STATUS OF CMD-3

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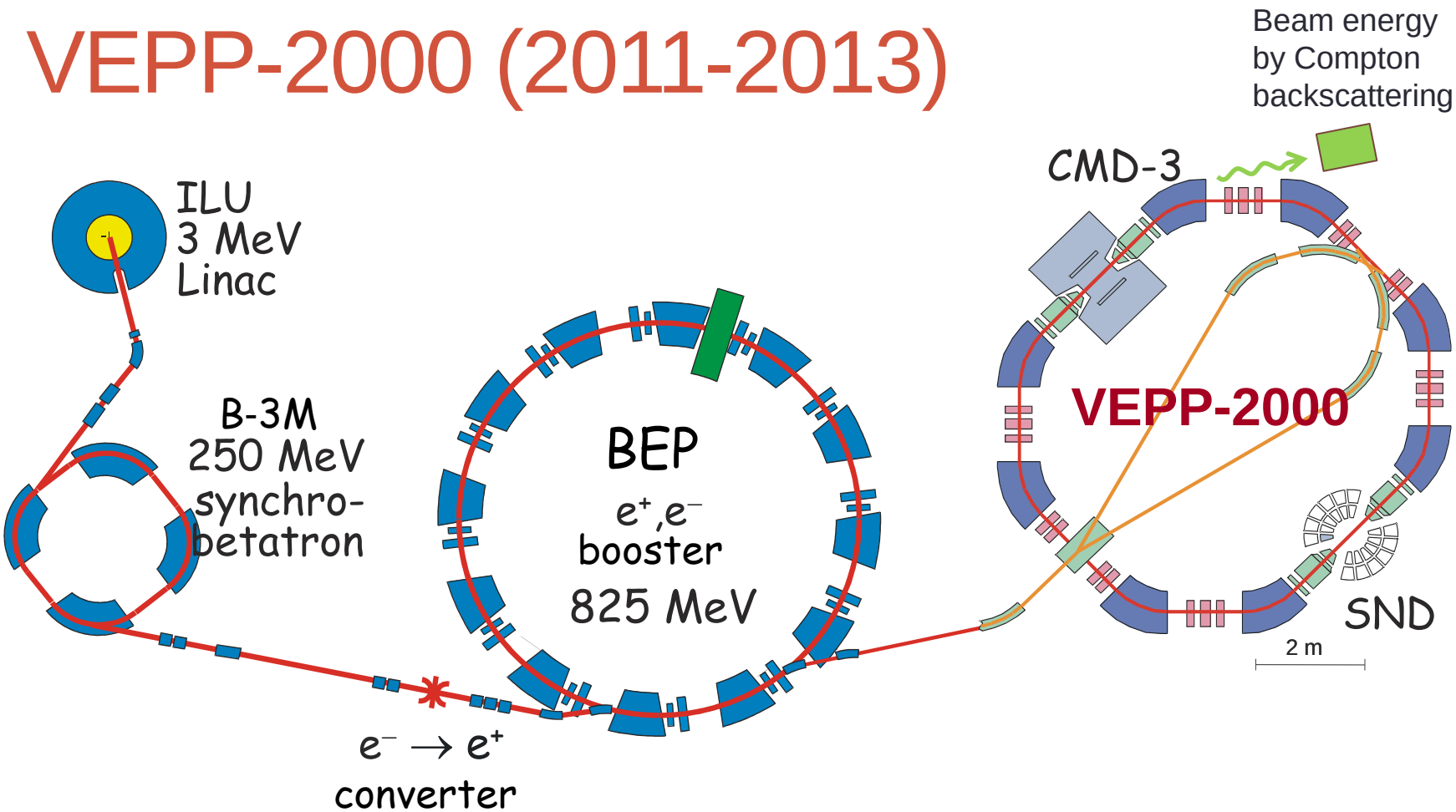
on behalf of CMD-3 collaboration

Budker Institute of Nuclear Physics
Novosibirsk State University

G-2 Theory Initiative Meeting, September 9-13, 2019

VEPP-2000 (2011-2013)



C.m. energy range is 0.32-2.0 GeV; unique optics – “round beams”

Design luminosity is $L = 10^{32} 1/cm^2 s$ @ $\sqrt{s} = 2$ GeV

Experiments with two detectors, CMD-3 and SND, started by the end of 2010

VEPP-2000 after upgrade (2017-2019)

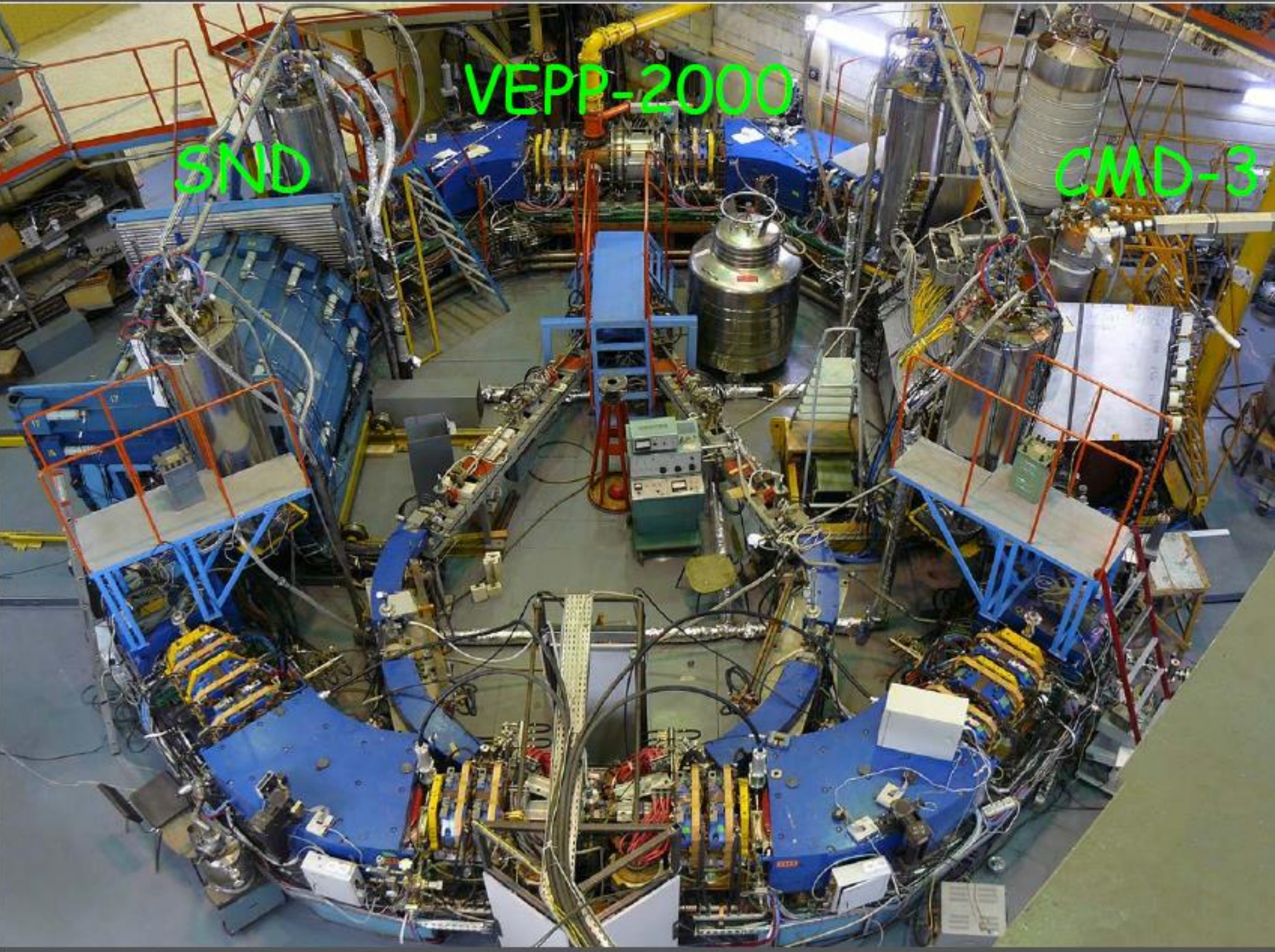
Collider upgrades:

