# Belle II Prospects for HVP Measurements


Toru Iijima

*Kobayashi-Maskawa Institute*

*Nagoya University*


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- HVP measurements at Belle II
- Status of SuperKEKB/Belle II
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References:

- "The Belle II Physics Book", arXiv:1808.10567
- Talks by Yosuke Maeda at
  - Workshop on HVP contributions to muon g-2, KEK, Feb. 12-14, 2018
  - Mini-workshop "Hints for New Physics in Heavy Flavors", Nagoya, Nov.15-17, 2019

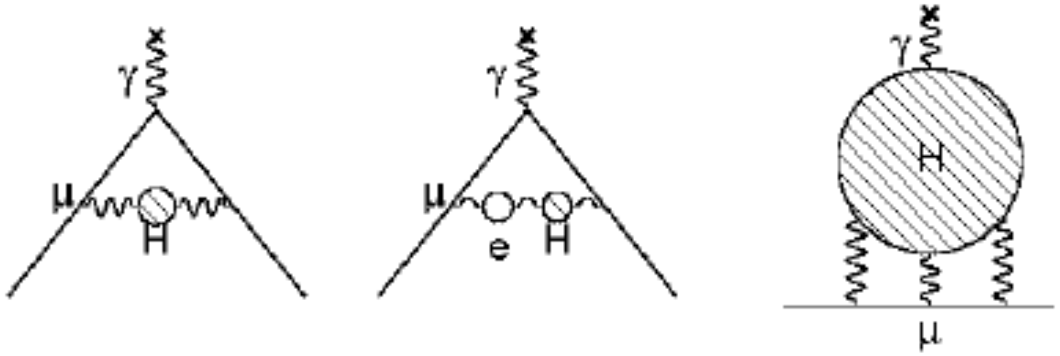
# $(g\text{-}2)_\mu$ status and SM prediction

- The world average (dominated by the BNL-E821 measurements):

$$a_\mu^{\mathrm{exp}} = 11659209.1(5.4)(3.3) \times 10^{-10}$$

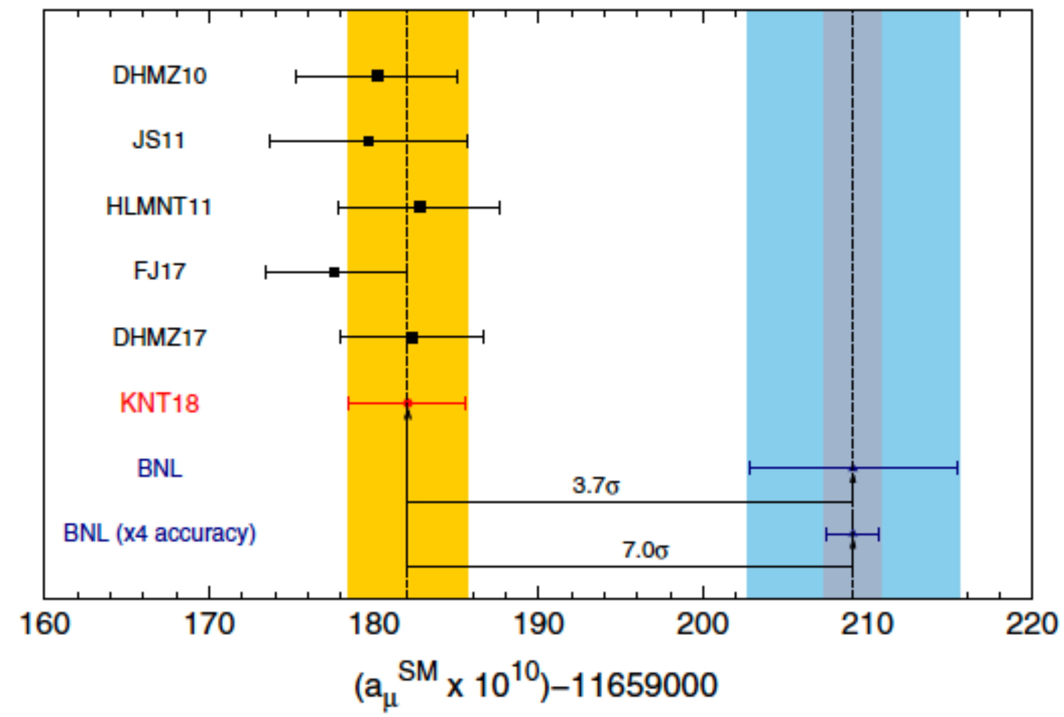
- The SM prediction:

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had,LO}} + a_\mu^{\mathrm{Had,HO}} + a_\mu^{\mathrm{Had,LbL}}$$



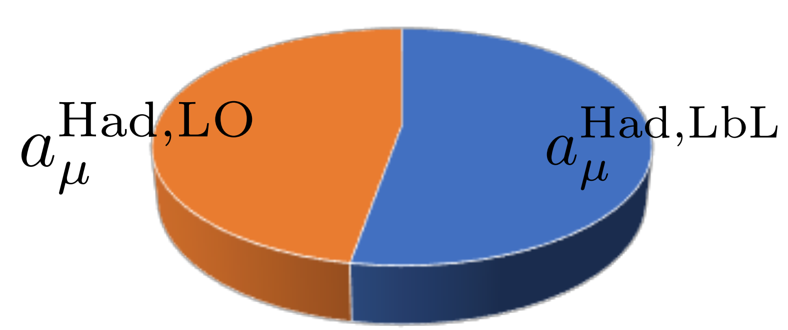

arXiv:1311.2198

PRD97, 114025 (2018)




- >3σ deviation from experiments
- SM uncertainty is dominated by hadronic contributions

Error² budget (e.g. in KNT18)



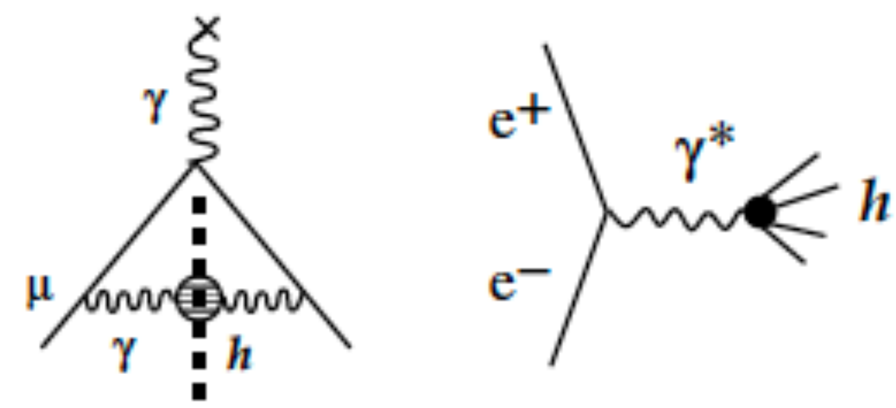
# $(g-2)_\mu$ and $\sigma(e^+e^- \to \text{hadrons})$

- The leading order hadronic effect ($a_\mu^{\text{Had, LO}}$) involves low-energy QCD, and calculation is difficult.

- Dispersion relation and optical theorem relate $a_\mu^{\text{Had, LO}}$ to the cross section $\sigma$ ($e^+e^- \to$ hadrons), which can be experimentally measured.

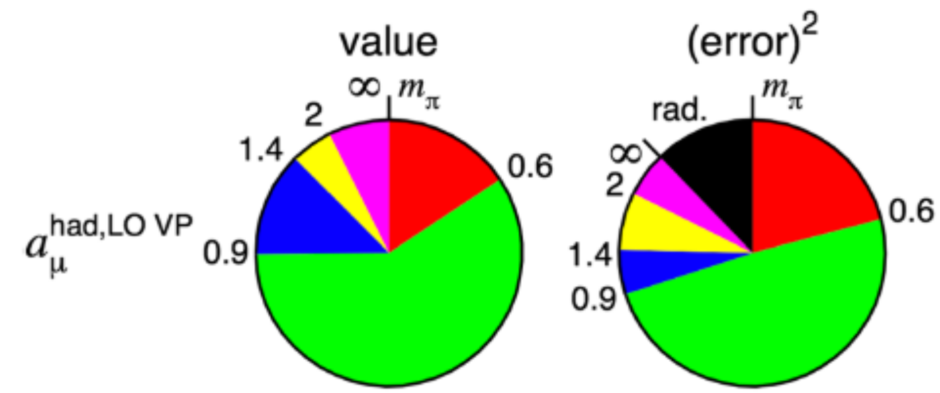
$$a_\mu^{\text{had;LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s),$$

$$\text{where} \quad R \equiv \frac{\sigma_{\text{tot}}(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$




arXiv:1311.2198

- The energy region below 0.9 GeV dominates, predominantly due to the $\pi^+\pi^-$ channel.




Fractional contribution to $a_\mu^{\text{Had, LO}}$

- These data are important also for determination of $\alpha_{\text{QED}}(M_Z)$.

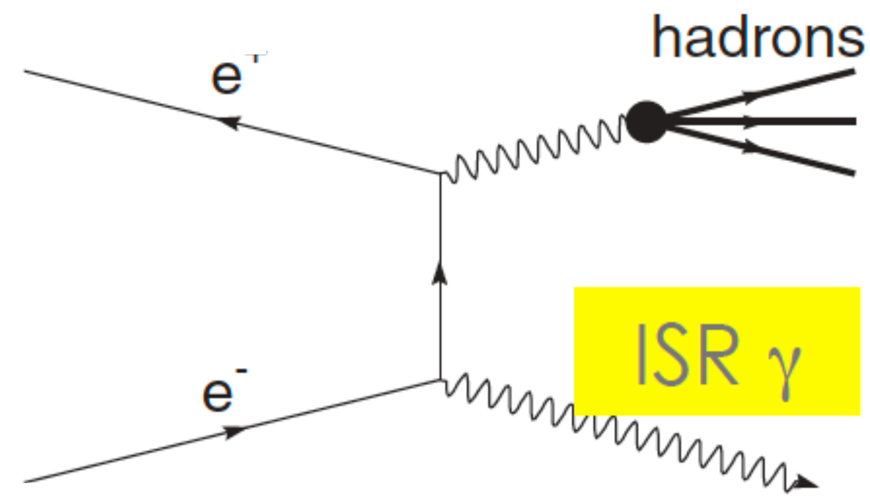
# Measurement Methods

Belle II strategy is to use the Initial State Radiation (ISR) method.

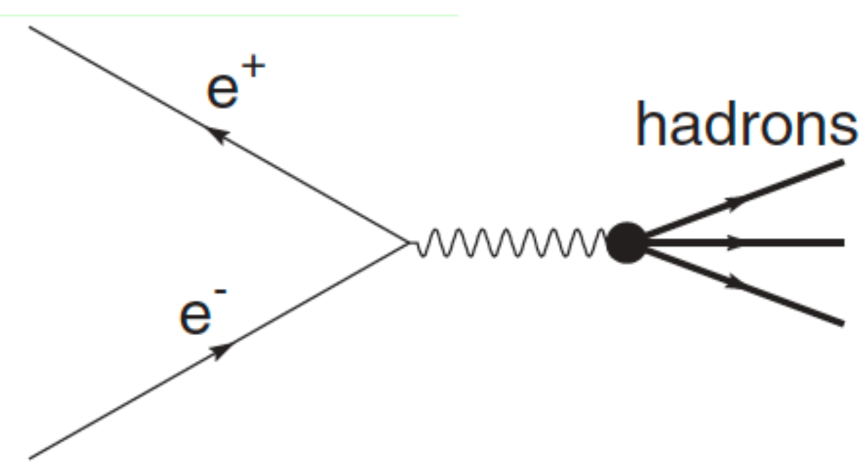
- Tag ISR photon
- Can scan wide energy range
- With the same experimental condition
- Lower statistics due to O(α) suppression
    - Can be compensated by high luminosity
- The method has been demonstrated by BaBar, BES, KLOE.

