Data Input to Hadronic Vacuum Polarization

Ivan Logashenko

Budker Institute of Nuclear Physics

International Physics School on Muon Dipole Moments and Hadronic Effects

In memoriam
Simon Eidelman

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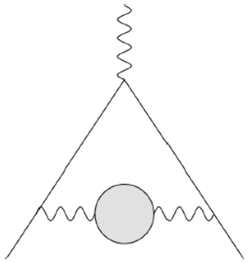
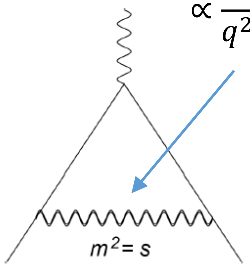
What do we need to measure

Dispersion relation:



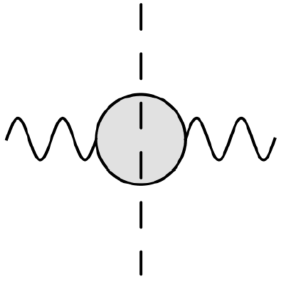
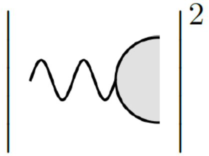
$$= \int_0^\infty \frac{ds}{s} \frac{1}{\pi} \mathrm{Im}\Pi'(s) \times$$



$\propto \frac{1}{q^2 - s}$

$a_\mu^{had}(LO)$ $\qquad$ $\frac{\alpha}{\pi} K_\mu(s)$

Optical theorem:

$2\ \mathrm{Im}$  $=$ $\Big|$  $\Big|^2$

$$\mathrm{Im}\ \Pi'^{(s)} = \frac{s}{4\pi\alpha} \sigma^0(e^+e^- \to \gamma \to hadrons + \cdots)$$

Lets put everything together:

This is what we need to measure

$$a_\mu^{had}(LO) = \frac{\alpha^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} \frac{ds}{s} R(s) K_\mu(s)$$

$$R(s) = \frac{\sigma^0(e^+e^- \to \gamma \to hadrons)}{4\pi\alpha^2/3s}$$

$\sigma^0(e^+e^- \to \mu^+\mu^-)$

$s = (\text{c.m. energy})^2$

R(s)

$$R(s) = \frac{\sigma^0(\quad q\bar{q}\ )}{\sigma^0(\quad \mu^+\mu^-)}$$

In the zeroth order of QCD and zero quark masses:

$$R^{(0)}(s) = 3\sum_f q_f^2$$

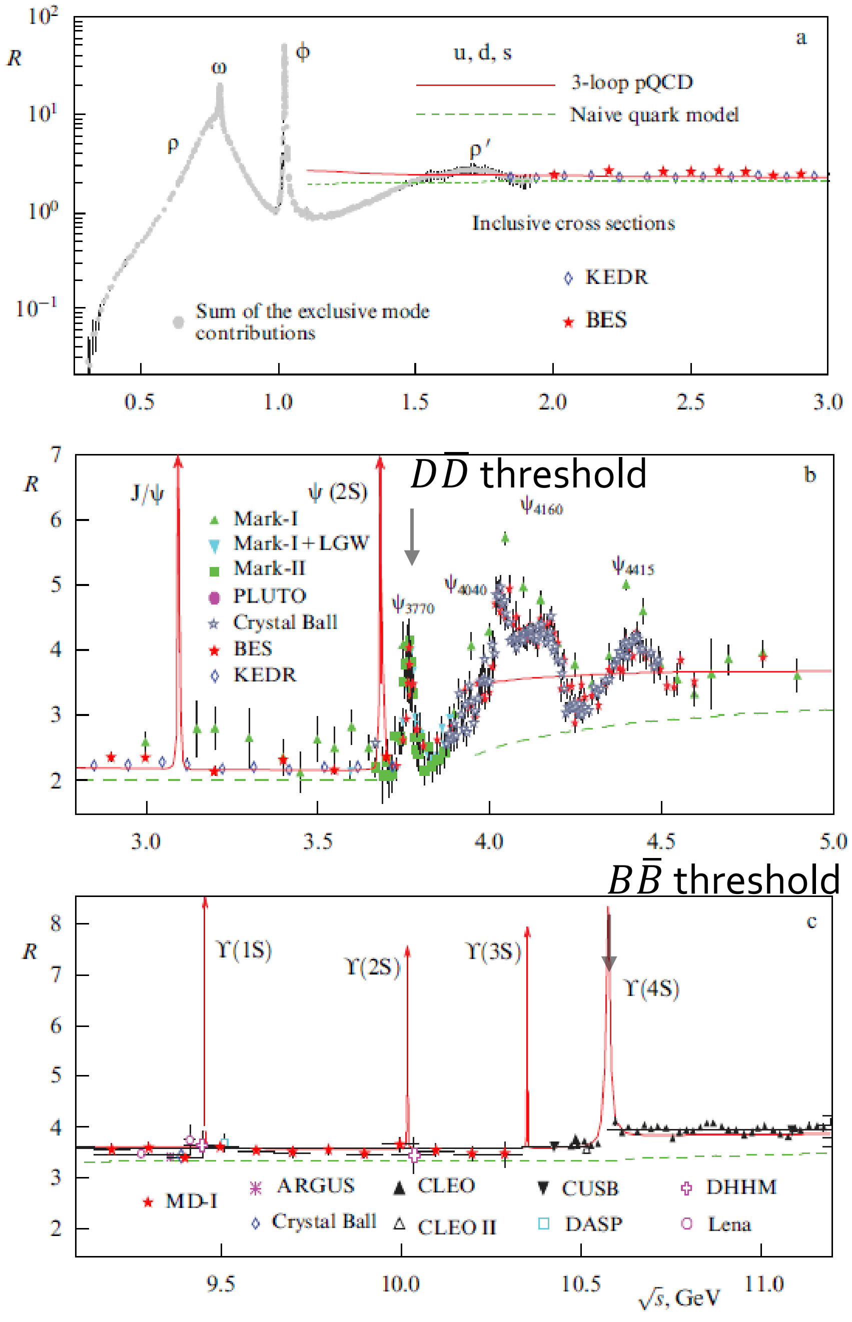
$$R(u,d,s) = \frac{6}{3}$$

$$R(u,d,s,c) = \frac{10}{3}$$

$$R(u,d,s,c,b) = \frac{11}{3}$$

Full pQCD calculation includes NNLO contribution, quark masses, running α_s,…

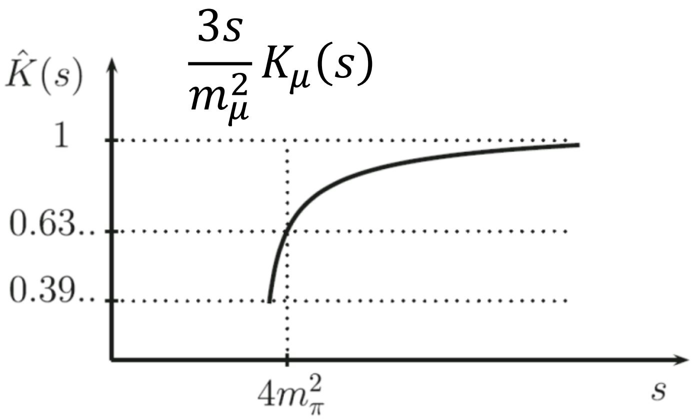
Good agreement of data vs pQCD at $\sqrt{s} > 2$ GeV and away from resonances



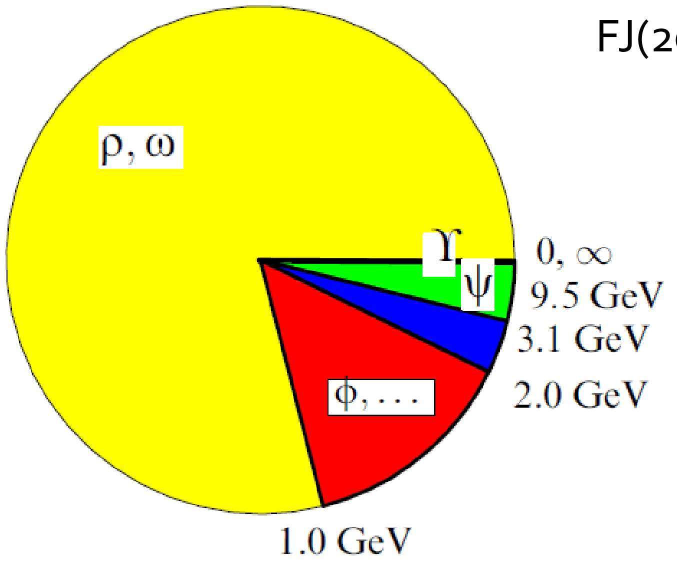
Contribution of various energies

In a_μ^{had} integral, the main contribution comes from low energies

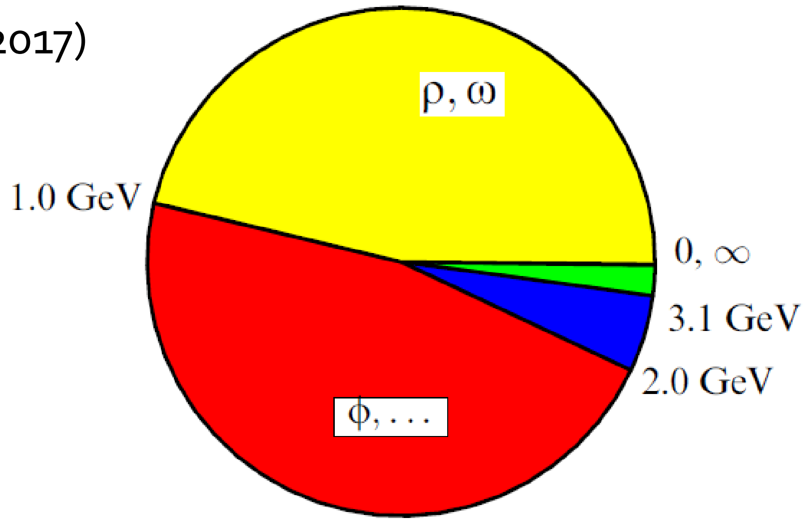
$$a_\mu^{had}(LO) = \frac{\alpha^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} \frac{ds}{s} R(s) K_\mu(s) \sim \int \frac{R(s)}{s^2} ds$$



FJ(2017)



Contribution to the integral



Contribution to the error of integral

When we measure R(s) in order to calculate hadronic contribution to a_μ, we are focused at low energies $\sqrt{s} \lesssim 2$ GeV

How well do we need to measure R(s)

From the White Paper (Physics Reports 887 (2020) 1):

$$a_\mu^{\rm had}(LO) = 693.1(4.0) \times 10^{-10}$$

The expected final precision of the Fermilab measurement

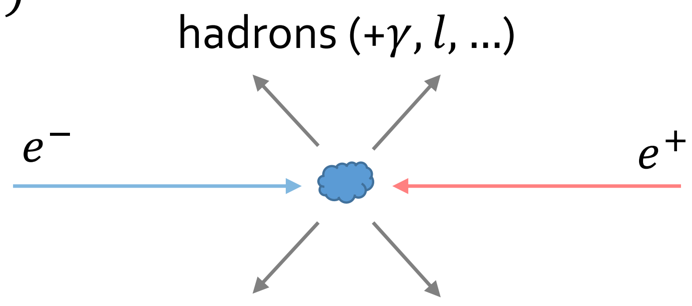
$$\Delta a_\mu = 1.6 \times 10^{-10}$$

We need to know $R(s)$ to 0.23% to match Fermilab precision

Now the hadronic contribution is known to 0.57%

Energy scan approach

Direct measurement of $\sigma(e^+e^- \to hadrons)$ (energy scan approach):



- performed at electron-positron collider
- collect data at different beam energy
- at each energy point: select final states with hadrons, subtract background and normalize to luminosity

Number of signal events

Number of background events

$$\sigma = \frac{N_{obs} - N_{bg}}{\varepsilon \cdot \int \mathcal{L} dt}$$

Detection efficiency:
- kinematical limits of detector (fiducial volume) – detector never has 4π coverage
- detector response

Luminosity integral
- measured by selection of monitoring events with known cross section

Exclusive vs inclusive measurement

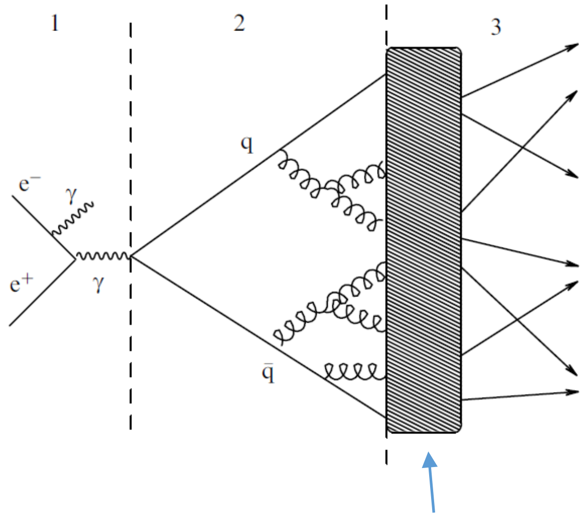
Detection efficiency is (usually) calculated using MC simulation

- In order to calculated ε, we need to know the energy and angular distributions of final particles (including all correlations)

$$\sigma = \frac{N_{obs} - N_{bg}}{\varepsilon \cdot \int \mathcal{L} dt}$$

For high energies, where multiplicity is large enough, there are effective models of hadronization, which describe data reasonably well

At low energy the detection efficiency varies significantly between different final states and different paths of hadronization (intermediate states)



At low energies we have to measure cross section for each possible final state separately and then calculate sum to get R (***exclusive approach***)

At high energy we can measure total cross section directly (***inclusive approach***)

The practical boundary between two approaches in $\sqrt{s} = 2$ GeV.

The $a_\mu^{had}(LO)$ calculation is mostly based on exclusive measurements.

The top exclusive hadronic cross sections in the world [of a_μ]

In exclusive approach, we calculate a_μ integral for each final state and sum them:

$$a_\mu^{had}(LO) = \sum_{X=\pi^0\gamma,\pi^+\pi^-,\ldots} a_\mu^X(LO) = \sum_X \frac{1}{4\pi^3}\int \sigma^0(e^+e^- \to X) K_\mu(s) ds$$

Channel	$a_\mu^{\mathrm{had,LO}}$ $[10^{-10}]$
$\pi^0\gamma$	$4.41 \pm 0.06 \pm 0.04 \pm 0.07$
$\eta\gamma$	$0.65 \pm 0.02 \pm 0.01 \pm 0.01$
$\pi^+\pi^-$	$507.85 \pm 0.83 \pm 3.23 \pm 0.55$
$\pi^+\pi^-\pi^0$	$46.21 \pm 0.40 \pm 1.10 \pm 0.86$
$2\pi^+2\pi^-$	$13.68 \pm 0.03 \pm 0.27 \pm 0.14$
$\pi^+\pi^-2\pi^0$	$18.03 \pm 0.06 \pm 0.48 \pm 0.26$
$2\pi^+2\pi^-\pi^0$ (η excl.)	$0.69 \pm 0.04 \pm 0.06 \pm 0.03$
$\pi^+\pi^-3\pi^0$ (η excl.)	$0.49 \pm 0.03 \pm 0.09 \pm 0.00$
$3\pi^+3\pi^-$	$0.11 \pm 0.00 \pm 0.01 \pm 0.00$
$2\pi^+2\pi^-2\pi^0$ (η excl.)	$0.71 \pm 0.06 \pm 0.07 \pm 0.14$
$\pi^+\pi^-4\pi^0$ (η excl., isospin)	$0.08 \pm 0.01 \pm 0.08 \pm 0.00$
$\eta\pi^+\pi^-$	$1.19 \pm 0.02 \pm 0.04 \pm 0.02$
$\eta\omega$	$0.35 \pm 0.01 \pm 0.02 \pm 0.01$
$\eta\pi^+\pi^-\pi^0$(non-ω,ϕ)	$0.34 \pm 0.03 \pm 0.03 \pm 0.04$
$\eta 2\pi^+2\pi^-$	$0.02 \pm 0.01 \pm 0.00 \pm 0.00$
$\omega\eta\pi^0$	$0.06 \pm 0.01 \pm 0.01 \pm 0.00$
$\omega\pi^0$ ($\omega \to \pi^0\gamma$)	$0.94 \pm 0.01 \pm 0.03 \pm 0.00$
$\omega 2\pi$ ($\omega \to \pi^0\gamma$)	$0.07 \pm 0.00 \pm 0.00 \pm 0.00$
ω (non-$3\pi, \pi\gamma, \eta\gamma$)	$0.04 \pm 0.00 \pm 0.00 \pm 0.00$
K^+K^-	$23.08 \pm 0.20 \pm 0.33 \pm 0.21$
K_SK_L	$12.82 \pm 0.06 \pm 0.18 \pm 0.15$

From DHMZ'19

The larger the contribution, the better precision is required

$e^+e^- \to \pi^+\pi^-$ is by far the most challenging and has got the most attention (73% of total hadronic contribution!)

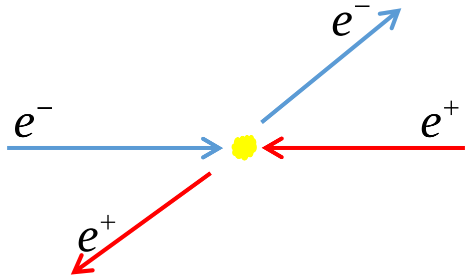
Luminosity measurement

We need to know luminosity integral in order to normalize the measured hadronic cross section.

For that we use *monitoring process* with known cross section

$$\int \mathcal{L}dt = \frac{N_{obs} - N_{bg}}{\varepsilon \cdot \sigma_{known}}$$

The most popular monitoring process is
large angle Bhabha scattering $e^+e^- \to e^+e^-$:
easily identifiable, large cross section

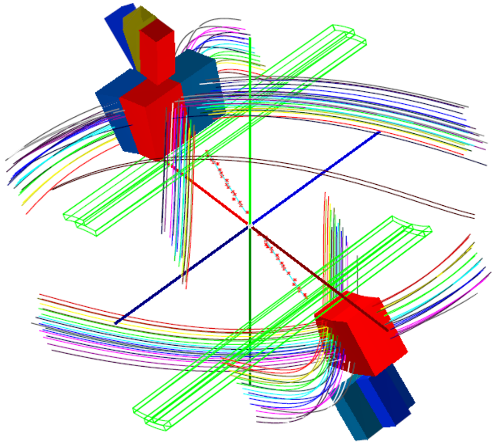


Other good processes for luminosity measurement:

- $e^+e^- \to \mu^+\mu^-$ — *Has many advantages, but relatively small cross section and large background*
- $e^+e^- \to \gamma\gamma$ — *Natural for final states with neutrals*
- $e^+e^- \to e^+e^-\gamma$
- $e^+e^- \to e^+e^-\gamma\gamma$

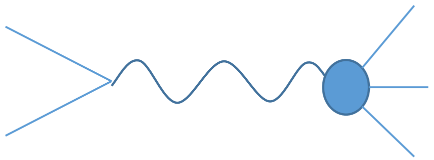
Often used for online measurement

All these are QED processes – the cross section can be calculated



$e^+e^- \to e^+e^-$ in CMD-3

Radiative corrections



We want to measure $e^+e^- \to H$, but these events are accompanied by similar events where photons are emitted by any of the particles.

