# Towards First Physics at Belle II

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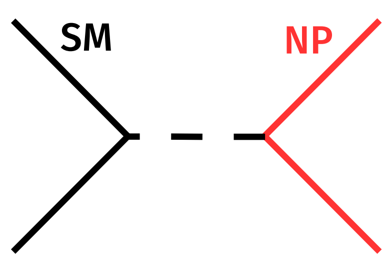
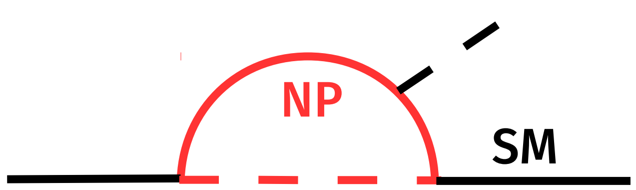
15-June-2016, CAP 2016, Ottawa

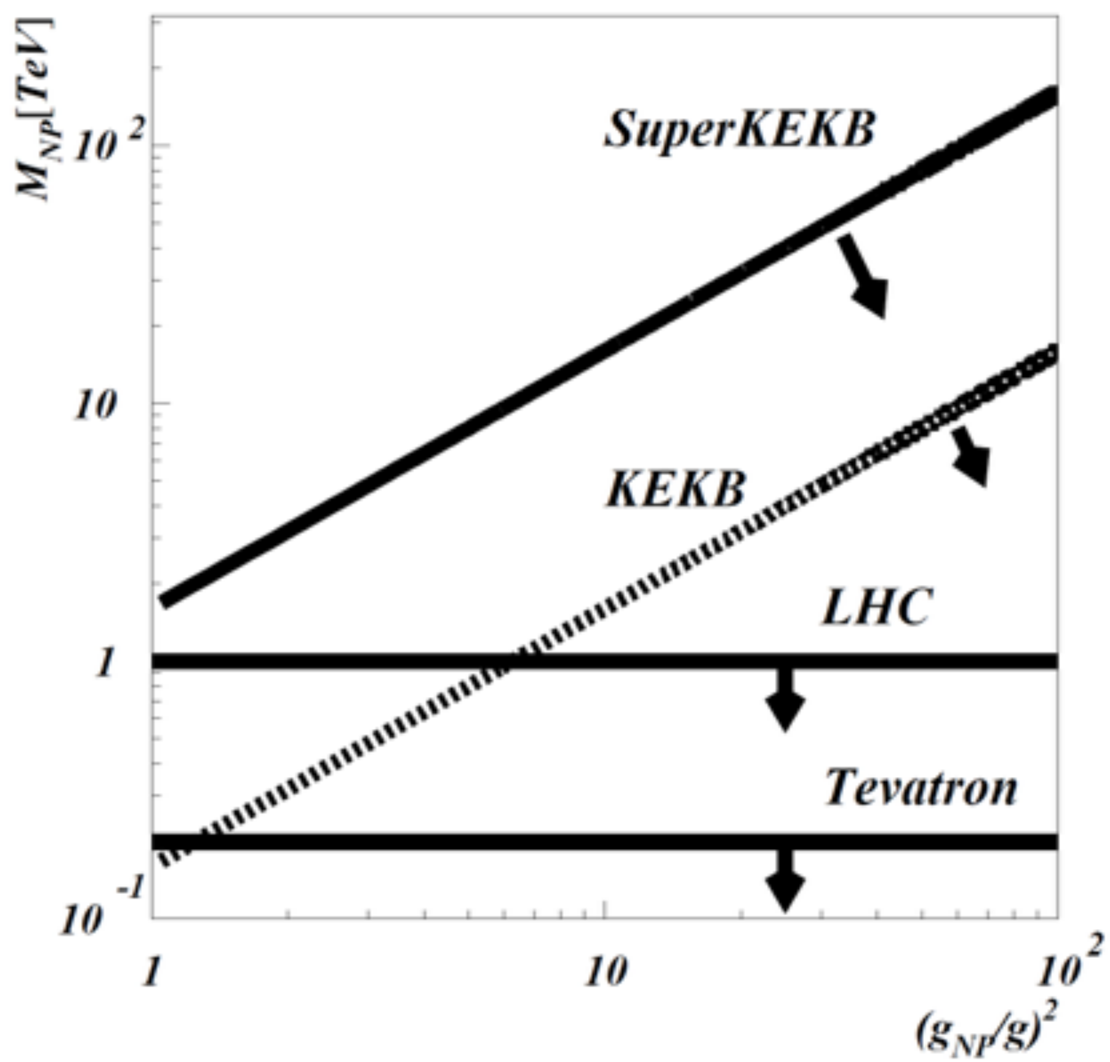
# Energy or Intensity?

- Energy frontier:
  - Production of New Physics (NP) from collisions.
  - Limited by beam energy.




- Intensity frontier:
  - NP in virtual processes.
  - Limited by statistics.



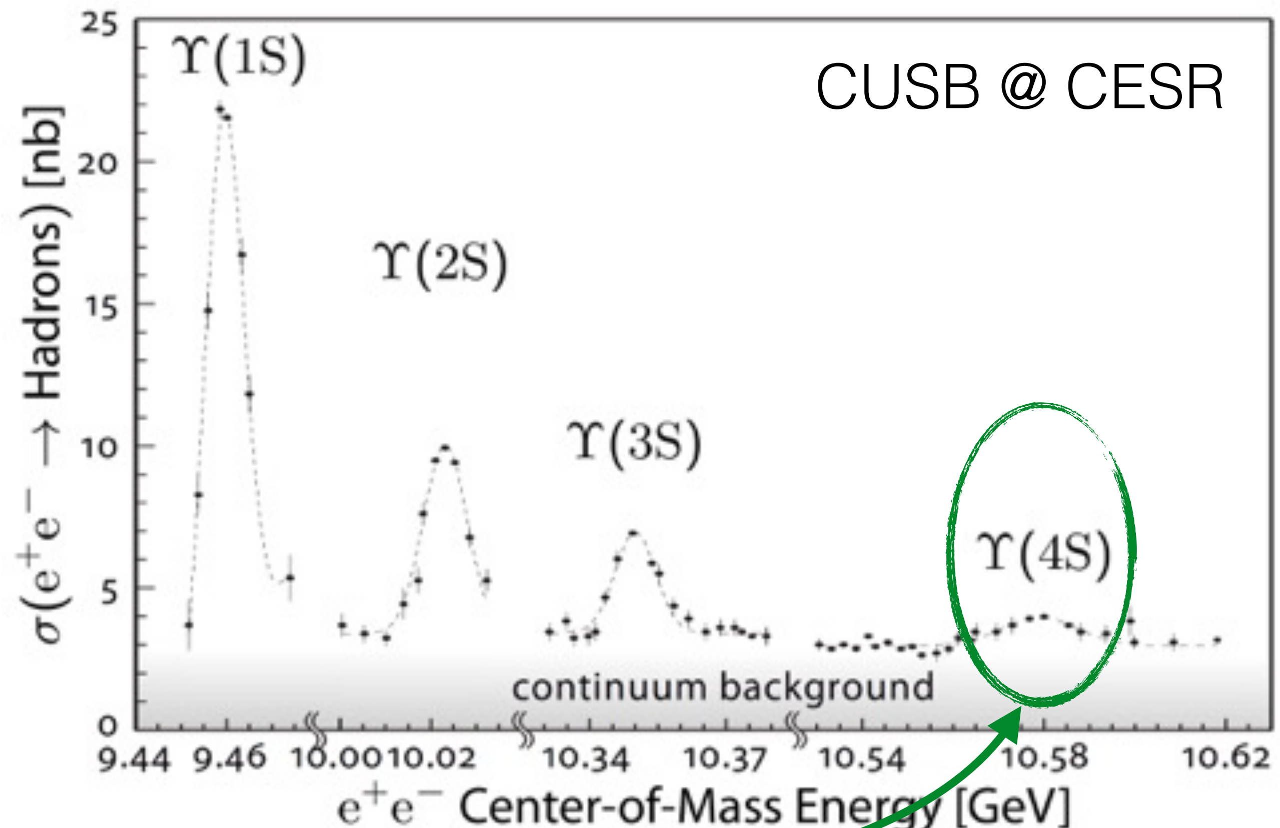



# Belle and BaBar.

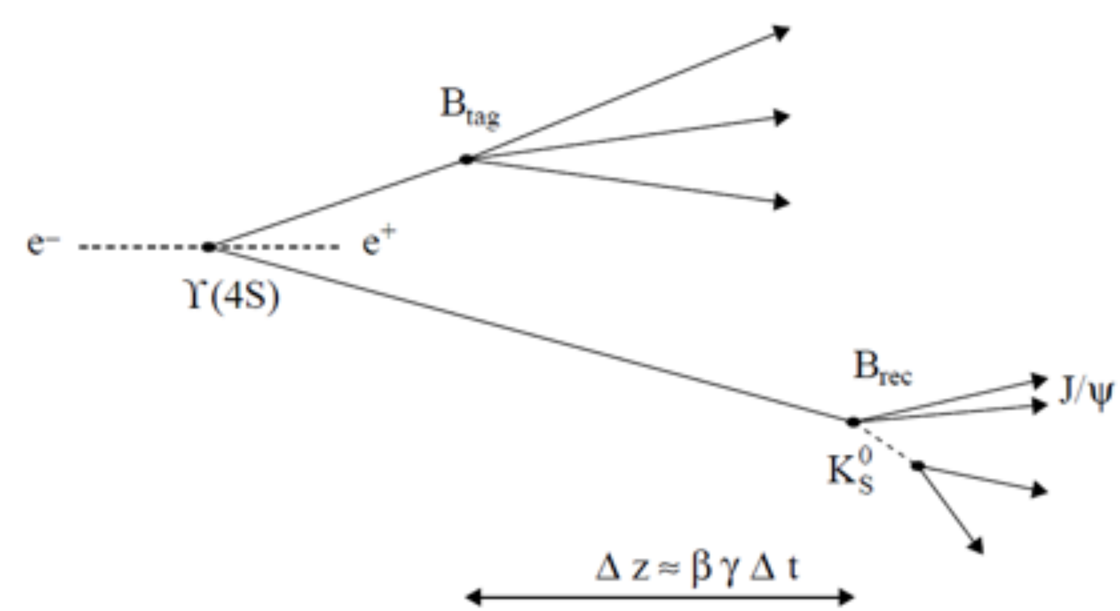
- Belle at KEKB, Japan and BaBar at PEP-II, USA.

- Very high luminosity:
  ~2×10$^{34}$ /cm$^2$/s (Belle)

- Collision energy at Y(nS):
  Mainly at **$E_{CM}$ = 10.58 GeV.**
  BR(Y(4S)→BB) > 96%




- Asymmetric beam energies:
  8 GeV (e$^-$) / 3.5 GeV (e$^+$) (Belle)
  → Boosted BB pairs.



# (Some) Belle II Physics.

relative errors.

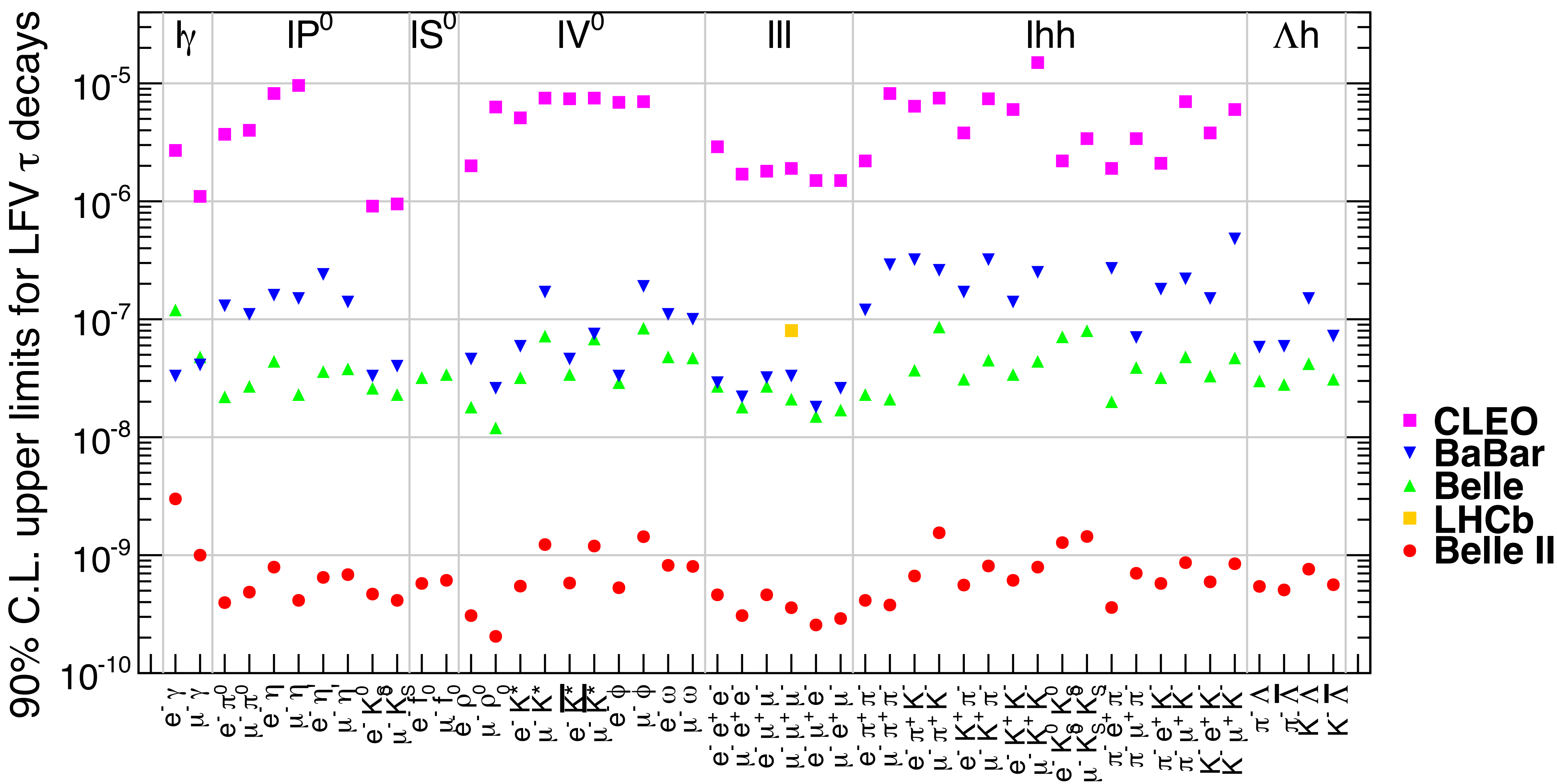
| Observables | Belle (2014) | Belle II 5 $ab^{-1}$ | Belle II 50 $ab^{-1}$ | $\mathcal{L}_s$ [$ab^{-1}$] |
|---|---|---|---|---|
| $\sin 2\beta$ | $0.667 \pm 0.023 \pm 0.012$ | $\pm 0.012$ | $\pm 0.008$ | 6 |
| $\alpha$ | | $\pm 2^\circ$ | $\pm 1^\circ$ | |
| $\gamma$ | $\pm 14^\circ$ | $\pm 6^\circ$ | $\pm 1.5^\circ$ | |
| $S(B \to \phi K^0)$ | $0.90^{+0.09}_{-0.19}$ | $\pm 0.053$ | $\pm 0.018$ | >50 |
| $S(B \to \eta' K^0)$ | $0.68 \pm 0.07 \pm 0.03$ | $\pm 0.028$ | $\pm 0.011$ | >50 |
| $S(B \to K^0_S K^0_S K^0_S)$ | $0.30 \pm 0.32 \pm 0.08$ | $\pm 0.100$ | $\pm 0.033$ | 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 |
| $\mathcal{B}(B \to \tau\nu)$ [$10^{-6}$] | $96 \pm 26$ | $\pm 10\%$ | $\pm 5\%$ | 46 |
| $\mathcal{B}(B \to \mu\nu)$ [$10^{-6}$] | $< 1.7$ | $5\sigma$ | $>> 5\sigma$ | >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 |
| $\mathcal{B}(B \to X_s\gamma)$ [$10^{-6}$] | $\pm 13\%$ | $\pm 7\%$ | $\pm 6\%$ | $< 1$ |
| $A_{CP}(B \to X_s\gamma)$ | | $\pm 0.01$ | $\pm 0.005$ | 8 |
| $S(B \to K^0_S\pi^0\gamma)$ | $-0.10 \pm 0.31 \pm 0.07$ | $\pm 0.11$ | $\pm 0.035$ | $> 50$ |
| $S(B \to \rho\gamma)$ | $-0.83 \pm 0.65 \pm 0.18$ | $\pm 0.23$ | $\pm 0.07$ | $> 50$ |
| $C_7/C_9$ $(B \to X_s\ell\ell)$ | $\sim 20\%$ | $10\%$ | $5\%$ | |
| $\mathcal{B}(B_s \to \gamma\gamma)$ [$10^{-6}$] | $< 8.7$ | $\pm 0.3$ | | |
| $\mathcal{B}(B_s \to \tau^+\tau^-)$ [$10^{-3}$] | | $< 2$ | | |

Statistical precision
≈ systematic uncertainty

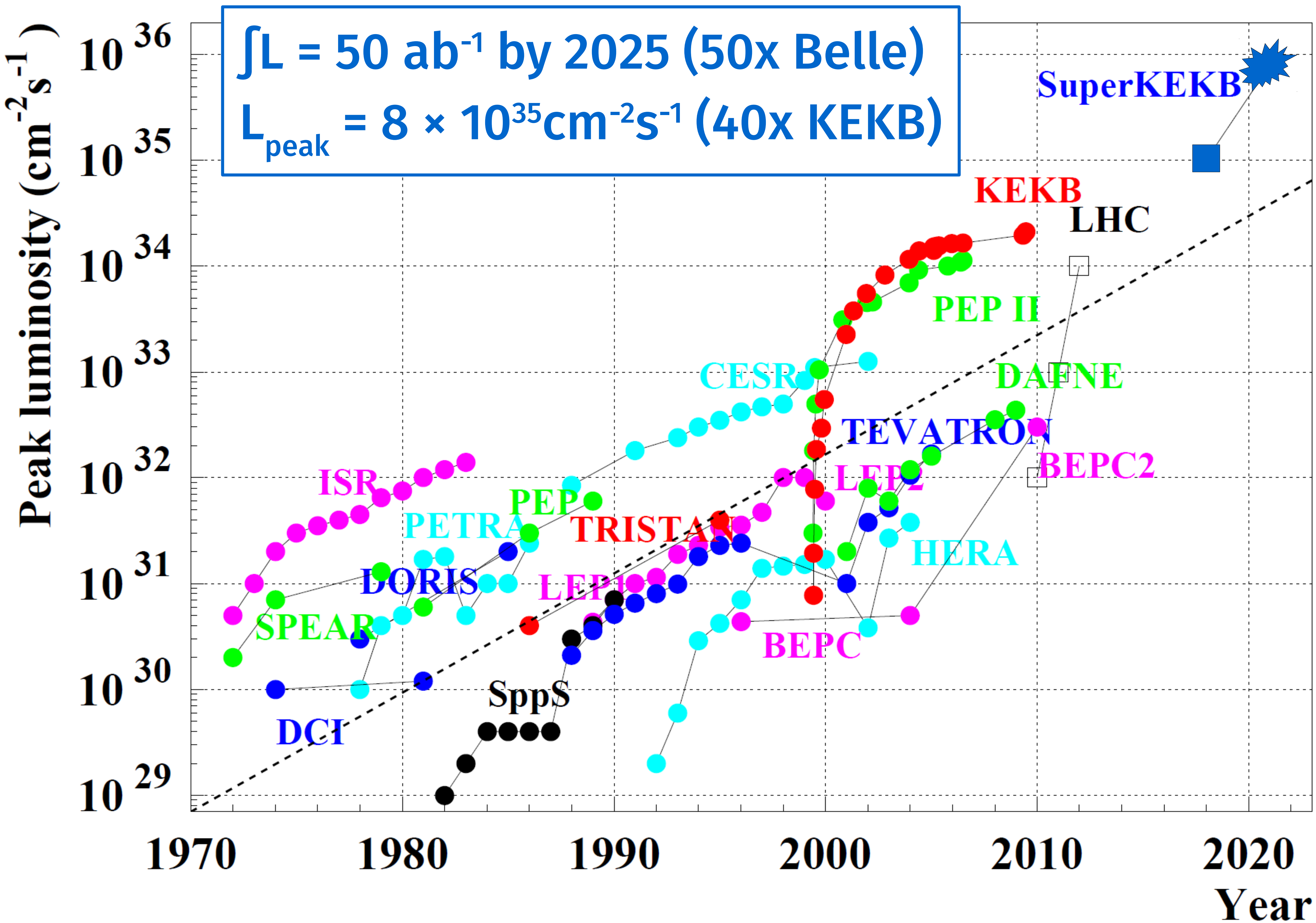
*B. Golob et al., BELLE2-NOTE-PH-2015-002*

