Time For Hyperons

- Towards Reconstruction of Long-Lived Particles on Free-Streaming Data at PANDA at FAIR

Jenny Regina

Department of Physics and Astronomy
Uppsala University

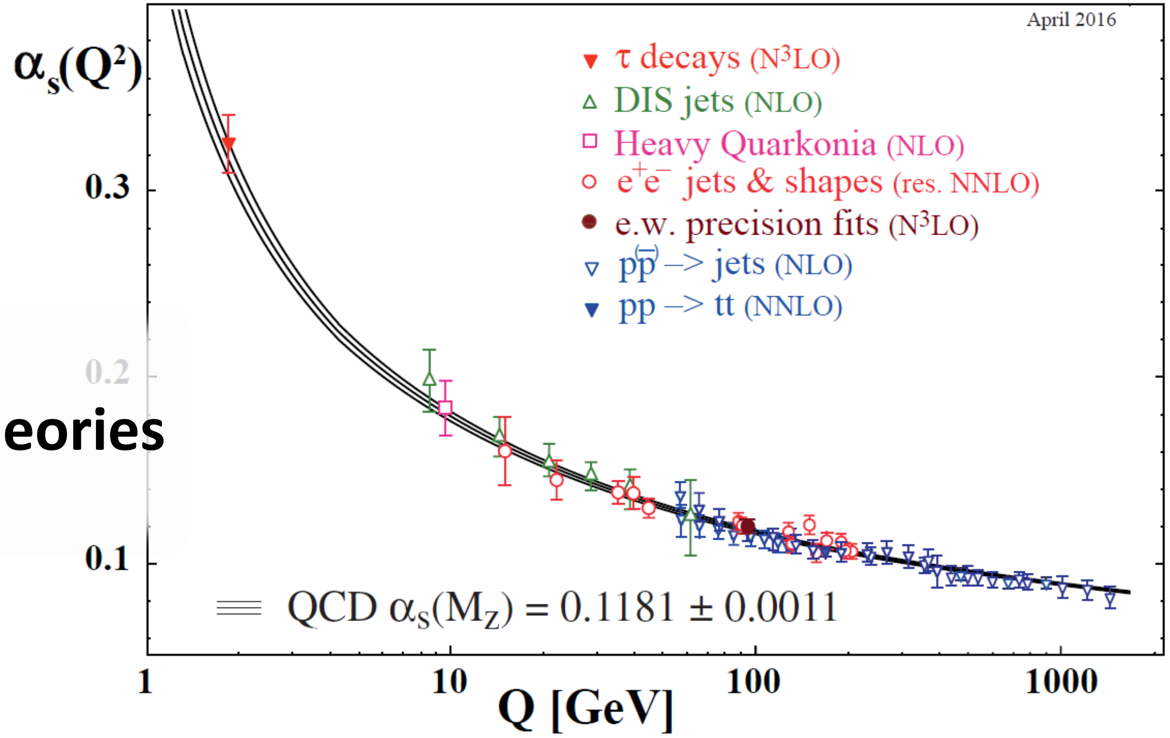
Half-Time Seminar,
Online,
May 07, 2020

Outline:

- Hyperons
- PANDA at FAIR
- Hyperon detector signatures
- Time-sorted Data
- Clusterization Procedure
- Quality-Assurance
- Results

Quantum Chromodynamics

- **Strong QCD**
  - **Effective theories**
- **Confinement**



- **Perturbative QCD**
- **Asymptotic Freedom**

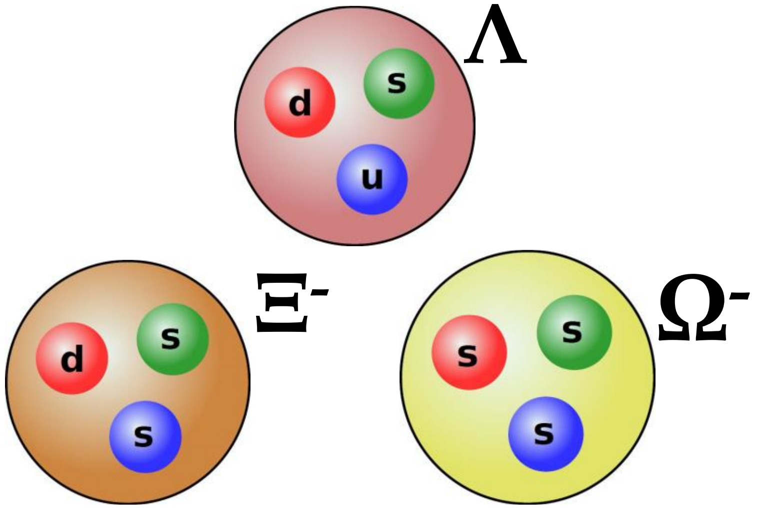
Nuclei **Hadrons** **Particles (*e.g.* quarks, gluons)**

Relevant degrees of freedom in intermediate to lower ranges?

Hyperons – What are they?

Baryons containing one or more *s (c)* quark

- Relatively long life-times
  - Need tracking algorithms working for particles for particles from displaced vertices
- Λ involved in many decays
  - Reconstruction of Λ crucial for performing hyperon physics



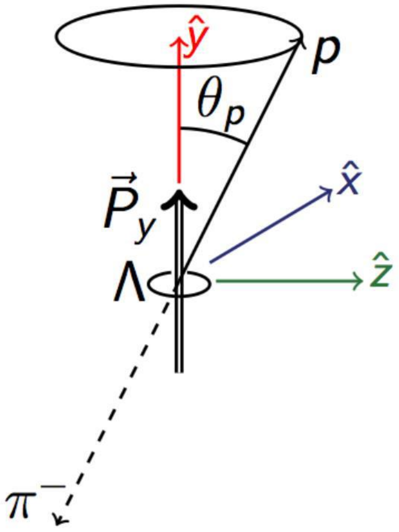
Hyperon and Quark Content	$c\tau$ $[cm]$	Mean lifetime [s]	Mass $[GeV/c^2]$	Main decay and branching ratio
Λ (uds)	8.0	$2.60 \cdot 10^{-10}$	1.116	$p\pi^-$ (64 %)
Σ^+ (uus)	2.4	$8.01 \cdot 10^{-11}$	1.189	$p\pi^0$ (52 %)
Σ^0 (uds)	$2.2{\cdot}10^{-9}$	$7.4 \cdot 10^{-20}$	1.193	$\Lambda\gamma$ (100 %)
Σ^- (dds)	2.4	$1.48 \cdot 10^{-10}$	1.197	$n\pi^-$ (100 %)
Ξ^0 (uss)	8.7	$2.90 \cdot 10^{-10}$	1.315	$\Lambda\pi^0$ (99 %)
Ξ^- (dss)	4.9	$1.64 \cdot 10^{-10}$	1.321	$\Lambda\pi^-$ (100 %)
Ω^- (sss)	2.5	$8.21 \cdot 10^{-11}$	1.672	ΛK^- (68 %)

Scale: m_s ~ 100 MeV ~ Λ_{QCD} ~ 220 MeV → **Probes QCD in the confinement domain!**

Hyperons – Why are they interesting to study?

$\Lambda \rightarrow p\pi^-$

Polarization accessible via weak, parity-violating decay

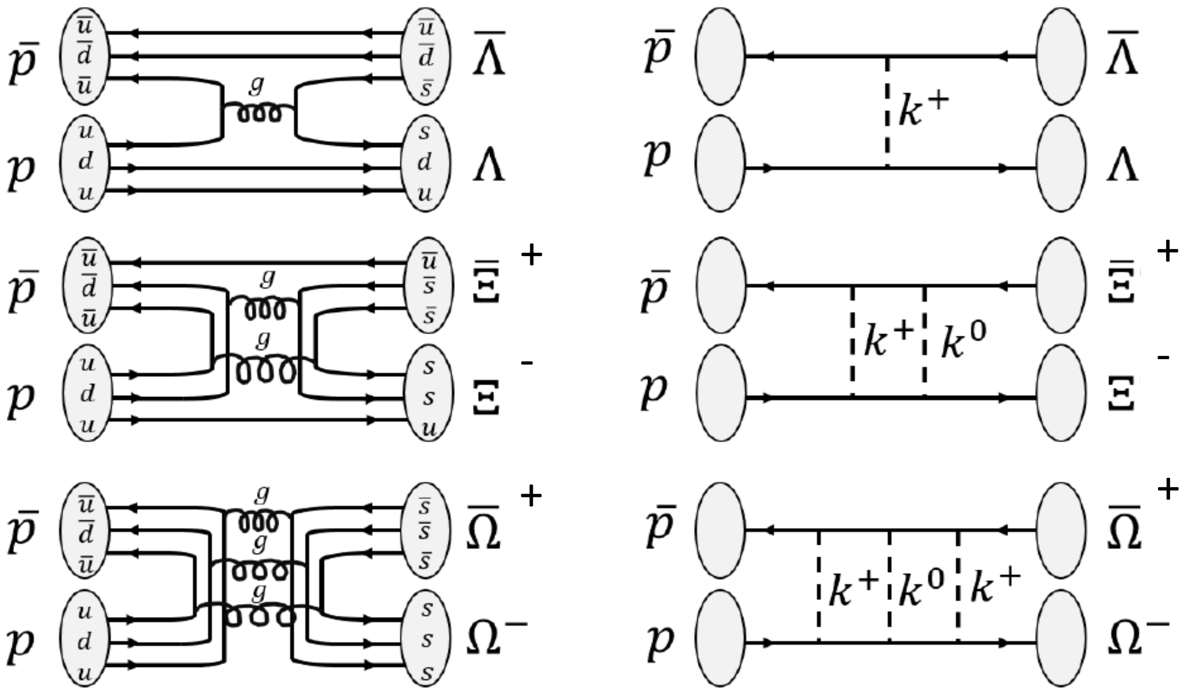


$I(\cos(\theta_p)) = N(1+\alpha P_\Lambda(\cos(\theta_p))$

P_Λ: polarization

α: asymmetry parameter

Quark model (left) and Meson exchange model (right)

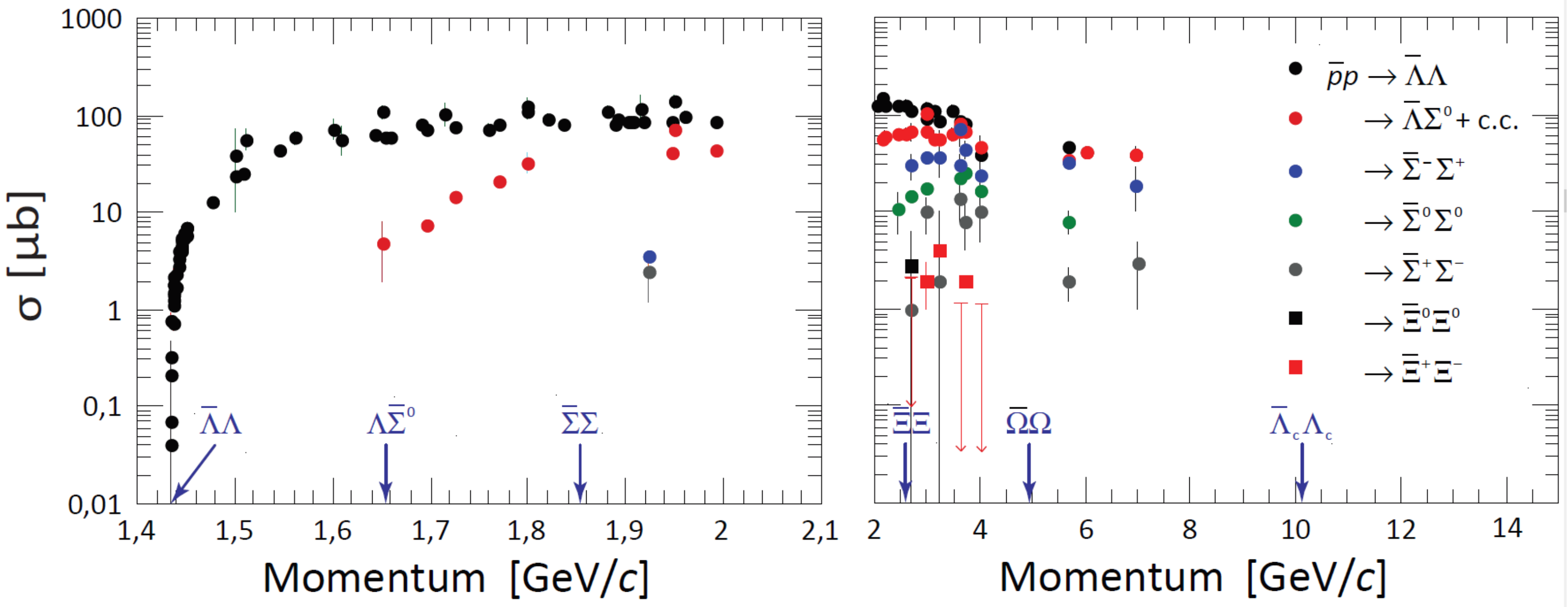


- **Rich set of spin observables** obtainable for **hyperon decays**
  - Theoretical predictions [*] relate sign and value of some observables to the production model

➡ Hyperon spin observables can shed light on relevant degrees of freedom!

[*] What can we learn from antihyperon-hyperon production? M.Alberg, Nucl. Phys. A 655 (1999) 1.

Hyperons – Why are they interesting to study?



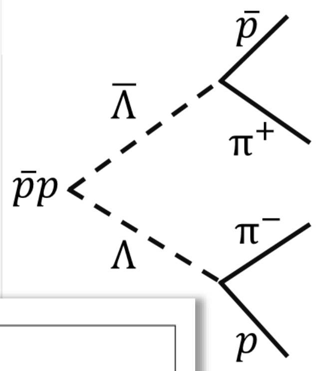
T. Johansson, Proceedings of 8th Int. Conf. on Low Energy Antiproton Physics 95 (2003)

Scarce data bank:

- for multi-strange hyperons
- above 4 GeV/c
- No data for *e.g.* Ω

Need more data!

$\bar{p}p \to \bar{\Lambda}\Lambda$

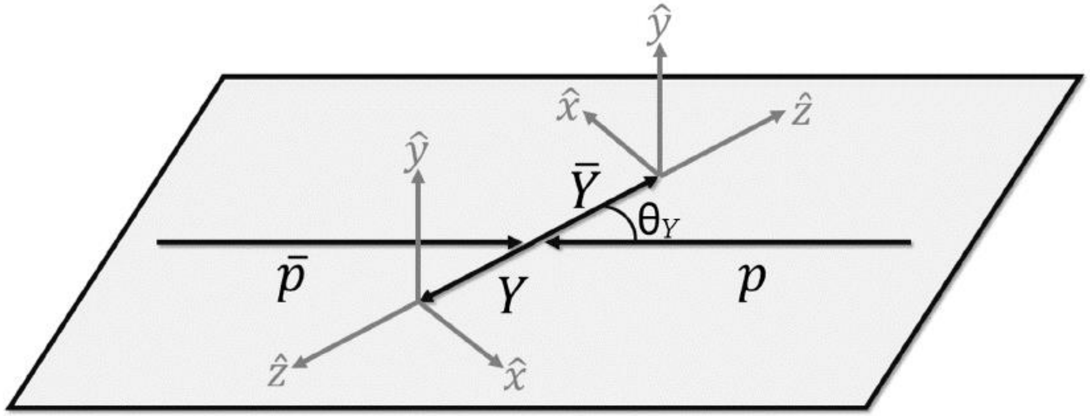


- Angular distribution: *forward peaking*

$$\hat{x} = \hat{y} \times \hat{z},$$

$$\hat{y} = \frac{\bar{p}_{beam} \times \bar{p}_{\bar{Y}}}{|\bar{p}_{beam} \times \bar{p}_{\bar{Y}}|},$$

$$\hat{z} = \bar{p}_{\bar{Y}},$$



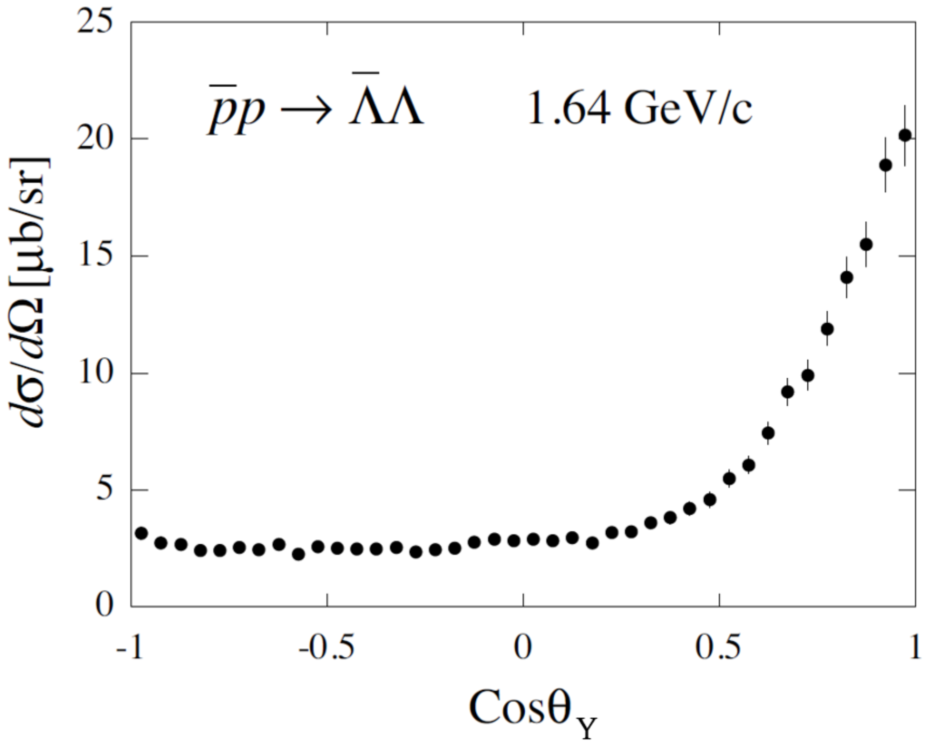
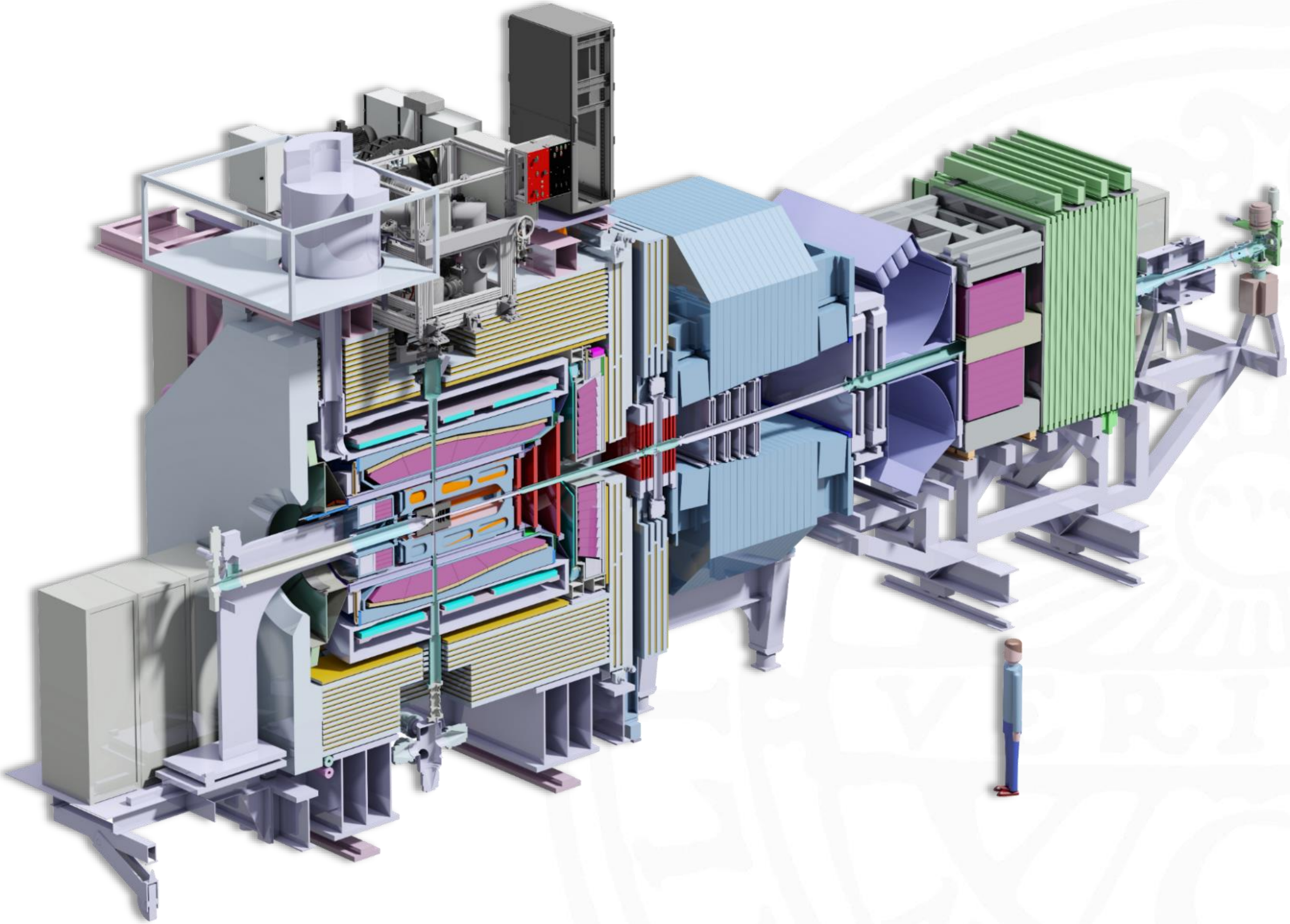


Figure above from: E. Klempt et al. *Antinucleon-nucleon interaction at low energy: scattering and protonium*, Physics Reports **368** (2002)119-316.

