Comparison between theoretical predictions and measurements of luminosity background in the Belle II Silicon Vertex Detector

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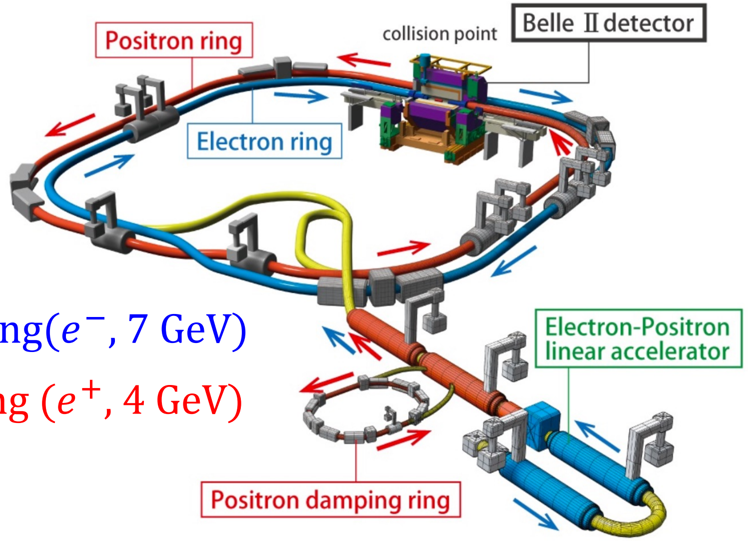
SuperKEKB

- e^+e^- collider with $\sqrt{s}$ @ $\Upsilon(4S)$ resonance
- Asymmetric energy for electron beam (HER, 7 GeV) and positron beam (LER, 4 GeV)
- Target peak luminosity: 6.5×10^{35} cm^{-2} s^{-1} (30 times of KEKB)
  - 0.38×10^{35} cm^{-2} s^{-1} achieved in 2021 run

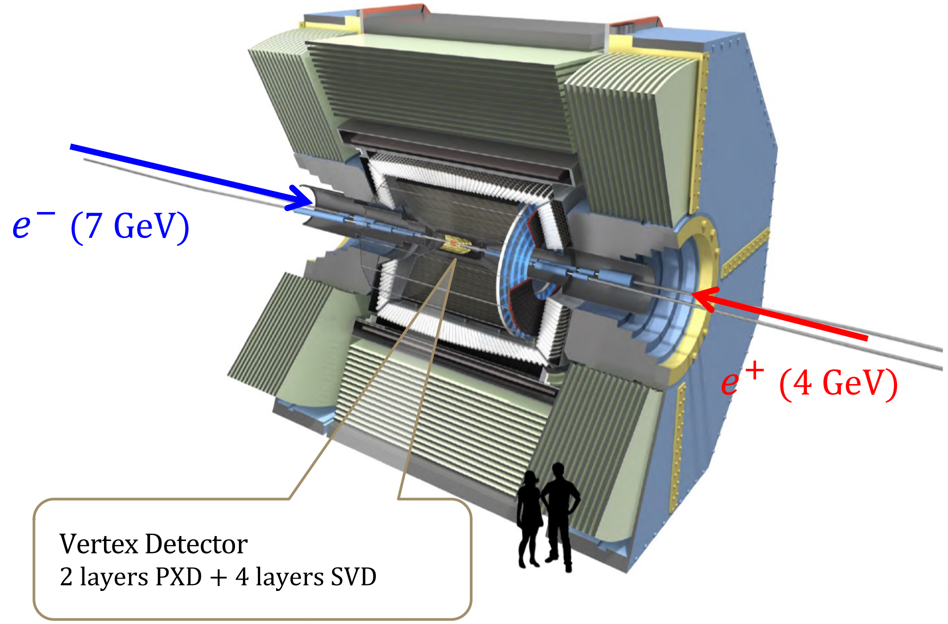
HER: High Energy Ring(e^-, 7 GeV)

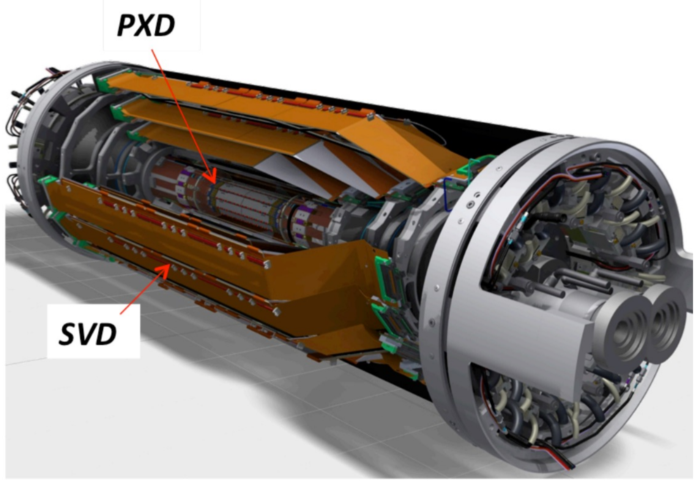
LER: Low Energy Ring (e^+, 4 GeV)



Belle II Vertex Detector

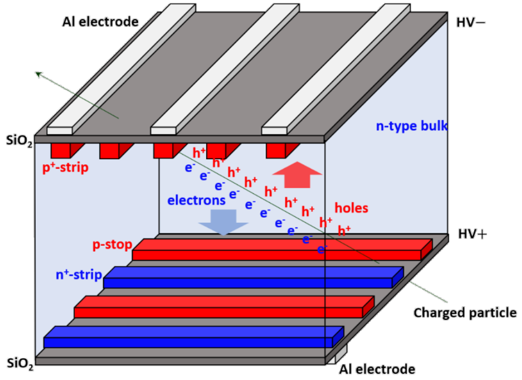
- Belle II Vertex Detector is placed at innermost of Belle II detector, mainly responsible for decay vertex detection and tracking
  - Layer 1~2: Pixel Detector (PXD)
  - Layer 3~6: Silicon Vertex Detector (SVD)
- This study uses data from 4 SVD layers
- SVD
  - Double-sided Silicon Strip Detector (DSSD)
    - Providing 2-D spatial information
  - Low material budget: 0.7% X_0 per layer
  - 172 DSSD sensors in total, with sensor area being 1.2 m^2 and 224k readout strips





