Measurements of the hadronic cross sections via ISR at Belle II

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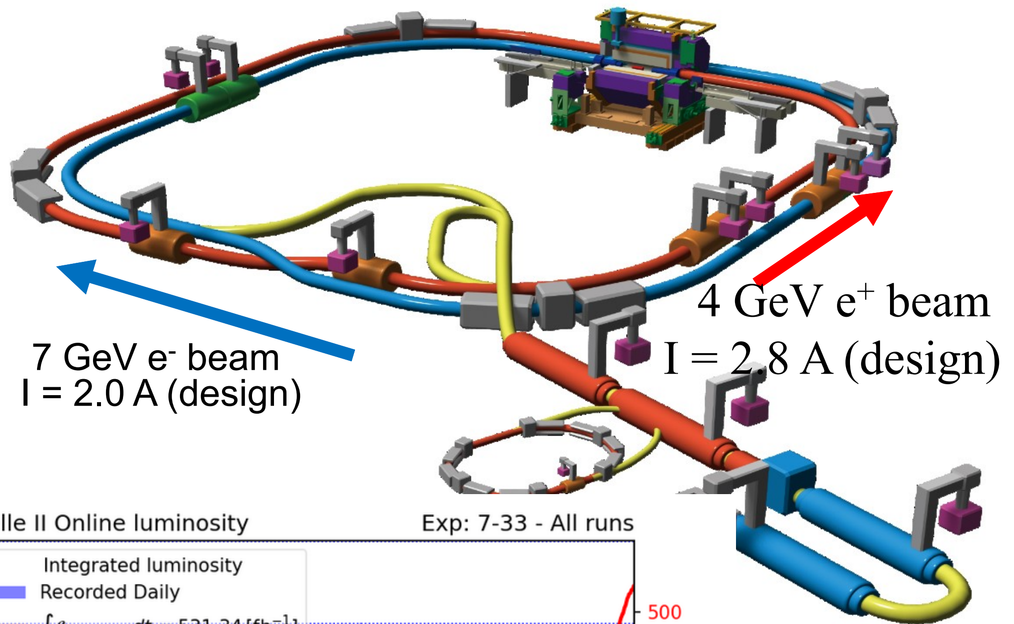
SuperKEKB collider

World record instantaneous luminosity: 4.7×10^{34} /cm^2/s

- Asymmetric e^+e^- collider
  - $\sqrt{s} = M(\Upsilon(4S)) = 10.58$ GeV
  - Design luminosity : 6×10^{35} cm^{-2}s^{-1}
- Improvements from KEKB
  - Nano beam scheme
  - Higher design beam currents

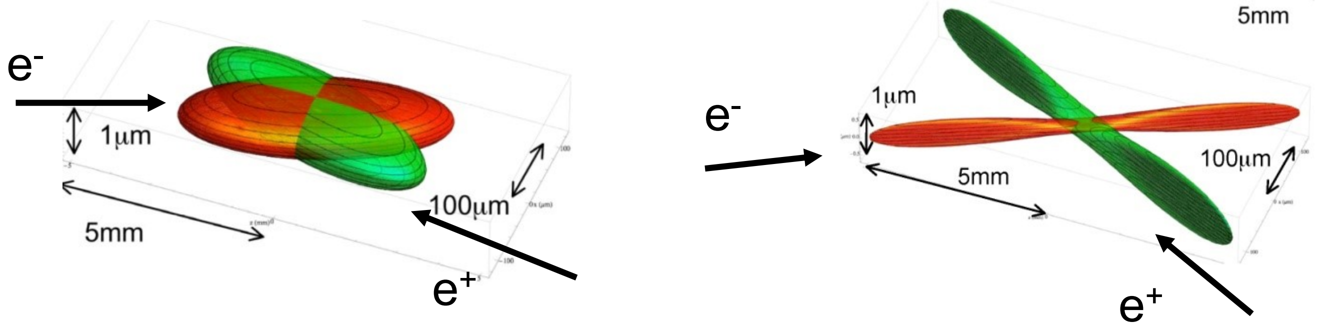


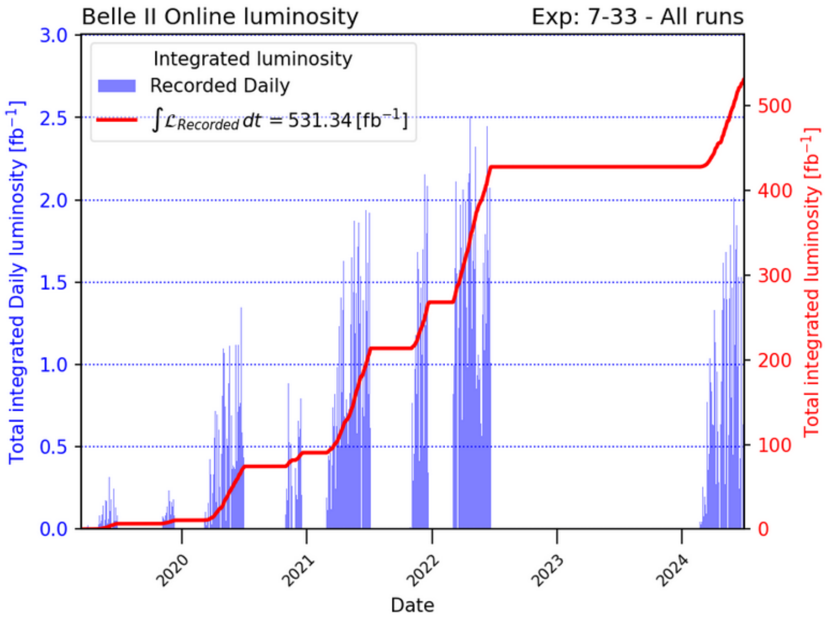
KEKB

$\sigma_x \sim 100\mu m, \sigma_y \sim 2\mu m$

Nano-Beam SuperKEKB

$\sigma_x \sim 10\mu m, \sigma_y \sim 60nm$





Belle II Detector

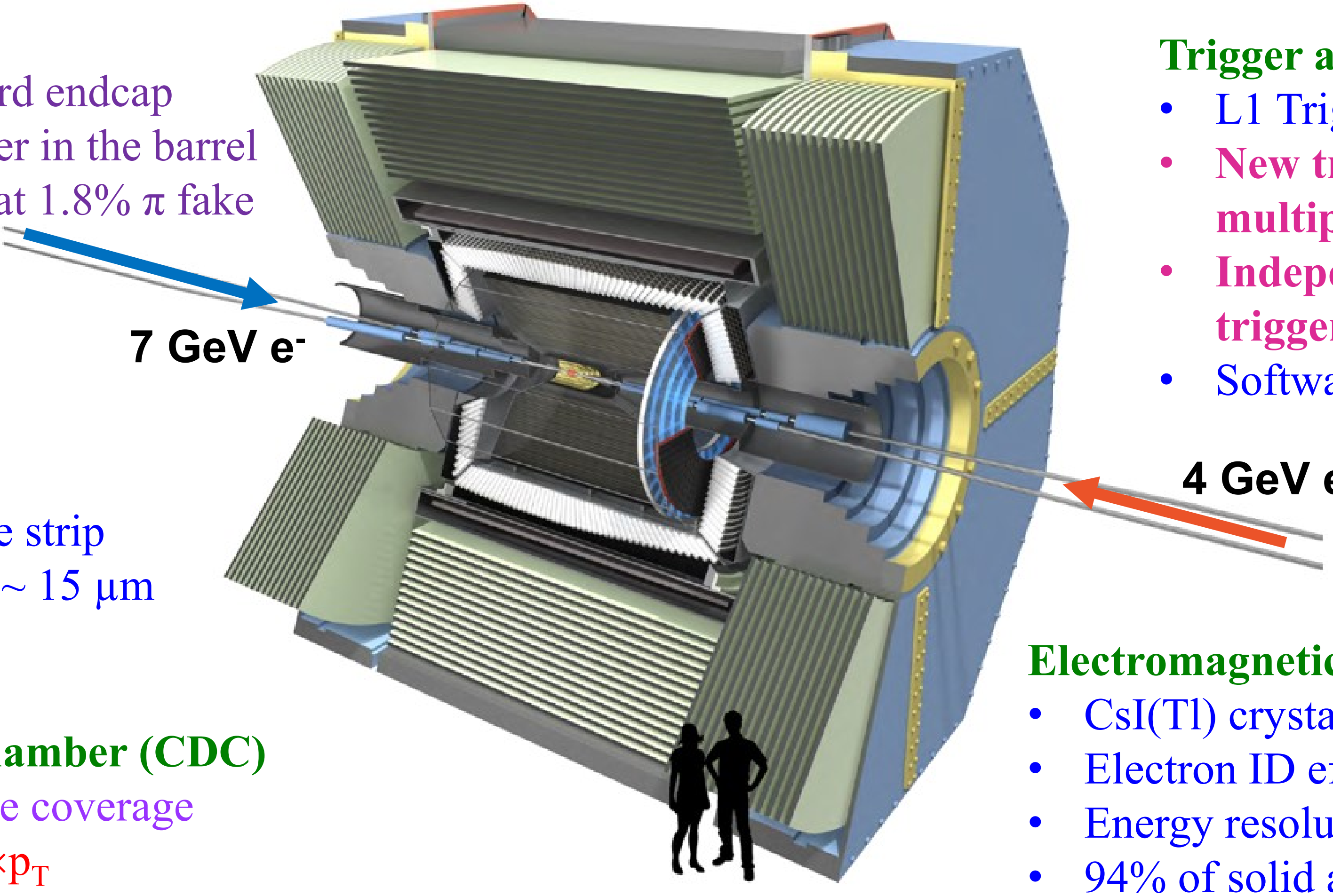
Near-hermetic multipurpose detector

At SuperKEKB collider

K-long and Muon Detector (KLM)
Alternating iron and detector plates
Scintillator / Resistive Plate Chamber
Muon ID efficiency 90% at 2% fake

Particle Identification
Aerogel RICH in the forward endcap
Time-of-Propagation counter in the barrel
K/π ID : K efficiency 90% at 1.8% π fake

Trigger and DAQ
- L1 Trigger rate 30 kHz (design)
- **New trigger line for low-multiplicity events**
- **Independent CDC and ECL trigger modes**
- Software based HLT



Vertex Detector (VXD)
Inner 2 layers : Pixel
Outer 4 layers : Double side strip
σ(Track impact parameter) ~ 15 μm

Electromagnetic Calorimeter (ECL)
- CsI(Tl) crystals + Waveform fit
- Electron ID eff. 90% at <0.1% fake
- Energy resolution 1.6-4%
- 94% of solid angle coverage

Central Drift Chamber (CDC)
91% of solid angle coverage
$\sigma(p_T)/p_T \sim 0.4\% \times p_T$
dE/dx resolution 5% (low-p PID)

Belle II physics program

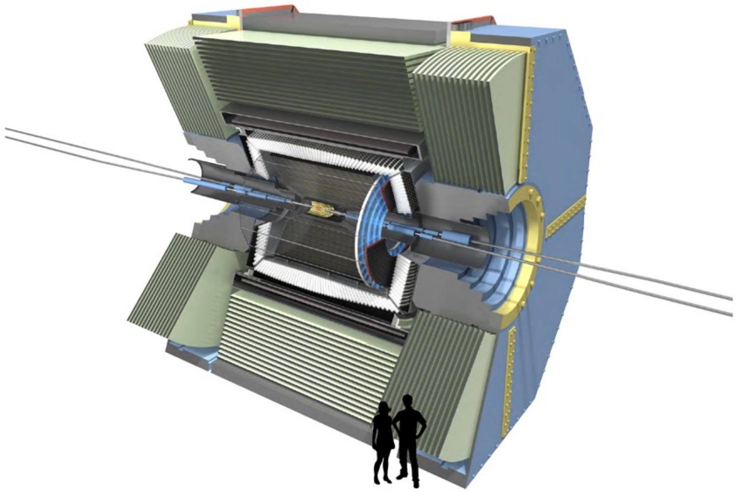
Snowmass White Paper arXiv:2207.06307v2 [hep-ex]

Collected data:

- ~ 362 fb^{-1} at Y(4S)
- 42 fb-1 off-resonance, 60 MeV below Y(4S).
- 19 fb-1 energy scan between 10.6 to 10.8 GeV for exotic hadron studies.

