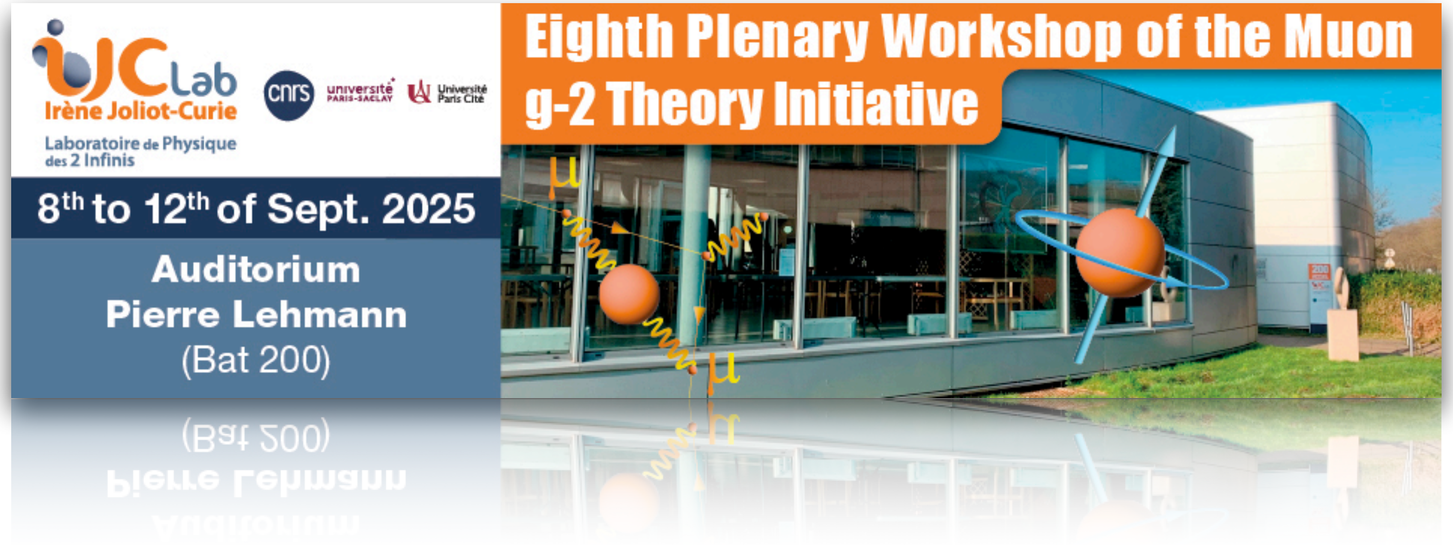
$e^+e^- \to \pi^+\pi^-(\gamma)$ measurement at Belle II



- Introduction
- ISR method and trigger
- $e^+e^- \to \pi^+\pi^-(\gamma)$ status
- Summary

Qingyuan Liu
On behalf of the Belle II collaboration
Sept. 08, 2025

University of Hawai'i Mānoa

Introduction

Muon g-2 and HVP

- Anomalous magnetic moment of muon in SM:

$$a_\mu^{SM} \equiv (g_\mu - 2)/2 = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLBL}$$

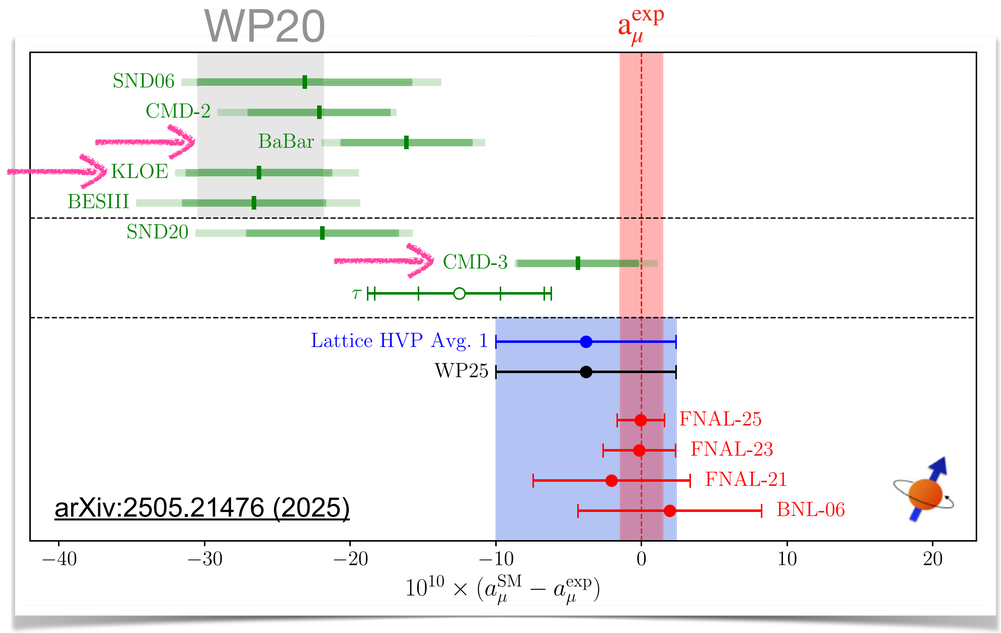
- Uncertainty is dominated (>85%) by the **leading order** (LO) **Hadronic Vacuum Polarization** (HVP)
  - Can be calculated by either **Lattice QCD** (used in WP25) or
  - **Dispersion integral** (used in WP20) over the bare cross section $\sigma^0(s)$ of $e^+e^- \to \text{hadrons}(\gamma)$

$$a_\mu^{HVP,LO} = \frac{\alpha^2}{3\pi^2}\int_{M_\pi^2}^{\infty}\frac{K(s)}{s}R(s)ds$$

$$K(s) = \frac{x^2}{2}(2-x^2) + \frac{(1+x^2)(1+x)^2}{x^2}\left(\log(1+x) - x + \frac{x^2}{2}\right) + \frac{1+x}{1-x}x^2\log x$$

$$x = \frac{1-\beta_\mu}{1+\beta_\mu}, \qquad \beta_\mu = \sqrt{1-\frac{4m_\mu^2}{s}},$$

- Current tensions
  - Lattice QCD vs dispersive approach (w/o CMD-3)
  - $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$ measurements among KLOE, BaBar and CMD-3
  - …

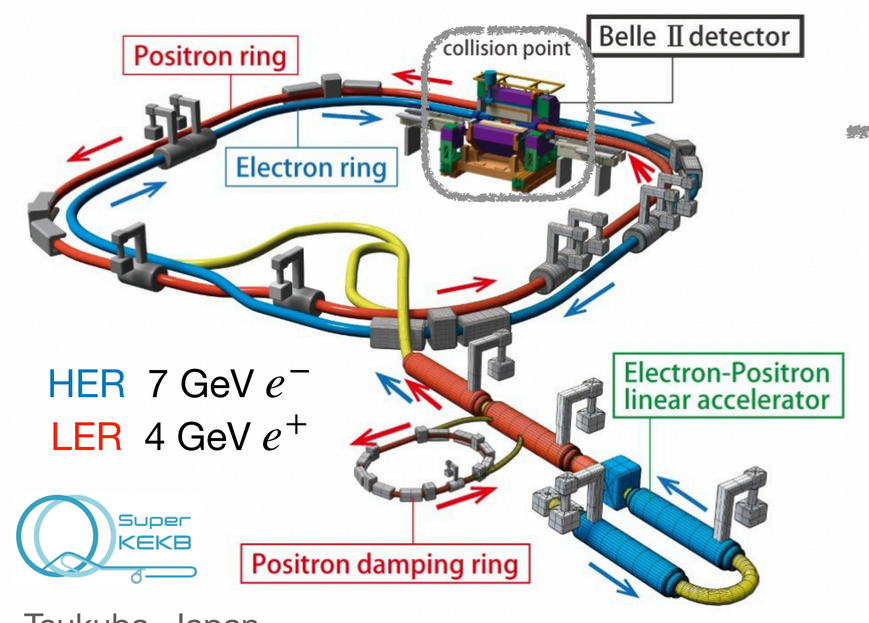


Belle II has published the measurement of $\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$: PhysRevD.110.112005

Introduction

SuperKEKB

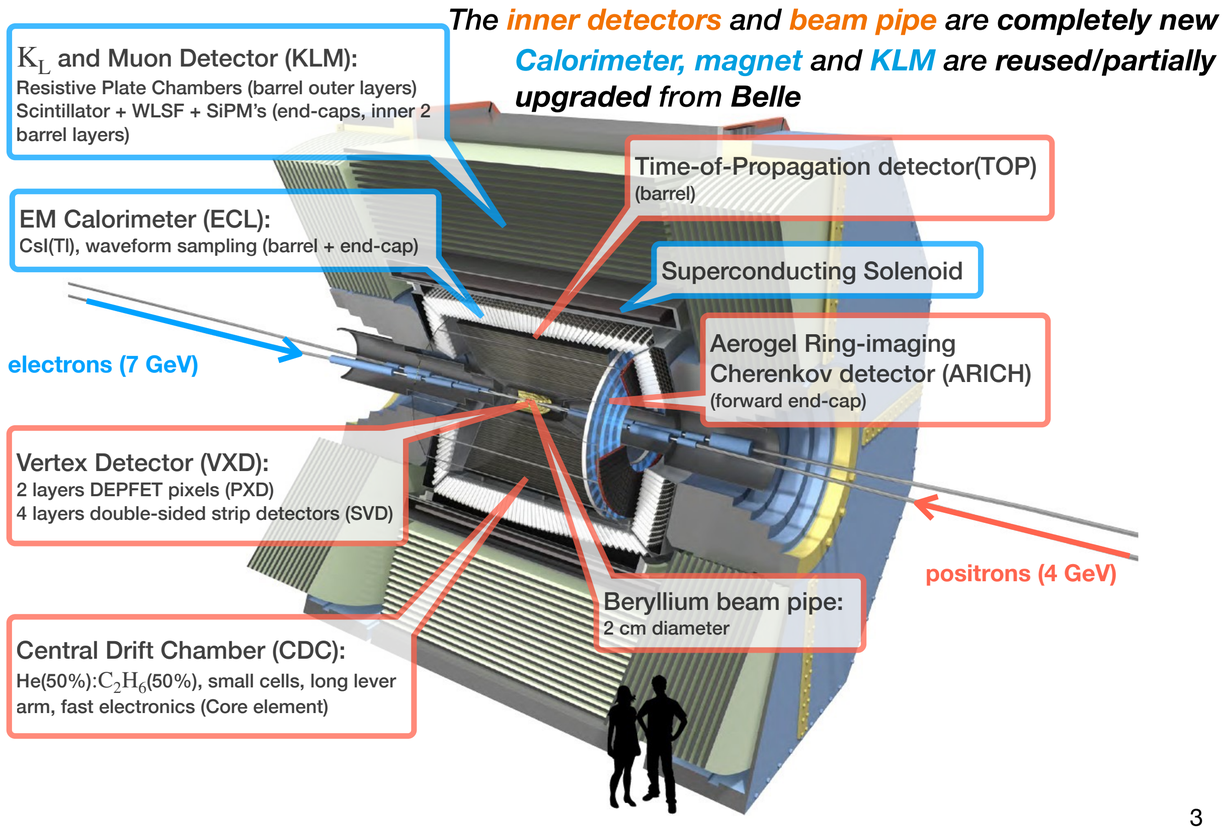
- **Asymmetric**-energy e^+e^- collider
- $E_{cm} = M_{\Upsilon(4S)} \approx 10.58$ GeV, B factory
- Goal: $L_{peak} = 6 \times 10^{35}\,cm^{-2}s^{-1}$
  - **Nano-beam** scheme and **increased currents**
  - $5.1 \times 10^{34}\,cm^{-2}s^{-1}$ (**Dec 2024**, world record)



