Searches for New Physics on the Intensity Frontier: The Belle II Experiment

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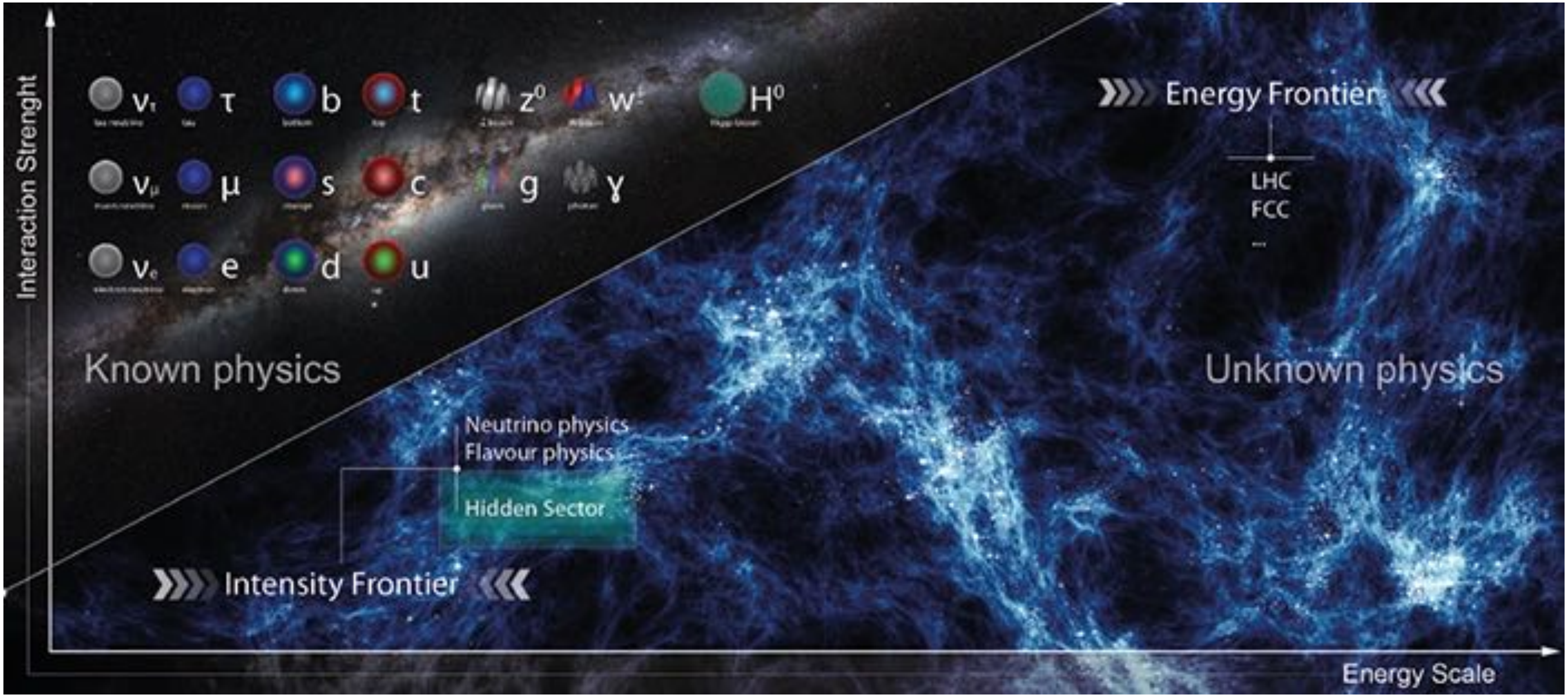
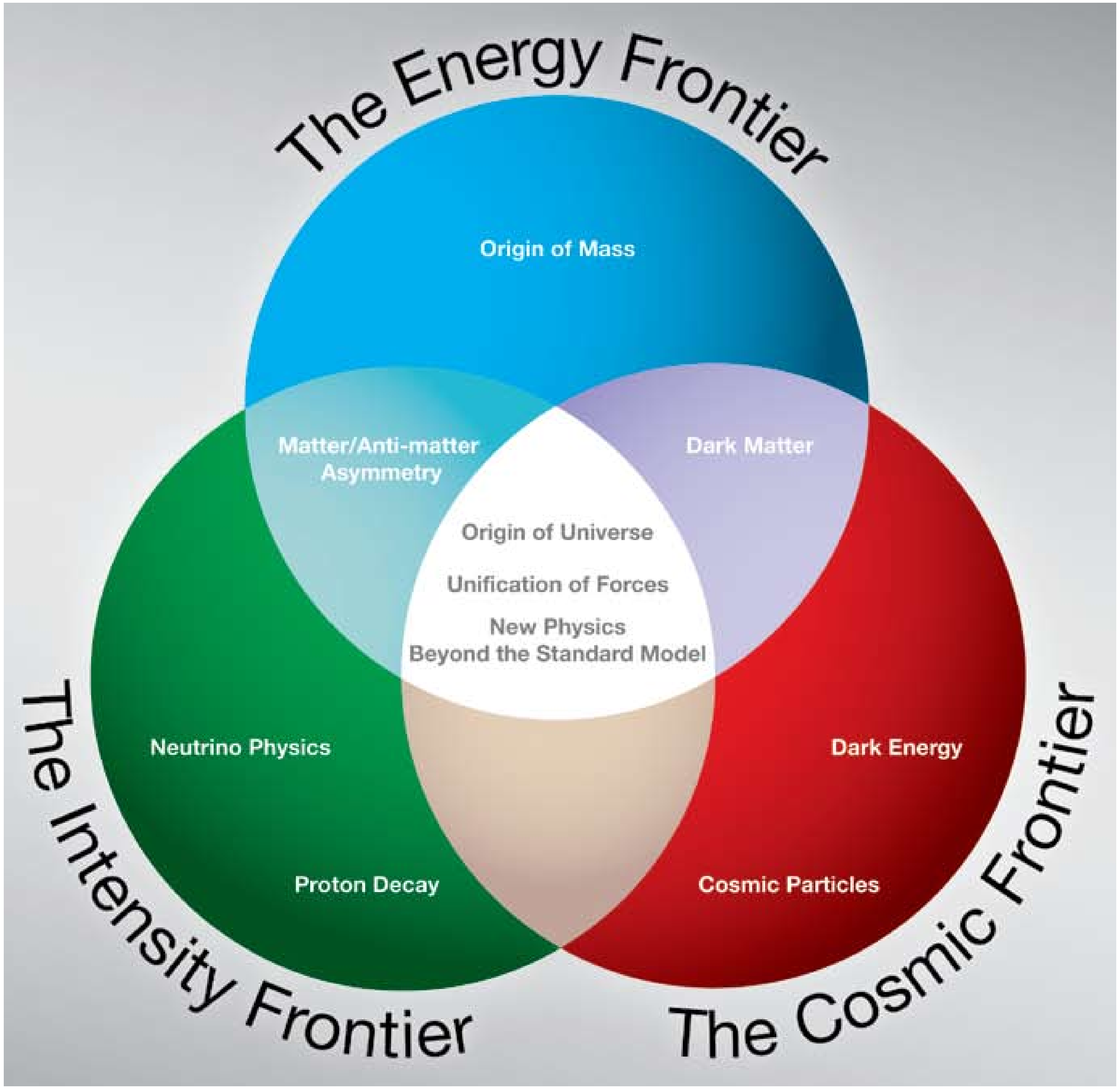
Andreas Warburton
McGill University / [UCL]
31 March 2017

Frontiers…



Cern Courier, March 2016, p. 25
R. Jacobsson & D. Dominguez



P5 / HEPAP

Particle physics is pursuing a variety of approaches to find evidence for the new physics we know must exist


GREAT POWER
GREAT RESPONSIBILITY
GOD
SPIDER MAN
SANTA
KNOWS IF YOU HAVE BEEN NAUGHTY OR NICE
SPANISH INQUISITION
WEARS RED SUIT
STEPHENWILDISH.CO.UK

C. Hearty

Outline

- The B Factory Era
  - 3 Decades of Detectors & Flavour Measurements

- Next generation: Belle II physics program (two examples)
  - $B \to D^* \tau \nu$
  - Dark Sector

- Belle II Experimental Challenges
  - Accelerator and Detector Upgrades
  - Understanding and Monitoring the Backgrounds
  - Schedules and Status

The B Factory Era

Three Decades of *B*-Factory results: *a rich harvest*

Goals of (heavy) flavour physics:

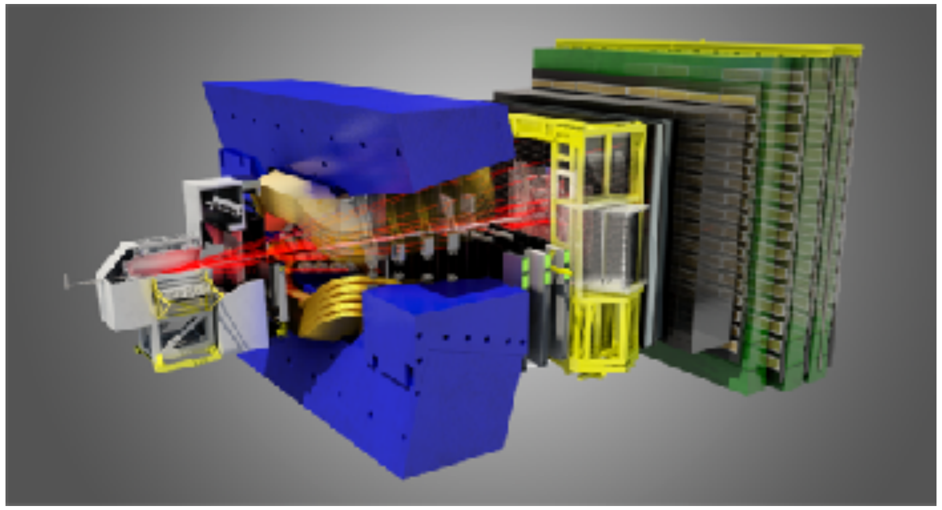
- Study the flavour mixing and *Charge-Parity violation* (*CP*) in all its aspects
- Look for new physics far beyond the current energy frontier in rare and forbidden processes
- By these measurements we hope to get insight into the mystery of the observed flavour structure

Large contributions from *B*-Factory experiments:

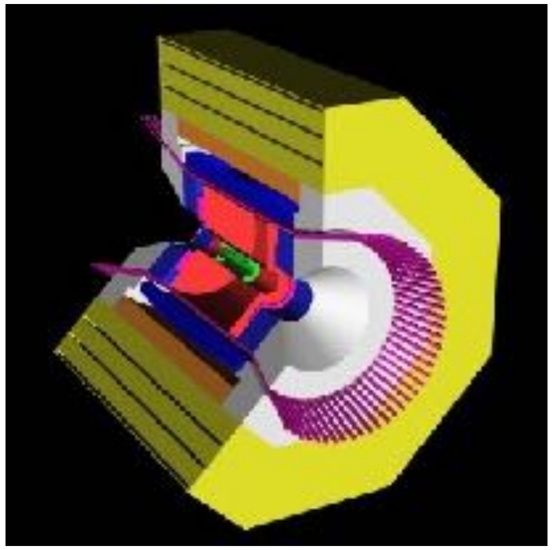
- Symmetric e^+e^- and hadronic experiments set the path
- Flavour physics at the luminosity frontier shaped by BaBar and Belle; plus recent huge contributions from LHCb
- Origin of *CP* in the SM was topic of the physics Nobel prize in 2008

