Belle II status and prospects

JAN STRUBE, FOR THE BELLE II COLLABORATION

Pacific Northwest National Laboratory and University of Oregon

New Probes for Physics Beyond the Standard Model, KITP, Santa Barbara, CA

Legacy of the B Factories

e.g.: "The Physics of the B Factories", EPJC 74, 3026 (2014)

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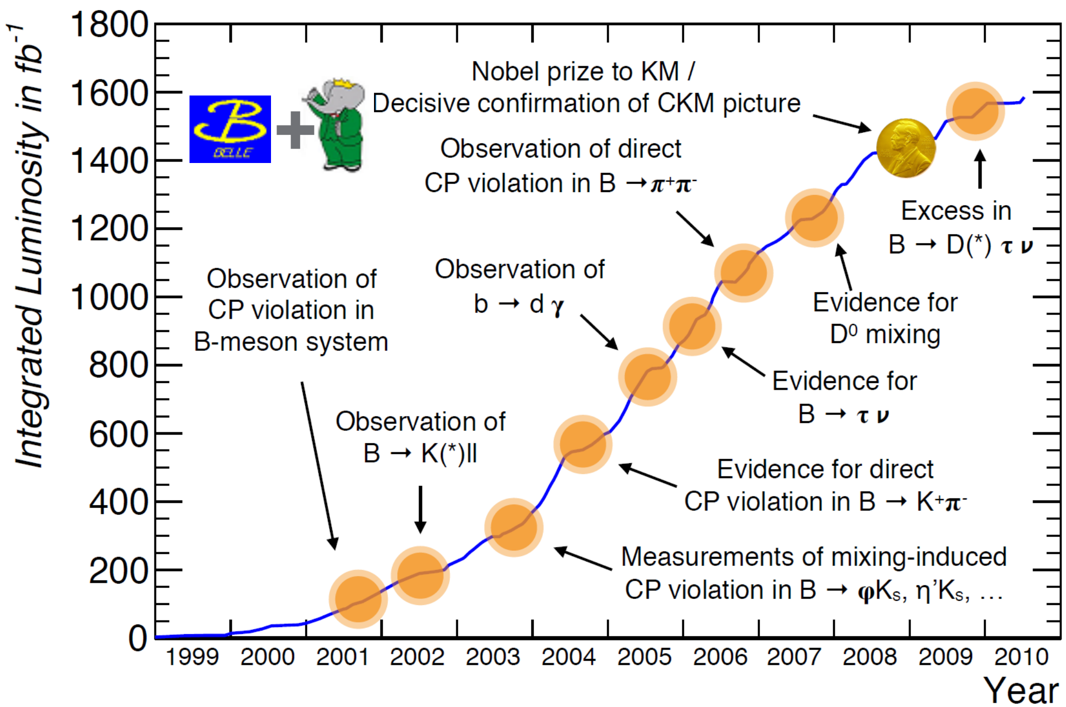
- **Flavor physics**
  - CKM matrix elements / unitarity triangle
  - CPV in B decays
- **Limits on BSM Physics**
  - Rare decays
  - New physics search loops
    $b \to s\gamma$, $b \to sll$
  - Search for LFV τ decays
- **New particles**
  - "XYZ" four-quark states



"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature".

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Makoto Kobayashi

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Toshihide Maskawa

2008

Physics at Belle II

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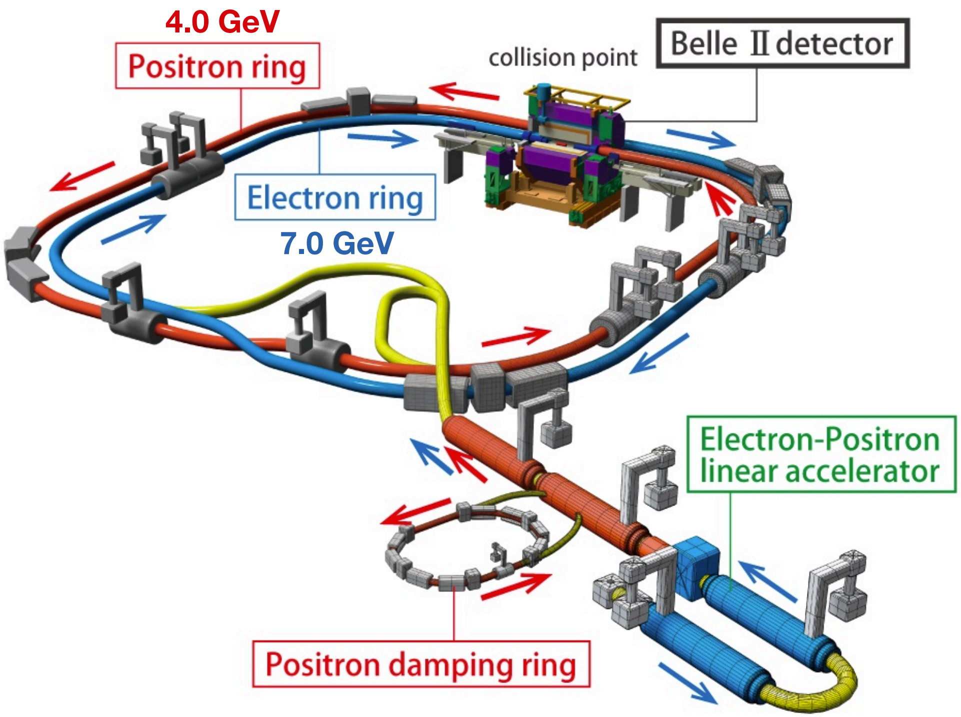
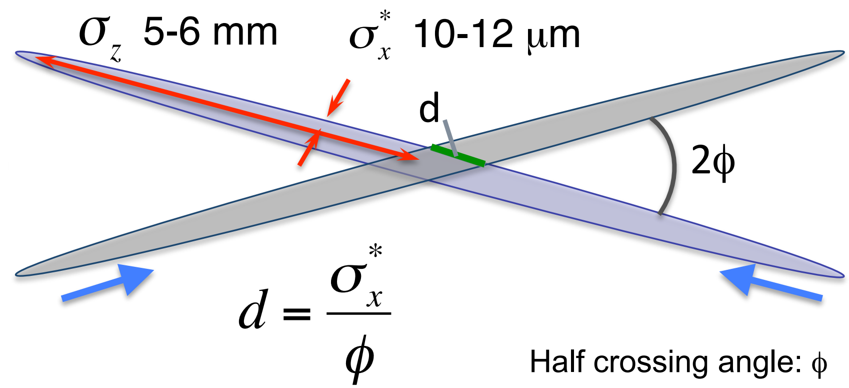
- Motivation: Search for new interactions in rare processes
- Perform a comprehensive suite of precision measurements
  - Phases, CP asymmetries, differential branching ratios, …
- Measurements at an e^+e^- machine
  - Low background, negligible trigger bias, absolute branching ratios
  - Systematics complementary to LHCb

- Detector features:
  - Better hermeticity than BaBar (no projective cracks in the ECL)
  - Better charged particle ID than Belle
  - Dedicated single-photon trigger
  - Improved event reconstruction

The nano-beams of SuperKEKB



Nanobeams at SuperKEKB



Beam energies: 7 GeV / 4 GeV
I = 2.6 A / 3.6 A
Crossing angle: 83 mrad
Target luminosity: 8×10^{35} $cm^{-2}s^{-1}$

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

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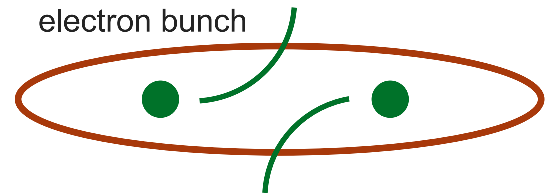
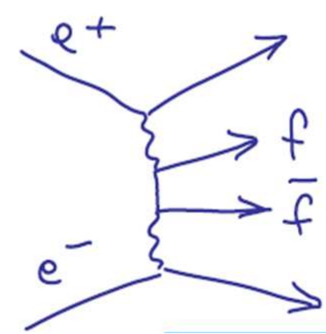
Beam-Induced Background Processes

These processes are irreducible and affect reconstruction performance and detector lifetime

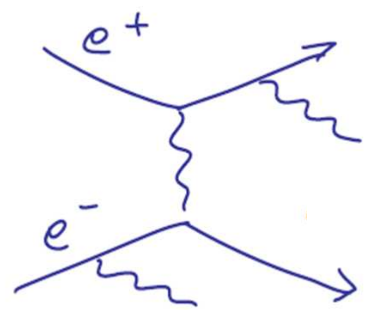
Touschek scattering
- Intra-bunch scattering
- rate $\propto$ (beam size)$^{-1}$, $(E_{beam})^{-3}$
- Most dangerous background at SuperKEKB
- Photons upstream hit nuclei and produce ~10^{11}/cm^2/year neutrons (1 MeV equivalent)



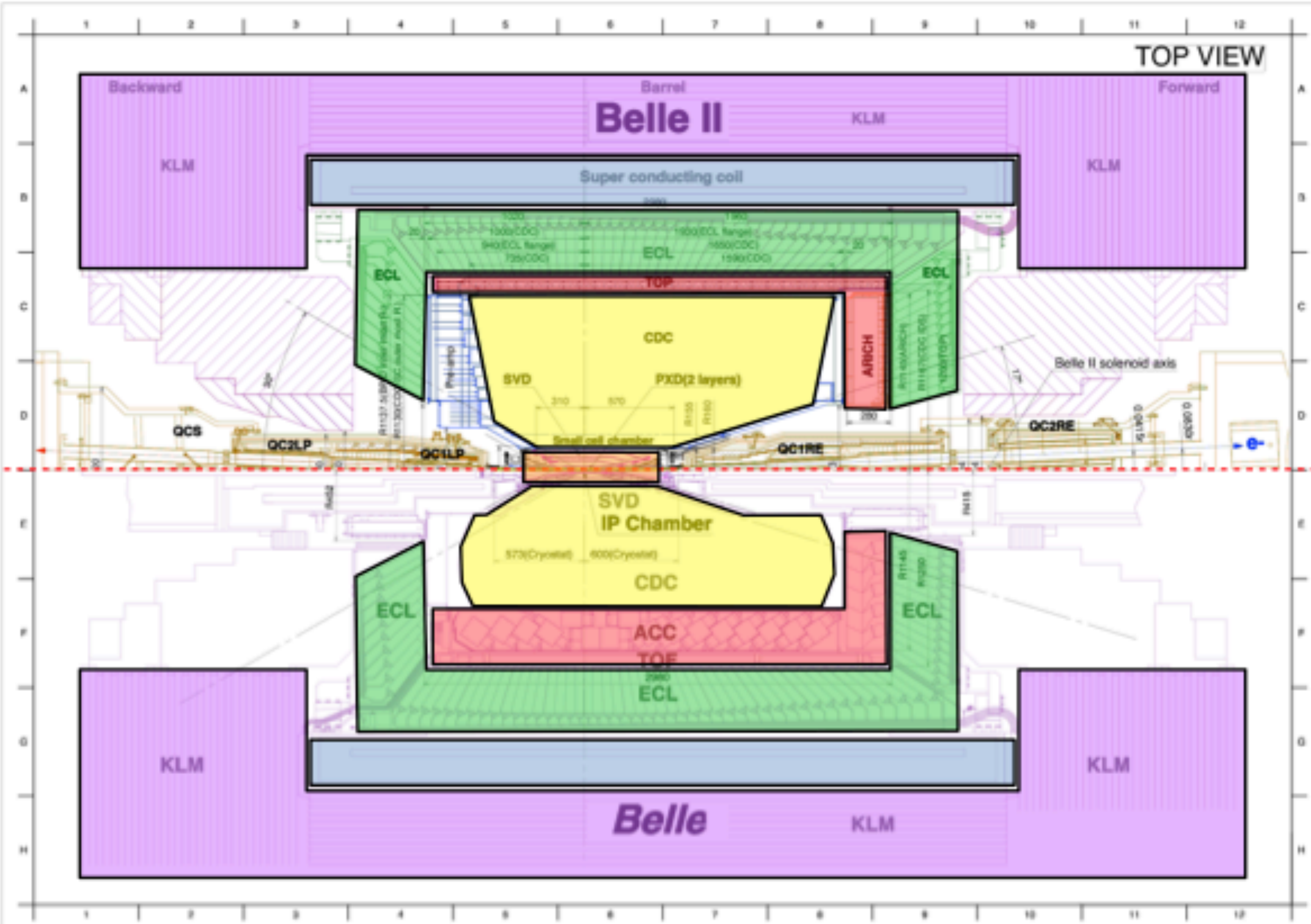
2-photon process
- Generated electron-positron pair might enter the detector
- 0.2% occupancy on PXD



Radiative Bhabha
- Rate $\propto$ Luminosity (KEKB x 40)
- EM showers from outgoing beam
- Neutrons from photon

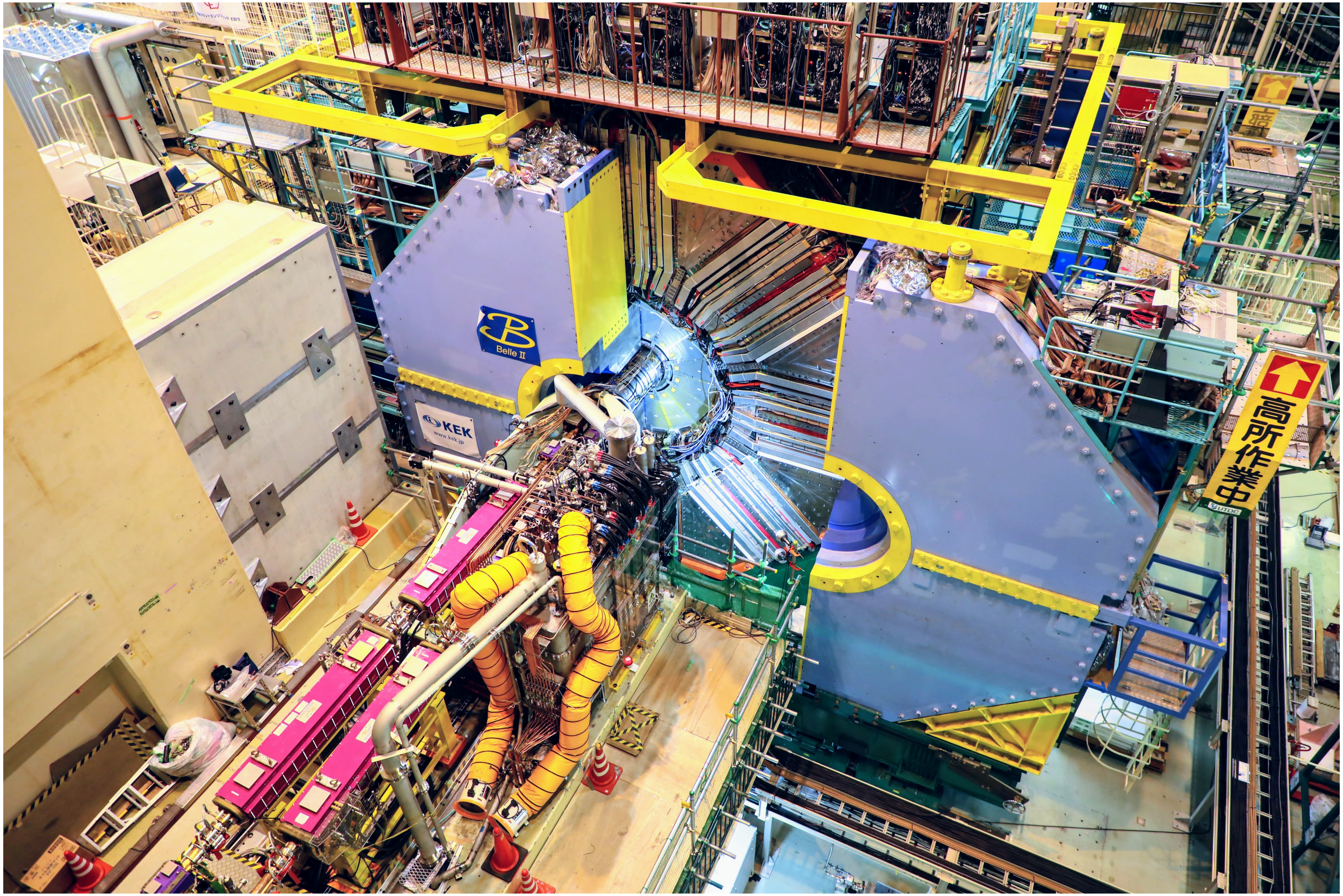


Belle II Detector Upgrade



K_L/Muon System
Magnet Coil
EM Calorimeter
π/K Identification
Drift Chamber
Silicon Tracking

The Belle II detector in the beam line



(Some) Members of the Belle II collaboration

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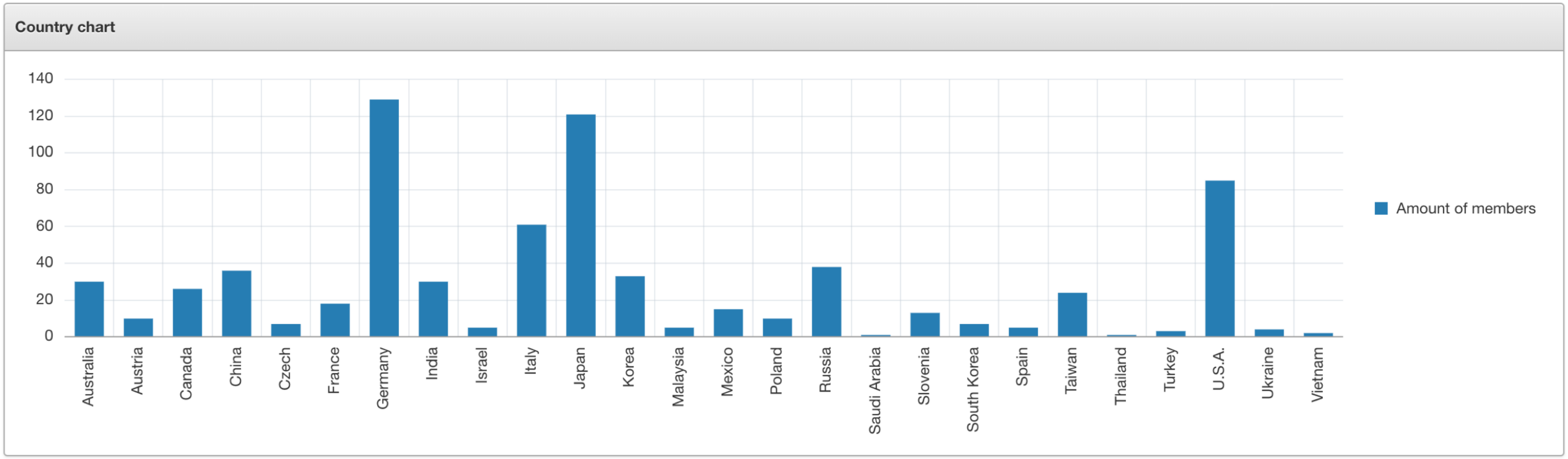
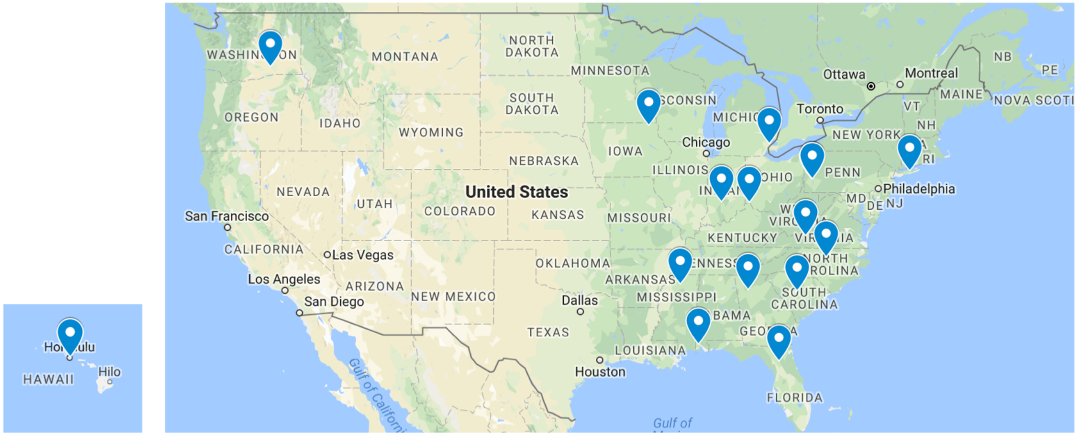
The Belle II collaboration



