Hadron physics at Belle II

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KHuK Strategiemeeting
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Outline

- Belle II status
- Numbers
  (statistics of XYZ, D mesons, hyperons, ...)
- Width of X(3872)
- Proton formfactor
- Comparison of Belle II to other experiments
  (systematics)

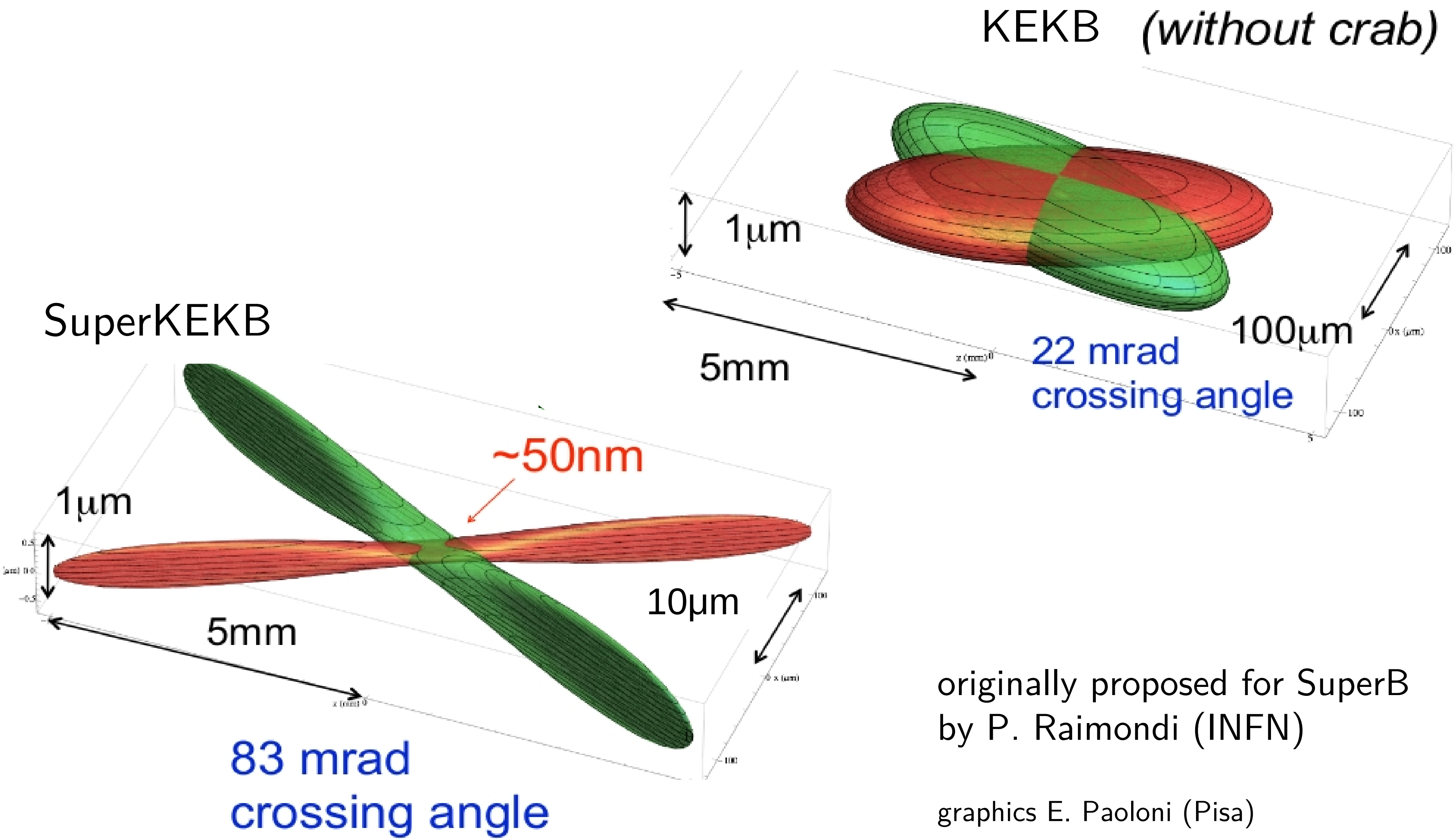
Status of Belle II

SuperKEKB asymmetric B meson factory, $e^+ e^- \rightarrow B\bar{B}$

adjusted to Y(4S) resonance, $\sqrt{s}=10.6$ GeV

Upgrade: peak luminosity x40, integrated luminosity x50

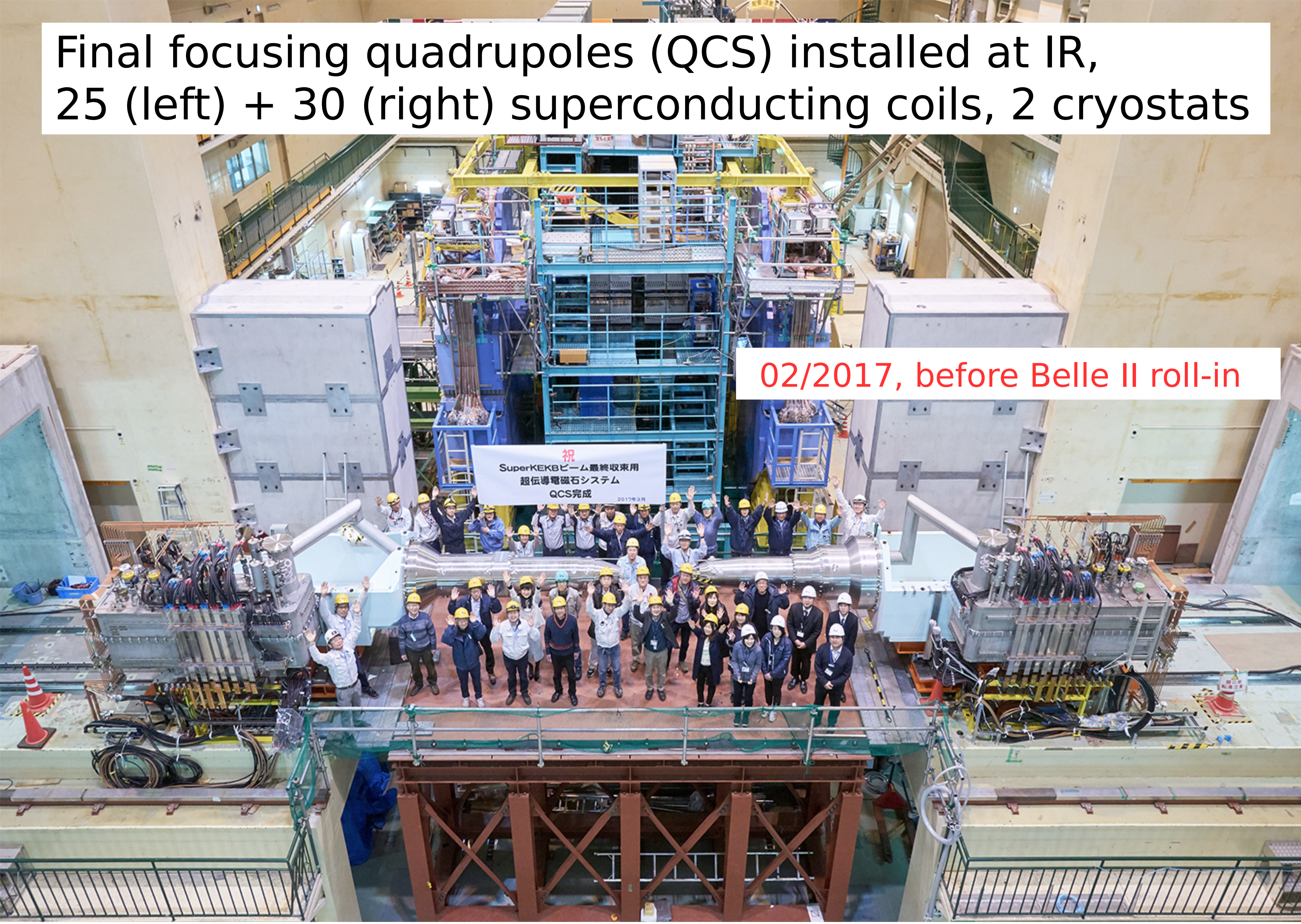
Nano-Beam Scheme



originally proposed for SuperB by P. Raimondi (INFN)

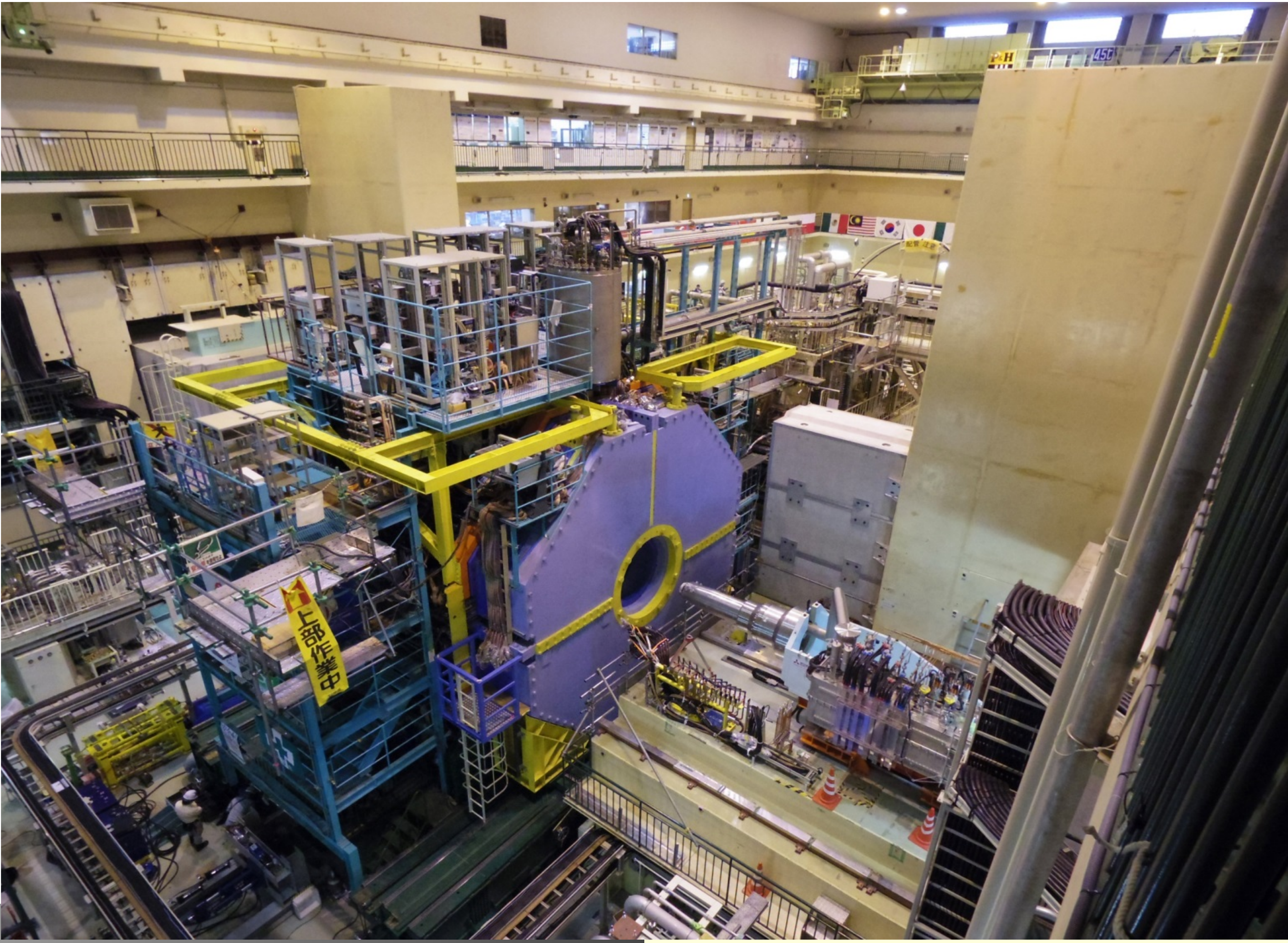
graphics E. Paoloni (Pisa)

Final focusing quadrupoles (QCS) installed at IR, 25 (left) + 30 (right) superconducting coils, 2 cryostats



02/2017, before Belle II roll-in

ROLL-IN, 11.04.2017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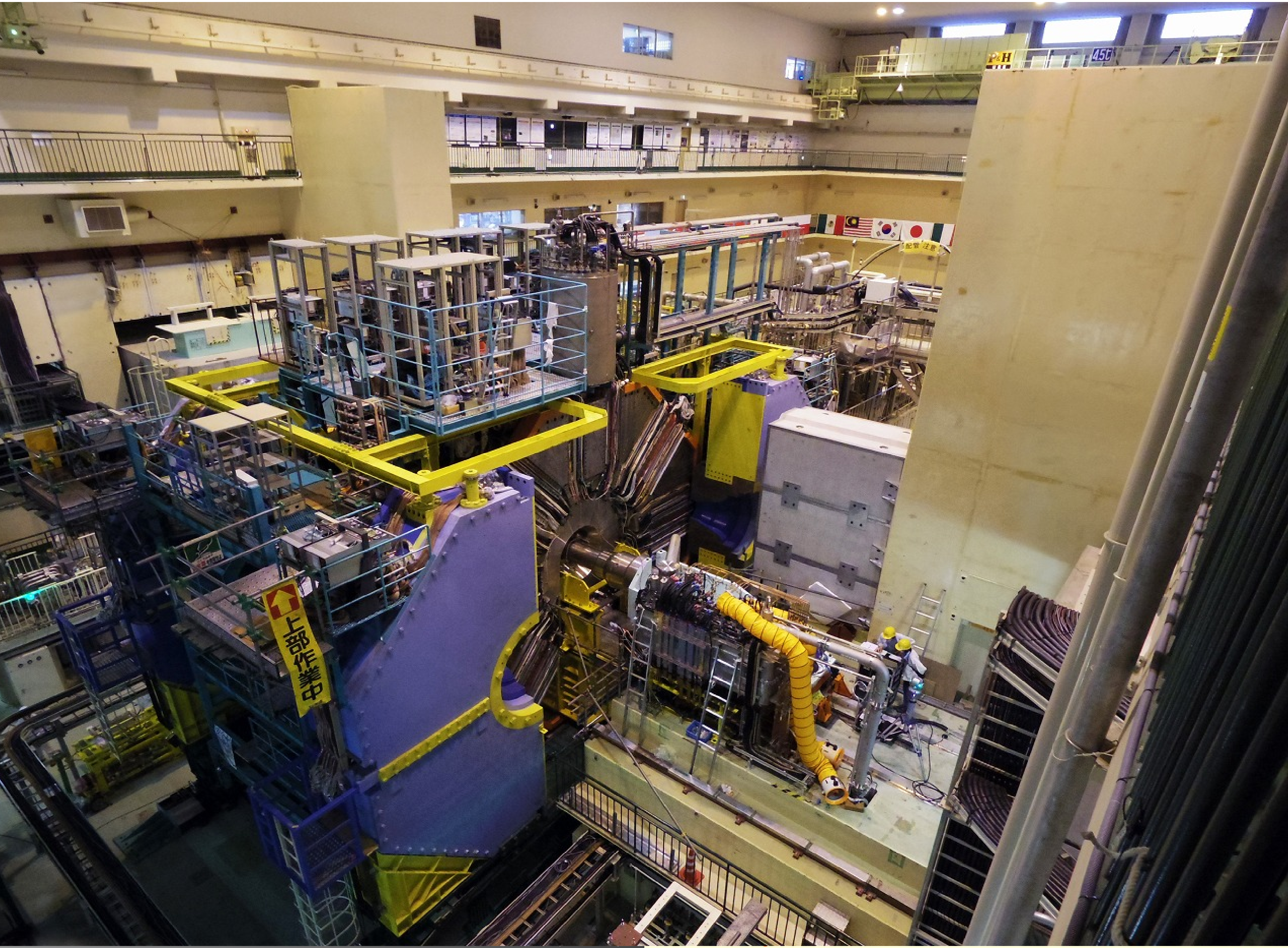
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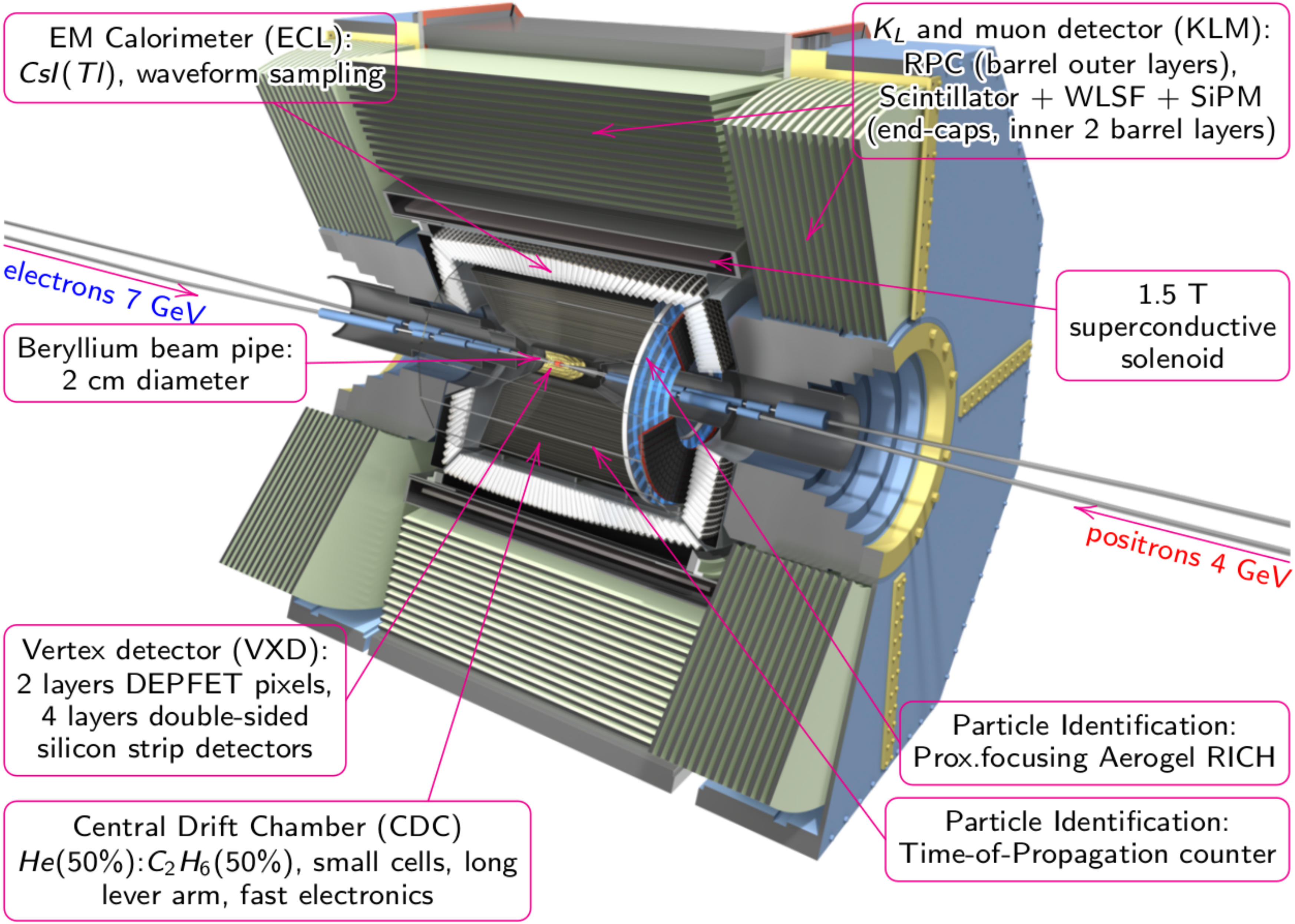
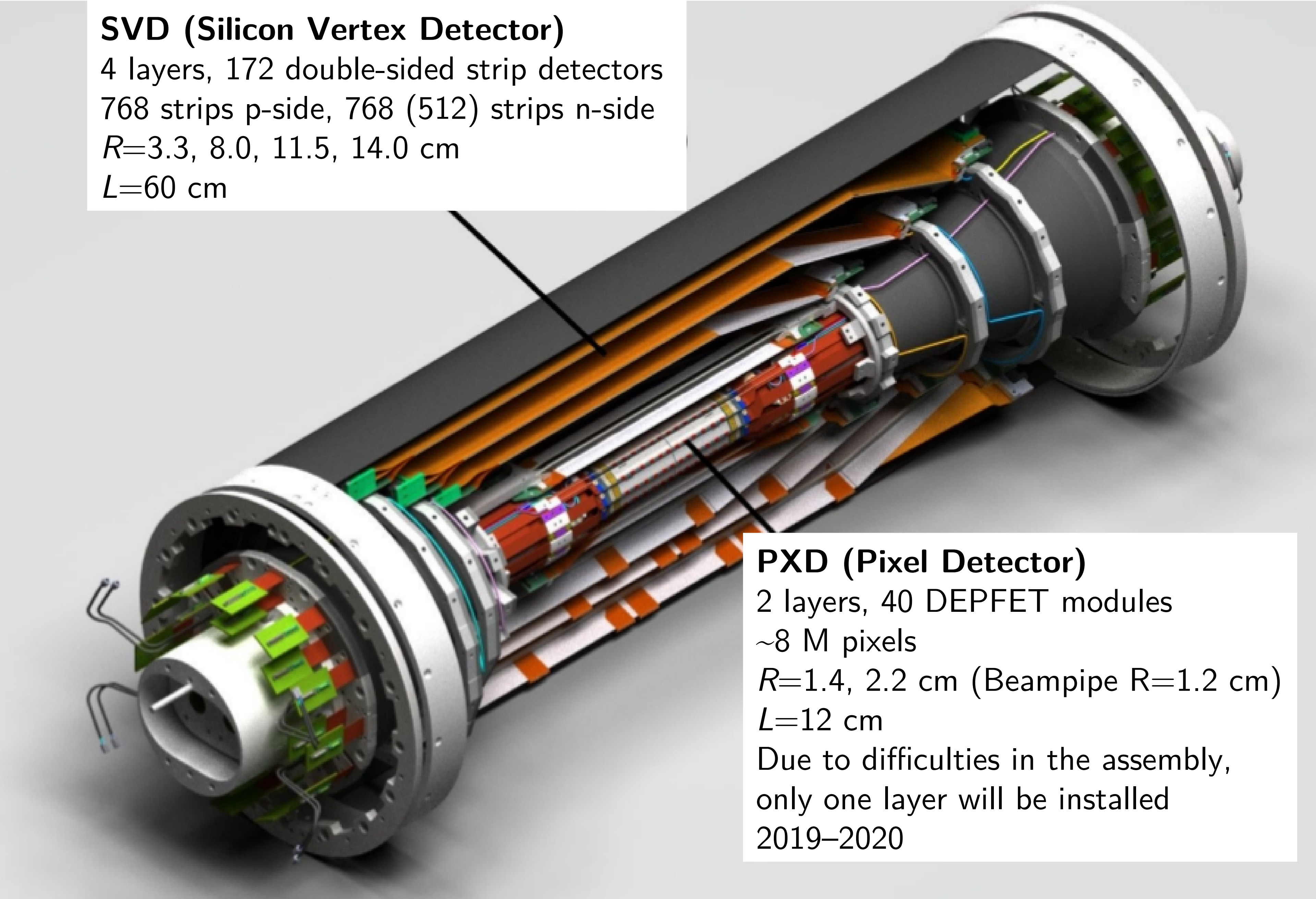
Belle II