PANDA – anti-Proton ANnihilation at DArmstadt

Physics Pillars

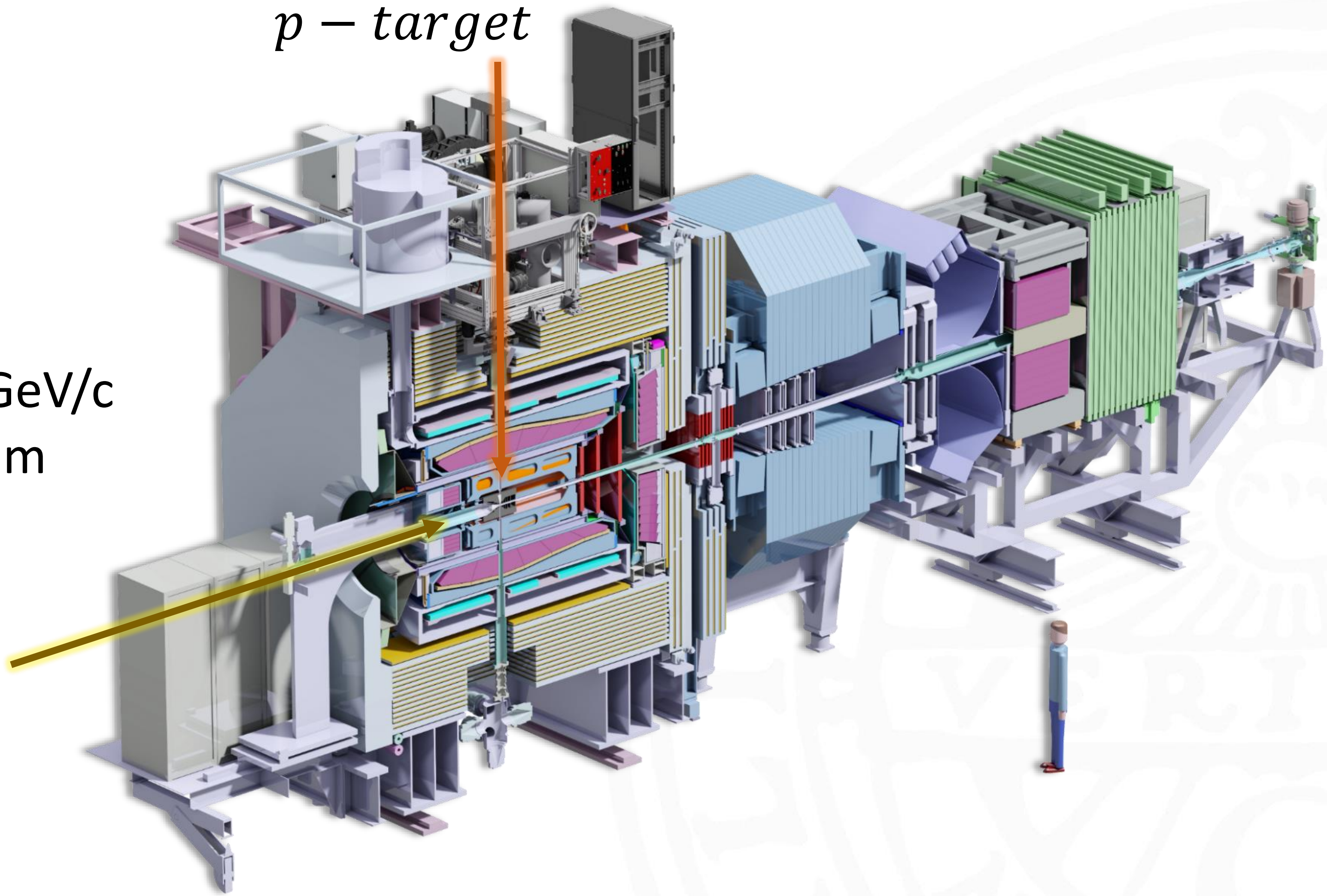
- Nucleon structure
- Strangeness physics
- Charm and exotics
- Hadrons in nuclei



PANDA – anti-Proton ANnihilation at DArmstadt

Beam / Target

- Stored anti-proton beam
    - 1.5 GeV/c < p_{beam} < 15 GeV/c
    - Quasi-continuous beam
- Proton target
    - Fixed

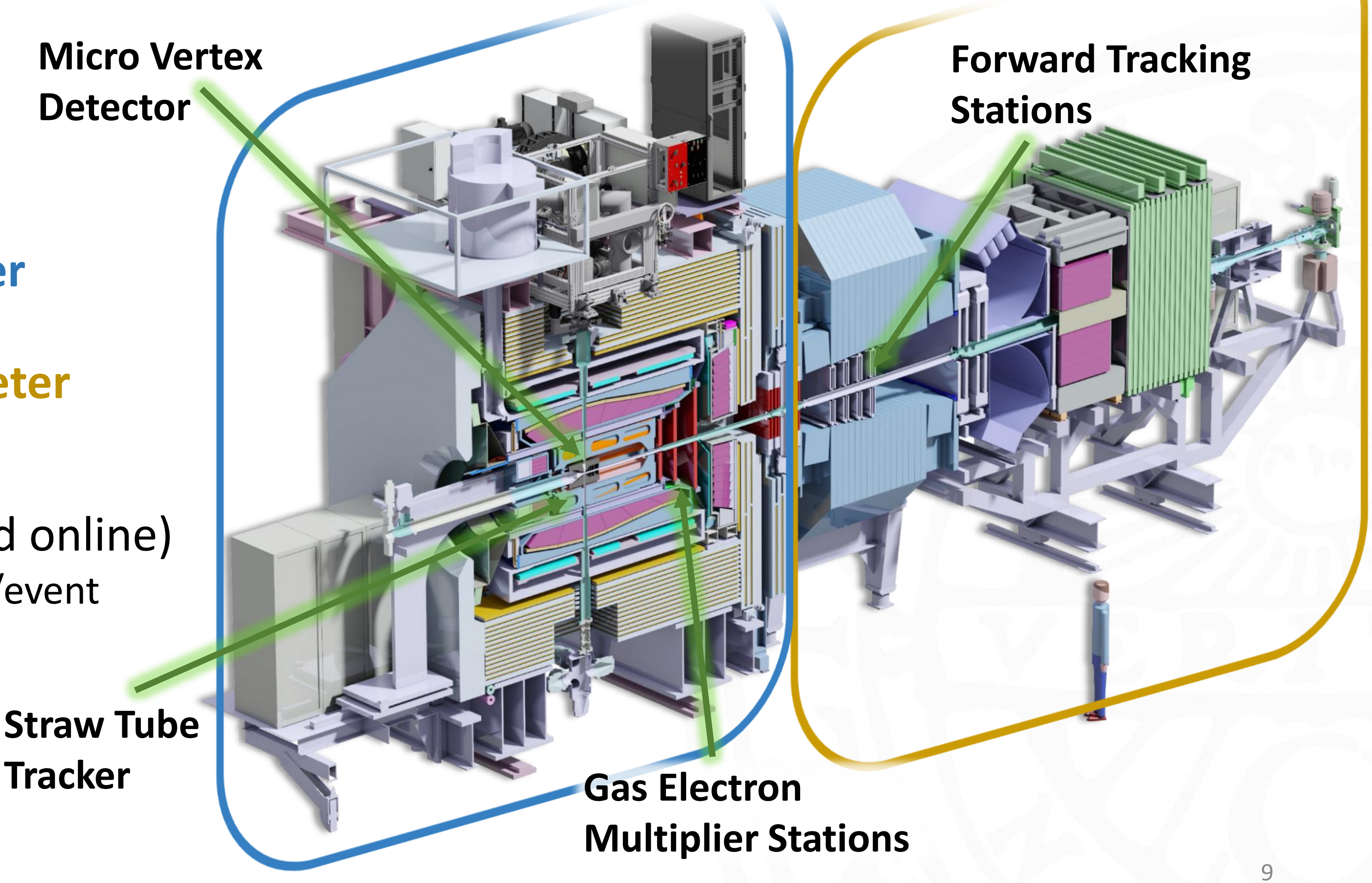


PANDA – anti-Proton ANnihilation at DArmstadt

Detector

- Almost full 4π
- **Target spectrometer**
  - solenoid field
- **Forward spectrometer**
  - dipole field

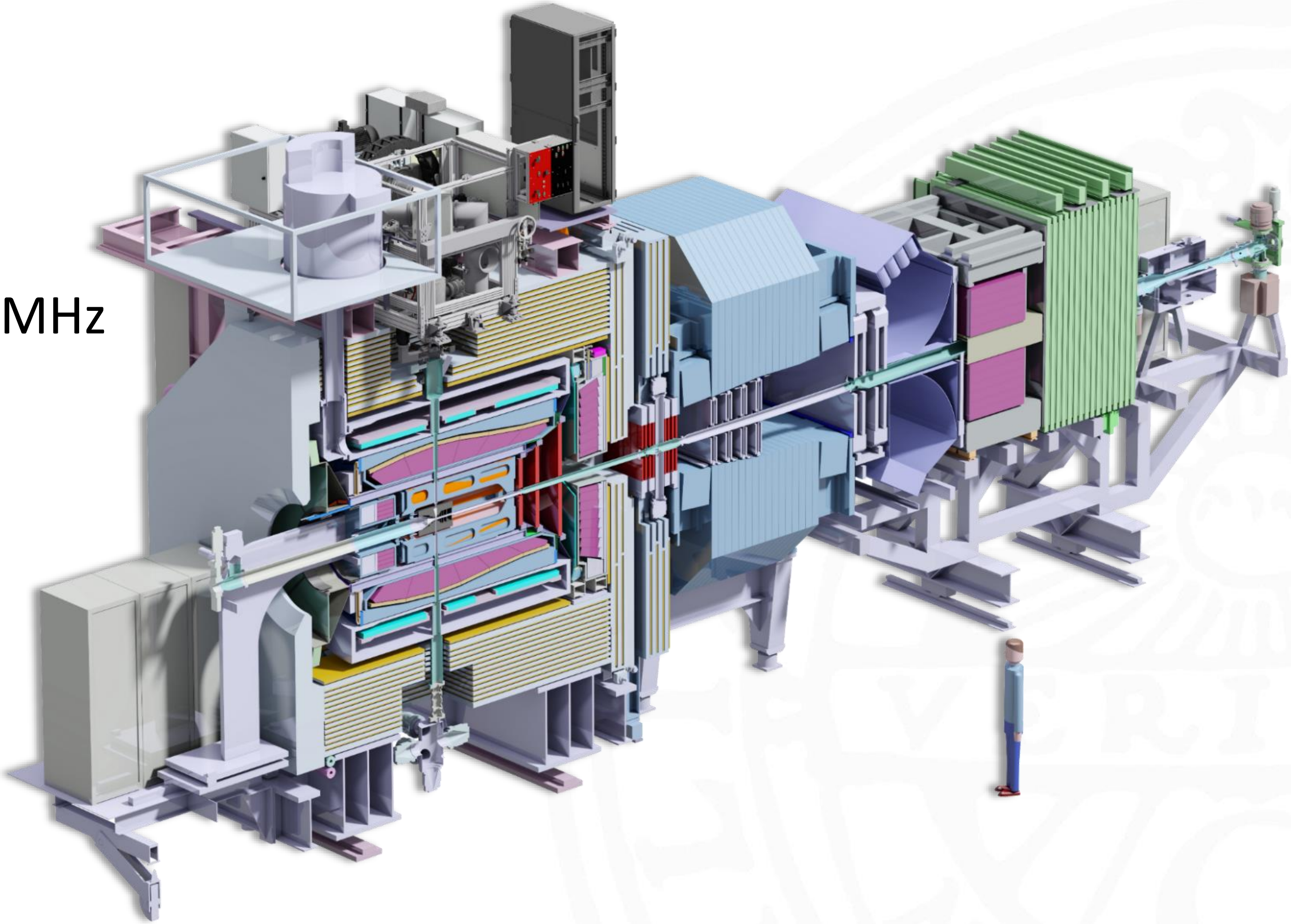
- Tracking (offline and online)
  - Mainly < 10 tracks/event
- Vertexing
- PID
- Calorimetry



PANDA – anti-Proton ANnihilation at DArmstadt

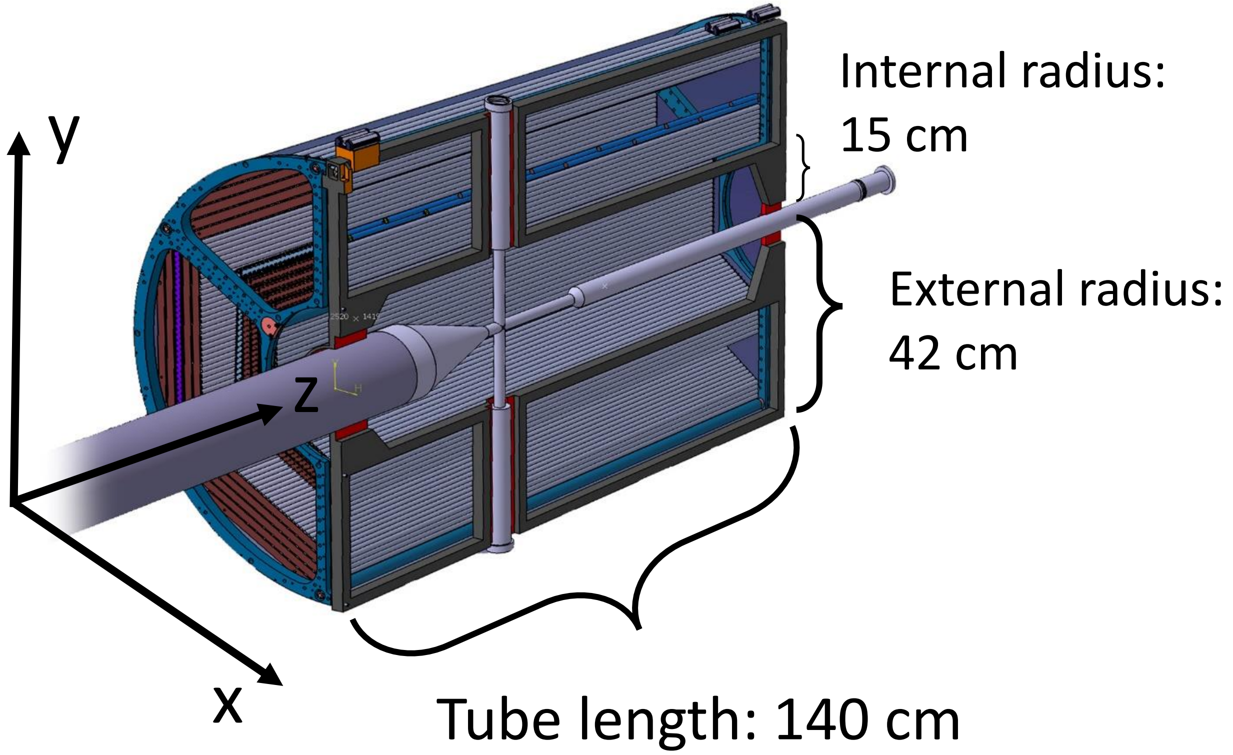
Readout

- Average interaction rate:
  - Phase2 (full luminosity): 20 MHz
  - Phase1: 2 MHz
- Continuous readout
- Background and signal similar
  - Software-based event filtering
    - Tracking Information



Straw Tube Tracker of PANDA

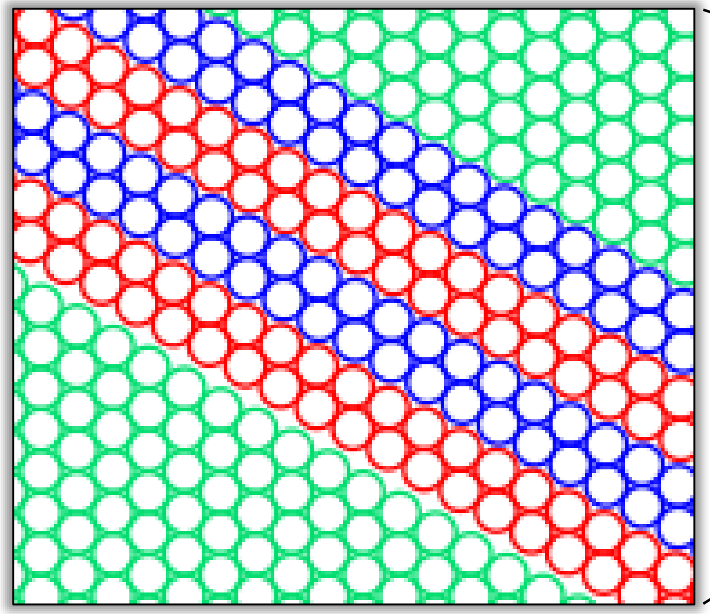
- 4 224 closely packed single channel readout drift tubes

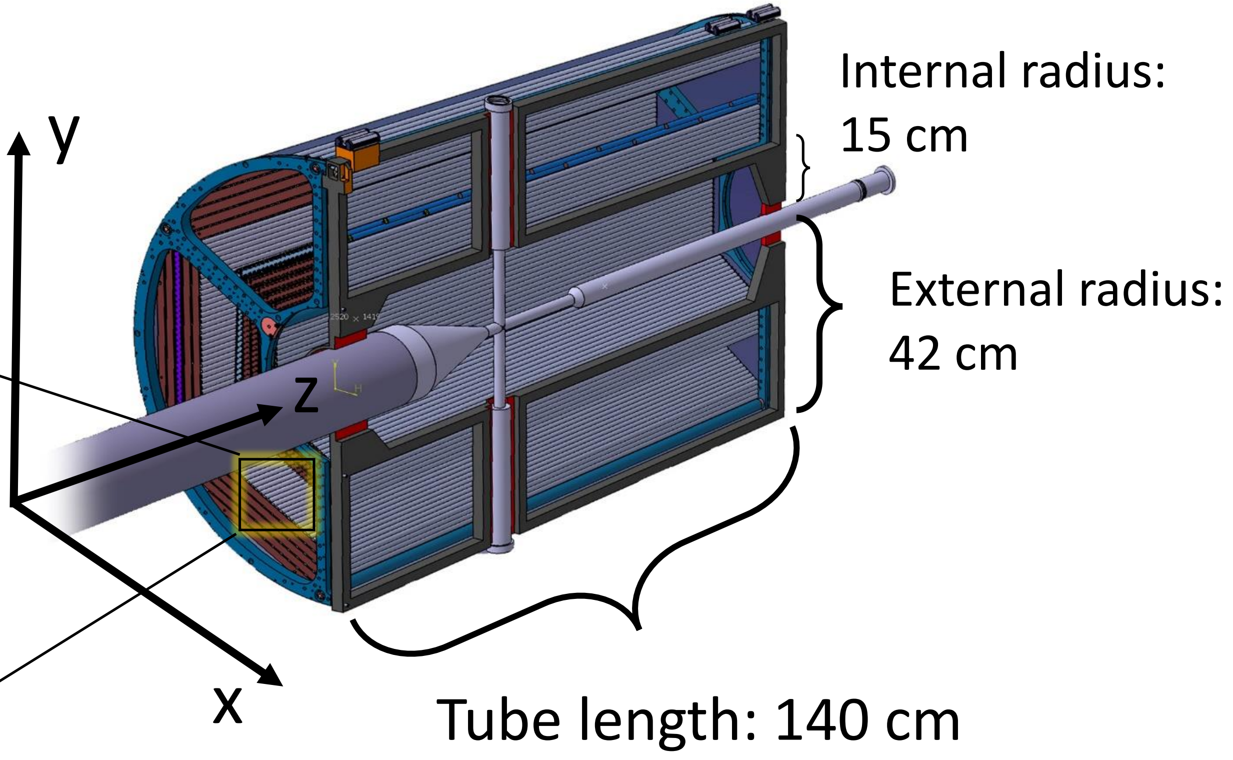


Straw Tube Tracker of PANDA

- 4 224 closely packed single channel readout drift tubes

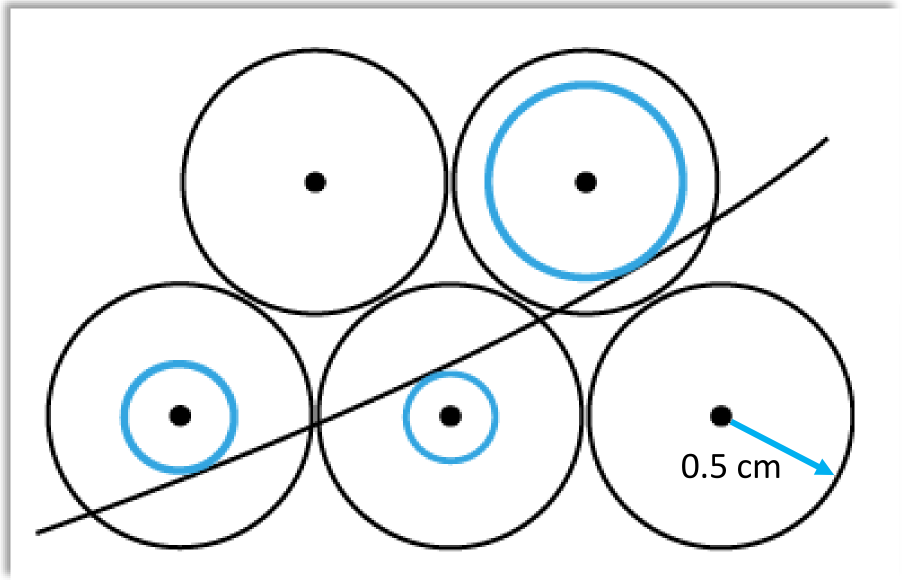
- ~ 19 radial layers for xy reconstruction (green)
- 8 central layers consisting of tilted ($\pm 3^o$) tubes for z reconstruction (red and blue)



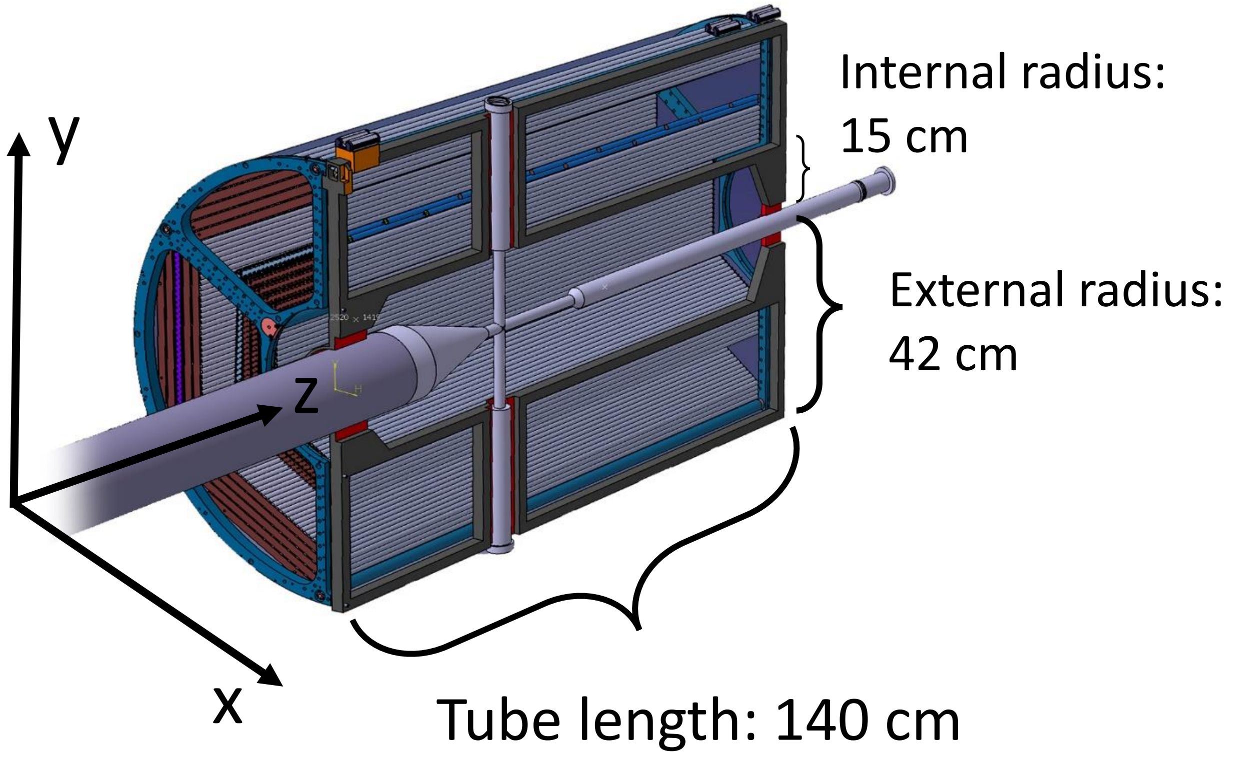


Straw Tube Tracker of PANDA

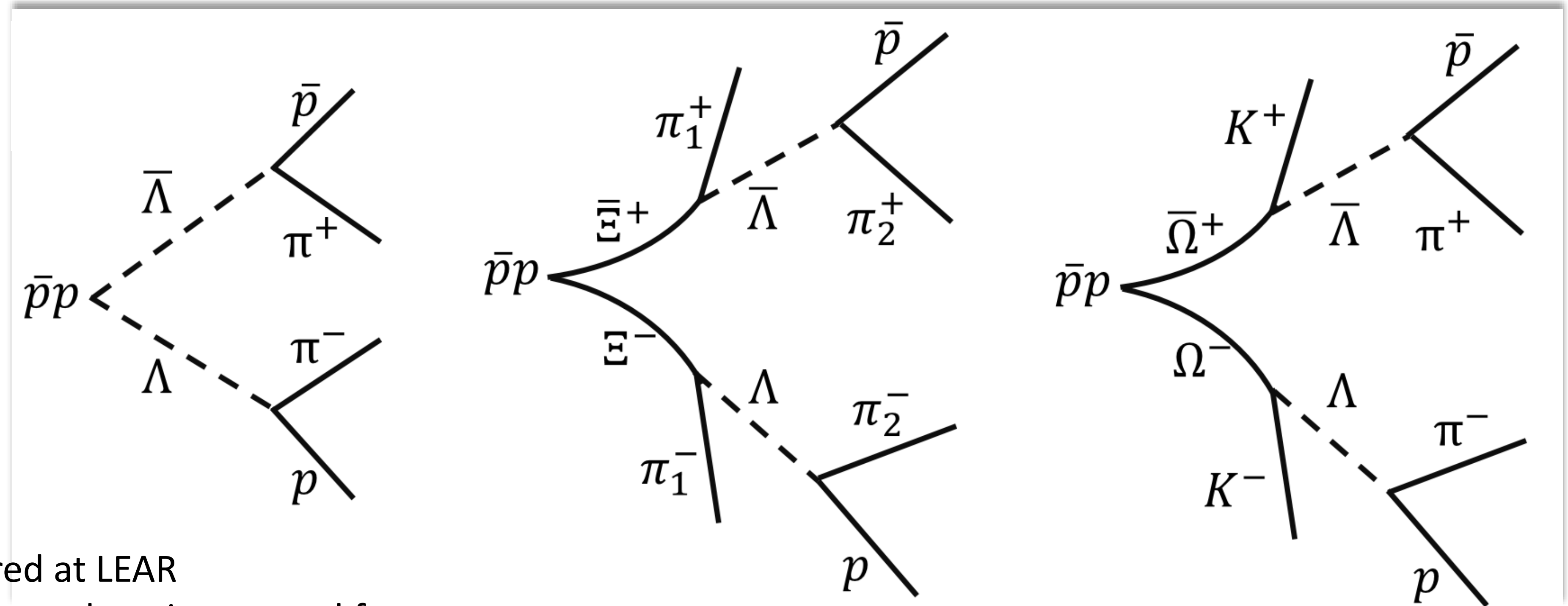
Drift Circles:
Circle through point of closest approach of track to anode wire



