# Measurement of Hadronic Vacuum Polarization contributions to muon (g-2) at Belle (II)


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# Motivations for precise hadronic cross section measurements

- Tests of perturbative QCD
  - QCD sum rules, quark masses, quark and gluon condensates
  - Higher order QCD corrections - $\Lambda_{QCD}$, $\alpha(s)$
- Hadronic corrections to fundamental parameters:
  - Running fine structure constant - $\alpha(M_Z^2)$
  - Anomalous magnetic moment of the muon
- measurement of parameters of light vector mesons ρ, ω, φ, ρ', ρ'', .....
- Search of and study of the exotic resonance states (X, Y, Z, ...)
- Study of the final states dynamics and test of theoretical models
- comparison with spectral functions of the hadronic tau decays via CVC
- Study of nucleon-antinucleon pair production – nucleon ectromagnetic form factors, search for NNbar resonances, ..

# Lepton dipole moments

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

Magnetic Dipole Moment

$$\vec{\mu} = g \left( \frac{q}{2m} \right) \vec{s}$$

Electric Dipole Moment

$$\vec{d} = \eta \left( \frac{q}{2mc} \right) \vec{s}$$

**An essential difference between $\mu$ and *d* is:**
**$\mu$ – is calculated and precisely measured while *d* ≈ 0.**

# Anomalous magnetic moments

| Particle | $a_l$ =(g-2)/2 | SM |
|---|---|---|
| e | 0.001 159 652 180 91 (26) | 0.001 159 652 181 64 (76) |
| μ | 0.001 165 920 89 (64) | 0.001 165 918 23 (43) |
| τ | >-0.052 and <0.013 (95%) | 0.001 177 21(5) |

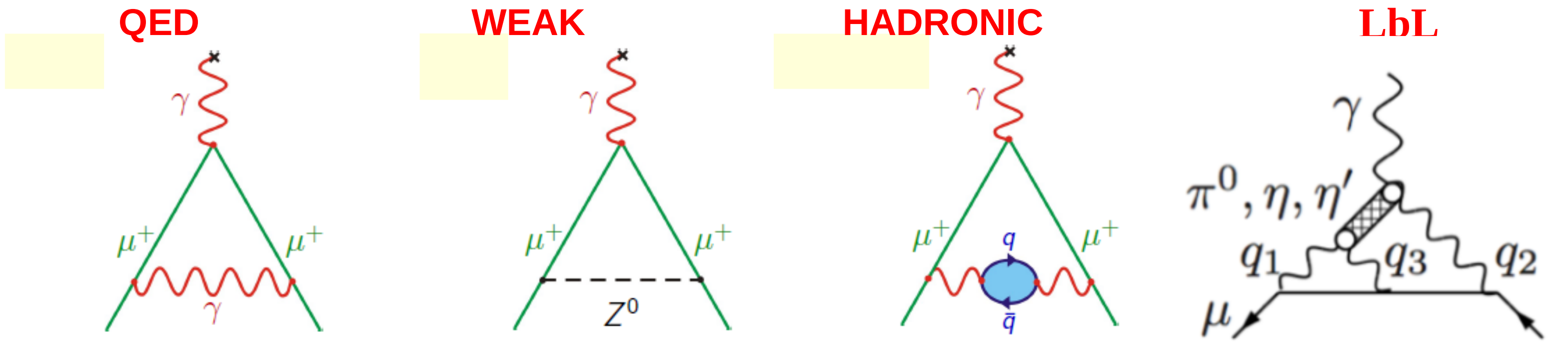
**$a_e$ tests QED to the precision of the fine structure constant α.**

**$a_\mu$ is more sensitive to heavy particle exchanges by a factor of $(m_\mu/m_e)^2$ ~42,000.**

# $a_\mu$- SM calculations and experiment

## Muon anomaly, $a_\mu = (g-2)_\mu/2$

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



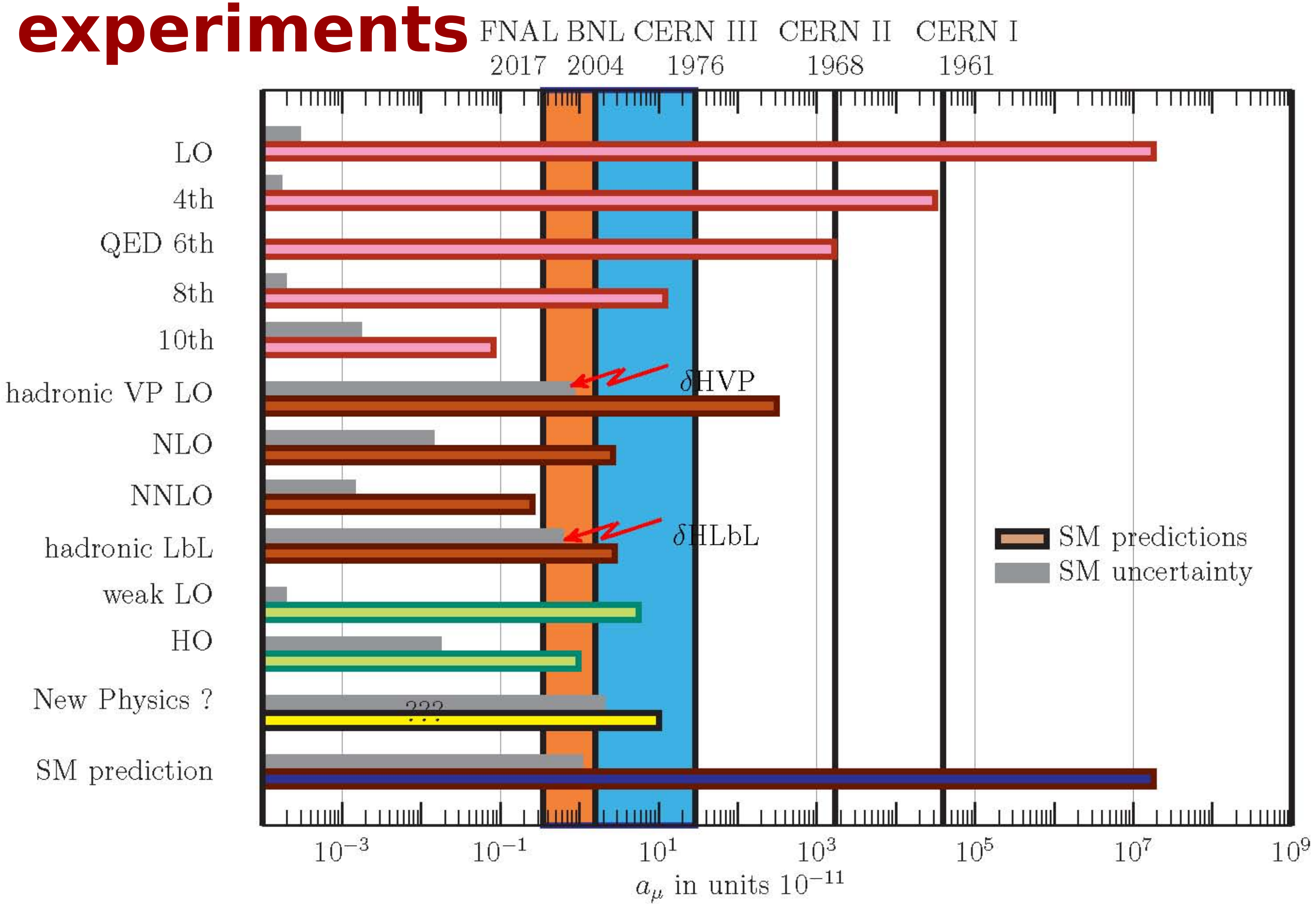

| Source | Value ($10^{-10}$) | Uncertainty ($10^{-10}$) |
|---|---|---|
| QED | 11 658 471.895 | 0. 008 |
| Weak | 15.4 | 0.2 |
| Hadronic + LbL | 693.0 | 4.9 |
| BNL E821 | 11 659 208.9 | 6.4 |
| BNL – SM Theory | 28.7 | 8.0 |

