Belle II — Upgrade and Outlook

In the Context of the
European Strategy for Particle Physics

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UNIVERSITÄT BONN

Belle II

Belle II & SuperKEKB

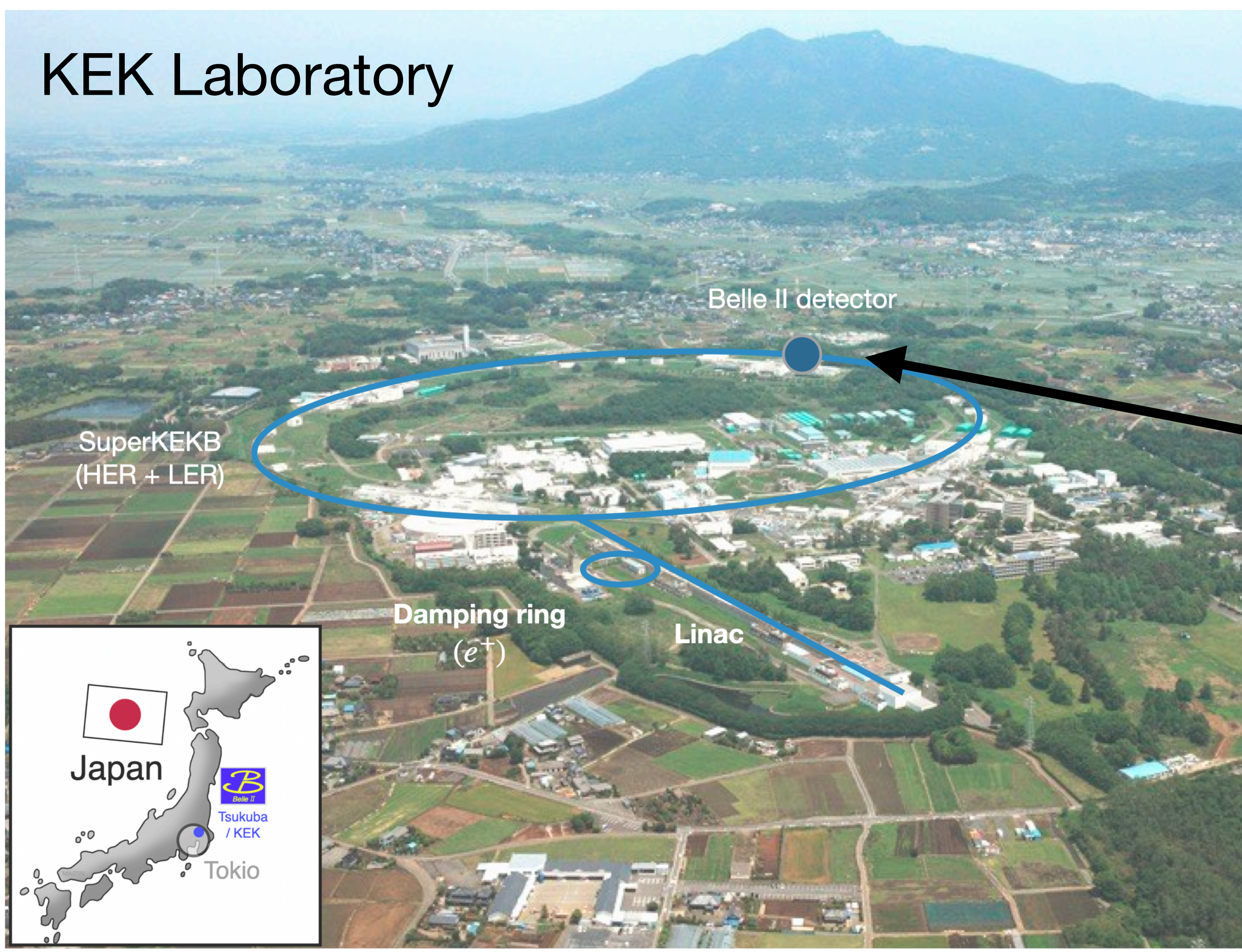
Belle II operates at **KEK** recording collisions of e^+e^- near $\sqrt{s} \sim 10.58\,\mathrm{GeV}$

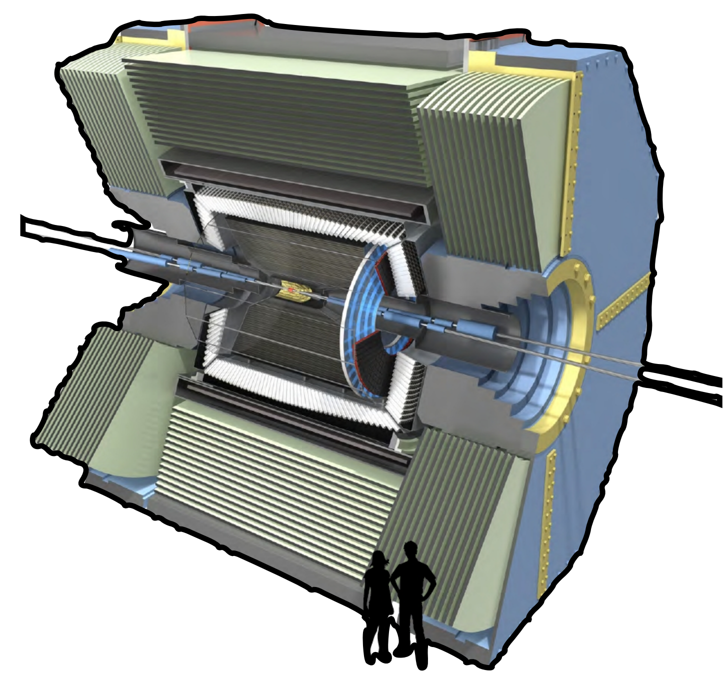
Provides clean laboratory to study beauty, charm and light quarks, τ-leptons

Physics program very broad covering precision measurements, searches for exotic states of matter, precision QCD for g-2, light dark matter, …

Gudrun Hiller's talk yesterday

Complementary to LHCb





4π detector with
excellent tracking, neutral, PID

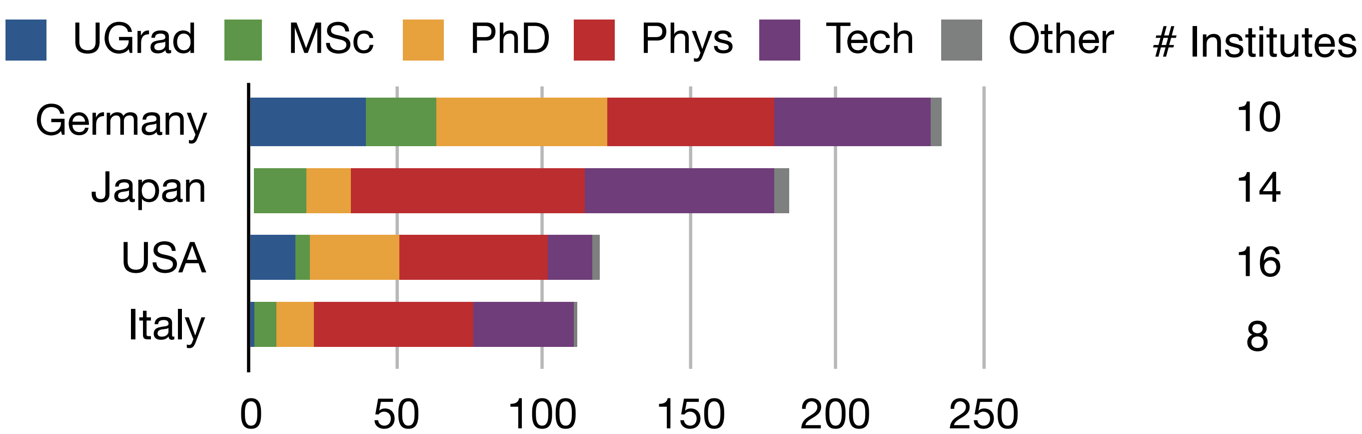
Belle II Collaboration Structure

JENNIFER2
EU grant n.822070

Bundesministerium für Bildung und Forschung

Germany is major contributor to Belle II:
237 / 1195 **Members** (= ~ 20%)

Four largest countries by members / institutes



(30 Postdocs, 56 PhD students, 65 MSc. & BSc. students,
55 technical members, 27 Group leaders & Staff, 5 Emeriti & Visitors)

HELMHOLTZ
SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

DFG

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

UNIVERSITÄT BONN

TUM

KIT Karlsruher Institut für Technologie

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

DESY.

MAX PLANCK HALBLEITERLABOR

MAX-PLANCK-INSTITUT FÜR PHYSIK

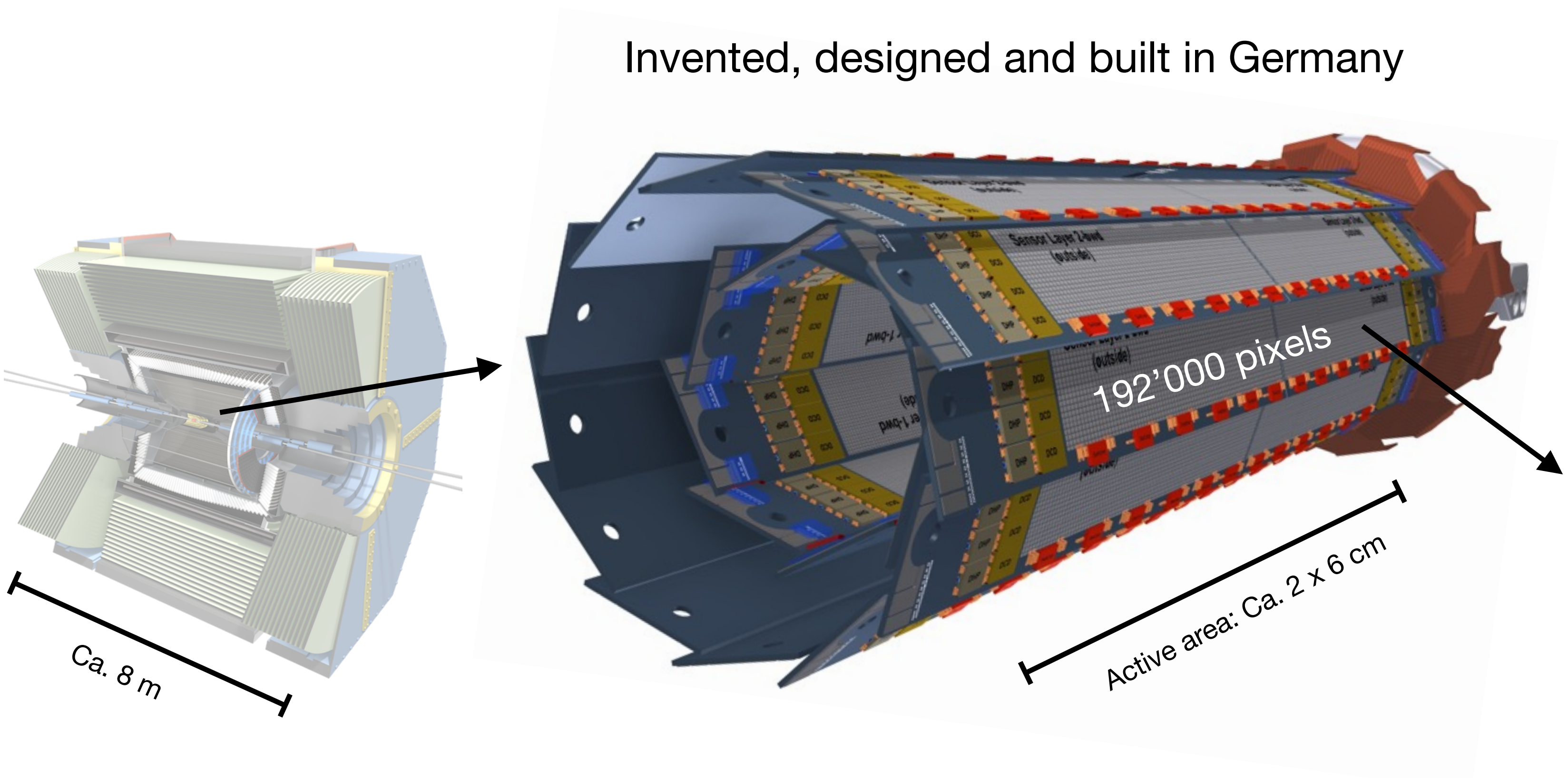
Strong involvement in physics: **18 of 40**
published Belle II papers from German groups

