Low multiplicity physics at Belle II – a talk of two halves

Jim Libby (IIT Madras)

Outline

- First half
  - $\sigma(e^+e^- \longrightarrow \pi^+\pi^-[\pi^0])$ and its relation to the anomalous magnetic moment of the muon a_μ
  - Status of these measurements at Belle II

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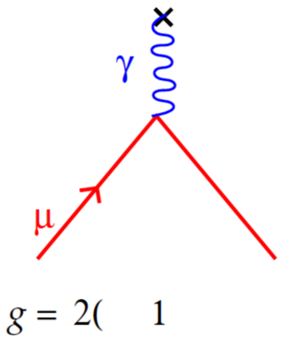
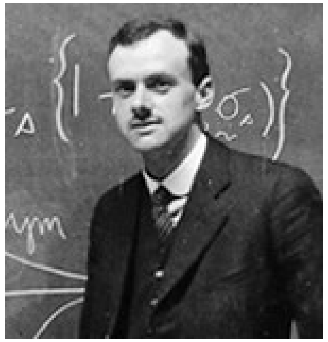
  - Status of these measurements at Belle II
- Second half
  - Introduction to the dark sector
  - Recent low-multiplicity measurements at Belle II

Magnetic moment

- A particle with charge and spin generates a magnetic moment:

$$\vec{\mu} = g \frac{e}{2m} \vec{S}$$





- Classical physics: $g = 1$
- Relativistic quantum mechanics prediction for a point-like particle: $g = 2$ (Dirac, 1928)
- For the electron, experimentally found to be $g_e = 2.00238(10)$ (Foley & Kusch, 1948)

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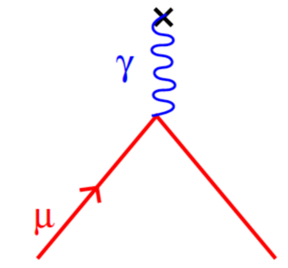
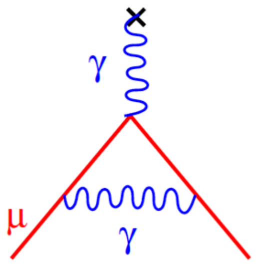
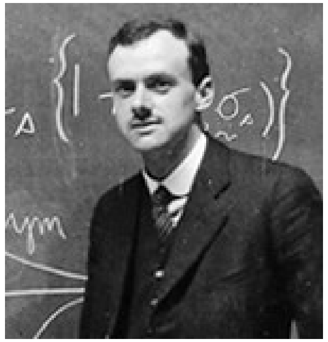
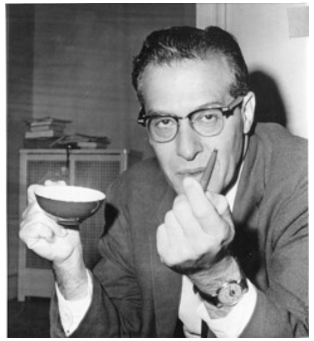




$g = 2(\quad 1 \qquad\qquad + .00116\ldots\quad)$





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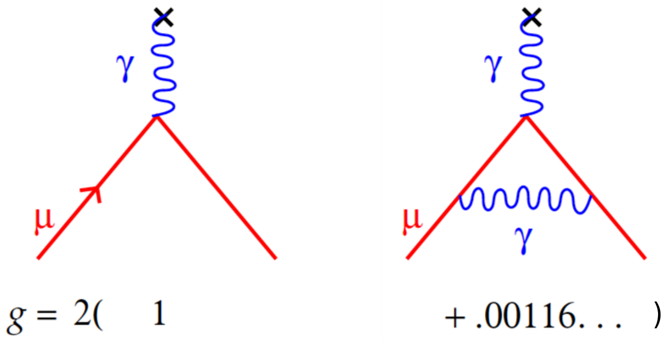

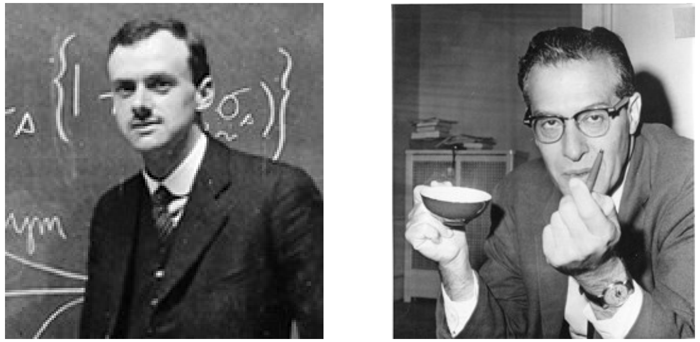

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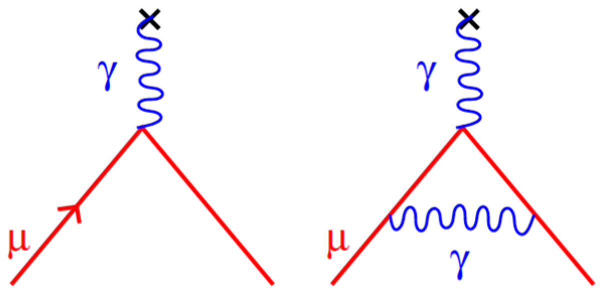
- **Muons are ~40,000x more sensitive to loop processes due to their larger mass**

2020 status of a_μ



QED

a_μ(x10^{-11}): 116584718.9(0.1)

Contribution	Section	Equation	Value $\times 10^{11}$	References
Experiment (E821)		Eq. (8.13)	116 592 089(63)	Ref. [1]
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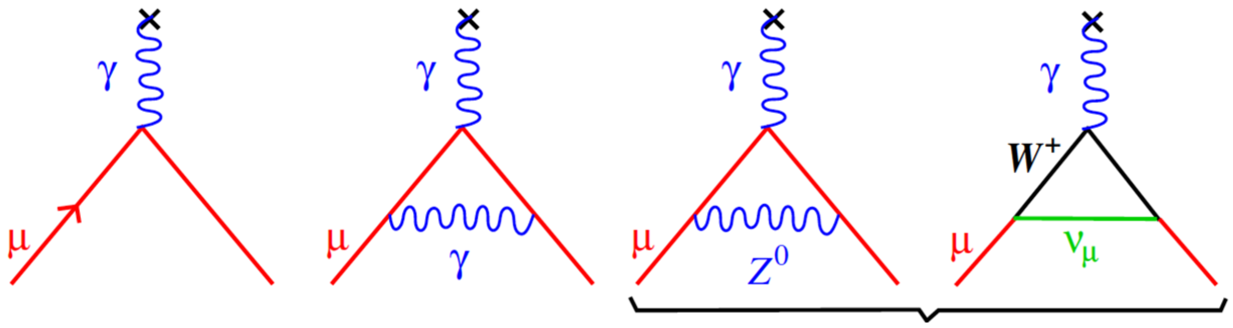

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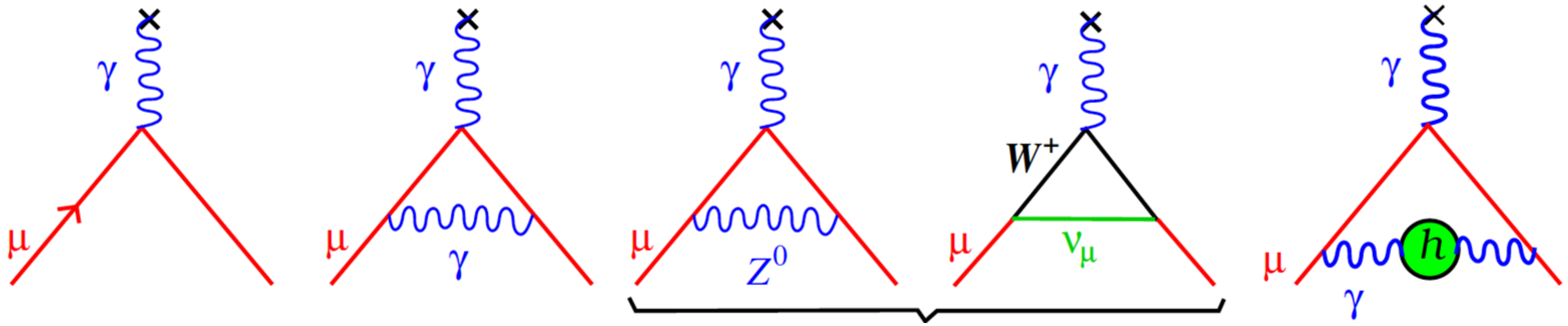

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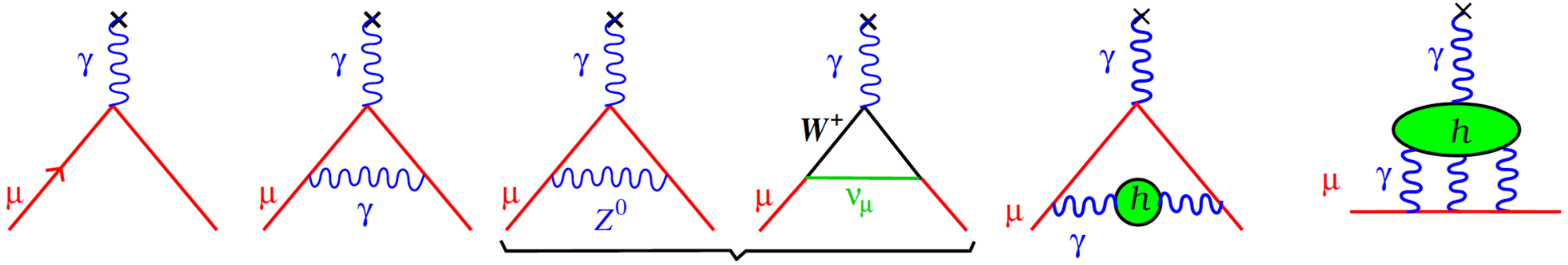

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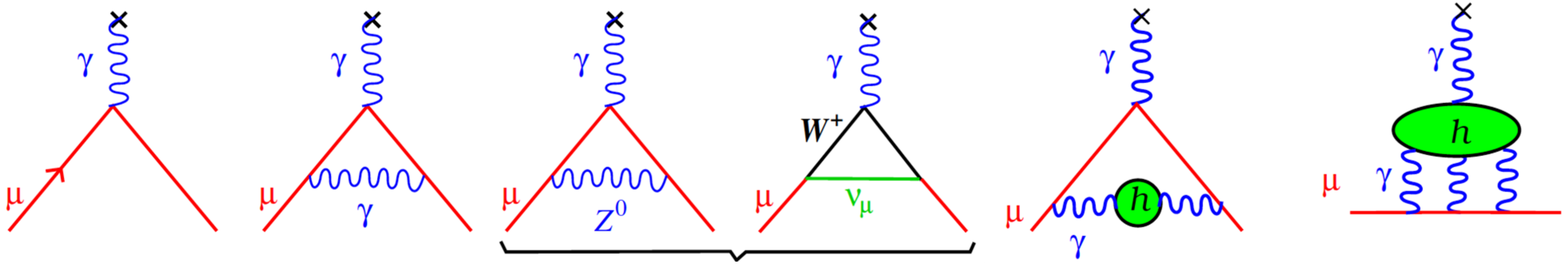

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Total SM Value	Sec. 8	Eq. (8.12)	116 591 810(43)	Refs. [2–8, 18–24, 31–36]
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	Sec. 8	Eq. (8.14)	279(76)	

3.7 sigma

Beyond the SM physics in the loop?

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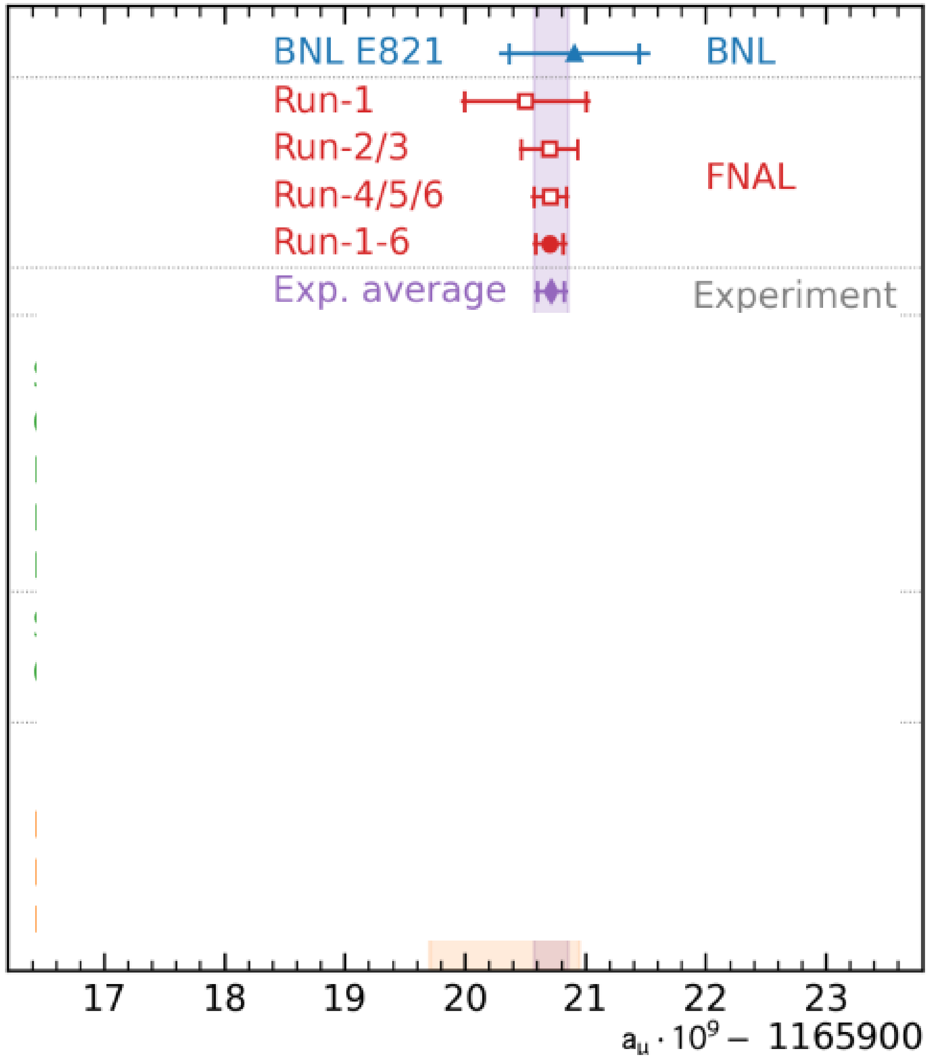
Status today



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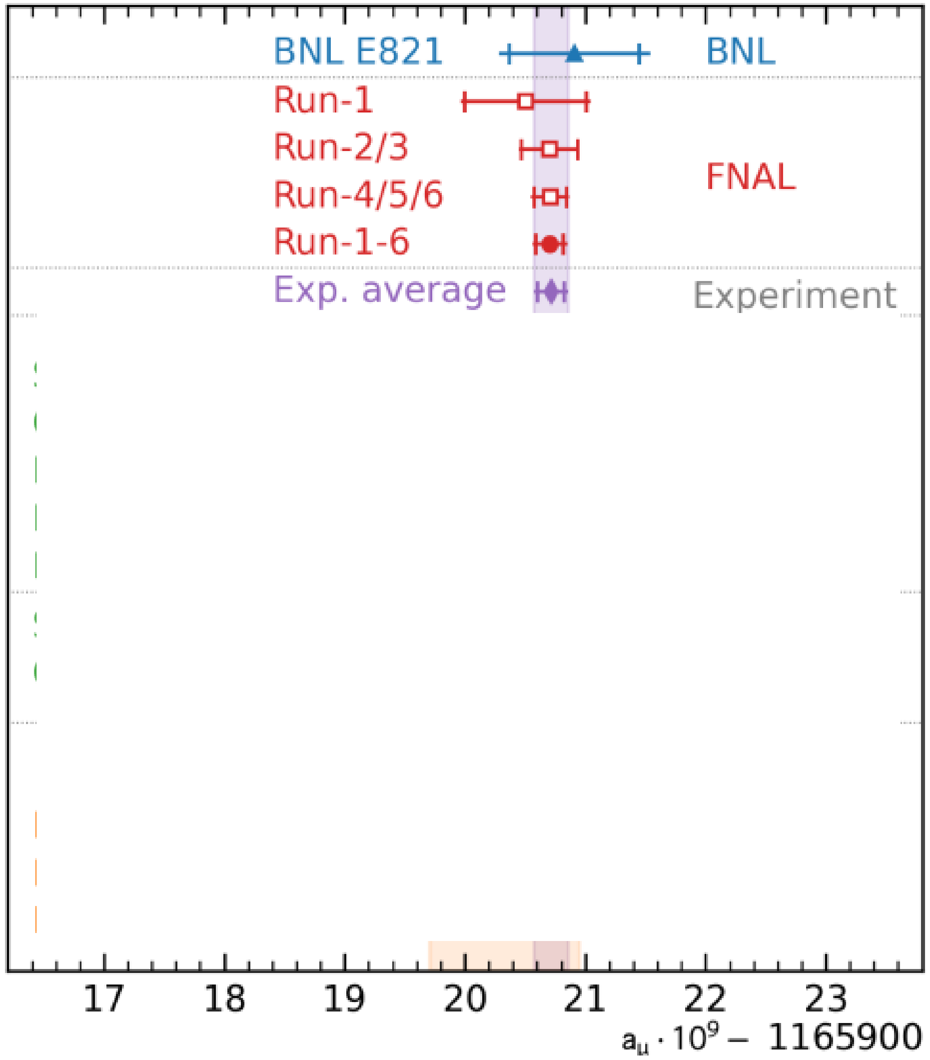

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- **Excellent agreement!**

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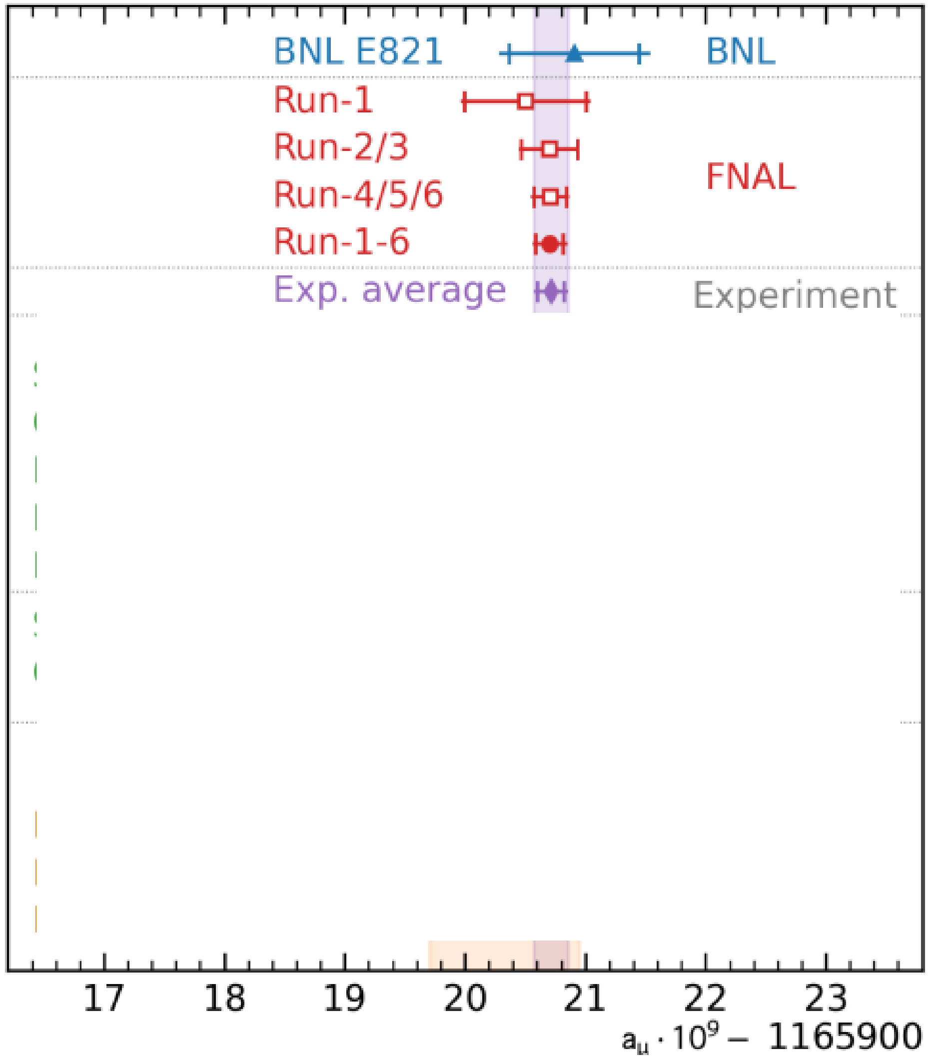

