ee→ππ cross section measurement in Belle II

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for the Belle II collaboration

13th Feb, 2018
workshop on HVP contributions to muon g-2
@KEK

Fermion pair production in e^+e^- collisions

- cross section is well understood

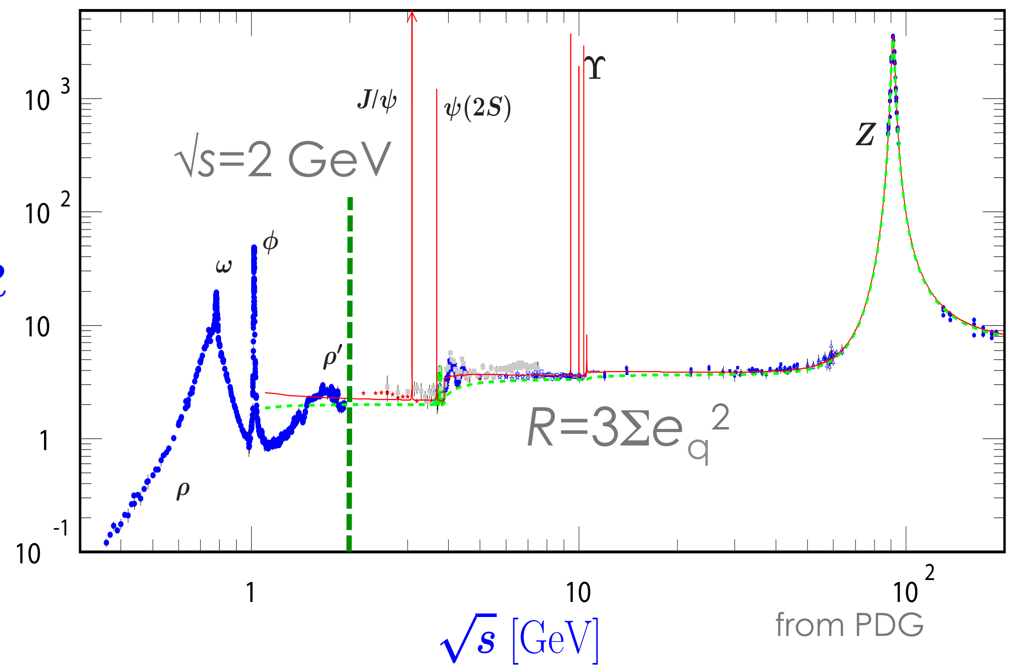
can be neglected at $M_\mu^2/s \ll 1$

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}\sqrt{1 - 4M_\mu^2/s}\,(1 + 2M_\mu^2/s)$$

86.85 nb / (s [GeV^2/c^4])

- quark production is also well described at large √s
  - charge/flavor/color
- for small √s (<2 GeV), experimental data is necessary
  - low energy QCD

R=σ(ee→hadrons)/σ(ee→μμ)



from PDG

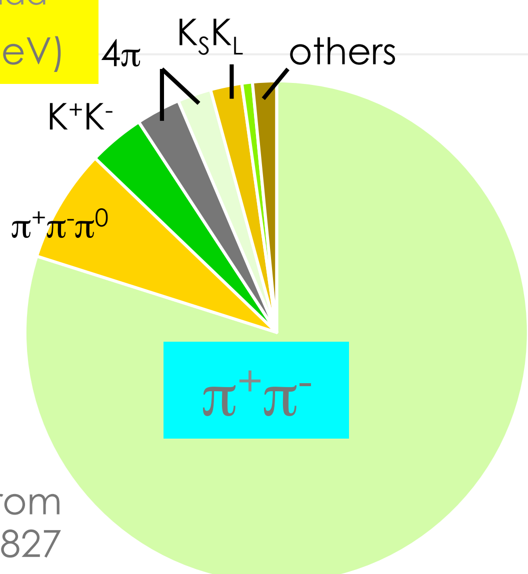
light hadron production

- Hadron production cross section is an important input for hadronic contribution a_μ^{had} of μ g-2

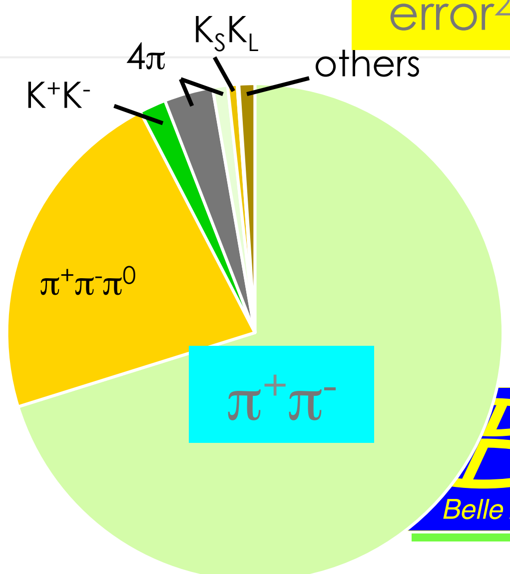
$$a_\mu^{(4)}(\text{vap, had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \left(\int_{m_{\pi^0}^2}^{E_{cut}^2} ds \frac{R_{had}^{data}(s)\,\hat{K}(s)}{s^2} + \int_{E_{cut}^2}^{\infty} ds \frac{R_{had}^{pQCD}(s)\,\hat{K}(s)}{s^2}\right)$$

$K(s)$: Kernel function

contribution to a_μ^{had} ($\sqrt{s}$<1.8 GeV)



error²

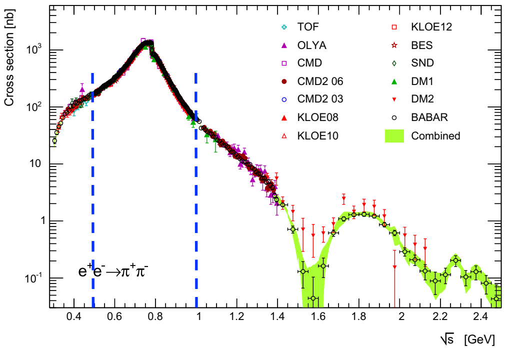


- ππ mode gives dominant contribution ($\sqrt{s}$<1.8 GeV)

values are taken from
Eur. Phys. J. C (2017) 77:827

ππ cross section measurement

- Very precise measurements (≲1%) have been done by several experiments
- small discrepancy (a few %) between two measurements →this is disturbing error shrinkage
- confirmation by an independent experiment is necessary



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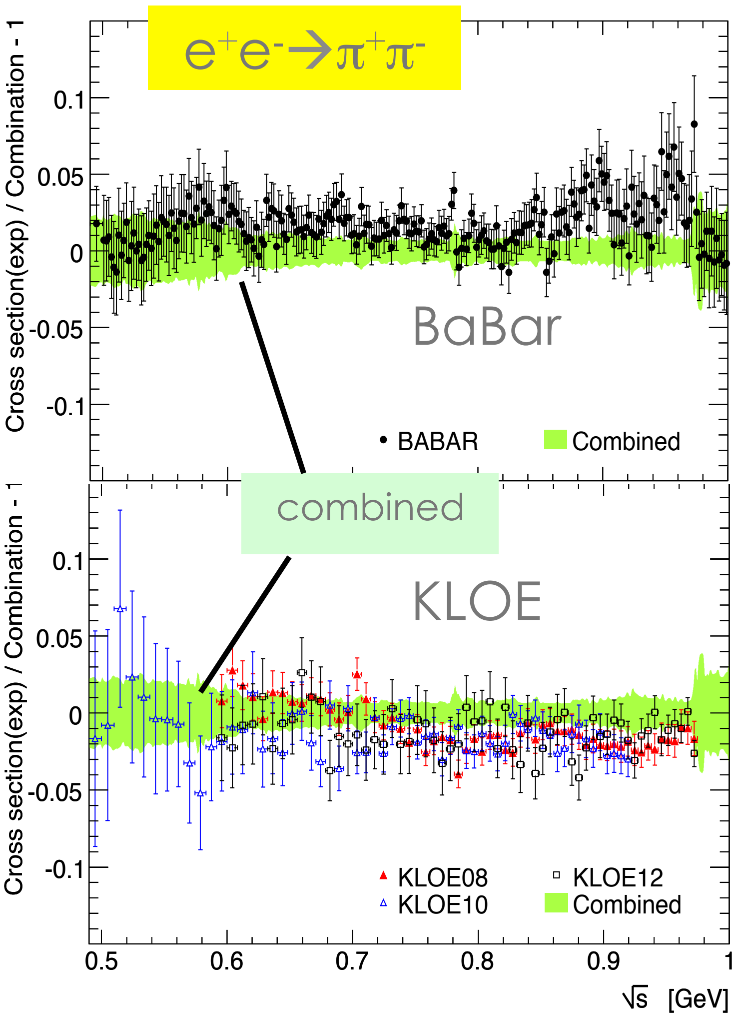
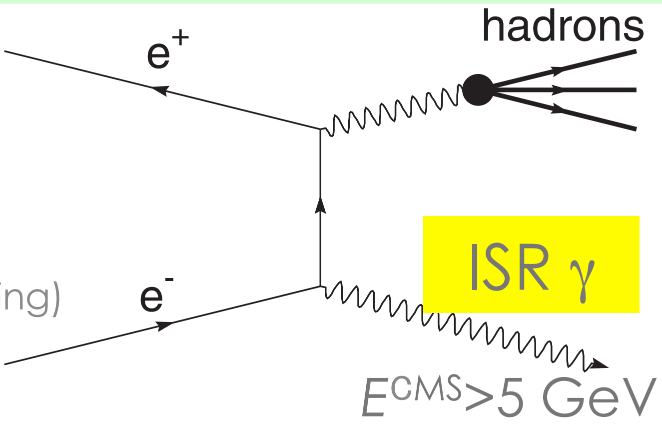


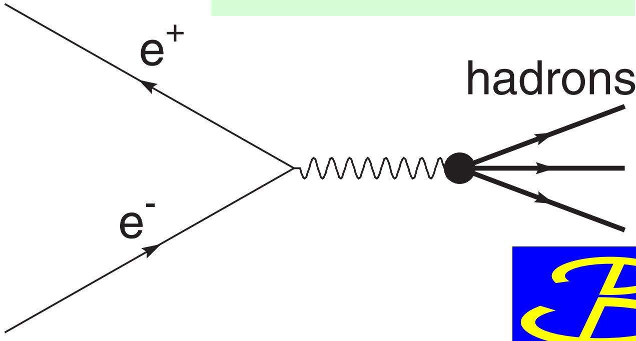
ee→ππ measurement at Belle II

- Belle II strategy
  - radiative return method
    - require energetic γ
    - distribution of invariant mass of hadrons →(BG subtraction and unfolding) →cross section for each √s
  - simultaneous measurement of ππγ (signal) and μμγ (normalization)
    - various error cancellation
- study items with simulation
  - dedicated trigger
  - geometrical acceptance
  - PID

radiative return method

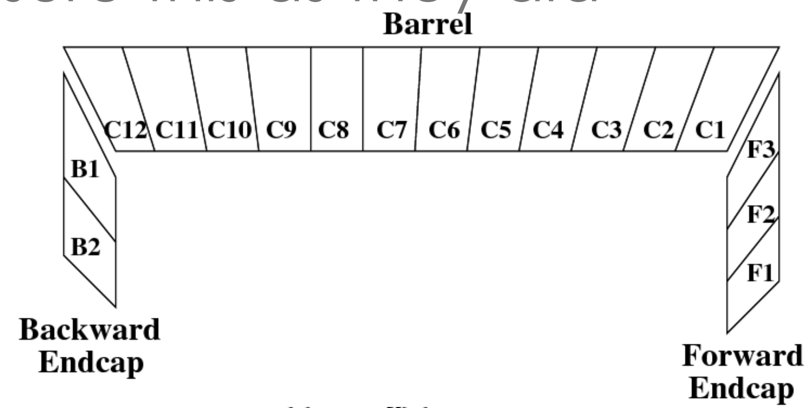


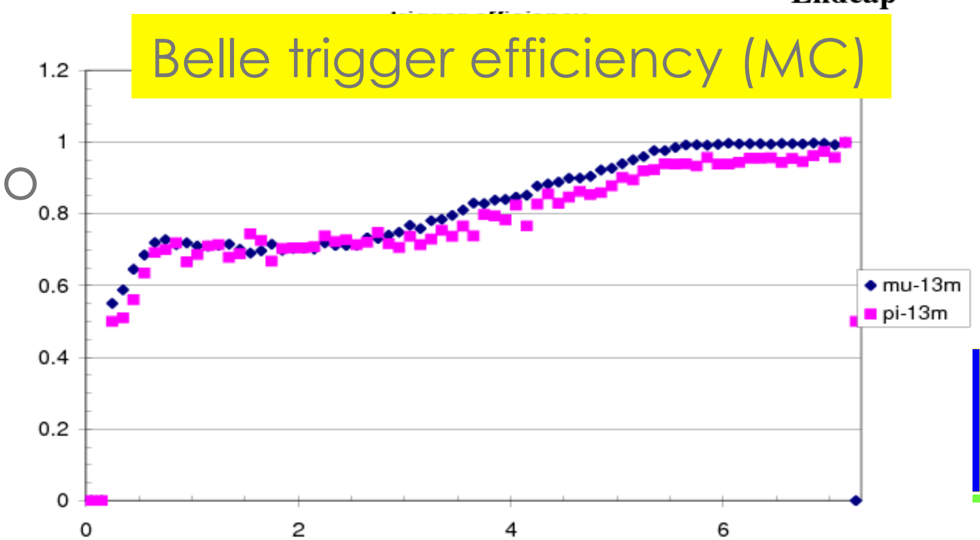
scan method



trigger for ππγ measurement

- Belle was not able to measure this as they did not have proper trigger
  - low efficiency due to Bhabha veto based on only θ angle (energy sum of the same θ region(s))
  - run-by-run instability
- new trigger in Belle II
  - improved Bhabha veto using both θ and ϕ information
  - photon trigger

