Common issues in

charged particle tracking *– using mostly Belle II as an example*

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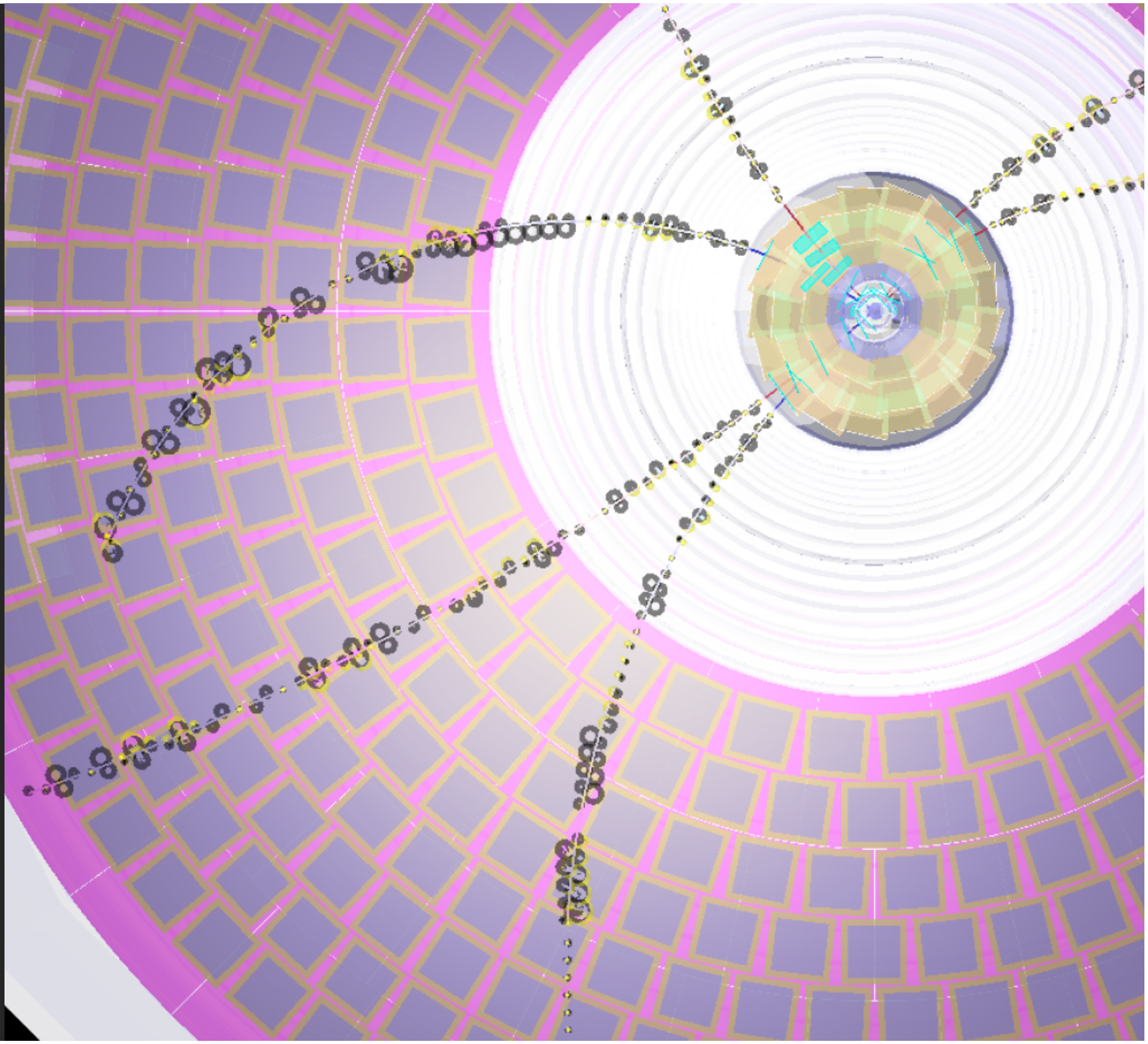
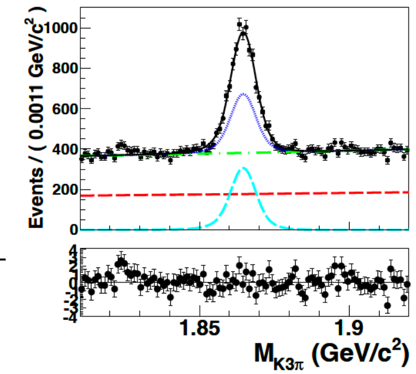


References

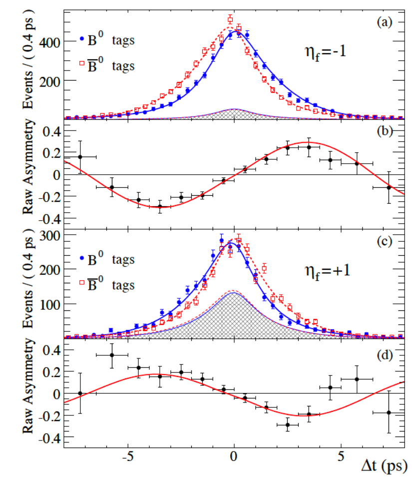
- *Detectors for particle radiation, K. Kleinknecht, Cambridge University Press*
  - *Relatively short overview of particle detectors*
- *Particle Detectors, C. Grupen, Cambridge University Press*
  - *Comprehensive overview of particle detectors*
- *Passage of particles through matter (review #34), PDG, Groom & Klein, et. al.*
  - *Good reference*
- *Particle detectors at accelerators (review #35), PDG, various authors*
  - *Detailed comparison of detector technologies*
- *Track finding at Belle II, Belle II Tracking Group*
  - *Detailed description of Belle II track finding*
- *Track and vertex reconstruction: From classical to adaptive methods, A. Strandlie & R. Frühwirth, Rev. of Mod. Phys. 82 (2010)*

Tracks for physics analysis

- ▷ *Every physics analysis depends on well-measured tracks*
  - ↳ *It's how you get the 4-momenta of most particle candidates (e.g. $\pi^{\pm}$, $K^{\pm}$, $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$, $p/\bar{p}$, K_S, D, B, J/ψ, ROE, …)*
- ▷ ***Mass resolution** of composed particles depends on*
  - ↳ *Track momentum (p) resolution*
  - ↳ *Opening angle resolution, and thus track angle (ϕ and θ) resolution*
  - ↳ *Smaller signal mass region means less background*
- ▷ ***Vertex resolution** depends on*
  - ↳ *Track impact parameter (d_0 and z_0) resolution*
  - ↳ *Important for measurements of time-dependent CPV, $B\bar{B}$ and $D\bar{D}$ mixing, B and D lifetimes, and also for background rejection*



Wrong-sign $D^0 \to K^+\pi^+\pi^-\pi^-$ decay from Belle PRD 88, 051101 (2013)



sin2β measurement from BaBar PRD 79, 072009 (2009)

Track Reconstruction

▷***3 main steps*** *to determine momentum vectors of charged particles*

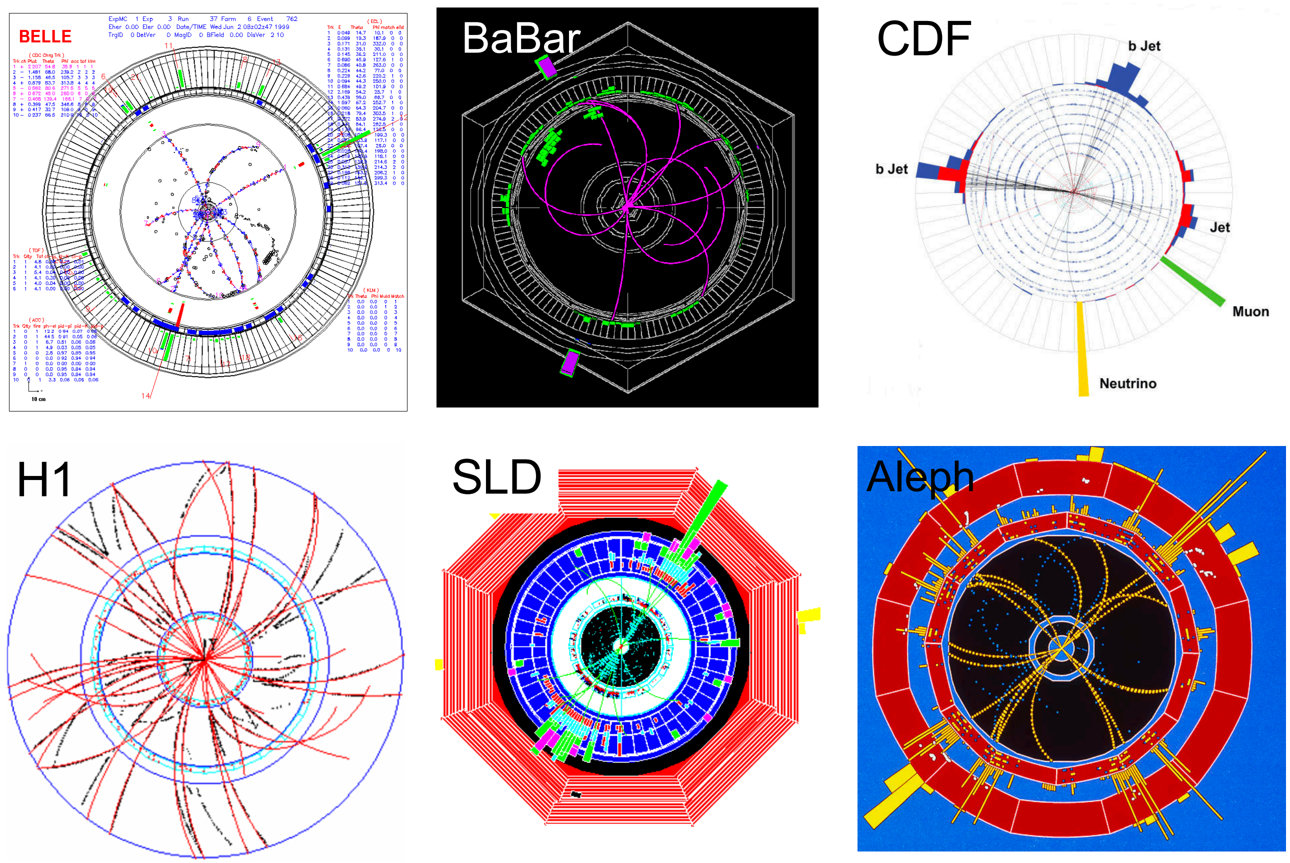
1. *Let particles interact with detector material so that they leave hits along their trajectory*
   ↳ *Build and operate a detector with precise and efficient position measurement*

2. *Identify the hits created by each charged particle*
   ↳ *Pattern recognition (a.k.a. connect the dots)*

3. *Determine best estimate for particle momentum*
   ↳ *Fit hits to a trajectory for track parameters*

