Performance and Background Expectations of the Belle II Pixel Vertex Detector at SuperKEKB

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

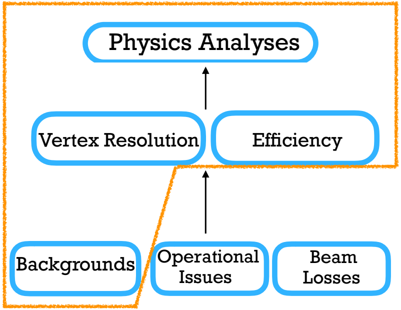
Belle II

DESY.

Introduction

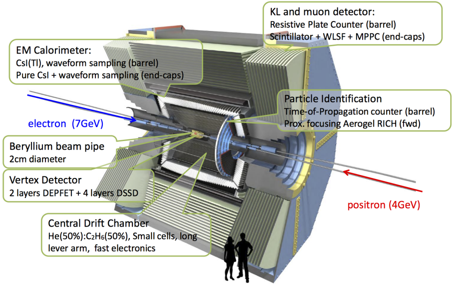
- The Pixel Vertex Detector at Belle II (PXD) was presented in the talk by Felix Mueller on Tuesday @ 20:35

This talk covers:

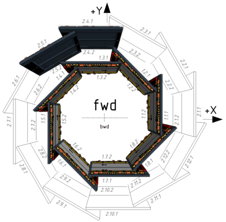


Current layout:

Belle II Detector

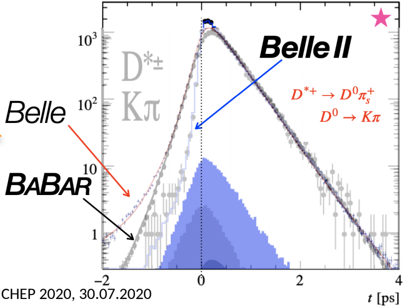


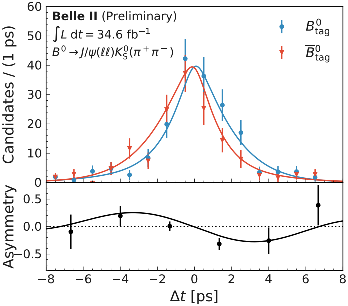
full first layer: L1
partial second layer: L2



Physics Analyses @ ICHEP Sensitive to PXD Performance

- D^0 lifetime measurement (see talk by Giulia Casarosa today @11:37):
  - updated measurement of Belle II shows factor 2 improvement in proper time resolution w.r.t Belle and Babar
  - measured value well-compatible with world average
- B^0 lifetime measurement (see talk by Cyrille Praz today @13:10)
- CP violation measurements (see talk by Niharika Rout today @13:14)
- CPV and CKM summary (see plenary talk by Doris Kim next Wednesday @08:45)





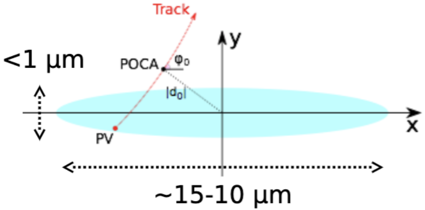
PXD Performance: Vertex Resolution and Hit Efficiency

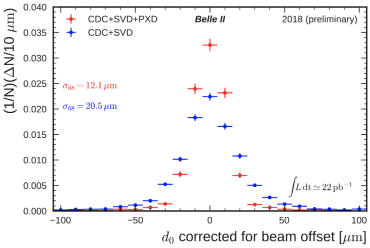
Vertex resolution measurement:

- very good vertex resolution measured with horizontal tracks in dimuon events
- such high resolution also owed to excellent alignment and tracking performance

Hit efficiency:

- hit efficiency := number of tracks with an associated PXD cluster hit / total number of sensor-intercepting tracks
- requirement: the cluster must be < 0.5 mm from track
- very high and stable **hit efficiency** $>$ **99%** in regions without known defects





