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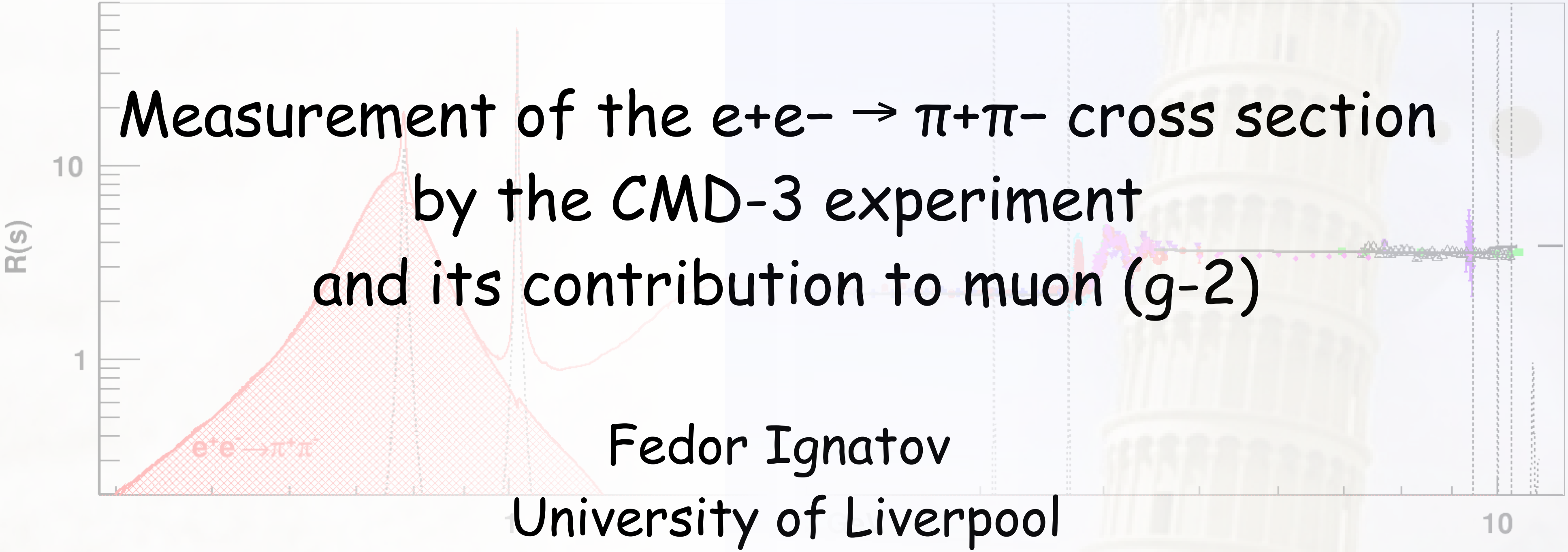
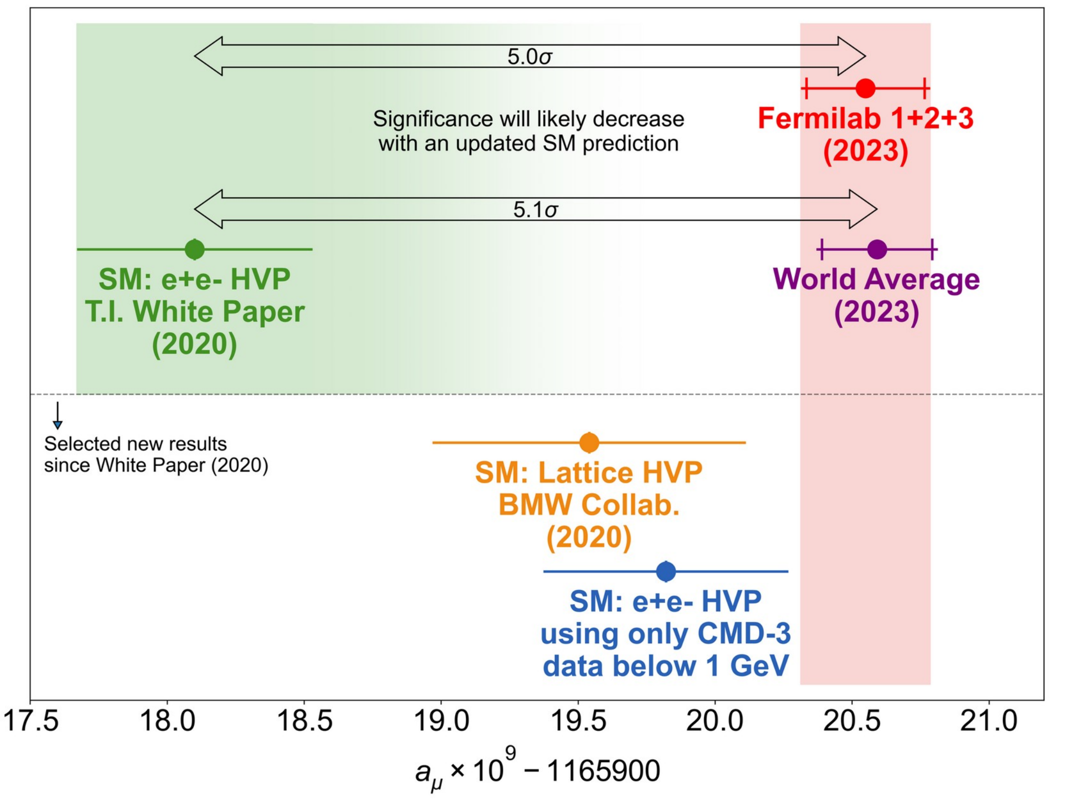


Measurement of the $e+e- \to \pi+\pi-$ cross section by the CMD-3 experiment and its contribution to muon (g-2)

Fedor Ignatov
University of Liverpool

7 May 2024
Pisa, Italy

Muon g-2 experiment vs theory landscape



Plot from James Mott:
https://indico.fnal.gov/event/60738/
Alex Keshavarzi:
https://indico.fnal.gov/event/57249/contributions/271581/

FermiLab muon g-2 measurement (end of 2023) improves BNL experiment by factor 2

Next year: further 1/2 improvement expected after analysis of the full statistic

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Theory Initiative (TI) White paper consensus in 2020 gives single number for the SM prediction based on e+e- data

Since TI White Paper:

From BMW collab. first Lattice calculation with competitive precision (confirmations from others group are under way)

CMD-3 measurement of e+e- → π+π- with high statistics gives additional input on the theoretical side

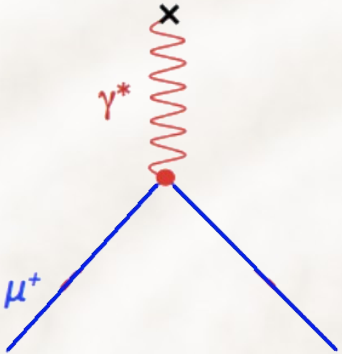
End of year: new TI white paper is expected before new g-2 result

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:

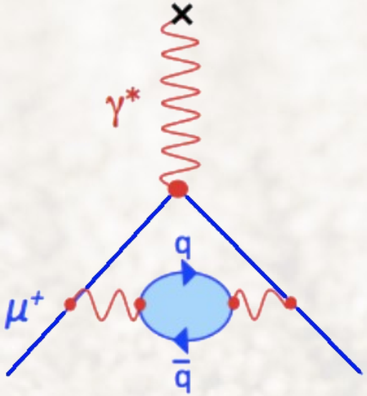
$$\vec{\mu} = g \frac{e}{2m} \vec{s}$$

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

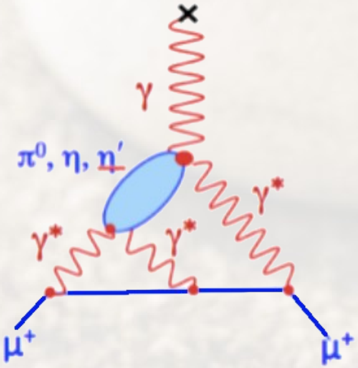


Quantum loop effects via vacuum fluctuations lead to the calculated deviation:
the anomalous magnetic moment a = (g-2)/2 ~ $\alpha/2\pi$ ~ 0.00116 **"g-2 anomaly"**

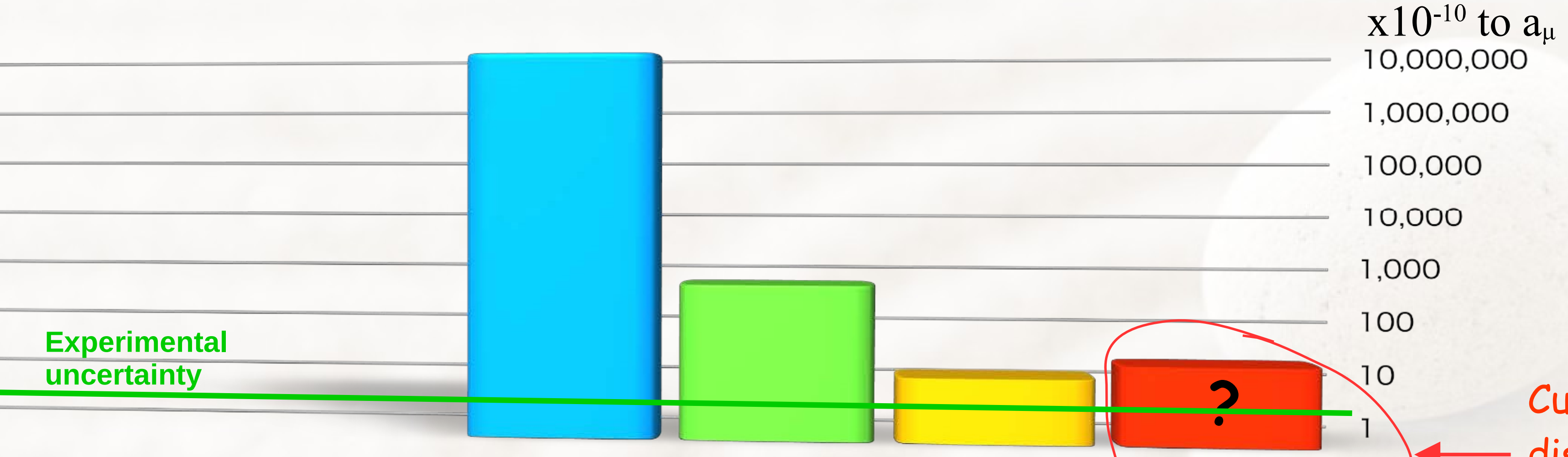
HLO



HLbL



Muon g-2 theory SM



Current level of discrepancy in theory vs experiment

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

Precision relative to a_μ : 1 ppb HVP: 340ppb + LbL: 160ppb 9ppb < 2300ppb

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

Stefano Laporto, 2017: 1100 digits 4 loops calculation to evaluate analytical formula

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

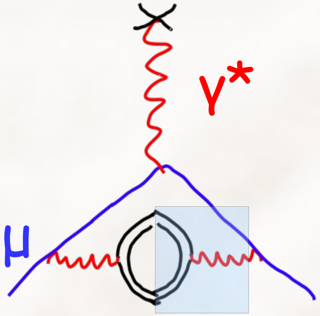
Hadronic: HVP: the value is based on the hadronic cross-section e+e- data, lattice, tau data

LBL: model-dependent calculations using transition form factors, lattice

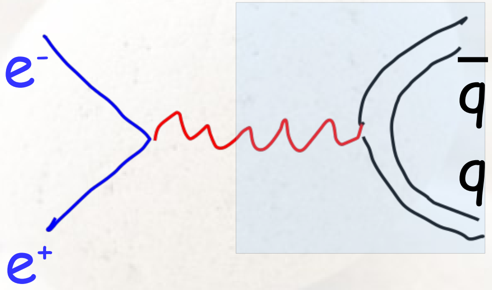
g-2 experiments at FNAL, new J-PARC: 540 → 140 ppb

g-2 and e+e- → hadrons

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

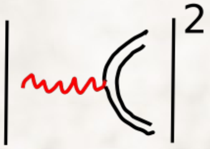


can be expressed from e+e- -> hadrons cross section



using Dispersion relation integral:

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

2Im  $=\sum_{\text{had}}\int d\Phi$  - and the optical theorem (unitarity)

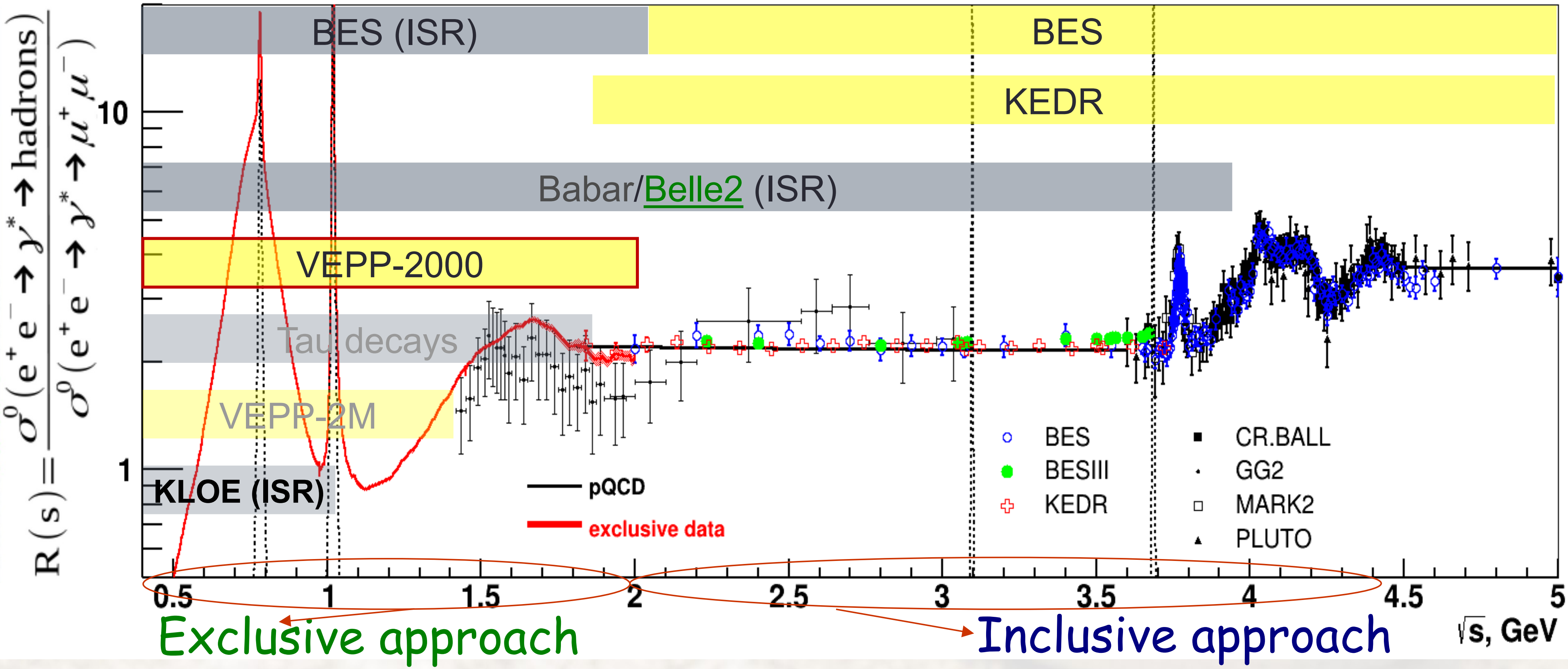
$$a_\mu^{\text{had,LO}}=\left(\frac{\alpha m_\mu}{3\pi}\right)^2\int_{s_{th}}^{\infty}\frac{1}{s^2}\tilde{K}(s)R(s)ds,\qquad \tilde{K}(s)=0.6\div1.0$$

Weighting function ~ $1/s^2$, therefore

lower energies contribute the most: <2GeV gives 93% of the integral

R(s) measurement

Two techniques: ISR vs Energy scan



Exclusive approach

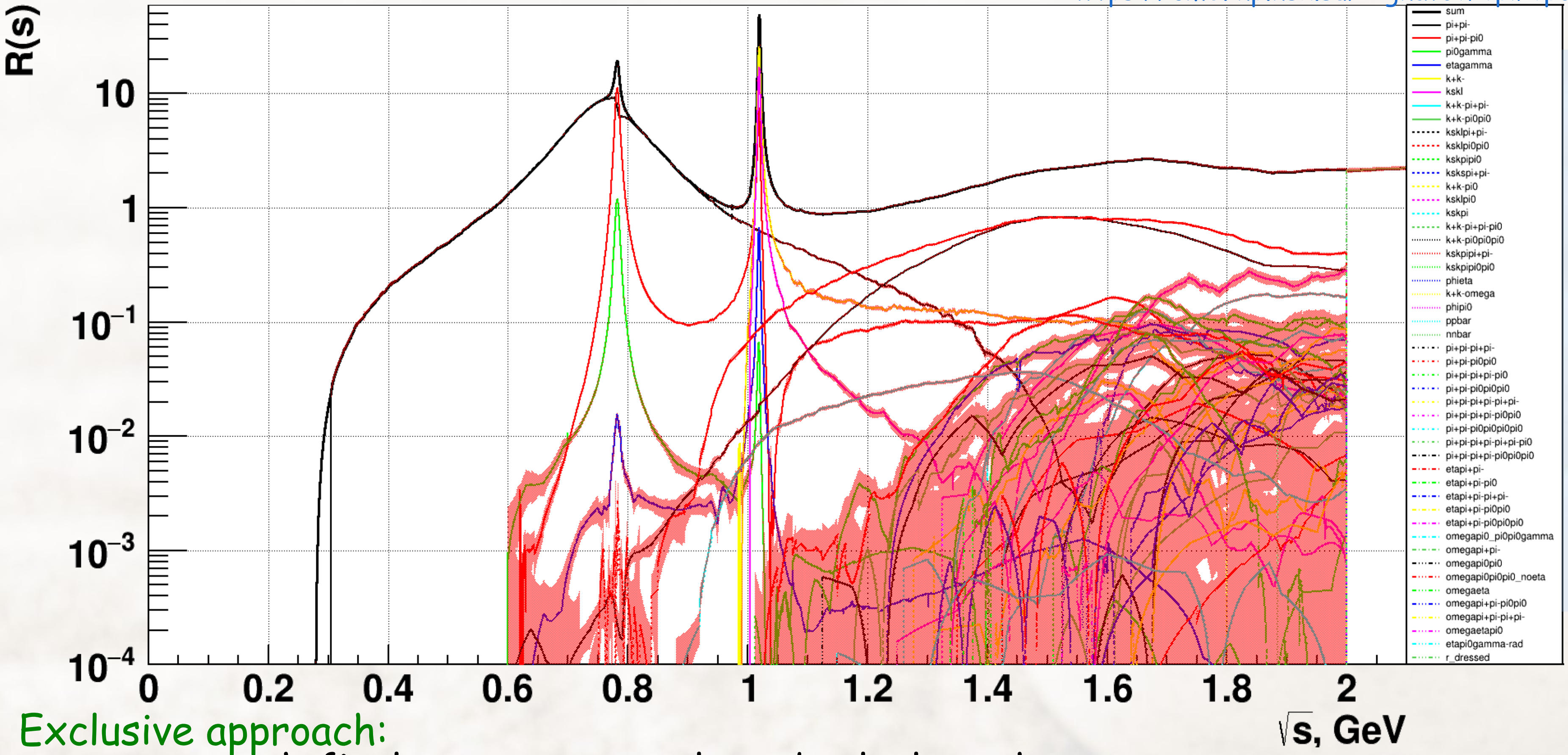
Inclusive approach

- ✗ 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- → 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

~49 different detectors,

~51 channels, which gives

~305 datasets.

R(s) in dispersion relations (a_μ^{had}, etc)

Covers the 57-years history of hadron production on colliders
(starting from first e+e- → ρ → $\pi\pi$ at VEPP-2 in 1967)

e+e- data contributing to R(s) come from:
~49 different detectors , ~51 channels,
which gives ~305 datasets.

The evaluation of a_μ^{had} from e+e- low energy data combines many heterogeneous data samples:

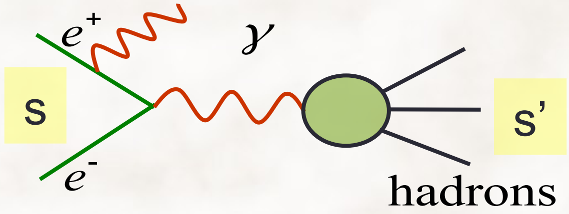
Very delicate procedure to merge them together
Some of data are disregarded by new experimental results.
It raise many issues in the estimation of the systematic errors,
correlation between datasets, etc...

Hall of Fame:
ACO ADONE ALEPH
AMY ARGUS BABAR
BBar BCF BELLE
BELE2 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

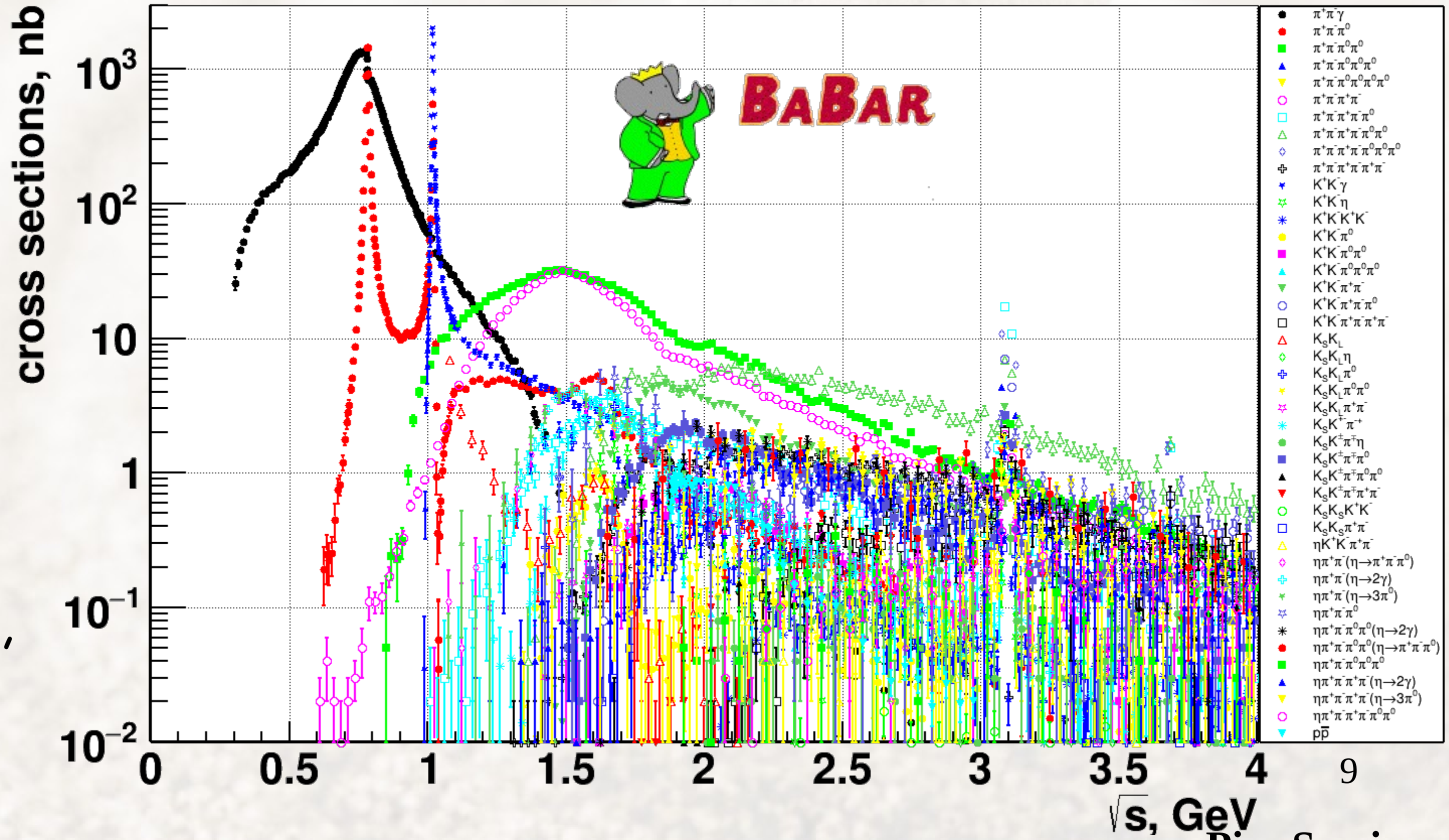
ISR approach

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

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



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

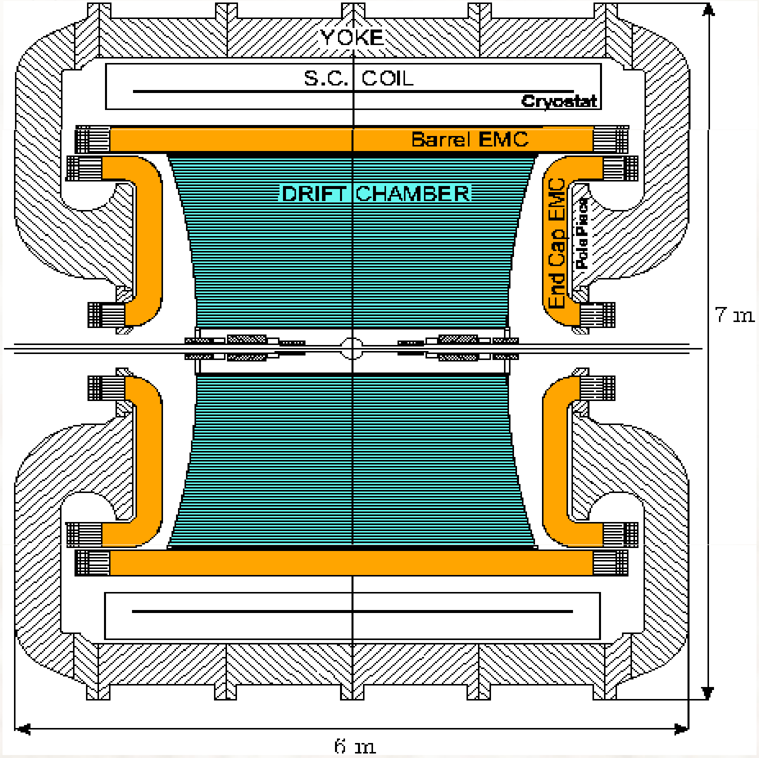


KLOE ISR+ VP

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- → 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 GeV² (before CMD-3)