# (Some) Belle II Physics.

*B. Golob et al., BELLE2-NOTE-PH-2015-002*



# Peak luminosity over time.

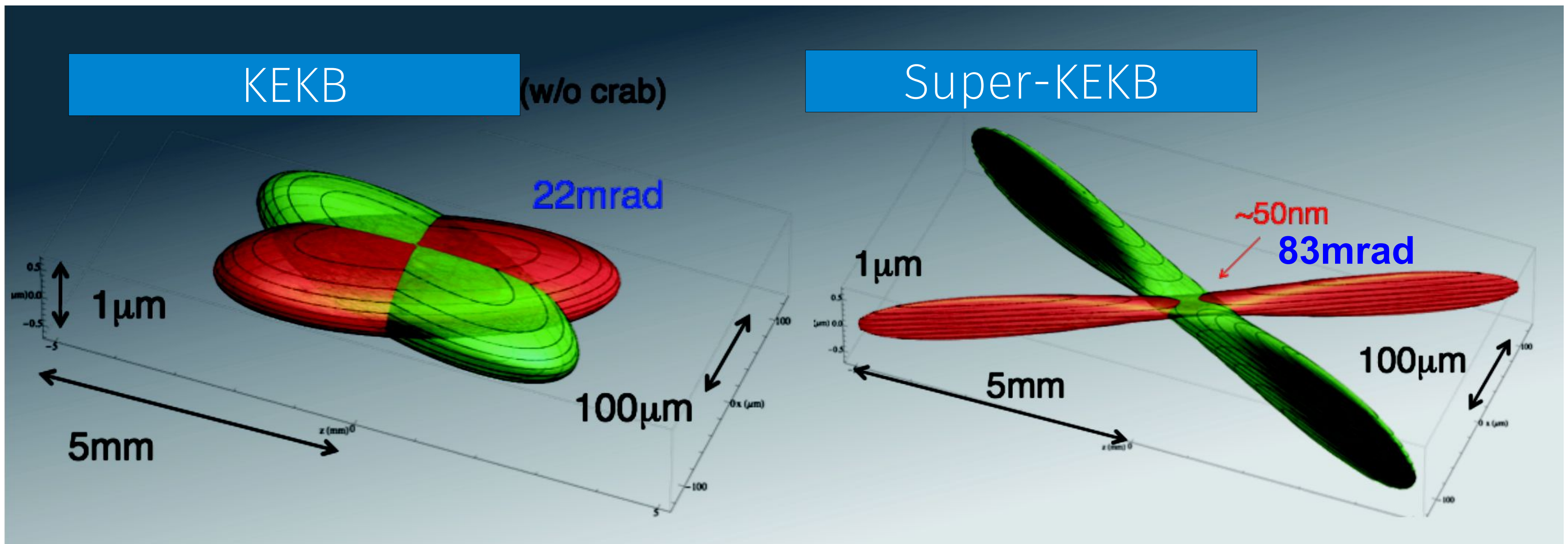


# SuperKEKB: Nano Beam Scheme.

beam current

$$L = \frac{\gamma_\pm}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

vertical beta function at IP



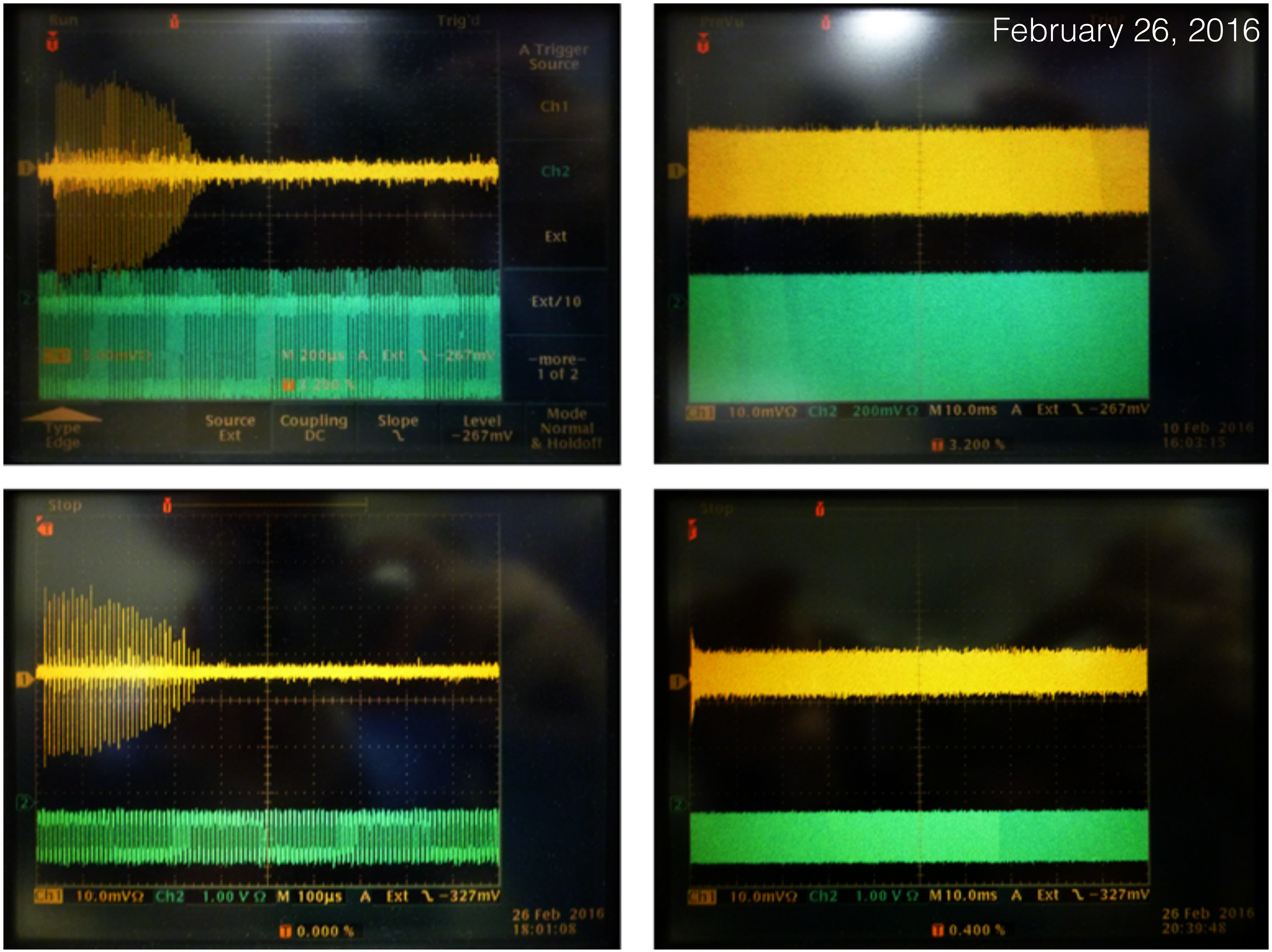

| | E (GeV) LER/HER | $\beta^*_y$ (mm) LER/HER | $\beta^*_x$ (cm) LER/HER | φ (mrad) | I (A) LER/HER | L ($cm^{-2}s^{-1}$) |
|---|---|---|---|---|---|---|
| KEKB | 3.5/8.0 | 5.9/5.9 | 120/120 | 11 | 1.6/1.2 | $2.1 \times 10^{34}$ |
| SuperKEKB | 4.0/7.0 | 0.27/0.30 | 3.2/2.5 | 41.5 | 3.6/2.6 | $80 \times 10^{34}$ |

factor 20

factor 2-3

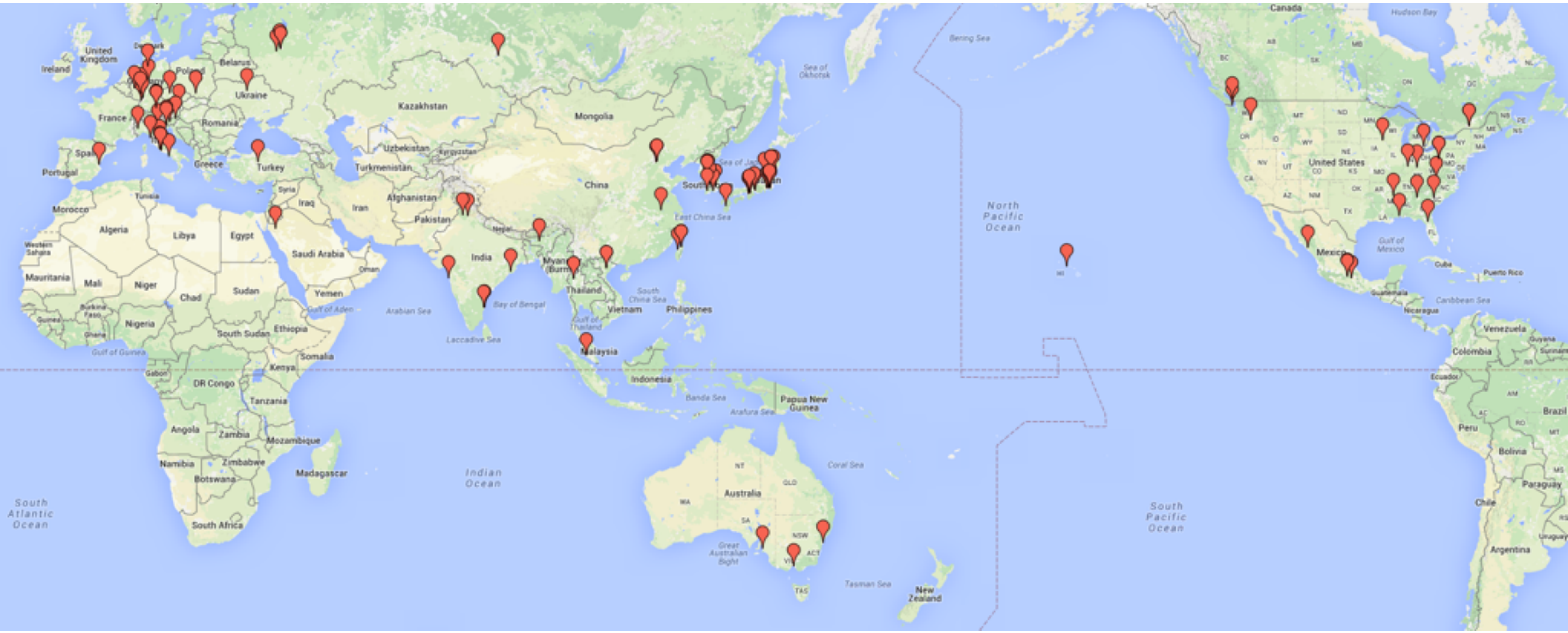
# SuperKEKB is running!

February 26, 2016



May 31, 2016: LER beam current at 825 mA, HER at 730 mA.

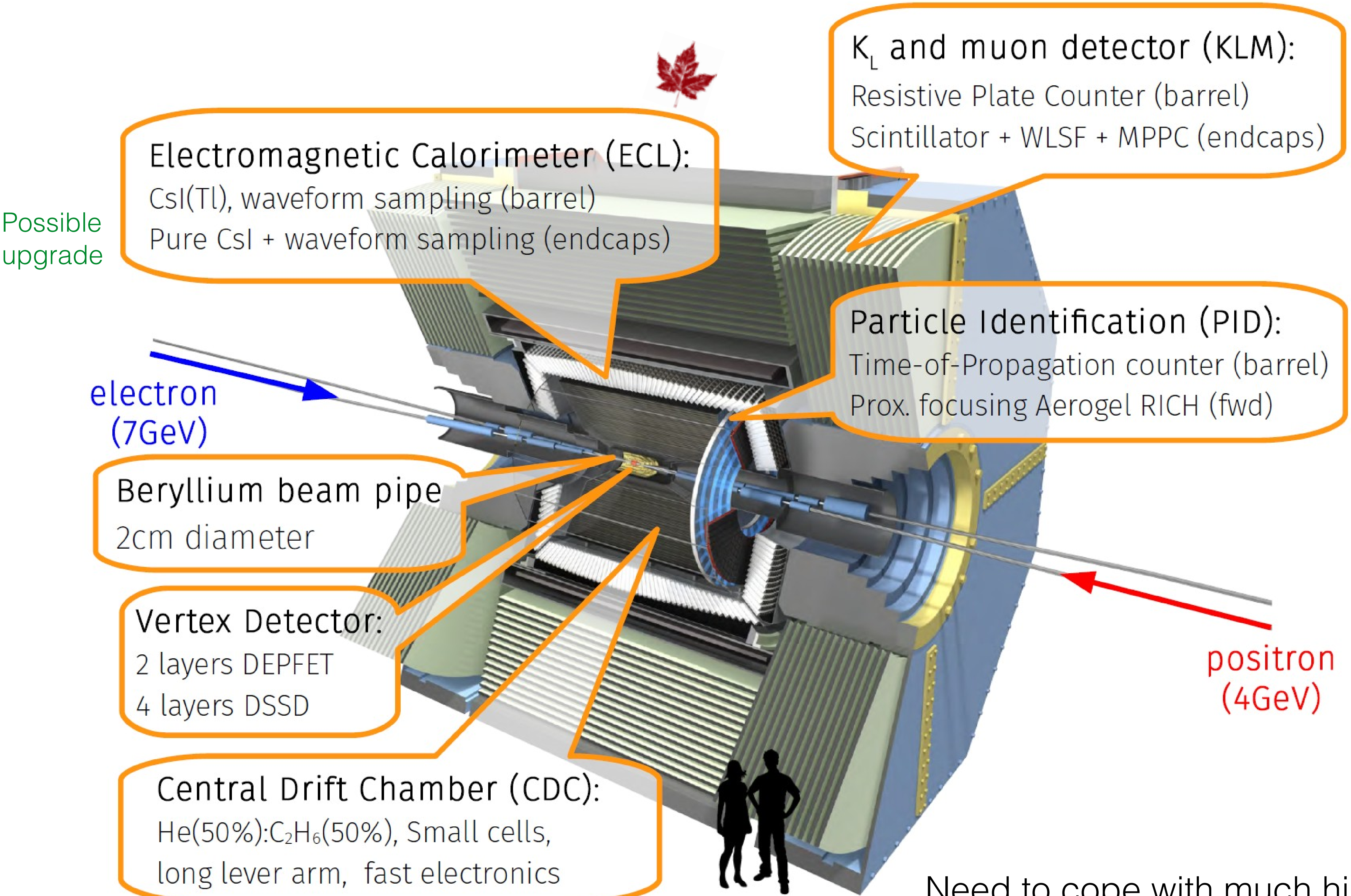
# Belle II Collaboration.




620 members
(including 220 grad students)
100 institutes

UBC
UVictoria
McGill
UMontreal

# Belle II Detector.




Need to cope with much higher luminosity and beam background.

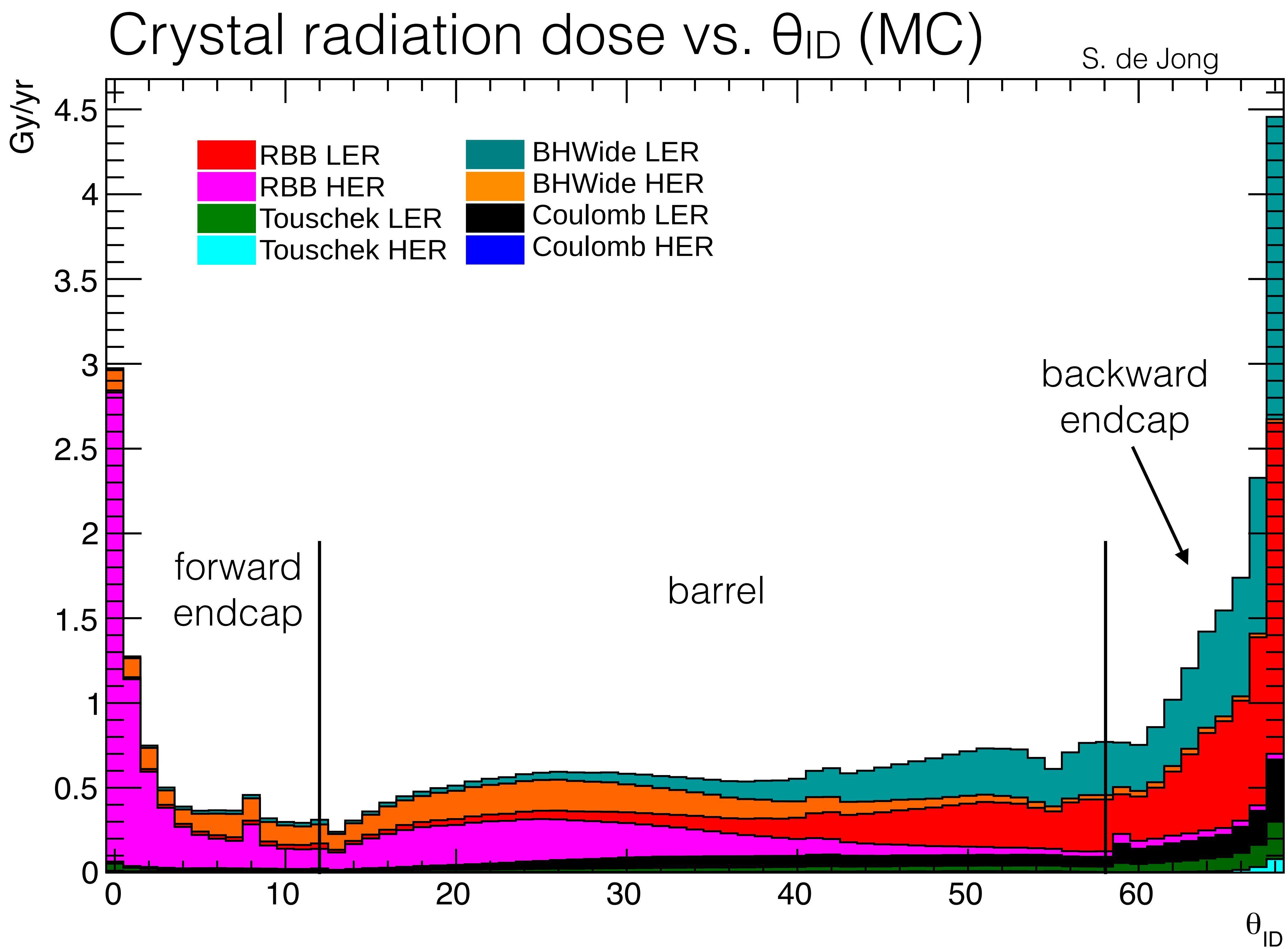
# Belle II Detector: Calorimeter (ECL).