Tsukuba, Japan

Belle II

- Target L_{int}: $50\,ab^{-1}$
  - Physics data taking with full setup in March 2019
  - $575\,fb^{-1}$ has been recorded by Dec. 2024
- Upgraded detectors, trigger and DAQ **vs** Belle



Introduction

Belle II Talks at the Eighth Plenary Workshop of the Muon g-2 Theory Initiative

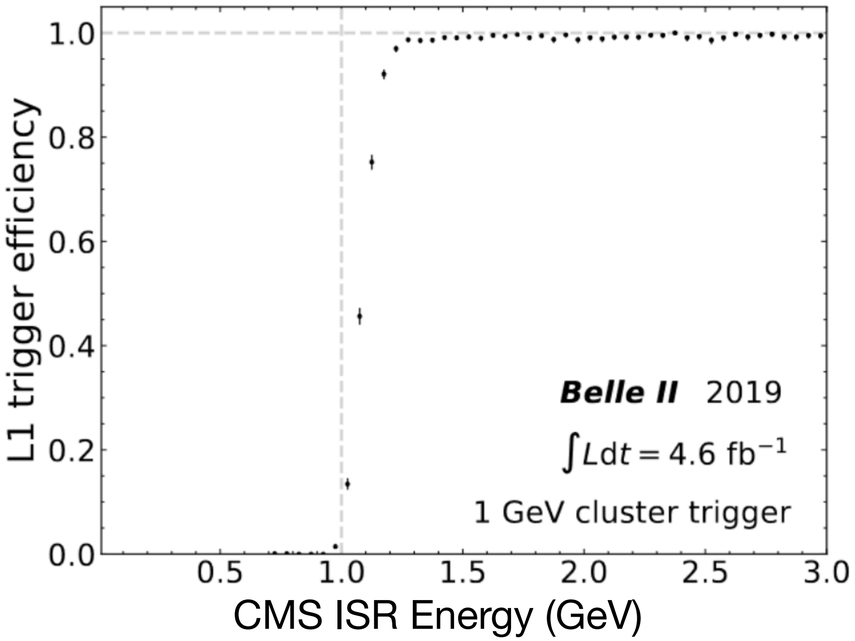
- Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement (this talk)
- Tau decays at Belle II and super tau-charm factory by Prof. Changzheng Yuan
- Belle-II plans for Transition Form Factor Measurements by Prof. Hisaki Hayashii

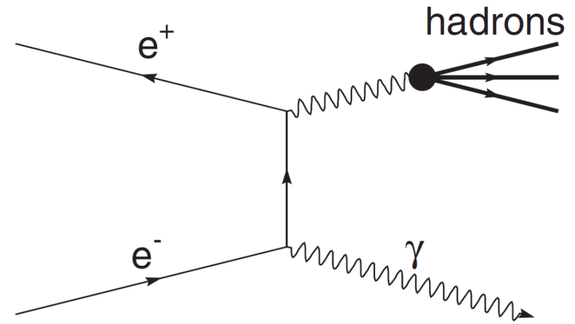
ISR method and trigger in Belle II

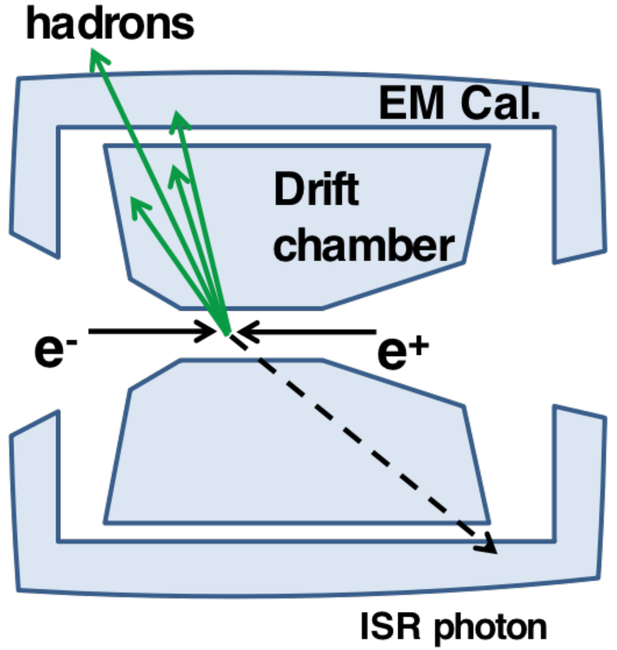
Scan over masses of the hadronic system via initial state radiation (ISR)

- Fixed center-of-mass energy $\sqrt{s} \approx 10.58$ GeV
- Scan $s' = (1 - 2E_\gamma^*/\sqrt{s})s$, E_γ^* is the ISR photon energy in c.m.s.
- Efficient **L1 trigger for ISR** events using ECL (cluster energy $\geq$ 2.0 GeV)
  - Studied with independent track trigger for **μμγ**: **99.9%** in barrel region

    → **0.1% uncertainty** **Not possible with Belle trigger!**



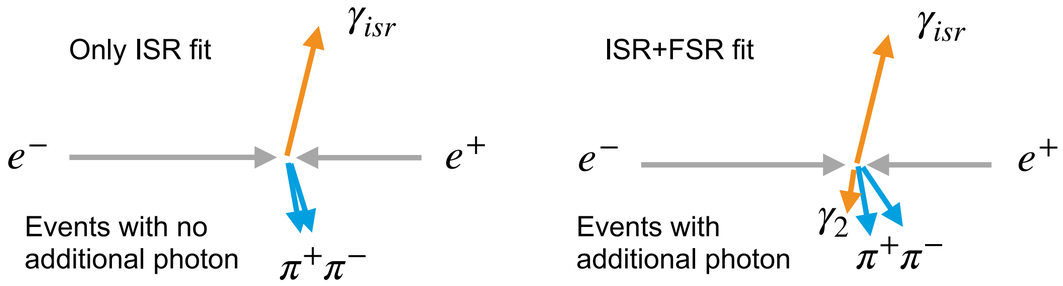


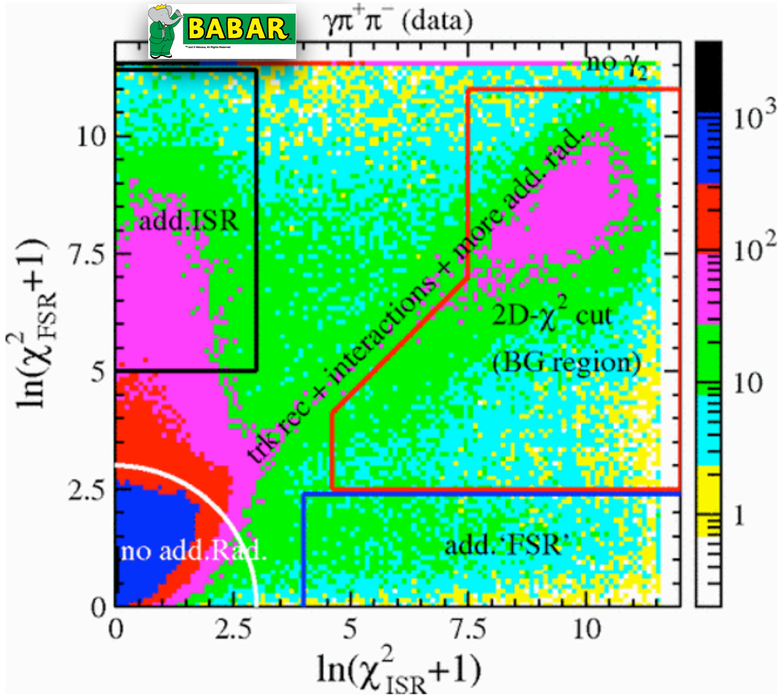


$e^+e^- \to \pi^+\pi^-(\gamma)$ measurement at Belle II

Following BaBar's original approach [Phys. Rev. D 86, 032013]

- Reconstruction for **R-ratio** measurement
  - 1 hard photon + 1 optional photon
  - 2 tracks w/o particle identification (PID) in preselection
- Double kinematic fits for selecting signal events and disentangling QED corrections:
  - **"ISR" fit** for **all events after preselection**
    - 3 measured particles: 2 tracks and γ_{isr}
      - ISR energy not used
    - Assume 1 unmeasured photon (**ISR**) along beam directions
  - **"FSR" fit** only for **events with γ_2 reconstructed**
    - 4 measured particles: 2 tracks, γ_{isr} and γ_2
      - ISR energy not used
- **PID** to separate μμ/KK/ππ





$e^+e^- \to \pi^+\pi^-(\gamma)$ measurement at Belle II

Following BaBar's original approach [Phys. Rev. D 86, 032013]