Maximum drift time of electrons: **250 ns**



Decay Topologies and Simulation

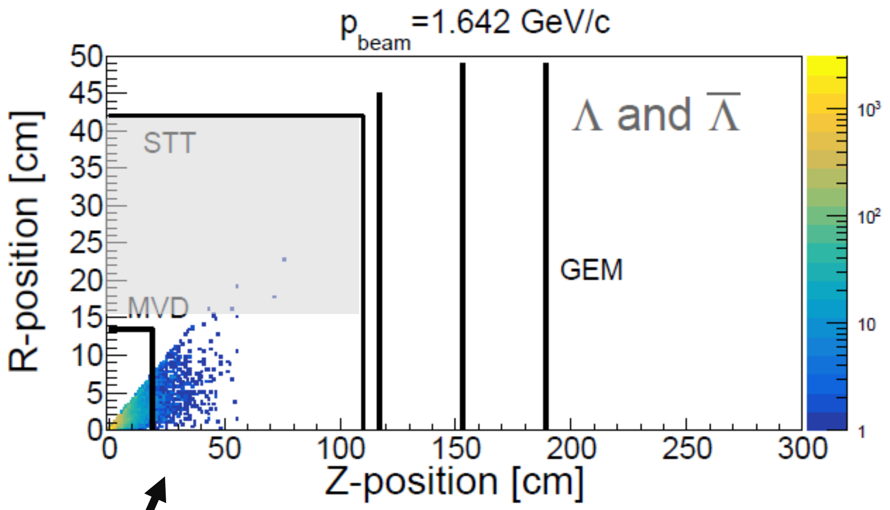


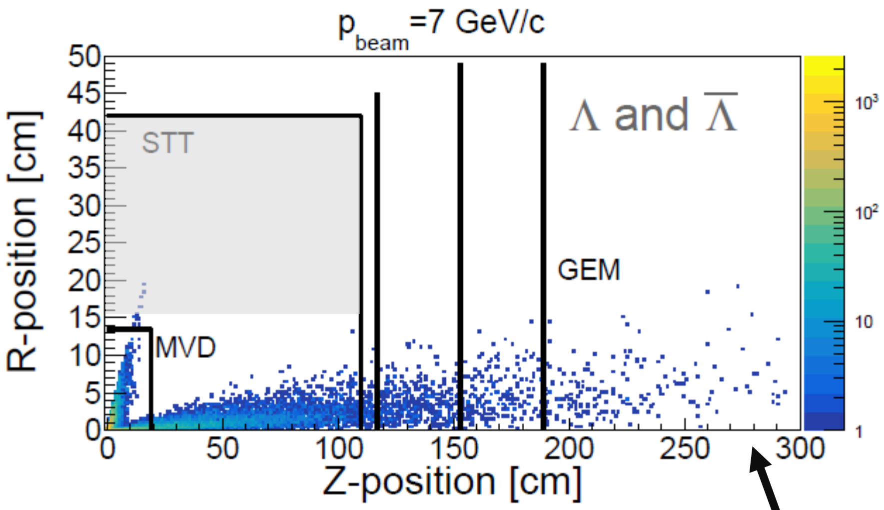
- Measured at LEAR
- Provide good testing ground for tracking algorithms
- Forward peaking angular distribution
- Simulated in EvtGen at p_{beam}=1.642, 7.0 and 15.0 GeV/c

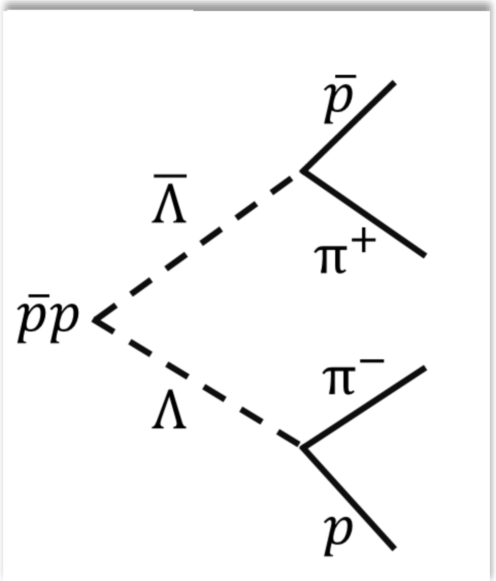
- PANDA will be first to measure angular distribution
- Isotropic angular distribution used in simulations
- Simulated in EvtGen at p_{beam}=7.0 GeV/c

- No measured cross section
- Isotropic angular distribution used in simulations
- Simulated in EvtGen at p_{beam}=15.0 GeV/c

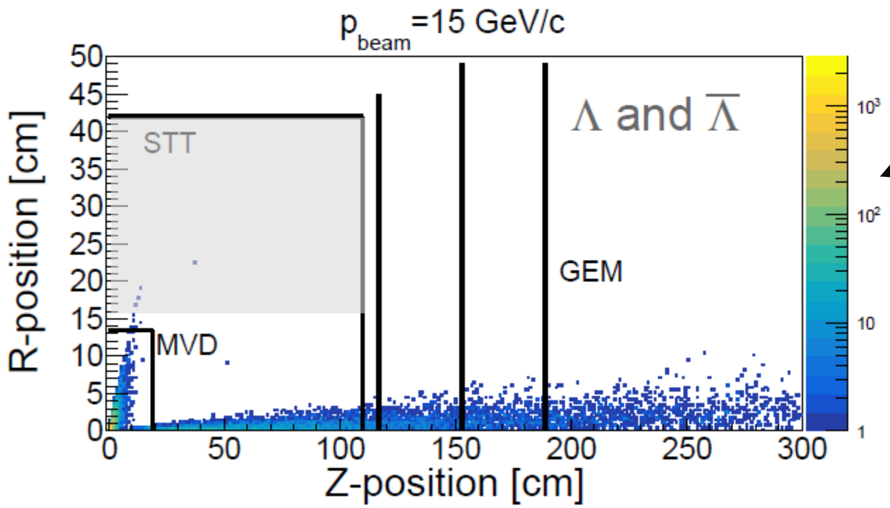
$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, Vertex distributions







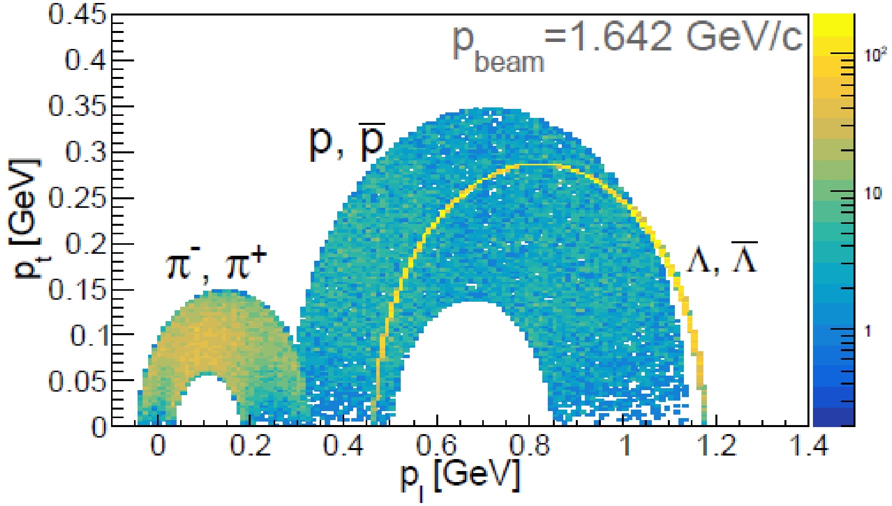
- All decay vertices within STT volume
- Many decay vertices within MVD

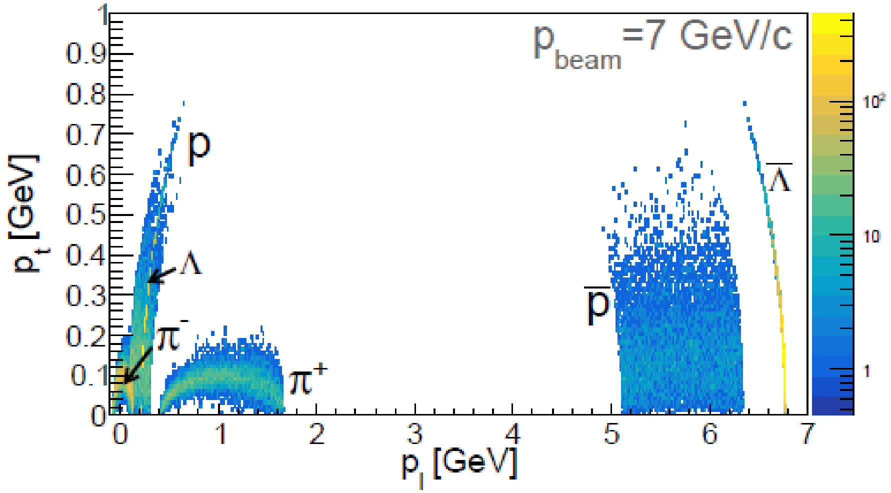


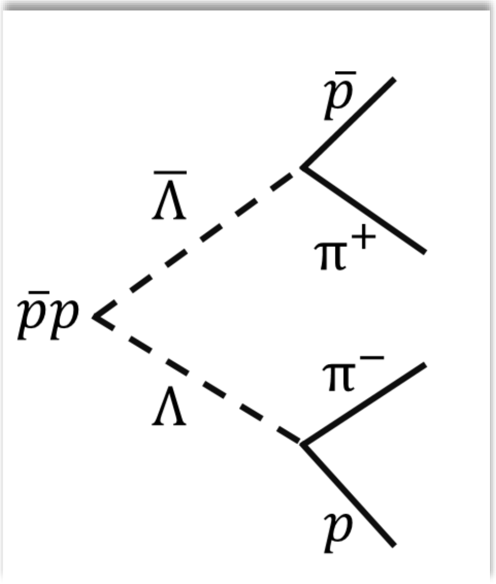
- All Λ decay vertices within STT volume
- Many Λ decay vertices within MVD
- Many $\bar{\Lambda}$ decay vertices within STT but some also at larger z

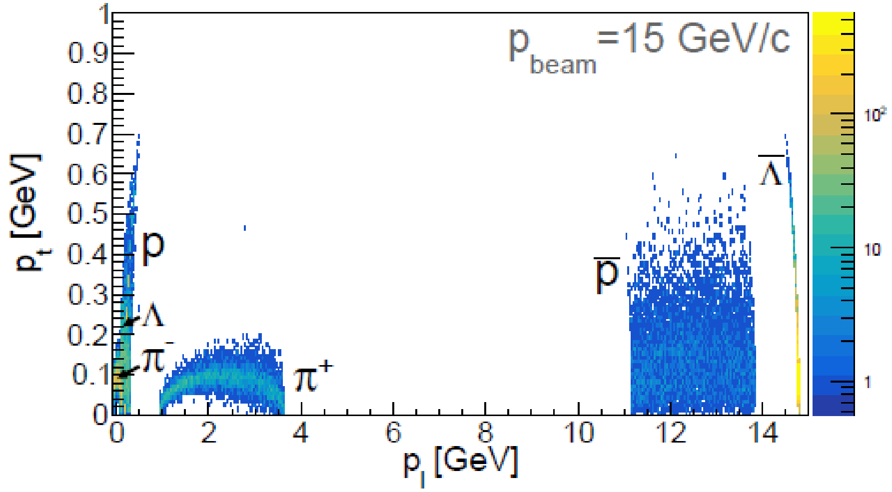
- Separation between decay vertices of $\bar{\Lambda}$ and Λ apparent at larger p_{beam}
- $\bar{\Lambda}$ decay at larger z

$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, Momentum distributions



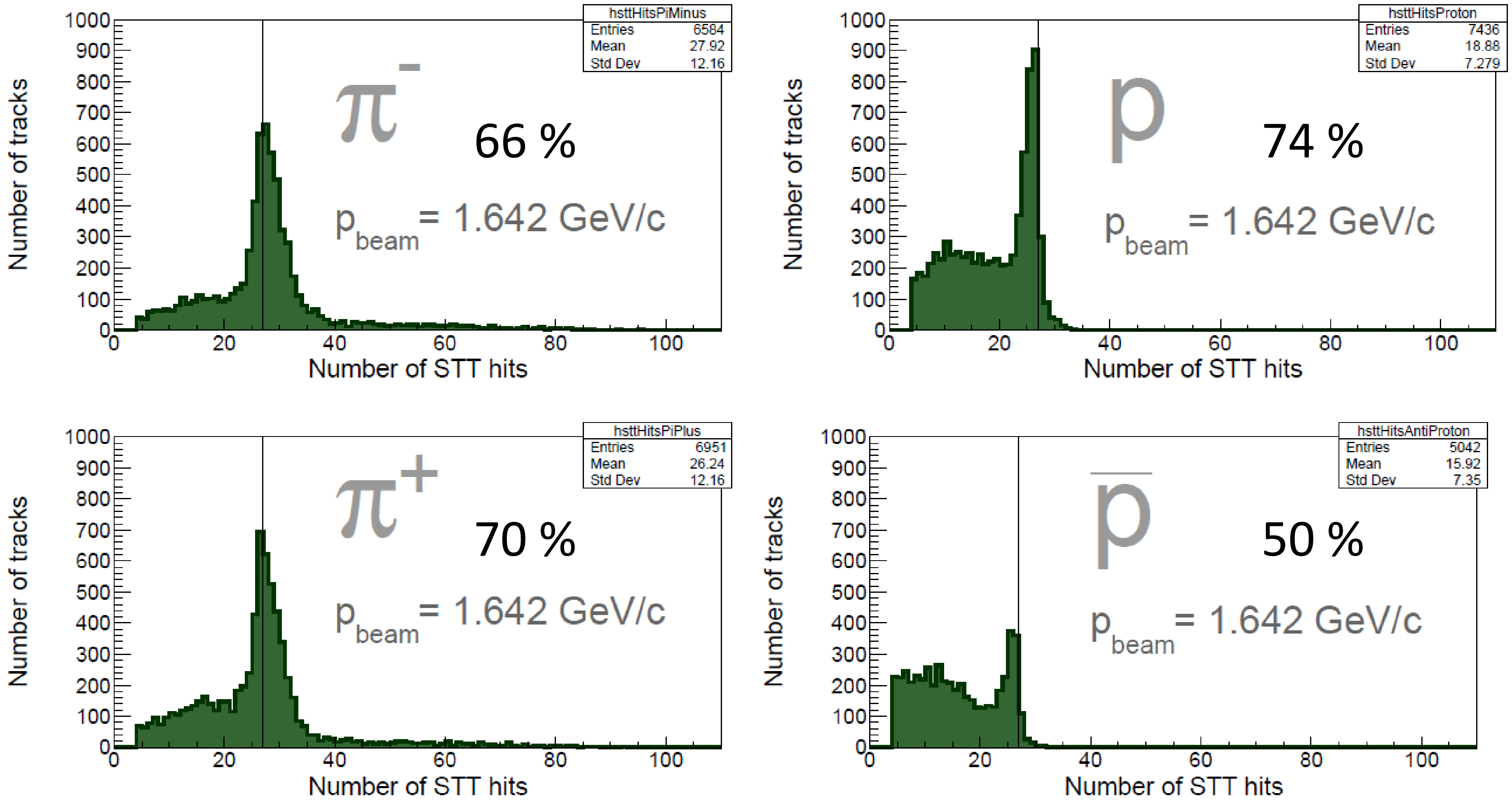


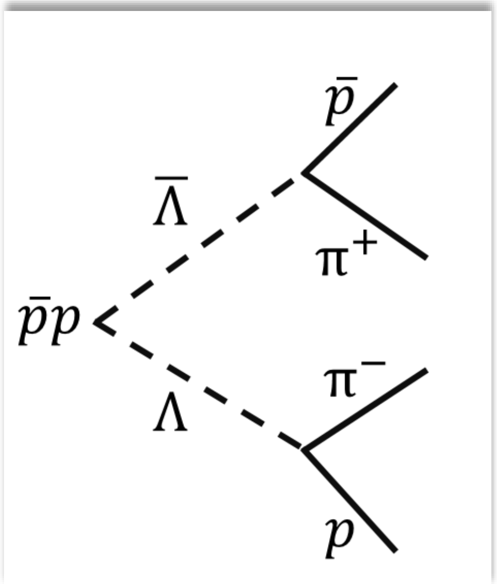




- Overlap between momentum regions of particles – antiparticles at lower p_{beam}
- Clear distinction between momentum regions of particles – antiparticles at larger p_{beam}
- Particles obtain very low p_l at higher p_{beam}
    - Backward in CM system

$\bar{p}p \to \bar{\Lambda}\Lambda$, STT hits / Track

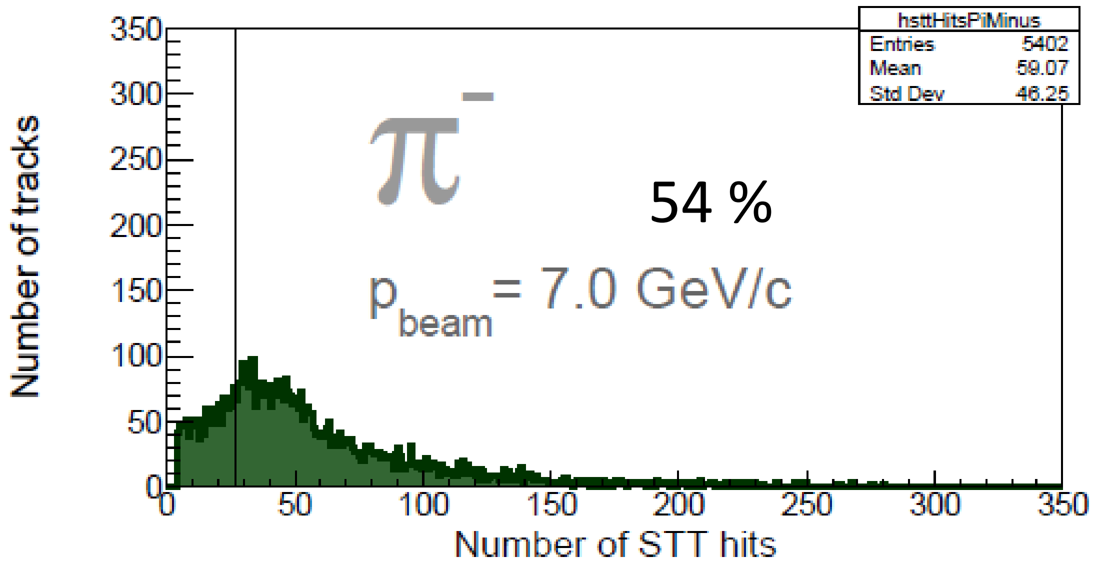


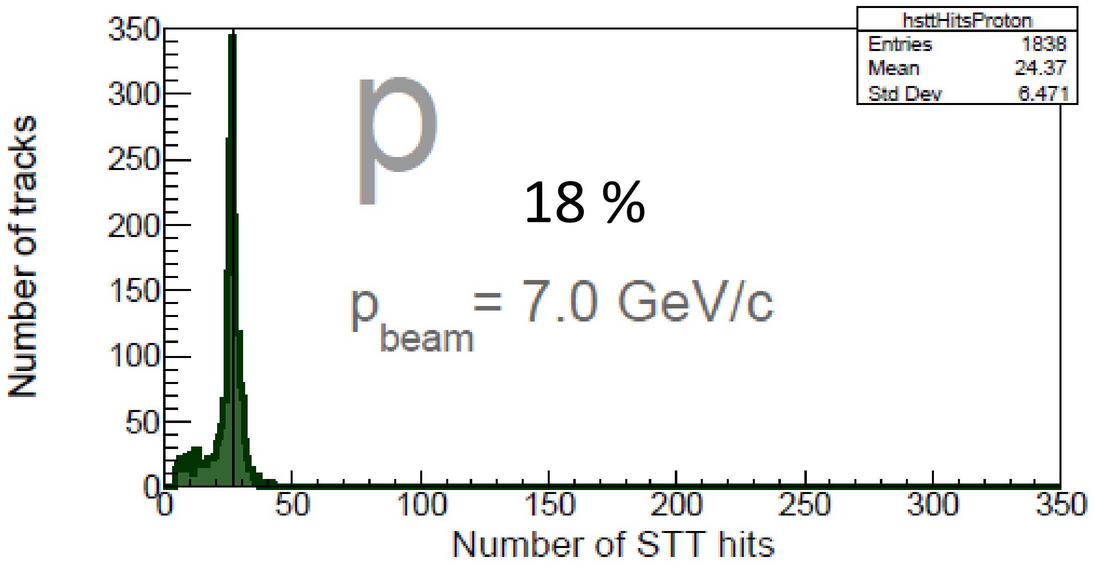


% refers to no. of tracks with ≥ 4 STT hits

→ Good STT coverage for final state particles

$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, STT hits / Track



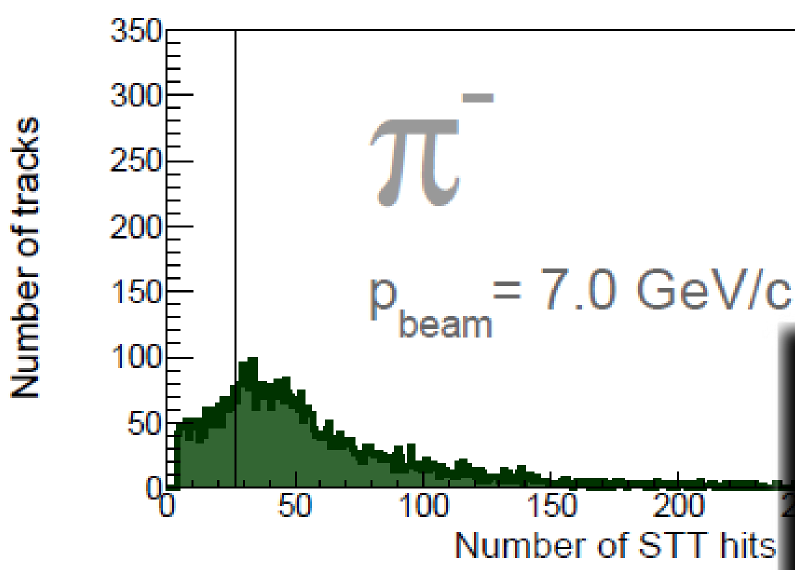


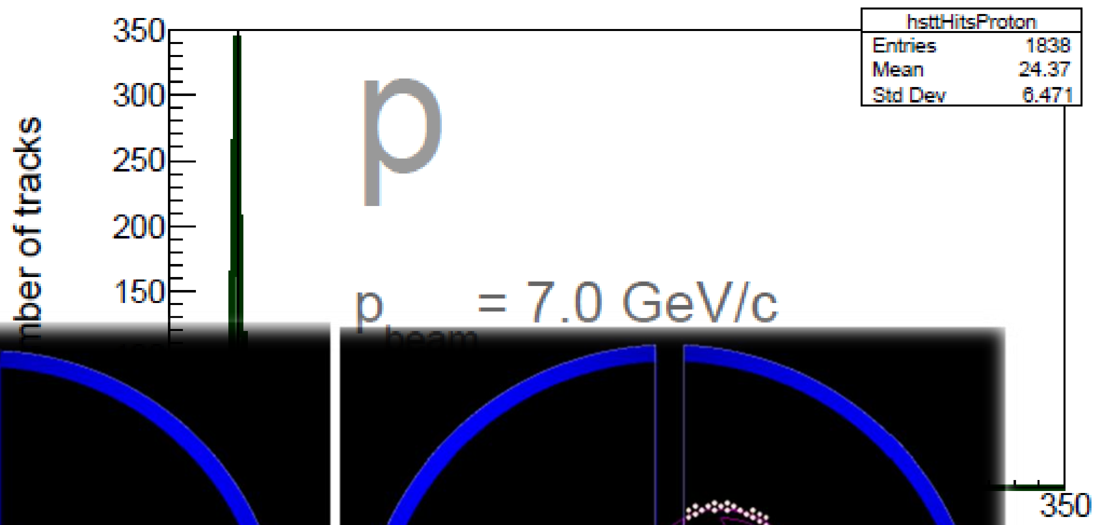
% refers to no. of tracks with ≥ 4 STT hits

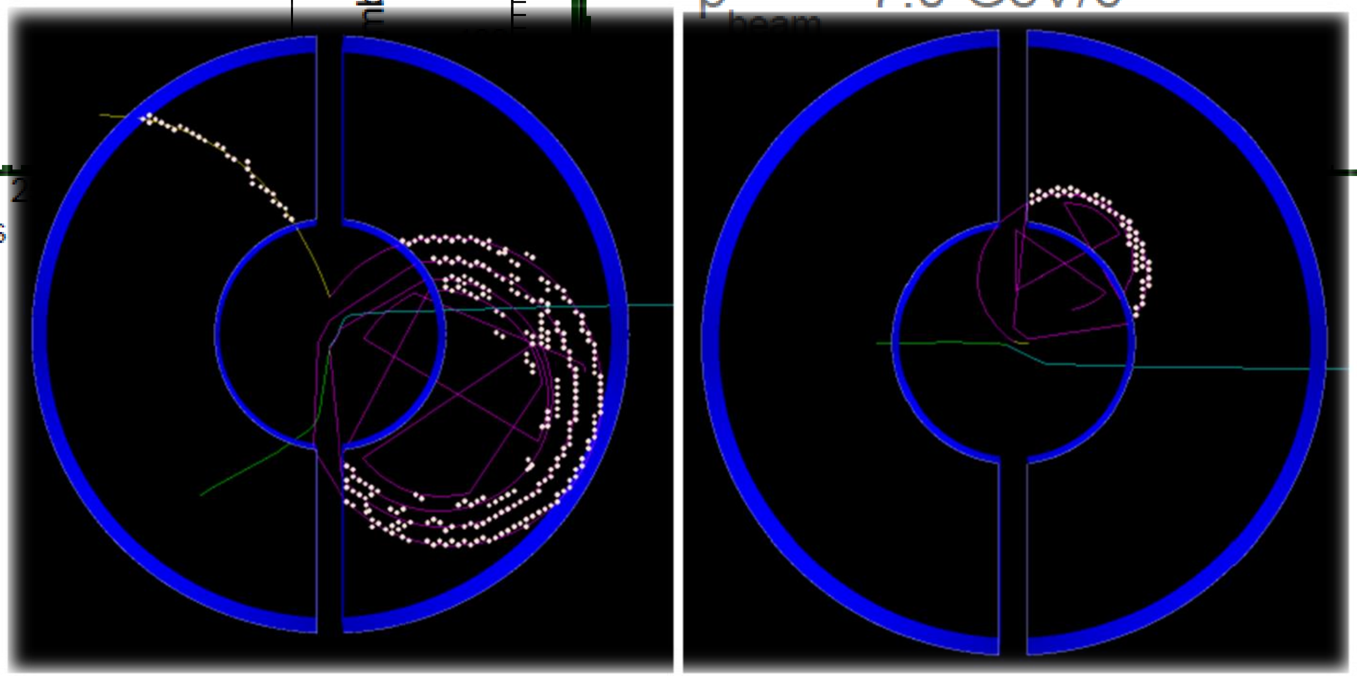
- Long tail at larger number of hits for π^-
  - Indicates spiralling behavior
- Antiparticles going into FS
- Similar at 15 GeV/c

