Tracking performance and interaction point properties at the Belle II experiment

Cyrille Praz, *on behalf of the Belle II collaboration*

VERTEX 2020

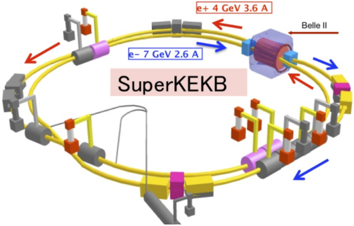
Outline

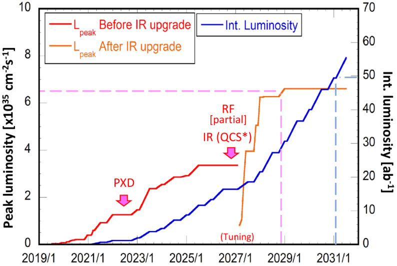
Belle II talks and posters at VERTEX 2020

- Qingyuan Liu, *Operational Experience and Performance of the Belle II Pixel Detector*, [A02].
- Giuliana Rizzo, *The Belle II Silicon Vertex Detector: Performance and Operational Experience in the first year of data taking*, [A03].
- Yuma Uematsu, *A Study for Hit-time Reconstruction of Belle II Silicon Vertex Detector*, [P02].
- Sagar Hazra, *Particle identification in Belle II silicon vertex detector*, [P03].
- Katsuro Nakamura, *Development of the thin and fine-pitch silicon strip detector aiming for the Belle II upgrade*, [P05].
- Cyrille Praz, *Tracking performance and interaction point properties at the Belle II experiment*, [A07].
- Jerome Baudot, *Upgrade of the vertex detector of the Belle II experiment*, [B01].

SuperKEKB

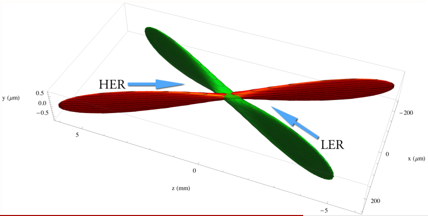
- e^+e^- collider.
- $\sqrt{s} = 10.6\,\mathrm{GeV} = \mathrm{m}(\Upsilon(4S))c^2$.
- $\mathrm{BR}(\Upsilon(4S) \to B\bar{B}) > 96\%$.
- $\int_{2019}^{\mathrm{present}} L\,\mathrm{d}t \approx 70\,\mathrm{fb}^{-1}$.
- World highest instant. luminosity.
  - $L = 2.4 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ achieved in June 2020.

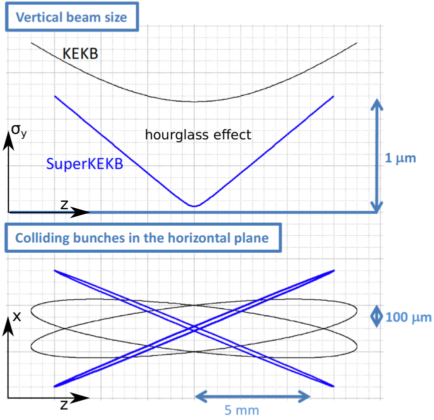




Nano-beam scheme (idea from Pantaleo Raimondi)

- Goal: $\beta_y^* = 0.3\,\mathrm{mm}$.
- Hourglass effect limited if $\sigma_z^{eff} < \beta_y^*$.
- Half crossing angle:
  - $\phi_x \approx 40\,\mathrm{mrad}$.
- Nominal beam spot parameters:
  - $\sigma_x \approx 10\,\mu\mathrm{m}$.
  - $\sigma_z^{eff} = \frac{\sigma_x}{\sin\phi_x} \approx 0.25\,\mathrm{mm}$.
  - $\sigma_y \approx 50\,\mathrm{nm}$.