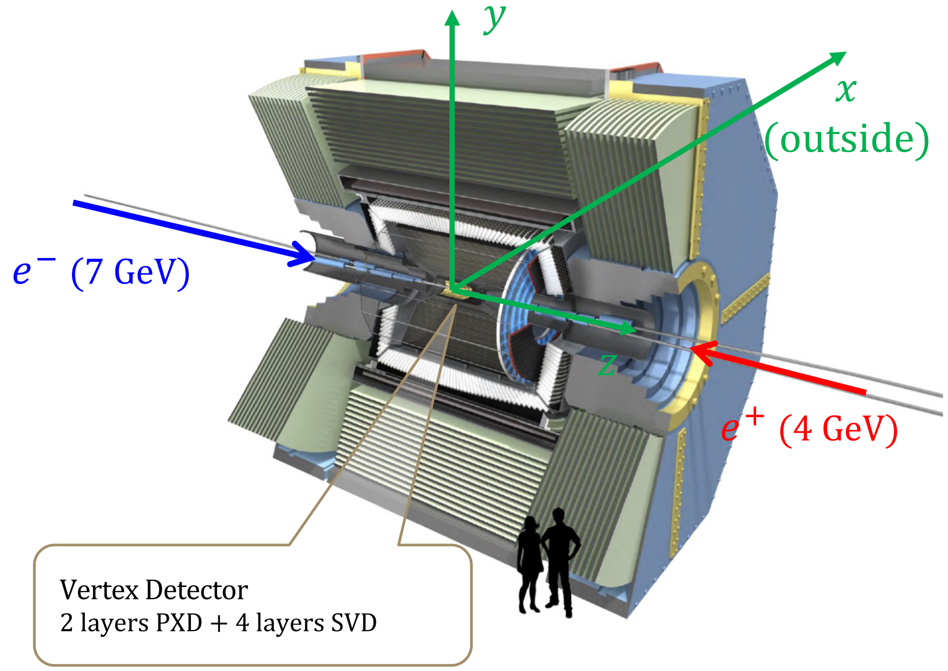
Belle II vertex detector

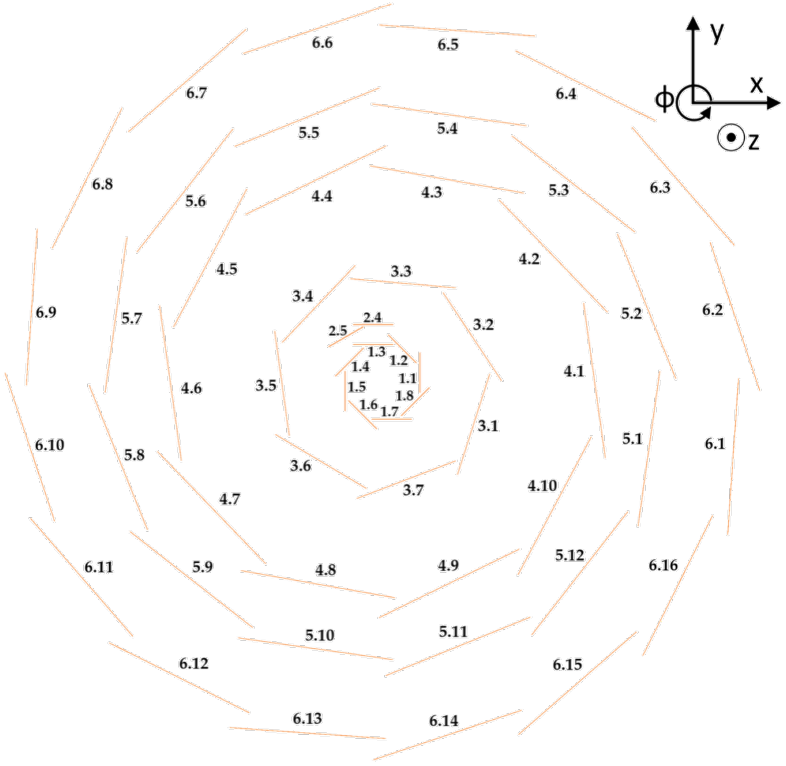
DSSD

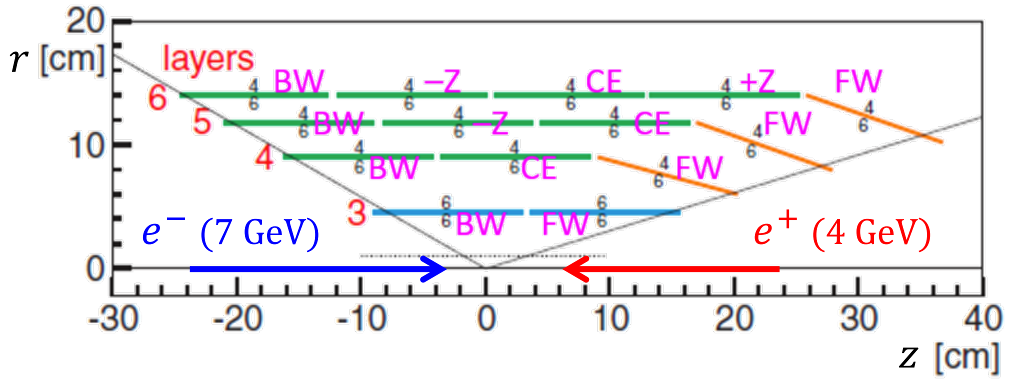


Structure of Belle II SVD

- 4 layers (Named as Layer 3~6)
- Each layer consists of 7~16 ladders.
- Each ladder consists of 2~5 DSSD sensors
- 172 sensors in total

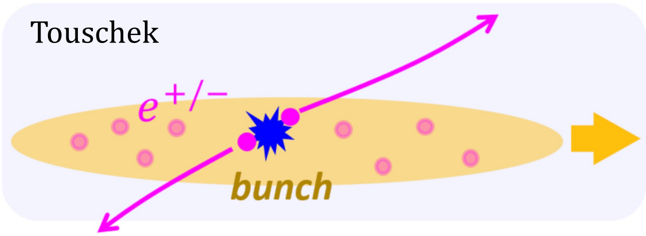


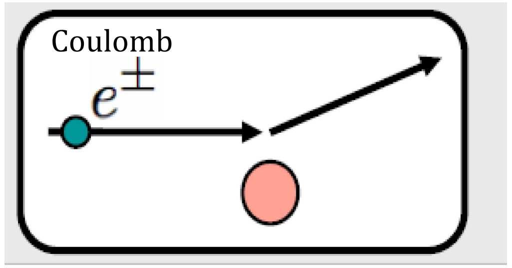


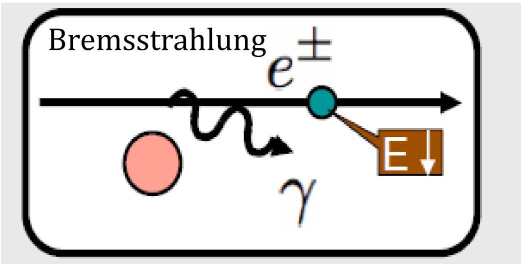


Beam Background sources

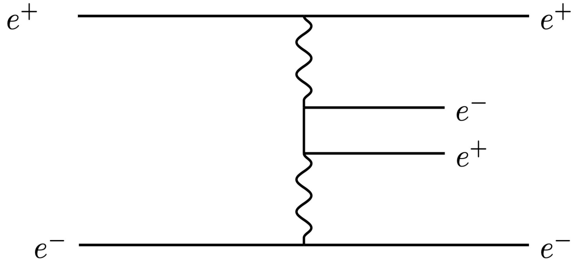
I: beam current
σ_x: beam size in x direction
σ_y: beam size in y direction
σ_z: bunch length
n_b: # of bunches
P: pressure inside beam-pipe



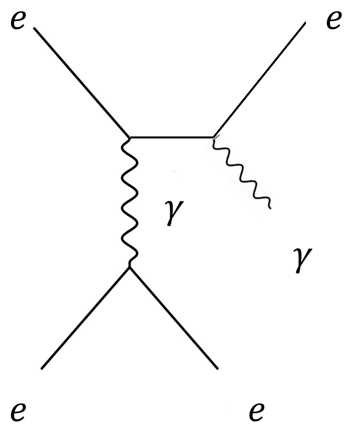




- Single-beam background (Beam-particle scattering)
  - Touschek effect
    - Intra-bunch scattering
    - Rate $\propto I \cdot \frac{I/n_b}{\sigma_x \sigma_y \sigma_z}$
  - Beam-gas scattering
    - Beam-gas scattering including Coulomb scattering and Bremsstrahlung
    - Rate $\propto I \cdot P$
  - Other sources: synchrotron radiation etc.
    - Neglectable when calculating SVD occupancy
- Luminosity backgrounds (Colliding beams)
  - $ee \to eell$ via two photon process
  - Radiative Bhabha
  - Rate $\propto \mathcal{L}$



