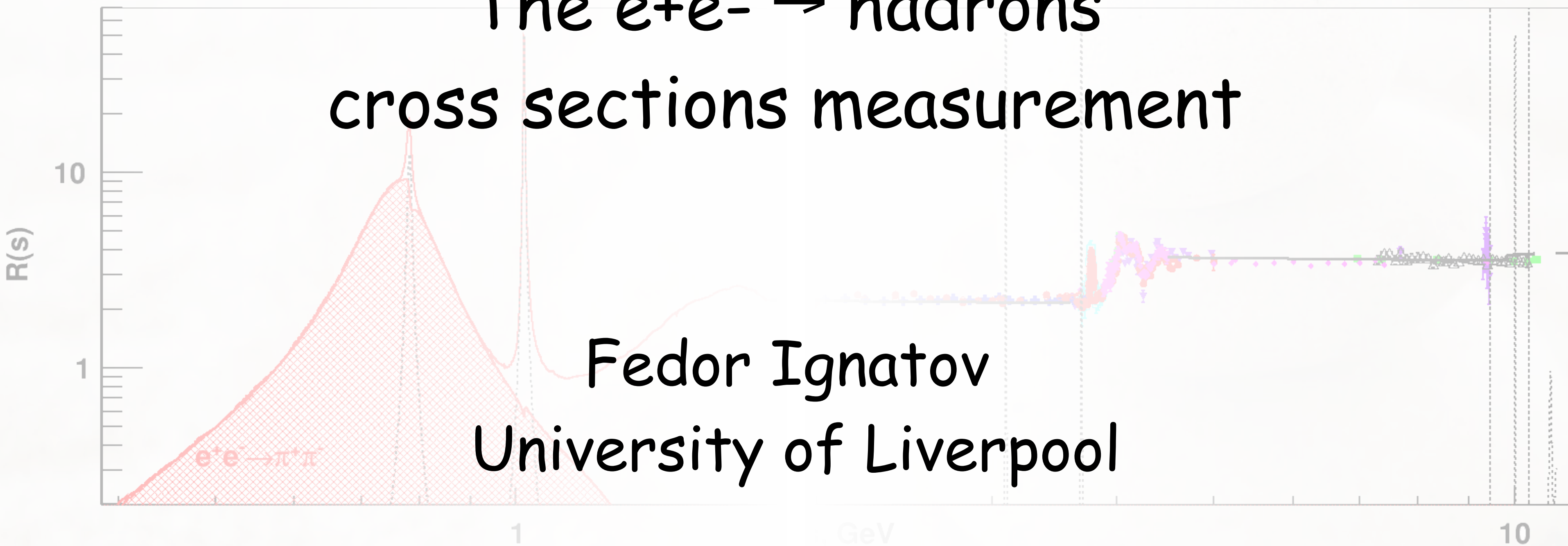
LEVERHULME TRUST

The e+e- → hadrons cross sections measurement



Fedor Ignatov
University of Liverpool

XXV Roma Tre g-2 Topical Seminar
Rome, 11 December 2023

Colliders History

1961	AdA	Frascati	Italy
1965	Princeton-Stanford(e-e-)	Stanford	USA
1965	VEP-1(e-e-)	Novosibirsk	USSR
1966	VEPP-2	Novosibirsk	USSR
1967	ACO	Orsay	France
1969	ADONE	Frascat	Italy
1971	CEA	Cambridge	USA
1971	ISR	CERN	Switzerland
1972	SPEAR	Stanford	USA
1974	DORIS	Hamburg	German
1974	VEPP-2M	Novosibirsk	USSR
1976	DCI	Orsay	France
1977	VEPP-3	Novosibirsk	USSR
1978	VEPP-4	Novosibirsk	USSR
1978	PETRA	Hamburg	Germany
1979	CESR	Cornell	USA
1980	PEP	Stanford	USA
1981	Sp-pbarS	CERN	Switzerland
1982	p-pbar	Fermilab	USA
1987	TEVATRON	Fermilab	USA
1989	SLC	Stanford	USA
1989	BEPC	Beijing	China
1989	LEP	CERN	Switzerland
1992	HERA	Hamburg	Germany
1994	VEPP-4M	Novosibirsk	Russia
1999	DAFNE	Frascati	Italy
1999	KEKB	Tsukuba	Japan
1999	PEP-II	Stanford	USA
2001	RHIC	Brookhaven	USA
2008	BEPCII	Beijing	China
2009	LHC	CERN	Switzerland
2010	VEPP-2000	Novosibirsk	Russia.
2018	SuperKEKB	Tsukuba	Japan

(Physics start date)

Green - e+e-
Dark green - e+e- Novosibirsk

1961: AdA was the first matter antimatter storage ring with a single magnet (weak focusing) in which e+/e- were stored at 250 MeV

Touschek effect (1963); first e+e– interactions recorded – limited by luminosity ~ $10^{25}cm^{-2}s^{-1}$

SLAC & Novosibirsk VEP-1 works independently

1965: First physics at collision with e-e- scattering

(QED radiative effects confirmed)

1967: VEPP-2 First e+e- → hadron production

$L \sim 10^{28}cm^{-2}s^{-1}$

56 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

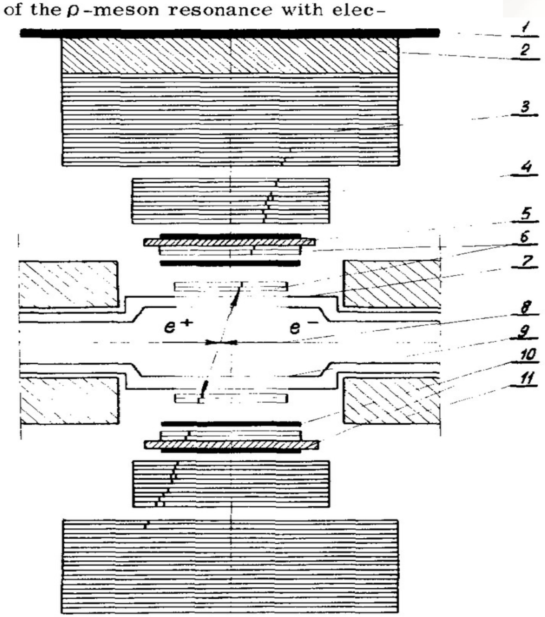


Fig. 1. Spark chambers system:
1) Anticoincidence scintillation counter
2) Lead absorber 20 cm thick
3) "Range" spark chamber
4) "Shower" spark chamber
5) Duraluminium absorber 2 cm thick
6) Thin-plate spark chambers

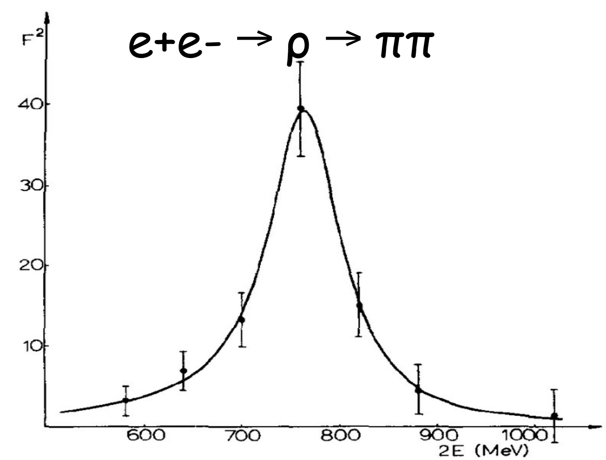


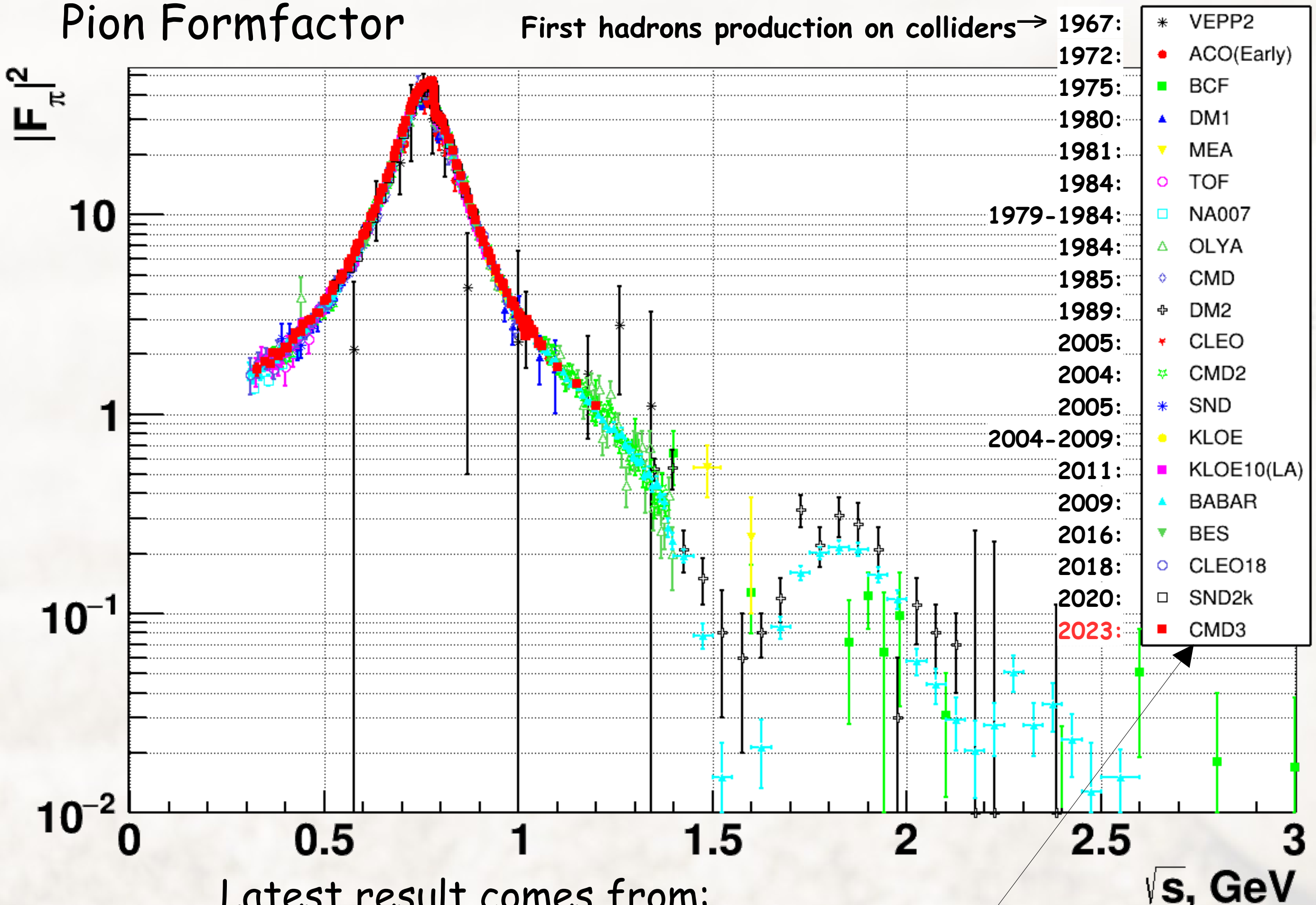
Fig. 2. Experimental values of F^2 (E) approximated by the Breit-Wigner formula.

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

Pion Formfactor

First hadrons production on colliders →



Latest result comes from:

CMD-3 Collaboration, "Measurement of the e+e−→π+π− cross section from threshold to 1.2 GeV with the CMD-3 detector", arXiv: 2302.08834

<u>Before 1985</u>

Low statistical precision

Systematics >10%

NA7 A few points with >1-5%

<u>1985 - VEPP-2M</u>

with more detailed scan

OLYA systematics 4%

CMD 2%

<u>2004 with CMD2 at VEPP-2M</u>

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

<u>New ISR method</u>

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

KLOE: 0.8%

BaBar: 0.5%

BES: 0.9%

CLEO: 1.5%

<u>New direct data at VEPP-2000:</u>

SND2k : 0.8% (with 1./10 of avail4Data)

CMD-3: 0.7%

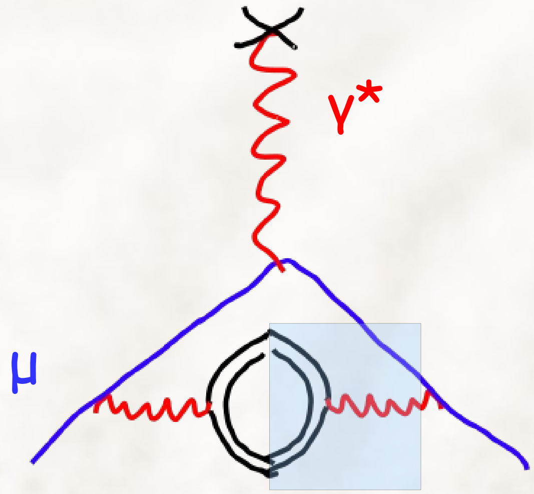
New g-2, etc experiments require precision ~ 0.2%

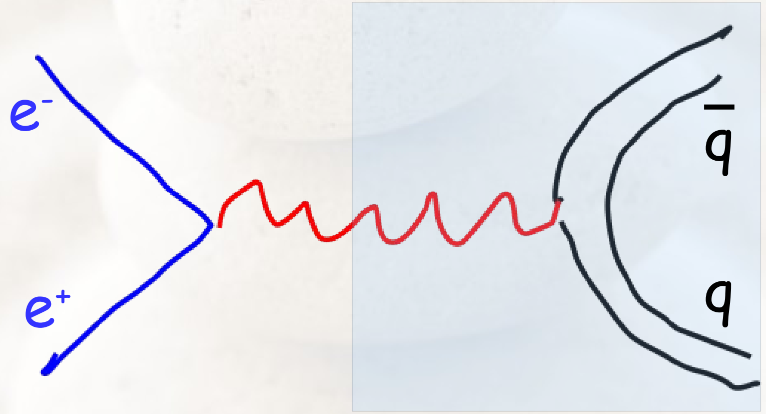
g-2 and e+e- → hadrons

Hadronic part of
Muon precession anomaly (g-2)/2

can be expressed by dispersion relation integral from

e+e- -> hadrons cross section

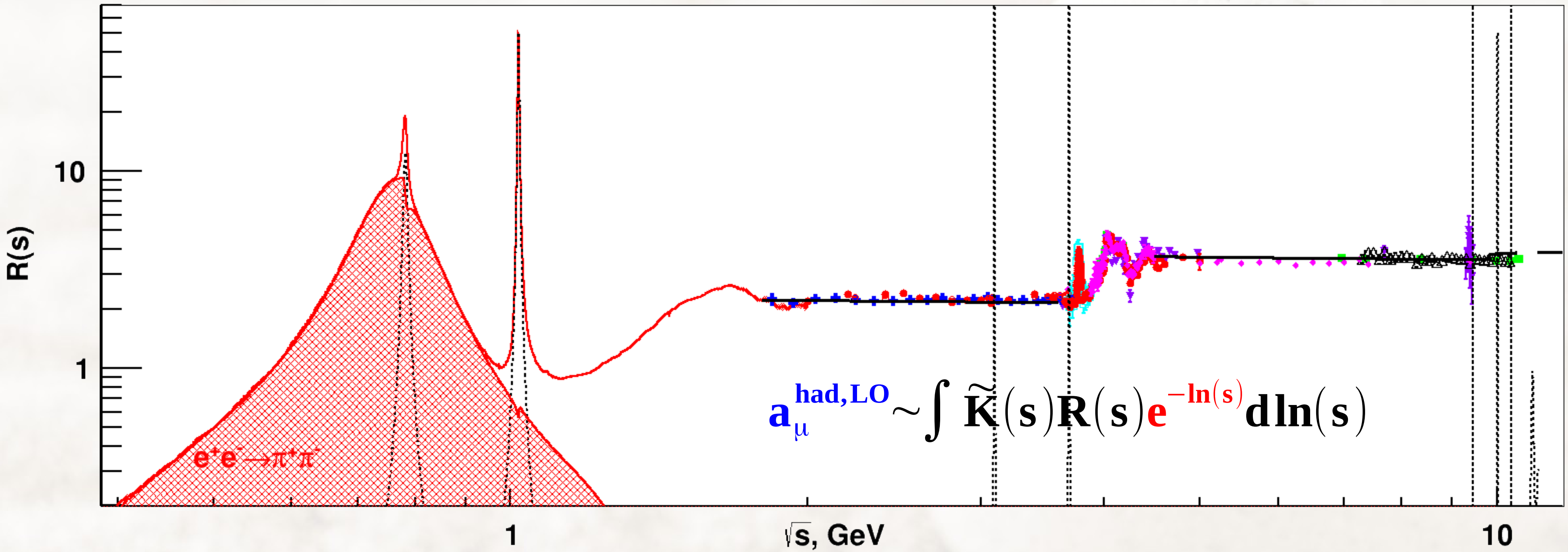




$$a_\mu^{had,LO} = \frac{m_\mu^2}{12\pi^3} \int_{4m_\pi^2}^{\infty} \frac{\sigma_{e^+e^- \to \gamma^* \to hadrons}(s) K(s)}{s} ds$$

Dispersion relation is based on analyticity and unitarity

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



$$a_\mu^{had,LO} \sim \int \tilde{K}(s) R(s) e^{-\ln(s)} d\ln(s)$$

$e^+e^- \rightarrow \pi^+\pi^-$ gives main contribution to R(s) at $\sqrt{s} < 1$ GeV and this channel is most important for muon (g-2)/2

White Paper 2020 (e-Print: 2006.04822)

From muon g-2 Theory Initiative

Theoretical prediction e+e- data driven

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

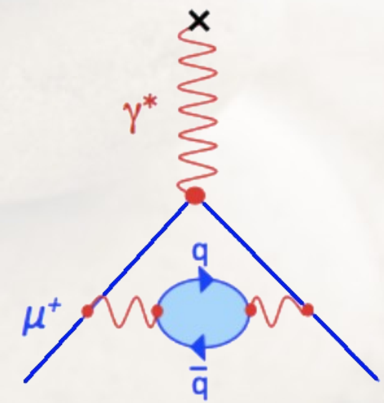
Hadronic part from measured cross-section

LO hadronic 693.1 ± 4.0 × 10^{-10}

		KLOE/BABAR difference	Relative precision
$\pi^+\pi^-$	506.0 ± 1.9	± 2.8	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

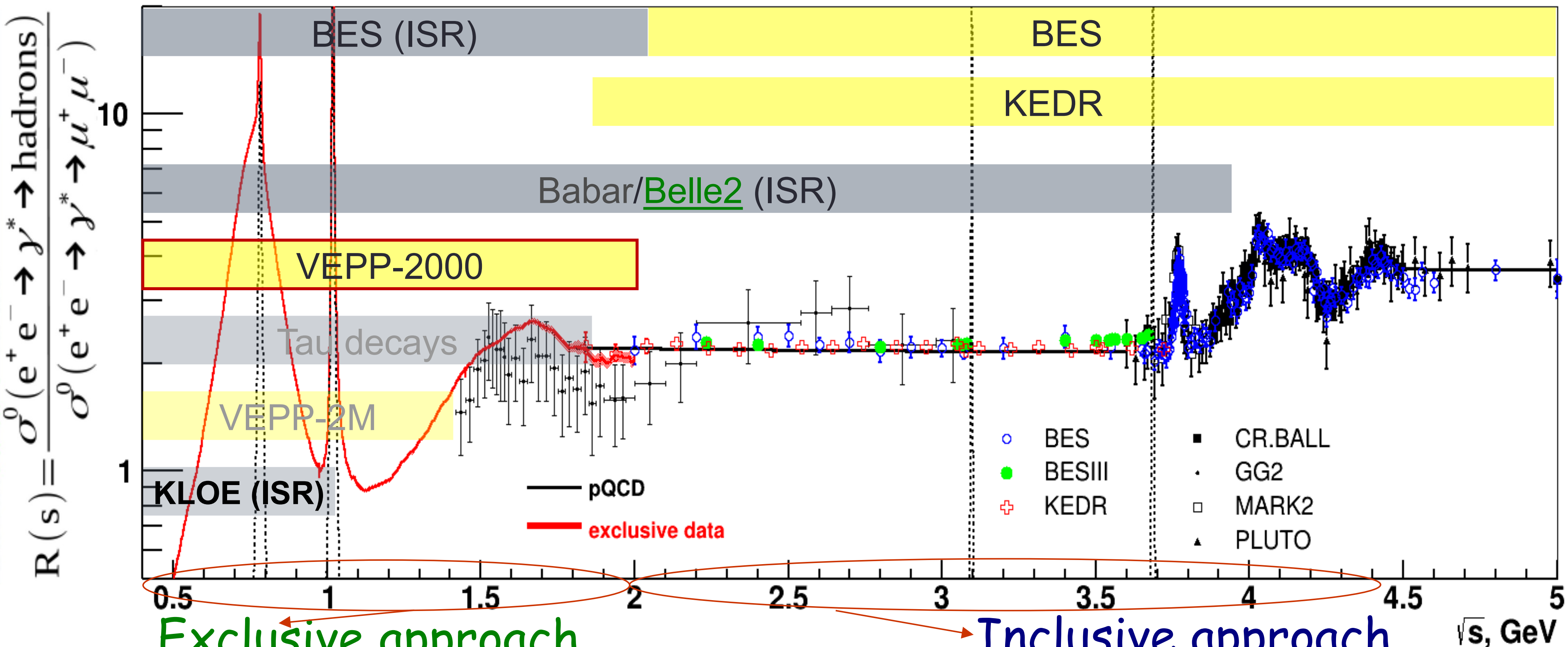
Biggest contribution to uncertainty comes from inconsistency between BaBar/KLOE e+e- → π+π- measurements



New BaBar 3π data since WP20 reduced this to ± 0.6 ×10^{-10}

R(s) measurement

Two techniques: ISR vs Energy scan



Exclusive approach

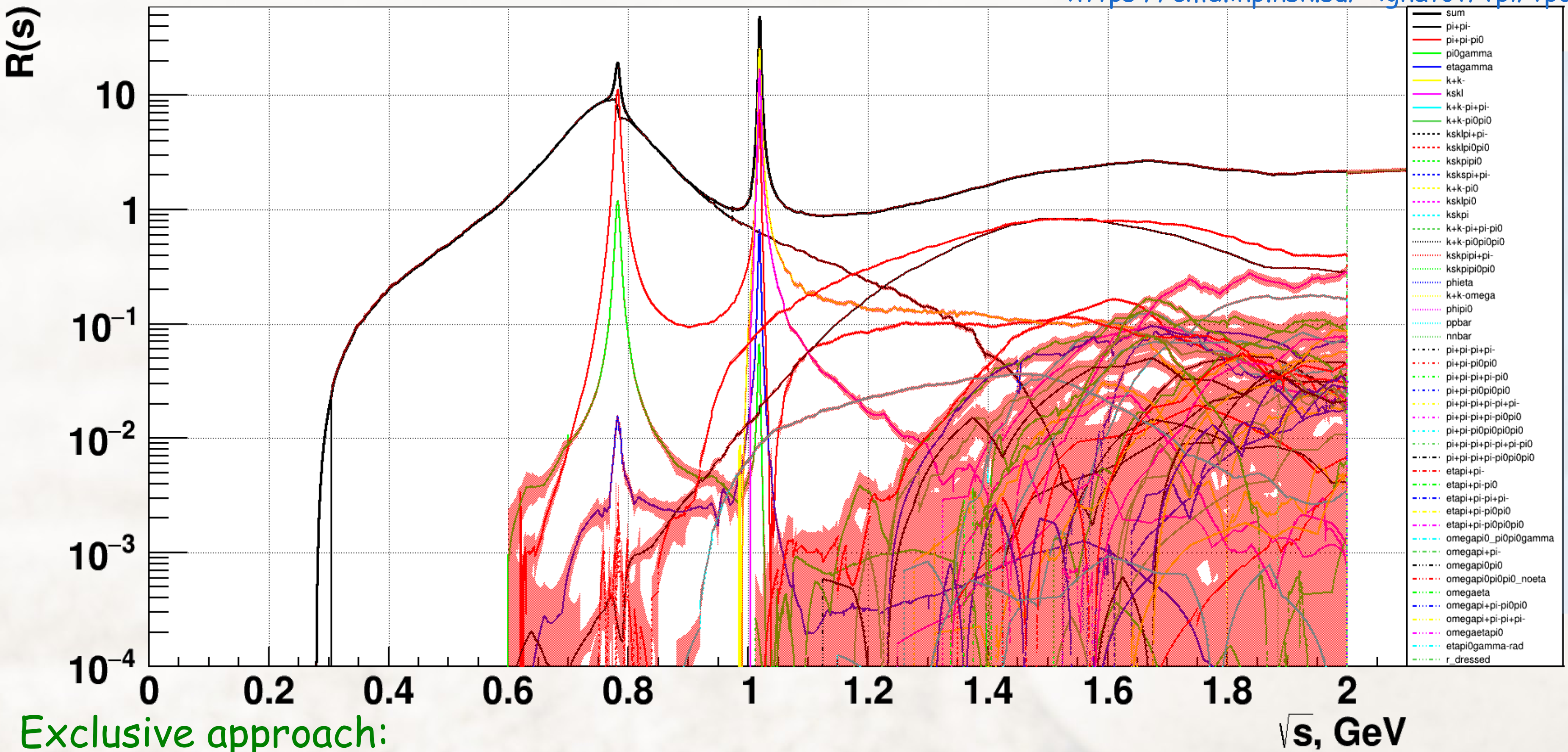
Inclusive approach

- ✗ Two techniques : Energy scan vs Initial State Radiation (ISR)
- ✗ Two approaches : Exclusive (each channel measured separately) vs Inclusive (total hadronic cross section)

Different experiments (with own systematic effects) contribute to R(S) measurement

Exclusive measurements

https://cmd.inp.nsk.su/~ignatov/vpl/vpolplot.html



PrecisionSM: initiative to make annotated database for $e^+e^- \to$ hadrons cross sections
https://precision-sm.github.io/

Exclusive approach:
- ✗ measure each final state separately and calculate the sum
- ✗ gives better precision
- ✗ should take care that nothing missed

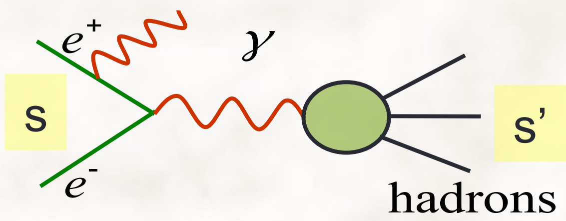
Inclusive approach ($\sqrt{s}$ > 2 GeV):
- ✗ select events with any hadron(s) in the final state
- ✗ possible because of many modes and high track multiplicity

It includes
~48 different detectors,
~50 channels, which gives
~305 datasets.