750+ members from 26 countries, 106 institutions

In the US:
85 members in 16 institutions

Working on:
Distributed Computing
Conditions Database
Particle ID
Readout Electronics
Background / Commissioning



The Belle II detector

SuperKEKB Projected Luminosity

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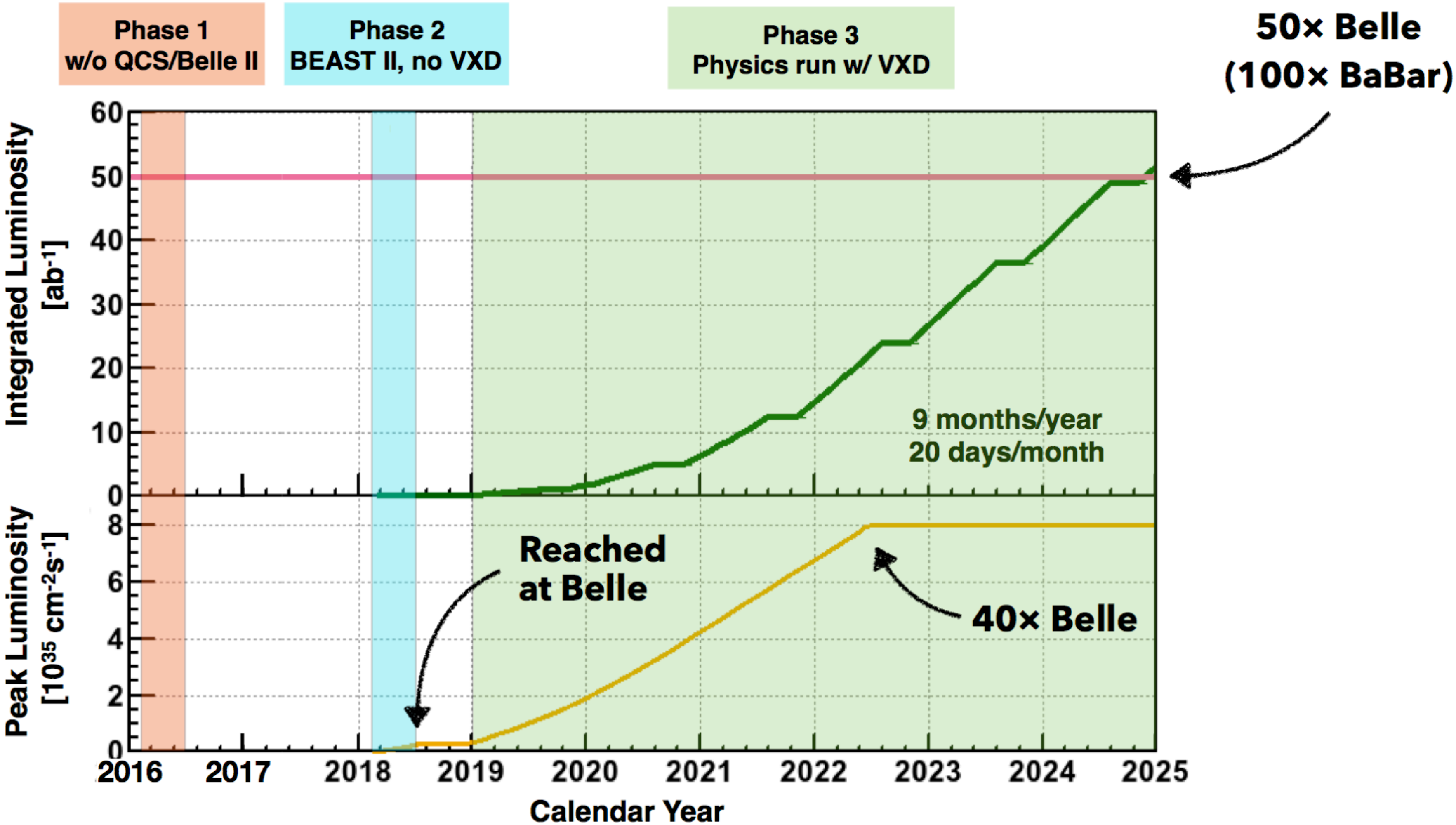

Latest Status

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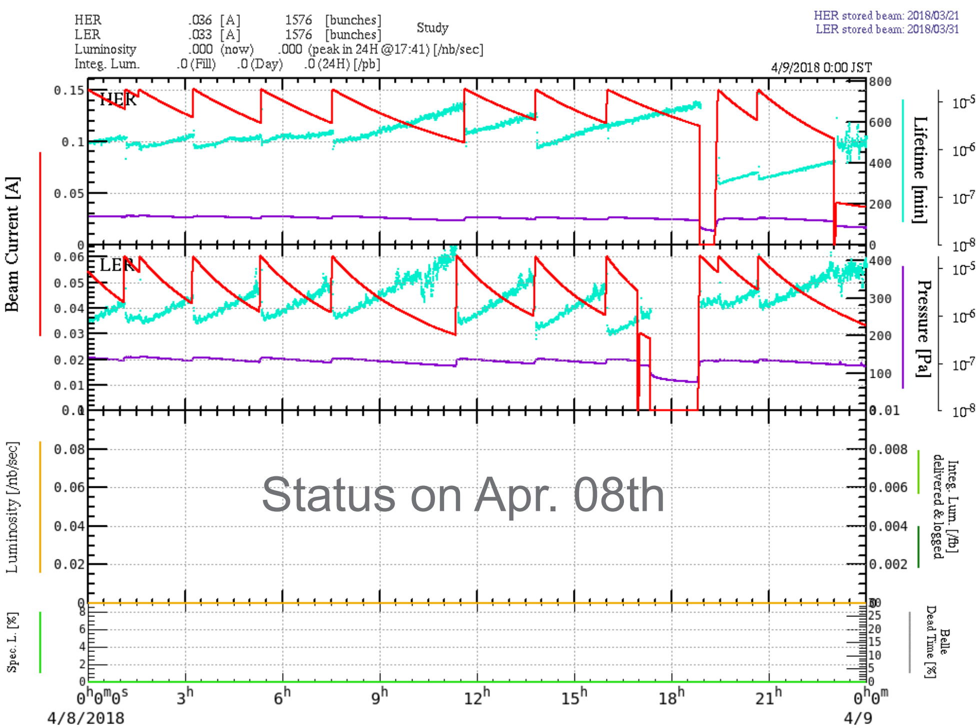
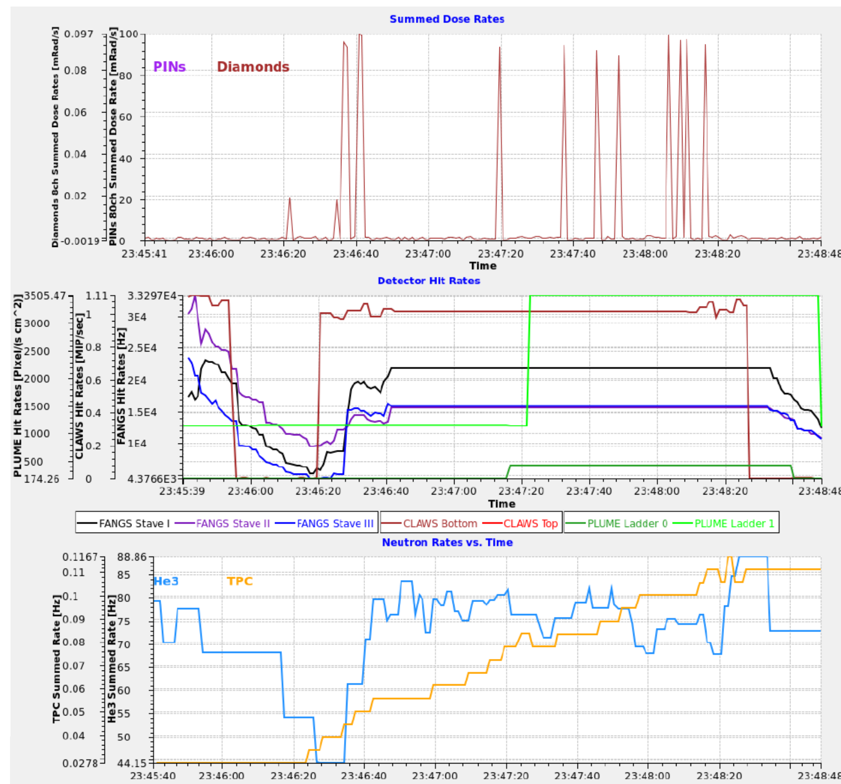
- Beam in High Energy Ring, injecting Low Energy Ring next

SuperKEKB Status



BEAST II Backgrounds

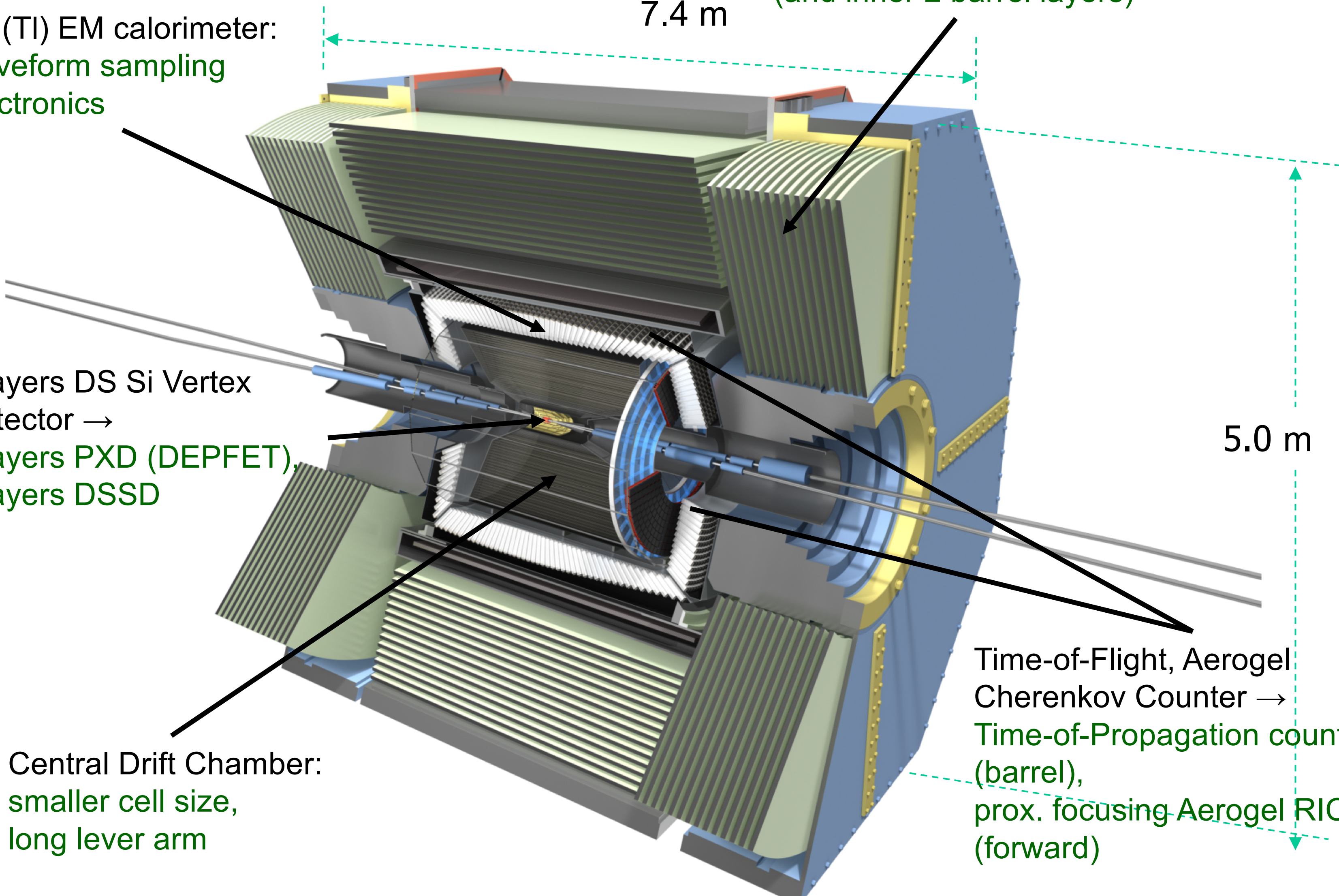


- Close to first collisions!

The Belle II Detector

RPC μ & K_L counter:
scintillator + Si-PM
for end-caps
(and inner 2 barrel layers)

CsI(Tl) EM calorimeter:
waveform sampling
electronics



4 layers DS Si Vertex
Detector →
2 layers PXD (DEPFET),
4 layers DSSD

Time-of-Flight, Aerogel
Cherenkov Counter →
Time-of-Propagation counter
(barrel),
prox. focusing Aerogel RICH
(forward)

Central Drift Chamber:
smaller cell size,
long lever arm

The K^0_L – Muon detector (KLM)

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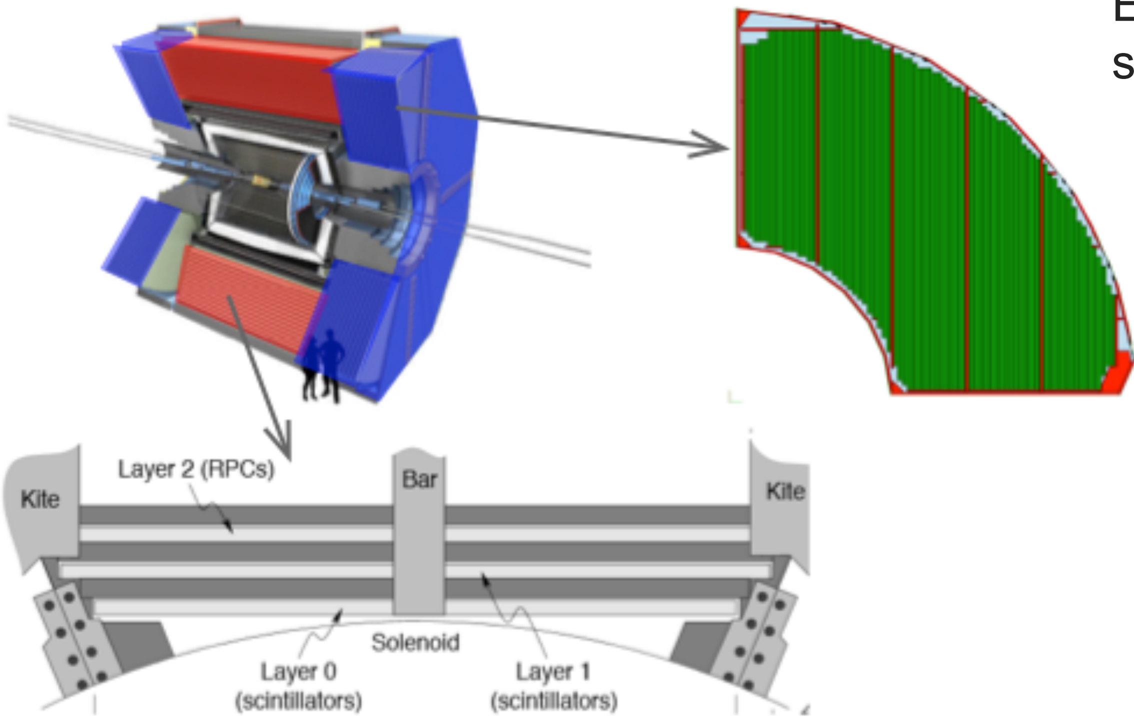
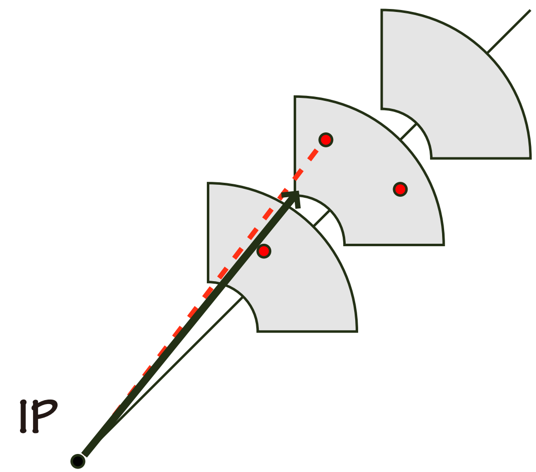


