Status and prospects of the Belle II experiment.

Sam Cunliffe
Birmingham, 05.12.2018

Status

- The project
- The apparatus
- Where we are in data-taking
- First results

and prospects

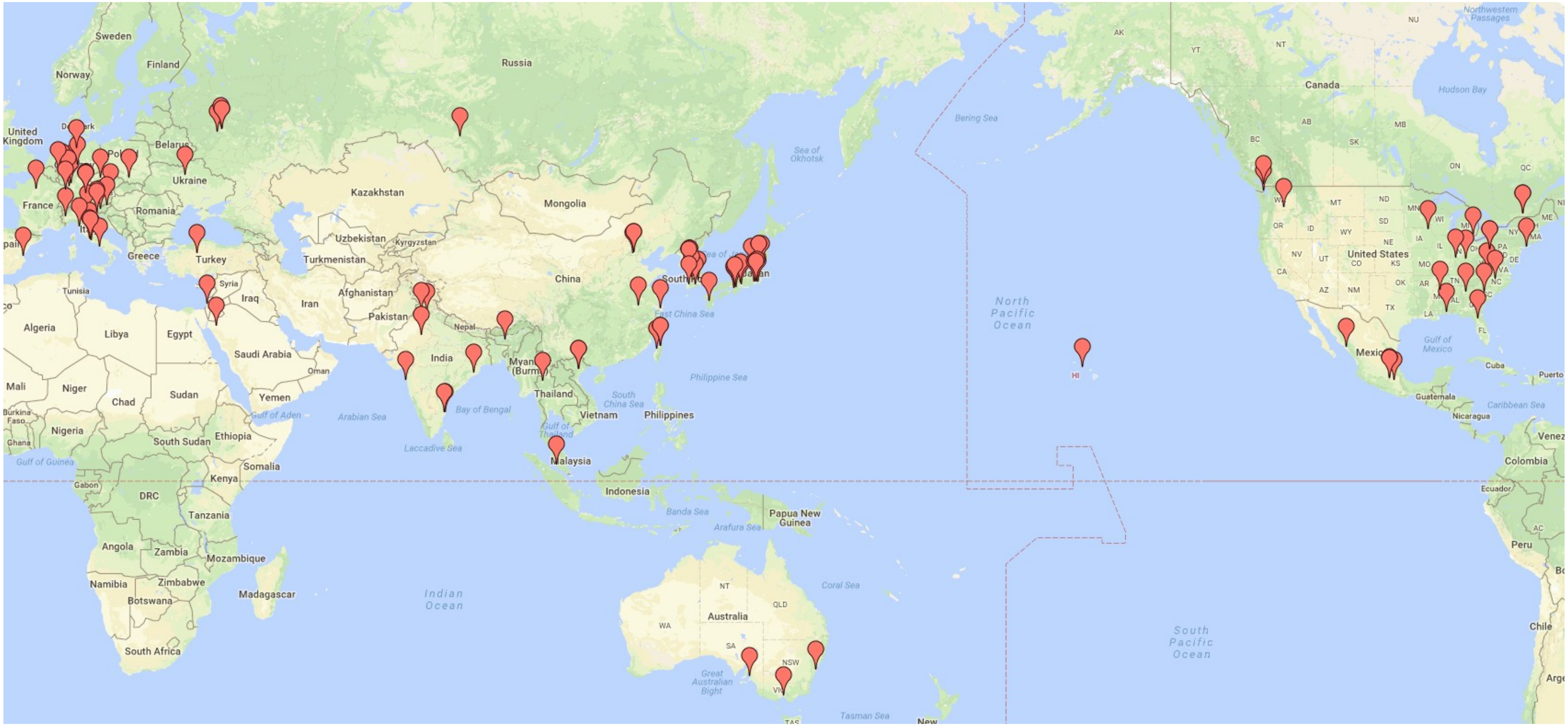
- dark sector
- $b \rightarrow s\ell\ell$

Status

Belle II at SuperKEKB

The project

- 700+ physicists
- 100+ institutes
- 23 countries



Belle II at SuperKEKB

The project

- Located at KEK, Tsukuba.
  (Japanese national HEP laboratory)
- つくば市
- 高エネルギー加速器研究機構

Belle II at SuperKEKB

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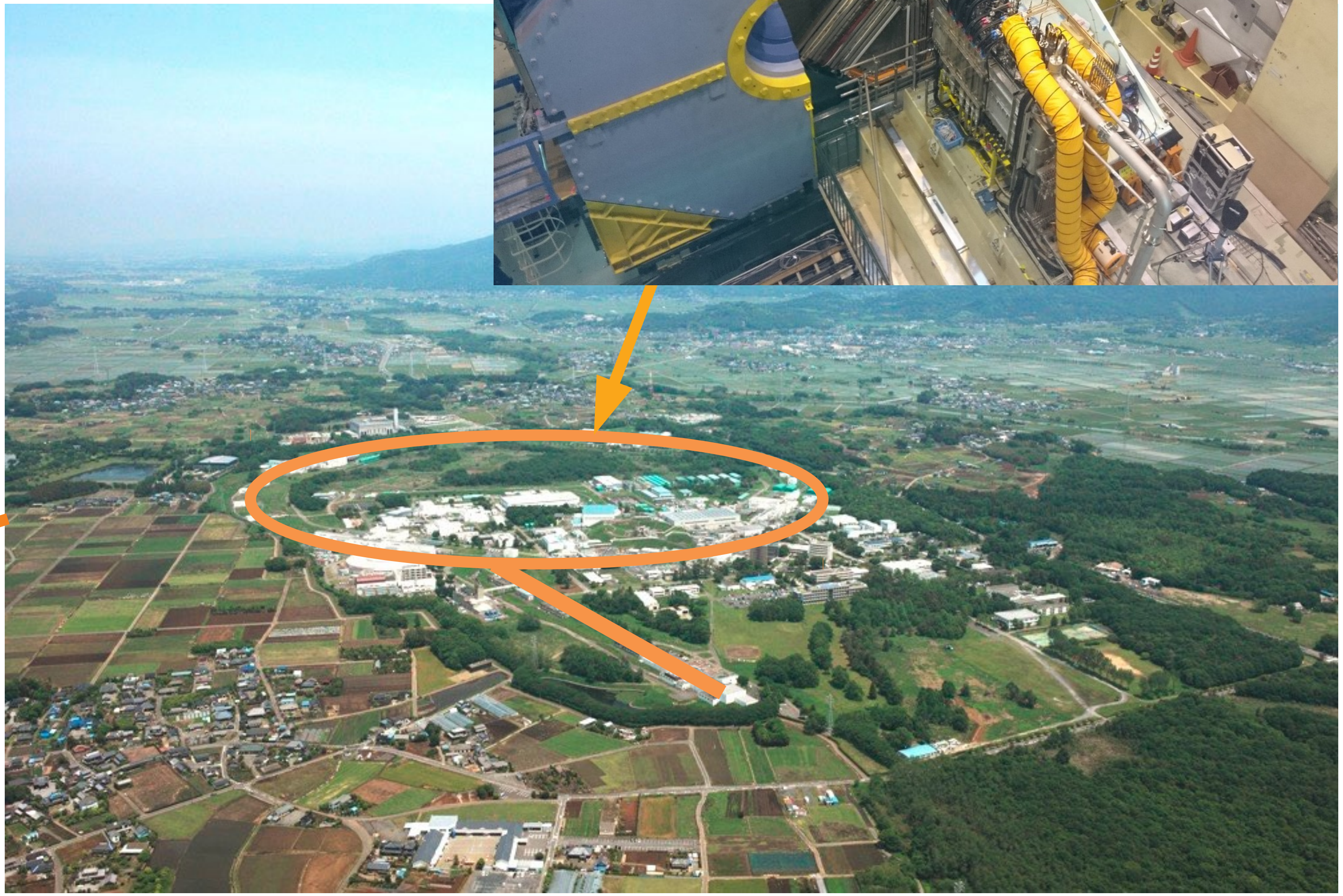
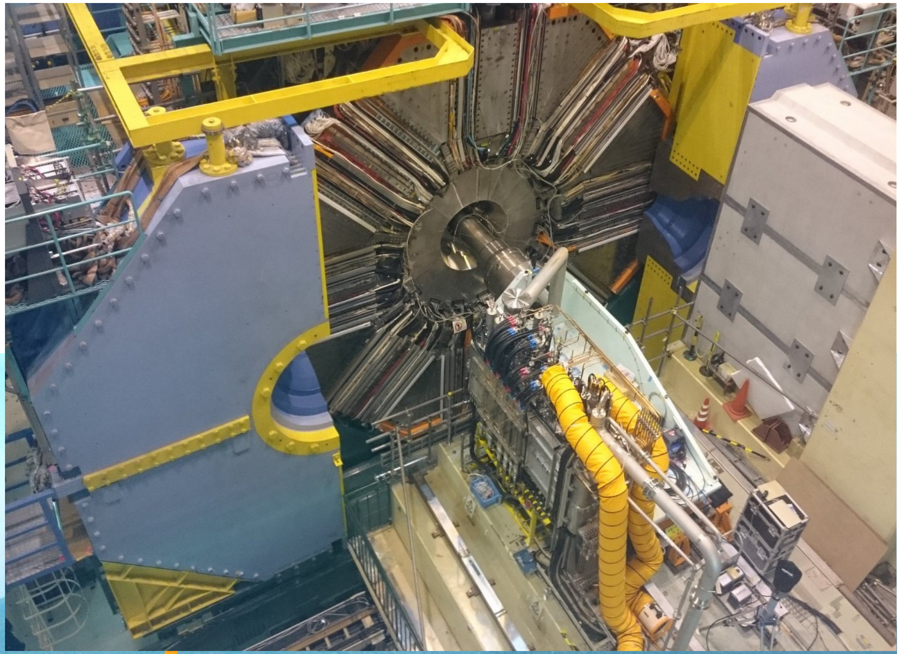
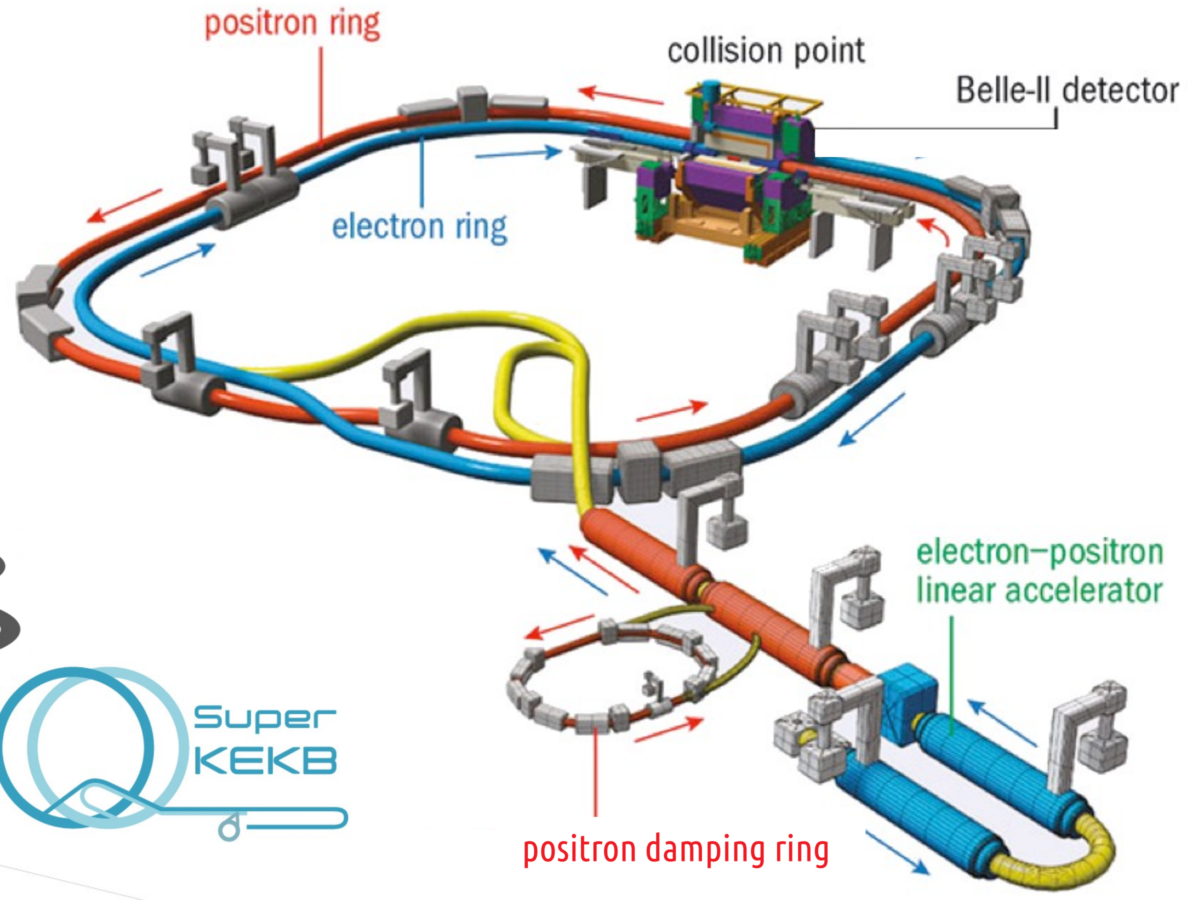
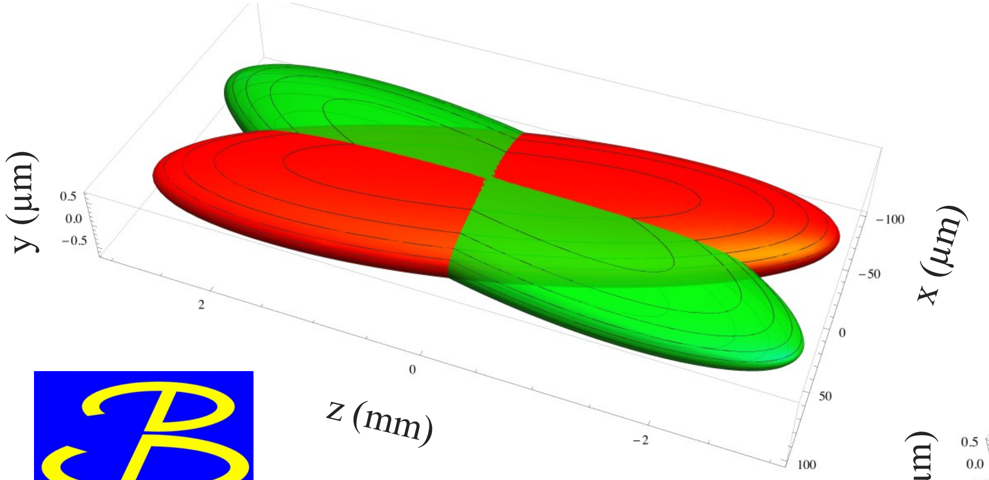


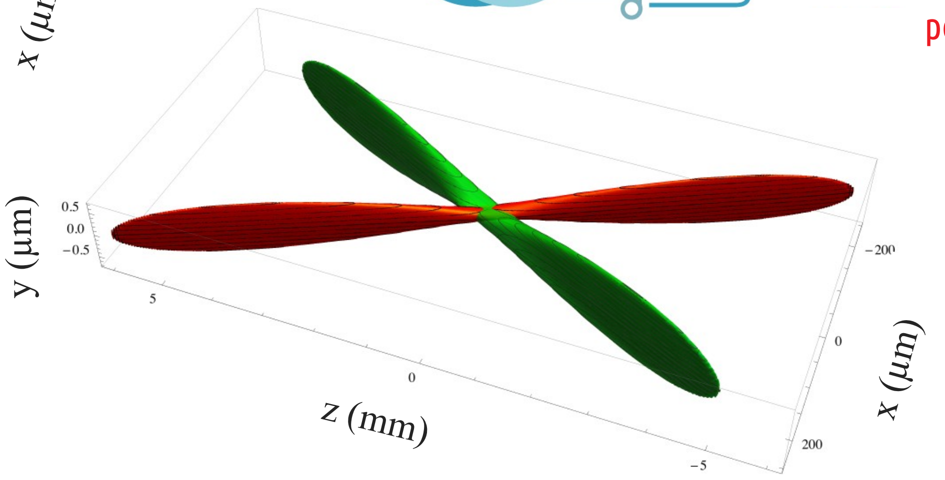


SuperKEKB

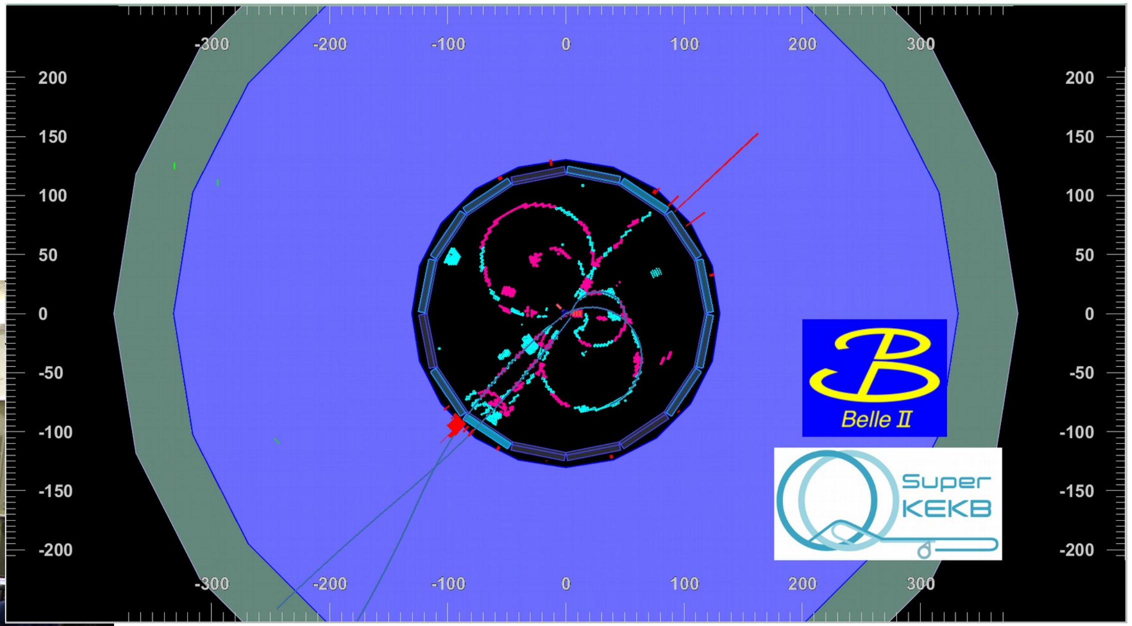
- Reason for the second iteration of the project: **upgraded accelerator**.
- A factor **40** increase in instantaneous luminosity
  - ×2 from upgraded ring (higher beam current)
  - ×20 β* from final focus magnets.





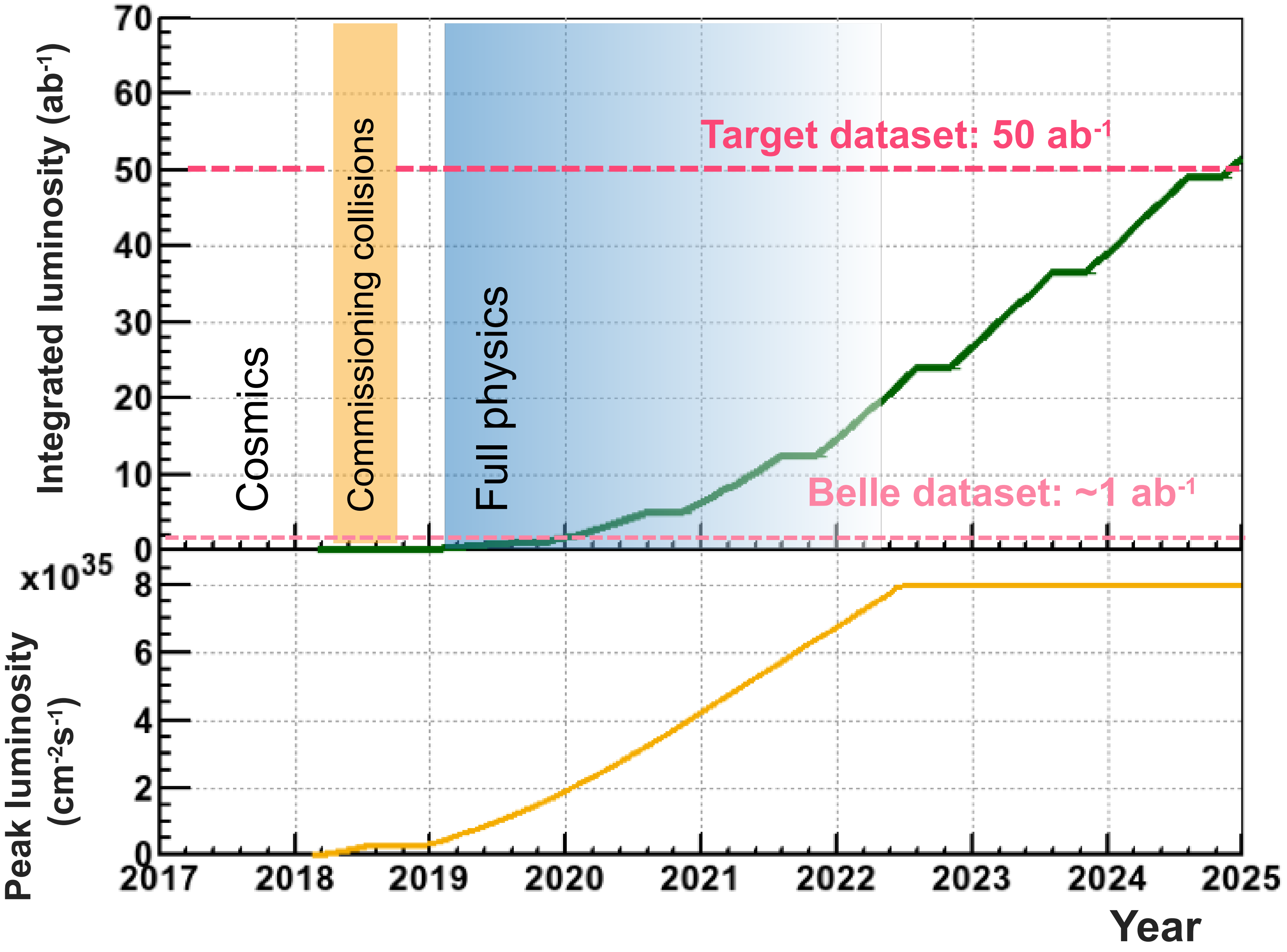


First collisions

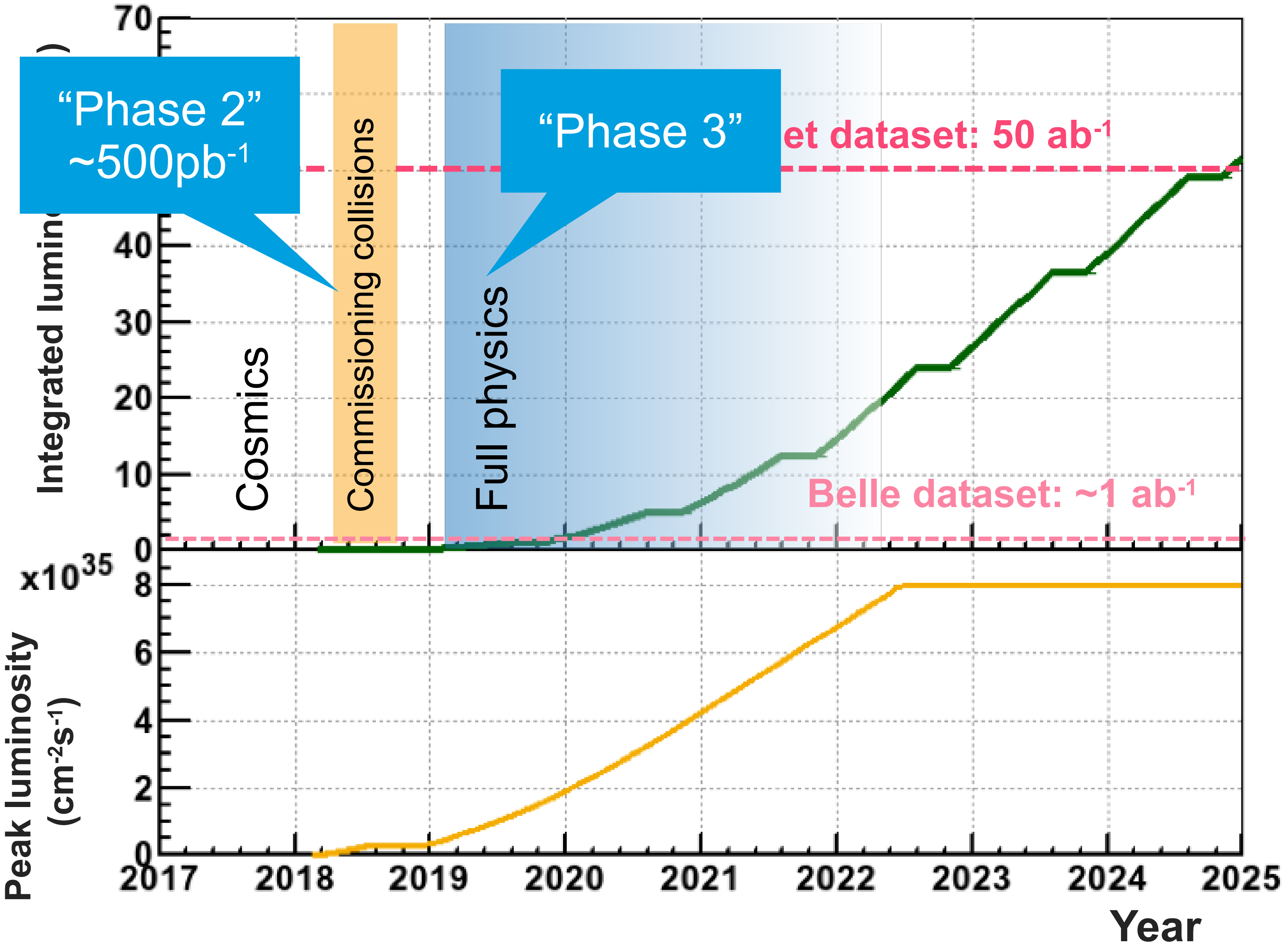


- 2018 年 4 月 26 日
  - Probably $e^+e^- \rightarrow qq$
- **500 pb^{-1} calibration data recorded this year.**

Data?