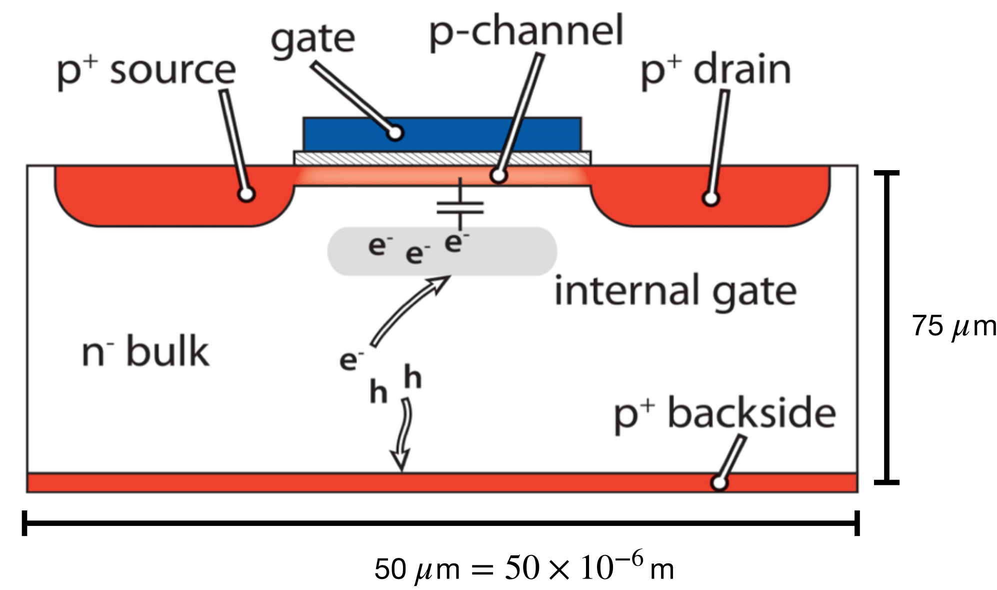
Well represented in the management of the collaboration:

Institutional Board chair, **Spokesperson-elect**, 3 of 8 Physics sub-groups coordinated by German group members, several coordinators in performance, software, PXD project leader, …

Existing German Contributions to Belle II

Major technology contribution: **Silicon Pixel Detector** (PXD) based on *depleted p-channel field-effect transistor* (**DEPFET**) design



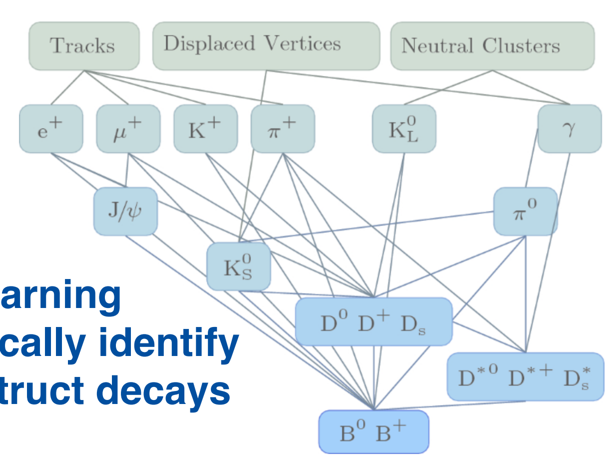


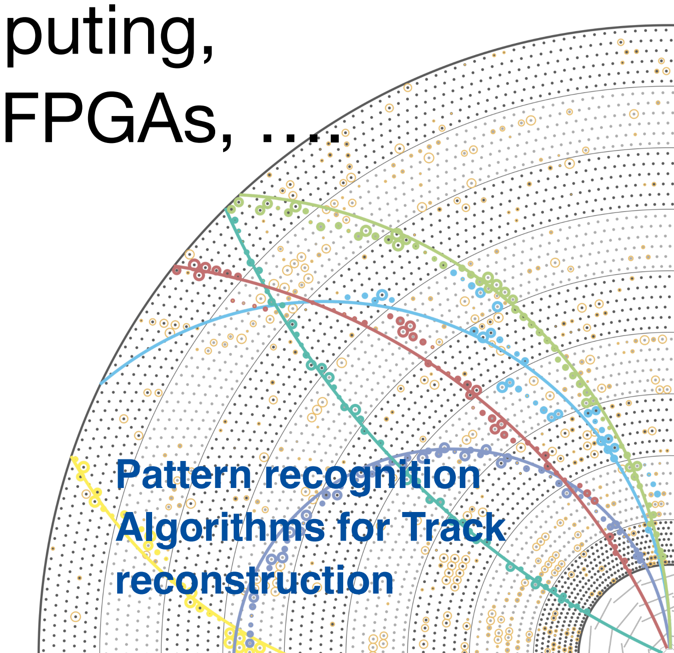
Other key contributions: Software & Reconstruction, Computing, Use of Artificial Intelligence and Deep Learning, Triggering with FPGAs, ….