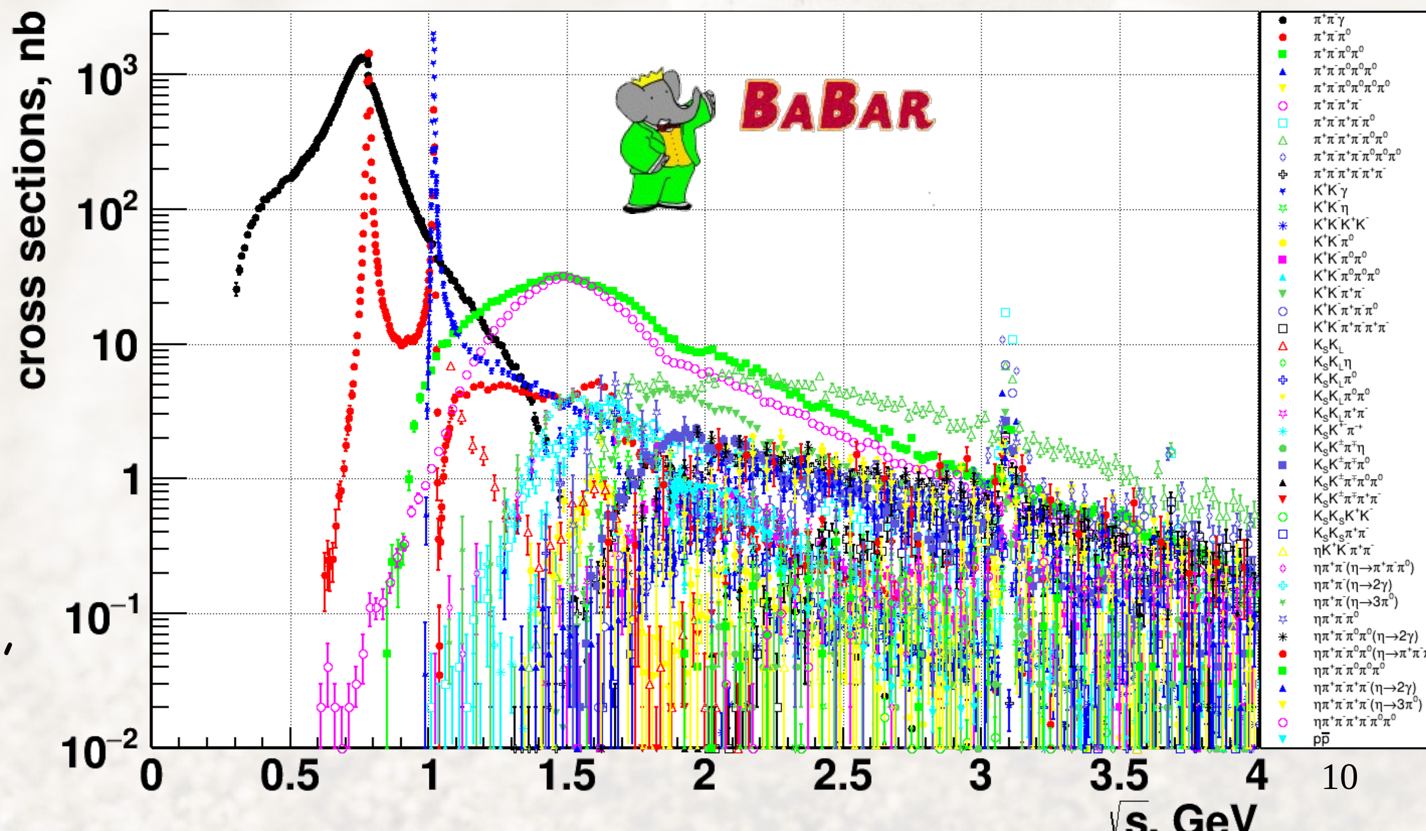
ISR approach

Additional approach to measuring of the hadronic cross-sections was fully developed over last decades: ISR (Initial State Radiation), advanced by KLOE and BaBar.

$$d\sigma(\ e^+e^- \rightarrow \text{hadrons} + \gamma\ ) = H(Q^2, \theta_\gamma\ ) \times d\sigma(\ e^+e^- \rightarrow \text{hadrons})$$

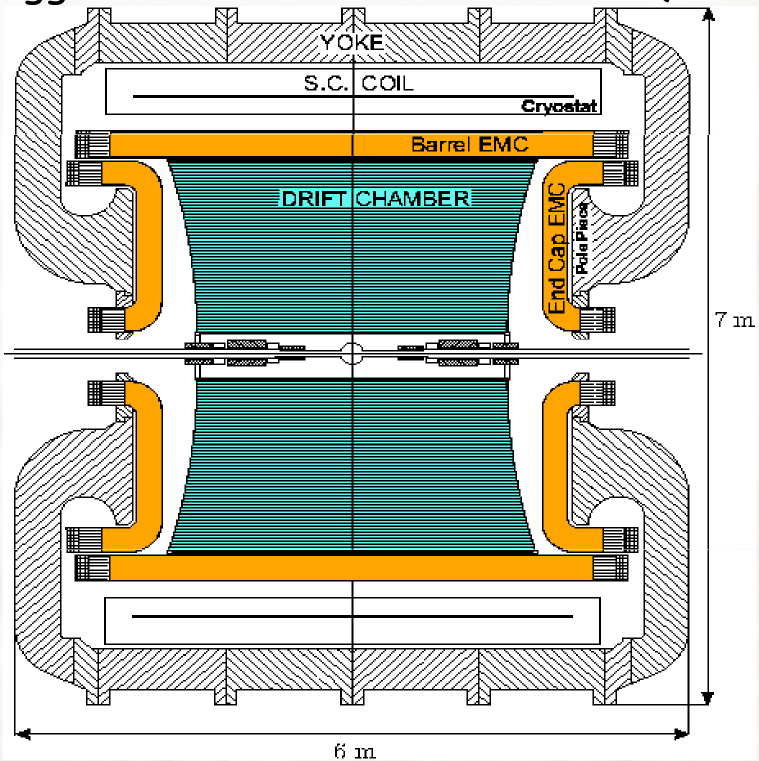


Main idea: cross-section is measured in a wide energy range, using events with hard photon, emitted by initial particles.



KLOE ISR+ VP

KLOE experiment
(2000 – 2006,2014 – 2018)
biggest Drift Chamber ever built (Ø4m)



KLOE new ISR analysis
of e+e-→π+π- channel on full
statistics x7 is underway in Liverpool

KLOE new ISR analysis
of e+e-→π+π- channel on full
statistics x7 is underway in Liverpool

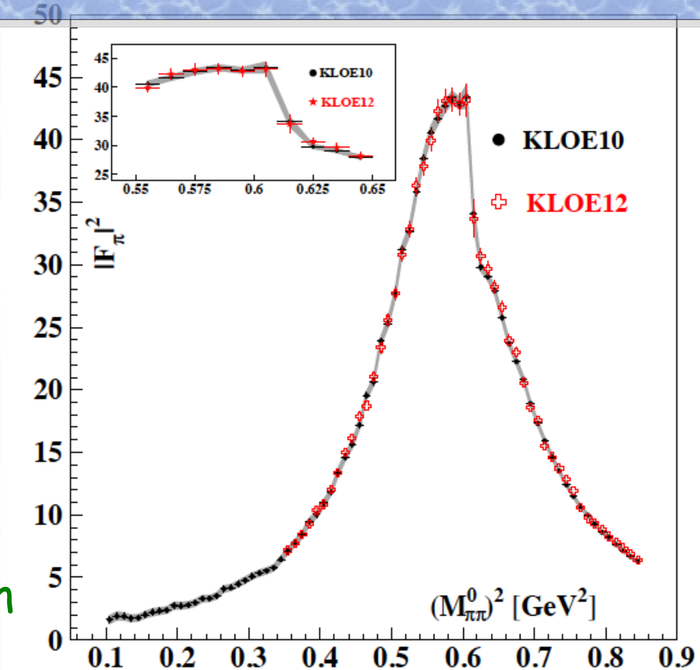
Measurement with ISR
e+e- → π+π-γ
JHEP 1803 (2018) 173

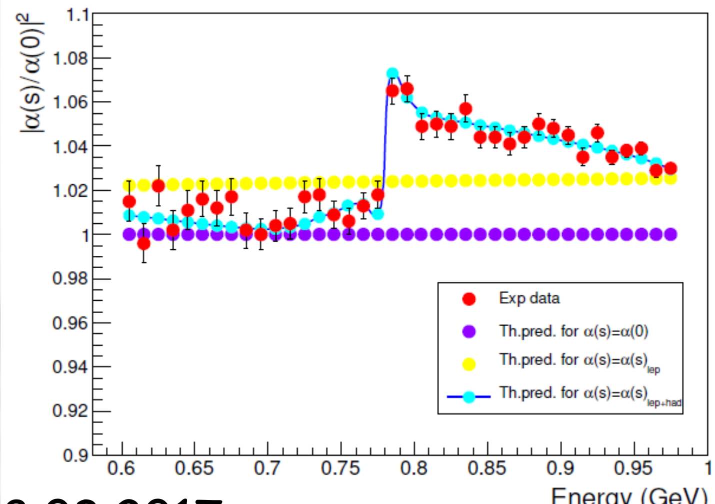
3 analyses:
with ISR photon on small angles/ large angle/ using radiator function from ISR μ+μ-

Best local stat. precision at $s=0.5-0.85$ GeV^2 (before CMD-3)

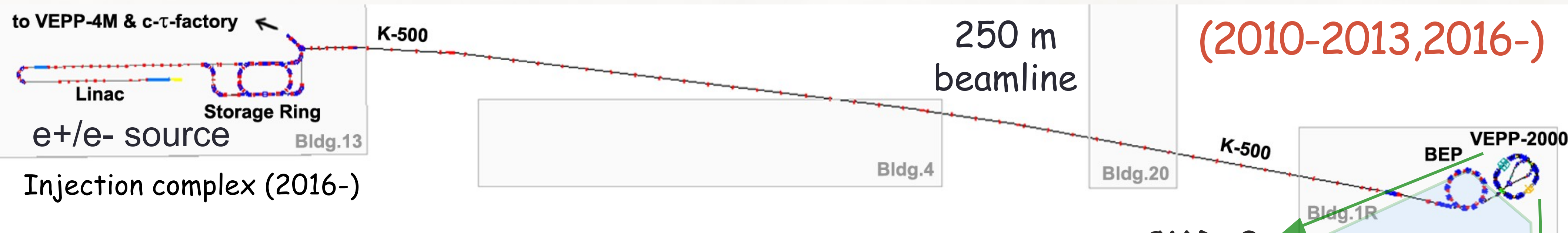
direct extraction of
$\alpha_{QED}(s)$ via e+e- → μ+μ-γ
Phys. Lett. B, 767 (2017), 485

See G. Venanzoni
CERN presentation at 28.03.2017





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

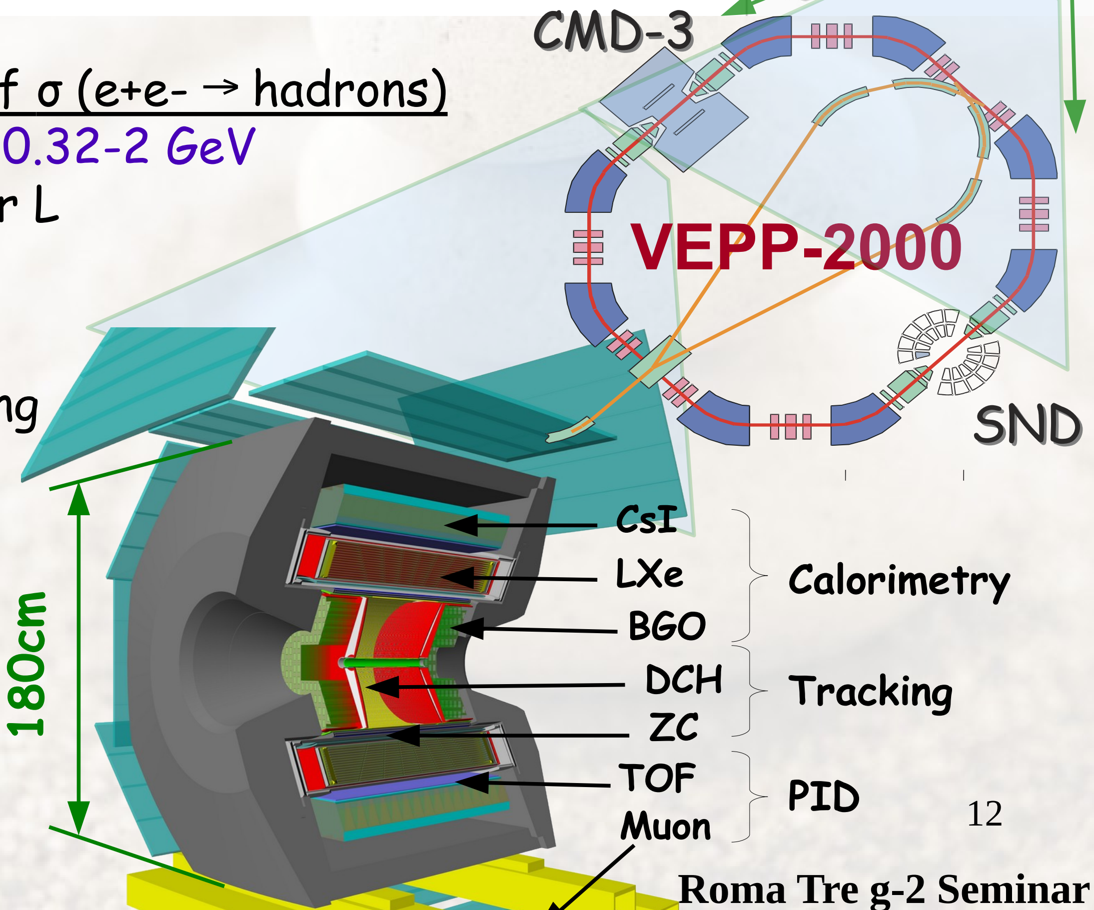
$L = 0.9\times10^{32}\ cm^{-2}s^{-1}$ at 2E= 2 GeV

Energy monitoring by Compton backscattering

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

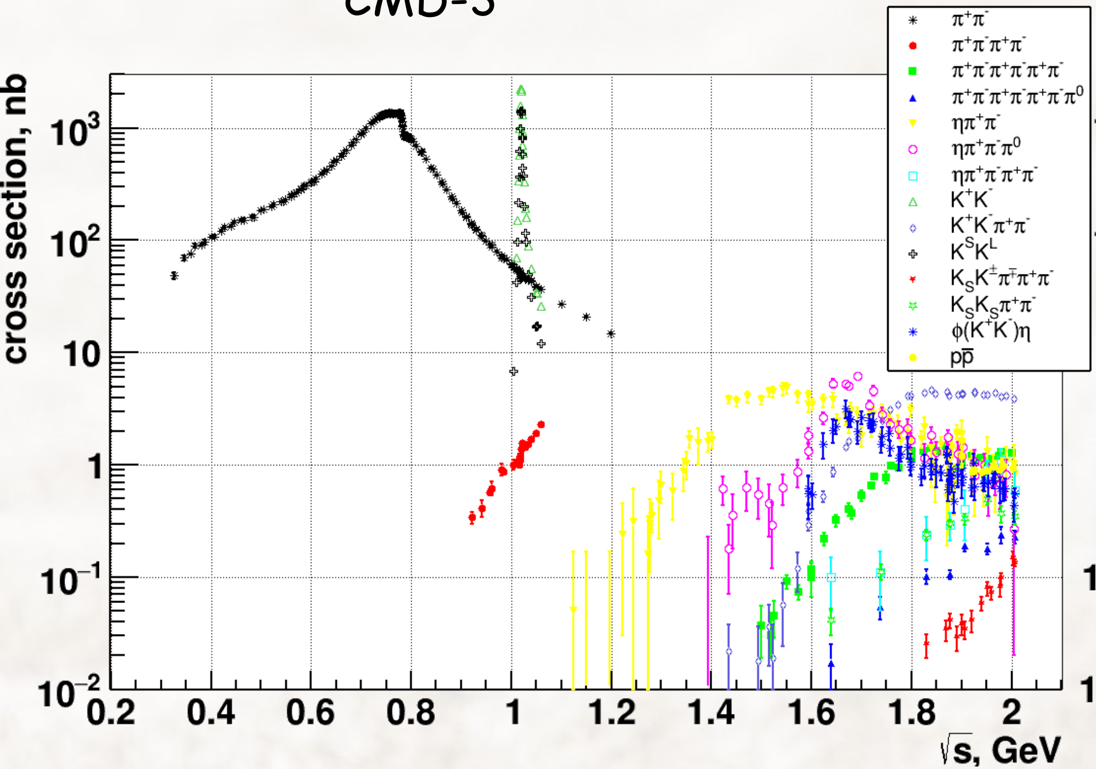
Two detectors: CMD-3 and SND

started by the end of 2010

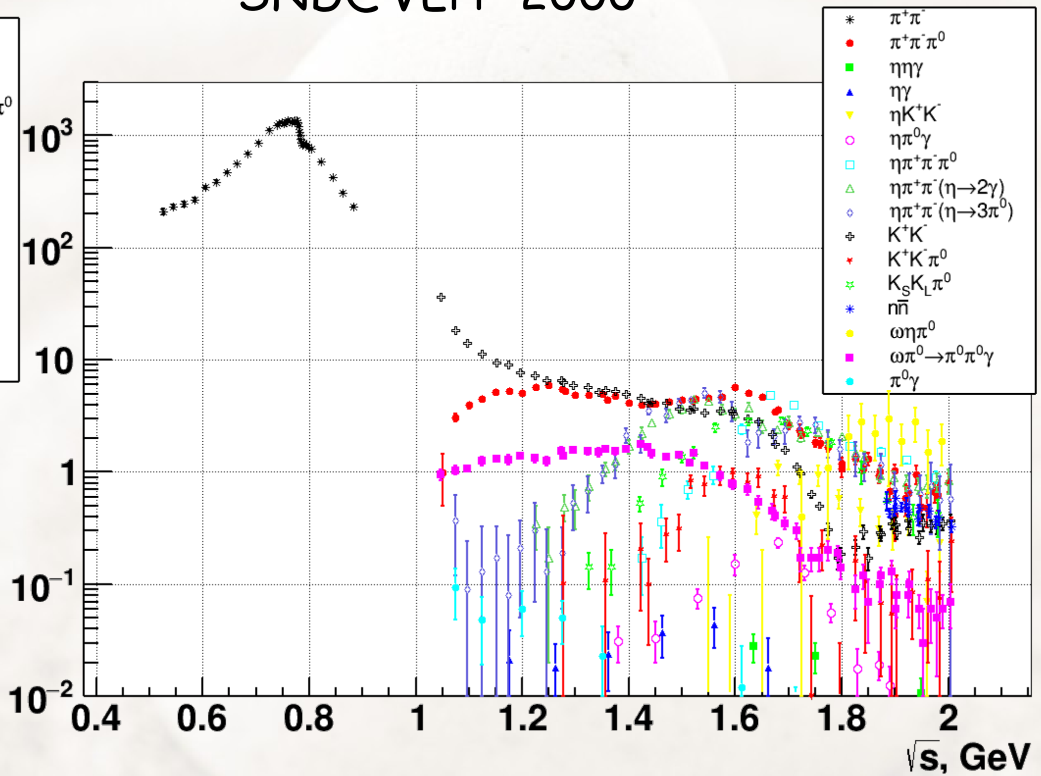


CMD-3 & SND published

CMD-3



SND@VEPP-2000



<u>Many channels is under analysis</u>

e+e- → π+π- by CMD3

Advantages of the CMD-3 $\pi^+\pi^-$ analysis vs previous scan experiments:

- ✗ Better detector:

  vs CMD-2: new drift chamber → reconstruction efficiency, momentum resolution x2 better ; 2 systems to control the detection volume; novel LXe calorimeter; etc

- ✗ Large collected statistics (34m of $\pi^+\pi^-$ events, x30 of CMD-2):

  sharper view on the detector effects → more detail study of systematic effects,

  more consistency checks

- ✗ e/μ/π separation:

  3 independent methods for cross checks

- ✗ fiducial volume determination:

  very conservative estimation of systematic contribution (0.5/0.8%),

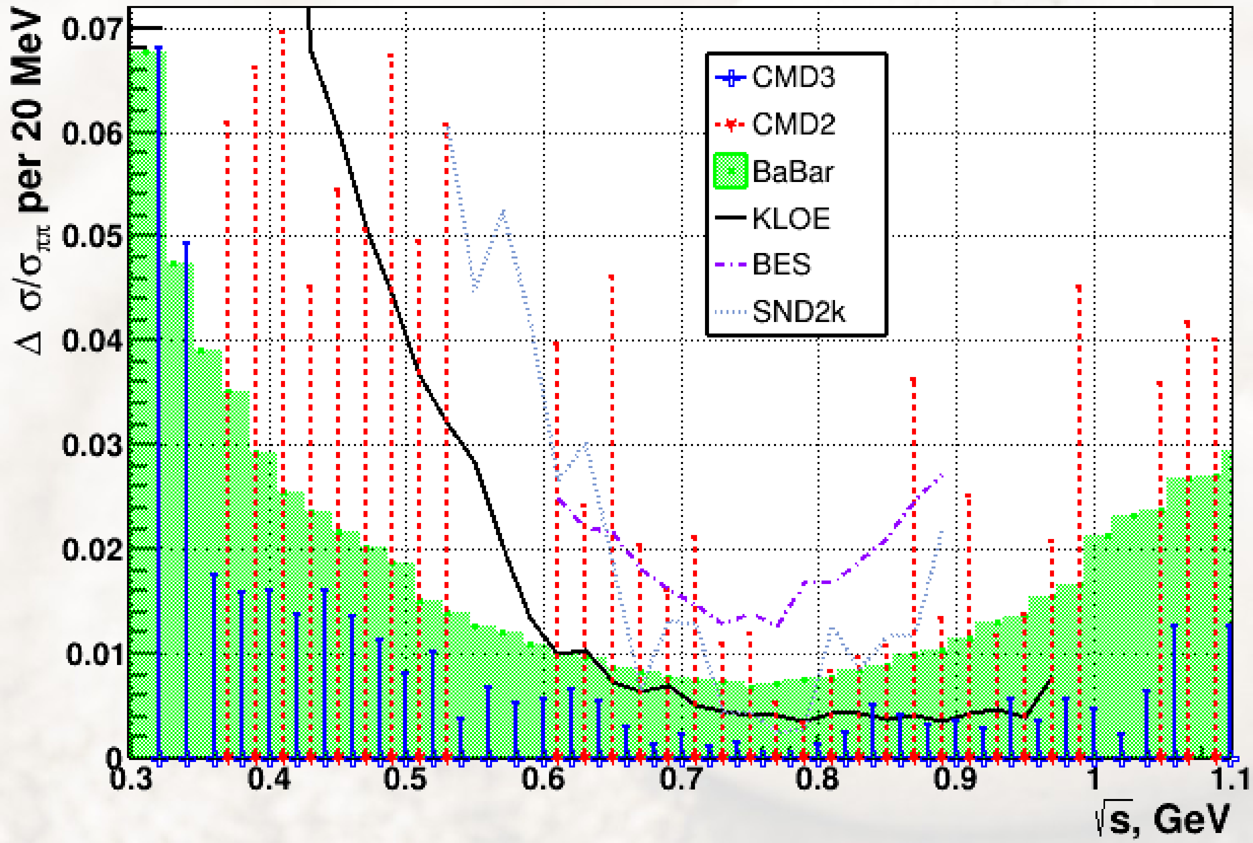
  <0.1% consistency in forward-backward asymmetry vs prediction, variation with angle cut

e+e- → π+π- by CMD-3

Statistical precision of CMD-3 cross section measurement
is a few times better than any other experiments

Full statistic is used
collected during ρ scans

3 seasons of data taking:
RHO2013
RHO2018
LOW2020

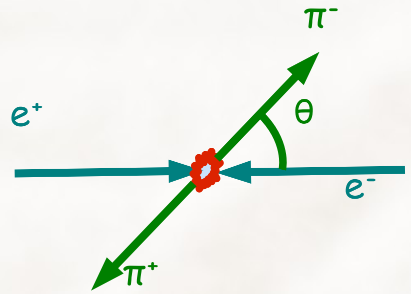


Analysis based on L = 61.9 pb^{-1} at √s < 1 GeV (+25.7 pb^{-1}, 1.0-1.2 GeV)

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

e/μ/π separation in π+π- CMD3

Very simple topology,
just 2 collinear tracks back to back:

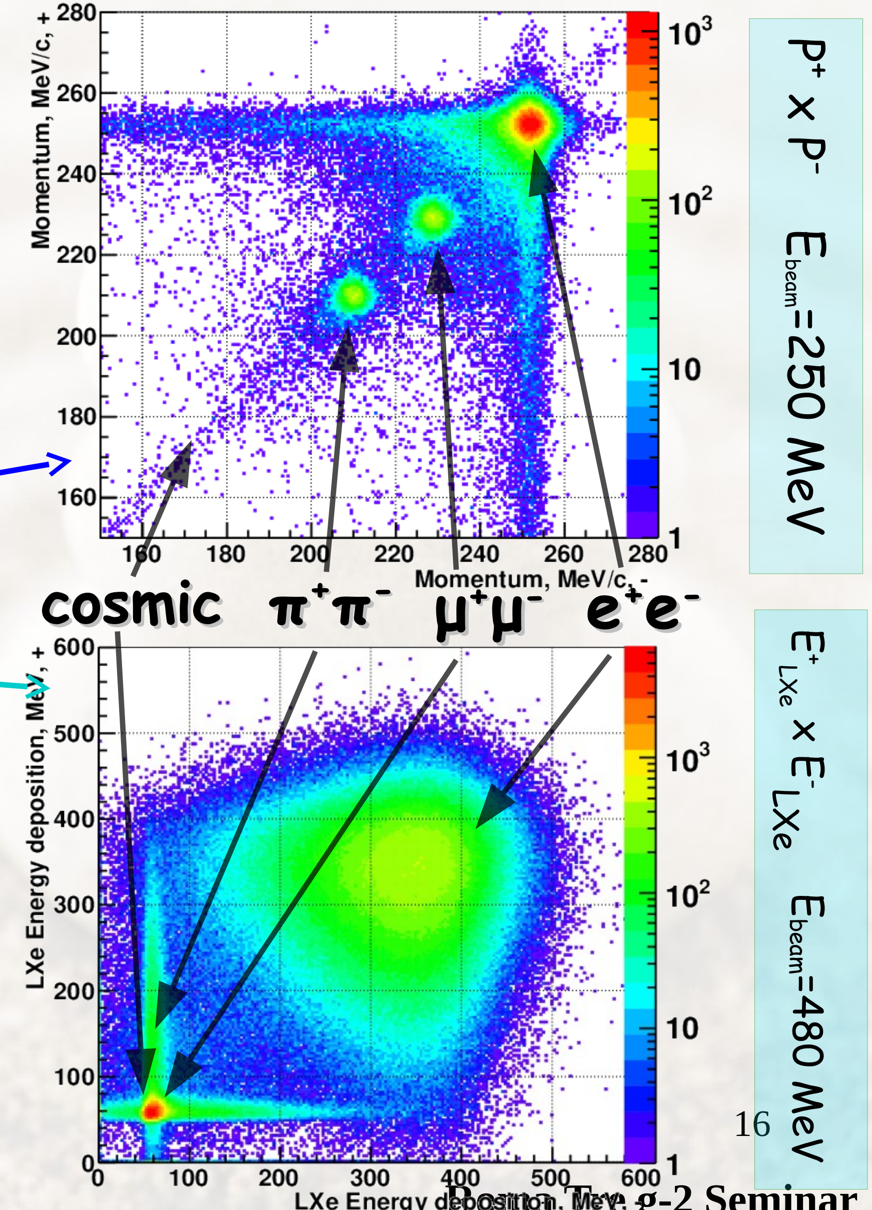


events separation either

1) by momentum
2) or by energy deposition
3) additional cross-check
   by angle distribution

Underway analysis:

4) using shower profile at $\sqrt{s}$>1GeV

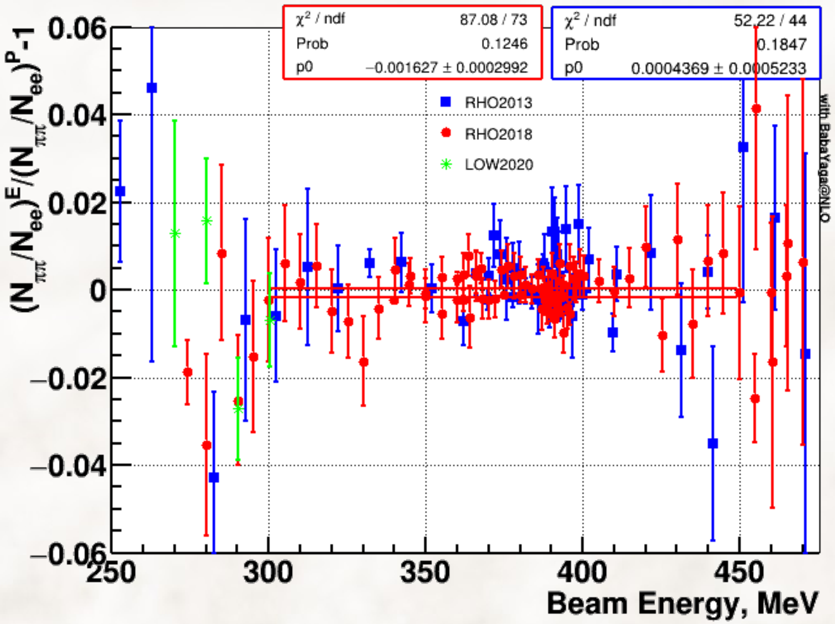


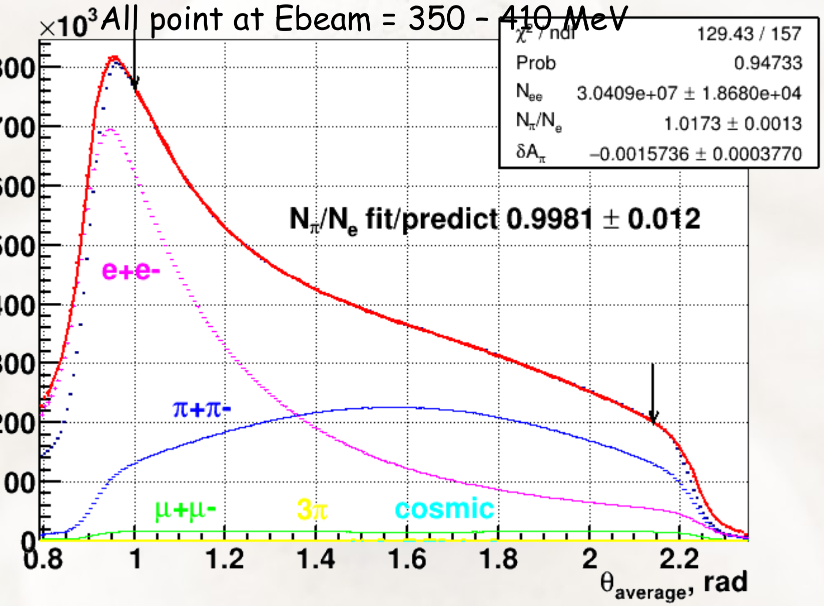
e/μ/π separation

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 √s = 0.7 – 0.82 GeV points

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

by energies in LXe Δ $N_{\pi\pi}$ /N_{ee} = -0.09 +- 0.024%

from theta with free δA: = -0.20 +- 0.12%

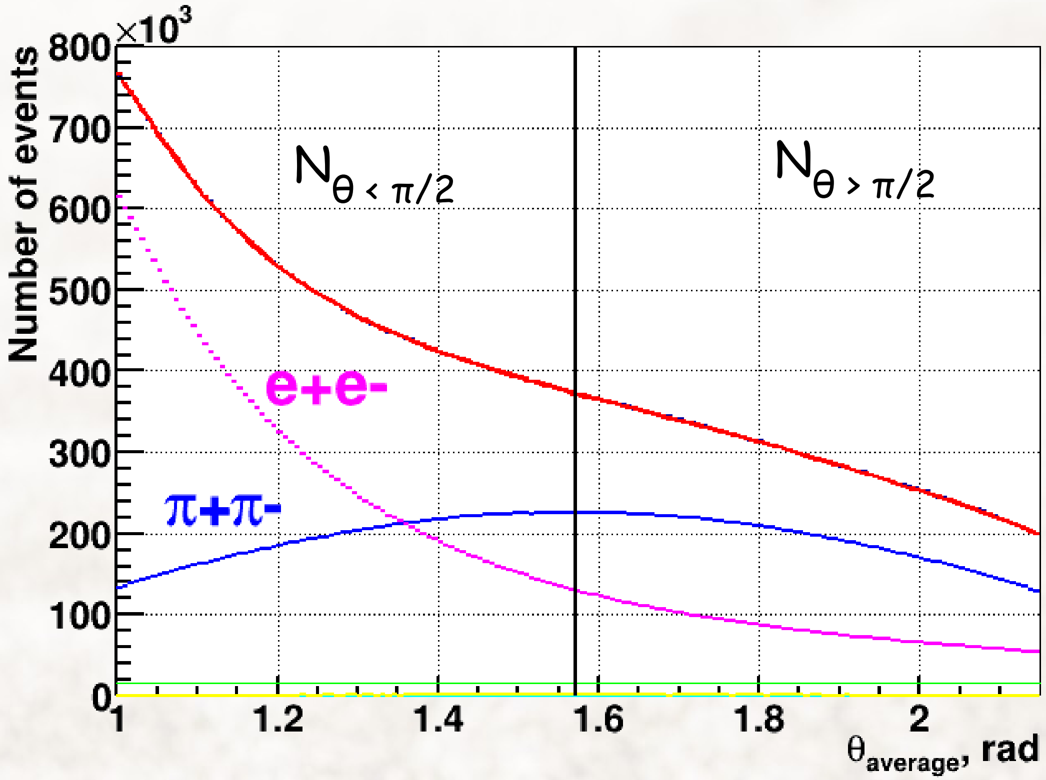
with fixed δA=0: = +0.21 +- 0.07%

consistency at ~ 0.2%

Common stat from √N: 0.026%

Forward backward charge asymmetry

dσ/dθ spectra



Asymmetry definition:

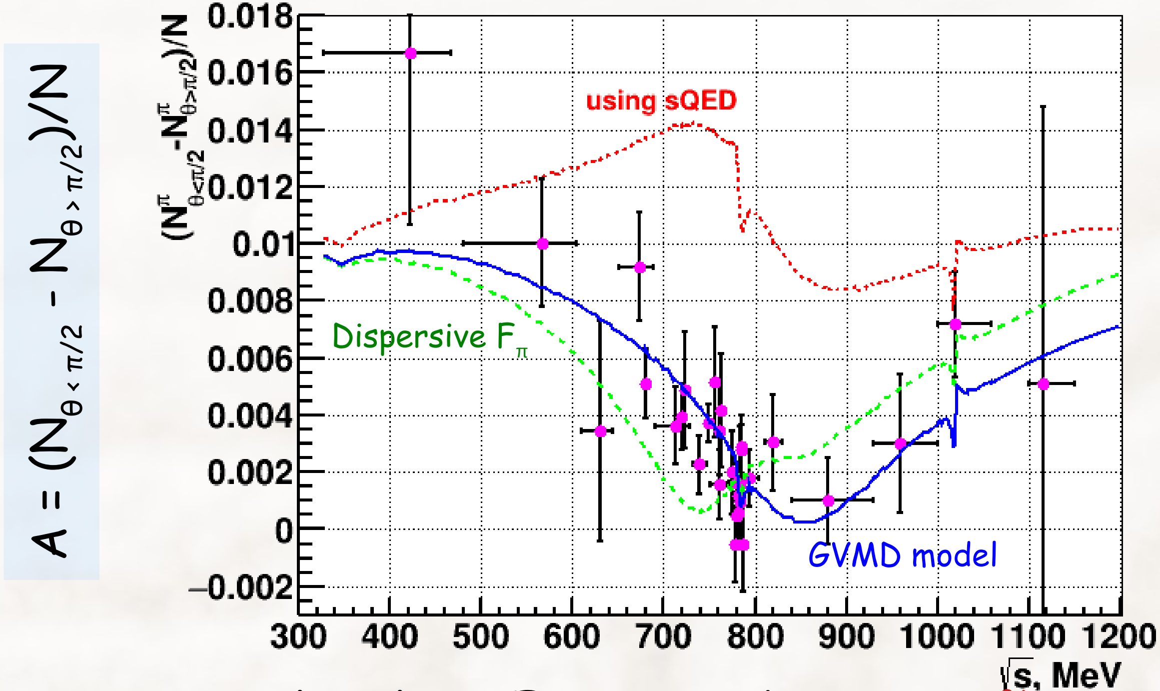
$A = (N_{\theta < \pi/2} - N_{\theta > \pi/2})/N$

Sensitive to:

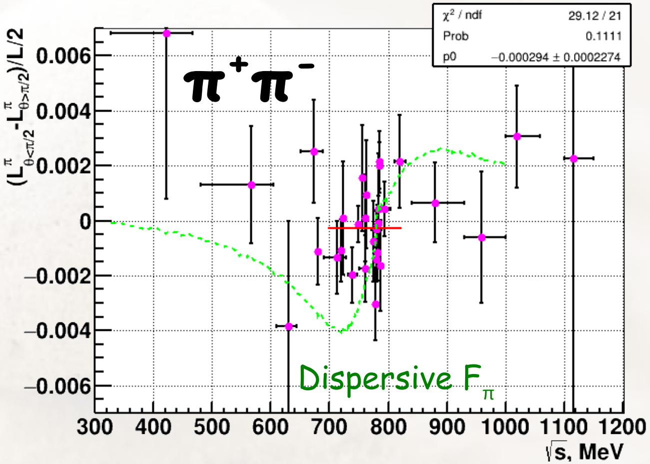
- ✗ angle-related systematics
- ✗ used model of γ-π interaction

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

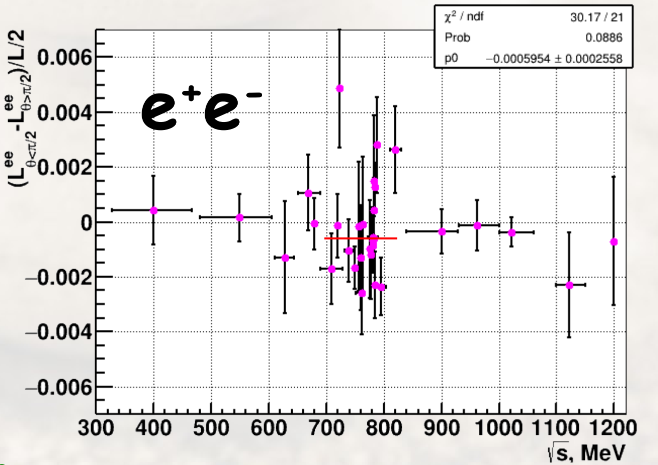
Charge asymmetry in e+e- -> π+π-



Relative to GVMD prediction



to BaBaYaga@NLO



Conventional scalar QED 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:

$\pi^+\pi^-$: ⟨δA⟩ = -0.029 ± 0.023 %

e^+e^-: ⟨δA⟩ = -0.060 ± 0.026 %

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

Radiative corrections for e+e- → X+X-(γ)

Measurement of $e^+e^- \to \pi^+\pi^-(\gamma)$ requires high precision calculation of radiative corrections.

Most recent e+e- -> X+X- (gamma) generators include:
exact NLO + Higher Order terms in some approximation or fixed order NNLO
Precision on integrated cross section ~ 0.1%

LO – 2 particle born cross section

LO	α^0		
NLO	αL	α	
NNLO	$\frac{1}{2}\alpha^2 L^2$	$\frac{1}{2}\alpha^2 L$	$\frac{1}{2}\alpha^2$
h.o.	$\sum_{n=3}^{\infty} \frac{\alpha^n}{n!} L^n$	$\sum_{n=3}^{\infty} \frac{\alpha^n}{n!} L^{n-1}$	$\cdots$

Red - next order resummation:
Parton Shower(PS), SF (Structure functions), YFS (Yennie-Frautschi-Suura exponentiation) + NLO

Logarithmically enhanced correction by L= $\log(s/m^2)$
-> $\alpha^2 L^2 \sim \alpha$

MC Generators Landscape

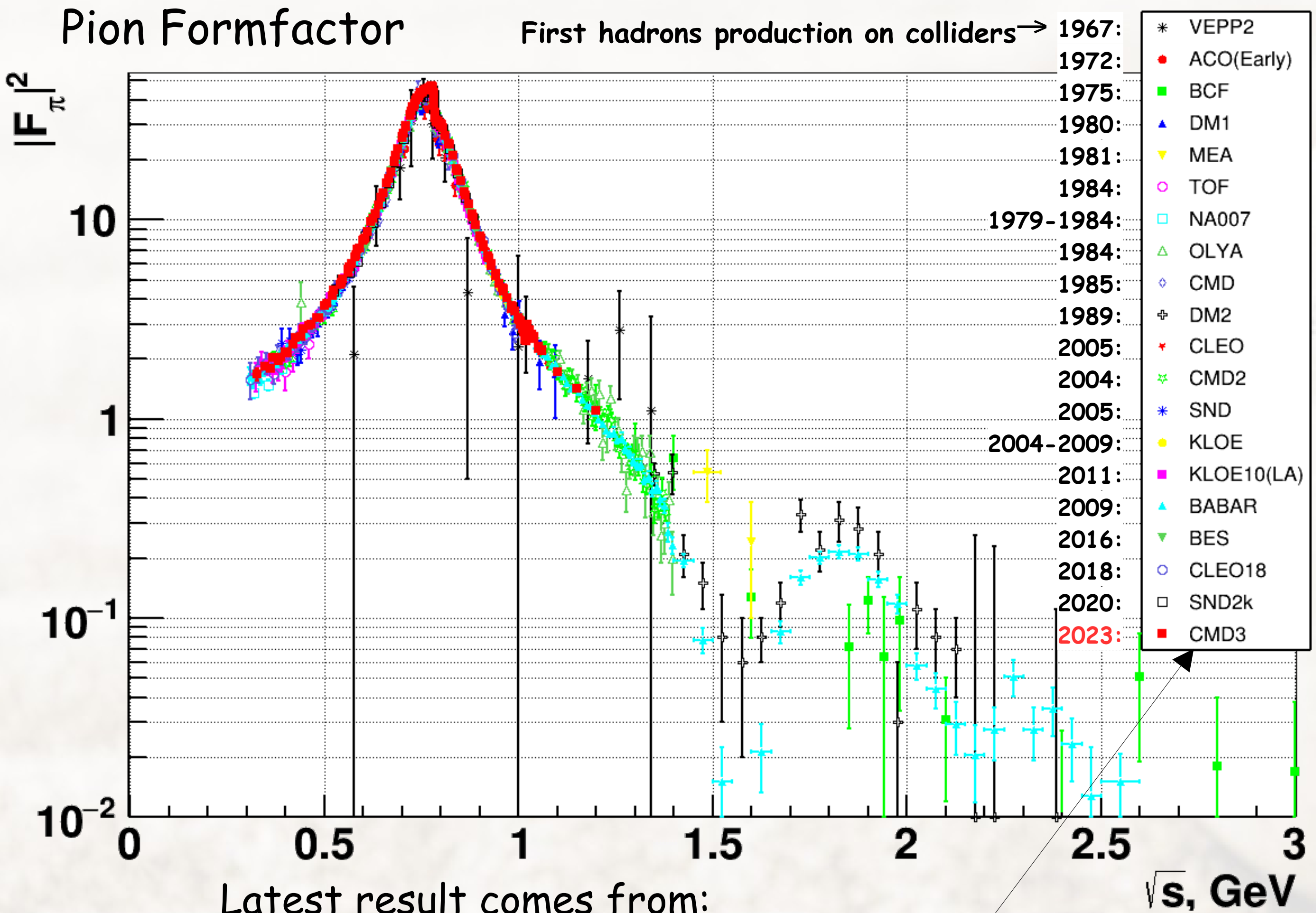
BabaYaga@NLO	(NLO + PS)	e+e-, μ+μ-
MCGPJ	(NLO + SF)	e+e-, μ+μ-, π+π-
Phokhara with ISR photon (NNLO)		μ+μ-, π+π-
AfkQED with ISR (NLO+SF for μμ, ISR at LO + SF for ππ)		μ+μ-, π+π-
MCMULE integrator (NNLO)		e+e-, μ+μ-
BHWIDE	(NLO+YSF)	e+e-
KKMC	(NLO+ up $\alpha^2 L$ + CEEX)	μ+μ-
Sherpa	(NLO+YSF)	e+e-, μ+μ-
etc....		

used at low energies

pions in sQED approximation (except MCGPJ)

- ✗ Great consistency on integrated cross section
- ✗ Major inconsistencies between generators are seen in the differential cross sections predictions.
- ✗ ISR measurement start from NLO (require additional α order for same precision as for scan)
- ✗ Only two precise generators for ππ : MCGPJ for scan, Phokhara for ISR (even both non-overlapped)

e+ e– → π+ π– today



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CLEO: 1.5%

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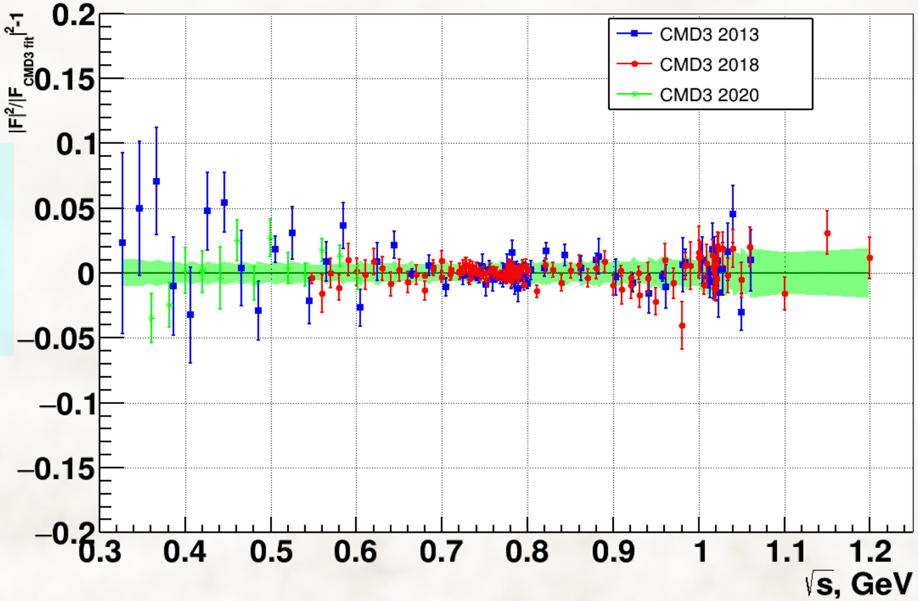
CMD-3: 0.7%

New g-2, etc experiments require precision ~ 0.2%

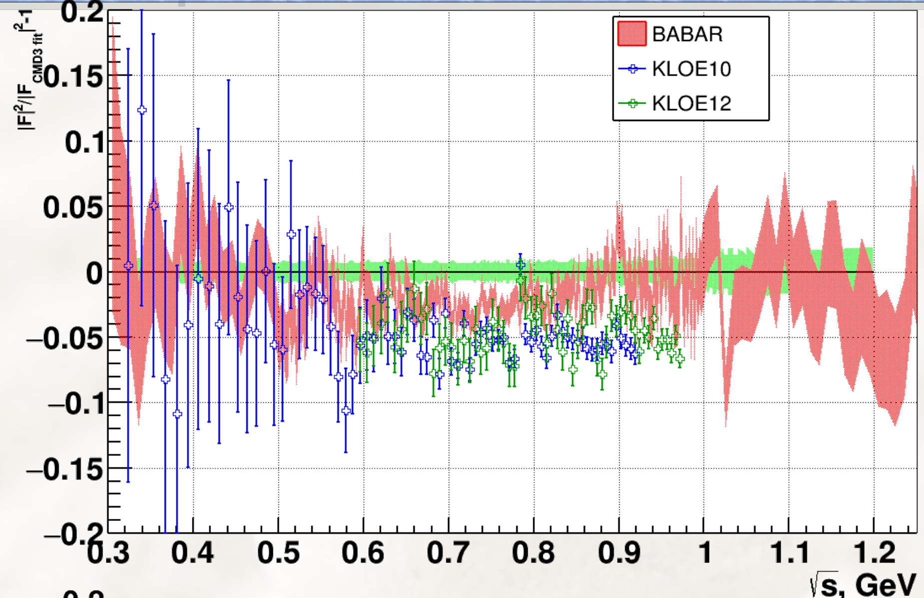
CMD-3 vs other experiments

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

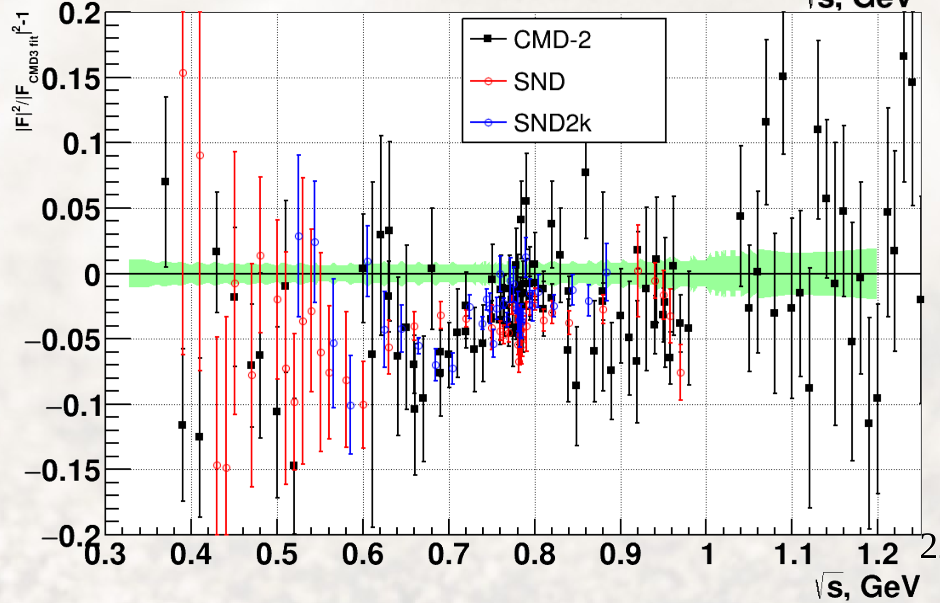
CMD-3



vs ISR



vs direct scan



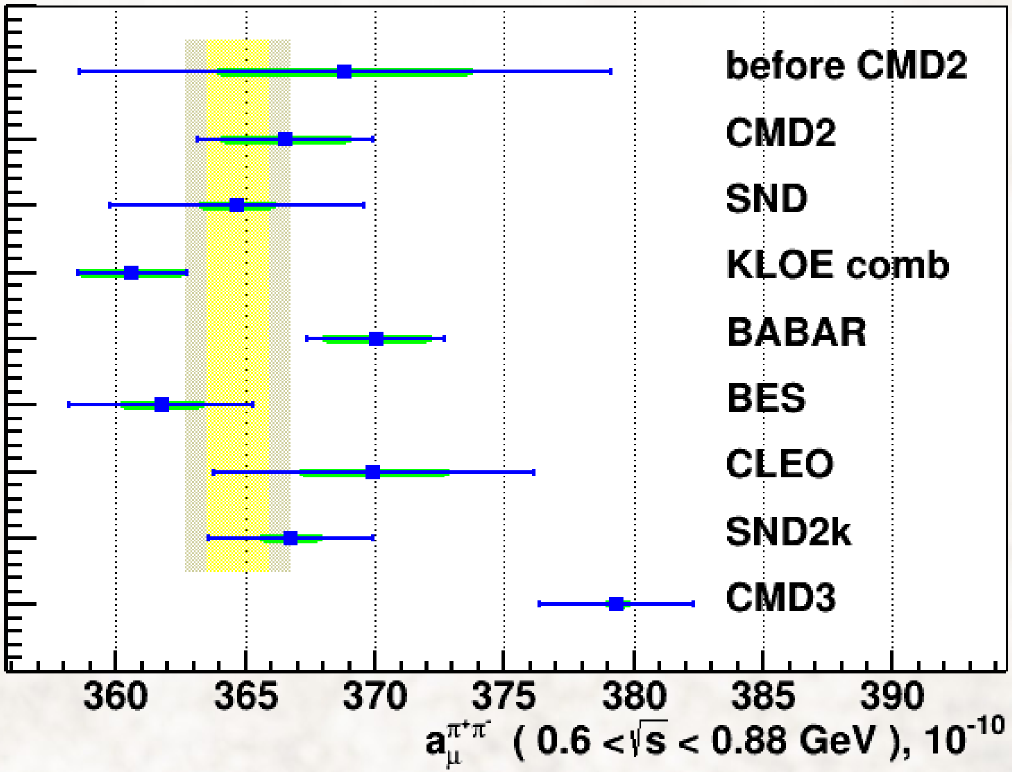
CMD-3

- ✗ Statistical precision is a few times better than any other experiments
- ✗ Cross section is higher by ~ 2-5%

The π+ π− contribution to a_μ^{had}

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

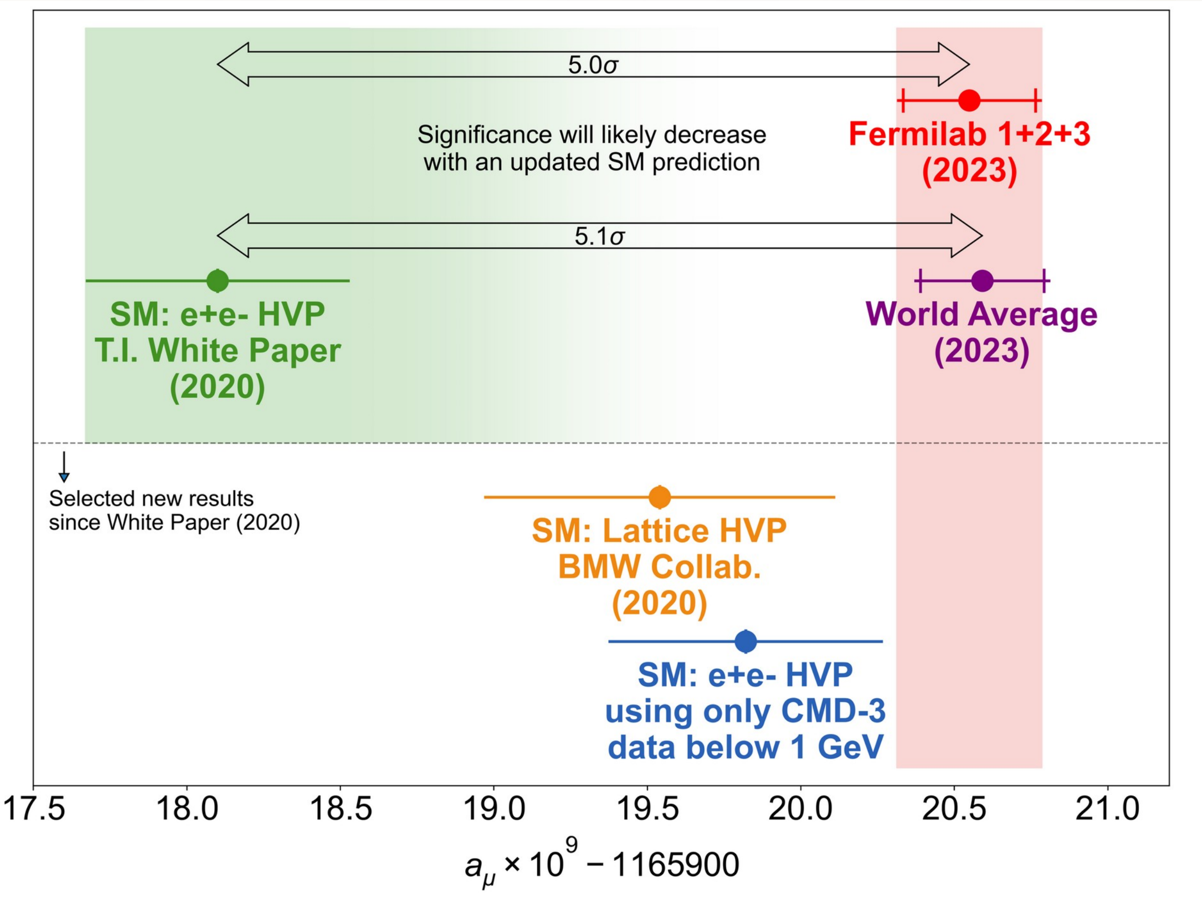
$0.6 < \sqrt{s} < 0.88$ GeV



	$a_\mu^{\pi\pi,LO}$, 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

The impact of CMD-3 on SM prediction of a_μ^{had}



Using only 2π from CMD-3

(+ others outside of CMD-3 √s range):

$a_\mu^{\pi\pi,LO}$ = 526.0(4.2) x10^{-10}

+20.0x10^{-10} to TI WhitePaper

The CMD-3 is only one now over many other e+e- experiments (BaBar, KLOE, BES, CMD-2, SND, ...)

Unfortunately at the moment, we don't know the reasons of the disagreement between different experiments.