Integrated luminosity (ab-1)
70
60
50
40
30
20
10
0
Cosmics
Commissioning collisions
Full physics
Target dataset: 50 ab-1
Belle dataset: ~1 ab-1
x10^35
8
6
4
2
0
Peak luminosity (cm-2s-1)
2017
2018
2019
2020
2021
2022
2023
2024
2025
Year

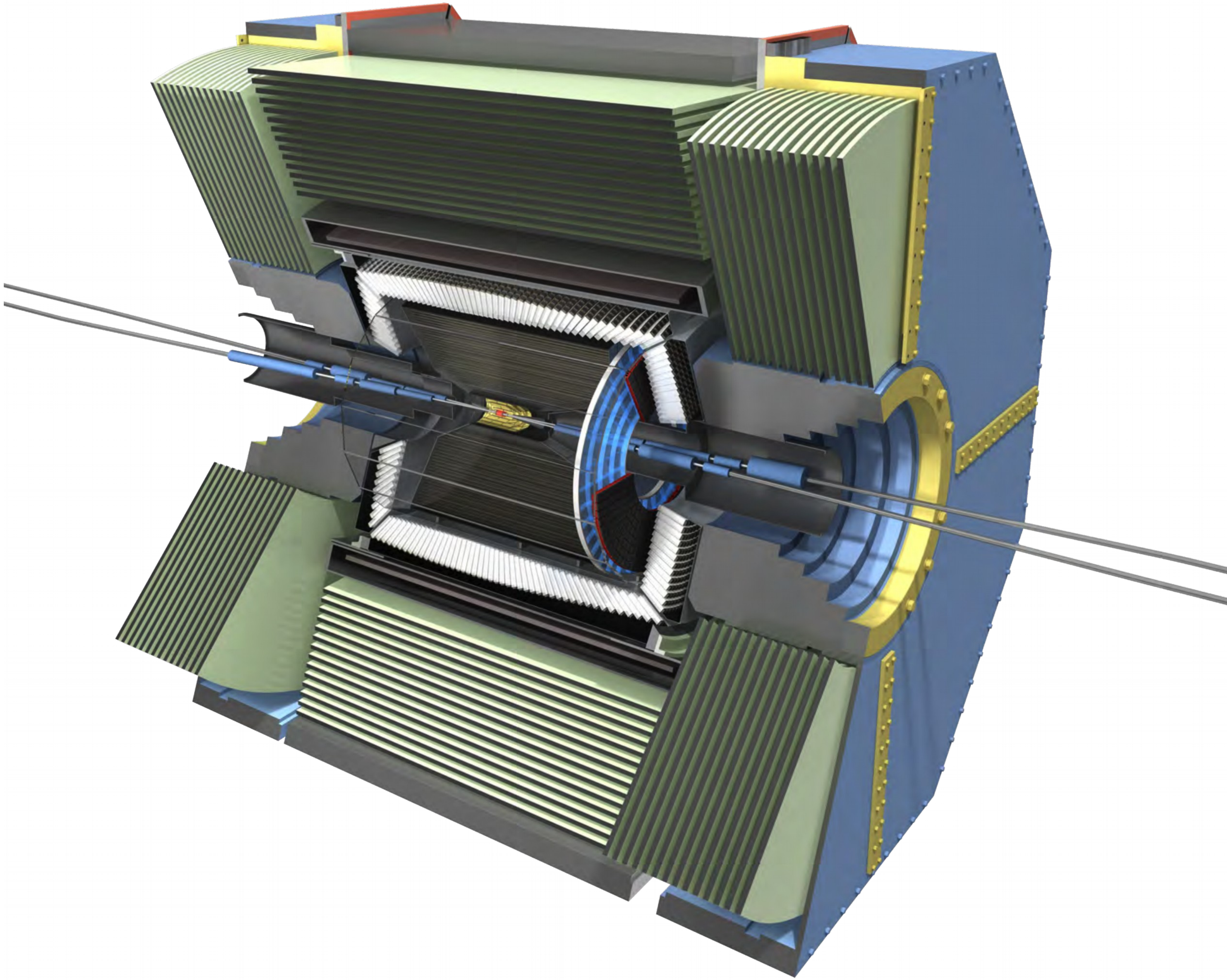
Data?



“Phase 2”
~500pb-1
“Phase 3”
Cosmics
Commissioning collisions
Full physics
et dataset: 50 ab-1
Belle dataset: ~1 ab-1
Integrated lumin
Peak luminosity (cm-2s-1)
x10^35
70
40
30
20
10
0
8
6
4
2
0
2017
2018
2019
2020
2021
2022
2023
2024
2025
Year

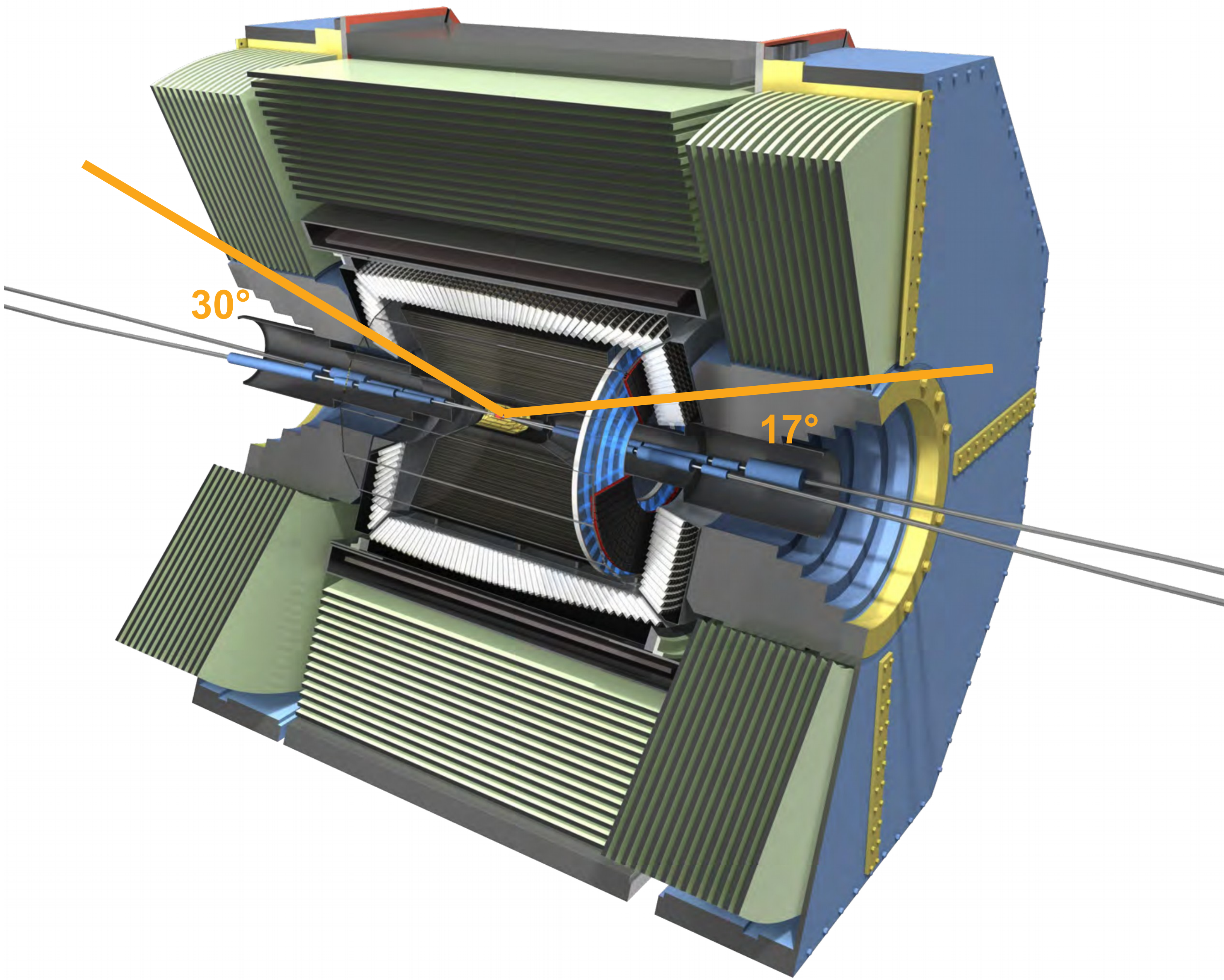
Belle II

The detector



Belle II

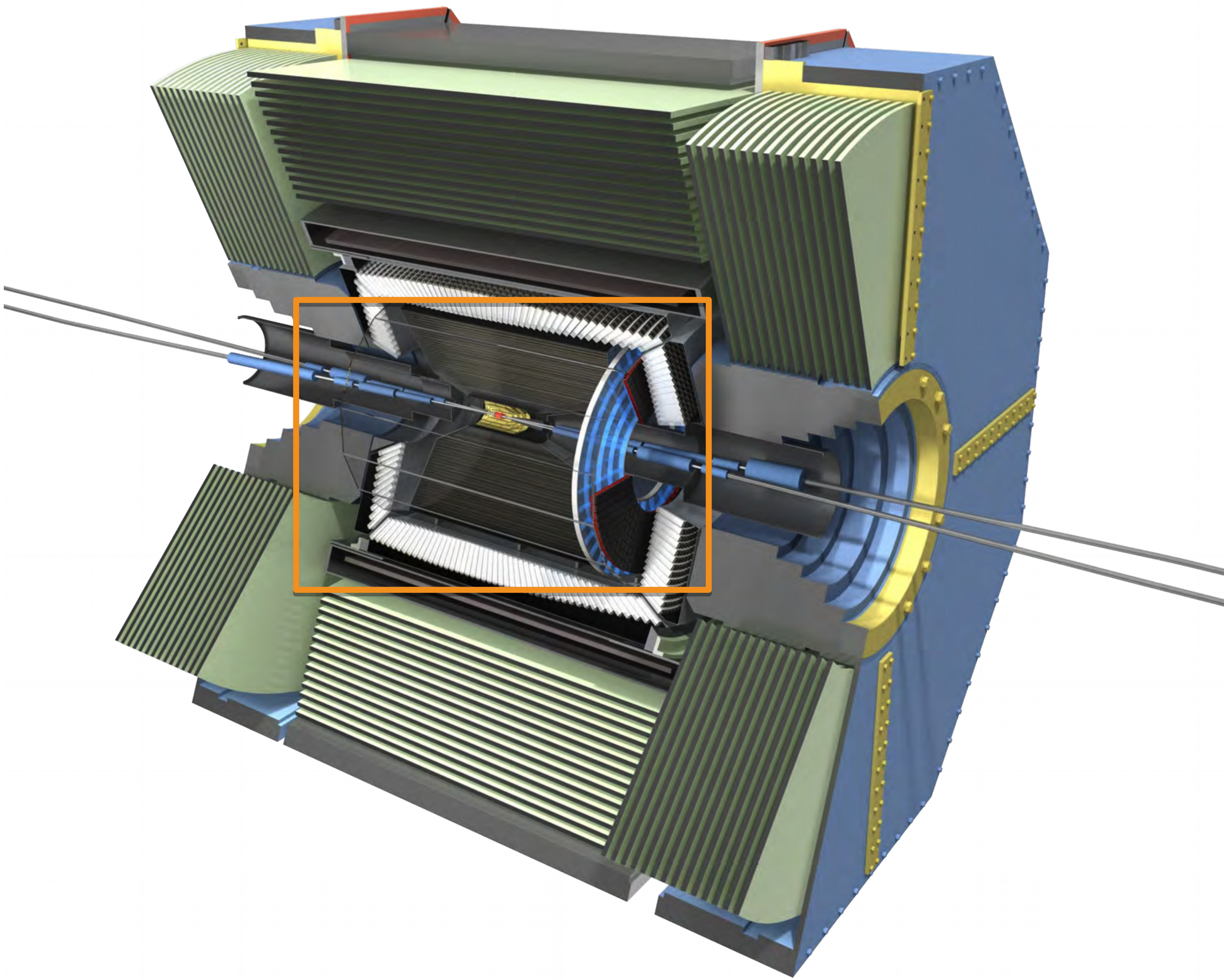
The detector



Direction of boost
Direction of electron beam
"Forward"

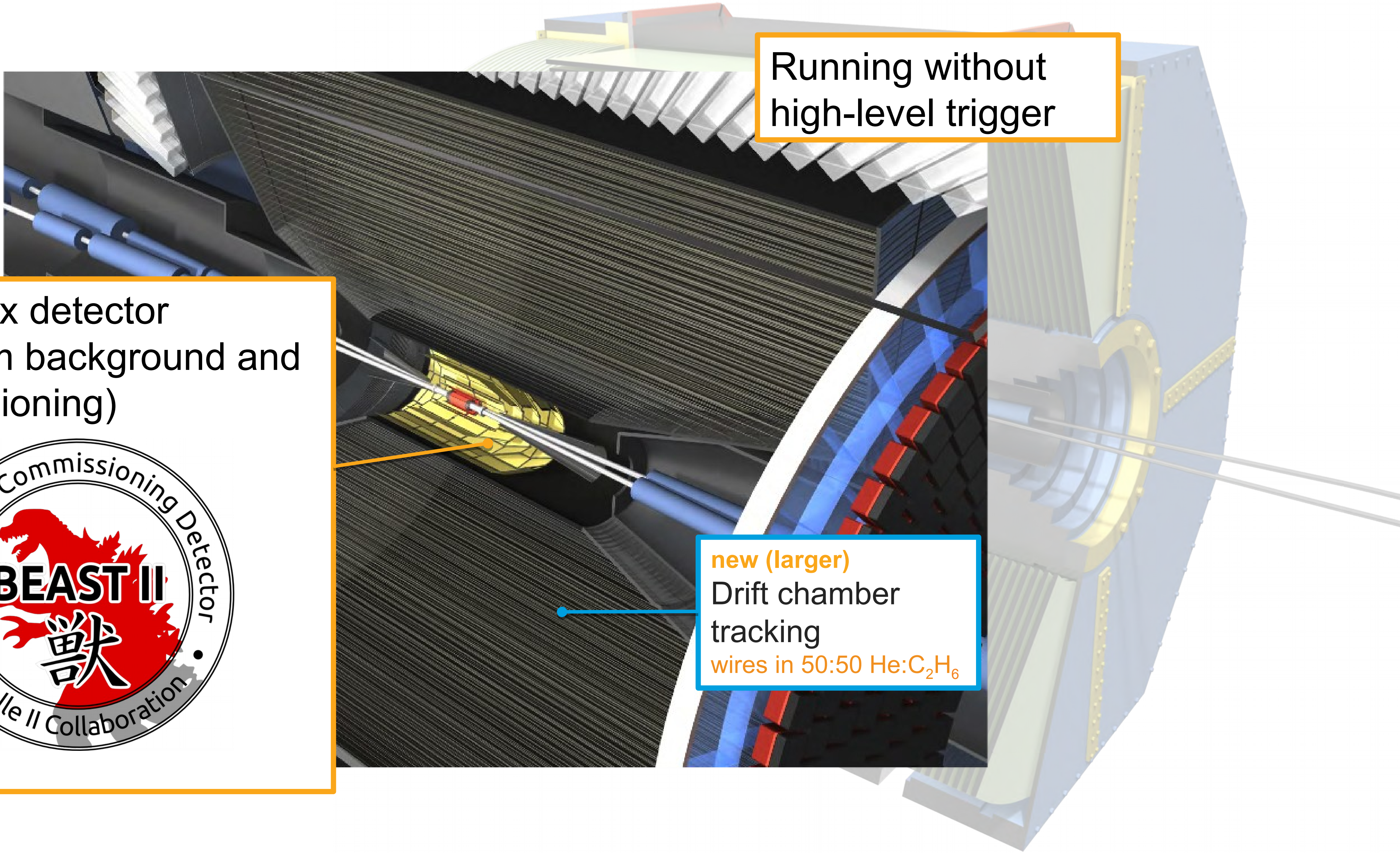
Belle II

The detector



Belle II

The detector
In phase 2



Running without high-level trigger

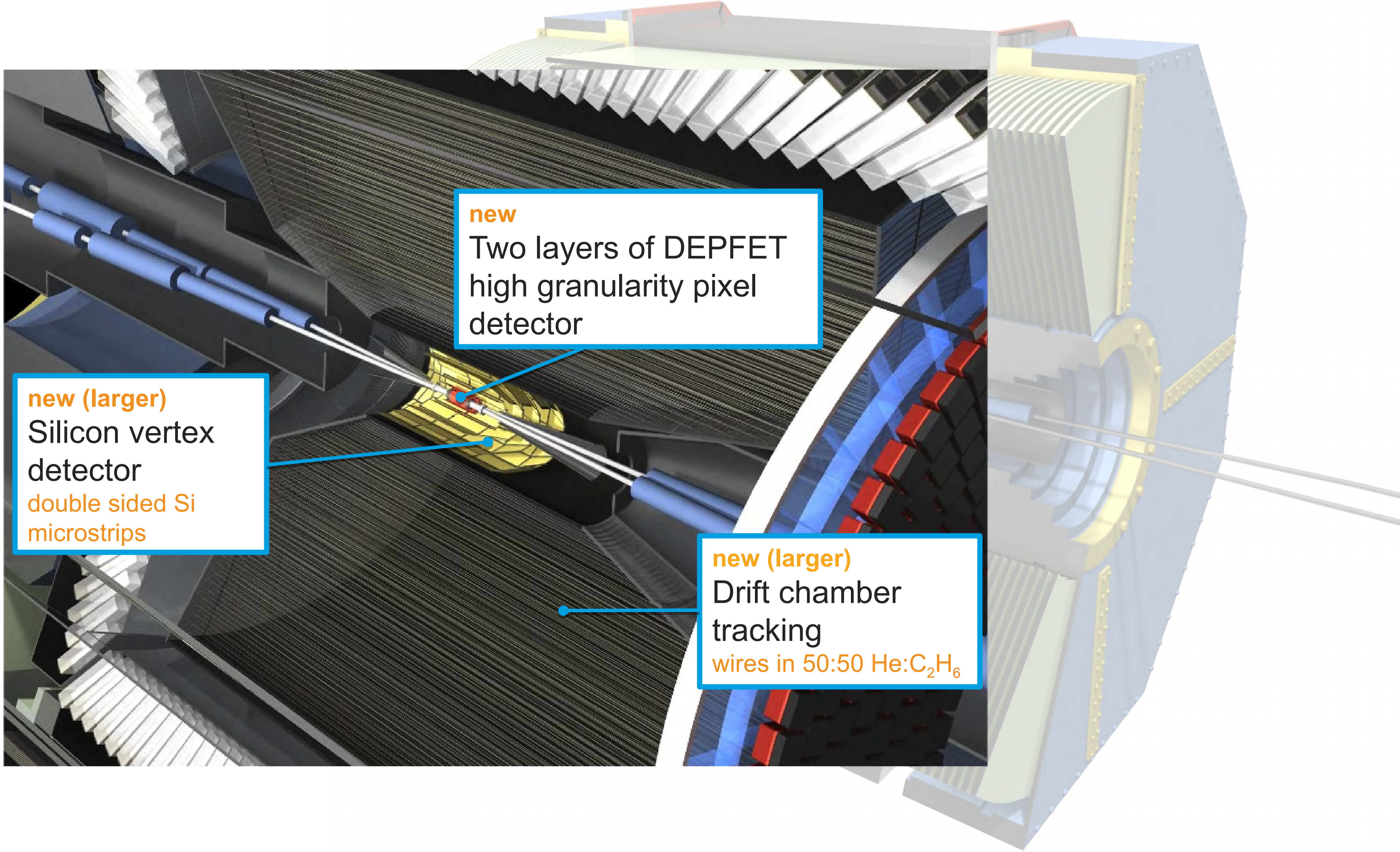
1/8 vertex detector (for beam background and commissioning)

SuperKEKB Commissioning Detector
BEAST II
獣
Belle II Collaboration

new (larger)
Drift chamber tracking
wires in 50:50 He:C_2H_6

Belle II

The detector



Recent news

Belle II Collaboration added 3 new photos.
August 22 ·

After many years of development, assembly, and testing in Germany, the first half-shell of #Belle2's pixel detector arrived safely at KEK on August 21, 2018.

126 Likes 15 Shares

Belle II Experiment @belle2collab · Nov 22

VerteX Detector (VXD) successfully installed in #Belle2. The Belle II detector is now complete!