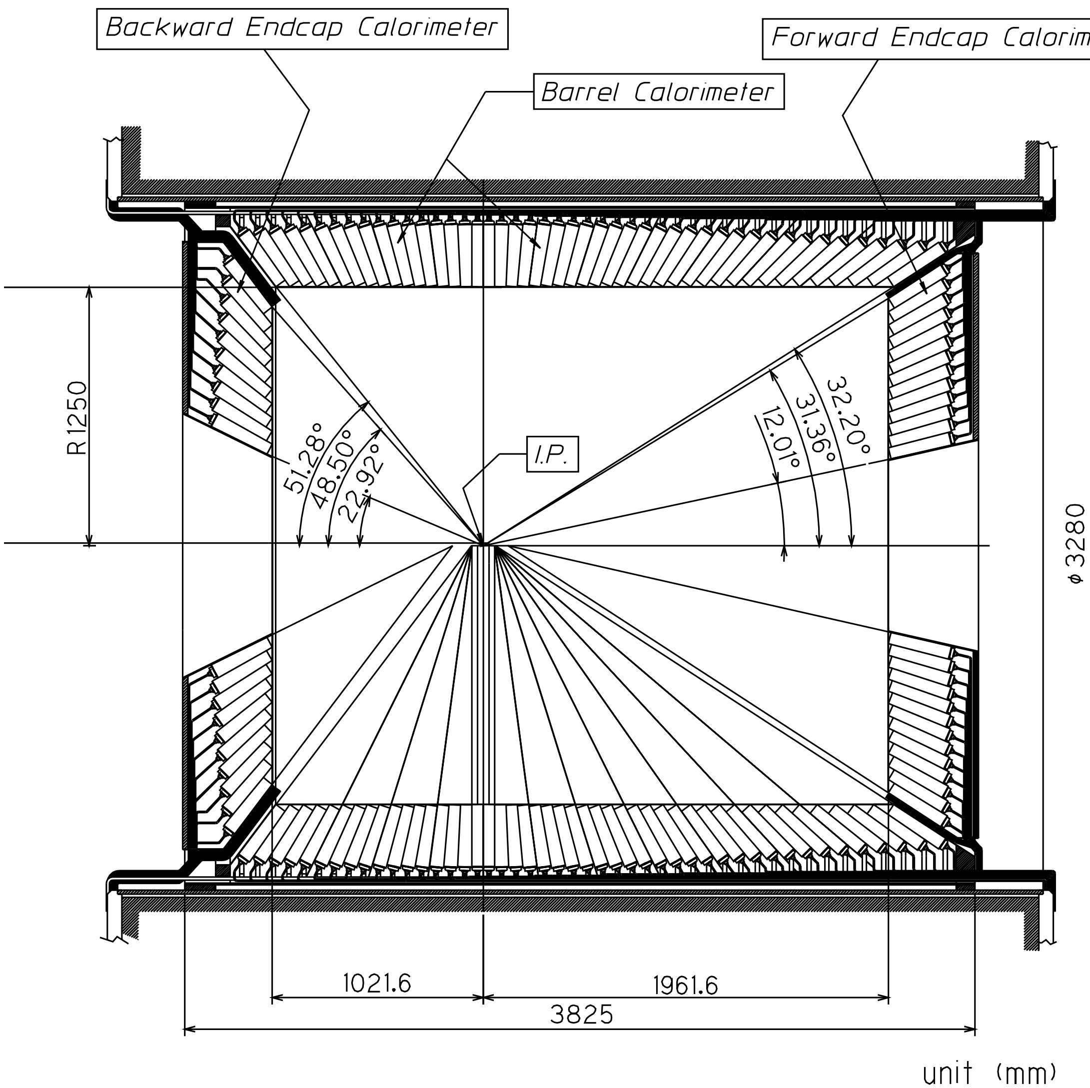
Endcap KLM:
scintillator strips (14 layers)



Barrel KLM:
Inner 2 layers: Scintillator strips
Outer 13 layers: RPC (glass, not bakelite)

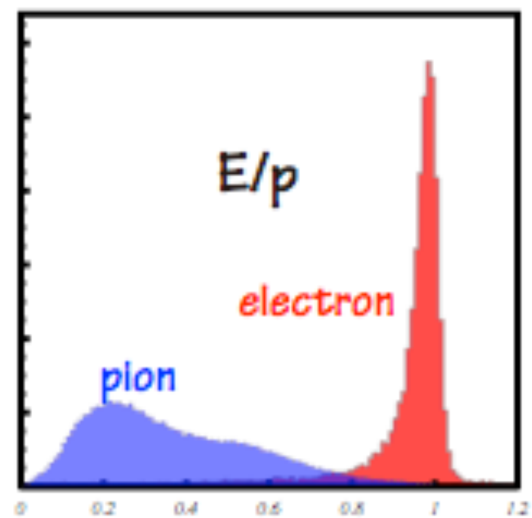
Angular resolution of hit from the IP: better than 10 mrad (4 cm)

The Electromagnetic Calorimeter



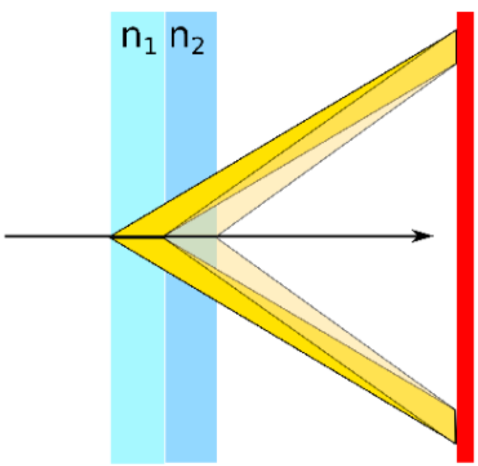
8736 CsI (Tl) crystals, each 6 cm x 6 cm x 30 cm (in total: 16.1 X_0)

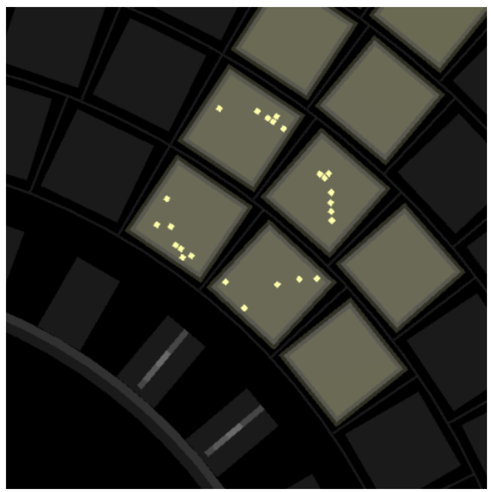
The ratio E/p can be used to distinguish electrons from pions

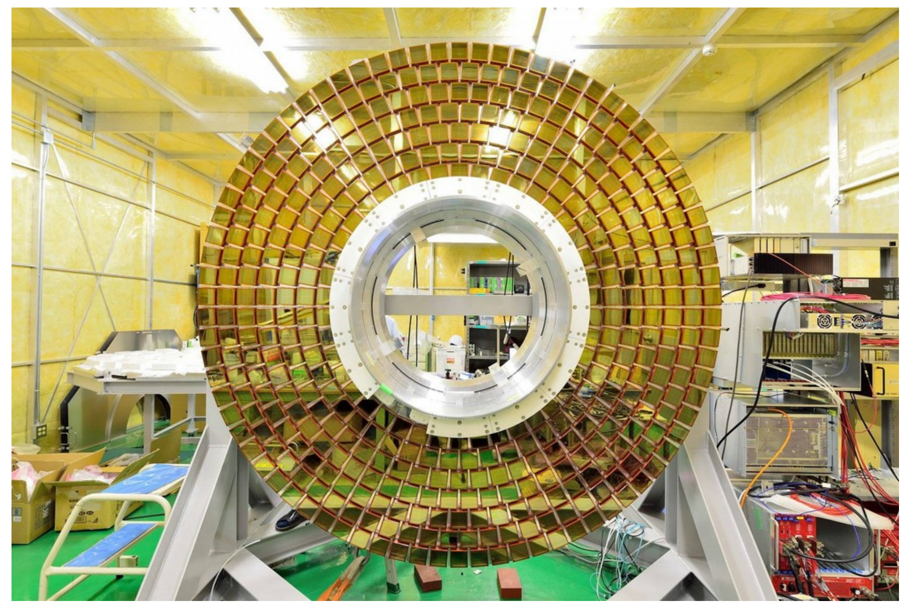


Endcap Particle ID

- Aerogel Ring Imaging Cherenkov Detector
- Two aerogel layers with different refractive indices (1.045/1.055) result in a sharper image
- K/π separation for a wide momentum range (0.7 GeV – 4.0 GeV)

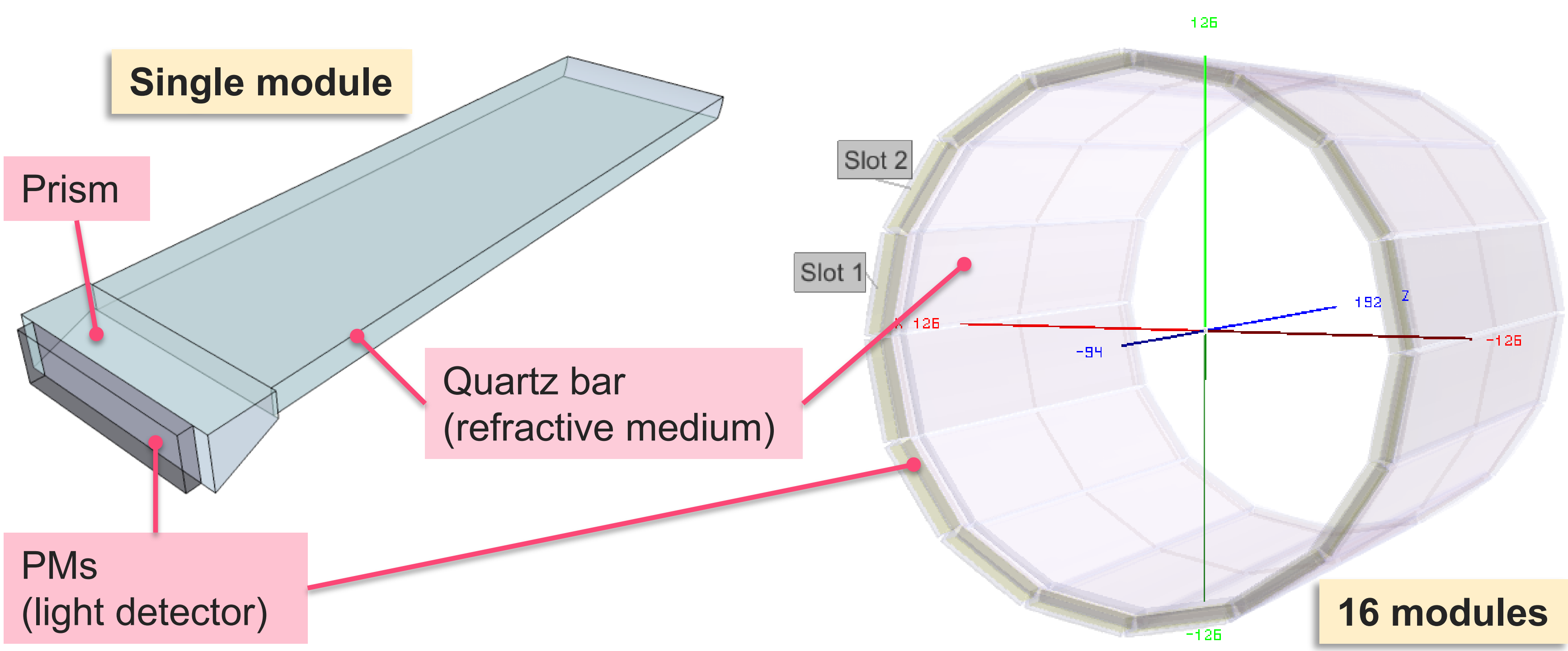




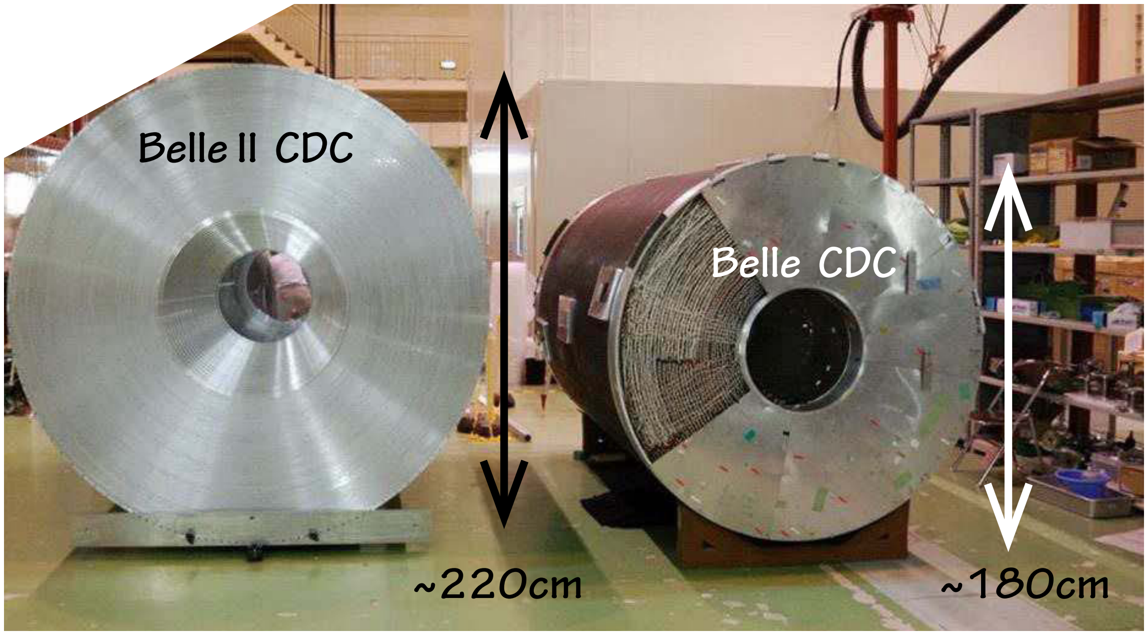


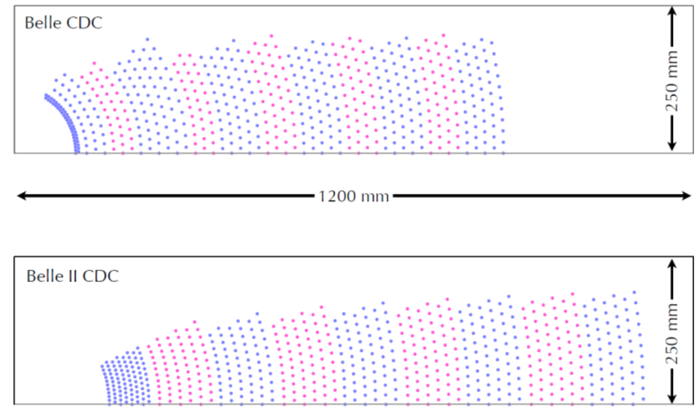
Barrel Particle ID

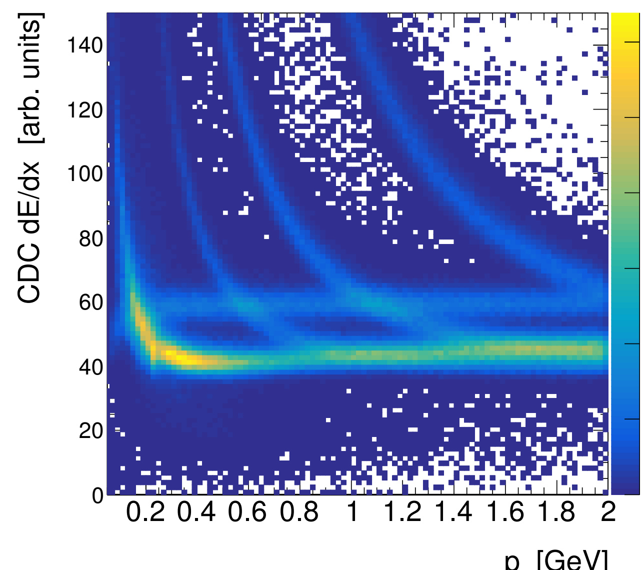
- imaging Time-Of-Propagation (**iTOP**) detector
  - Hexadecagonal prism quartz shell
  - Bank of PMTs on one end, mirror on other
  - Makes an **image** where one of the axes is “time” (of propagation)



Central Tracker upgrade





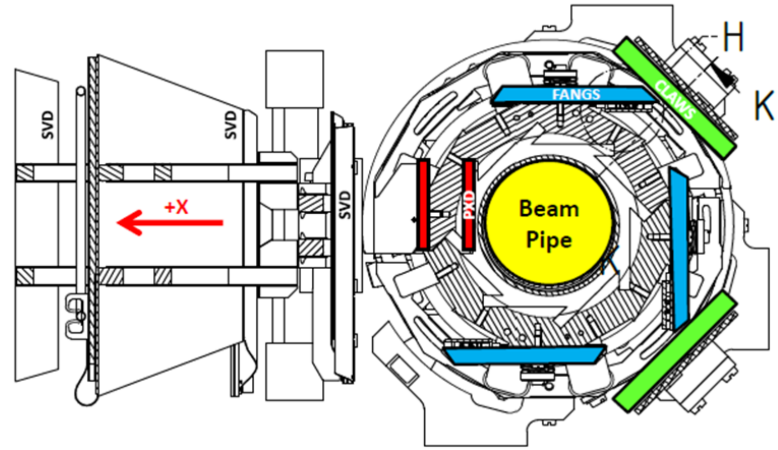


- Increased outer radius, thanks to a compact iTOP detector
  - Better dE/dx measurement (particle ID)
  - Better momentum resolution
- Larger inner radius to avoid high rad regions and to make room for vertex detector
- Smaller cells in inner region to increase radiation tolerance

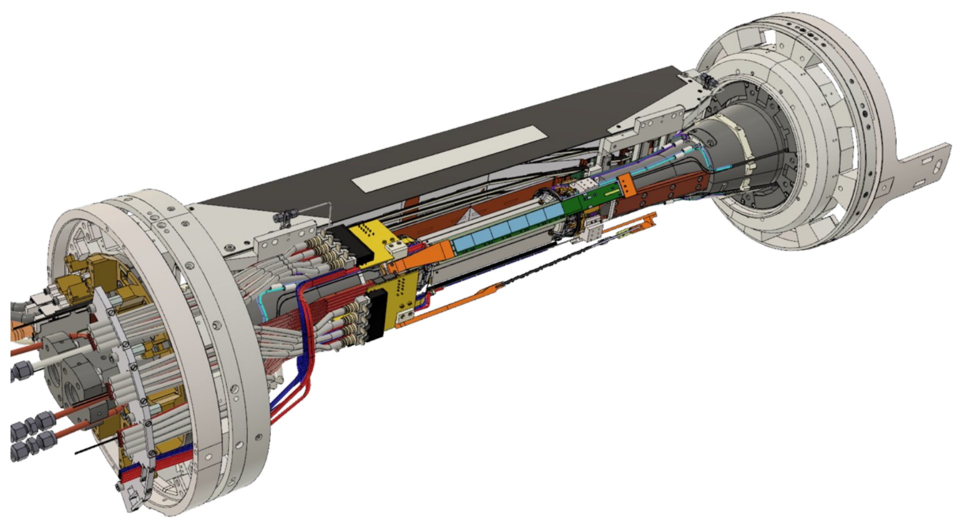
Background monitoring

arXiv:1802.01366 (2018)