James Mott: https://indico.fnal.gov/event/60738/

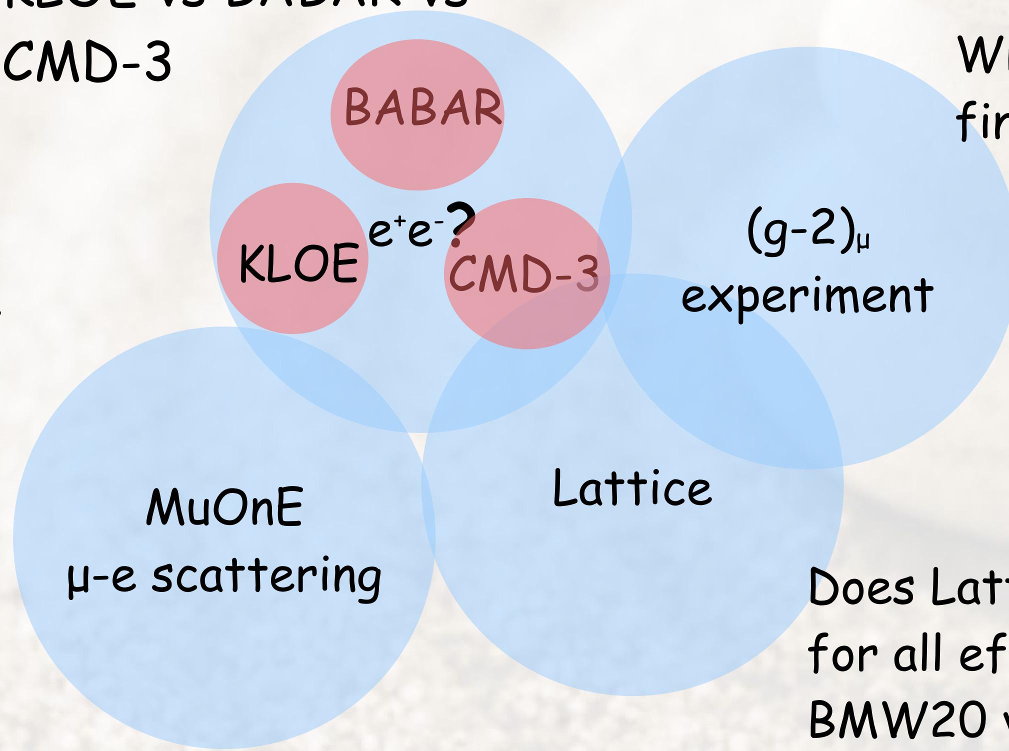
Alex Keshavarzi: https://indico.fnal.gov/event/57249/contributions/271581/

Question of comparison:

e+e- vs $(g-2)_\mu$ 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

Scan with ISR approaches

Both methods stress different systematics

Direct energy scan	ISR method
✗ Accelerator should be re-tuned for each $\sqrt{s}$ c.m.s energy is known better (compton backscattering methods gives $\delta E/E < 10^{-4}$)	✗ All $\sqrt{s}$ measured at same time $M_{\pi\pi}$ = rely on momenta measurement by DCH, spectra must be unfolded from resolution, ISR & FSR must be de-factorized
✗ Less stringent on radiative corrections	✗ Needs +1 order on alpha for same precision
✗ $\pi^+\pi^-$ collinear events are better defined (momenta peaked at E_{beam})	✗ Higher background from other channels
✗ Limited acceptance (efficiencies of multihadron processes (3π,4π,..) depend on models describing dynamics)	✗ At BABAR energies hadron system is boosted all tracks in acceptance range (but needs to reconstruct overlapped tracks)
✗ Significant effect from pion decays and nuclear interaction at the threshold energies	✗ Boosted particles have higher energies: smaller effect from decays, nuclear interaction losses
	✗ More complicated PID

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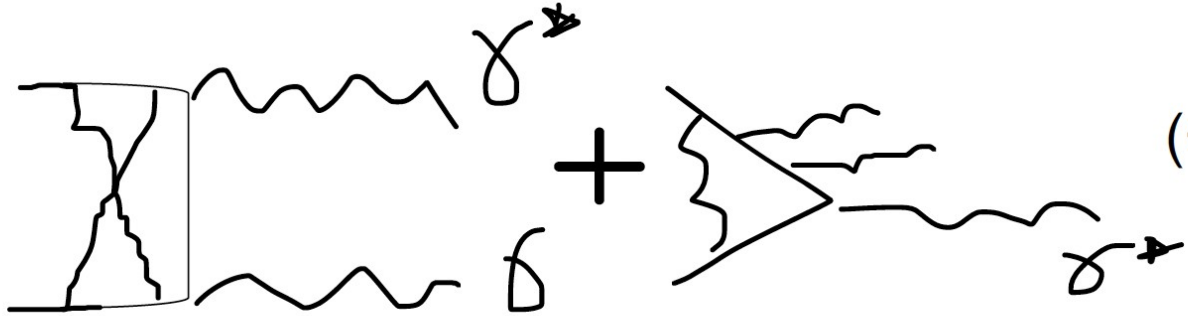
Towards NNLO MC generator ….

(N^{3}LO for ISR relative to born 2 particles)



(+ others…)

- STRONG2020 (Virtual) meeting: 24-26 November 2021 (https://agenda.infn.it/event/28089/)
- N^{3}LO kick-off workstop/thinkstart 3-5 August 2022, IPPP Durham (https://conference.ippp.dur.ac.uk/event/1104/)
- WorkStop on "**Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e+e- collision**" on **05-09 June 2023** at the University of Zurich

(Strong interplay with MUonE theory activities)

5th Workstop / Thinkstart: Radiative corrections and Monte Carlo tools for Strong 2020

5–9 Jun 2023
University of Zurich
Europe/Zurich timezone

Enter your search term

https://indico.psi.ch/event/13707/
https://indico.psi.ch/event/13708/

- Overview
- Timetable
- Contribution List
- My Conference
  - My Contributions
- Registration
- Participant List
- Code of Conduct

Contact

yannick.ulrich@durham....

In this workstop, we will discuss radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions. This is to be seen as part of the Strong 2020 effort. We will cover

- leptonic processes at NNLO and beyond
- processes with hadrons
- parton shower
- experimental input

Each area will be given at least half a day, starting with an open 1h seminar followed by a lengthy discussion.

Just like previous workstops, this is an in-person event. We try to gat
who actively work on this topic to make very concrete progress. It sh
but to actually learn from each other and put together the jigsaw piec

Additionally to the workstop that is only by-invite only, there is a broa
the workstop.

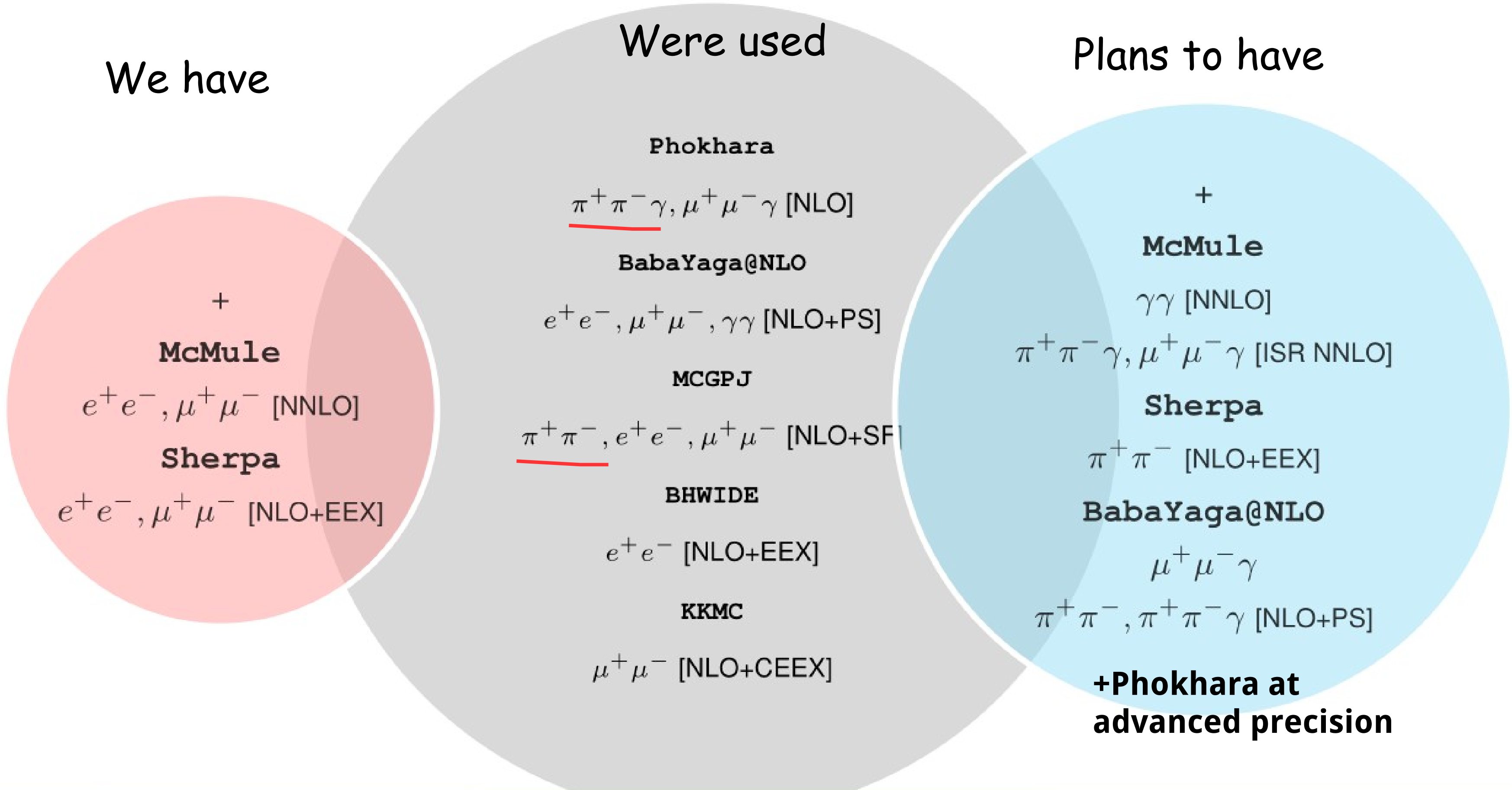
The effort to bring forward MC tools precision!

Towards NNLO (and above) precision

Can help mitigate questions to theoretical parts of ISR & scan measurements

Radcor and MC tools, 7-9 June 2023, Zurich
Carlo Carloni Calame, WP4: parton shower

Workstop/Thinkstart outcome for WP4

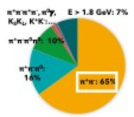


Unfortunately until now, only single precise generators are available for e+e- → π+π-(γ) process:

For scan experiment: MCGPJ with declared 0.2% precision

For ISR: Phokhara with 0.5% precision

$e^+e^- \to \pi^+\pi^-$: Perspectives



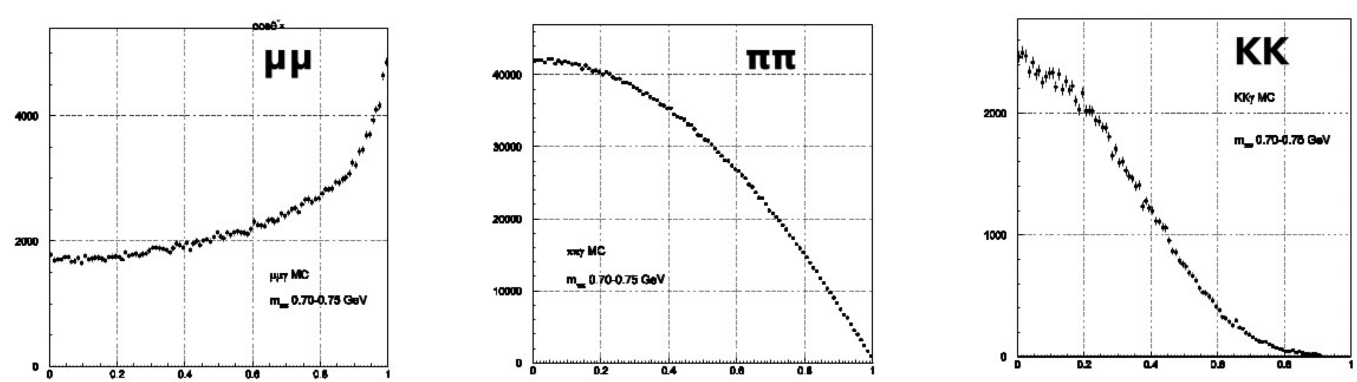
BaBar

✗ Using new particle separation method

✗ x7 in statistics

✗ will be interesting to see new asymmetry study (stress of MC prediction)

- Reanalysis of **full dataset** (2x)
- New approach to μμ/ππ/KK separation:
  - Minimal PID conditions (negligible systematics)
  - Fit angular distribution (ϑ^*) in ππ rest frame
- Larger angular and momentum acceptance (8x)
- **Results expected in 2023**



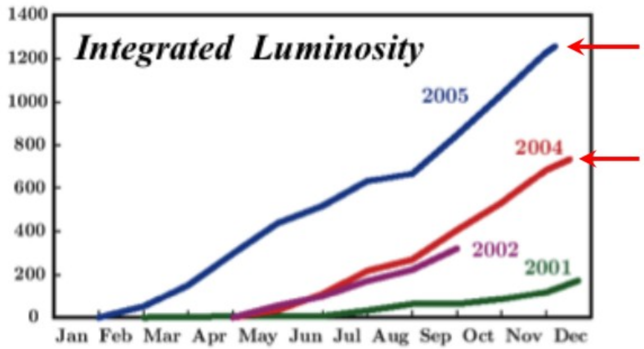
Future improvements using KLOE data

KLOE

- ✗ x7-8 in statistics
- ✗ Modernized and more robust analysis techniques
- ✗ Stress of systematic effects

Effort to analyze new data by Liverpool group + external team backed by theoretical group effort

There are about 1.7 pb^{-1} of KLOE data taken in 2004 - 2005 on tape:



- data is taken at $\sqrt{s} = m_\phi$, which makes the large angle analysis cuts unfeasible
- essentially "replay" KLOE08 and KLOE12 analysis with the newer data
- use increased statistics to improve systematic uncertainties (old KLOE analyses are not limited by statistics)
- benefit from modern analysis techniques

Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e+e- collisions, 7-9 June 2023, Zurich

Thomas Lenz, Feasibility Studies for an Inclusive R-Measurement using ISR with BESIII

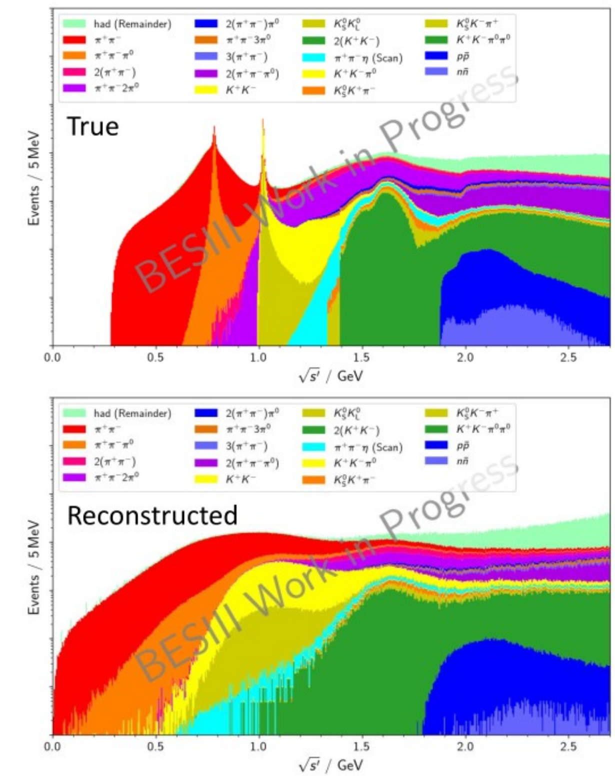
BES

- ✗ Inclusive measurement of output hadronic spectra after ISR
- ✗ New independent approach
- ✗ high efficiency to find hadronic states

New Inclusive Approach Using ISR

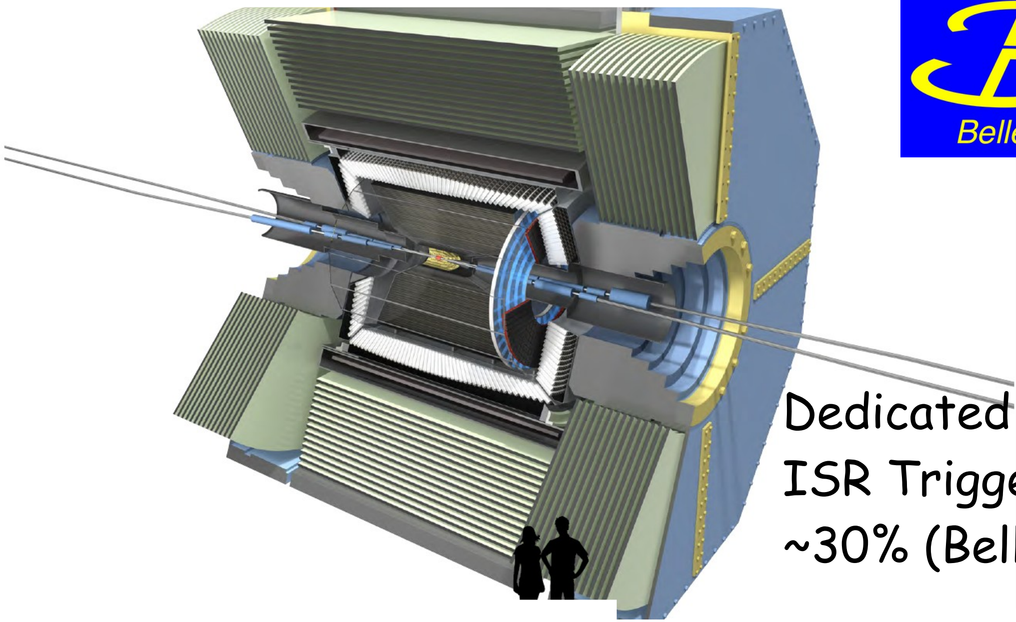
Challenges:

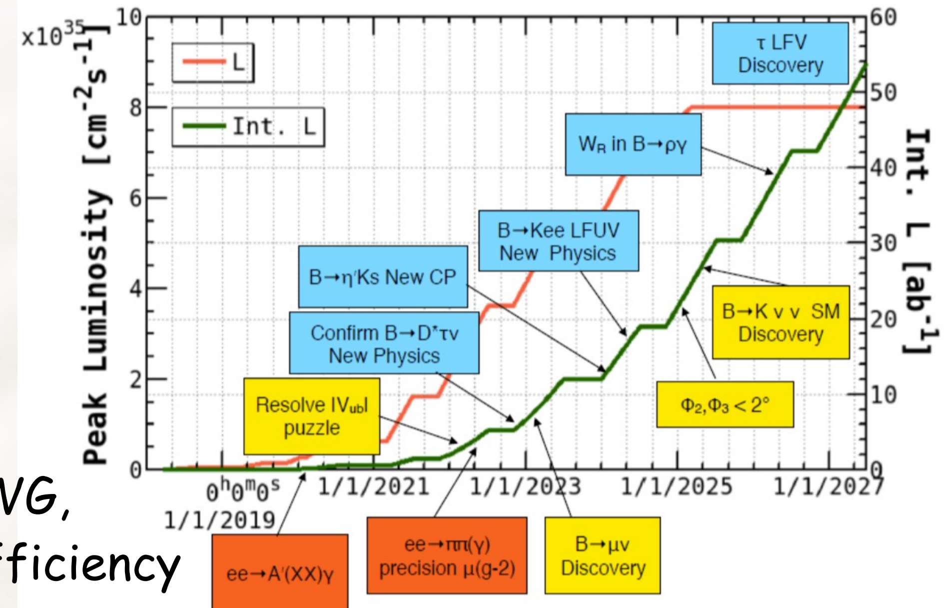
- Background from radiative charmonia and high-energetic π^0/η decays
  - Upper limit to mass range
- Mass resolution limited by EMC
  - Requires unfolding
- Subtract QED events using MC simulation
  - High precision QED MC needed



Belle2 ISR program

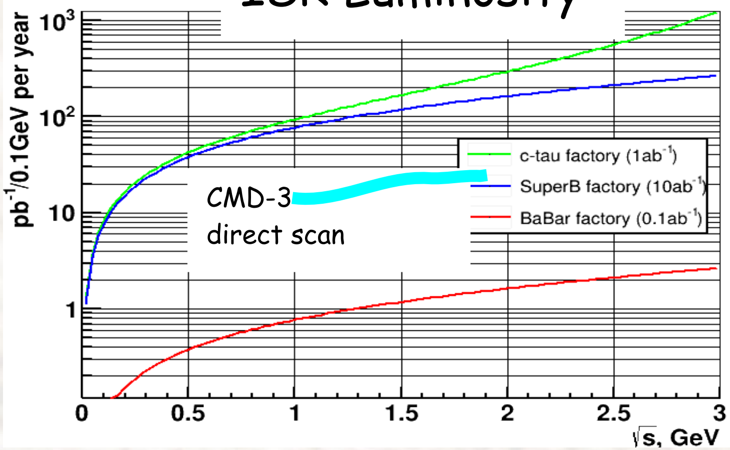
x50-100 of Belle,BaBar statistics



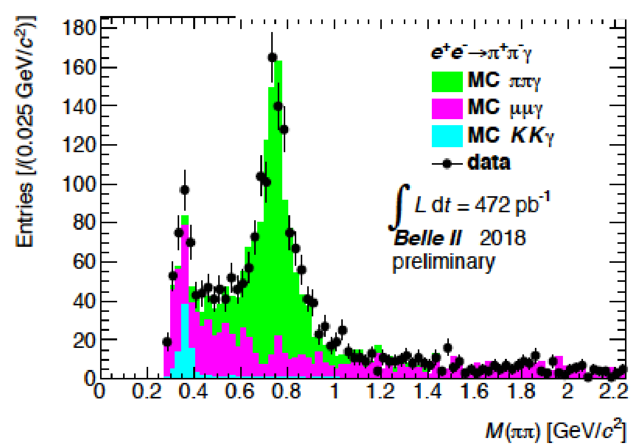


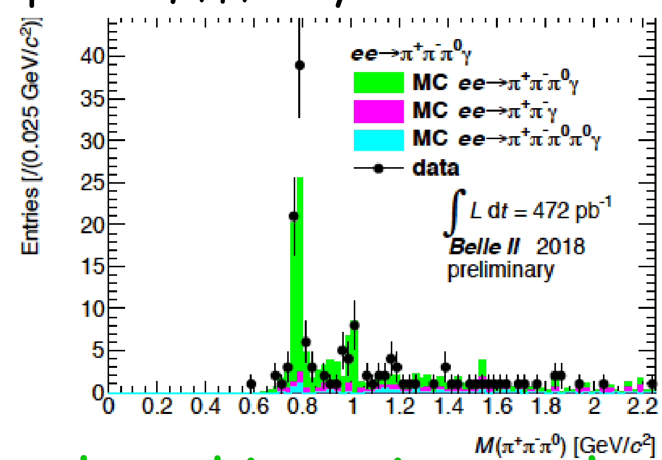
Dedicated ISR WG,
ISR Trigger inefficiency
~30% (Belle) → <1% (Belle2)

ISR Luminosity



First sample of ρ,φ,ω by ISR



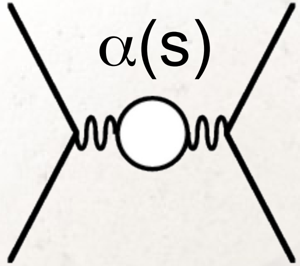


σ(e+e+→ 3π) expected to be released in coming months

a_μ^{HLO} from time-like to space-like data

Dispersion integral to a_μ^{had} is usually expressed via time-like data:

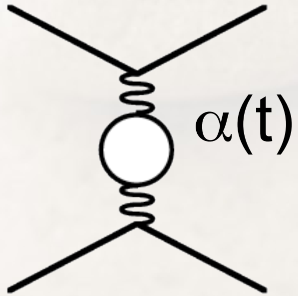
$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\cdot\sigma(s)_{(e^+e^-\to had)}$$



s>0

Also can be rewritten by using space-like region:

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\cdot\Delta\alpha_{had}\left(-\frac{x^2\, m_\mu^2}{1-x}\right)$$



$t=q^2<0$

Systematic precision challenge

10^{-5} requirement at differential cross section measurement

Reference papers

A new approach to evaluate the leading hadronic corrections to the muon g-2 ☆

C. M. Carloni Calame[a], M. Passera[b], L. Trentadue[c], G. Venanzoni[d]

[a] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[b] INFN, Sezione di Padova, Padova, Italy
[c] Dipartimento di Fisica e Scienze della Terra "M. Melloni"

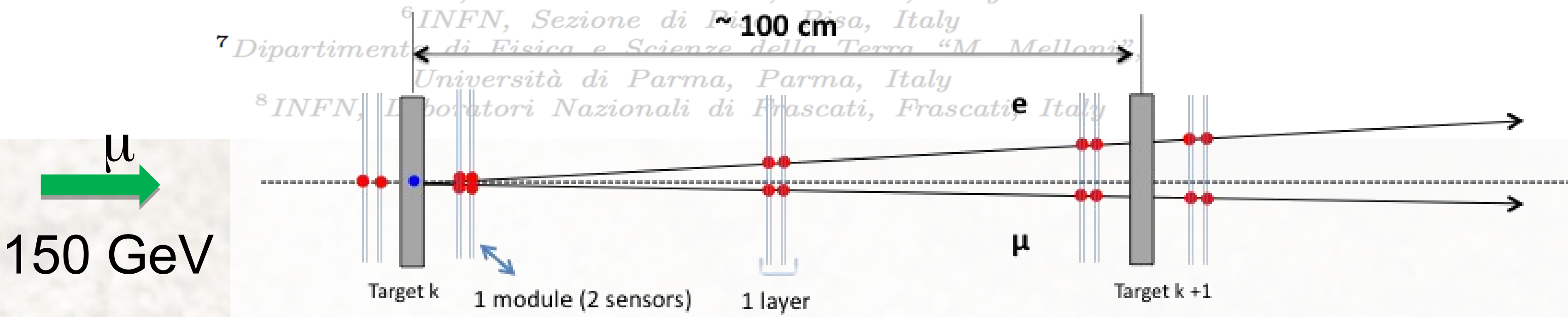
Phys. Lett. B 746 (2015) 325

Measuring the leading hadronic contribution to the muon g-2 via μe scattering

G. Abbiendi[1], C. M. Carloni Calame[2], U. Marconi[1], C. Matteuzzi[3], G. Montagna[4,2], O. Nicrosini[2], M. Passera[5], F. Piccinini[2], R. Tenchini[6], L. Trentadue[7,3], and G. Venanzoni[8]

[1] INFN, Sezione di Bologna, Bologna, Italy
[2] INFN, Sezione di Pavia, Pavia, Italy
[3] INFN, Sezione di Milano Bicocca, Milano, Italy
[4] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[5] INFN, Sezione di Padova, Padova, Italy
[6] INFN, Sezione di Pisa, Pisa, Italy
[7] Dipartimento di Fisica e Scienze della Terra "M. Melloni", Università di Parma, Parma, Italy
[8] INFN, Laboratori Nazionali di Frascati, Frascati, Italy

Eur. Phys. J. C (2017) 77: 139.



backups

CMD-3 $\pi\pi$ more details

E-Print: 2302.08834 [hep-ex]

Two long seminars:

KEK seminar, 17 March 2023: https://kds.kek.jp/event/45889/

TI seminar, 27 March 2023: https://indico.fnal.gov/event/59052/

Radiative correction aspects:

5th Workstop Radio MC, 5 June 2023: https://indico.psi.ch/event/13707/

Discussion on the analysis with the list of 49 questions prepared by the panelist nominated from the g-2 TI Steering Committee: https://indico.ijclab.in2p3.fr/event/9697/