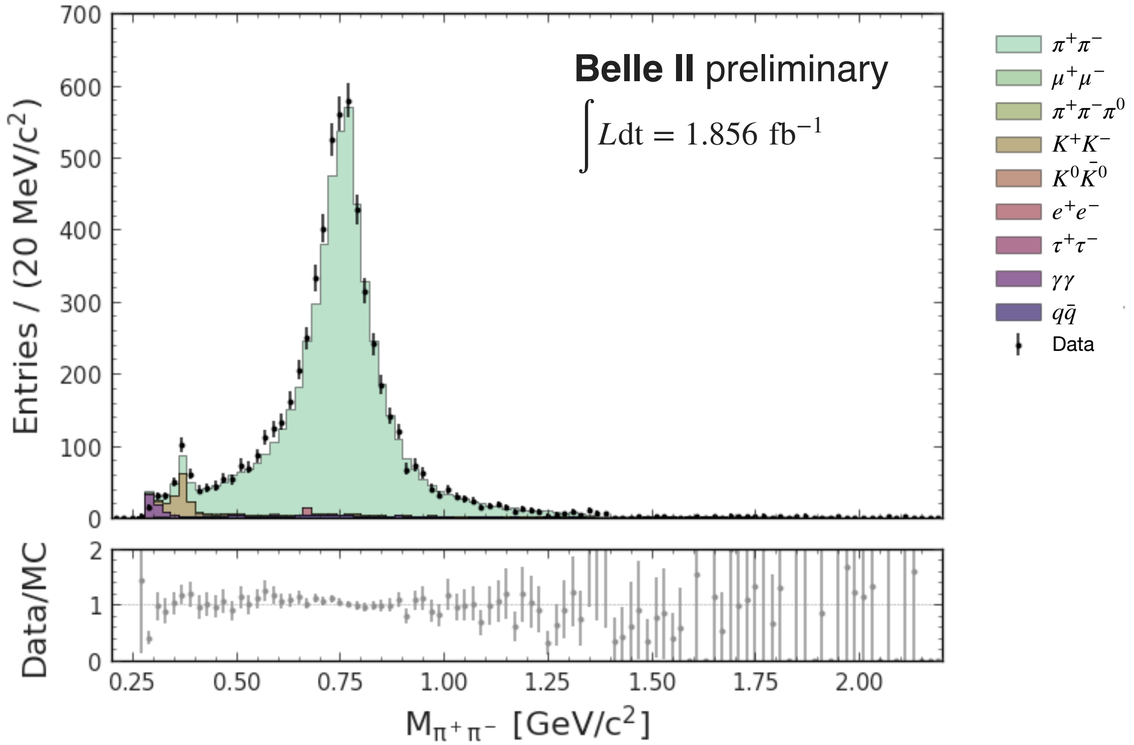
- Data set : 427 fb^{-1} (data taken before 2023)
- QED validation using $e^+e^- \to \mu^+\mu^-(\gamma)$
- Target systematic uncertainty: 0.5%
  - Relying on data-driven approaches for efficiency corrections

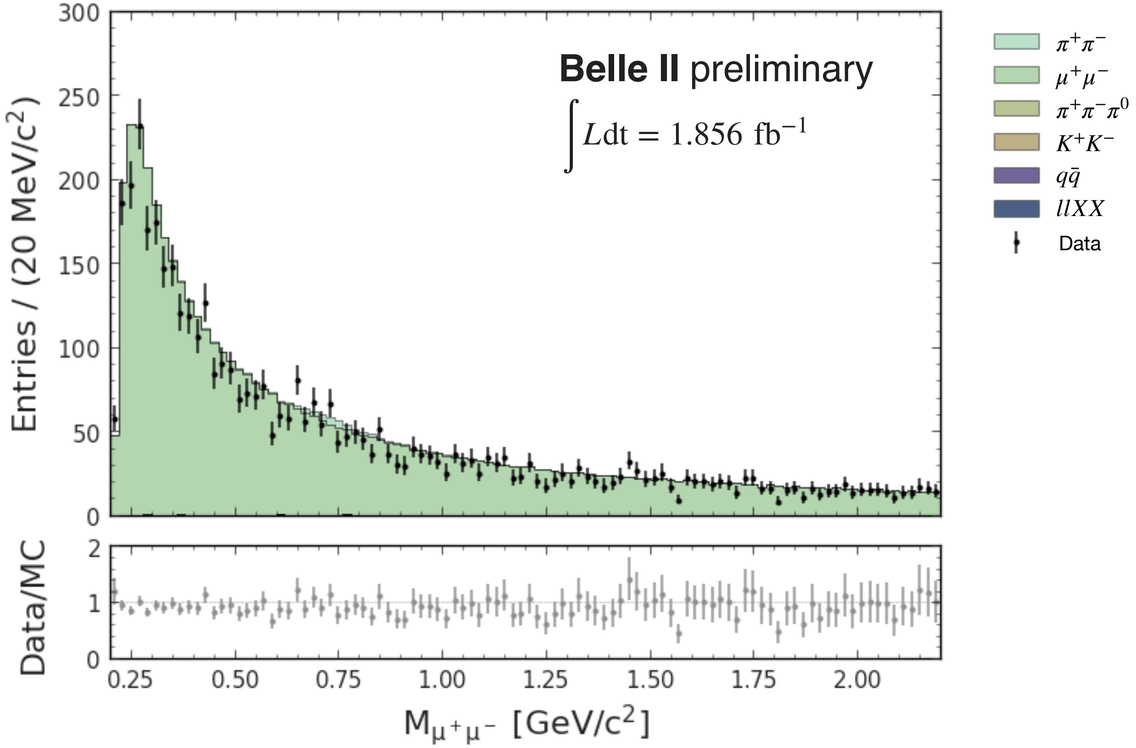
$$\epsilon^{\text{data}} = \epsilon^{\text{MC}} \left(\frac{\epsilon^{\text{data}}}{\epsilon^{\text{MC}}}\right)_{\text{trigger}} \left(\frac{\epsilon^{\text{data}}}{\epsilon^{\text{MC}}}\right)_{\chi^2} \left(\frac{\epsilon^{\text{data}}}{\epsilon^{\text{MC}}}\right)_{\text{PID}} \left(\frac{\epsilon^{\text{data}}}{\epsilon^{\text{MC}}}\right)_{\text{tracking}}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

Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Sanity check with 1.856 fb^{-1} data

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





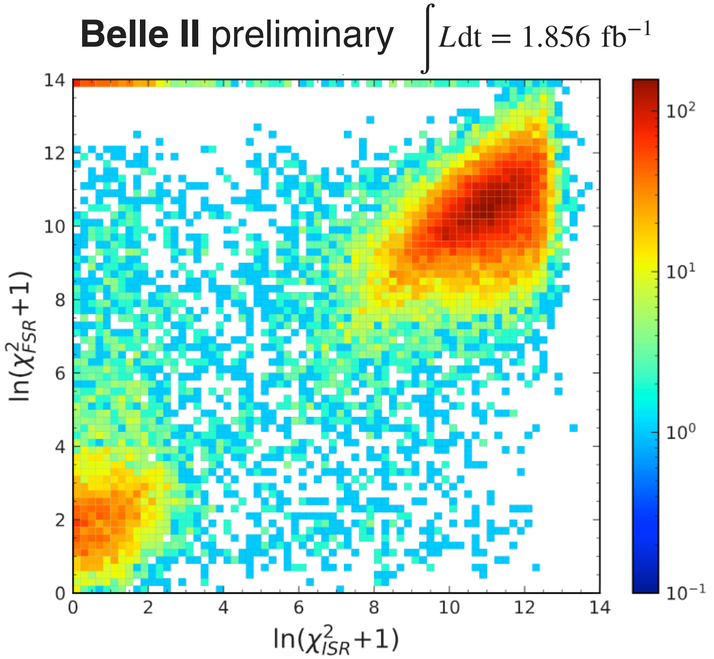
Reasonable data-MC agreement before any efficiency corrections

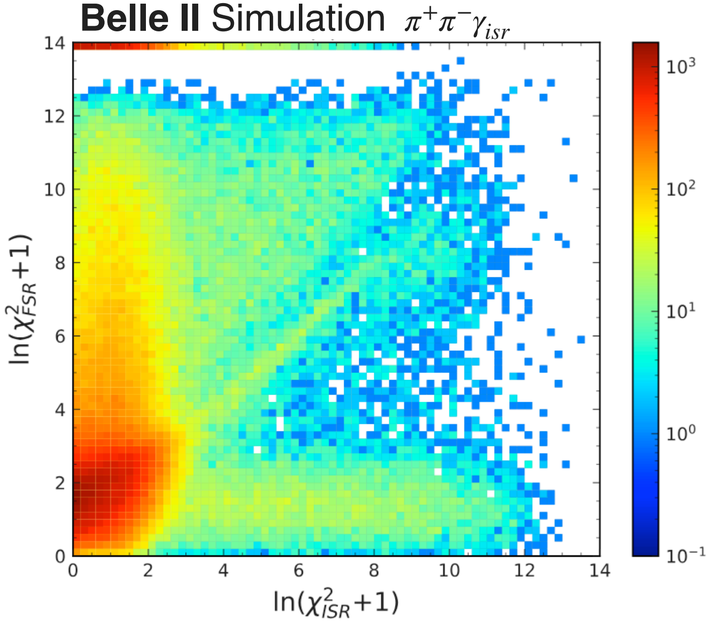
Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Sanity check with 1.856 fb^{-1} data