Belle II Software Framework

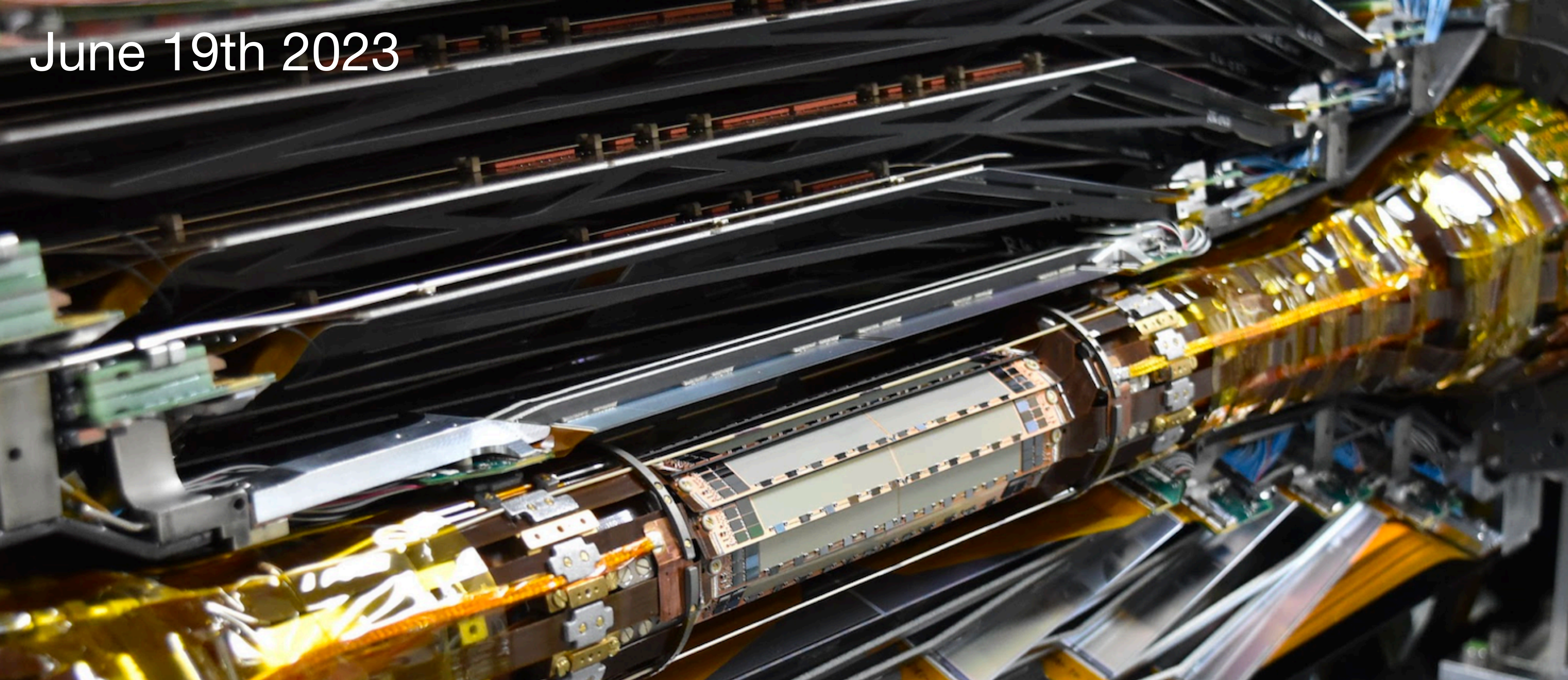
basf2

Machine Learning to automatically identify and reconstruct decays





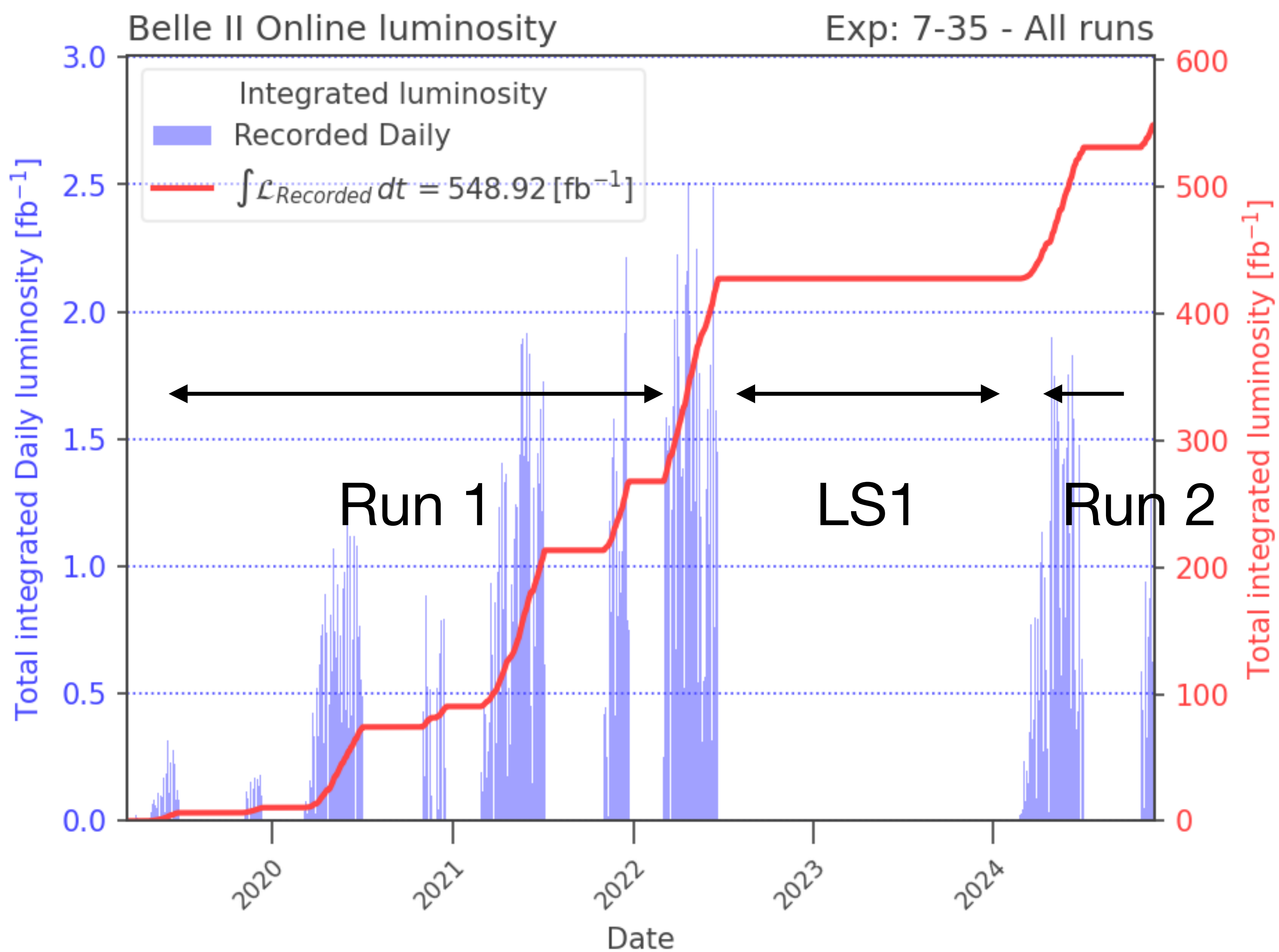
June 19th 2023



The current status and plans to ca. 2030

Run 2 of experiment started Jan 29th 2024 Collected ca. 0.55/ab = BaBar

→ During **Run 1**: Achieved world record inst. luminosity of $4.71 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$



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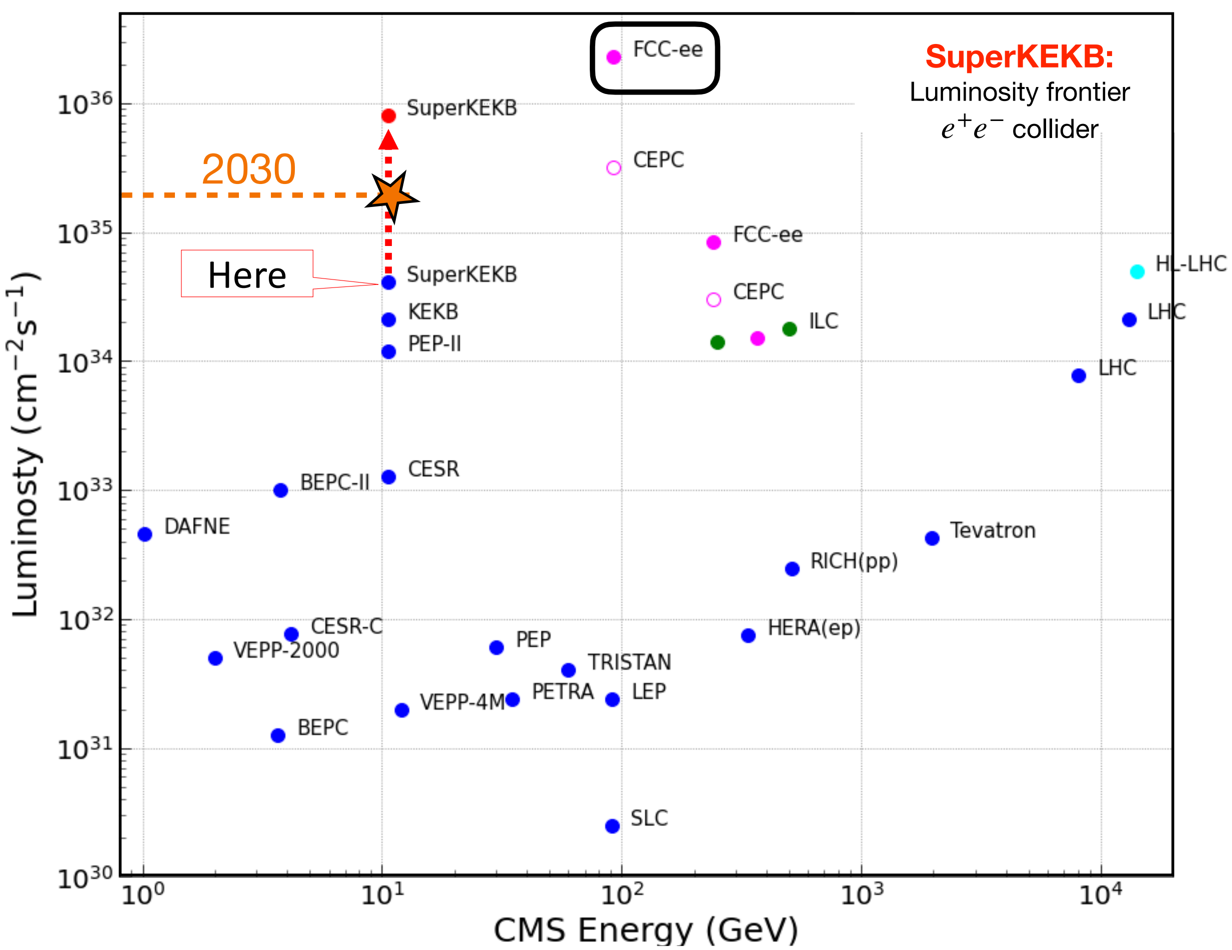
SuperKEKB & Belle II goals until 2030 ⟶ $\sim 2 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ & collect ca. 5/ab



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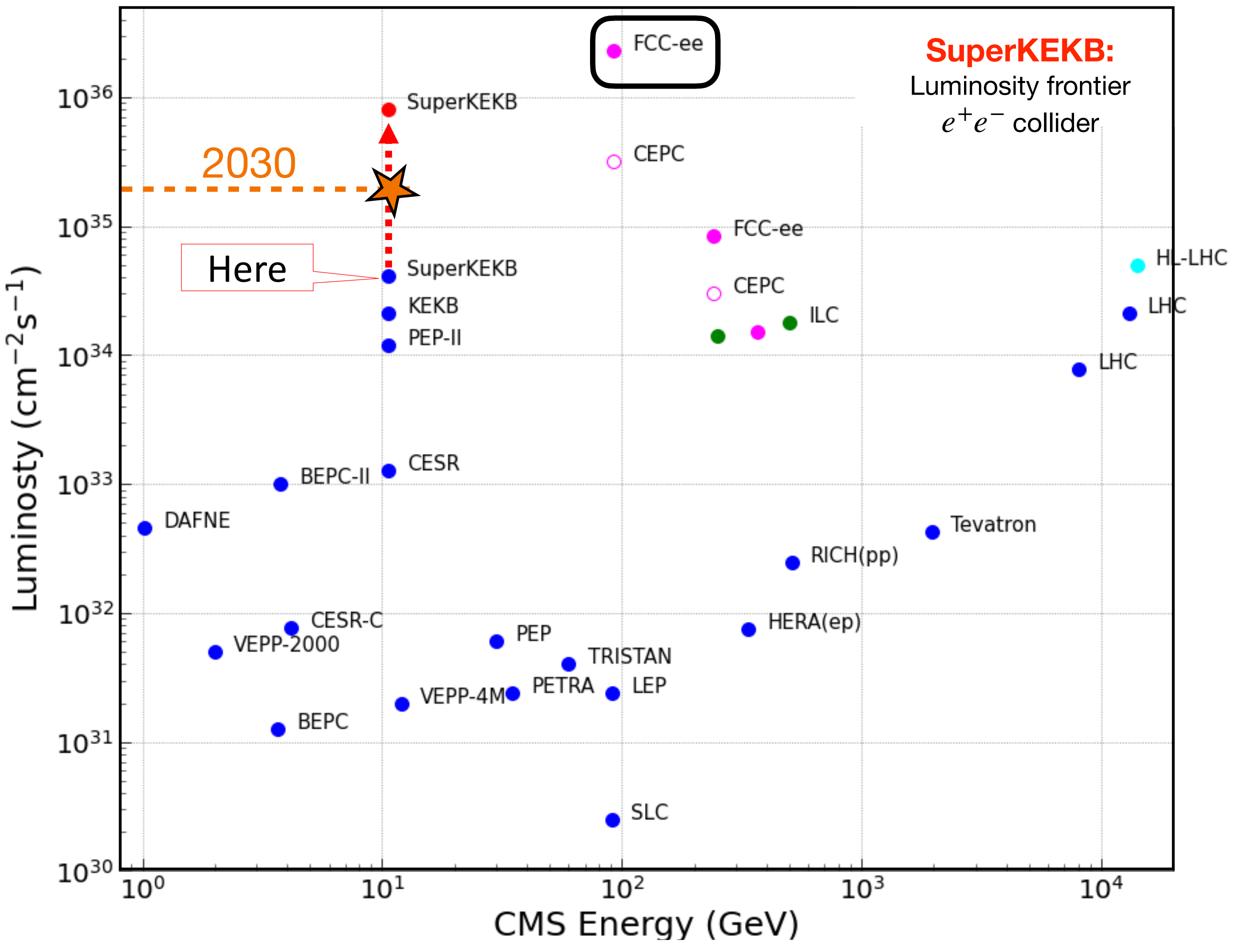
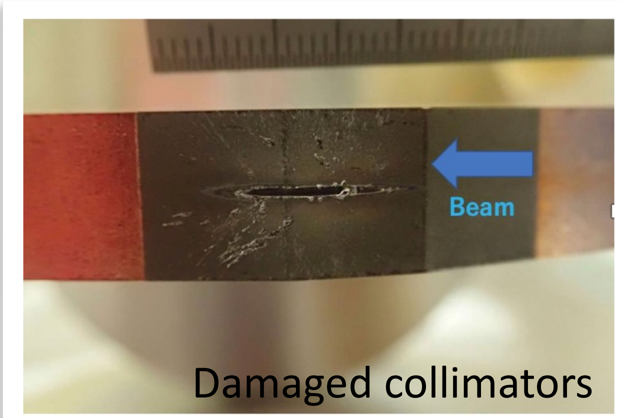