EM Calorimeter (ECL):
$CsI(Tl)$, waveform sampling
K_L and muon detector (KLM):
RPC (barrel outer layers),
Scintillator + WLSF + SiPM
(end-caps, inner 2 barrel layers)
electrons 7 GeV
1.5 T
superconductive
solenoid
Beryllium beam pipe:
2 cm diameter
positrons 4 GeV
Vertex detector (VXD):
2 layers DEPFET pixels,
4 layers double-sided
silicon strip detectors
Particle Identification:
Prox.focusing Aerogel RICH
Central Drift Chamber (CDC)
$He(50\%)$:$C_2H_6(50\%)$, small cells, long
lever arm, fast electronics
Particle Identification:
Time-of-Propagation counter

Belle II VXD (Vertex Detector)

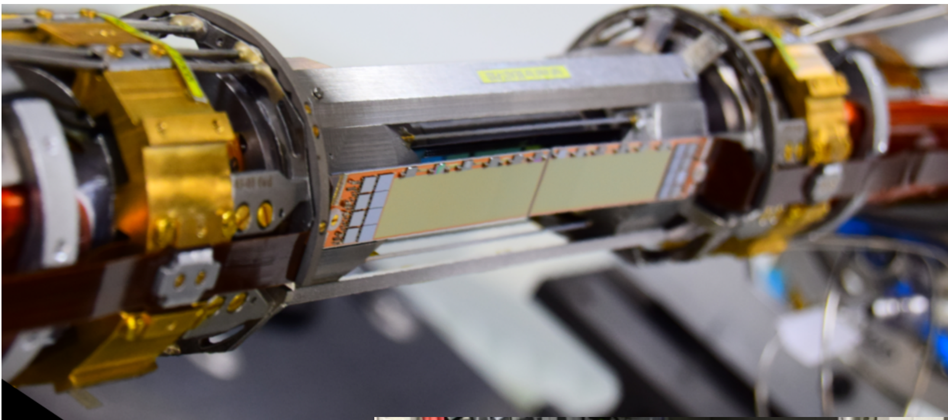
SVD (Silicon Vertex Detector)
4 layers, 172 double-sided strip detectors
768 strips p-side, 768 (512) strips n-side
R=3.3, 8.0, 11.5, 14.0 cm
L=60 cm

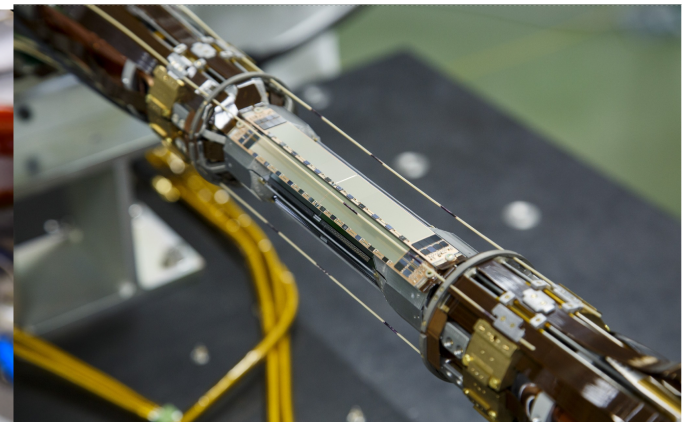


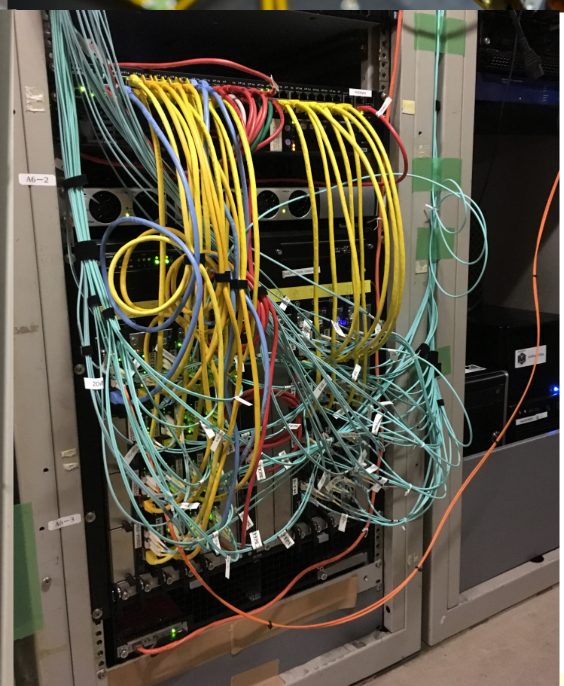
PXD (Pixel Detector)
2 layers, 40 DEPFET modules
~8 M pixels
R=1.4, 2.2 cm (Beampipe R=1.2 cm)
L=12 cm
Due to difficulties in the assembly, only one layer will be installed 2019–2020

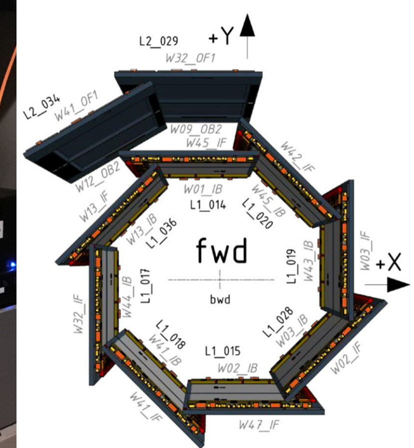
Belle II PXD readout

Phase II	Phase III
~200.000 pixels (1/10 of PXD)	~4.000.000 pixels (1/2 of PXD)









Belle II schedule

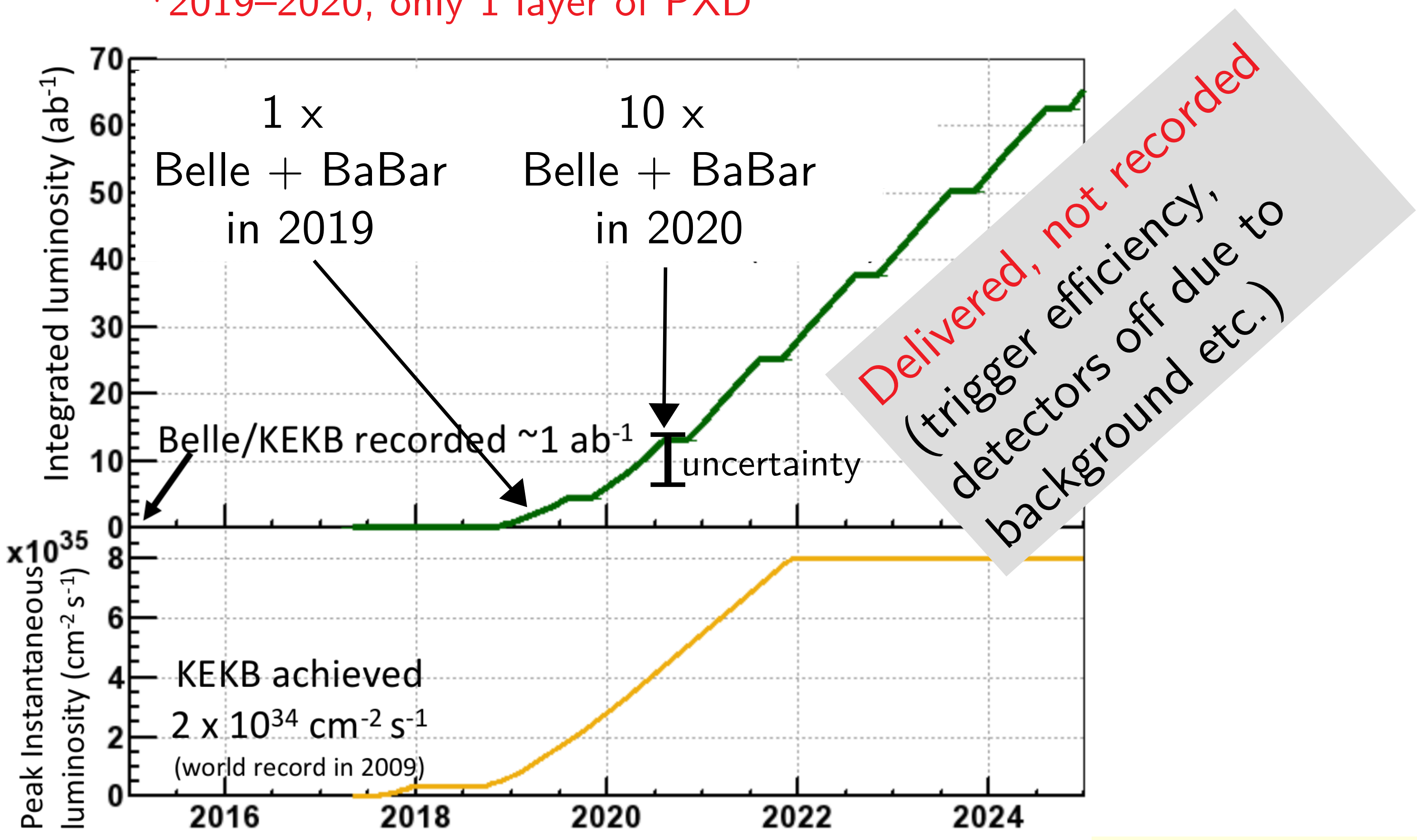
Phase I: 2016, beam operation, reached ≥1 A

Phase II: 2018, collisions, Belle II detector w/o* VXD

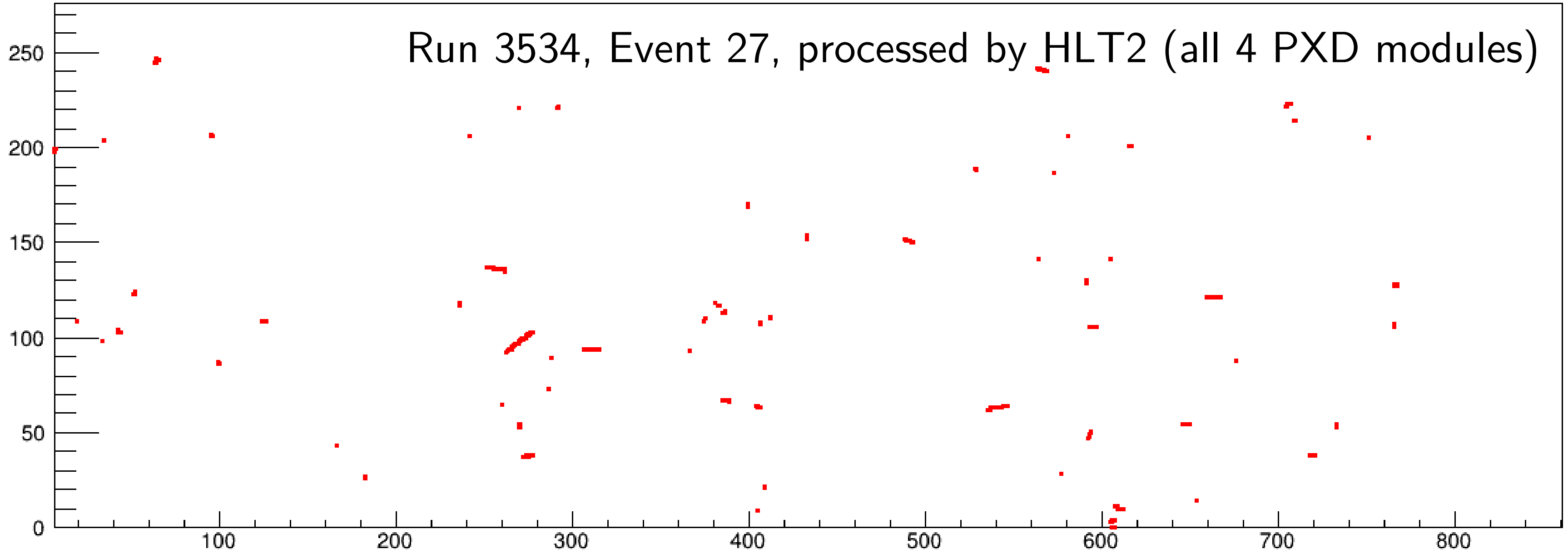
(4 PXD modules, 4 SVD ladders)

Phase III: starts March 2019, full Belle II*, physics data taking

*2019–2020, only 1 layer of PXD



PXD event for phase II

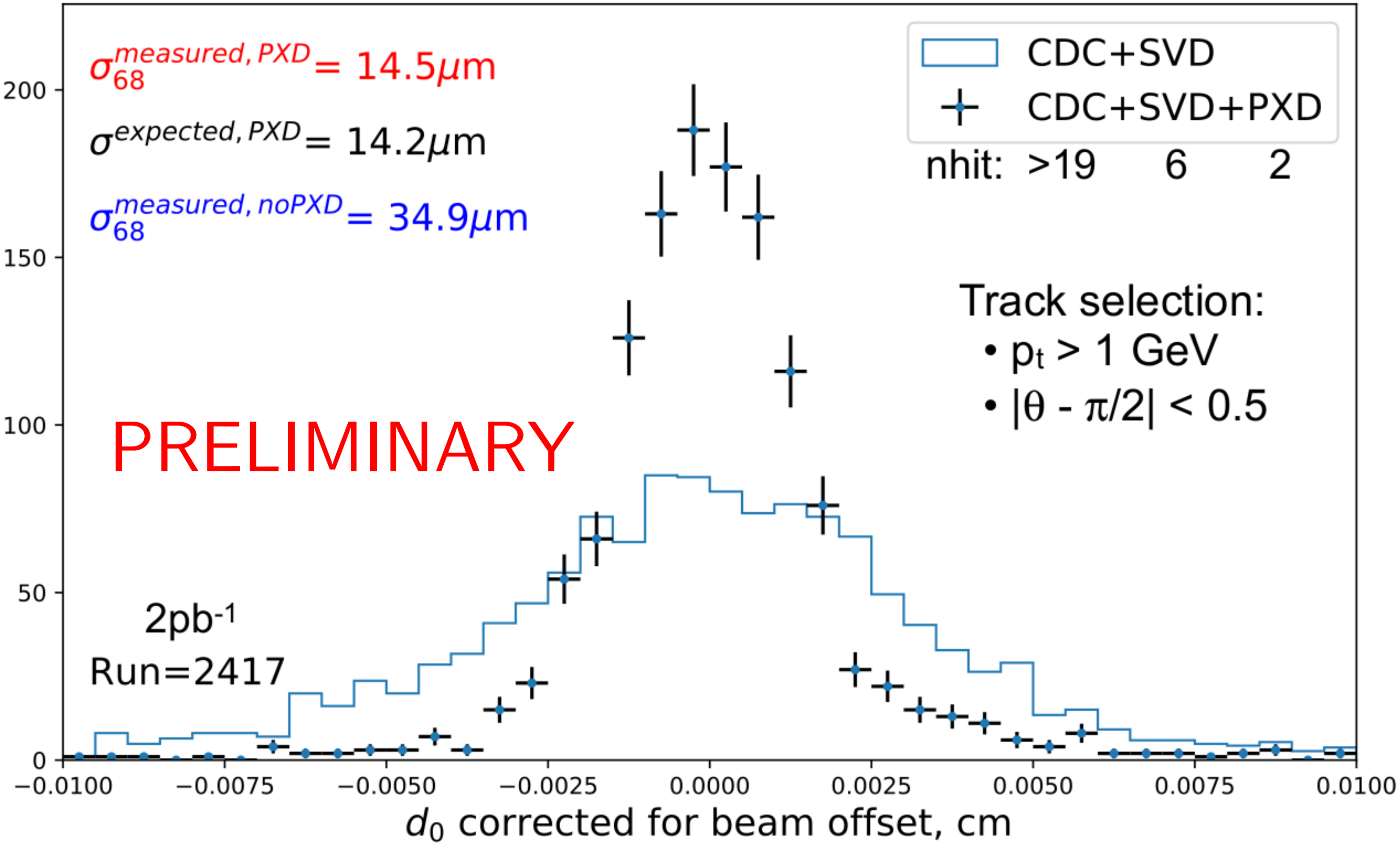


Phase II Achievements

- Integrated luminosity 500 pb^{-1} (~0.5 M B mesons)
- trigger ⩽5 kHz (factor ~10 more than Belle)
- Peak luminosity 5.5×10^{33} cm^{-2} s^{-1}
  (surpassing BaBar design luminosity, 3.0×10^{33} cm^{-2} s^{-1})

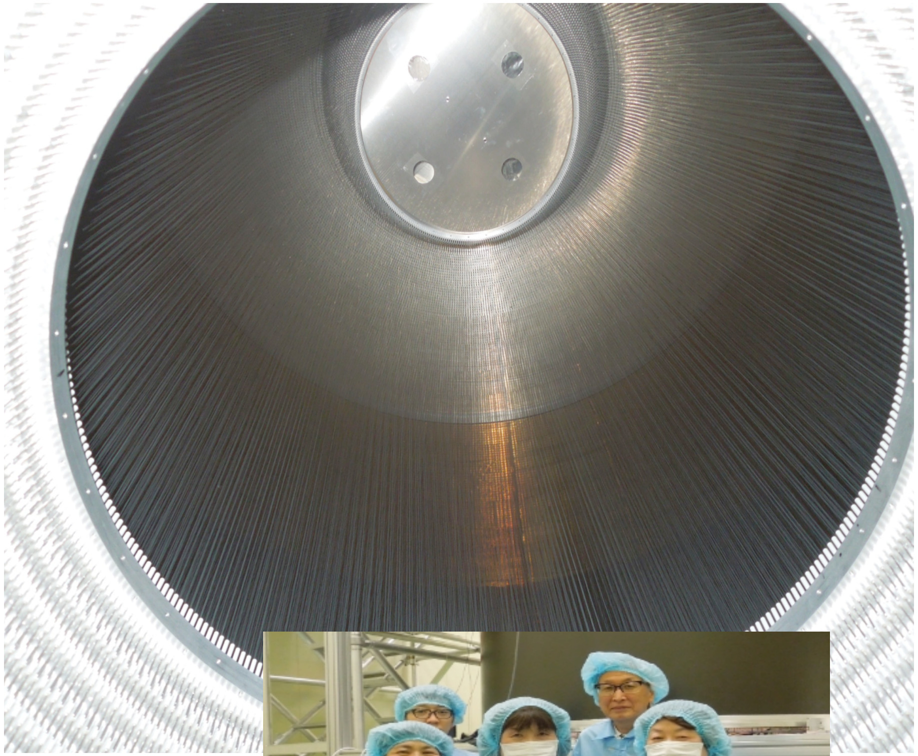
PXD resolution for phase II

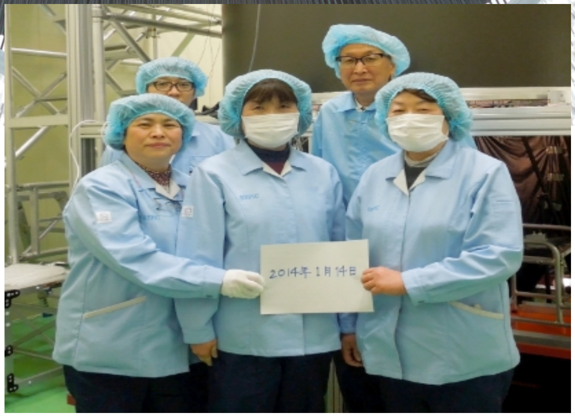
Carsten Niebuhr, B-Factory Advisory Committee 10/2018

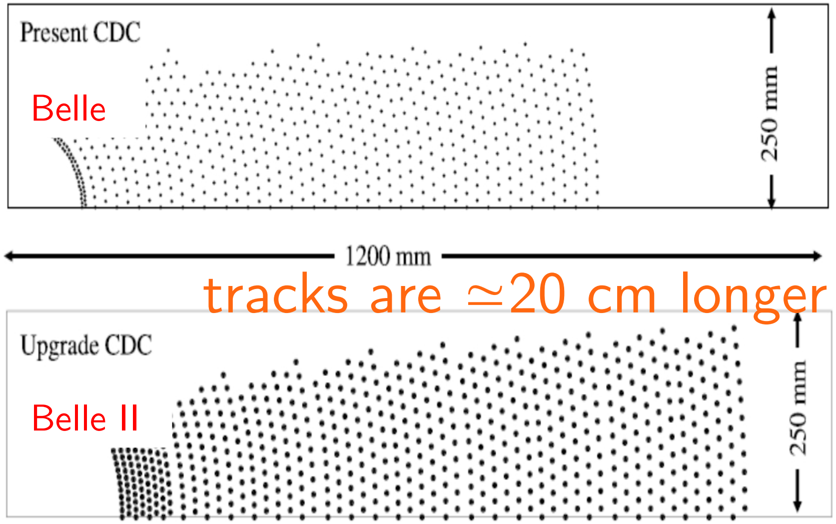


CDC (Central Drift Chamber)