Direct scan method
e.g. : Novosibirsk

ISR method



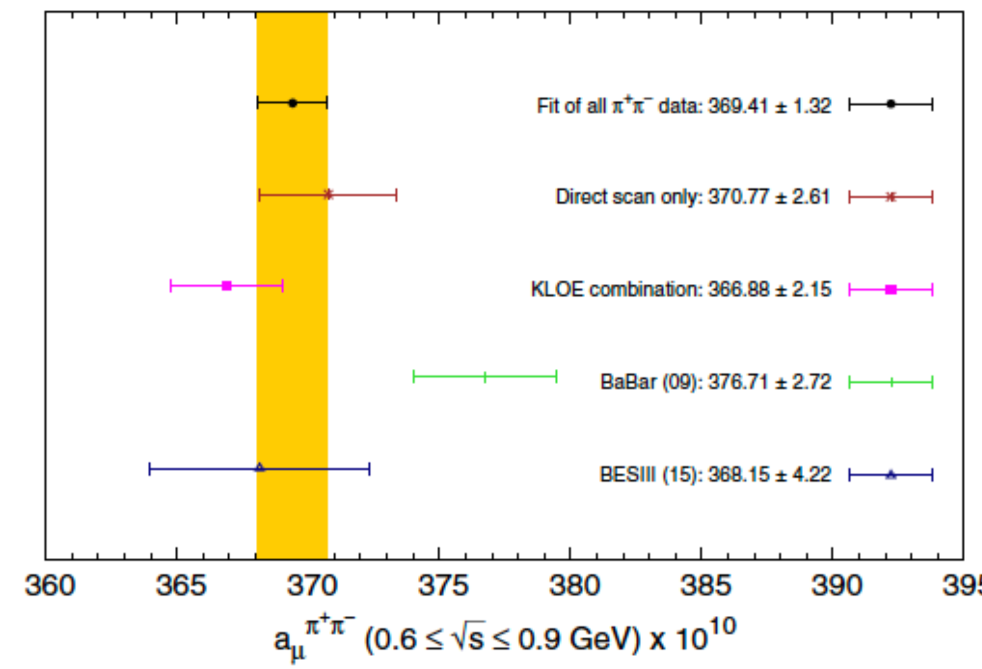

Direct scan method

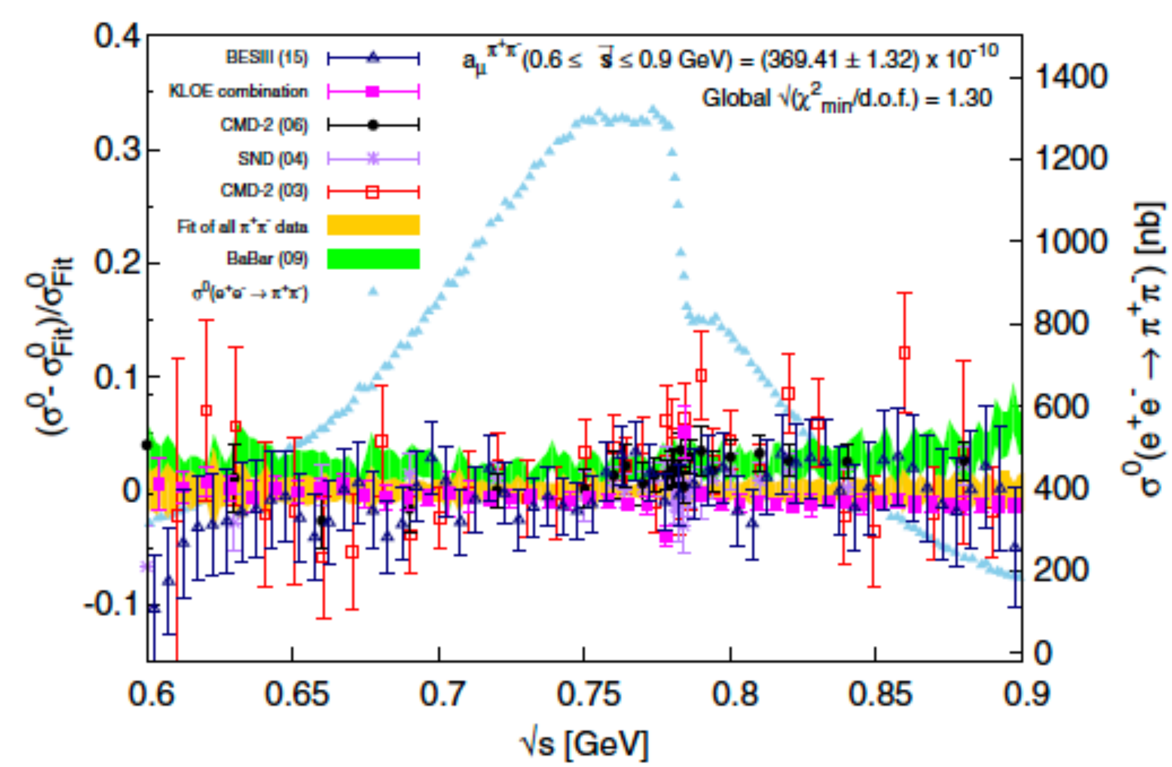


# Present Experimental Status ($\pi^+\pi^-$)

- The $\pi^+\pi^-$ channel has the most significant contribution to $a_\mu^{Had, LO}$, dominating both its mean value and uncertainty.
- Already measured precisely (≲1%), by several experiments.
- Small discrepancy (a few %) among measurements.
  - New ISR data from KLOE and BES III have improved the estimate in the ρ region.
  - Tension exists between BaBar and others
- Must be confirmed by Belle II
  - w/ target precision of → 0.5%

Comparison of each experimental data and the fit in the ρ region




PRD97, 114025 (2018)

# Advantages in Belle II

- High luminosity provides large statistics not only for signals themselves, but also for control samples need to estimate systematic uncertainties.
- The measurement is programed from the beginning of the experiment, therefore, well-designed & optimized triggers can be used.
  - Belle suffered from large efficiency loss because the measurement was not considered for the trigger design.
- Larger detector coverage (less asymmetry w.r.t BaBar)
- Lessons from previous experiments, as well as improved generators, can be utilized.

PHOKHARA ↔ AfkQED

e.g. systematic errors in the BaBar measurements.

- Relatively large error in PID.

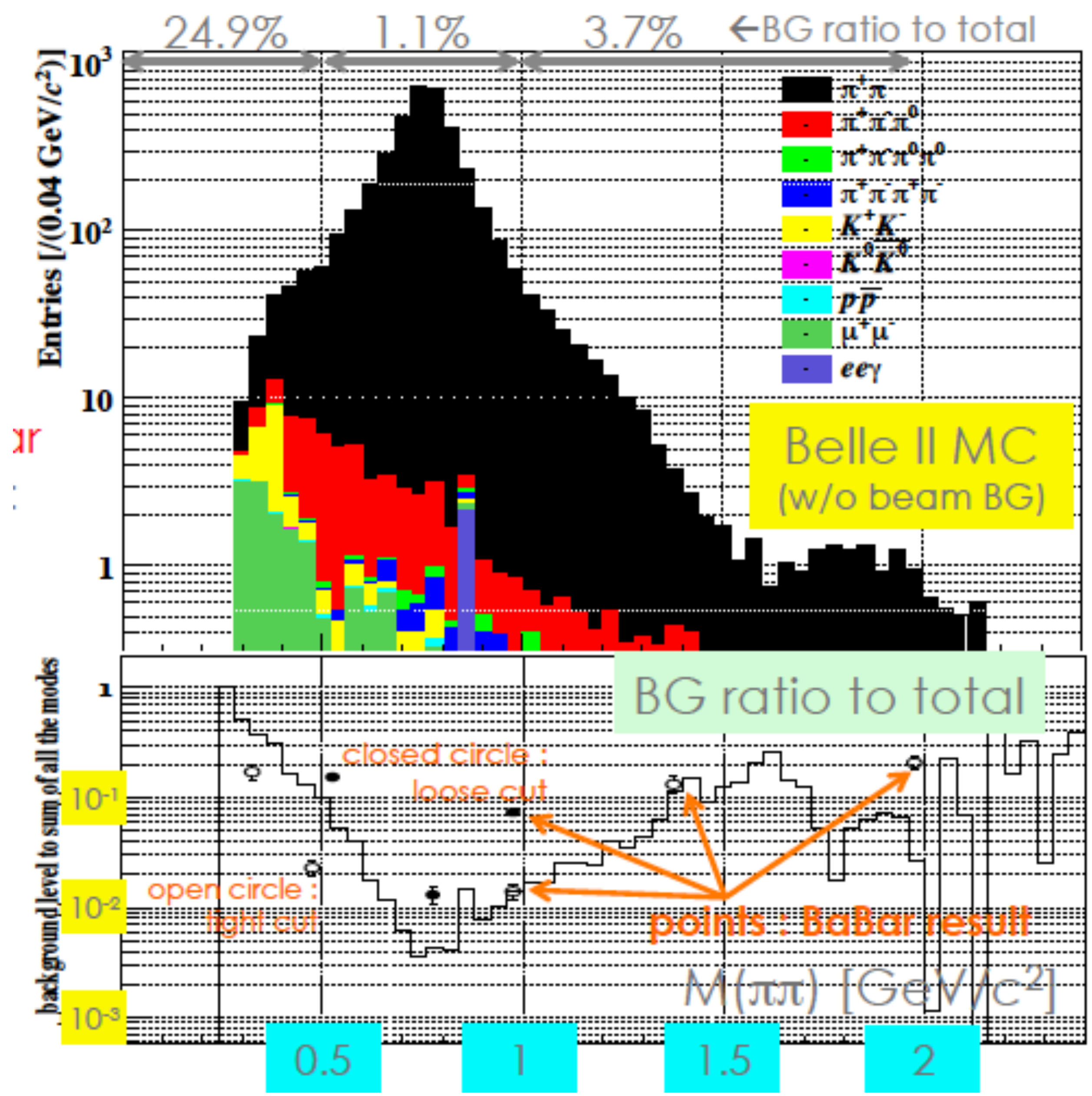
With large data sample, PID error may be removed if ππγ and μμγ can be separated using angular distribution difference.
arXiv:1808.10567

| Sources | 0.3-0.4 | 0.4-0.5 | 0.5-0.6 | 0.6-0.9 | 0.9-1.2 | 1.2-1.4 | 1.4-2.0 | 2.0-3.0 |
|---|---|---|---|---|---|---|---|---|
| trigger/ filter | 5.3 | 2.7 | 1.9 | 1.0 | 0.7 | 0.6 | 0.4 | 0.4 |
| tracking | 3.8 | 2.1 | 2.1 | 1.1 | 1.7 | 3.1 | 3.1 | 3.1 |
| $\pi$-ID | 10.1 | 2.5 | 6.2 | 2.4 | 4.2 | 10.1 | 10.1 | 10.1 |
| background | 3.5 | 4.3 | 5.2 | 1.0 | 3.0 | 7.0 | 12.0 | 50.0 |
| acceptance | 1.6 | 1.6 | 1.0 | 1.0 | 1.6 | 1.6 | 1.6 | 1.6 |
| kinematic fit ($\chi^2$) | 0.9 | 0.9 | 0.3 | 0.3 | 0.9 | 0.9 | 0.9 | 0.9 |
| correl $\mu\mu$ ID loss | 3.0 | 2.0 | 3.0 | 1.3 | 2.0 | 3.0 | 10.0 | 10.0 |
| $\pi\pi/\mu\mu$ non-cancel. | 2.7 | 1.4 | 1.6 | 1.1 | 1.3 | 2.7 | 5.1 | 5.1 |
| unfolding | 1.0 | 2.7 | 2.7 | 1.0 | 1.3 | 1.0 | 1.0 | 1.0 |
| ISR luminosity | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 |
| sum (cross section) | 13.8 | 8.1 | 10.2 | 5.0 | 6.5 | 13.9 | 19.8 | 52.4 |

PRD 86, 032013 (2012)

# Expected Background and Efficiency

- With particle ID cuts applied, the background is dominated by other ISR modes ($\pi^+\pi^-\pi^0$, $K^+K^-$, …),
  - O(%) level, similarly to BaBar
  - High background at low mass; $\pi^+\pi^-\pi^0$ with low energy $\pi^0$ (can be reduced by e.g. kinematical fit, …)
- Efficiency = 49% for $50° < \theta_{ISR} < 110°$
  - Expect > 1M events with $500 fb^{-1}$
- Early Belle II run will provide results with competitive errors to previous experiments




Y. Maeda, workshop on HVP contributions to muon g-2, KEK, Feb. 12-14, 2018

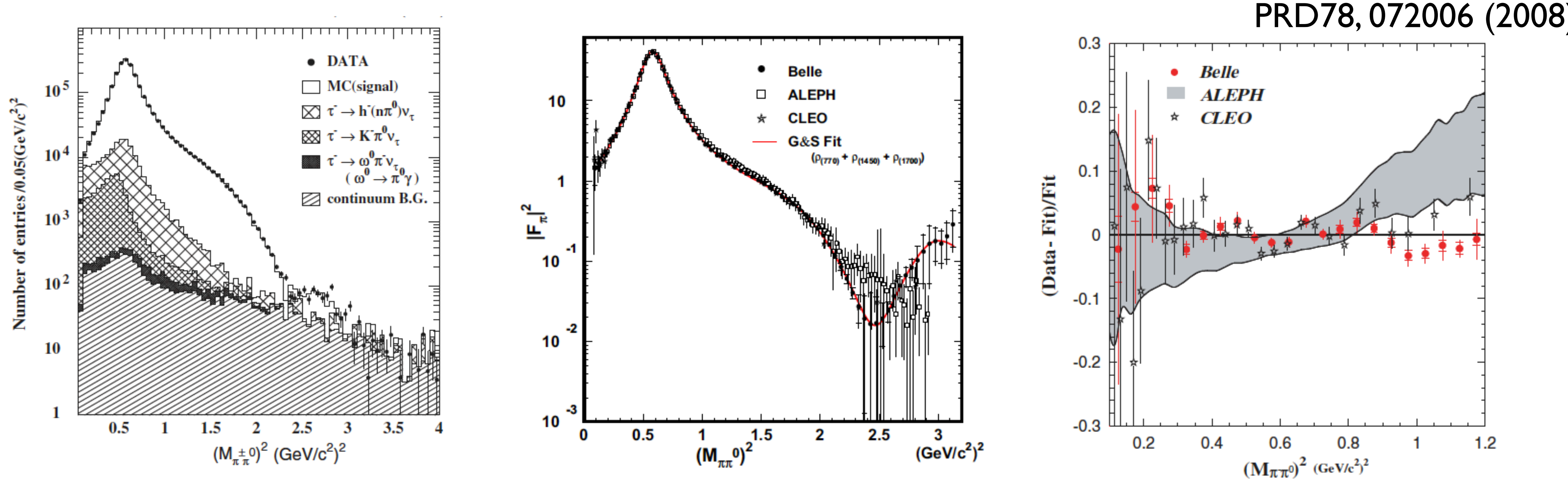
With larger data sample, errors can shrink to ~1% → ~0.5%

# τ Spectral Functions

- HVP can be estimated also by τ hadronic spectral functions and CVC, together with isospin breaking corrections.
- Earlier results showed discrepancy between e+e- and τ based evaluations, but more recent studies with γ-ρ mixing and Hidden Local Symmetry (HLS) show that two are rather compatible.

e.g. : $\tau \to \pi\pi^0$ form factor by Belle, compared to CLEO and ALEPH

PRD78, 072006 (2008)




$$\mathcal{B}(\tau^- \to \pi^-\pi^0\nu_\tau) = (25.24 \pm 0.01 \pm 0.39)\%$$

$$a_\mu^{\pi\pi} = (523.5 \pm 1.5(\text{exp}) \pm 2.6(\text{Br}) \pm 2.5(\text{isospin})) \times 10^{-10} \quad \sqrt{s} = 2m_\pi - 1.8\,\text{GeV}/c^2$$

# SuperKEKB Accelerator

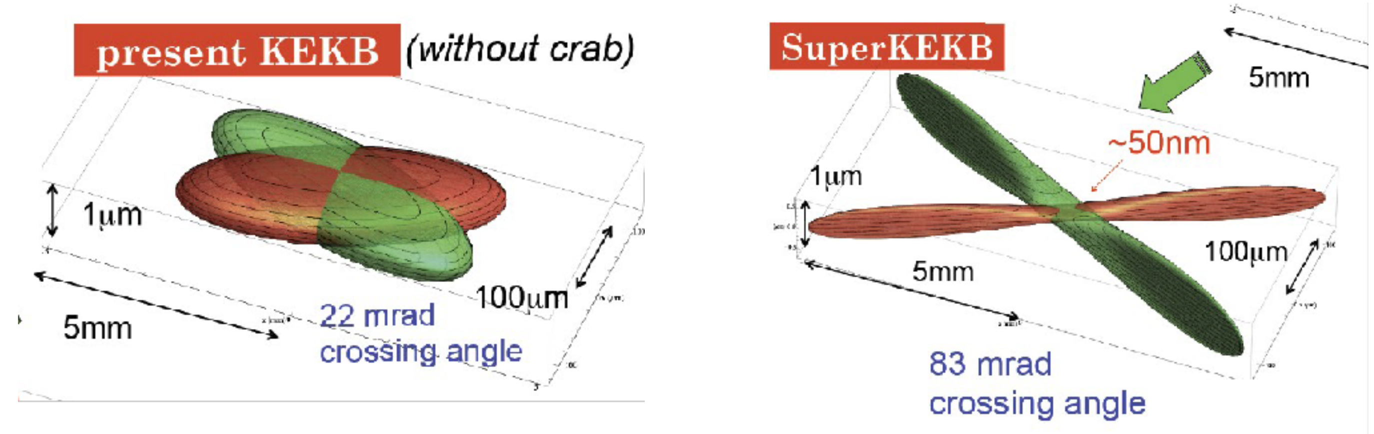
- Low emittance ("nano-beam") scheme employed (originally proposed by P. Raimondi)

