Motivations and prospects for Belle II upgrade(s)

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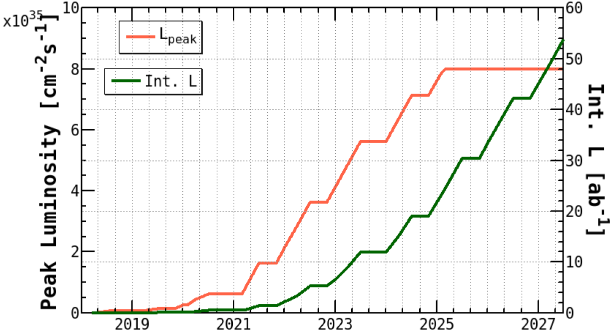
GDR-InF annual workshop 2019

Outline

A two stage approach

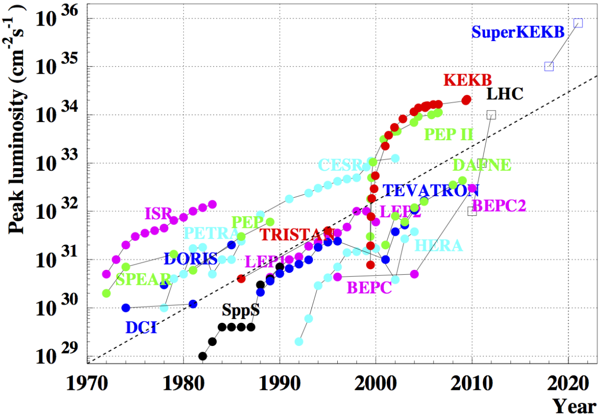
- When superKEKB will reach the full instantaneous luminosity Belle II will still have to accumulate half of the final dataset
  - Optimal performance is key to reach our physics goals. Consolidation upgrade may be valuable
- After the collection of 50 ab^{-1} could we still gain something with a larger dataset?
  - Belle III may be a major actor in flavour physics in > 2030 complementing LHCb Upgrade II



Why a consolidation upgrade?

The intensity frontier

SuperKEKB will reach the record luminosity of 8×10^{35} cm^{-2} s^{-1} (x40 Belle) corresponding to $\sim$ 1 kHz of $\Upsilon(4S)$ ($\sigma \sim$ 1.1 nb)

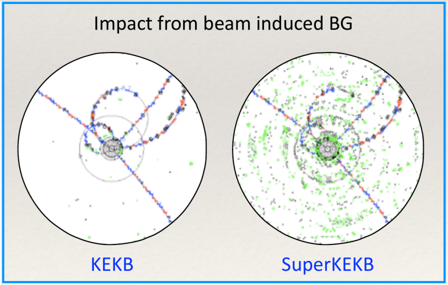


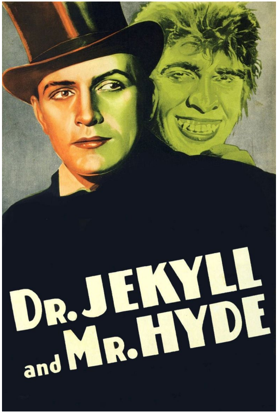
(@ LHC $\sim$ 5 MHz of $b\bar{b}$ thanks to xsec 5×10^5 larger than e^+e^- collider)

A rich man's problem

$$\mathcal{L} \propto \frac{I}{\sigma_{beam}} \text{ BUT Bkg} \propto \frac{I^2}{\sigma_{beam}}$$

SuperKEKB achieves $x40\ \mathcal{L}$ with $x2\ I$ and $\sigma_{beam}/20$ wrt KEKB





2 kinds of beam backgrounds ...