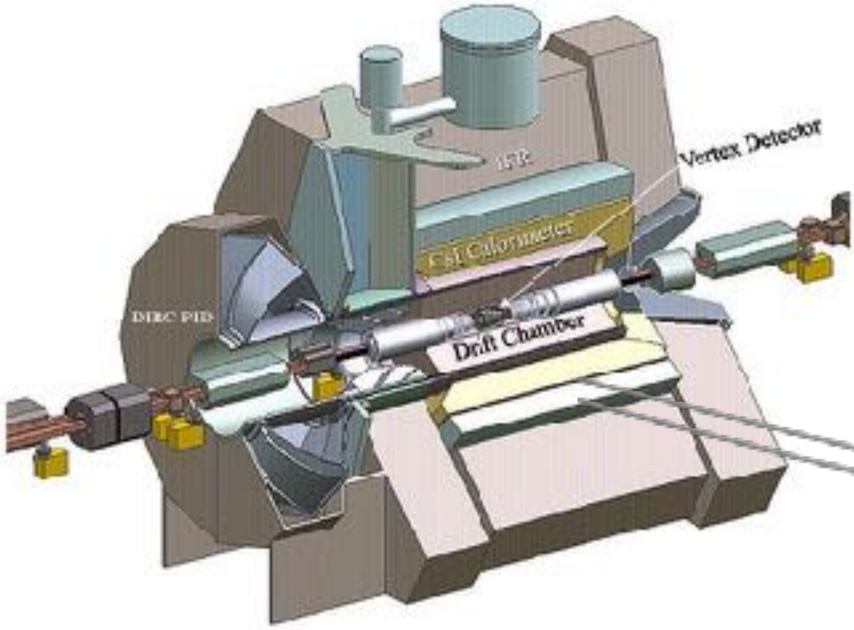
F. Bernlochner

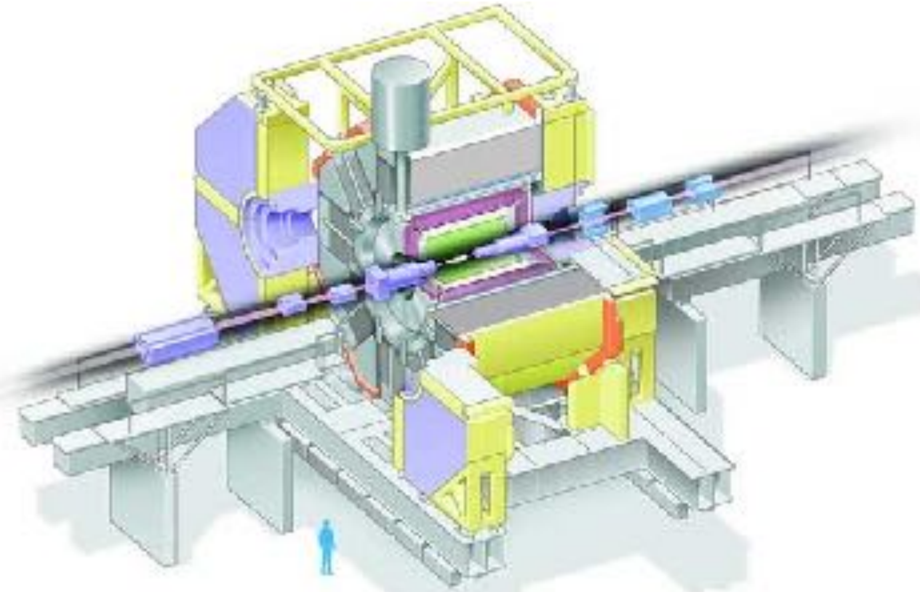
The B-Factories

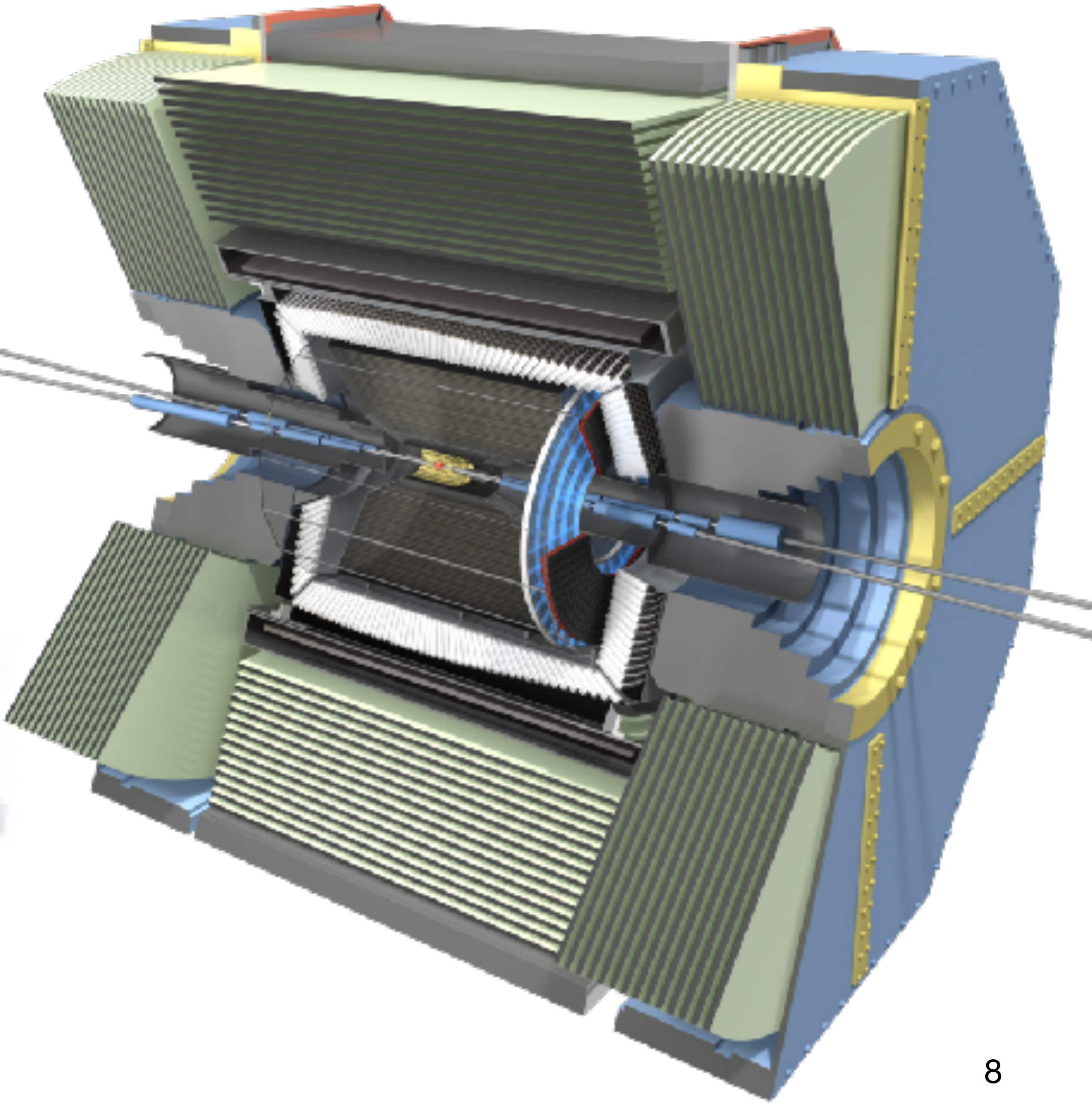



Vincent Pál



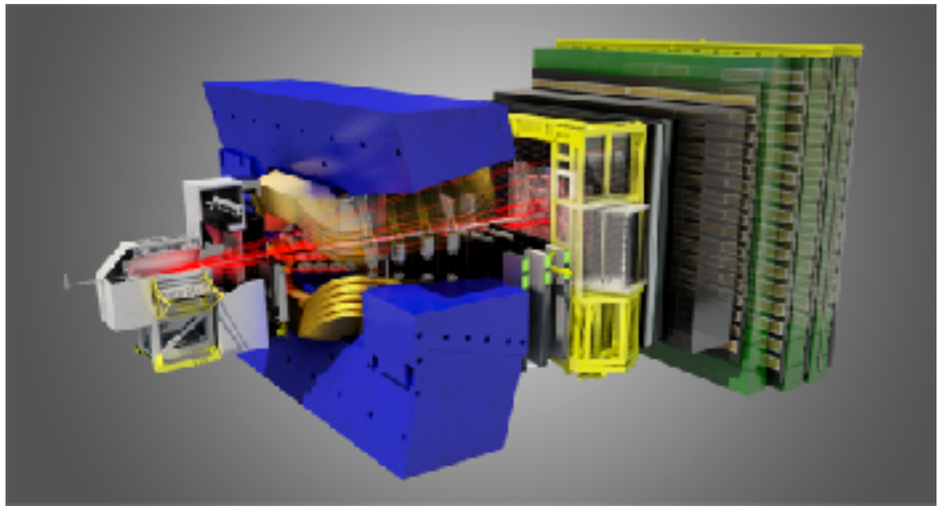






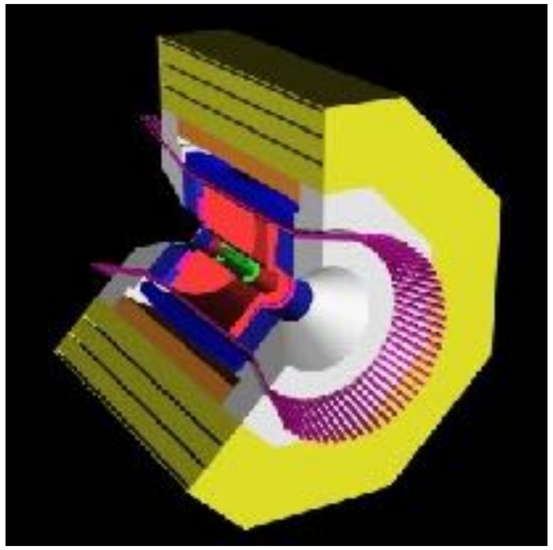
The B-Factories

HERA-B

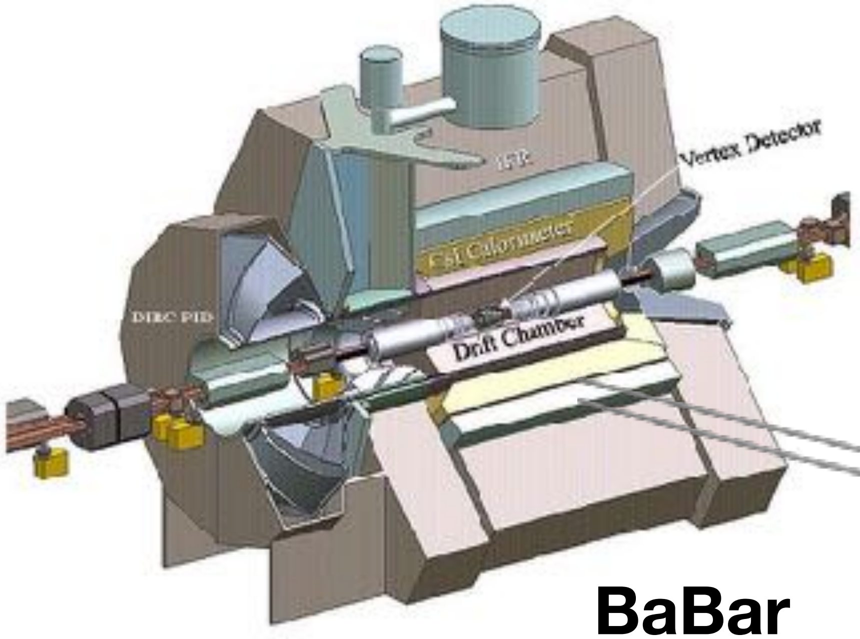


LHCb

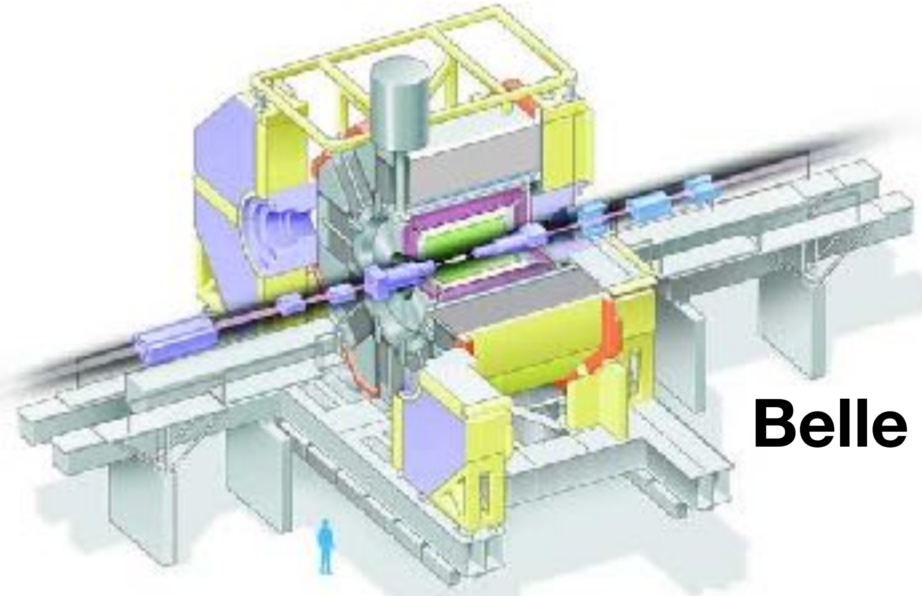
ARGUS



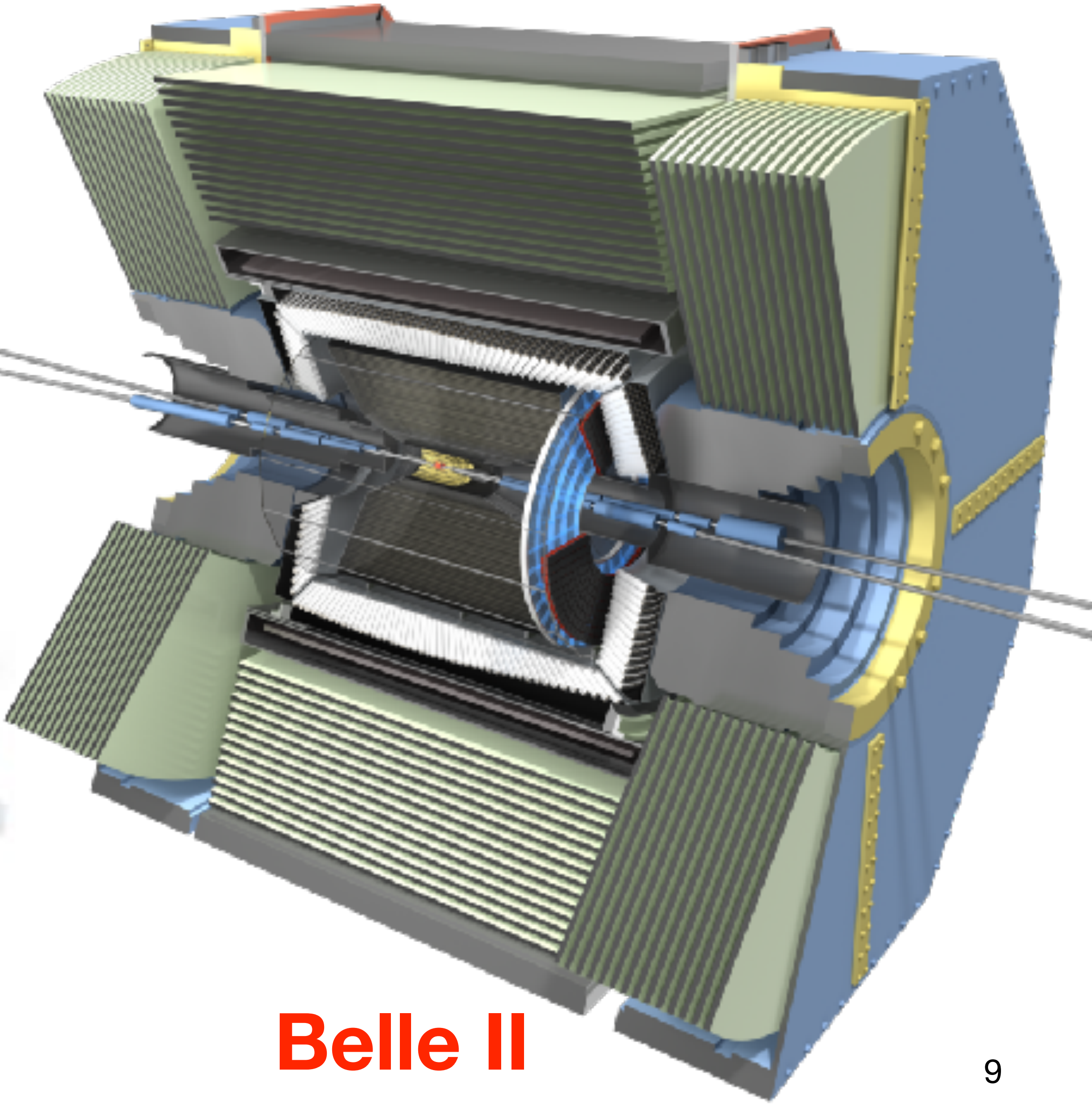
CLEO



BaBar

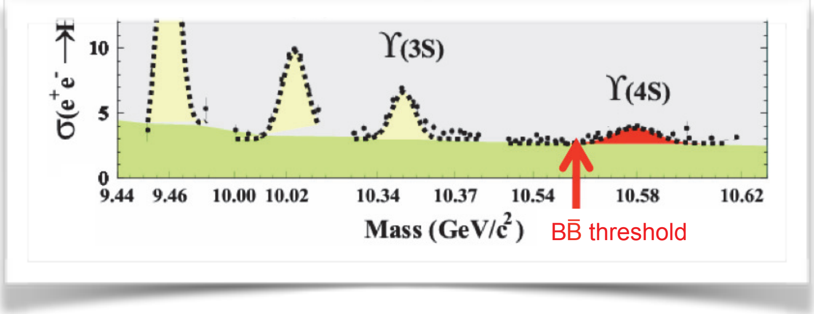


Belle



Belle II

The B-Factories



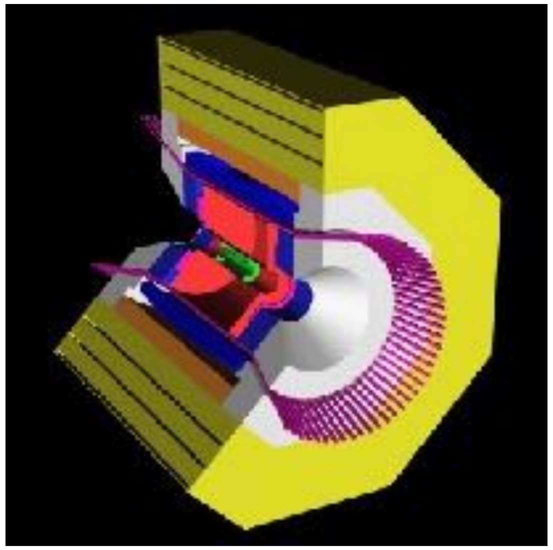
Collision cross section to hadrons in nb

$$e^+ \longrightarrow \underset{\langle b\bar{b}\rangle}{\Upsilon(4S)} \longleftarrow e^-$$

$$\sqrt{s} = 10.58\,\mathrm{GeV}$$


Vincent Pál

ARGUS



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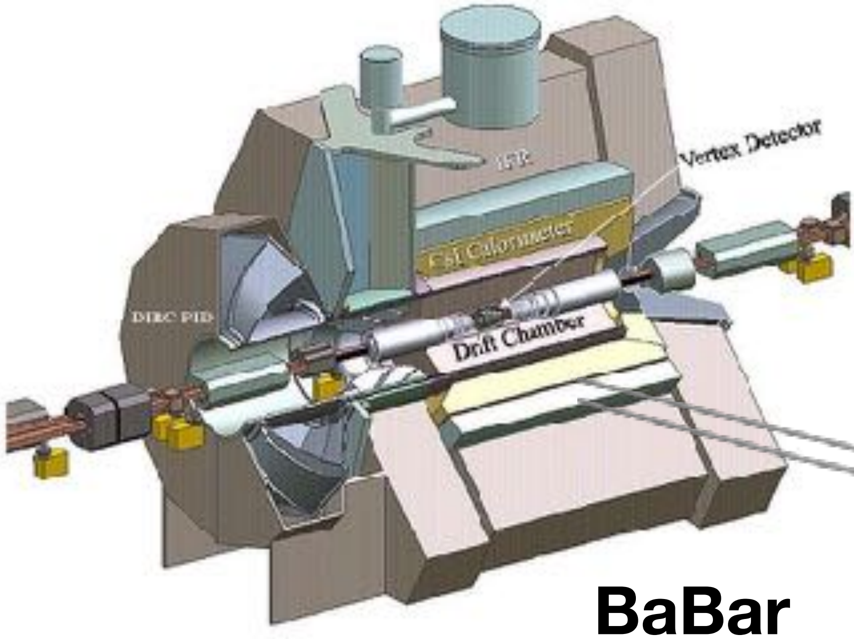
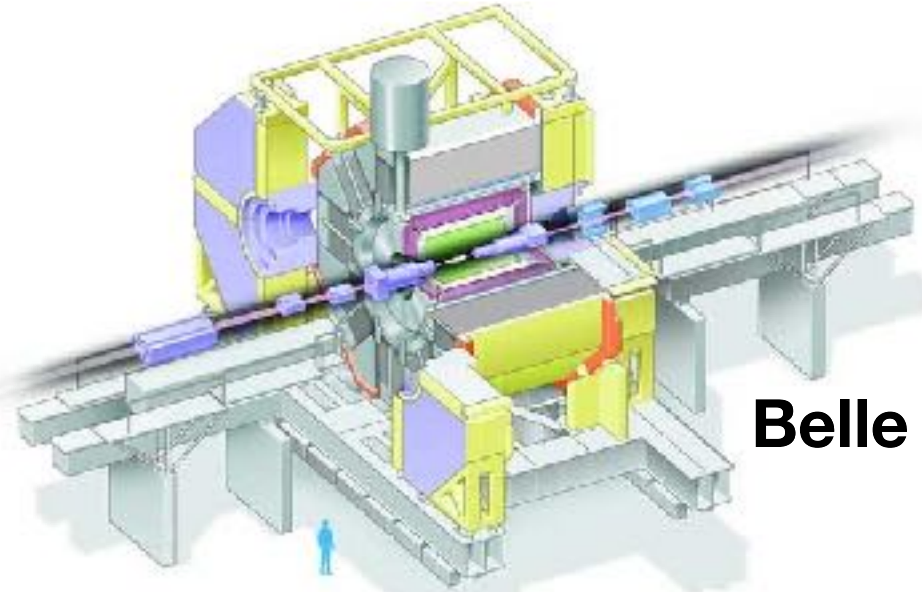
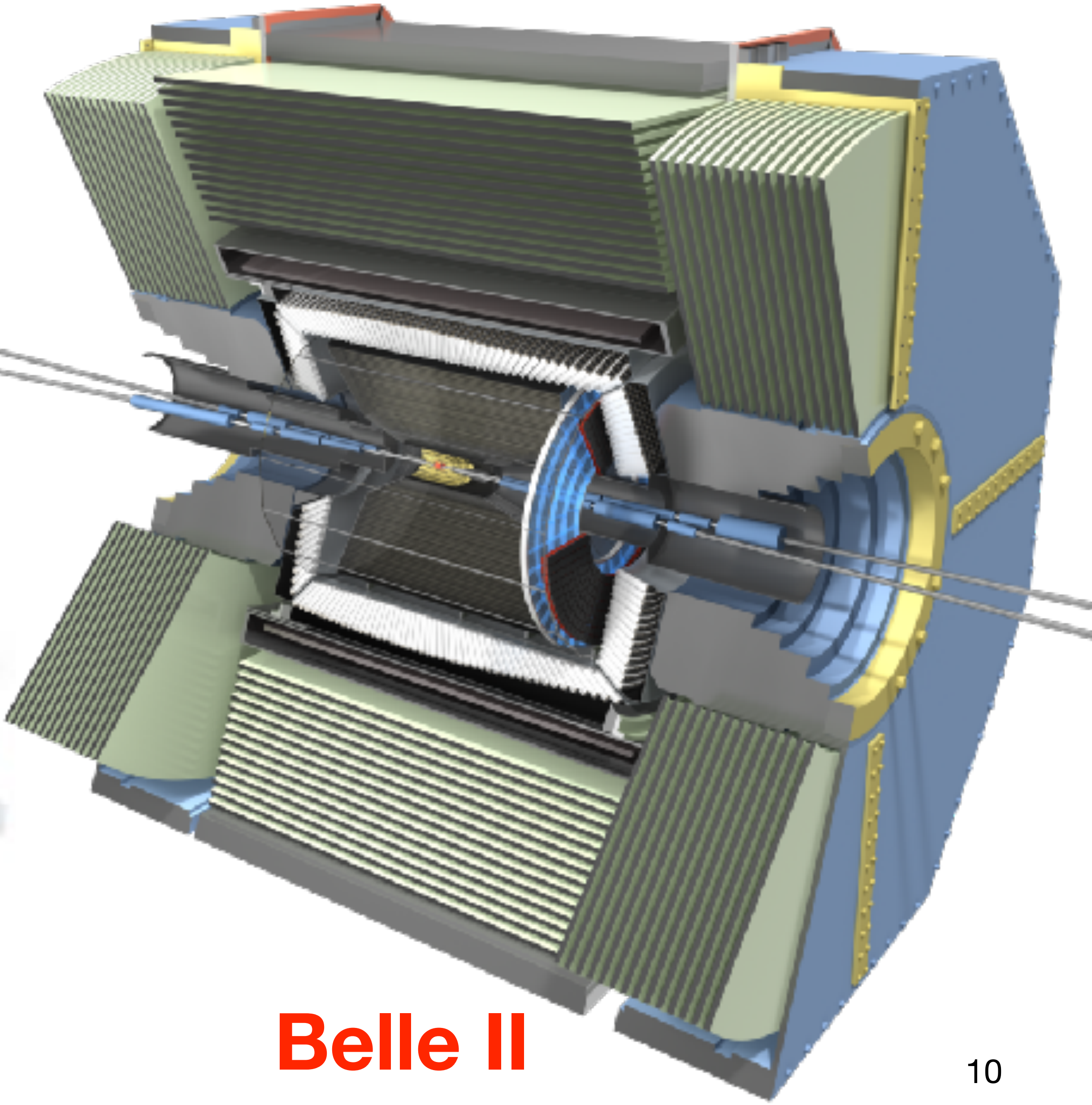


BaBar



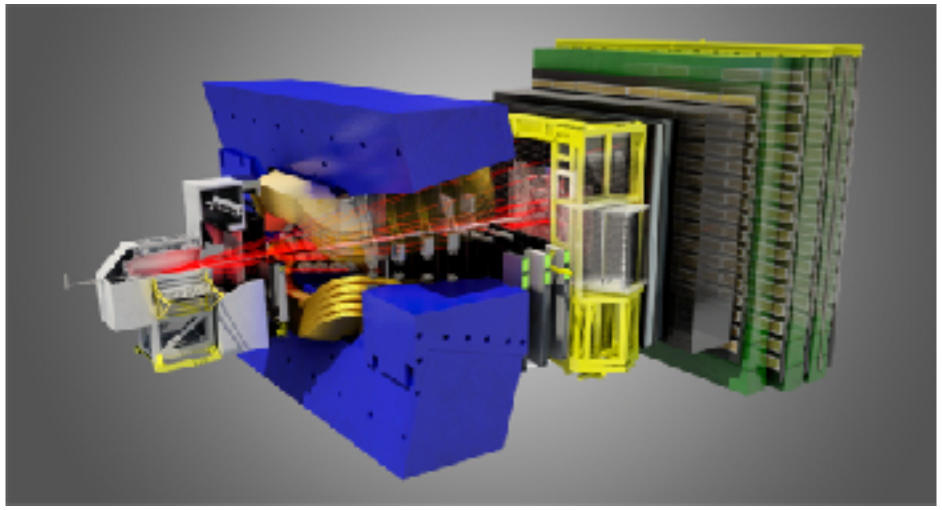
Belle



Belle II

The B-Factories

HERA-B



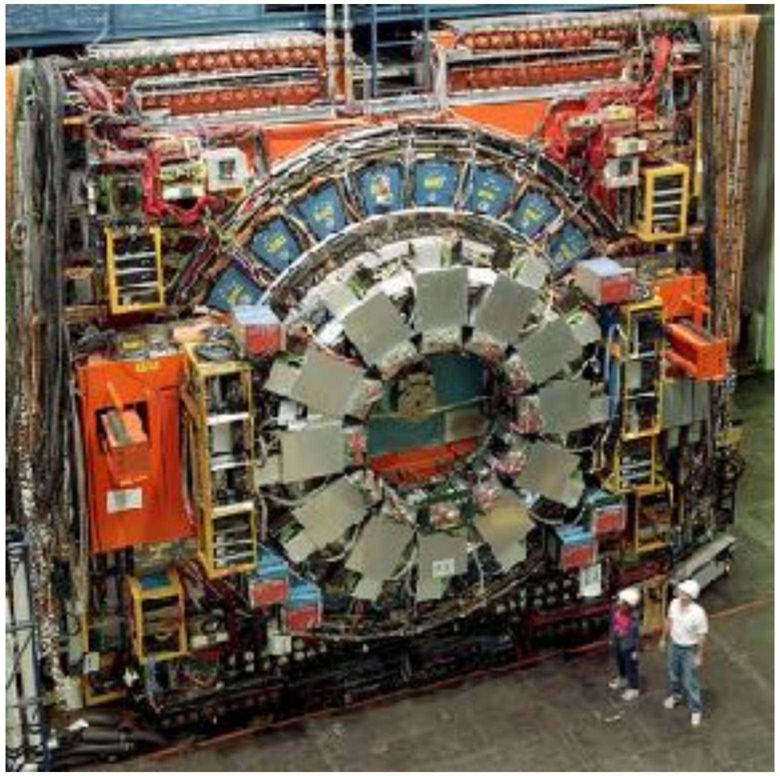
LHCb

proton-atom collisions

proton-proton collisions

Note: also proton-antiproton collisions

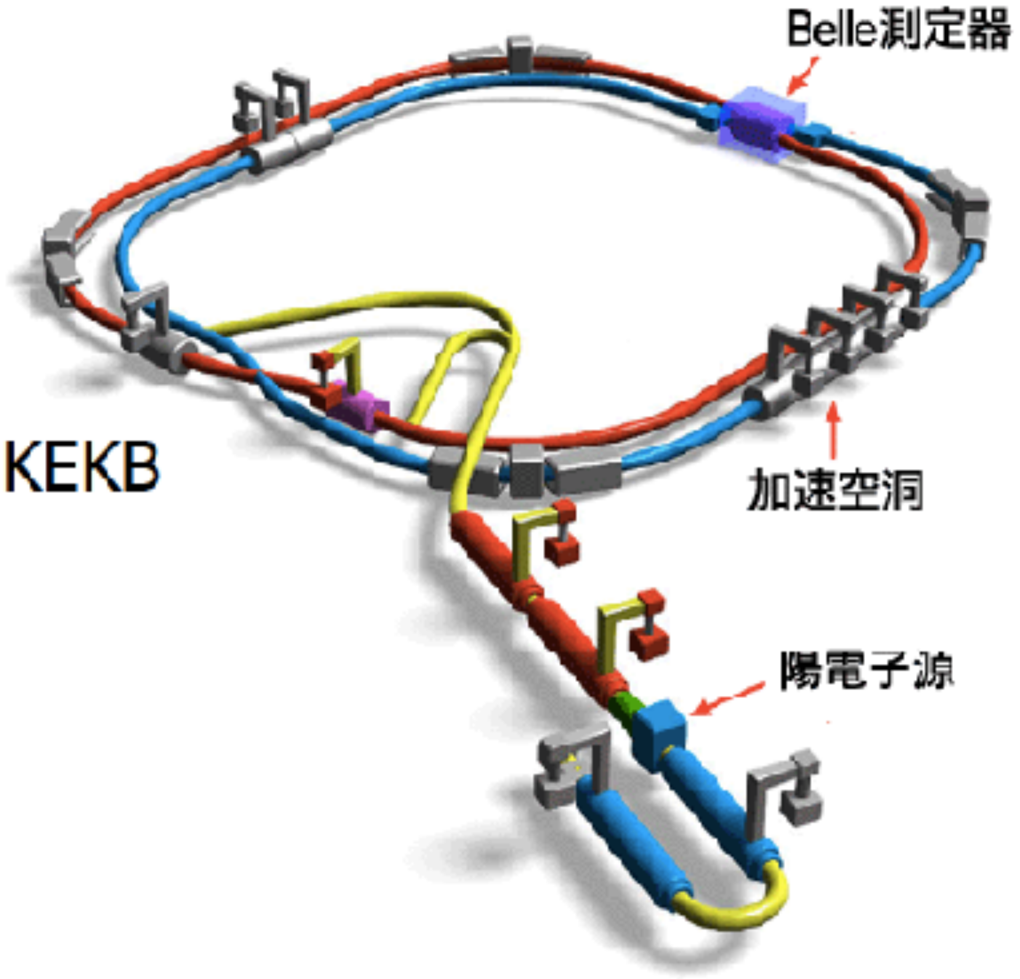
(And proton-proton: ATLAS & CMS)

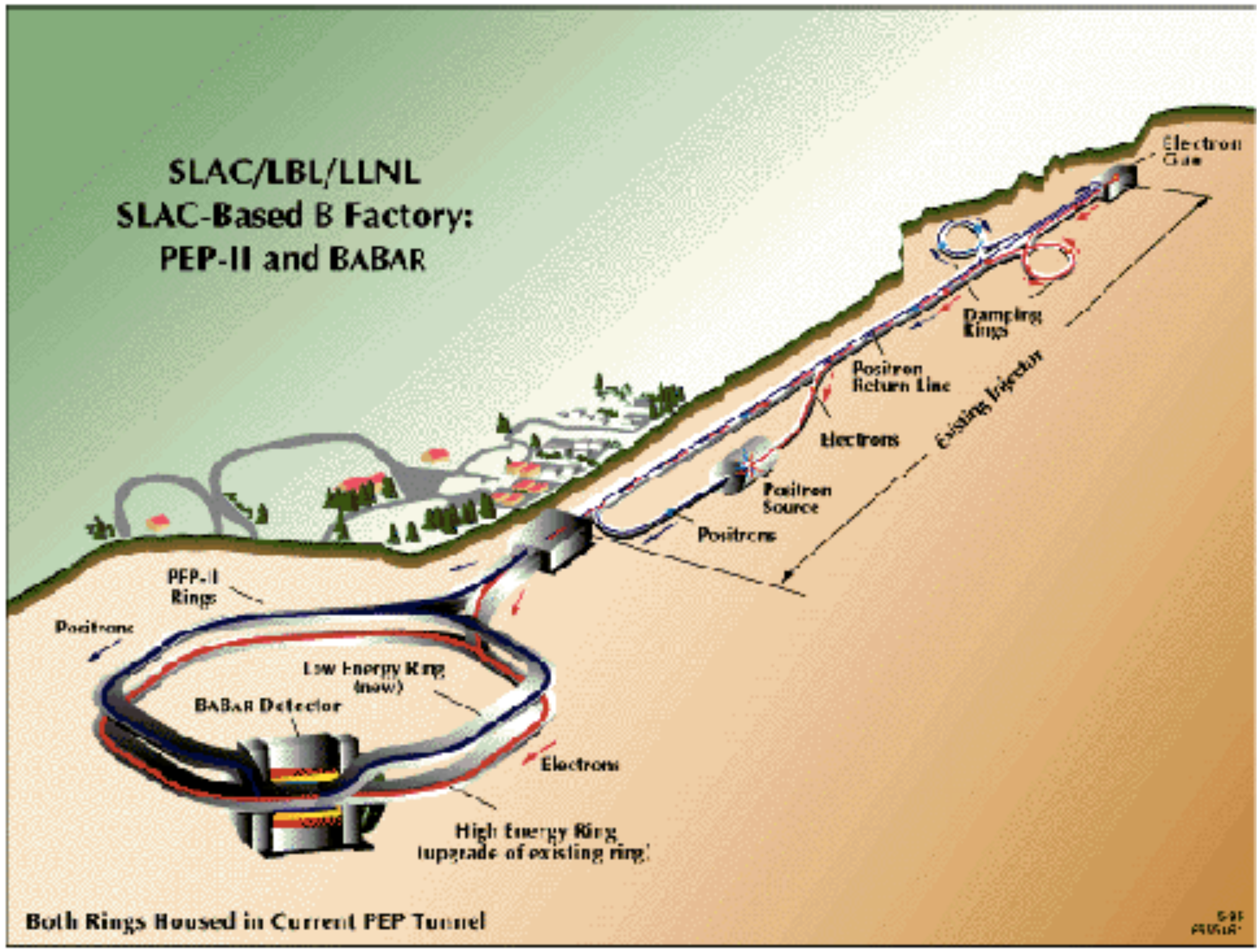


CDF

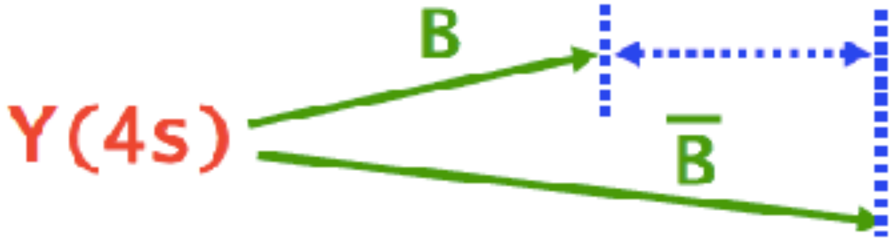
DZero

Flavour physics at the luminosity frontier with asymmetric B factories





$\sqrt{s}=10.58$ GeV



$$\Delta z \sim c\beta\gamma\tau_B \sim 200\mu m$$

BaBar	$p(e^-)=9$ GeV	$p(e^+)=3.1$ GeV	$\beta\gamma=0.56$
Belle	$p(e^-)=8$ GeV	$p(e^+)=3.5$ GeV	$\beta\gamma=0.42$

Peter Krizan

To a large degree shaped flavour physics in the previous decade

The CKM Picture of Quarks in the Standard Model

The CKM Matrix source of *C*harge*P*arity*V*iolation in SM

- Unitary 3x3 Matrix, parametrizes rotation between mass and weak interaction eigenstates in Standard Model

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

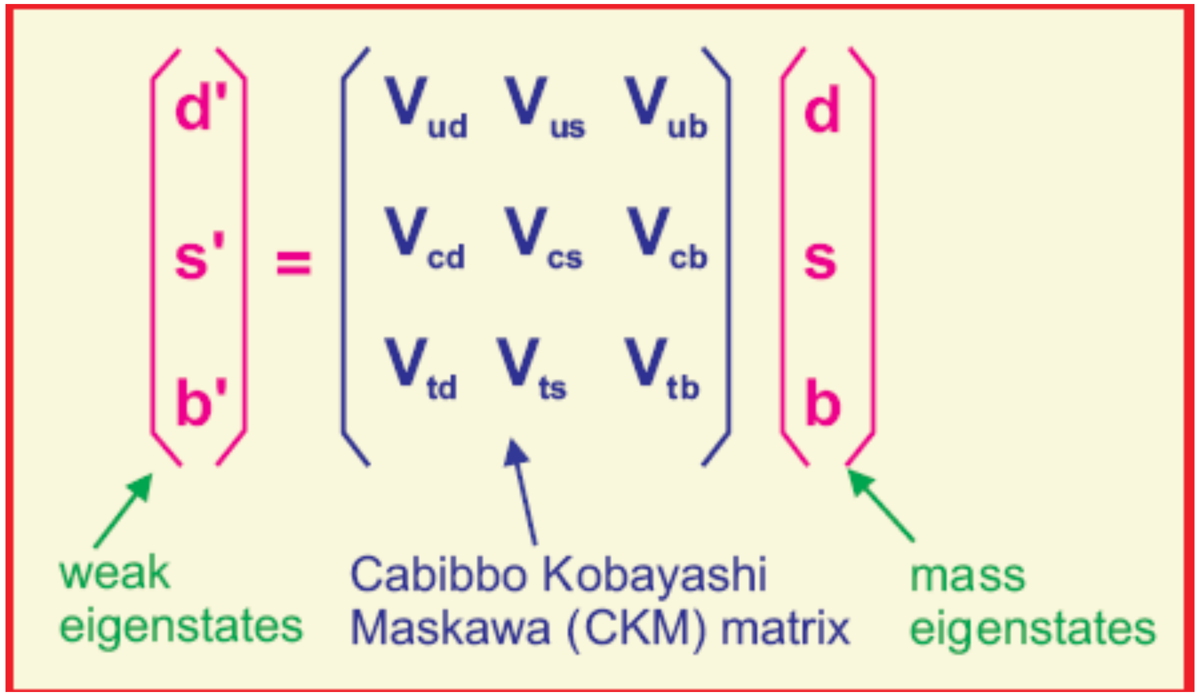
Weak Eigenstates CKM Matrix Mass Eigenstates