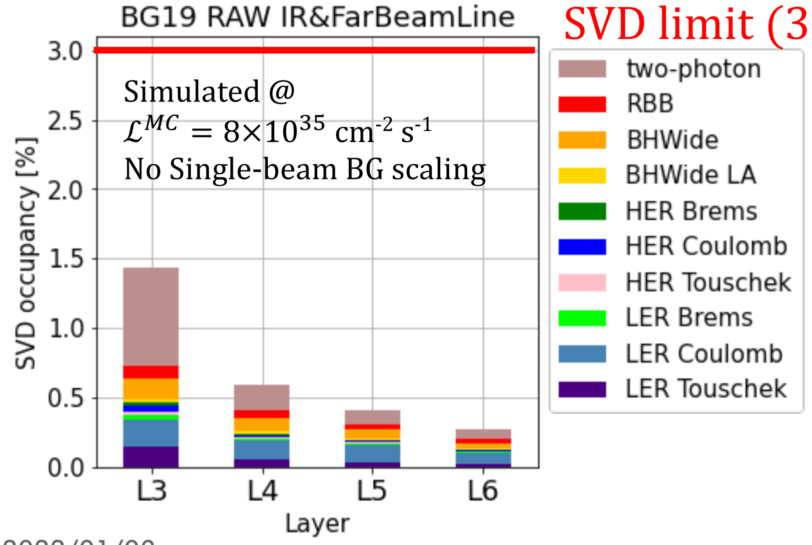
Two-photon process



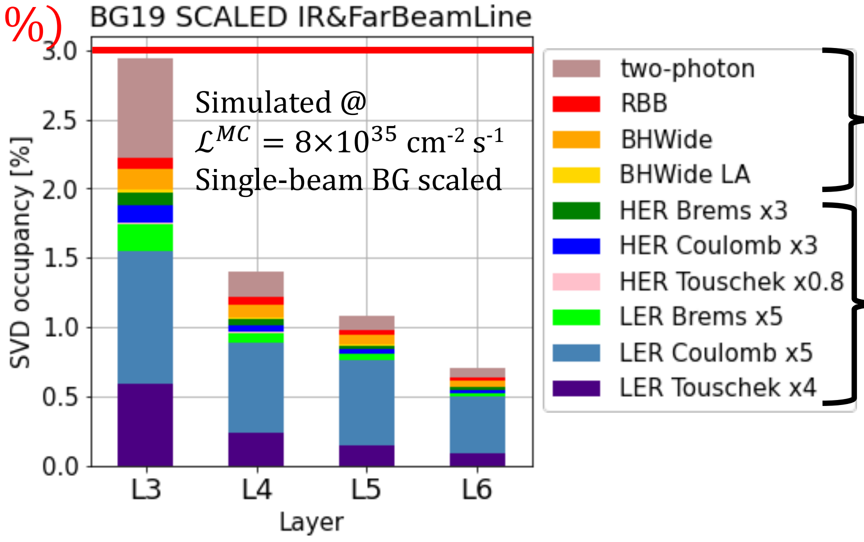
Radiative Bhabha

Motivation

- High occupancy introduced by beam background degrades the performance of tracking system and takes up precious bandwidth for DAQ system
- Simulation near target peak luminosity ($\mathcal{L}^{MC}$ = 8×10^{35} cm^{-2} s^{-1}) shows the average occupancy in Layer 3 (nearest to beam pipe) is very close to the 3% limit.
  - Discrepancy between single-beam BG MC and data with a factor of 0.8~5 observed.
  - Occupancy estimates are corrected by those factors
- It's important to know the discrepancy of MC from data for luminosity component



SVD limit (3%)

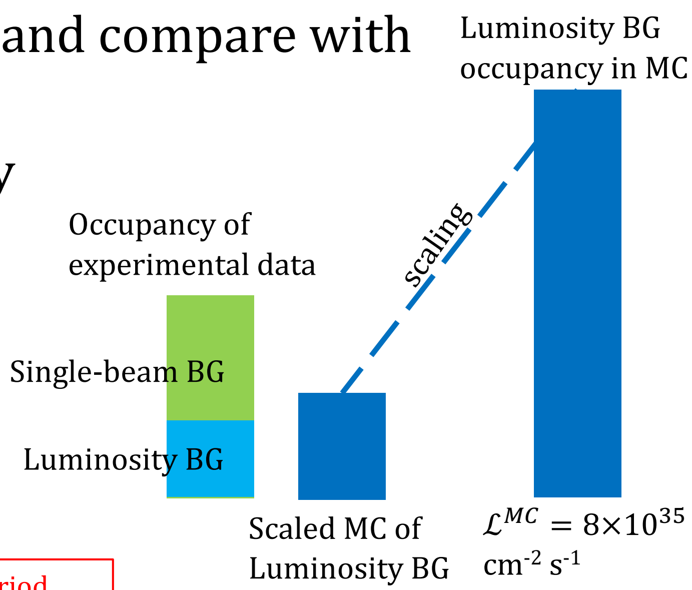


Luminosity background

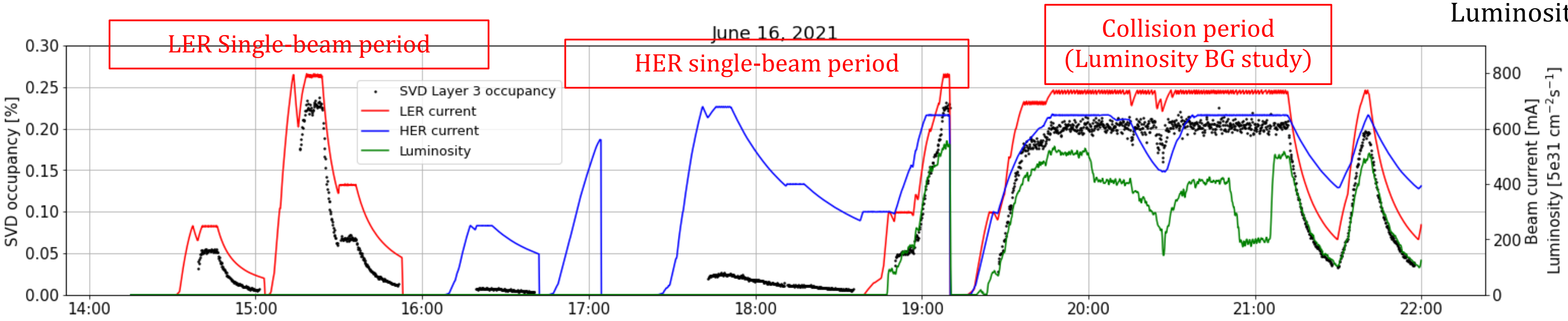
Single-beam background

Analysis strategy and dataset

- Luminosity BG could only be measured when beams collide, with interference from single-beam BG
- Inject only one beam (LER or HER) to study the single-beam BG
- Collide LER with HER. Subtract single-beam BG contribution from total occupancy by extrapolating single-beam study results to collision period. The remaining occupancy is from luminosity BG.
- Scale luminosity background occupancy in MC to current luminosity level and compare with experimental data
- Calculate Data/MC ratio of average occupancy to describe this discrepancy



- 2021.06.16 beam background study data
  - LER & HER single-beam period for single-beam background study
  - Collision period for luminosity background study
  - Each datapoint stands for average occupancy within 10 seconds



Modeling of single-beam BG

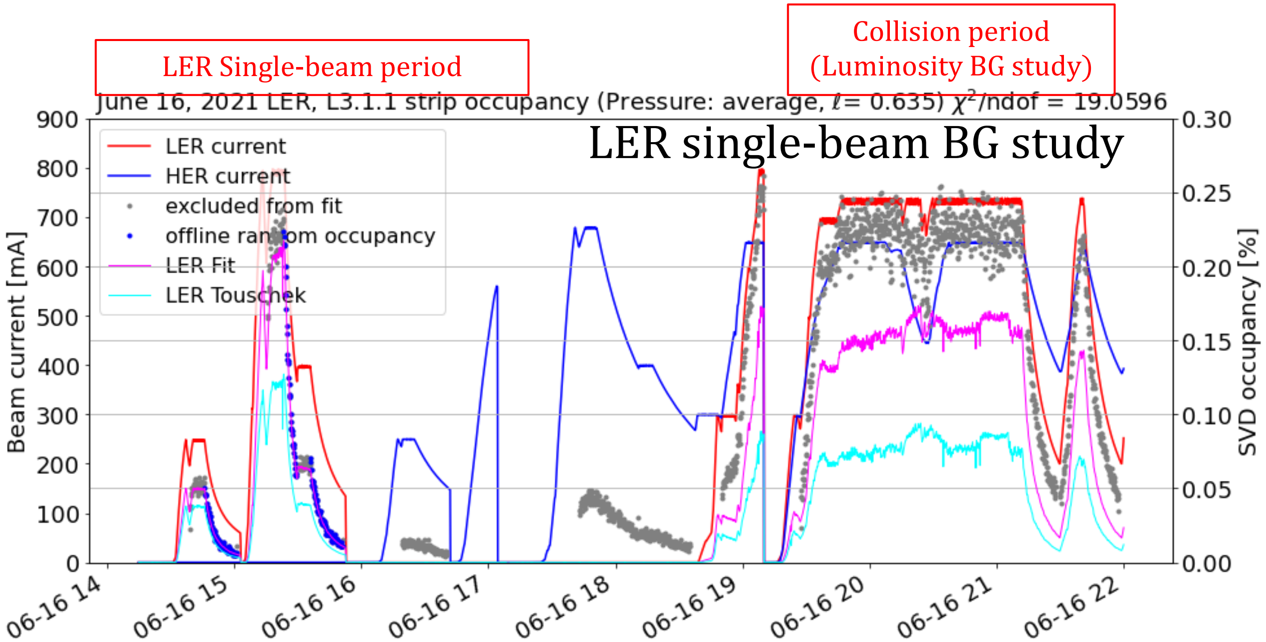
- For each sensor, fit occupancy to single beam BG model:

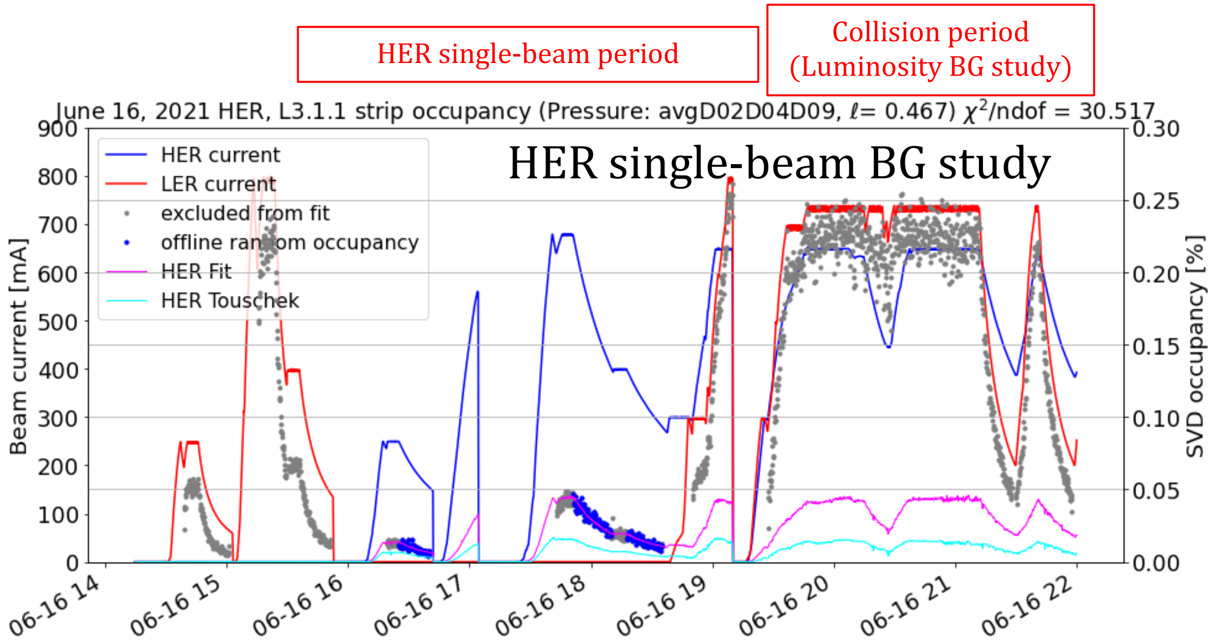
$$\mathcal{O}_{\text{singlebeam}}(I, P, \sigma, n_b | T, B) = T \cdot \frac{I^2}{\sigma_x \sigma_y \sigma_z n_b} + B \cdot IP$$

I: beam current
σ_x: beam size in x direction
σ_y: beam size in y direction
σ_z: bunch length
n_b: # of bunches
P: pressure inside beam-pipe

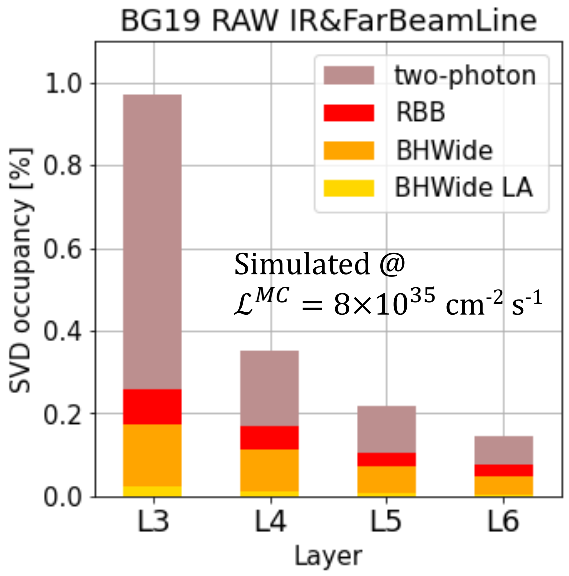
  - Beam parameters (I, P, σ, n_b) can be monitored/calculated in real time
  - Verifying beam current (I) and number of bunches (n_b) to separate Touschek and Beam-gas components

- Fitting results are extrapolated to collision period to estimate single-beam BG contribution during collision.





Simulation of luminosity BG



Event generator ($\mathcal{L}^{MC} = 8\times10^{35}$ cm^{-2} s^{-1})

- Two-photon process: AAFH[1]
- Radiative Bhabha (including RBB, BHWide and BHWide LA) : BBBREM[2] and BHWIDE[3]

Event info

Geant4

- Simulate interaction with detector

Energy deposition info

Belle II software (basf2)

- simulate the signal propagation inside sensor and generate hit information.
- Calculate occupancy based on hit information

BG event occupancy

[1] F.A. Berends, et al., “Complete lowest-order calculations for four-lepton final states in electron-positron collisions”
[2] R. Kleiss, et al, “BBBREM — Monte Carlo simulation of radiative Bhabha scattering in the very forward direction”
[3] S. Jadach, et al., “BHWIDE 1.00: O(α) YFS exponentiated Monte Carlo for Bhabha scattering at wide angles for LEP1/SLC and LEP2”

Luminosity BG analysis procedure

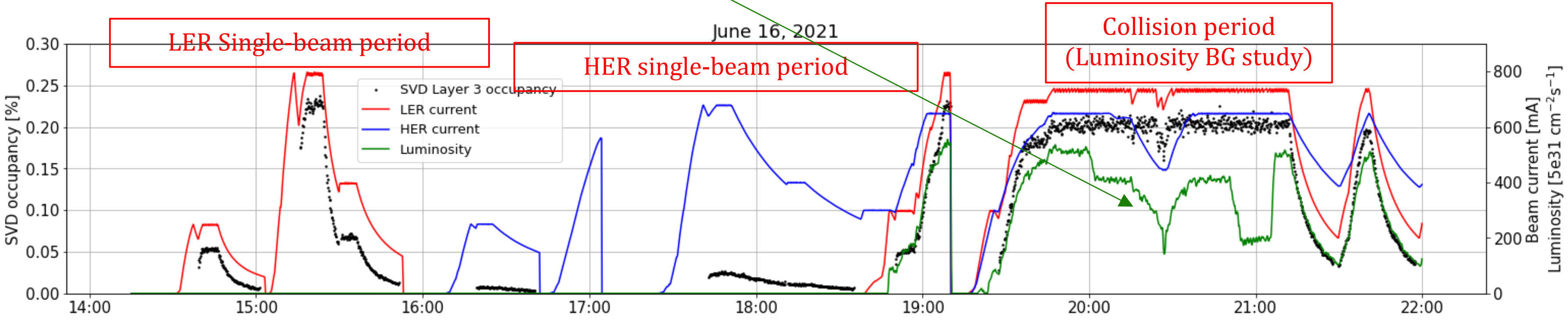
$\mathcal{L}^{MC} = 8\times10^{35}\ \mathrm{cm^{-2}s^{-1}}$

