Belle II Vertex Detector Performance

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*for the **Belle II PXD Collaboration***
*& **Belle II SVD Collaboration***

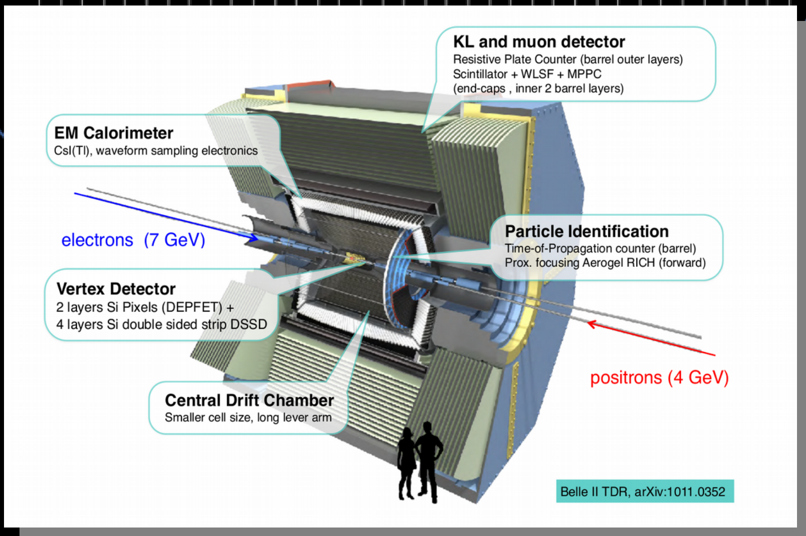
VERTEX 2019

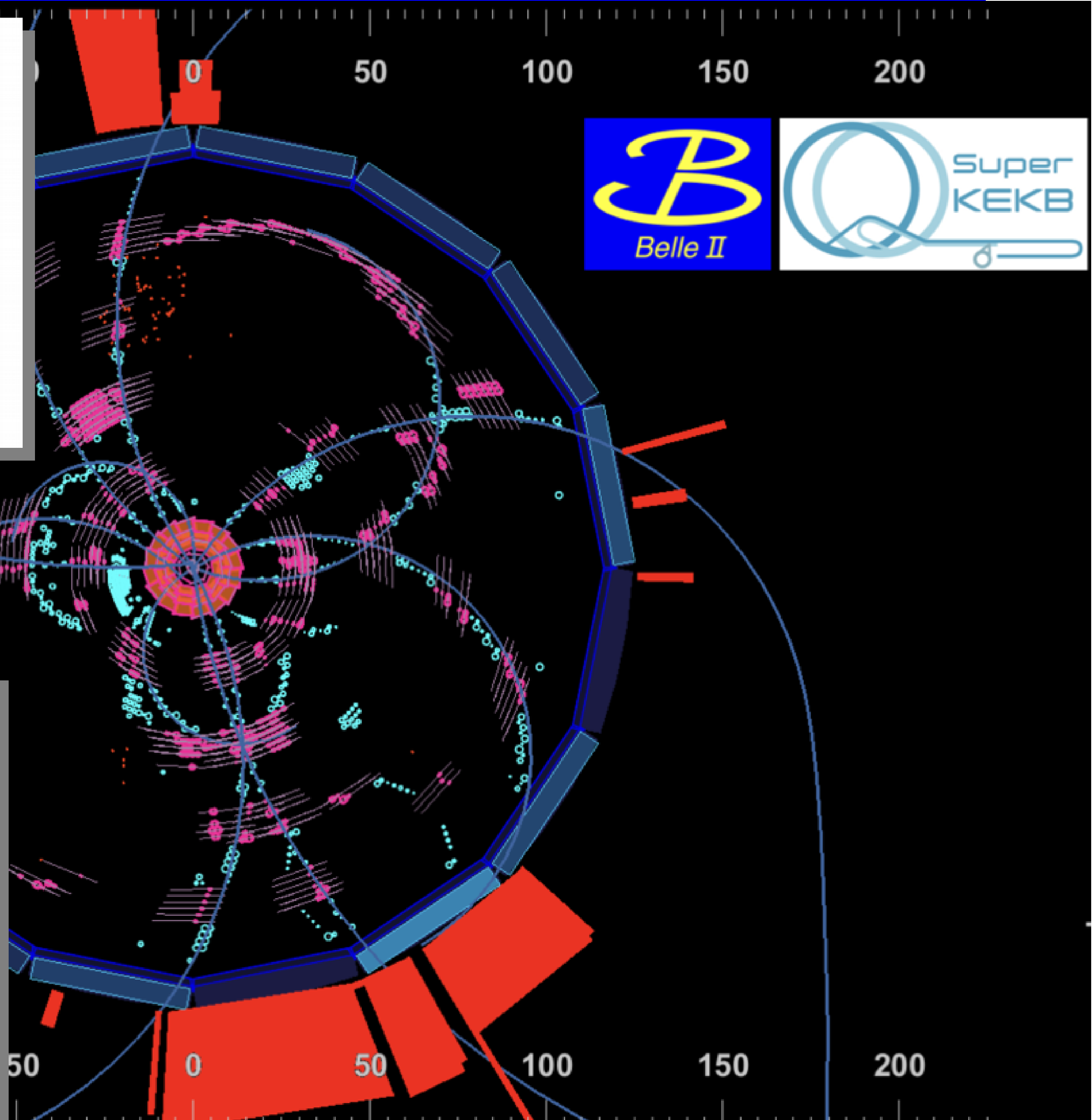
The 28th International Workshop on Vertex Detectors

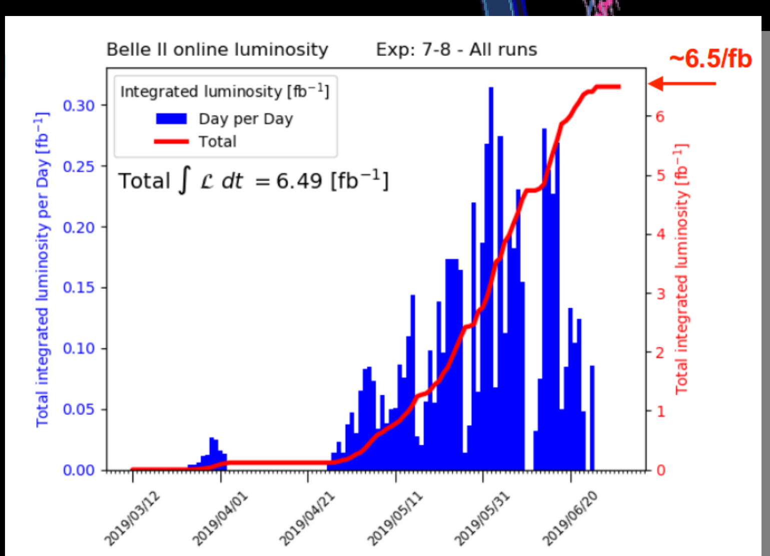
13 – 18 October 2019

Lopud Island, Croatia

We got the first physics data...

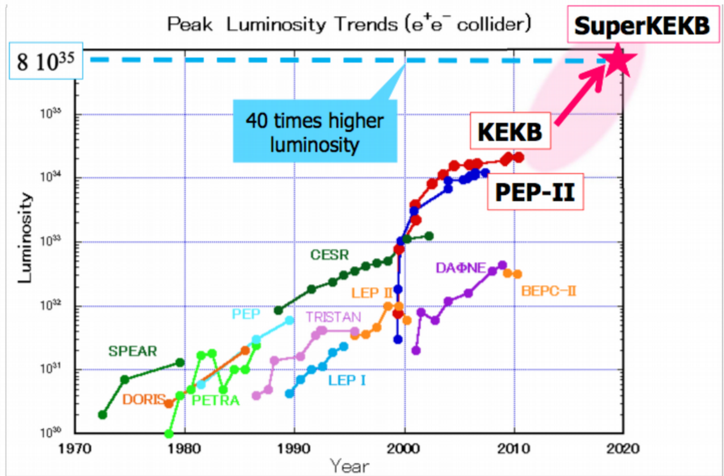






… but we want much more!

$\mathscr{L}_{peak} = 2 \cdot 10^{34} \rightarrow 8 \cdot 10^{35}\ cm^{-2}s^{-1}$



Belle II has a broad physics program at the **precison** frontier – key ingredients:

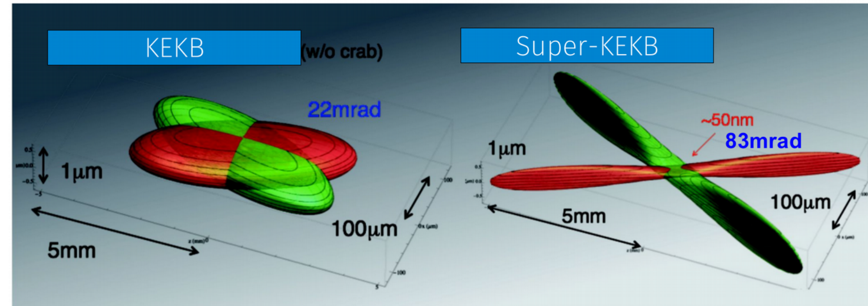
Increase statistics – record 50ab^{-1} of data by increasing luminosity (squeeze beams & larger currents)

Reduce systematics – state-of-the-art detector and *software*

beam current

$$L = \frac{\gamma_{\pm}}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

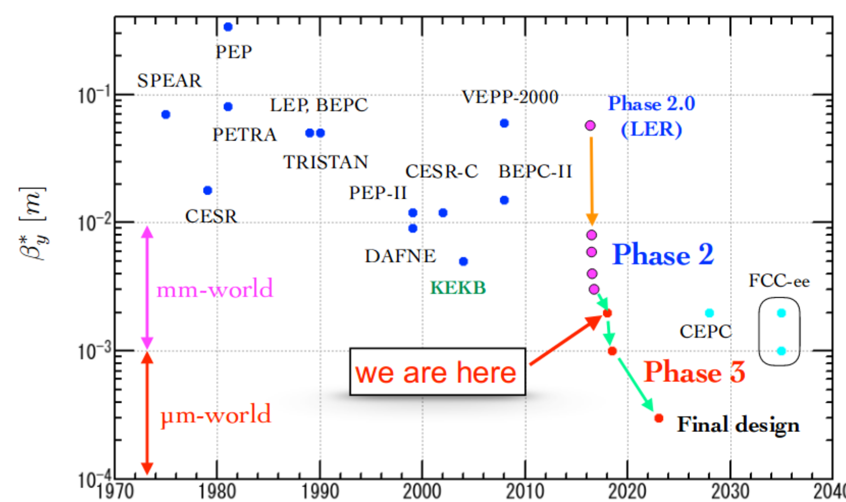
vertical beta function at IP



	E (GeV) LER/HER	β*$_y$ (mm) LER/HER	β*$_x$ (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