- Fully parametrized by **four** parameters if unitarity holds: three real parameters and one complex phase that, if non-zero, indicates *CPV*
- Can be visualized using triangle equations, e.g.

$$V_{CKM} V_{CKM}^{\dagger} = \mathbf{1} \qquad \rightarrow \qquad V_{ub}^{*} V_{ud} + V_{cb}^{*} V_{cd} + V_{tb}^{*} V_{td} = 0$$

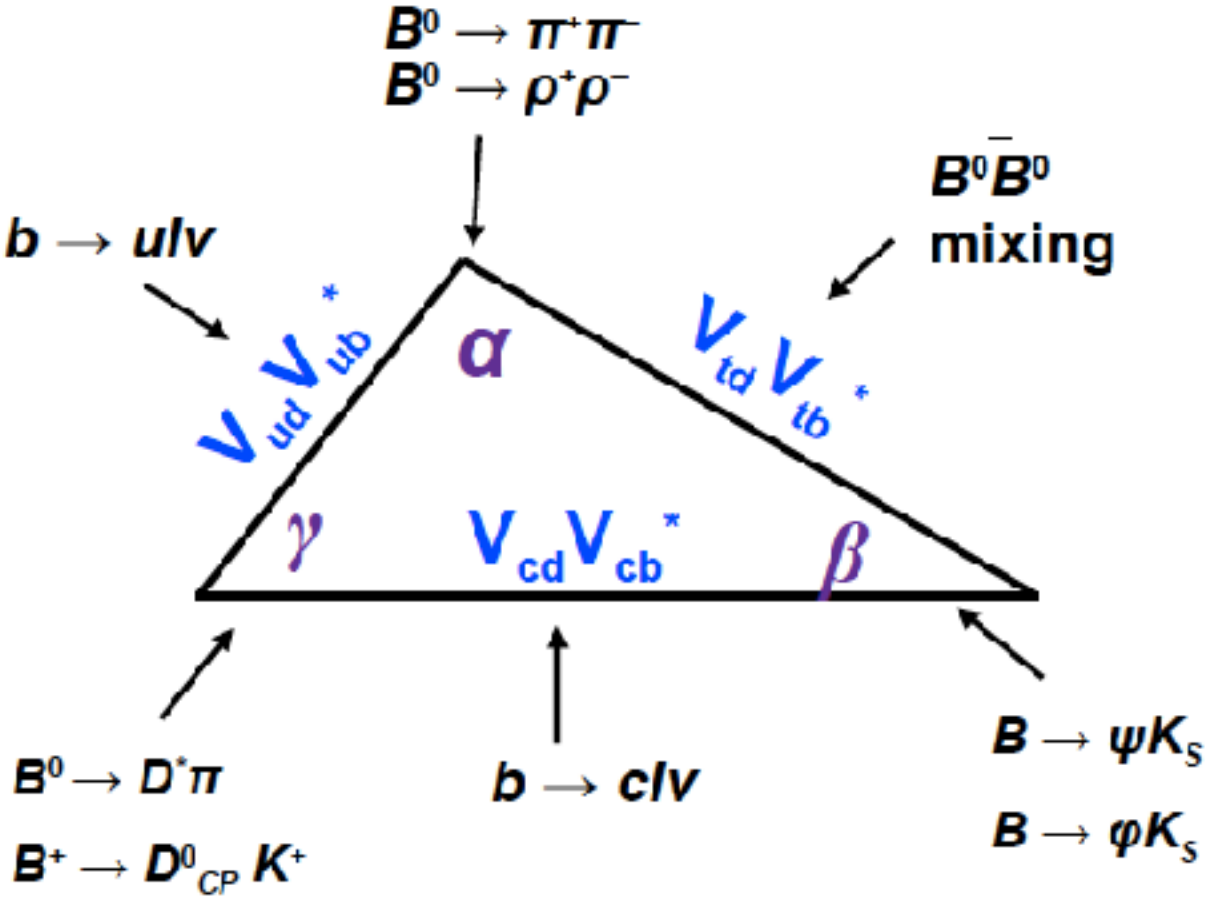
B Factories: CP Violation in the B-Meson System

Quark Mixing Matrix



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM Unitarity Triangle



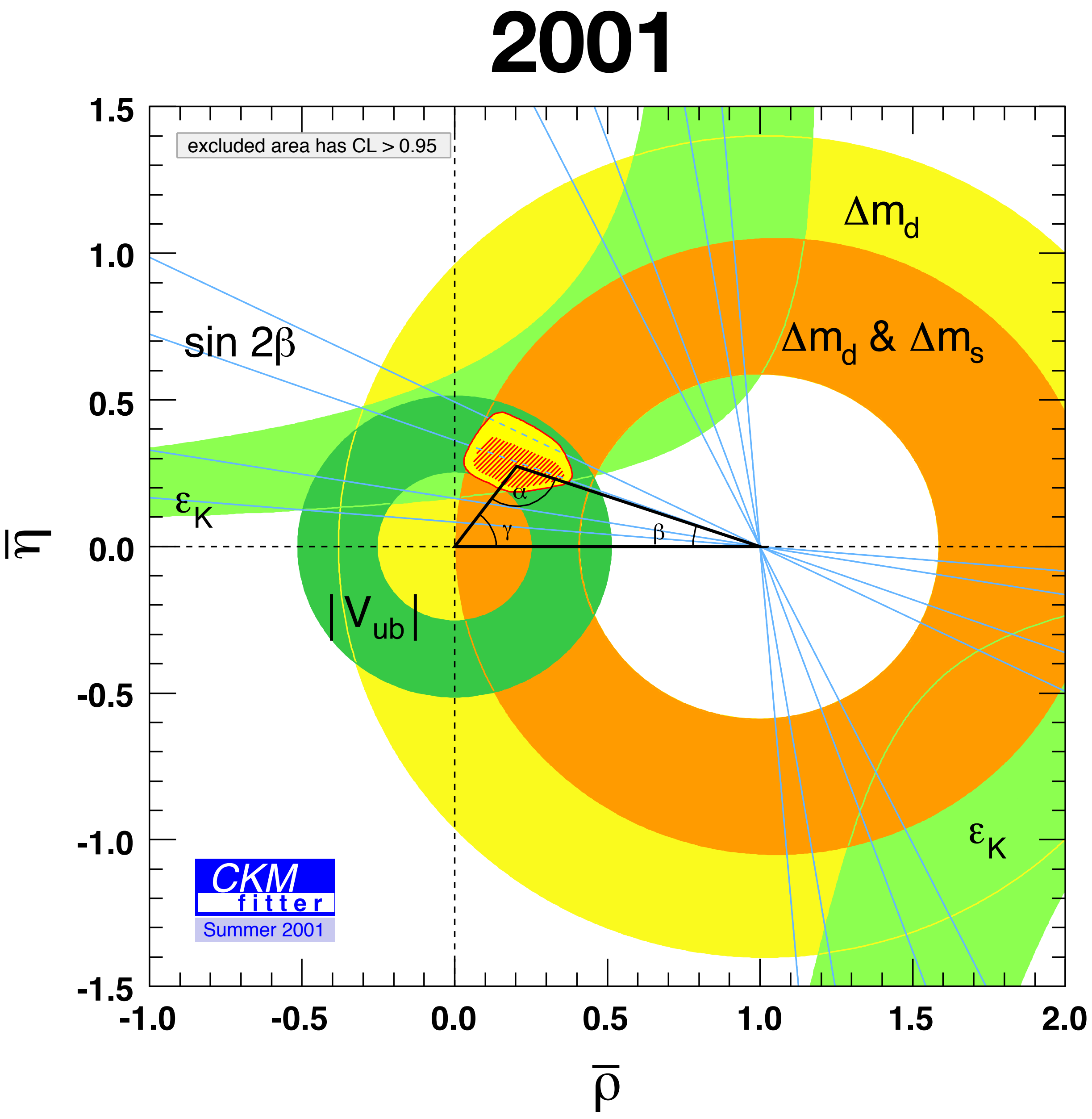
Over-constraining the CKM matrix allows for non-trivial test of the SM

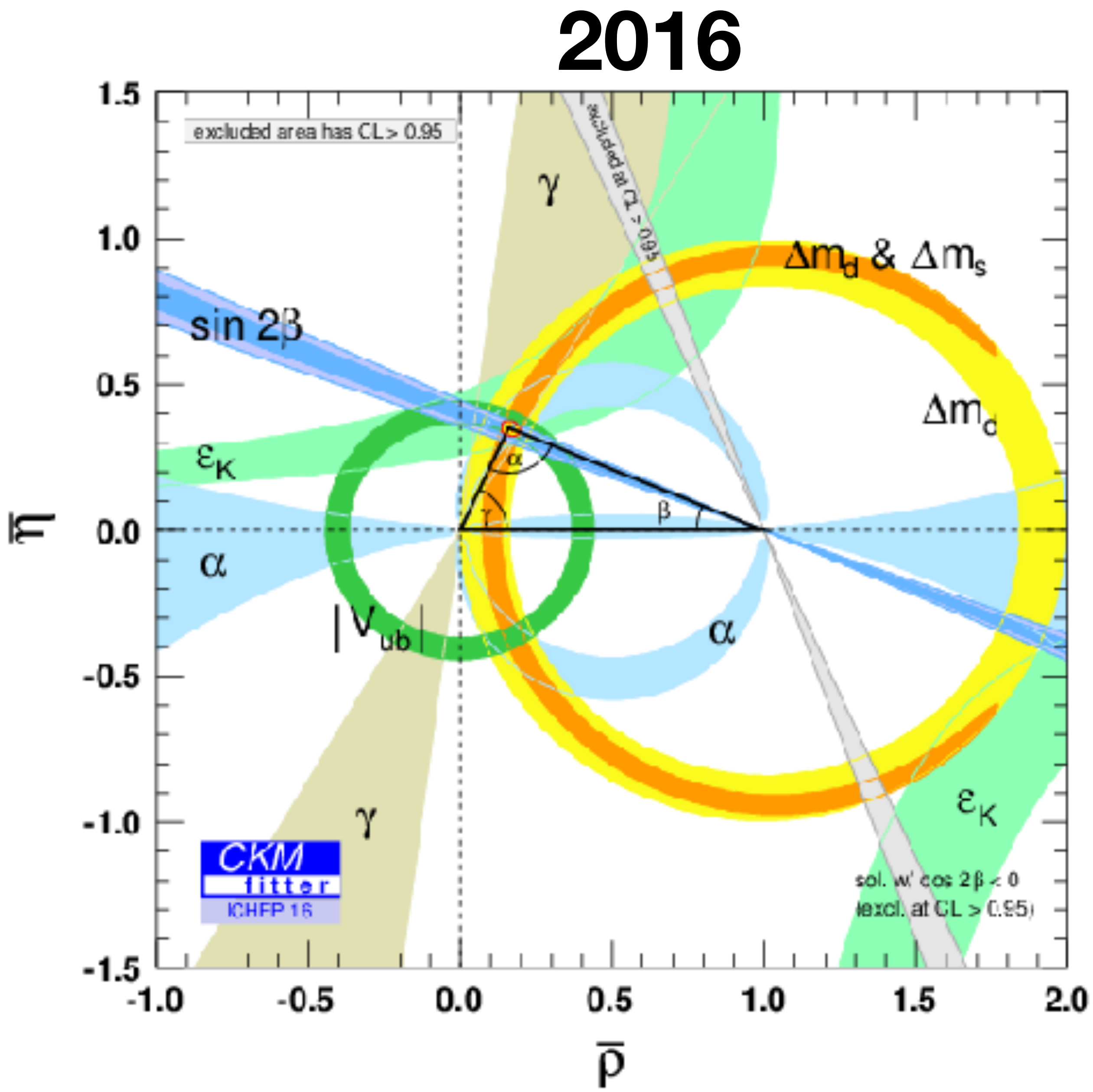
Presence of *CPV* phase encoded in apex of triangle in the complex plane

B Factories: CP Violation in the B-Meson System

From **discovery** (2001) by BaBar & Belle,
to **precision measurements**.

- Picture still holds 16 years later, constrained with remarkable precision
- But: there remains room for new physics contributions





Most Measurements Statistically Limited

Current open questions: *New physics and anomalies*

Can roughly be grouped into two categories:

- Fundamental questions that the SM in current form does not provide, e.g.
  - What is Dark Matter?
  - What causes the large CPV in the Universe?
  - Gravity?
- Existing anomalies in the Flavour sector, e.g.
  - Inclusive and exclusive $|V_{qb}|$ disagreement
  - Enhancements in semi-tauonic decays
  - Deviations in penguin decays
  - Very rare B_s and B decays — not an anomaly!

Flavour and energy frontier experiments are *complementary* probes:

Evidence for BSM?		FLAVOR **(Belle II & LHCb)** yes	no
ATLAS & CMS	yes	complementary information	distinguish models
	no	tells us where to look next	flavor is the best microscope

Zoltan Ligeti

Anomalies — what is there to learn?

If one carries out many measurements, one of course will every once in a while measure something that does not fit *(cf. look elsewhere effect)*

It is interesting though, that some measurements show persistent differences that either cannot be statistical in nature or show up for several experiments that don't use the same observables in their measurements

- Could point to a common systematic error all measurements underestimate (our limited understanding of QCD could be the culprit) and similar models for backgrounds are used
- Or are we seeing an emergence of the first recent sign of New Physics?

To discern one from the other we need to keep measuring

- Future results from the LHC and the intensity frontier will either confirm or reject these anomalies

The Belle II experiment will play an important role in this

The Belle II Physics Program

Belle II Physics

- We know there must be new physics, but we don't know what it is
- Our approach is to make a large number of measurements for which the outcomes can be accurately predicted using the Standard Model
- Because of quantum effects, these are sensitive to massive particles, even beyond the reach of the LHC
    - B-mixing ⟹ heavy top quark; Higgs mass prediction

Predicted uncertainties on a selection of proposed Belle II measurements

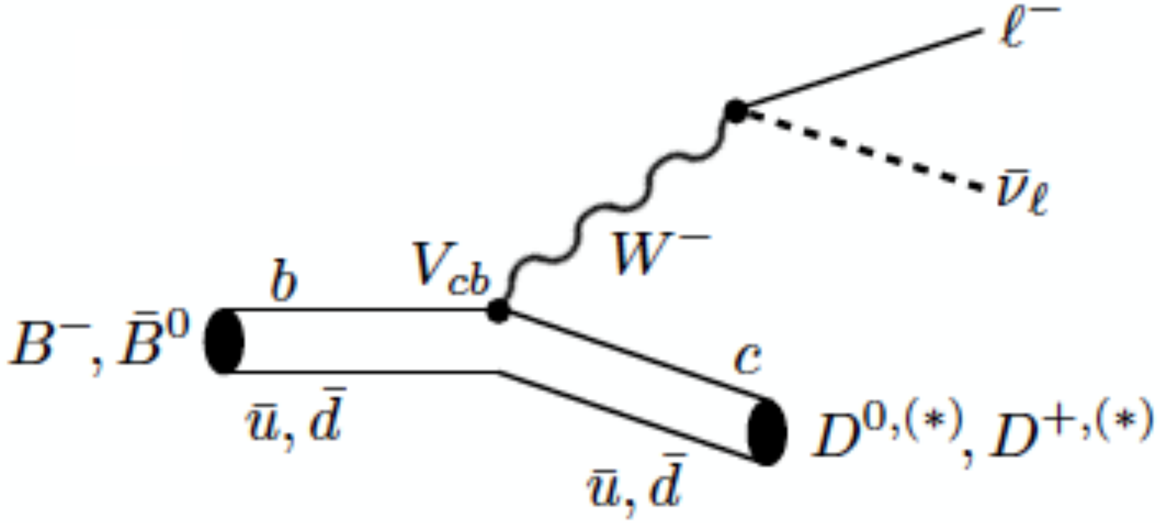
Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	± 0.012	± 0.008	6
α		$\pm 2^\circ$	$\pm 1^\circ$	
γ	$\pm 14^\circ$	$\pm 6^\circ$	$\pm 1.5^\circ$	
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	± 0.053	± 0.018	>50
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	± 0.028	± 0.011	>50
$S(B \to K_S^0 K_S^0 K_S^0)$	$0.30 \pm 0.32 \pm 0.08$	± 0.100	± 0.033	44
$\lvert V_{cb} \rvert$ incl.	$\pm 2.4\%$	$\pm 1.0\%$		< 1
$\lvert V_{cb} \rvert$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$	< 1
$\lvert V_{ub} \rvert$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$	2
$\lvert V_{ub} \rvert$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$	20
$\lvert V_{ub} \rvert$ excl. (untag.)	$\pm 9.4\%$	$\pm 4.2\%$	$\pm 2.2\%$	3
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	96 ± 26	$\pm 10\%$	$\pm 5\%$	46
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7	5σ	$>> 5\sigma$	>50
$R(B \to D\tau\nu)$	$\pm 16.5\%$	$\pm 5.6\%$	$\pm 3.4\%$	4
$R(B \to D^*\tau\nu)$	$\pm 9.0\%$	$\pm 3.2\%$	$\pm 2.1\%$	3
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ $[10^{-6}]$	< 40		$\pm 30\%$	>50
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ $[10^{-6}]$	< 55		$\pm 30\%$	>50
$\mathcal{B}(B \to X_s\gamma)$ $[10^{-6}]$	$\pm 13\%$	$\pm 7\%$	$\pm 6\%$	< 1
$A_{CP}(B \to X_s\gamma)$		± 0.01	± 0.005	8
$S(B \to K_S^0\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 0.11	± 0.035	> 50
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	± 0.23	± 0.07	> 50
C_7/C_9 $(B \to X_s\ell\ell)$	~20%	10%	5%	
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	< 8.7	± 0.3		
$\mathcal{B}(B_s \to \tau^+\tau^-)$ $[10^{-3}]$		< 2		

Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \times 10^{-3}(1 \pm 0.053 \pm 0.038)$	$\pm 2.9\%$	$\pm(0.9\%\text{-}1.3\%)$	> 50
$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \times 10^{-3}(1 \pm 0.037 \pm 0.054)$	$\pm(3.5\%\text{-}4.3\%)$	$\pm(2.3\%\text{-}3.6\%)$	3-5
y_{CP} $[10^{-2}]$	$1.11 \pm 0.22 \pm 0.11$	$\pm(0.11\text{-}0.13)$	$\pm(0.05\text{-}0.08)$	5-8
A_Γ $[10^{-2}]$	$-0.03 \pm 0.20 \pm 0.08$	± 0.10	$\pm(0.03\text{-}0.05)$	7 - 9
$A_{CP}^{K^+K^-}$ $[10^{-2}]$	$-0.32 \pm 0.21 \pm 0.09$	± 0.11	± 0.06	15
$A_{CP}^{\pi^+\pi^-}$ $[10^{-2}]$	$0.55 \pm 0.36 \pm 0.09$	± 0.17	$\pm$ 0.06	> 50
$A_{CP}^{\phi\gamma}$ $[10^{-2}]$	$\pm$ 5.6	± 2.5	± 0.8	> 50
$x^{K_S\pi^+\pi^-}$ $[10^{-2}]$	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	± 0.14	± 0.11	3
$y^{K_S\pi^+\pi^-}$ $[10^{-2}]$	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	± 0.08	± 0.05	15
$\lvert q/p \rvert^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	± 0.10	± 0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ $[^\circ]$	$-6 \pm 11 \pm {}^{4}_{5}$	± 6	± 4	10
$A_{CP}^{\pi^0\pi^0}$ $[10^{-2}]$	$-0.03 \pm 0.64 \pm 0.10$	± 0.29	± 0.09	> 50
$A_{CP}^{K_S^0\pi^0}$ $[10^{-2}]$	$-0.10 \pm 0.16 \pm 0.09$	± 0.08	± 0.03	> 50
$Br(D^0 \to \gamma\gamma)$ $[10^{-6}]$	< 1.5	$\pm 30\%$	$\pm 25\%$	2
	$\tau \to \mu\gamma$ $[10^{-9}]$	< 45	< 14.7	< 4.7
	$\tau \to e\gamma$ $[10^{-9}]$	< 120	< 39	< 12
	$\tau \to \mu\mu\mu$ $[10^{-9}]$	< 21.0	< 3.0	< 0.3

- **Ideally, a pattern of deviations from the SM will elucidate the nature of the New Physics**

Belle2-Note-021

$\bar{B} \to D\tau^-\bar{\nu}_\tau$ and $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$



arXiv:1703.01766

- Fraction of B mesons that decay to $D^{(*)}\tau\nu$ should be equal to $D^{(*)}\mu\nu$ or $D^{(*)}e\nu$, except for mass difference (lepton universality)

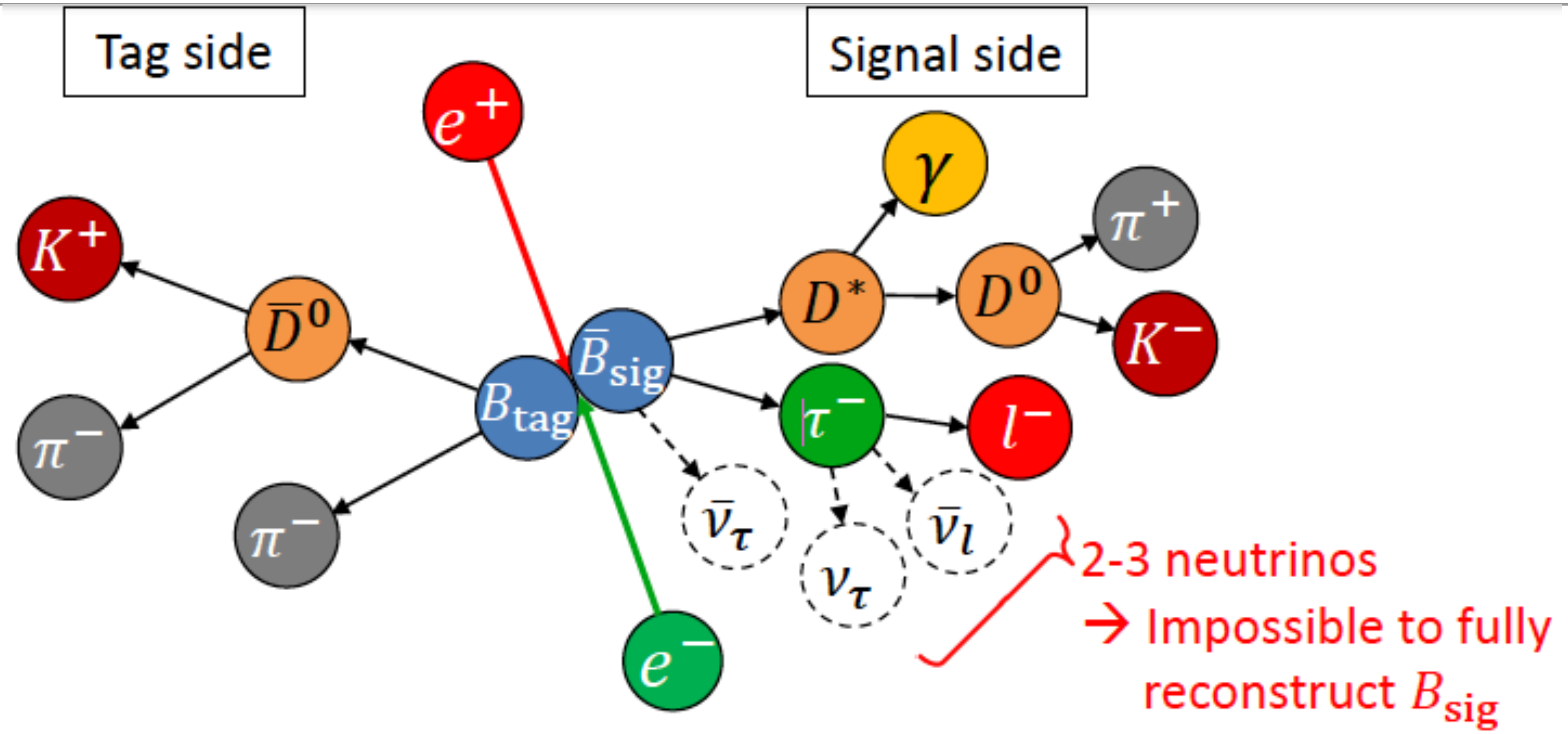
$$R(D^*) \equiv \frac{\mathcal{B}\big(B \to D^*\tau^-\bar{\nu}_\tau\big)}{\mathcal{B}(B \to D^*\ell^-\bar{\nu}_\ell)} \qquad R(D) \equiv \frac{\mathcal{B}\big(B \to D\tau^-\bar{\nu}_\tau\big)}{\mathcal{B}(B \to D\ell^-\bar{\nu}_\ell)} \qquad \ell = e \text{ or } \mu$$

- Charged Higgs would affect decay to τ, but not e or μ.

- The tau decays to e or μ plus neutrinos
  ⟹ same particles are reconstructed in the final state, other than the neutrinos, which we can’t detect.

- If we can’t detect neutrinos, how do we know we have the correct final state?