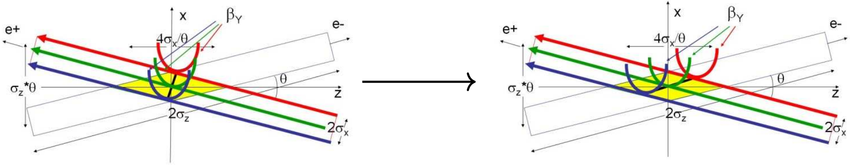




[BELLE2-TALK-CONF-2018-142]
[1809.01958]

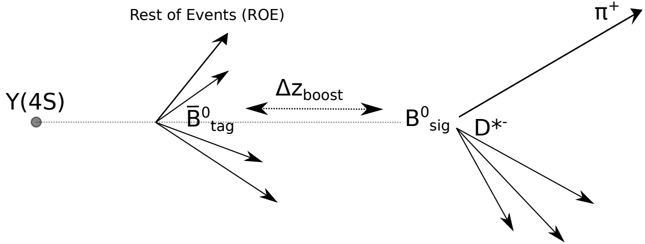
Crab waist transformation

- Since 2020, SuperKEKB has introduced the crab waist transformation to further increase luminosity. [0702033], [1608.06150]
  - Align min(β_y) of one beam along the trajectory of the other beam.
  - Additional benefits are lower background and improved beam lifetime.



Importance of the impact parameter resolution

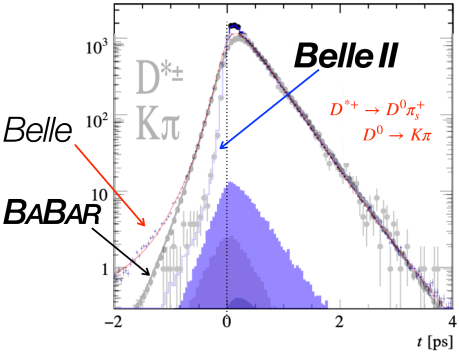
- SuperKEKB has a smaller Lorentz boost compared to KEKB.
- Belle II has a better impact parameter resolution (factor $\sim 1.5 - 2$) thanks to its pixel detector and a smaller beam pipe diameter.
  - $(\beta\gamma)_{\text{SuperKEKB}} \approx 0.28 < 0.42 \approx (\beta\gamma)_{\text{KEKB}}$.
  - Precise measurements of decay vertices is crucial for time-dependent studies.



- B mesons nearly at rest in the $\Upsilon(4S)$ frame.
  - $\Delta t \approx \frac{\Delta z_{\text{boost}}}{c(\beta\gamma)_{\Upsilon(4S)}}$, $\quad \Delta z_{\text{boost}} = \mathcal{O}(100\,\mu\text{m})$.

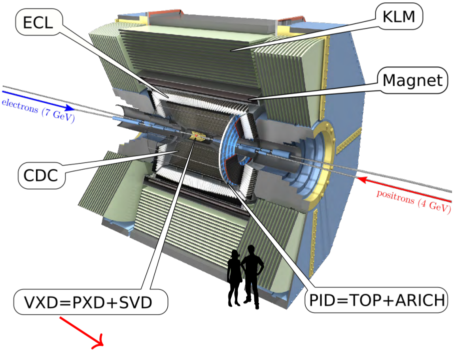
Proper-time resolution

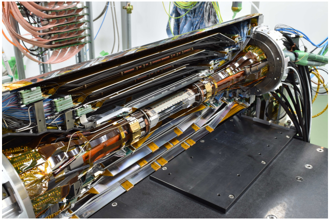
- Thanks to the Belle II vertex detector, the proper-time resolution is a factor ~ 2 better than at Belle and Babar.
- Example of a D meson lifetime measurement [BELLE2-TALK-CONF-2020-046]:



The Belle II detector

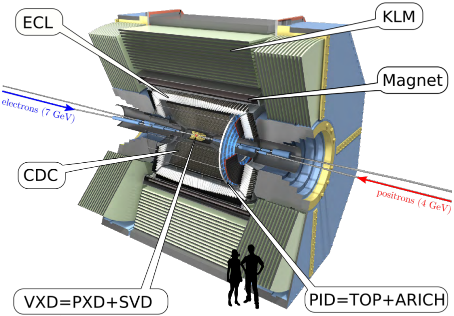
- Pixel Detector (PXD).
- Silicon Vertex Detector (SVD).
- Central Drift Chamber (CDC).
- Calorimeter (ECL).
- Aerogel Ring-Imaging Cherenkov (ARICH).
- Time-Of-Propagation (TOP) counter.
- K_L^0 and μ detection (KLM).