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

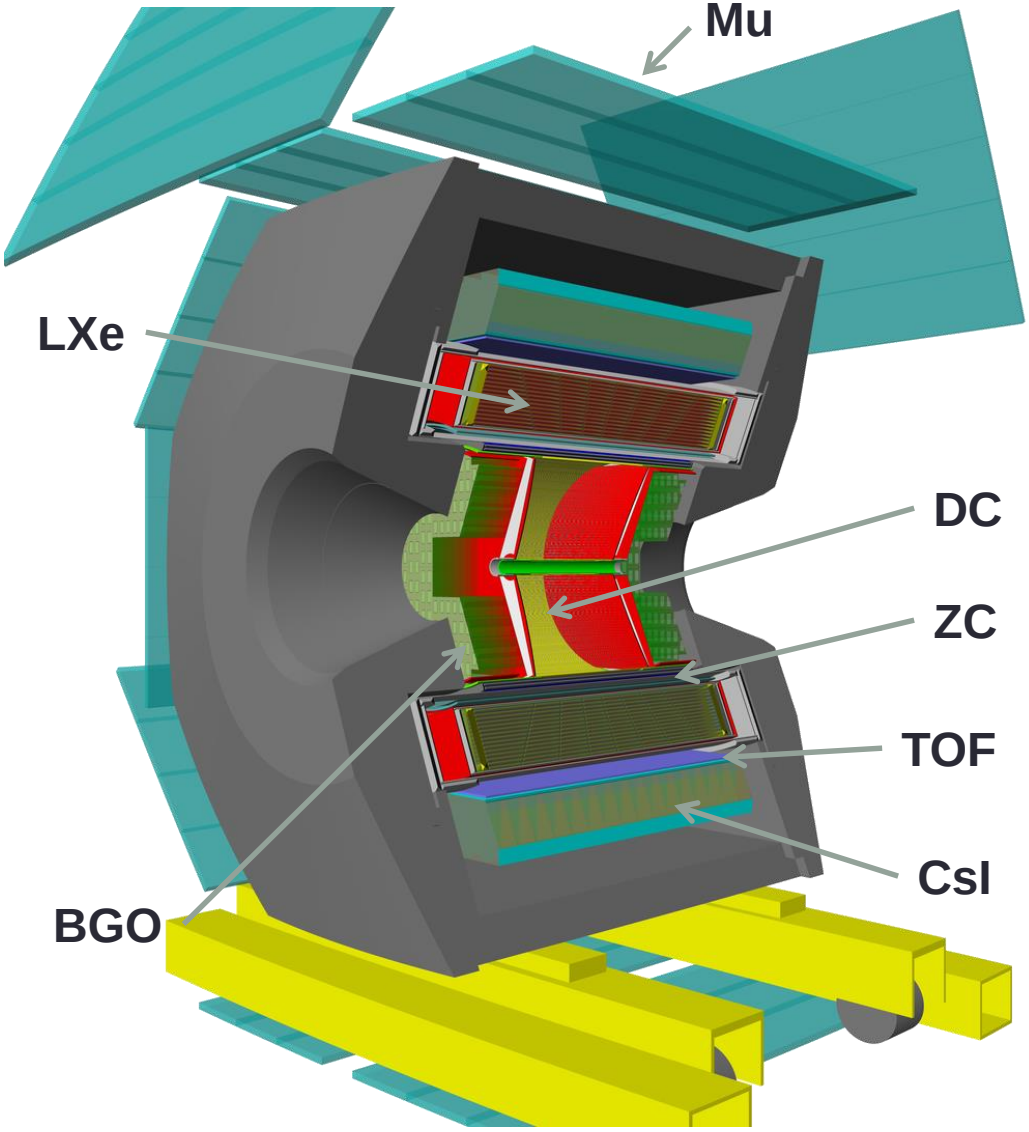
CMD-3 upgrades:

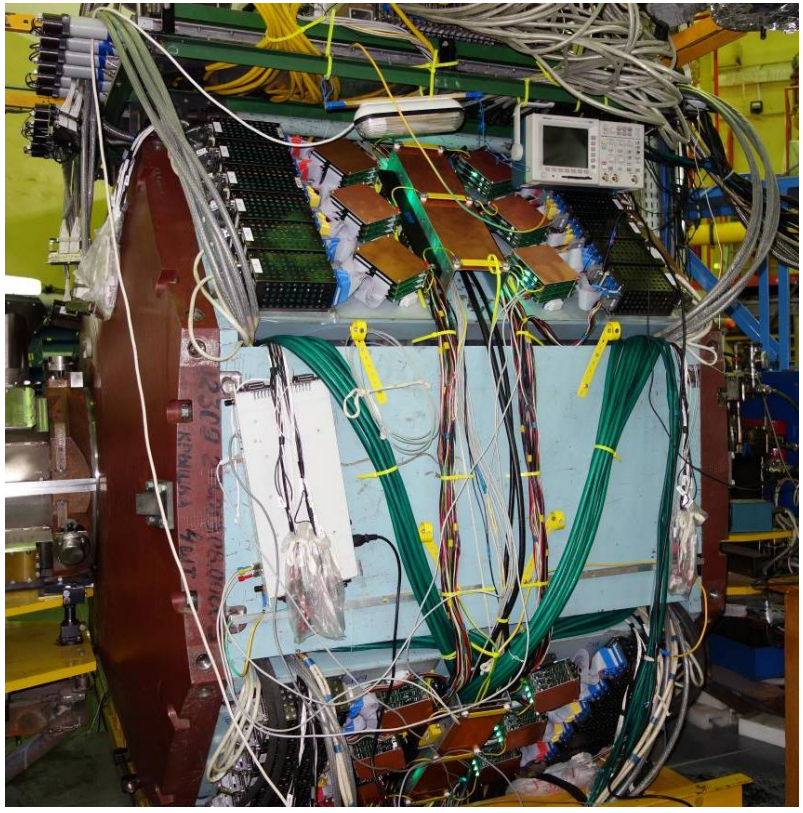
- New electronics for Lxe calorimeter
- New TOF system
- DAQ and electronics upgrades

Detectors resumed data taking by the end of 2016


VEPP-2000
SND
CMD-3

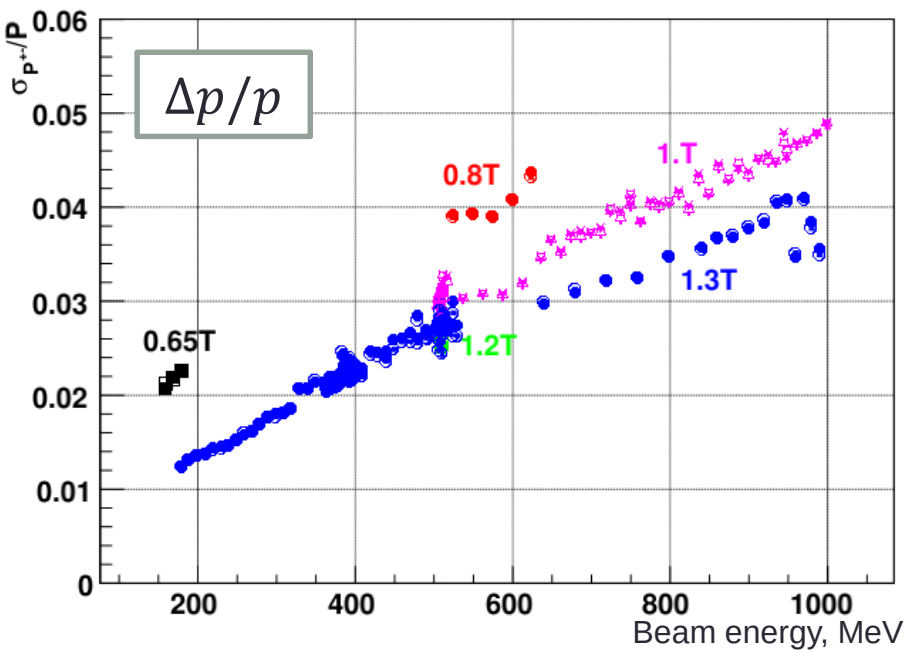
Detector CMD-3

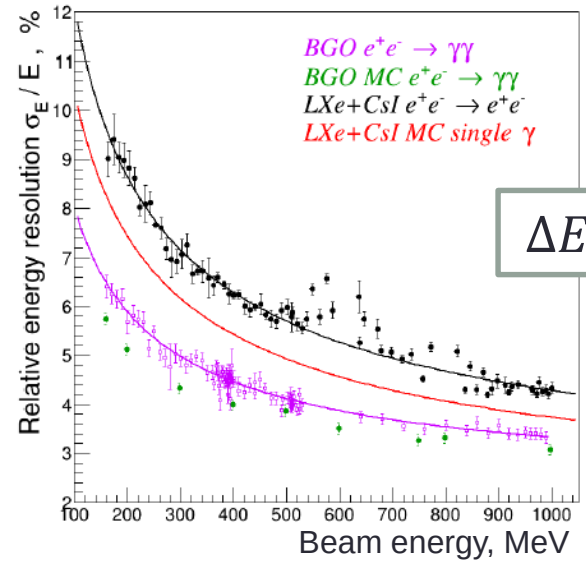


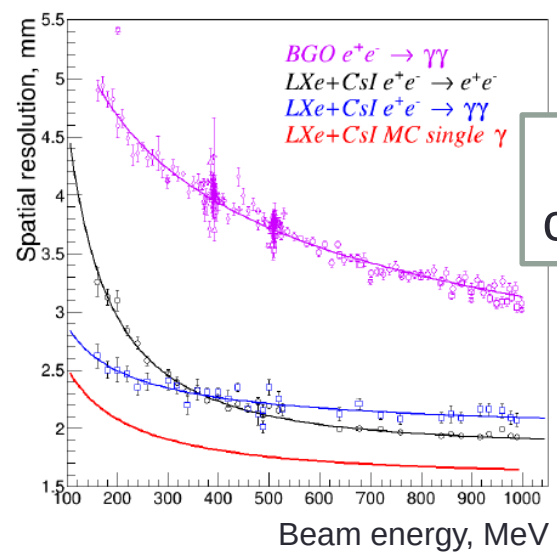


CMD-3 Performance (2011-2013)