Precision CKM tests and searches for non-SM CP violation in B decays

Non-SM probes from semileptonic, radiative, and leptonic B decays



Precise particle metrology: Masses and lifetimes measurements

Charm physics

Direct searches for light non-SM physics and Dark Sector studies

Tau lepton physics

Quarkonium, exotics, and hadron spectroscopy
High precision measurements of the hadronic cross section demanded by HVP in muon (g-2) and other precise QCD tests

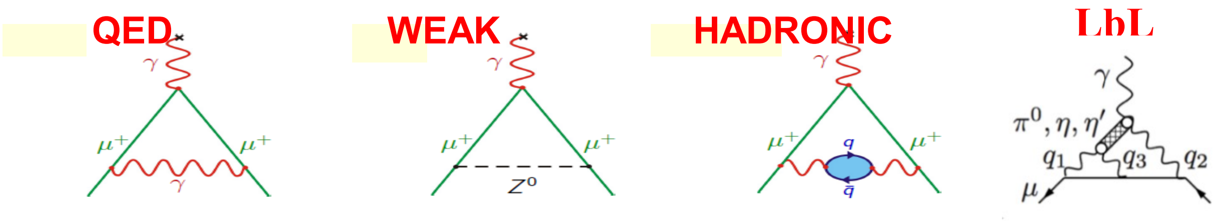
Muon anomaly, $a_\mu=(g-2)_\mu/2$: SM calculations and experiment

$$a_\mu^{theory(SM)} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$

Two approaches for estimating the HVP contribution:
Dispersion relations (w/ inputs from ee → hadrons data)
Lattice QCD

$$a_\mu^{had} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds\,\frac{K(s)}{s}R(s)$$

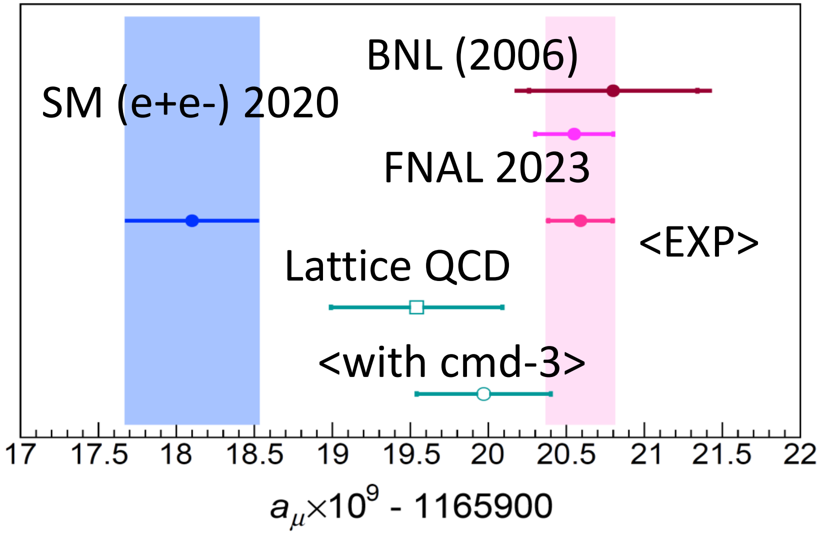
$$R(s) = \frac{\sigma(e^+e^- \to \gamma^* \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



Contribution	Value $\times 10^{11}$
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (pheno + lattice + NLO)	92(18)
Total SM Value Section	116 591 810(43)
Exp. (E821) - SM	279(76)

$\pi^+\pi^- \sim 73$ %,
$\pi^+\pi^-\pi^0$ ~7%

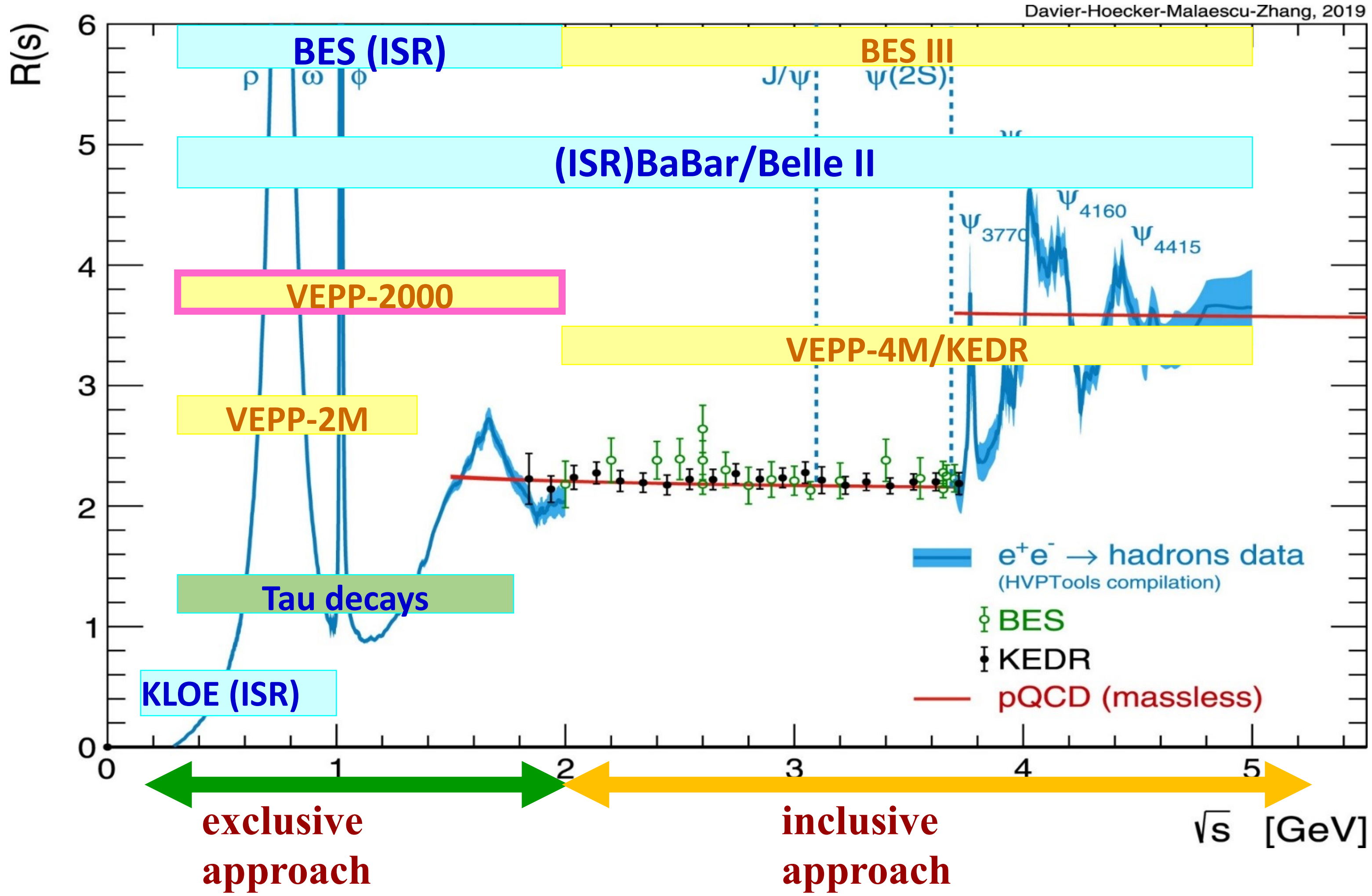
FNAL 116 592 055(24)$\times 10^{-11}$(0.20 ppm)

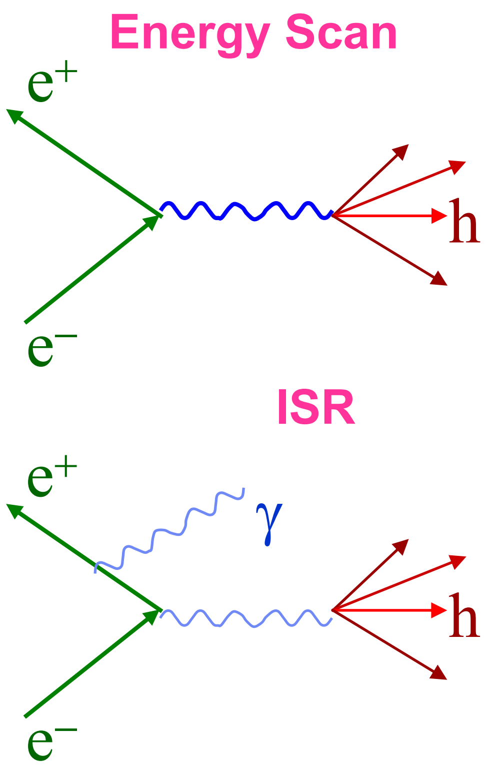


The table is from:
"The anomalous magnetic moment of the muon in the Standard Model",
T. Aoyama et al., Physics Reports 887 (2020) 1–166

$e^+e^- \to \pi^+\pi^-$ PRD 109 112002 (2024)

R measurement – exclusive vs inclusive





$$s' = 2\sqrt{s}E_{ISR}$$

ISR photons mostly go at small angles, only about 10% of them are emitted into detector acceptance

The figure is from:
"The anomalous magnetic moment of the muon in the Standard Model",
T. Aoyama et al., Physics Reports 887 (2020) 1–166.

HVP measurements at Belle II

In comparison to Belle:

- New low-multiplicity trigger effectively distinguish ISR events from e^+e^- and $\gamma\gamma$ subjected to prescaling.
- Two independent triggers based on the Tracker and Calorimeter which provide efficiency estimation from the data
- Almost 100% efficiency for energetic ISR

Two channels are under study now.

$e^+e^- \to \pi^+\pi^-$

Target 0.5% precision using 363 fb^{-1} data

Try to following BaBar methods as a base line

$e^+e^- \to \pi^+\pi^-\pi^0$

Mass range : 0.6-3.5 GeV,

Target precision : $\delta a_\mu(3\pi) \sim 2\%$

At present the results is published in arXiv:2404.04915 and by PRD and accepted by PRD.