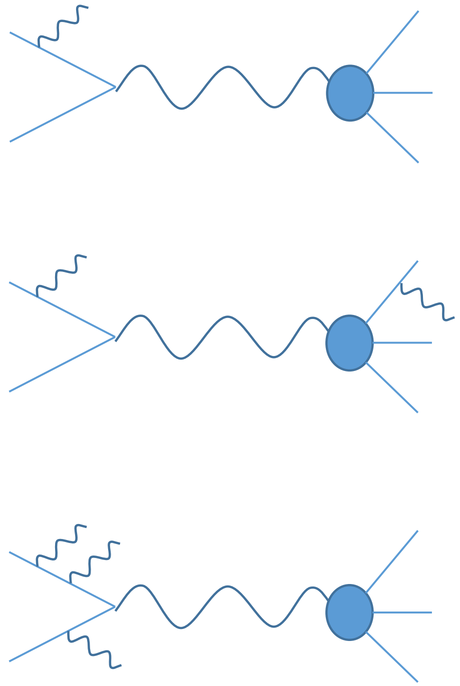
Radiation of high-energy γ is suppresses by α, but radiation of soft photons is enhanced.

Radiation changes both the cross-section and the kinematics of the final state:

$$\sigma = \frac{N_{obs} - N_{bg}}{\varepsilon(\delta) \cdot (1+\delta) \cdot \int \mathcal{L} dt}$$

And we have to calculate radiative corrections to the cross section of monitoring process as well

Radiative processes



ISR FSR

Initial *Final*

state radiation

How to calculate radiative corrections

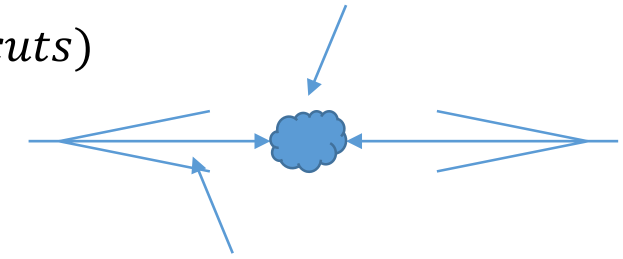
Main idea: allow each initial particle to emit any number of photons (jets).
The amount of energy carried by photons is described by structure function.

Hard process at $s' = x_1 x_2 s$

$$\sigma_{vis}(s) = \int_0^1 dx_1 dx_2 D(x_1, s) D(x_2, s) \sigma_0(x_1 x_2 s) \cdot \Theta(cuts)$$

we measure this

we want to know this



photon "jet" $D(x, s)$

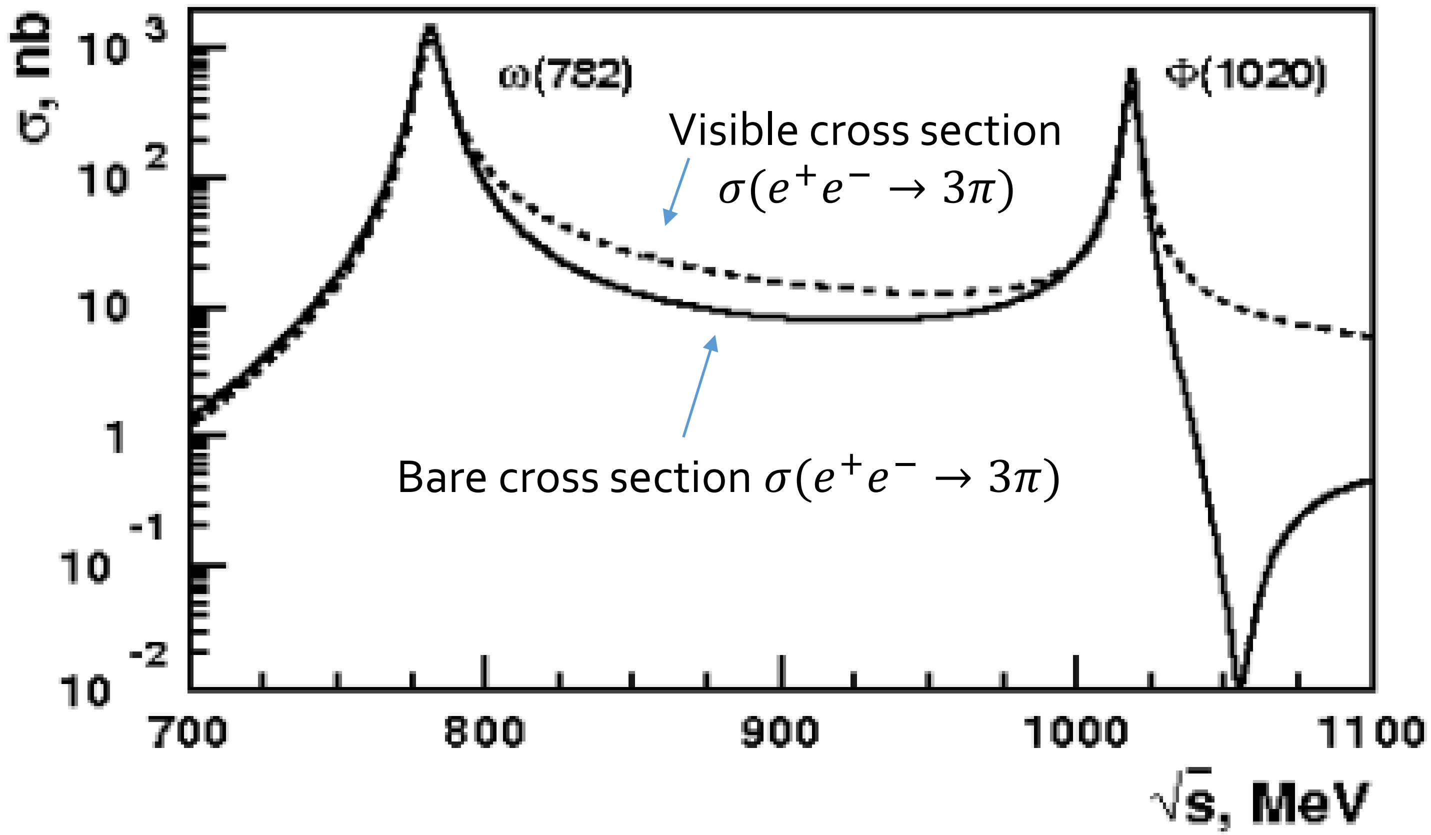
The radiative correction depends on the measured cross-section – need to use iterative procedure.

Structure functions are known to high precision (<0.1%). Main limitation is from kinematics: we don't take into account angular distribution of photons in the jet.

This approach is ok for ~1% measurements and is typically used for multi-hadron events.

Typical value for radiative corrections is ~10% (can be much larger near narrow resonances)

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



Radiative corrections for precise measurements

Calculation of radiative corrections for high-precision final states (e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, $\gamma\gamma$,...) is much more complicated. Usually, it is implemented as MC generator and used together with the full detector simulation for proper evaluation of detector efficiency

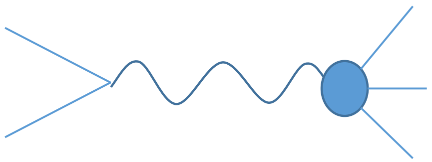
Extensive review: Eur.Phys.J. C66 (2010) 585-686

MCGPJ (VEPP-2000)	BABAYAGA (e^+e^-)	PHOKHARA (KLOE, BABAR)
1 real γ (from any particle) + jets along all particles	1 real γ + $n\gamma$ generated iteratively by emitting one γ at a time	1 ISR γ + 1 real γ + soft Many final states, intended for ISR measurements

These generators include ISR, FSR, virtual corrections, vacuum polarization and (partially) interference between various contributions.

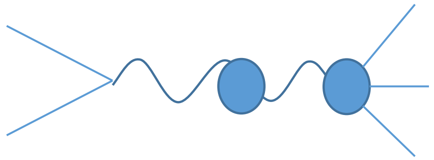
FSR from hadrons is model-dependent, e.g., assume point-like pions.

Vacuum polarization



$\sigma^0(e^+e^- \to \gamma \to X)$

In a_μ calculation



$\sigma(e^+e^- \to \gamma^* \to X)$

In experiment

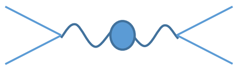
In the calculation of a_μ, we assume the lowest order photon propagator $1/q^2$. But the real propagator includes higher order effects (loop corrections): $1/(q^2 - \Pi(q^2))$. Therefore the measured cross section have to be corrected:

$$\sigma^0(e^+e^- \to X) = \sigma(e^+e^- \to X) \times \frac{|\alpha(s)|^2}{\alpha^2}$$

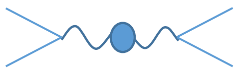
The running fine structure constant is also calculated via dispersion relation based on R(s):

$$\Delta\alpha_{had}(s) = -\frac{\alpha s}{3\pi}\int_0^\infty \frac{R(s')}{s'(s - s' - i0)} ds'$$

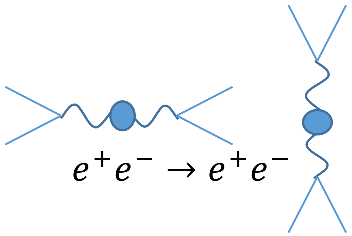
Nice way to avoid this correction is to use $e^+e^- \to \mu^+\mu^-$ for luminosity measurement



$e^+e^- \to X$



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



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

From measured cross section to input to a_μ calculation

"Visible" cross section
$\sigma(e^+e^-(\gamma) \to X(\gamma))$

Here we correct for all detector effects

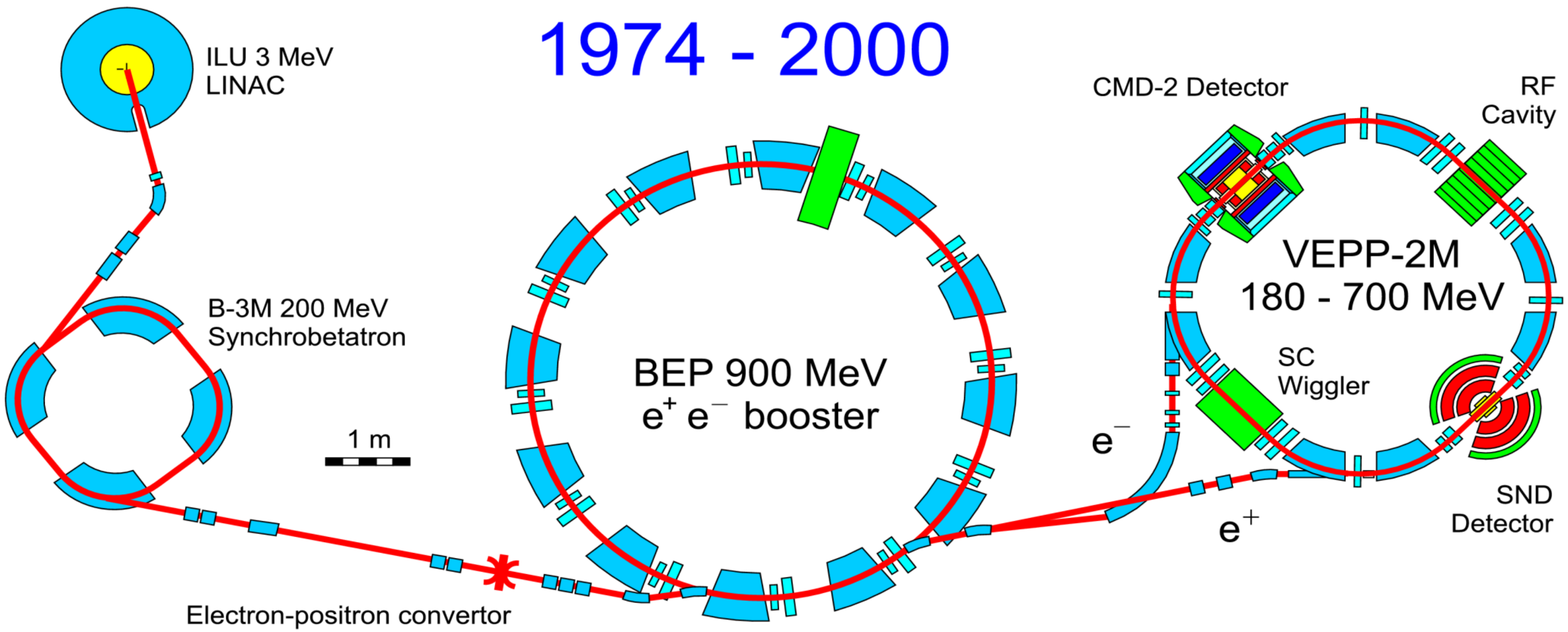
Adjust for radiative corrections (ISR, FSR)
$\sigma(e^+e^- \to X)$

This one is used to get parameters of the resonances (mass, width,…)

Adjust for vacuum polarization and return back FSR
$\sigma^0(e^+e^- \to X(\gamma))$

This one is used in the a_μ integral

VEPP-2M (1993-2000)



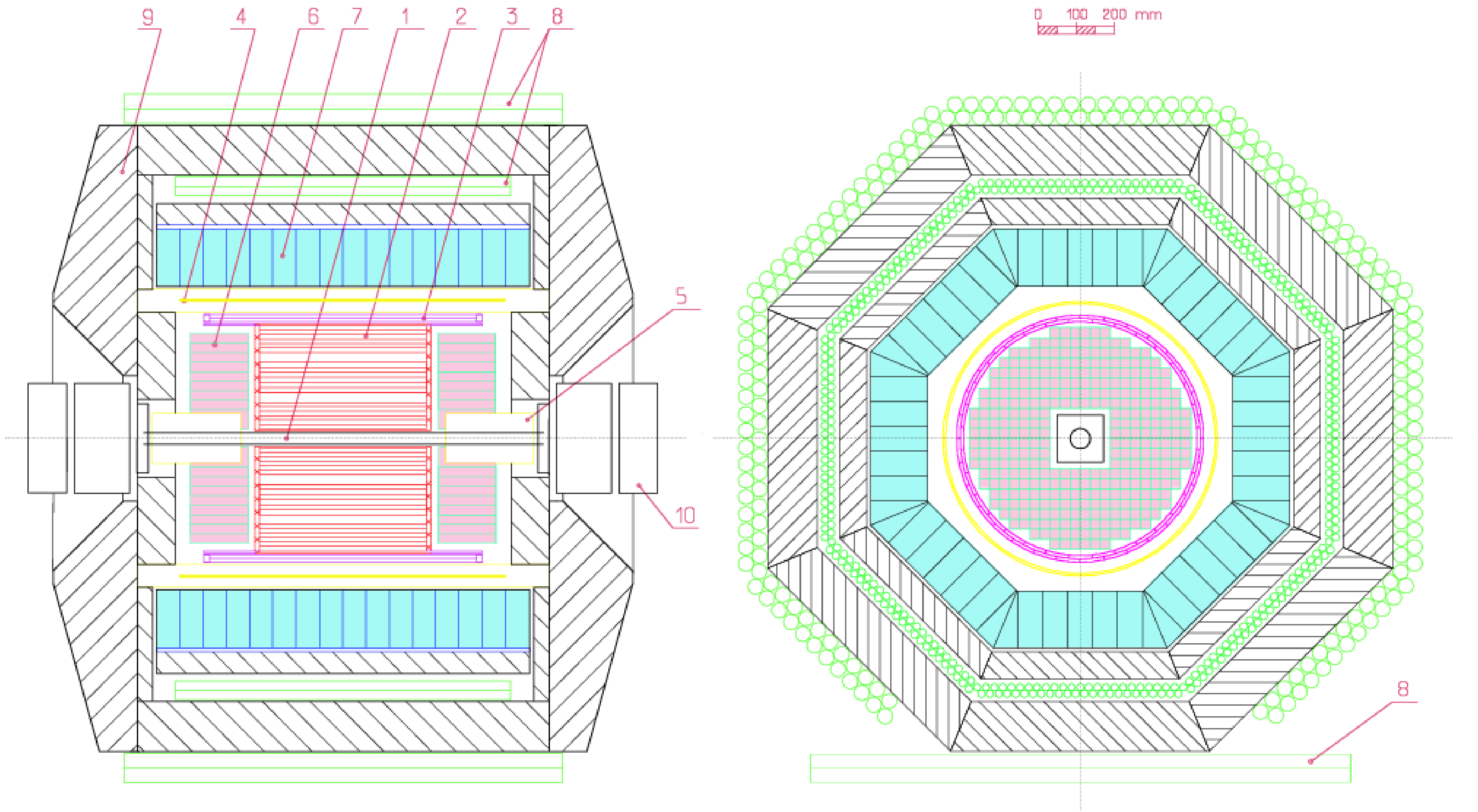
Energy range: 0.36 – 1.4 GeV

Luminosity up to $5*10^{30}$ 1/cm^{2}s

Lets set the scale:

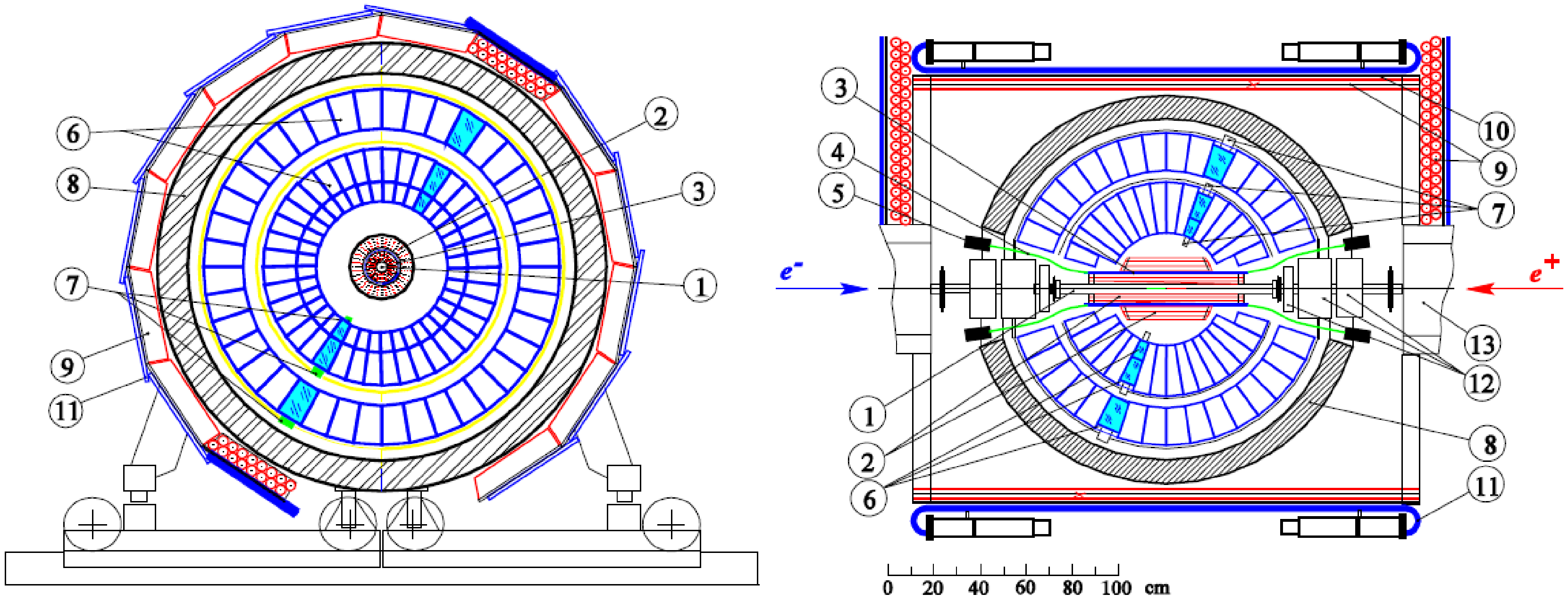
$\sigma(e^+e^- \to \pi^+\pi^-)$ at ρ peak (0.77 GeV) ~ 1000 nb
$L = 10^{30}\ cm^{-2}s^{-1}$ corresponds to 1 Hz for σ = 1000 nb