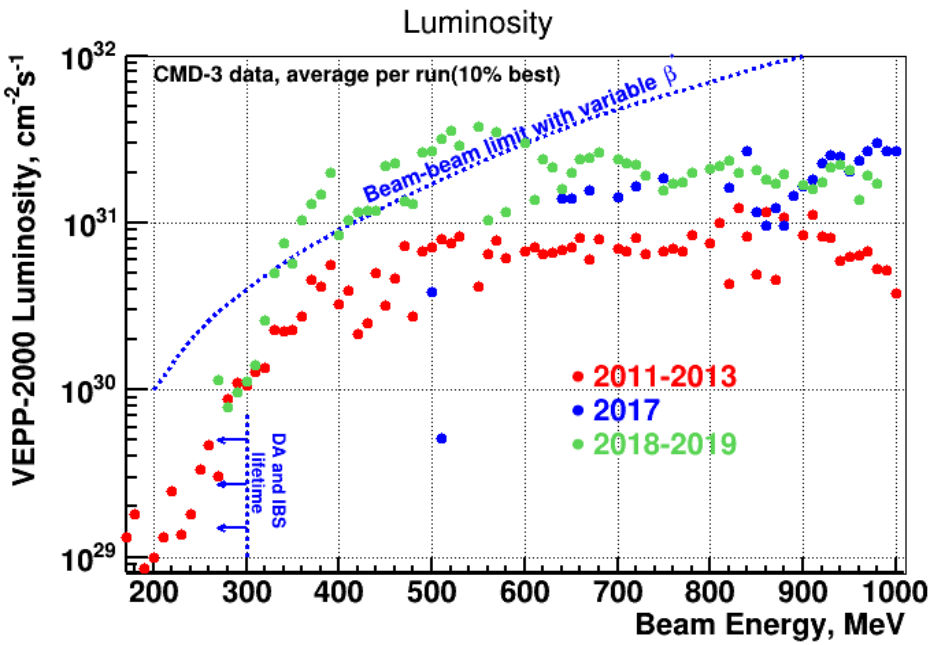
- 1.0-1.3 T magnetic field
- Tracking: $\sigma_{R\varphi} \sim 100\ \mu, \sigma_z \sim 2-3$ mm
- Combined EM calorimeter (LXE, CsI, BGO), 13.5 X_0
  - $\sigma_E/E \sim 3\% - 10\%$
  - $\sigma_\Theta \sim 5$ mrad

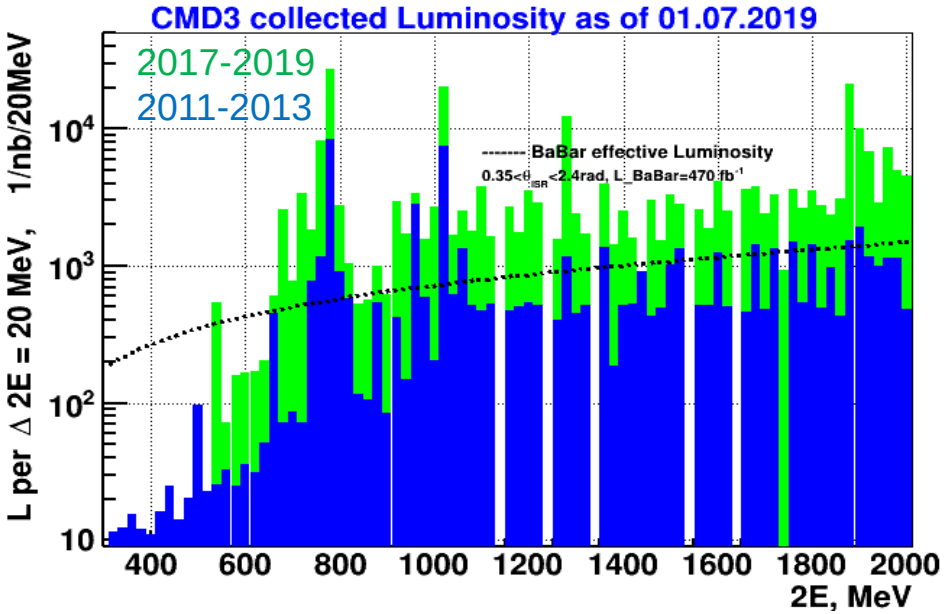






Collected luminosity





2017-2019: big improvement in luminosity, still way to go

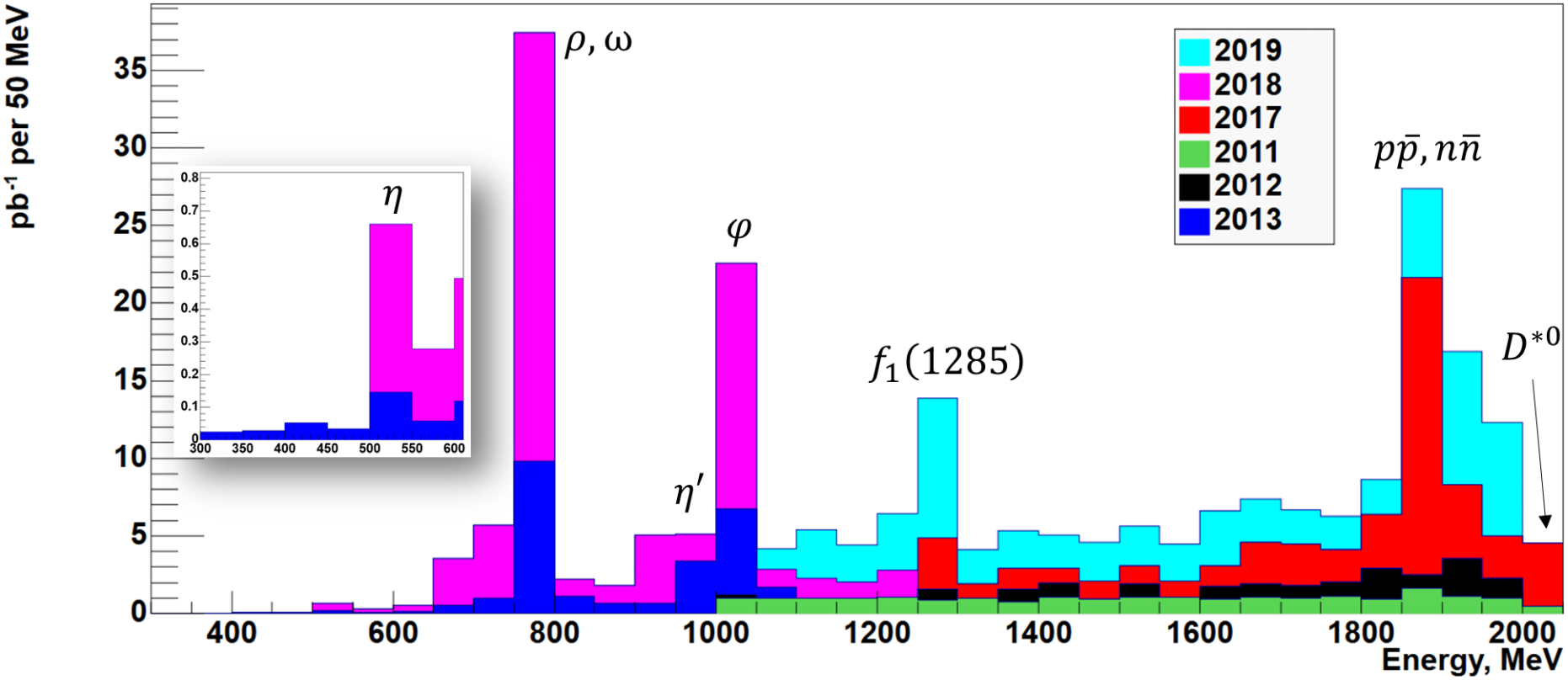
Above 1 GeV: ~180 pb^{-1} collected

$2.007\ \mathrm{GeV}\ (e^+e^- \to D^{0*})$	$4\ \ 1/pb$
$p\bar{p}$ and $n\bar{n}$ threshold	$14\ \ 1/pb$
Overall:	
$1.00 - 2.007\ \mathrm{GeV}$	$180\ \ 1/pb$