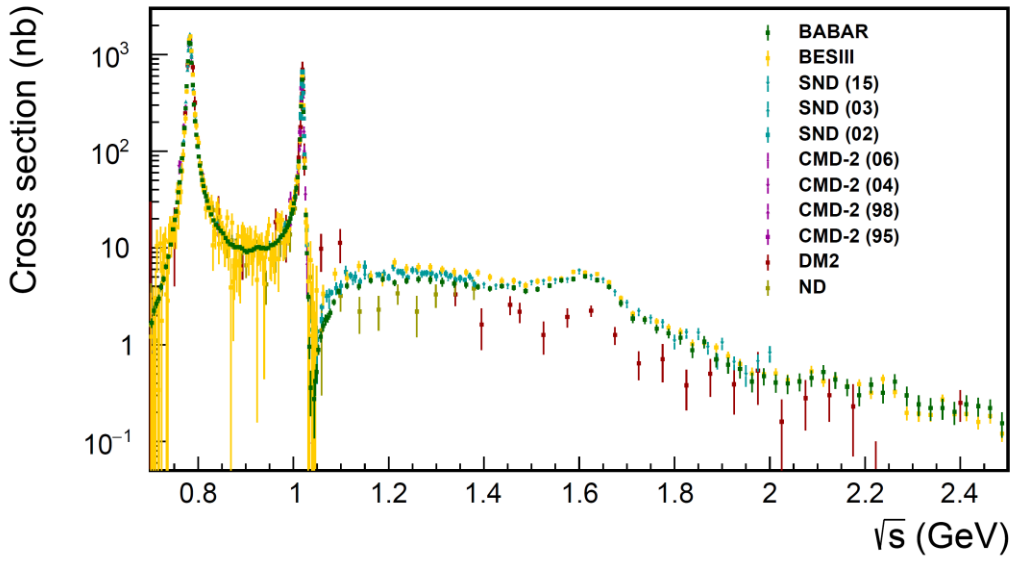
Previous measurements of $e^+e^- \to \pi^+\pi^-\pi^0$

Recent measurements:

- Preliminary result from BES III [arXiv:1912.11208]
- BABAR has updated its results with full data [Phys. Rev. D 104, 112003 (2021)]

As for the $e^+e^- \to \pi^+\pi^-\pi^0$ contribution $a_\mu(3\pi)$, the uncertainty of $a_\mu(3\pi)$ is 2-3% for combination and 1.3% for BABAR alone.

- The difference in the cross section between the experiments below 1.1 GeV produces the error.



$e^+e^- \to \pi^+\pi^-\pi^0$ analysis

Dataset : 2019-2021 191 fb^{-1}

- **Blind analysis**
  - Study of analysis methods using MC and validation using 10% data.
  - Final confirmation under way using full data set.
- **Key items**
  - Trigger
  - Background reduction and estimation
  - Efficiency corrections
  - Unfolding

Event selection

Two tracks + ≥ three photons : $e^+e^- \to \pi^+\pi^-\pi^0 \gamma_{ISR} \to \pi^+\pi^-\gamma\gamma\gamma_{ISR}$

Tracks : dr < 0.5 cm and |dz| < 2 cm and p_T > 0.2 GeV/c

Photons : E > 100 MeV + at least one photon must be energetic ISR (E^{CMS}> 2 GeV in barrel ECL)

π^0 reconstruction

Invariant mass of two photons within 0.123-0.147 GeV/c^2

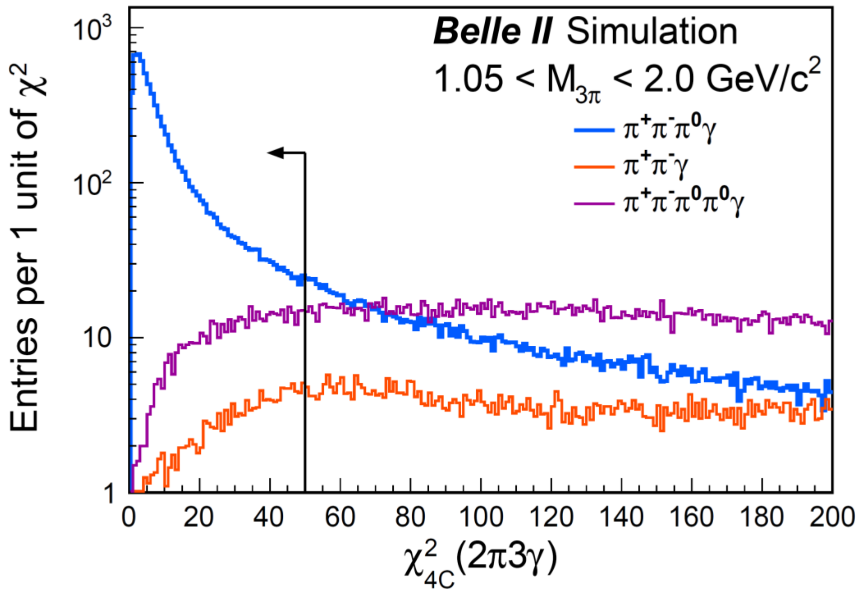
$\chi^2_{4C}(3\pi\gamma) < 50$ is used for the cross section measurement

➢ Four-vector kinematic fit (4C-KFit)

➢ Fit to positions and momenta

➢ Constrain to initial e^+e^- four-momentum

➢ Select small χ2 to extract signal-like event

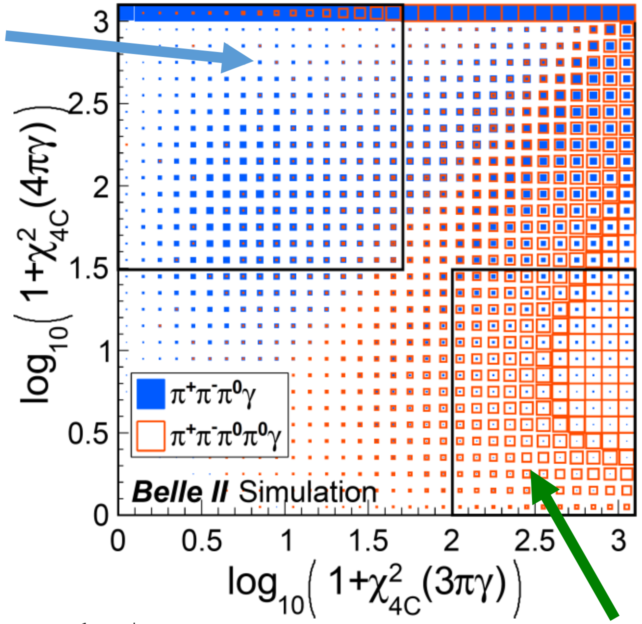


Background suppression

A) Background not containing real π^0 : $e^+e^- \rightarrow e^+e^-\gamma, \pi^+\pi^-\gamma, \mu^+\mu^-\gamma$
Pion/Electron ID : $L(\pi/e) > 0.1$, $M^2_{recoil}(\pi^+\pi^-) > 4\ GeV^2/c^4$

B) Charged kaon : $e^+e^- \rightarrow K^+K^-\pi^0\gamma$
Pion/Kaon ID : $L(\pi/K) > 0.1$

C) $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\gamma$
Reconstruct $\pi^+\pi^-\pi^0\pi^0\gamma$ (with additional π^0)
4C kinematic fit under $\pi^+\pi^-\pi^0\pi^0\gamma$ hypothesis,
and $\chi^2_{4C}(4\pi\gamma) > 30$

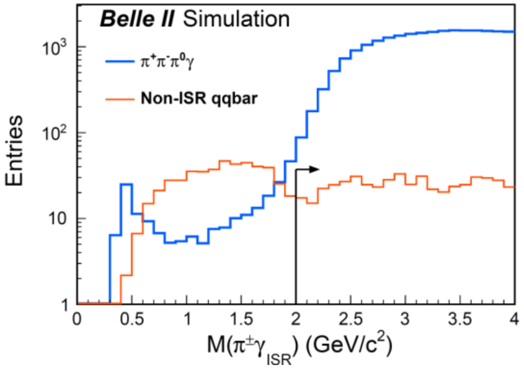


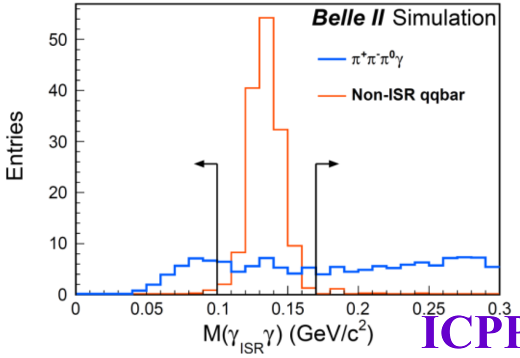
Background not containing real ISR : Non-ISR qqbar (dominated by $\pi^+\pi^-\pi^0\pi^0$) and $\tau^+\tau^-$

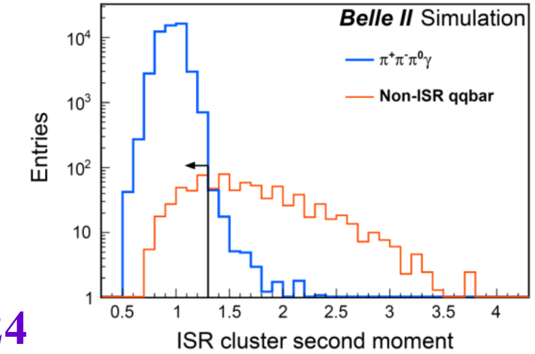
i. $M(\pi^\pm\gamma_{ISR}) > 2$ GeV/c2 to reduce high momentum $\rho^\pm \rightarrow \pi^+\pi^0$

ii. $M(\gamma_{ISR}\gamma)$ cut to reduce ISR candidate from π^0-decay photon

iii. Cluster shape cut to reduce ISR-like photon in which two photons from of π0 are merged