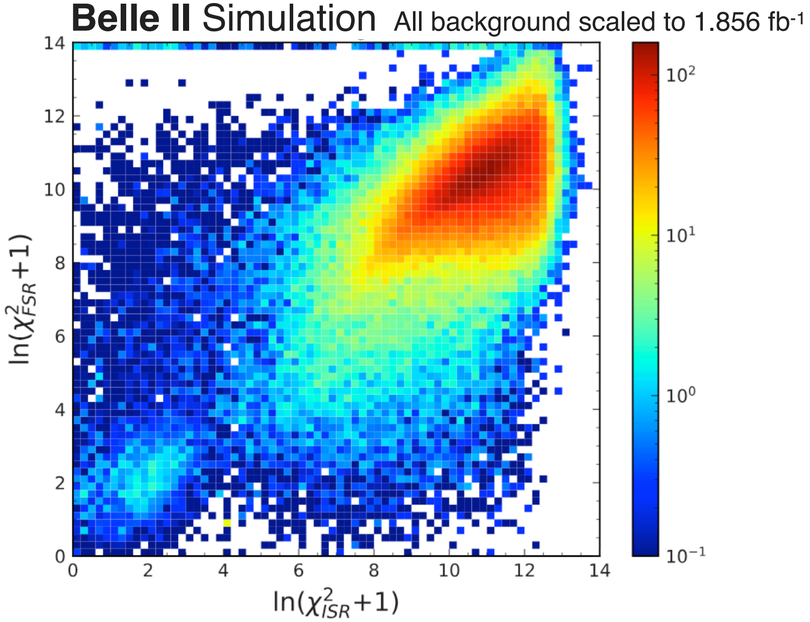
- Preliminary selections: ISR in ECL inner barrel, $E^*_{ISR} > 2$ GeV, PID, $P_{\text{track}} > 1$ GeV, χ^2_{ISR} cut only

$\pi^+\pi^-$ channel





PHOKHARA



PHOKHARA, KKMC, PYTHIA and EvtGen

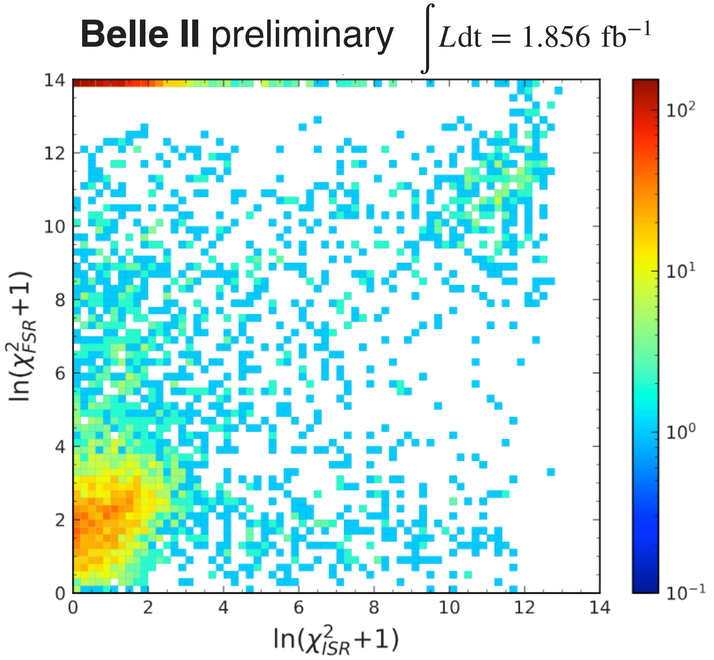
Reasonable data-MC agreement before any efficiency corrections

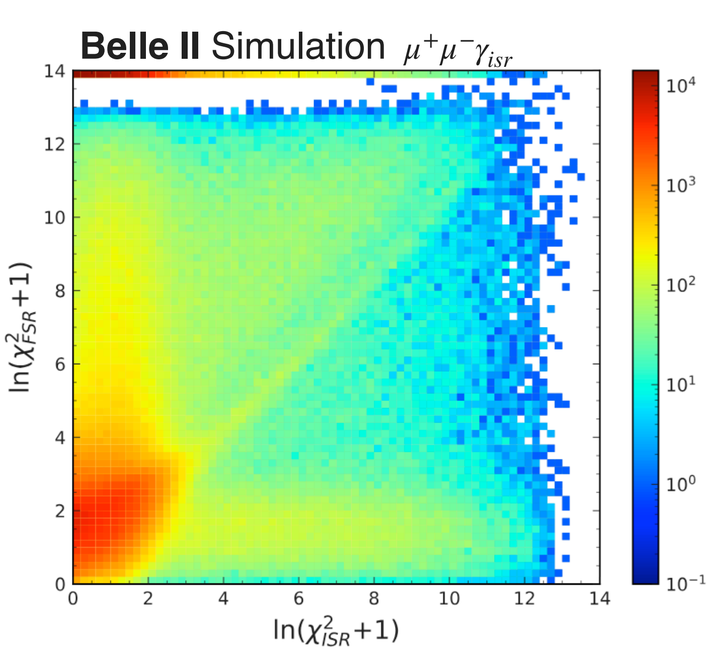
Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Sanity check with 1.856 fb^{-1} data

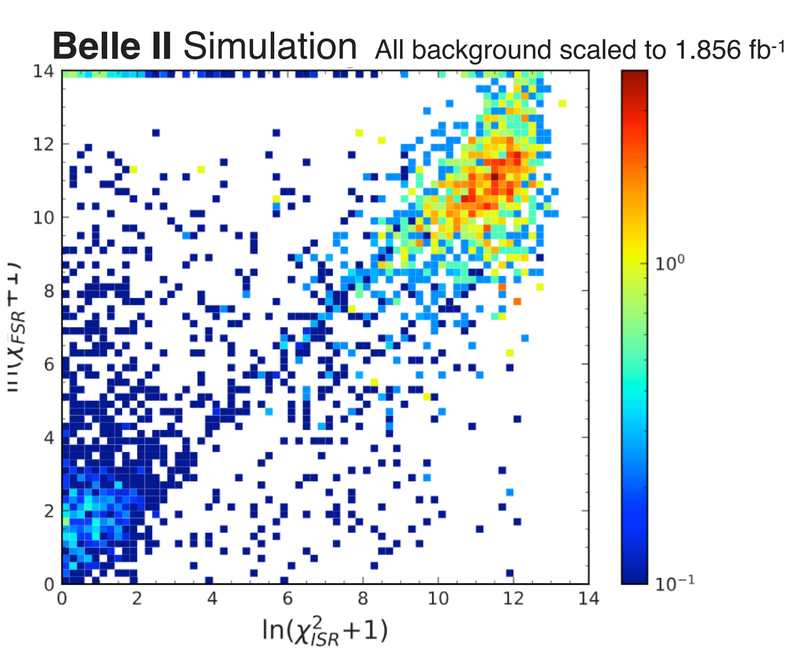
- Preliminary selections: ISR in ECL inner barrel, $E^*_{ISR} > 2$ GeV, PID, $P_{\text{track}} > 1$ GeV, χ^2_{ISR} cut only

$\mu^+\mu^-$ channel





KKMC



PHOKHARA, KKMC, PYTHIA and EvtGen

Reasonable data-MC agreement before any efficiency corrections

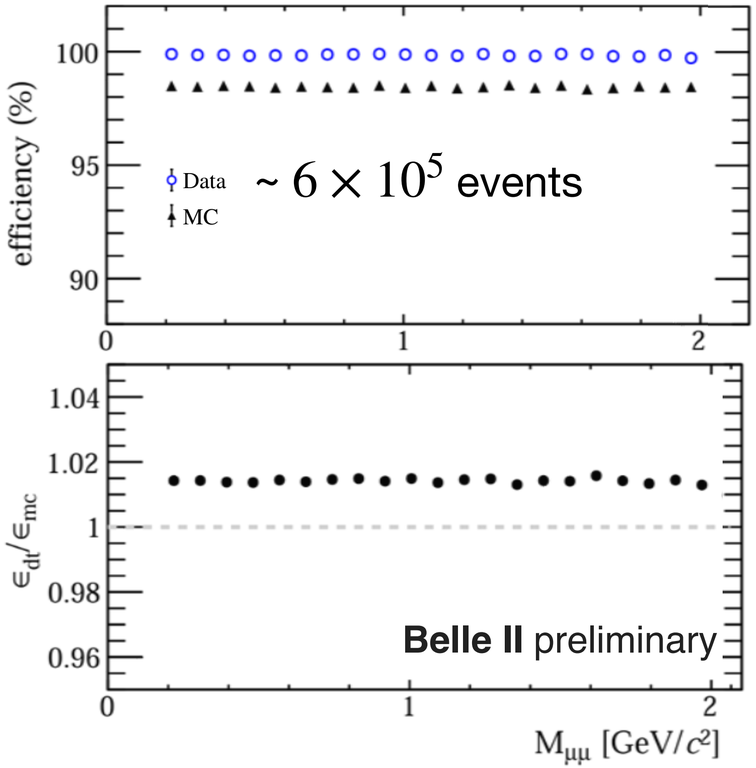
Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Trigger study with $e^+e^- \to \mu^+\mu^-(\gamma)$ events and preliminary selections

- 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:

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

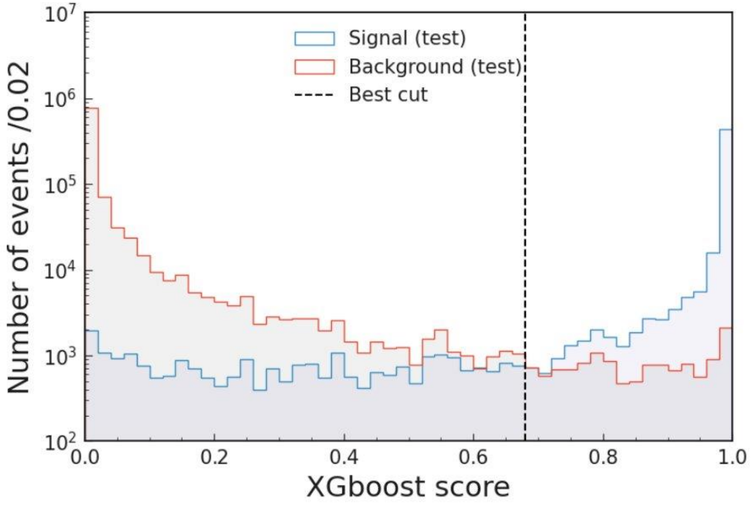
- Great data efficiency but underestimated MC efficiency → using data efficiency directly

