Measurement of cross section of light hadron production in e^+e^- collisions in the Belle II experiment

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for the Belle II collaboration

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2018 WPI-next mini-workshop
"Hints for New Physics in Heavy Flavors"

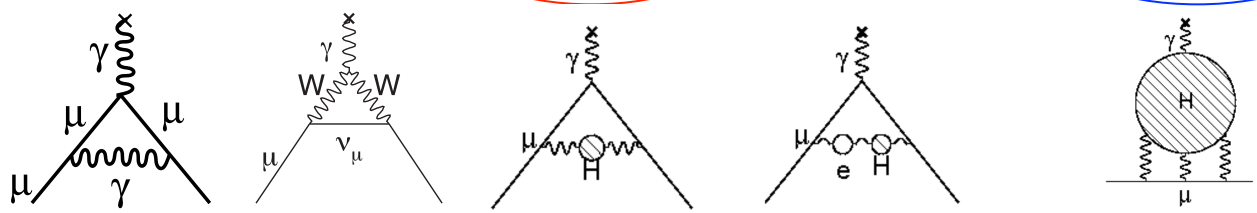
World Research Unit for
Heavy Flavor Particle Physics

Belle II

muon g-2 and the ee→ππ process

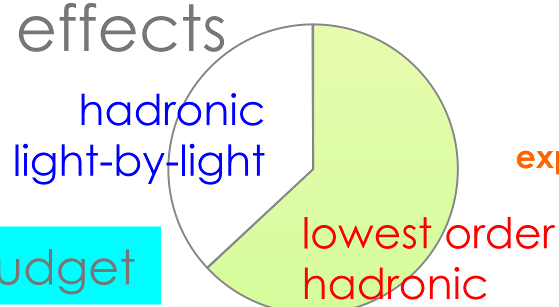
- muon *g*-2 SM value

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



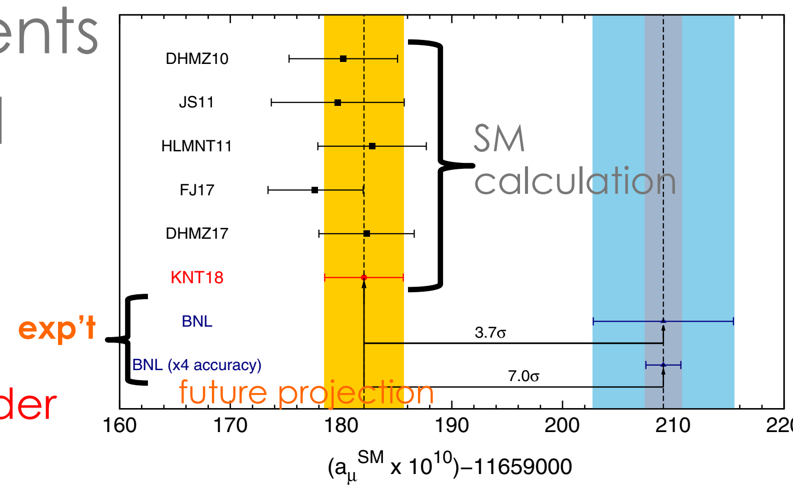
arxiv:1311.2198

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



error² budget

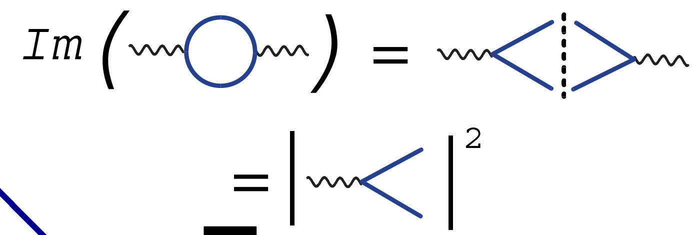
from arXiv1311.2198



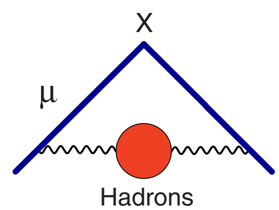
PRD97, 114025 (2018)

muon g-2 and the ee→ππ process

2007 Rep. Prog. Phys. 70 795



- leading order hadronic effect
  - hadronic loop
  - involves low energy QCD →calculation is difficult
  - but, **ee→(hadrons)** cross section data can be used
- ee→ππ gives the largest contribution



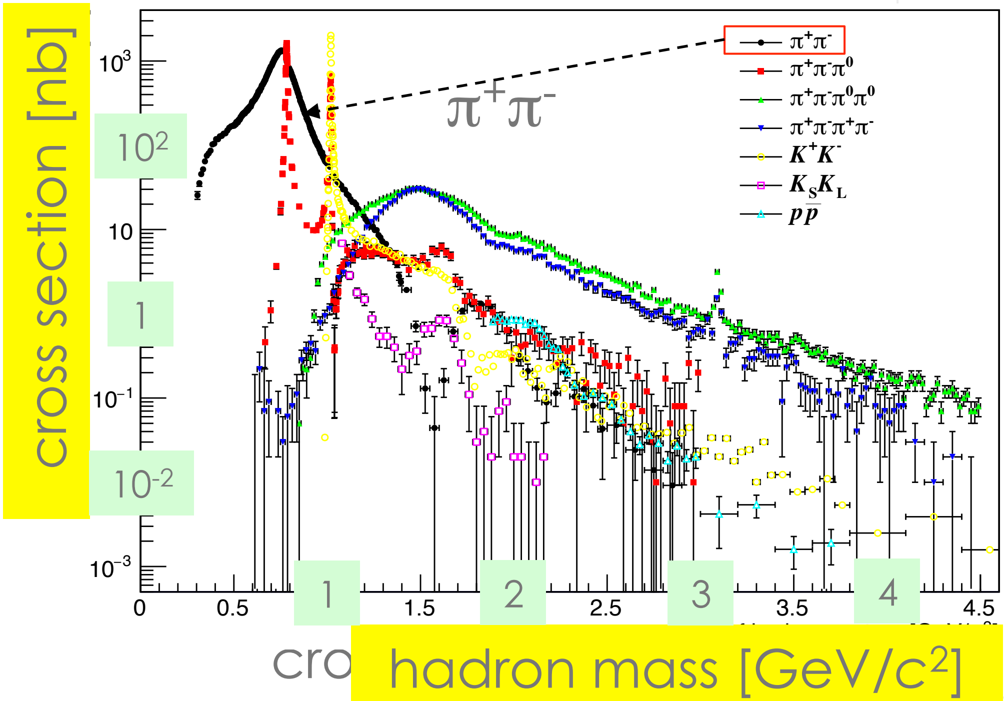
dispersion relation & optical theorem

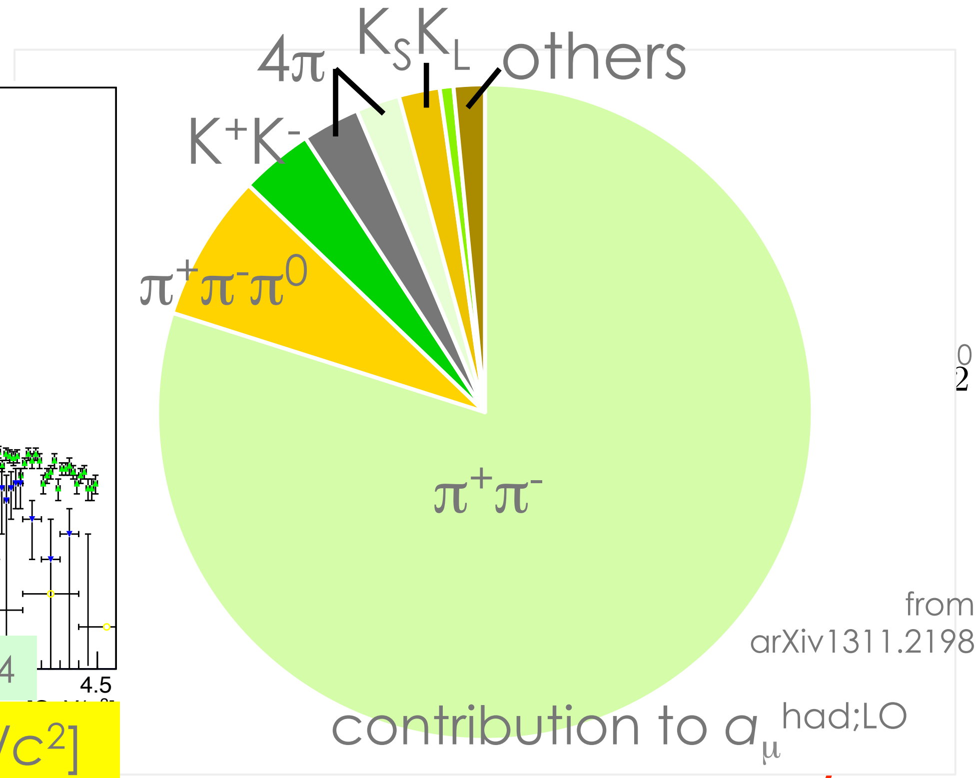
O(1)

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

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

Belle II





- **ee→ππ gives the largest contribution**

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

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

Belle II

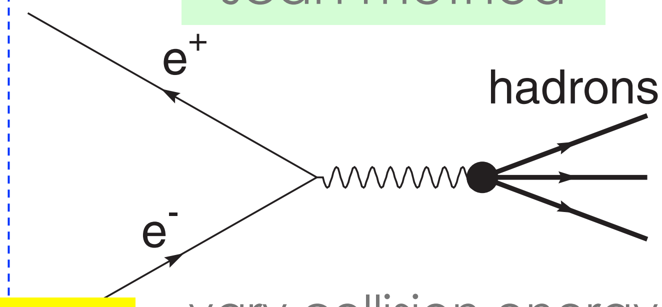
measurement methods

- **direct scan**:
  - change collision energy and measure # of events
  - e.g. CMD3 and SND in Novosibirsk

☺fine scan is possible for sharp resonances
☹different conditions among different energy
☹difficulty in handling low-momentum particles

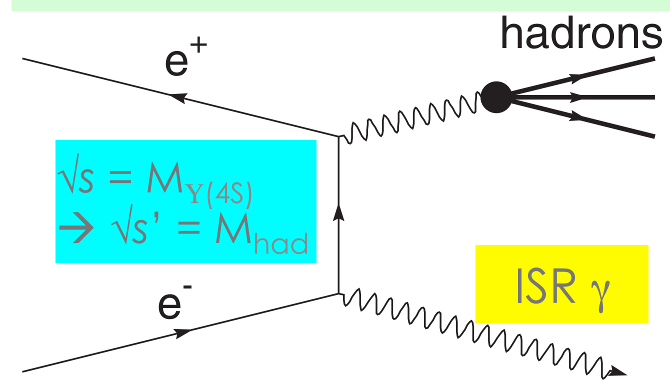
- radiative return method:
  - collision energy is fixed
  - require energetic γ (Initial State Radiation, ISR) → effectively low energy collision
  - measure mass spectrum of final state hadrons
  - e.g. BaBar, BES III, KLOE

scan method



vary collision energy

radiative return method

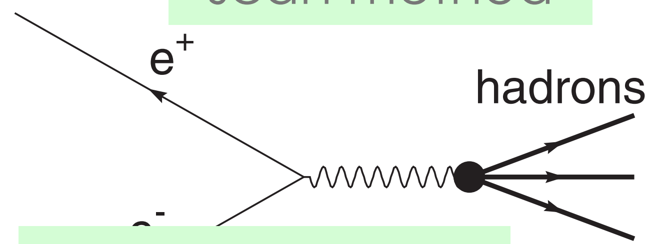


fixed collision energy

Belle II

measurement methods

scan method



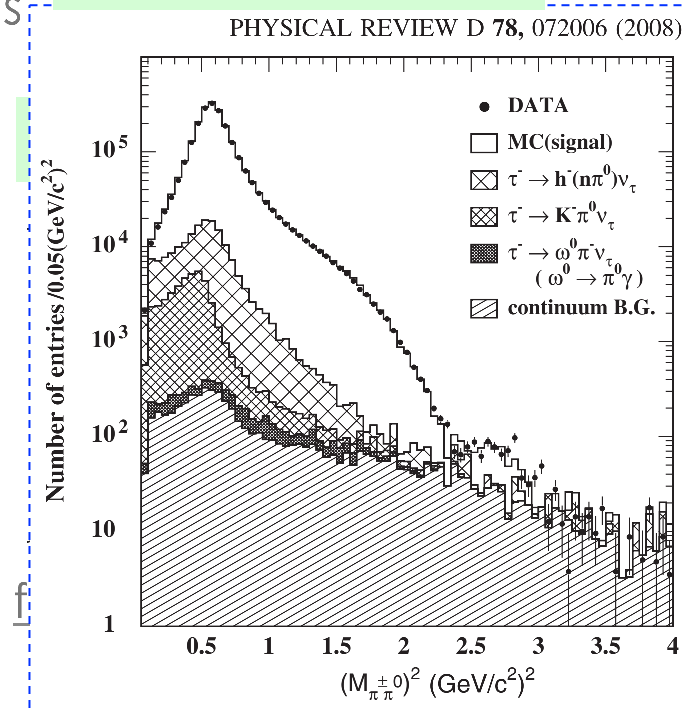
☺large statistics
☹uncertainty due to correction of iso-spin breaking effect

birsk

- **tau hadronic decay with CVC**:
  - Conserved Vector Current hypothesis
  - $\pi\pi$ mass spectrum in $\tau\to\pi\pi^0\nu_\tau$
  - e.g. LEP exp’ts, CLEO, Belle
- radiative return method:
  - collision energy is fixed
  - require energetic γ (Initial State Radiation, ISR) → effectively low energy collision
  - measure mass spectrum of final state hadrons
  - e.g. BaBar, BES III, KLOE

$M_{\pi\pi}{}^2$ in $\tau\to\pi\pi^0\nu_\tau$
(Belle result)

nergy



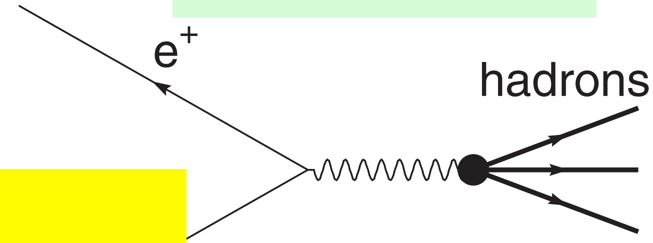
measurement methods

- direct scan:
  - change collision energy

☹low statistics due to ISR requirement (O(α))
☺but is compensated high luminosity machines
☺can scan cross section for wide energy range in the same experimental condition

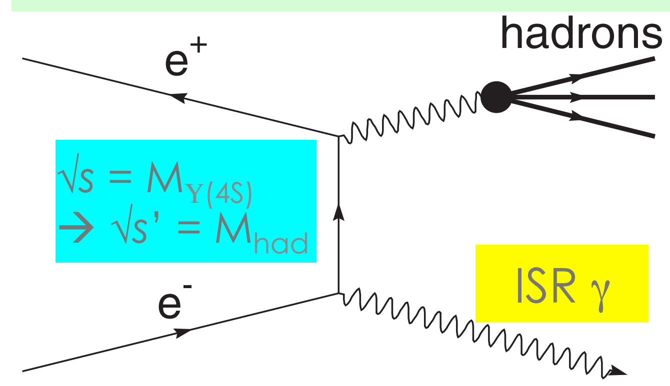
  - e.g. LEP exp'ts, CLEO, Belle
- **radiative return method**:
  - collision energy is fixed
  - require energetic γ
    (Initial State Radiation, ISR)
    →effectively low energy collision
  - measure mass spectrum
    of final state hadrons
  - e.g. BaBar, BES III, KLOE

