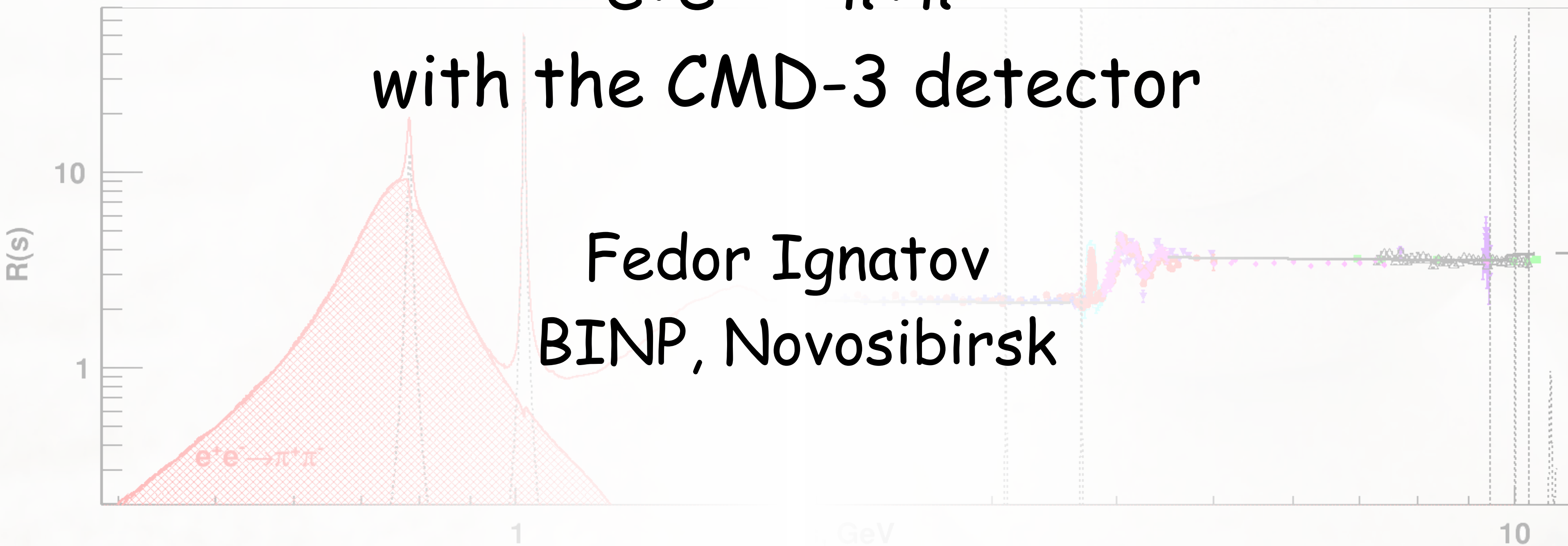
arXiv:2302.08834

$e^+e^- \to \pi^+\pi^-$ with the CMD-3 detector



Fedor Ignatov
BINP, Novosibirsk

17 March 2023

The Muon g-2 Theory Initiative Seminar

55 years of hadron production at colliders

Volume 25B, number 6 PHYSICS LETTERS 2 October 1967

INVESTIGATION OF THE ρ-MESON RESONANCE WITH ELECTRON-POSITRON COLLIDING BEAMS

V. L. AUSLANDER, G. I. BUDKER, Ju. N. PESTOV, V. A. SIDOROV, A. N. SKRINSKY and A. G. KHABAKHPASHEV
Institute of Nuclear Physics, Siberian Branch of the USSR Academy of Sciences, Novosibirsk, USSR

Received 1 September 1967

Preliminary results on the determination of the position and shape of the ρ-meson resonance with electron-positron colliding beams are presented.

When experiments with electron-positron colliding beams were planned [1, 2] investigation of the process

$$e^- + e^+ \rightarrow \pi^- + \pi^+$$

$$e^- + e^+ \rightarrow K^- + K^+$$

cor ter ide of cha cop

1 September 1967

Start of e+e- → hadrons measurements

Phys.Lett. 25B (1967) no.6, 433-435

VEPP-2, Novosibirsk

Detector was made from different layers of Spark chambers,
readouts by photo camera

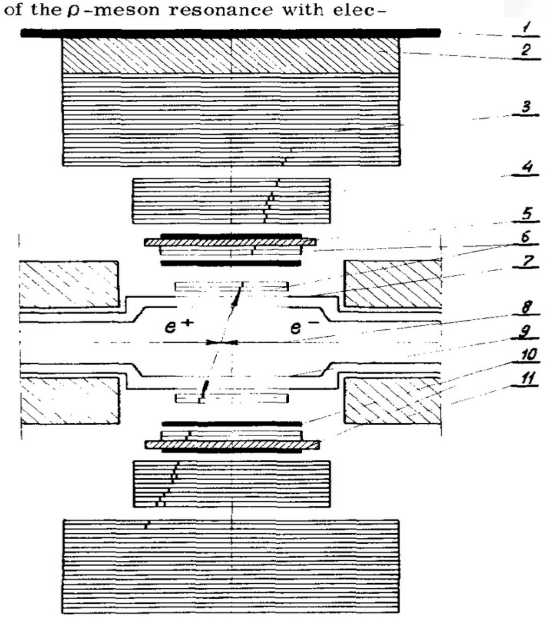


Fig. 1. Spark chambers system:
1) Anticoincidence scintillation counter
2) Lead absorber 20 cm thick
3) "Range" spark chamber
4) "Shower" spark chamber
5) Duraluminium absorber 2 cm thick
6) Thin-plate spark chambers

e+e- → ρ → ππ

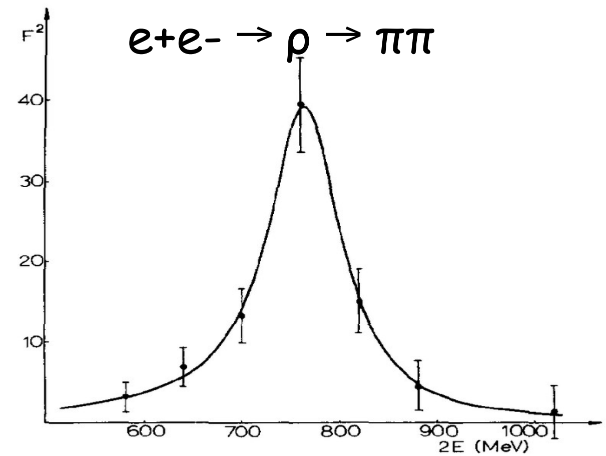
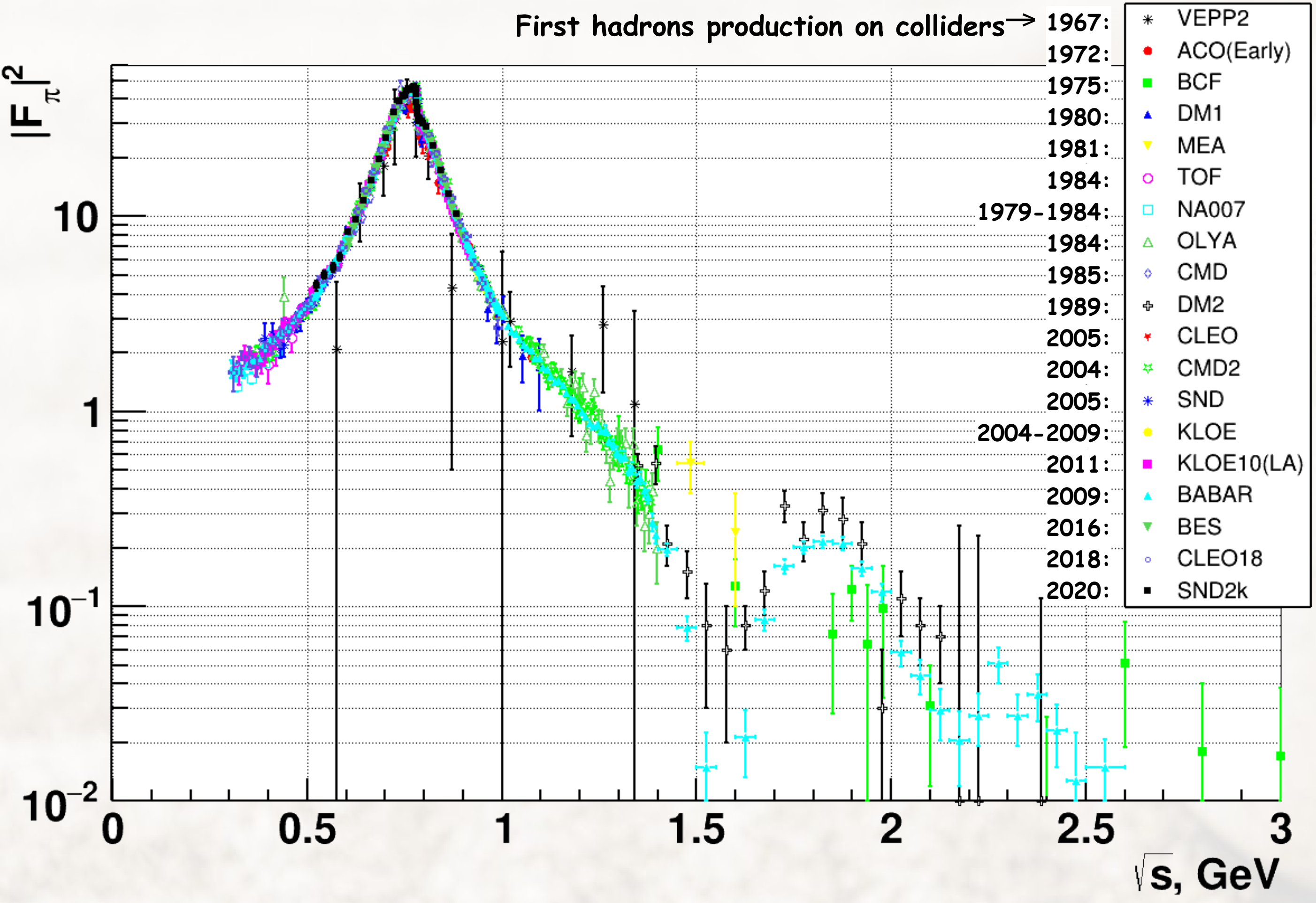


Fig. 2. Experimental values of F^2 (E) approximated by the Breit-Wigner formula.

ment geometry and F- modulus of the form factor for pion pair production [1]. In the case of QED with no other forces F=1. If the particles are produced at the angle 90° with respect to the beam axis then a=18. Integration over the solid angle gives a=20.4.

e+ e− → π+ π− today



New g-2 experiments and future e+e- as ILC, FCC-ee require average precision ~0.2%

Before 1985

Low statistical precision

Systematics >10%

NA7 A few points with >1-5%

1985 - VEPP-2M

with more detailed scan

OLYA systematics 4%

CMD 2%

2004 with CMD2 at VEPP-2M

was boost to systematics: 0.6%

(near same total statistic)

The uncertainty in a_μ(had) was improved by factor 3 as the result of VEPP-2M measurements

New ISR method

e+e- → γ + hadrons (limited only by systematics):

KLOE: 0.8%

BaBar: 0.5%

BES: 0.9%

CLEO: 1.5%

New direct data:

SND2k : 0.8% (with 1./10 of avail. data)

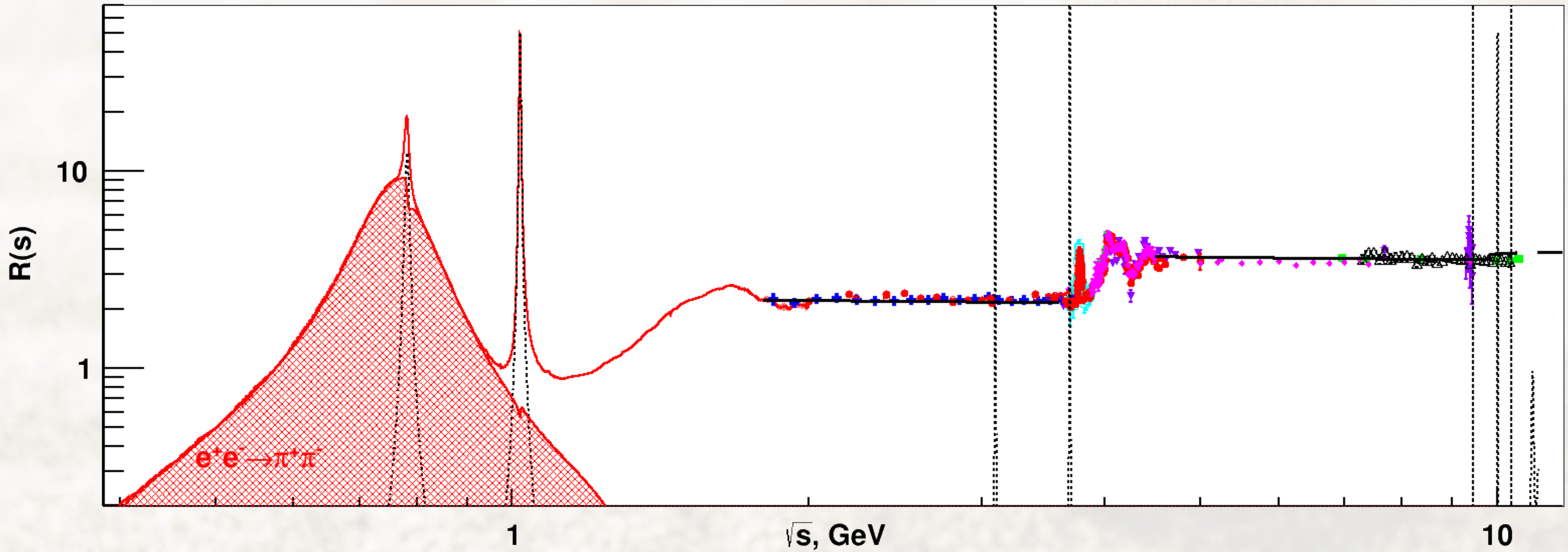
$$R(s) = \frac{\sigma^0(e^+e^- \to \gamma^* \to hadrons)}{\sigma^0(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

R(s) is one of the fundamental quantities in high energy physics:

its reflects number of quarks and colors → pQCD tests;

QCD sum rules → quark masses,quark and gluon condensates, Λ_{QCD}

Dispersion relations → $\alpha_{QED}(M_Z)$, hyperfine muonium splitting, muon (g-2)



$e^+e^- \to \pi^+\pi^-$ gives main contribution to R(s) at $\sqrt{s} < 1$ GeV

White Paper 2020 (e-Print: 2006.04822)

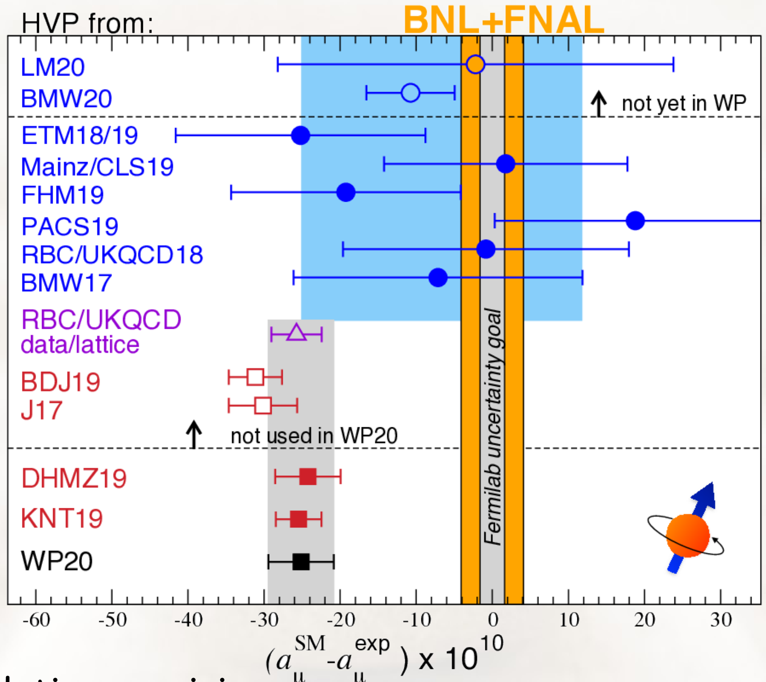
Experimental world average (E821+E989)

a_μ = 11 659 206.1 ± 4.1 x 10^{-10}

Theoretical prediction data driven

a_μ = 11 659 181.0 ± 4.3 x 10^{-10} **(WP20)**

Δa_μ = 25.1 ± 5.9 x 10^{-10}



e-Print: 2203.15810

Hadronic part from measured cross-section

LO hadronic 693.1 ± 4.0 x 10^{-10}

		Relative precision
$\pi^+\pi^-$	506.0 ± 1.9 ± 2.8 (KLOE/BABAR difference)	0.7%
$\pi^+\pi^-\pi^0$	46.4 ± 1.5 (mostly from omega region)	3.2%
$\pi^+\pi^-\pi^0\pi^0$	18.1 ± 0.7	3.9%
Inclusive($\sqrt{s}$>1.8-3.7 GeV)	34.0 ± 0.7 ± 0.7 (DV+QCD)	2.9%

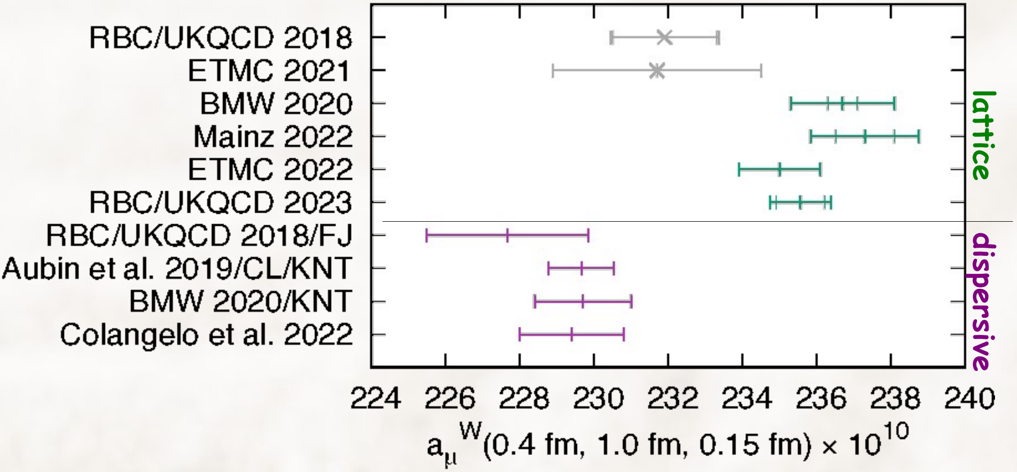
....

Light-by-light 9.2 ± 1.9

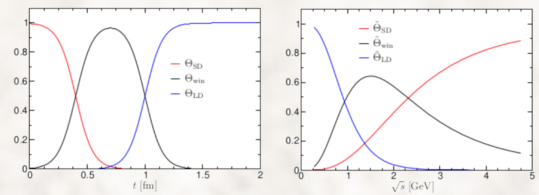
Dispersive vs Lattice

T.Blum et al, e-Print: 2301.08696 [hep-lat]

a_μ^{HVP} contribution from intermediate window in Euclidean time



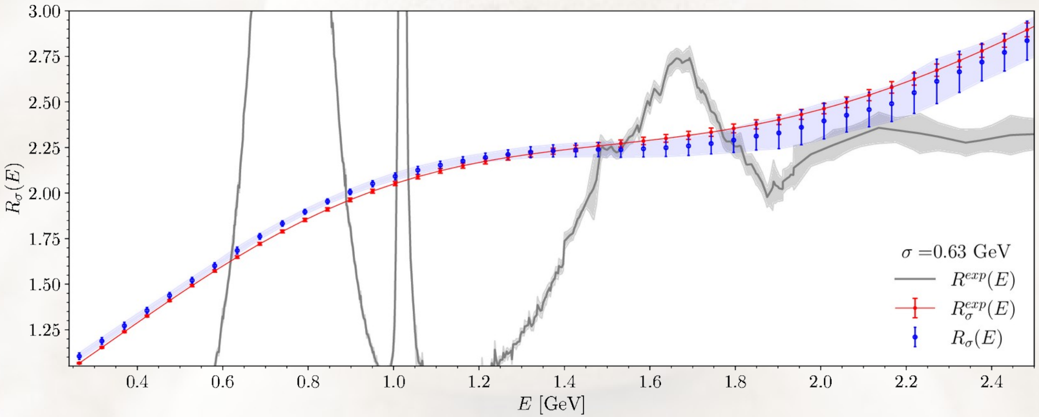
Windows definition

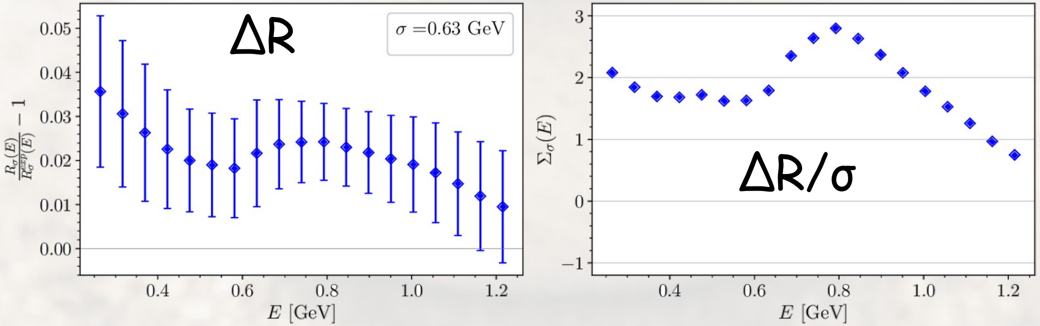


~4σ tension between Lattice/Dispersive

C. Alexandrou et al, e-Print: 2212.08467 [hep-lat]

R(s) is convolved with Gaussian kernel



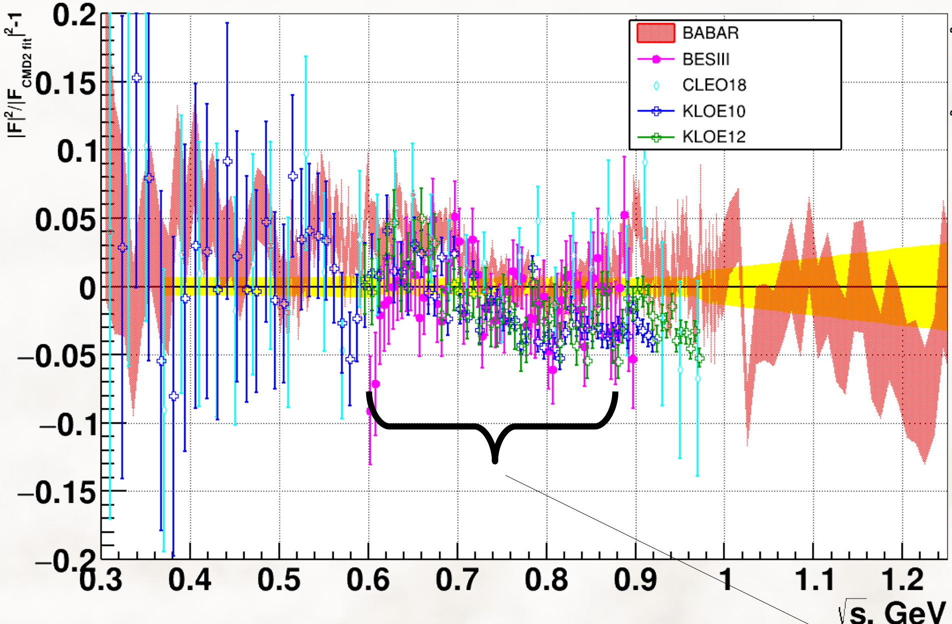


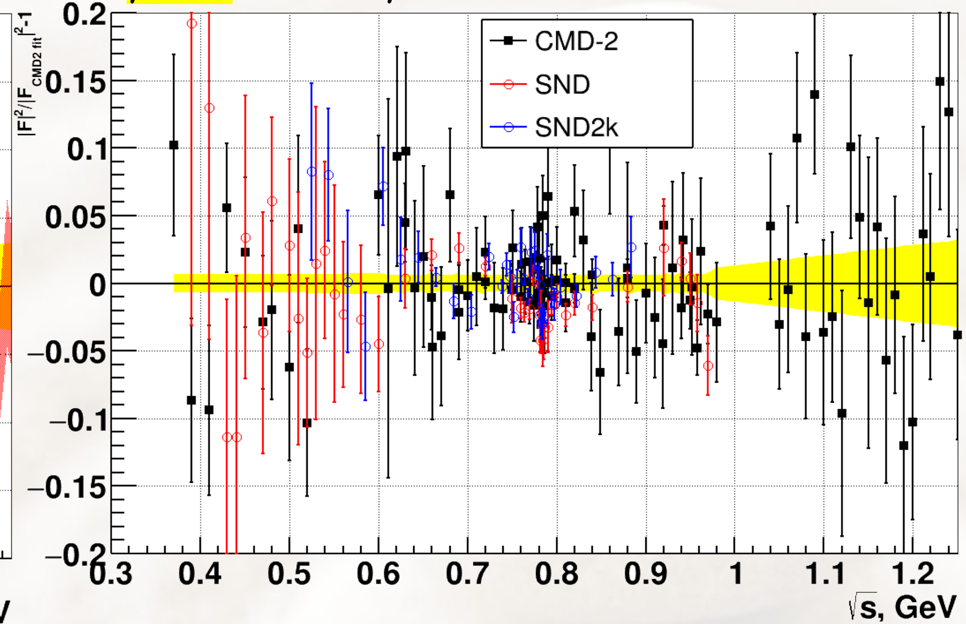
~3σ tension at rho energies

Question of comparison: e+e- vs $(g-2)_\mu$ vs lattice

The π+ π− contribution to a_μ^{had}

Relative to CMD-2 fit, yellow band – systematic value

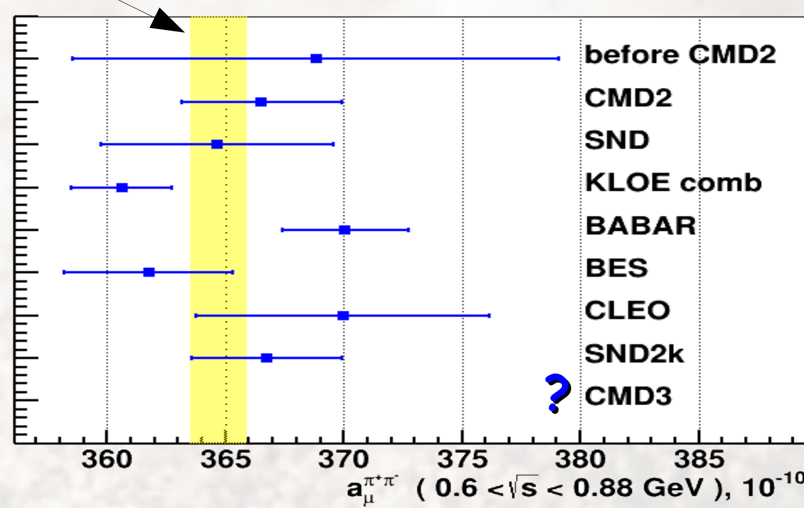




Integral precision
is limited by systematics

local inconsistencies larger
than claimed systematic errors
→ additional scale factor

Seen 2.9σ tension KLOE vs BaBar → KLOE/BABAR difference

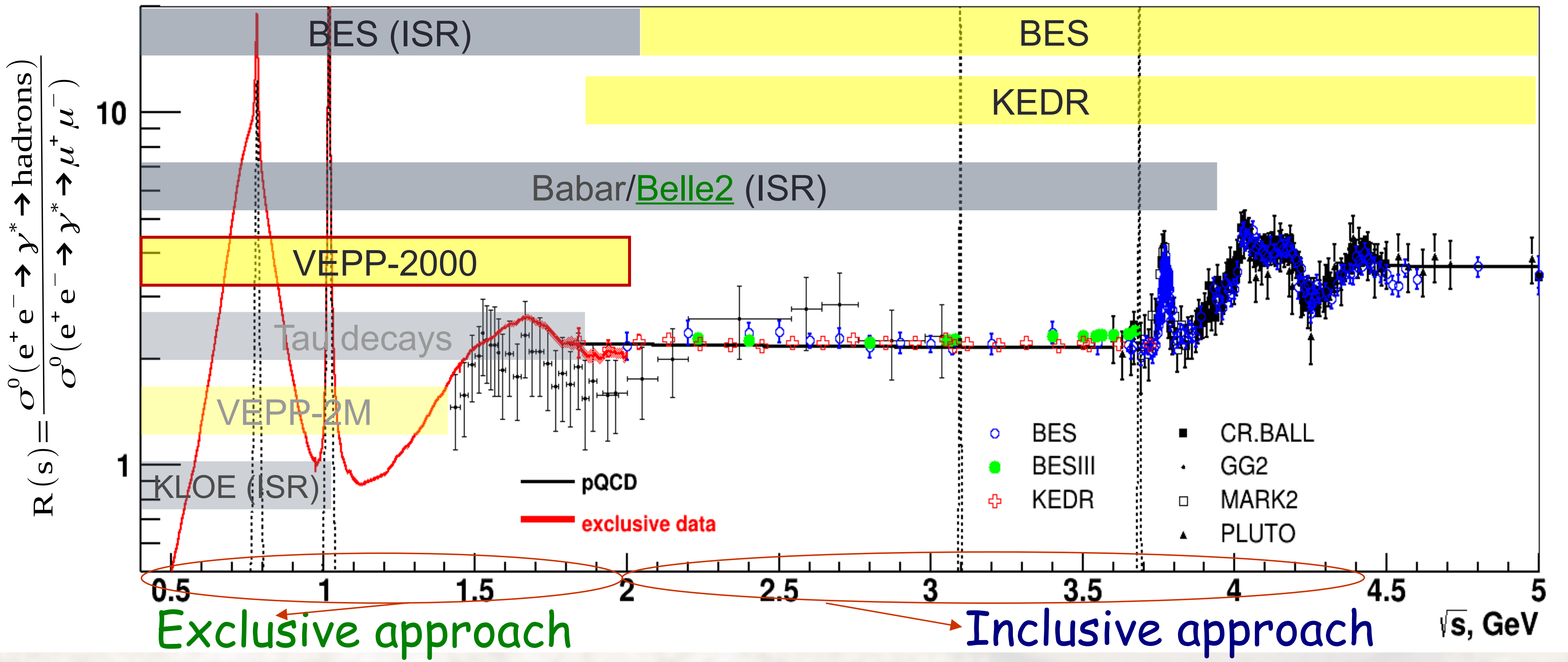


Systematic Error
(ρ-region)
CMD2: 0.6-0.8%
SND: 1.5%
KLOE: 0.8%
BABAR: 0.5%
BES: 0.9%
CLEO: 1.5%
SND2k : 0.8%
CMD3:

$a_\mu(\pi^+\pi^-) = 506.0 \pm 1.9 \pm 2.8 \times 10^{-10}$ (±0.7%)

R(s) measurement

Two techniques: ISR vs Energy scan



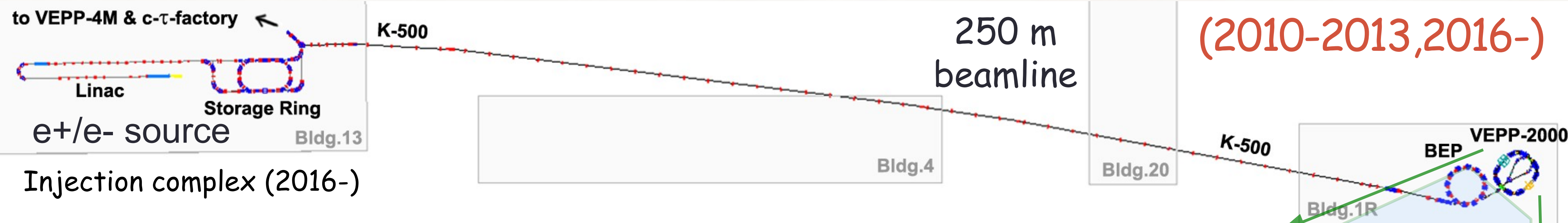
VEPP-2000: direct exclusive measurement of σ (e+e- → hadrons)

Only one working these days on scanning below <2 GeV

World-best luminosity below 2 GeV (except 1 GeV – where KLOE outperfomed everybody)

BESIII, KEDR – inclusive measurement of R(s) from 2 GeV to 5 GeV

VEPP-2000 e+e- collider



<u>VEPP-2000: direct exclusive measurement of σ (e+e- → hadrons)</u>

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

Unique optics, "round beams" to reach higher L

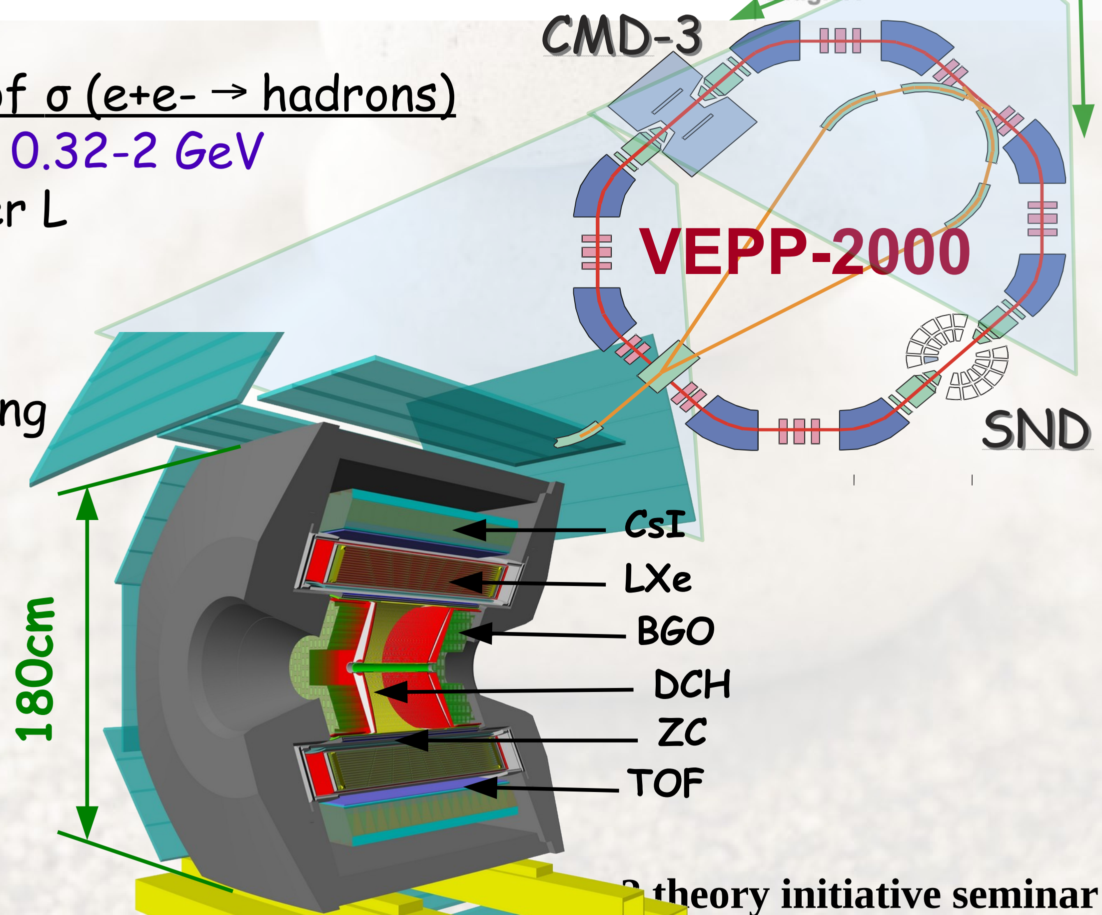
$L = 0.8\times10^{32}\ cm^{-2}s^{-1}$ at 2E= 2 GeV

Energy monitoring by Compton backscattering

$\sigma_{\sqrt{s}} \approx 0.1$ MeV

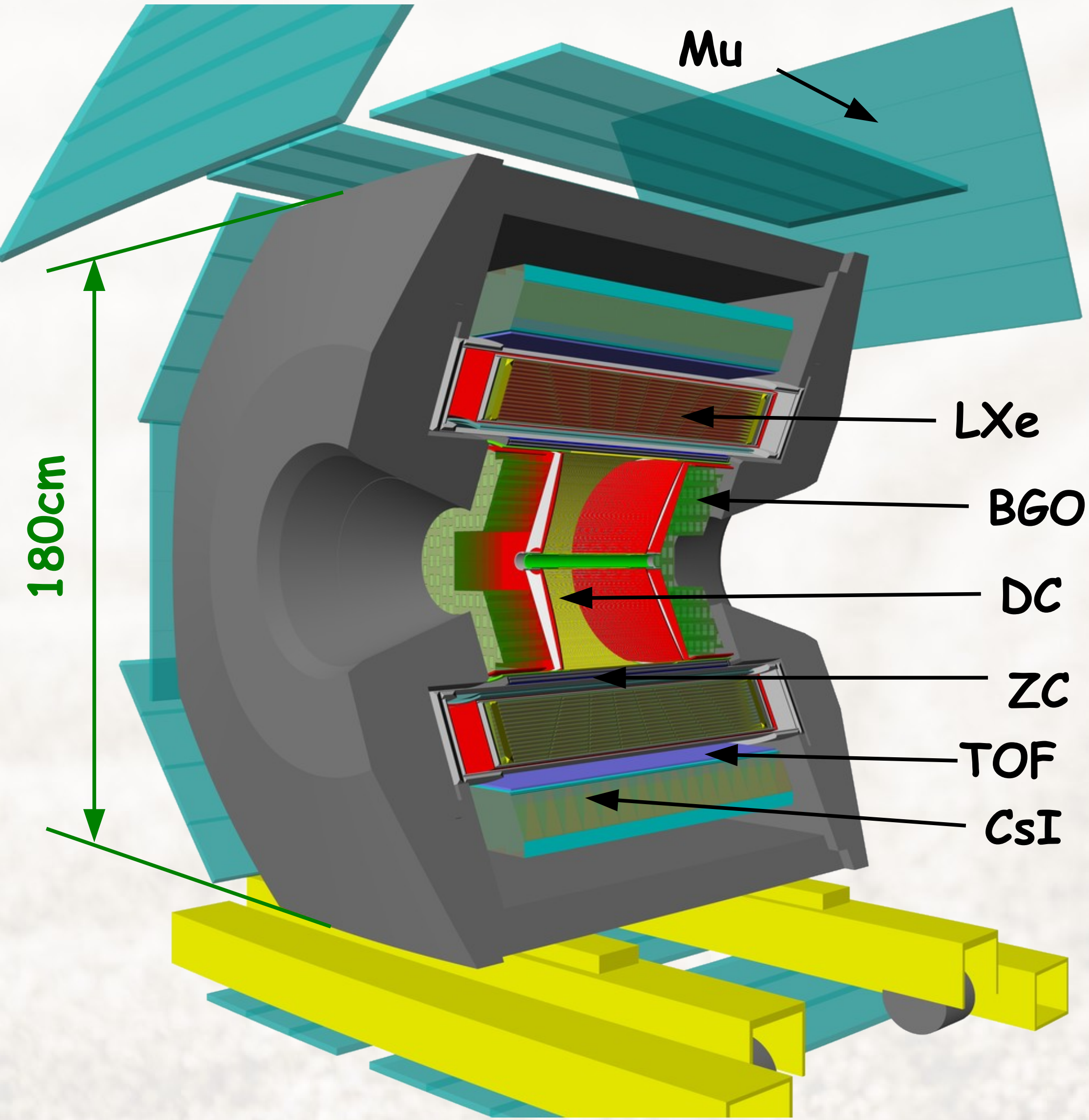
<u>Two detectors: CMD-3 and SND</u>

started by the end of 2010




VEPP-2000
collider ring
SND
CMD-3
6.65 m

CMD-3 detector



Tracking:

✗ Drift Chamber in 1.3 T magnetic field

$\sigma_{R\varphi}$ ~ 100 μm, σ_Z ~ 2.5mm

$\sigma_P/P \sim \sqrt{0.6^2+(4.4*p[GeV])^2}$,%

✗ **ZC-chamber worked until summer 2017**

σ_Z ~ 0.7mm by strip readout

Calorimetry:

✗ Combined EM calorimeter (LXe,CsI, BGO)
13.5 X_0 in barrel part

$\sigma_E/E \sim 0.034/\sqrt{E\,[GeV]} \oplus 0.020$ - barrel

$\sigma_E/E \sim 0.024/\sqrt{E\,[GeV]} \oplus 0.023$ - endcap

✗ LXe calorimeter with 7 ionization layers with strip readout

~2mm measurement of conversion point,
tracking capability,
shower profile (from 7 layers + CsI)

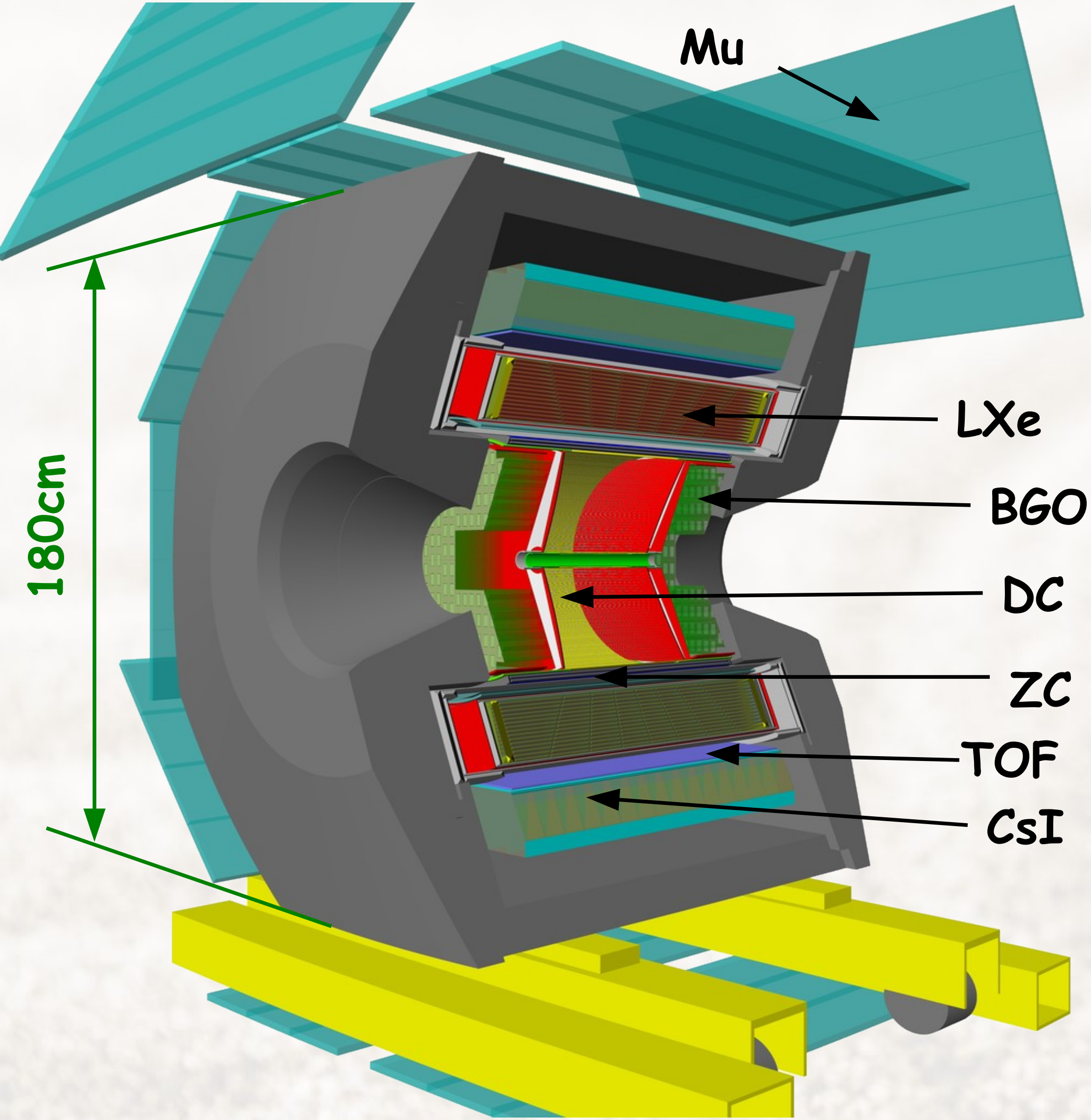
PID:

✗ TOF system (σ_T ~ 0.4 nsec)

particle id mainly for p, n

✗ Muon system

CMD-3 detector



Advantages compared to previous CMD-2:

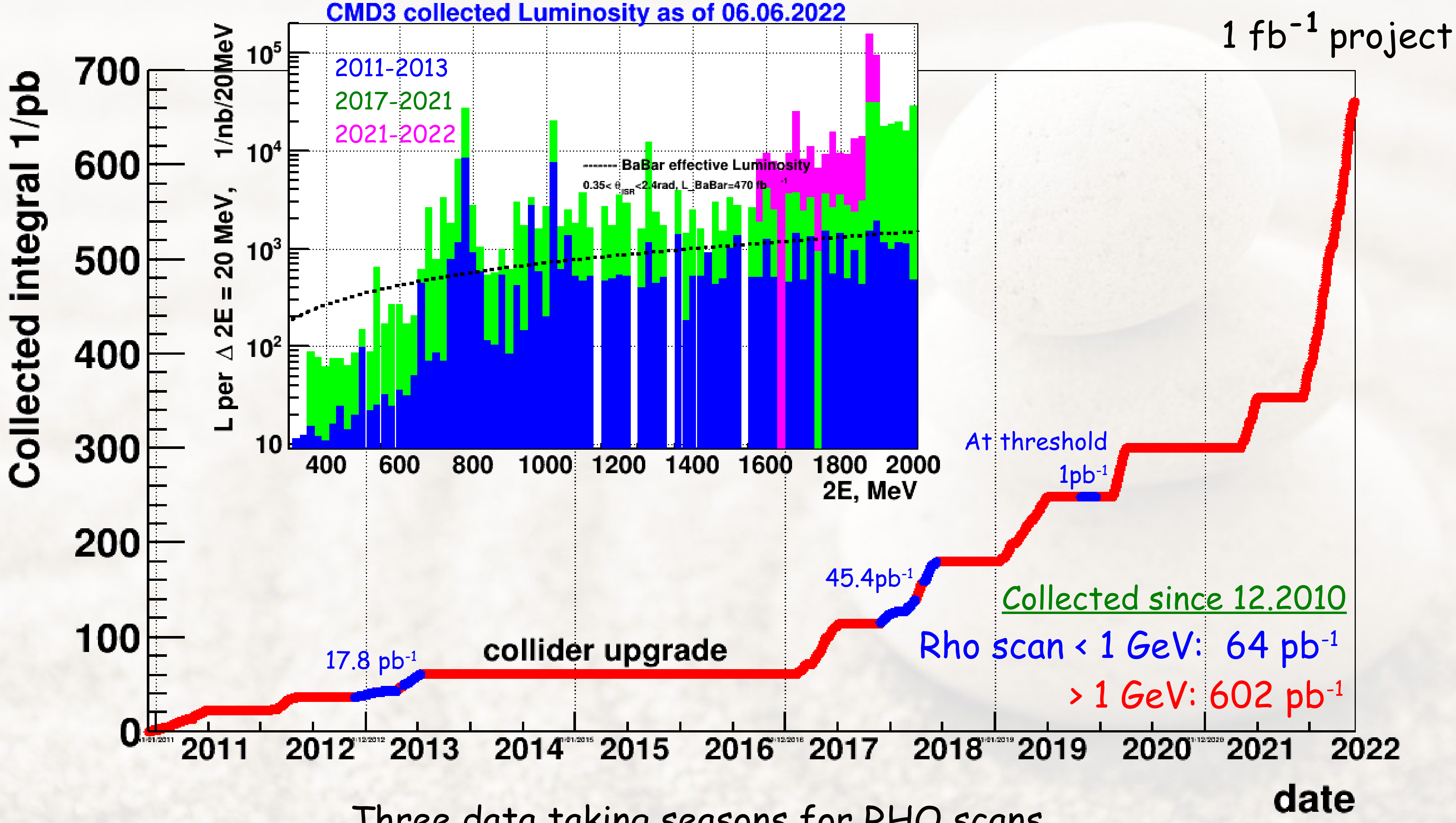
✗ new drift chamber with x2 better spatial resolution, higher B field
  better rec. efficiency (factor ~2-5)
  better momentum resolution (factor ~ 2)

✗ Unique LXe calorimeter with 7 ionization layers with strip readout
  ~2mm measurement of conversion point,
  tracking capability,
  shower profile (from 7 layers + CsI)

✗ thicker barrel calorimeter,
  $8.3\ X_0 \rightarrow 13.4\ X_0$
  better particle separation

✗ TOF system
  particle id (mainly p, n)

Overview of CMD-3 data taking runs



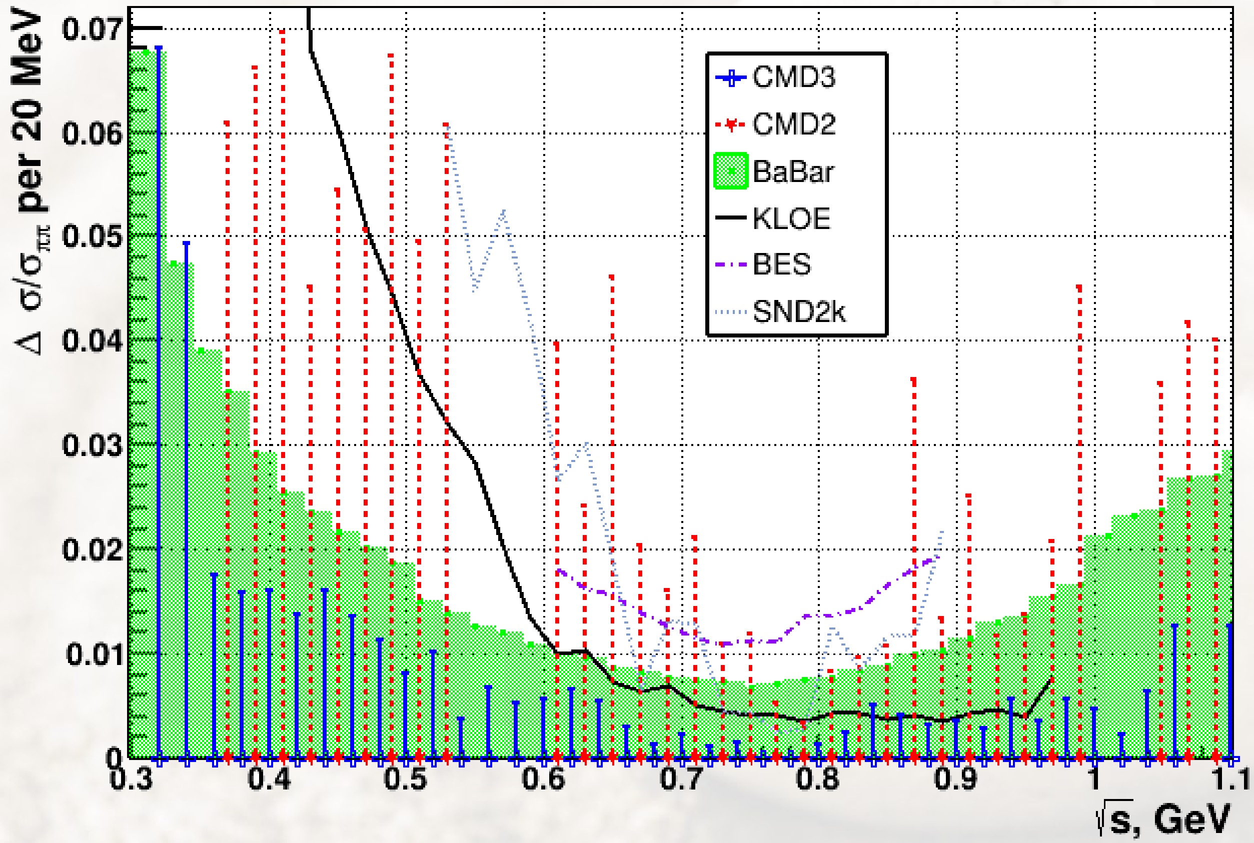
Three data taking seasons for RHO scans

e+e- → π+π- by CMD-3

Statistical precision of cross section measurement for seasons at <1 GeV (2013+2018+2020)
a few times better than any other experiments

Full statistic up to date with ρ scans

RHO2013
RHO2018
LOW2020

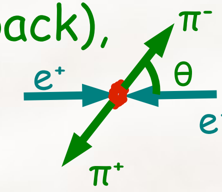


Analysis based on L = 61.9 pb^{-1} at $\sqrt{s}$ < 1 GeV (+25.7 pb^{-1}, 1.0-1.2 GeV)

34×10^6 $\pi^+\pi^-$, 3.7×10^6 $\mu^+\mu^-$, 44×10^6 e^+e^-
events selected at $\sqrt{s}$ < 1 GeV

e+e- → π+π- by CMD3

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



Analysis was performed trying to reach systematic ~0.35-0.5%

<u>Crucial pieces of analysis:</u>

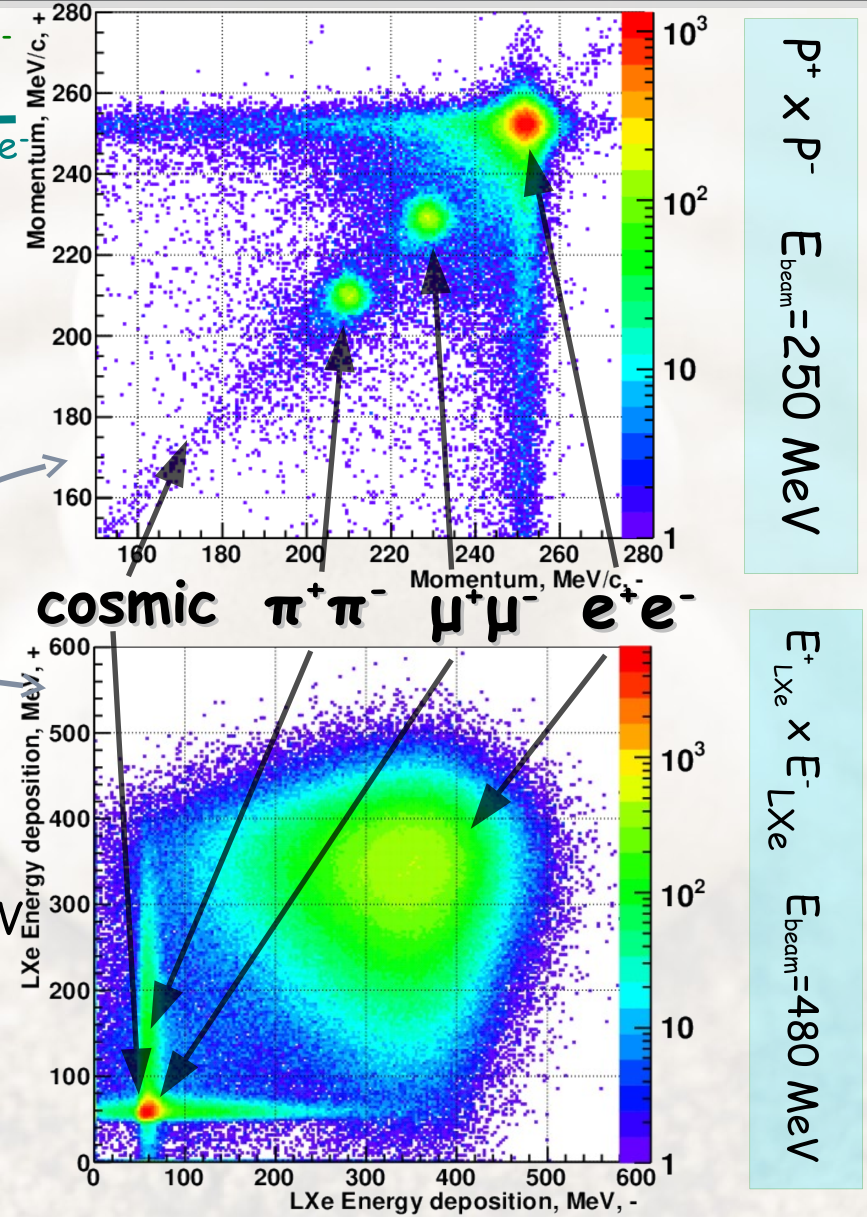
- ✗ e/μ/π separation
- ✗ radiative corrections
- ✗ precise fiducial volume
- ✗ ...

events separation either

1) by momentum
2) or by energy deposition

3) additional cross-check
   by angle distribution

4) using shower profile at >1GeV



Form Factor evaluation

$$\sigma_{e^+e^-\to\gamma\to\pi^+\pi^-} = \frac{\pi\alpha^2}{3s}\beta_\pi^3|F_\pi|^2$$

$$|F_\pi|^2 = \left(\frac{N_{\pi^+\pi^-}}{N_{e^+e^-}} - \Delta^{bg}\right)\frac{\sigma^0_{e^+e^-}\cdot(1+\delta^{rad}_{e^+e^-})}{\sigma^0_{\pi^+\pi^-}\cdot(1+\delta^{rad}_{\pi^+\pi^-})}\frac{\epsilon_{e^+e^-}}{\epsilon_{\pi^+\pi^-}}$$

Ratio $N_{\pi\pi}/N_{ee}$ is measured directly -> detector inefficiencies are partially cancelled out

Mostly no background, Applied if not accounted in particle separation

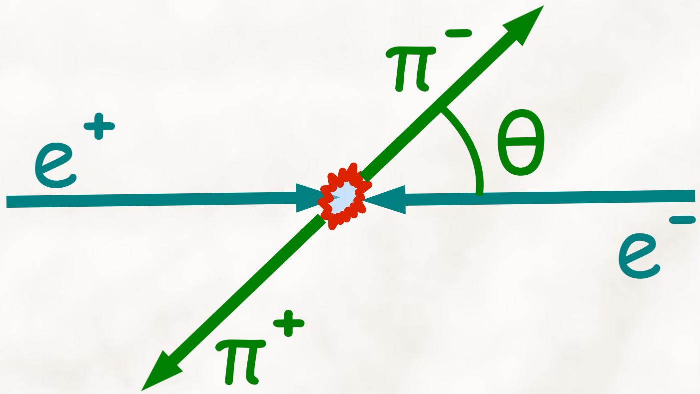
$$\Delta^{BG} = (N_{bg}/N_{ee})^{simul}$$

Evaluated as ratio to e+e- by simulation. Both BG and e+e- are taken from sim, inefficiencies cancelled out in same way

Radiative corrections defined in used acceptance, account for ISR and FSR effects, VP included in F_π definition.

Efficiency analysis rely mostly on the data. Important only difference between π+π- / e+e- (common cancelled out)

Simple event signature with 2 back-to-back charged particles



- Two charged collinear tracks:

$$|\Delta\phi|<0.15,\quad |\Delta\theta|<0.25 \qquad Q_1+Q_2=0, |\Delta t|<20\,\mathrm{nsec}$$

- Vertex position close to interaction point:

$$\rho_{average}<0.3\,\mathrm{cm},\ |Z_{average}|<5\,\mathrm{cm}$$

$$|\Delta\rho|<0.3\,\mathrm{cm},\ |\Delta Z|<5\,\mathrm{cm}$$

- Fiducial volume inside good region of the DCH:

$$1.<(\pi+\theta^{+}-\theta^{-})/2<\pi-1.\,\mathrm{rad}$$

- Quality of selected tracks:

$$\chi^2/ndf<10, N_{hits}\geq 10$$

- Filtration of low momentum and cosmic background:

$$0.45\,E_{beam}<p^{\pm}<E_{beam}+100\,\mathrm{MeV}/c,\quad p^{\pm}>1.15\,p_{K\pm}$$

Data sample includes events with: **e+e−, μ+μ−, π+π−, cosmic muons**

Almost no other background at √s <1 GeV

34×10^6 $\pi^+\pi^-$, 3.7×10^6 $\mu^+\mu^-$, 44×10^6 e^+e^- events selected at √s < 1 GeV

Event separation

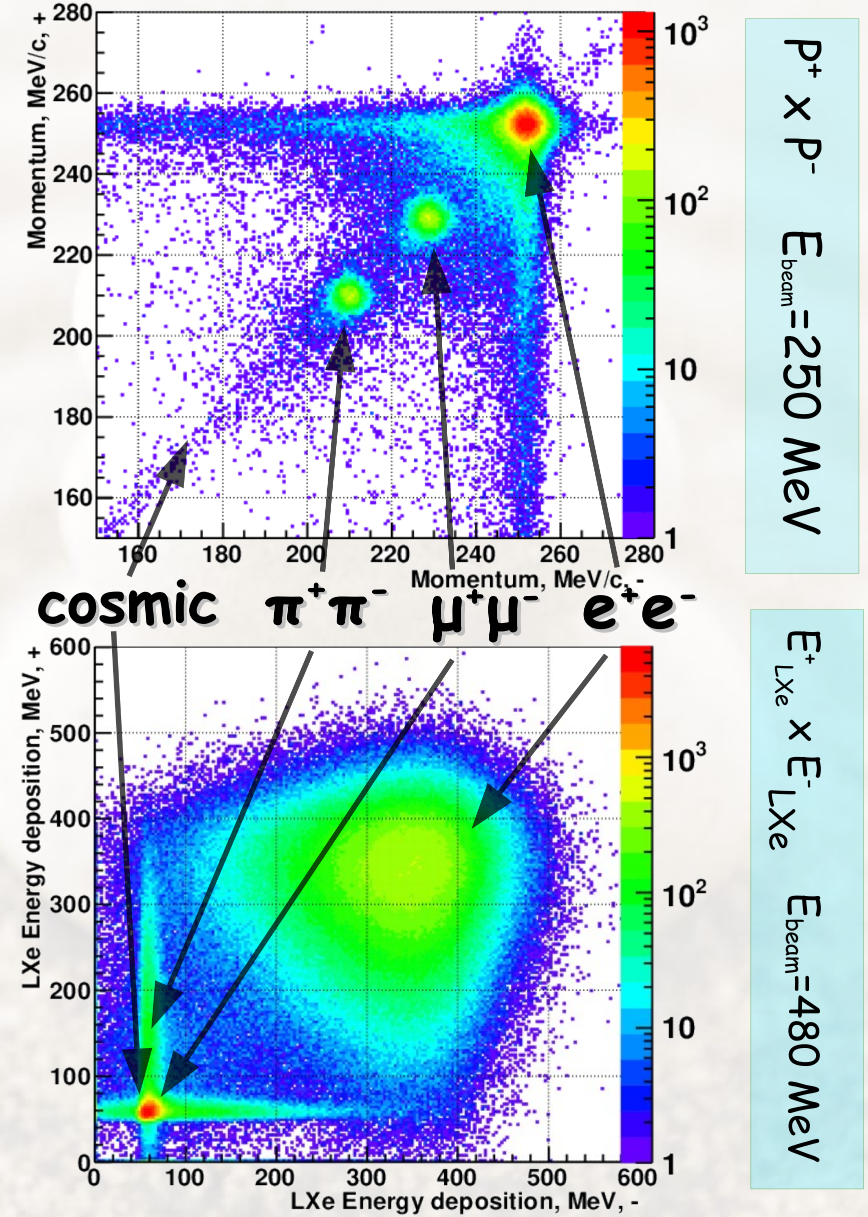
events separation either

1) by momentum

2) or by energy deposition

Separation of $\pi^+\pi^-$, $\mu^+\mu^-$, e^+e^-, ... final states is based on likelihood minimization:

$$-\ln L = -\sum_{events} \ln\left[\sum_i N_i f_i(X^+, X^-)\right] + \sum_i N_i$$



Event separation

Separation of $\pi^+\pi^-$, $\mu^+\mu^-$, e^+e^-, …. final states is based on likelihood minimization:

$$-\ln L = -\sum_{events} \ln\left[\sum_i N_i f_i(X^+, X^-)\right] + \sum_i N_i$$

<u>Momentum-based separation:</u>

PDFs are constructed as:

MC generator spectra are convolved with

X detector response function (momentum resolution, bremsstrahlung, pion decays)

36 free parameters in fit per each point

<u>Energy deposition-base separation:</u>

PDFs is described by a generic functional form (log-gaus, etc), trained on the data: by tagged electron, cosmic muons

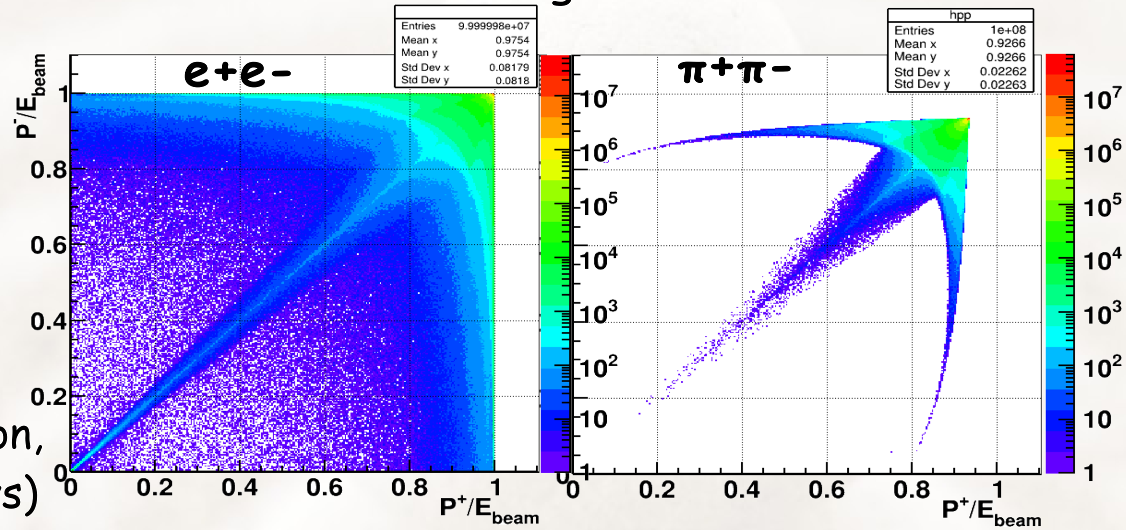
56 free parameters in fit

$N_{\pi\pi}/N_{ee}$ – one of the free parameters,

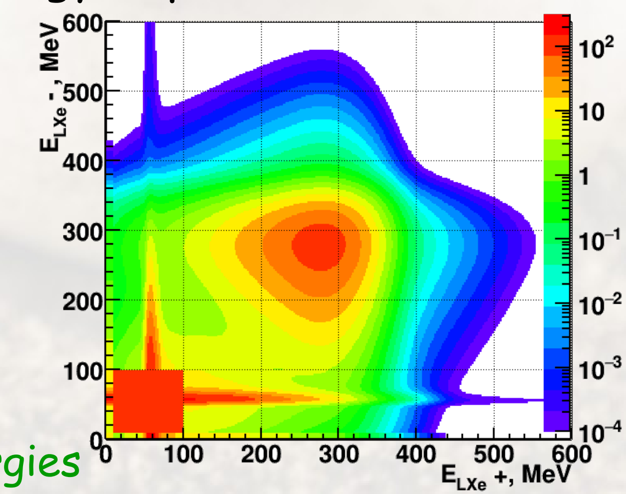
$N_{\mu\mu}/N_{ee}$ – fixed from QED (free at $\sqrt{s}<0.7$ GeV)

Possible biases are checked on full MC → systematics 0.2% at ρ energies

Momentum PDF's ingredients from MC generator



Energy deposition summed PDF



Angle distribution fit

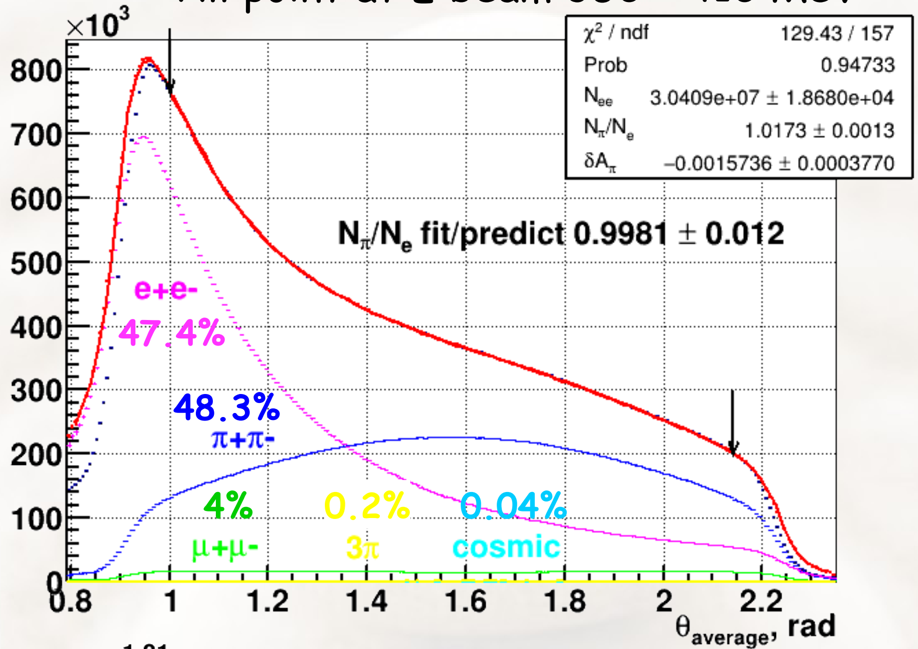
$d\sigma/d\theta$ spectra from MC Generators
+ all efficiencies/smearing effects
extracted from data and full simulation
(cosmic is taken from data itself)

$N_{\mu\mu}$ /N_{ee} - fixed from QED (+efficiencies)
N cosmic, 3π - from momentum based separation
$N_{\pi\pi}$/N_{ee} , δA - free parameters

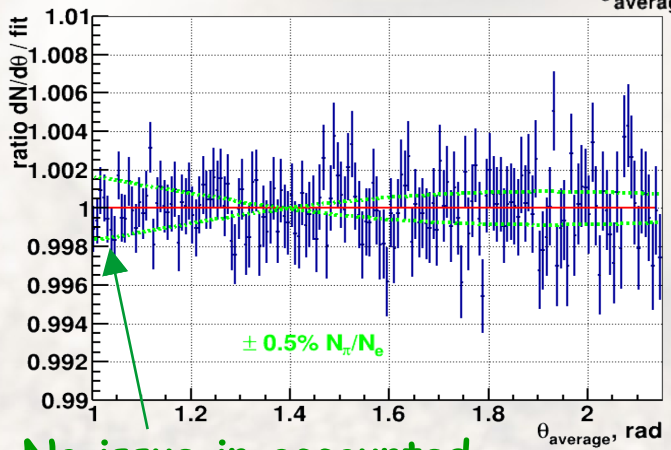
Combined fit on all points around ρ-peak
$\sqrt{s}$ = 0.7 – 0.82 GeV

$N_{\pi\pi}$ /N_{ee} = 1.0173 +- 0.0013

All point at E beam 350 – 410 MeV



Fit by θ distribution



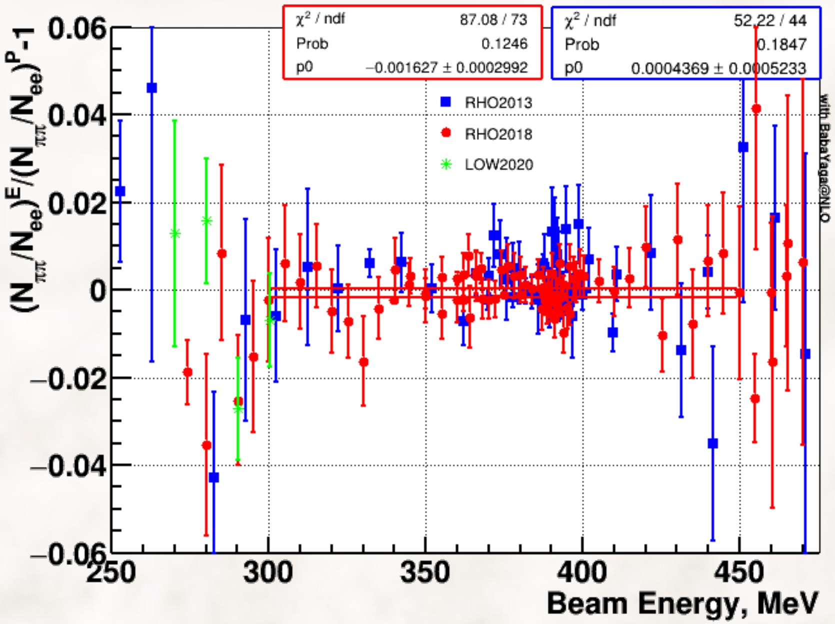
No issue in accounted efficiency at θ = 1 rad

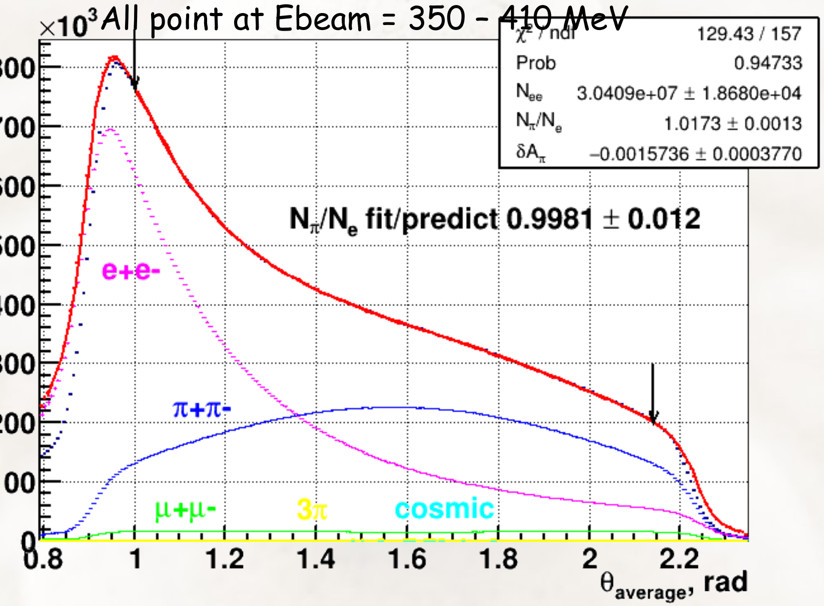
e/μ/π separation

3 methods for $N_{\pi\pi}/N_{ee}$ determination based on independent informations:

1) Momentum from DCH **2)** Energy deposition in LXe **3)** angles in DCH

E vs P separations





Fit by θ distribution

For sum of $\sqrt{s}$ = 0.7 – 0.82 GeV points

<u>by momenta</u> in DCH: $N_{\pi\pi}/N_{ee}$ = 1.0193 +- 0.00030

<u>by energies</u> in LXe $\Delta N_{\pi\pi}/N_{ee}$ = -0.09 +- 0.024%

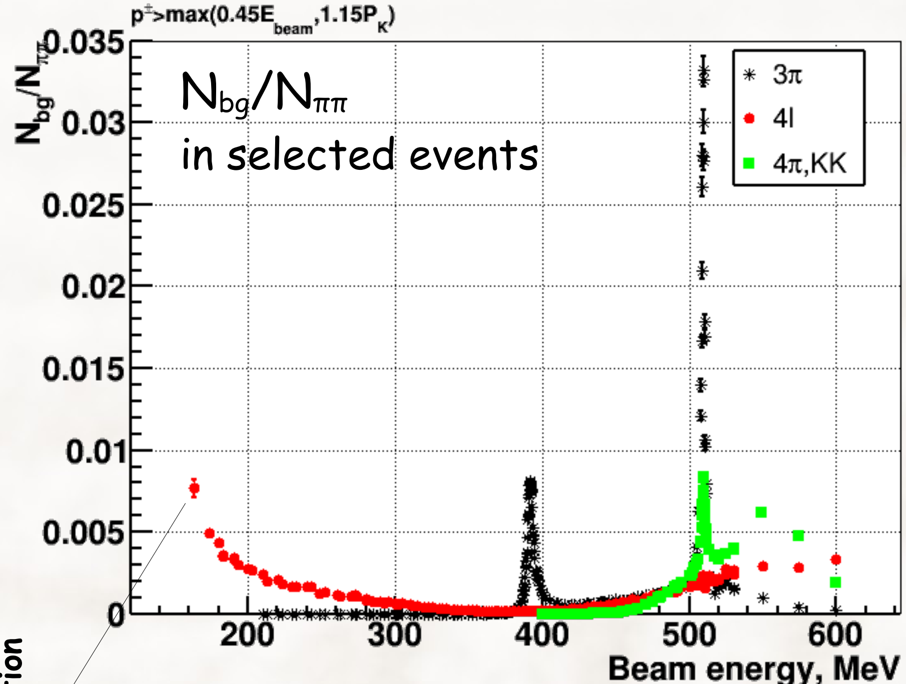
<u>from theta</u> with free δA: = -0.20 +- 0.12%

with fixed δA=0: = +0.21 +- 0.07%

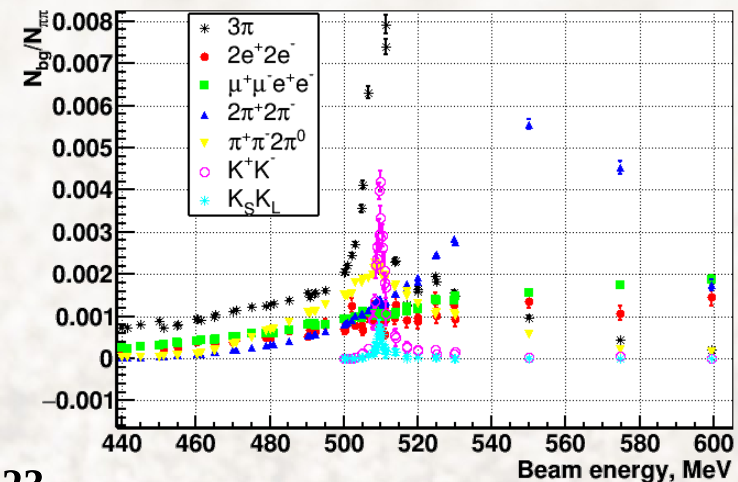
consistency at ~ 0.2%

Common stat from √N: 0.026%

Background



Effect on $N_{\pi\pi}/N_{ee}$ after separation only ~0.2%



All possible background contributions to the selected collinear data sample:

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

$e^+e^- \to e^+e^-e^+e^-,\ e^+e^-\mu^+\mu^-$

$e^+e^- \to K^+K^-,\ K_SK_L,\ \pi^+\pi^-\pi^+\pi^-,\ \pi^+\pi^-\pi^0\pi^0$

<u>Cross-check of proper accounting with stronger momentum cut:</u>

$P^{\pm} > 0.45\ E_{beam} \to > 0.6 E_{beam}$ ($> 1.15 p_K \to > 1.2 p_K$)

reduces by 30-50% 3π and to 1./5 of 2K,4π

$\to\ \Delta|F|^2/|F|^2$ ~ 0.02% (at ω)

0.05% (at φ)

BG systematic error to F_π:

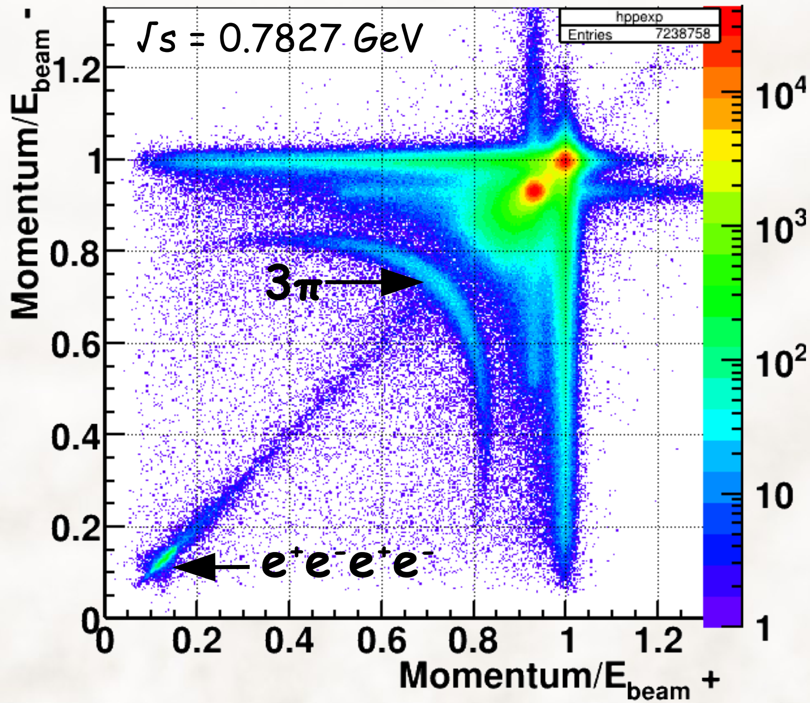
0.05% (at ω), 0.2% (at φ) ,

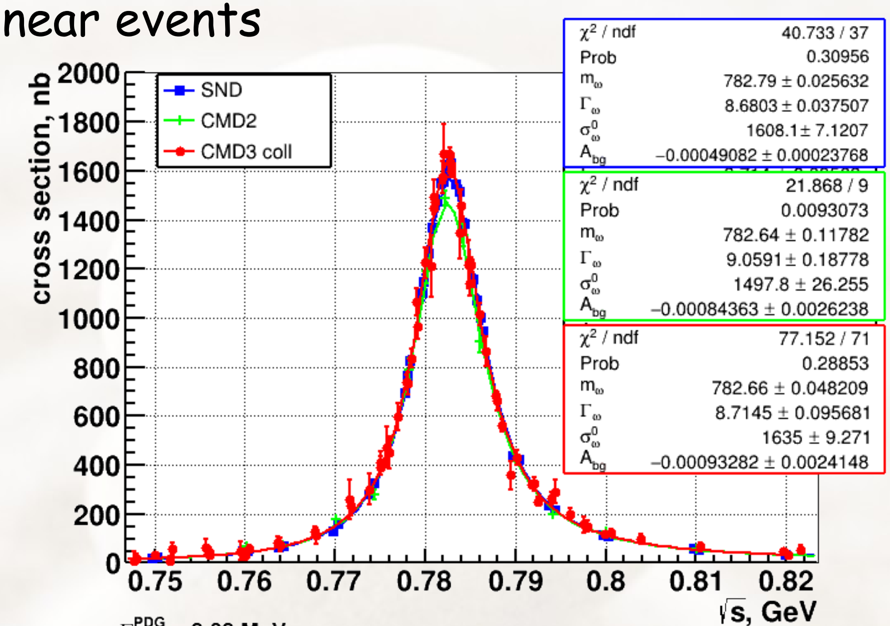
0.-0.15%($\sqrt{s}$=0.9-1.2GeV)

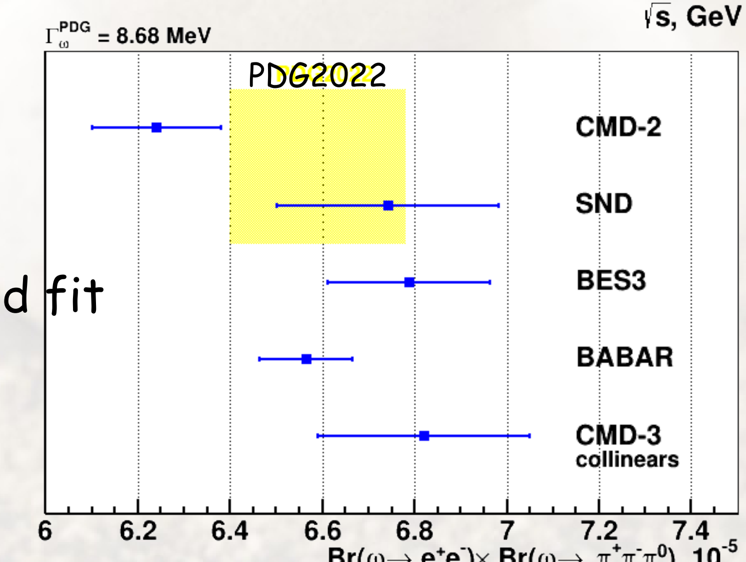
$e^+e^- \to \pi^+\pi^-\pi^0$

$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$ within collinear events

Collinear events are selected for 2π analysis







$e^+e^- \to \pi^+\pi^-\pi^0$ is background for $\pi^+\pi^-$ analysis (0.8% at ω)

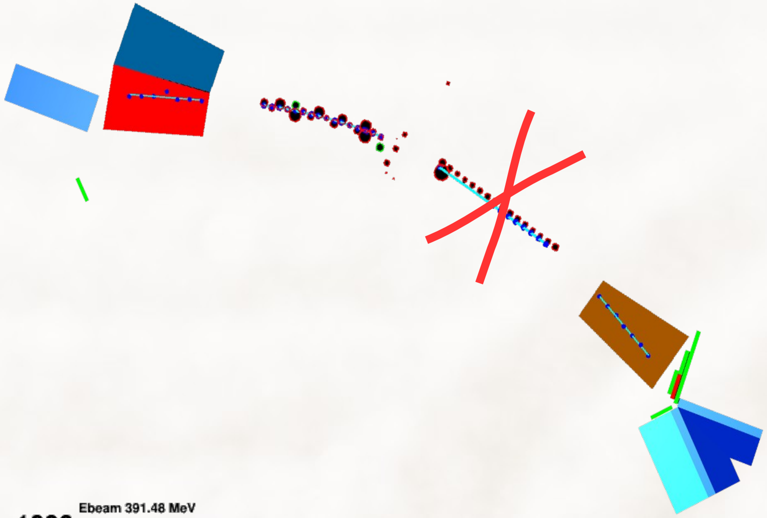
Number of 3π events is additional parameter in likelihood fit

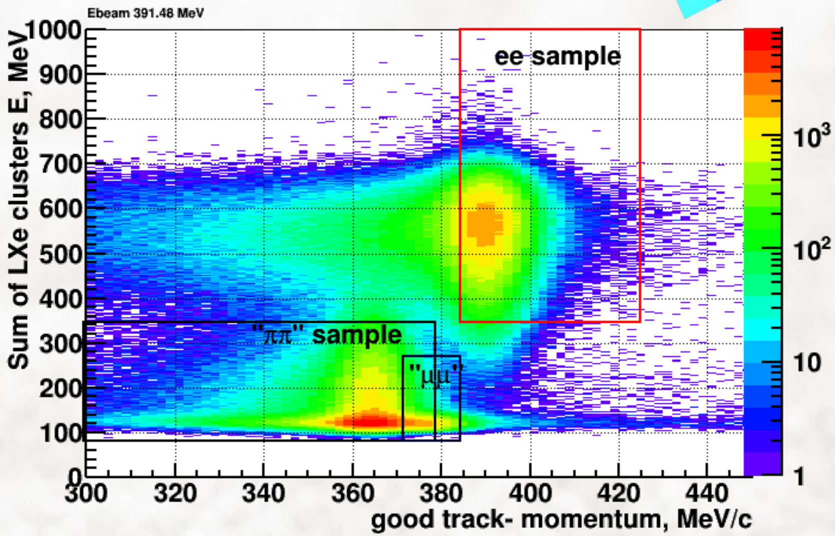
Main systematics (2.4%) inaccuracy of ρπ – model for efficiency determination, **total 3.3%**

$B(\omega \to e^+e^-)B(\omega \to \pi^+\pi^-\pi^0) = (6.82 \pm 0.04 \pm 0.23)\times 10^{-5}$

confirm SND@VEPP-2M result

Efficiency





Assuming independence of Calorimeter & Tracker,
Using the "test" sample based on LXe information:

two collinear clusters are detected + one good track

gives possibility to study track reconstruction inefficiency

Event type is tagged by
energy deposition and momentum of good track

The "test" sample includes only partially some specific losses (when second compatible cluster is not produced):
pion decay, nuclear interaction, .. (~30% ineff. accounted)
electron bremsstrahlung (~5% accounted)

N.B. Correlated inefficiency study was also performed
without requirement on detection of one good track

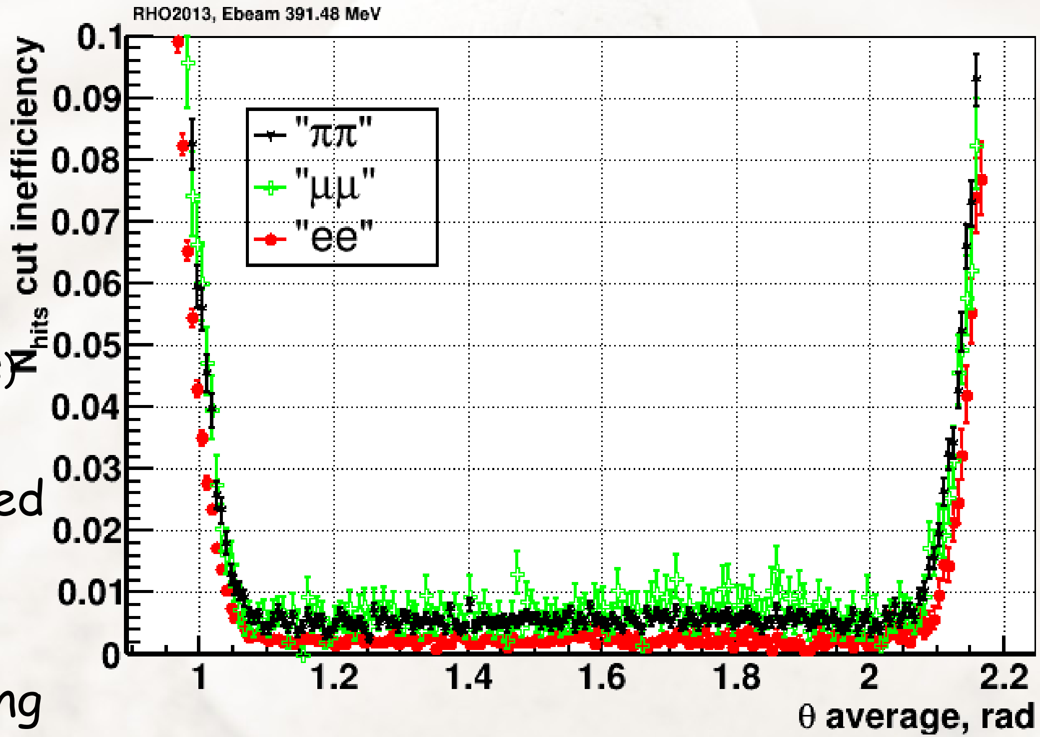
Inefficiency of Nhit cut

Number of hits on track starts
to decrease at edge of the DCH

Inefficiency need to be taken into account
in same θ_{event} definition (as average over two tracks)

Evaluated on the same collinear sample as used
in the $|F_\pi|^2$ measurement
Event types are tagged by Edep, P
Inefficiency is evaluated by Nhit cut releasing

$$\varepsilon^{nhits} = \frac{N^{events}(tracks\ with\ nhit \geq 10)}{N^{events}(tracks\ just\ reconstructed)}$$



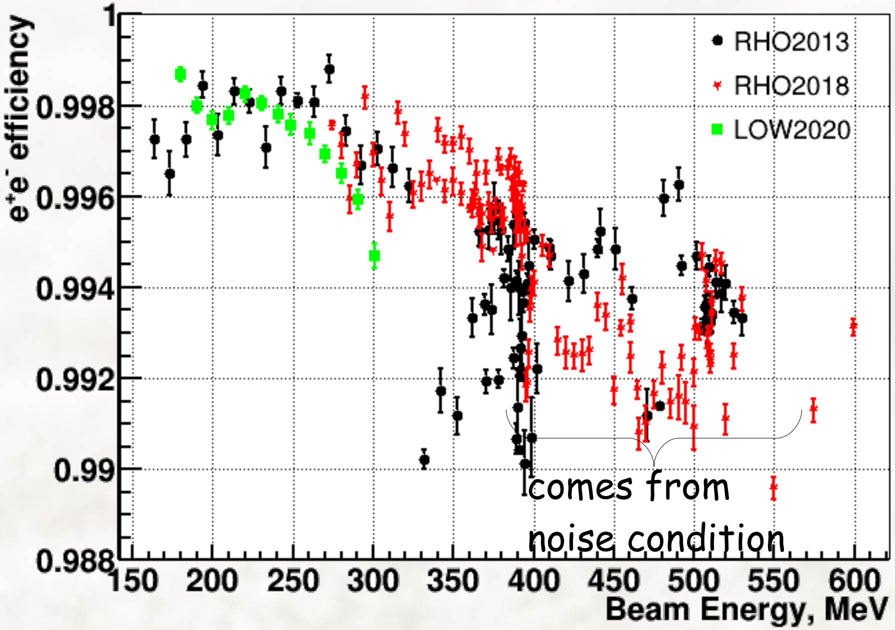
Base efficiencies

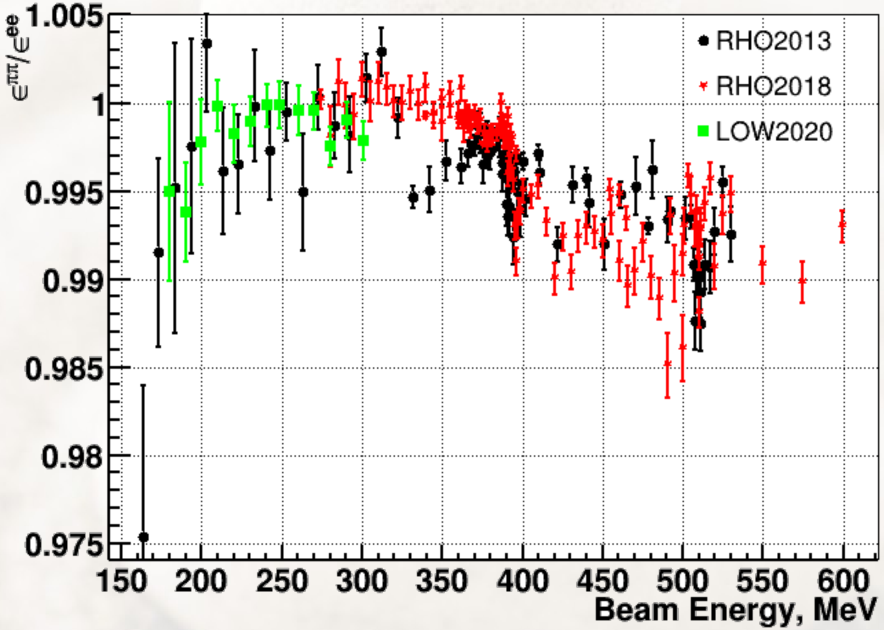
ε_{e+e-}

$\varepsilon_{\pi+\pi-}/\varepsilon_{e+e-}$

Efficiency without particles specific losses

Without Z,θ, brems



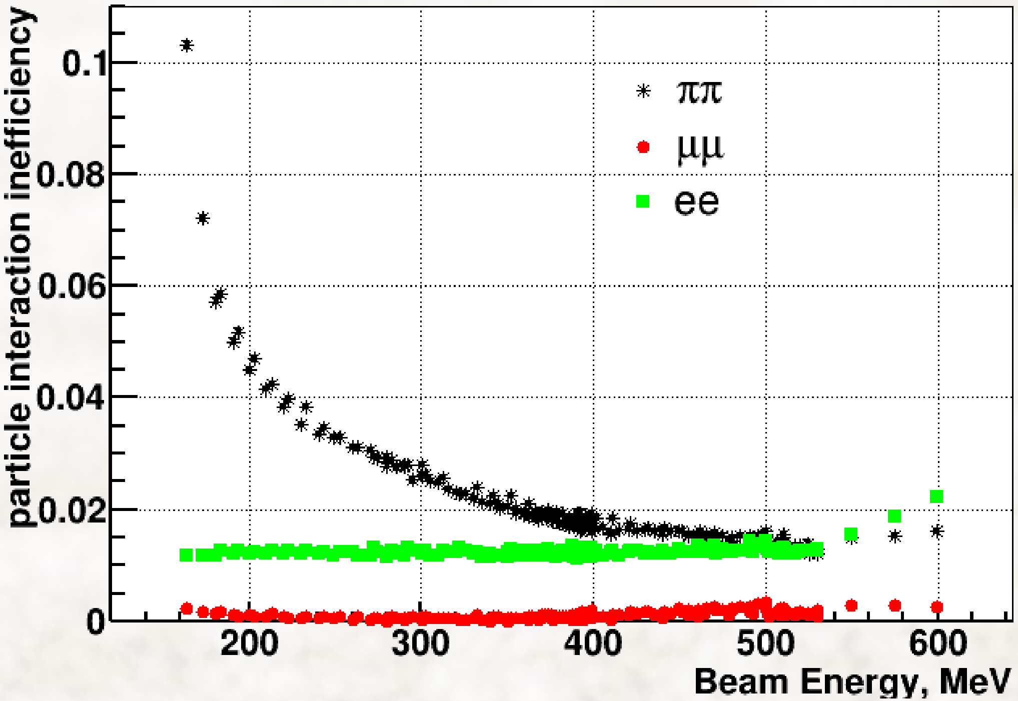


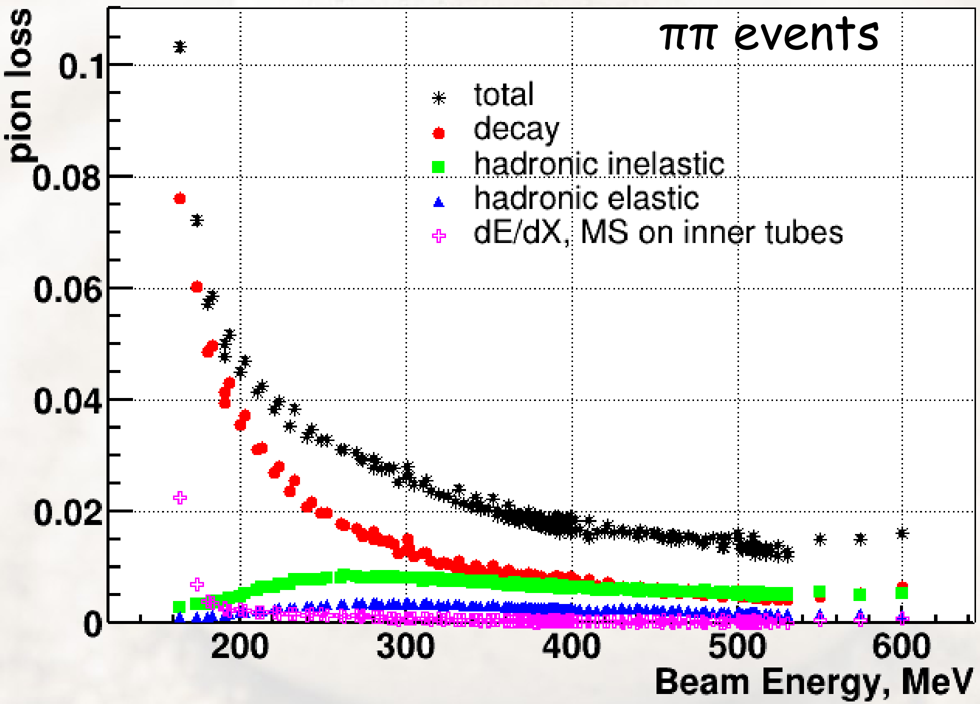
Particle specific losses

bremsstrahlung energy loss, decay in flight, nuclear interaction with materials, MS on the inner vacuum tube, ….

Taken from detailed full MC (includes detector conditions with time)

but it is also controlled by the data



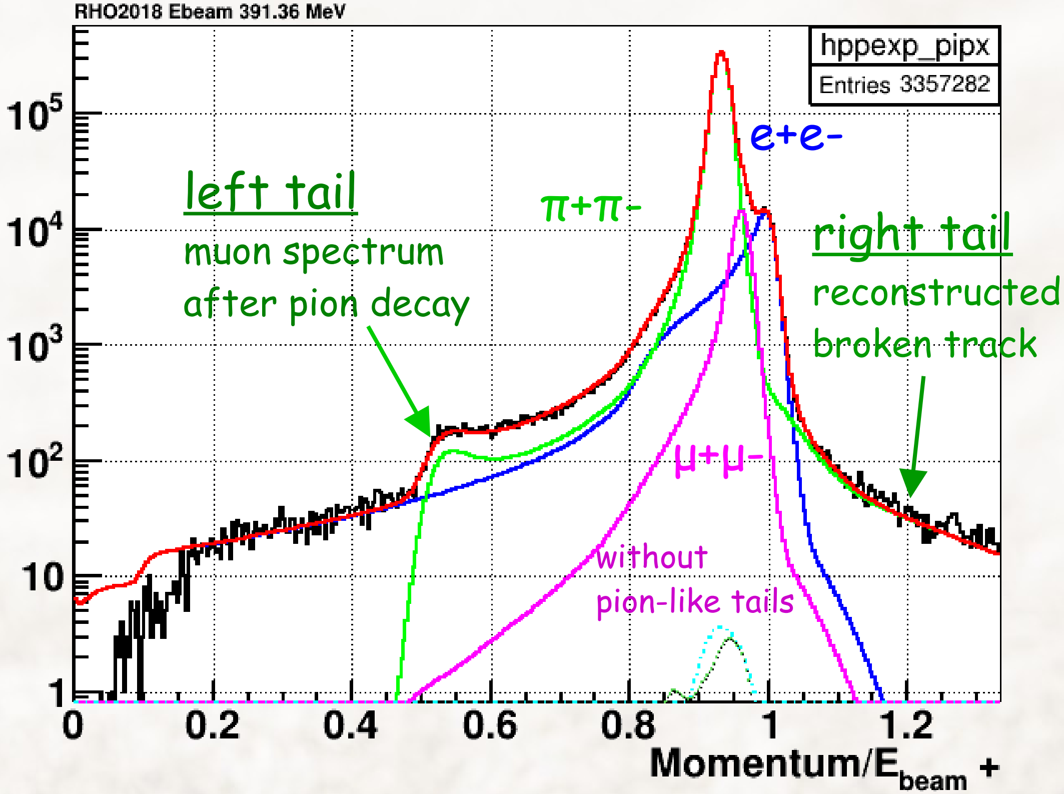


nucler interactions mostly on inner tube (systematics 0.2%)

most dangerous is decay in flight as it depends on detector conditions (syst. 0.2-0.1%)

Pion decay inefficiency

Experimental P+ spectrum
with $|P^- - P_\pi| < 10$ MeV



Decay in flight - depends on DCH efficiency

controlled by number of events in tails
in the data vs simulation

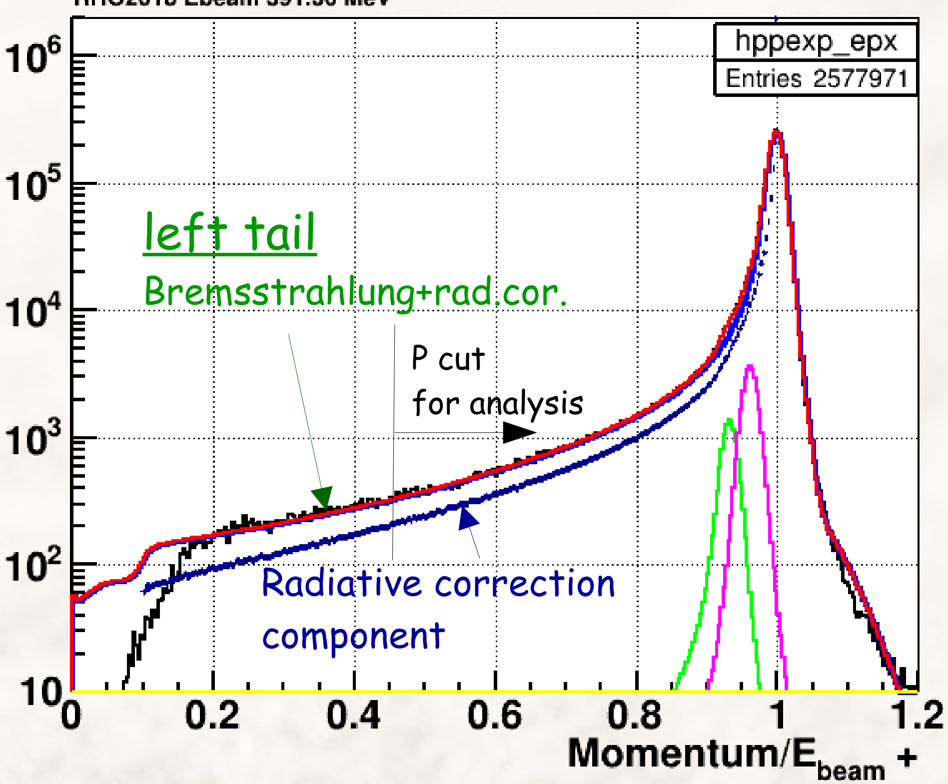
Tails function taken from full MC
(include DCH inefficiencies, resolutions, amplitudes, correlated noises per layers, etc..)
Number of events in tails are free parameters in momentum-based separation

$N^{event}_{in\ tails}$ consistent with sim at ~ 3%
→ systematic uncertainty of Nππ
0.2-0.1% (from low to ρ)
(N.B. simplified DCH descriptions gives 15% discrepancies on tails)

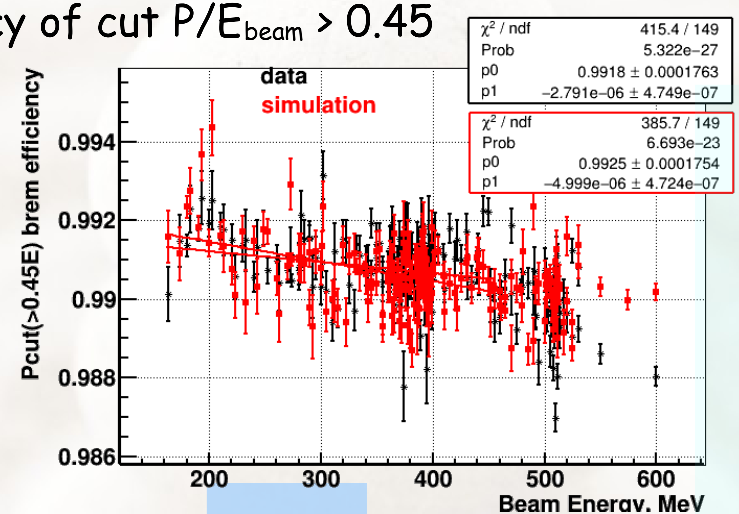
Additional crosscheck with «weak» cuts:
Nhits >= 10 → 8, χ2 < 10 → 20, |Δρ| < 0.3 → 0.6 cm
pion decay inefficiency changes by x1./(2.-2.5)
→ $\Delta|F|^2/|F|^2 < 0.05\%$

Bremsshtrahlung loss on vacuum tube

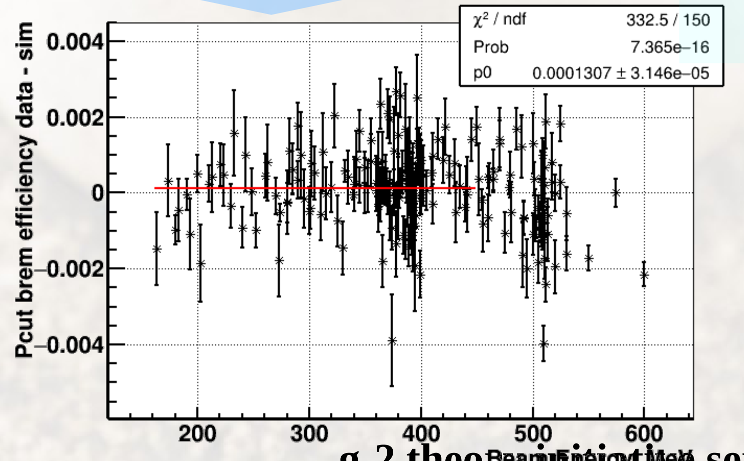
Experimental P+ spectrum with $|P^- - P_e| < 10$ MeV



Part of brems. correction (0.9% from 1.2%) can be extracted from fitted spectra: inefficiency of cut $P/E_{beam} > 0.45$



The data vs sim agree ~ 0.02%



MCGPJ vs BabaYaga spectra gives difference <0.015%

Brems. description is part of detector response function in momentum-based separation (with X/X0 as free param.)
X/X0 of inner wall consistent with sim. within <5%
→ Systematics on $|F_\pi|^2$ ~ 0.05%

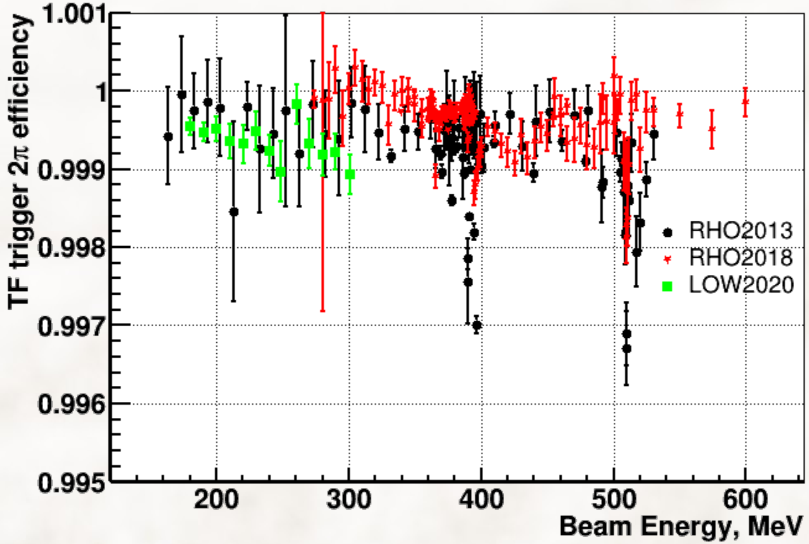
Trigger inefficiency

Two independent triggers were used based on tracking or calorimeter information

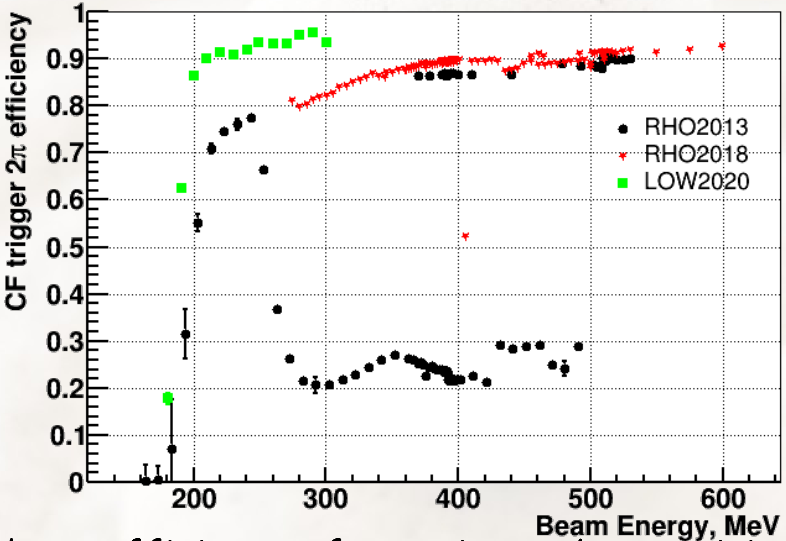
TF: 3 groups of fired wires in DCH from one track

CF: Energy deposition above threshold

TrackFinder 2π efficiency



ClusterFinder 2π efficiency



Having two "independent" triggers allows to study an efficiency of certain one by requiring that other presents in an event:

$$\epsilon_{TF}^{trig} = (N_{TF\&CF}/N_{CF})/(\epsilon_{TF\&CF}^{rec}/\epsilon_{CF}^{rec})$$

Efficiency correction accounts for correlation via time response

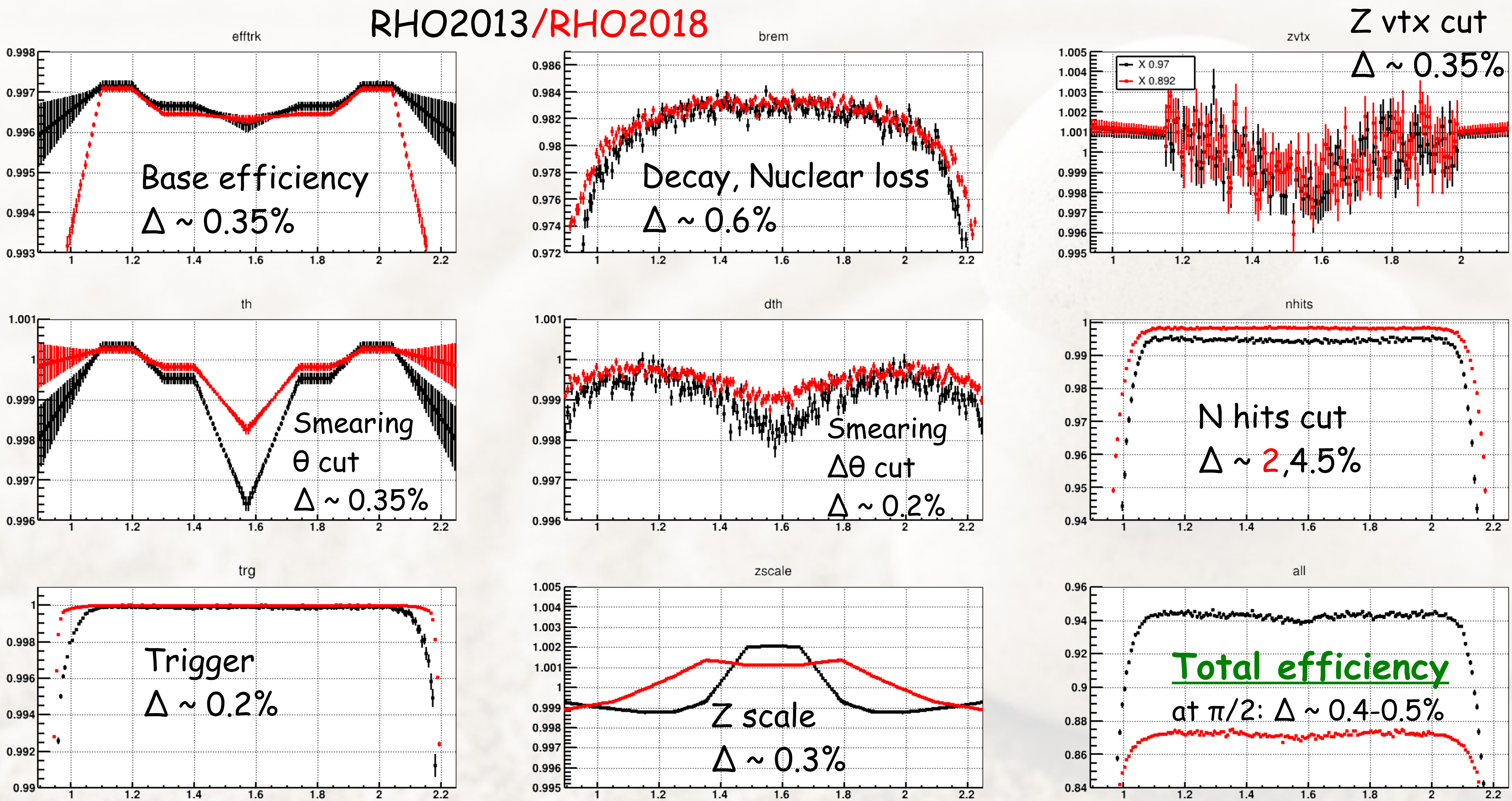
Trigger efficiencies are evaluated from dependence with polar angle (TF), with energy of two clusters (CF)

Total TF|CF: → ~ >0.9994 for 2π events (and higher for e+e-)

Out-of-sync trigger issue gives 0.1-0.5% effect to lose both tracks

→ trigger systematics <u>0.05% (<1GeV) – 0.3% (>1GeV)</u> – as difference between 2π/e+e-

π+π- efficiency vs θ polar angle



Average at ρ-peak over √s = 0.7-0.82 GeV

Radiative corrections

Measurement of $e^{+}e^{-} \to \pi^{+}\pi^{-}$ requires high precision calculation of radiative corrections.

