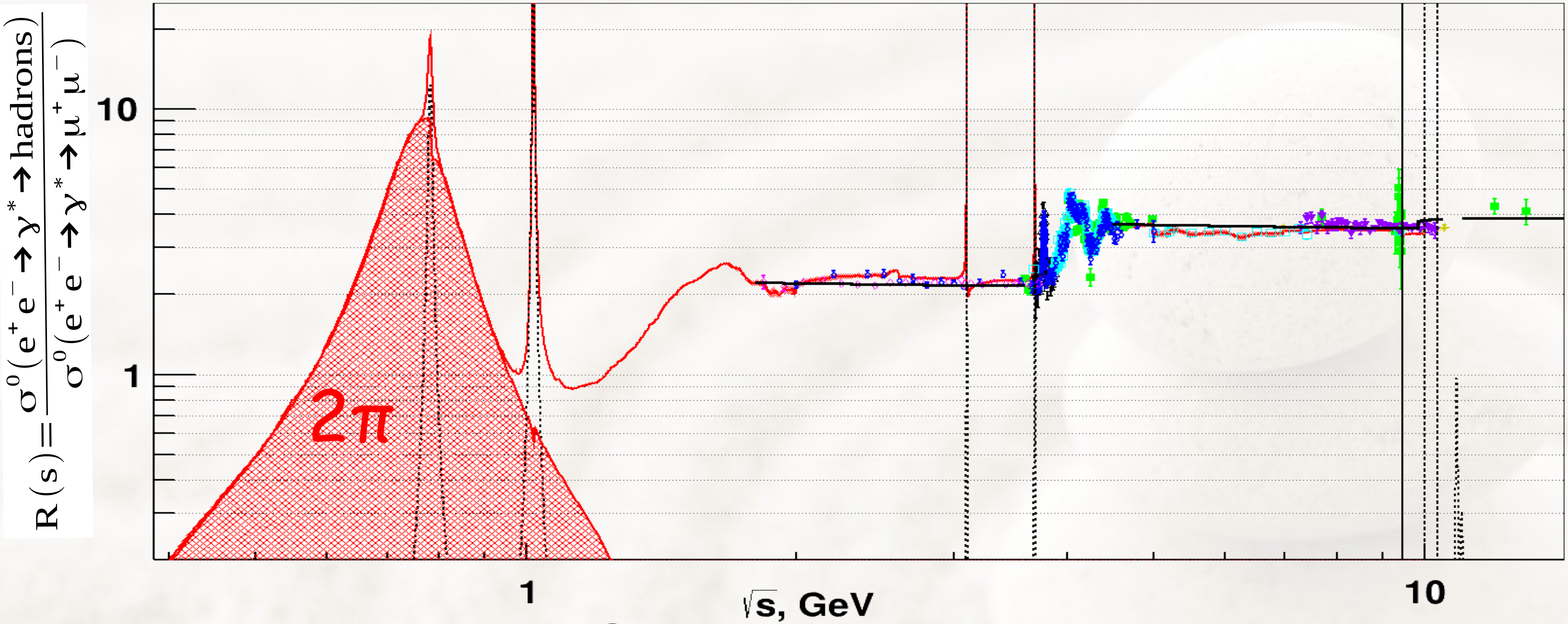
Асимметрия в 2π на детекторе КМД3: эксперимент и теория

Фёдор Игнатов,
Роман Ли

Экспериментальный семинар ИЯФ
17 Декабря 2021

Почему 2π



2π канал доминирует при 2E < 1 ГэВ

Дает определяющий вклад в приложениях где используются экспериментальные сечения для предсказаний СМ, например $\alpha_{QED}(M_Z)$, hyperfine muonium splitting, muon (g-2):

hadrons $a_\mu^{HVP} = 693.1 \pm 4.0 \times 10^{-10}$, LbL = $9.2 \pm 1.9 \times 10^{-10}$

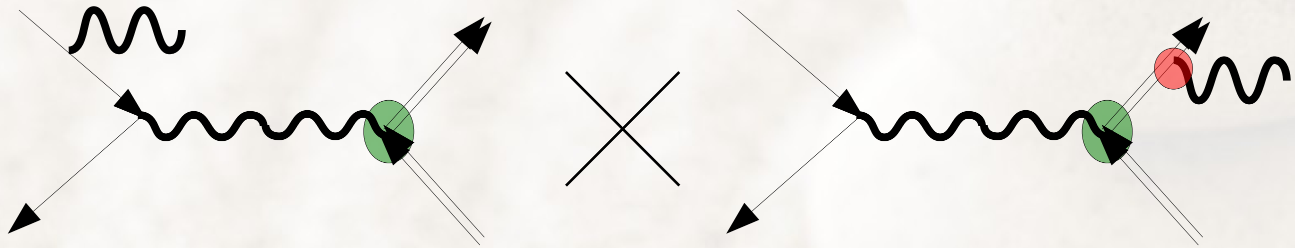
вклад от 2π = $506.0 \pm 3.4 \times 10^{-10}$ 73% величины и 85% полной ошибки

Планы нового эксперимента FermiLab $\pm 1.4 \times 10^{-10}$ → надо улучшить 2π в 2-3 раза

Почему Асимметрия в 2π

Для описания процесса $e^+e^- \to \pi^+\pi^-$ используются модели с различными предположениями взаимодействия пиона с фотоном.

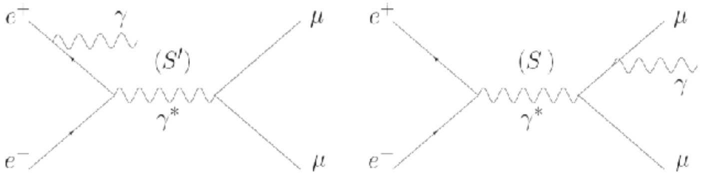
Зарядовая асимметрия в 2π в низшем порядке появляется из интерференции ISR & FSR:



Асимметрия очень чувствительна к этим моделям.

Subject 1: LO FSR contribution in ''ISR'' experiments

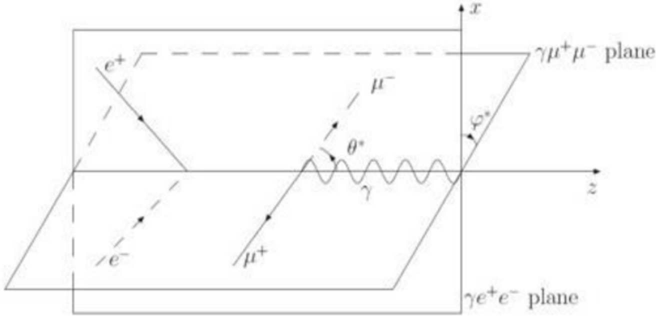
- ISR method used to measure hadronic cross sections: ee→Xγ X:QED ($\mu^+\mu^-$) or hadronic final states ($\pi^+\pi^-$)
- but radiation can be from initial state (LO ISR) or final state (LO FSR)



- LO FSR contribution (by theoretical prediction/estimation):
  - QED for $\mu\mu\gamma_{FSR}$ (use QED generators, AfkQed/Phokhara)
  - model dependent estimation for $\pi\pi\gamma_{FSR}$: very small if initial e^+e^- energy large (BABAR 10.58 GeV)
- how small is FSR for $\pi\pi\gamma$? BABAR analysis, *Phys.Rev.D* 92 (2015) 7, 072015; arxiv:1508.04008
- hard to do direct measurement, but the interference between the FSR and ISR amplitudes can be accessed through a charge asymmetry (C=$\pm$ 1)

$$\sigma \propto |\mathcal{M}|^2 = |\mathcal{M}_{\rm ISR}|^2 + |\mathcal{M}_{\rm FSR}|^2 + 2\mathcal{R}e(\mathcal{M}_{\rm ISR}\mathcal{M}^*_{\rm FSR})$$

$$A = \frac{|\mathcal{M}|^2 - |\mathcal{M}_{x^+\leftrightarrow x^-}|^2}{|\mathcal{M}|^2 + |\mathcal{M}_{x^+\leftrightarrow x^-}|^2} = \frac{2\mathcal{R}e(\mathcal{M}_{\rm ISR}\mathcal{M}^*_{\rm FSR})}{|\mathcal{M}_{\rm ISR}|^2 + |\mathcal{M}_{\rm FSR}|^2} = A_0 \cos\phi^*$$

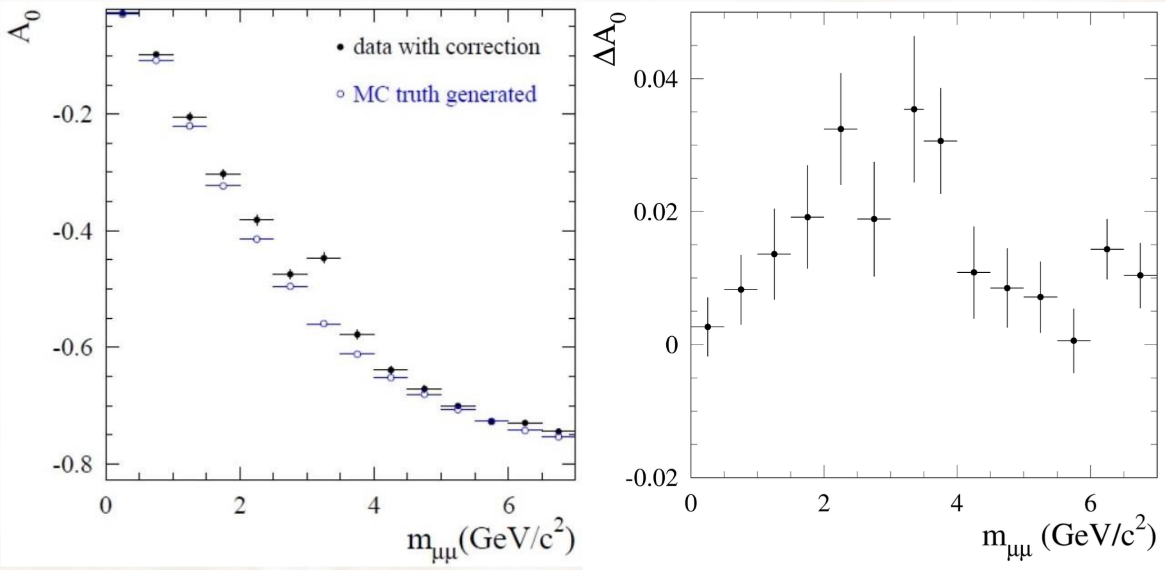


(b) In the x^+x^- c.m.

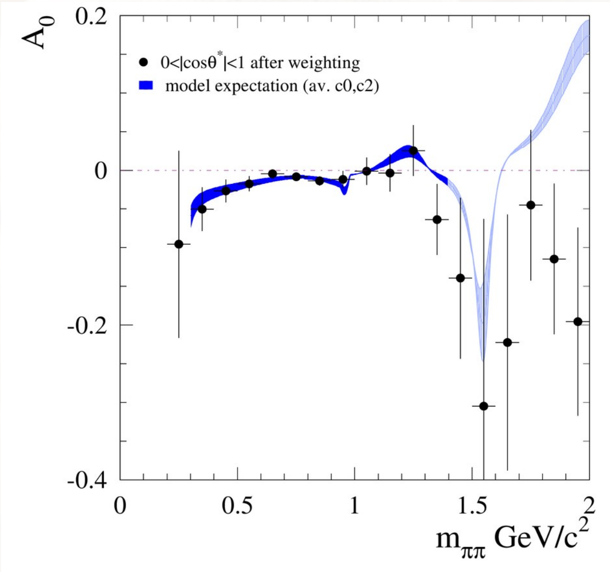
Асимметрия в BaBar

Slope of the charge asymmetry A_0

BABAR $\mu\mu\gamma$



BABAR $\pi\pi\gamma$



Inconsistency at 2.65 ± 0.38 % at 1.5 - 4 GeV

2.5 ± 0.78 % difference between $\cos\theta_{\gamma *}$ > or < 0

Systematic 1.4% (0.9% data, 1.0% generator)

Test of null asymmetry on $J/\psi \to \mu\mu$;

$A_0\,(J/\psi) = (1.3 \pm 1.6)\%$

A_0 ~ 1% around ρ (stat 0.1- 0.2%)