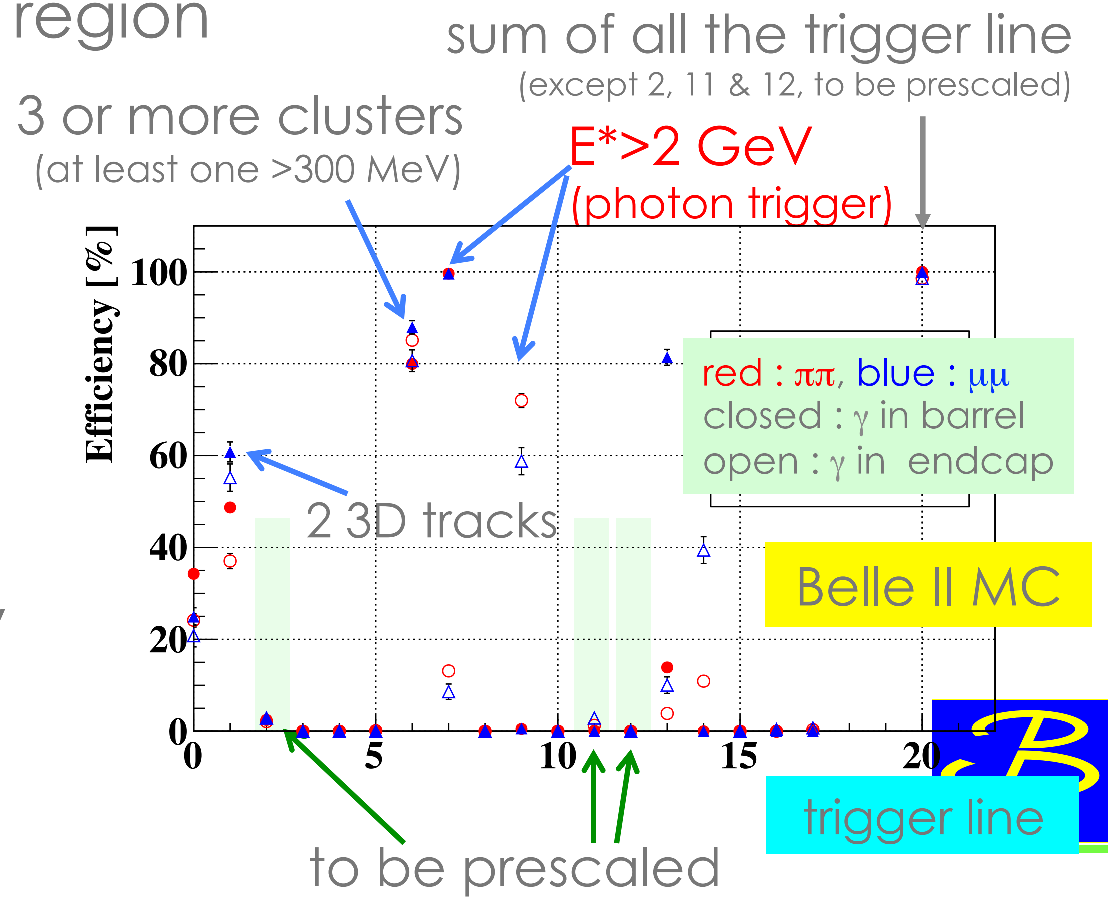




Belle trigger efficiency (MC)

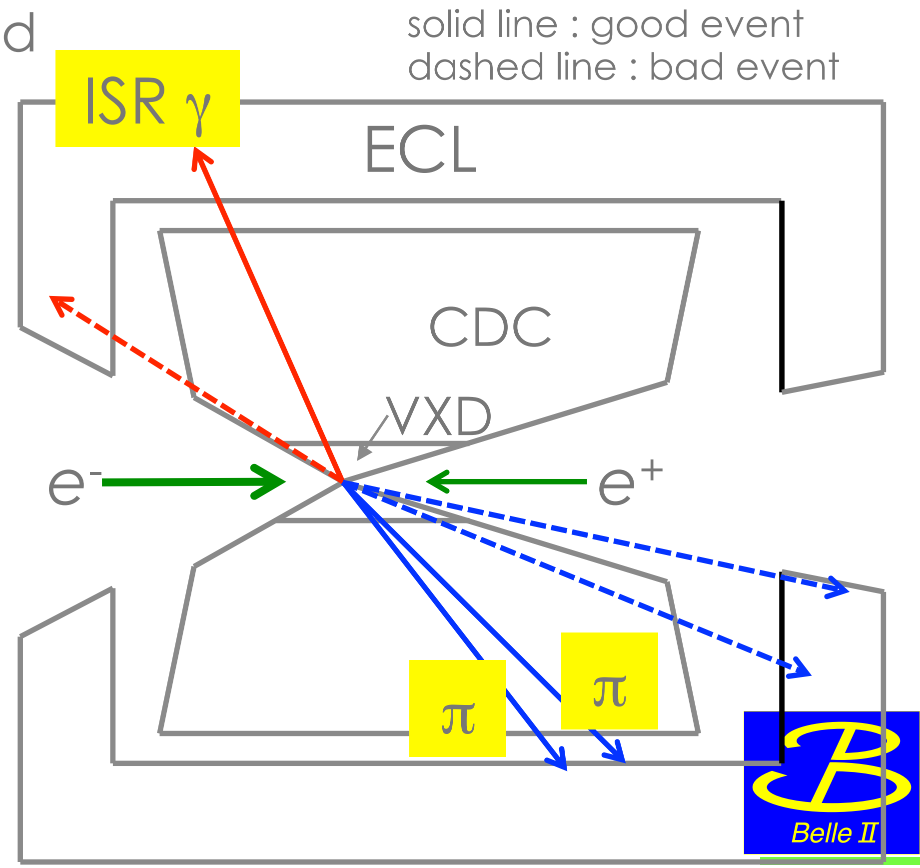
trigger simulation

- 100% efficiency for good events with ISR γ pointing the barrel region
  - Bhabha veto is considered
  - some loss (O(%)) for endcap, as designed (but these events are not used as discussed later)
- photon trigger is working effectively as expected



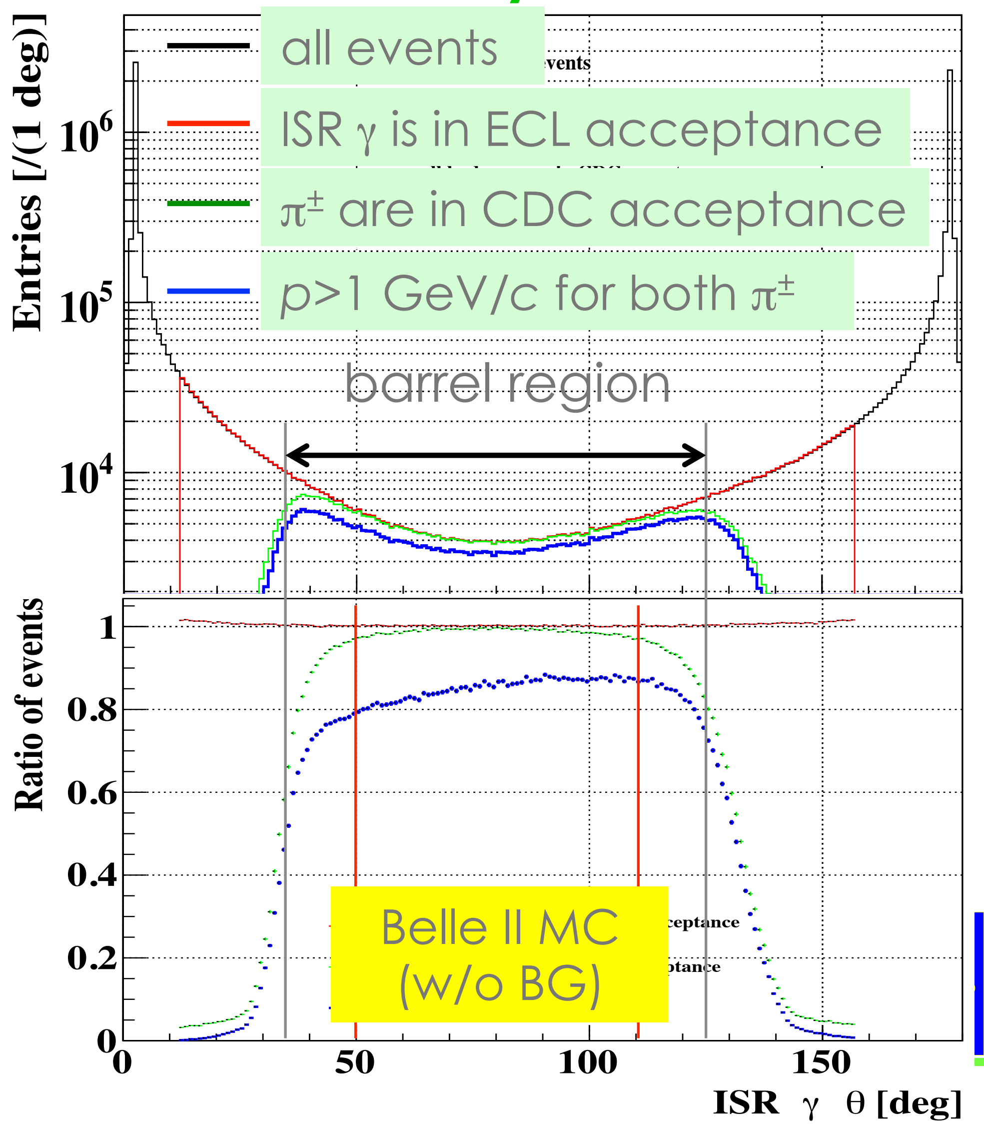
acceptance study

- $\pi\pi\gamma$ acceptance as a function of ISR γ θ angle
  - MC truth information is used (Phokhara generator)
  - can be calculated from radiator function
  - same emission probability between μ and π
- CDC acceptance
  - avoid edge regions, where tracking efficiency drops