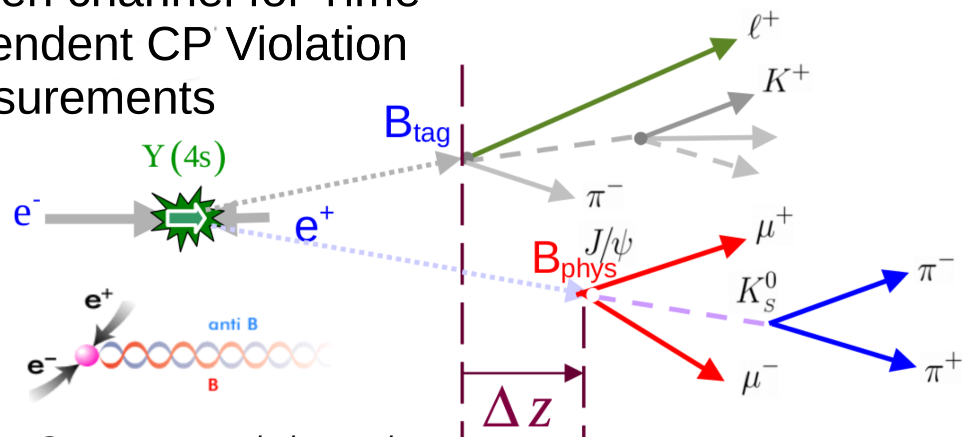
factor 20

factor 2-3



Vertexing @ Belle II

Golden channel for Time-Dependent CP Violation measurements



Quantum entangled neutral B meson pair production

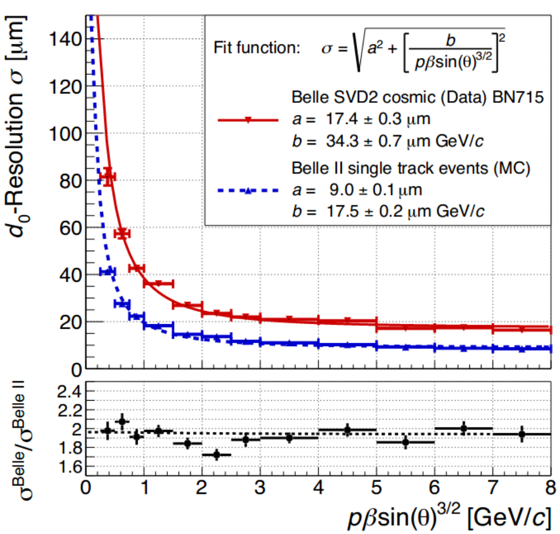
Belle ~ 200 μm
Belle II ~ 130 μm

$$\Delta z = \Delta t \cdot \beta\gamma c$$

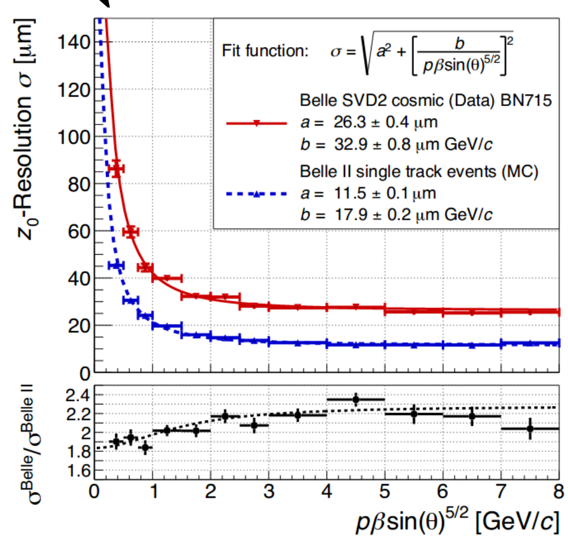
Typical Υ(4S) Event

- Υ(4S) center of mass is boosted
  - 7 GeV e− on 4 GeV e+ → βγ = 0.28
  - reduced boost w.r.t. Belle
- average multiplicities
  - 11 charged tracks
  - 5 neutral pions
  - 1 neutral kaon
- soft charged tracks momentum spectrum

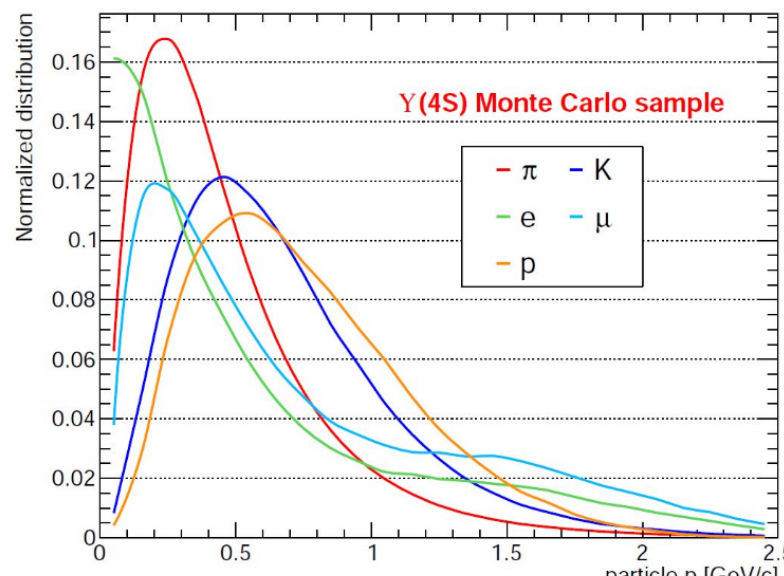
Belle data vs. Belle II MC simulation (2 layer PXD):



d_0 resolution



z_0 resolution

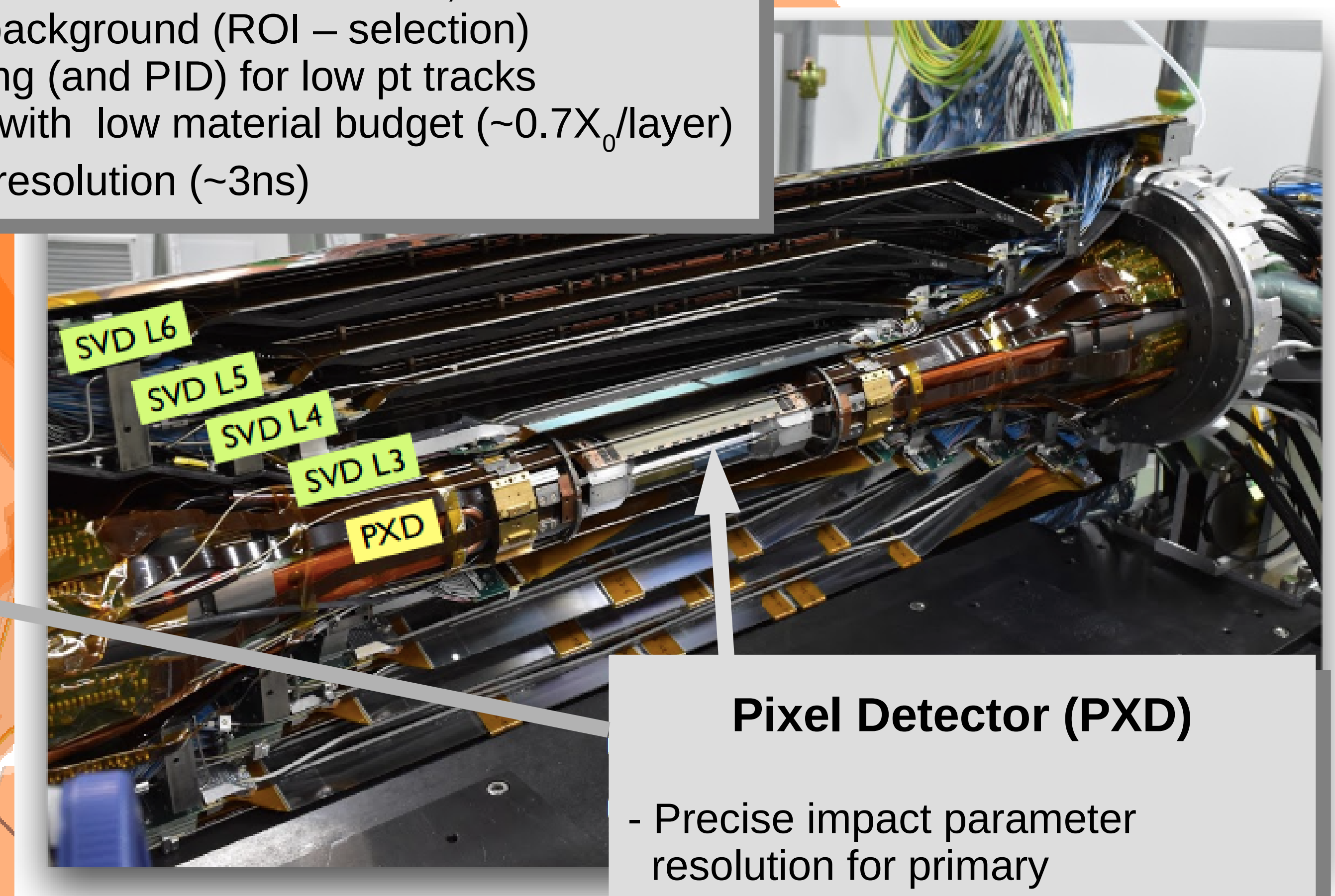


Single track vertex resolutions
~ 2 x times better than Belle

Belle II Vertex Detector in 2019 physics run

Silicon Vertex Detector (SVD)

- Extrapolate to pixel to match hits to tracks, despite machine background (ROI – selection)
- Standalone tracking (and PID) for low pt tracks
- 6 layers of DSSD with low material budget (~0.7X_0/layer)
- Excellent hit time resolution (~3ns)



Pixel Detector (PXD)

- Precise impact parameter resolution for primary and secondary vertices
- 8M DEPFET pixels in 2 layers* (~0.2X_0/layer)
- 1st layer @ 14mm from IP

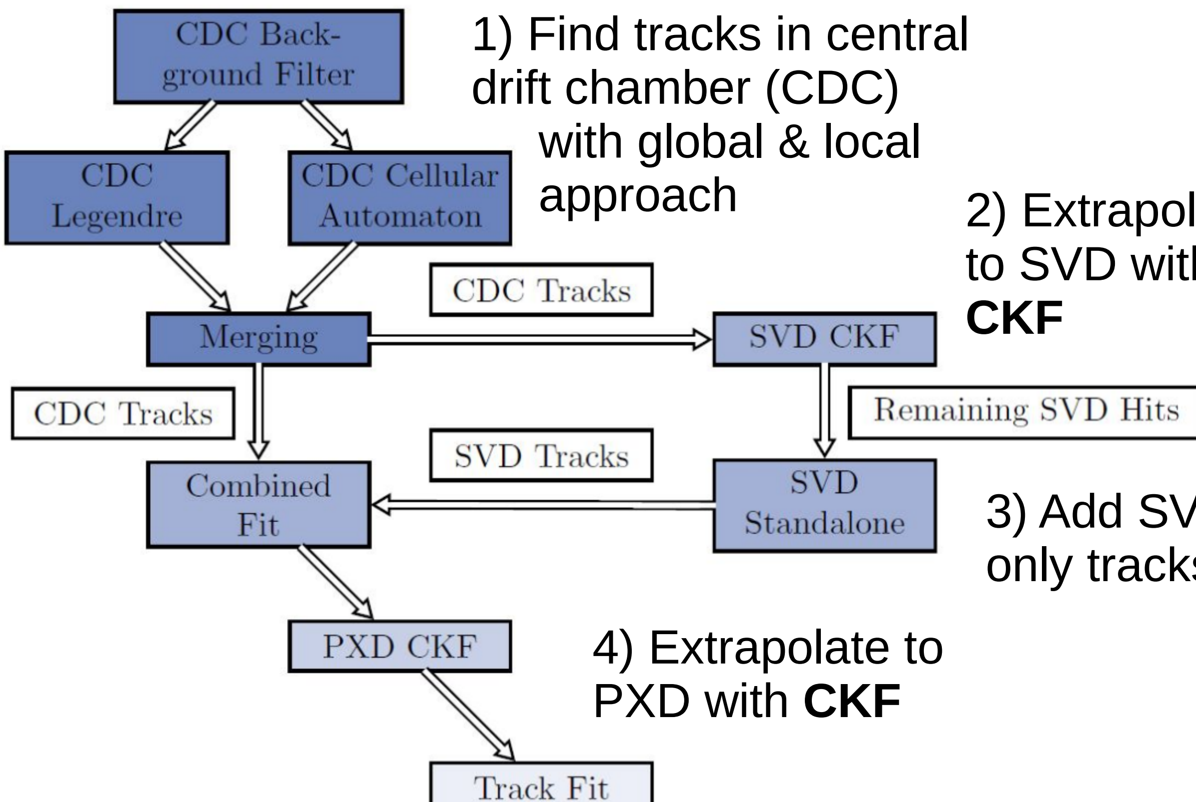
*2nd PXD layer has only 4 sensors installed (upgrade to full PXD in 2021)