Current **status**:

Sudden beam losses of unknown origin hinder the collider to reach stable operations

→ Cause **damage** to **collimators** & **detector**



D02V1 top side (95 µSv/h)

Other challenges to reach high luminosities:

- Low injection eff.
- Low beam lifetime
- Vertical emittance growth

→ Devoting significant fraction of running time for machine studies to understand instabilities

The current status and plans to ca. 2030

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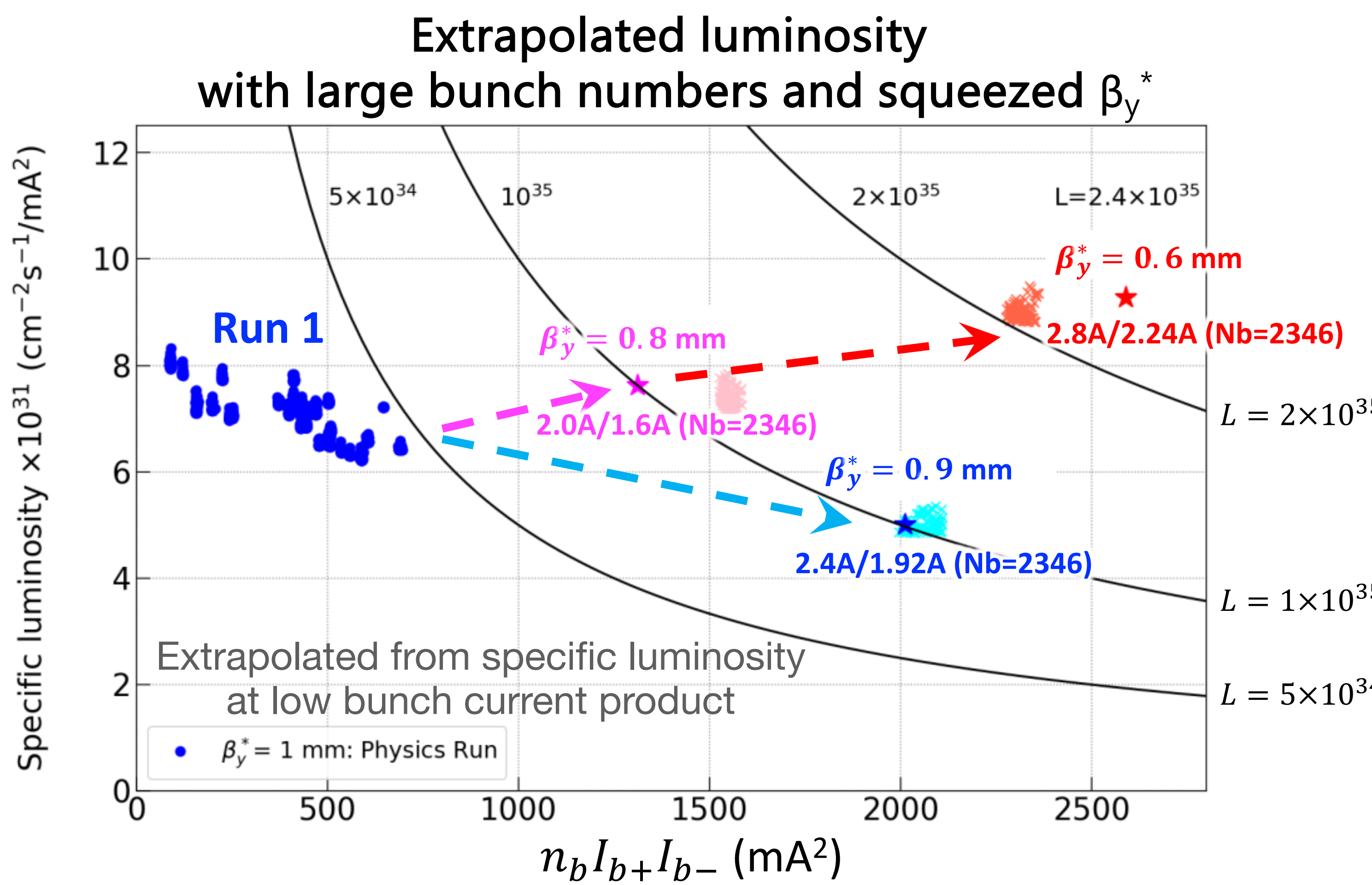
SuperKEKB & Belle II goals until 2030 ⟶ $\sim 2 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ & collect ca. 5/ab

Next immediate Goal: reach $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Then reach $2 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ by ca. 2030

Currently explore different strategies on how this can be reached



Accelerator and Detector Upgrade

With **current machine configuration**, maximally achievable inst. luminosity ca. $2 \times 10^{35}\,\mathrm{cm^{-2}\,s^{-1}}$

→ Falls short of desirable design value of $6 \times 10^{35}\,\mathrm{cm^{-2}\,s^{-1}}$

KEK and SuperKEKB team started discussions on how this can be rectified

- Upgrade of accelerator (linac & RF) and redesign of IR region on the table
- Timeline: ca. 2030 and after demonstrating operations with $10^{35}\,\mathrm{cm^{-2}\,s^{-1}}$ & delivering ca. 5/ab
- Opens possibility for upgrade of Belle II itself during a **long shutdown 2** (LS2)

SuperKEKB & future Higgs factory

SuperKEKB & **Belle II** can be seen as Higgs factory technology demonstrators

SuperKEKB & Belle II in the **ARC**, **P5** and **FCC-ee mid-term review** :

The ARC would like to emphasize that the SuperKEKB accelerator is a frontier machine and is a world leader in Accelerator Technology with ambitious goals for high peak and integrated luminosity. This accelerator is led by a highly dedicated group of experts who have encountered and overcome technical obstacles, and who will find new issues as they approach the ultimate accelerator design goals. The achievements accomplished by this team and the KEK laboratory are already being incorporated into future collider designs and the worldwide accelerator community is carefully watching the impressive progress of this very exciting enterprise.

ARC March 2024

From the P5 report and from international accelerator laboratories:
Need to make e+e- nanobeams work well at SuperKEKB for the future of HEP.

FUTURE CIRCULAR COLLIDER **mid-term review recommendations for FCC-ee acc. design**

from FCC SAC, FCC CRP, CERN SPC, and CERN FC

- **identify residual risks to achieving the design luminosity, with lessons to be learnt from other facilities like SuperKEKB, and specify required further critical-path R&D**

How SuperKEKB will achieve its target luminosity might influence design choices of e.g. FCC-ee or CEPC

Ongoing: FCC & SuperKEKB

Knowledge transfer with CERN team already happening

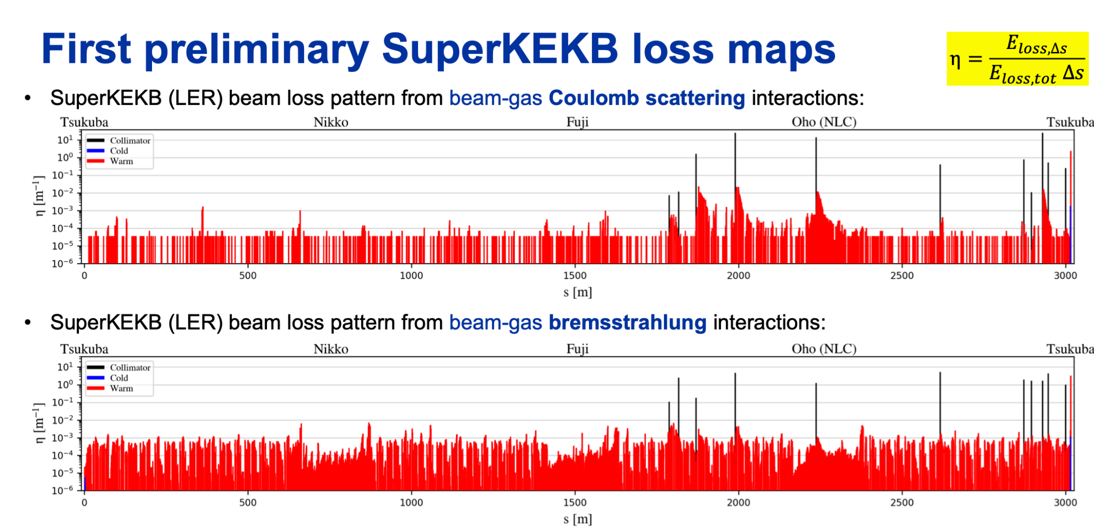
374 days of secondments CERN → KEK (12 visitors)
ca. 170 days KEK → CERN (3 visitors)

→ KEK member in FCC collaboration during CDR and feasibility study phase

FCC team interested in learning on a running machine about optics, sudden beam loss, vacuum, injection efficiency

SuperKEKB lattice included in **xsuite** to simulate IP feedback, machine vibrations, collimation, optics, impedance, beam-beam effects

G. Broggi



Frank Zimmermann & FCC-ee team

DESY also interested in knowledge transfer

Ongoing: FCC & SuperKEKB

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Relevant concepts for FCC-ee that SuperKEKB has **already** demonstrated:

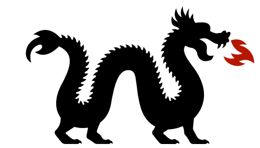
FCC-ee type **virtual crab waist** works (K. Oide, Phys. Rev. Accel. Beams 19, 111005)

Smallest β_y^* ever considered for FCC-ee: **1 mm and 0.8 mm**

e^+ **production rate similar** to FCC-ee; **top-up injection** with short (<10 min) beam lifetimes works

Further motivation for a Belle II upgrade

No spares for central detectors in case of accidents or unforeseen degradation ; many unforeseen issues appeared as well (high lumi = terra incognito)



Many Belle II groups working in R&D collaborations **(DRD3,DRD7,DRD8,…)** working on technologies that will allow us to **maximize physics output**

Detector Upgrade plans summarized in https://arxiv.org/abs/2406.19421

The Belle II Detector Upgrades Framework Conceptual Design Report

Abstract

We describe the planned near-term and potential longer-term upgrades of the Belle II detector at the SuperKEKB electron-positron collider operating at the KEK laboratory in Tsukuba, Japan. These upgrades will allow increasingly sensitive searches for possible new physics beyond the Standard Model in flavor, tau, electroweak and dark sector physics that are both complementary to and competitive with the LHC and other experiments.