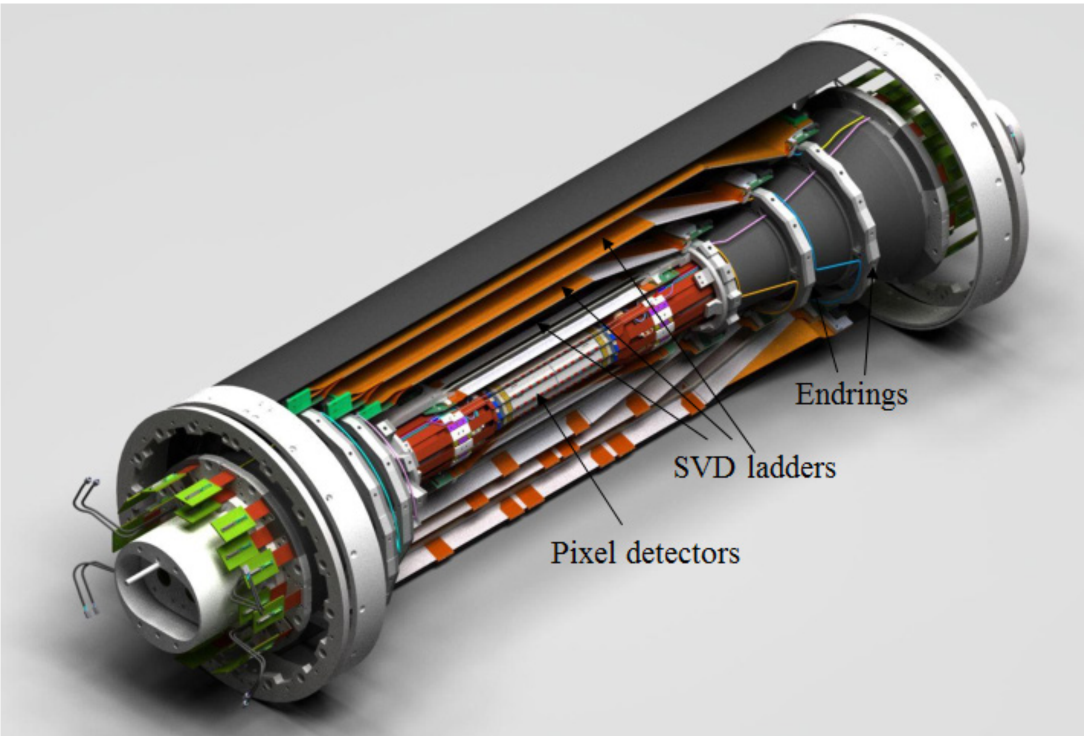
- **B**eam **E**xorcism for **A ST**able Belle **II**
- ~6μm beampipe thickness
- FANGS: ATLAS-style silicon pixel sensors
- CLAWS: Scintillator tiles w/ PMT
- PLUME: ILC style MIMOSA silicon pixel sensors
- Radiation-monitoring detectors
  - He3/TPCs, diamonds, PIN diodes



- Used now through phase II
  - Machine commissioning
  - Ensure radiation-safe environment
- To be replaced by full VXD



Silicon Vertex Tracker upgrades

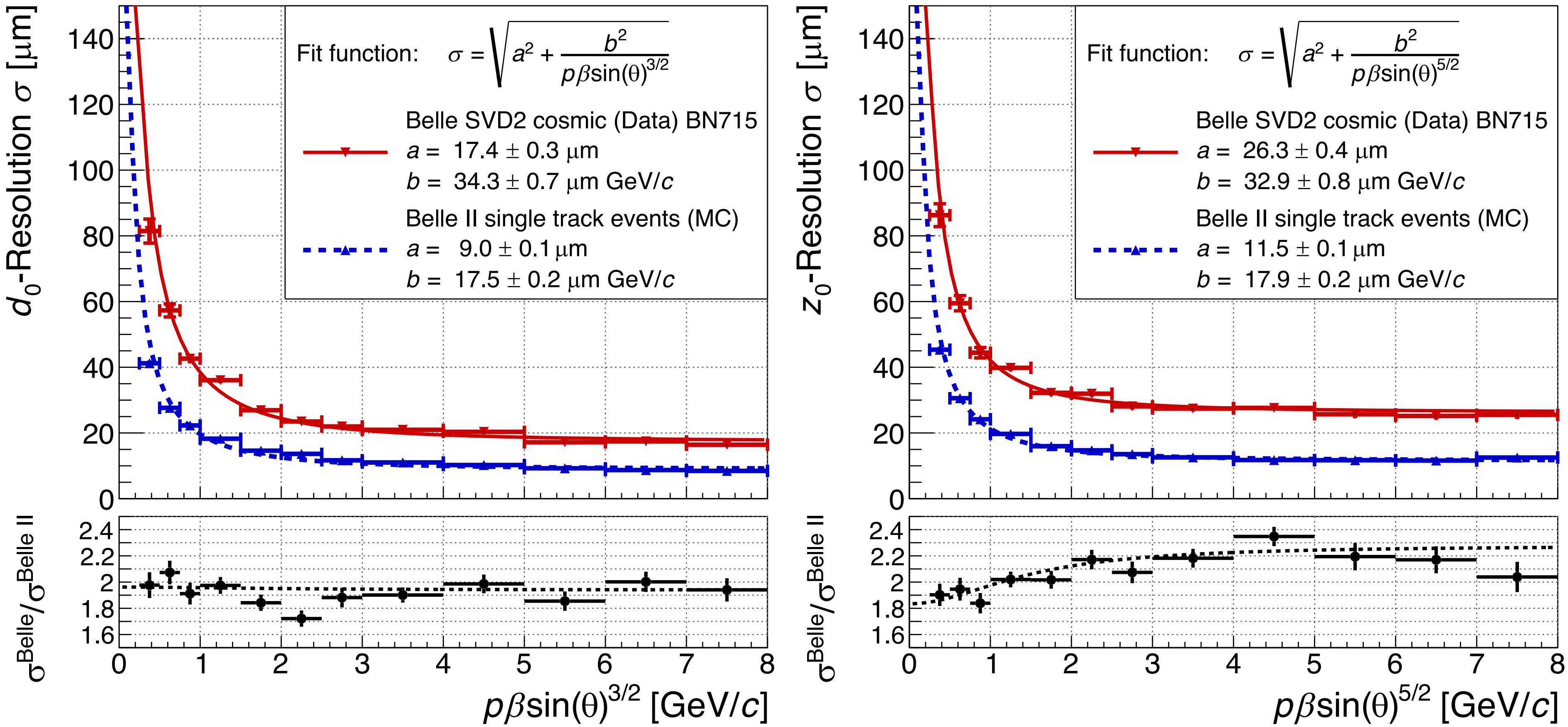


4 layers of double-sided
Silicon Strip Detectors
Outer Radius: 8 cm → 14 cm
Acceptance 17º < θ < 150º

Two layers of DEPFET pixels
R = 14 mm 8 ladders
R = 22 mm 12 ladders

+ new Be beam pipe, gold coated, 1 cm radius

Improved tracking performance



At Belle II:

Boost: $\beta\gamma = 0.284 \rightarrow$ decay length of a B meson: $\Delta z = c\Delta t\beta\gamma = 130\ \mu m$

Full event Reconstruction in Belle II

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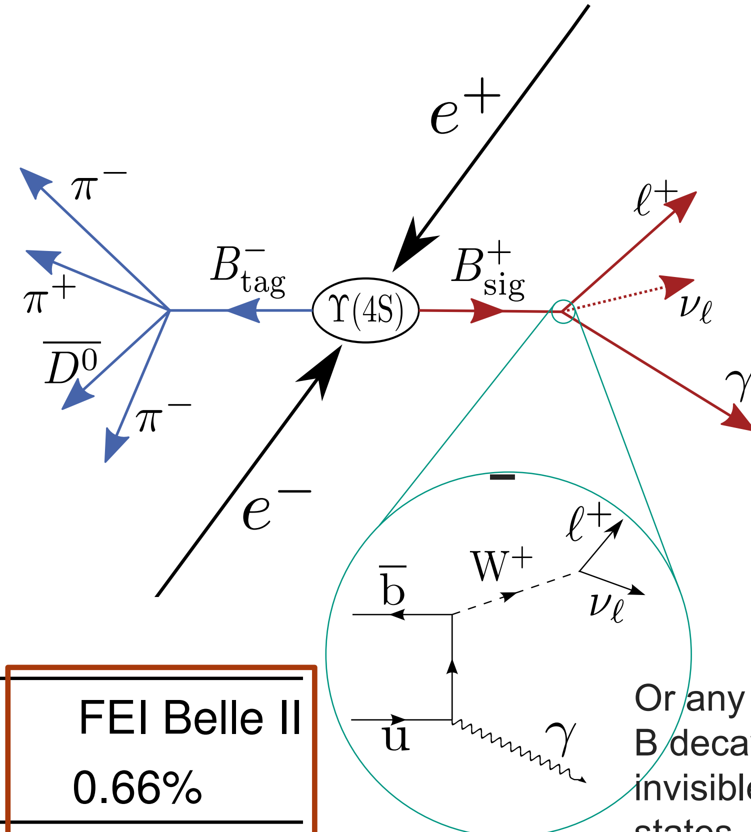
- Υ(4S) decays to a pair of B mesons
- The detector covers nearly 4 π

→ use the well-known collision energy and reconstruct one B meson to apply constraints on invisible decays of the other B meson

B → μν, B → τν, B → K(*)$\nu\nu$



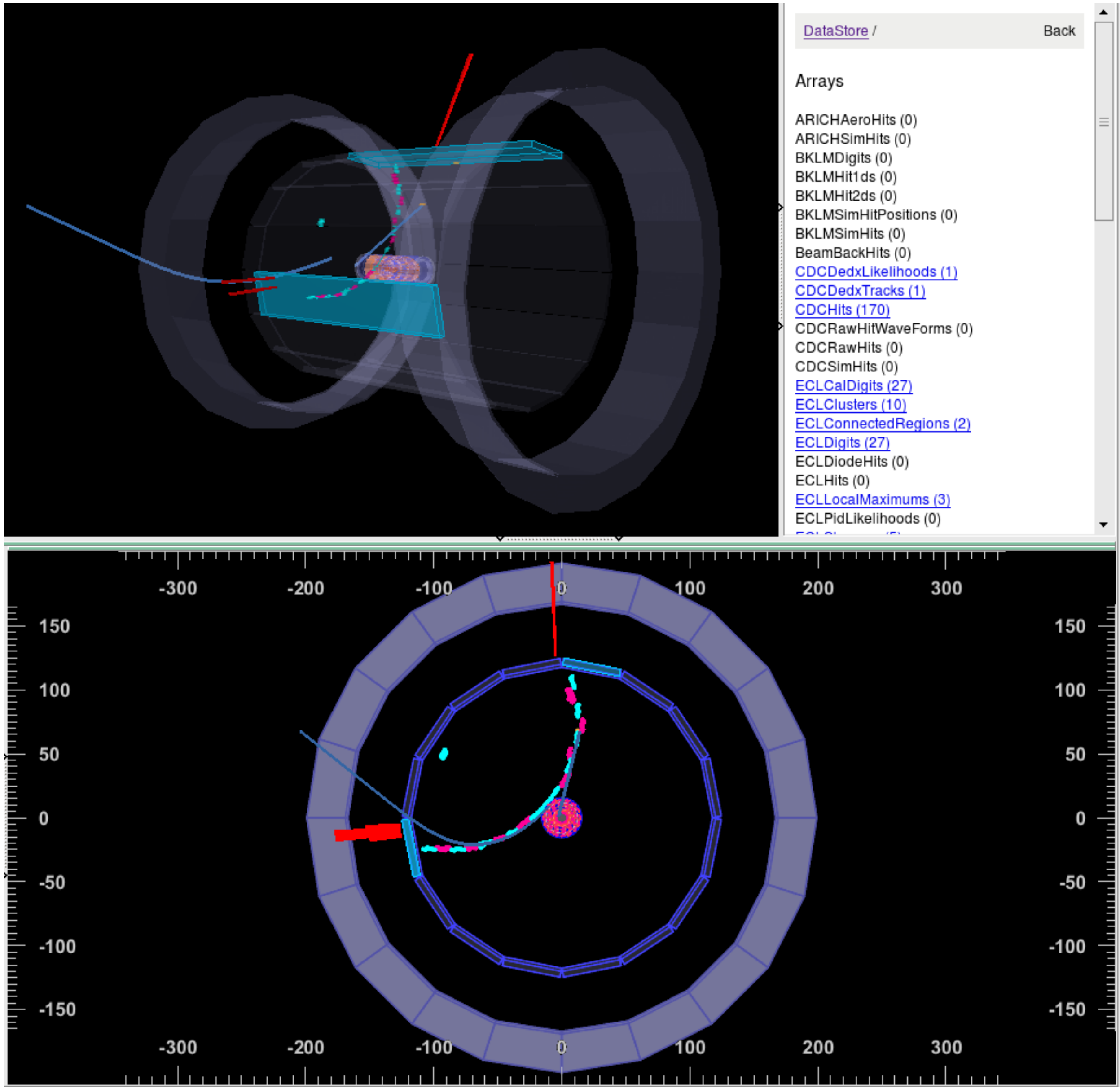
Or any other B decay with invisible final states

Tagging ϵ on MC

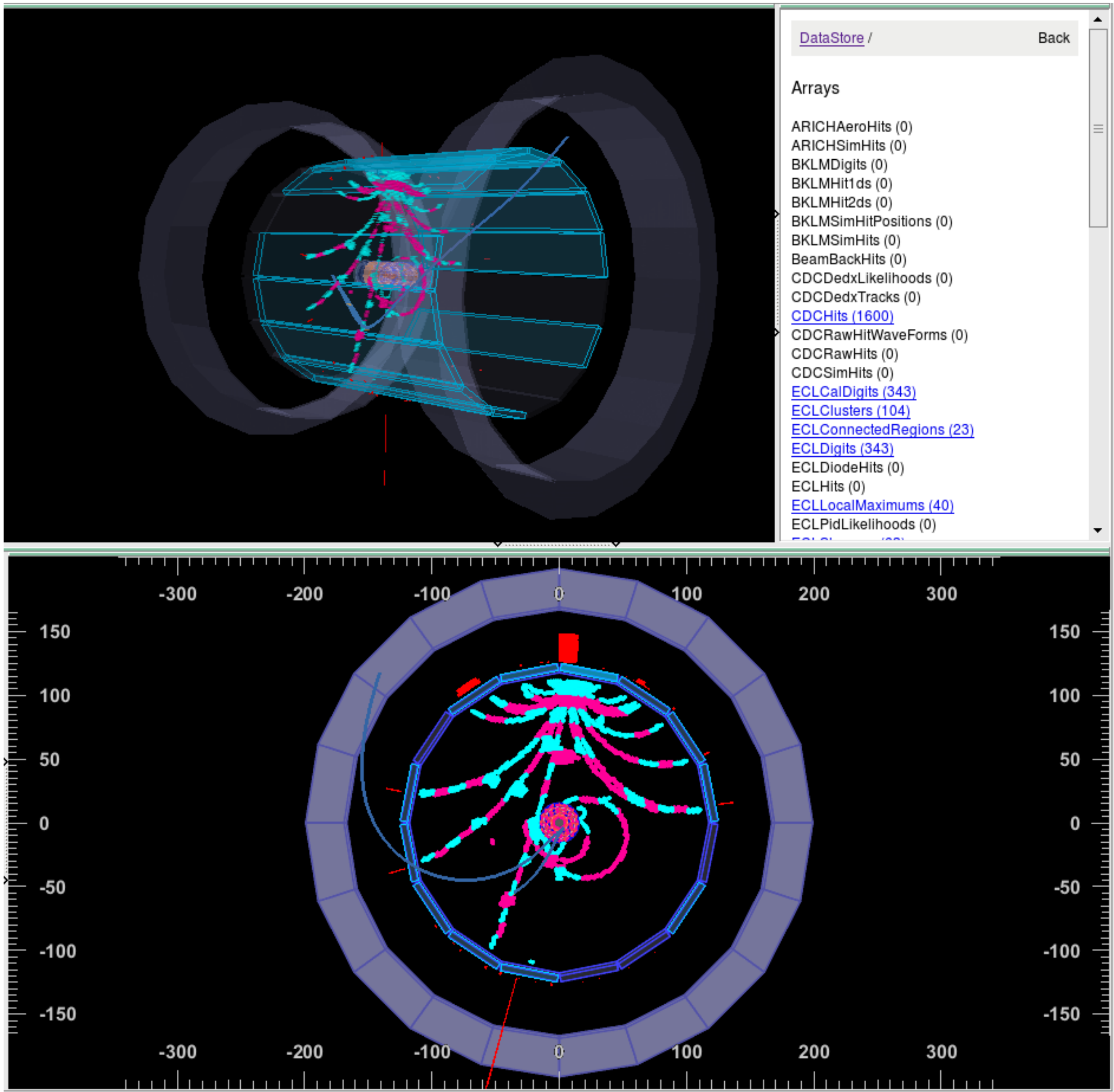
Tag	Belle	Belle w/ FEI	FEI Belle II
Hadronic B^+	0.28%	0.76%	0.66%
SL B^+	0.67%	1.80%	1.45%
Hadronic B^0	0.18%	0.46%	0.38%
SL B^0	0.63%	2.04%	1.94%

Incl. Belle II background

First bent track in CDC + ECL + TOP



First Shower in CDC + ECL + TOP



Physics Topics

Unitarity triangle(s)