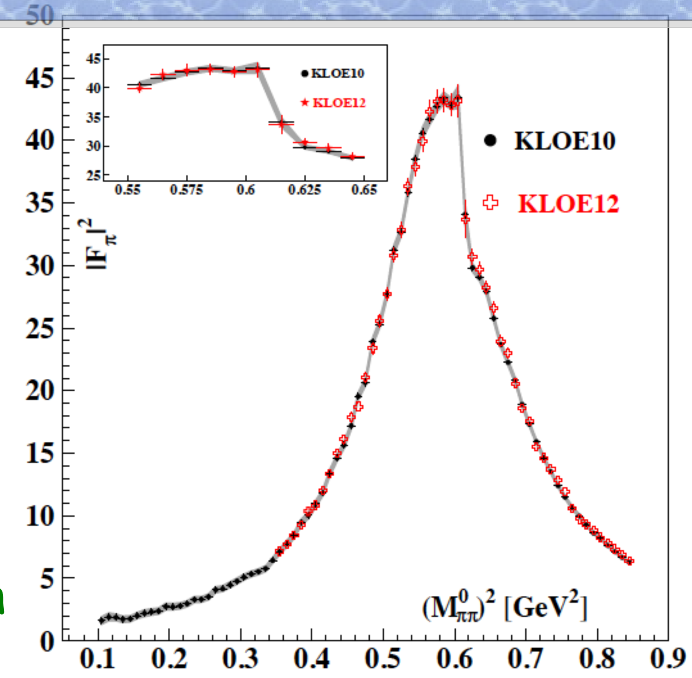
direct extraction of

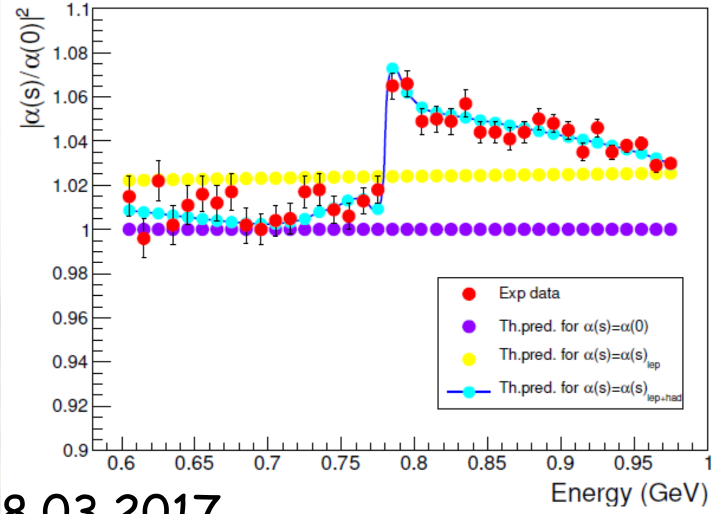
$\alpha_{QED}(s)$ via e+e- → μ+μ-γ

Phys. Lett. B, 767 (2017), 485

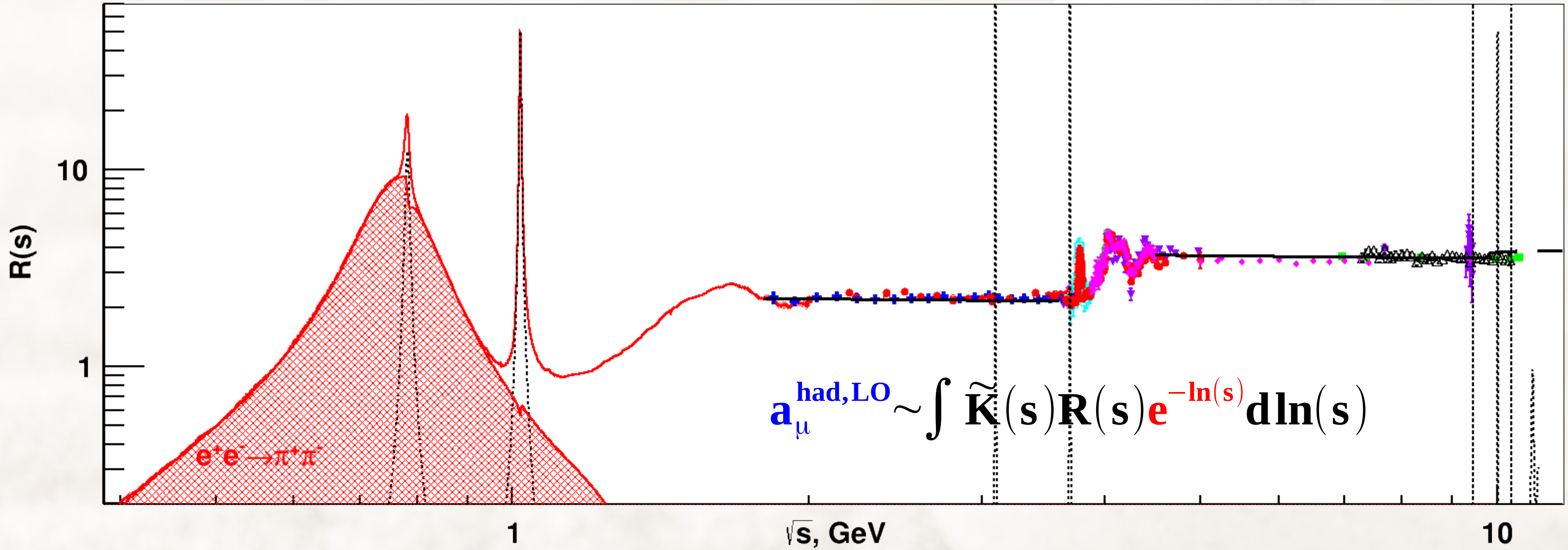
See G. Venanzoni

CERN presentation at 28.03.2017





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



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

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

HVP contributions to amu

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)**

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

Hadronic part from measured cross-section

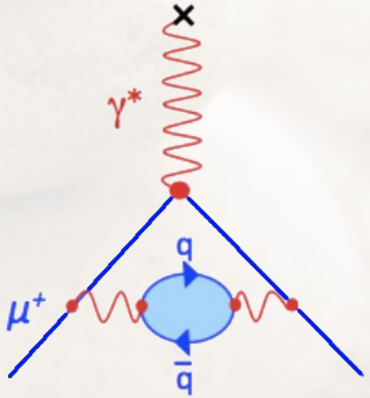
LO hadronic 693.1 ± **4.0** × 10^{-10}

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(√s>1.8-3.7 GeV)	34.0 ± 0.7 ± 0.7 (DV+QCD)	2.9%

…………………

Light-by-light 9.2 ± **1.9**

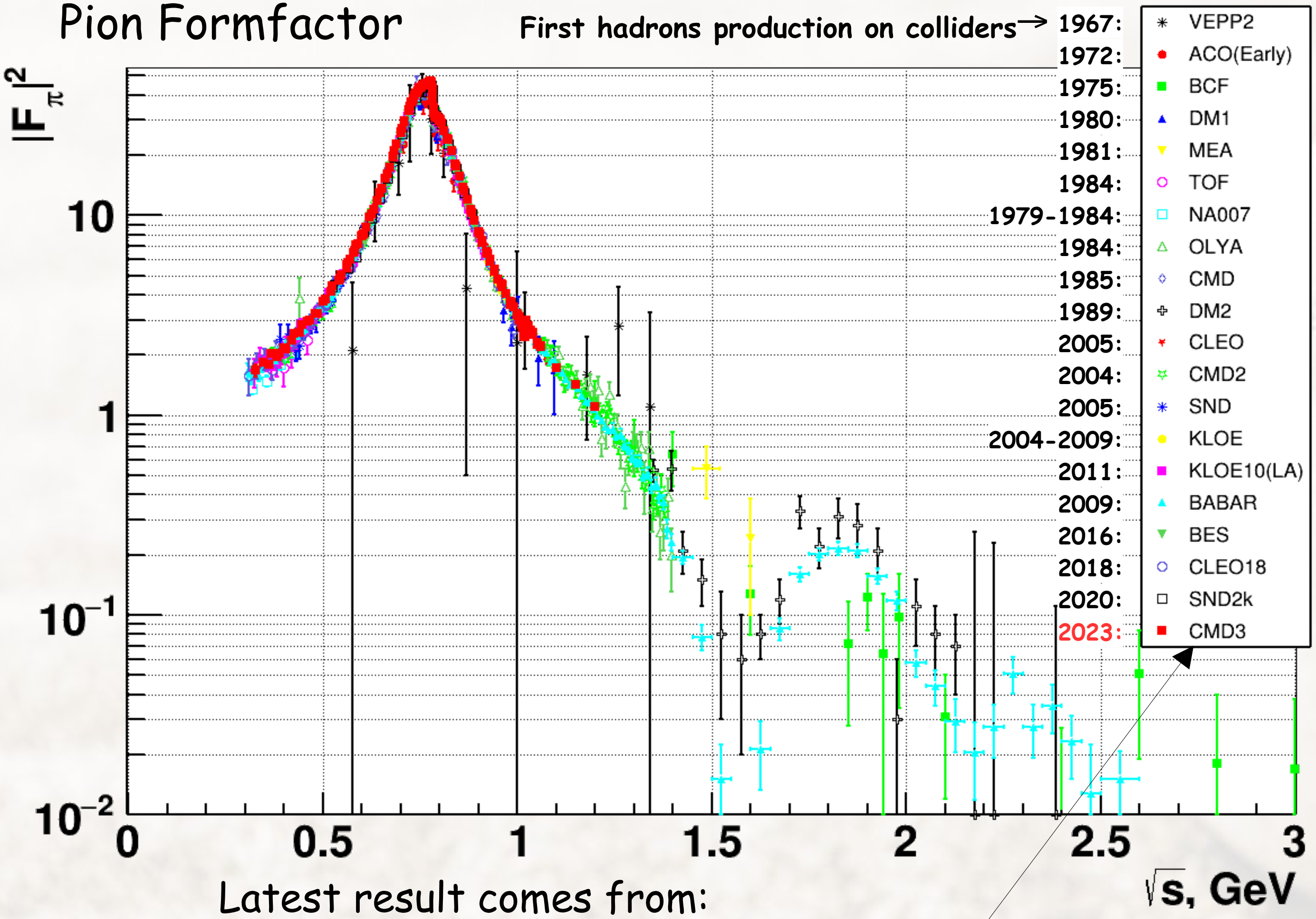


New BaBar/Belle2 3π data since WP20 reduced this to ± 0.6 ×10^{-10}

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

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%

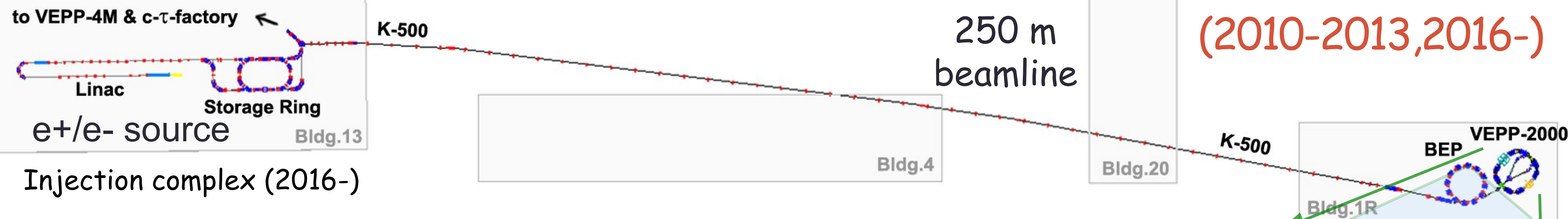
New direct data at VEPP-2000:

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

CMD-3: 0.7%

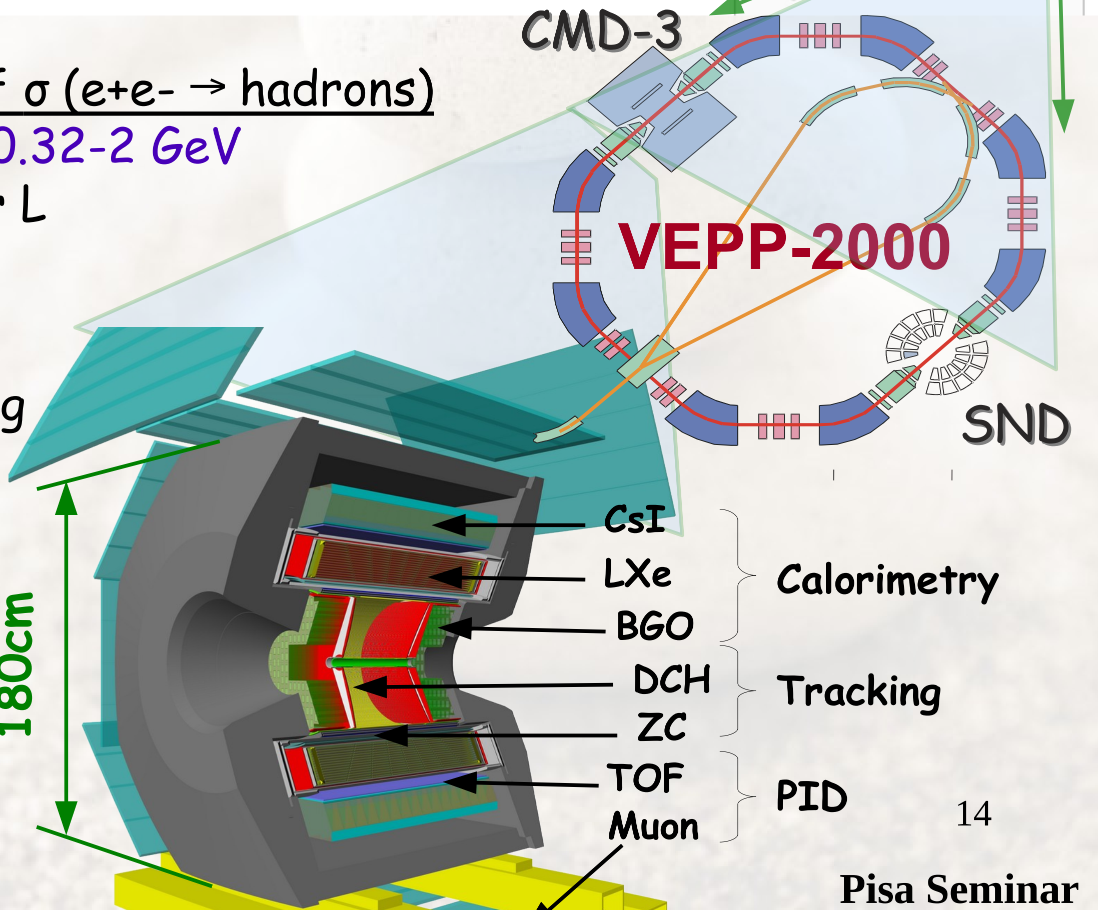
New g-2, etc experiments require precision ~ 0.2%

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

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

Energy monitoring by Compton backscattering

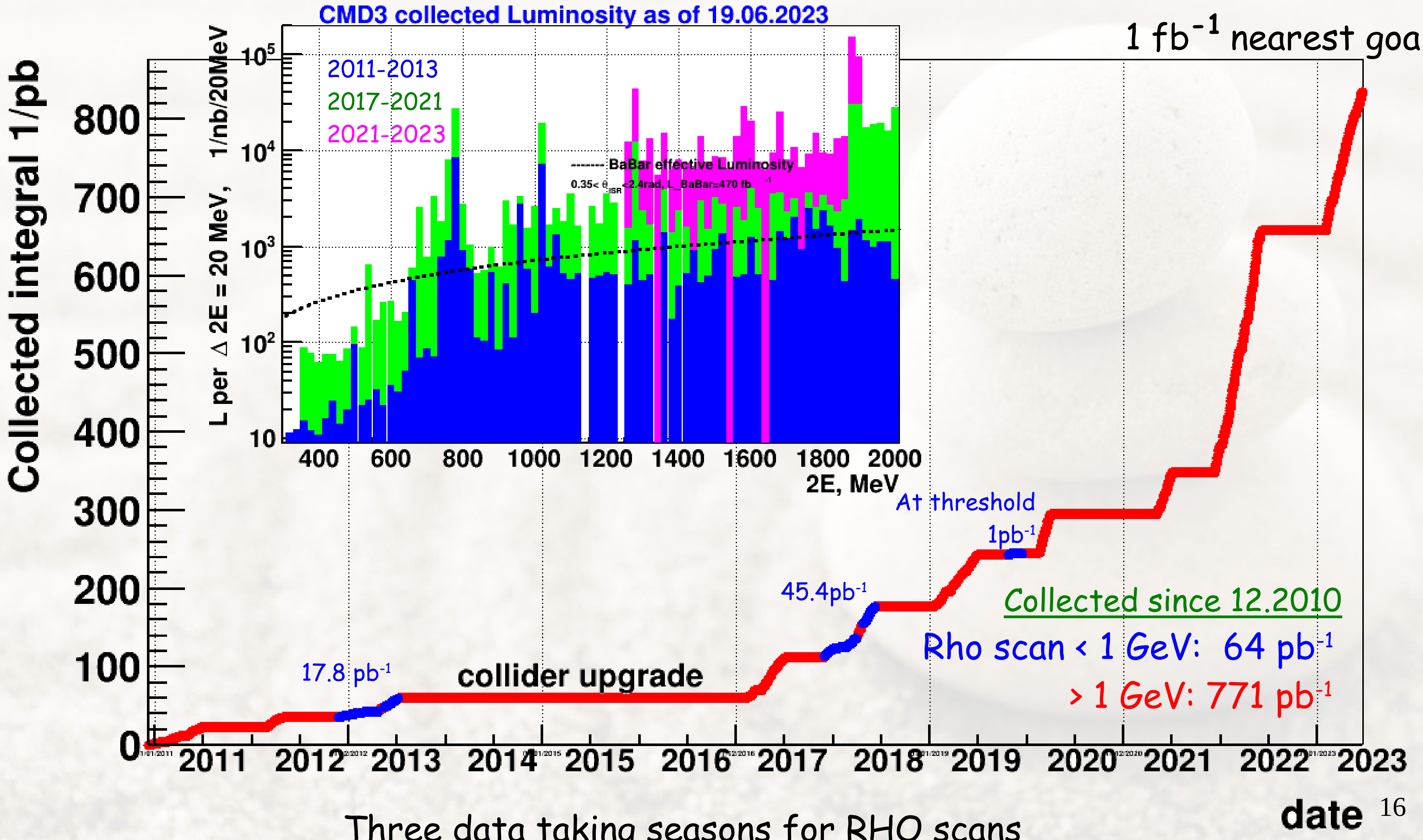
$\sigma_{\sqrt{s}} \approx 0.1$ MeV

Two detectors: CMD-3 and SND

started by the end of 2010


VEPP-2000
collider ring
SND
CMD-3
6.65 m

Overview of CMD-3 data taking runs



1 fb^{-1} nearest goal

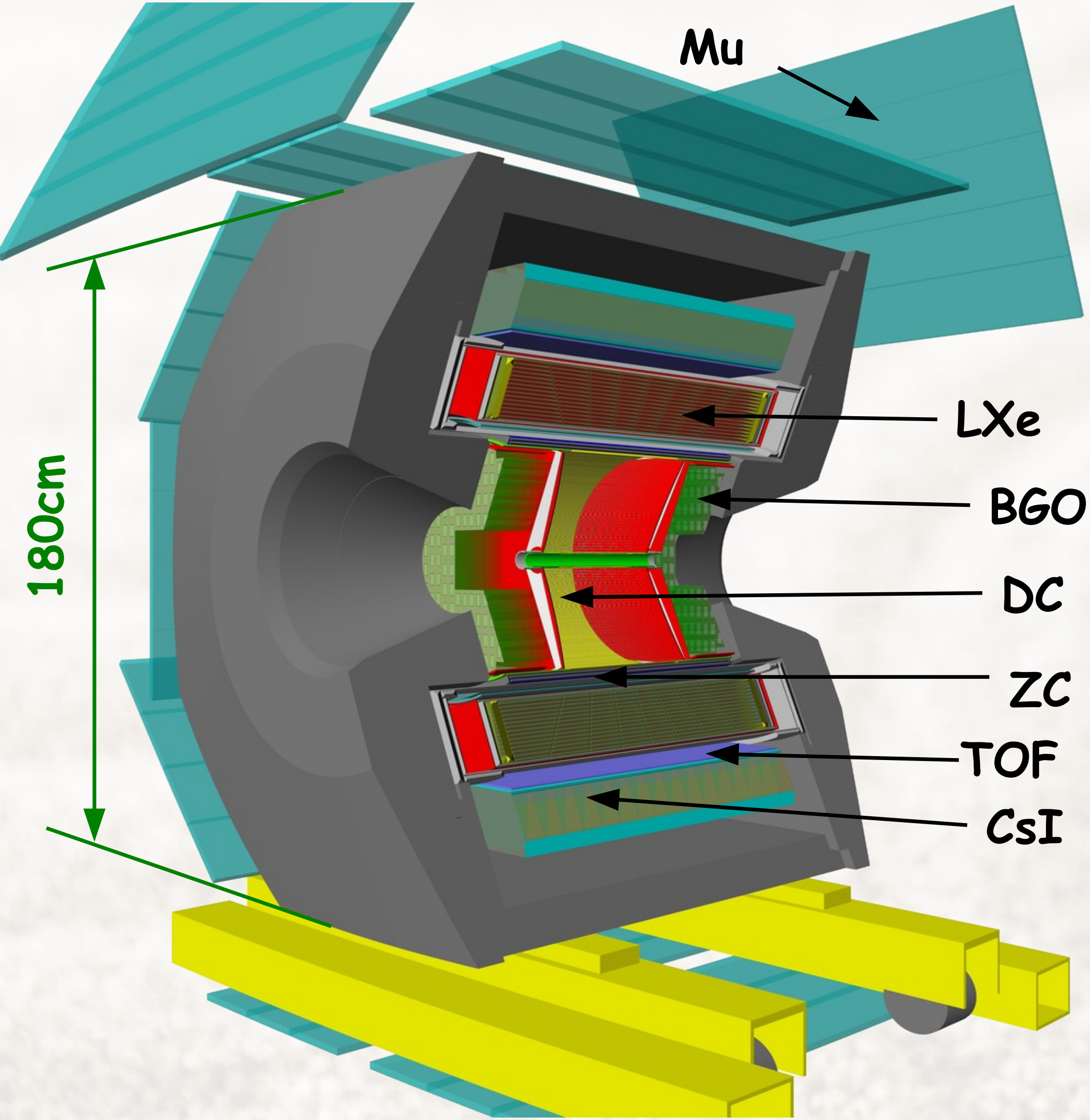
Collected since 12.2010

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

> 1 GeV: 771 pb^{-1}

Three data taking seasons for RHO scans

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- → 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%),

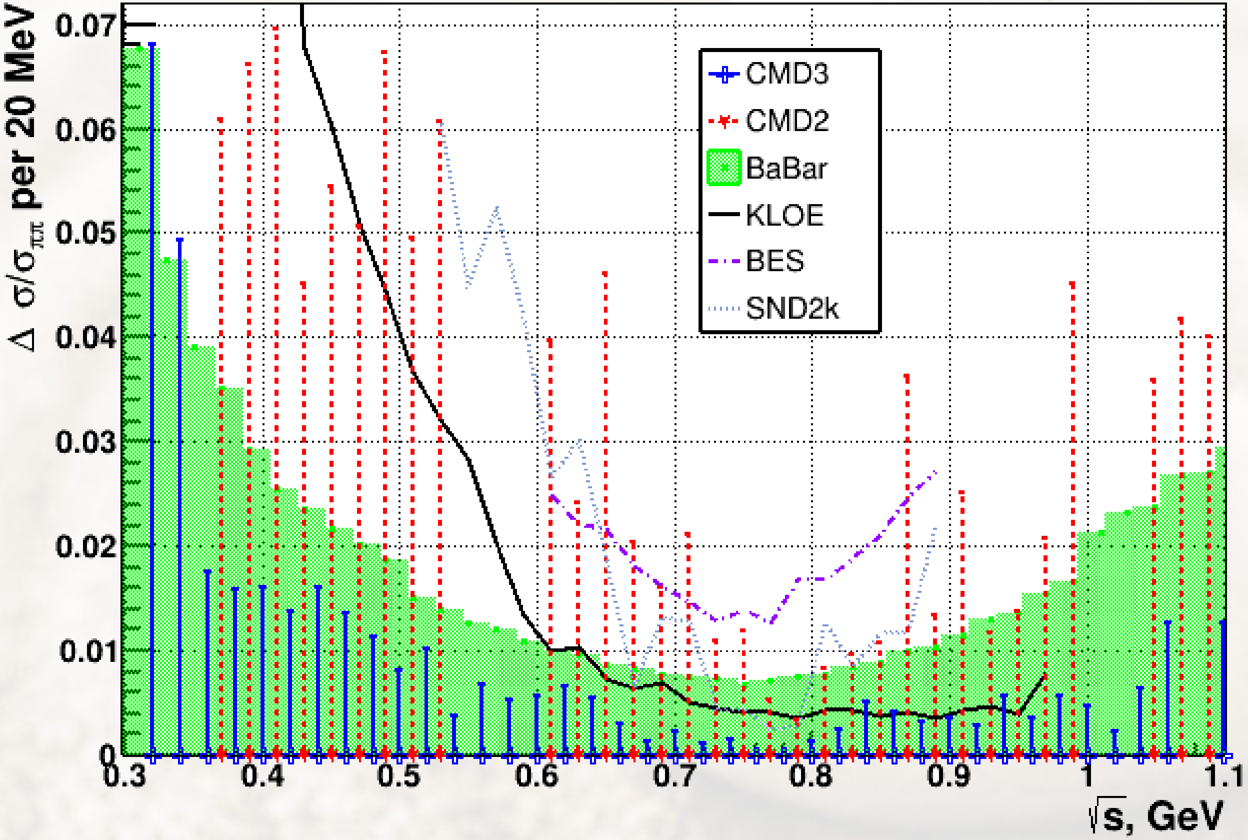
  <0.1% consistency in forward-backward asymmetry vs prediction, variation with angle cut

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

Form Factor evaluation

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

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

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

Mostly no background at ρ-peak energy region
In case of e+e- scan experiment

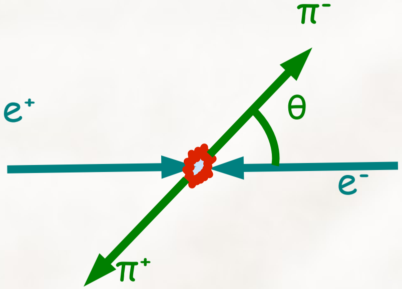
Radiative corrections defined in used acceptance,
account for ISR and FSR effects, VP included in F_π definition.
σ^0 – require precise determination of used spatial angle in the detector

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

Targeted precision ~ 0.1%

e/μ/π separation in π+π- CMD3

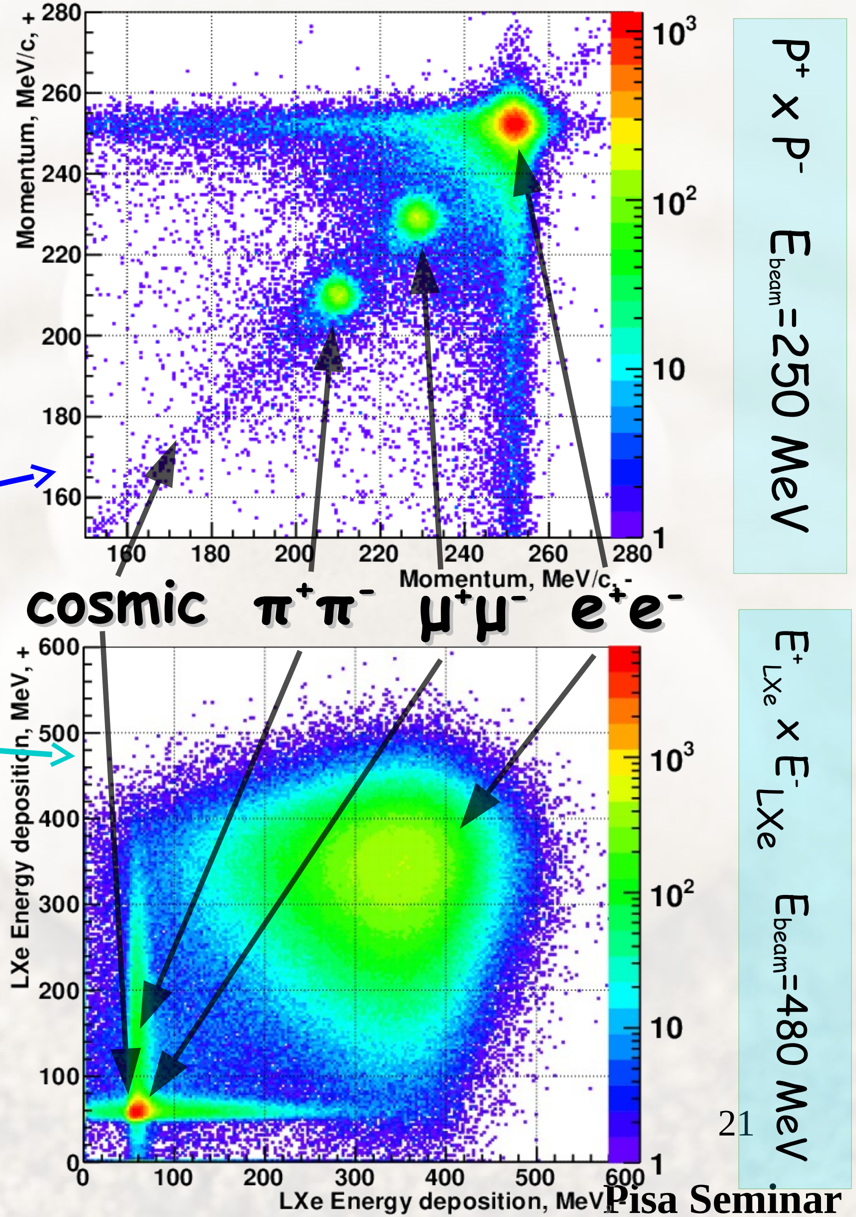
Very simple topology,
just 2 collinear tracks back to back:



Selected collinear events include $\pi^+\pi^-$, $\mu^+\mu^-$, e^+e^-, cosmic:

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 √s>1GeV
by neural network

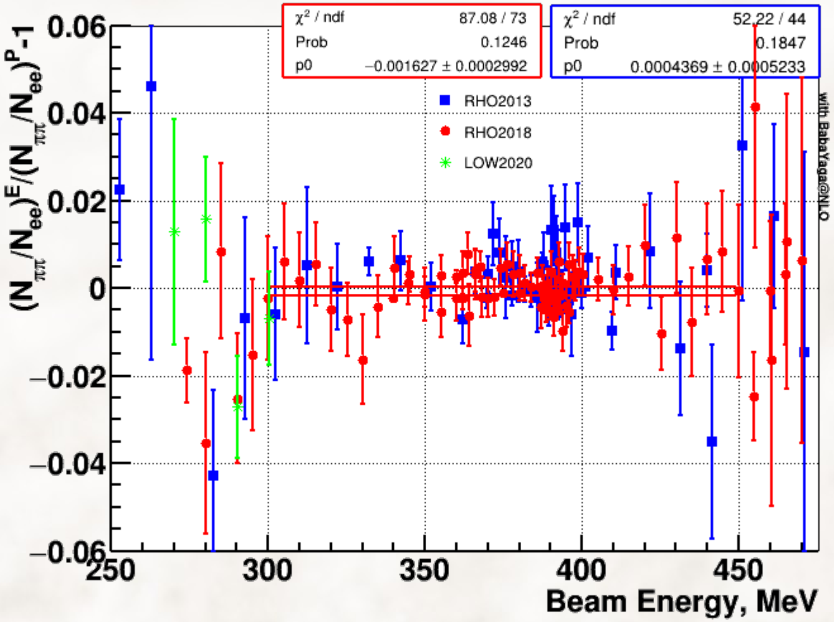


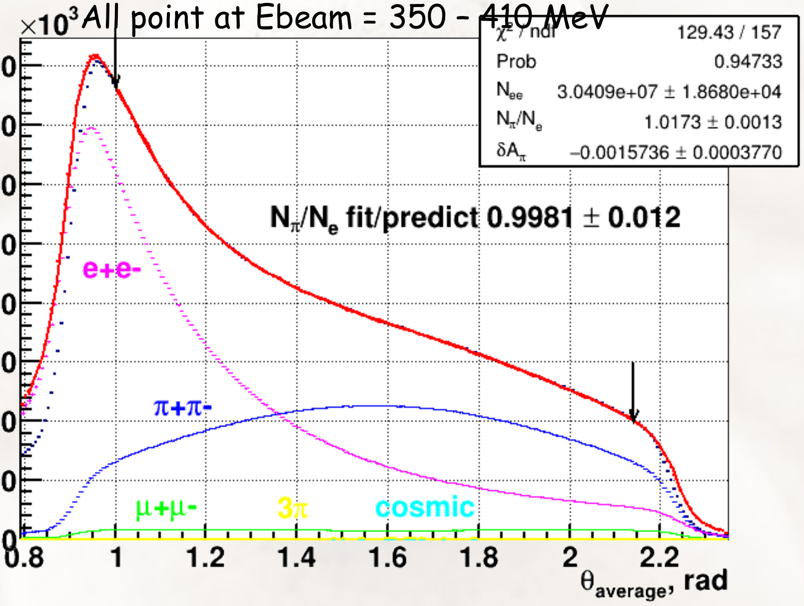
e/μ/π separation

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 $\Delta N_{\pi\pi}$ /N_{ee} = -0.09 +- 0.024%

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

with fixed δA=0: = +0.21 +- 0.07%

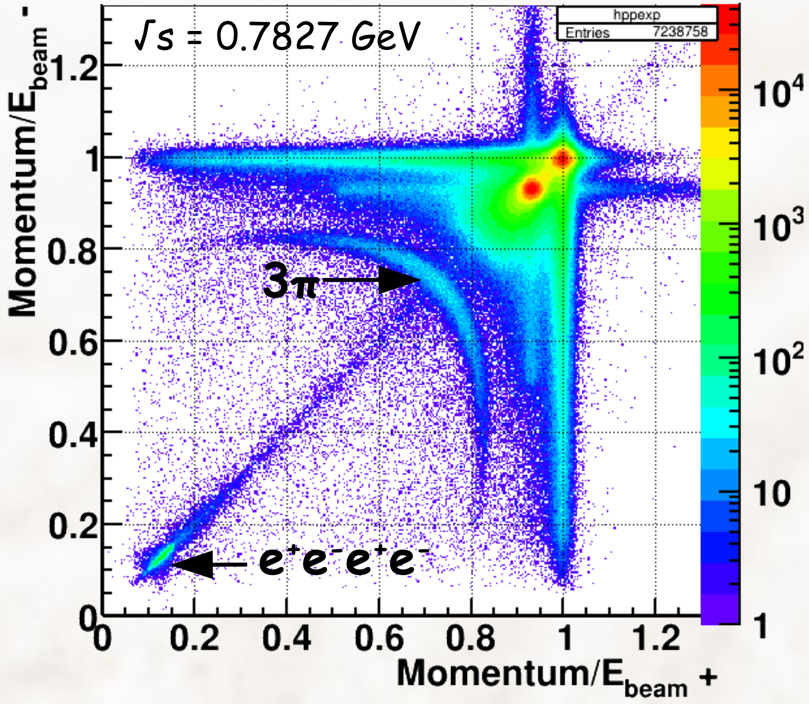
Common stat from √N: 0.026%

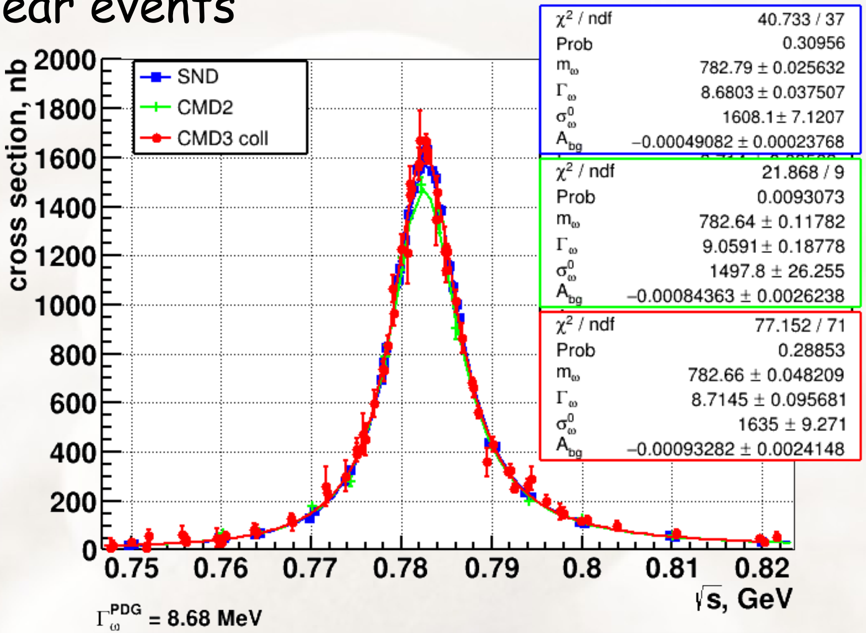
consistency at ~ 0.2%

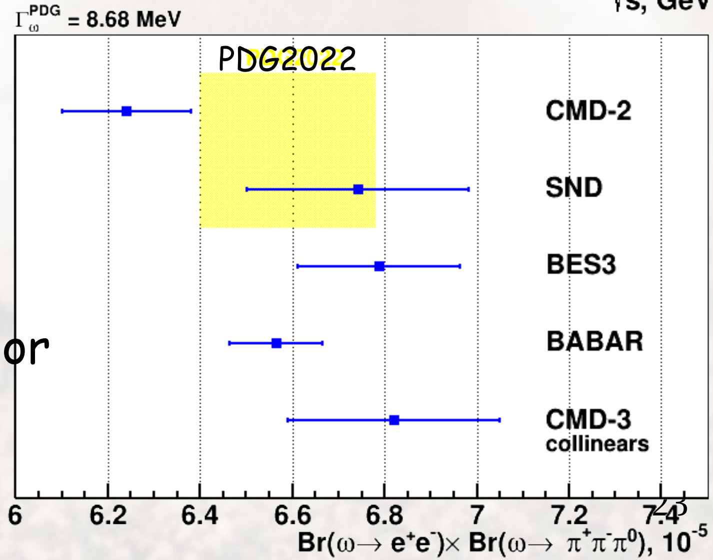
$e^+e^- \to \pi^+\pi^-\pi^0$ background

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)

3π events are well separated by momentum.

$\sigma(e^+e^- \to 3\pi)$ can be extracted from collinear sample used for 2π analysis (total systematic 3.3%, with 2.4% from ρπ – model for efficiency)

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

confirm SND@VEPP-2M result

Precision of fiducial volume

Polar angle measured by

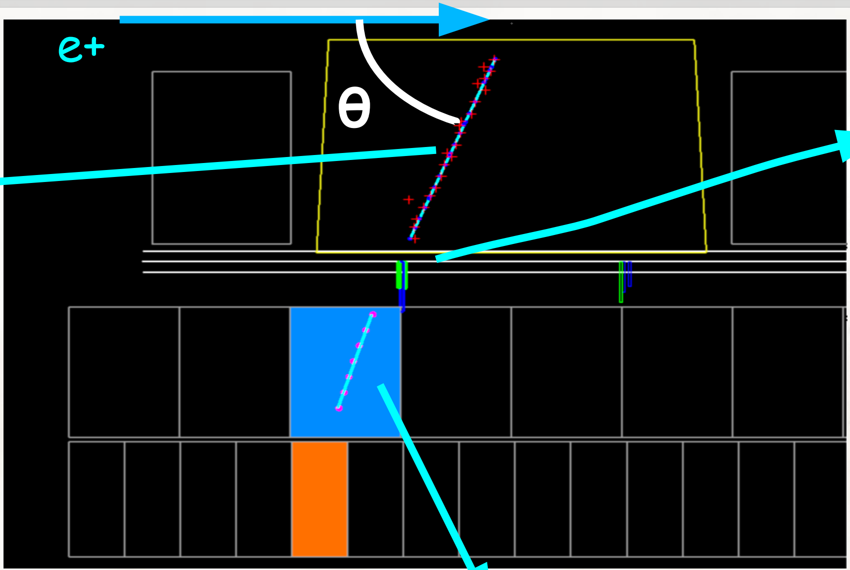
DCH chamber

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 25 years 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

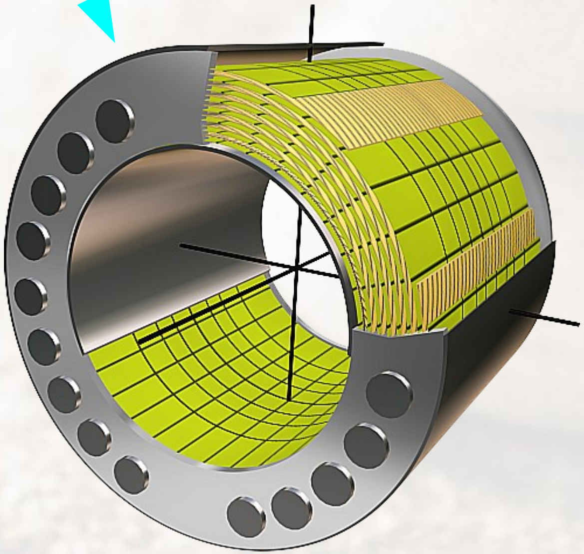
ionization collected in 7 layers with cathode strip readout,

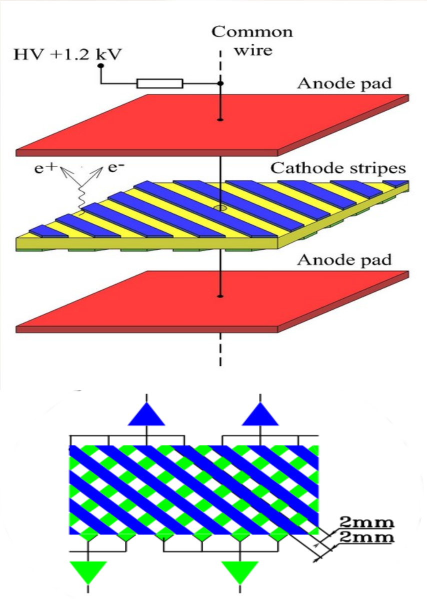
combined strip size: 10-15 mm

Coordinate resolution ~ 2mm

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

Can be spoiled by noise environment

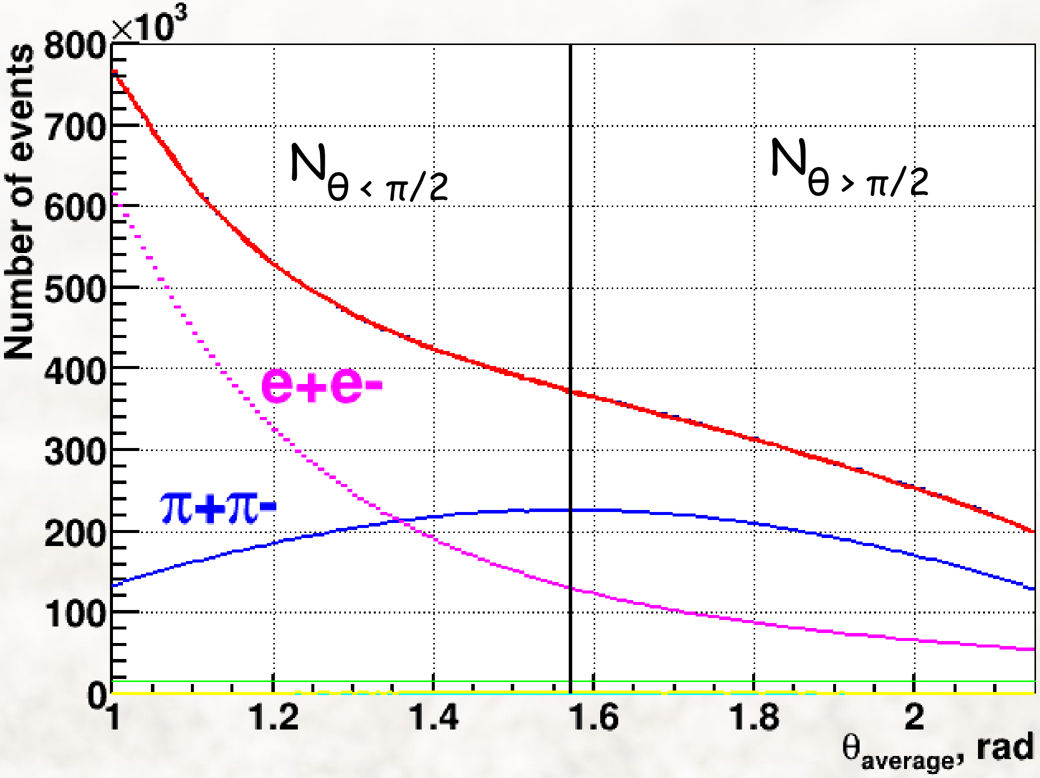




Consistency of both subsystem ~0.25%

Forward backward charge asymmetry

dσ/dθ spectra



Asymmetry definition:

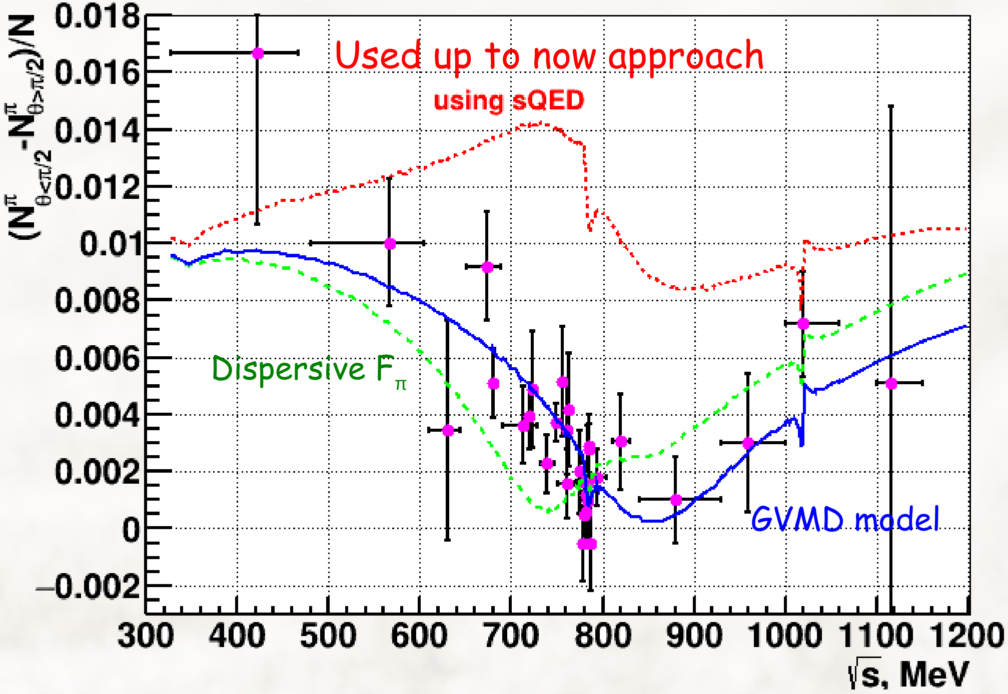
$A = (N_{\theta < \pi/2} - N_{\theta > \pi/2})/N$

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 (huge value when we are considering ~0.1% precision)

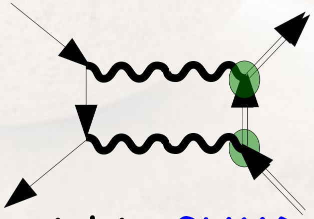
Charge asymmetry in e+e- -> π+π- by CMD-3

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



Conventional scalar QED approach to calculate radiative correction in MC generators gives ~ 1% inconsistency

Effect comes from γ-π vertex treatment in the box TVP diagram:



The theoretical model within GVMD was introduced, describes well the CMD-3 data. It was confirmed by calculation in dispersive formalism.

R.Lee et al., Phys.Lett.B 833 (2022) 137283
M.Hoferichter et al., JHEP 08 (2022) 295

Deviation from prediction in CMD-3

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

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

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

→ ~0.1% precision in θ angle systematics

Some ISR measurements could potentially be affected by incompleteness of sQED calculations…

Recently, additional indications appeared that the used MC generator for ISR is not sufficiently precise (fixed order NNLO not enough to describe experimental photons spectra).

$|F_\pi|^2$ systematic uncertainty

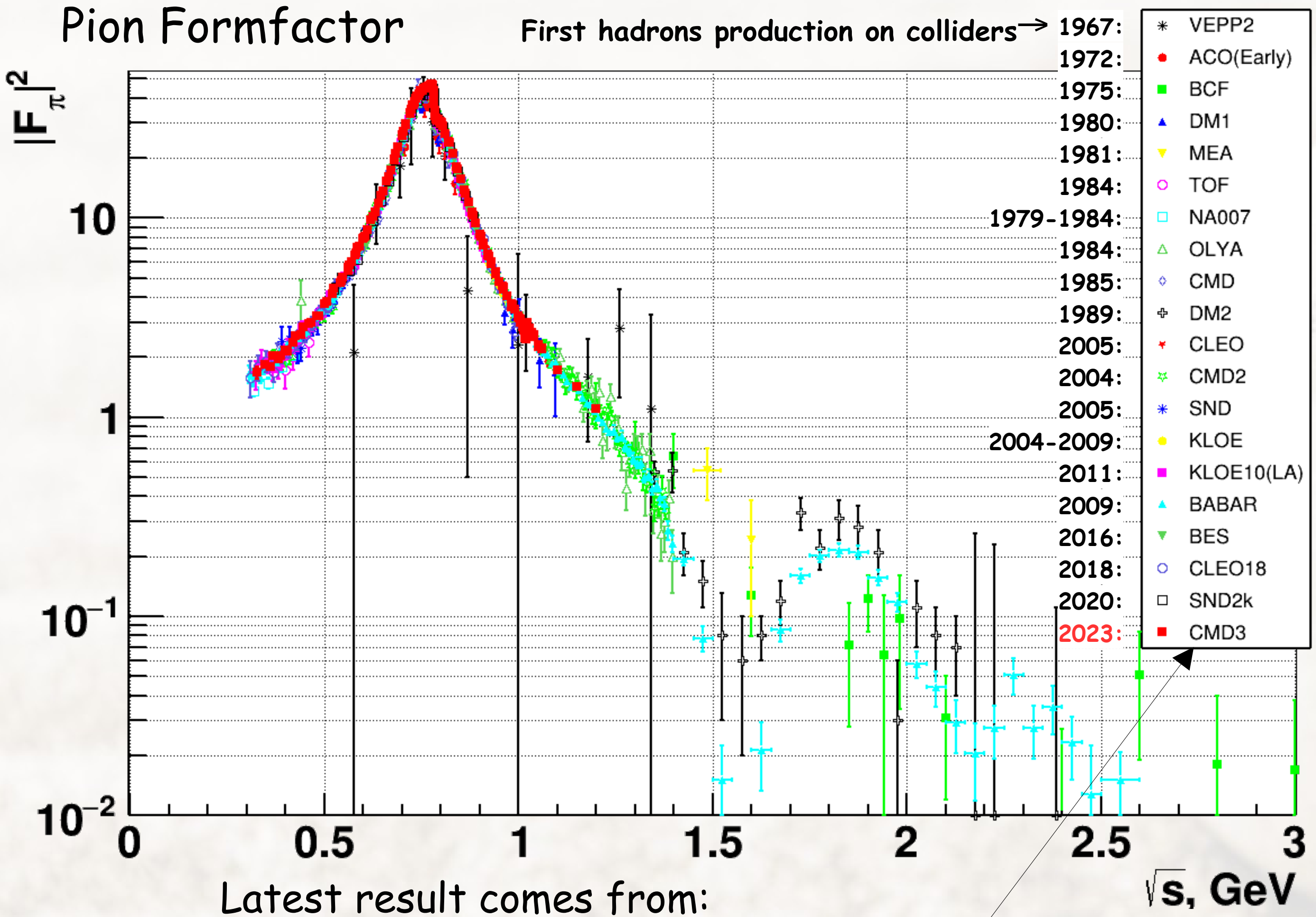
	At √s near ρ peak (except ω energies region)
✗ Radiative corrections	0.2% (2π) ⊕ 0.2% (Fπ) ⊕ 0.1% (e+e-) = **0.3%**
✗ e/μ/π separation	**0.2%**
✗ Fiducial volume	**0.5% / 0.8%** (2018/2013 data)
✗ Correlated inefficiency	**0.1%**
✗ Trigger	**0.05%**
✗ Beam Energy (by Compton $\sigma_E <$ 50 keV)	**0.1%**
✗ Bremsstrahlung loss	**0.05%**
✗ Pion specific loss	**0.2%** nuclear interaction **0.1%** pion decay
	0.7% / 0.9% (RHO2018/13)

Includes highly conservative θ-angle related systematic contribution:

despite that angle distributions, different datasets (2013/18) are consistent within ~<0.1%

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

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%

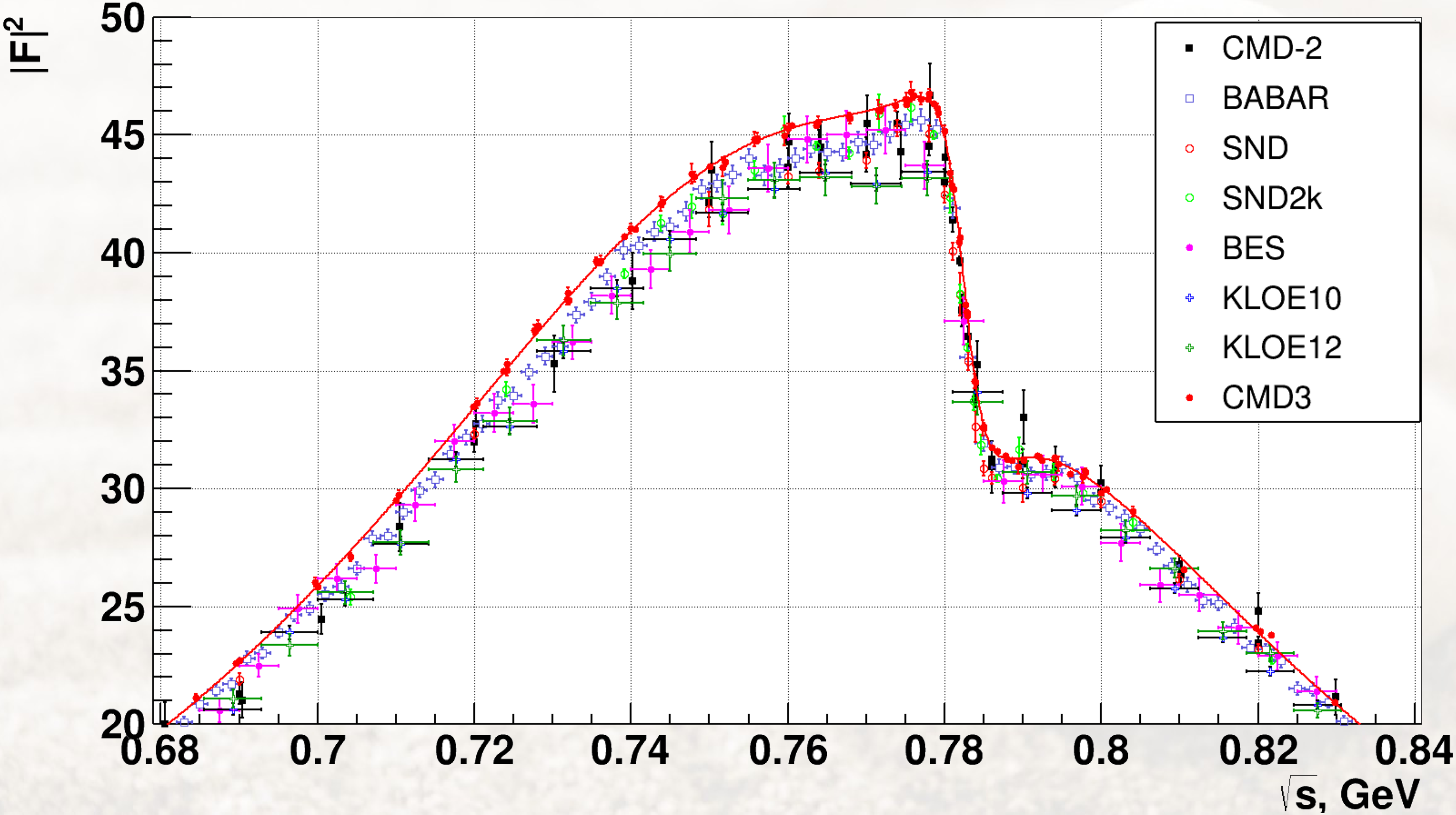
New direct data:

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

CMD-3: 0.7%

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

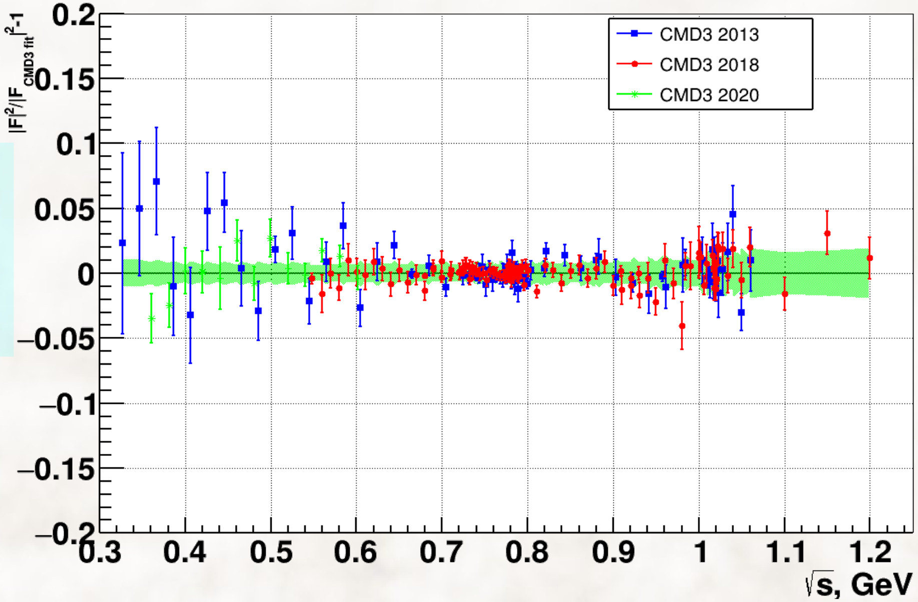
Other experiments

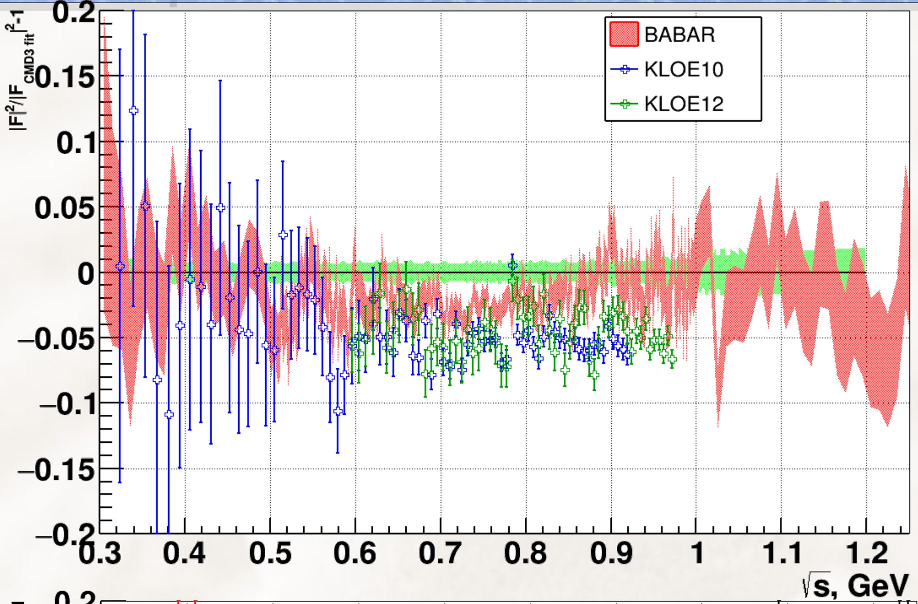


CMD-3 vs other experiments

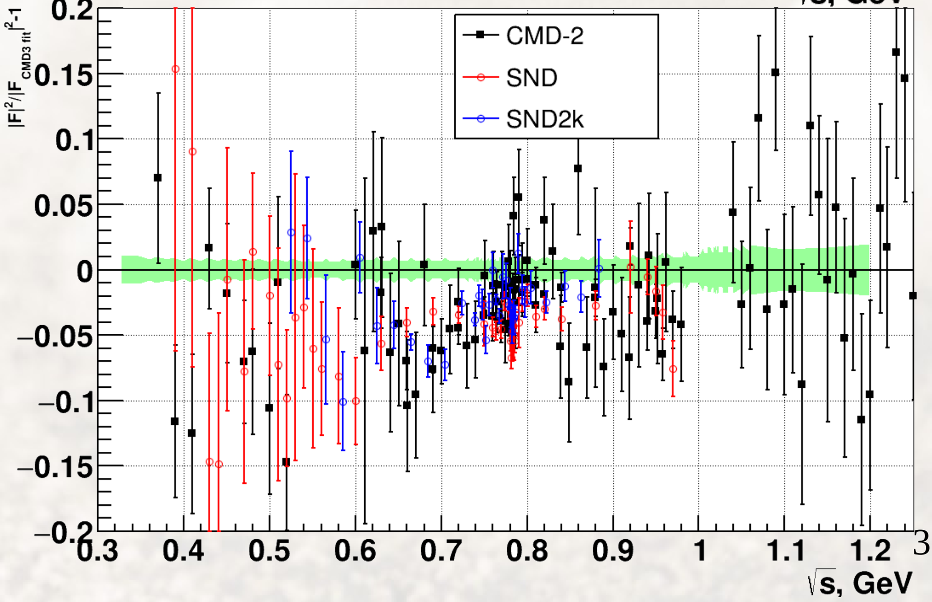
Relative to CMD-3 fit,
green band – systematic value

CMD-3





vs ISR



vs direct scan

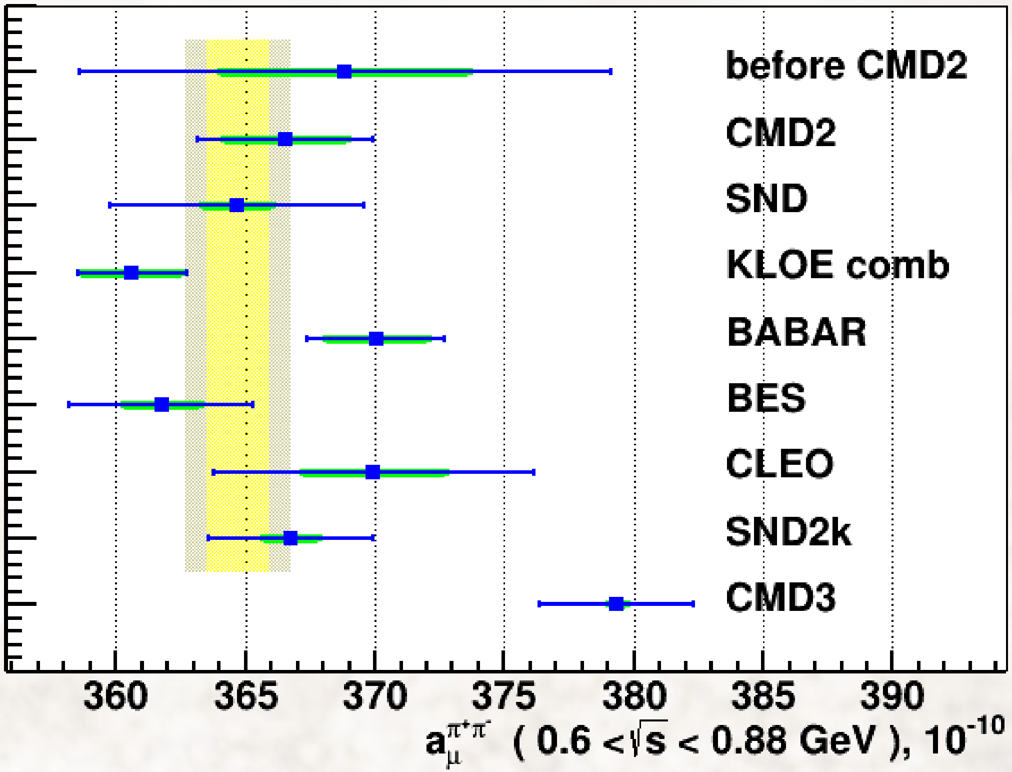
CMD-3

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

The $\pi+ \ \pi-$ 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

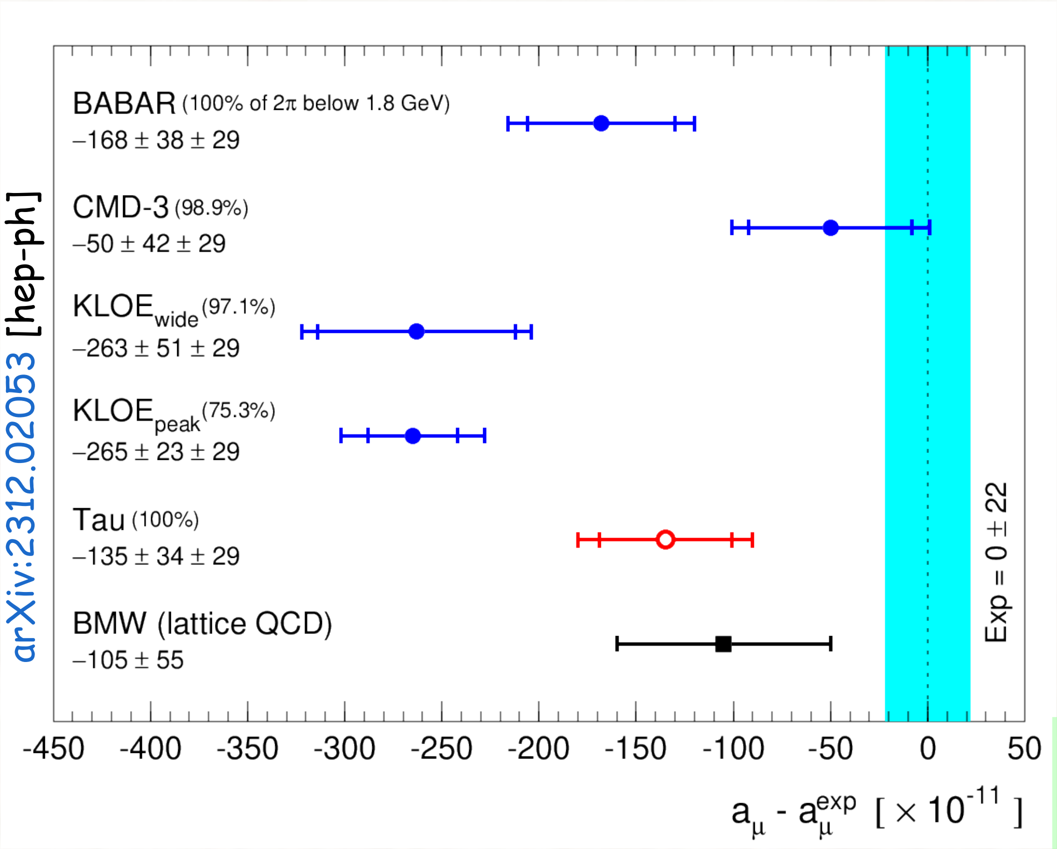


	$a_\mu^{\pi\pi,LO}$, 10^{-10}
before CMD2	368.8 ± 10.3
CMD2	366.5 ± 3.4
SND	364.7 ± 4.9
KLOE	360.6 ± 2.1
BABAR	370.1 ± 2.7
BES	361.8 ± 3.6
CLEO	370.0 ± 6.2
SND2k	366.7 ± 3.2
CMD3	379.3 ± 3.0

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 landscape of hadronic HVP to muon g-2

Using 2π contribution from single experiment



The situation is complicated on how to deal with inconsistent data to obtain the combined SM value of a_μ.

Introducing an additional scale factor in the total uncertainty due to inconsistencies (as was performed before for BaBar/KLOE tension) would sacrifice precision in the e+e- HVP

Needs to understand where the discrepancies in e+e- data come from

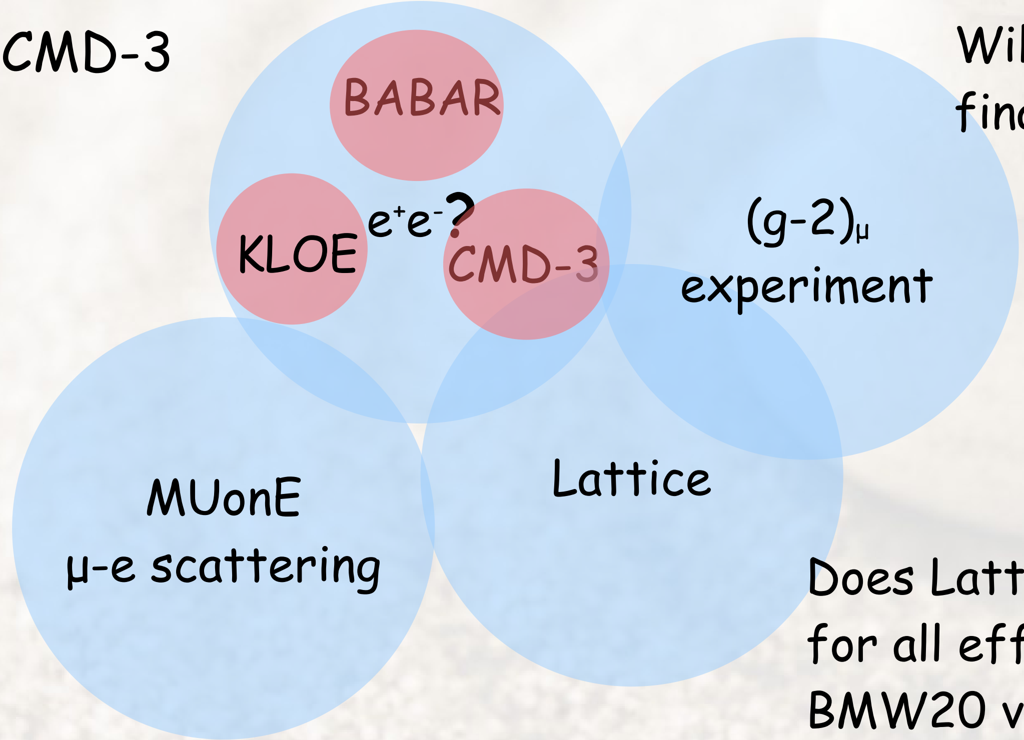
7th Workshop of the Muon g-2 Theory Initiative
September 9-13, 2024 @ KEK, Japan
https://conference-indico.kek.jp/event/257
Aim to produce 2nd TI White Paper by end of year

Puzzles in puzzle

Question of comparison:

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

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



BABAR

KLOE

e^+e^-?

CMD-3

$(g-2)_\mu$ experiment

MUonE
μ-e scattering

Lattice

Will it be confirmed?
final FNAL vs J-PARC

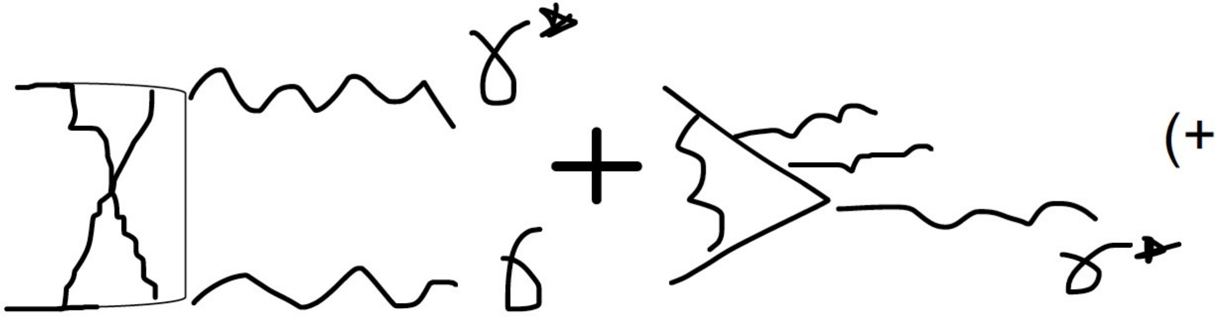
Hard effort against systematics

Does Lattice account for all effects?
BMW20 vs others

Radcor and MC tools, 7-9 June 2023, Zurich
Graziano Venanzoni, Workstop/thinkstart activities:
towards a NNLO MC generator for low-energy e+e- → hadrons

Towards NNLO MC generator ….

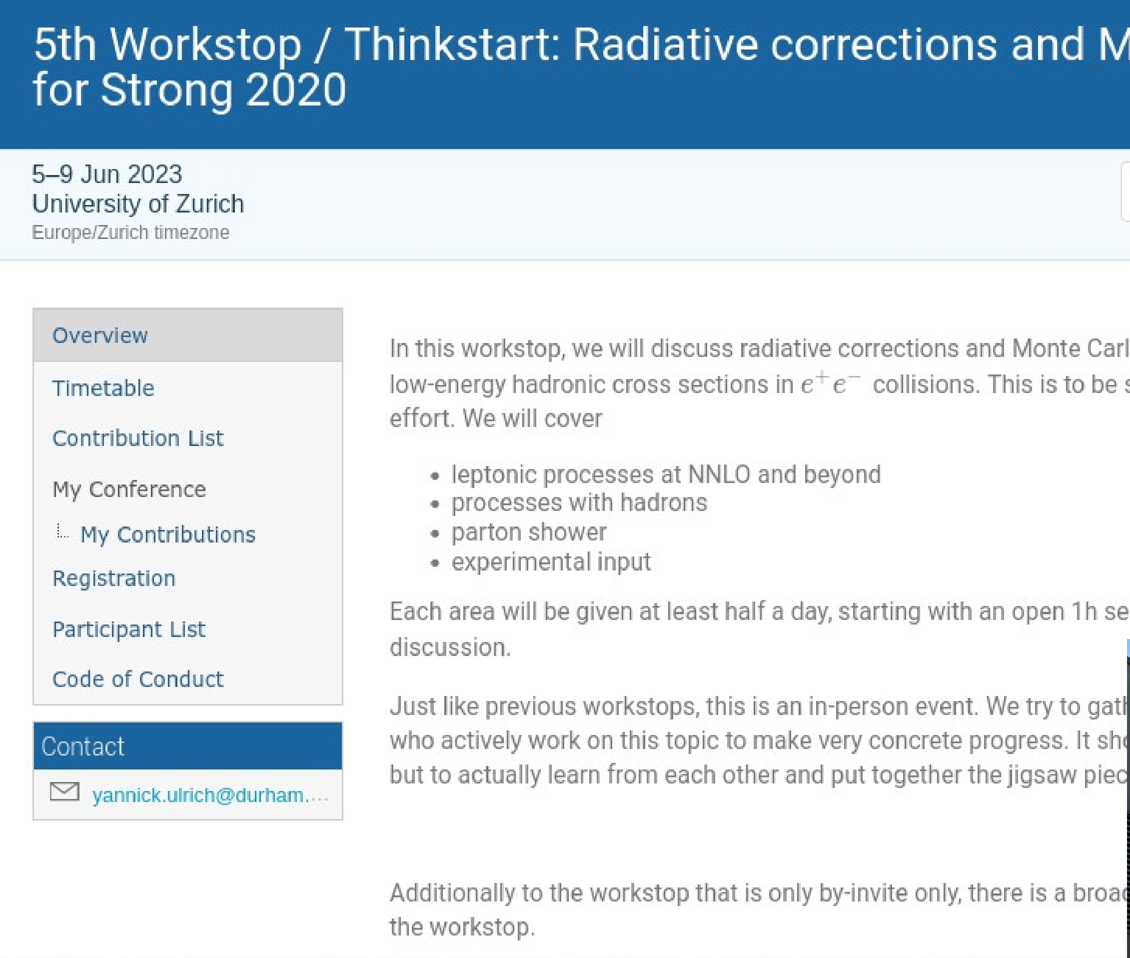
(N^{3}LO for ISR relative to born 2 particles)



(+ 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

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 gath
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.

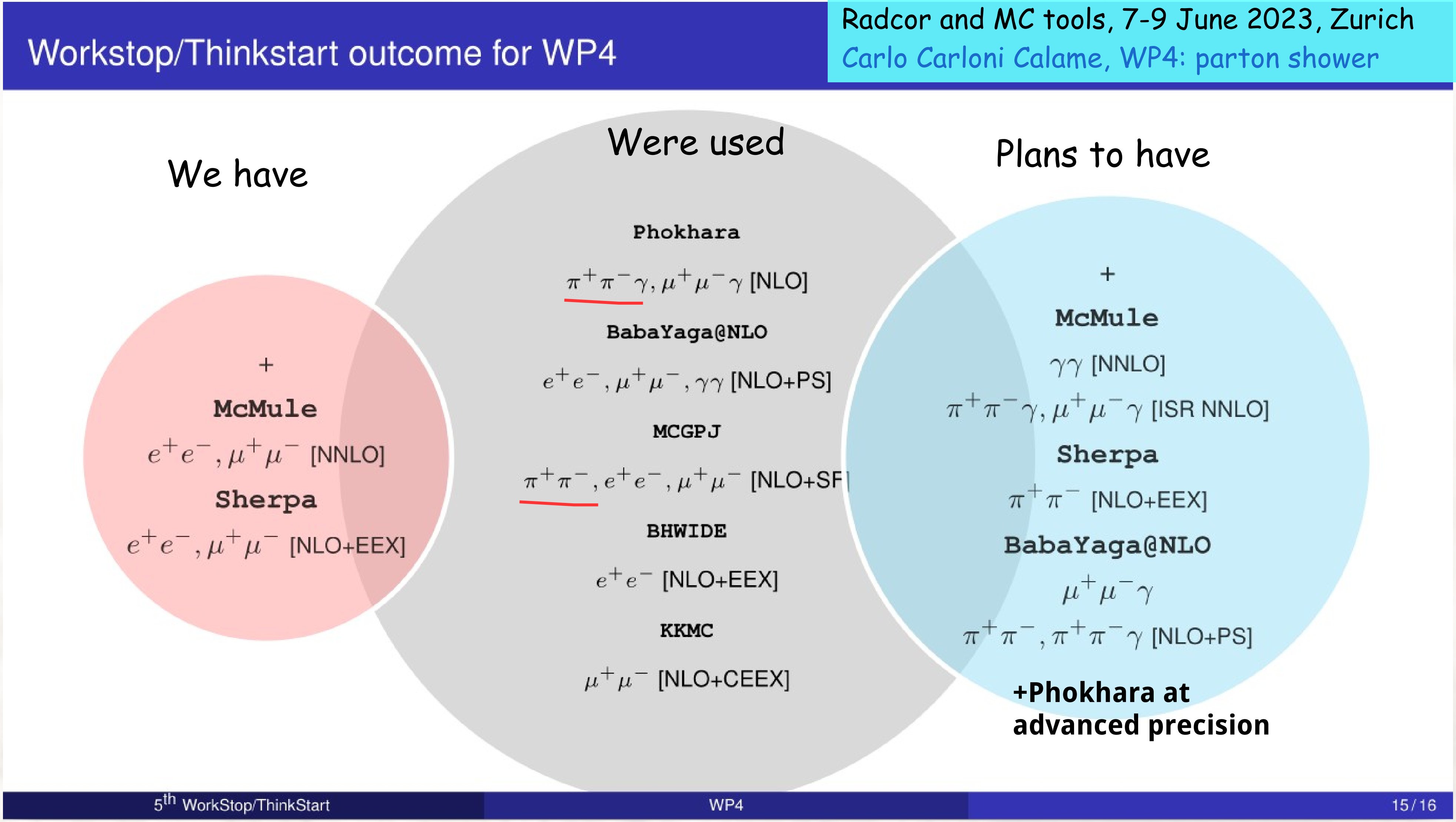
https://indico.psi.ch/event/13707/
https://indico.psi.ch/event/13708/

The effort to bring forward MC tools precision!

Towards NNLO (and above) precision

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

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]

+Phokhara at advanced precision

5th WorkStop/ThinkStart WP4 15 / 16

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

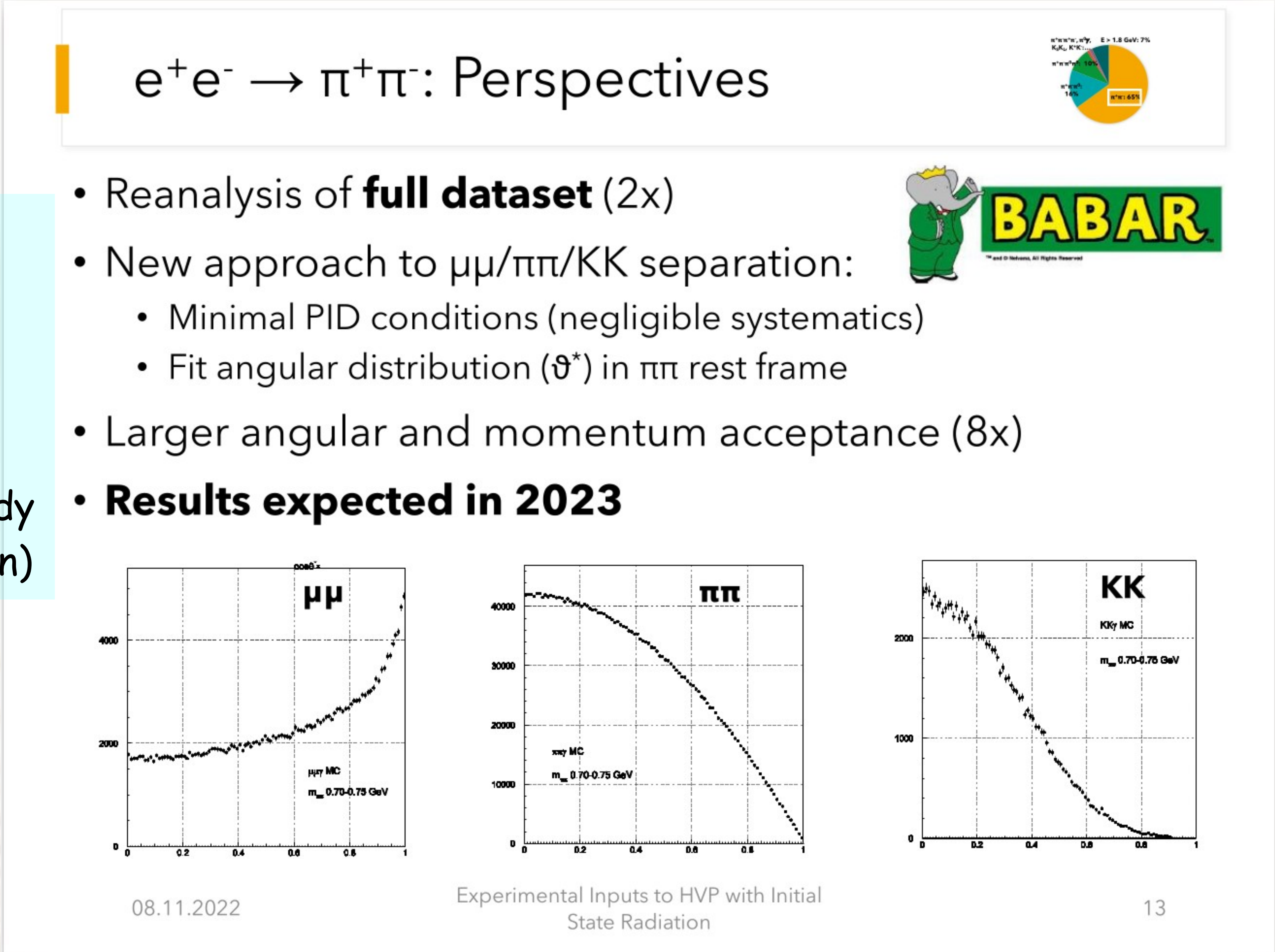
For scan experiment: MCGPJ with declared 0.2% precision

For ISR: Phokhara with 0.5% precision

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

BaBar

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



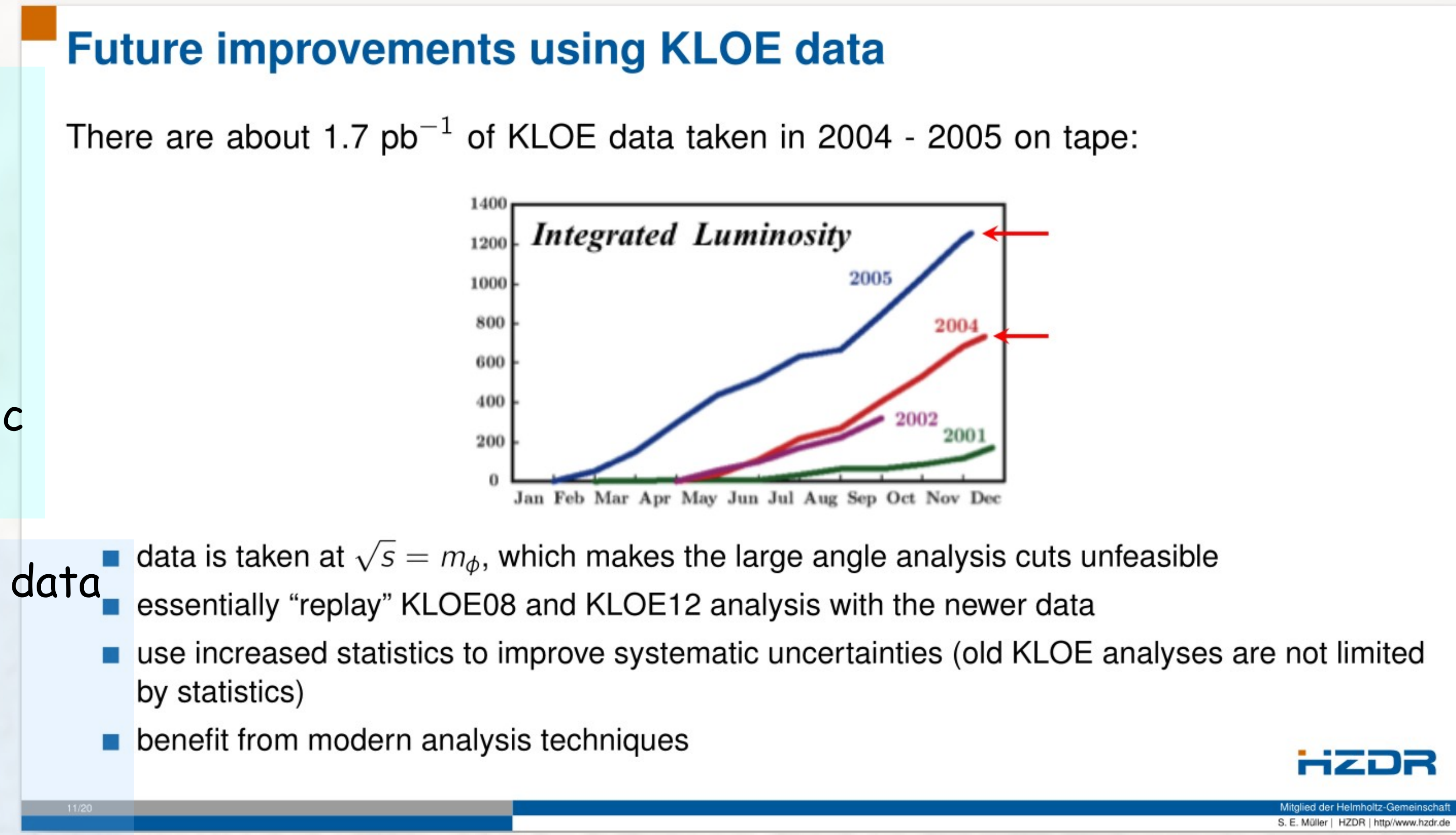
$e^+e^- \rightarrow \pi^+\pi^-$: Perspectives