Single beam

Touschek Coulomb interaction between particles in the beam ($\propto I^2/\sigma_{beam}E^3_{beam}$)

Beam-gas interactions with residual gas in the beampipe ($\propto I \times P_{vacuum}$)

Synchrotron radiation γ of 1-10 KeV ($\propto E^2_{beam}$)

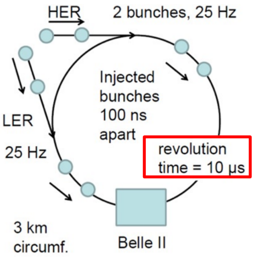
Luminosity backgrounds

$e^+e^- \to e^+e^-(\gamma)$ deviated particles interact with iron magnets causing showers that enter the detector ($\sigma \sim 300$ nb, ~ 70 nb in CDC acceptance)

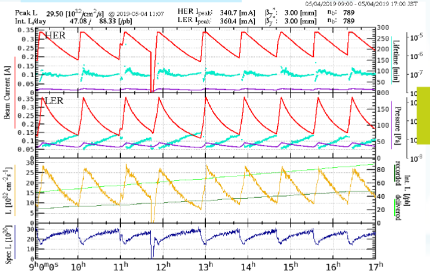
$e^+e^- \to \gamma\gamma \to e^+e^-e^+e^-$ low momentum electron spiral around the solenoid lines leaving multiple hits ($\sigma \sim 40$ nb)

... and an additional complication

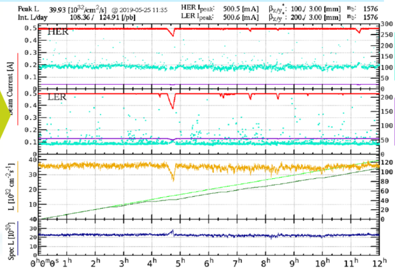
- SuperKEKB is a continuous collider: collisions every 4 ns (250 MHz)
- Continous injection every 20 ms to keep high instantaneous luminosity
- Newly injected bunches are noisier than the others for $\sim$ 400 revolutions (4 ms)
- Mask window of $\sim$ 2 μs at each noisy revolution needed



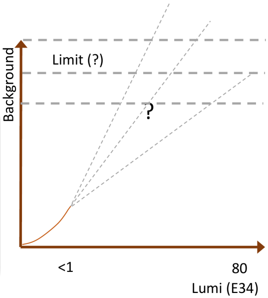
Decay mode run



Continuous injection mode run



- Single beam background difficult to simulate
- Campaigns to measure background on data found disagreement with simulations
  - Beam-gas greater by an order of magnitude
  - Touschek for e^- beam was expected very low while it is found to be sizeable (3 orders of magnitude discrepancy)
- If projected to full luminosity the background would limit physics performances with current detector



Warnings

- Errors associated by extrapolations are huge.
- Mitigation strategies eg. additional collimators may bring the backgrounds under control

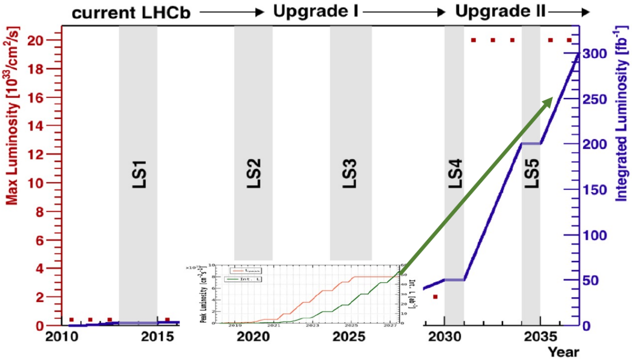
It is wise to be prepared for

1. at least keep the design performance in an harsher environment than originally foreseen
2. hopefully gaining from the technological improvements of the last decade plan for better performance

Why Belle III?

A first baseline proposal

- Assume a factor 5 increase on luminosity
  - target at the same time non trivial and non fictional
- Roughly similar time scale than LHCb Upgrade II
  - Benefit from complementarity and friendly competition



Could we still say something?

Belle II - LHCb Upgrade Comparison

Belle II
Higher sensitivity to decays with photons and neutrinos (e.g. $B\to K\nu\nu$, $\mu\nu$), inclusive decays, time dependent CPV in B_d, τ physics.

LHCb
Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

Overlap in various key areas to verify discoveries.

Upgrades
Most key channels will be stats. limited (not theory or syst.).
LHCb scheduled major upgrades during LS3 and LS4.
Belle II formulating a 250 ab^{-1} upgrade program post 2028.