- Precise measurement of $\gamma$ ($\pi^0$) and the so called 'extra energy' are crucial, in particular with respect to LHCb.

- A generic $\Upsilon(4S) \to BB$ decay creates 11 photons on average, almost only from $\pi^0$ decays. About half of the photons having energies less than 200 MeV. Lowest photon energy used for physics ~40 MeV.

- Reuse existing CsI(Tl) crystals from Belle (excellent energy resolution but quite slow). Belle achieved an energy resolution of about 1.8% at high energies.

# Belle II ECL: Background.



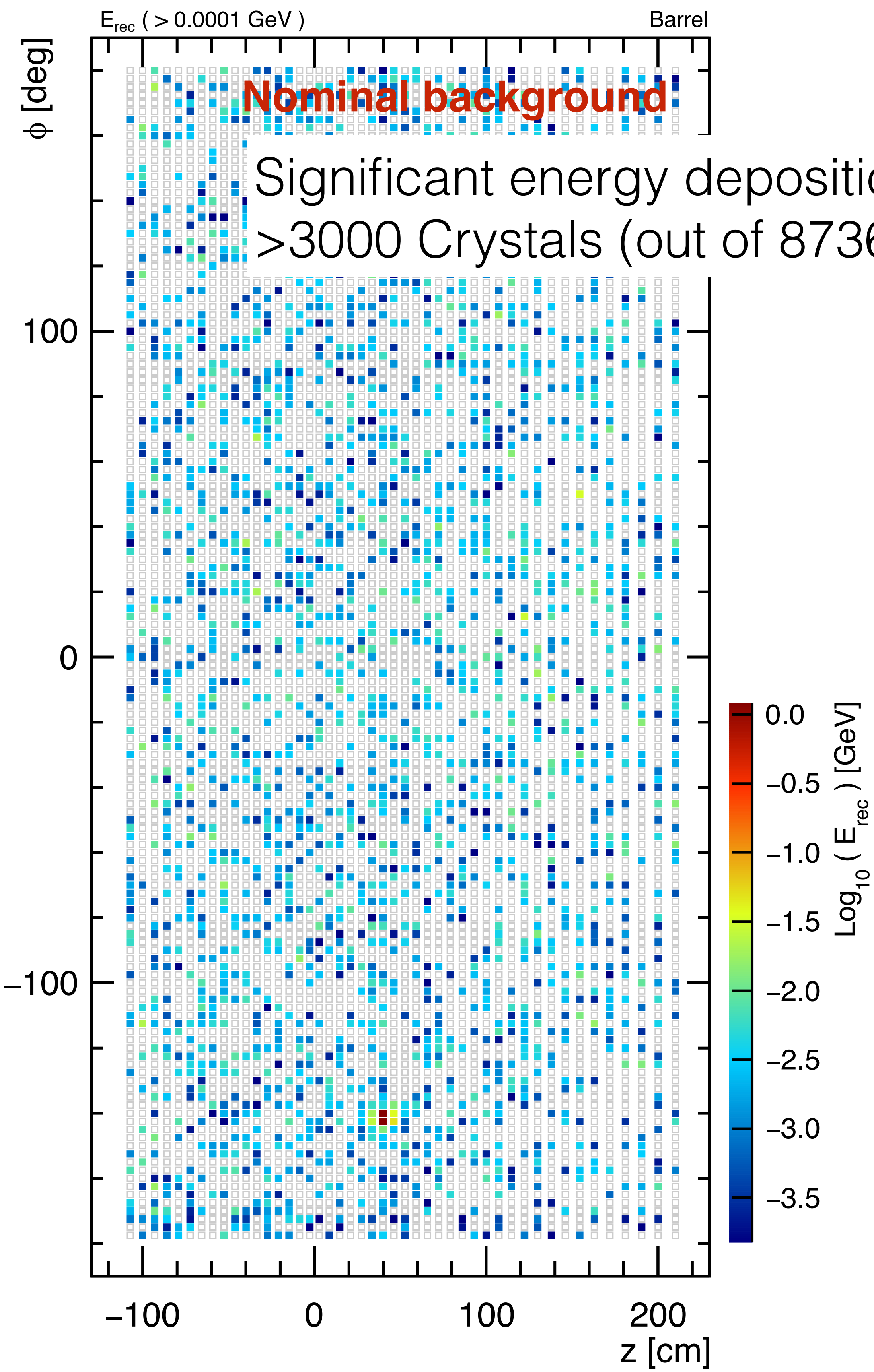
# Belle II Detector: Calorimeter (ECL).

- New digitization and waveform fitting electronics to cope with much higher beam background (pile up).

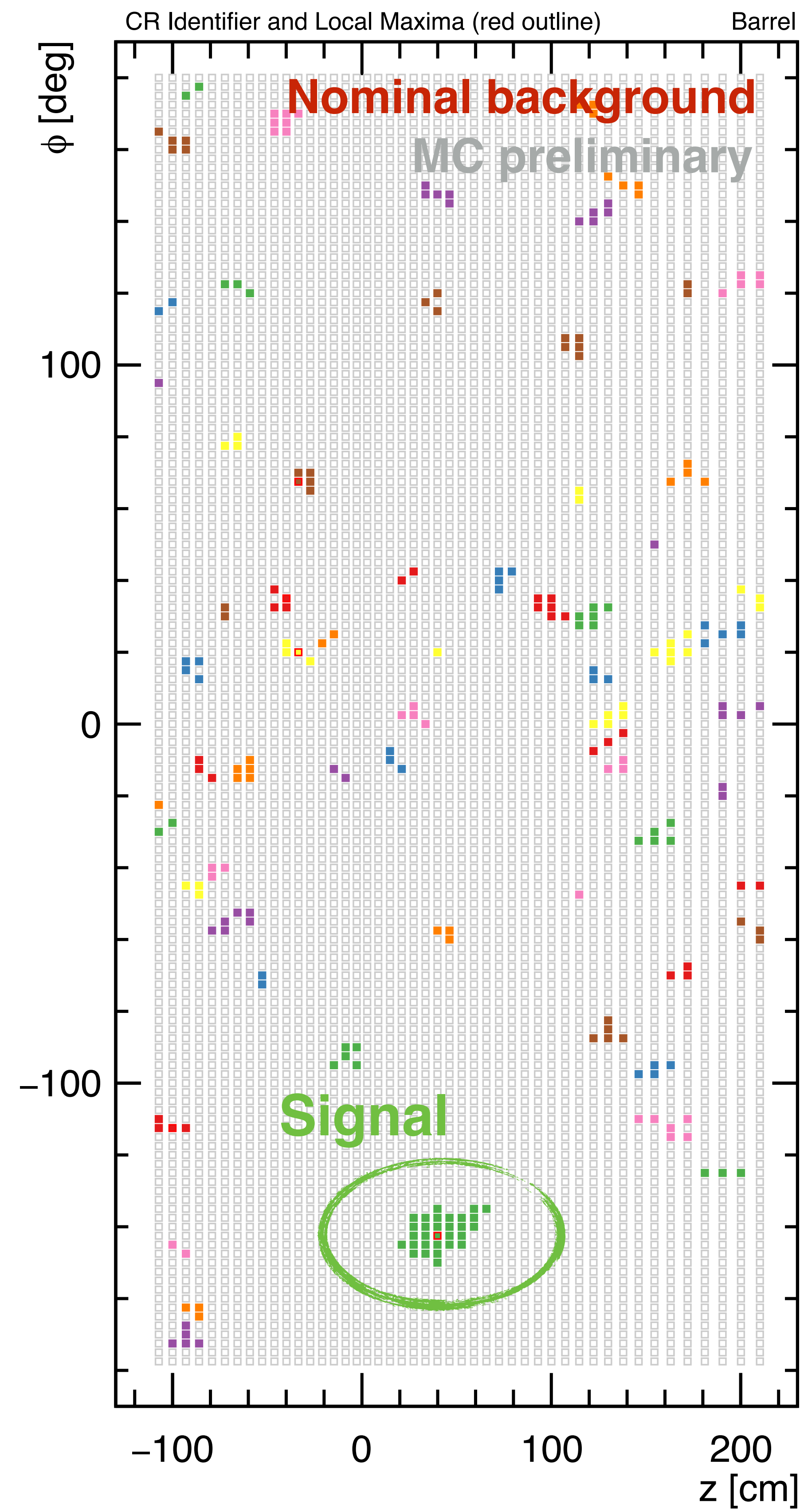
- New robust reconstruction (need a conceptually different approach for very high backgrounds) and calibration (including time).

- Possible upgrade of forward endcap crystals to pure CsI under study (worse energy resolution but very fast).

# Belle II ECL: Background.

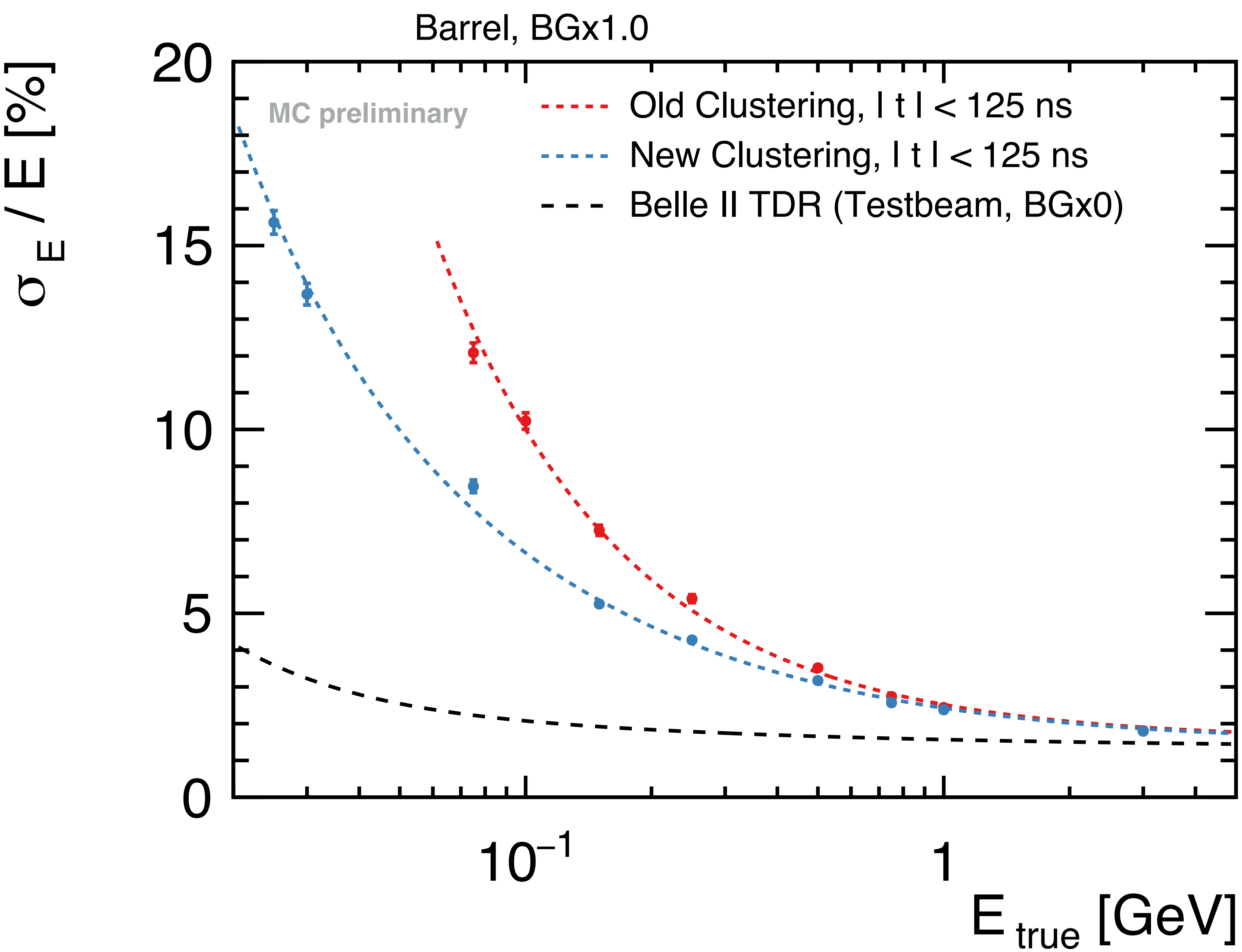



Significant energy deposition in >3000 Crystals (out of 8736).

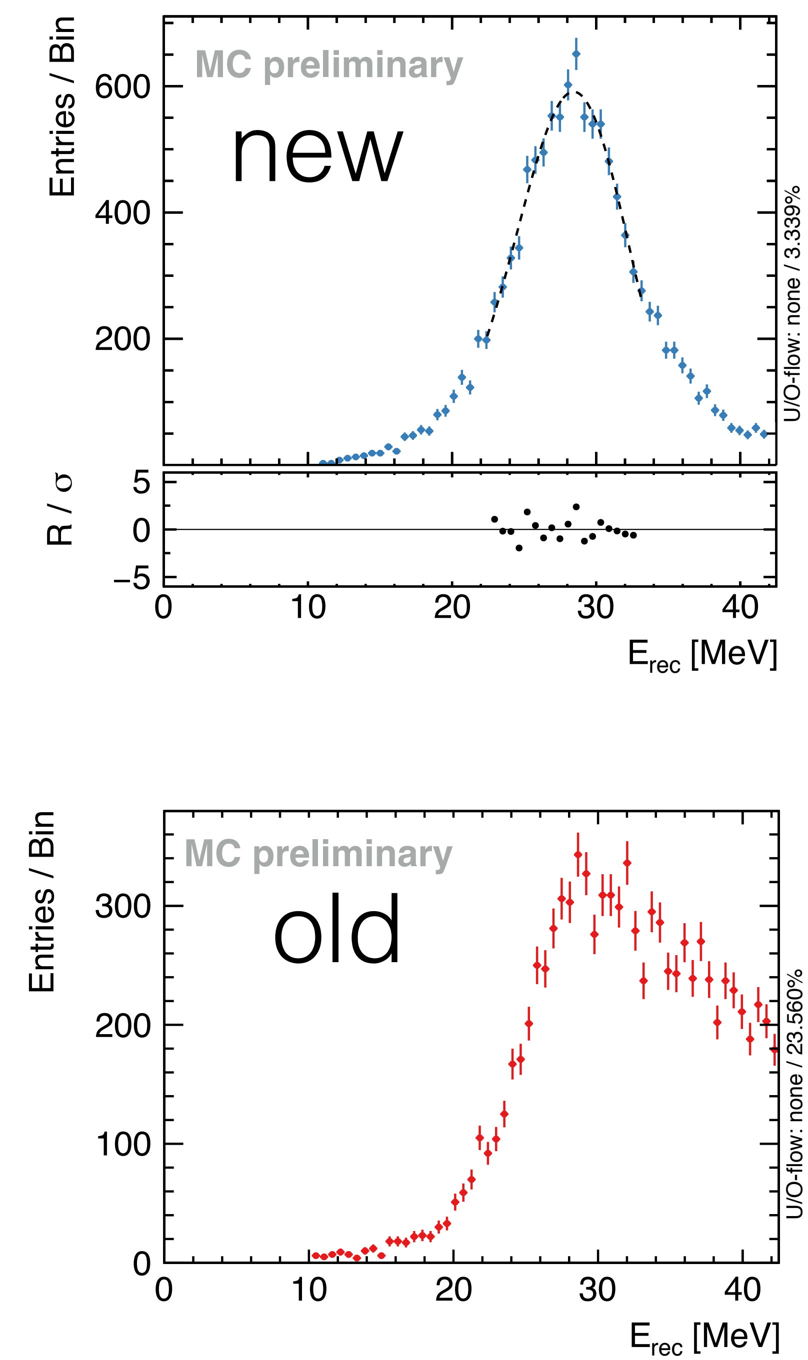


# Belle II ECL: Reconstruction.

Novel hypothesis based clustering.