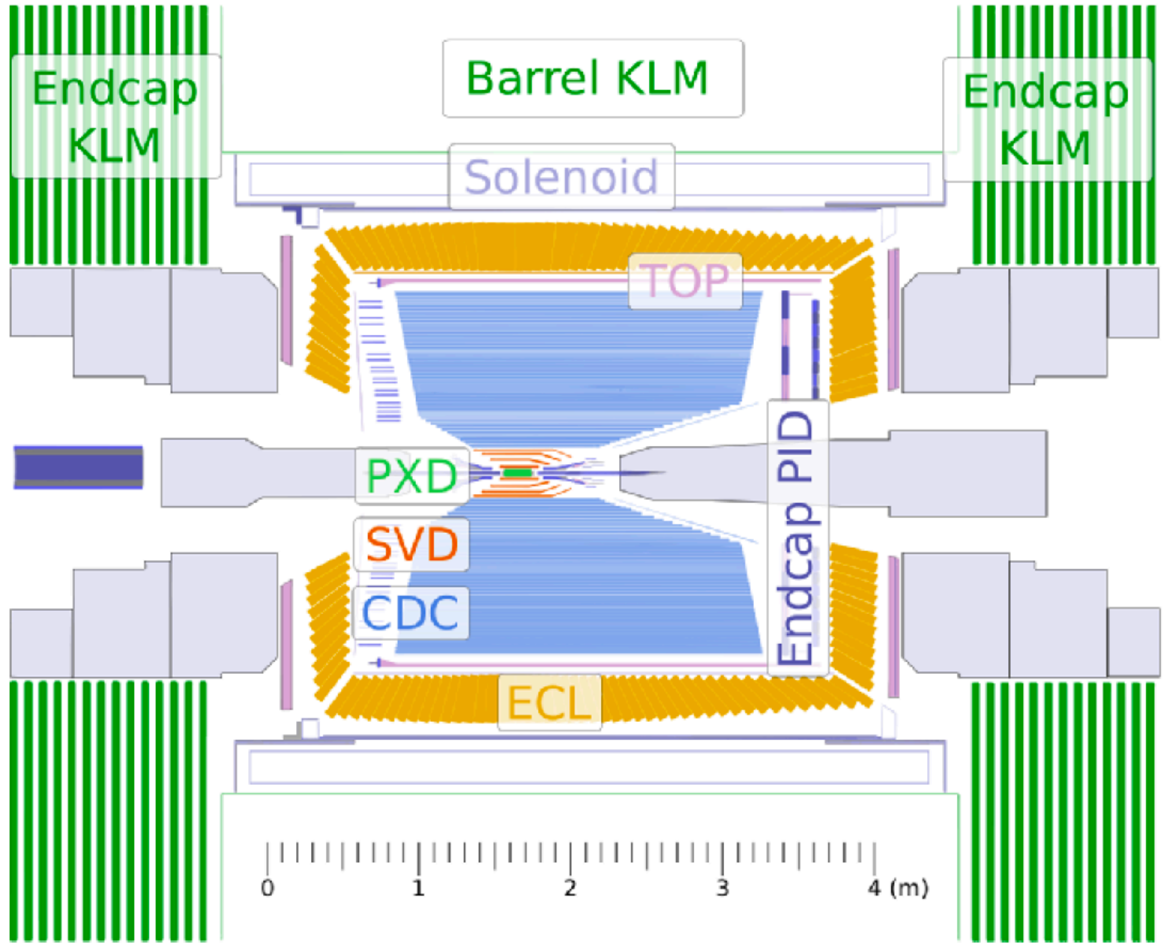
Tracking detectors at colliders

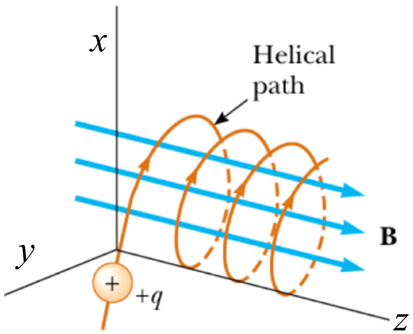
- ***Common design**: cylindrical geometry aligned with beam and solenoidal B field (~ 1 Tesla)*
- *A few layers of **silicon detectors** (strips and/or pixels) as innermost component*
  - *High spatial precision as close as possible to IP*
  - *Dominates impact parameter and vertex measurements*
- *Followed by a **drift chamber** with tens of layers*
  - *Dominates momentum measurement*
- *Tracking devices at forward spectrometers (e.g. LHCb), neutrino experiments, and other special detectors can look very different (I won't discuss them today)*

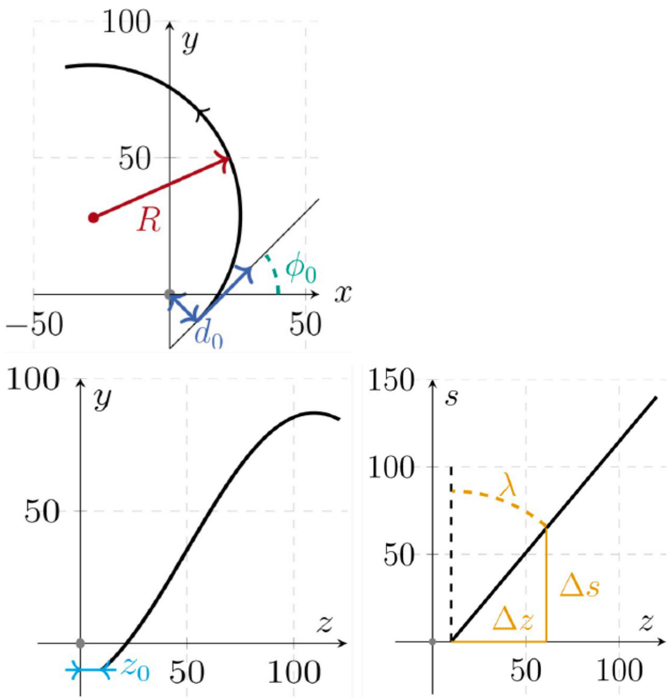


The Belle II tracking system

- ***V**erte**X** **D**etector (VXD)*
  - ***P**i**X**el **D**etector (PXD)*
    - *2 layers pixel*
    - *7.7M pixels*
  - ***S**ilicon **V**ertex **D**etector (SVD)*
    - *4 layers DSSD*
    - *224,000 r/o strips*
- ***C**entral **D**rift **C**hamber (CDC)*
  - *56 layers*
  - *14,336 sense wires (+42,240 field wires)*







Track parameterization

▷ *Charged particles in a uniform magnetic field move on a* ***helical trajectory*** *due Lorentz force*

▷ ***5 helix parameters***

↳ ***ω*** *: curvature ω = 1/R*

↳ *R is radius of curvature related to transverse momentum p_T*

↳ $p_T = 0.3\ BR$ *(from $F_{Lorentz} = F_{centripetal}$; B [T], R [m], p_T [GeV])*

↳ ***λ*** *: dip angle ($\theta = \pi/2 - \lambda$; $p = p_T/\sin\theta$)*

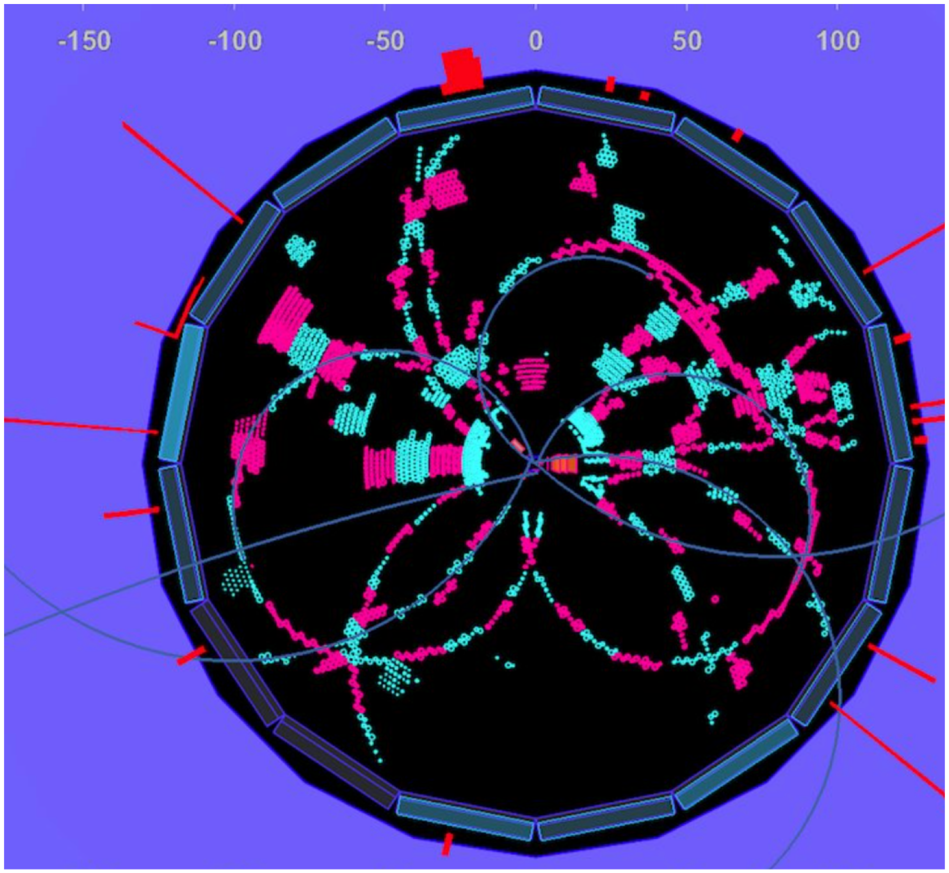
↳ *Point of closest approach (POCA) to origin*

↳ d_0 *: distance of POCA from origin*

↳ z_0 *: z coordinate of POCA*

↳ ϕ_0*: azimuthal angle at POCA*

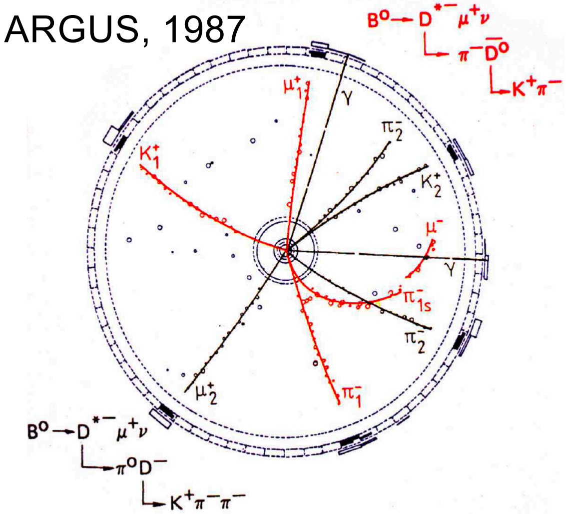
No curling !