- In Collision period:

$$\mathcal{O}_{data}(i) = O_B^{LER}(i) + O_B^{HER}(i) + a\cdot O_T^{LER}(i) + b\cdot O_T^{HER}(i) + \frac{\mathcal{L}^{Fit}}{\mathcal{L}^{MC}}\cdot O_{LUMI}^{MC}(i)$$

  - i : index of SVD sensor
  - $\mathcal{O}_{data}(i)$: occupancy of ith sensor
  - $O_B^{LER(HER)}(i)$: LER(HER) **Beam-gas** background occupancy on ith sensor, extrapolated from single-beam study
  - $O_T^{LER(HER)}(i)$: LER(HER) **Touschek** background occupancy on ith sensor, extrapolated from single-beam study
  - $O_{LUMI}^{MC}(i)$: luminosity background occupancy on ith sensor, from MC

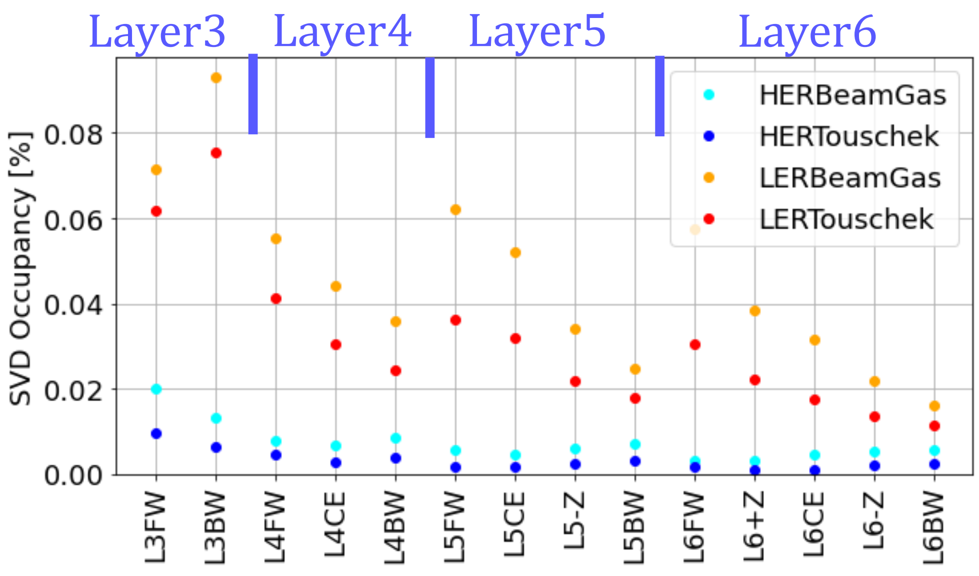
- Fit to the occupancy of all 172 sensors with three floating parameters :$\mathcal{L}^{Fit}$, a, b
- By comparing $\mathcal{L}^{Fit}$ with measured luminosity, one can calculate Data/MC ratio
- a and b (LER/HER Touschek scaling factor) represent the difference of Touschek occupancy with/without collision

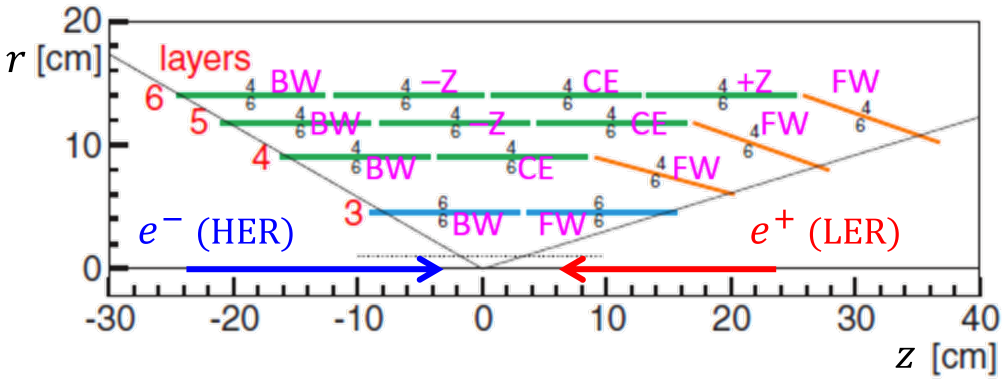


Single-beam background distribution versus Z

$$O_{data}(i) = O_B^{LER}(i) + O_B^{HER}(i) + a \cdot O_T^{LER}(i) + b \cdot O_T^{HER}(i) + \frac{\mathcal{L}^{Fit}}{\mathcal{L}^{MC}} \cdot O_{LUMI}^{MC}(i)$$

- Extrapolated single-beam background occupancy distribution versus Z
- LER BG peaks in FW direction while HER BG peaks in BW direction @ Layer 4,5,6
  - LER (HER) is injected into IP chamber from FW (BW) direction
  - LER and HER components can be separated by fitting