6th TI workshop, Bern, September 2023:

https://indico.cern.ch/event/1258310/contributions/5515288/

https://indico.cern.ch/event/1258310/contributions/5515290/

https://indico.cern.ch/event/1258310/contributions/5524516/

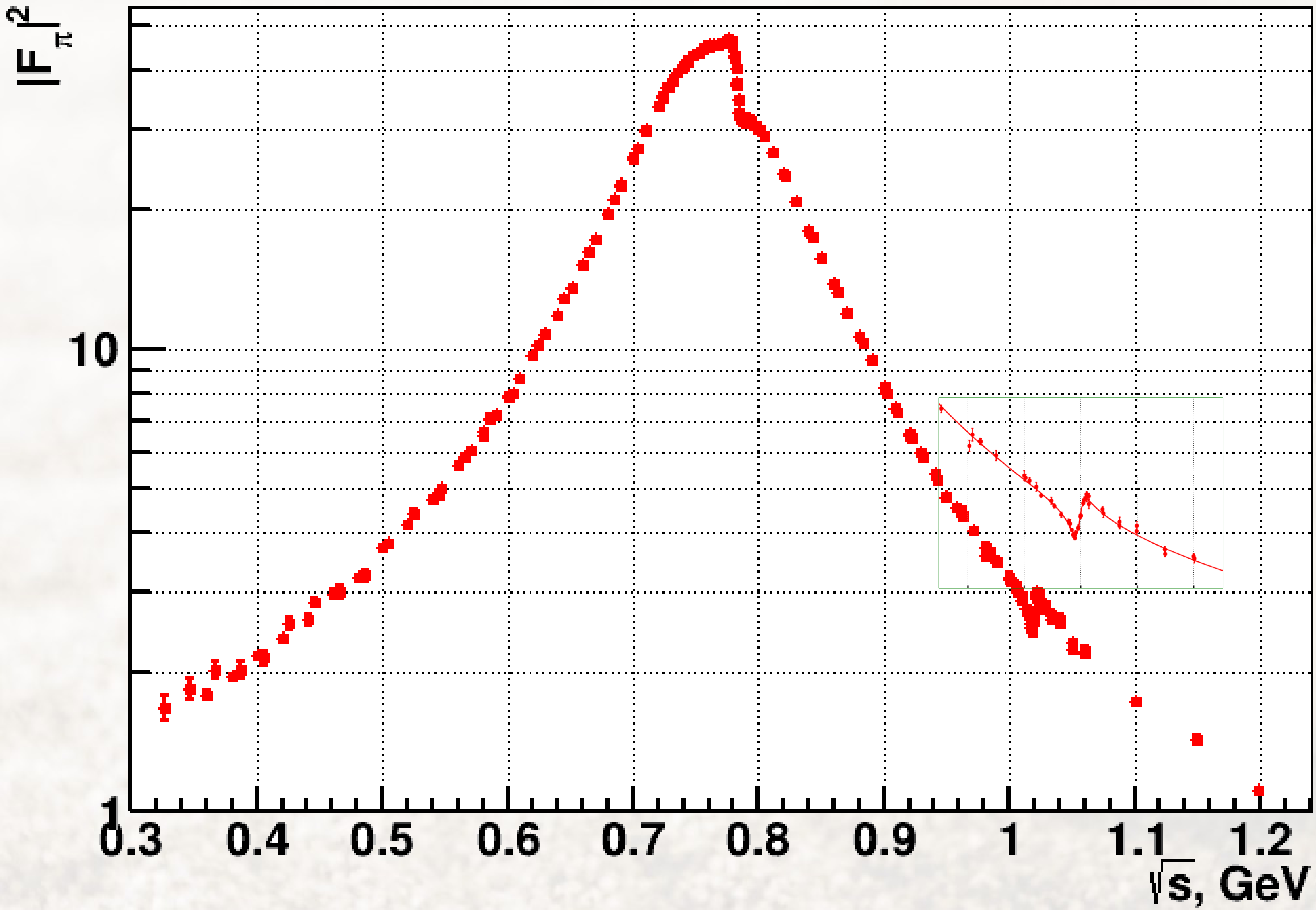
$|F_\pi|^2$ systematic uncertainty

	At $\sqrt{s}$ near ρ peak (except ω peak)
✗ Radiative corrections	0.2% (2π) ⊕ 0.2% (Fπ) ⊕ 0.1% (e+e-) = **0.3%**
✗ e/μ/π separation	**0.2%**
✗ Fiducial volume	**0.5%** / **0.8%** (RHO2013)
✗ Correlated inefficiency	**0.1%**
✗ Trigger	**0.05%**
✗ Beam Energy (by Compton σ_E< 50 keV)	**0.1%**
✗ Bremsstrahlung loss	**0.05%**
✗ Pion specific loss	**0.2%** nuclear interaction **0.1%** pion decay
	0.7% / **0.9%** (RHO2013)

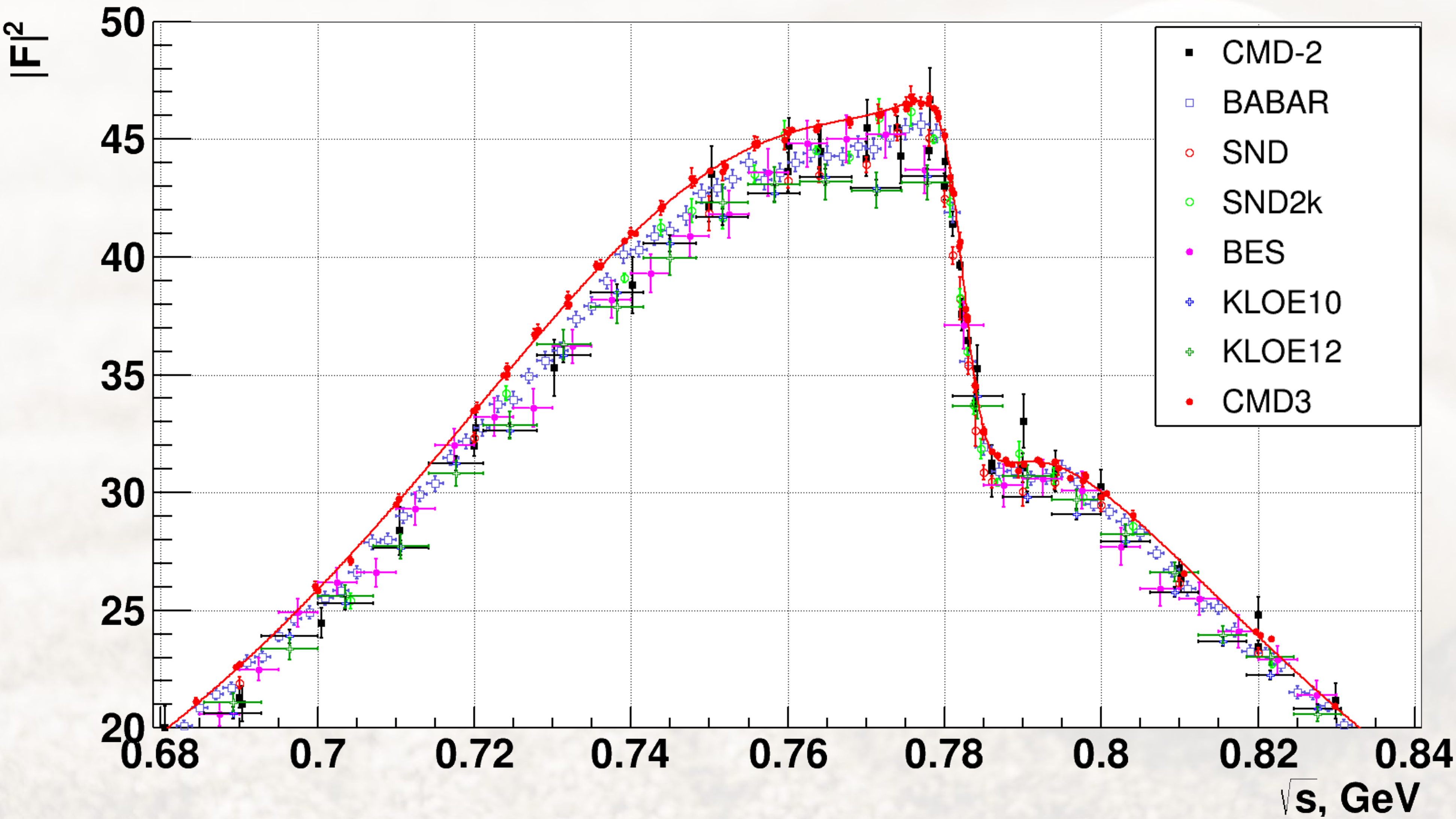
Quite conservative θ-angle related systematic contribution

The radiative correction is the next biggest part to the systematic table

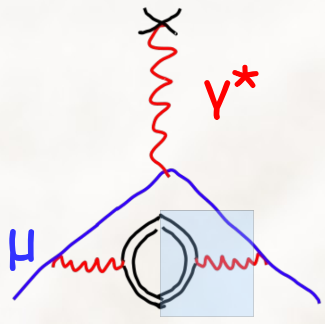
Form factor



Other experiments

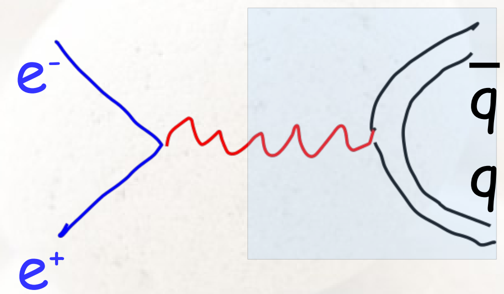


Hadronic part of
Muon precession anomaly (g-2)/2



can be expressed by
dispersion relation
integral from

e+e- -> hadrons cross section



Dispersion relation is based on analyticity:

 $= \int \frac{ds}{\pi(s-q^2)} \mathrm{Im}$ 

and the optical theorem (unitarity):

$2\mathrm{Im}$  $= \sum_{had} \int d\Phi \, \Big|$  $\Big|^2$

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

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

The pQCD doesn't work everywhere, the experimental cross-section σ(e+e- → hadrons) is used.

Weighting function ~ $1/s^2$, therefore
lower energies contribute the most:
<2GeV gives 93% of the integral,
π+π− gives 73% of the hadronic part of aμ

SM prediction for muon g-2

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}

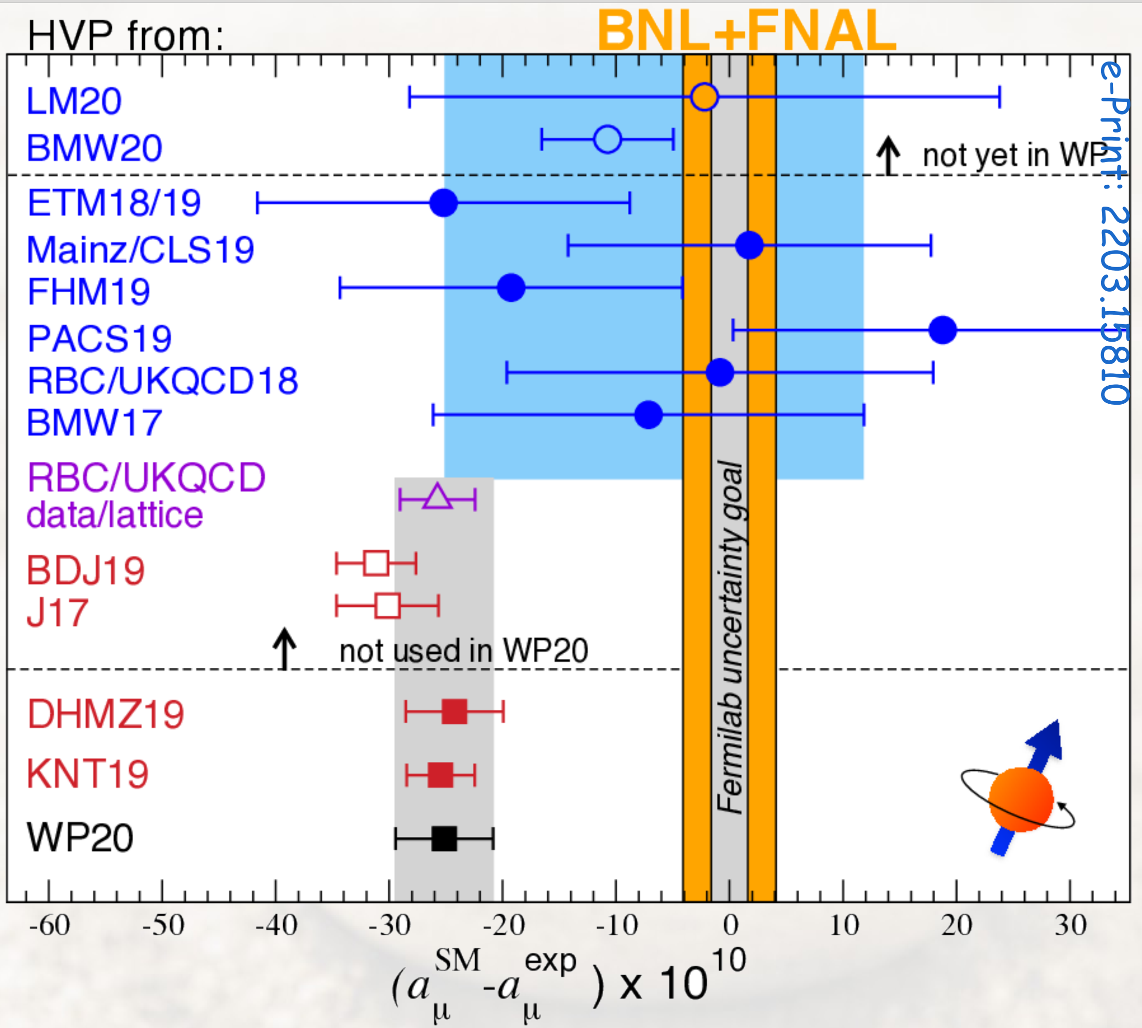
Δ (Exp – Theory) = 4.3 s

The first Lattice calculation reaches the sub-percent precision:

BMW20 (Nature 593 (2021) 7857, 51-55)

Δ (Exp – Lattice) = 1.5 s

Δ (e+e- – Lattice) = 2.1 s



DHMZ: M. Davier, A. Hoecker, B. Malaescu, Z. Zhang, Eur. , Phys. J. C 80 (3) (2020) 241

KNT: A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. D 101 (1) (2020) 014029

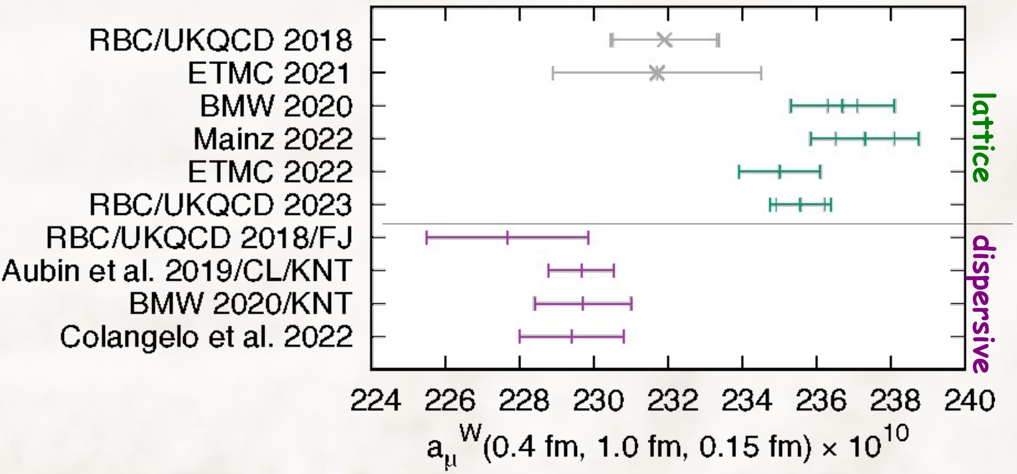
Dispersive vs Lattice

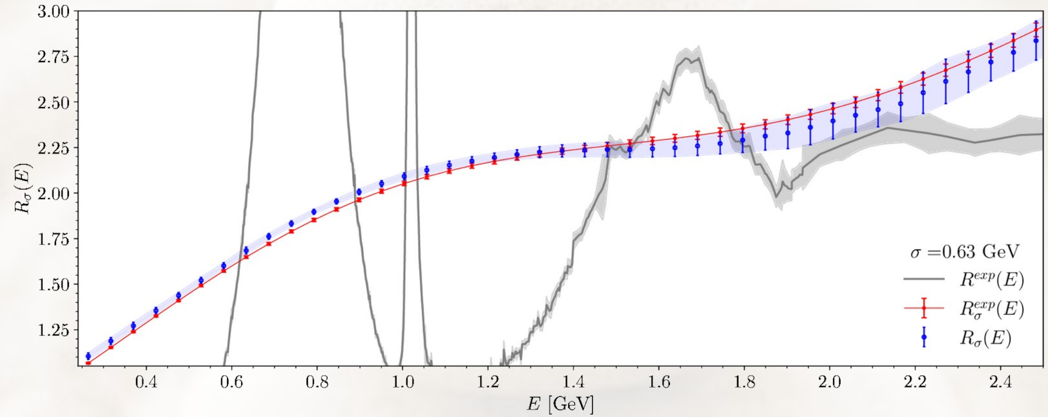
T.Blum et al, e-Print: 2301.08696 [hep-lat]

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

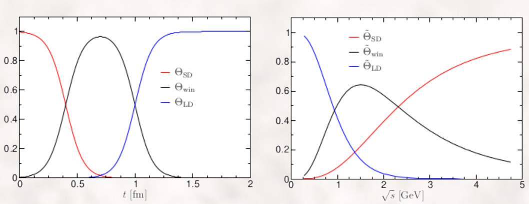
a^{HVP}_{μ} contribution from intermediate window in Euclidean time

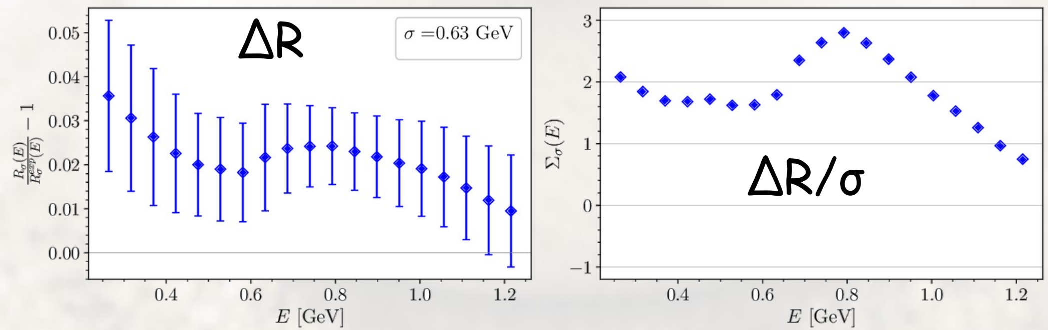
R(s) is convolved with Gaussian kernel





Windows definition





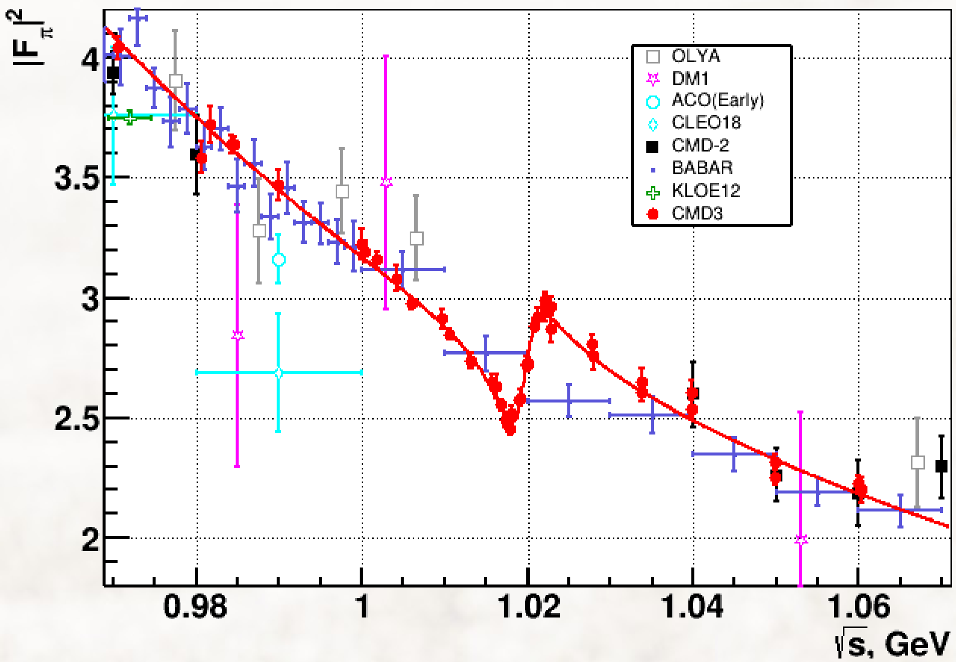
~4σ tension between Lattice/Dispersive e+e-

~3σ tension at rho energies

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

$\varphi \to \pi^+\pi^-$

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



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

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

CMD-3

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

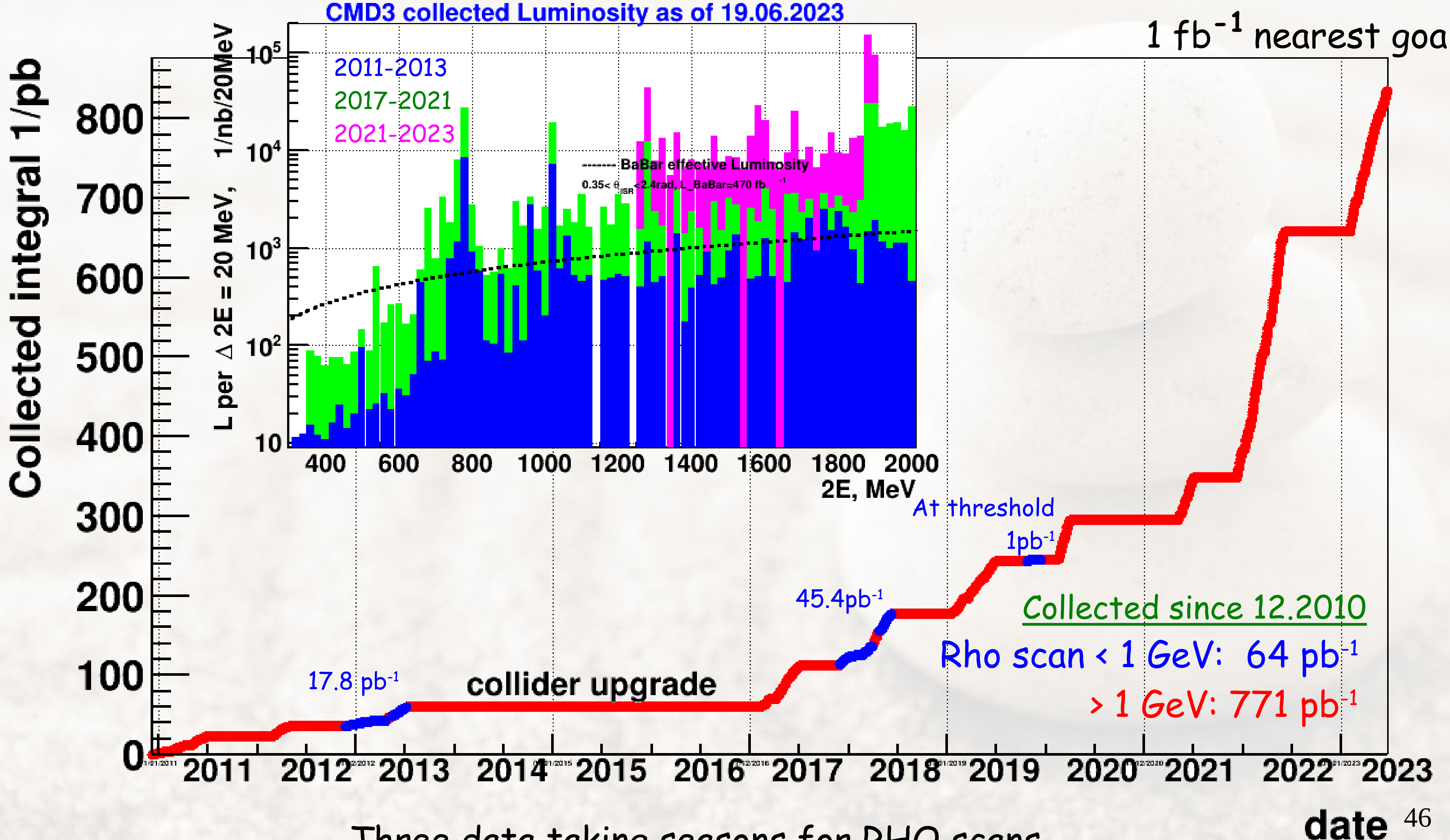
$\psi_\pi = (-34 \pm 5)^\circ$

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

SND

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)

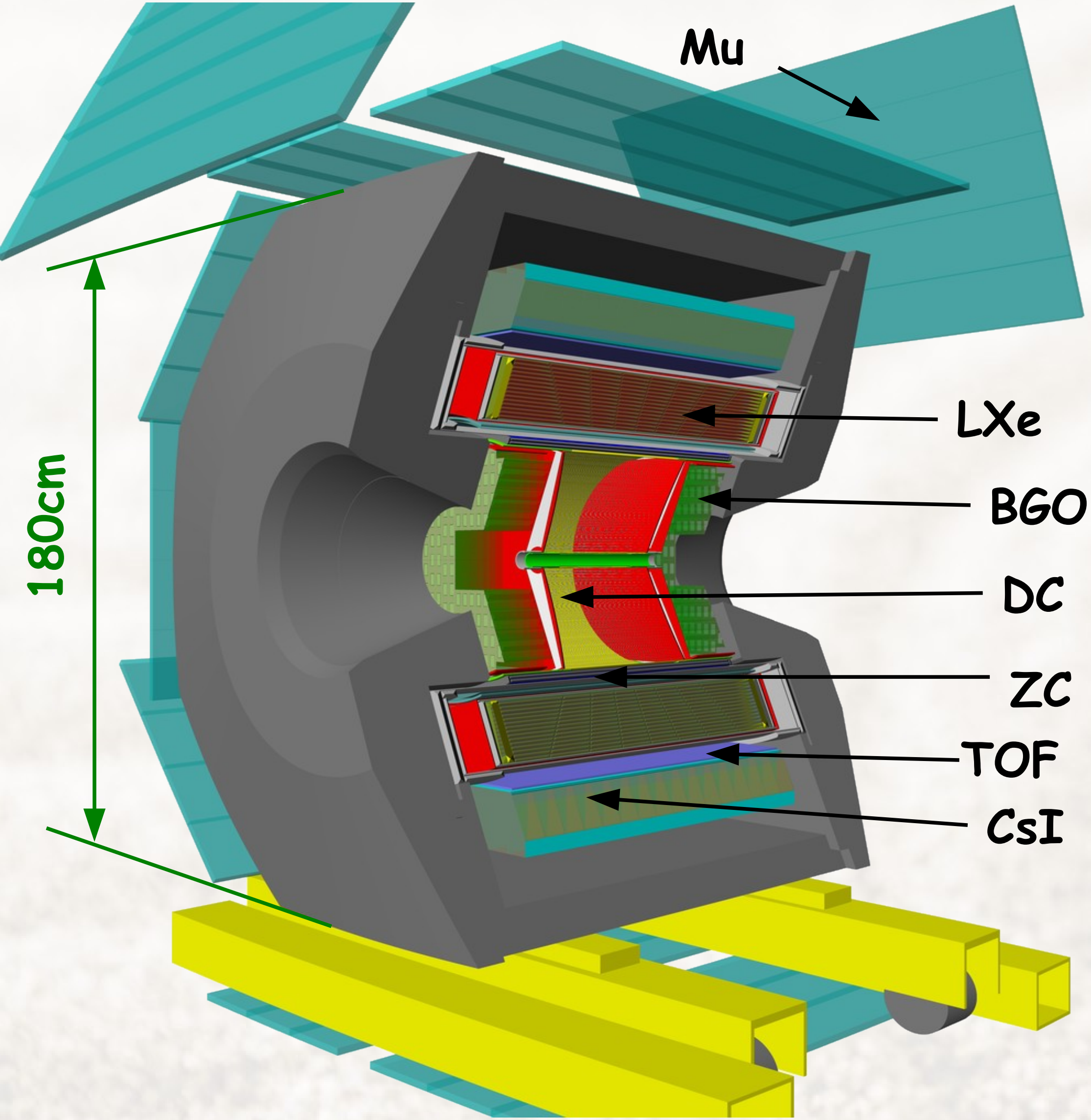
Overview of CMD-3 data taking runs



Three data taking seasons for RHO scans


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)

