Measurement of hadronic cross-sections at low energy e+e- colliders

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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 ~ 10^{28}cm^{-2}s^{-1}

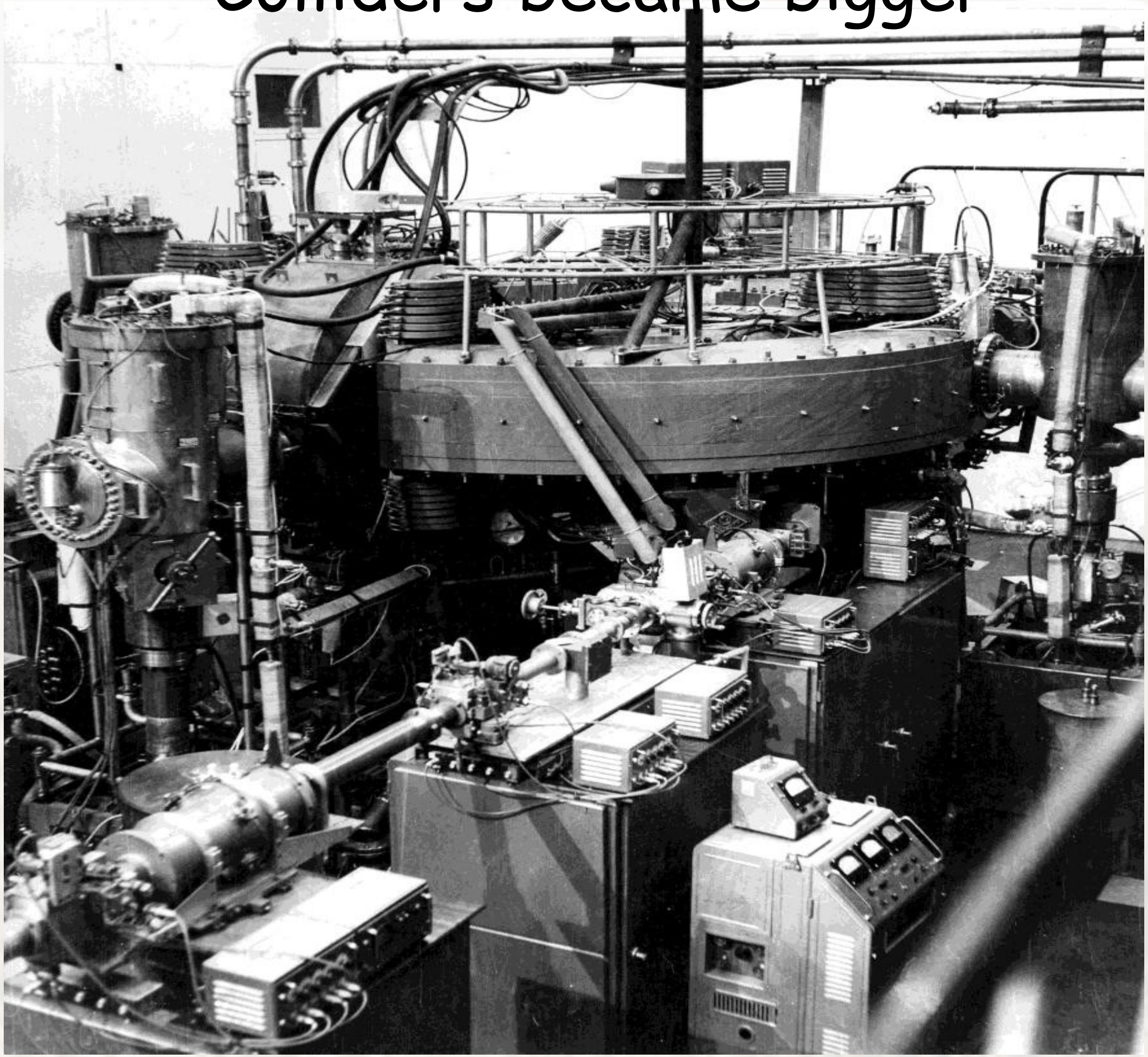
AdA, VEP-1

AdA
1961-1964

VEP-1
1964 - 1968

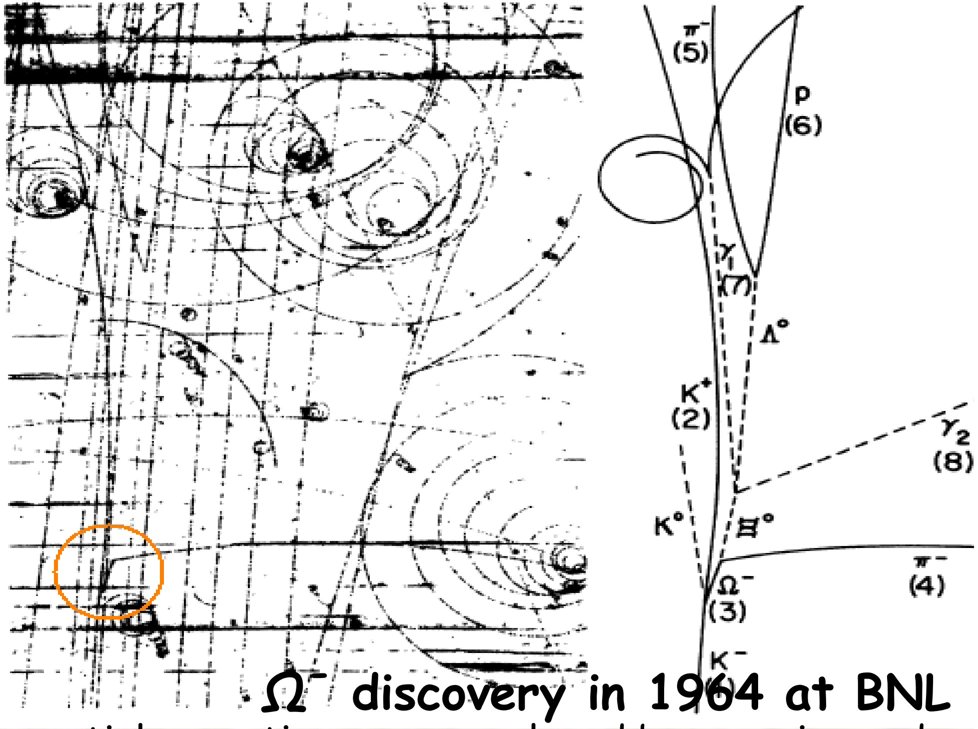
e+ e- collider VEPP-2 (1966-1970)

Colliders became bigger



Before colliders – fixed target experiments

Pions(etc) was produced by proton beams
Detection by
the wilson chamber(supersaturated vapor),
Scintillation crystals as counter
The bubble chambers(superheated liquid)



Ω^- discovery in 1964 at BNL

particle reactions were analyzed by scanning and measuring photographs, done by both skillful assistants and machines

<u>1952 – Discovery of resonances (Δ - baryon)</u>

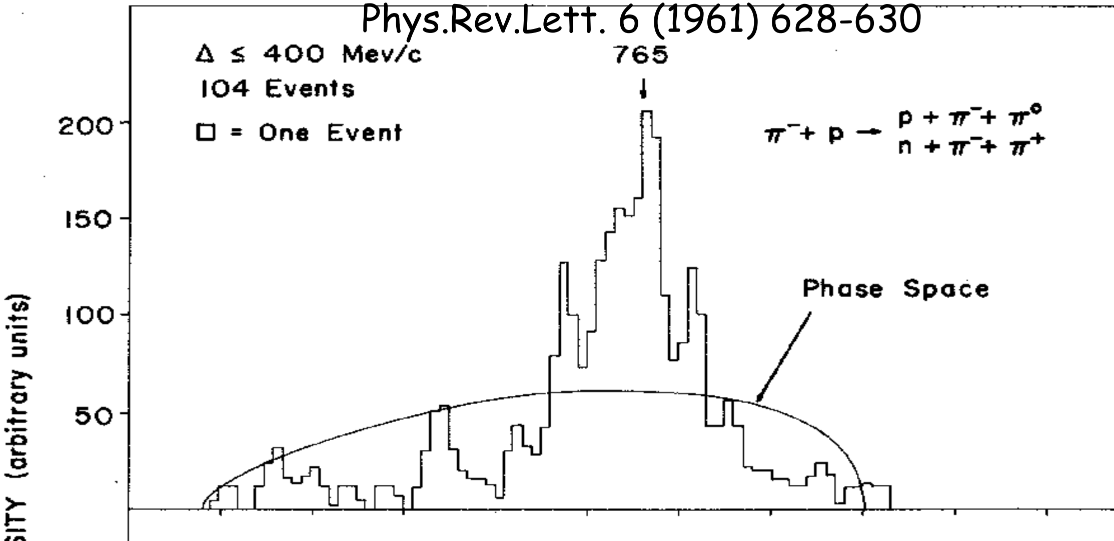
The first resonance in particle physics was discovered by E. Fermi's team
working at the Chicago Cyclotron in 1952.

H. L. Anderson, E. Fermi, E. A. Long, and D. E. Nagle, Phys. Rev. 85, 936

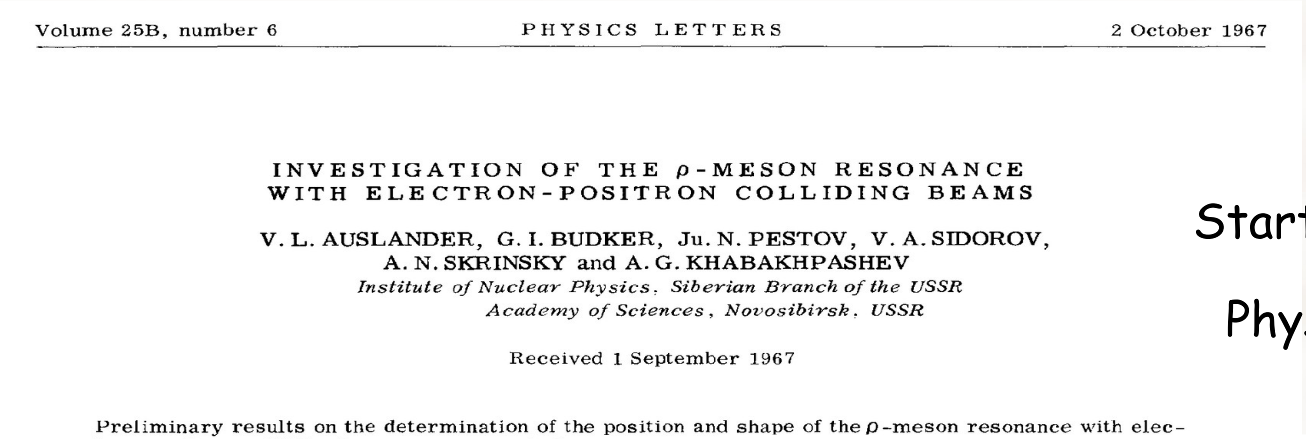
<u>1961 - Discovery of rho</u>

This ππ resonance, the ρ,
was observed by A. R. Erwin et al.
using the 14-inch hydrogen bubble chamber.
π- beam was produced by the proton beam from “the Cosmotron” - proton synchrotron, BNL

Evidence for a ππ Resonance in the I = 1, J=1 State
Phys.Rev.Lett. 6 (1961) 628-630



56 years of hadron production at colliders



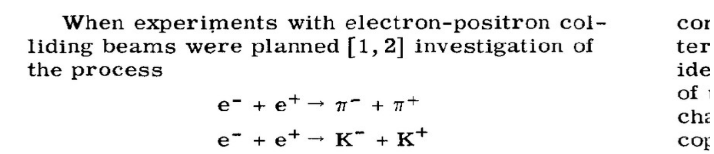
Volume 25B, number 6 PHYSICS LETTERS 2 October 1967

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

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

$$e^- + e^+ \to K^- + K^+$$

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1 September 1967

Start of e+e- → hadrons measurements

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

VEPP-2, Novosibirsk

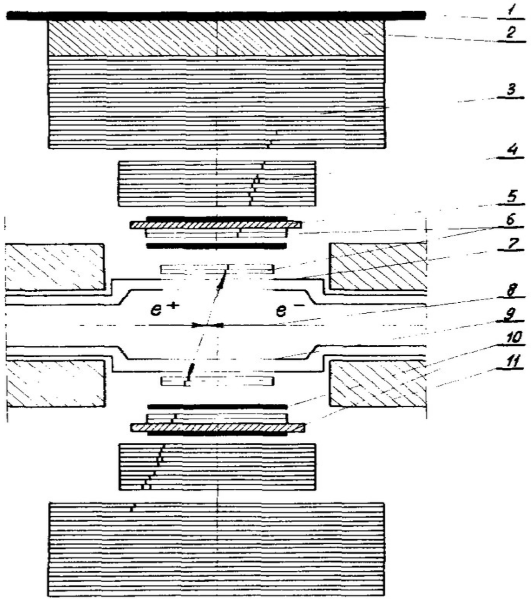


Fig. 1. Spark chambers system:
1) Anticoincidence scintillation counter
2) Lead absorber 20 cm thick
3) "Range" spark chamber
4) "Shower" spark chamber
5) Duraluminium absorber 2 cm thick
6) Thin-plate spark chambers

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

e+e- → ρ → ππ

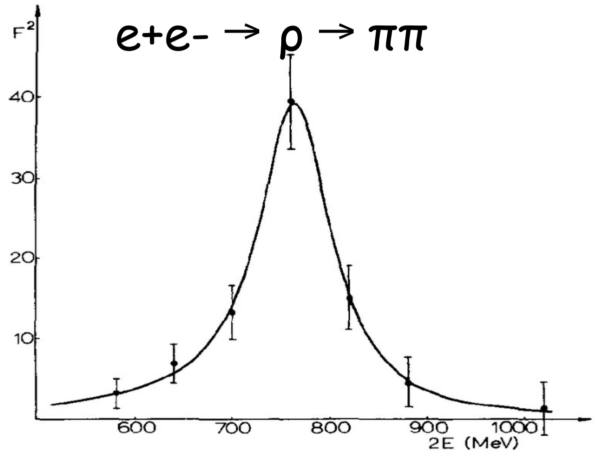
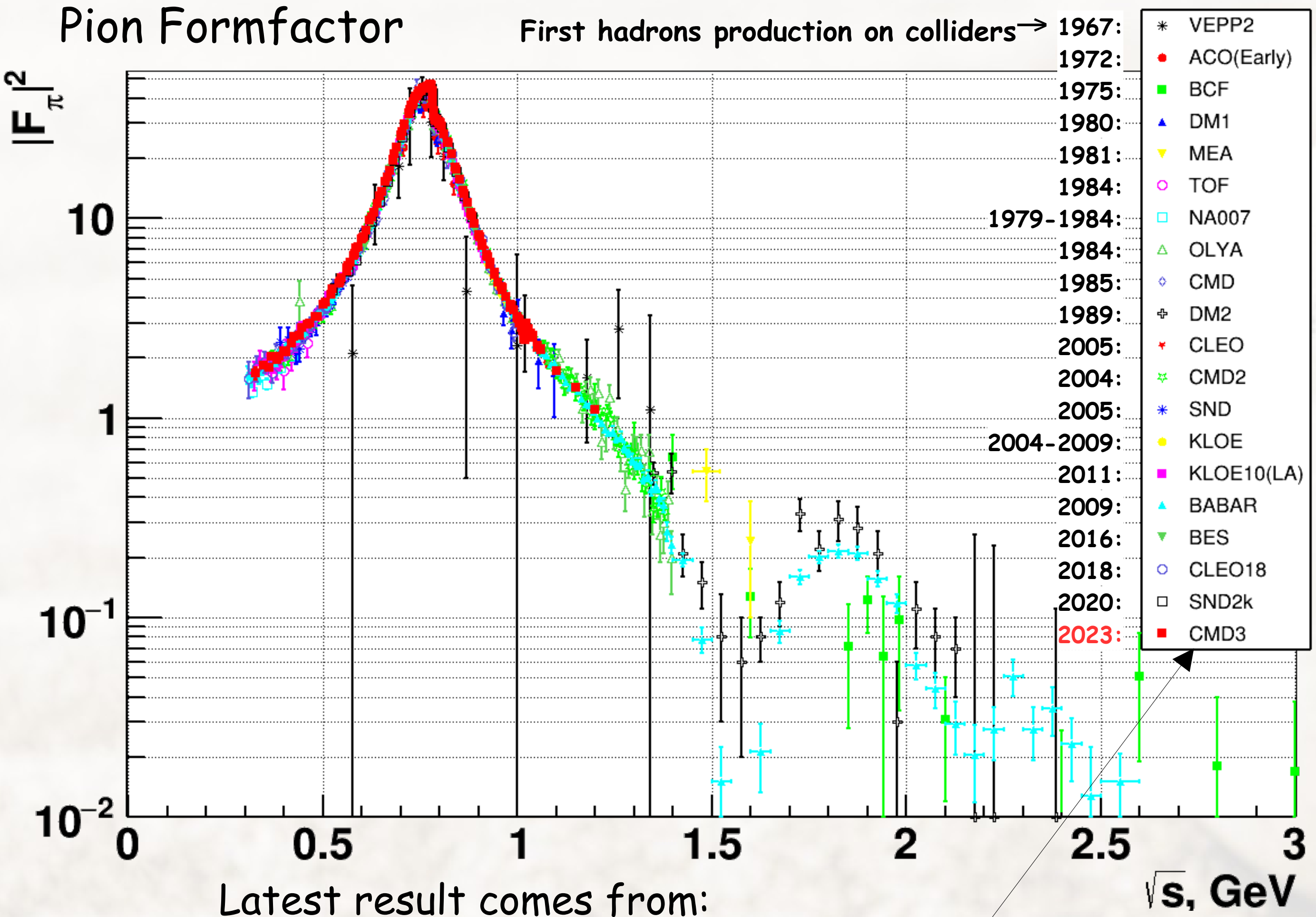


Fig. 2. Experimental values of F^2 (E) approximated by the Breit-Wigner formula.

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



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

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%

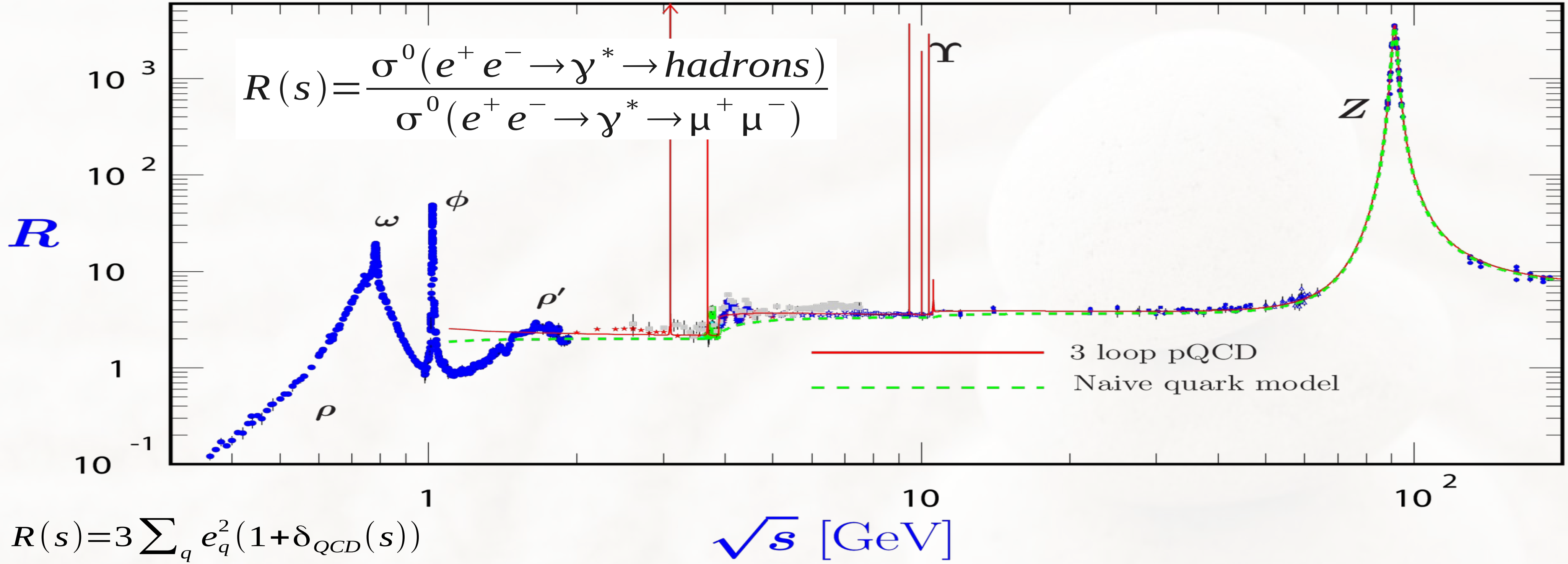
New direct data at VEPP-2000:

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

CMD-3: 0.7%

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

R(s)



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

$$R(s) = 3\sum_q e_q^2(1+\delta_{QCD}(s))$$

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}

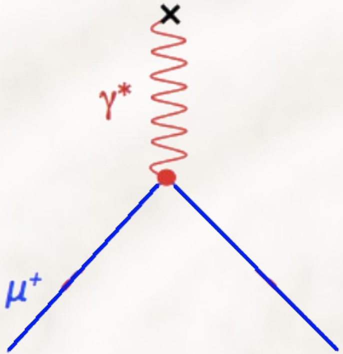
Dispersion relations → $\alpha_{QED}(M_Z)$, hyperfine muonium splitting, muon (g-2)

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:

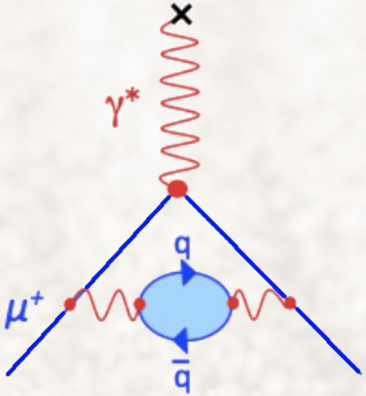
$$\vec{\mu} = g \frac{e}{2m} \vec{s}$$

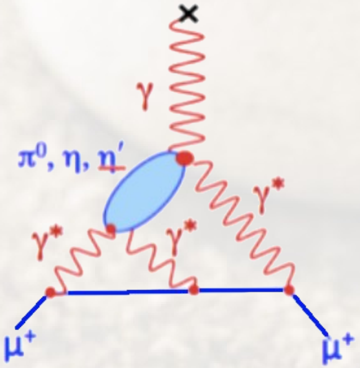
In Dirac theory, point-like, spin ½ particle has exactly g=2



Quantum loop effects via vacuum fluctuations lead to the calculated deviation:
the anomalous magnetic moment a = (g-2)/2 ~ α/2π ~ 0.00116

HLO



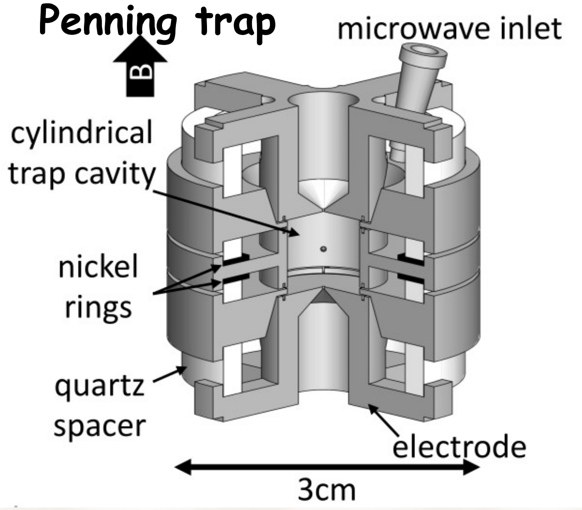


HLbL

Electron and muon g-2 Experiments

$a_e = 11\ 596\ 521.8059\ (0.0013)\ 10^{-10}$[0.13ppb]

Fan, Myers, Sukra, Gabrielse, PRL 130(2023) 7, 071801

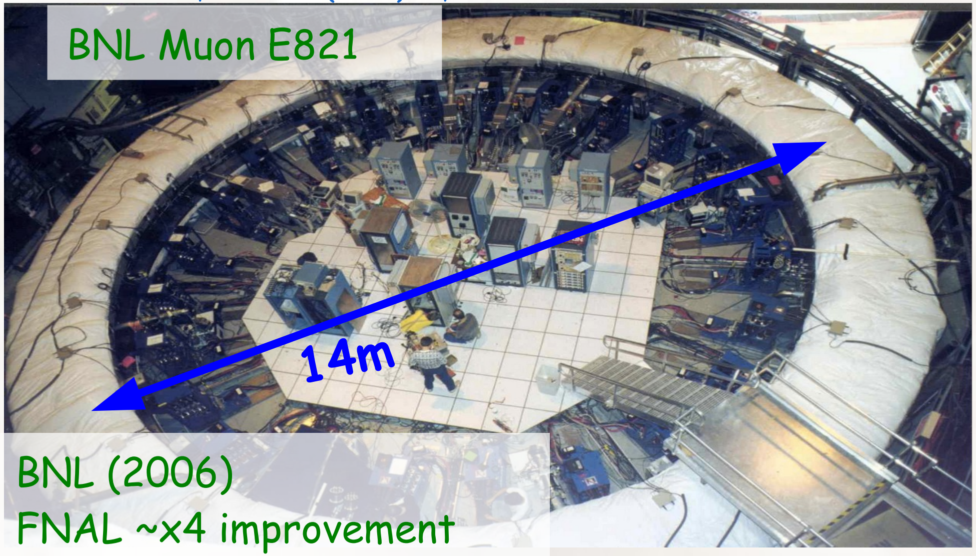


One electron
quantum cyclotron

Harvard Univ. (2008)
Northwestern (2022)
x2.2 improvement

$a_\mu = 11\ 659\ 206.1(4.1)\ 10^{-10}$[0.35ppm]

Bennet et al., PRD 73(2006)072003
B. Abi et al., PRL 126(2021) 14, 141801



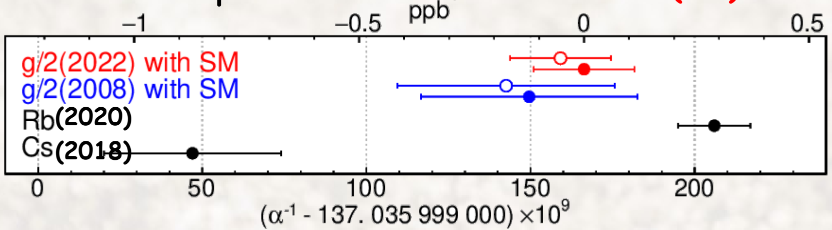
BNL (2006)
FNAL ~x4 improvement

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

Latest direct α_{QED} measurements using the recoil frequency of Cs-133 or Rb atoms disagree at 5.5σ.

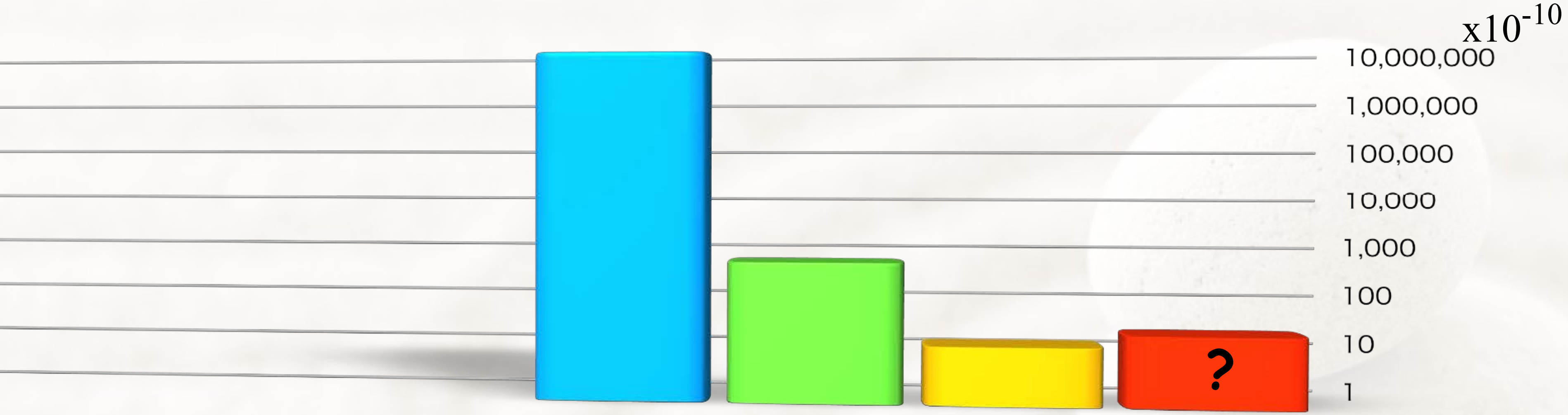
Tensions with experimental a_e are -3.9σ (Cs) or +2.1σ (Rb)

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



R. Parker et al., Science 360 (2018) 191 (Cs atom),
L. Morel et al., Nature 588 (2020) 7836, 61-65 (Rb atom)

Muon g-2 theory SM



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

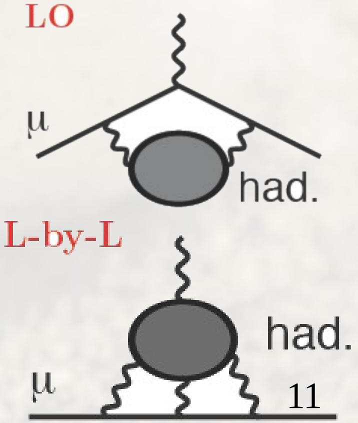
Precisions: 1 ppb HVP: 340ppb 9ppb < 2300ppb
\+ LbL: 160ppb

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

- **EW**: 2 loop (suppressed by $(M_\mu/M_W)^2$)

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

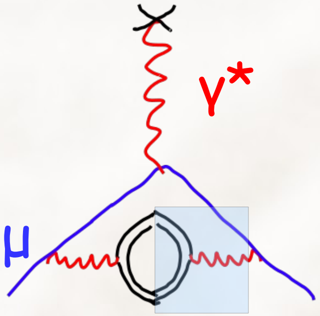
LBL: model-dependent calculations; measurement of transition formfactors can help, improvement is expected from lattice calculations



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

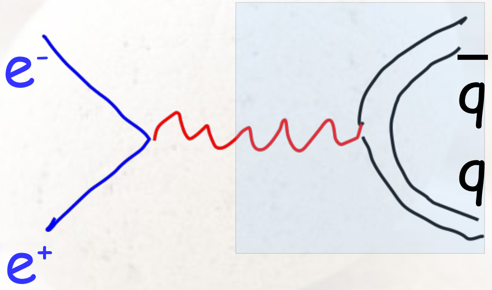
g-2 and e+e- → hadrons

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

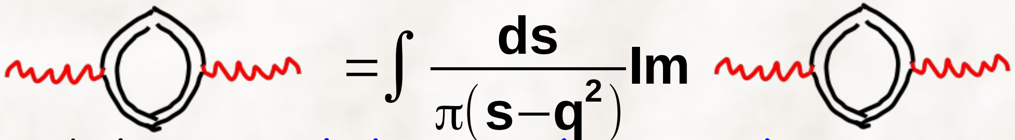


can be expressed by
dispersion relation
integral from

e+e- -> hadrons cross section

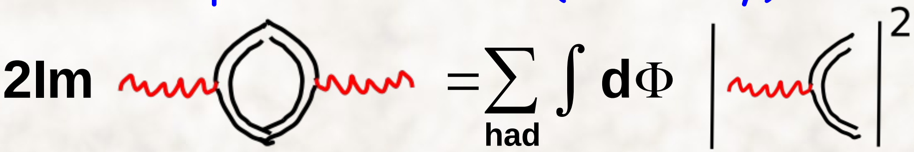


Dispersion relation is based on analyticity:



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

and the optical theorem (unitarity):



$$2\mathrm{Im} \quad = \sum_{had} \int d\Phi \; \left| \quad \right|^2$$

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

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

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

HVP contributions to amu

White Paper 2020 (e-Print: 2006.04822)

From muon g-2 Theory Initiative

Theoretical prediction e+e- data driven

$a_\mu = 11\,659\,181.0 \pm 4.3 \times 10^{-10}$ **(WP20)**

Hadronic part from measured cross-section

LO hadronic 693.1 $\pm$ 4.0 $\times 10^{-10}$

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

KLOE/BABAR difference

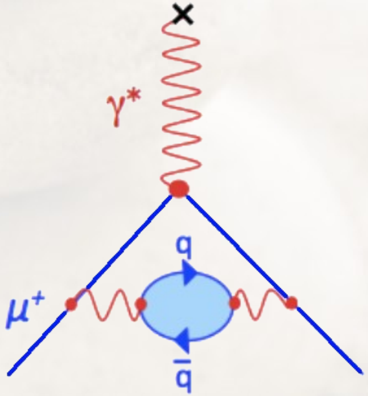
DV+QCD

			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		2.9%

……………….