- 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**

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

11/20

Mitglied der Helmholtz-Gemeinschaft
S. E. Müller | HZDR | http//www.hzdr.de

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

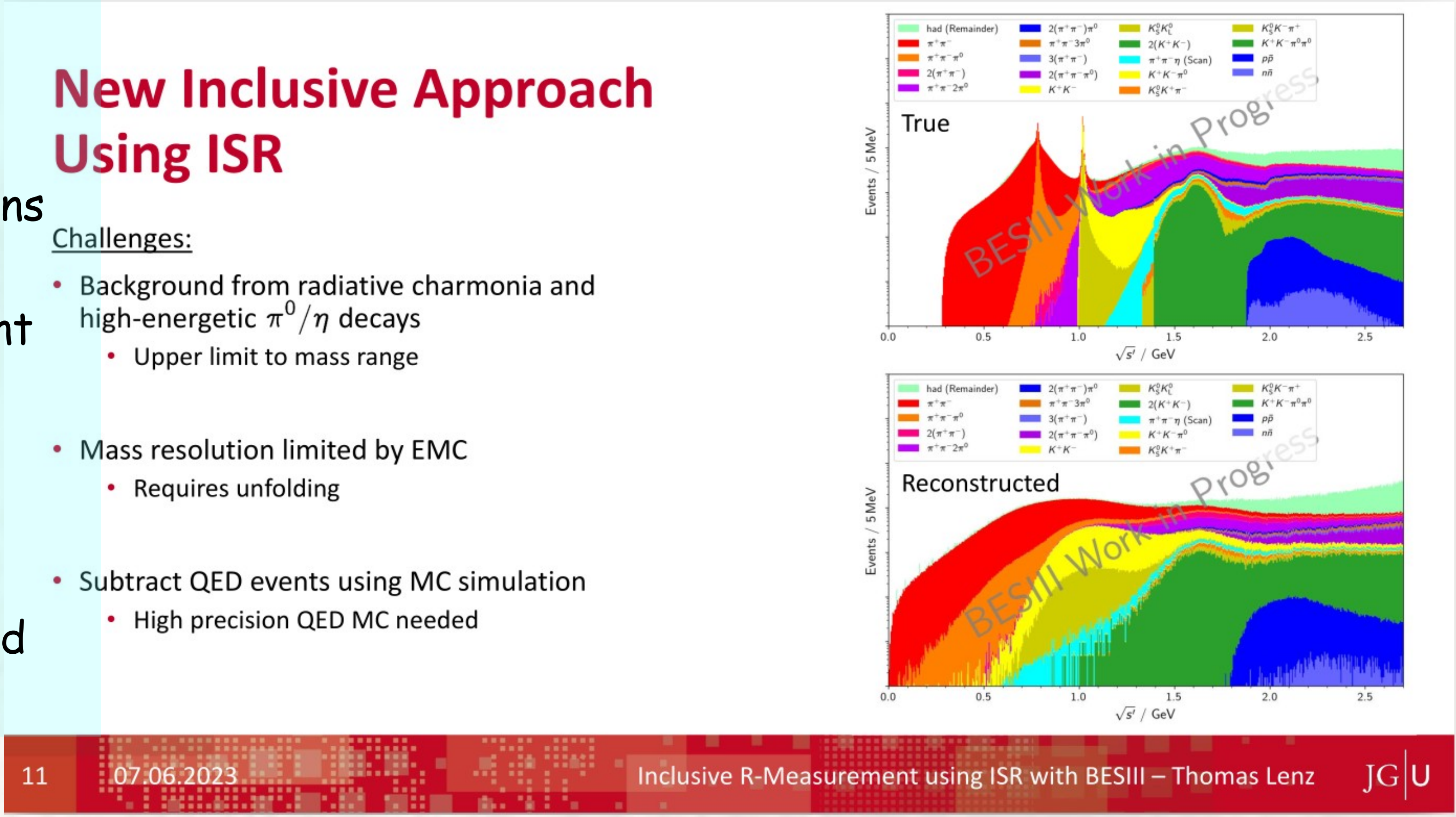
Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e+e- collisions, 7-9 June 2023, Zurich

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

BES

- ✗ x6 in statistics
- ✗ Helicity angle fit
- ✗ Normalization to muons

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



New Inclusive Approach Using ISR

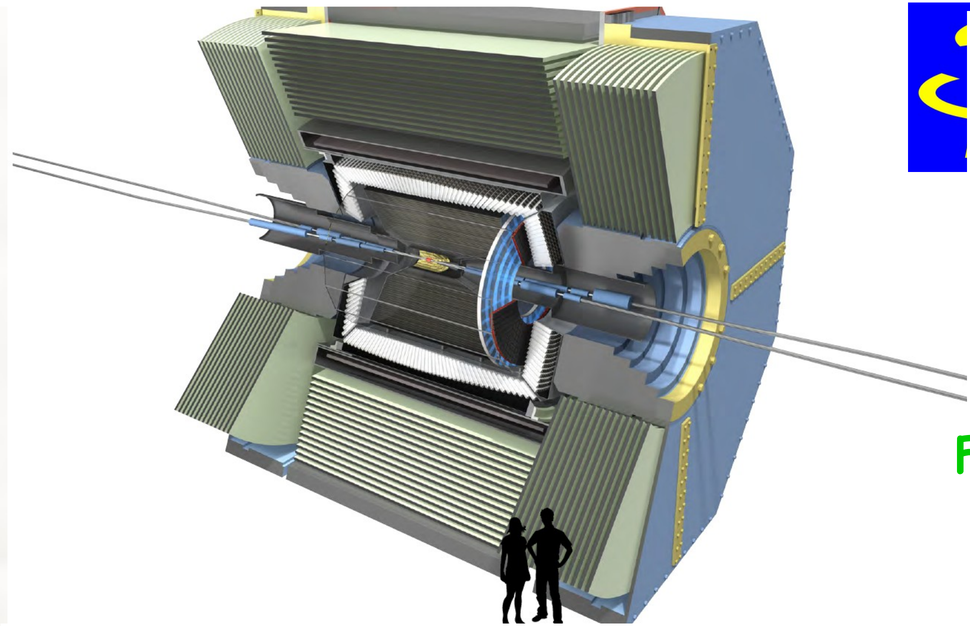
Challenges:

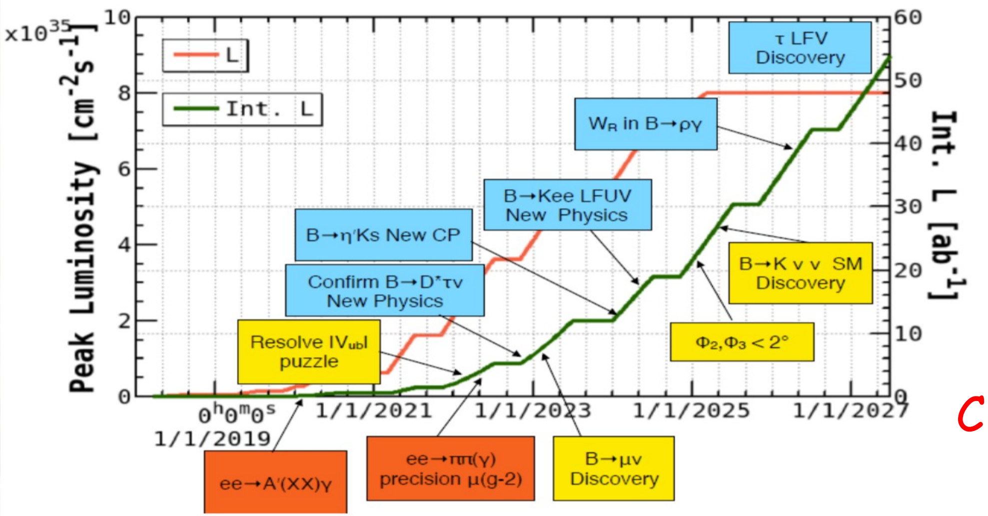
- Background from radiative charmonia and high-energetic π^0/η decays
  - Upper limit to mass range
- Mass resolution limited by EMC
  - Requires unfolding
- Subtract QED events using MC simulation
  - High precision QED MC needed

11 07.06.2023 Inclusive R-Measurement using ISR with BESIII – Thomas Lenz JG|U

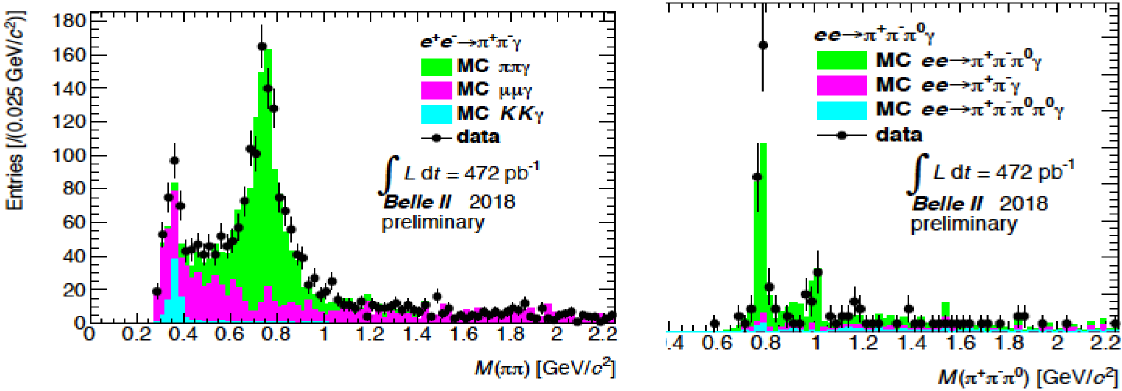
Belle2 ISR program

x50-100 of Belle,BaBar statistics

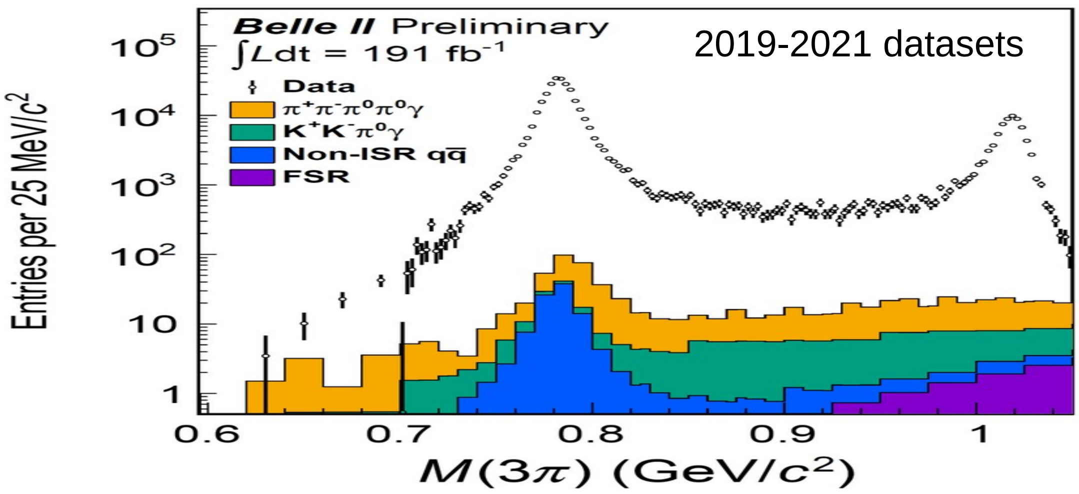




First sample of ρ,ω,φ by ISR on 2018 data



First $e^+e^-\to3\pi$ measurement came out last month



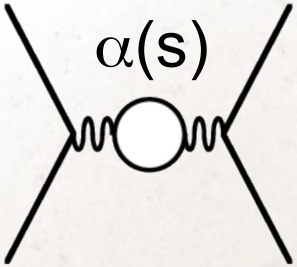
Cross section 5-10% higher than BaBar/SND data!!!

x100 more of data to be collected

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

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

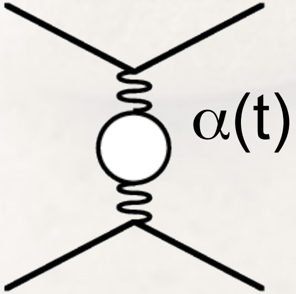
$$a_\mu^{HLO} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds\, K(s) \cdot \sigma(s)_{(e^+e^- \to had)}$$



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=q²<0

Systematic precision challenge

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

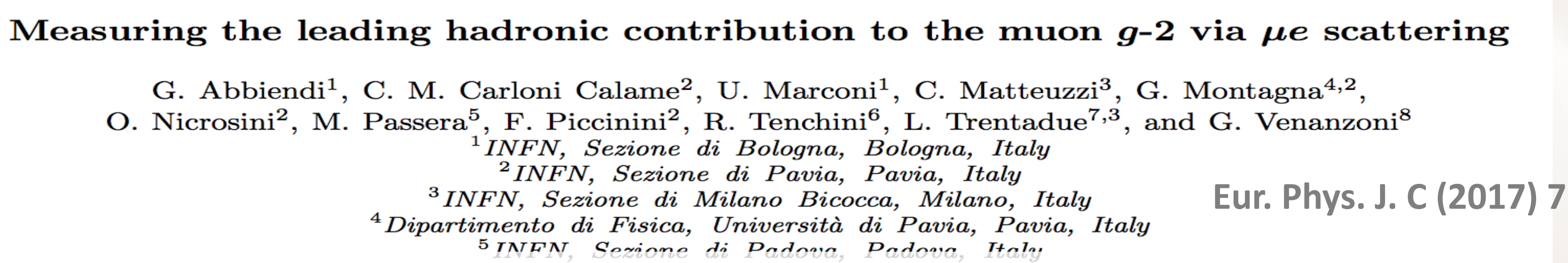
Reference papers

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

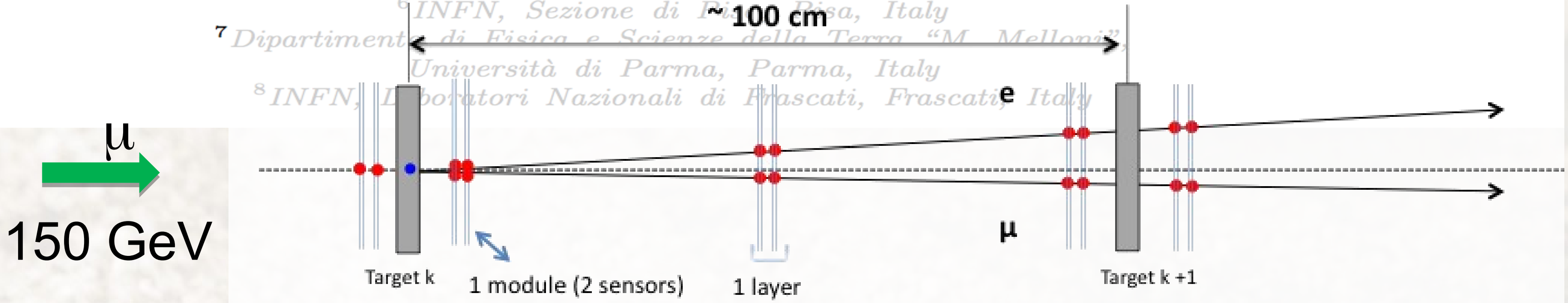


Measuring the leading hadronic contribution to the muon g-2 via μe scattering

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.



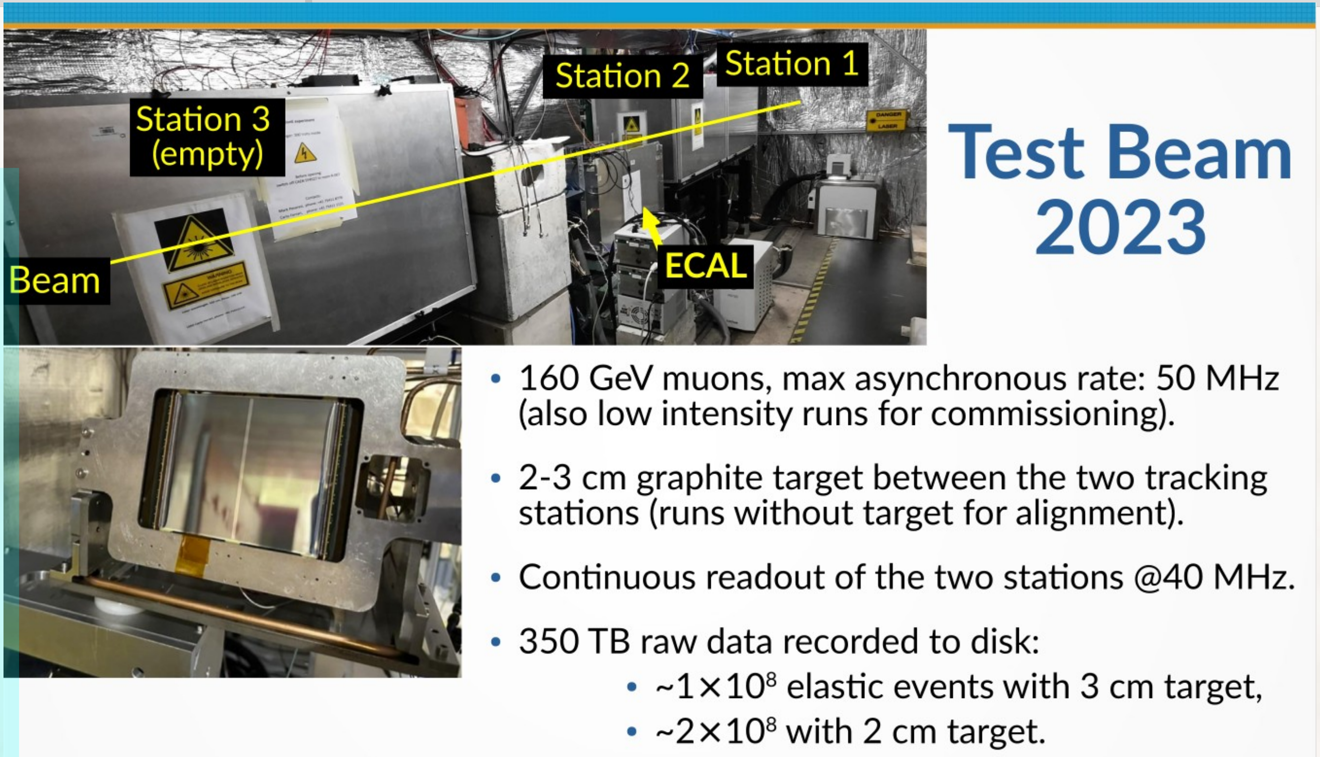
MUonE experiment

MUonE

✗ Test Beam 2023: proof of concept of the experimental proposal. Analysis is in progress to extract $\Delta\alpha_{lep}(t)$ with ~5% precision.

✗ Phase-1 proposal for SPSC for 4 week of beam time in 2025: main goal to determine $\Delta\alpha_{had}(t)$ with ~20% (using 3 stations)

✗ Full experiment with 40 stations after LS3 of LHC: goal to get a^{had}_{μ} with ~ 0.3%

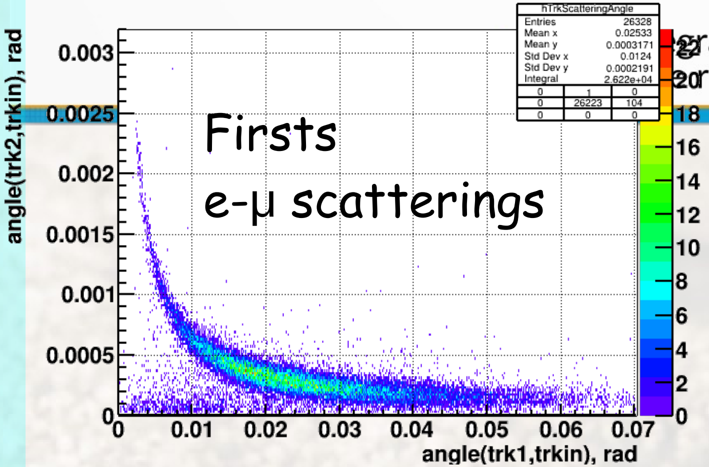


Test Beam 2023

- 160 GeV muons, max asynchronous rate: 50 MHz (also low intensity runs for commissioning).
- 2-3 cm graphite target between the two tracking stations (runs without target for alignment).
- Continuous readout of the two stations @40 MHz.
- 350 TB raw data recorded to disk:
  - ~1×10⁸ elastic events with 3 cm target,
  - ~2×10⁸ with 2 cm target.

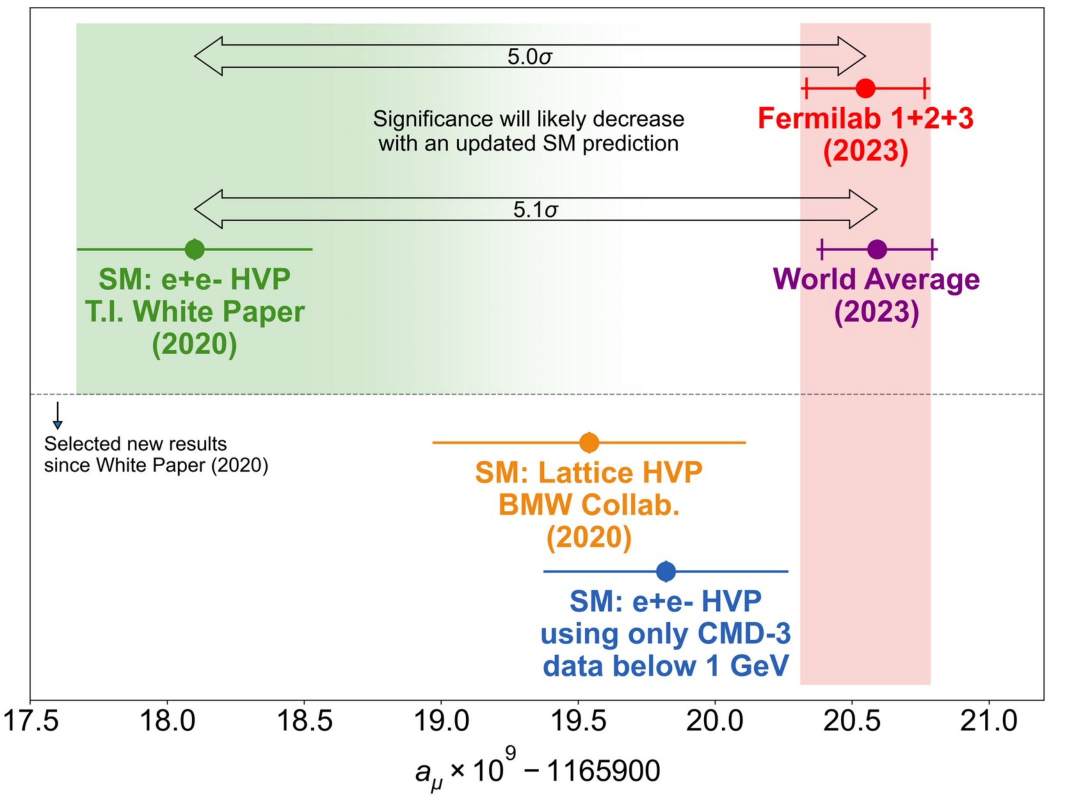
grated in the DAQ @40 MHz in the final run.

12



Firsts e-μ scatterings

Muon g-2 experiment vs theory landscape



Plot from James Mott:
https://indico.fnal.gov/event/60738/
Alex Keshavarzi:
https://indico.fnal.gov/event/57249/contributions/271581/

FermiLab muon g-2 measurement (end of 2023) improves BNL experiment by factor 2

Next year: further 1/2 improvement expected after analysis of the full statistic

---

Theory Initiative (TI) White paper consensus in 2020 gives single number for the SM prediction based on e+e- data

Since TI White Paper:

From BMW collab. first Lattice calculation with competitive precision (confirmations from others group are under way)

CMD-3 measurement of e+e- → π+π- with high statistics gives additional input on the theoretical side

End of year: new TI white paper is expected before new g-2 result

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/

Backup

"Like an elephant in a china shop" ESMA 2017

Scan with ISR approaches

Both methods stress different systematics

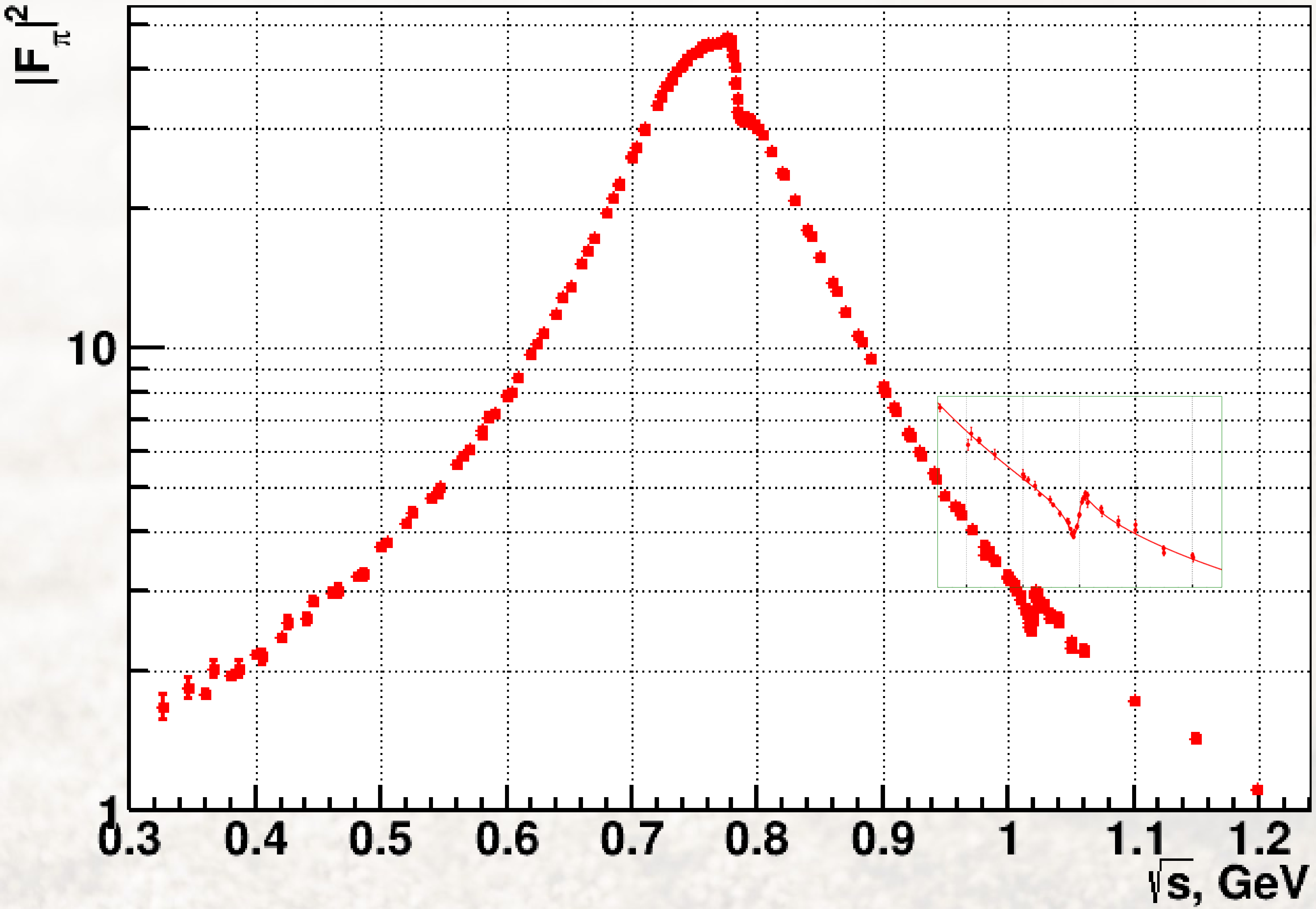
Direct energy scan

- Accelerator should be re-tuned for each $\sqrt{s}$
  c.m.s energy is known better
  (compton backscattering methods gives $\delta E/E < 10^{-4}$)
- Less stringent on radiative corrections
- $\pi^+\pi^-$ collinear events are better defined
  (momenta peaked at E_{beam})
- Limited acceptance
  (efficiencies of multihadron processes (3π,4π,..)
  depend on models describing dynamics)
- Significant effect from pion decays and nuclear interaction at the threshold energies