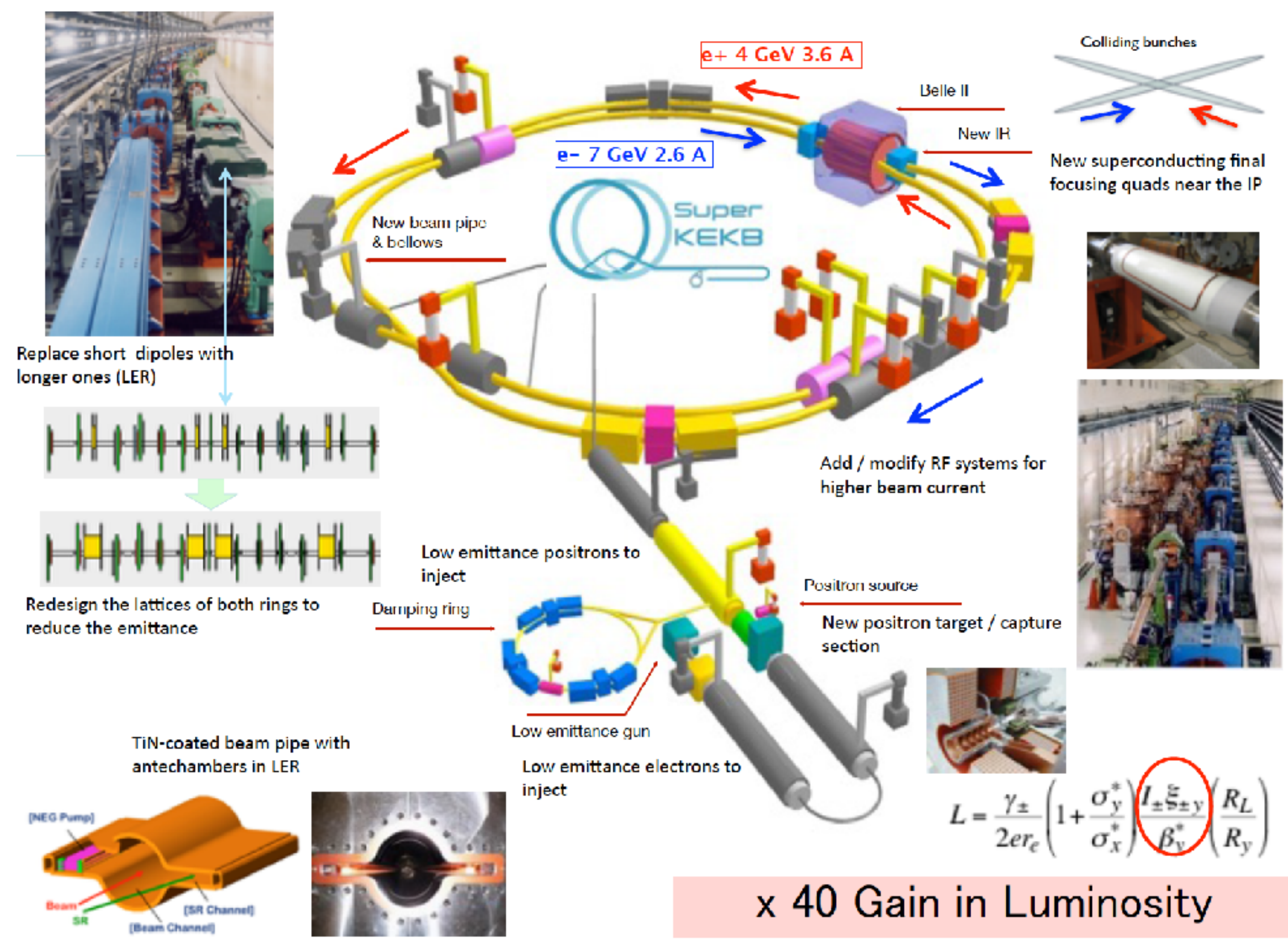
## Machine parameters

| | SuperKEKB LER/HER | KEKB LER/HER |
|---|---|---|
| E(GeV) | 4.0/7.0 | 3.5/8.0 |
| $\varepsilon_x$ (nm) | 3.2/4.6 | 18/24 |
| $\beta_y$ at IP(mm) | 0.27/0.30 | 5.9/5.9 |
| $\beta_x$ at IP(mm) | 32/25 | 120/120 |
| Half crossing angle(mrad) | 41.5 | 11 |
| I(A) | 3.6/2.6 | 1.6/1.2 |
| Lifetime | ~10min | 130min/200min |
| L($cm^{-2}s^{-1}$) | $80\times10^{34}$ | $2.1\times10^{34}$ |

x20

x2



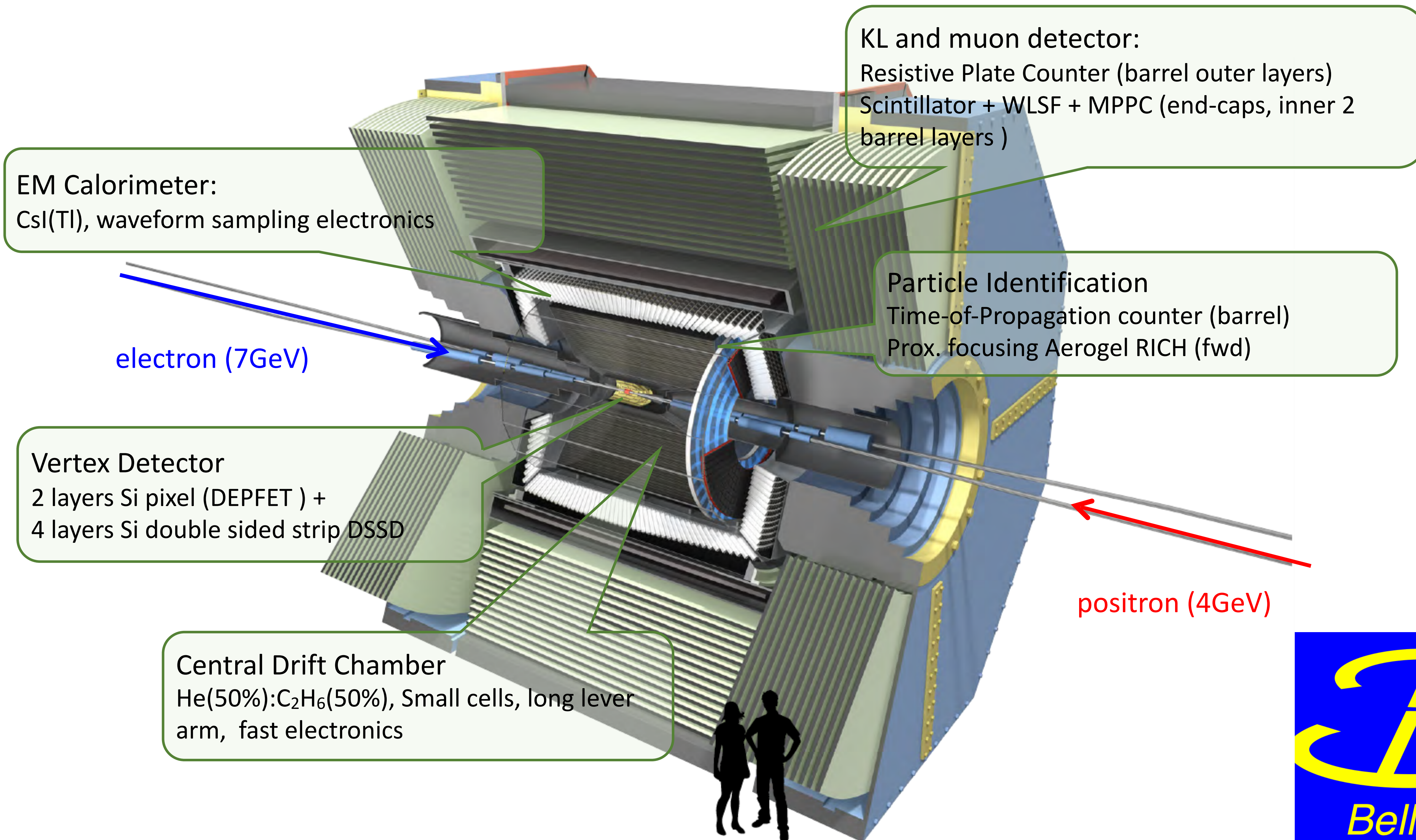




$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

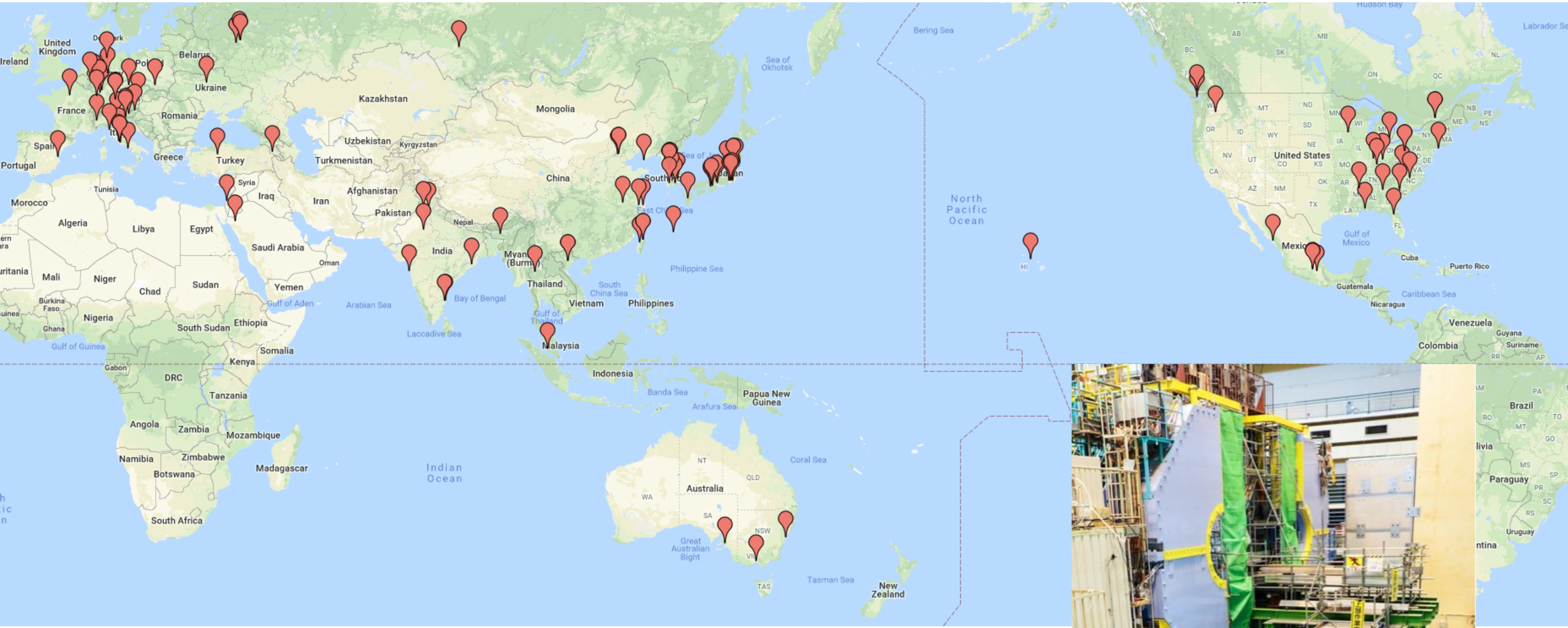
x 40 Gain in Luminosity

# Belle II Detector

- Deal with higher background (x10-20), radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)
- Improved performance and hermeticity



# The Belle II Collaboration



- Belle II has now grown to ~ 1000 researchers from 112 institutions in 26 countries.
- Large international collaboration hosted by KEK, Japan

# SuperKEKB/Belle II Plan

## Phase 1 (w/o QCS/Belle II)

- Accelerator basic tuning with single beams
- Feb-June, 2016

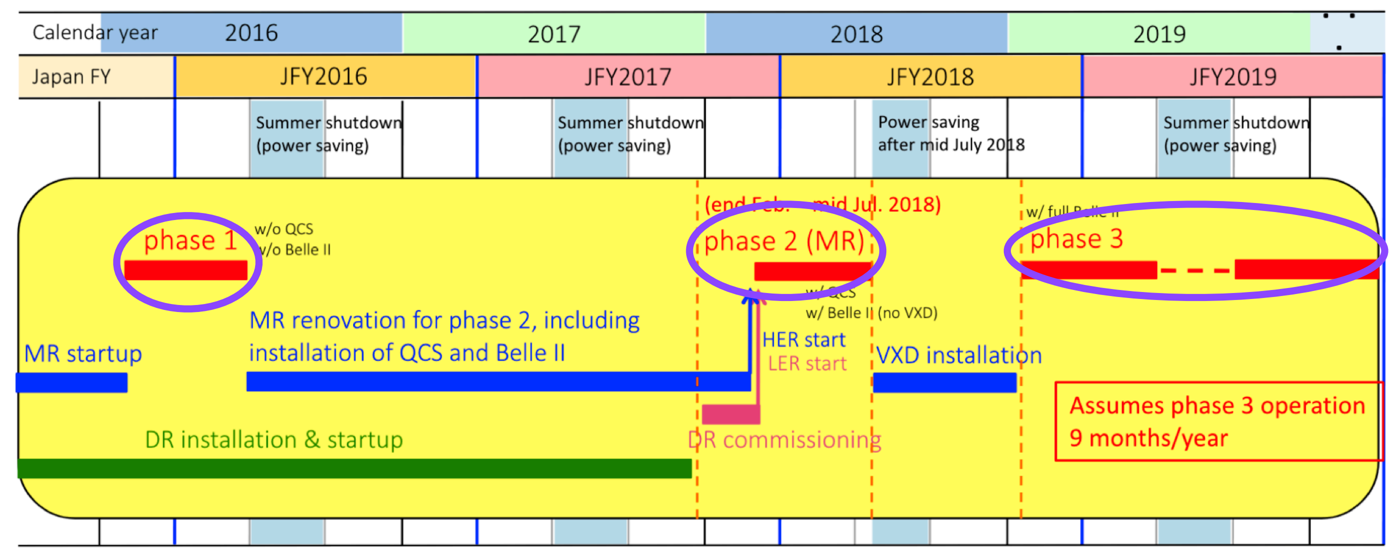
## Phase 2 (w/ QCS/Belle II but w/o VXD)