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

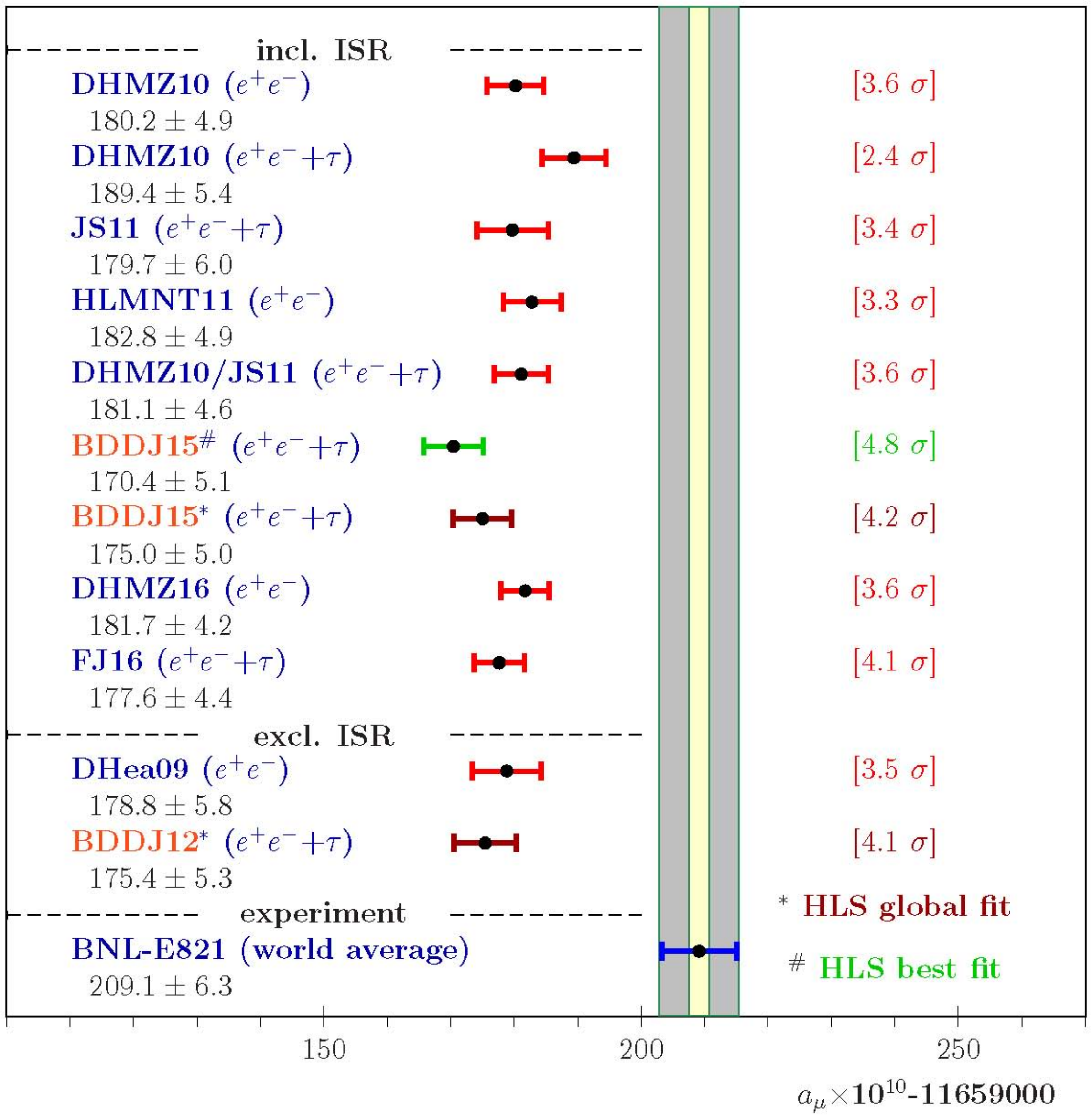
$$R(s) = \frac{\sigma(e^+e^- \to \gamma^* \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$a_\mu^{EXP} - a_\mu^{SM} = 3.6\sigma$ **(M. Davier et al., EPJC71(2011)1515)**

# Past and future of muon (g – 2) experiments




**Fred Jegerlehner,** arXiv:1705.00263v1 [hep-ph] 30 Apr 2017

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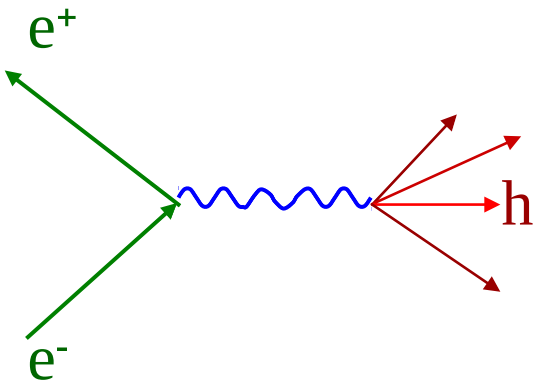
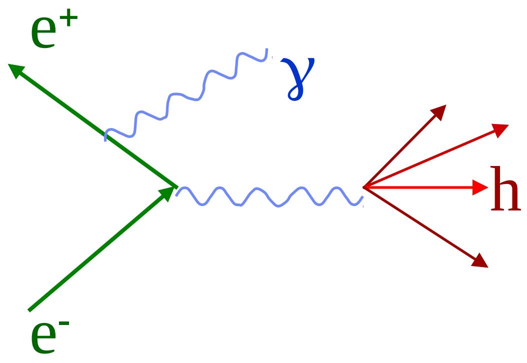
# Present data: Direct energy scan and ISR