ISR method

- 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
- Needs +1 order on alpha for same precision
- Higher background from other channels
- At BABAR energies hadron system is boosted
  all tracks in acceptance range
  (but needs to reconstruct overlapped tracks)
- Boosted particles have higher energies:
  smaller effect from decays, nuclear interaction losses
- More complicated PID

Form factor



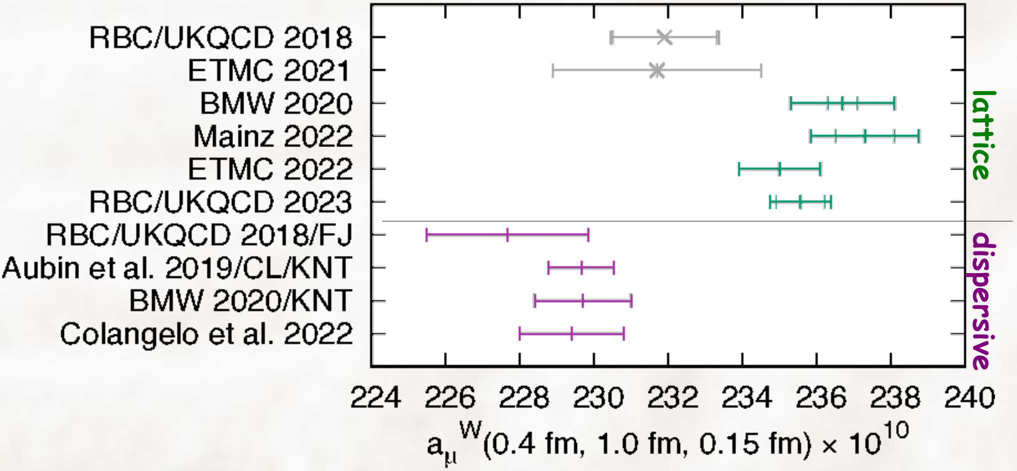
Dispersive vs Lattice

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

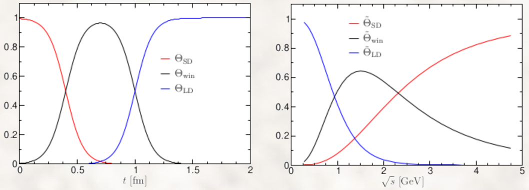
C. Alexandrou et al, e-Print: 2212.08467 [hep-lat]

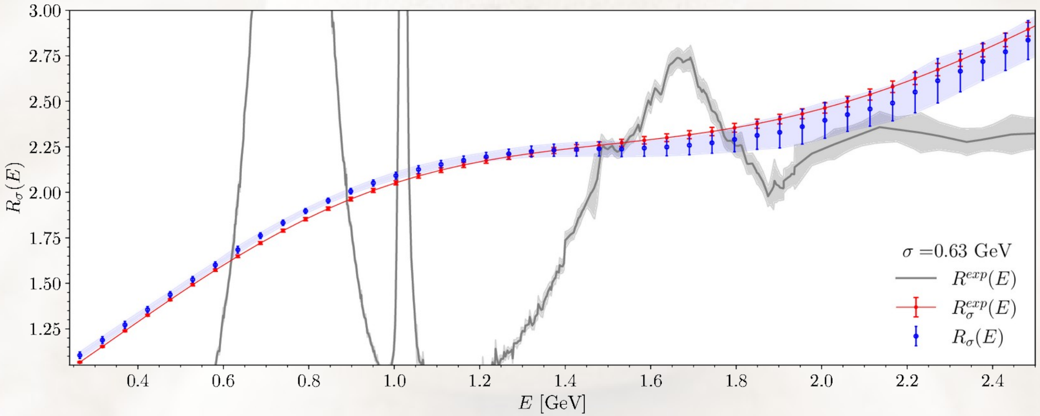
a^{HVP}_{μ} contribution from intermediate window in Euclidean time

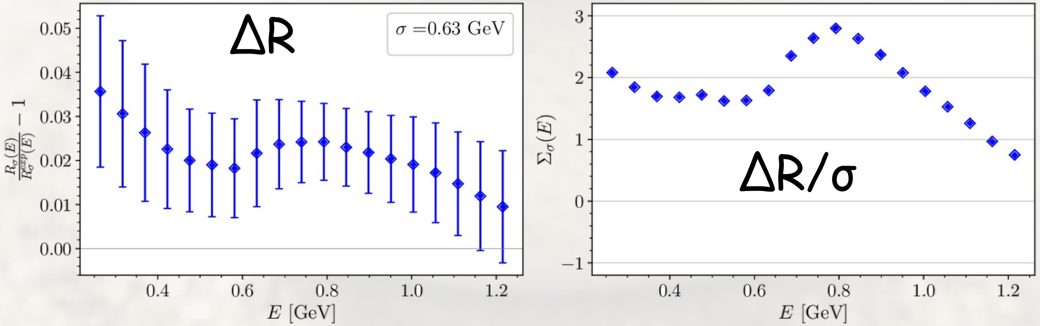
R(s) is convolved with Gaussian kernel



Windows definition







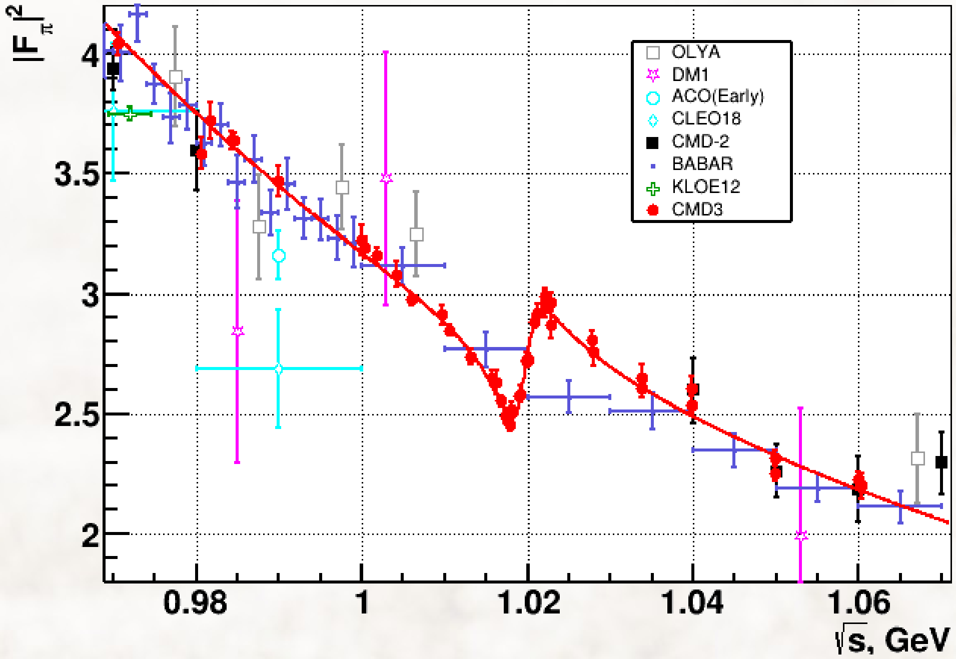
~4σ tension between Lattice/Dispersive e+e-

~3σ tension at rho energies

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

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

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



CMD-3

ψ_π = (-21.3 ± 2.0 ± 10.0)°

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

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

SND

ψ_π = (-34 ± 5)°

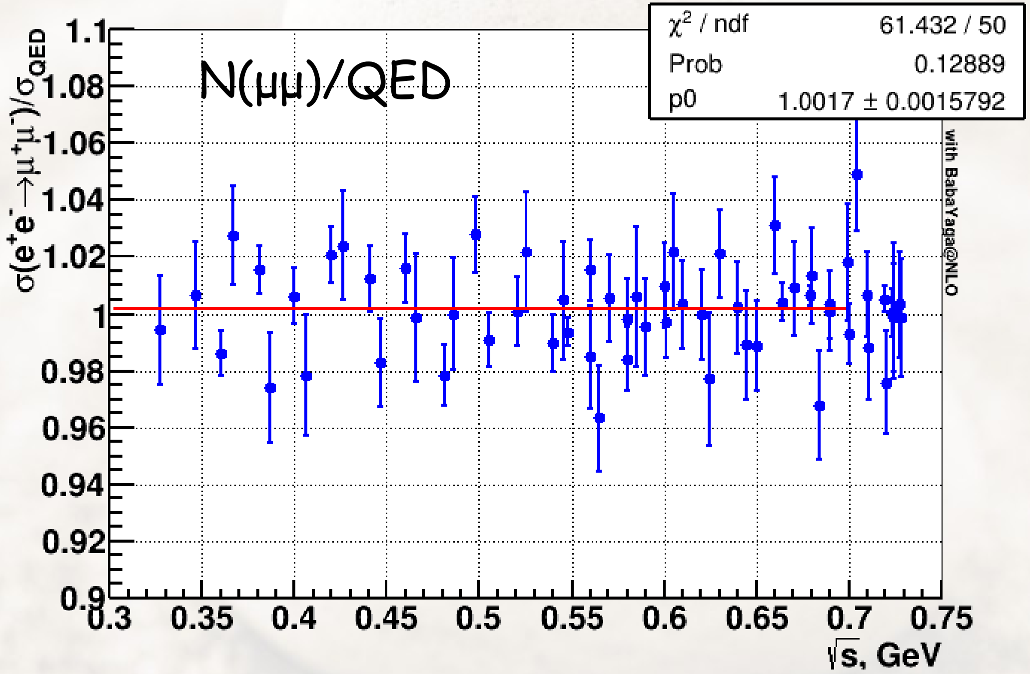
$B(\varphi\rightarrow e^+e^-)B(\varphi\rightarrow\pi^+\pi^-) = (2.1 \pm 0.4)\times10^{-8}$

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

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 %



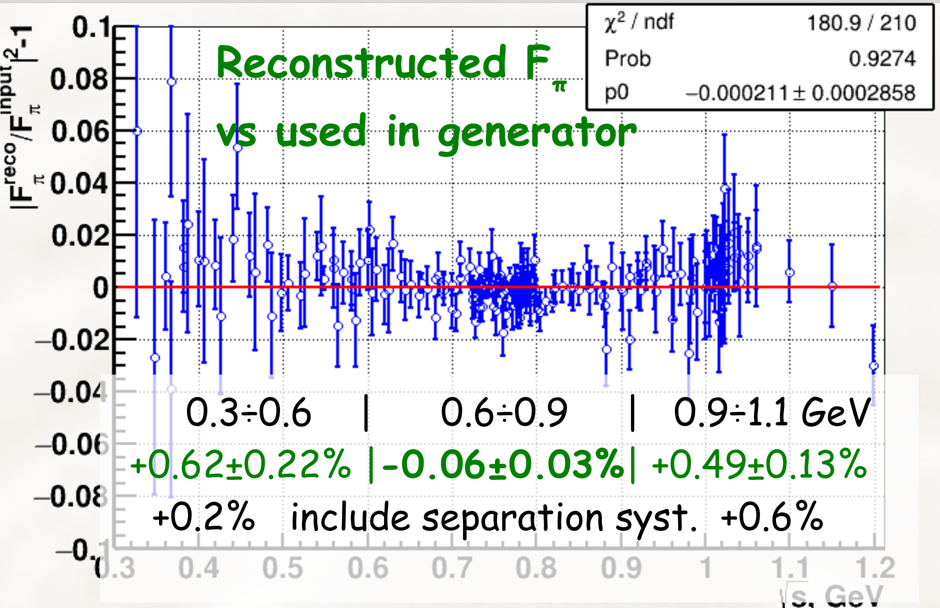
Many others self consistency checks were performed

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)

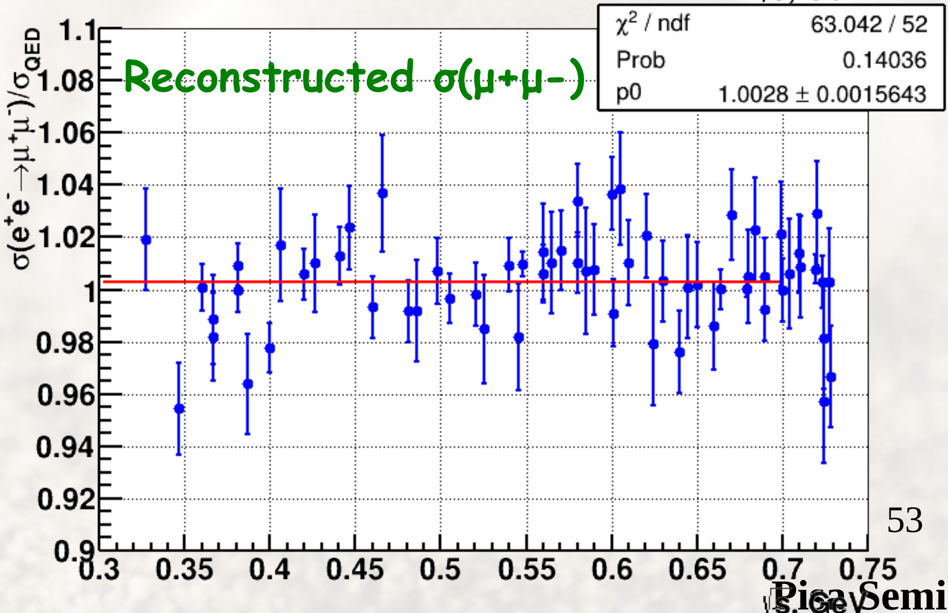
Same full analysis as for the data:
- efficiencies reconstructions,
- particle separation, etc
- same scripts,
- same intermediate files, etc

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-)

Angle distribution fit

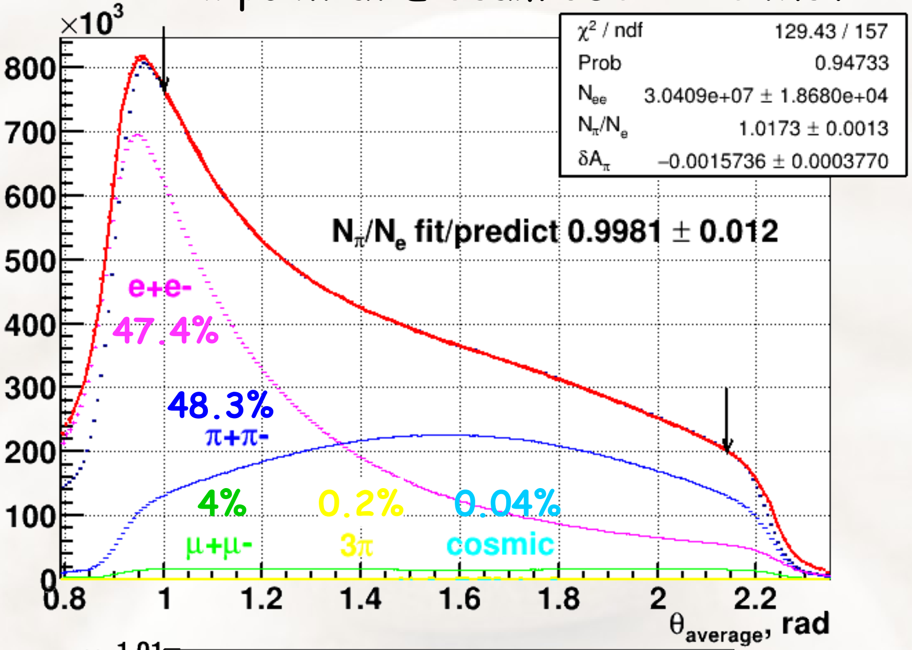
dσ/dθ spectra from MC Generators
+ all efficiencies/smearing effects
extracted from data and full simulation
(cosmic is taken from data itself)

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

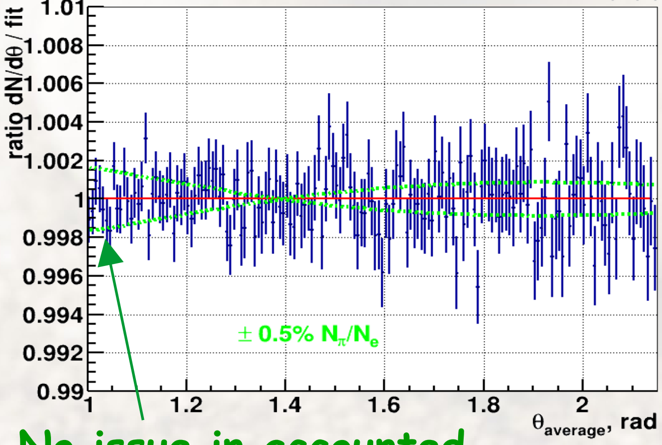
Combined fit on all points around ρ-peak
$\sqrt{s}$ = 0.7 – 0.82 GeV

$N_{\pi\pi}$ /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

$F\pi$ 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)

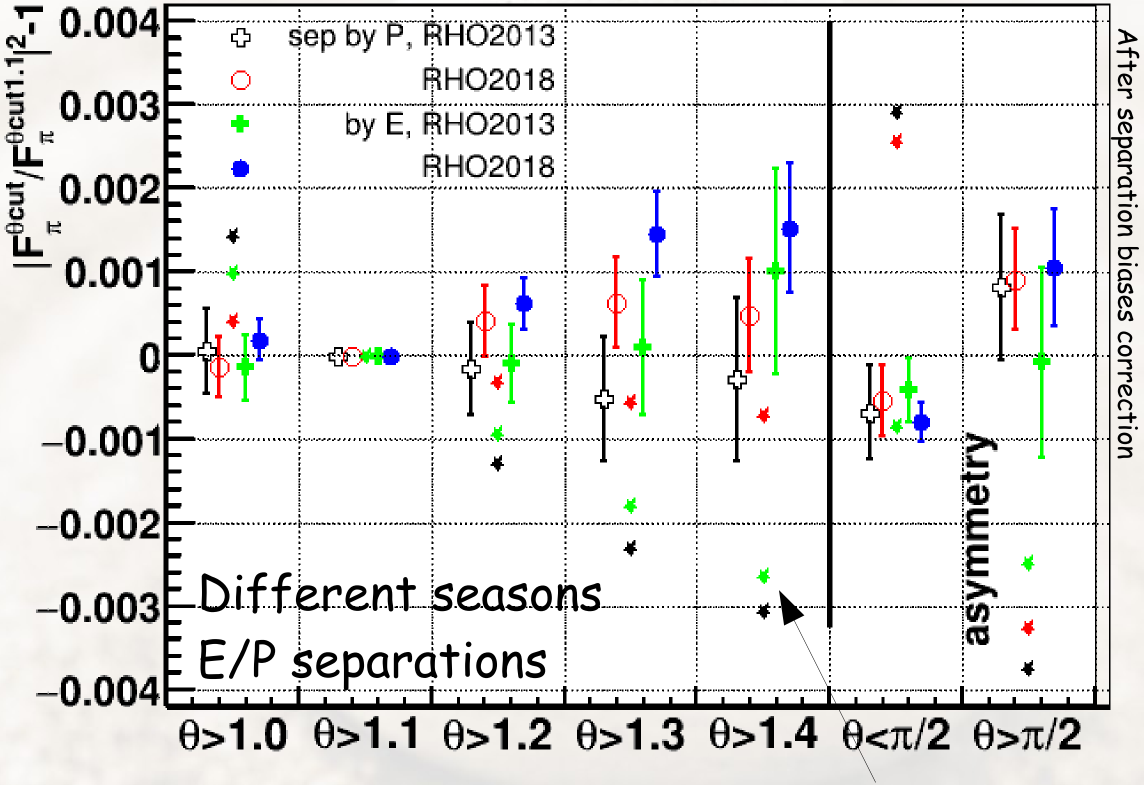
Simplest possible systematics in θ angle:

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

Average at 2E= 0.7-0.82 GeV



With 0.5% systematic at 1 rad

★Z-length mis-calibration

★θ bias

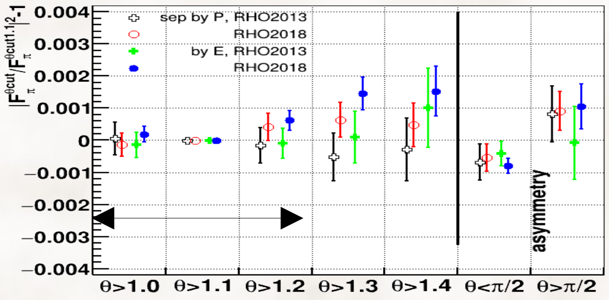
★θ bias opposite

Detection volume consistency check

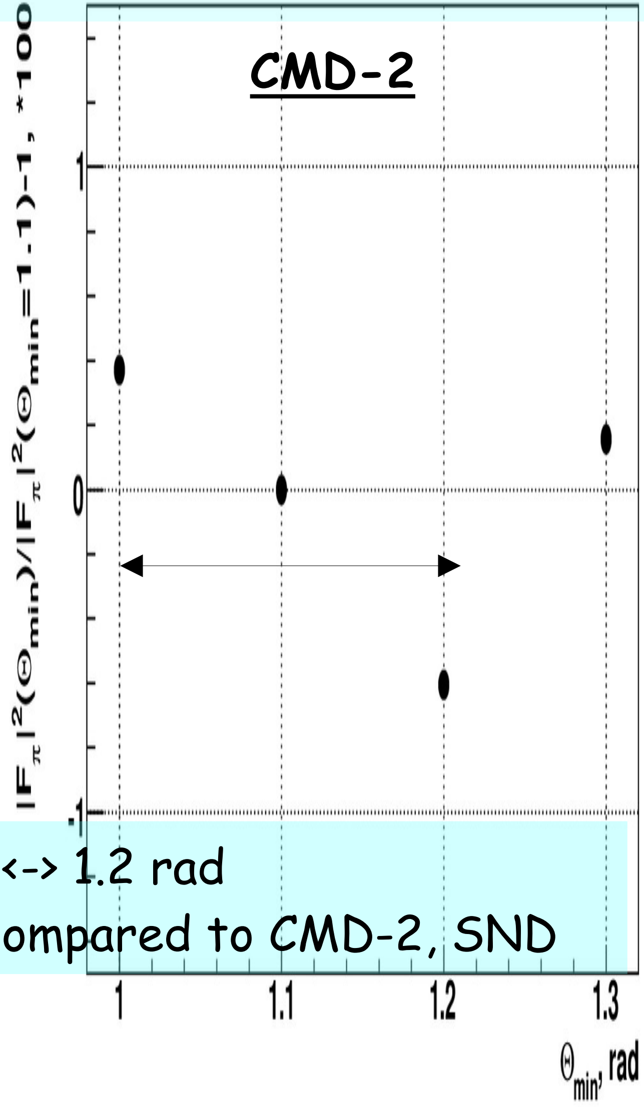
Variation of $\delta|F|^2$ vs θ-angle selection cut ($\theta_{cut} < \theta_{event} < \pi-\theta_{cut}$)

Same scale over Y-axis

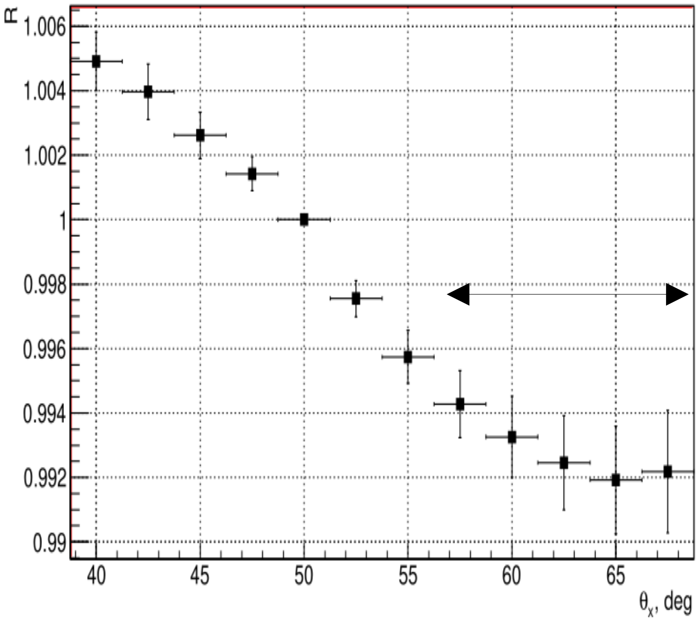
CMD-3



CMD-2



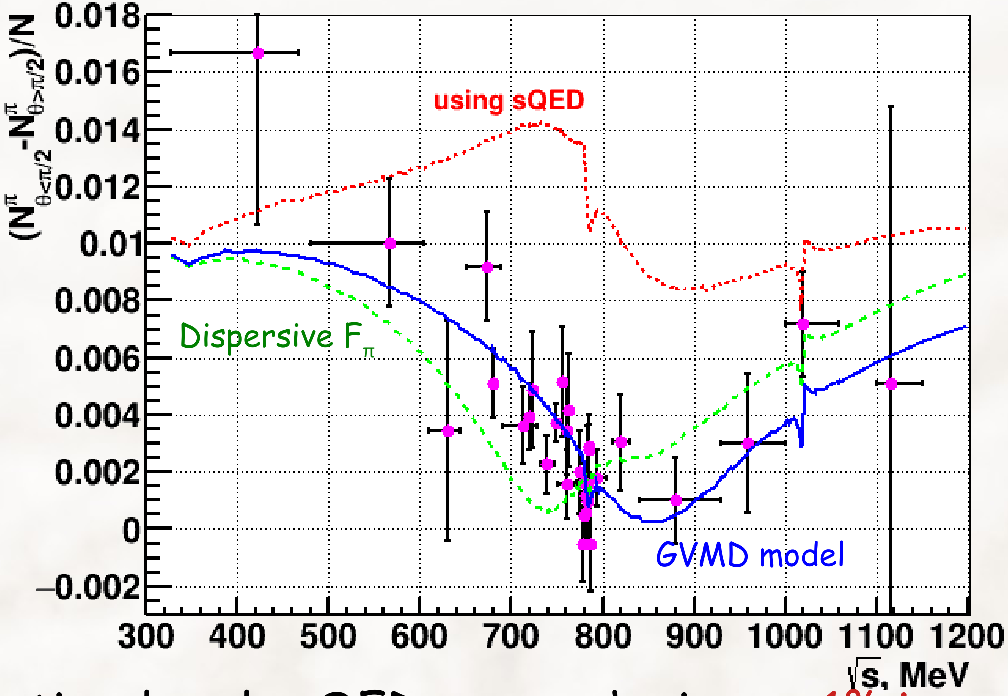
SND@VEPP-2000



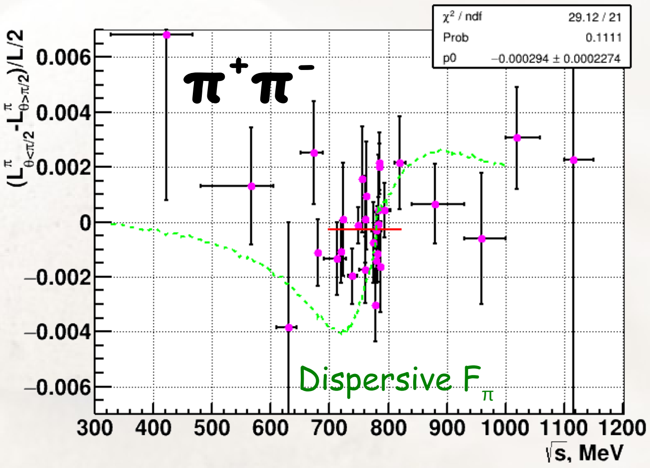
Changes of $\delta|F|^2/|F|^2$ vs θ_{cut} 1 <-> 1.2 rad
~10 times smaller for CMD-3 compared to CMD-2, SND