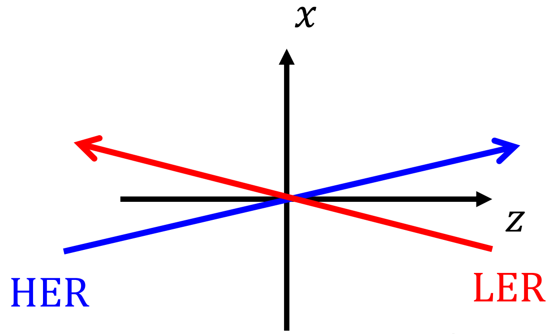


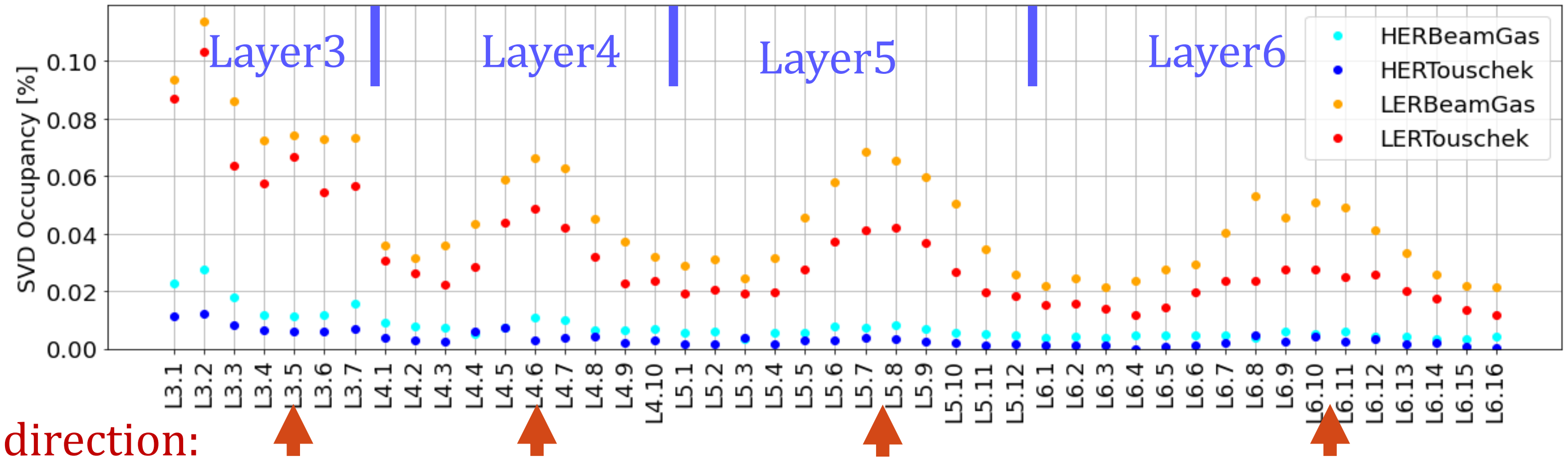


Single-beam background distribution versus ϕ

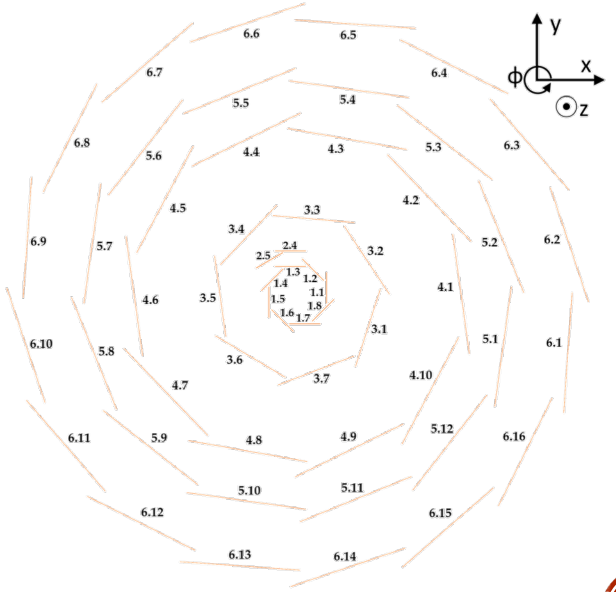
$$\mathcal{O}_{data}(i) = O_B^{LER}(i) + O_B^{HER}(i) + a \cdot O_T^{LER}(i) + b \cdot O_T^{HER}(i) + \frac{\mathcal{L}^{Fit}}{\mathcal{L}^{MC}} \cdot O_{LUMI}^{MC}(i)$$

- Extrapolated single-beam background occupancy distribution versus ϕ
- LER (positron beam) backgrounds dominate
- Single-beam background peaks in **–X** direction @ Layer 4,5,6
  - Beams are injected into IP chamber from –X direction





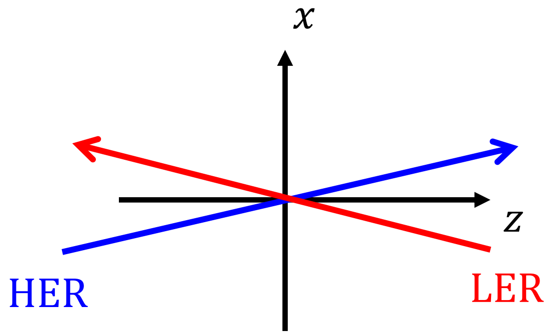
-X direction:

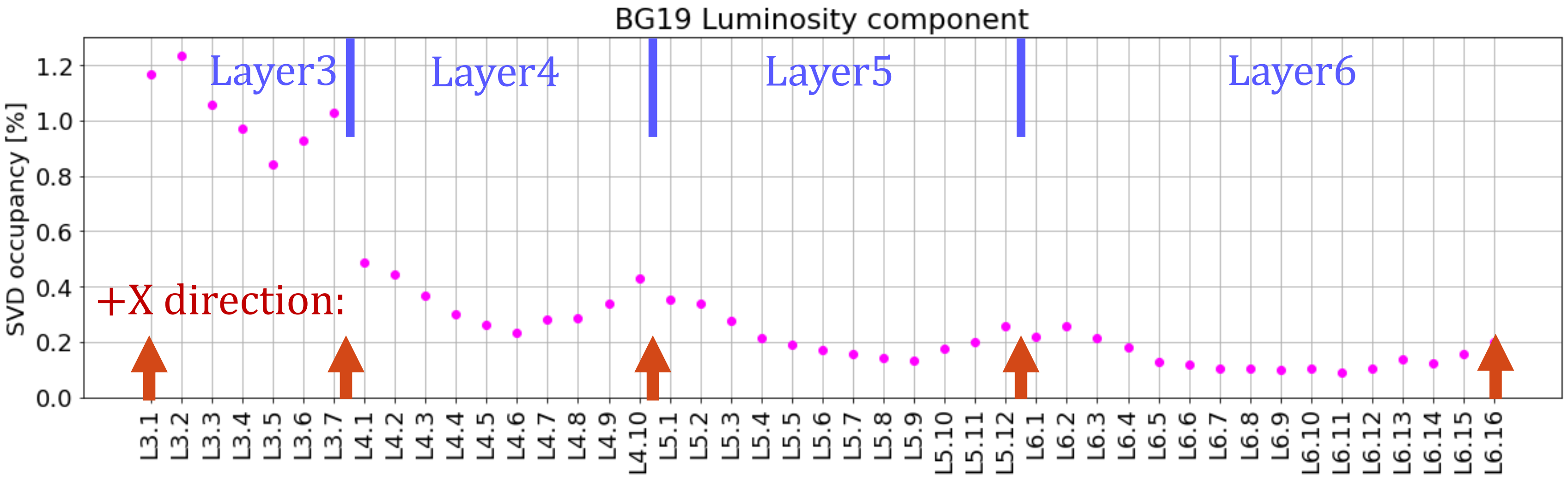


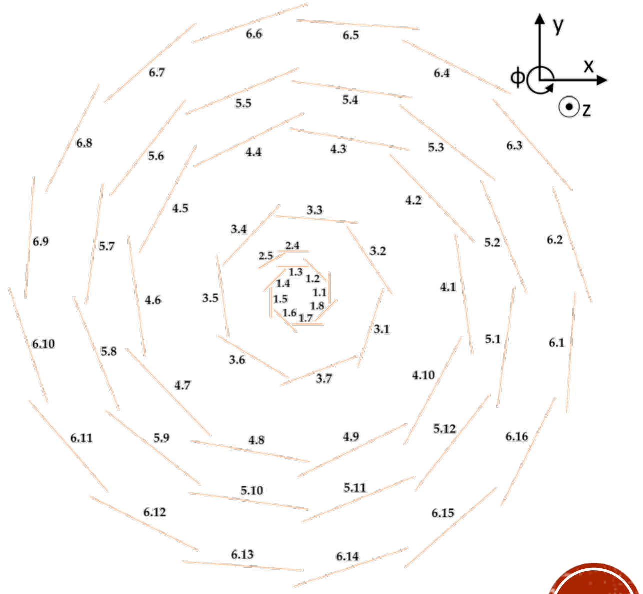
Luminosity background distribution versus ϕ

$$\mathcal{O}_{data}(i) = O_B^{LER}(i) + O_B^{HER}(i) + a \cdot O_T^{LER}(i) + b \cdot O_T^{HER}(i) + \frac{\mathcal{L}^{Fit}}{\mathcal{L}^{MC}} \cdot O_{LUMI}^{MC}(i)$$

- Simulated luminosity background occupancy distribution versus ϕ
- Luminosity BG peaks in **+X** direction
  - Center of mass momentum is >0 in X direction
  - Given that single beam components peak in –X @L456, Luminosity BG can be separated from Single beam BG by fitting