Track Finding @ Belle II

- Modular tracking design

  Finding, fitting and merging strategy can be adjusted to background conditions / detector degradation or to find cosmics

<u>Standard reconstruction track-finding workflow</u>



1) Find tracks in central drift chamber (CDC) with global & local approach

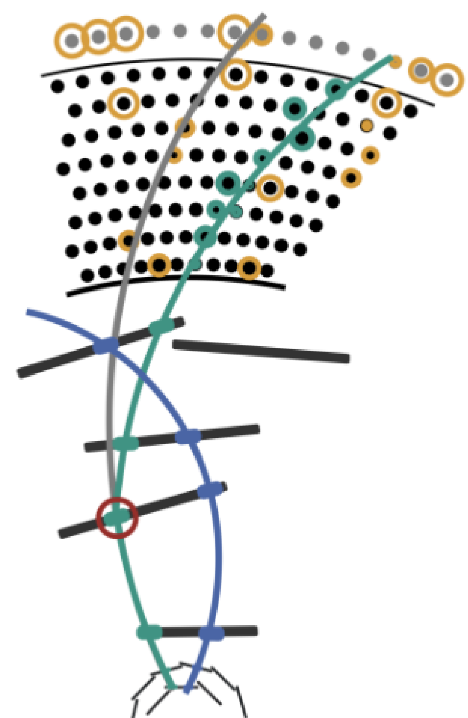
2) Extrapolate to SVD with **CKF**

3) Add SVD-only tracks

4) Extrapolate to PXD with **CKF**

Combinatorial Kalman Filter (**CKF**)

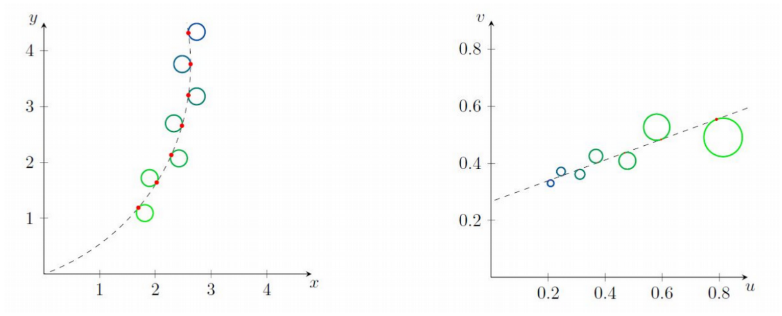
- Extrapolates track inward and looks for hits to attach, updating the track parameter predictions
- BDT based hit filtering and dumplicates removals



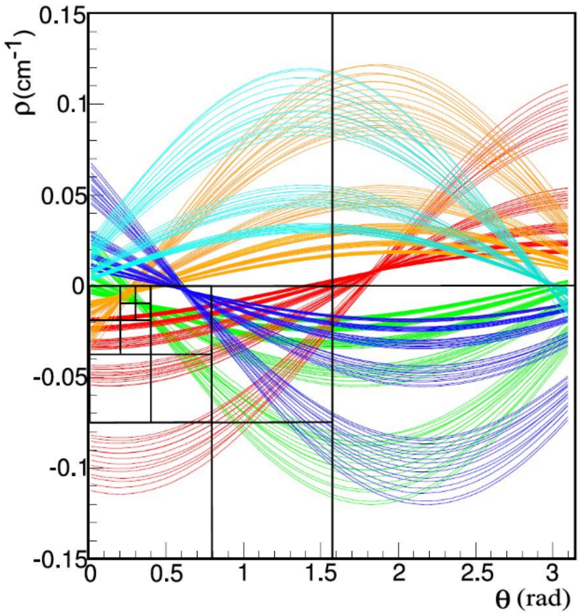
Track Finding @ Belle II: Central Drift Chamber (CDC)

Global CDC Track-Finding

Conformal transformation maps circles (helices in x-y plane) to straight lines

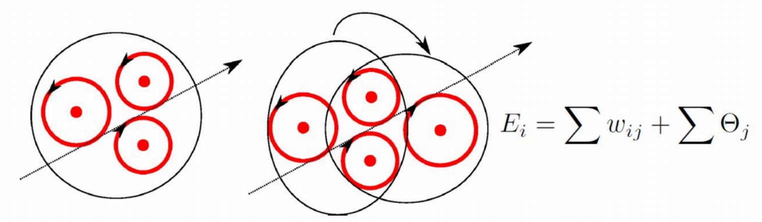


Find tracks as tangents to drift circles by determining points of maximal density in parameter space

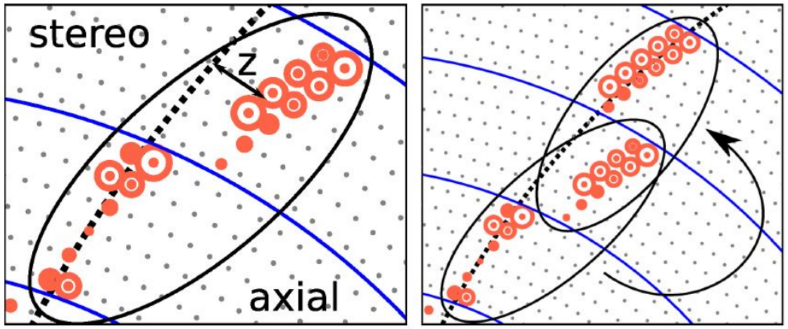


Local CDC Track-Finding

Cellular automation (CA) formed from triplets and linear segments (vertices) and neighboring triplets sharing hits (edges), weigths based on common fit quality

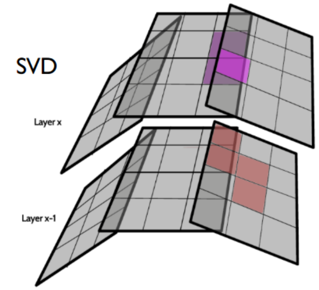


CA with vertices from pairs of segments in axial+stereo (z-measurement) layers, weights from Riemann fit in x-y and s-z

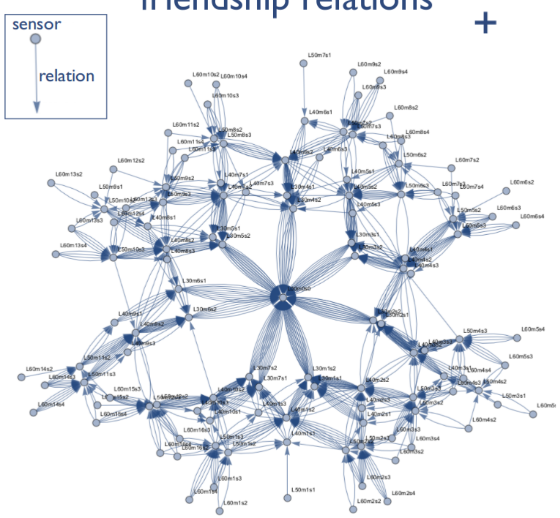


SVD Standalone Track Finding & Track Finding Performance on MC

Reduce combinatorics by combining space-points from compatible (friend) sectors and applying filters to reject background hits



friendship relations + filters



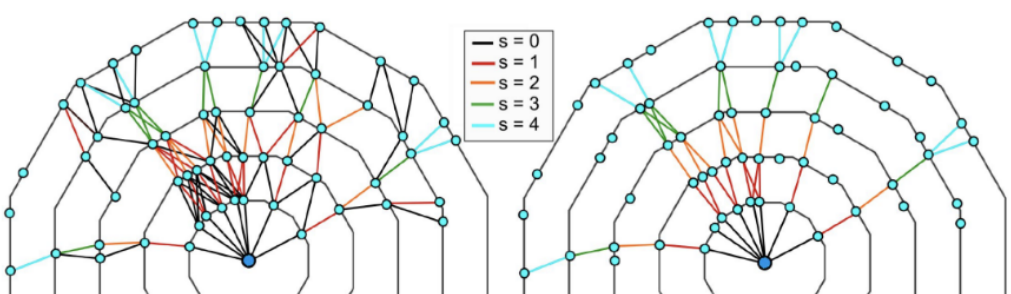
- Cut(Distance3D)
- Cut(Distance2D)
- Cut(SlopeRZ)
- Cut(Distance1DZ)
- Cut(CosXY)
- AllCuts = allowed region

\+

cluster time difference

Training of friendship relations and filters on MC → **SectorMap**

Space-points + SectorMap → Segment network → Cellular automaton finds longest paths:

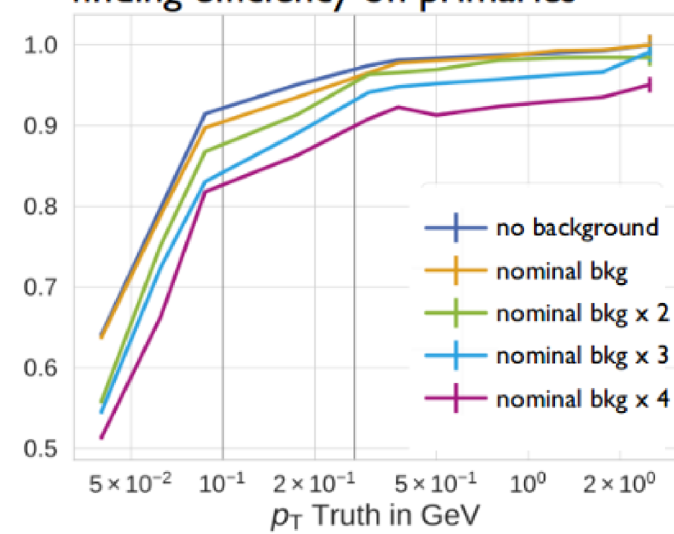


Fake and clone tracks (hits) removed based on quality indicator (triplet fit, Chi2 of triplets, p-value of competing tracks)

Overall track-finding performance on simulated events vs pt and beam background

(CDC + SVD + PXD 2021)

finding efficiency on primaries(*)