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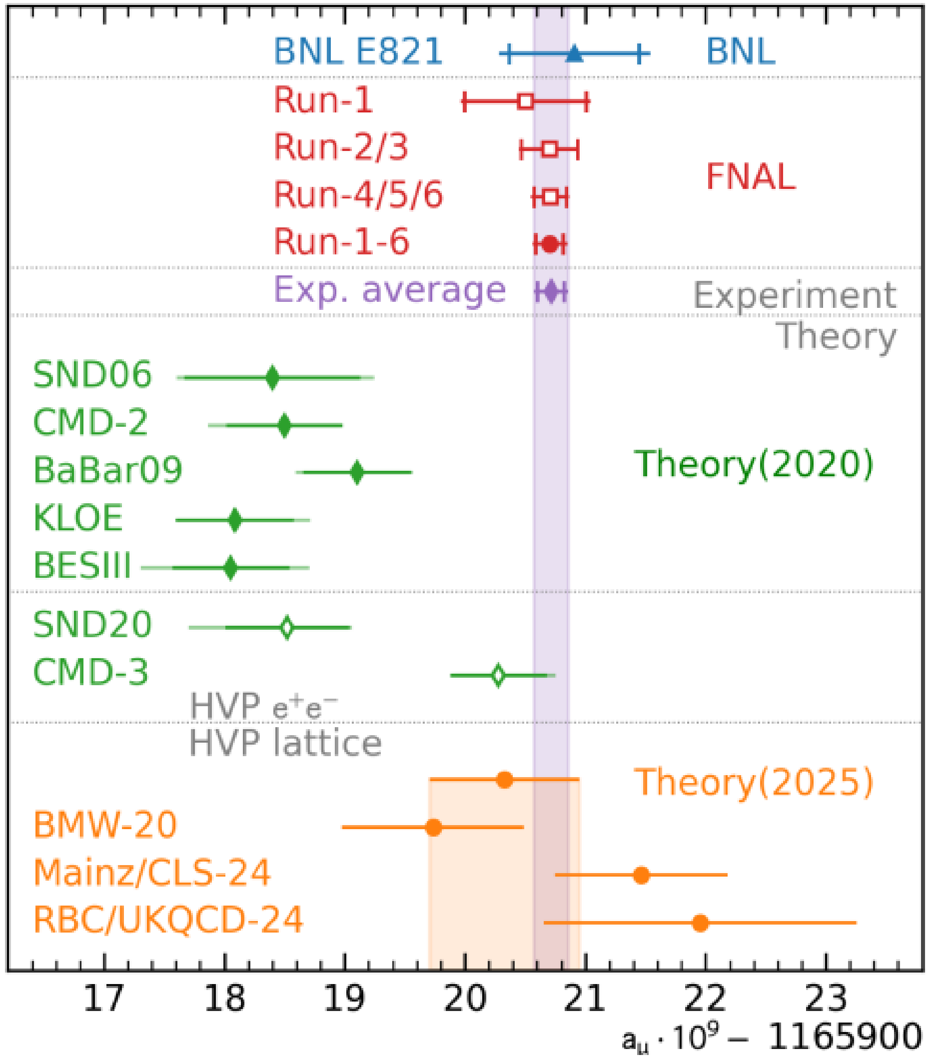

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  - Theory from lattice rather HVP e^+e^- a.k.a. **the dispersive method**

Dispersive method

- Integral over q^2 of the virtual photon

$$a_\mu^{\mathrm{HVP}} = \frac{\alpha}{\pi^2} \int_0^\infty \frac{dq^2}{q^2} K_0(q^2)\, \Pi_{\mathrm{had}}(q^2)$$

- *K* is a kinematic QED kernel that solely depends on the muon mass
- Π_{had} is the hadronic vacuum polarization function that describes the non-perturbative contribution from hadrons
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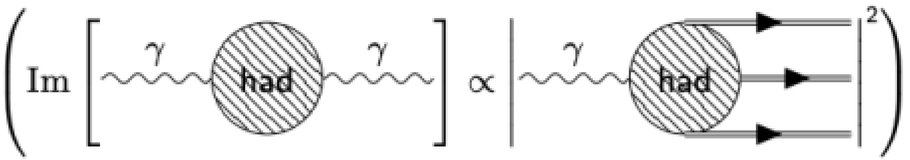

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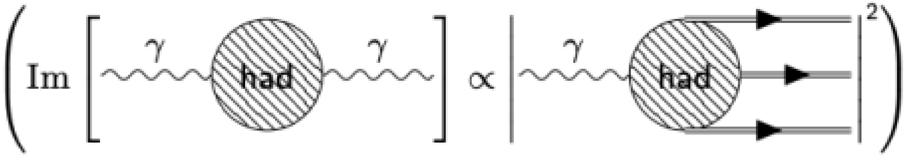
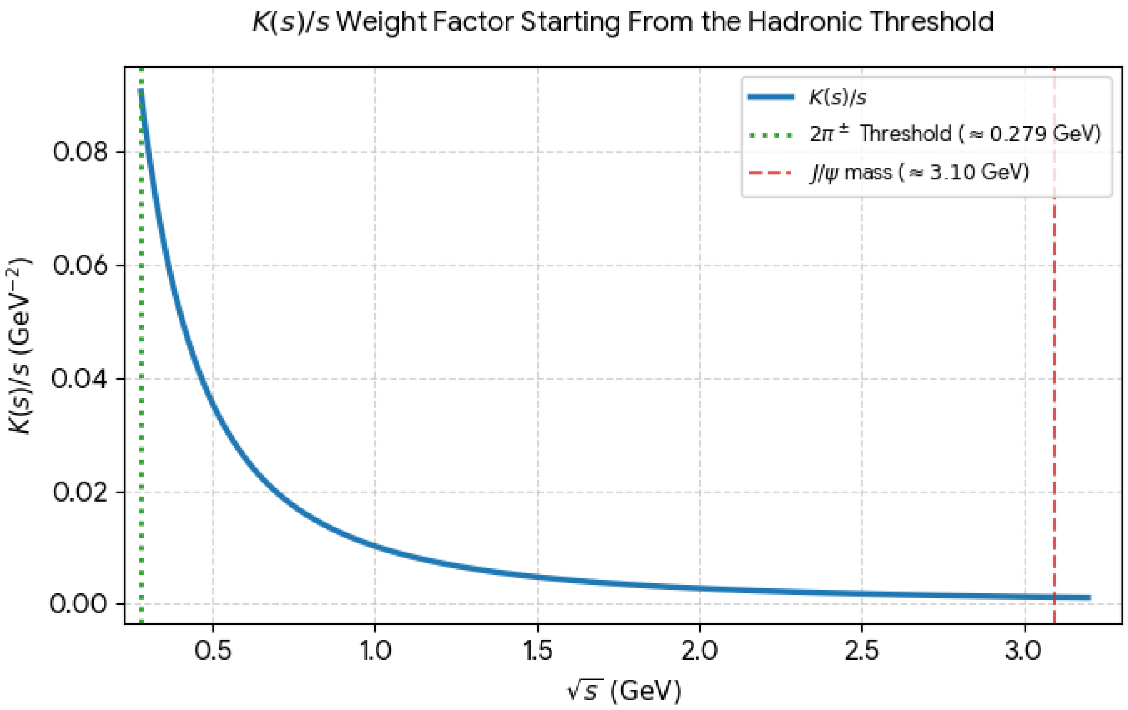


- Final expression

$$a_\mu^{\mathrm{HVP,LO}} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^\infty ds\, K(s)\sigma^{(0)}(e^+e^- \to \mathrm{hadrons}),$$

Kernal function and cross section ratio

- K(s)/s makes clear the region close to threshold is most important



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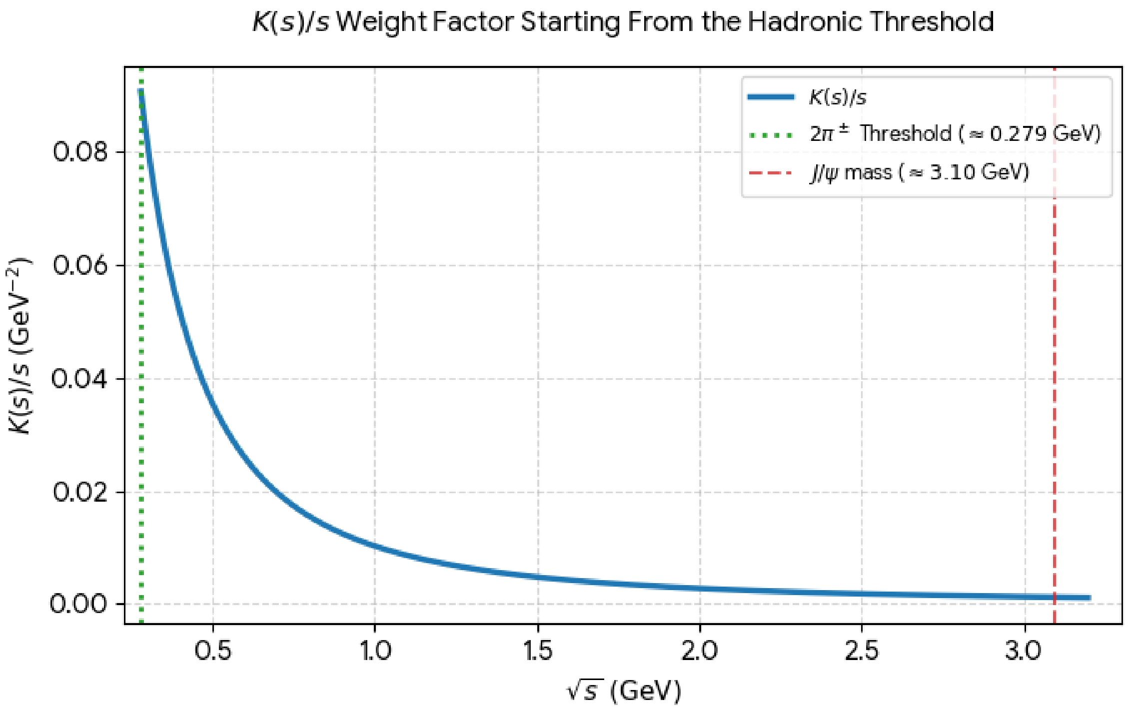
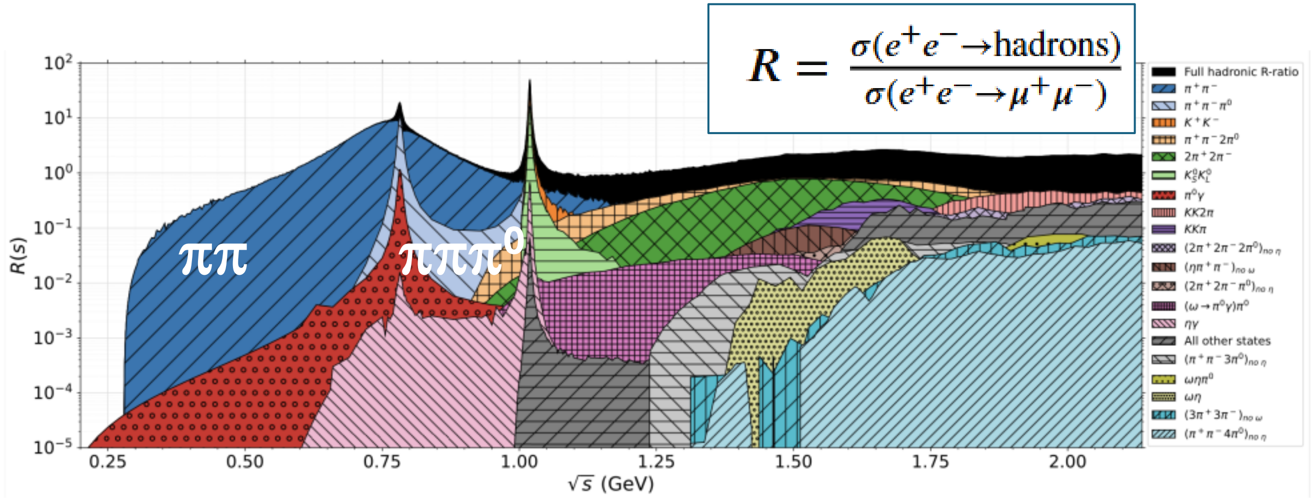
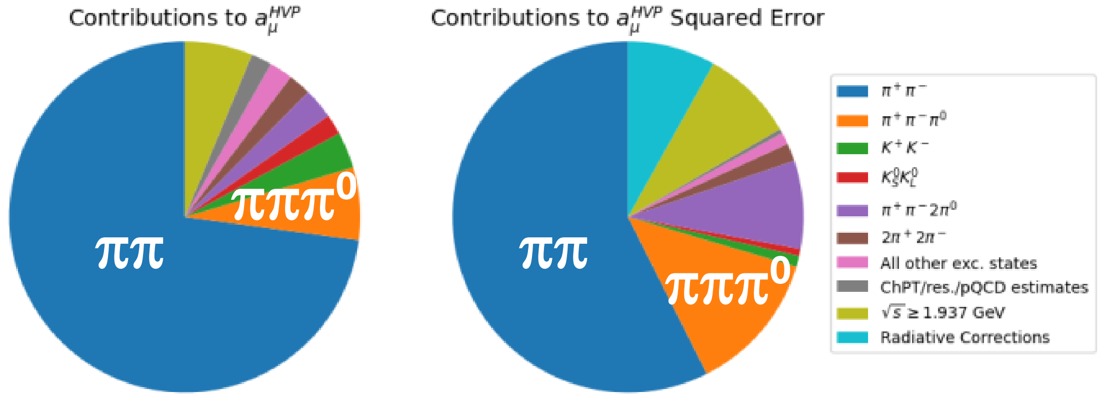
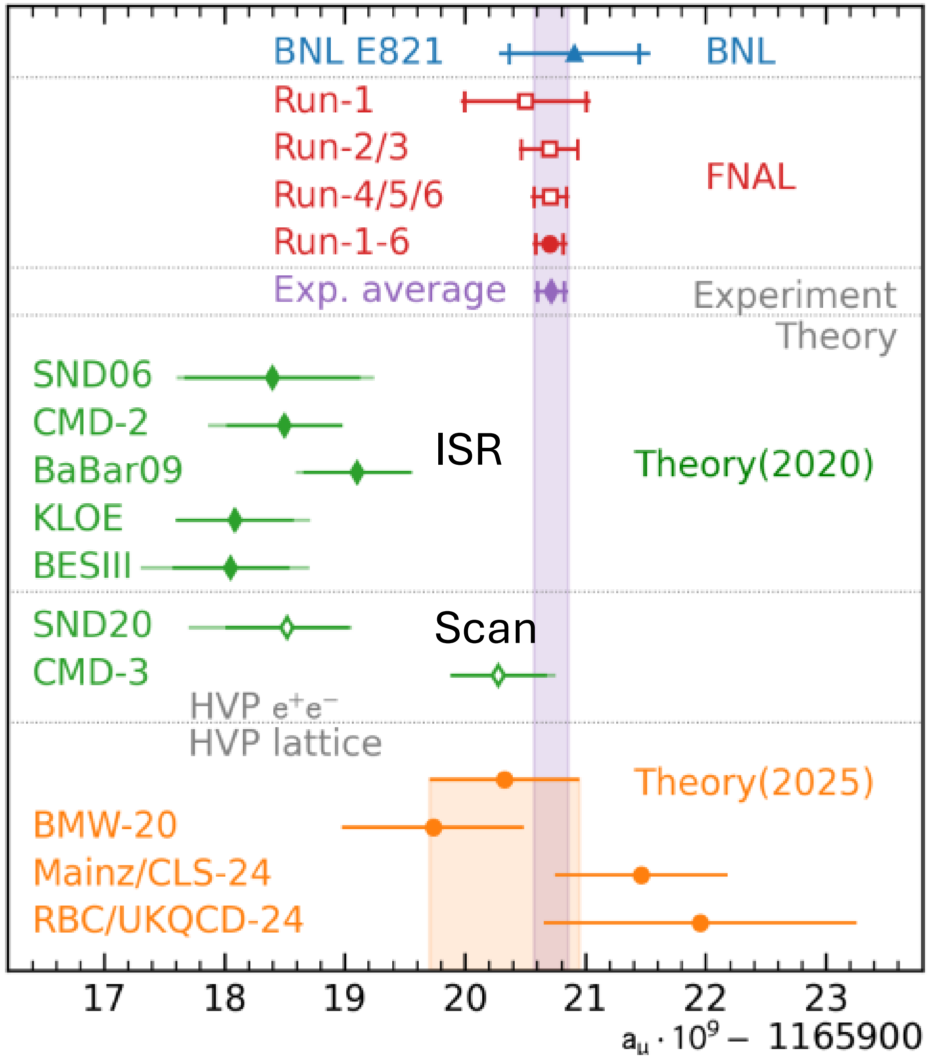