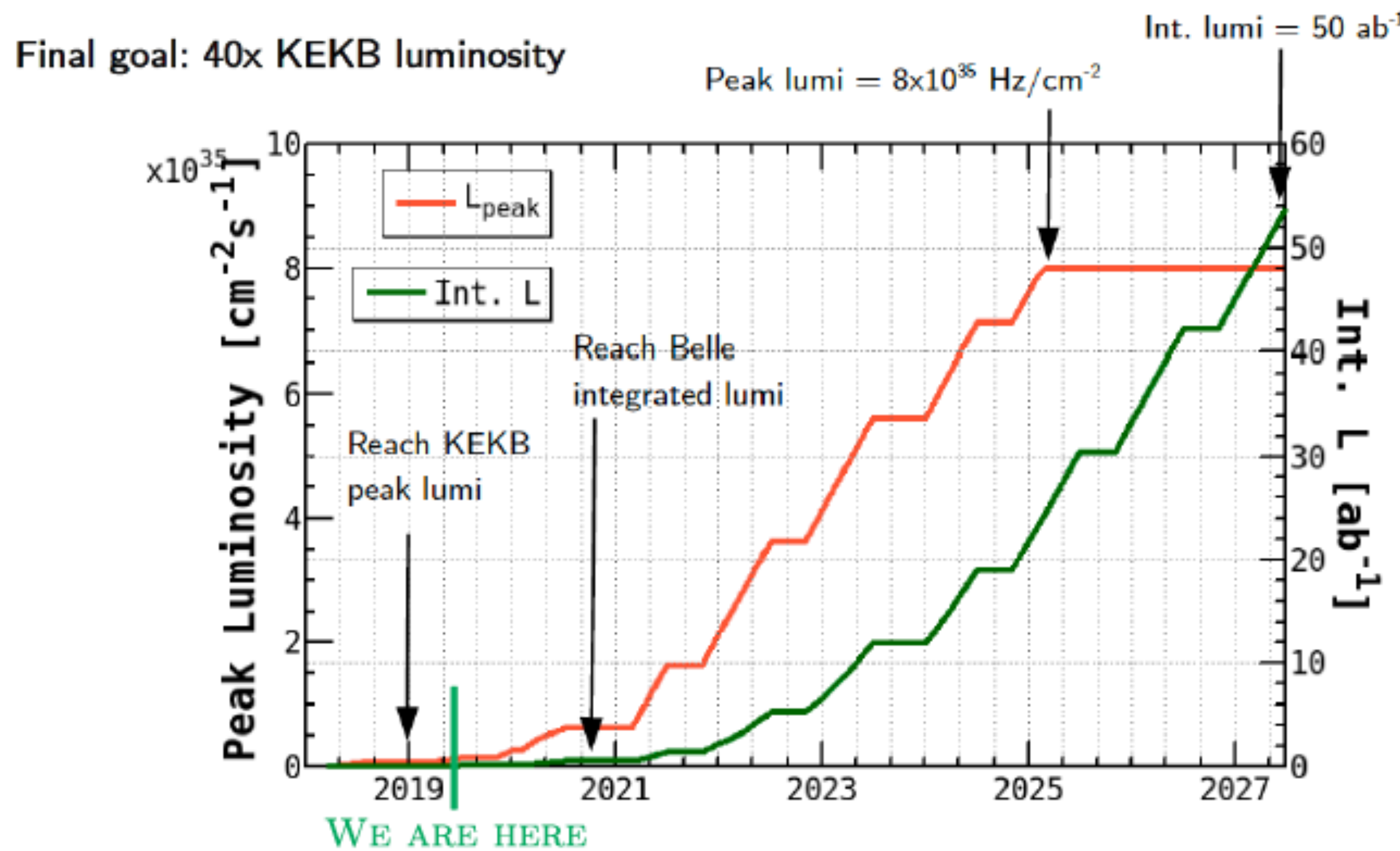
- Verification of nano-beam scheme
- Understand beam background
- Physics run (April 27 - June 17, 2018)

## Phase 3 (w/ full detector)

- Physics run (March 27 - July 1, 2019)
- 5ab$^{-1}$ by ~2022
- 50ab$^{-1}$ by ~2027

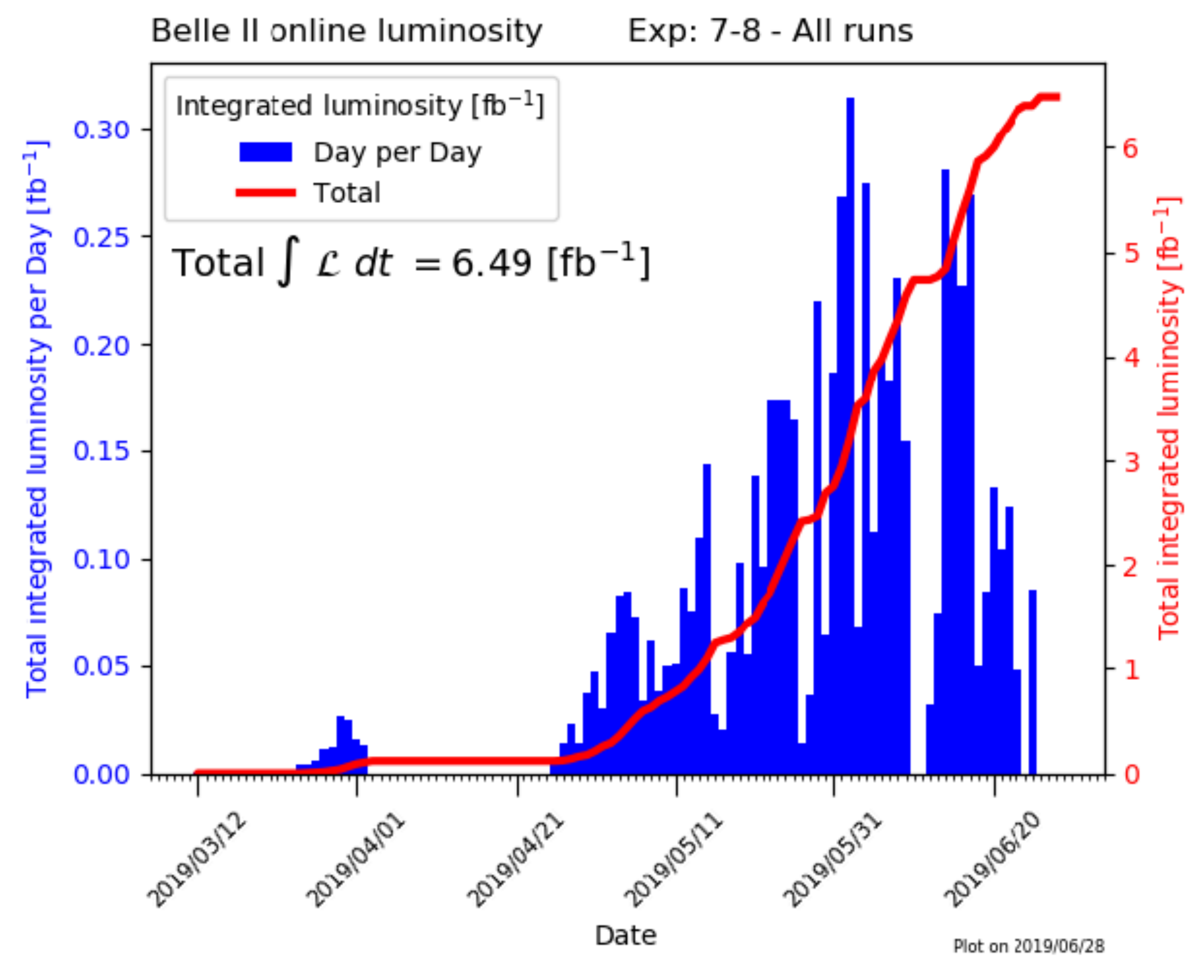
Global Schedule

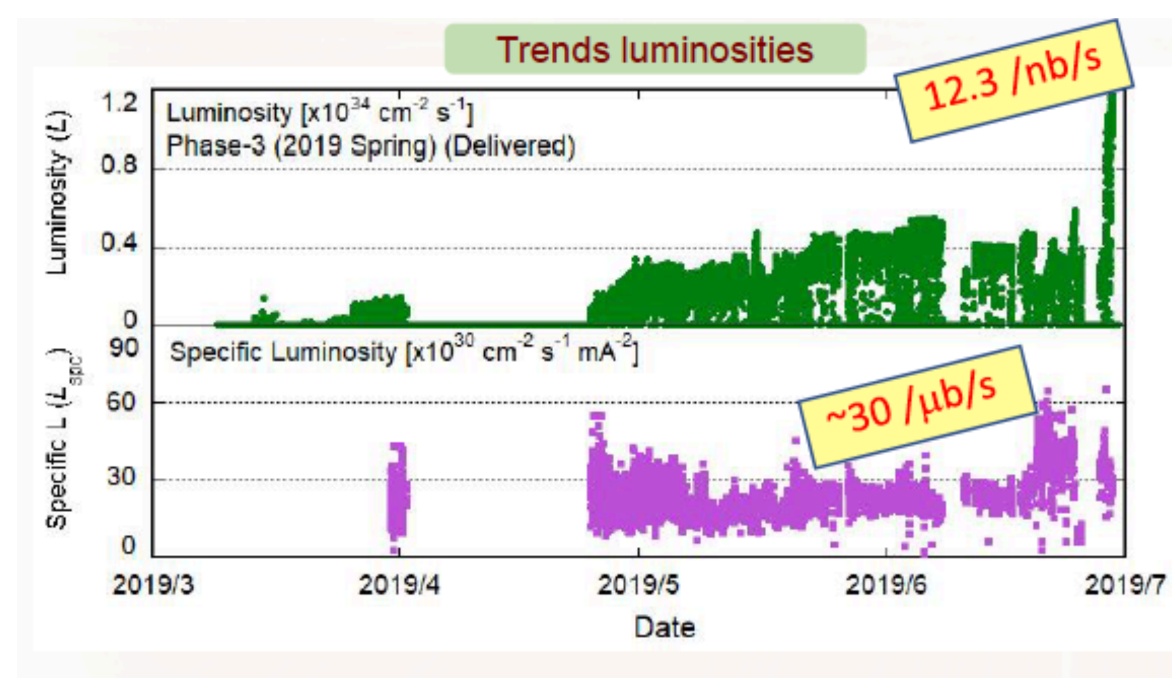


# SuperKEKB/Belle II Phase 3

- SuperKEKB operation started March
- $e^+e^-$ collision started on March 25.
  - Physics run from March 27 to July
- Accumulated ~6.49 $fb^{-1}$.
  - 0.83$fb^{-1}$ recorded below the $\Upsilon(4S)$
- $L_{peak}$ ~5 x $10^{33}cm^{-2}s^{-1}$ in physics runs with $\beta_y^*$ =3mm optics.
- $L_{peak}$ ~1.2 x $10^{34}cm^{-2}s^{-1}$ was recorded with $\beta_y^*$ =2mm optics and 820/830 mA (LER/HER).
  - Belle II was OFF due to high background.