Light-by-light 9.2 ± 1.9

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



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}

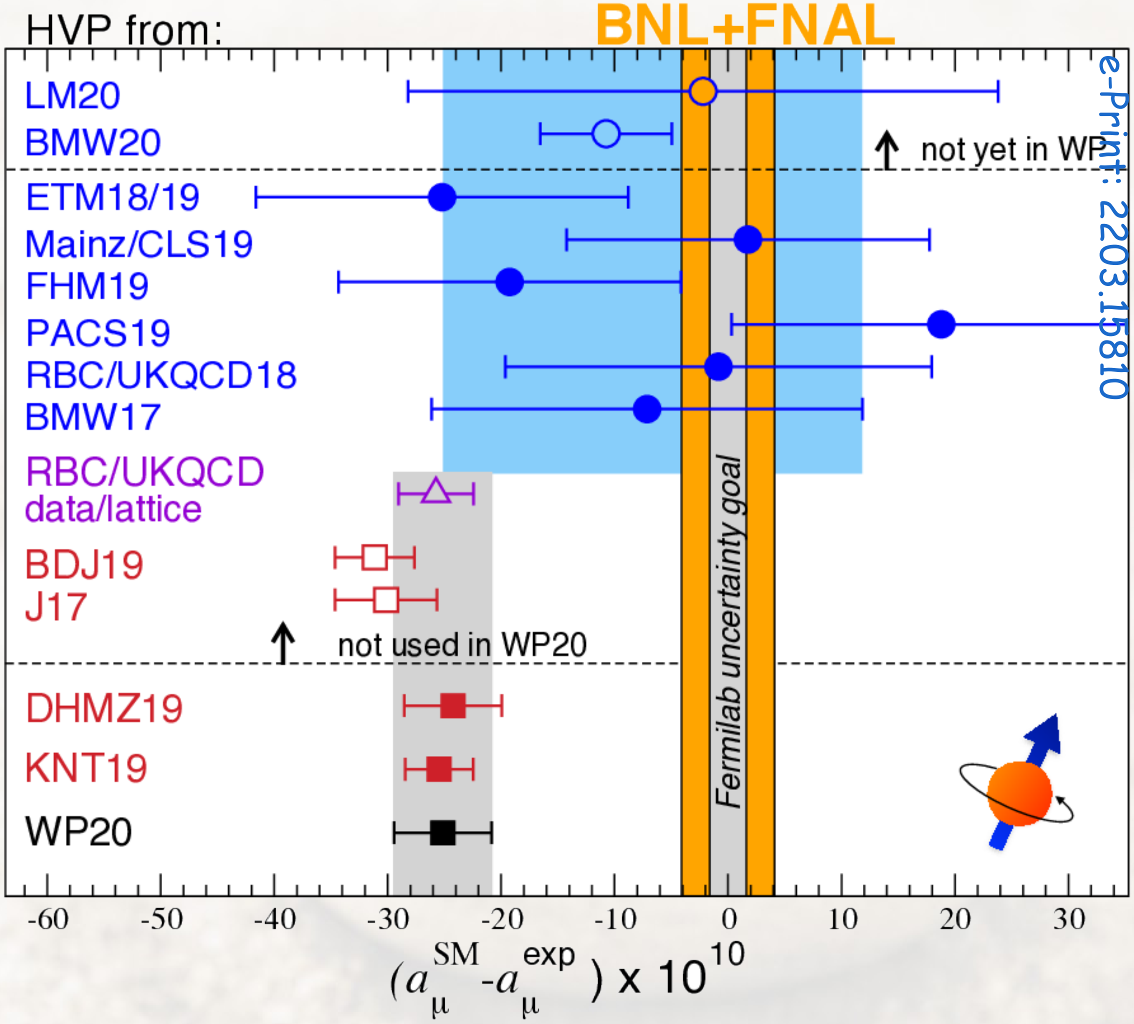
Δ (Exp – Theory) = 4.3 σ

The first Lattice calculation reaches the sub-percent precision:

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

Δ (Exp – Lattice) = 1.5 σ

Δ (e+e- – Lattice) = 2.1 σ



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

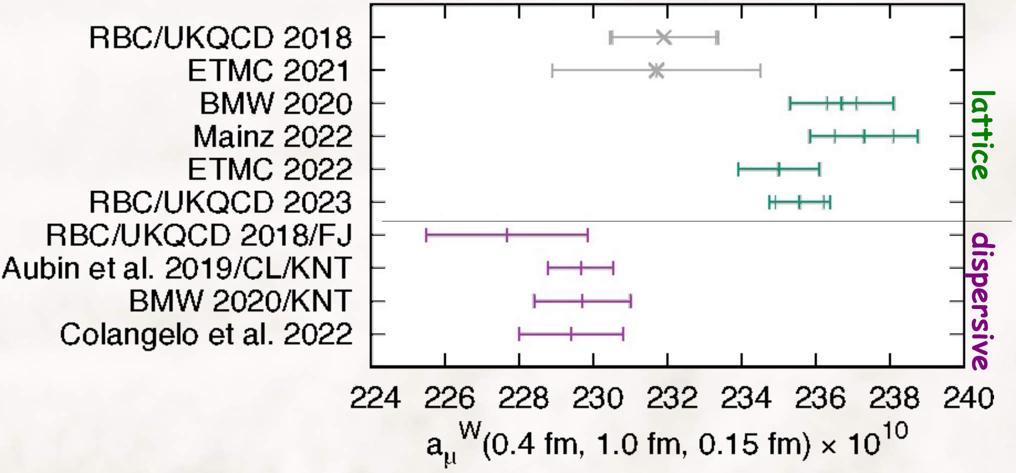
Dispersive vs Lattice

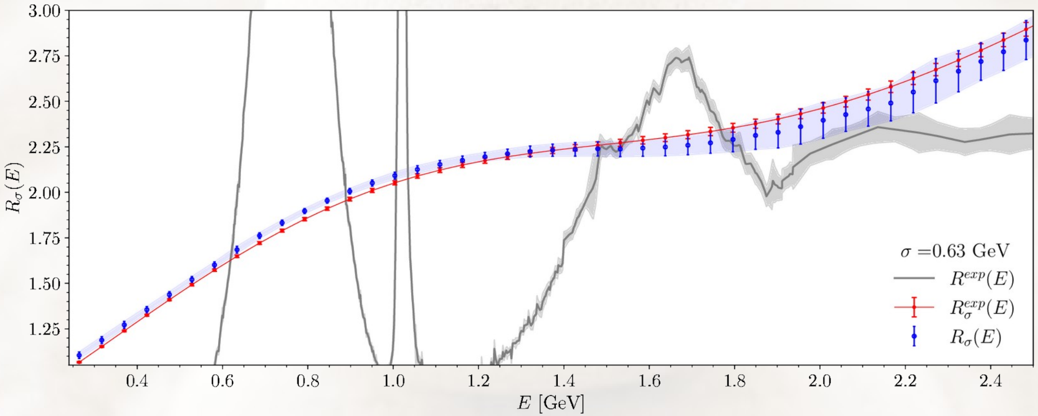
T.Blum et al, e-Print: 2301.08696 [hep-lat]

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

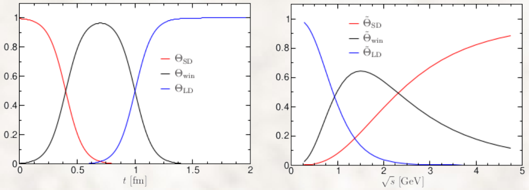
a^{HVP}_{μ} contribution from intermediate window in Euclidean time

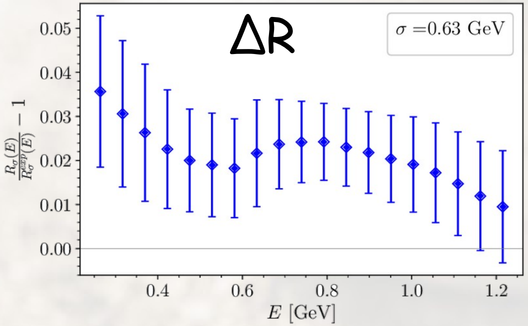
R(s) is convolved with Gaussian kernel

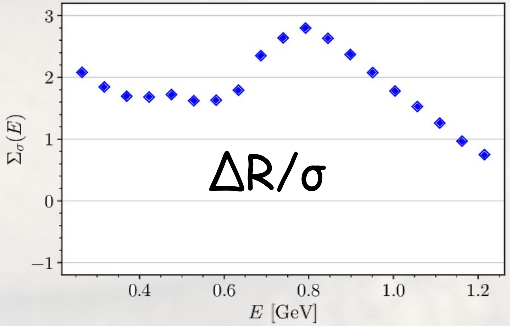




Windows definition







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

~3σ tension at rho energies

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

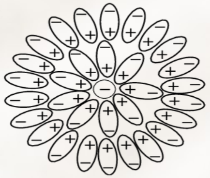
$\alpha_{QED}(M_Z)$ from e+e- data

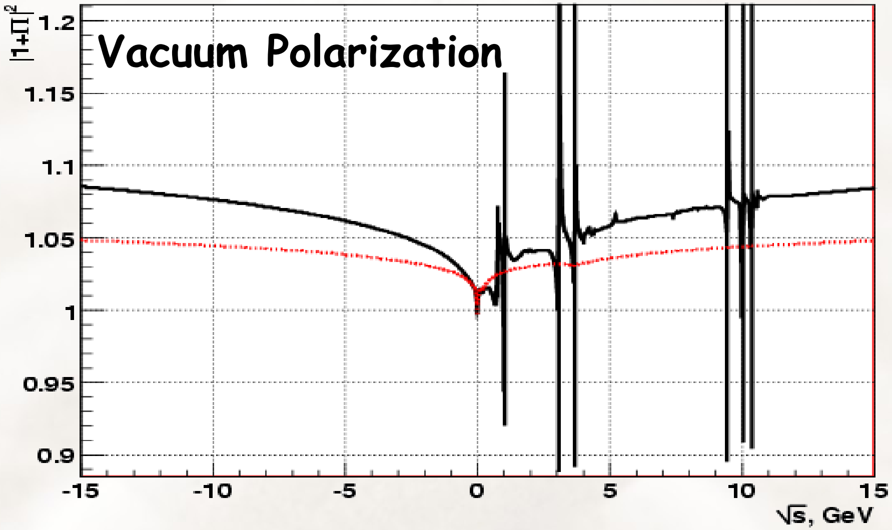
The electromagnetic fine structure constant $\alpha_{QED}(q^2)$ is a running parameter with momentum transfer q^2 due to Vacuum Polarization effects

-effective electron charge (charge screening)

$$\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)},$$

$$\Delta\alpha_{had}(s) = -\frac{\alpha(0)s}{3\pi}\int_0^\infty ds'\frac{R(s')}{s'(s'-s)-i\epsilon}$$



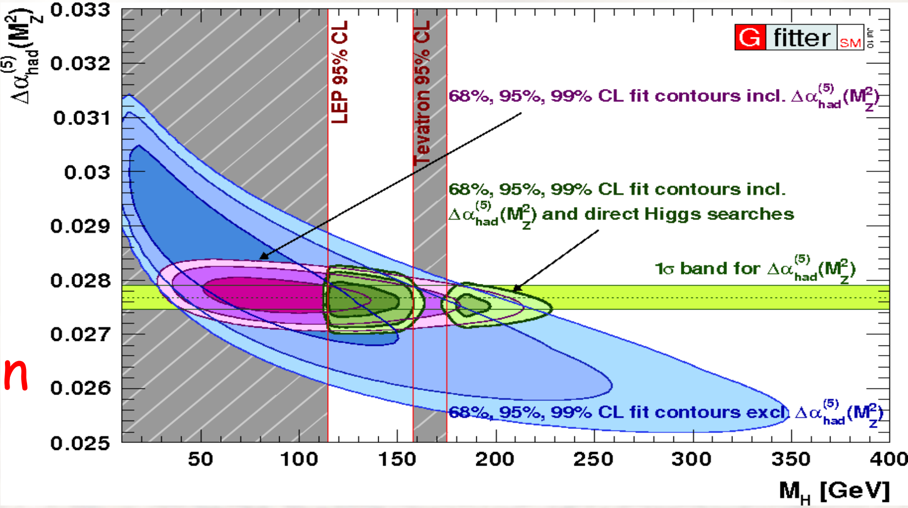


The $\alpha_{QED}(q^2)$ at mass of Z is used in predictions of electroweak model.

It is the least known EW parameter like $\delta G_\mu/G\mu \sim 0.9\times10^{-5}$, $\delta M_z/M_z \sim 2.3\times10^{-5}$

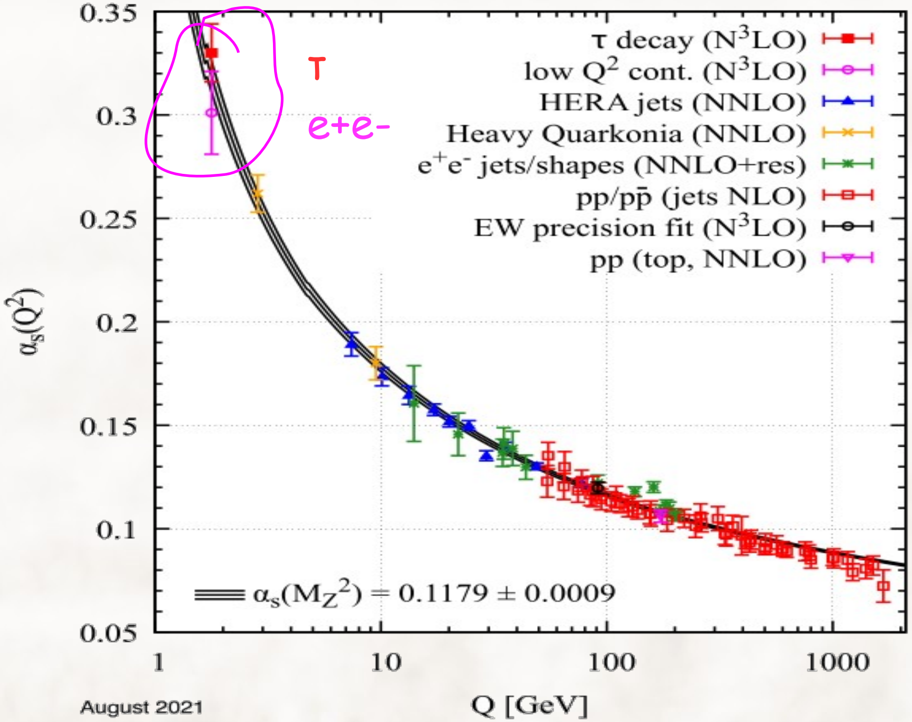
$\Delta\alpha_{QED}{}^{5had}(M_Z) = 276.1 \pm 1.1 \times 10^{-4}$

For future ILC, CLIC, FCC-ee it should be known with ~ 0.5-0.3 x 10^{-4}



Eur.Phys.J. C74 (2014) 3046

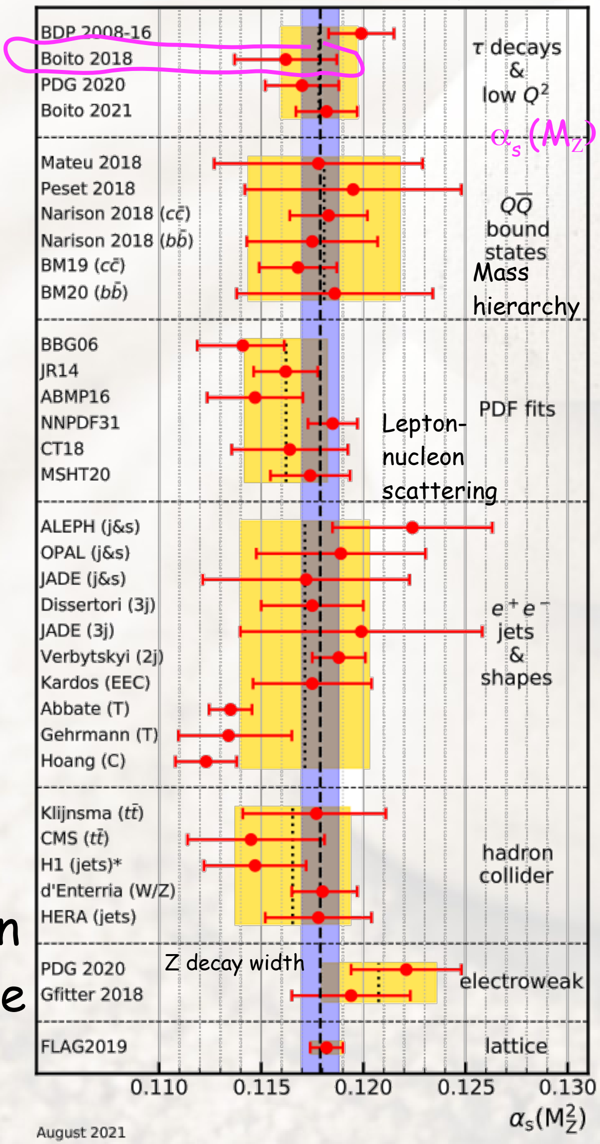
Current PDG α_s world average (NNLO)



Tau decays to hadrons give the best non-lattice α_s estimation

In future a leap in precision (<0.2%) can be obtained from W,Z decays with huge statistic (x10^4-10^5 LEP) at FCC-ee

Particle Data Group 22



$\alpha_s(M_Z)$

0.1178 ± 0.0019 (± 1.6%)

e+e- → hadrons

$\alpha_s(M_Z)$ = 0.1162 ± 0.0025 (±2.1%)

0.1181 ± 0.0037 (±3.1%)

0.1162 ± 0.0020 (±1.7%)

0.1171 ± 0.0031 (±2.6%)

0.1165 ± 0.0028 (2.4%)

0.1208 ± 0.0028 (2.3%)

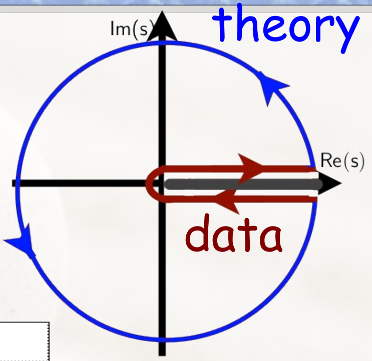
0.1182 ± 0.0008 (0.7%)

The strong coupling constant: State of the art e-Print: 2203.0827

Sum rules

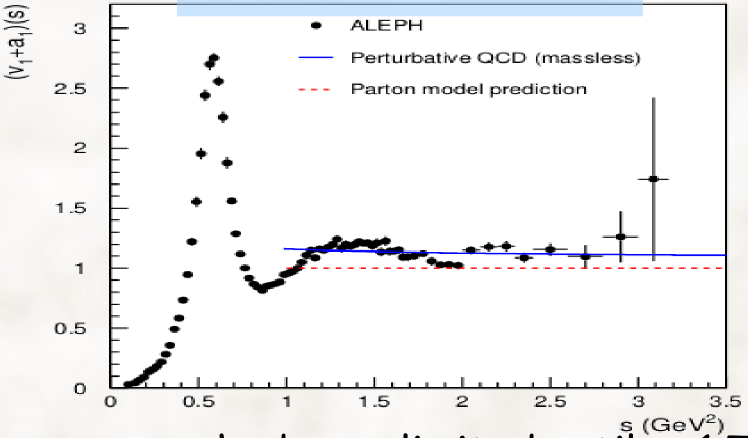
From analyticity and using Cauchy's theorem

$$\frac{1}{12\pi^2 s_0}\int_0^{s_0} ds\, w(s/s_0)R(s) = -\frac{1}{2\pi i s_0}\oint_{|z|=s_0} dz\, w(s/s_0)\Pi(z)$$

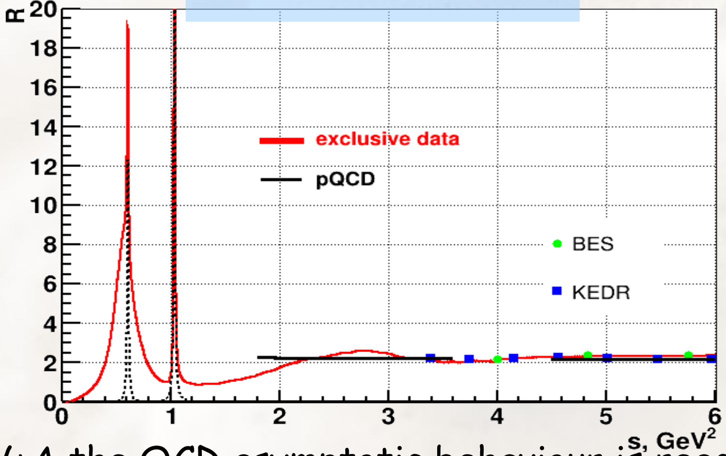


Integrated R(s) with different weights (pinched at s_0 where OPE is under question, w(y)~(1-y))

τ → ν + hadrons



e+e- → hadrons



τ → ν + hadrons limited until = 1.77 GeV (V+A the QCD asymptotic behaviour is reached faster)

e+e- → hadrons can be extended to upper s_0 limits

D.Boito et al., PRD 103 (2021) 3, 034028

$\alpha_s(m^2_\tau) = 0.3077 \pm 0.0065_{exp} \pm 0.0038_{theo}$

(DV modeling, FOPT selected, ± 0.008 FOPT vs CIPT)

$\alpha_s(m^2_Z) = 0.1182 \pm 0.0015$ (±1.3%)

D.Boito et al. , PRD 98 (2018) 7, 074030

$\alpha_s(m^2_\tau) = 0.298 \pm 0.016_{exp} \pm 0.006_{theo}$

(± 0.005 DV ± 0.003 higher orders, ± 0.003 FOPT vs CIPT)

$\alpha_s(m^2_Z) = 0.1162 \pm 0.0025$ (±2.1%)

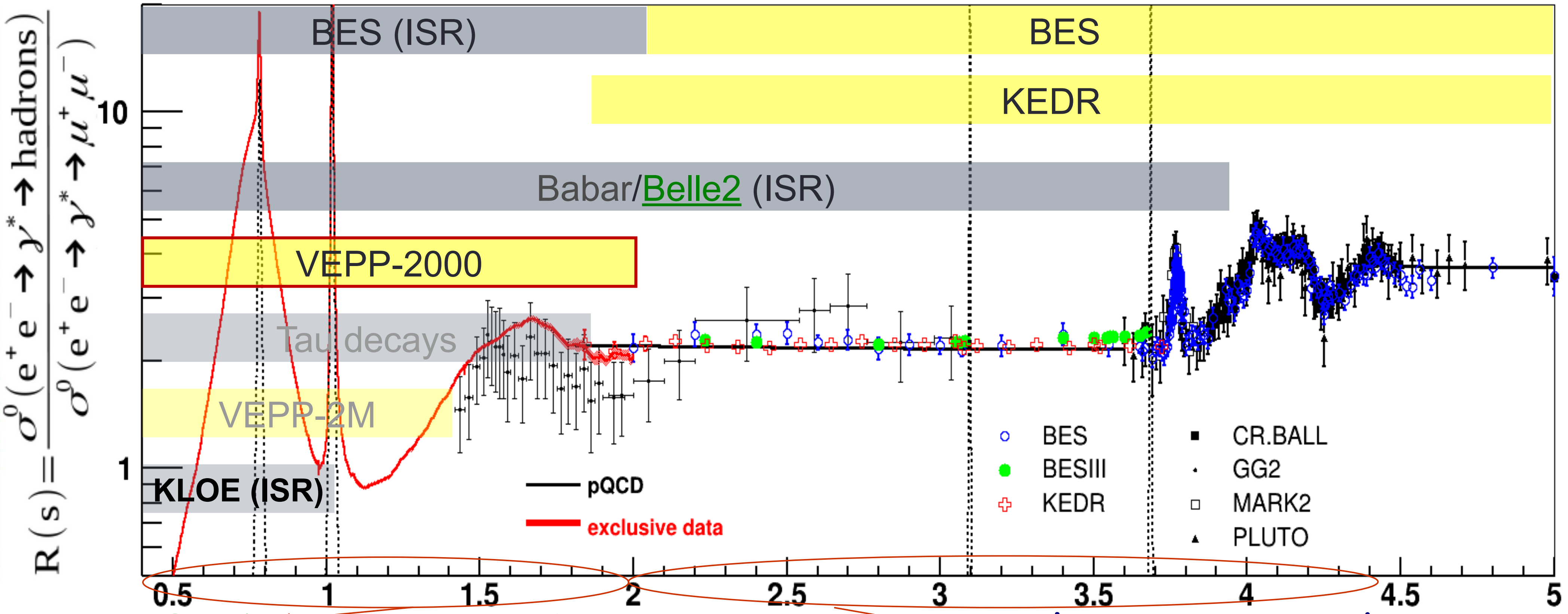
DV modelling with tOPE approx., FOPT vs CIPT limit precision (understanding can give x2 improvement)

See: D.Boito et al., EPJ Web Conf. 274 (2022) 03014   See: A.Pich et al., JHEP 07 (2022) 145

e+e-: Limited by data, Difference between FOPT and CIPT ~3 times smaller than in tau decays

R(s) measurement

Two techniques: Energy scan vs ISR



Exclusive approach

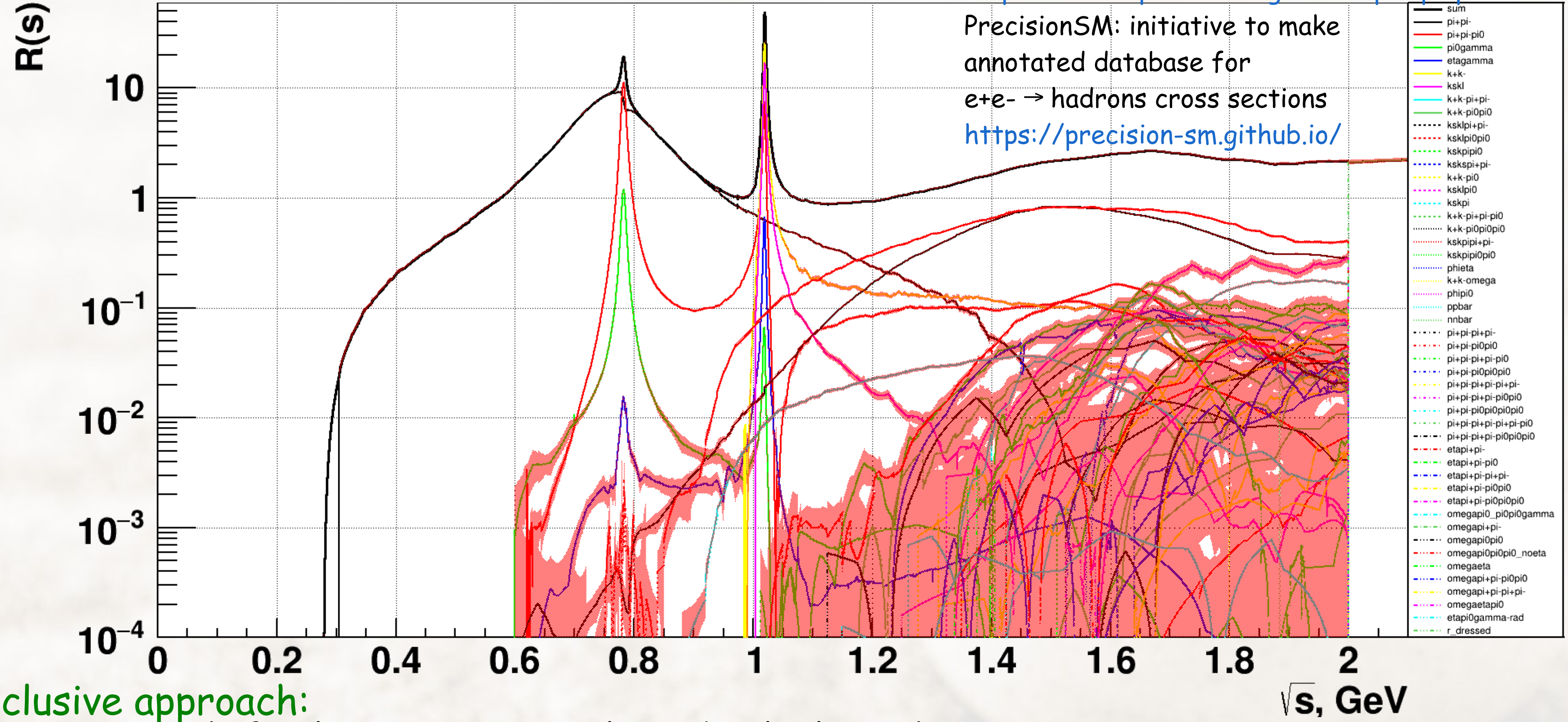
Inclusive approach

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

<u>VEPP-2000:</u> Only one working these days on scanning below <2 GeV with world-best luminosity per single bunch at this energies

Exclusive measurements

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



PrecisionSM: initiative to make
annotated database for
e+e- → 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

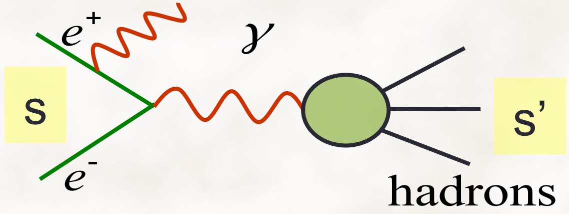
Inclusive approach (√s > 2 GeV):
- ✗ select events with any hadron(s) in the final state
- ✗ possible because of many modes and high track multiplicity