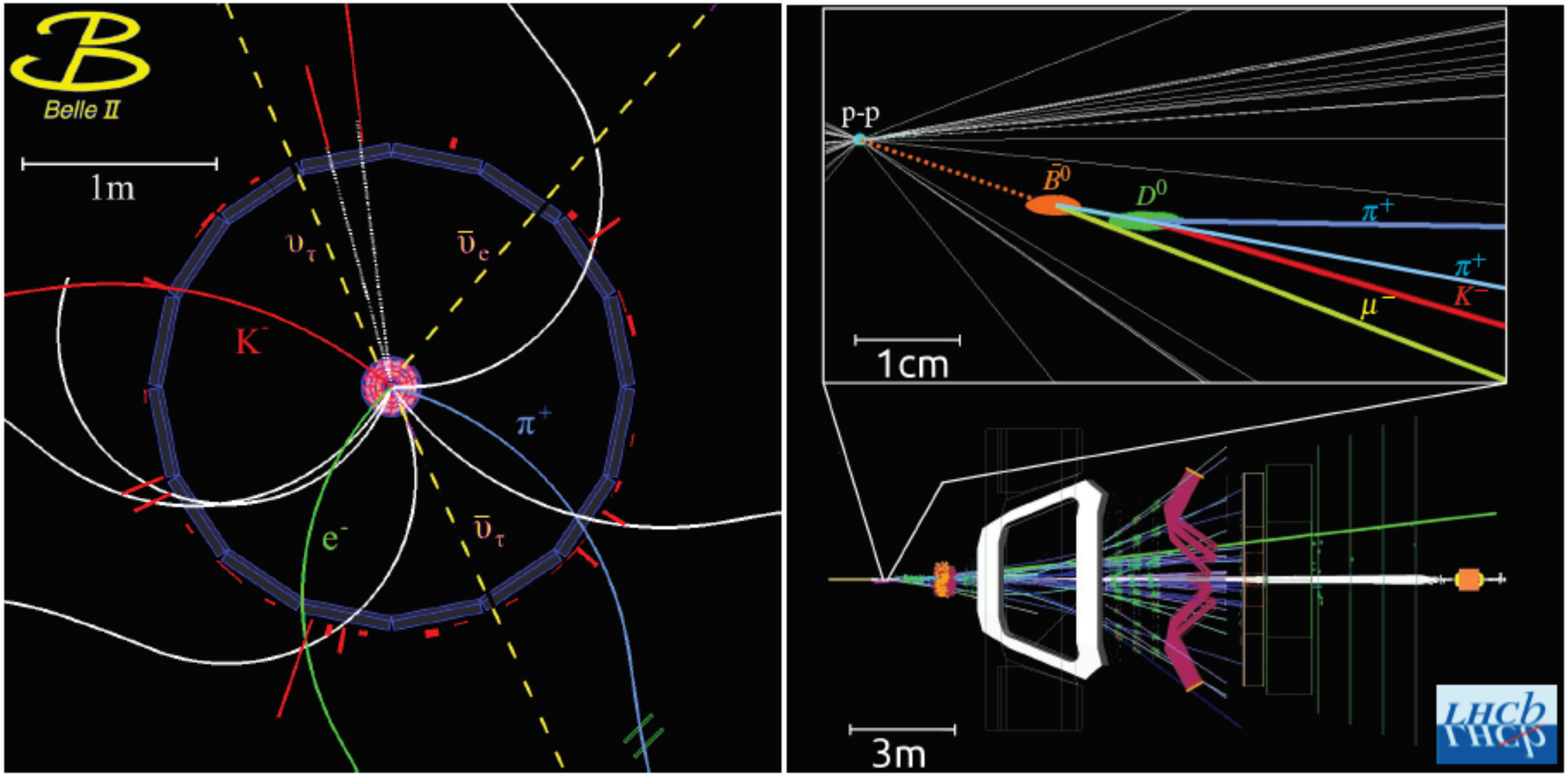
Reconstruction: Tag the companion B meson



- **Infer signal B-meson kinematics by reconstructing the tag B-meson (hadronic, semileptonic)**
- **A powerful tool for reconstructing events with neutrinos**
- **Not available at proton colliders like the LHC**

$$\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$$

Belle II vs. LHCb: Very different reconstructions



G. Ciezarek et al., arXiv:1703.01766

Separating $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ and $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$

- But how to distinguish $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ from $\bar{B} \to D^*\mu^-\bar{\nu}_\mu$?

  $\to \mu^-\bar{\nu}_\mu\nu_\tau$

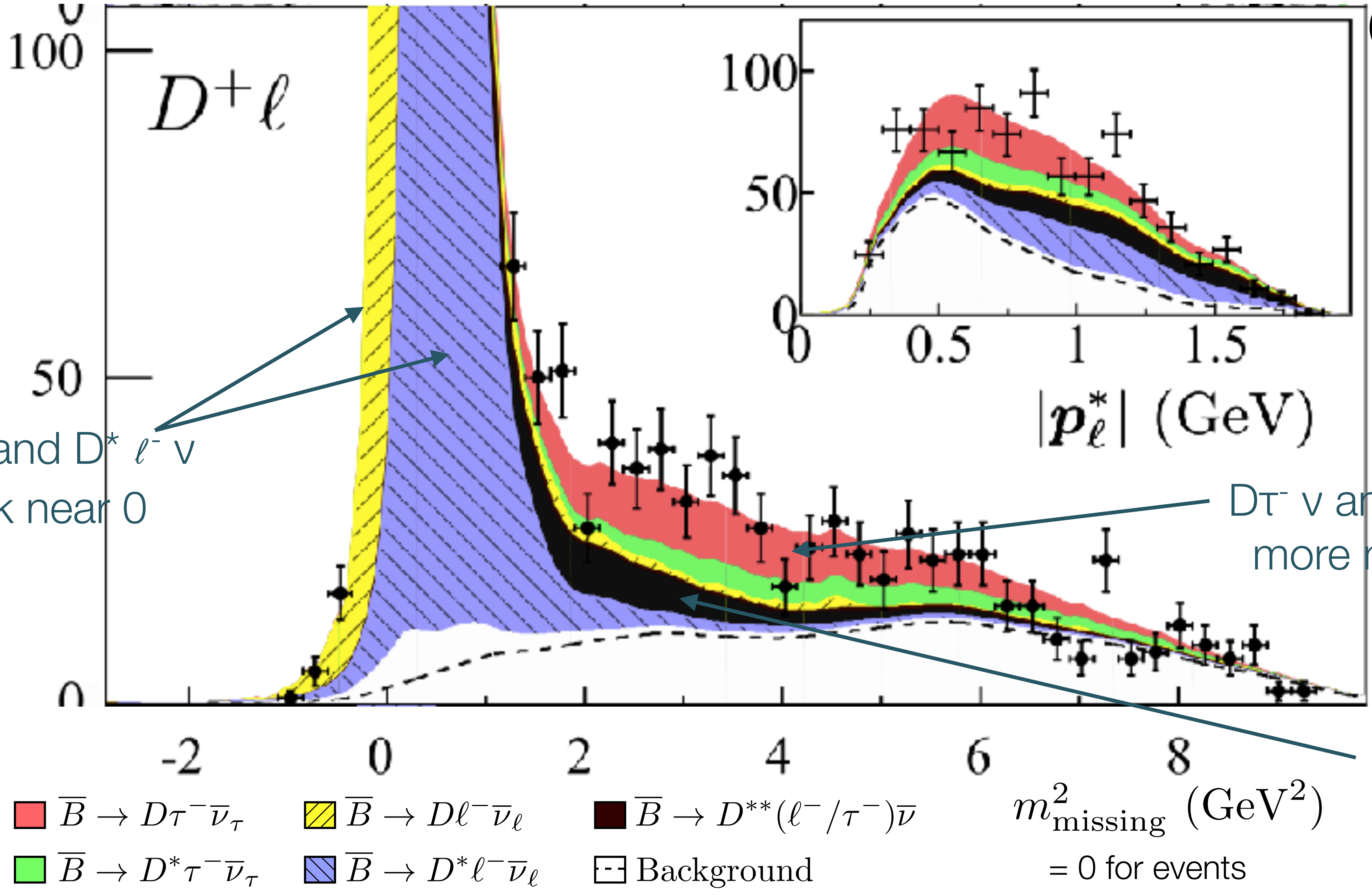
  - momentum of μ is lower

  - more neutrinos ⟹ more “missing” energy (or missing mass)

Distinguishing $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ and $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$

- A glimpse at how complicated it actually is…

(for illustration)



D ℓ^- ν and D* ℓ^- ν peak near 0

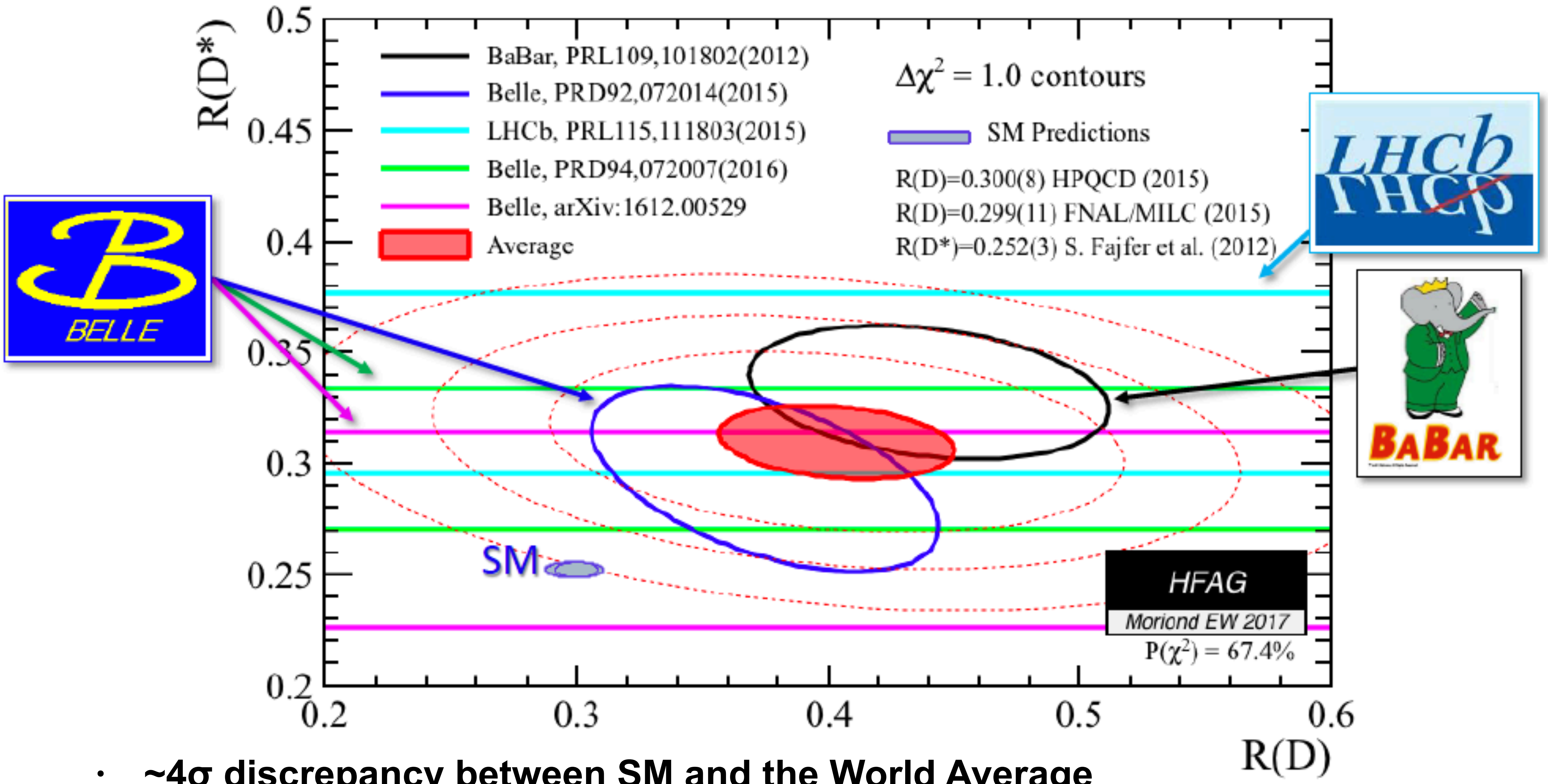
Dτ^- ν and D* τ^- ν have more missing mass

background with extra π^0

= 0 for events with only 1 ν

C. Hearty

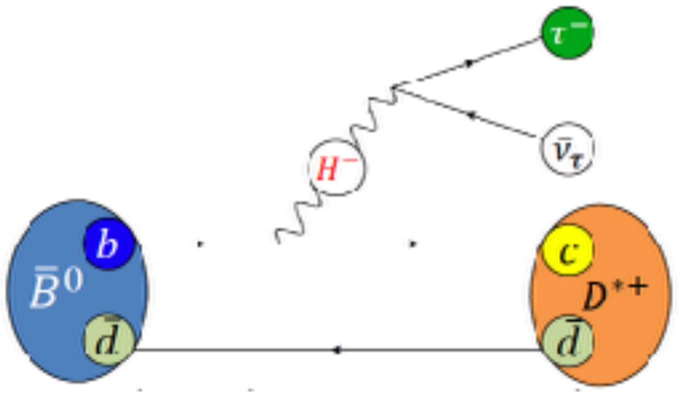
Current World Situation: Moriond EW 2017



- ~4σ discrepancy between SM and the World Average
- All experimental results so far measure larger R(D*) & R(D) than SM predicts

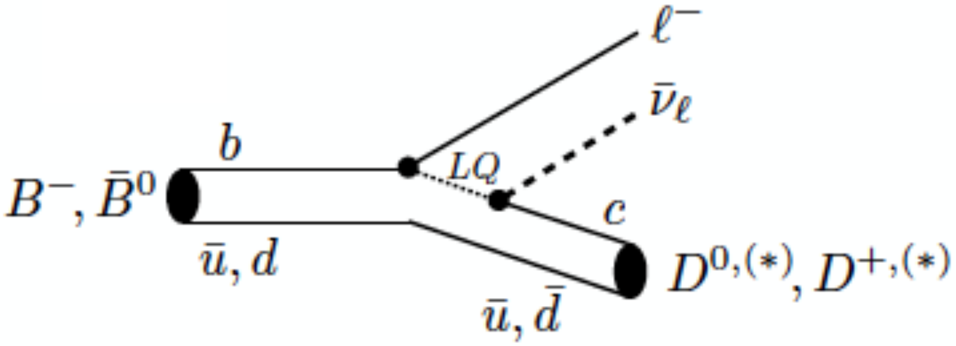
Potential Interpretations:

- Charged Higgs in extensions to SM



S. Hirose, Moriond EW 2017

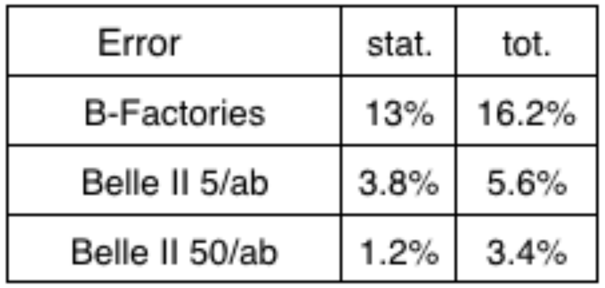
- Leptoquark mediators



G. Ciezarek et al., arXiv:1703.01766

- Other? Important to use Belle II to improve precision:
  - Target inclusive and light-meson $R(\pi)$ modes, excited states *R(D**)*
  - Differential measurements
  - Projected sensitivities:

$R(D)$



Error	stat.	tot.
B-Factories	13%	16.2%
Belle II 5/ab	3.8%	5.6%
Belle II 50/ab	1.2%	3.4%

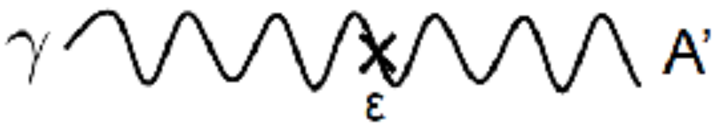
$R(D^*)$

Error	stat.	tot.
B-Factories	7.1%	9.0%
Belle II 5/ab	2.1%	3.2%
Belle II 50/ab	0.7%	2.1%

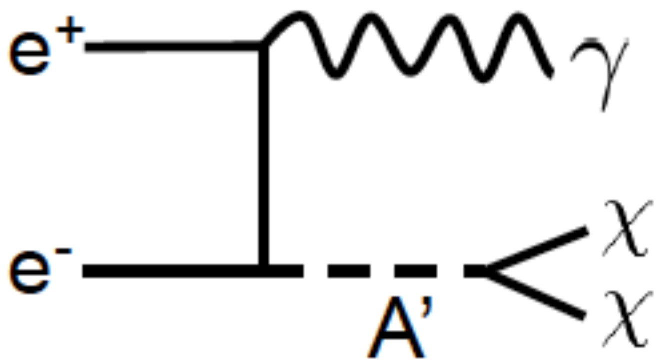
The Dark Sector

- The dark sector is hypothesized to contain massive particles that carry "dark charge" (like electric charge), which couples to a dark photon A′. Unlike the real photon, the A′ would not be massless.

- The A′ and γ mix with strength ε.



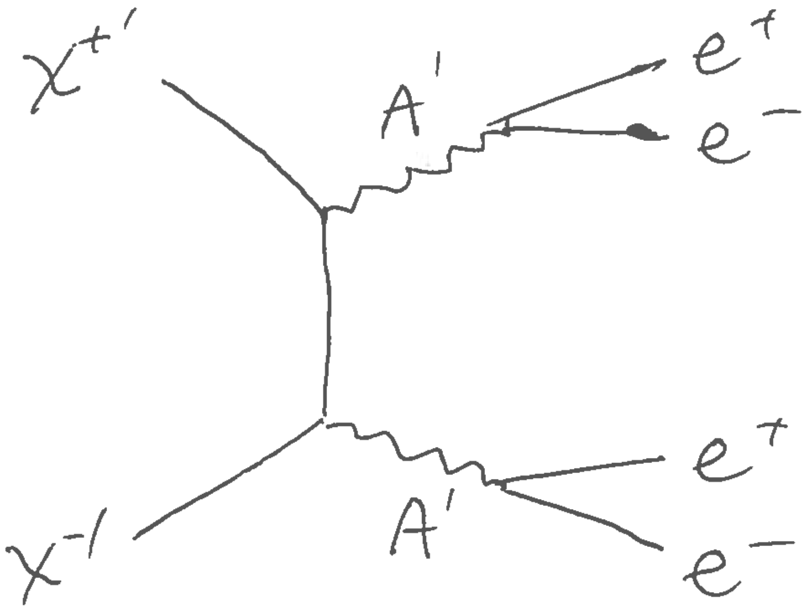
- Any process that creates a photon can create an A′.

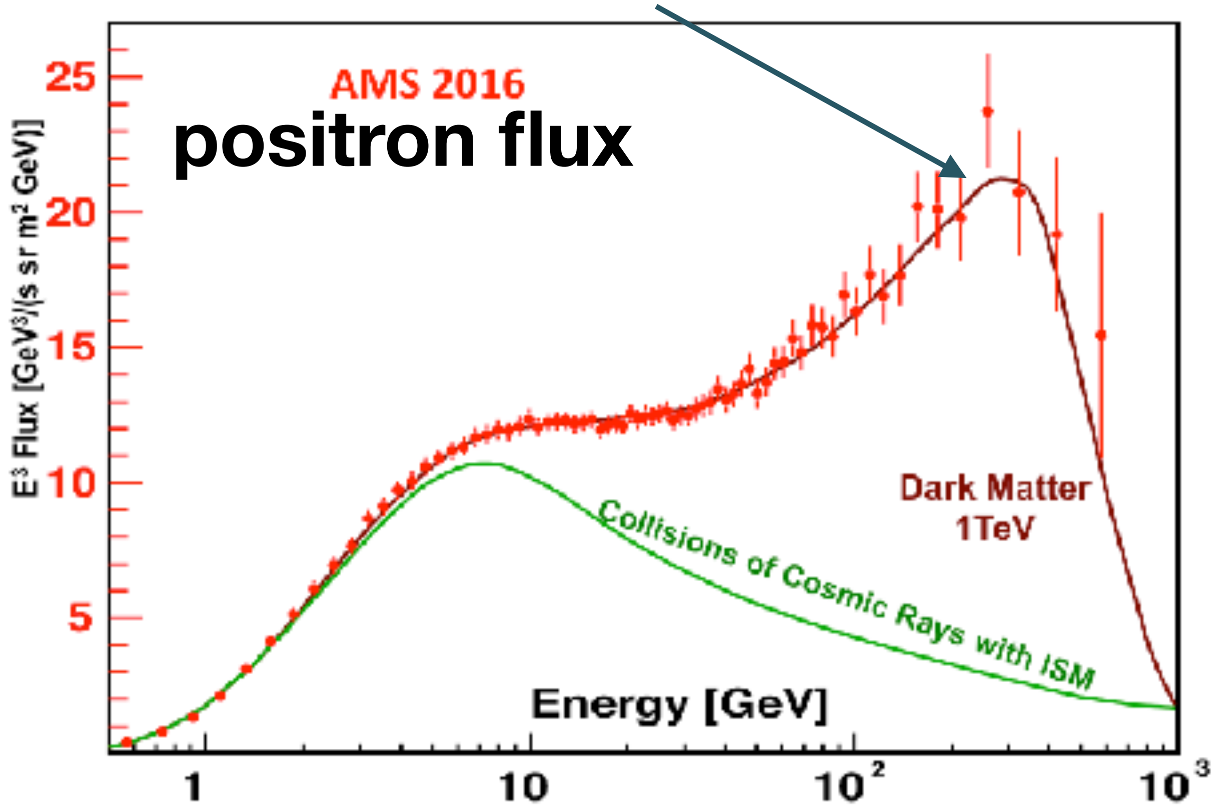


heavy dark fermions

Connection with Dark Matter

- In this model, dark matter would be heavy dark fermions. These could annihilate to produce a pair of dark photons, which could decay to e^+e^- $\Longrightarrow$ astronomical excess of e^+.
  - assuming that the A' is the lightest dark particle.

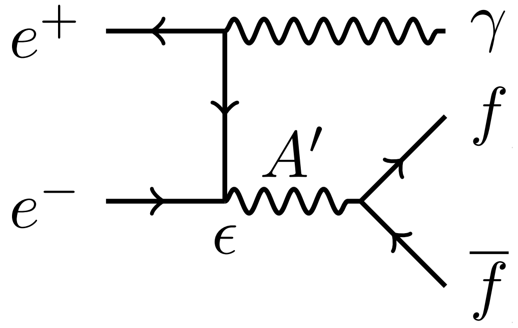


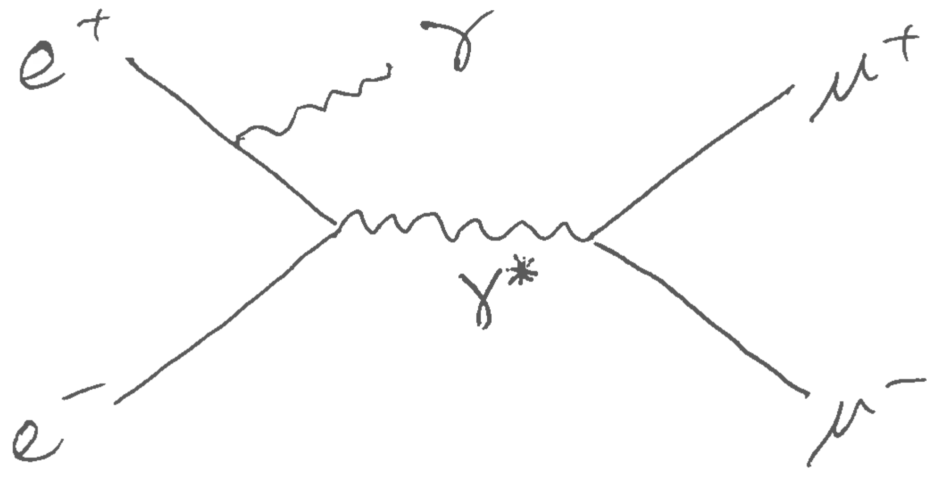


Should see rate drop above ~1/2 the dark matter mass

Note: High-Altitude Water Cherenkov Observatory (HAWC) observations point to significant Pulsar contributions [D. Hooper et al., March 2017]

Search for a dark photon at an e^+e^- collider





$$\sigma \propto \epsilon^2 \alpha^2 / E_{CM}^2$$

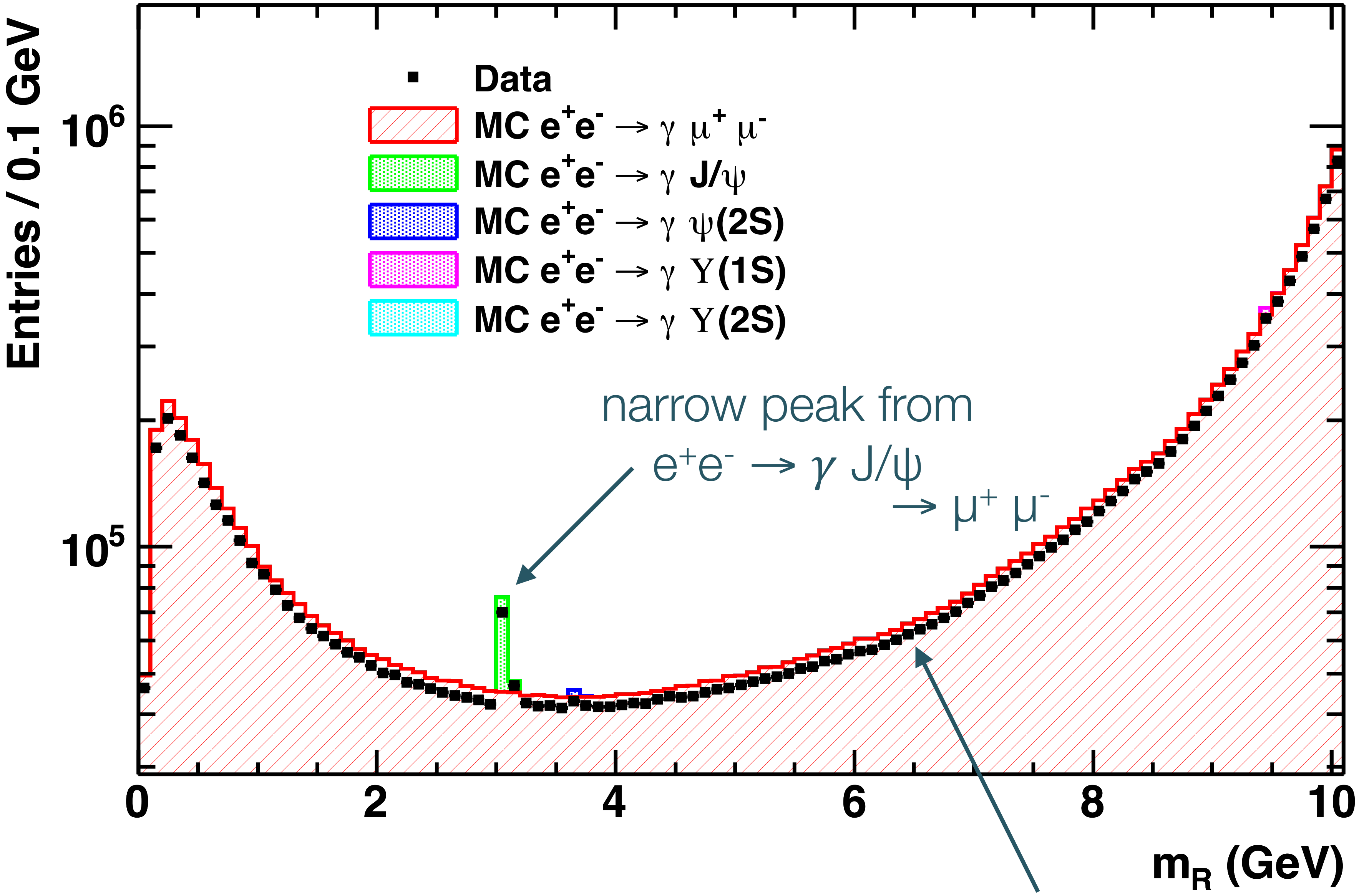
- Final state is a photon plus e^+e^- or $\mu^+\mu^-$. Very large backgrounds from SM processes.
- Difference is that the invariant mass of the $\mu^+\mu^-$ pair is the A' mass for signal, a smooth distribution for background.