TDR planned for 2027

LS2: ca. 2030 - 2032

Baseline scenario:

Timelines shown here under internal discussion to balance needs of various groups (detector, physics, accelerator)

Disclaimer : timelines under discussion (!)

Long shutdown 2 (LS2) between **ca. 2030-2032**

Currently foresee upgrades that require **no role-out** of the detector (would add at least 1 year)

Accelerator plans:

★	**Linac and high power RF reinforcements**	8B JPY	→ Increase beam current by **x 1.3**
★	**Mechanical isolation of SuperKEKB magnets; improve AC in power supply building; fast BPM readout electronics**	3-4B JPY	→ Increase stability

Note: 1B JPY = 6.6 MEuro

Likely funding source: MEXT & KEK

LS2: ca. 2030 - 2032

Motivation for IR redesign :

- Simplify IR (straighten orbits)
- Reduce chromatic x-y coupling
- Suppress emittance growth

→ Increase beam lifetime & inst. luminosity → Impact of SBLs & beam hot spots may be mitigated by additional redesign of vertex detector

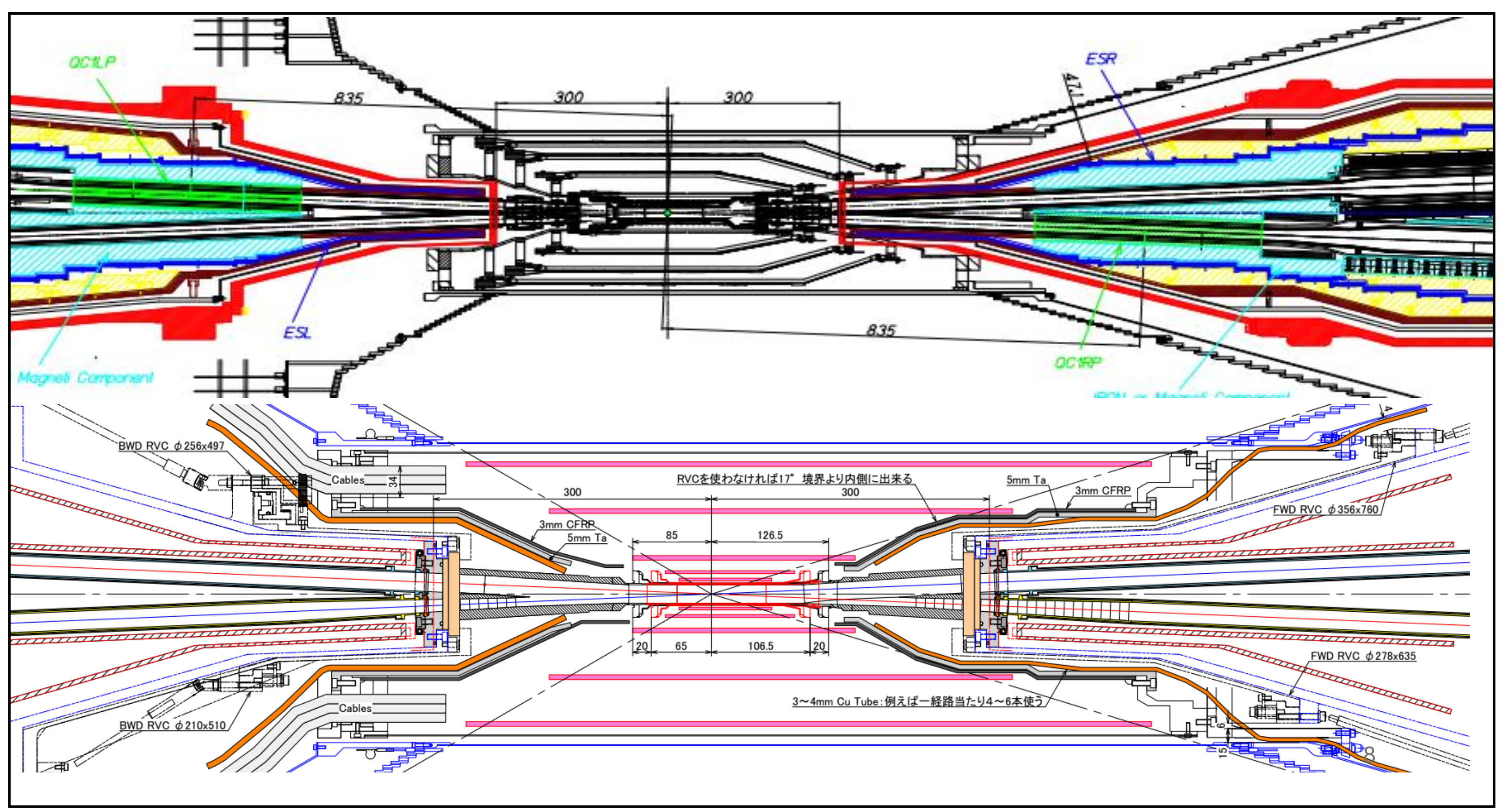
R&D ongoing, different options being explored, possibility envelope of IR will change:

Current Envelope

↓

Possible Redesign

- New RVC design
- Magnet material study ongoing (FEM analysis, coil winding test)
- Mechanics design under study



→ **Goal** of **new design**: Increase Luminosity by **x 2**

No cost estimate atm

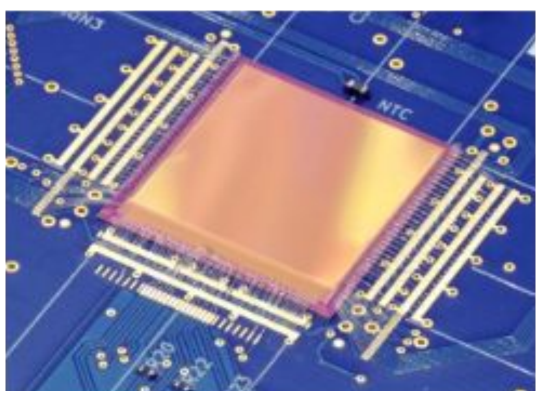
Likely funding source: MEXT & KEK

Detector Upgrade

Redesign of interaction region (or necessity for having a spare)

→ Development of **new CMOS-based tracking detector VTX**

International consortium of 15 partners with strong German participation (Bonn, Göttingen, LMU) and interest of DESY

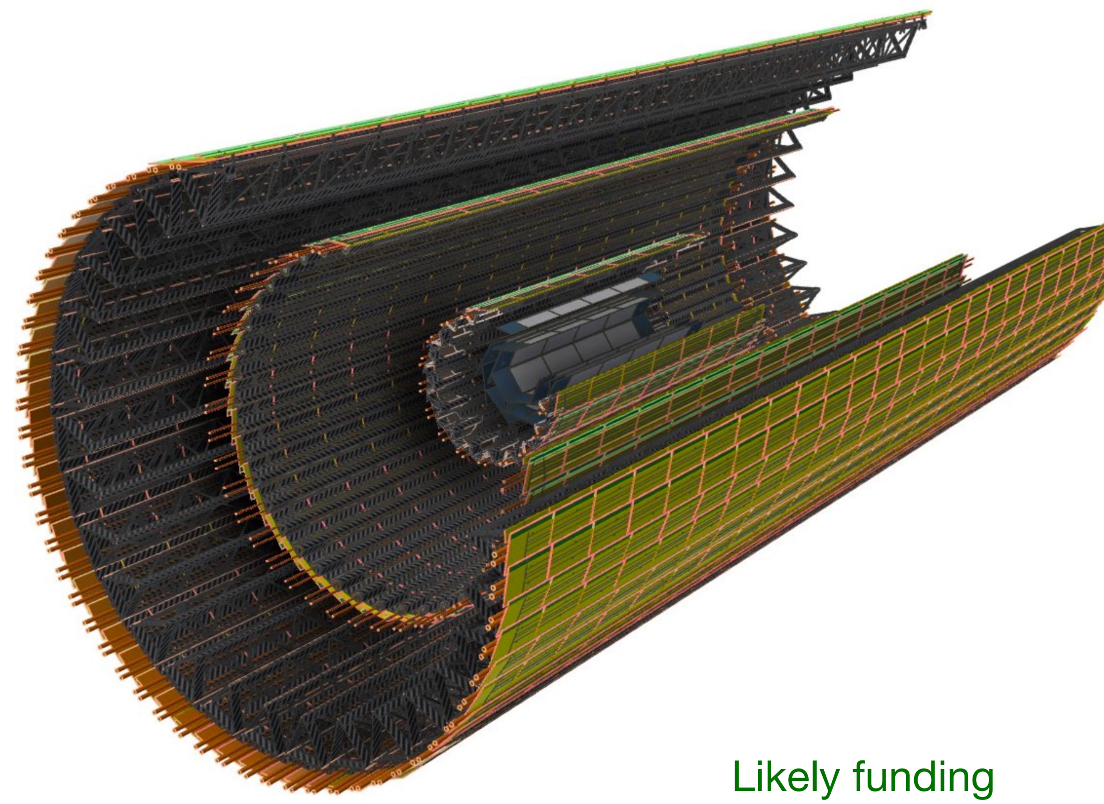


Design based of **TJ-Monopix2**

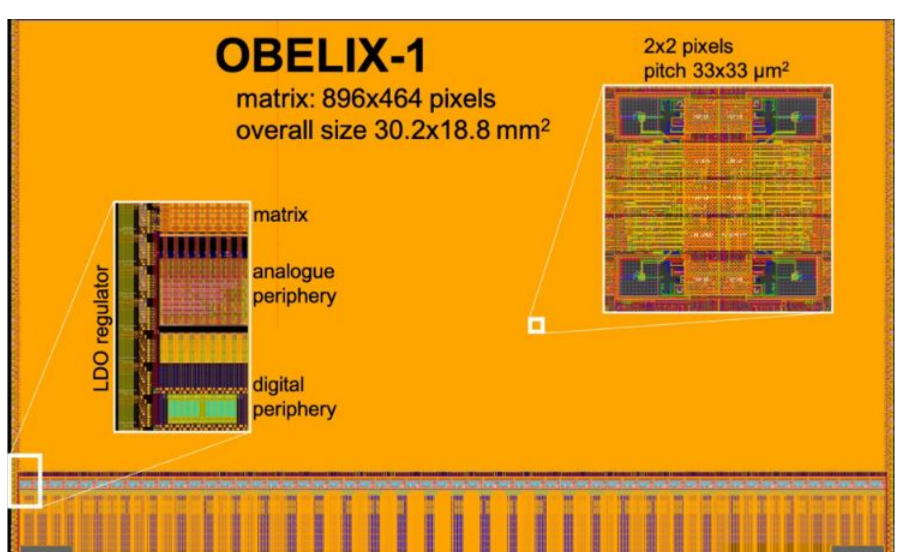
- Developed originally for ATLAS-ITk
- **German** initiative with CERN
- First CMOS-based vertex detector used in e^+e^-