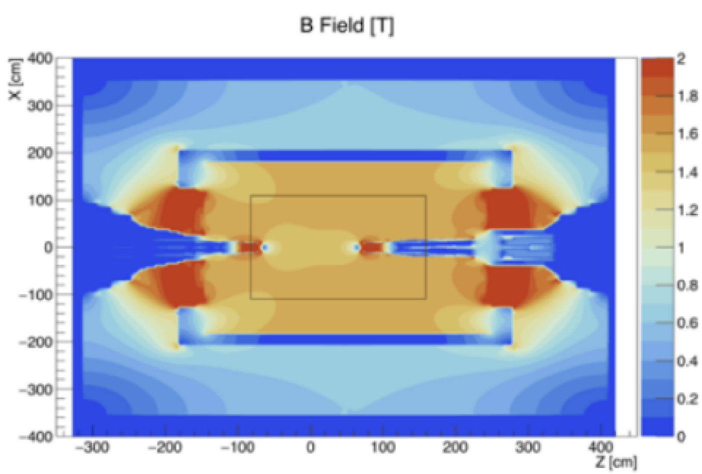
(*) factoring out the geometrical acceptance

- Track finding efficiency > 90% for p_t>100MeV/c @ nominal bkg.
- Robust against beam background
- Can find tracks down to 50MeV/c
- Acceptable performance with 2 x nominal background
- Optimizations still ahead

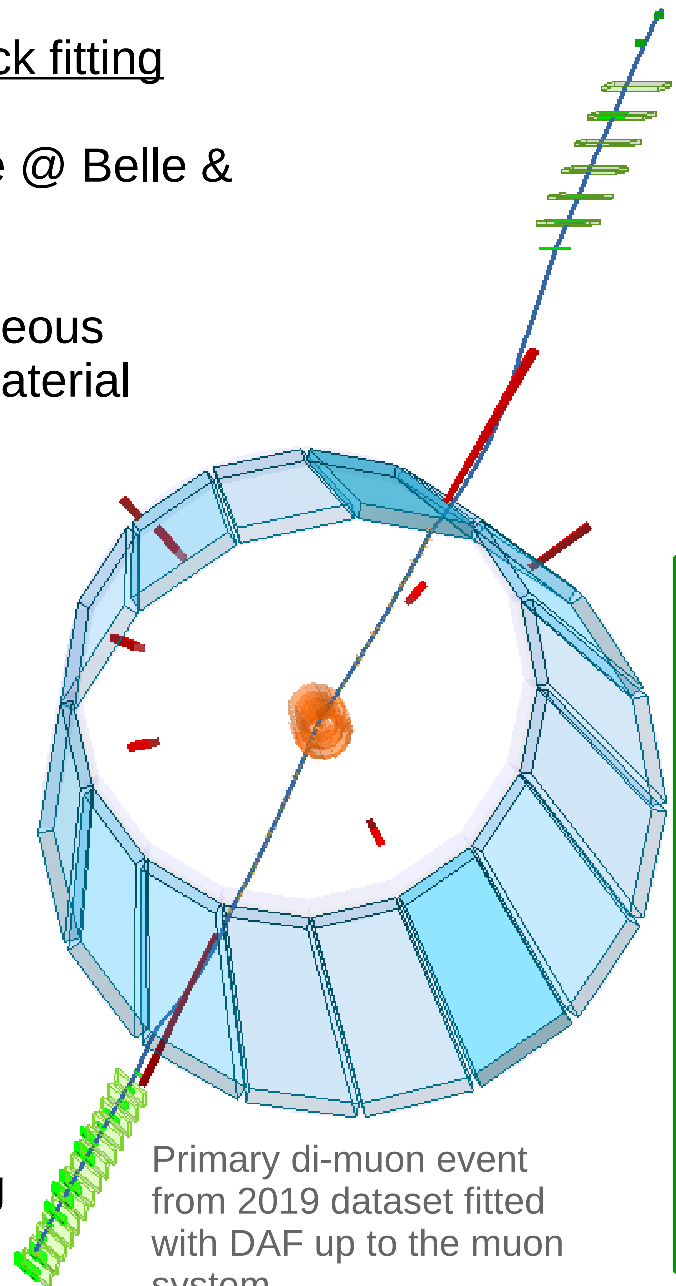
Track & Vertex Fitting @ Belle II

GENFIT Toolkit for generic track fitting

- rewritten based on experience @ Belle & COMPAS & PANDA
- any measurement type
- takes into account inhomogeneous magnetic field, energy loss & material effects



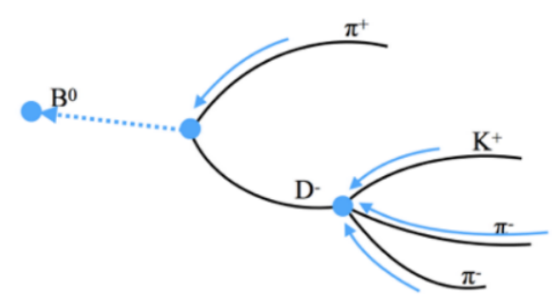
- several fitters implemented:
  - **Kalman**
  - **General Broken Lines** (for alignment)
  - **Deterministic Annealing Filter** (DAF) (our default)



Primary di-muon event from 2019 dataset fitted with DAF up to the muon system

Vertex Fitters @ Belle II

- **Kfit** – Belle (I) implementation, minimum least squares
- **Rave** – standalone implementation of CMS libraries, Kalman based
- **TreeFitter** – Belle II implementation of global decay chain fit, Kalman based, can use various constraints, fit neutrals, lifetimes ...

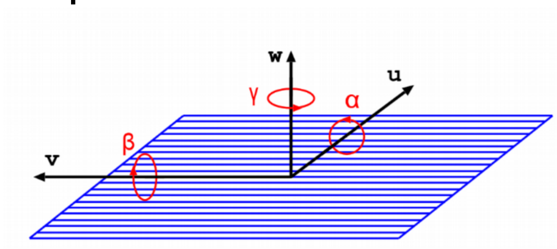


Track Based Alignment @ Belle II

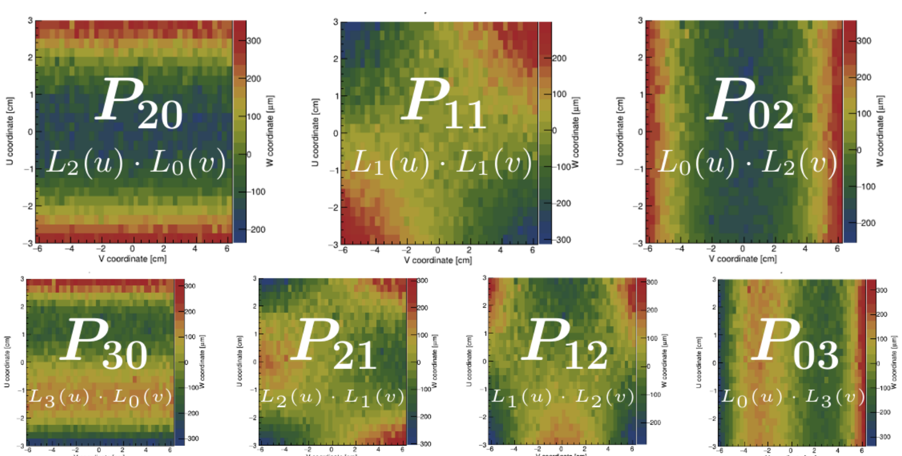
- Alignment & calibration are key ingredients to reach target performance of the detector
- Single fully integrated track based alignment method for pixel & strip, central drift chamber and muon system based on **Millepede II** and **General Broken Lines** track model

VXD alignment parameters

6 rigid body paramaters per half-shell (x 4), ladder (x 65) and sensor (x 212)



+ 3 + 4 (+ 5) parameters for surface deformations for each sensor (2D Legendre polynomials up to 4th order)

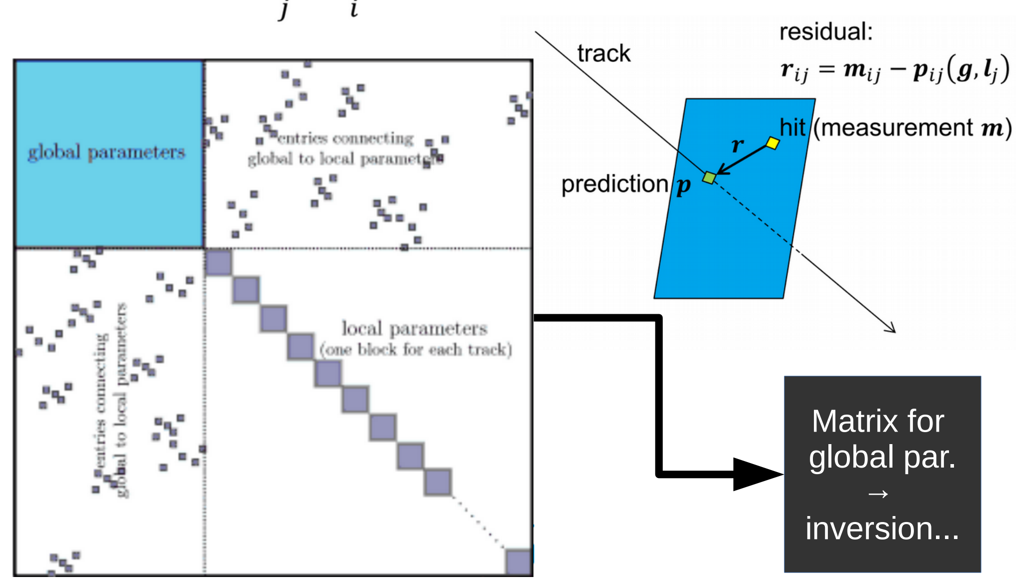


Millepede II

- Global linearized Chi2 minimization for very large number of parameters
- Used @ H1, CMS, Mu3e, COMPASS ...