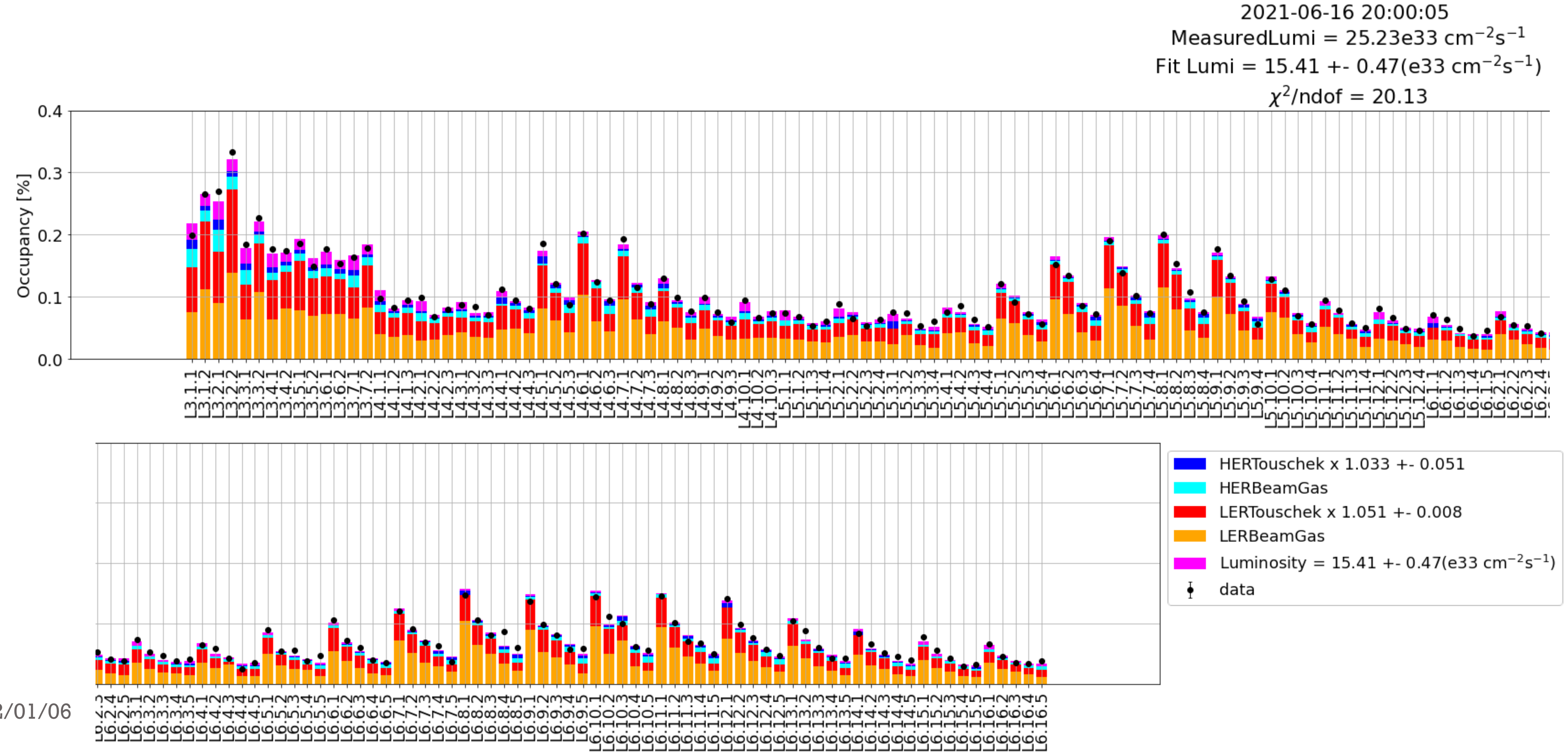




Occupancy fitting

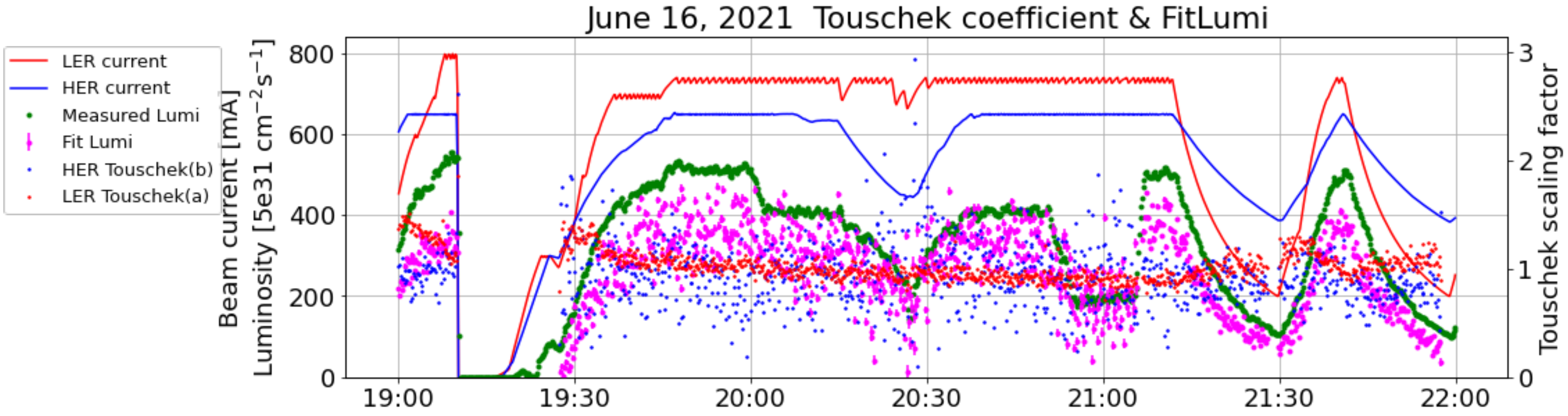
$$\mathcal{O}_{data}(i) = O_B^{LER}(i) + O_B^{HER}(i) + a \cdot O_T^{LER}(i) + b \cdot O_T^{HER}(i) + \frac{\mathcal{L}^{Fit}}{\mathcal{L}^{MC}} \cdot O_{LUMI}^{MC}(i)$$

- Shape of fit result agrees well with the shape of experimental data



Fit results

$$\mathcal{O}_{data}(i) = O_B^{LER}(i) + O_B^{HER}(i) + a \cdot O_T^{LER}(i) + b \cdot O_T^{HER}(i) + \frac{\mathcal{L}^{Fit}}{\mathcal{L}^{MC}} \cdot O_{LUMI}^{MC}(i)$$



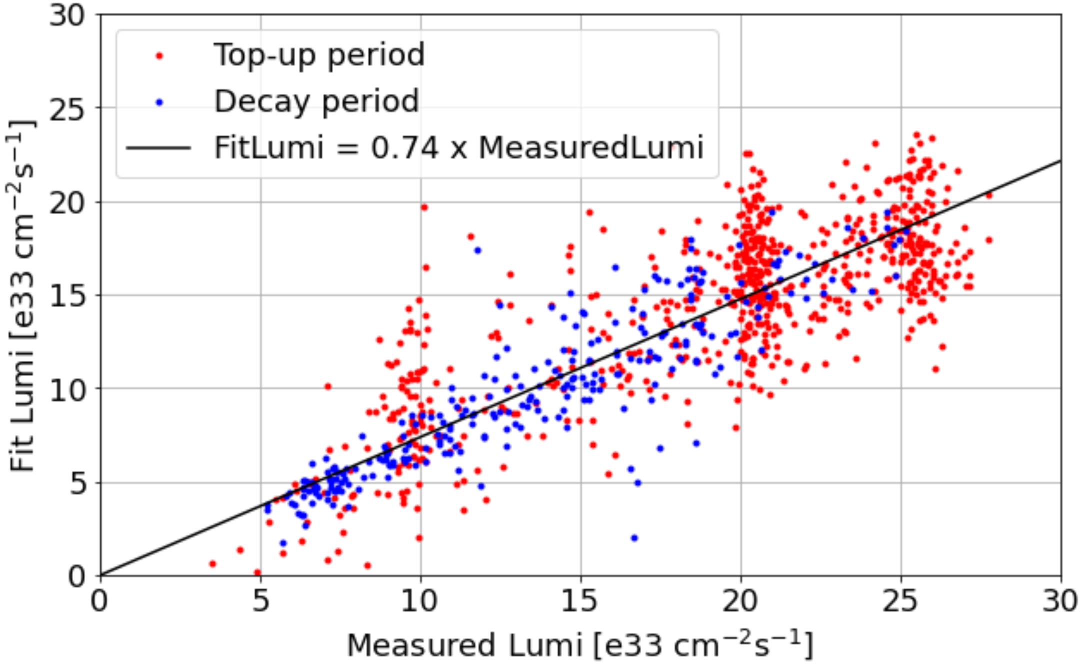
- FitLumi($\mathcal{L}^{Fit}$) shows the same trend as measured luminosity
- LER Touschek scaling factor (a) is close to 1
- HER Touschek scaling factor (b) suffers from large fluctuation
    - HER single-beam BG contribution is very small