11 22

@belle2collab

Recent news

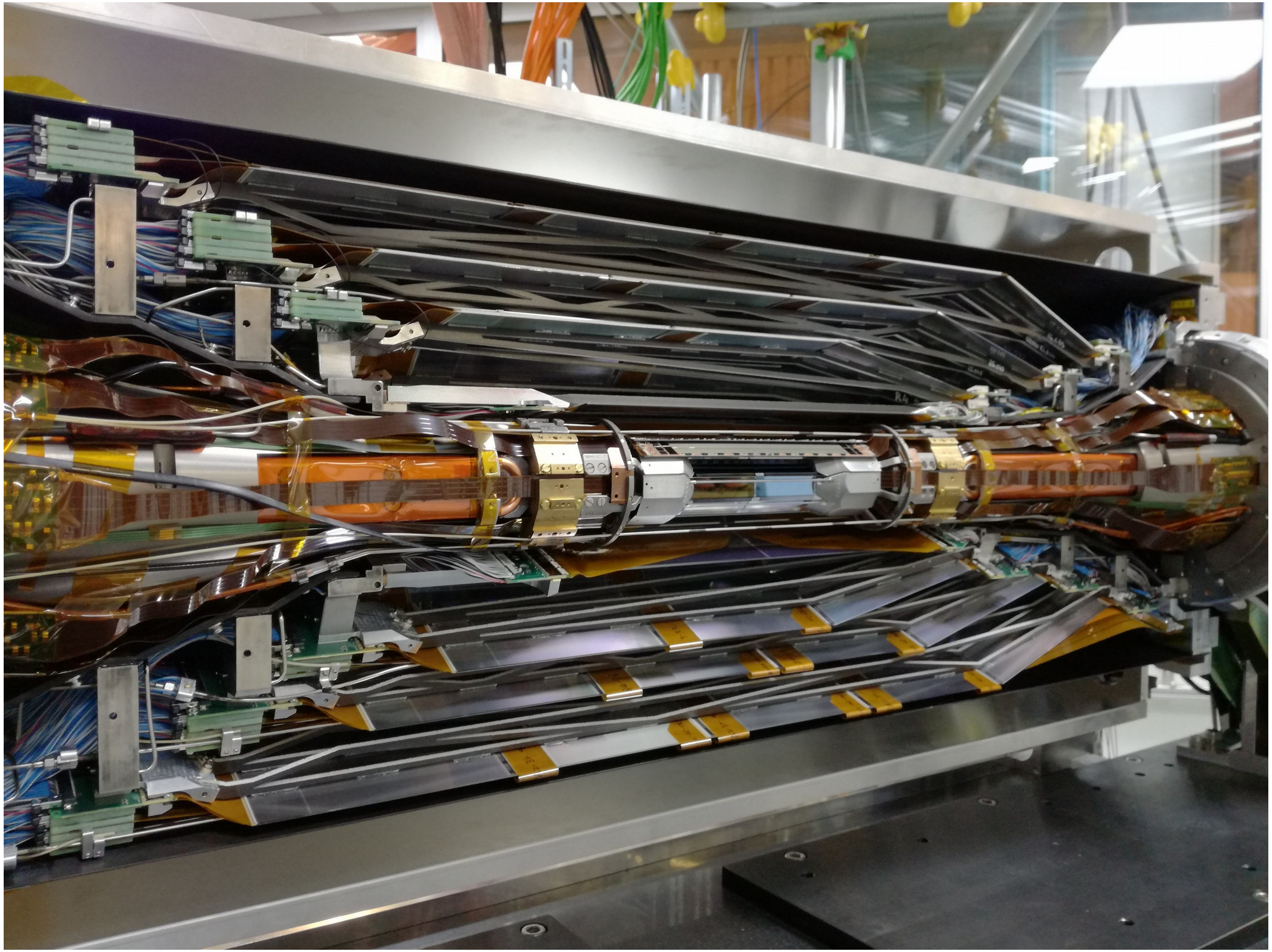
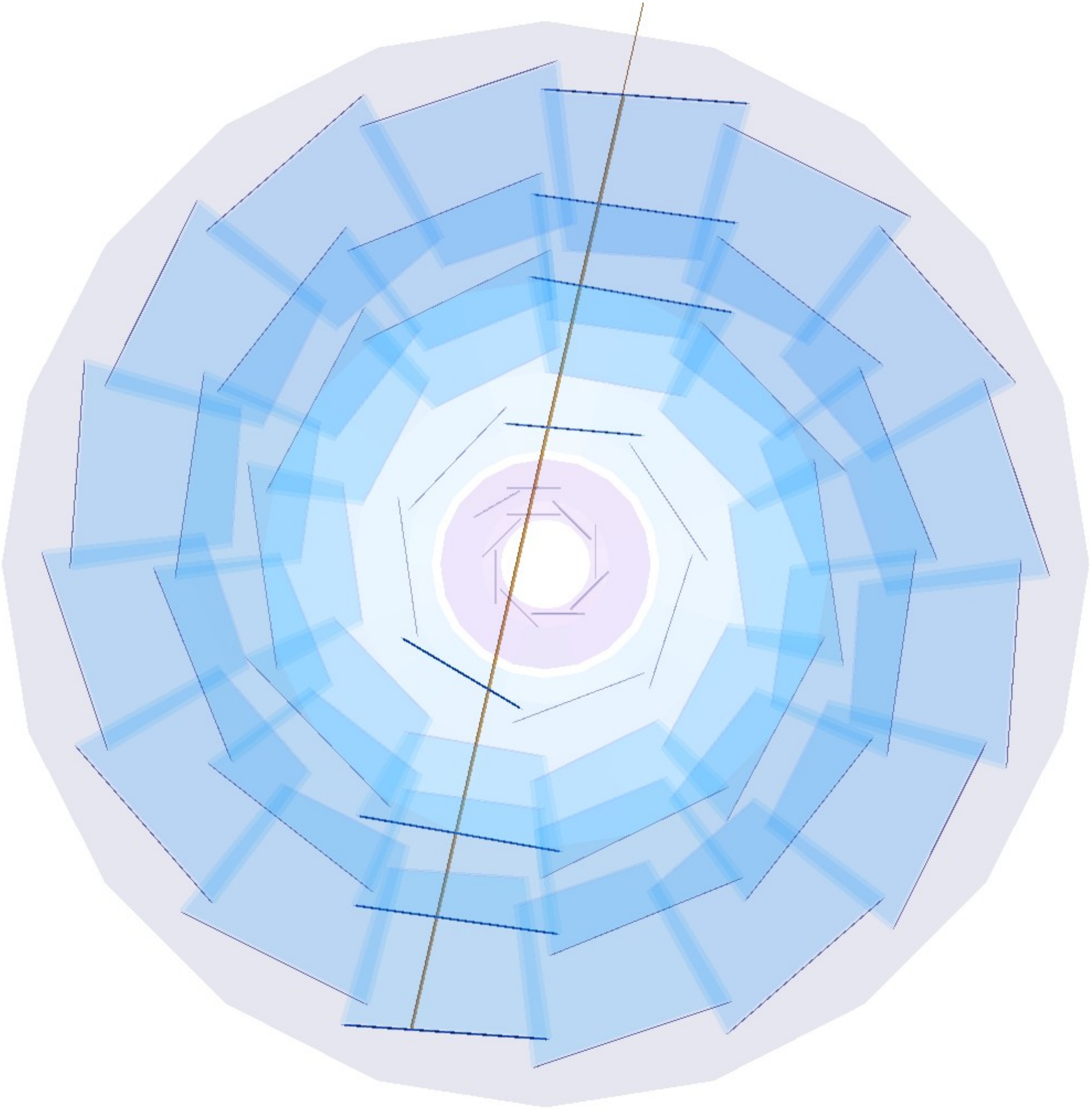


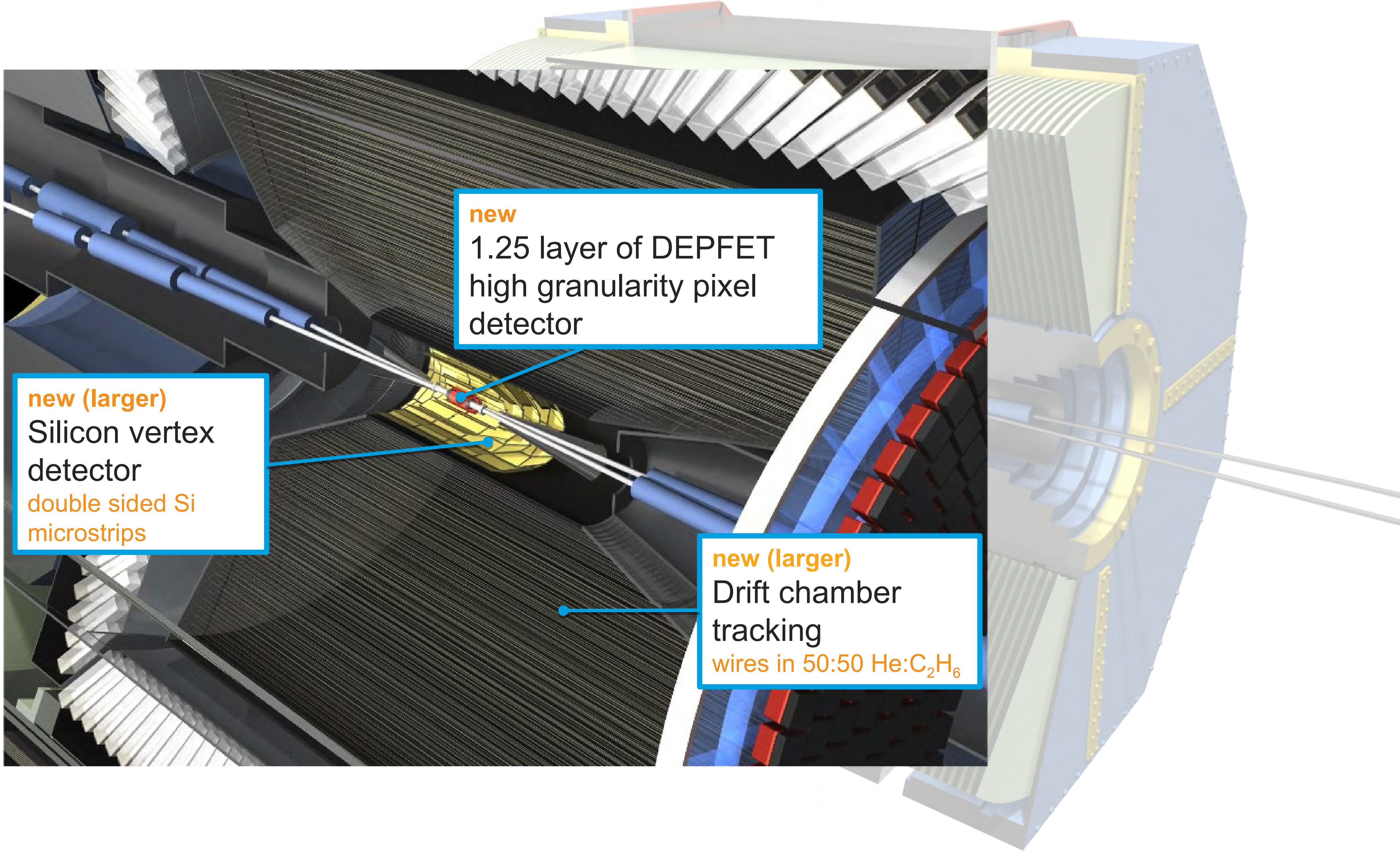
Photo: L. Zani

Recent news



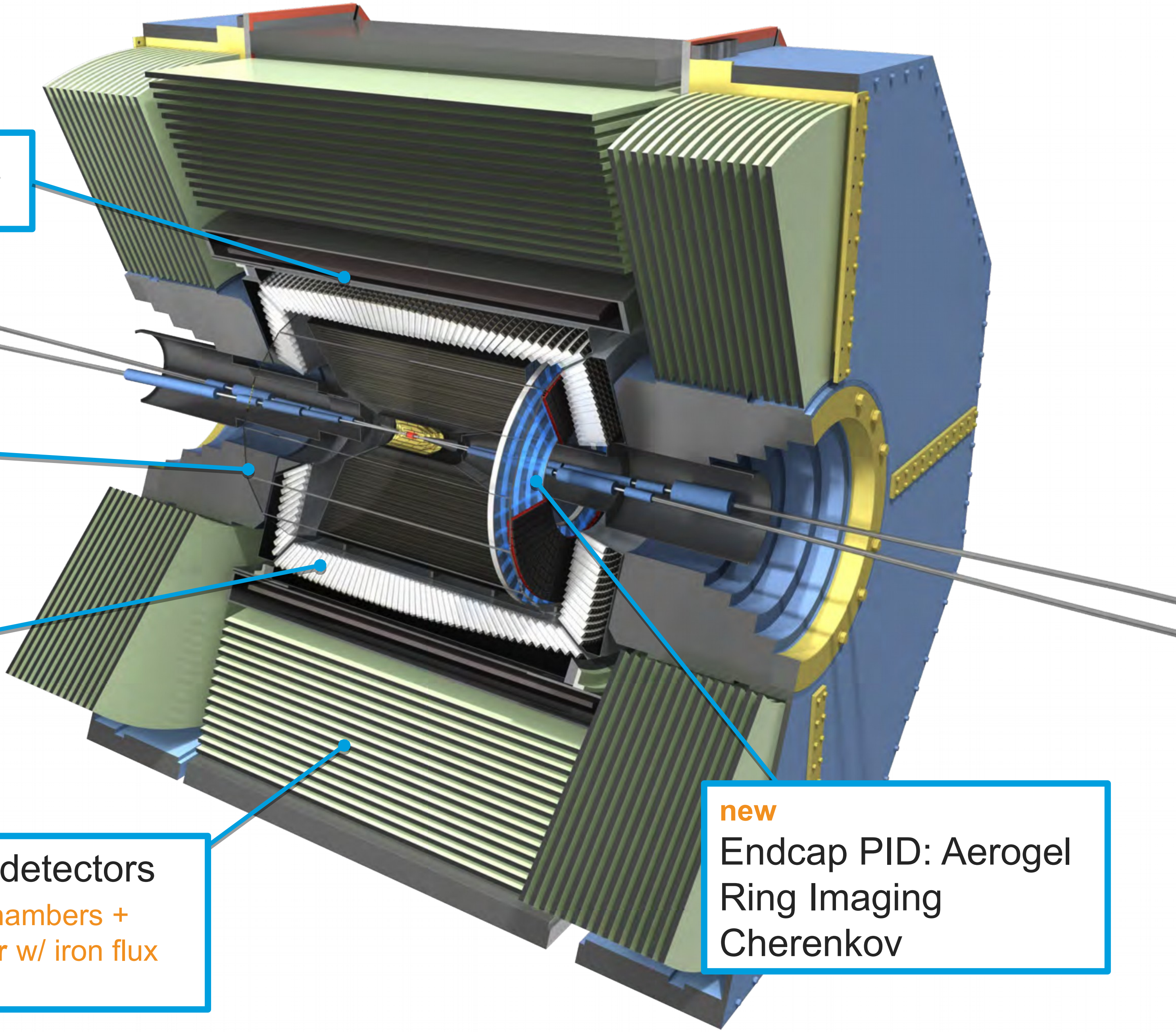
Belle II

The detector
early phase 3



Belle II

The detector



magnet
1.5T

new
Barrel particle ID
quartz bars totally internally reflect Cherenkov photons

Electromagnetic calorimeter
CsI(Tl) crystals… **new readout**

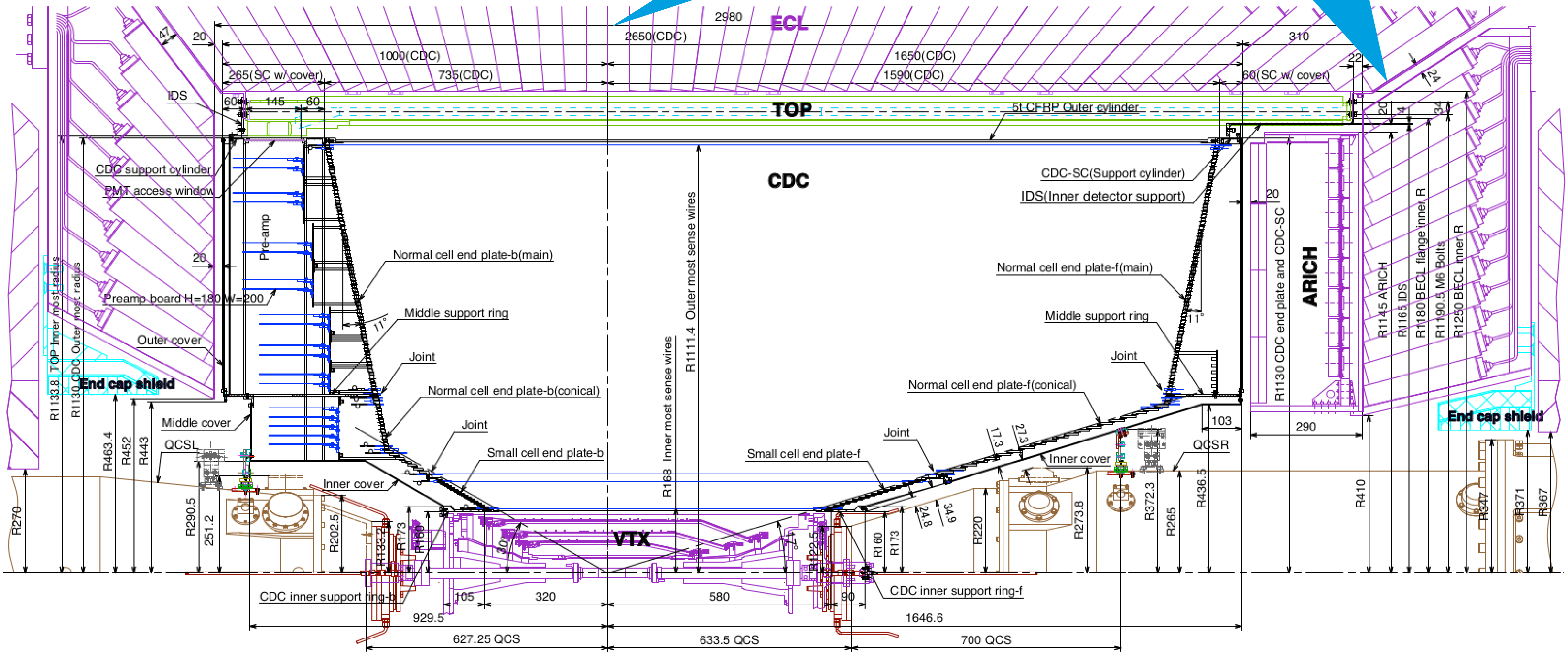
K_L and muon detectors
Resistive plate chambers + **(new) scintillator** w/ iron flux return

new
Endcap PID: Aerogel Ring Imaging Cherenkov

Calorimeter details

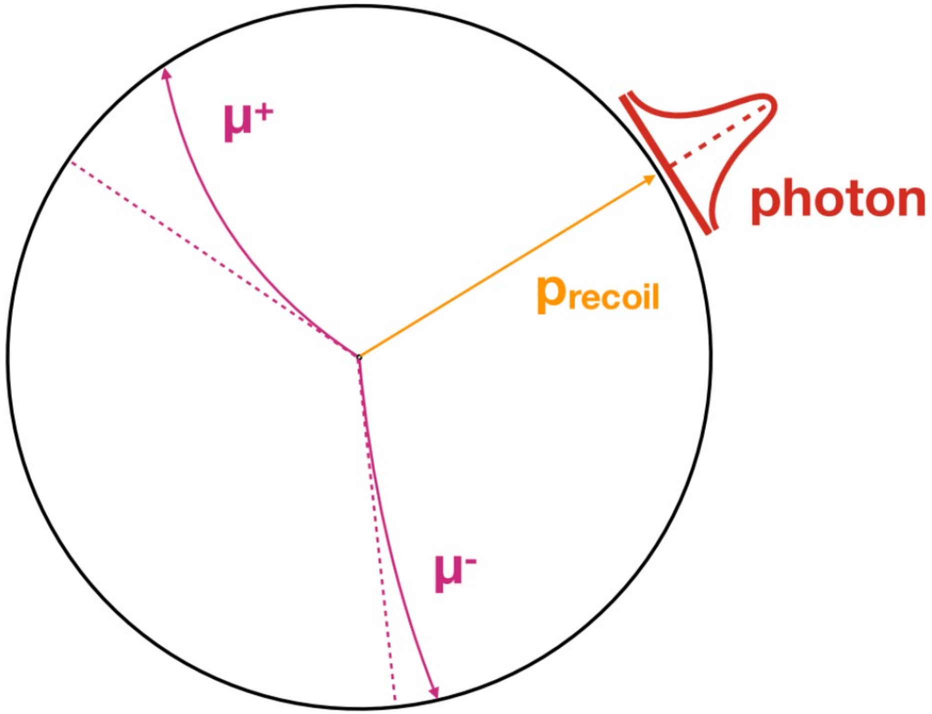
90° small gap

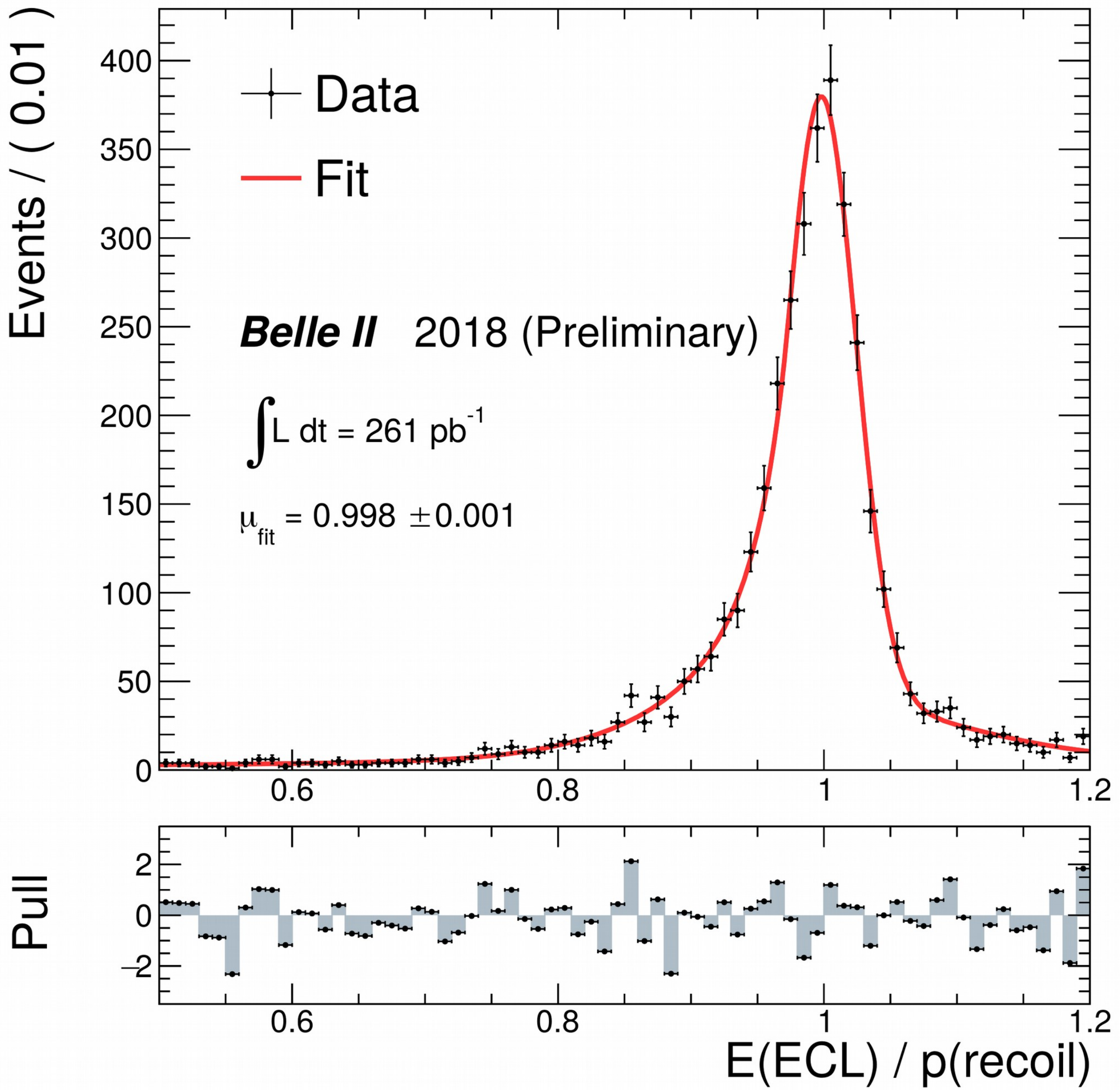
Endcap gaps



New tracking and clustering work well

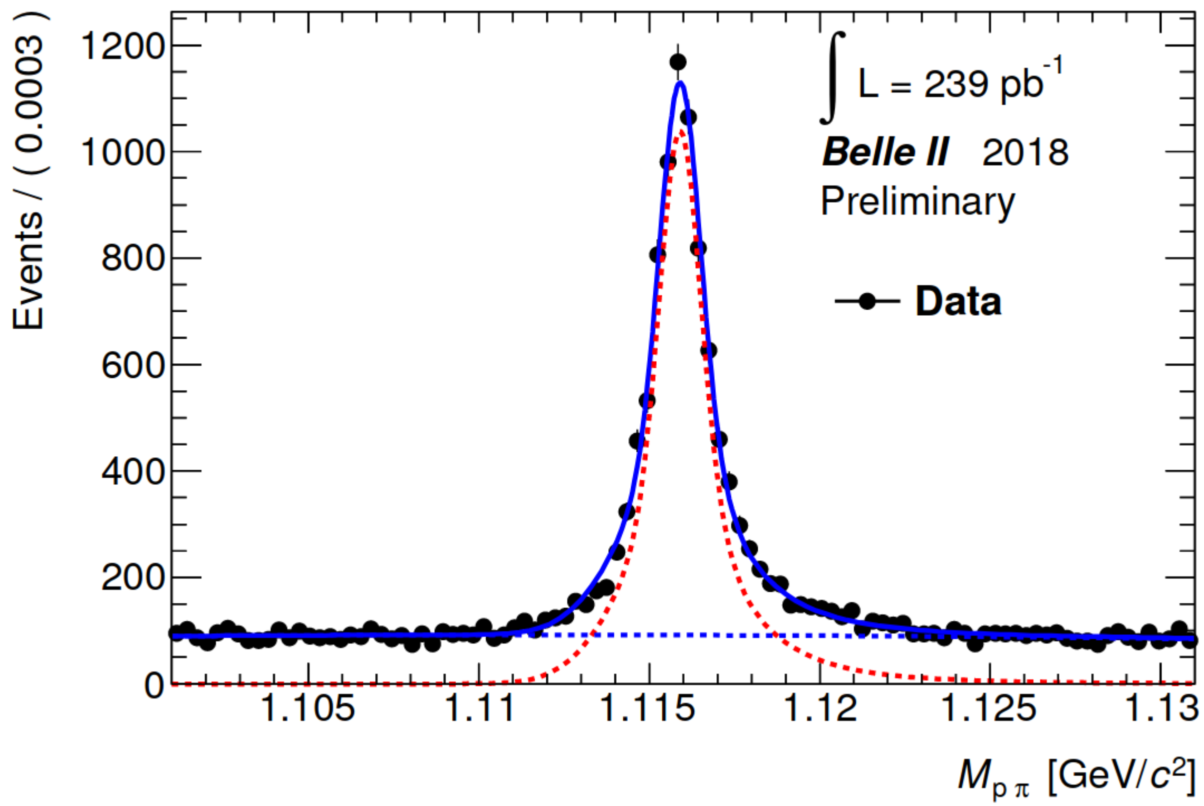
Radiative dimuon events in first data



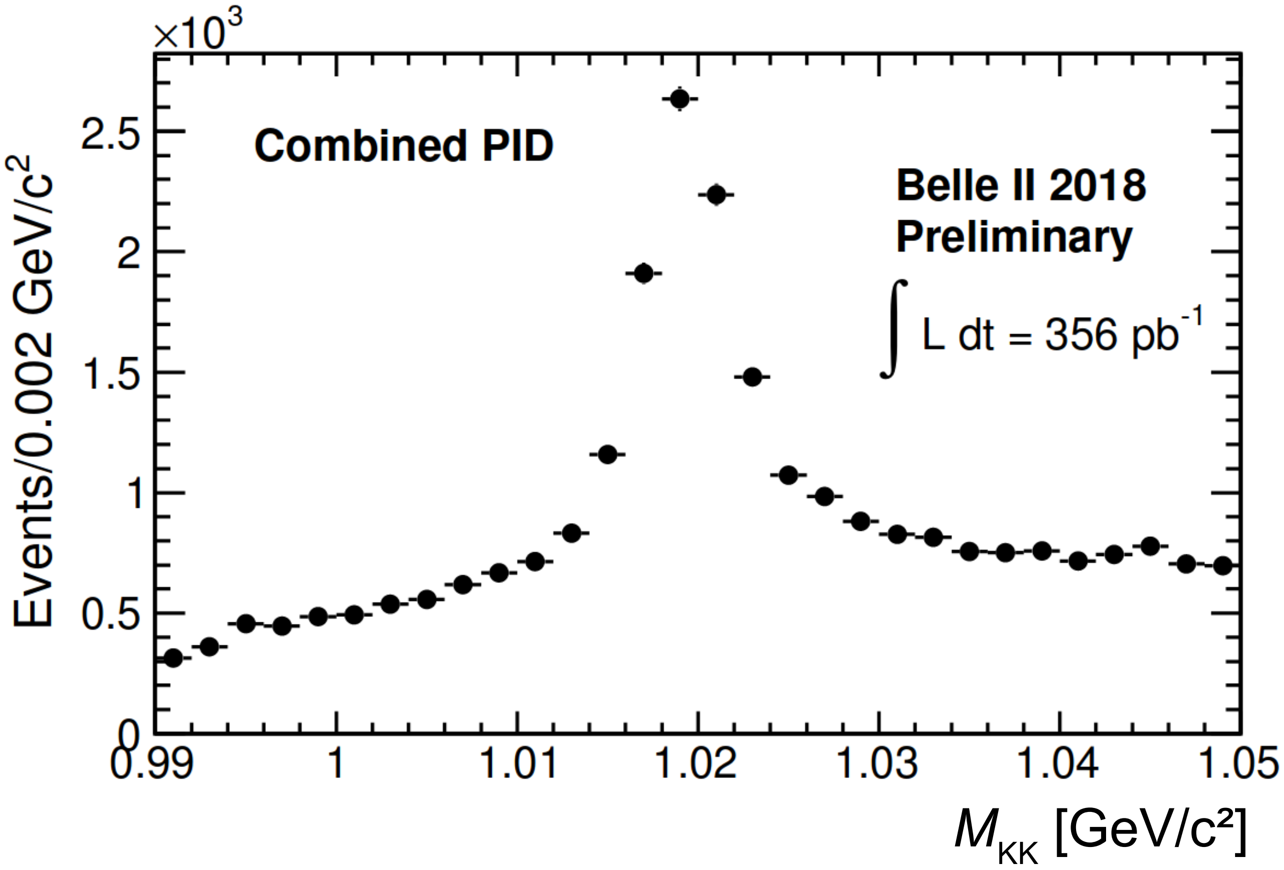


Rediscoveries!

