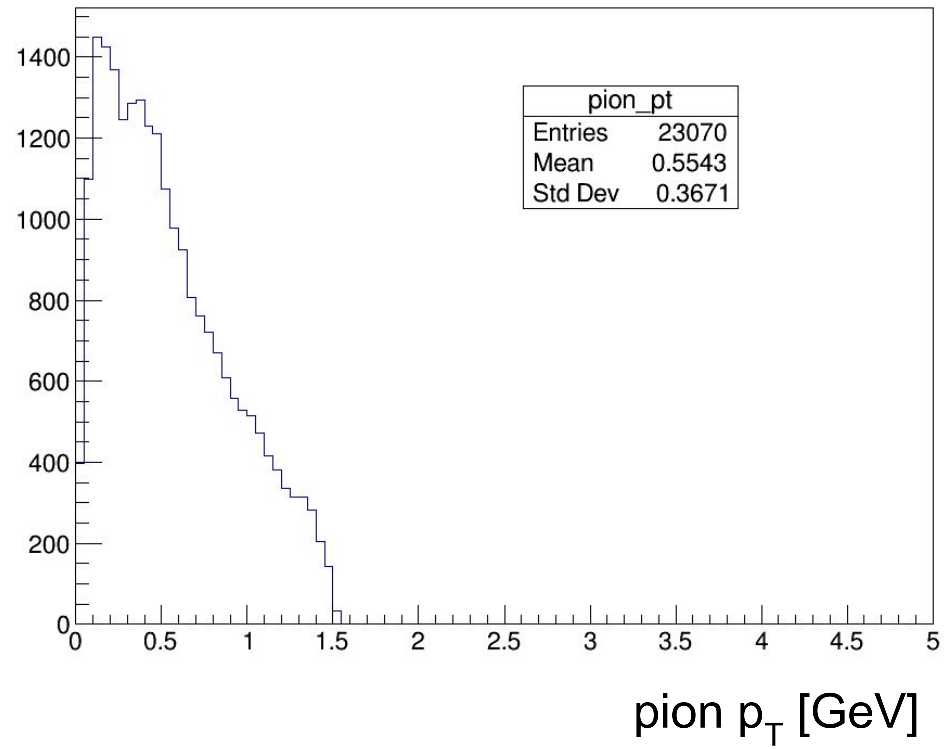
- Will investigate the displaced pion performance once the chargino part is settled.

Background estimation:

- Will build a “BIB track” database for Delphes level analysis
- Interesting for others?

BIB at 3 TeV

- Is help needed?
- Do we have an estimate of how much will it change wrt 1.5 TeV?



Random Extras

Momentum resolution

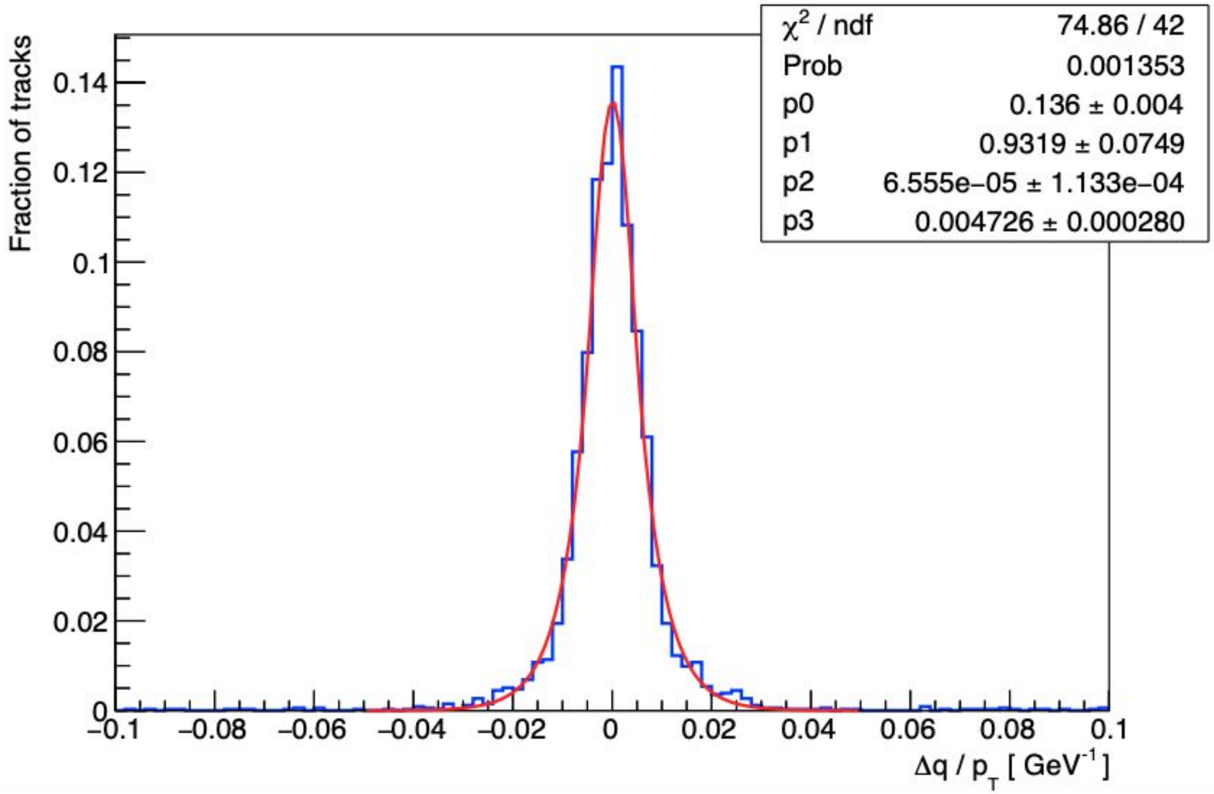
Look at q/p to get rid of charge-related biases

Not very good resolution.