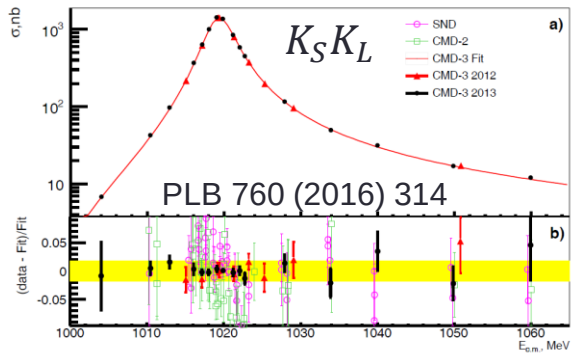
Below 1 GeV: ~60 pb^{-1} collected and counting

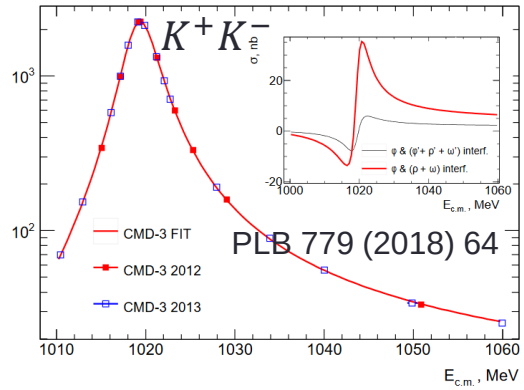
$0.32 - 1.00\ \mathrm{GeV}$	$63\ \ 1/pb$

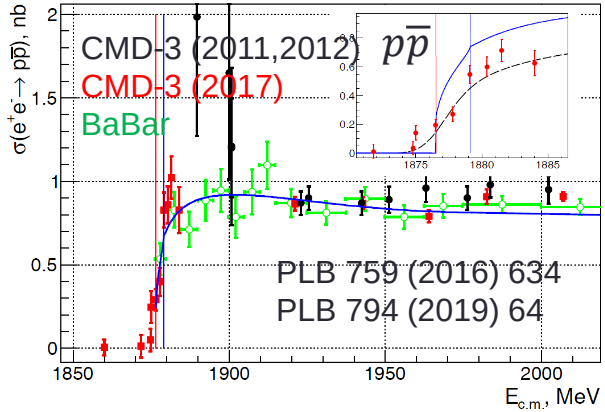
Overview of CMD-3 data

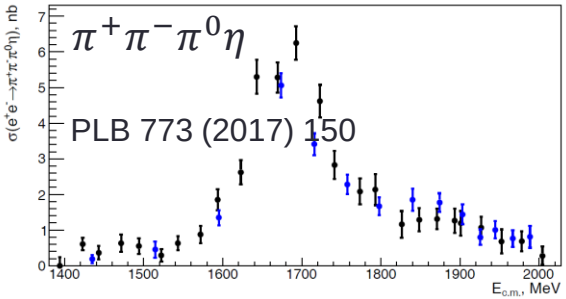


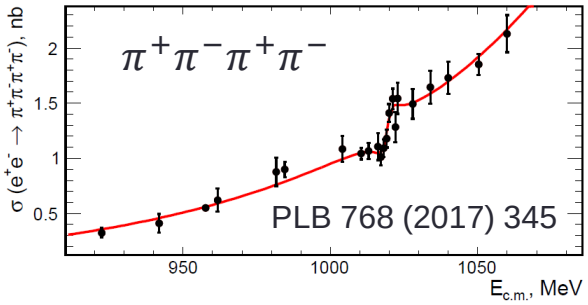
CMD-3 published results, mostly from 2011-2013