Minimize χ^2 w.r.t alignment parameters

$$\chi^2(\boldsymbol{g},\boldsymbol{l}) = \sum_{j}^{\text{tracks}} \sum_{i}^{\text{hits}} \boldsymbol{r}_{ij}^T(\boldsymbol{g},\boldsymbol{l}_j)\, V_{ij}^{-1}\, \boldsymbol{r}_{ij}(\boldsymbol{g},\boldsymbol{l}_j)$$

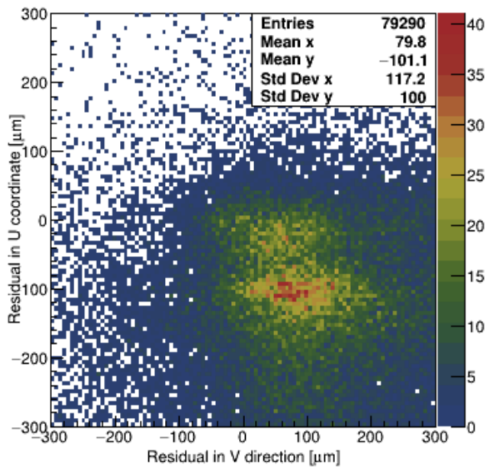


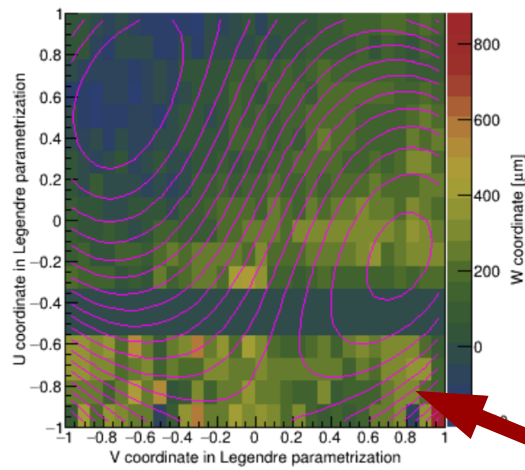
$\boldsymbol{g}$ ... alignment parameters (global)
$\boldsymbol{l}_j$ ... track parameters (local)

= up to 4230 VXD alignment parameters (Lorentz angle calibration under development)

Performance with data
Track-to-hit residuals & sensor deformations

Initially large displacements (100‘s of um) and sensor deformations (up to ~0.5mm for some SVD sensors)

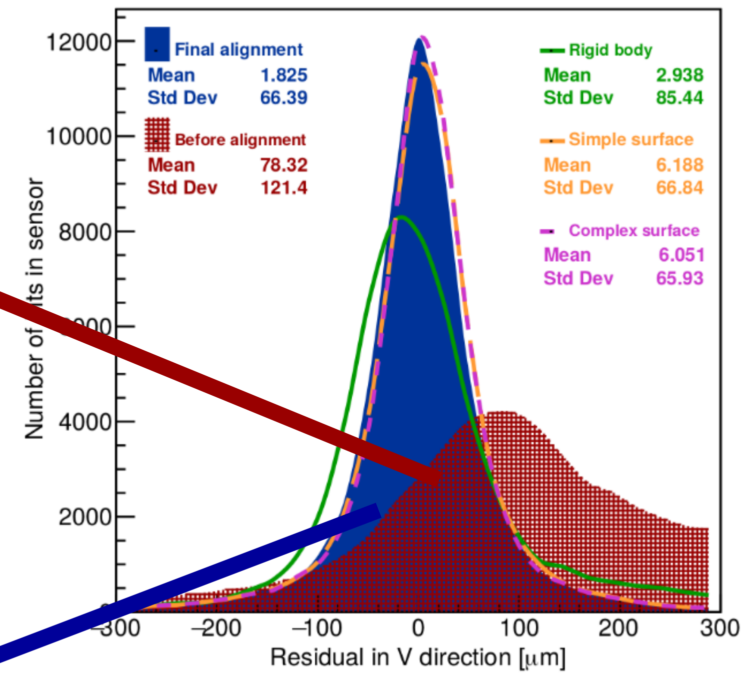


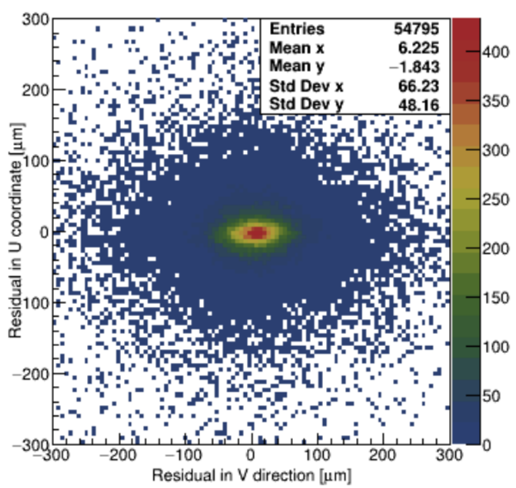


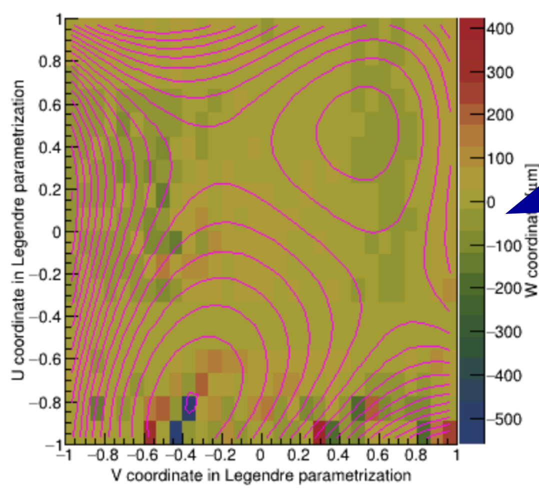
2D track-to-hit residuals in one SVD sensor (L4)

Sensor **deviation from flatness** derived from residuals dependence on angles of non-perpendicular tracks

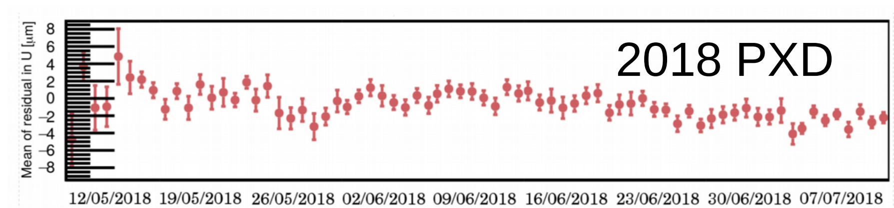
Sensor deformation have significant impact on track-to-hit residual distributions and resolutions







After alignment, the sensors are near to flat and residual distributions optimal



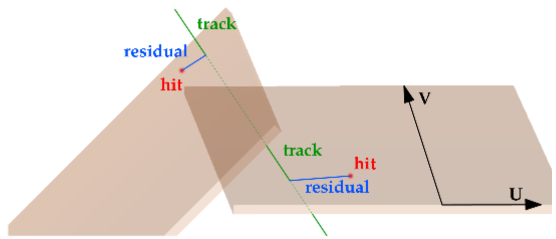
Monitoring stability using residuals after alignment (stable within < 10/20um for PXD/SVD)

Performance with 2019 (cosmic) data
Overlap Track-to-hit residuals

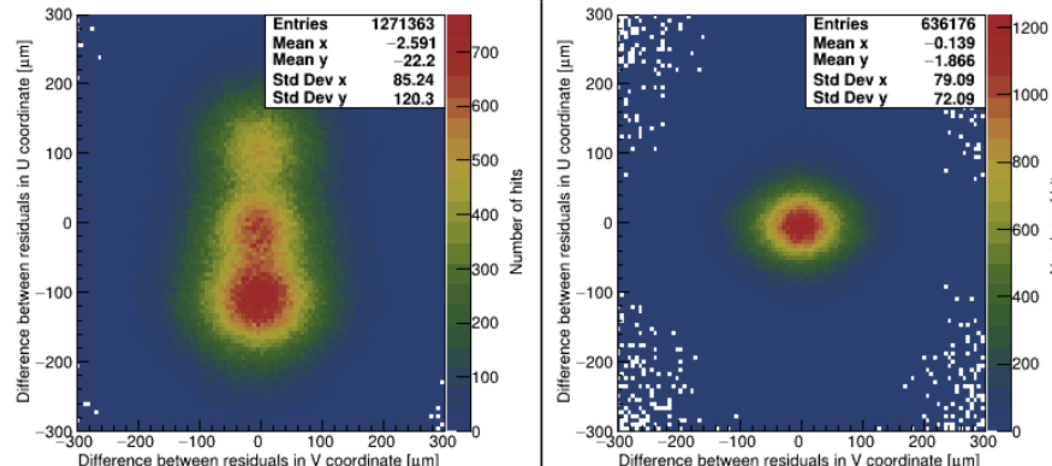
Powerfull method (but needs large statistics) to detect detector misalignment to which standard residuals (and alignment) are only weakly sensitive (weak modes), like radial expansion, twist etc.

<u>Separate tracks to 3 categories:</u>

1) With a double hit in some layer (direct neighbouring sensors) (< 10% of tracks)



February 2019 | April 2019



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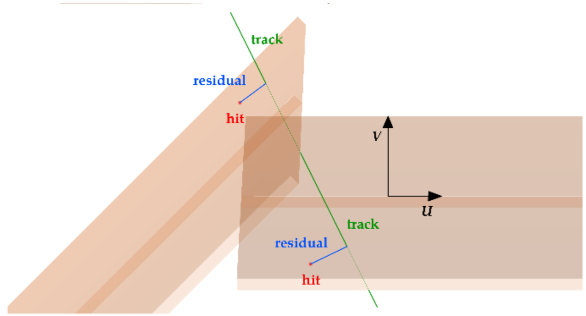
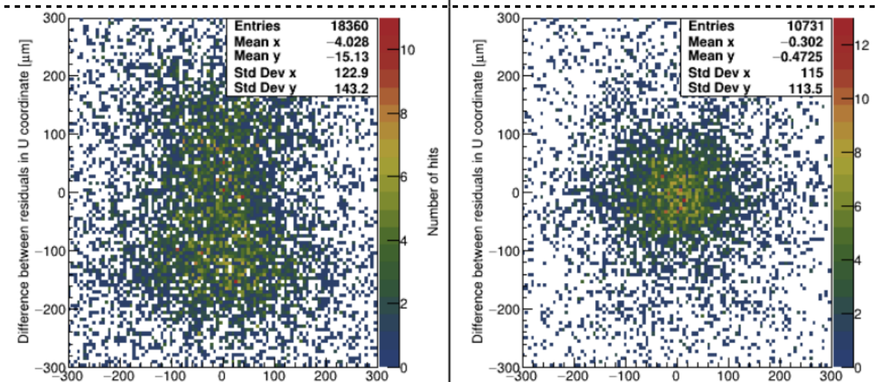
2) With a double hit in some layer (next neighbouring sensor) (additional 2 orders of magnitude smaller statistics)





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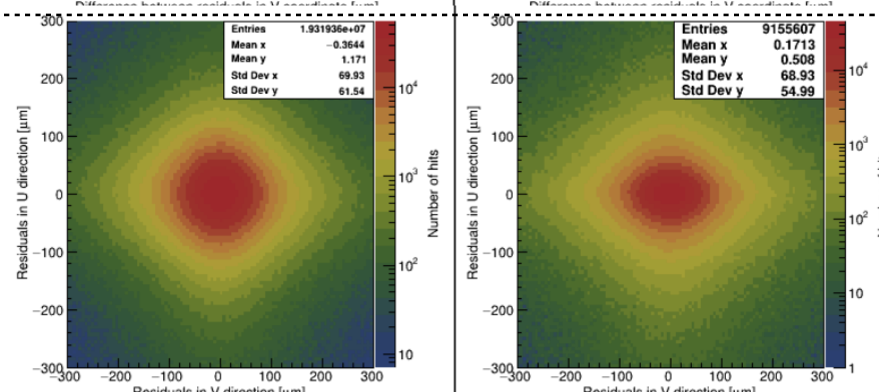
3) Others: „standard residuals“

Standard residuals did not show anything striking!



Initial validation with 2019 cosmics → found issue with wrong pitch size for SVD sensors in software. No indications of significant problems in overlap residuals afterwards (but still wider than simulations).