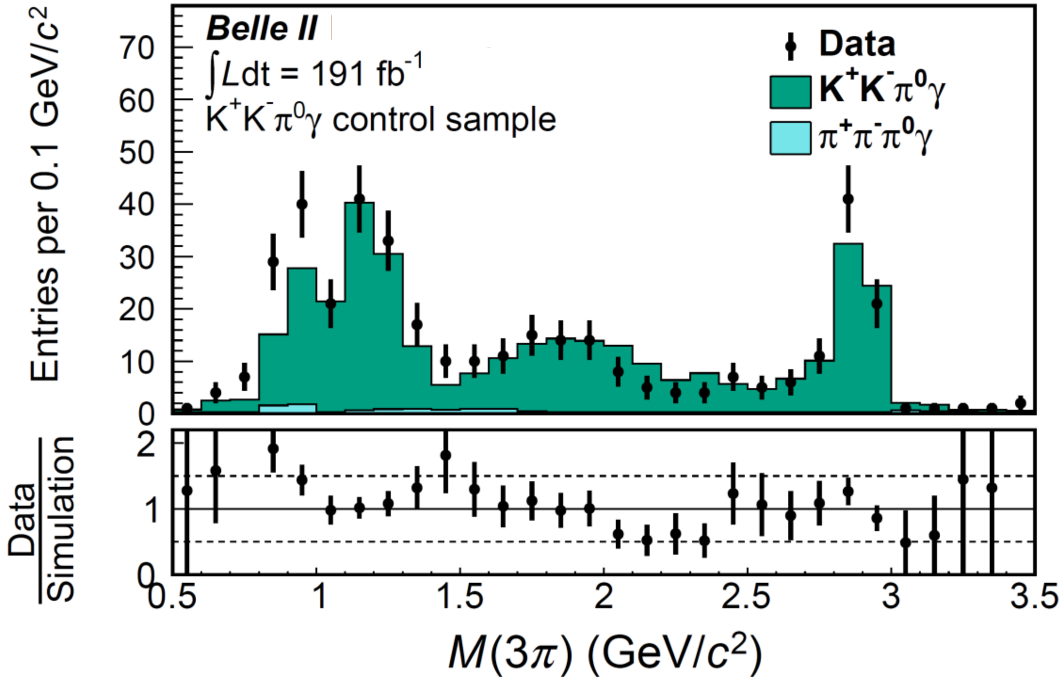


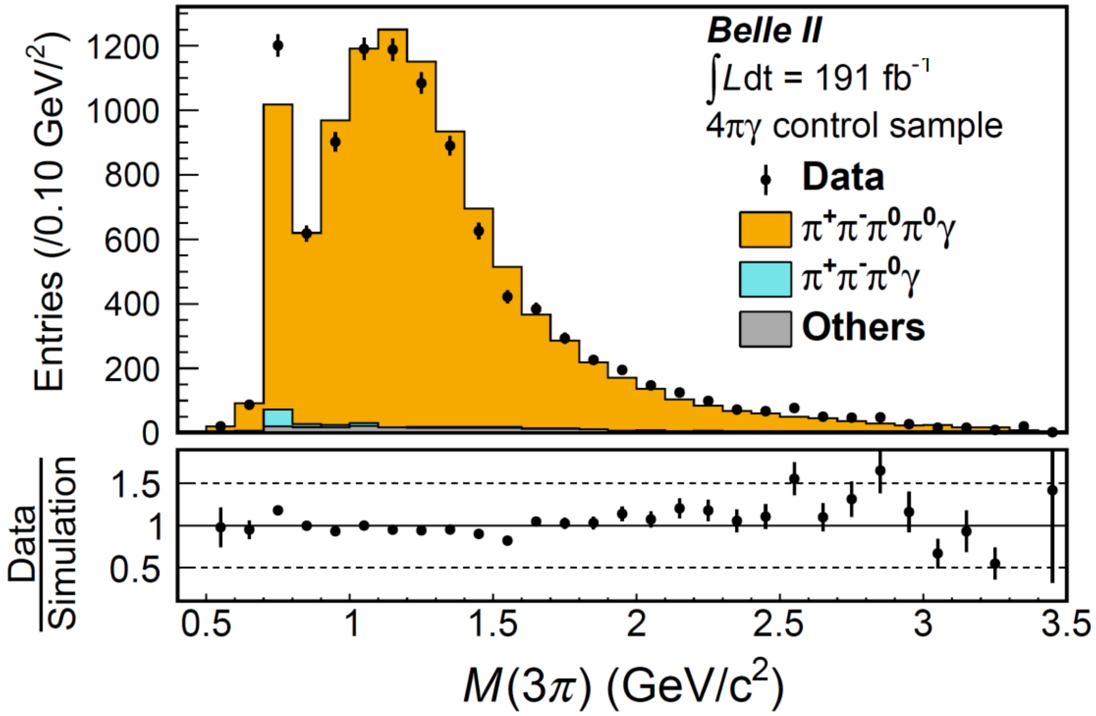




Background estimation

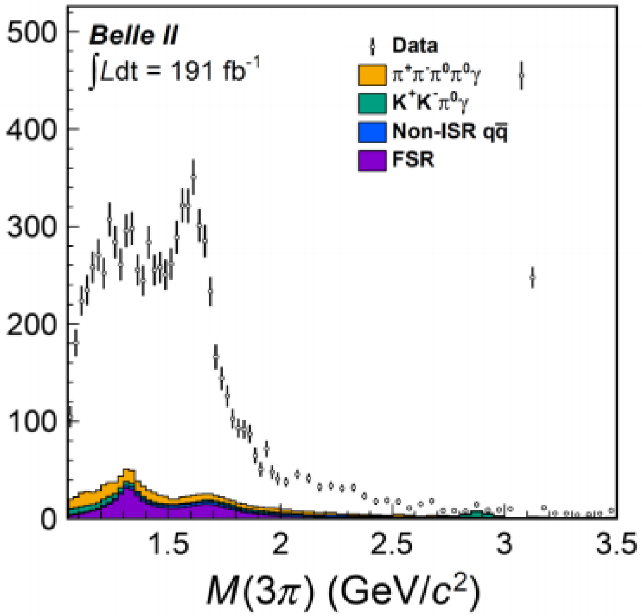
- ✓ By a mass-dependent data/MC ratio factor on the base of a control samples.
- ✓ $e^+e^- \to K^+K^-\pi^0\gamma$: Invert π/K-ID L(π/K) > 0.1 ⇒ L(π/K) < 0.1
- ✓ $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$: Reconstruct $\pi^+\pi^-\pi^0\pi^0\gamma$ and select $\chi2(4\pi\gamma) < 30$
- ✓ Non-ISR qqbar : $0.10 < M(\gamma_{ISR}\gamma) < 0.17$ GeV / large cluster second moment





Signal extraction after event selection

- The signal is estimated by fit of $M(\gamma\gamma)$ in each $M(3\pi)$ bin, in the 0.123-0.147 GeV/c mass range by sum of the signal peak and polynomial combinatorial background



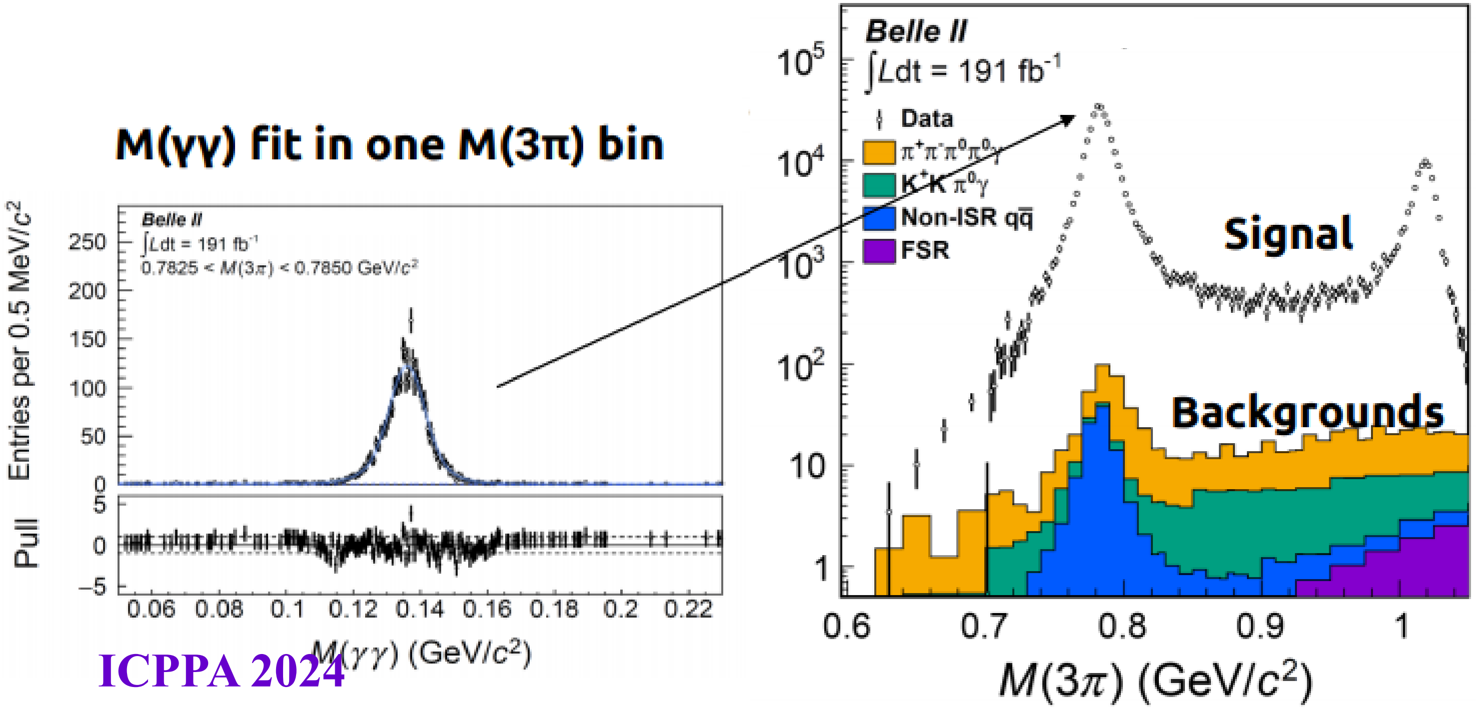
Detection efficiency is estimated first using MC of the x20 larger statistics.

Possible differences between data and MC are checked using data.

Main items important in this analysis:

- Trigger efficiency
- High energy photon detection efficiency
- Tracking efficiency
- π^0 efficiency
- χ^2 selection
- Background reduction cut efficiency