→ Somewhat lower STT coverage for final state particles larger p_{beam}

$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, STT hits / Track

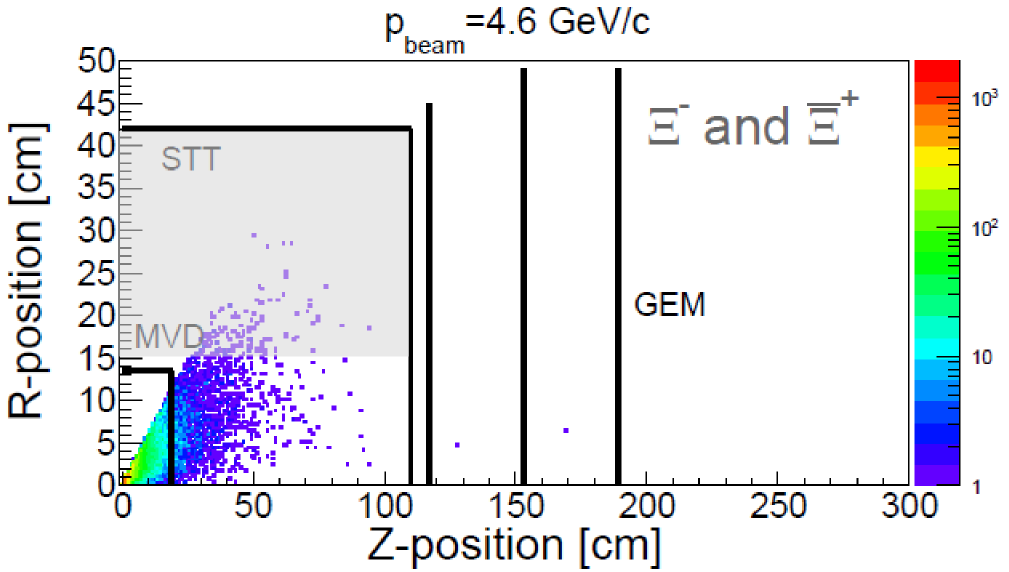


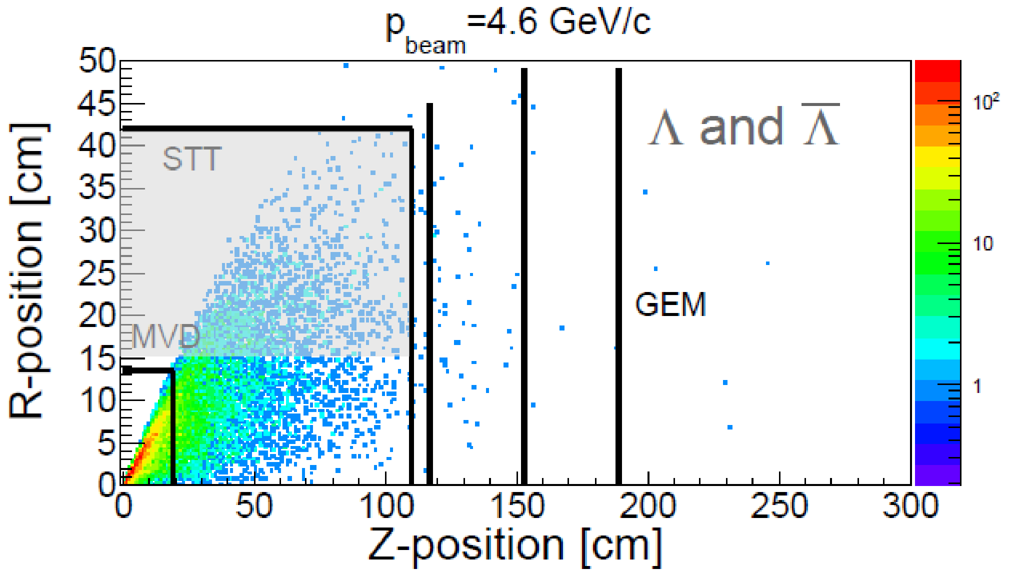


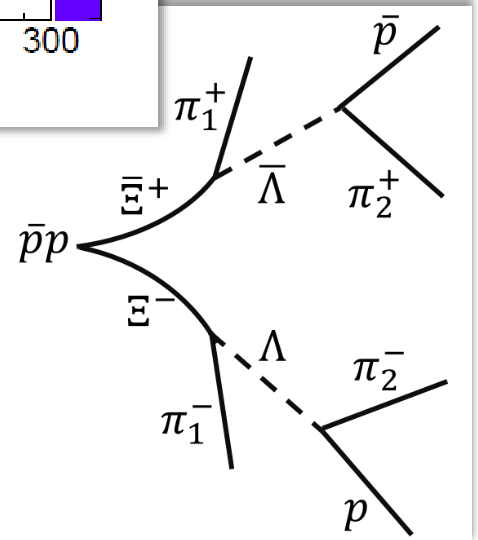


Curling particle trajectories:
Very challenging to reconstruct
Can block large parts of detector

$\bar{p}p \rightarrow \bar{\Xi}^{+}\Xi^{-}$





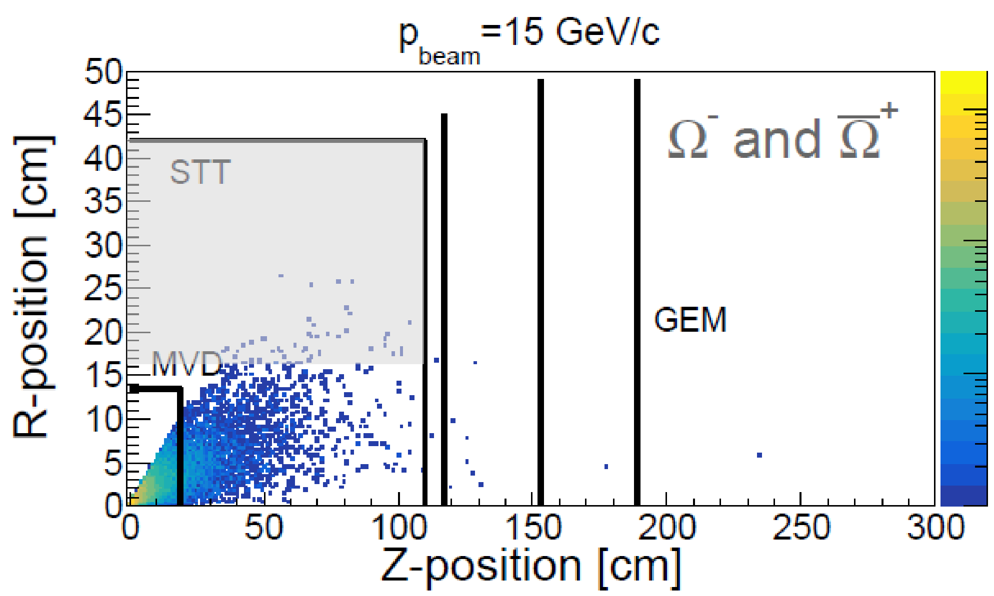


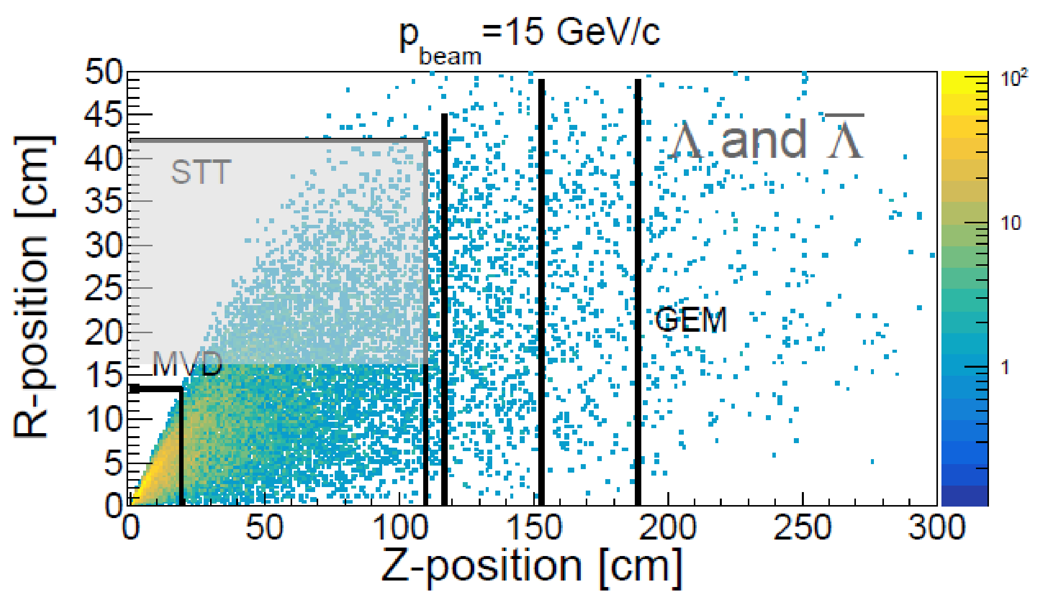
Particle type	% with ≥ 4 STT hits	Particle type	% with ≥ 4 STT hits
p	80	$\bar{p}$	79
π_1^-	67	π_1^+	67
π_2^-	62	π_2^+	62

- Most decay vertices within STT volume
- Many decay vertices within MVD volume

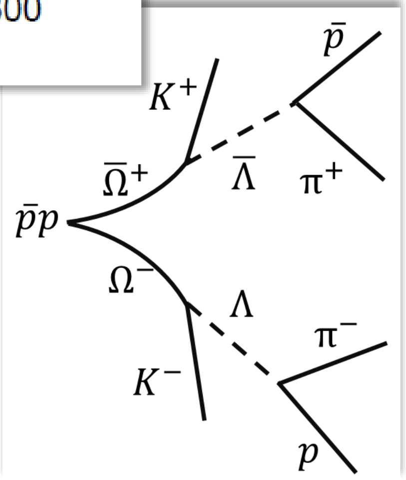
- Very good STT coverage for all final state particles

$\bar{p}p \rightarrow \bar{\Omega}^{+}\Omega^{-}$





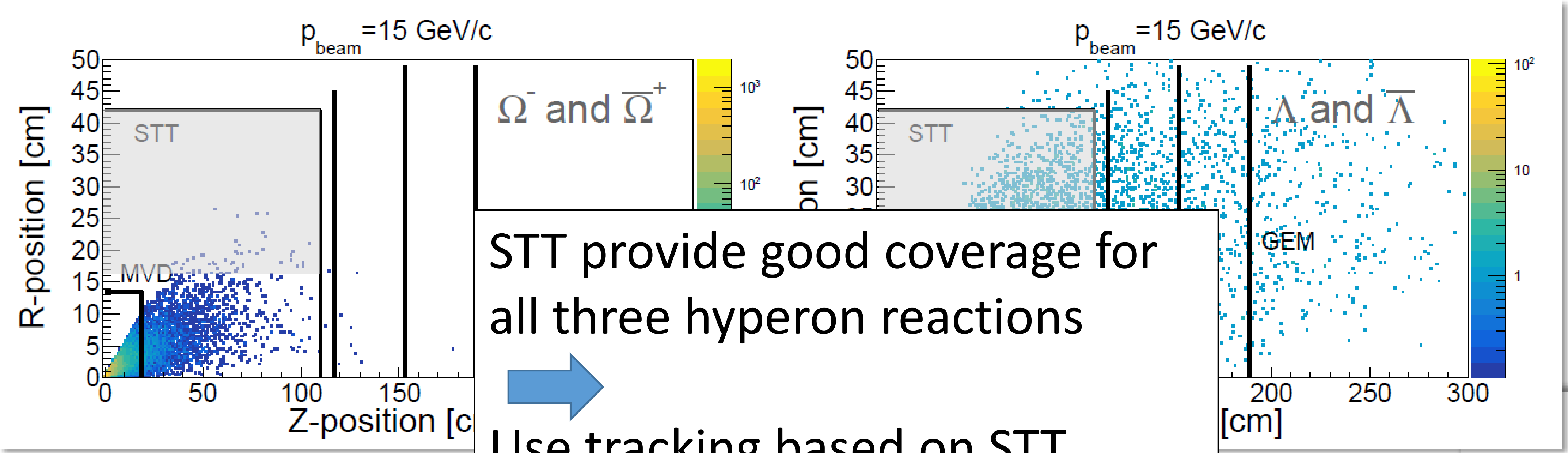
Particle type	% with ≥ 4 STT hits	Particle type	% with ≥ 4 STT hits
p	63	$\bar{p}$	61
π^-	56	π^+	55
K^-	63	K^+	63



- Most decay vertices within STT
- Many decay vertices within MVD
- Most in in forward (downstream) direction

- Very good STT coverage for all final state particles

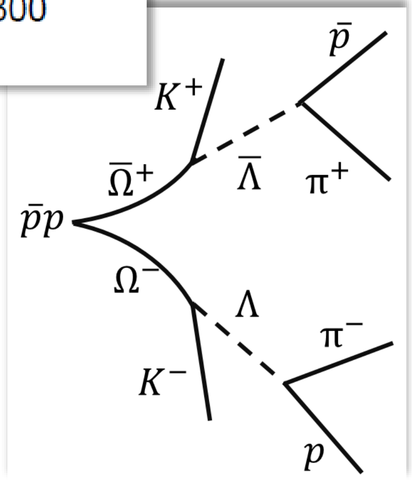
$\bar{p}p \to \bar{\Omega}^+\Omega^-$



STT provide good coverage for all three hyperon reactions

→ Use tracking based on STT

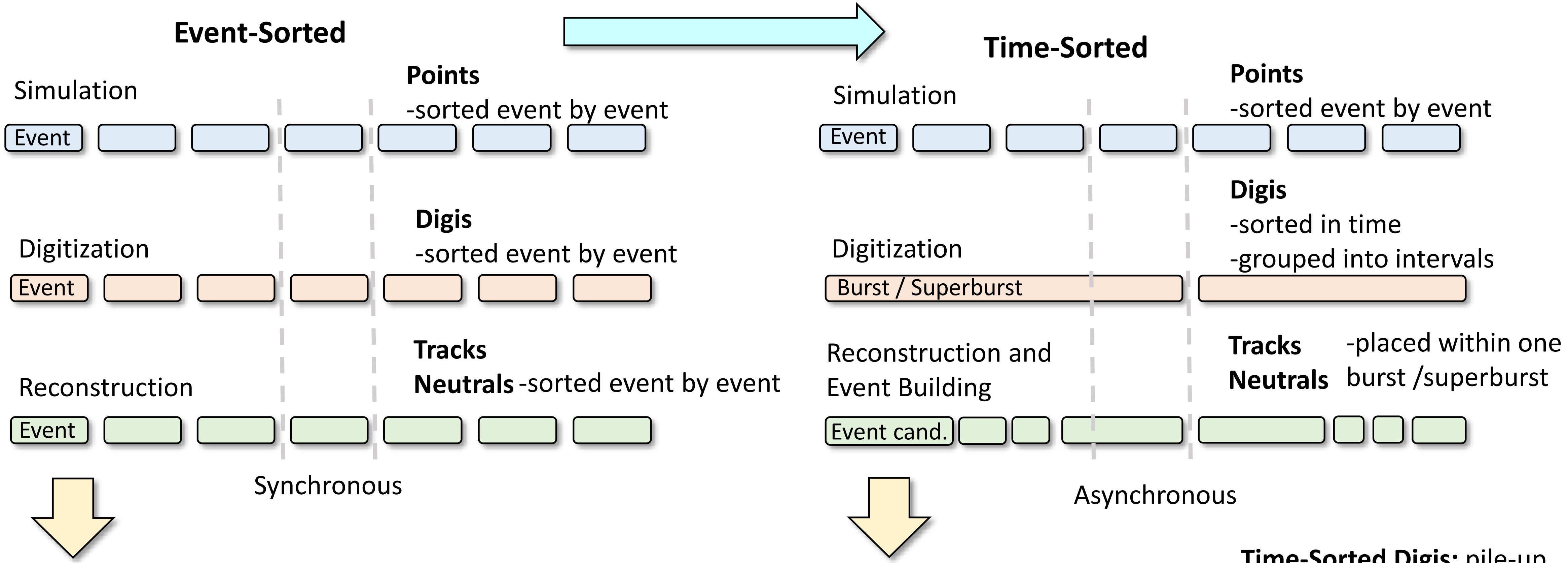
Particle type	% with ≥ 4 STT hits	Particle type	% with ≥ 4 STT hits
p	63	$\bar{p}$	61
π^-	56	π^+	55
K^-	63	K^+	63



- Most decay vertices within STT
- Many decay vertices within MVD
- Most in in forward (downstream) direction

- Very good STT coverage for all final state particles

Event-Sorted to Time-Sorted Data



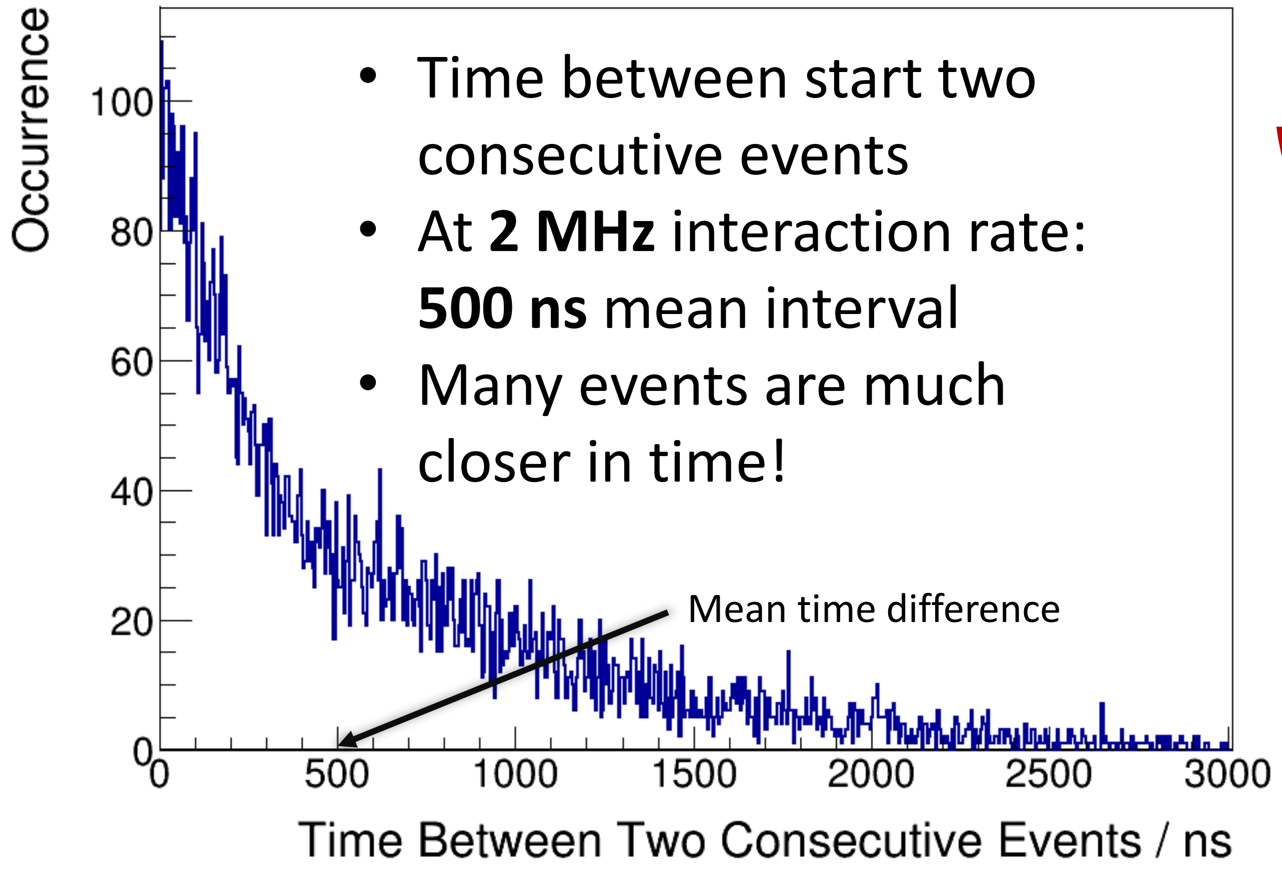
Data synchronous from reco. level passed to analysis

Data synchronous from reco. level passed to software trigger and analysis

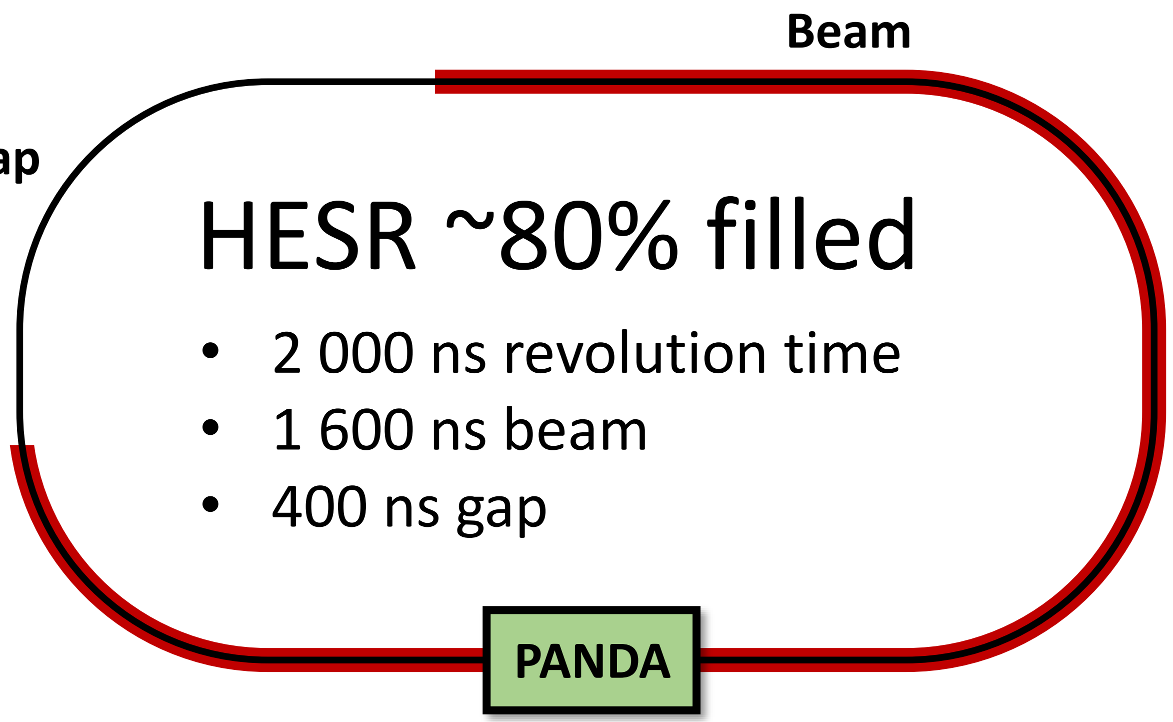
Time-Sorted Digis: pile-up between events, no prior knowledge which event a digi belongs to

Time Structure of Beam

High **E**nergy **S**torage **R**ing



- Time between start two consecutive events
- At **2 MHz** interaction rate: **500 ns** mean interval
- Many events are much closer in time!