Observable	Current Belle/ Babar	Current LHCb	Belle II (50 ab^{-1})	LHCb (23 fb^{-1})	Belle II Upgrade (250 ab^{-1})	LHCb upgrade II (300 fb^{-1})
CKM precision, new physics in CP Violation						
$\sin 2\beta/\varphi_1$ ($B\to J/\psi K_S$)	0.03	0.04	0.005	0.011	0.002	0.003
γ/φ_3	13°	5.4°	1.5°	1.5°	0.4°	0.4°
α/φ_2	4°	–	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert$ (Belle) or $\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ (LHCb)	4.5%	6%	1%	3%	<1%	1%
φ_s	–	49 mrad	–	14 mrad	–	4 mrad
$S_{CP}(B\to\eta' K_S$, gluonic penguin)	0.08	○	0.015	○	0.007	○
$A_{CP}(B\to K_S\pi^0)$	0.15	–	0.04	–	0.02	–
New physics in radiative & EW Penguins, LFUV						
$S_{CP}(B_d\to K^*\gamma)$	0.32	○	0.035	○	0.015	○
$R(B\to K^* l^+ l^-)$ ($1<q^2<6$ GeV$^2/c^2$)	0.24	0.1	0.03	0.03	0.01	0.01
$R(B\to D^*\tau\nu)$	6.4%	10%	1.5%	3%	<1%	1%
$Br(B\to\tau\nu)$, $Br(B\to K^*\nu\nu)$	24%, –	–	4%, 9%	–	1.7%, 4%	–
$Br(B_d\to\mu\mu)$	–	90%	–	34%	–	10%
Charm and τ						
$\Delta A_{CP}(KK-\pi\pi)$	–	8.5×10^{-4}	5.4×10^{-4}	1.7×10^{-4}	2×10^{-4}	0.3×10^{-4}
$A_{CP}(D\to\pi^+\pi^0)$	1.2%	–	0.2%	–	0.1%	–
$Br(\tau\to e\gamma)$	$<120\times10^{-9}$	–	$<12\times10^{-9}$	–	$<5\times10^{-9}$	–
$Br(\tau\to\mu\mu\mu)$	$<21\times10^{-9}$	$<46\times10^{-9}$	$<3\times10^{-9}$	$<16\times10^{-9}$	$<0.3\times10^{-9}$	$<5\times10^{-9}$

arXiv: 1808.08865 (Physics case for LHCb upgrade II), 1808.10567 (Belle II Physics Book)

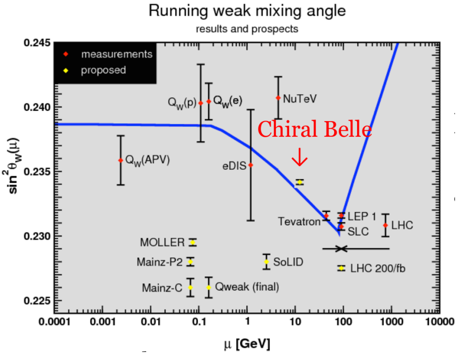
○ Possible in similar channels, lower precision
– Not competitive.

[Phillip Urquijo, Belle II VXD Open Workshop]

Adding a chiral twist

An electron beam with 70% polarisation would allow:

- improved precision on τ electric dipole moment and $(g-2)_\tau$
- reduced background in $\tau \to \mu\gamma$ and $\tau \to e\gamma$
- precise measurement of $\sin^2 \vartheta_W^{lepton}$ at unprobed energy scale



[Erler, arXiv:1704.08330]

- Feasibility still to be proved and discussion just started
- Still room for more inventive ideas (e.g. run at the $D\overline{D}$ and $\tau^+\tau^-$ threshold)

- In any case clear that the resilience to high beam background conditions will be a key element
- In the following I will focus on the vertex detector

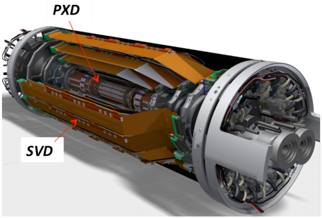
Technological requirements for an upgrade vertex detector