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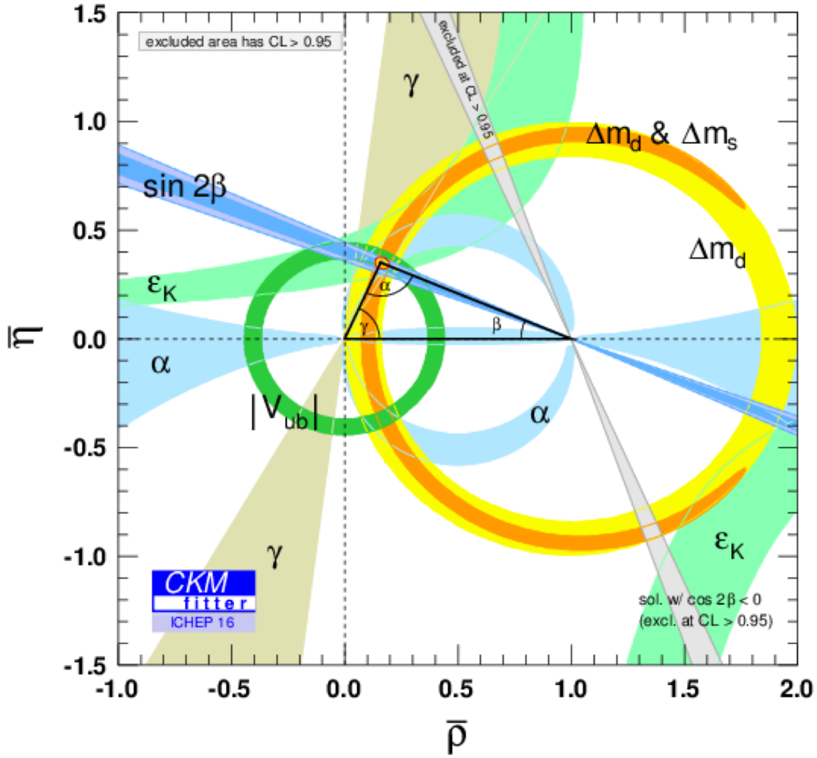
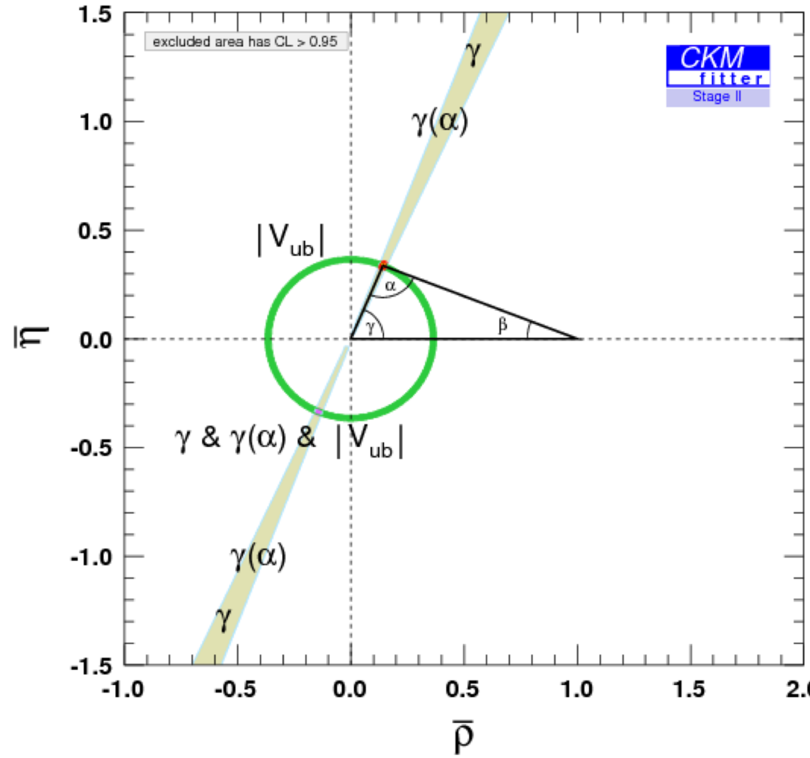
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity leads to constraints, e.g.
$V_{ud}{}^*V_{td} + V_{us}{}^*V_{ts} + V_{ub}{}^*V_{tb} = 0$

New physics in the weak sector would preclude us from closing the triangle



Current state



Expected state in ~2025 (LHCb + Belle II)

B → D* τν

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

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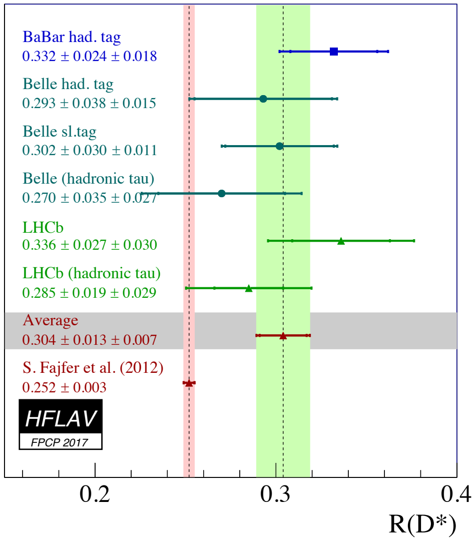
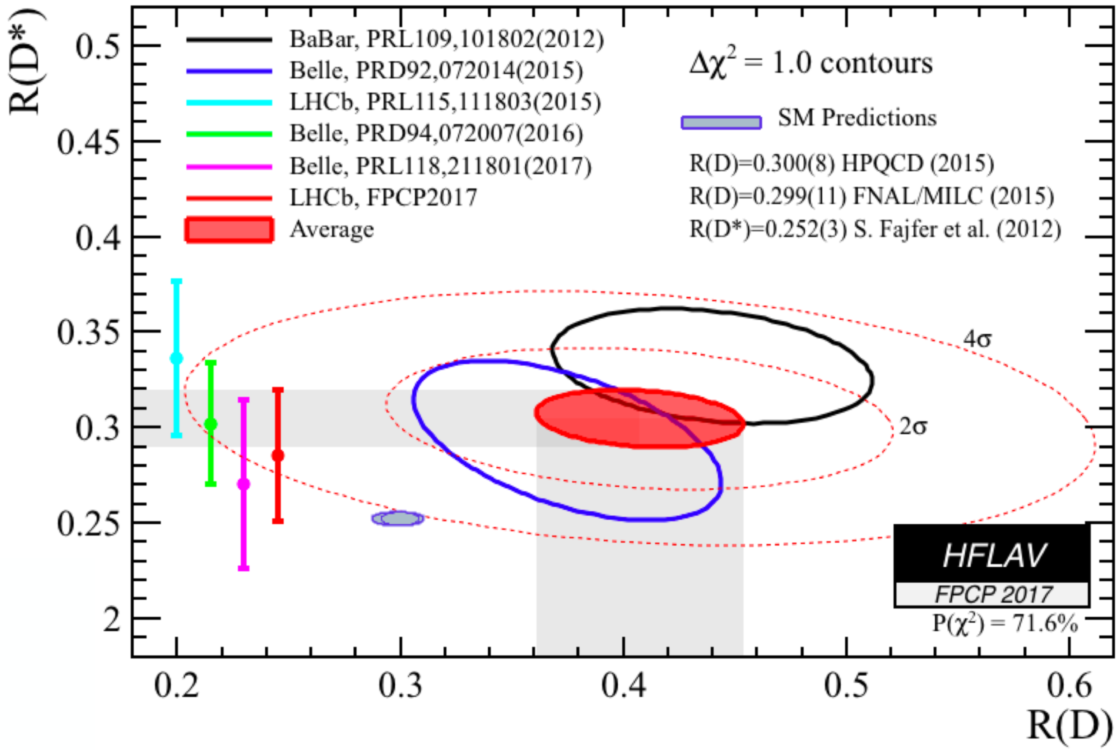
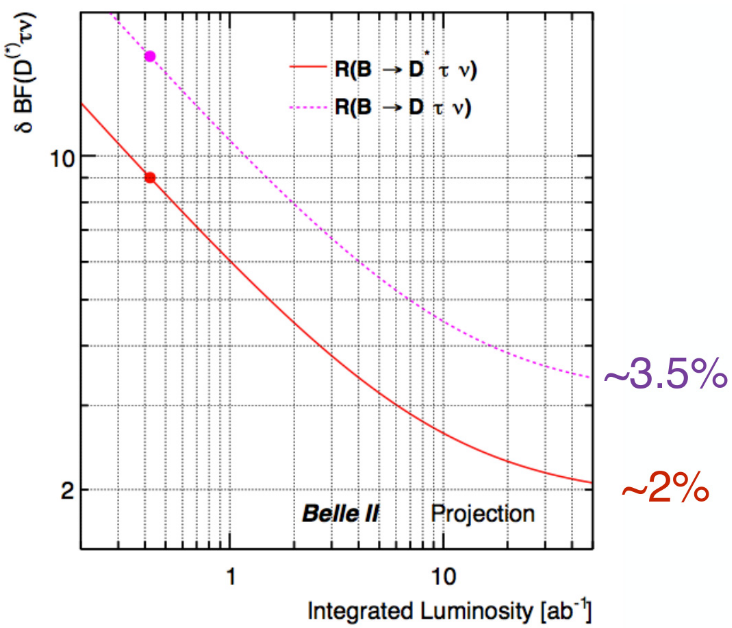
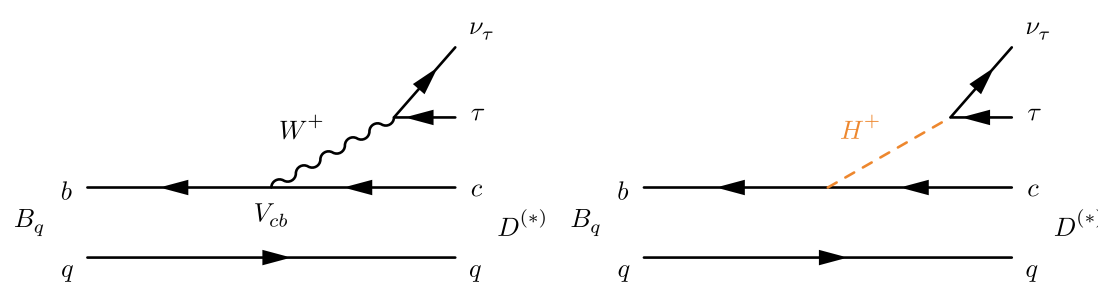
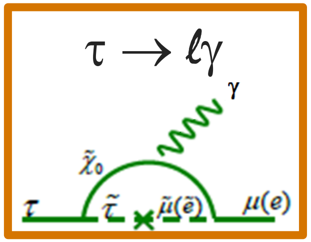


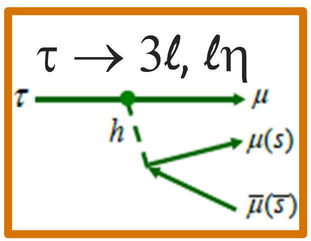


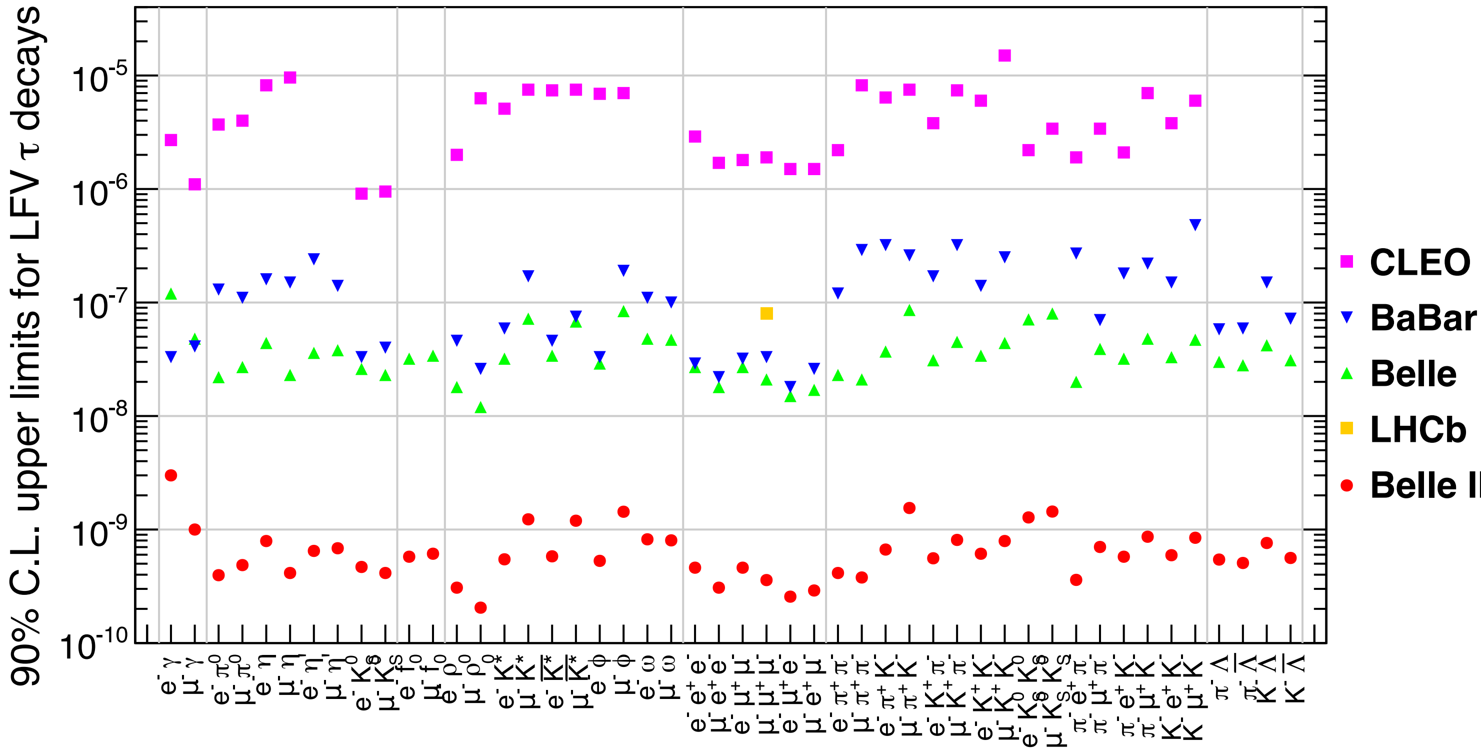




Lepton Flavor violation in tau decays





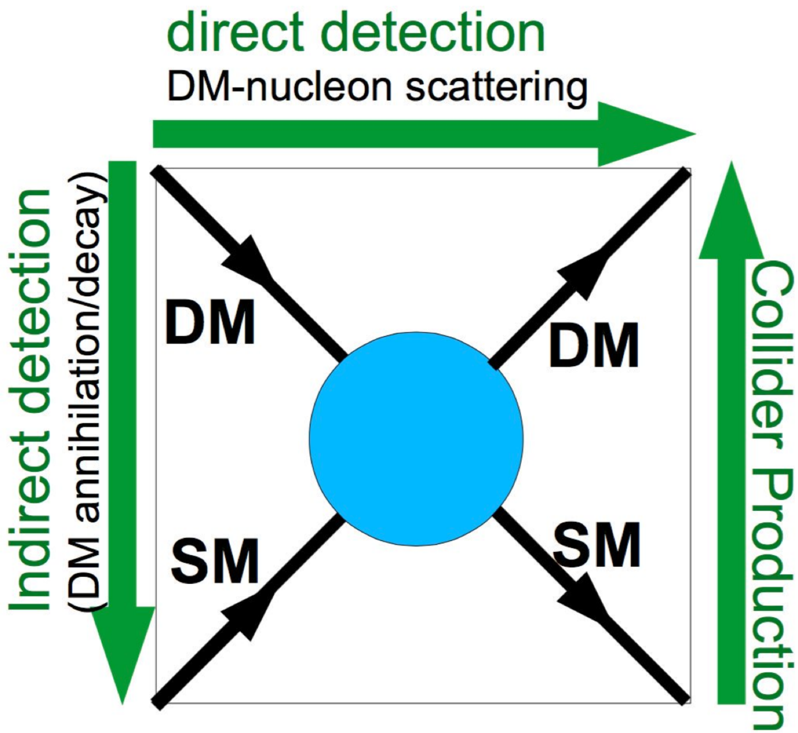


Large $\tau\tau$ production cross section in Belle II: 0.9 nb

LVF BR in SM ~10^{-25}, could be enhanced by new physics to ~10^{-10}-10^{-7}
➞ Belle II will be sensitive to a large fraction of these models

Dark Matter and Dark Sector

(make it, shake it, or break it)



At a collider: Cannot confirm stability on cosmic scale, an essential requirement for dark matter

But: Can find dark sector particle ~independent of the identity of the particles. (Unlike most direct detection experiments, which depend on a sizable cross section with nuclei)

Background to dark photon searches

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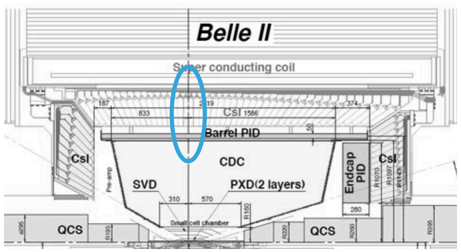
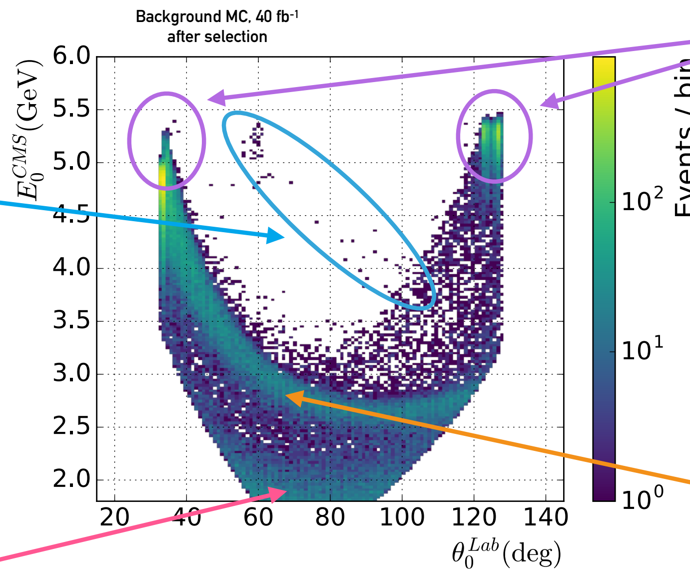
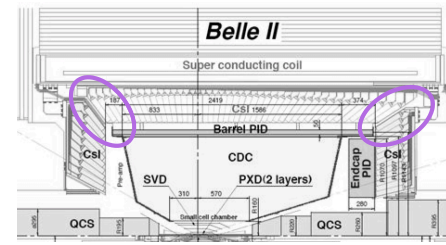
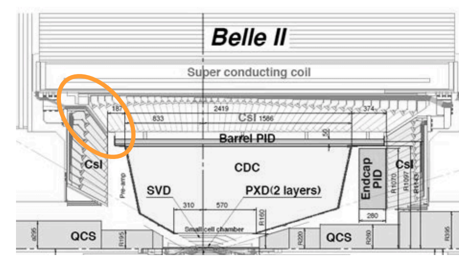


ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance





ee→2γ
1γ in ECL BWD or FWD gap

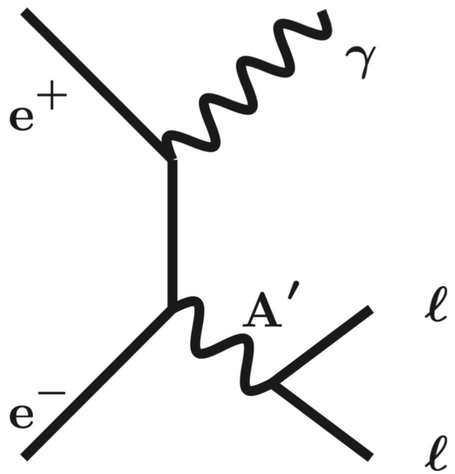


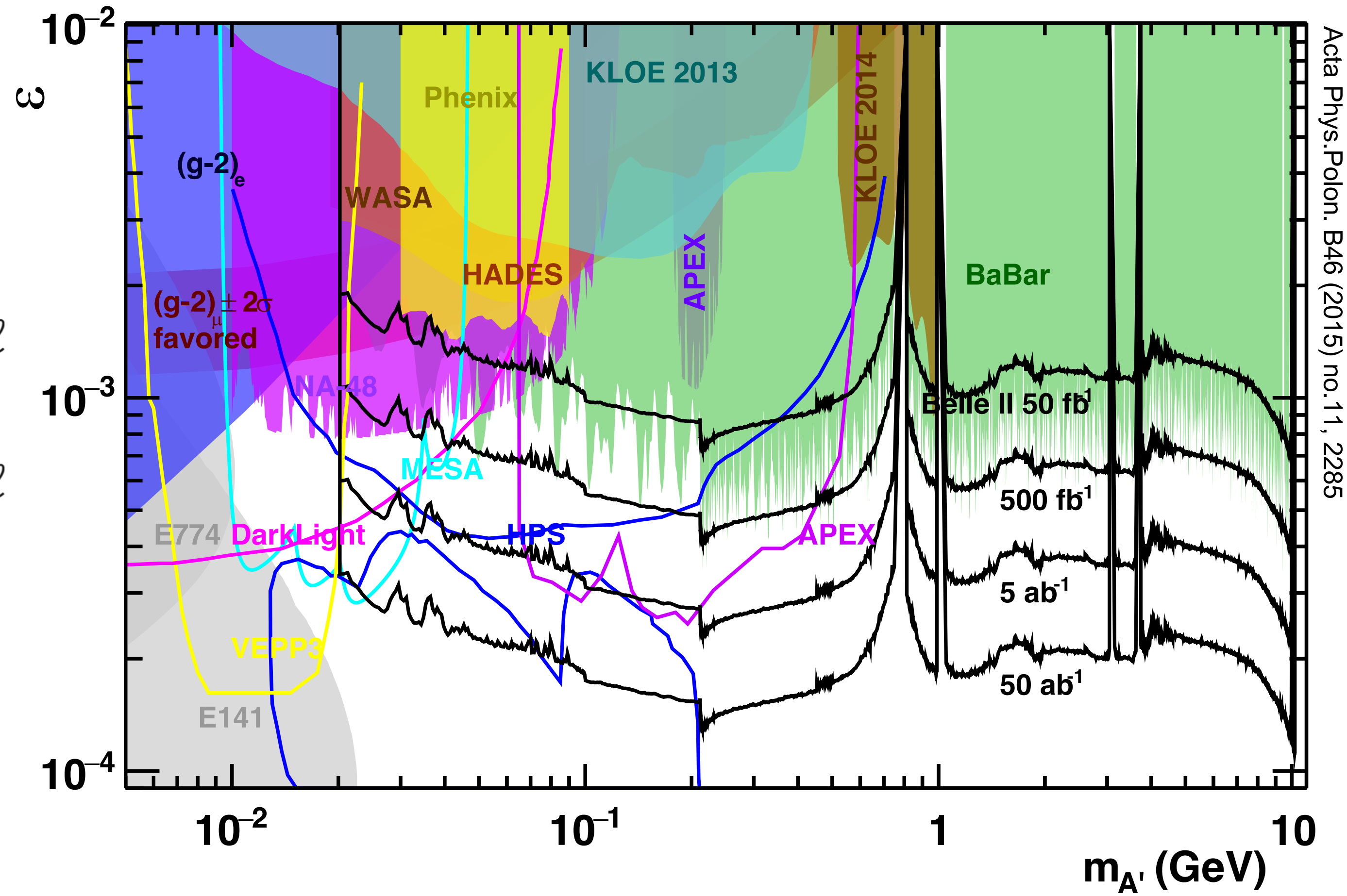
ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

ee→eeγ
both electrons
out of tracking acceptance

T. Ferber, DESY

Visible Dark Photon Search at Belle II





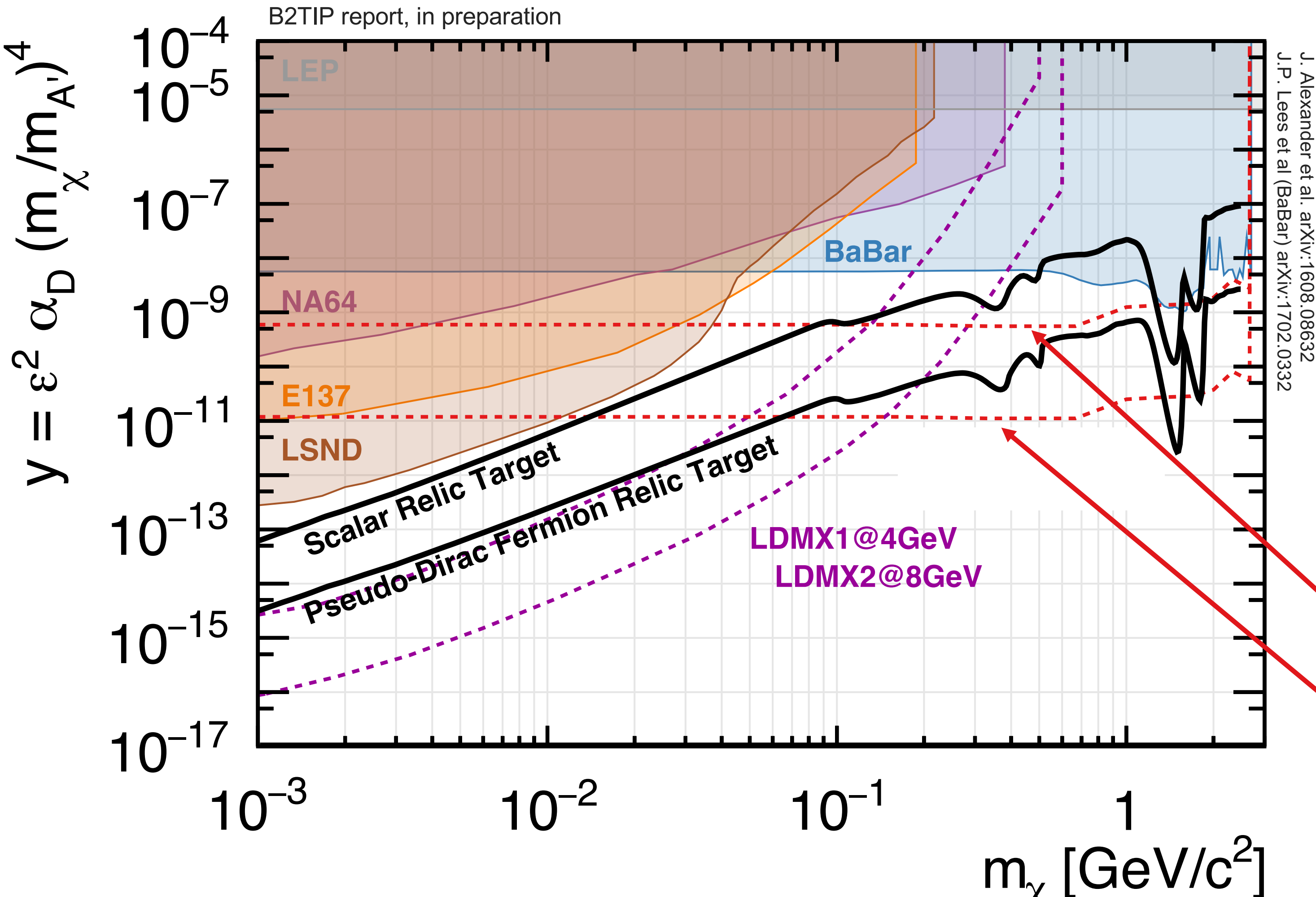
Unlike dark matter, mediators from portal interactions can have sizable SM couplings.

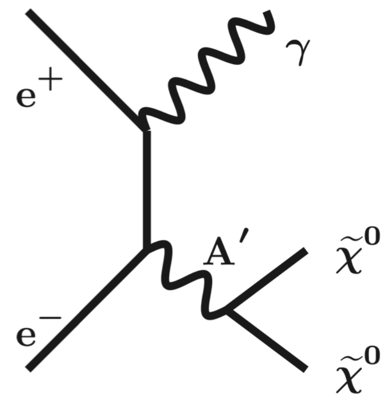
Detector signature: single photon + two tracks

See also SIMPs

(Hochberg, Y., Kuflik, E.&Murayama, H. J. High Energ. Phys. (2016) 2016: 90.)

Invisible Dark Photon Decays

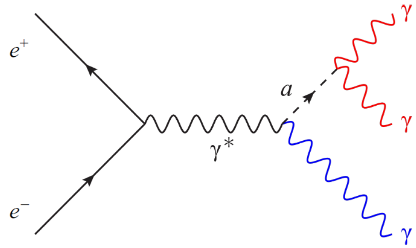




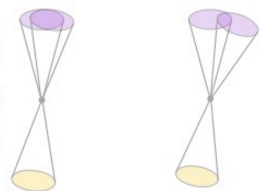
$$E^*_\gamma = \frac{\sqrt{s}}{2} - \frac{m^2_{A'}}{2\sqrt{s}}$$

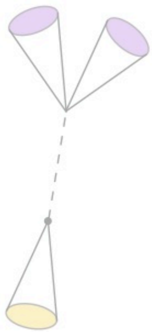
α_D=0.5
$m_{A'}$=3m_X

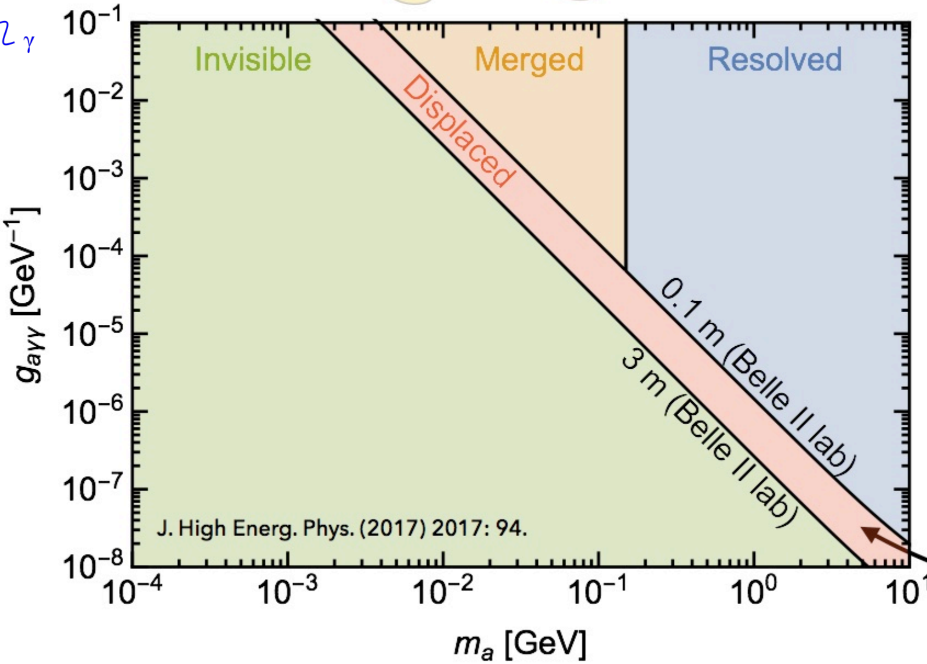
Searches for Axion-Like Particles (ALP)



Two of the photons overlap or **merge**.





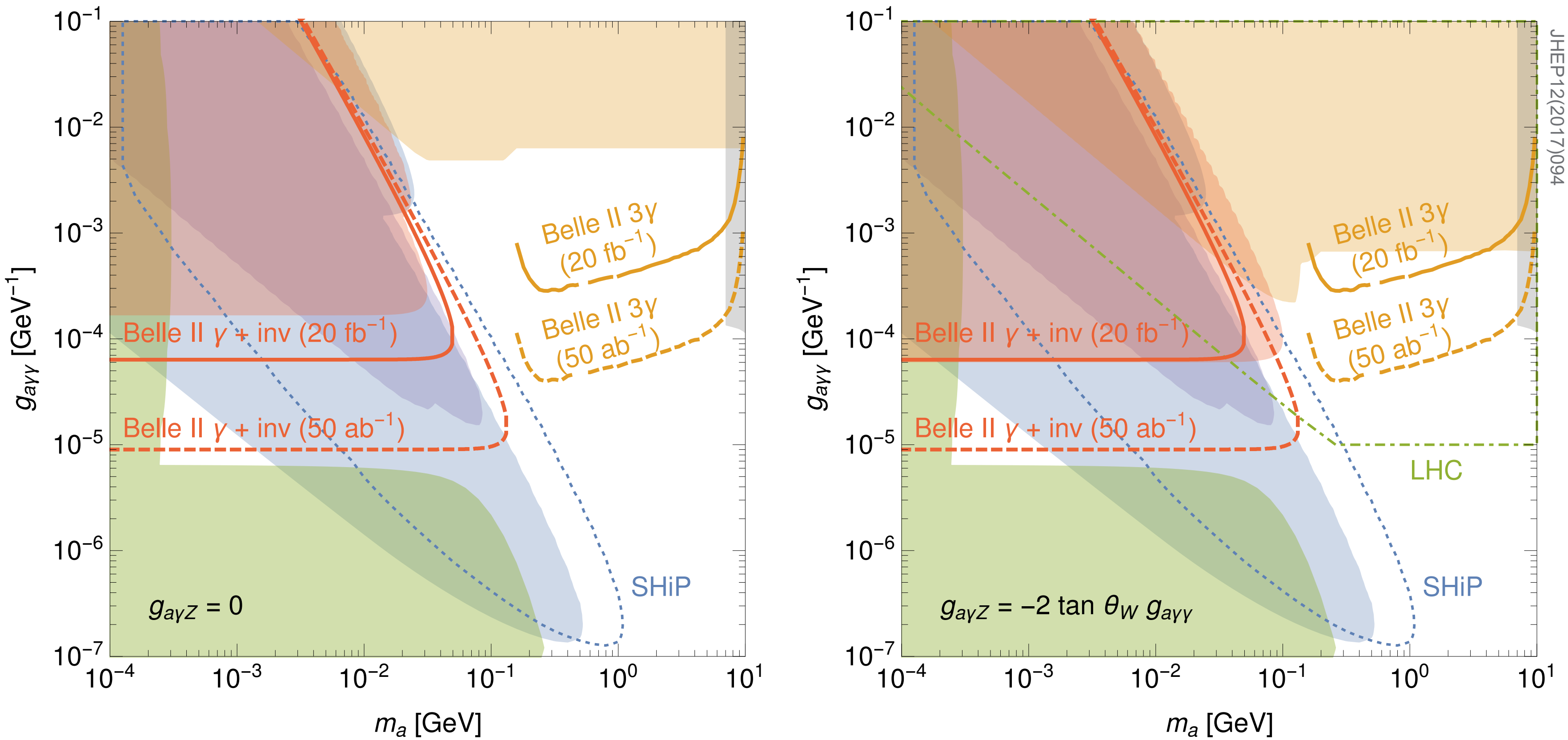


Three **resolved**, high energetic photons.

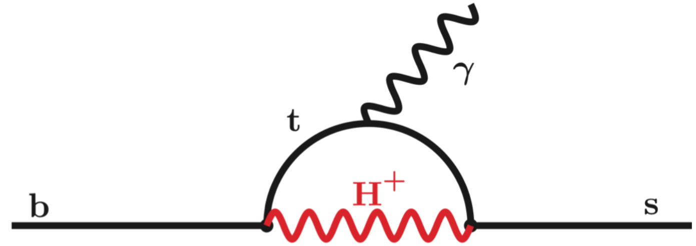
ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

The searches for invisible and visible ALP decays veto this region.

Projected Future Sensitivity for ALP searches

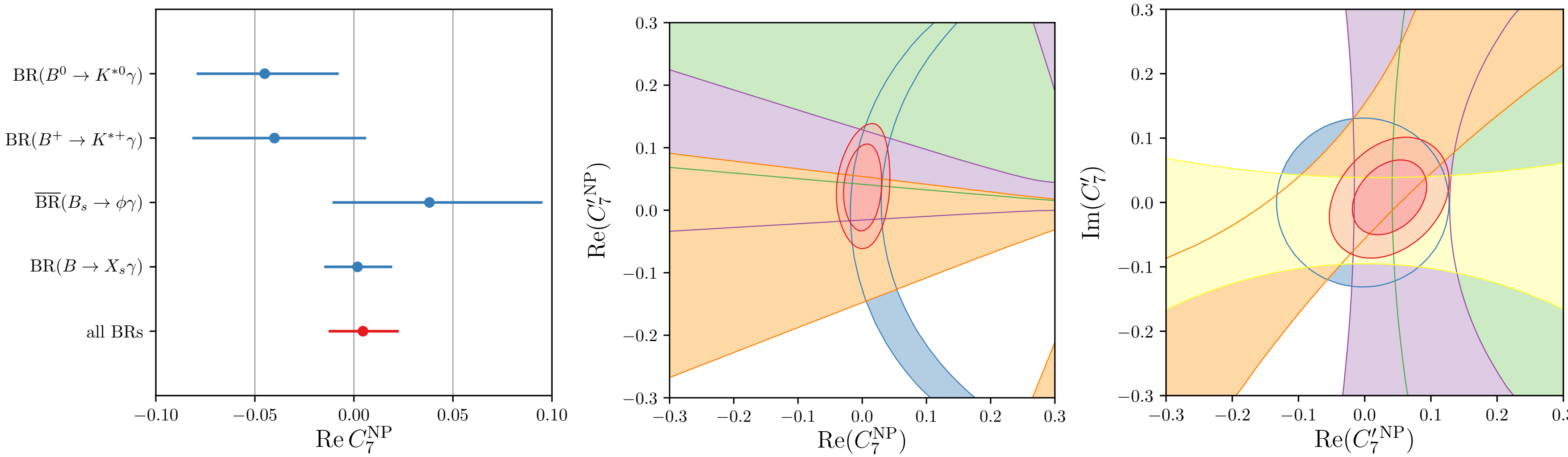


$B \rightarrow X_s\gamma$



World Average: $\mathcal{B}(B \rightarrow X_s\gamma) = (3.27 \pm 0.14) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV)
Standard Model: $\mathcal{B}(B \rightarrow X_s\gamma) = (3.36 \pm 0.23) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV)
[Misiak et al, Eur.Phys.J. C77 (2017) no.3, 201]

Charged Higgs bound (2HDMTypeII): $M_{H+} > 580$ GeV @ 95%C.L.