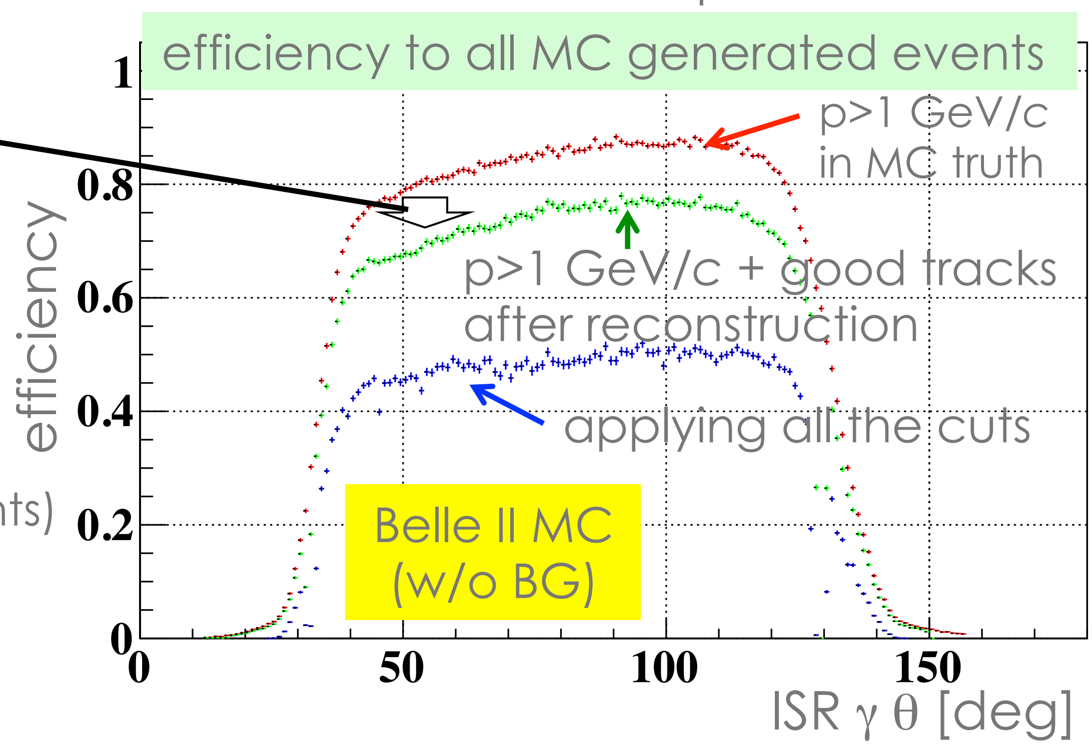
acceptance study

- efficiency is flat for large angle ISR γ →by limiting ISR γ θ angle, acceptance can be kept high
  - lose some events, but can be easily compensated by Belle II high stat.
- 10-20% loss due to momentum cut (p>1 GeV/c)
  - for good muon−ID



event selection efficiency

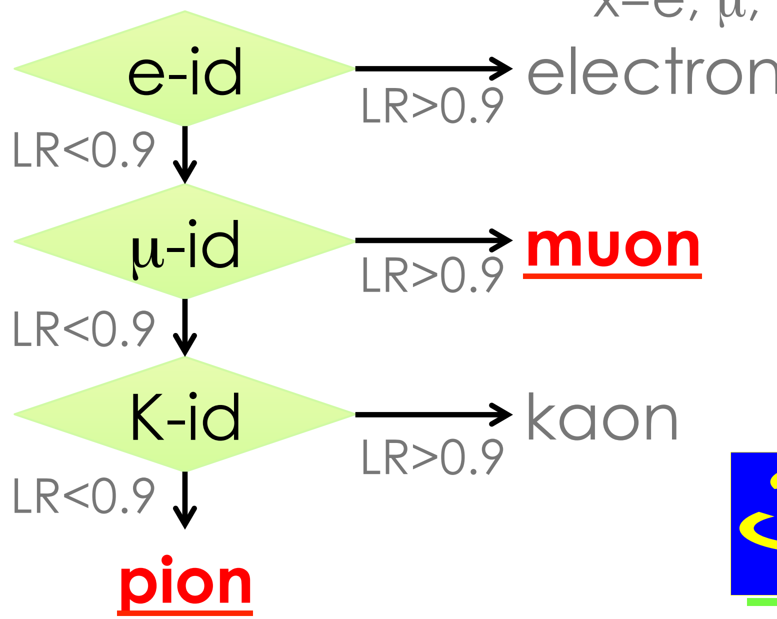
- selection criteria (tentative)
  - exactly two "good" track
  - $10 < E^*_{\pi\pi\gamma} < 11$ GeV, $P^*_{\pi\pi\gamma} < 0.5$ GeV/c
    - suppress events with add. ISR and from other processes
  - PID cut
- some loss after reconstruction
  - partially due to γ conversion /π interaction
- total eff. : 49% (to all MC generated events)
  - $50^\circ < \theta_{ISR} < 110^\circ$



PID algorithm

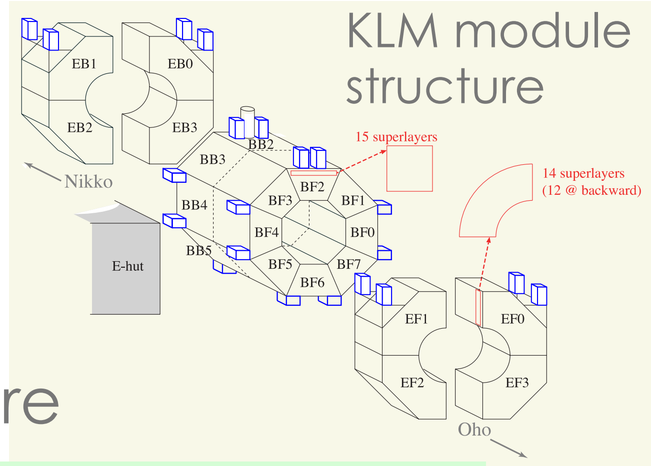
- assign unique PID for each track
- require both tracks to be identified as the particle of interest
- study items
  - $\mu\mu \leftrightarrow \pi\pi$ cross feed
  - correlated efficiency loss

likelihood ratio (LR) = $L_X/(L_X+L_\pi)$
x=e, μ, K

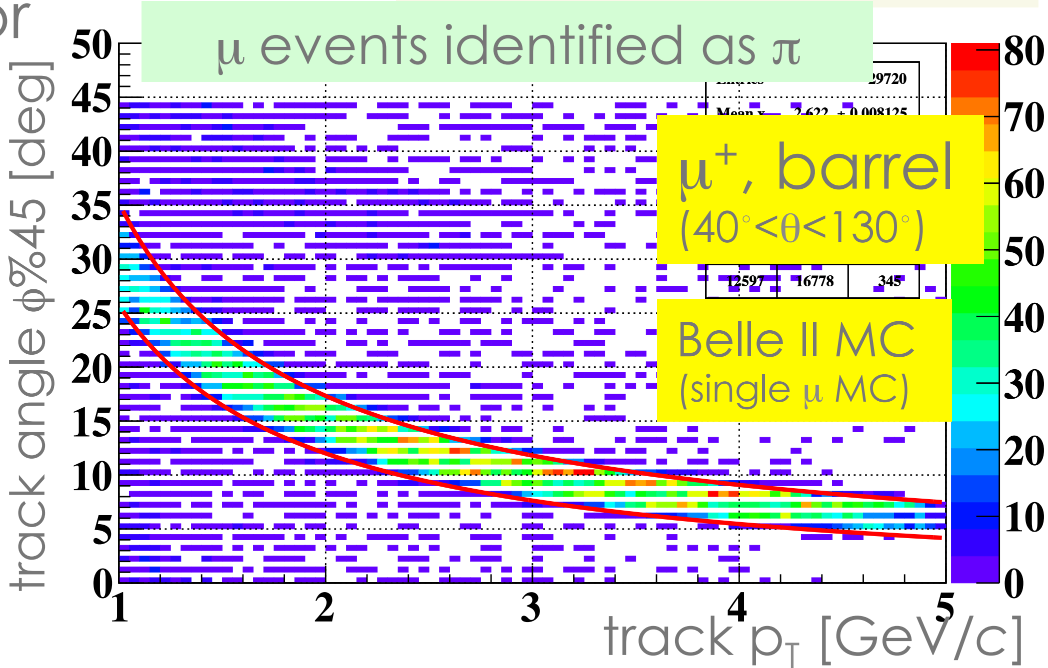


Belle II

muon/pion separation

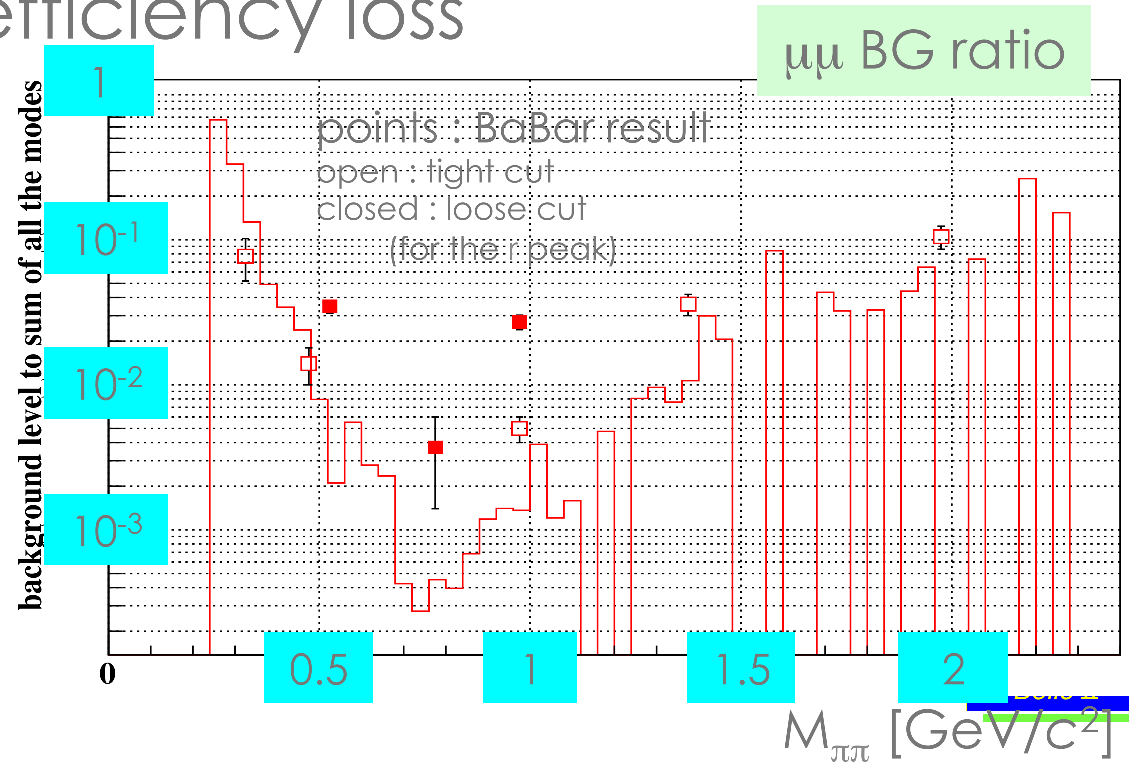


- mis-identified muons tend to be recognized as pions →μ-id ineff. = fake π
- avoiding KLM module gaps, where μ-id efficiency is poor
  - visible in p_T-ϕ plane
  - set veto regions (for barrel/endcap, positive/negative μ)
  - require at least one track to be outside of the veto regions



μμ BG in ππ analysis

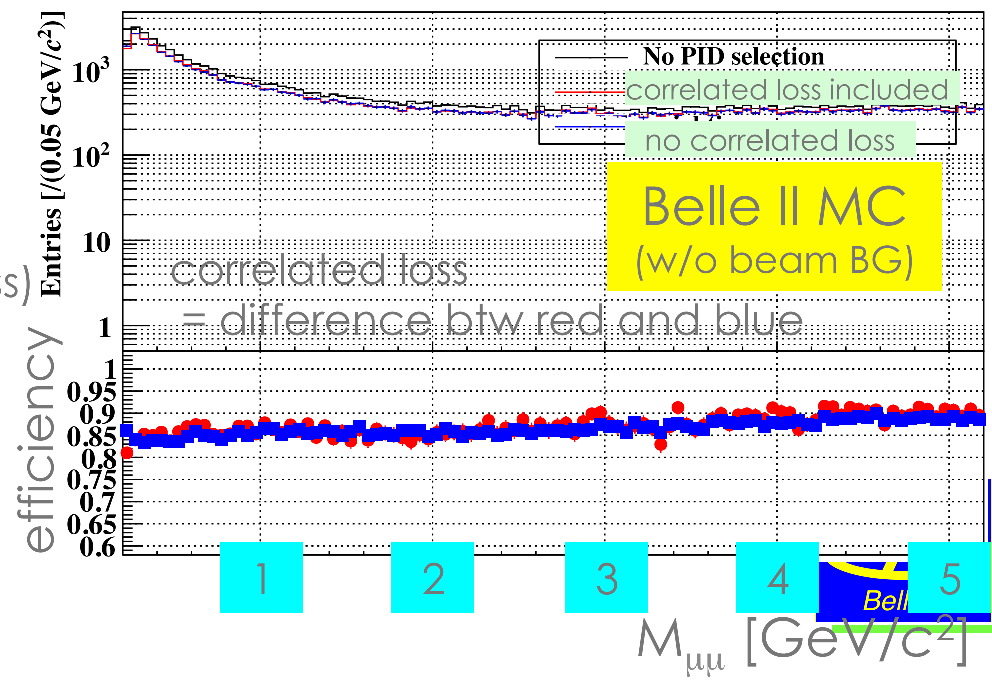
- reduction by a factor of 5
  by introduction of KLM module gap veto
- 9% additional efficiency loss
- the same level
  with BaBar



correlated loss of PID eff.