Two high precision MC generators is used
MCGPJ(0.2%, e+e-,μ+μ-,π+π-) vs BabaYaga@NLO (0.1%, e+e-,μ+μ-)
They include exact NLO + Higher Order terms in some approximation.

e+e- → e+e-(γ) : great consistency <0.1% in the total cross section
e+e- → μ+μ-(γ) : Mass term in FSR is missed in most of generators
(effect 0.4% at $\sqrt{s}$=0.32 GeV)
e+e- → π+π-(γ) : only MCGPJ available with 0.2% precision
(for energy scan experiments)

Achieved precision in current analysis is also sensitive
for precision of differential cross sections predictions
e/π separation by momentum requires $d\sigma/dP^{+}dP^{-}$ spectra as initial input
Asymmetry study requires $d\sigma/d\theta$ spectra

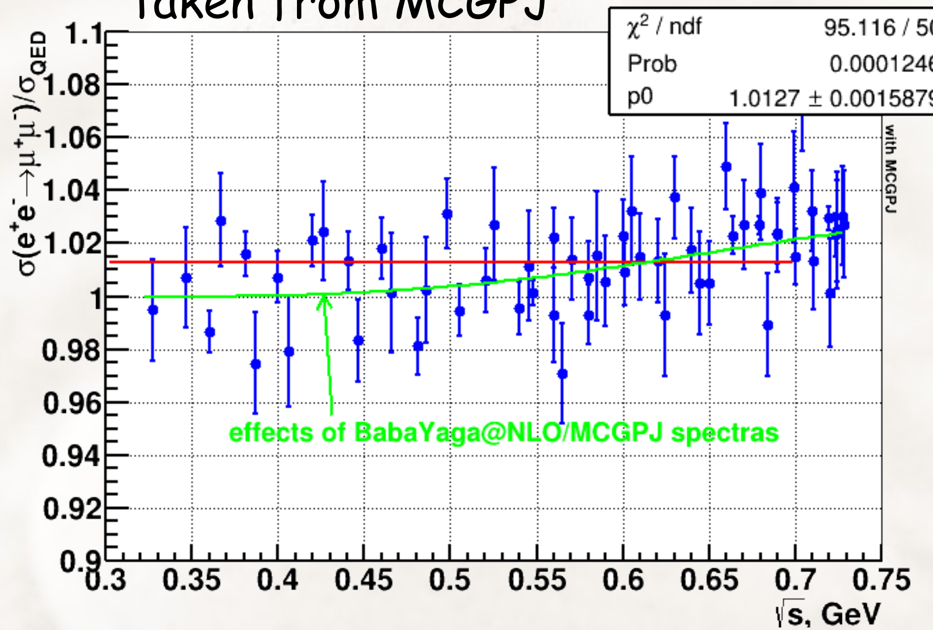
Radiative corrections

BaBaYaga@NLO shows better agreement with the data:

1) Momentum spectras better describe data:
gives consistent results in $N_{\mu\mu}$/QED
(effect on $|F_\pi|^2$ ~0.2% at $\sqrt{s}$=0.78 GeV, and rising to 1.5% at 0.9 GeV when using momentum-based separation)

2) Experimental asymmetry in e+e- data
relative to BabaYaga@NLO:
δA = -0.060 ± 0.026 %
relative to MCGPJ
δA = -0.140 ± 0.026 %
BabaYaga@NLO consistent with NNLO MCMule
δA = +0.006 ± 0.003 % at $\sqrt{s}$=0.76 GeV

effect on $N_{\mu\mu}$/QED
when input $d\sigma/dP^+dP^-$ spectra
taken from MCGPJ



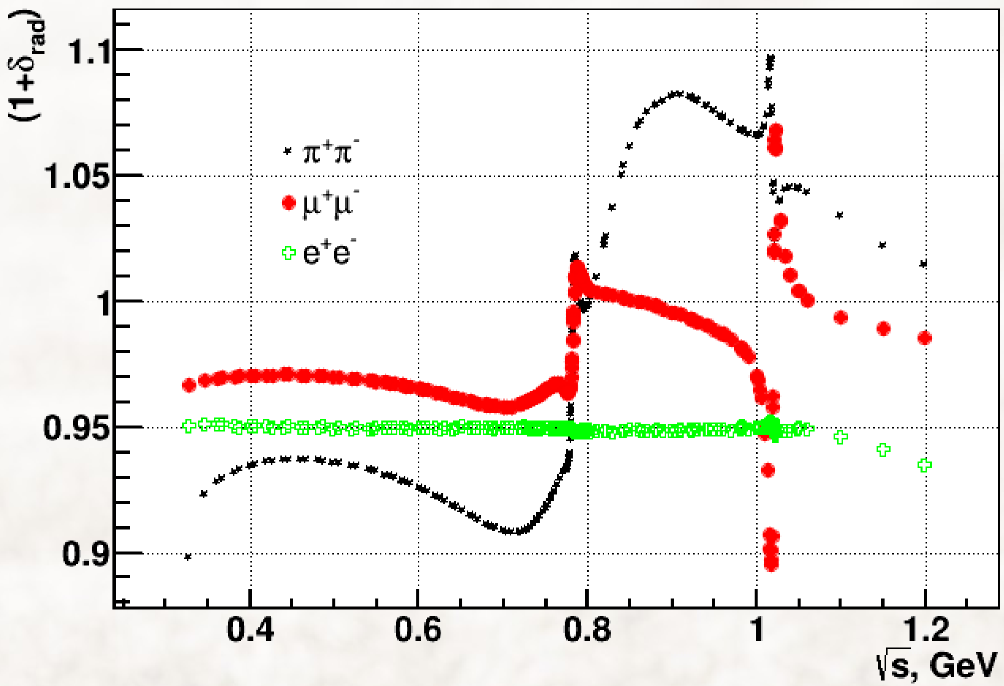
<u>We adopted generators usage in this way:</u>
e+e- : BabaYaga@NLO
μ+μ- : BabaYaga@NLO (differential cross section)
MCGPJ (integral)
π+π- : MCGPJ

MCGPJ/BabaYaga@NLO difference gives systematics on $|F|^2_\pi$ when using momentum-based separation
Better NNLO generators are needed for higher precision

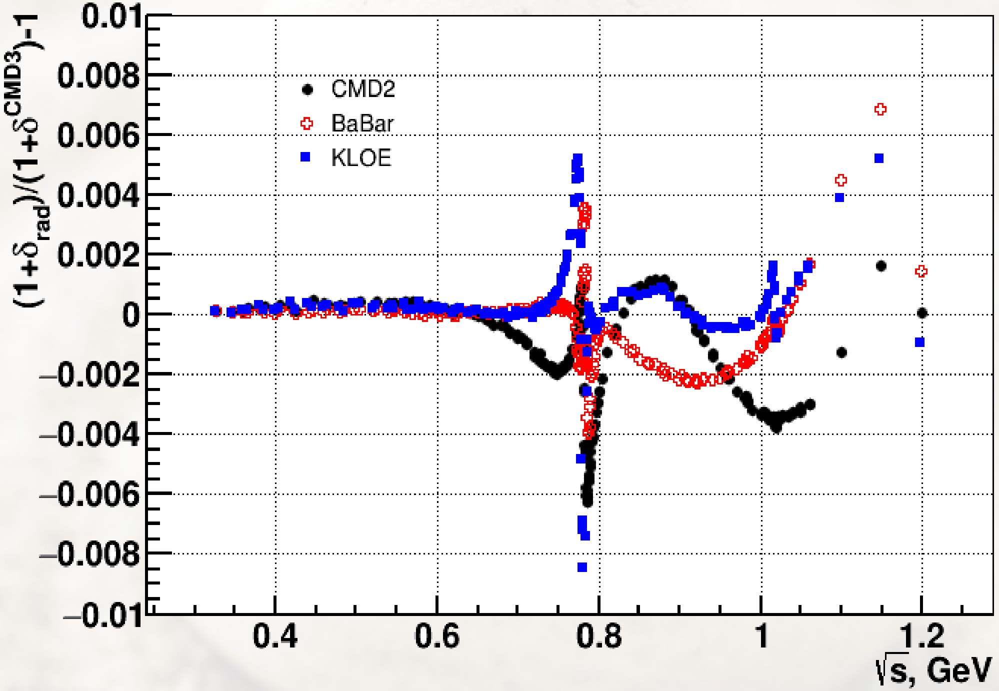
Radiative corrections

Radiative corrections within

$1.<(\pi+\theta^{+}-\theta^{-})/2<\pi-1.\mathrm{rad},\ |\Delta\phi|<0.15,\ |\Delta\theta|<0.25$



Effect on 2π radiative correction from different $|F|^2_\pi$ parametrizations (over different datasets)



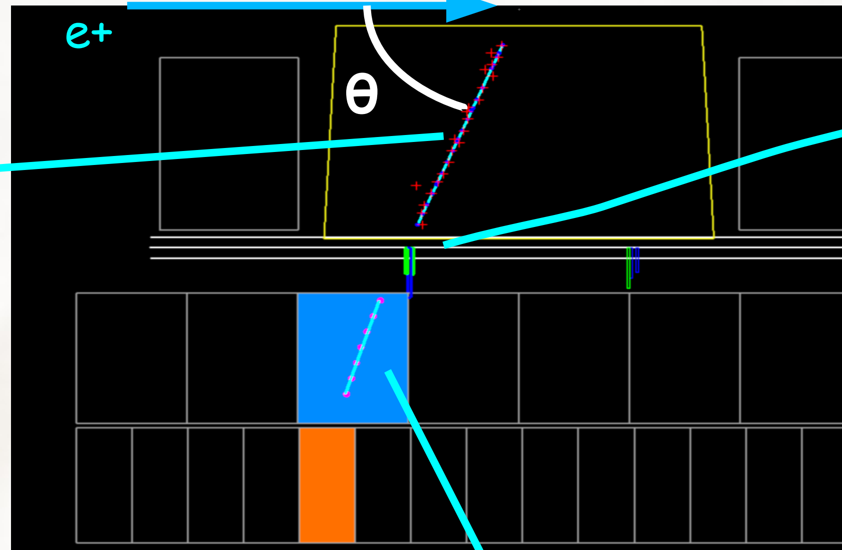
Systematic uncertainty

0.2% (π + π −) ⊕ 0.2% (Fπ , s > 0.74 GeV) ⊕ 0.1% (e+ e−)

N.B. KLOE/BABAR systematic difference in derivative 4%/0.4GeV,
in CMD-3 is also possible up 1%/0.1 GeV → same 0.2% estimation (from Fπ model)

Precision of fiducial volume

Polar angle measured by
DCH chamber
with help of charge division method
(Z resolution ~ 2mm),
Unstable, depends on calibration and thermal stability of electronic
Calibration done relative to LXe (ZC)



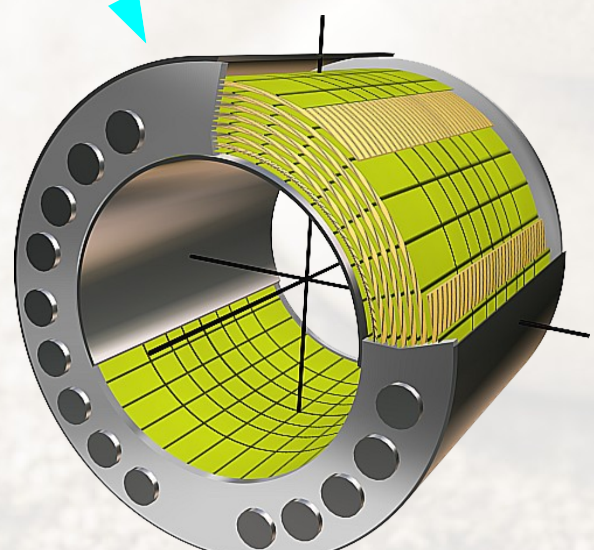
ZC chamber
(was in operation until mid 2017)
multiwire chamber
with 2 layers and with strip readout along Z coordinate

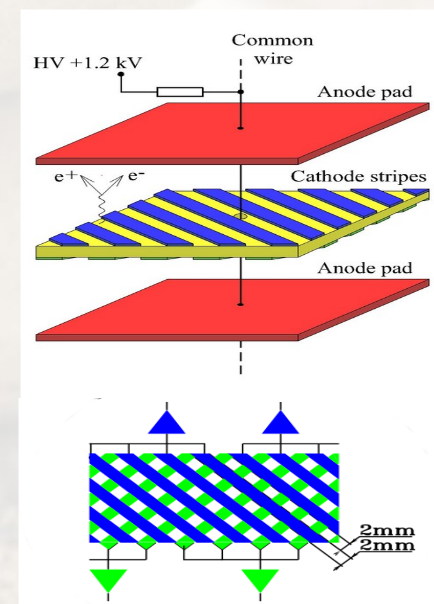
strip size: 6mm
Z coordinate resolution ~ 0.7 mm
(for θ_{track} ~ 1 rad)

LXe calorimeter
ionization collected in 7 layers with cathode strip readout,

combined strip size: 10-15 mm
Coordinate resolution ~ 2mm

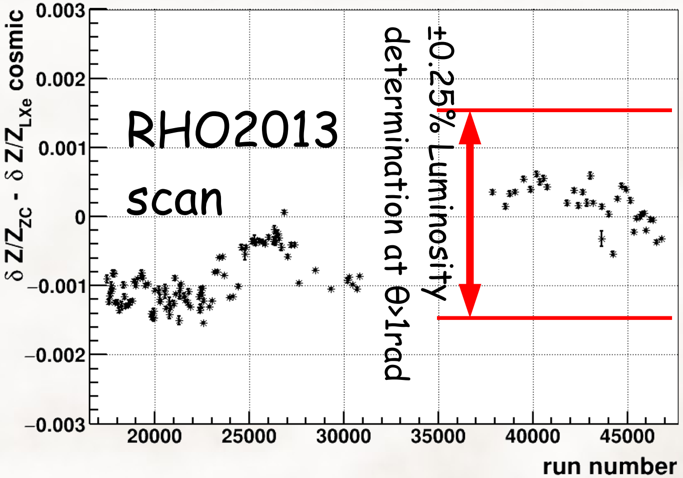
strip precision, coordinate biases ~ 100 μm should give ~0.1% in Luminosity determination
Can be spoiled by noise environment





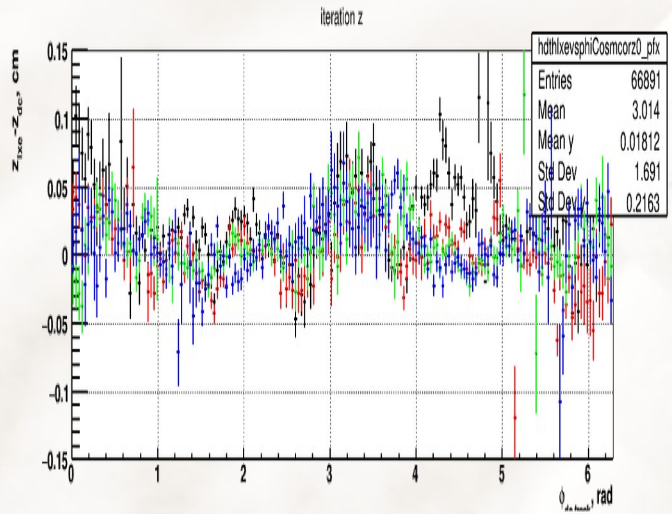
Precision of fiducial volume

Monitoring of z-measurement between ZC vs LXe



Variation because of
DCh instability, different B field,
ZC, LXe noise level

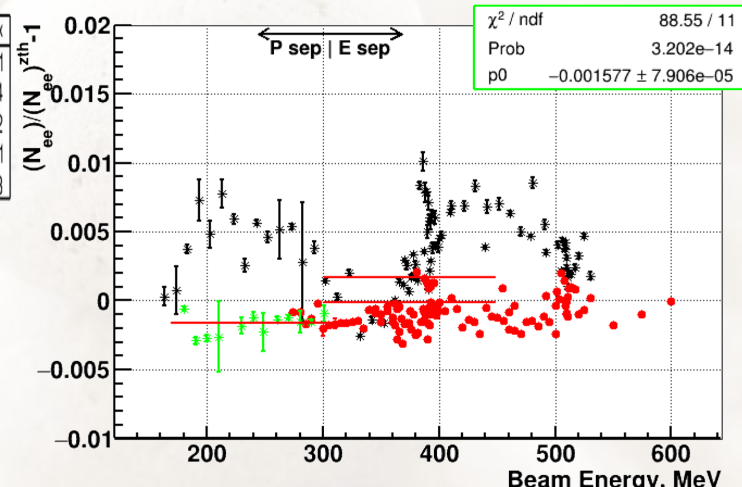
DC tracks vs LXe points



δz ~ 0.5 mm instability over regions at R=40 cm
(by φ, track direction, etc)

N.B. in average ‹δz› should be better

Inner DC radius effect:
θ – angle with Z vertex constrained vs unconstrained case for 2 tracks



Inner layers operate at low HV→
Low resolution, higher systematics
<u>During RHO2013:</u> 4 middle layers in DCH were switched off
→ higher weights of inner layers

N.B. θ – angle is defined with vertex constrain
→ inner radius biases should be suppressed

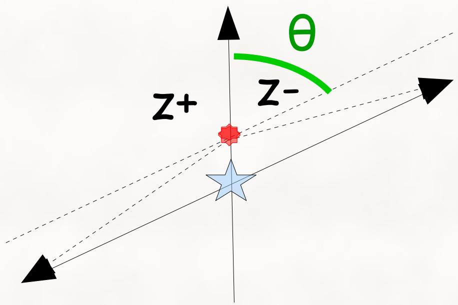
<u>Systematic uncertainty to $|F_\pi|^2$</u>

ZC/LXe comparison		LXe/ DC comparison		Inner DC radius effect:
0.25%	⊕	0.3%	⊕	0.7%(RHO2013)/0.3%(RHO2018)

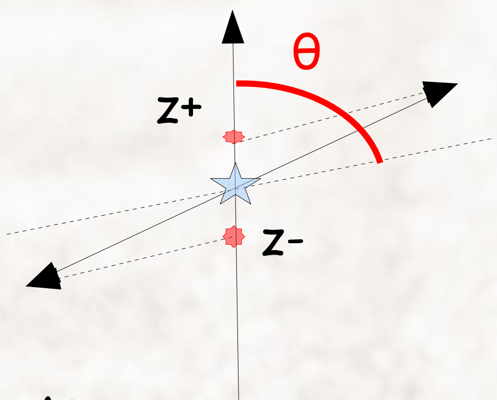
= 0.8% (RHO2013) / 0.5%(RHO2018)

DCH's Inner radius effect on polar angle

$\theta^{event} = (\theta^{+} + \pi - \theta^{-})/2$



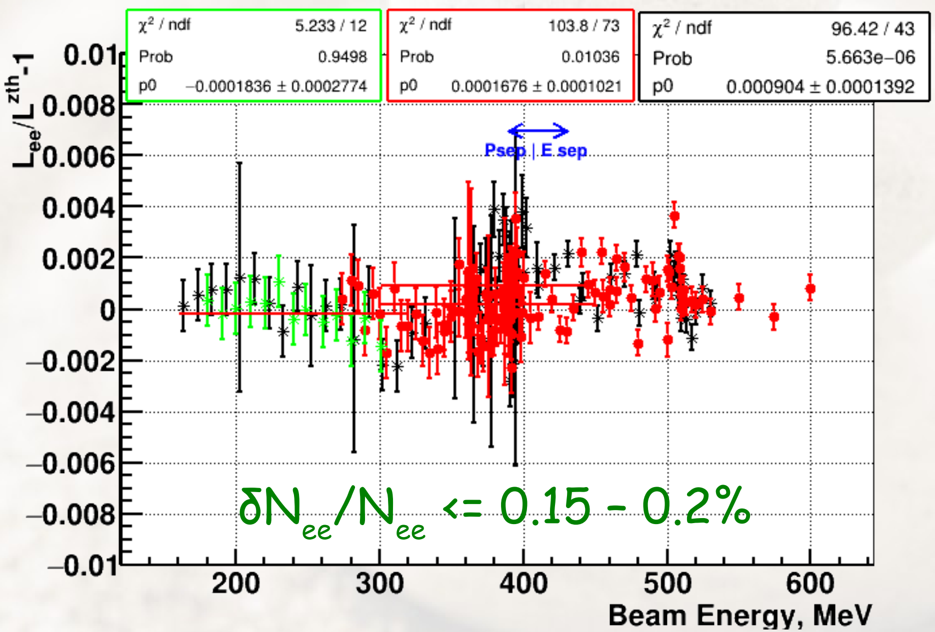
common Z vertex bias of +/- tracks doesn't give bias to θ^{event}



ΔZ at inner vertex gives bias to θ^{event}

The analysis uses θ angle with Z vertex constrain
→ inner radius biases should be suppressed

ΔZ correction can be applied for vertex unconstrained case, + additional vs LXe monitoring on the same collinear events sample



Comparison of Constrain/unconstrained θ-angle after ΔZ, + vs LXe corrections

Conservative angle related systematics is kept 0.3/0.7%(RHO2013) as Z-vertex constrained/unconstrained cases differences for θ^{event} (without corrections)

Fπ within different θ selection

Dependence on theta cut $\theta_{cut} < \theta^{event} < \pi - \theta_{cut}$

or asymmetrical selection $1 < \theta^{event} < \pi/2$ (or $\pi/2 < \theta^{event} < \pi-1$)

$|F_\pi|^2$ stable at <0.05-0.1% level within different angle selections

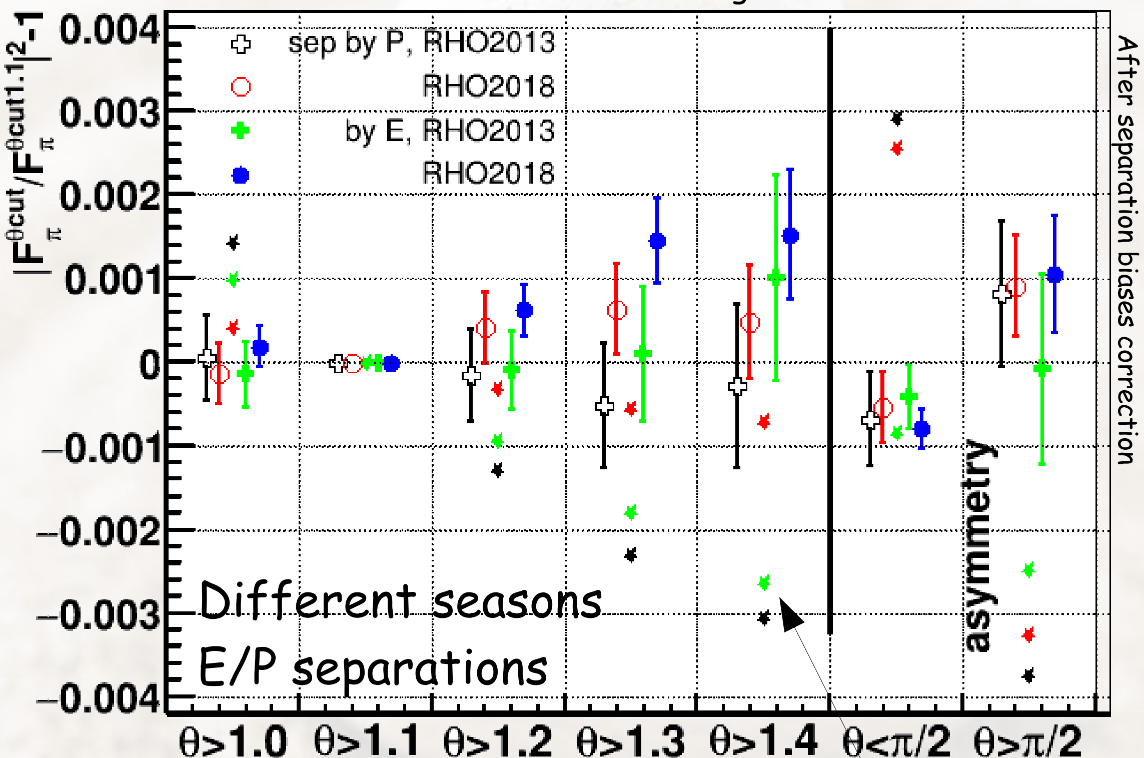
Angle related systematic uncertainty estimation is quite conservative:
0.8% (RHO2013) / 0.5%(RHO2018)

Simplest possible systematics in θ angle:

- Z – length mis-calibration
- Θ^{event} common bias

should be seen with ~0.3-0.4% on this plot

Average at 2E= 0.7-0.82 GeV



With 0.5% systematic at 1 rad

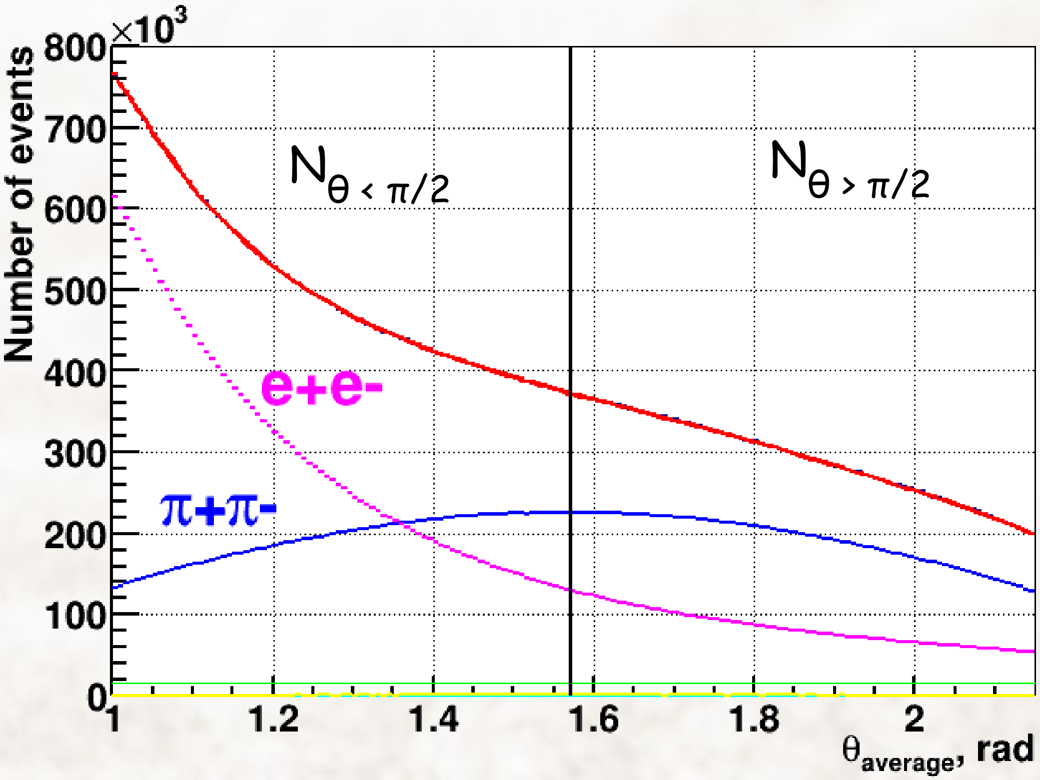
★Z-length mis-calibration

★θ bias

★θ bias opposite

Forward backward charge asymmetry

$d\sigma/d\theta$ spectra



Asymmetry definition:

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

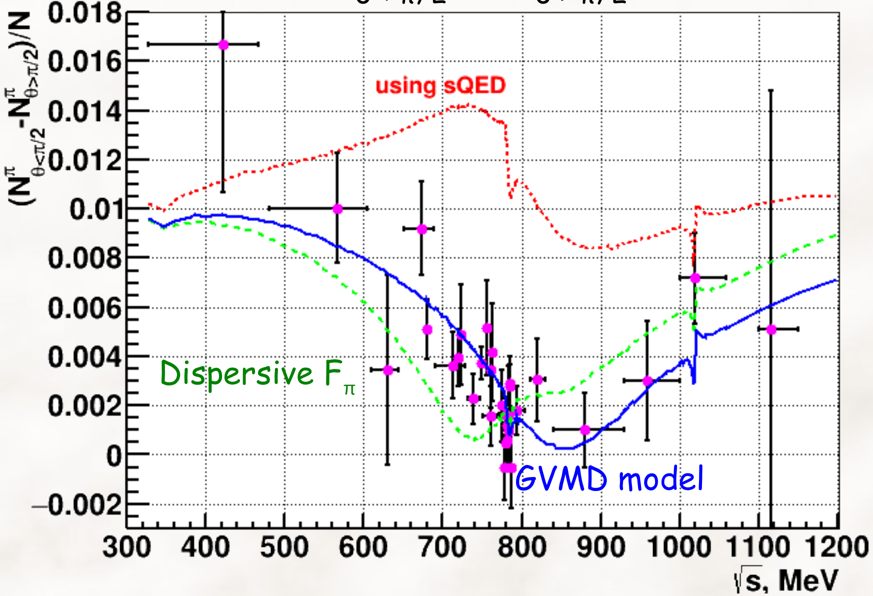
Sensitive to:

- angle-related systematics
- used model of γ-π interaction

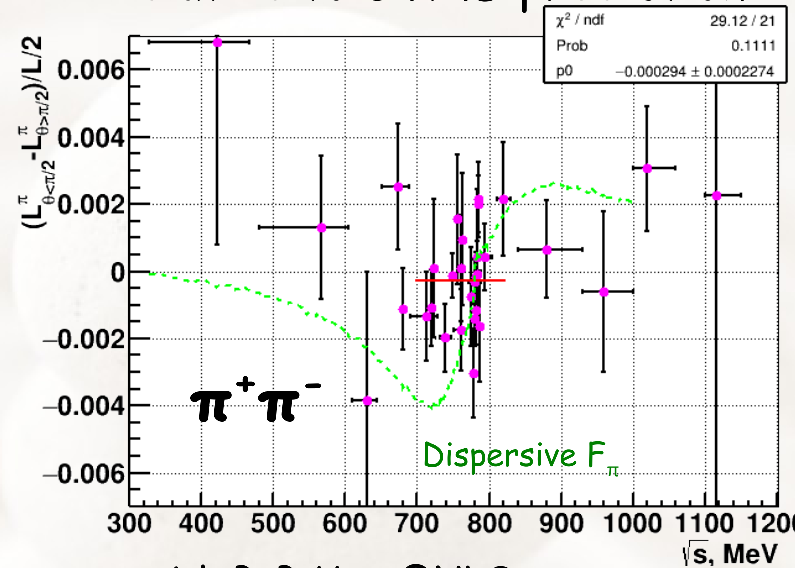
At first try:
1% inconsistency for π+π- was observed between data and MC prediction

Charge asymmetry in e+e- -> π+π-

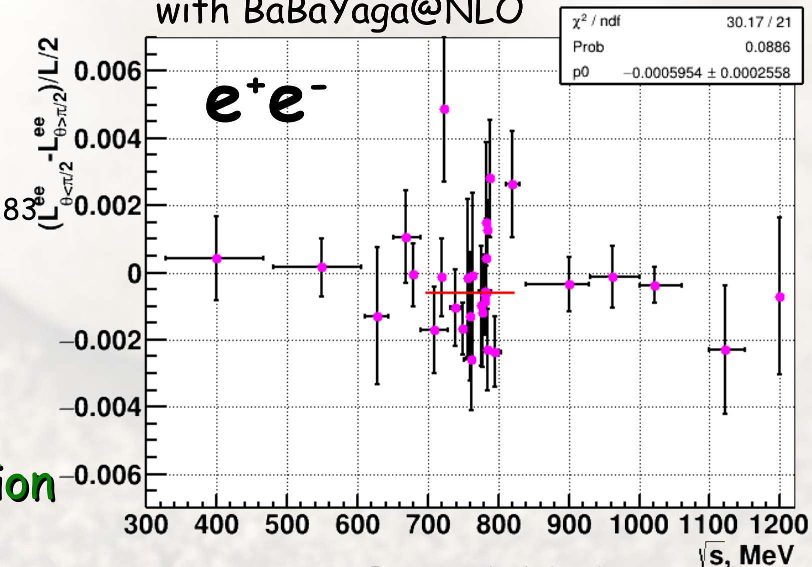
$A = (N_{\theta<\pi/2} - N_{\theta>\pi/2})/N$



Relative to GVMD prediction



with BaBaYaga@NLO



Conventional sQED approach gives ~ 1% inconsistency

The theoretical model within GVMD was introduced,

describes well the CMD-3 data R.Lee et al., Phys.Lett.B 833 (2022) 137283

was confirmed by calculation in dispersive formalism

M.Hoferichter et al., JHEP 08 (2022) 295

Average at $\sqrt{s}$ = 0.7-0.82 GeV:

$\pi^+\pi^-$: $\langle\delta A\rangle$ = -0.029 ± 0.023 %

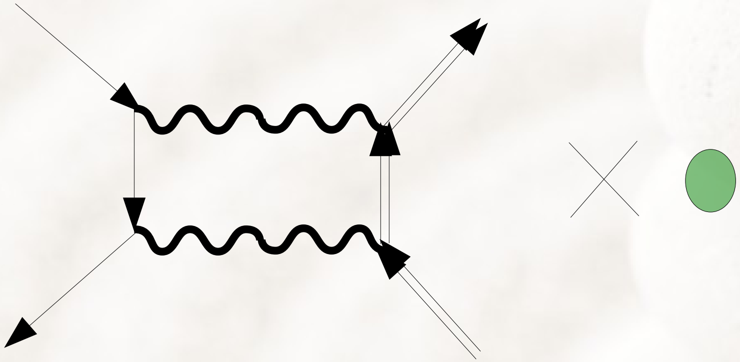
e^+e^-: $\langle\delta A\rangle$ = -0.060 ± 0.026 %

Ensure our θ angle systematics estimation for $|F_\pi|^2$

sQED assumptions for radiative corrections

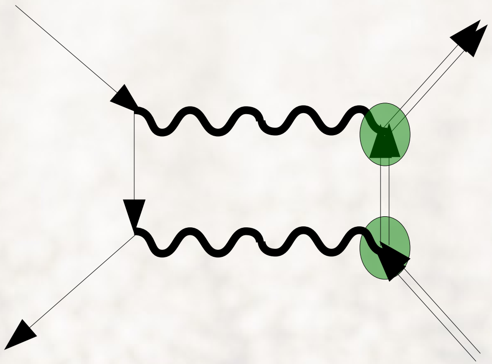
The radiative correction calculations is commonly done in the sQED approach,
It's mean that the calculations are performed without form factor,
then final Amplitude is scaled by $F(q^2)$

Scalar QED approach



$A = sQED*F(s)$

Proper way

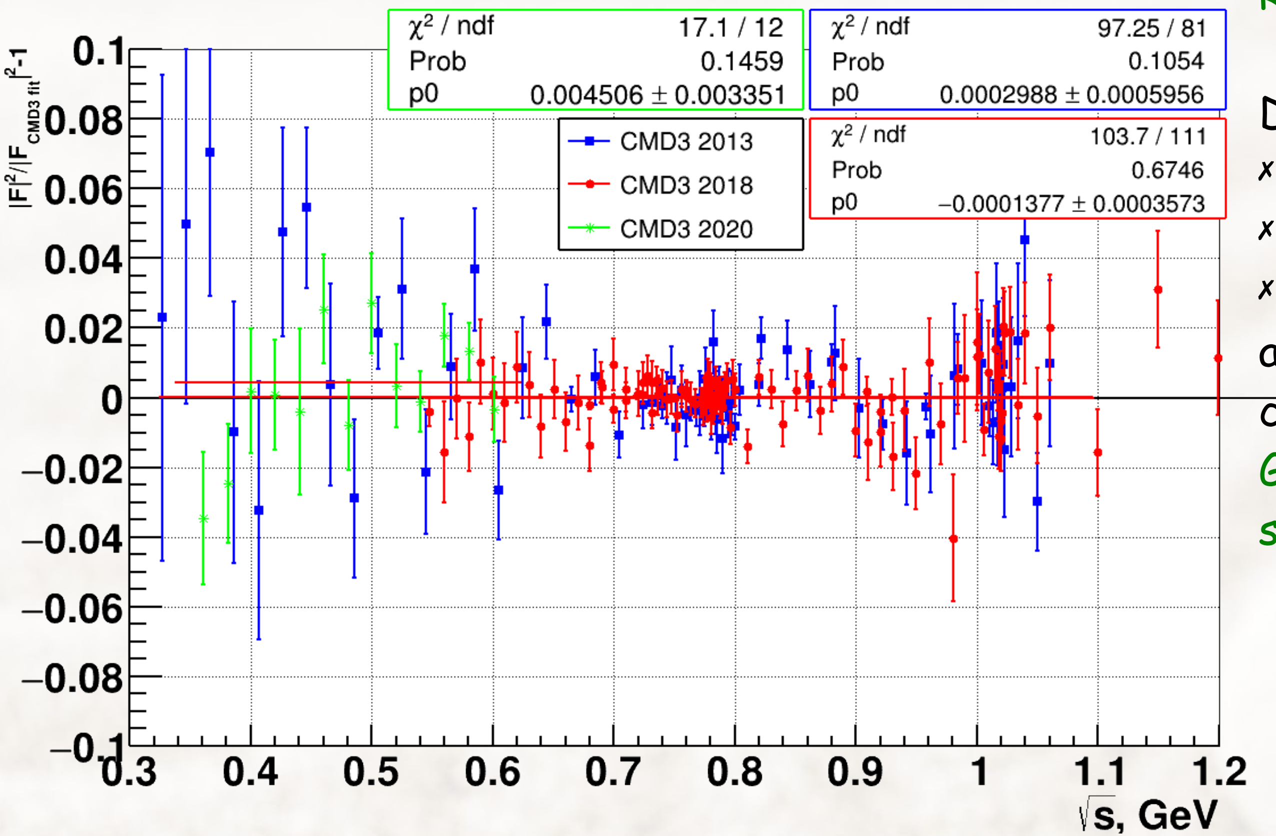


$A \sim \int F(q_1)F(q_2)$

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

N.B. It will be important to re-calculate radiative corrections with above sQED for ISR measurement

Consistency checks



Result consistent between seasons within < 0.1%

DCH was in very different conditions:

- correlated noise
- 4 middle layers off (HV-related) in 2013
- etc....