π^0, φ^0, Λ^0, τ, J/ψ



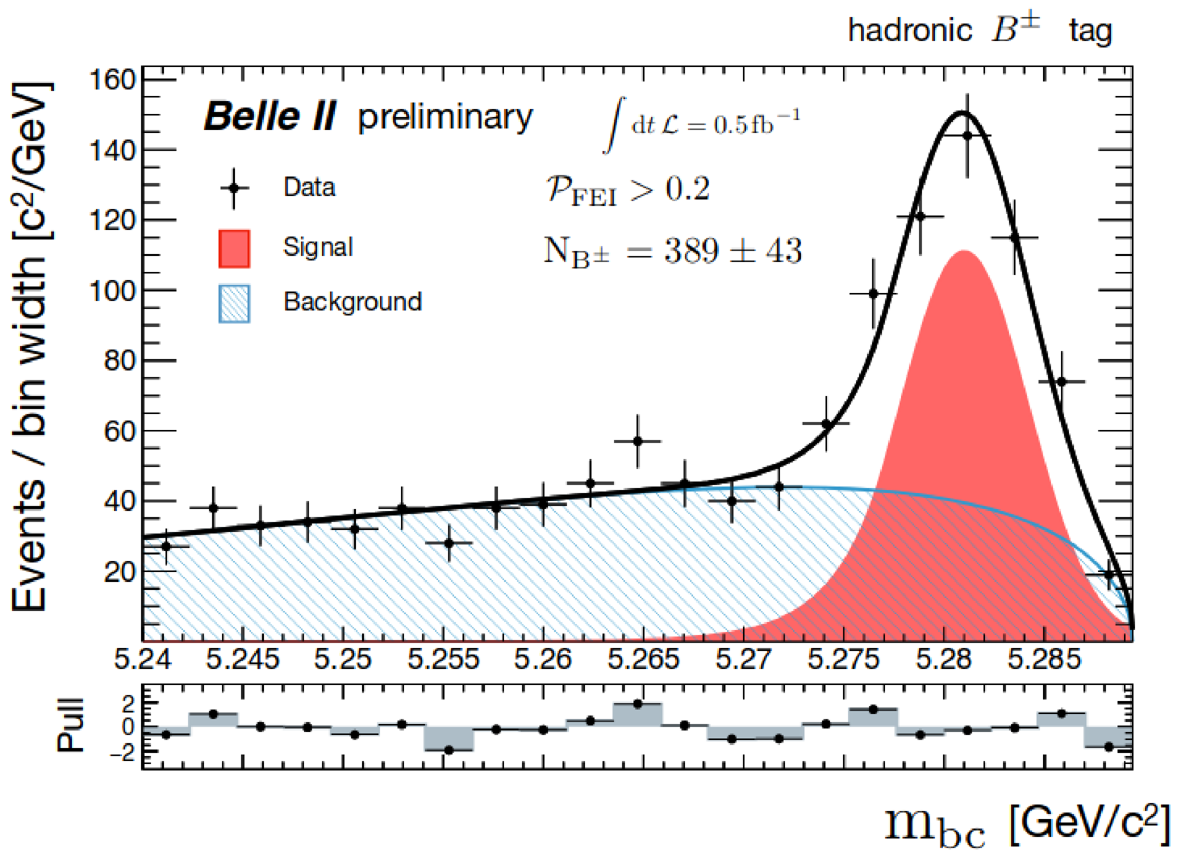
$\Lambda^0 \rightarrow p\pi$



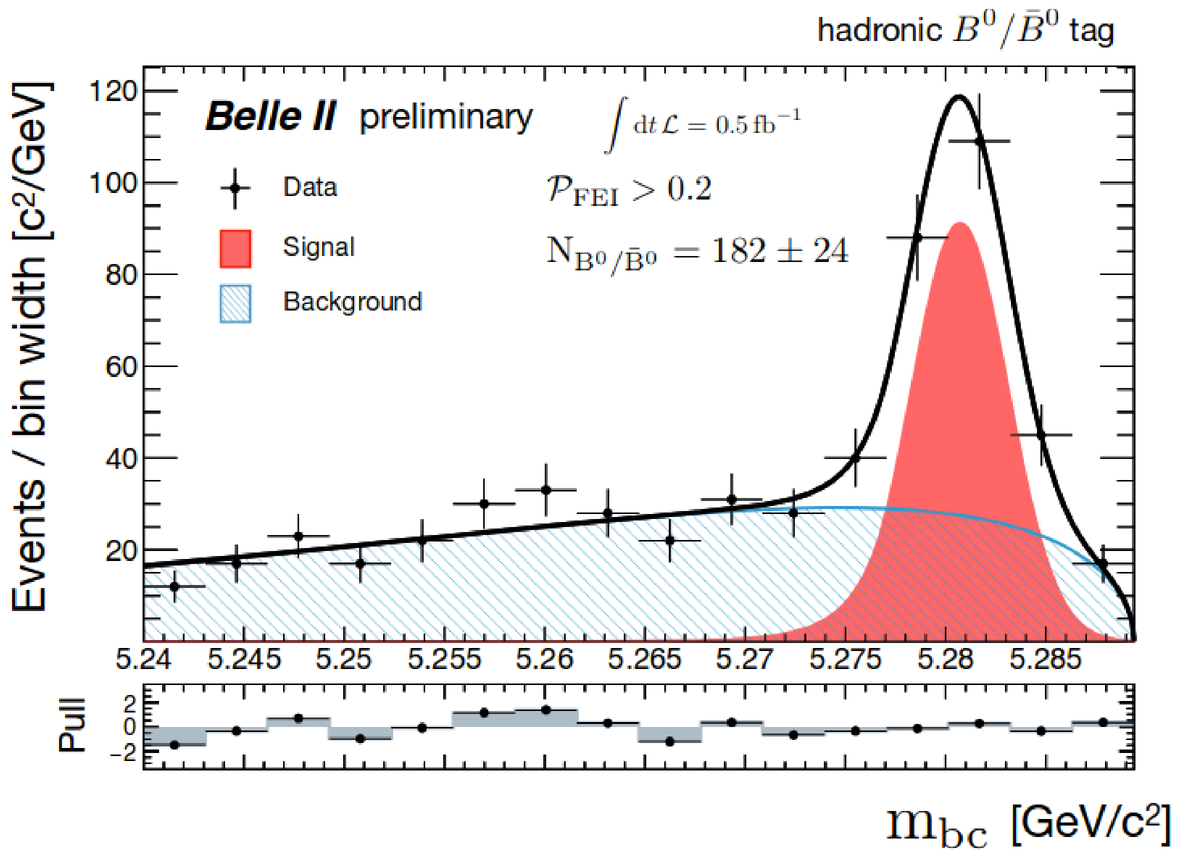
$\varphi^0 \rightarrow K^+K^-$

Rediscoveries!

B mesons



$B^{\pm}$



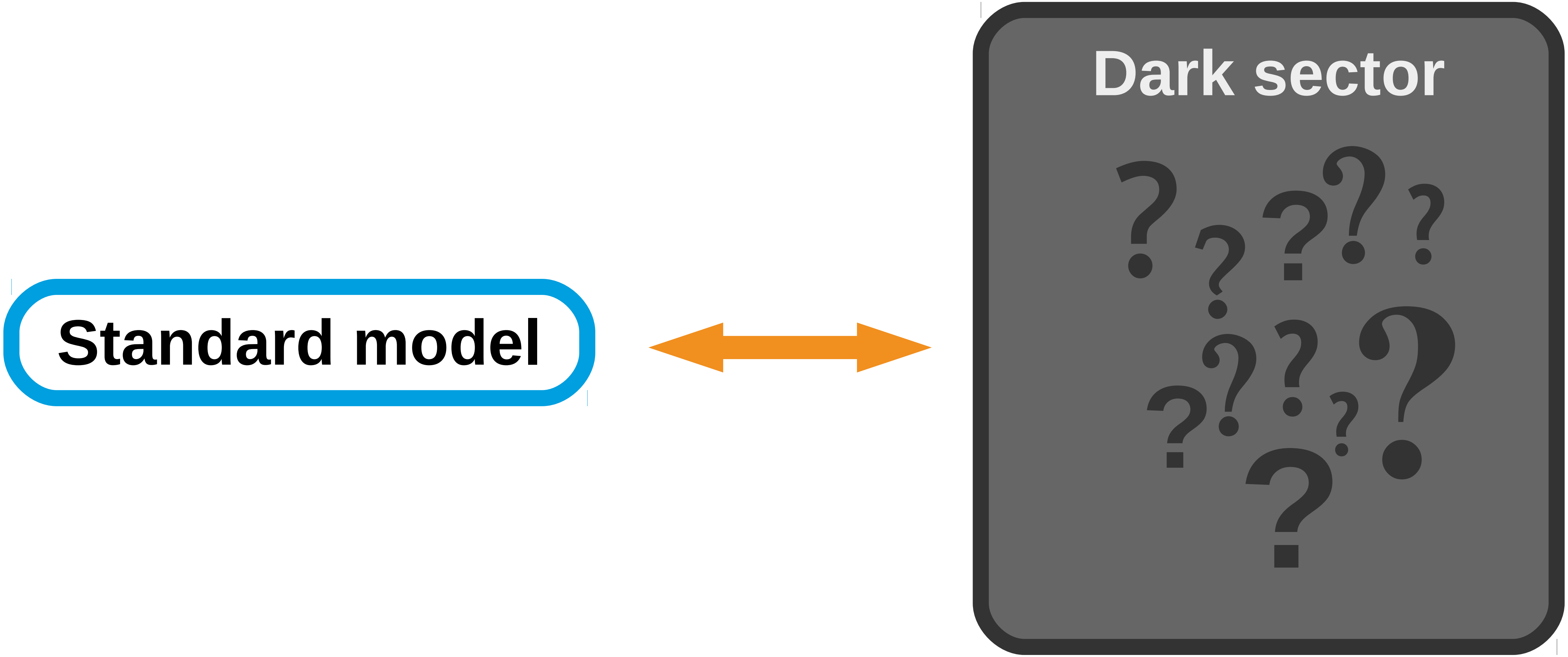
B^0

Prospects

dark sector

$b \to s\ell\ell$

Perhaps dark matter doesn’t interact directly.


Standard model
Dark sector

Dark sector physics in a nutshell

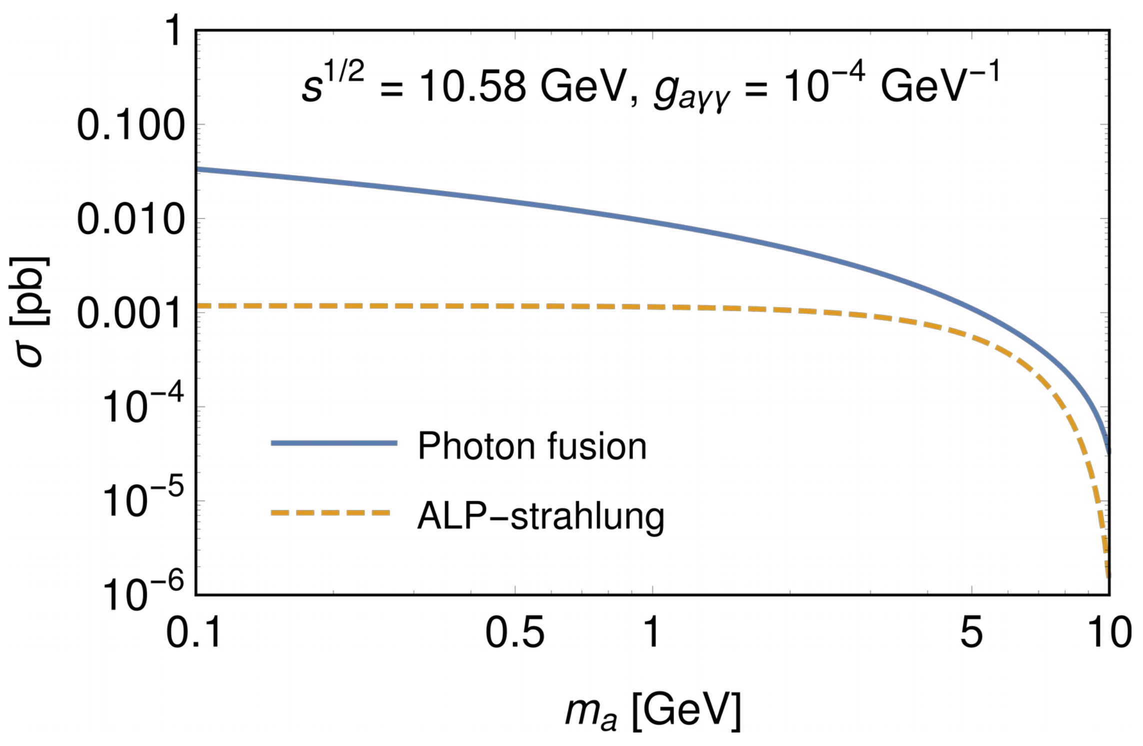
- **Dark sector** can contain one or more dark matter particles.
- Interact with **SM** via coupling/mixing with a **portal** particle.
- Many theory possibilities.
- Categorise theories by the portal particle.
  - Axion-like particle: generic scalar
  - Dark photon: vector
  - Z': vector, maybe LFV
  - Higgs: scalar w/ mass coupling
  - Neutrinoes.
- Add terms to SM Lagrangian… see what happens.

Axion-like particle

Theory

- Axion-like particle a.
- Couples to EW sector post EWSB:

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4} a F_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} a Z_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} a W_{\mu\nu}\tilde{W}^{\mu\nu}$$



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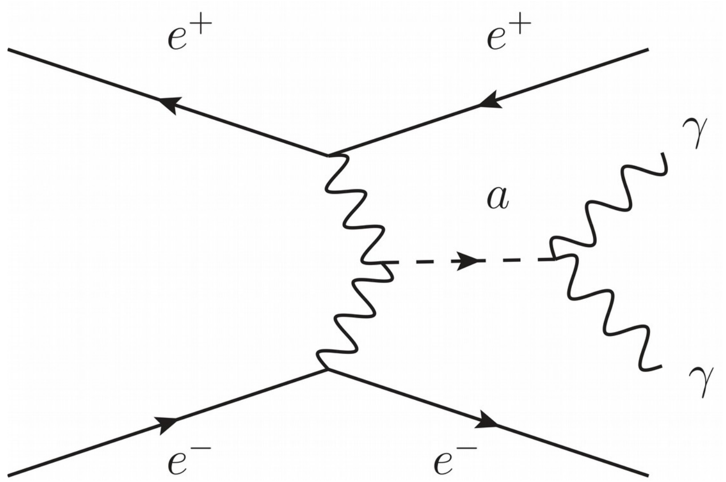
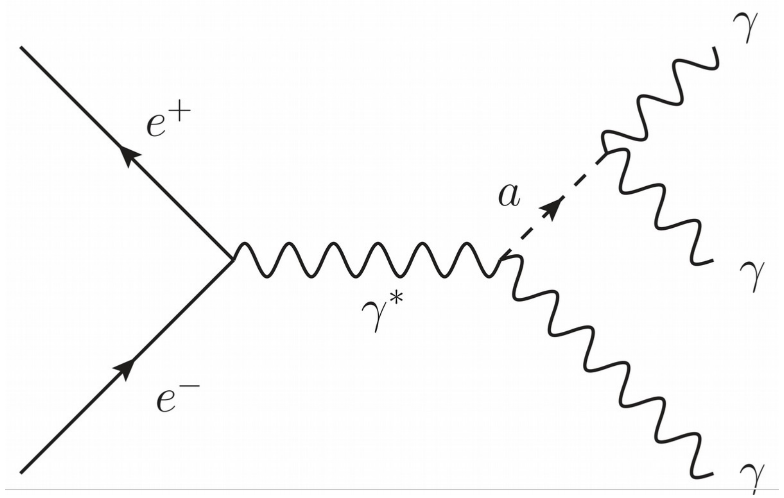
Photon fusion



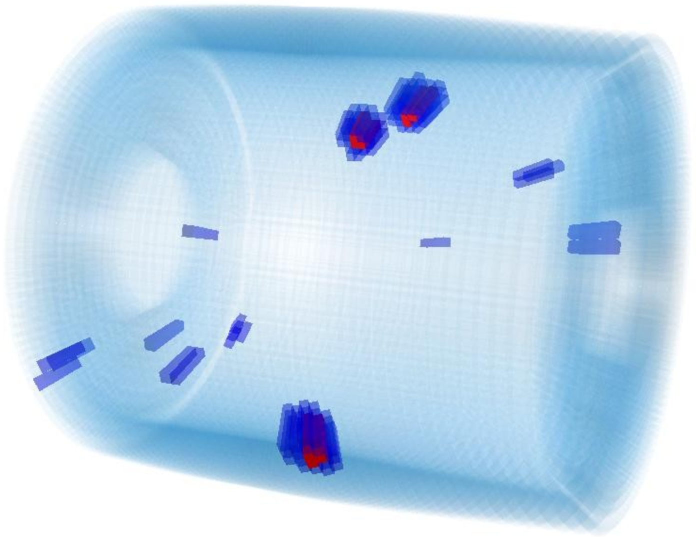
ALP-strahlung

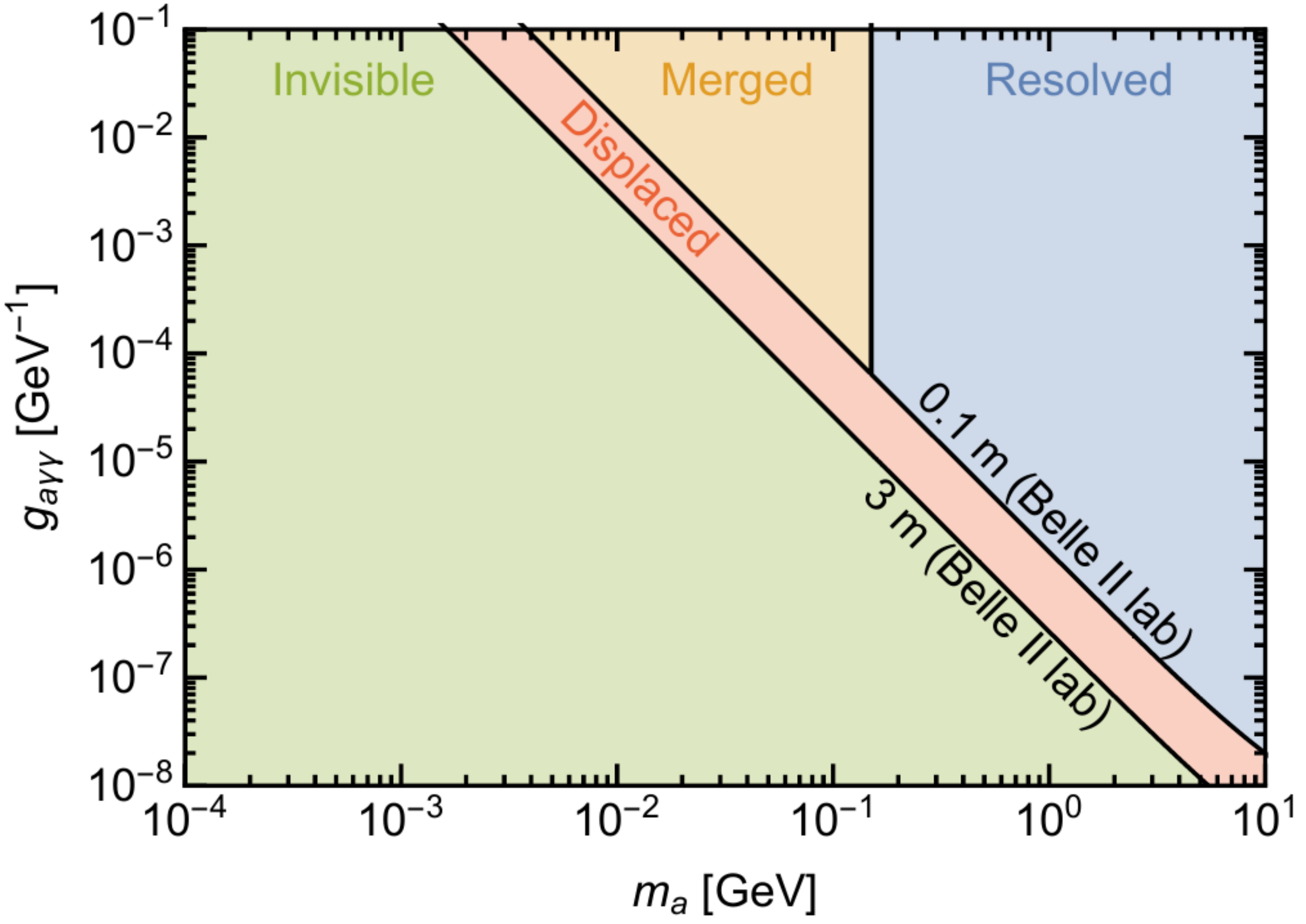


Axion-like particle

Analysis

- Experimentally easier: ALP-strahlung.
  - Do this first.
- Three photons that add up to the beam energy + bump on diphoton mass. Nothing else in event.
- **The** SM background: ee → γγ(γ).