A. Wright Phi to Psi

Status today



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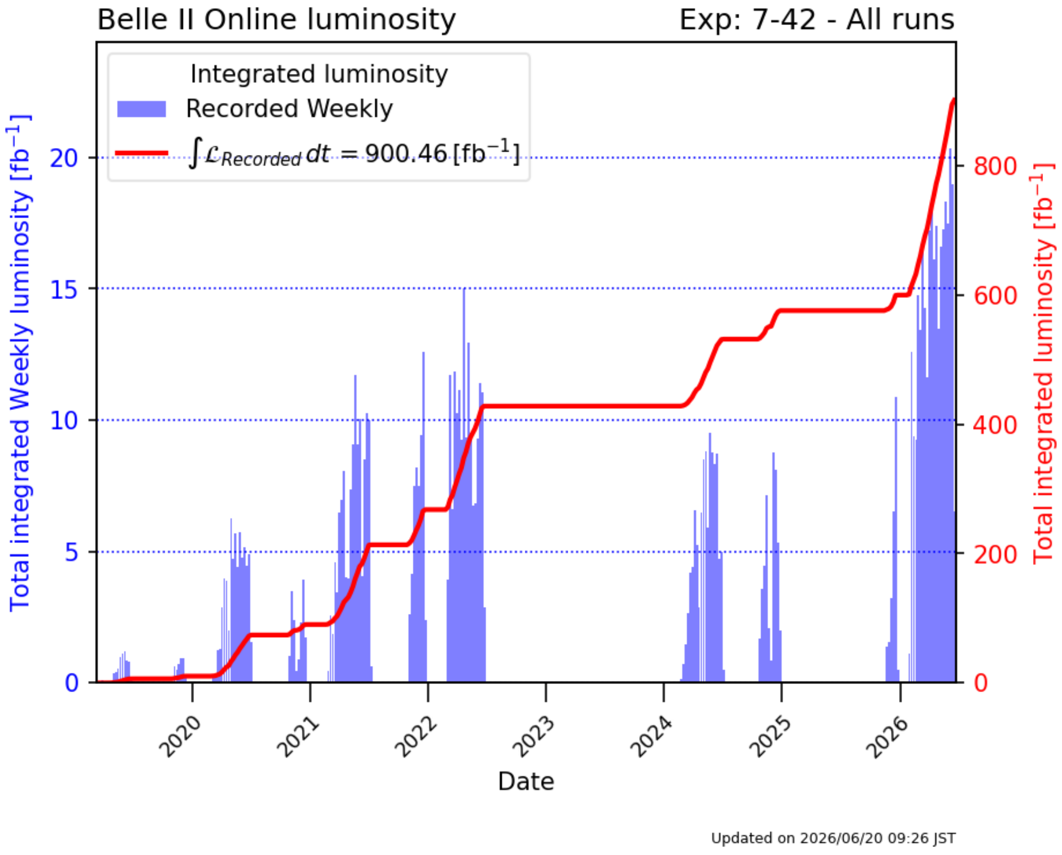
- What changed
  - Lattice now provides the theory value
  - But why does the dispersive disagree
  - New measurements required – enter Belle II

Data sample and detector

- SuperKEKB and luminosity
  - nanobeam scheme to increase instantaneous luminosity by factor 30 to collect multi-ab^{-1} sample
  - **World record instantaneous luminosity March 2026**
    - **5.2×10^{34} cm^{-2}s^{-1}**
    - Target 6×10^{35} cm^{-2}s^{-1}
  - Run 1 2019-2022
    - 365 fb^{-1} at Υ(4S) + 42 fb^{-1} off-resonance to characterize continuum
  - Run 2 2024-
    - + ~500 fb^{-1} so far and exceeded the Belle Υ(4S) dataset – KEK press release



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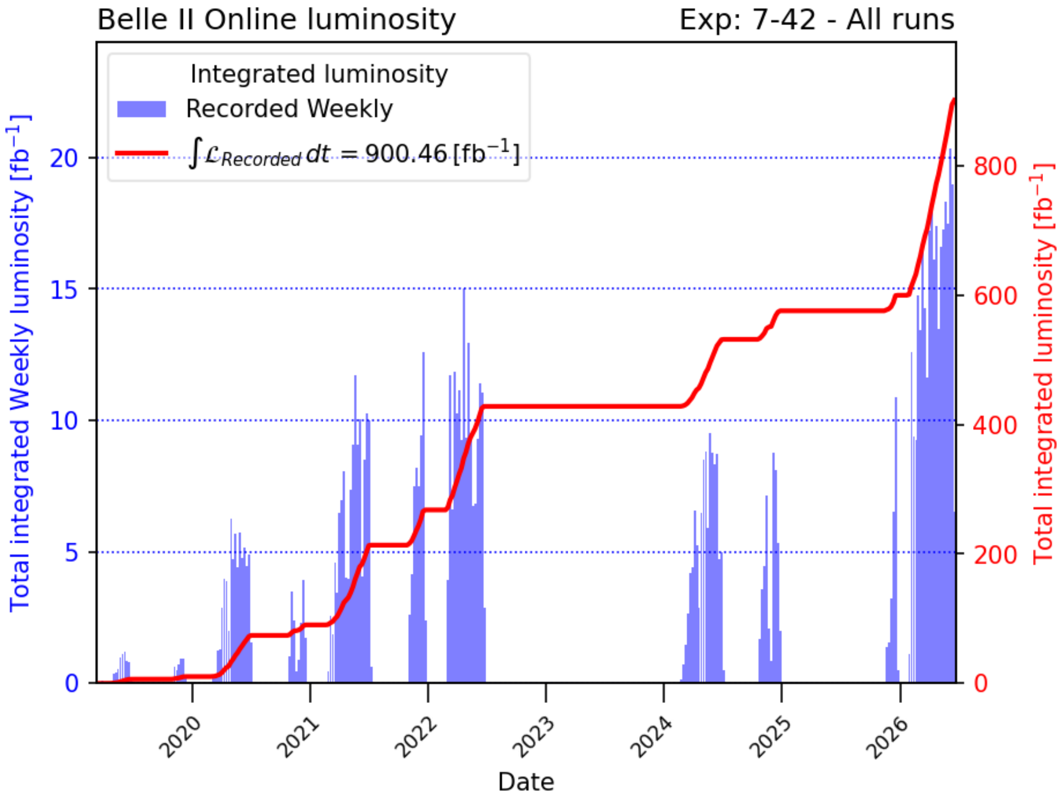
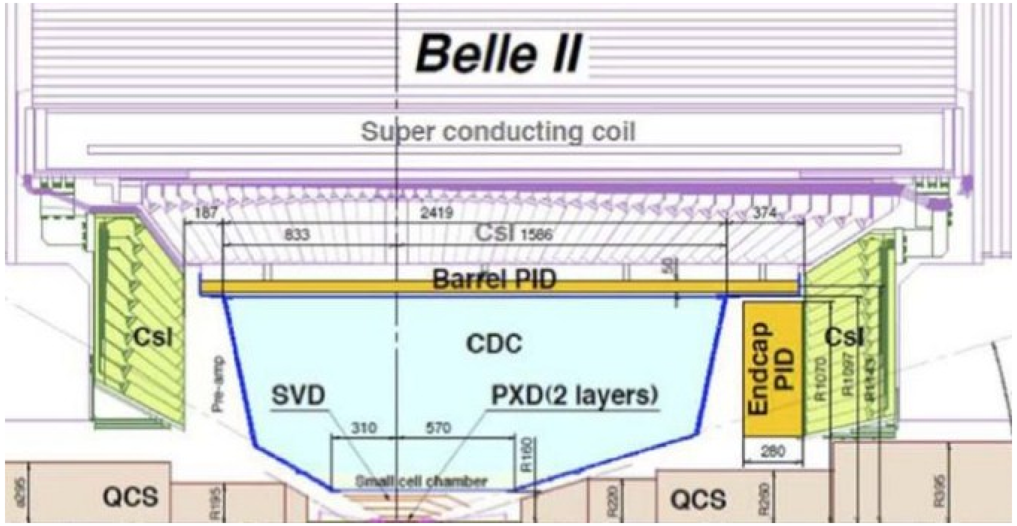
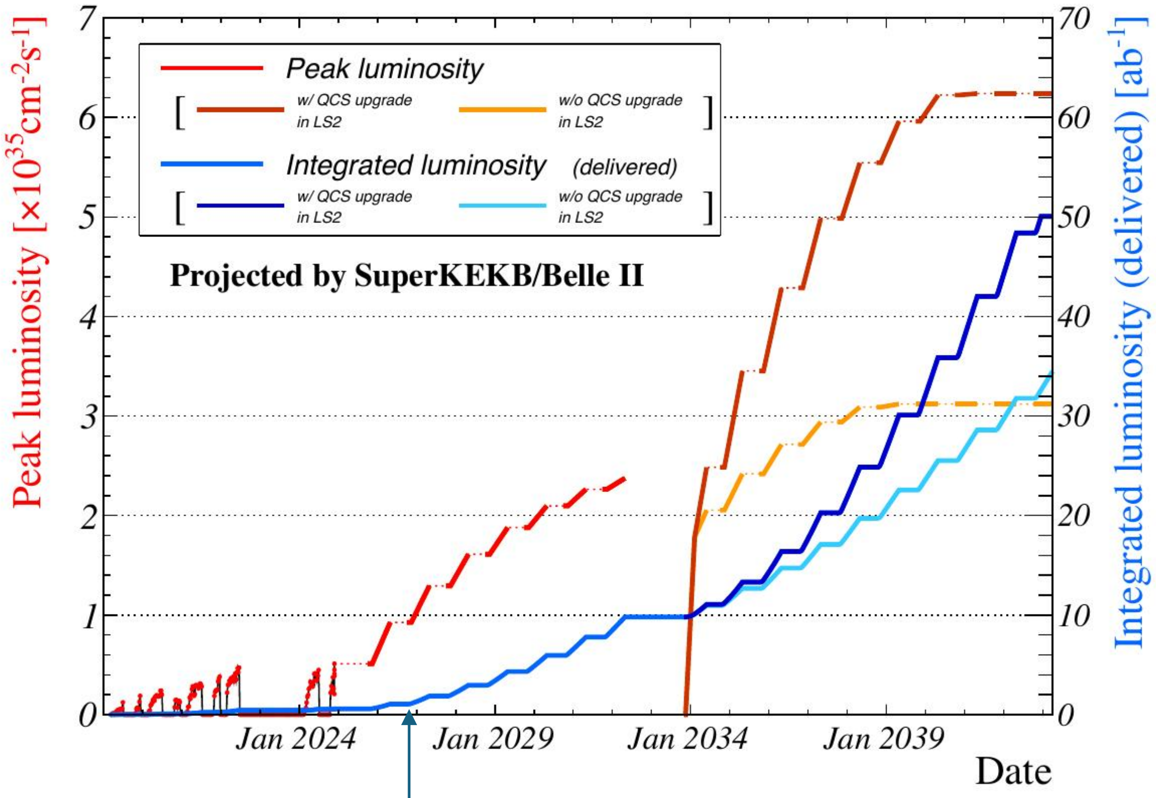
- Belle II detector
  - Si vertexing, low-mass tracking, particle ID, and crystal calorimetry
  - beam-background mitigation key



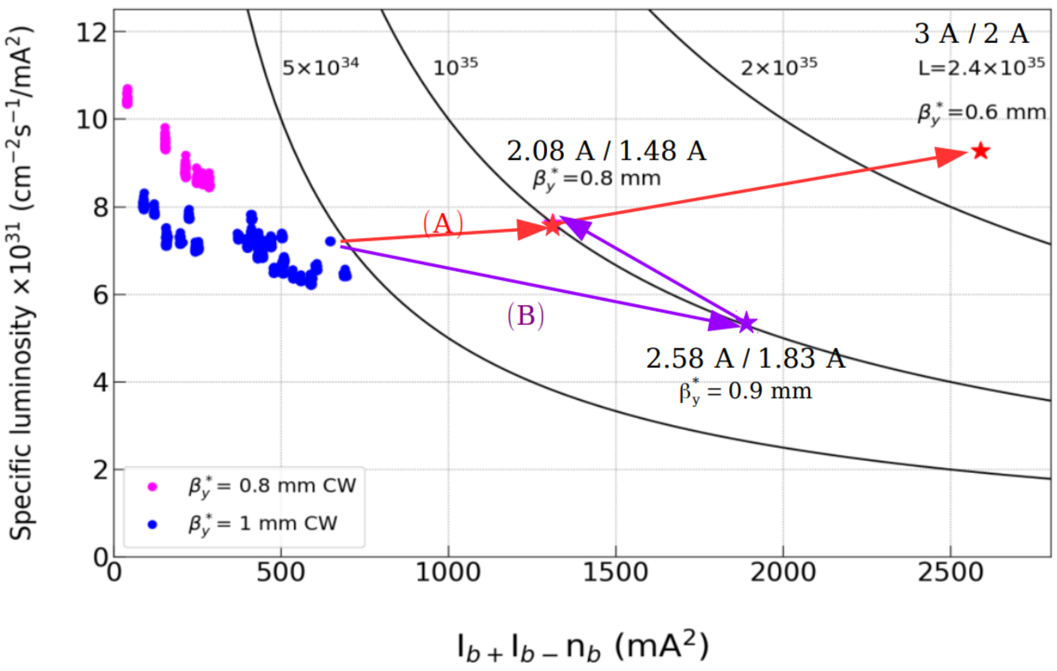


Only the start of the journey



Today

From K. Trabelsi at Flavours at FCC



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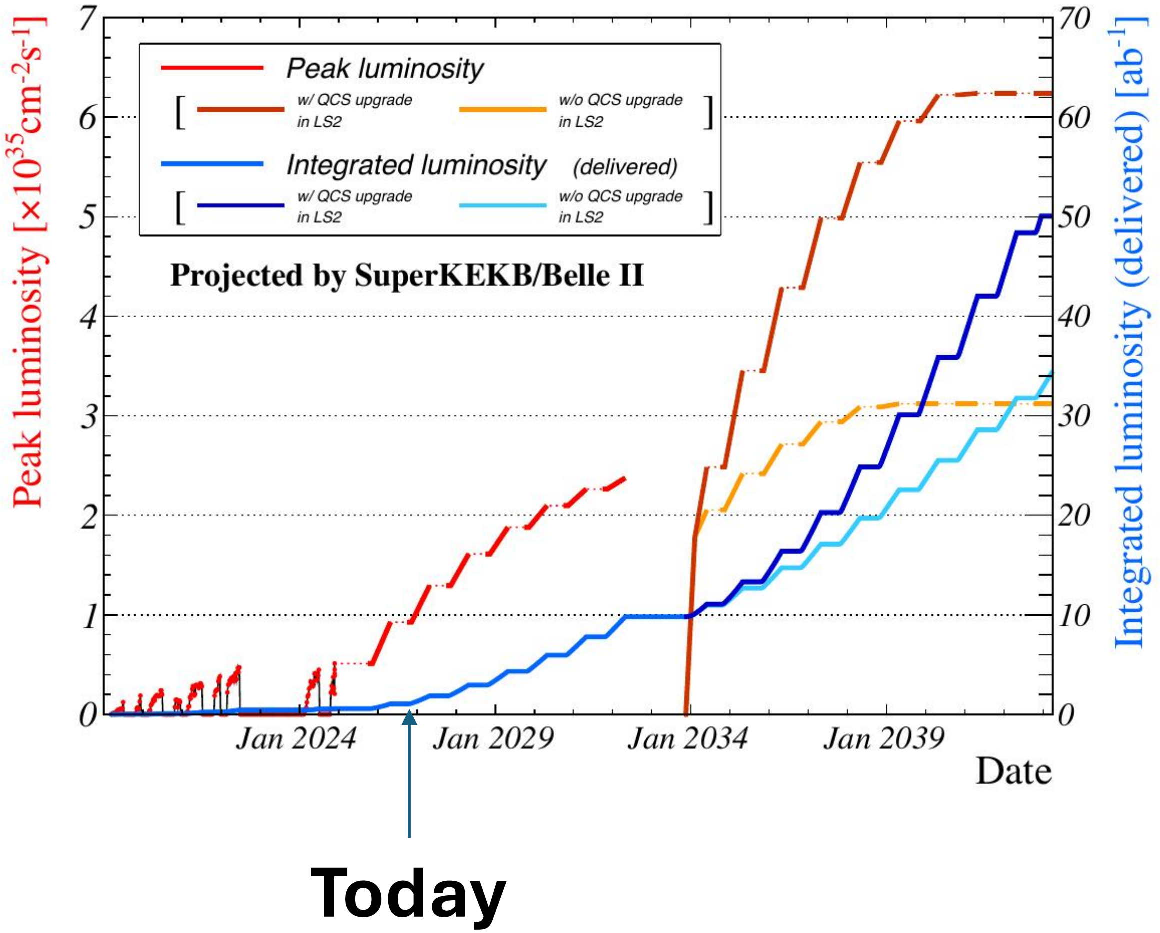

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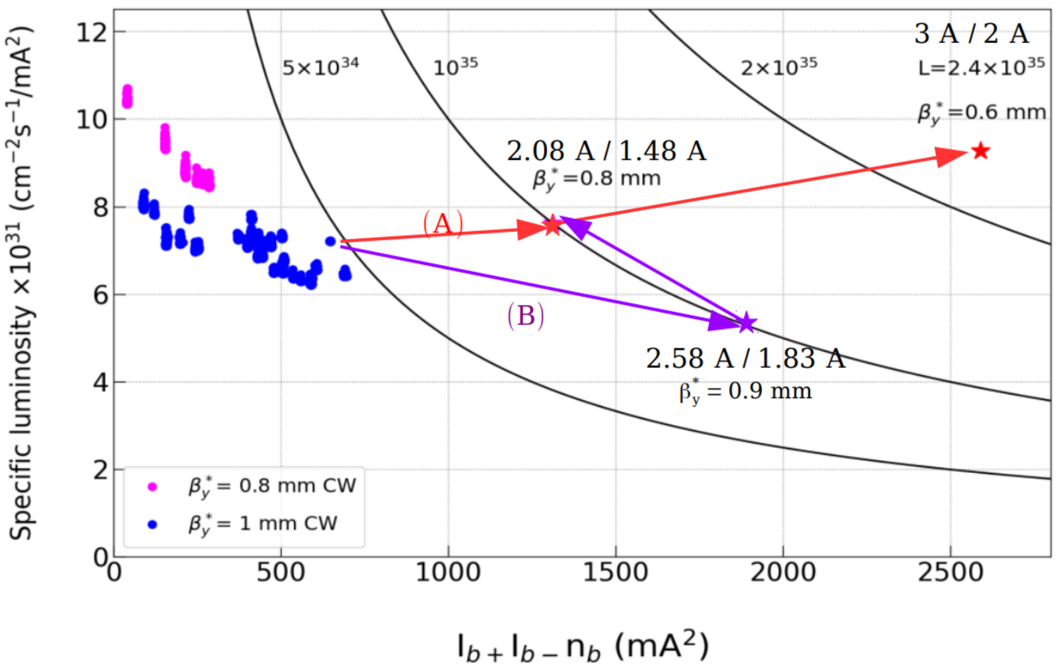


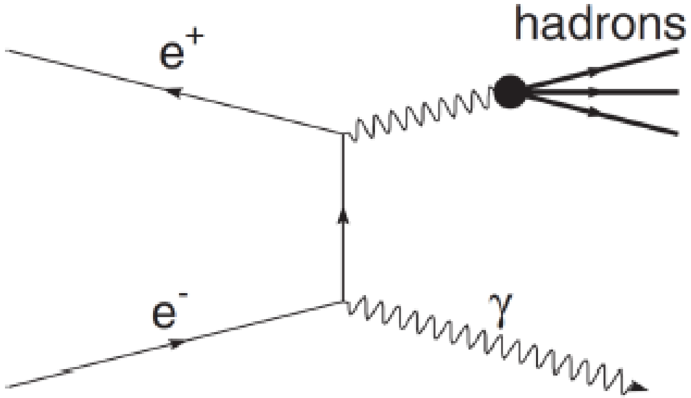
Currently 0.9 mm/1.6 A/ 1.2 A

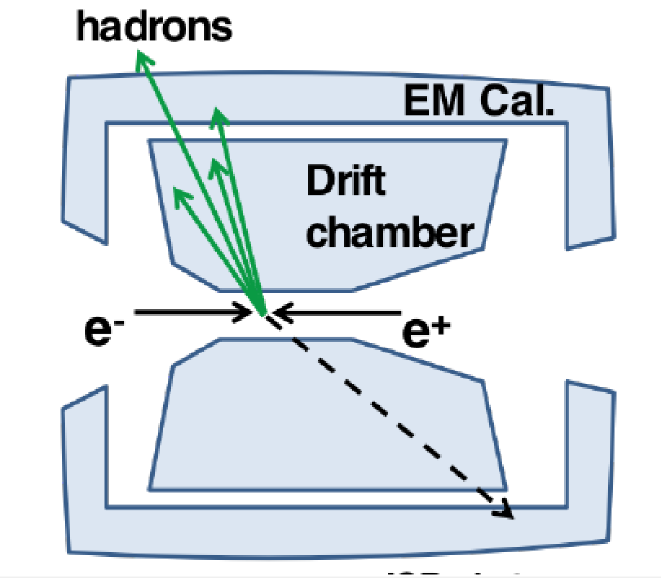
High backgrounds, low injection efficiency