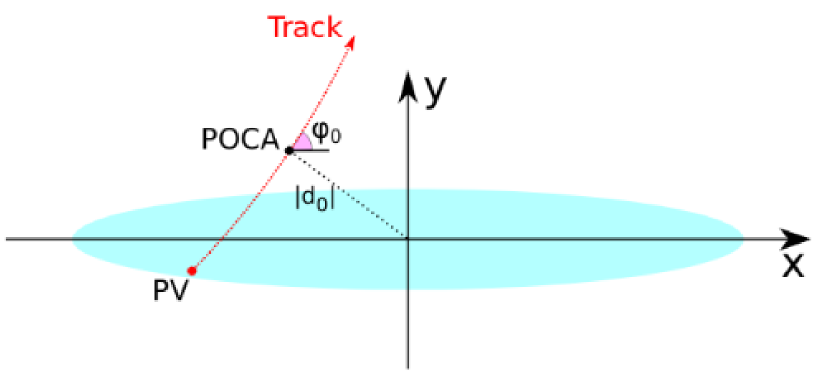
Performance with 2019 data
Measuring vertex resolution (1/3)

<u>Standard method</u>
Compare two tracks
with common vertex

Difference of + and – track parameters at point of closest approach (POCA) to origin measure vertex resolution

$$\Delta d_0 \equiv d_0(t_-) + d_0(t_+).$$

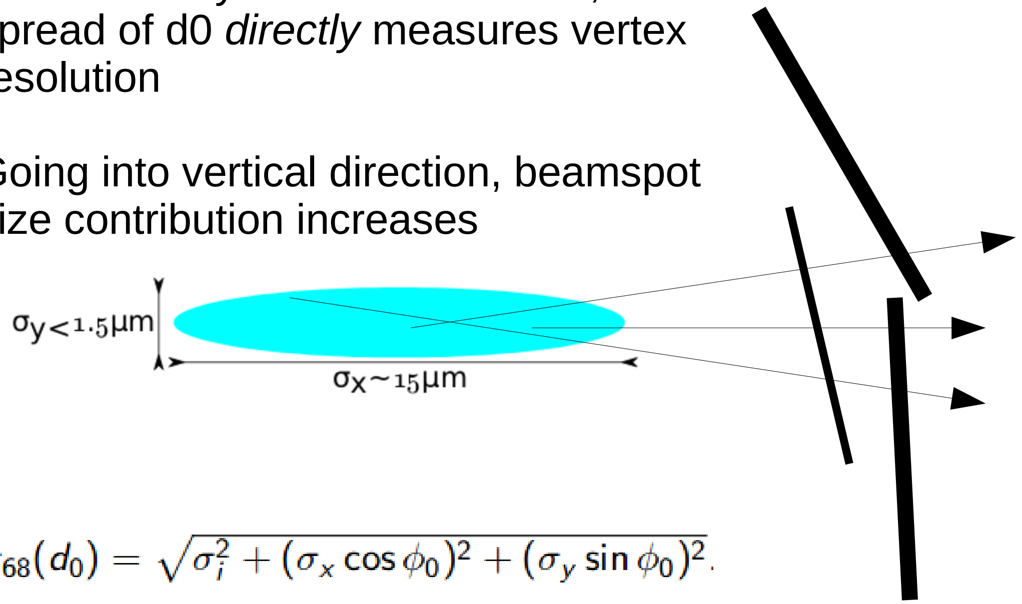
Track parameters @ POCA:



<u>Trick with super-small beamspot</u>
and single tracks

Our **vertical beamspot size** is so tiny, that for nearly **horizontal tracks**, the spread of d0 *directly* measures vertex resolution

Going into vertical direction, beamspot size contribution increases

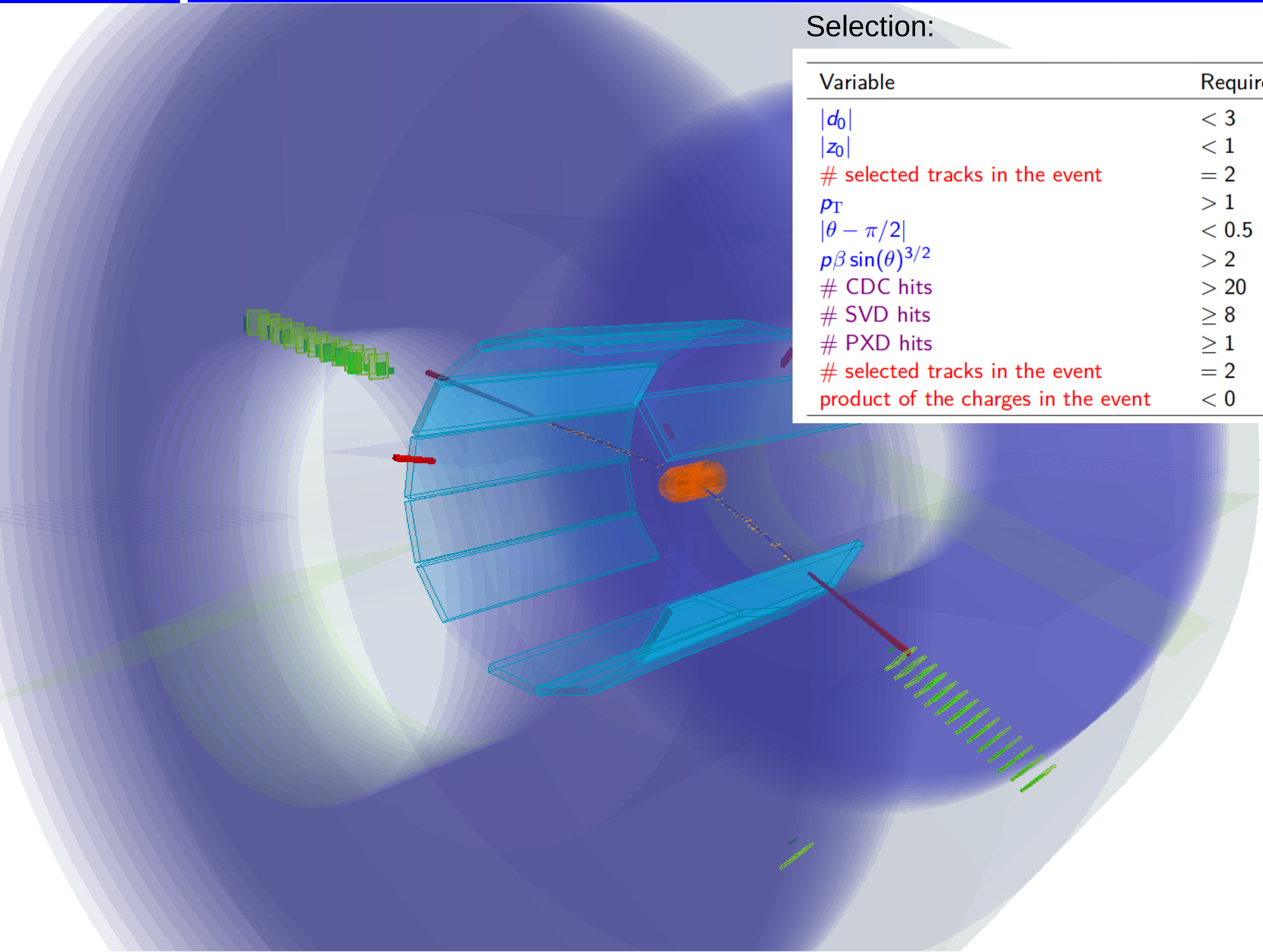


$$\sigma_{68}(d_0) = \sqrt{\sigma_i^2 + (\sigma_x \cos\phi_0)^2 + (\sigma_y \sin\phi_0)^2}.$$

Beamspot sizes derived from machine parameters for initial physics runs in 2019:

$$\sigma_x = 14.8\,\mu\text{m},\ \sigma_y = 1.5\,\mu\text{m},\ \sigma_z = 357\,\mu\text{m}.$$

Measuring vertex resolution (2/3)
Look at di-muon and Bhabha events…



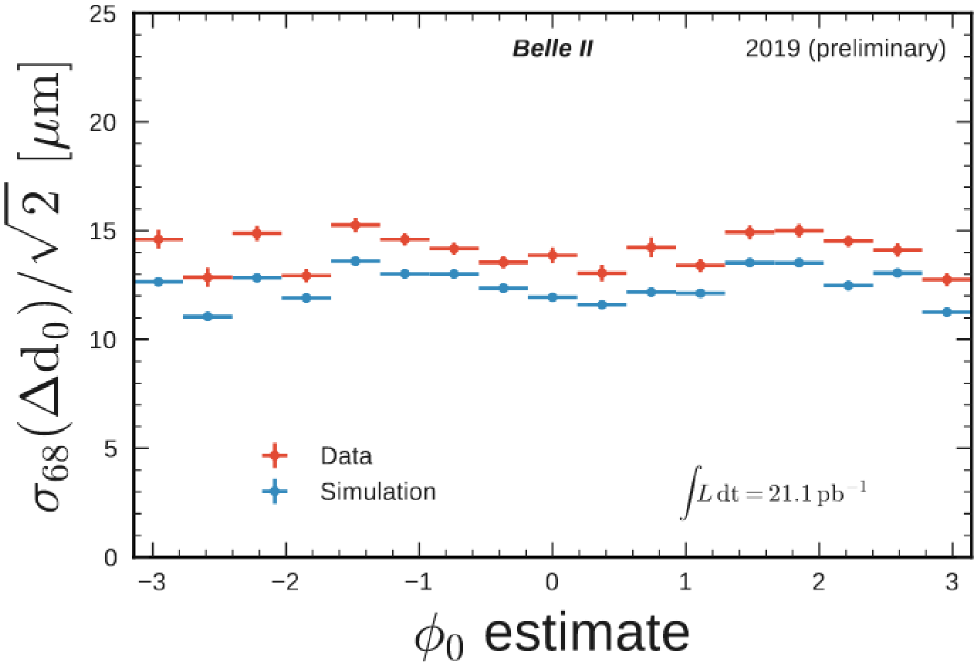
Selection:

Variable	Requirement	Unit
$\|d_0\|$	< 3	mm
$\|z_0\|$	< 1	cm
# selected tracks in the event	$= 2$	
p_T	> 1	GeV/c
$\|\theta - \pi/2\|$	< 0.5	
$p\beta \sin(\theta)^{3/2}$	> 2	GeV/c
# CDC hits	> 20	
# SVD hits	≥ 8	
# PXD hits	≥ 1	
# selected tracks in the event	$= 2$	
product of the charges in the event	< 0	C^2

Performance with 2019 data
Measuring vertex resolution (3/3)

<u>Standard method</u>

$$\Delta d_0 \equiv d_0(t_-) + d_0(t_+).$$

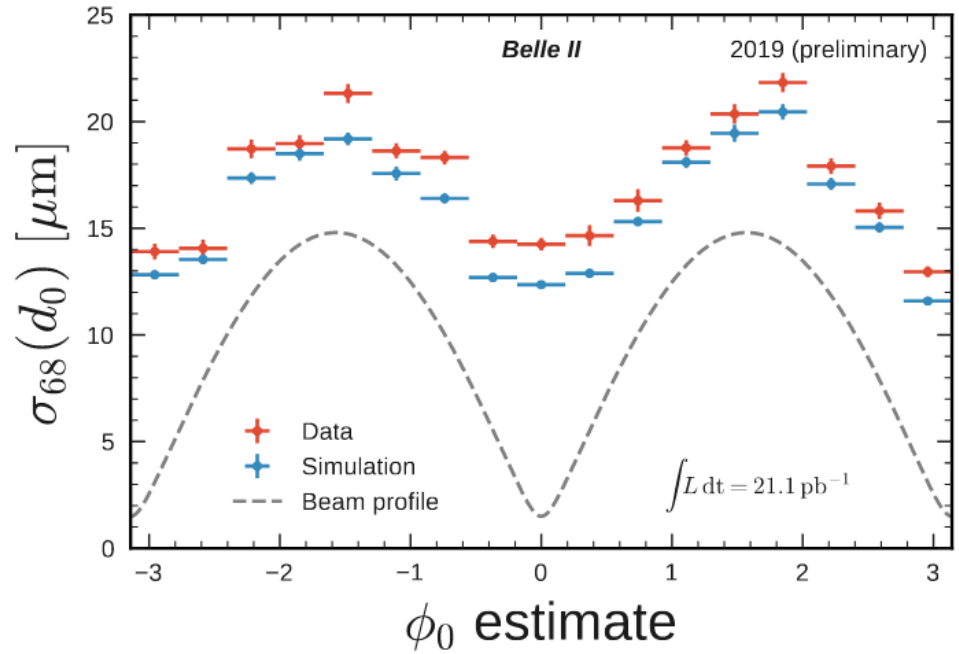


d_0 resolution estimate:

- Data: $\hat{\sigma}(d_0) = \sigma_{68}(\Delta d_0)/\sqrt{2} = 14.1 \pm 0.1\ \mu\mathrm{m}$,
- Simulation: $\hat{\sigma}(d_0) = \sigma_{68}(\Delta d_0)/\sqrt{2} = 12.5 \pm 0.1\ \mu\mathrm{m}$.