Wire stringing finished (01/2014), 51456 wires







Improved resolution:

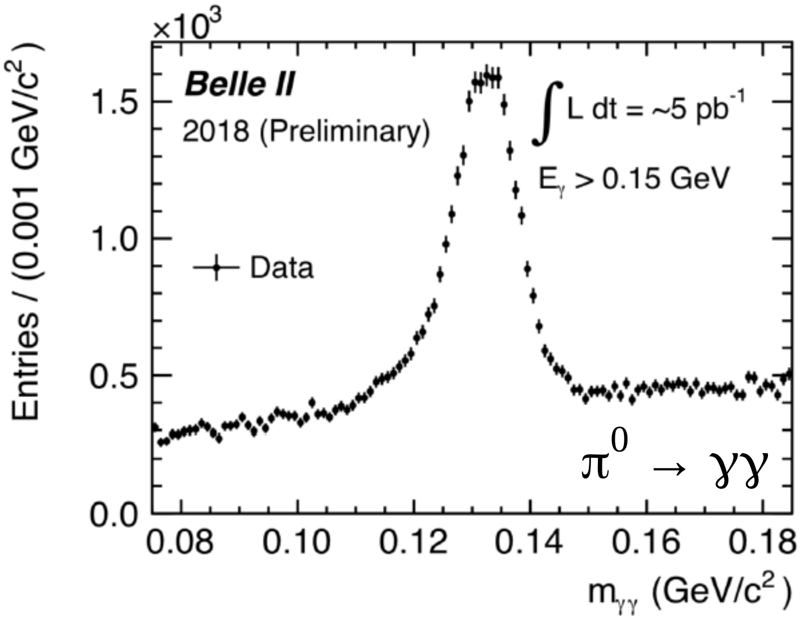
$\sigma(p_T)/p_T =$

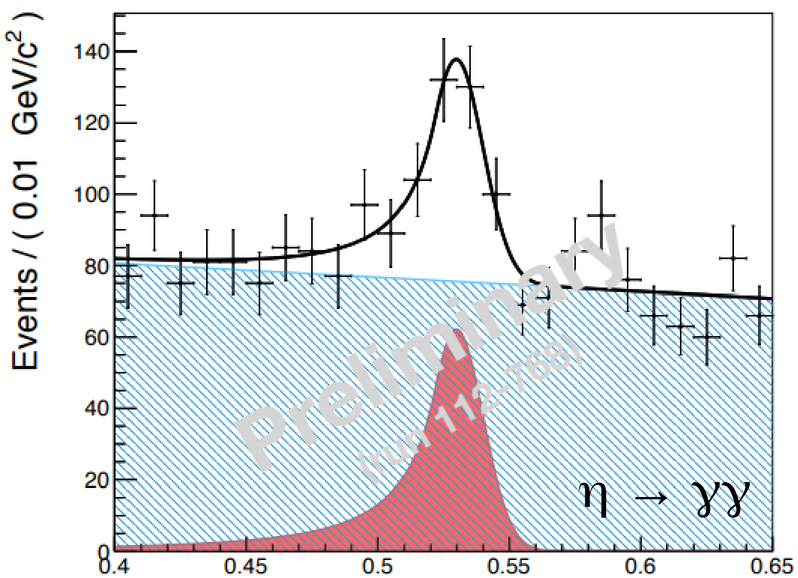
$0.19\ p_T \oplus 0.30/\beta$ (Belle)

$0.11\ p_T \oplus 0.30/\beta$ (Belle II)

dE/dx 6.8% → 4.8%

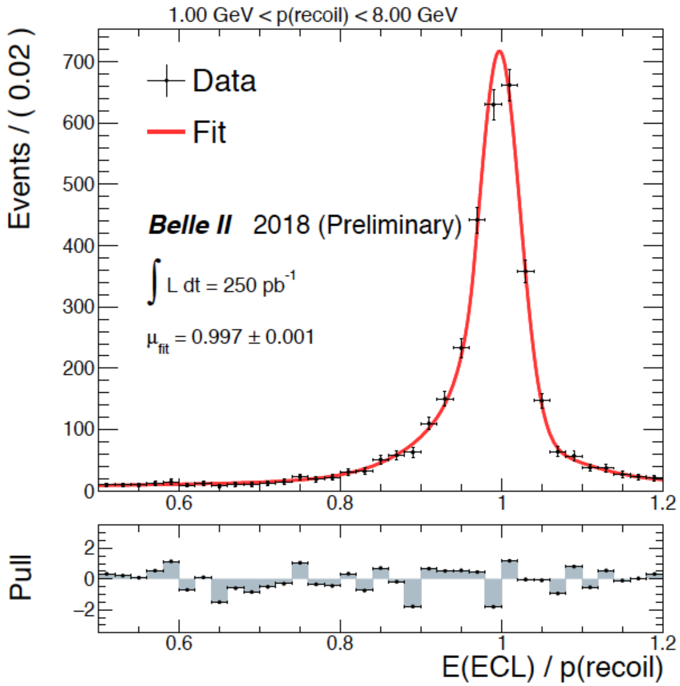
Phase II data: neutral clusters





Single Photon Lines

$e^+e^- \rightarrow \gamma\mu^+\mu^-$

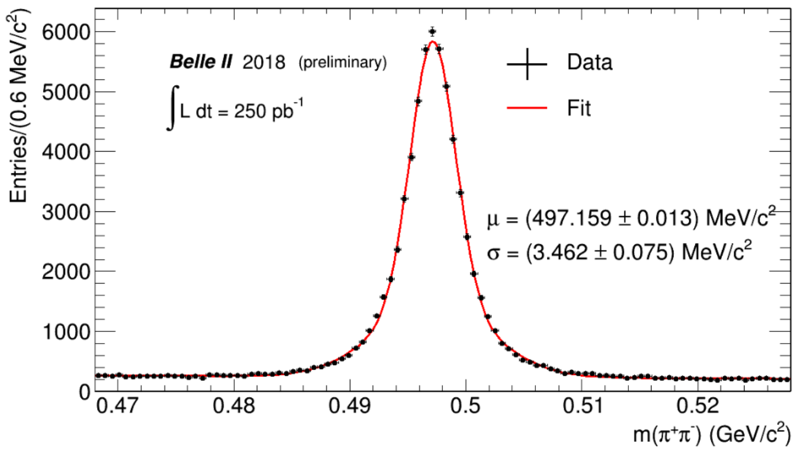


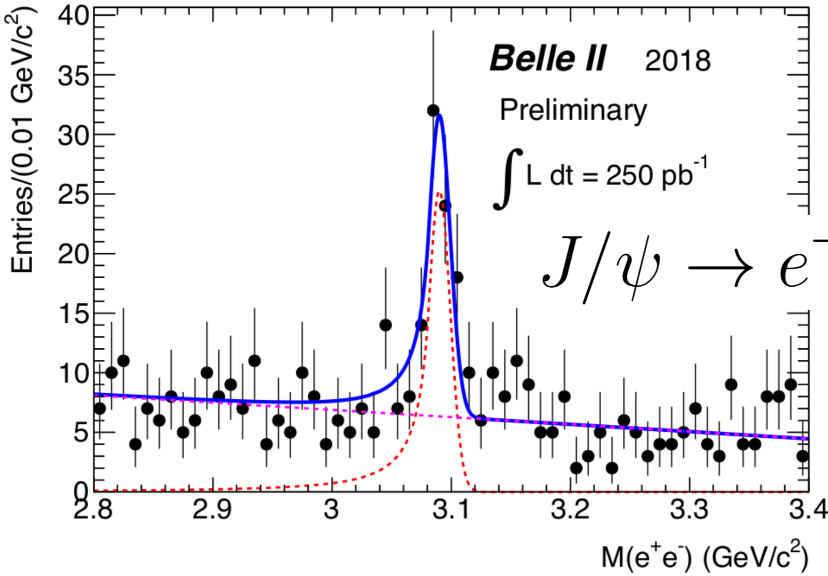
NEW at Belle II:
single photon <u>trigger</u>
for dark sector searches

$e^+e^- \rightarrow \gamma X$

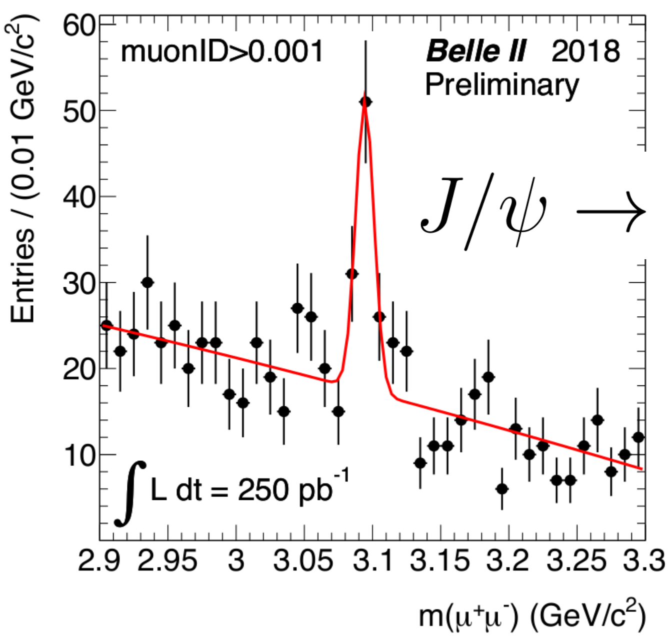
Phase II data: charged tracks

$K_s \to \pi^+\pi^-$





$J/\psi \to e^+e^-$



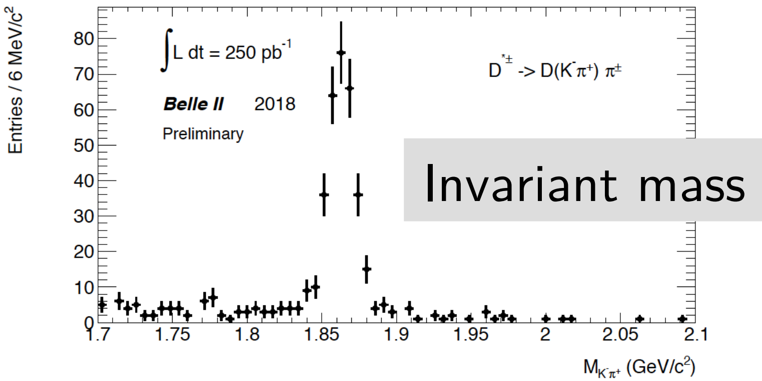
$J/\psi \to \mu^+\mu^-$

Continuum, not B decays!

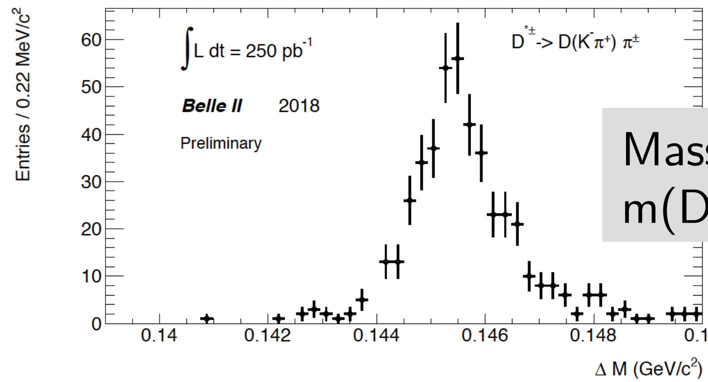
$e^+e^- \rightarrow c\,\bar{c}$

$D^{*+} \rightarrow D^0\,\pi^+$

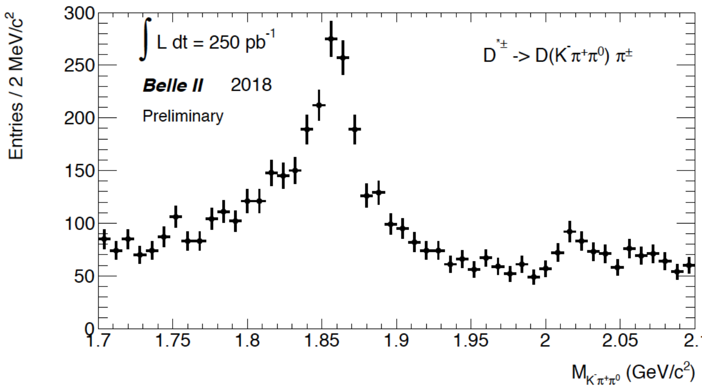
$D^0 \rightarrow K^-\,\pi^+,\ K^-\,\pi^0\pi^+,\ K^-\,\pi^+\pi^-\pi^+$

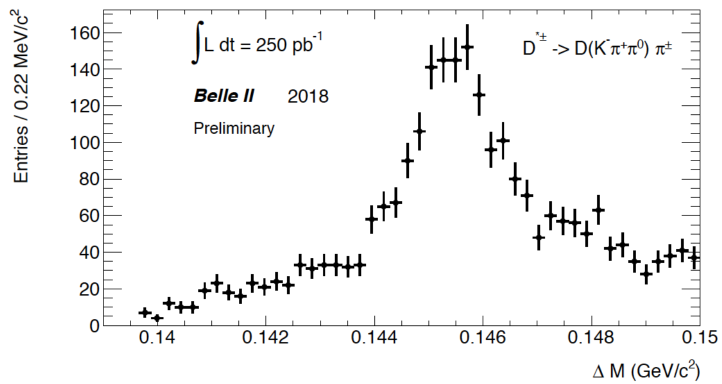


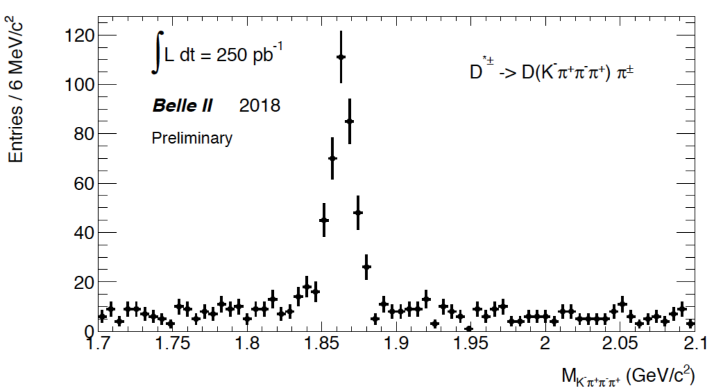
Invariant mass

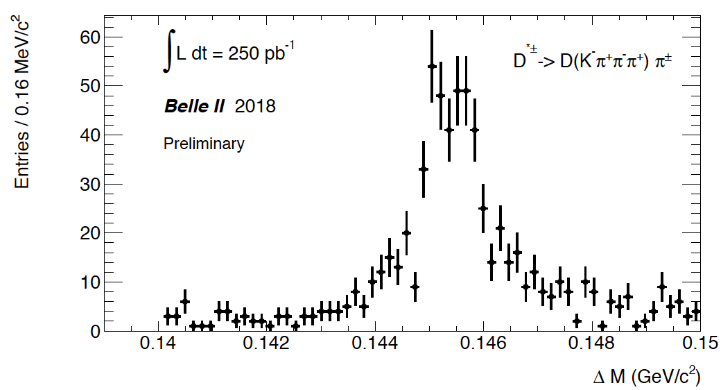


Mass difference m(D*)–m(D)

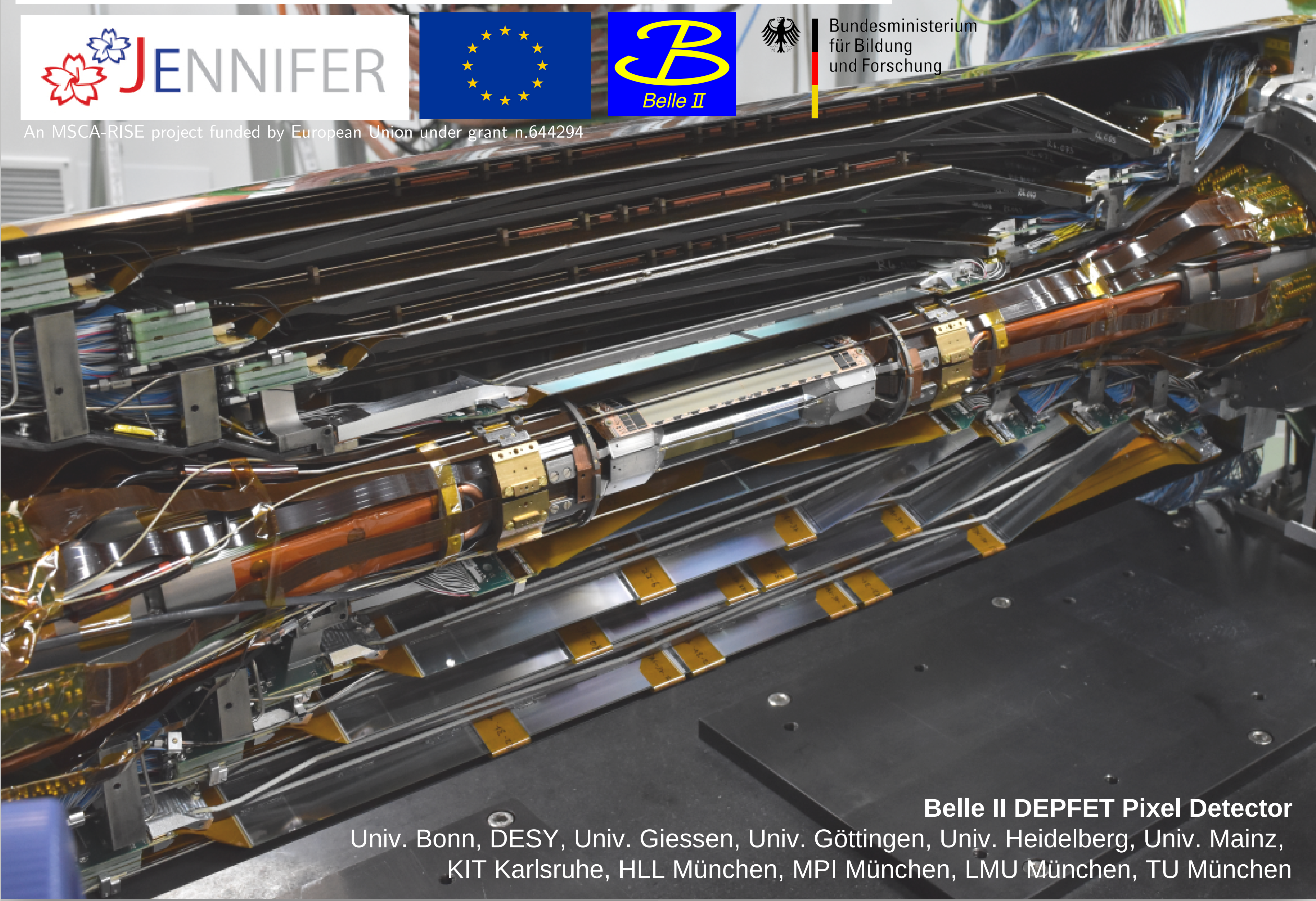








Vertex detector for phase III (halfshells)



An MSCA-RISE project funded by European Union under grant n.644294

Bundesministerium für Bildung und Forschung

Belle II DEPFET Pixel Detector

Univ. Bonn, DESY, Univ. Giessen, Univ. Göttingen, Univ. Heidelberg, Univ. Mainz, KIT Karlsruhe, HLL München, MPI München, LMU München, TU München