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Axion-like particle

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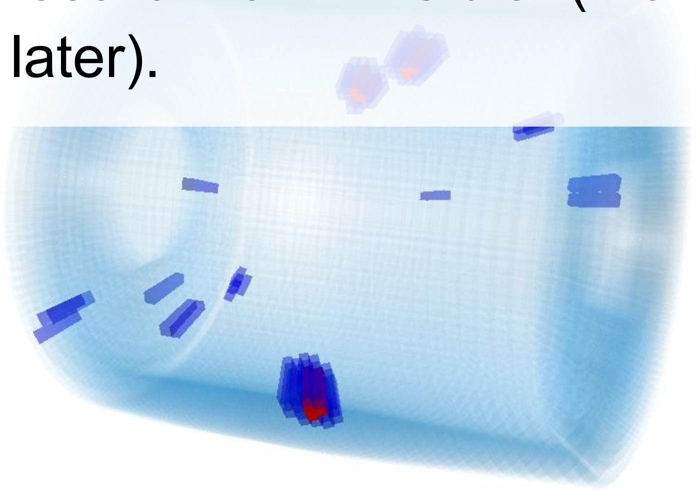
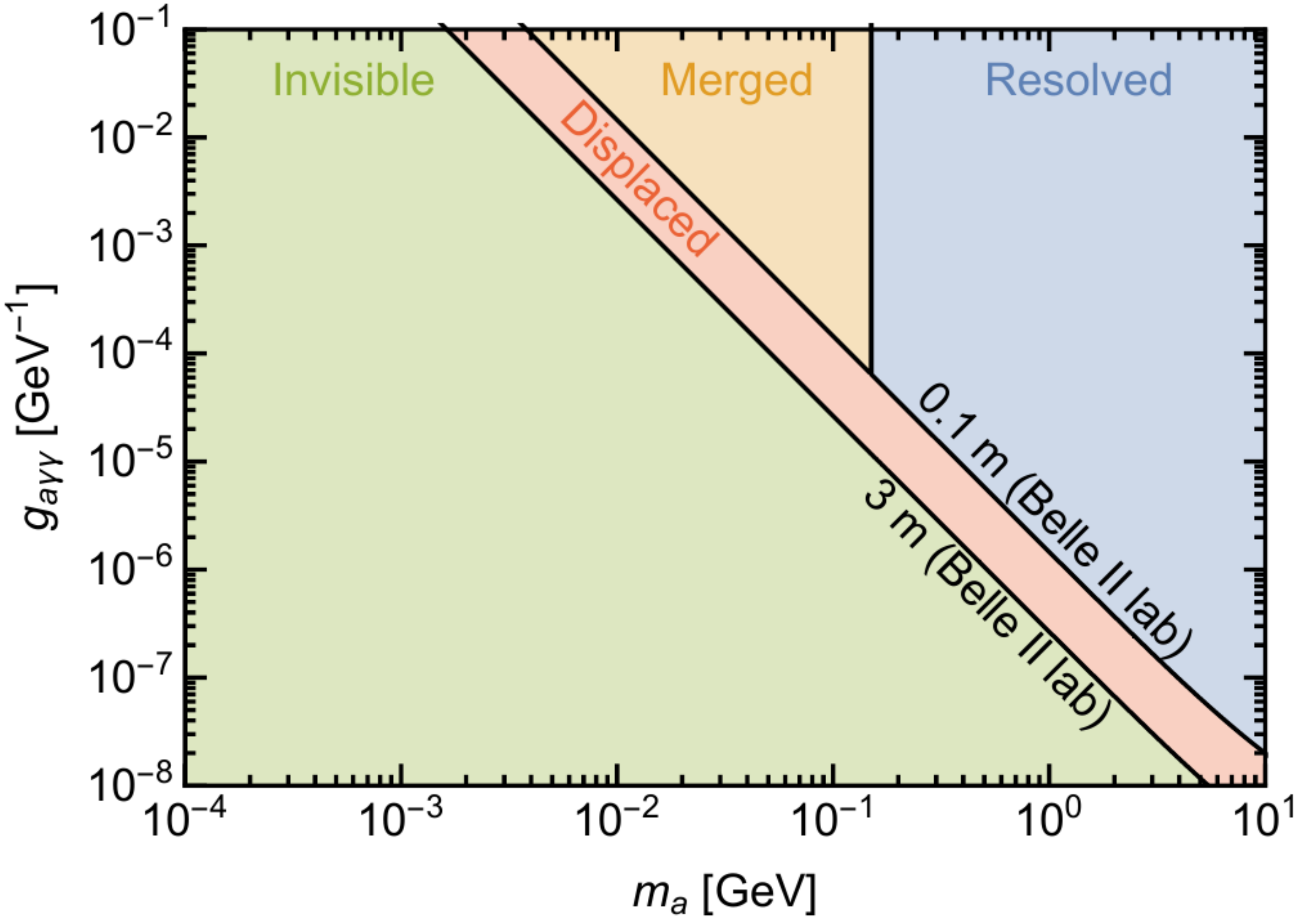
- Also search for “invisible” (more on that later).





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Axion-like particle

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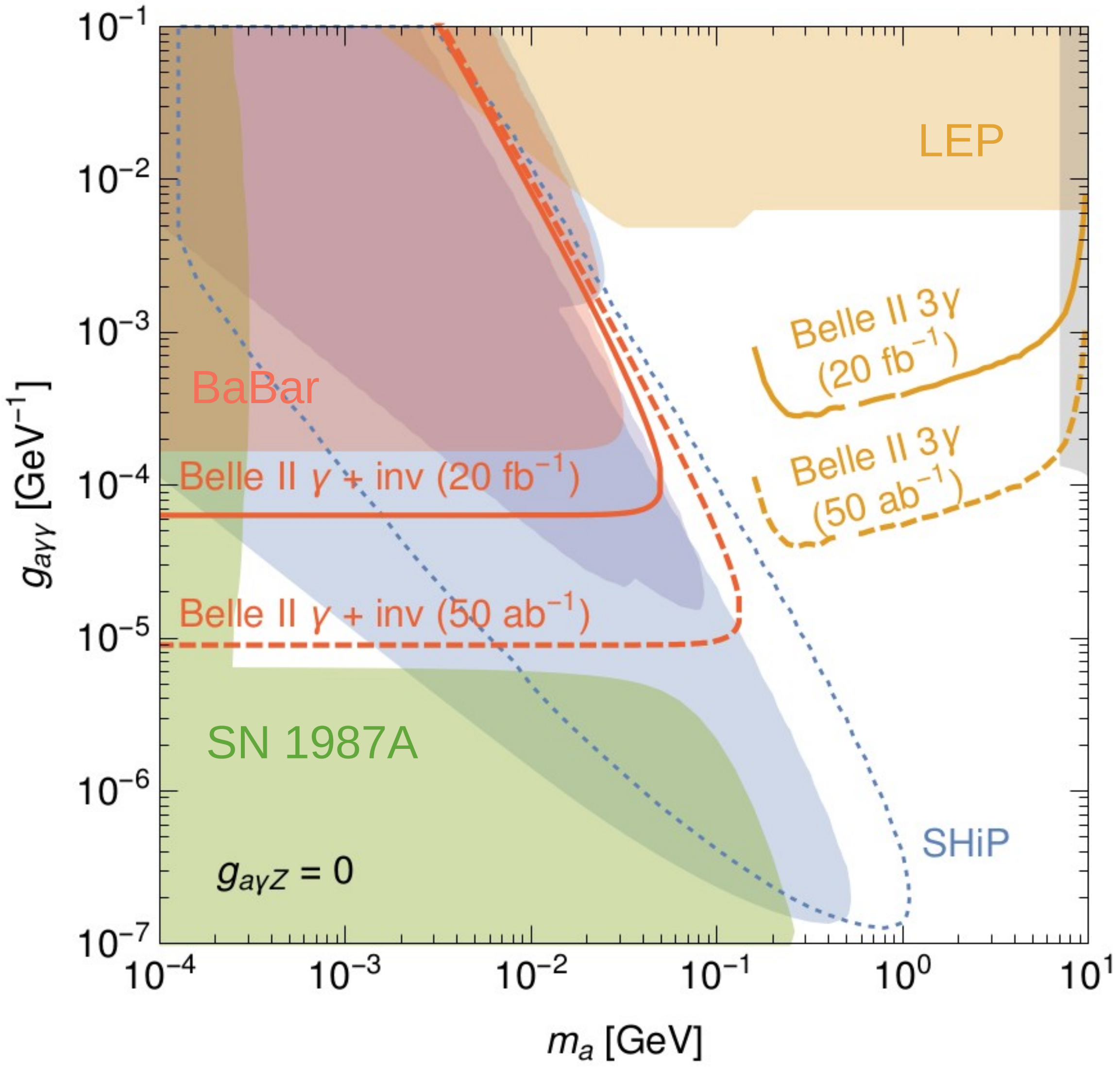
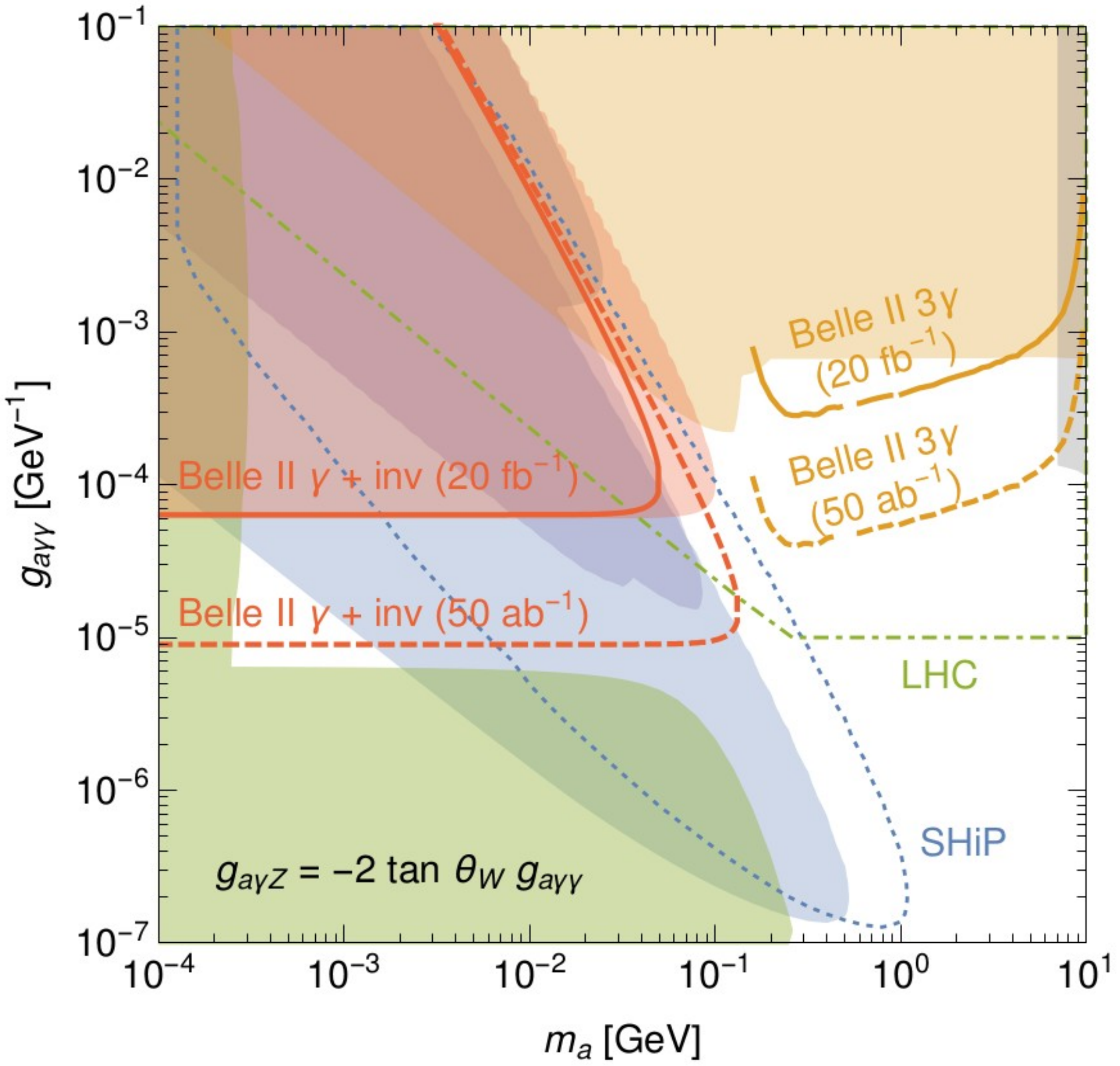
Physics reach





Axion-like particle

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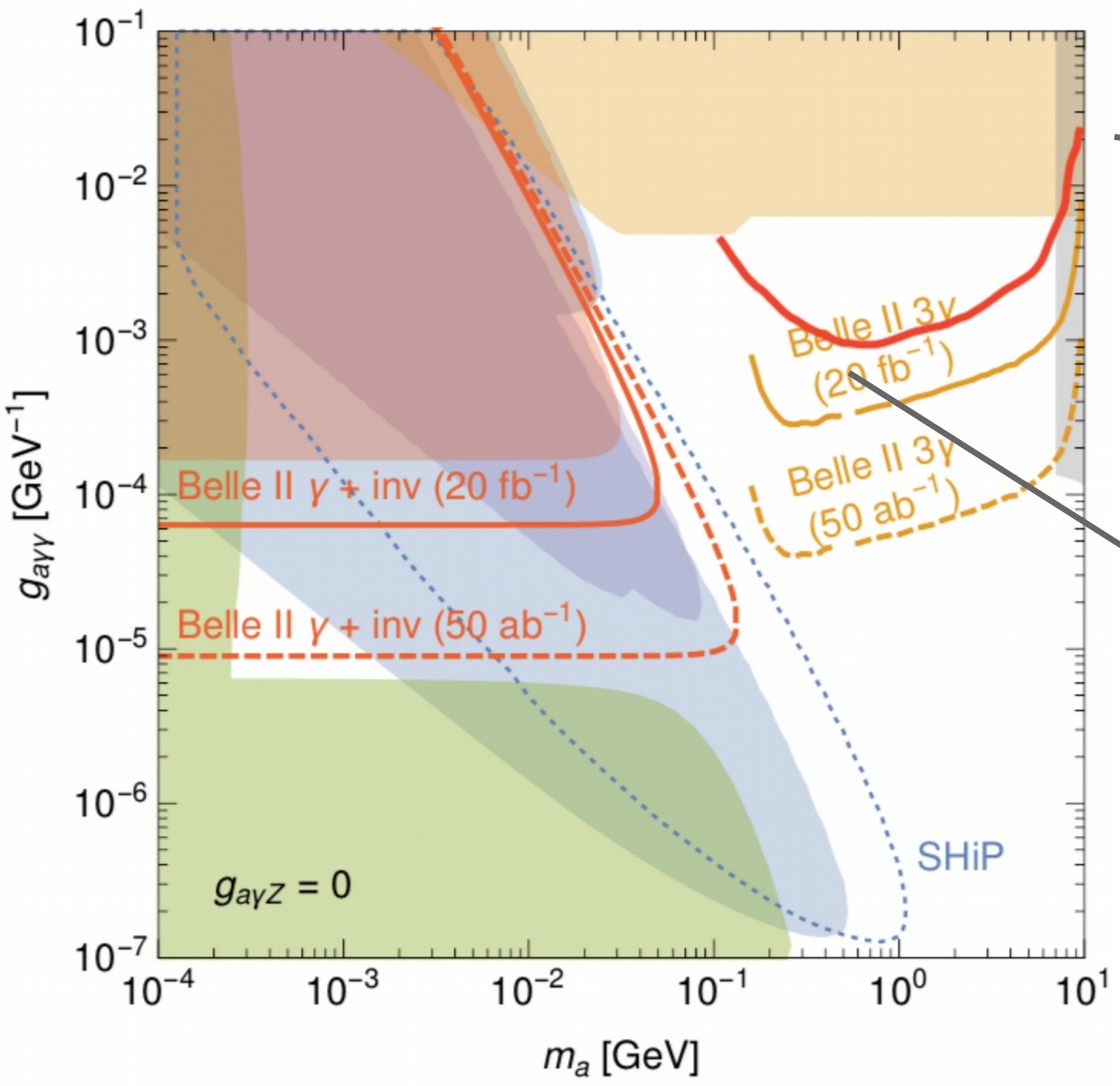
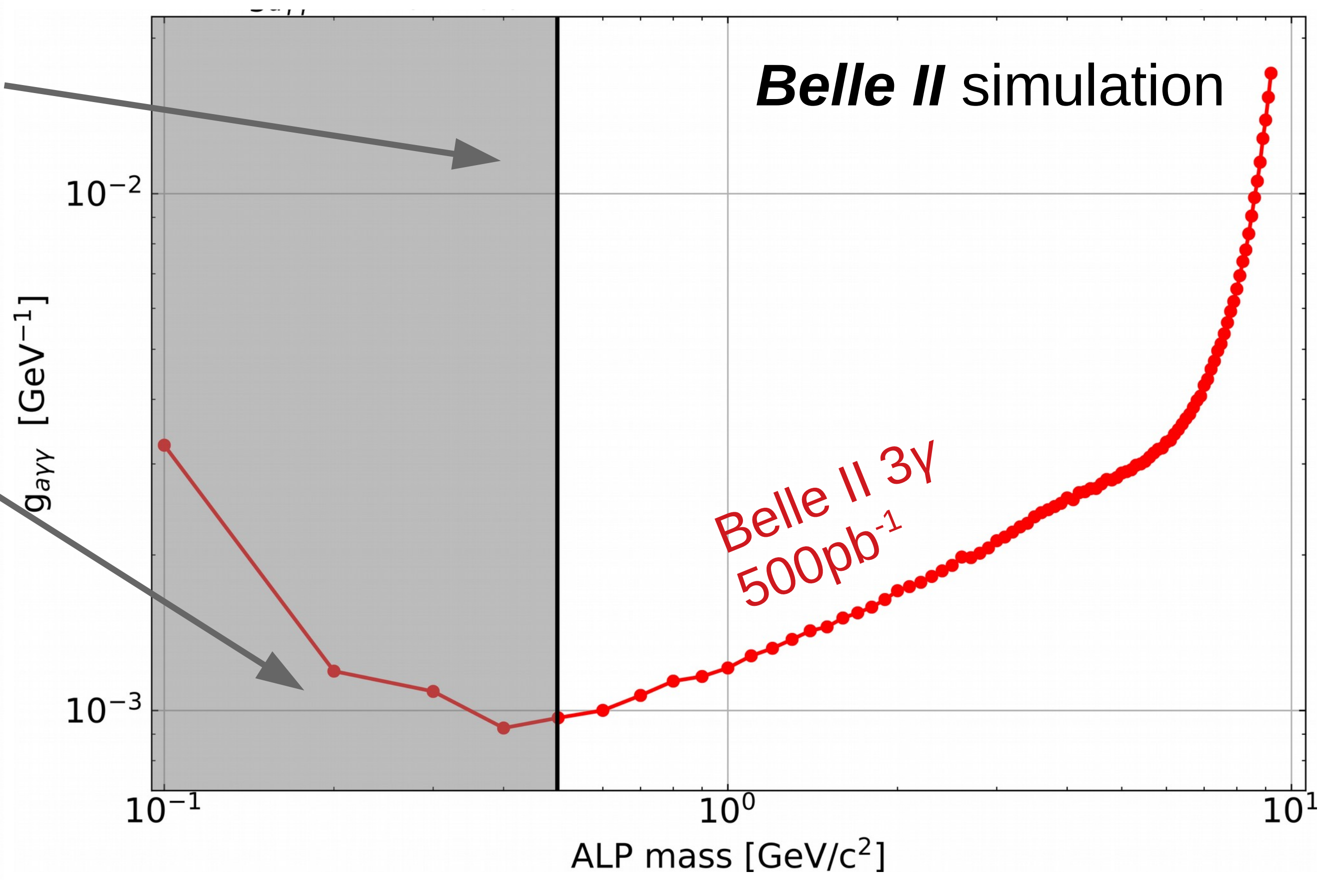
Physics reach





Dark photon

Theory

- Massive vector particle A', mixes with the SM photon:

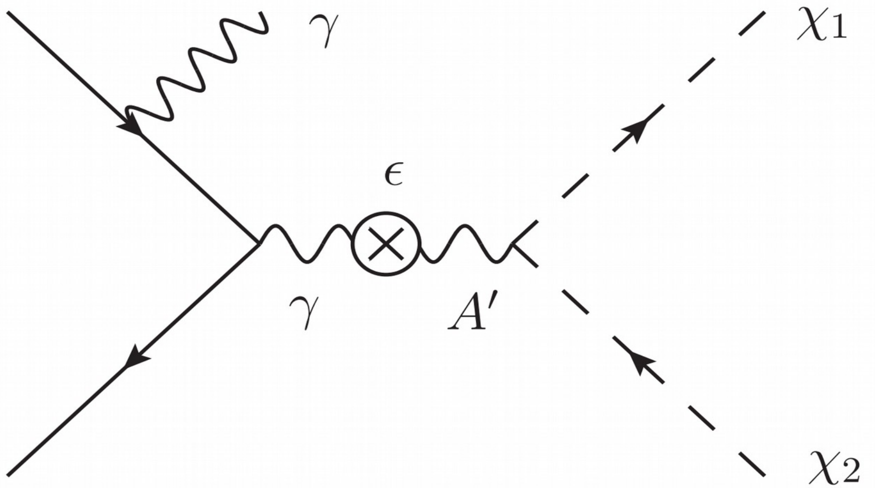
$$\mathcal{L} \supset \epsilon g_D A'_\mu J^\mu_{\mathrm{EM}}$$

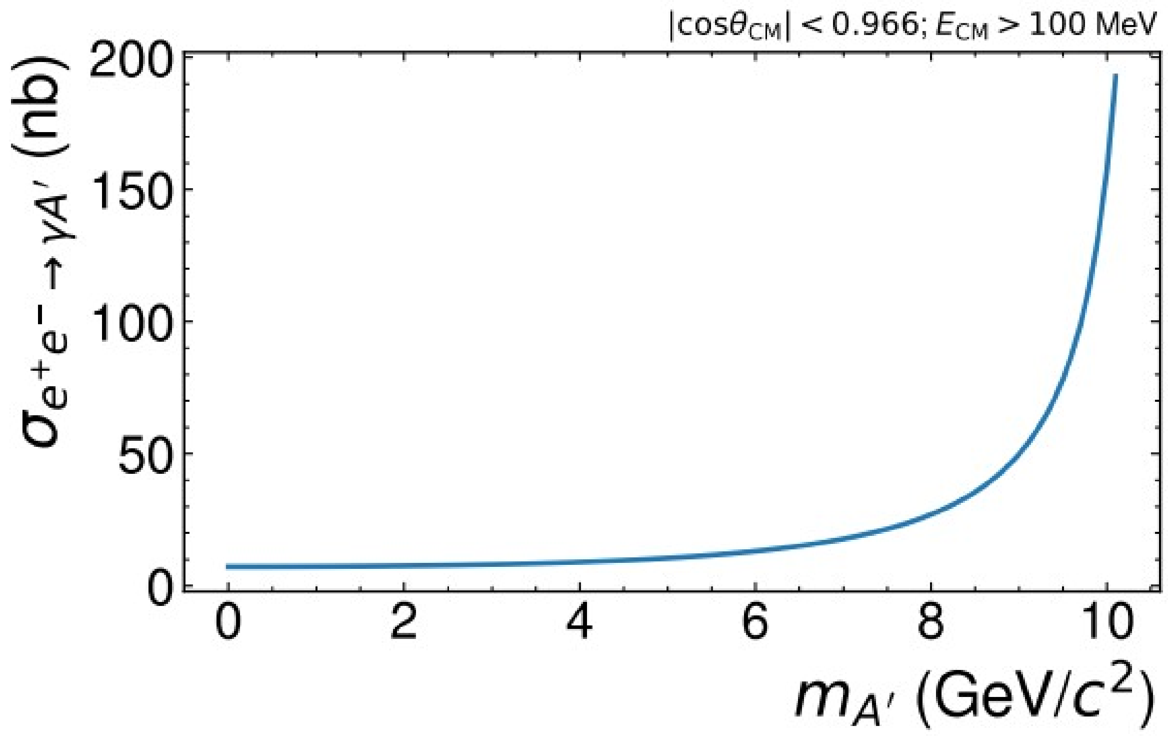
- Depending on dark photon/dark matter ratio:
  - Can decay directly to dark matter final state. Experimentally invisible A' → $\chi_1\chi_2$
  - Can decay to two leptons A' → l^+l^-

- Experimentalist's trick: require ISR photon.