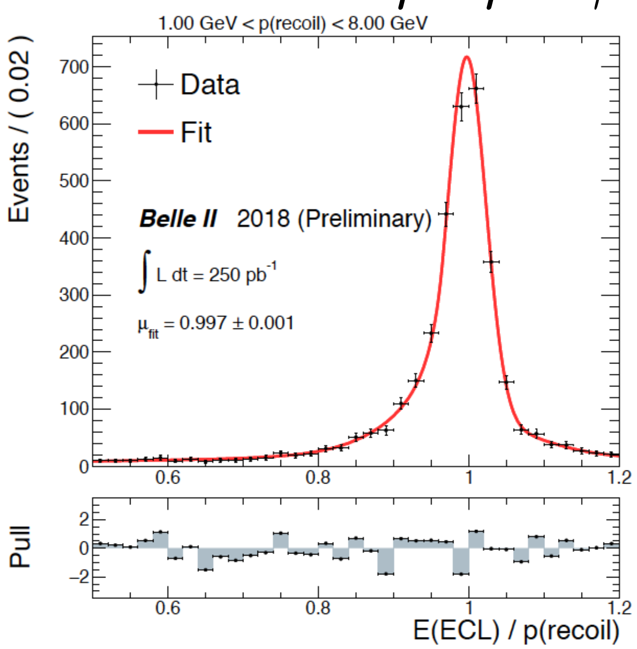



# Belle II Performance

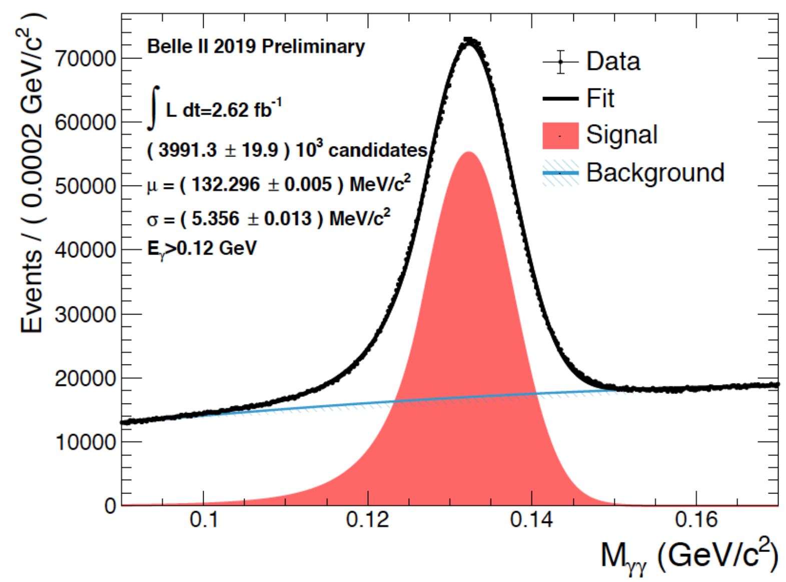
## Snapshots

- Signals involving photons

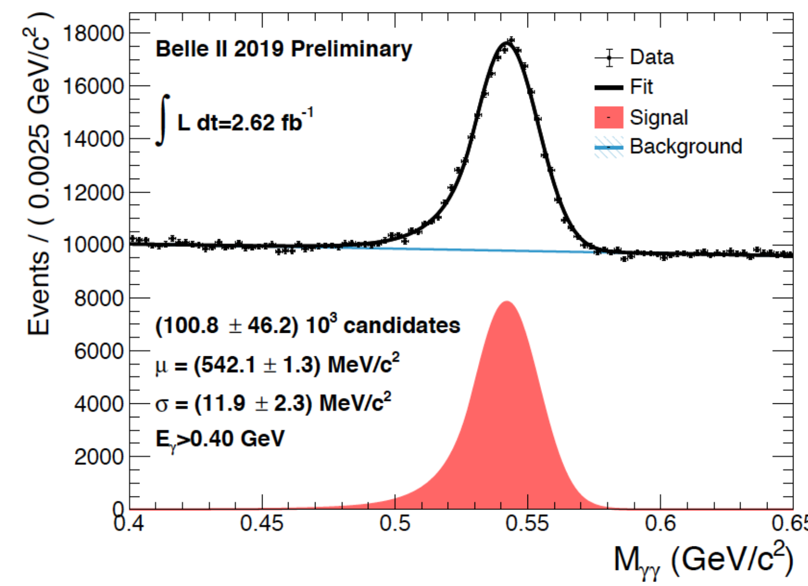
$e^+e^- \to \mu^+\mu^-\gamma$




$\pi^0 \to \gamma\gamma$

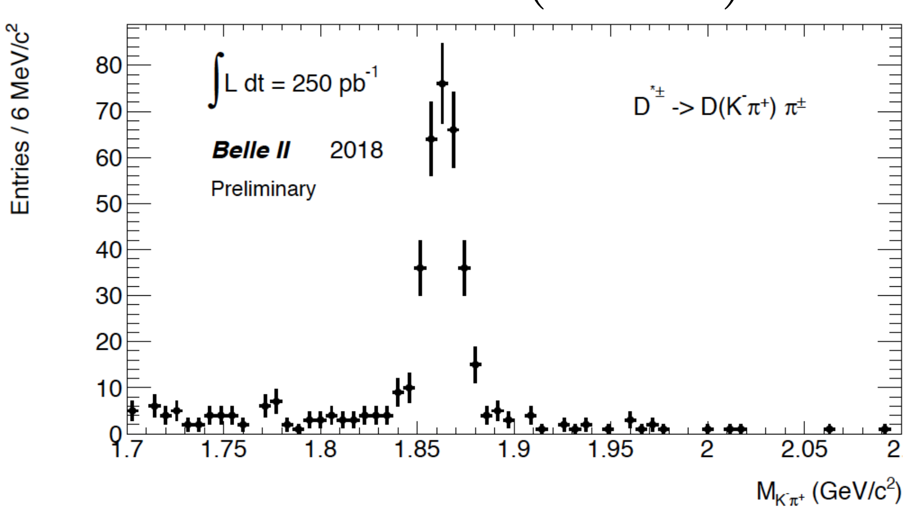



$\eta \to \gamma\gamma$

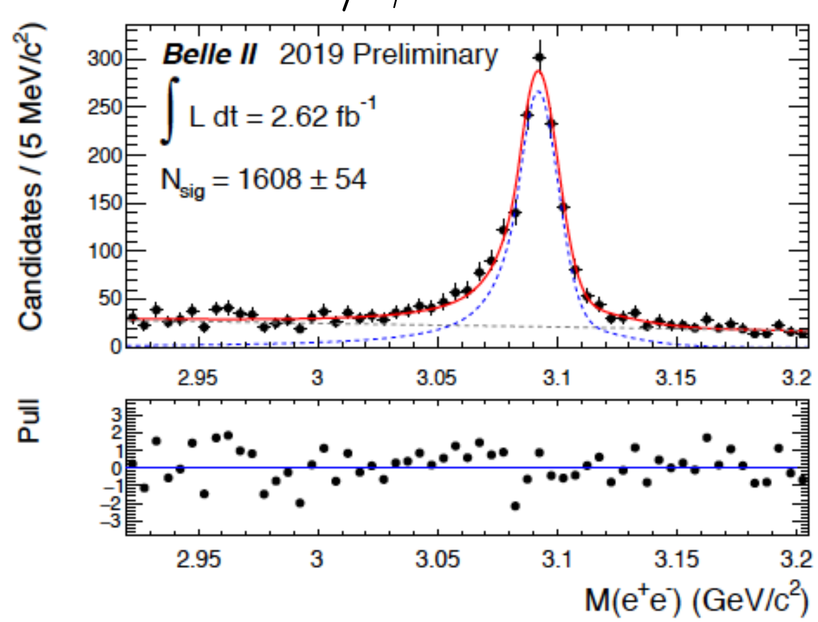



- Signals involving charged tracks

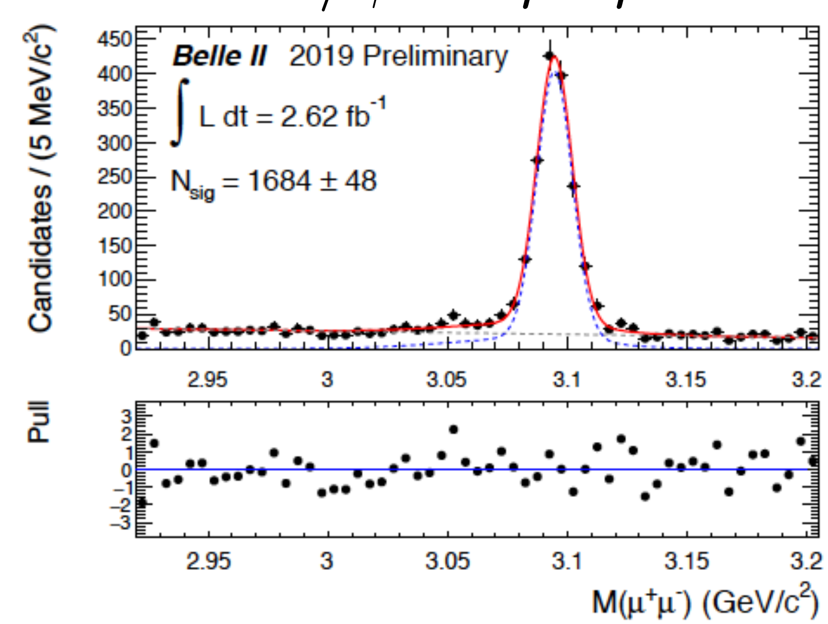
$D^{*+} \to D^0(K^-\pi^+)\pi^+$




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

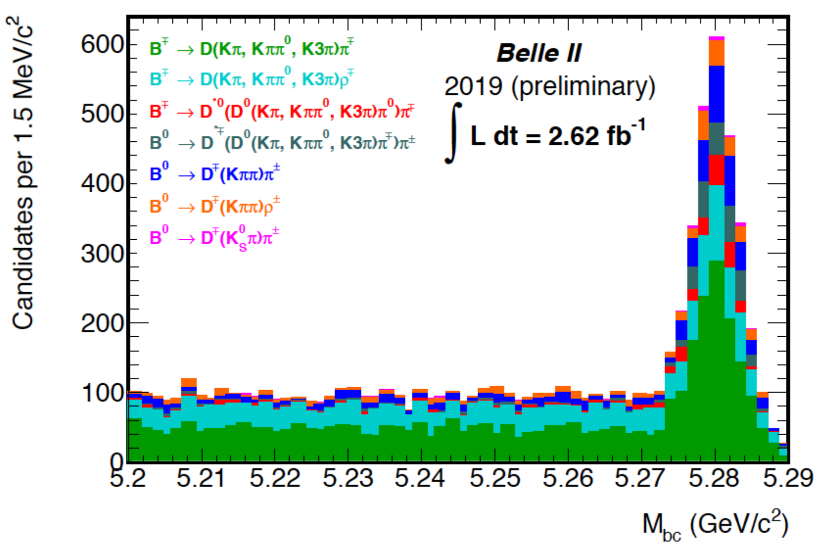



$J/\psi \to \mu^+\mu^-$

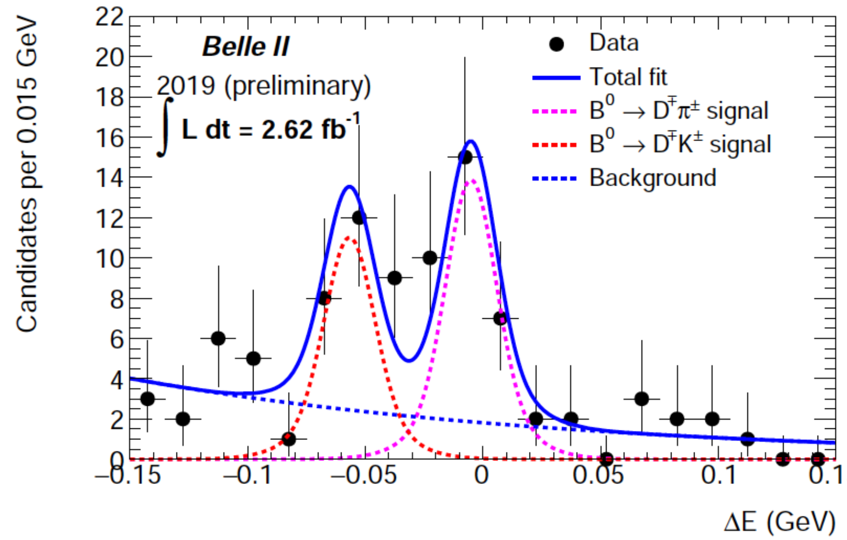


# First Belle II Physics Plots

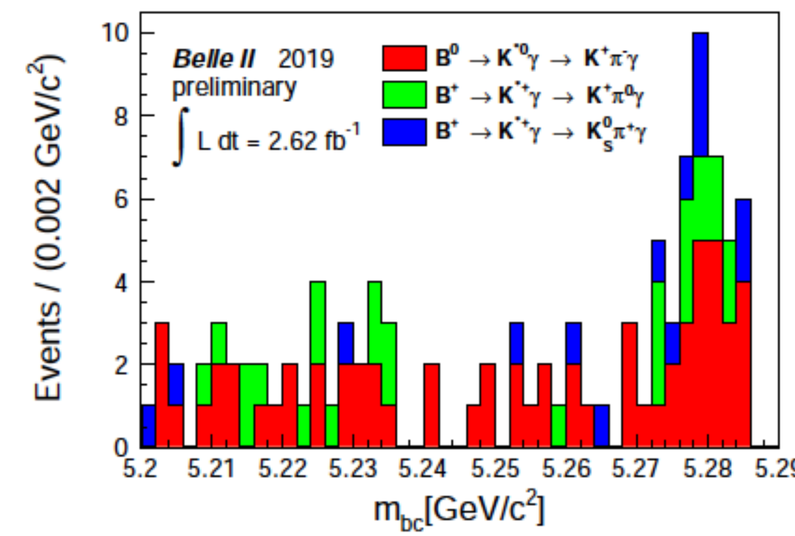
## Rediscovery of B mesons



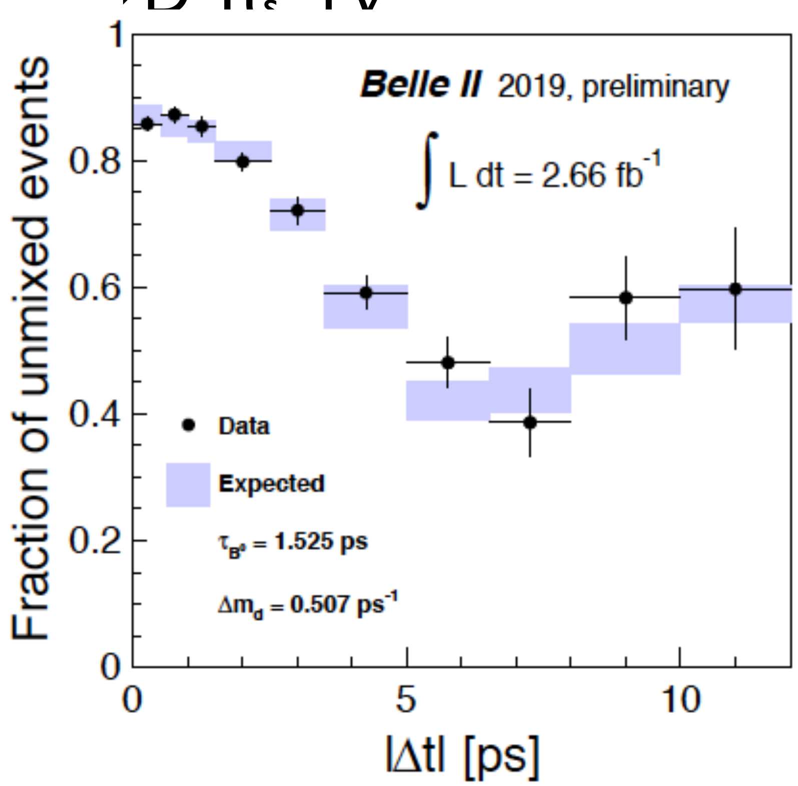

## Evidence for $B^0 \to D^- K^+$



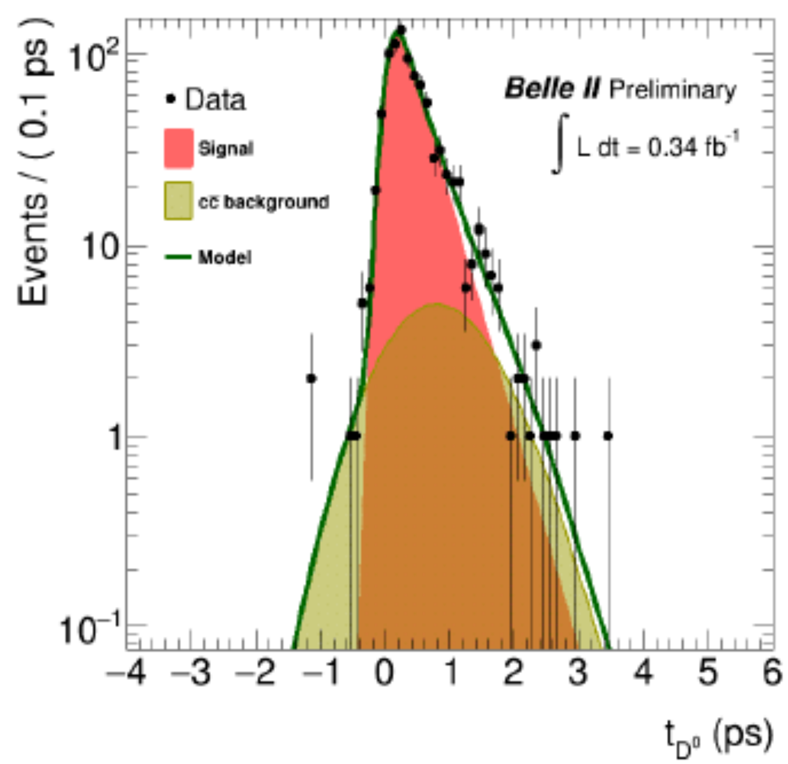

## Observation of $B \to K^*\gamma$



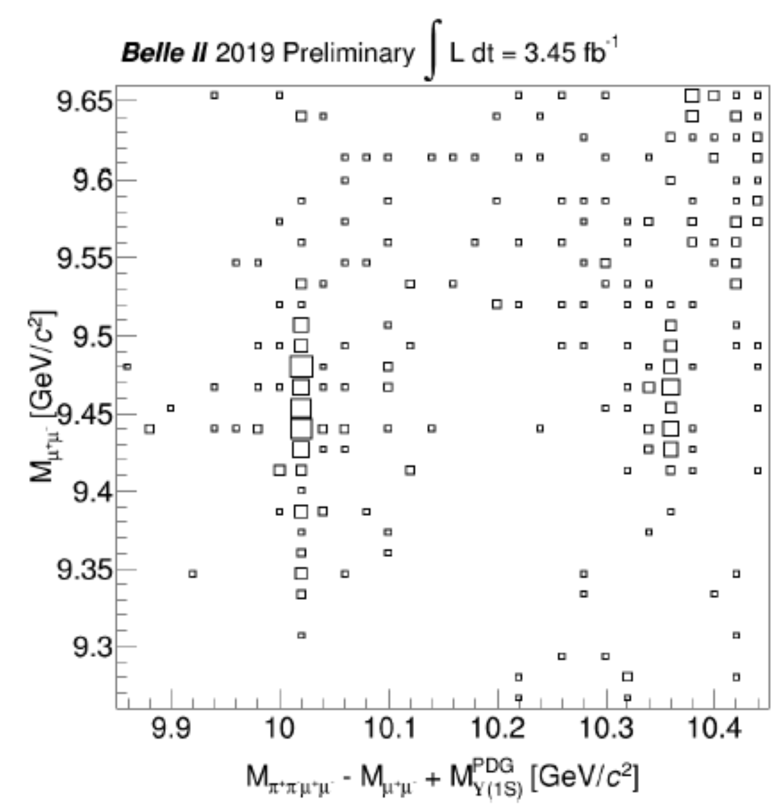