scan method



vary collision energy

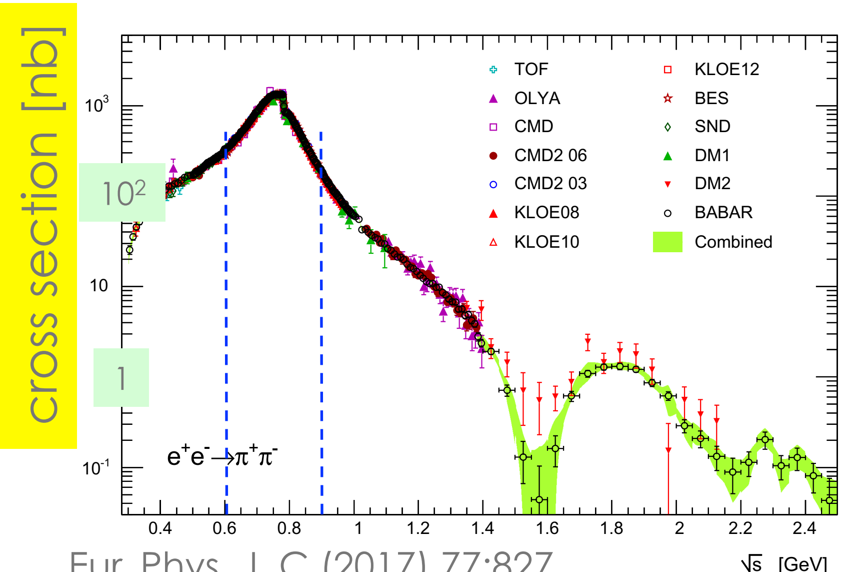
radiative return method



fixed collision energy

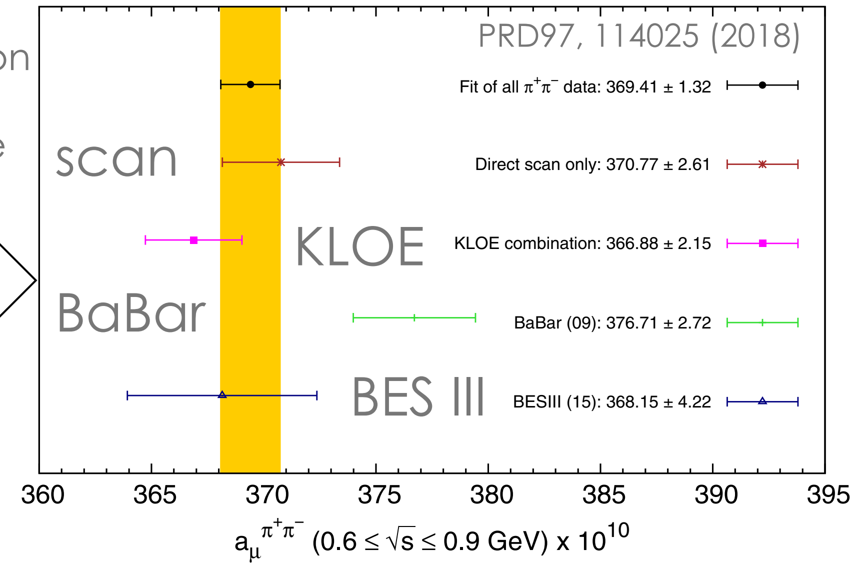
Belle II

status of ππ cross section measurement



Eur. Phys. J. C (2017) 77:827

contribution for the ρ resonance to a_μ^{had}



- Already measured precisely(≲1%) by several experiments
- small discrepancy (a few %) among measurements
- must be confirmed by Belle II
- target : 0.5% precision (similar or better than Babar)

advantages in Belle II

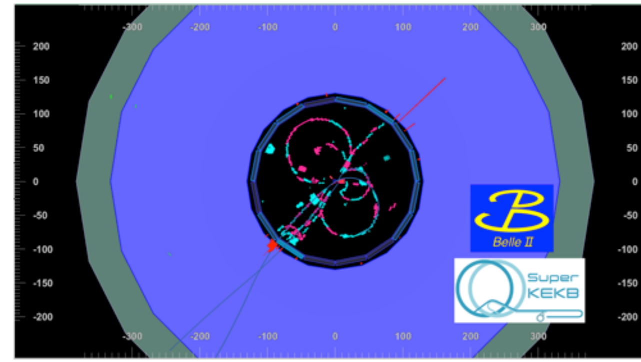
- large statistics
  - signal events themselves
  - control samples for estimation of systematic uncertainty
- well-designed triggers
  - Neither Belle and BaBar had optimized trigger for this measurement
  - Belle suffered from large efficiency loss due to trigger
- larger detector coverage
- better generator
- lessons from the BaBar measurement
  - All are giving comparable uncertainty, but PID-related ones are relatively large

list of systematic errors in BaBar (PRD86 032013)

Sources
Trigger/filter
Tracking
π-ID
Background
Acceptance
Kinematic fit (χ^2)
Correl. $\mu\mu$ ID loss
$\pi\pi/\mu\mu$ non-cancel.
Unfolding
ISR luminosity
Sum (cross section)

first look at the Belle II data

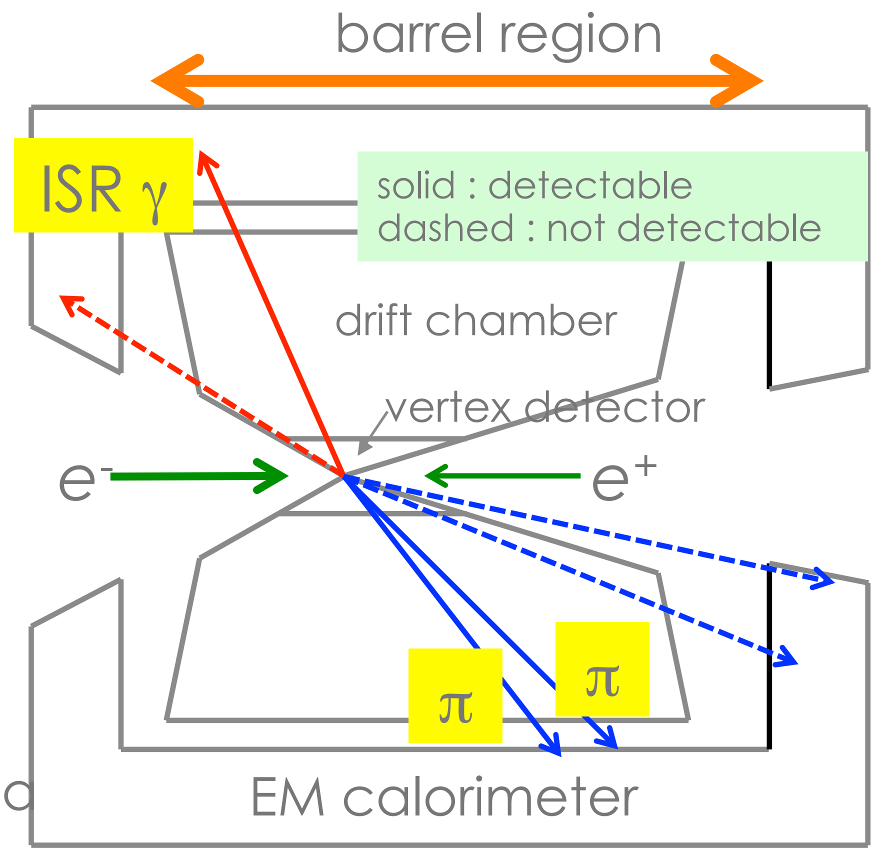
- Belle II phase2 operation
  - commissioning of the accelerator with collisions
  - end of March – middle of Jul
  - the first collision at 26th April
- full data of 472 pb^{-1} was used
- goal of the analysis
  - to observe ρ meson peak in the mass spectrum
  - yield comparison with MC simulation
  - study of trigger efficiency



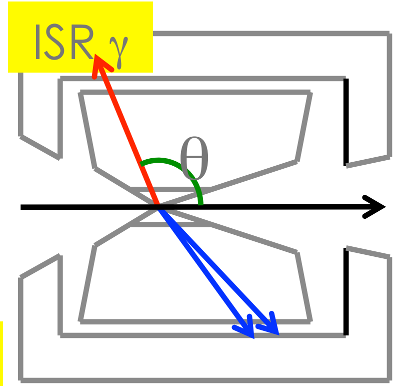
celebration of the first collision (26^{th} Apr.)

analysis procedure

- select events with
  - one energetic photon (E^{CMS}>3 GeV)
  - two charged tracks (p>1 GeV/c)
- selection criteria
  - **photon points to central part of the barrel region** ($50^\circ<\theta_{ISR}<110^\circ$)
  - E/p<0.8 →remove Radiative Bhabha (ee→eeγ) contribution
  - 10<M(ππγ)<11 GeV/c^2 →no other extra particles



analysis procedure



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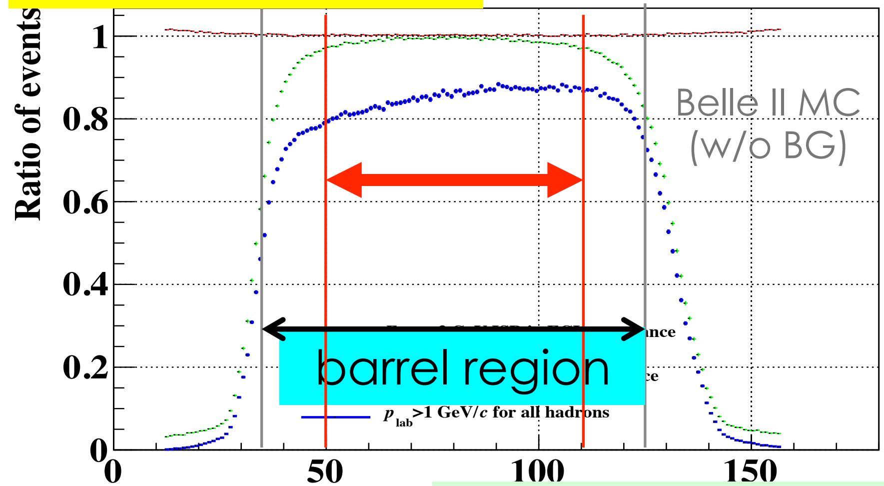
acceptance for $\pi^\pm$



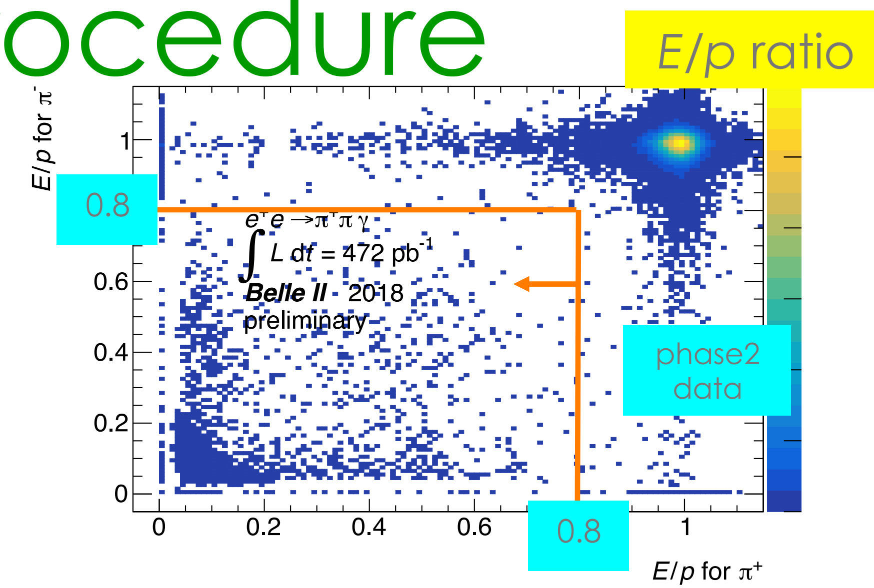
θ angle of ISR γ [°]

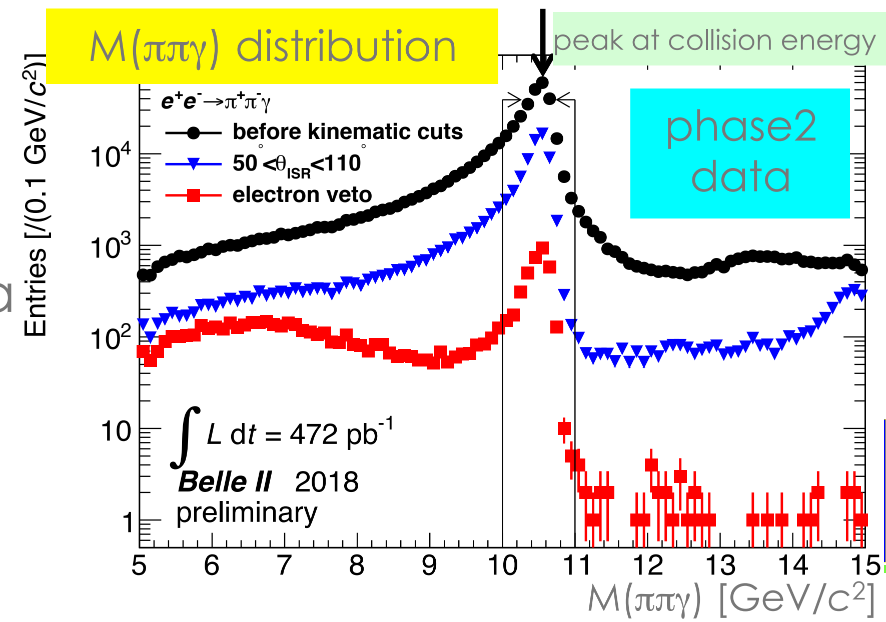
both pions are in CDC

p>1 GeV/c

analysis procedure

- select events with
  - one energetic photon (E^{CMS}>3 GeV)
  - two charged tracks (p>1 GeV/c)
- selection criteria
  - photon points to central part of the barrel region $50^\circ<\theta_{ISR}<110^\circ$
  - ***E/p*<0.8** →remove Radiative Bhabha (ee→eeγ) contribution
  - **10<M(ππγ)<11 GeV/c²** →no other extra particles

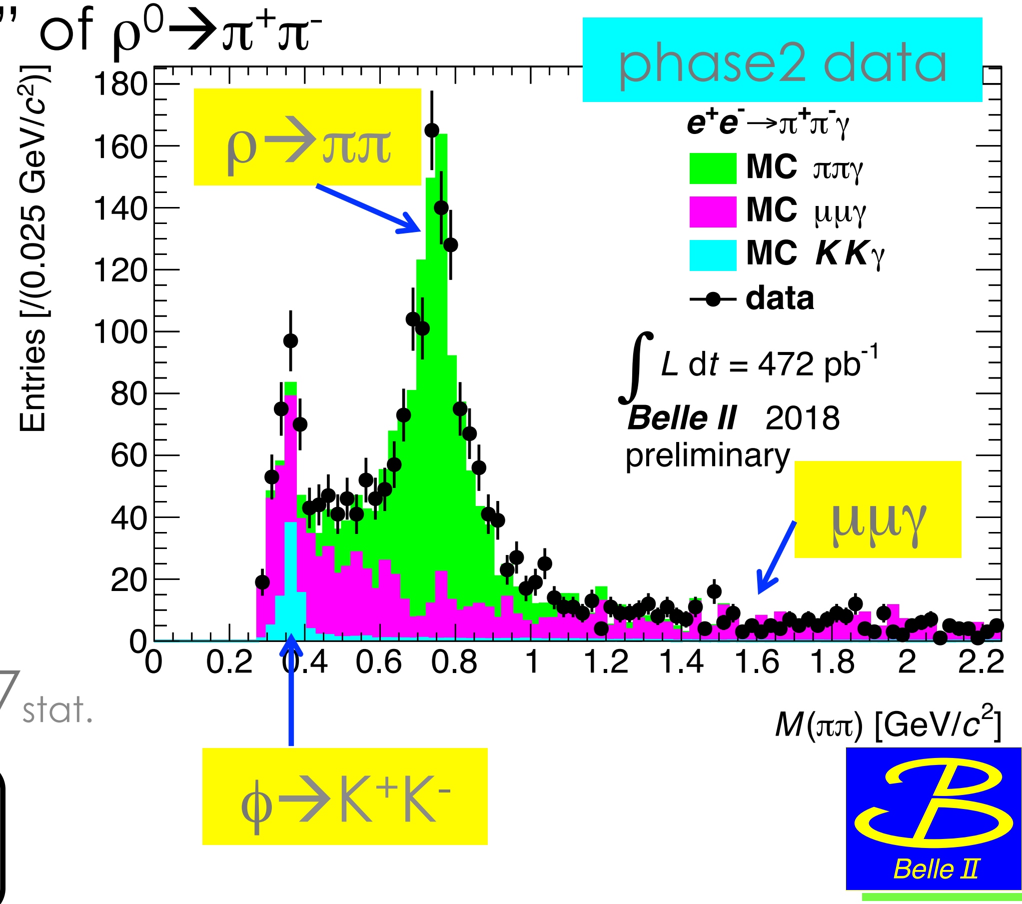




$\pi\pi$ mass spectrum

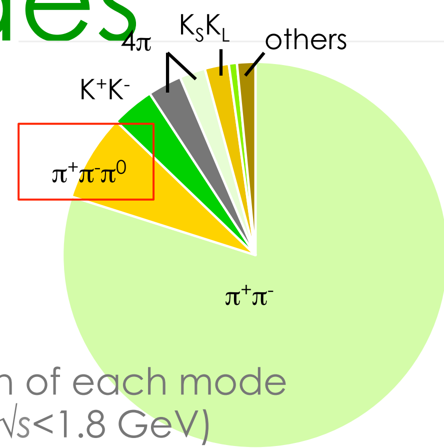
- ρ meson peak is clearly observed!
  Belle II first "rediscovery" of $\rho^0 \to \pi^+\pi^-$
- no PID cuts except for the E/p cut $\to$ contribution from $\mu\mu\gamma$ / $KK\gamma$
  - peak at low mass due to $\phi \to K^+K^-$
  - high mass (>1 GeV/c^2) is dominated by $\mu\mu\gamma$
- reasonable data/MC agreement
  - data/MC = $1.065 \pm 0.037_{stat.}$ (0.5-1 GeV/c^2)

  (MC trigger efficiency is assumed to be 100%)