<u>Trick with super-small beamspot</u>

$$\sigma_{68}(d_0) = \sqrt{\sigma_i^2 + (\sigma_x \cos\phi_0)^2 + (\sigma_y \sin\phi_0)^2}.$$



Minimum @ ~ 14um for horizontal tracks (beam profile only contributes ~ 1.5um)

→ Both methods agree (also the slight discrepancy to MC simulation)

Impact parameter resolution in d0:

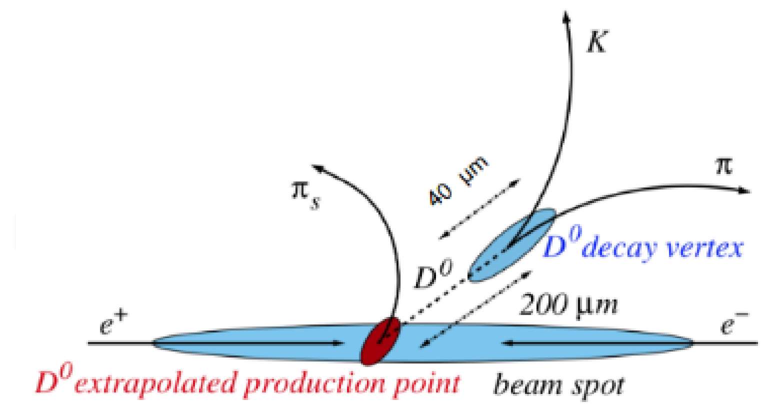
14.1 +/- 0.1 (stat) um

MC simulation probably too optimistic + sensor parameters not optimal + ...

Performance with 2019 data
D0 Lifetime Measurement

D* → pi_{slow} D0 (→ K pi)

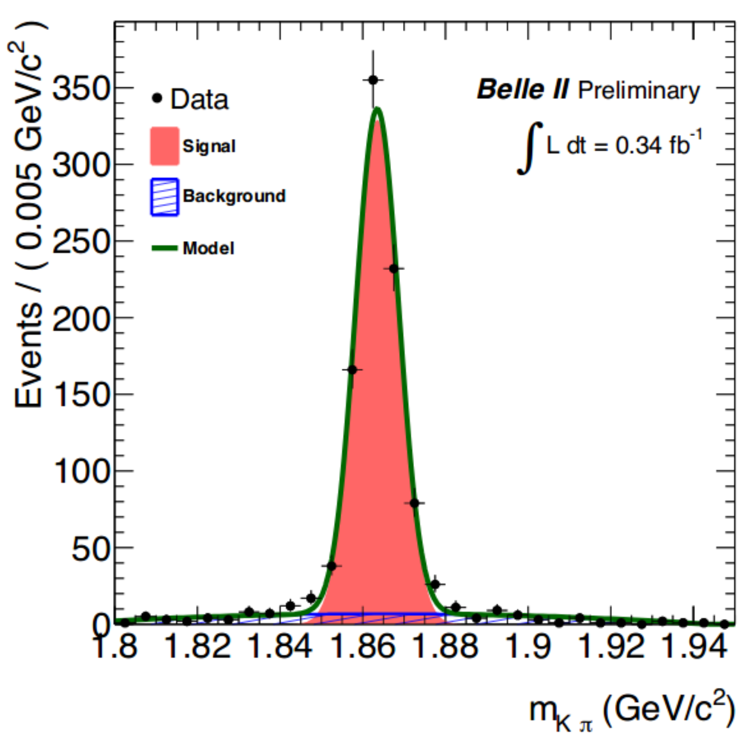
- Powerful test of reconstruction performance: VXD reconstruction, tracking and vertex fitting
- Using **TreeFitter** for full decay chain fit → direct extraction of long-living particle lifetimes
- Short-lived D* constrained to measured beamspot

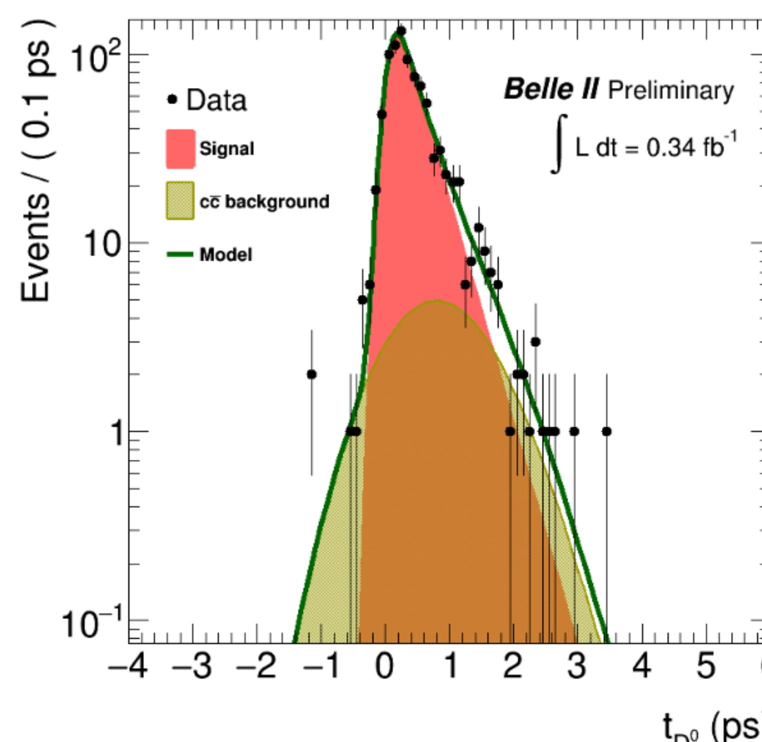


Extracted D0 lifetime: 370 +/- 40 (stat) fs
(using only small fraction of 2019 data)

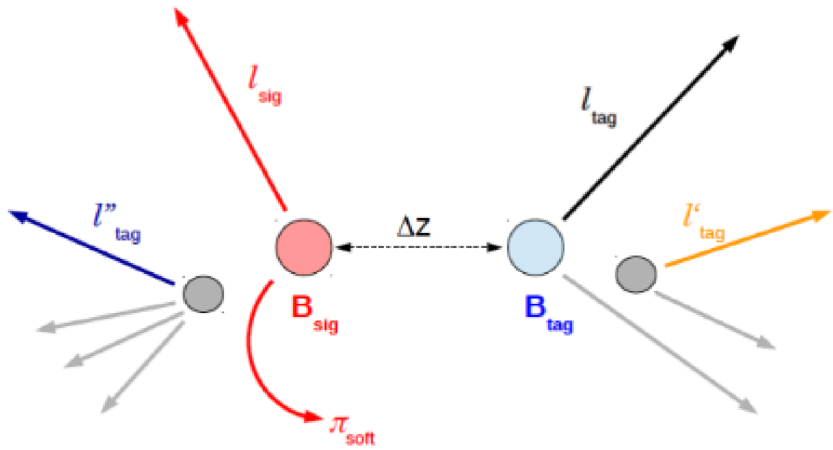
PDG:

VALUE (10^{-15} s)	EVTS
410.1± 1.5 OUR AVERAGE	





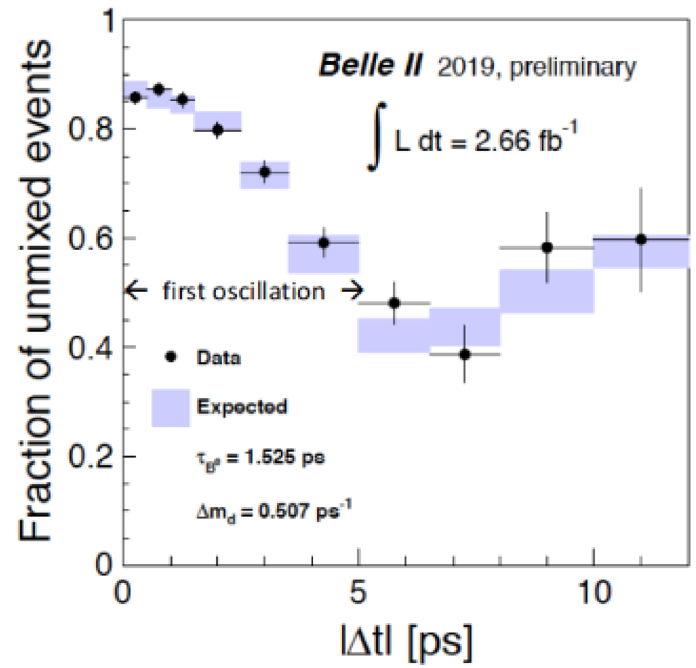
Performance with 2019 data
Measuring B0 – anti-B0 mixing

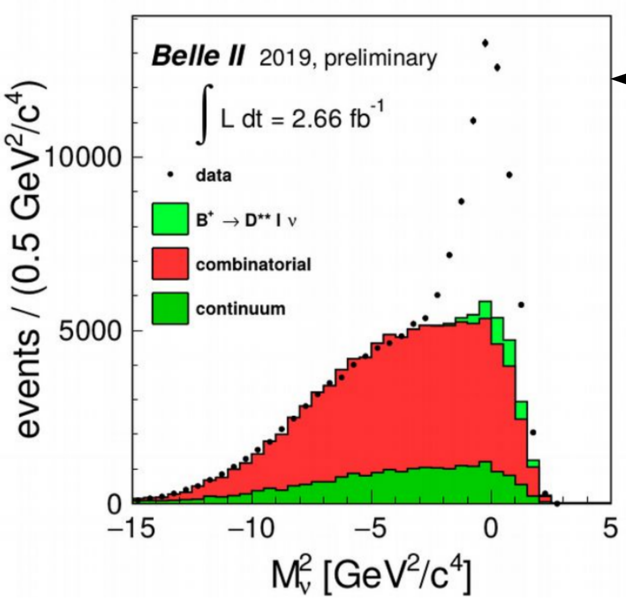


Semileptonic B^0s decays on both sides:

- $B^0_{sig} \rightarrow D^* l_{sig} \nu$ ($D^{*-} \rightarrow D^0 \pi_{soft}$)
- $B^0_{tag} \rightarrow l_{tag}$

$$A(|\Delta t|) = \frac{N_U(|\Delta t|)}{N_U(|\Delta t|) + N_M(|\Delta t|)}$$





Vertices determined by extrapolating lepton tracks to the beamspot → delta Z (+ boost) → delta t (from initial state determined from tag side decay)

Signal and tag side leptons should have opposite charge (determines B0 flavour) – but same charge (Mixed) events start to appear over time
→ neutral B meson mixing

Conclusion

- Data taking started! Autumn run starts soon
- B-Physics requires excellent performance of vertex reconstruction
  - Includes also track finding, fitting and detector calibration (including alignment)
- Performance validations and monitoring with first data from low-level (residuals) to physics-level studies confirm all parts of the vertex ecosystem work

Transverse impact parameter (d_0) resolution*: ~ 14 um

(close to expectations)

  - But we still need some „fine-tuning“ and understand subtle features (visible only because we are so precise :-)
- Most fun still ahead!