## B-B mixing w/ $B \to D^{*+} l \nu \to D^0 \pi_s^+ l \nu$




## Charm lifetime

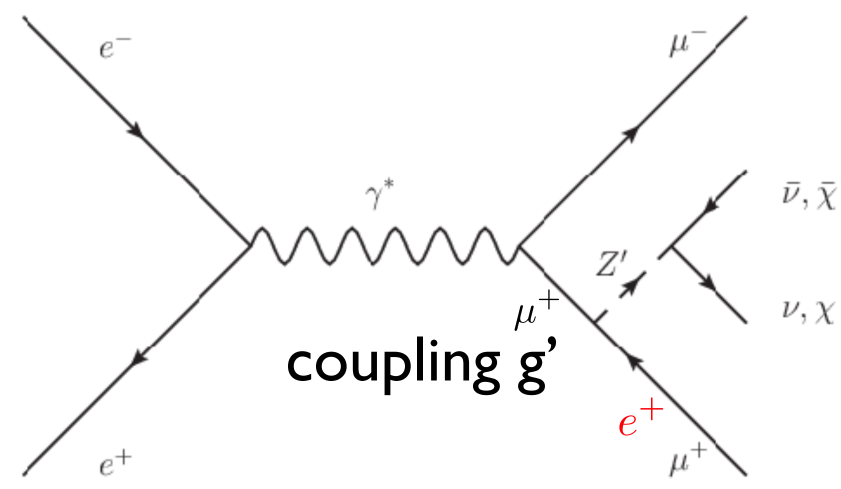



## Υ(2S), Υ(3S) via ISR

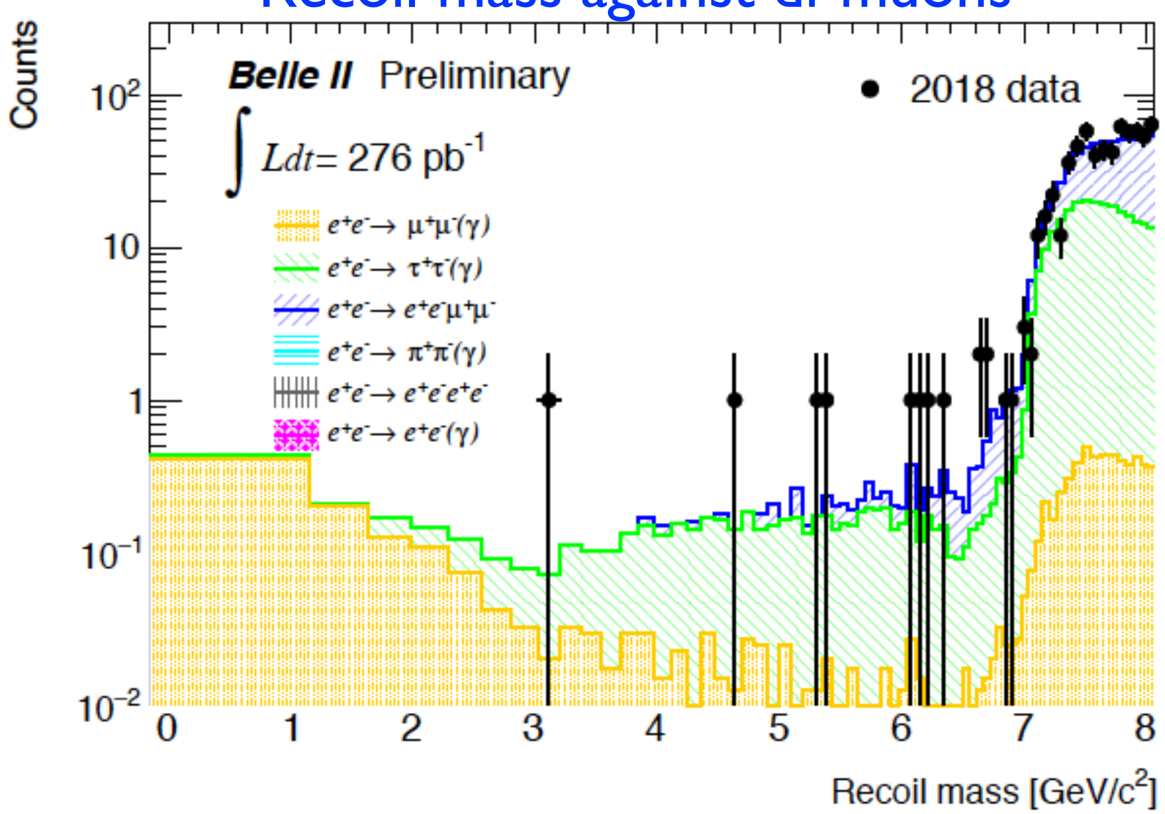


# Search for Dark Sector (Belle II First Physics)

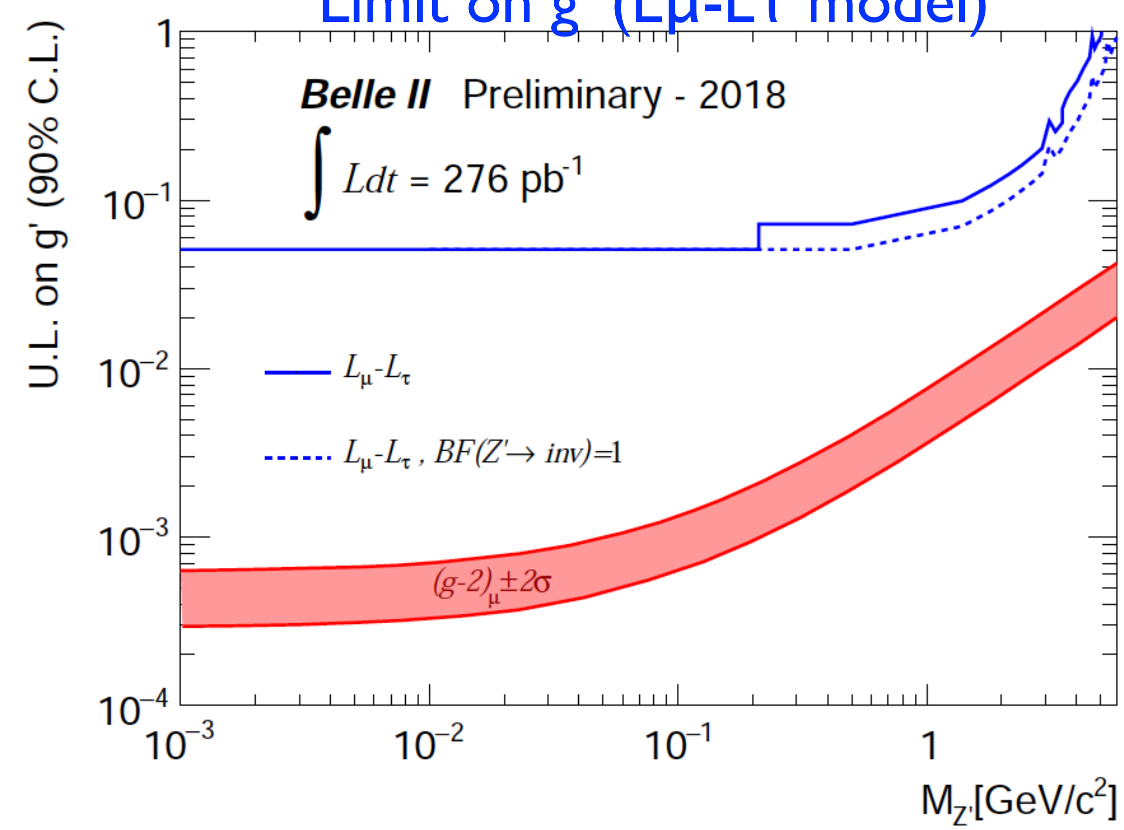
- A novel result on the dark sector (Z' → nothing) recoiling against di-muons or an electron-muon pair.
- Both possibilities are poorly constrained at low Z' mass and in the first case, could explain the muon g-2 anomaly.




Recoil mass against di-muons



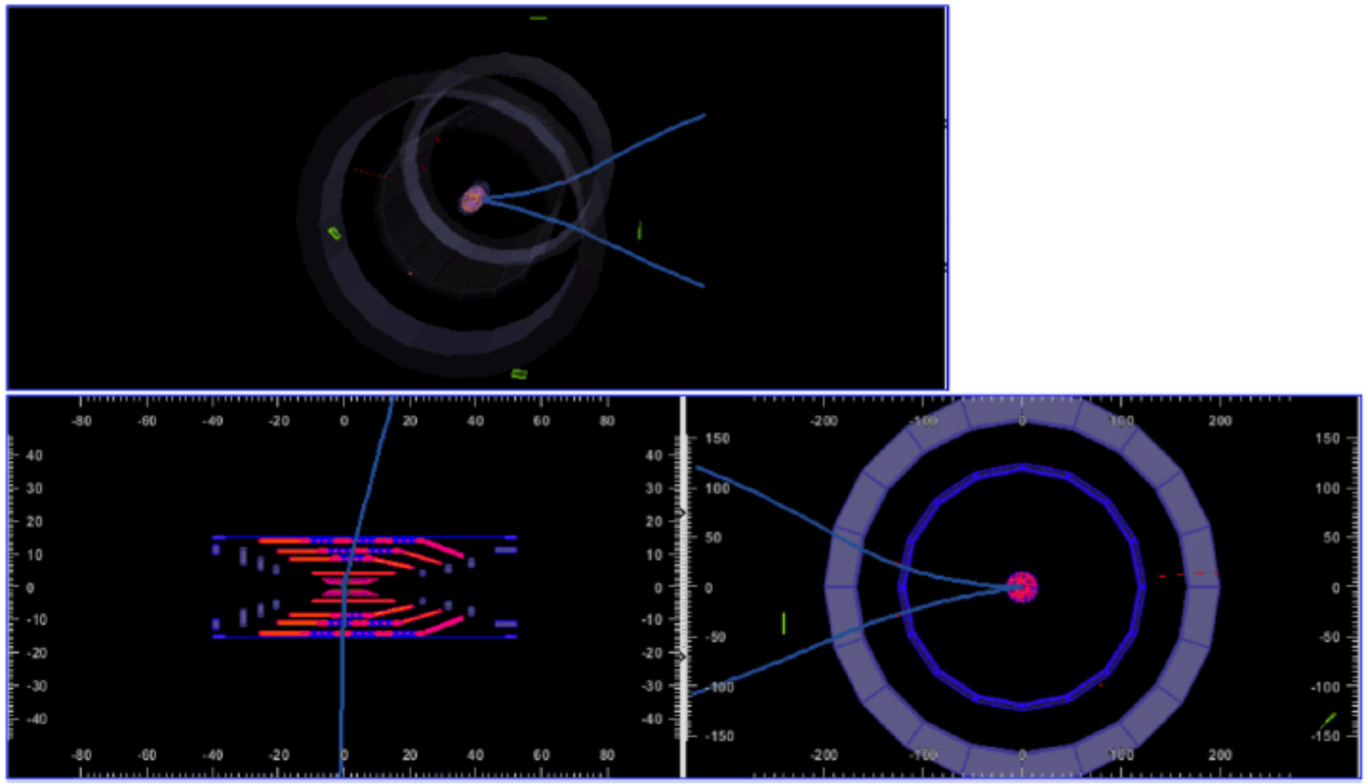

Limit on g' (Lμ-Lτ model)




These demonstrate how well Belle II controls low multiplicity events.

# First Look at the Belle II Data

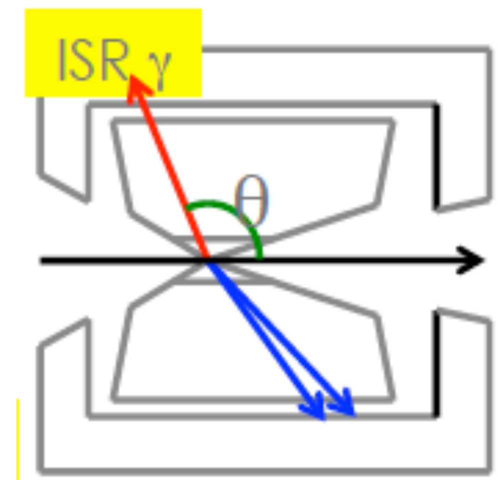
- Data collected during the Phase 2 physics run: 472 $pb^{-1}$
- Goal of the analyses :
  - To observe ρ meson peak in the mass spectrum
  - Comparison to a MC simulation
  - Study of trigger efficiency