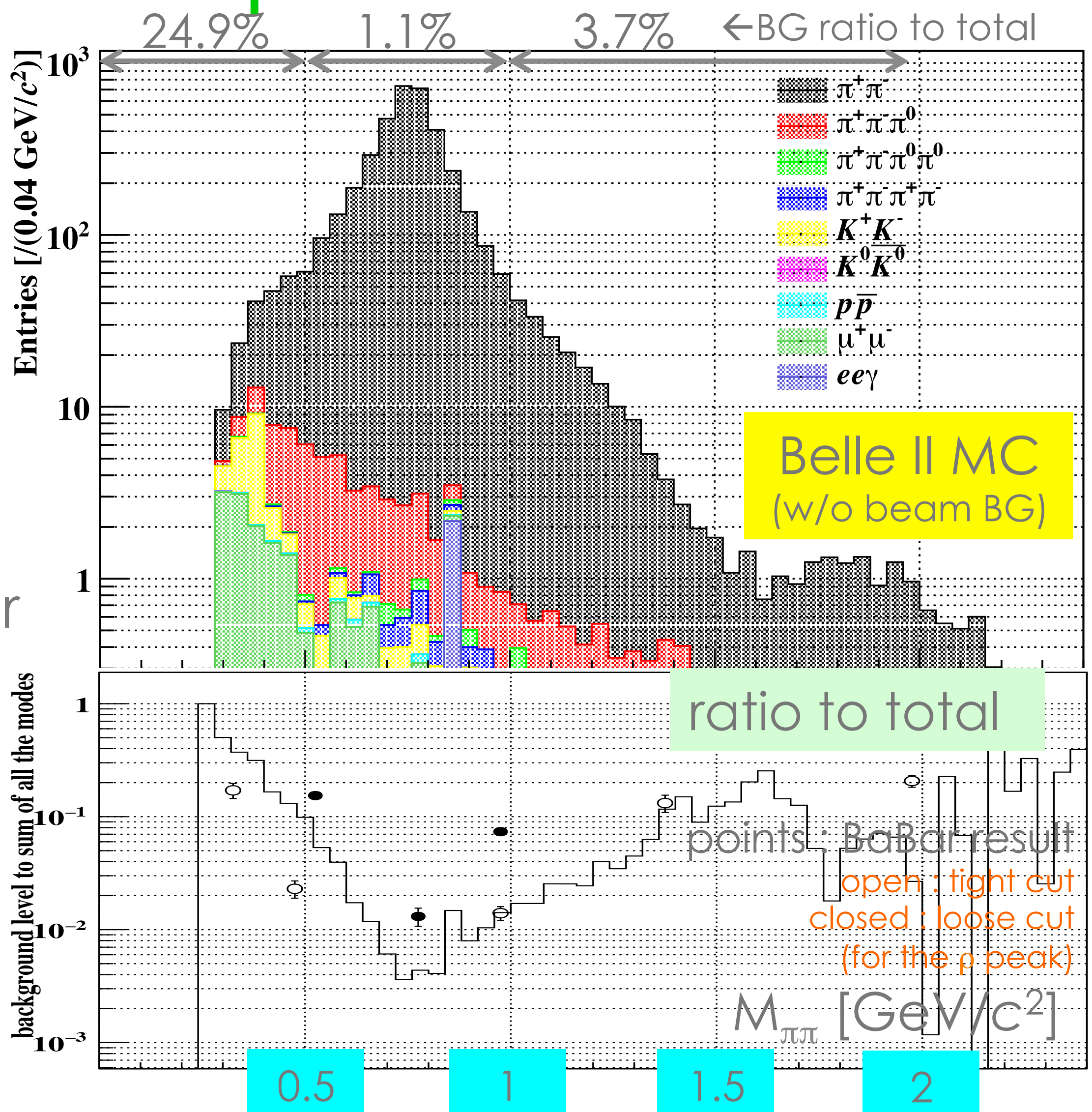
- additional efficiency loss can exist due to two tracks close to each other
- compare two efficiencies
  - μ-id for both tracks (including correlated loss)
  - product of μ-id efficiency, which was taken from single μ MC (do not include correlated loss)
- significant correlated efficiency loss was not seen

ee→μμγ simulation



background processes

- other ISR modes, are considered
  - BG from qqbar, BBbar and ττ is small
- O(%) level BG for $M_{\pi\pi}$>0.5 GeV/c^2
  - similar to or better than BaBar
- worse in low mass region
  - $\pi\pi\pi^0$ with low-E π^0
  - optimization of event selection

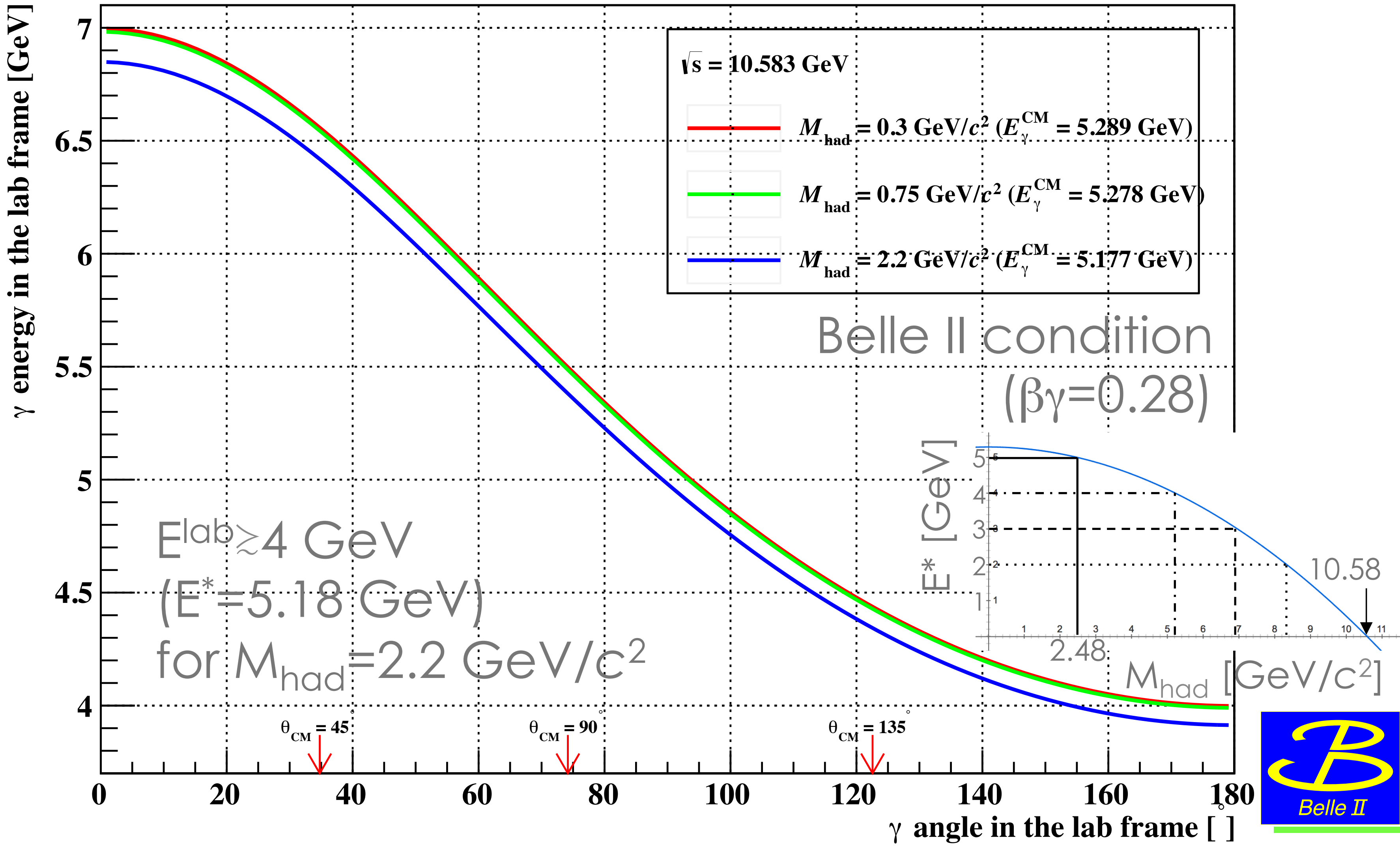


summary

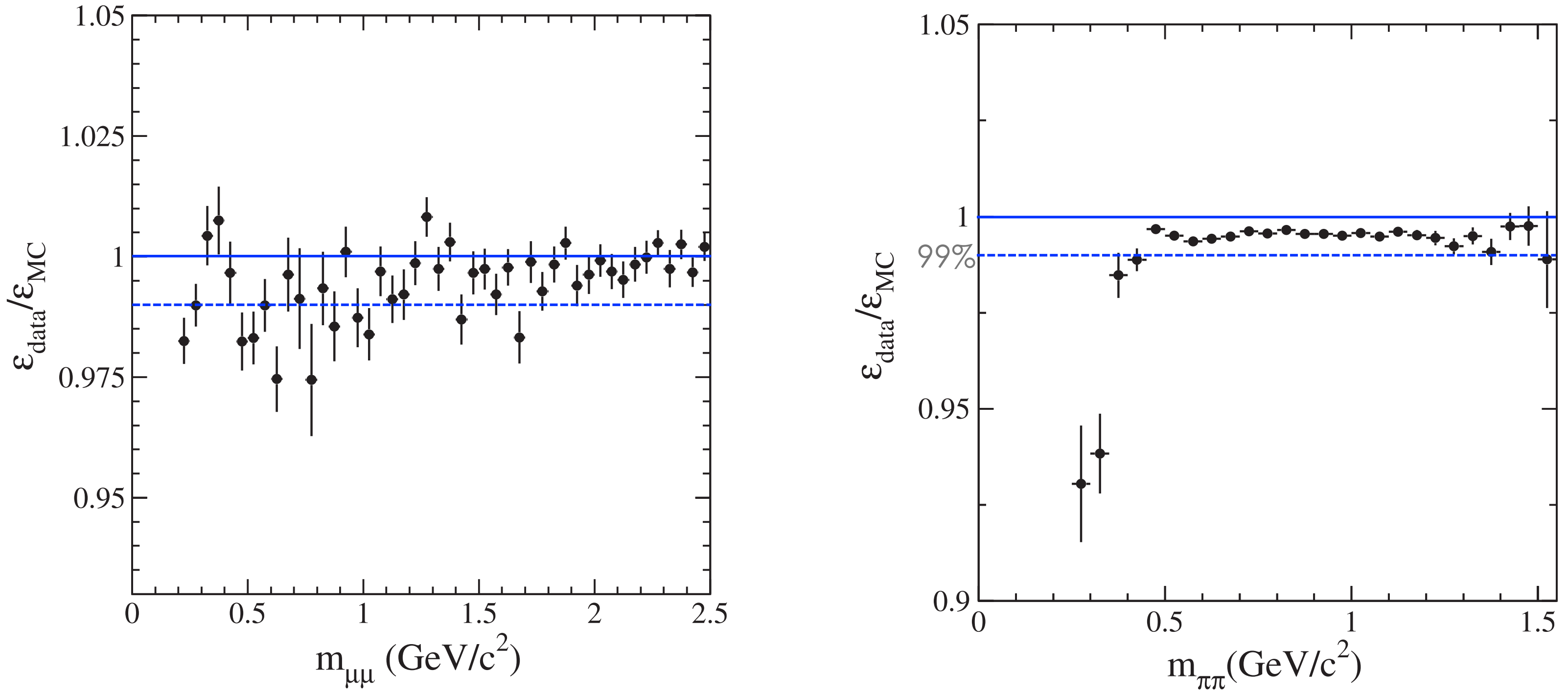
- Precision measurement of ee→ππ cross section in Belle II is important for better understanding of muon *g*-2 anomaly
- Several simulation studies are performed for the ee→ππγ mode, which shows
  - 100% L1 trigger efficiency for events with large angle ISR
  - BG level is found to be competitive to BaBar analysis with tentative event selection and PID
- further studies
  - selection optimization
  - effect of beam background