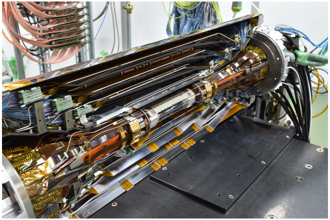




Tracking subdetectors

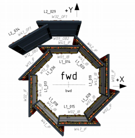
- Pixel Detector (PXD).
- Silicon Vertex Detector (SVD).
- Central Drift Chamber (CDC).
- Calorimeter (ECL).
- Aerogel Ring-Imaging Cherenkov (ARICH).
- Time-Of-Propagation (TOP) counter.
- K_L^0 and μ detection (KLM).

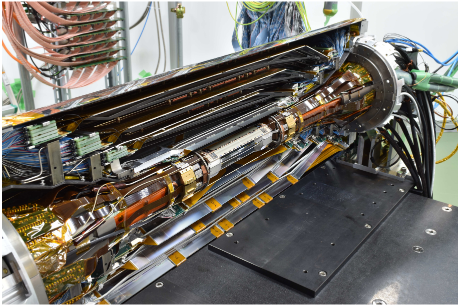


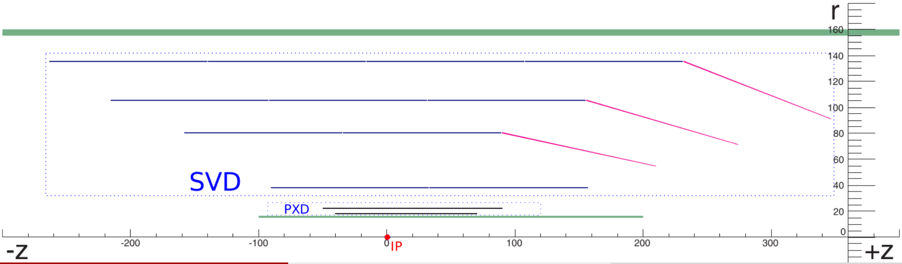


VXD (=PXD+SVD)

- PXD.
  - Pixel detector.
  - 2 layers.
  - Radii: 14, 22 mm.
- SVD.
  - Double-sided silicon strips.
  - 4 layers.
  - Radii: 39 to 135 mm.

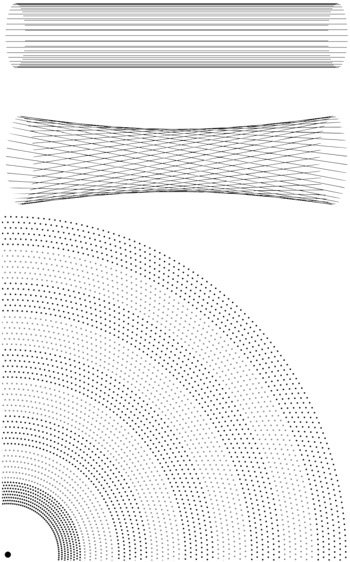






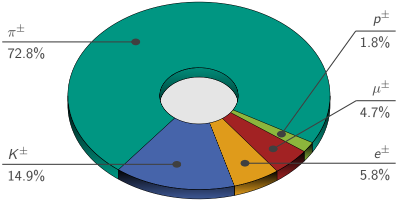
CDC

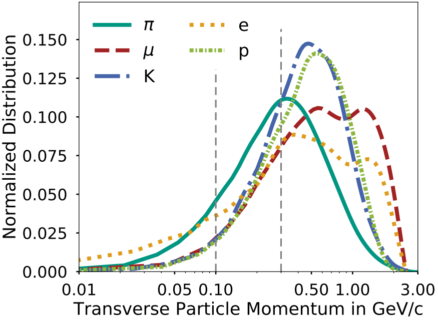
- Drift chamber.
- $\approx 50\,000$ wires.
- 56 layers.
  - Radii: 168 to $1111.4\,\mathrm{mm}$.
- 9 superlayers.
  - axial orientation (A).
  - stereo orientation (U,V).
- Configuration:
  - AUAVAUAVA.



Charged particles from simulated $\Upsilon(4S)$ events

- $p_{\mathrm{T}} < 100\,\mathrm{MeV}/c$:
  - Track does *not* reach CDC.
  - Detected by standalone SVD.
- $p_{\mathrm{T}} \in [100,\, 300]\,\mathrm{MeV}/c$:
  - Track can curl inside CDC.