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

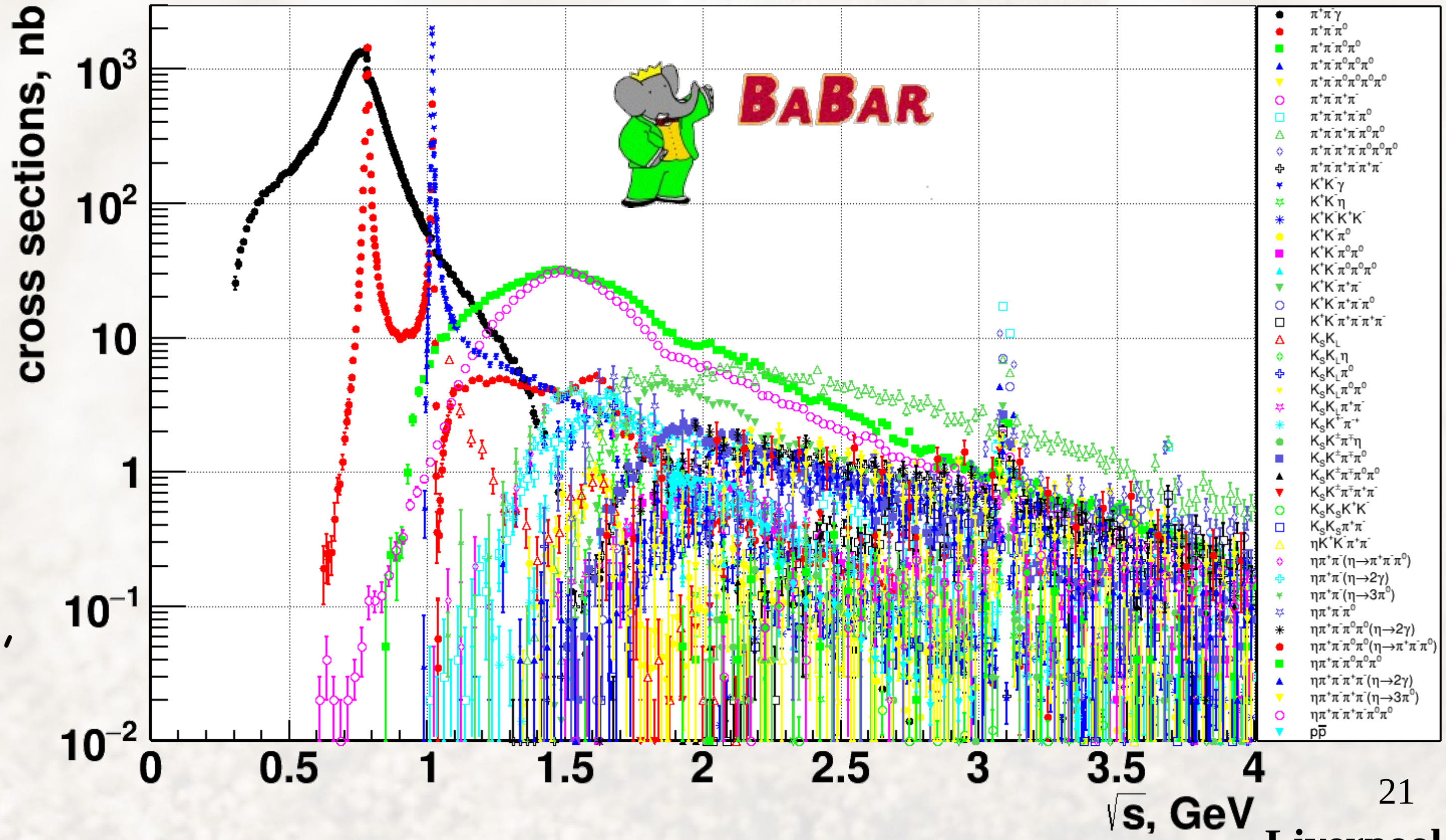
ISR approach

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

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

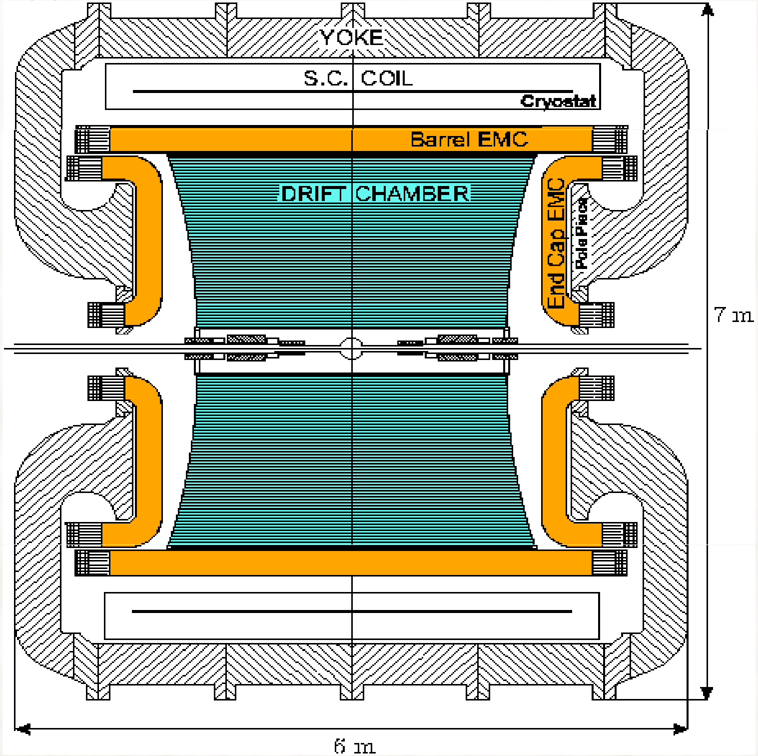


Main idea: cross-section is measured in a wide energy range, using events with hard photon, emitted by initial particles.



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

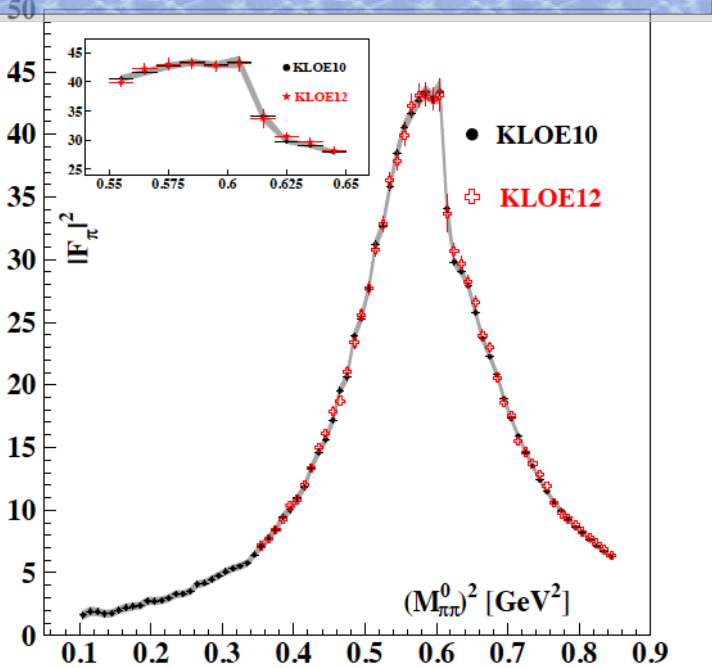
Measurement with ISR
$e^+e^- \to \pi^+\pi^-\gamma$
JHEP 1803 (2018) 173

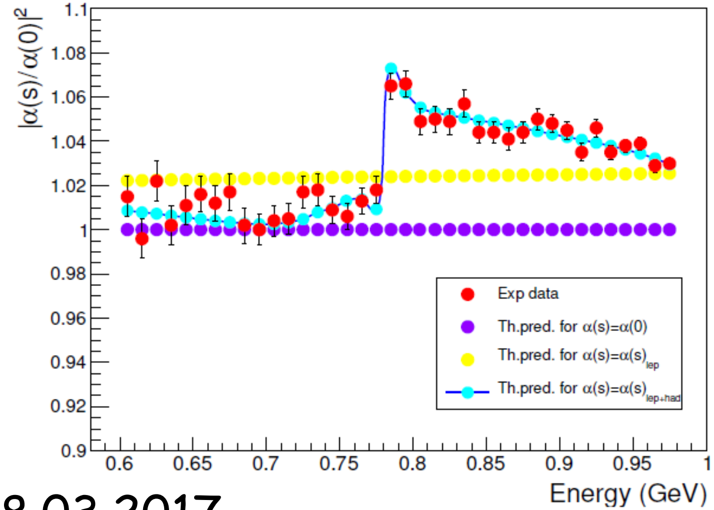
3 analyses:
with ISR photon on small angles/ large angle/ using radiator function from ISR $\mu^+\mu^-$

Best local stat. precision at s=0.5-0.85 GeV²
(before CMD-3)

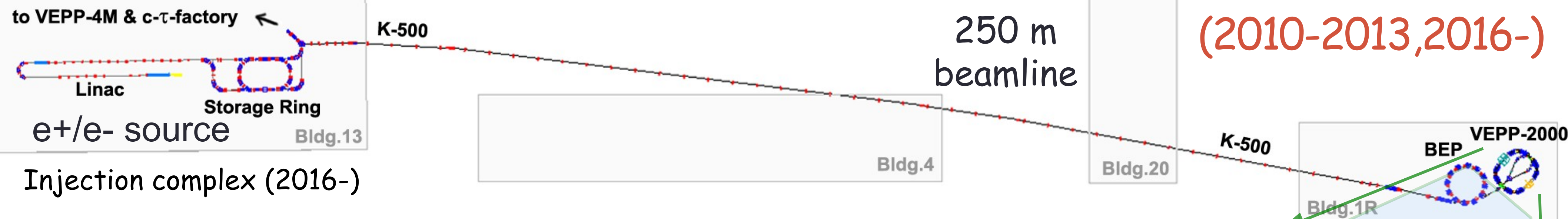
direct extraction of
$\alpha_{QED}(s)$ via $e^+e^- \to \mu^+\mu^-\gamma$
Phys. Lett. B, 767 (2017), 485

See G. Venanzoni
CERN presentation at 28.03.2017





VEPP-2000 e+e- collider



(2010-2013,2016-)

Injection complex (2016-)

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

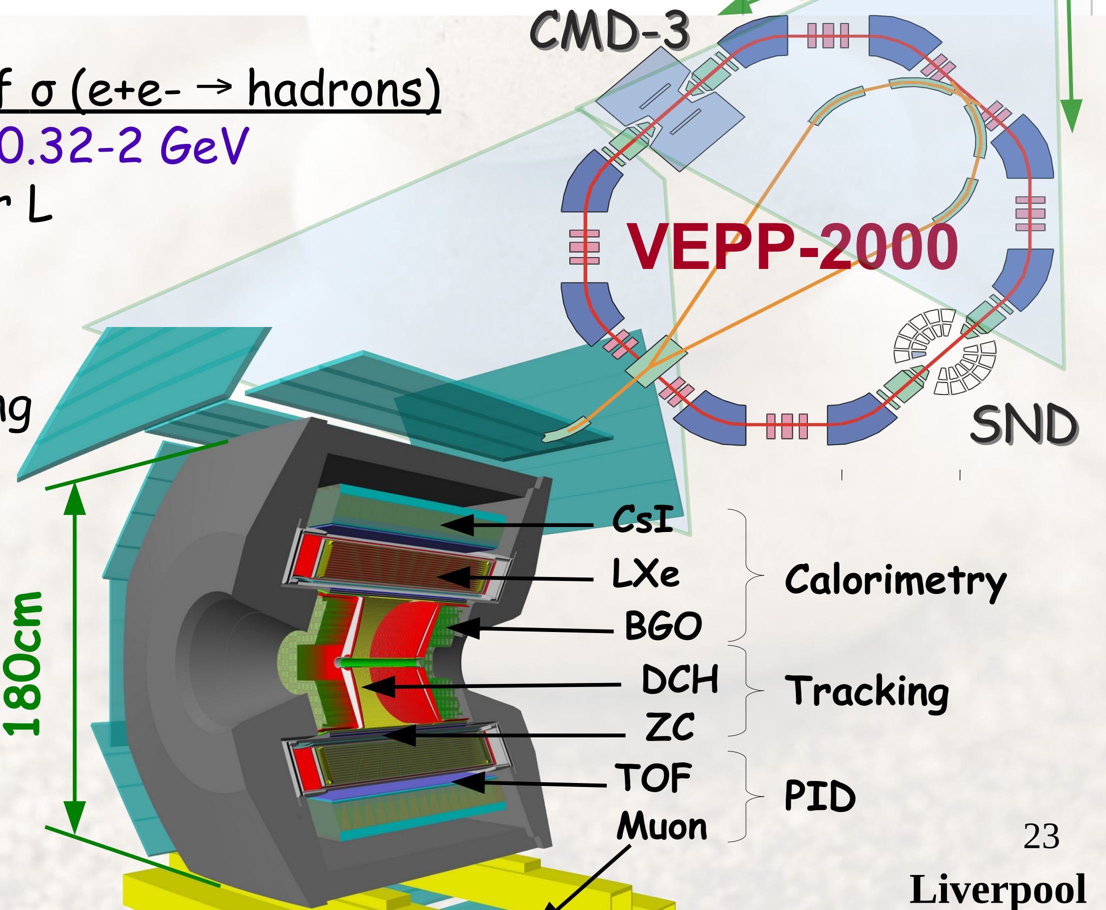
$L = 0.9\times10^{32}\ cm^{-2}s^{-1}$ at 2E= 2 GeV

Energy monitoring by Compton backscattering

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

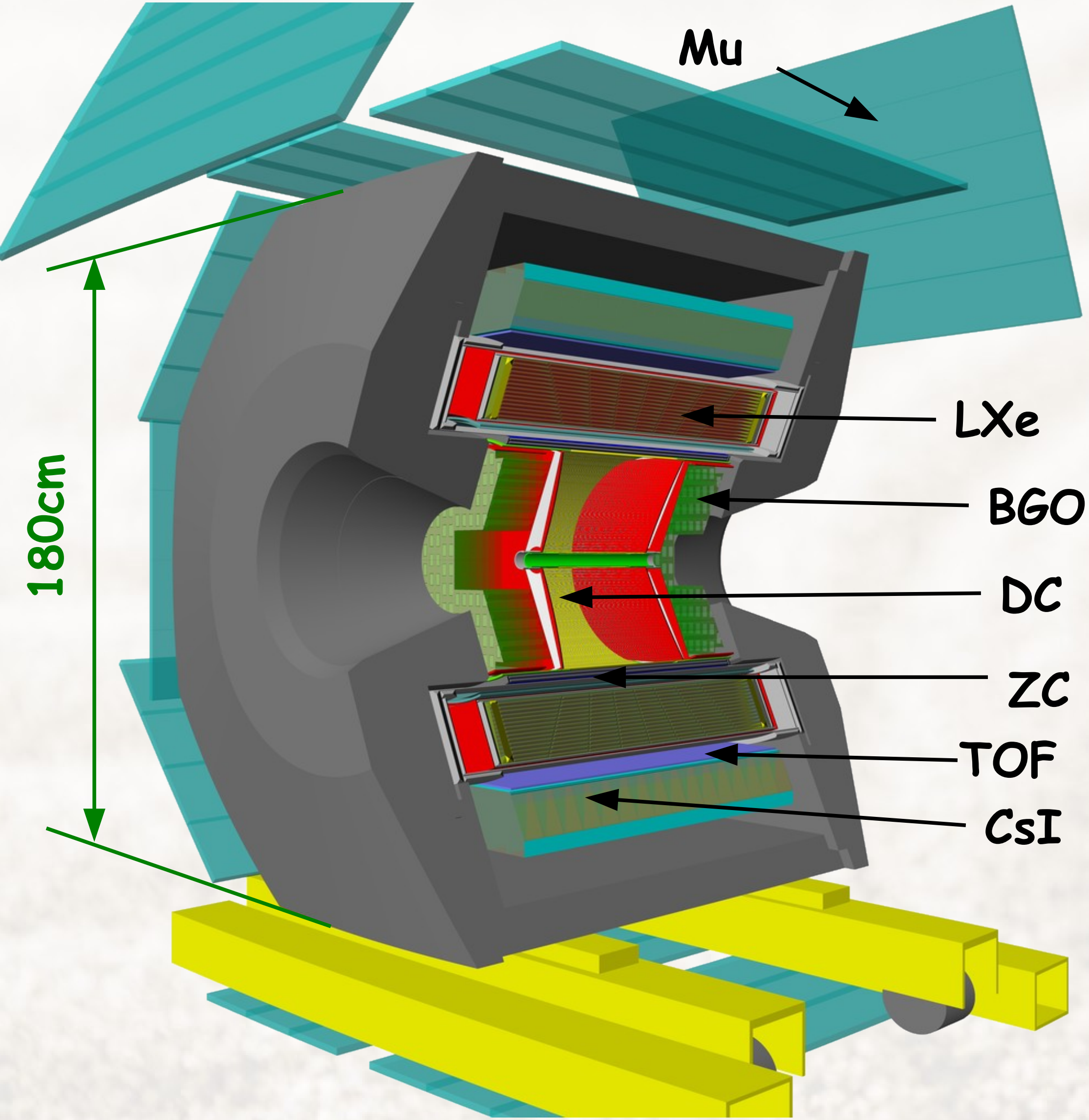
Two detectors: CMD-3 and SND

started by the end of 2010




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

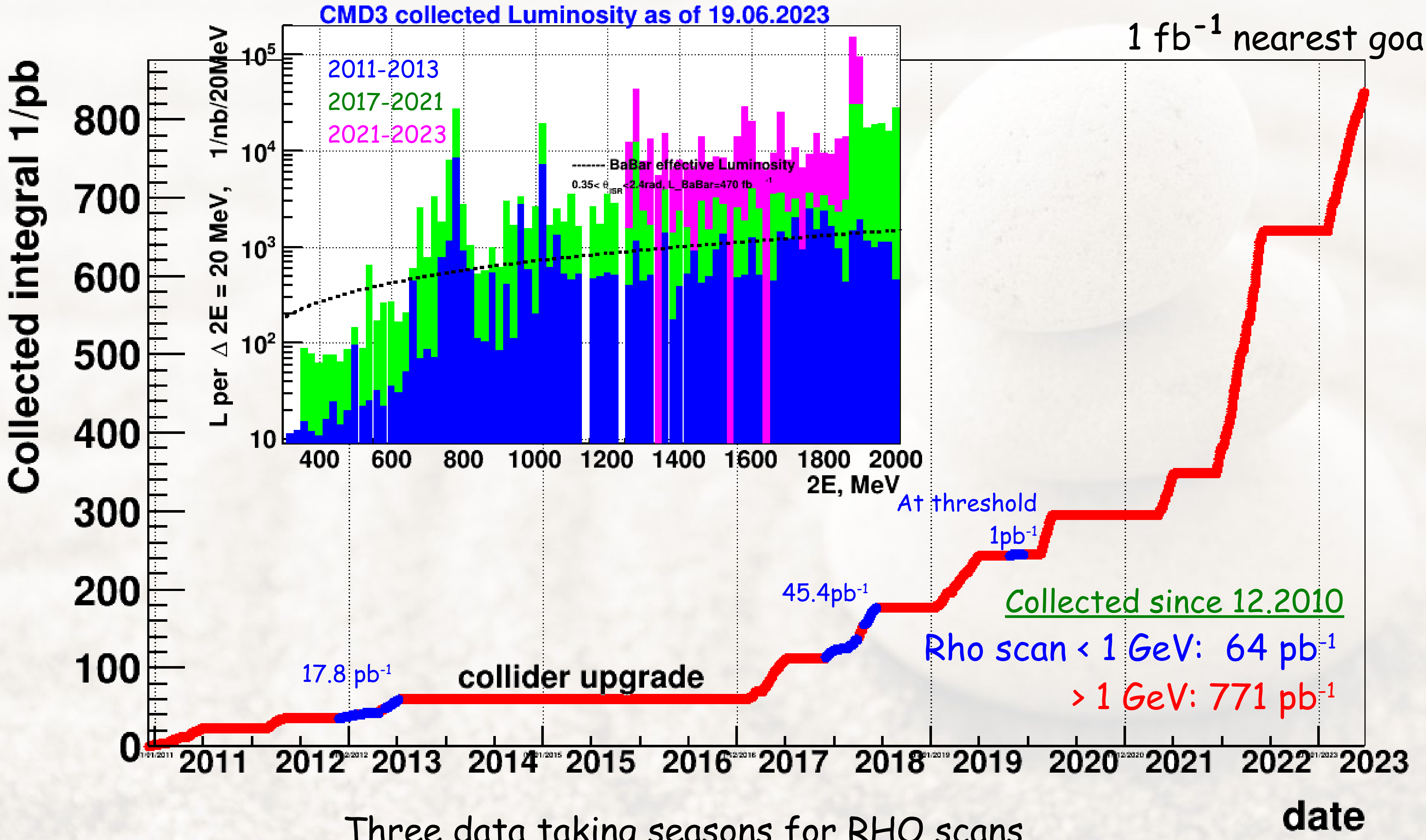
Calorimetry:

- ✗ 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

Overview of CMD-3 data taking runs



$1\ fb^{-1}$ nearest goal

Collected since 12.2010

Rho scan < 1 GeV: 64 pb^{-1}

> 1 GeV: 771 pb^{-1}

Three data taking seasons for RHO scans

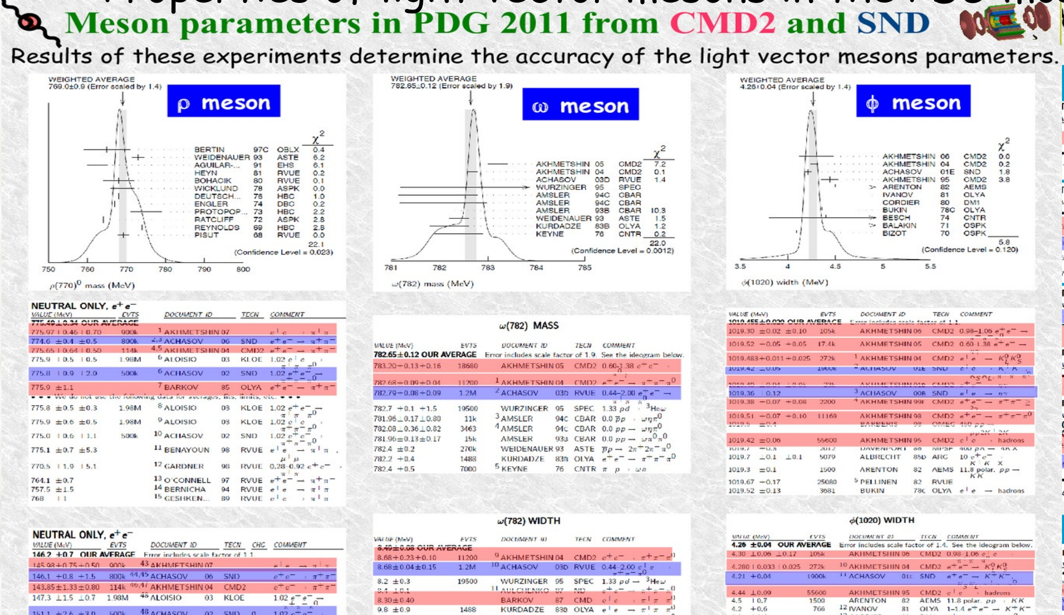
Physics at VEPP-2000

The physics program includes not only precise measurement of total R(s) = hadron production cross-section at low energies (by sum of exclusive channels).

But also:

- ✗ study of production dynamics, ChPT
- ✗ properties of light vector mesons, their decays,
- ✗ nucleon formfactors at threshold,
- ✗ two photon physics,
- ✗ search of exotics,
- ✗ and so on…

Properties of light vector mesons in the PDG mostly comes from Novosibirsk measurements



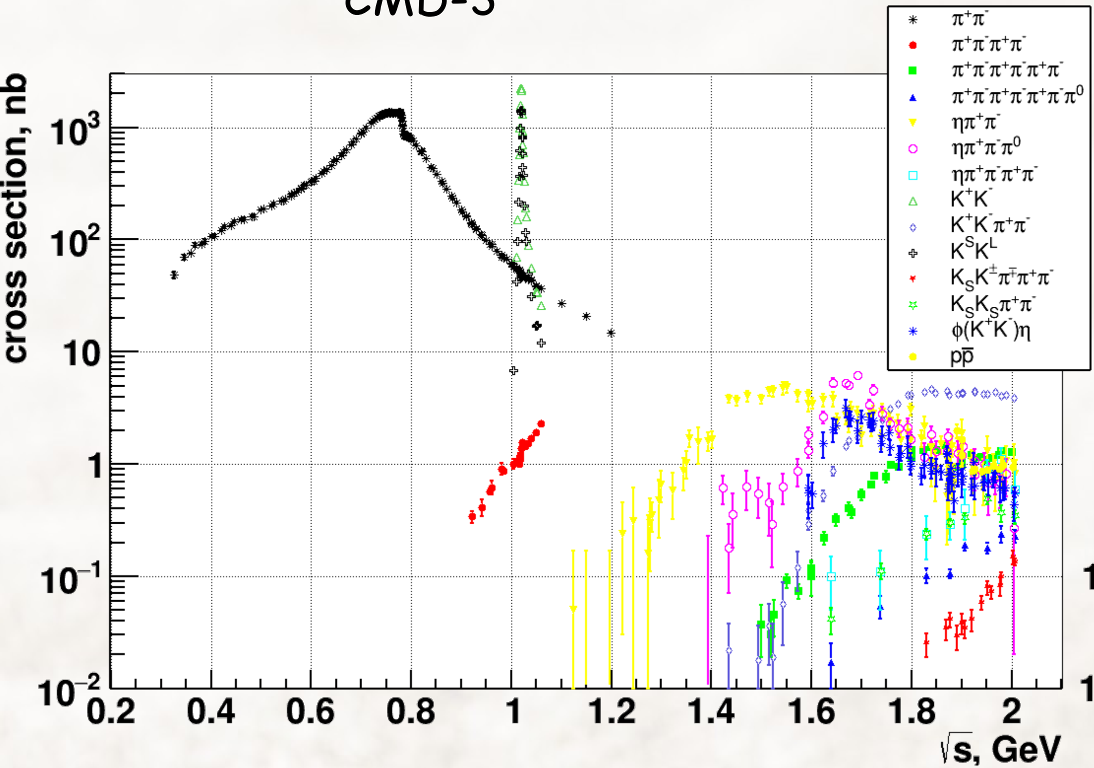
Meson parameters in PDG 2011 from CMD2 and SND

Results of these experiments determine the accuracy of the light vector mesons parameters.

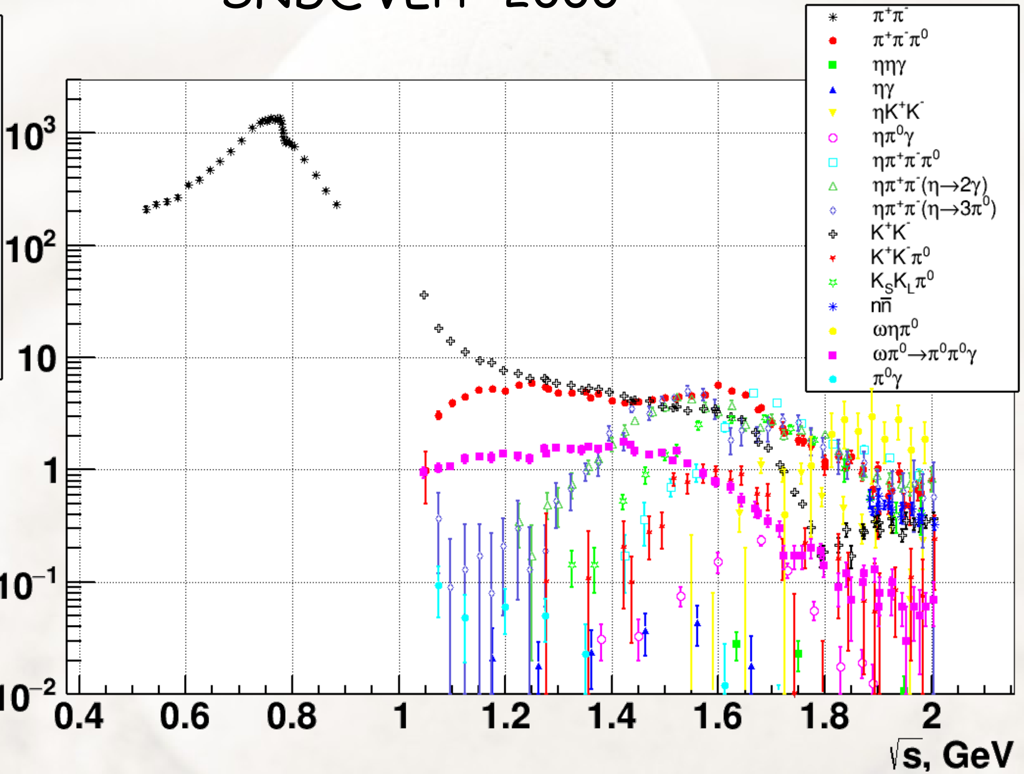
Rare decays

CMD-3 & SND published

CMD-3

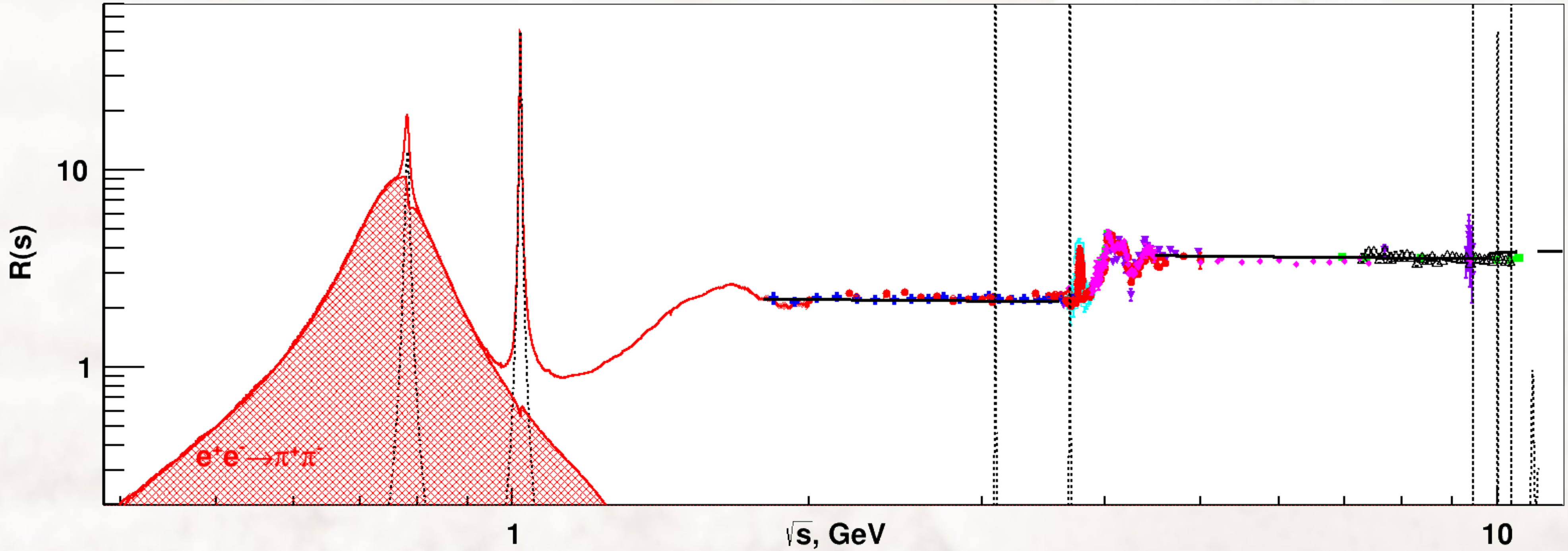


SND@VEPP-2000



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

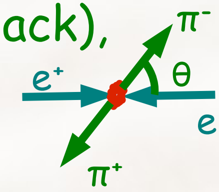
$$R(s)=\frac{\sigma^0(e^+e^-\to\gamma^*\to hadrons)}{\sigma^0(e^+e^-\to\gamma^*\to\mu^+\mu^-)}$$



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

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:

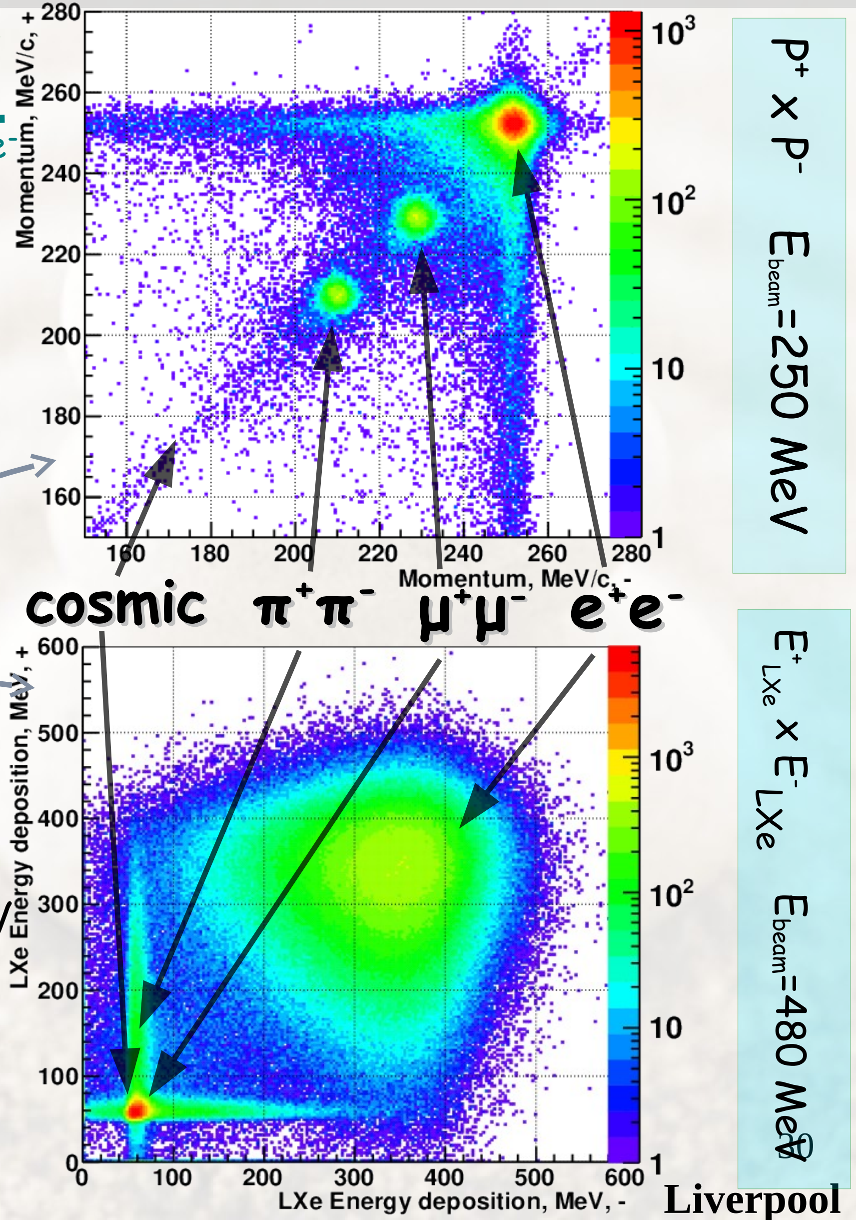
- ✗ e/μ/π separation
- ✗ radiative corrections
- ✗ precise fiducial volume
- ✗ ...