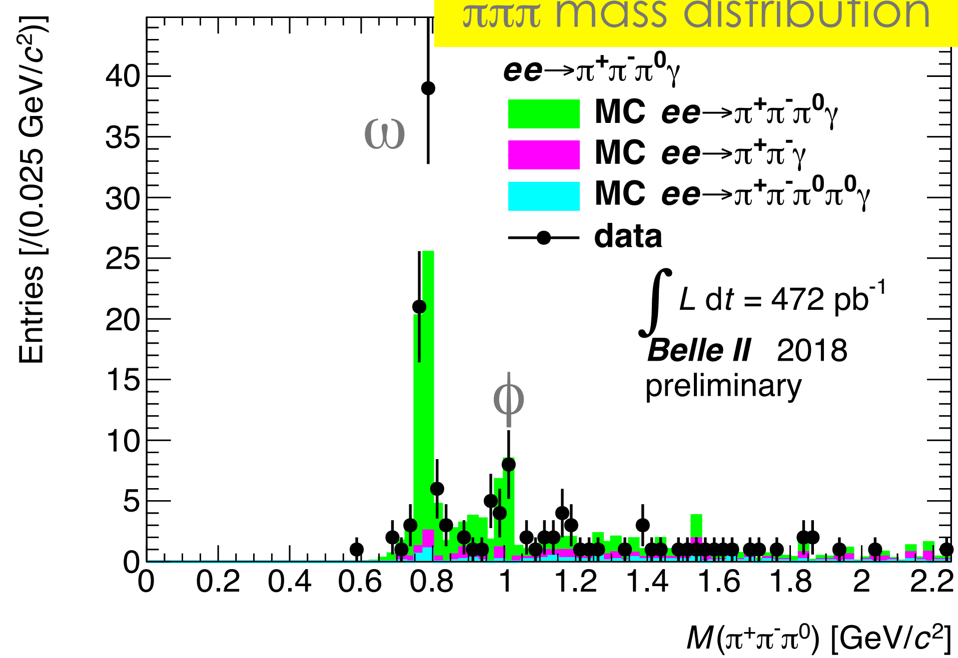
results for other modes

- the ee→$\pi\pi\pi\gamma$ process is also studied with phase2 data
  - 2nd biggest contribution to $a_\mu^{had;LO}$
- ω, ϕ peaks are successfully observed "rediscovery"
- reasonable data/MC agreement



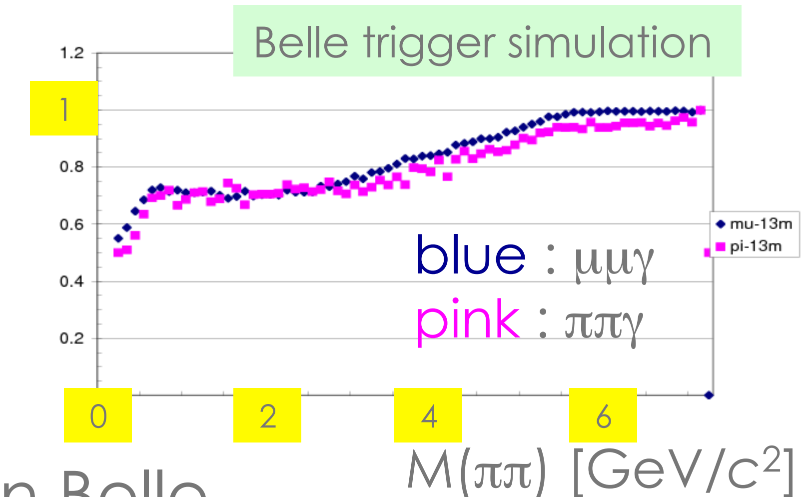
contribution of each mode to $a_\mu^{had;LO}$ ($\sqrt{s}$<1.8 GeV)

$\pi\pi\pi$ mass distribution



trigger efficiency for ππγ

- high trigger efficiency is necessary for precision measurement
- Belle II trigger for ee→ππγ
  - total calorimeter energy > 1 GeV
  - Bhabha veto
    ←loss of this veto must be small



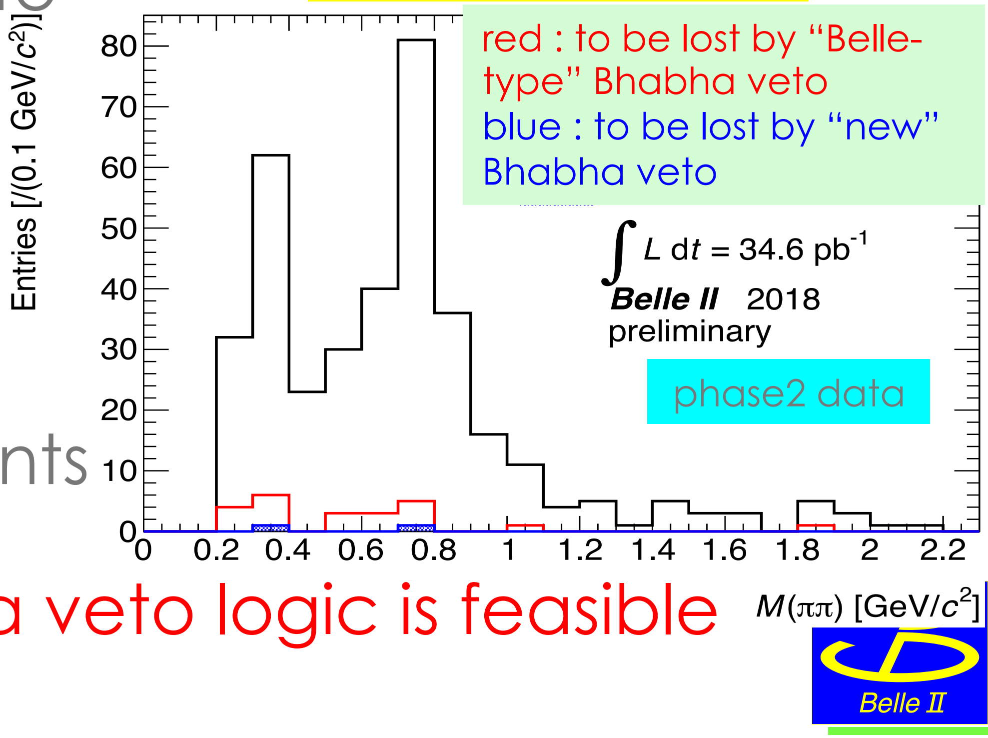
- large loss by Bhabha veto in Belle
  →precision measurement was difficult
- all Bhabha events were collected in phase2
  - Efficiency loss can be easily evaluated by counting the number of events with Bhabha trig.

efficiency loss by Bhabha veto

- two kinds of Bhabha veto logic
  - "Belle-type" Bhabha veto
  - "new" Bhabha veto
- results of loss evaluation
  - "Belle-type" : $(6.4\pm1.3_{stat})\%$
  - "new" logic : 2 events / 360 events **$(0.6\pm0.4_{stat})\%$**

→the "new" Bhabha veto logic is feasible for future runs

M(ππ) distribution

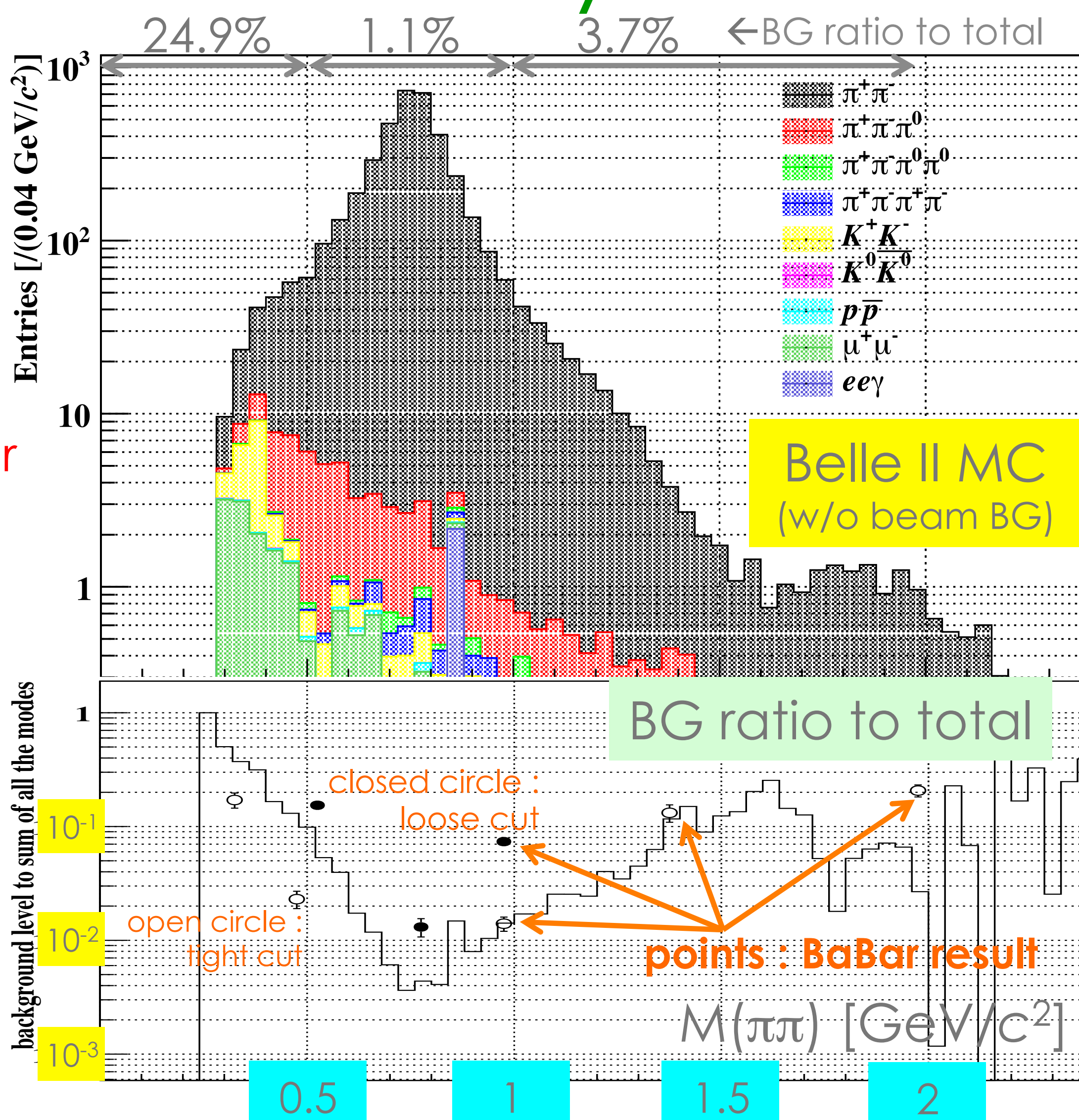


expected performance by MC sim.

- apply PID cuts
- BG contribution
  - dominant BG: other ISR modes ($\pi^+\pi^-\pi^0$, K^+K^-,..)
  - O(%) level BG ; same level with BaBar
  - high BG at low mass: $\pi\pi\pi^0$ with low-E π^0

  ←can be reduced (kinematic fit…)
- efficiency
  - 49% for $50<\theta_{ISR}<110^\circ$
  - expect >1M events with 500 fb^{-1}

→can have results with early Belle II data!!



summary

- ee→ππ cross section measurement in Belle II with ISR method is critical to reduce uncertainty of theoretical value for muon *g*-2
- In Phase2 data, ρ meson peak was clearly observed and good data-MC agreement was confirmed
- Peaks for ω, $\phi \to \pi^+\pi^-\pi^0$ are also observed.
- Although Belle suffered from large efficiency loss due to Bhabha veto in the trigger level, such loss is evaluated to be small ($\lesssim$1%) with a new Bhabha veto logic in phase2 data.
- The first O(100) fb^{-1} data will give enough signal events, which will be expected in a few years

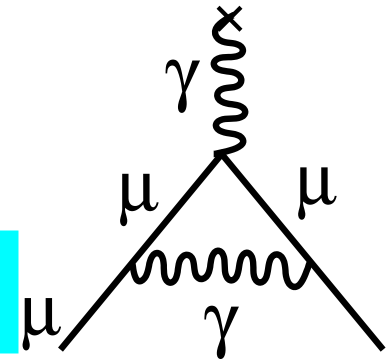
backup slides

muon g-2

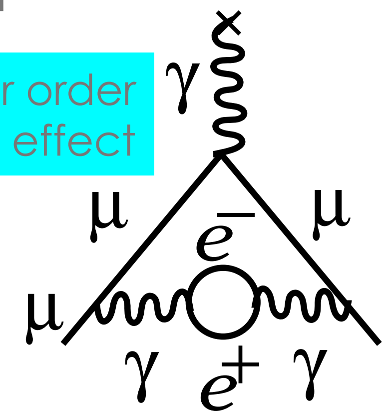
$$\vec{\mu}_\ell = g_\ell \frac{Qe}{2m_\ell}\vec{s}$$

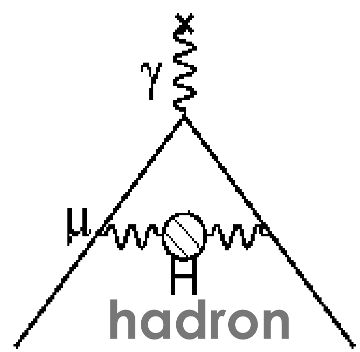
- “g-factor” of μ (also e) is slightly larger than 2 due to QED effect
  - $a_\mu = (g-2)/2$
  - ~3σ discrepancy btw theo. and exp.
    - both have ~0.5 ppm precision
- strong interaction and weak interaction also contribute
  - strong : ~60 ppm
  - weak : ~1.3 ppm

“Schwinger” O(α)



higher order QED effect

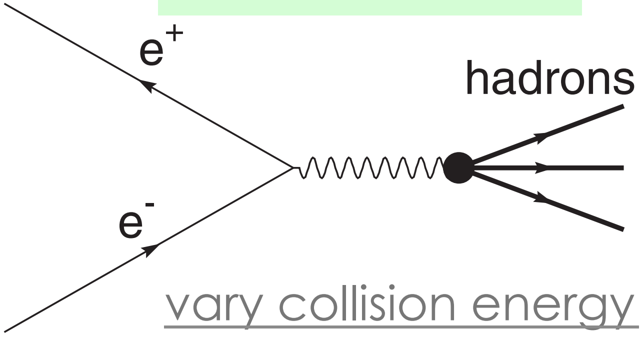




ee→ππ measurement at Belle II

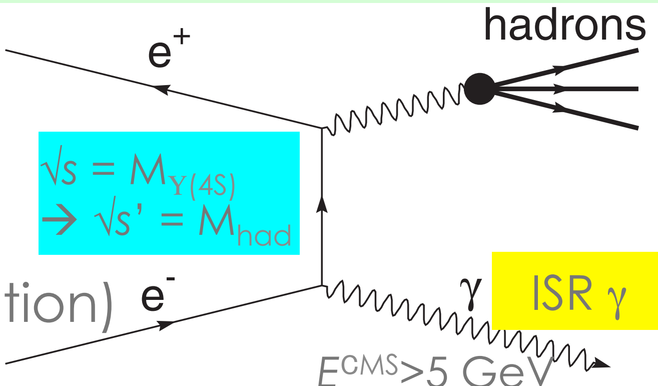
- radiative return method:
  detect ee→ππγ events
  - require energetic γ
    (Initial State Radiation, ISR)
    →effectively low energy collision
  - hadron inv. mass distribution
    →corrections
    (BG, eff., unfolding…)
    →cross section for each √s
- simultaneous measurement of ππγ (signal) and μμγ (normalization)
  - cancellation of various errors

scan method



vary collision energy

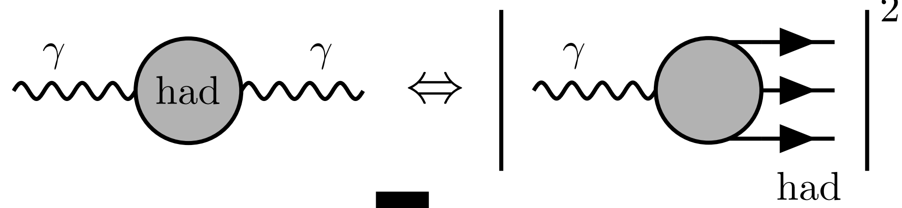
radiative return method



fixed collision energy

hadronic contribution

Physics Reports 477 (2009) 1–110



- lowest order
  - ~60 ppm contribution $\Pi_\gamma^{\prime\,\mathrm{had}}(q^2)$ $\sim \sigma_{\mathrm{tot}}^{\mathrm{had}}(q^2)$
  - **related to hadron production cross section from e^+e^-**
  - dominating theo. uncertainty
- higher order
  - smaller uncertainty
- light-by-light
  - (not discussed here)

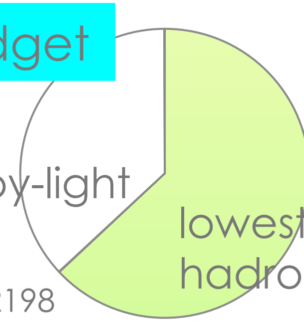
optical theorem

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

O(1)