Intensity frontier is challenging

Initial state radiation (ISR) method

- Scan over masses of the hadronic system via ISR
- Scan $s' = s\left(1 - \frac{2E_\gamma^*}{\sqrt{s}}\right)$, where E_γ^* is ISR photon energy in c.m. frame and $\sqrt{s} = 10.58\ \mathrm{GeV}$
- Technique used by BaBar, KLOE and BESIII but **NOT Belle**





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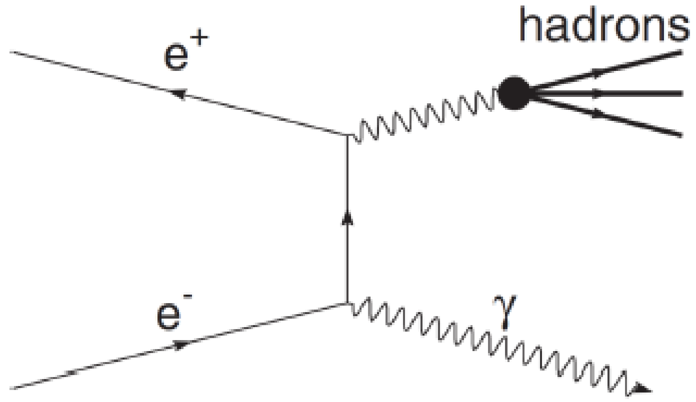

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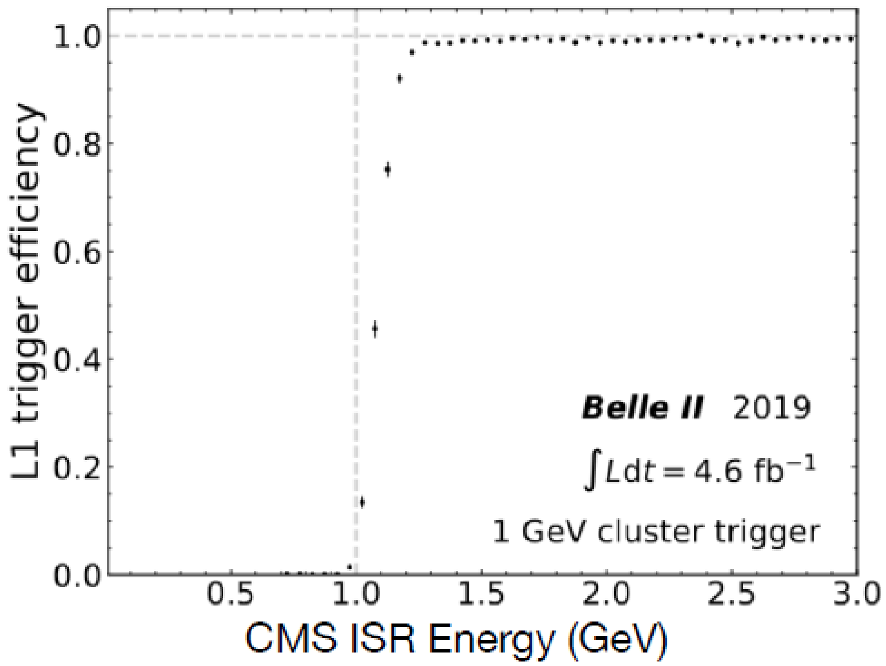
- Technique used by BaBar, KLOE and BESIII but **NOT Belle**
- New at Belle II: L1 trigger for ISR using ECL cluster energy > 1 GeV
- Trigger efficiency measured using independent track trigger lines in $e^+ e^- \rightarrow \mu^+ \mu^- \gamma$ events
  - Efficiency = (99.9±0.1)%



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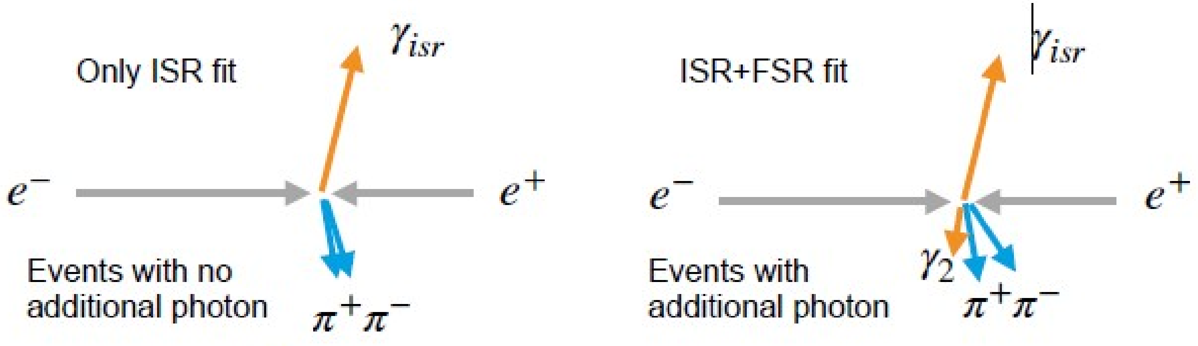
1. Reconstruction for **R-ratio** measurement
  - 1 hard photon + 1 optional photon
  - 2 tracks w/o particle identification (PID) in preselection



Measurement outline (part 1)

- Following BaBar 2012 method
  - PRD **86**, 032013 (2012)
  - Updated without PID – angular distribution to separate muons and pions – preliminary

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     - 3 measured particles: 2 tracks and γ_{ISR} (energy not used)
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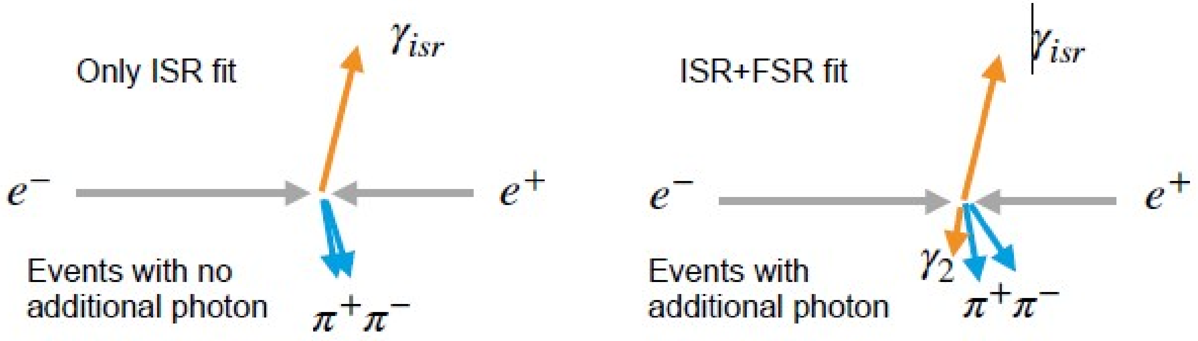
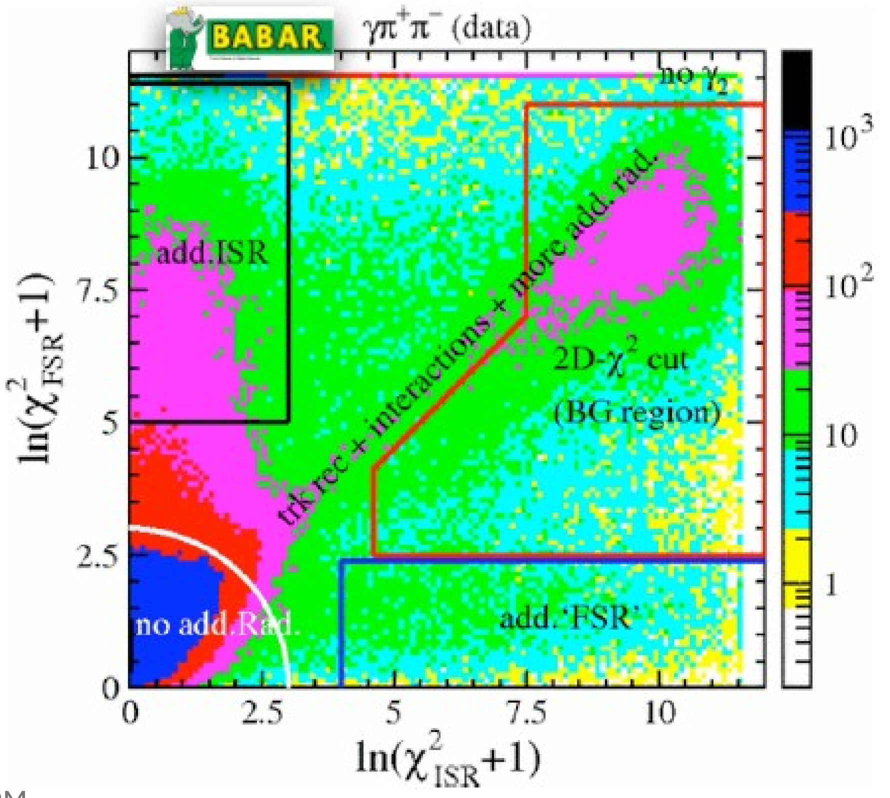
   - **“FSR” fit** only for **events with γ_2 reconstructed**
     - 4 measured particles: 2 tracks and 2 photons (ISR energy not used)





6

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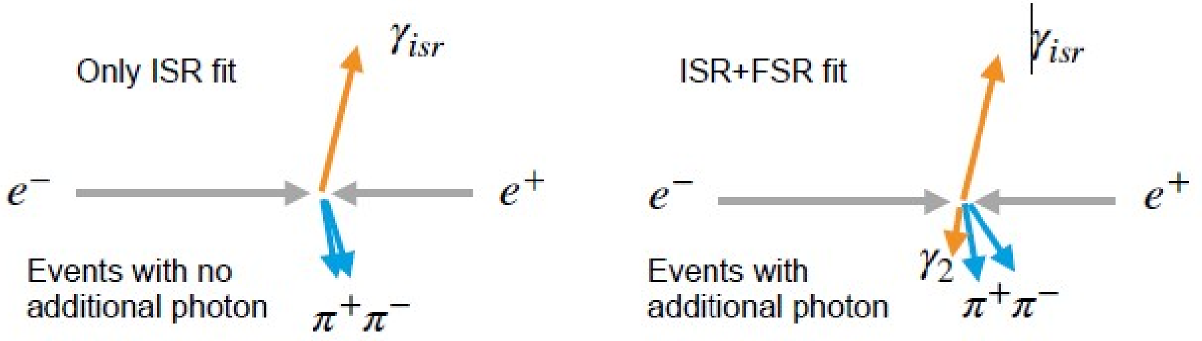
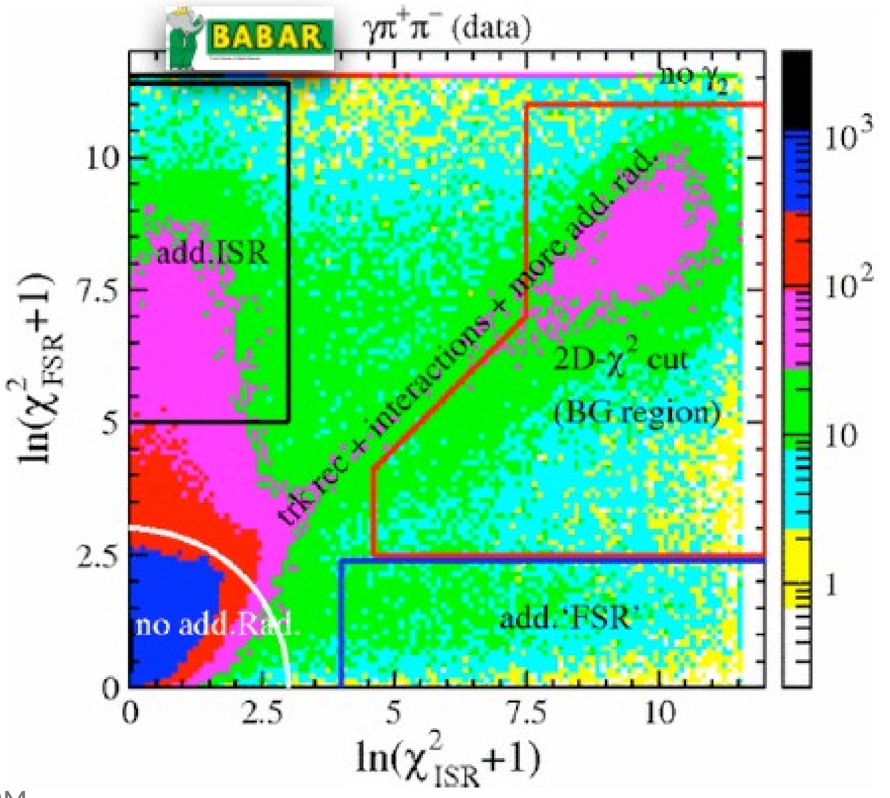
3. PID to classify $\pi\pi$, KK and $\mu\mu$ events





6

Measurement outline (part 2)

- Data set : 427 fb-1 (Run 1)
- QED validation using $e^+ e^- \rightarrow \mu^+ \mu^-(\gamma)$, i.e., radiator function
- Target systematic uncertainty: **0.5%**
- Relying on data-driven approaches for efficiency corrections

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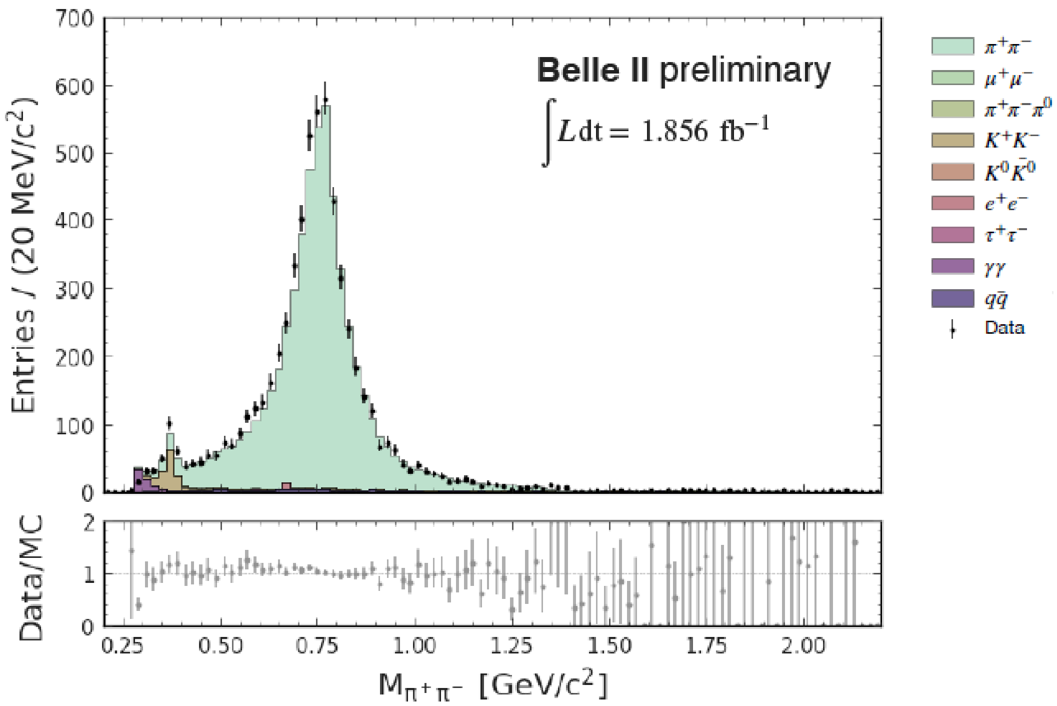
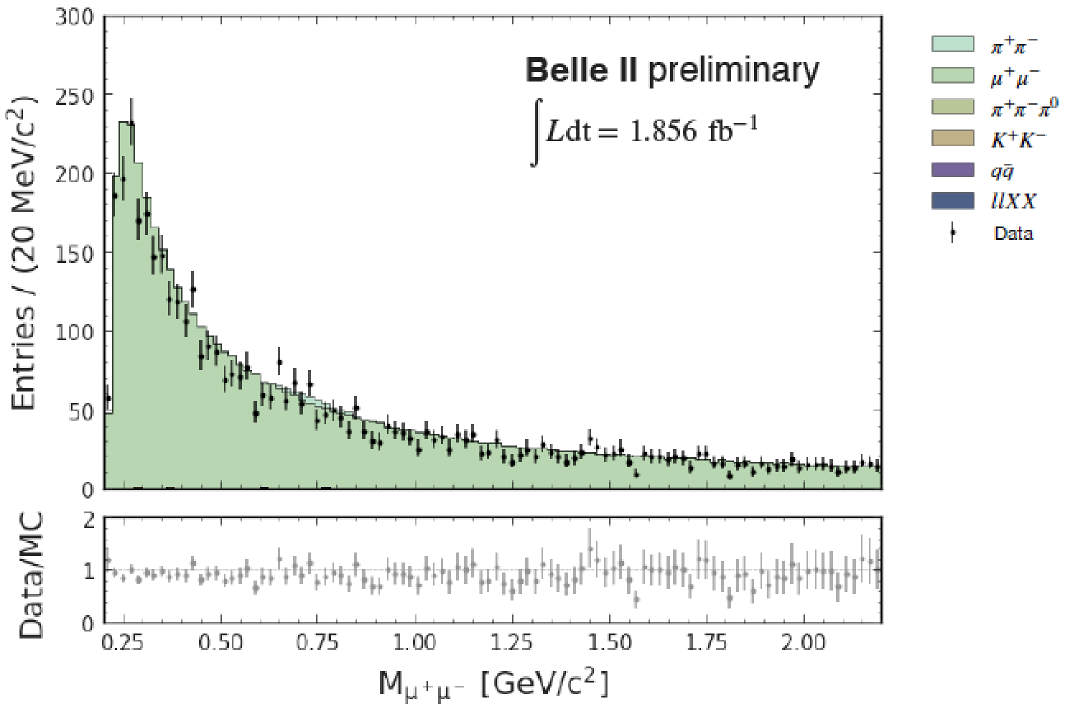
$$\epsilon^{\text{data}} = \epsilon^{\text{MC}} \left(\frac{\epsilon^{\text{data}}}{\epsilon^{\text{MC}}} \right)_{\text{trigger}} \left(\frac{\epsilon^{\text{data}}}{\epsilon^{\text{MC}}} \right)_{\chi^2} \left(\frac{\epsilon^{\text{data}}}{\epsilon^{\text{MC}}} \right)_{\text{PID}} \left(\frac{\epsilon^{\text{data}}}{\epsilon^{\text{MC}}} \right)_{\text{tracking}}$$

Small sample check ($1.9\ fb^{-1}$)

Next few slides from
[Q. Liu @ g-2 Theory Initiative]

- Preliminary selections: ISR in ECL inner barrel, $E^*_{ISR} > 2$ GeV, PID, $P_{track} > 1$ GeV, χ^2_{ISR} cut only