Systematic 0.1 – 0.17%

Fitted by model with FSR from quarks

free parameters for f_0+f_2

f_2 - consistent with prediction by V. Chernyak

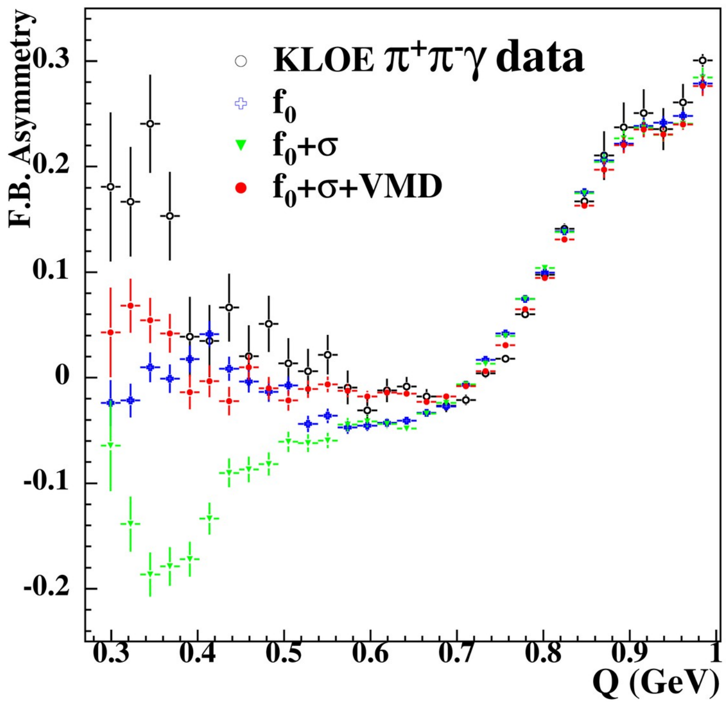
Асимметрия в KLOE

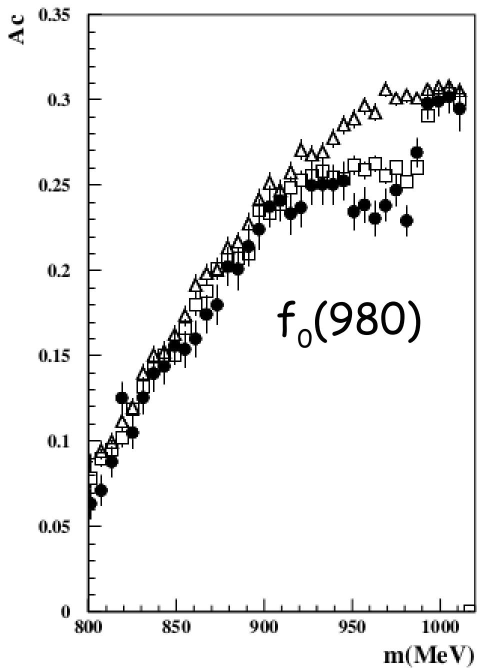
$$A = \frac{N(\theta_{\pi^+} > 90^\circ) - N(\theta_{\pi^+} < 90^\circ)}{N(\theta_{\pi^+} > 90^\circ) + N(\theta_{\pi^+} < 90^\circ)}$$

$\theta_\pi, \theta_\gamma > 45^\circ$

At φ- peak

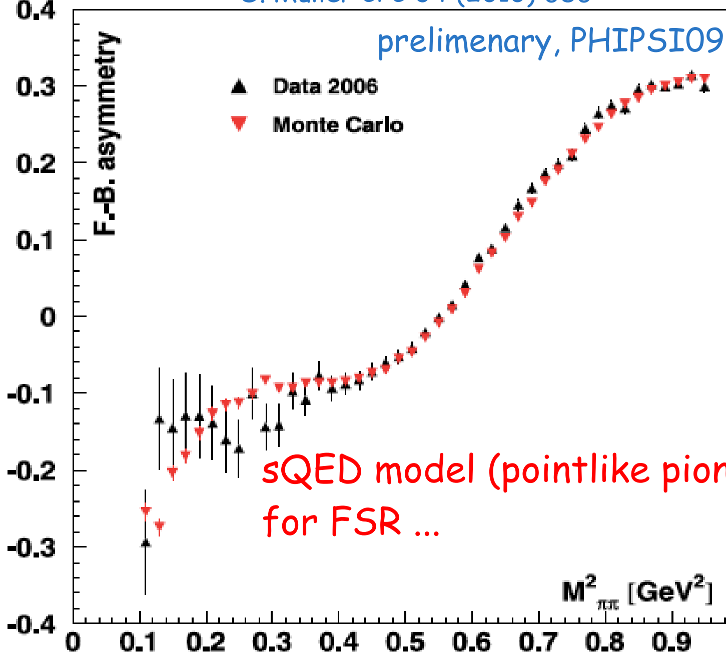
F. Ambrosino et al., PLB634 (2006) 148
G. Pancheri, O.Shekhovtsova, G. VenanzoniJETP 106 (2008), 470



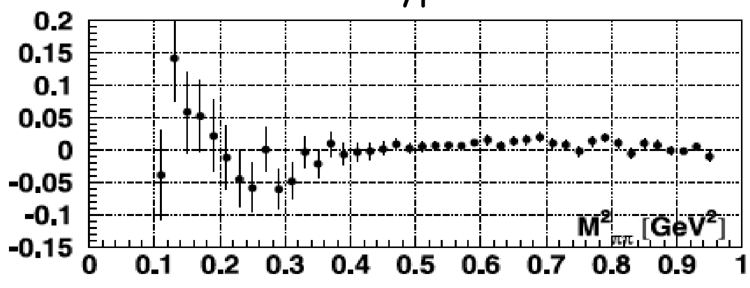


2006 φ off-peak data

P. Beltrame, Ph.D. Thesis (2009)
S. Muller CPC 34 (2010) 686



Согласие на уровне 1-2%



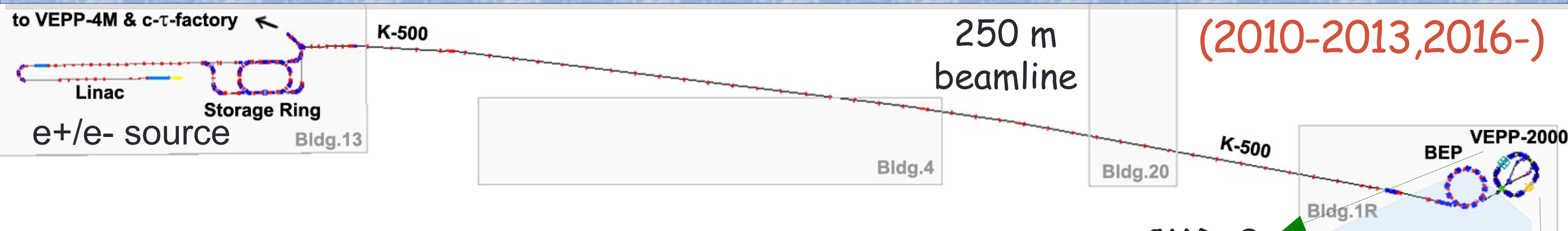
Вклады: $\varphi \to (f_0(980) + \sigma)\,\gamma$ in non structure model

$\varphi \to \rho^\pm \pi^\pm$, $\rho \to \pi\gamma$

Even more models in A. Gallegos et al. PLB 693 (2010) 467 :

Brem, DR , UχPT , LSM, RχPT , KLM etc ....

CMD3 at VEPP-2000 e+e- collider



VEPP-2000: direct exclusive measurement of σ (e+e- → hadrons)

Only one working this days on scanning 2E = 0.32-2 GeV

Unique optics, "round beams" to reach higher L

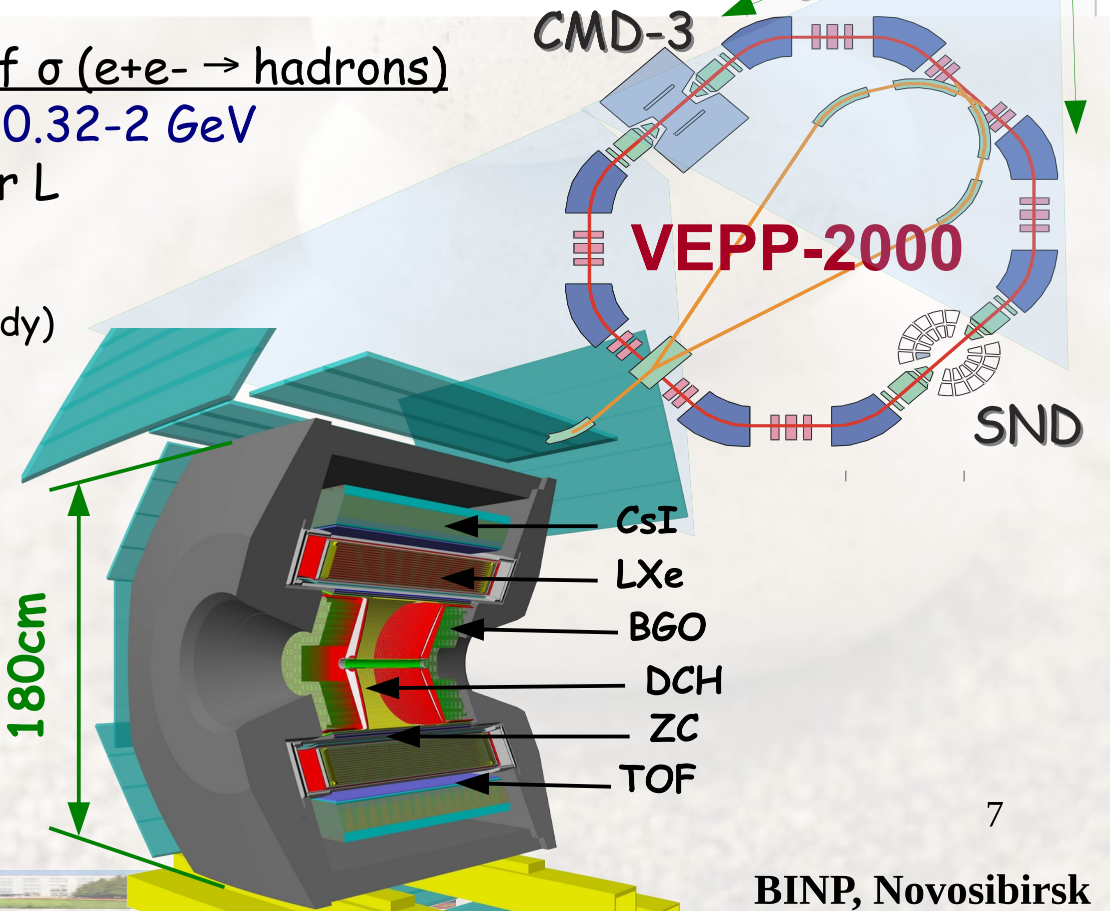
World-best luminosity below 2 GeV :

(except at 1 GeV point, where KLOE outperform everybody)

$L = 0.5\times10^{32}\ cm^{-2}s^{-1}$ at 2E= 2 GeV

Two detectors: CMD-3 and SND

Only CMD-3 has magnetic field and suitable for Asymmetry study



e+e- -> π+π- by CMD3

Very simple topology (just 2 track back to back),
but the most challenging channel
due to high precision requirement.

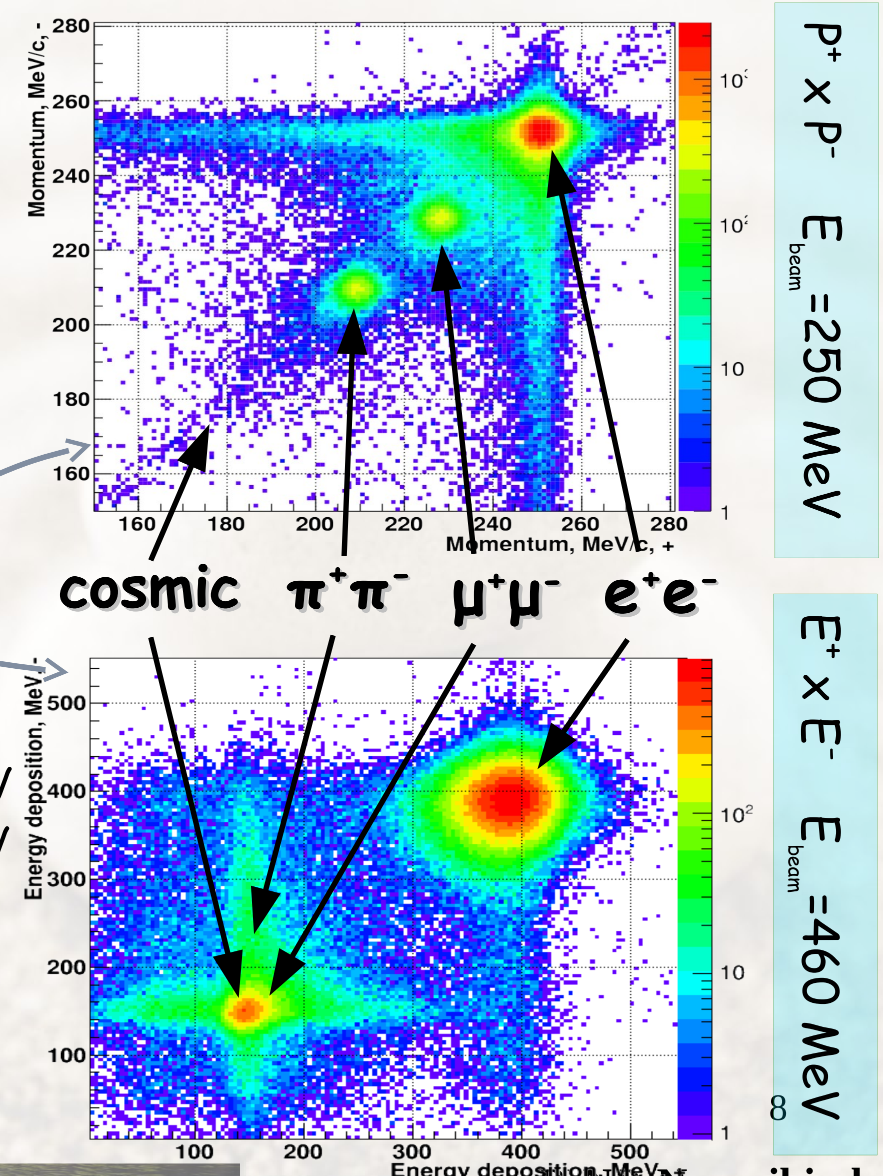
Original plans was to reach systematic ~0.35-0.5%

Crucial pieces of analysis:

- ✗ e/μ/π separation
- ✗ radiative corrections
- ✗ precise fiducial volume
- ✗ ...

events separation either
by momentum
or by energy deposition

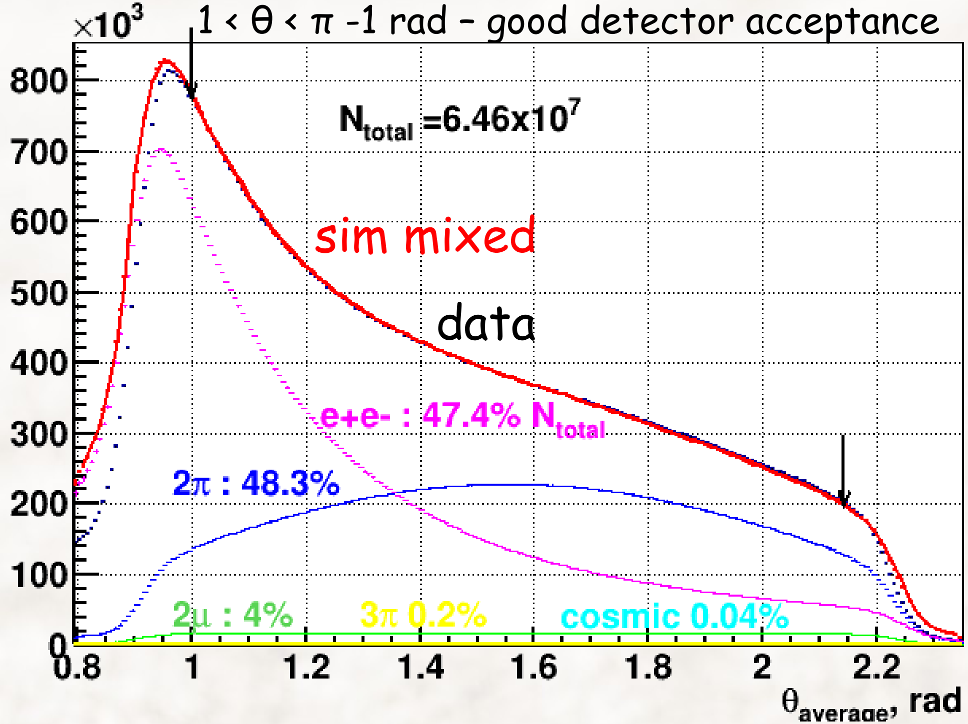
Momentums works better
at low energy 2E< 0.8 GeV
Energy deposition > 0.6 GeV



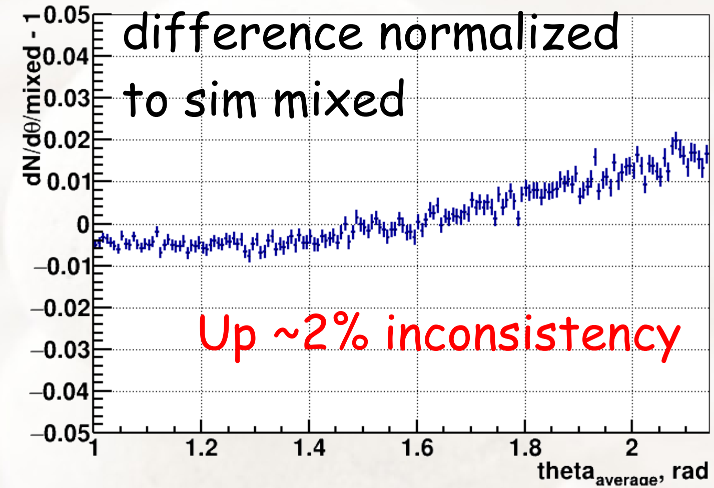
Fiducial volume cross check

All events at ρ-peak : E_{beam} = 350 – 410 MeV

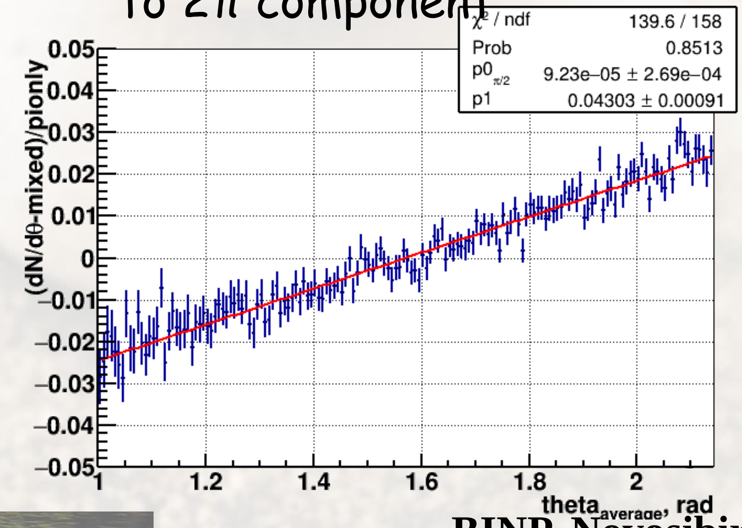
1 < θ < π -1 rad – good detector acceptance



(data – sim mixed) difference normalized to sim mixed



Difference normalized to 2π component

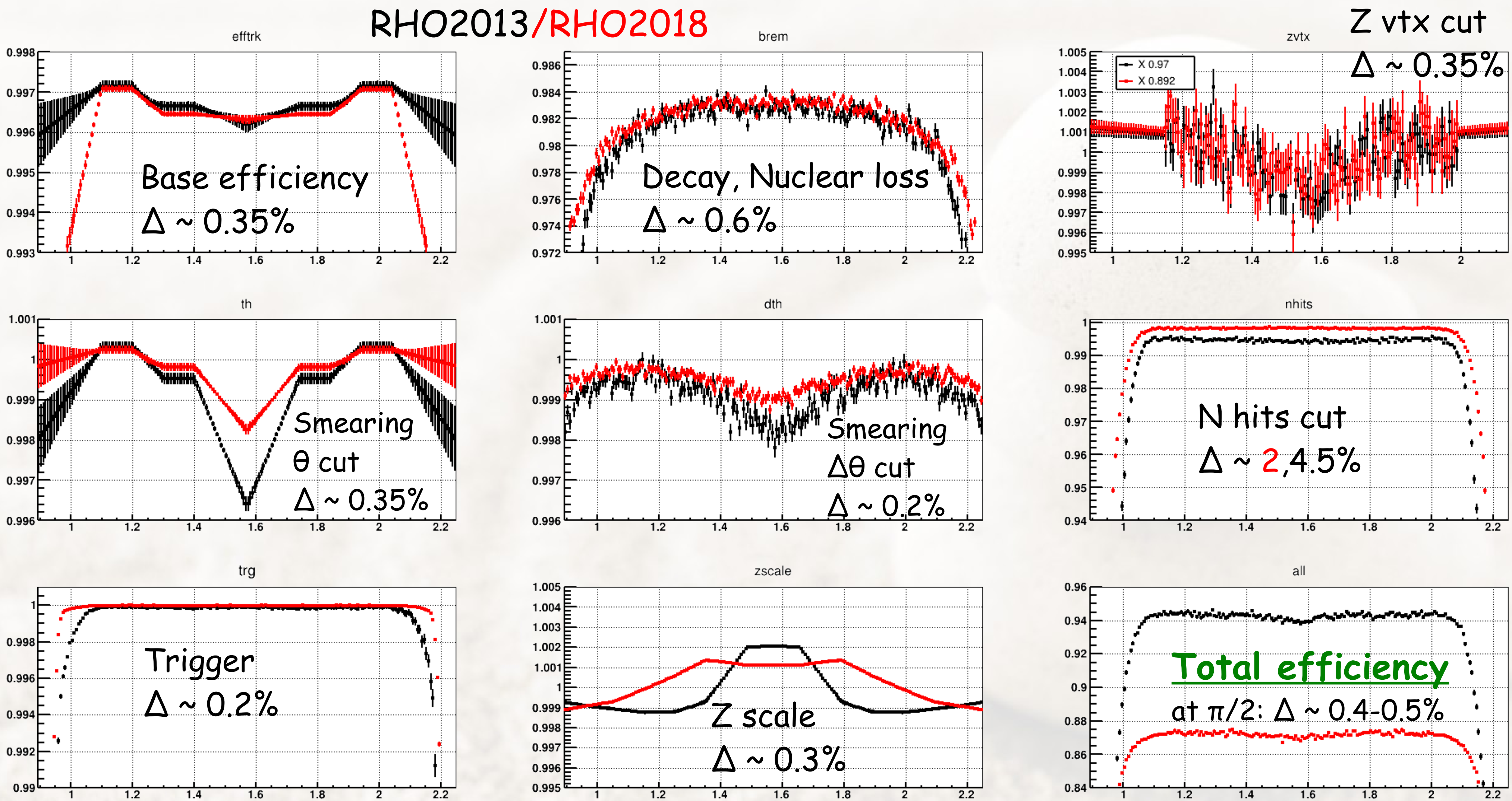


Sim mixed:

Generators spectra + all efficiencies/smearing extracted from data and full simulation

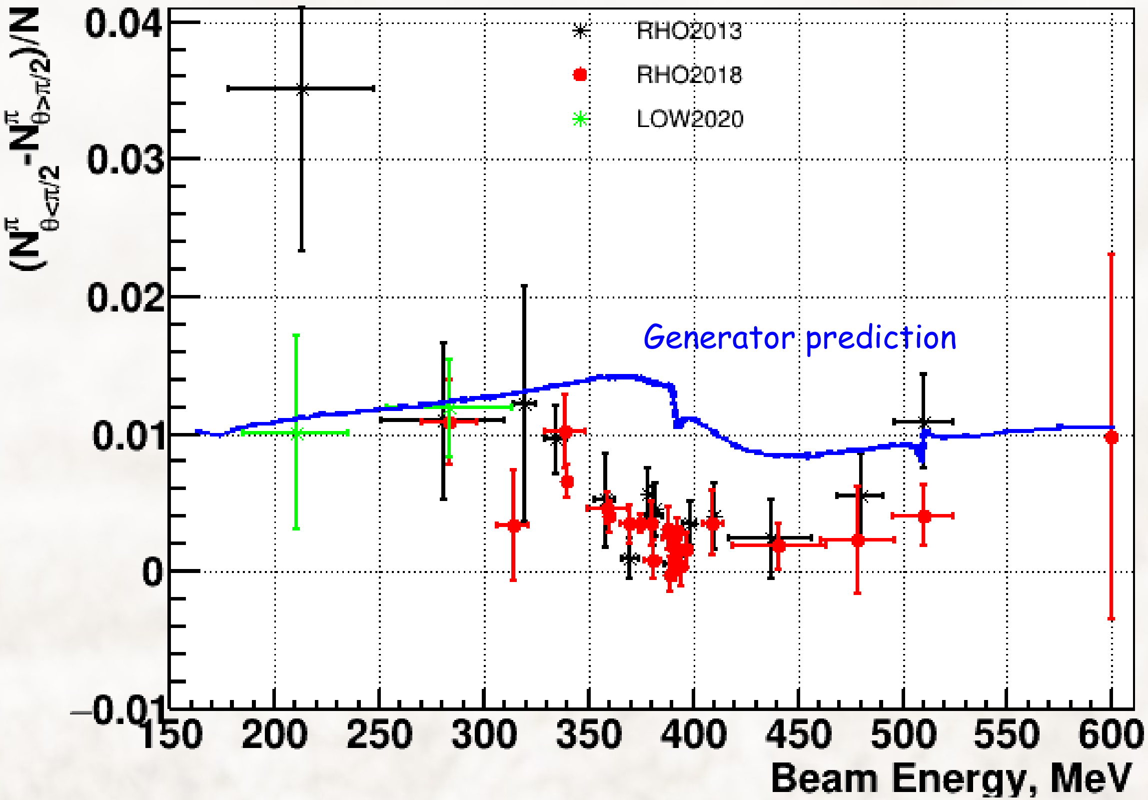
$N_{\pi\pi/ee/\mu\mu,etc}$ – from event separation

π+π- эффективность от θ угла



Сумма по всем точкам 350-410 МэВ

Asymmetry



Full 2π analysis redone for θ > and < π/2

Asymmetry definition:

$A = (N_{\theta < \pi/2} - N_{\theta > \pi/2})/N$

N - corrected with efficiencies, etc

with selection cuts:

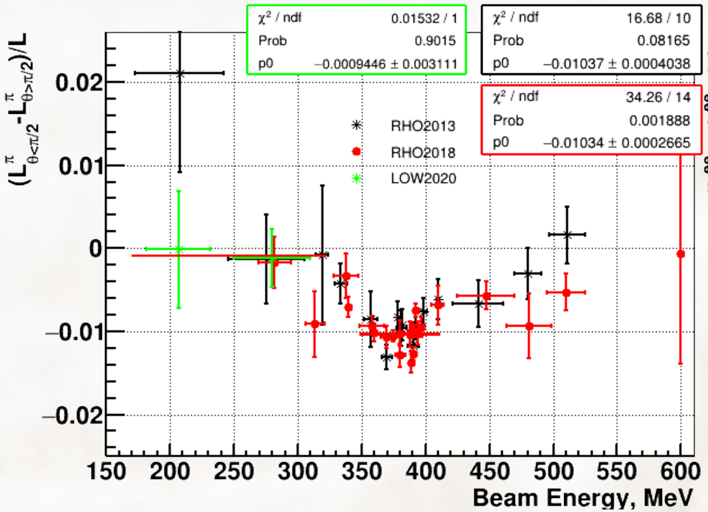
$|\Delta\varphi|<0.15$, $|\Delta\theta|<0.25$,