C. Hearty

BaBar search for A′ → $\mu^+\mu^-$

Method:
- Select single-photon final states
- reconstruct missing mass
- look for bump

- $0.22 < m_{A'} < 10.2$ GeV/c^2



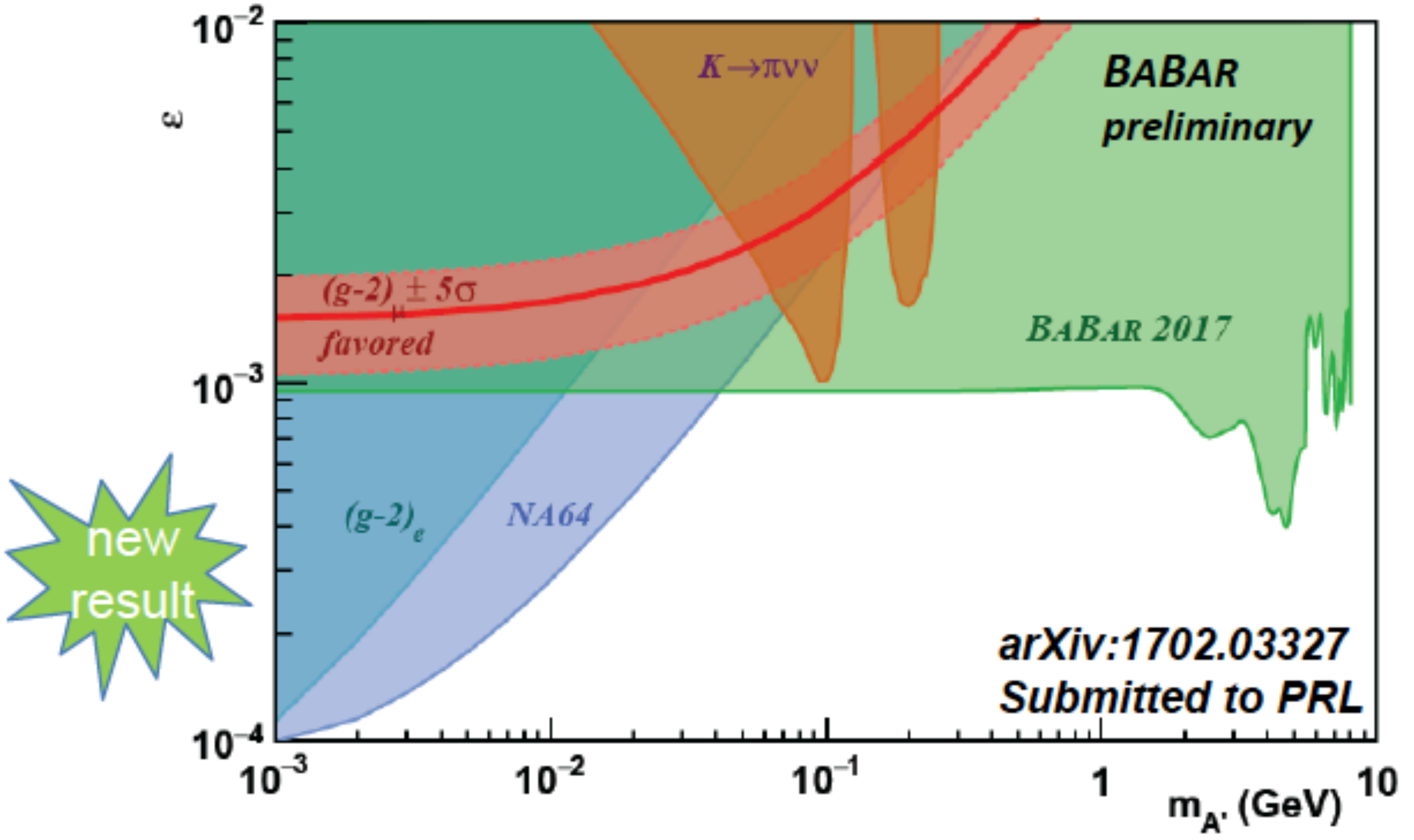
narrow peak from $e^+e^- \to \gamma\ J/\psi$ $\to \mu^+\mu^-$

smooth distribution from standard model muon pair production

C. Hearty

Latest limits from BaBar

Limits (90% CL) on the mixing parameter ε



new result

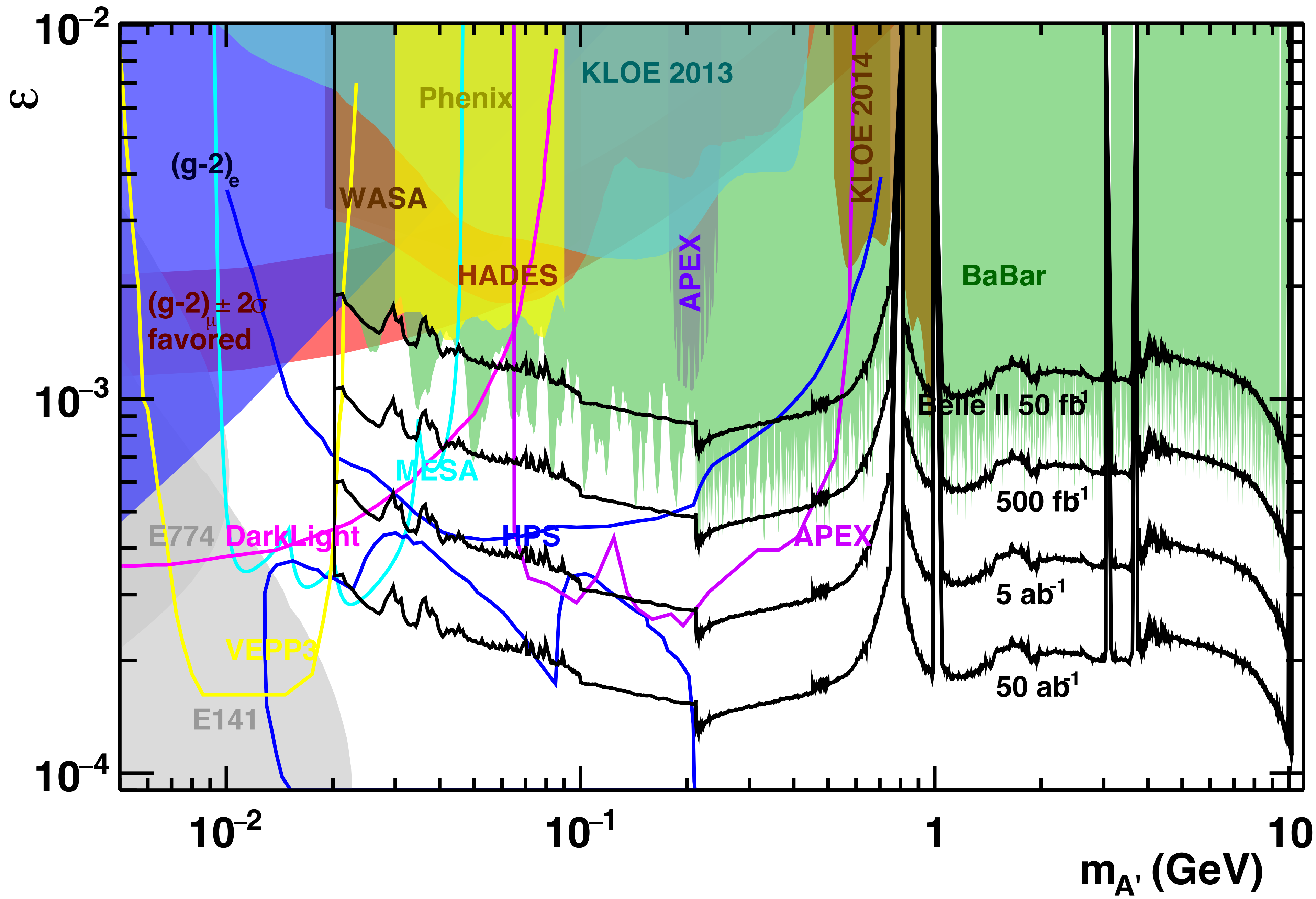
arXiv:1702.03327
Submitted to PRL

M. Roehrken, Moriond EW 2017

Note: BaBar ceased data taking in 2008

Measurement rules out the entire region preferred by the $(g-2)_\mu$ anomaly

Projected Belle II limits on A′ parameters

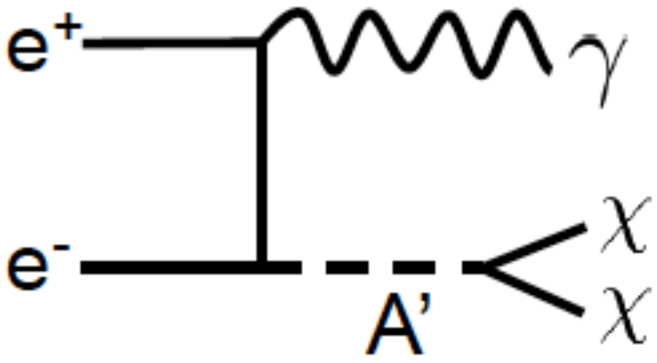


Belle2-Note-034

C. Hearty

- Many dedicated experiments planned (at JLab in particular), but Belle II has unique reach.

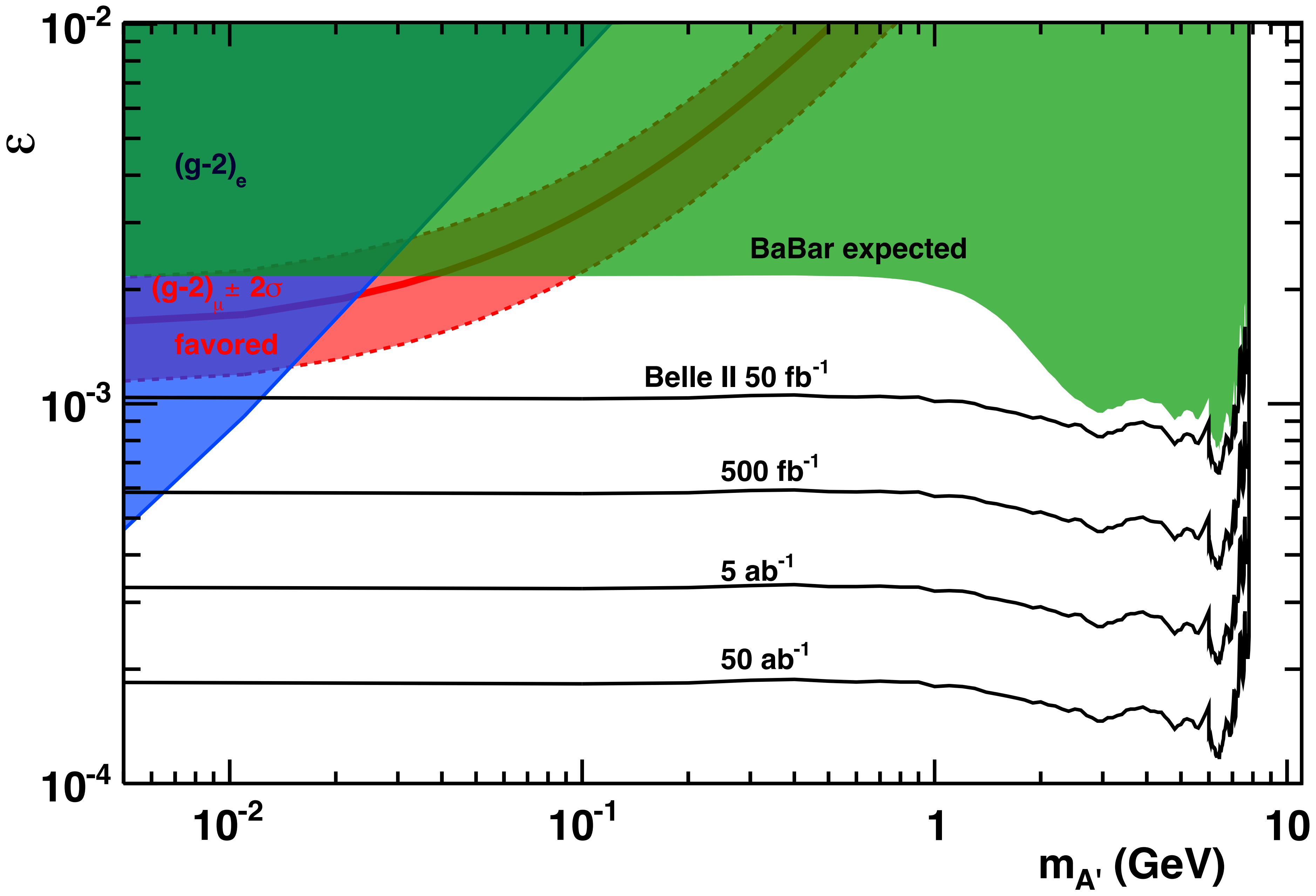
Invisible decays of the dark photon



- The A′ will decay to other dark particles if it can. These do not interact in the detector, so the observed final state is a single photon.

- Very challenging measurement; large backgrounds.

Belle II projection for A′ → invisible

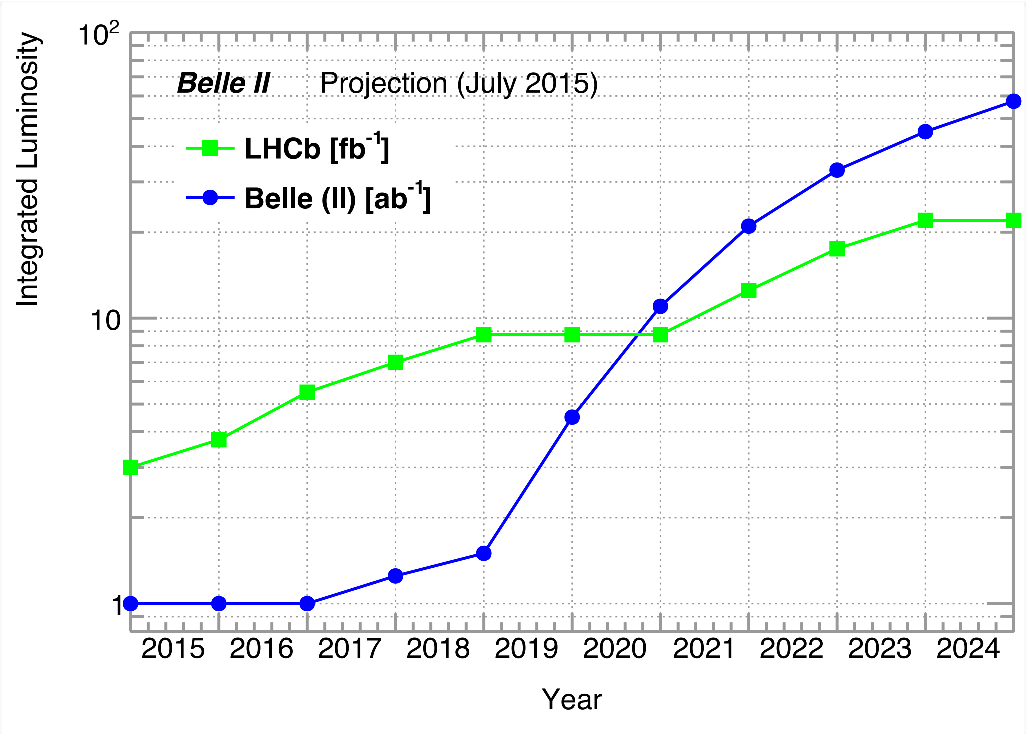


Belle2-Note-034

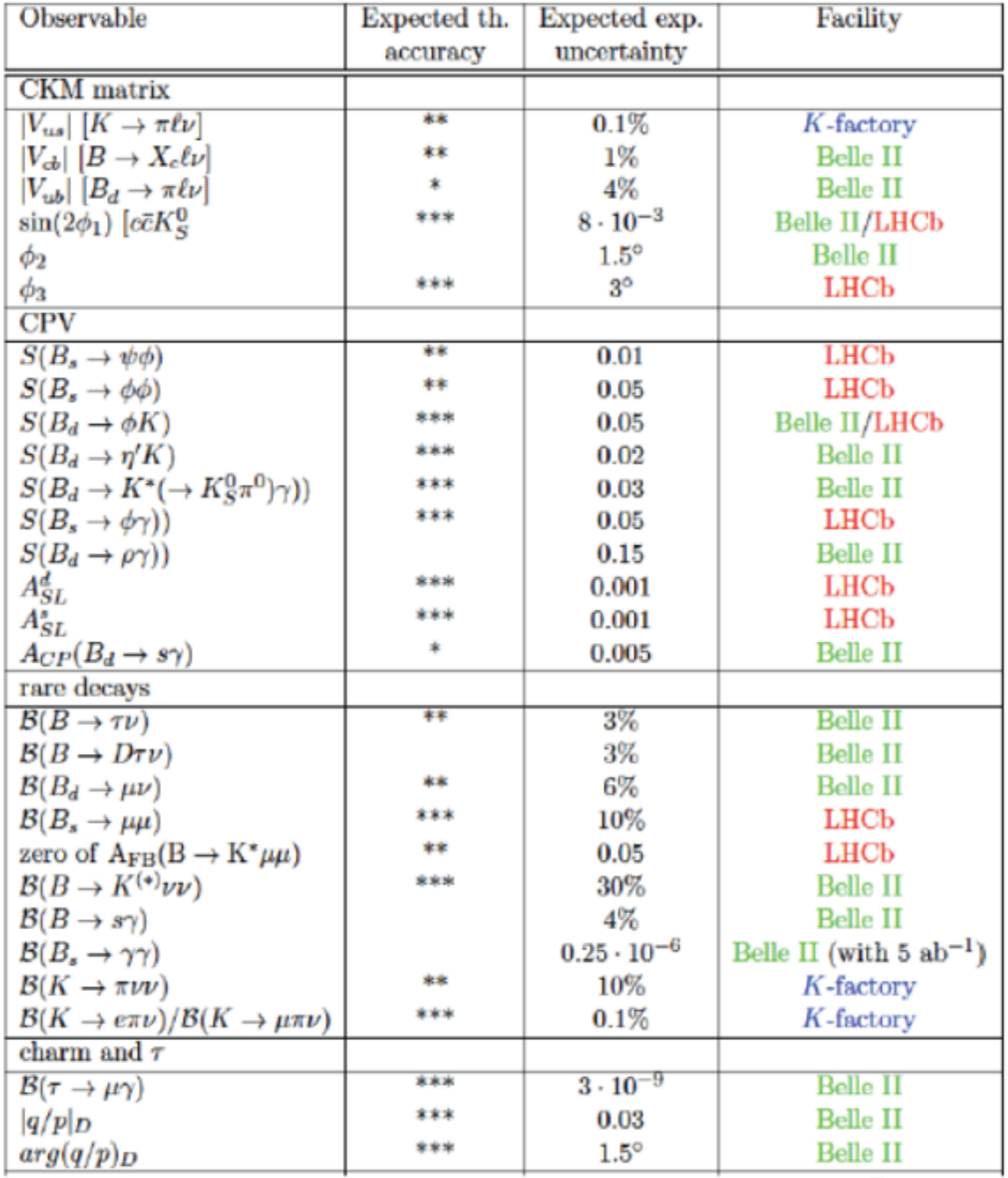
- With appropriate trigger and background suppression, Belle II can rapidly exceed probable BaBar limits.

What about LHCb?

- LHCb is running and exceeding expectations
- There are overlaps between the physics programs, but also numerous unique strengths
  - Large baryonic samples and decays into visible particles play into **LHCb's** corner
  - Missing particles, inclusive measurements, low multiplicity final states with few constraints are **Belle II**'s forte
  - For some channels there will be neck-and-neck competition!



B. Golob



Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\lvert V_{us}\rvert$ $[K \to \pi\ell\nu]$	**	0.1%	K-factory
$\lvert V_{cb}\rvert$ $[B \to X_c\ell\nu]$	**	1%	Belle II
$\lvert V_{ub}\rvert$ $[B_d \to \pi\ell\nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K^0_S$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5°	Belle II
ϕ_3	***	3°	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K^0_S\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A^d_{SL}	***	0.001	LHCb
A^s_{SL}	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $\mathrm{A_{FB}(B \to K^*\mu\mu)}$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\lvert q/p\rvert_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II

Experimental challenges


食券
Ticket Vender
2000
1000
おつり·返却
初めてご来店のお客様には、
『らーめん』をオススメします。
チャーシュー ¥300
ねぎ ¥200
キャベツ ¥200
のり ¥100
コーン ¥100
とろ玉子 ¥100
ほうれん草 ¥80
バター ¥80
ライス ¥150
小ライス ¥100

C. Hearty

RAS-HJ22V 013

リモコン

■運転内容、タイマー予約内容などを室内機に送信します。
☆図の液晶表示は、リセットスイッチを押した直後の表示を示します。
本ルームエアコンには無い機能も表示されます。

代替品

送信マーク
送信したとき、点灯します。 表示されます

運転／停止ボタン
押すと運転、もう一度押すと停止します。

X **エアコンクリーンボタン**
エアコンクリーン運転を開始します。
(☞13ページ)

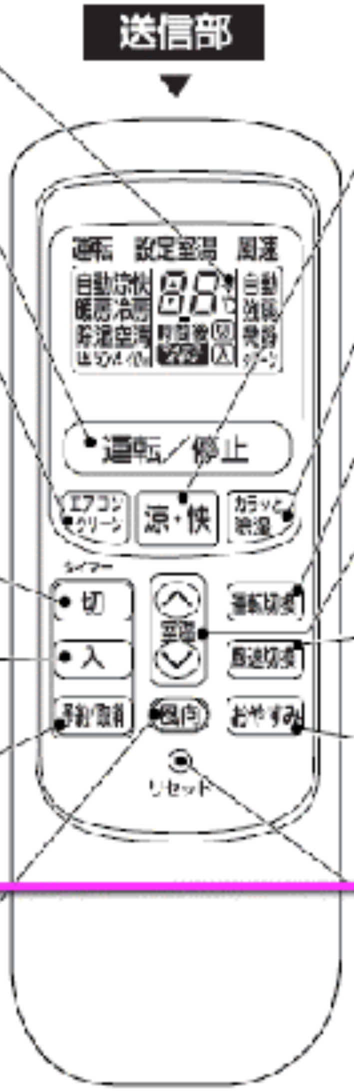
タイマー合わせ部

切 タイマーボタン
切 タイマーの時間を選びます。

入 タイマーボタン
入 タイマーの時間を選びます。

予約／取消ボタン
タイマー予約の内容を室内機に予約します。もう一度押すと、タイマー予約を取り消します。(☞14ページ)

自動風向ボタン
上下風向板をスイングさせたり、お好みの角度に変えます。
(☞13ページ)



涼快ボタン X
涼快運転を開始します。(☞12ページ)

カラッと除湿ボタン
カラッと除湿運転を開始します。
(☞12ページ) 除湿に変更になっています

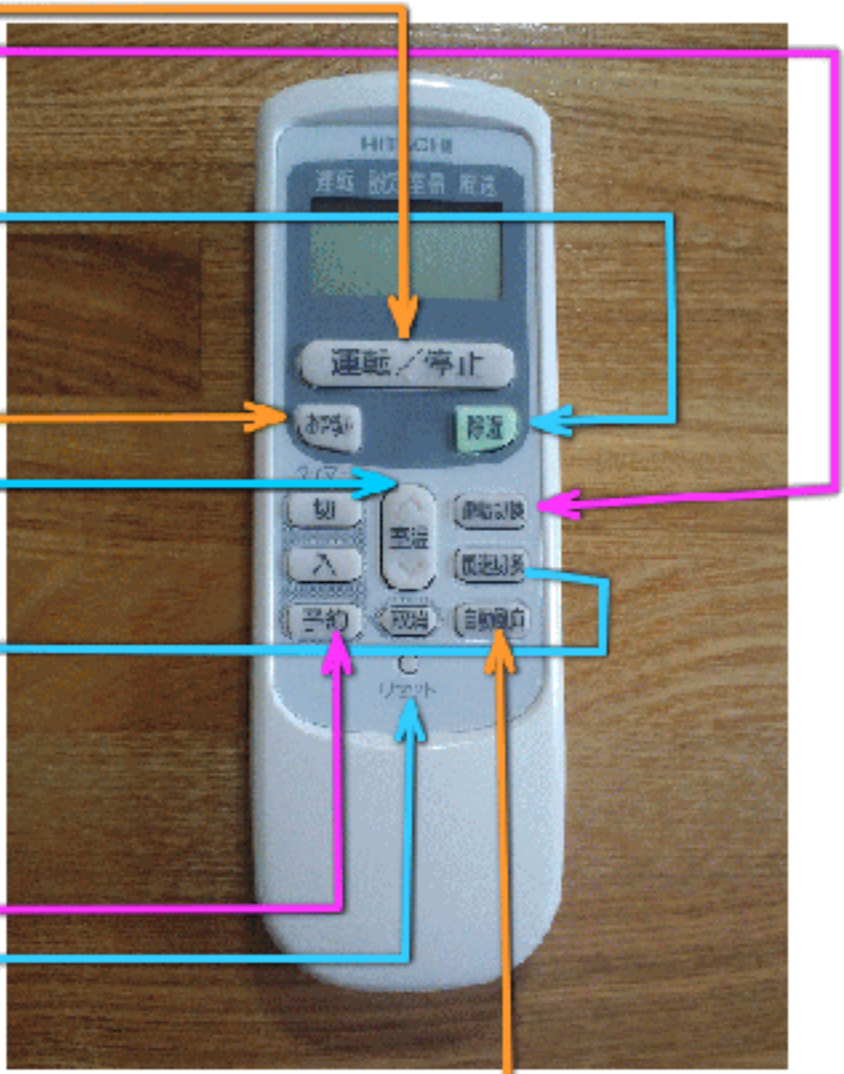
運転切換ボタン
運転の種類を選びます。(☞11ページ)