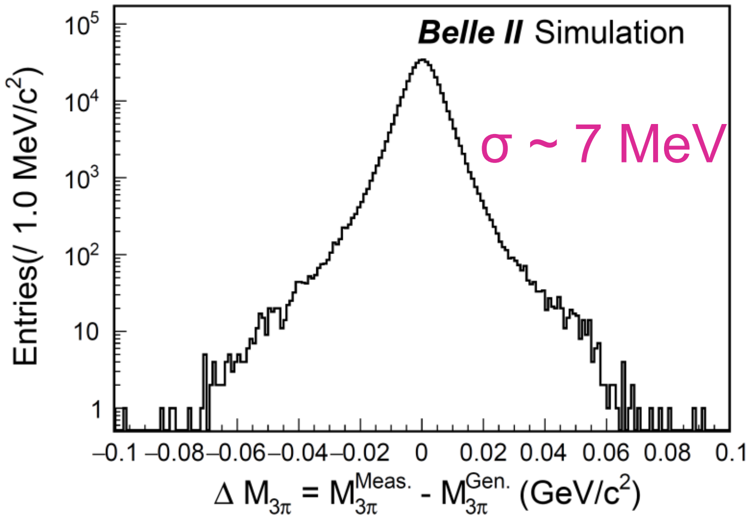
M(γγ) fit in one M(3π) bin



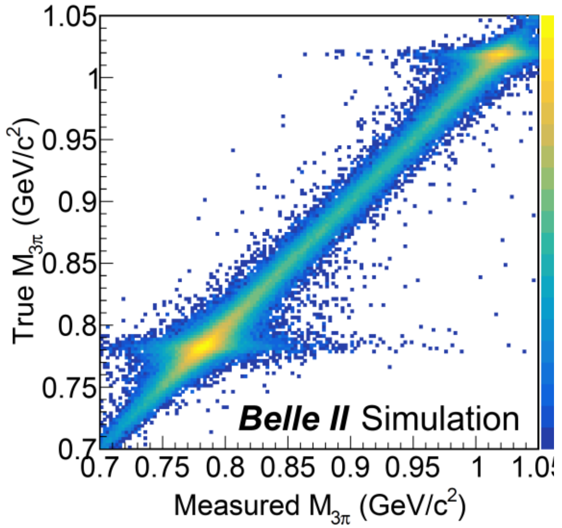
Unfolding

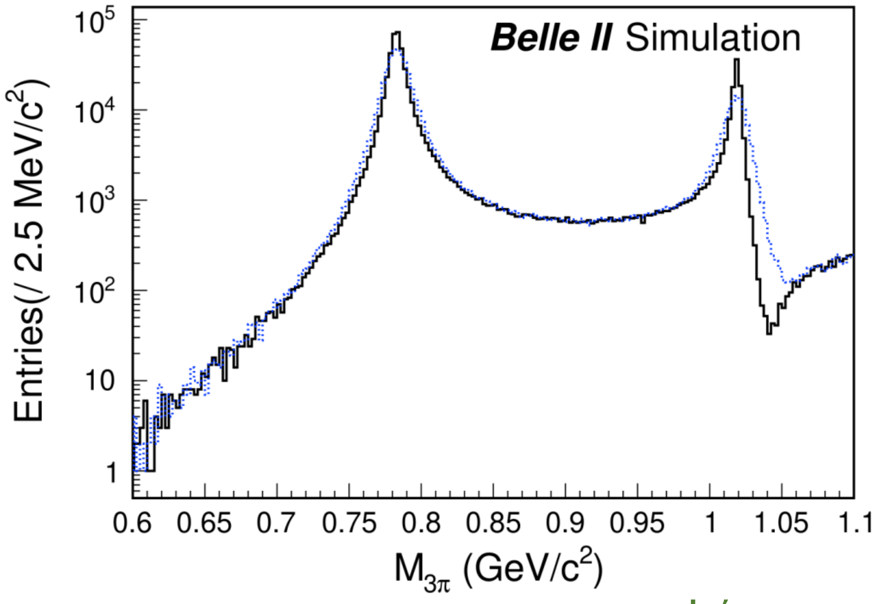
- The background-subtracted spectrum is unfolded to take into account the effect of detector response and final-state radiation.
- The data-MC resolution difference is determined by a Gaussian convolution fit to the ω, Φ, and J/ψ resonances.
  - The agreement is good typically with a mass resolution around 7-10 MeV.

3π mass resolution



Response function





ω resonance

Efficiency and Systematic uncertainty

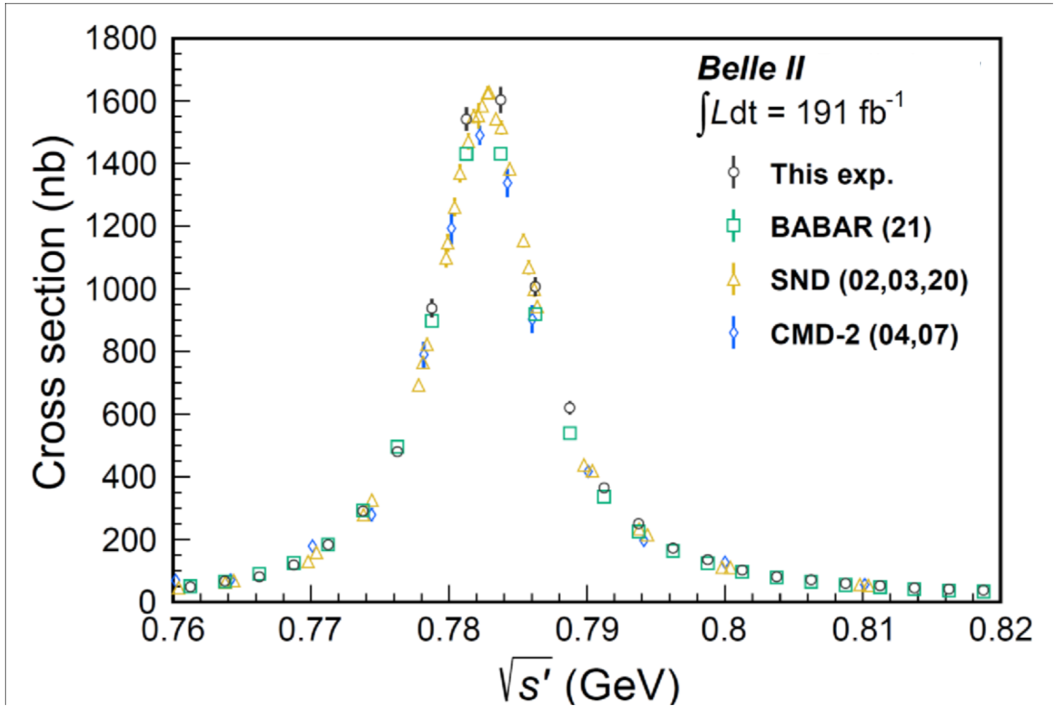
$$\sigma_{ee\to 3\pi} M_i = \frac{N_{i,unfolded}}{\varepsilon(M_i)\cdot L_{eff}(M_i)\cdot(1+\delta_{rad})}$$

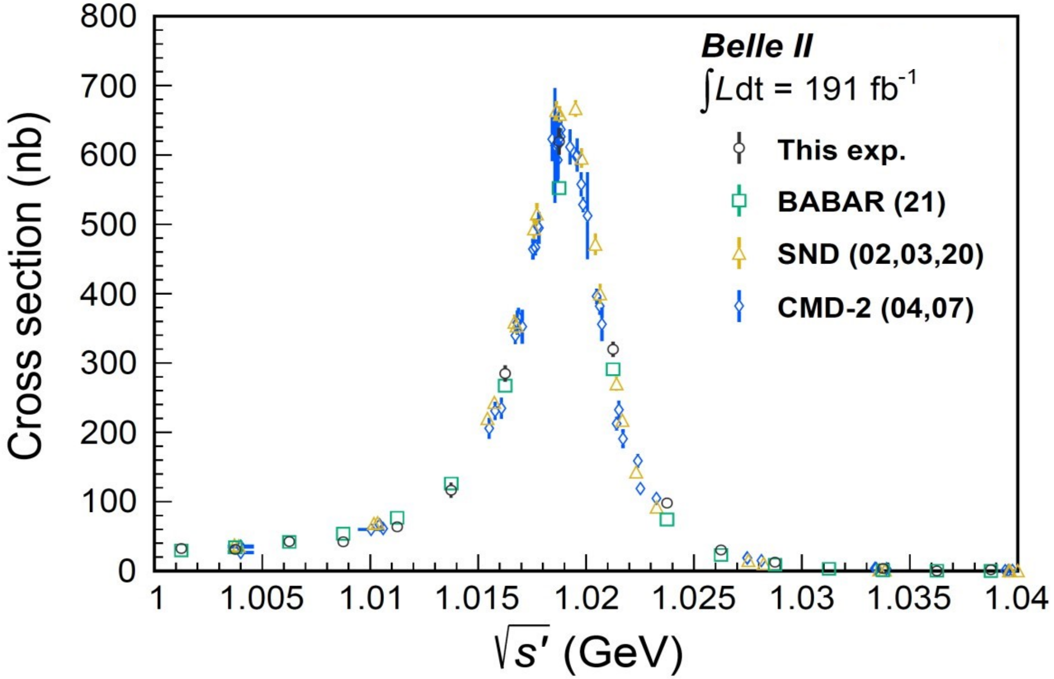
Efficiency $\varepsilon = \varepsilon_{MK}\Pi(1+\delta_i)$ Data-MC correction $\delta_i \sim O(1)\%$

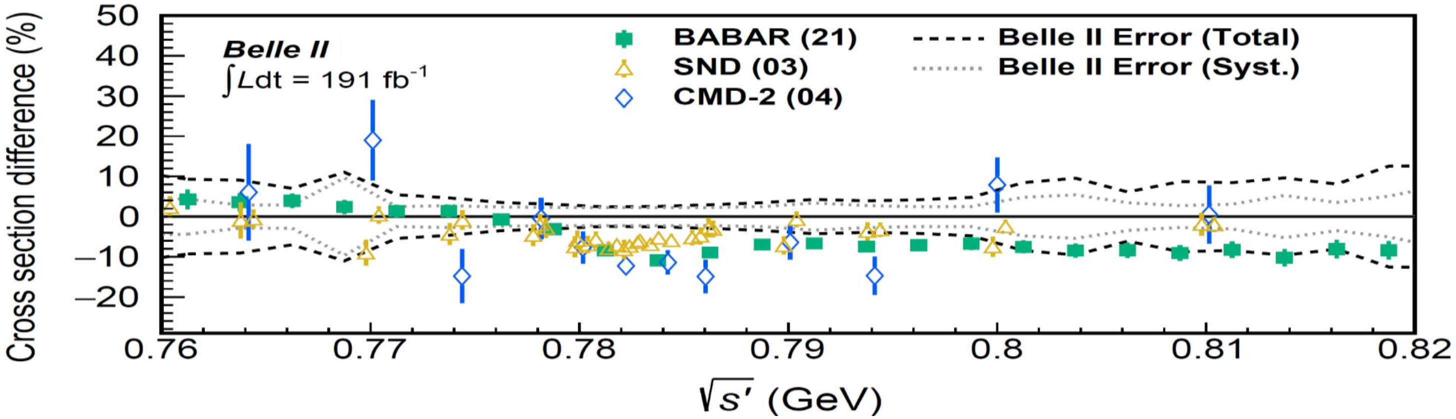
Source	Efficiency correction (%) 1.05 GeV/c2	M > 1.05 GeV/c2
Trigger	-0.1±0.1	-0.1±0.1
ISR photon detection	+0.2±0.7	+0.2±0.7
Tracking	-1.4±0.8	-1.7±0.8
π^0 detection	-1.4±1.0	-1.4±1.0
Background suppression	-1.9±0.2	-1.8±1.9
$\chi2$ distribution	0.0±0.6	0.3±0.3
MC generator	0.0±1.2	0.0±1.2
Total correction	-4.6±2.0	-4.6±2.0

Source	Systematic uncertainty (%) <1.05 GeV	>1.05GeV	
Trigger efficiency		0.1	0.2
ISR photon efficiency	0.7	0.7	
Tracking efficiency	0.8	0.8	
π^0 efficiency	1.0	1.0	
$\chi2$ criteria efficiency	0.6	0.3	
Background suppression efficiency	0.2	1.9	
MC generator	1.2	1.2	
Radiative correction	0.5	0.5	
Integrated luminosity	0.6	0.6	
Total systematics	2.2	2.8	