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

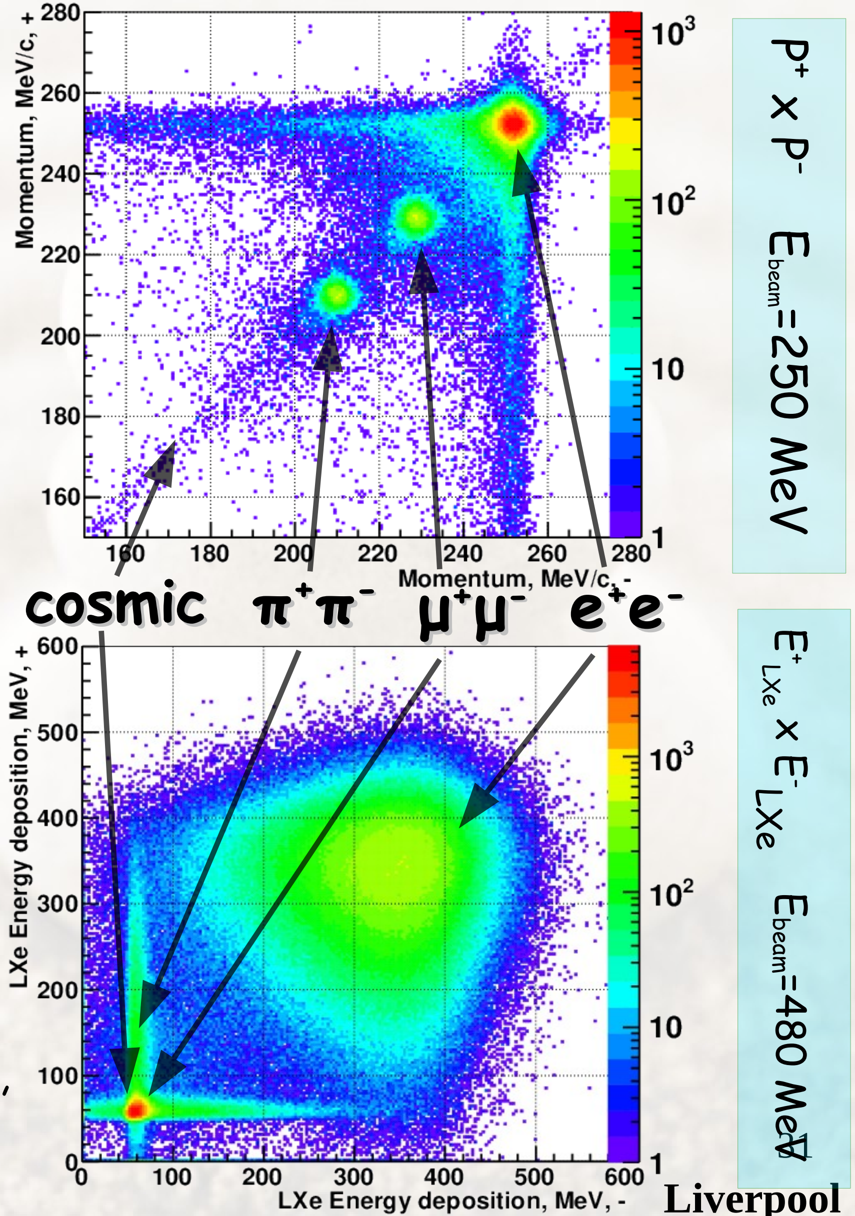
events separation is done either
1) by momentum
2) or by energy deposition

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

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

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

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



Angle distribution fit

dσ/dθ 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)

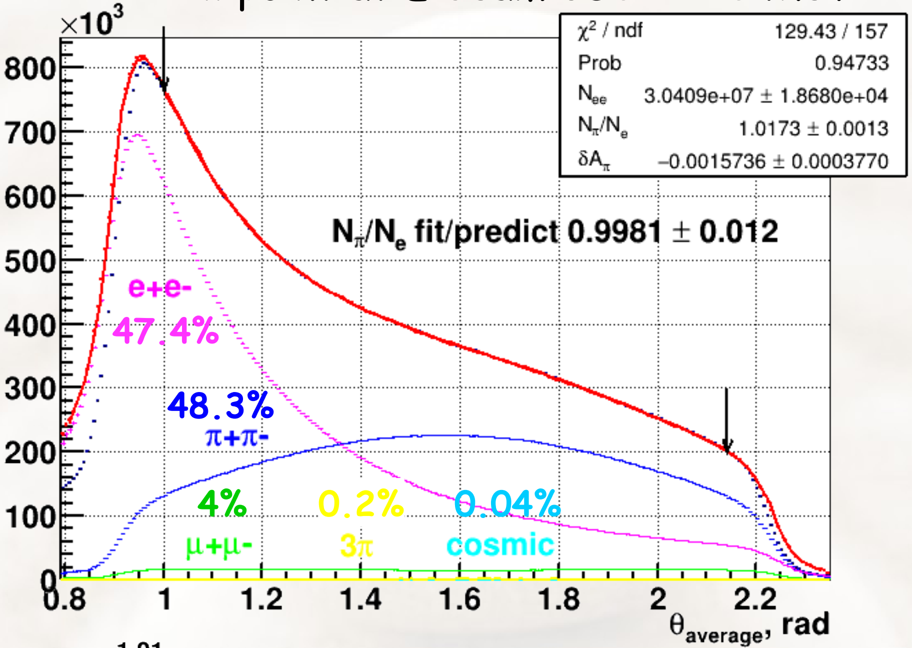
N cosmic, 3π - from momentum based separation

$N_{\pi\pi}/N_{ee}$, δA - free parameters

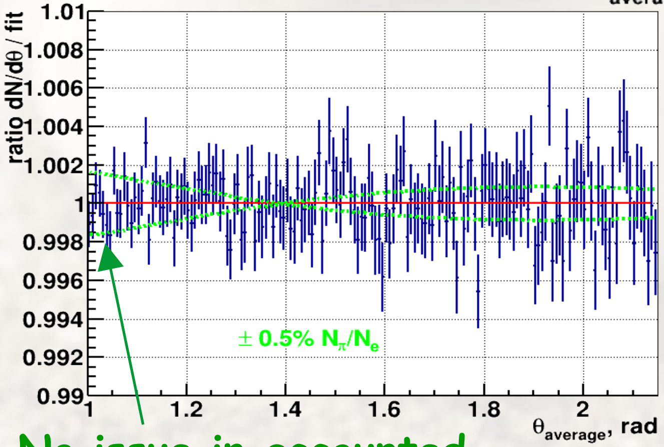
Combined fit on all points around ρ-peak
$\sqrt{s}$ = 0.7 – 0.82 GeV

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

All point at E beam 350 – 410 MeV



Fit by θ distribution



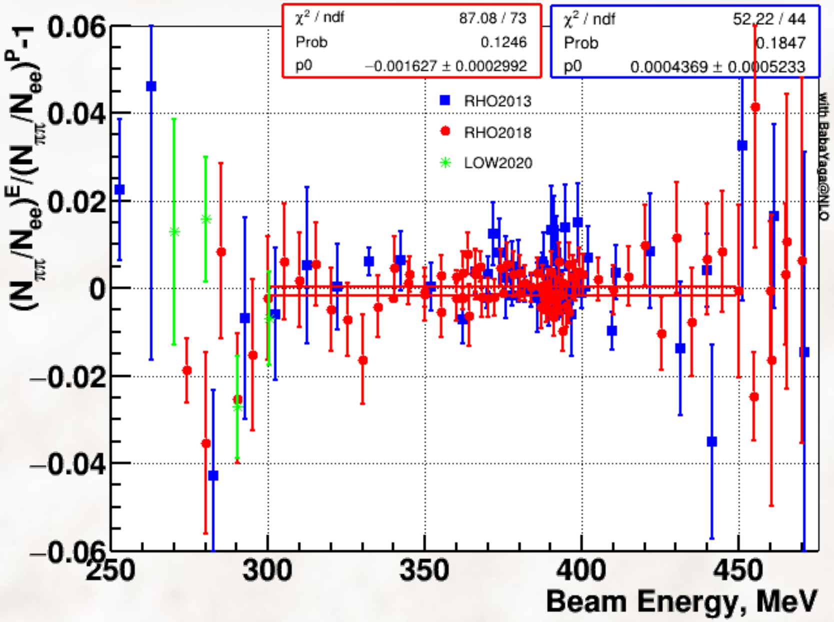
No issue in accounted efficiency at θ = 1 rad

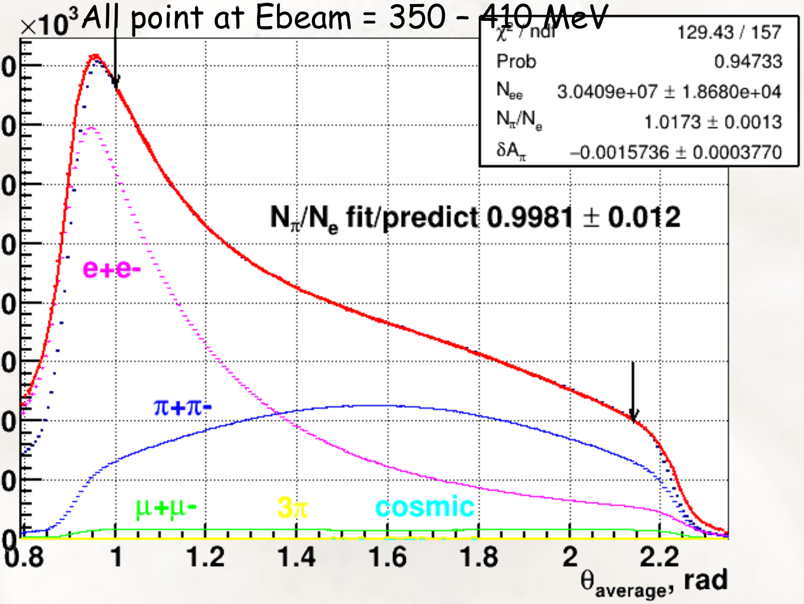
e/μ/π separation

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 √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 Δ $N_{\pi\pi}$ /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%

Common stat from √N: 0.026%

consistency at ~ 0.2%

Precision of fiducial volume

Polar angle measured by

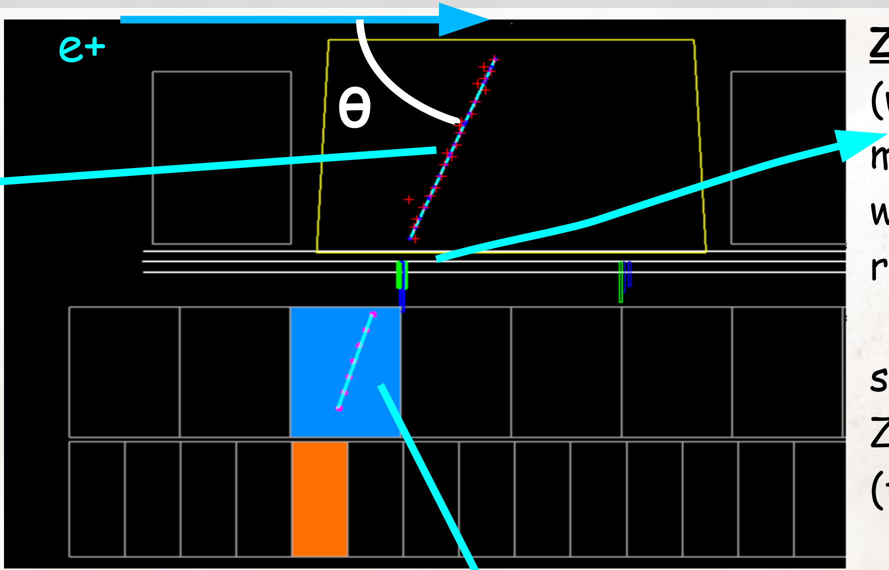
DCH chamber

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)

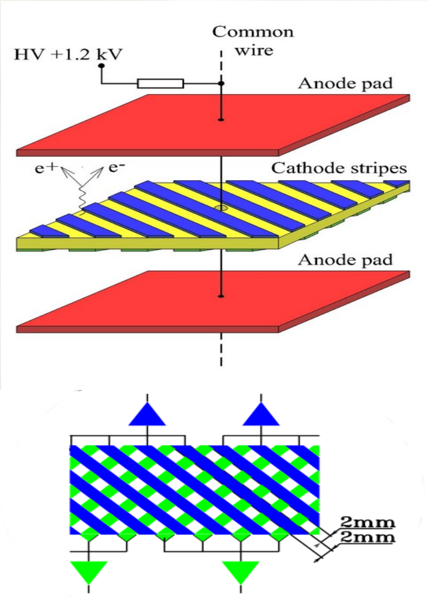
multiwire chamber

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

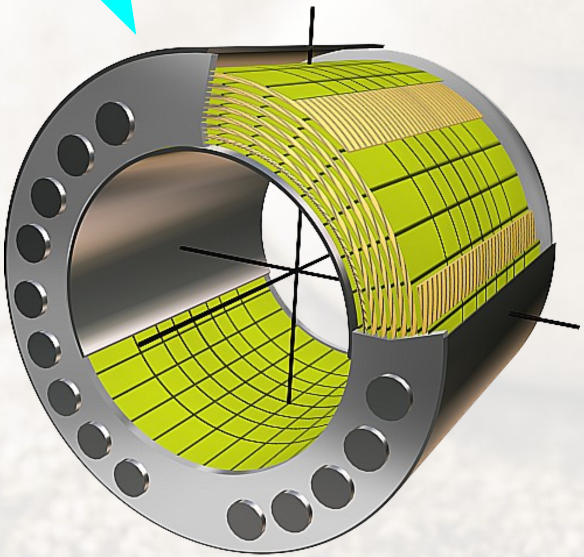
ionization collected in 7 layers with cathode strip readout,

combined strip size: 10-15 mm

Coordinate resolution ~ 2mm

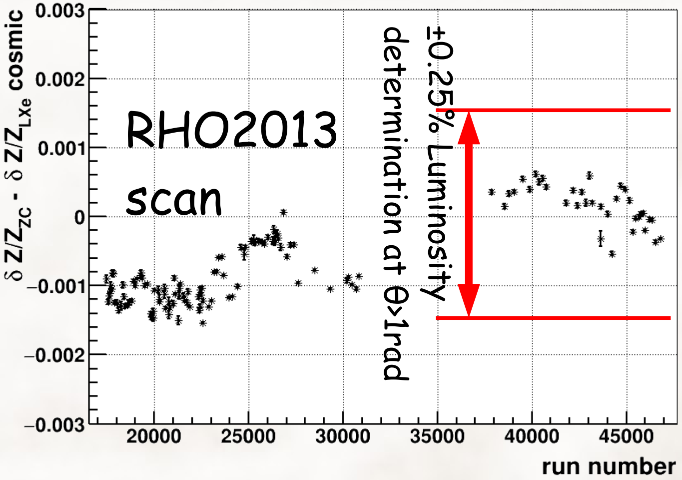
strip precision, coordinate biases ~ 100 μm should give ~0.1% in Luminosity determination

Can be spoiled by noise environment



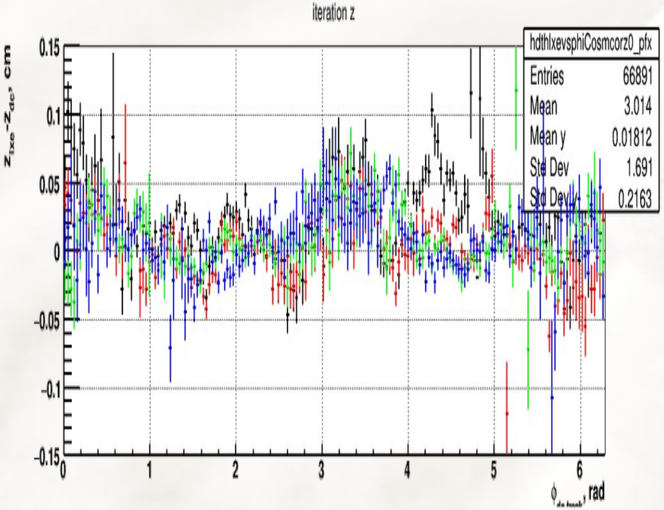
Precision of fiducial volume

Monitoring of z-measurement between ZC vs LXe



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

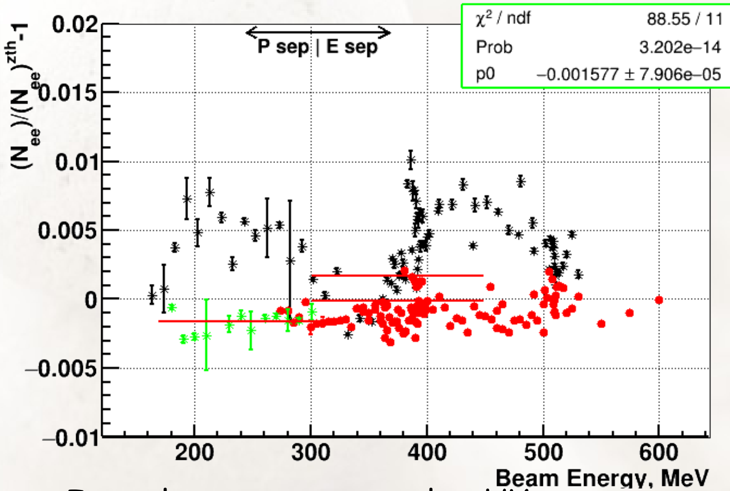
DC tracks vs LXe points



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

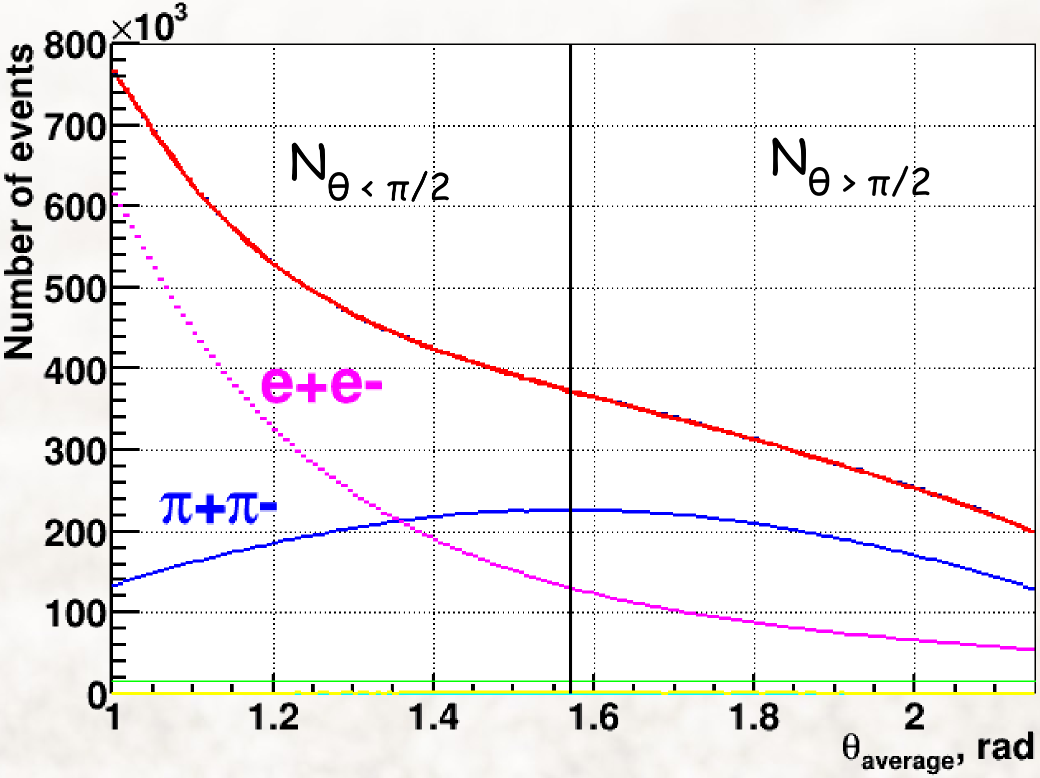
Systematic uncertainty to $|F_\pi|^2$

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)

Forward backward charge asymmetry

dσ/dθ spectra



Asymmetry definition:

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

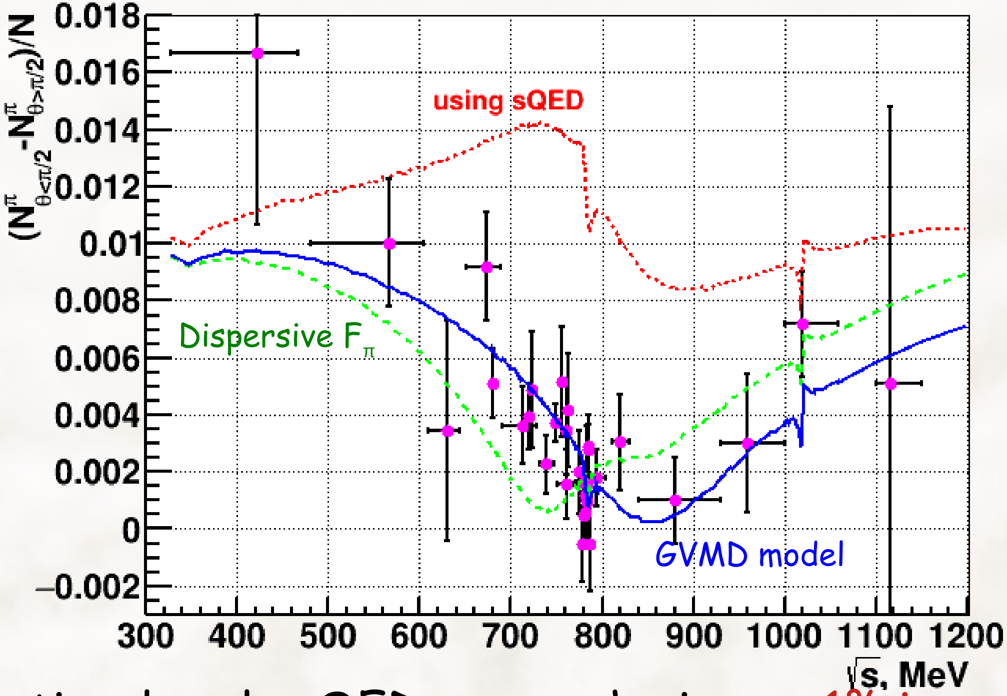
Sensitive to:

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

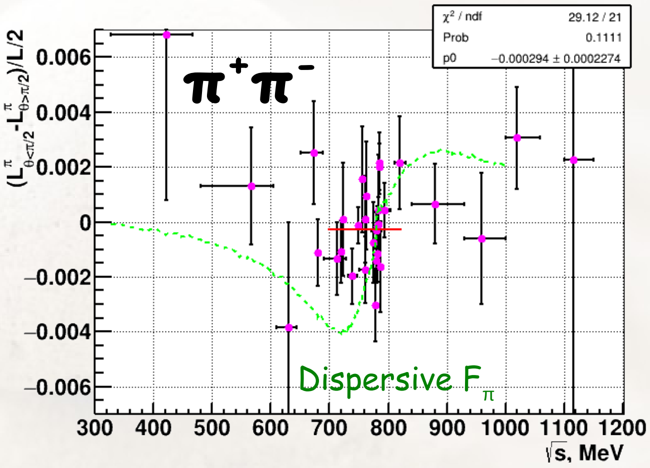
At first try:
1% inconsistency for π+π- was observed between data and MC prediction

Charge asymmetry in e+e- -> π+π-

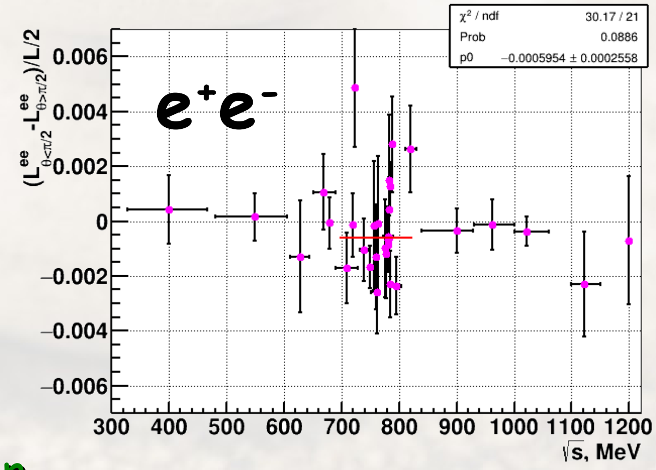
$A = (N_{\theta<\pi/2} - N_{\theta>\pi/2})/N$



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 √s = 0.7-0.82 GeV:

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

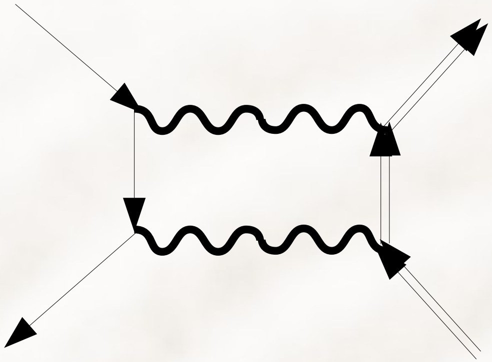
e^+e^-: $\langle\delta A\rangle = -0.060 \pm 0.026$ %

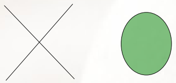
Ensure our θ angle systematics estimation for $|F_\pi|^2$

sQED assumptions for radiative corrections

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

Scalar QED simplification:
Loop integral without
Formfacor in vertices

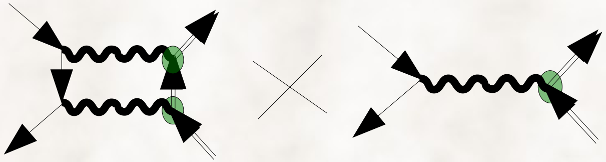




$A = \text{sQED}*F(s)$

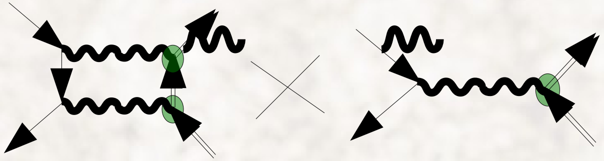
Proper way $A \sim \int F(q_1)F(q_2)$
gives x10 enhancement

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

$F\pi$ within different θ selection

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

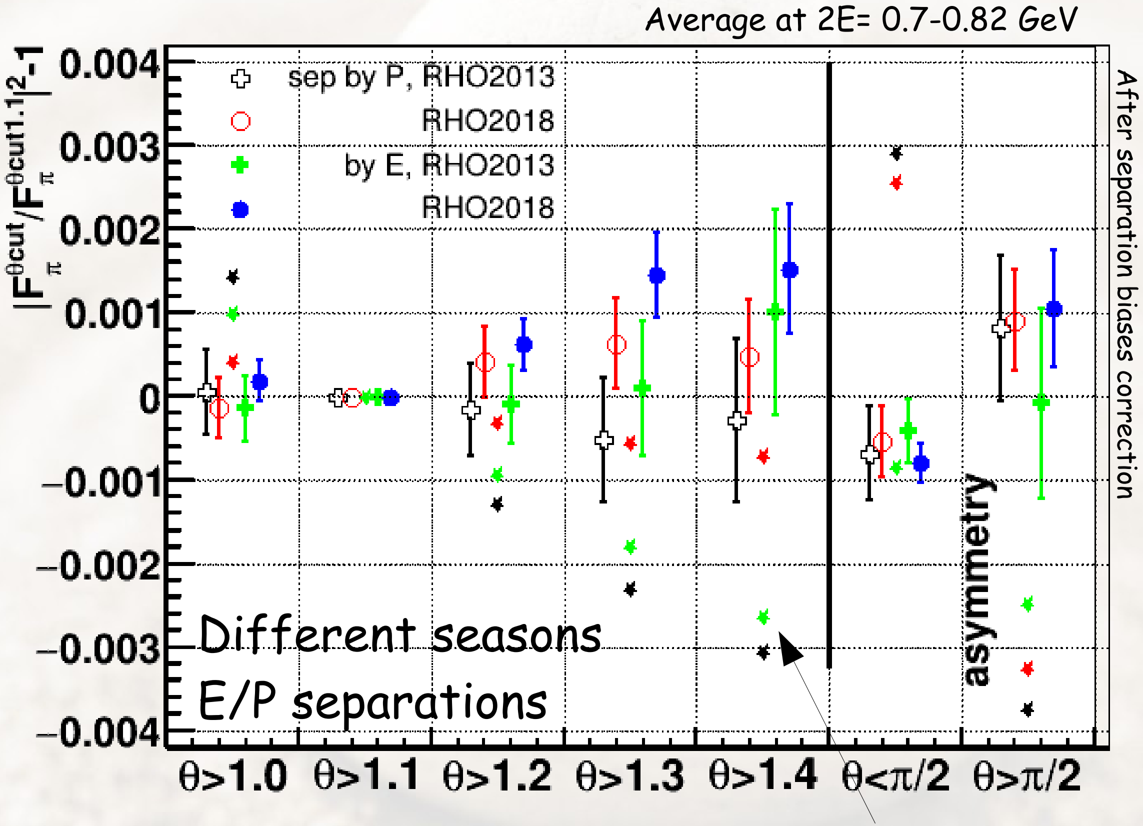
or asymmetrical selection $1 < \theta^{event} < \pi/2$ (or $\pi/2 < \theta^{event} < \pi-1$)