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

error² budget



from arXiv1311.2198

Belle II

Fermion pair production in e⁺e⁻ collisions

- cross section is well understood

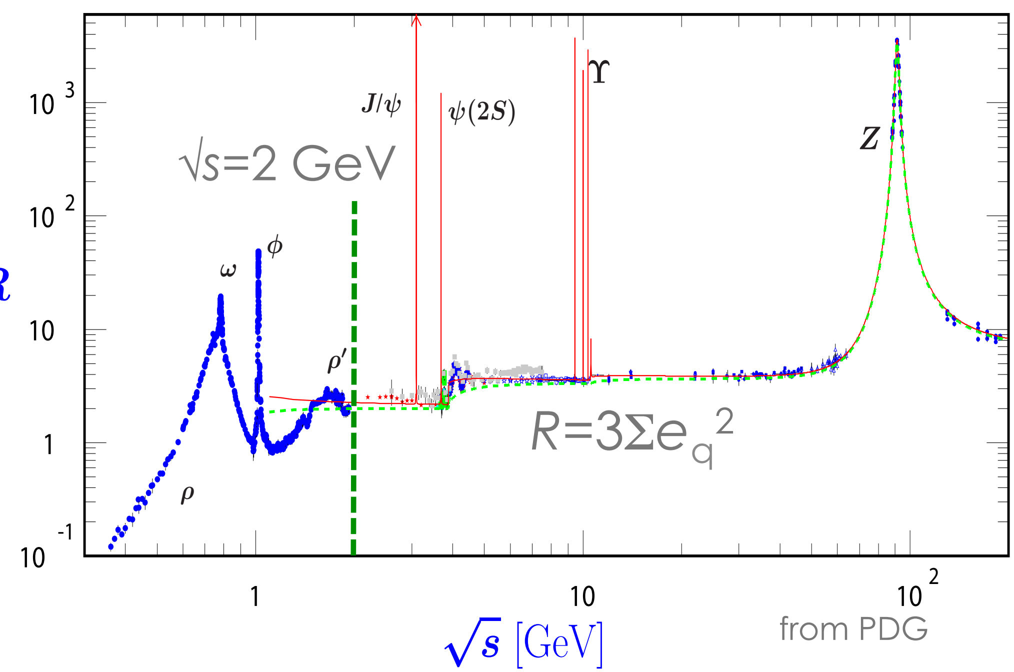
can be neglected at $M_\mu^2/s \ll 1$

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

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)



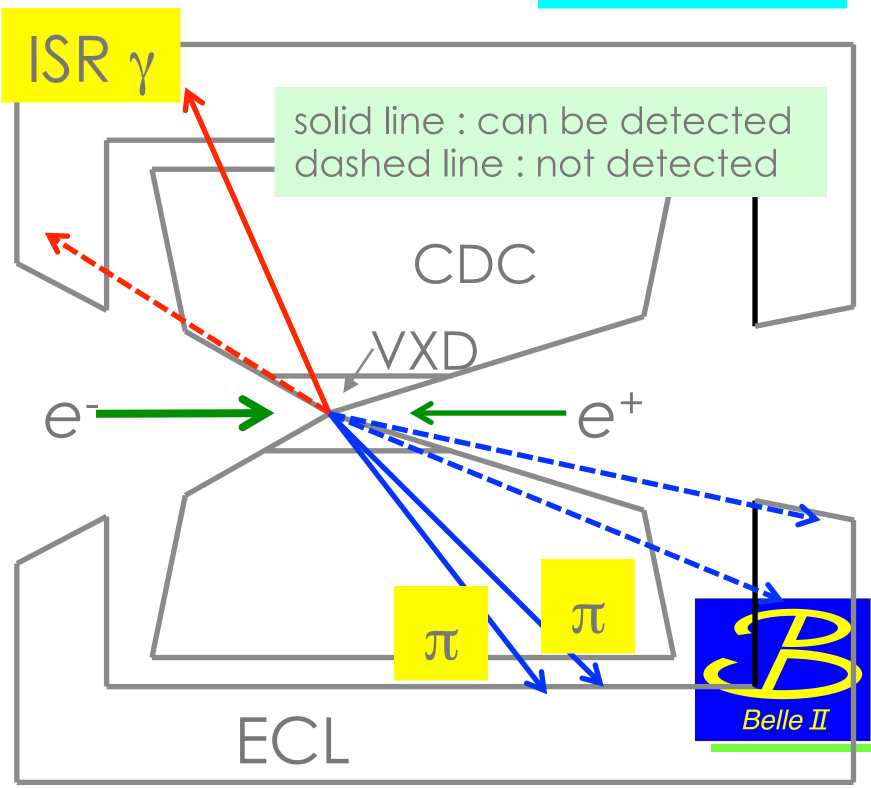
from PDG

syst. error table
in the BaBar result
PRD86 032013

Sources
Trigger/filter
Tracking
π-ID
Background
Acceptance
Kinematic fit (χ^2)
Correl. $\mu\mu$ ID loss
$\pi\pi/\mu\mu$ non-cancel.
Unfolding
ISR luminosity
Sum (cross section)

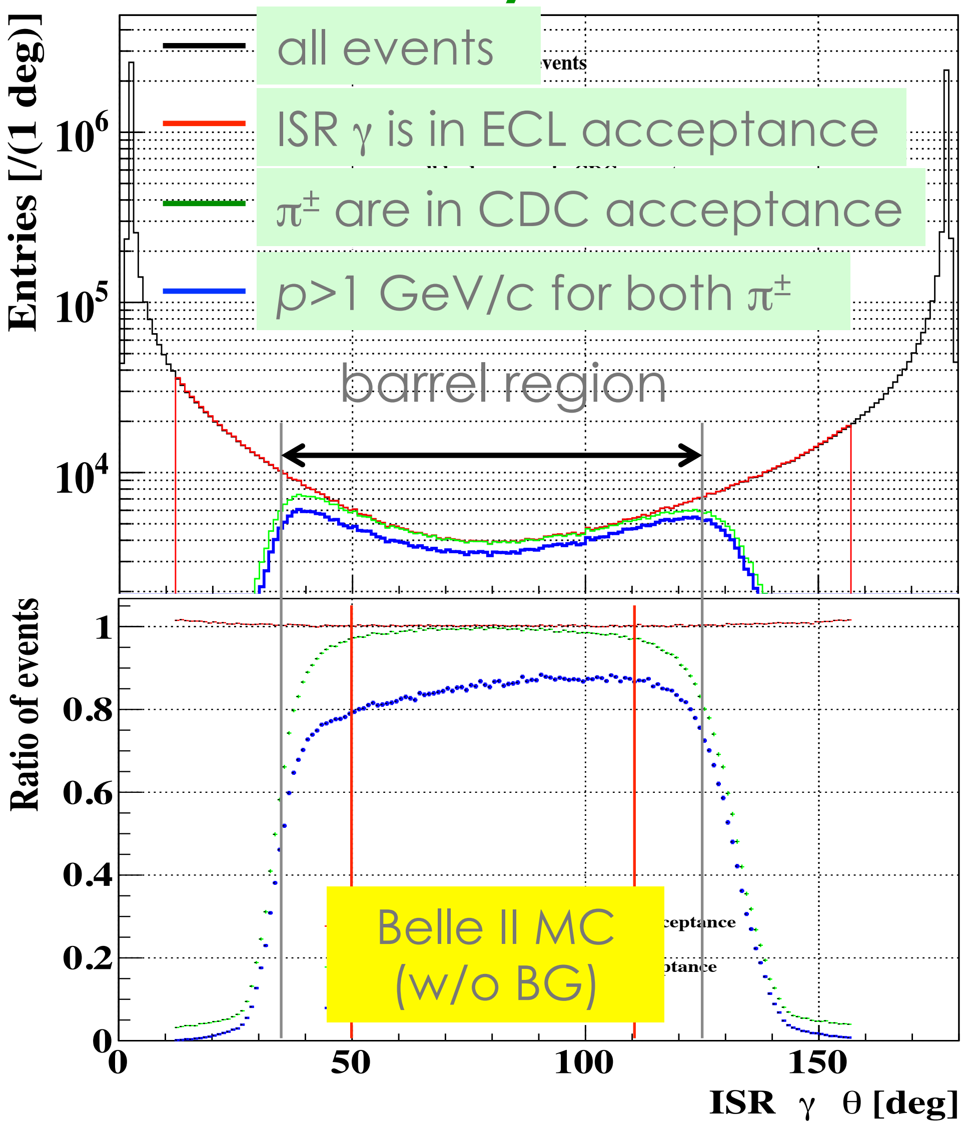
detection eff. study

- reduction of systematic errors is crucial →need to understand each efficiency within 0.5%
- important to keep high efficiency
  - geometrical acceptance
  - trigger efficiency
  - reconstruction efficiency
  - cut efficiency
    - momentum threshold
    - PID cut
    - ...
  - background / unfolding / normalization...



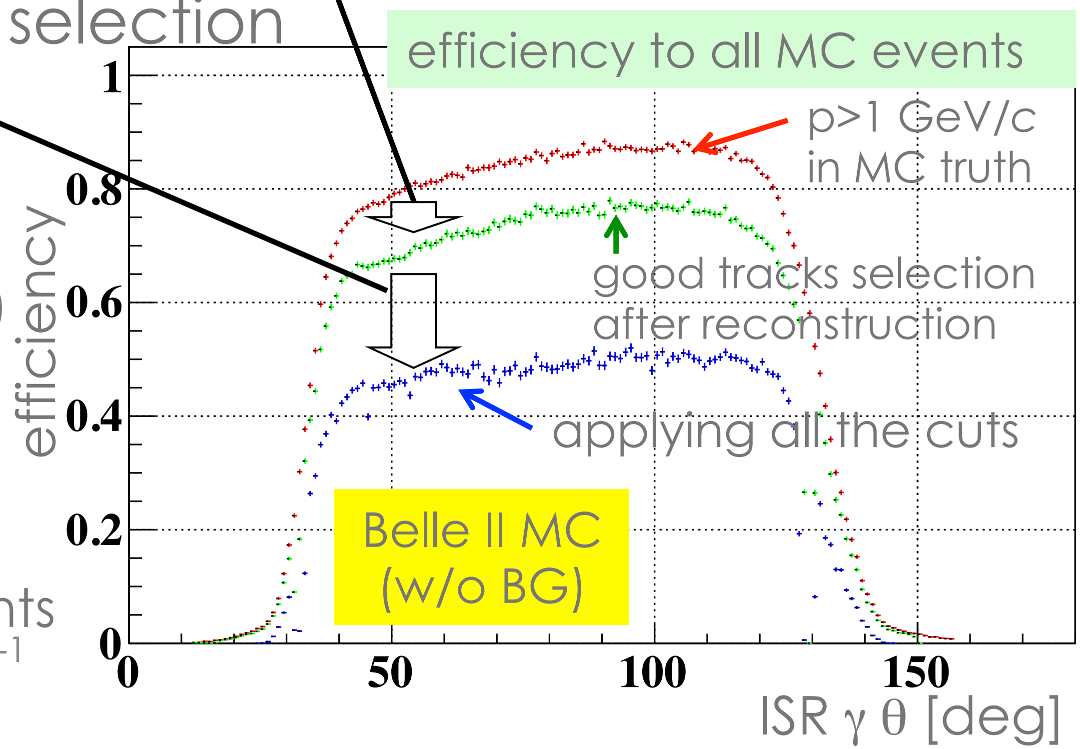
acceptance study

- 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

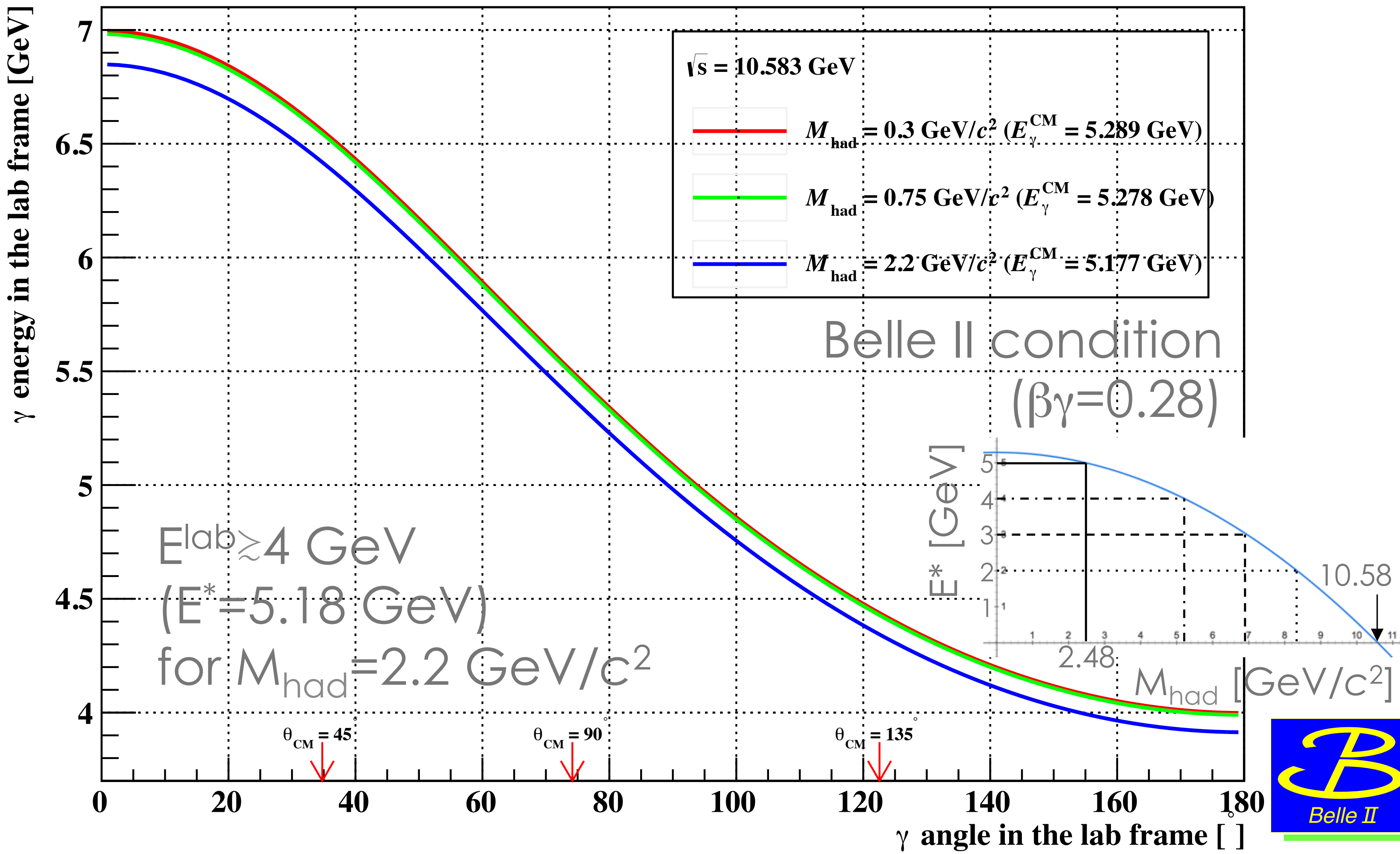


efficiency for each selection

- reconstruction efficiency
  - ~10% loss, due to γ conversion / π interaction
  - "good track" selection (fit quality, distance from the interaction point,…)
- efficiency of event selection cuts (tentative)
  - $10<E^{*}_{\pi\pi\gamma}<11$ GeV, $P^{*}_{\pi\pi\gamma}<0.5$ GeV/c
    - no other extra particles (add. ISR, …)
  - PID cut
- total eff. : 49% (to all MC generated events)
  - $50^{\circ}<\theta_{ISR}<110^{\circ}$
  - statistics : >1 M events / 500 fb^{-1}