Charge asymmetry in e+e- -> π+π-

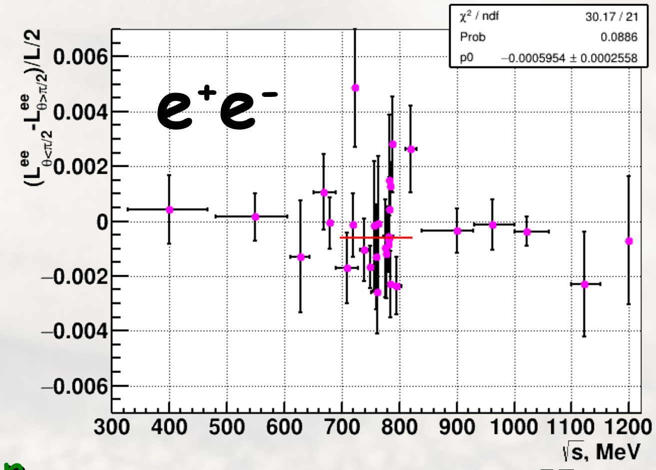
$A = (N_{\theta<\pi/2} - N_{\theta>\pi/2})/N$



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:

$\pi^+\pi^-$: <δA> = -0.029 ± 0.023 %

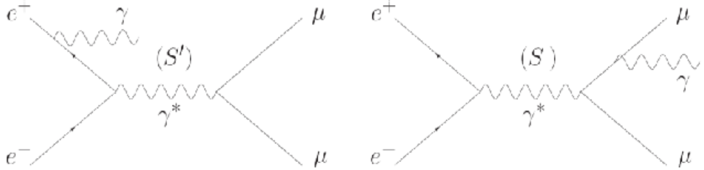
e^+e^-: <δA> = -0.060 ± 0.026 %

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

Asymmetry in BaBar

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

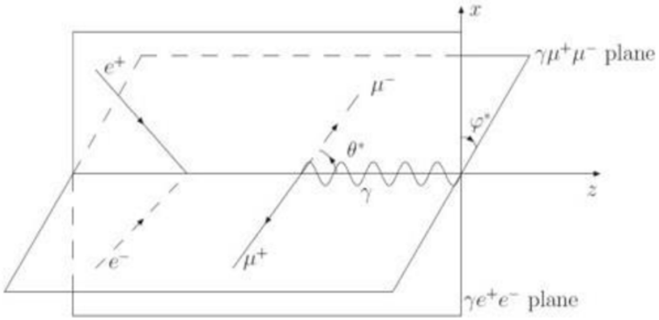
- ISR method used to measure hadronic cross sections: ee→Xγ X:QED ($\mu^+\mu^-$) or hadronic final states ($\pi^+\pi^-$)
- but radiation can be from initial state (LO ISR) or final state (LO FSR)



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

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

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



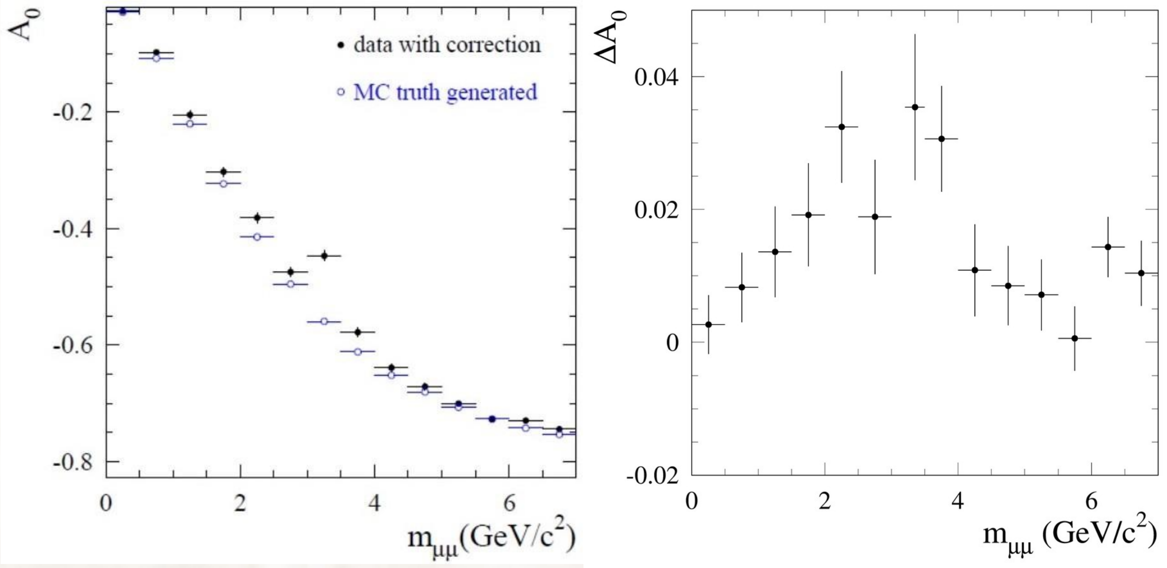
(b) In the x^+x^- c.m.

Asymmetry in BaBar

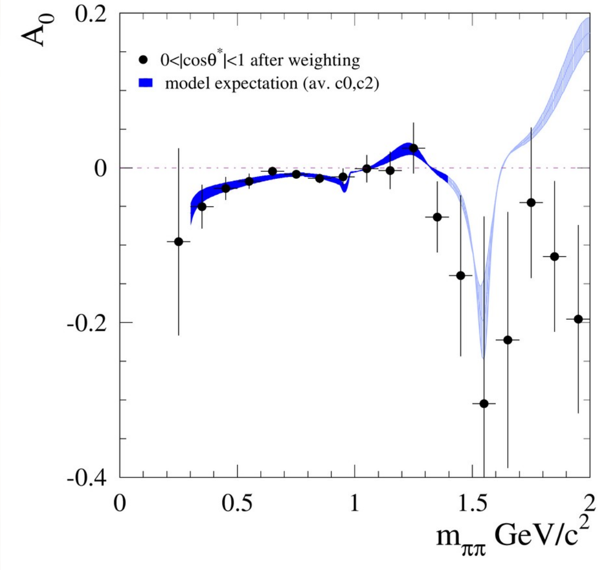
Phys.Rev.D 92 (2015) 7, 072015
e-Print: 1508.04008 [hep-ex]

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

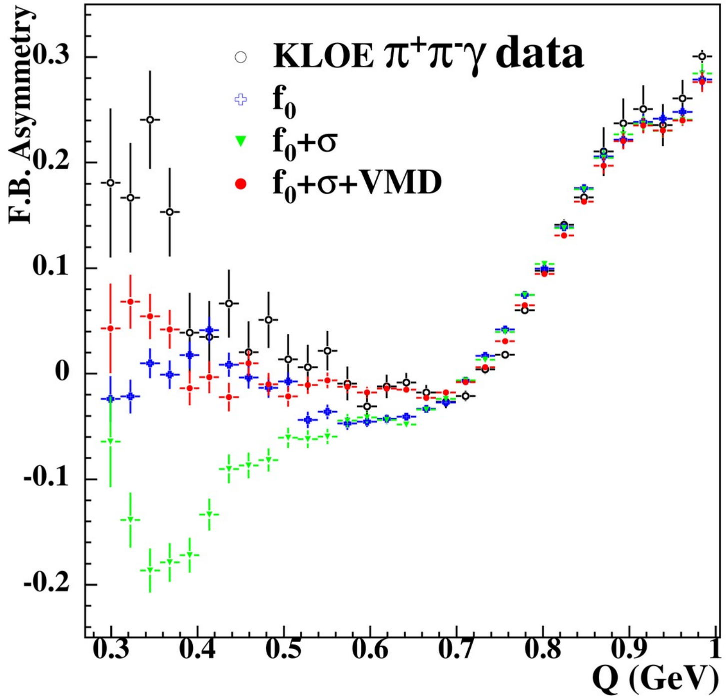
$$A = \frac{N(\theta_{\pi^+} > 90^\circ) - N(\theta_{\pi^+} < 90^\circ)}{N(\theta_{\pi^+} > 90^\circ) + N(\theta_{\pi^+} < 90^\circ)}$$

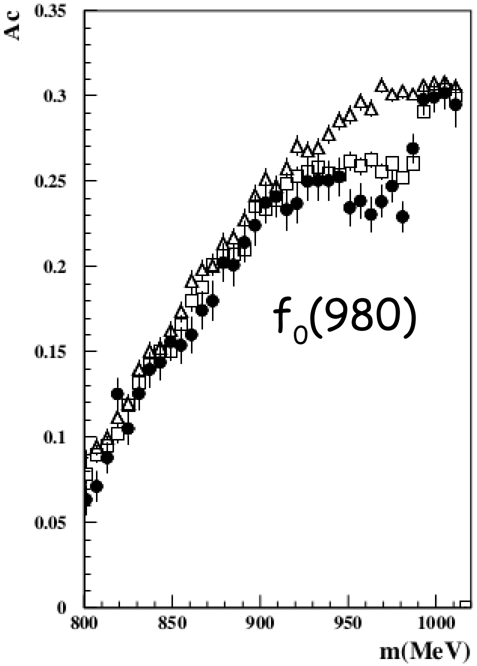
$\theta_\pi, \theta_\gamma > 45^\circ$

At φ- peak

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

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



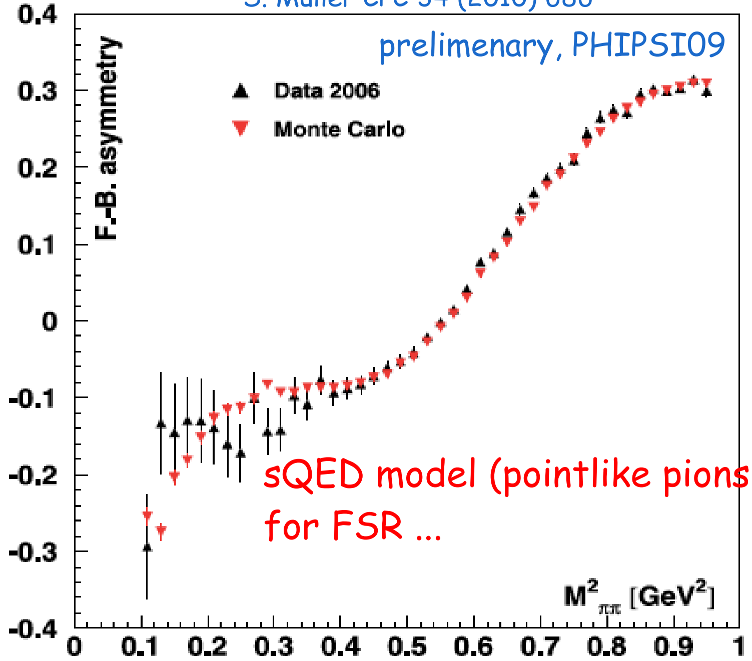


$f_0(980)$

2006 φ off-peak data

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

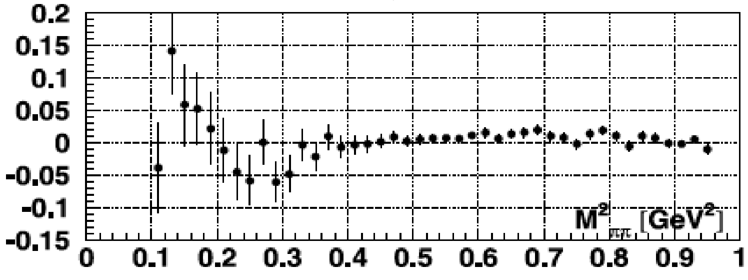
S. Muller CPC 34 (2010) 686



prelimenary, PHIPSI09

sQED model (pointlike pions) for FSR ...

Inconsistency at 1-2%



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

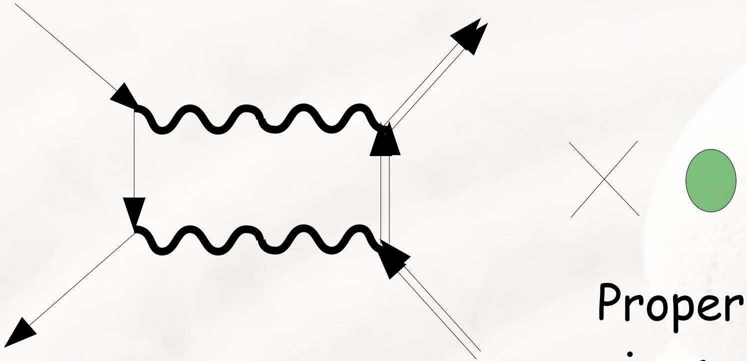
$\varphi \to \rho^\pm\pi^\pm$, $\rho \to \pi\gamma$

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

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

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

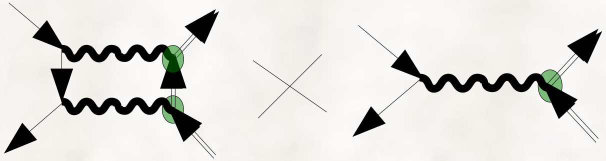
A = sQED*F(s)

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

How it can affect pion form factor measurements?

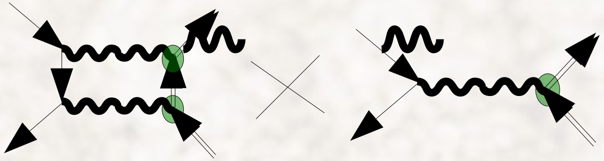
Usually event selections in analyses are charge/angle symmetric

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

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:

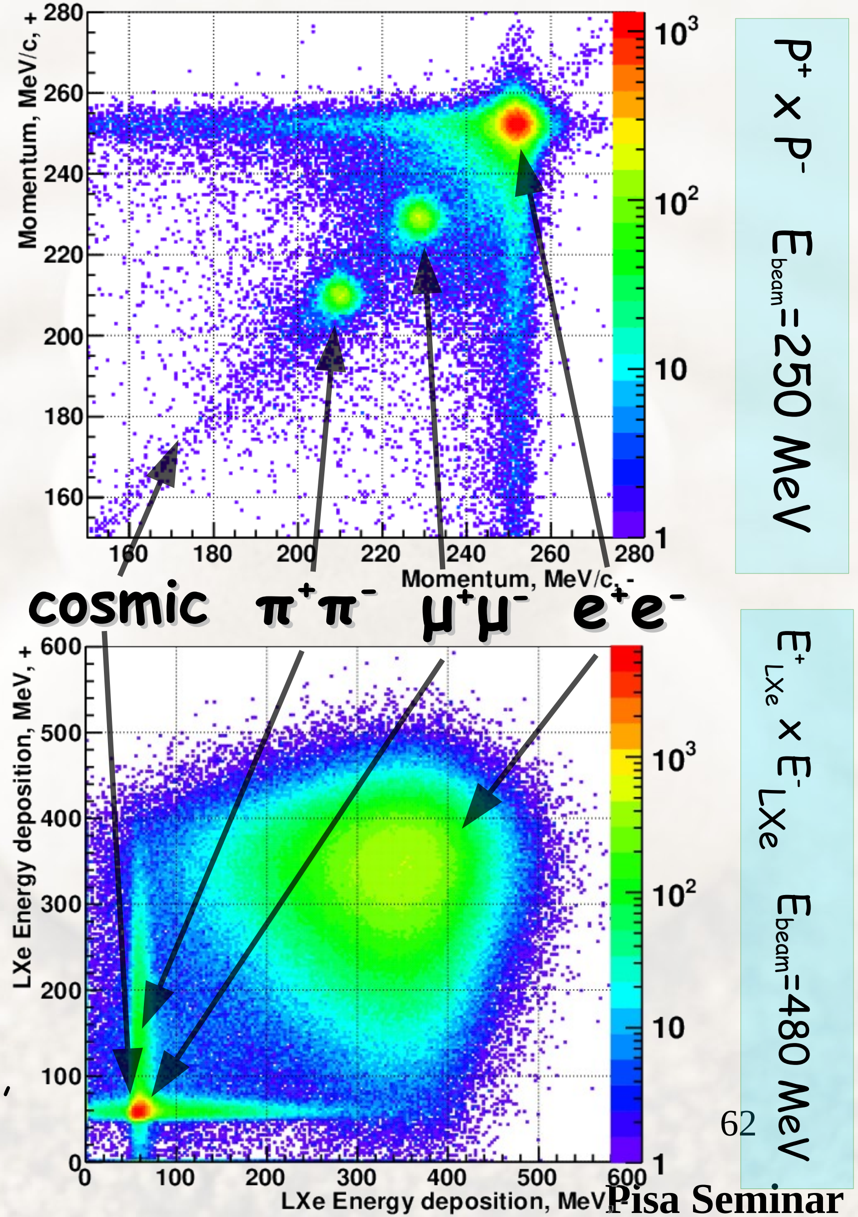
$$-\ln L = -\sum_{events} \ln\left[\sum_i N_i f_i(X^+, X^-)\right] + \sum_i N_i$$

Momentum-based separation:

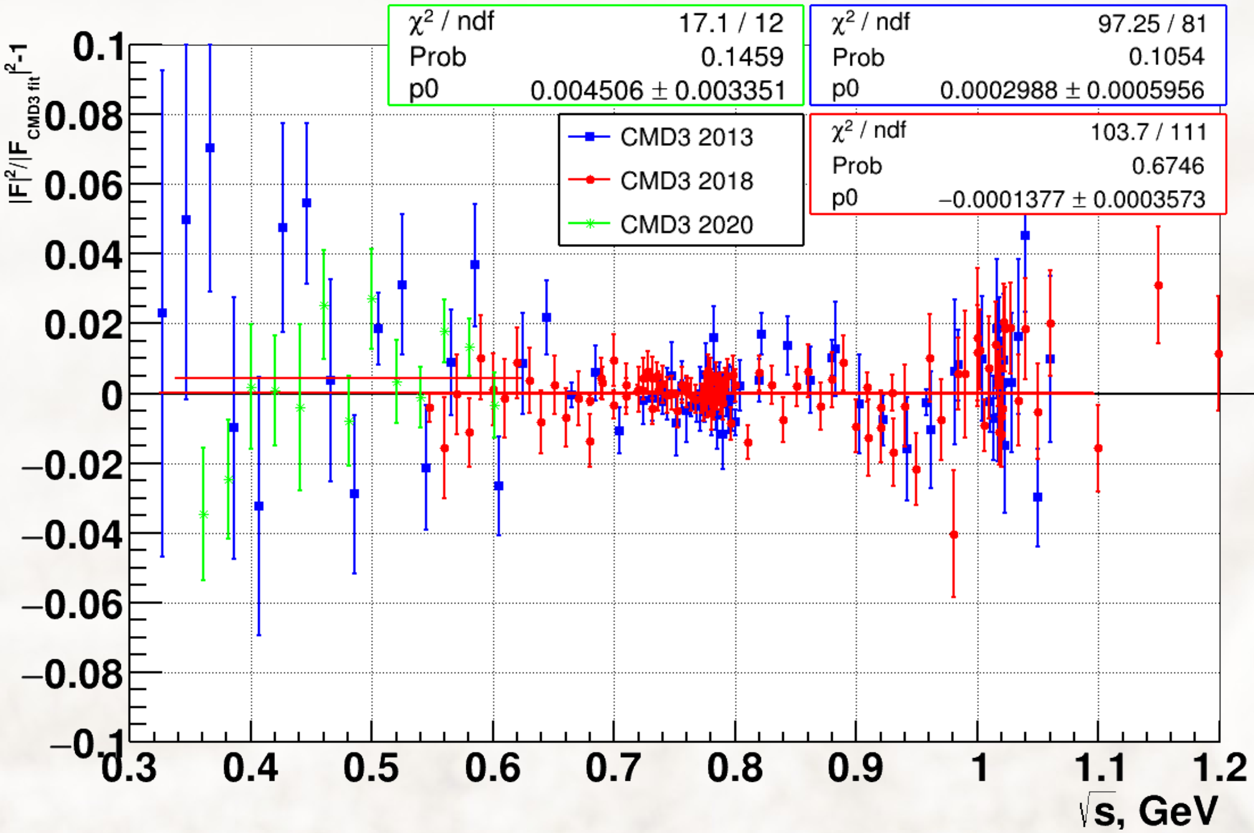
PDFs are constructed from MC generator spectra convolved with detector response function (momentum resolution, bremsstrahlung, pion decays)

Energy deposition-base separation:

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



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)

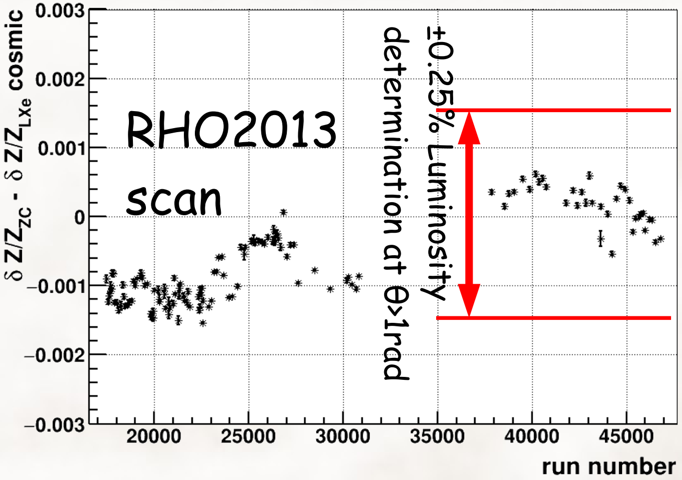
$|F_\pi|^2$ RHO2018/RHO2013 Δ = -0.04 ± 0.07 %

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

Monitoring of z-measurement
between ZC vs LXe

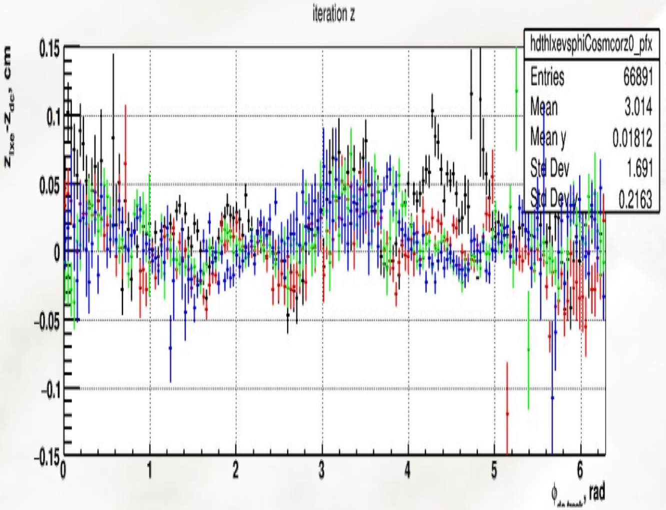


RHO2013
scan

±0.25% Luminosity
determination at θ>1rad

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

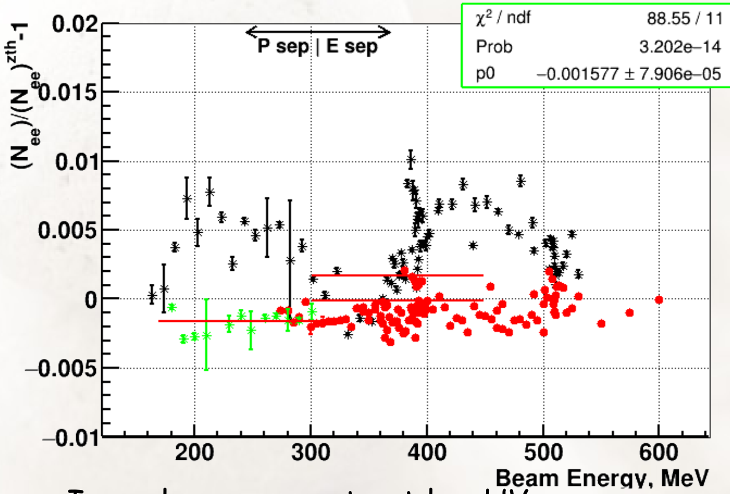
DC tracks vs LXe points



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

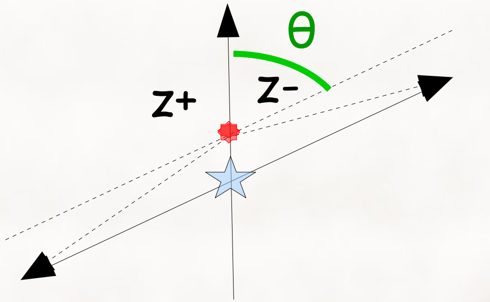
Systematic uncertainty to $|F_\pi|^2$

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

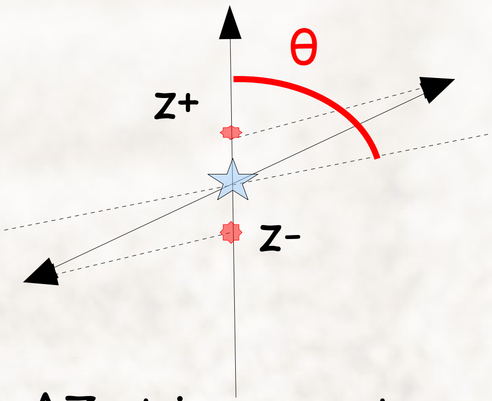
= 0.8% (RHO2013) / 0.5%(RHO2018)

DCH's Inner radius effect on polar angle

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



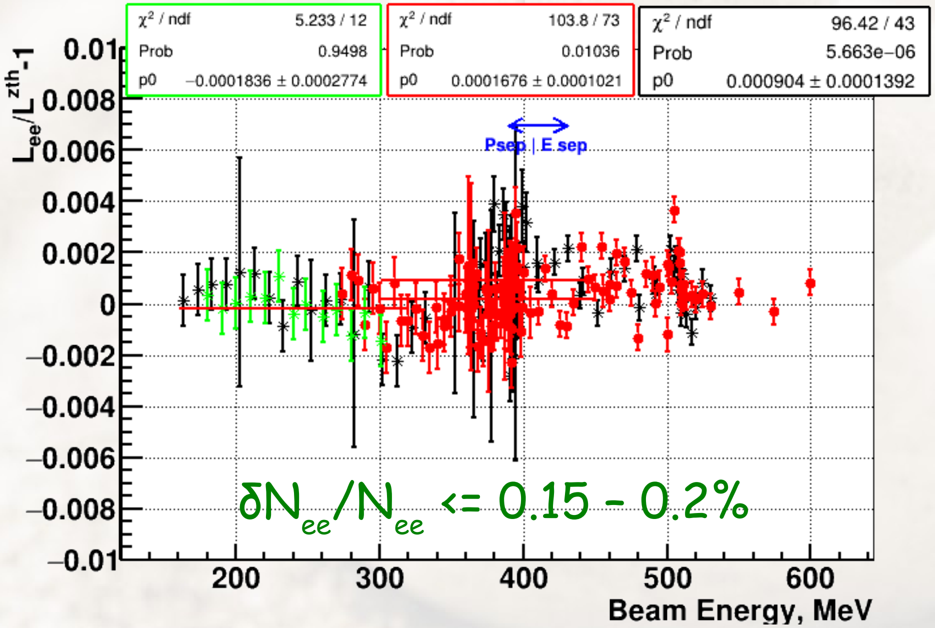
common Z vertex bias of +/- tracks doesn't give bias to θ^{event}