$|F_\pi|^2$ 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)

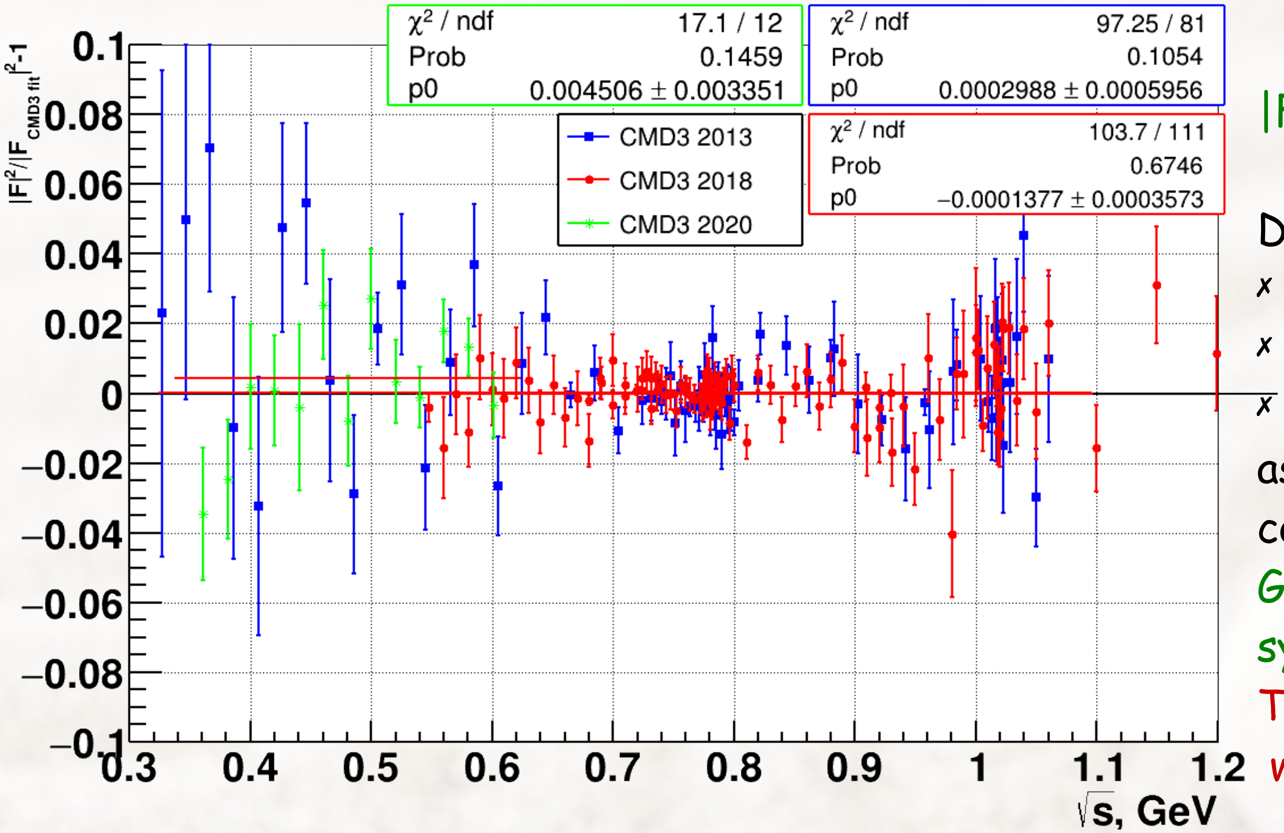
Simplest possible systematics in θ angle:
- Z – length mis-calibration
- Θ^{event} common bias

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



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

Consistency checks



$|F_\pi|^2$ 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

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

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

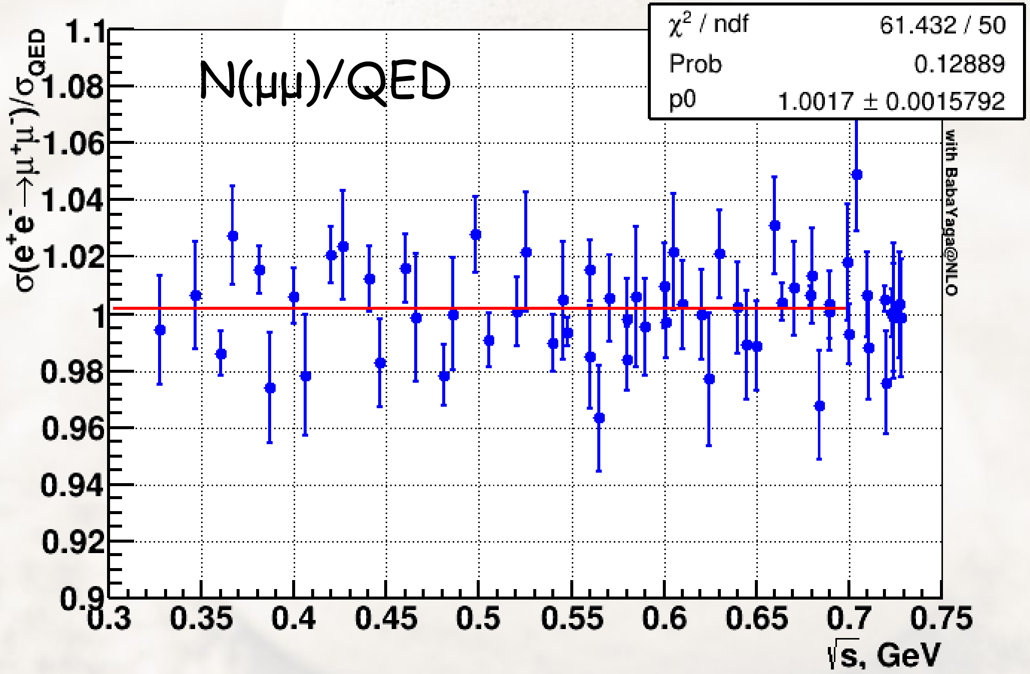
LOW2020/RHO2013 Δ = -0.5 ± 0.6 %

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

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 :   Δ = +0.17 ± 0.16 %



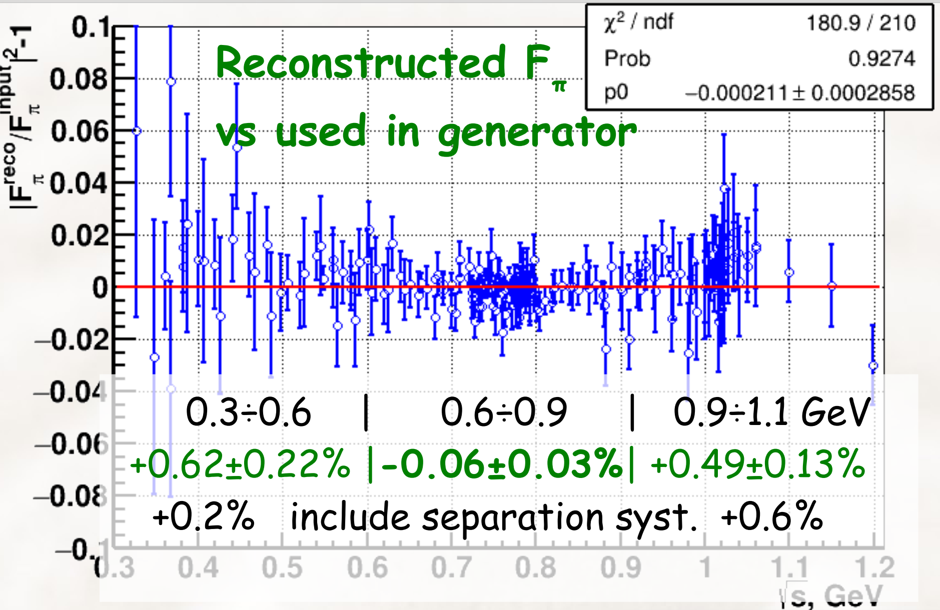
Many others self consistency checks were performed

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)

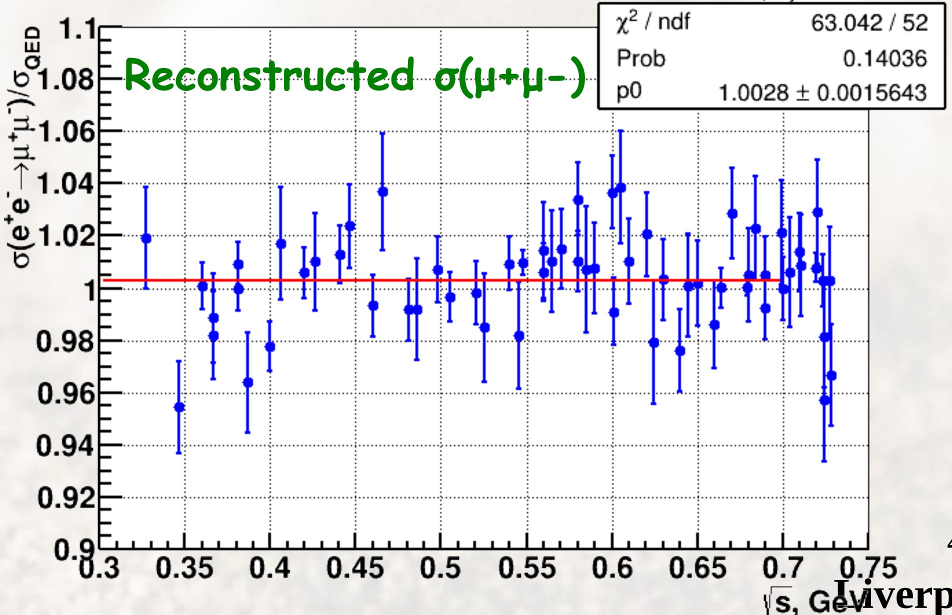
Same full analysis as for the data:
- efficiencies reconstructions,
- particle separation, etc
- same scripts,
- same intermediate files, etc

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



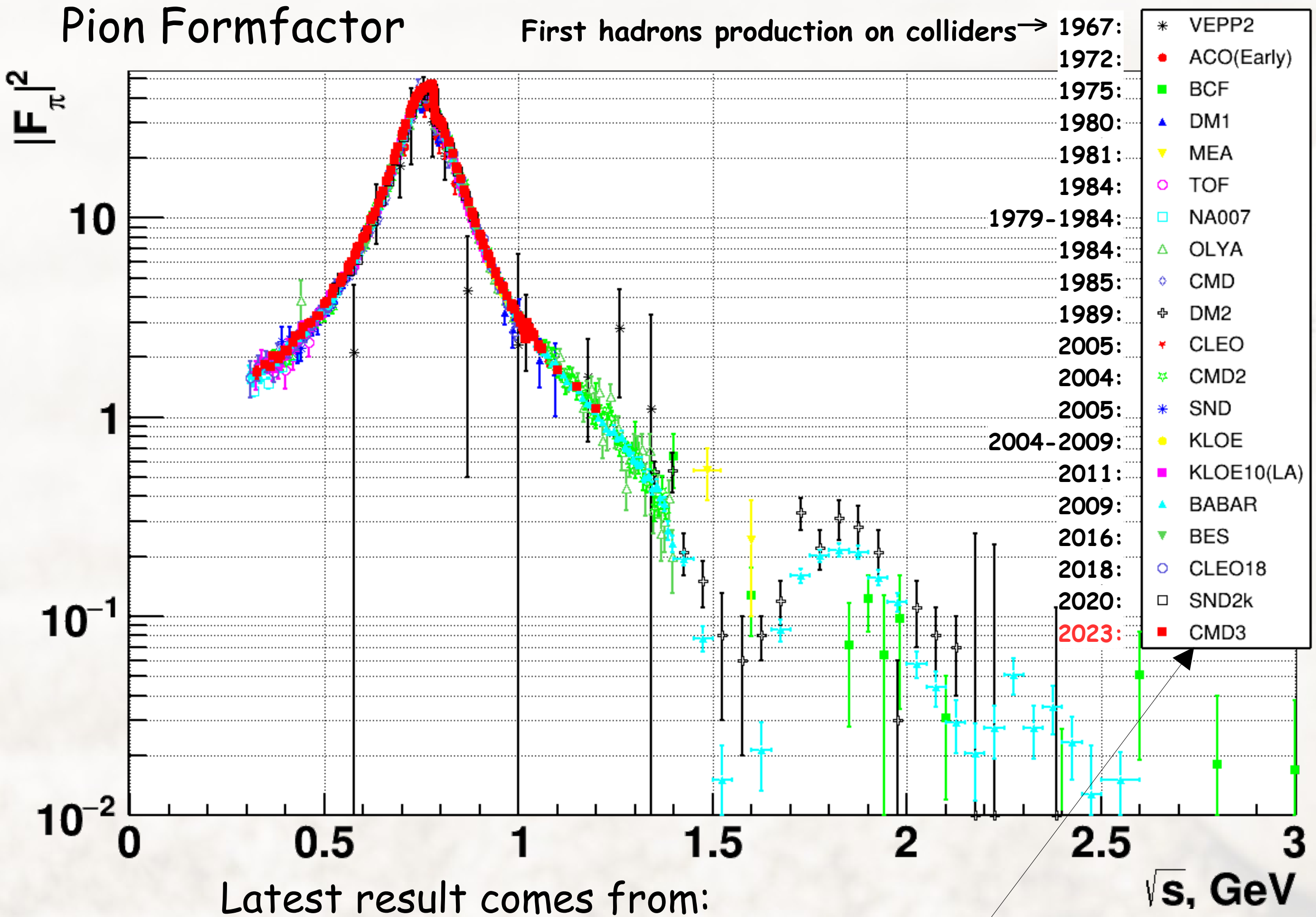
Reconstructed F_π vs used in generator

0.3÷0.6 | 0.6÷0.9 | 0.9÷1.1 GeV
+0.62±0.22% | **-0.06±0.03%** | +0.49±0.13%
+0.2% include separation syst. +0.6%



Reconstructed σ(μ+μ-)

e+ e− → π+ π− today



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

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%

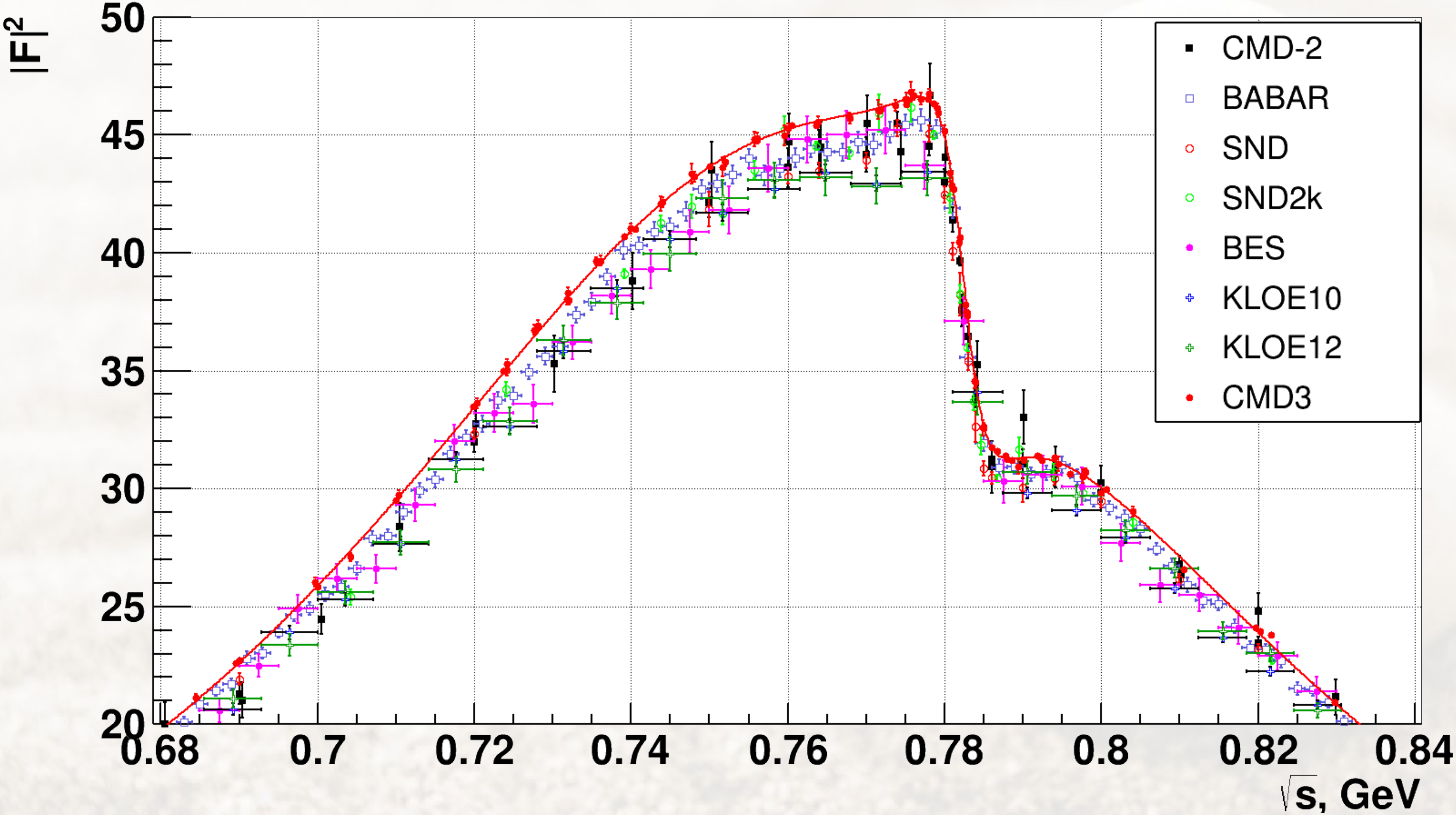
New direct data:

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

CMD-3: 0.7%

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

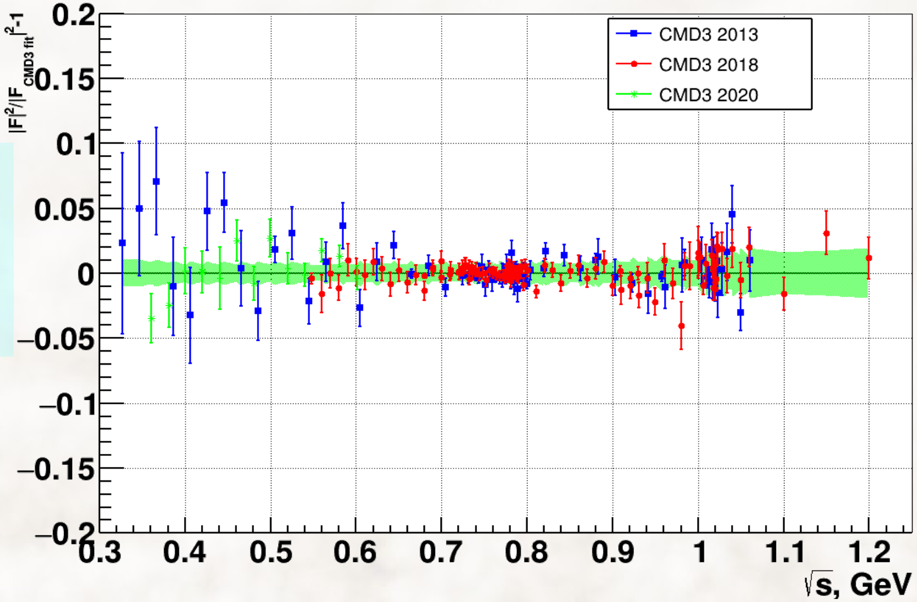
Other experiments



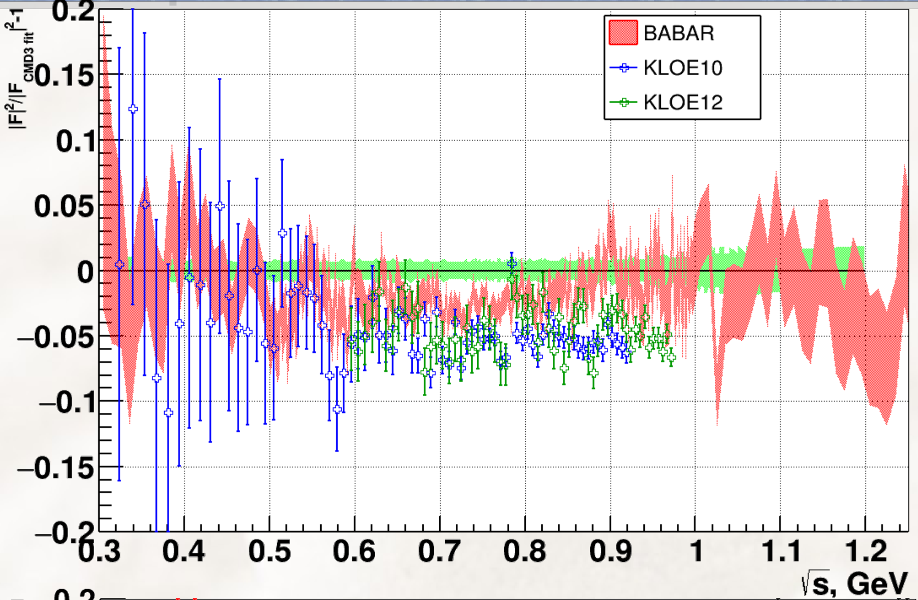
CMD-3 vs other experiments

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

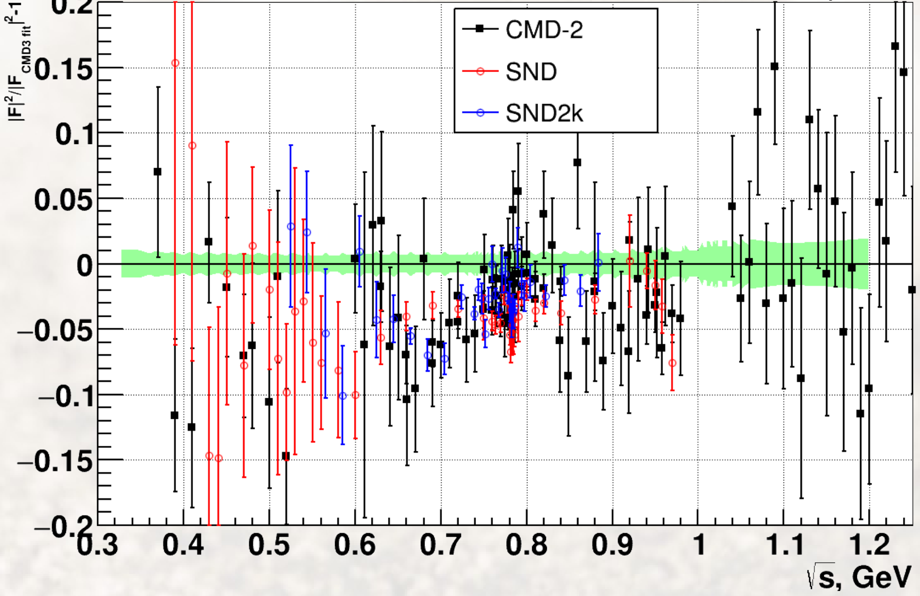
CMD-3



vs ISR



vs direct scan

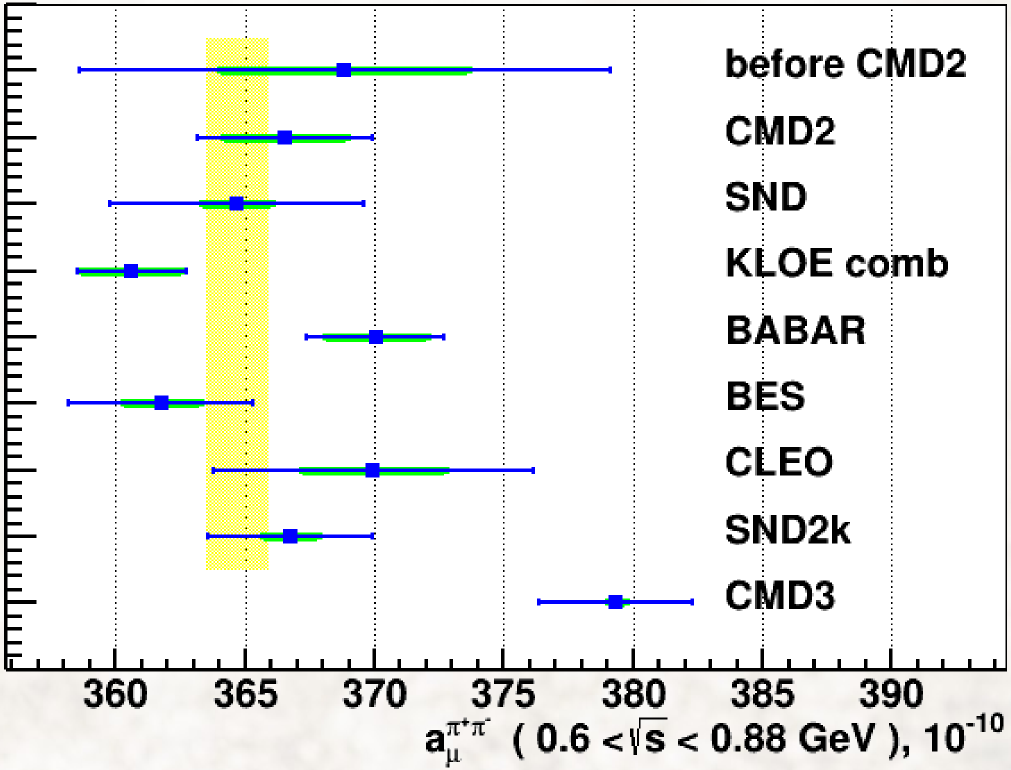


CMD-3

- ✗ 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}

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

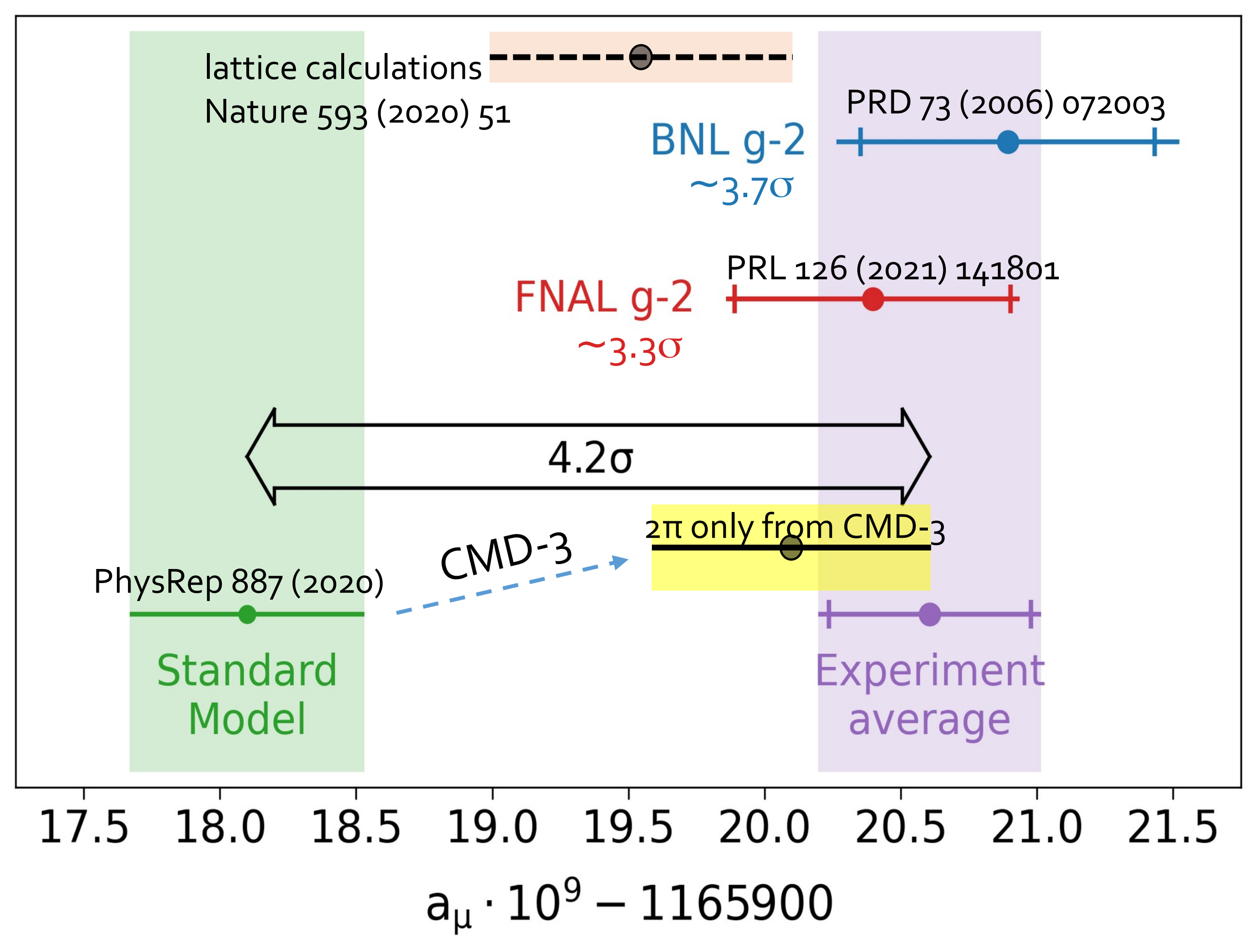


$0.6 < \sqrt{s} < 0.88$ GeV

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



If it will be only CMD-3 than SM will be solved.
But CMD-3 is only one now over many other experiments (BaBar, KLOE, BES, CMD-2, SND, ...)

