Physics Impact and Status of the R&D for the Belle II Vertex Detector Upgrade

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on behalf of the Belle II Collaboration

"Workshop Italiano sulla Fisica ad Alta Intensità"
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Belle II @ SuperKEKB

The mission of Belle II is:

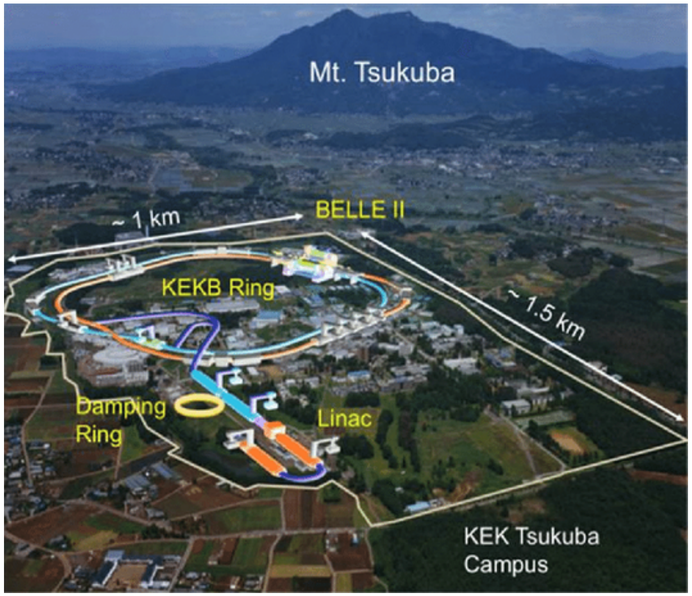
- to improve the precision of the CKM parameters, and confirm the consistency of the overall picture;
- to search for new phenomena in B, charm, and τ Physics;
- to discover and study the properties of new exotic particles;
- to probe the existence of a Dark Sector;
- … ;

In short: to perform any kind of **precision measurements** that may lead to the discovery of Physics beyond the Standard Model!

There is **competition** and **complementarity** with LHCb (that cannot do very well in finals states with π^0's, $\eta^{(')}$'s, K^0_L's ... and modes with difficult backgrounds which benefit a lot from the precise knowledge of the kinematics of the initial state)

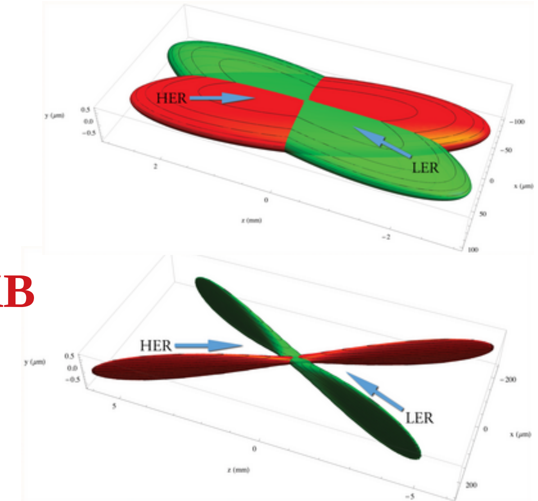
In order to achieve all this, we especially need… lots of data!

The SuperKEKB Collider

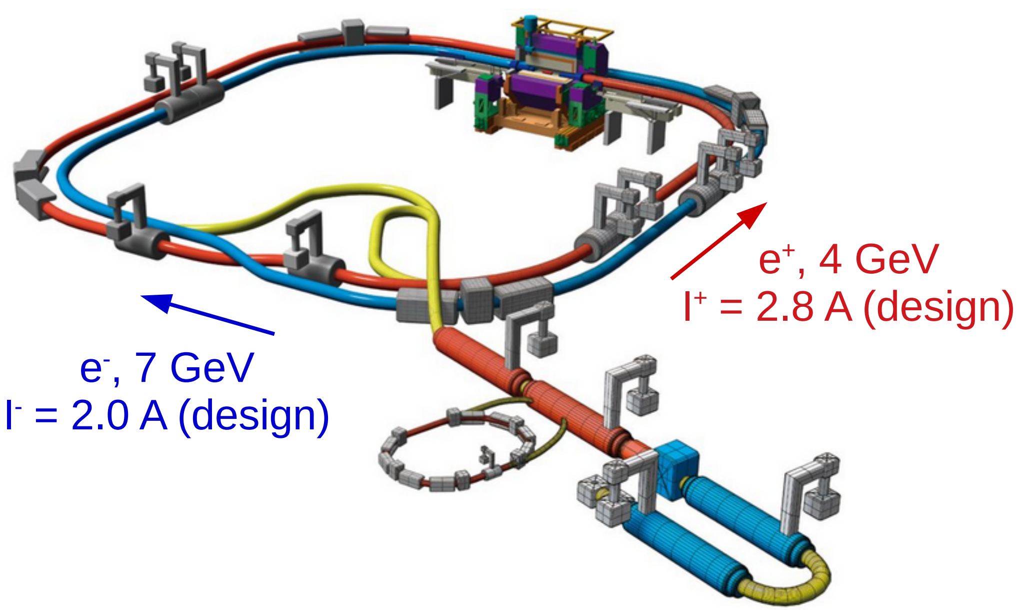


KEKB

SuperKEKB



$$L = \frac{N_+ N_- n_b f_0}{4\pi \sigma^*_{x,\mathrm{eff}} \sqrt{\varepsilon_y \beta^*_y}}$$



Improvements over KEKB:

x20 by ‘nanobeam scheme’ / crab-waist;

x1.5 by increasing beam currents.

Goals:

Instantaneous lumi: ~6 x 10^{35} $cm^{-2}s^{-1}$

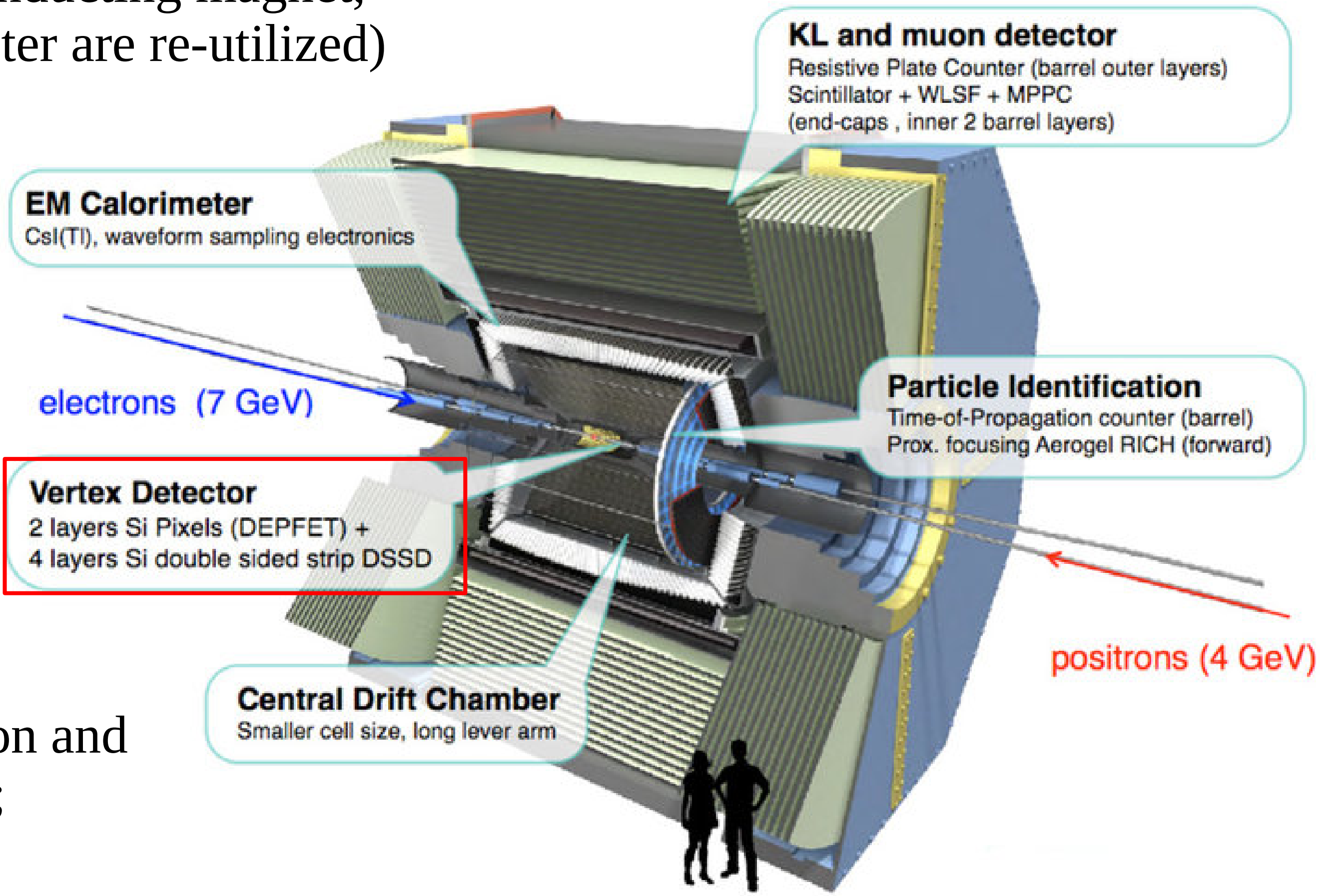
Integrated lumi: 50 ab^{-1}

K. Akai et al., NIM A 907 (2018) 188, arXiv:1809.01958 [physics.acc-ph].

The Belle II Detector

It looks like the old Belle, but practically it is an extensive upgrade!

(only the structure, the superconducting magnet, and the crystals of the calorimeter are re-utilized)



Highlights:

- improved vertexing resolution and K_S reconstruction efficiency;
- enhanced K/π separation;
- new trigger lines for Dark Sector searches, first Neural Network single track trigger;
- more efficient analysis tools, thanks to widespread use of machine learning techniques.

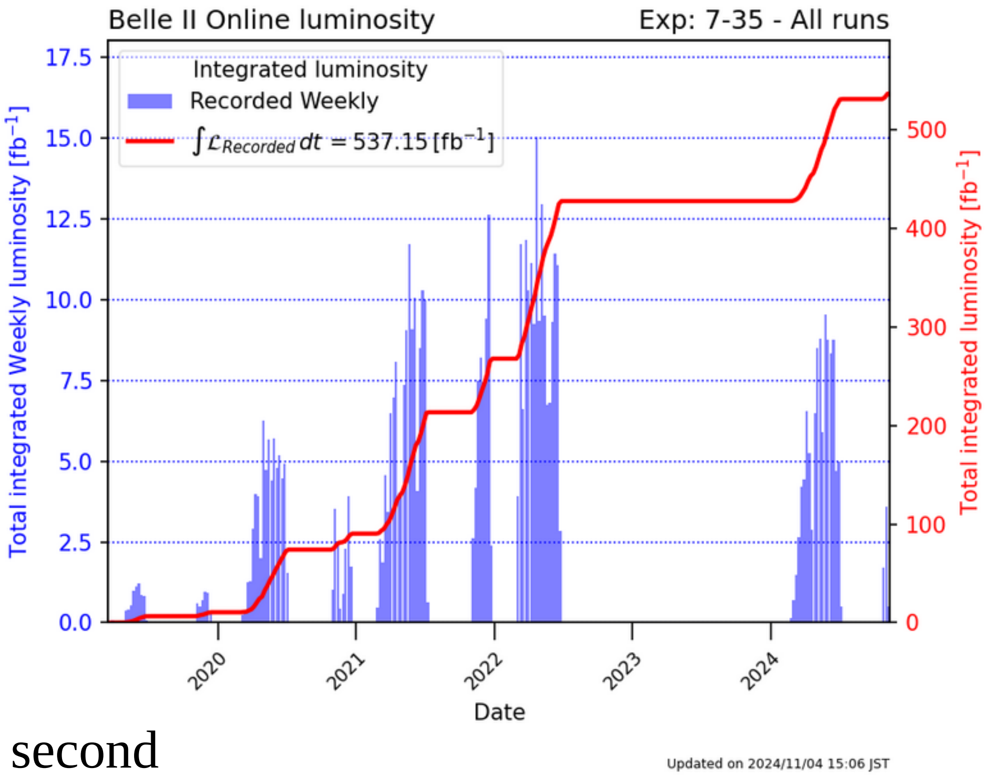
Data taking: off to a slow start

Run1 (2019 – 2022):

Record instantaneous luminosity (of any collider): 4.71×10^{34} cm^{-2} s^{-1};

Recorded in total **~424 fb^{-1}**, of which:

- **~362 fb^{-1}** taken at a CM energy of 10.58 GeV – Υ(4S);
- **~42 fb^{-1}** taken 60 MeV below the Υ(4S);
- **~19 fb^{-1}** taken around 10.75 GeV for exotic hadron searches.



Long Shutdown 1 (2022 – 2024):

Replaced of the original pixel detector (whose second layer was incomplete) with the "design" PXD2;

Replaced part of the TOP photosensors;

As of now, Belle II data set is between BaBar's and Belle's in terms of integrated luminosity

Run2 (2024 – …):

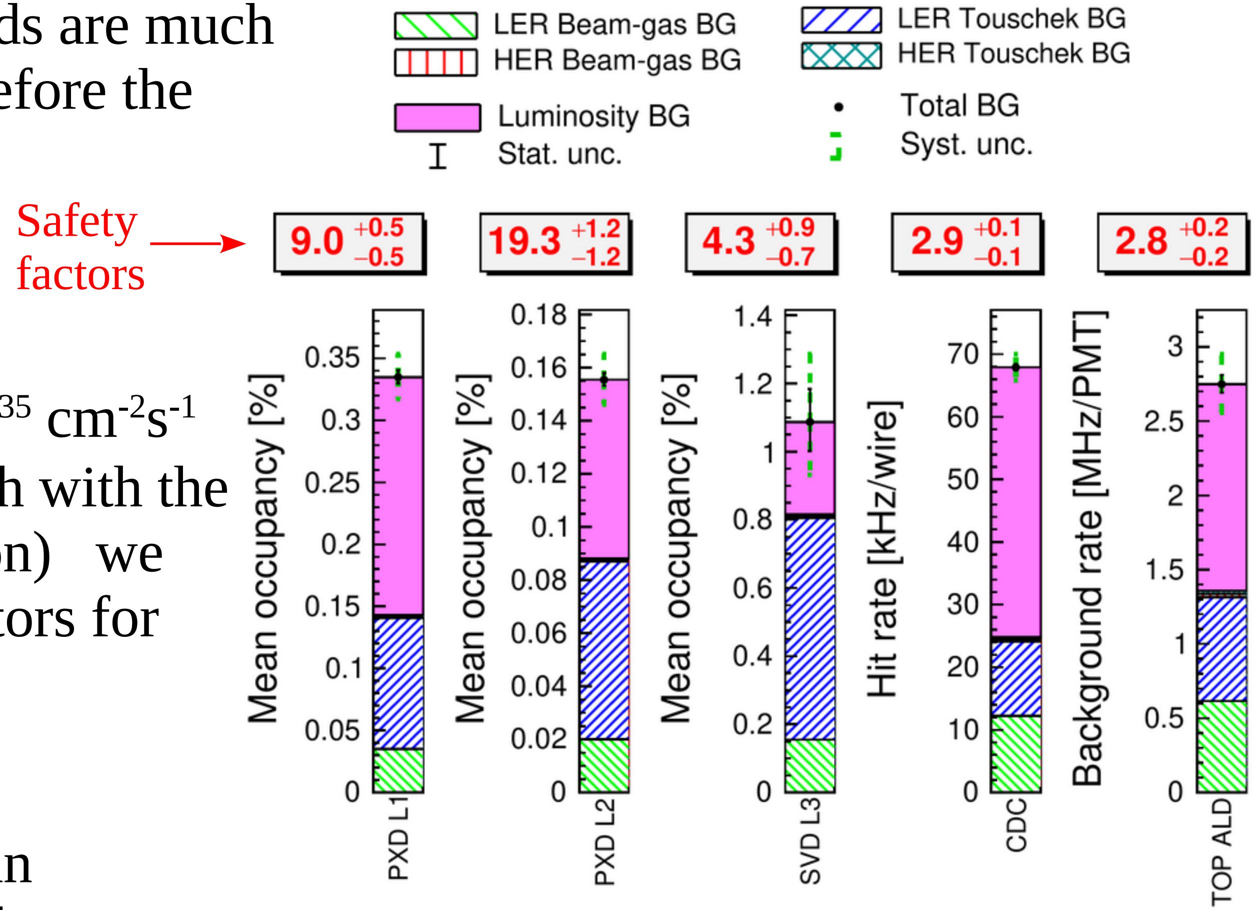
Restarted data taking, but difficult to ramp up the luminosity due to frequent "sudden beam losses" which cause large radiation spikes and force us to run with PXD2 off.