室温設定ボタン
室温を設定します。押し続けると早送りになります。(☞11ページ)

風速切換ボタン
風速を選びます。(☞11ページ)

おやすみタイマー運転ボタン
おやすみタイマー運転を開始します。
(☞15ページ)

リセットスイッチ
電池交換した後や、動作が正常でないときに押してください。



C. Hearty

Transformation of a *B*-Factory into a **Super** *B*-Factory

To achieve the necessary sensitivity to further push the intensity frontier, the instantaneous luminosity needed to increase from **$2.1\text{x}\ 10^{34}$ cm^{-2} s^{-1} to $8\ \text{x}\ 10^{35}$ cm^{-2} s^{-1}**

The key to this is a beam-configuration called the **nano-beam scheme** that squeezes the beam to a very small vertical spot size of about 50 nm

LER / HER	KEKB	SuperKEKB
Energy [GeV]	3.5 / 8	4.0 / 7.0
β_y^* [mm]	5.9 / 5.9	**0.27 / 0.30**
β_x^* [mm]	1200	**32 / 25**
$I_\pm$ [A]	1.64 / 1.19	**3.6 / 2.6**
$\zeta_{\pm y}$	0.129 / 0.09	**0.09 / 0.09**
ε [nm]	18 / 24	**3.2 / 4.6**
# of bunches	1584	2500
Luminosity [10^{34} cm^{-2} s^{-1}]	2.1	80

Lorentz factor

beam current

beam-beam parameter

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

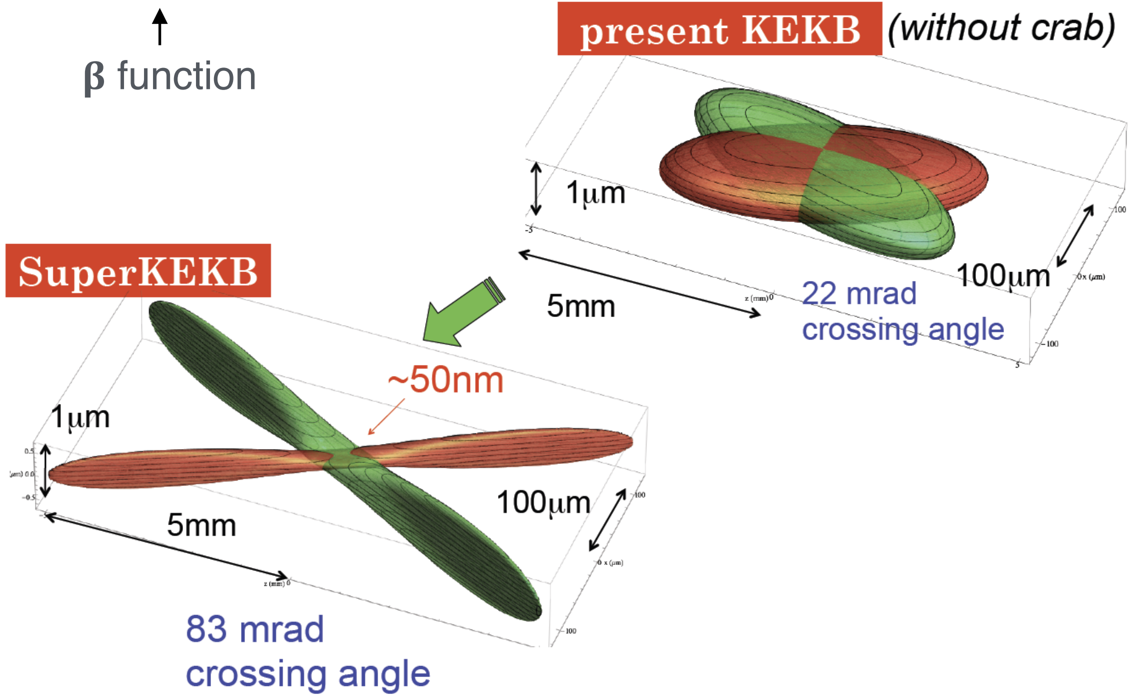
beam size aspect ratio

vertical β function

geometric factors

$$\zeta_{\pm y} \sim \sqrt{\beta^*/\epsilon} \longleftarrow \text{emittance}$$

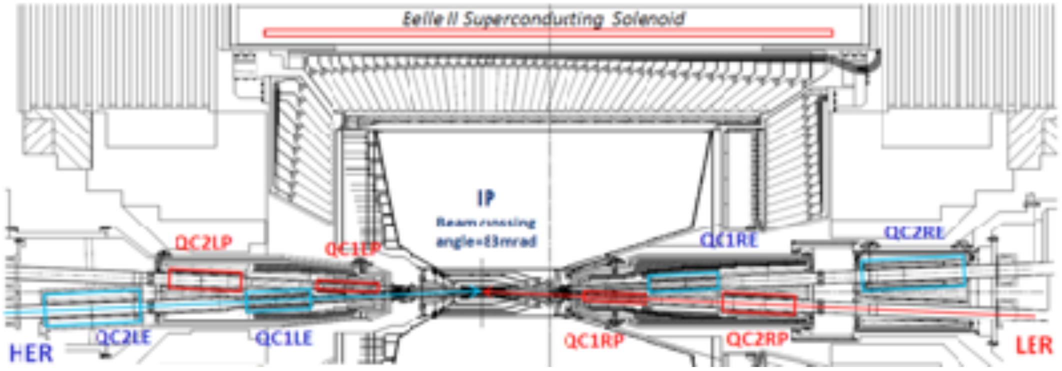
↑ β function

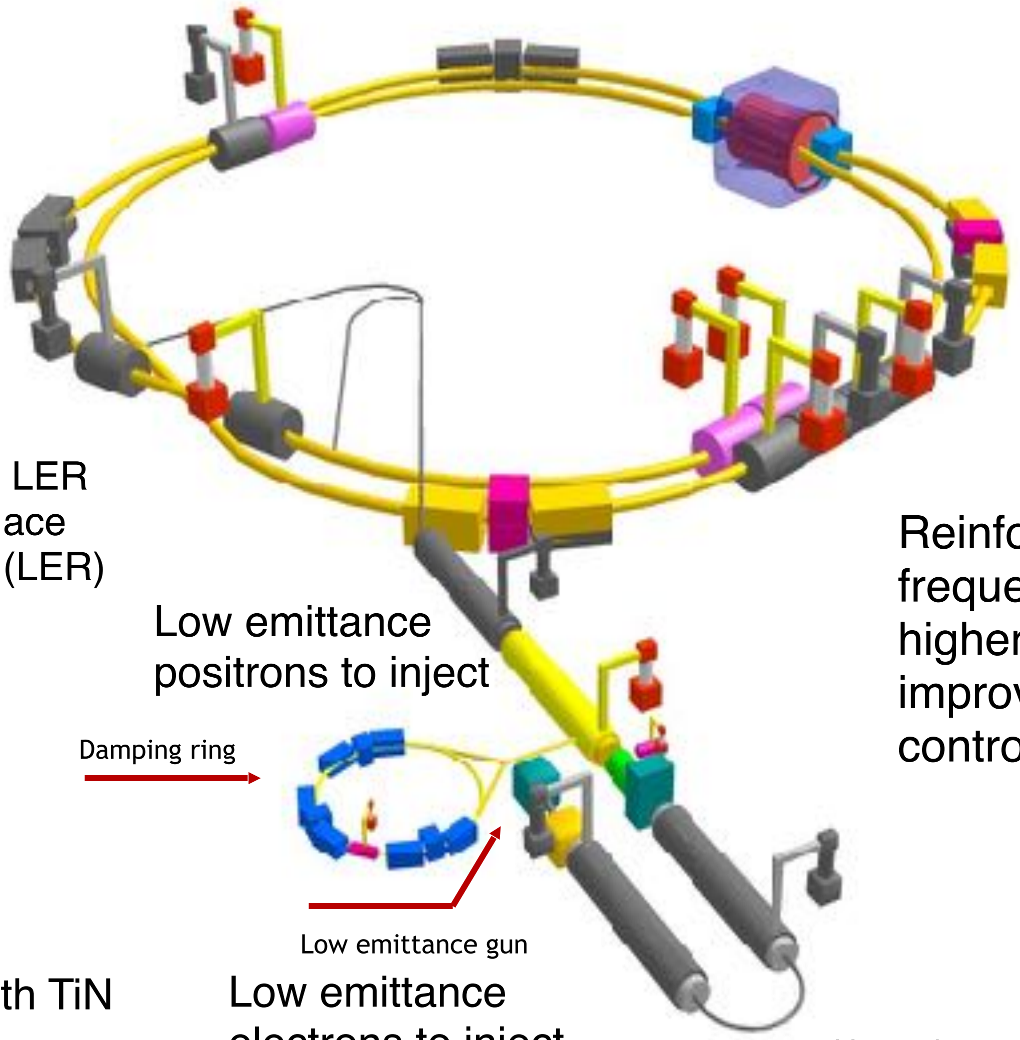


Major upgrade of existing accelerator needed

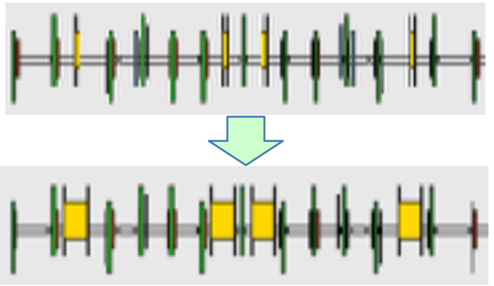
Transformation of a *B*-Factory into a **Super** *B*-Factory

New superconducting final focusing magnets near the IP





Redesign the lattices of HER & LER to squeeze the emittance. Replace short dipoles with longer ones (LER)



Low emittance positrons to inject

Damping ring

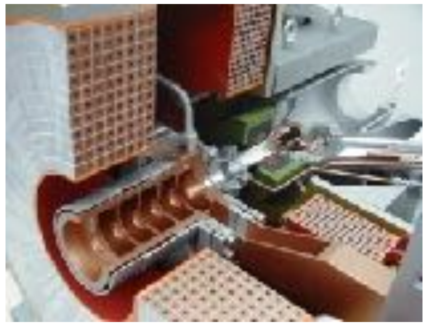
Low emittance gun

Low emittance electrons to inject

Reinforced RF (radio frequency) system for higher beam currents, improved monitoring & control system

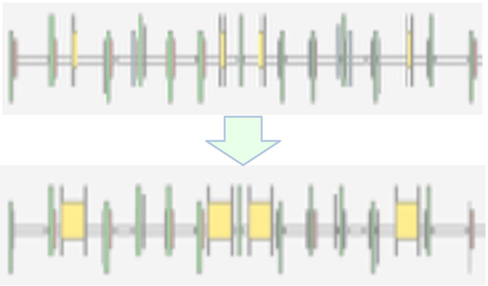
Replaced old beam pipes with TiN coated beam pipes with antechambers

Upgrade positron capture section



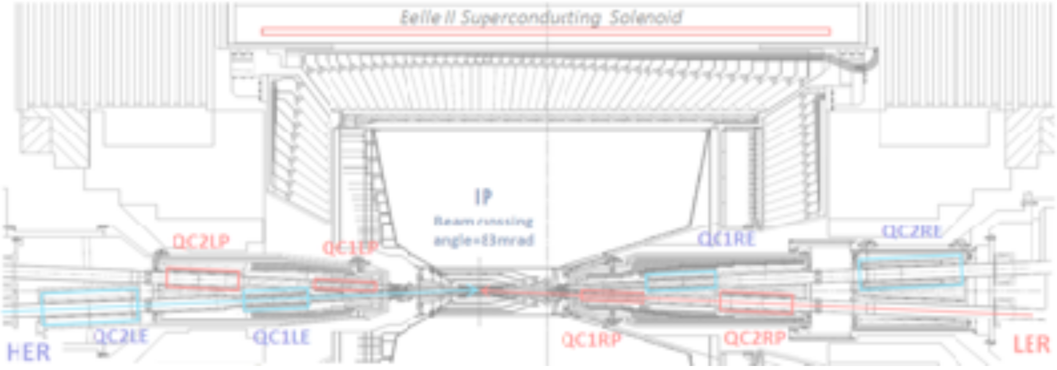
Transformation of a *B*-Factory into a **Super** *B*-Factory

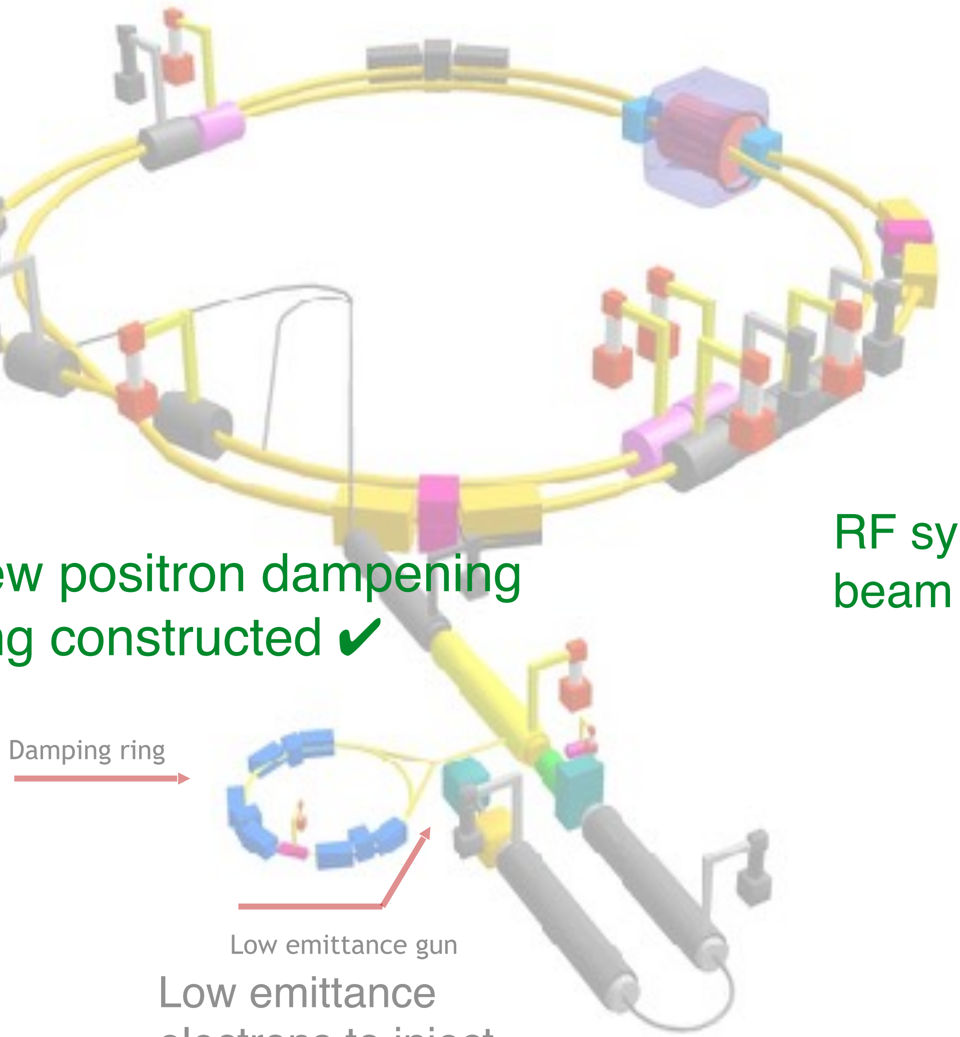
All magnets installed ✔



Beam pipes replaced ✔

Work on final focus magnets progressing well



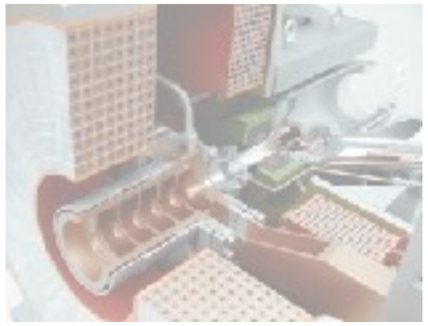


new positron dampening ring constructed ✔

Low emittance electrons to inject

RF system for higher beam currents upgraded ✔

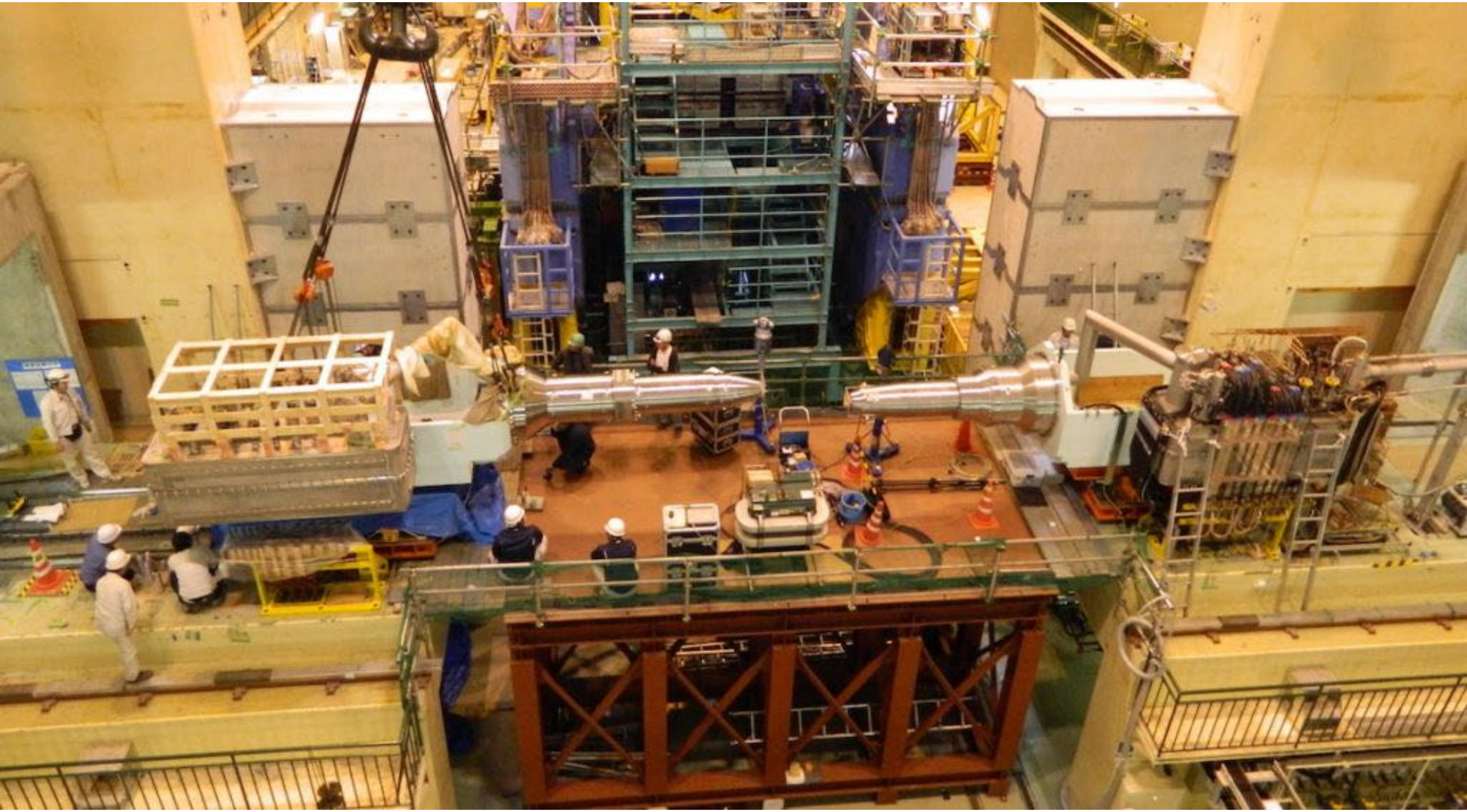
Upgrade positron capture section



new positron dampening ring constructed ✔

Arrived Feb. 2017: Last “missing part” of SuperKEKB

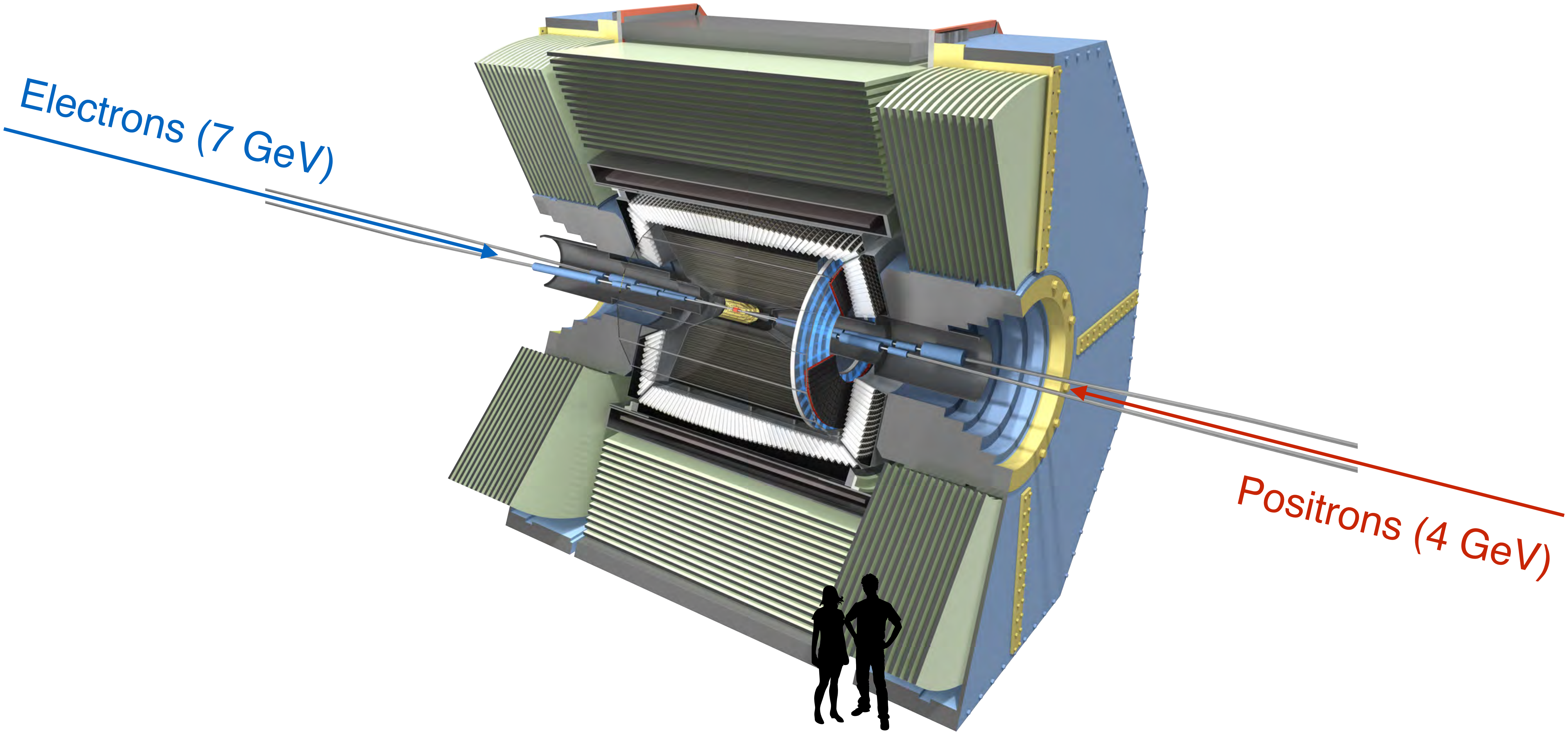
Recent View: Belle II Interaction Region