- ▷ *What minimum p_T does a track need to make it to the outer radius of the CDC in Belle II?*
  - ↳ $p_{T,min} = 0.3\ B(R_{out}/2)$
  - ↳ $R_{out} = 1.13\ m;\ B=1.5\ T$
  - ↳ $p_{T,min} = 250\ MeV$
- ▷ *It's more like 300 MeV due to energy loss*
  - ↳ *Curlers are spiraling inwards*
- ▷ *Tracks with momenta of 100 MeV or less only have hits in the VXD (60 MeV if there was no energy loss)*

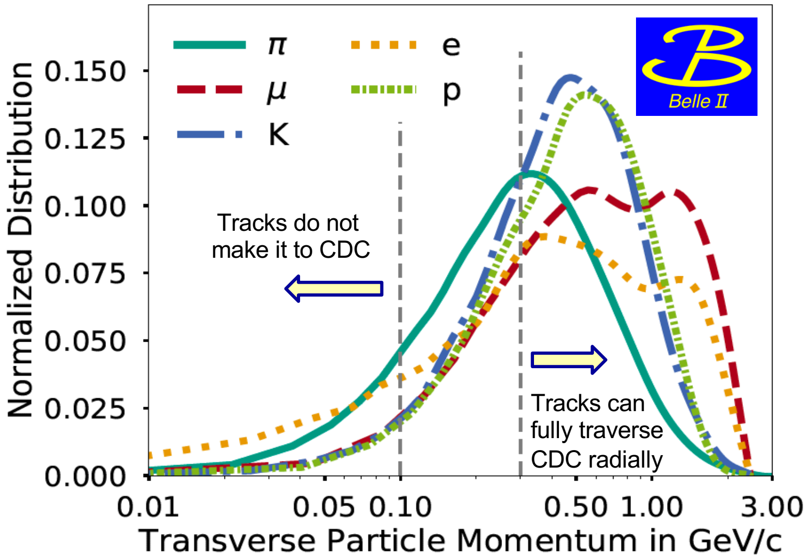
Tracking near the Υ(4S) resonance

- *e^+e^- collisions at 10.6 GeV*
- *On average ~10 tracks / event with an **average momentum of a few hundred MeV/c***
- *Mostly $\pi^\pm$(~75%), but also $K^\pm$, $e^\pm$, $\mu^\pm$, $p/\bar{p}$*
- *Dominant process for interacting with tracking detector material is ionization*



***Goal:** reconstruct these tracks*

- *with maximum precision and efficiency, and*
- *with as little background as possible*



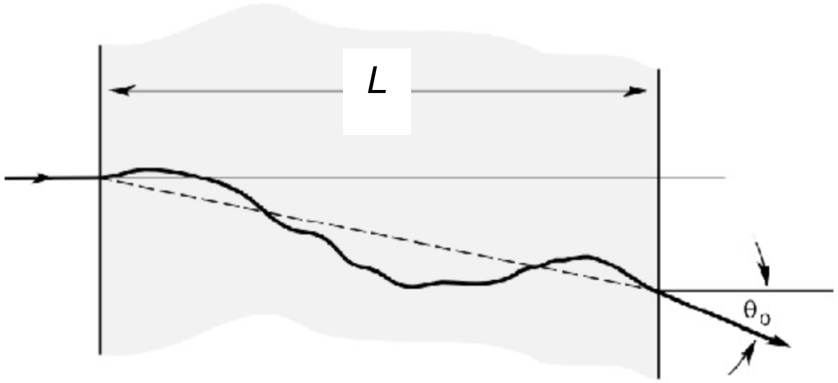
Track (parameter) resolutions

- Two main contributions
  - Single hit resolution (HR)
    - Depends on detector properties (e.g. strip/pixel pitch)
      - ~10 μm in silicon
      - ~100 μm in drift chamber
  - Multiple Coulomb scattering (MS)
    - Depends on momentum p and material thickness L and radiation length X_0

$$\sigma(\theta_0) \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$

    - L/X_0 of tracking systems typically O(1%)

A particle traversing matter is deflected by many small-angle scatters off nuclei

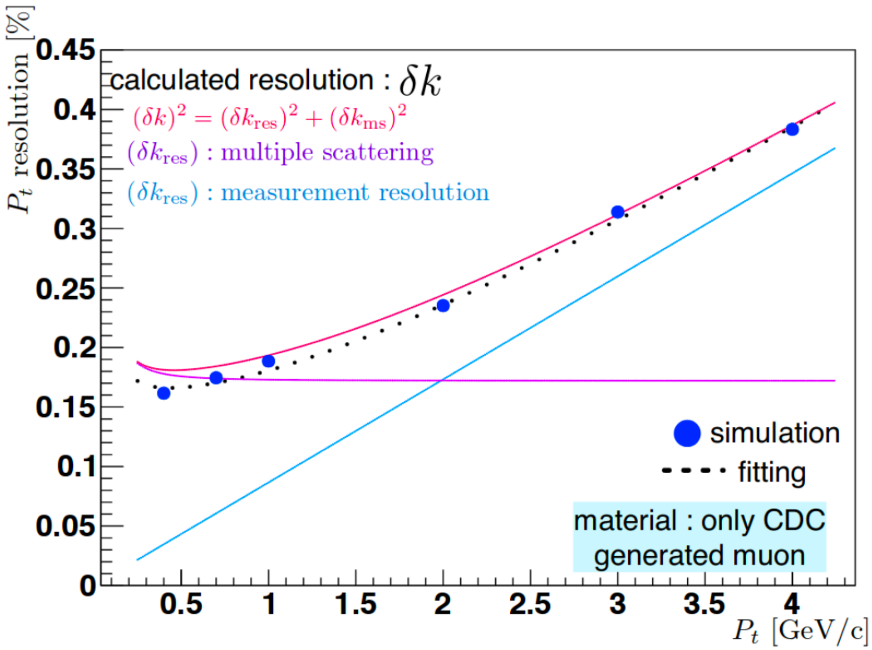


$$X_0 = 716.4\ \mathrm{g\,cm^{-2}}\,\frac{A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}$$

Z: atomic number
A: mass number

Momentum resolution rules of thumb

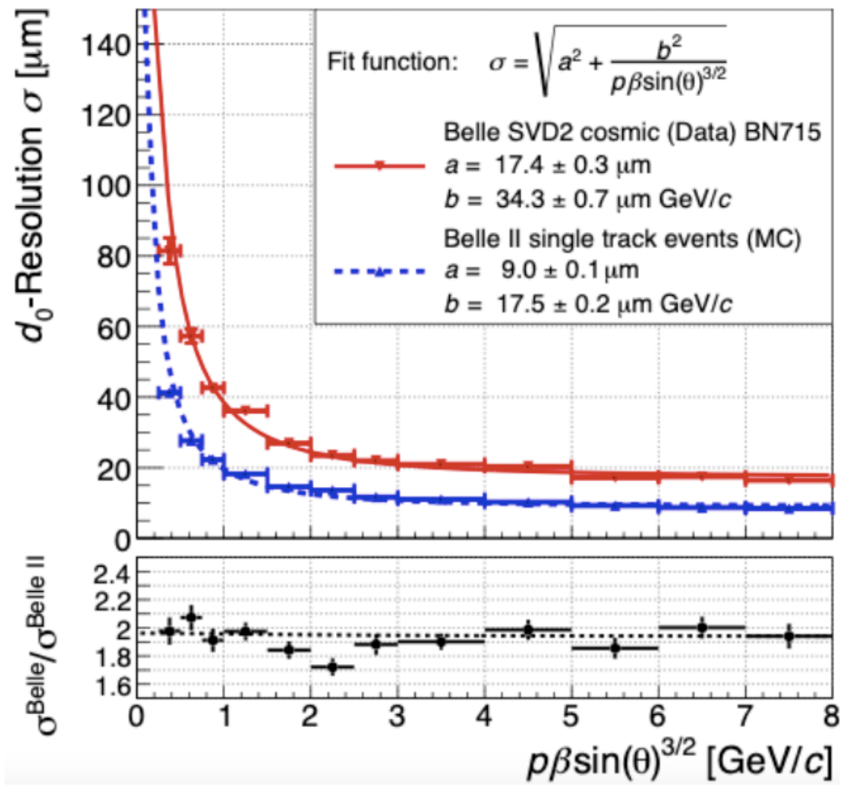
- *Hit resolution term (Glückstern formula)*
  - $\left(\frac{\sigma(p_T)}{p_T}\right)_{HR} \approx \sqrt{\frac{720}{N+4}}\frac{\sigma_{r\phi}}{0.3BL^2} \times p_T$
- *Multiple scattering term*
  - $\left(\frac{\sigma(p_T)}{p_T}\right)_{MS} \approx \sqrt{\frac{1.43\,L}{X_0}}\frac{0.05}{BL}$
- *Belle II CDC numbers ($B = 1.5\ T$):*
  - N=56, $\sigma_{r\phi} \approx 100 \times 10^{-6}\ m, L = 1\ m, X_0 \approx 600\ m$
    $\rightarrow \left(\frac{\sigma(p_T)}{p_T}\right)_{HR} \sim 0.08\ \% \times p_T$
    $\rightarrow \left(\frac{\sigma(p_T)}{p_T}\right)_{MS} \sim 0.17\ \%$
- ***Multiple scattering dominates for track momenta < 2 GeV***



Magnetic field B [T], N measurements with spatial resolution $\sigma_{r\phi}$ [m], distance from 1st to Nth measurement L [m], and radiation length X_0 [m]

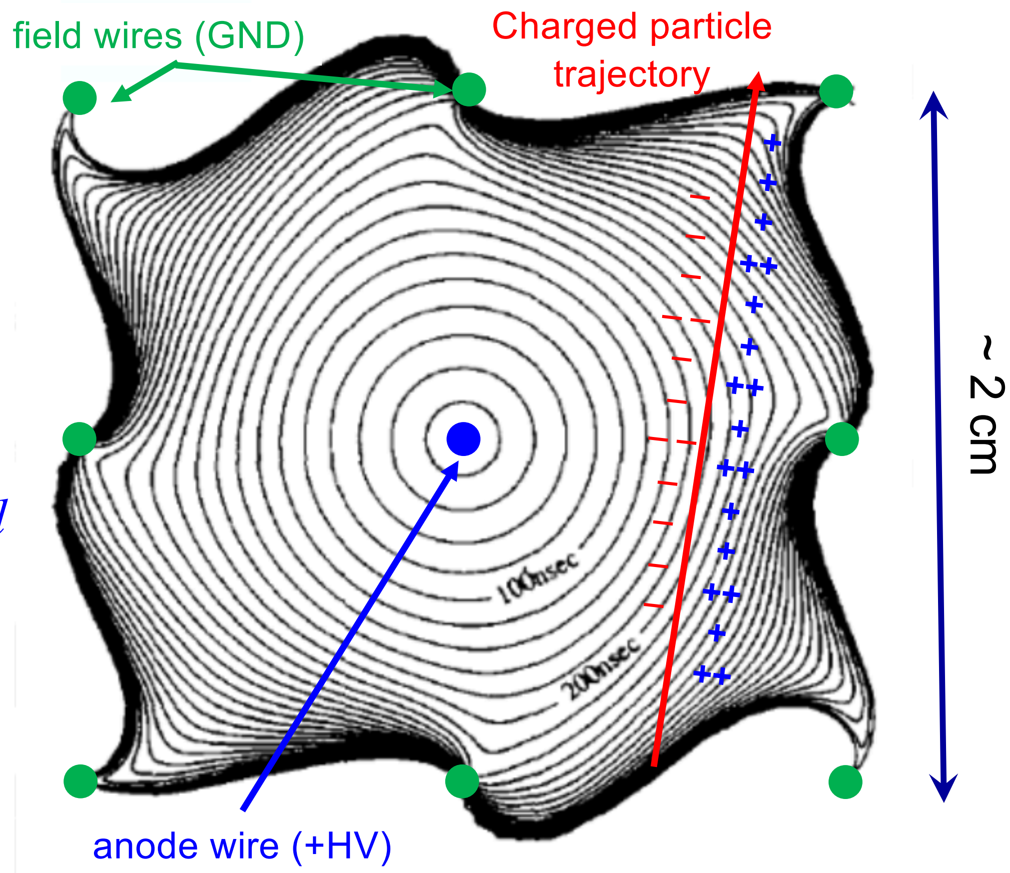
Impact parameter resolution

- Resolutions of track angles (ϕ and θ) and impact parameters (d_0 and z_0) are given by constant HR term and p-dependent MS term
- For example, for impact parameter d_0
  - $\sigma_{d0} = (\sigma_{d0})_{HR} \oplus \frac{(\sigma_{d0})_{MS}}{p\,(\sin\theta)^{3/2}}$
  - $(\sigma_{d0})_{HR} \propto \sigma_{hit}$
  - $(\sigma_{d0})_{MS} \propto \sqrt{\frac{L}{X_0}}$
- MS term dominates impact parameter resolution !
- Rules of thumb for Si vertex detector:
  - Innermost layer radius as small as possible (lever arm !)
  - Low-mass beam pipe (Be)
  - Small pitch (1-pixel clusters: $\sigma_{hit} = \frac{pitch}{\sqrt{12}}$)