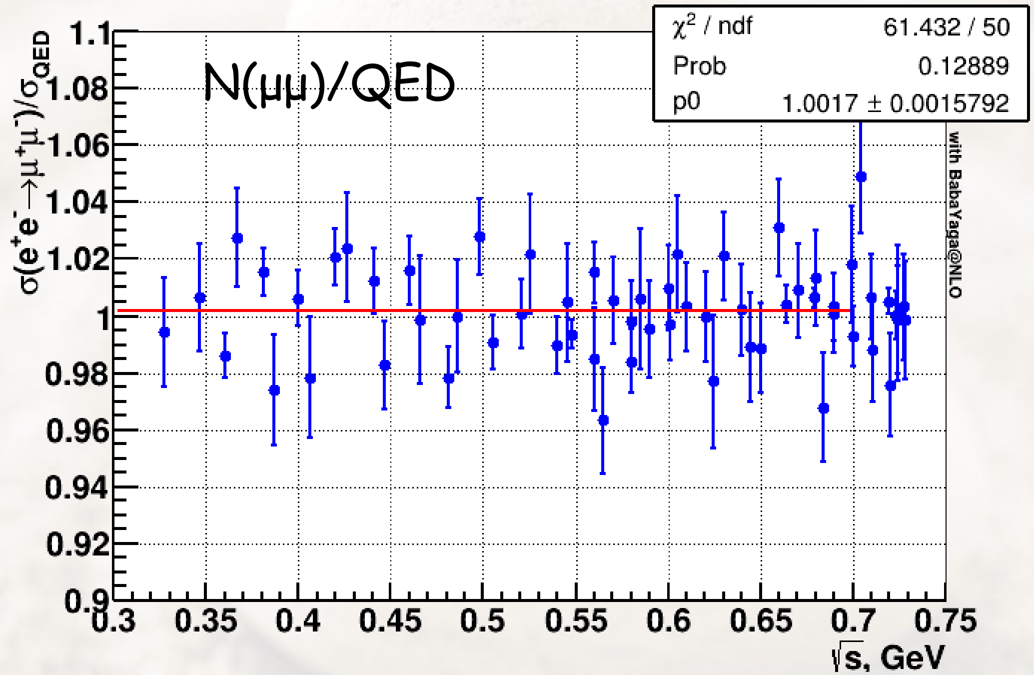
PID:

- ✗ TOF system (σ_T ~ 0.4 nsec)
  - particle id mainly for p, n
- ✗ Muon system

e+e- → μ+μ- cross section

One of consistency checks for e+e- → π+π- is provided by comparison of measured e+e- → μ+μ- cross section vs QED prediction

$N_{\mu\mu}$/QED : $\Delta = +0.17 \pm 0.16$ %



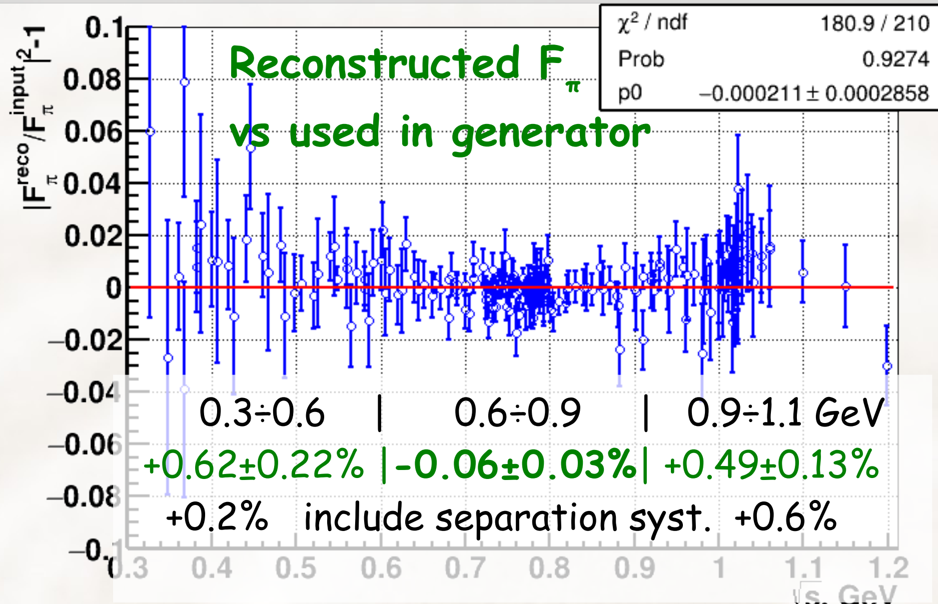
Many others self consistency checks were performed

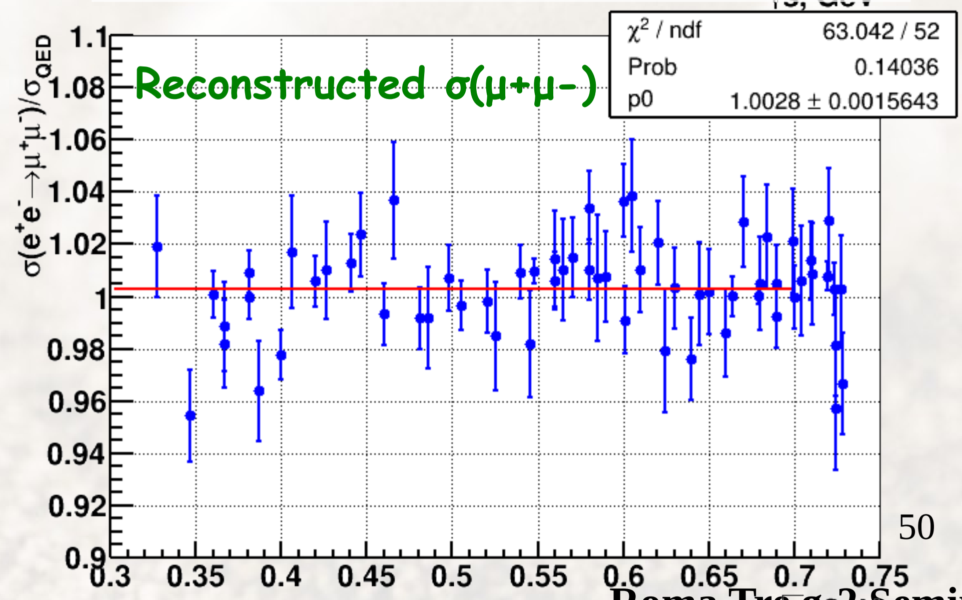
Analysis workflow cross check on MC

<u>Full analysis workflow was checked on mixed full MC data samples</u>
(MC 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





Angle distribution fit

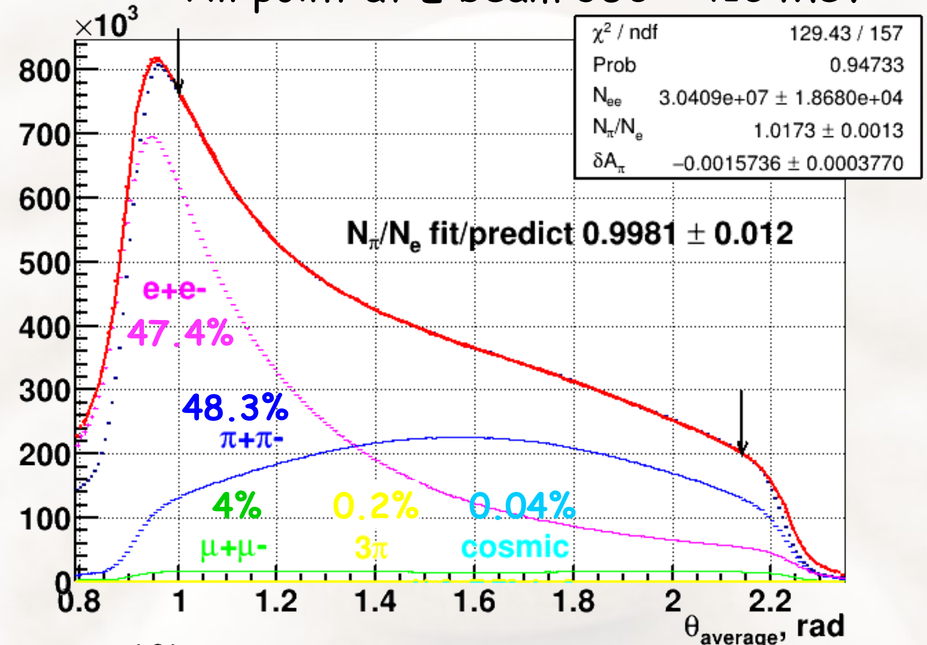
$d\sigma/d\theta$ spectra from MC Generators
+ all efficiencies/smearing effects
extracted from data and full simulation
(cosmic is taken from data itself)

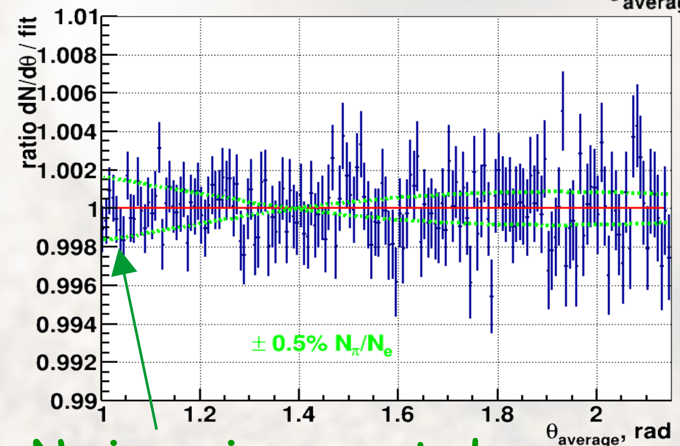
$N_{\mu\mu} / N_{ee}$ - fixed from QED (+efficiencies)
N cosmic, 3π - from momentum based separation
$N_{\pi\pi}/N_{ee}$, δA - free parameters

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





No issue in accounted efficiency at θ = 1 rad

Fit by θ distribution

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 $\pi/2 < \theta^{event} < \pi - 1$)

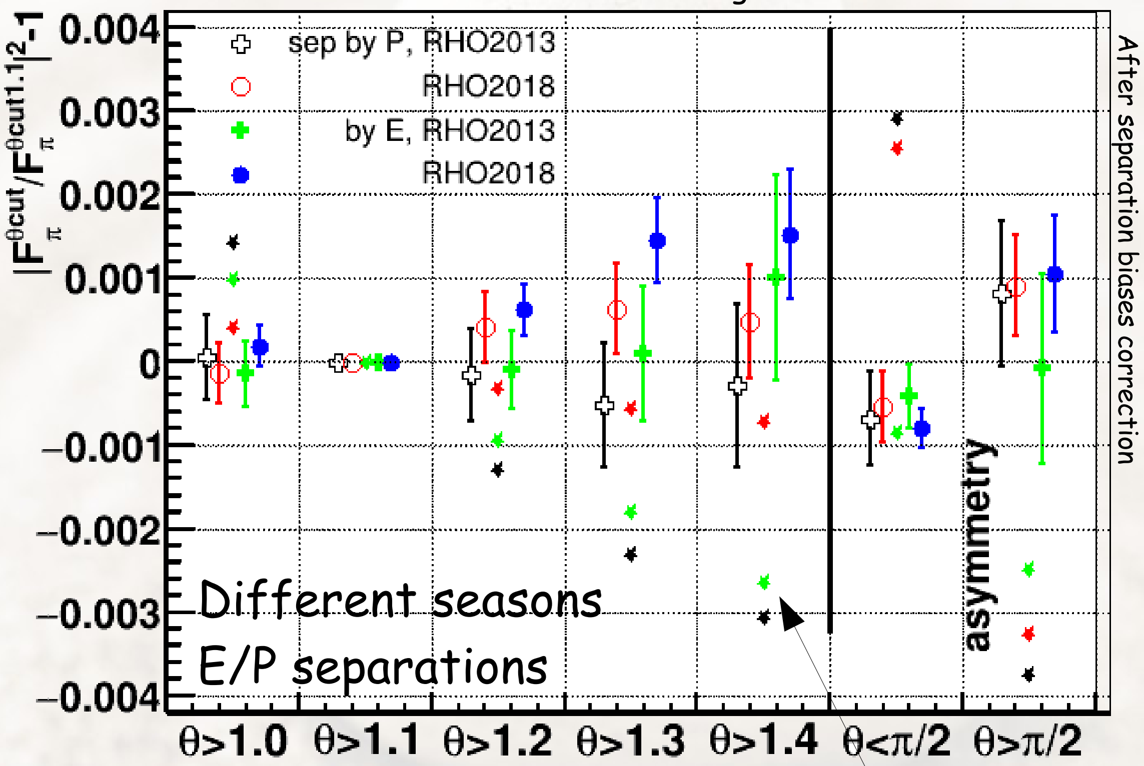
$|F_\pi|^2$ stable at <0.05-0.1% level within different angle selections

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

Simplest possible systematics in θ angle:
- Z – length mis-calibration
- Θ^{event} common bias

if gives 0.5% total in $|F_\pi|^2$ at Θ=1 rad should be seen with ~0.3-0.4% on this plot

Average at 2E= 0.7-0.82 GeV



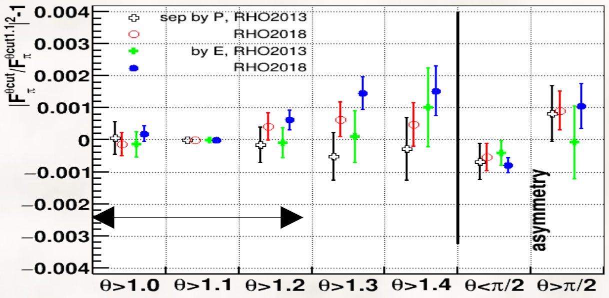
With 0.5% systematic at 1 rad
★Z-length mis-calibration
★θ bias
★θ bias opposite

Detection volume consistency check

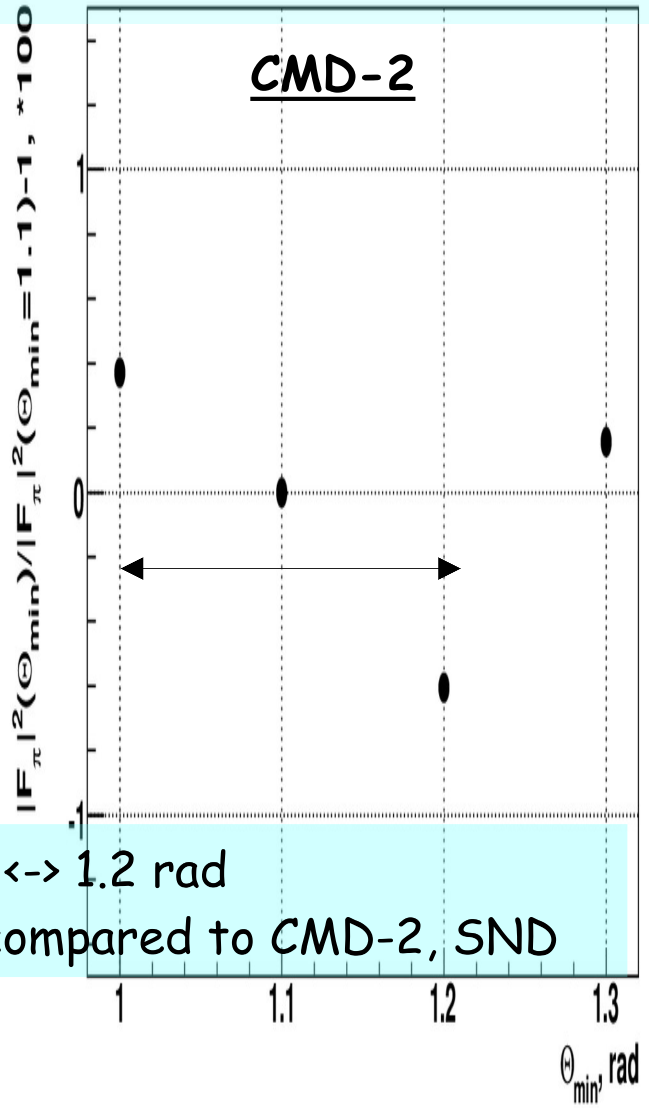
Variation of $\delta|F|^2$ vs θ-angle selection cut ($\theta_{cut} < \theta_{event} < \pi-\theta_{cut}$)

Same scale over Y-axis

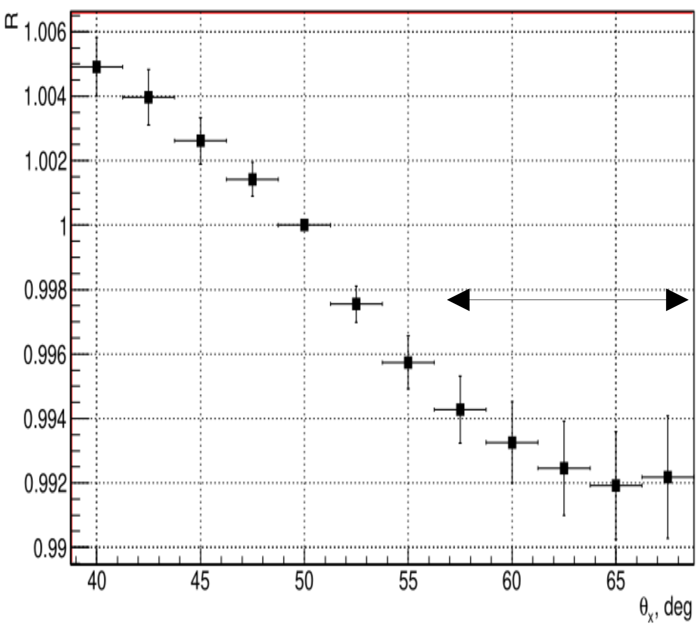
CMD-3



CMD-2



SND@VEPP-2000

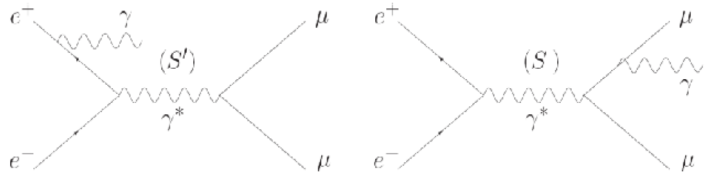


Changes of $\delta|F|^2/|F|^2$ vs θ_{cut} 1 <-> 1.2 rad
~10 times smaller for CMD-3 compared to CMD-2, SND

Асимметрия в BaBar

Subject 1: LO FSR contribution in ”ISR” experiments

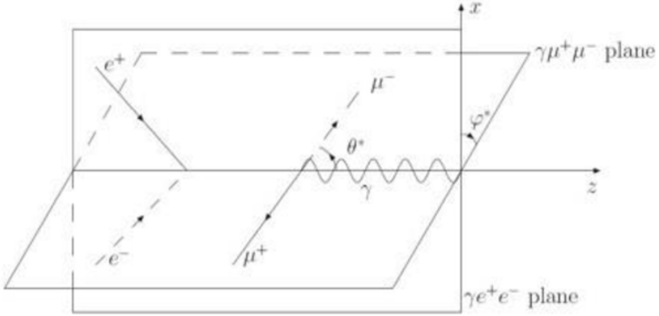
- ISR method used to measure hadronic cross sections: $ee \to X\gamma$ X:QED ($\mu^+\mu^-$) or hadronic final states ($\pi^+\pi^-$)
- but radiation can be from initial state (LO ISR) or final state (LO FSR)



- 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)

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

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



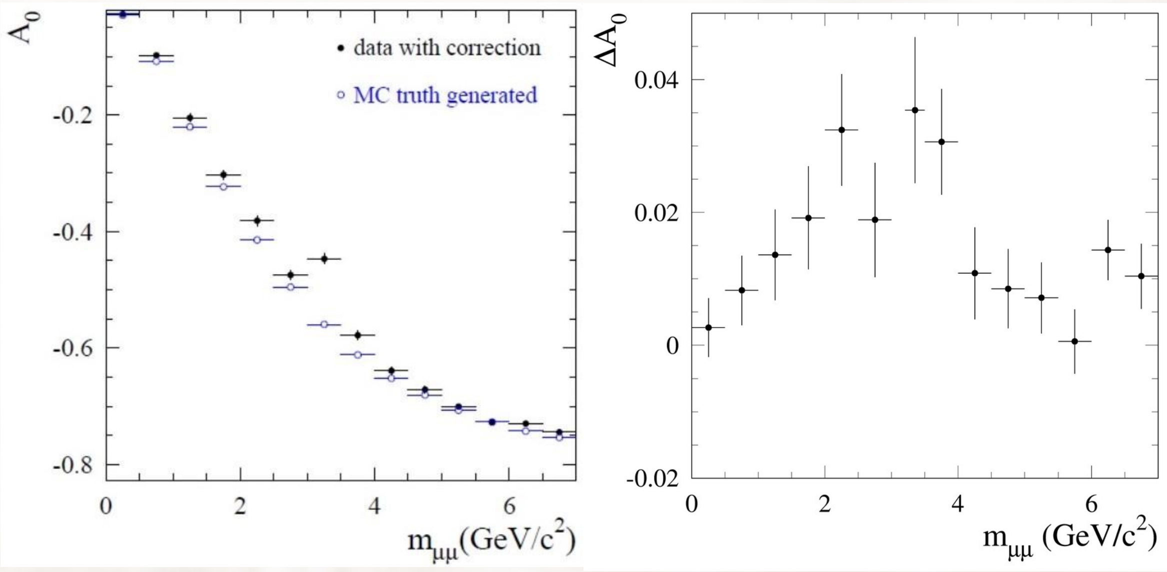
(b) In the x^+x^- c.m.

Asymmetry in BaBar

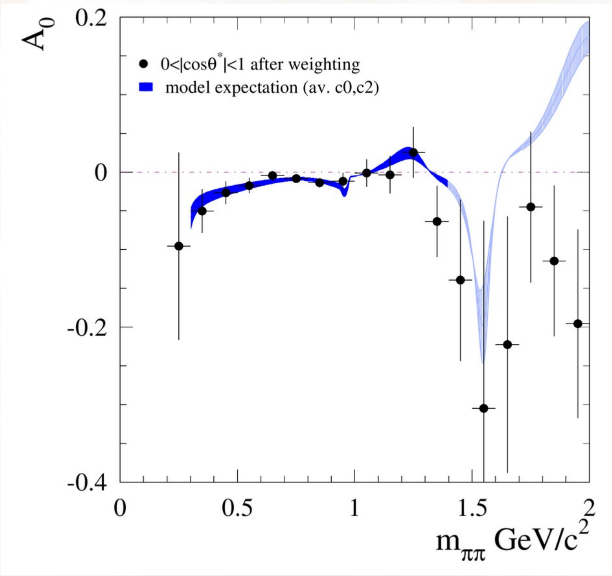
Phys.Rev.D 92 (2015) 7, 072015
e-Print: 1508.04008 [hep-ex]

Slope of the charge asymmetry A_0

BABAR μμγ



BABAR ππγ



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/ψ → μμ;
A_0 (J/ψ) = (1.3 ± 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

Asymmetry in KLOE

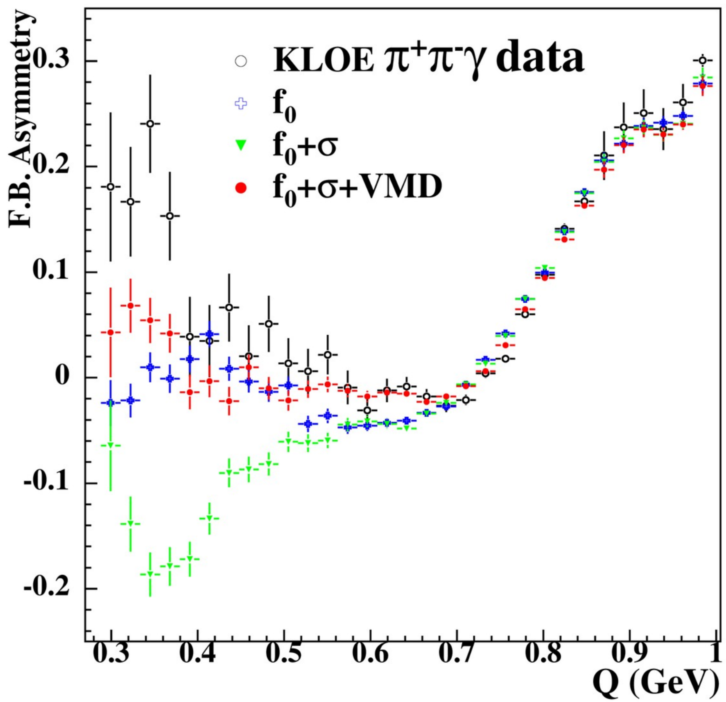
$$A = \frac{N(\theta_{\pi^+} > 90^\circ) - N(\theta_{\pi^+} < 90^\circ)}{N(\theta_{\pi^+} > 90^\circ) + N(\theta_{\pi^+} < 90^\circ)}$$

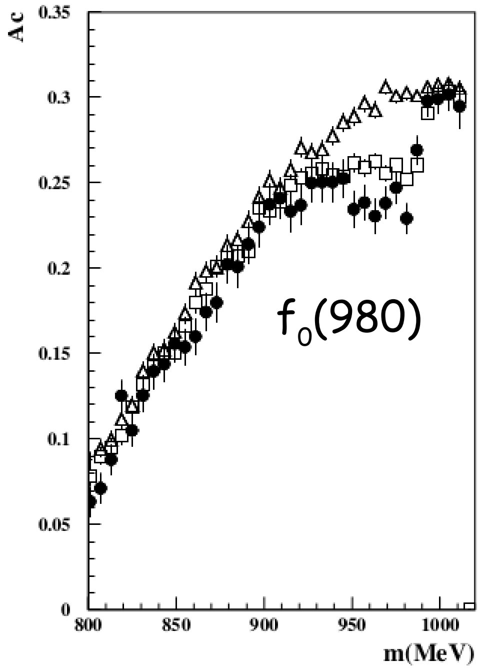
$\theta_\pi, \theta_\gamma > 45^\circ$

At φ- peak

F. Ambrosino et al., PLB634 (2006) 148

G. Pancheri, O.Shekhovtsova, G. VenanzoniJETP 106 (2008), 470

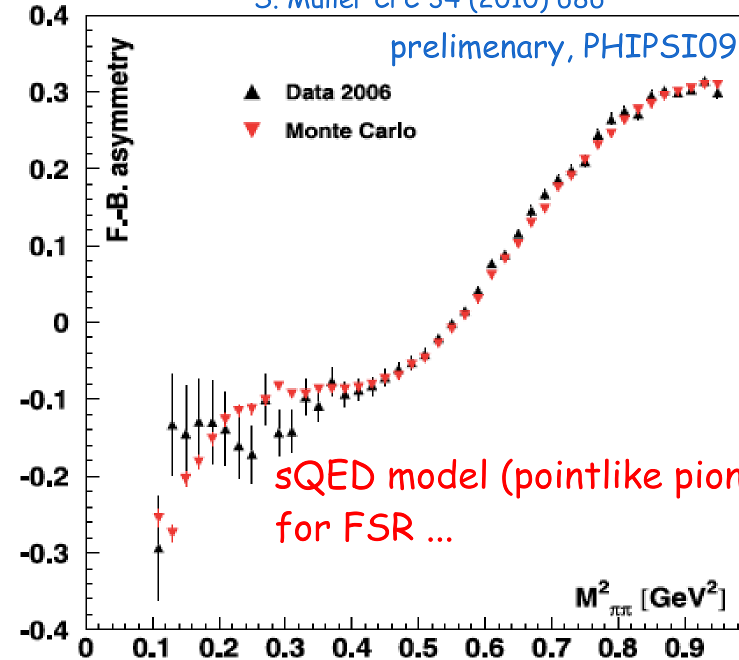




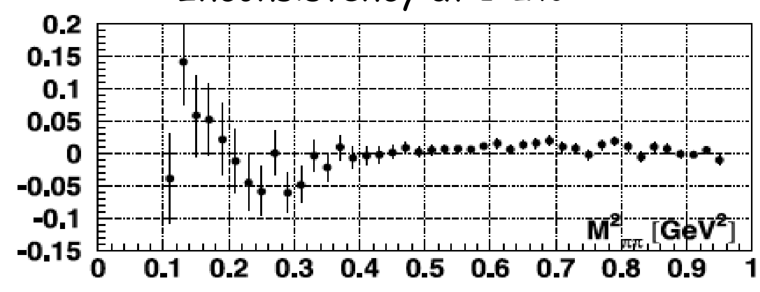
2006 φ off-peak data

P. Beltrame, Ph.D. Thesis (2009)

S. Muller CPC 34 (2010) 686



Inconsistency at 1-2%



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

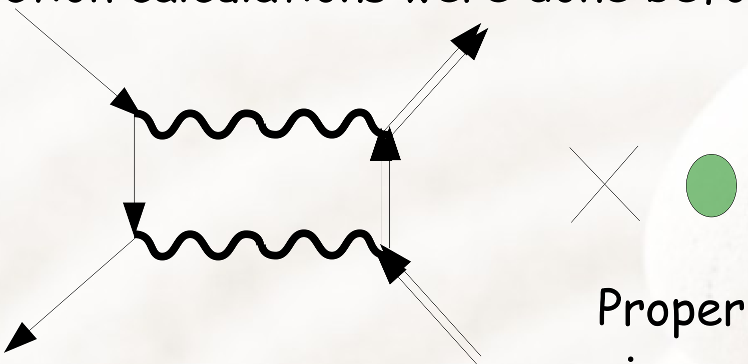
$\varphi \to \rho^\pm\pi^\pm$, $\rho\to\pi\gamma$

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

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

The radiative correction calculations were done before in the sQED approach,

Scalar QED simplification:
Loop integral without
Formfacor in vertices

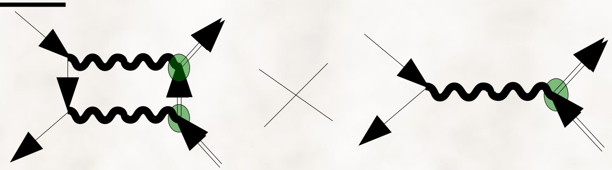


$A = sQED*F(s)$

Proper way $A \sim \int F(q_1)F(q_2)$
gives x10 enhancement

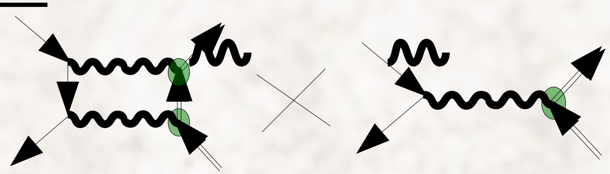
How it can affect pion form factor measurements?
Usually event selections in analyses are charge/angle symmetric

Scan experiment: 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

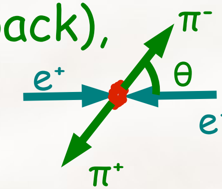
ISR experiment: Interference of ISR & box vs FSR (or v.v.)