CMD-2



1 - vacuum chamber
2 - drift chamber
3 - **Z**-chamber
4 - main solenoid
5 - compensating magnet
6 - **BGO** endcap calorimeter
7 - **CsI** barrel calorimeter
8 - muon range system
9 - iron yoke
10 - storage ring lenses

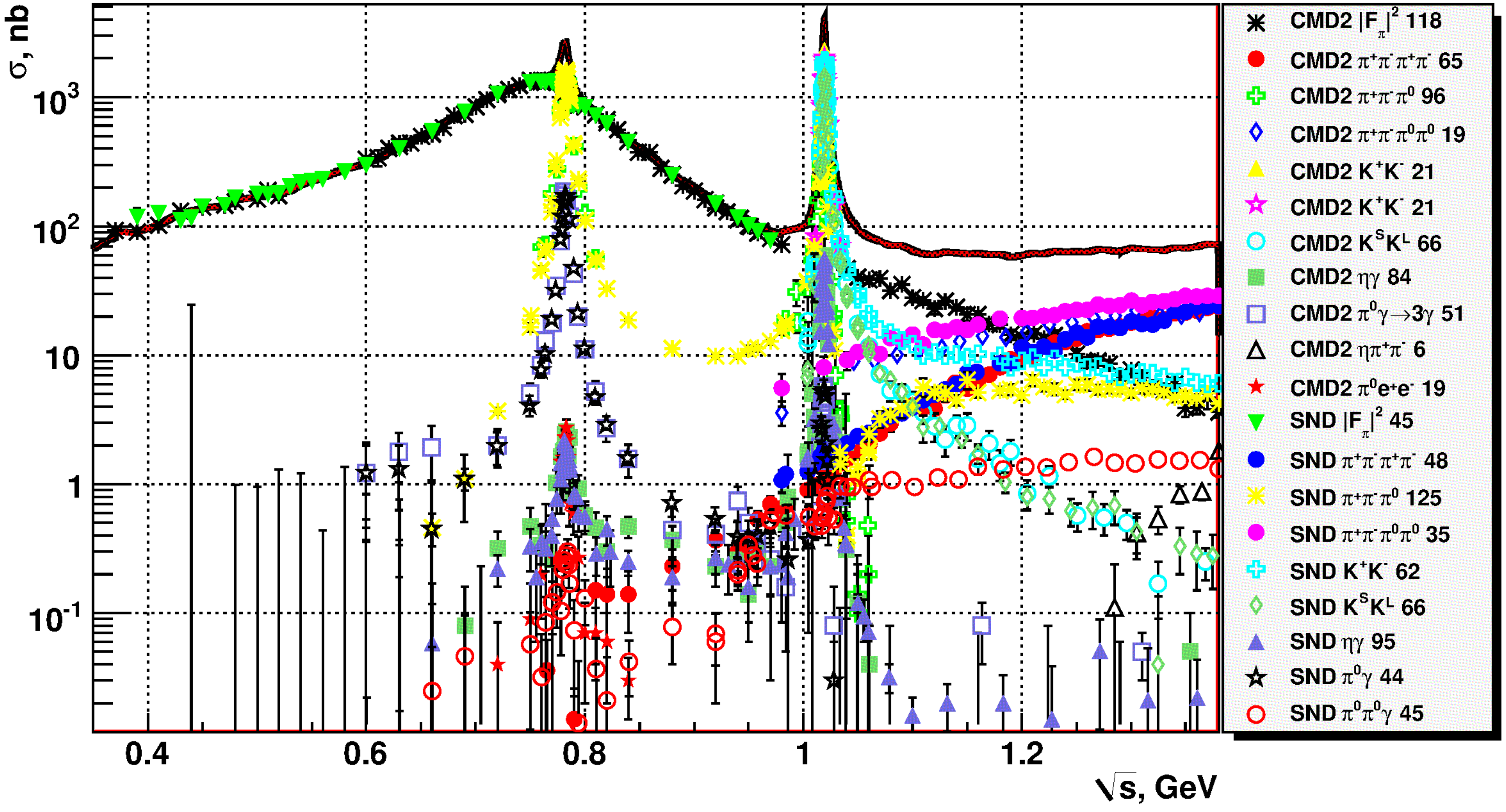
SND



- No magnetic field
- Spherical three-layer NaI calorimeter
- Small drift chamber around interaction point

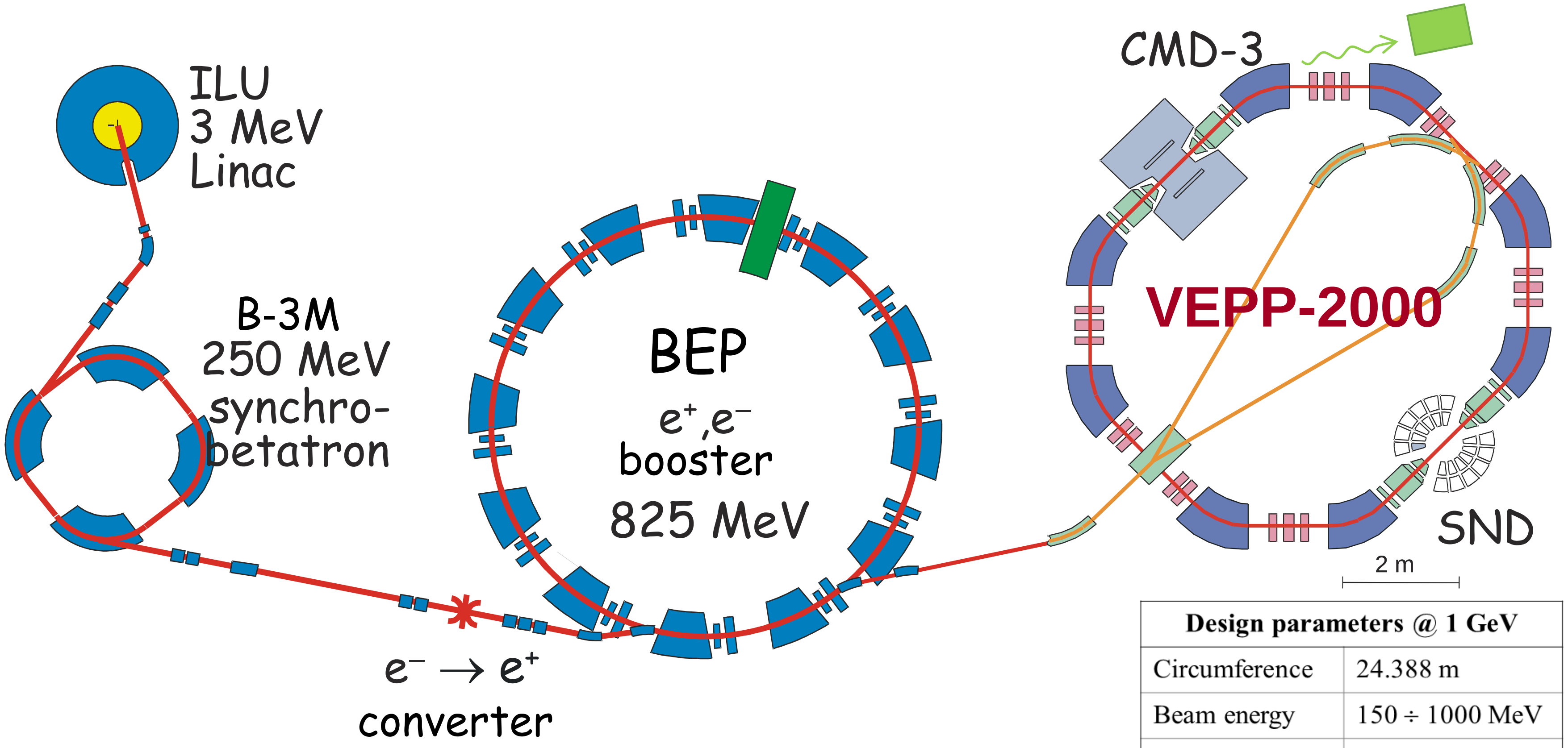
Optimized for neutral processes (e.g., $\pi^0\gamma$)

Overview of VEPP-2M measurements



VEPP-2000 (2011-2013)

Beam energy by Compton backscattering



Design parameters @ 1 GeV	
Circumference	24.388 m
Beam energy	150 ÷ 1000 MeV
N of bunches	1×1
N of particles	1×10^{11}
Betatron tunes	4.14 / 2.14
Beta*	8.5 cm
BB parameter	0.1
Luminosity	1×10^{32} cm^{-2}s^{-1}

C.m. energy range is 0.32-2.0 GeV

Unique optics – “round beams”

Experiments CMD-3 and SND started by the end of 2010

VEPP-2000 (2017-)

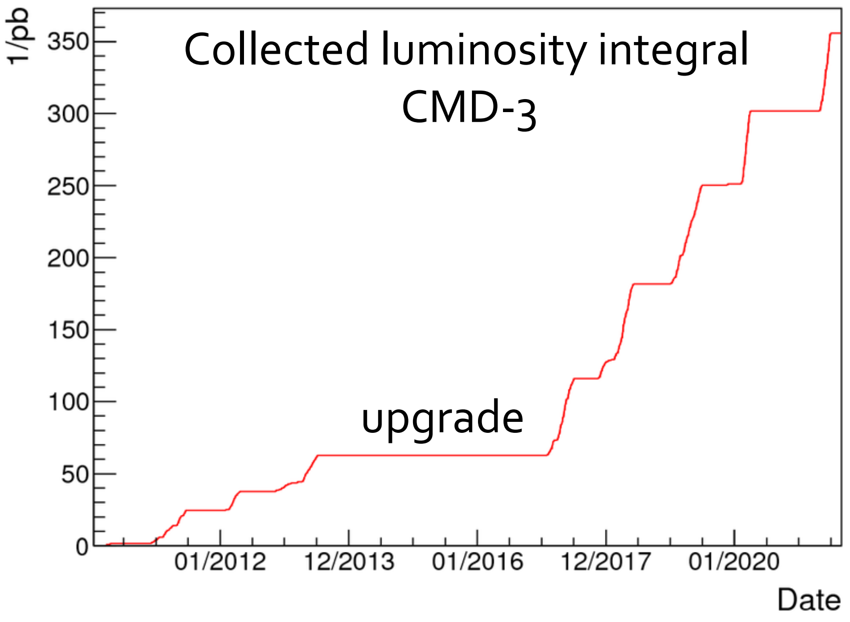
250 m beamline

VEPP-2000

New injection complex

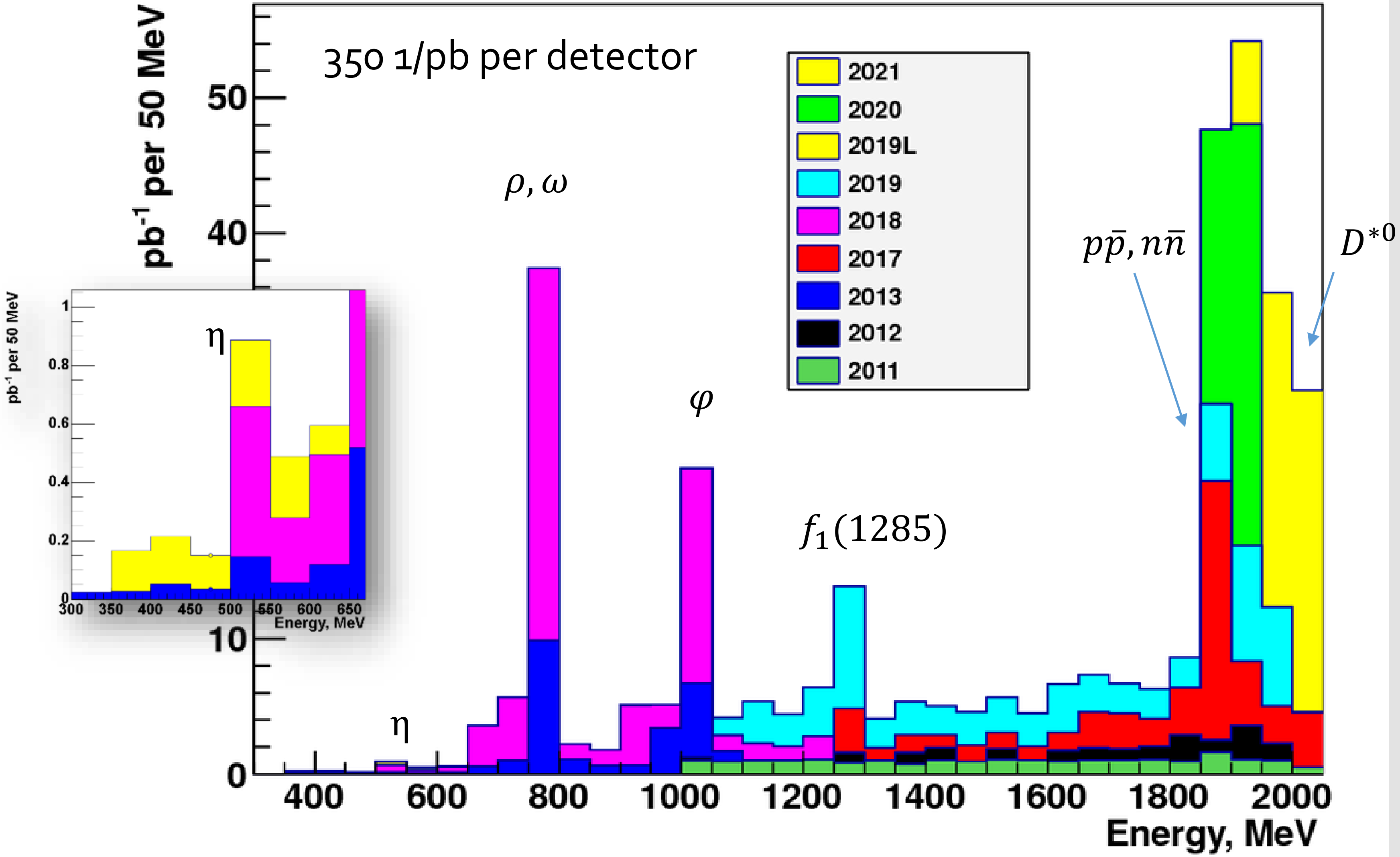
Major upgrade in 2013-2016:

- x10 more intense positron source
- booster up to 1 GeV (match VEPP-2000)

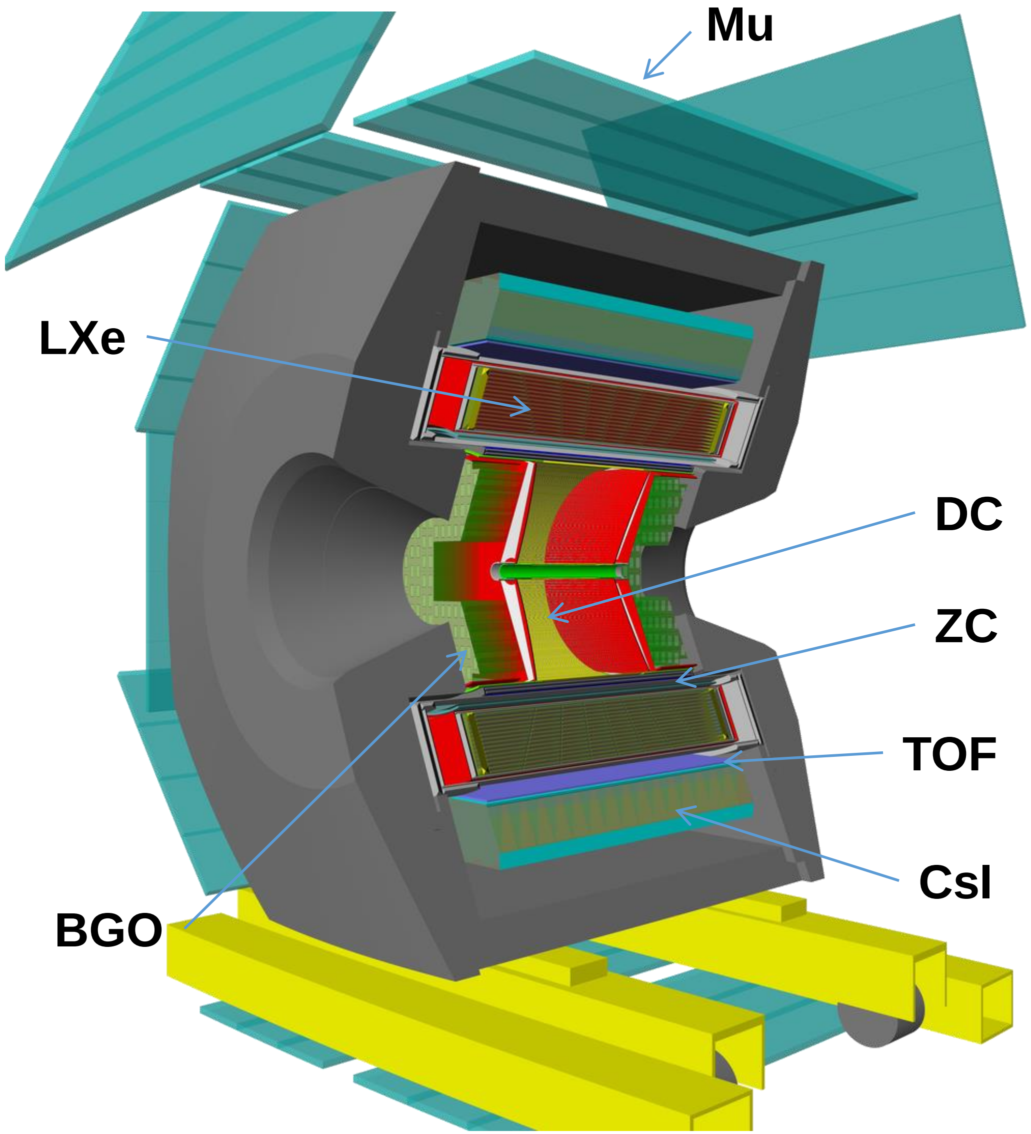


Detectors resumed data taking by the end of 2016

At what energies VEPP-2000 collected data



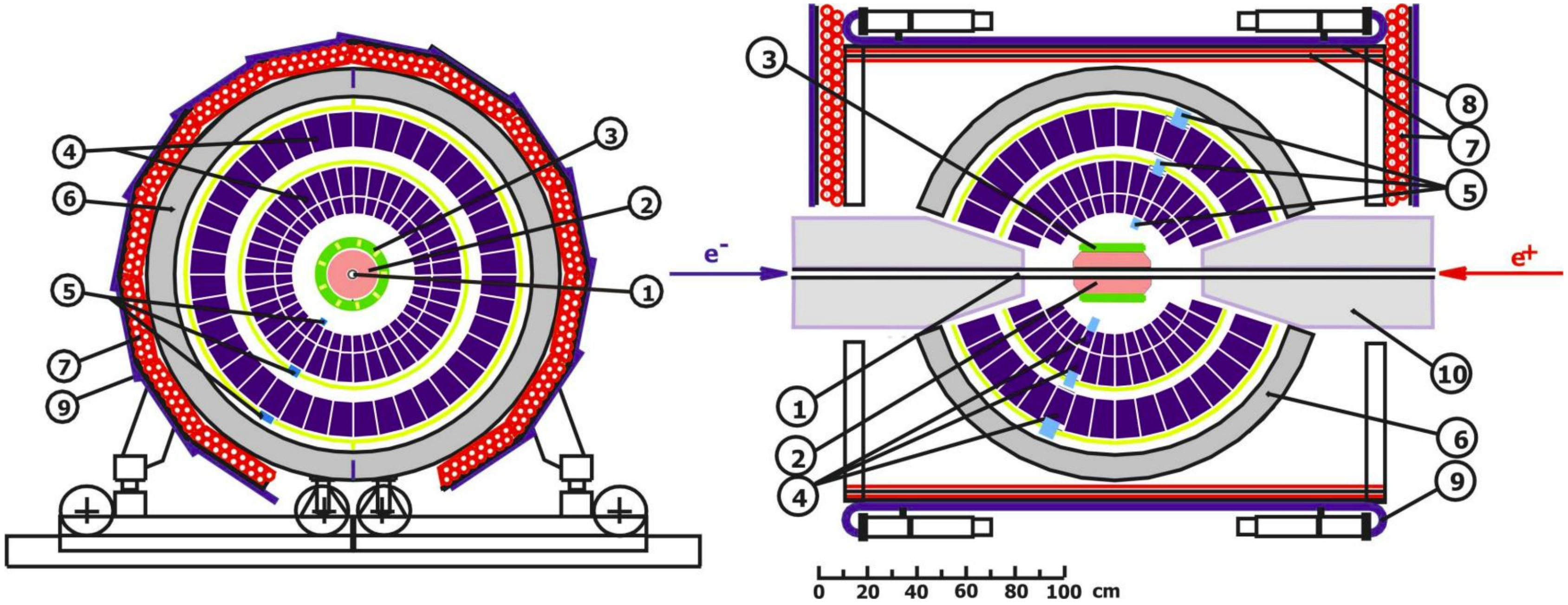
CMD-3



Advantages compared to CMD-2:

- new drift chamber with two times better resolution, higher B field
  - better tracking
  - better momentum resolution
- thicker barrel calorimeter ($8.3X_0 \rightarrow 13.4\ X_0$)
  - better particle separation
- LXe calorimeter
  - measurement of conversion point for γ's
  - measurement of shower profile
- TOF system
  - particle id (mainly p, n)

SND

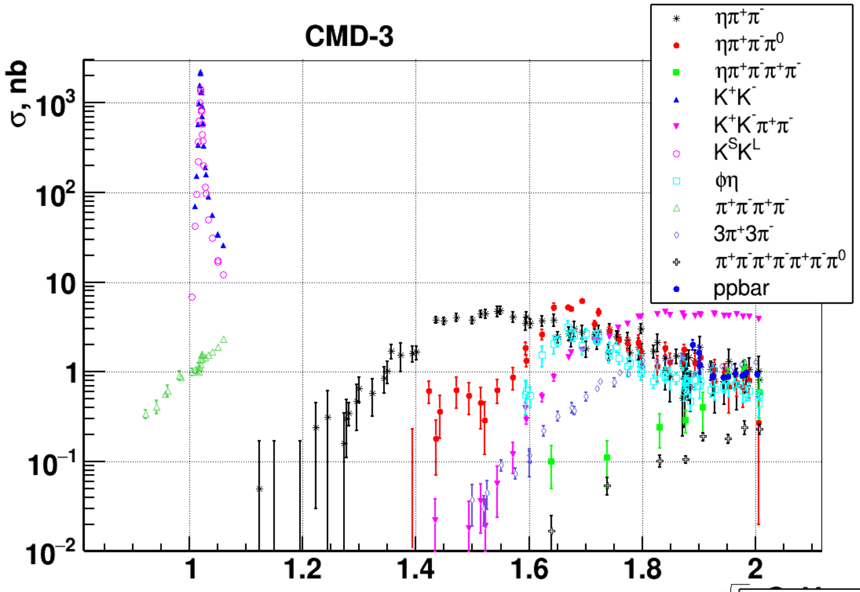


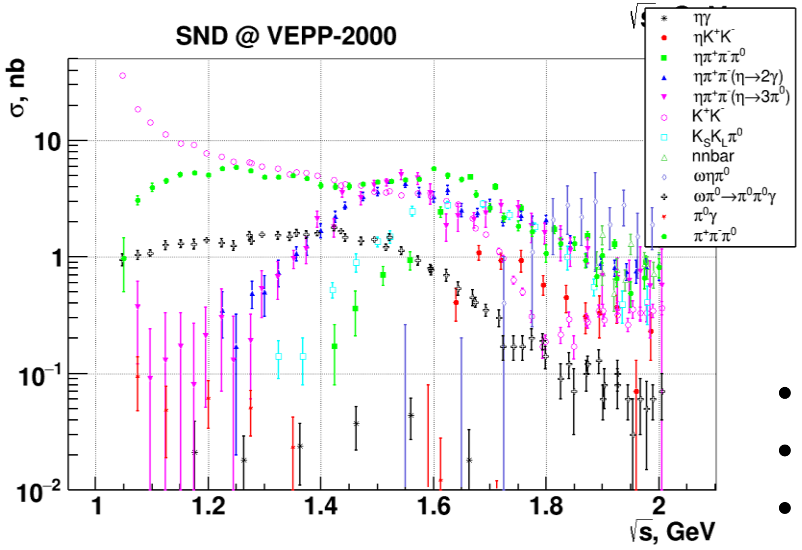
1 – beam pipe
2 – tracking system
3 – aerogel
4 – NaI(Tl) crystals
5 – phototriodes
6 – muon absorber
7–9 – muon detector
10 – focusing solenoid

Advantages compared to previous SND:

- new system - Cherenkov counter (n=1.05, 1.13)
  - e/π separation E<450 MeV
  - π/K separation E<1 GeV
- new drift chamber
  - better tracking
  - better determination of solid angle

Measurements at VEPP-2000



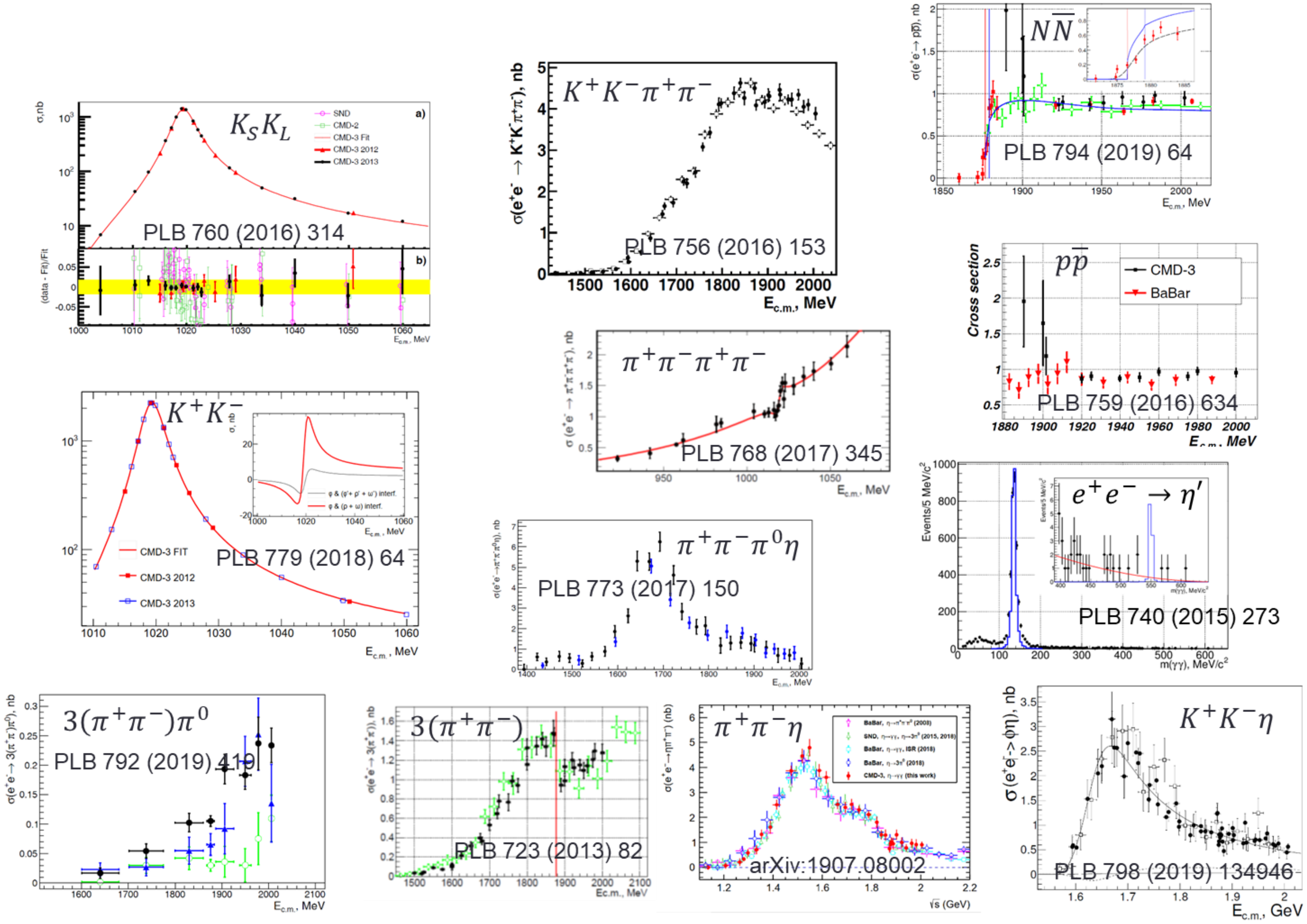


Final states under analysis at CMD-3

Signature	Final states (preliminary, published)
2 charged	$\pi^+\pi^-$, K^+K^-, K_SK_L, $p\bar{p}$
2 charged + γ's	$\pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-2\pi^0$, $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\eta$, $\pi^+\pi^-2\pi^0\eta$, $K^+K^-\pi^0$, $K^+K^-2\pi^0$, $K^+K^-\eta$, $K_SK_L\pi^0$, $K_SK_L\eta$
4 charged	$2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K_SK^\pm\pi^\mp$
4 charged + γ's	$2(\pi^+\pi^-)\pi^0$, $2\pi^+2\pi^-2\pi^0$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\omega$, $2\pi^+2\pi^-\eta$, $K^+K^-\omega$, $K_SK^\pm\pi^\mp\pi^0$
6 charged	$3(\pi^+\pi^-)$, $K_SK_S\pi^+\pi^-$
6 charged + γ's	$3(\pi^+\pi^-)\pi^0$
Neutral	$\pi^0\gamma$, $2\pi^0\gamma$, $3\pi^0\gamma$, $\eta\gamma$, $\pi^0\eta\gamma$, $2\pi^0\eta\gamma$
Other	$n\bar{n}$, $\pi^0e^+e^-$, ηe^+e^-
Rare decays	η', $D^*(2007)^0$

- More final states compare to VEPP-2M
- 1-2 order of magnitude more data
- The experiments are collecting data

CMD-3 published results

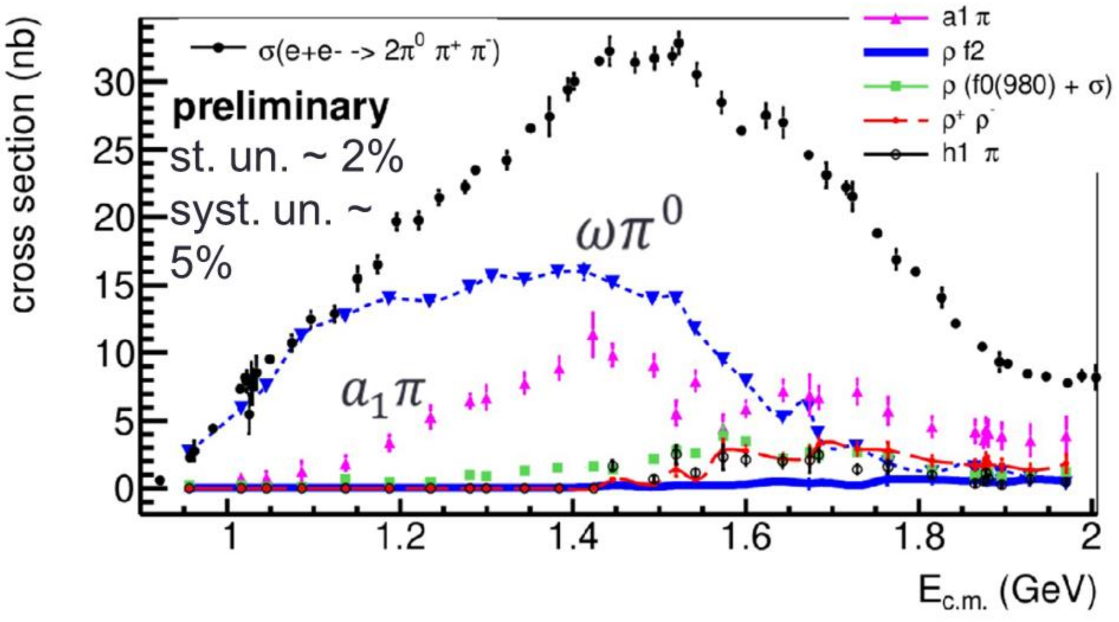


In order to measure hadronic cross section, you have to understand the dynamics of the process (to properly evaluate detector efficiency). **High statistics is crucial!**

Understanding of intermediate dynamics

Example: four pions at CMD-3

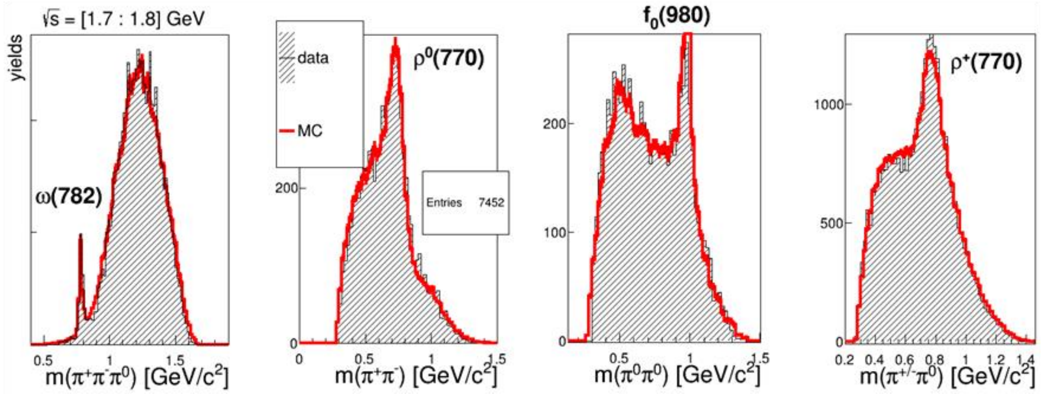
Simultaneous unbinned amplitude analysis of 150 000 $\pi^+\pi^-\pi^0\pi^0$ events and 250 000 $\pi^+\pi^-\pi^+\pi^-$ events.



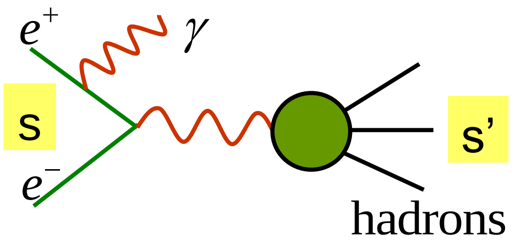
Amplitudes accounted for in the likelihood function:

- $\omega[1^{--}]\pi^0[0^{++}]$ (only $\pi^+\pi^-2\pi^0$)
- $a_1(1260)[1^+]\pi[0^-]$
- $\rho[1^{--}]f^0/\sigma[0^{++}]$
- $\rho f_2(1270)[2^{++}]$
- $\rho^+\rho^-$ (only $\pi^+\pi^-2\pi^0$)
- $h_1(1170)[1^{+-}]\pi^0$ (only $\pi^+\pi^-2\pi^0$)

Intermediate resonances observed in data:



ISR approach



The initial-state radiation (ISR) approach: take data at single energy point and identify $e^+e^- \to X + \gamma$ events to extract cross-section $e^+e^- \to X$ in the wide energy range.

The cross section is extracted from the spectrum of $e^+e^- \to \gamma_{ISR}X$ events:

$$\frac{dN_{X(\gamma)\gamma_{ISR}}}{d\sqrt{s'}} = \frac{dL_{ISR}^{eff}}{d\sqrt{s'}}\varepsilon_{X(\gamma)}(\sqrt{s'})\sigma_{X(\gamma)}(\sqrt{s'})$$

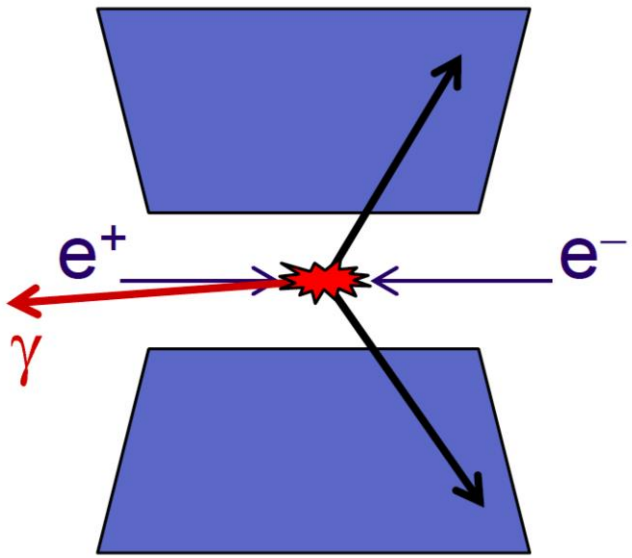
Effective luminosity

$$\frac{dL_{ISR}^{eff}}{d\sqrt{s'}} = L_{ee}\frac{dW}{d\sqrt{s'}}$$

Radiator function – probability to radiate ISR photon (with radiative corrections)

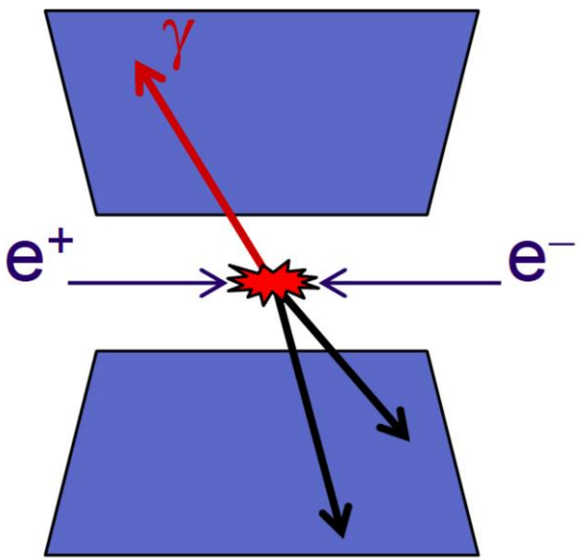
ISR luminosity is 2-3 orders of magnitude smaller than plain luminosity. Need high luminosity collider – "factory".