↓

OBELIX (Optimized BELle II pIXel)



	OBELIX
Pitch	33 μm
Signal ToT	7 bits
Integration time	50 To 100 ns
Time stamping	~5 ns for hit rate < 10 MHz/cm²
Hit rate max for 100% eff.	120 MHz/cm²
Trigger handling	30 KHz with 10 μs delay
Trigger output	~30 ns resolution with low granularity
Power (with hit rate)	120 to 200 mW/cm² (1 to 120 MHz/cm2)
Bandwidth	1 output 320 MHz



Likely funding source: National Agencies

VTX costs :

Component	Development	Production	Total (kEUR)
Sensors	380	1130	**1510**
Ladders	120	1400	**1520**
Assembly	130	630	**760**
DAQ & services	280	1060	**1340**
Installation	-	100	**100**
Total	**910**	**4320**	5230

Detector Upgrade

Likely funding source: National Agencies

Central Drift Chamber strongly affected by high backgrounds

Baseline plan: new FE electronics, but also explore scenarios of a (partial) replacements

Time of Propagation

Replacement of aging PMTs, new FE electronics, cooling system

Electromagnetic Calorimeter

Shaper DSP, new FE electronics, more performant FPGAs, explore SiPM for timing

K-Long and Muon Detector

RPC proportional mode, new FE electronics, HV system, gas recirculation system

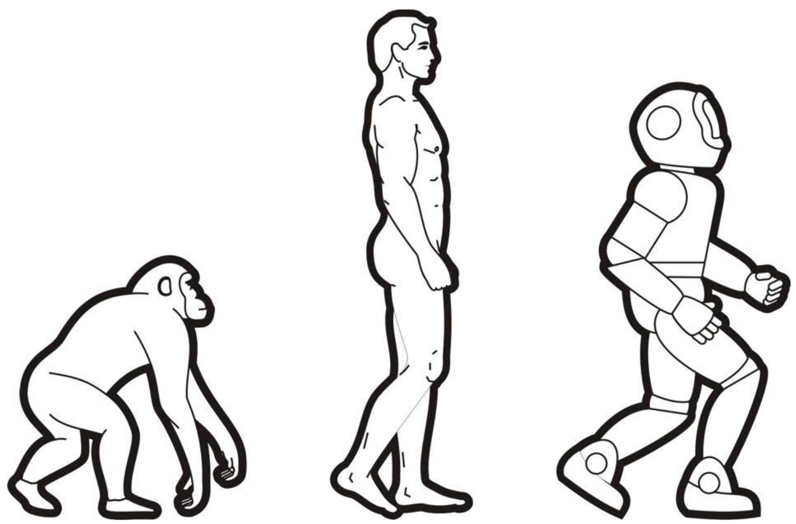
Trigger

New FPGA boards (UT5) and plan to focus on additional triggers for LLPs

Aftermath

To fully exploit the experimental program, **Belle II will pursue** an **upgrade**