$$E_{\gamma_{\mathrm{ISR}}} = \frac{s - m^2_{A'}}{2\sqrt{s}}$$

PhysRevD.80.015003

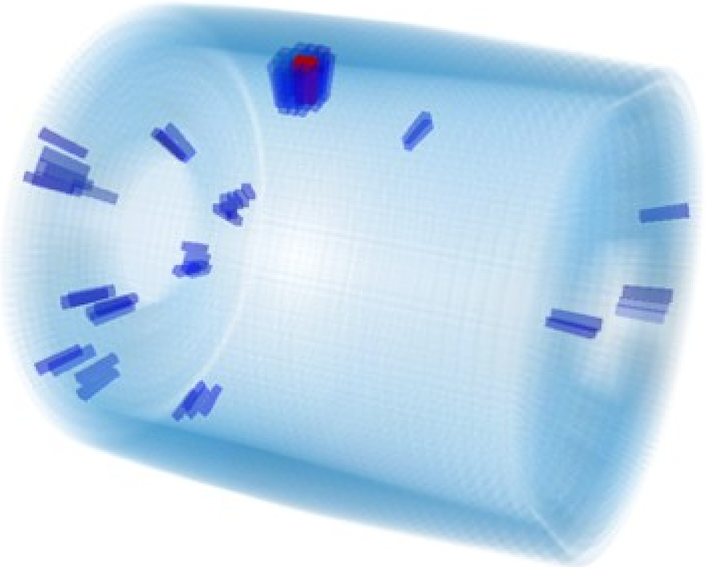


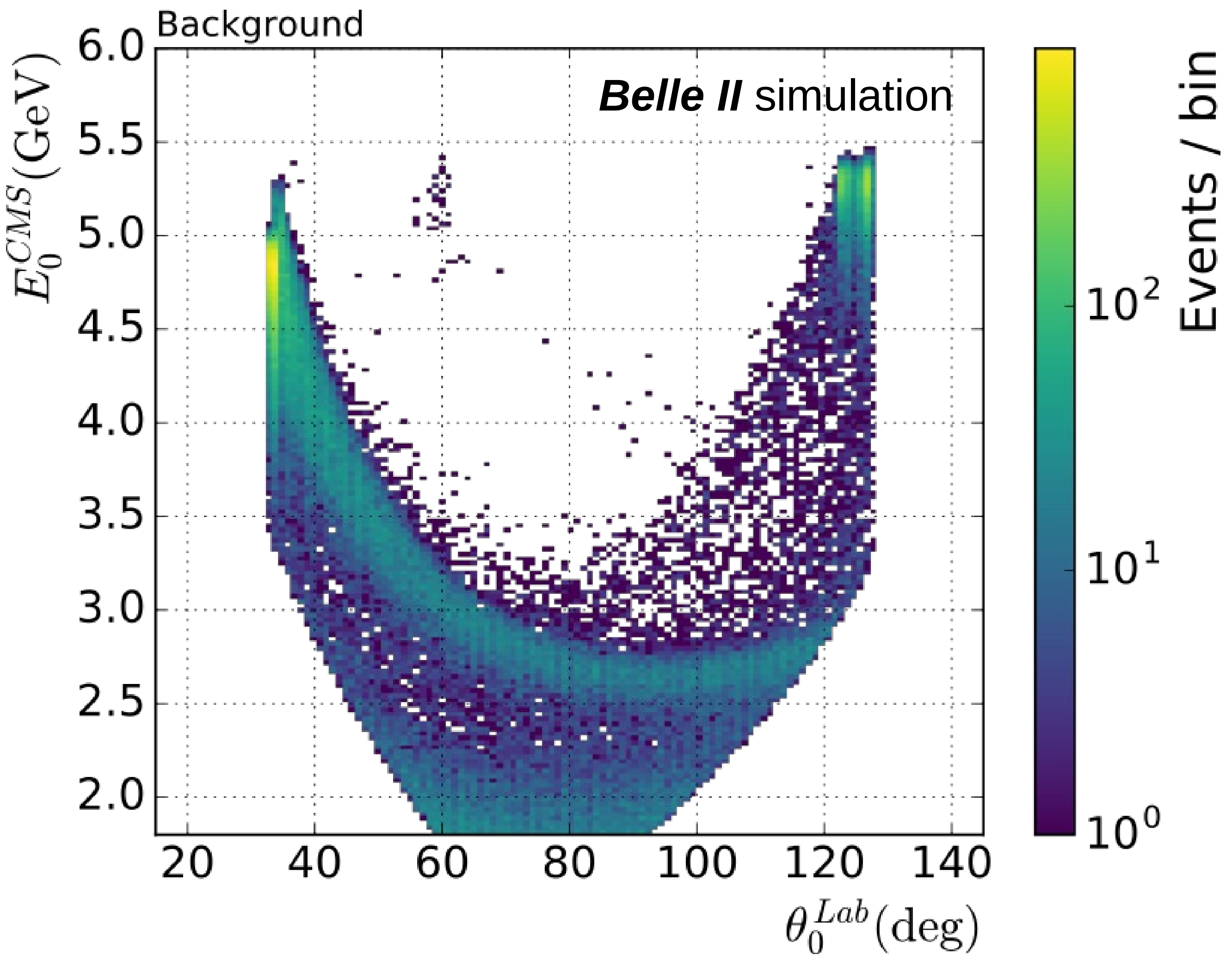


Dark photon

Analysis

- First analysis: **ee → γA' → γ($\chi_1\chi_2$)**
- Generic strategy: nothing in the event except one photon. (no tracks, other good photon clusters)
  - Bump search in recoil mass spectrum.
- **Backgrounds** ee → eeγ(γ) and ee → γγ(γ)





Dark photon

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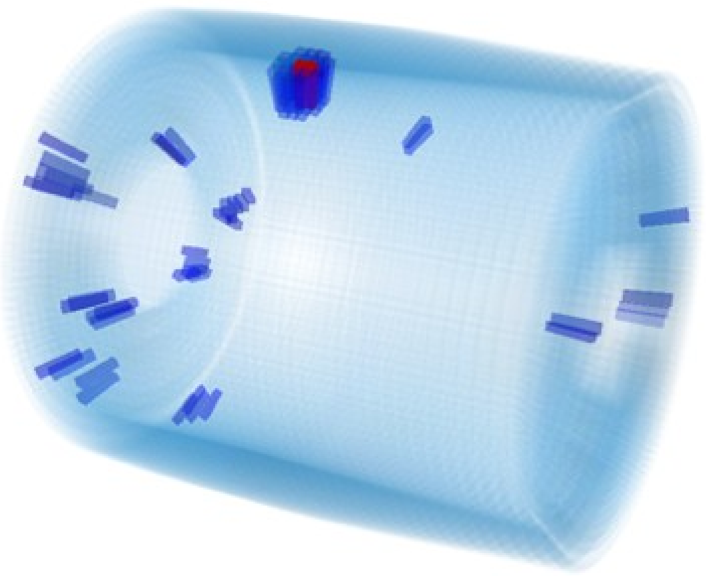
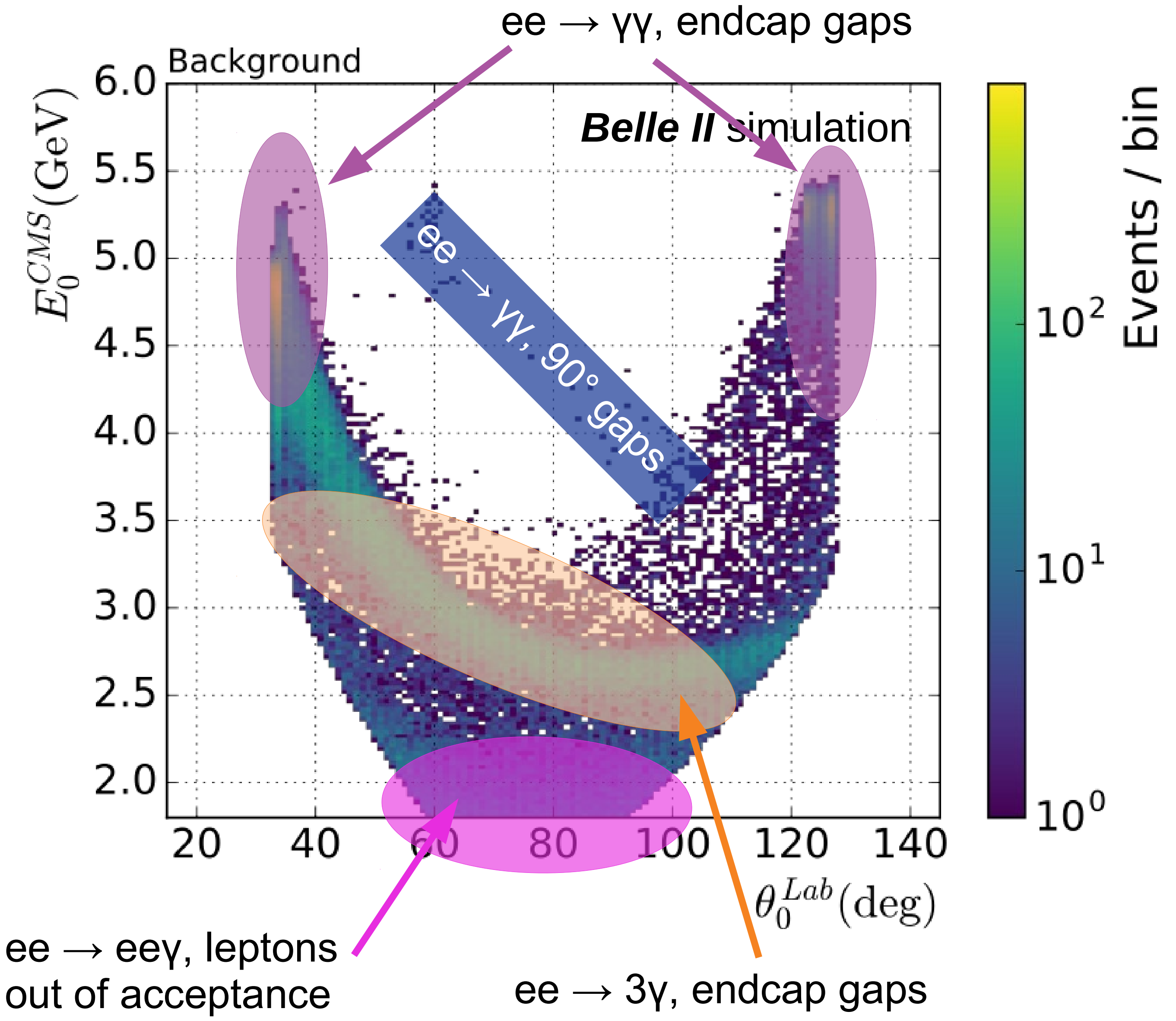
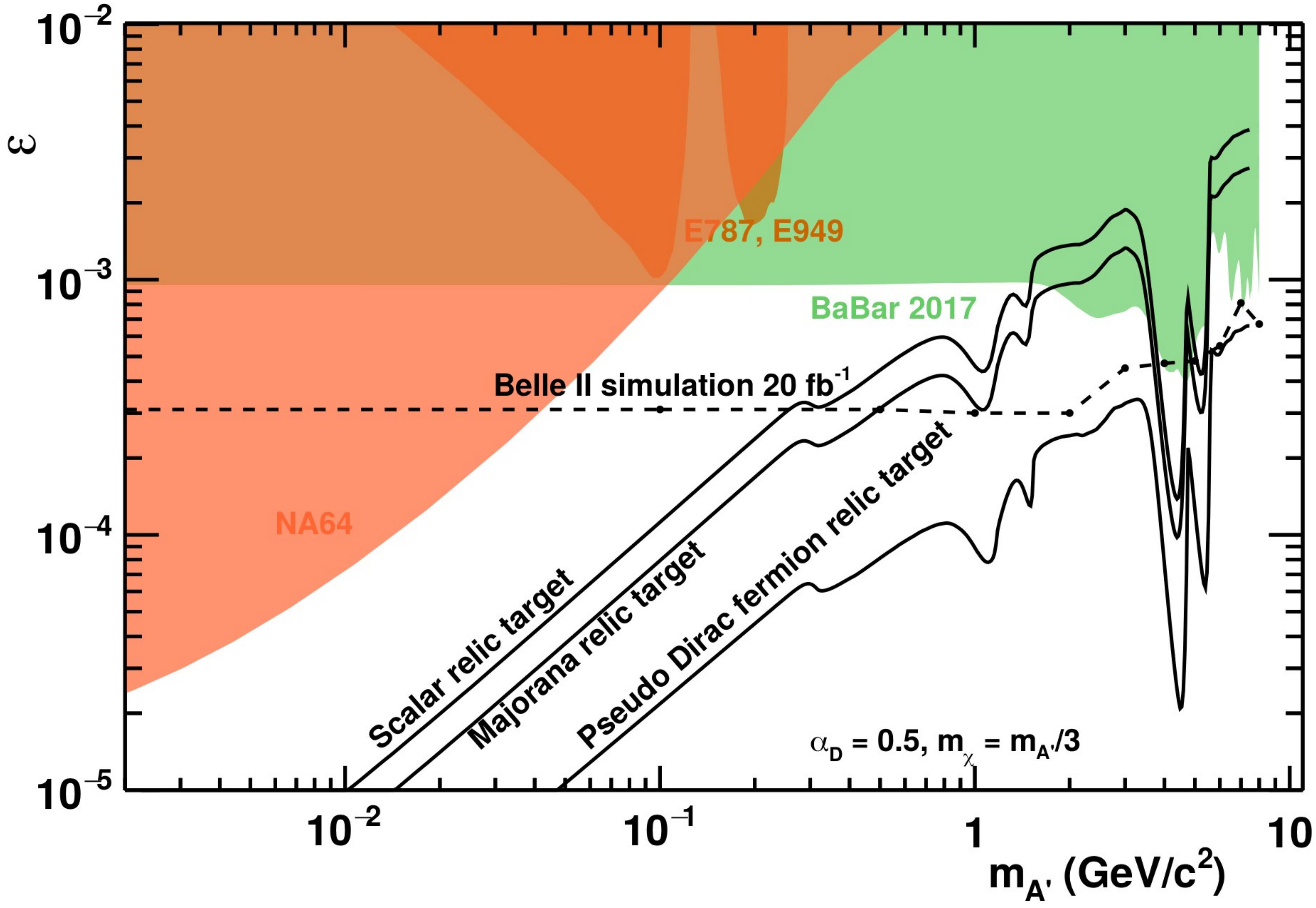




Dark photon

Physics reach



The Belle II Phyiscs book
arXiv:1808.10567
BaBar's analysis
[PRL.119.131804](PRL.119.131804)

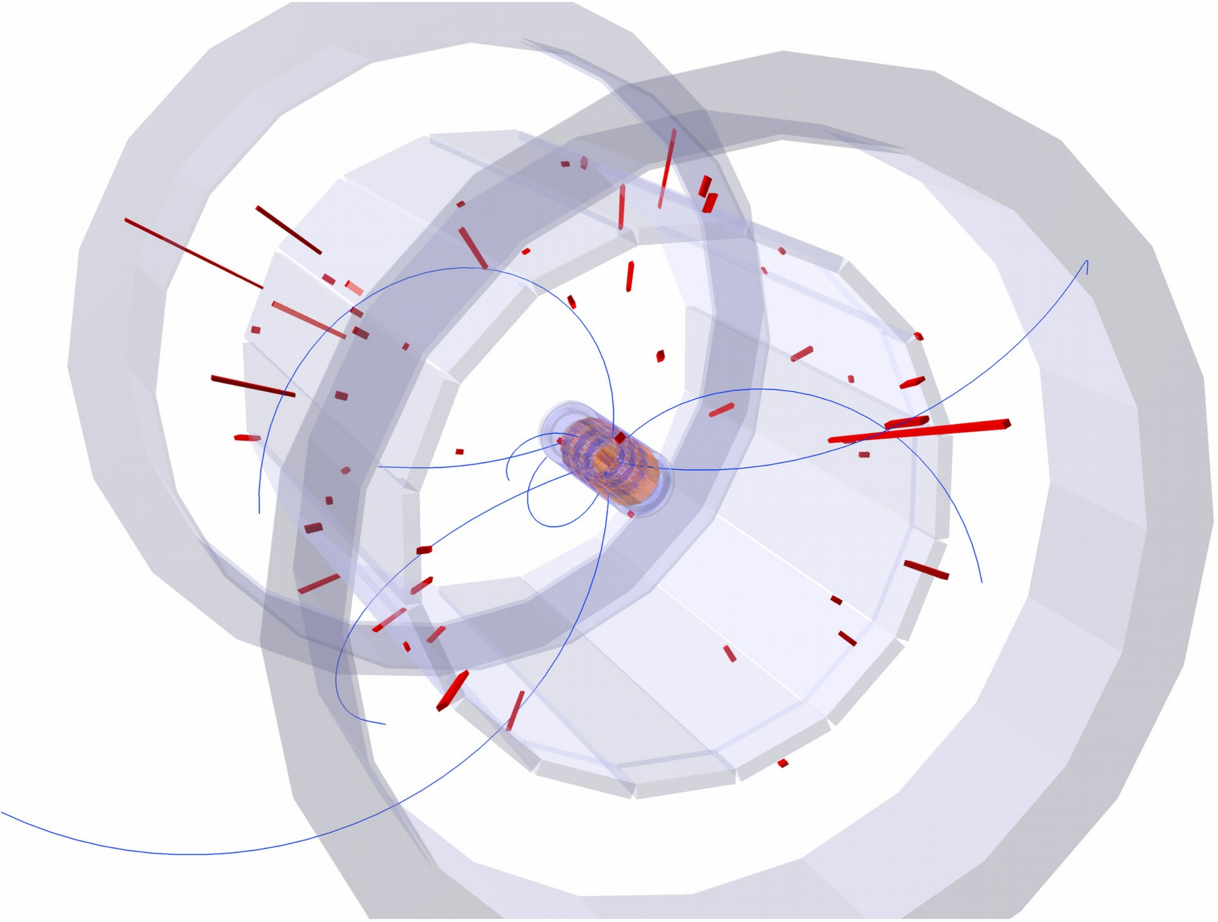
Prospects

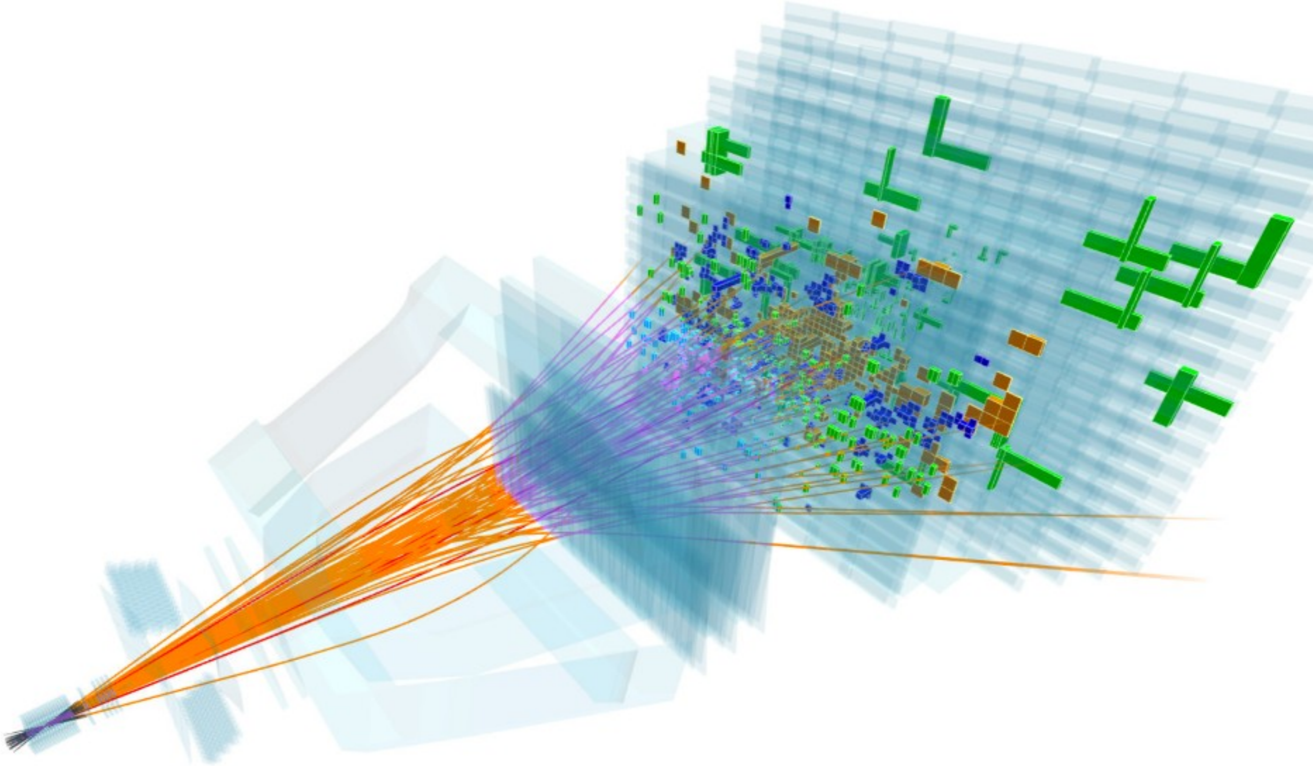
dark sector

$b \to s\ell\ell$

B physics from 2019+

Dramatis personae

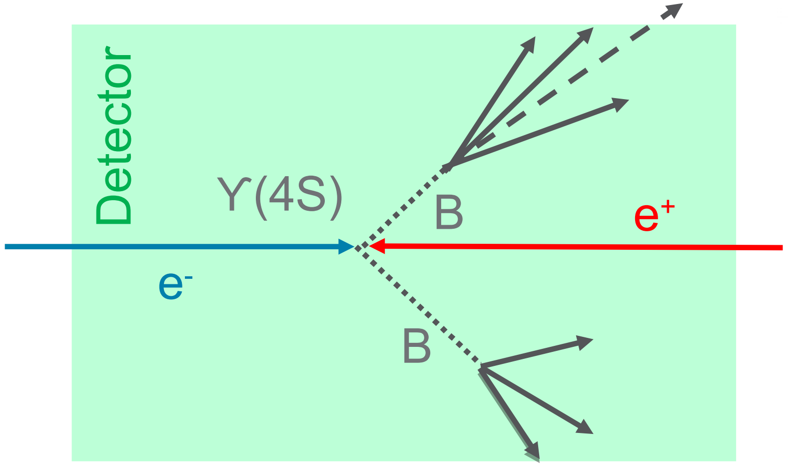




The field is lead by different shaped detectors

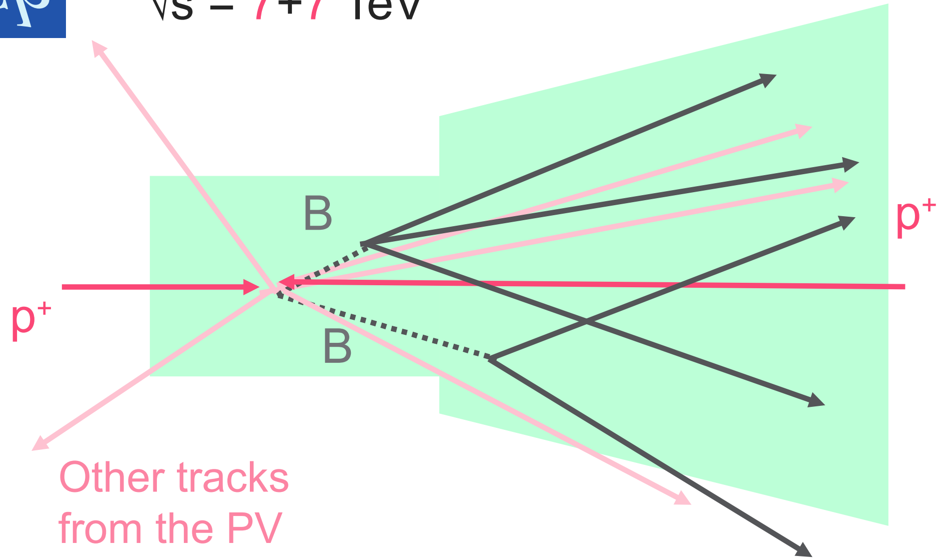
In different environments

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$
$\sqrt{s} = 2\sqrt{(7\times4)}$ GeV



- Collision energy known.
- Full event contained*.
- Can boost into CMS system.
- Missing energy / neutrinos.
- Good at neutrals γ, K_S^0, K_L^0, π^0, etc.

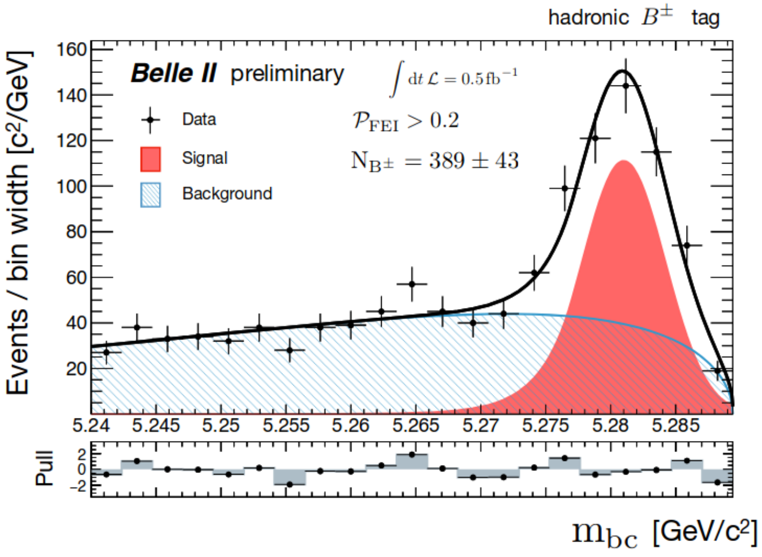
$pp \longrightarrow bb + ?$
$\sqrt{s} = 7+7$ TeV

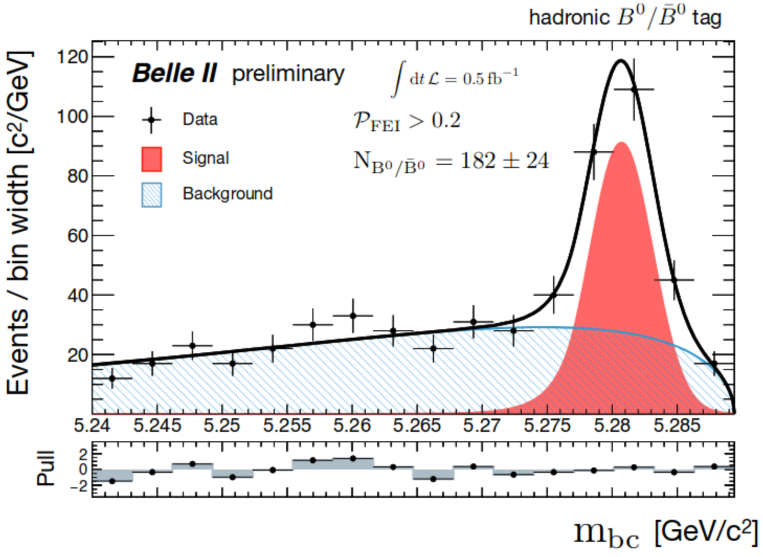


- BB system is not well constrained
- Collision energy not known
- Small angle coverage
- Running longer, high production!
- Trigger on displaced vertex.