Drift chamber principle in a nutshell

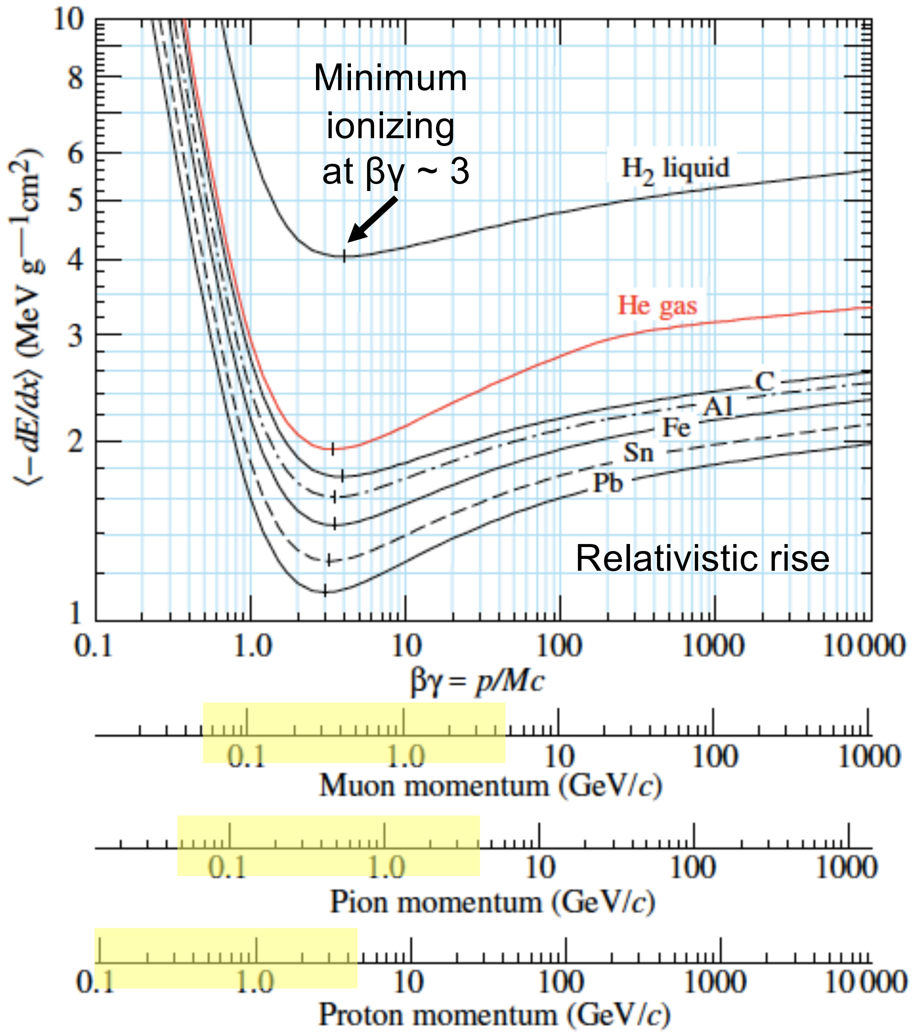
- ▷ *Charged particle traverses drift chamber and ionizes chamber gas along its trajectory*
- ▷ *Electrons drift towards nearest anode wire in electric (and magnetic) field*
- ▷ *Field wires shape the electric field*
- ▷ *Primary electrons get amplified in strong electric field near anode wire and form a detectable pulse*
- ▷ *Reconstruct charged particle trajectory (track) from pulses on many wires*



Energy loss by ionization

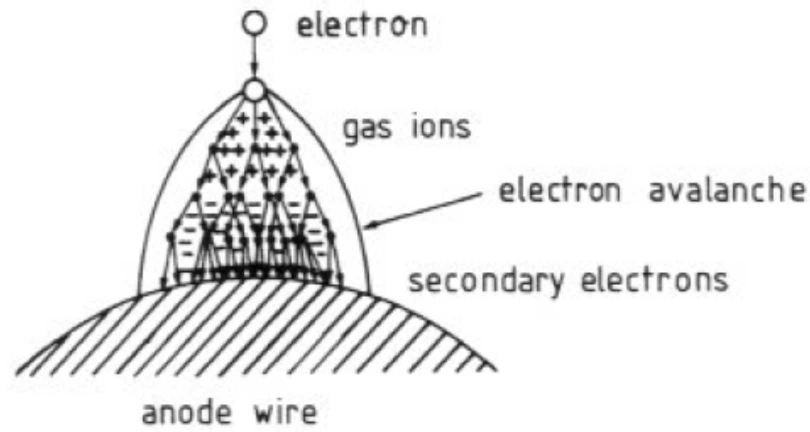
- *Dominant process for particle energies at Belle II*
- *Shape described by Bethe-Bloch formula*
- *How many electrons are released per CDC drift cell?*
  - $\langle -dE/dx \rangle/\rho \sim 2 \text{ MeV cm}^2\text{g}^{-1}$
  - Account for density of gas (He:C_2H_6 50:50):
    (ρ_{He}~ 0.2 g/l, ρ_{C2H6}~ 1.4 g/l, average is 0.8 g/l)
  - $\langle -dE/dx \rangle \sim 1.5 \text{ keV cm}^{-1}$
  - Drift cell diameter 6-18 mm
  - $\langle dE/\text{cell} \rangle \sim 1.5 \text{ keV /cell}$
  - Typical ionization energy ~ 30 eV

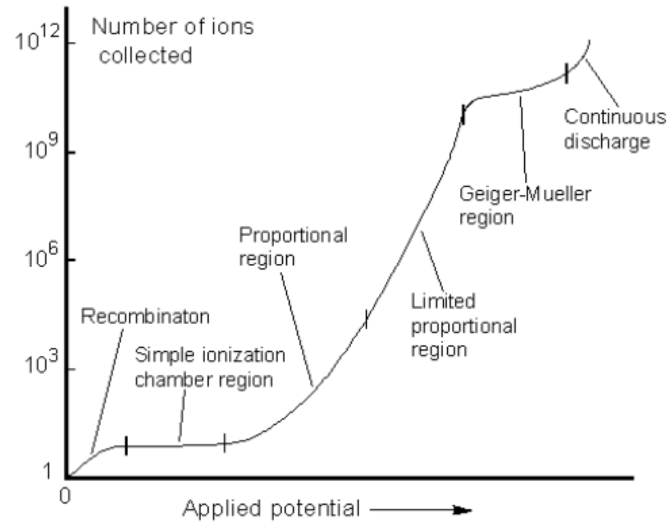
A charged particle will release O(50) electrons / cell.



Pulse formation

- Near anode wire electric field increases
$$E(r) \propto \frac{V_0}{r}$$
- Primary e^- gain enough energy to ionize gas molecules → e^- avalanche
- Amplification factor can be > 10^8
  - Depends on potential, gas, and geometry
  - It's about 10^5 for Belle II CDC (30 μm Au-plated W wires)
- For chambers operating in proportional mode the final # electrons is proportional to # primary electrons → important for PID





Position measurement

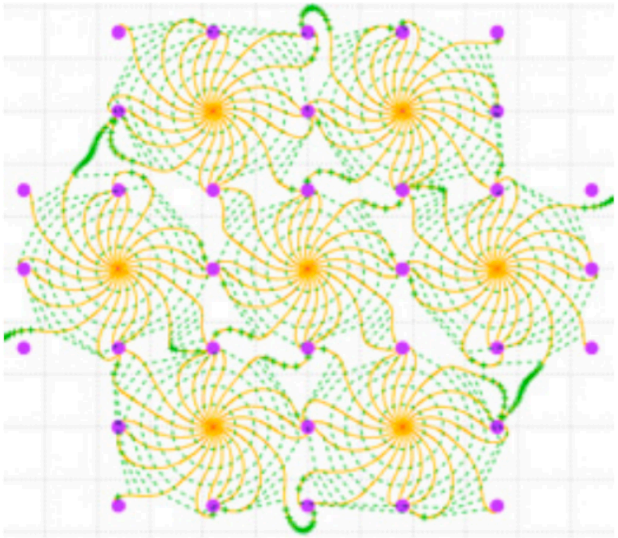
▷ *Drift time and distance are strongly correlated* $x = \int v_D(t)dt$

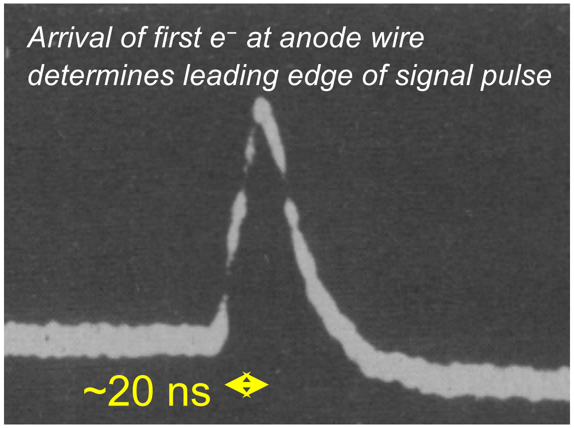
- ↳ *e^- drift velocity is nearly constant, independent of E field due to collisions with gas molecules*
- ↳ *Drift path is not radial due to B field*
- ↳ *Exact time-to-distance relation depends on many factors*
  - ↳ *gas, E field, B field, cell geometry, …*
  - ↳ *t-to-d relations are usually calibrated from data*

▷ *Measure arrival time of e^- on anode wire → ~1 ns time resolution of FEE*

- ↳ *Drift distance resolution of ~50 µm possible (v_D ~ 5 cm/µs)*

CDC isochrones and drift lines





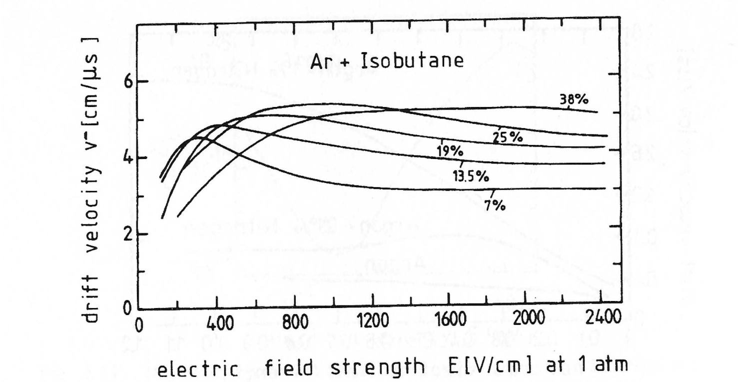
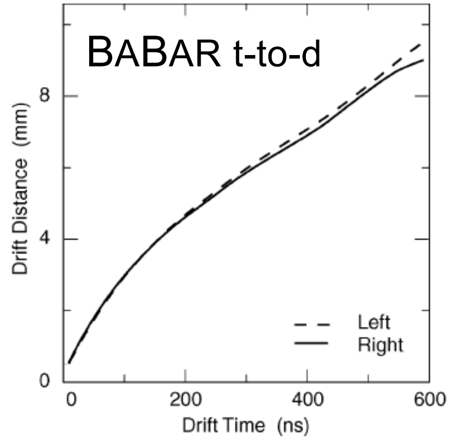


Fig. 1.20. Drift velocities for electrons in argon-isobutane mixtures [51, 93, 95, 96, 97].