Beam related backgrounds…

- The beam related backgrounds are much higher than we anticipated before the start of data taking;

- Extrapolating to $L = 2.8 \times 10^{35}$ cm^{-2}s^{-1} (which we think we can reach with the current machine configuration) we are still within the safety factors for all subdetectors;

- Going beyond that requires an upgrade of accelerator complex which may include a major redesign of the Interaction Region (IR).

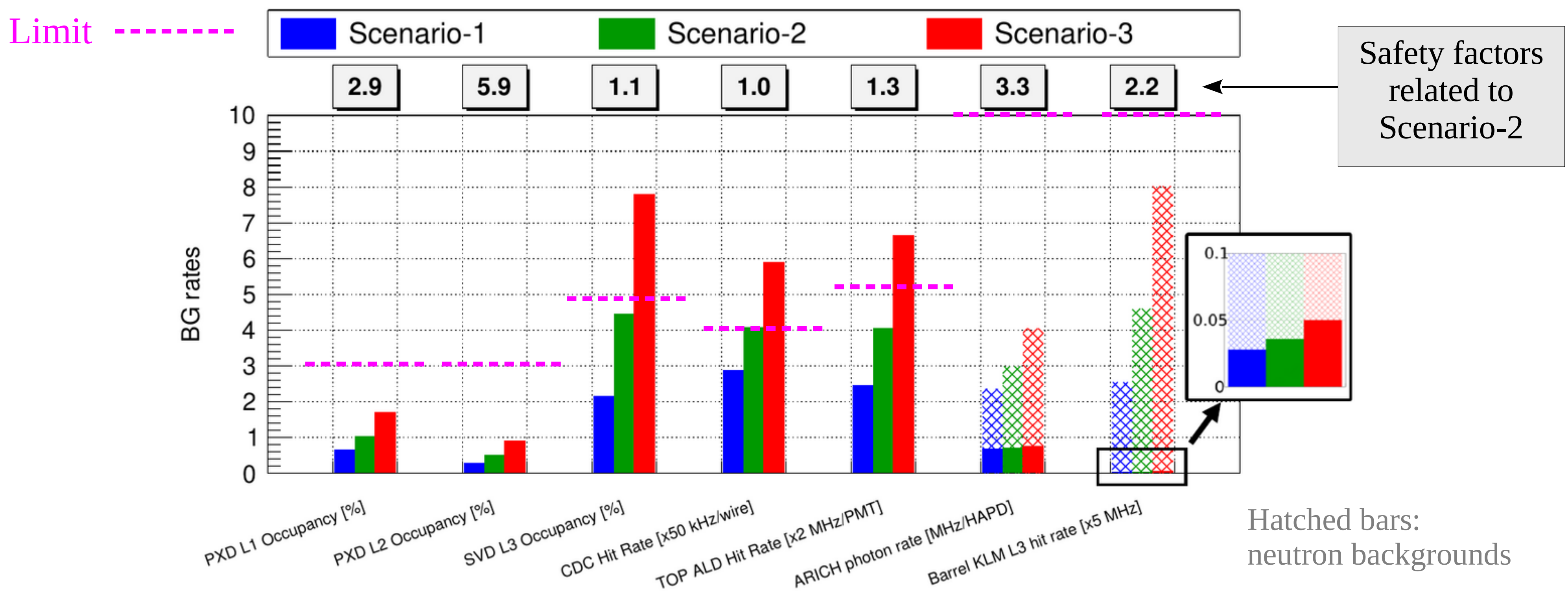


Extrapolations with current machine configuration for $L = 2.8 \times 10^{35}$ cm^{-2}s^{-1} (pre-LS2)

… and their extrapolations

We do not have (yet) the machine configuration that will bring us to 6 x 10^{35} $cm^{-2}s^{-1}$, thus we extrapolate based on three scenarios:

- **1-optimistic**: single beam contributions scaled by **x2** over pre-LS2;
- **2-intermediate**: single beam contributions scaled by **x5** over pre-LS2;
- **3-conservative**: single beam contributions scaled by **x10** over pre-LS2;



Outline

- Why do we need an upgrade?
- What are we going to upgrade?
- The new silicon vertex detector (VTX);
- What we expect to gain in terms of Physics.

Why we need an upgrade

Main motivations:

- **Survive the background** conditions we will have at 6 x 10^{35} $cm^{-2}s^{-1}$, much harsher than expected when Belle II was designed. Extrapolations show that some of the current subdetectors have no safety factor, and uncertainties are still large;
- **Prepare spares** for central detectors (VXD/CDC) in case of accidents or unforeseen degradation;
- **Improve the performance**, and thus extract more physics out of the luminosity delivered by the accelerator;

Bonus motivation:

- **Extend the physics reach** by adding the polarization to the electron beam (Chiral Belle II – not discussed today).

What we could upgrade

We are considering the upgrades for:

- the accelerator (interaction region);
- **the silicon vertex tracker;**
- the Central Drift Chamber (several options are under study);
- the PID detectors (new, more resilient photosensors);
- the Electromagnetic calorimeter (faster electronics and possibly new photosensors);
- the K_L and muon subdetector (running the RPC’s in avalanche mode or replacing them with scintillators with TOF capabilities);
- trigger (making heavy use of Machine Learning);

We recently submitted the Framework Conceptual Design Report: arXiv:2406.19421 [hep-ex], where most of this is covered!

VTX: the new silicon vertex tracker

Main requirement: **higher space-time granularity** to cope with higher beam related backgrounds;

Other requirements:

Radius	14-135 mm (same as current) θ acceptance will depend on the new IR design
Spatial resolution	< 15 μm
Time-stamping	50-100 ns
Total material budget	< 3.5% X_0
Trigger read-out	30 kHz, latency 10 μs
Average hit rate	up to 120 MHz cm^{-2}
Total Ionizing dose (inner)	100 kGy / year
NIEL fluence (inner)	5 x 10^{13} n_{eq} cm^{-2} / year

x4 safety factor over conservative scenario

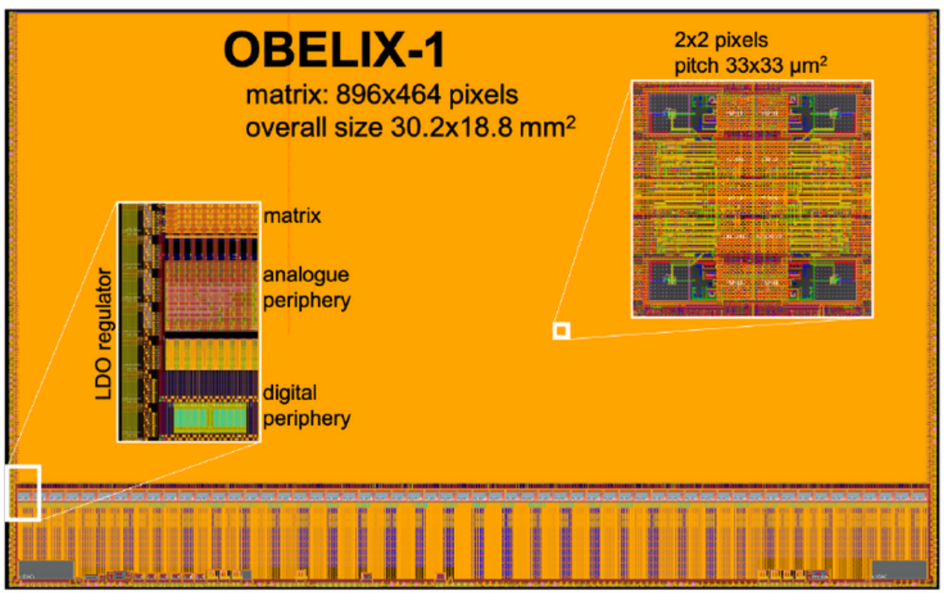
Baseline: **5 layers** (but seriously considering also the 6 layers option)