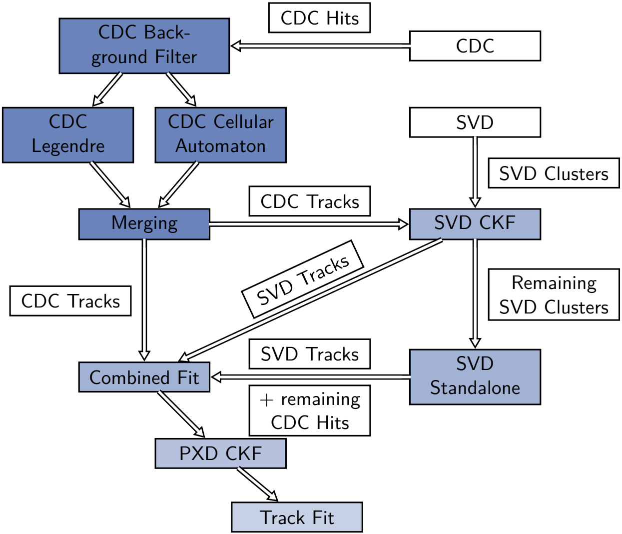




[doi: 10.1016/j.cpc.2020.107610]

Track reconstruction steps

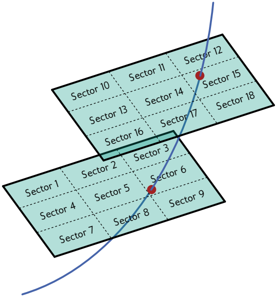
Belle II Tracking Group, *Track finding at Belle II*, Computer Physics Communications (2020). [doi: 10.1016/j.cpc.2020.107610]



SVD Standalone

[doi: 10.1016/j.cpc.2020.107610]

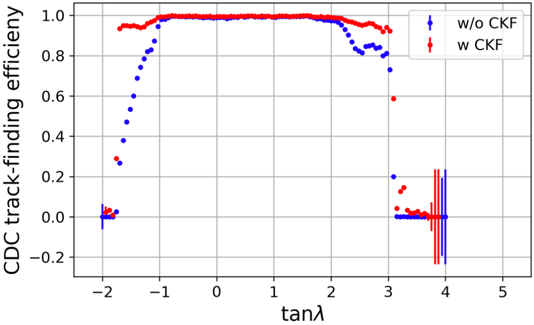
- Each SVD sensor is divided in 3×3 sectors.
- Sector map trained on simulated tracks to learn geometrical relations between sectors.
- Filters reject bad space point combinations (angle, timing).
- Cellular automaton yields a set of paths.
- Track candidates selected based on χ^2 and #degrees of freedom.



Standalone SVD to CDC extrapolation

- Extrapolating tracks found by the standalone SVD to the CDC improves the CDC track-finding effiency.
  - Significant improvement at large $|\tan \lambda|$.
- Addition of CDC hits improves momentum resolution of the full track.

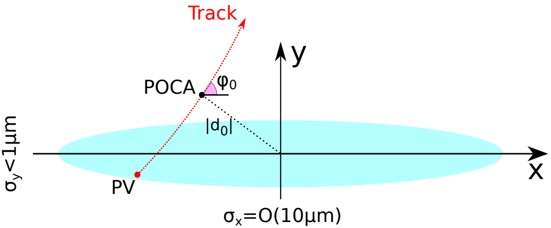
2-track events (data), $\lambda \equiv \frac{\pi}{2} - \theta$



Outline

Track parametrisation: 2D picture

- Blue area: high and low energy beams overlap.
- ϕ_0: azimutal angle at the point of closest approach (POCA).
- d_0: Transverse impact parameter at the POCA.

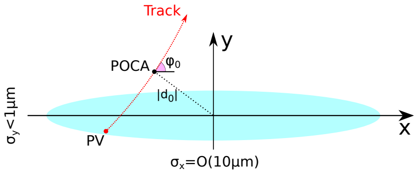


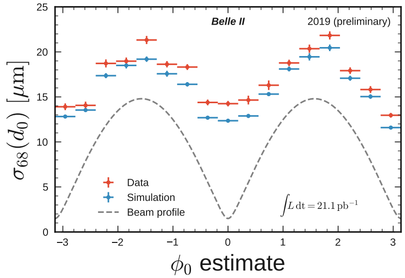
- $\sigma_{68}(d_0)$ depends on the intrinsic detector resolution σ_i and the beam spot size:
  - $\sigma_{68}(d_0) = \sqrt{\sigma_i^2 + (\sigma_x \sin\phi_0)^2 + (\sigma_y \cos\phi_0)^2}$.