Reasonable data-MC agreement before any efficiency corrections

Small sample check (1.9 fb^{-1})

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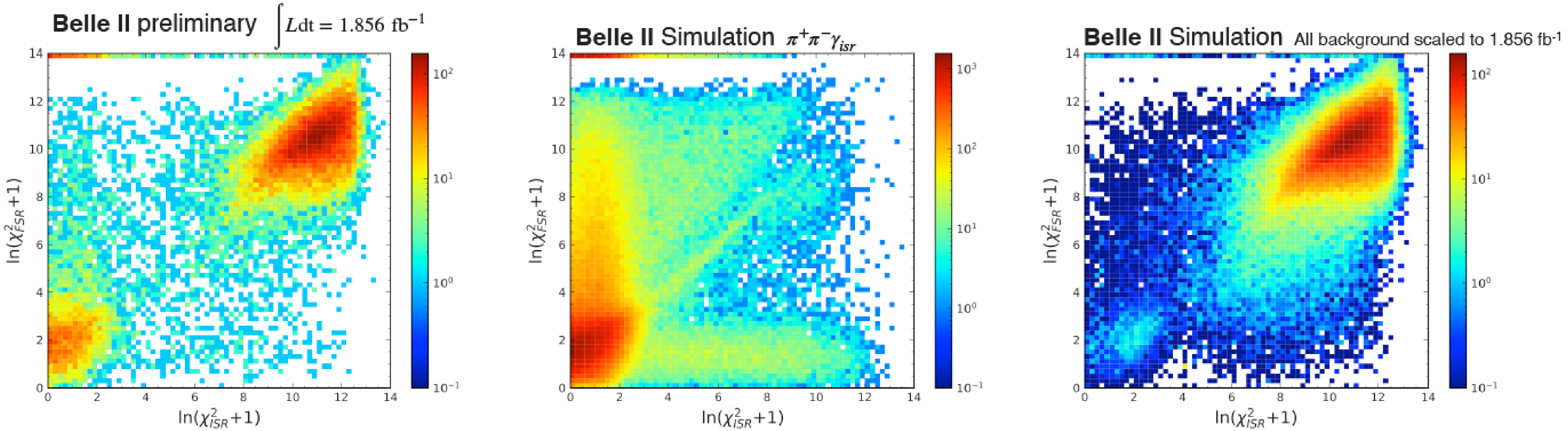
$\pi^+\pi^-$ channel



PHOKHARA

PHOKHARA, KKMC, PYTHIA and EvtGen

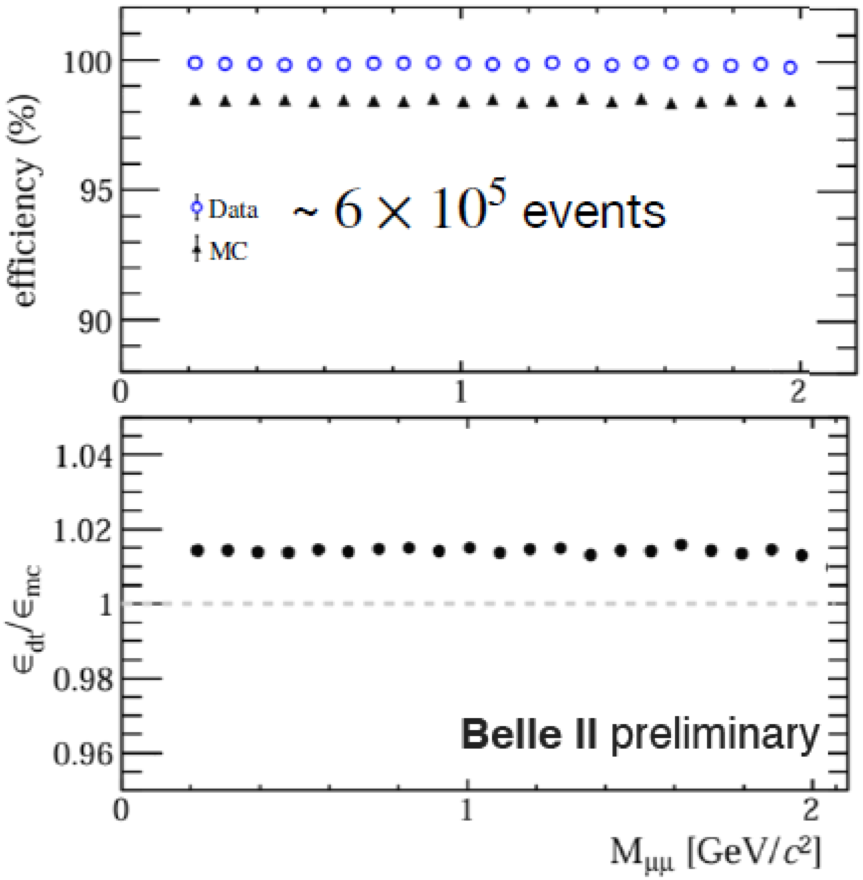
Reasonable data-MC agreement before any efficiency corrections

Trigger efficiency status: $e^+ e^- \rightarrow \mu^+ \mu^- (\gamma)$

- Trigger efficiency study using orthogonal trigger lines
  - Our ISR trigger: Total **ECL** energy above 1 GeV
  - Reference trigger: At least one 3D track with p > 0.7 GeV in **CDC**
- Trigger efficiency is then measured by:

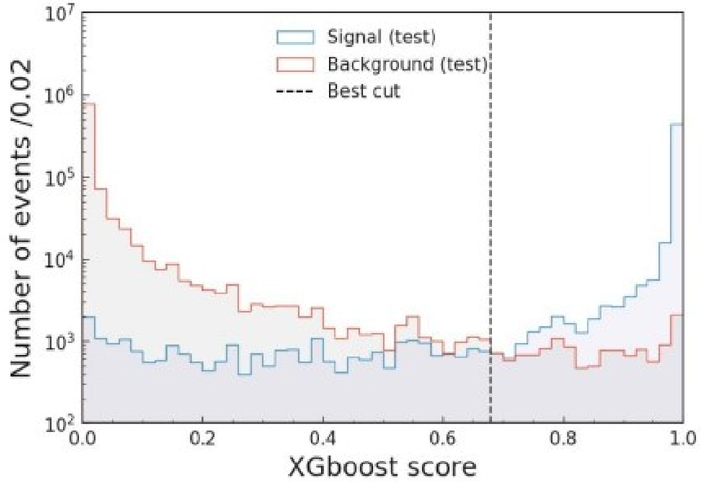
$$\epsilon_{\mathrm{ECL}} = \frac{N_{\mathrm{ECL} \bigcap \mathrm{CDC}}}{N_{\mathrm{CDC}}}$$

- MC underestimated but data efficiency is excellent and can be used directly

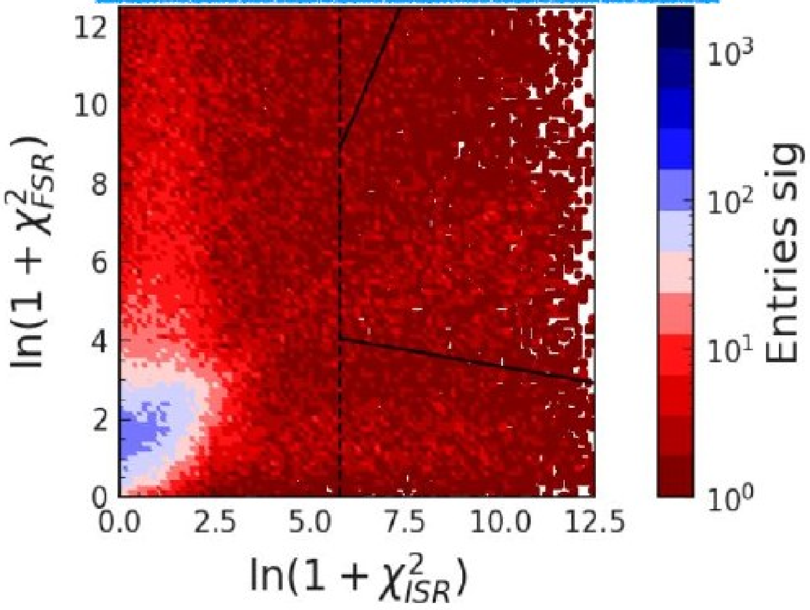


χ^2 selection status

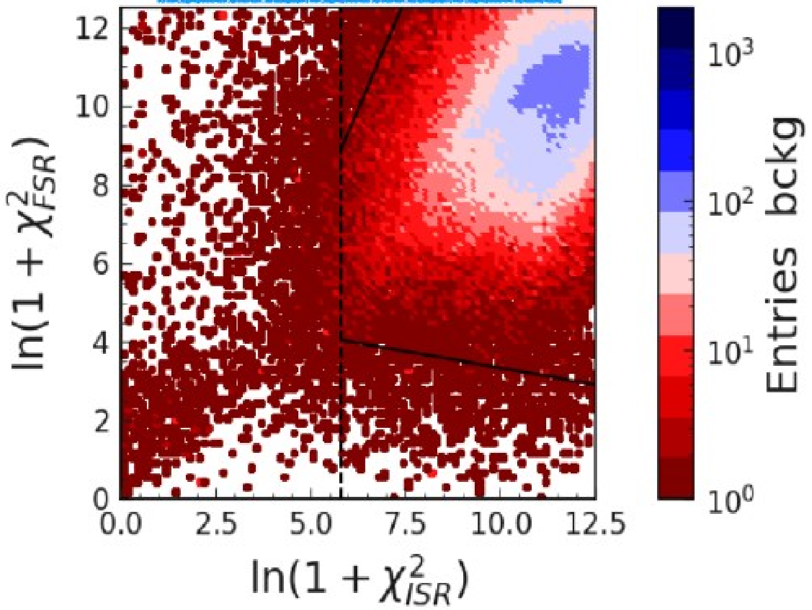
- BDT trained only with the two χ^2
- Approximate BDT by simple “linear cuts” for similar $S/\sqrt{S+B}$ and cut efficiency



Signal MC: $\pi^+\pi^-$/ $\mu^+\mu^-$ /K^+K^-



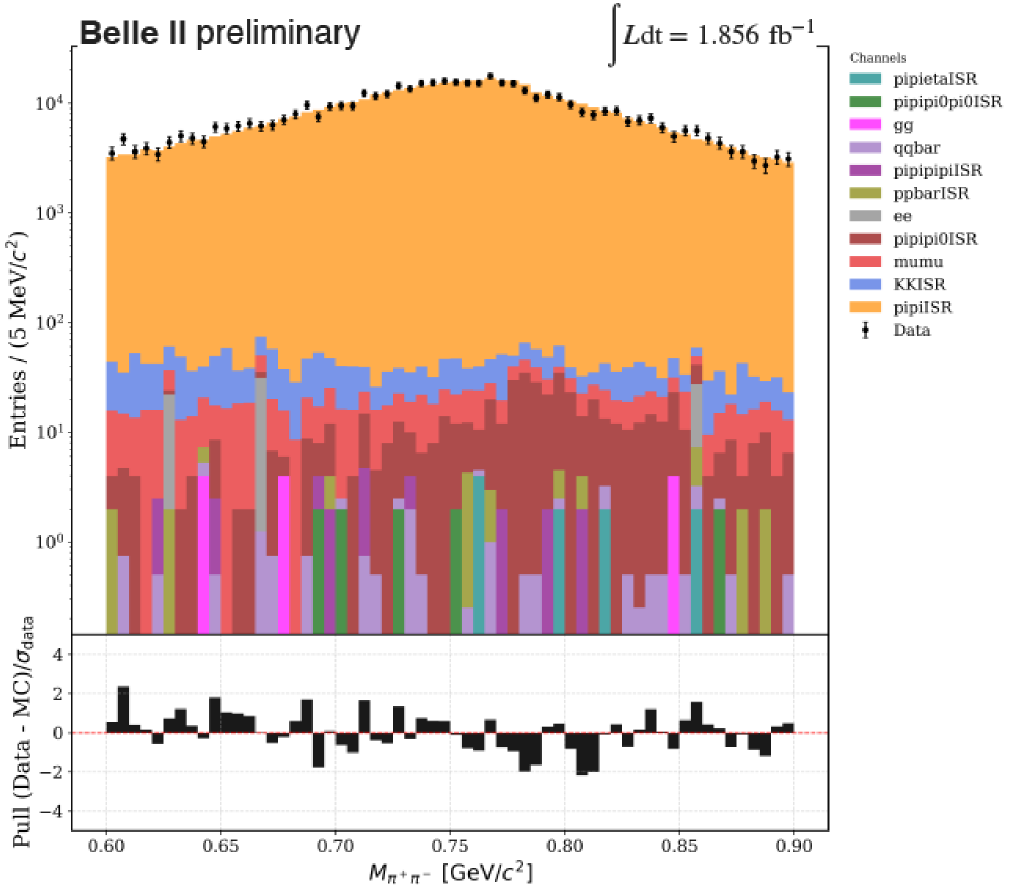
Background MC



PID status

- PID variables in Belle II
  - pionID = $\mathscr{L}_\pi/(\mathscr{L}_e + \mathscr{L}_\mu + \mathscr{L}_\pi + \mathscr{L}_K + \mathscr{L}_p + \mathscr{L}_d)$ is under investigation
  - The other solutions: binaryPID like $\mathscr{L}_\pi/(\mathscr{L}_\pi + \mathscr{L}_K)$, weightedPionID and Neural network based PID
- Tag and probe method to study the efficiency and mis-identification
  - Use χ^2_{ISR} and stringent PID cut for the tag
  - Enhance pion purity with the ρ region

ISR in CDC, $0.4<\theta_{\pi^\pm}<2.5$, and no PID cut on the probe

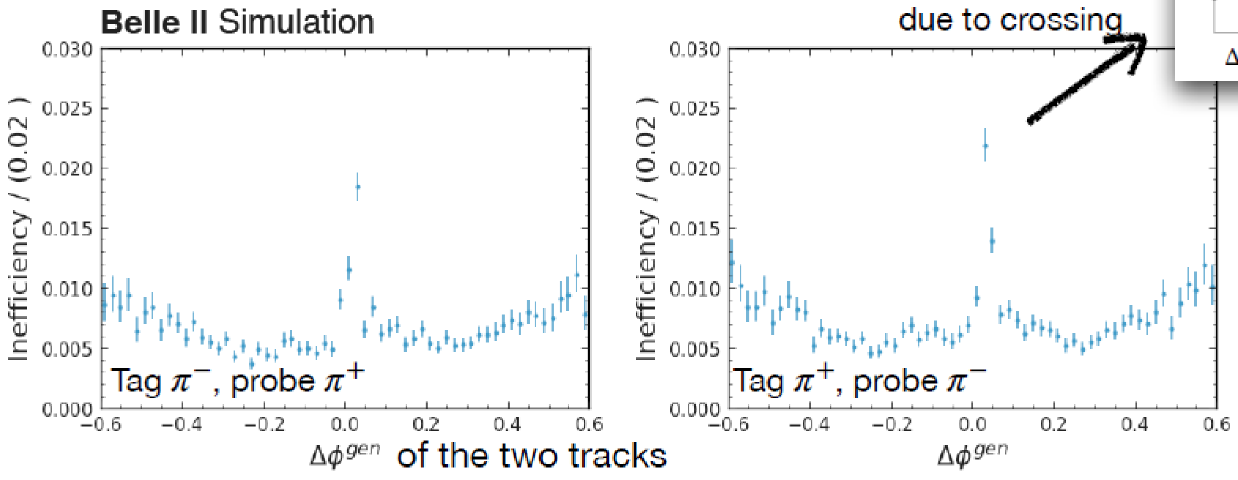


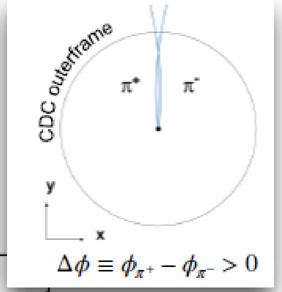
Tracking status

- Tracking inefficiency study with loose requirements (ISR in ECL inner barrel → in CDC, track P > 0.5 GeV instead of 1 GeV)
  - Inefficiency:

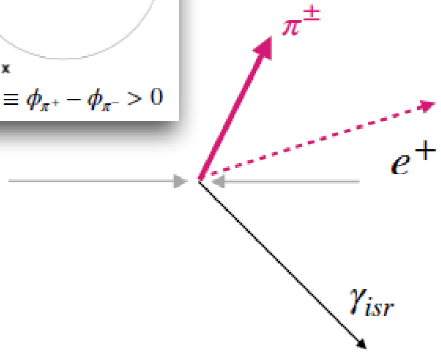
$$1 - \frac{\mathrm{N(predicted\ and\ reconstructed)}}{\mathrm{N(predicted)}}$$

Inefficiency peak due to crossing





- The $\pi^{+(\text{ or }-)}$: One track is selected with primary good track conditions
  - P > 0.5 GeV
  - [dr < 0.1] and [abs(dz) < 5.0]
  - Theta in CDC Acceptance
  - pValue > 0.0



MC-based "prediction"

- The MC track of the other pion is required to have
  - P > 0.5 GeV,
  - Theta in CDC Acceptance

- Atleast one reconstructed ISR Photon
  - E_{CM} > 2GeV
  - In CDC Acceptance

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Tracking status

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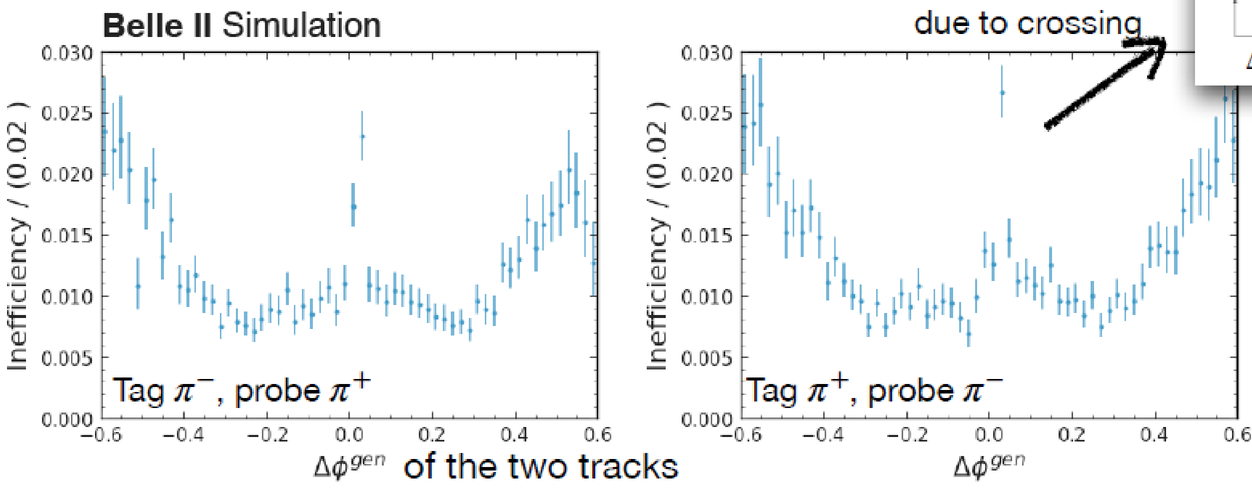