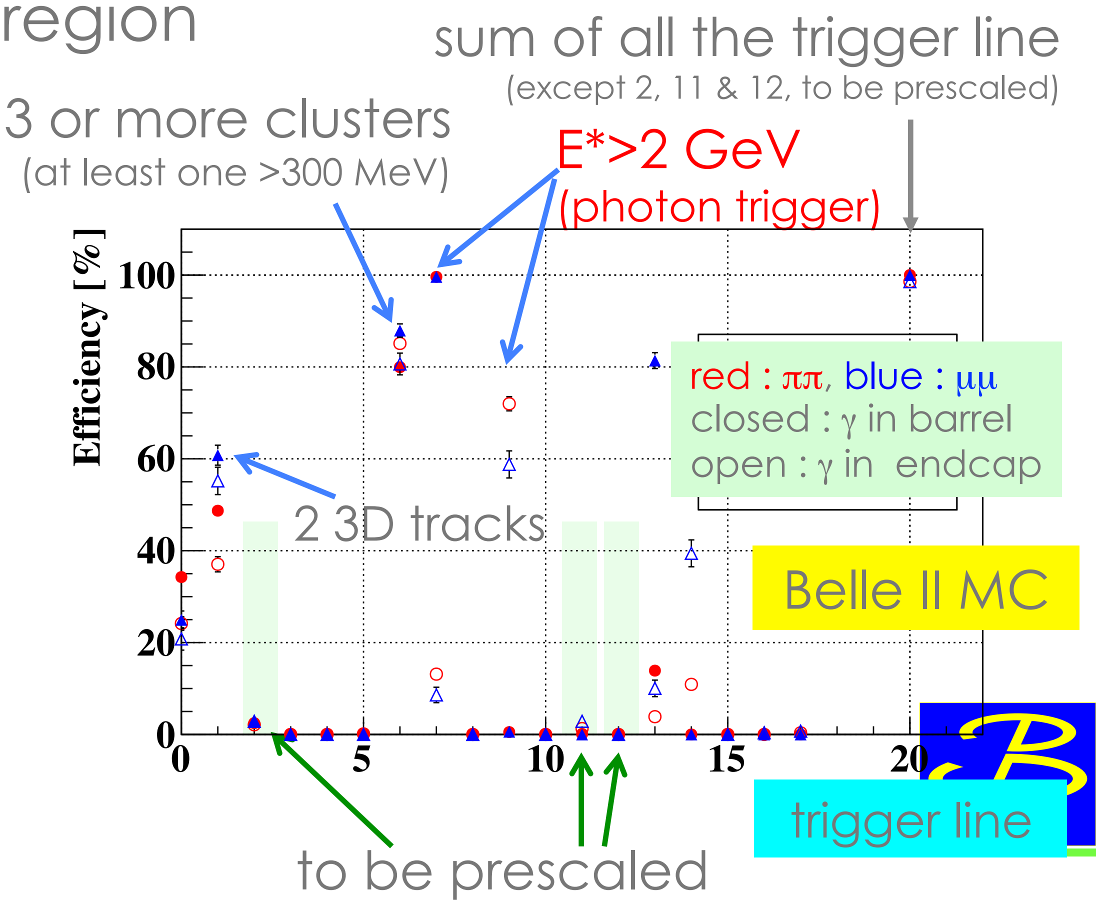


ISR γ energy in lab frame



trigger simulation

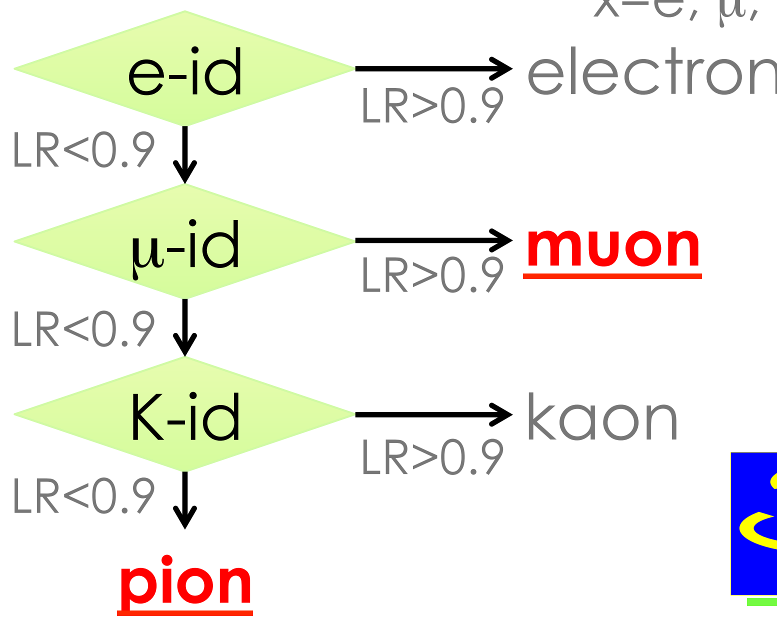
- 100% efficiency for good events with ISR γ pointing the barrel region
  - Bhabha veto is considered
  - some loss (O(%)) for endcap, as designed (but these events are not used as discussed later)
- photon trigger is working effectively as expected



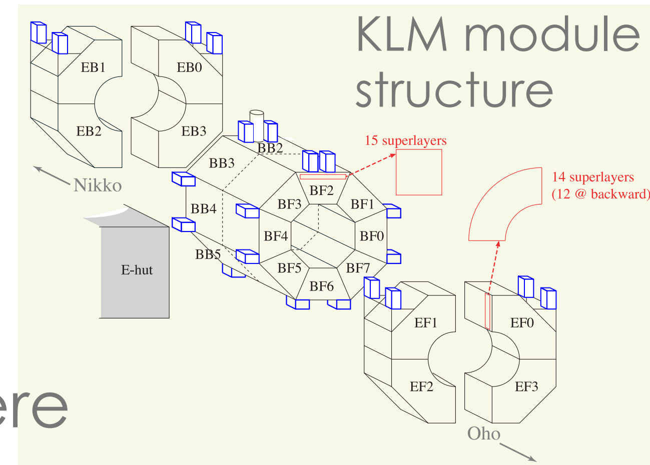
PID algorithm

- 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

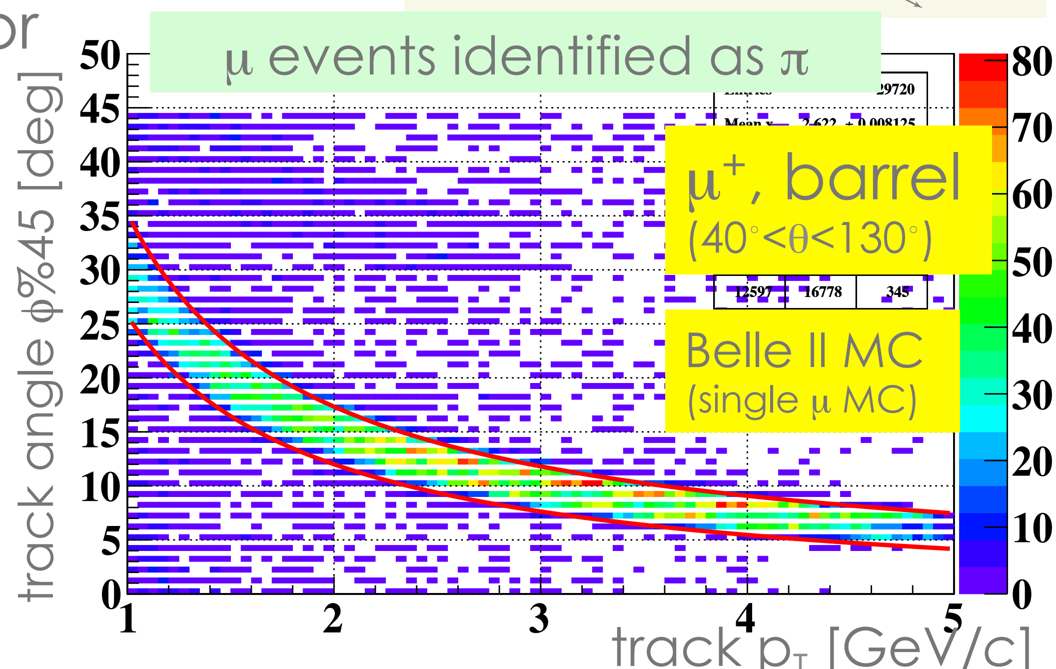
likelihood ratio (LR) = $L_x/(L_x+L_\pi)$
x=e, μ, K



muon/pion separation

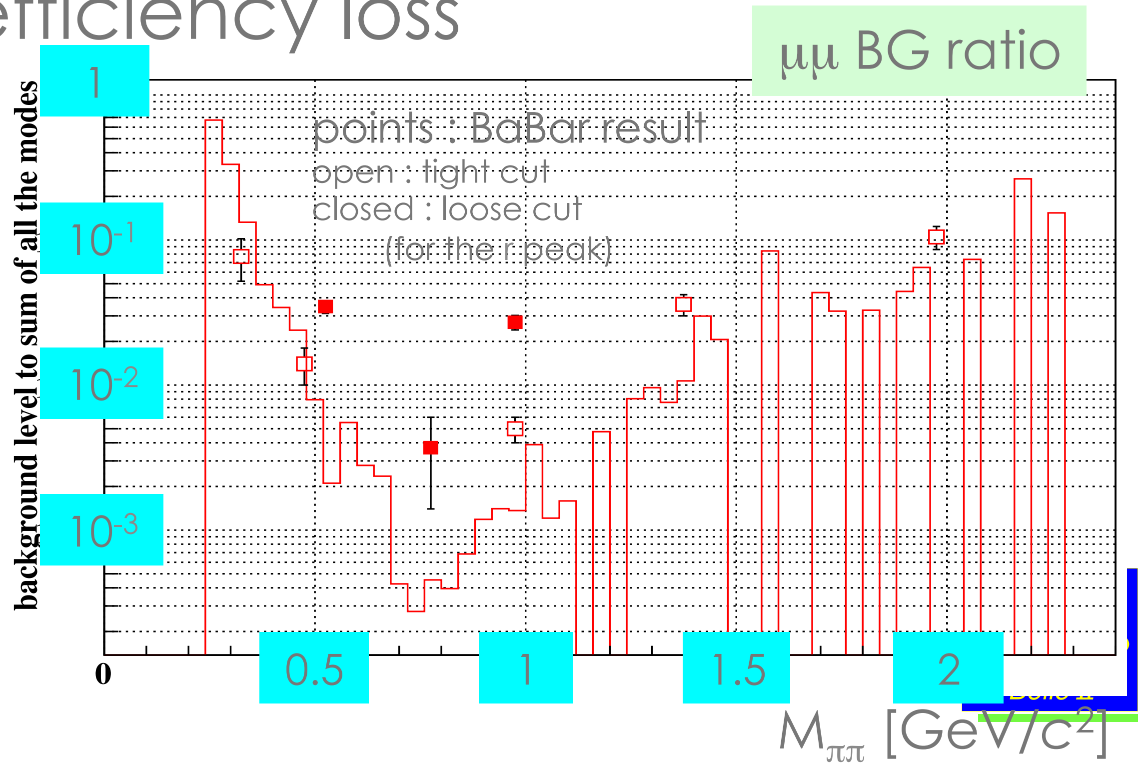


- mis-identified muons tend to be recognized as pions
  →μ-id ineff. = fake π
- avoiding KLM module gaps, where μ-id efficiency is poor
  - visible in p_T-ϕ plane
  - set veto regions (for barrel/endcap, positive/negative μ)
  - require at least one track to be outside of the veto regions



$\mu\mu$ BG in $\pi\pi$ analysis

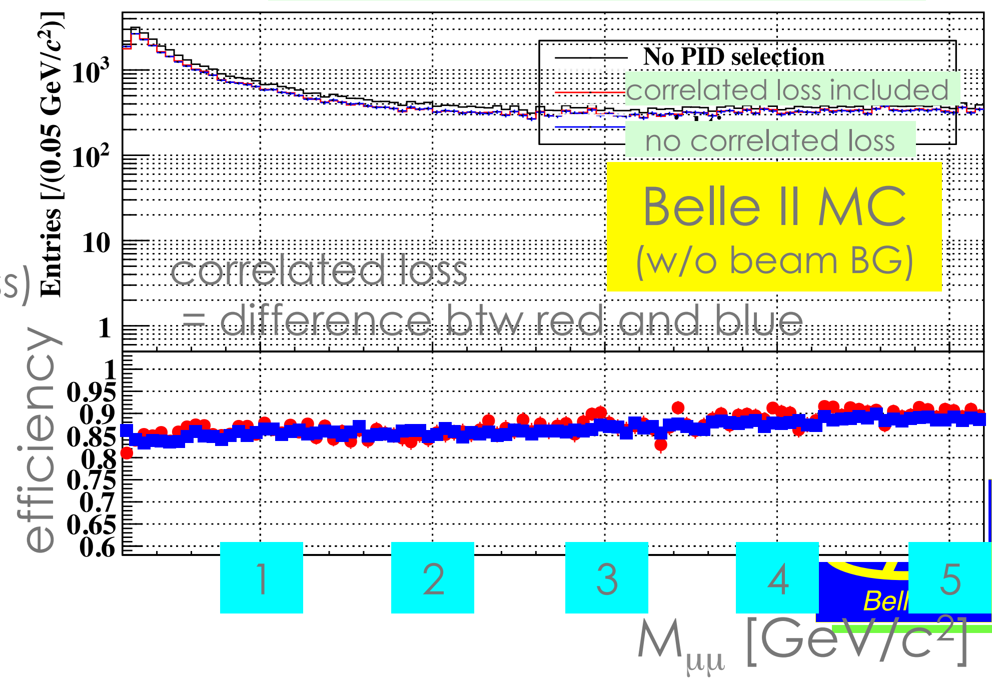
- reduction by a factor of 5
  by introduction of KLM module gap veto
- 9% additional efficiency loss
- the same level
  with BaBar



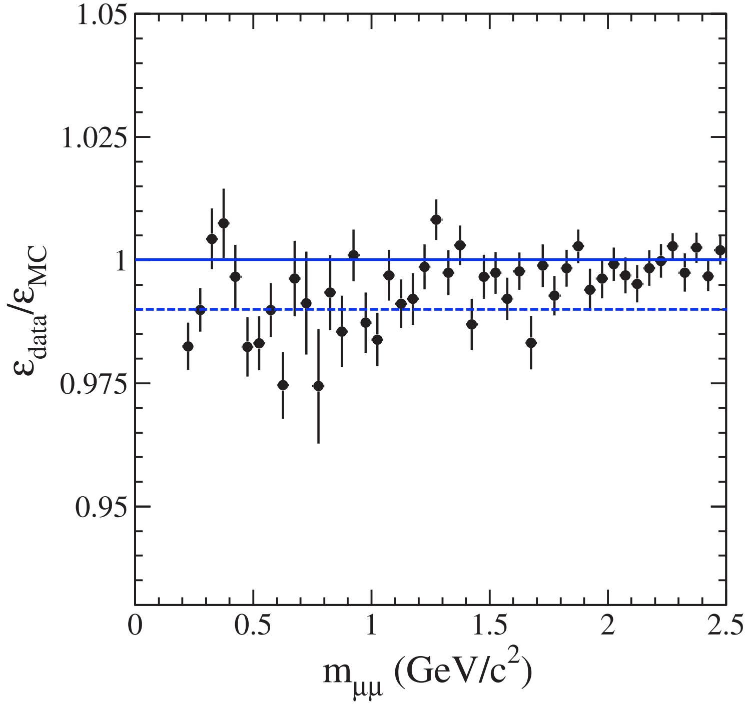
correlated loss of PID eff.

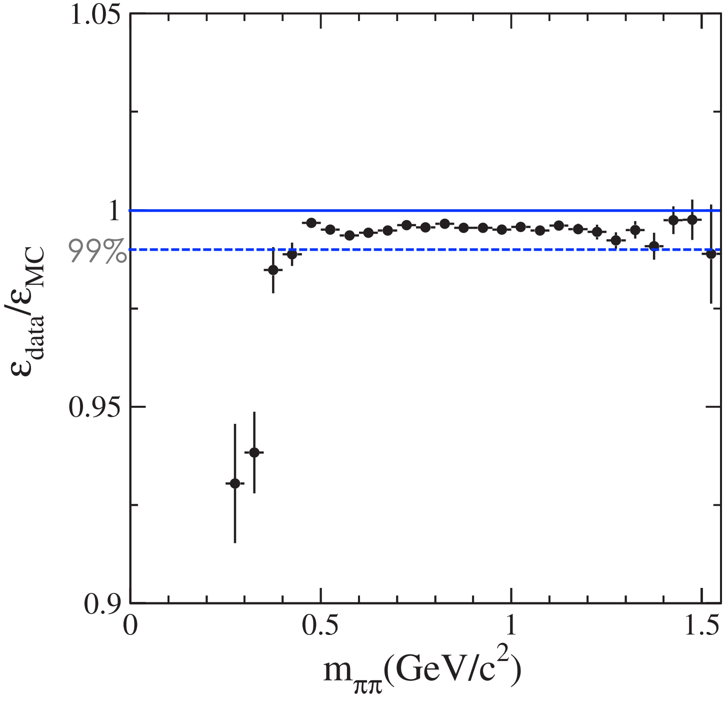
- additional efficiency loss can exist due to two tracks close to each other
- compare two efficiencies
  - μ-id for both tracks (including correlated loss)
  - product of μ-id efficiency, which was taken from single μ MC (do not include correlated loss)
- significant correlated efficiency loss was not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