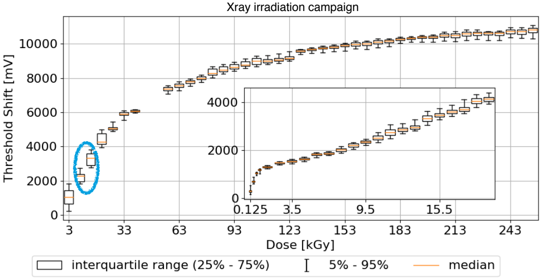
PXD Backgrounds @ Belle II

PXD background limit is set with occupancy $\mathcal{O}_{\mathbf{PXD}} <$ **3**% because of:

- limited bandwidth $\rightarrow$ corresponds to data rate @30 kHz trigger rate before significant data loss
- high vertexing performance $\rightarrow$ significantly increased probability to associate wrong hits to the track

PXD dose measurement:

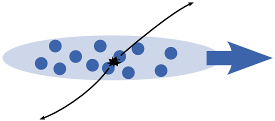
- expected yearly dose @$\mathcal{L} = 8 \times 10^{35}$ cm^{-2}s^{-1} is 20 kGy in L1
- preliminary dose estimate until now: < 20 kGy $\rightarrow$ more precise measurement in progress



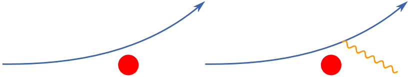
PXD Backgrounds @ Belle II

Single-beam backgrounds:

- **Touschek scattering** $\rightarrow$ scattering of particles within a bunch $\rightarrow$ **Touschek rate** $\propto N_{particles} \times \rho \rightarrow \mathbf{I} \times \frac{\mathbf{I}}{\sigma_y n_b}$



- **beam-gas scattering** $\rightarrow$ Coulomb scattering and Bremsstrahlung (scattering off gas molecules) $\rightarrow$ **Beam-gas rate** $\propto N_{gas\ molecules} \times N_{particles} \rightarrow \mathbf{P} \times \mathbf{I} \times \mathbf{Z^2_{eff}}$



- **synchrotron radiation background** $\rightarrow$ consequence of a radial acceleration of the beam's particles achieved in bending magnets and quadrupoles
- **injection background** $\rightarrow$ continuous injection of charge into beam bunch modifying the beam bunch

Single-beam backgrounds can be mitigated with beam-steering, collimators, and vacuum-scrubbing

Luminosity backgrounds:

- **two-photon background** $\rightarrow$ leading luminosity background ($e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-e^+e^-$), unlike any of the backgrounds above cannot be reduced!

PXD Backgrounds @ Belle II

Background decomposition performed in single-beam and luminosity runs:

- 1. perform single-beam background decomposition

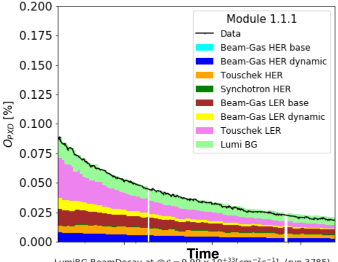
$$\mathcal{O}^{SB}_{PXD} = BPI + \frac{TI^2}{\sigma_Y n_b} + SI + Noise$$

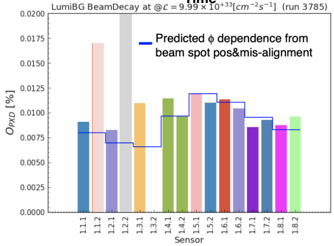
- 2. extrapolate single-beam background to luminosity run beam conditions
- 3. calculate $\mathcal{O}^{\text{LumiBG}}_{\text{PXD}}(\mathcal{L})$ from
  - $\mathcal{O}_{PXD} = \mathcal{O}^{LumiBG}_{PXD}(\mathcal{L}) + \mathcal{O}^{SB:extr}_{PXD}(B, T, S, I, P, \sigma_Y, n_b) + Noise$

Current Status:

- composition of PXD backgrounds is dominated by **reducible LER Coulomb** background
- data/MC factors $\in [0.5, 5]$ depending on component
- measurement of the **non-reducible luminosity** background is in **excellent** agreement with simulation prediction
- injection and SR backgrounds are **closely** monitored $\rightarrow$ SR presently dominated by HER injection