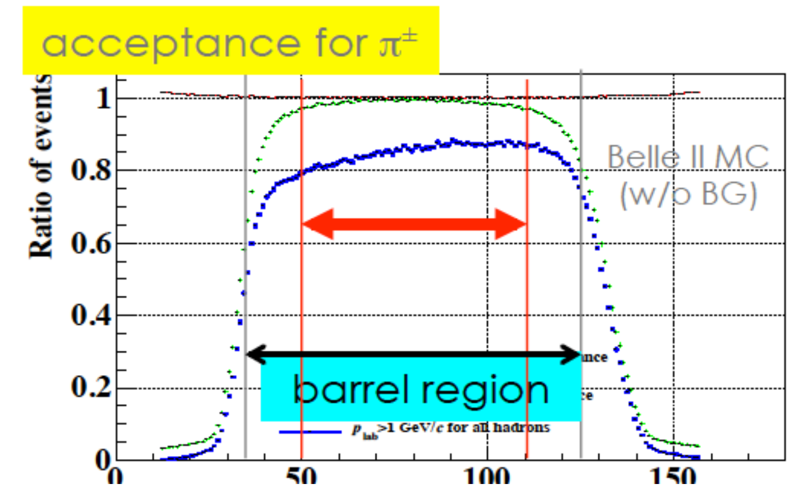


Example of an event display
for a ρ meson candidate

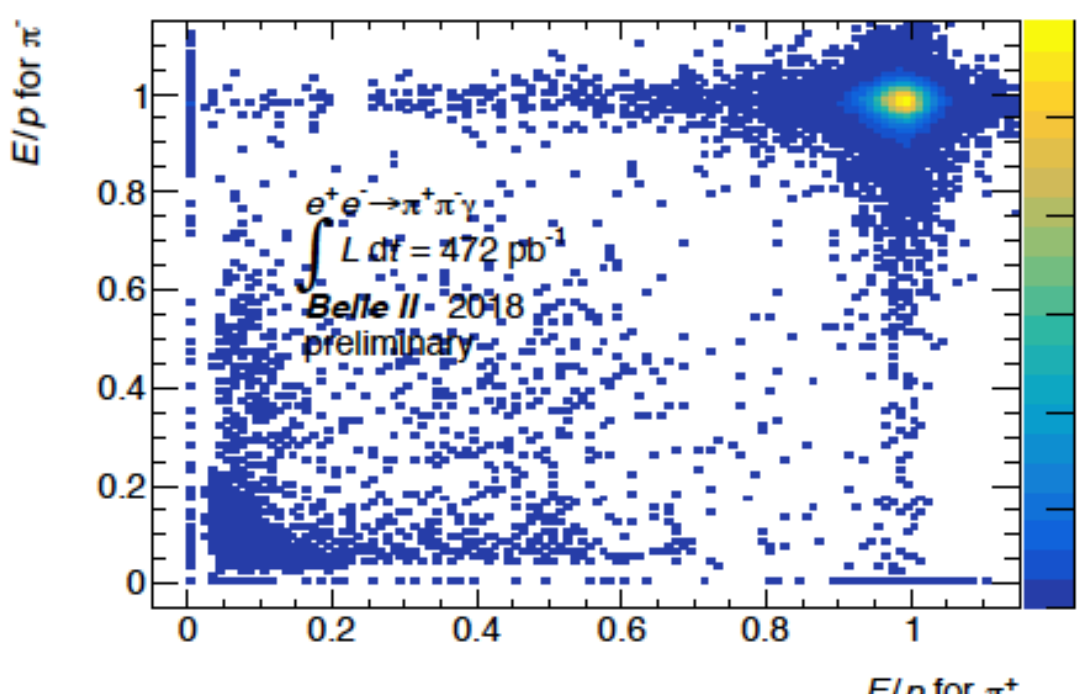
# Analysis Procedure

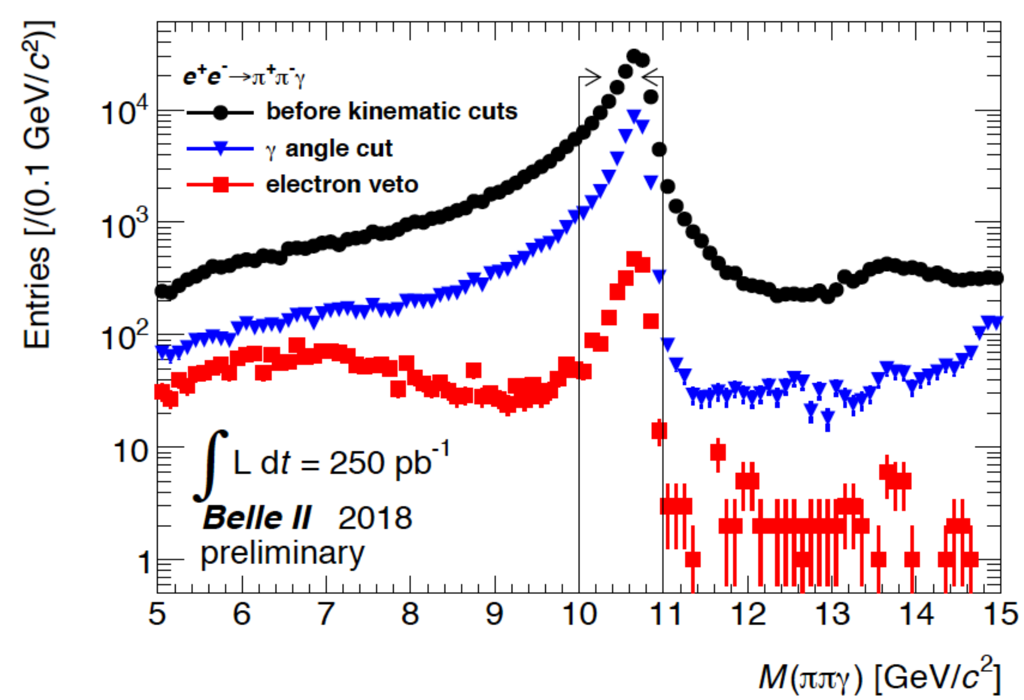
- Select events with
  - One energetic photon ($E^{CMS} > 3$GeV)
  - Two charged tracks ($p^{CMS} > 1$GeV/c)




- Selection criteria
  - Photon in the central part of the barrel region (50° < $\theta_{ISR}$ < 110°)
  - E/p < 0.8 to remove radiative Bhabha ($e^+e^- \to e^+e^- \gamma$) contribution
  - 10 < M(ππγ) < 11 GeV/$c^2$ and no other extra particles

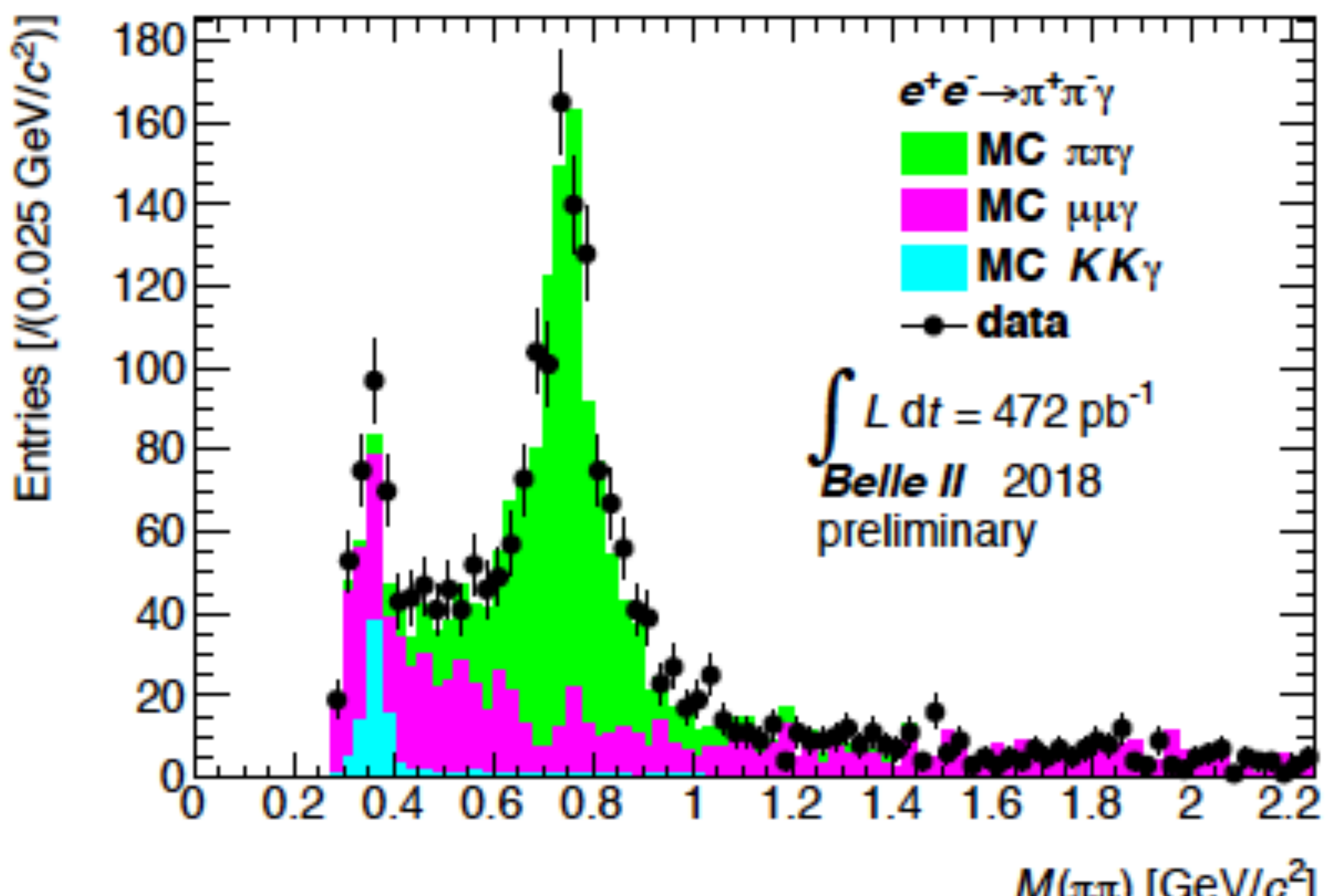



Y. Maeda, mini-workshop "Hints for New Physics in Heavy Flavors", Nagoya, Nov.15-17, 2019, also for plots in the following 3 slides

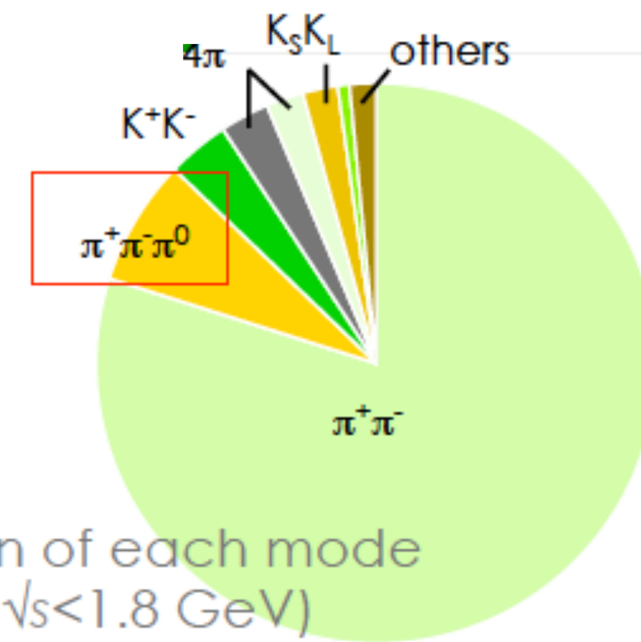
# ππ Mass Spectrum

- The ρ meson peak is clearly observed.
- No PID is used expect for E/p → contribution from μμγ and KKγ
- Reasonable Data/MC agreement
  - Data/MC = 1.065 ± $0.037_{stat}$ (0.5<E<1.0 GeV/$c^2$)
  - 100% trigger efficiency is assumed in MC

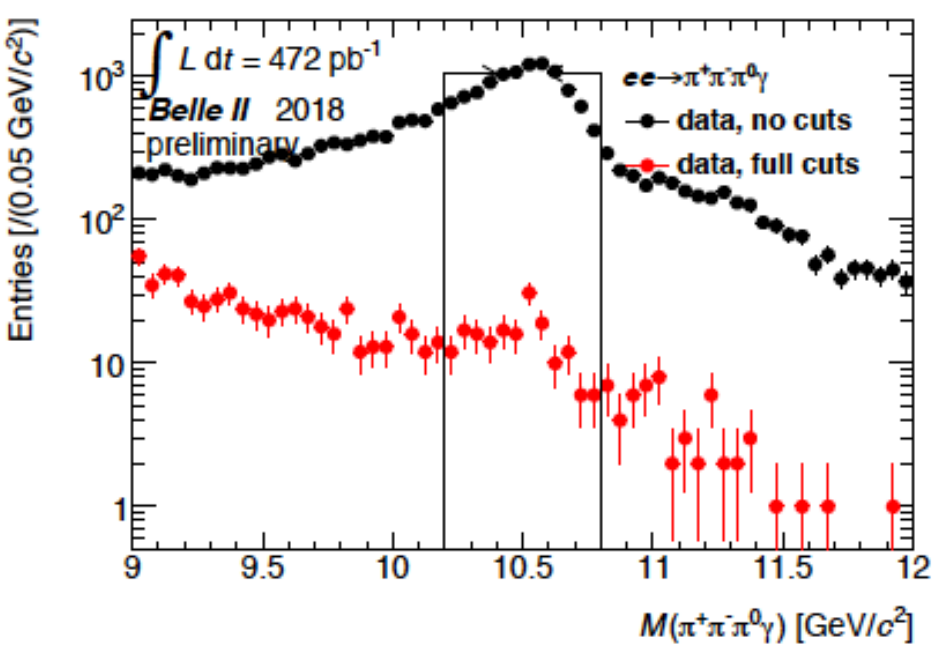


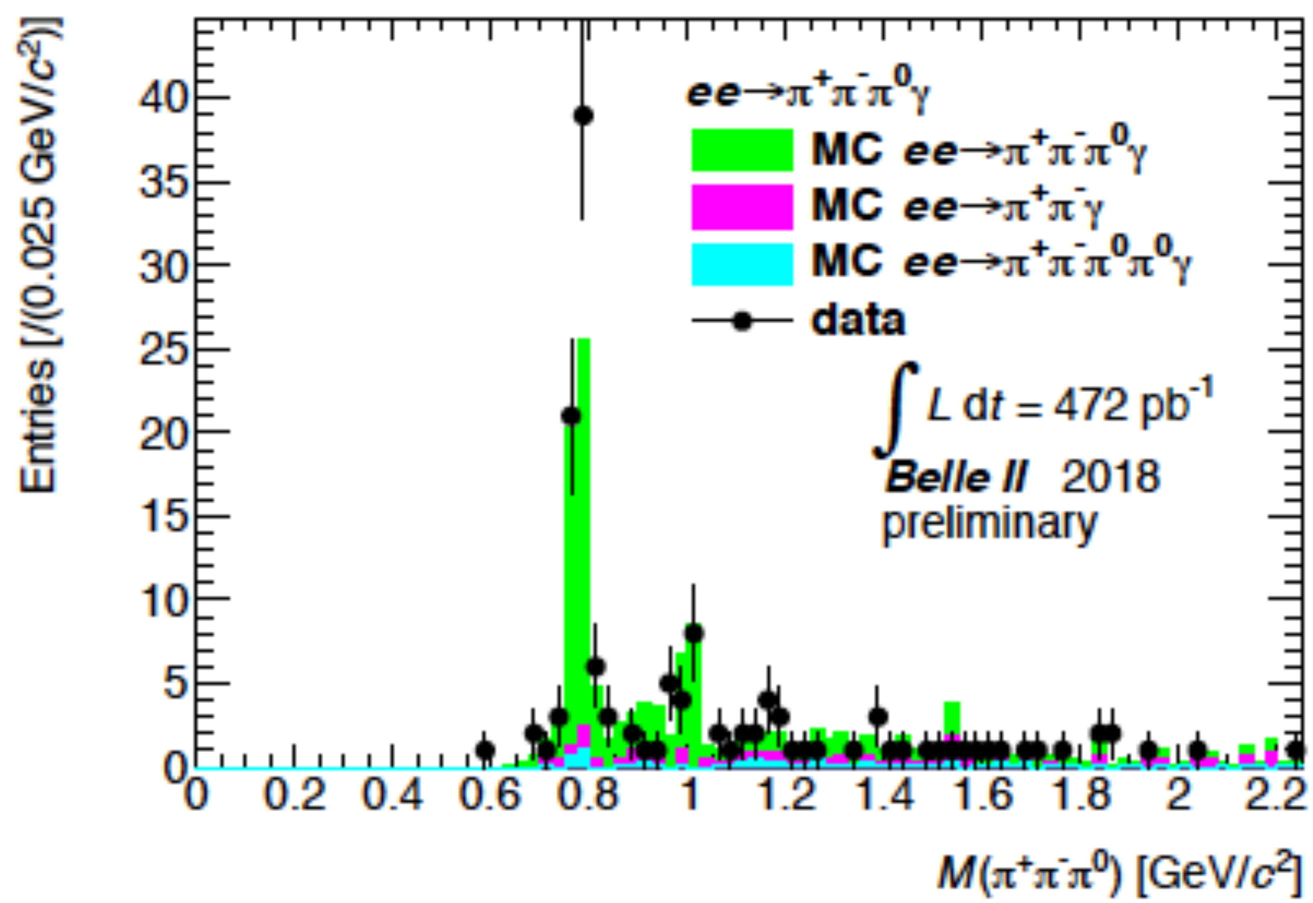
# Results for other modes

- The $e^+e^- \to \pi^+\pi^-\pi^0\gamma$ process is also studied.
  - 2nd largest contribution to HVP.
- The ω and φ peaks are clearly observed.
- Reasonable agreement between data and MC.