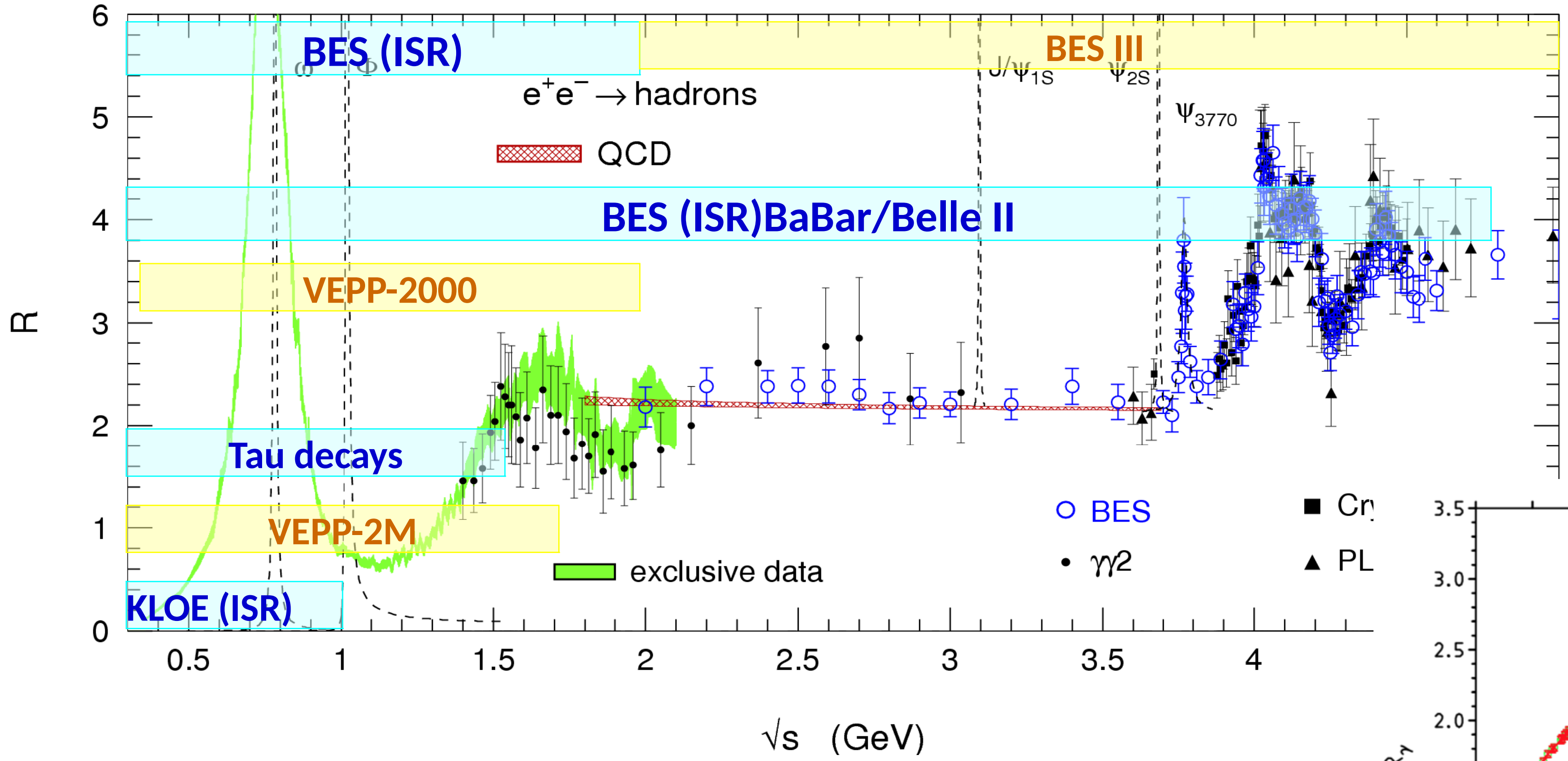

$$E^{h}_{CM} = \sqrt{s}$$

$$E^{h}_{CM} = M^{h}_{inv} = \sqrt{\sqrt{s}\left(\sqrt{s} - 2E_{\gamma}\right)}$$

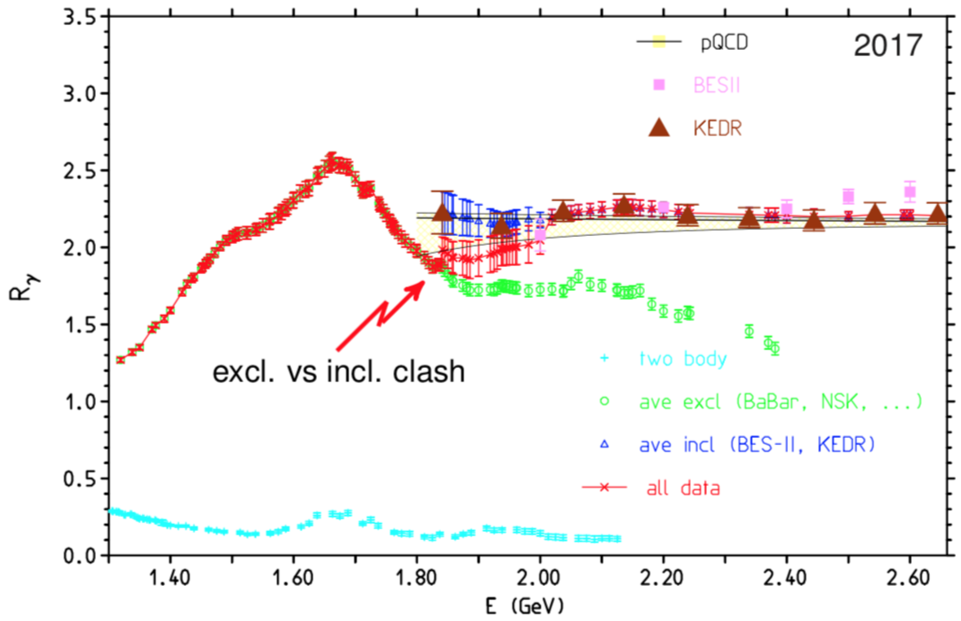
**Scan:** Novosibirsk – scan (CMD-2/SND at VEPP-2M, 0.36 < √s < 1.4 GeV, CMD-3/SND at VEPP-2000, 2m < √s < 2.0 GeV)
BES, BES II, BES III – Beijing 2-5 GeV