Numbers

NUMBER OF XYZ PER DAY

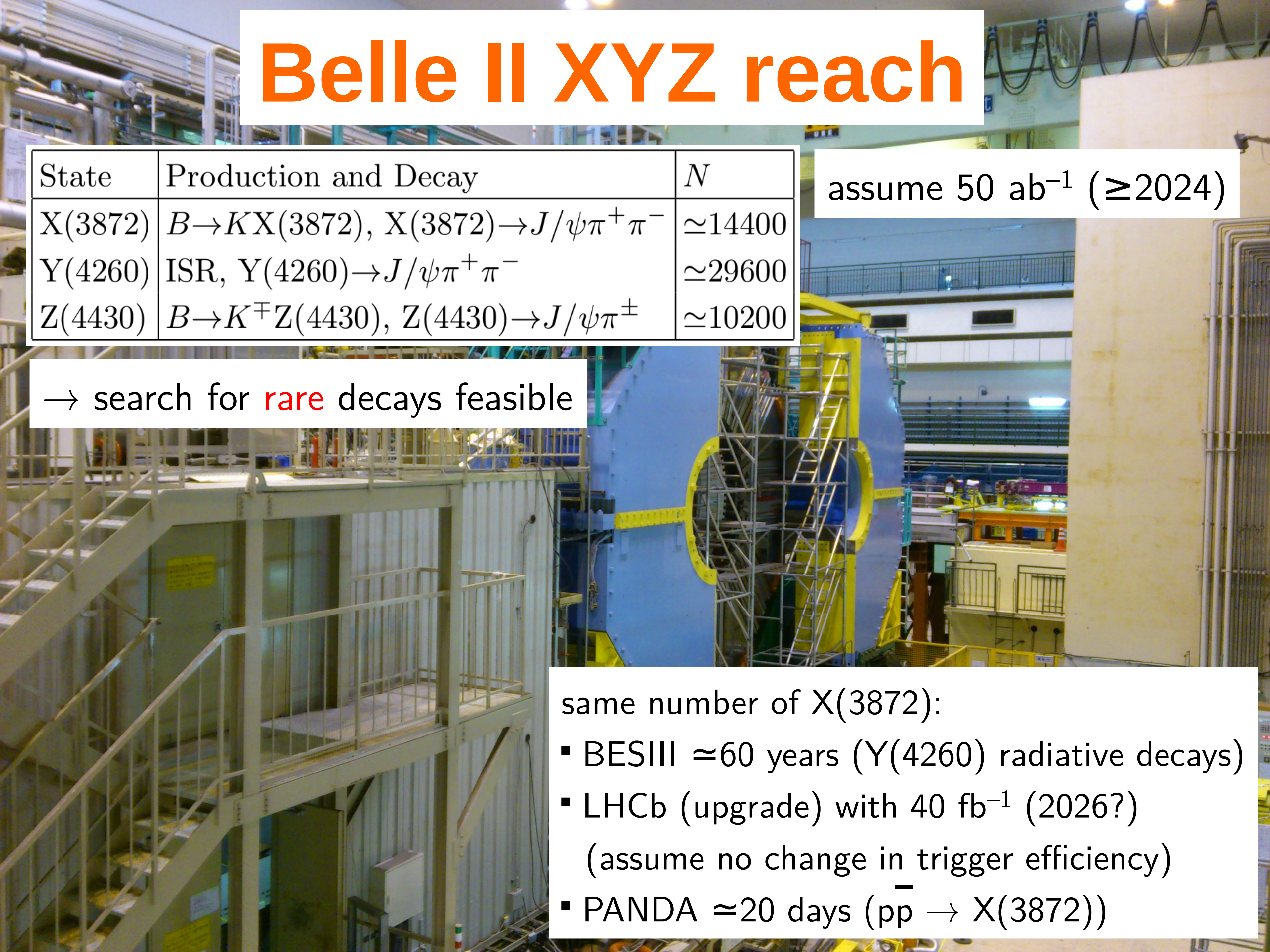
	BESIII	BELLE II (scaled from Belle, assume 40 fb^{-1} per day)
X(3872	0.7 (radiative)	8.5 (Belle was 0.2)
Y(4260)	50	23.6
Z(3900)	10	5.0
Z(4430)	–	8.3
	LHCb (assume 2 fb^{-1}/year) WILL BE INCREASED (UPGRADE)	$\bar{\text{P}}$ANDA E. Prencipe, A. Blinov, S.L., arXiv:1512.05496 [hep-ex] (startup, L=1 x 10^{31} cm^{-2} s^{-1})
X(3872)	1.7 (limited by high pT trigger)	65 (50 nb, $\mathcal{B}$= 5%)
Y(4260)	–	1900 ($<$67) (2 nb, $\mathcal{B}$=100%)
Z(3900)	–	405 ($<$14)
Z(4430)	4.7	–

Numbers are private estimates, by scaling from publications.
Events reconstructed in $J/\psi\pi(\pi)$.
Luminosity per day fixed (i.e. luminosity profiles not taken into account)

Rule of thumb for statistics of B mesons (scaling of cross sections):

Number of inverse ab at Belle II corresponds roughly to number of inverse fb at LHCb

Belle II XYZ reach



State	Production and Decay	N
X(3872)	$B \to K$X(3872), X(3872)$\to J/\psi\pi^+\pi^-$	$\simeq$14400
Y(4260)	ISR, Y(4260)$\to J/\psi\pi^+\pi^-$	$\simeq$29600
Z(4430)	$B \to K^\mp$Z(4430), Z(4430)$\to J/\psi\pi^\pm$	$\simeq$10200

assume 50 ab^{-1} (≥2024)

$\to$ search for rare decays feasible

same number of X(3872):

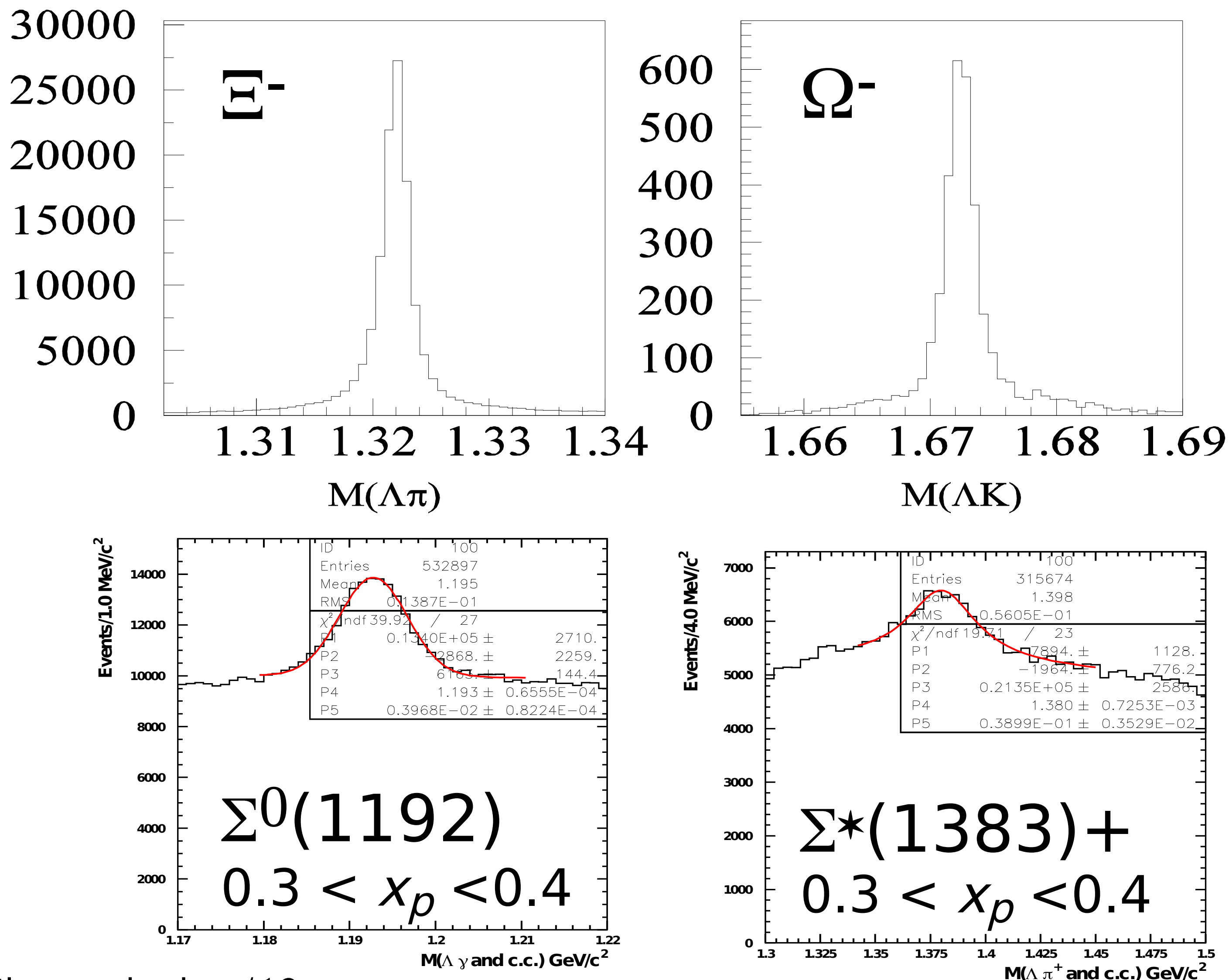
- BESIII $\simeq$60 years (Y(4260) radiative decays)
- LHCb (upgrade) with 40 fb^{-1} (2026?)
  (assume no change in trigger efficiency)
- PANDA $\simeq$20 days ($p\bar{p} \to$ X(3872))

Number of D^0 mesons

- PANDA
  cross section $\sigma(p\bar{p} \rightarrow D^0\bar{D}^0) \approx 9.8–425.6$ nb (background 8500 nb)
  assume high luminosity mode
  68% reconstruction efficiency (MVD TDR, 4 charged)
  $\rightarrow$ 2240–93.600 events per day
  (single tag, assume $K\pi$ decay on one side $\rightarrow$ BR=3.8%)
  x N days for dedicated charm data taking
- Belle I
  reconstruction efficiency ~20% (smaller than Panda)
  - cut $p_{cms}(D^0) \geq 2.2$ GeV/c
  12.9×10^6 $D^0 \rightarrow K\pi$ (976 fb^{-1}, CHARM2012)
  $\rightarrow$ 0.77–31.55 years of PANDA (50% duty cycle)
- Belle II
  132×10^6 $D^0 \rightarrow K\pi$ by 2020 (10 ab^{-1})
  in best case 7.7 years of PANDA (assuming higher cross section)
- BESIII $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$,
  $\sigma \simeq 15$ nb, BR=50%, 2900 pb^{-1} integrated luminosity recorded
  1.65×10^6 $D^0 \rightarrow K\pi$ (one side) on tape
  $\rightarrow$ 18–738 days of PANDA
  (but no boost, no vertex detector)

Hyperons in e+e– → X (continuum) at Belle

Full off-resonance data set 79.4 fb^{-1}, $\sqrt{s}$=10.52 GeV



M. Sumihama, hadron'13

Strange baryons in e+e– at Belle

$\Lambda + \bar{\Lambda}(\text{direct}): 373.9 \pm 0.5\ pb$ — $\Lambda + \bar{\Lambda}(\text{incusive})$

$-\ 97.0 \pm 1.5\ pb$	$\Sigma^0 + cc$	feeddown correction
$-\ 86.6 \pm 6.3\ pb$	$\Sigma^* + cc$	
$-\ 51.2 \pm 1.2\ pb$	$\Xi^-, \Xi^0 + cc$	
$-\ 3.3 \pm 0.3\ pb$	$\Lambda(1520) + \bar{\Lambda}(1520)$	
$-\ 23.6 \pm 31.2\ pb$	$\Lambda_c + cc$	

$= 112.2 \pm 31.8\ pb$

$\Sigma^0 + \bar{\Sigma}^0(\text{direct}): 97.0 \pm 1.5\ pb$

$-\ 4.0 \pm 0.3\ pb$	$\Sigma^{*-}, \Sigma^{*+} + cc$
$-\ 4.9 \pm 0.6\ pb$	$\Lambda(1520) + \bar{\Lambda}(1520)$
$-\ 7.2 \pm 3.9\ pb$	$\Lambda_c + cc$

$= 80.9 \pm 4.2\ pb$

$\Sigma*+$ + c.c. (direct) : 33.2 $\pm$ 2.4 pb — $\Sigma*+$ + c.c. (inclusive)

$-\ 0.4 \pm 0.06\ pb$ — $\Lambda(1520)$ + c.c.

$= 32.8 \pm 2.4$ pb

$\Lambda(1520)$+c.c. (direct) = 15.3 ± 0.5 pb — inclusive

– 0.34 ± 0.17 pb — $\Lambda c+$

= 15.0 ± 0.26 pb

example: 100 pb
assume 20% reconstruction efficiency
off-resonance data

Belle I, 79.4 fb^{-1}
~**1.6 M events**

Belle II, assume 5 ab^{-1}
~**10^8 events**

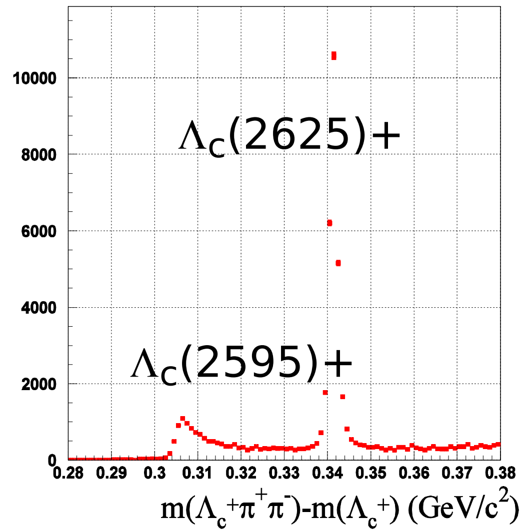
M. Sumihama, hadron'13

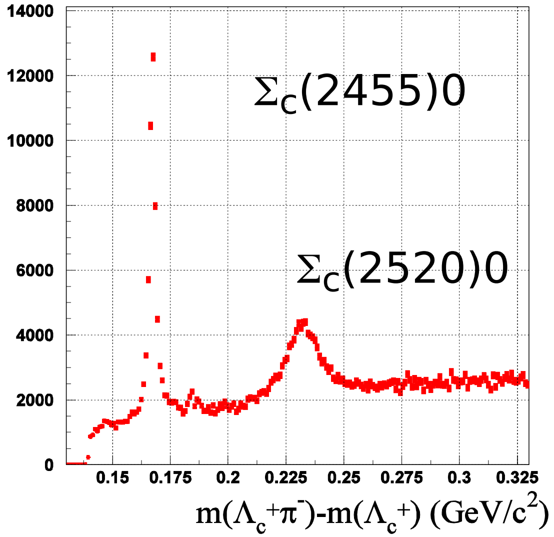
note GlueX
~10^4 Ξ in 10 days
w/ K_l beam project

Charmed-strange baryons in e+e− at Belle

- Λ_c^+ + c.c. (direct) = 189 ± 66 *pb* inclusive
  - (17.9 ± 6.0 *pb*) x 3 Σ_c0,+,++(2455) + c.c.
  - (18.8 ± 6.4 *pb*) x 3 Σ_c0,+,++(2520) + c.c.
  - (31.3 ± 10 *pb*) Λ_c+(2625) + c.c.
  - = 47.6 ± 16.2 *pb*

- Σ_c^0(2455) + c.c. (direct) = 17.9 ± 6.0 *pb*
- Σ_c^0(2520) + c.c. (direct) = 18.8 ± 6.4 *pb*
- Λ_c^+(2625) + c.c. (direct) = 31.3 ± 10 *pb*





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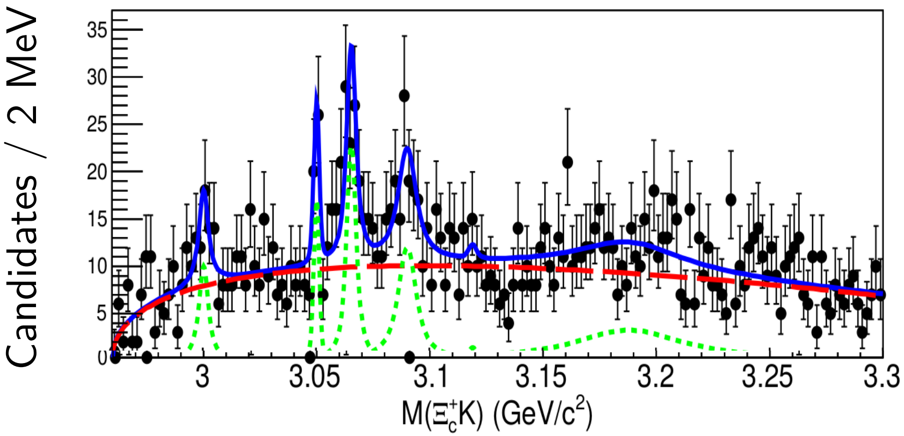
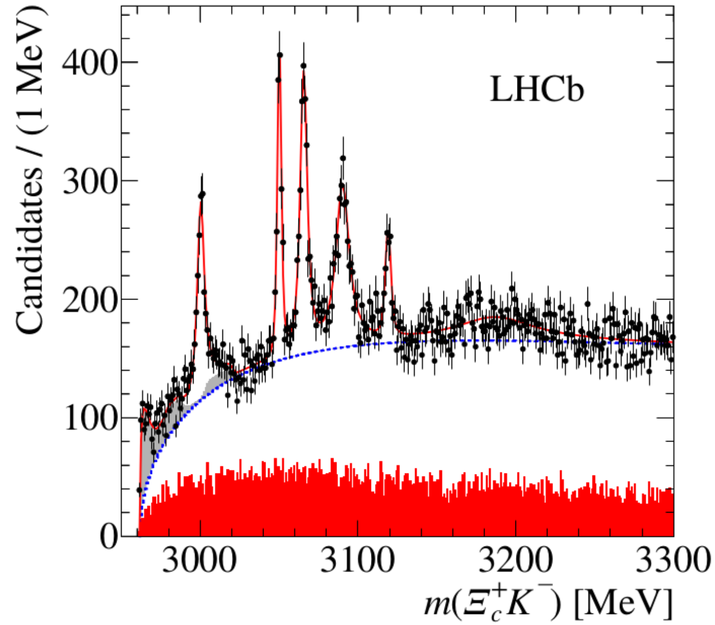
Ω_c* states



Belle, Phys. Rev. D 97 (2018) 051102
980 fb–1
Continuum, not B decays



LHCb, Phys. Rev. Lett. 118 (2017) 182001
3.3 fb^{-1}

Belle II $\rightarrow$ statistics x 50

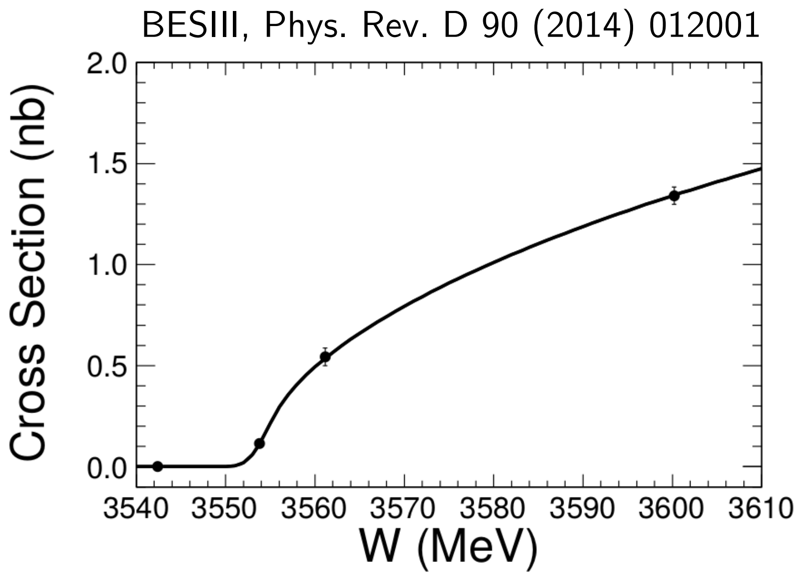
- P-wave „gap“ ?
- Input for predicted masses of stable tetraquarks

$e^+e^- \to \tau^+\tau^-$

Cross section Υ(4S) is 0.92 nb

Experiment	Number of τ pairs
LEP	~3x10^5
CLEO	~1x10^7
BaBar	~5x10^8
Belle	~9x10^8
Belle II	~10^{12}

E. Passemar,
COFI Workshop, 2018

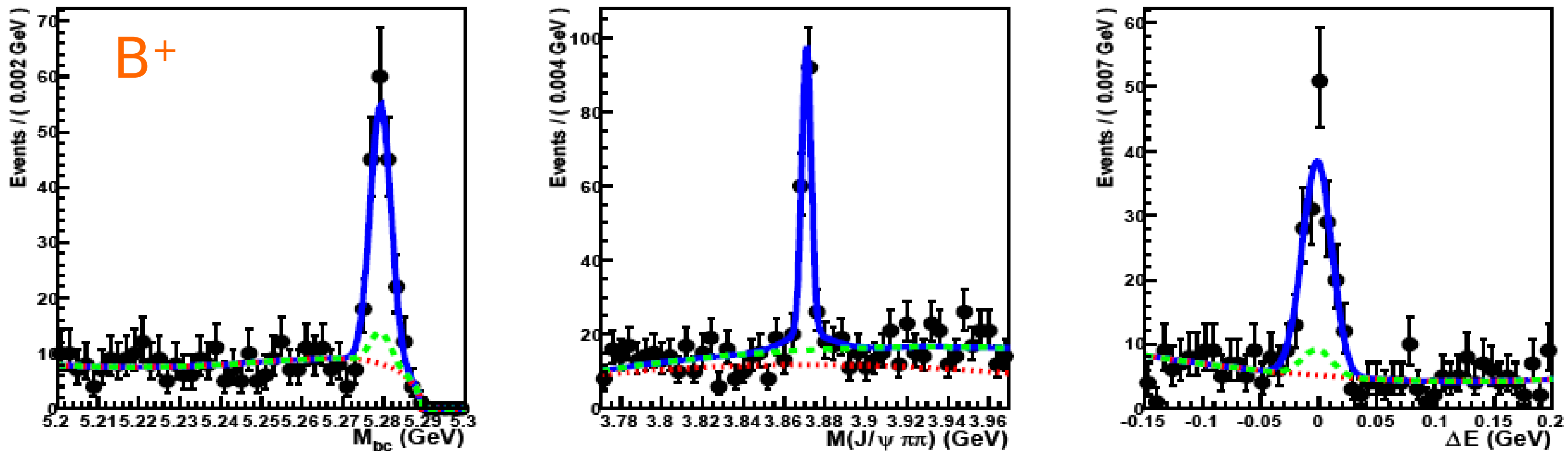


Cross section is comparable, but luminosity is different (BESIII ~1x10^{33}, Belle ~2x10^{34}, Belle II ~8x10^{35}, Super-tau-charm factory ~ few times x10^{35})

Width
Of
X(3872)

X(3872) Width Measurement at Belle I

$M_{bc} \equiv \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$ X(3872) → $J/\psi\, \pi^+ \pi^-$ $\Delta E \equiv E_B^{cms} - E_{beam}^{cms}$