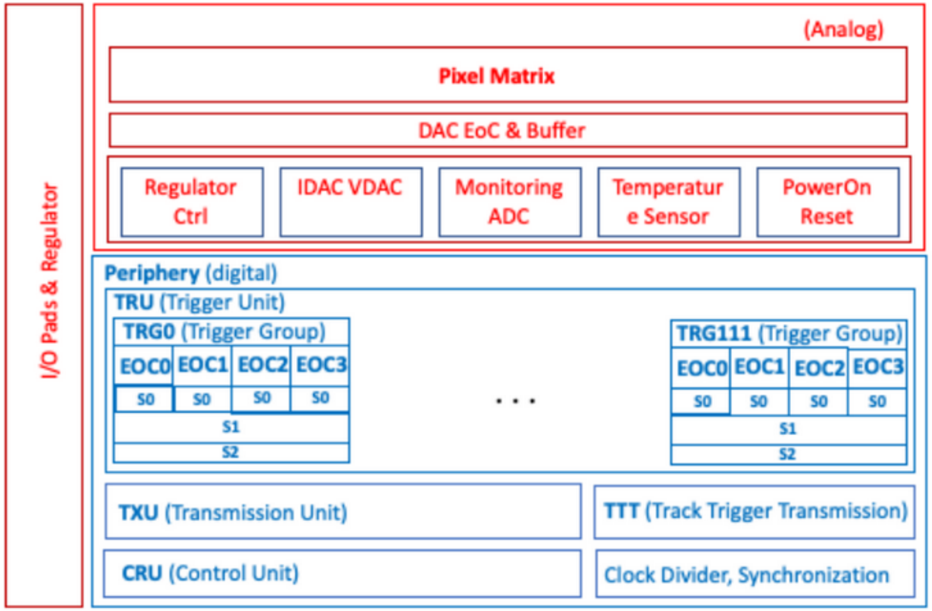
The OBELIX sensor

All layers will be equipped with the same kind of sensors;

Main candidate: **O**ptimised **BEL**le II monolithic p**IX**el sensor, monolithic active pixel CMOS sensor (MAPS);

Pitch: 33 μm, thickness < 100 μm, detection threshold 250-300 electrons, power dissipation up to 200-300 mW cm^{-2} depending on hit rate.

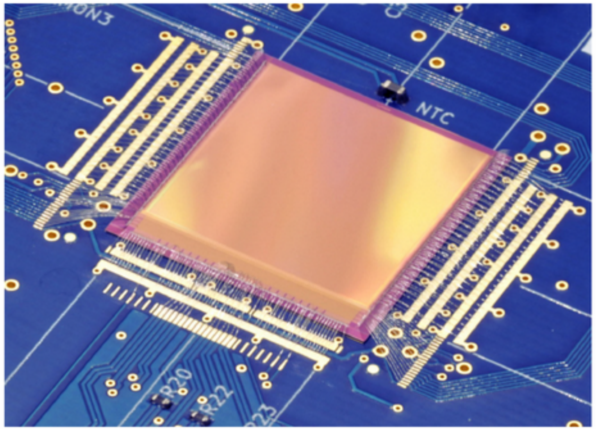


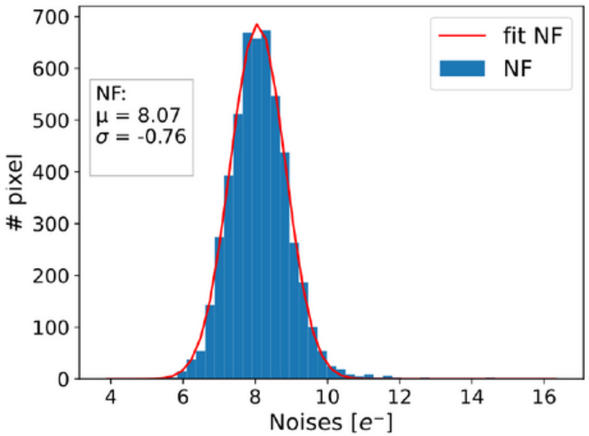


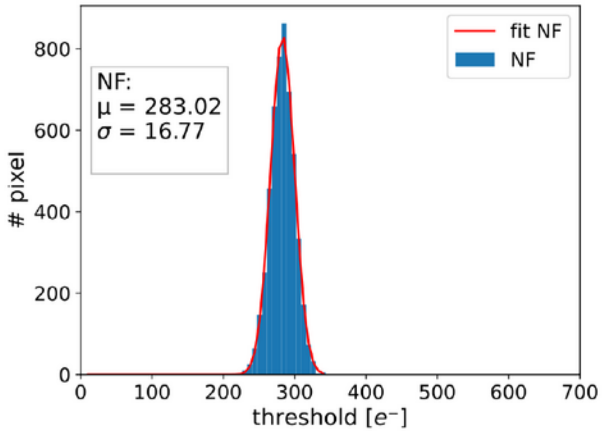
Forerunner sensor: TJ-Monopix2

- Decided to use the TJ-Monopix2 (developed for the ATLAS inner tracker) as a starting point, as its characteristics are close to our requirements;

L. Flores Sanz de Acedo et al., NIM A 980 (2020) 164403





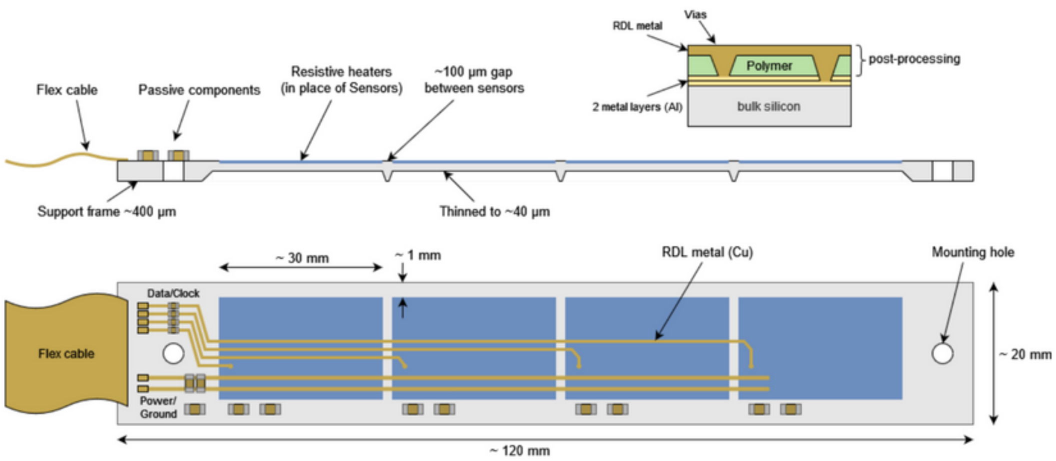


- Tested on 3-5 GeV e^- at DESY before and after irradiation (at 5 x 10^{14} n_{eq} cm^{-2}) in several test-beam campaigns in 2023 and 2024. Detection efficiency decreased only marginally from 99.9% to 99.5%, (threshold of 250-300) e^-, operating the sensor at relatively high temperature (45^o C);
- New campaign in 2025 to better explore performance with temperature dependence and evaluate cooling constraints for the innermost layers (higher BG rate → irradiation & power consumption);
- Spacial resolution and sensitive depth of the sensor consistent with our expectations.