Position resolution

▷ *Drifts chamber hit resolution depends on main 3 effects*

↳ *Number of primary e^- at leading edge (decreases rapidly for passage near anode wire)*

↳ *Diffusion of e^- while they drift to anode: $\sigma(d) \propto \sqrt{d}$*

↳ *Time resolution of FEE (position independent)*

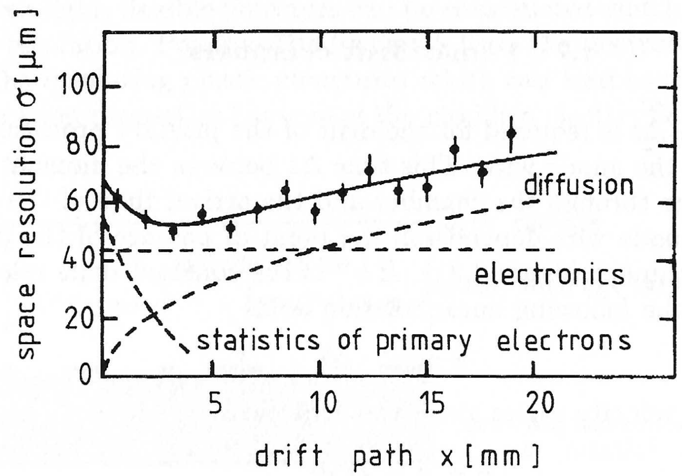


Fig. 4.32. Spatial resolution in a drift chamber as a function of the drift path [51, 223].

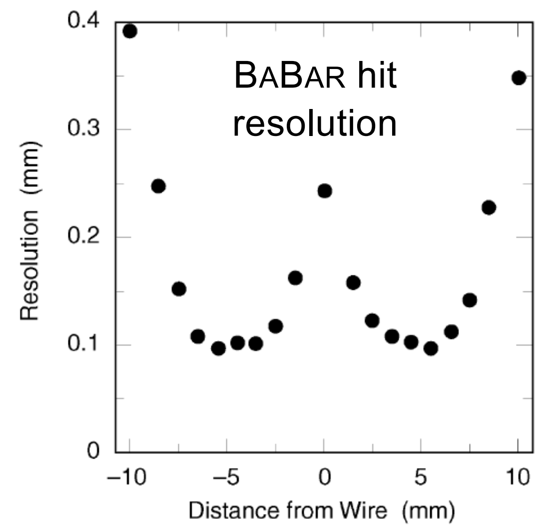


Fig. 37. DCH position resolution as a function of the drift distance in layer 18, for tracks on the left and right side of the sense wire. The data are averaged over all cells in the layer.

Drift chamber gas

▷ ***Main gas (or counting gas)***

↳ *Often a noble gas*

↳ *Low electron affinity → reduced recombination*

↳ *Ar is cheap and frequently used, He has large X_0*

▷ ***Quencher gas***

↳ *Often an organic compound*

↳ *UV photons (from deexitations) can release photo e^- from cathode wires leading to uncontrolled discharges → quencher gas absorbs γ effectively*

▷ ***Additives***

↳ *Very small amounts (typically < 1%)*

↳ *Can reduce aging, affect drift velocity, etc…*

Gas	X_0 [m]	N_P [ions/ cm]	V_d [μm/ ns]	σ_d [μm/ √cm]	Used by
50-50 He-C_2H_6	686	25	30	143	Belle II
50-50 Ar-C_2H_6	178	34	45	140	CLEOII
60-40 He-C_3H_8	569	33	27	136	CLEOIII/c
80-20 He-C_4H_{10}	807	23	24	151	BaBar

Radiation length X_0, number of primary ionizations N_p, drift velocity v_D, and diffusion coefficient σ_d for Y(4S) experiments

Ways to measure position along wire

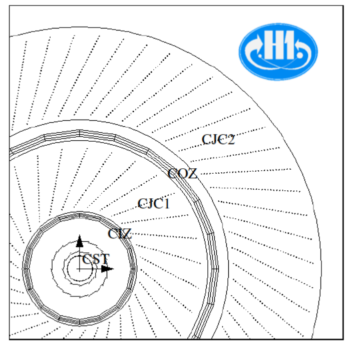
- *Add wires with perpendicular orientation (e.g. z chambers of H1 expt.)*
- *Measure charges on both ends of wire,* ***charge division*** *resolution ~ 1% of wire length*

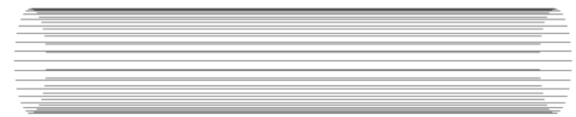
$$z = \frac{q_L - q_R}{q_L + q_R}$$

- ***Stereo wires****: layers of anode wires inclined by small angle γ ("stereo angle"):*

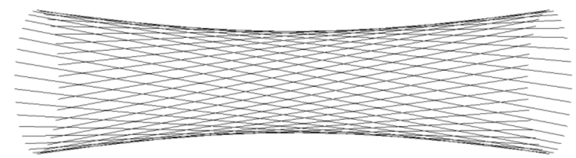
$$\sigma_z = \frac{\sigma_{r\varphi}}{\sin\gamma}$$

  - *Belle II: 1/sin(γ) ~ 13 – 22*

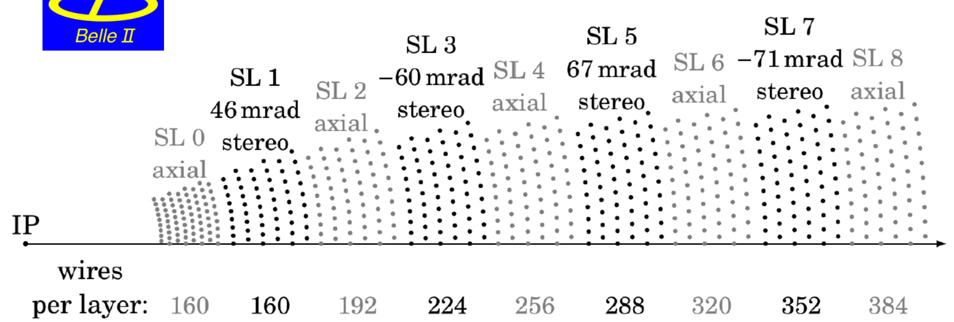




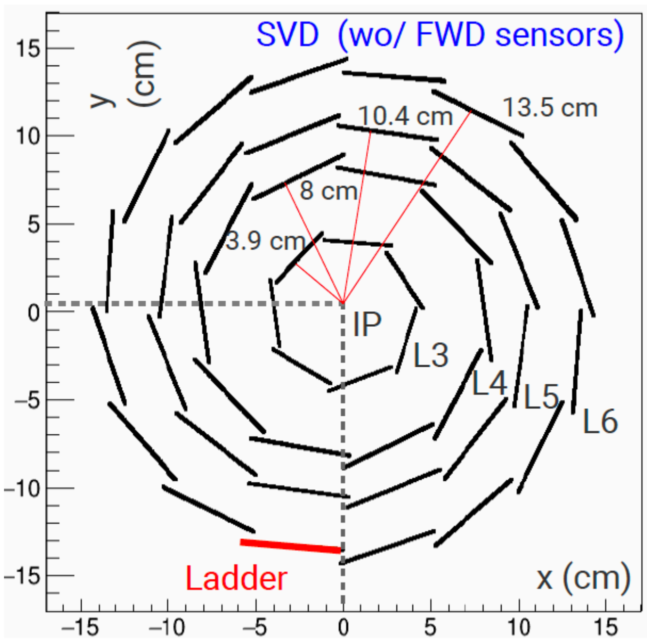
(a) An axial wire layer - sense wires are parallel to the beamline



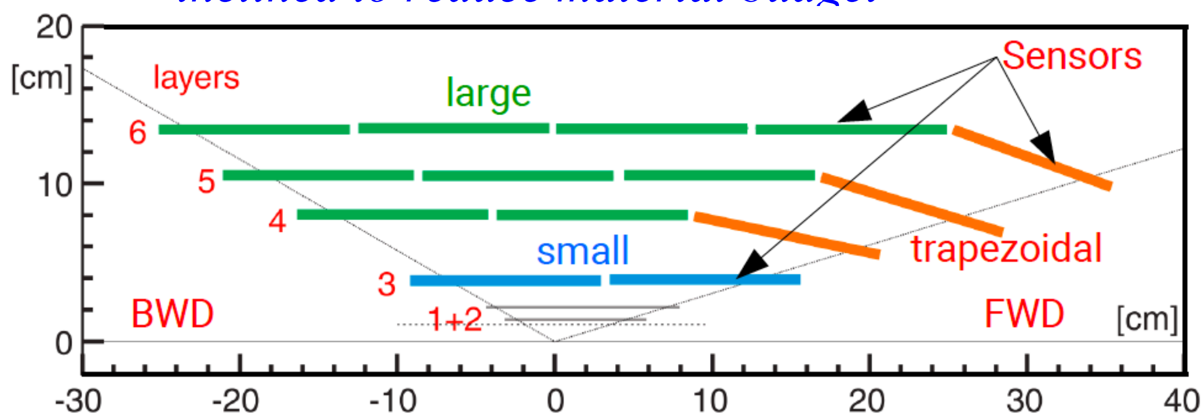
(b) A stereo wire layer - sense wires are skewed to the beamline (exaggerated)



SVD layout



▷ *Sensors in forward SVD are inclined to reduce material budget*

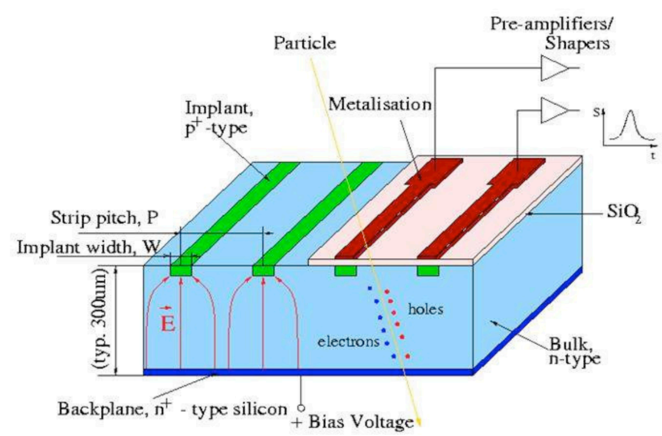


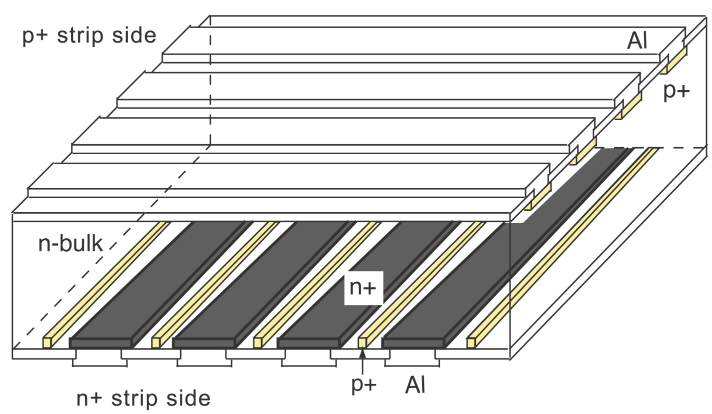
layer	type	readout strip (p/r-φ)	readout strip (n/z)	strip pitch (p/r-φ)	strip pitch (n/z)	number of sensors	sizes (mm)	thickness	total number of strips
4,5,6	large	768	512	75 μm	240 μm	120	125, 60	320 μm	**224000**
4,5,6 FWD	trapeizoidal	768	512	50-75 μm	240 μm	38	126, 61, 41	300 μm	
3	small	768	768	50 μm	160 μm	14	125, 40	320 μm	