$1< \theta_{average} <\pi -1$, $P^{+-} >0.45\ E_{beam}$

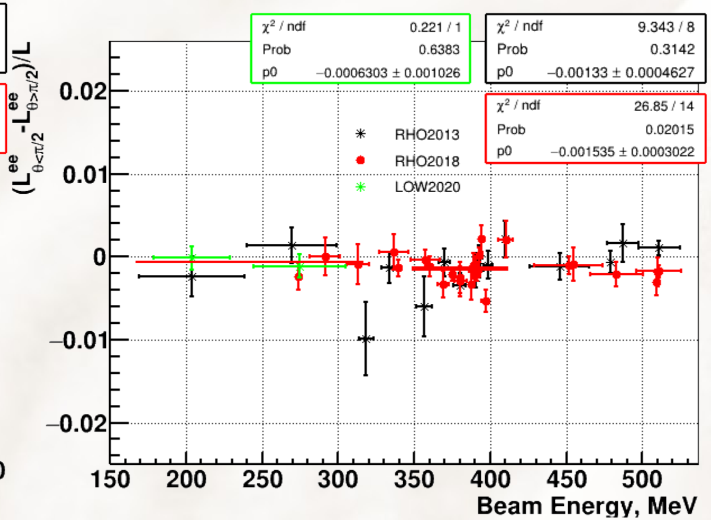
Asymmetry 2π/e+e-/2μ

Asymmetry relative to generator prediction

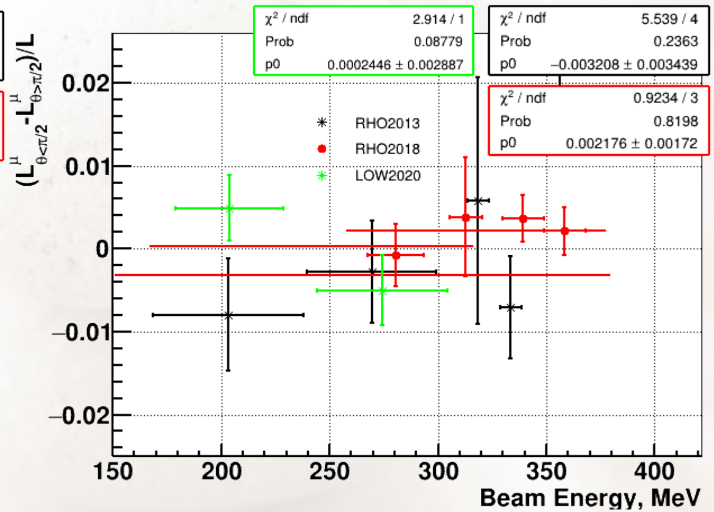
δA (π+π-)



δA (e+e-)



δA (μ+μ-)



Average at 2E=350-410 MeV

⟨δA⟩ = -1.04 ± 0.02 %

ρ - like behaviour

with MCGPJ:

⟨δA⟩ = -0.15 ± 0.03 %

with BaBaYaga@NLO:

-0.07 ± 0.03 %

Fixed order NNLO ~ -0.06

No trends for e+e-

⟨δA⟩ = 0.10 ± 0.14 %

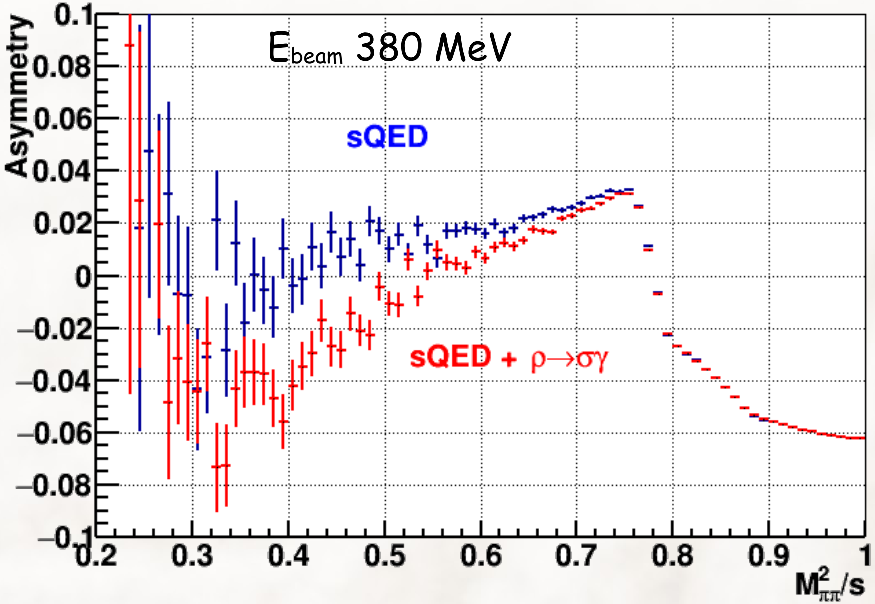
Nμμ can be extracted only at lowest energies

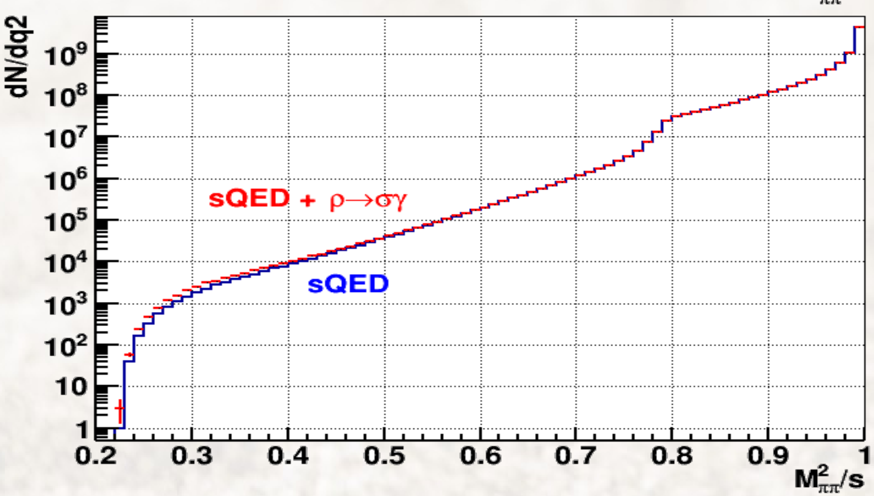
BabaYaga/MCGPJ difference gives ~ 0.08%

Detector systematic can be ~ 0.1%

Scalar production

Could it be: e+e- → ρ → σγ or $a_1^{\pm}\pi^{\pm}$?





With help of FASTERD generator

O. Shekhovtsova, G. Venanzoni, G. Panccheri, Comp.Phys.C. 180 (2009) 1206-1218

Mixed in ρ → σγ instead of φ → (f_0+σ)γ
in non structure model
with some rough σ production parameters

|δA| ~< 2×10^{-5} effect only in far tails

Br (ρ->σγ) ~ 1×10^{-4} [x2 Br(ρ→π0π0γ)]
Interference with sQED e+e- → $\pi^+\pi^-\gamma$: => ~ 1×10^{-3}
x Collinearity selection cuts 1×10^{-2}
Total rate ~ 10^{-5} too small to affect something

ρ → $a_1^{\pm}\pi^{\pm}$ effect should be same or less:
Phys.Rev.D 76 (2007) 033001

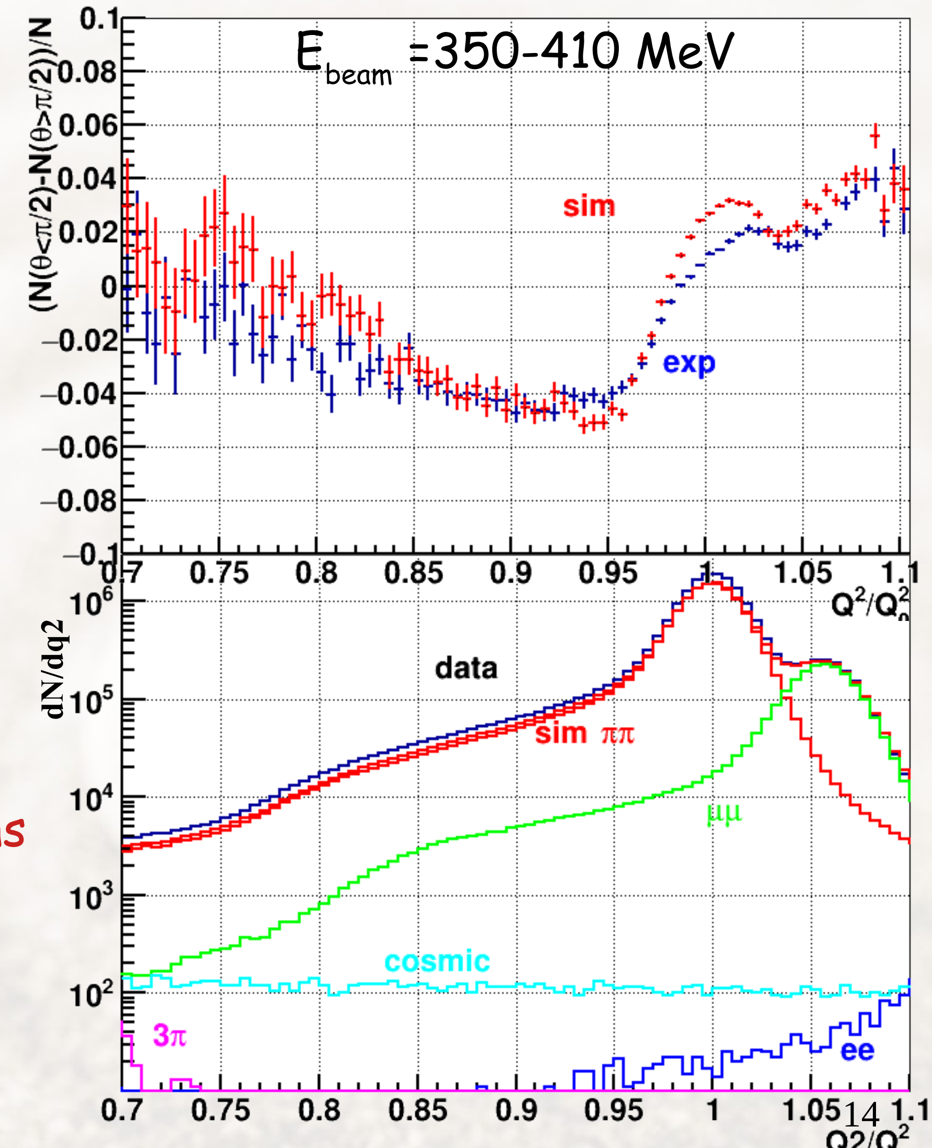
Asymmetry with Mπ2

<u>Asymmetry vs $M_{\pi\pi}^2$</u>

Sample of 2π can be selected by energy deposition as MIP with E_{LXe}^{+-}<100 MeV (with some admixture of 2μ)

Comparison with full mixed simulation

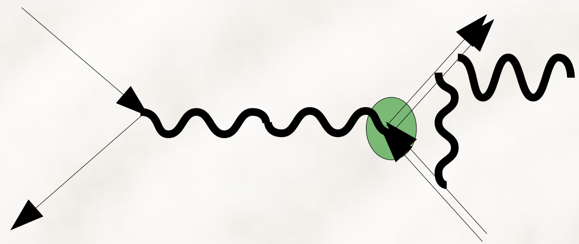
Main difference comes from $M_{\pi\pi}^2/s \sim 1$: correspond to virtual/soft radiative corrections



sQED assumptions

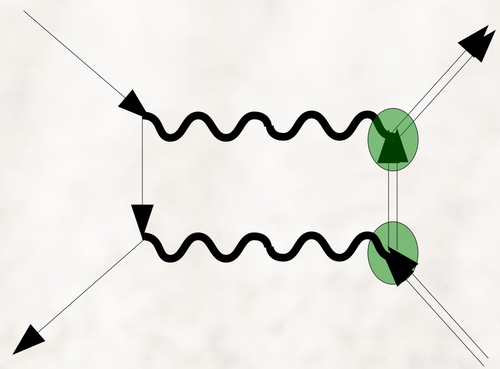
The radiative correction calculations is commonly done in the sQED approach,
It's mean that the calculations are performed without form factor,
then final Amplitude is scaled by $F(q^2)$

It works well for such amplitudes:



$A = sQED*F(s)$

But it is too naive for loop diagrams:



sQED: $|M^2| \sim |F(s)|^2$

Two pion vertex gives:

$|M^2| \sim F(s)*F((q_0-q)^2)*F(q^2)$

two cases of changes:

1) when 2 photon hard
$\sim F^2(s/4)/F(s)$ non IR term x10
2) 1 soft photon, one vertex go off-peak
$\sim F(s-2E\omega)/F(s)$ part of IR by 1./2