Paul, A. and Straub, D.M. J. High Energ. Phys. (2017) 2017: 27

Belle II projection:
$\Delta\mathcal{B}(B \rightarrow X_s\gamma)$ = 3.2% (inclusive, leptonic tag)
$\Delta\mathcal{B}(B \rightarrow X_d\gamma)$ = 14% (sum-of-exclusive)

B → K(*)ll and Lepton Flavor non-universality

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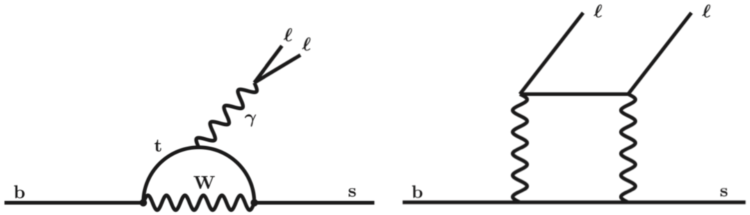
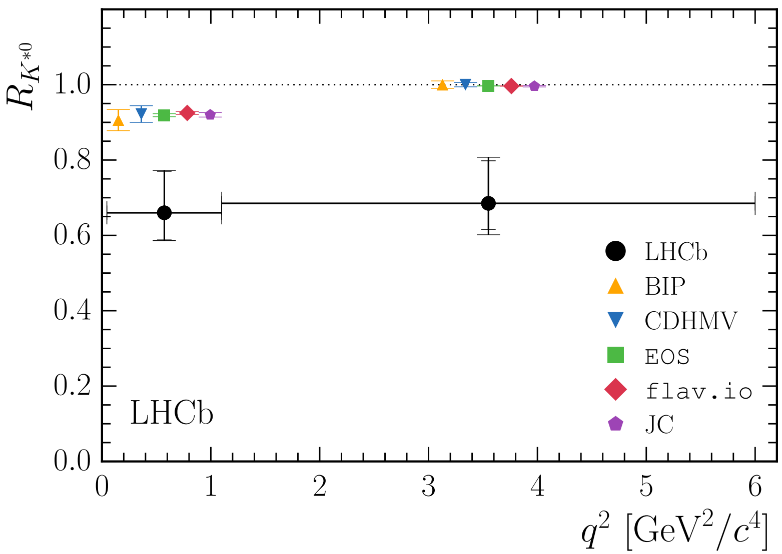
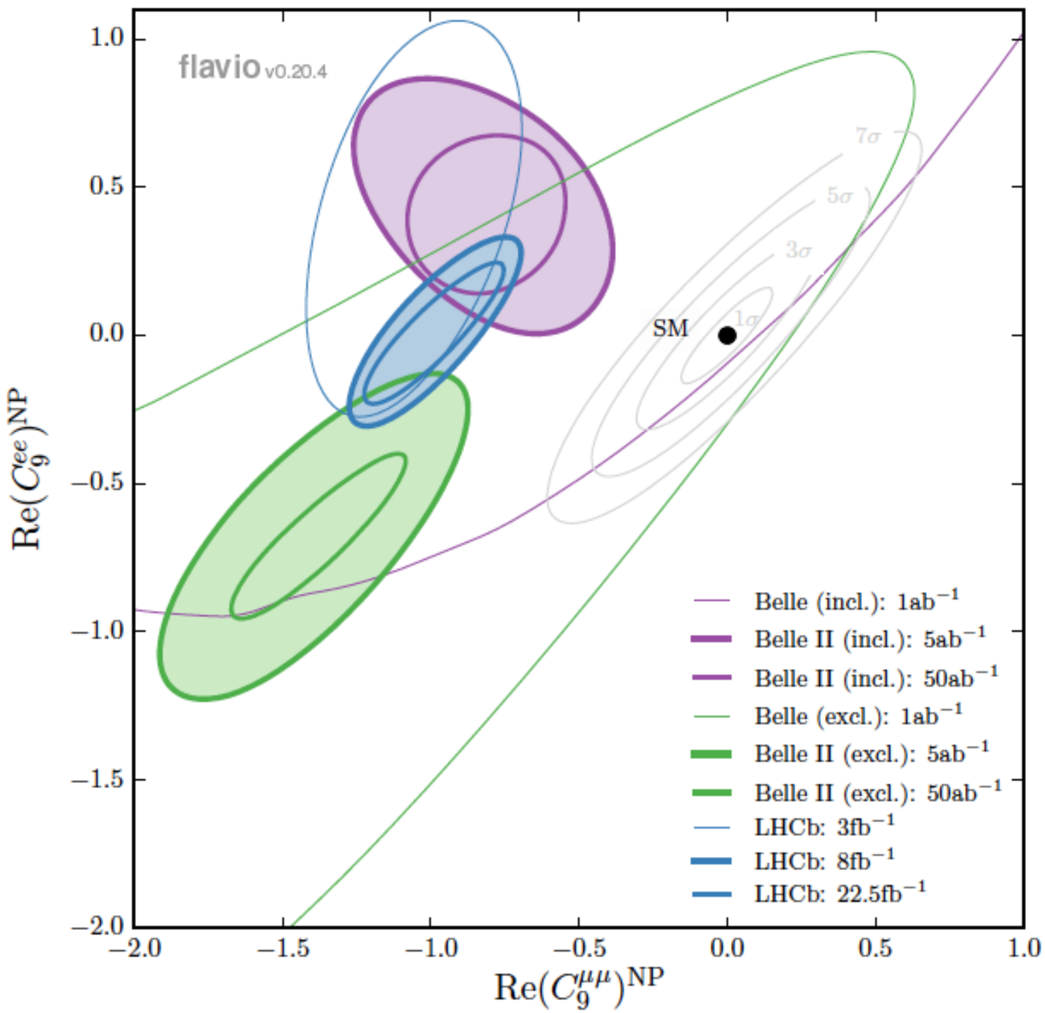
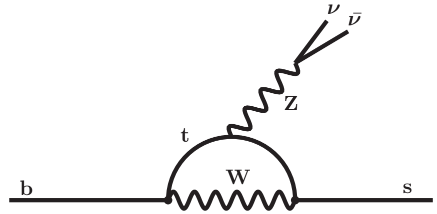


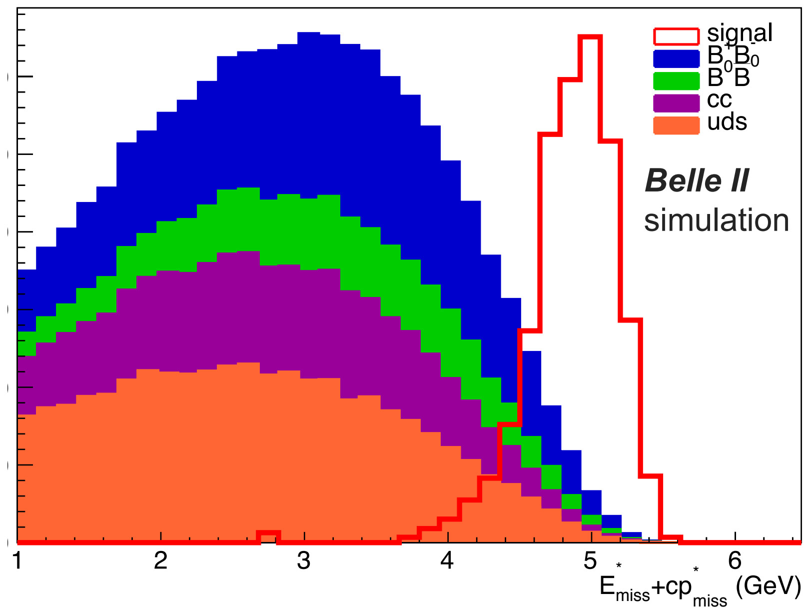


$$R_{K^{(*)}} = \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)}$$



$B \to K^*\nu\nu$





Source: B2tip report

Analysis is made possible by event reconstruction in a 4 π detector.

New physics coupling to third-generation leptons could enhance the decay while avoiding existing limits.

Current World Average Limit
$\mathcal{B}(B \to K^{*0}\bar{\nu}\nu) < 1.8 \times 10^{-5}$

Mode	$\mathcal{B}$ $[10^{-6}]$	Efficiency Belle $[10^{-4}]$	$N_{\mathrm{Backg.}}$ 711 fb^{-1} Belle	$N_{\mathrm{Sig-exp.}}$ 711 fb^{-1} Belle	$N_{\mathrm{Backg.}}$ 50 ab^{-1} Belle II	$N_{\mathrm{Sig-exp.}}$ 50 ab^{-1} Belle II	Statistical error 50 ab^{-1}	Total Error
$B^+ \to K^+\nu\bar{\nu}$	4.68	5.68	21	3.5	2960	245	20%	22%
$B^0 \to K^0_S\nu\bar{\nu}$	2.17	0.84	4	0.24	560	22	94%	94%
$B^+ \to K^{*+}\nu\bar{\nu}$	10.22	1.47	7	2.2	985	158	21%	22%
$B^0 \to K^{*0}\nu\bar{\nu}$	9.48	1.44	5	2.0	704	143	20%	22%
$B \to K^*\nu\bar{\nu}$ combined							15%	17%

Quarkonium Spectroscopy

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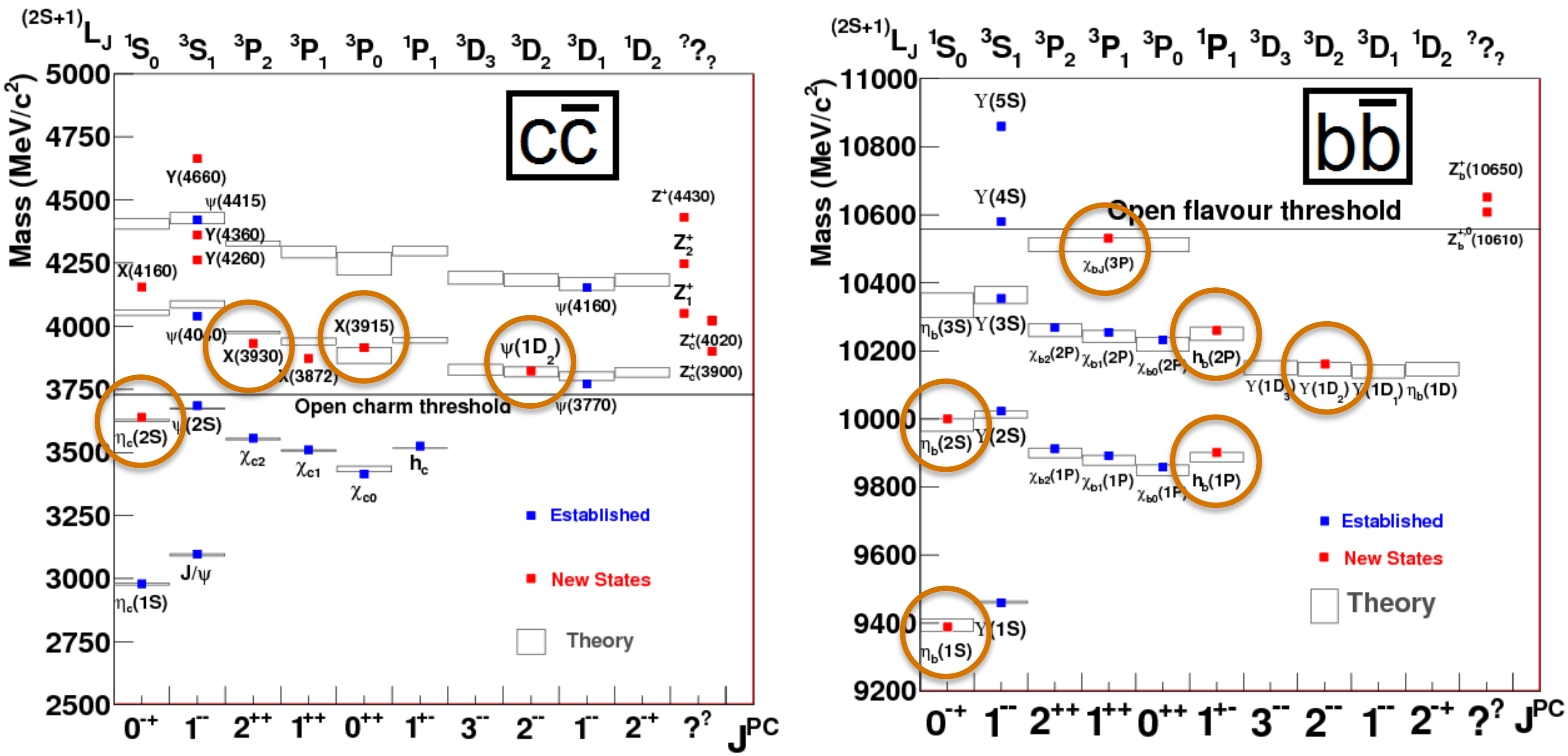
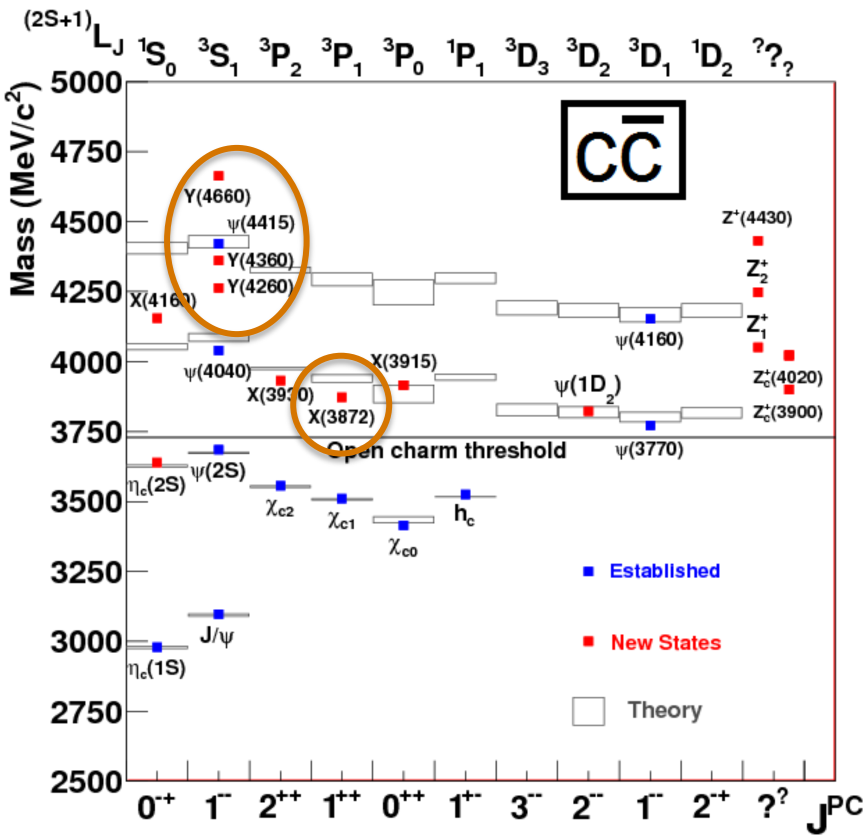
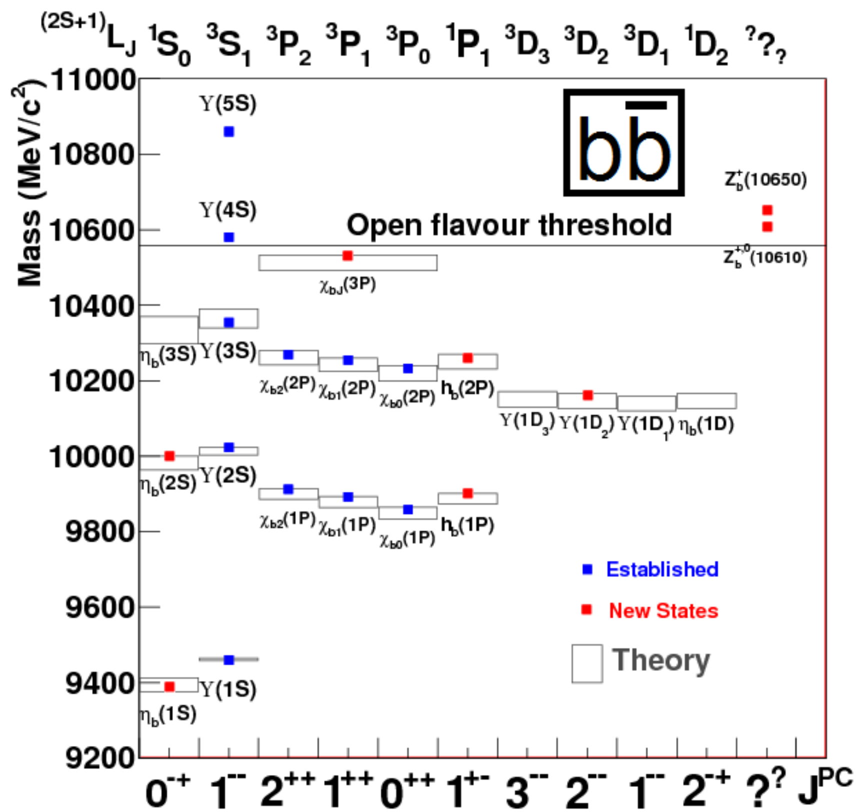


► **First discoveries of long-predicted conventional quarkonia**

Quarkonium Spectroscopy





First discoveries of long-predicted conventional quarkonia

Many discoveries are difficult to explain by quarkonium model

Quarkonium Spectroscopy

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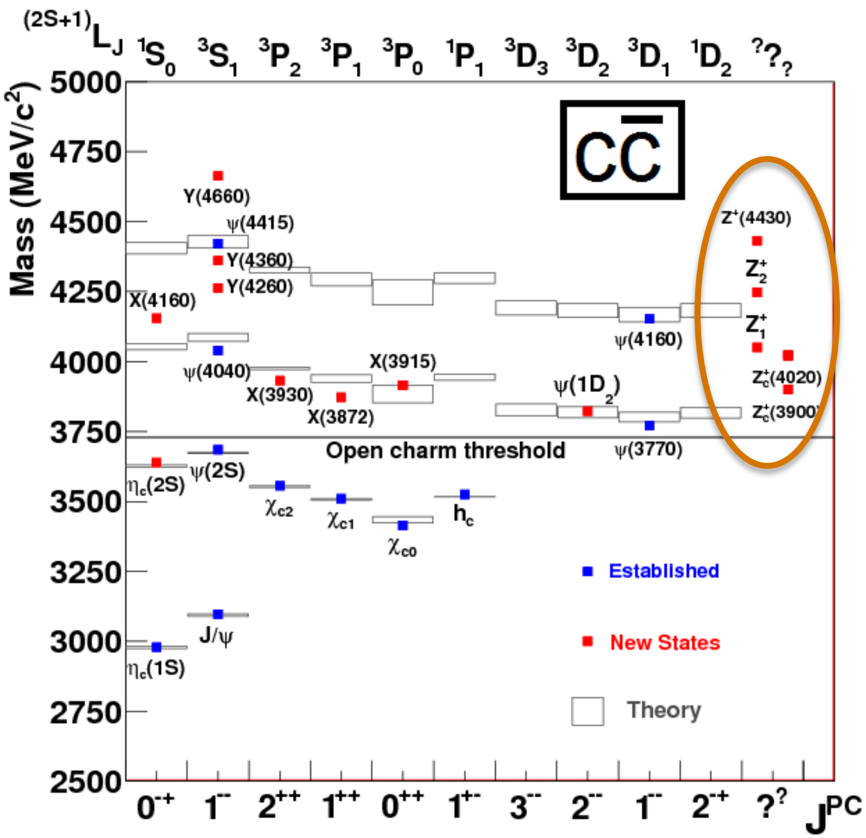