Silicon strip detectors

- ▷ *Reverse-biased semiconductor diode with fully depleted bulk*
- ▷ *Traversing charged particle creates ~23,000 electron-hole pairs in 300 μm Si*
  - ↳ *No avalanche process necessary*
- ▷ *Charge carriers drift to strip electrodes*
  - ↳ *Typical pitch ~ 50 μm, resolution ~10 μm*
- ▷ *Both charge types are read out in double sided strip detectors (DSSD)*
  - ↳ *Strips on p and n sides are orthogonal*
- ▷ *Charges from all strips can be stored at high clock frequency*
  - ↳ *Low pile-up from other BCs*

Principles of operation

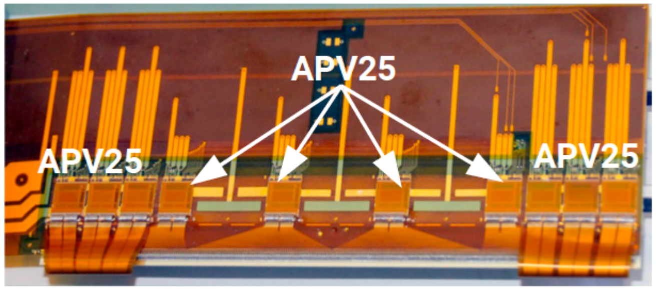


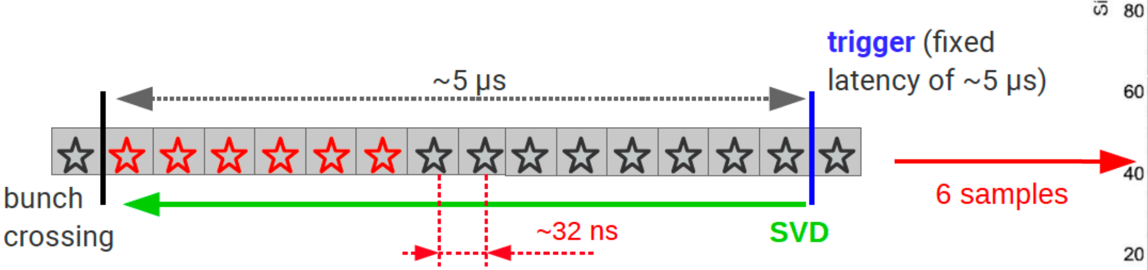


SVD readout

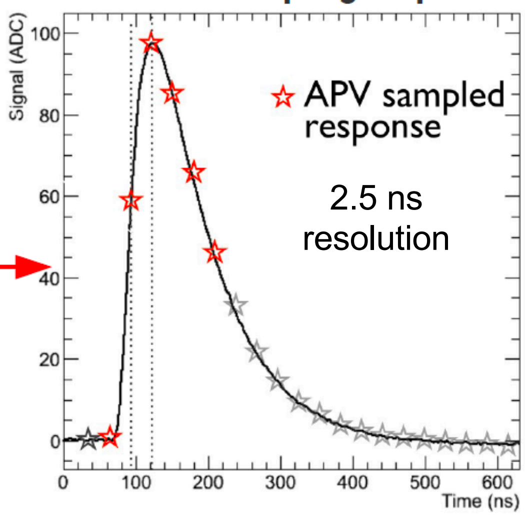
- ▷ *Can't record hits with FEE chips and read them out at the same time → pipelined readout*
- ▷ *SVD sensors are readout by APV25 chips* *(128 channels / chip)*
  - ↳ *32 MHz clock frequency*
  - ↳ *192 sample analog pipeline*

Readout front-end on a sensor





APV25 sampling output

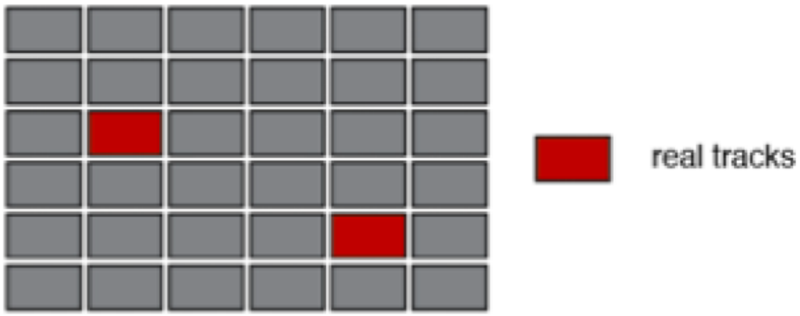


The ambiguity problem

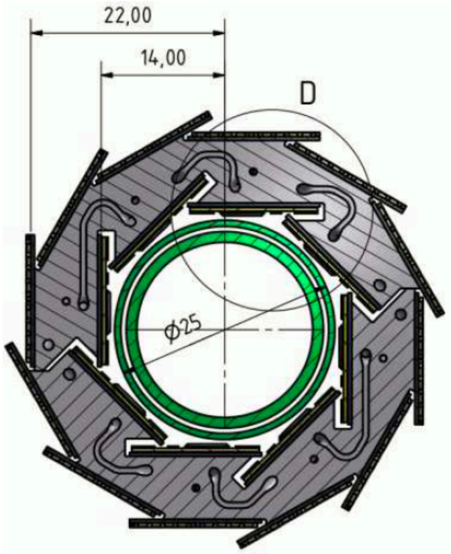
- ▷ *DSSD*
  - ↳ *For N hits on a DSSD sensor there will be also be $N^2 - N$ ghost hits*
  - ↳ *Total number of hit candidates is N^2*
  - ↳ *Needs to be resolved with external info*
  - ↳ *Combinatorial problem for high occupancy (close to IP)*
- ▷ *Pixel*
  - ↳ *Unique 3D position measurement for each hit*
  - ↳ *No ghost hits*
  - ↳ *… but number of channels scales with area for pixel detector, not with side length*

2 hits on the same DSSD sensor

2 hits on the same Pixel sensor



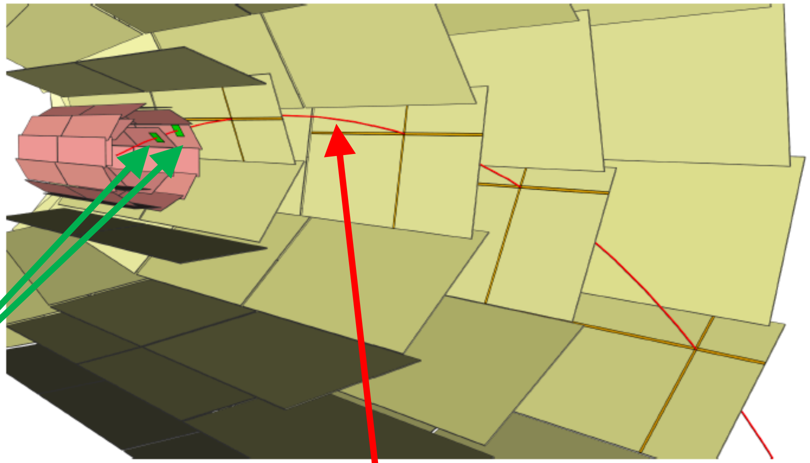
PXD layout



2 layers,
7.7M pixels total

	Inner layer	Outer layer
# ladders	8	12
Radius	1.4 cm	2.2 cm
Pixel size	50x50 μm^2	50x75 μm^2
# pixels	1600(z)x250(R-ϕ)	1600(z)x250(R-ϕ)
Thickness	75 μm	75 μm

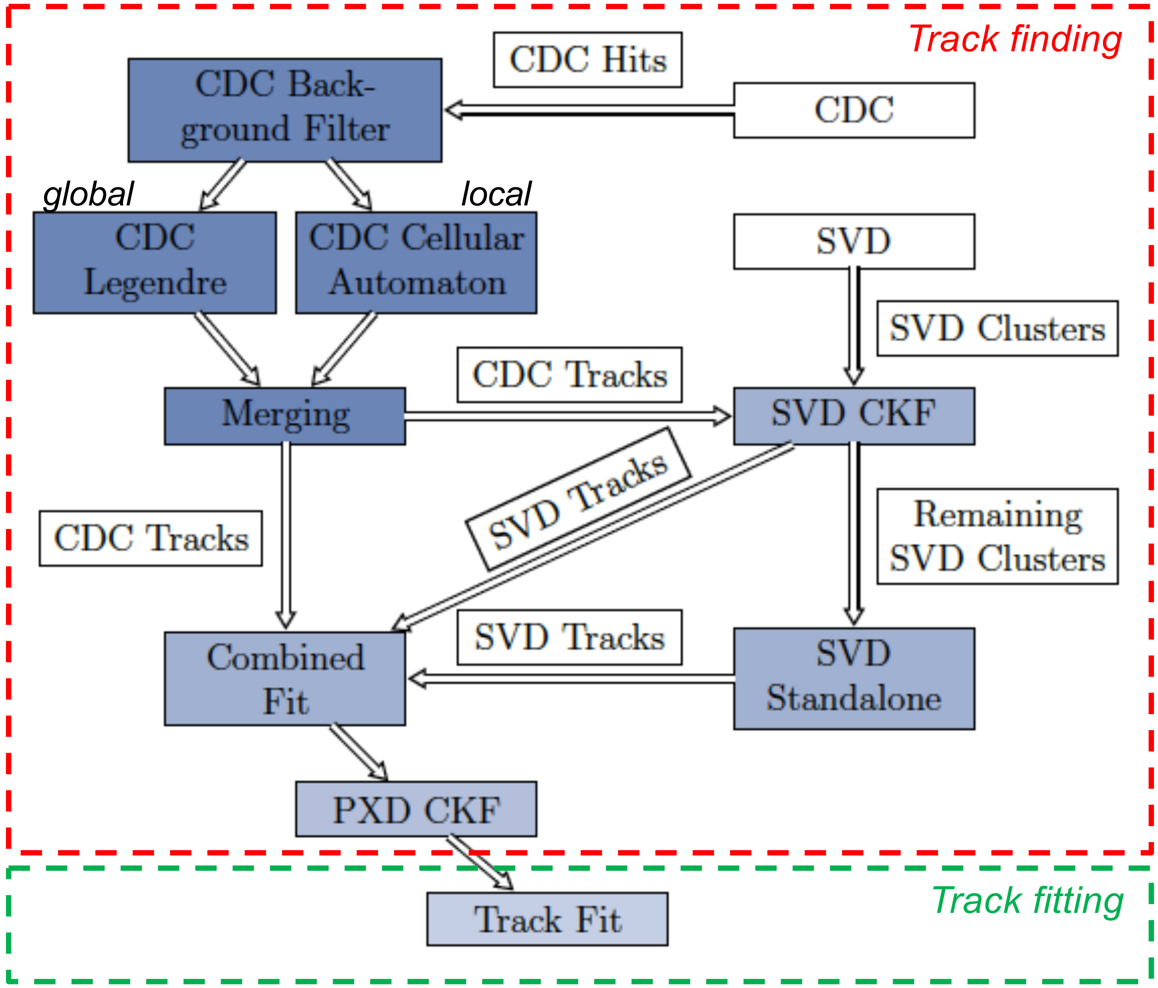
- ▷ *Cannot read out at same high rate as SVD*
  - ↳ *Integrate hits over many BCs (20 μs)*
  - ↳ *Read out only regions of interest (ROIs) determined from tracks in SVD and CDC*