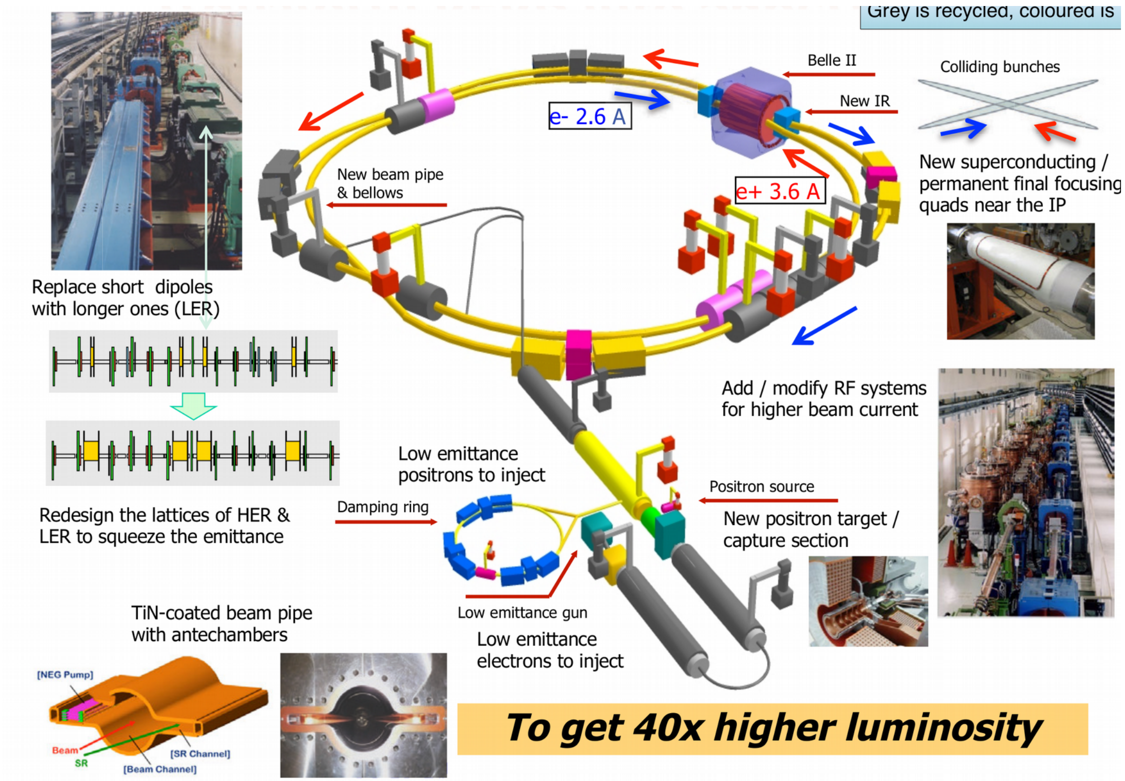
*Measured in 2019 spring data, before PXD accident. Will get even better with full PXD in 2021...

Thank you for your attention!

BACKUP

Belle II

KEKB → SuperKEKB

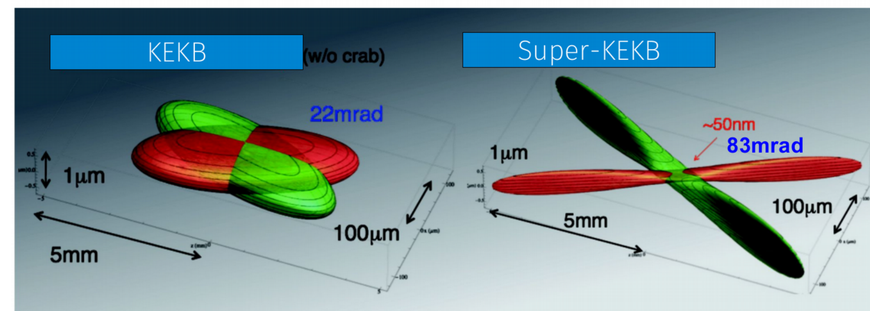


To get 40x higher luminosity

beam current

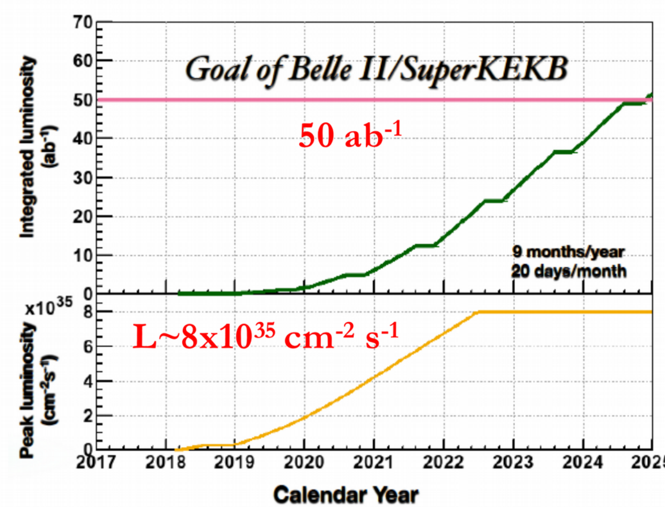
$$L=\frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

vertical beta function at IP



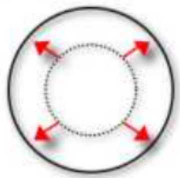
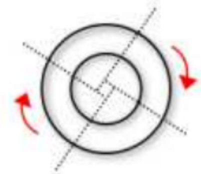
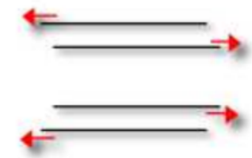
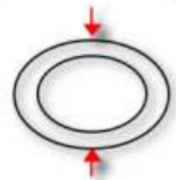
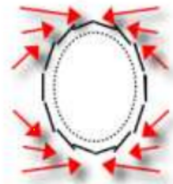
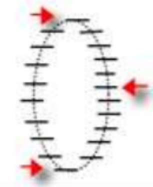
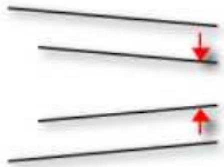
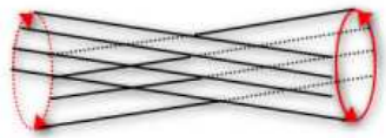
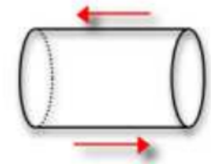
	E (GeV) LER/HER	β*$_y$ (mm) LER/HER	β*$_x$ (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20 factor 2-3



Belle II

Typical Weak Modes in Alignment for Detectors with B-Field & Cylindrical Symmet

	ΔR	Δϕ	ΔZ
R	**Radial Expansion** (distance scale) 	**Curl** (Charge asymmetry) 	**Telescope** (COM boost) 
ϕ	**Elliptical** (vertex mass) 	**Clamshell** (vertex displacement) 	**Skew** (COM energy) 
Z	**Bowing** (COM energy) 	**Twist** (CP violation) 	**Z expansion** (distance scale) 

→ For tracks from IP, such distortions leave Chi2 unchanged, but change parameters of the tracks → bias in track parameters: weak modes are the biggest **challenge** in track based alignment

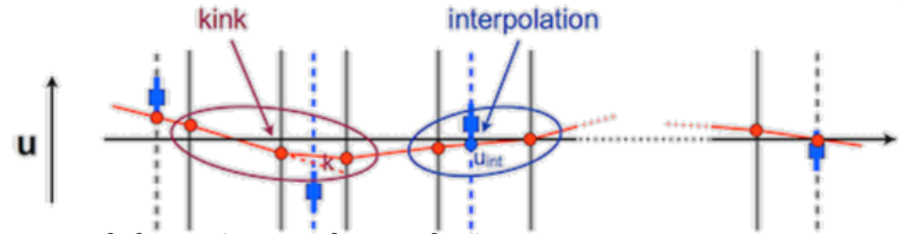
→ Several ways to reduce them: many track **topologies** (cosmics with/without magnetic field, tracks not from IP, vertex/mass constrained decays ...), detector **construction**: overlaps, survey or external **measurements** ...

General Broken Lines

GBL

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

- Track model with proper describtion of multiple scattering
- Track constructed from measurement and scattering points



- User has to provide at each point:
  - Residuals, measurement errors, projections from track coords.→ measurement coords.
  - Jacobians of propagation between adjacent points
  - Scattering errors at scatterers; derivatives of residuals w.r.t. align. params (for MP2)
- Track described by change of curvature and kinks at scattering points

$$\boldsymbol{x} = (\Delta q/p, \boldsymbol{u}_1, \dots, \boldsymbol{u}_{\#\ \text{of scatterers}})$$

- Track fit by minimization of:

$$\chi^2(\boldsymbol{x}) = \sum_{i=1}^{n_{\#\ \text{meas}}} (\boldsymbol{H}_{m,i}\boldsymbol{x} - \boldsymbol{m}_i)^T \boldsymbol{V}_{m,i}^{-1} (\boldsymbol{H}_{m,i}\boldsymbol{x} - \boldsymbol{m}_i) + \sum_{i=2}^{n_{\#\ \text{scat}}} (\boldsymbol{H}_{k,i}\boldsymbol{x})^T \boldsymbol{V}_{k,i}^{-1} (\boldsymbol{H}_{k,i}\boldsymbol{x})$$

from measurements

from kinks

- Interface to MP2

→ Integrated into GENFIT2 package
→ Profits from generic treatment of many different measurement types
→ Advanced treatment of material for multiple scattering estimation (thick scatterers)
→ Mathematically equivalent to Kalman Filter (but faster)

PXD + SVD Parameters

	layer	radius (cm)	thickness (μm)	r/φ pitch (μm)	Z pitch (μm)	# sensors	total # channels
PXD	1	1.4	75	50	55 – 60	2 x 8	**8 M**
	2(*)	2.2	75	50	70 – 85	2 x 12	
SVD	3	3.9	300 – 320	50	169	2 x 7	**225k**
	4	8.0	300 – 320	50	240	3 x 10	
	5	10.4	300 – 320	50	240	4 x 12	
	6	13.5	300 – 320	50	240	5 x 16	