**ISR:** SLAC – ISR (BaBar at PEPII, 2m < √s < 5 GeV)
Frascati – ISR (KLOE/KLOE-2 at DAFNE, 2m < √s < 1.02 GeV)
BES III

# Inclusive vs exclusive measurements

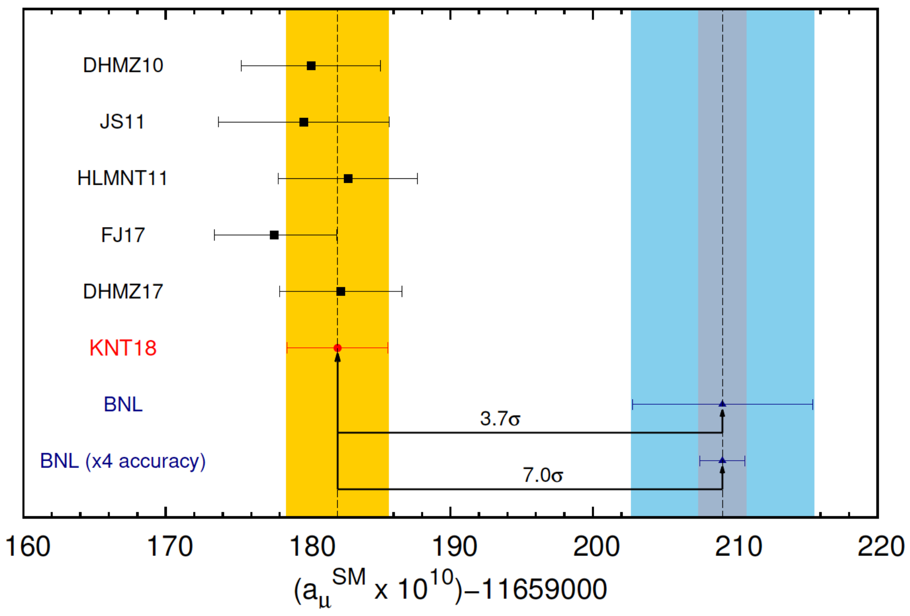


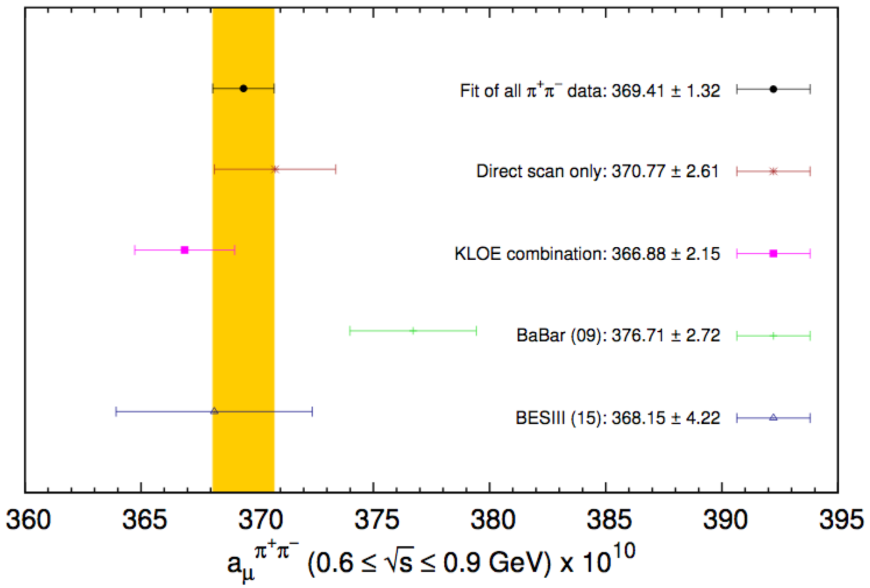

F.Jegerlehner arXiv:1804.07409

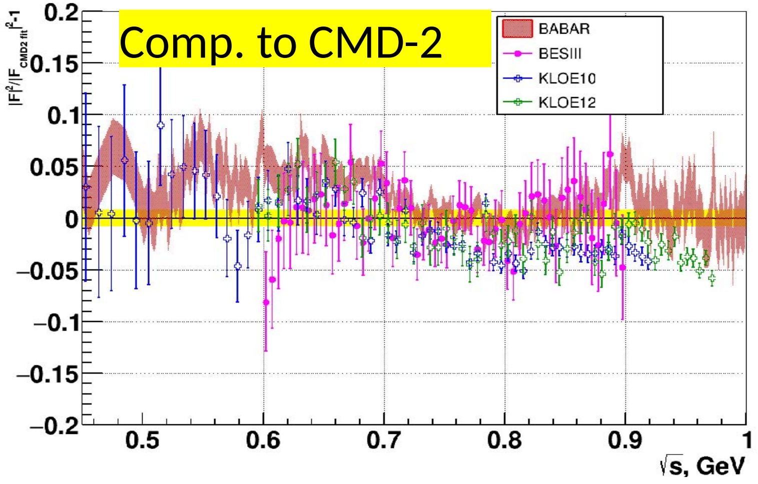


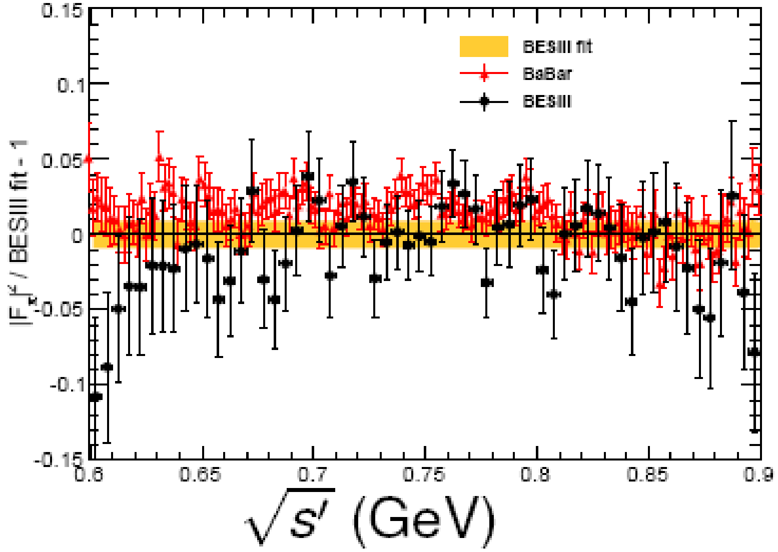

Below 2 GeV R is determined as a sum of the exclusive cross section. At higher ECM – inclusive cross section (systematics?)

# Why new more precise measurements are necessary?



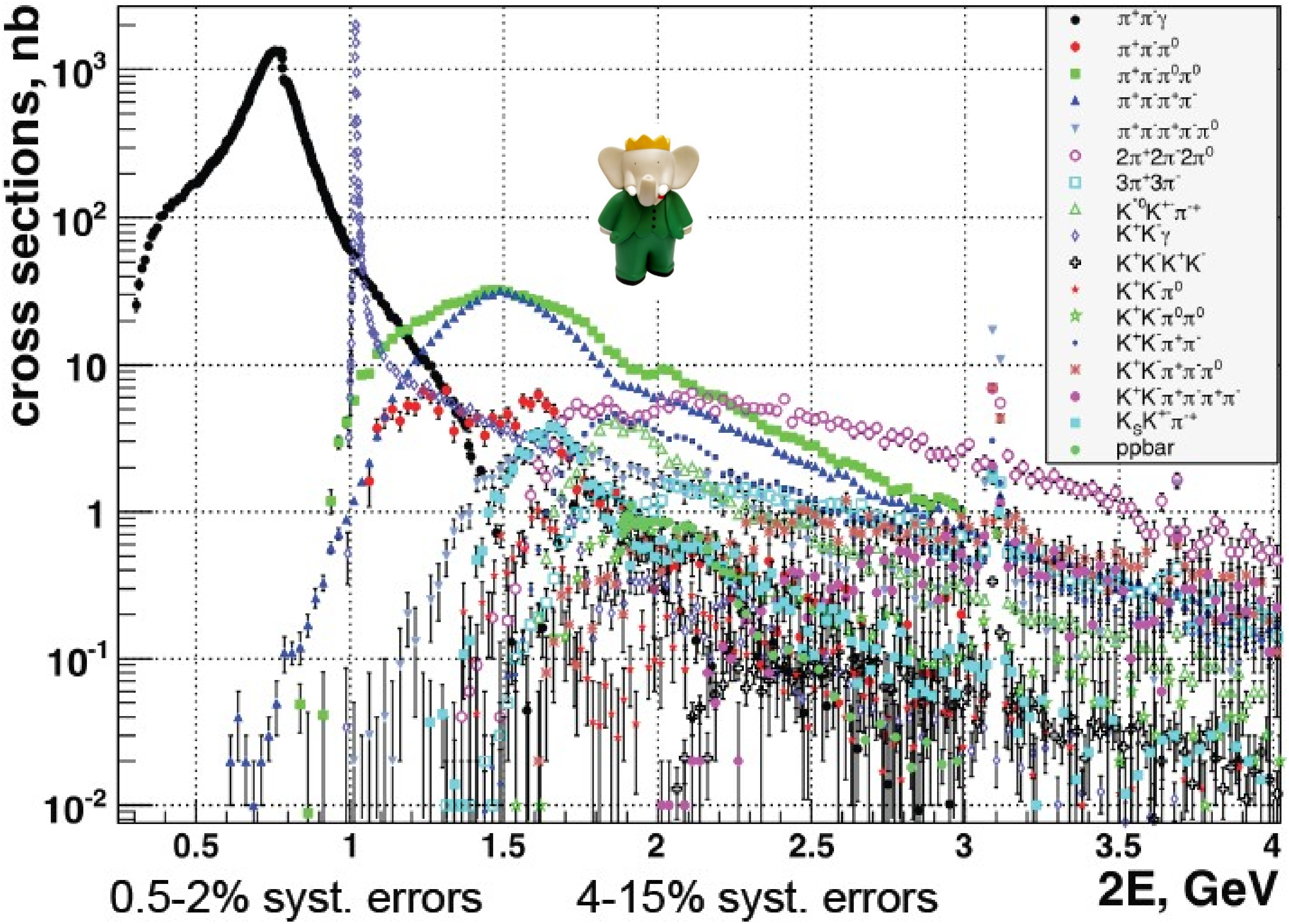



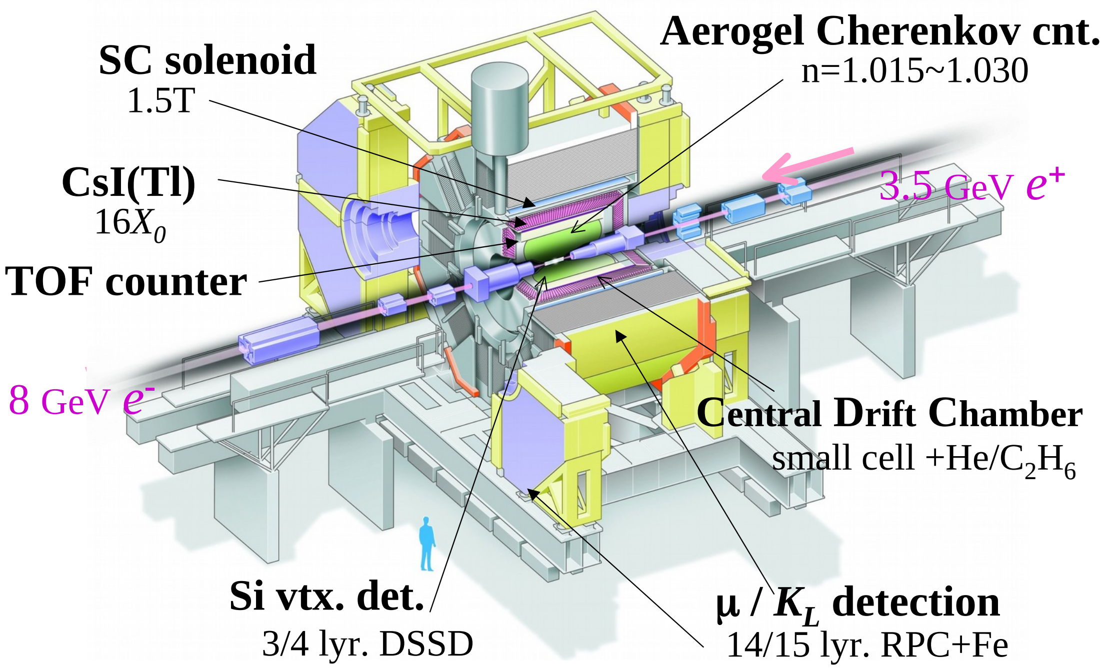



# BaBar ISR analyses

**22 final states were studied, ~20 papers on low energy ISR studies were published**



# Belle Detector




The primary goal of the Belle and BaBar experiments was to discover the CP violation in B mesons and to measure the parameters of CPV. This was achieved by both experiments in 2001