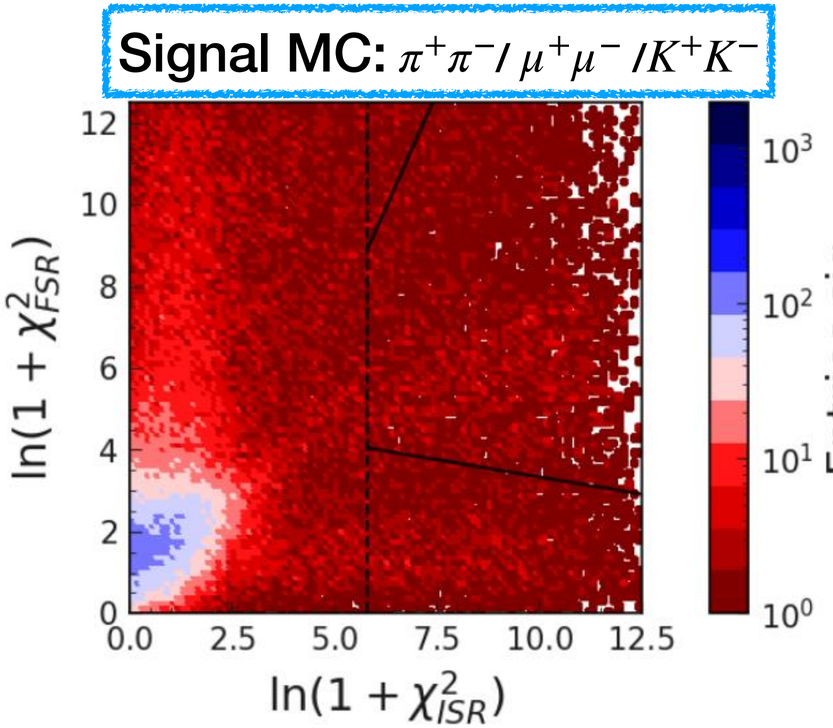


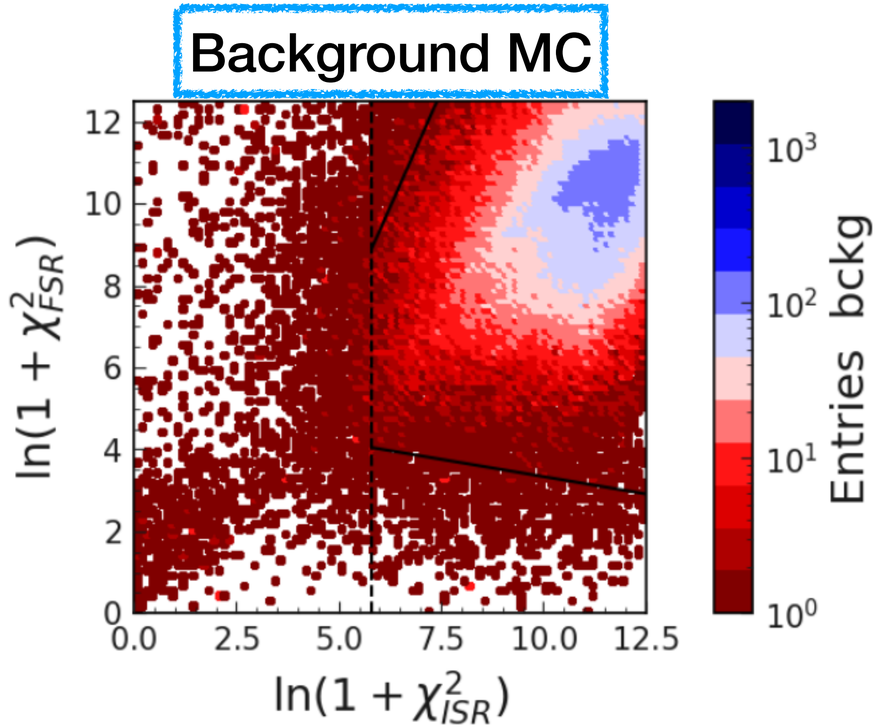
Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Optimizing χ^2 cuts using BDT results

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





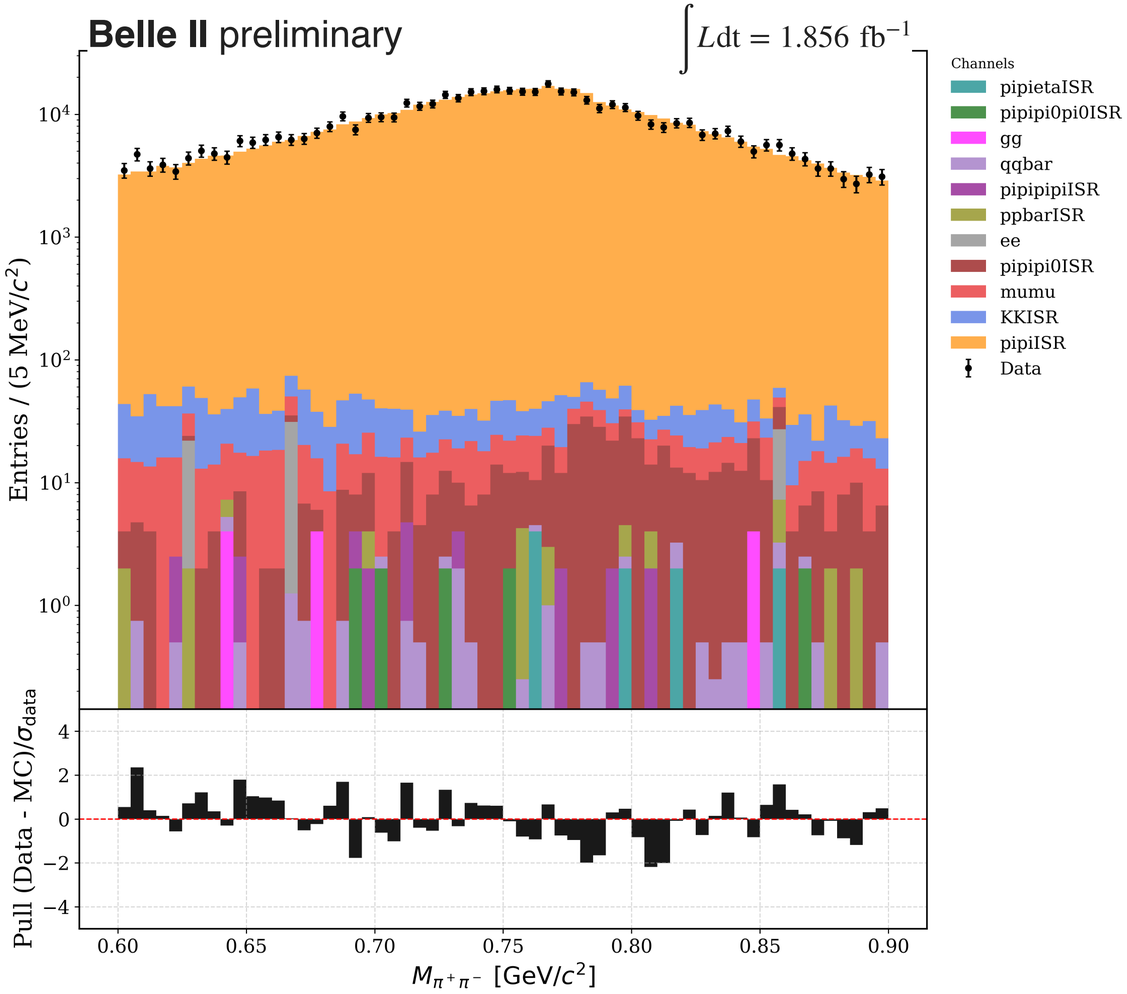


Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

PID study is ongoing

- 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

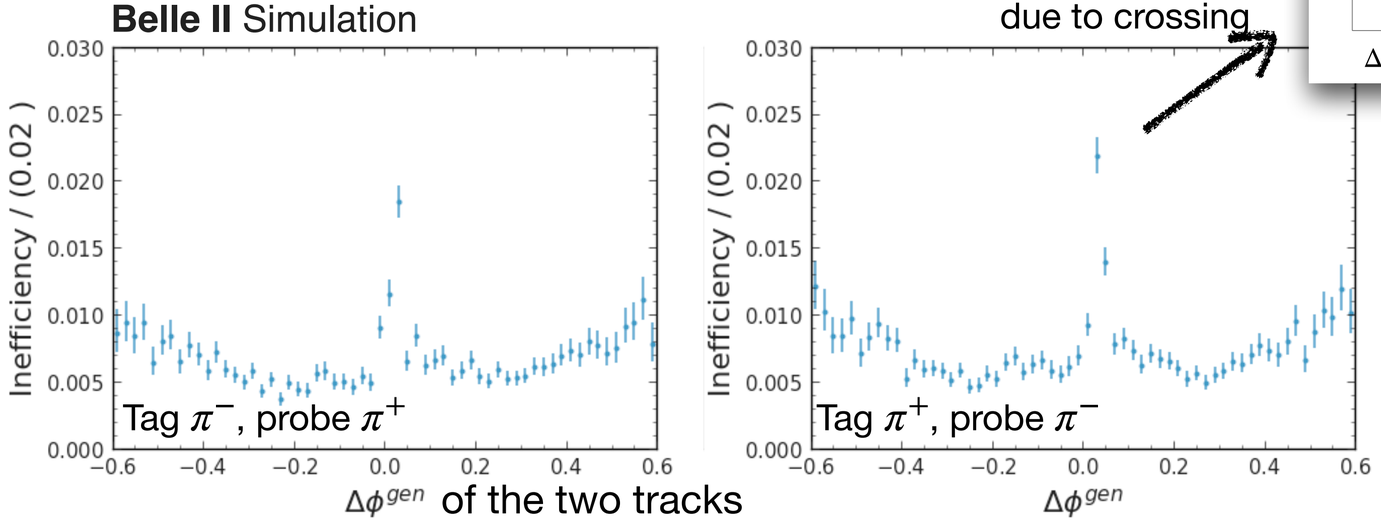


Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

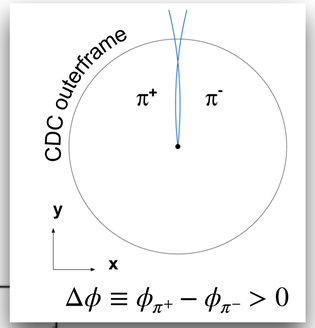
Promising tracking study: tracking inefficiency