The structure

Inner (2) layers:

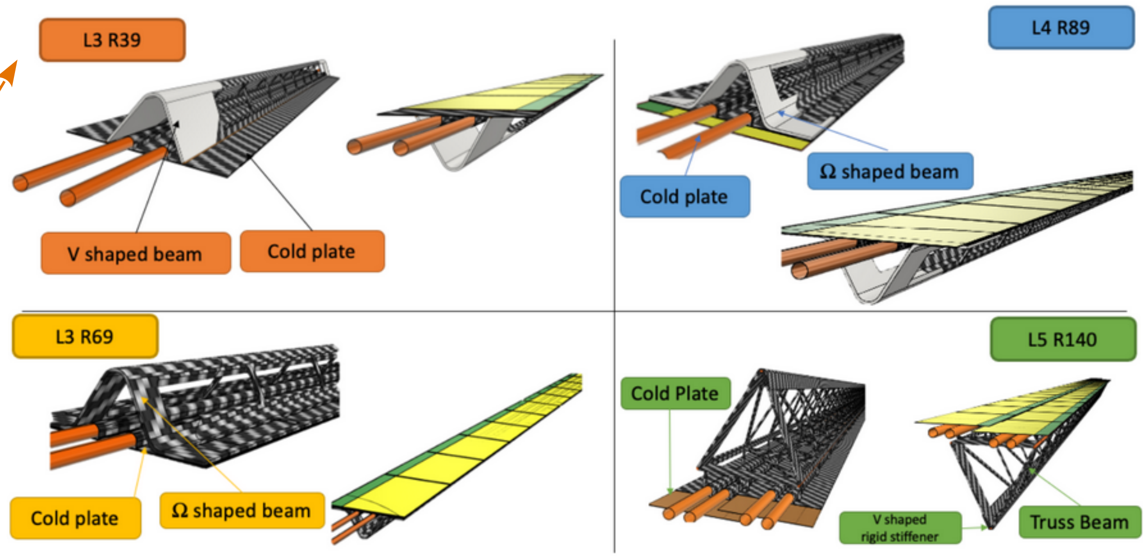
- ~0.2% X_0 thick
- air cooling alone might be marginal (several cooling options under evaluation, based on power consumption and chip temperature constraints after irradiation)
- attached to the beam pipe or supported by outer layers (to be decided)



Outer (3) layers:

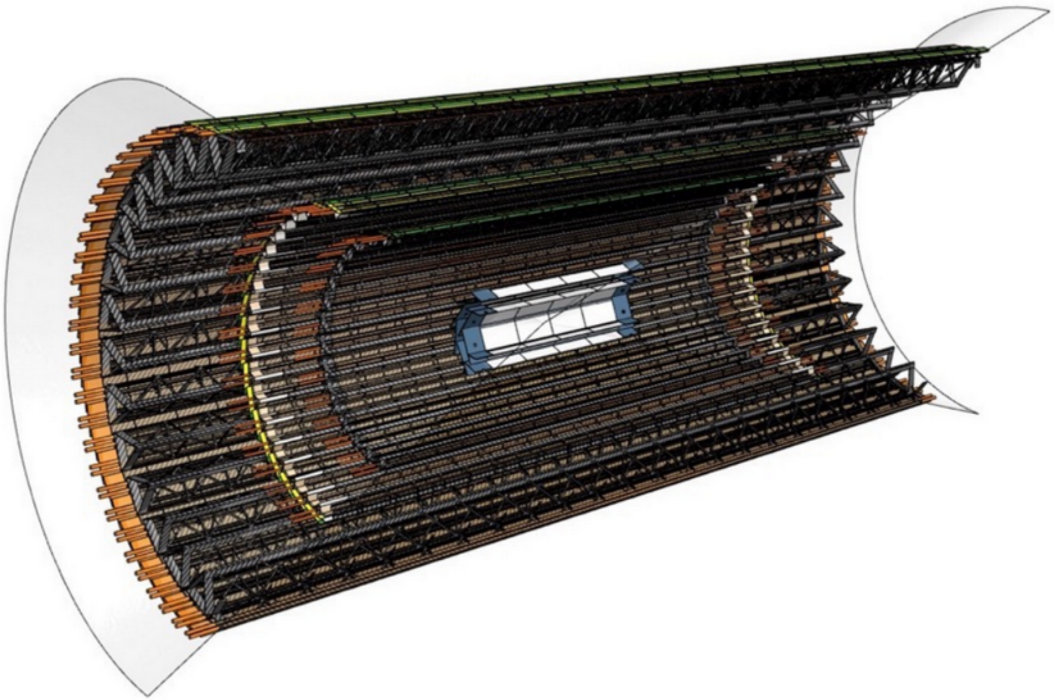
- 0.3-0.8% X_0 thick
- single phase liquid cooled
- requires carbon fiber support structure

Two alternative radii for Layer 3 currently under study



The new VTX

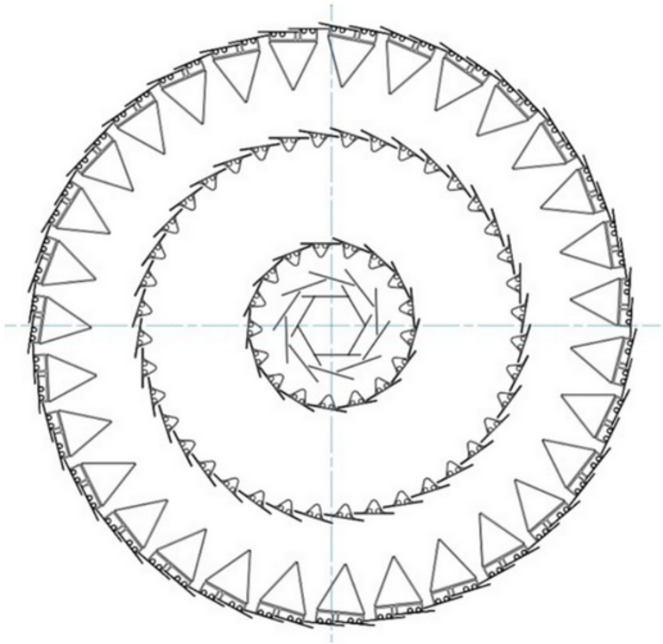
5-layer configuration:



	L1	L2	L3	L4	L5	Unit
Radius	14.1	22.1	39.1	89.5	140.0	mm
# Ladders	6	10	17	40	31	
# Sensors	4	4	7	16	2 × 24	per ladder
Expected hitrate*	19.6	7.5	5.1	1.2	0.7	MHz/cm^2
Material budget	0.2	0.2	0.3	0.5	0.8	% X_0

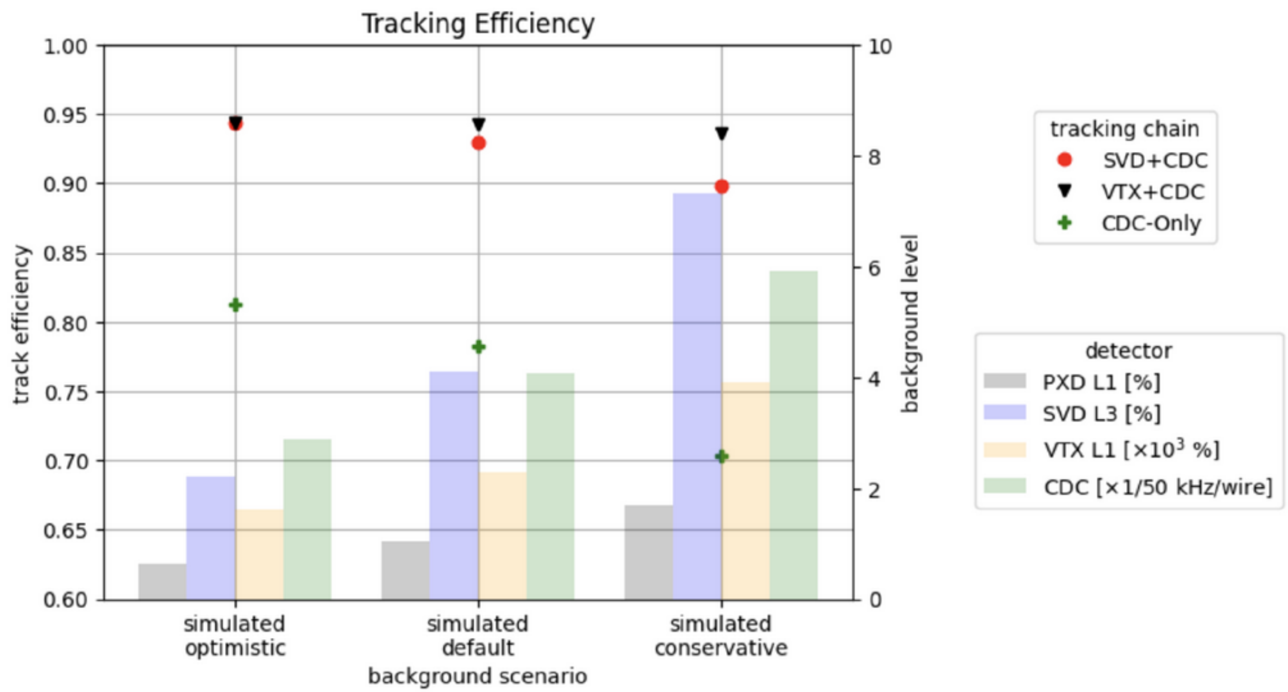
**Large uncertainty on BG extrapolation/possible changes in IR region*