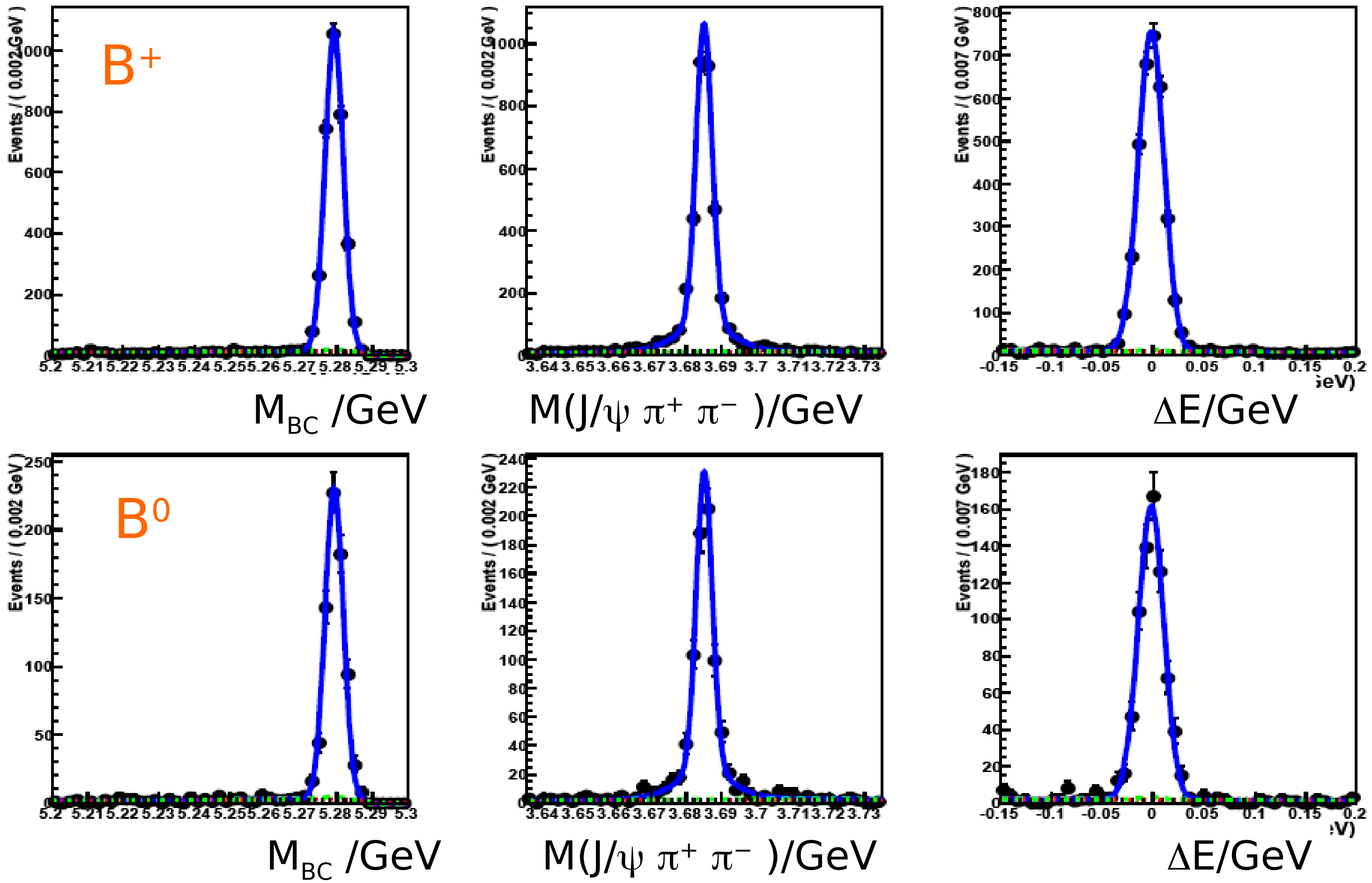
M_{BC} /GeV M($J/\psi\, \pi^+ \pi^-$)/GeV ΔE/GeV

- 3-dim fit (over-constraint)
- beam constraint applied
  $\Delta E/E = 7 \times 10^{-4}$
- upper limit on width < 1.2 MeV (90% C.L.)
- S/B≃10/1

Belle, Phys. Rev. D84 (2011) 052004

Reference Analysis: $B \to K\psi'$, $\psi' \to J/\psi\,\pi^+\pi^-$

$M_{bc} \equiv \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$ $\Delta E \equiv E_B^{cms} - E_{beam}^{cms}$



factor ~10 more statistics than X(3872) → use as reference signal

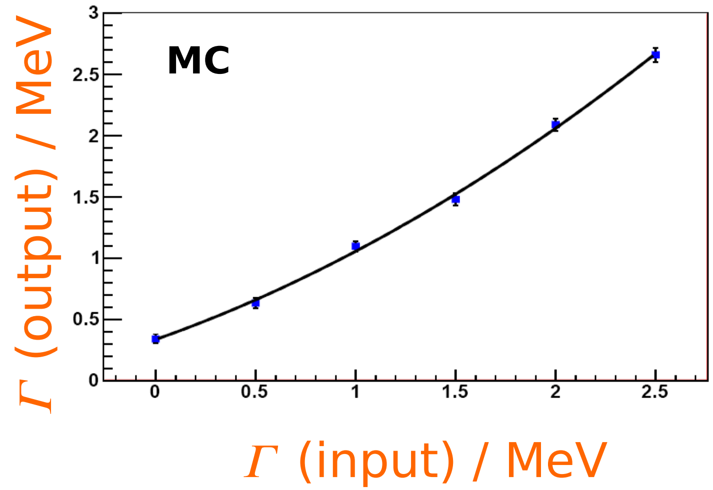
→ fix resolution parameters

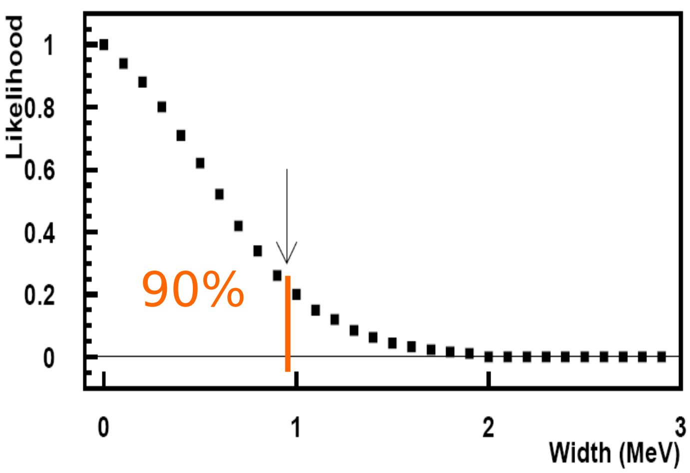
→ fix absolute mass scale (MC/data shift +0.92±0.06 MeV)

Measurement of width of X(3872)

- Correlation function from MC
  Γ (output) = f(Γ (input))
- 3-dim fits validated with ψ' width
  $\Gamma_{\psi'}=0.52\pm0.11$ MeV
  (PDG 0.304 ± 0.009 MeV)
  $\rightarrow$ bias 0.23 ± 0.11 MeV
- procedure for upper limit:
  width in 3-dim fit fixed
  n_{signal} and n_{BG} floating
  $\rightarrow$ calculate likelihood
- $\Gamma_{X(3872)}$ < 0.95 MeV + bias

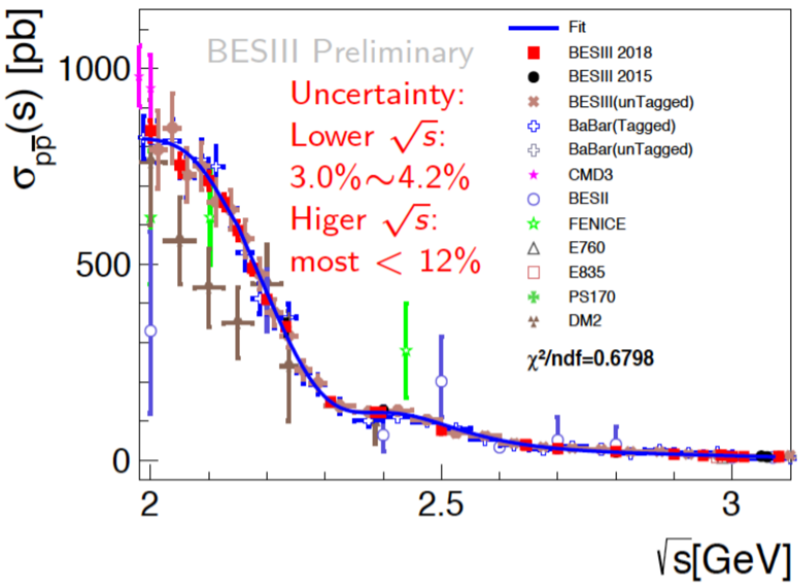
  1.2 MeV

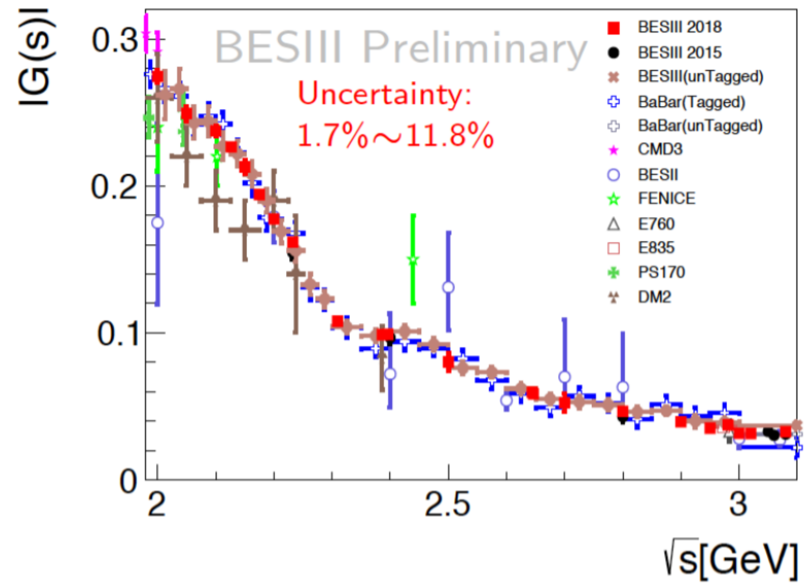




Proton Formfactor

Proton formfactor in e+e− → p $\bar{p}$, BESIII (Status 2018)





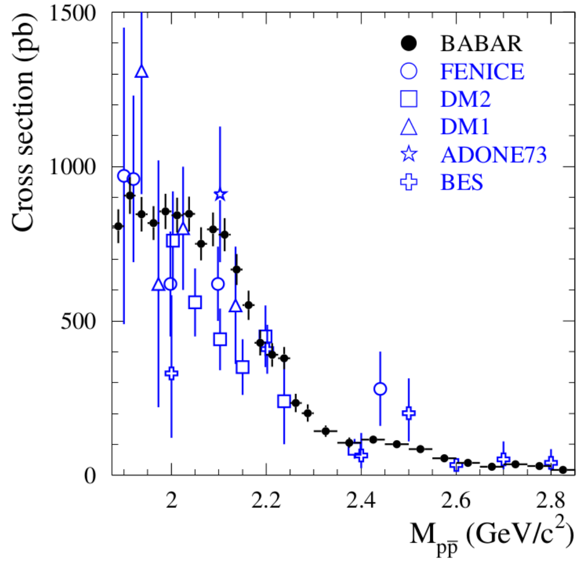
- Scan technique (black and red points):
  - 2012 data, 156.9 pb^{-1} [PRD 91, 112004 (2015)]
  - 2015 data, 688.5 pb^{-1} : preliminary results, improved precitions
- ISR technique (light brown points):
  - tagged (7.4 pb^{-1} above 3.773GeV), under reviewing
  - untagged (7.4 pb^{-1} above 3.773GeV): preliminary results

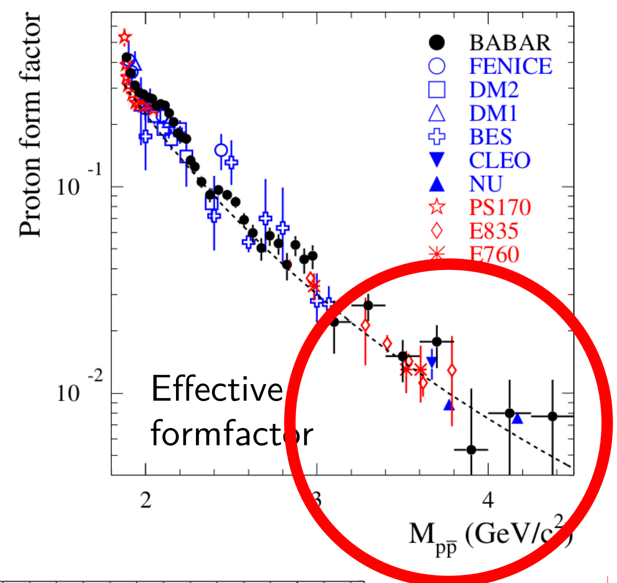
Monica Bertani, EUNPC‘18, 02.–7.09.2018

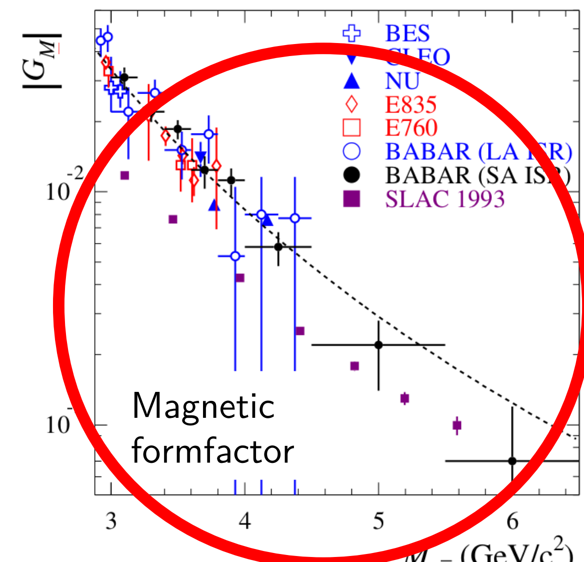
Proton formfactor in e+e– → p $\bar{p}$ (ISR), BaBar (Status 2015)

Not done at Belle:
trigger required
≥3 tracks
(but we had Level–1
2-track back-to-back trigger,
e^+e^- and $\mu^+\mu^-$,
downscaled)

Belle II: High Level Trigger !
(full tracking, topology,
neutral–only triggers, etc.)
Already operating in phase II
(≤5 kHz trigger rate)







Comparison with other Experiments

Belle II vs. other experiments

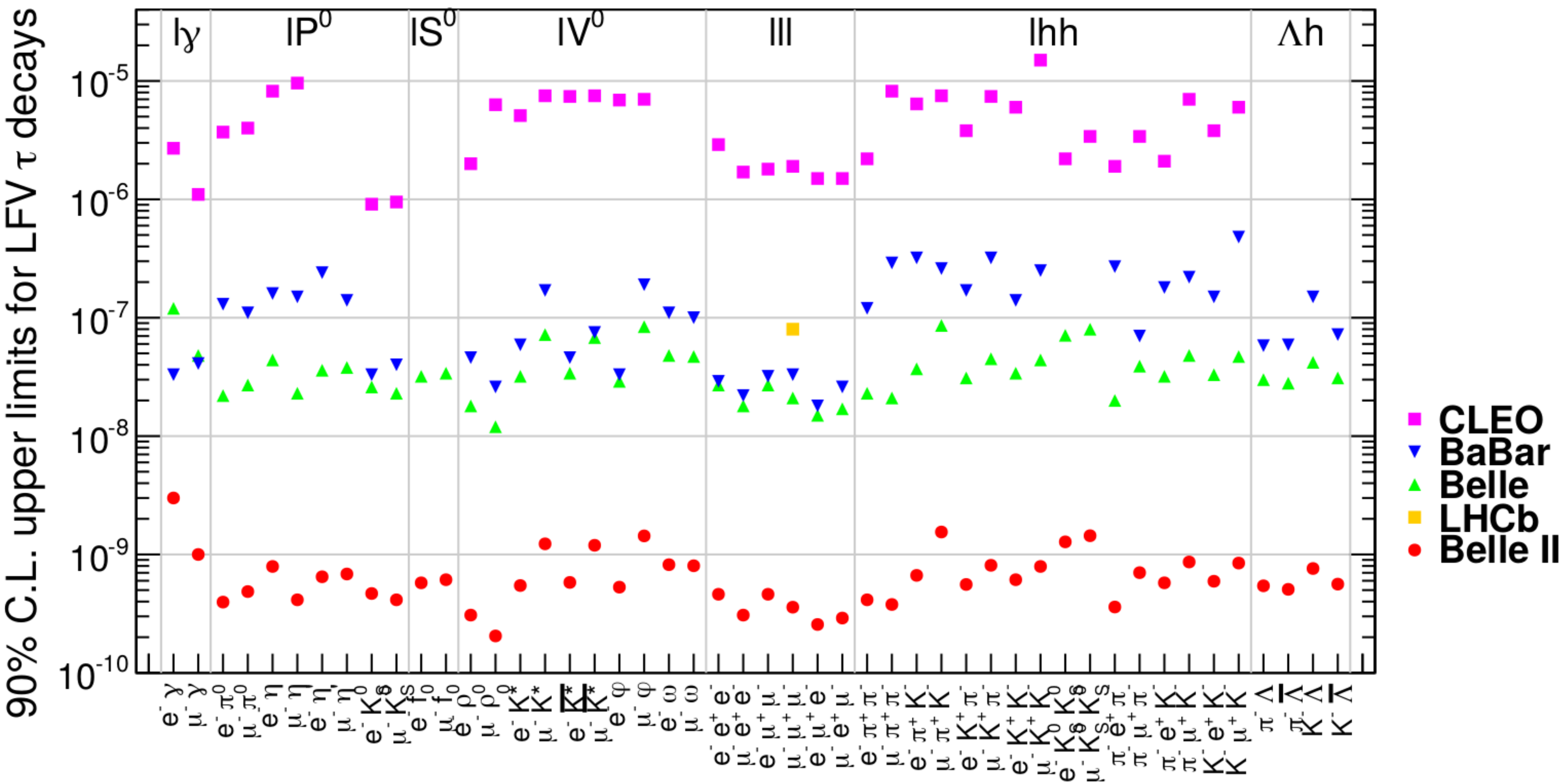
- Y(4260) unique at BESIII and Belle II
  (never seen at LHC, no ISR at hadron machines)
- Upsilon(5S) never seen at LHC
  $\rightarrow$ Z_b states
- $\rightarrow$ Upsilon(5S) is exotic itself
  (Y(1S) and Y(2S) transitions are factor $\geq 10^3$ too large)
- *Advantage:* initial state is precisely known, Y(4S)
  beam energies ~7 x 10^{-4} (relative), used as beam constraint in fits
  B meson mass resolution is factor ~10 better than LHCb
- D_{sJ} physics?
  - So far, D_{sJ} at LHCb only studied in DK
    advantage Belle II: $D_s\gamma$, $D_s\pi^0$ final states
    π^0 efficiency is roughly factor ~5 higher than LHCb
  - Width of $D_{sJ}(2460)$?
    Belle, Phys. Rev. D83 (2011) 051102
    Width of $D_{s1}(2536)$ was measured by Belle to 750$\pm$230 keV
    At PANDA, $D_{sJ}(2460)$ threshold is $p_{BEAM} \geq 9$ GeV
    $\rightarrow$ limit of e– cooling, no high resolution mode

Summary

- Belle II can address rare decays of XYZ states ($\mathcal{B}\sim10^{-4}$)
- Initial state is known (beam energies, precision 7 x 10^{-4})
  $\rightarrow$ sub-MeV widths of exotic states
- Start phase III (physics data taking) in March 2019
  $\rightarrow$ data taking $\sim$10 years
- Discussion on possible upgrade ($\geq$10 years) started
  - Factor $\sim$5 more luminosity under discussion (redesign of interaction region)
  - Beam polarisation (Weinberg angle)

BACKUP

Lepton flavor violation in τ decays



Belle II will reach 10^{-9} in many modes (50 ab^{-1})

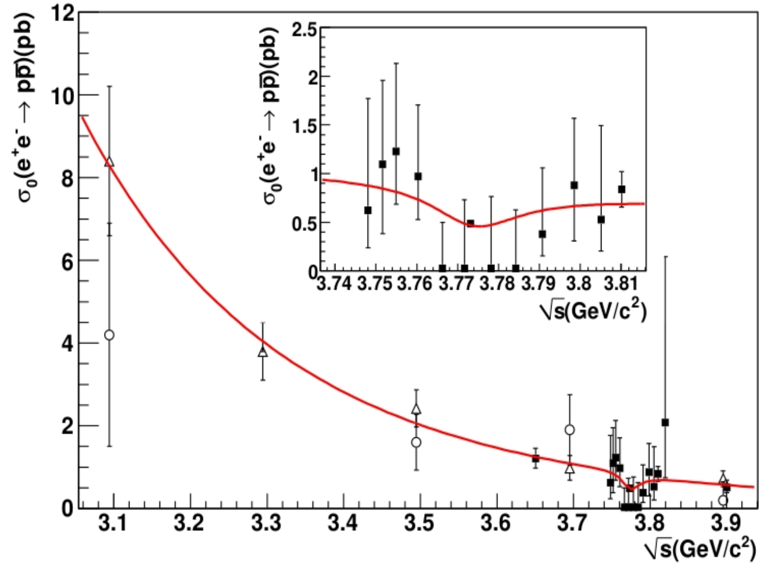
Cross section is 0.9 nb

Open charm cross section at PANDA (Experiment)

BESIII, Phys.Lett. B735(2014)101, arXiv:1403.6011[hep-ex]

$\psi(3770) \to D^0 D^0$ (50%)
$\psi(3770) \to D^+ D^-$ (50%)

Detailed balance:
determine
$\sigma(p\bar{p} \to \psi(3770))$
at PANDA
from
$\sigma(\psi(3770) \to p\bar{p})$
at BESIII