backup slides

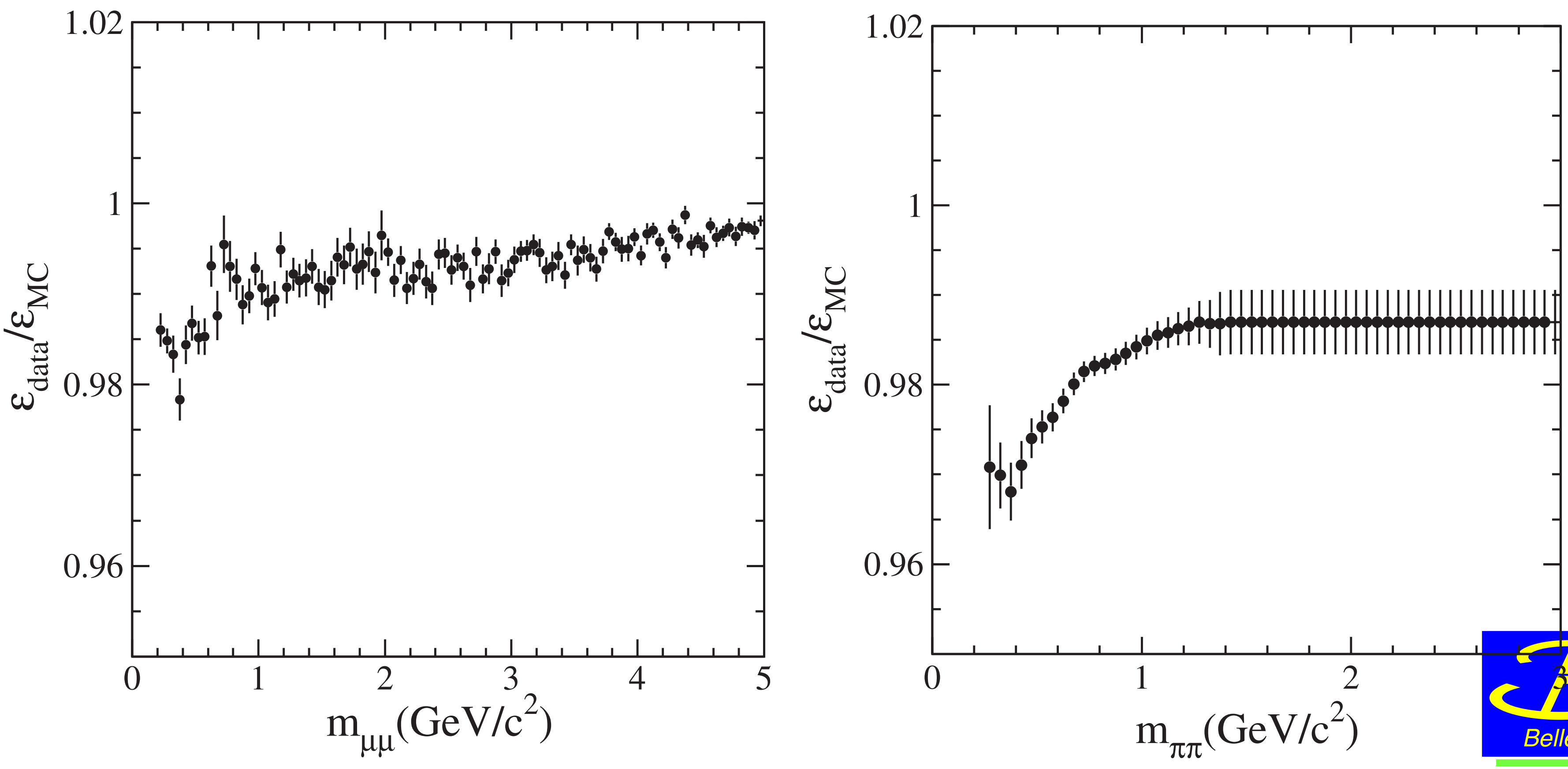
ISR γ energy in lab frame



BaBar trigger/filter eff. correction



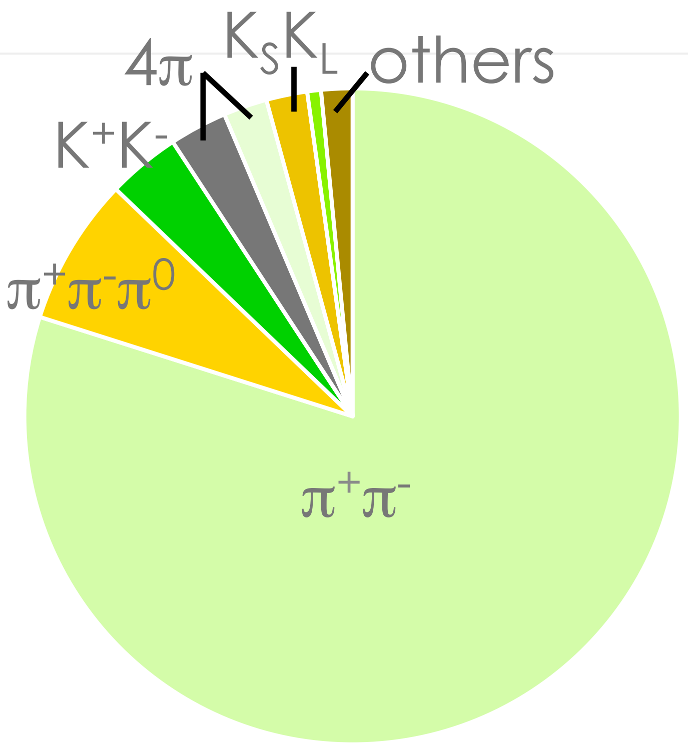
BaBar tracking eff. correction

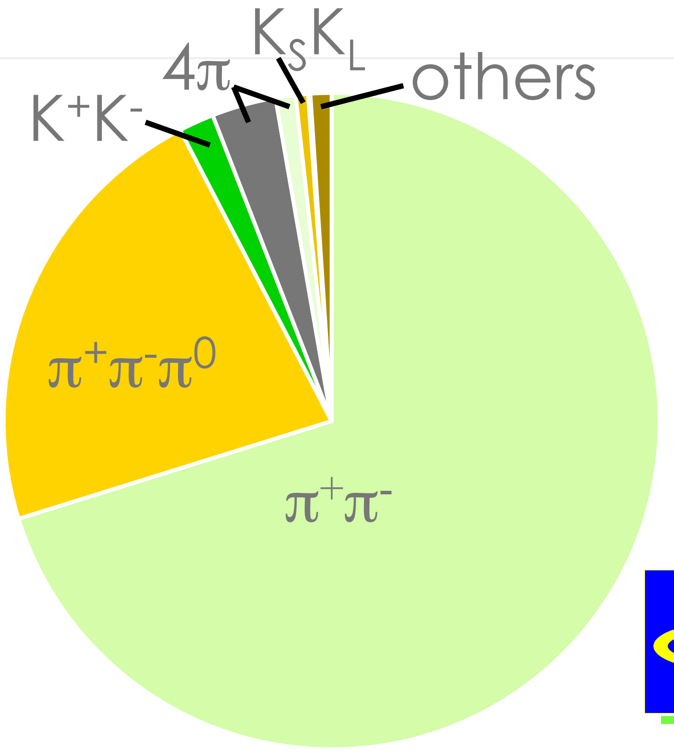


L1 trigger menu

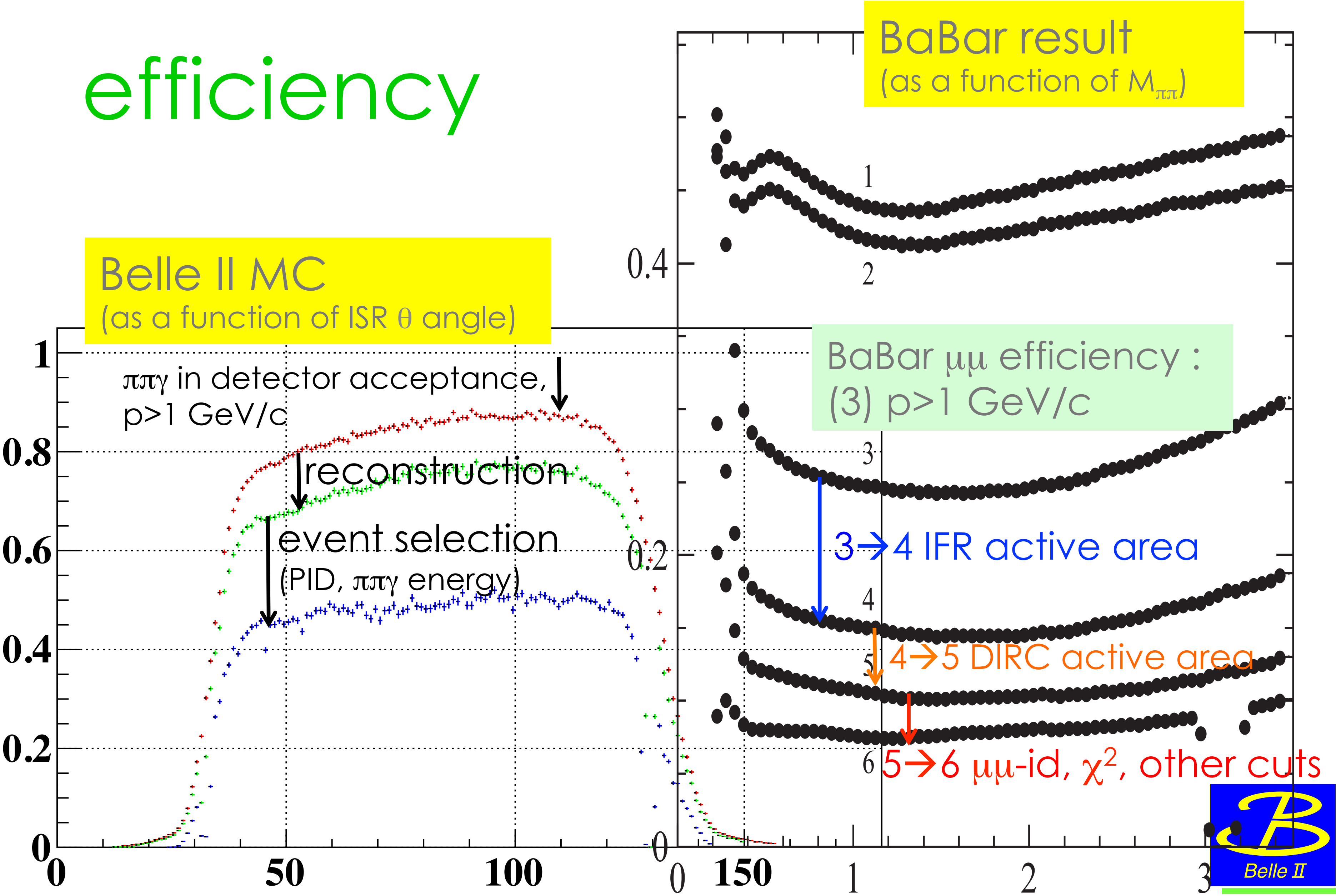
Bit	Phase 2 description	Prescale Phase 2	Changes for 2020	Prescale 2020
0	3 or more 3D tracks			
1	2 3D tracks, ≥1 within 25 cm, not a trkBhabha		2 3D tracks, ≥1 within 10 cm, not a trkBhabha	
2	2 3D tracks, not a trkBhabha	20		20
3	2 3D tracks, trkBhabha			2
4	1 track, <25cm, clust same hemi, no 2 GeV clust		1 track, <10cm, clust same hemi, no 2 GeV clust	
5	1 track, <25cm, clust opp hemi, no 2 GeV clust		1 track, <10cm, clust opp hemi, no 2 GeV clust	
6	≥3 clusters inc. ≥1 300 MeV, not an eclBhabha		≥3 clusters inc. ≥2 300 MeV, not an eclBhabha	
7	2 GeV E* in [4,14], not a trkBhabha			
8	2 GeV E* in [4,14], trkBhabha			2
9	2 GeV E* in 2,3,15,16, not eclBhabha			
10	2 GeV E* in 2,3,15 or 16, eclBhabha			
11	2 GeV E* in 1 or 17, not eclBhabha	10		20
12	2 GeV E* in 1 or 17, eclBhabha	10		20
13	exactly 1 E*>1 GeV and 1 E>300 MeV, in [4,15]			
14	exactly 1 E*>1 GeV and 1 E>300 MeV, in 2,3 or 16			5
15	clusters back-to-back in phi, both >250 MeV, no 2 GeV			
16	clusters back-to-back in phi, 1 <250 MeV, no 2 GeV		clust back-to-back in phi, <250 MeV, no 2 GeV, no trk>25cm	3
17	clusters back-to-back in 3D, no 2 GeV			5

Belle II


4π
K_SK_L
others
K^+K^-
$\pi^+\pi^-\pi^0$
$\pi^+\pi^-$


K_SK_L
4π
others
K^+K^-
$\pi^+\pi^-\pi^0$
$\pi^+\pi^-$

efficiency

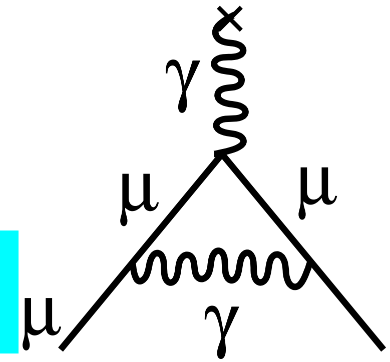

BaBar result
(as a function of $M_{\pi\pi}$)
Belle II MC
(as a function of ISR θ angle)
ππγ in detector acceptance,
p>1 GeV/c
reconstruction
event selection
(PID, ππγ energy)
BaBar μμ efficiency :
(3) p>1 GeV/c
3→4 IFR active area
4→5 DIRC active area
5→6 μμ-id, χ^2, other cuts
1
2
3
4
5
6
0.4
0.2
0
1
0.8
0.6
0.4
0.2
0
0
50
100
150
0
1
2
3
Belle II

muon g-2

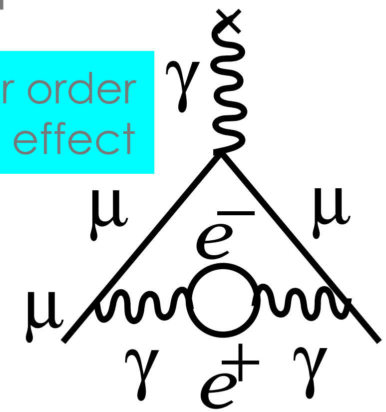
$$\vec{\mu}_\ell = g_\ell \frac{Qe}{2m_\ell}\vec{s}$$