Luminosity beam decay run: 17 min



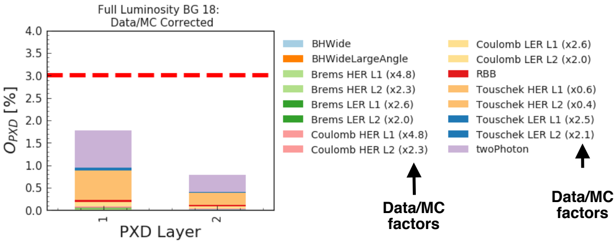


ϕ profile

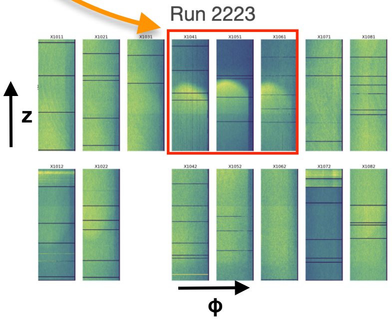
PXD Backgrounds @ SuperKEKB Original Design Optics

- Use data/MC factors to correct the design simulation
- HER Touschek and two-photon backgrounds will be **dominant** @ original design optics
- Extrapolation missing for injection and SR backgrounds, however SR currently has acceptable contribution to $\mathcal{O}_{PXD}$
- **Conclusion:** With our current understanding, $\mathcal{O}_{PXD} < 3\%$ at original design luminosity optics

Parameters @ Original Design Optics	LER	HER
Beam current [A]	3.6	2.6
N. of bunches	2500	2500
Vertical beam size [um]	24	10
β_x^* / β_y^* at IP [mm]	32/0.27	25/0.30
Pressure [nTorr]	1	1

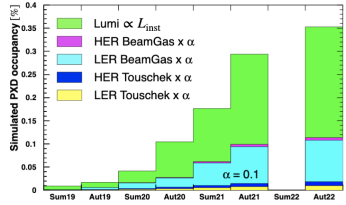


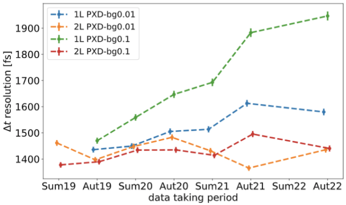
PXD sensor hit maps



Impact of PXD Backgrounds on ∆t Resolution

- ∆t is the difference in decay time between the two *B* mesons
- **Aim:** Study of ∆t resolution under 1-layer or 2-layer PXD configurations with future expected backgrounds in $B^0 \to J/\psi K_s^0$ decays
- **Caveat:** The preliminary results shown here are based on old MC $\to$ single-beam background composition + beam parameters changed $\to$ nevertheless **conclusions** below stay the same
- Study indicates that:
  - higher background increases the probability to assign wrong PXD hit to track
  - with only L1 in place expect significant performance degradation already in the next 2 years
  - this performance loss can be recovered by adding second PXD layer
- N.B.: New 2-layer PXD scheduled to be installed in 2022





Conclusion

Physics Analyses
Lifetimes, TDCPV

↑

Vertex Resolution
Very good

Efficiency
$> 99\%$

↑

Backgrounds

- So far, PXD dominated by LER Coulomb background
- Data/MC measured factors $\in [0.5,5]$
- Extrapolation to design optics yields $O_{PXD} < 3\%$, dominated by Touschek HER and two-photon backgrounds
- SR and Injection backgrounds are closely monitored
- Toy performance study of background impact on Δt resolution shows the need for L2

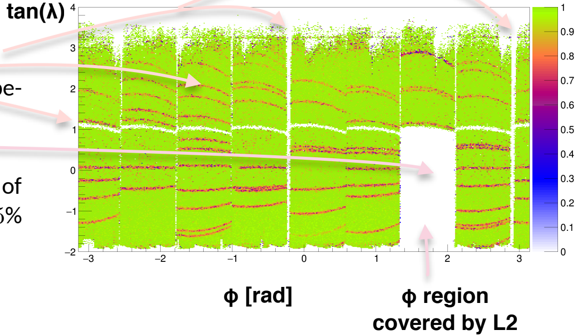
Thanks!