Small angle vs large angle ISR



Small angle (untagged) ISR

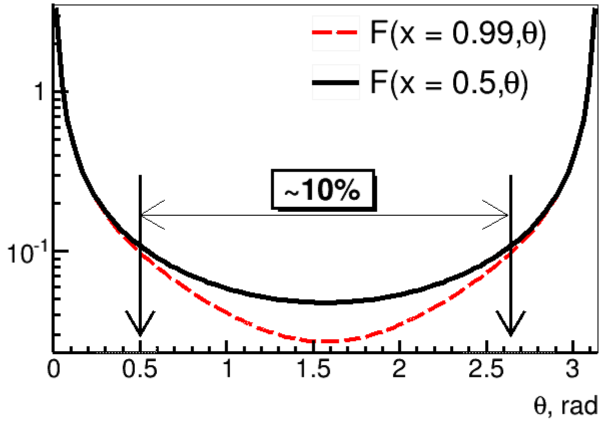
- ISR photon emitted along initial beam, undetected
- ISR photon is reconstructed from kinematics of the final state



Large angle (tagged) ISR

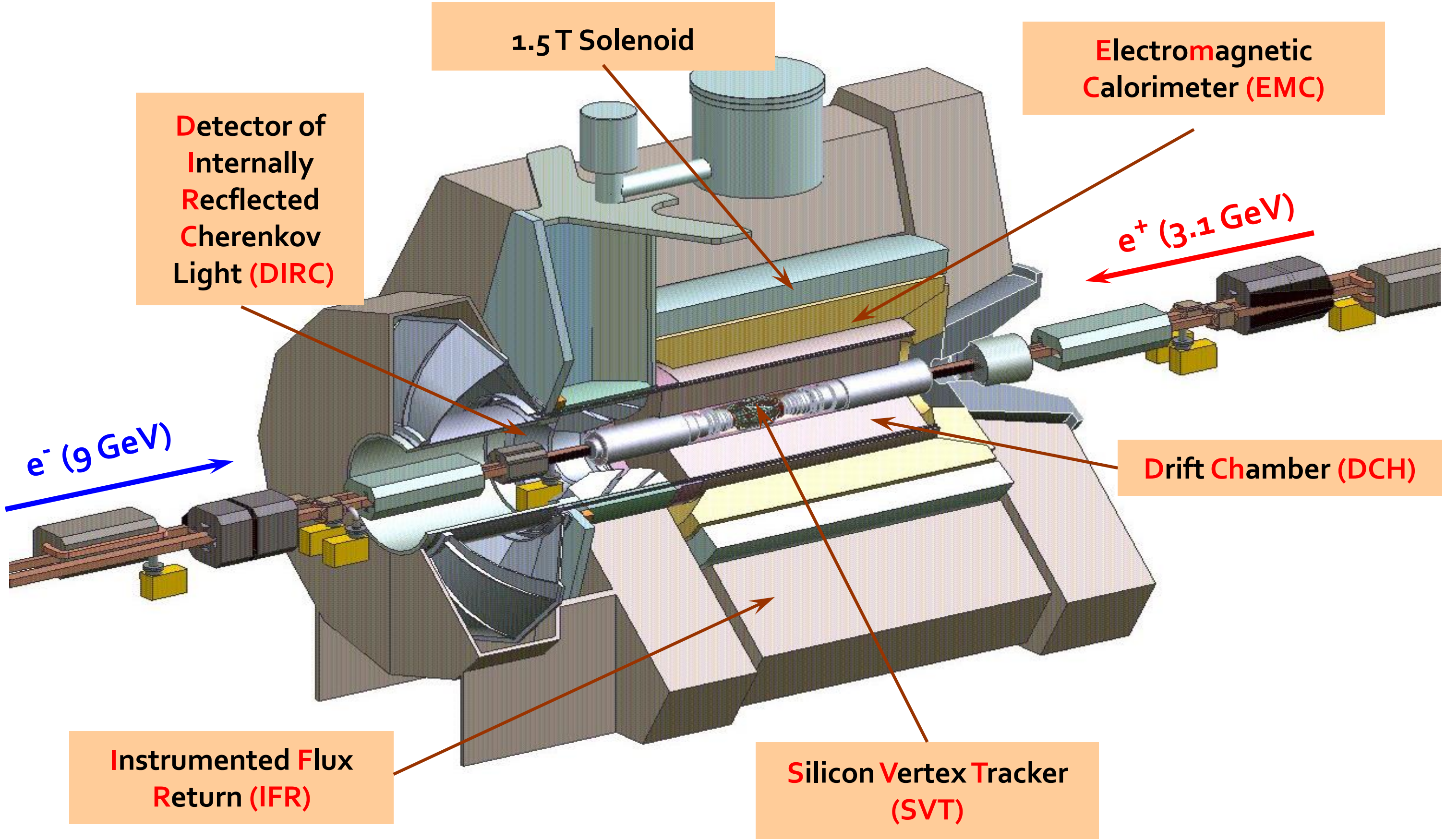
- ISR photon emitted at large angle and detected

Angular distribution of γ_{ISR}

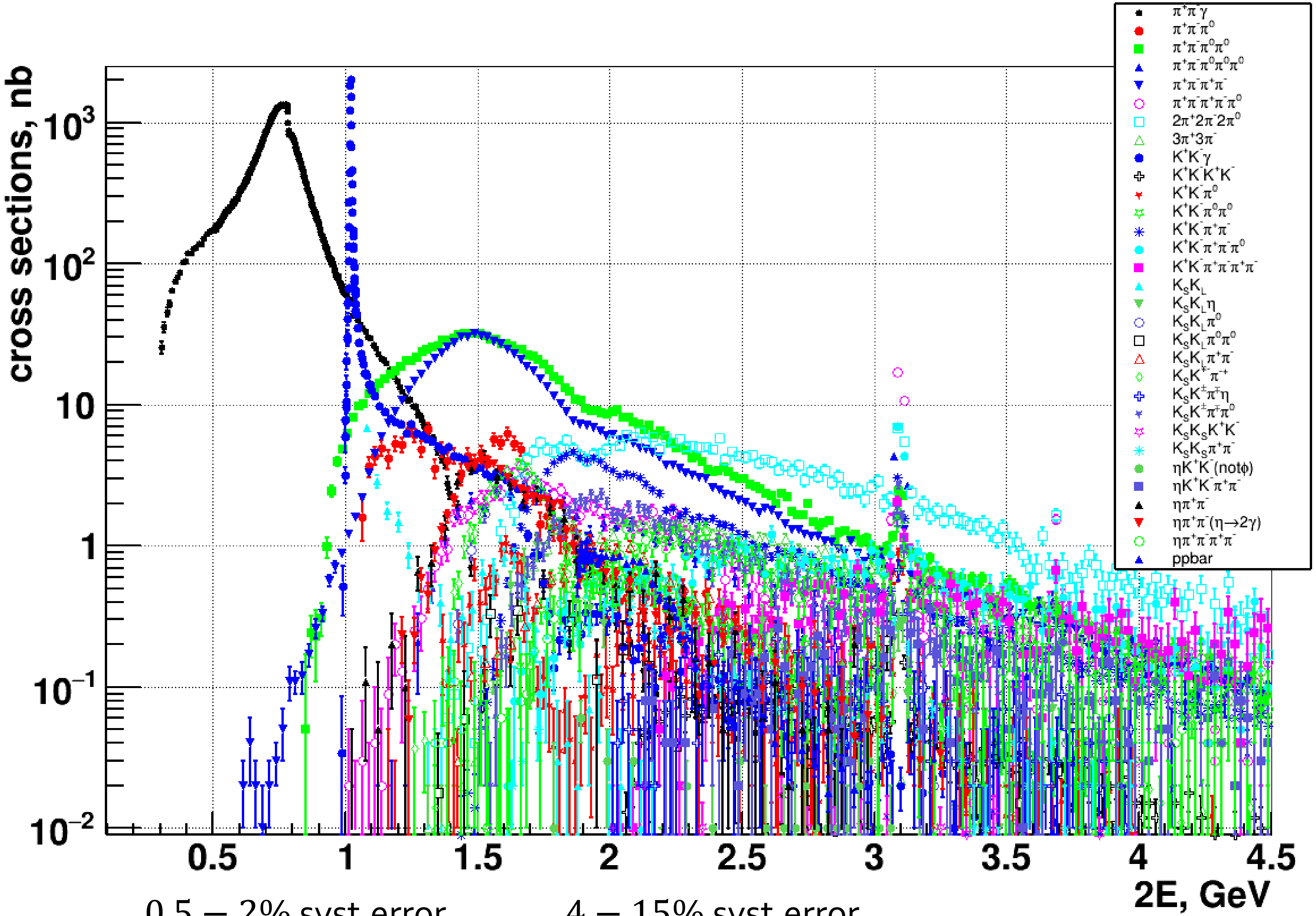


BABAR experiment (1999-2008)

PEP-II asymmetric e^+e^- collider at SLAC
9 GeV e^- and 3.1 GeV e^+
About 500 fb^{-1} collected in 1999-2008
Comprehensive program of ISR measurements, using a data sample of 469 fb-1 collected at and near $\Upsilon(4S)$ (10.58 GeV)



BABAR



0.5 – 2% syst.error   4 – 15% syst.error

BABAR measurements are mostly tagged

Tagged ISR method at BABAR

Fully exclusive measurement

- ✓Photon with $E_{CM} > 3$ GeV, which is assumed to be the ISR photon
- ✓All final hadrons are detected and identified

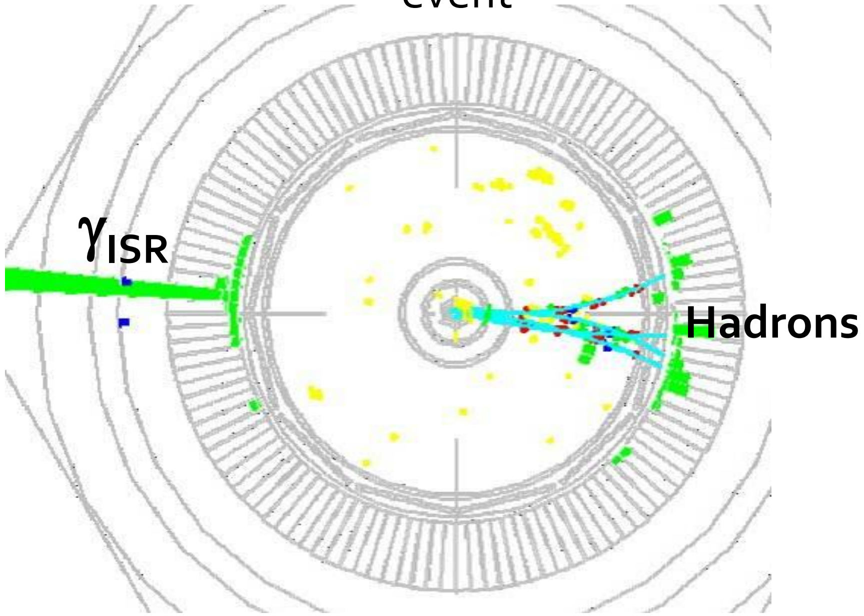
Large-angle ISR forces the hadronic system into the detector fiducial region

- ✓A weak dependence of the detection efficiency on dynamics of the hadronic system (angular and momentum distributions in the hadron rest frame) $\Rightarrow$ smaller model uncertainty
- ✓A weak dependence of the detection efficiency on hadron invariant mass $\Rightarrow$ measurement near and above threshold with the same selection criteria.

Kinematic fit with requirement of energy and momentum balance

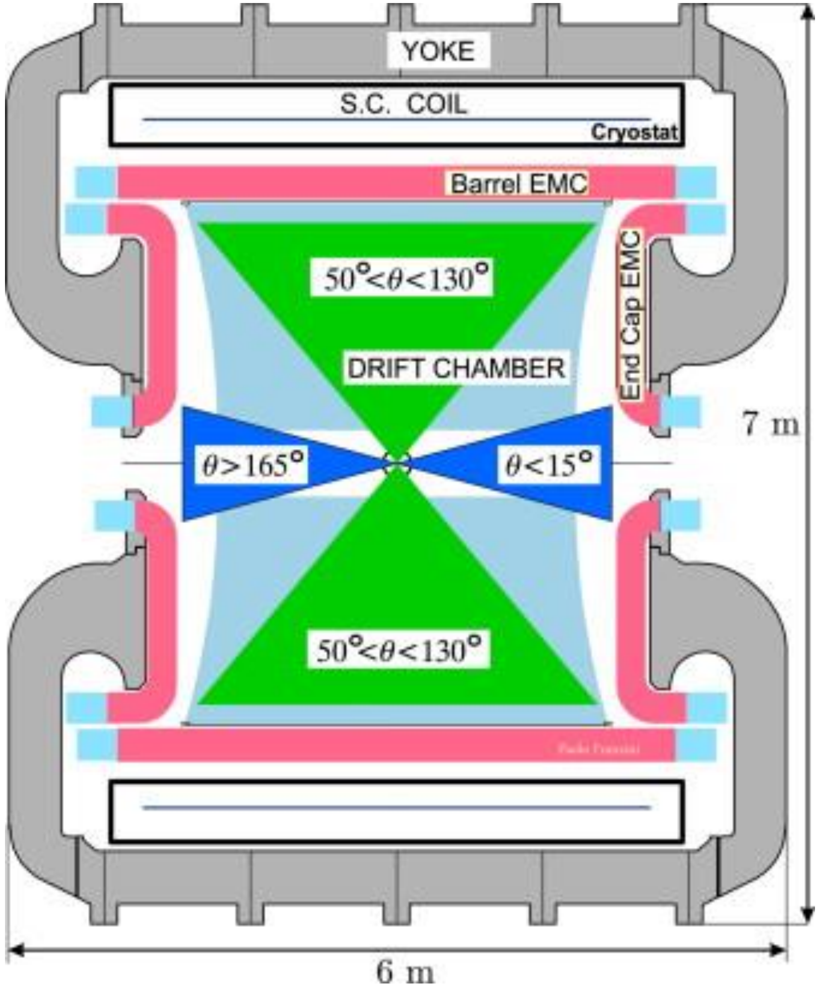
- ✓excellent mass resolution
- ✓background suppression

Generic BABAR ISR event



Can access a wide range of energy in a single experiment: from threshold to ~5 GeV

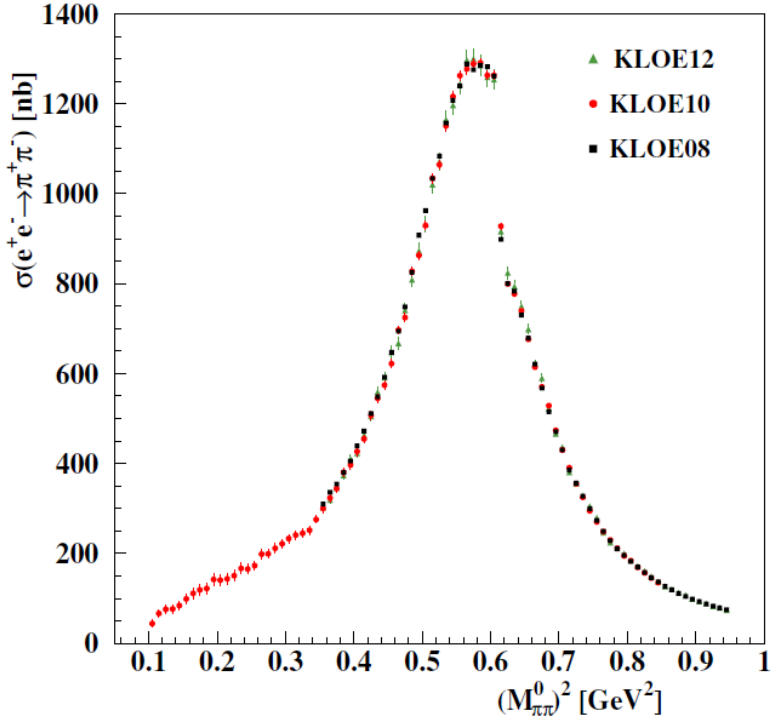
KLOE (2000-2006)



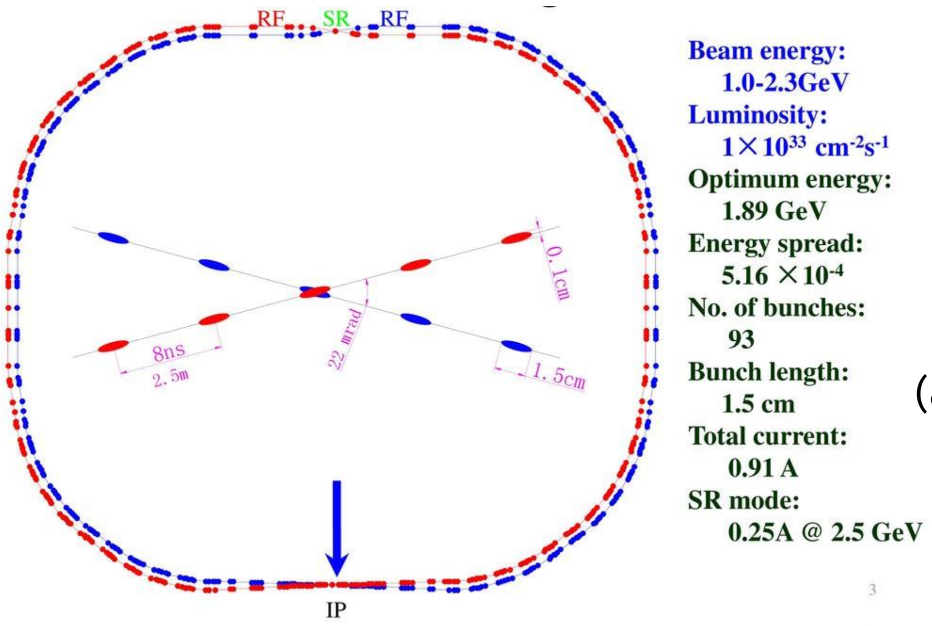
Installed at the DAFNE phi-factory

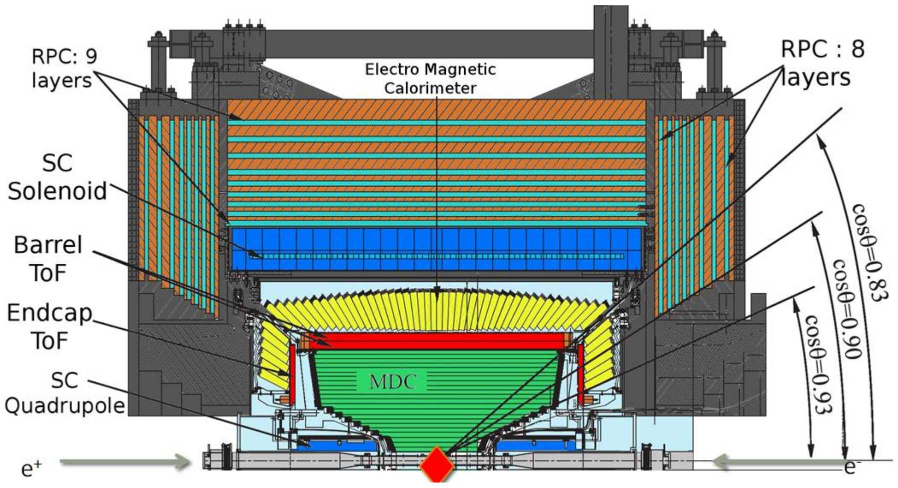
Mostly collected data at $\phi(1020)$ meson

ISR measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$, both tagged and untagged



BES-III

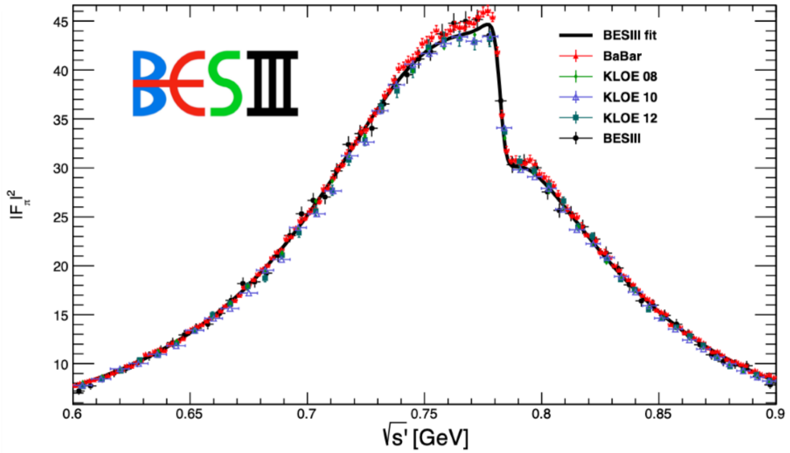




BEPC-II collider covers c.m.energy range from 2 to 5 GeV
"$c\tau$-factory"

BES-III detector is taking data
(and there were BES and BES-II before)

Tagged ISR measurement
$\sigma(e^+e^- \to \pi^+\pi^-)$



Statistics is limited compare to BaBar

Variety of ISR approaches

	Tagged ISR	Untagged ISR
Normalization to e^+e^-	KLOE-2010 $(\pi^+\pi^-)$ BABAR (most channels)	KLOE-2005 $(\pi^+\pi^-)$ KLOE-2008 $(\pi^+\pi^-)$ BABAR $(p\bar{p})$
Normalization to $\mu^+\mu^-(\gamma)$	BABAR $(\pi^+\pi^-)$* BES-III $(\pi^+\pi^-)$ CLEO-c $(\pi^+\pi^-)$	KLOE-2012 $(\pi^+\pi^-)$

ISR vs energy scan

- Energy scan analysis is generally simpler, but ISR measurements were done with superior detectors
- Before VEPP-2000, ISR measurements had more statistics
- In general, background is higher for ISR measurements
- ISR approach allows for larger detector coverage and smaller model-dependence
- In both approaches the visible cross-section is smeared and we need to unfold it:

Energy scan

The cross-section is smeared by ISR

$$\sigma_{vis}(s) = \int_0^1 dx_1 dx_2 D(x_1, s) D(x_2, s) \sigma_0(x_1 x_2 s)$$

The beam energy is known to high precision ($\sim 10^{-4} - 10^{-3}$)

The "unfolding" is done via radiative corrections

The "response" function is model-dependent, but it does not have unknown pieces

ISR

The cross-section is smeared by detector resolution

$$\frac{d\sigma_{vis}(s, s')}{ds'} = \frac{2s'}{s} W(s, s') \sigma_0(s')$$

The energy of the final state s' is reconstructed from the kinematics.