Peak lumi record at KEKB: L=2.1 x $10^{34}$/cm2/sec with crab cavities

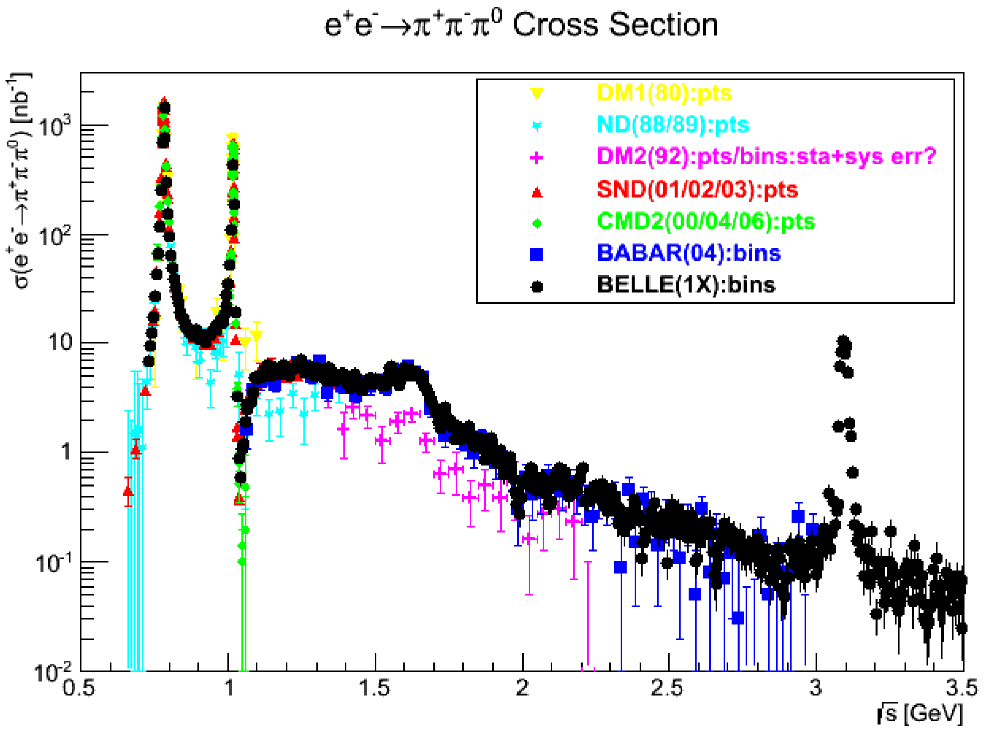
$E^- = 8$ GeV, $E^+ = 3.5$ GeV, $\sqrt{s}=10.58$ GeV, $\beta\gamma=0.42$

$$\int_{1999}^{2010} Ldt = 1\ ab^{-1}$$

F/B asymmetric detector

High vertex resolution, magnetic spectrometry, excellent calorimetry and sophisticated particle ID ability

# Belle: low mass ISR study




**526.6 fb$^{-1}$**

**(preliminary, suspended?)**

**Belle systematic error goal is 5%**

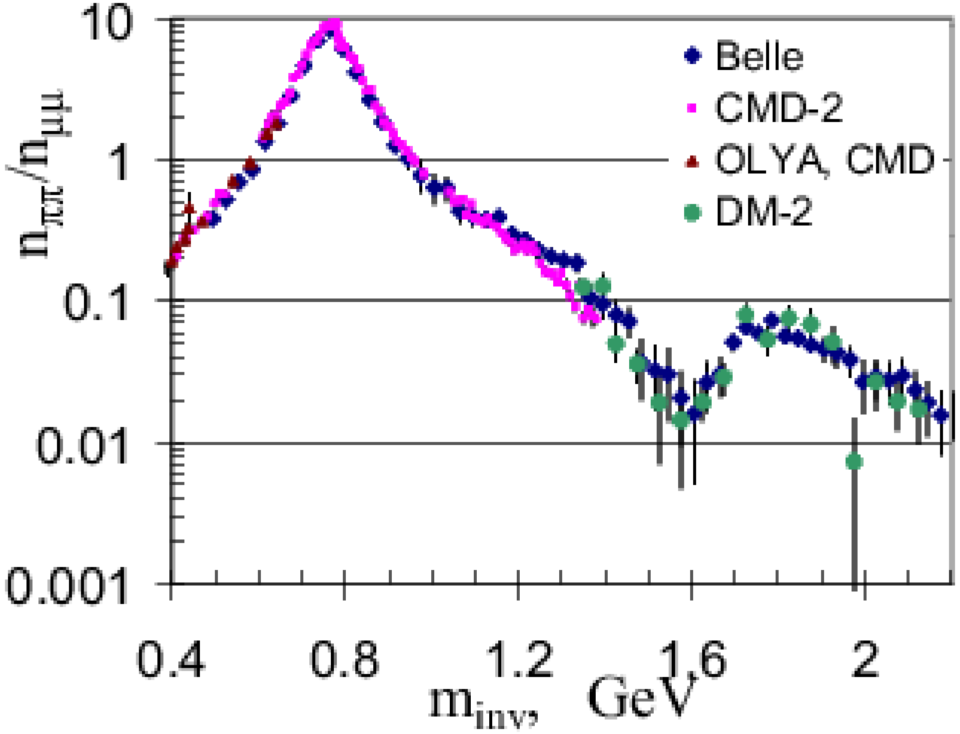
**But difficult to achieve.**

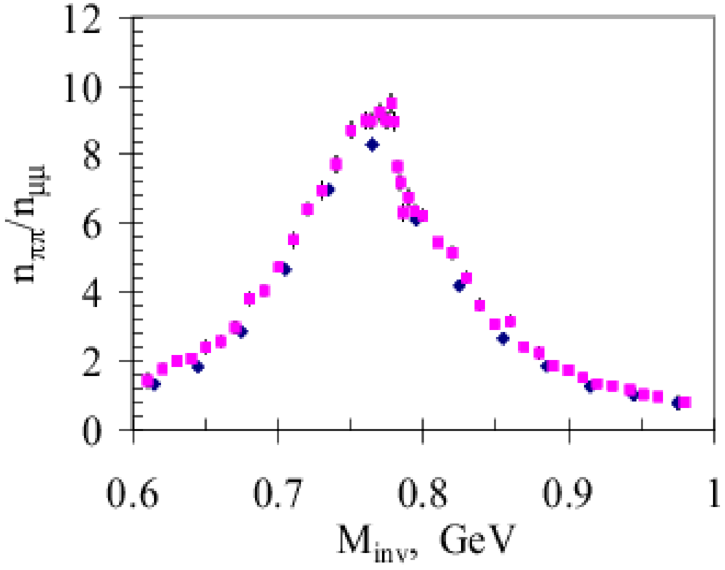
**Main problems:**
**Improper trigger**
**Lack of manpower: 2-3 people only vs ~20 at BaBar**

# $N_{\pi\pi}/N_{\mu\mu}$ ratio

By a simple separation procedure the numbers of $\pi\pi$ and $\mu\mu$ events are obtained and ratio is calculated