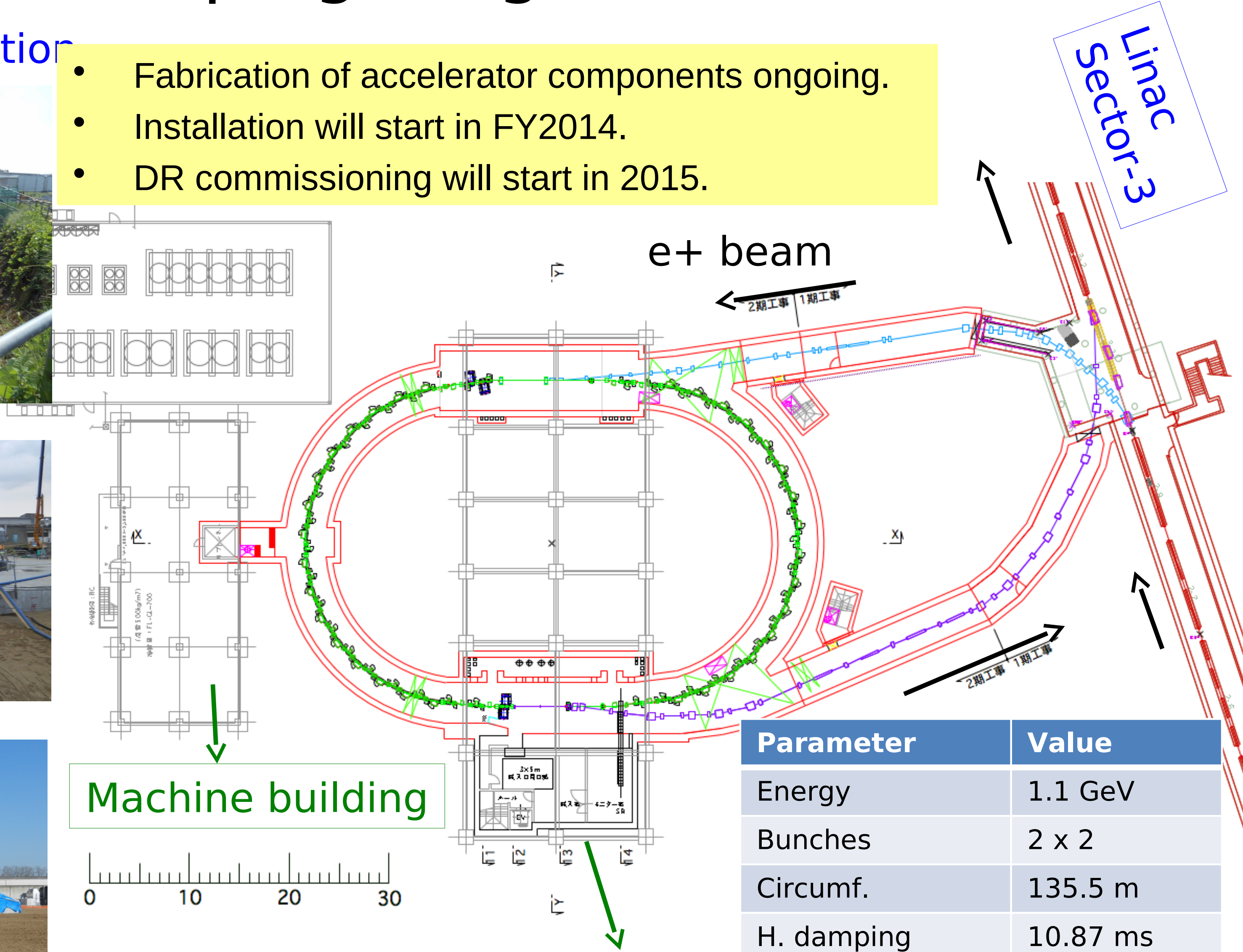


QM interference
of signal and background
2 solutions:
(9.8+11.8−3.9) nb
(425.6+42.9−43.7) nb

New Damping Ring for Positrons

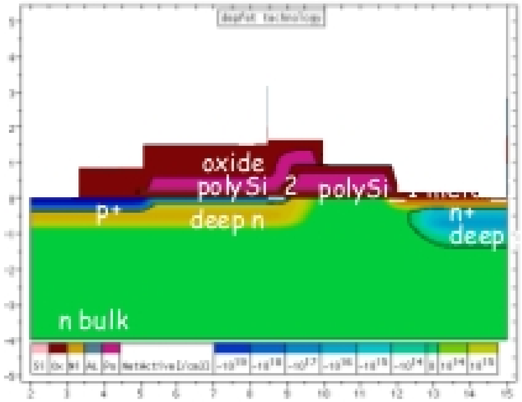
DR tunnel construction

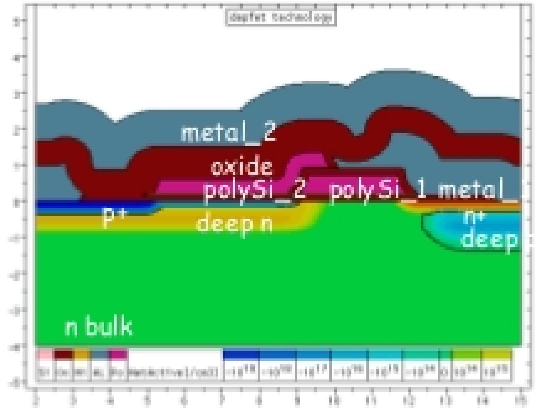
- Fabrication of accelerator components ongoing.
- Installation will start in FY2014.
- DR commissioning will start in 2015.

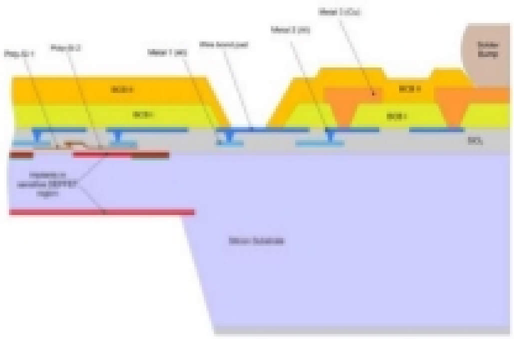


Parameter	Value
Energy	1.1 GeV
Bunches	2 x 2
Circumf.	135.5 m
H. damping	10.87 ms
Ext. emittance (H/V)	42.5/3.15 nm
Max. current	70.8 mA

DEPFET







Phase I – before metal

- Implantations
- Polysilicon
- Dielectric depositions

Phase II - Alu

- Metal 1
- isolation
- Metal 2

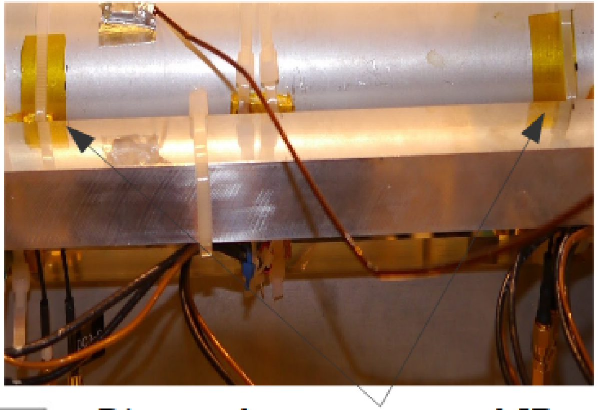
Phase III – thinning and Cu

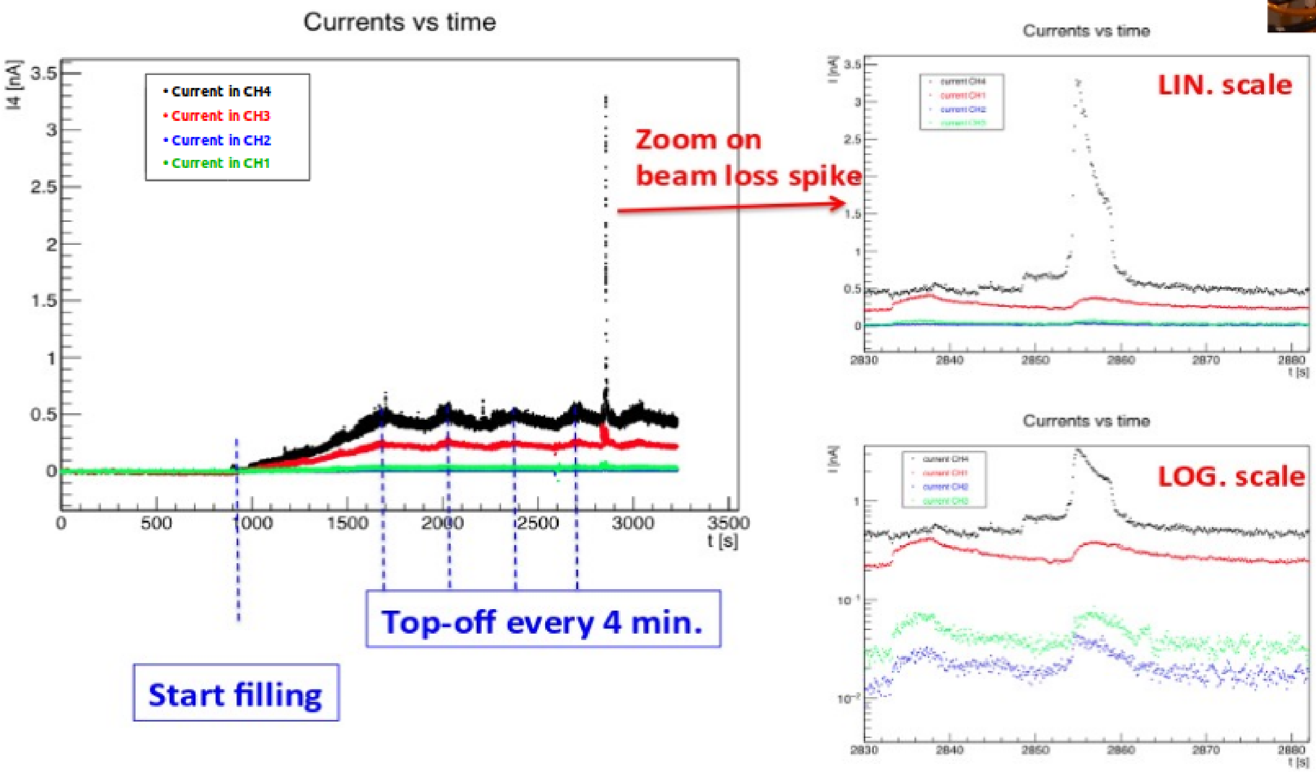
- Handle wafer removal
- Dielectric deposition
- Metal 3
- Passivation

☑ Phase II:EMCM production(s) for Alu/Cu

Belle II

Diamond detectors





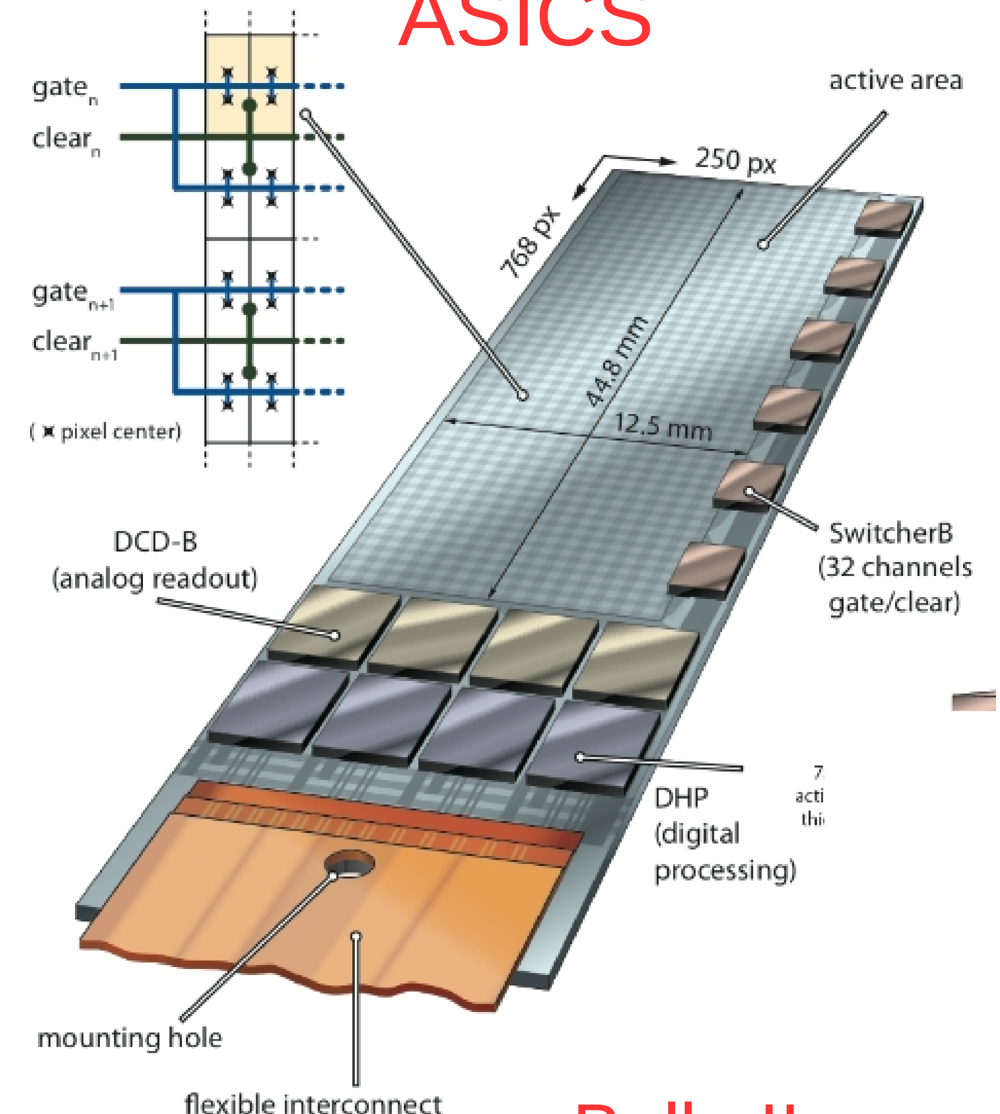
Ionizing current seen by diamond sensors at various locations during vacuum scrubbing

DCDB (Drain Current Digitizer)
ADC (for electrical current)
UMC 180 nm
256 input channels
8-bit ADC per channel
92 ns sampling time
Rad hard tested (7 Mrad)

DHP (Data Handling Processor)
IBM CMOS 90 nm, TSMC 65 nm
Zero suppression
Pedestal correction
Timing and trigger control
Rad. Hard tested (100 Mrad)

SwitcherB (Row Control)
AMS/IBM HVCMOS 180 nm
Gate and Clear signal
32x2 channels
Fast HV ramp for Clear
Rad. Hard tested (36 Mrad)

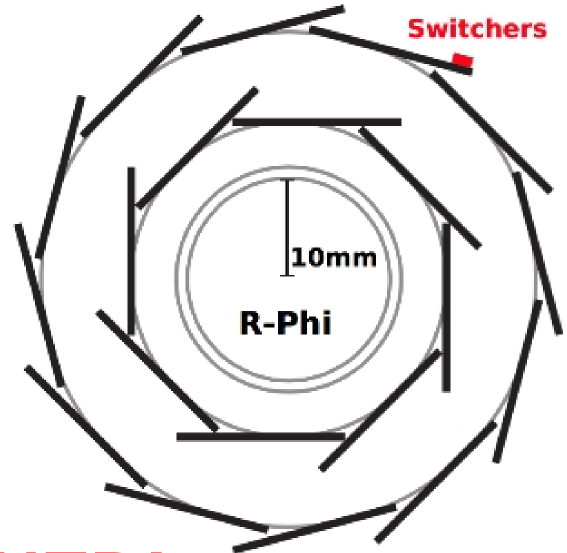
ASICS



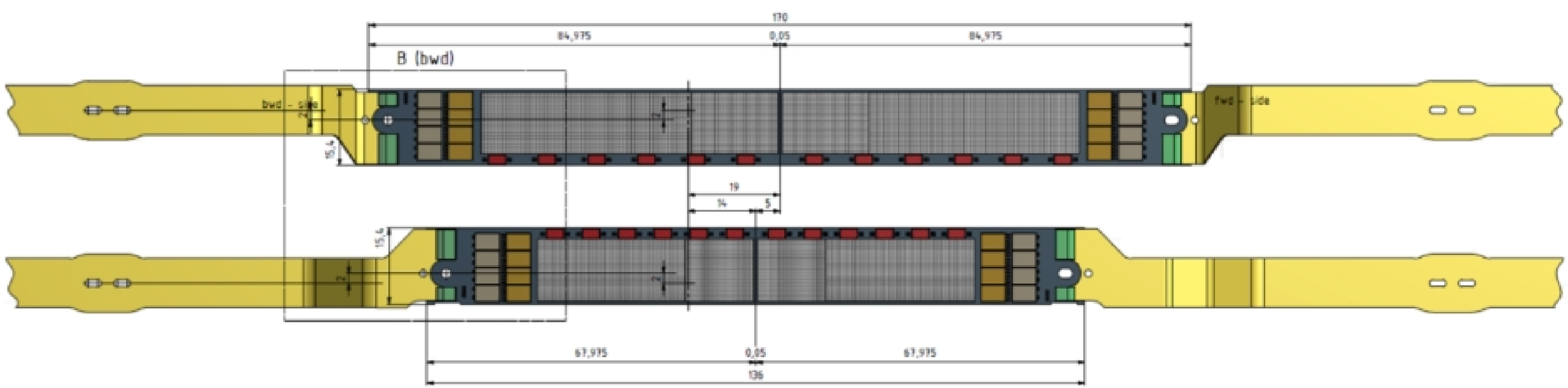
Belle II
~2 MRad / year

Belle II PXD

	Layer 1	Layer 2
Module	8	12
Radii	14 mm	22 mm
Ladder Size	15x136 mm^2	15x170 mm^2
Pixel Size	50x55 μm^2 50x60 μm^2	50x70 μm^2 50x85 μm^2
Pixels	250x1536	250x1536
Thickness	75 μm	75 μm



THINNED!



4 different module topologies (different Kapton connector designs):
inner/outer forward/backward

Summary of detector performance.

Measurement	Belle	Belle II
B Vertex Reconstruction (typical)	$\sigma_z = 61\,\mu m$	$\sigma_z = 26\,\mu m$
Tracking	$\sigma_{p_t}/p_t = 0.0019 p_t$ [GeV/c]$\oplus 0.0030/\beta$	$\sigma_{p_t}/p_t = 0.0011 p_t$ [GeV/c]$\oplus 0.0025/\beta$
$K\pi$ ID	Kaon efficiency $\epsilon_K \simeq 0.85$ with pion fake rate $\epsilon_\pi \simeq 0.10$ for $p = 2\,GeV/c$	$\epsilon_K \simeq 0.90$ with $\epsilon_\pi \simeq 0.04$ for $p = 2\,GeV/c$
Calorimetry	$\frac{\sigma E}{E} = \frac{0.066\%}{E} \oplus \frac{0.81\%}{\sqrt[4]{E}} \oplus 1.34\%$	$\frac{\sigma E}{E} = 7.7\%$ at 0.1 GeV, 2.25% at 1 GeV
Muon ID	Muon efficiency $\epsilon_\mu \simeq 0.90$ with fake rate $\epsilon \simeq 0.02$ for $p_t > 0.8\,GeV/c$ tracks	$\epsilon_\mu = 0.92 - 0.98$ with $\epsilon = 0.02 - 0.06$ for $p > 1\,GeV/c$
L1 Trigger	500 Hz typical average, Efficiency for hadronic events $\epsilon_{hadron} \simeq 1$	30 kHz max. average rate, $\epsilon_{hadron} \simeq 1$
DAQ	~5% dead time at 500 Hz L1 rate	<3% dead time at 30 kHz L1 rate

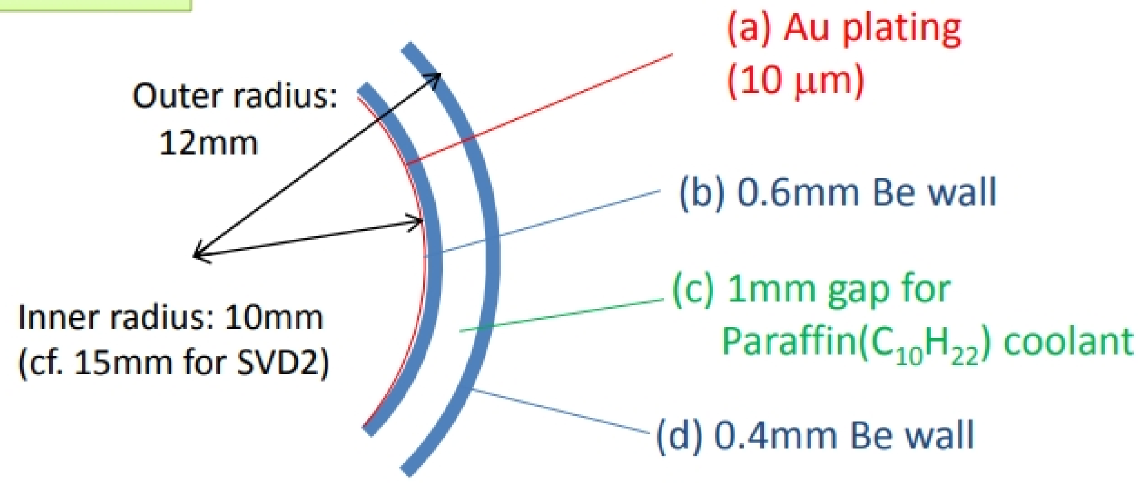
BEAST detectors in phase II

FANGS	Silicon pixel sensor : x-ray energy spectrum for SR
CLAWS	Scintillators w/ SiPMTs: Beam injection noise
PLUME	Two-side silicon pixel sensors: hit rate measurement in radially
Micro-TPC	Fast neutron from EM shower
He-3 tube	Thermal neutron
Scintillators +PIN diode	BG measurement around the final focus magnets
Diamond sensor	BG dose measurement @IP Aborting beam to protect VXD