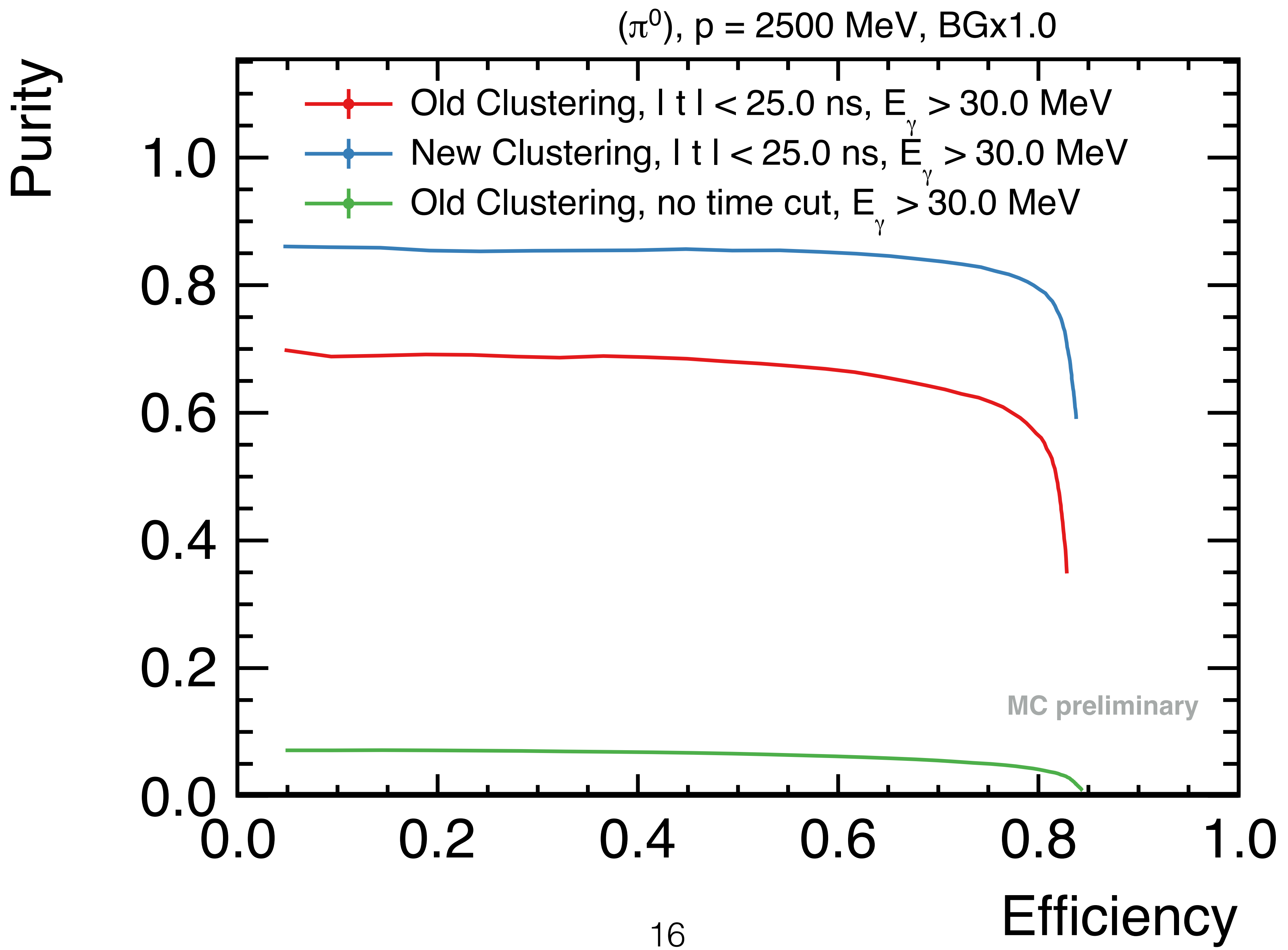



e.g. 30 MeV

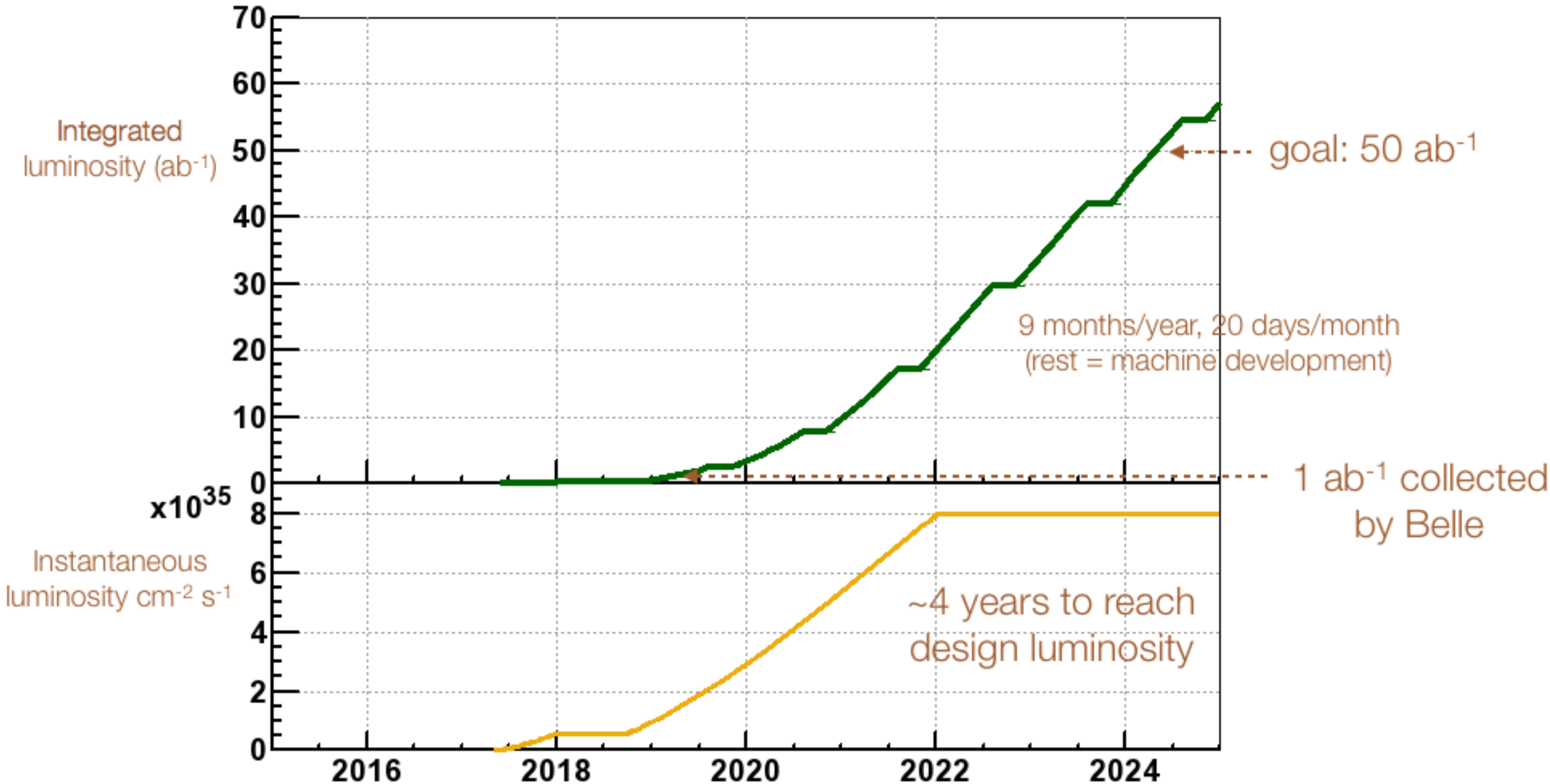


# Belle II ECL: Reconstruction.

$\pi^0$ reconstruction using two photon combinations: Significantly better energy and position reconstruction and overlap energy sharing.



# Belle II Luminosity Projection.



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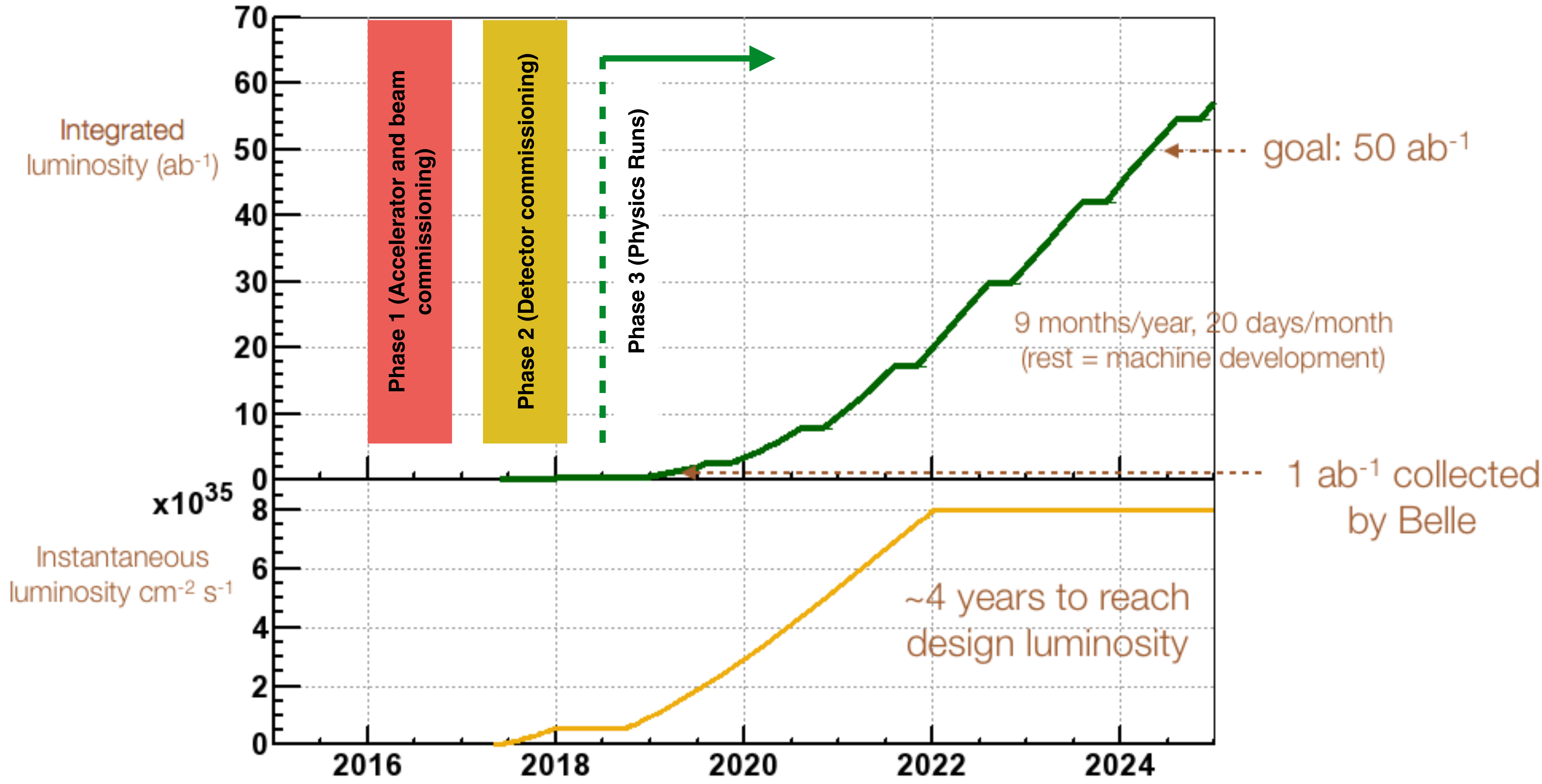
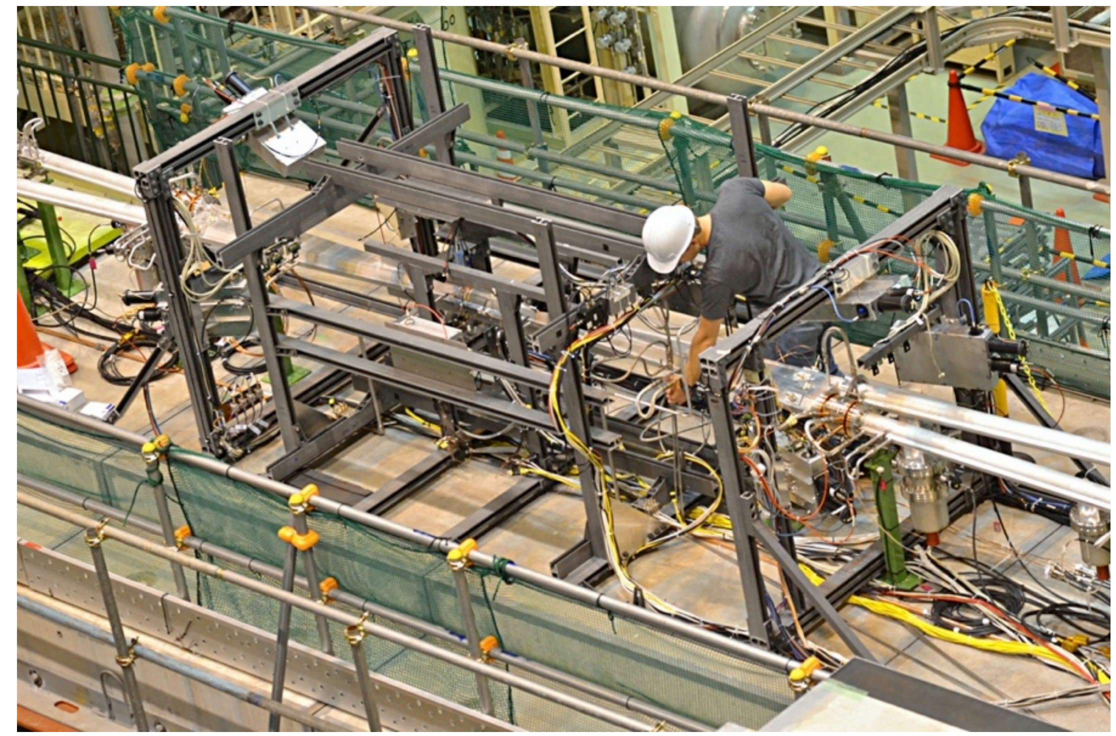
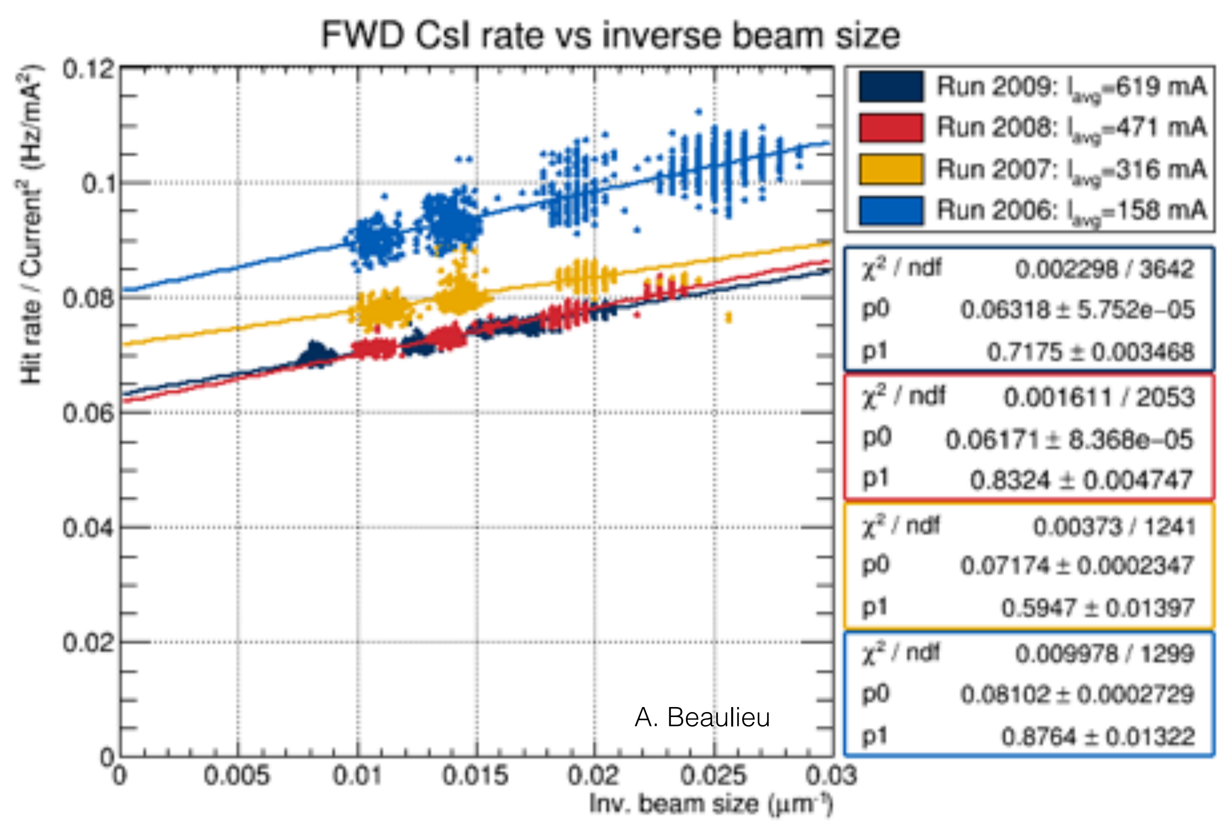


# Phase 1 (ongoing).

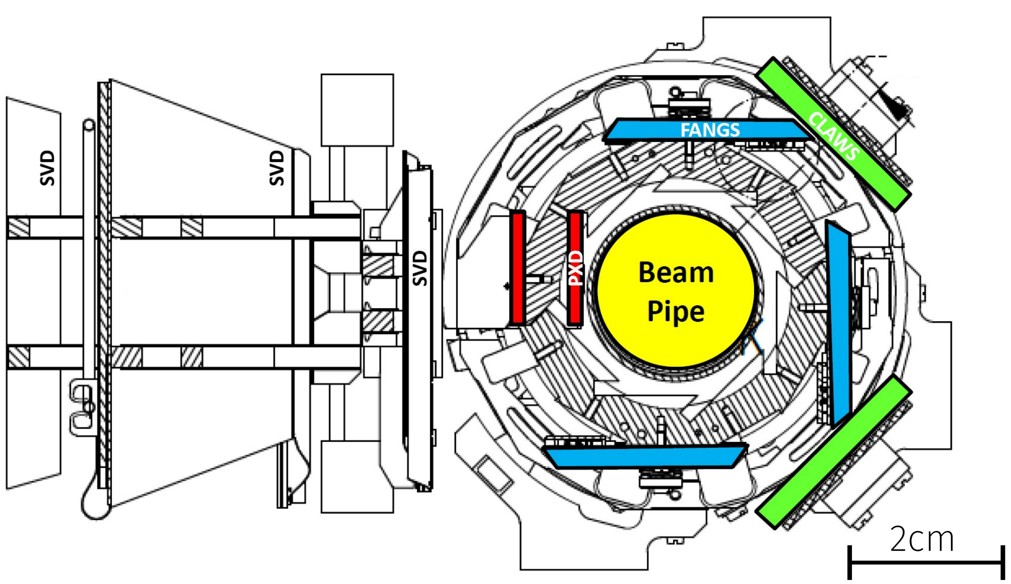
- No Belle II detector.
- BEAST II (**B**eam **E**xorcism for **A ST**able Belle II Experiment).
- Simple background detectors (diodes, TPCs, CsI crystals, He3 tubes).
- No final focus magnets.





# Phase 2: End of 2017.

- Final focus magnets (superconducting).
- Full Belle II outer detectors and drift chamber.
- No final vertex detectors.