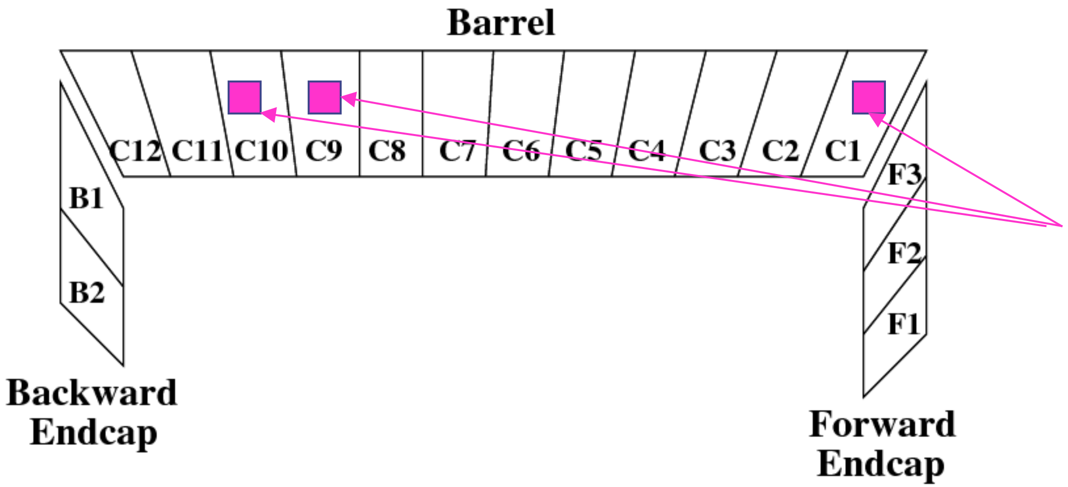
(just demonstration, not for usage!)

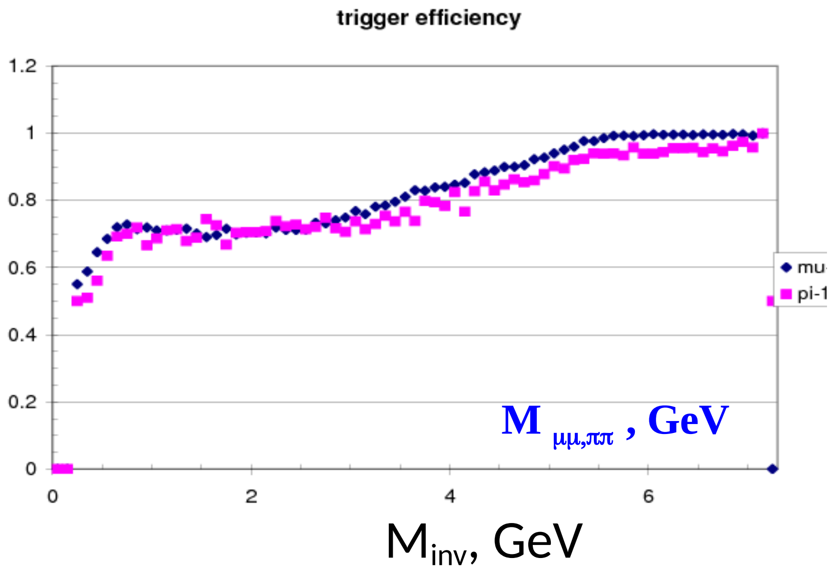



The difference ~5% can be caused by the different trigger efficiency for pion and muon events. This is a measure of systematics.

# Bhabha veto




| | Sum of rings | $E_{th}$,GeV |
|---|---|---|
| 1 | F1+F2+B1+B2 | 5 |
| 2 | F2+F3+B1+B2+C11 | 5.5 |
| 3 | F2 | 5 |
| 4 | F3+C10+C11 | 5 |
| 5 | C1+C9+C10 | 5 |
| 6 | C1+C2+C9 | 5 |
| 7 | C2+C8+C9 | 5 |
| 8 | C3+C7+C8 | 5 |
| 9 | C4+C6+C7 | 5 |
| 10 | C5+C6 | 5 |
| 11 | C10 | 3 |

Advanced Bhabha veto based on the cluster identification at the trigger level will be implemented at Belle II

# Design Concept of SuperKEKB

- Increase the luminosity by 40 times based on "Nano-Beam" scheme, which was first proposed for SuperB by P. Raimondi.

Luminosity Gain

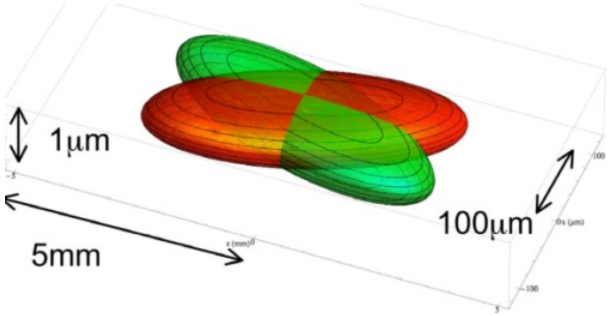
- Vertical β function at IP: 5.9 → 0.27/0.30 mm (× 20)
- Beam current: 1.7/1.4 → 3.6/2.6 A (× 2)
- Beam-beam parameter: .09 → .09 (× 1)

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right) = 8 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$$

- Beam energy: 3.5/8.0 → 4.0/7.0 GeV

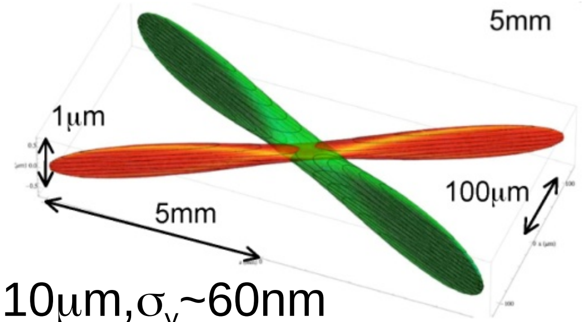
LER : Longer Touschek lifetime and mitigation of emittance growth due to the intra-beam scattering
HER : Lower emittance and lower SR power

**KEKB**




$\sigma_x$~100μm, $\sigma_y$~2μm

**Nano-Beam SuperKEKB**




$\sigma_x$~10μm, $\sigma_y$~60nm

| | E (GeV) LER/HER | $\beta^*_y$ (mm) LER/HER | $\beta^*_x$ (cm) LER/HER | φ (mrad) | I (A) LER/HER | L ($cm^{-2}s^{-1}$) |
|---|---|---|---|---|---|---|
| KEKB | 3.5/8.0 | 5.9/5.9 | 120/120 | 11 | 1.6/1.2 | $2.1 \times 10^{34}$ |
| SuperKEKB | 4.0/7.0 | 0.27/0.30 | 3.2/2.5 | 41.5 | 3.6/2.6 | $80 \times 10^{34}$ |

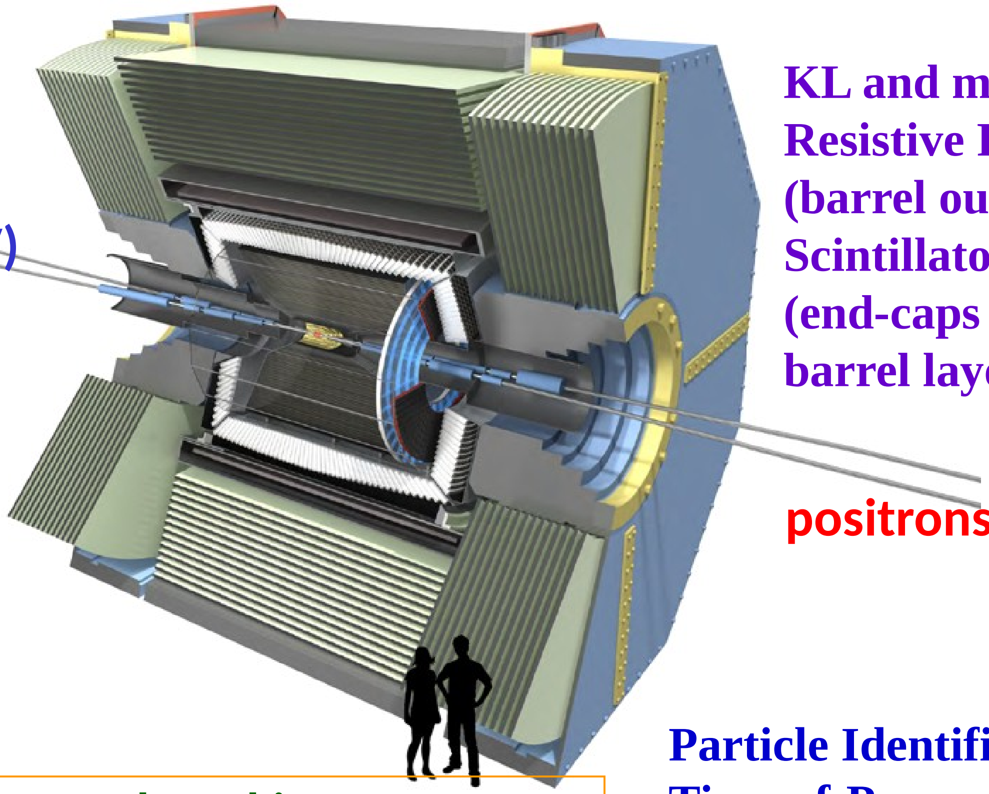
# Belle II Detector

EM Calorimeter:
CsI(Tl), waveform sampling electronics (barrel)
Pure CsI + waveform sampling (end-caps) later

electrons (7GeV)