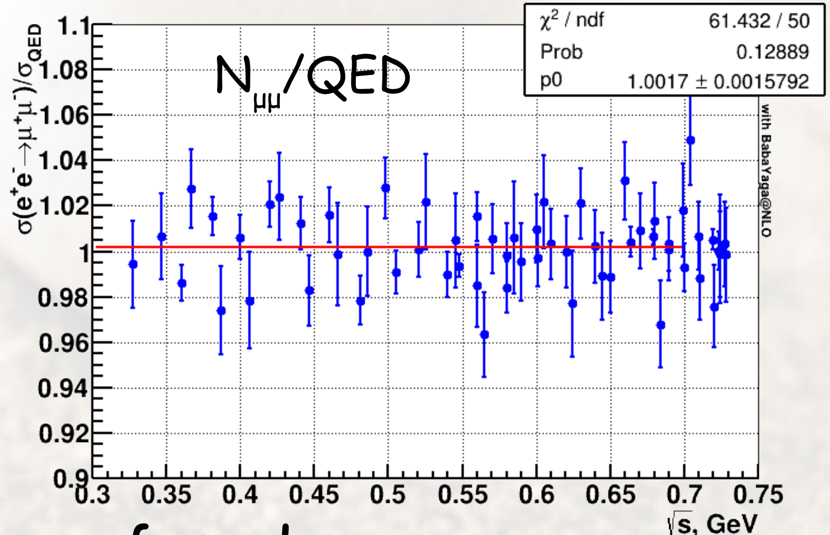
as result it gives ~x2 difference in some corrections

Good check of angle/tracking related systematics

$|F_\pi|^2$ RHO2018/RHO2013 Δ = -0.04 ± 0.07 %

LOW2020/RHO2013 Δ = -0.5 ± 0.6 %

$N_{\mu\mu}$/QED Δ = +0.17 ± 0.16 %



Many others consistency checks were performed

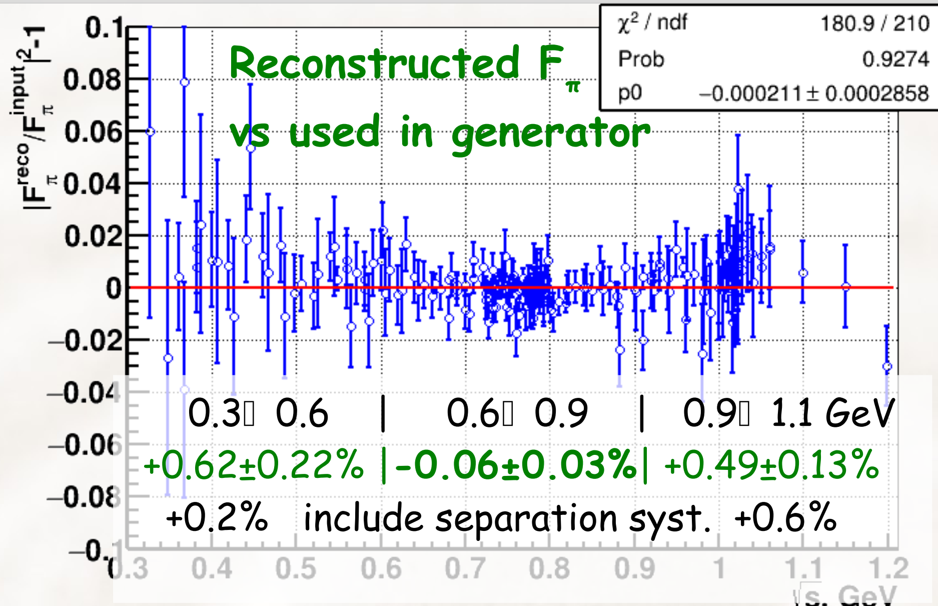
Analysis workflow cross check on MC

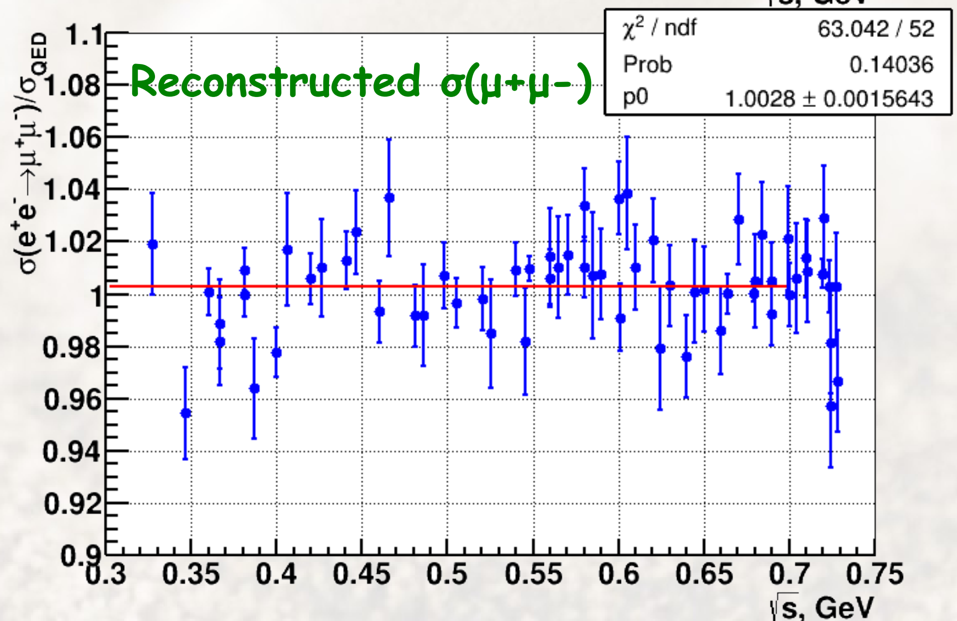
<u>Full analysis workflow was checked on mixed full MC data samples</u>
(with detector conditioned over time)

Same full analysis as for the data:

- efficiencies reconstructions,
- particle separation, etc
- same scripts,
- same intermediate files, etc

All underneath components (separation, efficiency reconstruction, etc) were also checked with better precision





$|F_\pi|^2$ systematic uncertainty

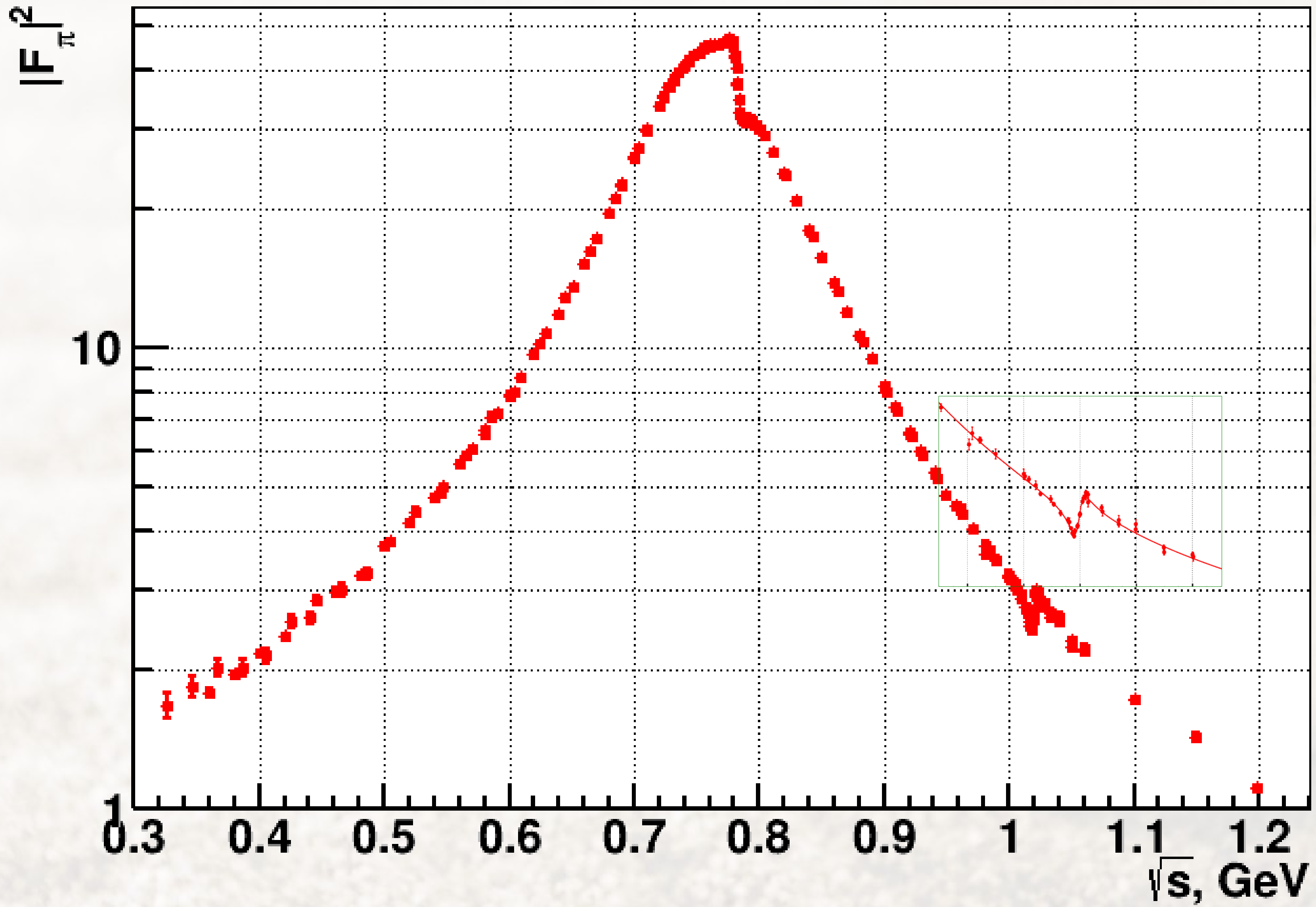
✗ Radiative corrections	**0.2%** (2π) ⊕ **0.2%** (Fπ) ⊕ **0.1%** (e+e-)
✗ e/μ/π separation	0.5 (low) – **0.2% (ρ)** – 0.6 (φ) %
✗ Fiducial volume	**0.5% / 0.8%** (RHO2013)
✗ Correlated inefficiency	**0.1% (ρ)** – 0.15%(>1 ГэВ)
✗ Trigger	**0.05% (ρ)** – 0.3% (>1 ГэВ)
✗ Beam Energy (by Compton σ_E< 50 keV)	**0.1%** (out of resonances), 0.5% (at ω, φ -peaks)
✗ Bremsstrahlung loss	**0.05%**
✗ Pion specific loss	**0.2%** nuclear interaction
	0.2%(low) - **0.1%** (ρ) pion decay
	0.8% (low) – **0.7%** (ρ) – 1.6% (φ)
	1.1% (low) – **0.9%** (ρ) – 2.0% (φ) (RHO2013)

Fixing of $N_{\mu\mu}$ adds scaling of correspondent sources with ~ (1+ a $N_{\mu\mu}/N_{\pi\pi}$)

at φ with $N_{\mu\mu}/N_{\pi\pi}$ ~ 1 : 1.05% / 1.2%(RHO2013) → 1.6% / 2.0% (RHO2013)

at 1.2 GeV with $N_{\mu\mu}/N_{\pi\pi}$ ~ 2.4 : 1.05% → 1.95% (RHO2018)

Form factor



Form Factor description

$$|F_\pi(s)|^2 = \left| \left(\mathrm{BW}_\rho^{\mathrm{GS}}(s) \cdot \left(1 + \delta_\omega \frac{s}{m_\omega^2}\,\mathrm{BW}_\omega(s) + \delta_\phi \frac{s}{m_\phi^2}\,\mathrm{BW}_\phi(s)\right) + \right.\right.$$
$$\left.\left. + a_{\rho'}\,\mathrm{BW}_{\rho'}^{\mathrm{GS}}(s) + a_{\rho''}\,\mathrm{BW}_{\rho''}^{\mathrm{GS}}(s) + a_{cont} \right) / (1 + a_{\rho'} + a_{\rho''} + a_{cont}) \right|^2$$

ρ, ρ', ρ'' - by the Gounaris-Sakurai parameterization (GS)
ω, φ - by the constant width relativistic Breit-Wigner
a_{cont} - constant for continuum contribution (partially absorb ρ', ρ'', ρ''' , …)

ρ', ρ'' – parameters fixed by combined fit together with CMD-2 and DM2 , √s>1.1 GeV

Form Factor description

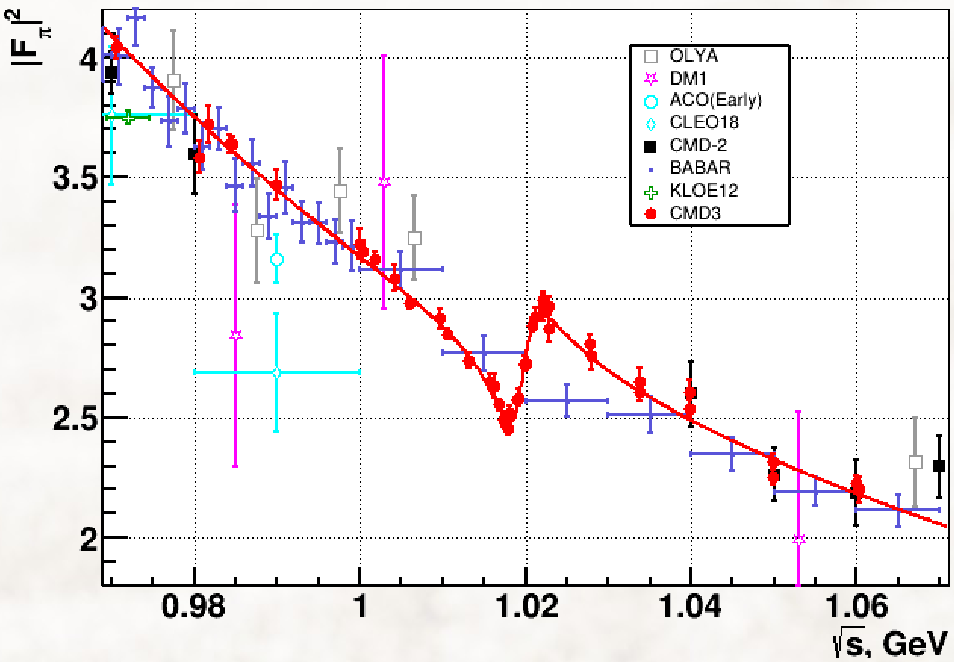
Parameter	value	$M_{\phi,\omega}, \Gamma_{\phi,\omega}$ constrained by PDG's values	PDG(2022) [56]
m_ρ, MeV	$775.41 \pm 0.08 \pm 0.07$	$775.4 \pm 0.07 \pm 0.07$	775.26 ± 0.23
Γ_ρ, MeV	$148.8 \pm 0.16 \pm 0.05$	$148.76 \pm 0.16 \pm 0.06$	147.4 ± 0.8
m_ω, MeV	$782.43 \pm 0.03 \pm 0.01$	$782.44 \pm 0.03 \pm 0.01$	782.66 ± 0.13
Γ_ω, MeV	$8.57 \pm 0.06 \pm 0.01$	$8.59 \pm 0.06 \pm 0.01$	8.68 ± 0.13
$\mathcal{B}_{\omega\to\pi^+\pi^-}\mathcal{B}_{\omega\to e^+e^-}$, 10^{-6}	$1.204 \pm 0.009 \pm 0.003$	$1.204 \pm 0.009 \pm 0.004$	1.28 ± 0.05
$\arg(\delta_\omega)$, rad	$0.167 \pm 0.008 \pm 0.01$	$0.169 \pm 0.008 \pm 0.012$	
m_ϕ, MeV	$1019.761 \pm 0.128 \pm 0.022$	$1019.465 \pm 0.016 \pm 0$	1019.461 ± 0.016
Γ_ϕ, MeV	$4.681 \pm 0.271 \pm 0.058$	$4.25 \pm 0.013 \pm 0$	4.249 ± 0.013
$\mathcal{B}_{\phi\to\pi^+\pi^-}\mathcal{B}_{\phi\to e^+e^-}$, 10^{-8}	$3.65 \pm 0.24 \pm 0.02$	$3.51 \pm 0.22 \pm 0.03$	2.2 ± 0.4
$\arg(\tilde{\delta}_\phi)$, rad	$2.883 \pm 0.052 \pm 0.011$	$2.77 \pm 0.023 \pm 0.006$	
$\lvert a_{cont}\rvert$	$0.0975 \pm 0.0011 \pm 0.0096$	$0.0971 \pm 0.001 \pm 0.0106$	
$\arg(a_{cont})$, rad	$2.337 \pm 0.021 \pm 0.286$	$2.344 \pm 0.02 \pm 0.309$	
χ^2/ndf	212.53 / 195	223.42 / 199	
m'_ρ, MeV	1226.22 ± 24.76		1465 ± 25
Γ'_ρ, MeV	272.97 ± 45.53		$400. \pm 60$
m''_ρ, MeV	1604.66 ± 30.8		1720 ± 20
Γ''_ρ, MeV	249.39 ± 52.24		$250. \pm 100$
$\lvert a'_\rho\rvert$	0.3589 ± 0.0693		
$\lvert a''_\rho\rvert$	0.1042 ± 0.031		
$\arg(a'_\rho)$, rad	-1.831 ± 0.07		
$\arg(a''_\rho)$, rad	3.384 ± 0.234		
χ^2/ndf	288.87/240		
CMD3+CMD2+DM2	χ^2 = 220.08(CMD3)+25.30(CMD2)+40.10(DM2)+3.39(PDG)		
	ndf= 207+29+20+4 - 12($\rho, \omega, \phi, cont$) - 8(ρ', ρ'')		

Both errors are statistical

Second error correspond to ρ', ρ'' fixing

$\varphi \rightarrow \pi^+\pi^-$

First direct $|F_\pi|^2$ measurement around φ resonance



CMD-3

$\psi_\pi = (-21.3 \pm 2.0 \pm 10.0)^\circ$

$B(\varphi\to e^+e^-)B(\varphi\to\pi^+\pi^-) = (3.51 \pm 0.33 \pm 0.24)\times10^{-8}$

Previous measurement using detected $N_{\pi+\pi-}$ or visible cross-section by OLYA, ND, SND (Phys.Lett.B474:188-193,2000)

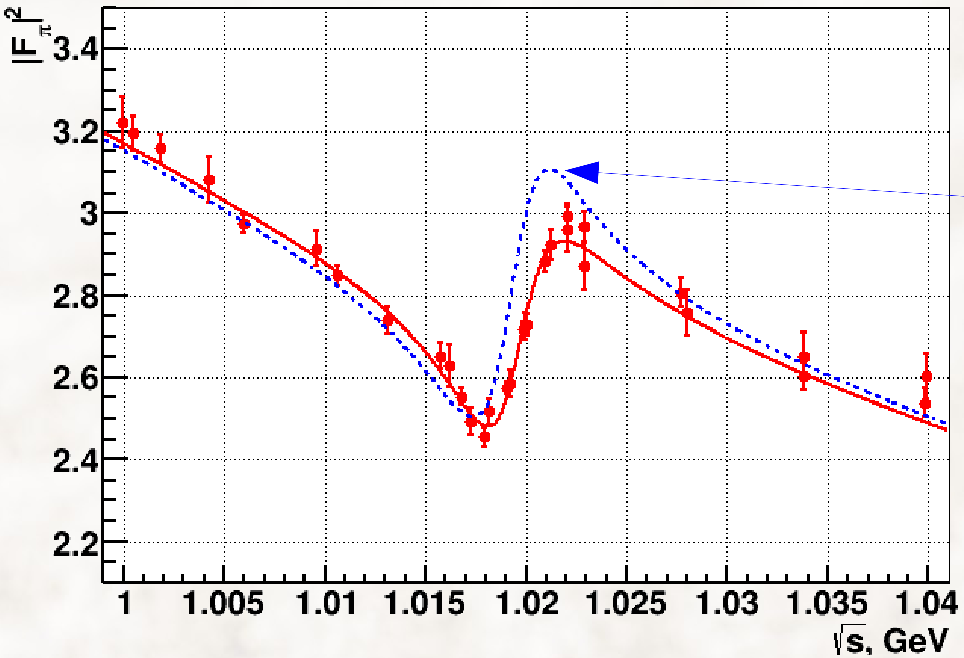
SND

$\psi_\pi = (-34 \pm 5)^\circ$

$B(\varphi\to e^+e^-)B(\varphi\to\pi^+\pi^-) = (2.1 \pm 0.4)\times10^{-8}$

N.B. radiative correction uncertainty (from F_π parametrisation) gives ~1.5 scale factor of total statistical and systematic errors (both for Br and ψ_π)

$\varphi \to \pi^+\pi^-$ via VP term



Assuming no direct $\varphi \to \pi^+\pi^-$
if interference comes from VP

non resonant F_π with
vacuum polarization term

$$\left| F_\pi^{\delta_\phi=0}(s)\,\frac{1-P_{not-\phi-res}(m_\phi^2)}{1-P(s)} \right|^2$$

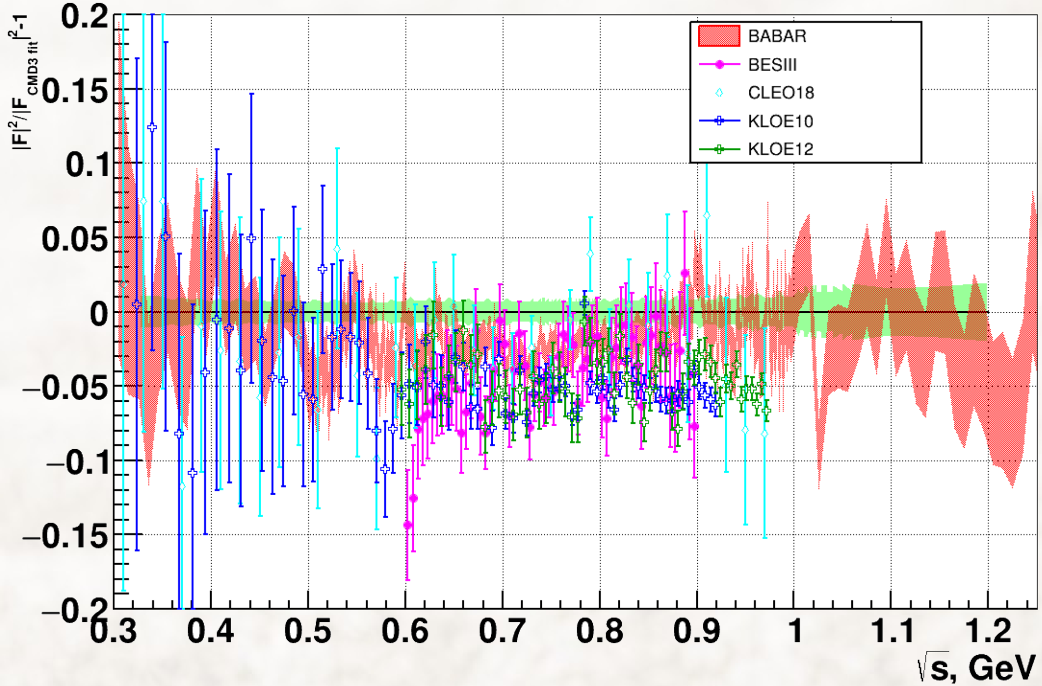
$B_{\varphi\to e+e-}B_{\varphi\to\pi+\pi-}$ = $(3.51 \pm 0.43)\times 10^{-8}$

$(B_{\varphi\to e+e-}B_{\varphi\to\pi+\pi-})^{VP}$ ~ 5.3×10^{-8} - as expected from VP only effect

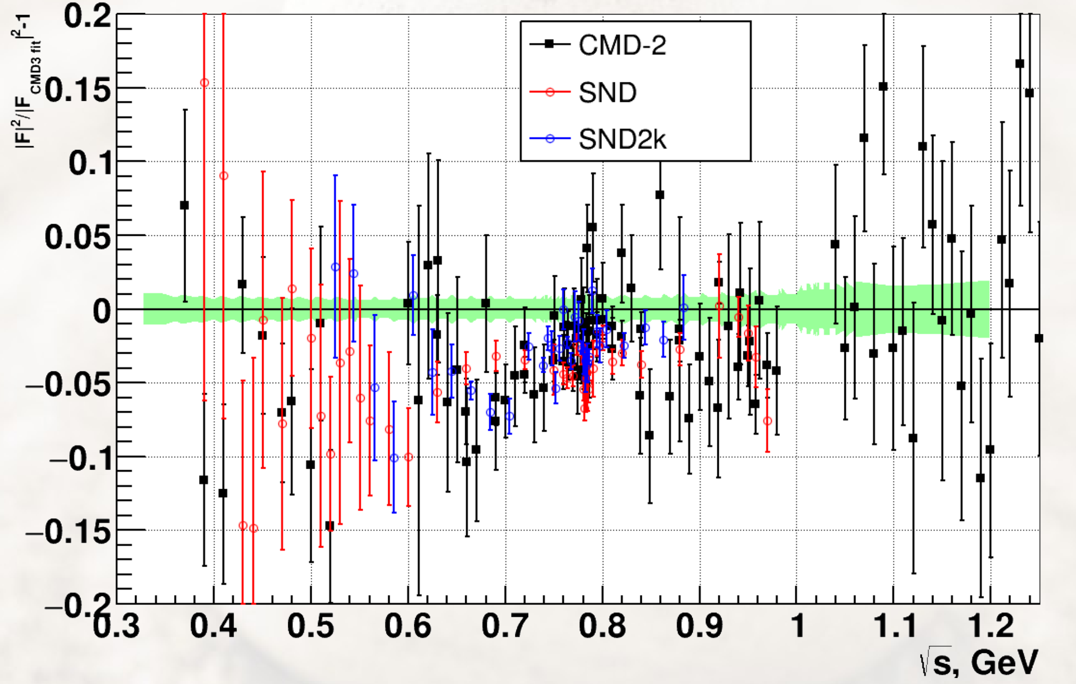
Other experiments

Relative to CMD-3 fit, yellow band – systematic value

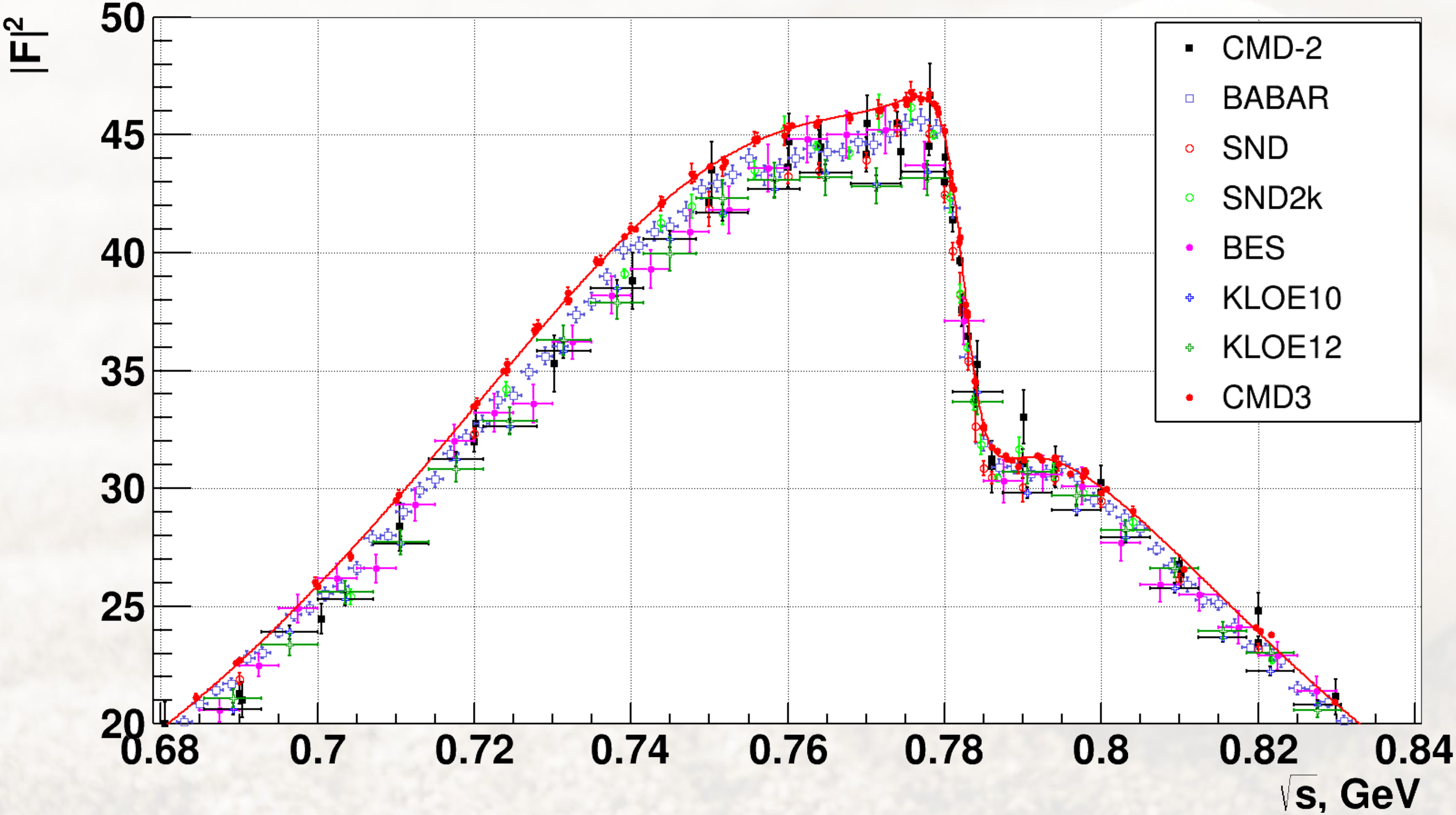
vs ISR



vs direct scan



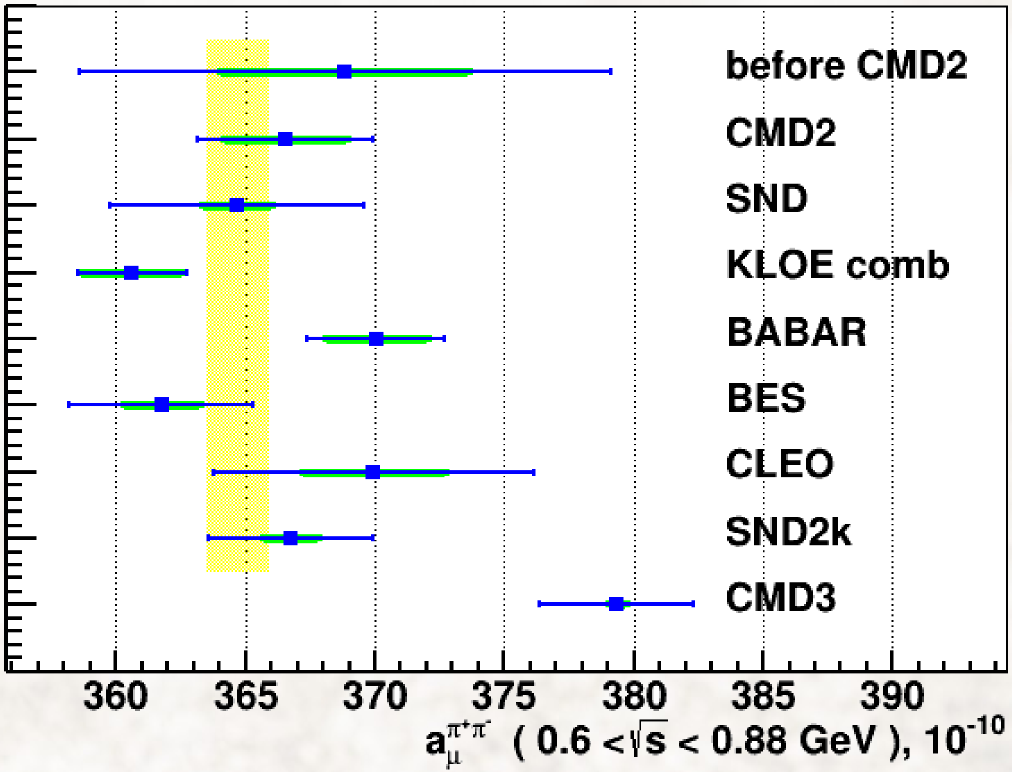
Other experiments



The π+ π− contribution to a_μ^{had}

$$a_\mu^{had,LO} = \frac{m_\mu^2}{12\pi^3}\int_{4m_\pi^2}^{\infty} \frac{\sigma_{e^+e^-\to\gamma^*\to hadrons}(s)K(s)}{s}ds$$

$0.6 < \sqrt{s} < 0.88$ GeV



	$a_\mu^{\pi\pi,LO}$, 10^{-10}
before CMD2	368.8 ± 10.3
CMD2	366.5 ± 3.4
SND	364.7 ± 4.9
KLOE	360.6 ± 2.1
BABAR	370.1 ± 2.7
BES	361.8 ± 3.6
CLEO	370.0 ± 6.2
SND2k	366.7 ± 3.2
CMD3	379.3 ± 3.0

RHO2013	380.06 ± 0.61 ± 3.64
RHO2018	379.30 ± 0.33 ± 2.62 $\times 10^{-10}$
Sum	379.35 ± 0.30 ± 2.95

Conclusion

- VEPP-2000 collider is only one working this days on direct scanning below <2 GeV for measurement of exclusive σ (e+e- → hadrons)
- CMD-3 pion formfactor measurement is based on full data set at $\sqrt{s}$ < 1 GeV

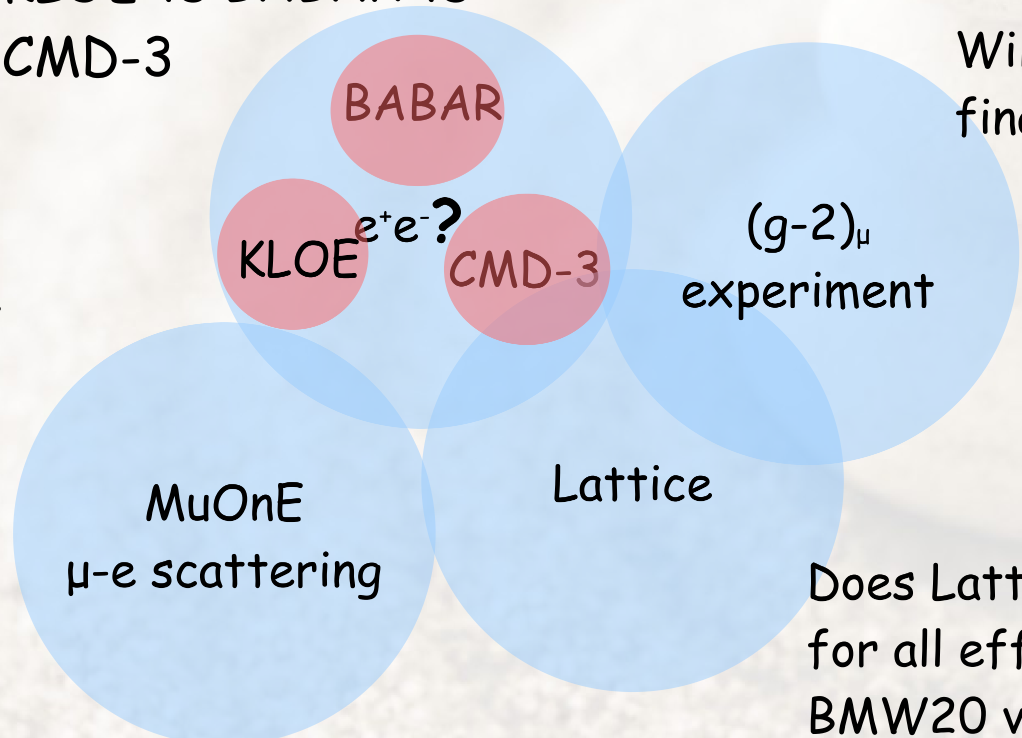
  34×10^6 of π+π- events was used in analysis (at $\sqrt{s}$<1 GeV)
- Total systematic uncertainty 0.7% (RHO2018) / 0.9%(RHO2013)
- New KLOE, BaBar analyses, SND@VEPP-2000, Belle-2 data are underway

Puzzles in puzzle

Question of comparison:

e+e- vs $(g\text{-}2)_\mu$ vs lattice

Where difference comes from:
KLOE vs BABAR vs CMD-3



Will it be confirmed?
final FNAL vs J-PARC

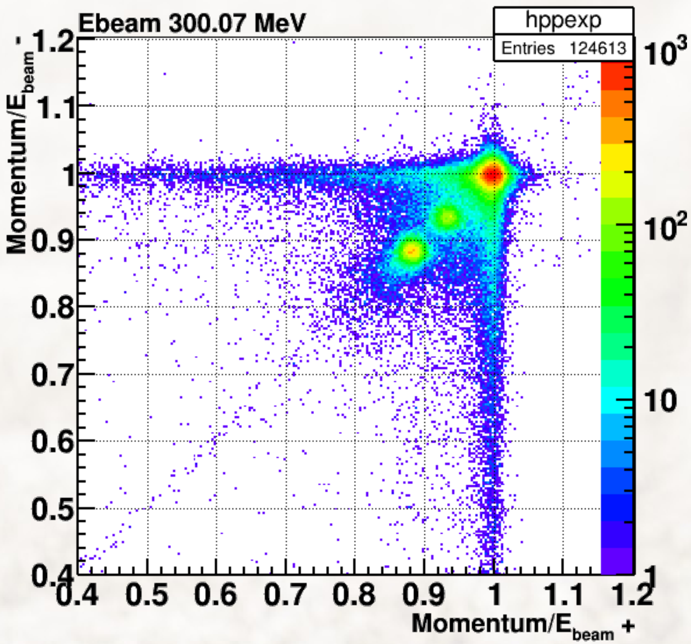
Hard effort against systematics

Does Lattice account for all effects?
BMW20 vs others

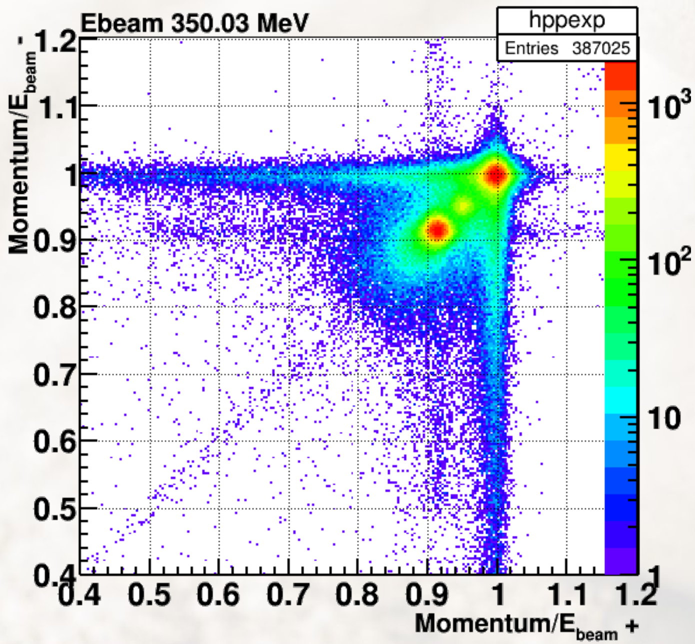
Question 2

Fig.3-4 show 2D-plots for the momentum and energy deposition methods at 2 CM energies, one where each method work best (0.5 GeV for momentum and 0.956 GeV for energy) and the other at their limit where they do not perform well but are still used (0.9 GeV for momentum and 0.548 GeV for energy). In the comparison with other experiments the problematic region is 0.6 - 0.8 GeV. Need to see the corresponding plots at these energies, i.e. 0.6, 0.7, 0.8 GeV.