=> charge-even
can affect integrated cross-section

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

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%

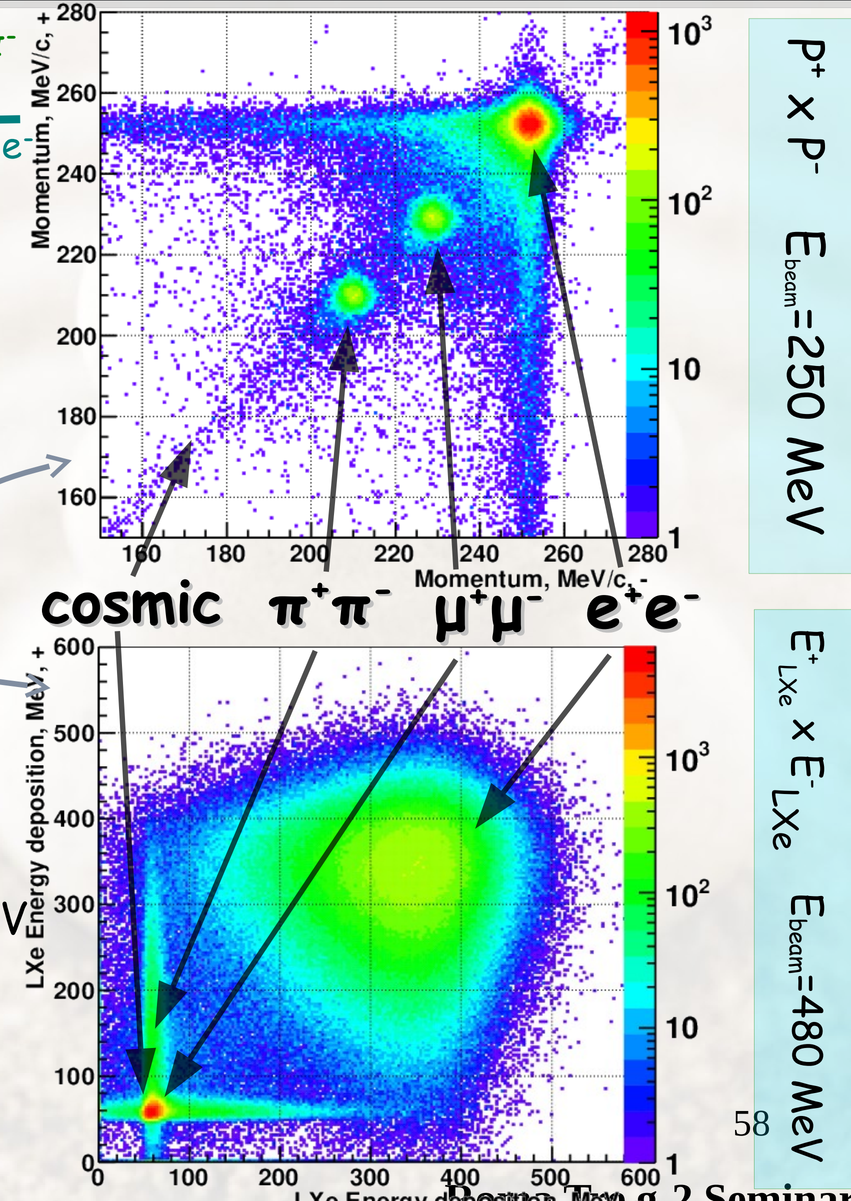
Crucial pieces of analysis:

- ✗ 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



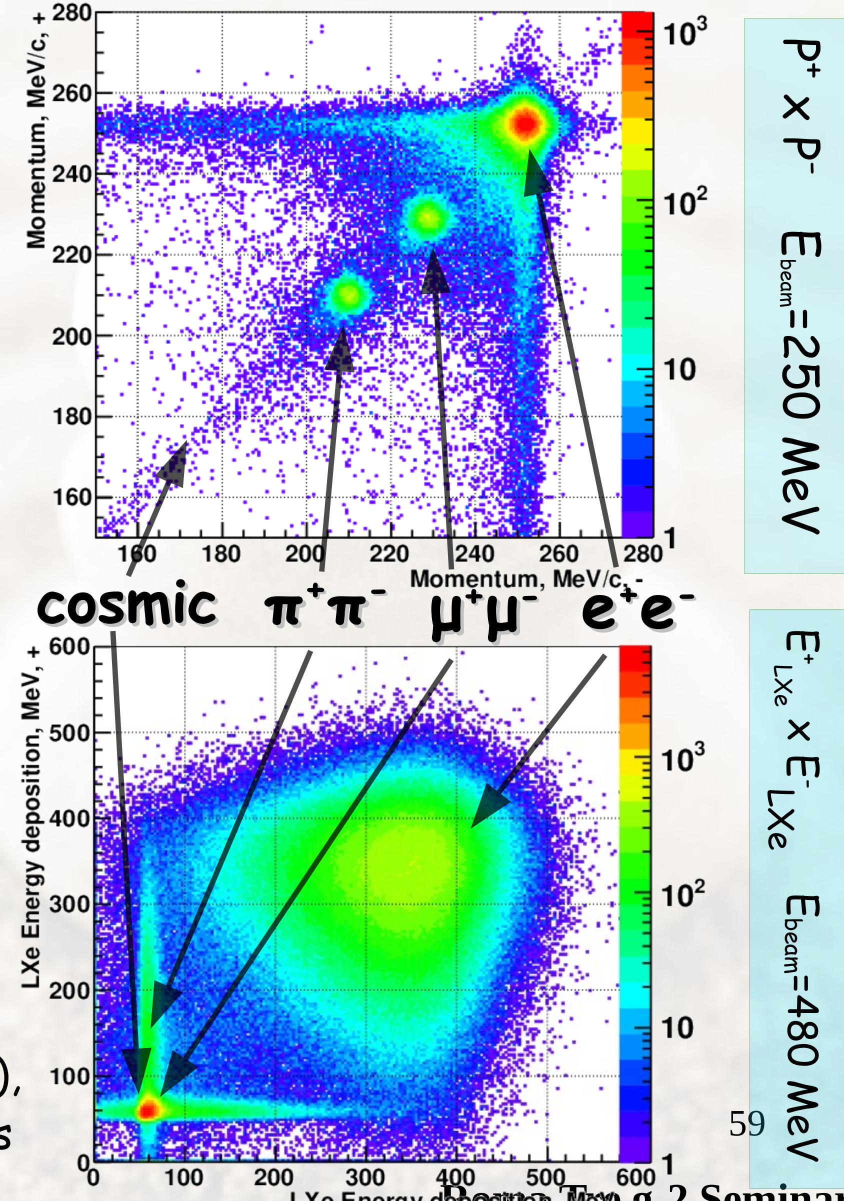
N.B. Higher statistics (x30 to previous CMD-2) gives more sharper view on detector effects, allows much more detail study of systematic contributions.

Event separation

events separation is done either
1) by momentum
2) or by energy deposition

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

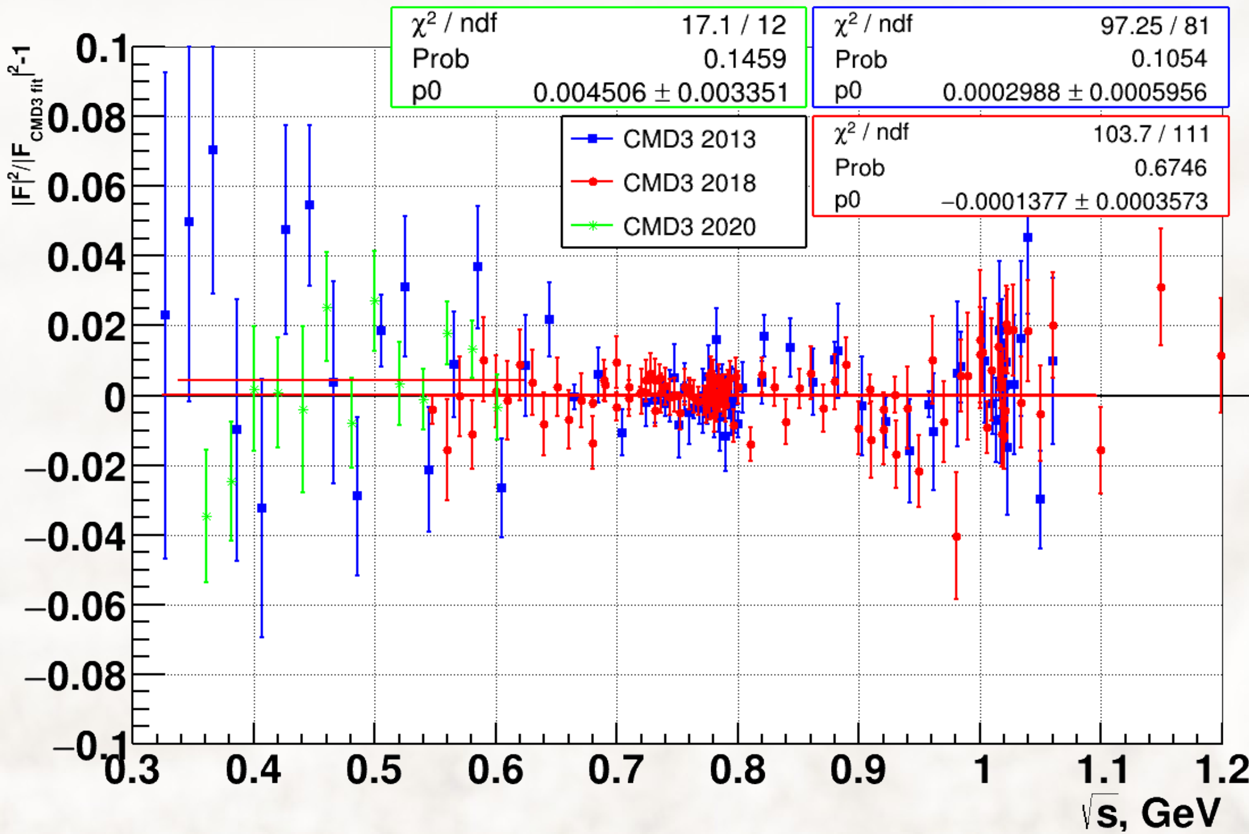
$$-\ln L = -\sum_{events} \ln\left[\sum_i N_i f_i(X^+, X^-)\right] + \sum_i N_i$$



<u>Momentum-based separation:</u>
PDFs are constructed from
MC generator spectra convolved with
detector response function (momentum resolution,
bremsstrahlung, pion decays)

<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

Consistency checks



Result consistent between data taking season within < 0.1%

DCH was in much worse conditions in 2013:

- ✗ 4 middle layers off (HV-related)
- ✗ different correlated noise
- ✗ etc….

~x2 difference in some corrections

Good check of angle/tracking related systematics

Total θ-related systematic uncertainty was estimated 0.5%(RHO2018)
0.8%(RHO2013)

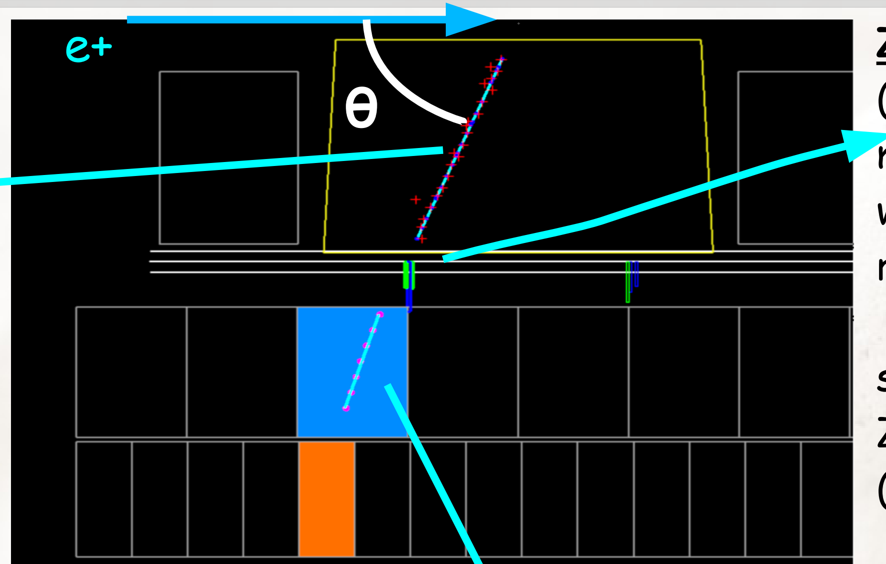
$|F_\pi|^2$ RHO2018/RHO2013 Δ = -0.04 ± 0.07 %

LOW2020/RHO2013 Δ = -0.5 ± 0.6 %

Consistency between seasons can hint that RHO2013 systematic uncertainty should be as good as for RHO2018

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)



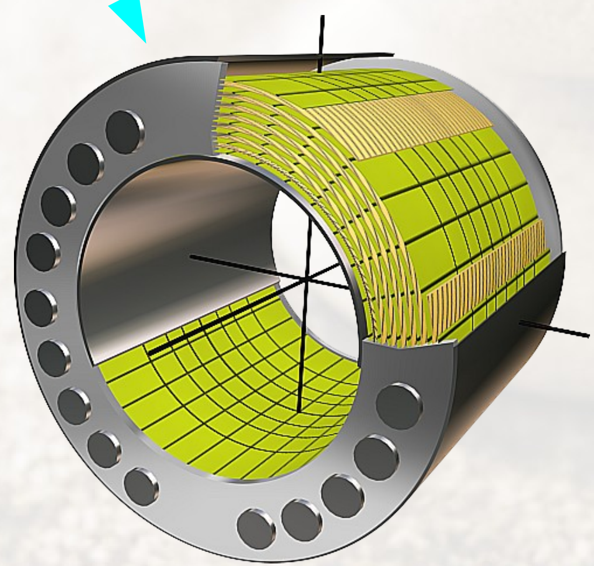
ZC chamber
(was in operation until mid 2017)
multiwire chamber
with 2 layers and with strip readout along Z coordinate

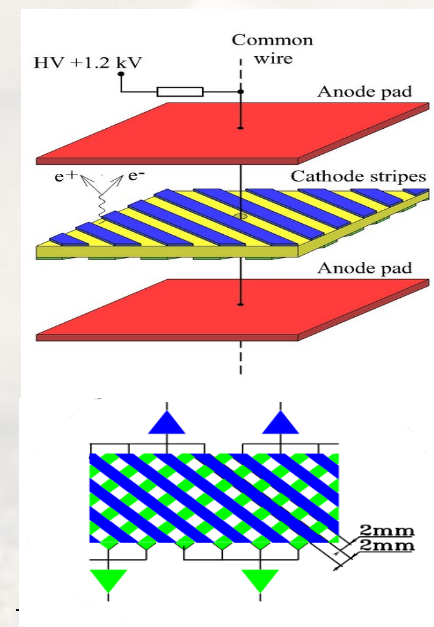
strip size: 6mm
Z coordinate resolution ~ 0.7 mm
(for θ_{track} ~ 1 rad)

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

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

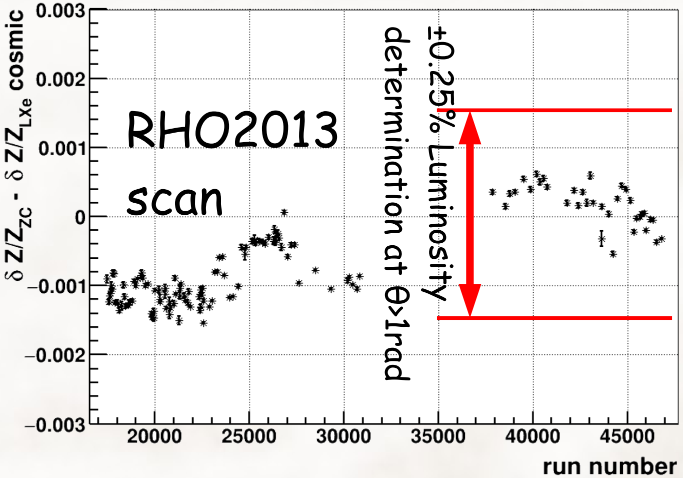
strip precision, coordinate biases ~ 100 μm should give ~0.1% in Luminosity determination
Can be spoiled by noise environment





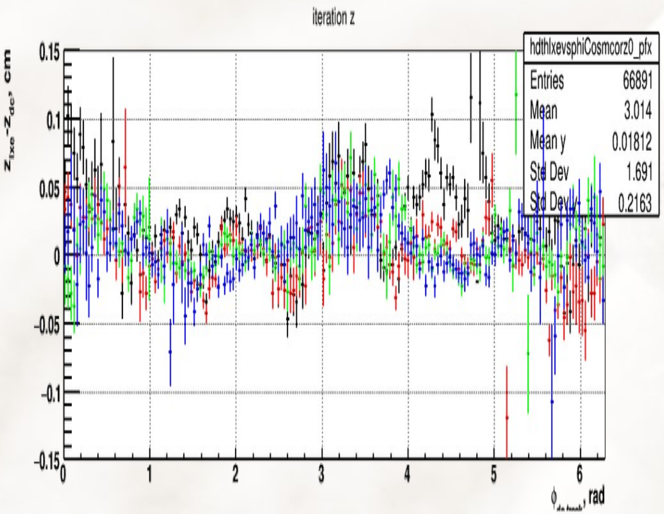
Precision of fiducial volume

Monitoring of z-measurement between ZC vs LXe



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

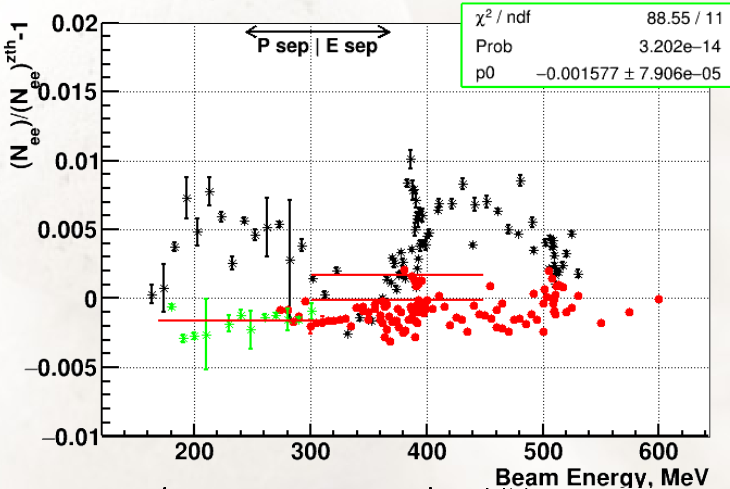
DC tracks vs LXe points



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
During RHO2013: 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

Systematic uncertainty to $|F_\pi|^2$

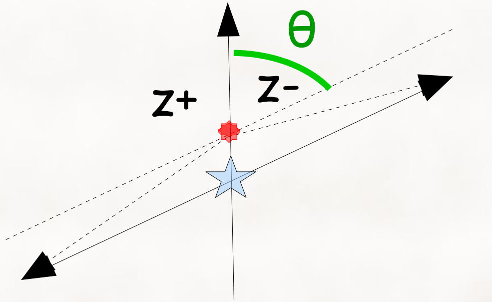
ZC/LXe comparison — LXe/ DC comparison — Inner DC radius effect:

0.25% ⊕ 0.3% ⊕ 0.7%(RHO2013)/0.3%(RHO2018)

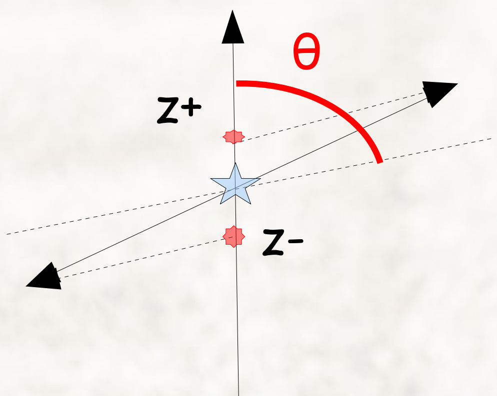
= 0.8% (RHO2013) / 0.5%(RHO2018)

DCH's Inner radius effect on polar angle

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



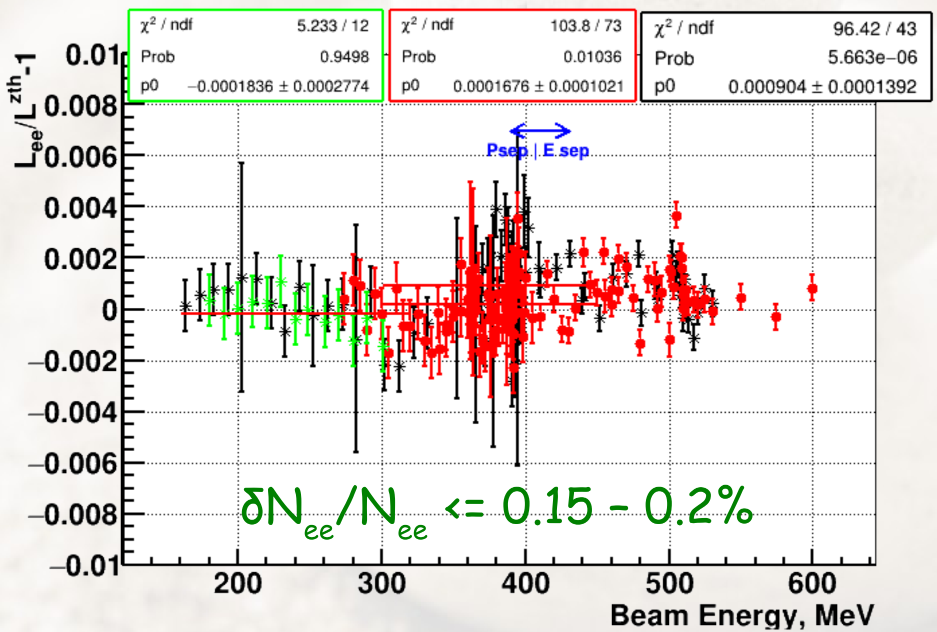
common Z vertex bias of +/- tracks doesn't give bias to θ^{event}



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

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

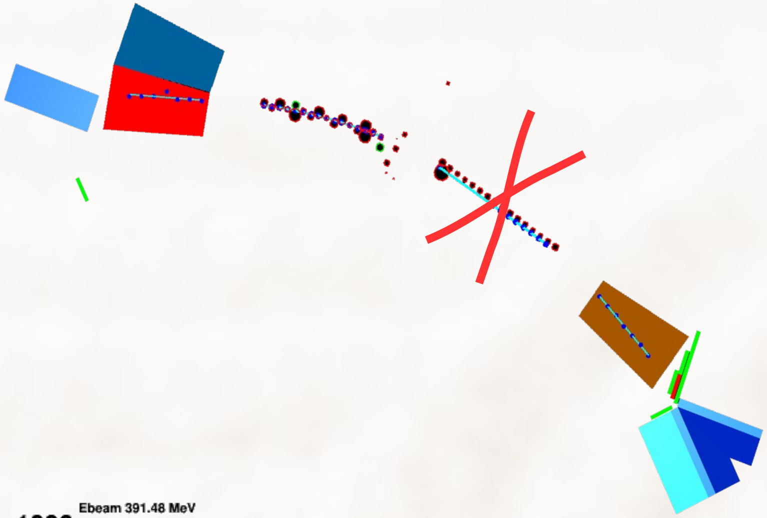
ΔZ correction can be applied for vertex unconstrained case, + additional vs LXe monitoring on the same collinear events sample

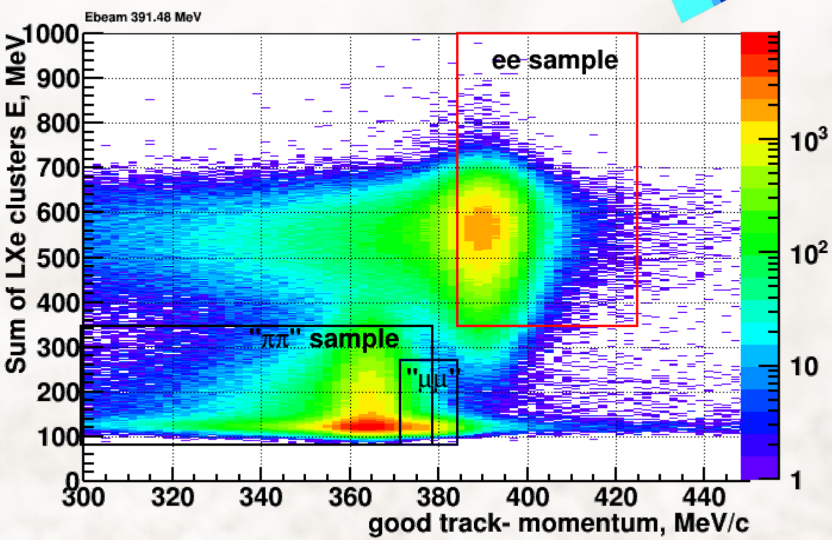


Comparison of Constrain/unconstrained θ-angle after ΔZ, + vs LXe corrections

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

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)