Central Drift Chamber
Smaller cell size, long lever arm

Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD



KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

positrons (4GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

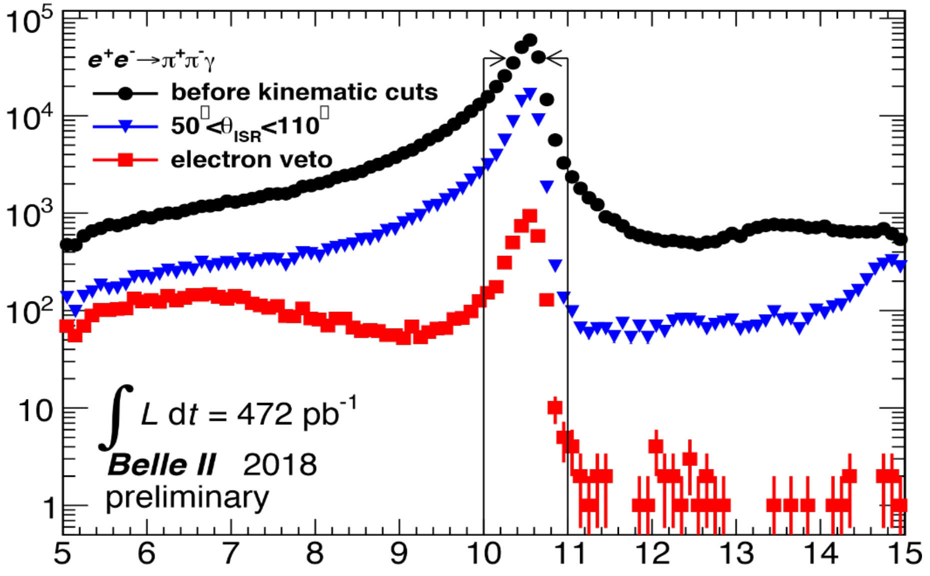
+ New software, improved tracking, ...
+ Optimization for low multiplicity trigger
+ Improved simulation, generators and GRID

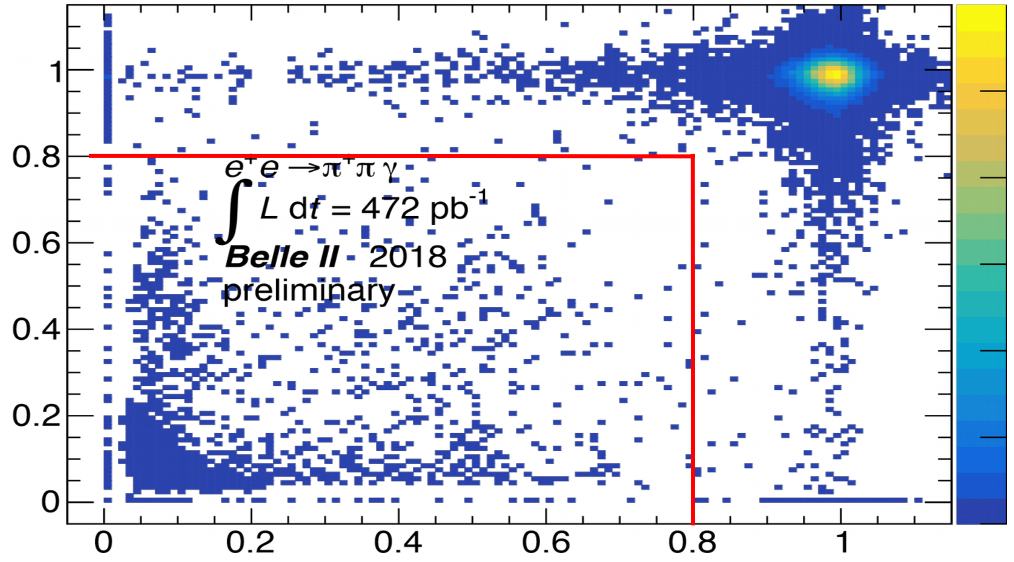
# Belle II first look to ISR (Phase II)

Events with one photon (Eg> 3 GeV, 50 < θ < 110) and 2 tracks from IP were selected and 10< Etot <11 GeV.

**Analysis done by Y.Maeda**

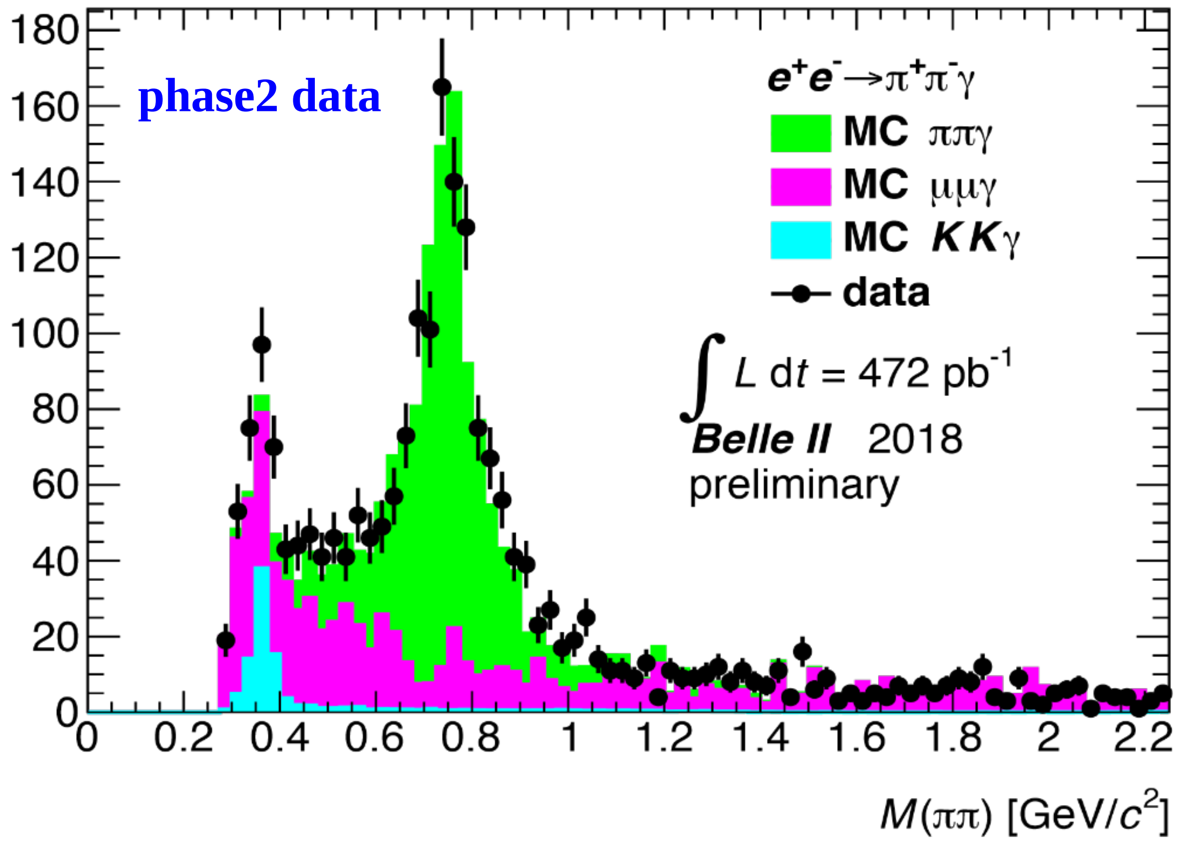
E/p ratio for each of positive and negative charged tracks.