If the detector response function is known, the unfolding is the robust procedure.

But tails in the response function can lead to large effects.

Inclusive measurements

Inclusive measurements were systematically performed at $\sqrt{s} \gtrsim 2$ GeV

Signal events: one or more hadrons in the final state + any number of extra particles
Cuts on multiplicity, sphericity,...
With or without particle identification

$$\sigma_{\mathrm{mh}}^{\mathrm{obs}}(s) = \frac{N_{\mathrm{mh}} - N_{\mathrm{res.bg}}}{\int \mathcal{L}\,\mathrm{d}t}$$

$$R = \frac{\sigma_{\mathrm{mh}}^{\mathrm{obs}}(s) - \sum \varepsilon_{\mathrm{bg}}(s)\,\sigma_{\mathrm{bg}}(s) - \sum \varepsilon_{\psi}(s)\,\sigma_{\psi}(s)}{\varepsilon(s)\big(1+\delta(s)\big)\,\sigma_0^{e^+e^-\to\mu^+\mu^-}(s)}$$

The analysis depends on the same ingredients as the exclusive measurement: event selection, luminosity measurement, calculation of radiative corrections, evaluation of detector efficiency

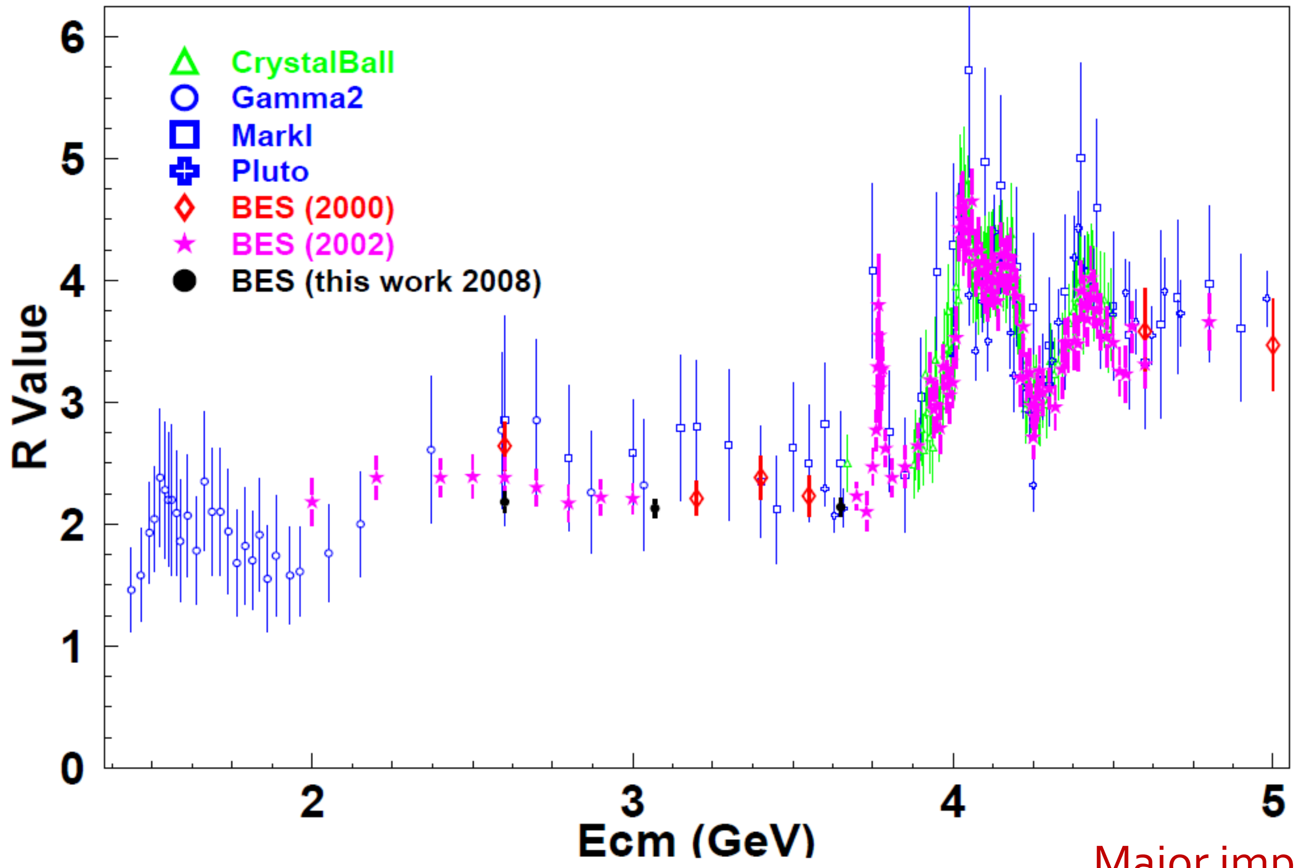
Key difficulty: to properly model hadronic events for evaluation of efficiencies and radiative corrections. There are dedicated MC generators: JETSET, LUARLW

"Typical" good precision: $\frac{\delta R}{R} \sim 3\%$, best achieved $\sim 2\%$.

Important to have large detection efficiency (now $\sim 75\%$)

PRL88(2002)101802
PLB677(2009)239

BES-II



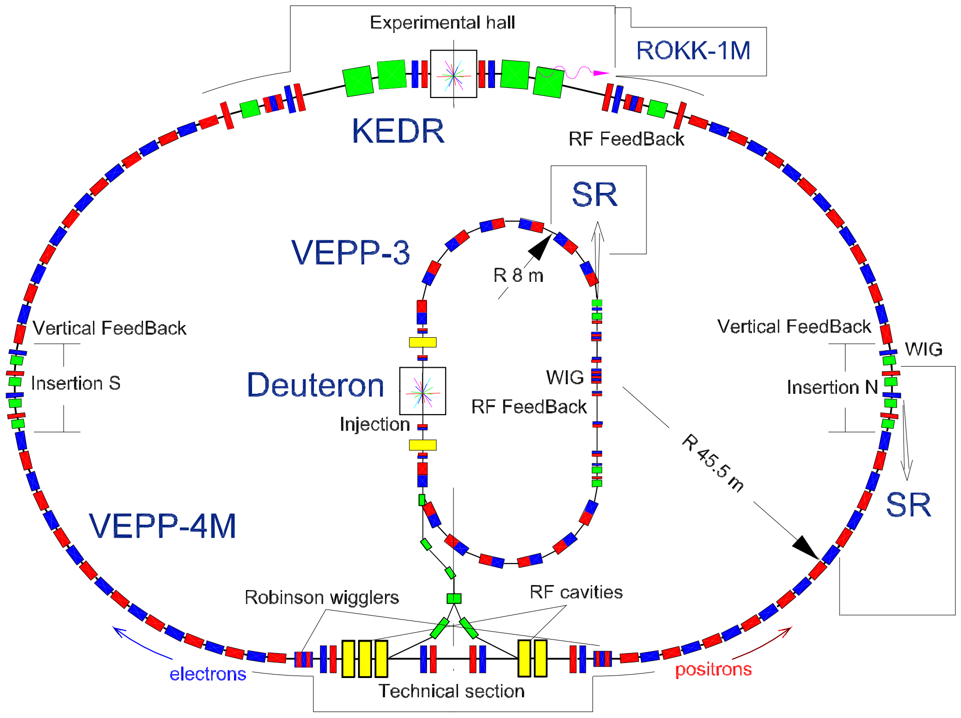
Major improvement!

BES-II performed detailed R(s) scan between 2 and 5 GeV

- 3 – 5% statistical error per point
- 5 – 8% systematical error

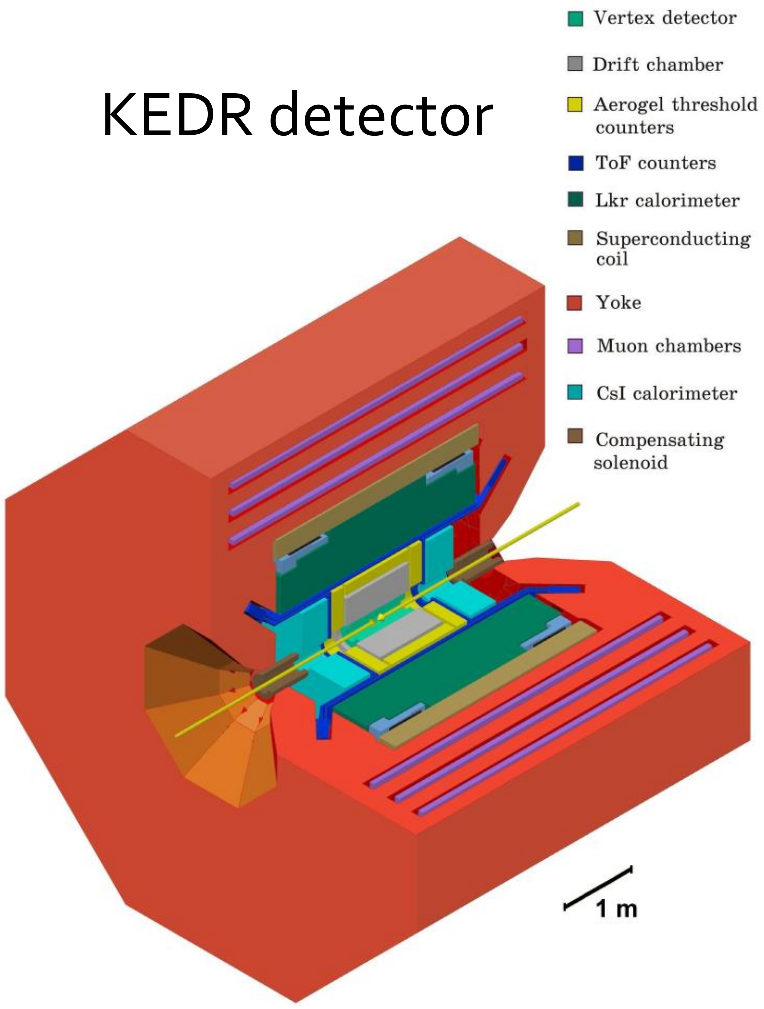
BES-III collected a lot of R(s) data (125 points), not published yet

KEDR



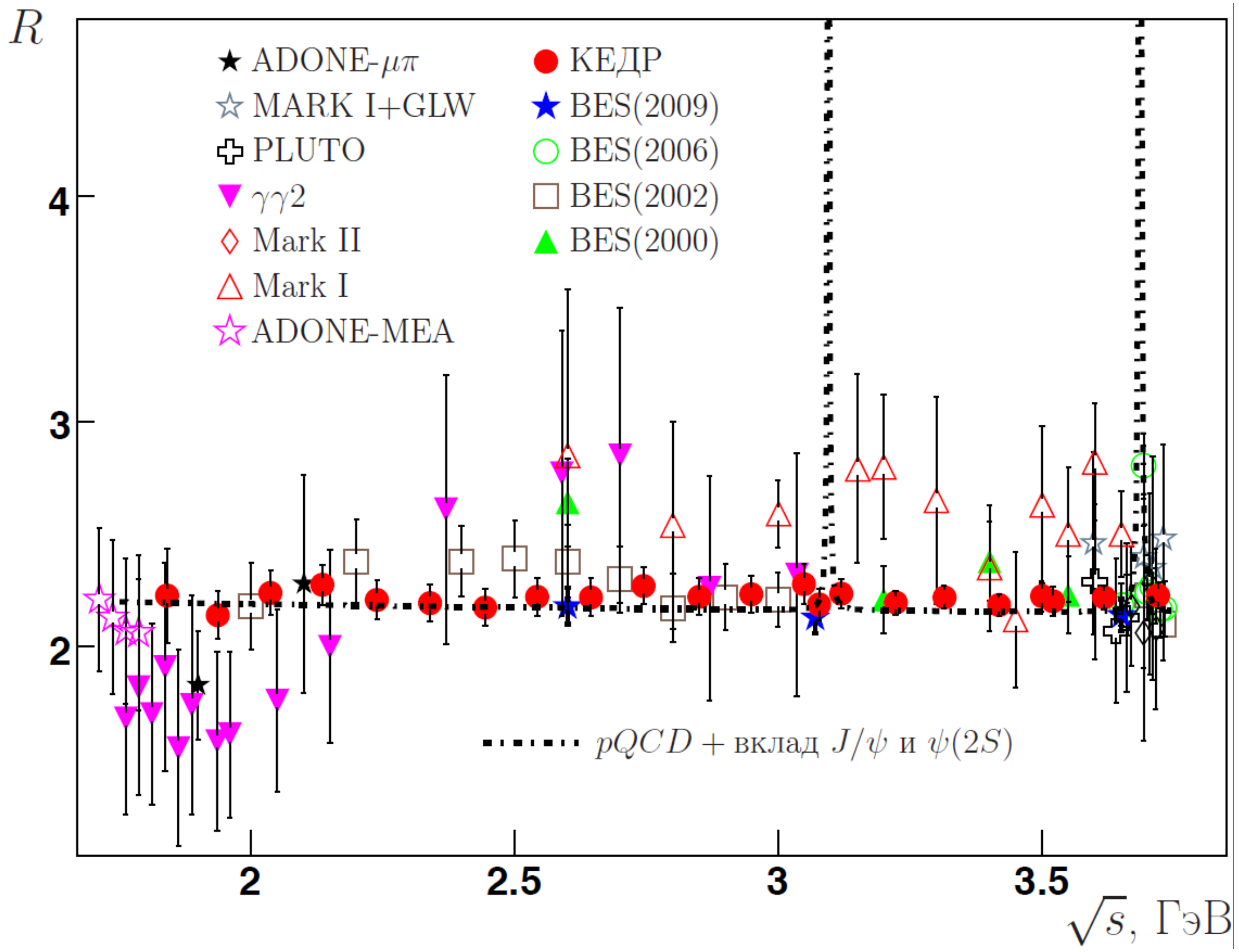
VEPP-4M collider

KEDR detector



Beam energy range 0.925-5.3 GeV
Luminosity $\sim 4 \cdot 10^{31}\ cm^{-2}s^{-1}$
Beam energy is determined to 20-30 keV (using Compton backscattering and resonance depolarization)

KEDR



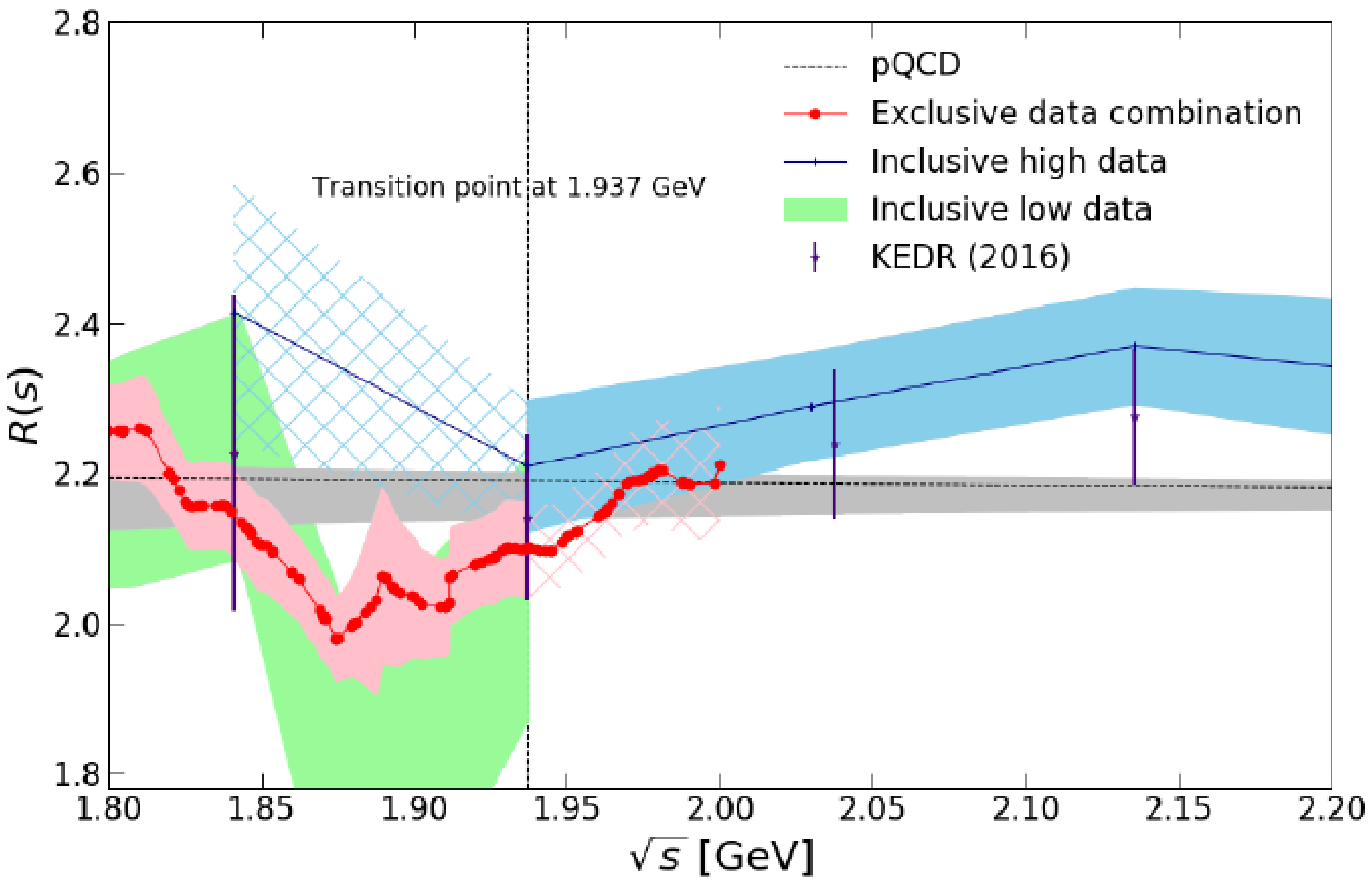
KEDR performed detailed R(s) scan between 1.8 and 3.7 GeV