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

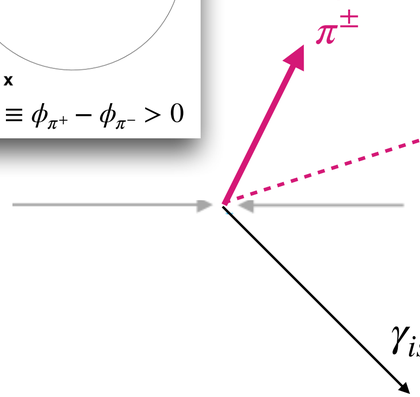
$$1 - \frac{\mathrm{N(predicted\ and\ reconstructed)}}{\mathrm{N(predicted)}}$$



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

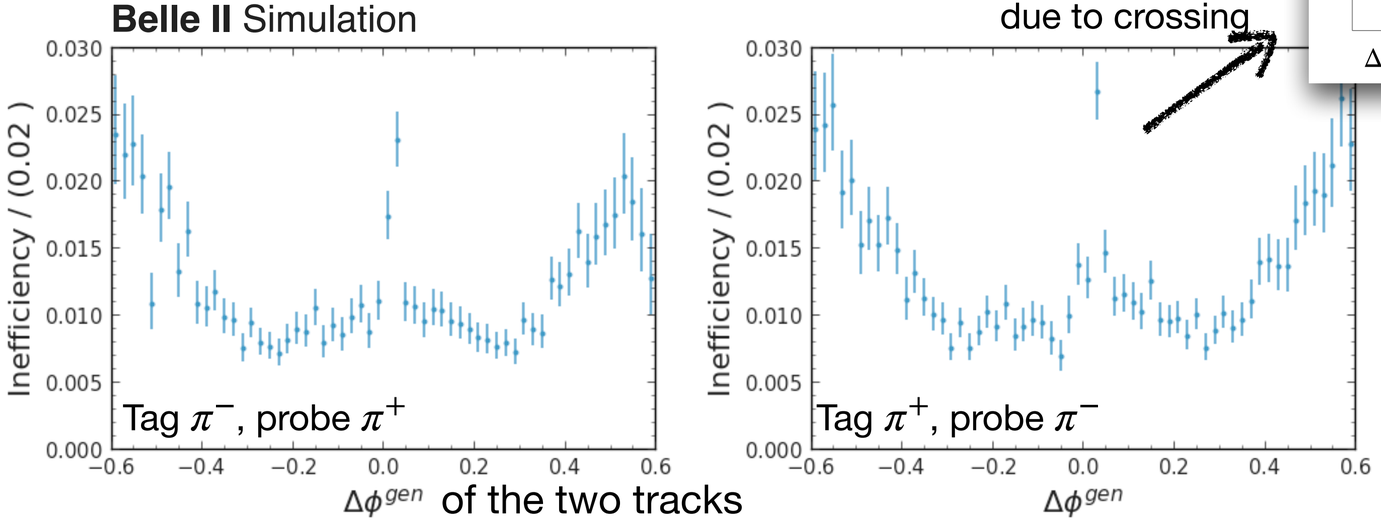
- Atleast one reconstructed ISR Photon
  - E_{CM} > 2GeV
  - In CDC Acceptance

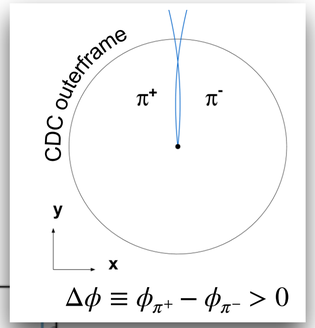
Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Promising tracking study: tracking inefficiency

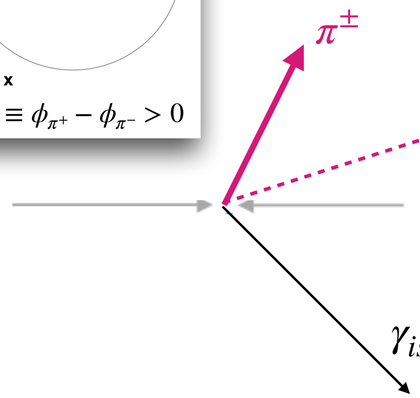
- Tracking inefficiency study with loose requirements (ISR in ECL inner barrel → in CDC, track P > 0.5 GeV instead of 1 GeV)
  - Inefficiency:

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





- 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



Data-driven prediction

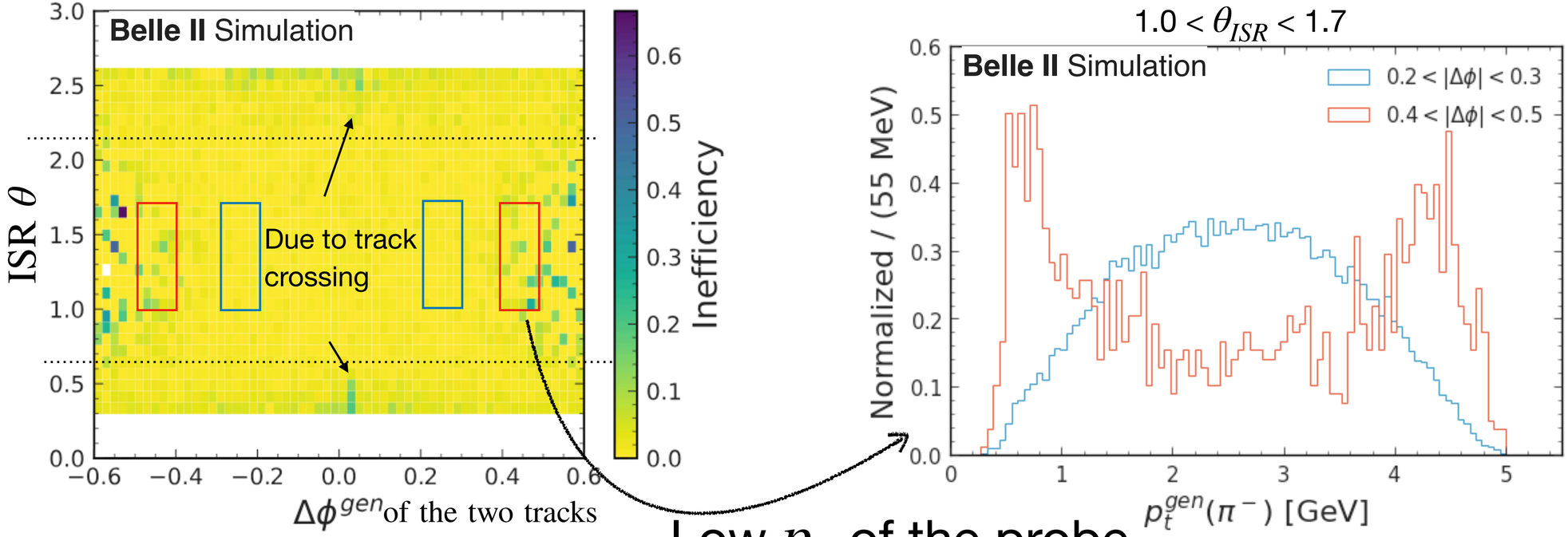
- The recoil (calculated by 1C fit) is required to have
  - P > 0.5 GeV, $\chi^2 < 1$
  - Theta in CDC Acceptance

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

Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Promising tracking study: tracking inefficiency

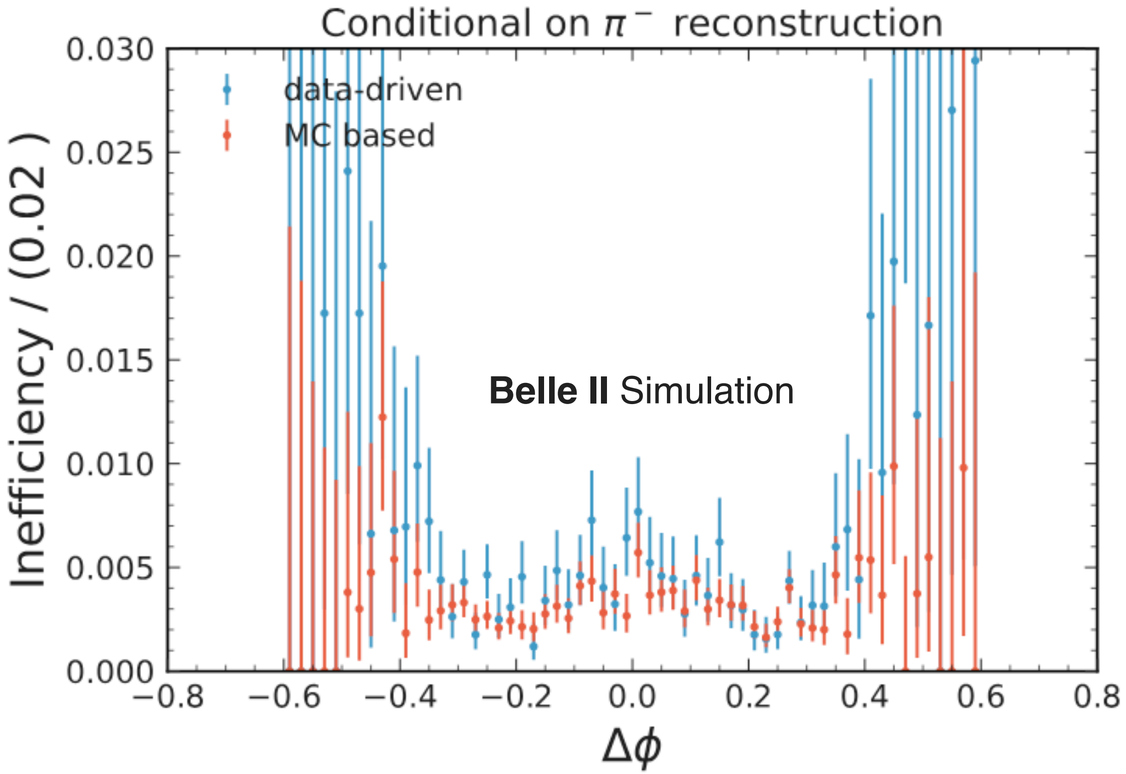
- Understanding of the inefficiency peaks with π^+ as the tag (probing π^-)
  - ISR in ECL inner barrel ($0.65 < \theta < 2.16$) will reduce the inefficiency peak !