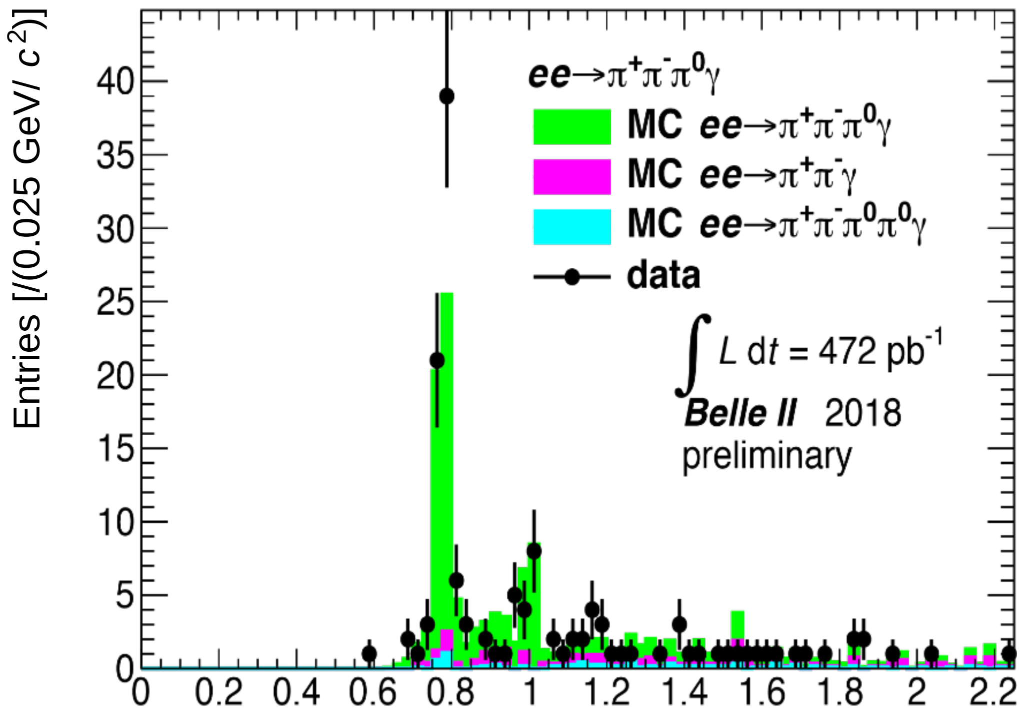

**full data of 472 pb-1 was used**

# ππ mass spectrum




MC cross sections are taken from the Phokhara generator output, data/MC(ππ) = 1.065±0.037(stat)

# πππγ process with phase-2 data

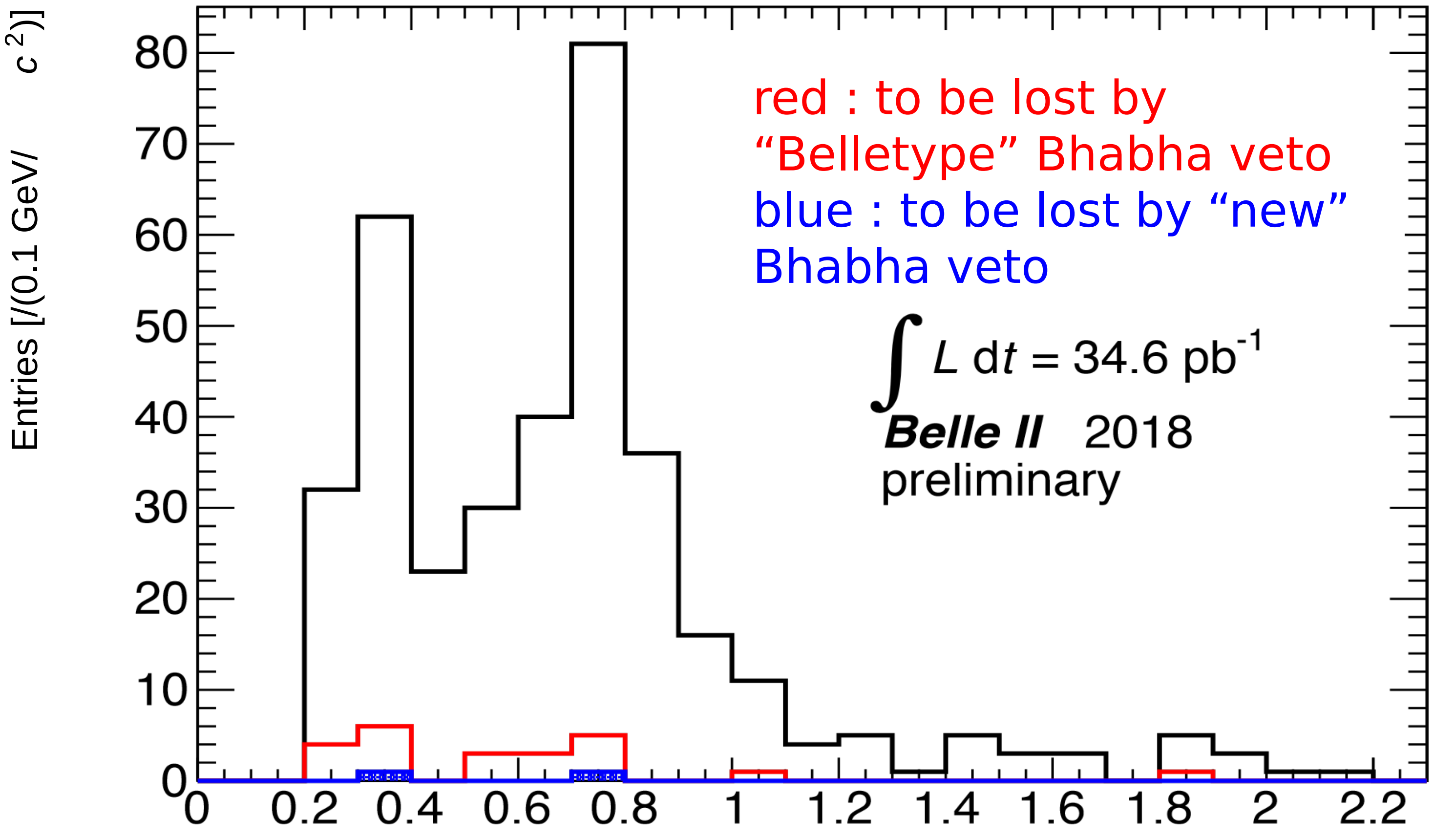


# Influence of the Bhabha veto

Two kinds of Bhabha veto logic:
1.Modified “Belle-type” Bhabha veto
2.Clusterized “new” Bhabha veto

1.: (6.4±1.3stat)%
2.: **(0.6±0.4stat)%**

the “new” Bhabha veto logic is feasible for future runs



# Conclusion

- **At present the discrepancy between experiment and SM in the muon (g-2) is, probably, the largest among observed.**
- **Two experiments on muon (g-2) measurement are in progress. We anticipate 3-4 times better precision in several years.**
- **Measurement of $e^+e^- \to \pi^+\pi^-$ cross section in Belle II with ISR method is critical to reduce uncertainty of theoretical value for muon ($g$-2)**
- **Analysis of the Phase 2 data provided the $e^+e^- \to \pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ in a good agreement with MC simulation**
- **It was found that the new trigger logic provides high efficiency and low loss of the ISR event caused by the Bhabha veto**
- **New and more precise experimental data on the hadronic cross-sections are been waiting from Belle II in the Phase 2.**