39 mm radius
Layer 3 geometry
(nominal)



Alternative geometry
has Layer 3
at 69 mm radius

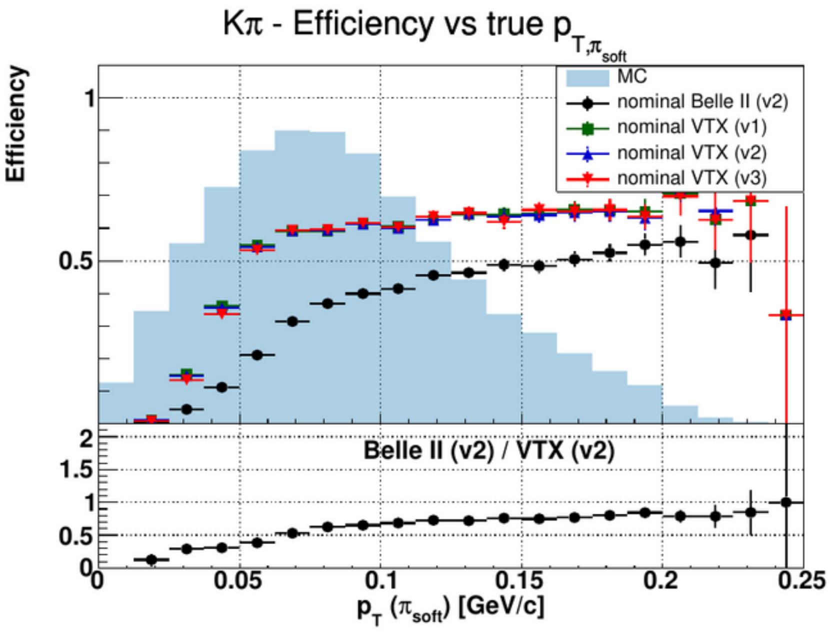
Physics performance

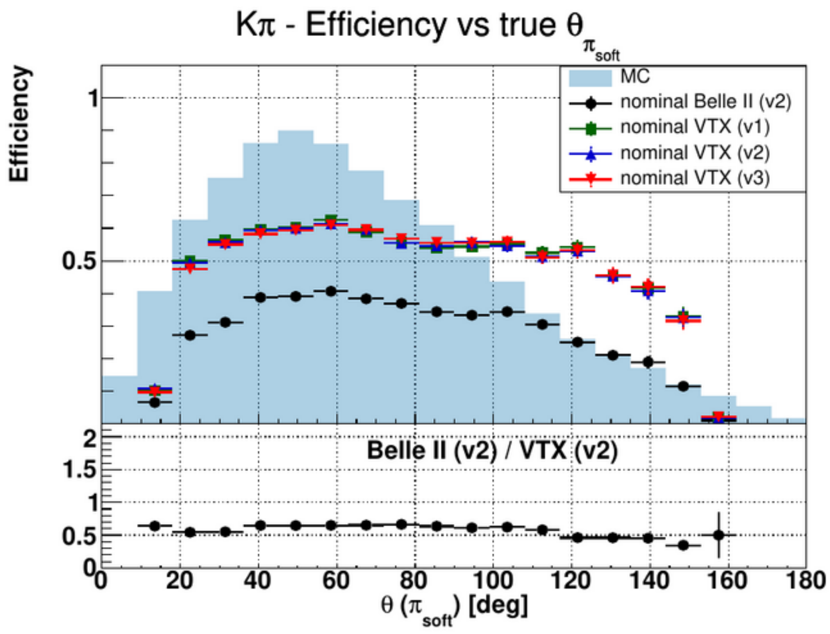


The mission of VTX:

- **keep tracking efficiency high**: the Central Drift Chamber (CDC) will suffer at higher backgrounds. The current vertex detector (SVD) helps a lot, but we need to do better!
- improve low momentum tracking efficiency;
- improve momentum and vertexing resolution;
- keep K_s reconstruction efficiency high.

Low momentum tracking efficiency

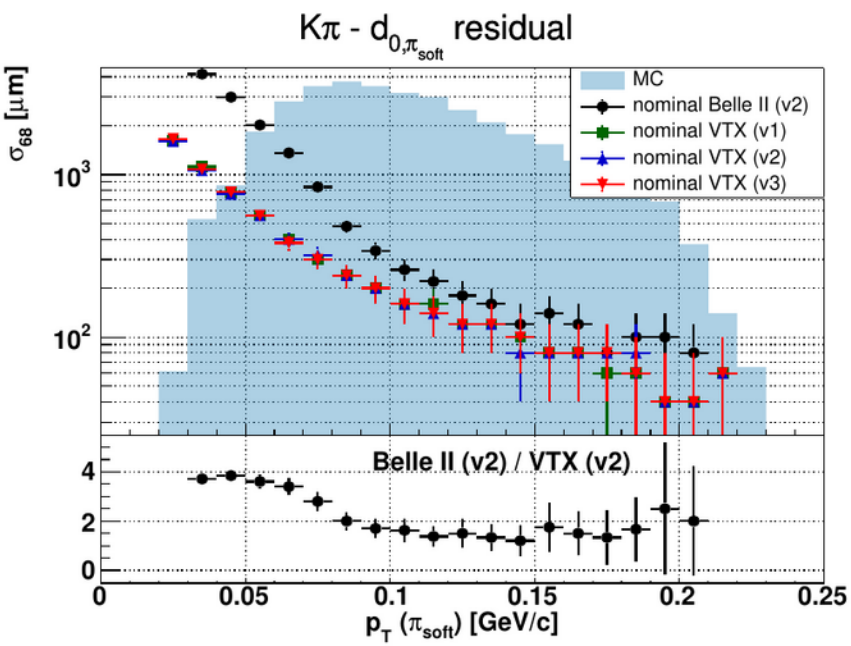


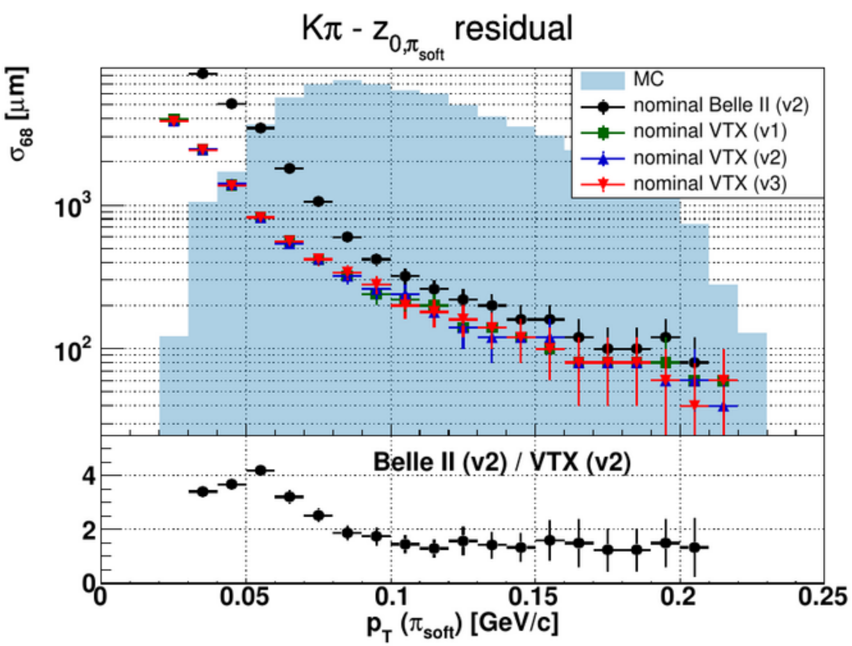


- Low p tracking efficiency studied in simulation on $D^{*+} \rightarrow D^0(\rightarrow K\pi)\ \pi^+_{soft}$ events;
- Overall VTX is a factor ~2 better than current detector, close to ~4 at very low (< 50 MeV/c) p_T;
- Performance is practically insensitive to background conditions;

This is of enormous consequence for the Belle II physics program: improved D^* reconstruction will boost analyses that rely on hadronic or semileptonic B tagging!