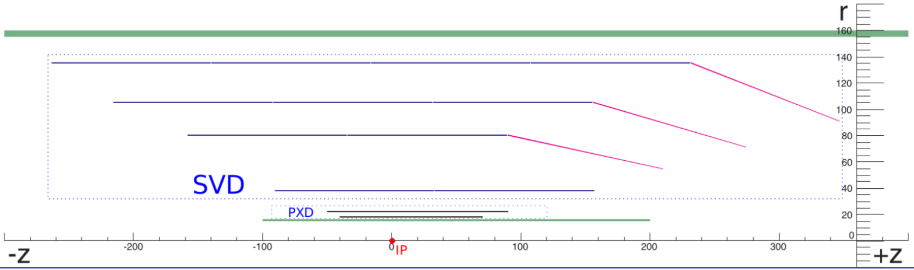
The current vertex detector

PXD 1.2 layers of pixels,
$\sim$ 20 μs time resolution
TID $>$ 200 KGy; NIEL $= 100 \times 10^{12}\, n_{eq}\,\mathrm{cm}^{-2}$

SVD 4 layers of double-sided silicon strips,
$\sim$ 30 ns time resolution
TID $=$ 100 KGy; NIEL $= 10 \times 10^{12}\, n_{eq}\,\mathrm{cm}^{-2}$

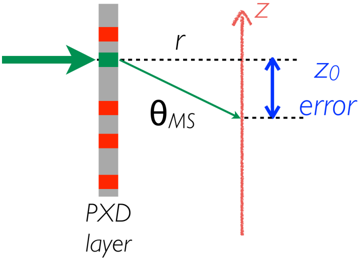
- $\sim$ 10 μm space resolution
- 3.2% X_0 total material budget
- 14-135 mm

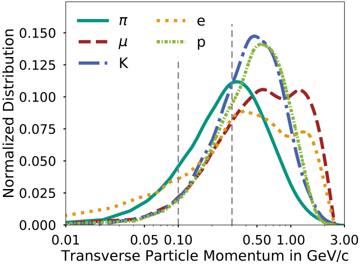




Our upgrade vertex detector should allow:

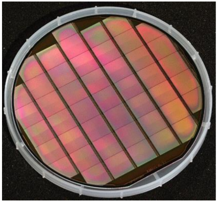
- good impact parameter resolution
  - be close to the interaction point (< 14 mm)
  - high spatial resolution (~ 10 µm)
- tracking for low momentum tracks
  - low material budget ($0.1 - 0.3\% X_0$ per layer)
    - ★ low power dissipation (< 100 mW/cm^2)
- good tracking performances even with large beam background
  - high spatial resolution (~ 10 µm)
  - high time resolution (< 100 ns)
- long usage
  - radiation hard (first layer TID $= 500$ KGy; NIEL $= 250 \times 10^{12}$ n_{eq} cm^{-2})

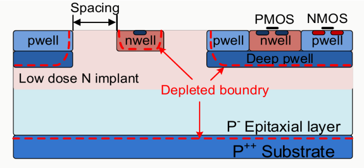




Some initial studies

CMOS pixel sensors: a natural candidate





- Invented in the late '60 for light, now industrial technology (low production costs)
- Signal processing on chip
  - active — in-pixel aplification: high signal-to-noise ratio
  - monolitic — no additional FEE readout
- Operation at room temperature
- Small pixel size possible down to a few μm^2
- Radiation hard

Different flavours

Heavy-ion optimisation

- STAR-ALICE-CBM: IPHC, CERN+collaborators
- Pixel size $\sim 30\ \mu$m
- Radiation tolerance ~ 1 MGy
- Time resolution $2 - 5\ \mu$s
- Power dissipation $\sim 50 - 300$ mW/cm^2

LHC driven optimisation

- ATLAS: Marseille, Bonn, Geneva, Liverpool
- Pixel size $40 - 150\ \mu$m
- Radiation tolerance ~ 1 GGy
- Time resolution 25 ns
- Power dissipation ~ 1 W/cm^2

... other efforts also ongoing

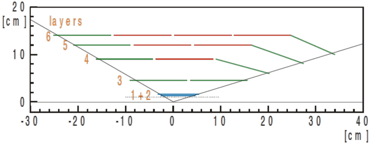
2020 couple of CMOS sensor architectures will exist on full-scale chips close to match Belle II consolidation upgrade requirements (100 MHz/cm^2)

$\sim$ 2025 moved from full-size prototype to final sensors

$\sim$ 2028 possible to reach likely Belle III requirements (600 MHz/cm^2)