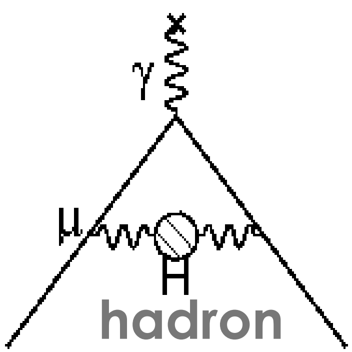
- "g-factor" of μ (also e) is slightly larger than 2 due to QED effect
  - $a_\mu=(g-2)/2$
  - ~3σ discrepancy btw theo. and exp.
    - both have ~0.5 ppm precision
- strong interaction and weak interaction also contribute
  - strong : ~60 ppm
  - weak : ~1.3 ppm

"Schwinger"
O(α)



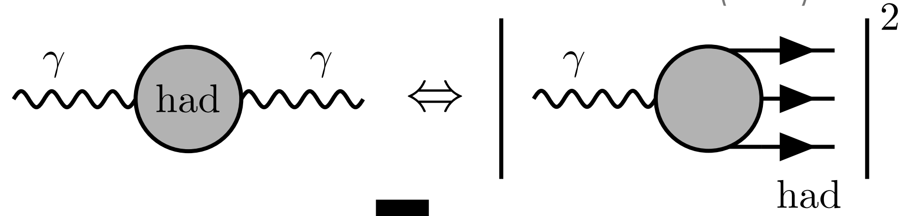
higher order
QED effect





hadronic contribution

Physics Reports 477 (2009) 1–110

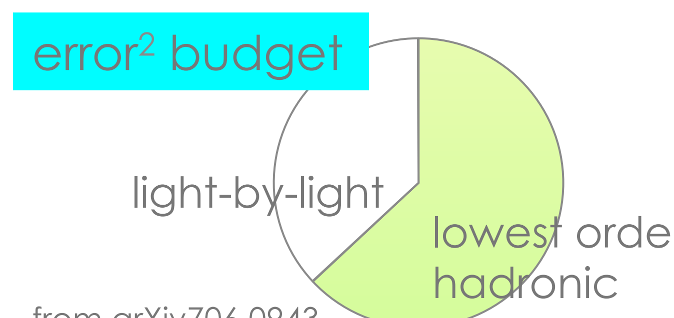


- lowest order
  - ~60 ppm contribution $\Pi'^{\,\mathrm{had}}_{\gamma}(q^2)$ $\sim \sigma^{\mathrm{had}}_{\mathrm{tot}}(q^2)$
  - **related to hadron production cross section from e⁺e⁻** — optical theorem
  - dominating theo. uncertainty
- higher order
  - smaller uncertainty
- light-by-light
  - (not discussed here)

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

O(1)

$$R_{\mathrm{had}}(s) = \sigma(e^+e^- \to \mathrm{hadrons}) \Big/ \frac{4\pi\alpha(s)^2}{3s}$$

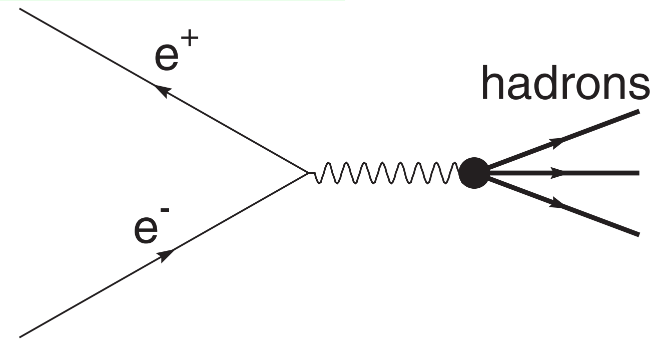


from arXiv706.0943

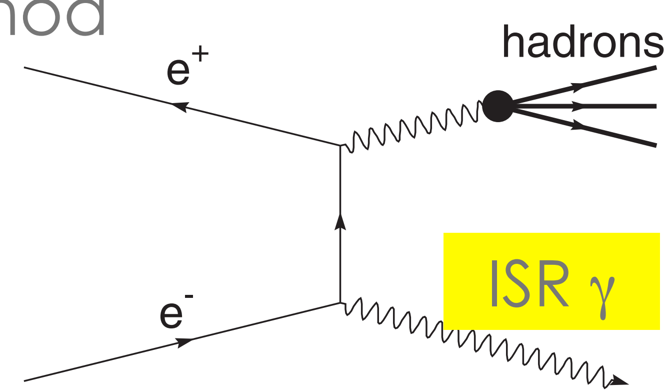
R measurement

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

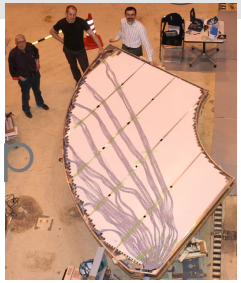
R(s): need *s* dependence

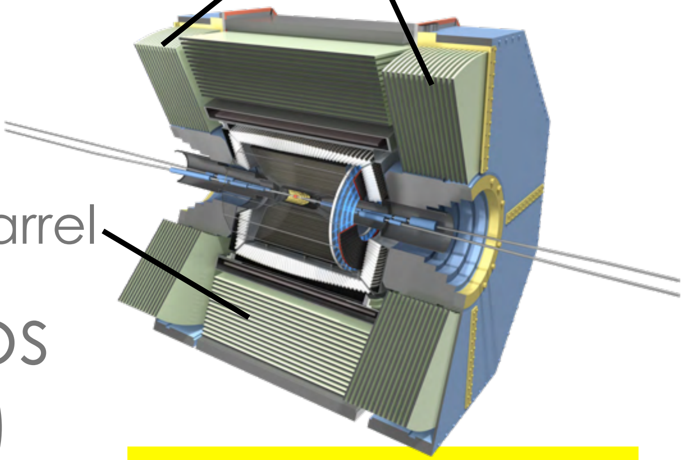


- scan method
  - ☺large statistics
  - ☹limited energy range
  - ☹point-to-point errors
  - being performed in Novosibirsk
- Initial State Radiation (ISR) method (colliders with fixed energy)
  - tag ISR photon (E>3 GeV)
  - ☺can scan wide energy range
  - ☺same exp'tal condition
  - ☹lower statistics due to ISR O(α)
    ←can be compensated by high luminosity
  - performed by BaBar / BES / KLOE

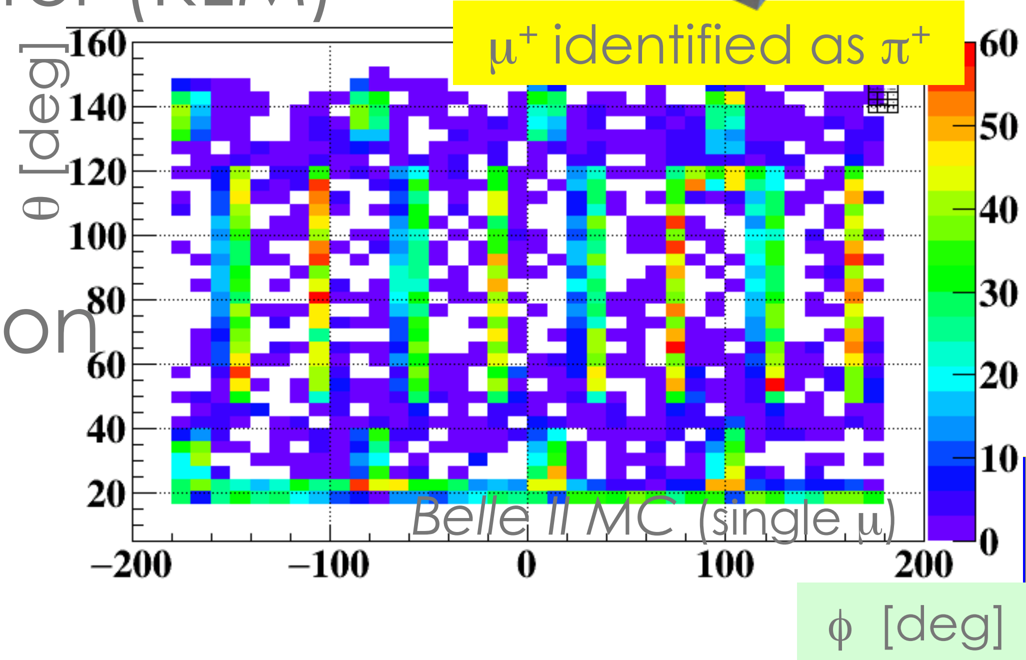


KLM gap effect



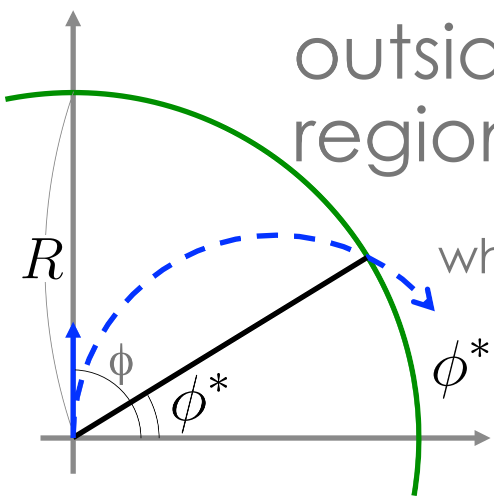


- muon ID inefficiency → fake π
- derived from module gaps of the K_L-μ detector (KLM)
  - also very forward region (θ<25°), not covered by KLM
- Avoiding this region helps to reduce $\mu\mu \rightarrow \pi\pi$ bkg



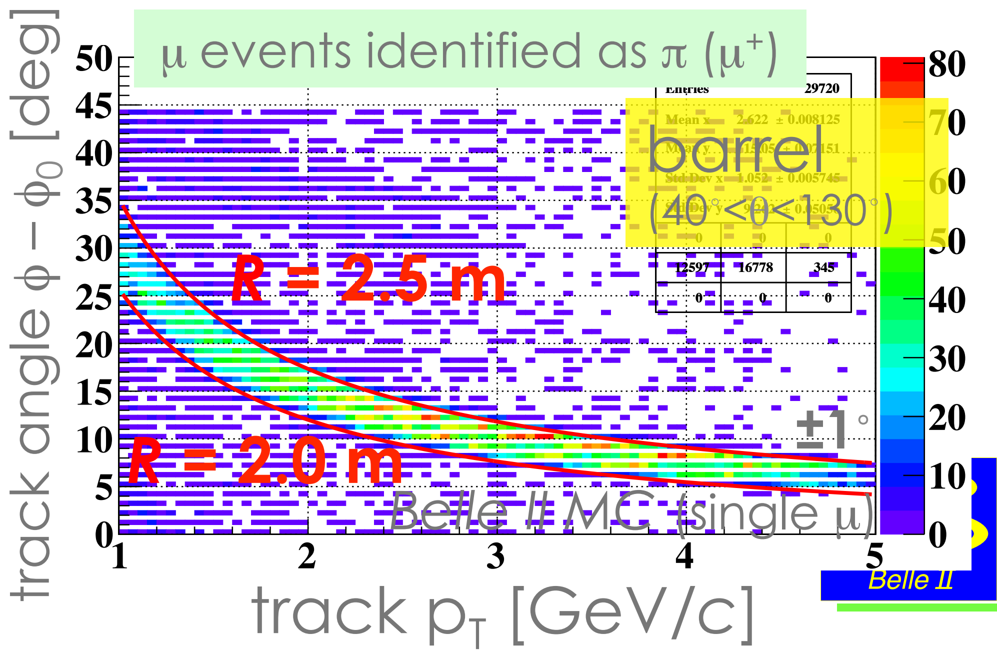
KLM-gap veto cut

- veto regions in track p_T-ϕ plane
  (φ is measured with respect to gap angle ϕ_0)
  - defined for each of particle charge and θ direction (endcap or barrel)
  - require at least one track to be outside this veto region