Result: cross section below 1.05 GeV

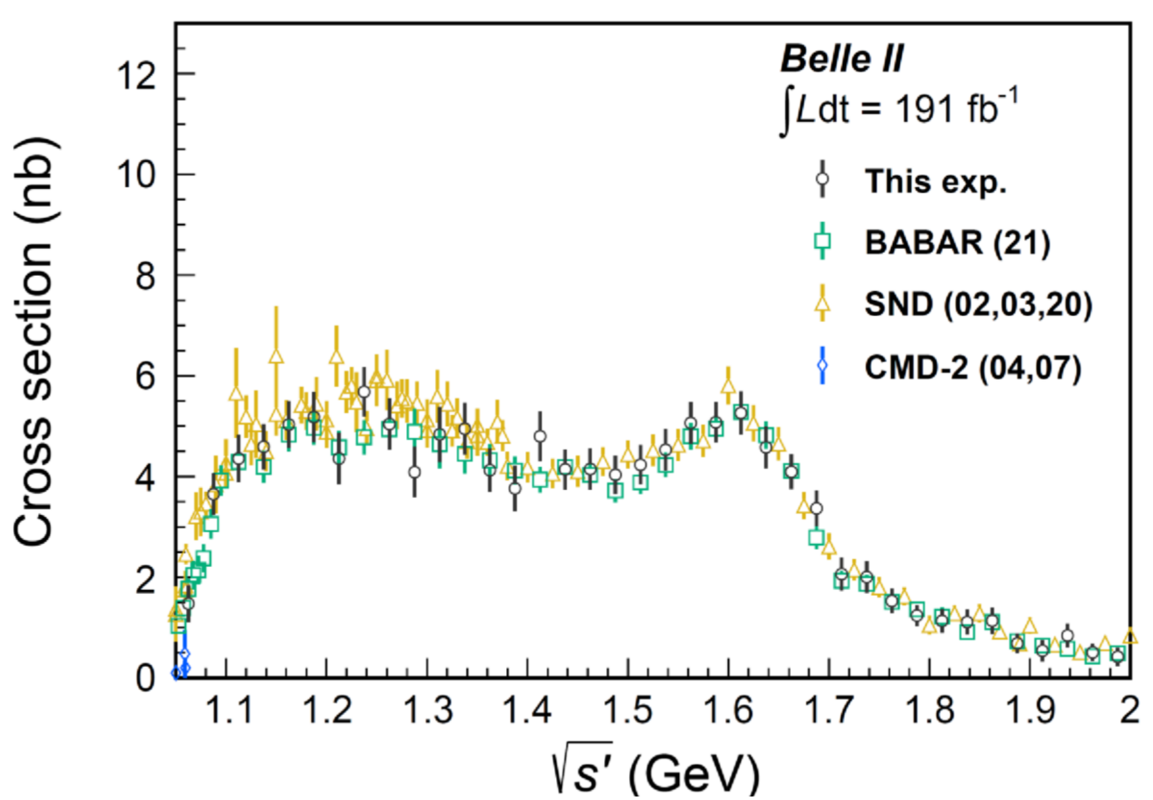


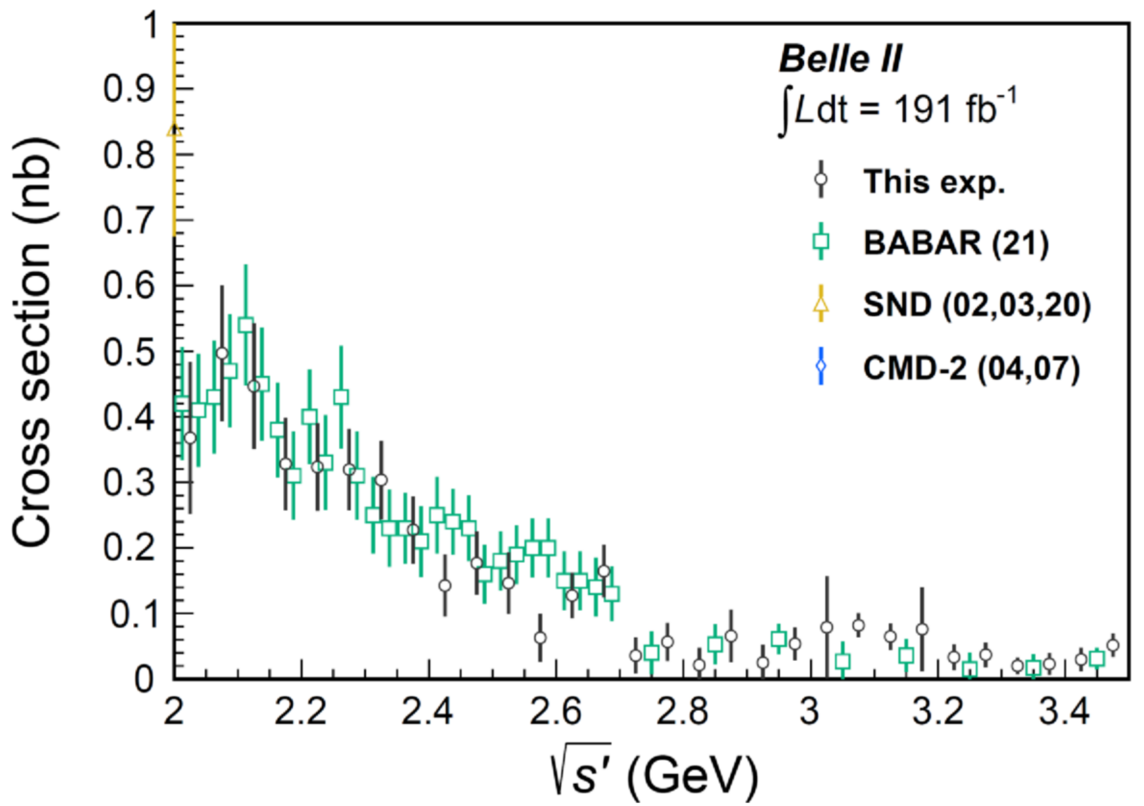




Result: cross section above 1.05 GeV

Good agreement with BABAR result





3π contribution to a_μHVP

a_μ(LO,HVP, 3π [0.62- 1.8 GeV]) = (48.91 ± 0.25stat ± 1.07syst) $\times 10^{-10}$

BABAR alone [PRD104 11 (2021)] 45.86±0.14±0.58 -3.2±1.3 (6.9%)
Global fit [JHEP08 208 (2023)] 45.91±0.37±0.38 -3.0±1.2 (6.5%)

Source	Systematic uncertainty (%)
Efficiency corrections	1.63
Monte Carlo generator	1.20
Integrated luminosity	0.64
Simulated sample size	0.15
Background subtraction	0.02
Unfolding	0.12
Radiative corrections	0.50
Vacuum polarization corrections	0.04
Total	2.19

6.5% higher than the global fit result with 2.5σ significance
This difference 3×10^{-10} corresponds 10% of $\Delta a_\mu = a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = 25\times10^{-10}$

Conclusion

Belle II has collected 531 fb^{-1} data.

World record instantaneous luminosity: 4.7×10^{34} $/cm^2/s$

- Measurements related to muon g-2 are active and in progress at Belle II.

- Good trigger efficiency thanks to the upgrade is confirmed
- The $e^+e^- \to \pi^+\pi^-\pi^0$ cross section has been measured with systematic uncertainty of 2.2%
- The largest uncertainty arises from NLO/NNLO calculation in MC generator
- Our results are about 2.5σ greater than BABAR and global fit
- a_μ (HVP, 3π) $=(48.91 \pm 0.25\text{stat} \pm 1.07\text{syst}) \times 10^{-10}$
- The paper is released in arXiv:2404.04915 and accepted by PRD for publication
- Other channels analyses are expected

Back up

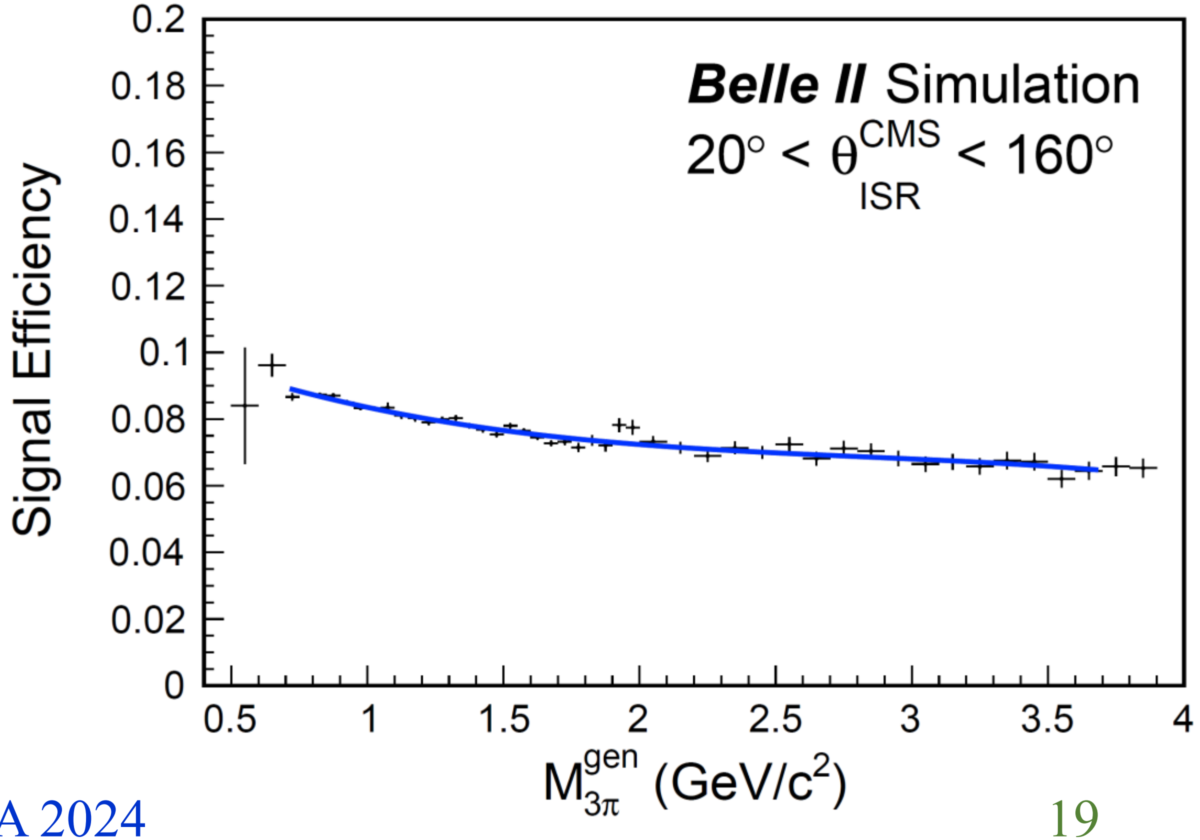
Signal efficiency and data-MC corrections

Efficiency $\varepsilon = \varepsilon_{MK} \Pi(1 + \delta_i)$ Data-MC correction $\delta_i \sim O(1)\%$

1st order signal efficiency is estimated using MC of the x10 larger statistics

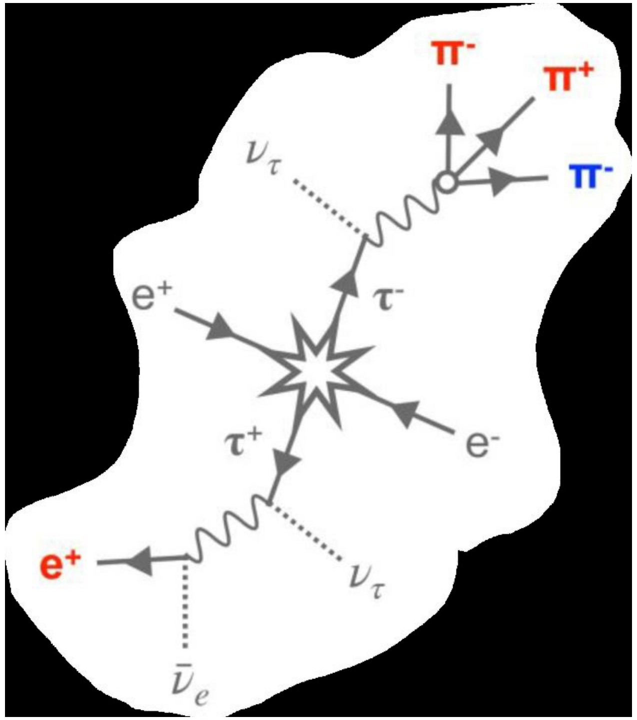
- Possible differences between data and MC are checked in data-driven way
- Trigger efficiency
- Tracking efficiency
- ISR photon efficiency
- $\pi 0$ efficiency
- Selection efficiency
- Higher-order ISR effects