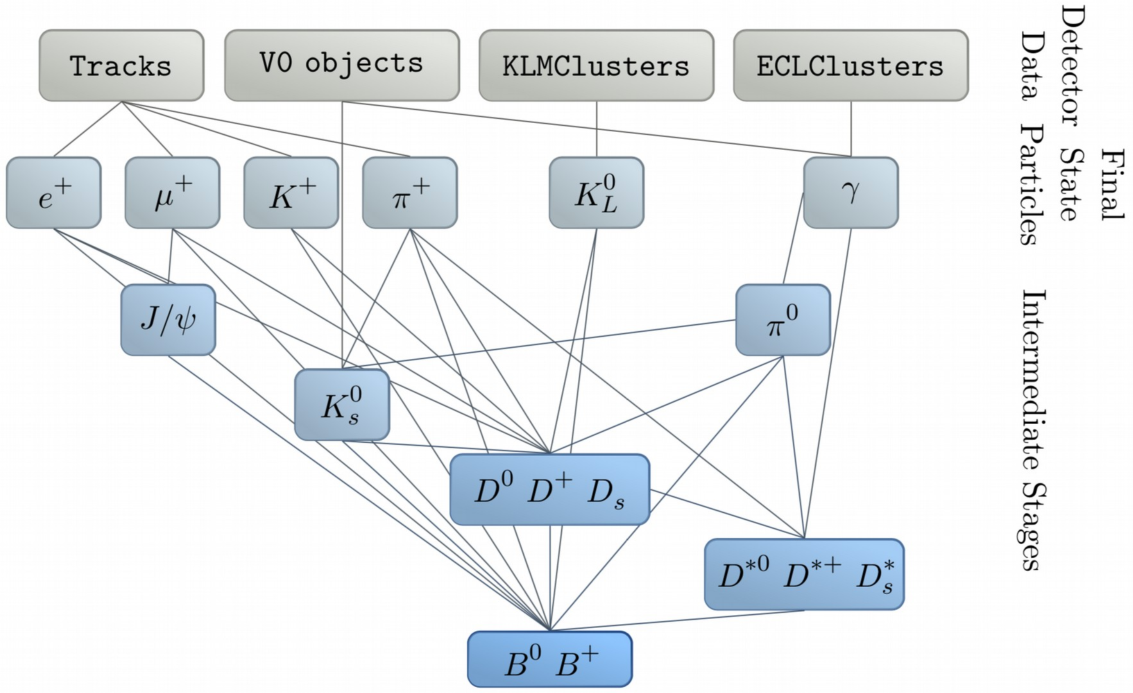
Full event interpretation

arXiv:1807.08680



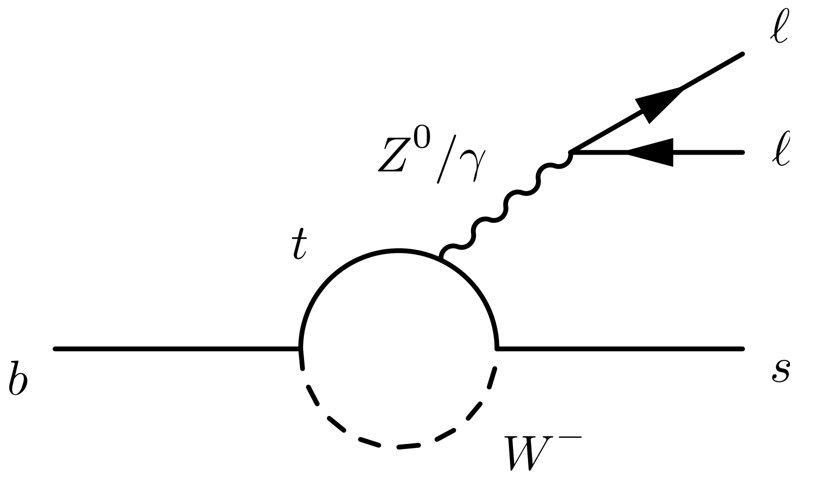


- “Generic” B meson reconstruction FastBDT.
- Layered classifier (track/neutral classifier, feeds up into combined classifier, ...).
- Return a B candidate, and a probability.
- BDT speed ⇒ can use many more channels.
- Factor ~2 improvement on Belle algorithm.
- O(2%) efficiency.



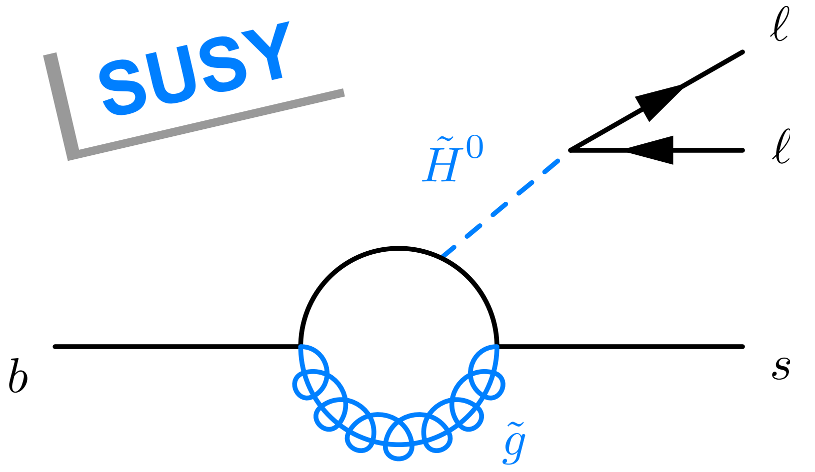
Is new physics in the b-quark loop processes?

b → sℓℓ in a nutshell



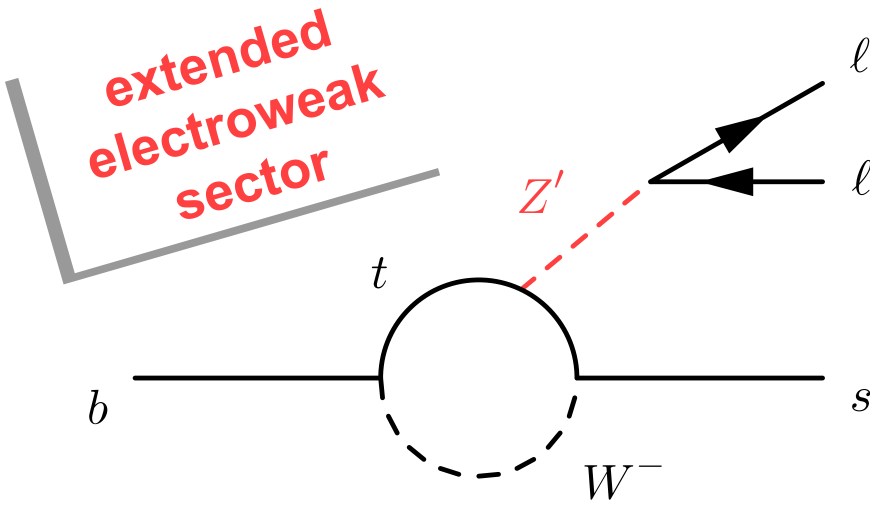
- Perhaps new physics is very high mass scale.
- Should interact indirectly through loops (off mass-shell)
- Rare b-quark transitions are interesting, b → s is the "goldilocks" mix of *heavy-to-light* w/ relatively high rates.
- Measure a scattering of observables, interpret in an effective field theory context.
    - Wilson coefficients ↔ effective couplings.
    - Stupid numbering scheme: 9 is "vector", 10 is "axial vector"
- Theorists run global fits. **There is tension with the SM**.

$b \to s\ell\ell$ in a nutshell



- Perhaps new physics is very high mass scale.
- Should interact indirectly through loops (off mass-shell)
- Rare b-quark transitions are interesting, $b \to s$ is the "goldilocks" mix of *heavy-to-light* w/ relatively high rates.
- Measure a scattering of observables, interpret in an effective field theory context.
    - Wilson coefficients ↔ effective couplings.
    - Stupid numbering scheme: 9 is "vector", 10 is "axial vector"
- Theorists run global fits. **There is tension with the SM**.

b → $s\ell\ell$ in a nutshell



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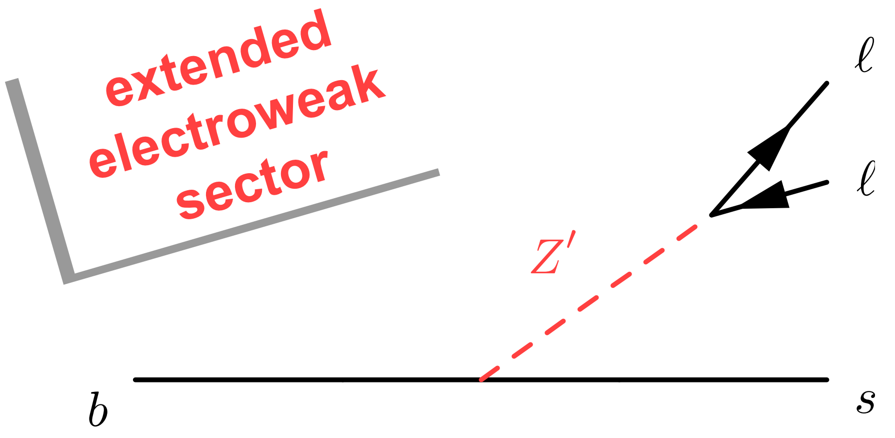

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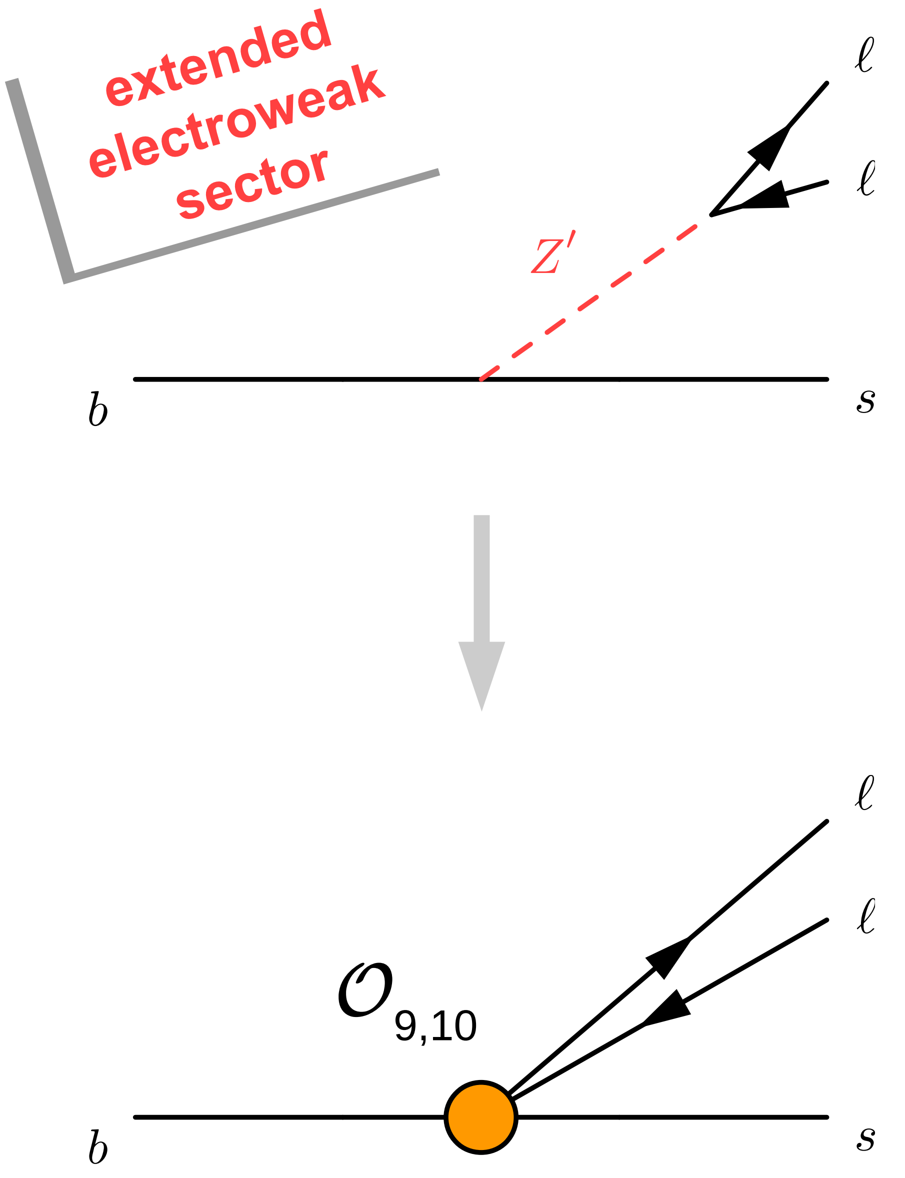
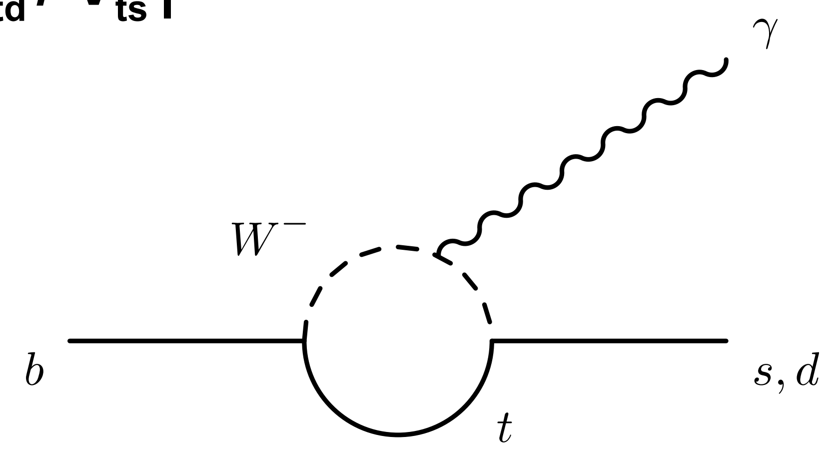
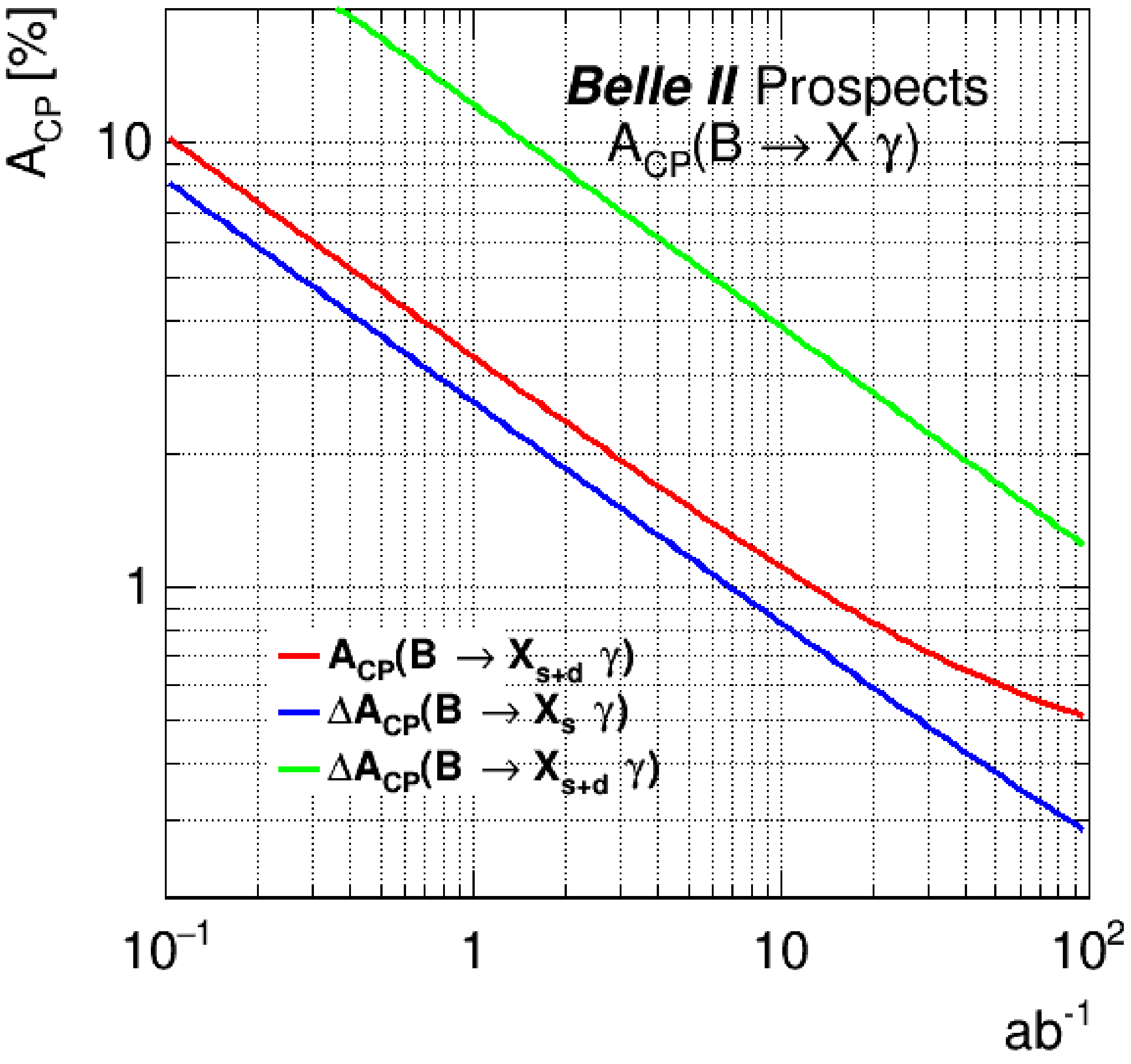


Inclusive B → Xγ

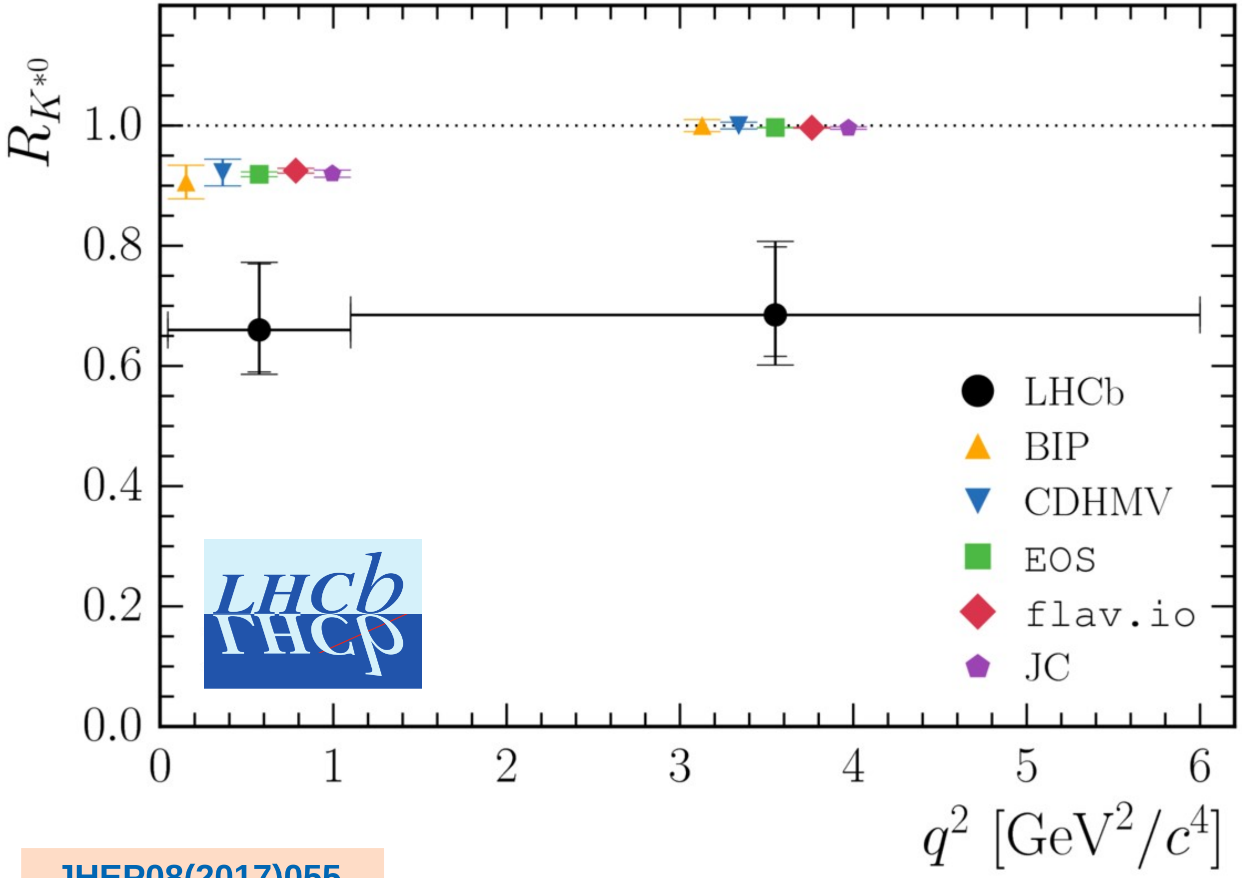
- Belle II 'golden channel'.
  - High yield. Usually good S/B ratio.
- Sub-percent-level uncertainties for $\mathbf{A_{CP}}$, $\mathbf{\Delta A_{CP}}$, Isospin asymmetry ($\mathbf{\Delta_{0+}}$) w/ $50 ab^{-1}$
- Percent-level uncertainties for branching fraction, and time-dependent CPV ($\mathbf{S_{CP}}$), and $\mathbf{| V_{td} / V_{ts} |}$

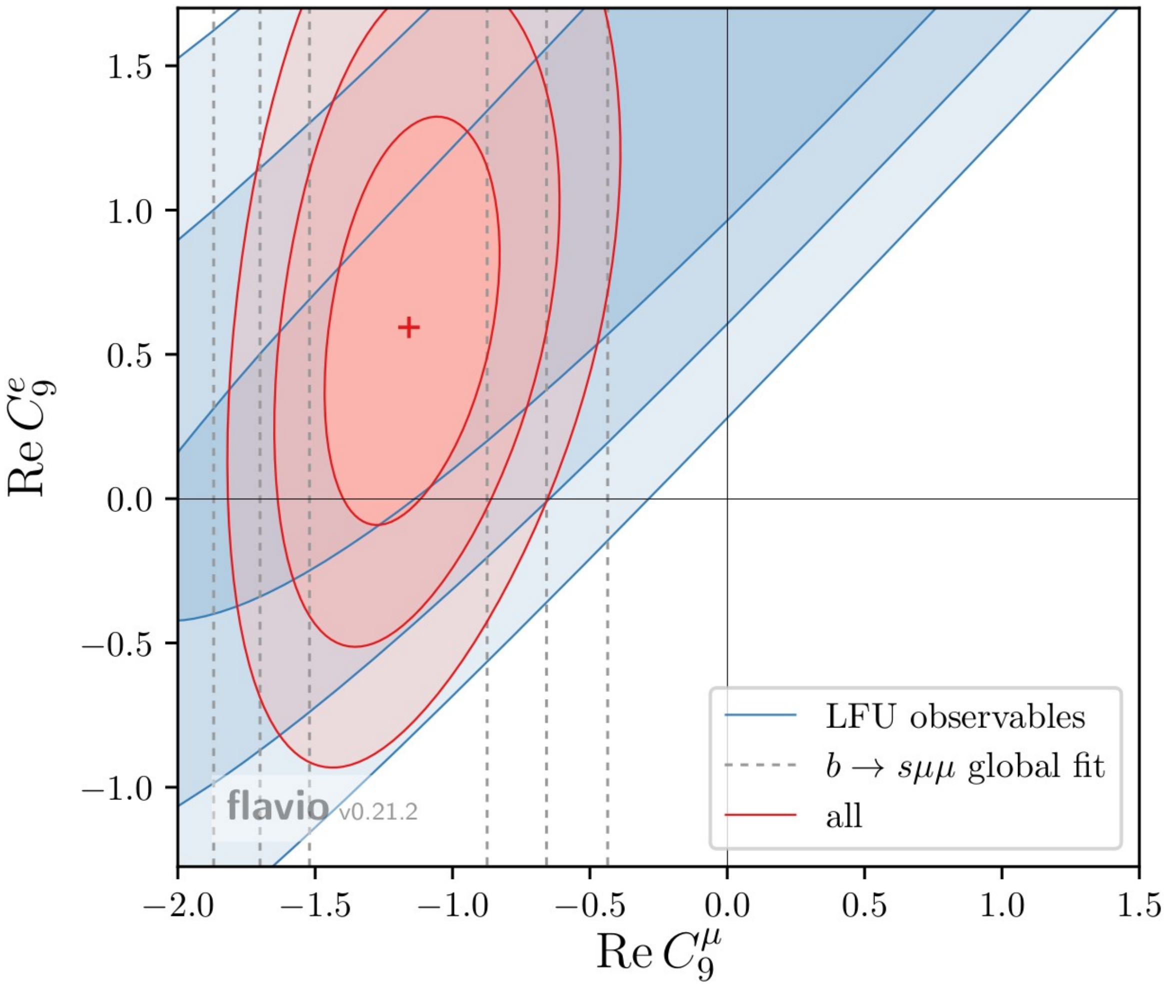




LHCb has left things in an interesting state

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}\left[B^0 \to K^{(*)0}\mu^+\mu^-\right]}{\mathcal{B}\left[B^0 \to K^{(*)0}e^+e^-\right]}$$