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

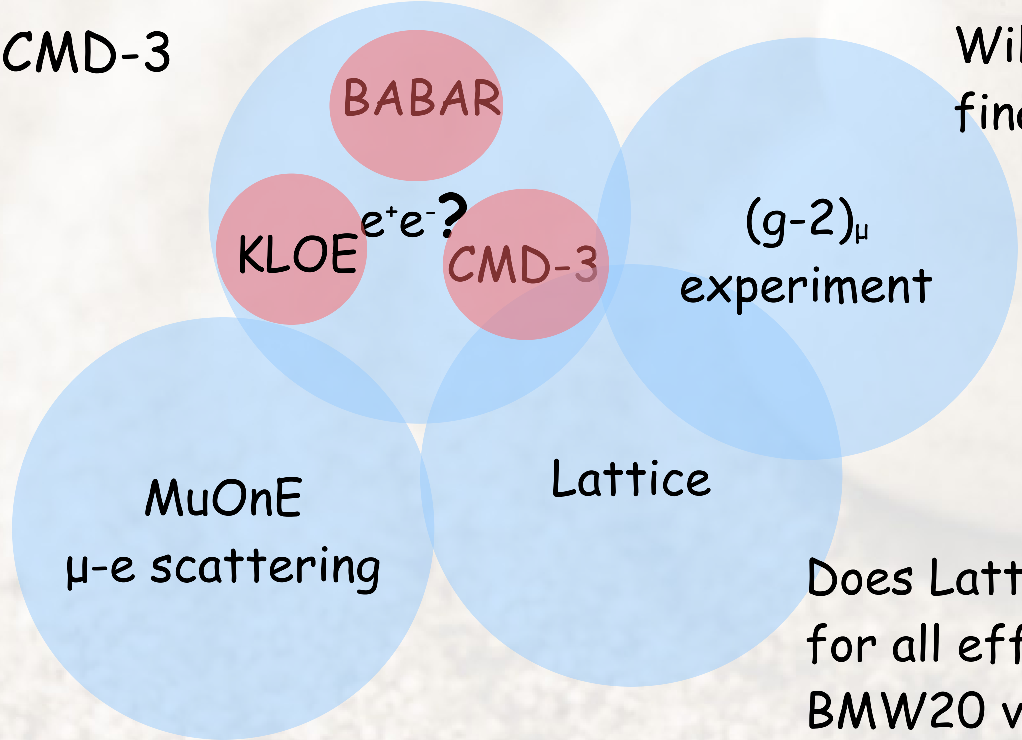
"Like an elephant in a china shop" ESMA 2017

Puzzles in puzzle

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



BABAR

KLOE

e^+e^-?

CMD-3

$(g-2)_\mu$
experiment

MuOnE
μ-e scattering

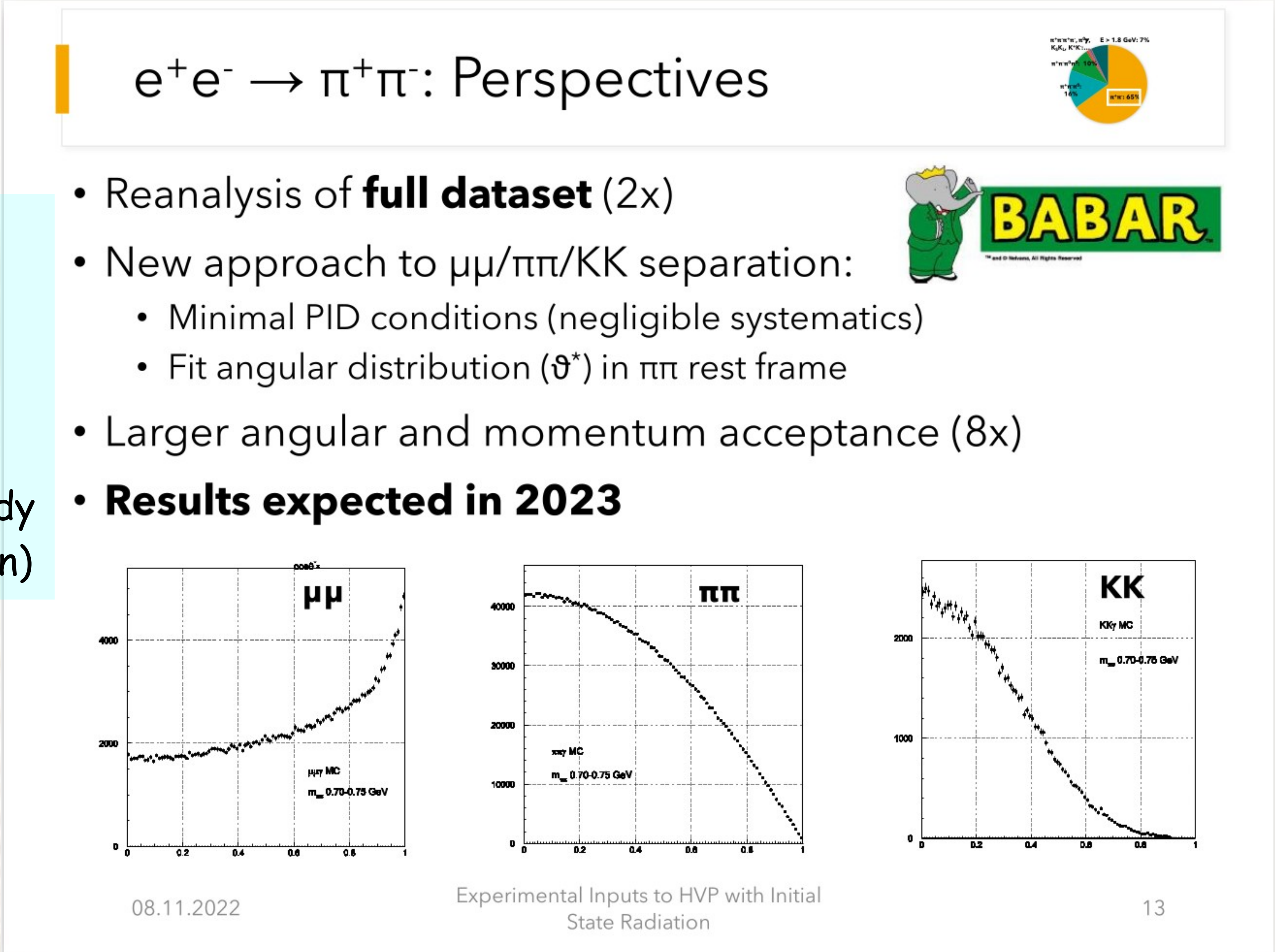
Lattice

Hard effort against systematics

Does Lattice account for all effects?
BMW20 vs others

BaBar

- ✗ Using new particle separation method
- ✗ x7 in statistics
- ✗ will be interesting to see new asymmetry study (stress of MC prediction)



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

- 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**

08.11.2022

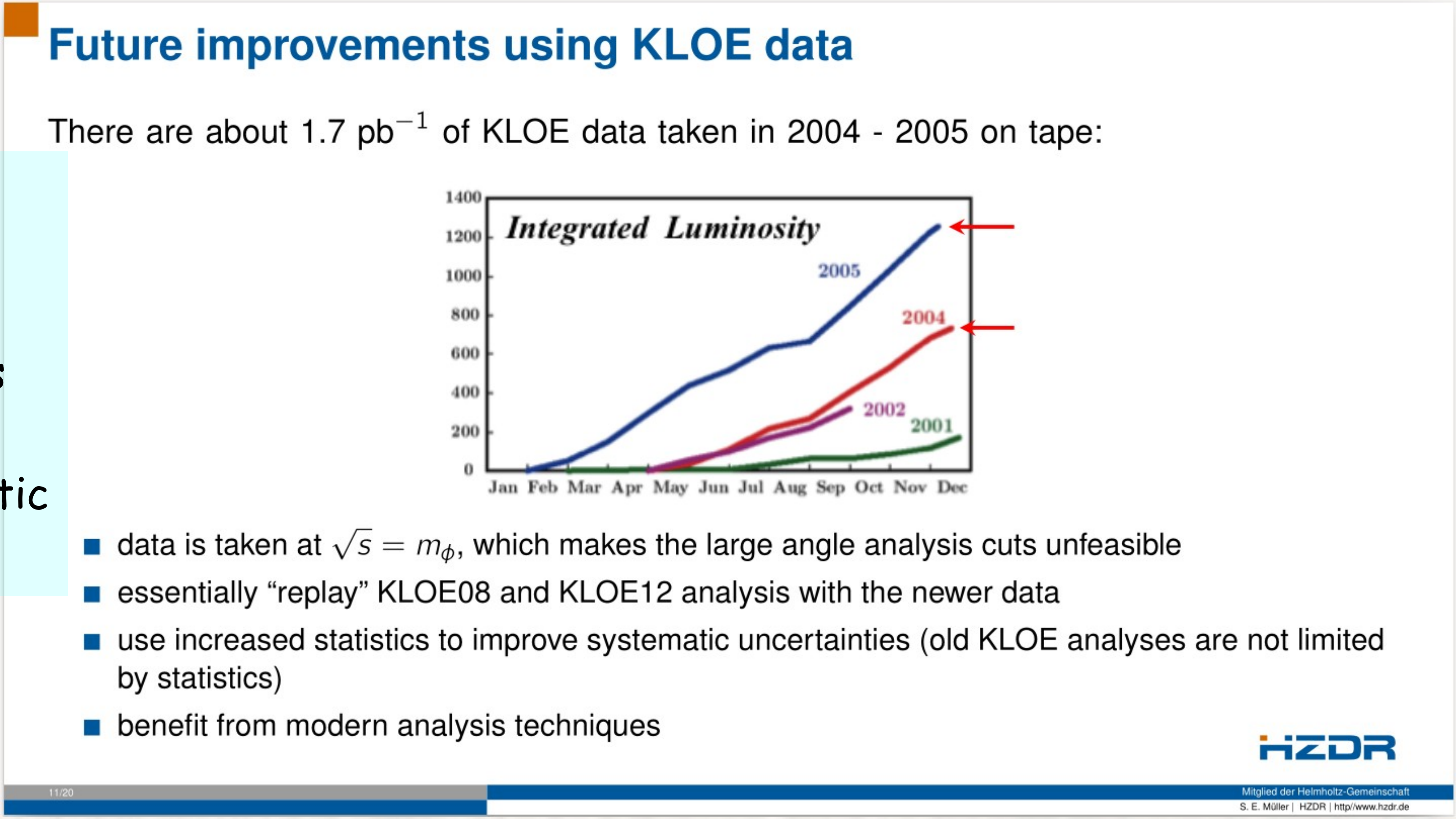
Experimental Inputs to HVP with Initial State Radiation

13

Workshop on Muon Precision Physics,7-9 November 2022, Liverpool
Stefan Mueller, Status of e+e- data from ISR

KLOE

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



Future improvements using KLOE data

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

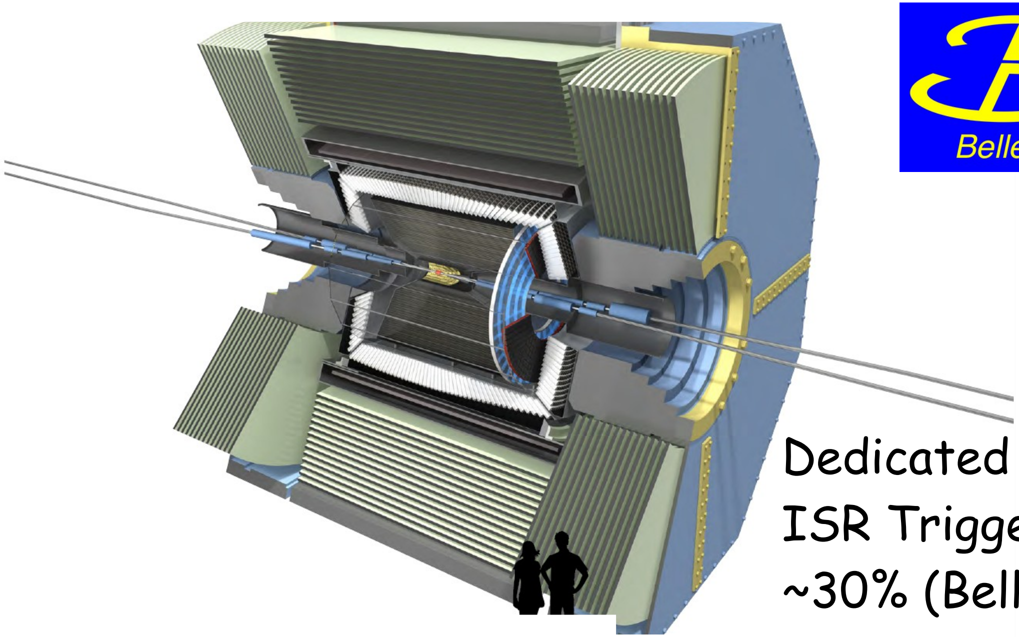
KLOE 2pi activities

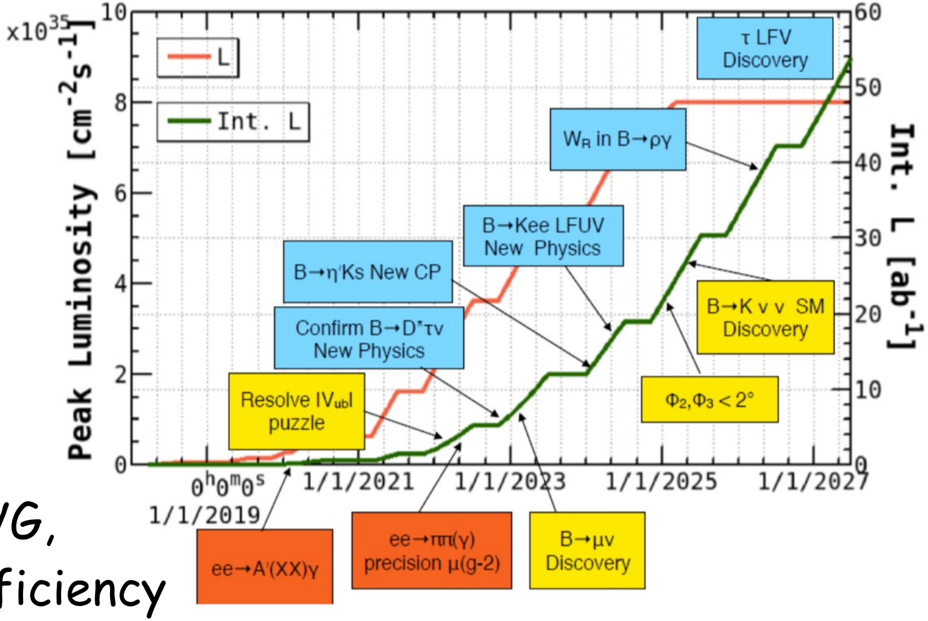
- ✗ New effort to analyse high statistics KLOE 2004/05 data not yet analysed (L~1.7 fb-1)
- ✗ New blind analysis, unbiased from previous results of KLOE & other experiments
- ✗ Significant involvement from theoretical groups

  => 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

Belle2 ISR program

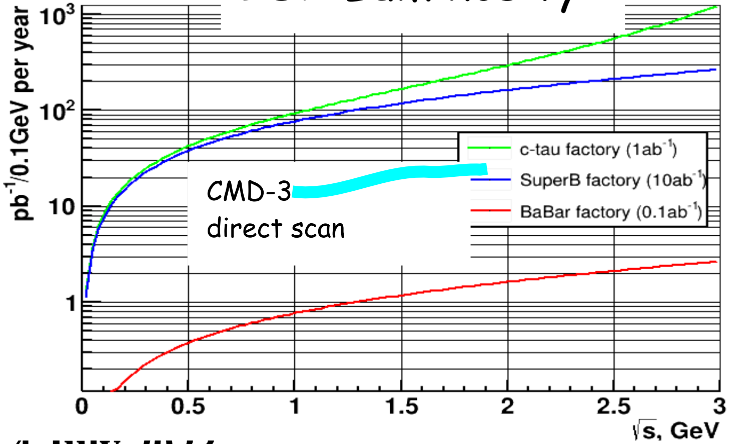
x50-100 of Belle,BaBar statistics



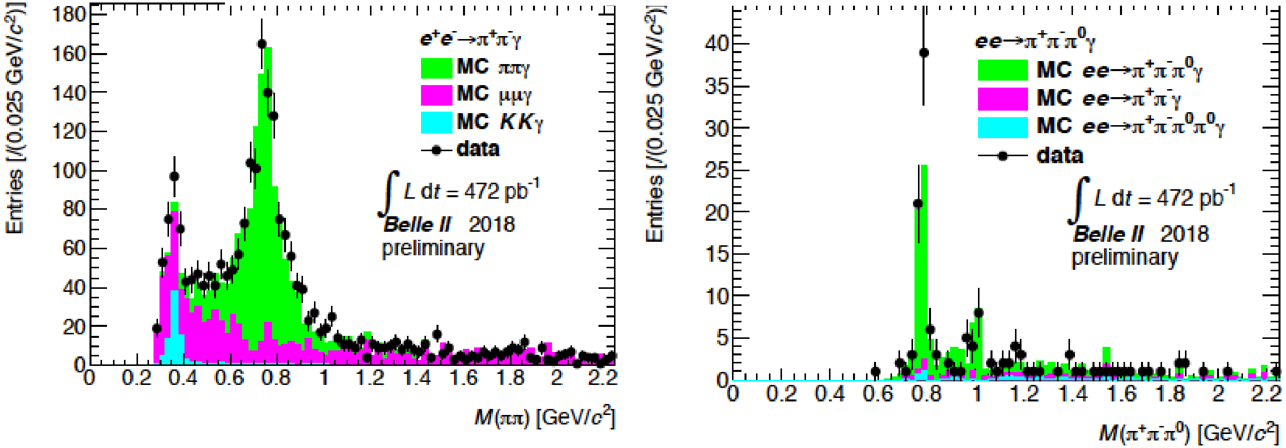


Dedicated ISR WG,
ISR Trigger inefficiency
~30% (Belle) → <1% (Belle2)

ISR Luminosity



First sample of ρ,φ,ω by ISR



R(s) in dispersion relations (a_μ^{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...

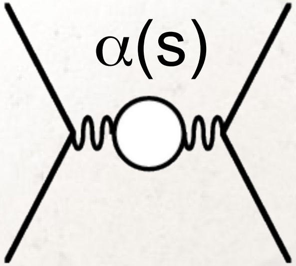
Hall of Fame:

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

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

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

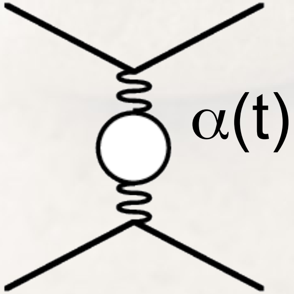
$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\cdot\sigma(s)_{(e^+e^-\to had)}$$



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

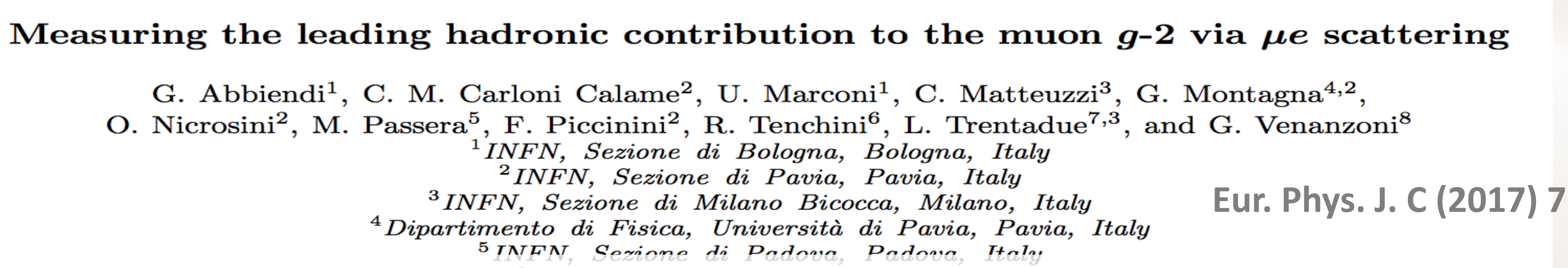
Reference papers

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

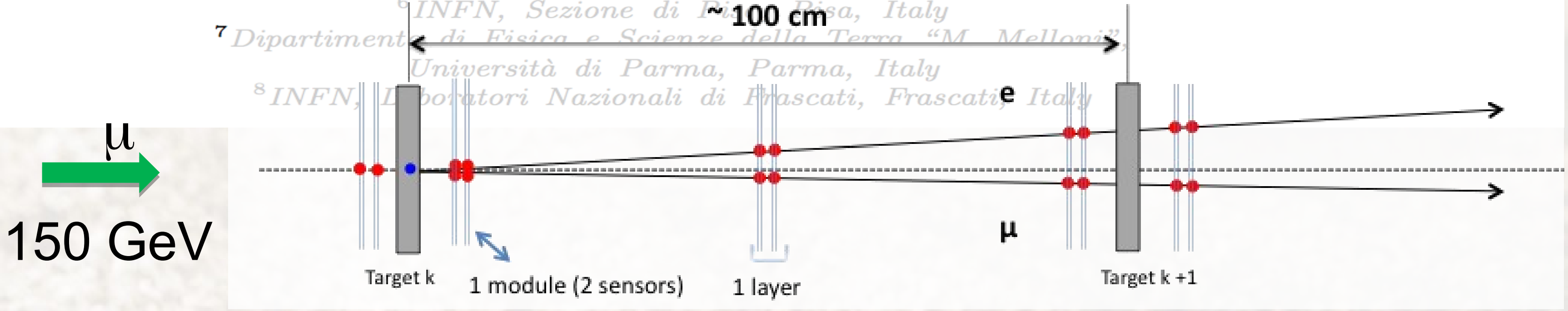


Measuring the leading hadronic contribution to the muon g-2 via μe scattering

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

2π analysis more details:

Presentation at the TI seminar, 27 March 2023:

https://indico.fnal.gov/event/59052/

E-Print: 2302.08834 [hep-ex]

$|F_\pi|^2$ 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)

After quite conservative θ-angle related contribution, the radiative correction is the next biggest part to the systematic table

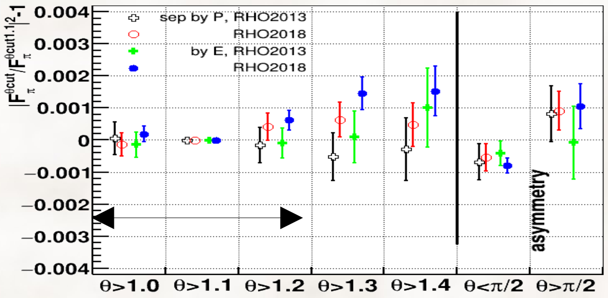
Indirectly theoretical knowledge present in the particle separation and fiducial volume determination as the consistency check

Detection volume consistency check

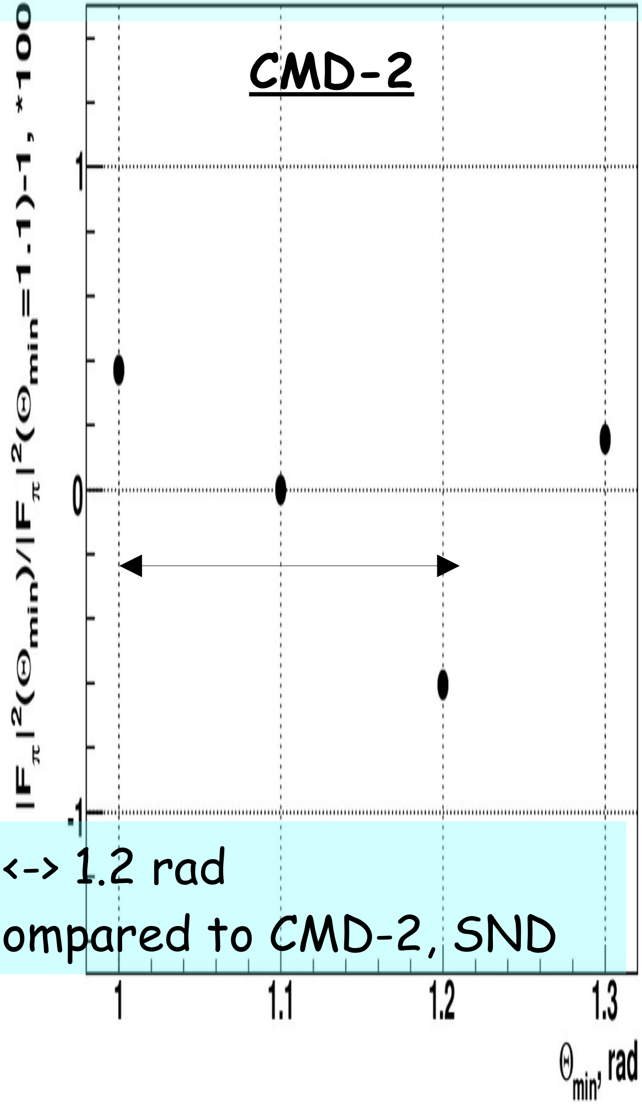
Variation of $\delta|F|^2$ vs θ-angle selection cut ($\theta_{cut} < \theta_{event} < \pi-\theta_{cut}$)

Same scale over Y-axis

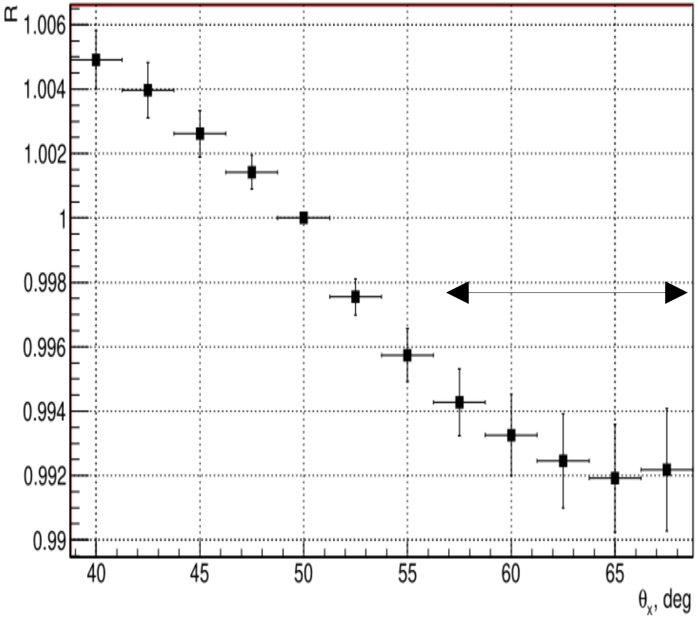
CMD-3



CMD-2



SND@VEPP-2000

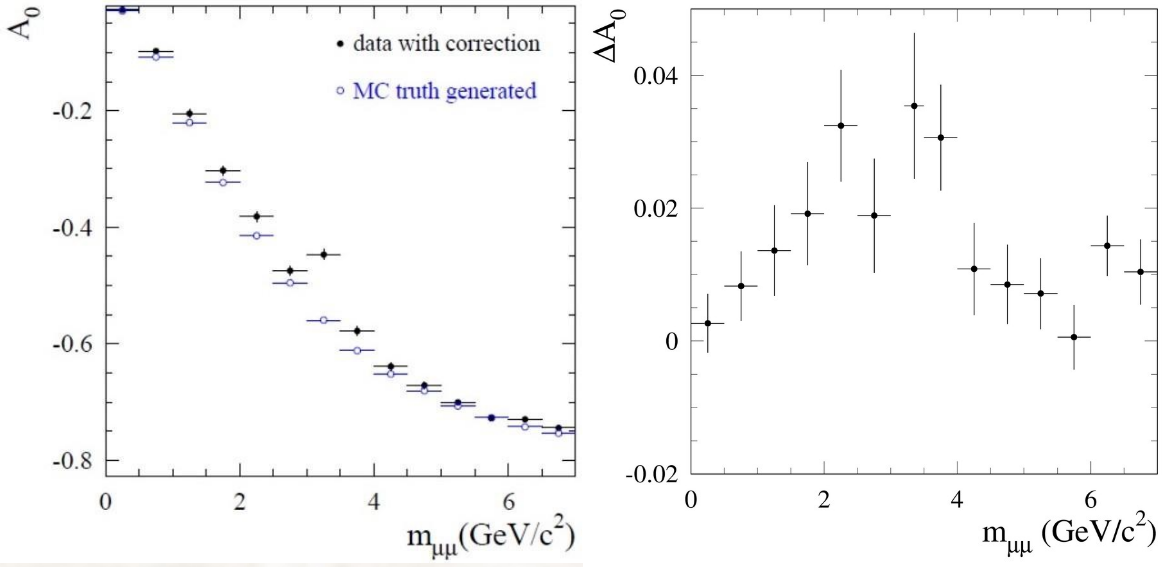


Changes of $\delta|F|^2/|F|^2$ vs θ_{cut} 1 <-> 1.2 rad
~10 times smaller for CMD-3 compared to CMD-2, SND

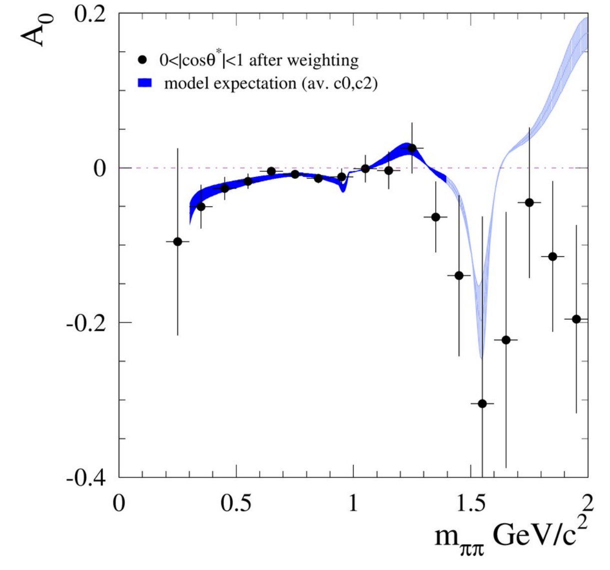
Asymmetry in BaBar

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

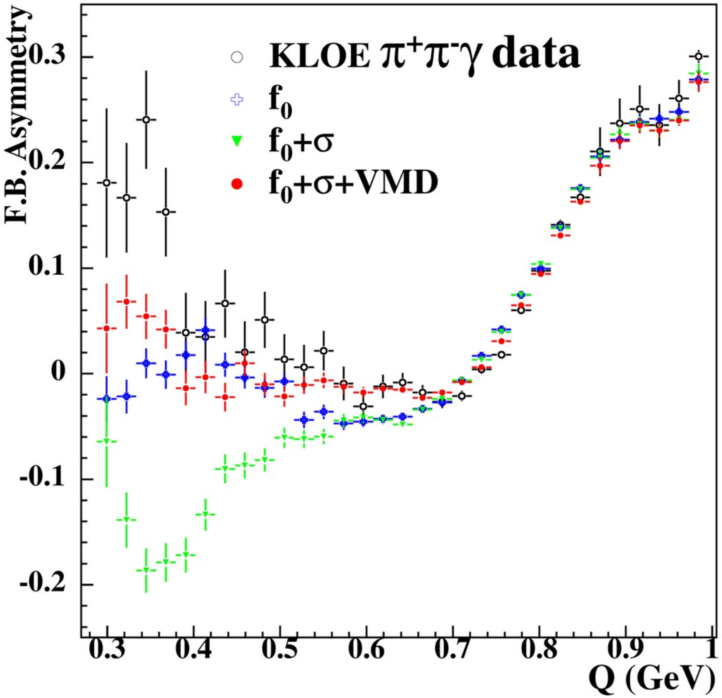
$$A = \frac{N(\theta_{\pi^+} > 90^\circ) - N(\theta_{\pi^+} < 90^\circ)}{N(\theta_{\pi^+} > 90^\circ) + N(\theta_{\pi^+} < 90^\circ)}$$

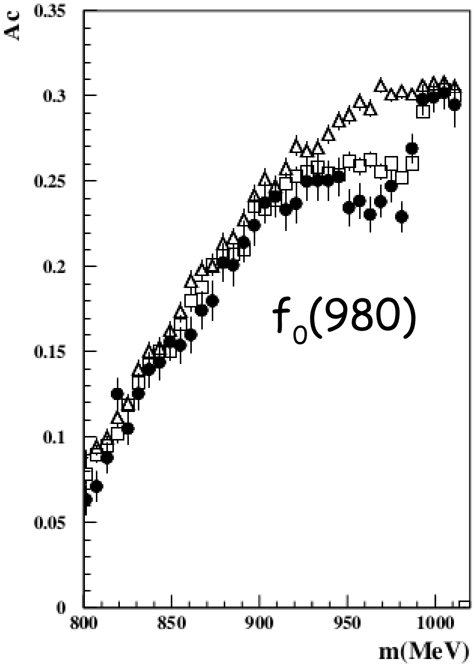
$\theta_\pi, \theta_\gamma > 45^\circ$

At φ- peak

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

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

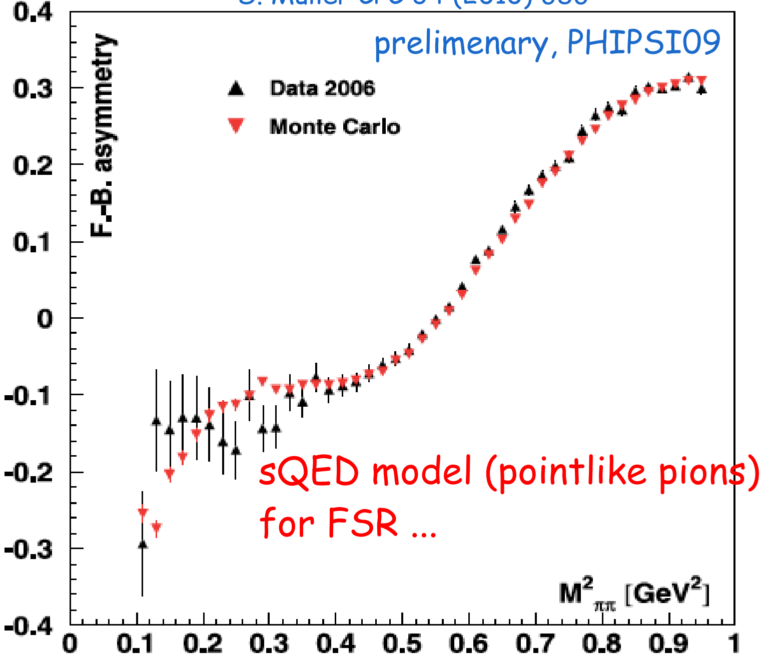




2006 φ off-peak data

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

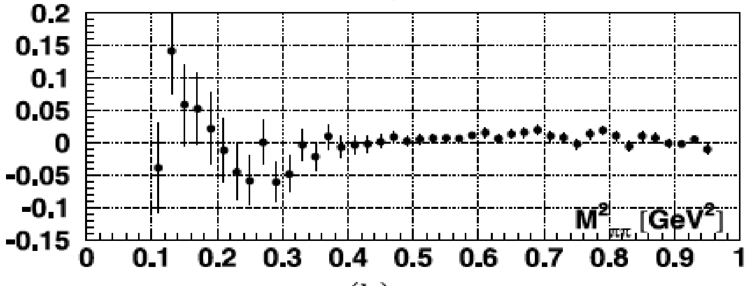
S. Muller CPC 34 (2010) 686



prelimenary, PHIPSI09

sQED model (pointlike pions) for FSR ...