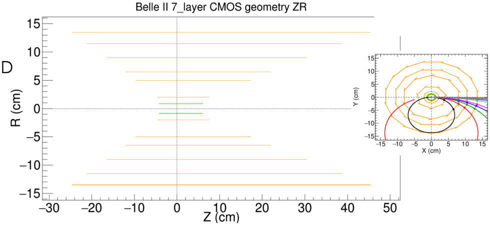
A first look at possible geometries

Yifan Jin (when @ IPCH) used parametric tool Guariguanchi (developped by Alejandro Perez Perez when @ IPHC) to study effect of different geometries on physics performance



True Belle II VXD

Guariguanchi VXD

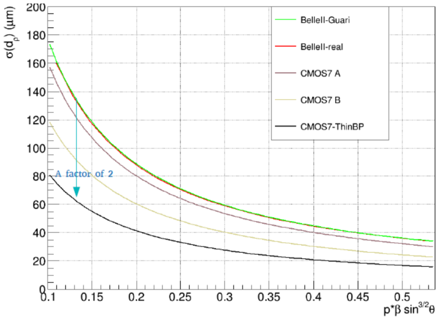


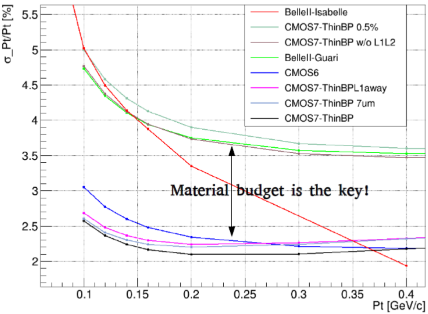
Needed $\sim 1\,\mathrm{m}^2$ of silicon
($3000 - 4000$ circuits of $3 \times 2\,\mathrm{cm}^2$ taking into account overlaps)

Some preliminary conclusions

Impact parameter and momentum resolution dominated by multiple scattering in beampipe

- Spacial resolution of $\sim 10\ \mu m$ adequate
- Effort should be put in reducing material budget





Now effort to repeat and expand these studies with the Belle II software (Tristan Fillinger @ IPHC)

A fresh start

- Effort started in Belle II to plan for an upgrade
- First workshop @ CERN this July on upgrade vertex detector (link)
- Participation from all three French Belle II institutes

Conclusions

- Belle II data taking just started but it is never too soon to start planning ahead
  - for a consolidation upgrade to guarantee Belle II physics reach in the harsh beam background conditions of the design instantaneous luminosity
  - for Belle III to capitalise on the expertise gained in Belle II and complement LHCb Upgrade II at the flavour intensity frontier in the years to come
- Discussion started with a strong involvement of the French community

BACKUP

Legend geometry study

CMOS7-ThinBP

BP 0.8-0.9 cm	0.9 cm	2.0 cm	5.0 cm	6.5 cm	9.0 cm	11.5 cm	13.5 cm
0.4%	0.05%	0.05%	0.15%	0.3%	0.3%	0.3%	0.3%

- BelleII-Guari
- BelleII-real
- CMOS6
- CMOS7 A
- CMOS7 B
- CMOS7L1away(0.15X0)
- CMOS7-ThinBP(0.15X0)
- CMOS7L1away
- CMOS7-ThinBP 10um
- CMOS7-ThinBP 7um
- CMOS7L3L4
- CMOS7-ThinBP

BP 0.8-0.9 cm	1.2 cm	2.0 cm	5.0 cm	6.5 cm	9.0 cm	11.5 cm	13.5 cm
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0.4%	0.05%	0.05%	0.15%	0.3%	0.3%	0.3%	0.3%

Hit rates (MHz.cm^{-2})

Nominal lumi ~ 2025

Upgraded lumi

safety

Layer	Radius (mm)	L = 8x10^{35} cm^{-2}.s^{-1} Nominal bkg	L = 40x10^{35} cm^{-2}.s^{-1} Nominal bkg	L = 40x10^{35} cm^{-2}.s^{-1} 5x bkg
PXD 1	14	**22.6**	**113**	**565**
PXD 2	22	**11.3**	**56**	**280**
SVD 3	39	**1.41**	**7**	**35**
SVD 4	80	**0.29**	**1.5**	**8**
SVD 5	108	**0.22**	**1.1**	**6**
SVD 6	135	**0.15**	**0.8**	**4**

Nominal bkg: currently expected from simulations

[Jérôme Baudot, Belle II VXD Open Workshop]