- 2 – 3% statistical error per point
- 2 – 3% systematical error

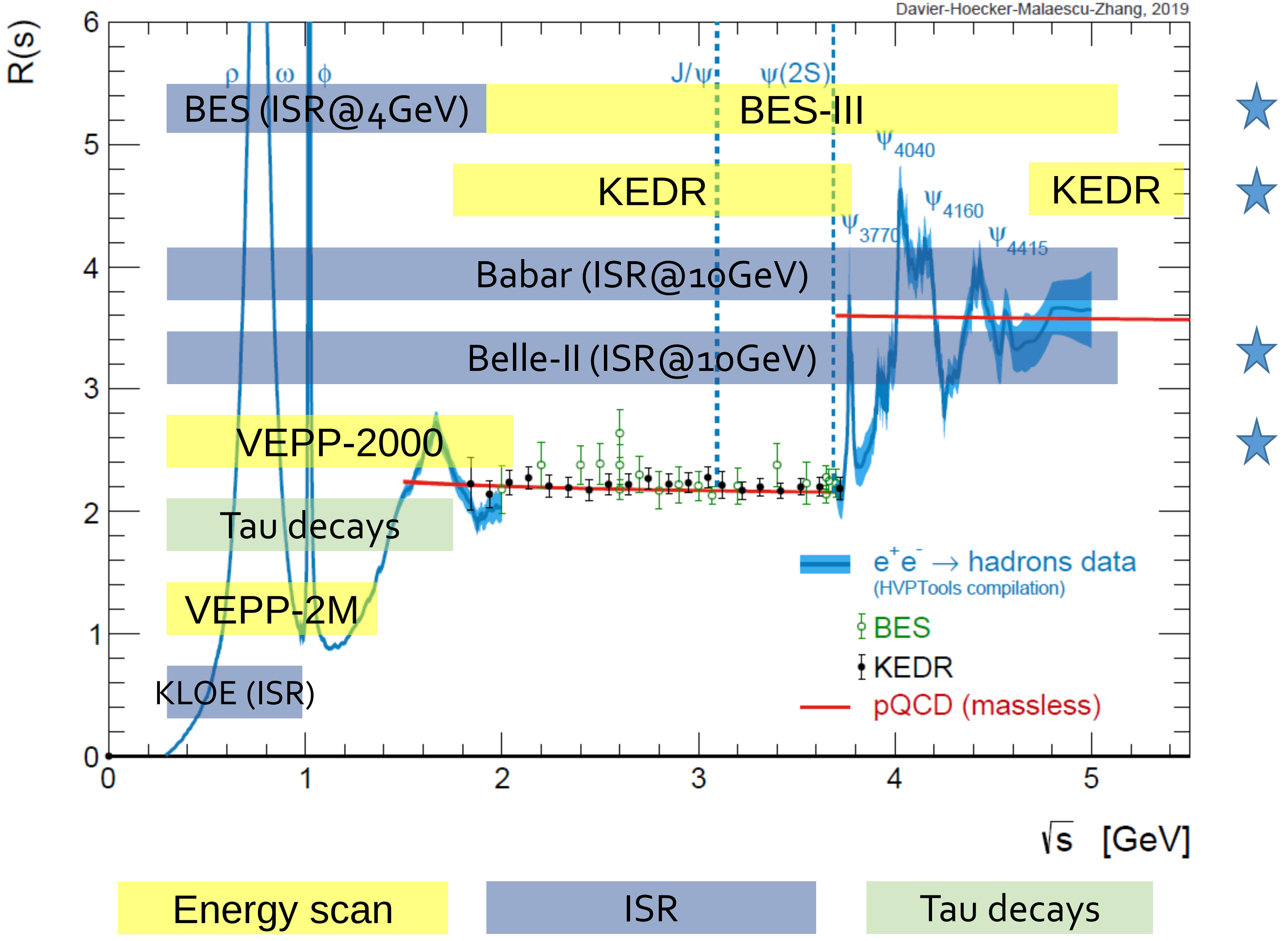
Most precise measurement

KEDR collected R(s) data between 4.7 and 7.0 GeV (17 points)

Is there agreement between inclusive and exclusive?



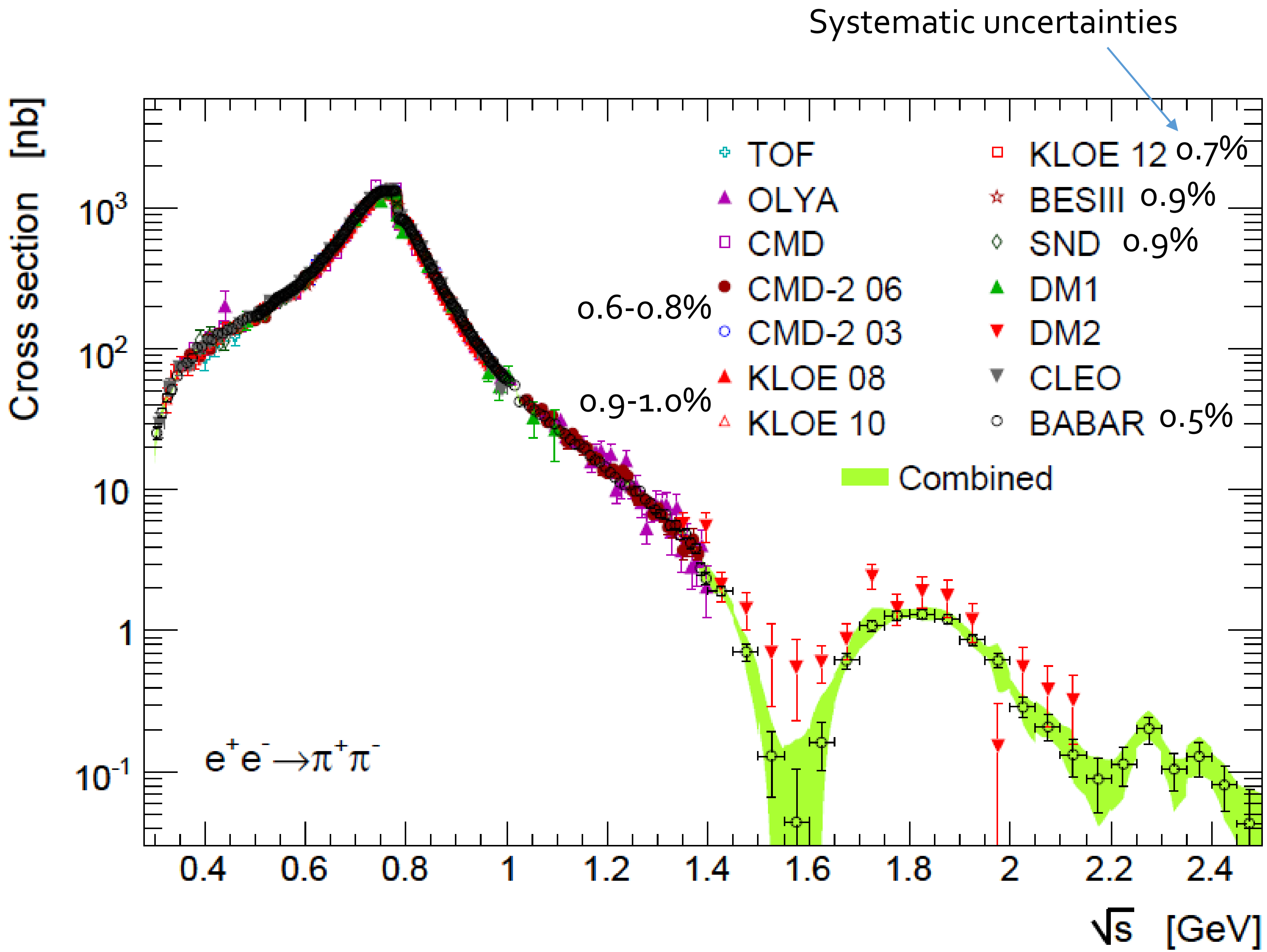
Where the measurements are done



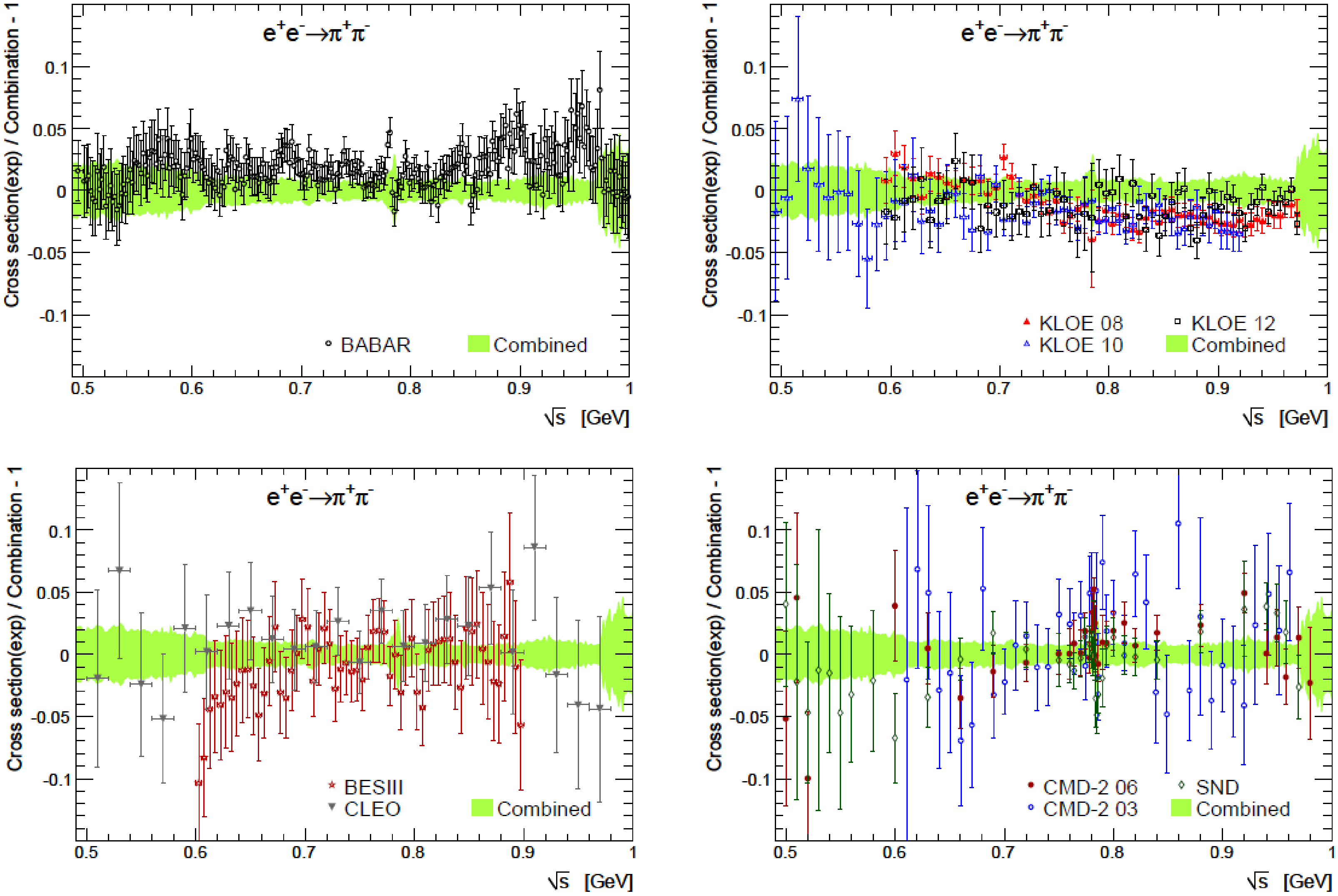
What to expect in near future

- VEPP-2000 has collected 350 1/pb per detector. The ultimate goal is 1000 1/pb per detector – many more data! Possibility to study intermediate dynamics.
- $e^+e^- \to \pi^+\pi^-$ cross section is about to be published by CMD-3 – record statistical precision
- SND published $e^+e^- \to \pi^+\pi^-$ cross section only using small portion of data - more results to be expected
- New analysis of BABAR $e^+e^- \to \pi^+\pi^-$ data based on angular distribution
- BELLE-II is taking data – expect new BABAR-like comprehensive ISR measurement
- BES-III plans to collect x10 of ISR data
- There is progress in development of new generators for radiative corrections calculations – very important for reaching higher accuracy (below 0.5%)
- With new high statistics measurements it will be possible to perform detailed comparison between ISR and energy scan

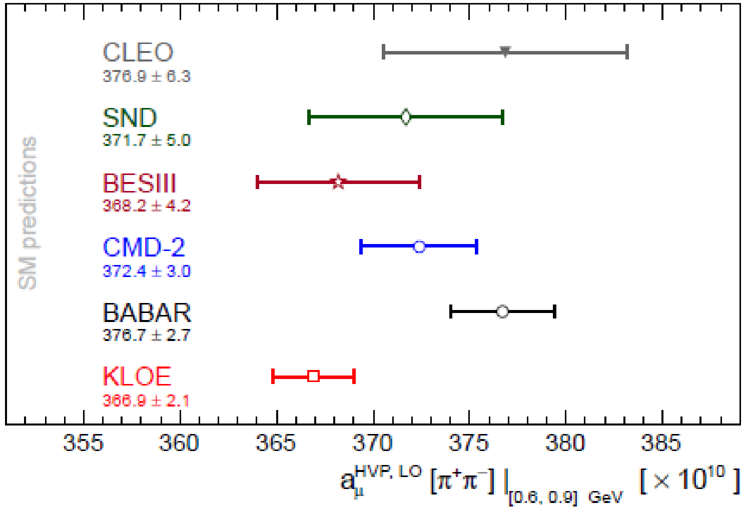
Status of $e^+e^- \to \pi^+\pi^-$



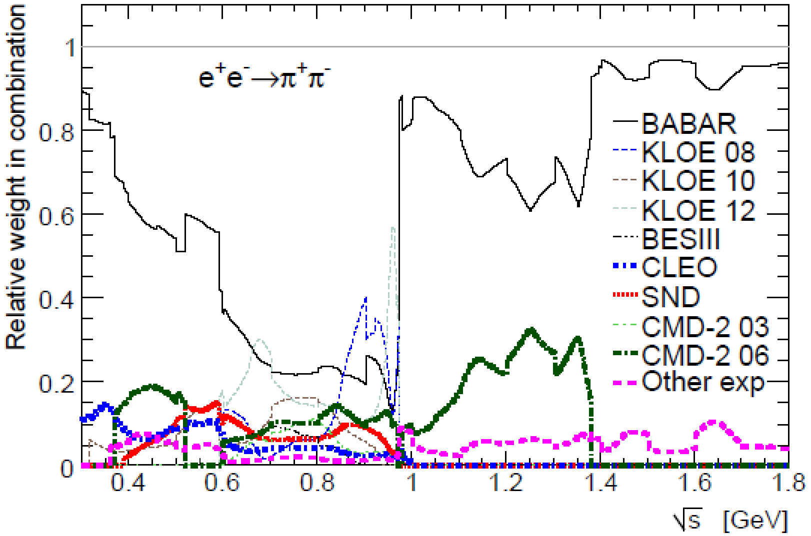
Status of $e^+e^- \to \pi^+\pi^-$



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



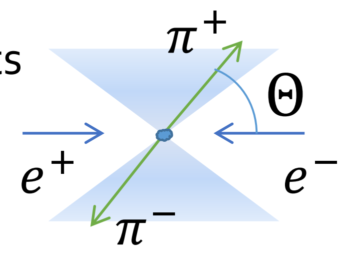
Infamous KLOE/BABAR tension (more pronounced in the spectra)



a_μ calculation is BABAR dominated outside of ρ energy region (0.6-0.9 GeV)

CMD-3 $e^+e^- \to \pi^+\pi^-$ analysis

Very simple kinematics, but the most challenging analysis due to high precision requirement: need to take into account many effects (which can affect result by 0.1% or more)



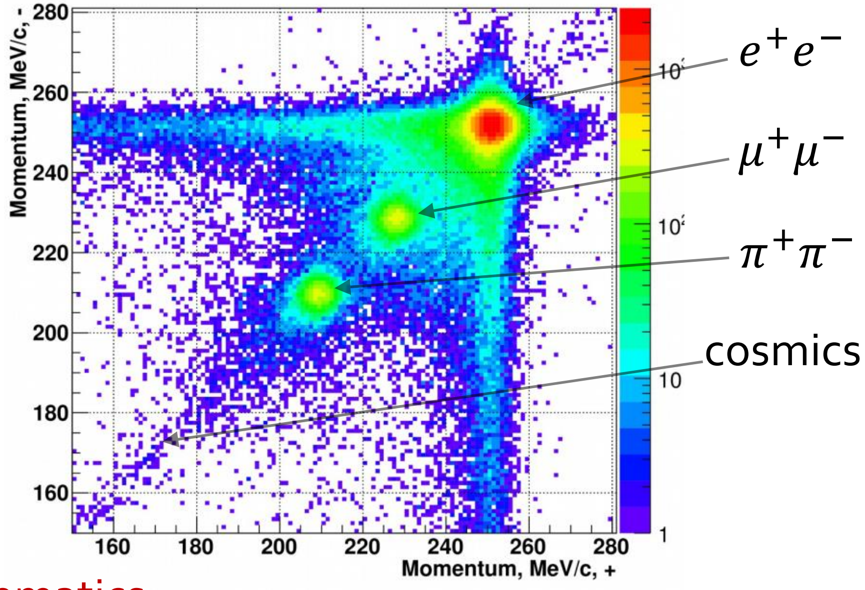
Main background: $e^+e^- \to e^+e^-, \mu^+\mu^-$

Measurement at CMD-3:

- several scans of the whole energy region below 2 GeV (took data in ρ region in 2013, 2018, 2020)
- employ correlations of the final particles: $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ separation either
  - by 2D momentum or
  - by 2D energy deposition

  independent measurements!
- many things to study: fiducial volume, pion decays, pions interactions in detector,backgrounds,…