Inconsistency at 1-2%



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

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

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

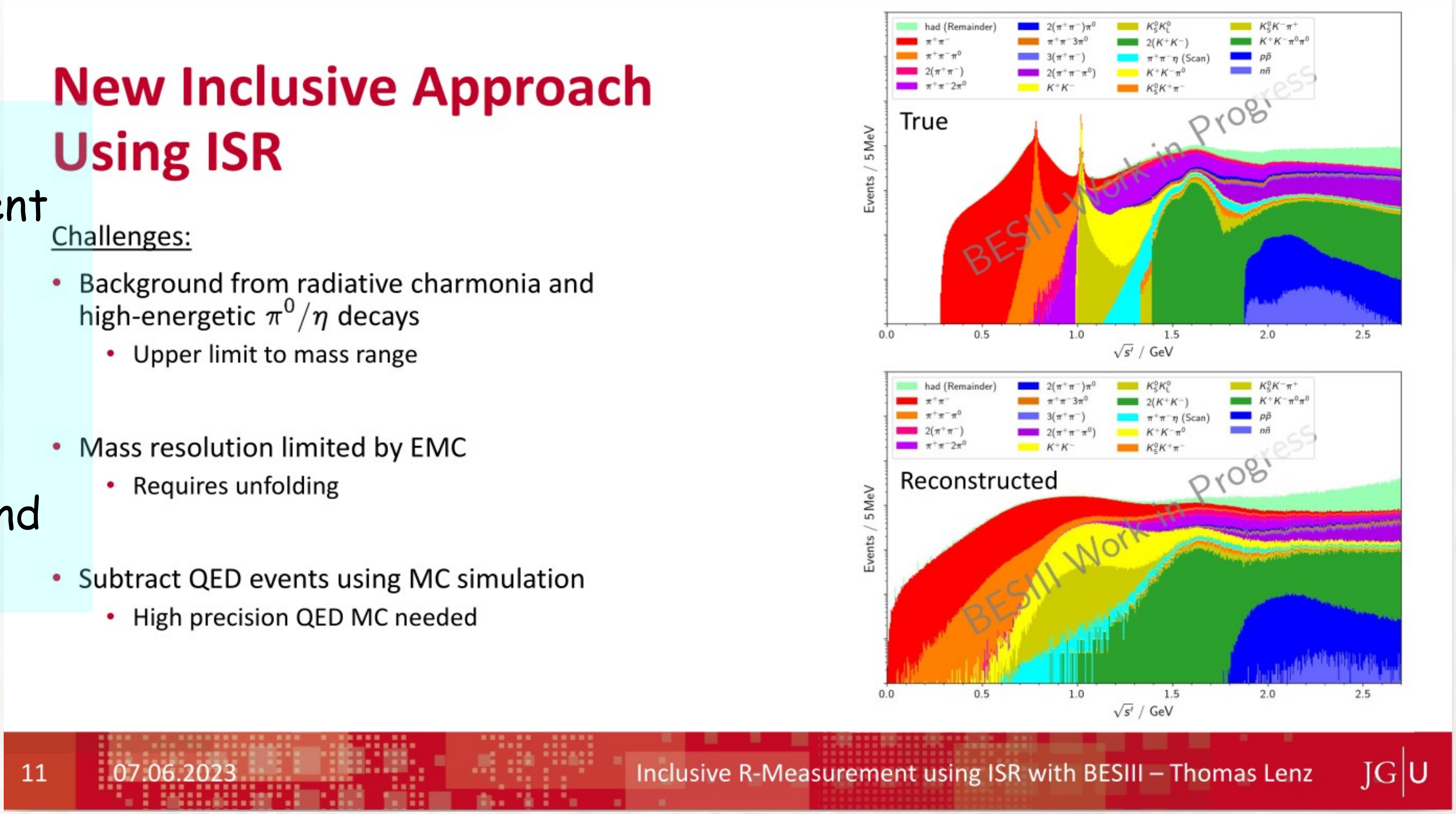
Brem, DR , UχPT , LSM, RχPT , KLM etc ....

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

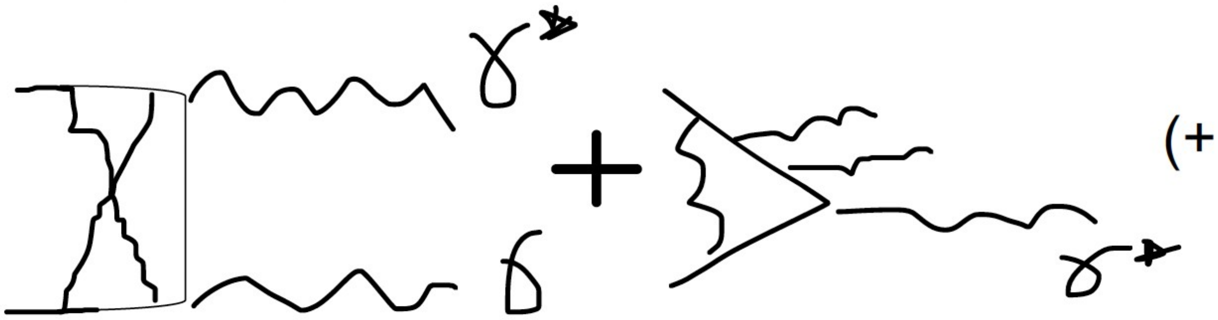


New Inclusive Approach Using ISR

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

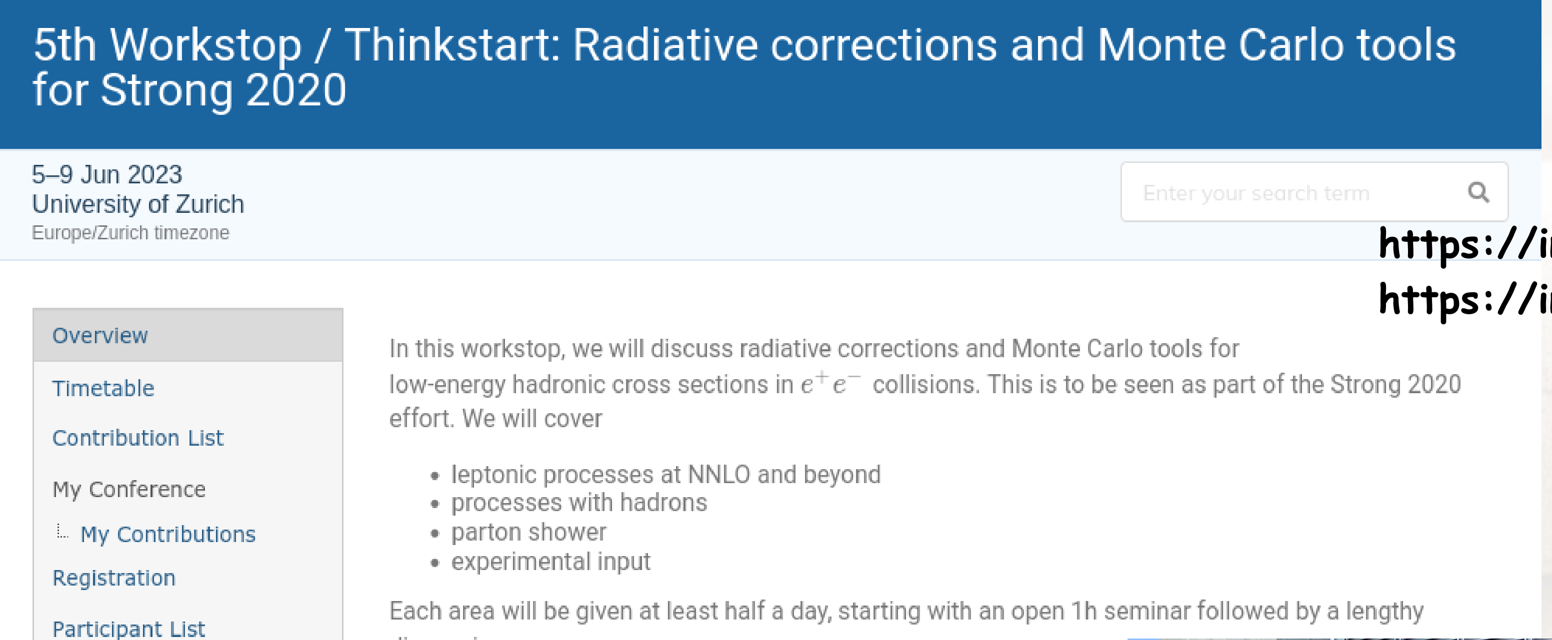
Towards NNLO MC generator ….



(+ others…)

- STRONG2020 (Virtual) meeting: 24-26 November 2021 (https://agenda.infn.it/event/28089/)
- N³LO 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

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 gath
who actively work on this topic to make very concrete progress. It sho
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 broad
the workstop.

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

The effort to bring forward MC tools precision!
Towards NNLO (and above) precision
Can help mitigate questions to theoretical parts of ISR & scan measurements

5th WorkStop

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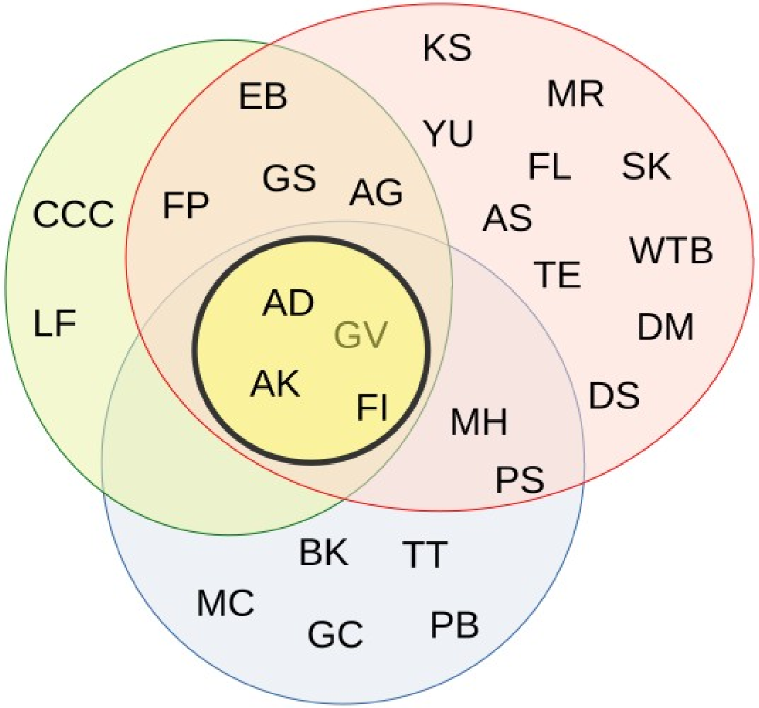
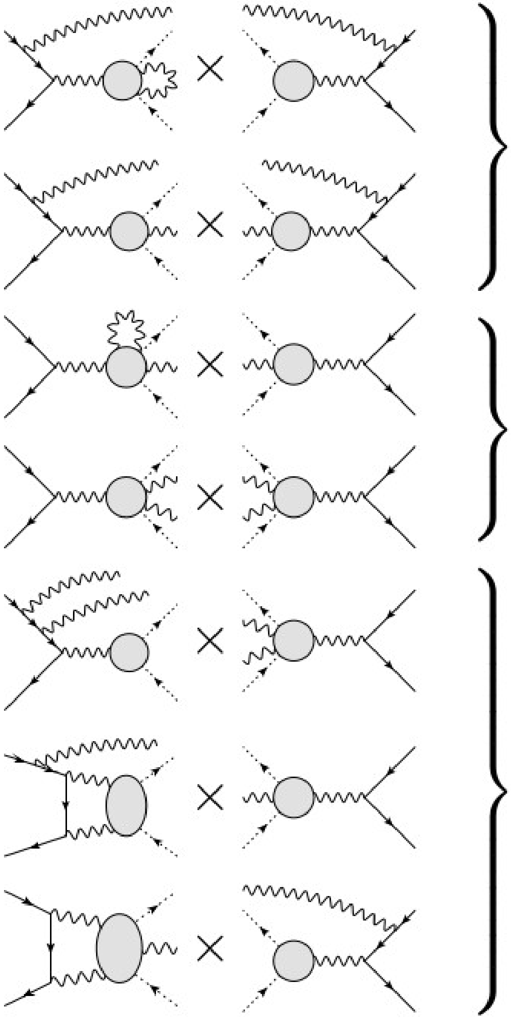
WP1:	QED for leptons at NNLO
WP2:	Form factor contributions at N^{3}LO
WP3:	Processes with hadrons
WP4:	Parton showers
WP5:	Experimental input



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



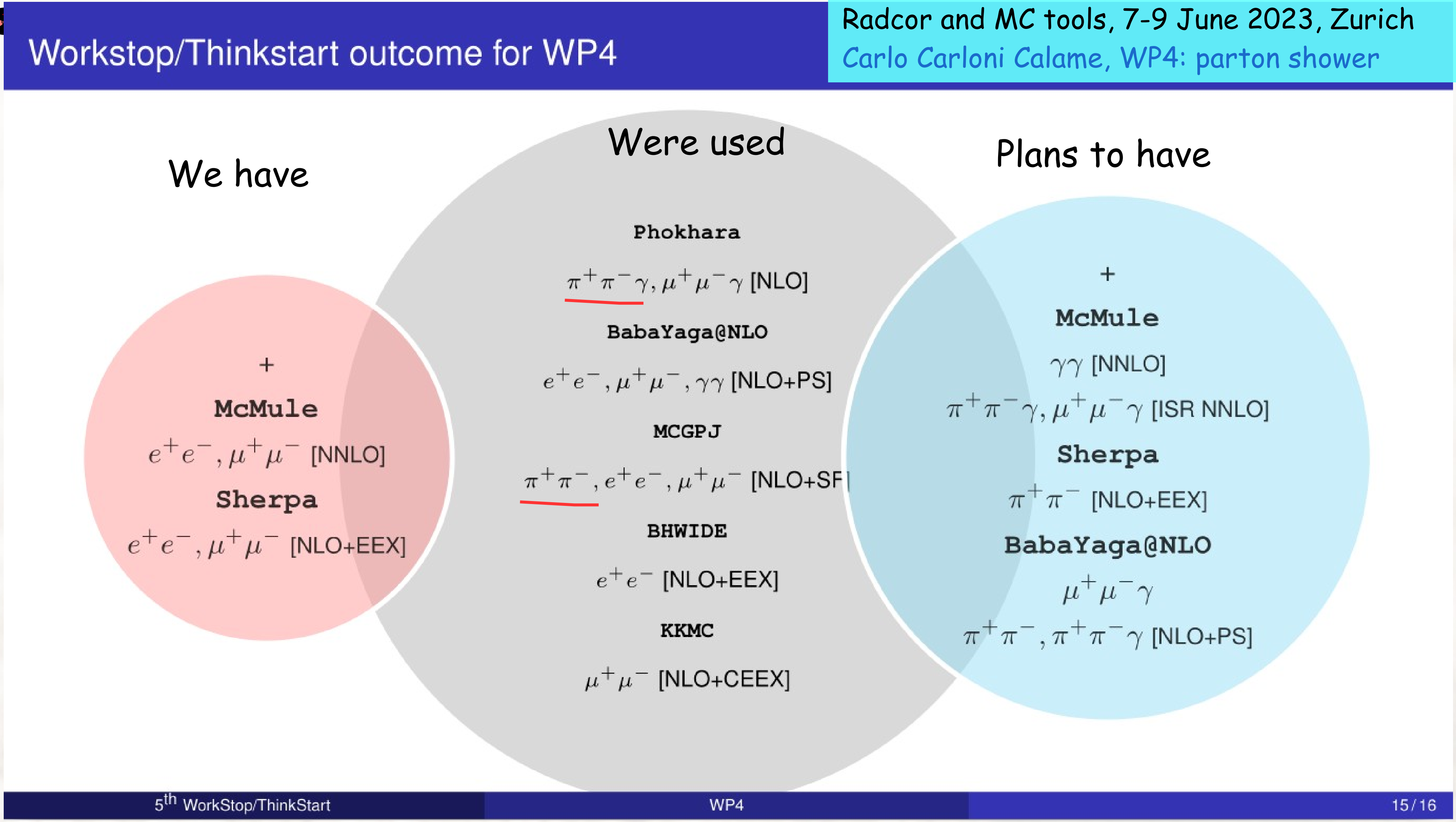
PHOKHARA: sQED + resonance approximations
dispersive approach by Colangelo et al.

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

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



Workstop/Thinkstart outcome for WP4

We have

+

McMule

$e^+e^-, \mu^+\mu^-$ [NNLO]

Sherpa

$e^+e^-, \mu^+\mu^-$ [NLO+EEX]

Were used

Phokhara

$\underline{\pi^+\pi^-\gamma}, \mu^+\mu^-\gamma$ [NLO]

BabaYaga@NLO

$e^+e^-, \mu^+\mu^-, \gamma\gamma$ [NLO+PS]

MCGPJ

$\underline{\pi^+\pi^-}, e^+e^-, \mu^+\mu^-$ [NLO+SF

BHWIDE

e^+e^- [NLO+EEX]

KKMC

$\mu^+\mu^-$ [NLO+CEEX]

Plans to have

+

McMule

$\gamma\gamma$ [NNLO]

$\pi^+\pi^-\gamma, \mu^+\mu^-\gamma$ [ISR NNLO]

Sherpa

$\pi^+\pi^-$ [NLO+EEX]

BabaYaga@NLO

$\mu^+\mu^-\gamma$

$\pi^+\pi^-, \pi^+\pi^-\gamma$ [NLO+PS]

5th WorkStop/ThinkStart WP4 15/16

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

Radiative corrections

Measurement of $e^{\pm}e^{-} \to \pi^{\pm}\pi^{-}$ 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-)
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)

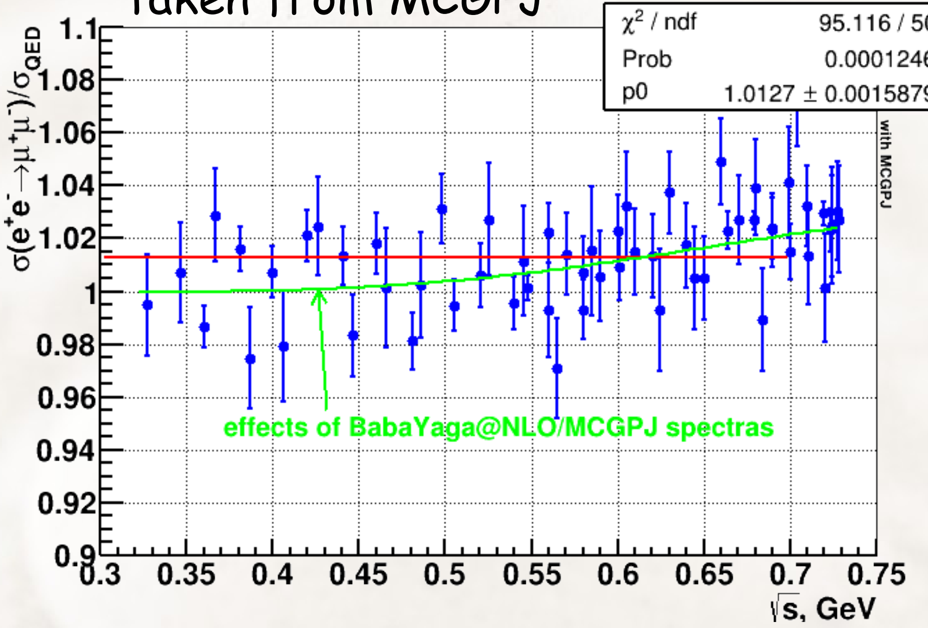
Achieved precision in current analysis is also sensitive
for precision of differential cross sections predictions
e/π separation by momentum requires $d\sigma/dP^{+}dP^{-}$ spectra as initial input
Θ-angle (asymmetry) study requires $d\sigma/d\theta$ spectra

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 √s=0.78 GeV, and rising to 1.5% at 0.9 GeV when using momentum-based separation)

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



2) Experimental asymmetry in e+e-

Data vs BabaYaga@NLO:

δA = -0.060 ± 0.026 %

Data vs MCGPJ

δA = -0.140 ± 0.026 %

BabaYaga@NLO consistent with NNLO MCMule

δA = +0.006 ± 0.003 % at √s=0.76 GeV

<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

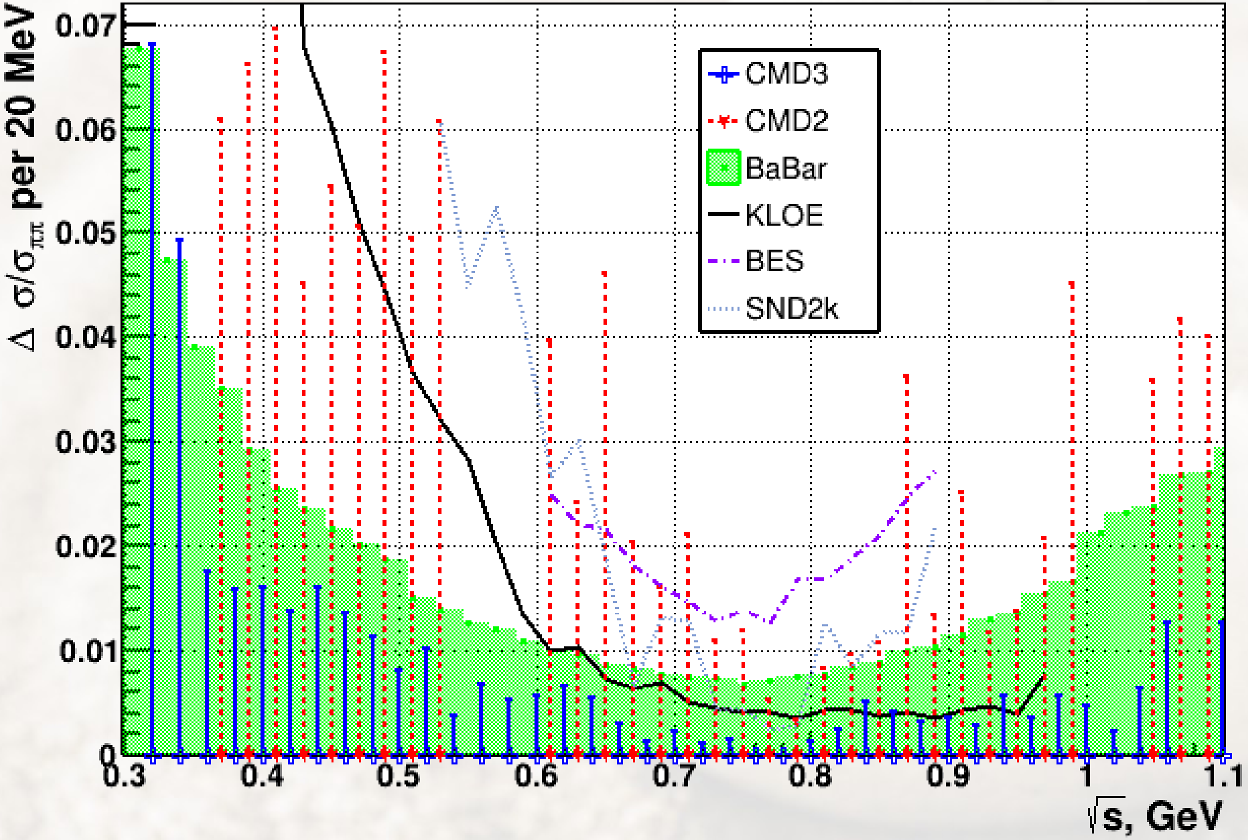
Better NNLO (+VP + next log terms) generators are quite desirable for higher precision

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

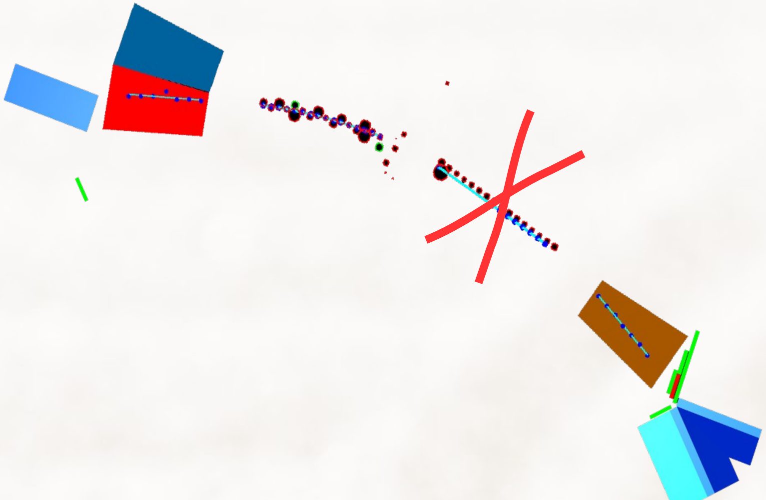
3 seasons of data taking:
RHO2013
RHO2018
LOW2020

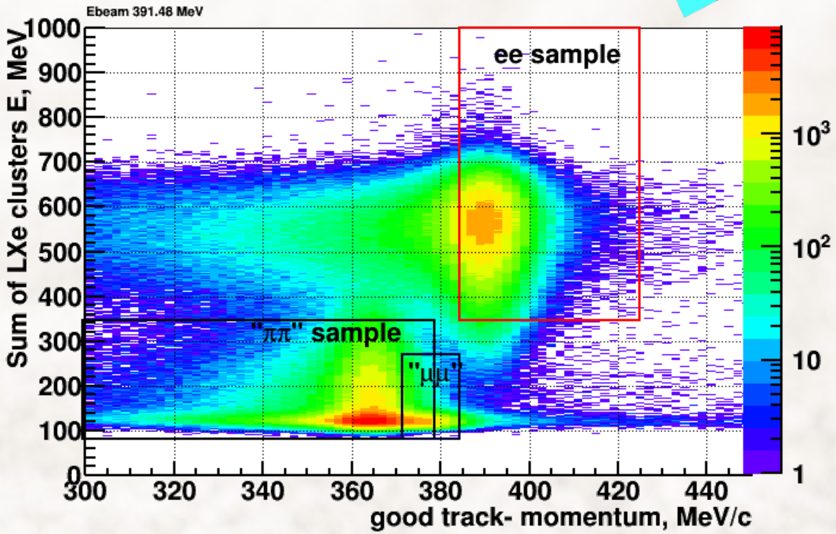


Analysis based on L = 61.9 pb^{-1} at $\sqrt{s}$ < 1 GeV (+25.7 pb^{-1}, 1.0-1.2 GeV)

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

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)

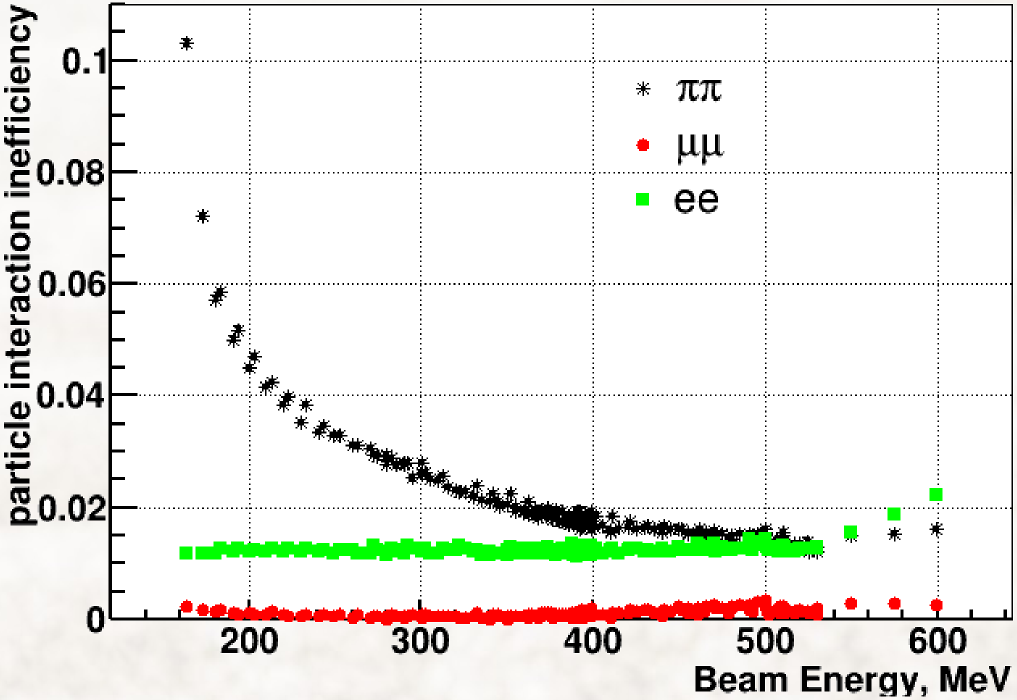
N.B. Correlated inefficiency study was also performed
without requirement on detection of one good track