Strong modification of loop integral parts

with $|F(M_\rho^2)|^2 \sim 45$

Proper way will be to put $F(q^2)$ to each vertex

Thanks to Roman Lee, this calculations was done with above sQED

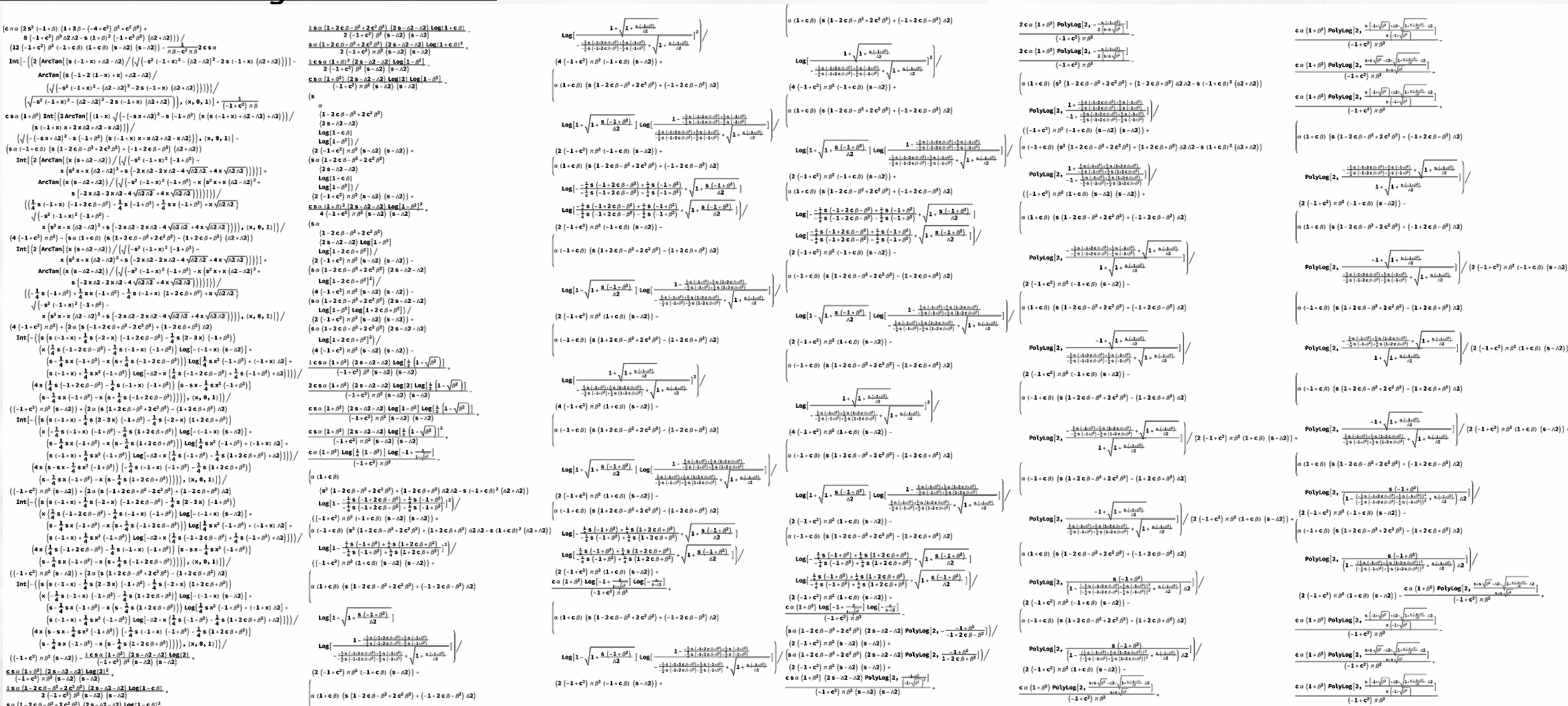
Virtual + soft corrections

Point Like formula consistent with A.B. Arbuzov et al., Mod.Ph.Lett.A 35 (2020) 25, 2050210 , inconsistent with A.Hoefer et al. Eur.Ph.J.C 24 (2002) 51-69

$$\delta_{odd}^{Virt}(\lambda)+\delta_{odd}^{Soft}(\lambda,\Delta)=\frac{\alpha}{\pi}\Big\{4\ln\left(\frac{1+\beta c}{1-\beta c}\right)\ln\frac{\sqrt{s}}{2\omega_0}+\ln\left(\frac{1+\beta}{1-\beta}\right)\ln\left(\frac{1+\beta c}{1-\beta c}\right)+\frac{c}{\beta(1-c^2)}\ln^2(1-\beta^2)-\frac{2c(1+\beta^2)}{(1-c^2)\beta^2}\left[\frac{\pi^2}{12}+\frac{1}{4}\ln^2\left(\frac{1+\beta}{1-\beta}\right)+Li_2\left(\frac{1-\beta}{1+\beta}\right)\right]$$

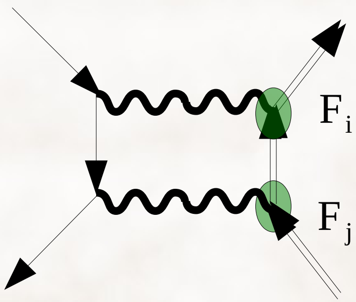
$$+\left\{\frac{(1-\beta c)^2}{(1-c^2)\beta^2}\ln(1-\beta c)\ln\left(\frac{1-\beta c}{1-\beta^2}\right)+2Li_2\left(\frac{(1+c)\beta}{1+\beta}\right)+2Li_2\left(\frac{(1+c)\beta}{1+\beta c}\right)+\frac{1-2\beta c+\beta^2}{(1-c^2)\beta^2}\left[\frac{\pi^2}{12}+Li_2\left(\frac{1-2\beta c+\beta^2}{1-\beta^2}\right)\right]\right\}-\{c\to -c\}\Big\}$$

Double FF in box diagram addition:



Calculations by Roman Lee (BINP)

Analytical calculation was done
with constant BW parametrization:
(off mass shell effect in FF was out of scope)



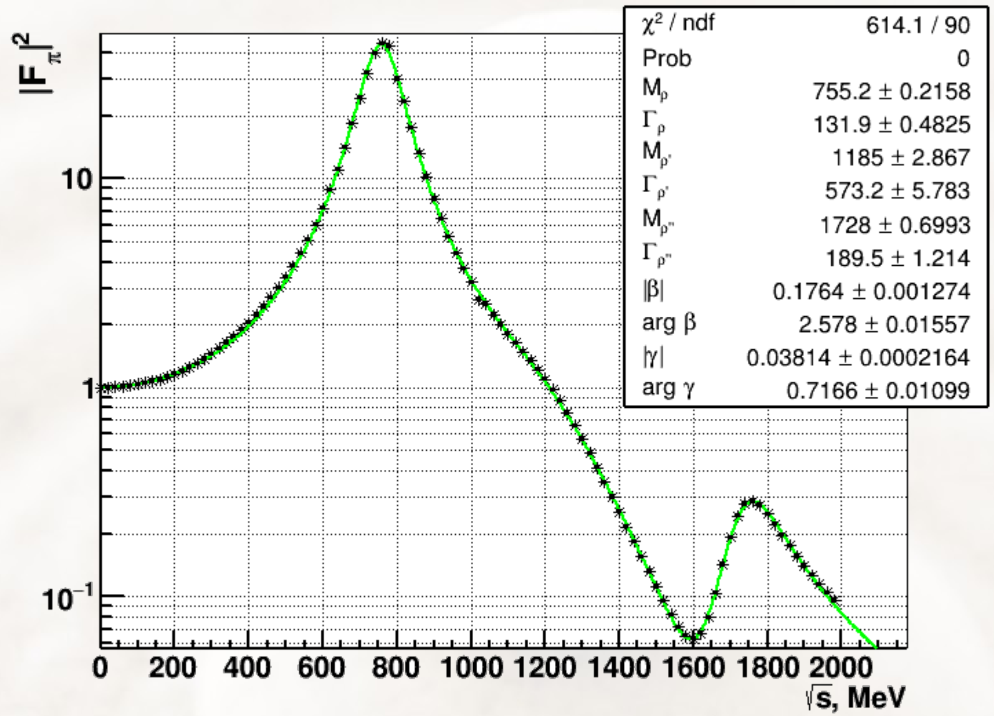
$$F_i(q^2)=\frac{\Lambda_i^2}{\Lambda_i^2-q^2},\ \Lambda^2=M^2-i\,M\Gamma$$

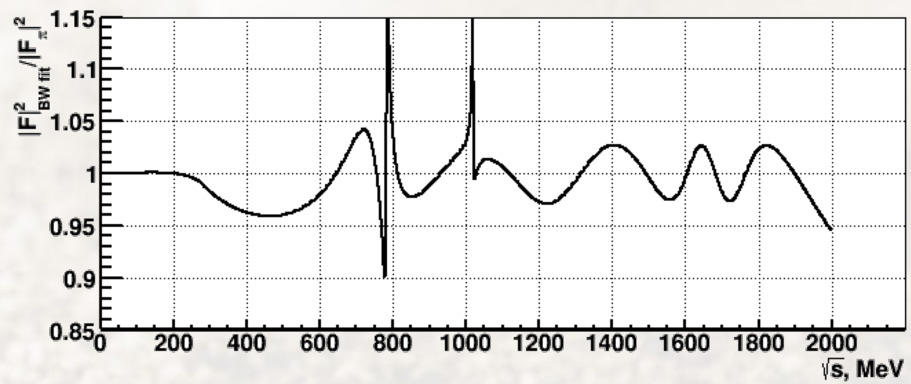
$$F_j(q^2)$$

Full GS function was re-parametrized
by sum of constant BW:

$$F(s)=\sum \alpha_i \frac{\Lambda_i^2}{\Lambda_i^2-s}$$

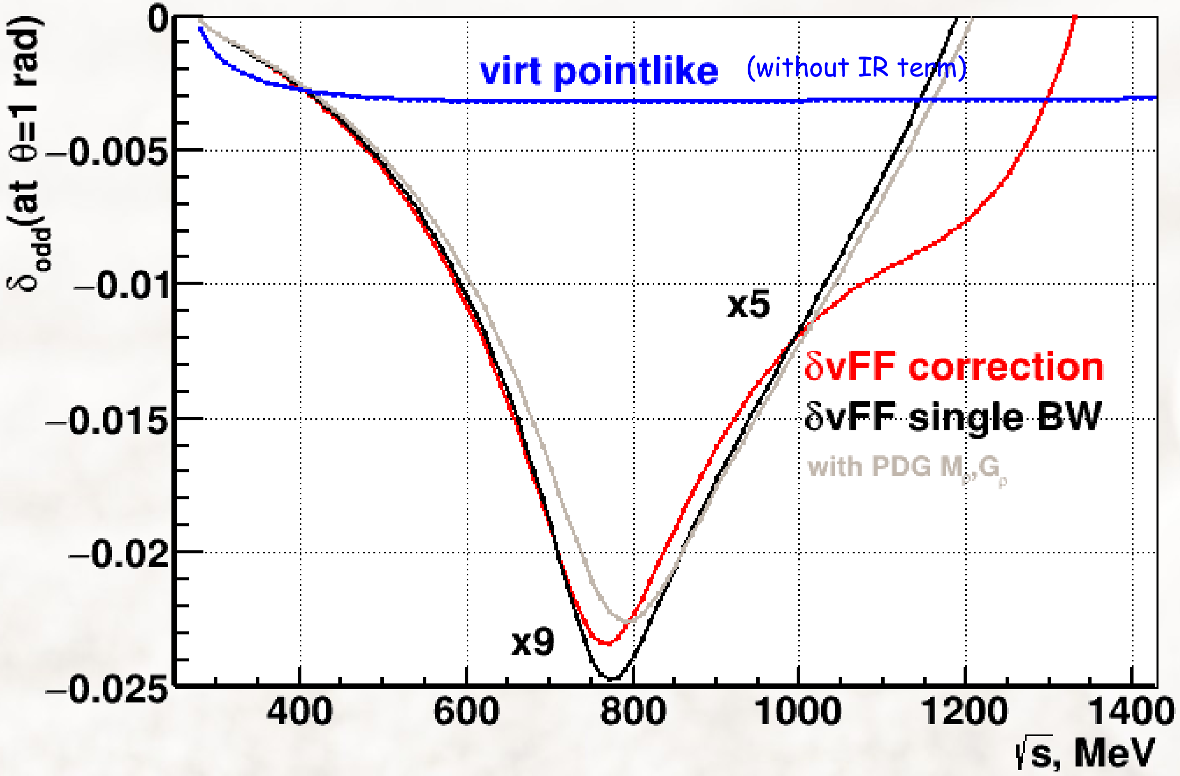
3 BW gives ~ 5% precision

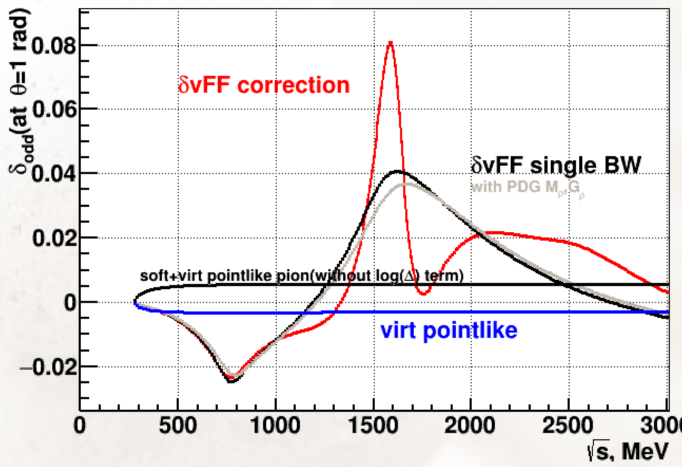


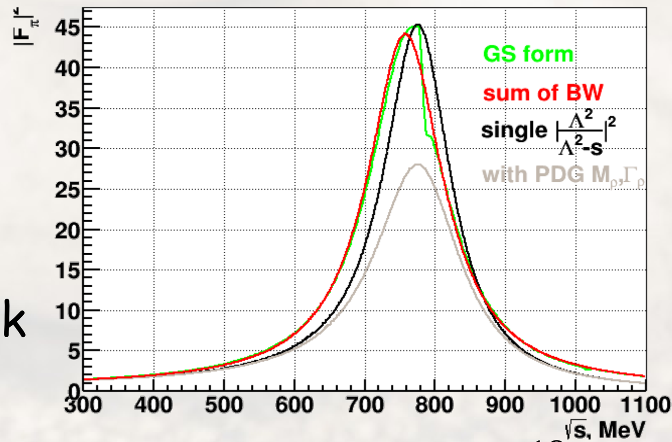


Virtual + soft corrections

$$d\sigma/d\theta = d\sigma^{Born}/d\theta * (1+\delta^{PL}_{odd}(s,\theta)+\delta^{vFF}(s,\theta))$$