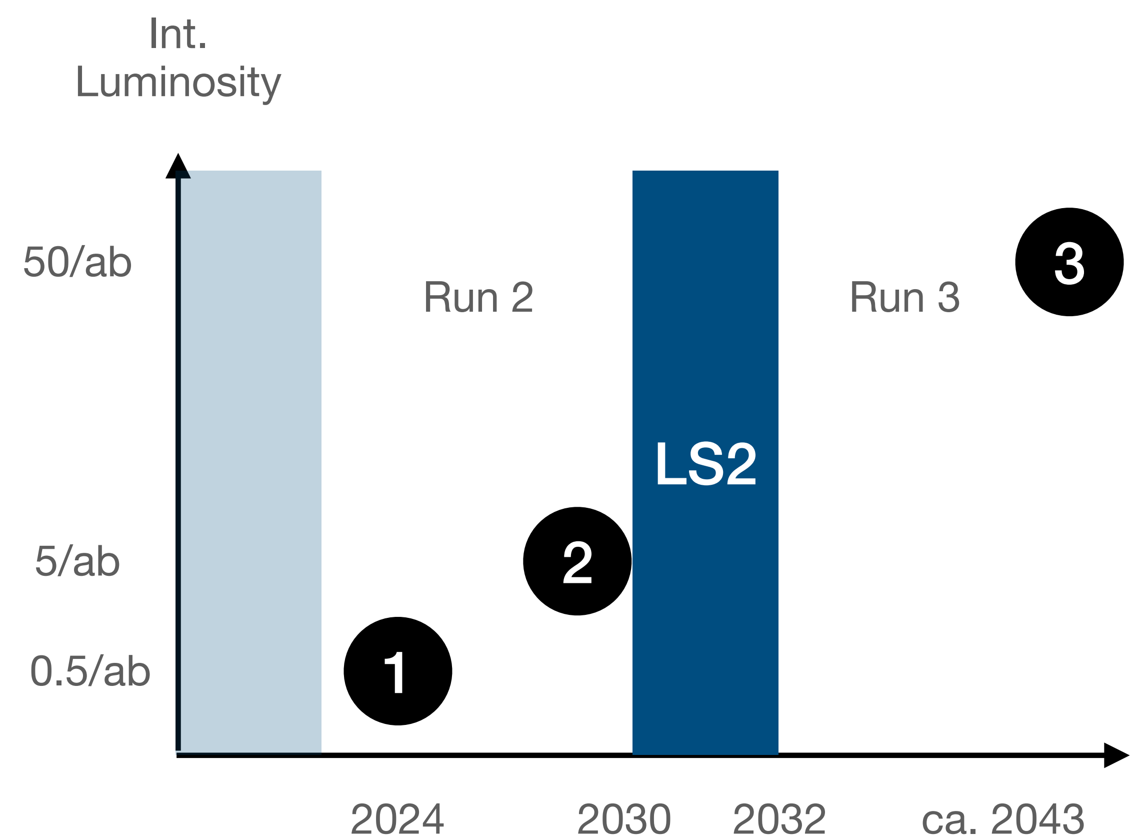
Belle II Timeline



1 Run 1: 0.5 ab^{-1}
B-factory level measurements

2 Run 2: 5 ab^{-1}
Precision measurements

3 Run 3 50 ab^{-1}
Rare phenomena



Interactions started with MEXT to discuss funding of program until 2043

↓

Belle II has the intention to run **until the end of HL-LHC / beg. of FCC-ee**

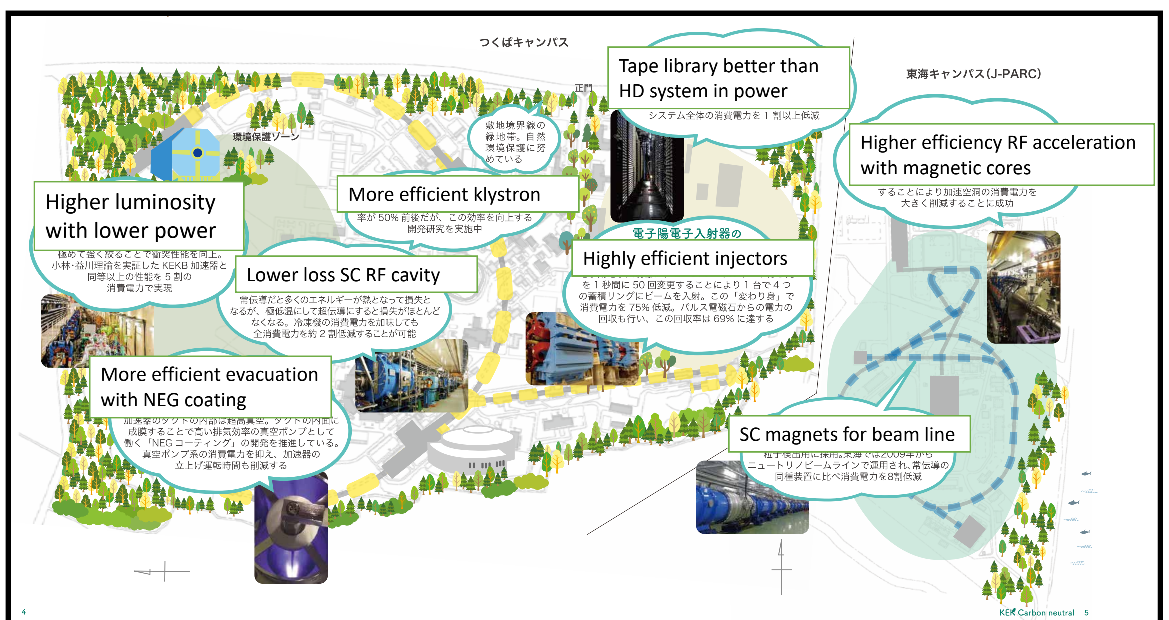
A Word on Sustainability

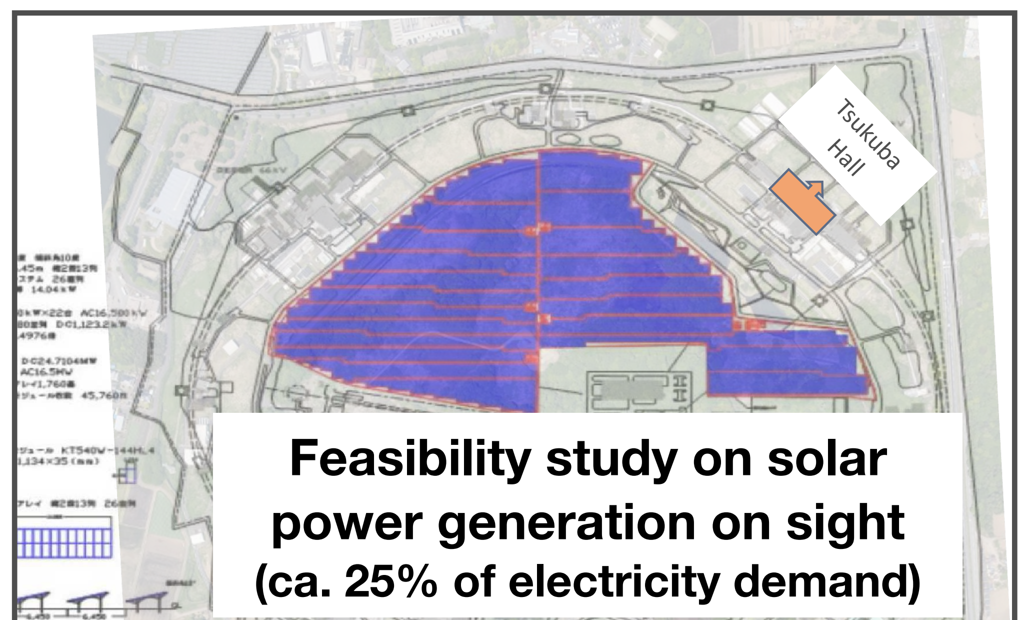
Japanese government committed in 2020 to net zero by 2050

→ Electricity footprint in Japan post Fukushima very different than than e.g. in Geneva → CO_2 emissions **factor of 6 higher**

KEK (Tsukuba + Tokai) are among the **largest academic emitters** of CO_2 (ca. 155'000 tCO_2e/a, ca. 80'000 tCO_2e/a from SuperKEKB)

KEK GD committed to reduction of footprint, direct action on accelerator infrastructure planned:





Feasibility study on solar power generation on sight (ca. 25% of electricity demand)

Belle II also discussing how emissions can be reduced

(ca. 3400 tCO_2e/a Det. Operation & Gas emissions, 400 tCO_2e/a Computing, 1000 tCO_2e/a Travel)

Executive Summary for ESPP

Belle II has a **very strong physics case, complementary to LHCb** or other existing facilities :

Belle II to LHCb is a bit like the LHC to FCC-ee for Higgs: unbiassed & clean access to B-Meson decays

SuperKEKB is a **Higgs factory demonstrator:**

Many concepts relevant for a high luminosity e^+e^- facility can be tested knowhow transfer very useful and desired (cf. FCC team secondments)

Also lessons from SuperKEKB:

- Design luminosity of SuperKEKB too optimistic, let's be careful with the FCC-ee / CEPC design
- Actual beam conditions very different from simulations
- Sudden beam losses of the type observed in SuperKEKB have never been seen at PEP-II or KEKB ; origin unclear

Belle II Upgrade opportunity to test technologies for FCC-ee / CEPC detectors

E.g. VTX tracker based on CMOS conceivable design choice for Higgs factory experiments

"SuperKEKB and Belle II allow the demonstration of concepts relevant for a future Higgs factory "

More Information

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Impact on Flavor physics if Belle II does not record 50/ab

Answer depends on what luminosity will be achievable, but …

Rare decays program will be severely impacted

Some examples from the **Belle II Physics book** : arXiv:1808.10567

Tau and low multiplicity

Process	Observable	Theory	Sys. dom. (Discovery) $[\mathrm{ab}^{-1}]$	vs LHCb/BESIII	vs Belle	Anomaly	NP
$\tau \to \mu\gamma$	$Br.$	★★★	>50	★★★	★★★	★	★★★
$\tau \to \ell\ell\ell$	$Br.$	★★★	>50	★★★	★★★	★	★★★
$\tau \to K_S^0\pi\nu$	$\lvert\Im(\eta_s)\rvert$	★★★	>50	★★★	★★★	★★	★★
$e^+e^- \to \gamma A'(\to$invisible$)$	σ	★★★	>50	★★★	★★★	★	★★★
$e^+e^- \to \gamma A'(\to \ell^+\ell^-)$	σ	★★★	>50	★★★	★★★	★	★★★
$e^+e^- \to \gamma a'(\to \gamma^+\gamma^-)$	σ	★★★	>50	★★★	★★★	★	★★★
$\Upsilon(1S) \to$ invisible	★★★	$Br.$	>50	★★★	★★★	★	★★★
$\chi_{b0}(1P) \to \tau\tau$	★★★	$Br.$	>50	★★★	★★★	★	★★★
π form factor	$g-2$	★★	-	★★★	★★	★★	★★★
ISR $e^+e^- \to \pi\pi$ g-2	$g-2$	★★	-	★★★	★★★	★★	★★★

Semileptonic

Process	Observable	Theory	Sys. dom. (Discovery) $[\mathrm{ab}^{-1}]$	vs LHCb	vs Belle	Anomaly	NP
$B \to \pi\ell\nu_\ell$	$\lvert V_{ub}\rvert$	★★★	10-20	★★★	★★★	★★	★
$B \to X_u\ell\nu_\ell$	$\lvert V_{ub}\rvert$	★★	2-10	★★★	★★	★★★	★
$B \to \tau\nu$	$Br.$	★★★	>50 (2)	★★★	★★★	★	★★★
$B \to \mu\nu$	$Br.$	★★★	>50 (5)	★★★	★★★	★	★★★
$B \to D^{(*)}\ell\nu_\ell$	$\lvert V_{cb}\rvert$	★★★	1-10	★★★	★★	★★	★
$B \to X_c\ell\nu_\ell$	$\lvert V_{cb}\rvert$	★★★	1-5	★★★	★★	★★	★★
$B \to D^{(*)}\tau\nu_\tau$	$R(D^{(*)})$	★★★	5-10	★★	★★★	★★★	★★★
$B \to D^{(*)}\tau\nu_\tau$	P_τ	★★★	15-20	★★★	★★★	★★	★★★
$B \to D^{**}\ell\nu_\ell$	$Br.$	★	-	★★	★★★	★★	-

EWP

Process	Observable	Theory	Sys. dom. (Discovery) $[\mathrm{ab}^{-1}]$	vs LHCb	vs Belle	Anomaly	NP
$B \to K^{(*)}\nu\nu$	$Br., F_L$	★★★	>50	★★★	★★★	★	★★
$B \to X_{s+d}\gamma$	A_{CP}	★★★	>50	★★★	★★★	★	★★
$B \to X_d\gamma$	A_{CP}	★★	>50	★★★	★★★	-	★★
$B \to K_S^0\pi^0\gamma$	$S_{K_S^0\pi^0\gamma}$	★★	>50	★★	★★★	★	★★★
$B \to \rho\gamma$	$S_{\rho\gamma}$	★★	>50	★★★	★★★	-	★★★
$B \to X_s\ell^+\ell^-$	$Br.$	★★★	>50	★★★	★★	★★	★★★
$B \to X_s\ell^+\ell^-$	R_{X_s}	★★★	>50	★★★	★★★	★★	★★★
$B \to K^{(*)}e^+e^-$	$R(K^{(*)})$	★★★	>50	★★	★★★	★★★	★★★
$B \to X_s\gamma$	$Br.$	★★	1-5	★★★	★	★	★★
$B_{d,(s)} \to \gamma\gamma$	$Br., A_{\mathrm{CP}}$	★★	>50	★★	★★	-	★★
$B \to K^*e^+e^-$	P_5'	★★	>50	★★★	★★	★★★	★★★
$B \to K\tau\ell$	$Br.$	★★★	>50	★★	★★★	★★	★★★

+ loss on input from CKM parameters

Discussion Items Facility Talks

2) Facility talks (Thursday morning and Thursday early afternoon)

a) General experimental introduction to the respective facility
   a. note: the physics questions should have been answered already by the physics talks on Wednesday afternoon. So a short recap of the physics should be sufficient here.

b) What are the current estimates on time schedule, costs and possible funding?

c) What are the current organisational structures (collaboration and international composition)?

d) Where is still R&D needed? Are there potential risk of failure?

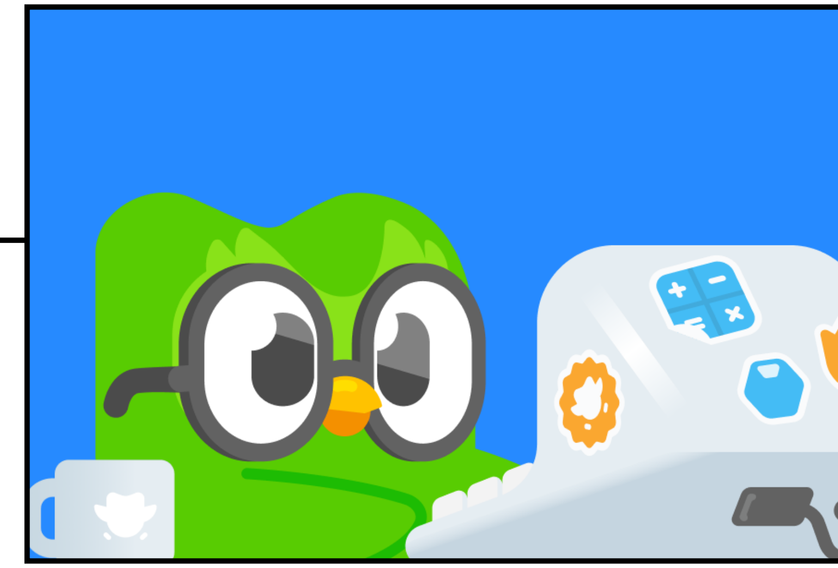
e) What is the (political) status of the facility? Are possible sites proposed?

f) Are there specific German interests in the facility? Do special strengths of German groups play a role?

g) What is the political situation of the facility in other countries or international organizations? Is there special support expected?

h) What are the estimates wrt. sustainability? Try to be as concrete as possible. (tunnel, components, running)