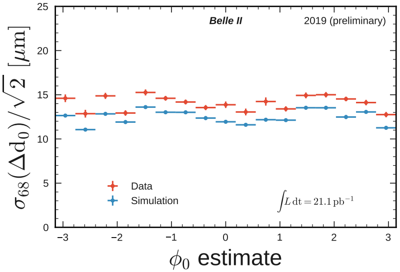
Beam spot size and impact parameter resolution (2019)

- Select tracks in 2-track events.

Variable	Requirement	Unit
$\lvert d_0\rvert$	< 3	mm
$\lvert z_0\rvert$	< 1	cm
# selected tracks in the event	$= 2$	
p_T	> 1	GeV/c
$\lvert\theta_0 - \pi/2\rvert$	< 0.5	
$p\beta\sin(\theta_0)^{3/2}$	> 2	GeV/c
# PDX hits	≥ 1	
# SVD hits	≥ 8	
# CDC hits	> 20	
# selected tracks in the event	$= 2$	
product of the charges in the event	< 0	C^2



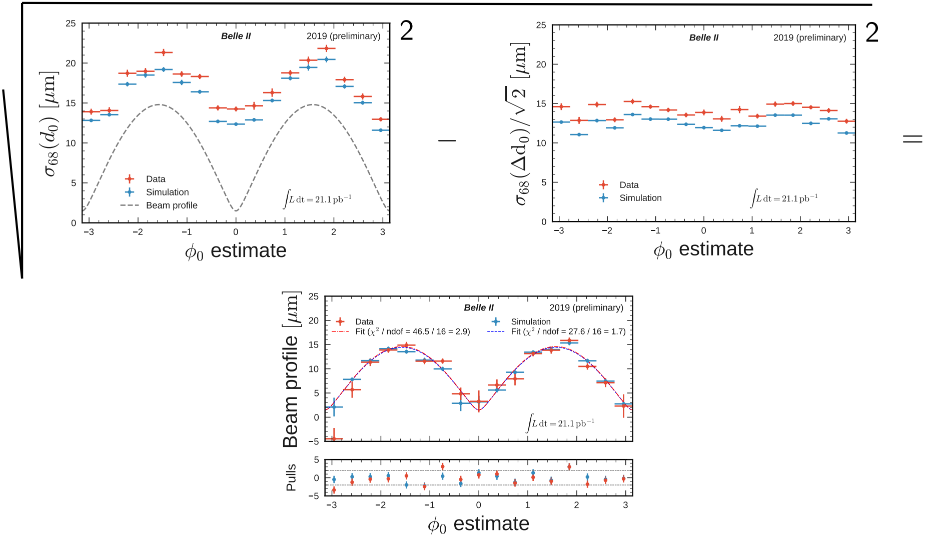




- $\sigma_{68}(.)$: half of the symmetric range around the median containing 68% of the distribution.

Beam spot size measurement: 1st method (2019)

- Unfolding of the beam profile.



Beam spot size measurement: 2nd method (2020)

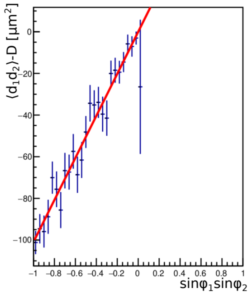
- The beam spot size can be obtained from the correlation of the impact parameters d_1 and d_2 in 2-track events.[1]
  - Beam spot size and resolution separated $\Longrightarrow$ no unfolding needed.
- $d_1 = x_{\mathrm{IP}} \sin\phi_1 - y_{\mathrm{IP}} \cos\phi_1$
- $d_2 = x_{\mathrm{IP}} \sin\phi_2 - y_{\mathrm{IP}} \cos\phi_2$
- $d_1 d_2 = (x_{\mathrm{IP}} \sin\phi_1 - y_{\mathrm{IP}} \cos\phi_1) \cdot (x_{\mathrm{IP}} \sin\phi_2 - y_{\mathrm{IP}} \cos\phi_2)$
- $\langle d_1 d_2 \rangle = \sigma_x^2 \sin\phi_1 \sin\phi_2 + \sigma_y^2 \cos\phi_1 \cos\phi_2 + C \cdot (\sin\phi_1 \cos\phi_2 + \sin\phi_2 \cos\phi_1)$.
  - $C = -\langle x_{\mathrm{IP}} y_{\mathrm{IP}} \rangle$.