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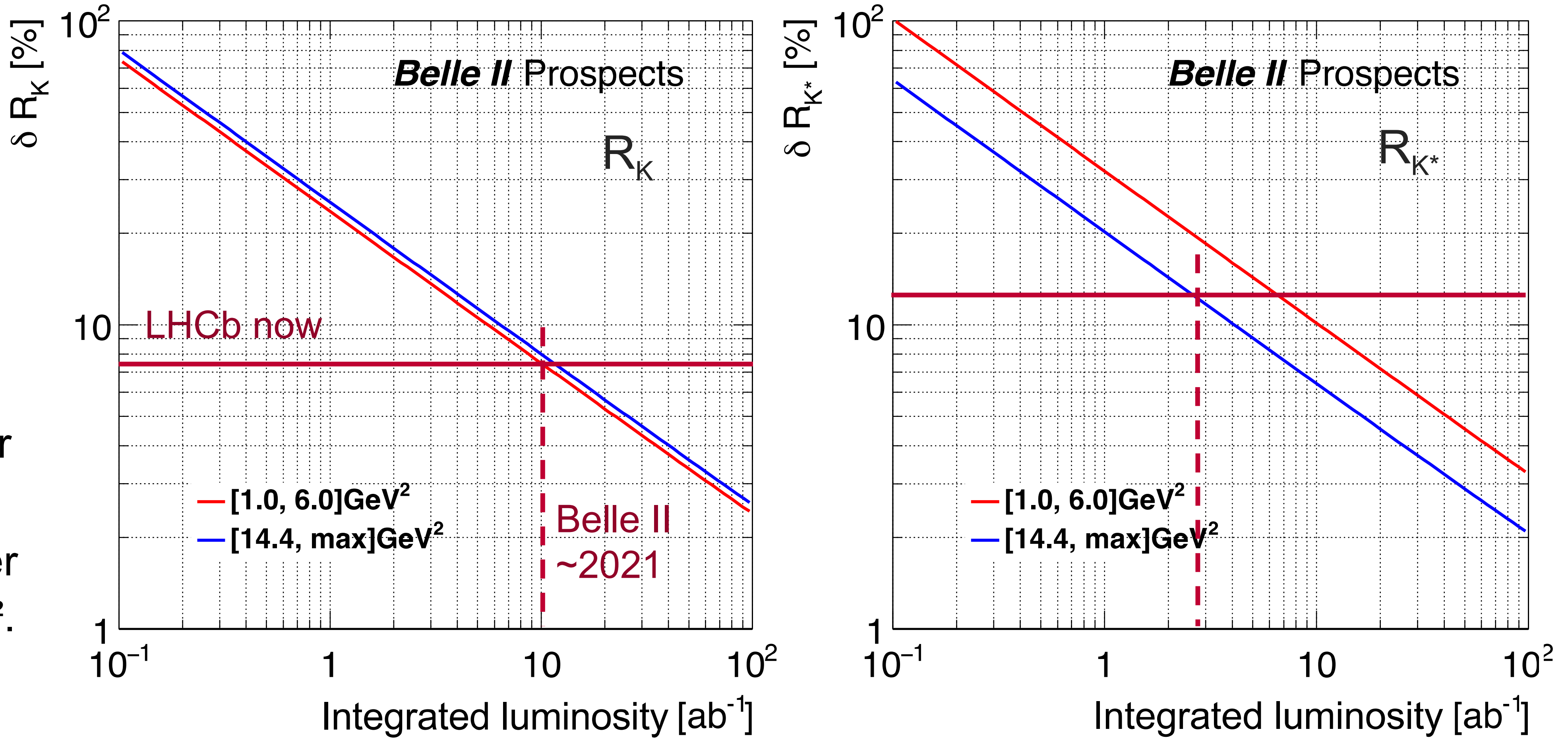
PhysRevD.96.055008

Lepton universality ratios with $B \to K^{(*)}\ell^+\ell^-$

- Not a Belle II golden channel.
  - We won't beat LHCb with charged final states.
- Similar results to LHCb (now) in ~2021.
- Confirm or refute LHCb w/ indep. 5σ in ~2023.



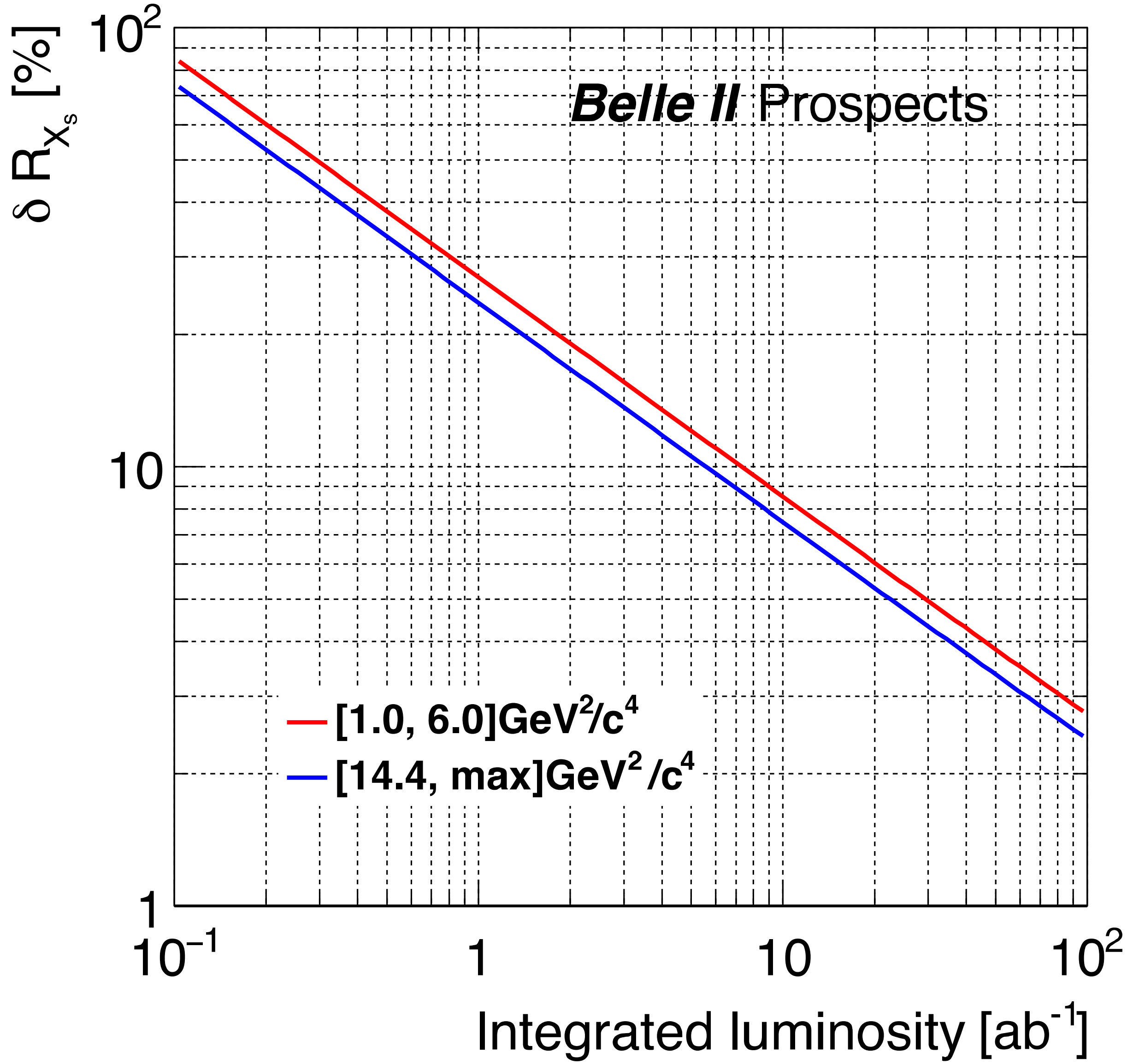
Belle II:

- e and μ are similar analysis objects.
- Should have better precision at low q^2.
- $K^{*+} \to K_s \pi^+$; K_L^0

Lepton universality ratios with $B \rightarrow X\ell^+\ell^-$

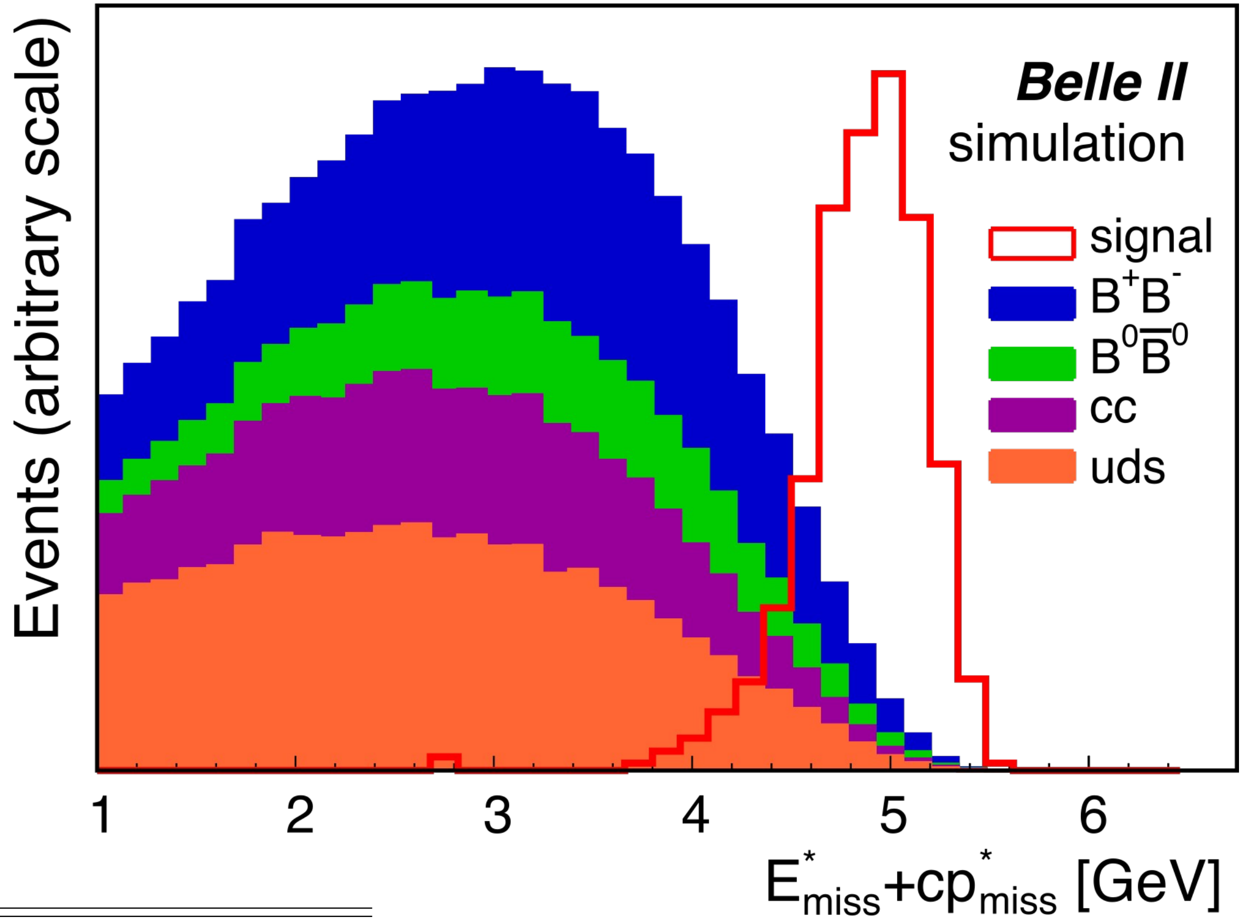
- Additional ratio built from inclusive decays R_X possible at Belle II.
- Uncertainty below 10% w/ 10 ab^{-1}.
- Could also do fully inclusive.
- Better precision at low/high q^2.

$$R_X \equiv \frac{\mathcal{B}\left[B \rightarrow X\mu^+\mu^-\right]}{\mathcal{B}\left[B \rightarrow Xe^+e^-\right]}$$



$B \to K^{(*)}\nu\bar{\nu}$

- **The** golden channel.
- Observable with Belle II (assuming SM rate)
  - 10-12% uncertainty w/ $50ab^{-1}$.
- Pin down C_9.
- Exploit **E^*_{miss} + cp^*_{miss}** (missing energy plus sum of missing 3-momentum in the CMS).



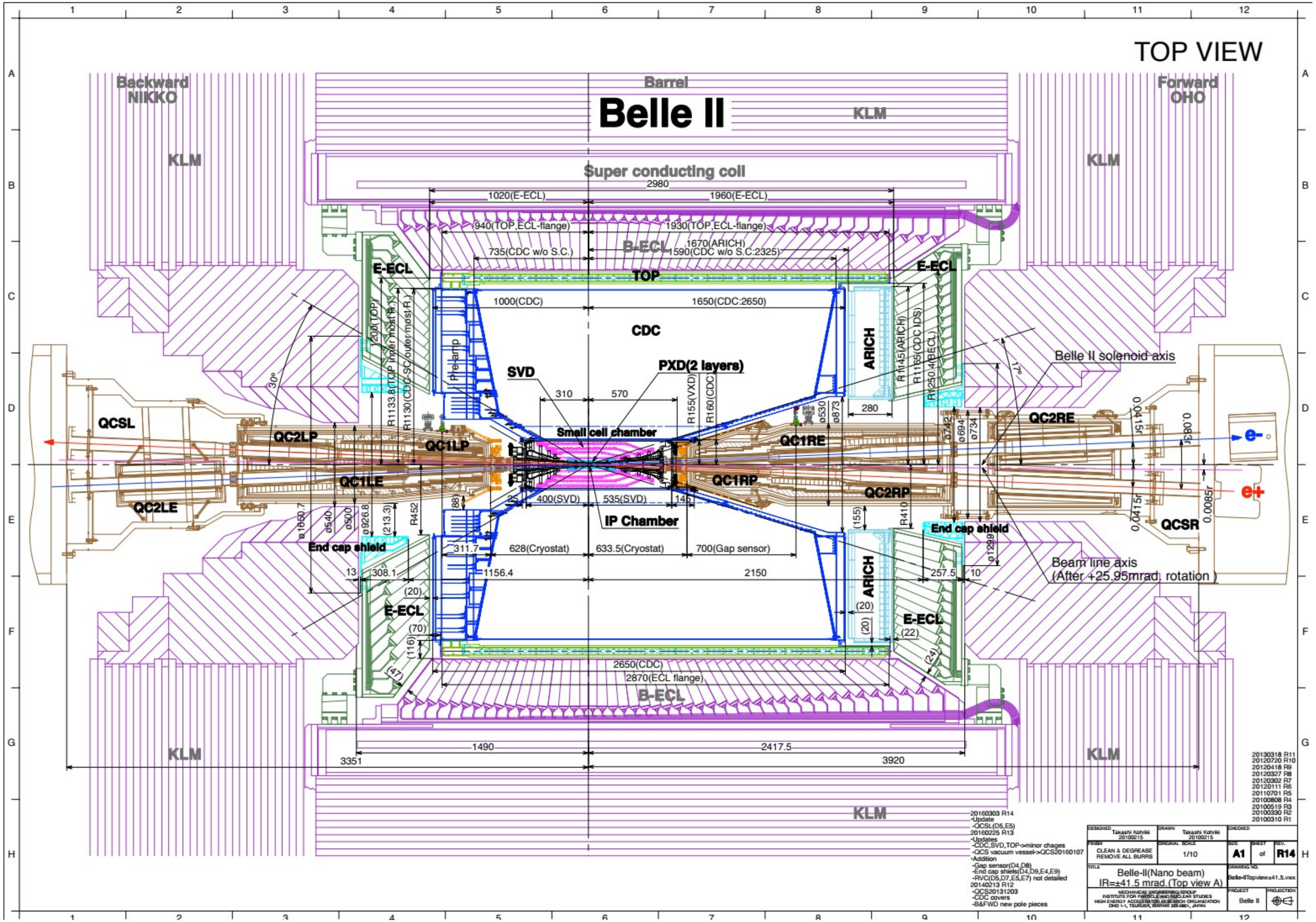
Mode	$\mathcal{B}$ $[10^{-6}]$	Efficiency Belle $[10^{-4}]$	$N_{\text{Backg.}}$ 711 fb^{-1} Belle	$N_{\text{Sig-exp.}}$ 711 fb^{-1} Belle	$N_{\text{Backg.}}$ 50 ab^{-1} Belle II	$N_{\text{Sig-exp.}}$ 50 ab^{-1} Belle II	Statistical error 50 ab^{-1}	Total Error
$B^+ \to K^+\nu\bar{\nu}$	4.68	5.68	21	3.5	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%

Conclusions

- Belle II, a B factory with 50x more data.
- "Full physics" data starting next year.
- 500 pb^{-1} commissioning data available now.

$ee \to \gamma a \to 3\gamma$	Direct production a to two photons	◌		?
$ee \to \gamma A'$	Direct production A' or a to invisible	○		○
$B \to X\gamma$	Improve precision	◌	?	◌
$B \to K^{(*)}\nu\bar{\nu}$	Observe if SM	◌	×	×
$B \to X\ell^+\ell^-$; R_X	Orthogonal check of LHCb	○	?	
$B \to K^{(*)}\ell^+\ell^-$; R_{K,K^*}	Indep. check of LHCb's indications of LNU		◌	×

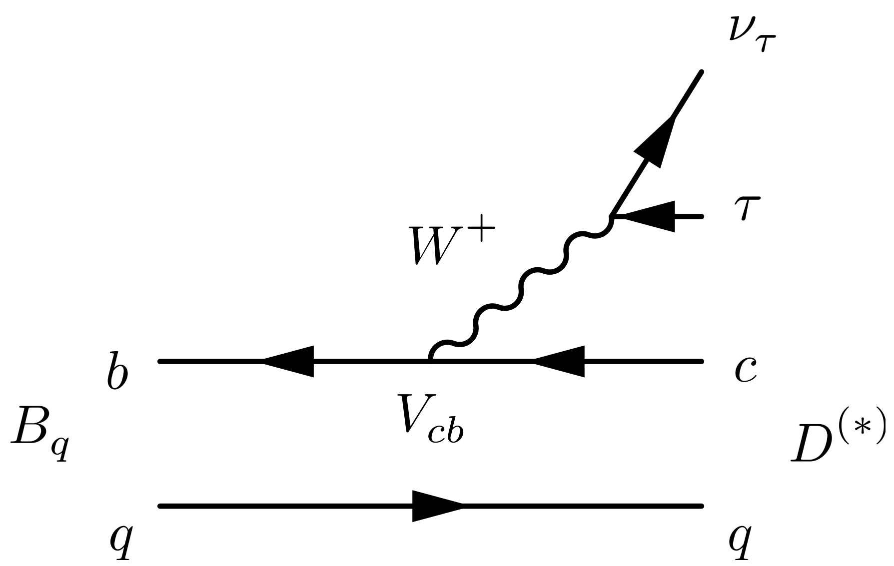
Appendix

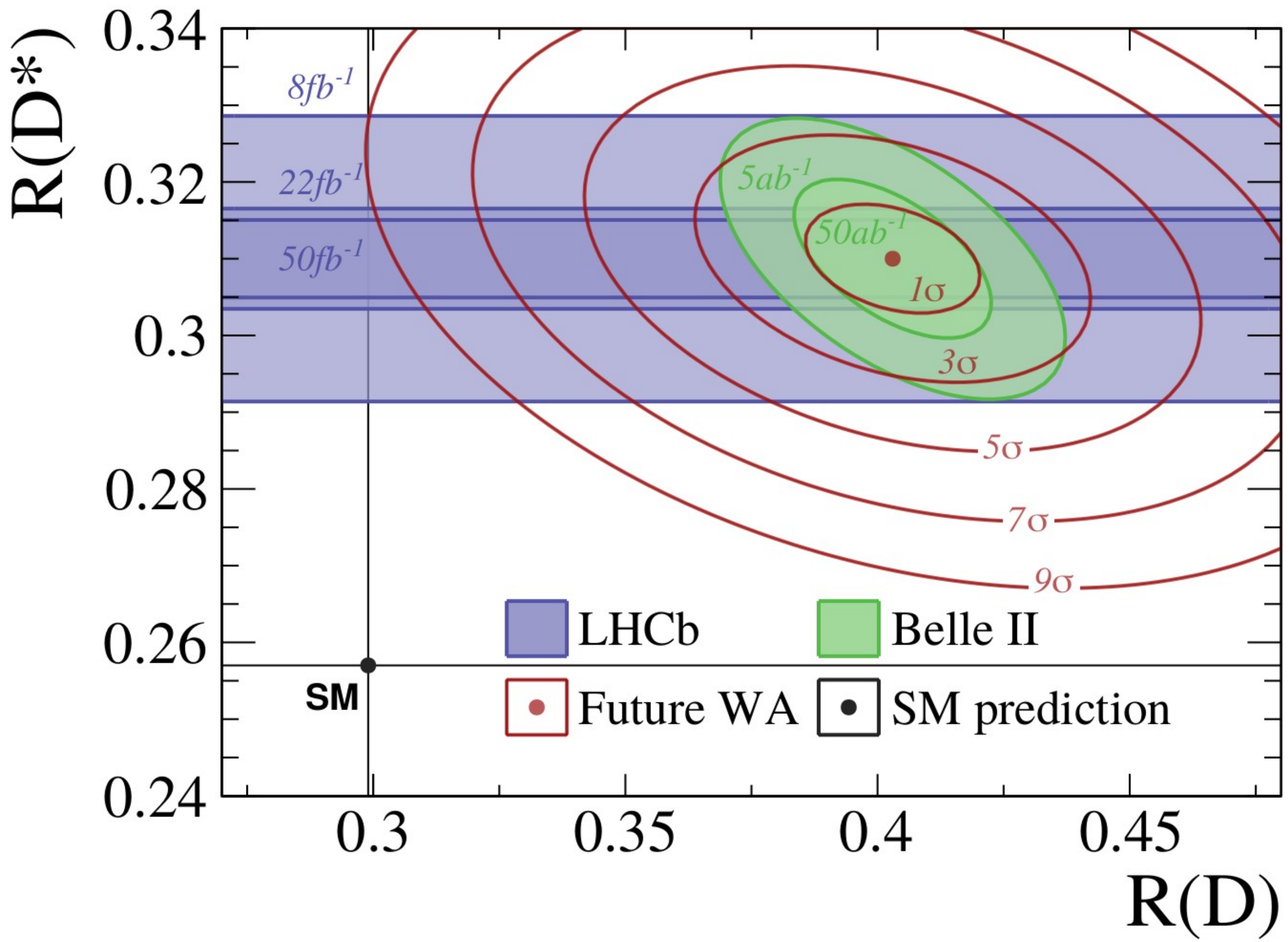


TOP VIEW
Backward
NIKKO
Barrel
Belle II
KLM
Forward
OHO
KLM
KLM
Super conducting coil
2980
1020(E-ECL)
1960(E-ECL)
940(TOP,ECL-flange)
1930(TOP,ECL-flange)
B-ECL
1670(ARICH)
735(CDC w/o S.C.)
1590(CDC w/o S.C:2325)
E-ECL
TOP
E-ECL
1000(CDC)
1650(CDC:2650)
CDC
ARICH
SVD
PXD(2 layers)
Belle II solenoid axis
310
570
280
QCSL
QC2LP
QC1LP
Small cell chamber
QC1RE
QC2RE
e-
QC1LE
QC1RP
QC2RP
e+
QC2LE
400(SVD)
535(SVD)
IP Chamber
End cap shield
QCSR
End cap shield
311.7
628(Cryostat)
633.5(Cryostat)
700(Gap sensor)
Beam line axis
(After +25.95mrad. rotation)
308.1
1156.4
2150
257.5
E-ECL
ARICH
E-ECL
2650(CDC)
2870(ECL flange)
B-ECL
1490
2417.5
3351
3920
KLM
KLM
KLM
Belle-II(Nano beam)
IR=±41.5 mrad.(Top view A)

B → D$^{(*)}\tau^{\pm}\nu$

- Systematic uncertainty overtakes statistics at 5 ab^{-1}.
- With 50 ab^{-1}:
  - Percent-level uncertainties.
  - Moves into the realm of "*ridiculously significant*".





$$R_{D^{(*)}} \equiv \frac{\mathcal{B}\left[B \to D^{(*)}\tau^+\nu\right]}{\mathcal{B}\left[B \to D^{(*)}\ell^+\nu\right]}$$

Contact

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