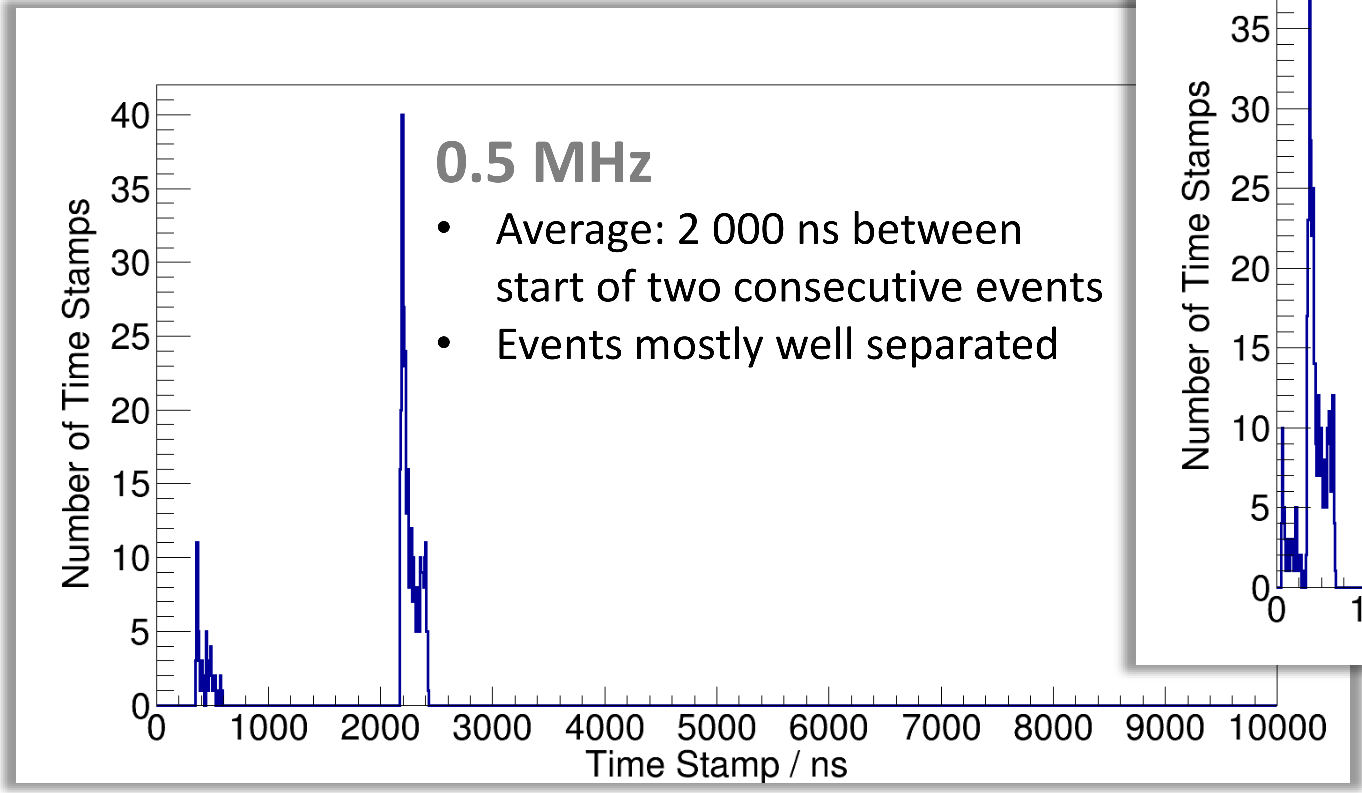
HESR ~80% filled

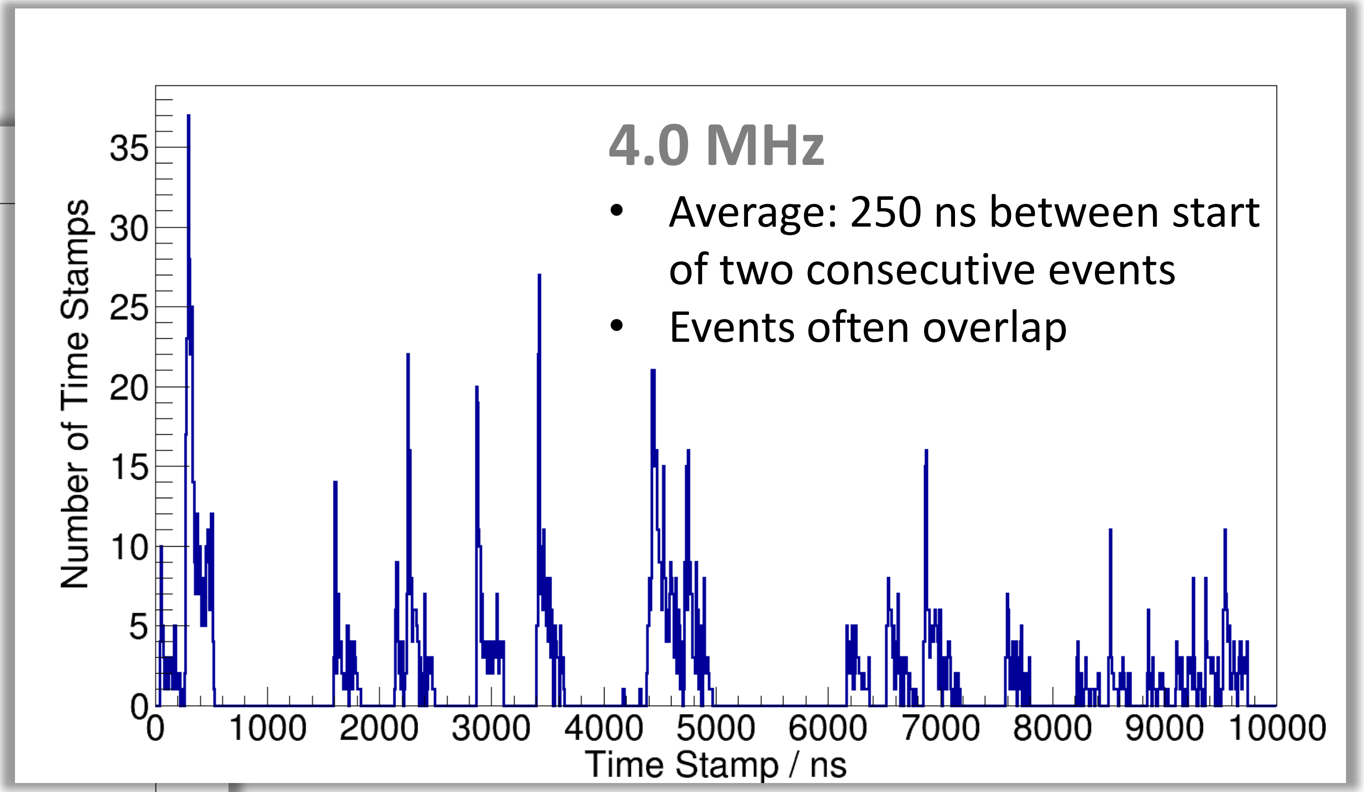
- 2 000 ns revolution time
- 1 600 ns beam
- 400 ns gap

- Natural data bunches of 2 000 ns
- Event mixing within data bunches
- Need to disentangle tracks belonging to different events

Time Distribution

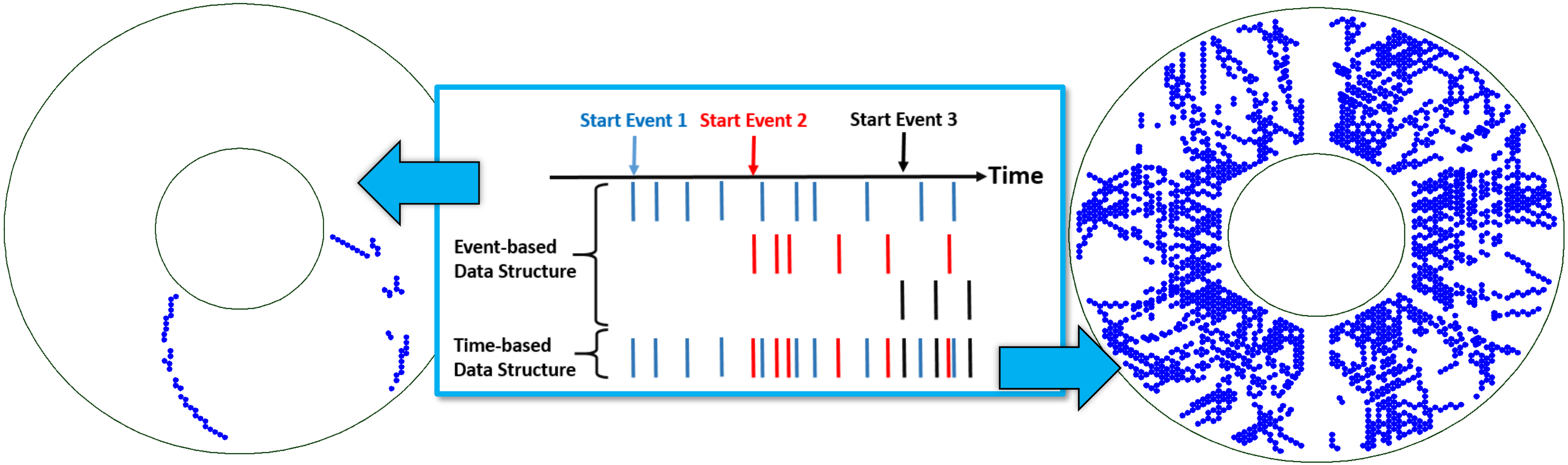
Relevant range of interaction rates for Phase1: **0.5 – 4.0 MHz**





Event mixing also occur but to smaller extent at lower interaction rate!

Event Mixing in the Straw Tube Tracker



- One event
- Almost possible to find tracks by eye using spatial neighborhood relations

- Event mixing (40 events)
- Not possible to cluster track hits by only spatial neighborhood relations

➡ 4D tracking!

Cellular Automaton Hit Clusterization

Algorithm developed by J. Schumann [1]
Time-based modifications by J. Regina

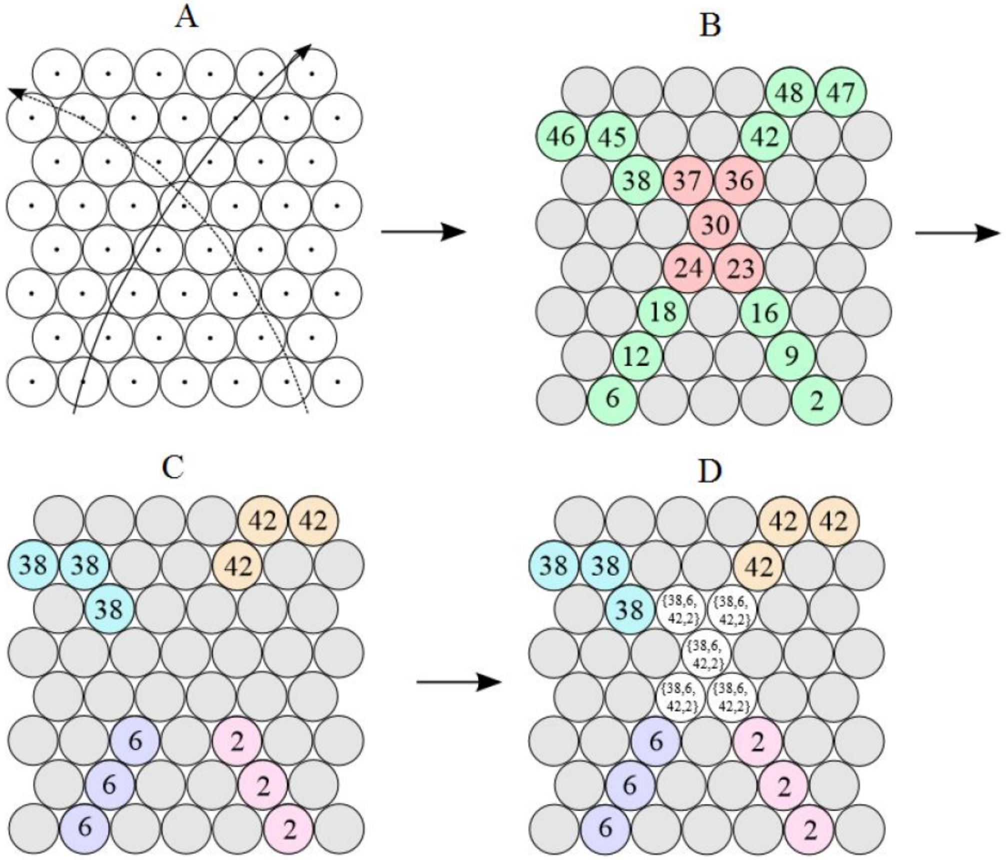
A. Tracks traverse STT
B. Hit tubes are numbered
C. Unambiguous hits are iteratively renumbered until hits in one cluster have same number
D. Ambiguous hits are given all numbers possible

Parallelizable
- Implemented on GPUs
- Candidate for online usage

Does not use IP as constraint
- Suitable for reconstructing secondary tracks
- Will be used following a primary track finder

≥ 3 STT hits required

4D tracking: hits can only be combined if timestamps < 250 ns (or certain set value)



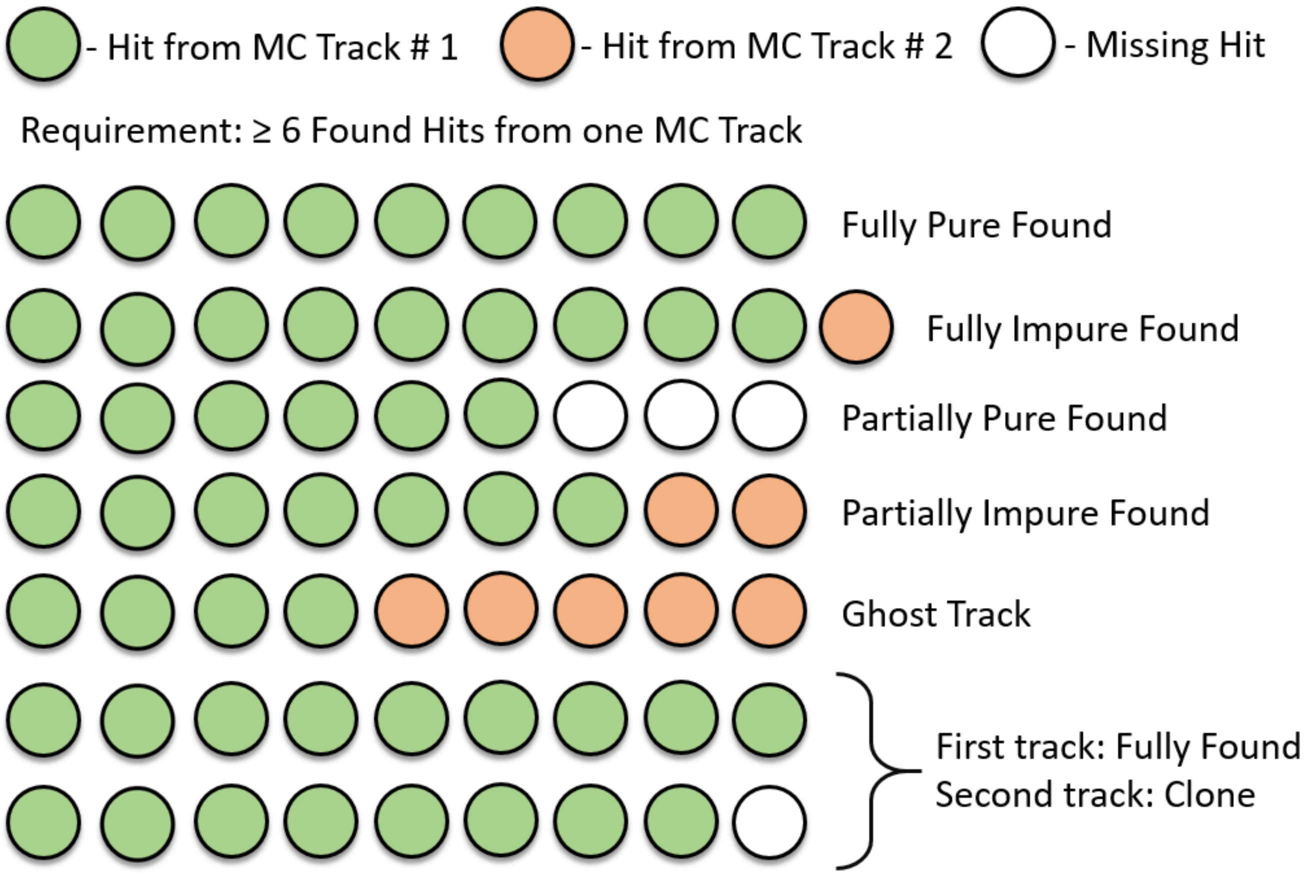
[1] Jette Shumann, *Entwicklung eines schnellen Algorithmus zur Suche von Teilchenspuren im "Straw Tube Tracker" des PANDA-Detectors*, Bachelor Thesis, 2013

Tracking Quality Assurance

- **Q**uality **A**ssurance (QA) for tracking algorithms
- Momentum resolutions
- Number of *true*, *false* and *missing* hits / track
- Track Categories

- To give ***fair*** representation of tracking algorithm:
  - compare to only tracks which could be reconstructed in relevant detectors
- <u>Reference track set:</u> ***ideally*** reconstructed with certain hit requirement
- ***True MC track*** is defined as the one which gave rise to the majority of hits the reconstructed track

Track Categories



Fully Purely found
- All and only true hits found

Fully Impurely found
- All hits from one track found
- Impurities allowed up to 30% of all hits in reco track

Partially Purely found
- Majority of found hits belong to same MC track
- Not all hits of MC track found
- Impurities not allowed

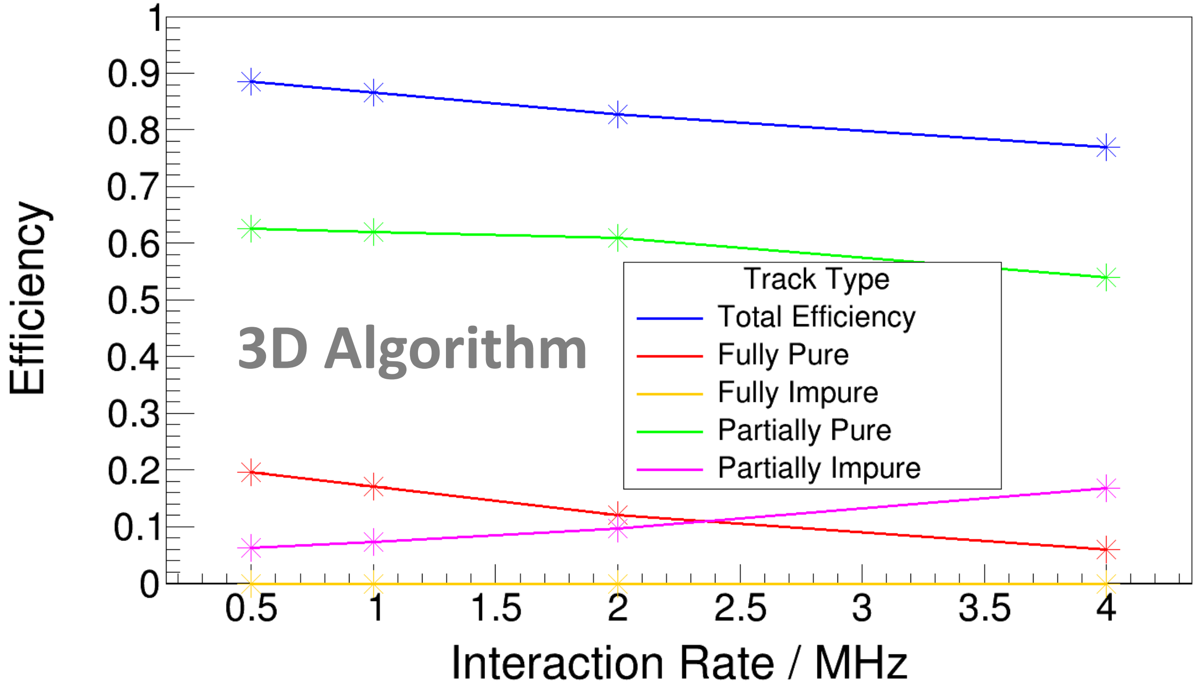
Partially Impurely found
- >70% of all hits belong to one MC Track
- Not all hits of MC track found
- Impurities allowed

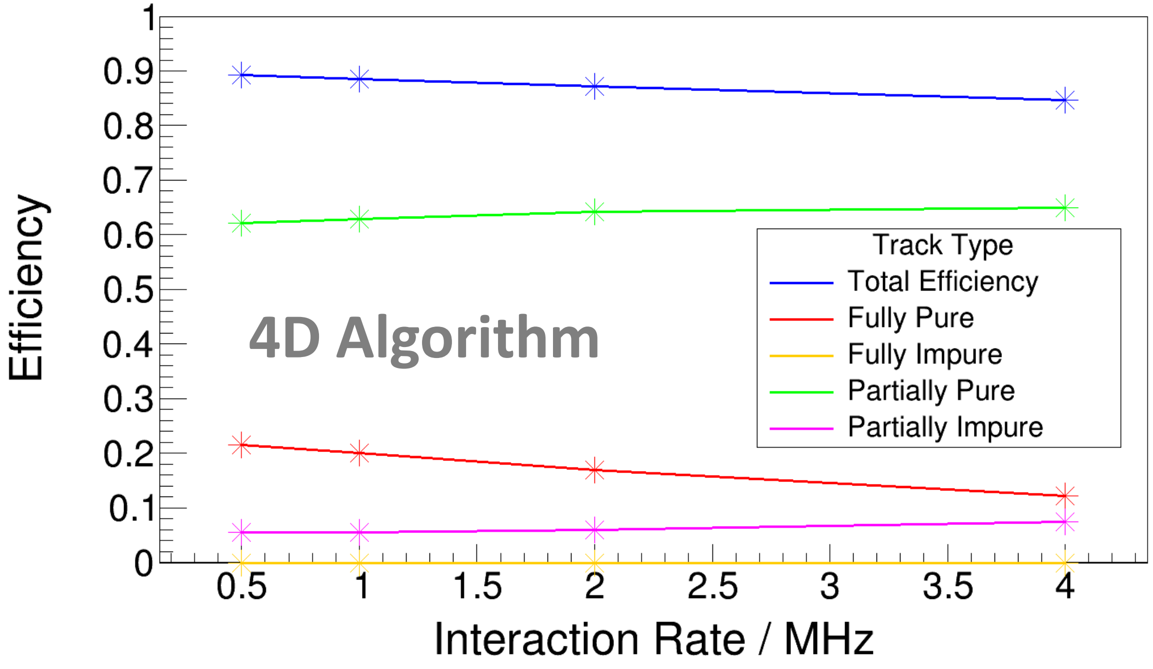
Ghosts
- Reco track does not correspond to a MC track

Clones
- One track was found more than once

Efficiencies
– Time-Based Reconstruction

- $\bar{p}p$ background reactions
- p_{beam} = 6.2 GeV/c





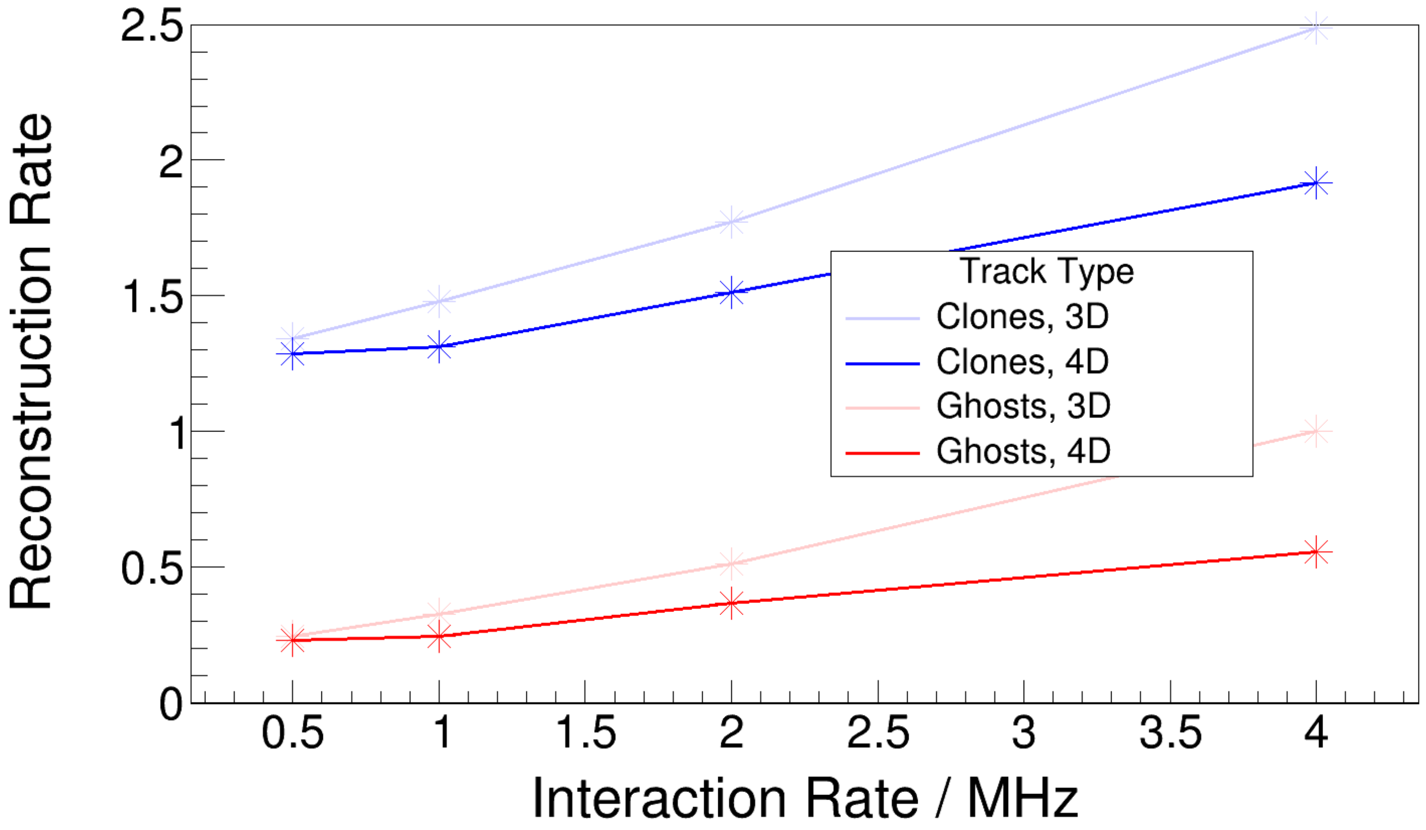
- **Total efficiencies stable** over relevant range of interaction rates
- At lower interaction rates time-stamps do not have dramatic effects
- At higher interaction rates time-stamps lead to higher efficiencies