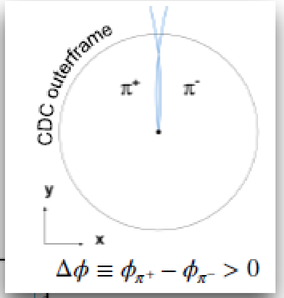

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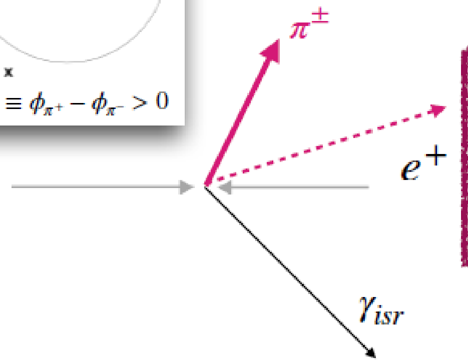

Data-driven prediction

- The recoil (calculated by 1C fit) is required to have
  - P > 0.5 GeV, $\chi^2 < 1$
  - Theta in CDC Acceptance

- Atleast one reconstructed ISR Photon
  - E_{CM} > 2GeV
  - In CDC Acceptance

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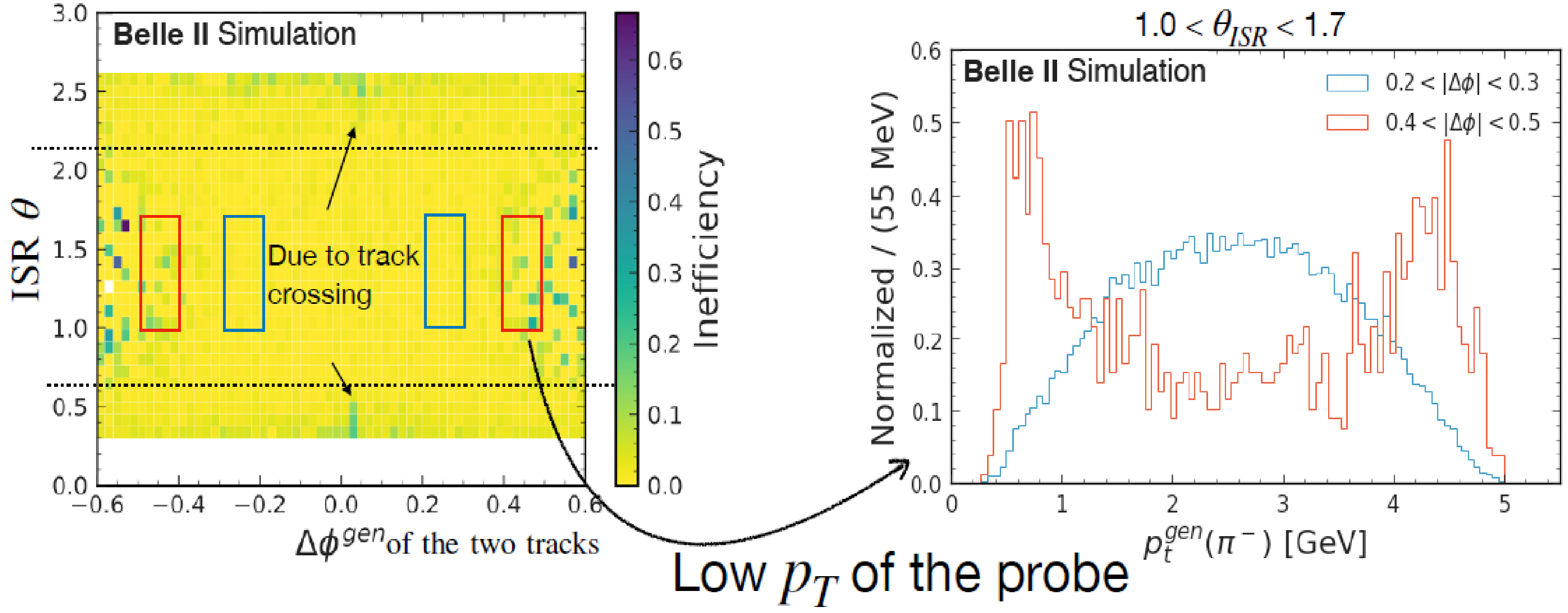
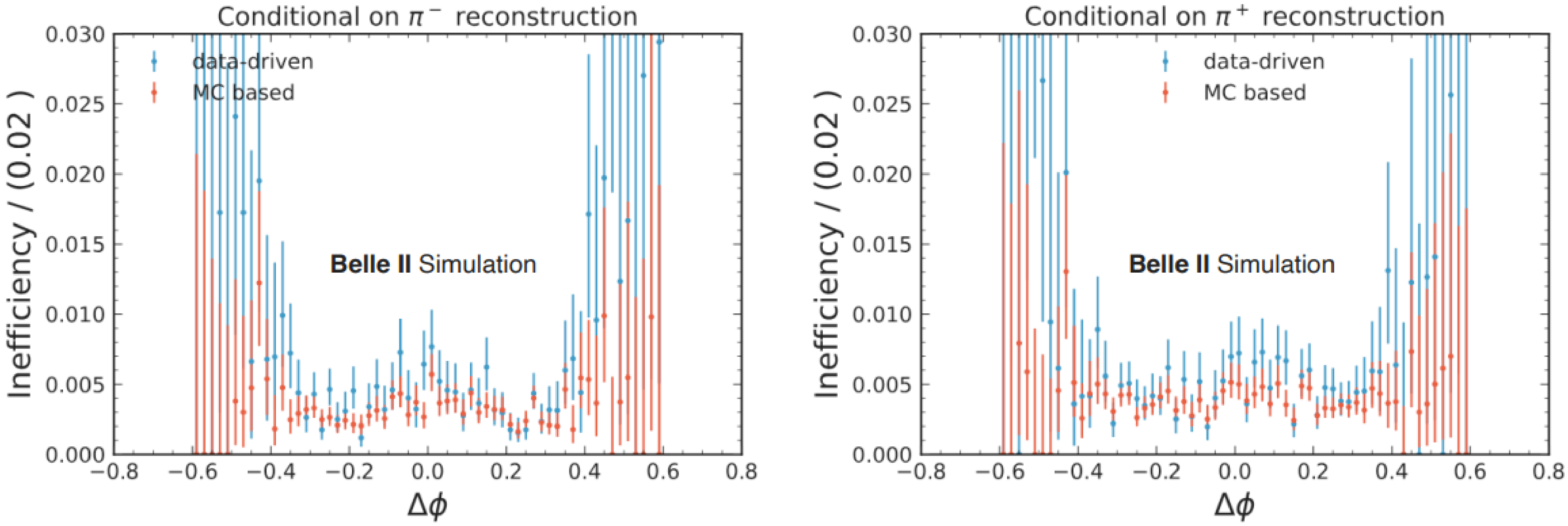
Tracking study

- Understanding of the inefficiency peaks with π^+ as the tag (probing π^-)
  - ISR in ECL inner barrel ($0.65 < \theta < 2.16$) will reduce the inefficiency peak !



Tracking study

- Tracking inefficiency study with ISR in ECL inner barrel region and track P > 1 GeV
  - Good agreement between the data-driven approach and the MC-based one



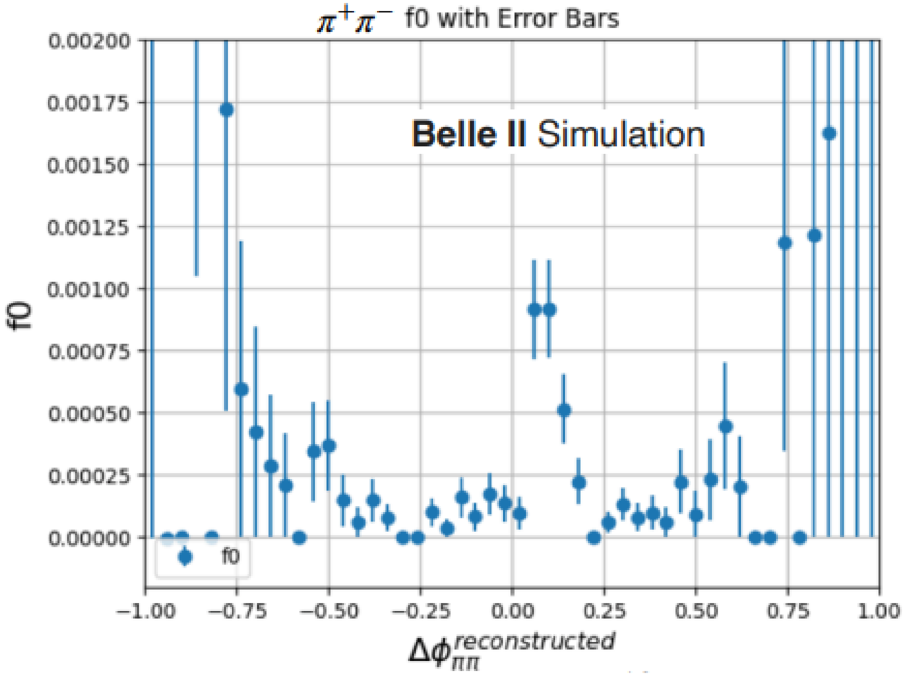
Tracking status: correlated loss correction

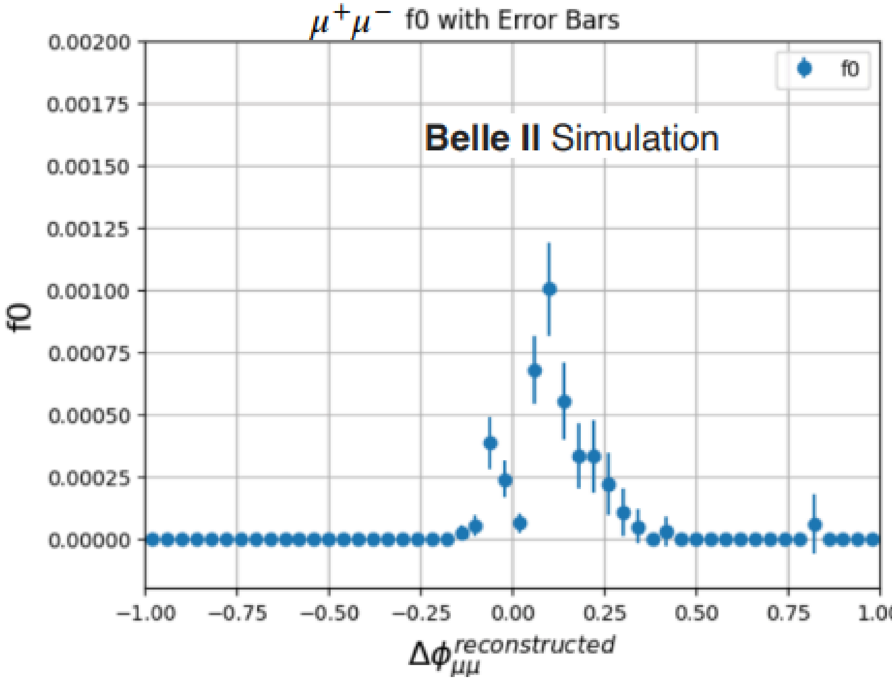
- Correction factor $f_0 = \frac{N_0}{N} - \frac{N_1^2}{4NN_2}$
  - N_0, N_1, N_2 are number of events with zero, one and two tracks
  - $N = N_0 + N_1 + N_2$, with N estimated by lifting track cuts for the tag

- Ongoing studies:
  - inefficiency caused by extra track reconstruction
  - Background subtraction and efficiency projection using data from the ρ region

ISR in CDC

$P_{\pi^\pm} > 1$ GeV





Conclusion on $e^+e^- \rightarrow \pi^+\pi^-(\gamma)$

- The key selection components and their control studies in place
  - Trigger
  - χ^2 selection
  - PID
  - Tracking
- Blinding strategy in place too to allow large samples to be used
- These will be combined for the *R* measurement
- Where it sits will be important in understanding the current incompatibility of the LQCD and dispersive predictions

Phys. Rev. D 110, 112005 (2024)

$\boldsymbol{\sigma(e^+e^- \to \pi^+\pi^-\pi^0)}$

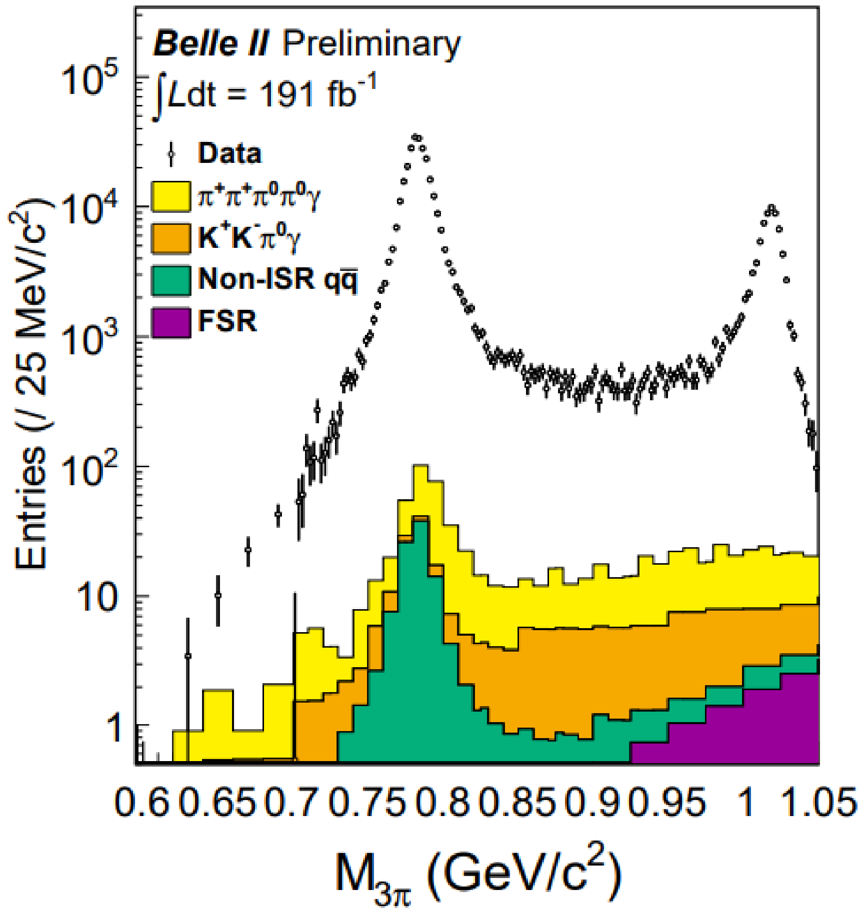
Signal process : $e^+e^- \to \gamma_{\text{ISR}}\pi^+\pi^-\pi^0(\to \gamma\gamma)$

Signal spectrum, Efficiency

$$\frac{dN_{\text{signal}}}{dm} = \sigma_{ee\to 3\pi} \cdot \varepsilon \cdot \frac{d\mathcal{L}_{\text{eff}}}{dm}$$

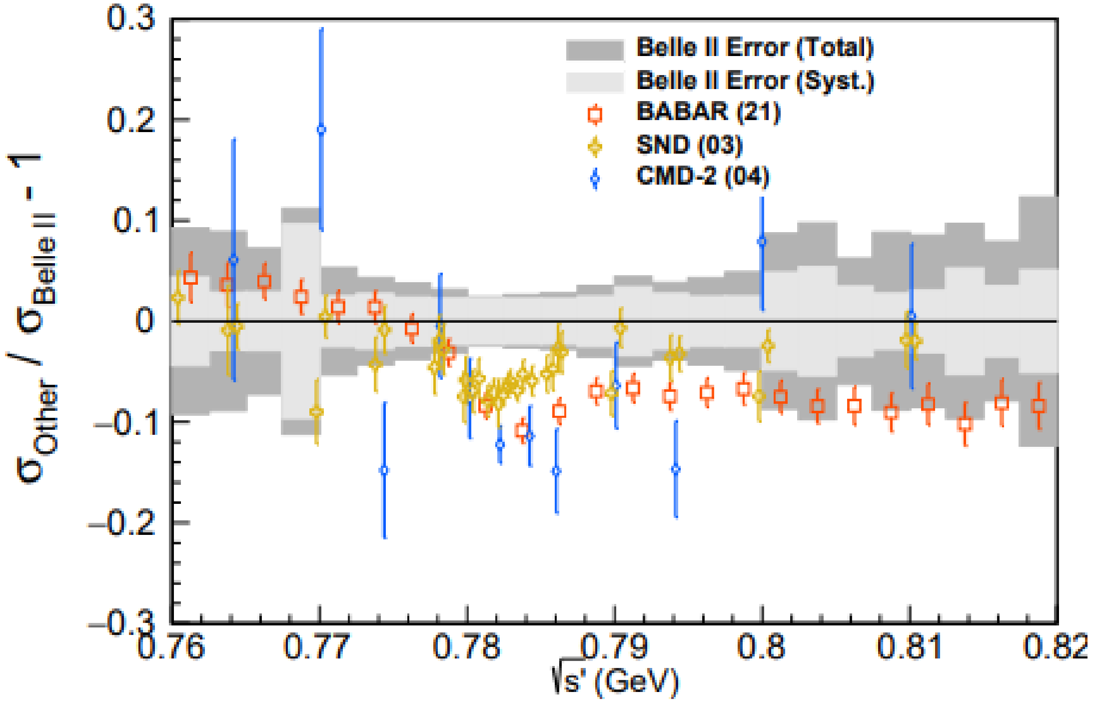
3π mass, Cross section, Effective luminosity

- Initial-state radiation technique – wide invariant mass range
- Partial Run 1 data set – 191 fb^{-1}
- Selection via kinematic fits
- Key challenge is π^0 efficiency
  - Custom determination using ω decay
- Background control samples for $e^+e^- \to \pi^+\pi^-\pi^0\,\pi^0\gamma_{ISR}$, $e^+e^- \to q\bar{q}\gamma_{ISR}$ and $e^+e^- \to K^+K^-\pi^0\gamma_{ISR}$



Phys. Rev. D 110, 112005 (2024)