Integrated dose : film dosimeters

Beam pipe parameters

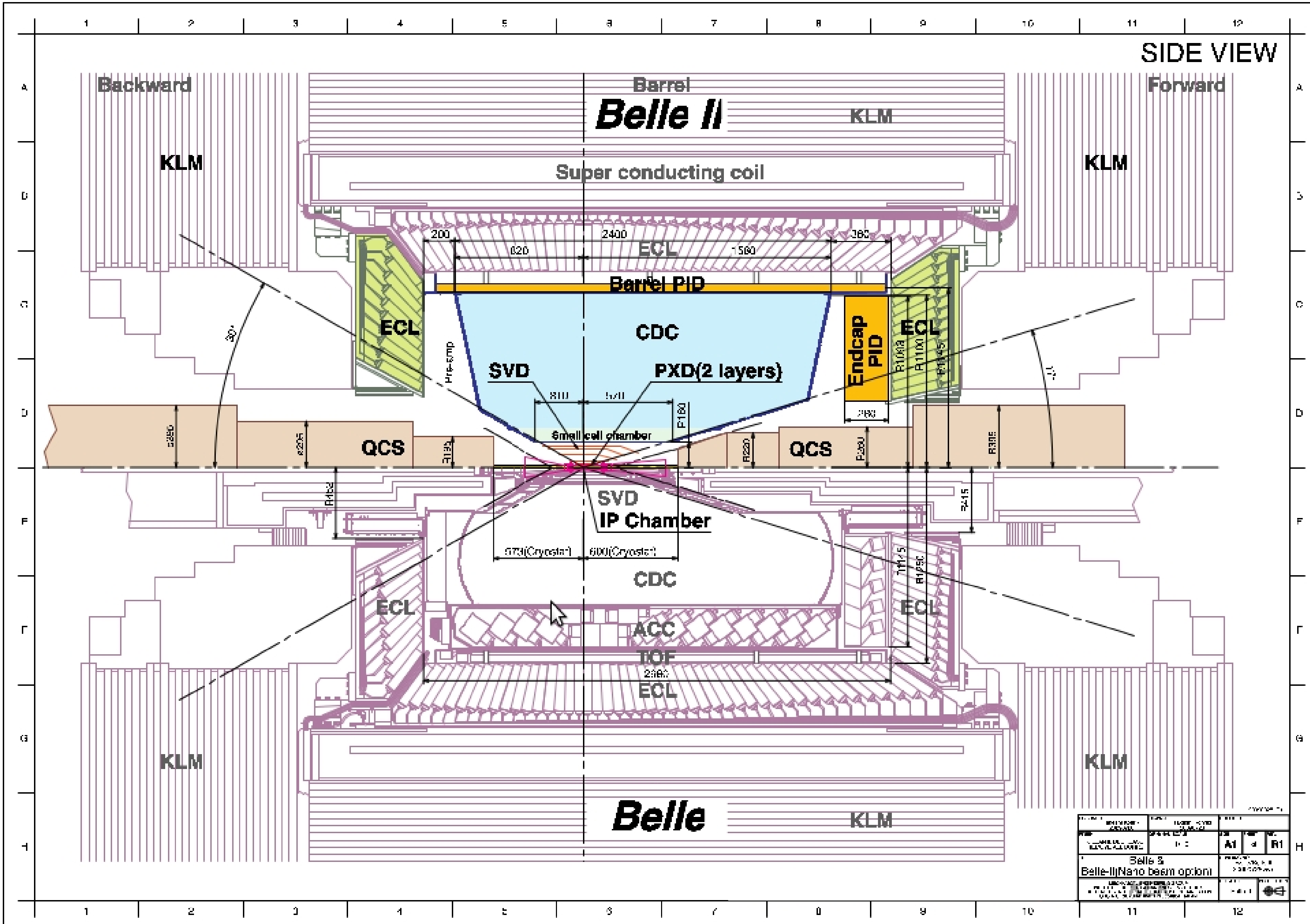
Be center part



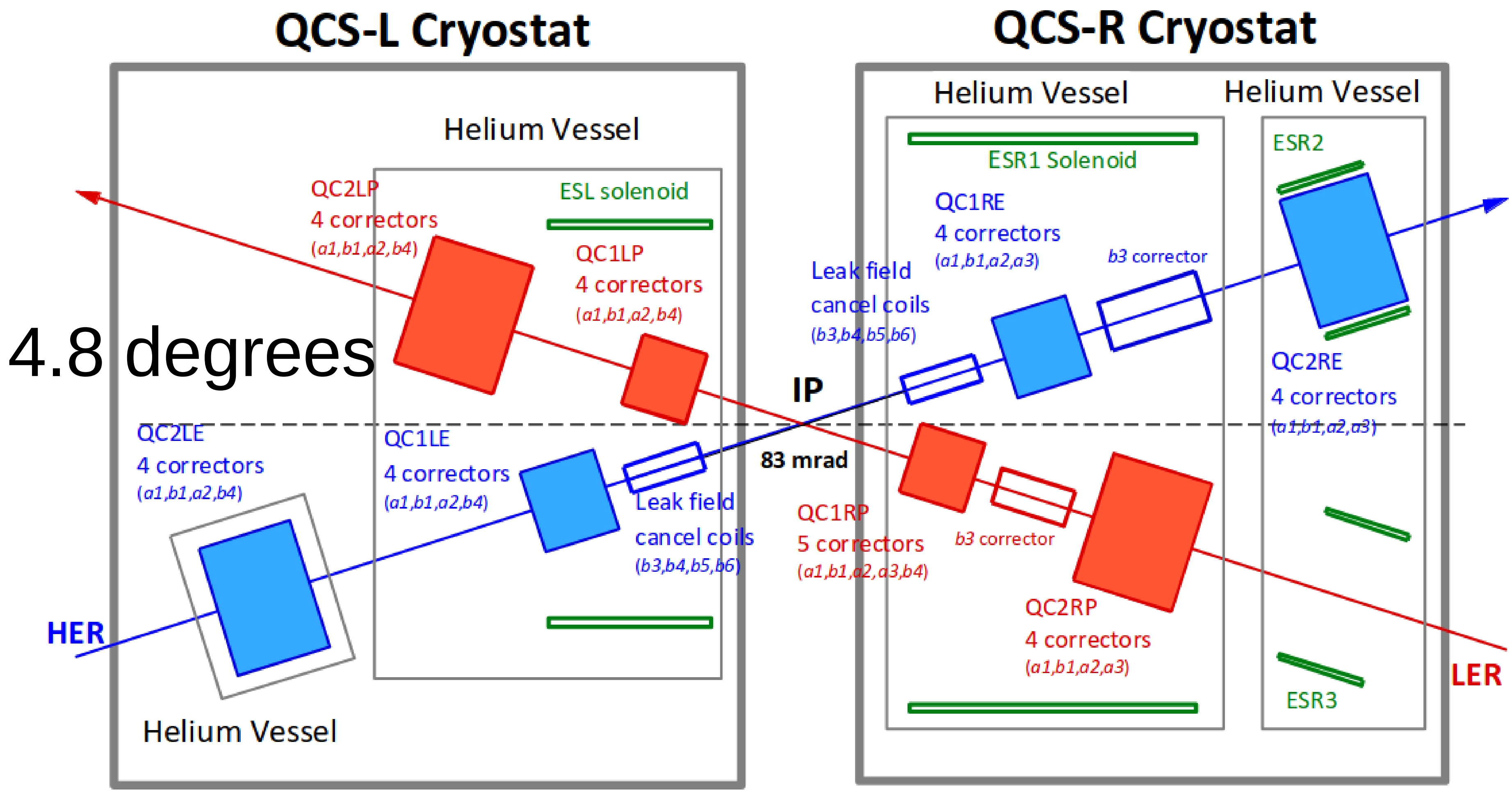
Ta crotch part

Inner radius: 10mm
Ta thickness: 4mm
Au plating on inner surface
Dig drains on outer surface to put water cooling pipes
Saw tooth structure to prevent reflected SR lights to hit Be part

H.Nakayama(KEK) XIV SuperB General Meeting (28 Sep. 2010)


SIDE VIEW
Backward
Barrel
Forward
Belle II
KLM
KLM
KLM
Super conducting coil
ECL
Barrel PID
ECL
CDC
ECL
Endcap PID
SVD
PXD(2 layers)
Small cell chamber
QCS
QCS
SVD
IP Chamber
CDC
ECL
ECL
ACC
TOF
ECL
KLM
KLM
Belle
KLM

Configuration of IR magnets

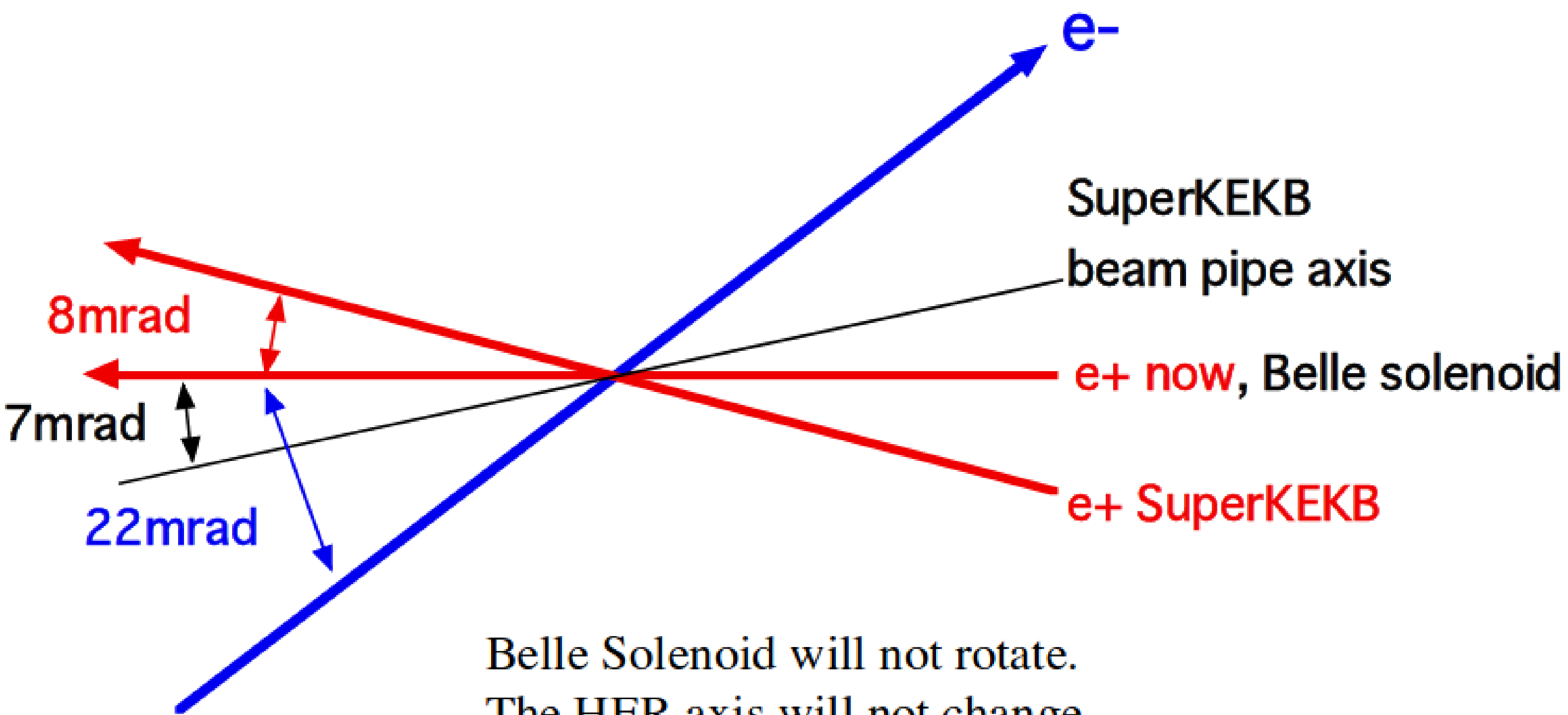


25 SC magnets in QCSL

4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
16 SC correctors: a1, b1, a2, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
1 compensation solenoid

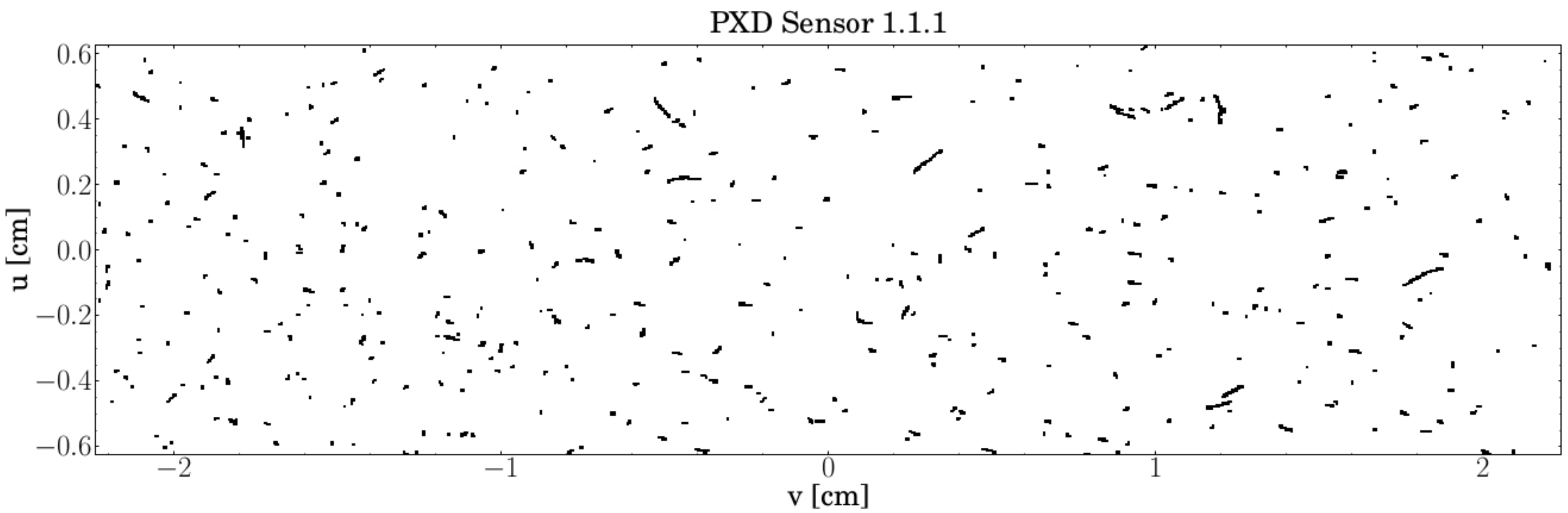
30 SC magnets in QCSR

4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
19 SC correctors: a1, b1, a2, a3, b3, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
3 compensation solenoid



Belle Solenoid will not rotate.
The HER axis will not change.
The LER axis will rotate by 8mrad.
The beam pipe (and SVD) have a finite angle of 7mrad with respect to Belle Solenoid.
QCS magnets will be set parallel to Belle Solenoid.

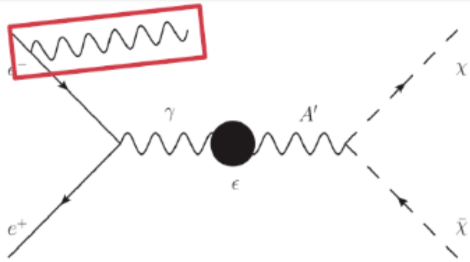
2–photon background



for 1 PXD ladder, for only 1 readout frame

Event generator **BDK**: P. H. Daverfeldt, F. A. Berends and R. Kleiss, Comp. Phys. Comm. 40(1986)285

Invisible dark photon: experimental signature



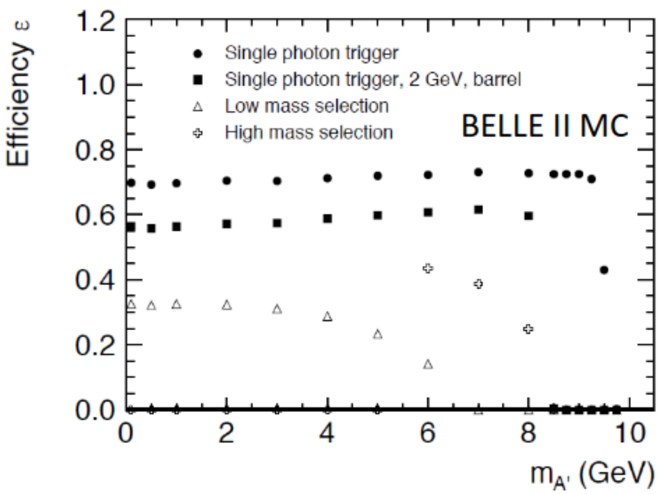
Only **one photon** in the detector.

Needs a **single photon trigger**

(*not available in Belle, ≈ 10% of data in BaBar*)

$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$

→ Bump in recoil mass or photon energy

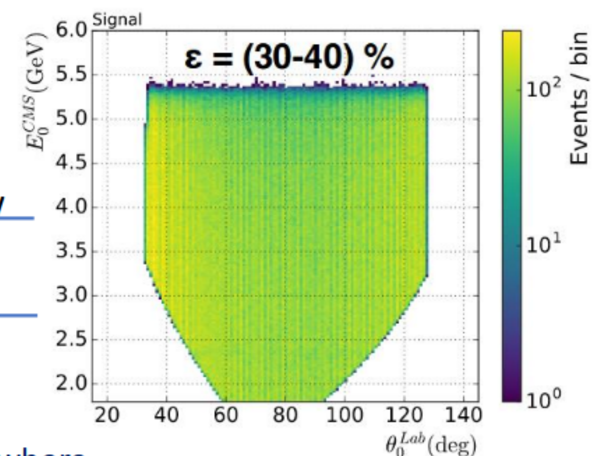


Limited mainly by acceptance

Backgrounds

$e^+e^- \rightarrow e^+e^-\gamma(\gamma)$, $e^+e^- \rightarrow \gamma\gamma(\gamma)$

Trigger logic	L1 rate at full luminosity
E > 1 GeV + 2nd cluster E < 300 MeV	4 kHz (barrel) 7 kHz (endcaps)
E > 2 GeV + Bhabba & γγ vetoes	5 kHz (barrel)



Probably not sustainable in deep Phase 3, where some prescaling or threshold adjustment will be needed

E. Graziani – Dark Sector Searches with Belle II – SUSY2018 10

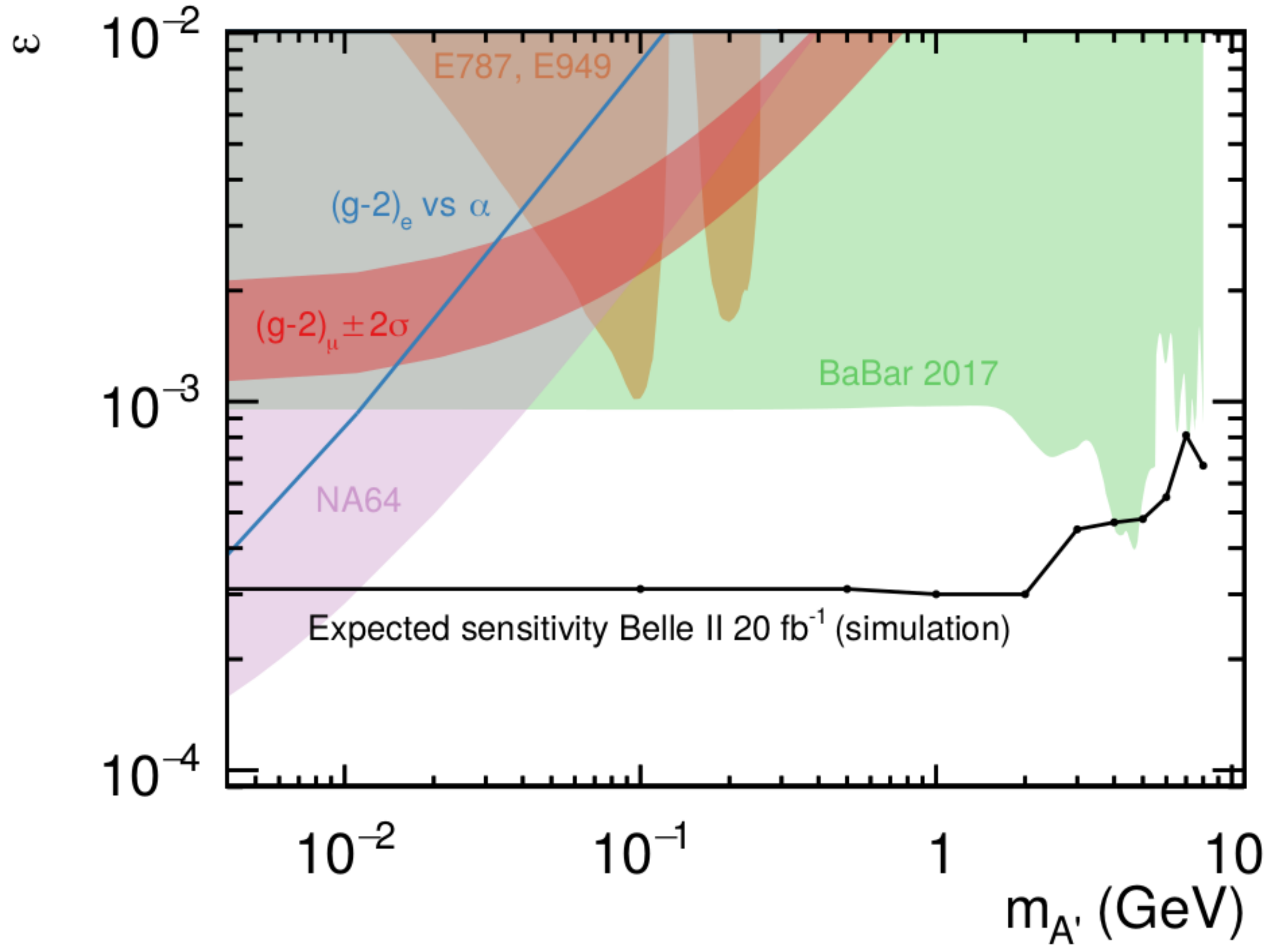
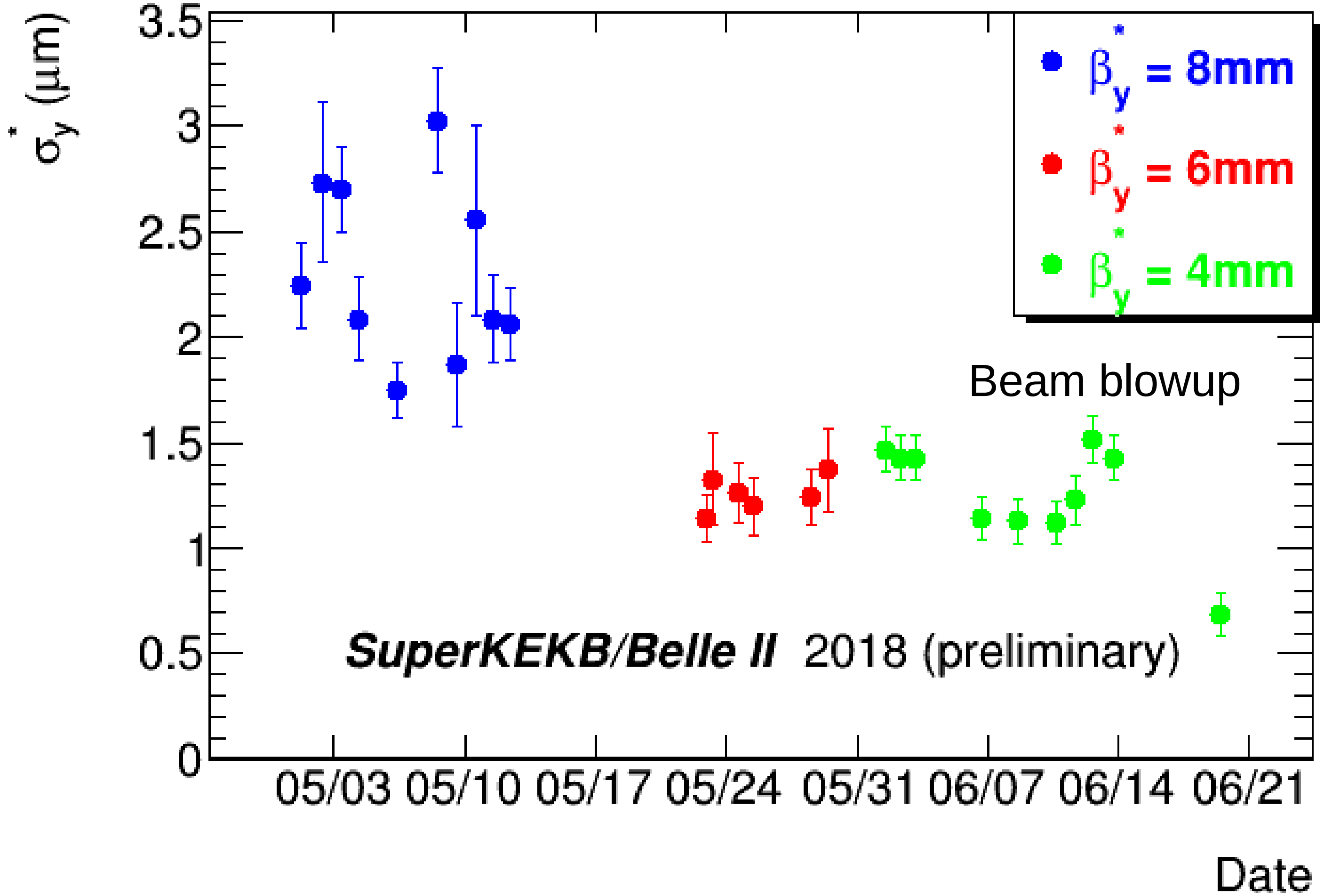