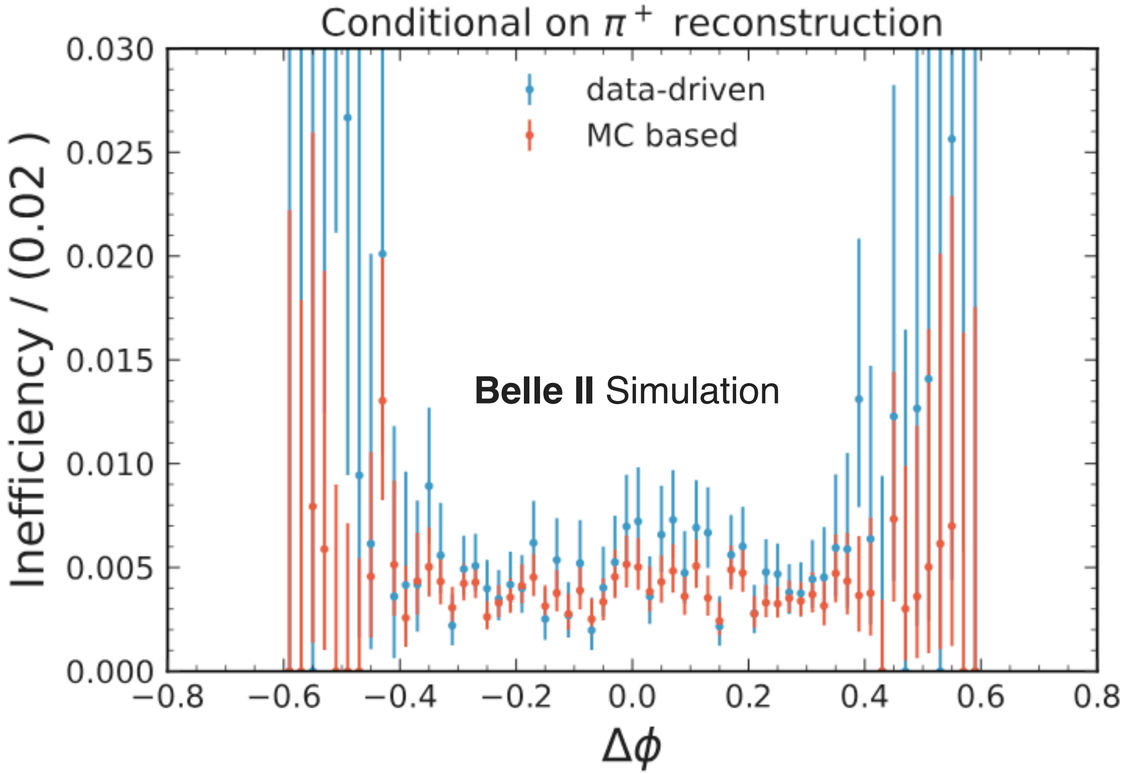


Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Promising tracking study: tracking inefficiency

- 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





Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

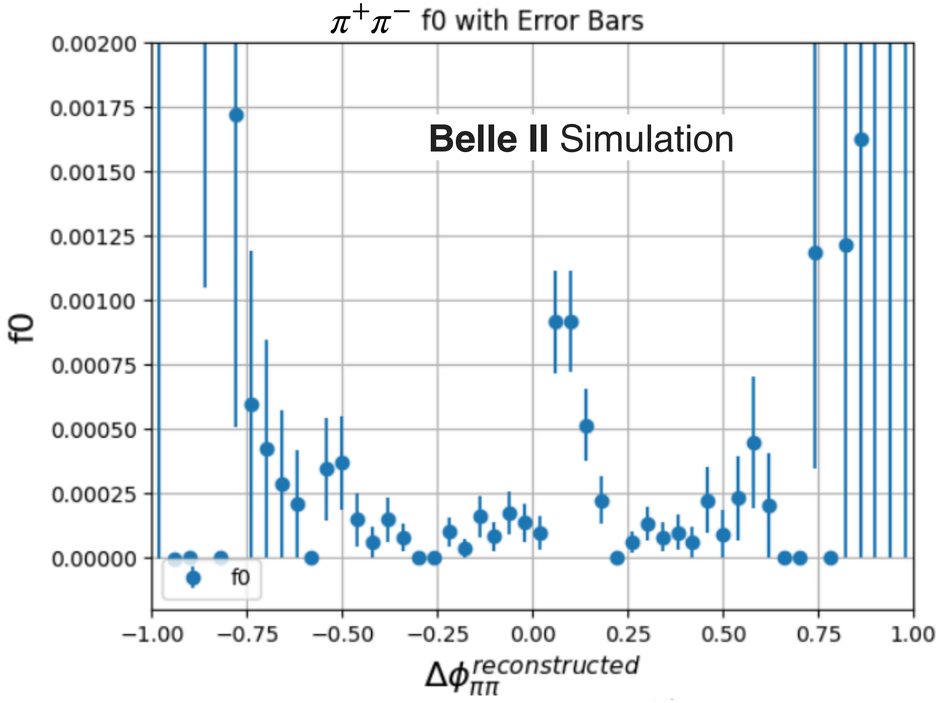
Promising tracking study: correlated track loss

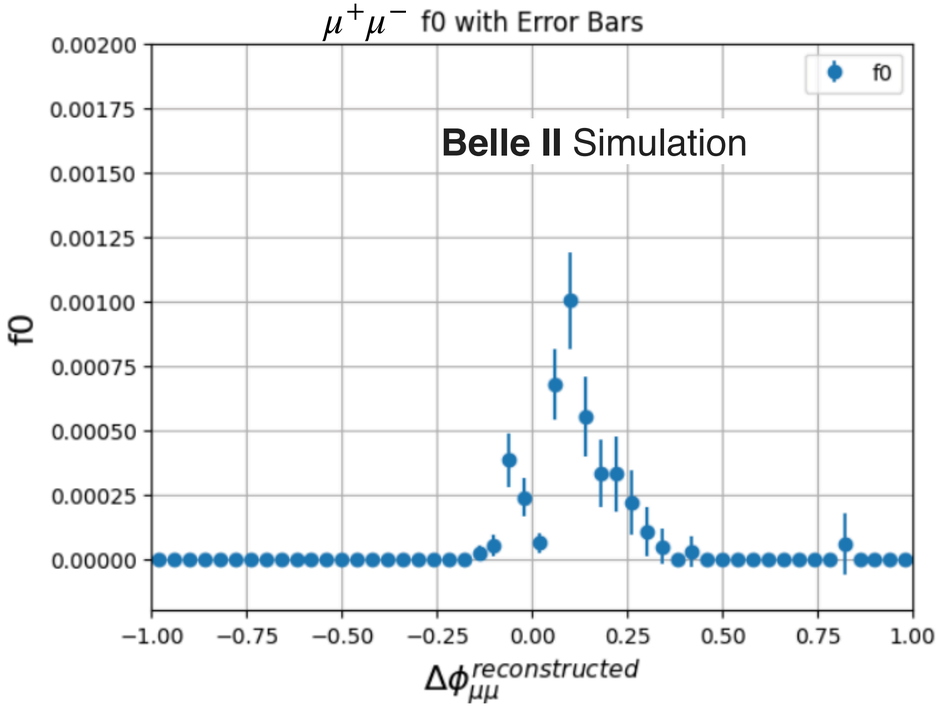
- Correction factor $f_0 = \frac{N_0}{N} - \frac{N_1^2}{4NN_2}$
  - N_0, N_1, N_2 are number of events with zero, one and two tracks
  - $N = N_0 + N_1 + N_2$, with N estimated by lifting track cuts for the tag

- 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





Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Blinding strategy

- Current status:
  - Tracking, PID and χ^2 study are only using MC for now
  - Trigger study already checked $e^+e^- \to \mu^+\mu^-(\gamma)$ data but with preliminary selections

- Several strategies with varying blinding levels are under discussion, considering factors like effectiveness, complexity, and necessity.

→ Backup slides

Summary

- **Successful sanity check** with 1.856 fb^{-1} data out of 427 fb^{-1}
  - Reasonable data-MC agreement even without any efficiency correction
- **Trigger** study (preliminary selection) with muons confirmed **99% efficiency in data**
- Optimizing the 2D χ^2 cut using BDT with an approximated cut shape
- PID performance is being studied with “tag and probe” method
- Single track **inefficiency** and **correlated track loss** have been studied with **MC**
  - Good agreement between the data-driven approach and the MC-based one
  - Ready to check data after the blinding strategy is settled
- Target systematic uncertainty: ~ 0.5%

Thanks!

Backup

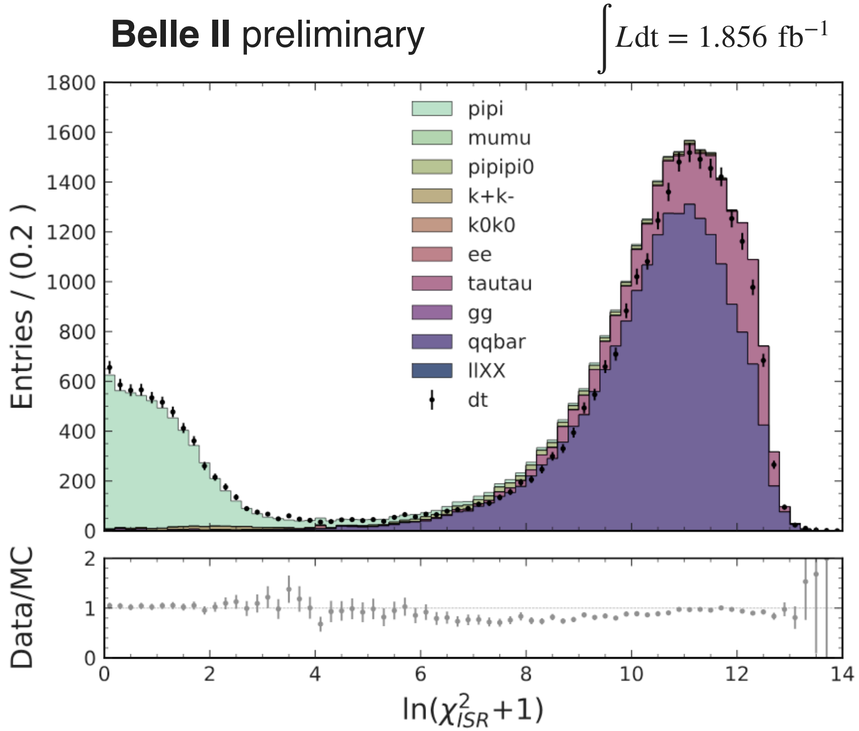
Preliminary selection (not optimized yet)