A little Japanese Lesson



KEK = High Energy Accelerator Research Organization

MEXT = Ministry of Education, Culture, Sports, Science and Technology

BPAC = Belle II Program Advisory Committee

ARC = Accelerator Review Committee

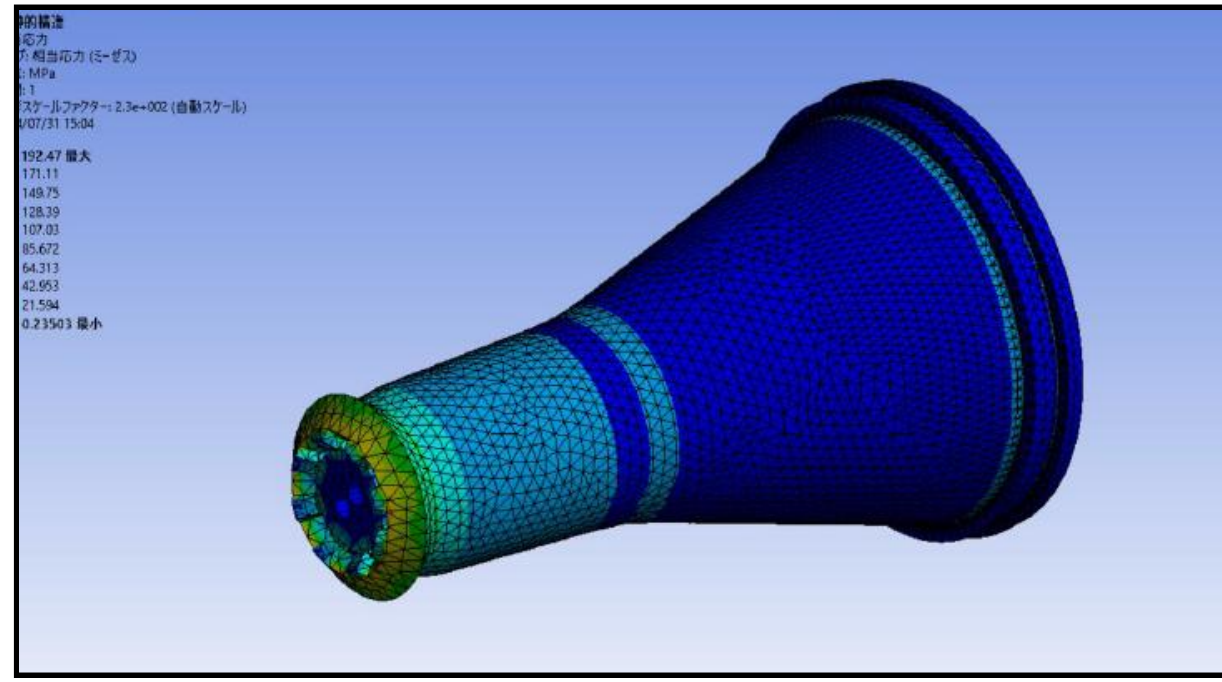
Status of IR Redesign Studies at KEK

QC1 magnet studies (Nb3Sn)

FEM analysis and coil winding tests

Mechanics design around tip of QCS

Vacuum seal ; thermal isolation ; mechanical integration



New RVC (remote vacuum connection) design

FEM analysis ongoing

New IP beam pipe

Base design being studied. Idea is to keep it similar but shorter

MEXT Roadmap for SuperKEKB & Belle II

[Annual plan] (Japanese fiscal year)

Research items		2023 1st year	2024 2nd	2025 3rd	2026 4th	2027 5th	2028 6th	2029 7th	2030 8th	2031 9th	2032 10th	2033 11th and later	Remarks
1. Continue operation and improve accelerator performance in parallel with accumulating physics data													Continue performance improvement after 10 years.
	Performance indicator	0.4				3					15		Integrated luminosity (/ab)
2. Maintenance/upgrade of major components Systematically conduct renewal of aging components to improve energy efficiency. Achieve the target performance by modifying the interaction region (IR). Improve the performance of the injector and beam transport line (BT) for efficient operation.			IR upgrade, BT remediation, High-power RF reinforcement										Minor items excluded. Search for efficient measures in terms of budget (electricity) according to collision performance and radiation dose. Flexible operation is required.
	Main ring	Energy efficiency improvement											
	Injector	Injector upgrade											
	Belle II	Replacement of vertex detector, photosensors, etc.											
		Measures for radiation, renewal of aging components, etc.											
	Performance indicator					Start of IR upgrade		End of IR and detector upgrade			Completion of aging component renewal		
3. Report physics results obtained by analyzing the data, publish them in academic papers, and disseminate them widely. Open up a new paradigm in elementary particle physics, or show the next path necessary for that.			Results on dark matter search etc.		Results on lepton universality etc.				Results on CP violation etc.				
	Performance indicator	5				40					190		Num. of publications

SuperKEKB Beam Parameters:

$$\mathscr{L}_{\text{Belle}} = 2.11 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$$

Intensity frontier needs massive increase in Luminosity

$$\mathscr{L}_{\text{Belle II}} = 6 \times 10^{35}\,\text{cm}^{-2}\,\text{s}^{-1}$$

Luminosity of a circular collider:

beam current **x 1.5**

$$L = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\,\zeta_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

vertical β function **x 1/20**

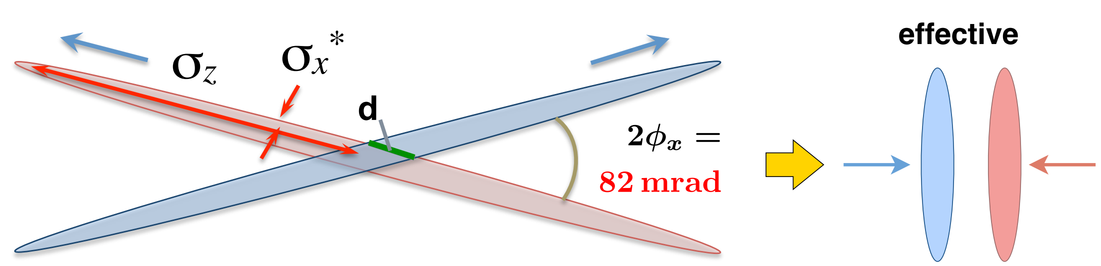
LER / HER	KEKB	SuperKEKB	L-Faktor
Energy [GeV]	3.5 / 8	4.0 / 7.0	
β_y^* [mm]	5.9 / 5.9	**0.27 / 0.30**	**x 20**
β_x^* [mm]	1200	**32 / 25**	
$I_\pm$ [A]	1.64 / 1.19	**2.8 / 2.0**	**x 1.5**
$\zeta_{\pm y}$	0.129 / 0.09	**0.09 / 0.09**	**x 1**
ε_x [nm]	18 / 24	3.2 / 4.6	
ε_y [nm]	140 / 140	13 / 16	
# of bunches	1584	1800	
Luminosity [10^{34} cm^{-2} s^{-1}]	2,1	**60**	**x 30**

Key: **Nano beam scheme**

Squeeze vertical beam spot size down to ca. **50 nm** using superconducting focusing magnets

Idea from P. Raimondi

→ Major upgrade of accelerator and detector needed



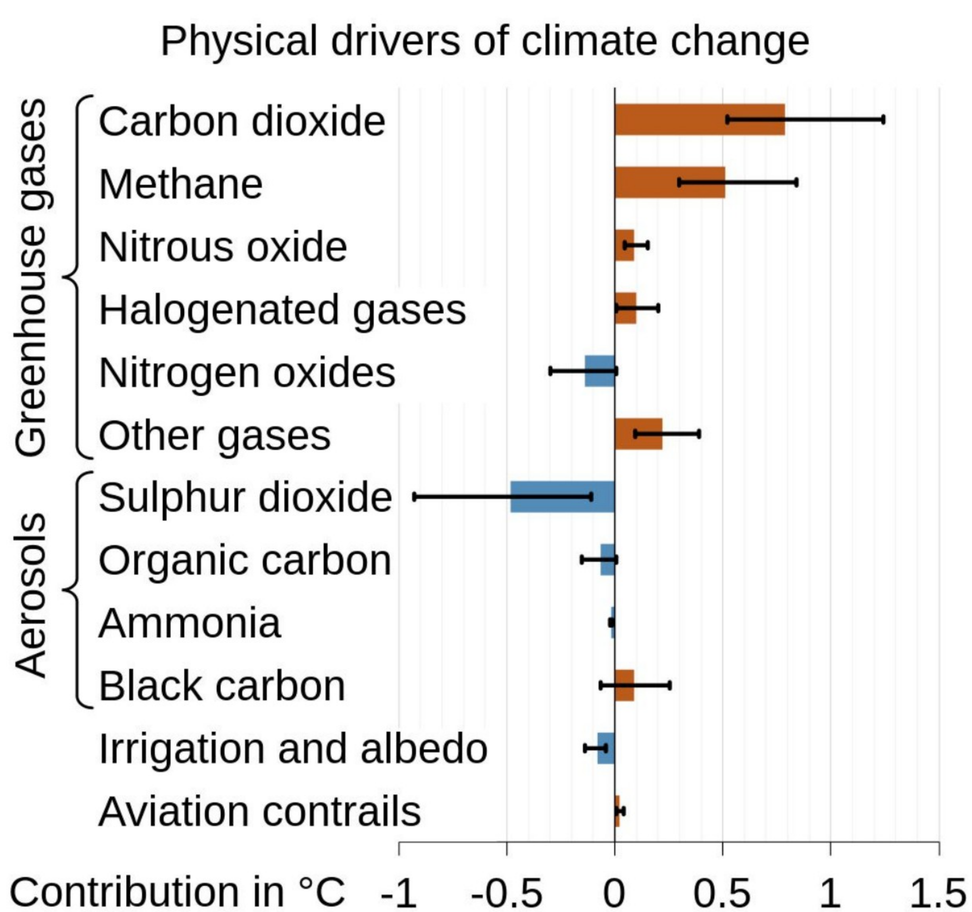
Half crossing angle: ϕ

overlap region (≠ bunch length)

$$\sigma_z^{\text{eff}} = \frac{\sigma_x^*}{\phi_x} < \beta_y^*$$

final focusing magnets near the IP

Global Warming Potential



Global Warming Potential

Gas	Use	GWP
CO2	reference	1
CF4	wire chambers, gas electron multiplier	7390
C2H2F4	resistive plate chambers	1430
SF6	resistive plate chambers	22800

Gas	Use	GWP
He2	50% CDC	0
C2H6 (ethane)	50% CDC	8
N2	cryogenics	0, but forms N2O with 298
HFC-134a	KLM	1300

Ca. 2000 tCO_2e/a

Travel to Japan

45th B2GM flight emission estimate

- 209 participants
- 56 participants were assumed to not take a plane due to being located in Japan
- the location and therefore emissions of 8 participants could not be determined
- the other 145 participants spent **313 t CO_2e** flying to NGO (~2.2t per person)
- this is an underestimate because direct flights were assumed.