$\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0)$



Source	0.62–1.05 GeV/c^2	
Trigger	0.1	(−0.09)
ISR photon detection	0.7	(+0.15)
Tracking	0.8	(−1.35)
π^0 detection	1.0	(−1.43)
Kinematic fit (χ^2)	0.6	(+0.0)
Event selection	0.2	(−1.90)
Generator	1.2	
Integrated luminosity	0.6	
Radiative corrections	0.5	
MC statistics	0.2	
Background subtraction	0.3–0.5	
Unfolding	0.7–15	
Total uncertainty	2.2-15	
(Total correction $\varepsilon/\varepsilon_{\rm MC} - 1$)		(−4.61)

$$a_\mu^{3\pi} = (49.02 \pm 0.23 \pm 1.07) \times 10^{-10},$$

2.6σ tension with BaBar

Halftime

Actually more like final quarter

Dark sector

- ~85% of the matter in the Universe is non-luminous dark matter

Dark sector

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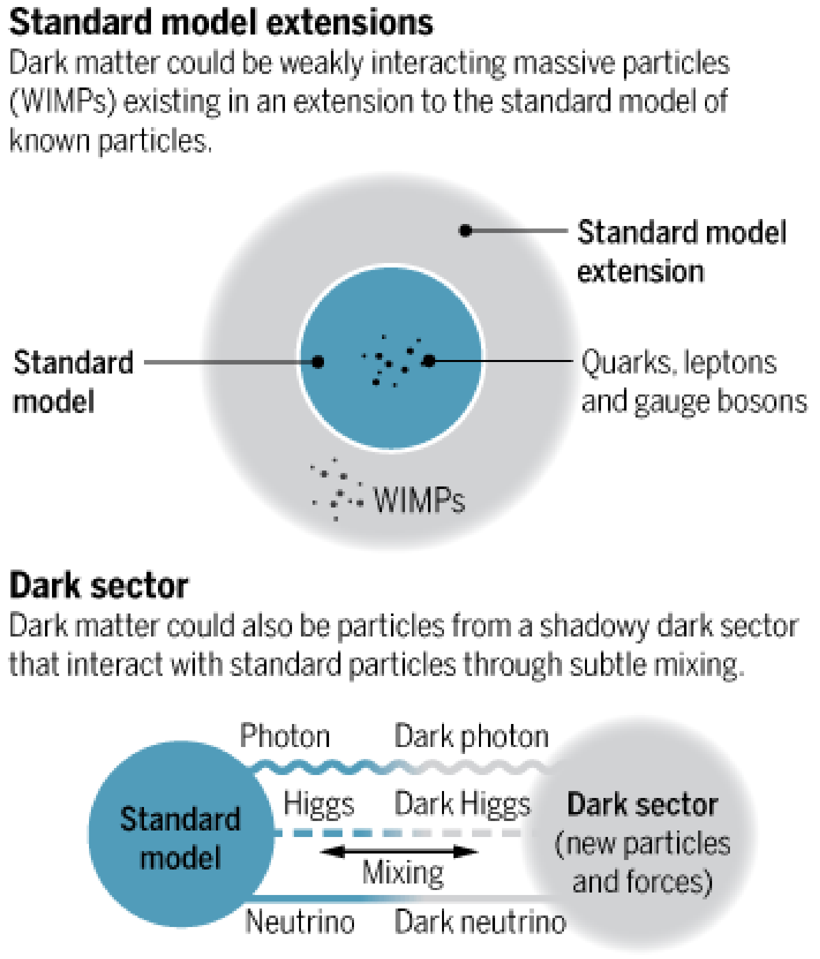
- Rather than SM extension, dark matter may belong to a hidden sector, with its own particles and interactions
  - The visible and dark sectors can couple through weak 'portal' interactions



+axion-like particle portal

Figure from Science

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  - The visible and dark sectors can couple through weak 'portal' interactions
- **Belle II: can search in the range few 100 MeV to 10 GeV**

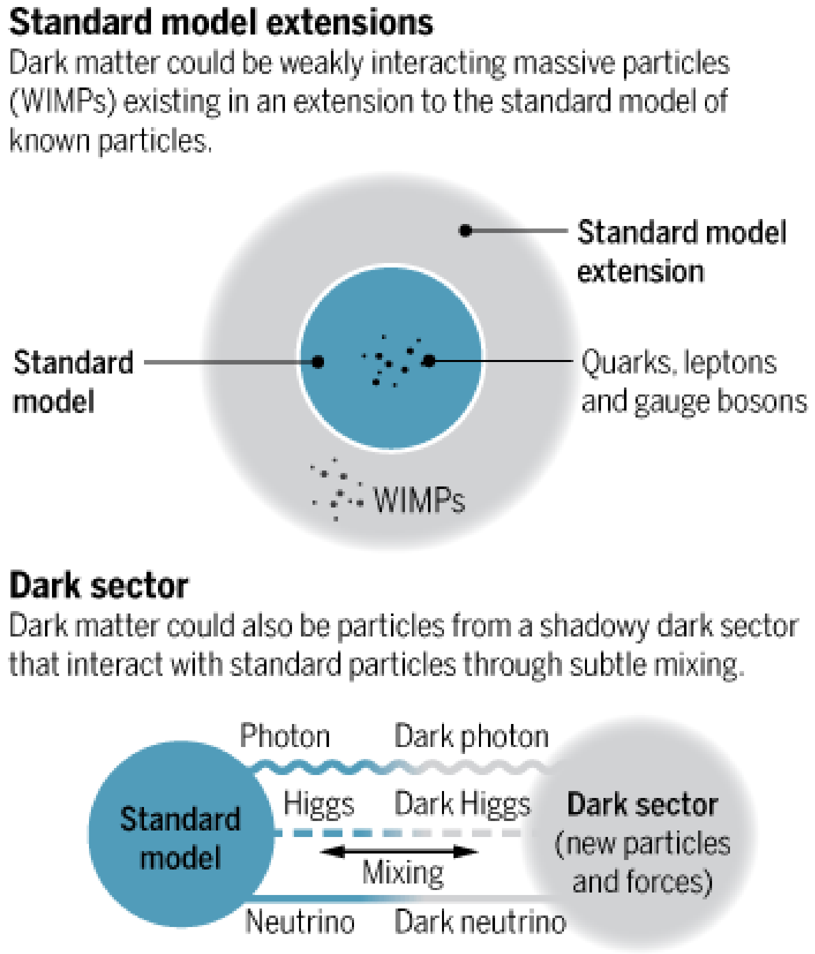

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Figure from [Science]

Belle II low multiplicity results

1. $Z' \to \mu\mu$ PRL **124**, 141801 (2020)
2. Axion-like particle PRL **125**, 161806 (2020)
3. Dark photon and dark Higgs PRL **130**, 071804 (2023)
4. $Z' \to \mu\mu$ PRL **130**, 231801 (2023)
5. $\tau\tau$ resonance PRL **131**, 121802 (2023)
6. $\mu\mu$ resonance in 4μ final state PRD **109**, 112015 (2024)
7. Inelastic dark matter PRL **135**, 131801 (2025)
8. ALP search PRL in preparation

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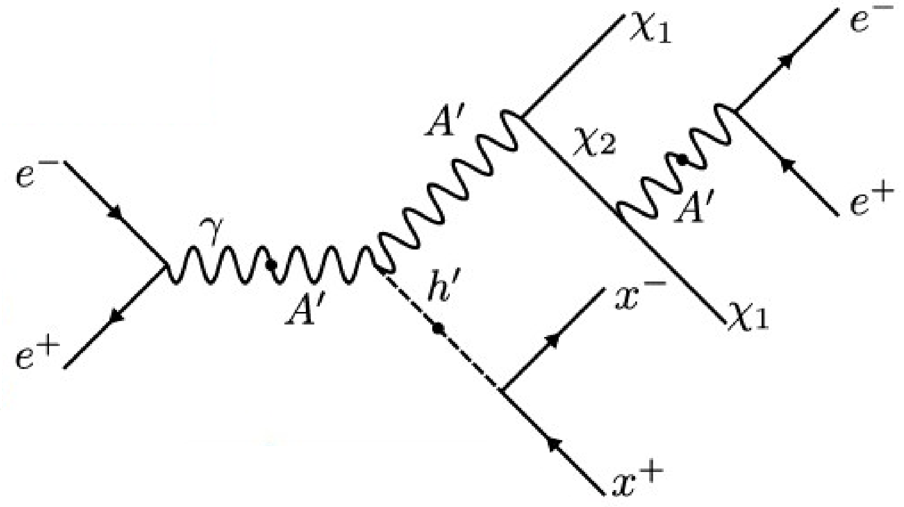
This talk

Inelastic DM: Introduction

- Complex structure with dark Higgs h′ and photon A ′- PRD 64, 043502 (2001)
  - 2 DM particles χ_1 and χ_2 with $\Delta m = m(\chi_1) - m(\chi_2) > 0$
  - **So χ_1 is stable DM candidate**
  - Also, $m(A') > m(\chi_1) + m(\chi_2)$ so that $A' \to \chi_1 \chi_2$



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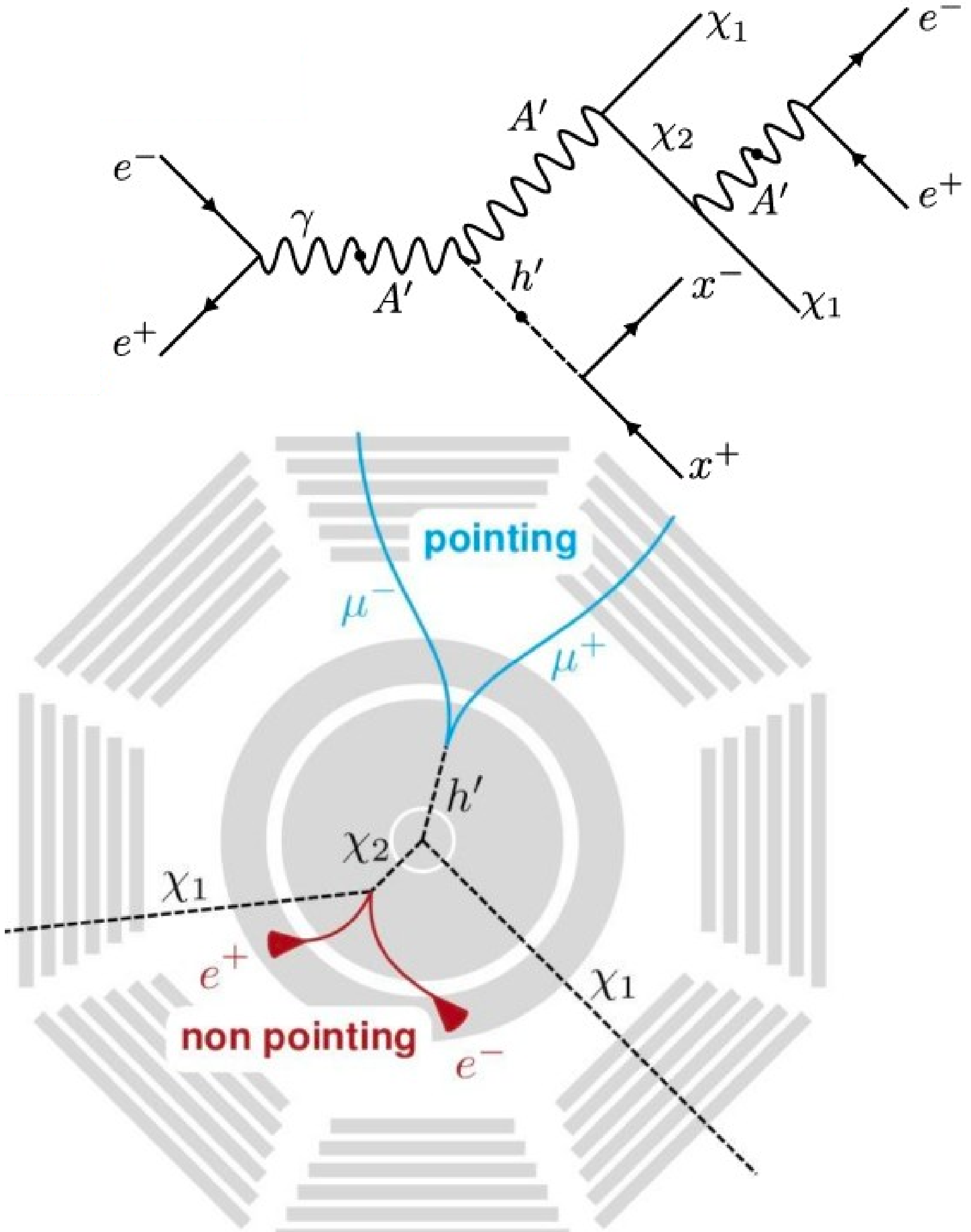
  - Also, $m(A') > m(\chi_1) + m(\chi_2)$ so that $A' \to \chi_1 \chi_2$
- Experimental signature
  - Two two-track displaced vertices
    - $h' \to x^+ x^- \ (x = \mu, \pi, K)$
    - $\chi_2 \to \chi_1 A'(e^+e^-)$ (L1 ECL trigger)
  - Missing energy
  - **Very small SM background**



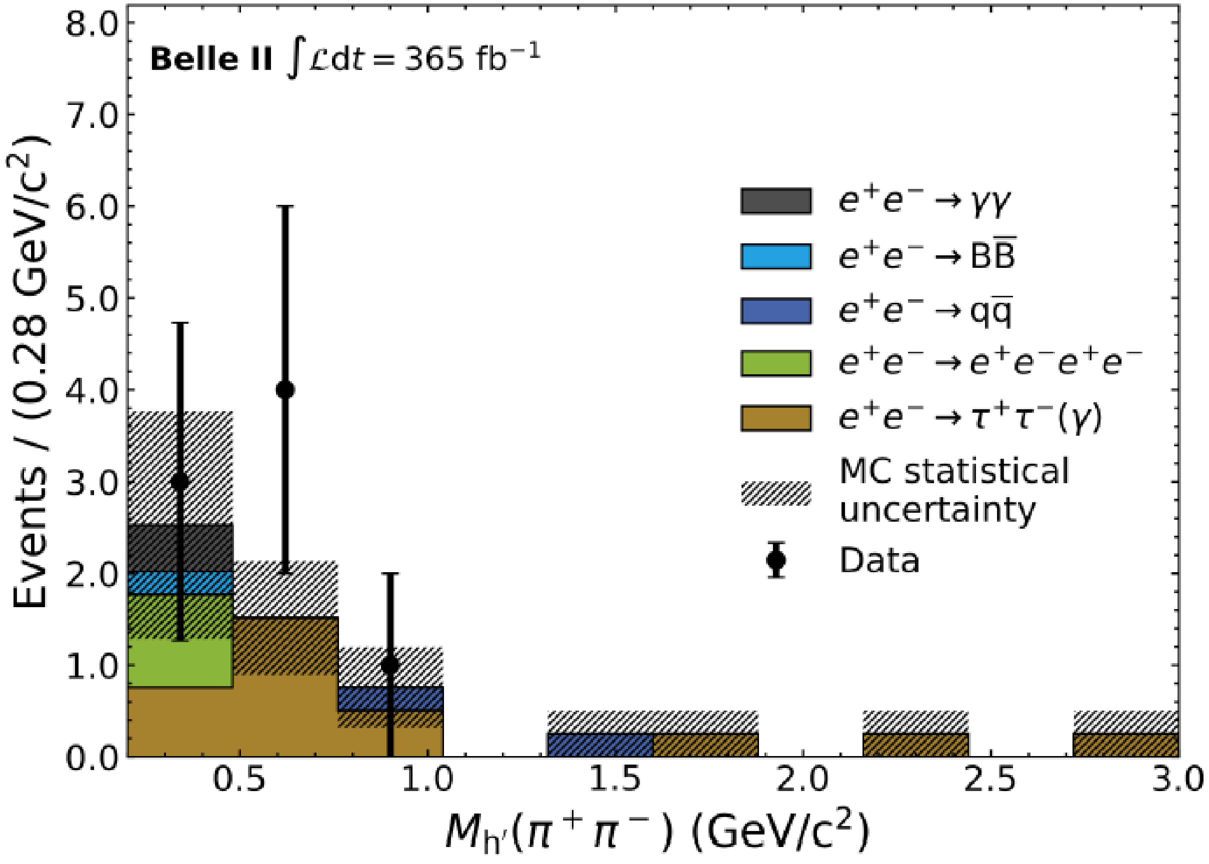
adapted from Duerr, Ferber et al, JHEP04 (2021) 146

Inelastic DM: Results

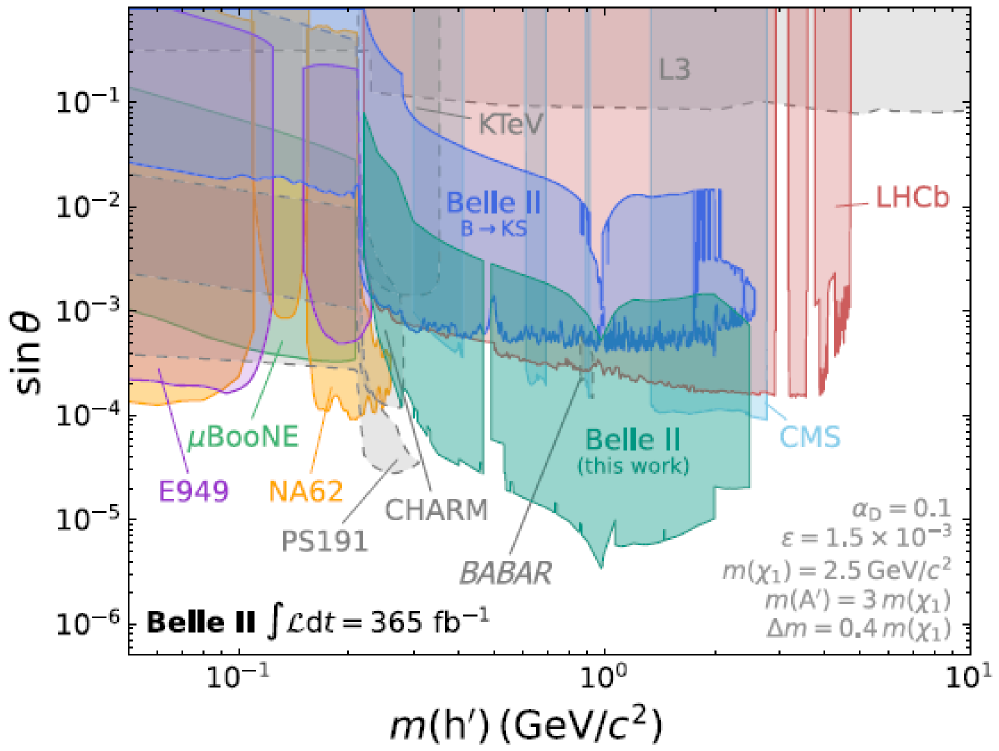
- Cut-and-count in narrow window of $M(xx)$
  - Background from $M(xx)$ sideband
  - Full mass range for $M(\mu\mu)$ and $M(KK)$, split at 1 GeV for $M(\pi\pi)$

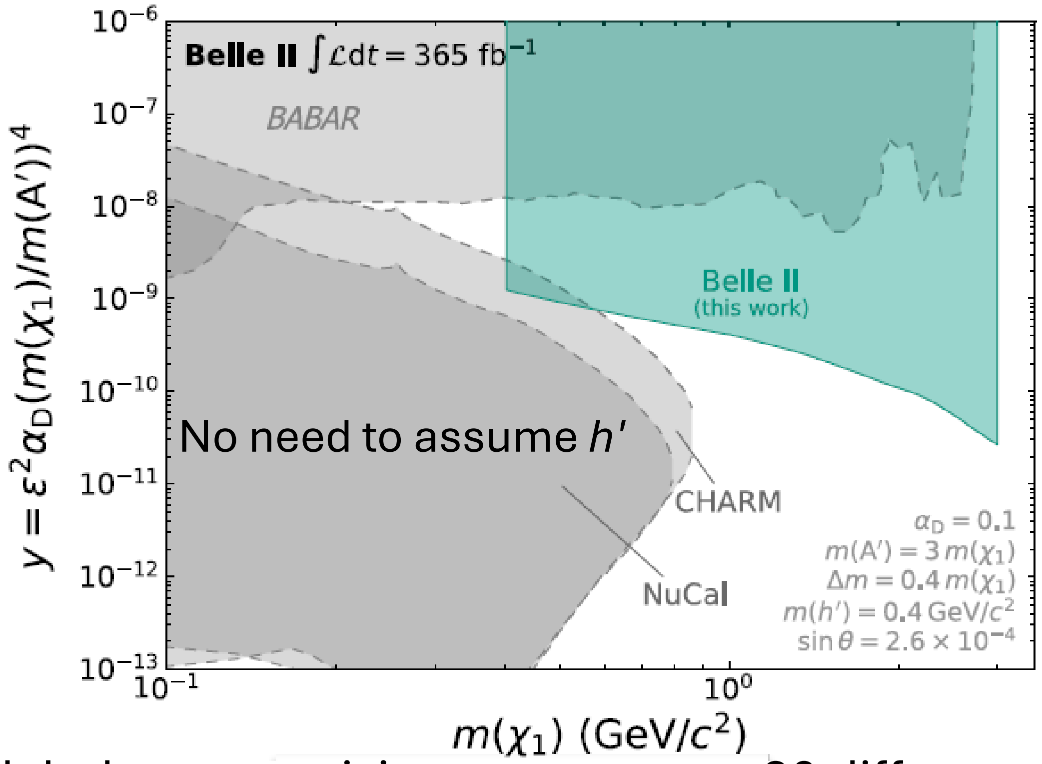
Inelastic DM: Results

- Cut-and-count in narrow window of *M(xx)*
  - Background from *M(xx)* sideband
  - Full mass range for $M(\mu\mu)$ and *M(KK)*, split at 1 GeV for $M(\pi\pi)$
- 8 events in $\pi\pi$, 1 in *KK* and 0 in $\mu\mu$
  - All consistent with background
  - Largest local significance 2.9σ, which is 1.1σ once look-elsewhere effect is considered