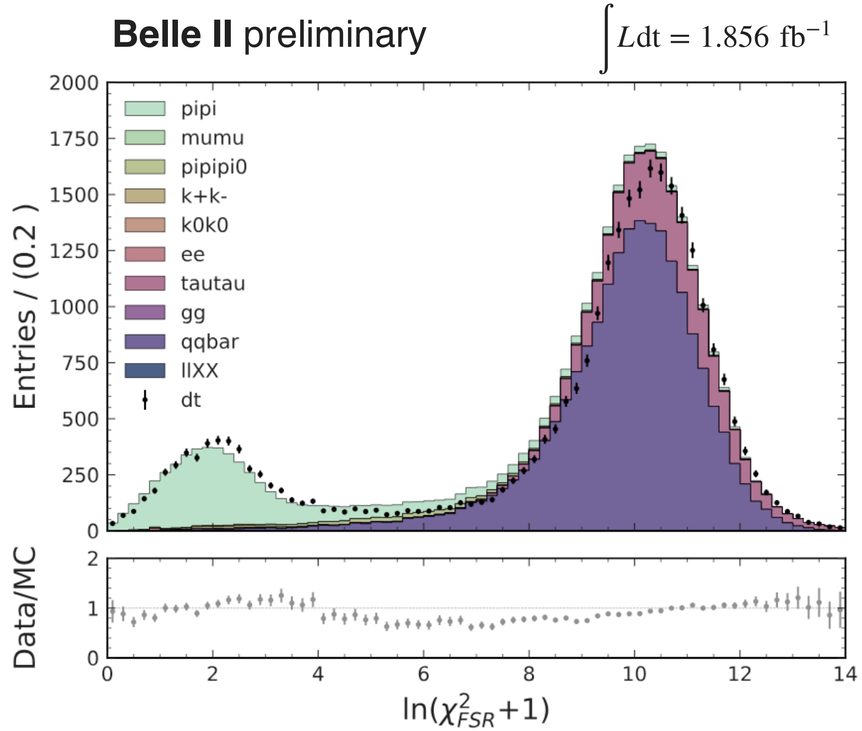
- Preliminary selection ← **HiE** trigger line
    - ISR (highest E^* in case of multiple candidates)
        - with $E^*_{ISR} > 2$ GeV, and in **ECL inner barrel** region: **(32.2+5, 128.7-5)**
    - The optional photon:
        - All clusters in **CDC acceptance** (smallest χ^2_{FSR} in case of multiple candidates)
    - Two tracks:
        - $dr < 2.0$ cm, $|dz| < 5.0$ cm and $p > 1.0$ GeV in **KLM inner barrel** region
        - PID(`pionID_noSVD` or `muonID_noSVD`) > 0.01
    - $M_{2-track} < 3.5$ GeV
    - Kinematic: Prob(χ^2_{ISR})>0, not optimized yet

Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Sanity check with 1.856 fb^{-1} data

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

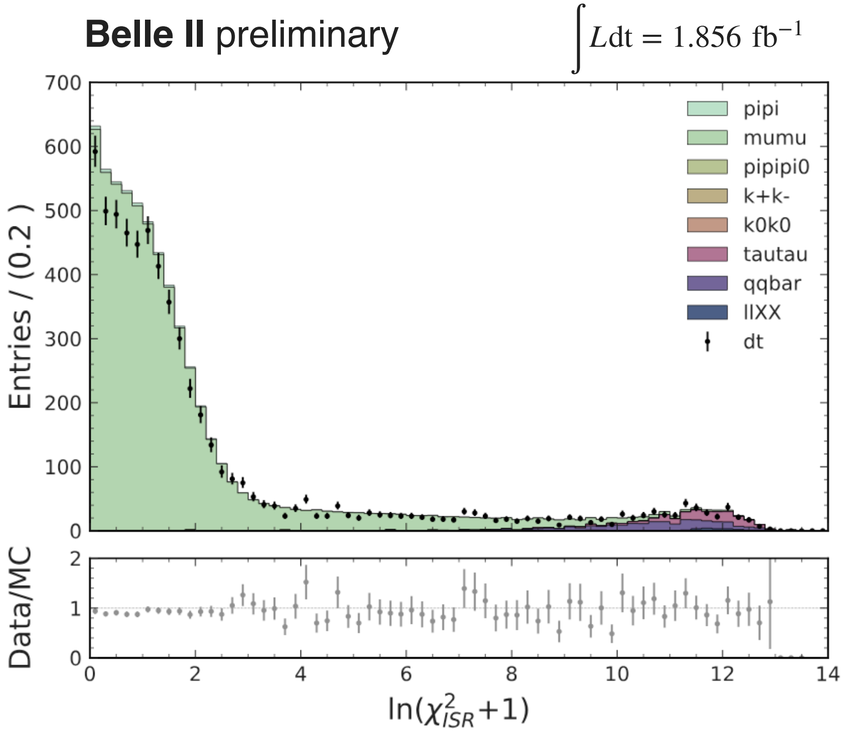


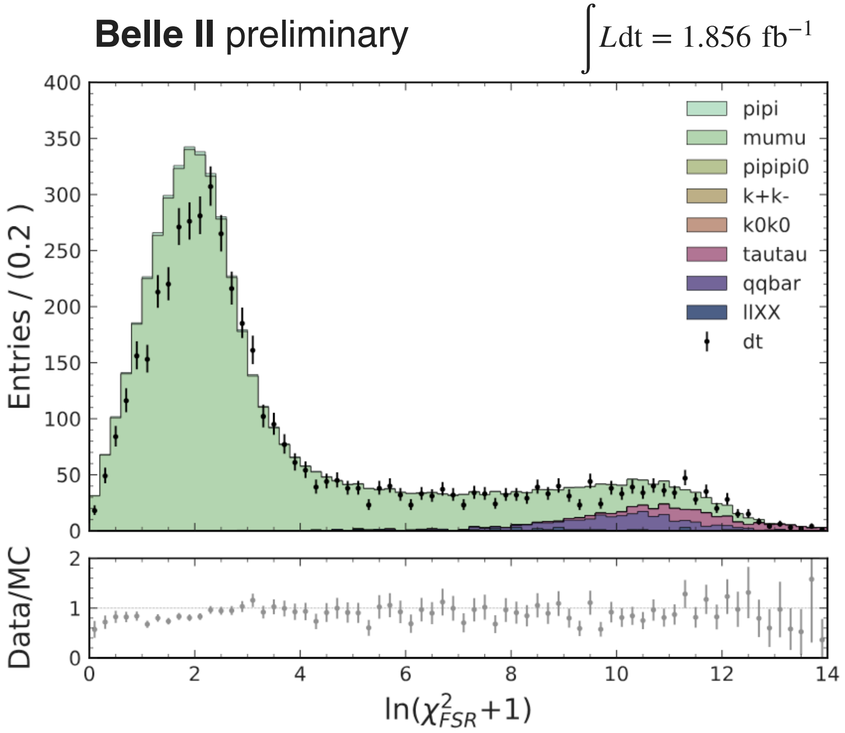


Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Sanity check with 1.856 fb^{-1} data

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





Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Trigger study with $e^+e^- \to \mu^+\mu^-(\gamma)$ events and preliminary selections

The hie trigger efficiency $(0 < M_{\mu\mu} < 1.0\ \mathrm{GeV}/c^2)$

$\sqrt{s}$ [MeV/c^2]	ϵ_{data} [%]	ϵ_{data} stat. [%]	ϵ_{MC} [%]	ϵ_{MC} stat. [%]
187.50	99.87	0.03	98.42	0.04
212.50	99.87	0.02	98.52	0.03
237.50	99.84	0.02	98.41	0.03
262.50	99.85	0.02	98.45	0.03
287.50	99.88	0.02	98.47	0.04
312.50	99.86	0.02	98.53	0.04
337.50	99.82	0.03	98.45	0.04
362.50	99.91	0.02	98.50	0.04
387.50	99.86	0.03	98.52	0.05
412.50	99.86	0.03	98.46	0.05
437.50	99.82	0.04	98.46	0.05
462.50	99.86	0.03	98.39	0.05
487.50	99.82	0.04	98.45	0.05
512.50	99.91	0.03	98.37	0.06
537.50	99.78	0.04	98.44	0.06
562.50	99.82	0.04	98.46	0.06

$\sqrt{s}$ [MeV/c^2]	ϵ_{data} [%]	ϵ_{data} stat. [%]	ϵ_{MC} [%]	ϵ_{MC} stat. [%]
587.50	99.81	0.04	98.49	0.06
612.50	99.89	0.03	98.44	0.06
637.50	99.86	0.04	98.44	0.06
662.50	99.87	0.04	98.45	0.06
687.50	99.92	0.03	98.53	0.06
712.50	99.82	0.05	98.34	0.07
737.50	99.81	0.05	98.41	0.07
762.50	99.88	0.04	98.48	0.06
787.50	99.89	0.04	98.59	0.06
812.50	99.93	0.03	98.46	0.07
837.50	99.88	0.04	98.53	0.07
862.50	99.86	0.05	98.41	0.07
887.50	99.92	0.03	98.37	0.07
912.50	99.90	0.04	98.51	0.07
937.50	99.83	0.05	98.52	0.07
962.50	99.87	0.05	98.42	0.07
987.50	99.89	0.04	98.51	0.07

Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ measurement

Blinding strategy

- Current status:
  - Tracking, PID and χ^2 study are only using MC for now
  - Trigger study already checked $e^+e^- \to \mu^+\mu^-(\gamma)$ data but with preliminary selections
- Several strategies with varying blinding levels are under discussion (effectiveness, complexity, necessity , …, etc)
  - Apply a hidden **scale** or **removal** factor at the **reconstruction** or **analysis level**
  - Scale the MC with an arbitrary factor for each study → **offset on data-to-MC** ratios
  - **Manipulate mass spectra** simultaneously (**mass dependent** scale/removal) for both data and MC → blind the cross-section, ensuring similar data-to-MC ratios to the unblinded data
  - …

Modified R value / default