Data/MC ratio for luminosity BG

- FitLumi ∝ MeasuredLumi (intercept is fixed at 0)
- Average occupancy in Data = occupancy in MC scaled to fitLumi
- Average occupancy in MC = occupancy in MC scaled to MeasuredLumi
- Using the above formula,

$$\frac{\text{Data}}{\text{MC}} \equiv \frac{\text{average occupancy in Data}}{\text{average occupancy in MC}} = \frac{\text{FitLumi}}{\text{MeasuredLumi}}$$

- Data/MC = 0.74



Results of three luminosity BG studies

- Luminosity background was studied three times in May 2020, June 2020 and June 2021
- Data/MC seems to converge to 0.75
- LER Touschek scaling factor (a) seems to converge to 1
- HER Touschek scaling factor (b) is suffering from large fluctuation
  - Occupancy contributed by HER single-beam BG is very small

$$\mathcal{O}_{data}(i) = O_B^{LER}(i) + O_B^{HER}(i) + a \cdot O_T^{LER}(i) + b \cdot O_T^{HER}(i) + \frac{\mathcal{L}^{Fit}}{\mathcal{L}^{MC}} \cdot O_{LUMI}^{MC}(i)$$

Dataset	June2021	June 2020	May 2020
Data/MC	0.74	0.74	0.75
a (average)	1.04	1.02	0.73
b (average)	0.95	0.55	1.21

Summary

- Luminosity background was measured and compared with theoretical predictions
- Luminosity background still small compared to single-beam background.
- Shapes of overall background distributions in data and MC agree well
- However, measured luminosity background normalization 25% smaller than predicted
- This discrepancy is not yet understood

- Data with higher luminosity is desired to verify this method of comparison

Backup

Traditional method

Traditional

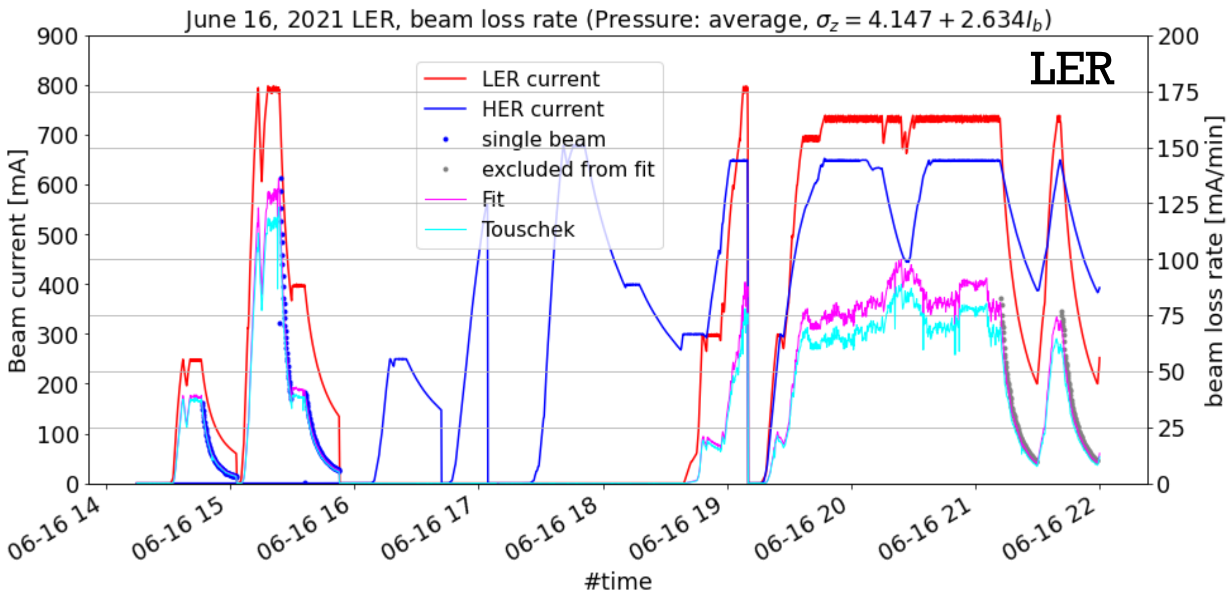
- Layer 3 average occupancy from luminosity background:

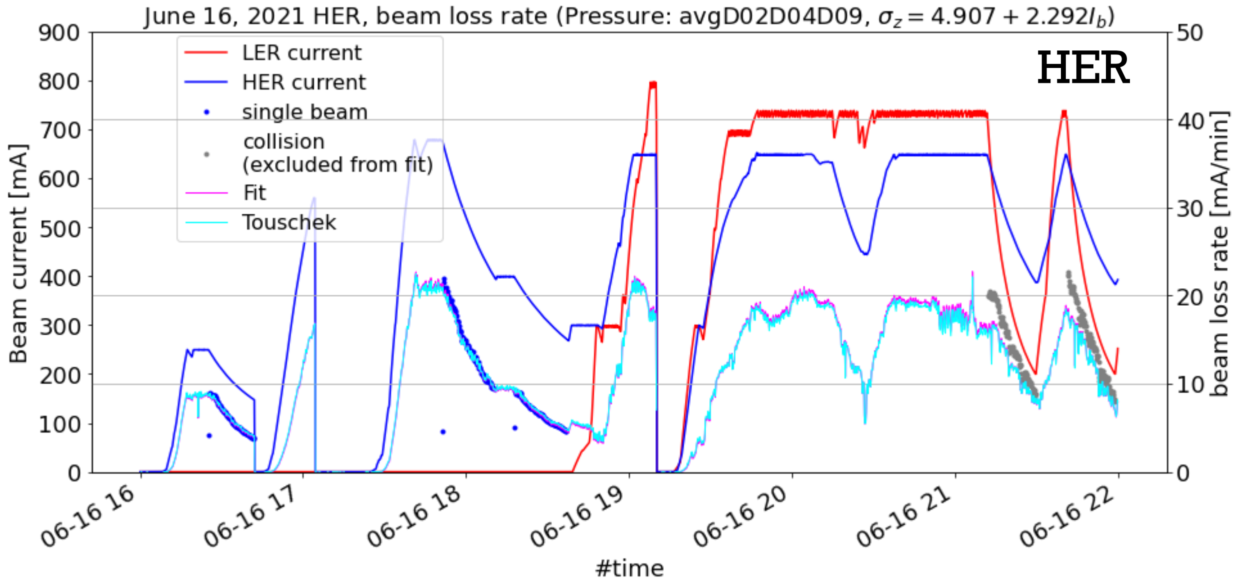
$$\mathcal{O}_{\mathrm{lumi}}(\propto \mathcal{L}) \equiv \mathcal{O}_{data} - a \cdot O_T^{LER} - b \cdot O_T^{HER} - O_B^{LER} - O_B^{HER}$$

  - $\mathcal{O}_{data}$: layer3 average occupancy of real data
  - $O_T^{LER(HER)}$: occupancy of LER(HER) Touschek component, derived from single-beam analysis
  - $O_B^{LER(HER)}$: occupancy of LER(HER) Beam-gas component, derived from single-beam analysis
- a and b (LER/HER Touschek scaling factor):
  - Representing the difference of Touschek occupancy with/without collision
  - Beam optics may change between the single-beam and the collision
- Perform single-beam fit for total beam loss rate $-\frac{\mathrm{d}I}{\mathrm{d}t} = \mathcal{O}_{\mathrm{single}}(I, P_{mean}, \sigma, n_b | B'_i, T')$
- Compare measurement during collision and single beam fit results
- Take any difference as the Touschek scaling factor a and b (average over time)

Beam lifetime fit

- a,b = <(beam_loss_rate@collision – BeamGasFit) / TouschekFit>
- LER Touschek scaling factor $a = 1.07$
- HER Touschek scaling factor $b = 1.17$





Luminosity BG estimation

- LER Touschek scaling factor $a = 1.07$
- HER Touschek scaling factor $b = 1.17$
- Data/MC $= 0.34 \sim 0.95$. Large disagreement between decay and injection data