[1] S. Donati and L. Ristori, *Measuring beam width and SVX impact parameter resolution*, Tech. rep. CDF-Note-4189, Batavia, USA: FERMILAB, 2003, [url]. See also [1405.6569].

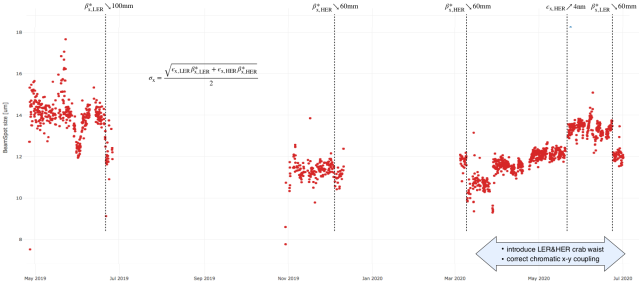
Beam spot size measurement: 2nd method (2020)

- $\langle d_1 d_2 \rangle \underbrace{- \sigma_y^2 \cos\phi_1 \cos\phi_2 + C(\sin\phi_1 \cos\phi_2 + \sin\phi_2 \cos\phi_1)}_{D} = \sigma_x^2 \sin\phi_1 \sin\phi_2.$

Linear fit

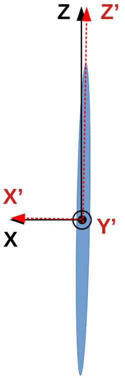


Time dependence of σ_x

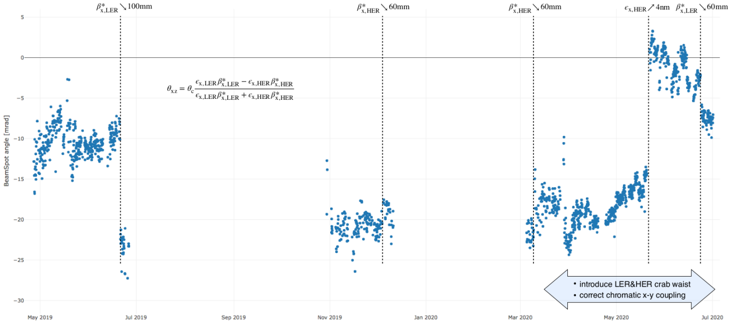


Beam spot orientation

- Also possible to measure the beam spot orientation w.r.t. the Belle II coordinate system.



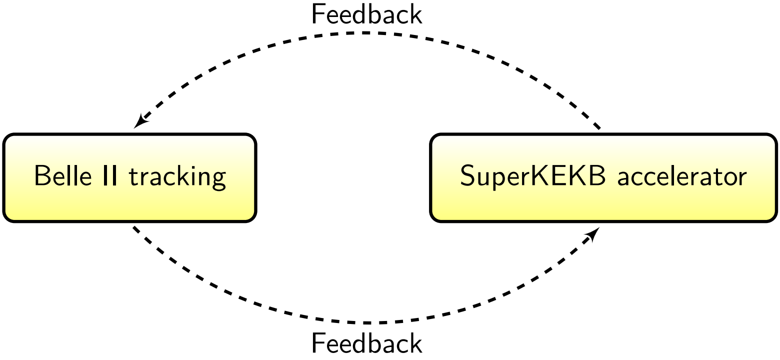
Time dependence of θ_{xz}



Beam spot parameters

- The tracking group is currently developing an algorithm to fully measure the beam spot average position and 3D profile.

- Comparison with accelerator values allows to cross-check consistency.



Conclusion and outlook

- SuperKEKB has a smaller boost compared to KEKB, but Belle **II** compensates with a better impact parameter resolution thanks to its pixel detector.
- Beam spot parameters can be measured from the Belle **II** tracking.
  - Comparison with accelerator values allows for cross-checks.
  - The results can be used to improve simulation.

Questions

Thank you for your attention.

Track parametrisation: full picture

[1901.11198], [github]