Backup

PXD Performance: Hit Efficiency Details

- Hit efficiency := number of tracks with an associated PXD cluster hit / total number of sensor-intercepting tracks
- Requirement: the cluster must be < 0.5 mm from track
- Visible structures in the hit efficiency plot:
  - ϕ-gaps between half shells (will be fixed in 2022)
  - θ-inefficiencies $\rightarrow$ dead switcher gates + space between modules
  - 1 dead module in L1
- Efficiency calculation excludes the above regions of dead gates ($< 2\%$ of pixels), and of dead module ($\approx 5\%$ of pixels)
- Dead gates caused by beam losses close to IP
- **Hit efficiency $>$ 99%**

L1 efficiency; Run 5705 from 15.06.2020



PXD Performance: Hit Efficiency Selection

- Offline analysis track requirements:
  - $p_t > 0.4$ GeV/c
  - SVD hits > 5
  - $|\Delta z_0| < 1$mm
  - $|dca' < 3\sigma_{dca}|$
- Online analysis:
  - $p_t >= 1.0$ GeV/c
  - the cluster < 0.5mm from track
  - $|\Delta z_0| < 1$cm and $|dr| < 0.5$cm
  - track pos. != at the border (min. 10 pixels)
  - position error for track on plane must be less than half the distace

PXD Backgrounds @ Belle II: Detailed Analysis

Current measurement strategy for backgrounds:

- 1. perform single-beam background decomposition for LER and HER

LER	$\mathcal{O}_{\text{PXD}}^{\text{LER}} = B_0 I + B_1 I^2 + \frac{TI^2}{\sigma_Y n_b} + Noise$
HER	$\mathcal{O}_{\text{PXD}}^{\text{HER}} = B_0 I + B_1 I^2 + \frac{TI^2}{\sigma_Y n_b} + S \times (spf/cf) I + Noise$

- 2. extrapolate single-beam background to luminosity run beam conditions
- 3. calculate $\mathcal{O}_{\text{PXD}}^{\text{LumiBG}}(\mathcal{L})$ from
  - $\mathcal{O}_{\text{PXD}} = \mathcal{O}_{\text{PXD}}^{\text{LumiBG}}(\mathcal{L}) + \mathcal{O}_{\text{PXD}}^{\text{LER:extr}}(B_0, B_1, T, I, \sigma_y, n_b) + \mathcal{O}_{\text{PXD}}^{\text{HER:extr}}(B_0, B_1, T, S \times (spf/cf), I, P, \sigma_y, n_b) + Noise$

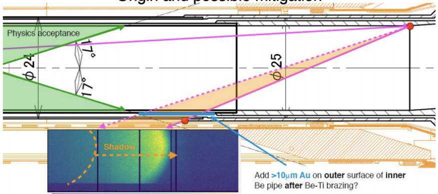
Category	Energy	Cluster Size
spf: Soft Photon Flux	6 < E < 10 KeV	1
cf: Charged Flux	E > 10 KeV	> 1

PXD Backgrounds @ Belle II: Synchrotron Radiation

Synchrotron radiation characteristics and mitigation options:

- ▷ backscatter from forward part of the Ti beam pipe
- ▷ characteristic footprint on -x modules throughout injection period
- ▷ modelling of SR generation during HER injection in progress
- ▷ possible mitigation: beam-steering, gold-plating of the beam pipe, improved design of central beam pipe for 2022 in progress

Origin and possible mitigation

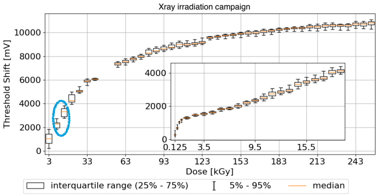


Currently SR has low impact on the smooth running and performance of the PXD due to the low rate, however:

- ▷ this could change drastically with changing optics
- ▷ still need to measure the impact of dense localized SR, total dose due to SR, make an extrapolation to design conditions

PXD Dose Measurement

- PXD Dose measurement was performed in Phase 2 data (see thesis by Harrison Schreeck for details)
- To estimate the PXD dose in Phase 3:
  - observe threshold shifts in Phase 3
  - diamond dose in Phase 3 corrected with Phase 2 measured PXD/Diamond calibration factors
  - current dose estimate in Phase 3: < 20 kGy
  - **needs dedicated study**
- Challenges:
  - diamond sensors not at the same location as PXD and not sensitive to SR (see details in the talk by Yifan Jin on Tuesday @ 11:05)
  - PXD does not take data for part of injection because of injection veto



Diamond System in Belle II