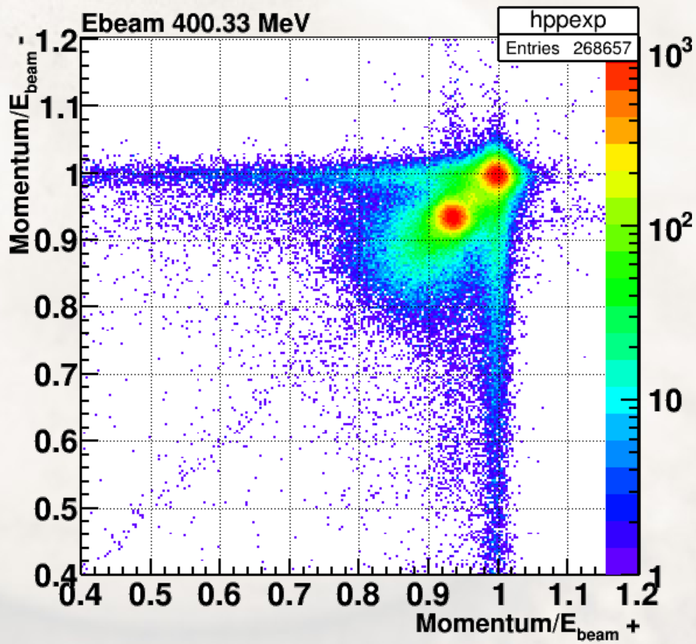
0.6 GeV



0.7 GeV



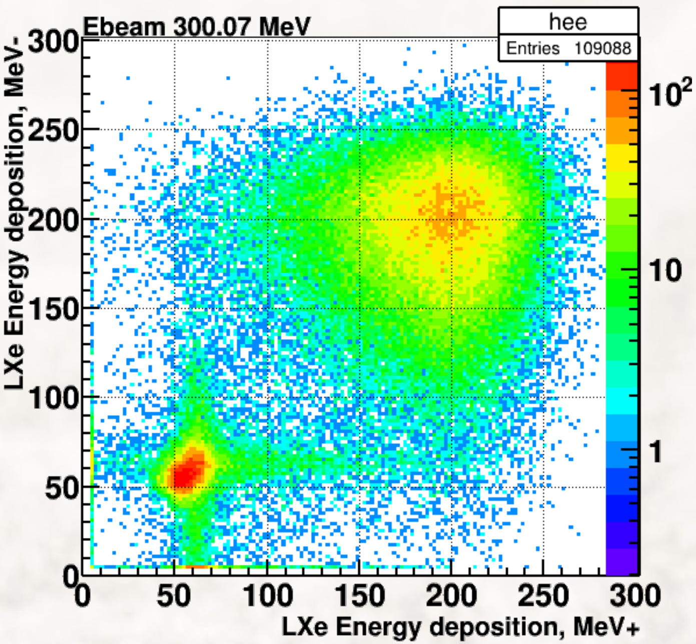
0.8 GeV



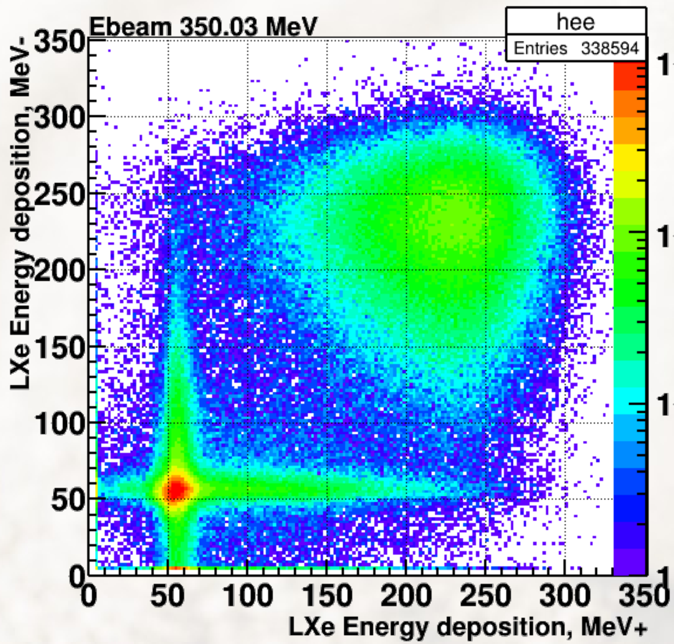
Question 2

Question 2
Fig.3-4 show 2D-plots for the momentum and energy deposition methods at 2 CM energies, one where each method work best (0.5 GeV for momentum and 0.956 GeV for energy) and the other at their limit where they do not perform well but are still used (0.9 GeV for momentum and 0.548 GeV for energy). In the comparison with other experiments the problematic region is 0.6 - 0.8 GeV. Need to see the corresponding plots at these energies, i.e. 0.6, 0.7, 0.8 GeV.

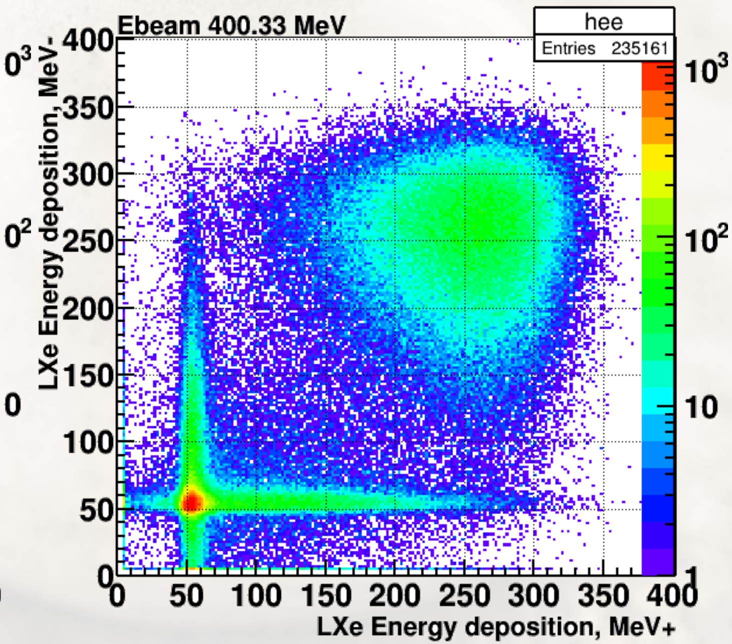
0.6 GeV



0.7 GeV



0.8 GeV



Question 6

Question 6
The 2D reference distributions contain 36 and 57 parameters treated as nuisance parameters in the likelihood fit. Provide more information on the nature of these parameters, their time dependence, the checks with data and how they impact the systematic uncertainty on the cross section. Is it possible to show a data-MC comparison for individual PDFs, e.g. by applying strong cuts for one of the tracks?

Separation of $\pi^+\pi^-$, $\mu^+\mu^-$, e^+e^-, ... final states is based on likelihood minimization:

$$-\ln L = -\sum_{events} \ln\left[\sum_i N_i f_i(X^+, X^-)\right] + \sum_i N_i$$

<u>Momentum-based separation:</u>

MC generator spectra are convolved with detector response function (resolution, brems., pion decays)

36 free parameters in fit per each point

<u>PDF(e+e-) detector response addition:</u> brems. + 3 Gauss per axis + sigma (x-y correlation):

$b^0(1-p/p_0)^{-1-b1-f(b0)}$ X (ΣGauss(1/p'))

2 + 8*2 + 1 = 19 parameters

<u>PDF(μ+μ-):</u> 3 Gauss from e+e- + 1 Gauss(p) per axis + sigma (x-y correlation):

2*2 + 1 = 5 parameters

<u>PDF(π+π-):</u> 3 Gauss from e+e- + 1 Gauss(p) per axis + sigma (x-y correlation) + fixed from MC form of pion decays tails (ratio in tail free):

2x2 + 1 + 2 = 7 parameters

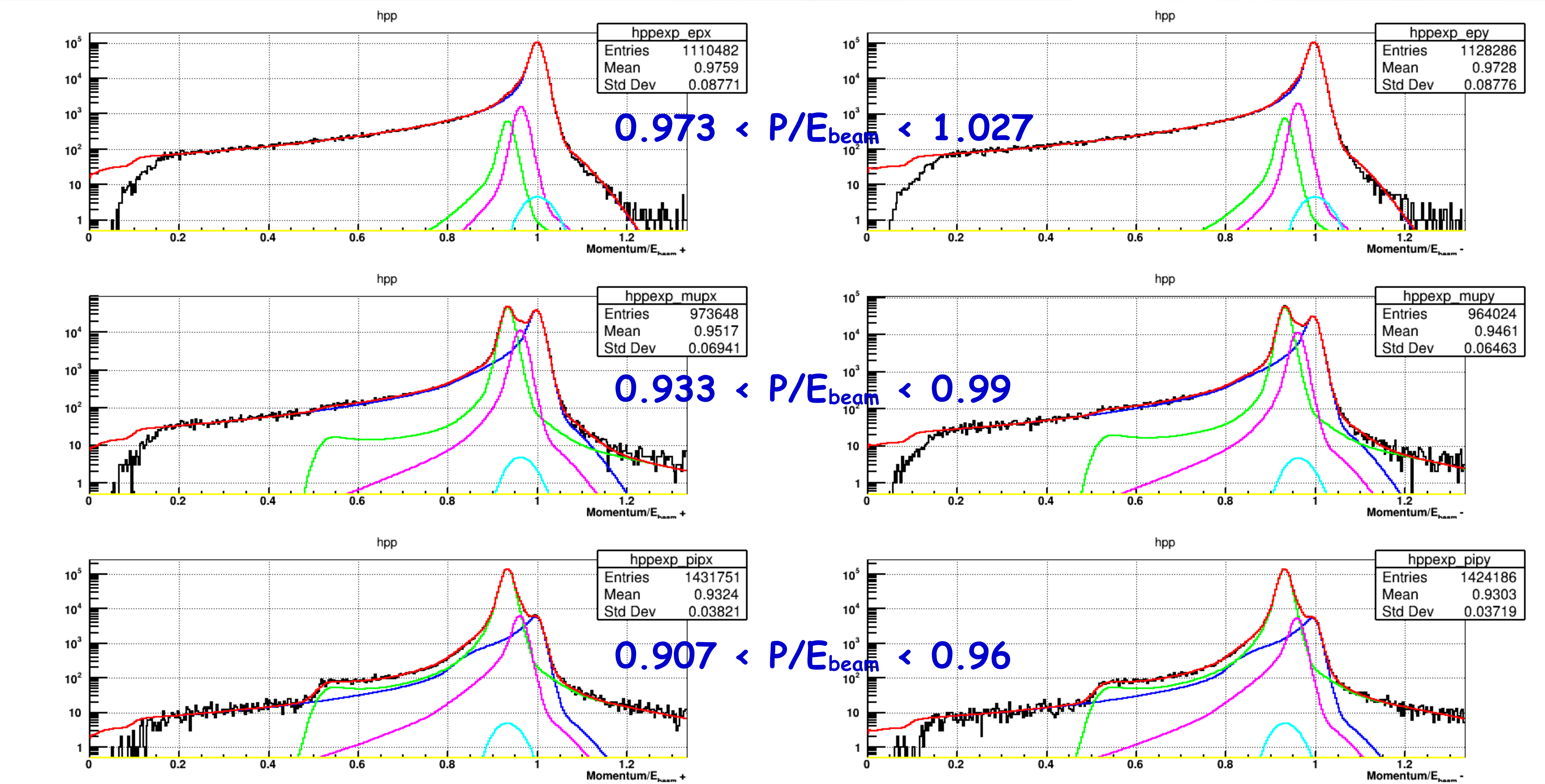
<u>PDF(cosmic):</u> form fixed from clean cosmic sample selected by time of event

<u>PDF(3π, 4l):</u> form fixed from from full MC

N_{ee} , $N_{\pi\pi}/N_{ee}$, $N_{\mu\mu}/N_{ee}$, $N_{3\pi}/N_{ee}$, N_{cosmic}/N_{ee} - 5 parameters

Fit result

Ebeam 391.48 MeV

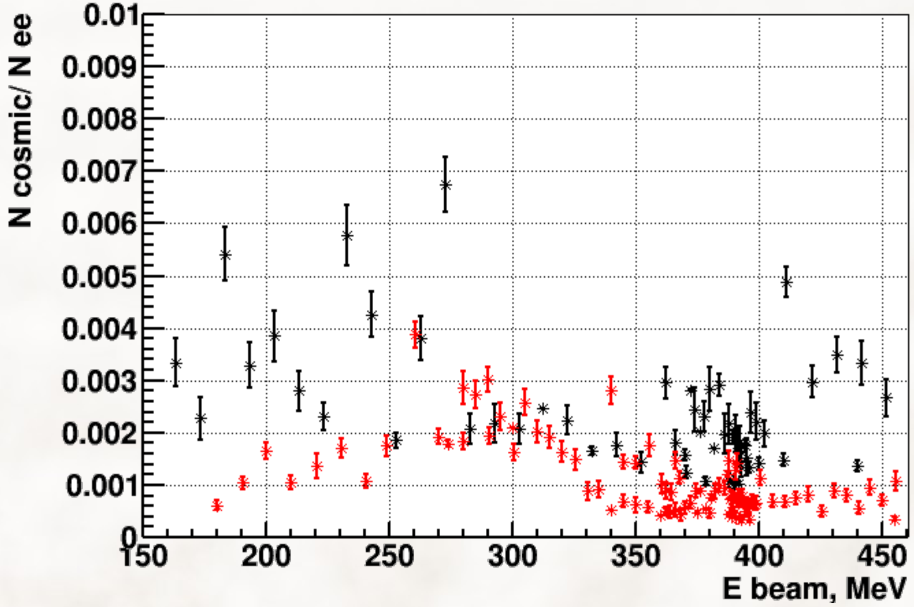


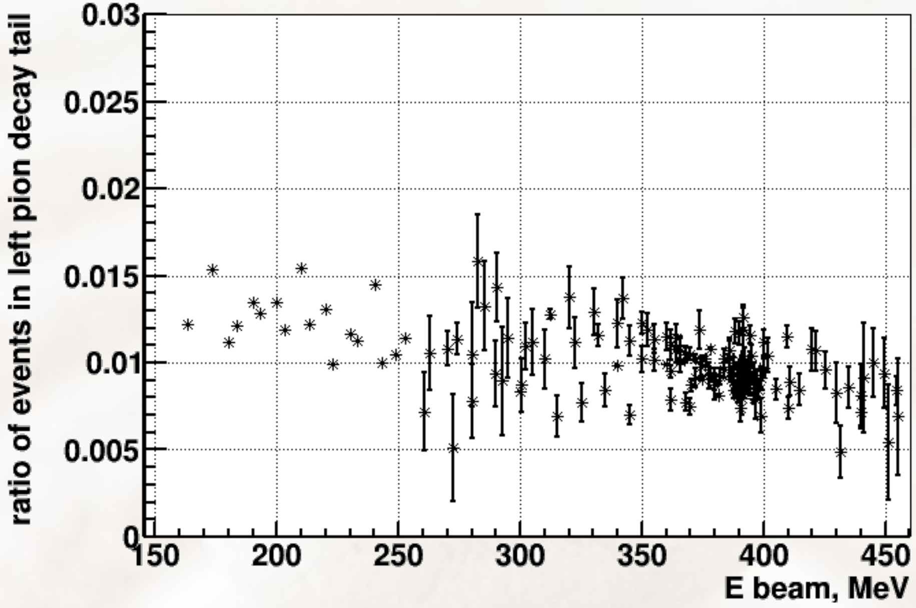
$0.973 < P/E_{beam} < 1.027$

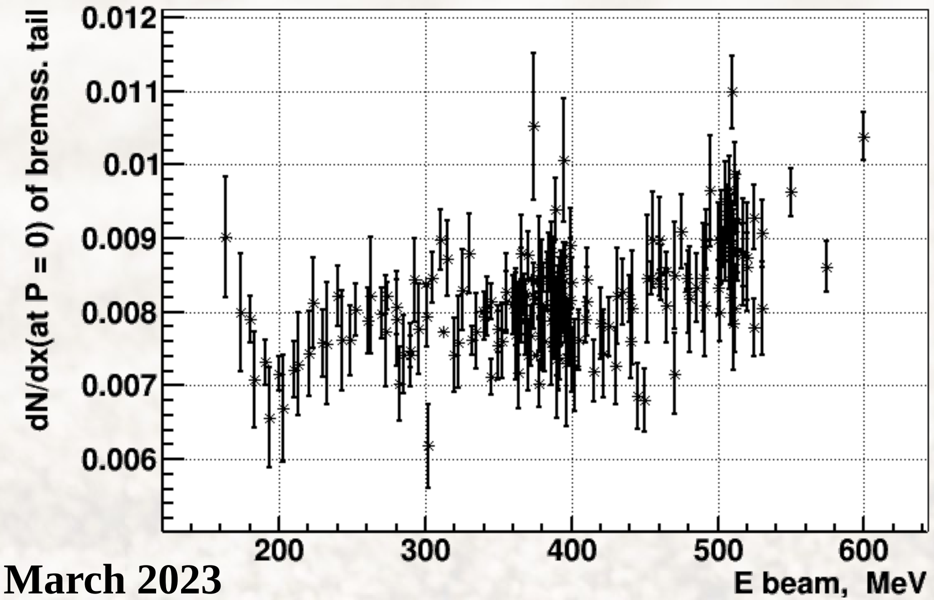
$0.933 < P/E_{beam} < 0.99$

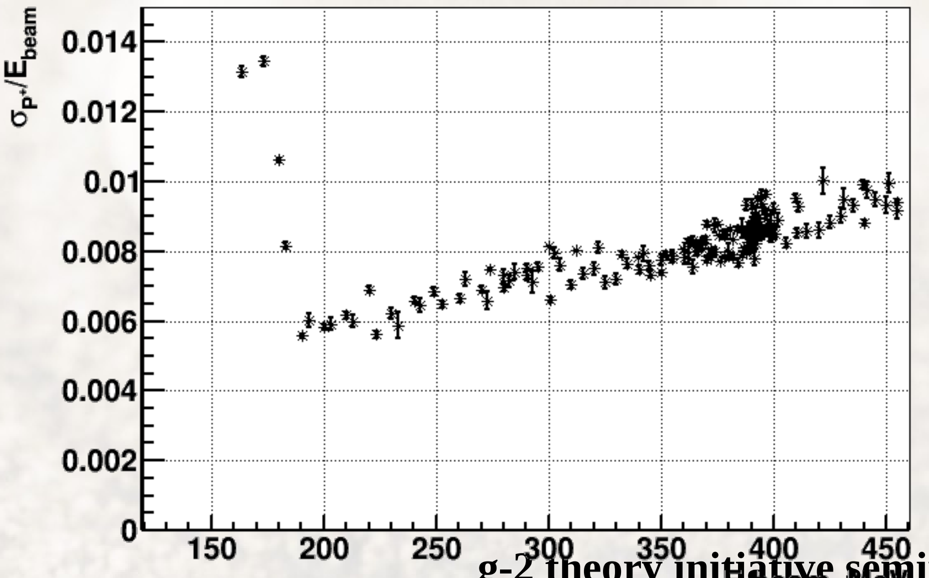
$0.907 < P/E_{beam} < 0.96$

Some parameters dependences









Question 6

Question 6
The 2D reference distributions contain 36 and 57 parameters treated as nuisance parameters in the likelihood fit. Provide more information on the nature of these parameters, their time dependence, the checks with data and how they impact the systematic uncertainty on the cross section. Is it possible to show a data-MC comparison for individual PDFs, e.g. by applying strong cuts for one of the tracks?

Energy deposition-based separation:

PDFs is described by a generic functional form (log-gaus, etc),
trained on the data: by tagged electron, cosmic muons

56 free parameters in fit

PDF(e+e-): (2 Logarithmic Gaus + 1 Gaus) + 0-Energy probability – all per axis + fixed from MC X-Y correlation $\Sigma a_i f(k_i X+, k_i X-)$

10*2 + 1*2 = 22 parameters

PDF(μ+μ-): form fixed from clean cosmic sample selected by time of event, and momentum, $N_{\mu\mu}/N_{ee}$ fixed from QED

PDF(π+π-): MIP as "2 Logarithmic Gaus + 1 Gaus, 1 shift fixed" + MIP probability + 0-Energy probability + Hadronic tail by sum of decreasing gausses as $\Sigma a_i \text{Gauss}(X-(E^{max}-E^{mip})*i/n+E^{mip}, \sigma_0)$ – all per axis

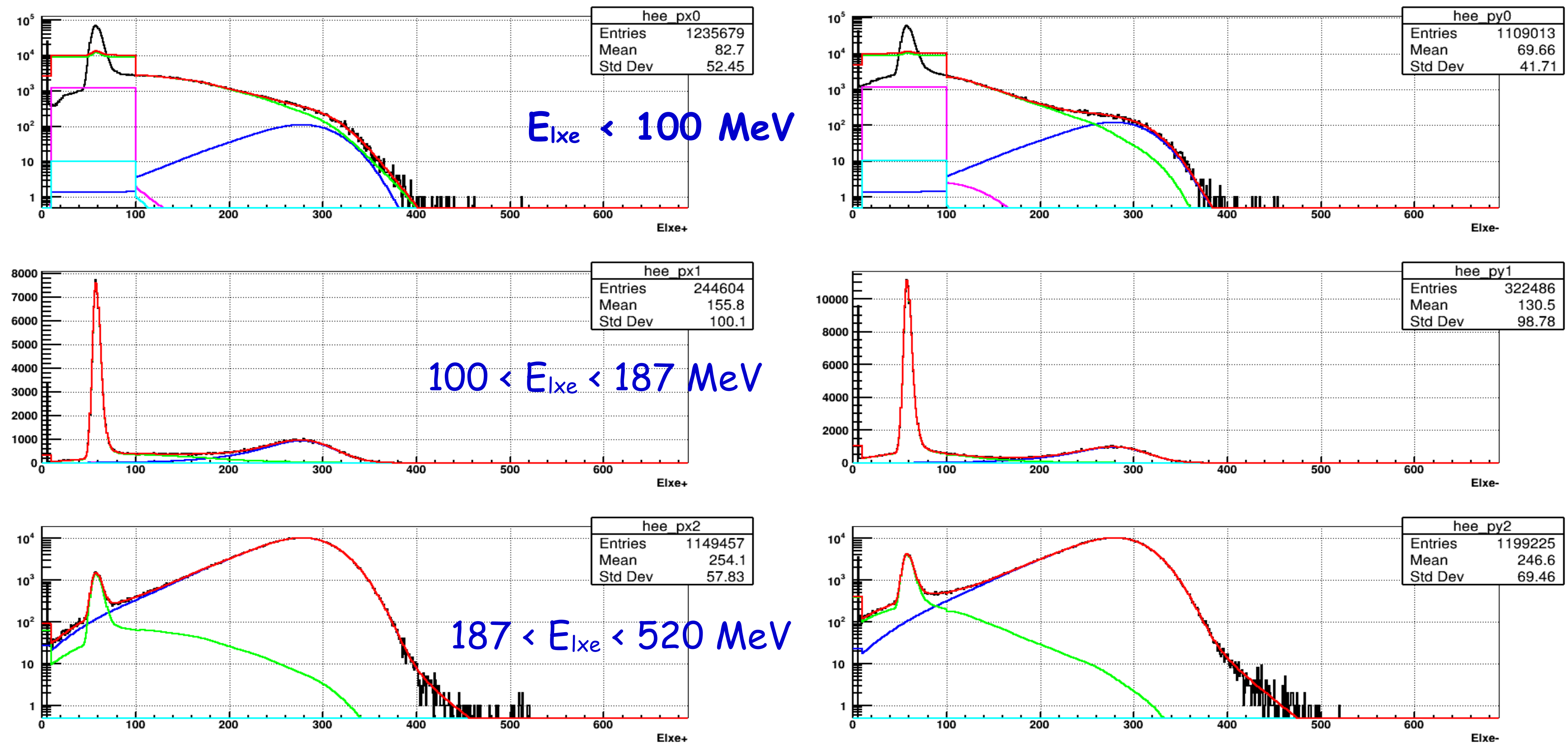
9*2 + 1*2 + 1*2 + 5*2 = 32 parameters

PDF(cosmic): form fixed from clean cosmic sample selected by time of event, N fixed from time distribution

N_{ee} , $N_{\pi\pi}/N_{ee}$ - 2 parameters

Fit result

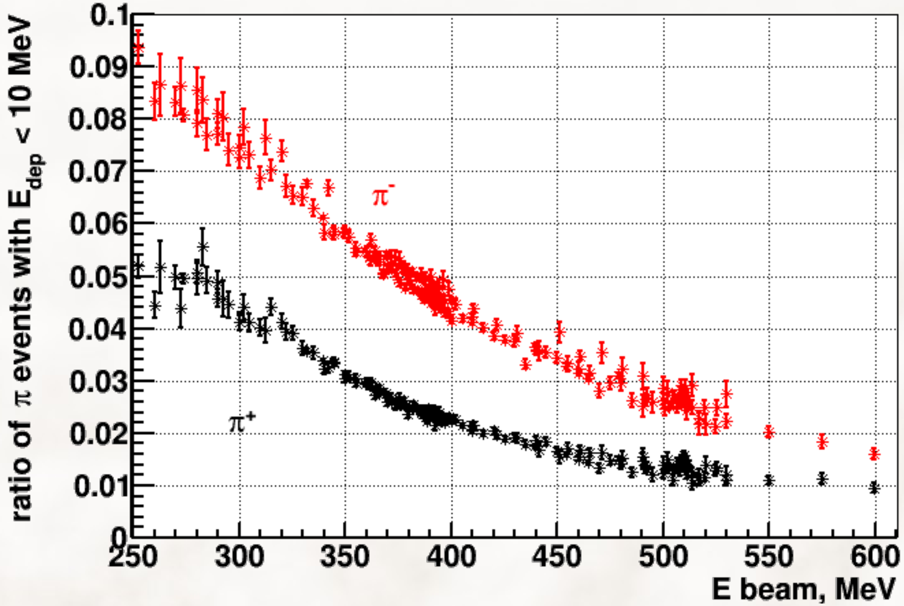
Ebeam 391.48 MeV

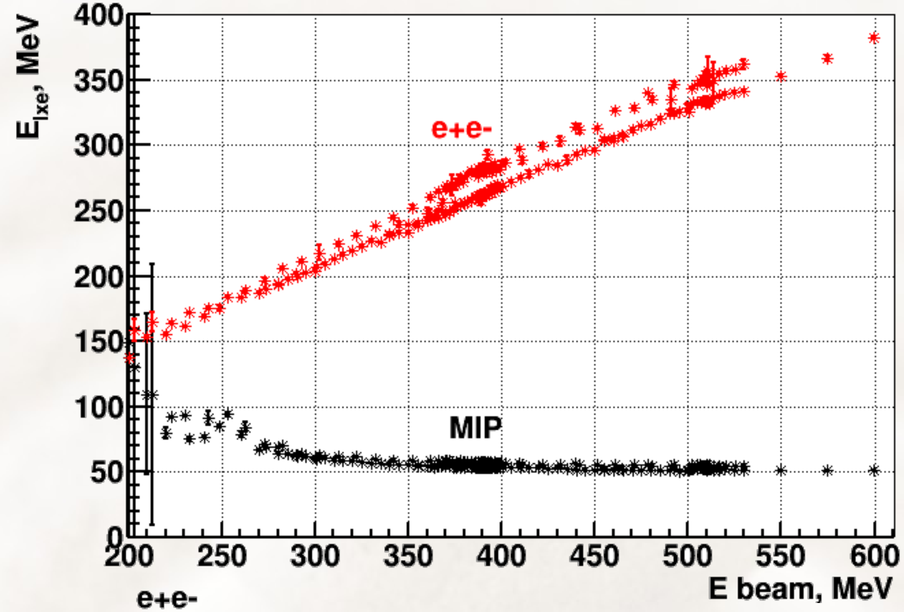


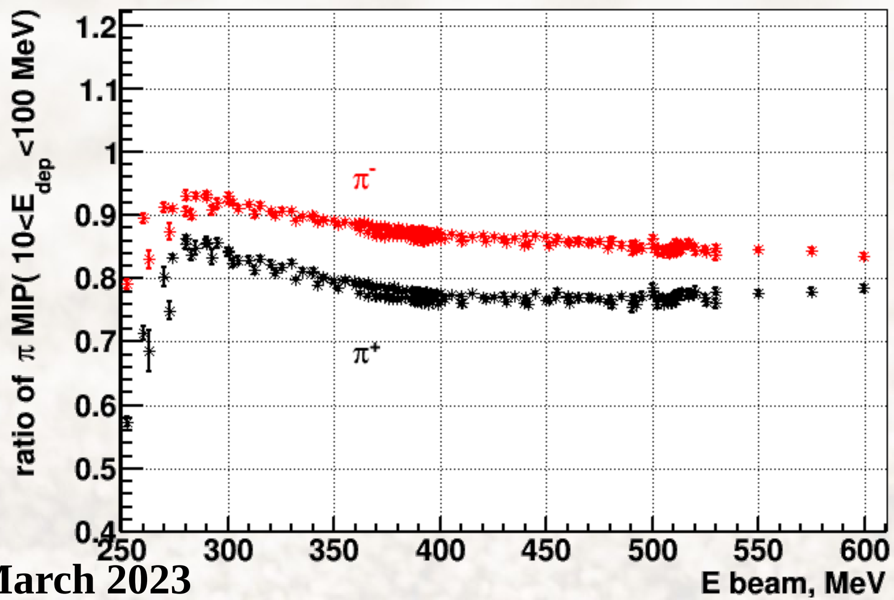
Muon & Pion MIP PDFs are strongly overlap,

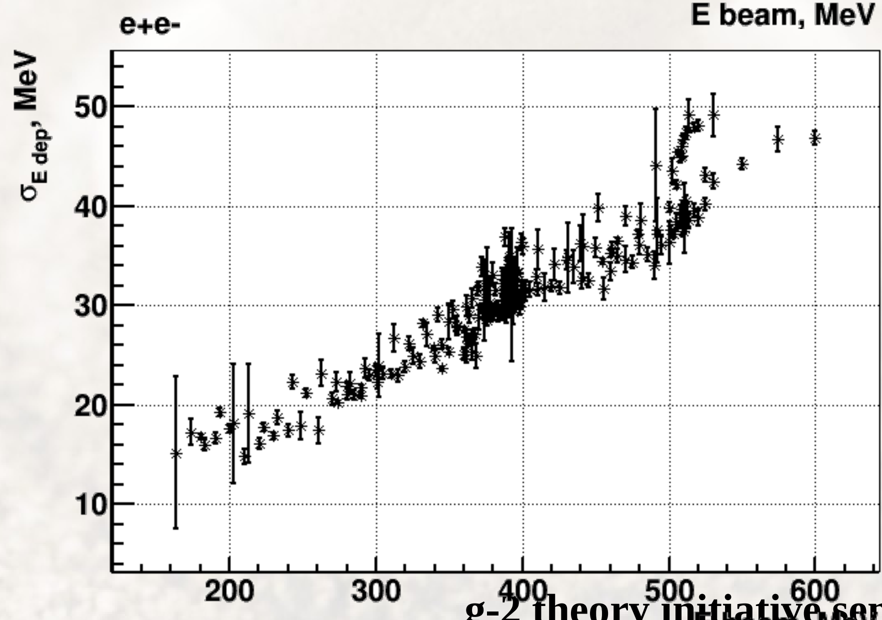
In 10 < E_{lxe}^{+-} < 100 MeV constant PDF was used to suppress likelihood systematic biases from not exact PDF descriptions

Some parameters dependences









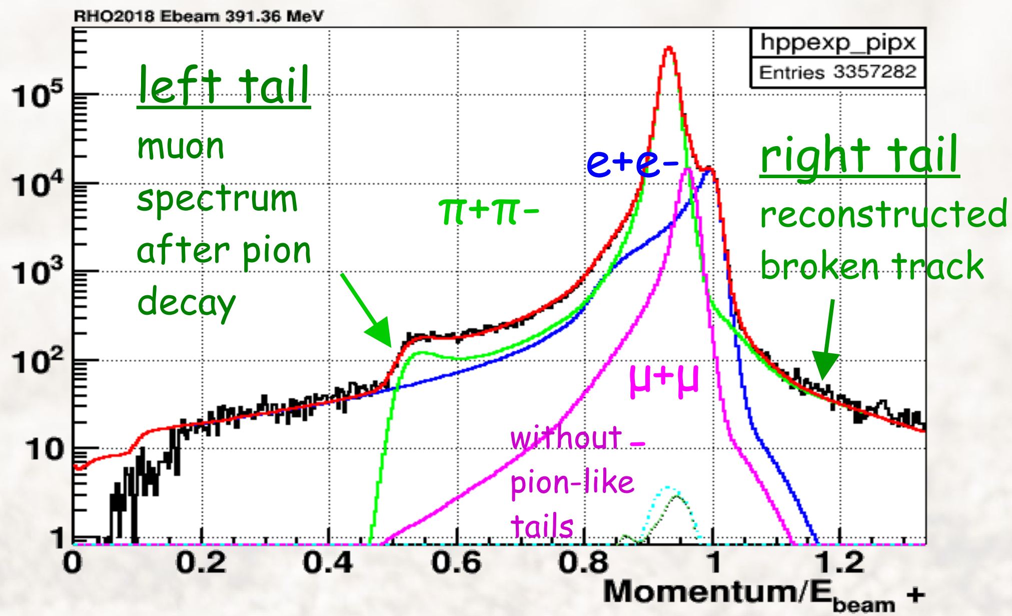
Question 6 & 19

Question 6: The 2D reference distributions contain 36 and 57 parameters treated as nuisance parameters in the likelihood fit. Provide more information on the nature of these parameters, their time dependence, the checks with data and how they impact the systematic uncertainty on the cross section. Is it possible to show a data-MC comparison for individual PDFs, e.g. by applying strong cuts for one of the tracks?

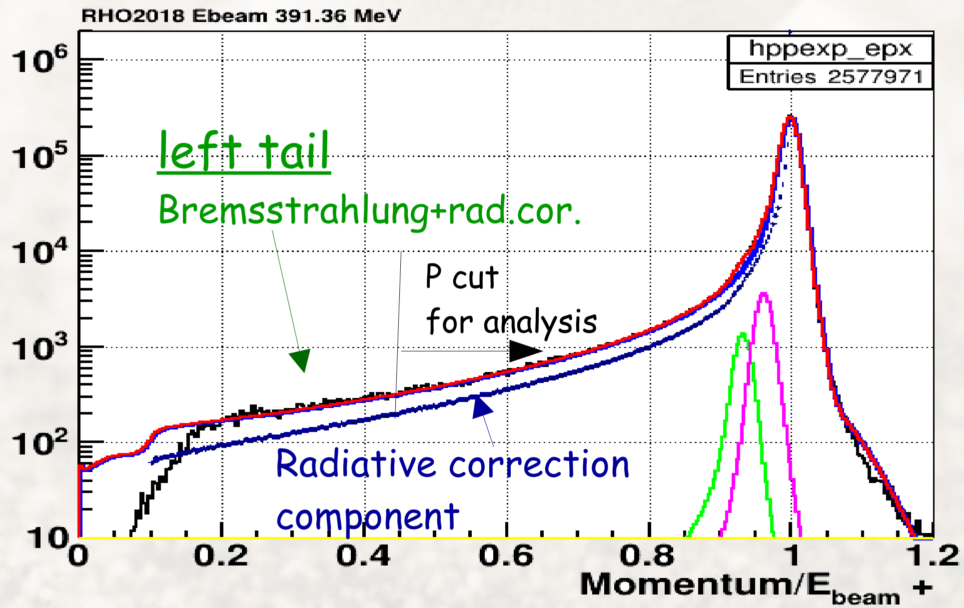
Question 19: Tracking plots (efficiency plot?) are given for MC simulation only. Need to see data/MC tests.

The PDFs are obtained from data itself, they are not necessary to be same as in simulation. Some features of PDF give possibility to control particle specific losses (pion decay, bremsstrahlung loss) – given in slides 27,28.

Experimental P+ spectrum with $|P^- - P\pi| < 10$ MeV



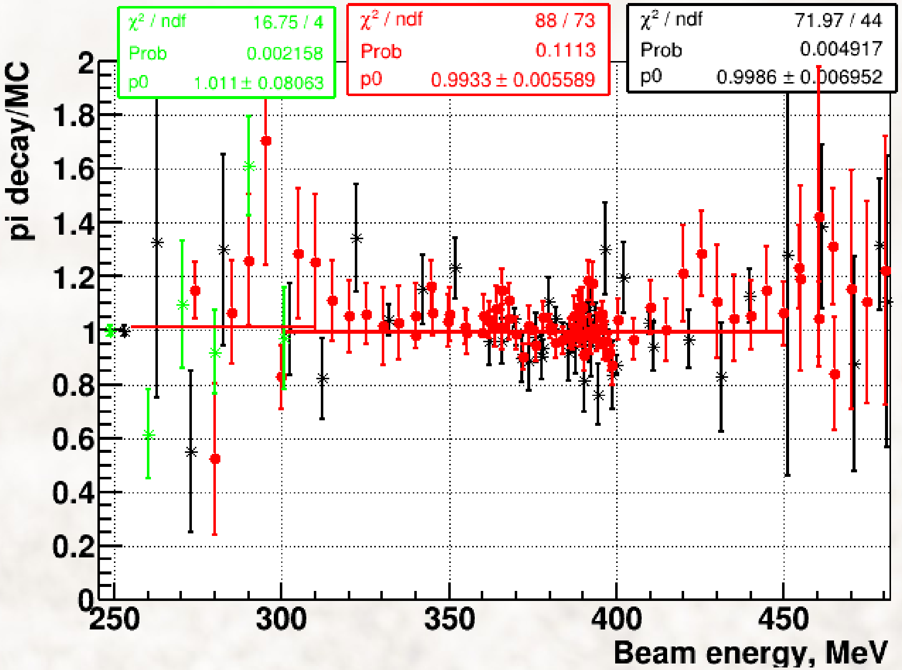
Experimental P+ spectrum with $|P^- - Pe| < 10$ MeV



Data/MC checks for particle specific losses

Some features of PDF give possibility to control particle specific losses (pion decay, bremsstrahlung loss) – slides 27,28.