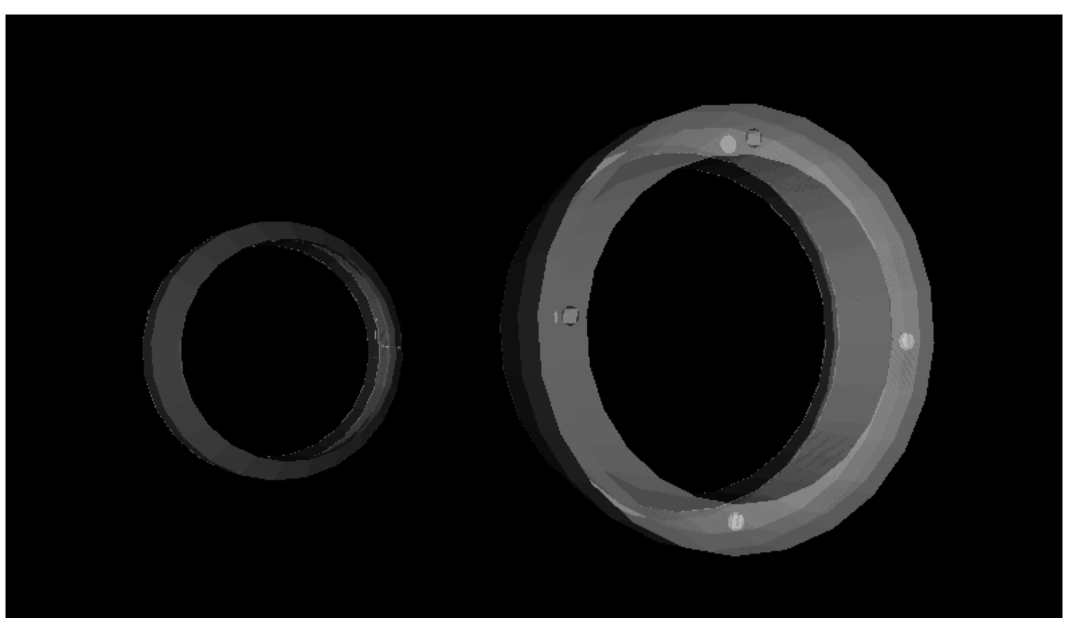



# Phase 2: Beam Background Monitoring.

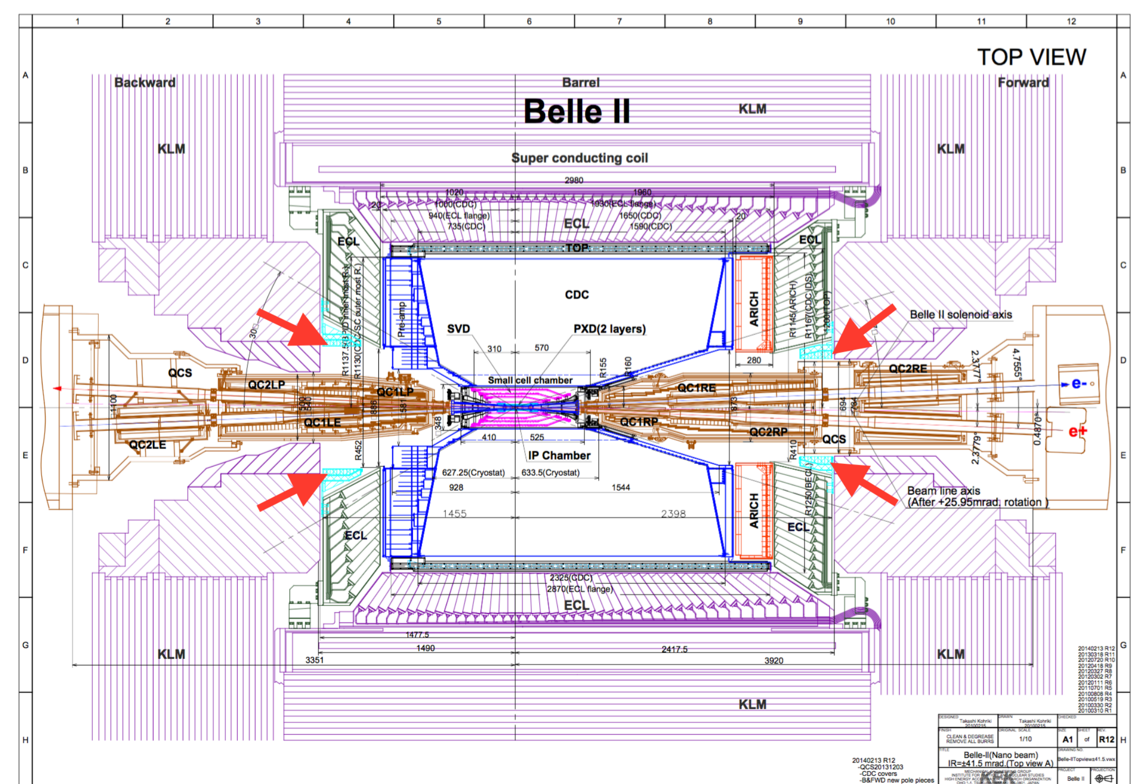
- Goal: Providing live background rate information to SuperKEKB operators during Phase 2 (Detector commissioning) and Phase 3 (Physics run).

- 4 LYSO or CsI crystals with photopentode readout in each endcap shield.

- Readout time fast enough to observe injection backgrounds.



McGill
UMontreal



# Phase 2: First Physics.

- Main purpose of Phase 2 is detector and accelerator commissioning.

- Unlike at the energy frontier, Belle II needs more data than Belle+BaBar to address anomalies (and find new physics). Possible scenarios for the very first data include:

    - Run at non-Υ(4S) energy.

    - Implement special triggers (that may have too high rate at full luminosity): Search for a dark photon decaying invisibly.

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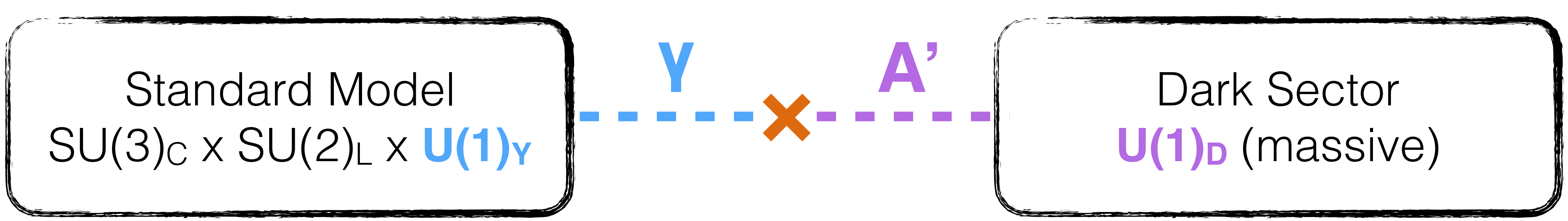
  - Implement special triggers (that may have too high rate at full luminosity): Search for a dark photon decaying invisibly.

# Dark photons.

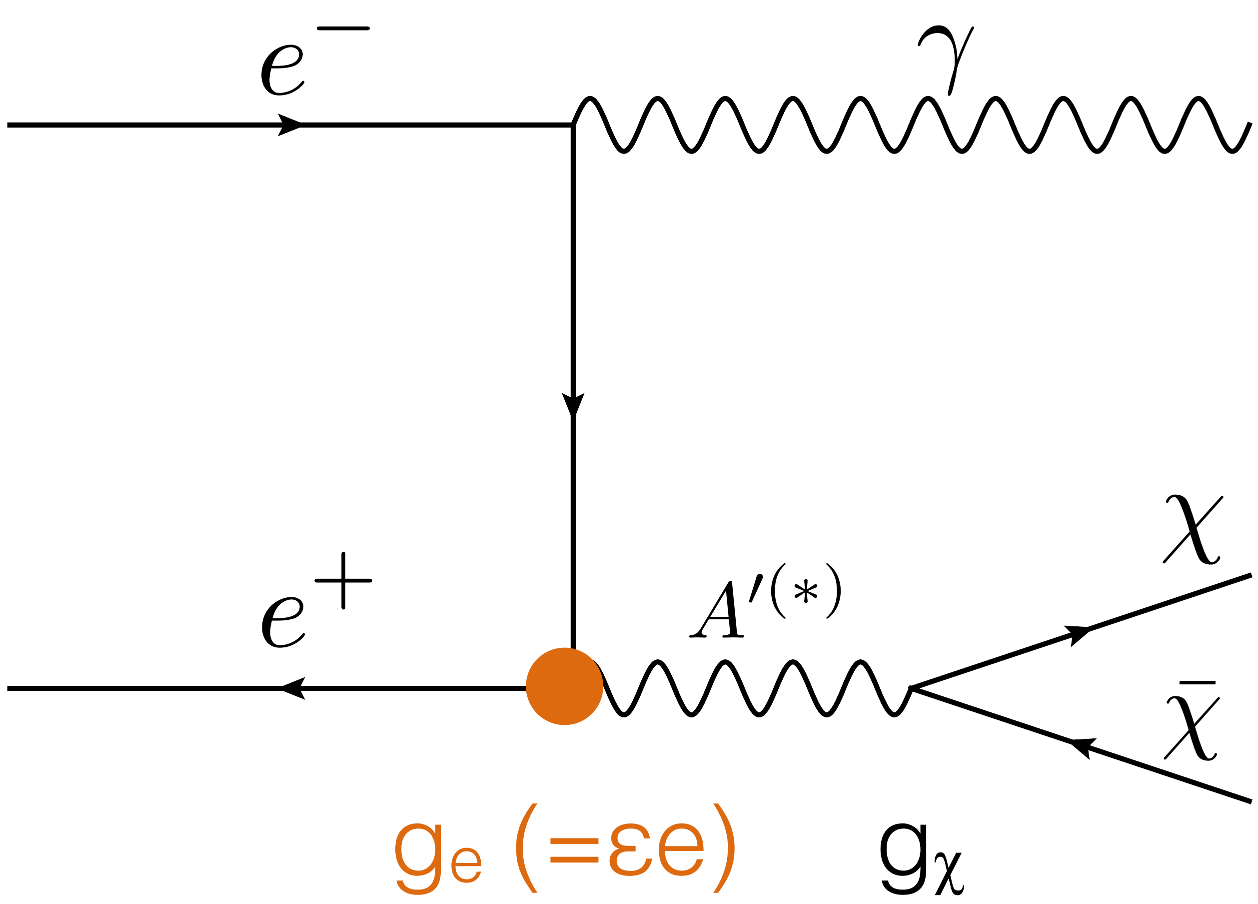
- We know there is dark matter (DM), but we don't know what it is.
- We know DM couples very weakly to SM particles.
- In the so called "vector portal", a dark photon **A'** mixes* with the SM photon **γ** with strength **ε**:

*Holdom, Phys. Lett B166, 1986



# Dark photon decaying invisibly.

- If DM is part of a dark sector, the dark photon A’ can decay into dark matter $\chi$:



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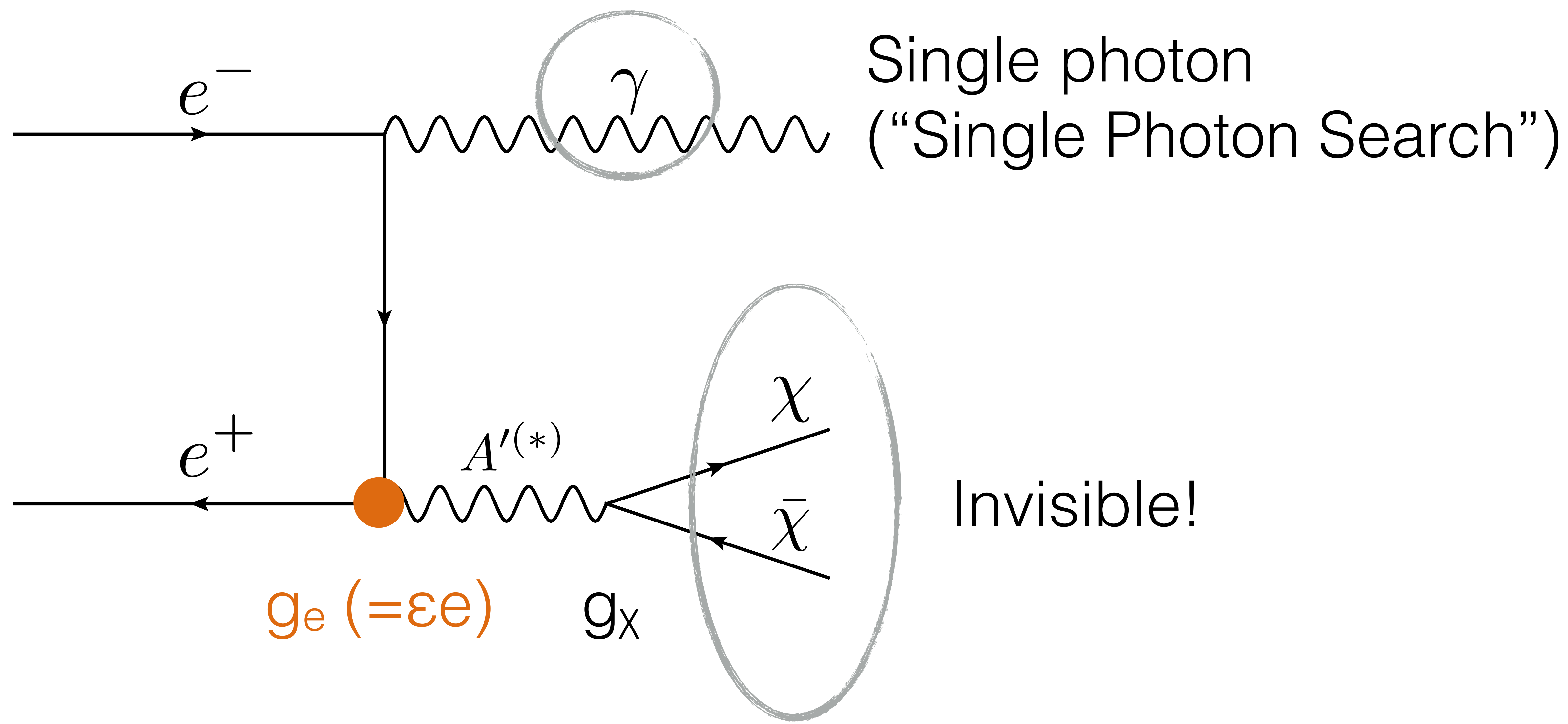
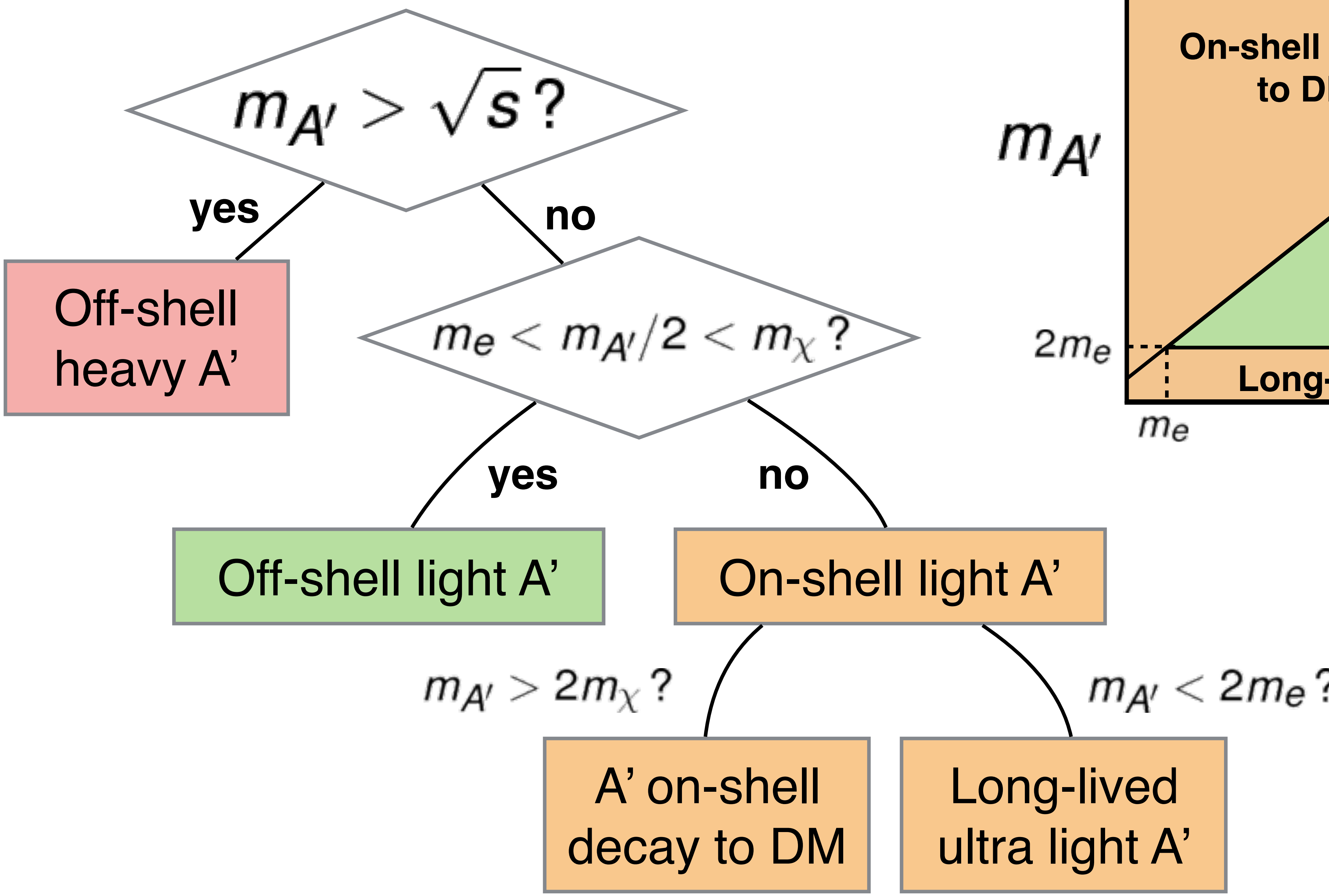
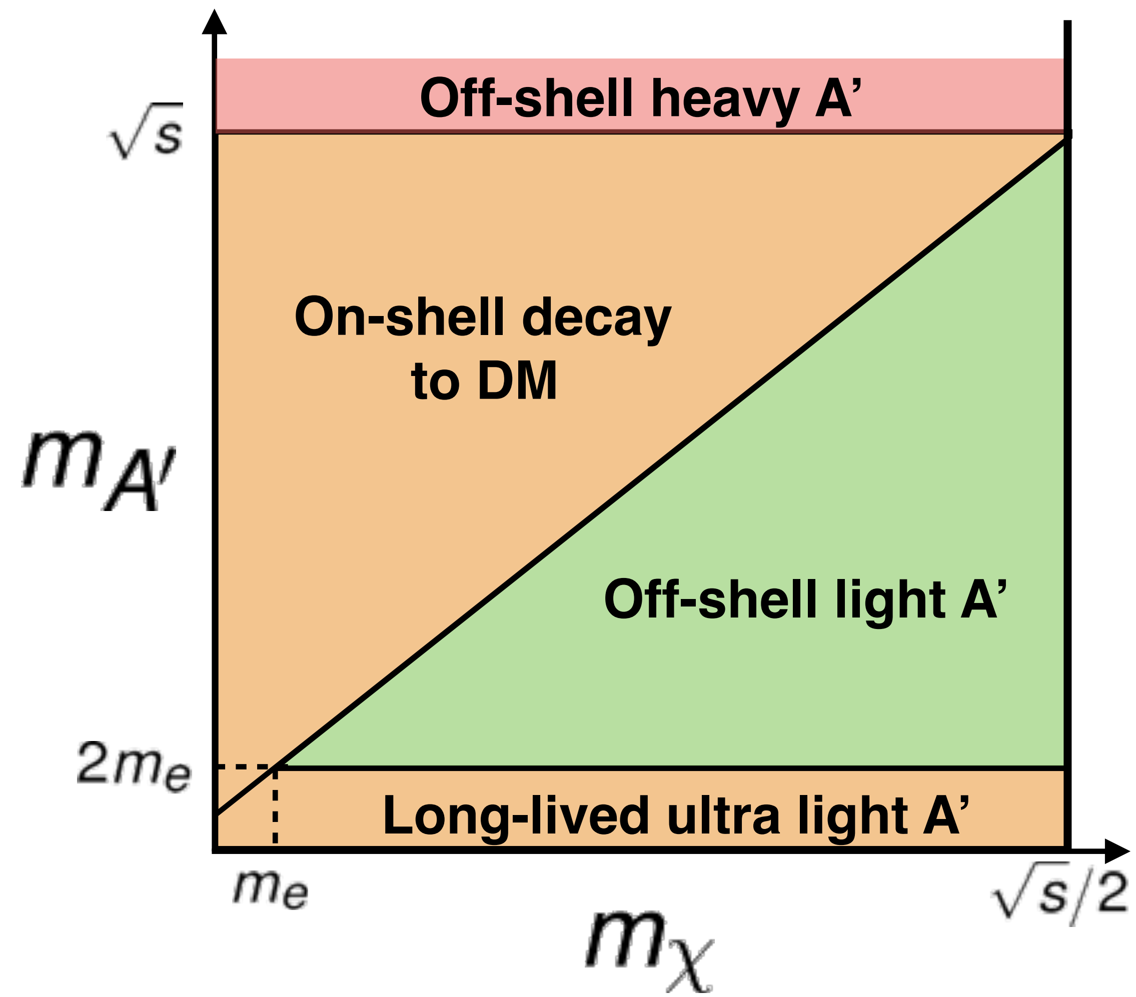