ee→μμγ simulation



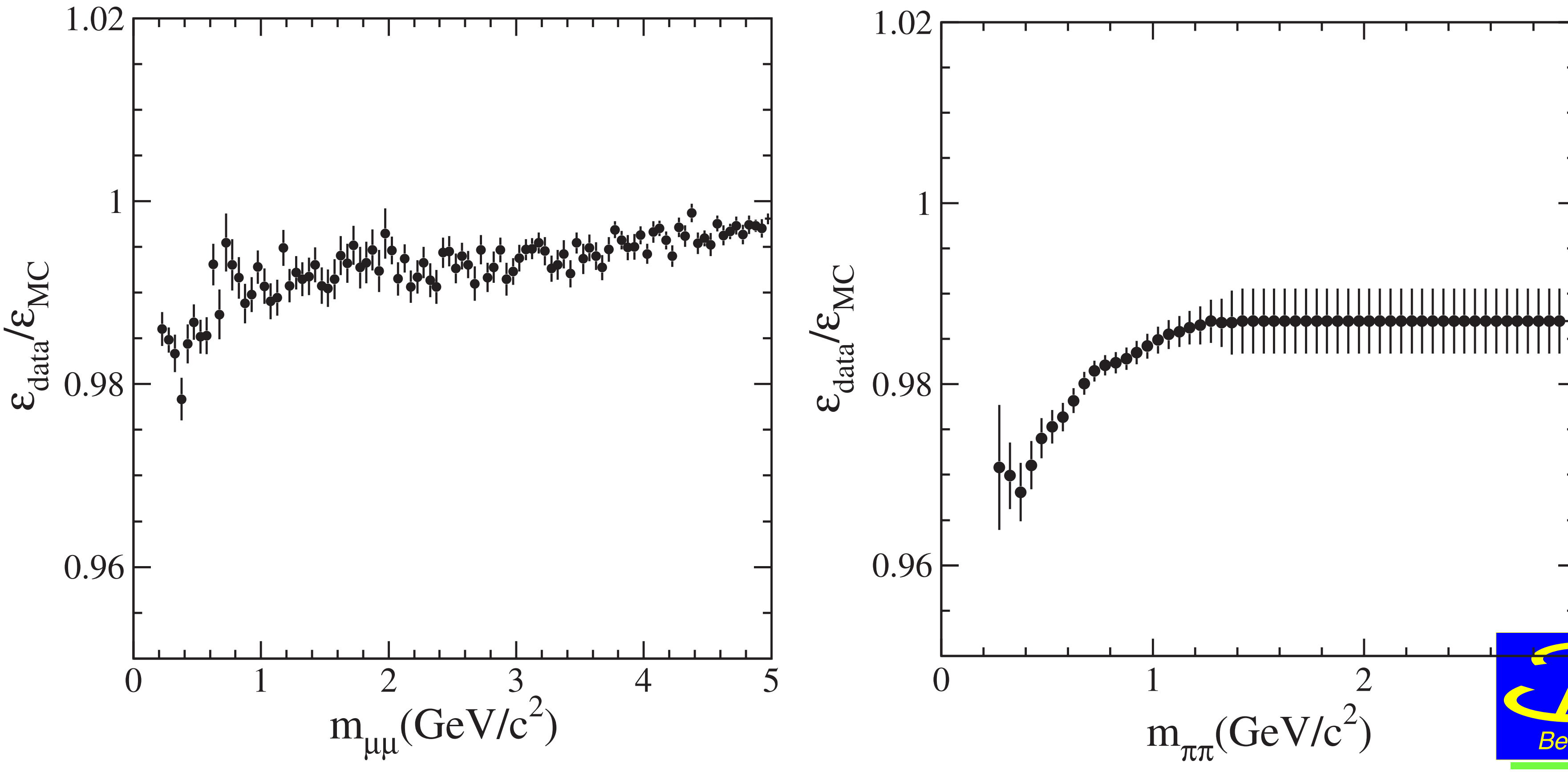
BaBar trigger/filter eff. correction





Belle II

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

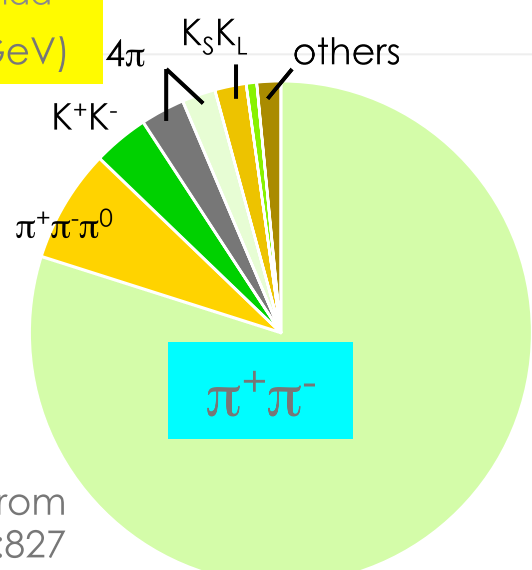
light hadron production

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

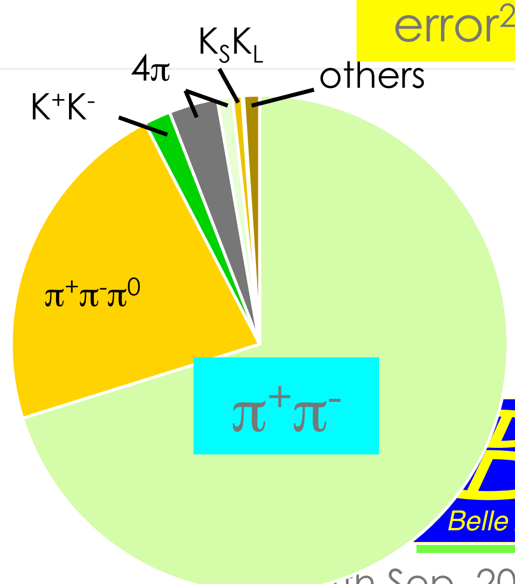
$$a_\mu^{(4)}(\text{vap, had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \left(\int_{m_{\pi^0}^2}^{E_{\text{cut}}^2} ds \frac{R_{\text{had}}^{\text{data}}(s)\,\hat{K}(s)}{s^2} + \int_{E_{\text{cut}}^2}^{\infty} ds \frac{R_{\text{had}}^{\text{pQCD}}(s)\,\hat{K}(s)}{s^2}\right)$$

$K(s)$: Kernel function

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

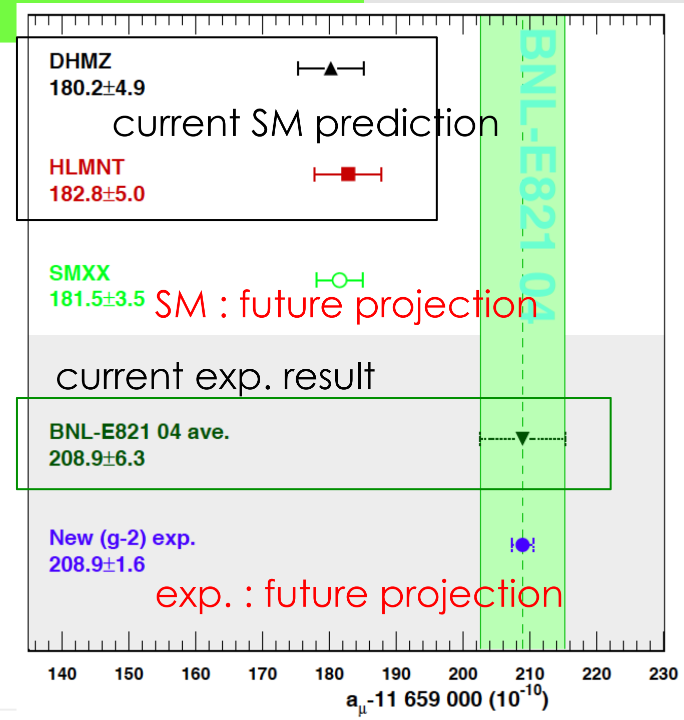


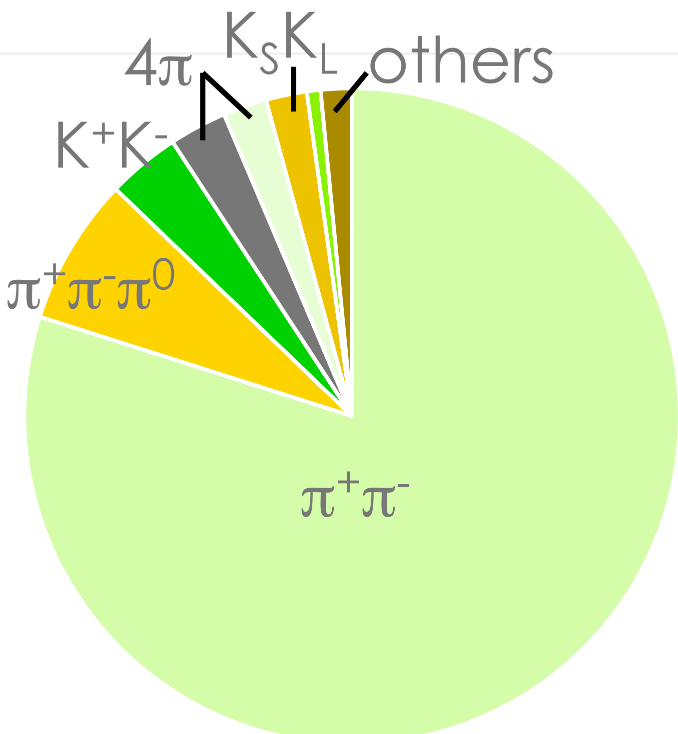
error^2

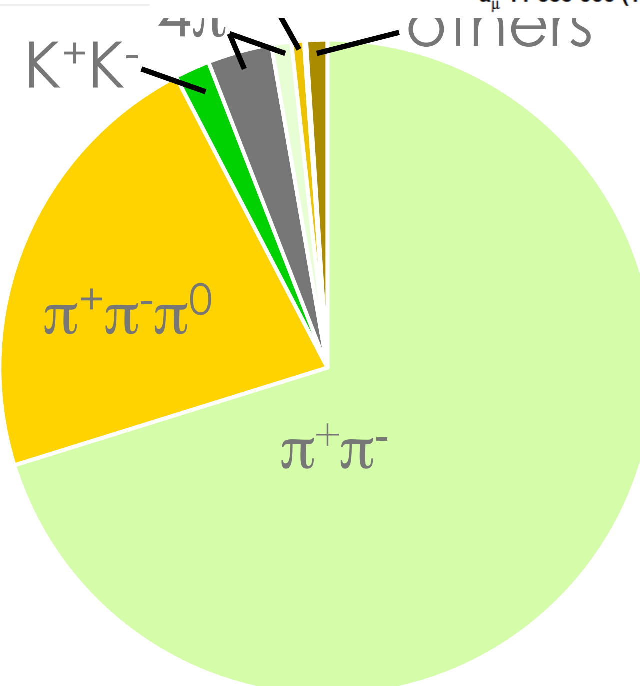


- ππ mode gives dominant contribution ($\sqrt{s}$<1.8 GeV)

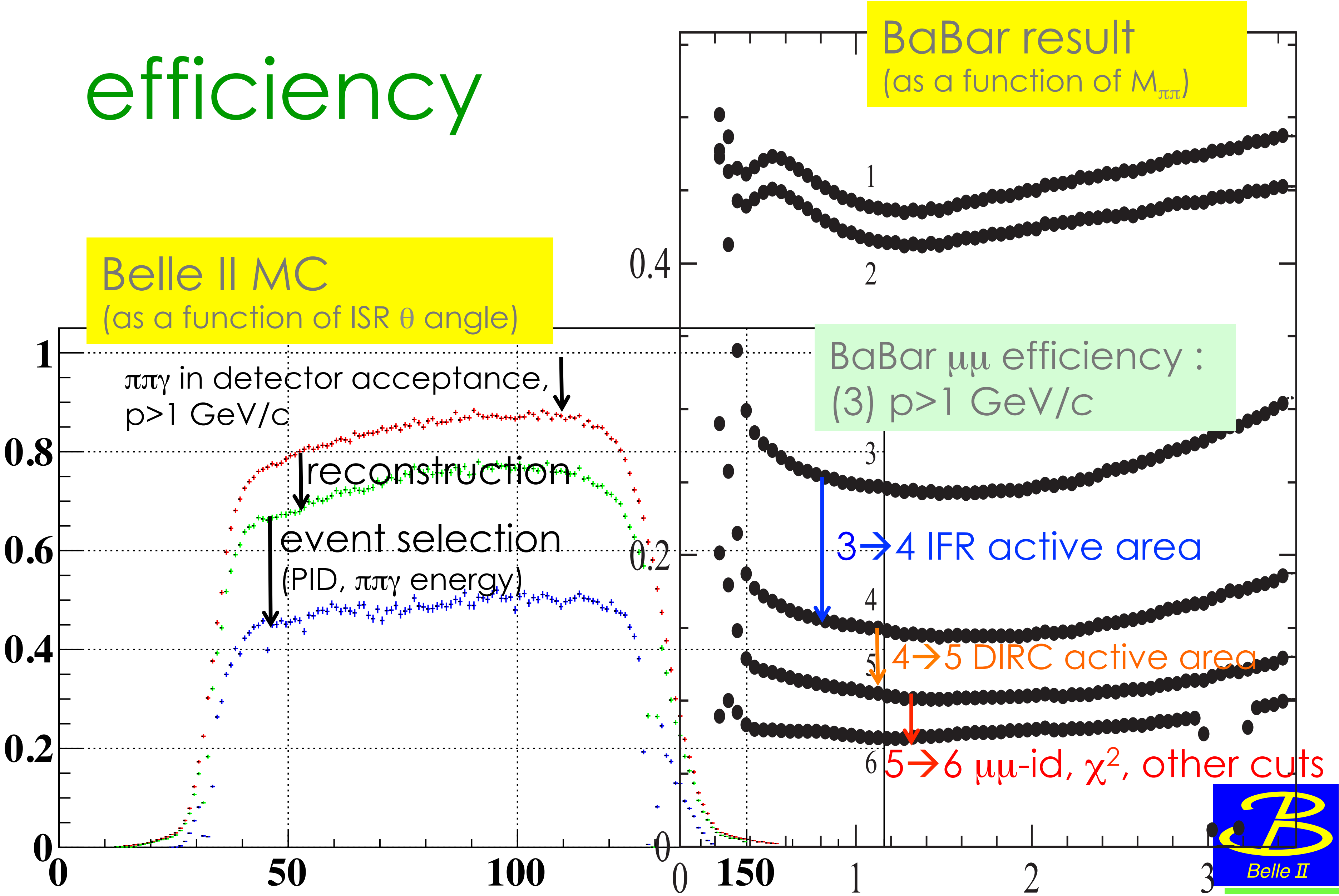
values are taken from Eur. Phys. J. C (2017) 77:827


DHMZ
180.2±4.9
current SM prediction
HLMNT
182.8±5.0
SMXX
181.5±3.5
SM : future projection
BNL-E821 04
current exp. result
BNL-E821 04 ave.
208.9±6.3
New (g-2) exp.
208.9±1.6
exp. : future projection
140 150 160 170 180 190 200 210 220 230
a_μ-11 659 000 (10^{-10})


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


K^+K^-
$\pi^+\pi^-\pi^0$
$\pi^+\pi^-$

efficiency

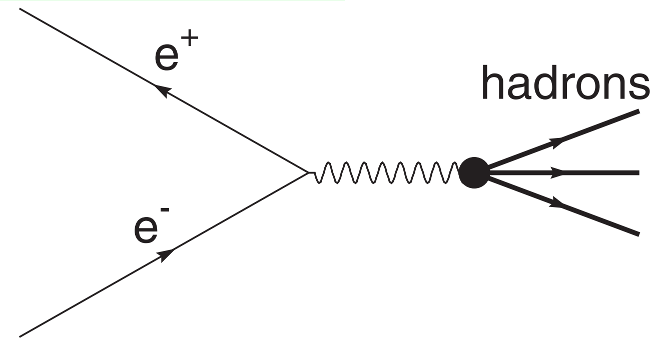

Belle II MC
(as a function of ISR θ angle)
ππγ in detector acceptance, p>1 GeV/c
reconstruction
event selection
(PID, ππγ energy)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
BaBar result
(as a function of $M_{\pi\pi}$)
BaBar μμ efficiency :
(3) p>1 GeV/c
3→4 IFR active area
4→5 DIRC active area
5→6 μμ-id, χ^2,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

R measurement

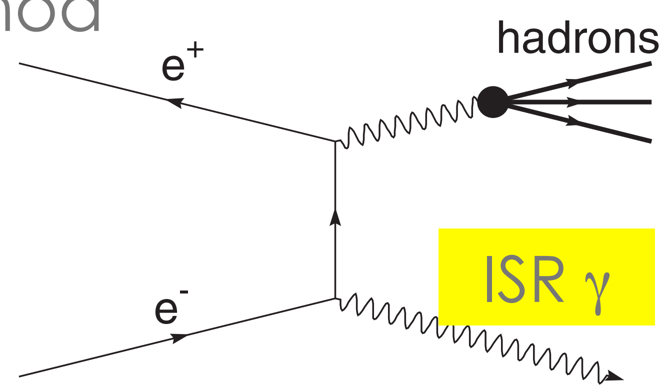
$$a_\mu^{\mathrm{had;LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

R(s): need *s* dependence

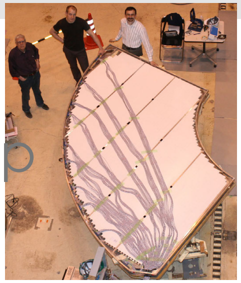
- scan method
  - ☺large statistics
  - ☹limited energy range
  - ☹point-to-point errors
  - being performed in Novosibirsk



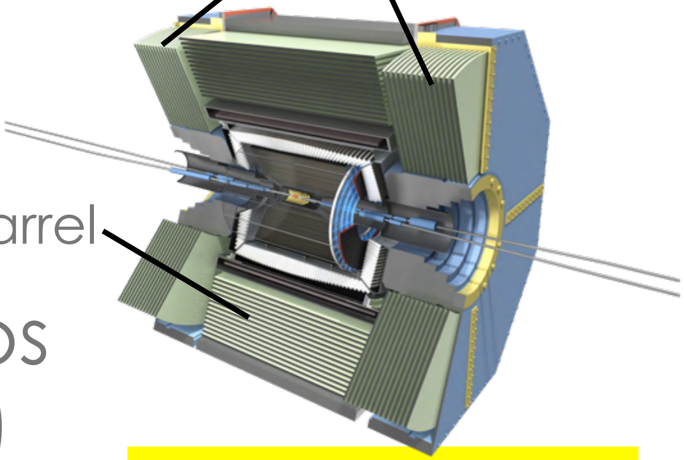
- Initial State Radiation (ISR) method (colliders with fixed energy)
  - tag ISR photon (E>3 GeV)
  - ☺can scan wide energy range
  - ☺same exp’tal condition
  - ☹lower statistics due to ISR $O(\alpha)$
    ←can be compensated by high luminosity
  - performed by BaBar / BES / KLOE