Red line - with sum of BW,

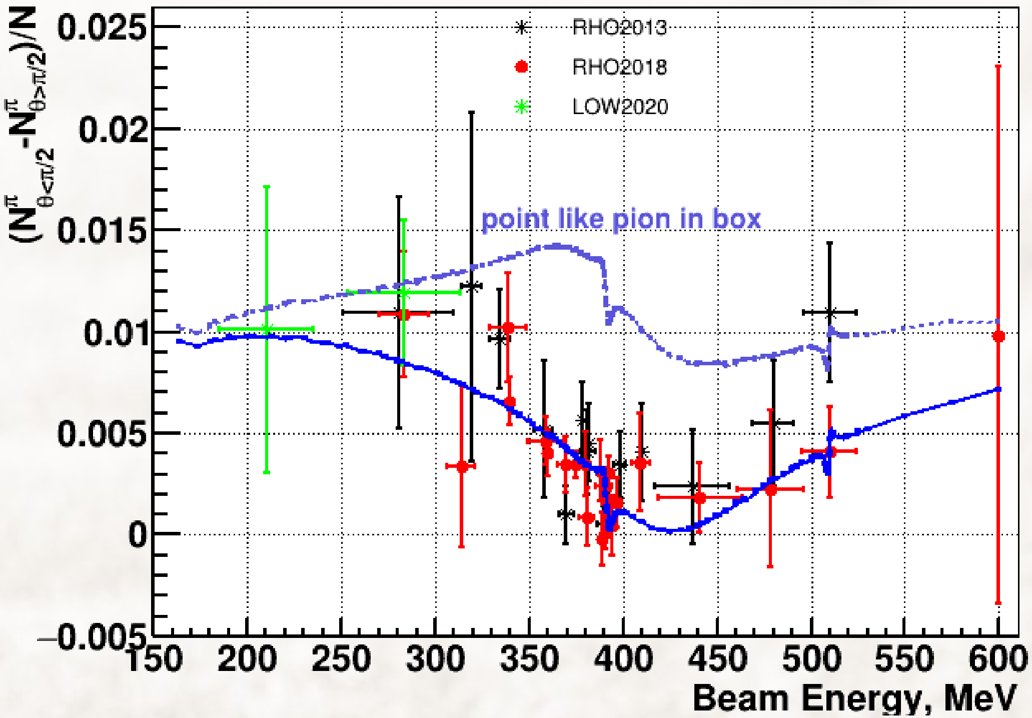
for comparison (black,grey) with single BW: result stable at ρ-peak

Enhancement of virtual correction by x5-10 factor!

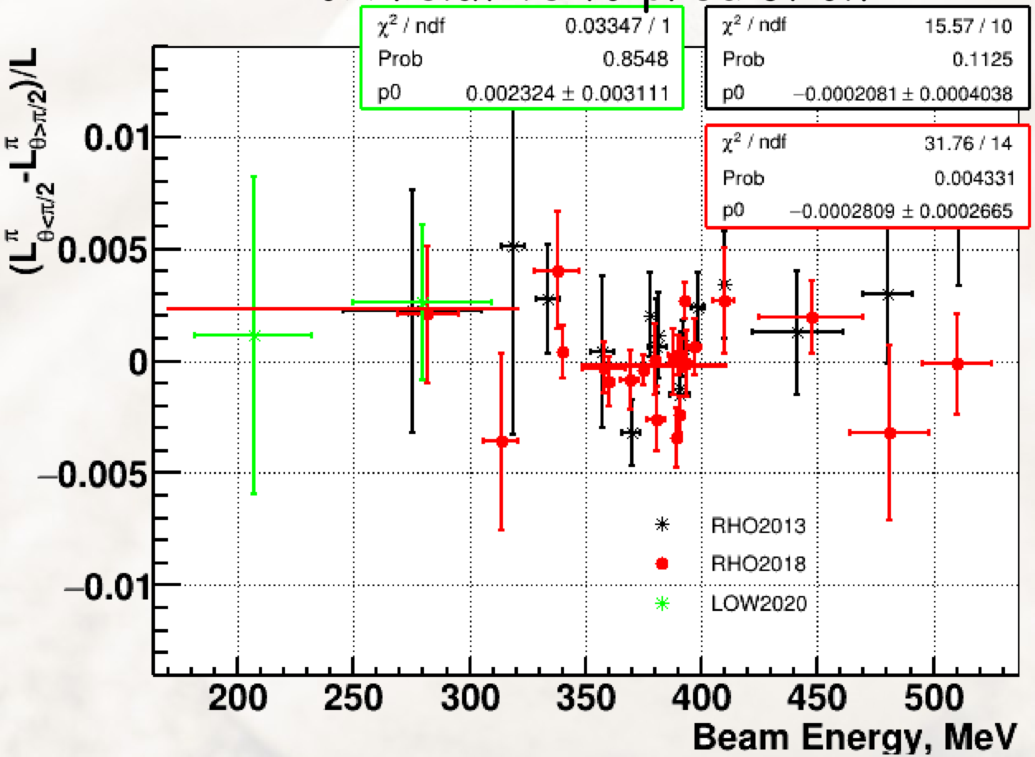
Asymmetry

After plugging δvFF in MCGPJ generator

Asymmetry



δA relative to prediction



at 2E=350-410 MeV

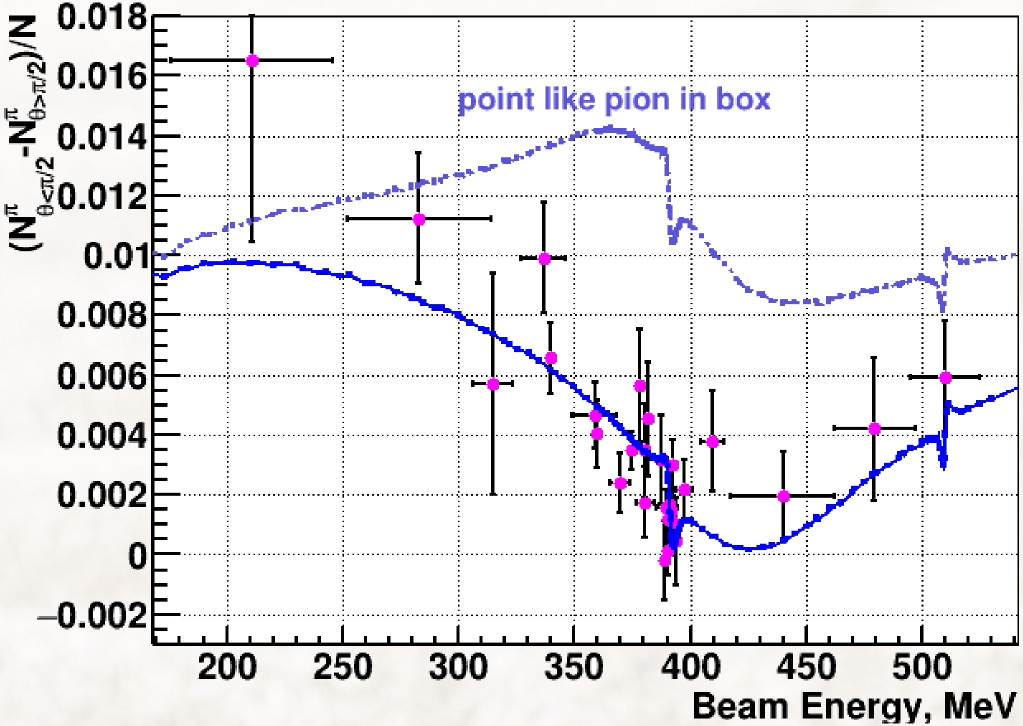
‹δA› = -1.035 ± 0.022 %

‹δA› = -0.026 ± 0.022 %

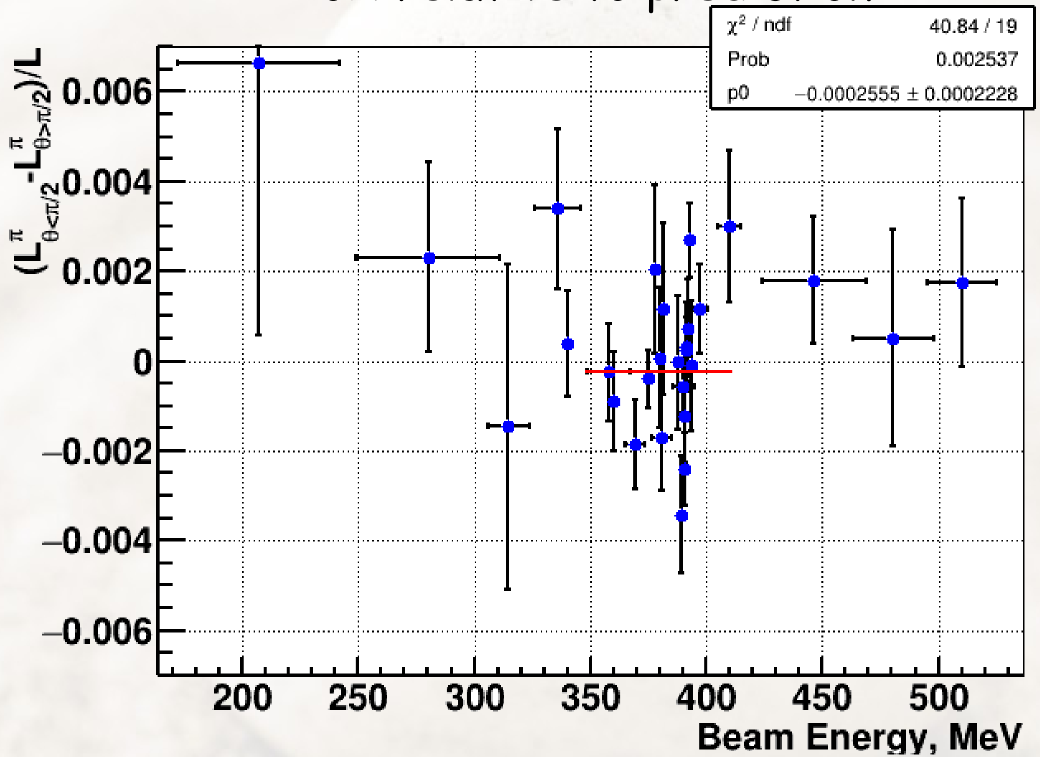
Asymmetry

After plugging δvFF in MCGPJ generator

Asymmetry



δA relative to prediction



at 2E=350-410 MeV

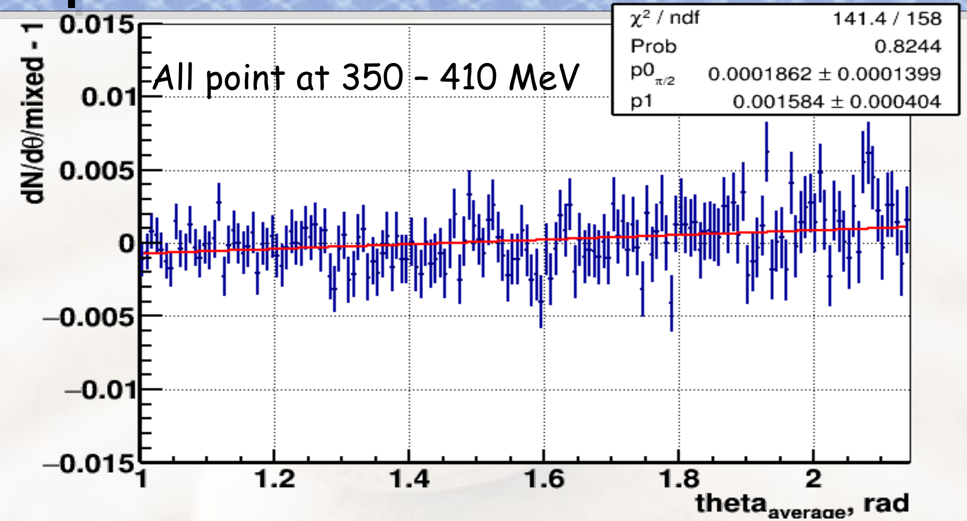
$\langle\delta A\rangle$ = -1.035 ± 0.022 %

$\langle\delta A\rangle$ = -0.026 ± 0.022 %

Final angle spectra

Still some disagreement in $dN/d\theta$ between data and prediction at level ~ 0.1%:

1) Bhabha generator or Asym. in 2π
2) detector inefficiencies
3) $N_{\pi\pi} / N_{ee}$



But already it allow to fit angle spectra with released $N_{\pi\pi} / N_{ee}$, Asym parameters.
For sum of 350-410 MeV points
Event separation by momentums:

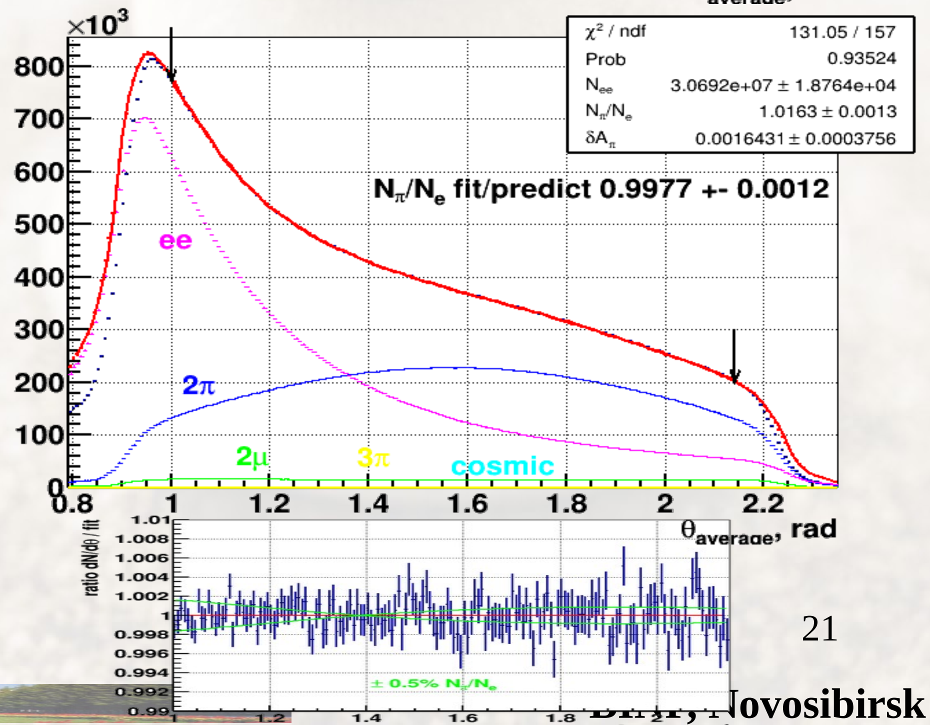
$N_{\pi\pi} / N_{ee}$ = 1.0187 +- 0.00028

by energies in LXe $\Delta N_{\pi\pi} / N_{ee}$ = +0.05 +- 0.033%

from theta with free δA: = -0.23 +- 0.12%

with fixed δA=0: = +0.20 +- 0.08%

Common stat from √N: 0.025%

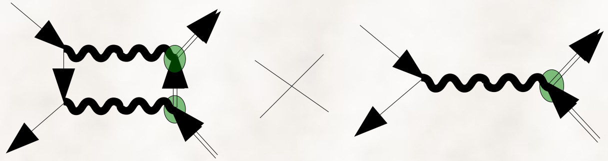


We have 3 fully independent methods for $N_{\pi\pi} / N_{ee}$ determination, they are consistent at ~ 0.2%

How it can affect pion form factor measurements?

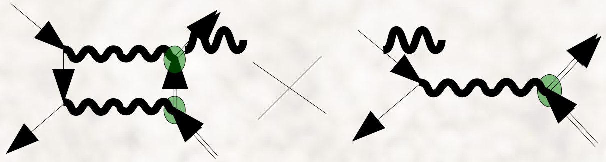
Usually event selections in analyses are charge/angle symmetric

Main effect at lowest order comes from:
Interference of box vs born diagrams



=> only charge-odd contribution
effect is integrated out
in full cross-section

Interference of ISR & box vs FSR (or v.v.)



=> charge-even
can affect integrated cross-section

The team:
F. Campanario, G. Rodrigo, Sz. Tracz (Valencia)
H.C., J. Gluza, (Katowice)
T. Jeliński, D. Zhuridov (left physics)

Henryk Czyz
the Muon g-2 Theory Initiative Worksop 2019

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

Status - finished: arXiv:1903.10197

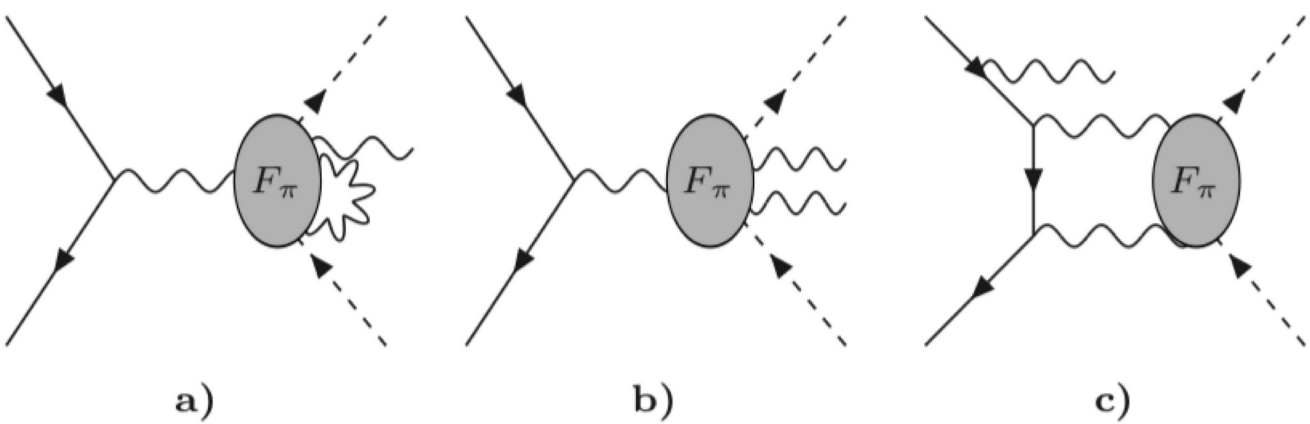
F. Campanario et al.
Phys.Rev.D 100 (2019) 7, 076004

$\Rightarrow$ sQED + form factors:
FSR at NLO and pentaboxes ready and fully tested

$\Rightarrow$ Phokhara10.0
http://ific.uv.es/$\sim$ rodrigo/phokhara/

FSRNLO

TVP (two virtual photon)



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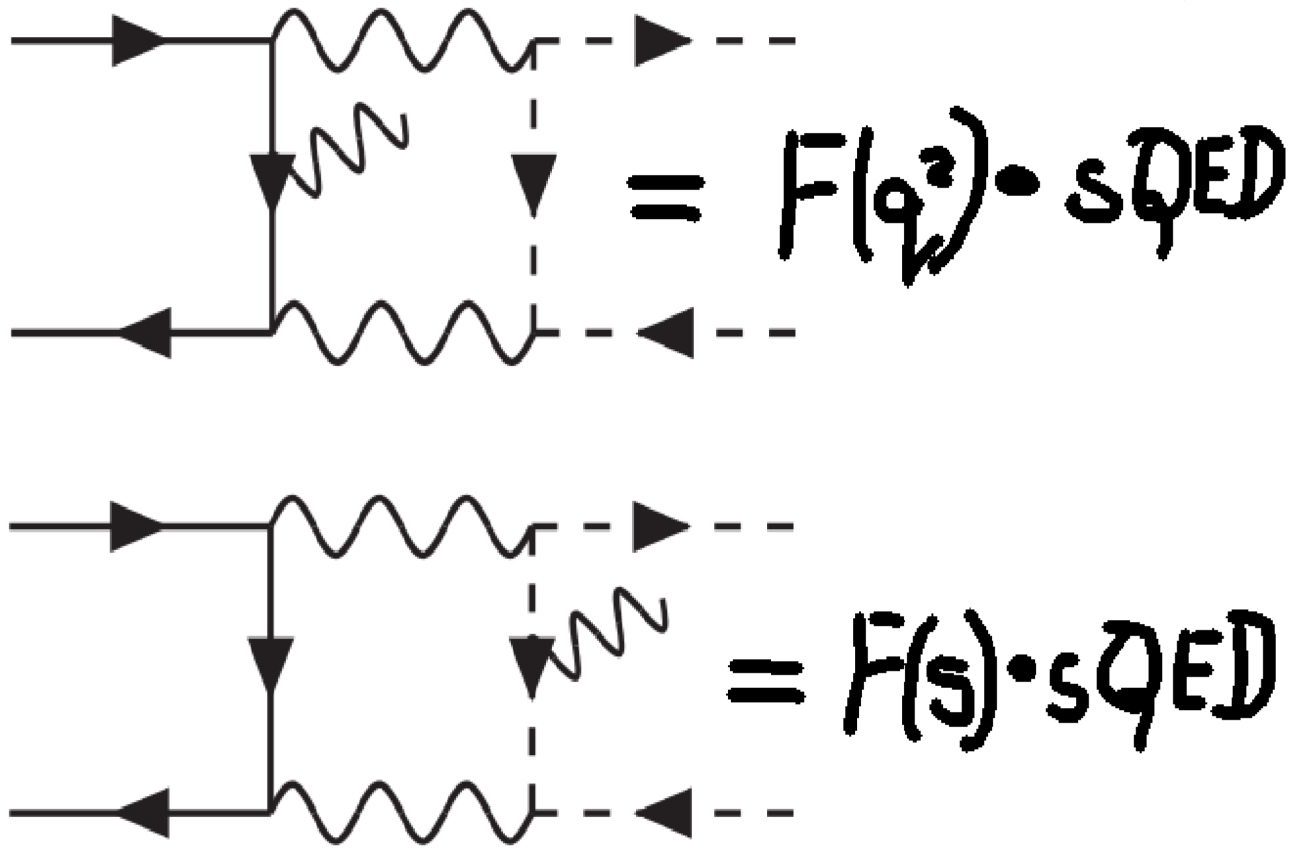
Initiative Worksop 2019

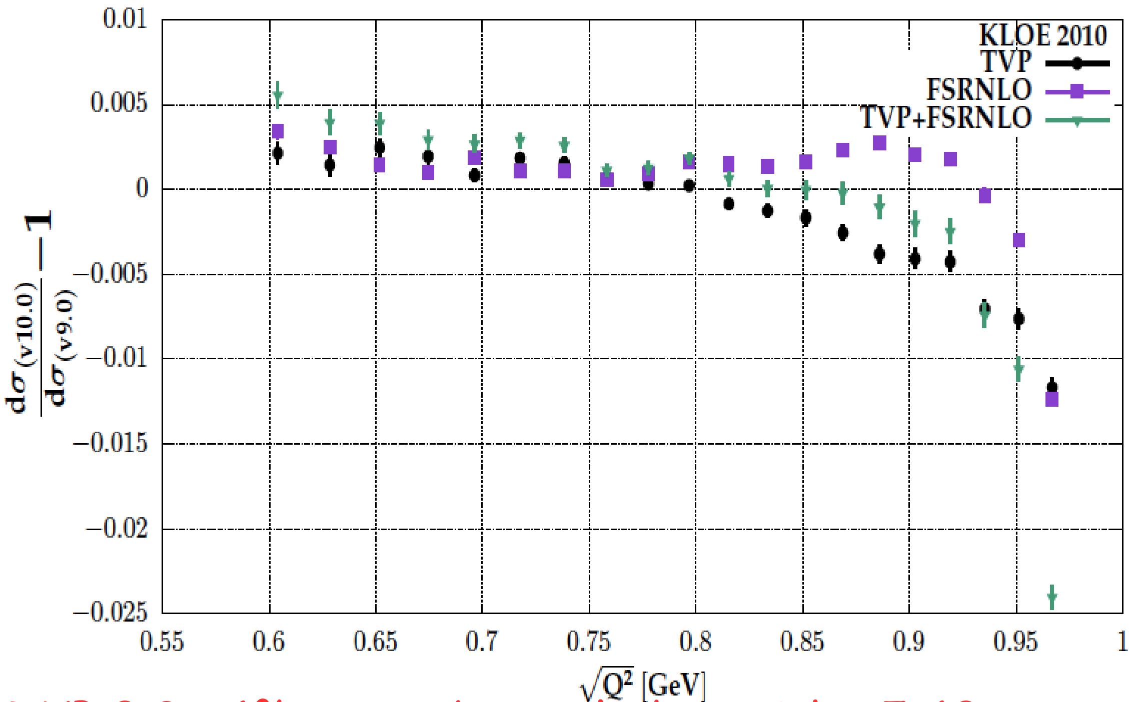
Model assumptions



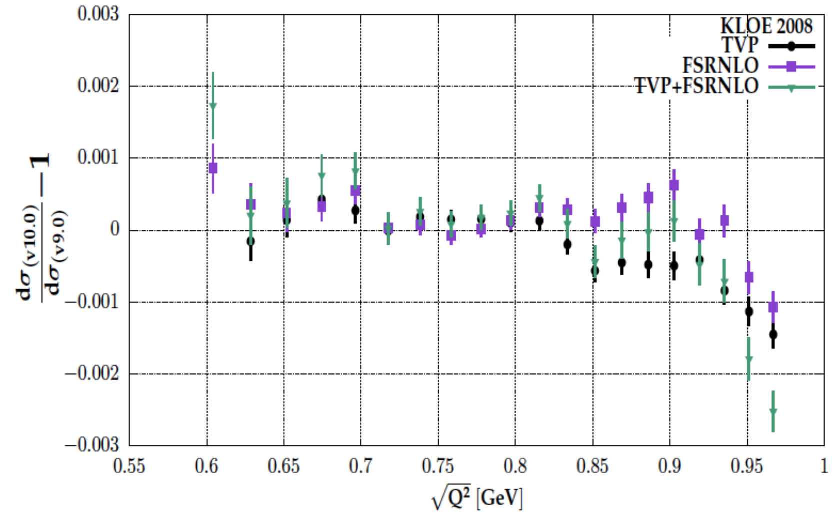
H. Czyż Radiative corrections in PHOKHARA and EKHARA MC generators, 12