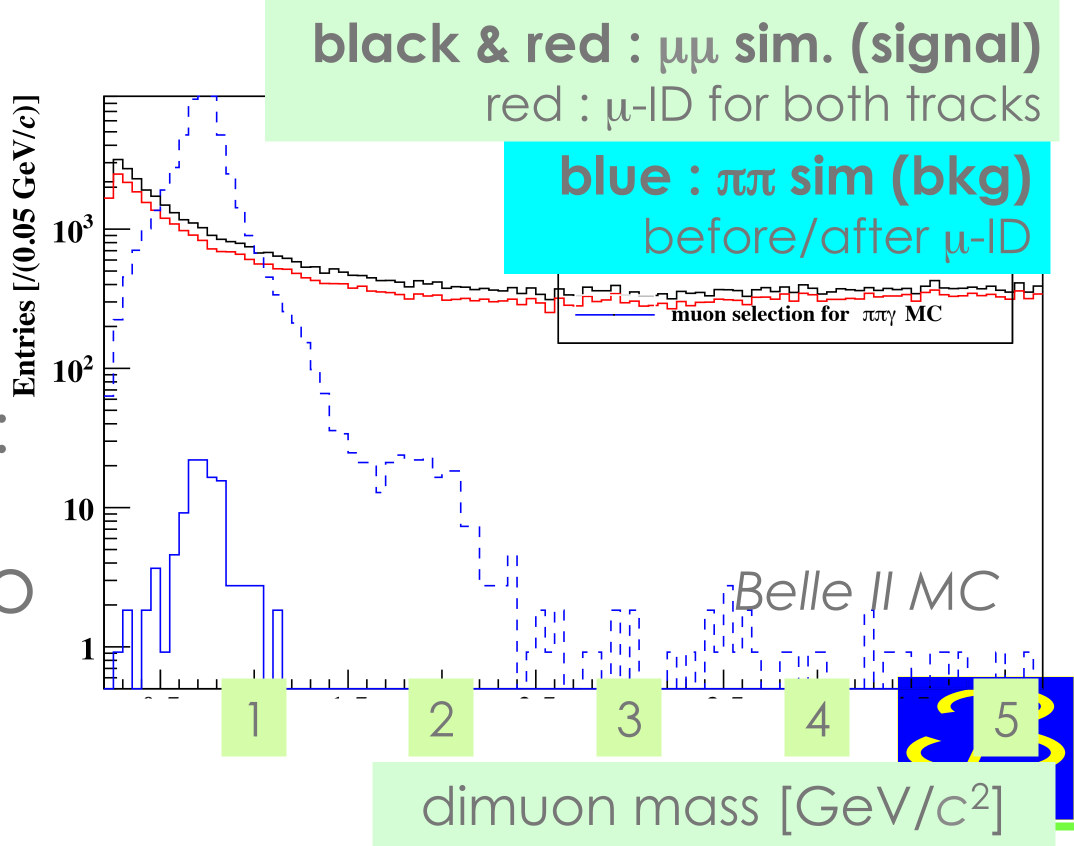
when track φ=90°

$$\phi^* = \cos^{-1}\frac{cBR}{2p_T}$$



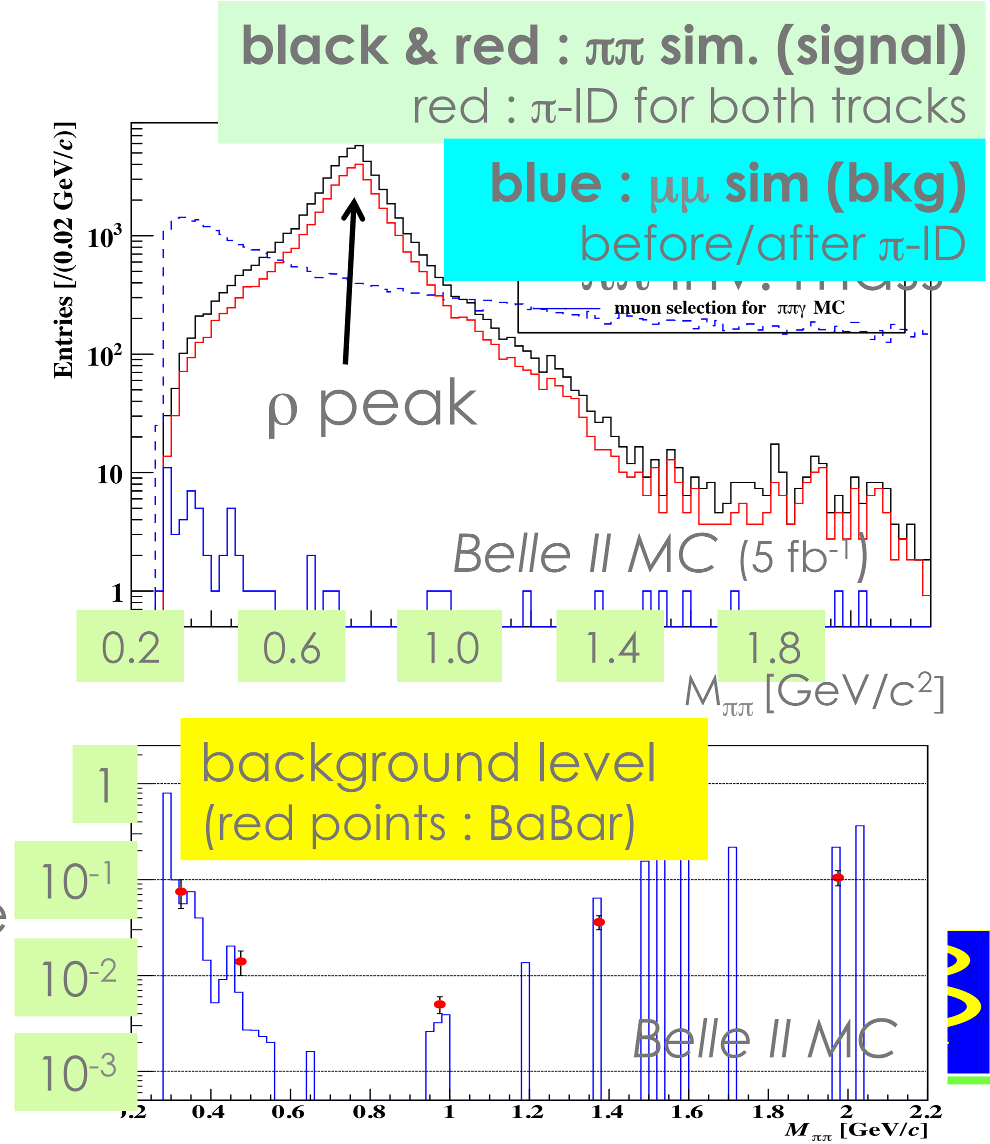
PID performance – μμ mode

- μμ/ππ modes can be background for each other
- MC stat. : ~5 fb^{-1} equiv.
- μμ-ID eff.
  - ~80%
  - loss by veto cut: 5%
- ππ→μμ bkg. ratio
  - ~0.4% ($M_{\mu\mu}$<1 GeV/c^2)



PID performance – ππ mode

- ππ–ID cut efficiency
  - 69%
  - loss by veto cut: 8.8%
- μμ→ππ background
  - 0.15% (<1 GeV/c^2)
    ←**factor 5 reduction**
    due to the veto cut
  - same level as BaBar
- required statistic
  - 5.3k evts / 5 fb^{-1}
    →>100 fb^{-1}
    possible in early stage of Belle II run
  (BaBar : 232 fb^{-1} PRD86 032013)



radiator function

- probability to emit ISR γ to produce a particle system (X) with mass of m

$$\frac{d\sigma_{\text{vis}}(s,m)}{dm} = \frac{2m}{s}\varepsilon(s,m)W(s,x)\sigma_0(m)$$

observed spectrum

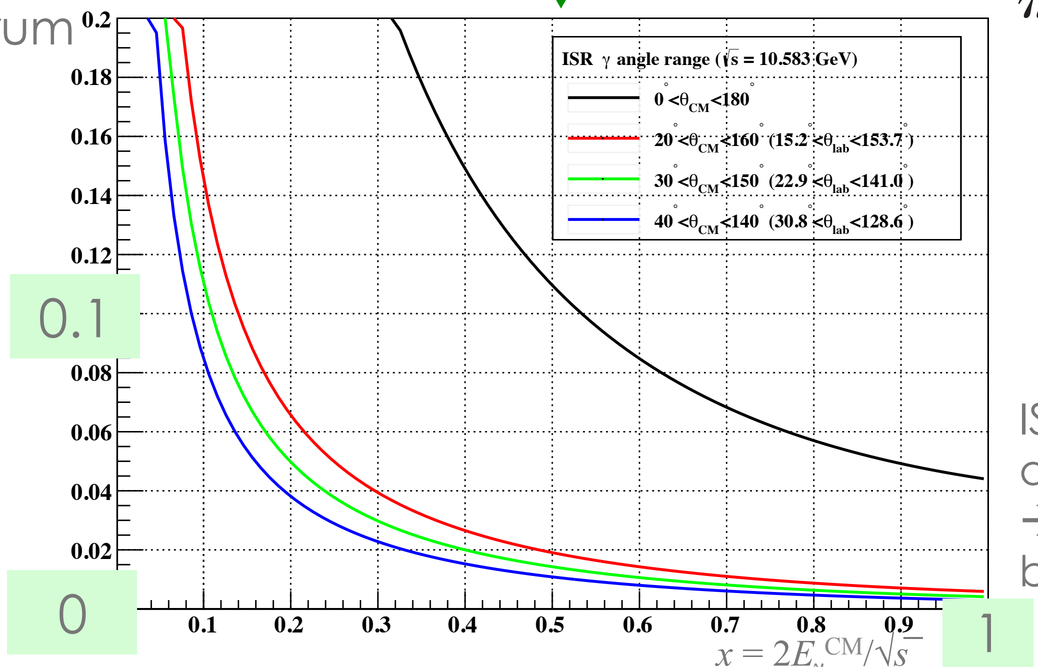
cross section for $e^+e^- \to X$ at m

$$W_0(0,x) = \frac{\alpha}{\pi x}\left(\ln\frac{s}{m_e^2} - 1\right)(2 - 2x + x^2)$$

$$m = 2E_0\sqrt{1-x}$$

$$E_0 = \sqrt{s}/2$$

$$x = 2E_\gamma^{\text{CM}}/\sqrt{s}$$



ISR γ to forward and backward directions is dominant
→only ~10% of ISR γ can be detected

Belle II

ISR luminosity

- 2m/s : to change x to m $\quad m = 2E_0\sqrt{1-x}$

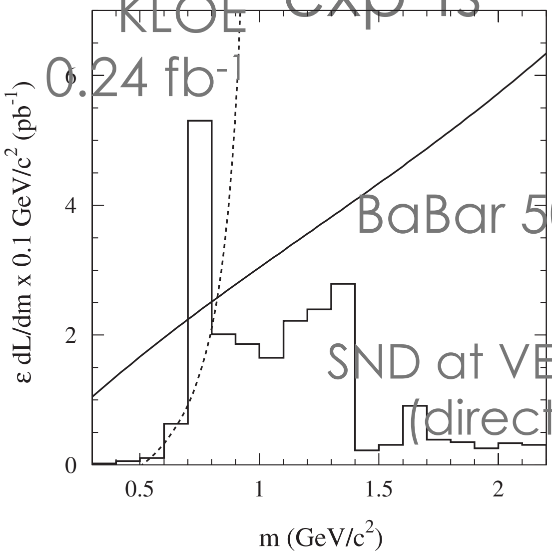
$$\frac{d\sigma_{\rm vis}(s,m)}{dm} = \frac{2m}{s}\varepsilon(s,m)W(s,x)\sigma_0(m)$$

- can be compared with direct scan exp'ts

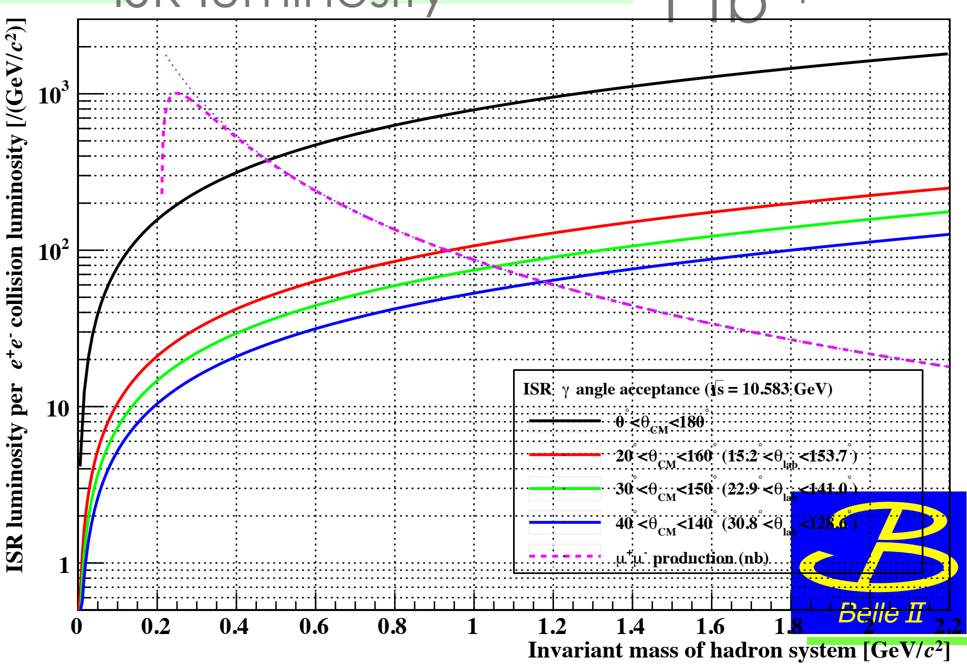
KLOE 0.24 fb^{-1}

BaBar 500 fb^{-1}

SND at VEPP-2M (direct scan)