$n_{possible}$ ~ 2 670

Requirement: ≥ 6 STT hits

$$eff = \frac{n_{found}}{n_{possible}}$$

Fake Rate
– Time-Based Reconstruction

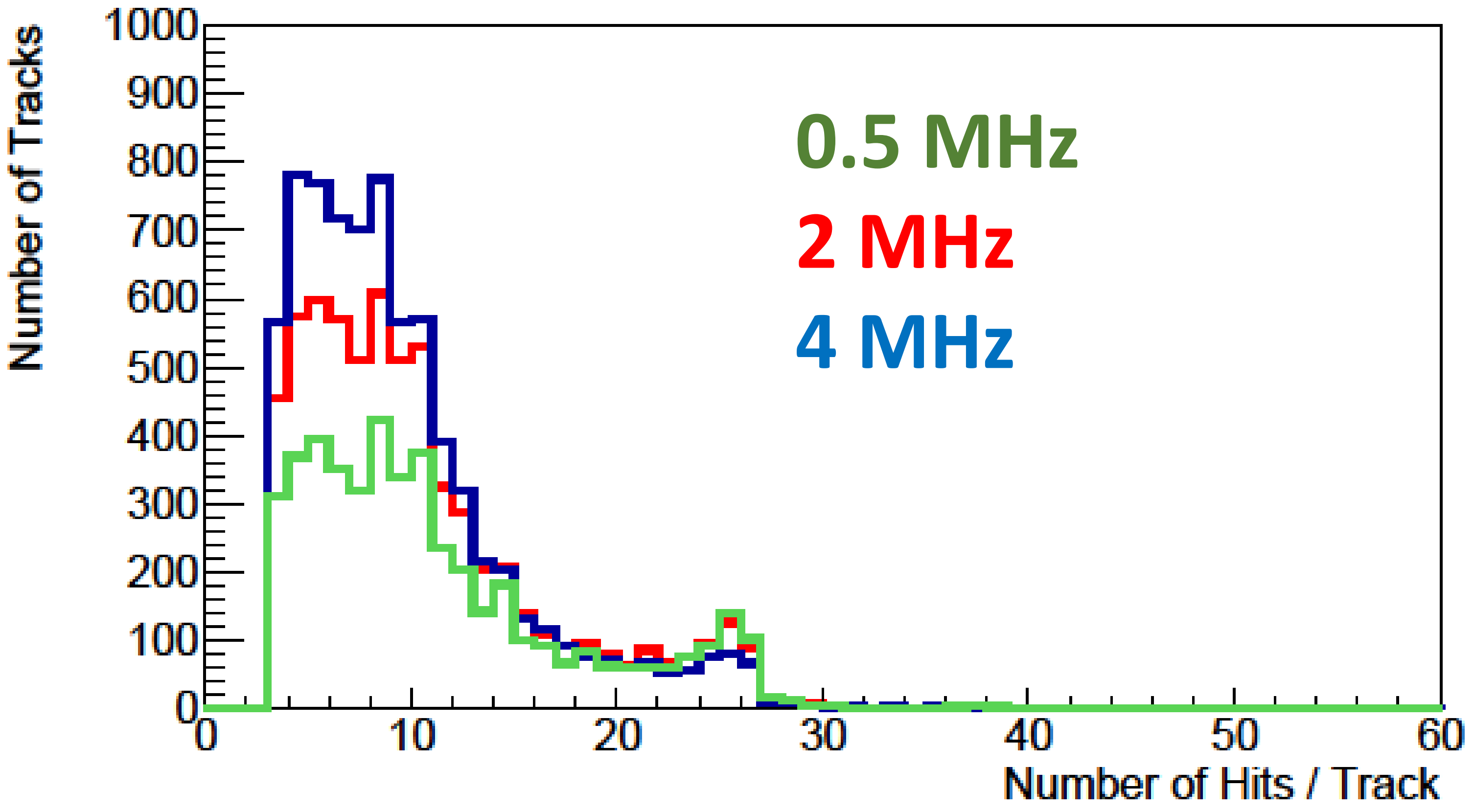


Ghost Rate$= \frac{n_{ghosts}}{n_{possible}}$

Clone Rate$= \frac{n_{clones}}{n_{possible}}$

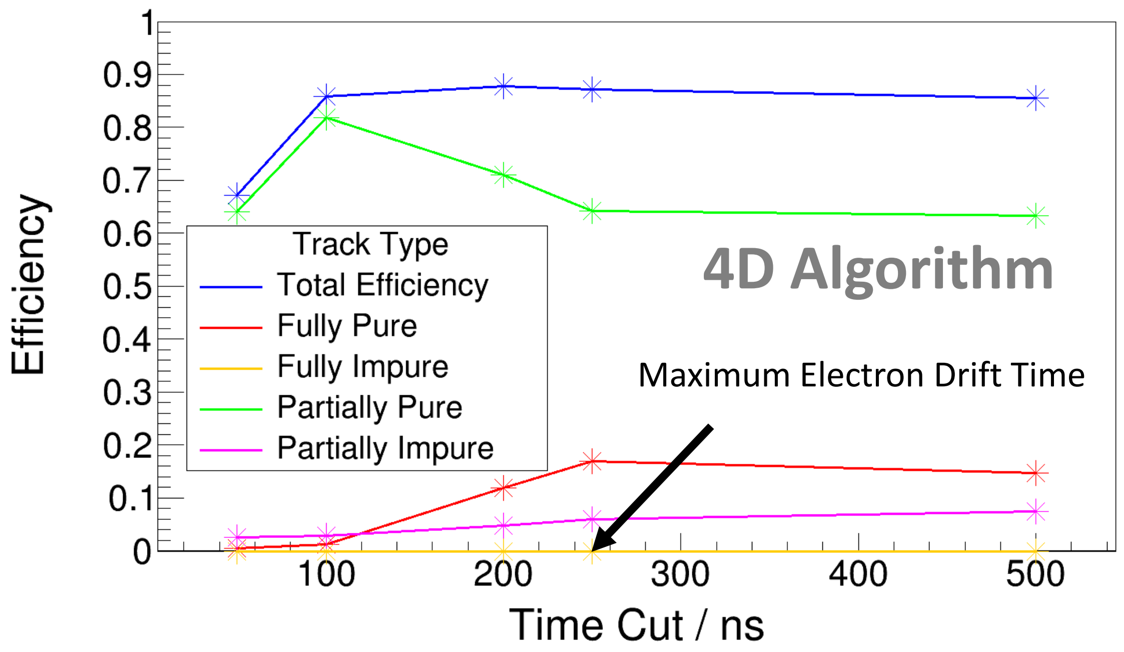
- High fake rates, especially clones, at all interaction rates
- Increase in fake rate is more dramatic with 3D tracking
- Time-stamp inclusion reduces fake rate with orders of magnitude at higher interaction rates

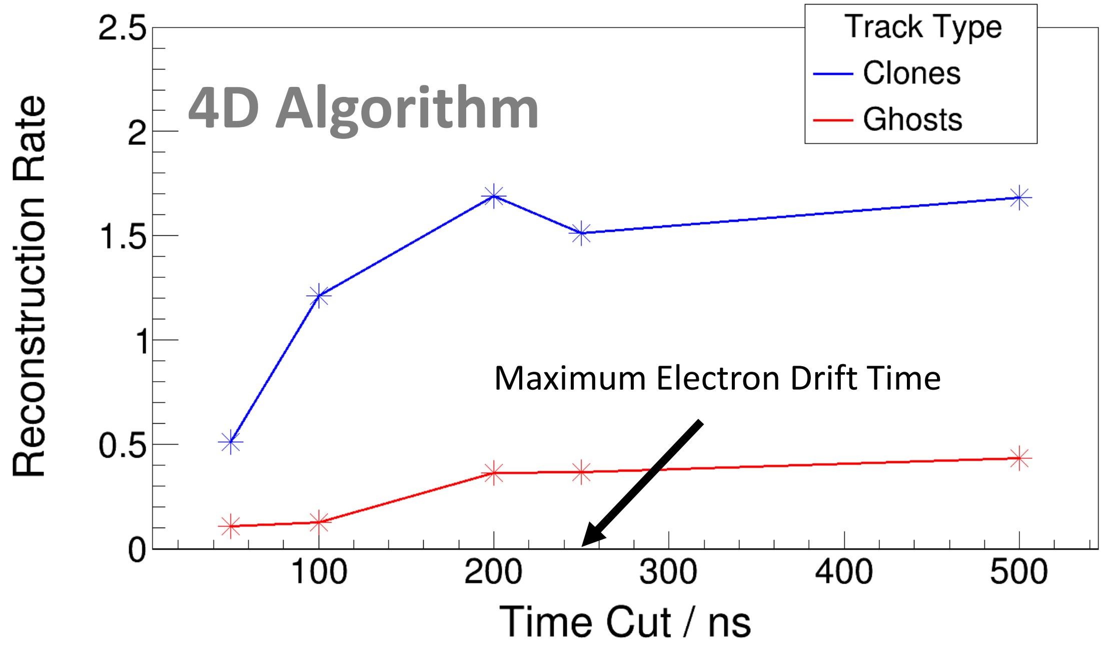
Hits per Track



- Pattern resembles characteristic STT hit distribution at all interaction rates
- Tracks reconstructed in shorter tracklets at higher interaction rates
- More tracks at higher interaction rates

Efficiencies
– Time-Based Reconstruction at 2.0 MHz





$n_{possible}$~ 2 670

Requirement: ≥ 6 STT hits

$$eff = \frac{n_{found}}{n_{possible}}$$

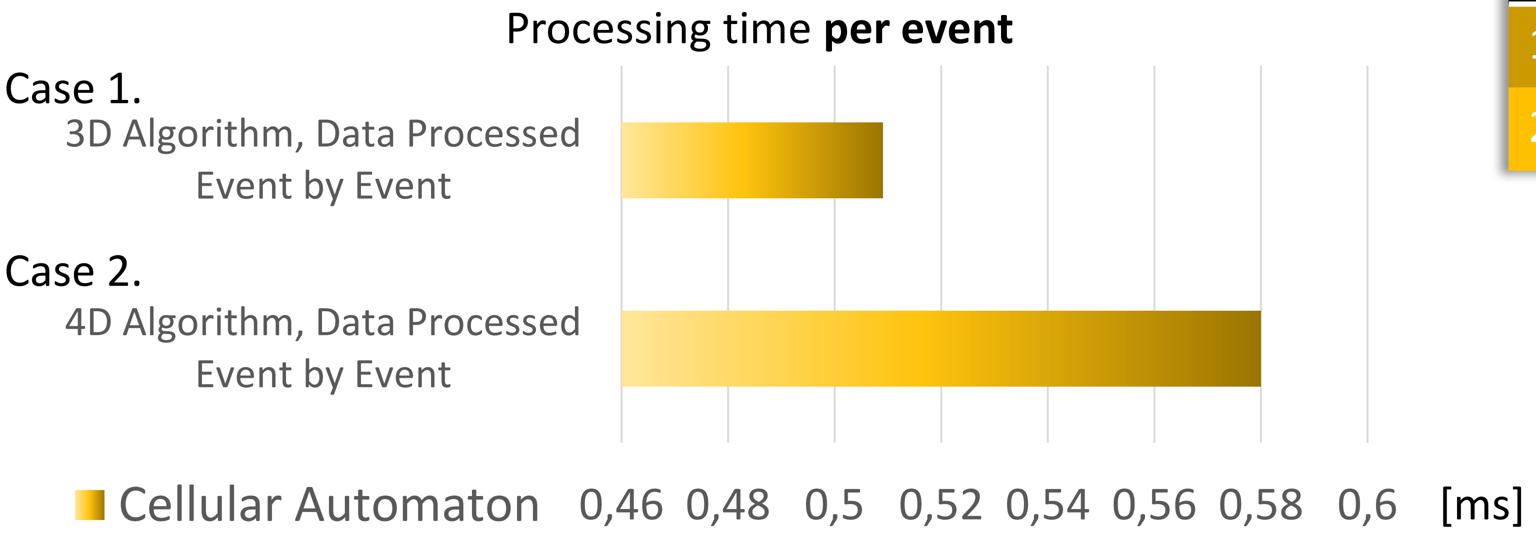
Tightening the time-cut:

1) greatly decreases the clone rate
2) Slightly decreases efficiency

$$\text{Ghost Rate} = \frac{n_{ghosts}}{n_{possible}}$$

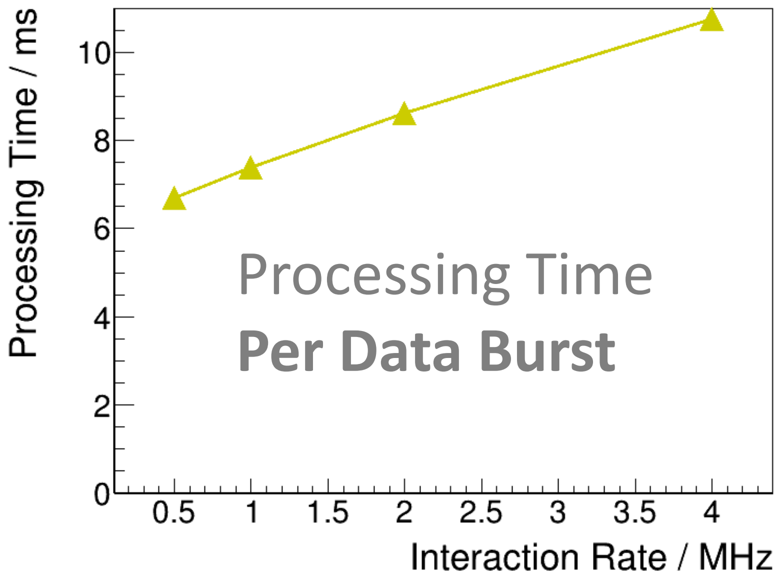
$$\text{Clone Rate} = \frac{n_{clones}}{n_{possible}}$$

Processing Time



Case	Processing time [ms]	% of full reconstruction processing time
1	0,51	5,1
2	0,58	5,8

< 1 % difference



Total processing time (full reconstruction: total track finding + a track fitting): **10 ms / event** on i7 3.4 GHz Processor

Average time / event for 10 000 generated background sample events

Average time / data chunk for 100 chunks containing background events

Track reconstruction performed without a pre-processing event building

Summary

- **Hyperons**
  - Tool for probing QCD at intermediate-lower energy scales
  - Can be reconstructed using STT information at PANDA
- **Cellular Automaton-based hit clusterization**
  - Algorithm can accept time sorted hit data
  - Efficiency stable over interaction rate 0.5-4.0 MHz
  - Time-stamp utilization suppresses fake rate at higher interaction rates

Outlook

- **For PANDA tracking:**
  - Ghost and clone cleanup procedure
  - Try the Cellular Automaton together with primary track finder
  - (= track finder using IP as constraint)
- **For me personally:**
  - Join PANDA phase0 project: PANDA@HADES
  - Hyperon analysis on data
  - Vertex fitting tool + kinematic fitter

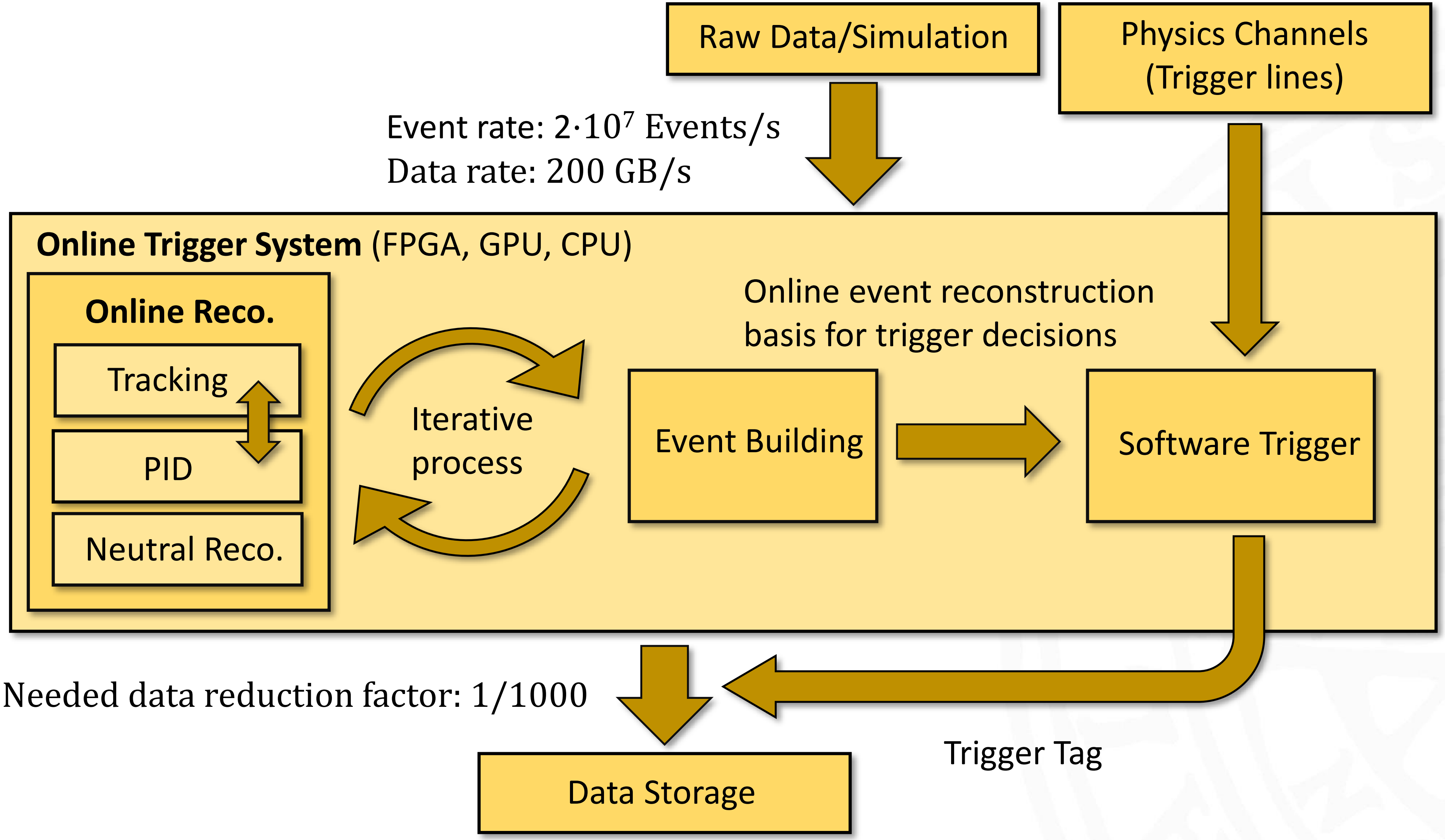
Summary

- **Hyperons**
  - Tool for probing QCD at intermediate-lower energy scales
  - Can be reconstructed using STT information at PANDA
- **Cellular Automaton-based hit clusterization**
  - Algorithm can accept time sorted hit data
  - Efficiency stable over interaction rate 0.5-4.0 MHz
  - Time-stamp utilization suppresses fake rate at higher interaction rates

Thank You!

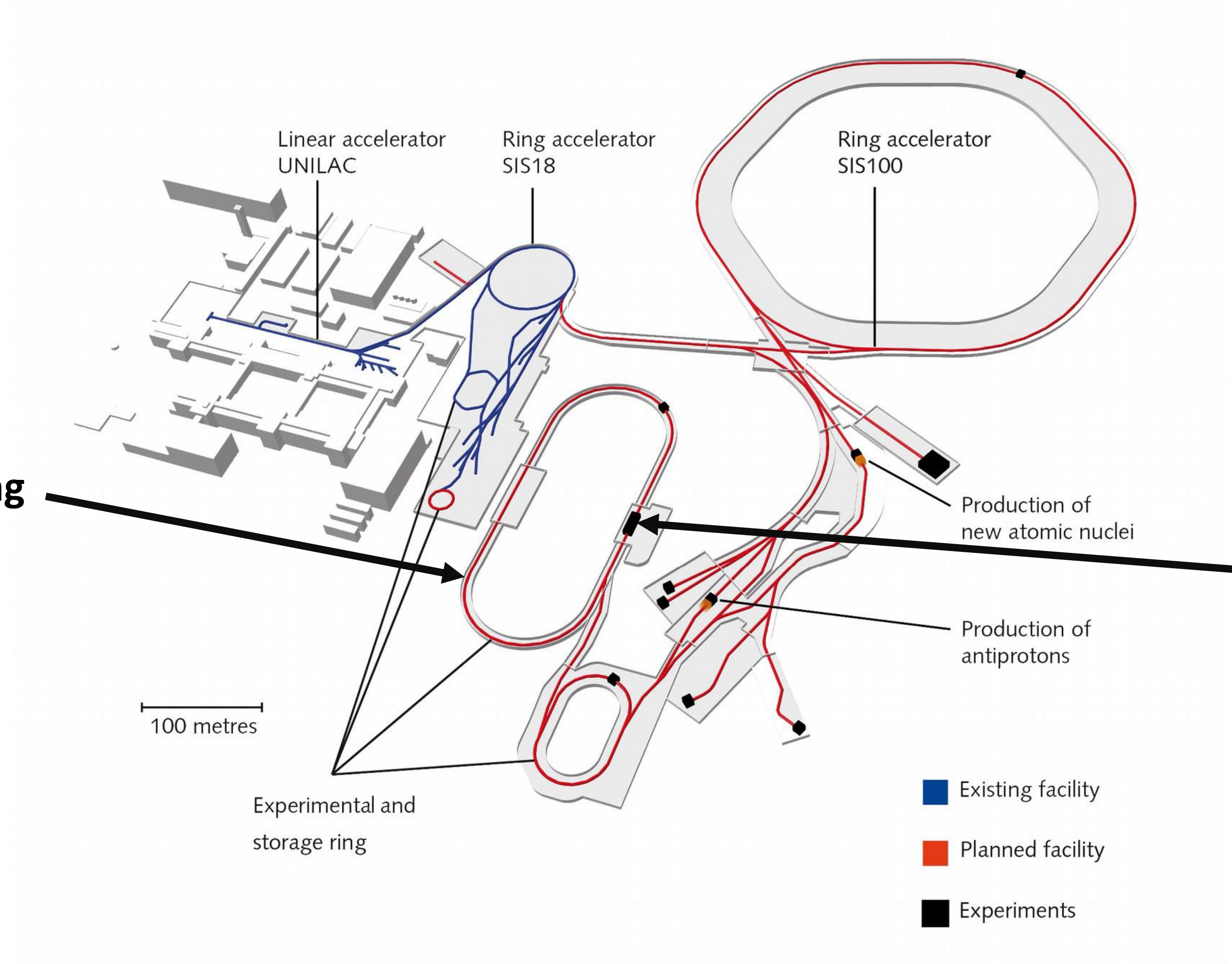
Backup

Software Trigger of PANDA



FAIR – Facility for Anti-proton and Ion Research

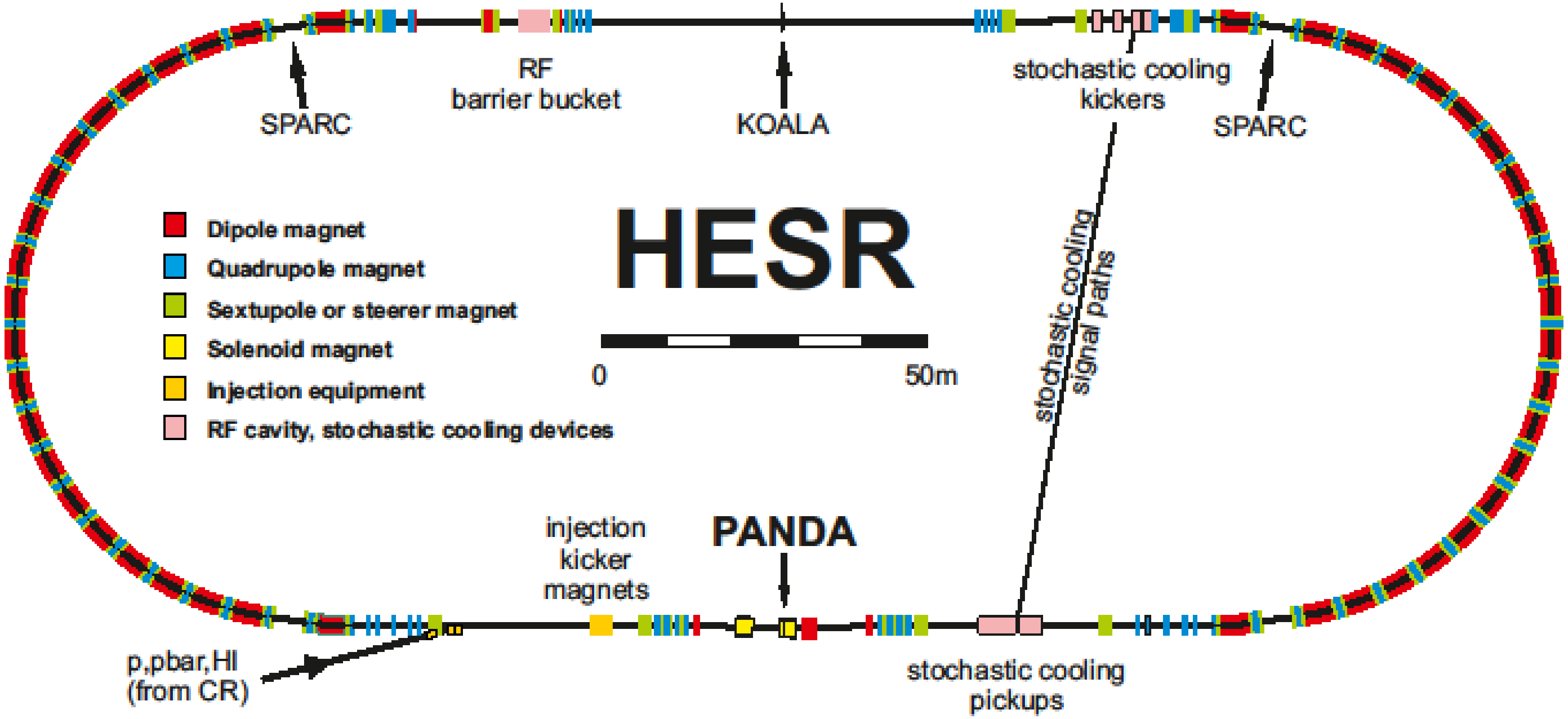
High Energy Storage Ring (HESR)