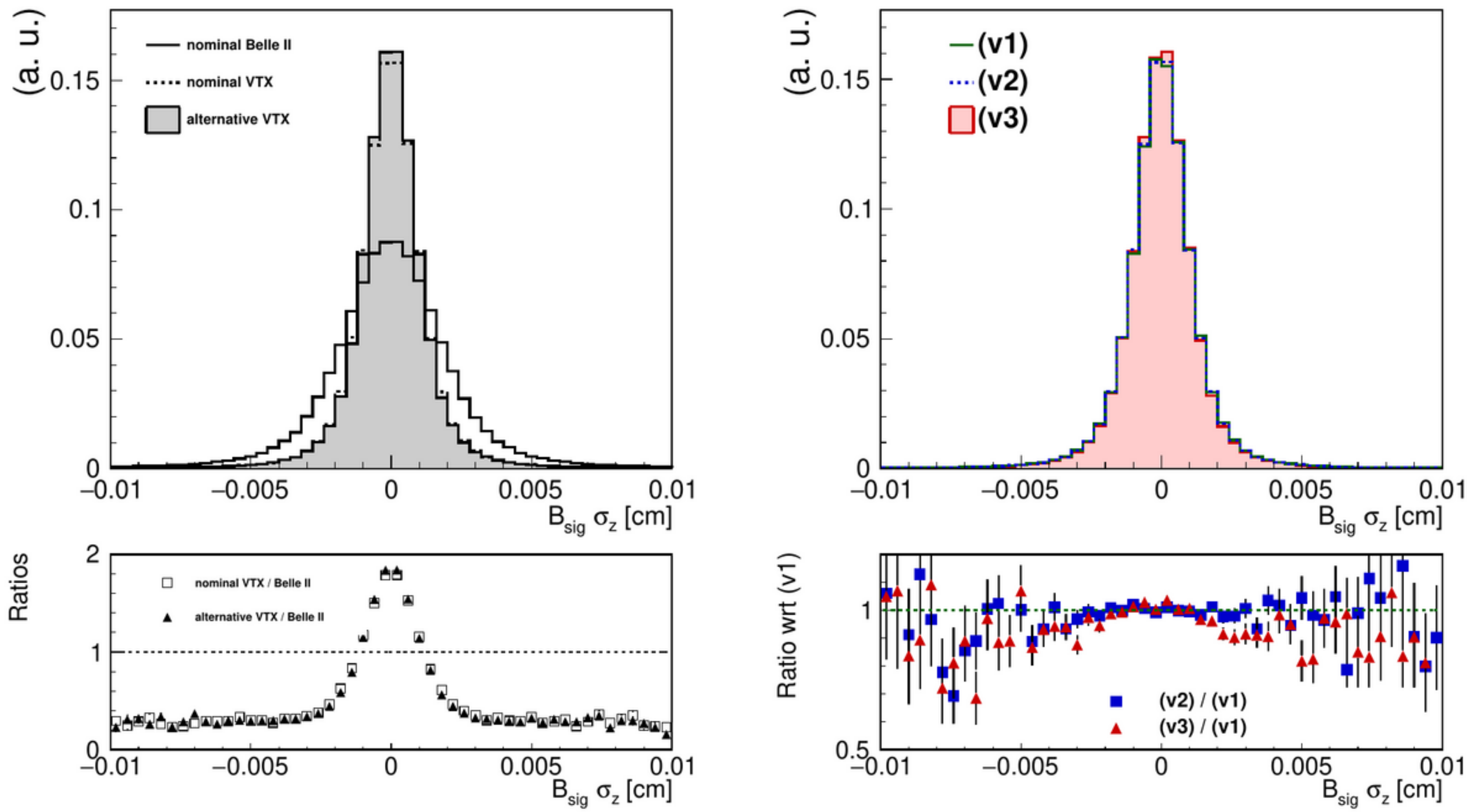
Low momentum tracking resolution





- Similar comments can be made for the POCA resolution in the transverse plane (d_0) and along the beam axis (z_0) of the soft pion;
- A factor ~2 improvement overall, with massive gain at very low p_T;
- No visible degradation with increasing beam backgrdounds.

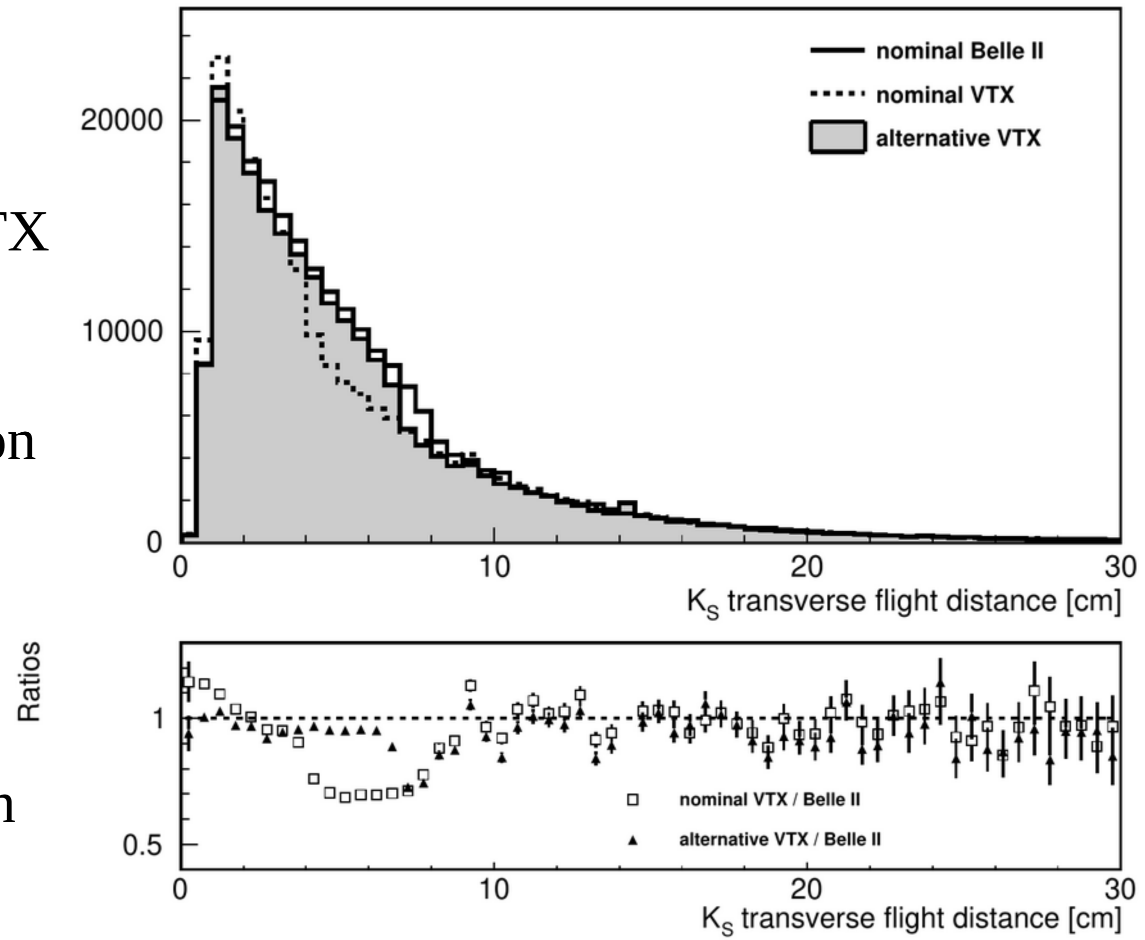
B vertex resolution



- We study the B decay vertex resolution using $B^0 \rightarrow J/\psi K_S$;
- ~35% better resolution on the signal B vertex along the boost axis for both nominal and alternative geometries;
- Very little dependence on the background conditions for VTX.