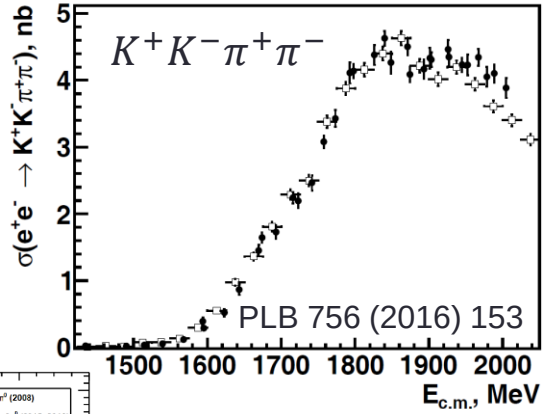


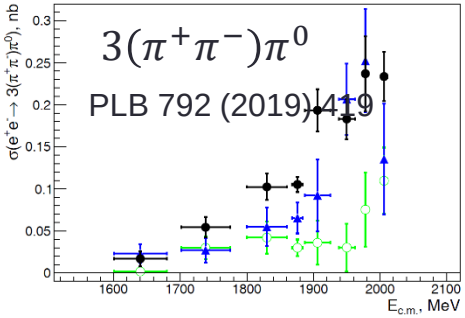


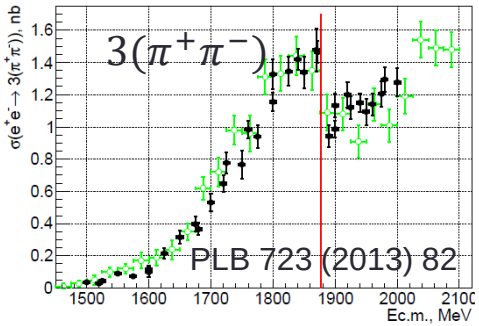


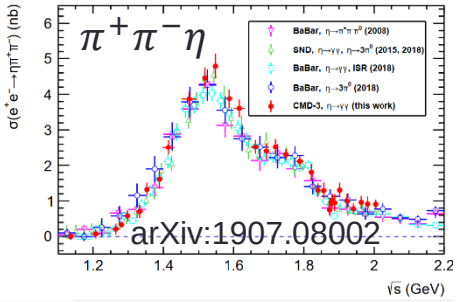


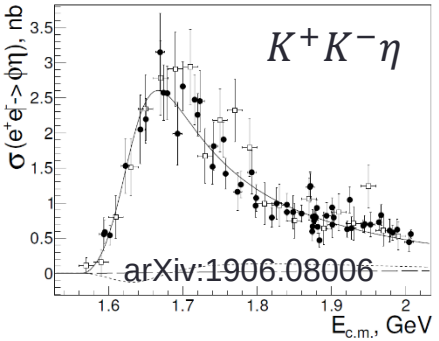






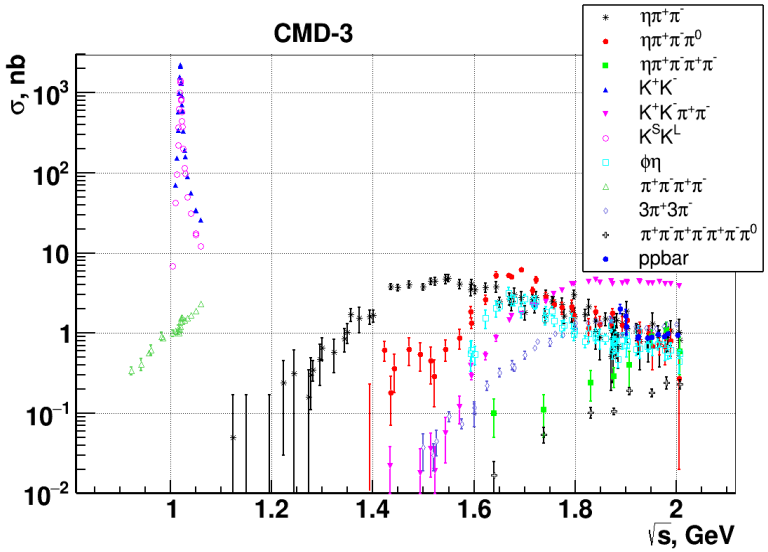


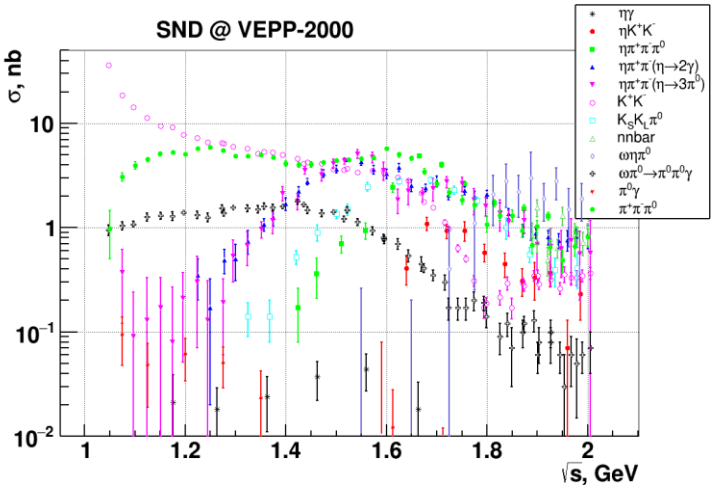




Overview was done by Simon Eidelman yesterday

Exclusive channels $e^+e^- \to hadrons$





Final states under analysis at CMD-3

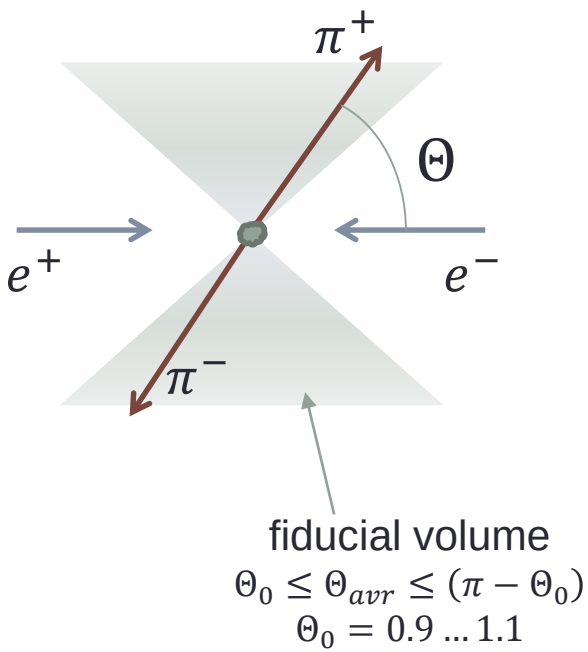
Signature	Final states (preliminary, published)
2 charged	$\pi^+\pi^-$, K^+K^-, K_SK_L, $p\bar{p}$
2 charged + γ's	$\pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-2\pi^0$, $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\eta$, $\pi^+\pi^-2\pi^0\eta$, $K^+K^-\pi^0$, $K^+K^-2\pi^0$, $K^+K^-\eta$, $K_SK_L\pi^0$, $K_SK_L\eta$
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', $D^*(2007)^0$

Overview of the $e^+e^- \to \pi^+\pi^-$ analysis

- We select events with 2 back-to-back tracks in the detector at large angle
- Selected event sample consists of $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ pairs and background (mostly cosmic)

Key pieces of analysis to reach high precision:

- $e/\mu/\pi$ separation
- radiative corrections
- various pion-specific corrections