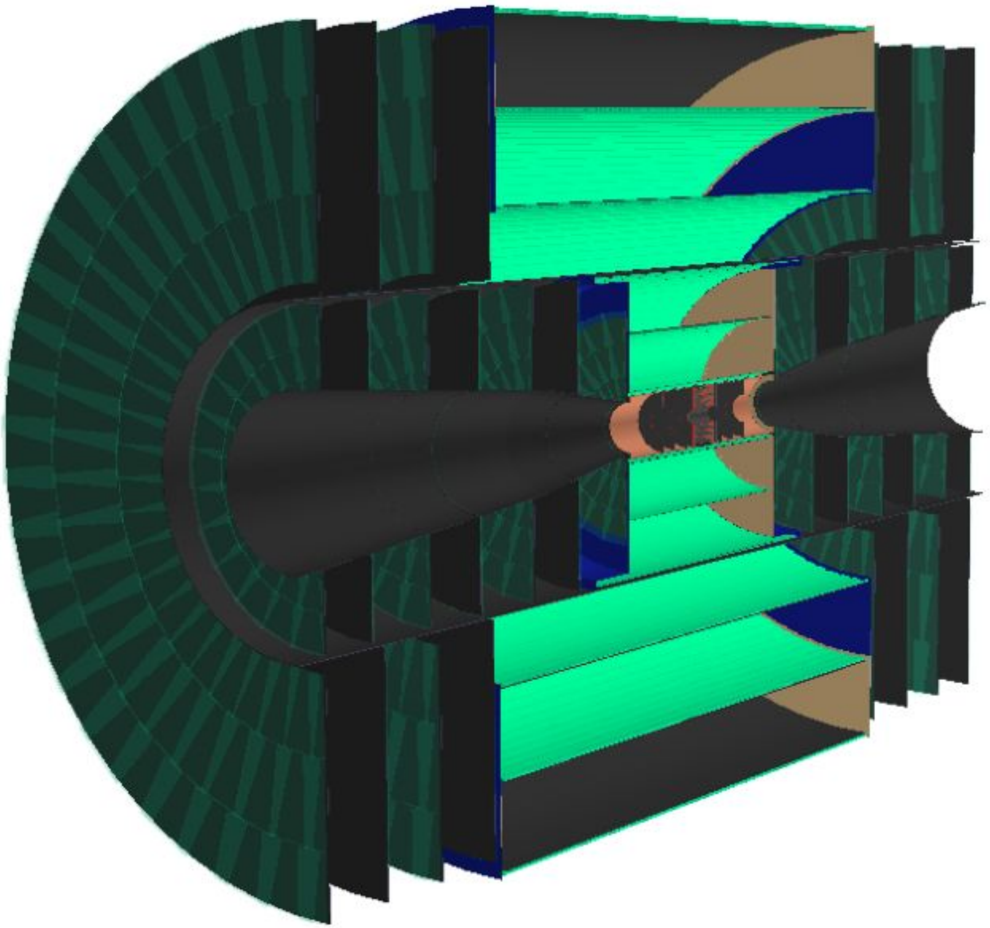
- Not surprising: these are 10 cm-long 5 TeV tracks in a 4T B field.
- Response function (reco-truth) shown on the right
- Fitted with double-sided crystal ball

$$f(z) = \begin{cases} \exp(\alpha(z + \alpha/2)) & (z < -\alpha) \\ \exp(-z^2/2) & (-\alpha < z < \alpha), \\ \exp(-\alpha(z - \alpha/2)) & (z > \alpha) \end{cases}$$

$$z = \frac{\Delta(q/p_T) - \beta}{\sigma},$$



The tracking system



- Vertex Detector (VXD)
  - 4 double-sensor barrel layers:
    - at r = 3.1, 5.1, 7.4, 10.2 cm;
    - 50-μm thick Si sensors;
  - 4+4 double-sensor disks:
    - at |Δz| = 8.0, 12.0, 20.0, 28.0 cm;
    - 50-μm thick Si sensors.
- Inner Tracker (IT)
  - 3 barrel layers (100-μm thick):
    - at r = 12.7, 34.0, 55,4 cm;
  - 7+7 disks (100-μm thick):
    - at |Δz| = 52.4, 80.8, 109.3, 137.7, 166.1, 194.6, 219.0 cm;
- Outer Tracker (OT)
  - 3 barrel layers (100-μm thick):
    - at r = 81.9, 115.3, 148.6
  - 4+4 disks (100-μm thick):
    - at |Δz| = 131, 161.7, 188.3, 219 cm.

Machine parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
$\langle B \rangle$	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63