MC detection efficiency (no correction)

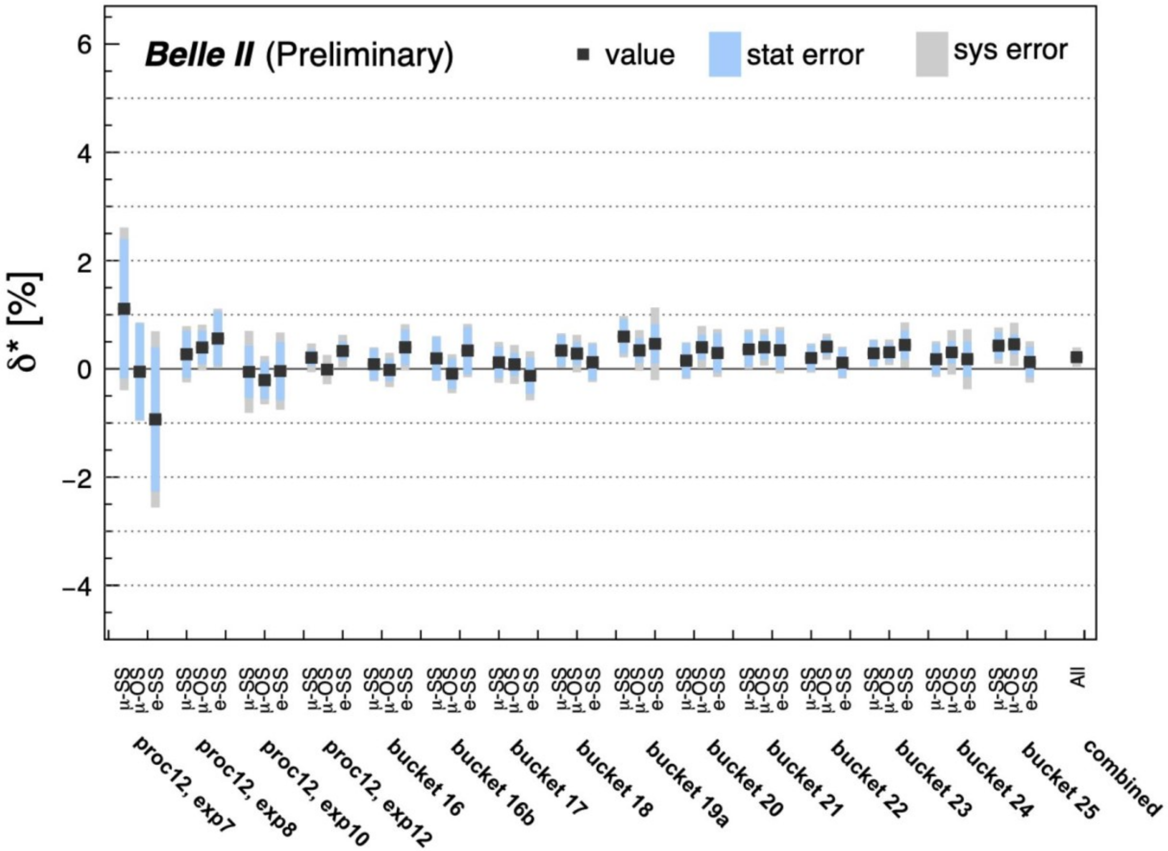


Tracking efficiency

Tracking efficiency for pions is studied with the $e^+e^- \rightarrow \tau^+\tau^-$ process.
 Data-MC differences are confirmed to be small with 0.3% uncertainty per track.



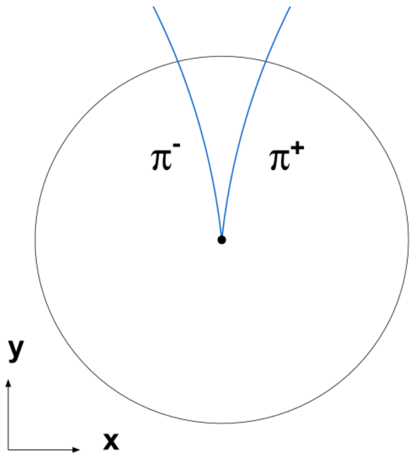
Data-MC discrepancy of tracking efficiency



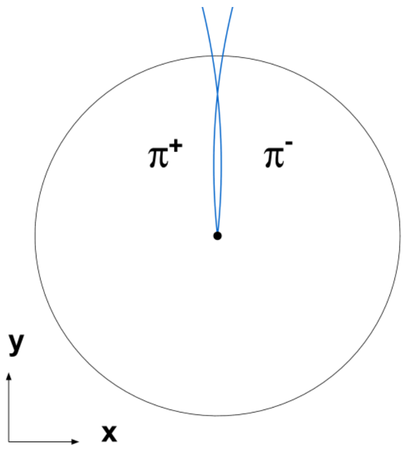
Tracking efficiency: Track loss

- Track loss due to shared hits on the drift chamber is confirmed using the $e^+e^- \to \pi^+\pi^-\pi^0\gamma$
- Define $\Delta\varphi \coloneqq \varphi(\pi^+) - \varphi(\pi^-)$
- The Inefficiency due to track loss is given by
- The track loss is 5.0% in data and 4.0% in MC
- In total, the correction factor of tracking is (-1.4±0.8)%.
- Dependency on no. of CDC hits and duplicated tracks are also studied.

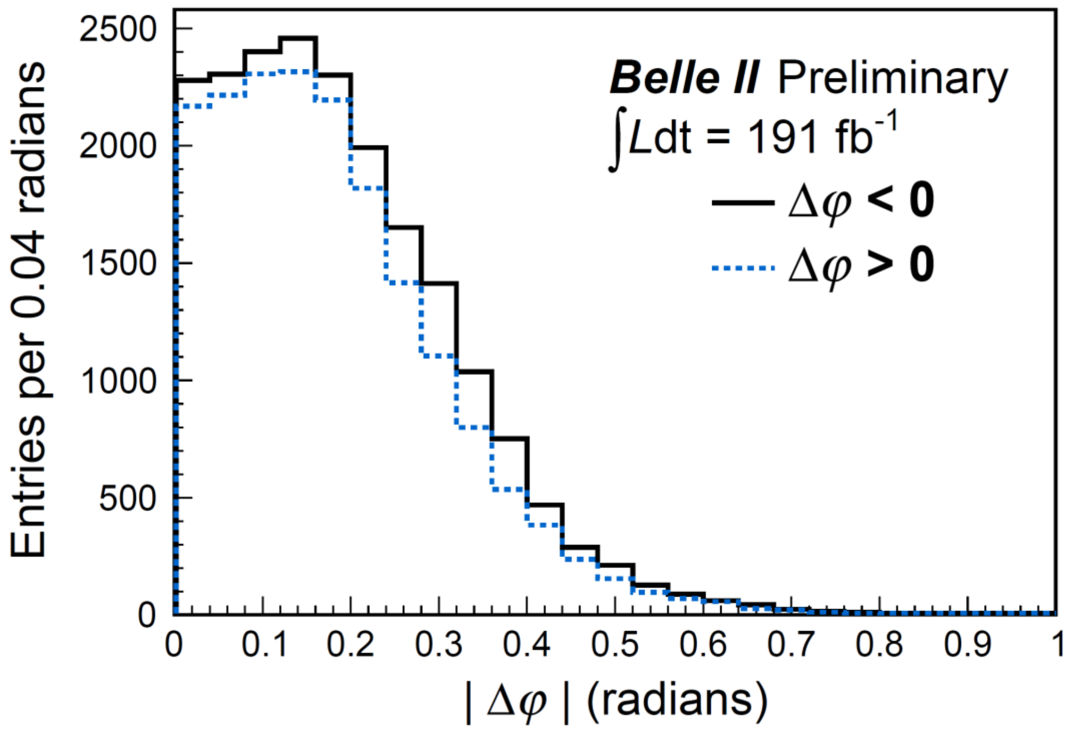
$$f = \frac{N(\Delta\varphi<0) - N(\Delta\varphi>0)}{2N(\Delta\varphi<0)}$$



Δφ < 0



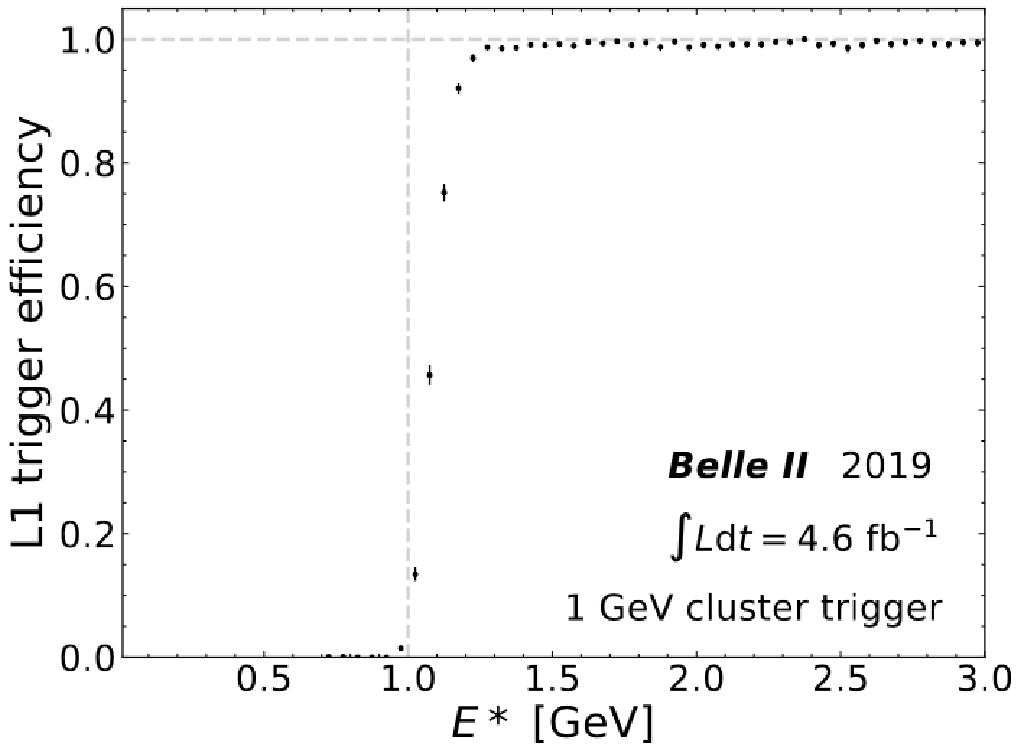
Δφ > 0



Trigger efficiency

- ISR events are triggered by the calorimeter
- The efficiency can be measured by using the events triggered independently by the tracker
- Efficiency for energetic ISR in barrel region: 99.9%
- The uncertainty related is small, 0.1%
- This also benefits other final-state measurements