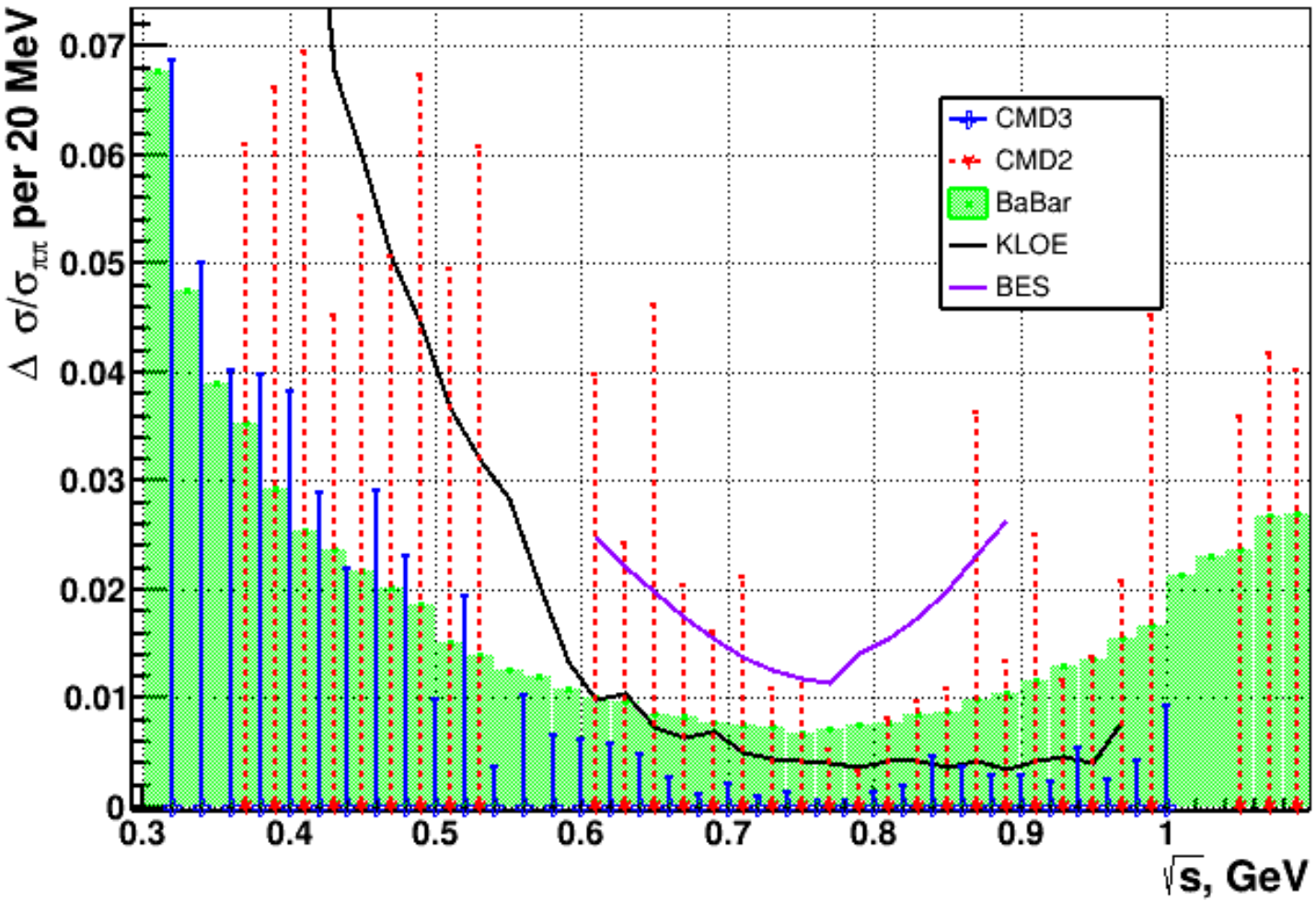


Available data:

- 0.32-1.0 GeV (below ϕ):
  - 2013 energy scan – no HV on 2 middle layers of DC
  - 2018 energy scan – few times more statistics
- 1.0-2.0 GeV (above ϕ):
  - 2011-2012 energy scan – no beam energy monitoring
  - 2017, 2019 energy scan – data analysis just started

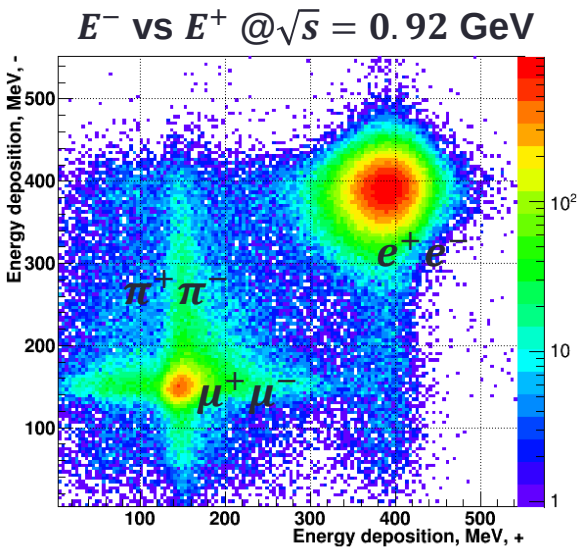
$e^+e^- \to \pi^+\pi^-$: statistics

Statistical accuracy $\Delta\sigma/\sigma$ in 20 MeV bins



Separation of $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

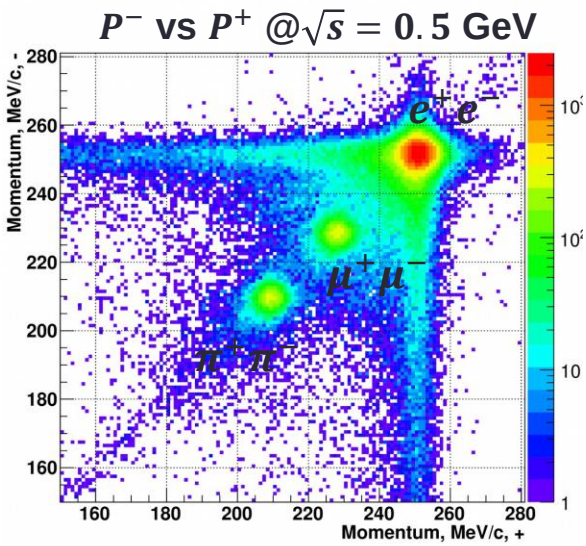
Separation of $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ final states is based on binned likelihood minimization:



- using energy deposition

prime approach at CMD-2

$$-\ln L = -\sum_{bins} n_i \ln\left[\sum_{X=ee,\mu\mu,\pi\pi,bg} N_X f_X(E^+, E^-)\right] + \sum_X N_X$$



- using momentum

prime approach at CMD-3

$$-\ln L = -\sum_{bins} n_i \ln\left[\sum_{X=ee,\mu\mu,\pi\pi,bg} N_X f_X(p^+, p^-)\right] + \sum_X N_X$$

$\pm$ sign reflects energy deposition and momentum of particle with corresponding charge

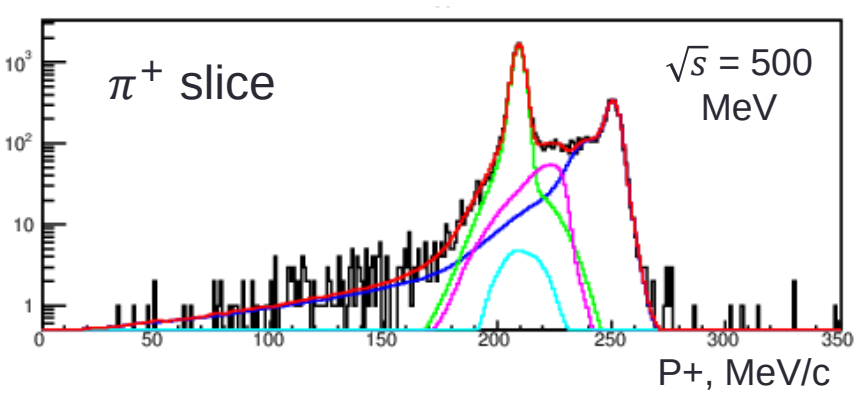
Also: working to employ machine learning and angular distribution

Where to get p.d.f.s $f_X(p^+, p^-)$ and $f_X(E^+, E^-)$?