PANDA

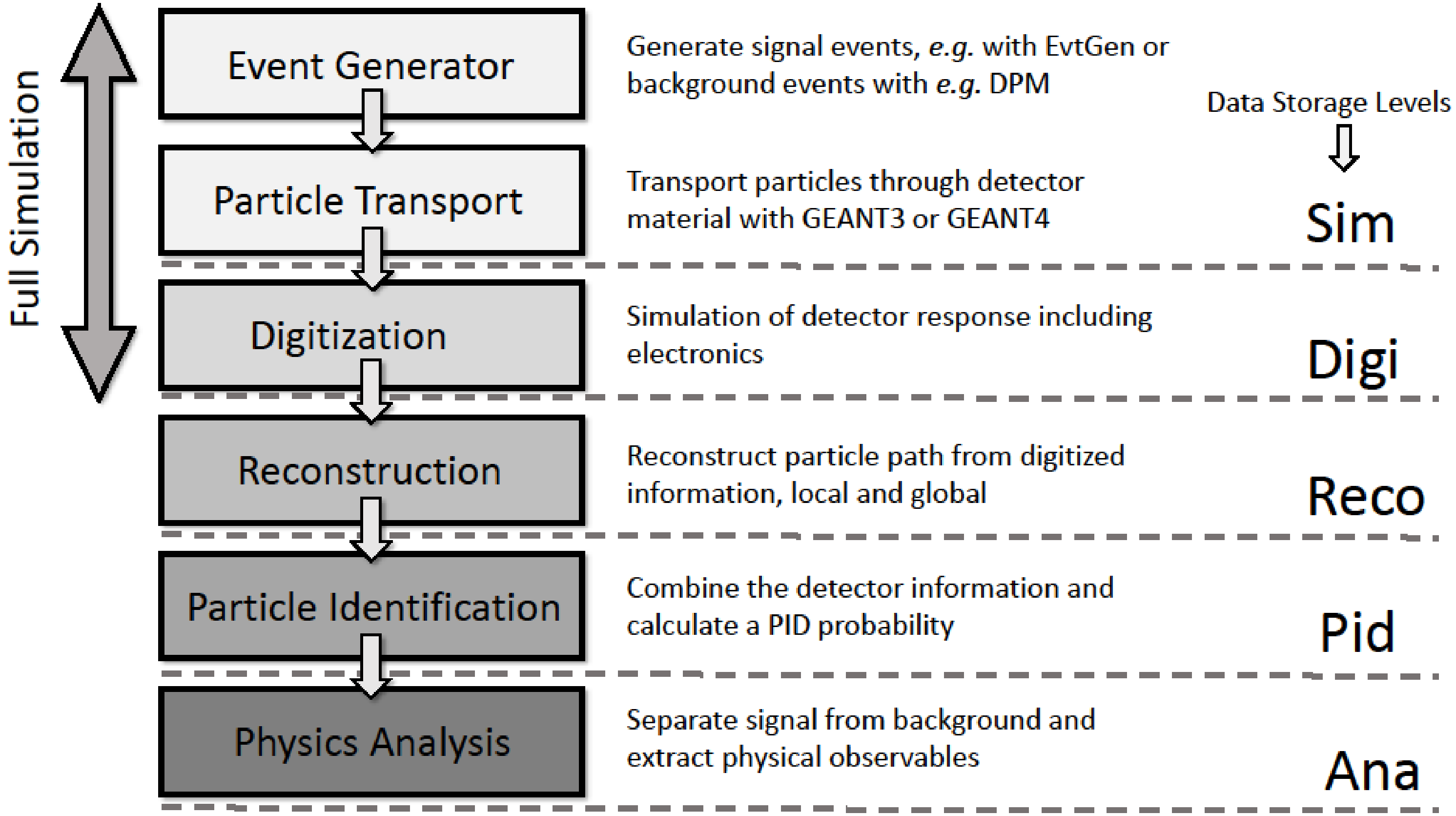
HESR – High Energy Storage Ring

Quasi Continuous Beam:
interaction rate Poisson Distributed



PandaRoot

- Official PANDA software
- Based on ROOT and VMC (Virtual Monte Carlo)



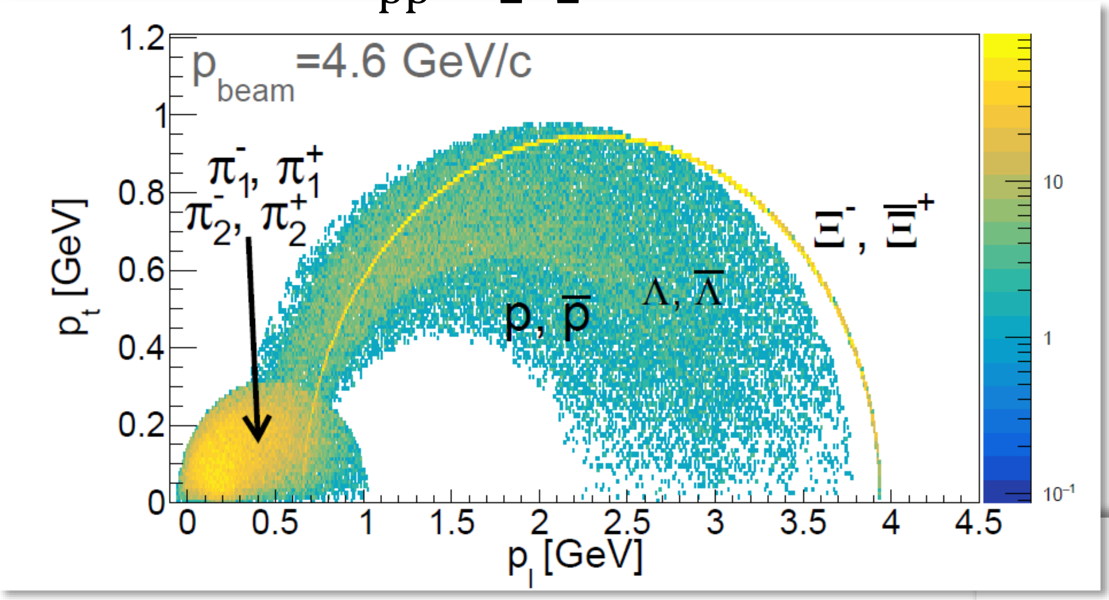
C++

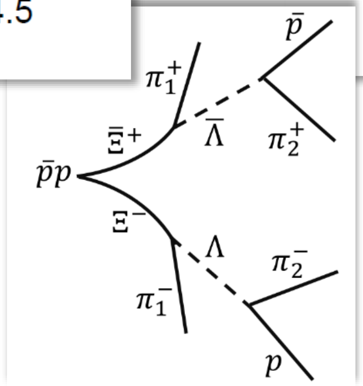
Detector geometry descriptions, event display, track followers *e.g.* Geane ...

Derived from FairRoot common for many FAIR experiments

$\bar{p}p \rightarrow \bar{\Xi}^{+}\Xi^{-}$, $\bar{p}p \rightarrow \bar{\Omega}^{+}\Omega^{-}$, Momentum Distribution

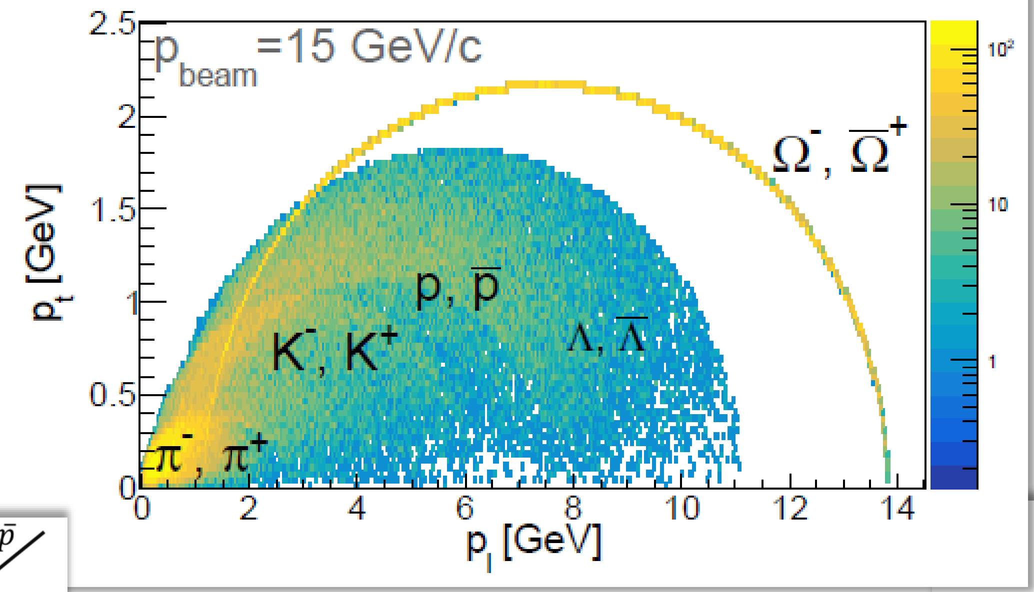
$\bar{p}p \rightarrow \bar{\Xi}^{+}\Xi^{-}$

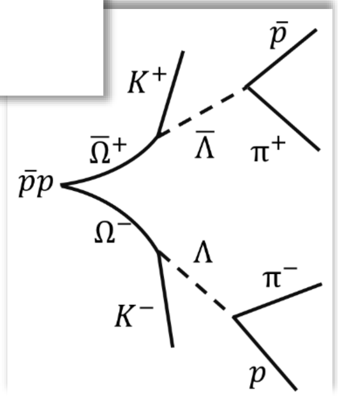




- Overlap between momentum regions of particles – antiparticles
- Pions obtain low momentum

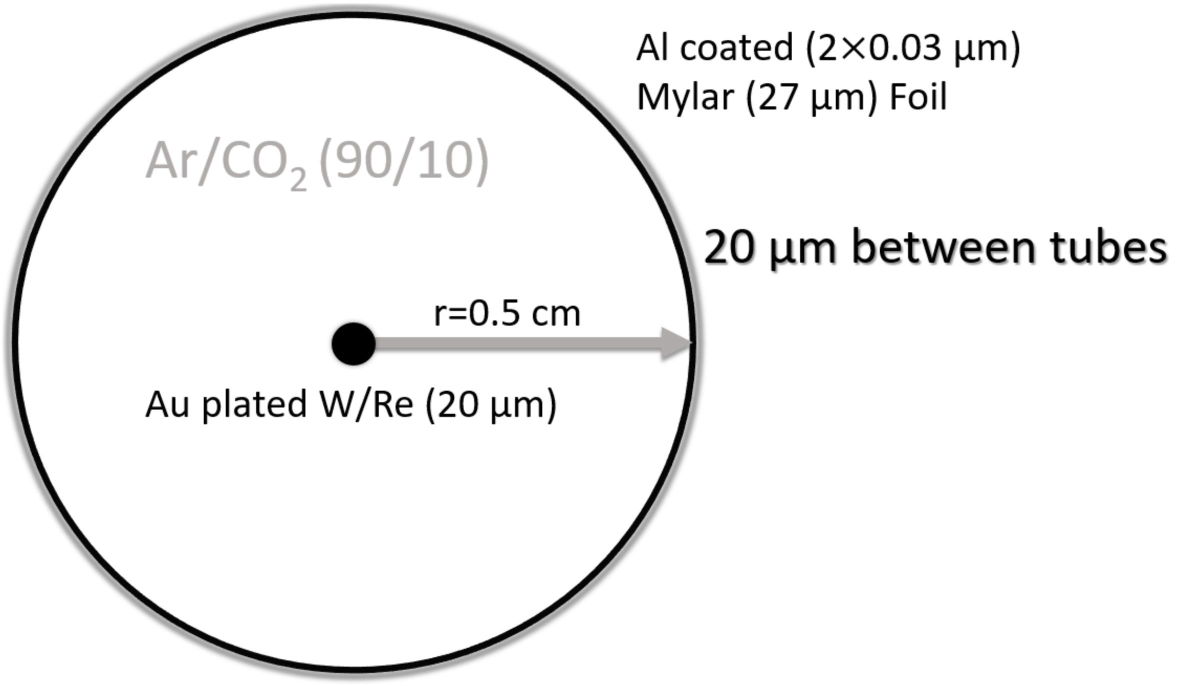
$\bar{p}p \rightarrow \bar{\Omega}^{+}\Omega^{-}$

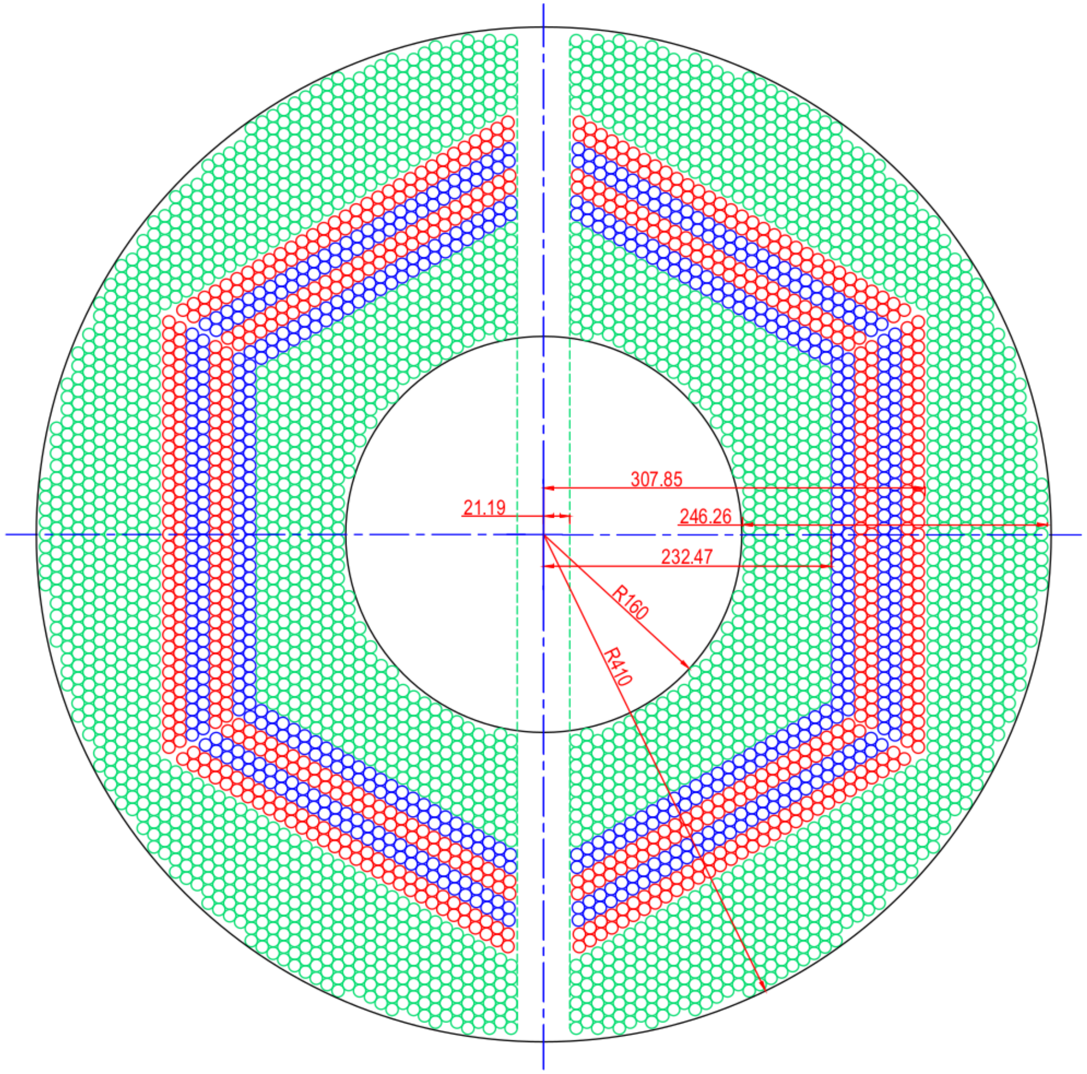




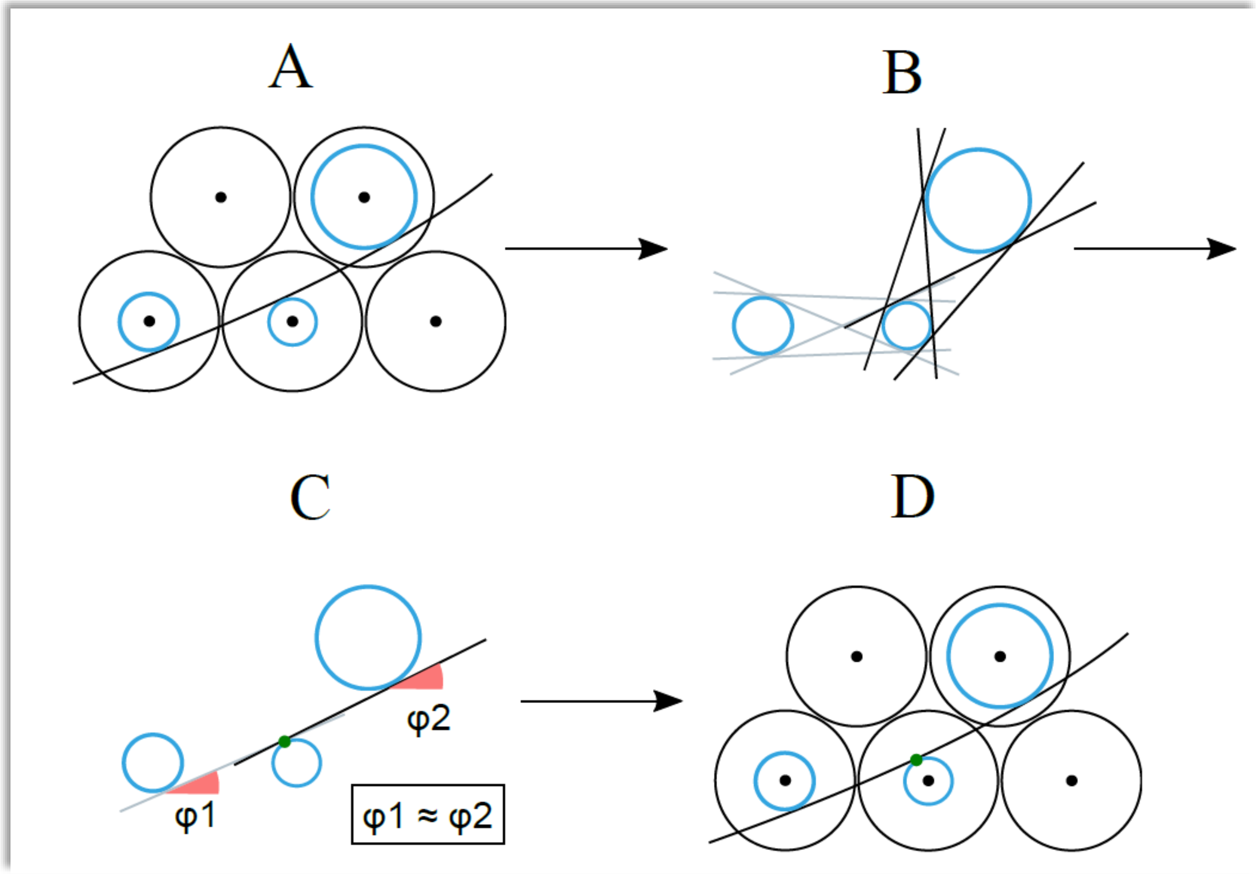
- Overlap between momentum regions of particles – antiparticles
- Pions obtain low momentum

The Straw Tube Tracker (STT) of PANDA





Isochrones in Track Finder

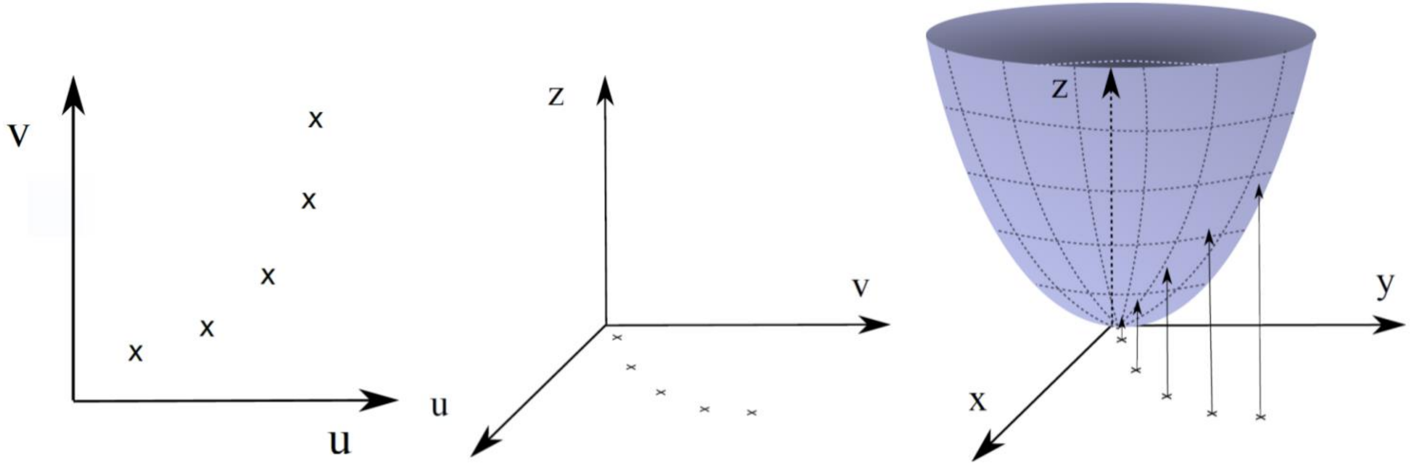


A. Tracks traverse STT
B. Find lines which tangent two adjacent isochrones
C. Obtain angle of all lines. Keep the two lines with smallest difference between angles
D. Position where these lines tangent center isochrone →corrected hit position

Assumption of stright line travel path between two isochrones

The Riemann Fit

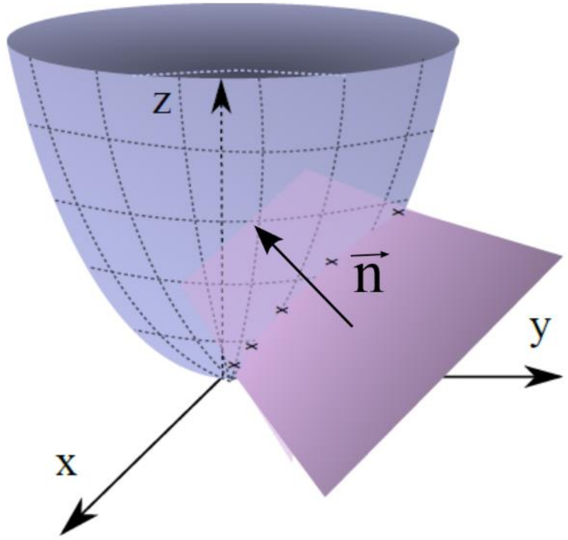
Linearizes track fitting problem -> Fast!