# Dark photon decaying invisibly.

Minimal ingredients:
$m_e, m_{A'}, m_\chi, \sqrt{s}$

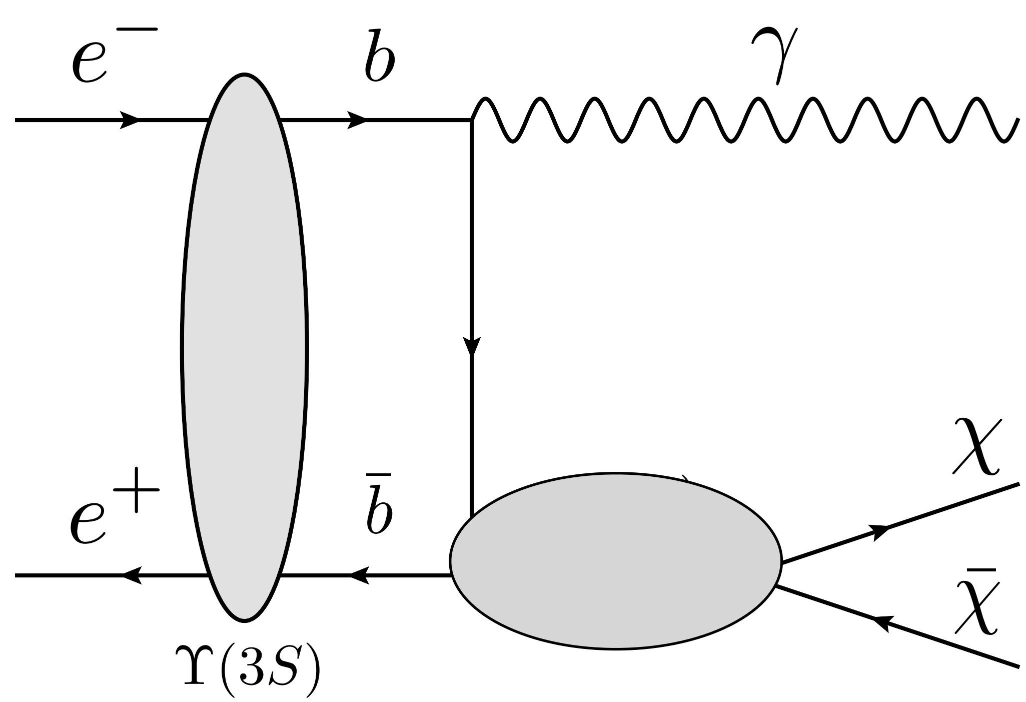


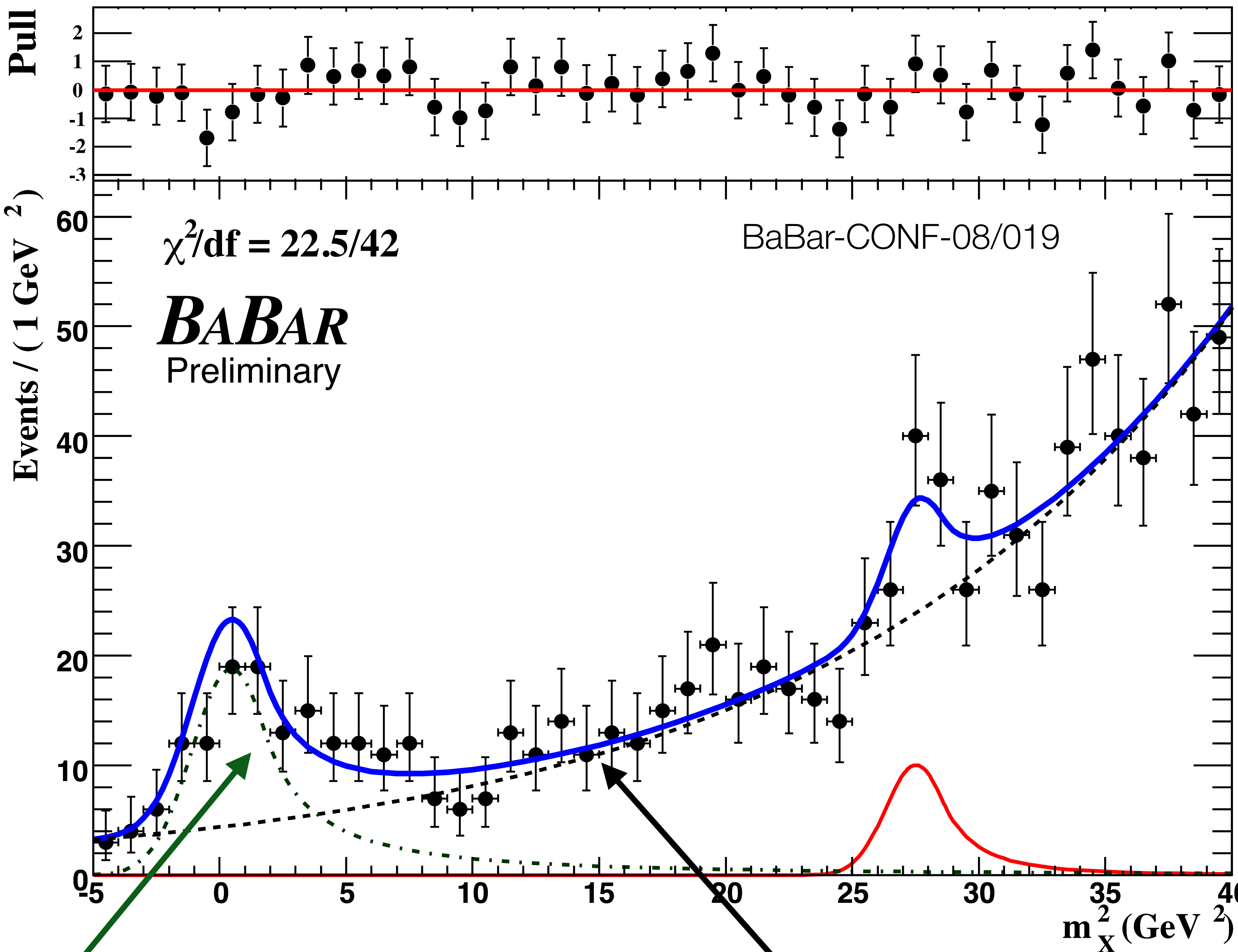
# Dark photon decaying invisibly at BaBar.

- BaBar recorded 57 $fb^{-1}$ with a single photon trigger ($E^* \gtrsim$ 1-2 GeV, trigger rate ~1/3 of all triggers). Belle never had a single photon trigger.

- BaBar used about 28 $fb^{-1}$ in a search for a light Higgs via $\Upsilon(3S) \to \gamma A^0$, $A^0 \to$ invisible (unpublished, BaBar-CONF-08/019).



# Dark photon decaying invisibly at BaBar.

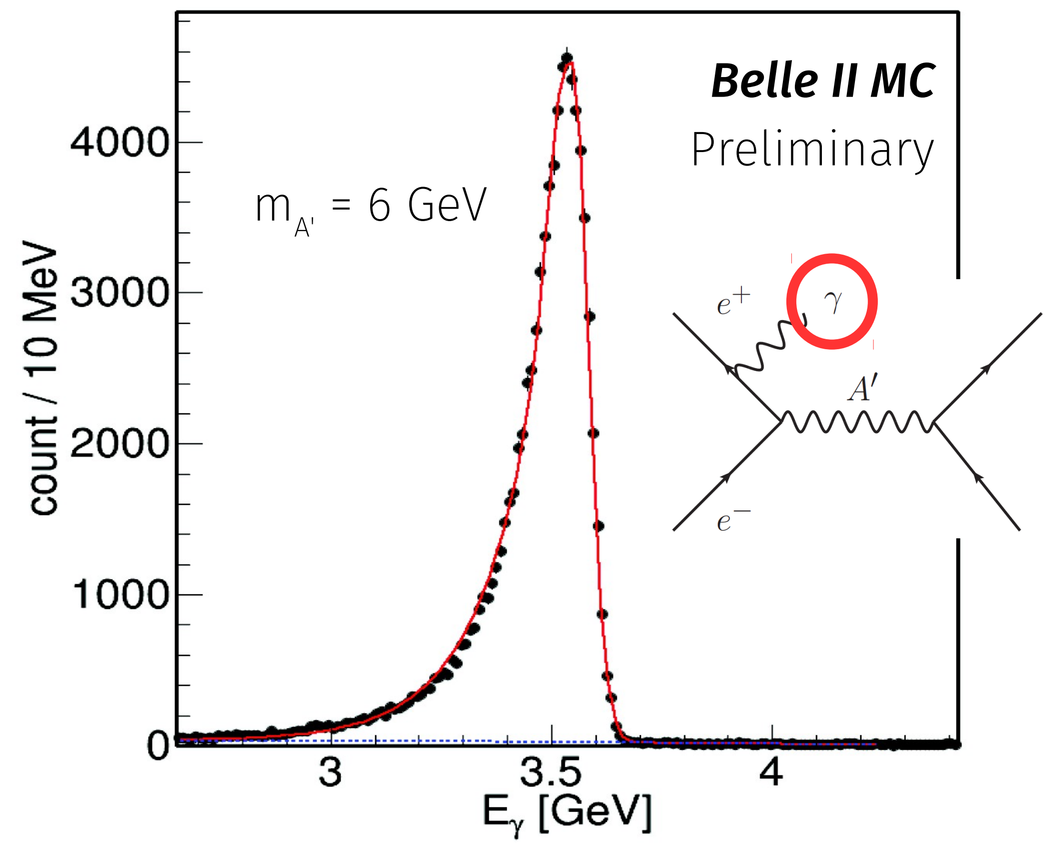



Background from ee→γγ where one γ is undetected.

Background from ee→γγ(γ) and ee→ee(γ) with two undetected particles.

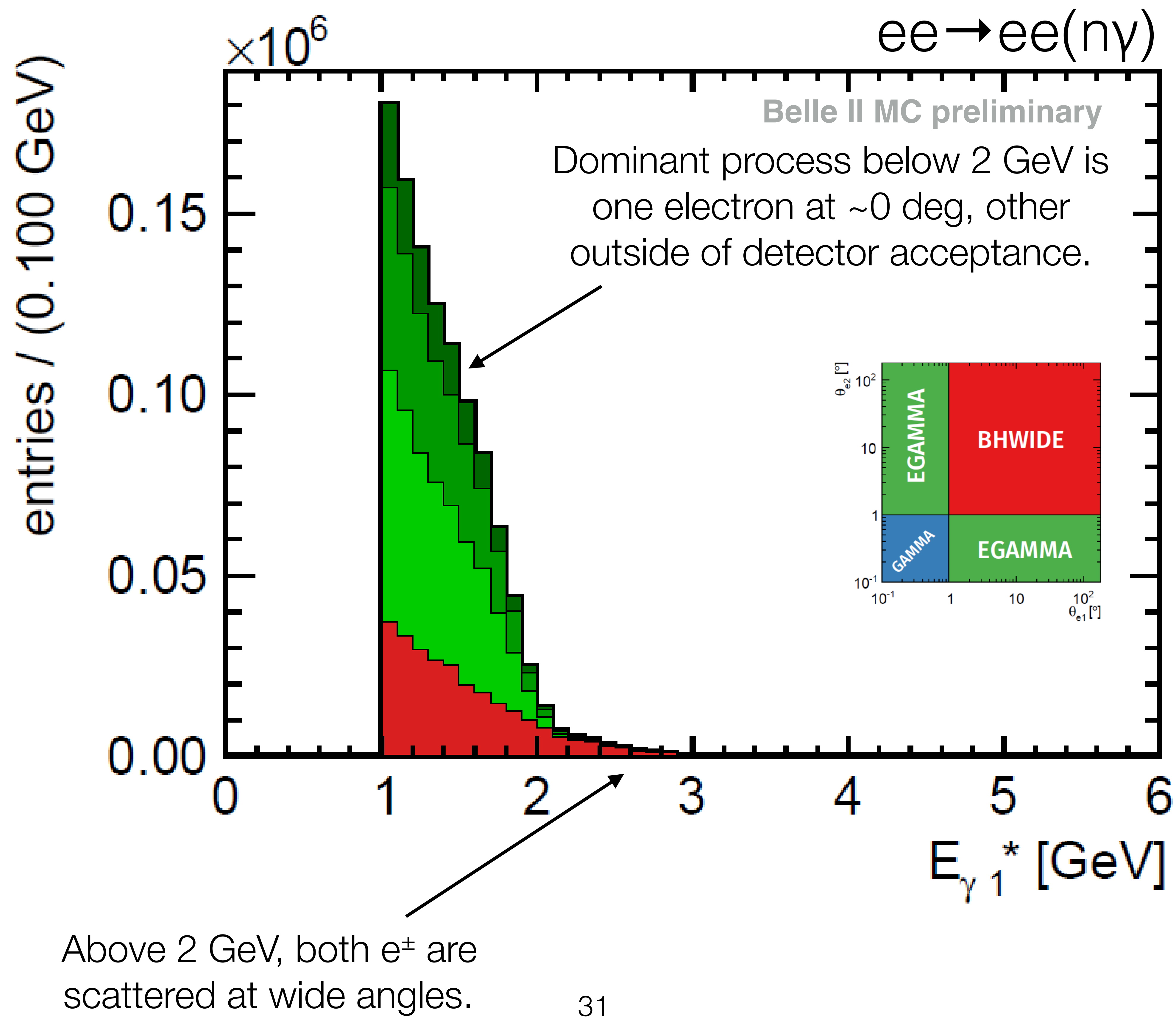
# Dark photon decaying invisibly at Belle II.

- General requirement:
  - Trigger (both to collect signal events and to understand backgrounds).
  - Understanding of peaking background (for on-shell decays).




  - Understanding of (absolute) continuum QED backgrounds (off-shell decays). For on-shell decays this is a smooth exponential.

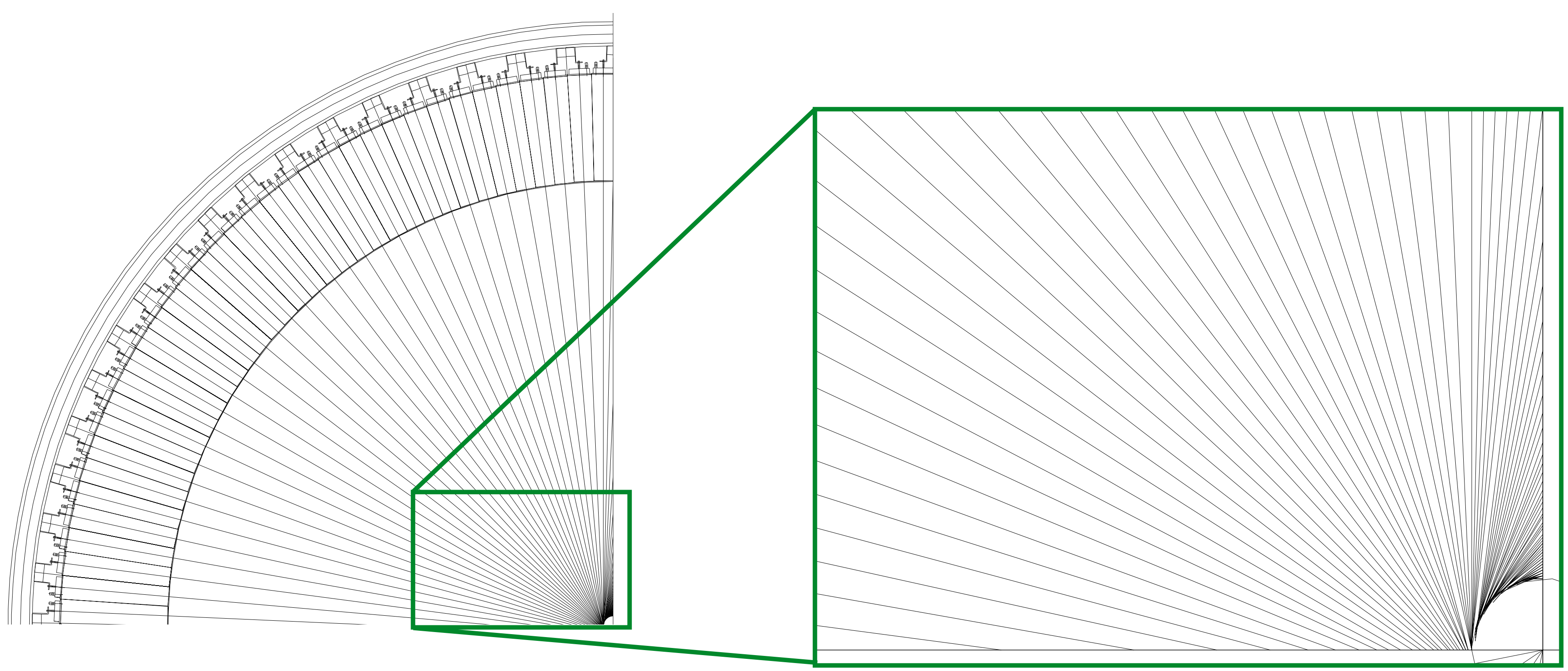
# Dark photon decaying invisibly at Belle II: Background ($E^* > 1$GeV, γ in barrel).