Inelastic DM: model interpretation





Exclusions dependent on couplings, masses and dark sector mixing parameters - 30 different combinations shown in paper - example above

PRL 135, 131801 (2025) – **Editors' suggestion**

Axion like particles (ALP) - Introduction

- *CP* violating effects possible in the SM Lagrangian strong interactions, but not seen e.g., n-EDM
  - strong *CP* problem

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11

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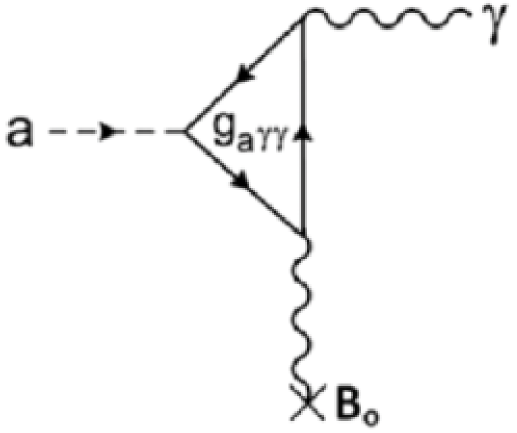
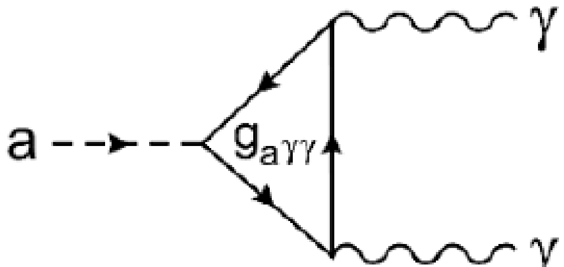
  - strong *CP* problem
- Peccei-Quinn solution was to introduce an axion particle
- Such particles can also act as a DM candidate or portal to the dark sector
- Motivates search in its couplings to photons
  - Complements searches for its interaction with a magnetic field

$$L_{QCD} \ni \theta \frac{\alpha_s}{32\pi} G\tilde{G} \quad \Longrightarrow \quad \left[\theta - \frac{a(x)}{f_a}\right] \frac{\alpha_s}{32\pi} G\tilde{G}$$





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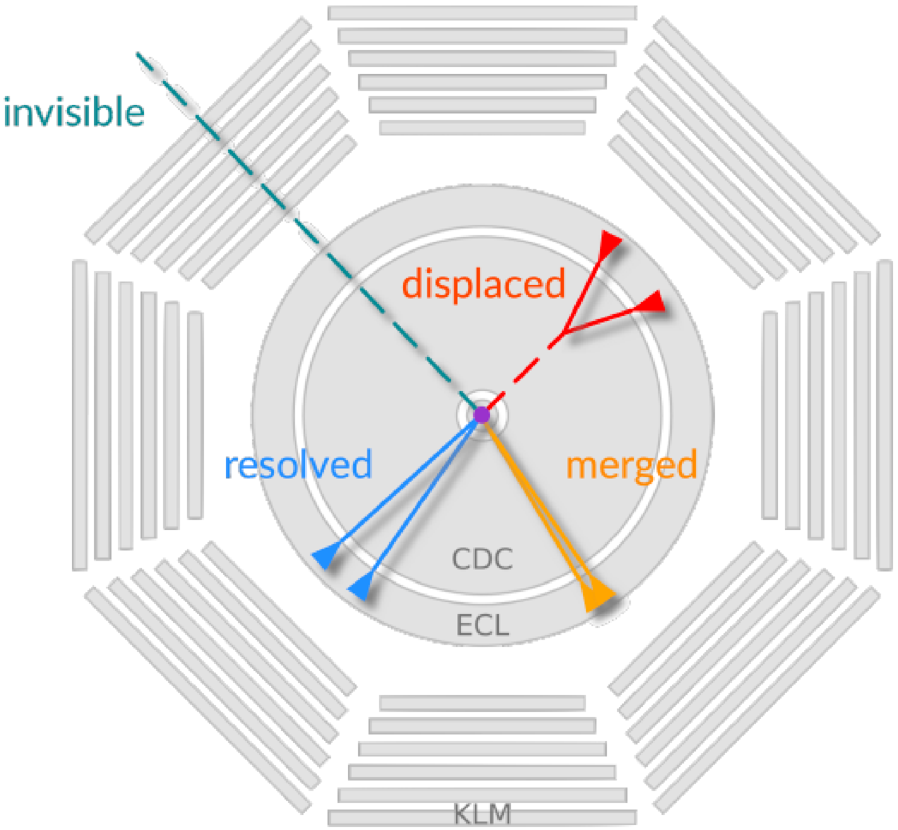
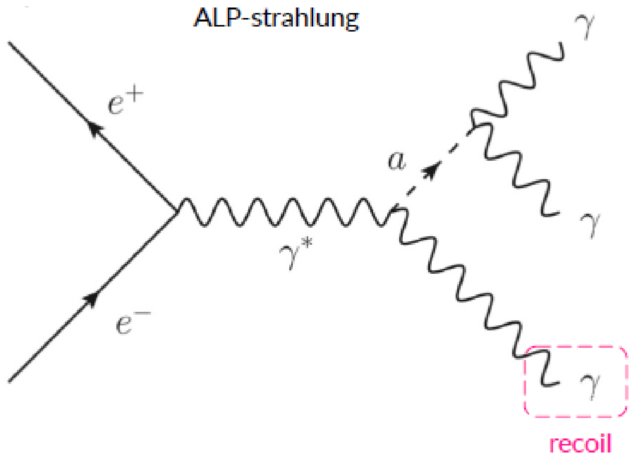
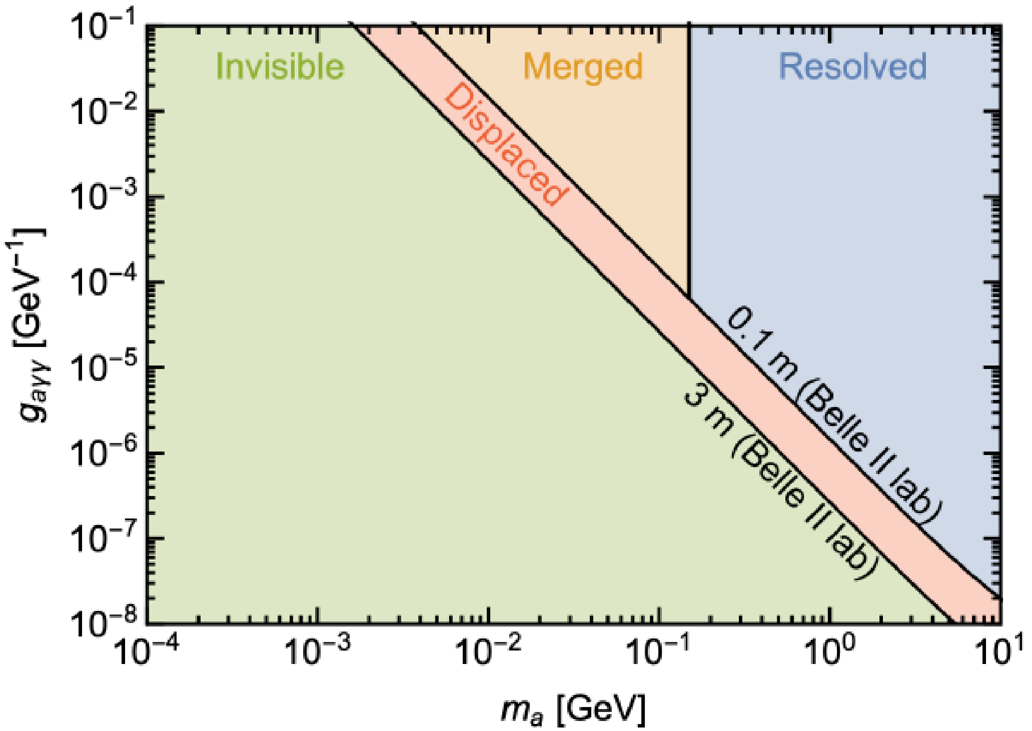
ALP search a→γγ at Belle II

- Search for ALP in $e^+e^- \to \gamma a$ for $a \to \gamma\gamma$ (i.e. 3γ final state)







ALP search at Belle II: method

- Assume a→γγ dominant
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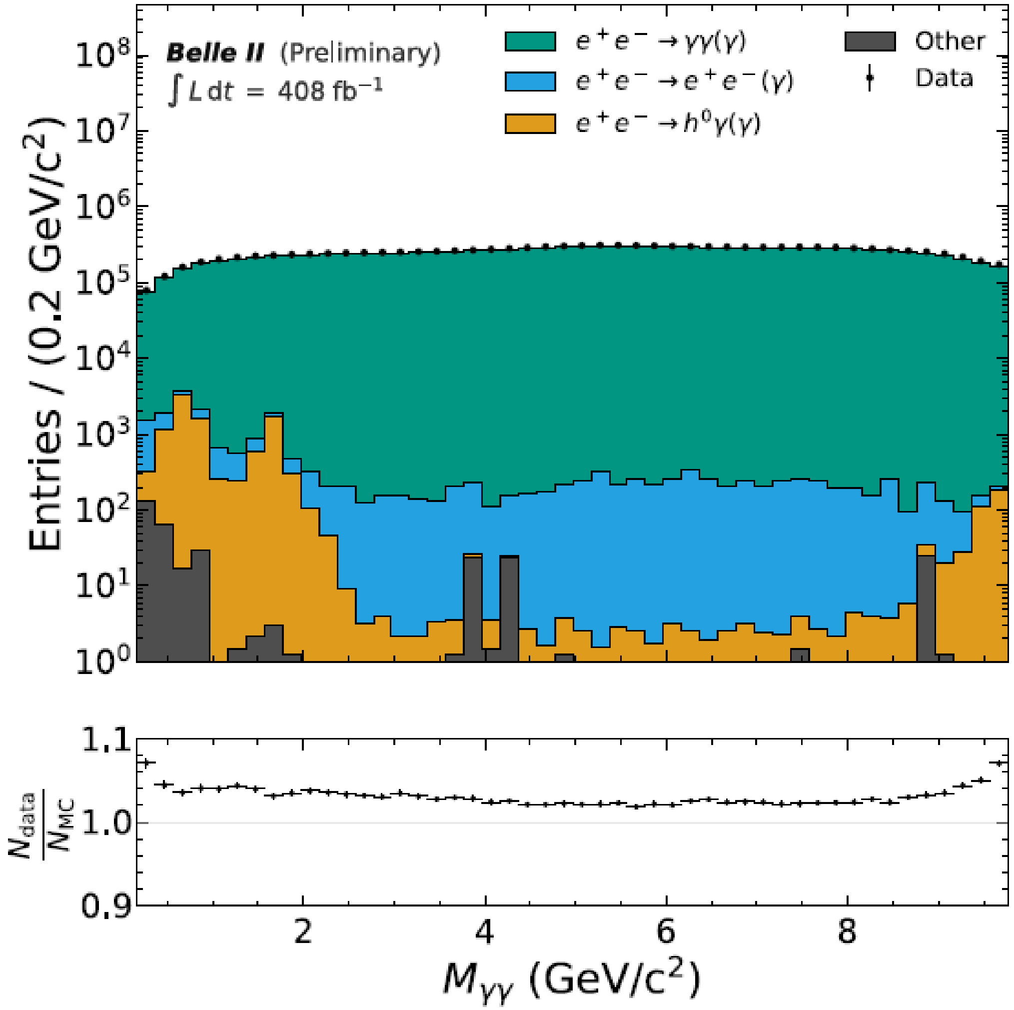
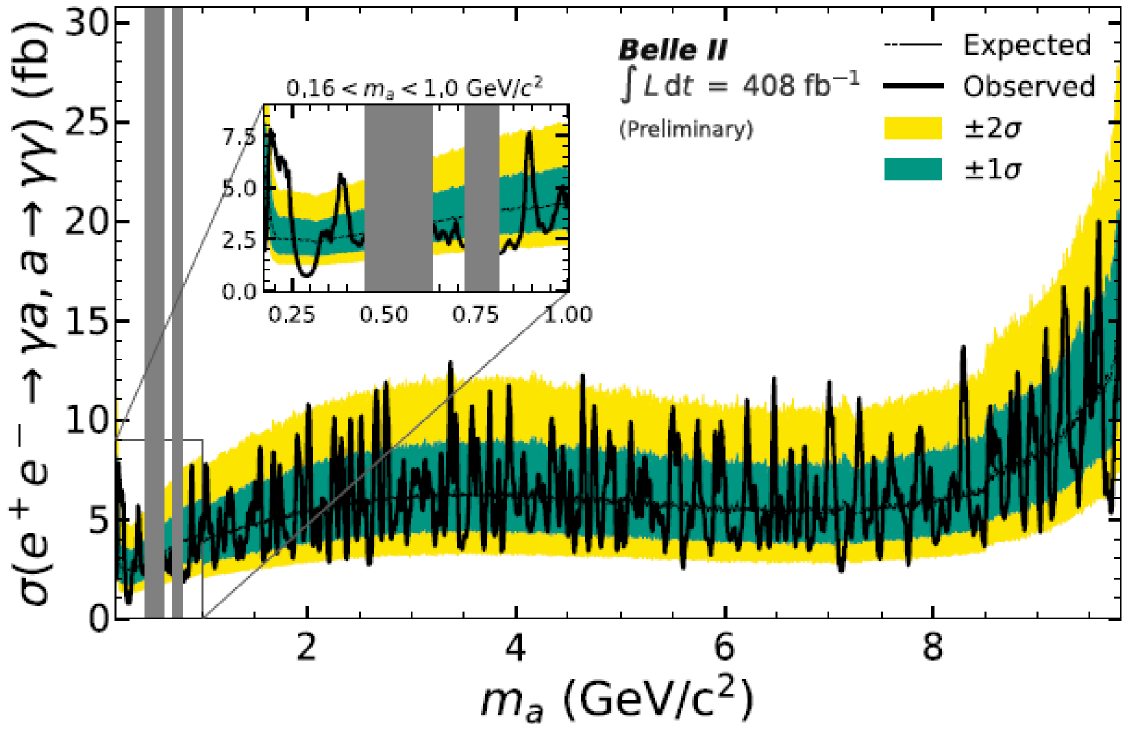
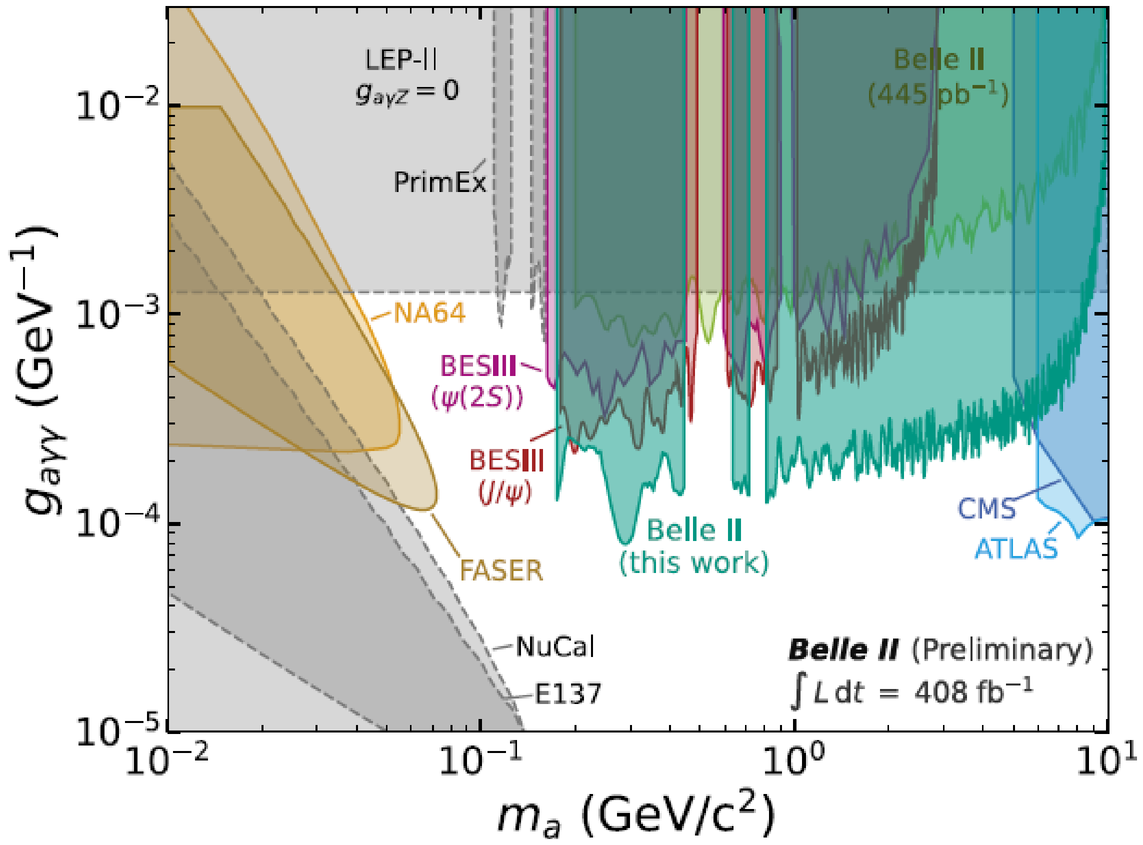
  - $e^+e^- \to \gamma a(\gamma\gamma)$
- Assuming their total 4-momentum the same as the incoming beams
- Dominant QED background $e^+e^- \to \gamma\gamma(\gamma)$ - combinatorial – suppressed by multivariate
  - Also, dedicated π^0, ω and η vetoes
- Scan M(γγ) and fit for resonance



ALP search at Belle II: Results

Paper in preparation





- Search m(a) from 0.17 to 9.8 GeV
- Largest significance at 0.22 GeV
  - 3.3σ local (1.4σ global)

- Interpret as limit on $g_{a\gamma\gamma}$
- World leading in m(a) from 0.17 to 5 GeV
- Nearly an order of magnitude better than our earlier publication with 0.445 fb^{-1}

Conclusion

- $\sigma(e^+e^- \longrightarrow \pi^+\pi^-[\pi^0])$
  - Even though g–2 is no longer an anomaly, still a powerful probe of new physics
  - If differences among inputs to the dispersive method understood, then path to a more accurate theory prediction – lattice + dispersive – possible
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  - Low multiplicity events with a few tracks and photons allow probes of many different models – two examples
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- **The above complement the more traditional quark flavour, tau and spectroscopy programme at Belle II**

Full time

Really full time – this seems more likely