Points to be fitted | Add z-dimension | Map onto paraboloid

For STT, u=x, v=y

$z=x^2+y^2$



Calculation of plane through 3D points
simple eigenvalue determination

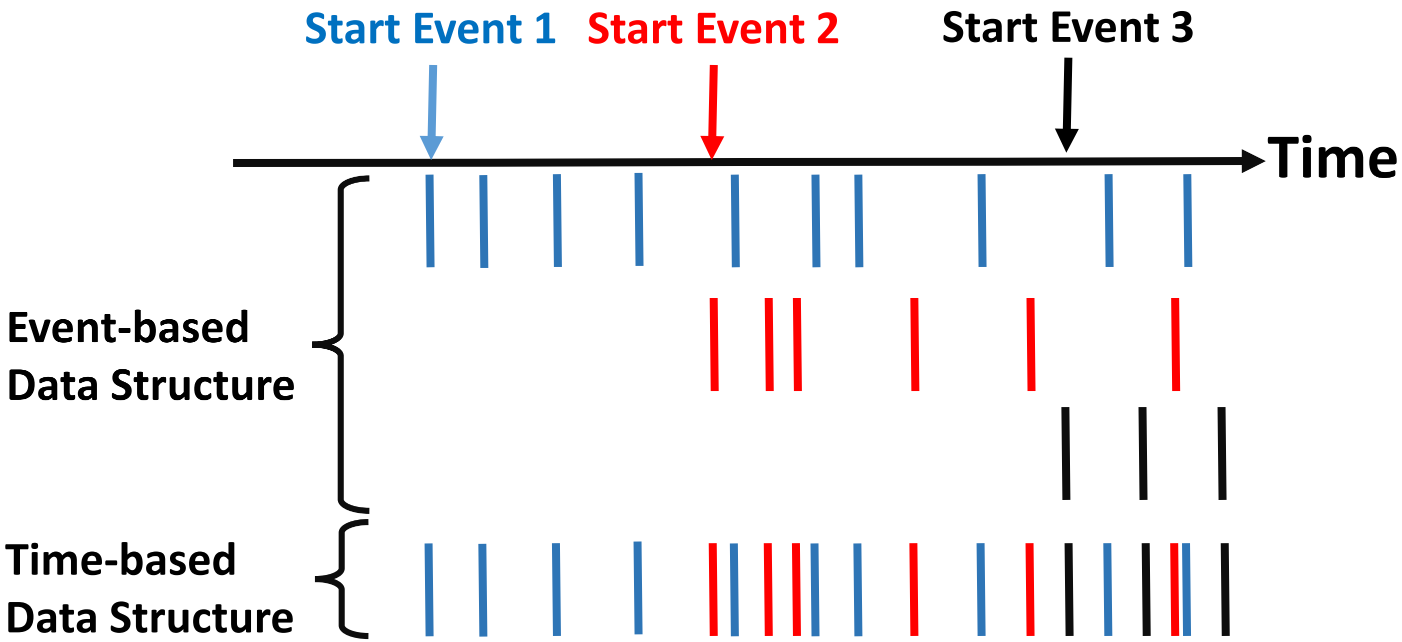
From $\vec{n}$, cirlcle parameters are known:

$$u_0 = -\frac{n_1}{2n_3}, \quad v_0 = -\frac{n_2}{2n_3}$$ Circle center

$$\rho^2 = \frac{1 - n_3^2 - 4cn_3}{4n_3^2}$$ Radius

$c+n_1x+n_2y+n_3z=0$

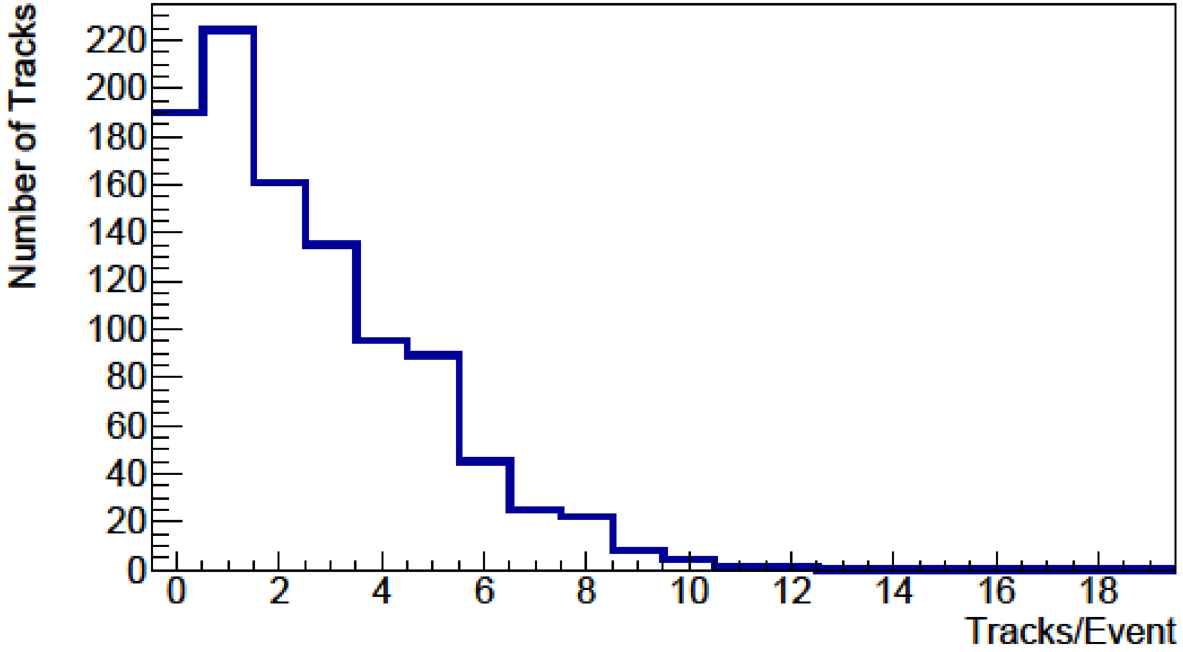
Time-based Data Structure



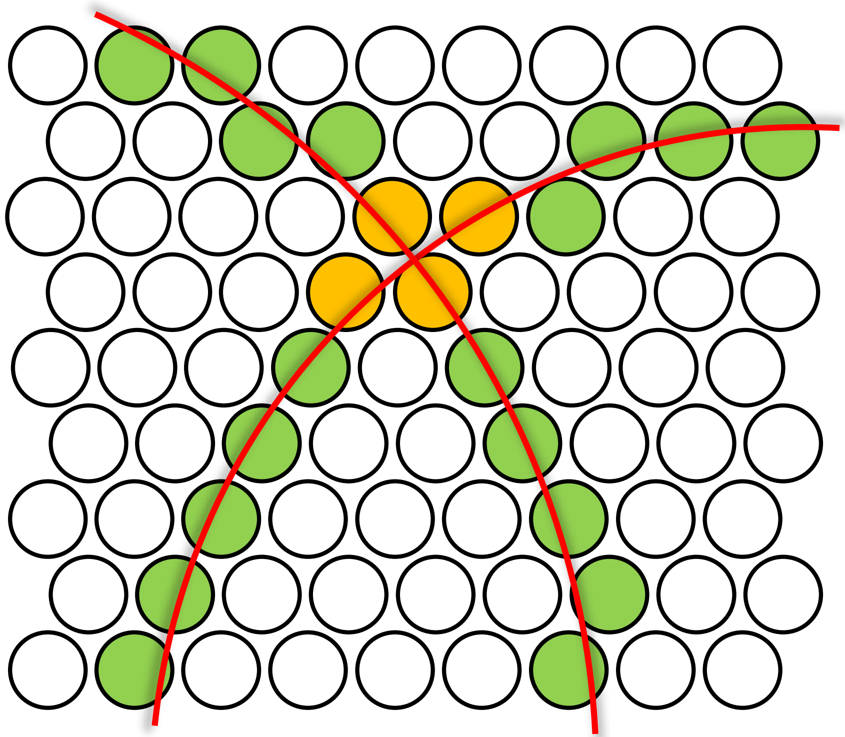
Classically, online track reconstruction is performed on event-based data structure **– this is changing!**

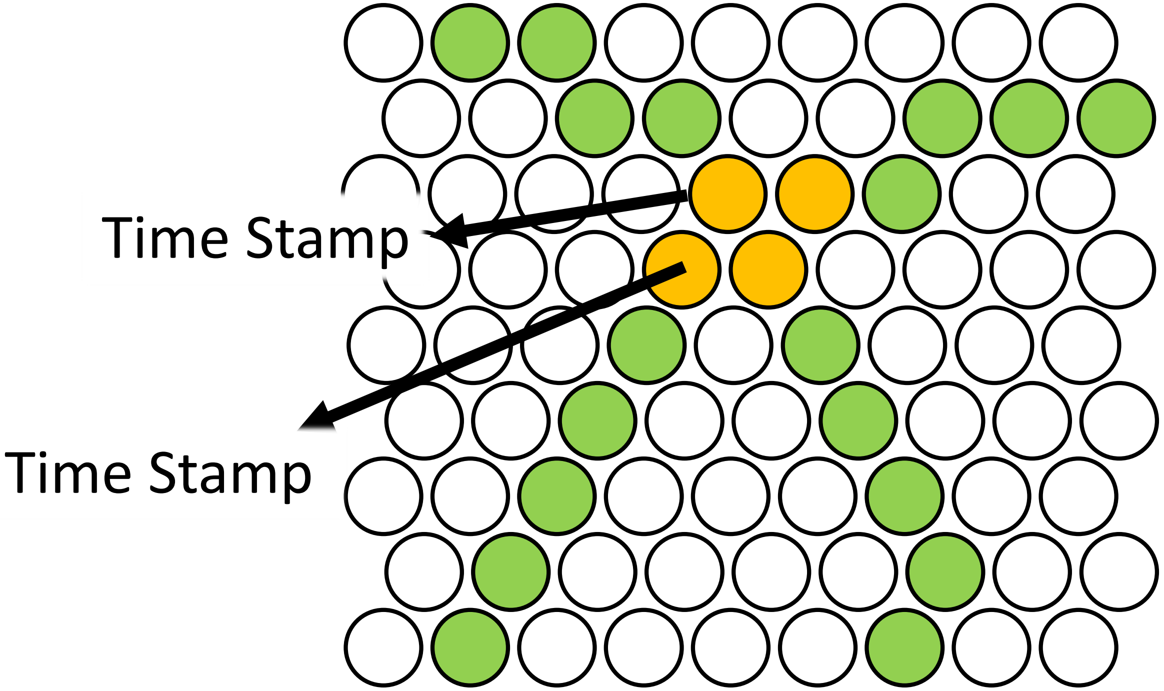
Tracks per event

- Tracks with > 5 Straw Tube Tracker hits (tracks which have a chance of being reasonable well reconstructed)
- Mean 2.5-3



Time Clustering



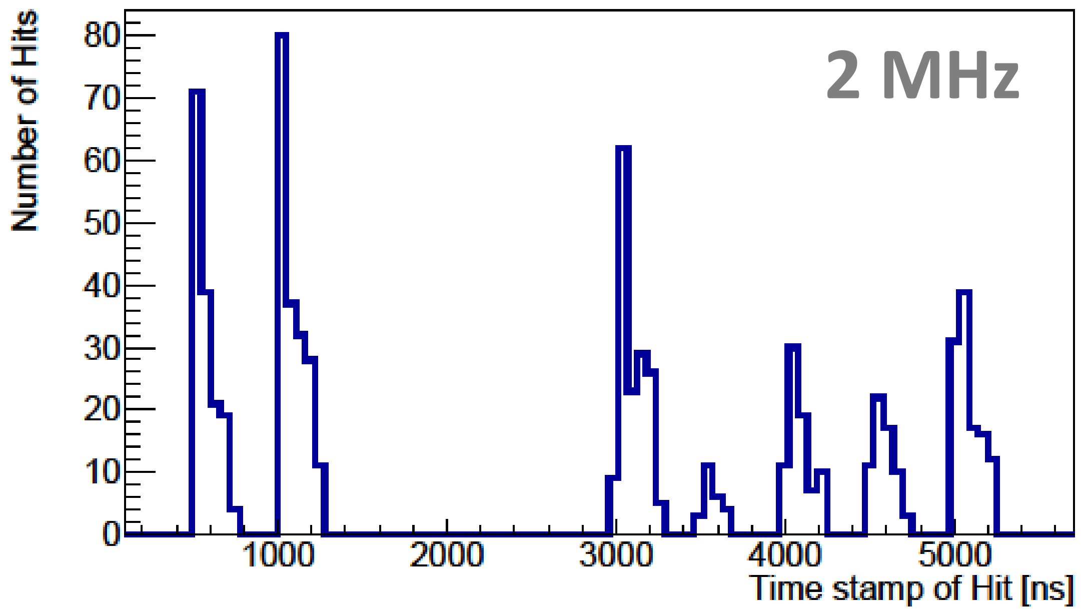


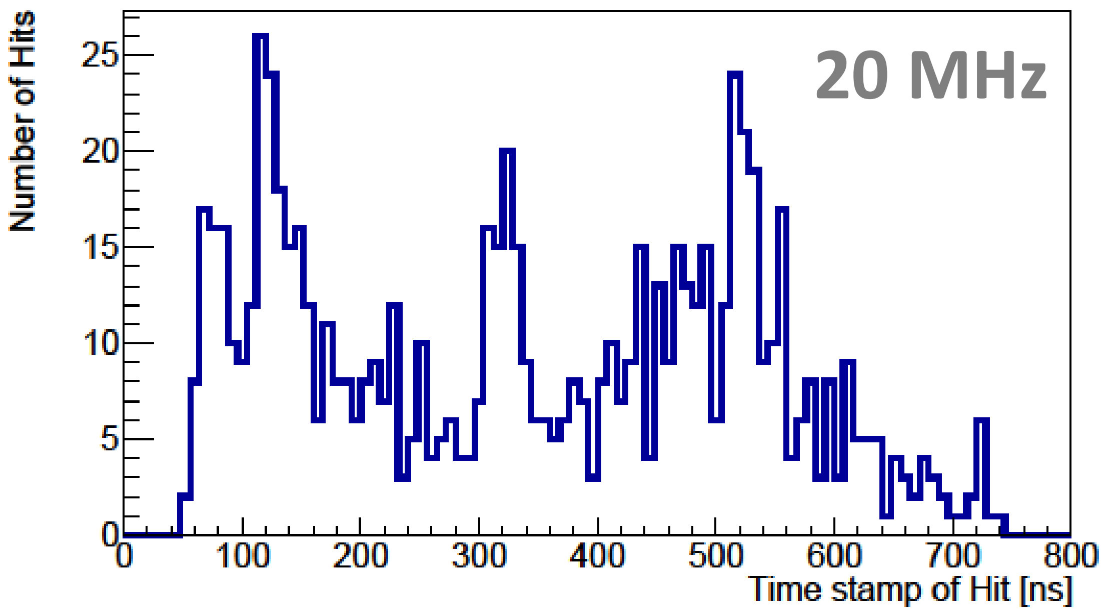
1. Ask every hit for its time stamp
2. Compare it to time stamps of its spatial neighbors
3. if Δ Time Stamp < Cluster Time Neighbors accepted

Cluster Time = 250 ns

Event Mixing at PANDA

Hits in the Straw Tube Tracker





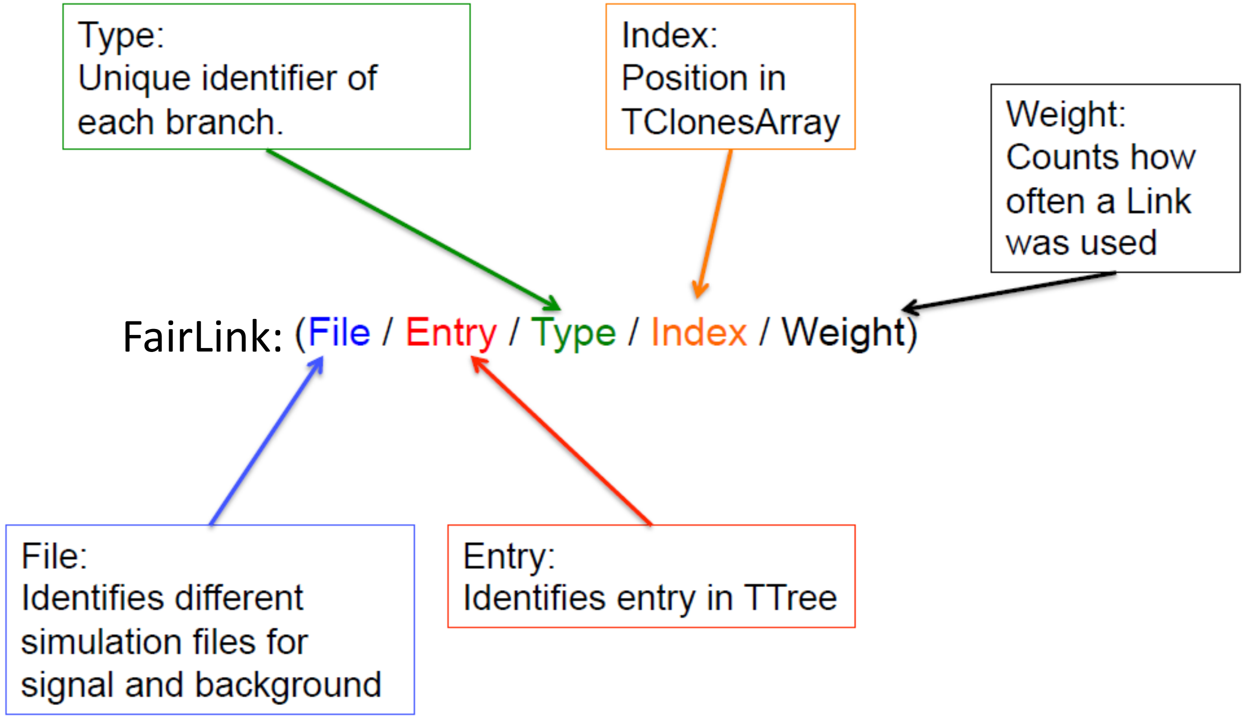
- **500 ns** between start of two consecutive events
- Clearly separated events (mostly)!

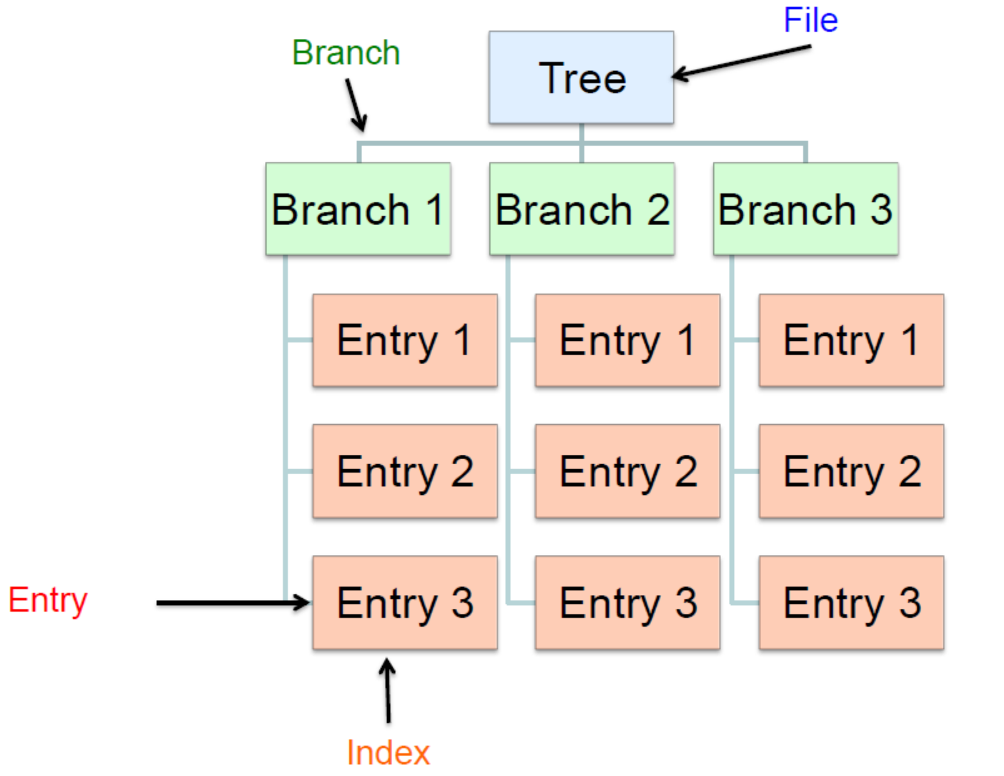
- **50 ns** between start of two consecutive events
- Event mixing!

Event mixing also occur but to smaller extent at lower interaction rate due to quasi continuous beam!

Data Storage

FairLinks: pointers set in one data stage for an object. They are pointing back to the objects used to create the object in question

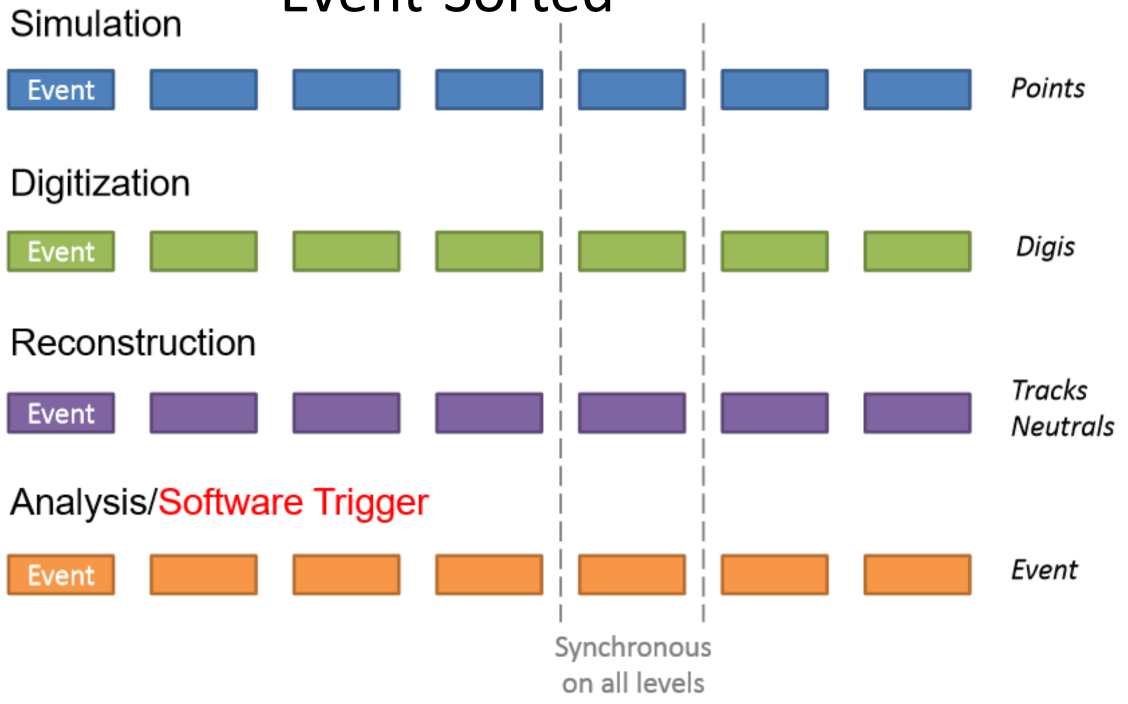




Branch: data objects, *e.g.* Hits, tracks
Entry: event number
Index: Position in TClonesArray

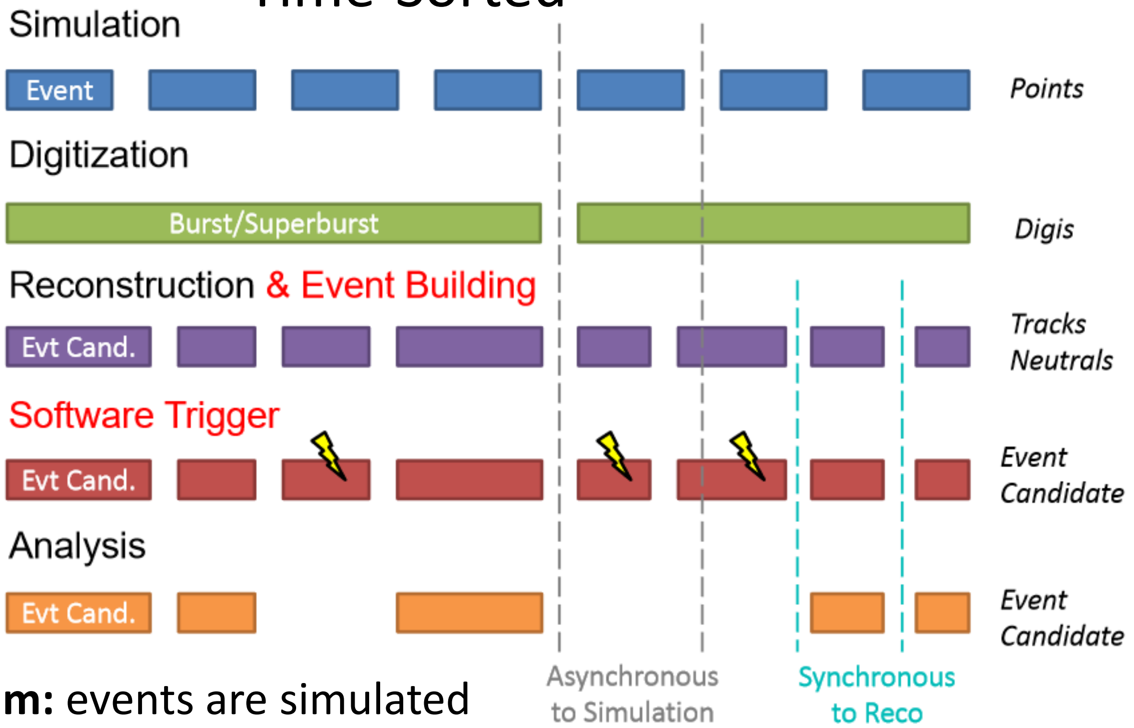
Event-Sorted vs. Time-Sorted Data

Event-Sorted



Sim: events are simulated
Digi: Digis are sorted event by event
Reco: Reconstruction is done event by event

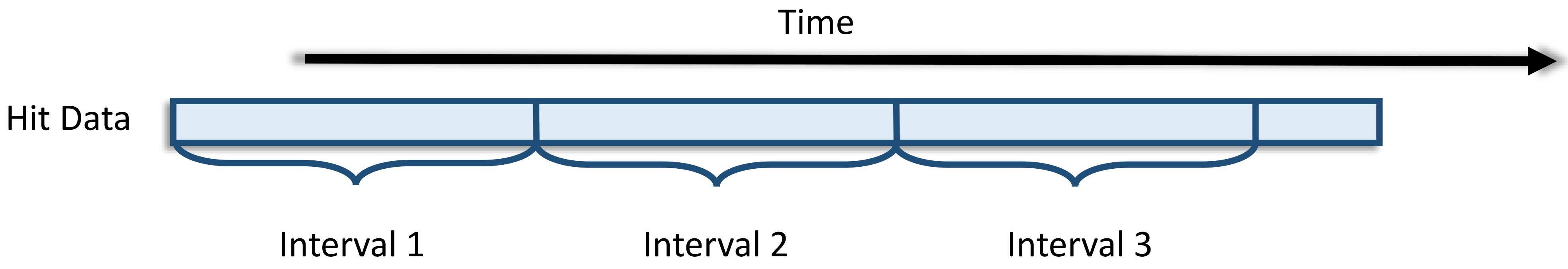
Time-Sorted



Sim: events are simulated
Digi: Digis are sorted time-wise. They are grouped into bursts
Reco: Reconstruction is done on hits without prior knowledge of which event the hits belong to

Fetching the Time-Sorted Data

- Fixed time intervals of same length



- Search for gap in hit data and cut between intervals there
- Intervals will have varying length