Fig. 209: Projected upper limits on ε for the process $e^+e^- \to \gamma A'$, $A' \to$ invisible, for a 20 fb^{-1} Belle II data set (solid black curve).

How do we measure the vertical height of nanobeams ?
→ Width of luminosity scans with diamond detectors



At Phase 2 peak luminosity the vertical spot is ~700 nm high. There is still beam-beam blowup at high currents. At low currents, the vertical spot size is 330 nm high (the final goal is O(50nm) with full capability of the QCS system).

Number of $c\bar{c}$ pairs
(ideal, assume duty factor 100% and ε=100%)

- Belle (II) / BaBar
  $\sigma(e^+e^- \to c\bar{c}X) \simeq 1.2$ nb ($\sqrt{s} \simeq 10.6$ GeV)

Belle I	1–2 fb^{-1}/day	→ 4.4–8.8	x 10^8 $c\bar{c}$ per year
Belle II	40 fb^{-1}/day	→ 17.5	x 10^9 $c\bar{c}$ per year

- BESIII
  Example: on J/ψ resonance, $\sigma(e^+e^- \to J/\psi) = 2450$ nb
  BESII, Phys. Lett. B355(1995)374

  $\mathcal{L} = 6.5 \times 10^{32}\ cm^{-2}\ s^{-1}$

  → 50 x 10^9 per year*

- PANDA
  Example: on J/ψ resonance, $\sigma(p\bar{p} \to J/\psi) = 5250$ nb
  from detailed balance (M. Galuska, S.L. et al., arXiv:1311.7597)

  HESR high resolution $\mathcal{L} = 2 \times 10^{31}\ cm^{-2}\ s^{-1}$ → 3.3 x 10^9 per year*

  HESR high luminosity $\mathcal{L} = 2 \times 10^{32}\ cm^{-2}\ s^{-1}$ → 33 x 10^9 per year*

*(if all year on-resonance)

Number of X(3872)

- Consider only $[J/\psi\pi+\pi-]$ decay mode
- PANDA, assume $\sigma(p\bar{p} \to X(3872))$=50 nb

  statistics ~130 (1300) per day on peak for $\mathcal{L}$=2 x 10^{31} (10^{32}) cm^{-2} s^{-1}
  efficiency ~50% (4 charged, exclusive)
  high boost β_{cms}=0.89 (fixed target) $\to$ $\beta\gamma$=1.95
  mass resolution ~50-100 MeV (unfitted)
- Belle II
  statistics ≃1500 by 2021
  effiency 15-20%
  small boost $\beta\gamma$=0.43 (Belle), $\beta\gamma$=0.28 (Belle II)
  mass resolution ~10-20 MeV (unfitted)
- BESIII
  $e+e- \to Y(4260) \to \gamma X(3872)$ BESIII, Phys. Rev. Lett. 112(2014)092001
  ≃1200 Y(4260) per day (σ≃60 pb, integrated luminosity ≃20 pb^{-1}/day)
  but branching fraction small, only ≃0.5% (≃20 events in ~4 weeks)
  rare

The cross sections of the e^+e^- annihilation into hadrons are described in terms of the electromagnetic form factors (FF). In case of production of proton-antiproton pair

$$e^+e^- \to p\overline{p} \tag{1}$$

the cross section depends on two such functions, electric (G_E) and magnetic (G_M) FFs:

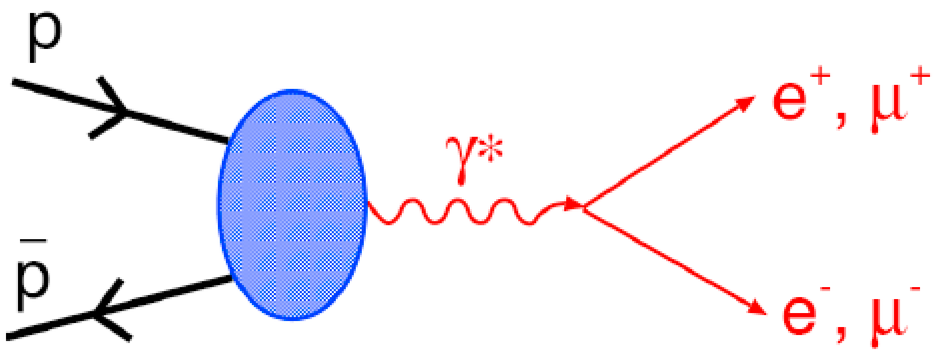
$$\sigma_{p\overline{p}}(s) = \frac{4\pi\alpha^2\beta C}{3s}\left[|G_M(s)|^2 + \frac{1}{2\tau}|G_E(s)|^2\right] \tag{2}$$

where s is the e^+e^- center-of-mass (c.m.) energy squared, $\beta = \sqrt{1-4m_B^2/s}$, C is the Coulomb interaction factor [$C = y/(1-e^{-y})$ with $y = \pi\alpha(1+\beta^2)/\beta$ for protons, and $C = 1$ for neutrons], $\tau = s/4m_B^2$.
From the measurement of the total cross section the linear combination of squared form factors

$$F(s)^2 = \frac{2\tau|G_M(s)|^2 + |G_E(s)|^2}{2\tau+1} \tag{3}$$

can be determined. The function $F(s)$ is called the effective form factor. It is this function that is measured in most of experiments.

Transverse Spin Physics

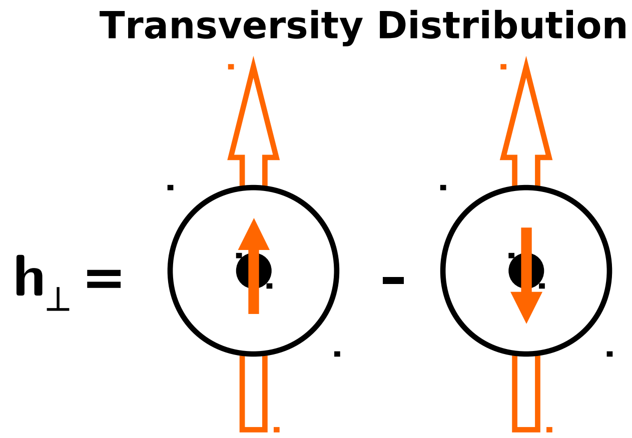


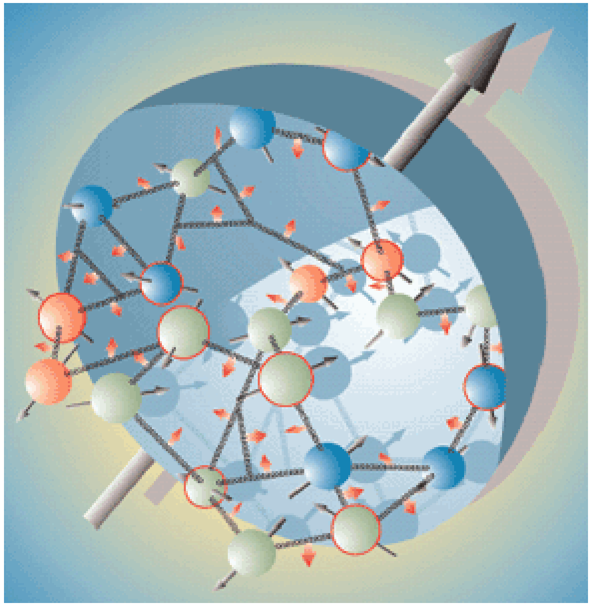
Transversity

- Spin alignment of quarks
  with respect to the nucleon spin

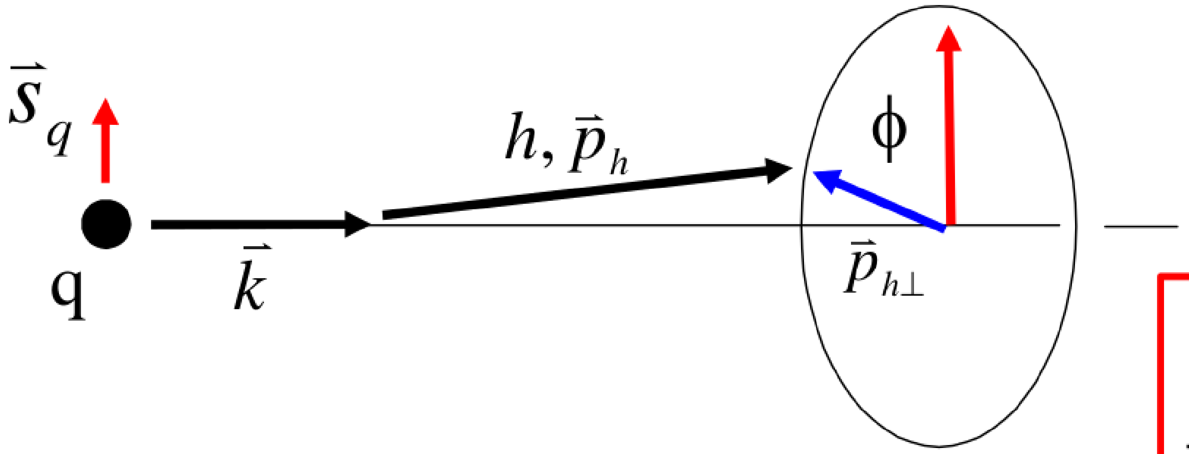
- Experimental challenge:
  - simultaneous flip
    of struck quark and target
    $\rightarrow$ chiral-odd
  - but all hard QCD interactions
    conserve chirality
    $\rightarrow$ chiral-even

- Integral over $h_\perp =$
  nucleon tensor charge
  (deformation of quark distribution
  in a polarized nucleon)





J.C. Collins, Nucl. Phys. B396(1993)161



$\vec{k}$	: quark momentum
$\vec{s}_q$	: quark spin
$\vec{p}_h$	: hadron momentum
$\vec{p}_{h\perp}$	: transverse hadron momentum
$z_h = E_h / E_q$	
$= 2\,E_h / \sqrt{s}$	: relative hadron momentum

Collins Effect:
Fragmentation of a transversely polarized quark *q* into spin-less hadron *h*.

Azimuthal dependence:

$$\propto \left(\vec{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q$$

$$\propto \sin\phi$$

Number density for finding hadron h from a transversely polarized quark, q:

$$D_{q\uparrow}^{h}(z, \vec{p}_{h\perp}) = \underbrace{D_1^{q,h}(z)}_{\text{unpolarized FF}} + \underbrace{H_1^{\perp q,h}(z, p_{h\perp}^2)}_{\text{Collins FF}} \frac{(\hat{k} \times \vec{p}_{h\perp}) \cdot \vec{s}_q}{z M_h}$$

vector product induces sin(φ) modulation

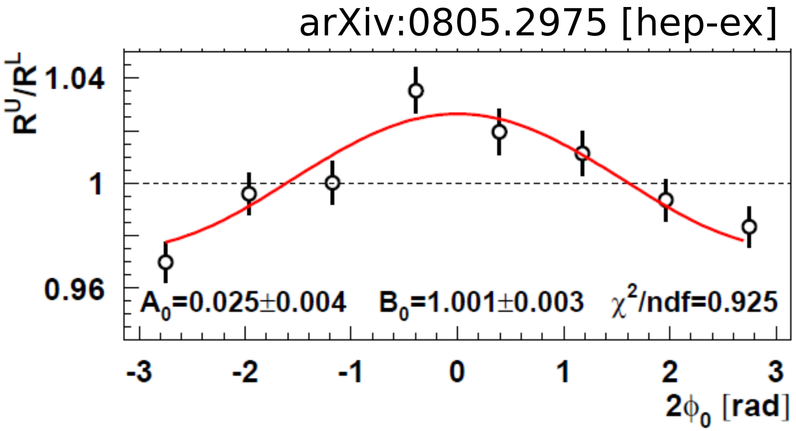
φ = angle between p_T and plane normal to quark spin

Collins- and Asymmetries
in SIDIS and pp are of the form

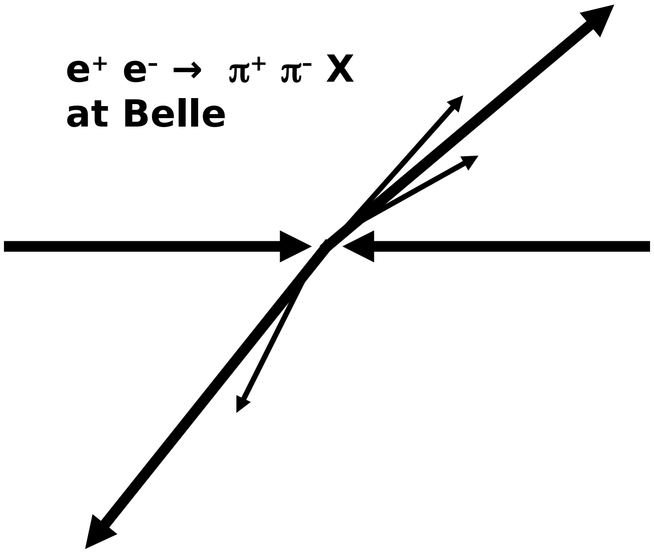
~ Transversity (x) x CFF(z)

Collins- Asymmetries
in e^+e^- are of the form

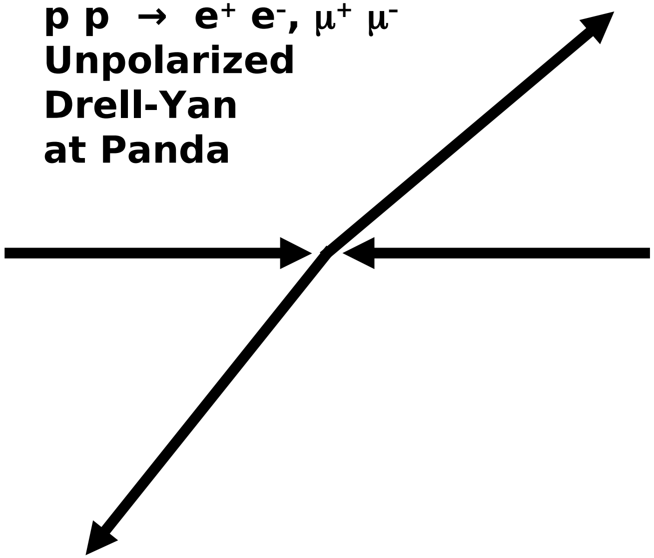
~ $CFF(z_1)$ x $CFF(z_2)$



$e^+ e^- \rightarrow \pi^+ \pi^- X$
at Belle



$p \bar{p} \rightarrow e^+ e^-, \mu^+ \mu^-$
Unpolarized
Drell-Yan
at Panda

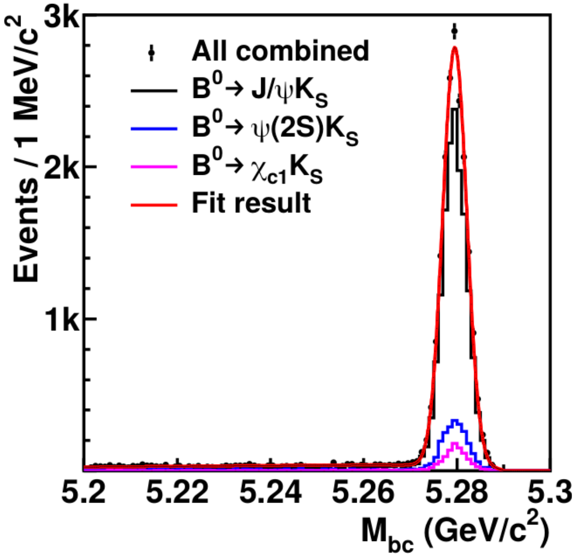


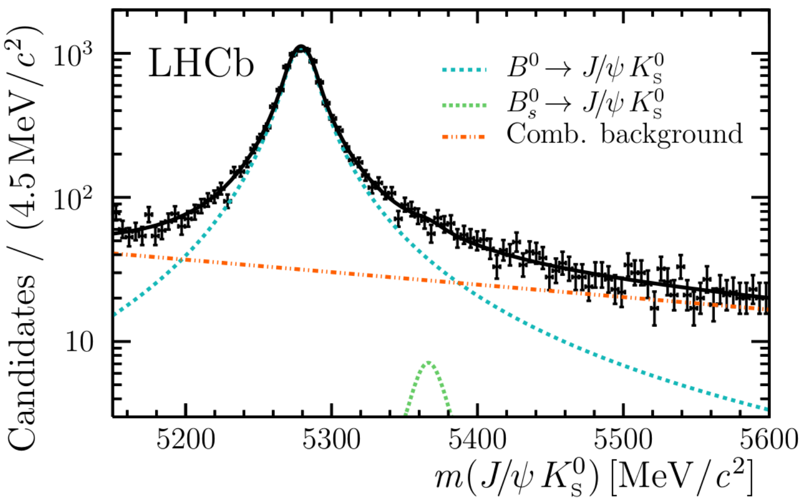
Large Asymmetries observed (~ 18%)

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3} \times \left(1 + \lambda \cos^2\theta + \mu \sin^2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi\right) \quad (1.2)$$

ν ~ Transversity

B meson mass reconstruction: example $B \to J/\Psi\ K_s$





Belle, 711/fb
PRL 108 (2012) 171802
arXiv:1201.4643 [hep-ex]

FWHM ~2–3 MeV

LHCb, 3/fb
JHEP 11 (2017) 170
arXiv:1709.03944 [hep-ex]

FWHM ~20–30 MeV

Note: resolutions not mentioned
in the papers (not part of systematics)

$$m_B = \sqrt{E_B^2 - \boldsymbol{p}_B^2}$$

At B factories, both beam energies are known to precision **≤0.1 MeV.**

„Energy substituted mass" in CLEO
or „beam constrained mass" in Belle:

Boosted (masses are already assigned)

$$m_{\mathrm{ES}}^{\mathrm{CLEO}} = m_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^{\star 2} - \boldsymbol{p}_B^{\star 2}}$$

„Energy substituted mass" in BaBar:

Not boosted (mass independent)

$$m_{\mathrm{ES}} = \sqrt{(s/2 + \boldsymbol{p}_B \boldsymbol{p}_0)^2 / E_0^2 - \boldsymbol{p}_B^2}. \qquad (7.1.8)$$

where $(E_0, \boldsymbol{p}_0)$ is the four-momentum of the CM system in the laboratory.

Luminosity increase

1. beam current

1.64/1.19 A $\rightarrow$ 3.6/2.6 A for e+ (e–) beam

$\rightarrow$ factor 2 increase in luminosity

2. beta function

β_y*

5.9 mm $\rightarrow$ 0.27 mm

$\sigma_y \rightarrow$ 59 nm

''nanobeam''

$\rightarrow$ factor 20 increase in luminosity

$\rightarrow$ total factor 40 increase in luminosity

$$\sigma_y(z) \propto \sqrt{\beta_y(z)}$$

$$\beta_y(z) = \beta_y^*(1 + \frac{(z - Z_0)^2}{\beta_y^{*2}})$$

Z_0 is position of minimum beta function („waiste“)