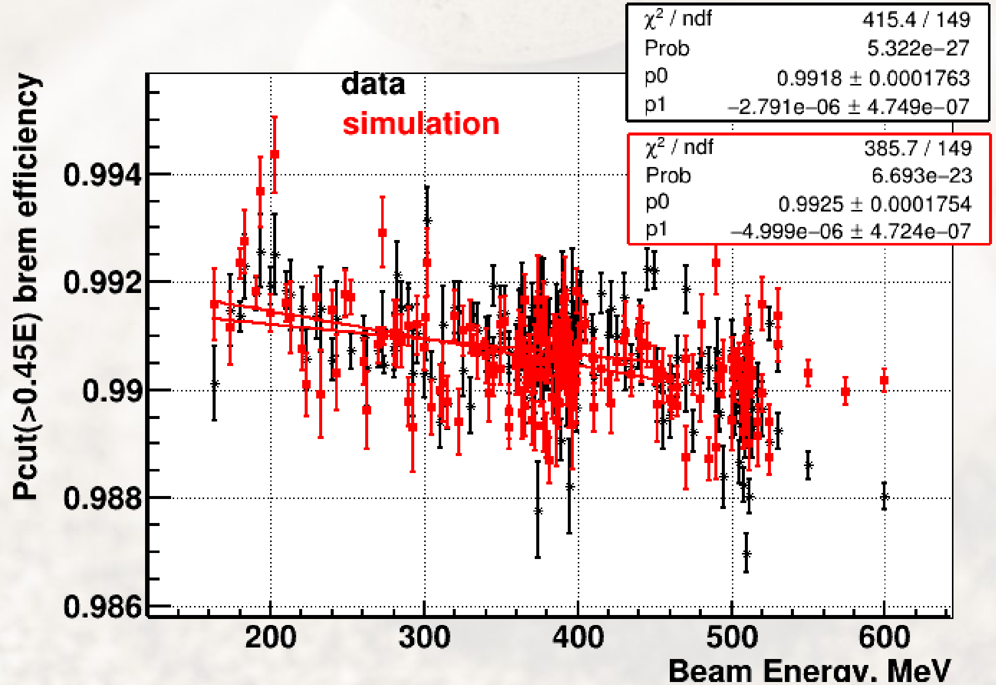
N events in Left+Right pion decay tails in PDF
The monitoring tool to control the reconstruction efficiency of decayed tracks in Data vs MC



Relative consistency ~ 2-3%

N events in Left + Right tails ΔData/MC:
RHO2013: 0.0014+-0.007, RHO2018: 0.007+-0.006

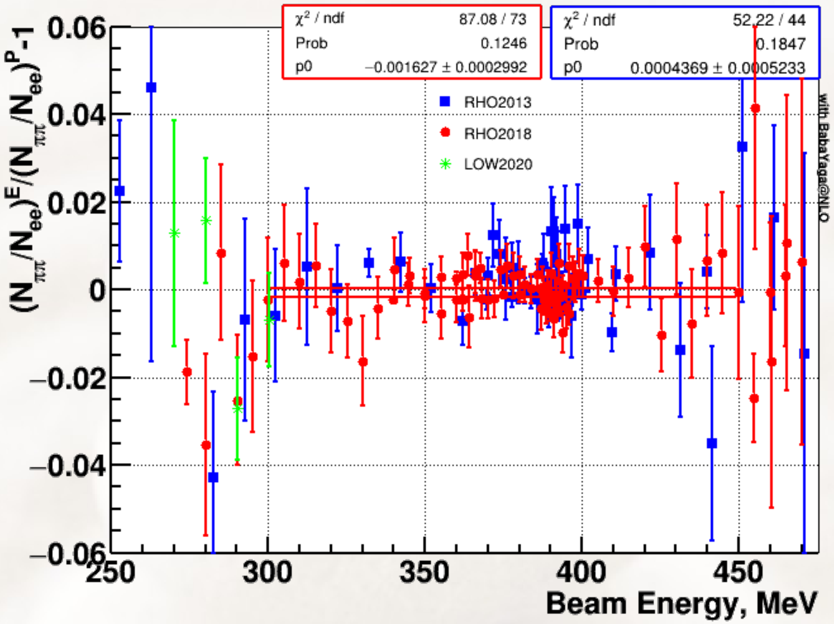
Left tail in electron momentum spectra describe radiative + bremsstrahlung loss
N of events of brems. part at cut $P/E_{beam} < 0.45$ gives part of brems. correction (0.9% of total 1.2%)



Relative consistency in inefficiency ~ 2%

Question 8

Fig.8: the double ratio $N_{\pi\pi}/N_{ee}$ for the 2 methods is fitted between 0.6 and 0.9 GeV and found to be consistent with 1 within 0.2%. The fit is dominated by the large statistics at the ρ peak while uncertainties are much larger in the tails. Is it reasonable to quote a constant systematic uncertainty on this ratio of 0.2% throughout the range 0.381-1 GeV?



The Logic is different:

Possible biases are checked on full MC → systematics are estimated independently per each separation method.
Comparison of different methods gives the additional cross-check and ensure us, at least at central region, that 0.2% systematic uncertainty estimation is safe.

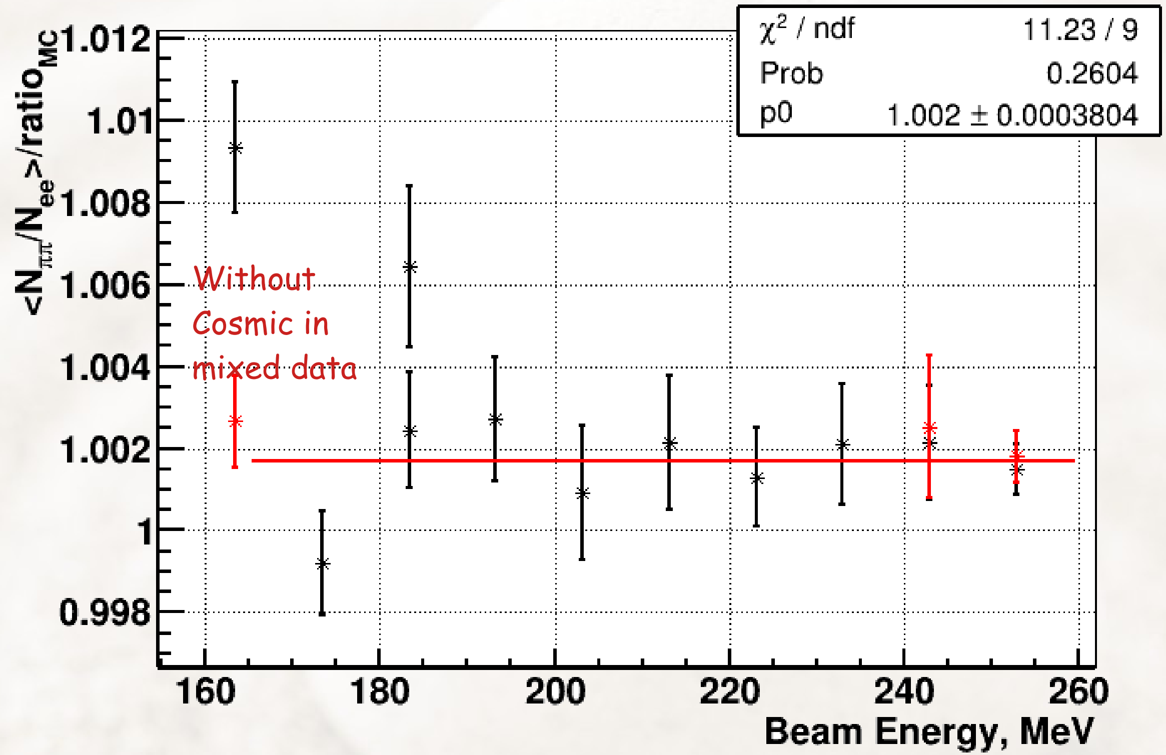
Question 8

The separation biases of likelihood minimization was checked on mixed samples of full MC

At lowest points statistical precision per point is low ~2-7%

100 independent mixed data samples were produced:
$\langle N\pi\pi/Nee \rangle$ ~ +0.2%
$\langle N\mu\mu/Nee \rangle$ ~ +0.2%

Momentum-based separation on full MC



At $\sqrt{s}$ < 0.381 GeV, the detector was operated with reduced magnetic field B=0.65T (1T) instead of 1.3 T → there is not enough data for cosmic PDF determination → systematics 0.5%
At lowest points stronger cut $|t^{event}-t^{beam}|$ < 10 nsec to suppress cosmic events was applied

Question 18

Tracking: clarify the separation made between 'base efficiency' (track selection cuts) and inefficiency from sources specific to particle type (decay, multiple scattering, bremsstrahlung, nuclear interactions).

The efficiency analysis is based as much as possible on data itself.
The test sample for efficiency study was selected by 2 collinear clusters in calorimeter.
Unfortunately it is doesn't cover the full data sample used in the particles separations.
Some events, when second cluster is not present, are not taken into account in test sample.
Test sample covers only ~30% of pion specific inefficiency (from ~2%-pion decay, nuclear interact)
~ 5% of electron specific (from ~1% - bremsshtrahlung)

Also some of inefficiencies like cuts on Nhits, Z_{vtx}, resolution in θ are studied separately

Particle specific losses were taken from full MC (and controlled by data).
This corrections are applied as for full $\pi^+\pi^-$, e^+e^-, … data samples used in analysis(added), as also for each specific test samples used in efficiency study (subtracted to exclude double-counting).

Question 26

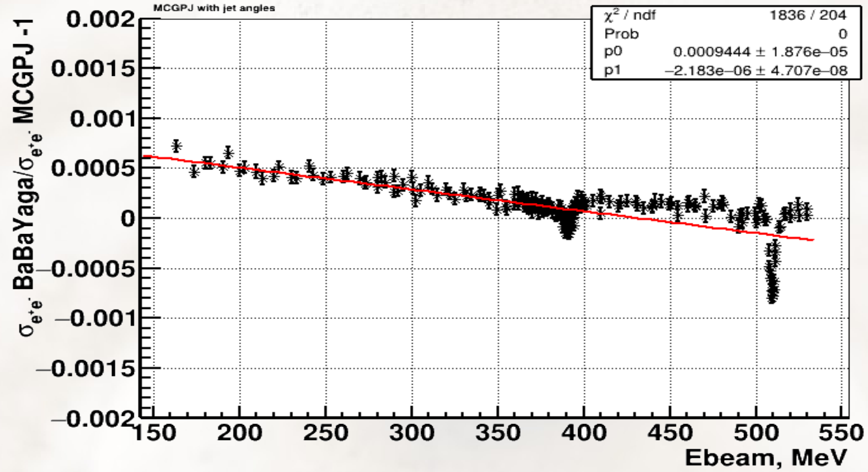
Two generators used (MCGPJ, BabaYaga) NLO+NNLO approximative with some differences found for ee: give more information. Does it affect also the $\mu\mu$ and $\pi\pi$ samples?

Please see more details in: https://agenda.infn.it/event/28089/contributions/147298/

Yes, μ+μ- and π+π- differential cross sections have also some uncertainty

<u>e+e-:</u>

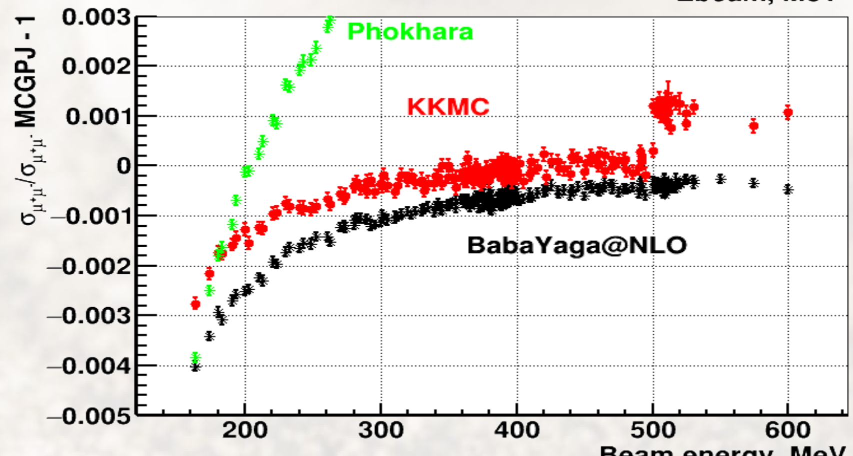
Integrated cross-section is consistent at the level <0.1% between generators



<u>μ+μ-:</u>

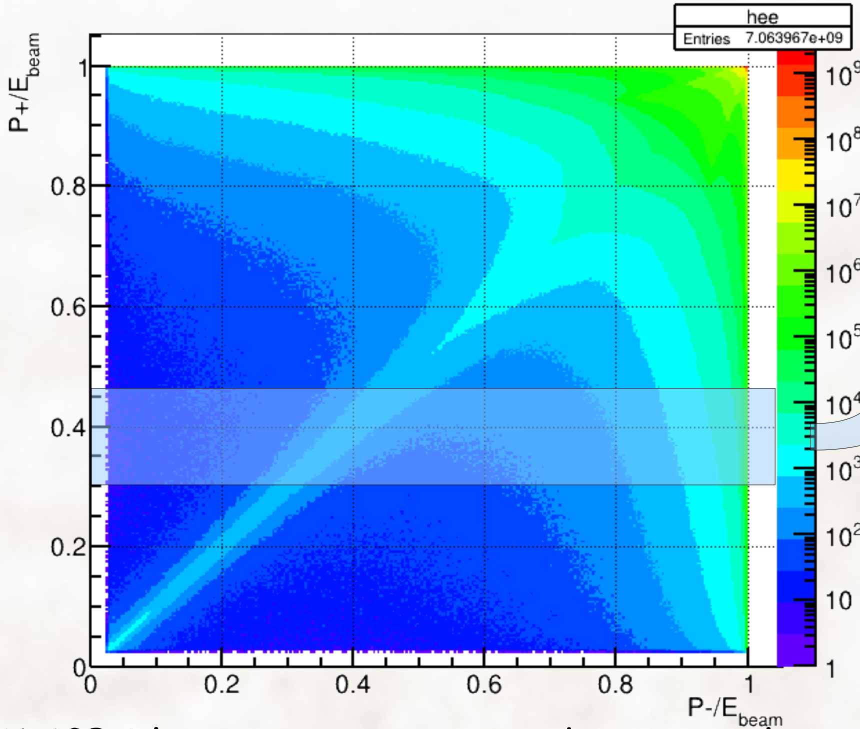
Integrated cross-section is inconsistent up 0.4%

BabaYaga@NLO, KKMC, etc – missed mass term in FSR (arXiv:hep-ph/0505236)

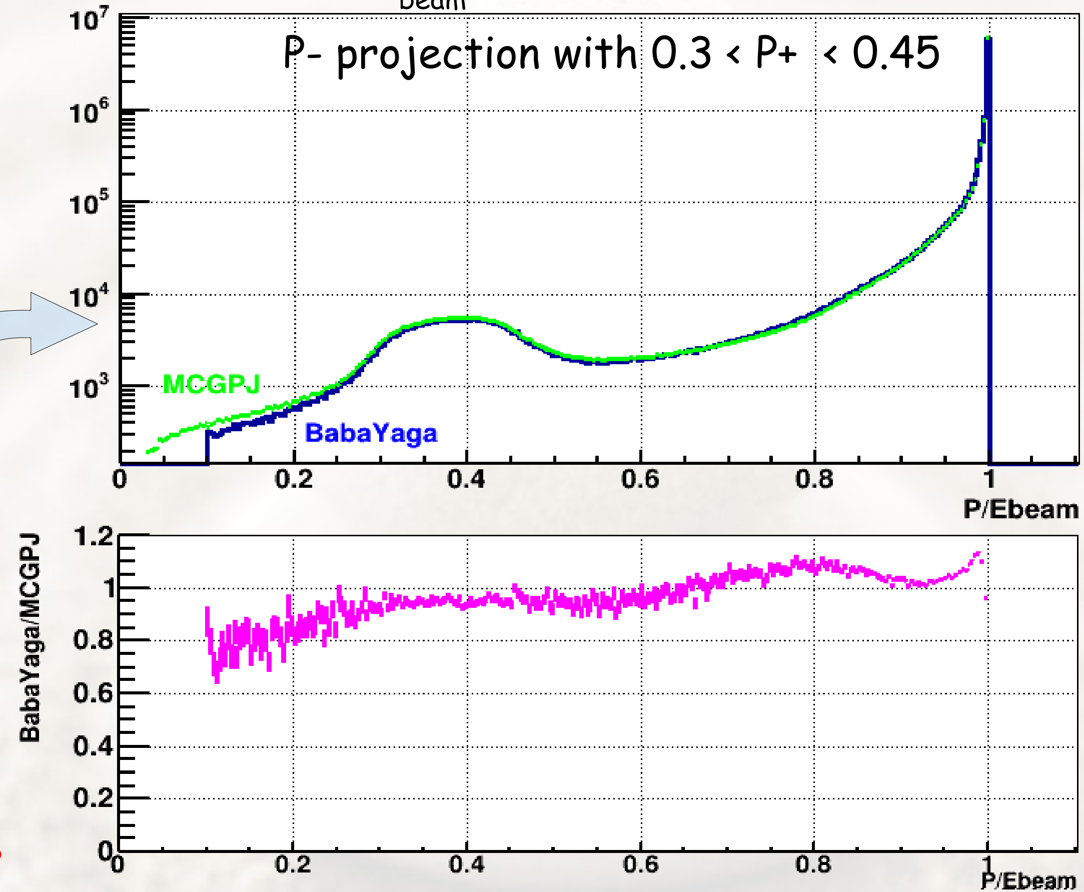


MCGPJ vs BabaYaga bhabha P+ vs P- spectrum

Differential over momentum spectrum comparison



E_{beam} 391.48 MeV



MCGPJ last improvement with jets angles reduce discrepancy from x1.6-3 to x1.1

Momentum spectrum still disagree at level ~ 10%

Tails comes from e+e- → e+e- γγ , NNLO order

Very desirable to have more precise generators

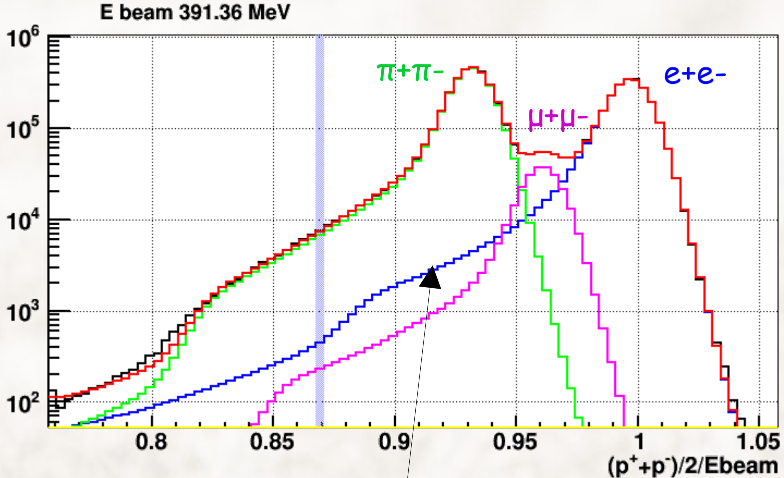
Such discrepancy gives ~0.1-0.2% systematic for π+π- at ρ-peak using momentum analysis at CMD3

Differential cross section effect on form factor

Differential cross section knowledge is necessary for momentum-based separation (not used in energy deposition separation)

Effect ~ 0.1-0.2% at ρ-peak

Effect comes when momentum peaks from π+π- and e+e- become close

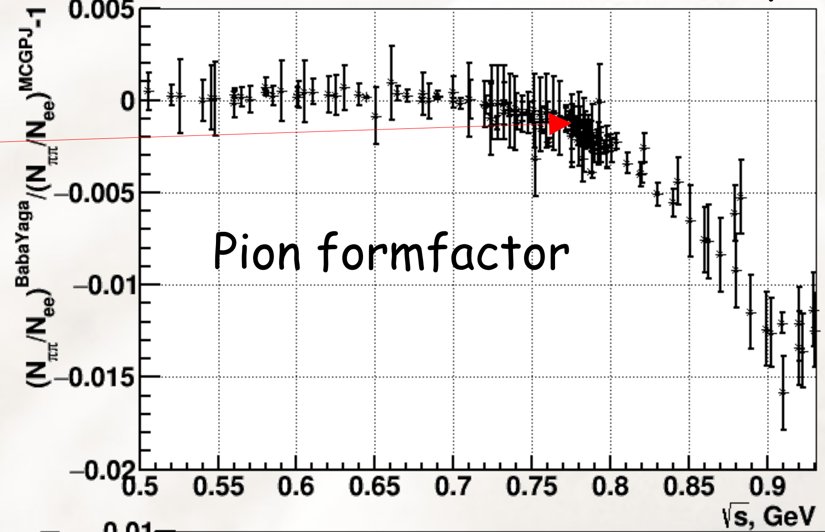


Important here soft photons radiation distribution:

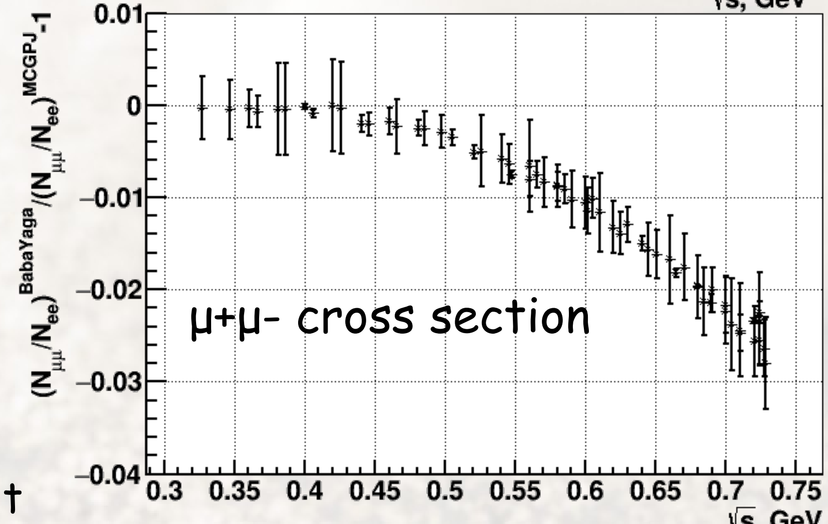
Looks like BaBaYaga@NLO approach with iterative photons generation gives better result

Difference of MCGPJ vs BabaYaga@NLO

Cumulative from e+e- and μ+μ- spectra



μ+μ- effect <0.05-0.1%



μ+μ- effect ~ 1/4 - 1/3

Questions 30, 32

Question 30: How can you justify a 0.2% error for the ππ mode in MCGPJ given the large uncertainties seen for the Bhabha mode?
Question 32: The RC are large +8% at 0.9 GeV and -9% at 0.7 GeV. What is the uncertainty specific to this analysis, from the used generators. The number 0.2% quoted is for the integrated cross sections ('declared' by MCGPJ authors) , but apparently not listed in Table 2. Also what about NLO+HO differential cross sections? Need to be clarified.

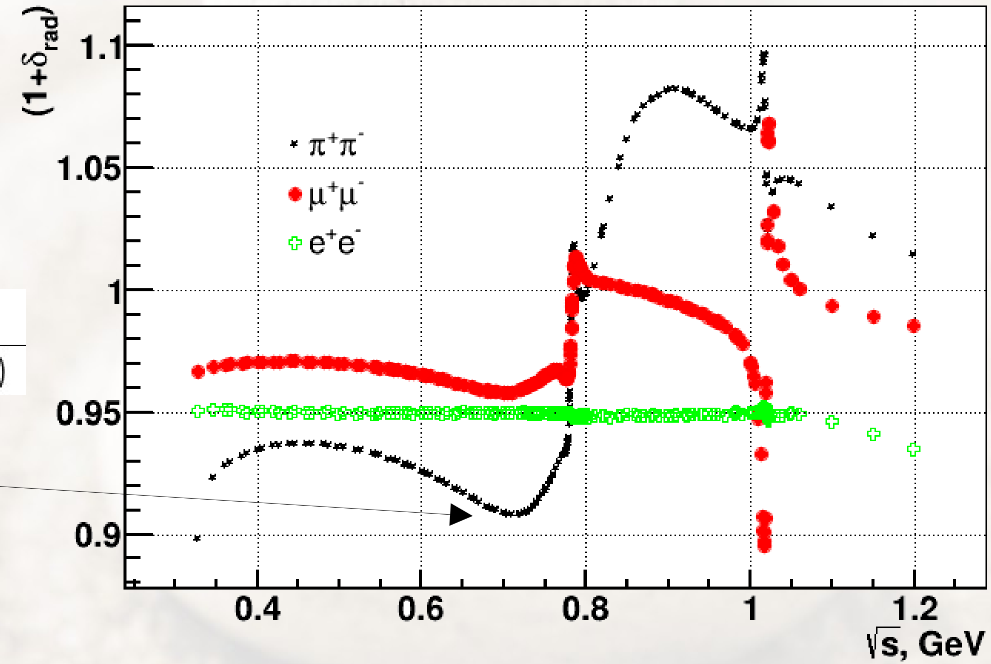
N.B. Integrated cross section in Bhabha mode was always consistent between generators at ~ < 0.1%

0.2% from MCGPJ is listed in Systematics Table 2:

Contribution
$0.2\%\ (\pi^+\pi^-) \oplus 0.2\%\ (F_\pi, \sqrt{s} > 0.74\ \text{GeV}) \oplus 0.1\%\ (e^+e^-)$

+8%/-9% wave comes from F_π and ISR

Uncertainty from different F_π parametrizations is second part in radiative correction uncertainty



Differential cross section doesn't affect energy deposition-based separation.
Looking on Nμμ/Nee in momentum-based separation, the effect from ππ spectra probably is smaller than from e+e- spectra (0.1-0.2% at ρ)

ππ generator

For ππ mode

Unfortunately only MCGPJ available with declared 0.2% precision (for energy scan experiments)

Phokara and BabaYaga 3.5 are incomplete at NLO level for energy scan mode: there is no FSR

Very desirable to have new precise generator with above sQED which will cover ISR up to $E\gamma=0$

The table with applied radiative corrections in this analysis is part of arXiv submission,
It will be useful for cross-checks if new generators will be appeared.

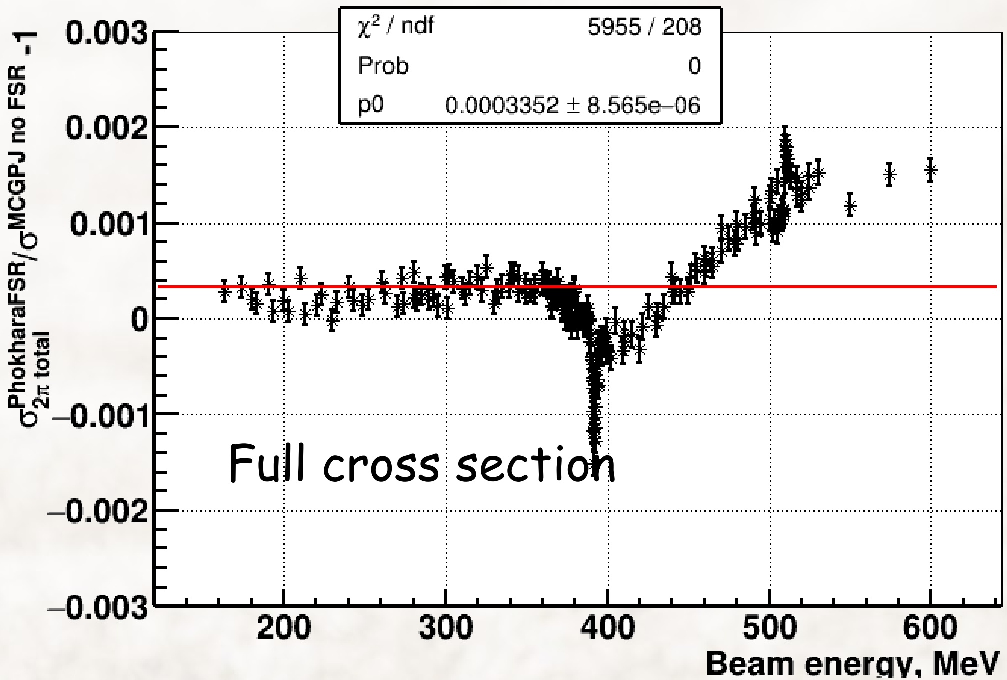
Some cross checks to compare MCGPJ/Phokara were performed

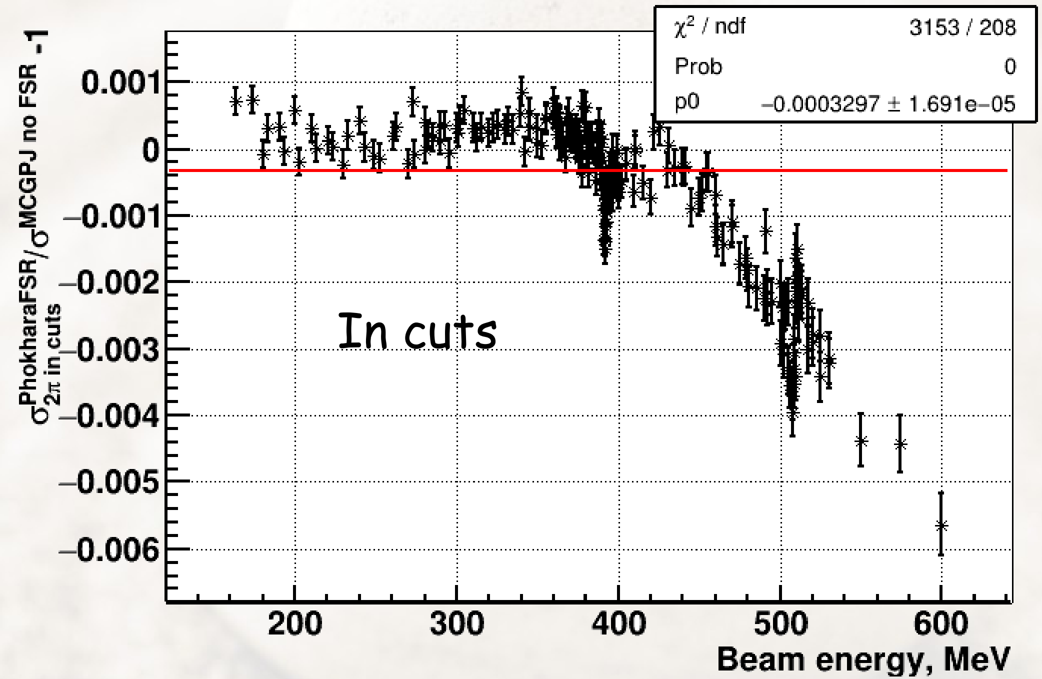
At E_{beam} 391.48 MeV point: If to use Phokara momentum spectra for ππ PDF instead of MCGPJ → 0.03% difference on F_π

MCGPJ/Phokara

ISR and Fπ cross check

MCGPJ with FSR off,
Phokara 10 with same |Fπ| as in MCGPJ, additional VP off



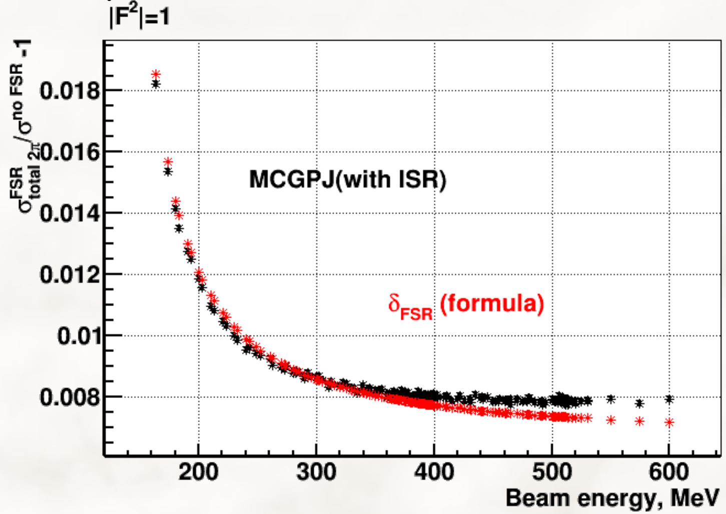


Cross section is consistent at ~0.05% at ρ-peak
(at phi ~ 0.25%)

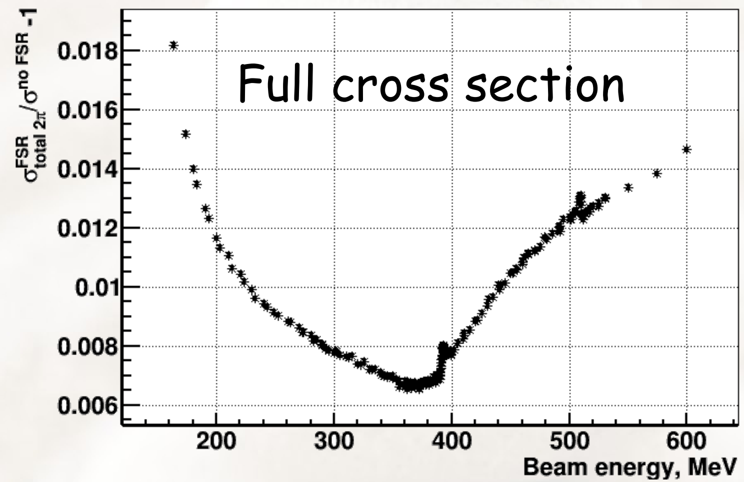
MCGPJ FSR contribution

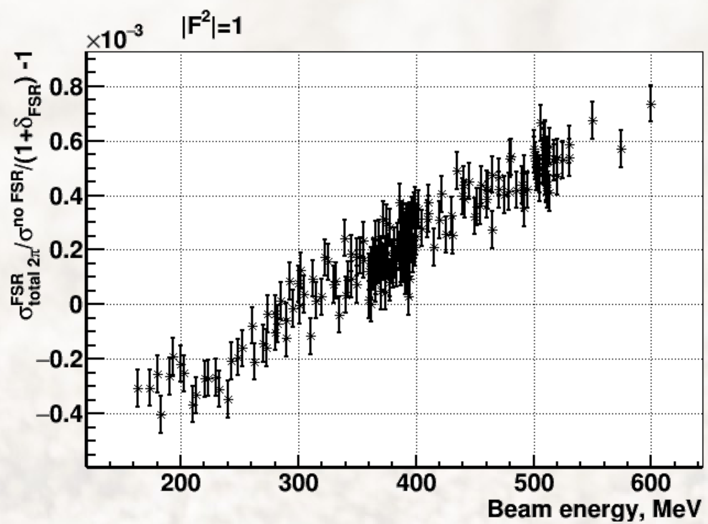
With Fpi=1 FSR is consistent with analytical formula at < 0.05%

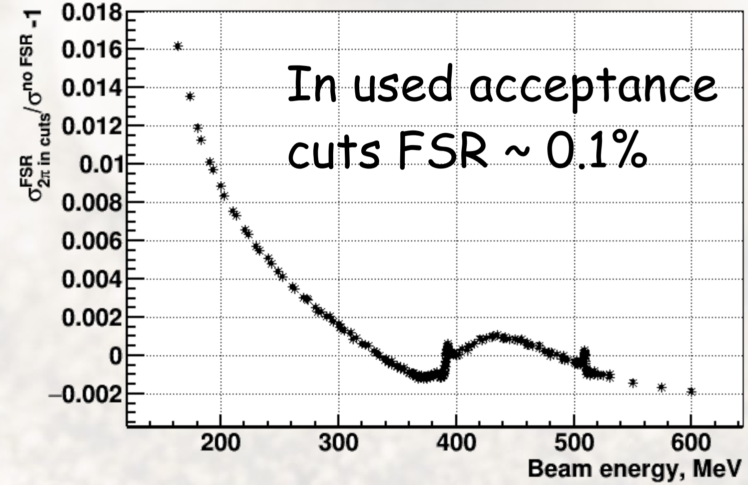
With full formfactor behaviour it is different because of ISR return.
Looks reasonable



$$\frac{\sigma^{\mathrm{FSR}}}{\sigma^{\mathrm{no\,FSR}}}-1$$







Question 43

Since it is only mentioned without any detail in the conclusion, can you clarify how the blinding of the results was achieved?

It was not "fully" blinding way.
The analysis was driven by self-consistency checks without comparing with others and by list of effects which should be checked giving effects ~0.1% .
The main blocking difficulties were:

Consistency between momentum/energy deposition-based separations

(initial version of Energy based method (with LXe+CsI total energy) was having bias even on full MC data)

Discrepancy in angle distribution

The detailed comparison with previous experiments appeared only at final stage,
when it was performed accurate fitting of final measurement, iterative recalculation of radiative correction with CMD-3 form factor parametrization, with different parametrization over different experiments, etc

The collaboration was blinded to the last moment, the day before of the public institute seminar:
The discussions on all steps of the analysis over many years in local collaboration meetings, the paper preparation, the discussion on the systematic contribution (with all effects and problems involved) were without looking on final formfactor and comparison with others.

Question 46

The paper cannot avoid a study and a discussion concerning the CMD-2/CMD-3 strong discrepancy which are absent at the moment, despite similar detectors, analysis and group: outline the major differences in the detector and the analysis procedure, compare distributions, dig out where the problem occurs. seen for the Bhabha mode?

We don't know at the moment the source of difference between experiments.
In principal CMD-2/CMD-3 detectors are totally different:
CMD-3 allows to study systematics at higher statistical level.
New Drift Chamber, new LXe calorimeter(with tracking capabilities),
new electronics, new implementation of trigger system, ….
Peoples involved in analysis at ρ-peak are different (except exchanged experiences)

Question 48

The central values of the K+K-, π+π-, ancillary 3π measurements all tend to be higher than other experiments at a similar level of 4%, which of course for the 2π channel looks most spectacular. Have possible common systematic effects across channels been investigated?