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

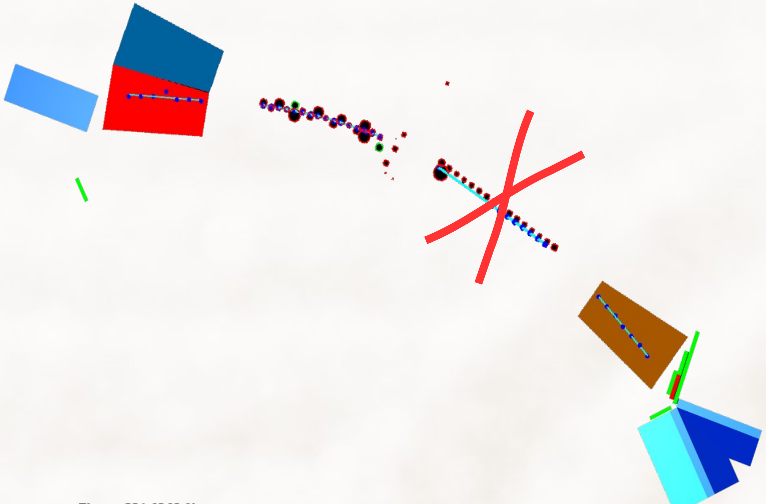


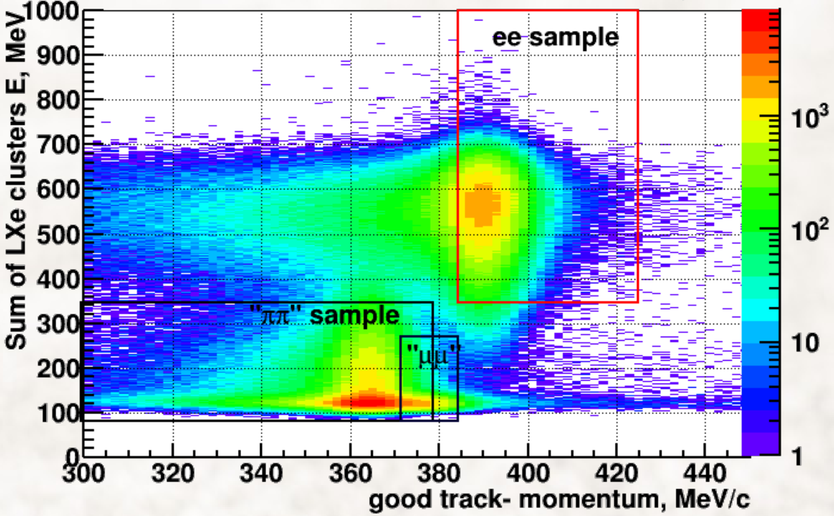
$\delta N_{ee}/N_{ee}$ <= 0.15 - 0.2%

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

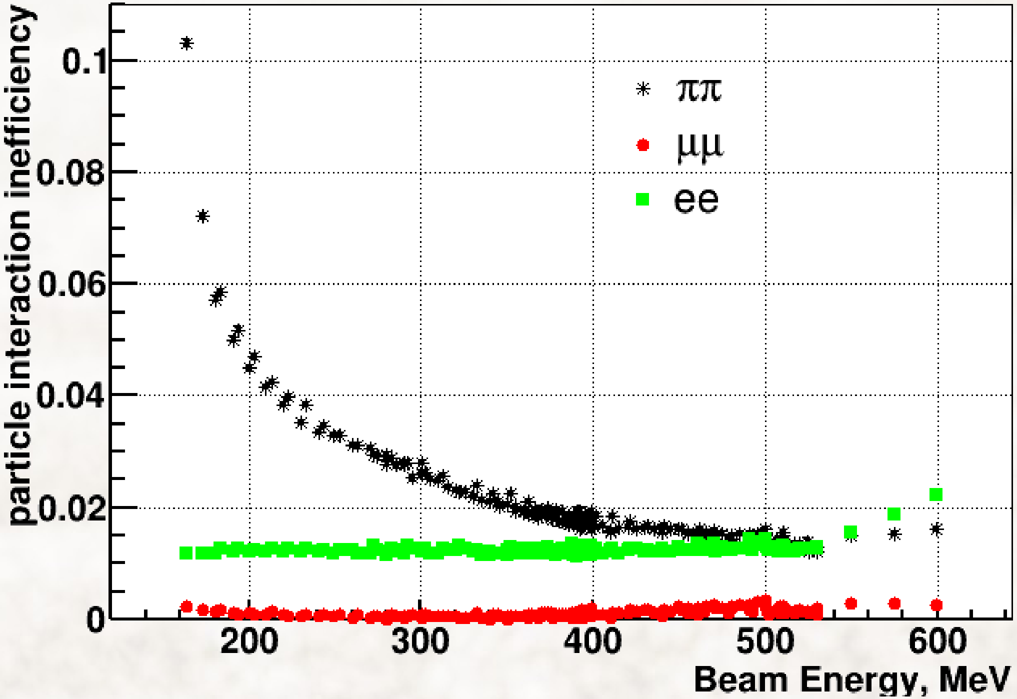
The "test" sample includes only partially some specific losses (when second compatible cluster is not produced):
pion decay, nuclear interaction, .. (~30% ineff. accounted)
electron bremsstrahlung (~5% accounted)

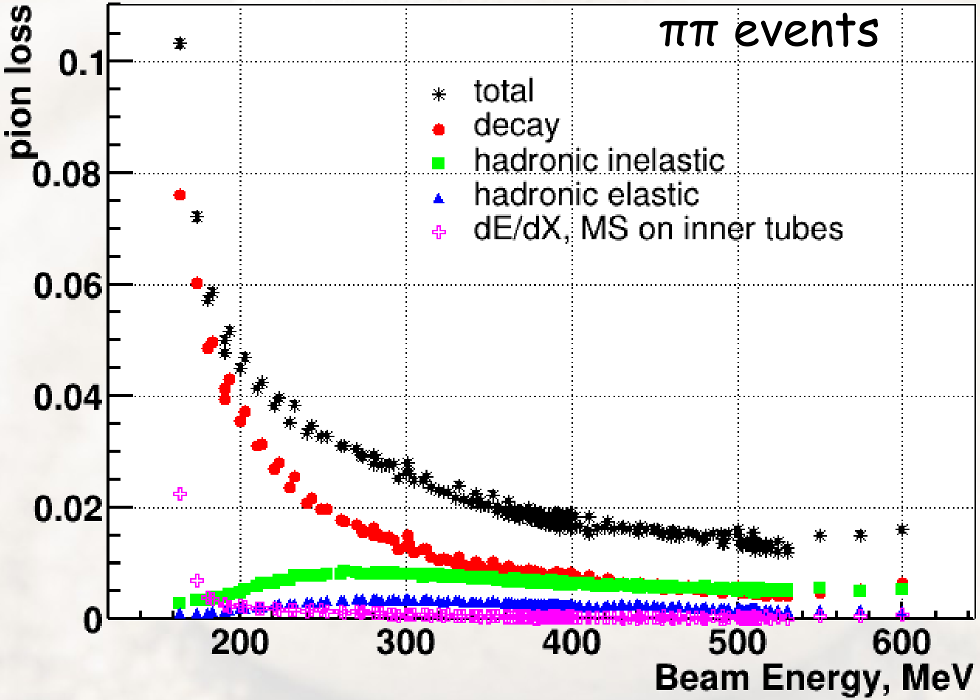
N.B. Correlated inefficiency study was also performed
without requirement on detection of one good track

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



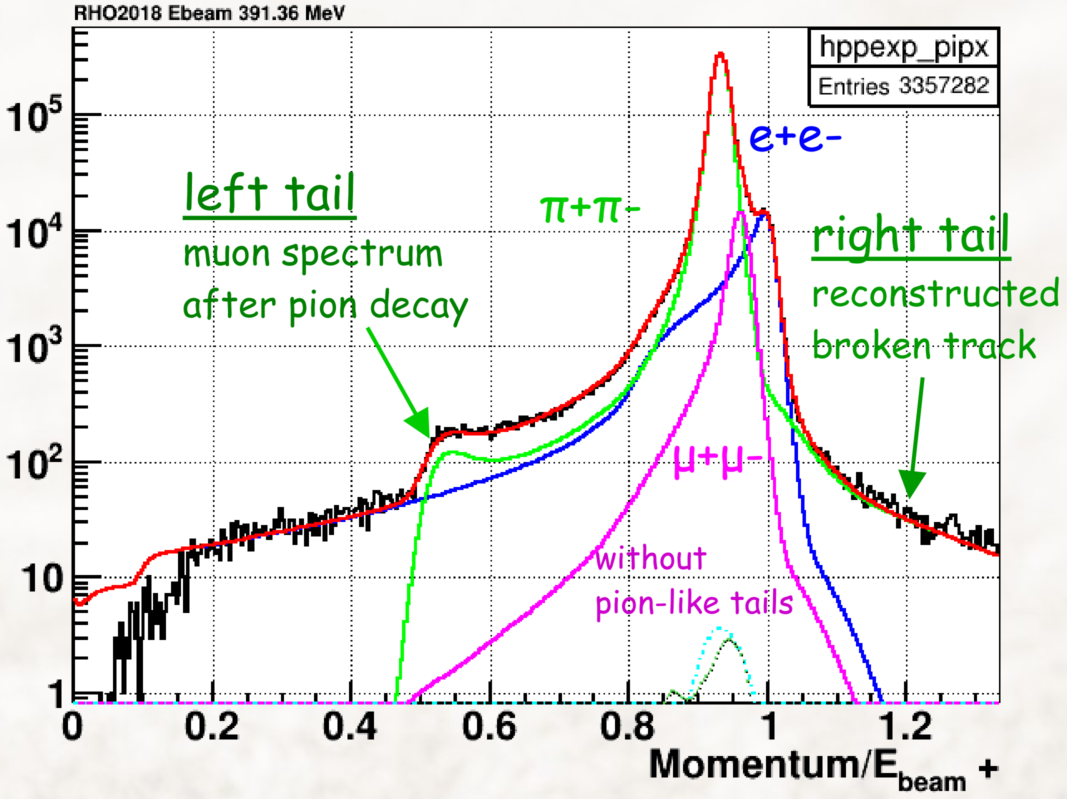


nucler interactions mostly on inner tube (systematics 0.2%)
most dangerous is decay in flight as it depends on detector conditions (syst. 0.2-0.1%)

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

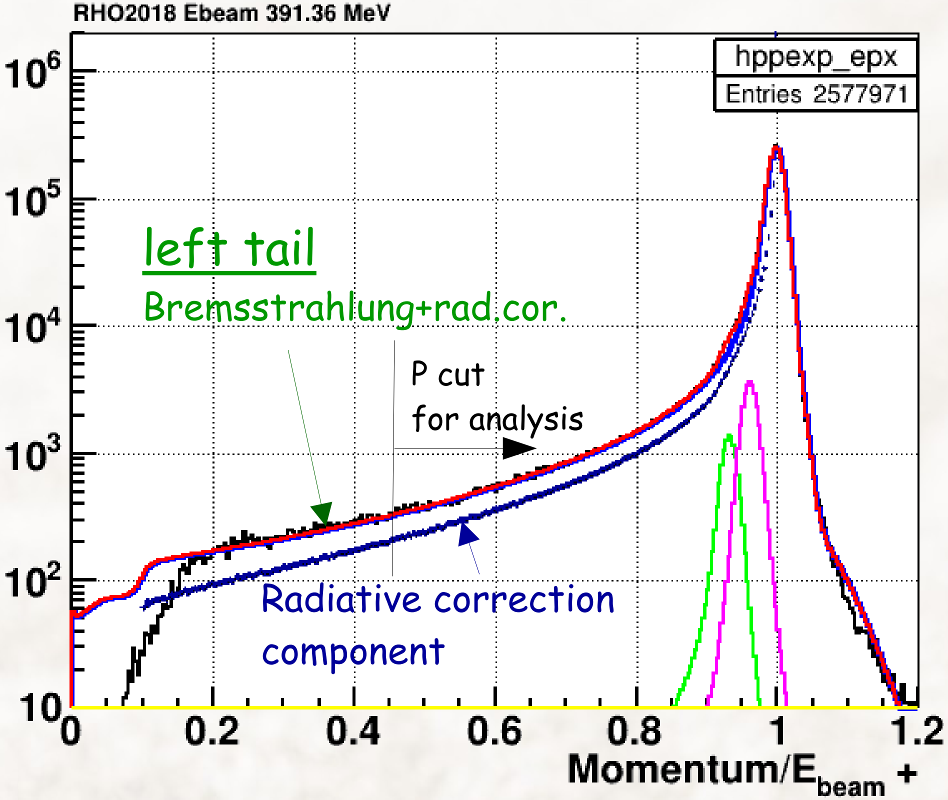
Tails function taken from full MC
(include DCH inefficiencies, resolutions,
amplitudes, correlated noises per layers, etc..)
Number of events in tails are free parameters
in momentum-based separation

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



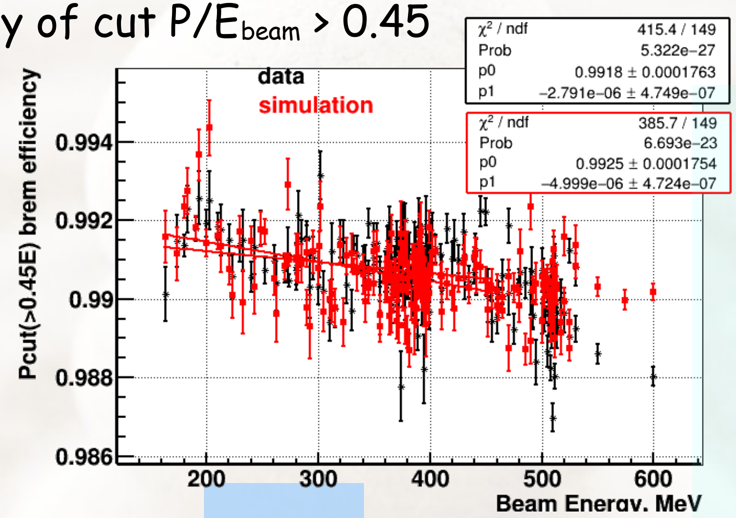
left tail

Bremsstrahlung+rad.cor.

P cut
for analysis

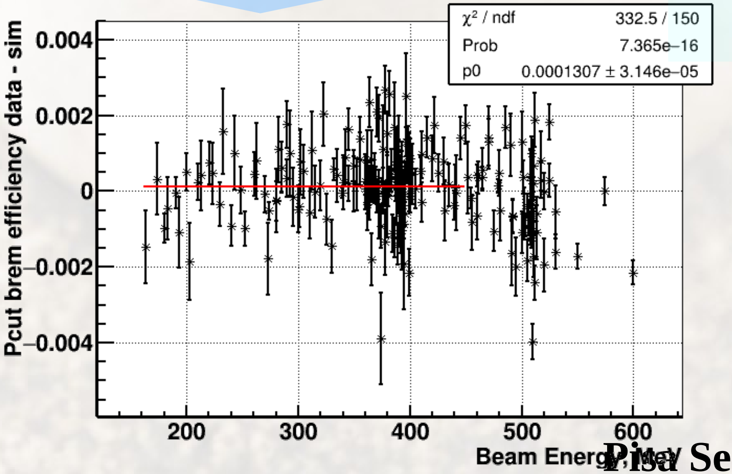
Radiative correction
component

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%

$|F_\pi|^2$ 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 $N_{\mu\mu}/N_{\pi\pi} \sim 1$: 1.05% / 1.2%(RHO2013) → 1.6% / 2.0% (RHO2013)

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

Possible concerns in the analysis related to MC tools:

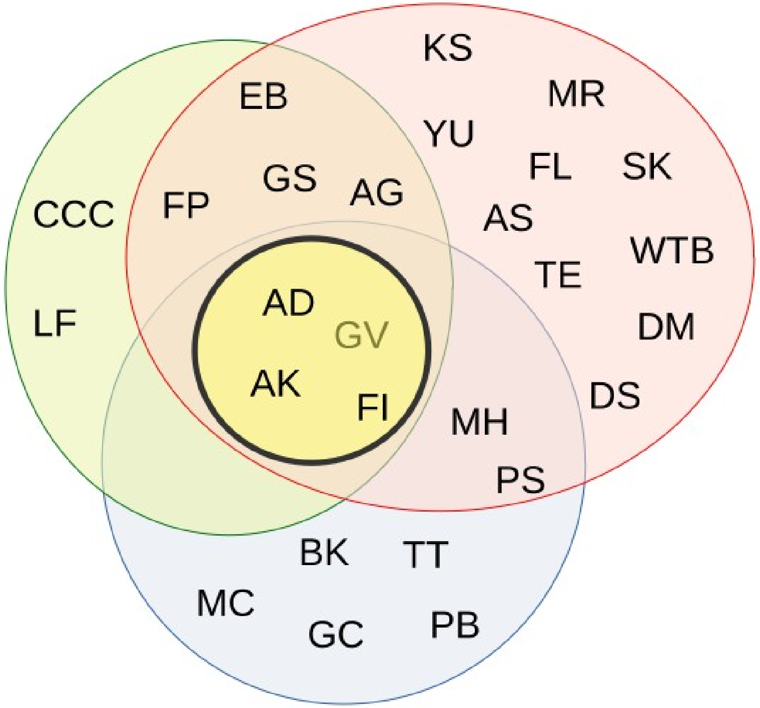
- ✗ Radiative corrections for the $\pi^+\pi^-$ total cross section
  - ✗ MCGPJ were used by several previous experiments, the cross-check with a new generator will be very valuable
- ✗ Differential cross section over momentum for the particle separation
  - ✔ E/P separations, $\sigma(e^+e^- \to \mu^+\mu^-)$/QED 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

5th WorkStop

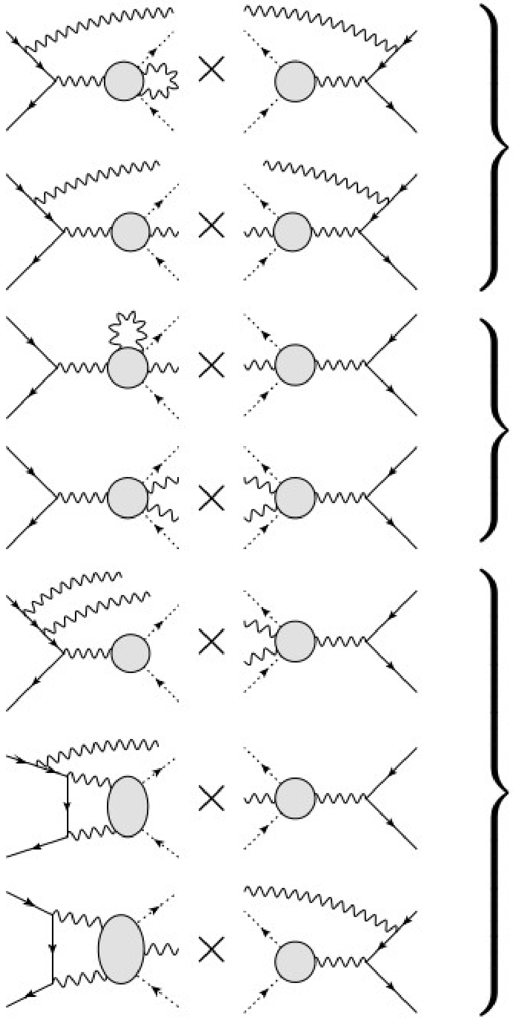
Team: P. Beltrame, E. Budassi, C. Carloni Calame, G. Colangelo, M. Cottini, A. Driutti, T. Engel, L. Flower, A. Gurgone, M. Hoferichter, F. Ignatov, S. Kollatzsch, B. Kubis, A. Kupsc, F. Lange, D. Moreno, F. Piccinini, M. Rocco, K. Schönwald, A. Signer, G. Stagnitto, D. Stöckinger, P. Stoffer, T. Teubner,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

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



Radcor and MC tools, 7-9 June 2023, Zurich
Peter Stoffer, WP3: Processes with hadrons

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

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

Measurement of $e^+e^- \rightarrow \pi^+\pi^-(\gamma)$ 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)

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.

$e^+e^- \to e^+e^-(\gamma)$: great consistency <0.1% in the total cross section
$e^+e^- \to \mu^+\mu^-(\gamma)$: most generators have an issue at threshold (except only MCGPJ)
(Mass term in FSR is missed - effect 0.4% at $\sqrt{s}$=0.32 GeV)
$e^+e^- \to \pi^+\pi^-(\gamma)$: 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 π+π- total cross section
- ✗ Differential cross sections over momentum, angles for the e+e- → π+π-, e+e-, μ+μ- 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.

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-

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

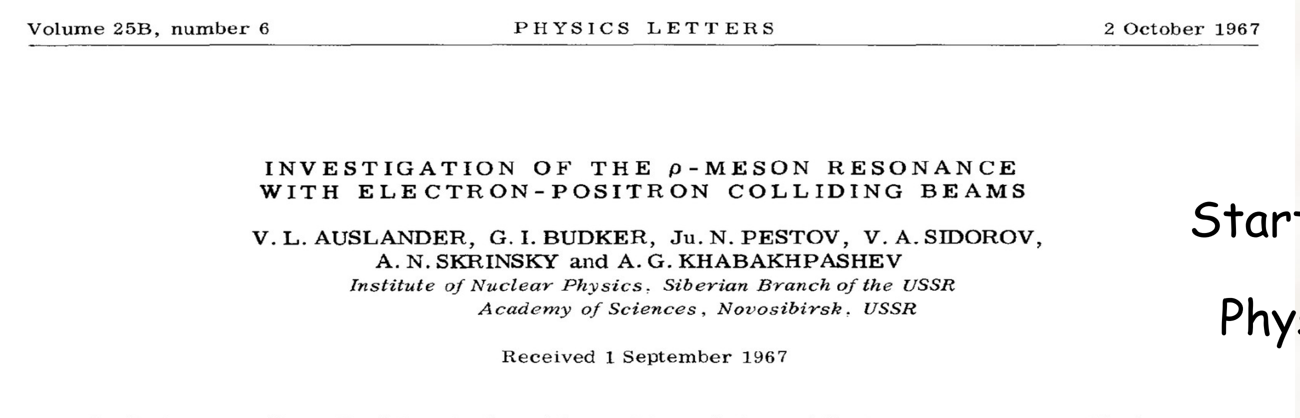
1965: First physics at collision with e-e- scattering

(QED radiative effects confirmed)

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

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

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

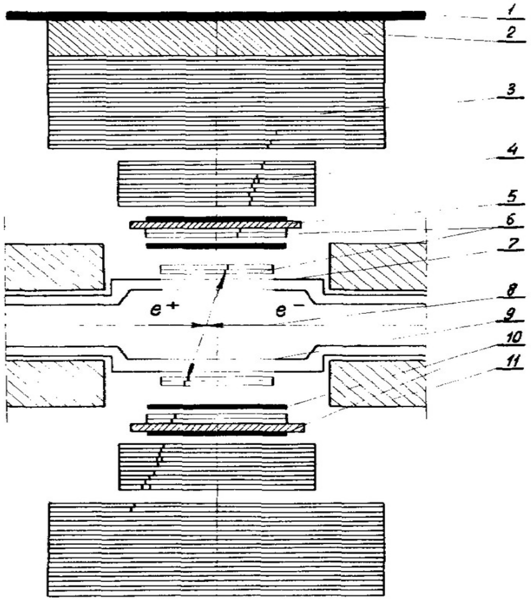


Fig. 1. Spark chambers system:
1) Anticoincidence scintillation counter
2) Lead absorber 20 cm thick
3) "Range" spark chamber
4) "Shower" spark chamber
5) Duraluminium absorber 2 cm thick
6) Thin-plate spark chambers

1 September 1967

Start of e+e- → hadrons measurements

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

VEPP-2, Novosibirsk

e+e- → ρ → ππ

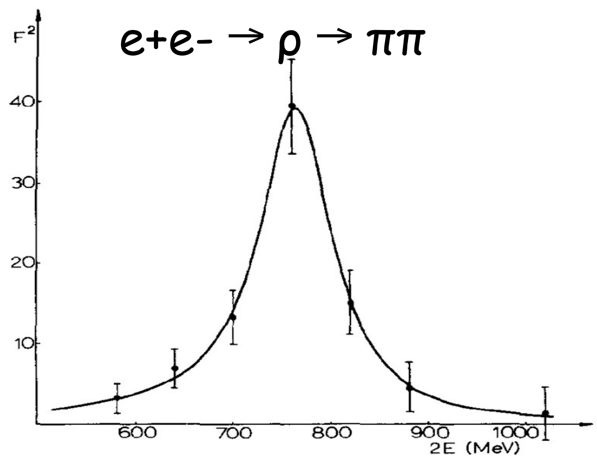
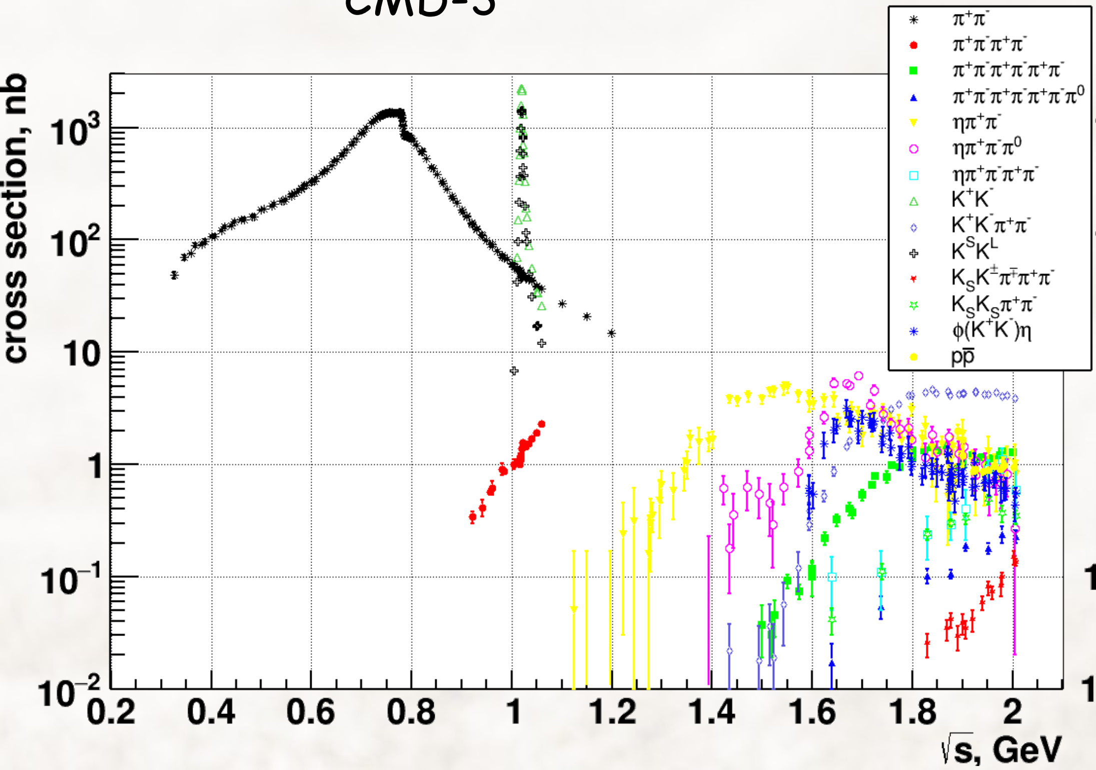


Fig. 2. Experimental values of F^2 (E) approximated by the Breit-Wigner formula.

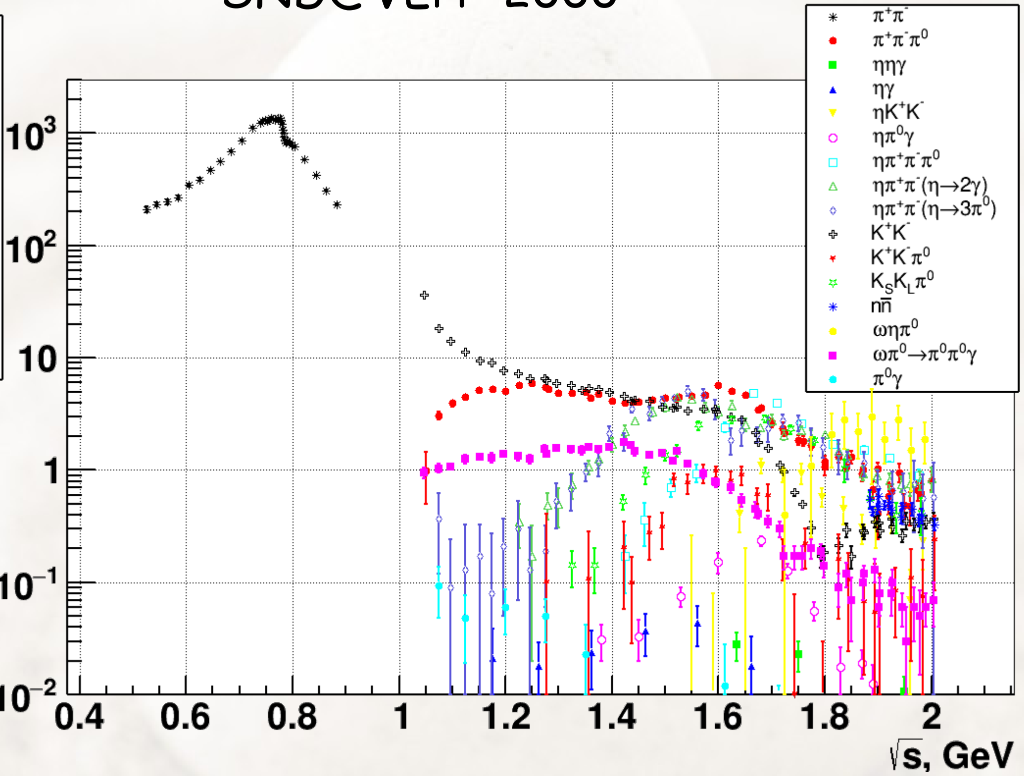
ment geometry and *F*- modulus of the form factor for pion pair production [1]. In the case of QED with no other forces *F*=1. If the particles are produced at the angle 90° with respect to the beam axis then *a*=18. Integration over the solid angle gives *a*=20.4.

CMD-3 & SND published

CMD-3



SND@VEPP-2000



Many channels is under analysis