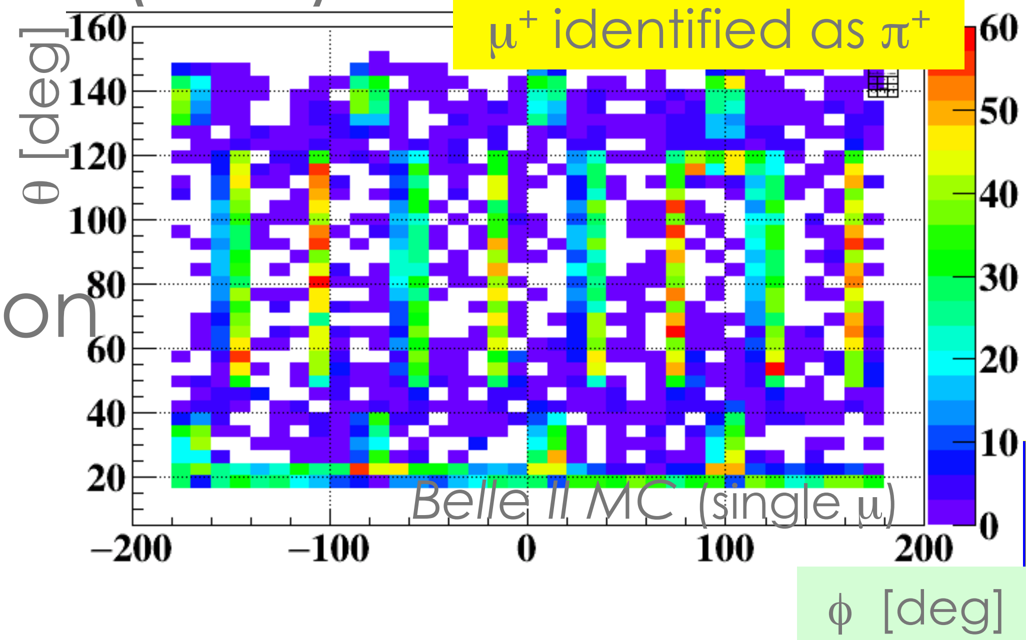
Belle II



KLM gap effect

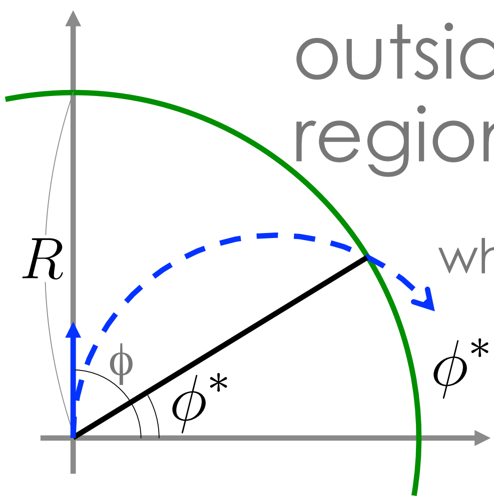


- muon ID inefficiency → fake π
- derived from module gaps of the K_L-μ detector (KLM)
  - also very forward region ($\theta<25°$), not covered by KLM
- Avoiding this region helps to reduce $\mu\mu \to \pi\pi$ bkg



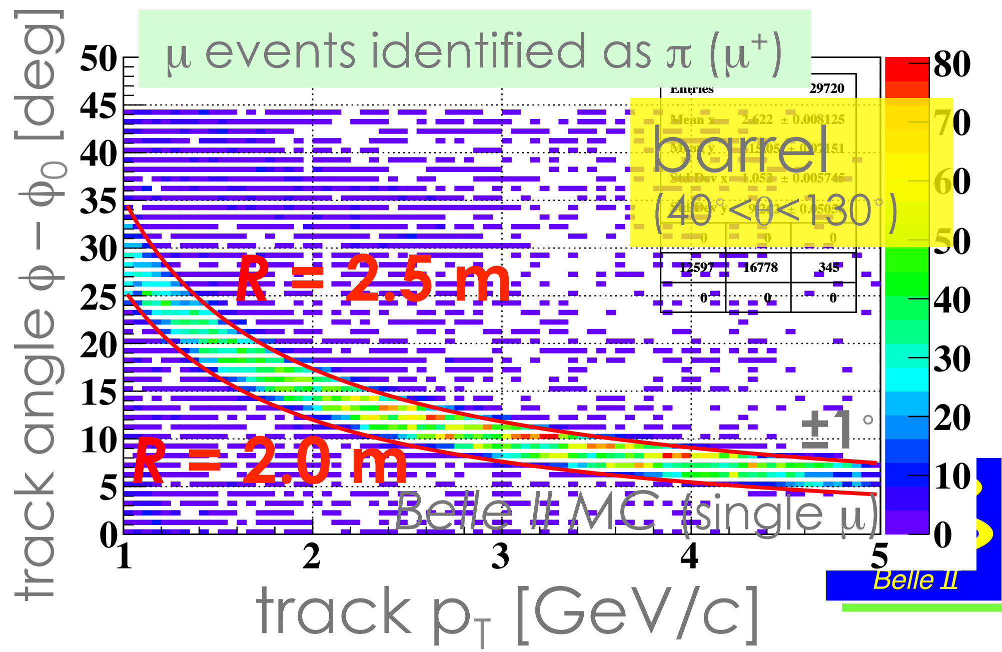
KLM-gap veto cut

- 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



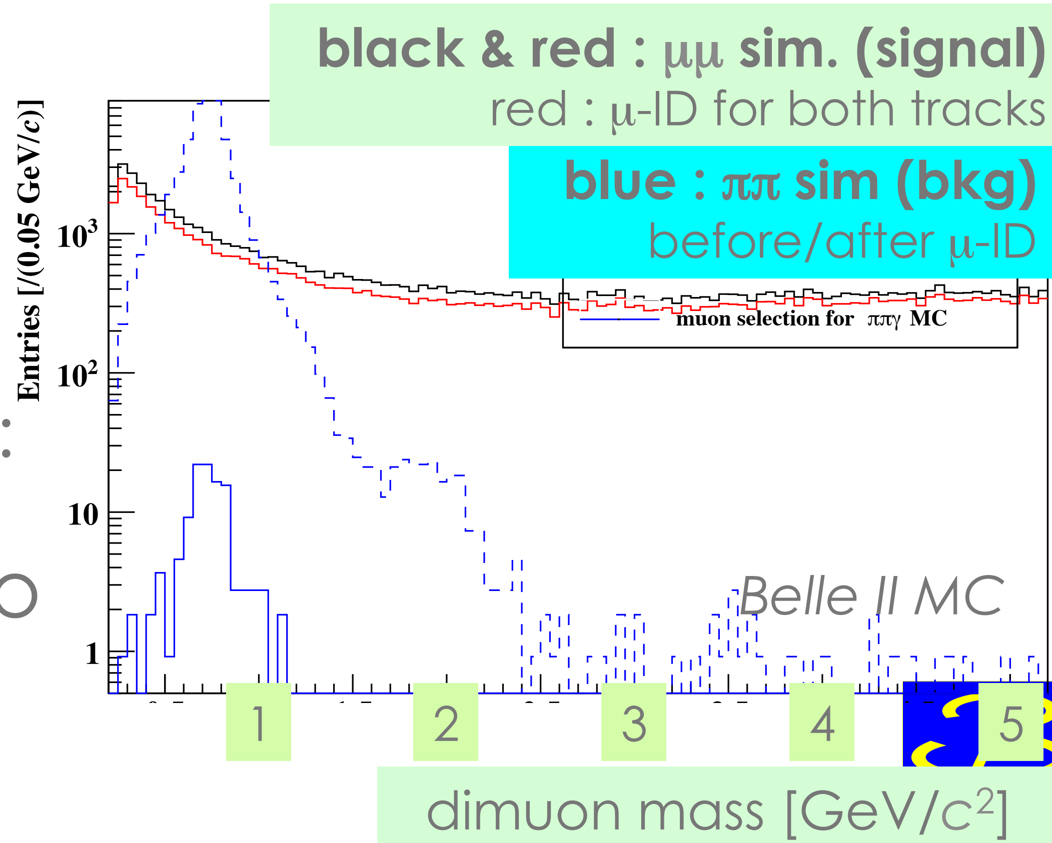
when track ϕ=90°

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



PID performance – μμ mode

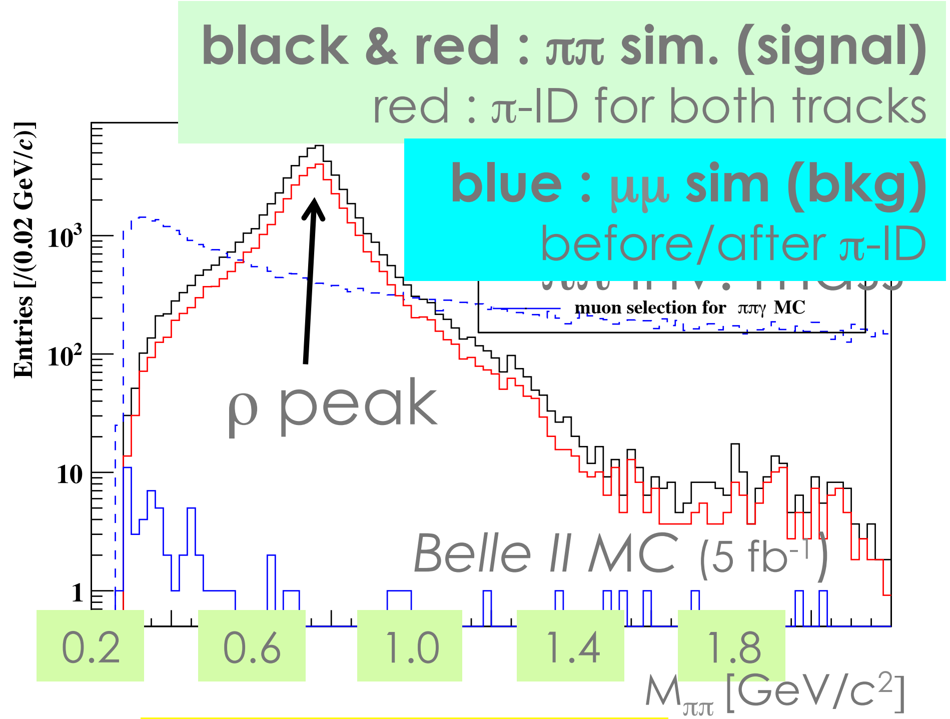
- μμ/ππ modes can be background for each other
- MC stat. : ~5 fb^{-1} equiv.
- μμ-ID eff.
  - ~80%
  - loss by veto cut: 5%
- ππ→μμ bkg. ratio
  - ~0.4% ($M_{\mu\mu}$<1 GeV/c^2)

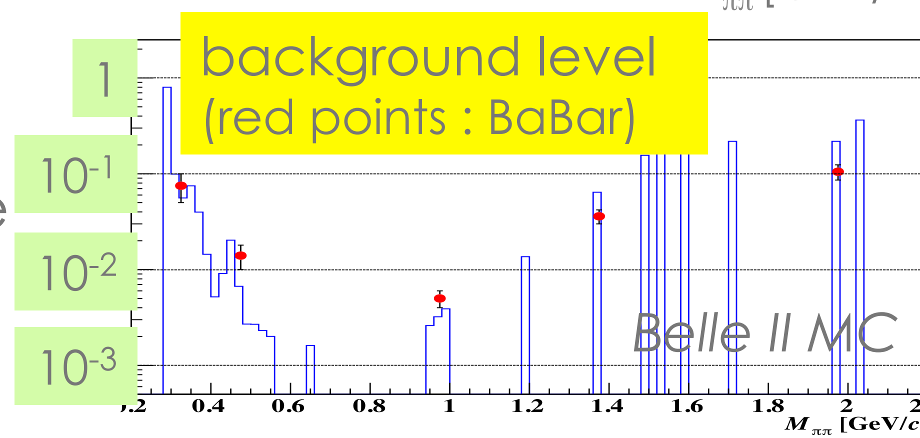


PID performance – ππ mode

- 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

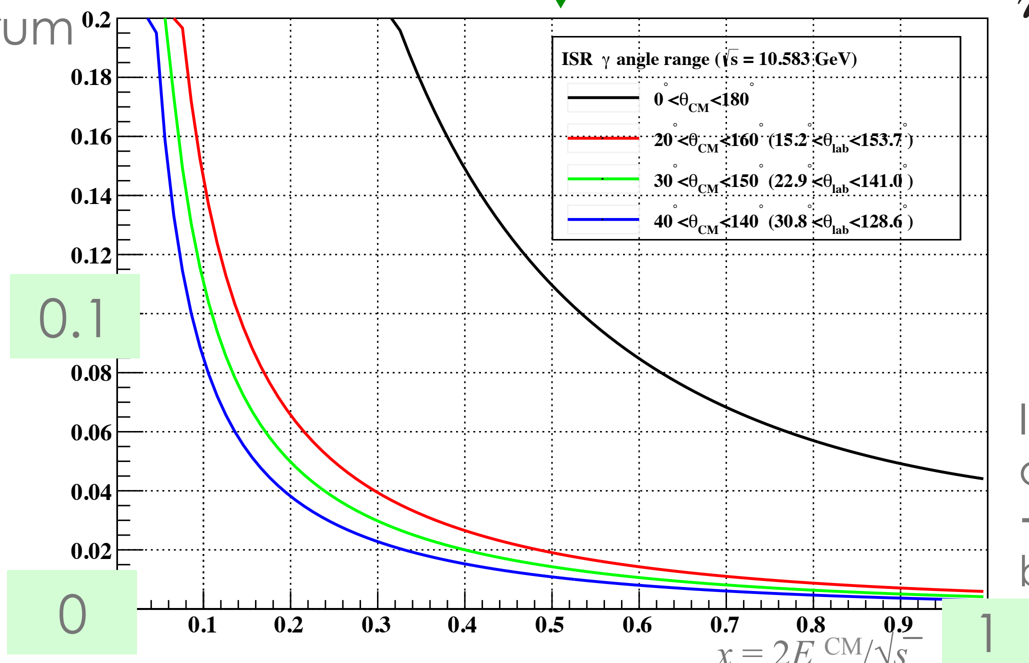
- probability to emit ISR γ to produce a particle system (X) with mass of m