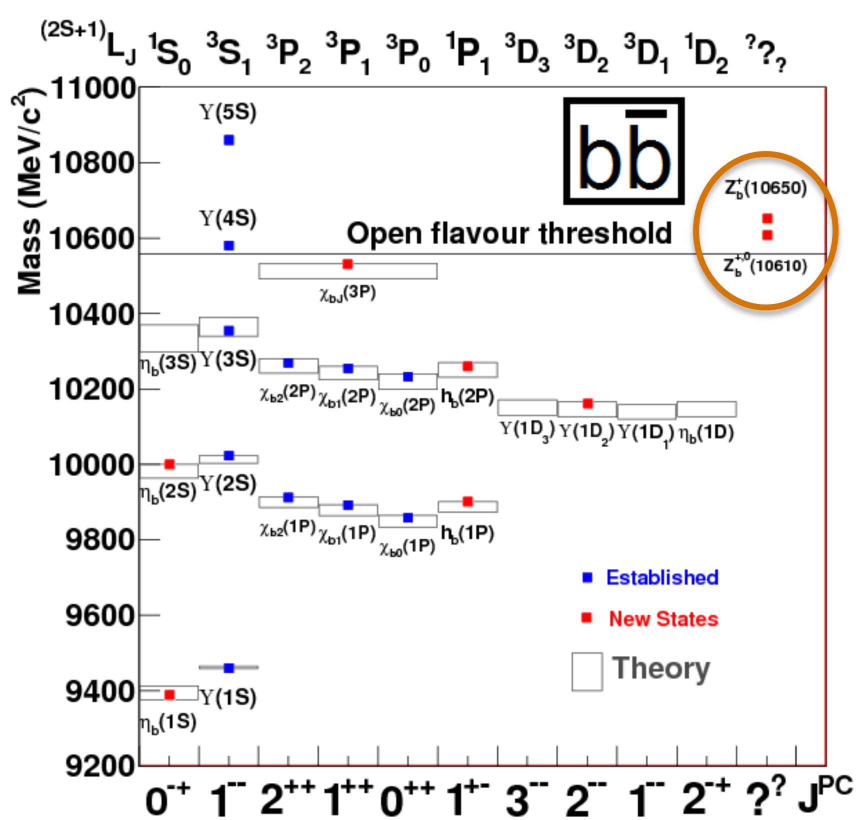

- First discoveries of long-predicted conventional quarkonia
- Many discoveries are difficult to explain by quarkonium model
- **Several states have non-zero charge, cannot be a $c\bar{c}$/$b\bar{b}$ pair**

Summary and conclusions

- The SuperKEKB accelerator has completed upgrades to eventually produce 50 times the Belle data sample.
- The Belle II detector has been upgraded to carry out the physics program at this machine.
- The physics program has the potential to make many important contributions to particle physics over the next ~10-15 years
  - Competition with LHCb will keep both experiments on their toes
  - Belle II has a clear advantage for measuring decays with missing energy
  - Searches for dark sector particles will happen in a mass window that is complementary to the searches at ATLAS and CMS
- The detector is ready for first collisions in SuperKEKB, and the collaboration looks forward to an exciting time ahead


Thank you for your attention

Acknowledgements

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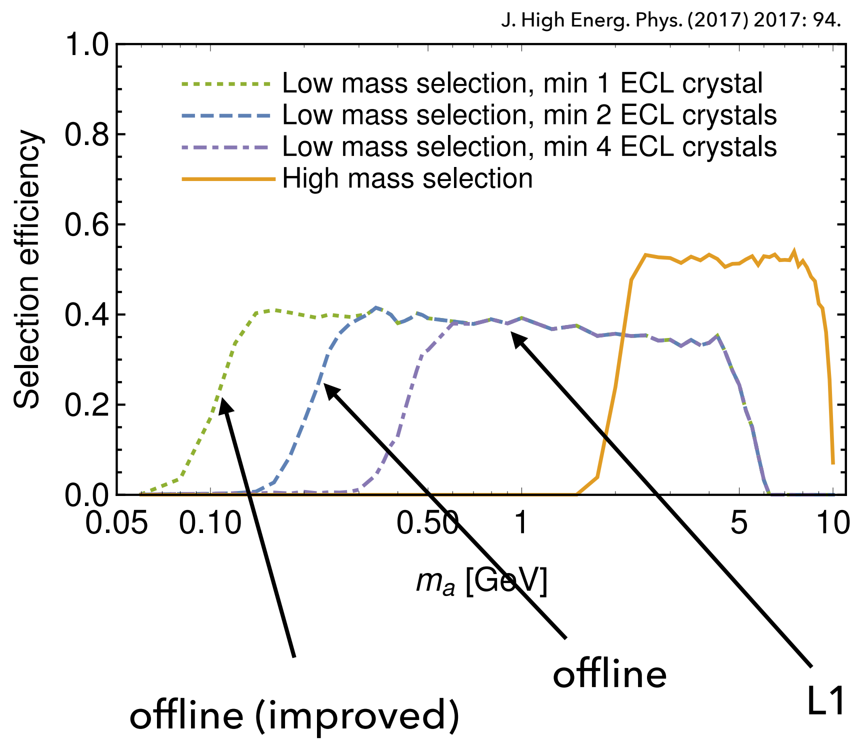
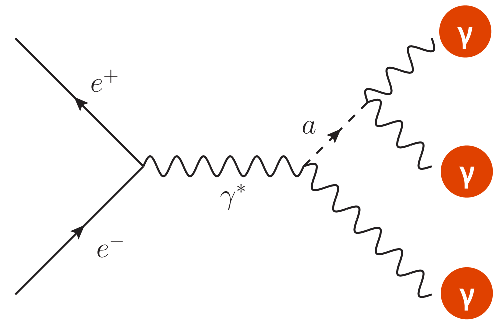
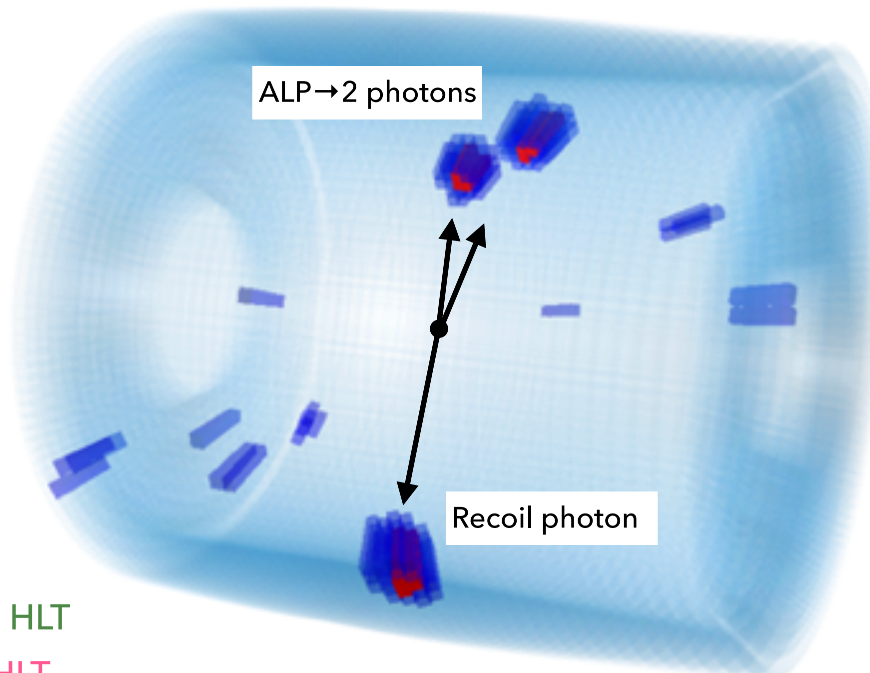
- Material taken from
- Sam Cunliffe
- Bryan Fulsom
- Takanori Hara
- Oskar Hartbrich
- Hiroyuki Nakayama
- Torben Ferber
- Peter Lewis

Backup

Axion-like Particles coupling to photons





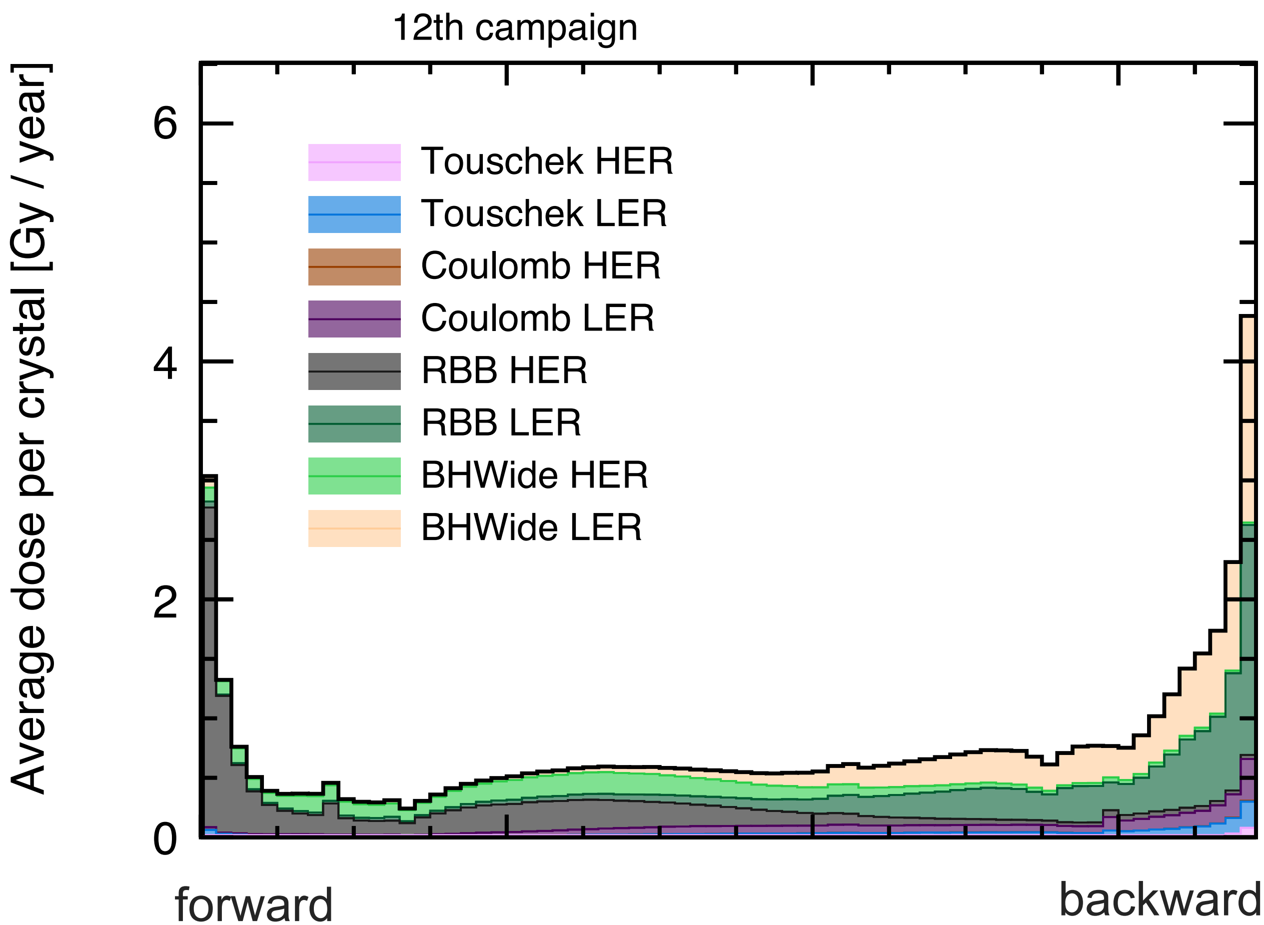


5 nb	basic physics (BB, $q\bar{q}$, tau pairs)
4 nb	$\mu^+\mu^-$ and $\gamma\gamma$
5 nb	$e^+e^-e^+e^-$ and $e^+e^-\mu^+\mu^-$
40 nb	wide-angle Bhabhas [17°,150°]
63 nb	debris from low-angle Bhabhas
117 nb	total

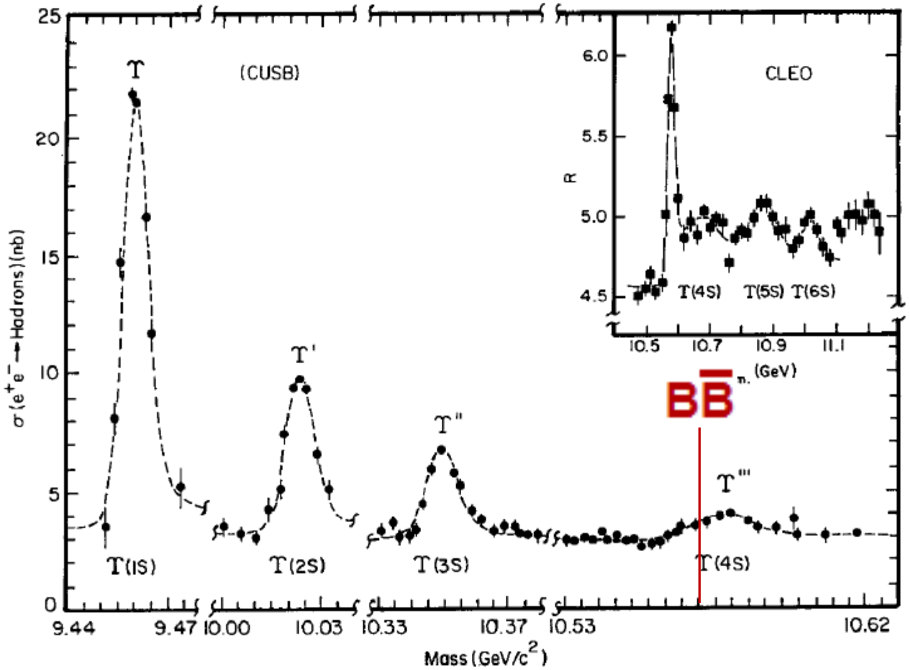
Rather easy at HLT

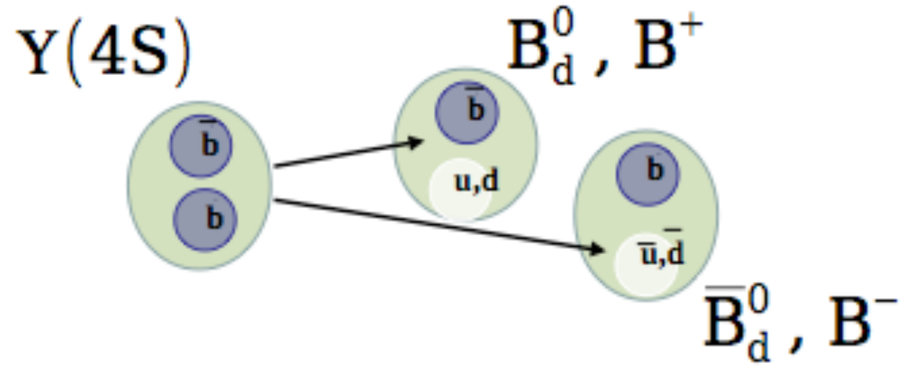
Hard even at HLT

Background in the ECL



Physics at B factories





- Electron positron collision at Y(4S) resonance produces two B mesons
- Created in an L=1 coherent state

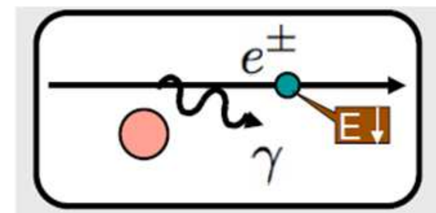
Cross sections

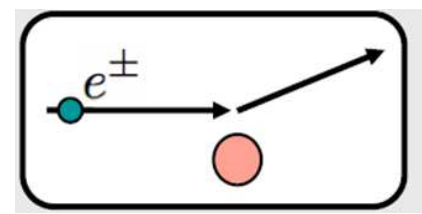
- $\sigma(e^+e^- \rightarrow b\bar{b})$ = 1.1 nb
- $\sigma(e^+e^- \rightarrow c\bar{c})$ = 1.3 nb
- $\sigma(e^+e^- \rightarrow s\bar{s})$ = 0.4 nb
- $\sigma(e^+e^- \rightarrow u\bar{u})$ = 1.6 nb
- $\sigma(e^+e^- \rightarrow d\bar{d})$ = 0.4 nb
- $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ = 0.9 nb

More background sources

Beam-gas scattering

- Scattering by remaining gas, rate ∝ IxP
- Vacuum level at SuperKEKB will be similar to KEKB
- Vacuum level in IR region could be worse than KEKB, but scattered particles will be lost far downstream of the IP and not enter the detector

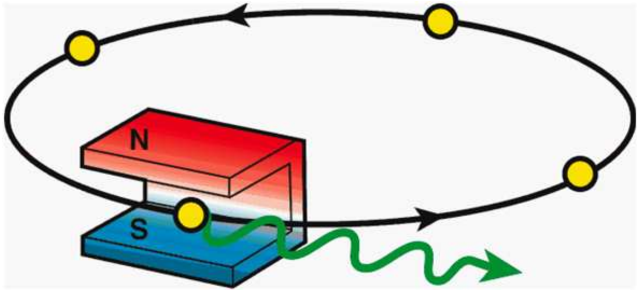




Even more background sources

Synchrotron radiation

- Rate $\propto E^2B^2$: Mainly from HER
- Photons are emitted inside upstream final focusing magnet
  - Hit IP beam pipe and penetrate
- Mediation: Gold coating of beam pipe



Back-scattering synchrotron radiation

- Beams are strongly bent by downstream magnet and emit synchrotron radiation
- Photons can hit the downstream beam pipe and scatter back into the detector
- At Belle II, much less bending close to the detector than in Belle