# Dark photon decaying invisibly at Belle II: Peaking backgrounds.

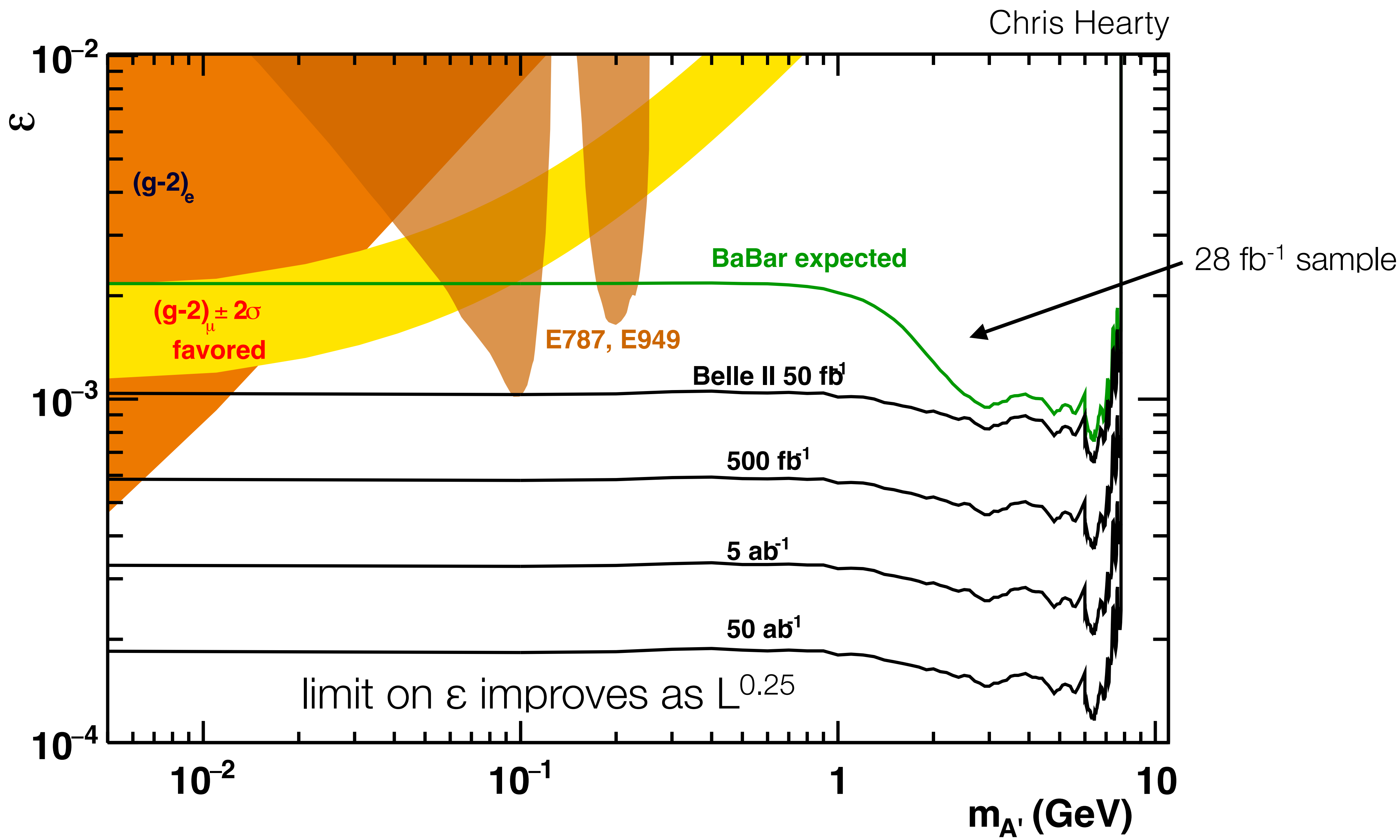
- Unlike BaBar, Belle II Barrel ECL is not projective in $\phi$: No "gaps" between the crystals, only between barrel and endcaps.

- The probability that a photon does not interact in an ECL crystal is about $(e^{(-7/9)})^{L/X0} \approx 3.4\times10^{-6}$ ($L/X_0 \approx 16.2$).



# Dark photon decaying invisibly at Belle II.

- Extrapolating from BaBar preliminary result; correct for different angular distribution of signal; improved systematic error at low mass.

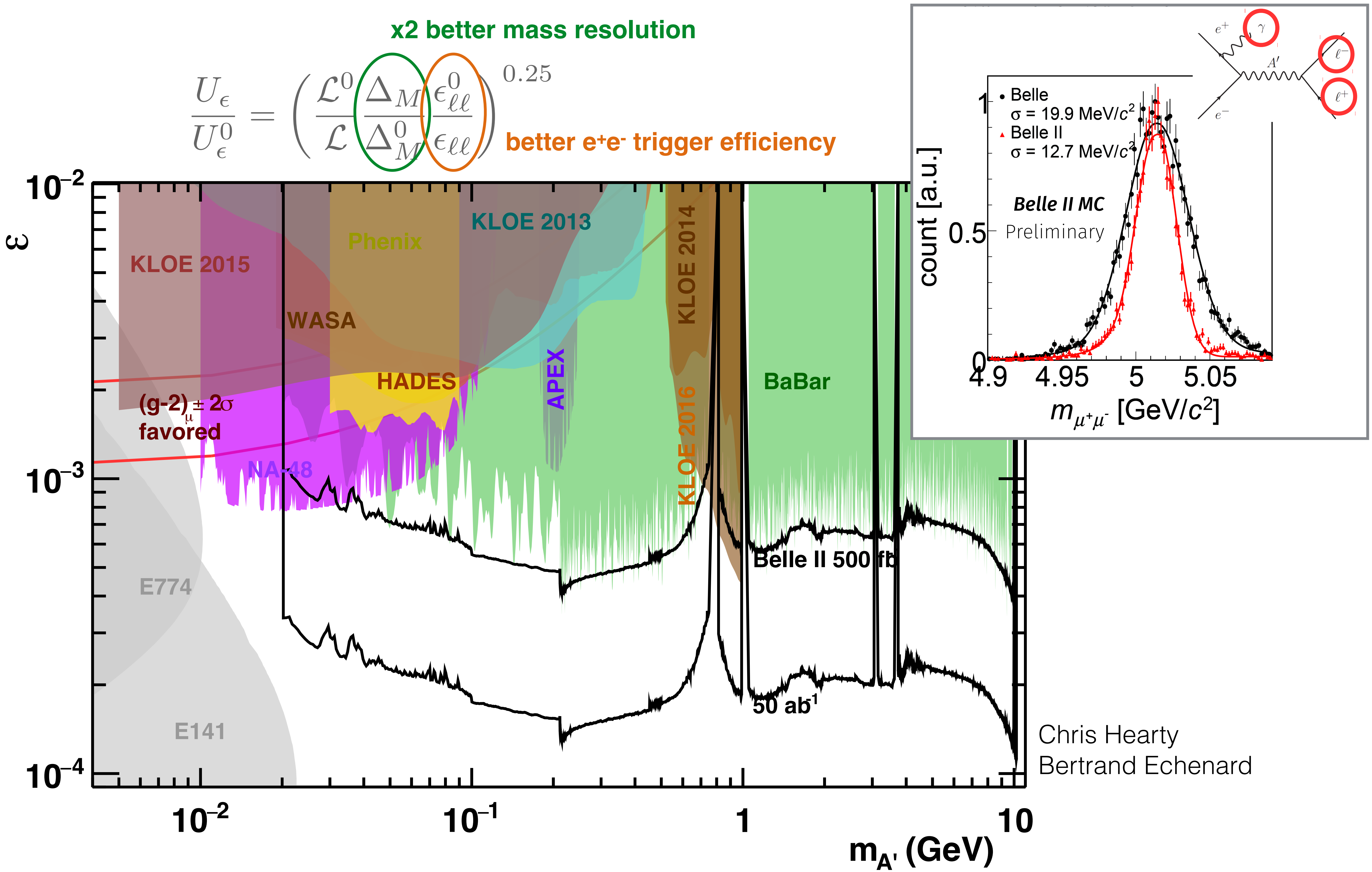


# Dark photon decaying visibly at Belle II.

x2 better mass resolution

$$\frac{U_\epsilon}{U_\epsilon^0} = \left(\frac{\mathcal{L}^0}{\mathcal{L}} \frac{\Delta_M}{\Delta_M^0} \frac{\epsilon_{\ell\ell}^0}{\epsilon_{\ell\ell}}\right)^{0.25}$$

better e⁺e⁻ trigger efficiency



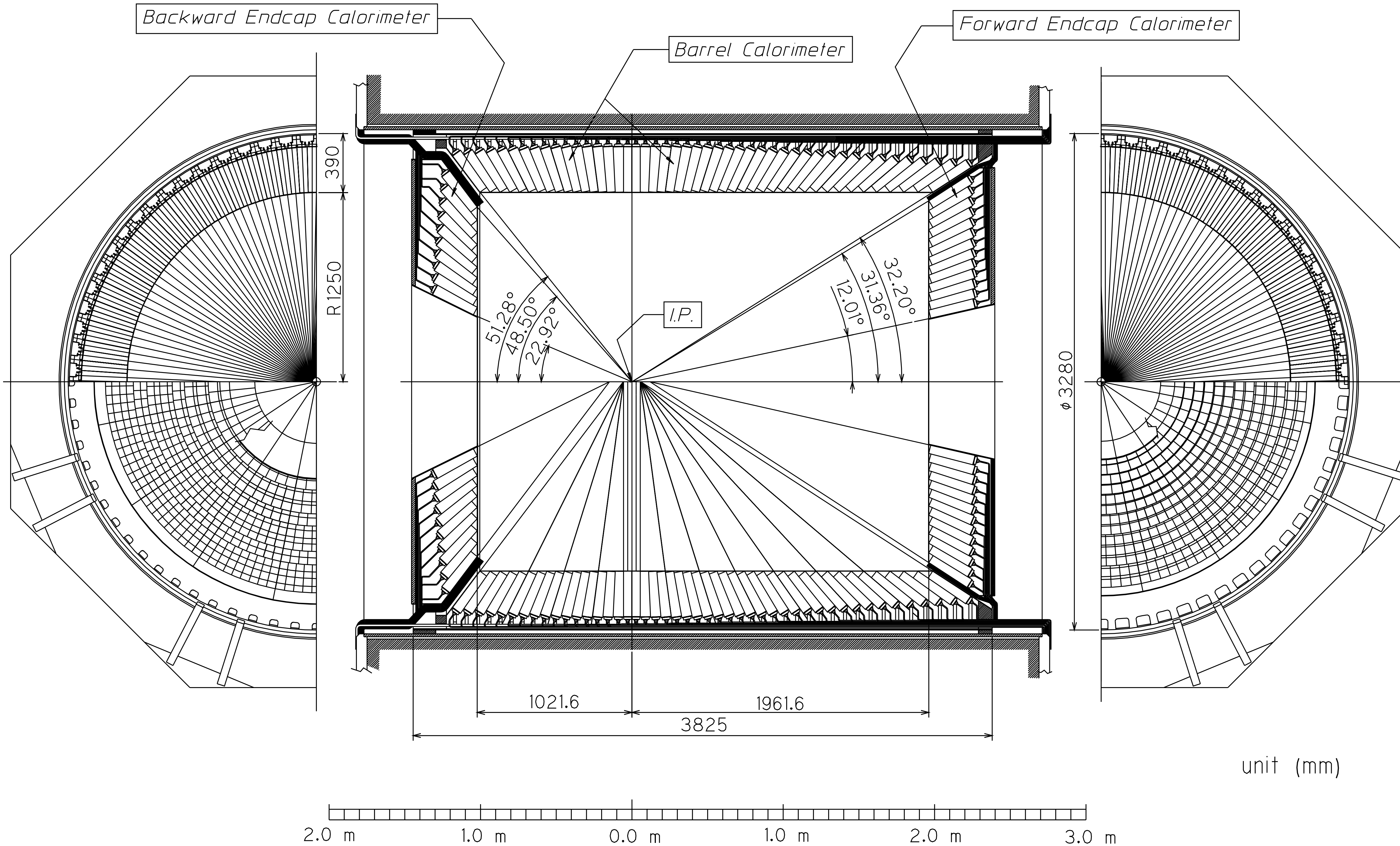

Chris Hearty
Bertrand Echenard

# Summary

- Belle II offers high sensitivity to New Physics at the intensity frontier, largely complementary to LHCb.
- Significantly higher beam background require new reconstruction software. The calorimeter software development and calibration is one main contribution of the Canadian groups.
- Belle II will start detector commissioning end of 2017, significant Canadian contribution in beam background simulations and measurements. The search for a dark photon decaying invisibly may be possible even in that phase.
- Physics data taking starts end of 2018. “50 $\times$ Belle” by 2024.

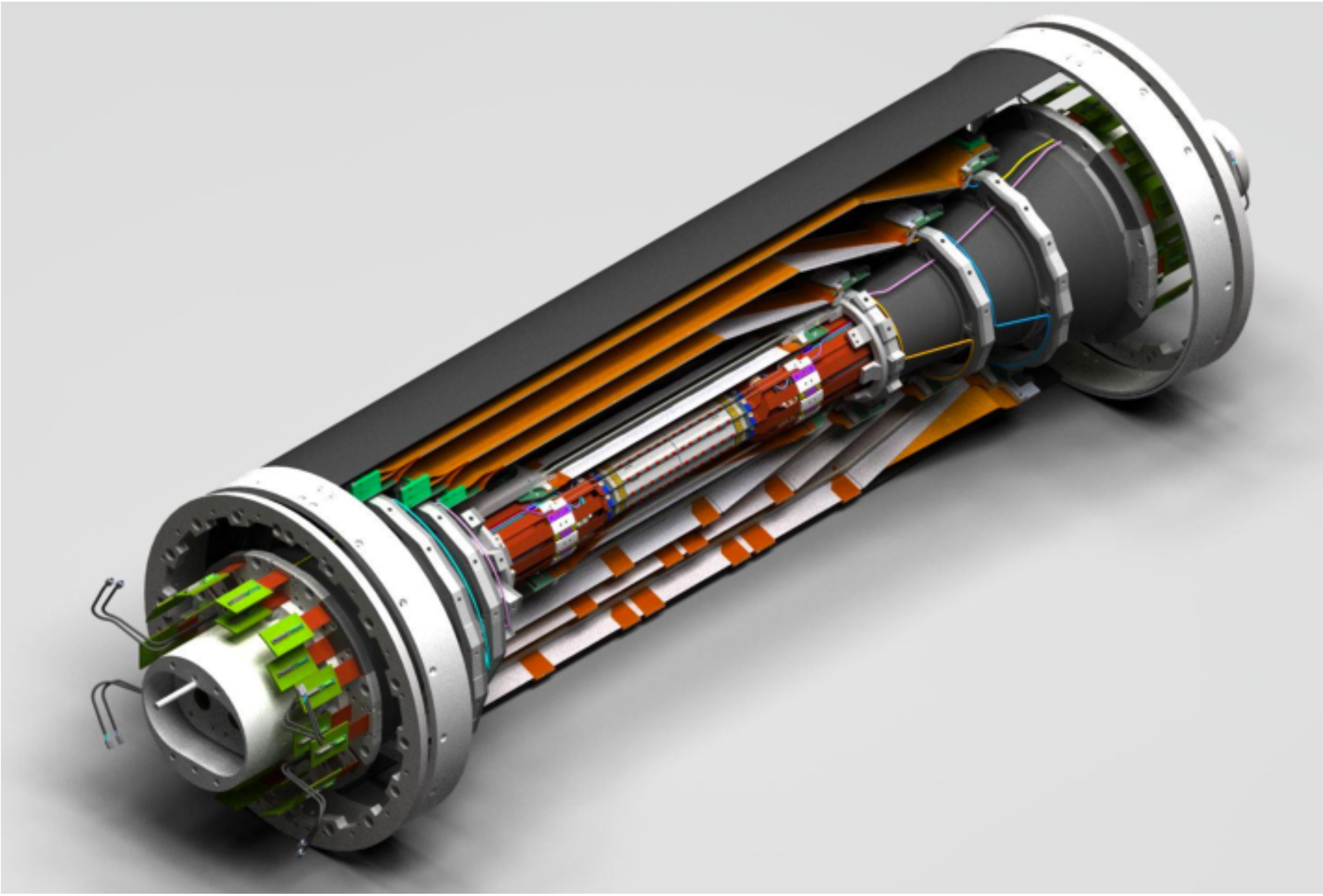
# Backup slides

# ECL.

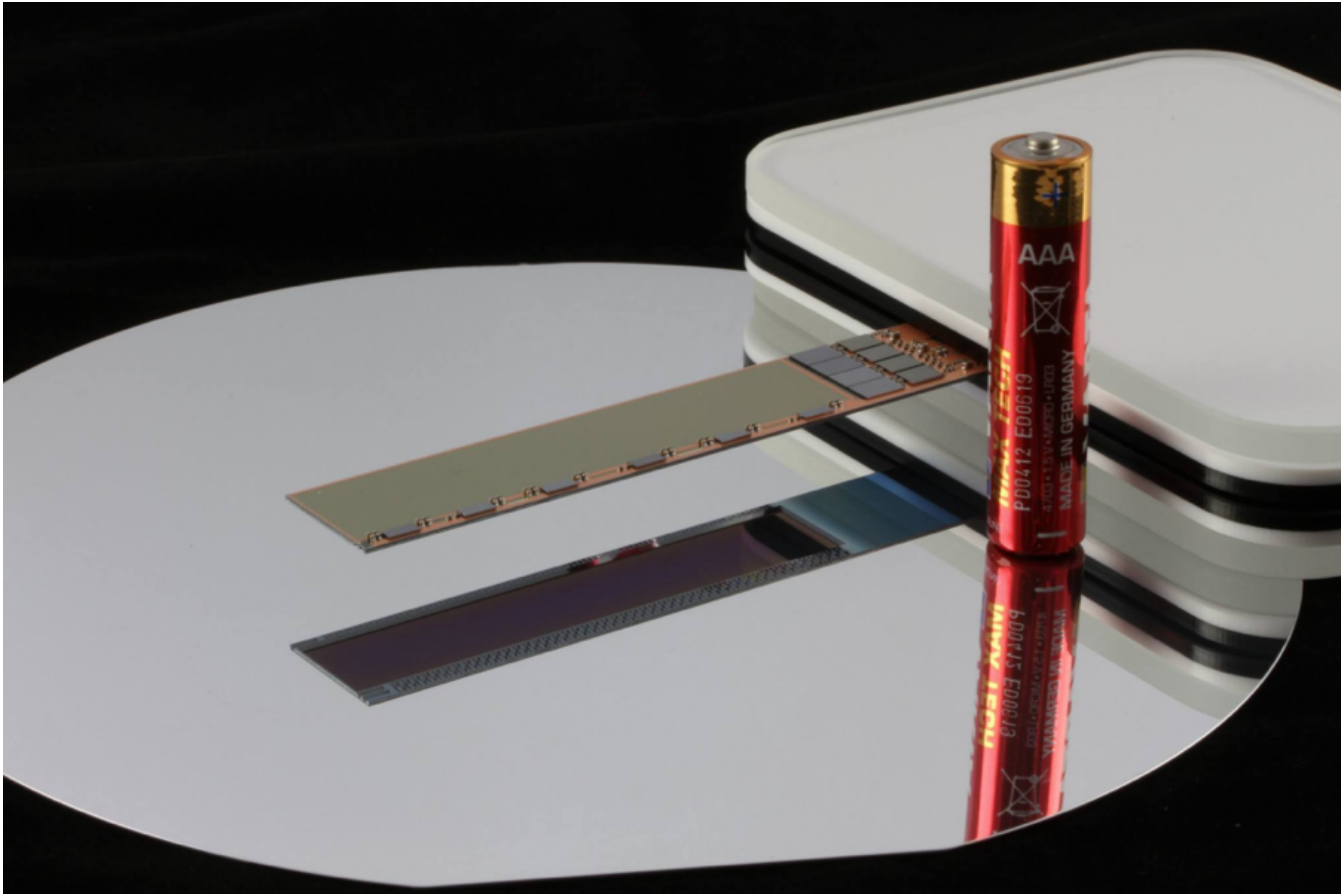


Backward Endcap Calorimeter
Barrel Calorimeter
Forward Endcap Calorimeter
390
R1250
I.P.
51.28°
48.50°
22.92°
32.20°
31.36°
12.01°
ϕ3280
1021.6
1961.6
3825
unit (mm)
2.0 m
1.0 m
0.0 m
1.0 m
2.0 m
3.0 m