Track reconstruction

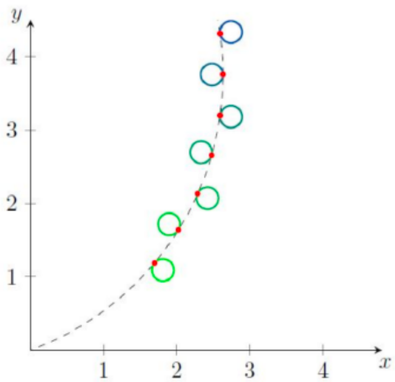
- *2 steps of track reconstruction*
  - ***Track finding*** *(pattern recognition a.k.a. connect the dots): find the hits that belong to the same charged particle trajectory − hard*
  - ***Track fitting:*** *determine its 5 track parameters − not quite so hard*

Belle II track reconstruction

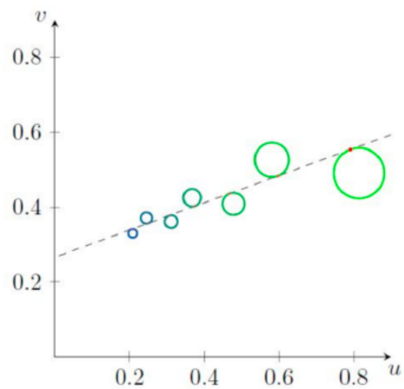


Global track finding in CDC

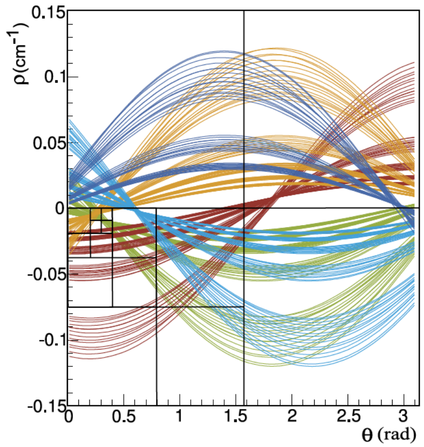
- *Looking for (circular) tracks coming from the IP*
  - *Start with 2D r-ϕ info from axial wires*
  - *Track can have gaps*
- *After two transforms (Hough and Legendre), every* ***hit*** *described by 2 sinusoids in conformal ρ-θ space*
- *Hits from same track go through a common point*
- *Track finding now reduced to search for highest-density region in ρ-θ space*
- *Remove hits from found track and repeat*
- *Stereo wire info is then added in a similar way*



Hough transform turns tracks from IP into straight lines

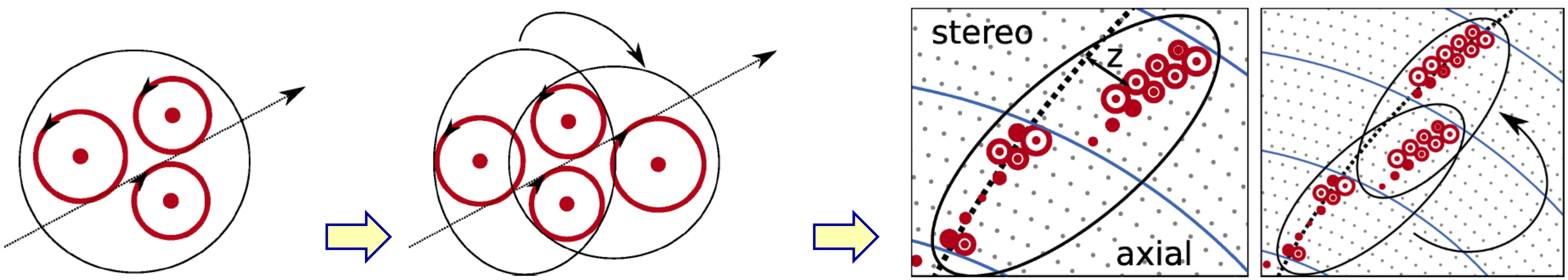


Legendre transform turns drift circles into sinusoids



Local track finding in CDC

- *Combine adjacent*
  - ***Hits*** → ***triplets*** → ***segments*** → *tracks*
- *More efficient than global track finding for tracks displaced from IP*
- *Tracks from global and local algorithms are reconciled*
  - *Matching done with BDT based on # of common hits, track parameters, etc.*

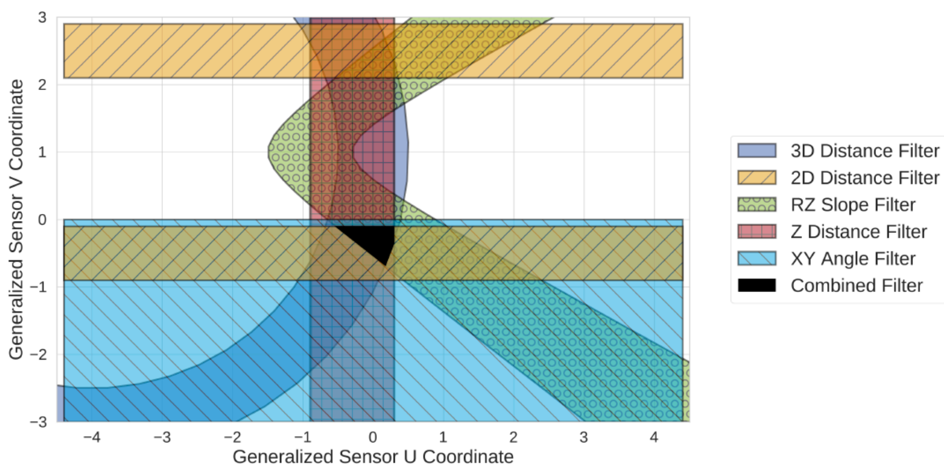


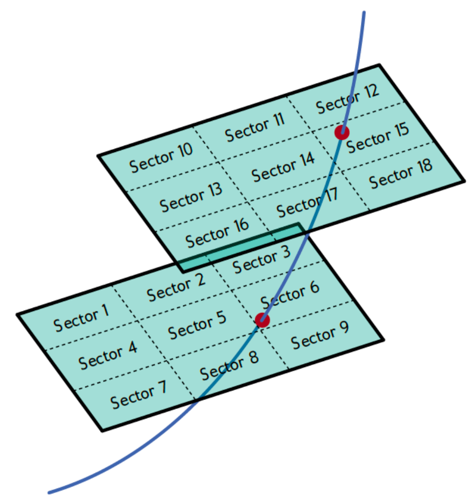
Using the SVD clusters

- ▷ *Extrapolate CDC tracks inward and add SVD clusters to them*
- ▷ *Apply SVD stand-alone track finding on unassociated clusters*
  - ↳ *Sector-on-sensor concept & filters signif. reduce # combinations*
- ▷ *Each SVD cluster can only be assigned to one track*

Sector-on-sensor concept defines the possible cluster locations

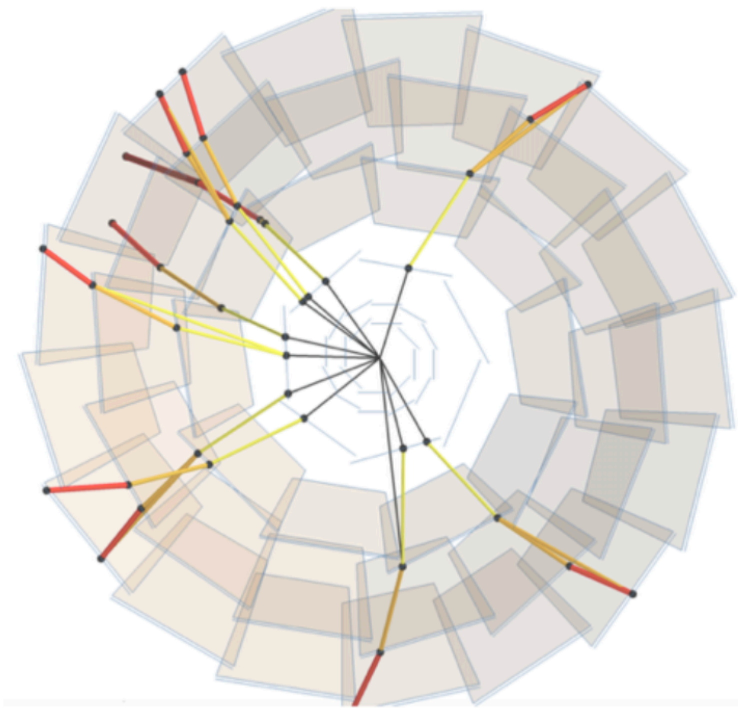
Only clusters that pass all filters can be combined





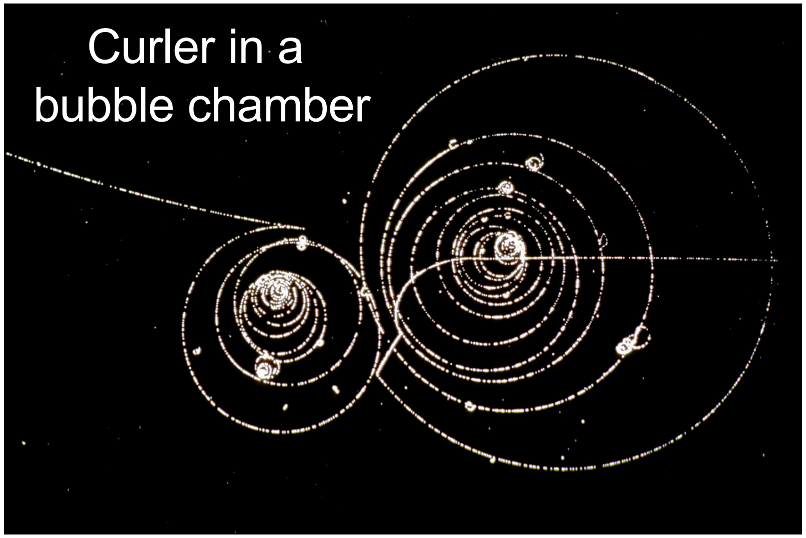
Adding the PXD clusters to tracks

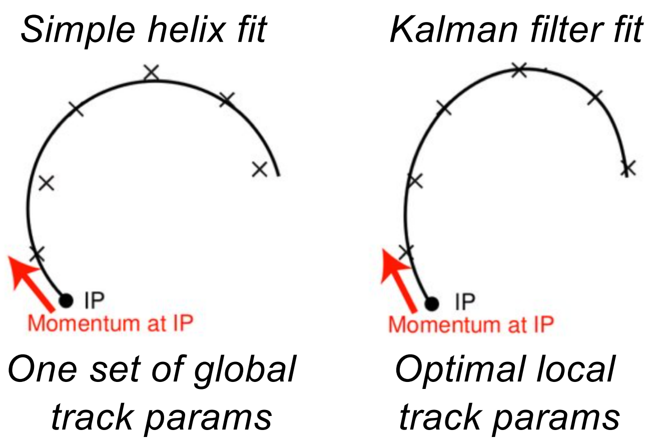
- ▷ *No PXD standalone pattern recognition*
- ▷ *CDC/SVD tracks are extrapolated inward and regions of interest (ROIs) are defined for readout (online)*
- ▷ *During the offline reconstruction PXD clusters near the tracks are added in the ROIs*