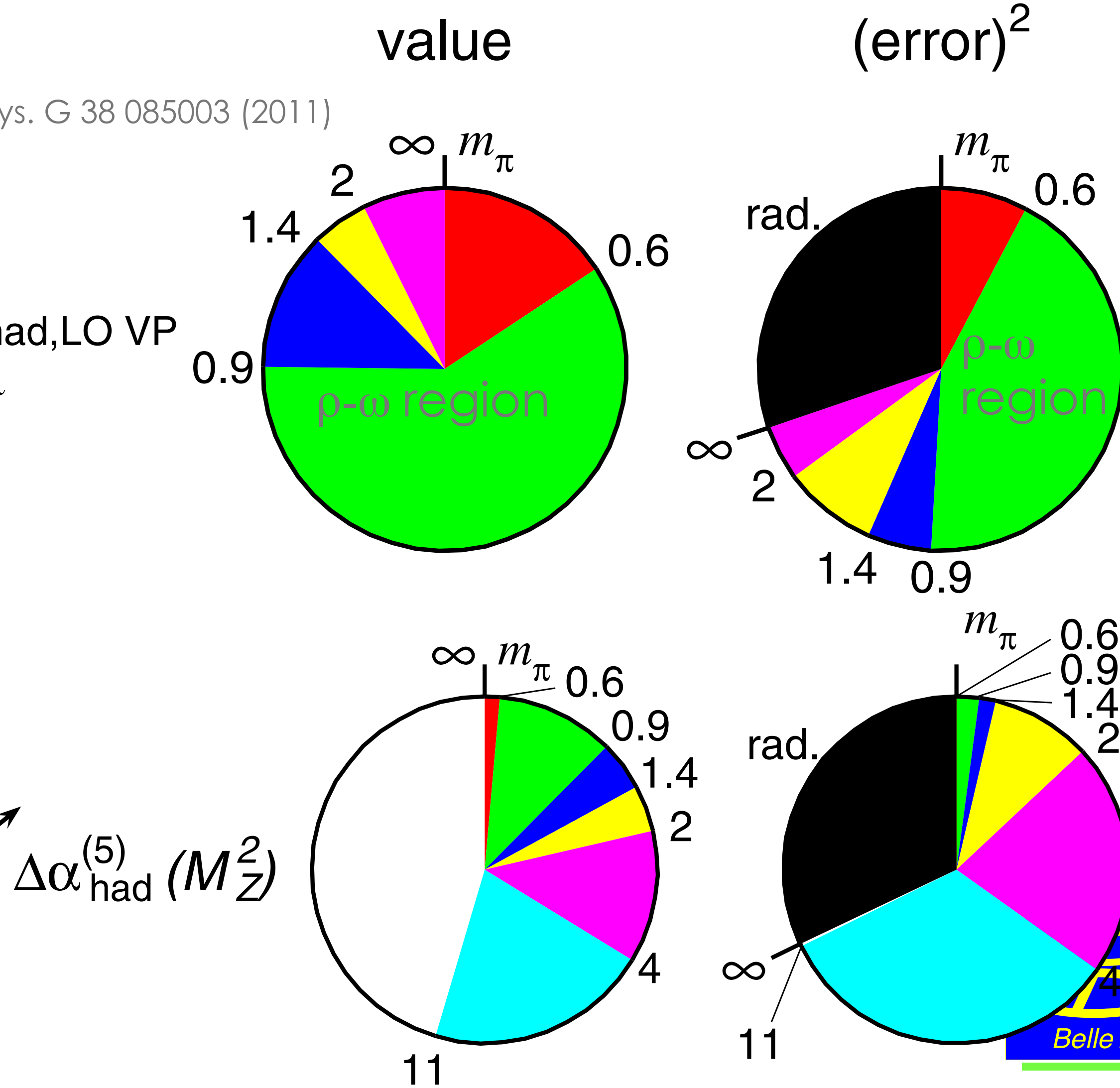


ISR luminosity 1 fb^{-1}

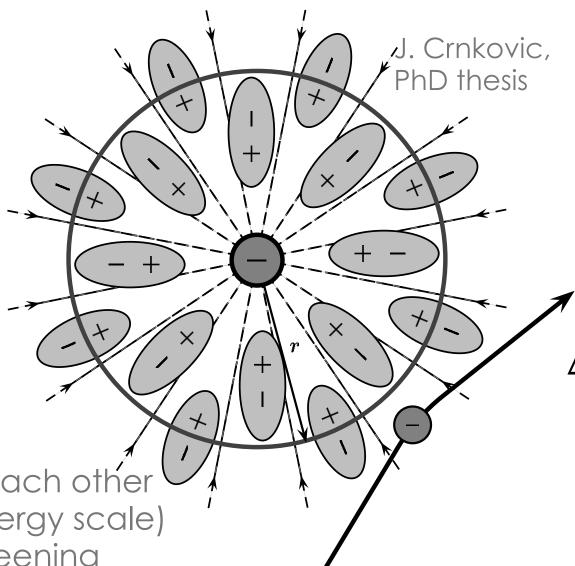


contribution of HVP

J. Phys. G 38 085003 (2011)



"charge screening"



J. Crnkovic, PhD thesis

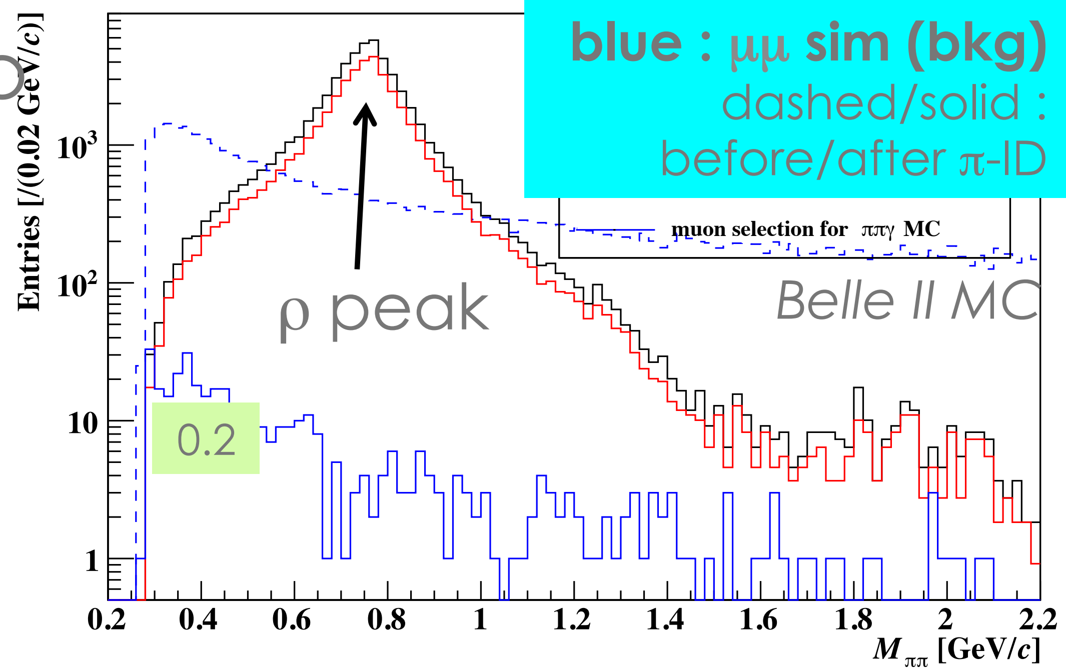
closer to each other
(= high energy scale)
→ less screening
→ stronger interaction

without veto cuts (ππ)

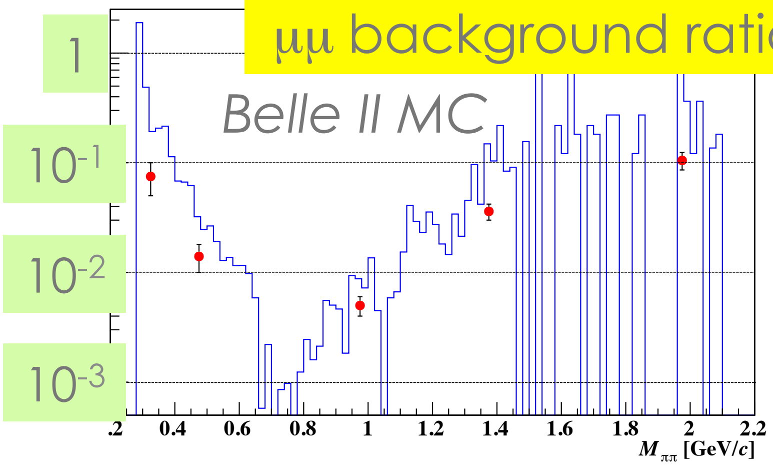
- ππ efficiency ~ 75%
- μμ→ππ bkg. ratio ~ 0.85%
- comparison with BaBar ana. (PRD86 032013)

black & red : ππ sim. (signal)
red : π-ID for both tracks

blue : μμ sim (bkg)
dashed/solid : before/after π-ID



μμ background ratio



red points : BaBar analysis
slightly worse in this analysis

cut optimization

	μμ efficiency	ππ→μμ BG	ππ efficiency	μμ→ππ BG
no veto cut	85.2%	0.39%	75.3%	0.83%
loose cut	80.9%	0.39%	68.7%	0.15%
tight cut	58.2%	0.40%	46.2%	0.10%

M<1 GeV/c^2

- tight cut (require both tracks to be outside the veto regions) loses efficiency, while background reduction is not so large

current situation of e g-2

PRL100, 120801

- measurement : $a_e^{exp} = 1\,159\,652\,180.73\,(28) \times 10^{-12}$ ± 0.24 ppb
  (Harvard U)
- theory

8th and 10th order of QED calculation — hadronic contribution — α

$$a_e(\text{theory}) = 1\,159\,652\,181.78\,(6)(4)(2)(77) \times 10^{-12}$$ [0.67 ppb]

PRL109, 111807

- QED mass-dependent term : $2.7478(2) \times 10^{-12}$
- had

$$a_e(\text{had.v.p.}) = 1.866(10)_{\text{exp}}(5)_{\text{rad}} \times 10^{-12},$$

1.5 ppb

$$a_e(\text{NLO had.v.p.}) = -0.2234(12)_{\text{exp}}(7)_{\text{rad}} \times 10^{-12},$$

$$a_e(\text{had.}\,l\text{-}l) = 0.035(10) \times 10^{-12},$$

- weak

$$a_e(\text{weak}) = 0.0297\,(5) \times 10^{-12}$$

current situation of μ g-2

$$a_\mu^{exp} = 1\,165\,920\,89\,(63) \times 10^{-11} \quad \pm 0.54\ \text{ppm}$$

- measurement :
  (BNL E821)
- theory
  - QED

8th and 10th order of QED calculation

order	with α^{-1}(Rb)	with $\alpha^{-1}(a_e)$
2	116 140 973.318 (77)	116 140 973.213 (30)
4	413 217.6291 (90)	413 217.6284 (89)
6	30 141.902 48 (41)	30 141.902 39 (40)
8	381.008 (19)	381.008 (19)
10	5.0938 (70)	5.0938 (70)
a_μ(QED) × 10^{11}	116 584 718.951 (80)	116 584 718.846 (37)

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lepton mass

α

$$a_\mu^{\rm QED} = 116\ 584\ 718.951\ (0.009)(0.019)(0.007)(.077) \times 10^{-11}$$

  - hadron

$$a_\mu^{\rm had;LO} = (6\ 923 \pm 42) \times 10^{-11}$$

$$a_\mu^{\rm had;NLO} = (-98.4 \pm 0.6_{\rm exp} \pm 0.4_{\rm rad}\ ) \times 10^{-11}$$

$$a_\mu^{\rm HLbL} = (105 \pm 26) \times 10^{-11}$$

  - weak

$$a_\mu^{\rm EW} = (153.6 \pm 1.0) \times 10^{-11}$$

Belle II