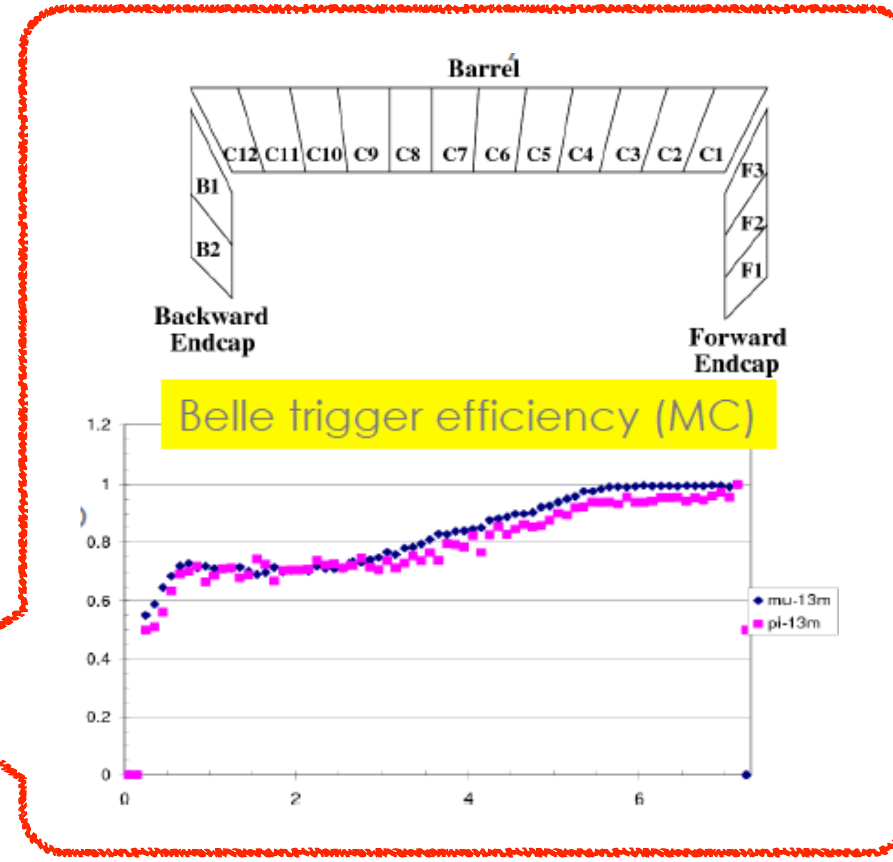

contribution of each mode to $a_\mu^{had;LO}$ ($\sqrt{s}$<1.8 GeV)



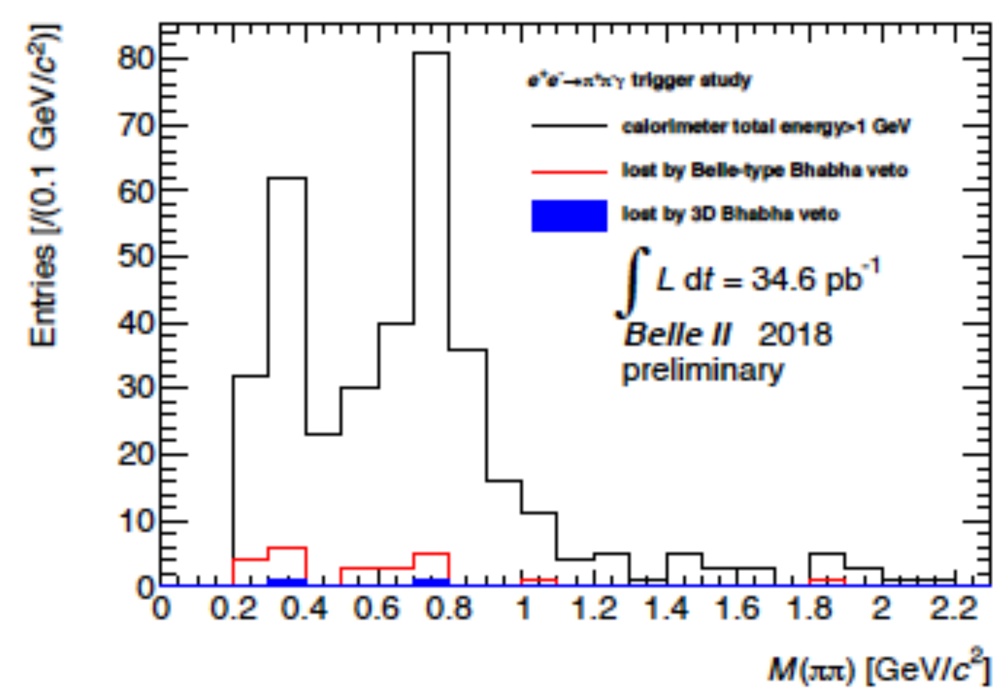



# Trigger Efficiency

- High trigger efficiency is necessary for precision measurements.
- Belle II trigger for e+e- → ππγ.
  - Total calorimeter energy > 1 GeV
  - Bhabha veto (← loss due to this veto must be small)
    - "Belle-type Bhabha": based on only θ angle
    - "3D Bhabha": based on both θ and φ




- All Bhabha events were collected in Phase 2, and efficiency loss can be easily evaluated by counting #events w/ Bhabha trig.
  - Belle type : (6.4 ± 1.3 stat)%
  - 3D Bhabha :(0.6 ± 0.4 stat)%
    - 2 events lost / 360 events



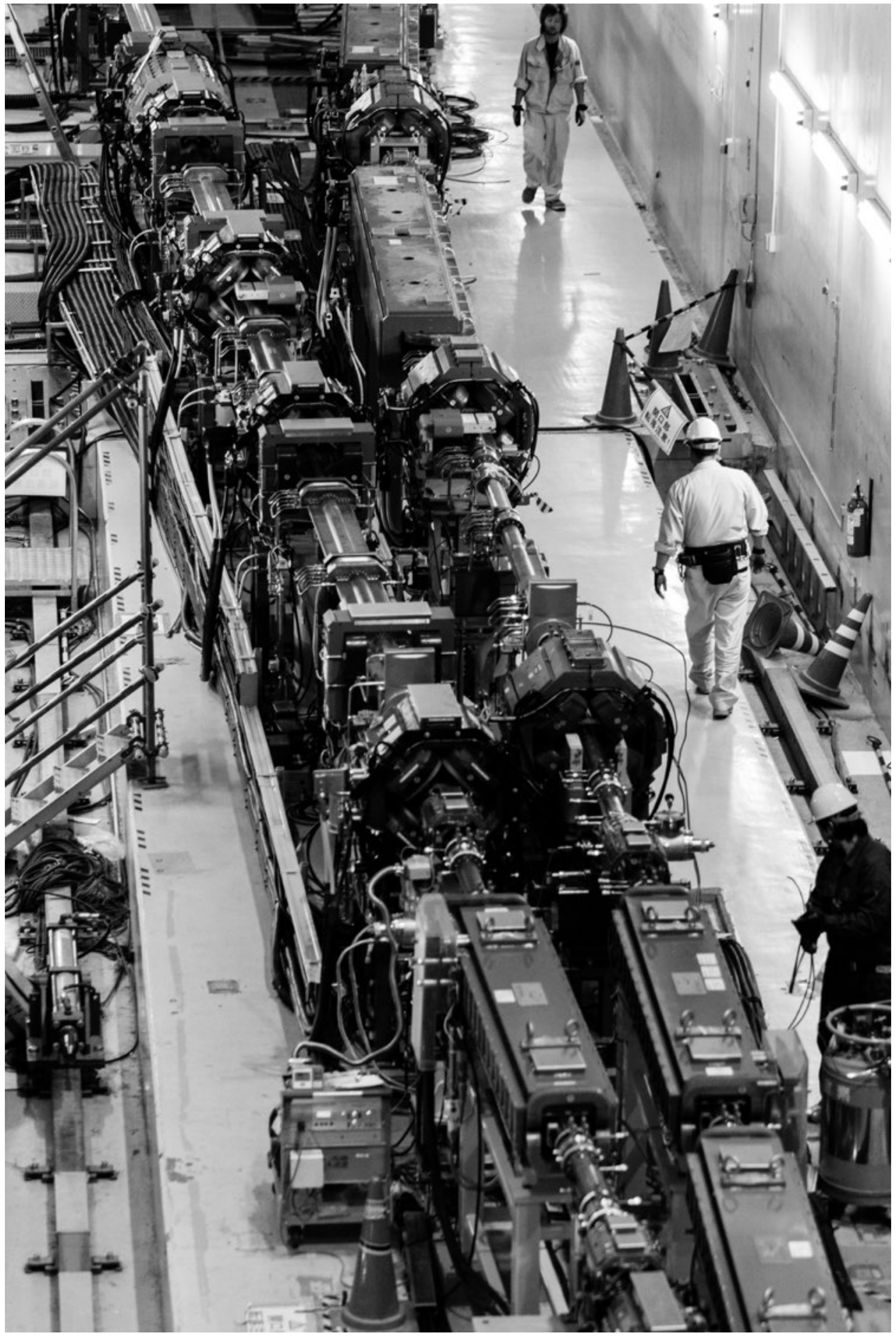

The New Bhabha veto logic works !

# Summary

- Precision measurement of $\sigma(ee \to \text{hadron})$ in Belle II with the ISR method will provide estimate of HVP effects, which is critical inputs to reduce uncertainty in the SM prediction $(g-2)_\mu$.
- The SuperKEKB/Belle II project has just started its data taking runs, and accumulated $O(fb^{-1})$ data by now.
- The first look at early Belle II data has shown ;
  - Clear peak of the $\rho$ meson ($\pi^+\pi^-$ mode).
  - Also $\omega$ and $\varphi$ peaks ($\pi^+\pi^-\pi^0$ mode).
  - Reasonable agreement between data and MC.
  - Small efficiency loss due to Bhabha veto; $\lesssim$1% w/ new 3D Bhabha veto logic.
- $O(100)fb^{-1}$ data expected within 1 year will provide the first result for HVP.
- Also possible to perform
  - $\tau$ spectral function measurement
  - Two-photon processes ($e^+e^- \to \gamma\gamma e^+e^-$ w/ double-tag) to constrain $a_\mu^{HAD, LbL}$

*Stay Tuned !*

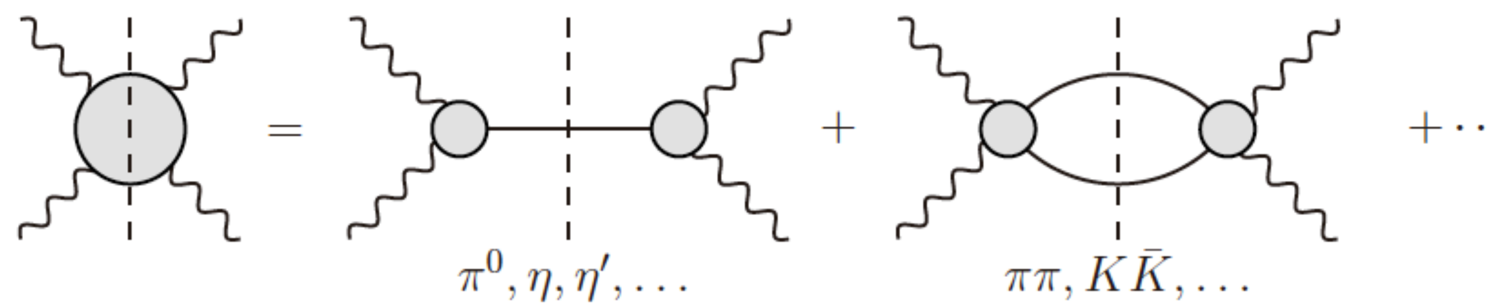
# Backup Slides



# Two-photon Physics for $a_\mu^{HAD, LbL}$

arXiv:1808.10567

- $\gamma\gamma$ physics allows one to constrain important input quantities needed for a data-driven analysis of $a_\mu^{HAD, LbL}$ , with dispersion theory.
- Expansion in terms of the mass of intermediate states are dominated by pseudo scalar poles, $\pi^0$, $\eta$, $\eta'$, followed by two-meson states, $\pi\pi$, KK, and higher contributions.




- Two-photon processes, $e^+e^- \rightarrow \gamma\gamma e^+e^-$, can be studied at Belle II , both with single-tag and double-tag.
- Double-tag data are useful for HLbL.
  - Q2 of two virtual photons
  - Exclusive reconstruction of final-state hadrons
  - No data so far for W< 5GeV.
  - Careful Bhabha-veto trigger design.

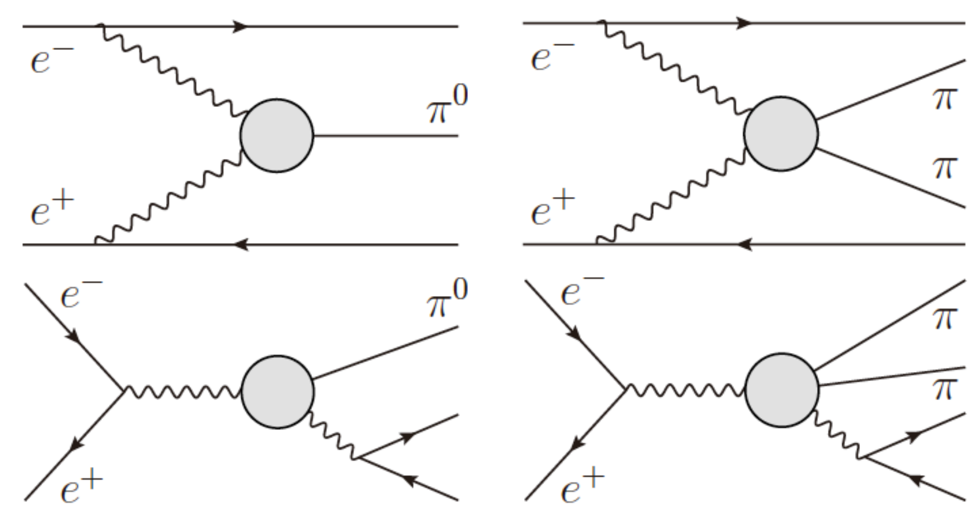



Fig. 200: $e^+e^- \to e^+e^-\pi^0$ and $e^+e^- \to e^+e^-\pi\pi$ in space-like (top) and time-like (bottom) kinematics.