3π process is well consistent with others experiment (except CMD-2)

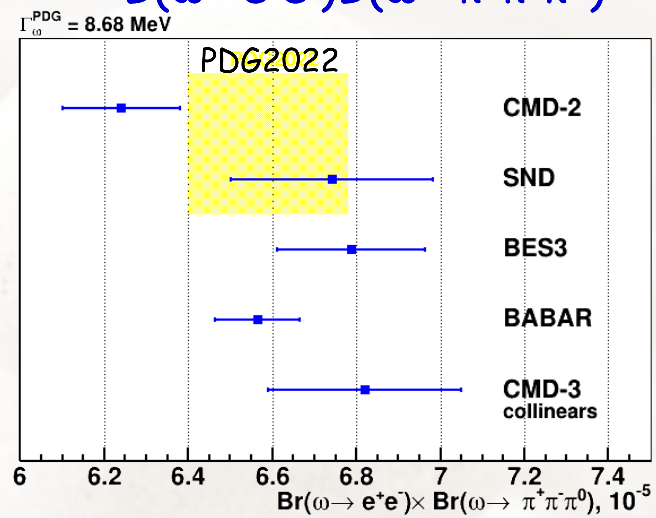
The common excesses in K+K- and π+π- to others experiment are seen, it could be correlated or could be not….

Possible common sources:

- ✗ Detector related:
  e+e- trigger efficiencies, tracker efficiencies, …. :
  - ✗ not seen in Nμμ/Nee ratio
  - ✗ effort to catch triggers TF vs CF correlations was performed
  - ✗ not seen problems in angle distribution (if some resolution effect unaccounted…)

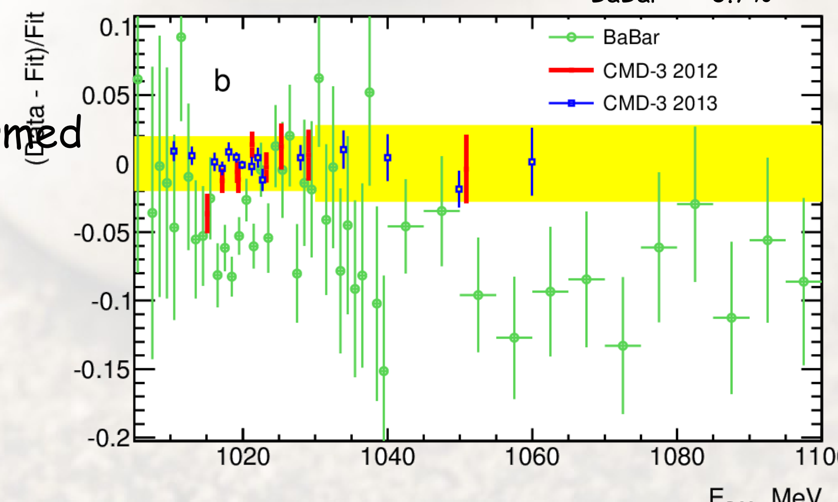
  for future scans: new trigger system under commissioning, new DCH, ZC under consideration
- ✗ Radiative correction for K+K-/π+π- from MCGPJ generator: discussed in previous slides

$B(\omega\to e^+e^-)B(\omega\to\pi^+\pi^-\pi^0)$



e+e- → K+K-

Systematics at φ
CMD-3 2%
BaBar 0.7%



Question 49

What are the plans for publishing this analysis: short/long papers?
Do you intend to perform additional checks before submitting to a journal?

Analysis is finished.

(in fact, analysis was finished about a year ago, since then it was form factor fitting, polishing, paper preparation, internal paper reviewing, ...)

many self consistency checks were already performed, further may be with a better detector

Current plans:

short paper is under preparation, additional text polishing of the long paper
and to submit both versions to journals in April (middle?)

Future plans, other papers:

New ρ scans with improved detector and possibly some specific systematics checks are expected

Analysis at $\sqrt{s} > 1$ GeV is in progress by another person
(exploiting full shower profile information by neural network,
as better separation is required at higher energies)

with same independent steps for efficiency determination, etc for formfactor evaluation
→ cross check between current and new analyses will be required at final stage

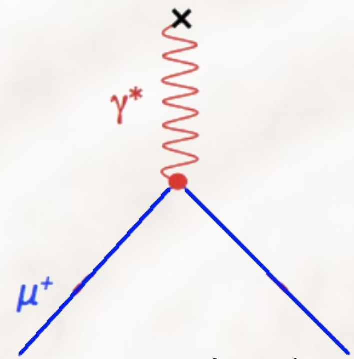
backups

What is g-2 and how it is connected to R(s)

The magnetic moment of the particle relates spins to its angular momentum via the gyromagnetic ratio, g:

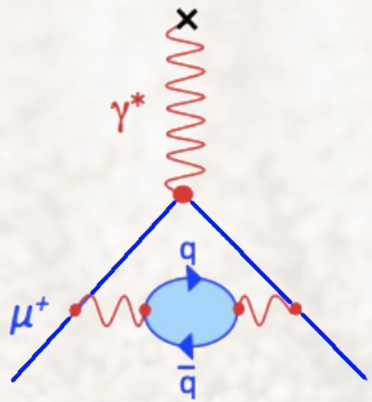
$$\vec{\mu} = g \frac{e}{2m} \vec{s}$$

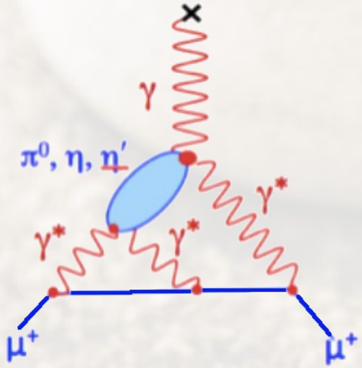
In Dirac theory, point-like, spin ½ particle has exactly g=2



Quantum loop effects via vacuum fluctuations lead a calculable deviation:
the anomalous magnetic moment a = (g-2)/2 ~ $\alpha/2\pi$ ~ 0.00116

HLO





HLbL

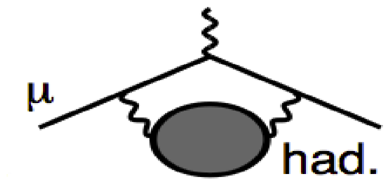
The hadronic contribution is calculated by integrating experimental cross-section σ(e+e- → hadrons).

Starting at high energy the pQCD estimation of σ(e+e- → hadrons) is used. At lower energies only the experimental data can be used.

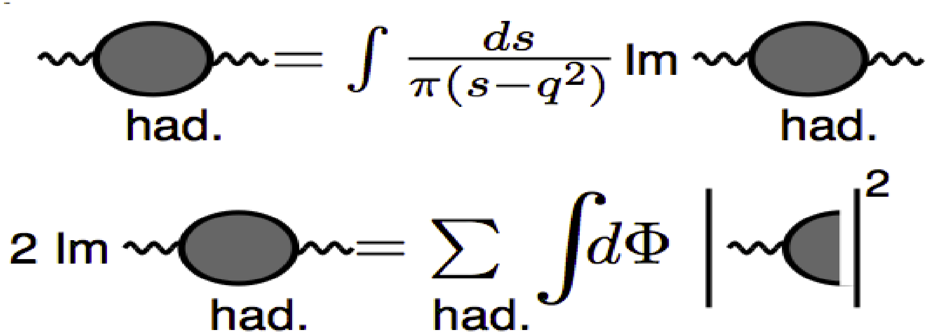
Weighting function ~ $1/s^2$, therefore lower energies contribute the most:

<2GeV gives 93% of the integral,
$\pi^+\pi^-$ gives the main contribution (73%) to a_μ

The diagram to be evaluated:



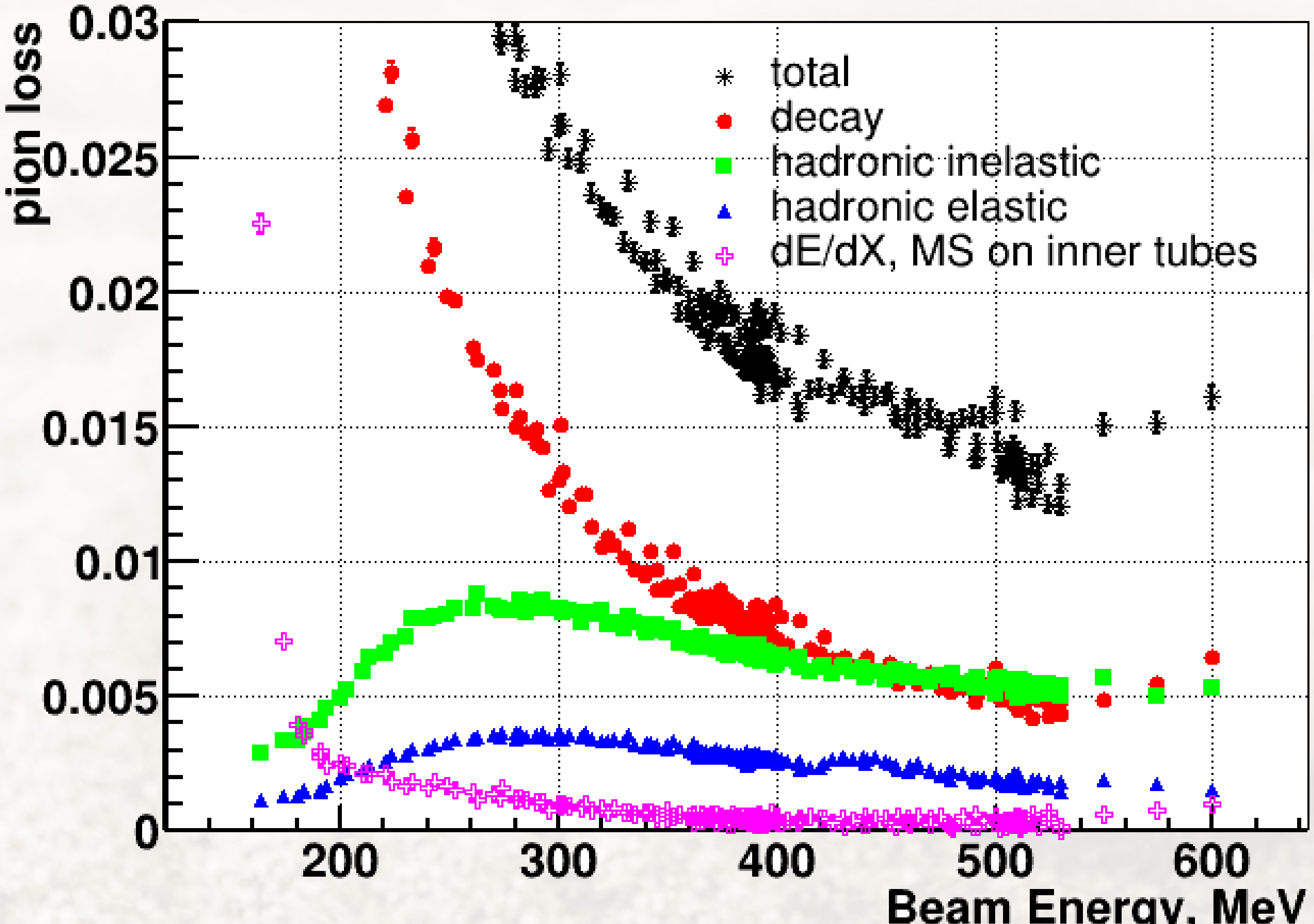
pQCD not useful. Use the dispersion relation based on analyticity and the optical theorem:



$$a_\mu^{had,\,LO} = \left(\frac{\alpha\, m_\mu}{3\,\pi}\right)^2 \int_{s_{th}}^{\infty} \frac{1}{s^2}\, \widetilde{K}(s)\, R(s)\, ds$$

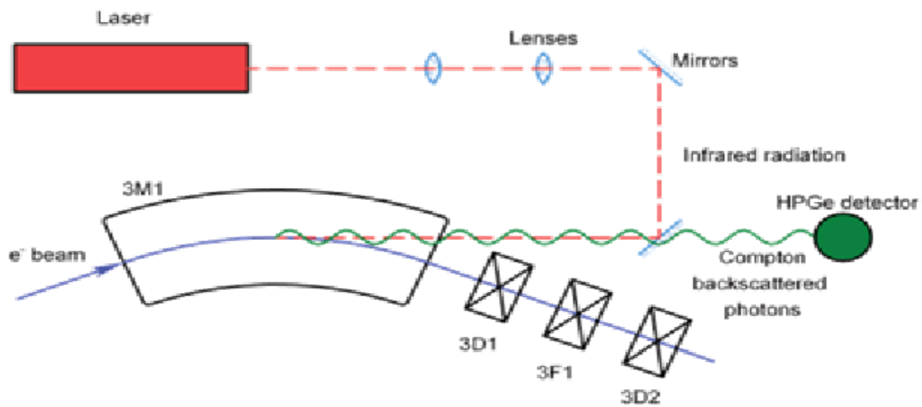
$$\widetilde{K}(s) = 0.6 \div 1.0$$

Pion specific inefficiency

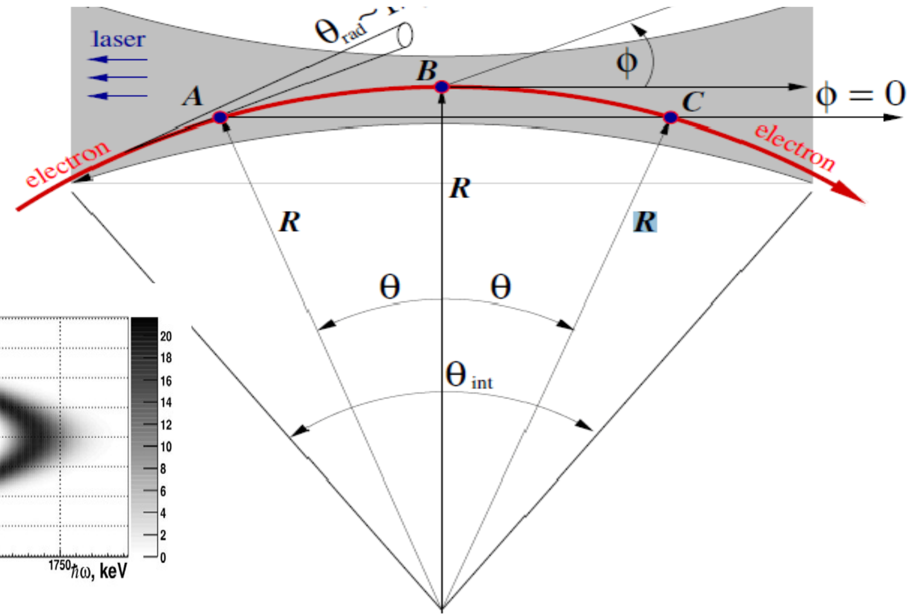


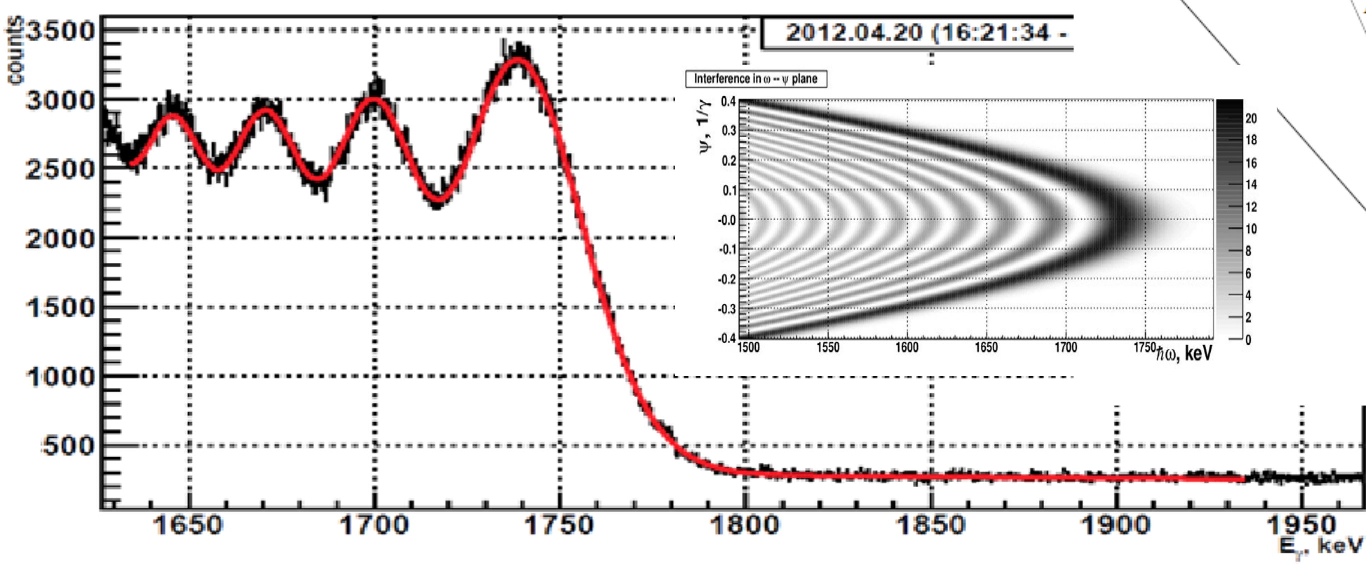
Energy measurement by Compton back scattering

Starting from 2012, energy is monitored continuously using compton backscattering



Interference of photons from A and B



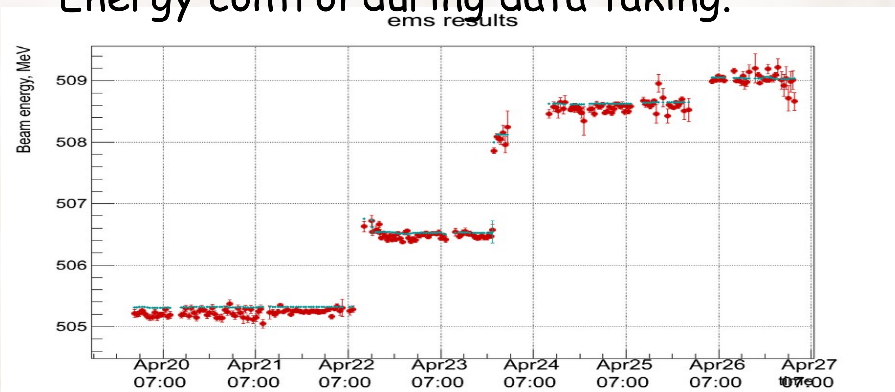


E = 993.662 ± 0.016 МэВ

M.N. Achasov et al. arXiv:1211.0103v1 [physics.acc-ph] 1 Nov 2012

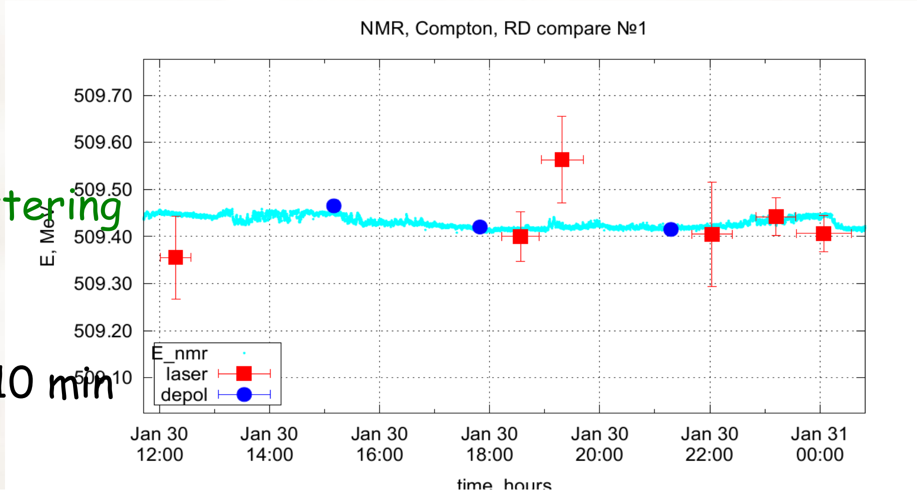
Beam energy measurement at VEPP-2000

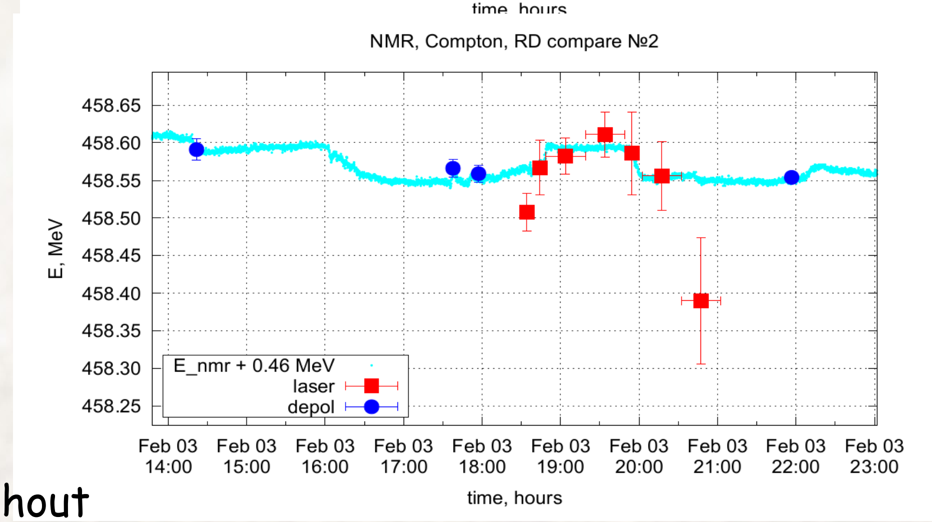
- Magnetic field control in bending magnets <u>$\delta E/E < 10^{-3}$</u>
  - 8x2 NMR probes, continuous control
  - Absolute calibration using:
    φ-meson (1019.455 ± 0.020 МэВ),
    ω-meson (782.65 ± 0.12 МэВ).
- Measurement of photon energy from back <u>$\delta E/E < 10^{-4}$</u> scattering laser light
  - Installed in 2012.
  - Needs beam current (20 мА), ~20-50 keV accuracy in 10 min
  - Energy control during data taking.



- Resonance depolarization method <u>$\delta E/E < 10^{-5}$</u>
  - Very high accuracy.
  - Special configuration of VEPP-2000: "warm" optics without CMD-3 field.

Methods comparison:





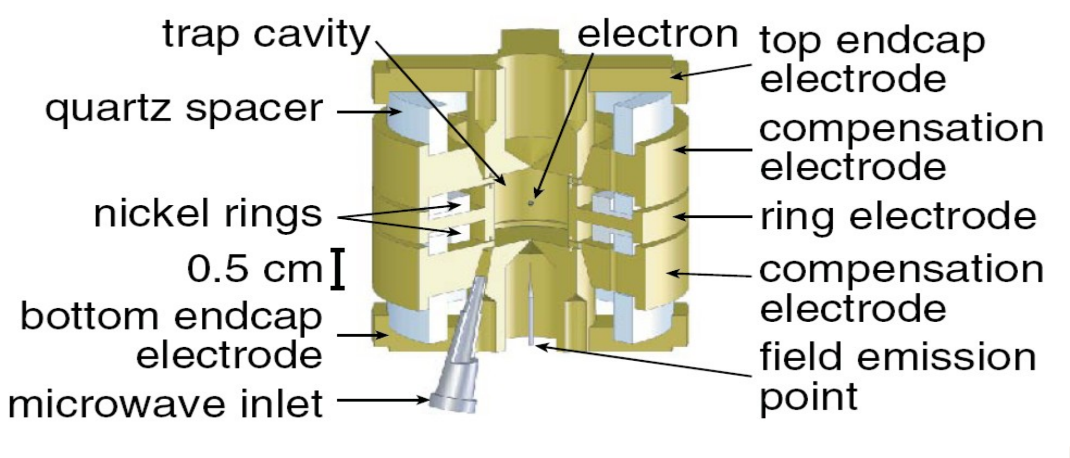
Electron and muon g-2 Experiments

$$\vec{\mu} = g\frac{e}{2m}\vec{s},\ g = 2(1+a)$$

a_e = 11 596 521.8073 (0.0028) 10^{-10}[0.24ppb]

a_μ = 11 659 208.9(6.3) 10^{-10}[0.54ppm]

Hanneke, Fogwell, Gabrielse, PRL 100(2008)120801



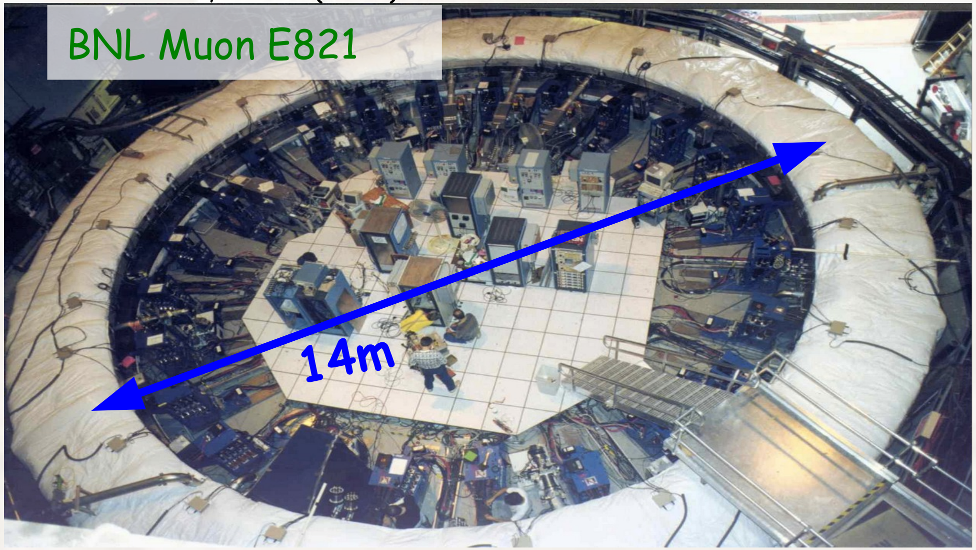
Harvard Univ. One electron quantum cyclotron

The value of a_e was used to get the best determination of fine-structure constant α.

R. Parker et al., Science 360 (2018) 191

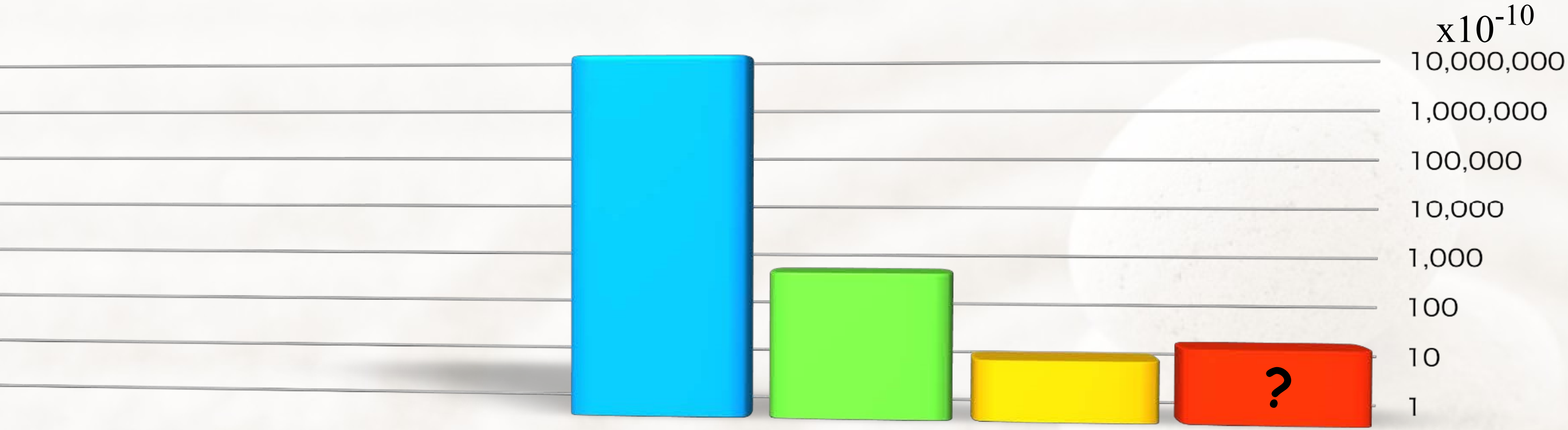
Recent α_{QED} measurement using the recoil frequency of Cs-133 atoms with 0.20ppb gives 2.5σ tension with experimental a_e

Bennet et al., PRD 73(2006)072003



Muon (g-2) is 40,000 times more sensitive to non-QED fields than electron (g-2) ~ $(m_\mu/m_e)^2$, providing more sensitive probe for New Physics.

Muon g-2 theory SM



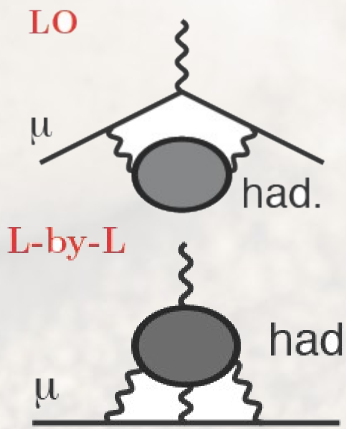
$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

Precisions: 7 ppb HVP: 210ppb + LbL: 220ppb 9ppb < 2300ppb

QED: Kinoshita et al., 2012: up to 5 loops (12672 diagrams), EW: 2 loop

Hadronic: HVP: the value is based on the hadronic cross-section e+e- data;

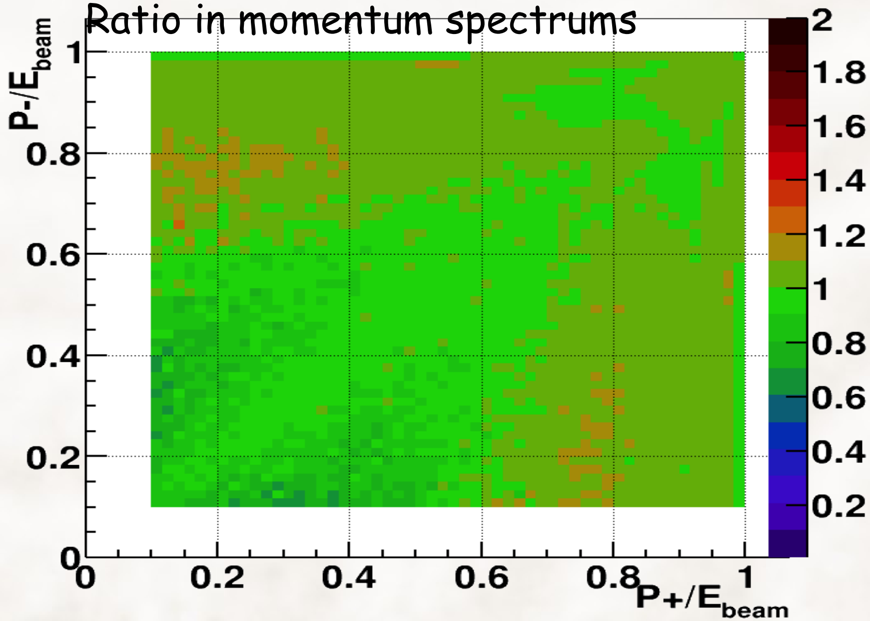
LBL: model-dependent calculations; measurement of transition formfactors can help, improvement is expected from lattice calculations

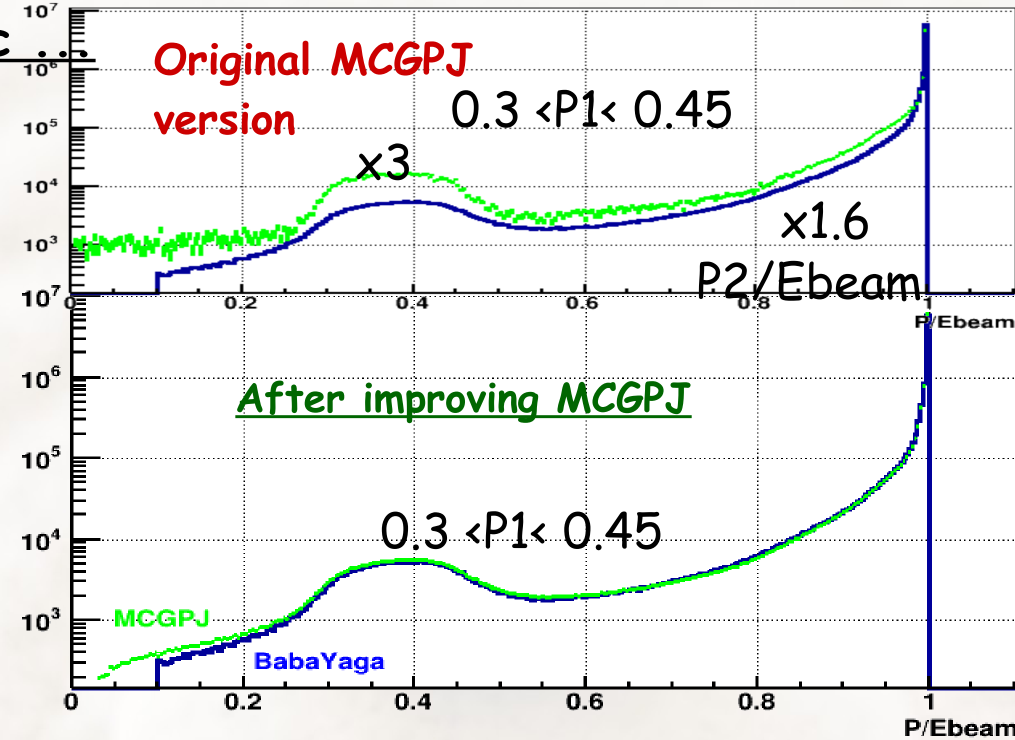


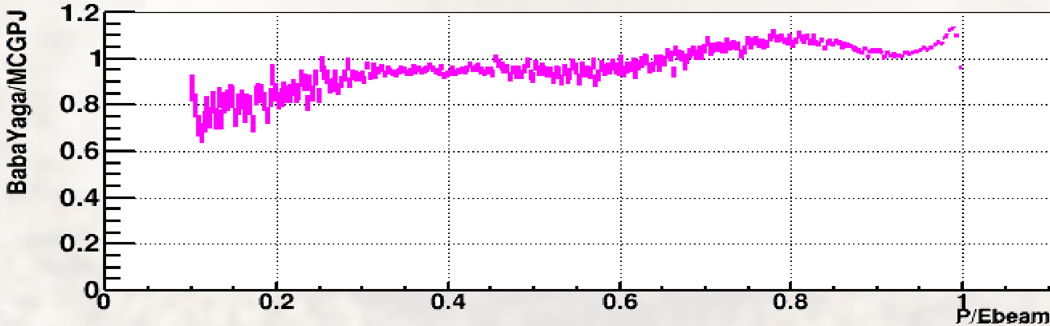
New g-2 experiments at FNAL, J-PARC: 540 → 140 ppb

MCGPJ vs BabaYaga spectra

After adding angular distribution for jets, etc ...







Momentum spectrum still disagrees at level ~ 10%

Need more experimental data for cross-check

We need more theoretical help

Result in |Fπ| systematic by momentum

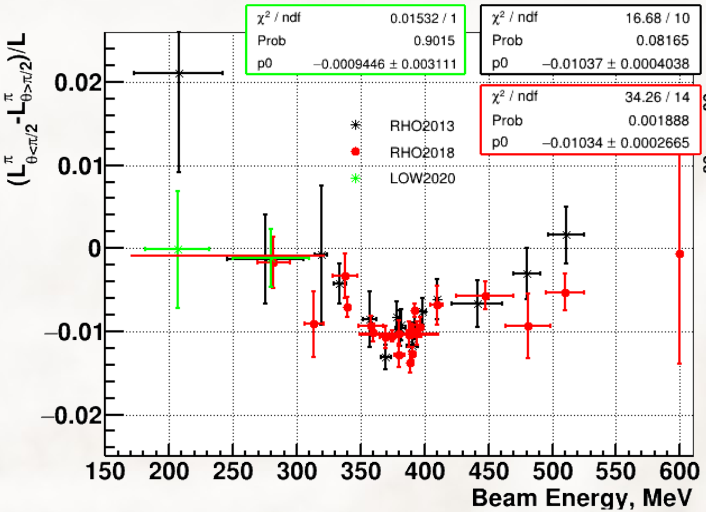
→ 0.0 - 0.4%

For precision ~<0.1% necessary to have exact e+e-→e+e-(γγ) NNLO generator

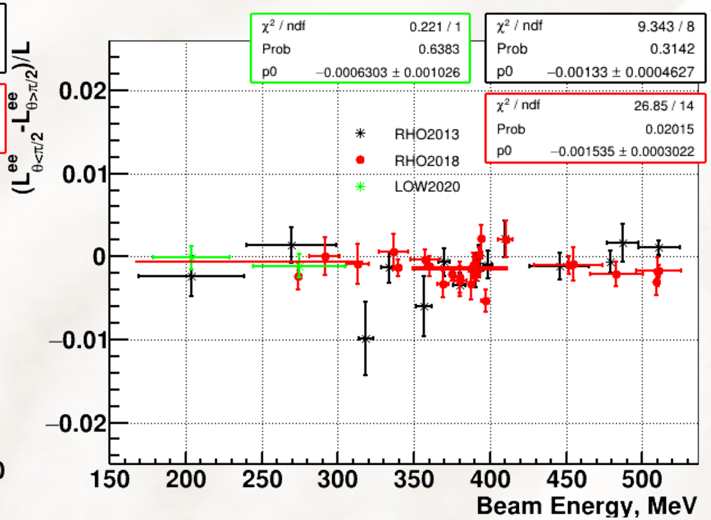
Asymmetry 2π/e+e-/2μ

Asymmetry relative to generator prediction

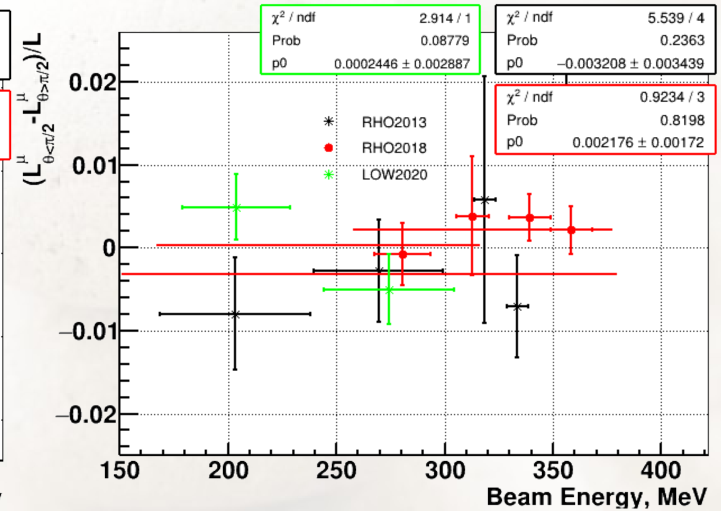
δA (π+π-)



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-

BabaYaga/MCGPJ difference gives ~ 0.08%

Detector systematic ~ 0.1%

⟨δA⟩ = 0.10 ± 0.14 %

Nμμ can be extracted only at lowest energies