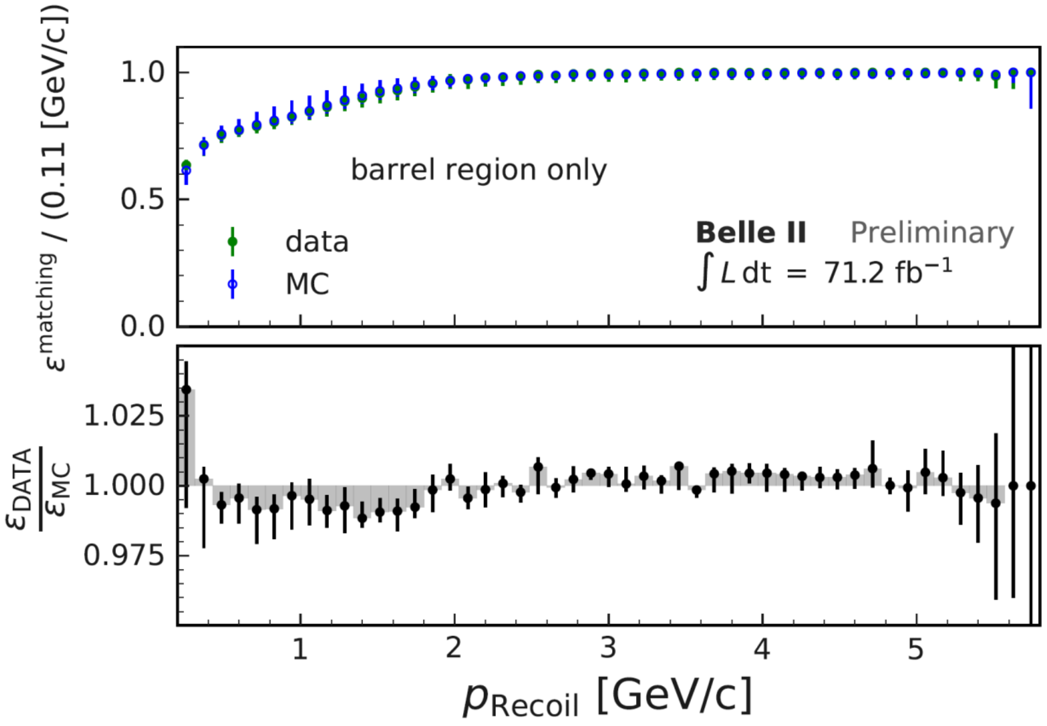
Belle II trigger efficiency measured by μμγ (data)
CMS ISR Energy (GeV)
ECL e- e+ CDC θ μ+ μ- ISR photon in barrel
→ Reference: triggered by track trigger
→ Probe: fire energy trigger



ISR photon detection efficiency

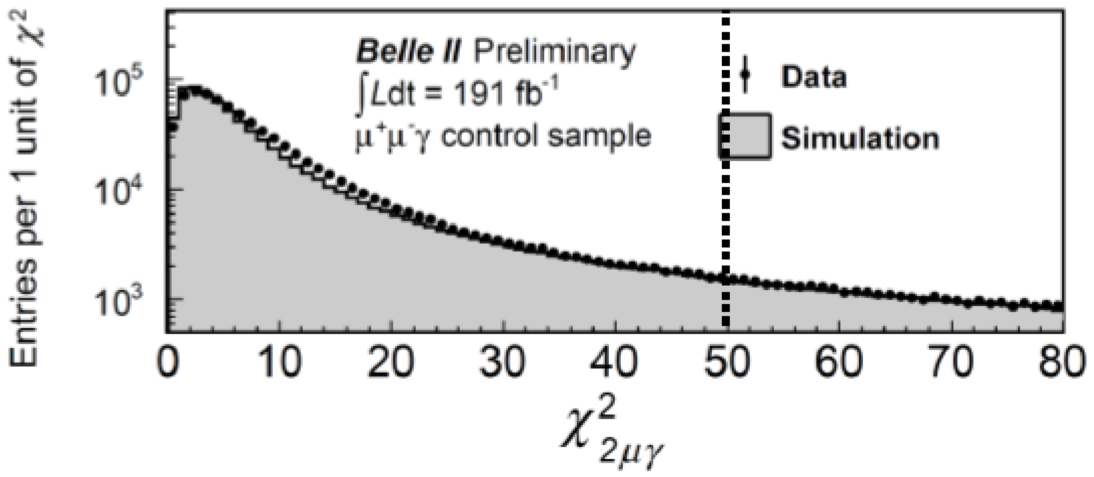
Photon detection efficiency is measured using $e^+e^- \to \mu^+\mu^-\gamma$ events

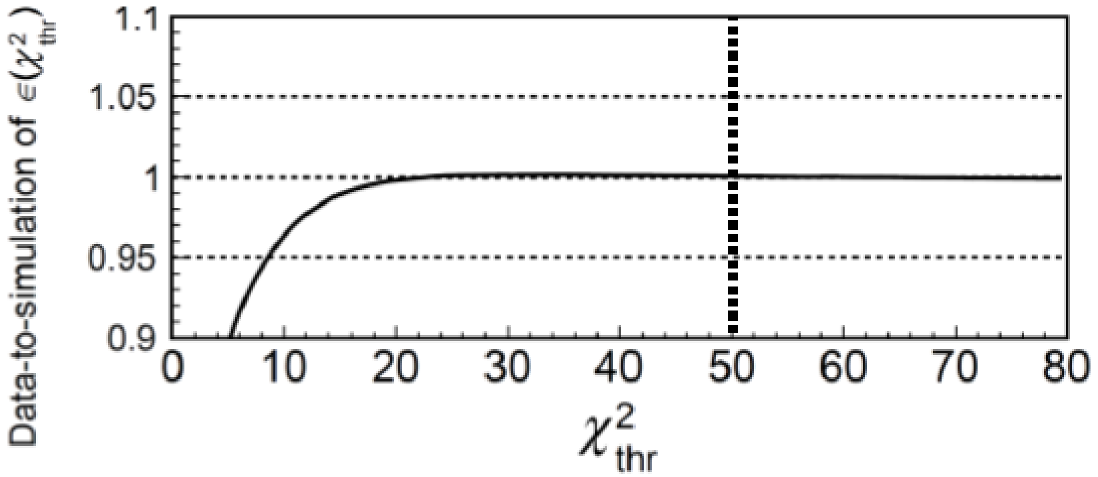
- Taking a match between a ECL cluster and the missing momentum of dimuon system
- Efficiency is in good agreement with 0.7% systematic uncertainty



χ2 selection efficiency

 ISR and tracks χ2-criteria efficiency is confirmed using $e^+e^- \to \mu^+\mu^-\gamma$ sample
 Confirm effects from differences in position, momentum, and energy of ISR and tracks
 Agreement confirmed within ±0.6% uncertainty
 Dependence on multi-ISR photon calculations is discussed on the next page





π^0 efficiency correction

Accurate evaluation of π^0 efficiency in e^+e^- experiment is a challenging task.

□ Exclusive processes that include a π^0 are limited.

□ Evaluate efficiency using the $e^+e^- \to \omega\gamma \to \pi^+\pi^-\pi^0\gamma$ events.

π^- Recoil momentum of $\pi^+\pi^-\gamma_{ISR}$

π^+ e^- e^+ ISR photon

$\varepsilon_{\pi^0} = N$ Full reconstruction : $\gamma_{ISR}\pi^+\pi^-\pi^0$

N Partial reconstruction : $\gamma_{ISR}\pi^+\pi^-$ Count $\omega \to \pi^+\pi^-\pi^0$ decay without using π^0 information.

$$M^2_{\pi^+\pi^-\pi^0_{recoil}} = (p_{\pi^+} + p_{\pi^-} + p_{recoil})^2$$

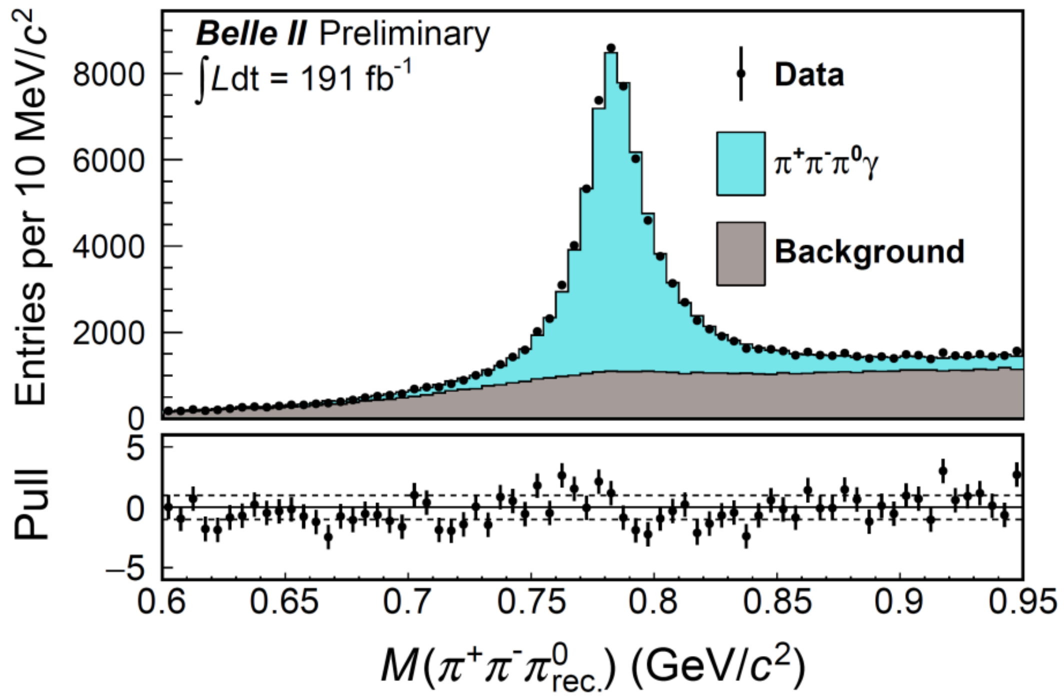
Count by reconstructing π^0 and fitting M(γγ)

□ ε_{π^0} are independently evaluated by the data and MC

□ Data/MC ratio = 0.986 ± 0.006_{stat}

□ The systematic uncertainty related to π^0 is 1.0%

□ The uncertainty is evaluated by variations of the M(γγ) signal pdf, background pdfs, and selections



□ π^0 momentum p_{recoil} is determined by kinematic fit to $\pi^+\pi^-\gamma$ with hypothesis that recoil mass equals π^0 mass

Higher-order ISR effects

Although a one-ISR photon emission process is set as the signal,
in reality there are processes with multiple photon emissions.
Two effects need to be considered from the existence of multiple photons:
A) Effective integrated luminosity Leff (radiative correction): 0.5% unc.
B) χ2 selection efficiency due to ISR photon calculations in generator: 1.2% unc.

Signal process

Leading-order (LO) ISR

Next-to-Leading-order (NLO) ISR

NNLO ISR