The Belle II Detector

To cope with the higher luminosity, a new detector is needed

Design concept similar to the B-Factory detectors Belle and BaBar

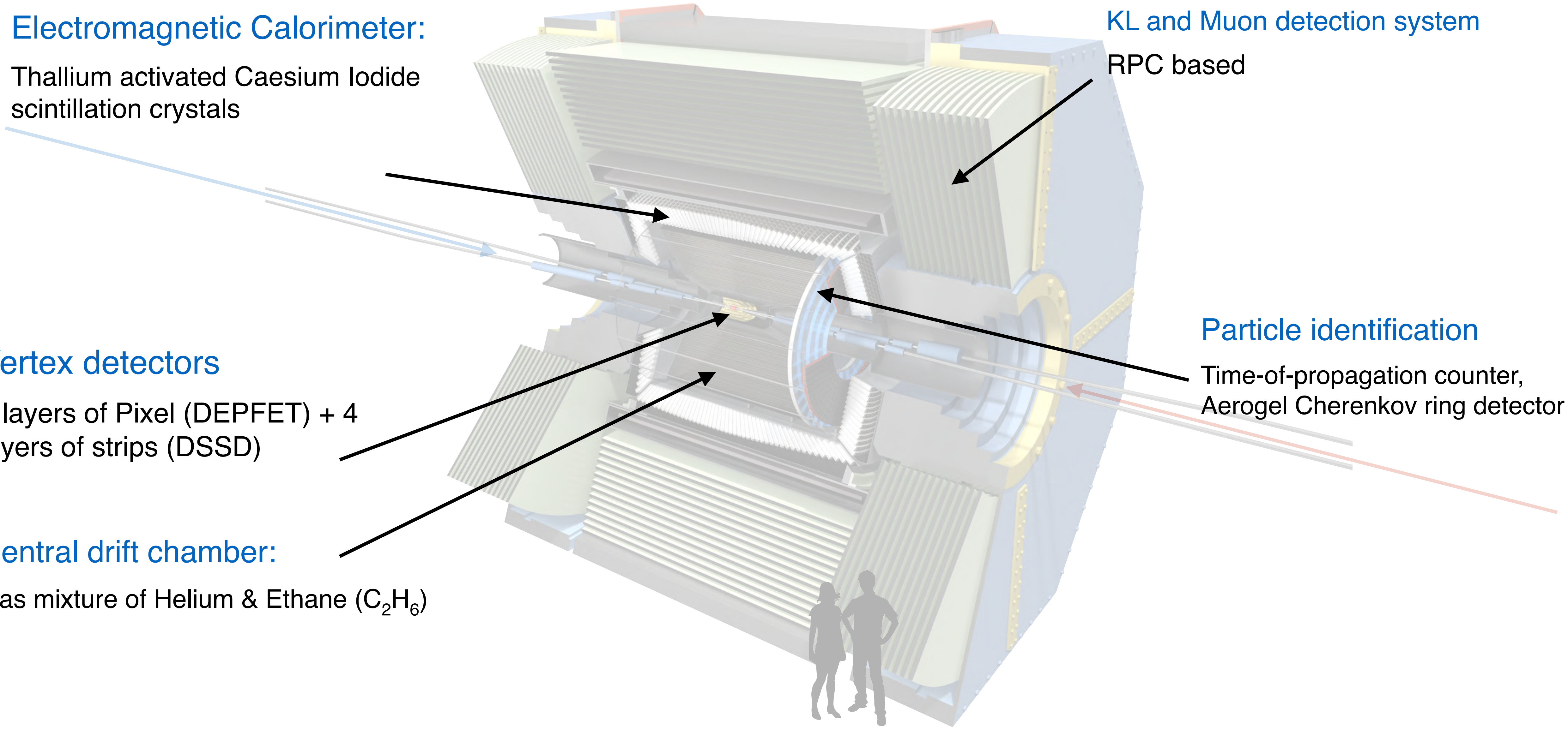


Needs to cope e.g. with 20-40 times larger beam backgrounds, many technological challenges

The Belle II Detector

To cope with the higher luminosity, a new detector is needed

Design concept similar to the B-Factory detectors Belle and BaBar



Electromagnetic Calorimeter:

Thallium activated Caesium Iodide scintillation crystals

KL and Muon detection system

RPC based

Particle identification

Time-of-propagation counter, Aerogel Cherenkov ring detector

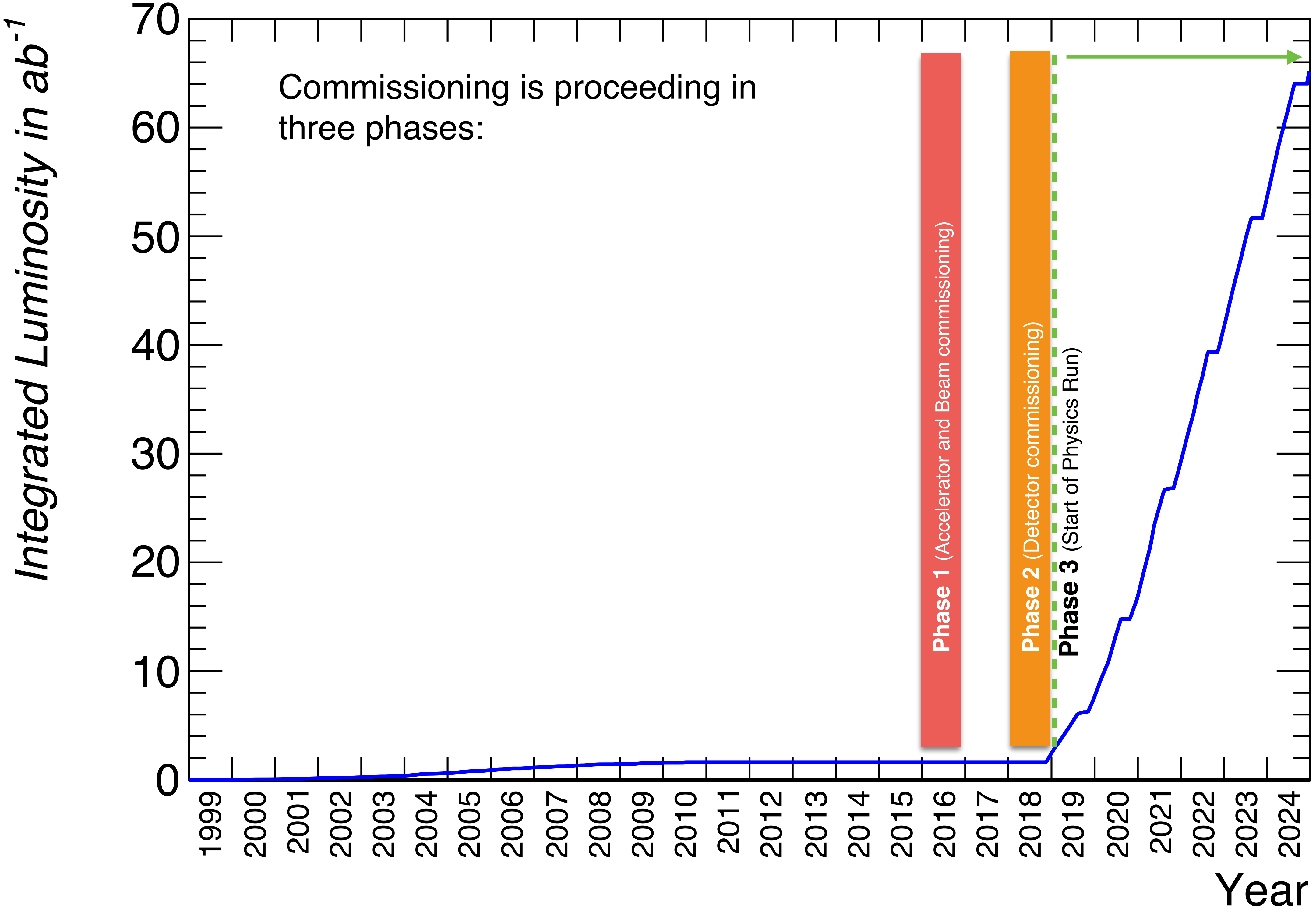
Vertex detectors

2 layers of Pixel (DEPFET) + 4 layers of strips (DSSD)

Central drift chamber:

Gas mixture of Helium & Ethane (C_2H_6)

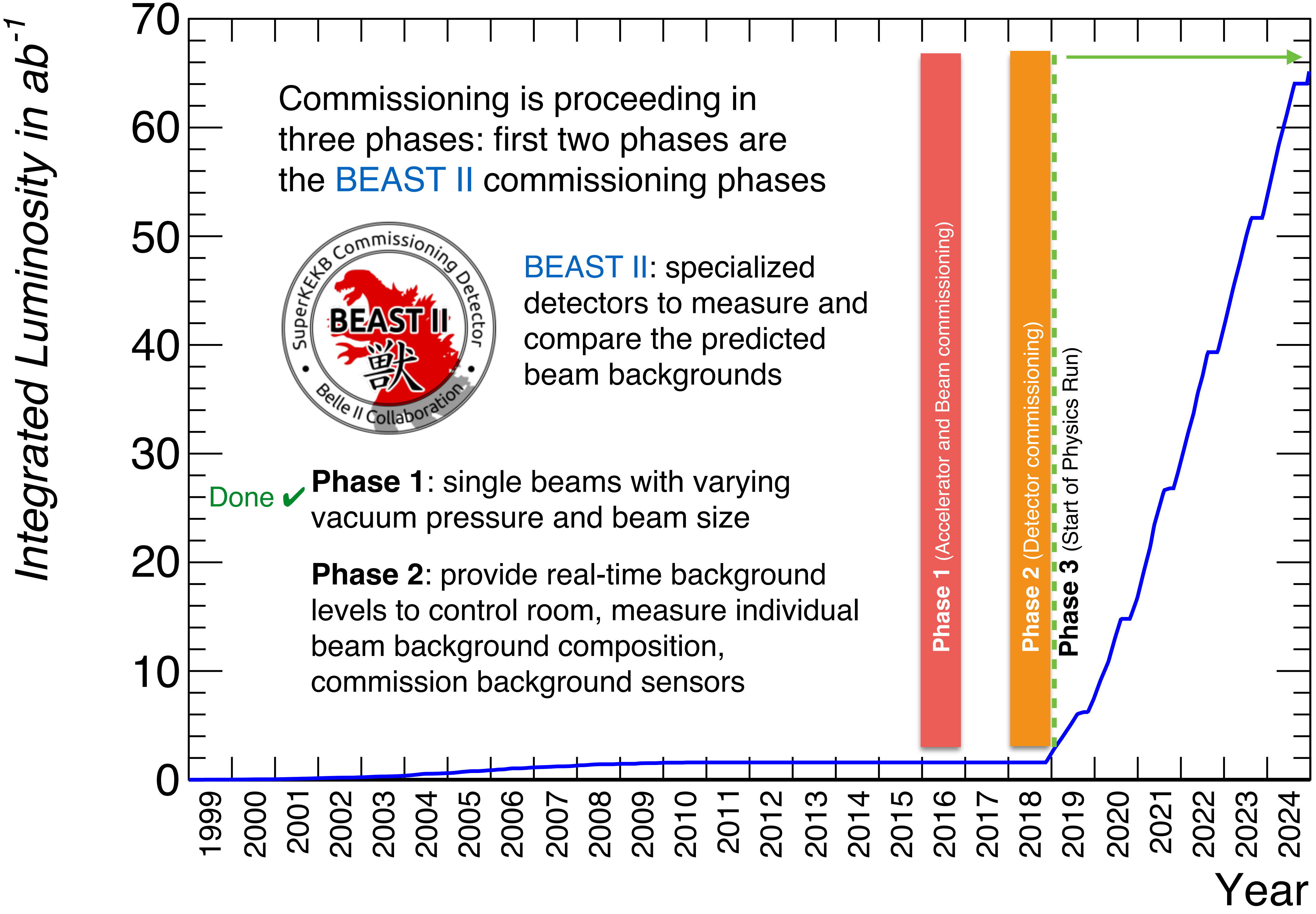
Belle II / SuperKEKB Luminosity projections



Commissioning is proceeding in three phases:

F. Bernlochner

Belle II / SuperKEKB Luminosity projections



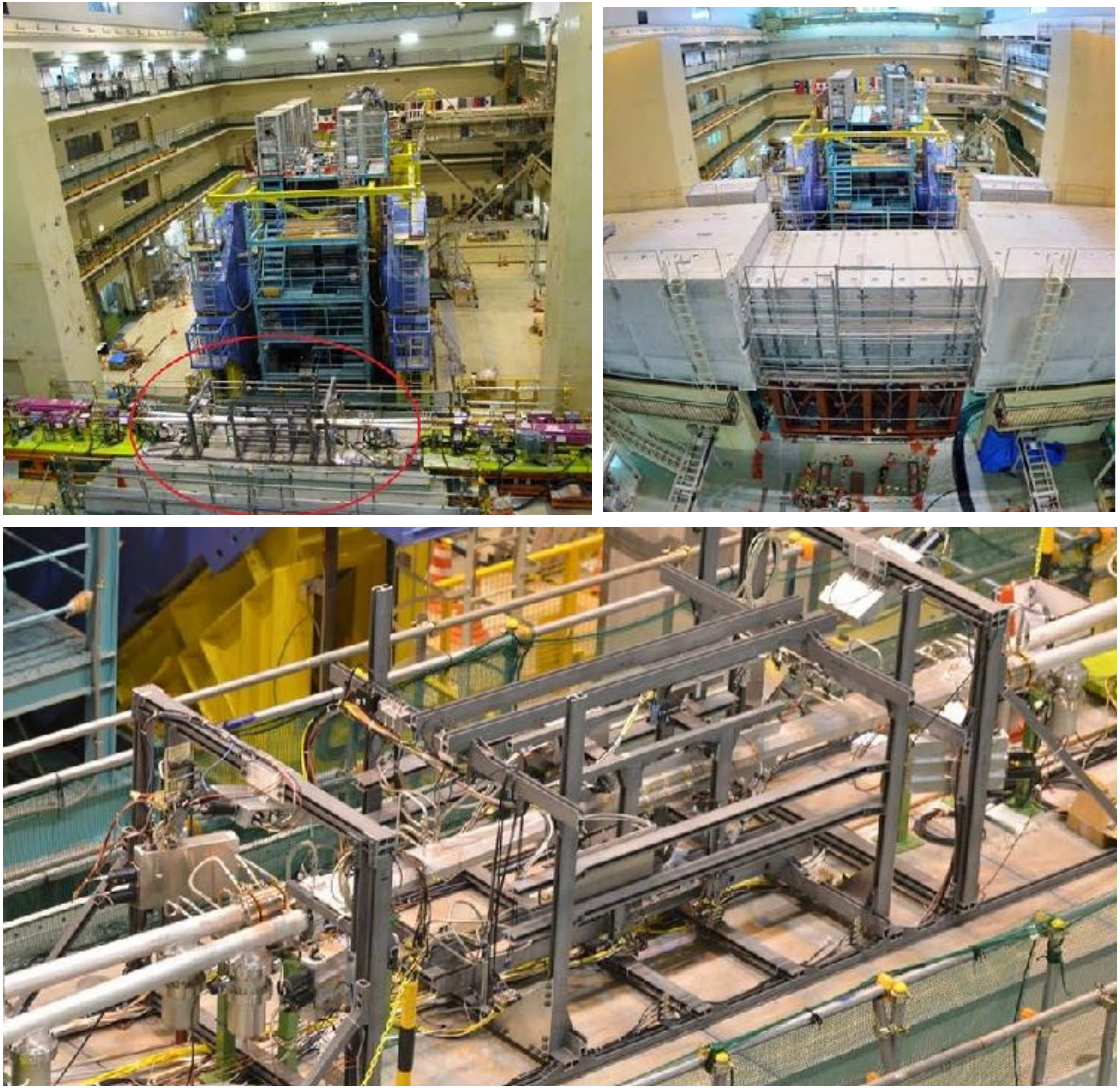
Commissioning is proceeding in three phases: first two phases are the BEAST II commissioning phases

BEAST II: specialized detectors to measure and compare the predicted beam backgrounds

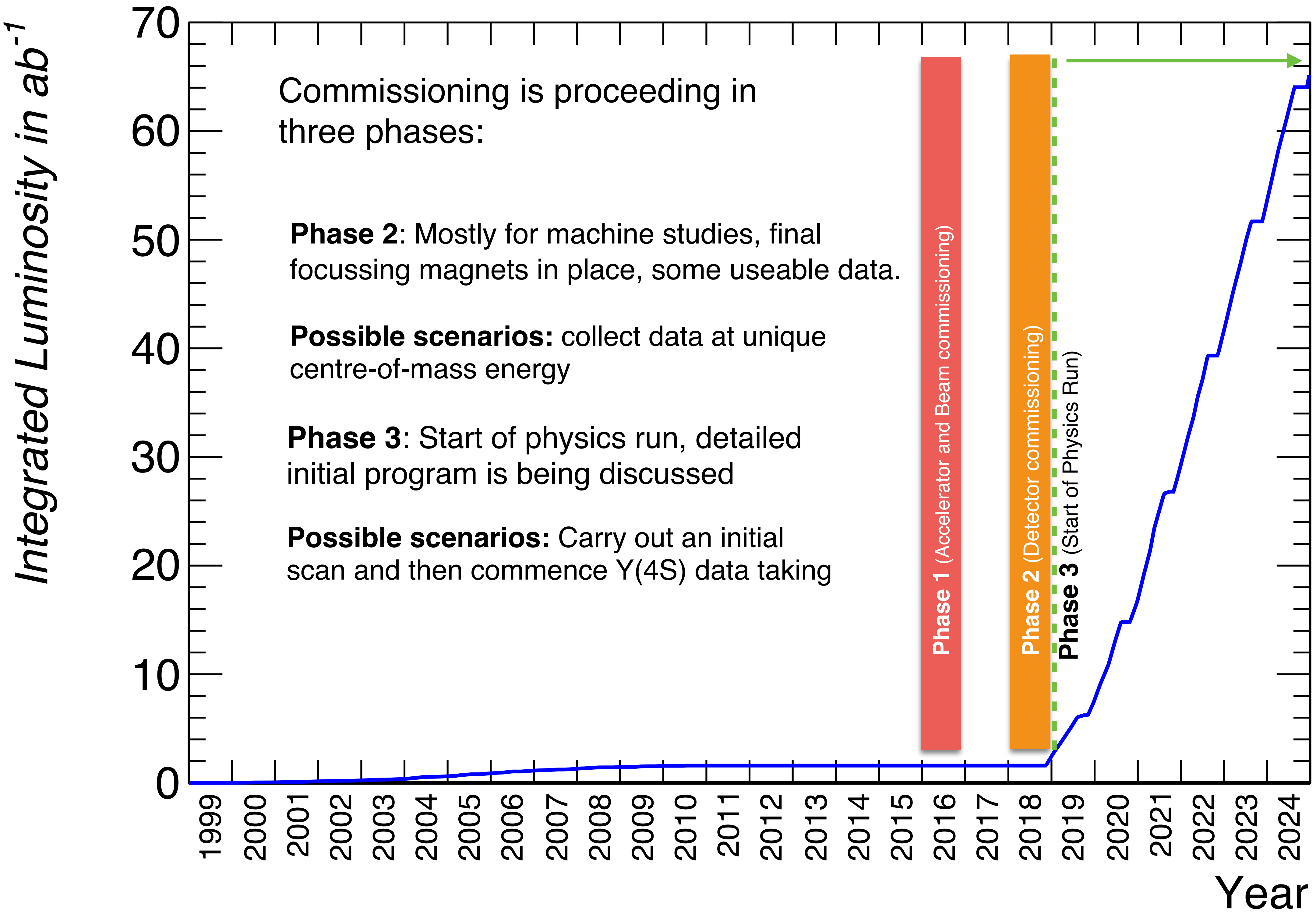
Done ✔ **Phase 1**: single beams with varying vacuum pressure and beam size

Phase 2: provide real-time background levels to control room, measure individual beam background composition, commission background sensors

BEAST II Phase 1 Setup



Belle II / SuperKEKB Luminosity projections



Commissioning is proceeding in three phases:

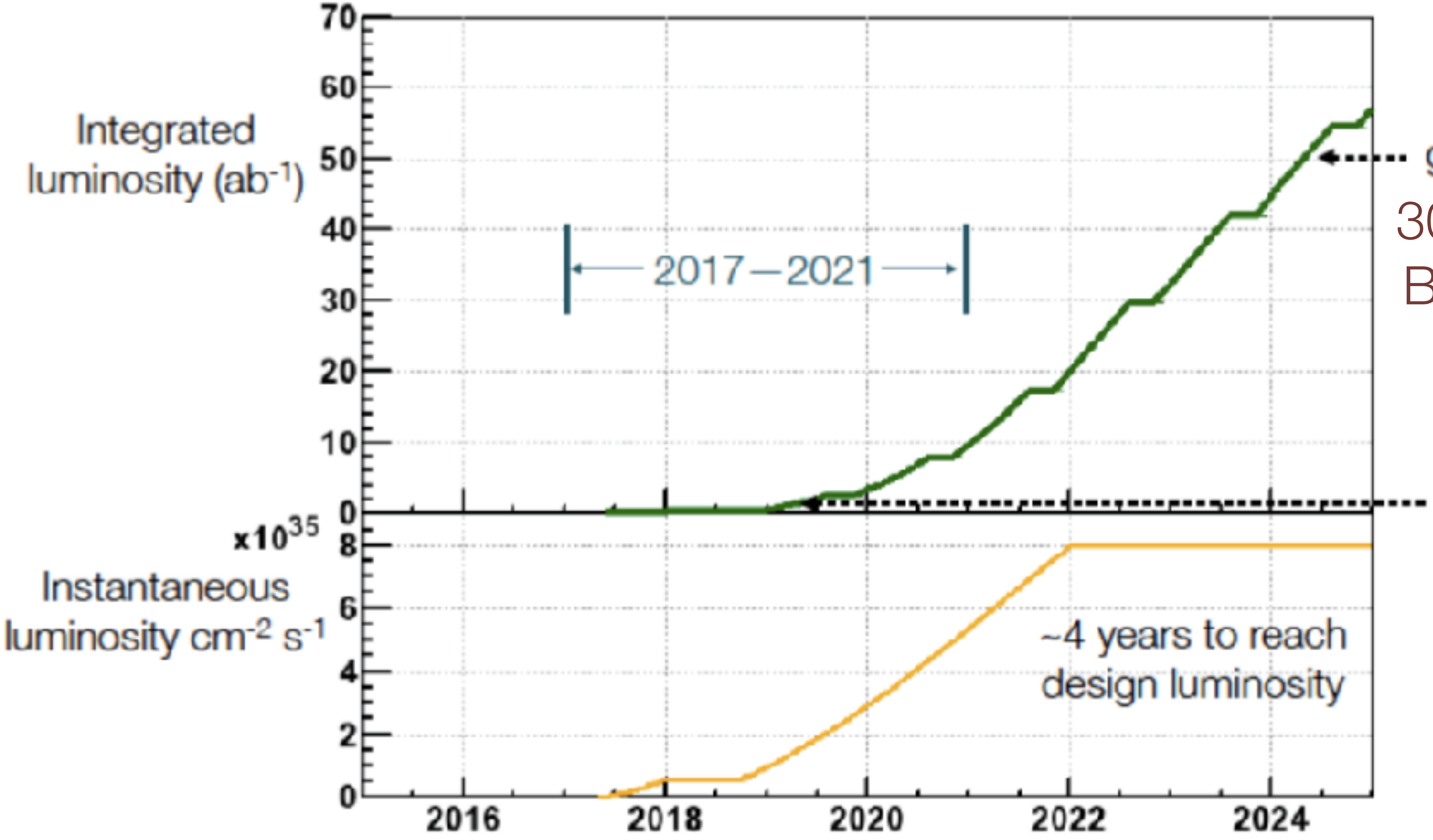
Phase 2: Mostly for machine studies, final focussing magnets in place, some useable data.