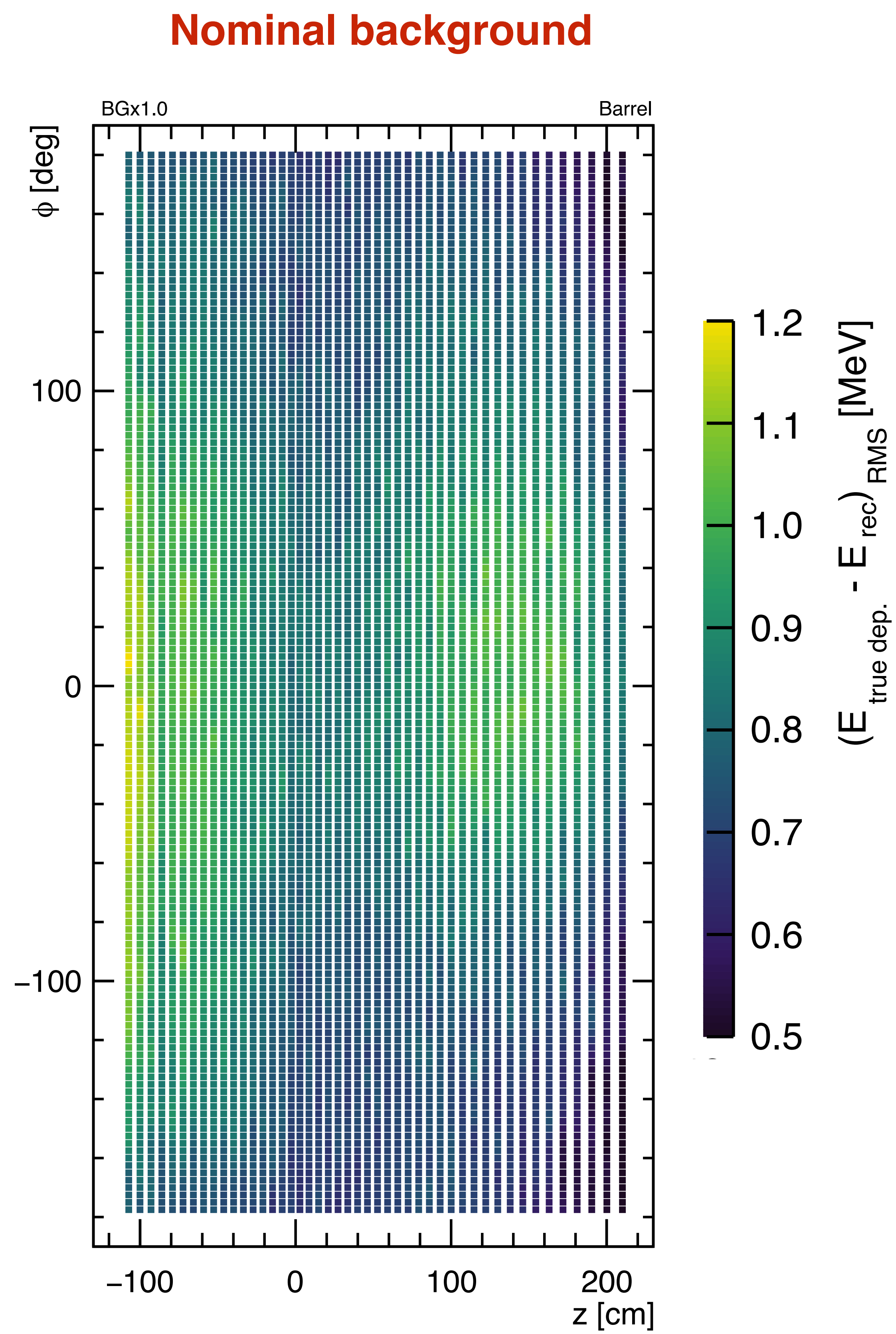
# Vertex detectors.



# PXD module 0.



# Belle II ECL: Background Noise (MC).



# Belle II vs. LHCb.

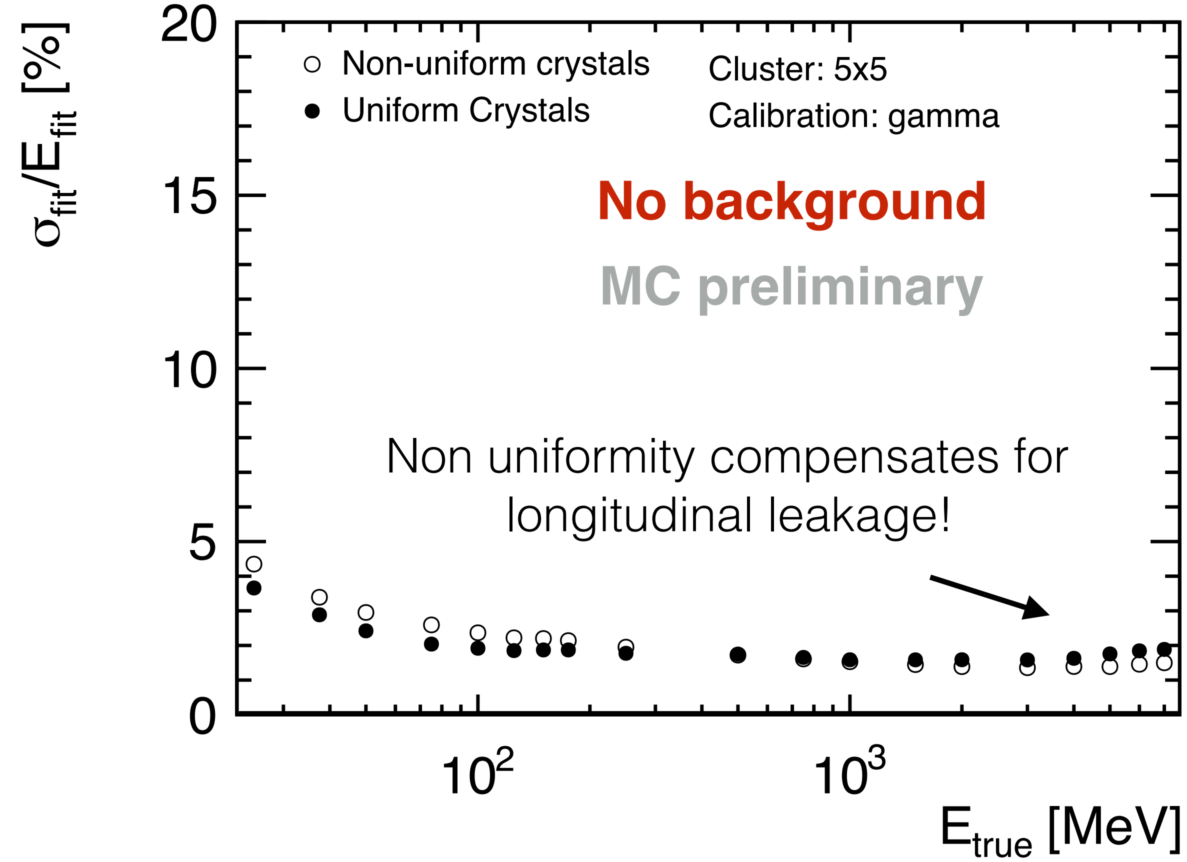
TABLE XLI: Expected errors on several selected flavour observables with an integrated luminosity of 5 $ab^{-1}$ and 50 $ab^{-1}$ of Belle II data. The current results from Belle, or from BaBar where relevant (denoted with a †) are also given. Items marked with a ‡ are estimates based on similar measurements. Errors given in % represent relative errors.

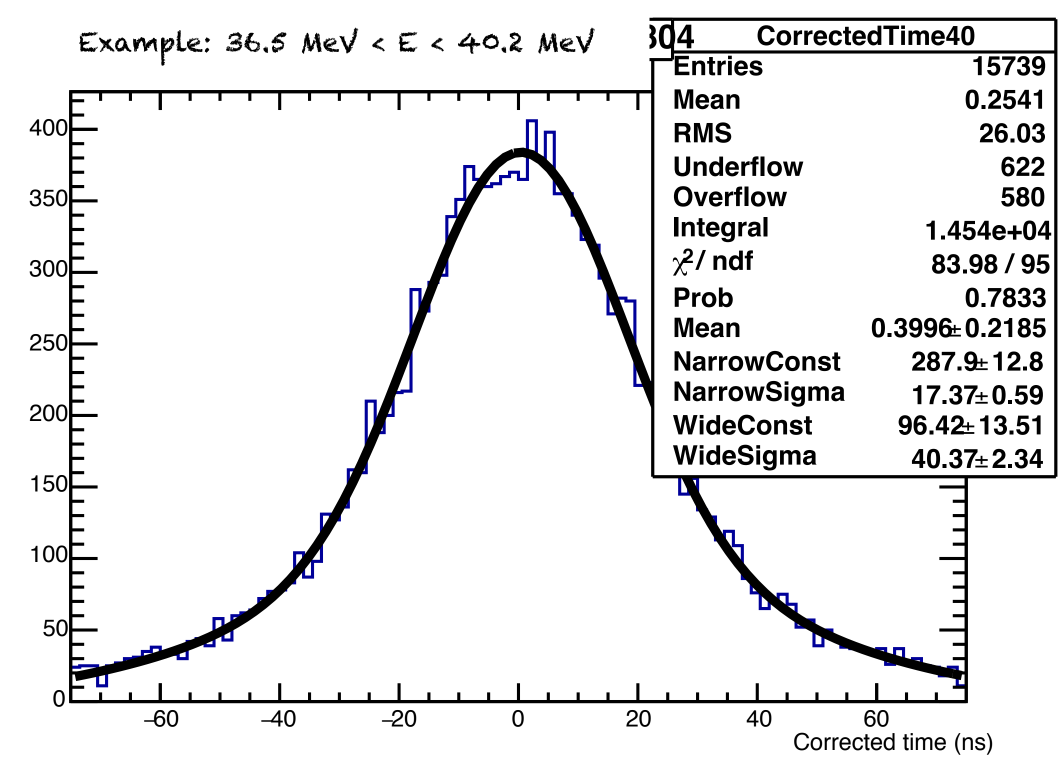
| | Observables | Belle or LHCb* (2014) | Belle II 5 $ab^{-1}$ | Belle II 50 $ab^{-1}$ | LHCb 8 $fb^{-1}$(2018) | LHCb 50 $fb^{-1}$ |
|---|---|---|---|---|---|---|
| UT angles | $\sin 2\beta$ | $0.667 \pm 0.023 \pm 0.012 (0.9^\circ)$ | $0.4^\circ$ | $0.3^\circ$ | $0.6^\circ$ | $0.3^\circ$ |
| | $\alpha$ [°] | $85 \pm 4$ (Belle+BaBar) | 2 | 1 | | |
| | $\gamma$ [°] $(B \to D^{(*)} K^{(*)})$ | $68 \pm 14$ | 6 | 1.5 | 4 | 1 |
| | $2\beta_s (B_s \to J/\psi \phi)$ [rad] | $0.07 \pm 0.09 \pm 0.01^*$ | | | 0.025 | 0.009 |
| Gluonic penguins | $S(B \to \phi K^0)$ | $0.90^{+0.09}_{-0.19}$ | 0.053 | 0.018 | 0.2 | 0.04 |
| | $S(B \to \eta' K^0)$ | $0.68 \pm 0.07 \pm 0.03$ | 0.028 | 0.011 | | |
| | $S(B \to K^0_S K^0_S K^0_S)$ | $0.30 \pm 0.32 \pm 0.08$ | 0.100 | 0.033 | | |
| | $\beta_s^{\text{eff}}(B_s \to \phi\phi)$ [rad] | $-0.17 \pm 0.15 \pm 0.03^*$ | | | 0.12 | 0.03 |
| | $\beta_s^{\text{eff}}(B_s \to K^{*0} \bar{K}^{*0})$ [rad] | – | | | 0.13 | 0.03 |
| Direct CP in hadronic Decays | $\mathcal{A}(B \to K^0 \pi^0)$ | $-0.05 \pm 0.14 \pm 0.05$ | 0.07 | 0.04 | | |
| UT sides | $\lvert V_{cb} \rvert$ incl. | $41.6 \cdot 10^{-3} (1 \pm 2.4\%)$ | 1.2% | | | |
| | $\lvert V_{cb} \rvert$ excl. | $37.5 \cdot 10^{-3} (1 \pm 3.0\%_{\text{ex.}} \pm 2.7\%_{\text{th.}})$ | 1.8% | 1.4% | | |
| | $\lvert V_{ub} \rvert$ incl. | $4.47 \cdot 10^{-3} (1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$ | 3.4% | 3.0% | | |
| | $\lvert V_{ub} \rvert$ excl. (had. tag.) | $3.52 \cdot 10^{-3} (1 \pm 10.8\%)$ | 4.7% | 2.4% | | |
| Leptonic and Semi-tauonic | $\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$ | $96 (1 \pm 26\%)$ | 10% | 5% | | |
| | $\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$ | $< 1.7$ | 20% | 7% | | |
| | $R(B \to D\tau\nu)$ [Had. tag] | $0.440 (1 \pm 16.5\%)^\dagger$ | 5.6% | 3.4% | | |
| | $R(B \to D^*\tau\nu)^\dagger$ [Had. tag] | $0.332 (1 \pm 9.0\%)^\dagger$ | 3.2% | 2.1% | ... | |
| Radiative | $\mathcal{B}(B \to X_s \gamma)$ | $3.45 \cdot 10^{-4} (1 \pm 4.3\% \pm 11.6\%)$ | 7% | 6% | | |
| | $A_{CP}(B \to X_{s,d} \gamma)$ $[10^{-2}]$ | $2.2 \pm 4.0 \pm 0.8$ | 1 | 0.5 | | |
| | $S(B \to K^0_S \pi^0 \gamma)$ | $-0.10 \pm 0.31 \pm 0.07$ | 0.11 | 0.035 | | |
| | $2\beta_s^{\text{eff}}(B_s \to \phi\gamma)$ | – | | | 0.13 | 0.03 |
| | $S(B \to \rho\gamma)$ | $-0.83 \pm 0.65 \pm 0.18$ | 0.23 | 0.07 | | |
| | $\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$ | $< 8.7$ | 0.3 | – | | |
| Electroweak penguins | $\mathcal{B}(B \to K^{*+} \nu\bar{\nu})$ $[10^{-6}]$ | $< 40$ | $< 15$ | 30% | | |
| | $\mathcal{B}(B \to K^+ \nu\bar{\nu})$ $[10^{-6}]$ | $< 55$ | $< 21$ | 30% | | |
| | $C_7/C_9$ $(B \to X_s \ell\ell)$ | ~20% | 10% | 5% | | |
| | $\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$ | – | $< 2$ | – | | |
| | $\mathcal{B}(B_s \to \mu\mu)$ $[10^{-9}]$ | $2.9^{+1.1*}_{-1.0}$ | | | 0.5 | 0.2 |

*B. Golob et al., BELLE2-NOTE-PH-2015-002*

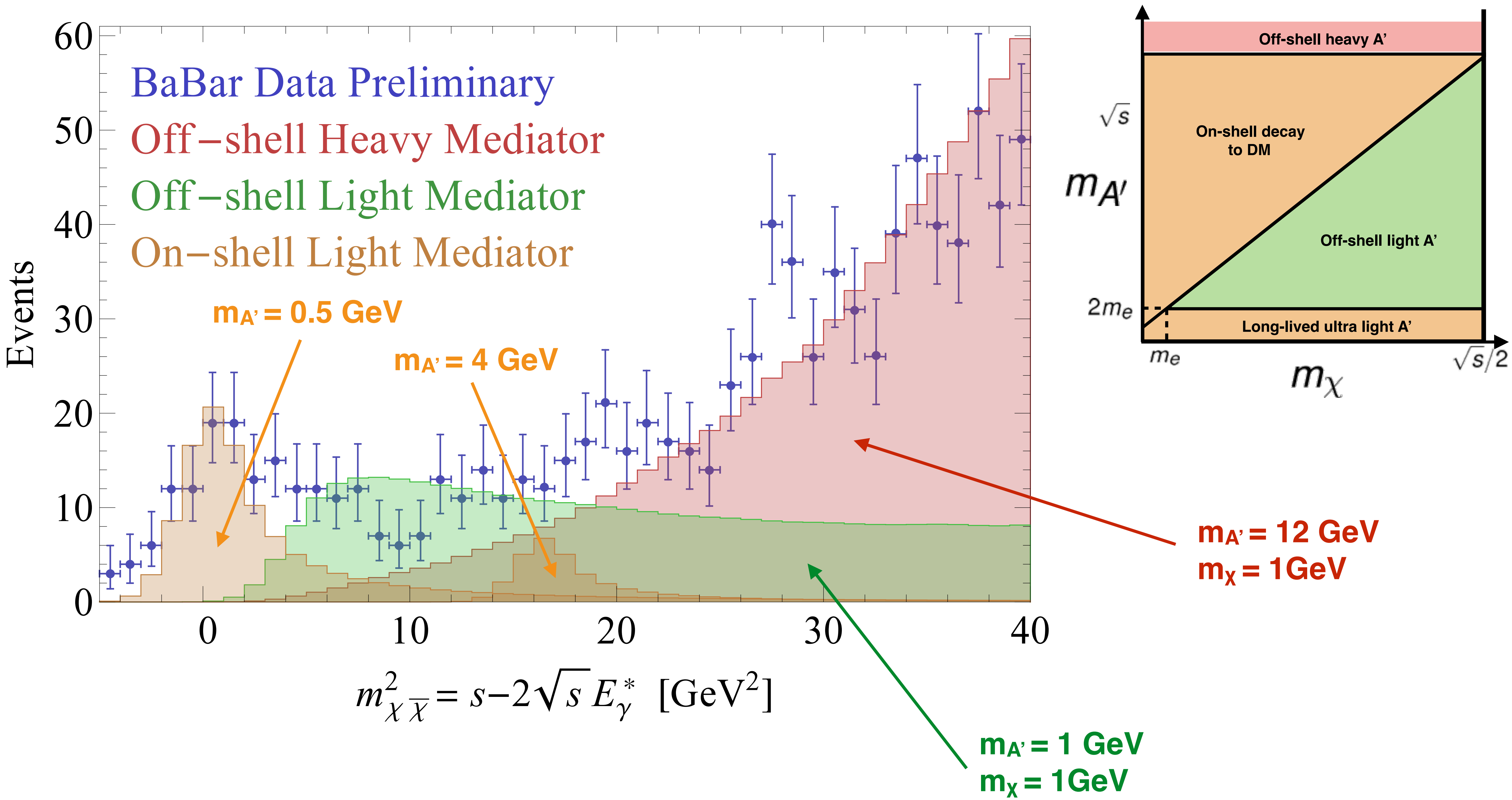
# Belle II ECL: Crystal Calibration.

- Energy calibration: Convert fitted amplitude to deposited energy. Possible non-uniform effects due to radiation damage.
- Time calibration: Convert fitted ADC clock ticks to time relative to zero (trigger). Depends on amplitude and background level.



# Dark photon decaying invisibly at BaBar.




R. Essig et al., JHEP 1311 (2013) 167
Y.M. Zhong, B2TIP Pittsburg 2016