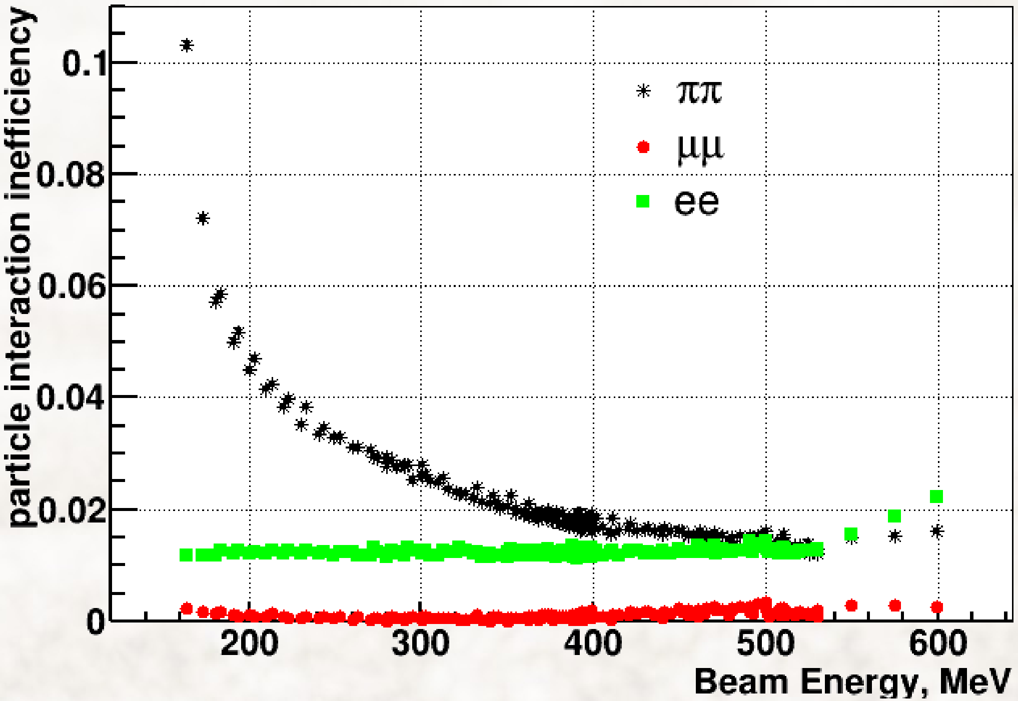
N.B. Correlated inefficiency study was also performed without requirement on detection of one good track

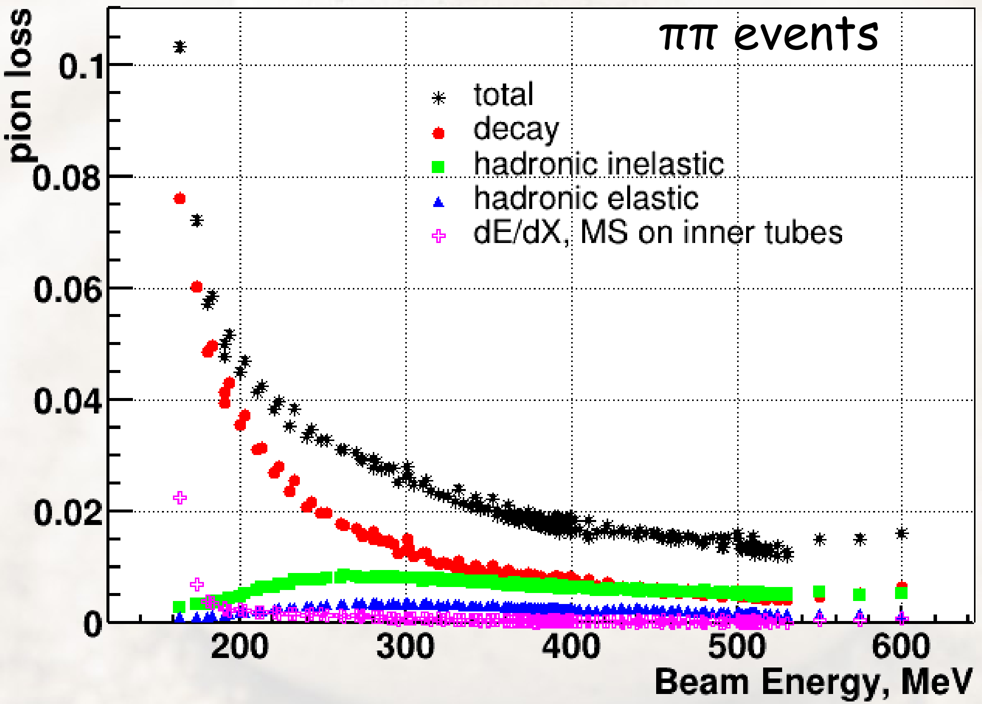
Particle specific losses

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



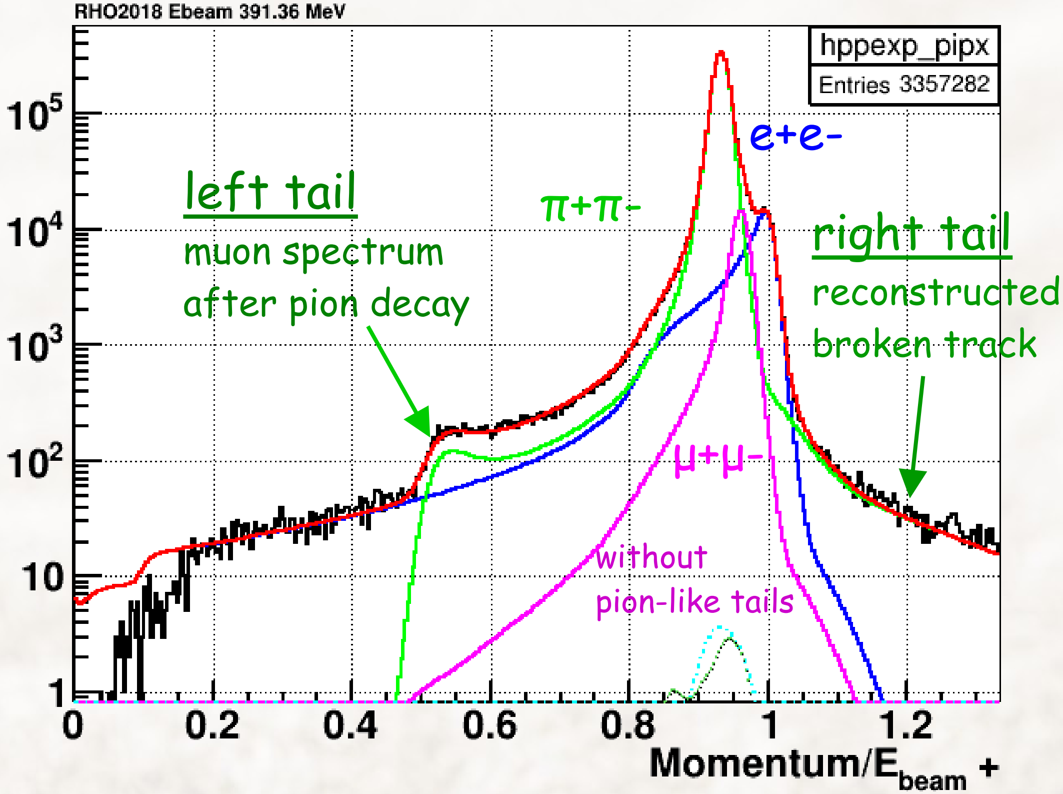


nucler interactions mostly on inner tube (systematics 0.2%)

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

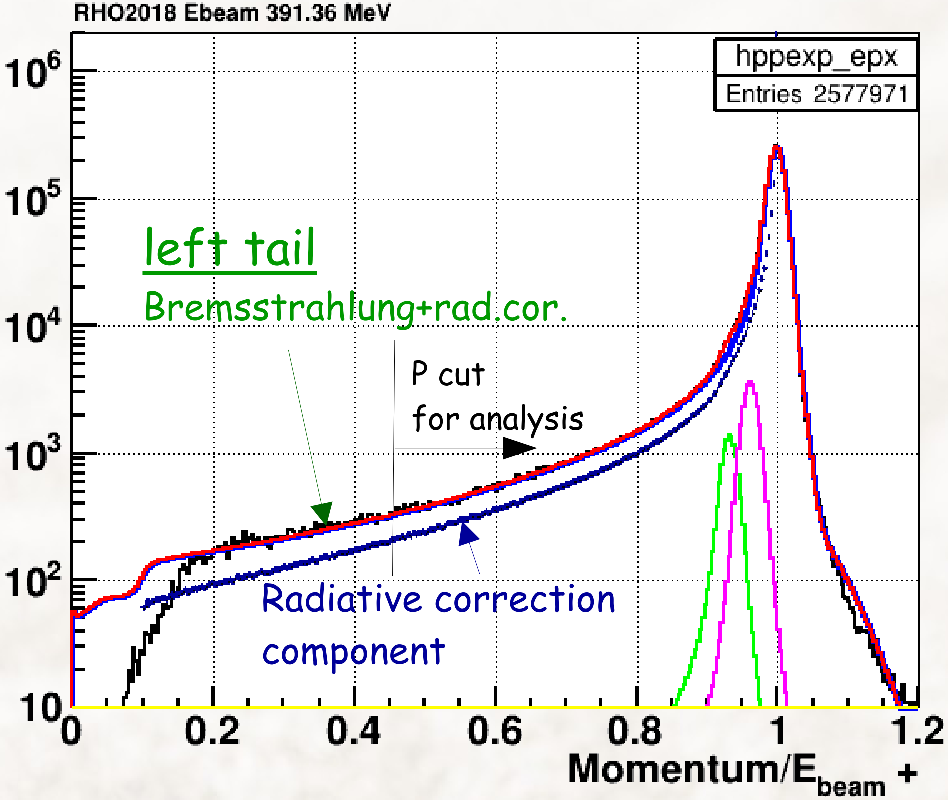
Tails function taken from full MC
(include DCH inefficiencies, resolutions,
amplitudes, correlated noises per layers, etc..)
Number of events in tails are free parameters
in momentum-based separation

$N^{event}_{in\ tails}$ 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)

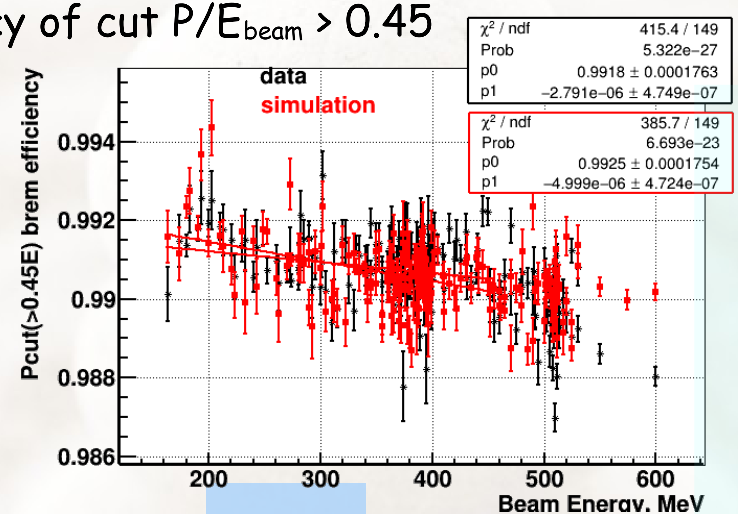
Additional crosscheck with «weak» cuts:
Nhits >= 10 → 8, χ2 < 10 → 20, |Δρ| < 0.3 → 0.6 cm
pion decay inefficiency changes by x1./(2.-2.5)
→ $\Delta|F|^2/|F|^2 < 0.05\%$

Bremsshtrahlung loss on vacuum tube

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

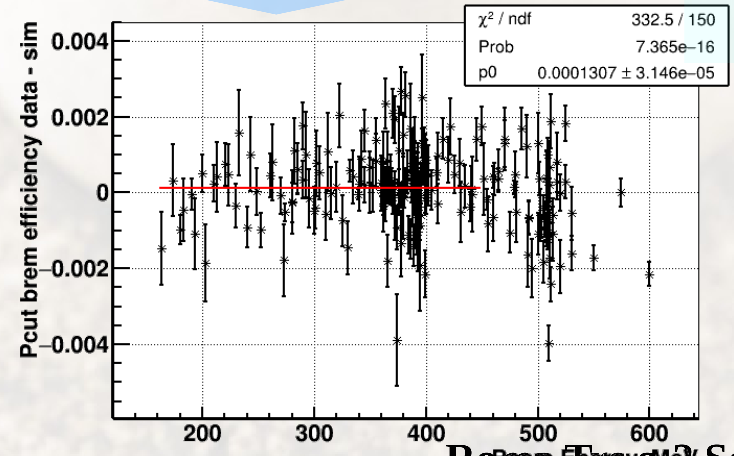


Part of brems. correction (0.9% from 1.2%) can be extracted from fitted spectra: inefficiency of cut $P/E_{beam} > 0.45$



MCGPJ vs BabaYaga spectra gives difference <0.015%

The data vs sim agree ~ 0.02%

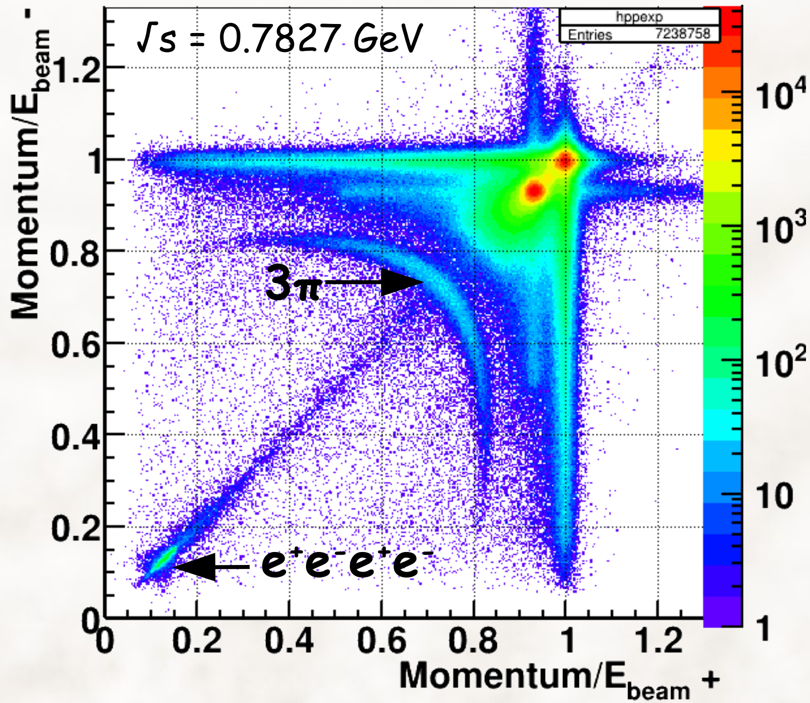


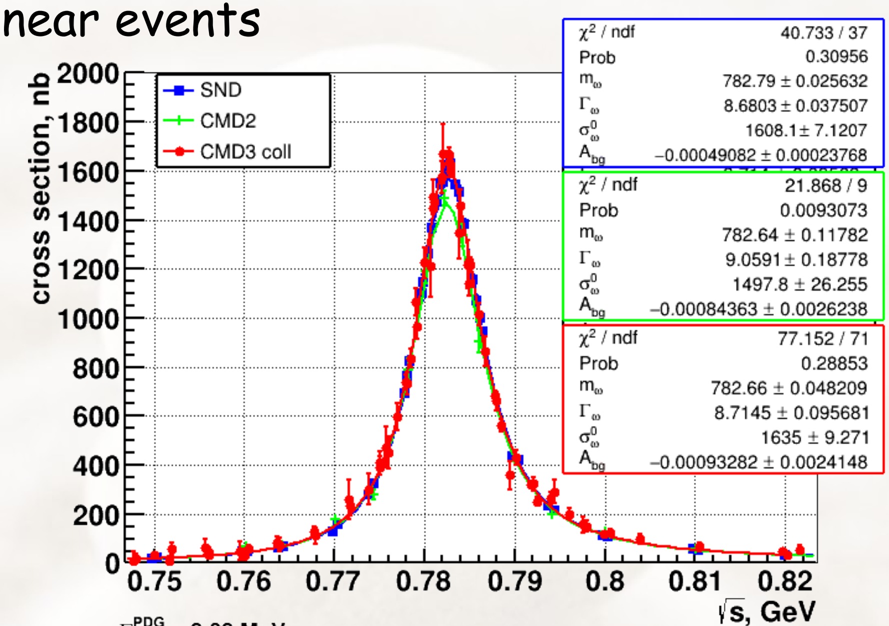
Brems. description is part of detector response function in momentum-based separation (with X/X0 as free param.)
X/X0 of inner wall consistent with sim. within <5%
→ Systematics on $|F_\pi|^2$ ~ 0.05%

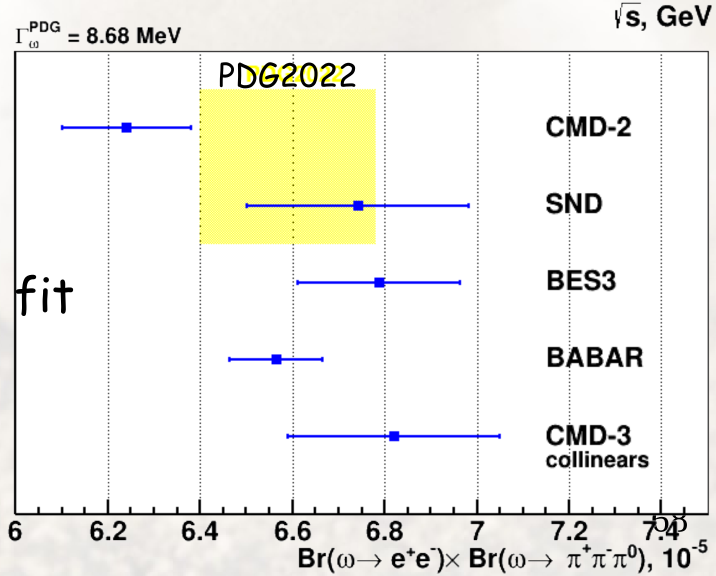
$e^+e^- \rightarrow \pi^+\pi^-\pi^0$

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

Collinear events are selected for 2π analysis







$e^+e^- \rightarrow \pi^+\pi^-\pi^0$ 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%**

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

confirm SND@VEPP-2M result

Form Factor evaluation

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

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

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

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

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 $\pi^+\pi^-$ / e^+e^- (common cancelled out)

$|F_\pi|^2$ 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)

Possible concerns in the analysis related to MC tools:

- ✗ Radiative corrections for the $\pi+\pi-$ total cross section
  - ✗ MCGPJ were used by several previous experiments, the cross-check with a new generator will be very valuable
- ✗ Differential cross section over momentum for the particle separation
  - ✔ E/P separations, $\sigma(e^+e^- \to \mu^+\mu^-)$/QED are consistent
- ✗ Differential cross section over polar angle for controlling of systematic uncertainty of the fiducial volume determination
  - ✔ quite remarkable consistency of data (asymmetry, θ – angle distribution, $|F_\pi|^2$ in different cuts) vs prediction

Progress in MC tools can help to give more confidence, or can help to highlight some detector related effects in the obtained CMD-3 result

R(s) in dispersion relations ($a\mu^{had}$, etc)

The current method based on e+/e- low energy data combines many heterogeneous data samples:
It includes ~48 different detectors , ~50 channels,
which gives ~305 datasets.
Very delicate procedure to combine them together

Some of data are disregarded by new experimental results.
It raise specific issues in the estimation of the systematic errors, correlation between datasets, etc...

Other complementary way will be very desirable...

Hall of Fame:
ACO ADONE ALEPH
AMY ARGUS BABAR
BBar BCF BELLE BES
BES3 BIG CBALL
CELLO CLEO CMD
CMD2 CMD3 CUSB
DASP DHHM DM1
DM2 FENICE GG2
JADE KEDR KLOE
LENA M3N MARK1
MARK2 MARKJ MD1
MEA MUPI NA007
ND OLYA PLUTO
SND SND2k SPEAR
TASSO TOF TOPAZ
VENUS VEPP2

KLOE 2pi activities

- New effort to analyse high statistics KLOE 2004/05 data not yet analysed (L~1.7 fb-1)
- New blind analysis, unbiased from previous results of KLOE & other experiments
- Significant involvement from theoretical groups

  => improvement of MC(s) to describe ISR and FSR events (PHOKHARA,…)
- Goal: 0.4% accuracy (a factor x2 syst, x3 stat improvement)
- Challenges and opportunities to get a clearer understanding of the puzzles
- The Liverpool + externals team:
  - Leverhulme International Professorship: G. Venanzoni
    F. Ignatov, P. Beltrame, E. Zaid, A. Kumari, N. Vestergaard, C. Devanne
  - Theory efforts: T. Teubner; W. Torres Bobadilla, J. Paltrinieri; T. Dave, P. Petit Rosas
    + contributors from the wider Theoretical Physics groups
  - External collaborators: A. Kupsc, S. Müller, L. Punzi, O. Shekhovstova,
    A. Keshavarzi, W. Wislicki, A. Lusiani, J. Wiechnik

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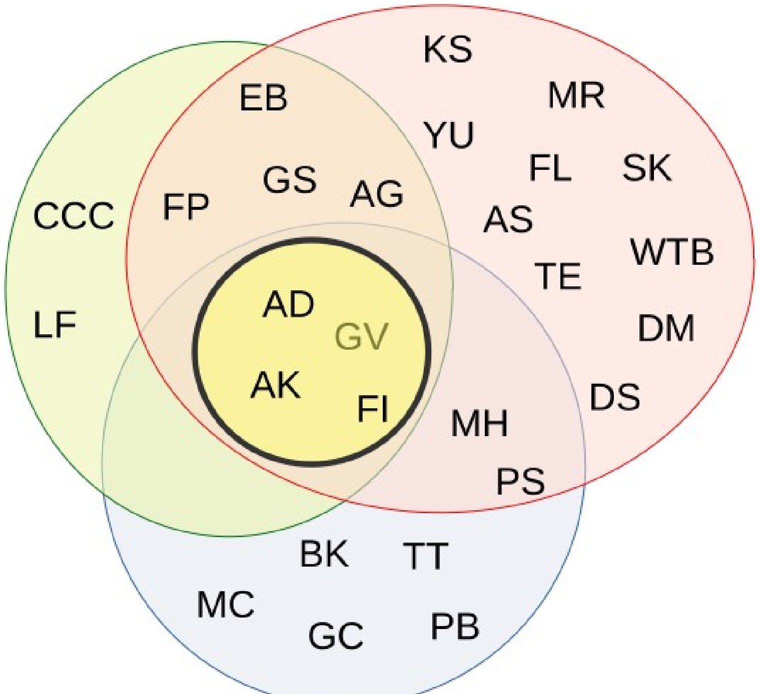
Universität Zürich

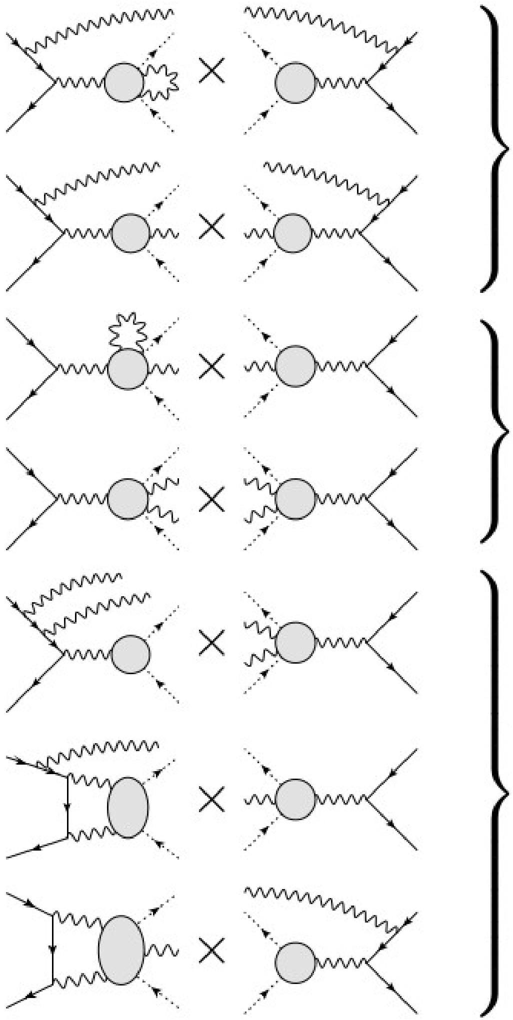
5th WorkStop

Team: P. Beltrame, E. Budassi, C. Carloni Calame, G. Colangelo, M. Cottini, A. Driutti, T. Engel, L. Flower, A. Gurgone, M. Hoferichter, F. Ignatov, S. Kollatzsch, B. Kubis, A. Kupsc, F. Lange, D. Moreno, F. Piccinini, M. Rocco, K. Schönwald, A. Signer, G. Stagnitto, D. Stöckinger, P. Stoffer, T. Teubner, W. Torres Bobadilla, Y. Ulrich, G. Venanzoni

WP1:	QED for leptons at NNLO
WP2:	Form factor contributions at N^3LO
WP3:	Processes with hadrons
WP4:	Parton showers
WP5:	Experimental input



ISR experiments: NLO (omitting pure QED corrections to LO)



PHOKHARA: sQED + resonance approximations
dispersive approach by Colangelo et al.

contained in PHOKHARA
pure FSR: sufficiently suppressed by experimental cuts?

???
PHOKHARA: sQED, multiplied by form factors *outside* loop
ISR–FSR interference
potential red flag identified during WorkStop

Charge-even correction, enhanced by Formfactor at above sQED: can affect normalization for F(s) extraction in the ISR approach

MC generators e+e- → e+e-

Several MC generators available with 0.1-0.5% precision.
Most recent e+e- -> e+e- (gamma) generators
include exact NLO + Higher Order terms in some approximation:

0.1%
e+e-, μ+μ-

BabaYaga@NLO (KLOE,BaBar, BESIII)
Parton shower approach: n photons with angle distribution,
interference for 1 photon radiation

Accuracy 0.2%
e+e-, μ+μ-, π+π-, etc

MCGPJ (VEPP-2000)
1 real photon (from any particle)
+ photon jets along all particles (collinear Structure function)
v2: + jets angle distributions

0.5% (~0.1%?)
e+e-

BHWIDE (LEP)
n real photons by Yennie-Frautschi-Suura (YFS) exponentiation method
interference on O(α) level

<0.1%
e+e-, etc

McMule
Fixed order NNLO

under development
e+e-, μ+μ- , ZH, ...

ReneSANCe (from Dubna)
NLO + leading log corrections for ISR

And there are other generators for μ+μ-:
PHOKHARA (KLOE) μ+μ-, π+π- etc , KKMC (μ+μ-), etc

MC generators e+e- → π+π- (γ)

Most precise 2π MC generators:

quoted accuracy 0.5% for differential cross section

PHOKHARA

developed for ISR process with 1 real photon + addition
Complete set of NLO to e+e- → π+π-γ:
most recent 10.0 version includes NNLO FSR,
and 1real + two virtual photon box diagram in sQED approx.
FSR from the pointlike pion (some models with intermediate f0,σ are possible)

No logarithmically enhanced corrections, no 0-photon soft part
has limited precision for scanned mode (w/o γ)

ISR

accuracy 0.2% for total cross section

MCGPJ

exact NLO (to e+e- → π+π-) + logarithmically enhanced correction
using ISR jets along beam with collinear structure functions
box diagram with above sQED approach (GVMD or dispersive)
FSR from the pointlike pion

No some of virtual, soft corrections for e+e- → π+π-γ
Not designed to be used for ISR studies

Scan mode

Both generators has different region of applicability

Radiative corrections

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

Two high precision MC generators were used

MCGPJ(0.2%, e+e-,μ+μ-,π+π-) vs BabaYaga@NLO (0.1%, e+e-,μ+μ-)

by Novosibirsk | by Pavia

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) : most generators have an issue at threshold (except only MCGPJ)

(Mass term in FSR is missed - effect 0.4% at √s=0.32 GeV)

e+e- → π+π-(γ) : only MCGPJ is available with 0.2% precision

(for energy scan experiments)

Major inconsistencies between generators are seen

in the differential cross sections predictions.

In CMD-3 analysis the differential spectra are used in:

e/π separation by momentum requires $d\sigma/dP^{+}dP^{-}$ spectra as initial input

Θ-angle (asymmetry) study requires $d\sigma/d\theta$ spectra

ππ radiative corrections

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

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

Possible future progress in MC tools towards NNLO precision can help with:

- Radiative corrections for the $\pi^+\pi^-$ total cross section
- Differential cross sections over momentum, angles for the $e^+e^- \to \pi^+\pi^-$, e^+e^-, $\mu^+\mu^-$ processes

Improvement in this field can give more confidence, or can highlight some detector related effects in the obtained CMD-3 result

The radiative correction table used in the analysis is part of the arXiv submission, It will be useful for cross-checks them if new generators will be appeared.