Possible scenarios: collect data at unique centre-of-mass energy

Phase 3: Start of physics run, detailed initial program is being discussed

Possible scenarios: Carry out an initial scan and then commence Y(4S) data taking

Longer term Belle II schedule



goal: 50 ab^{-1}

30x combined BaBar + Belle

1 ab^{-1} collected by Belle

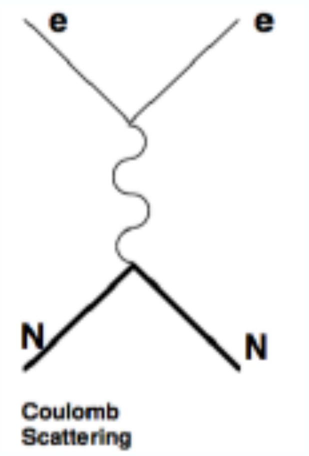
~4 years to reach design luminosity

Beam Backgrounds at SuperKEKB

- Deterioration of detector resolution, damage to detector components
- Expected ~40-fold increase in beam backgrounds compared to KEKB
- Scattered e^-/e^+ hit the beam-pipe and create electromagnetic showers and neutrons
- Simulations used to get an estimate of background rates in each sub-detector

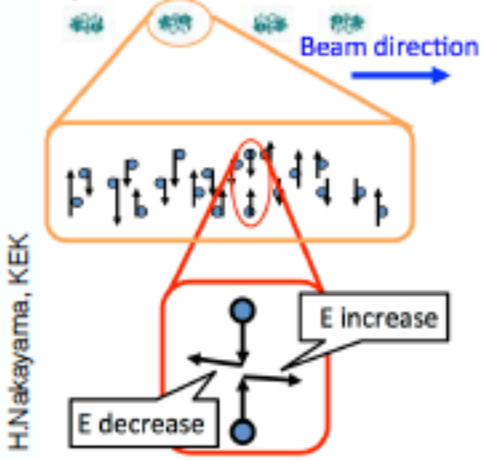
Beam-gas interactions

- Coulomb scattering of beam particles off of residual gas
- Bremsstrahlung
- Proportional to beam current



Touschek scattering

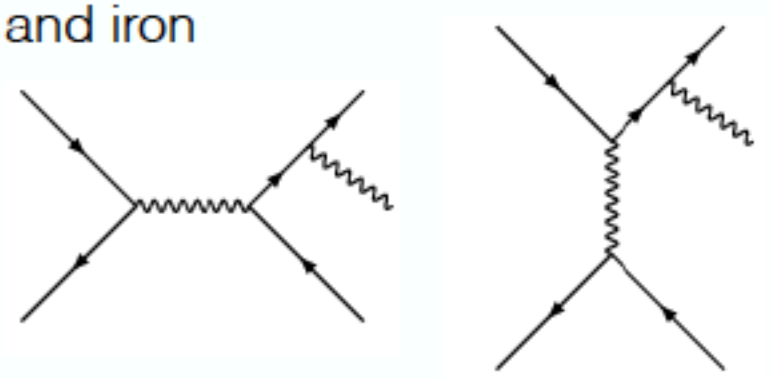
- Intra-beam scattering
- Scattering rate inversely proportional to beam size, proportional to beam current



H.Nakayama, KEK

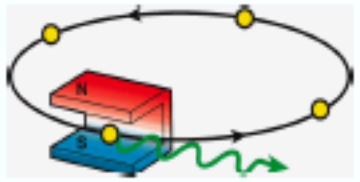
Luminosity backgrounds

- e^-e^+ Bhabha scattering
- Followed by photon emission
- Rate proportional to luminosity
- Neutrons copiously produced in a photo-nuclear reaction of photons and iron



Synchrotron radiation

- Collimators and shielding prevent scattered particles from reaching the detector



H.Nakayama, KEK

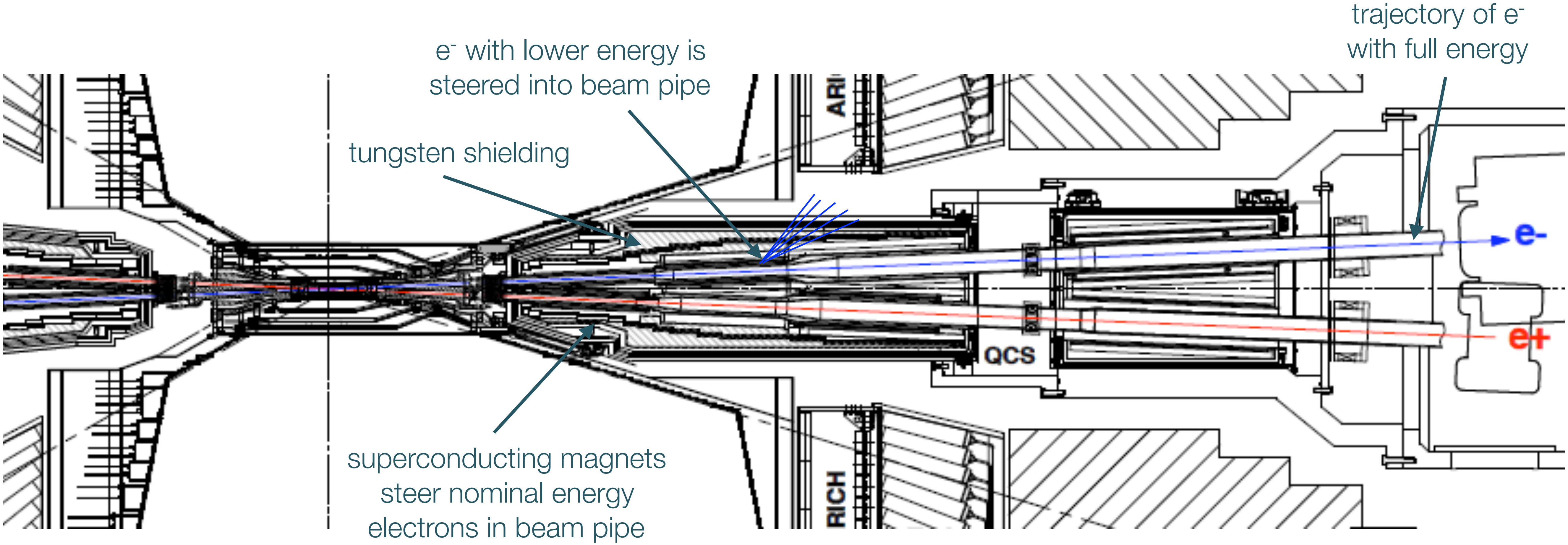
Injection background

- New particles injected every 100 ns
- Newly injected particles interact with existing beam particles
- Hard to simulate

A. Fodor (McGill)

Radiative Bhabhas: $e^+e^- \rightarrow \gamma\, e^+ e^-$

- Thousands per bunch crossing.

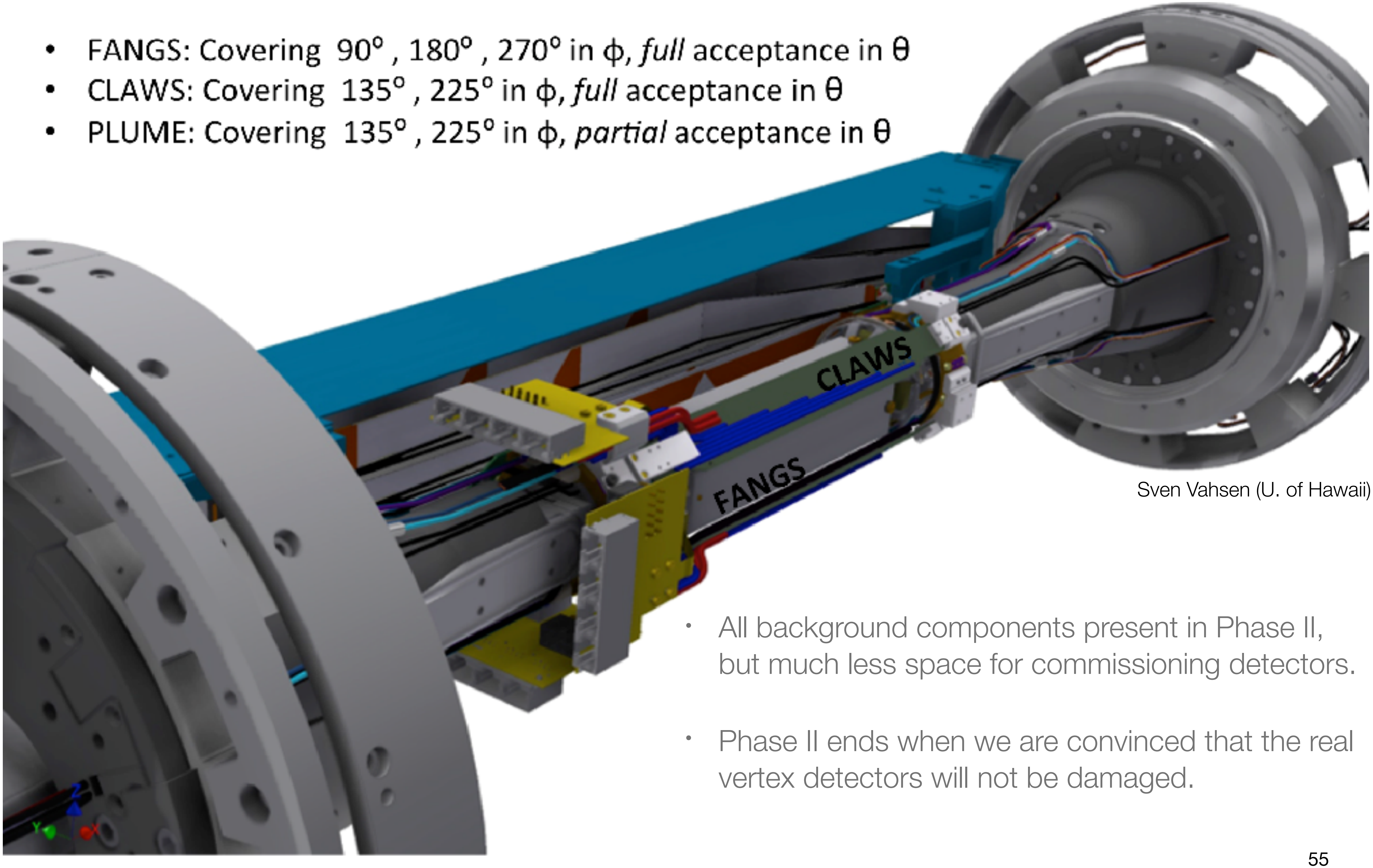


- Despite shielding, many 1—2 MeV photons reach the detector.
  - *e.g.* extraneous hits; compromised photosensor lifetimes

C. Hearty

BEAST II, Phase 2: Full Belle II but with specialized background detectors in place of Si Strips & Pixels

- FANGS: Covering 90° , 180° , 270° in ϕ, *full* acceptance in θ
- CLAWS: Covering 135° , 225° in ϕ, *full* acceptance in θ
- PLUME: Covering 135° , 225° in ϕ, *partial* acceptance in θ



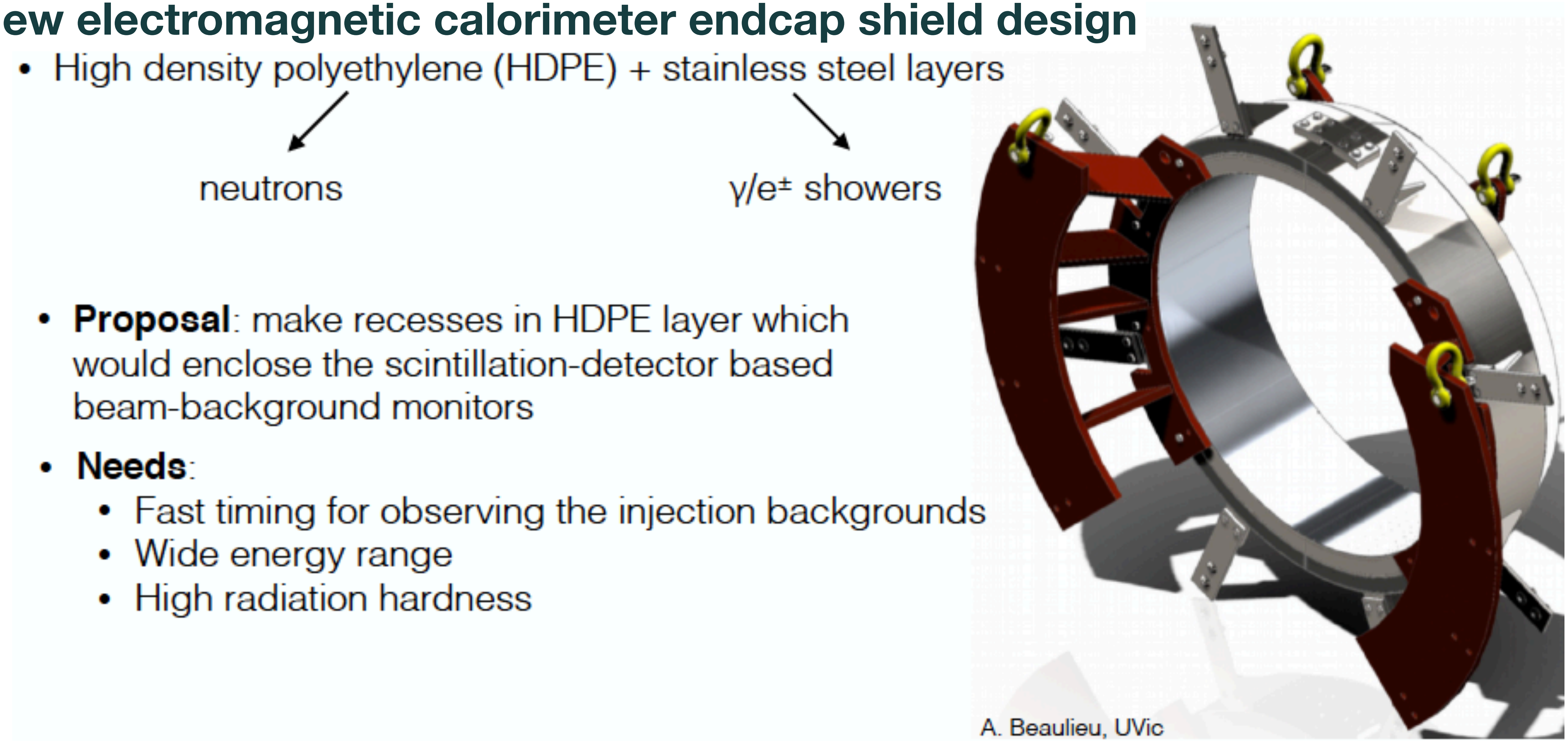
Sven Vahsen (U. of Hawaii)

- All background components present in Phase II, but much less space for commissioning detectors.
- Phase II ends when we are convinced that the real vertex detectors will not be damaged.

BEAST II Phases 2 & 3: Canadian Hardware Fast Real-Time Beam Background Monitors

- Measure "trickle injection" backgrounds from lost beam particles as individual bunches are topped up during live data-taking
  * Not included in background simulations: must be measured empirically in data
  * Fast feedback to SuperKEKB control room needed, for accelerator tuning

New electromagnetic calorimeter endcap shield design



- High density polyethylene (HDPE) + stainless steel layers

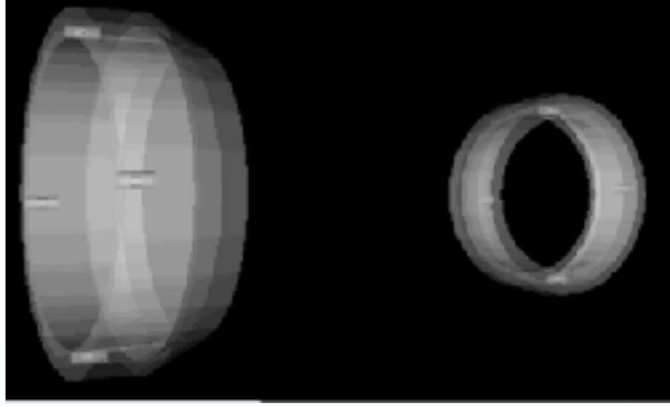
neutrons

$\gamma/e^{\pm}$ showers

- **Proposal**: make recesses in HDPE layer which would enclose the scintillation-detector based beam-background monitors
- **Needs**:
  - Fast timing for observing the injection backgrounds
  - Wide energy range
  - High radiation hardness

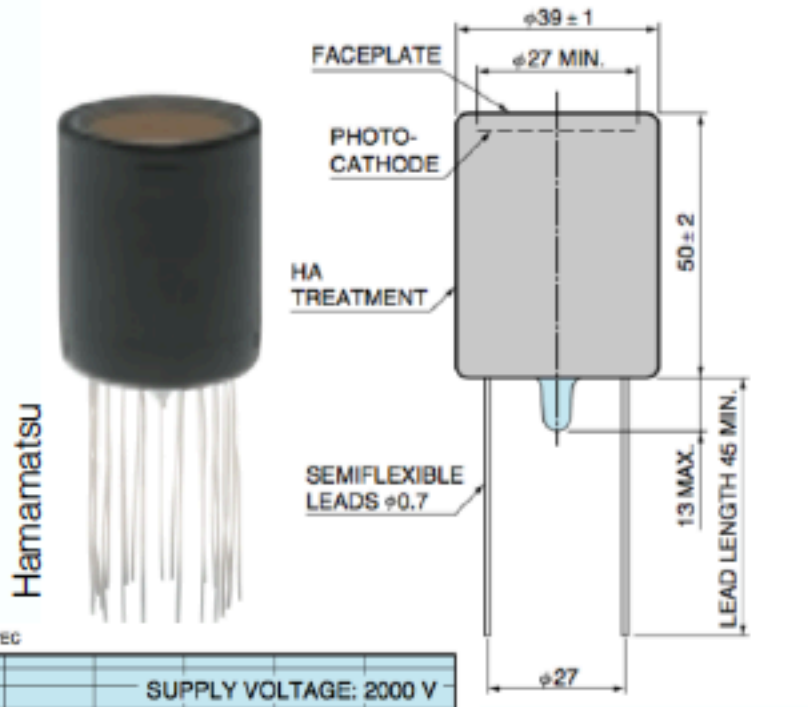
A. Beaulieu, UVic

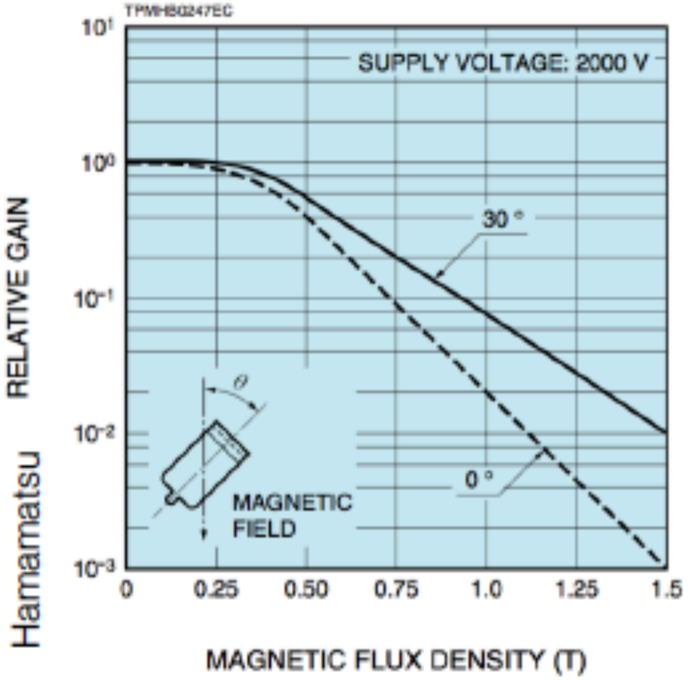
Beam Background Monitors: Design



Hamamatsu R7761-70 Photomultiplier

- suitable for operation in high magnetic field
- peak wavelength 420 nm
- gain 10^4 at 1.5 T
- compact design, 39 mm diameter

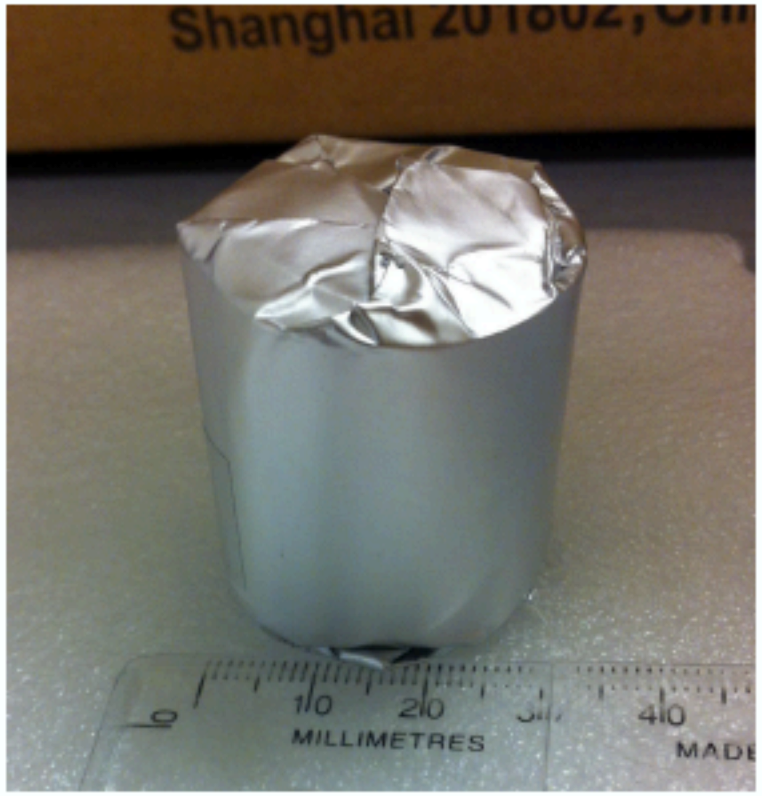




LYSO crystal

- wavelength of emission maximum at 420 nm
- short decay time of 40 ns
  →well matches the beam top-up time of 100 ns
- high light yield of 32000 photons/MeV
- radiation length of 1.14 cm
- good radiation hardness
- radioactive isotope ^{176}Lu

→ 30×30 mm cylindrical crystals



A. Fodor (McGill)

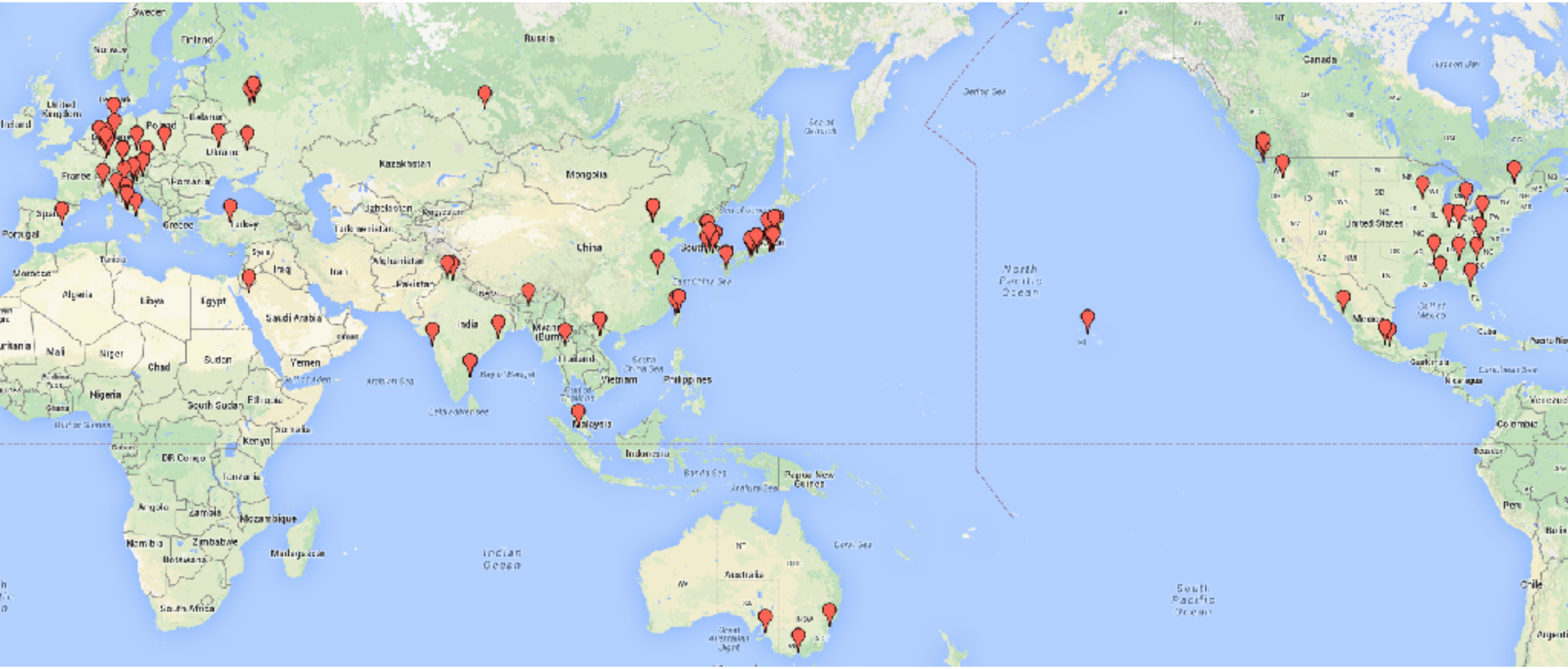
Belle II Canada Team

Montreal	🟨 Simon Lagrange
	Nikolai Starinski
	🟦 Jean-Pierre Martin
	🟦 Paul Taras
McGill	🟨 Racha Cheaib
	🟨 Robert Seddon
	🟨 Waleed Ahmed
	🟨 Andrea Fodor
	🟦 Steven Robertson
	🟦 Andreas Warburton
UBC	🟨 Derek Fujimoto
	🟨 Alon Hershenhorn
	🟧 Torben Feber (1 Oct 2015)
	🟦 Christopher Hearty
	🟦 Thomas Mattison
	🟦 Janis McKenna
UVic	🟨 Sam Dejong
	🟨 Alexandre Beaulieu
	🟨 Savino Longo
	🟧 Alexei Sibidanov
	🟦 Bob Kowalewski
	🟦 Michael Roney
	🟦 Randy Sobie

🟨 **Student**
🟧 **Postdoc**
🟦 **Faculty**

(From 2015: some student names have been replaced due to graduations)

The Belle II Collaboration

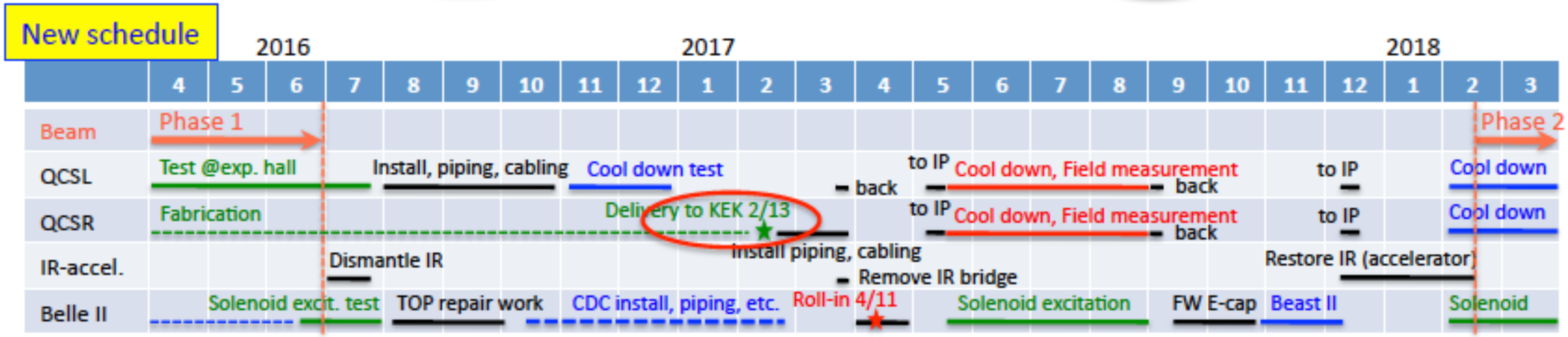


- 686 collaborators (~25% Japanese), 23 countries/regions.

(2015 figures)

C. Hearty

Next Steps…



K. AKAI, Overall status and schedule of SuperKEKB, Feb. 6, 2017 @B2GM

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- **Detector roll-in (to Interaction Region): April 11th**
- **This summer/fall: install beam-background monitors into calorimeter shields**
- **Cosmic-ray data-taking shifts (summer)**
- **Feb. 2018, start BEAST II Phase 2 data taking**
- **Dec. 2018, start Belle II Phase 3 physics data taking,**
  with Canadian beam-background monitors in long-term operation

Summary

- High-intensity flavour-physics measurements play an important role in our pursuit for answers to fundamental questions in particle physics

- Although operating at a relatively lower energy than the LHC, the Belle II experiment is sensitive to a broad range of new physics, through a large number of measurements

- The high luminosity and high resulting backgrounds are challenging for the experiment, but Belle II is on track for first collisions in 2018

Special Thanks:

- UCL ATLAS group (for office space at CERN!)
- Florian Bernlochner (U. Bonn)
- Christopher Hearty (UBC/IPP)
- Steven Robertson (McGill/IPP)

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