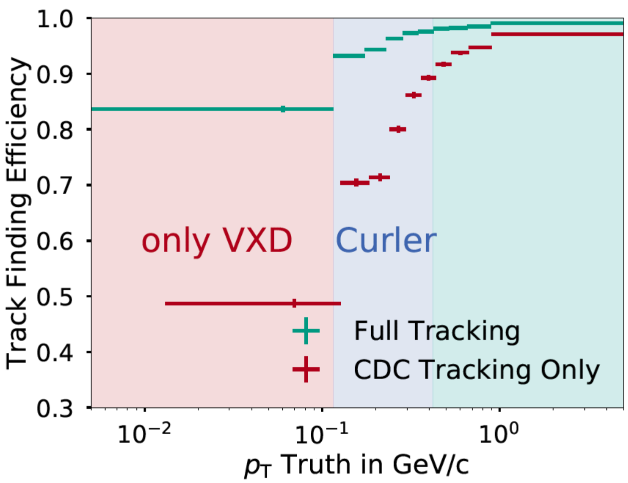
Track parameter fits

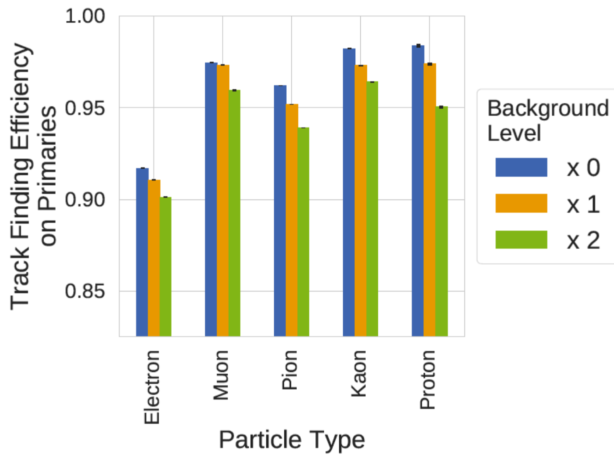
- ▷ *Tracks are not perfect helices !*
  - ↳ *Energy loss (curlers!), multiple scattering, and B field inhomogeneities cause distortions*
- ▷ *(Local) track parameters change along the track*
  - ↳ *Start with seed track params at outer radius, then add info from hits, material, and B field in small steps by "swimming" inward and updating the track parameters (Kalman filter)*
  - ↳ *Track parameters at both track ends are most important (i.e. extrapolate track to IP and TOP) → also swim outward*
  - ↳ *Material effects differ for particle types (e.g. $\pi^{\pm}$, $K^{\pm}$, $e^{\pm}$) → track fit done for various particle hypotheses*
  - ↳ *Also use KF to decide if hits consistent with track (e.g. when adding PXD clusters to track)*

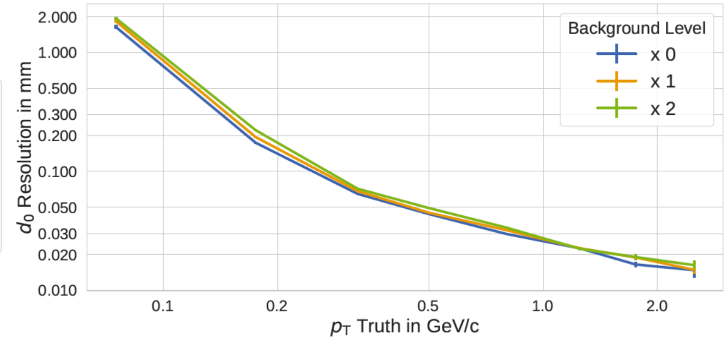


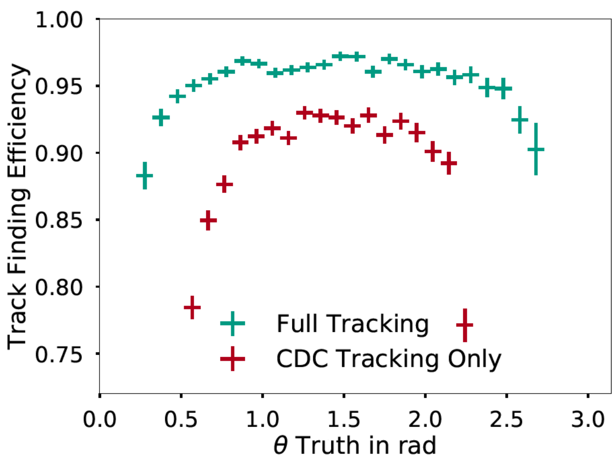


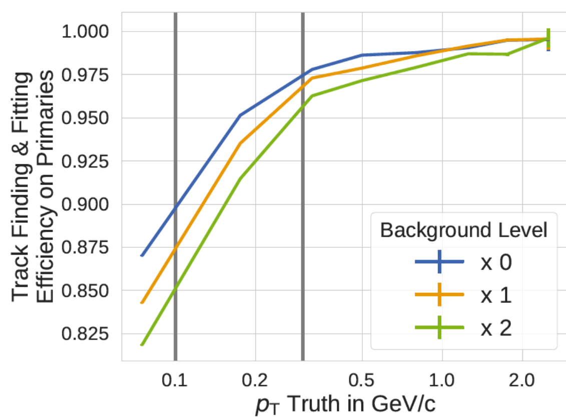
Belle II Tracking Performance

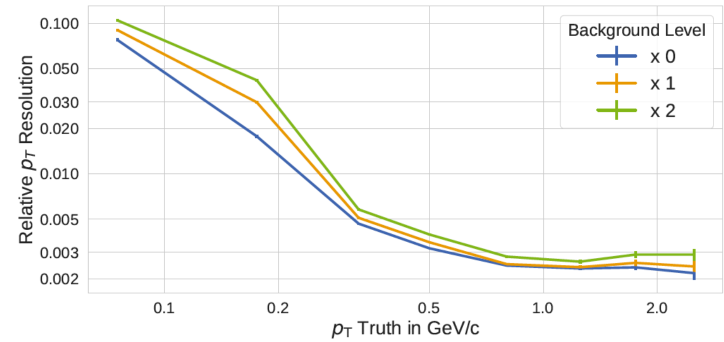












Nominal background level (1x) refers to a luminosity of 8 × 10^{35}

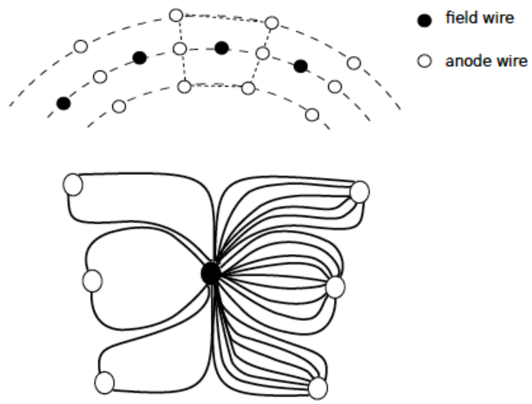
Conclusions

- *Silicon (strips and /or pixel) + drift chamber tracking system concept has proven to be well matched to the Y(4S) environment and is the base for the Belle II tracking system*

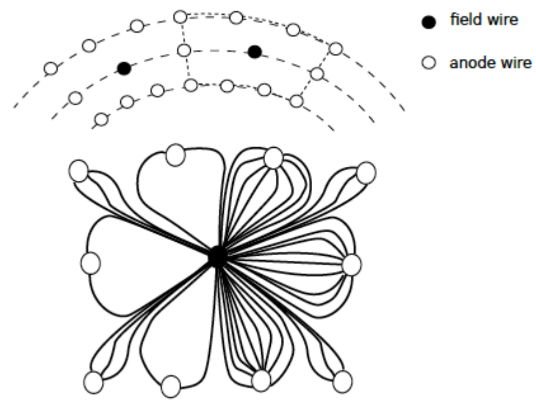
- *Expected to work well for backgrounds up to design luminosity*

Back-Up Slides

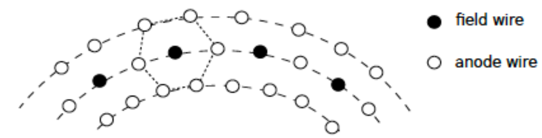
Drift cell geometries



open drift cell



closed drift cell



also hexagonal drift cell

- *Thin anode wires (Ø ~ 30 μm) and thicker field wires*
- *In general, the more wires the better the field geometry*
  - *But more work, and*
  - *More tension on end plates (4T for Belle II CDC)*

Belle II wire specs

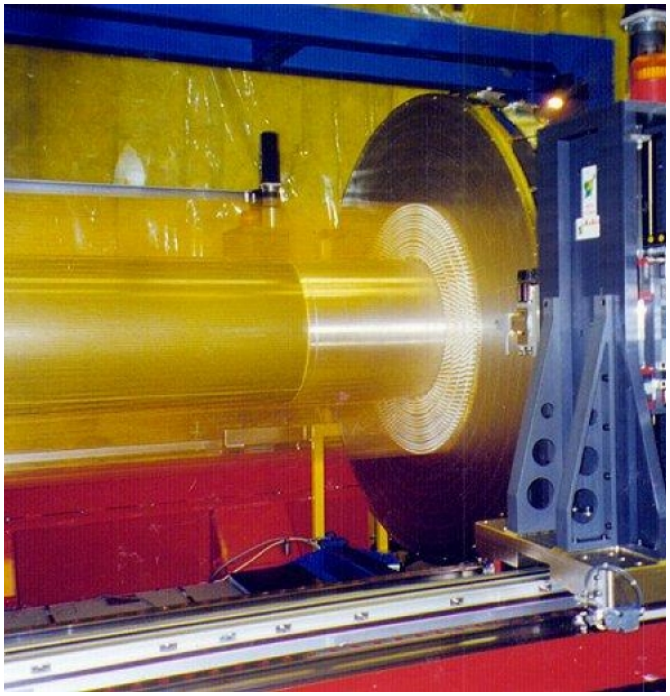
	Sense	Field
Material	Tungsten	Aluminum
Plating	Gold	No
Diameter (μm)	30	126
Tension (g)	50	80
Number of wires	14,336	42,240

Charged particle tracking

- *Two main technologies*
  - *Silicon (e.g. Belle II PXD, SVD)*
  - *Gas wire chambers (e.g. Belle II CDC)*

- *Silicon*
  - *High position resolution, but expensive (usually only a few layers)*
  - *Mostly used as vertex detectors relatively close to the beam interaction point*
- *Gas wire chambers*
  - *Typically, good precision; comparatively cheap; many layers simplify track finding*
  - *Used outside of silicon detectors*

Wires of the Babar drift chamber



Belle II Detector