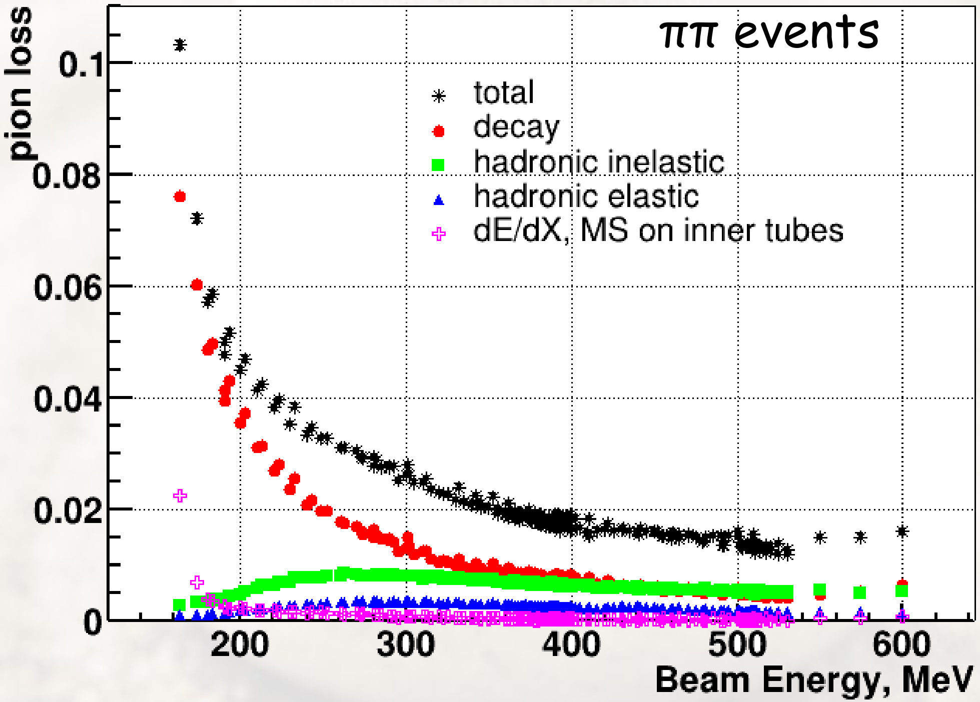
Particle specific losses

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



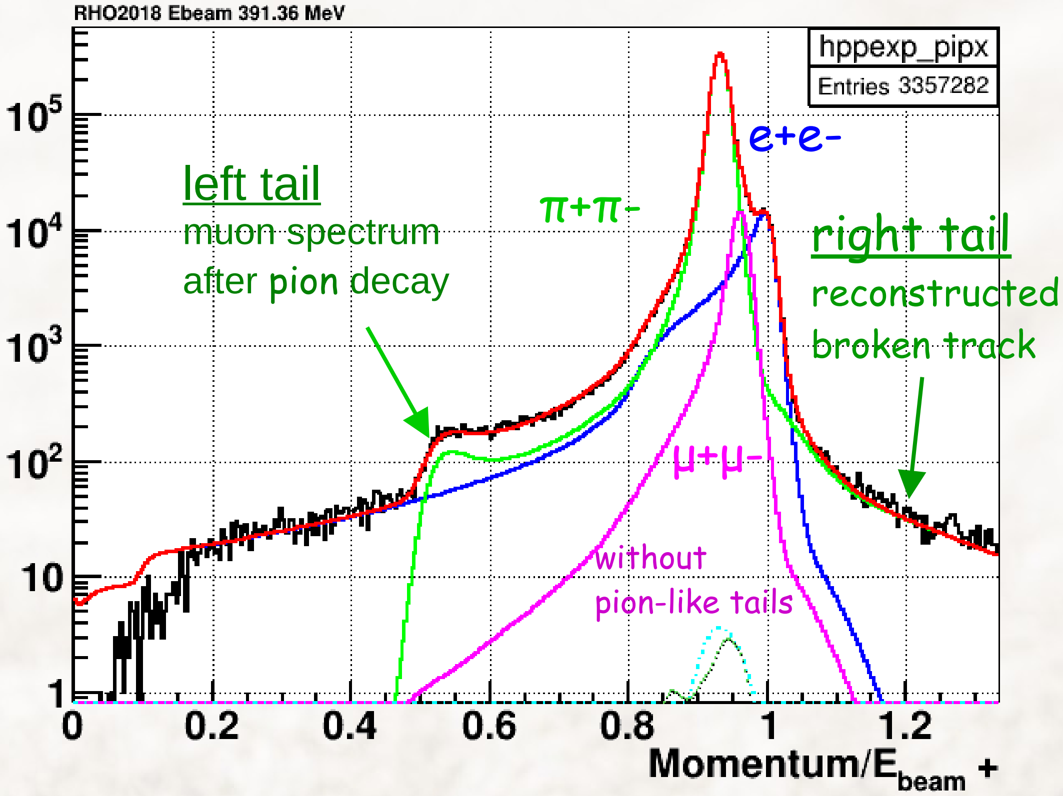


nucler interactions mostly on inner tube (systematics 0.2%)

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

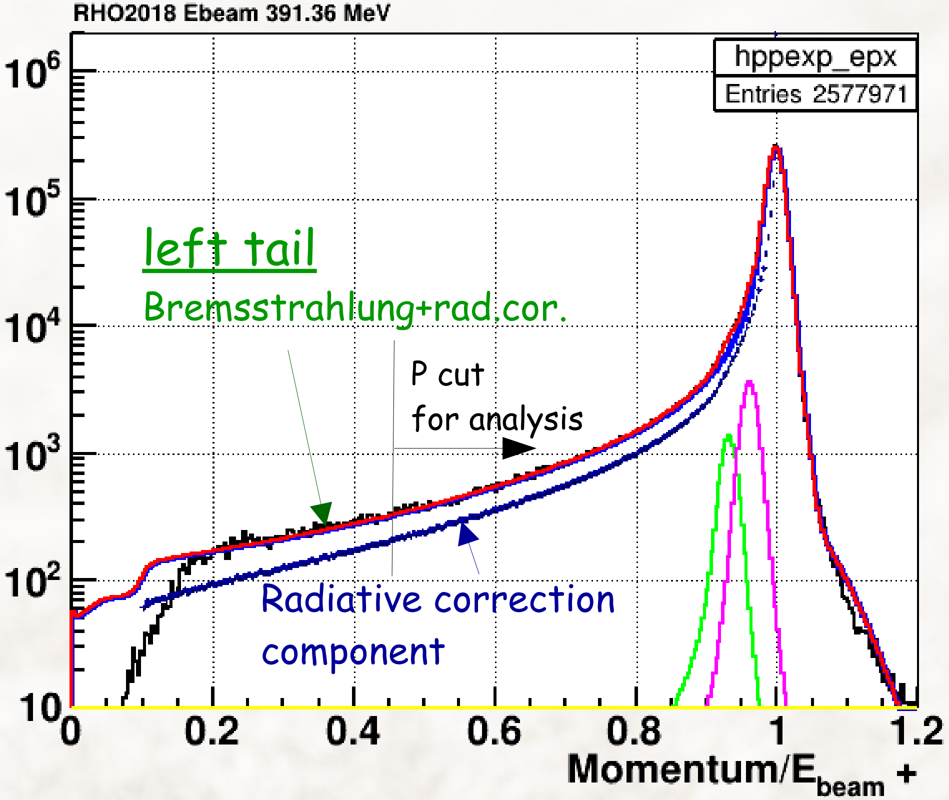
Tails function taken from full MC
(include DCH inefficiencies, resolutions,
amplitudes, correlated noises per layers, etc..)
Number of events in tails are free parameters
in momentum-based separation

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



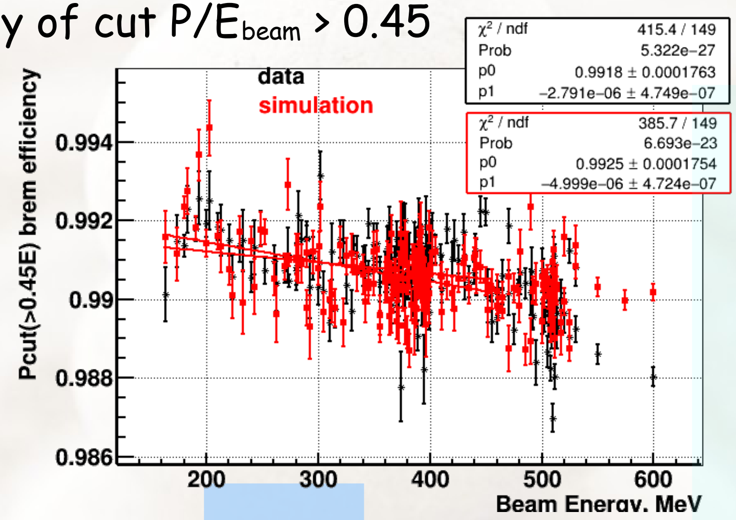
left tail

Bremsstrahlung+rad.cor.

P cut
for analysis

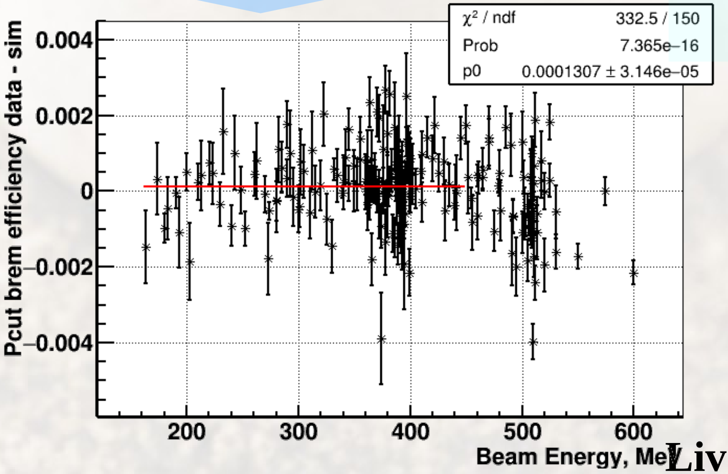
Radiative correction
component

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%

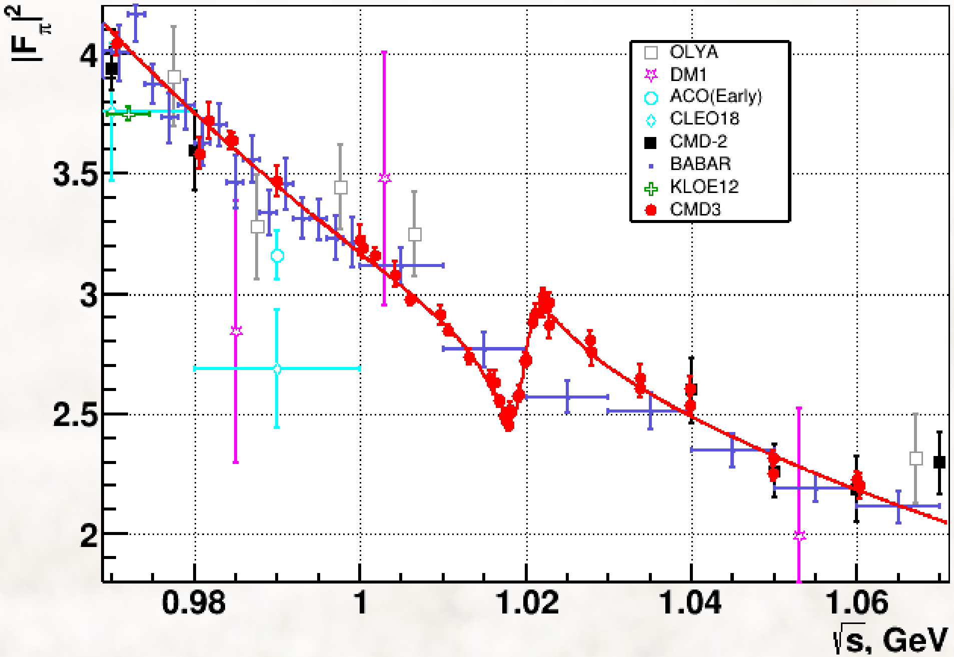
The data vs sim agree ~ 0.02%



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%

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

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



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

$B(\varphi \rightarrow e^+e^-)B(\varphi \rightarrow \pi^+\pi^-) = (3.51 \pm 0.33 \pm 0.24)\text{x}10^{-8}$

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)

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

$B(\varphi \rightarrow e^+e^-)B(\varphi \rightarrow \pi^+\pi^-) = (2.1 \pm 0.4)\text{x}10^{-8}$

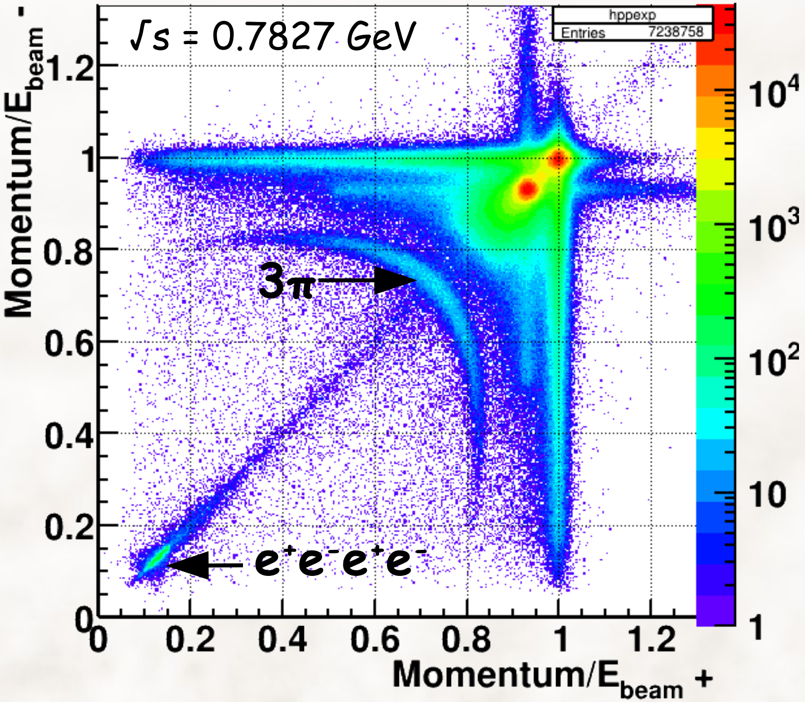
SND

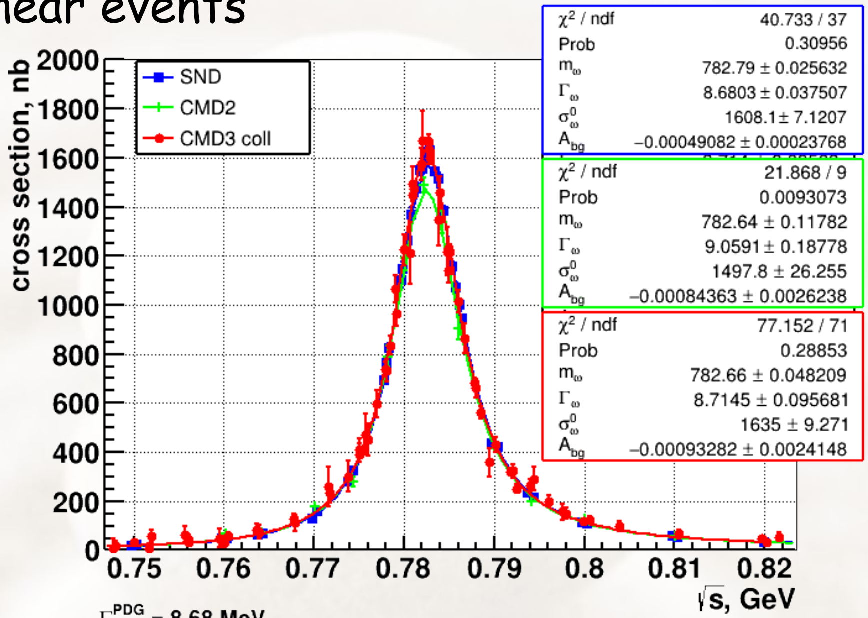
N.B. radiative correction uncertainty (from F_π parametrisation) gives ~1.5 scale factor of total statistical and systematic errors (both for Br and ψ_π)

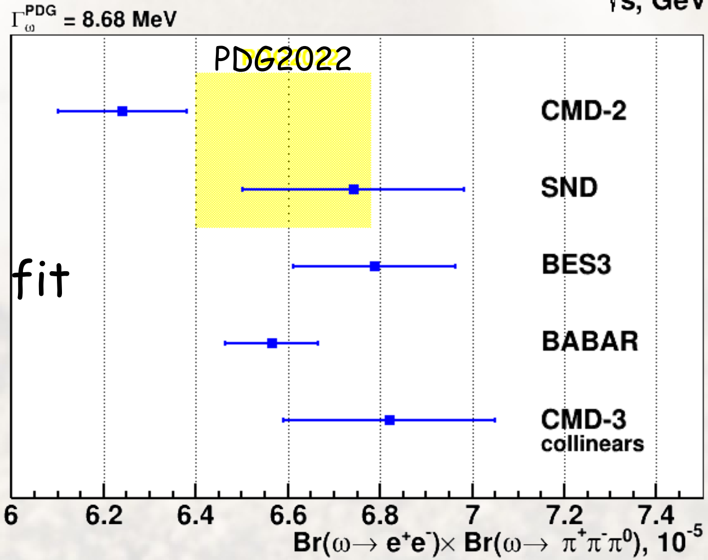
$e^+e^- \to \pi^+\pi^-\pi^0$

Collinear events are selected for 2π analysis

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







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

Possible concerns in the analysis related to MC tools:

- ✗ Radiative corrections for the π+π- 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

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

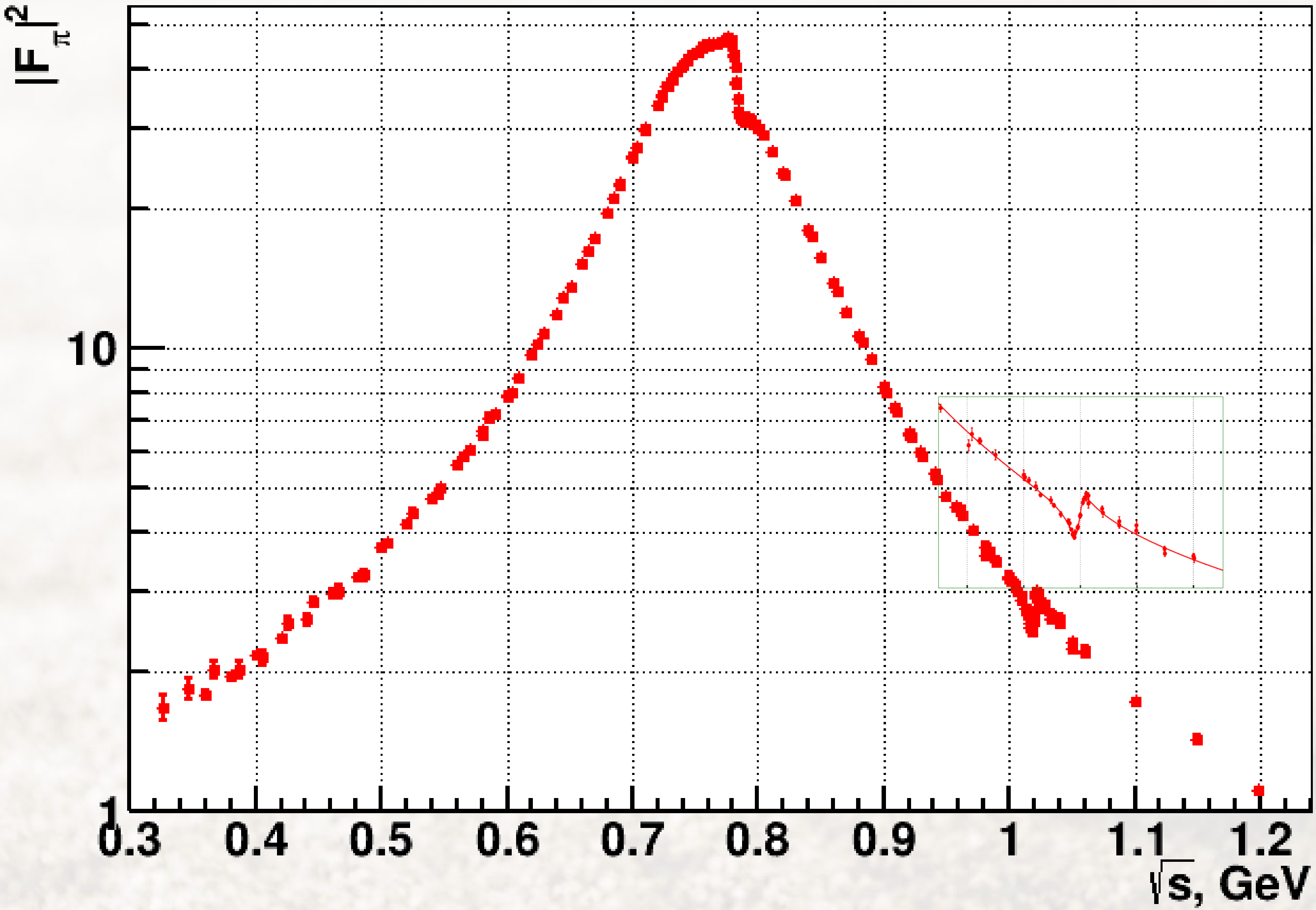
$$\Delta^{BG}=(N_{bg}/N_{ee})^{simul}$$

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

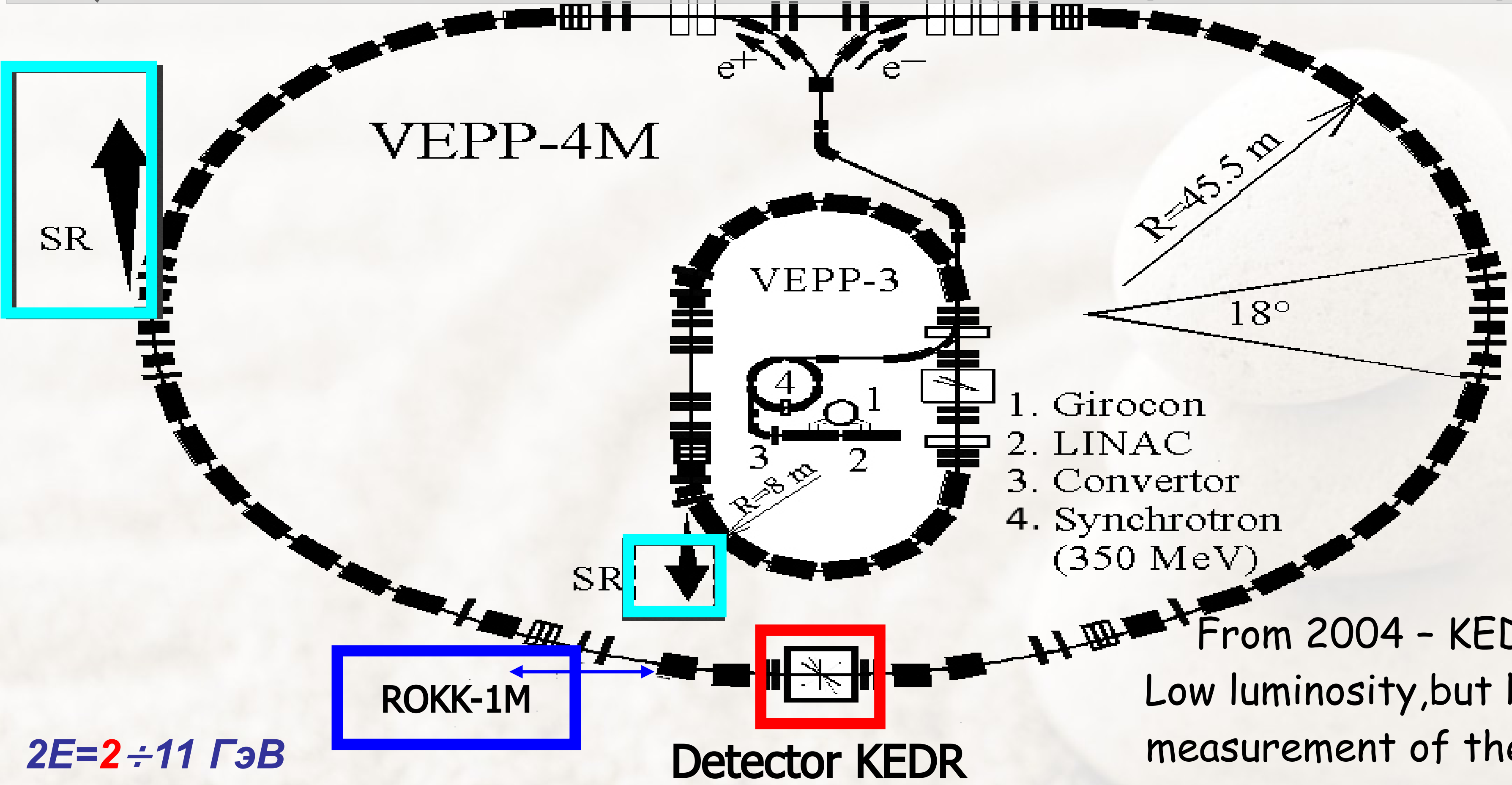
Radiative corrections defined in used acceptance, account for ISR and FSR effects, VP included in F_π definition.

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

Form factor



VEPP-4M Collider Complex (1994- 202?)



2E=2÷11 ГэВ

*L=2x10**30 см-2с-1*

*L= 8x10**31 см-2с-1*

From 2004 – KEDR experiment

Low luminosity,but high precision

measurement of the beam energy

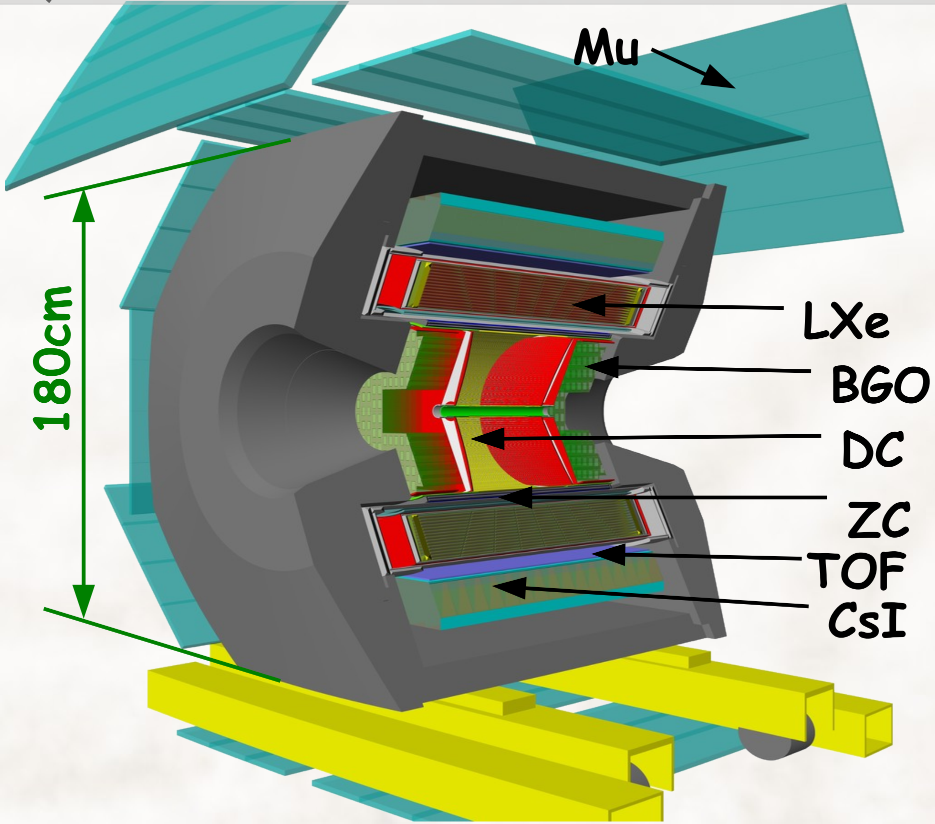
J/ψ δm/m ~ $2e^{-6}$ (only 6 particles known better)

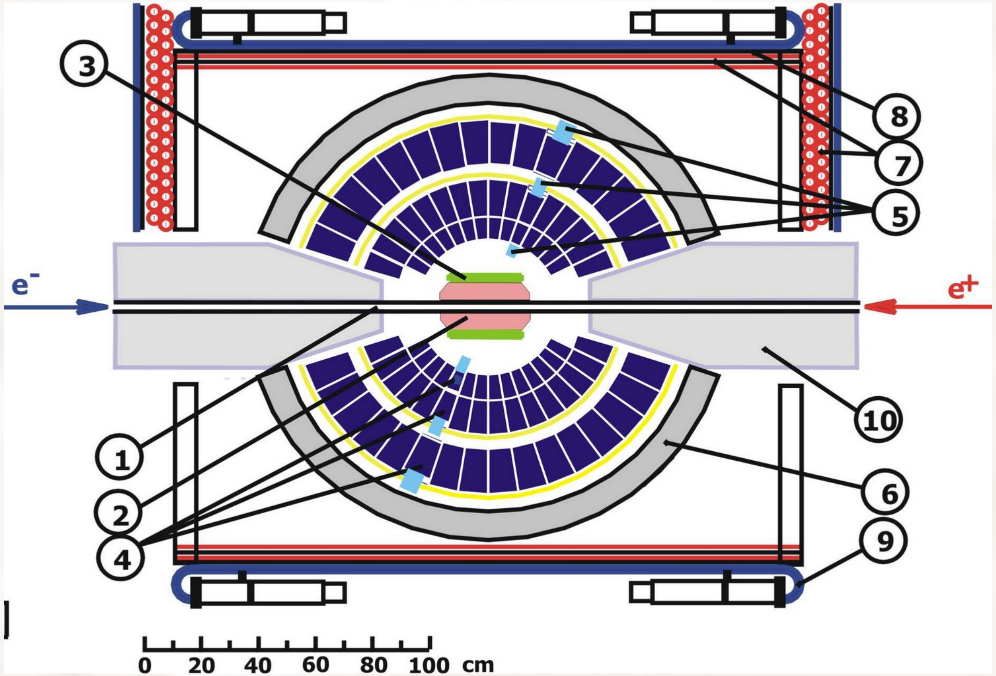
Best measurement of inclusive R(s), 2E<3.7 GeV

with ~2% systematic precision

Few more years to do scan above charm region

CMD-3 and SND





1.3 T magnetic field

Tracking: $\sigma_{R\varphi}$ ~ 100 μm, σ_Z ~ 2mm

Combined EM calorimeter (LXe,CsI, BGO):

σ_E ~ 3-8%,Tracking in LXe calorimeter

1 – beam pipe, 2 – tracking system, 3 – aerogel Cherenkov counter , 4 – NaI(Tl) crystals, 5 – phototriodes, 6 – iron muon absorber, 7–9 – muon detector

In 1996-2000 SND collected data at VEPP-2M