K_S reconstruction efficiency

- The only negative impact is on K_S reconstruction efficiency;
- The reason is that a standalone VTX track needs to have at least three hits. Consequence: K_S's decaying beyond L3 will have to rely only on the drift chamber;
- The alternative geometry (L3 at 6.9 mm radius) recovers part of the losses);
- Still, we expect ~5% less K_S's than with the current 6-layer detector;



- Considering the gains in the other areas, this is acceptable, but we are still pursuing the 6 layers geometry that would keep all the advantages.

Conclusions

- The Physics campaign of Belle II has just started producing beautiful results (please see talks by Michele, Laura, Debjit, and Foteini at this workshop) ...
- … but achieving our goals proves to be harder than we anticipated, mostly due to difficulties with the machine and higher backgrounds;
- We are planning an extensive upgrade to both machine and detector, that tentatively will happen around the year **2032**;
- The plans for replacing the current silicon detectors with a new monolithic active pixel CMOS sensor based VTX are well under way;
- The VTX promises to cope well with the background conditions we will have at 6×10^{35} $cm^{-2}s^{-1}$, it will maintain tracking performance high, and it will boost the physics sensitivity of Belle II in many areas of our program;
- Prototypes are being built and tested right now.

Backup slides

The Belle II Collaboration

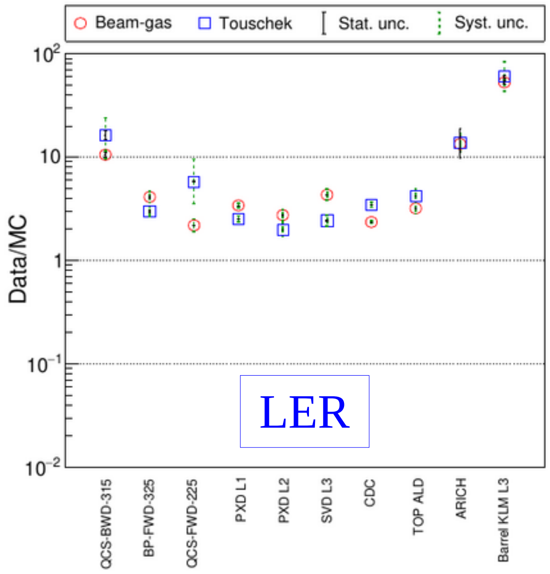
- ➔ 28 countries/regions;
- ➔ 122 institutions;
- ➔ ~1200 active members.

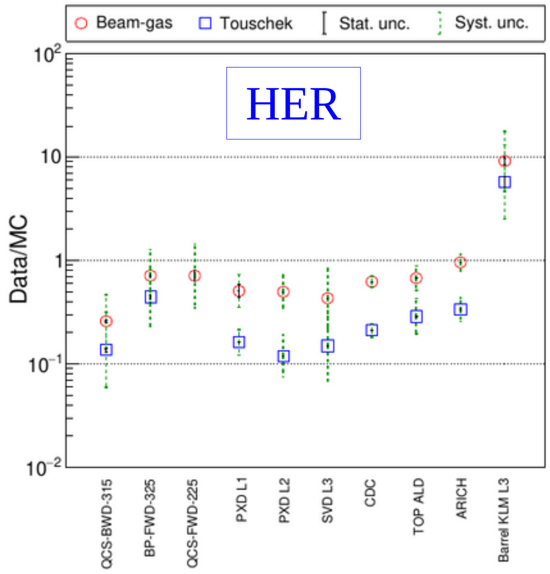
Measured backgrounds

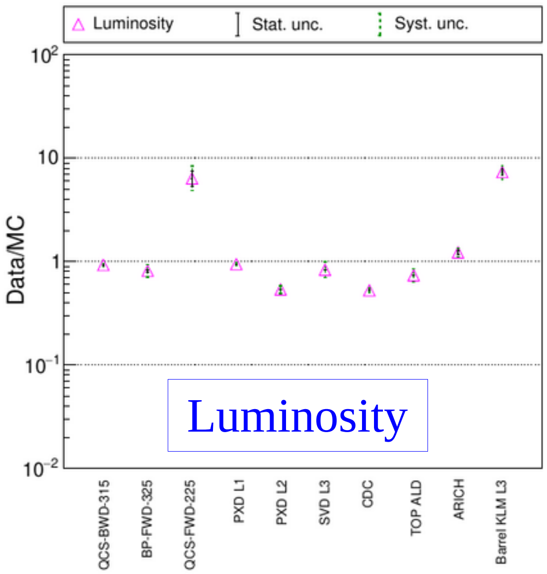
Detector	BG rate limit		Measured BG
Diamonds	1–2 rad/s		< 132 mrad/s
PXD	3 %		0.1 %
SVD L3, L4, L5, L6	4.7 %, 2.4 %, 1.8 %, 1.2 %		< 0.22 %
CDC	200 kHz/wire		22.3 kHz/wire
ARICH	10 MHz/HAPD		0.5 MHz/HAPD
Barrel KLM L3	50 MHz		4 MHz
	non-luminosity BG		
	Before LS1	After LS1	
TOP ALD	3 MHz/PMT	5 MHz/PMT	1.8 MHz/PMT
	+ luminosity BG		

Beam related backgrounds as measured in June 2021

Background simulations







Background extrapolations

Background component	Average Data/MC	Single-beam scaling			Total scaling		
		Sc.-1	Sc.-2	Sc.-3	Sc.-1	Sc.-2	Sc.-3
Beam-gas LER	3.46	2	5	10	6.92	17.30	34.60
Beam-gas HER	0.63	2	5	10	1.26	3.15	6.30
Touschek LER	3.44	2	5	10	6.88	17.20	34.40
Touschek HER	0.18	2	5	10	0.36	0.90	1.80
Luminosity	0.81	1	1	1	0.81	0.81	0.81

OBELIX specifications

Table 5.1: OBELIX sensor specifications, compared to the relevant specification of the TJ-Monopix2 sensor.

	Specification	TJ-Monopix2
Pixel pitch	$< 40\ \mu$m	$< 33\ \mu$m
Sensitive layer thickness	$< 50\ \mu$m	$30\ \mu$m and $100\ \mu$m
Sensor thickness	$< 100\ \mu$m	-
Hit rate capability in the matrix	> 600 MHz cm^{-2}	> 600 MHz cm^{-2}
Hit rate capability at the sensor output	> 120 MHz cm^{-2}	$\gg 100$ MHz cm^{-2}
Trigger delay	$> 10\ \mu$s	-
Trigger rate	30 kHz	-
Overall integration time	< 100 ns	-
(optional) Time precision	< 50 ns	-
Total ionizing dose tolerance	100 Mrad	-
NIEL fluence tolerance	$5 \times 10^{14}\ \mathrm{n_{eq}/cm^2}$	$1.5 \times 10^{15}\ \mathrm{n_{eq}/cm^2}$
SEU tolerance	frequently (min^{-1}) flash configuration	-
Matrix dimensions	around $30 \times 16\,\mathrm{mm}^2$	$19 \times 19\,\mathrm{mm}^2$
Overall sensor dimensions	around $30 \times 19\,\mathrm{mm}^2$	$20 \times 19\,\mathrm{mm}^2$
Powering	through voltage regulators	-
Outputs	one at < 200MHz	one at 160 MHz

Integration to DAQ