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

observed spectrum

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

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



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

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

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

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

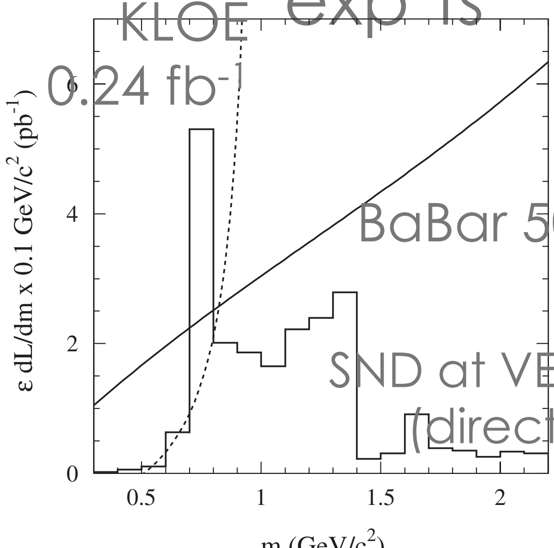
Belle II

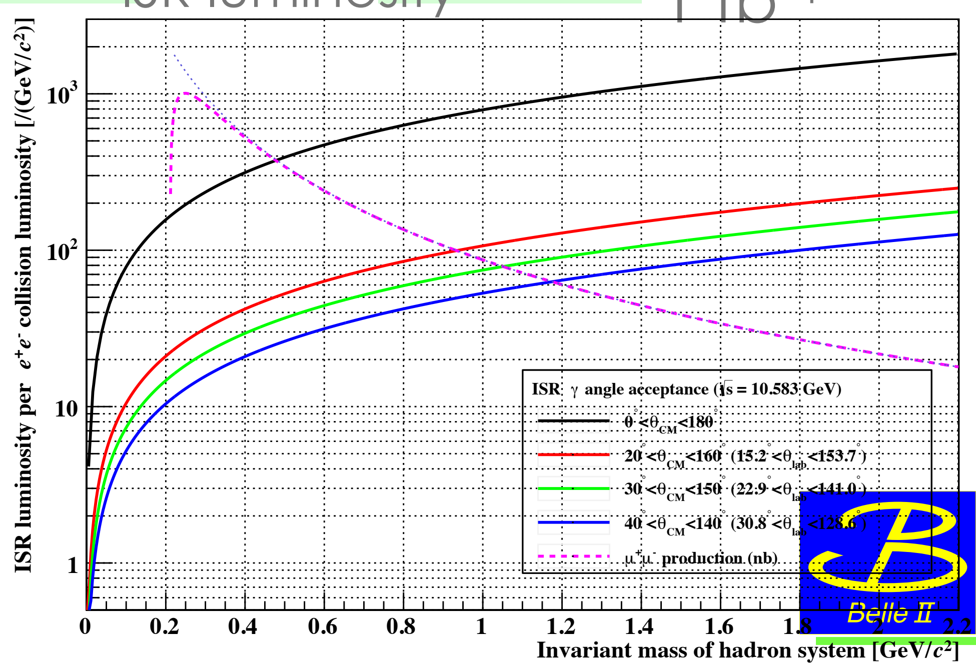
ISR luminosity

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

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

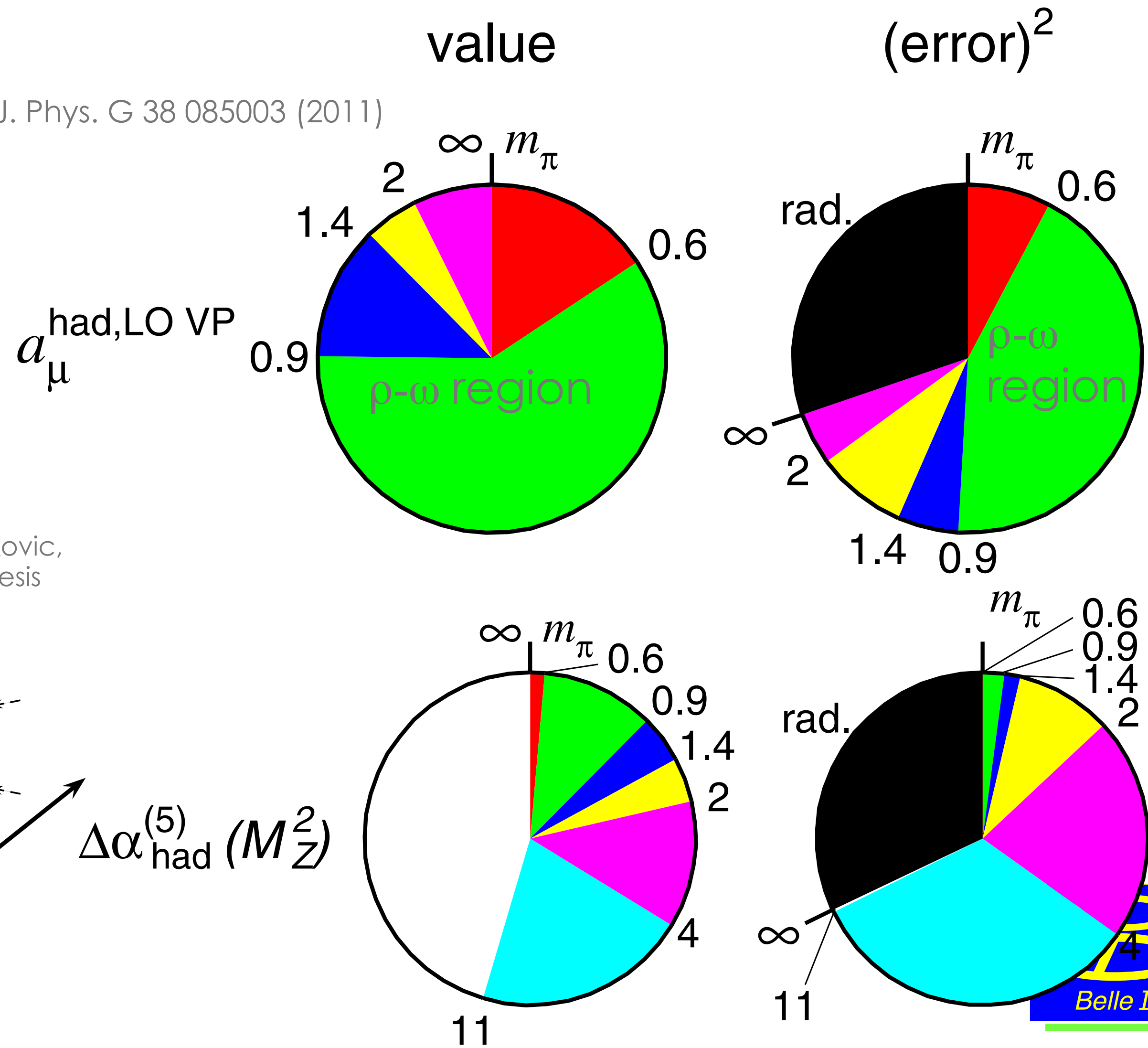
- can be compared with direct scan exp'ts



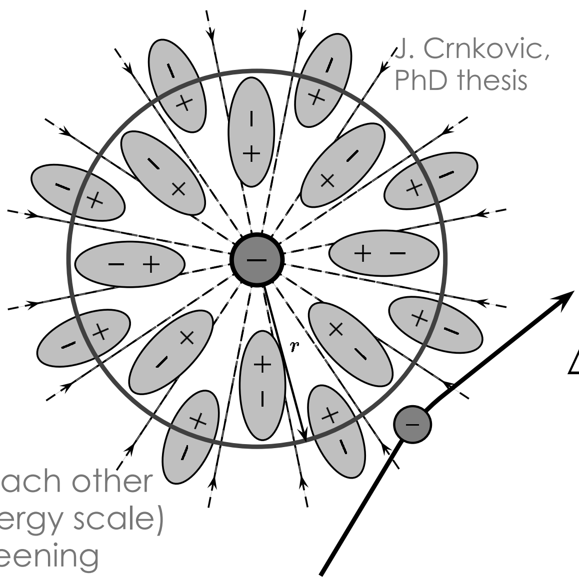


contribution of HVP

J. Phys. G 38 085003 (2011)



"charge screening"



J. Crnkovic, PhD thesis

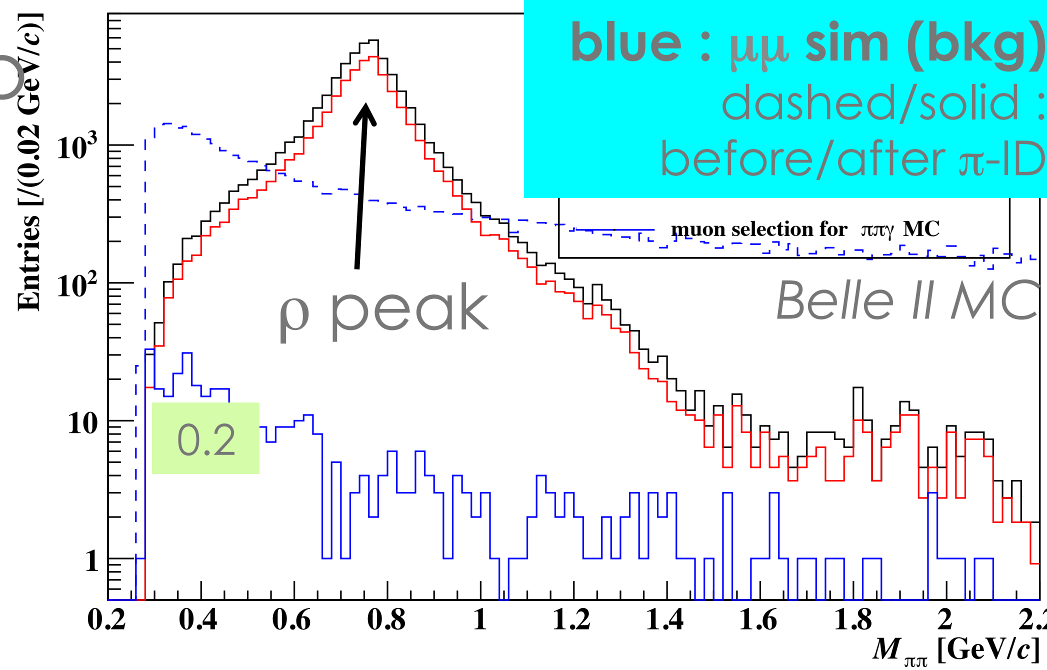
closer to each other
(= high energy scale)
→ less screening
→ stronger interaction

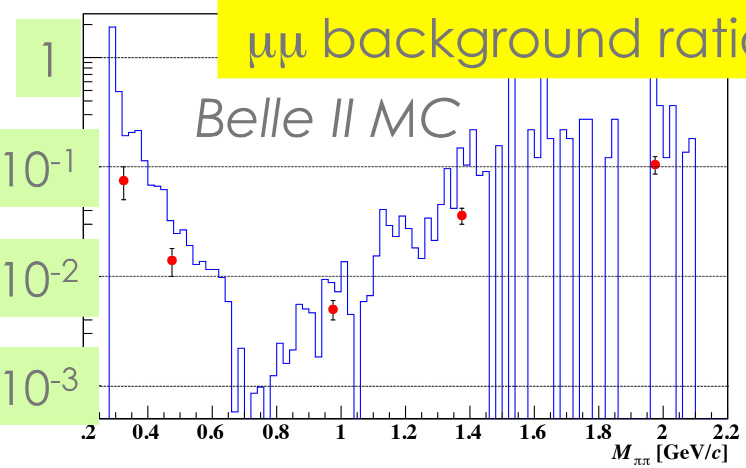
without veto cuts ($\pi\pi$)

- $\pi\pi$ efficiency ~ 75%
- $\mu\mu \rightarrow \pi\pi$ bkg. ratio ~ 0.85%
- comparison with BaBar ana. (PRD86 032013)

black & red : $\pi\pi$ sim. (signal)
red : π-ID for both tracks

blue : $\mu\mu$ sim (bkg)
dashed/solid : before/after π-ID





red points : BaBar analysis
slightly worse in this analysis

Belle II

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%

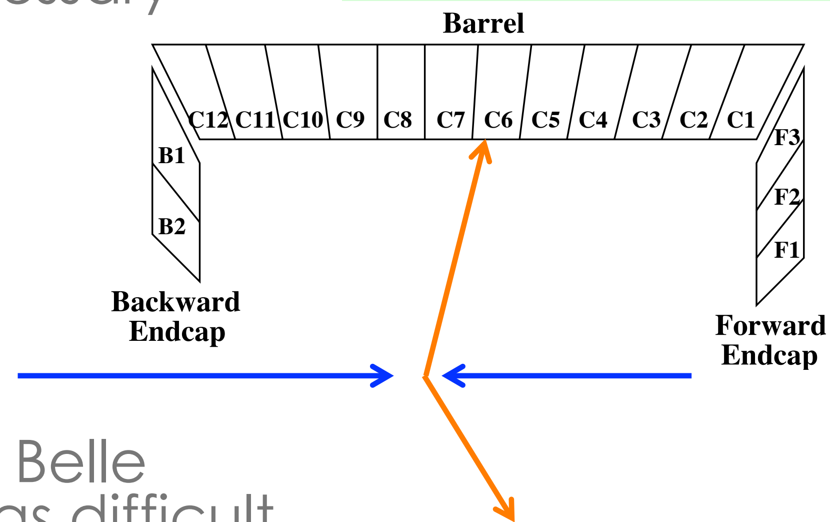
$M<1$ GeV/c^2

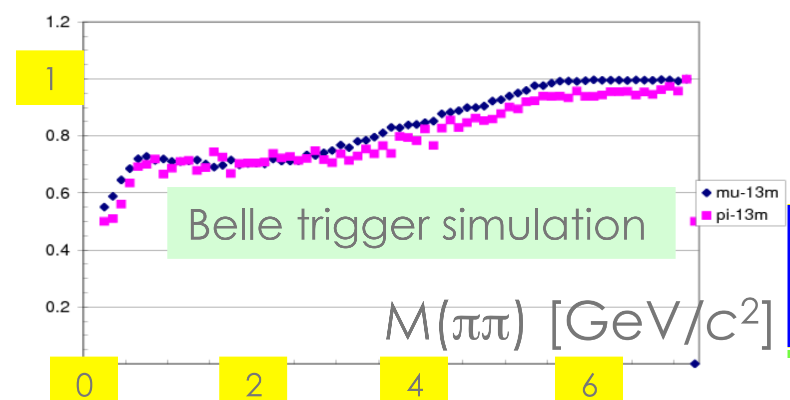
- tight cut (require both tracks to be outside the veto regions) loses efficiency, while background reduction is not so large

trigger efficiency for $\pi\pi\gamma$

- high trigger efficiency is necessary for precision measurement
- Belle II trigger for ee→$\pi\pi\gamma$
  - total calorimeter energy > 1 GeV
  - Bhabha veto ←loss of this veto must be small
- large loss by Bhabha veto in Belle →precision measurement was difficult
- Bhabha veto logic in Belle II
  - *2D Bhabha veto*: rely only on θ information
  - *3D Bhabha veto*: include ϕ information

Belle-type Bhabha veto





trigger efficiency study

- All the Bhabha events were recorded in phase2 data due to low luminosity
  - no loss of events by Bhabha veto
  - can evaluate expected loss directly

$$\text{loss} = \frac{\text{\# of events triggered by Bhabha trigger}}{\text{\# of all events}}$$

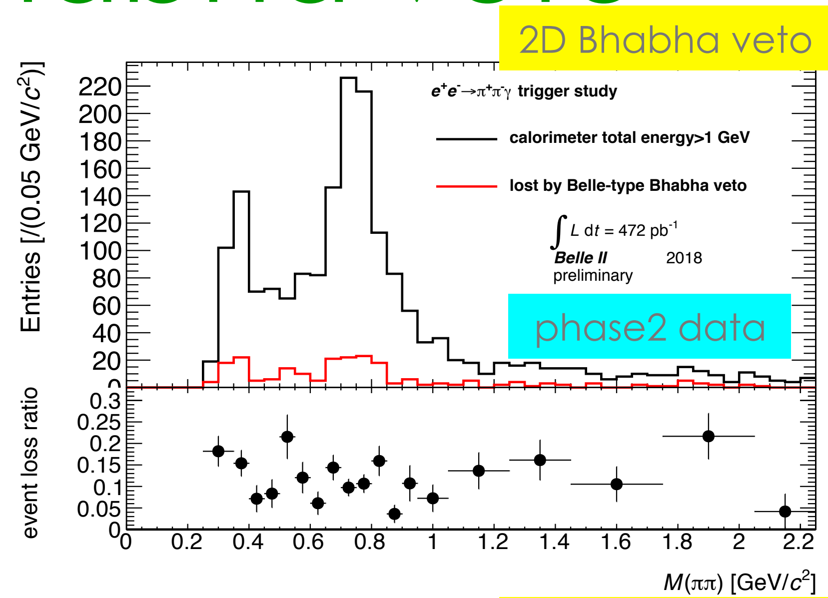
↑

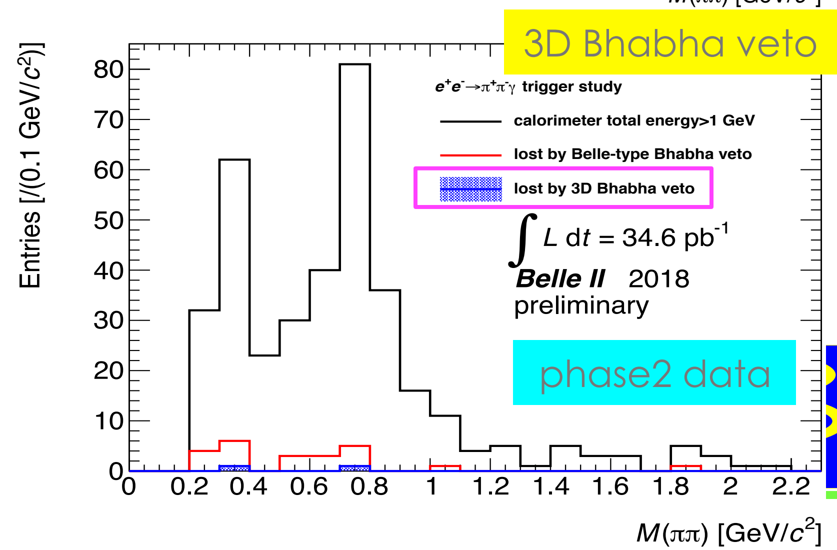
standard calorimeter trigger (total E>1 GeV && !2D-Bhabha)
OR
2D-Bhabha trigger

event loss by Bhabha veto

- 2D Bhabha
  - **(12.3±0.8$_{stat}$)%** (M(ππ)<2 GeV/c^2)
  - significantly large
- 3D Bhabha
  - available only for the last short period
  - loosen γ angle cut to increase statistics [50°,110°]→[17°,128°]
  - 2 events / 360 events **(0.6±0.4$_{stat}$)%**
  - much smaller loss

→can use the 3D Bhabha veto logic instead of the Belle-type Bhabha veto





current situation of e g-2

PRL100, 120801

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

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

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

PRL109, 111807

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

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

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

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

1.5 ppb

- weak

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

Belle II

current situation of μ g-2

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

- measurement : (BNL E821)
- theory
  - QED

8th and 10th order of QED calculation

lepton mass

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)

PRL109, 111808

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

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