P^- vs P^+ @$\sqrt{s} = 0.5$ GeV



High statistics is crucial! Goal: ~0.5% systematics

CMD-3 $e^+e^- \to \pi^+\pi^-$ analysis: radiative corrections

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

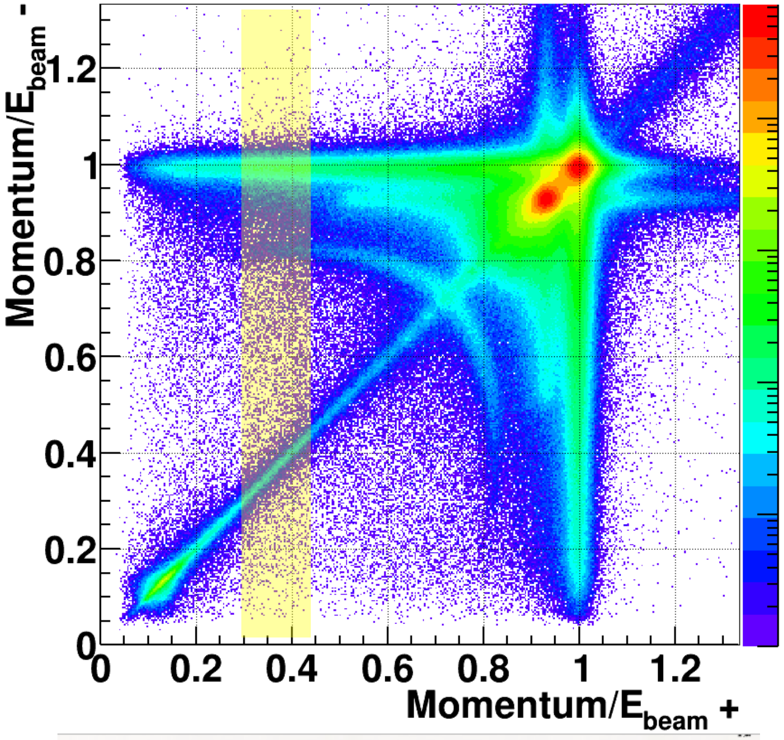
We use two high-precision MC generators for $e^+e^- \to e^+e^-$:

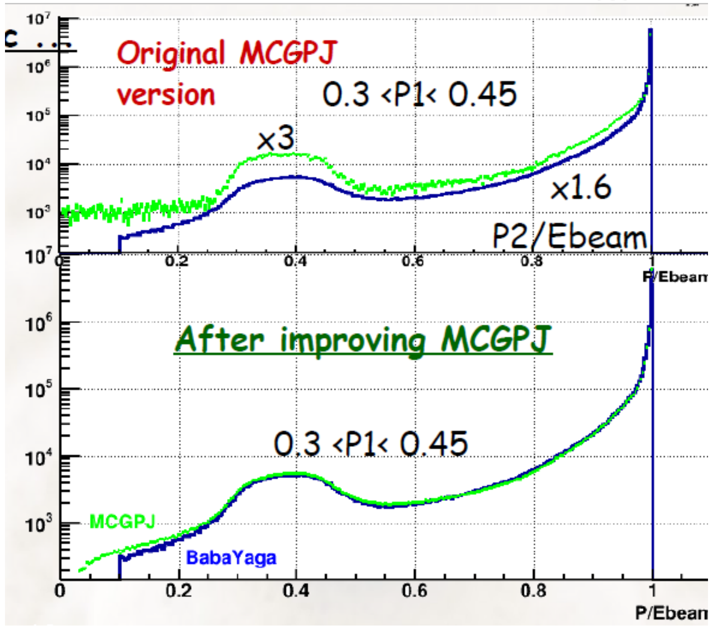
- MCGPJ generator (0.2%)
- BaBaYaga@NLO (0.1%)

With high statistics we've observed inconsistencies in tails of distributions, which were traced to particulars of MCGPJ generator

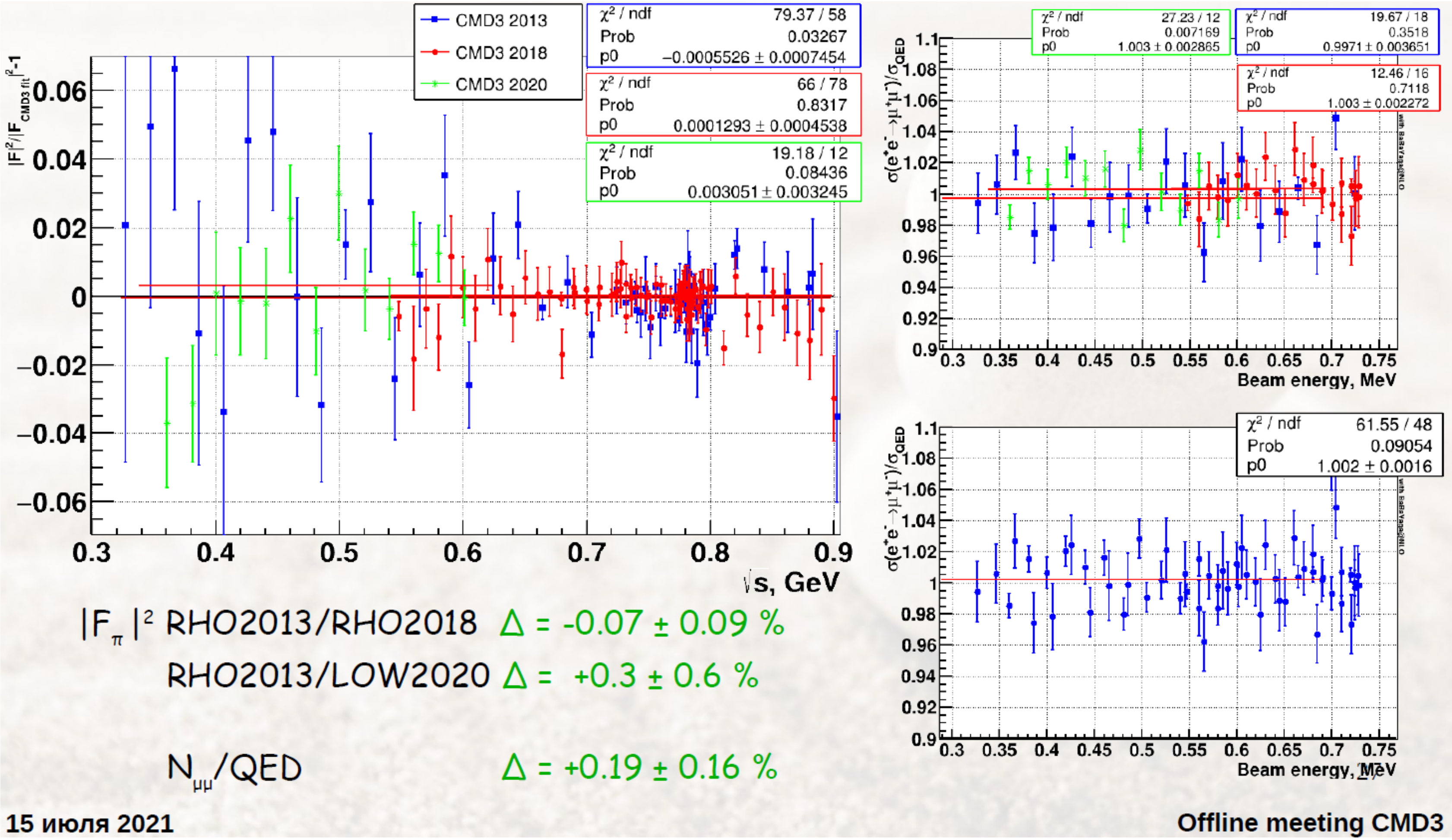
After improvements, tails of e^+e^- spectra still differ by few %,
which limits the precision to O(0.1%)

NNLO MC generator for $e^+e^- \to e^+e^-$ is needed for higher precision





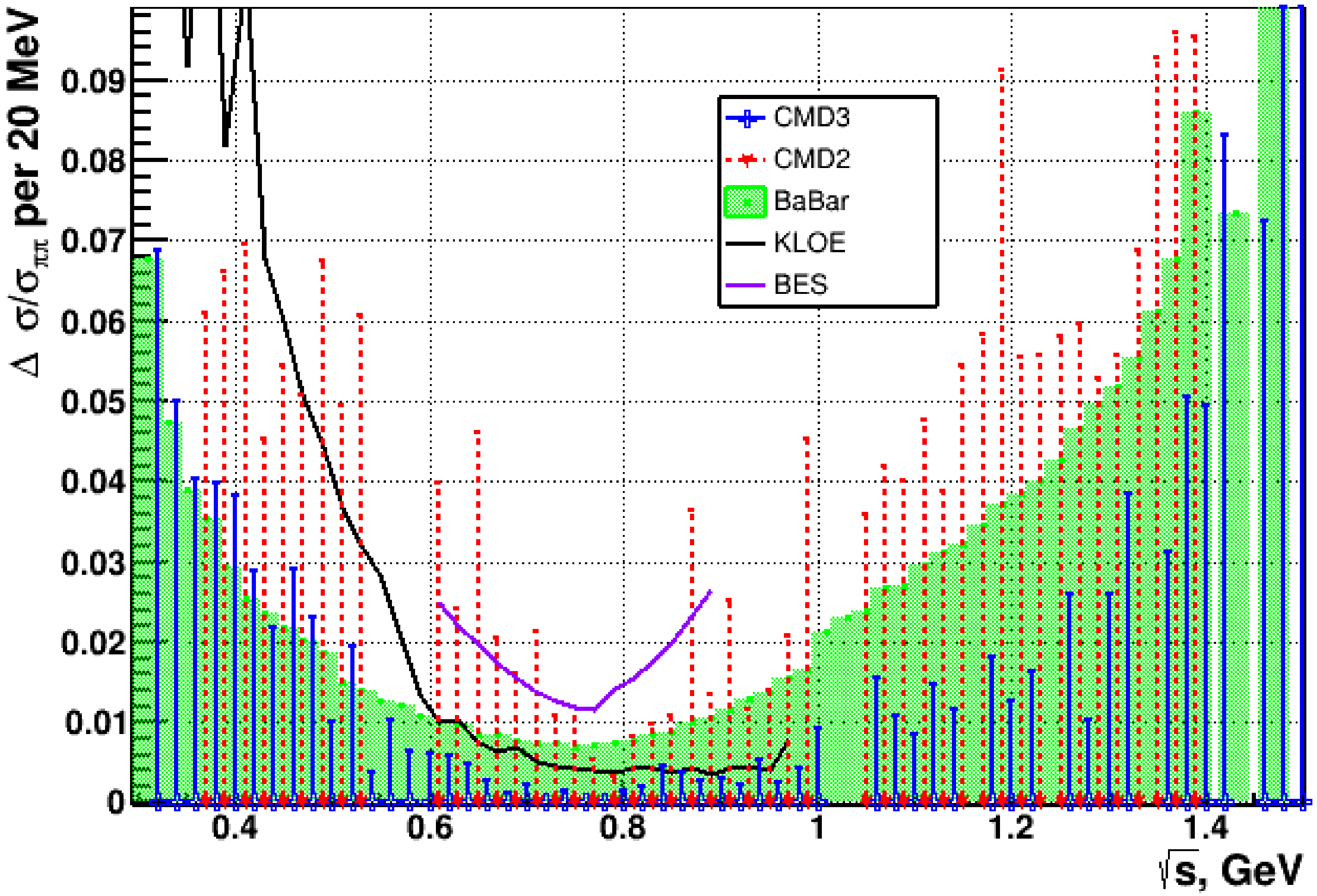
CMD-3 $e^+e^- \to \pi^+\pi^-$ analysis: internal checks



Comparison between different data sets

Comparison of measured $\sigma(e^+e^- \to \mu^+\mu^-)$ to QED

Statistical precision of CMD-3 data



Relative statistical accuracy $\Delta\sigma/\sigma$ of various data sets in 20 MeV energy bins

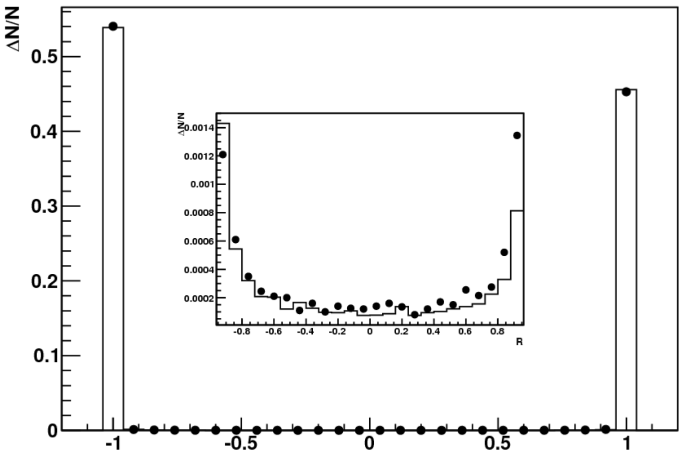
That's all I can say about CMD-3 2π analysis at the moment ☹

$e^+e^- \to \pi^+\pi^-$ at SND (2021)

First measurement of $e^+e^- \to \pi^+\pi^-$ at VEPP-2000

The analysis is based on 4.7 pb^{-1} data recorded in 2013 (1/10 full SND data set)

π/e separation using ML (BDT)



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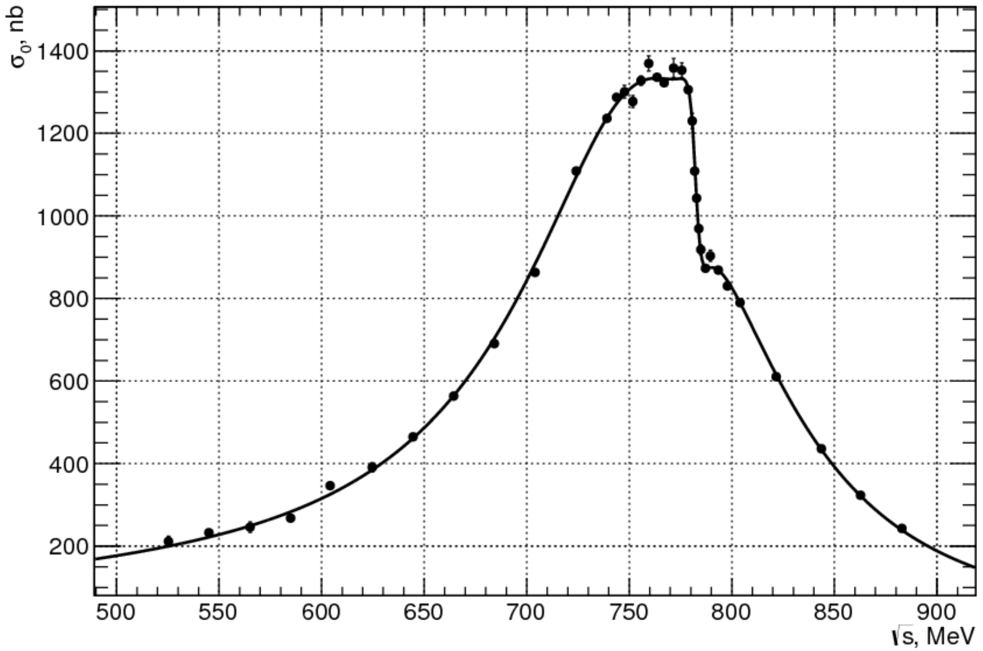
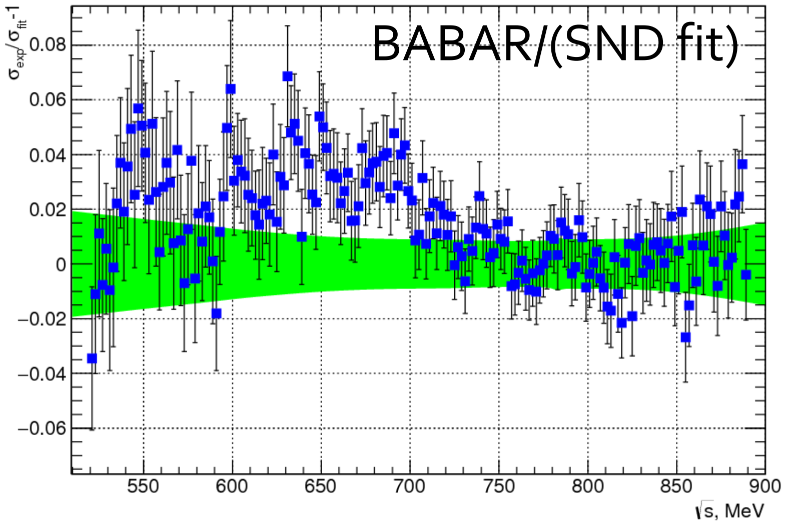
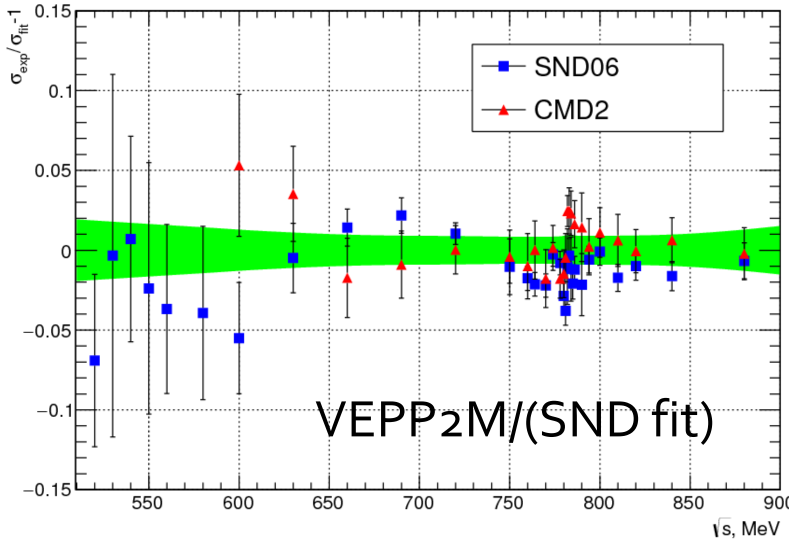


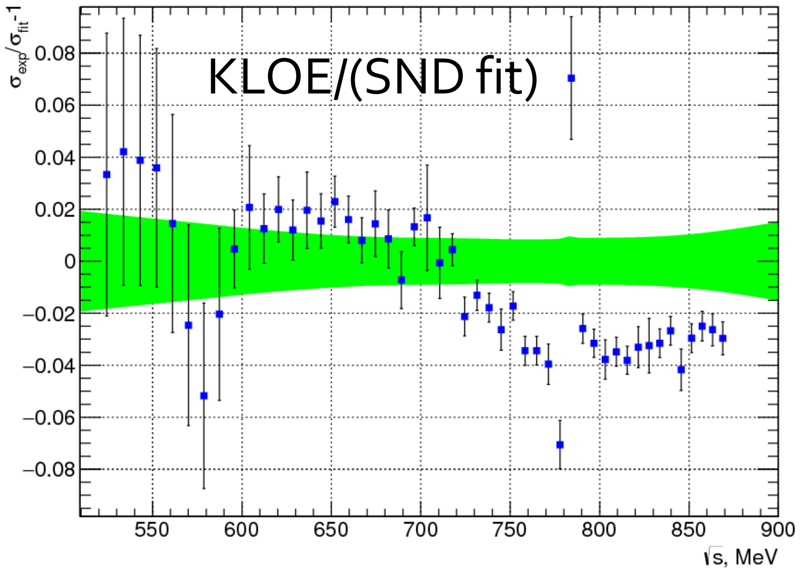
Systematic uncertainty on the cross section (%)

Source	< 0.6 GeV	0.6 - 0.9 GeV
Trigger	0.5	0.5
Selection criteria	0.6	0.6
e/π separation	0.5	0.1
Nucl. interaction	0.2	0.2
Theory	0.2	0.2
Total	**0.9**	**0.8**

$e^+e^- \to \pi^+\pi^-$ at SND (2021): comparison to other measurements







$0.53 < \sqrt{s} < 0.88$ GeV

	$a_\mu(\pi^+\pi^-) \times 10^{10}$
SND & VEPP-2000	$409.8 \pm 1.4 \pm 3.9$
SND & VEPP-2M	$406.5 \pm 1.7 \pm 5.3$
BABAR	$413.6 \pm 2.0 \pm 2.3$
KLOE	$403.4 \pm 0.7 \pm 2.5$