ISR measurements

Complete NLO: KLOE-large



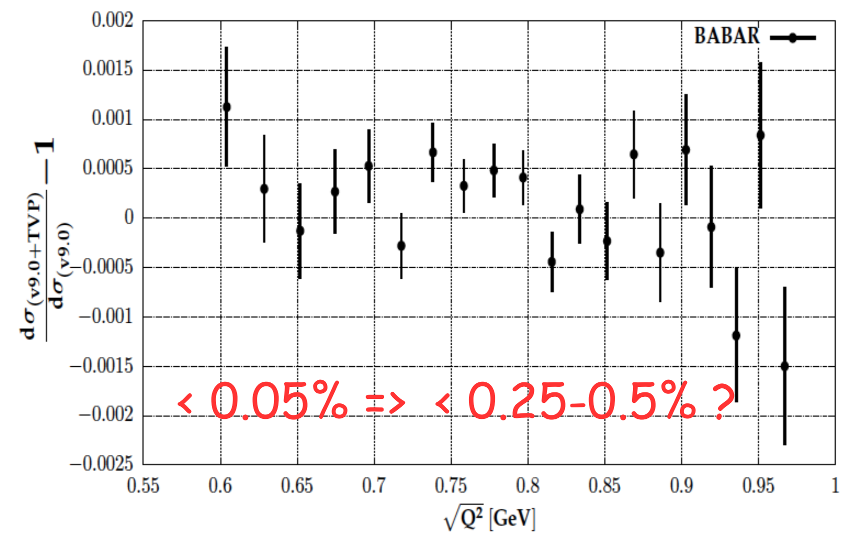
Complete NLO: KLOE-small



TVP 0.2 – 1% => can be scaled up with x5-10

to 1-5% correction?

Complete NLO: BaBar



< 0.05% => < 0.25-0.5% ?

KLOE-2010 with tag photon measurement can be affected

Summary

Измеренная зарядовая асимметрия в 2π на КМД-3
отличается на 1% (стат. точность 0.022%) от предсказания на основе sQED

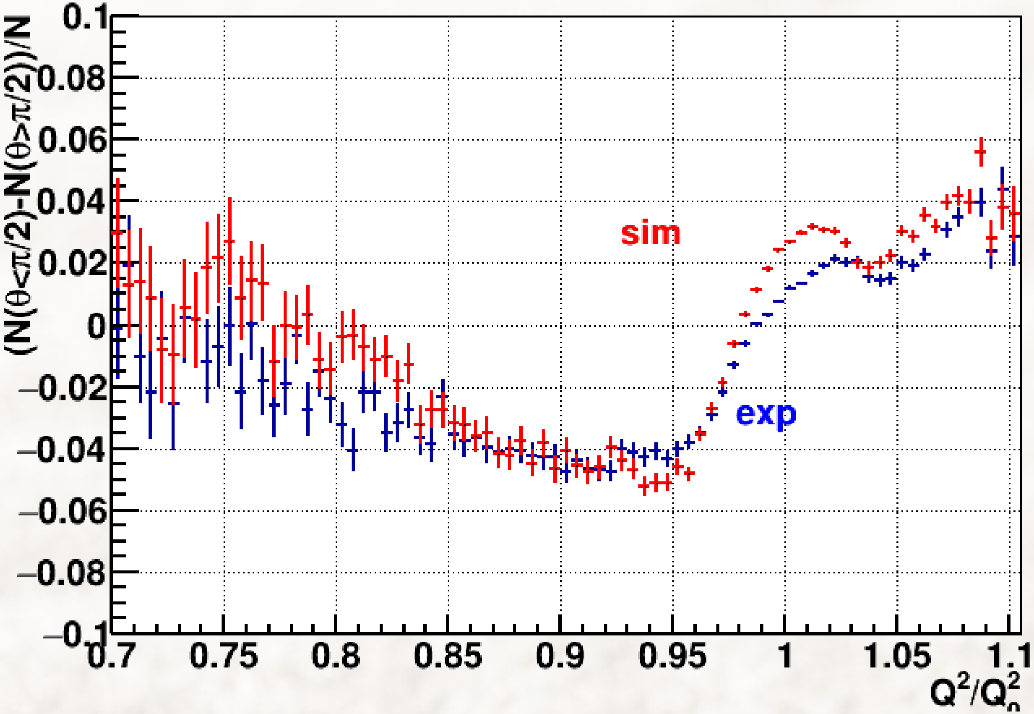
Более правильные учет Форм Фактора в двух-фотонной диаграмме
сильно усиливает её вклад
($\Delta\delta_{odd}$(Mρ,θ = 1 рад) = -2.3% при уровне желаемой точности генератора 0.1-0.2%)

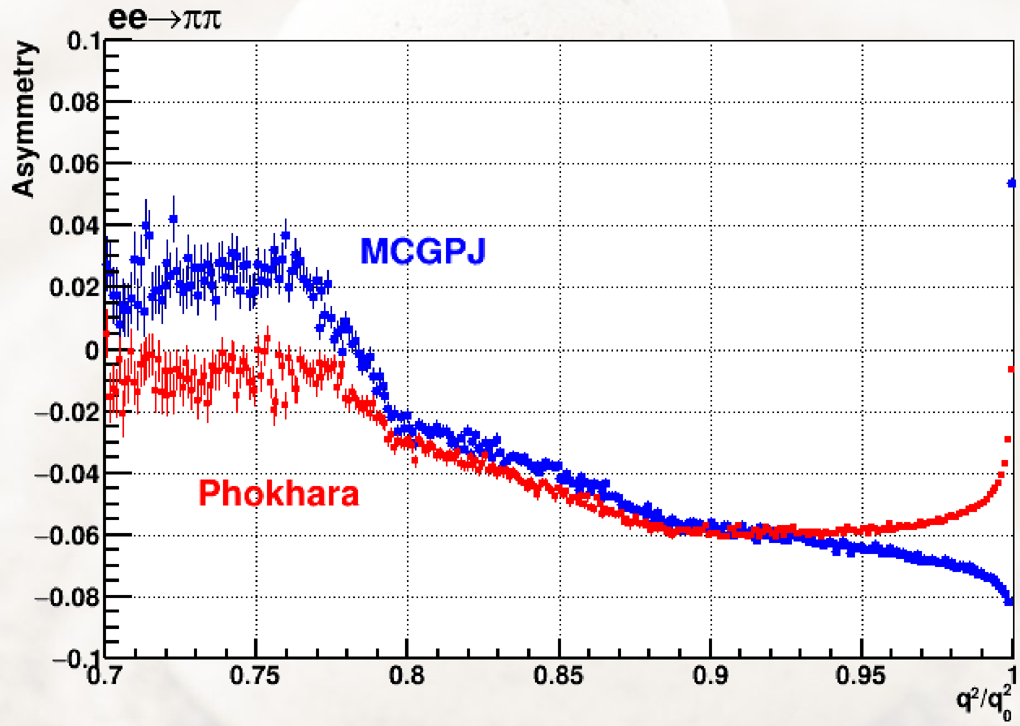
Существенный вклад может быть как в зарядово-нечётную,
так и в некоторых случаях (с ISR) в зарядово-чётную часть рад. поправки.

Учёт двойного ФФ в box-диаграмме хорошо описывает наблюдаемый эффект 2π
асимметрии в данных КМД-3.

backups

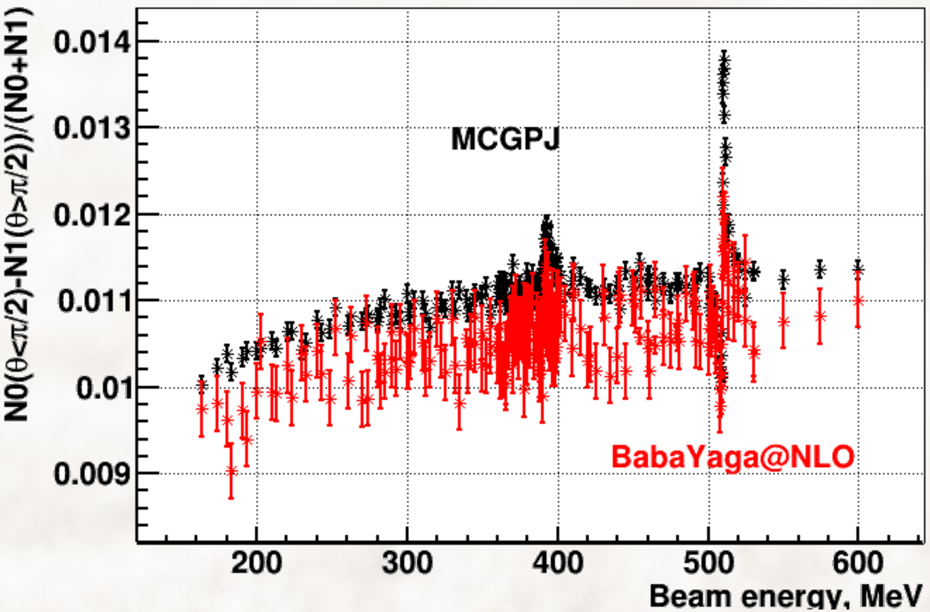
Generators MCGPJ/Phokhara

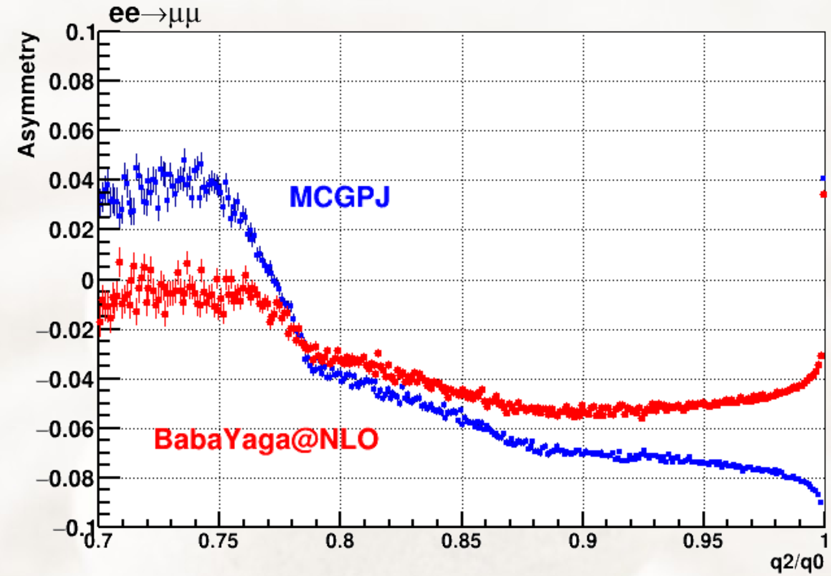


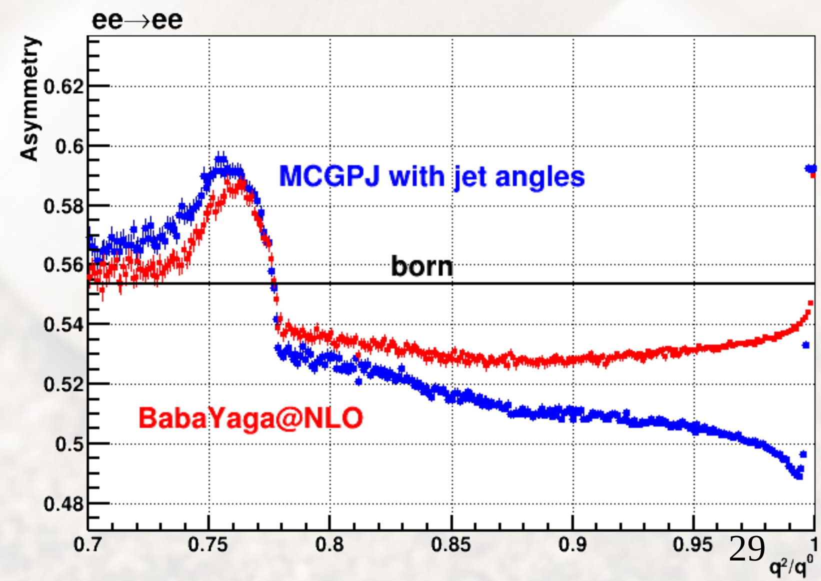


Generators MCGPJ/BabaYaga@NLO

Для μ+μ- интегральная асимметрия совпадает
между MCGPJ/BabaYaga@NLO
с абс. точностью ~0.05% (5% относительная точность)







BabaYaga@NLO моделирует фотоны рекурсивно
У нас только один фотон на большой угол
Поведение BabaYaga около q2~ 1 более физично
Скорее всего это отличие дает эффект в систематику
разделения по P из-за разницы генераторов

Asymmetry with q2

Ebeam 350-410 MeV, MIP: E_{LXe}^{+-}<100 MeV