Separation by momentum

Mostly predicted by MC

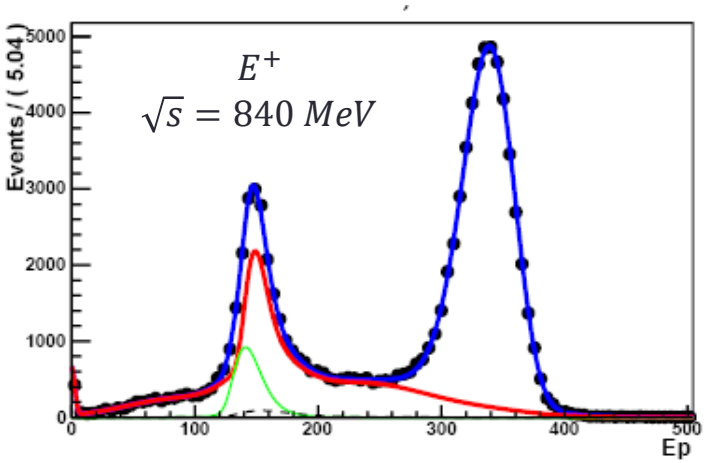
- "Ideal" p.d.f.s are generated using $e^+e^- \to X^+X^-(\gamma)$ MC generator MCGPJ
- "Ideal" p.d.f.s are smeared with detector resolution function to get $f_X(p^+, p^-)$



Separation by energy deposition

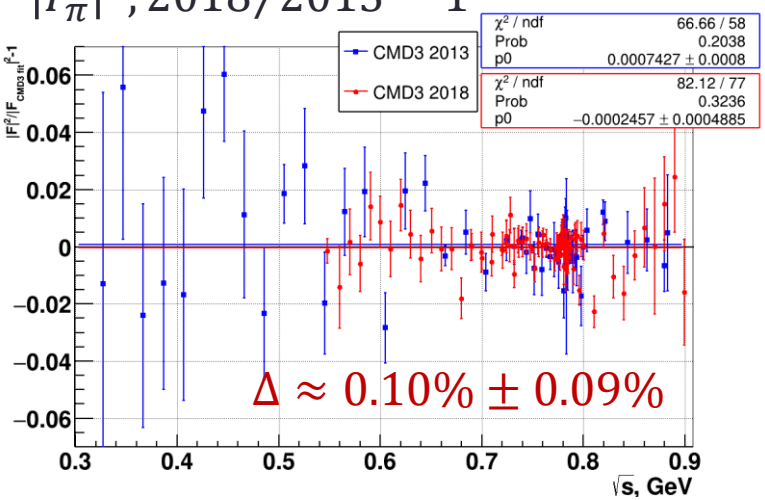
Mostly empirical

- $f_X(E^+, E^-)$ are constructed using the data:
  - tagged electrons and positrons
  - cosmic muons
  - tagged pions from $\varphi \to \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$

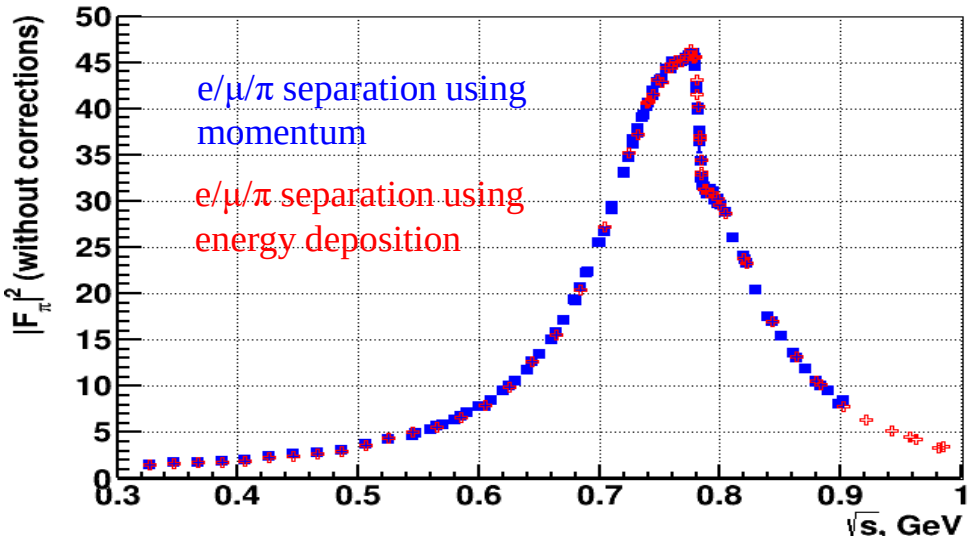


Current status

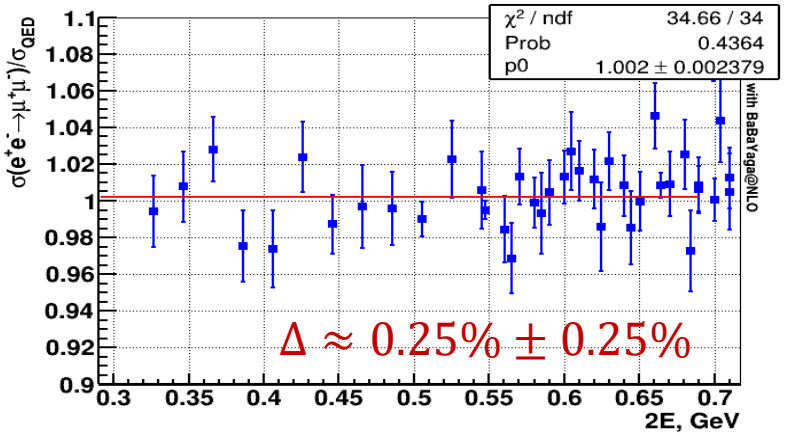
$|F_\pi|^2, 2018/2013 - 1$



$|F_\pi|^2$, "blinded" (no pion corrections)



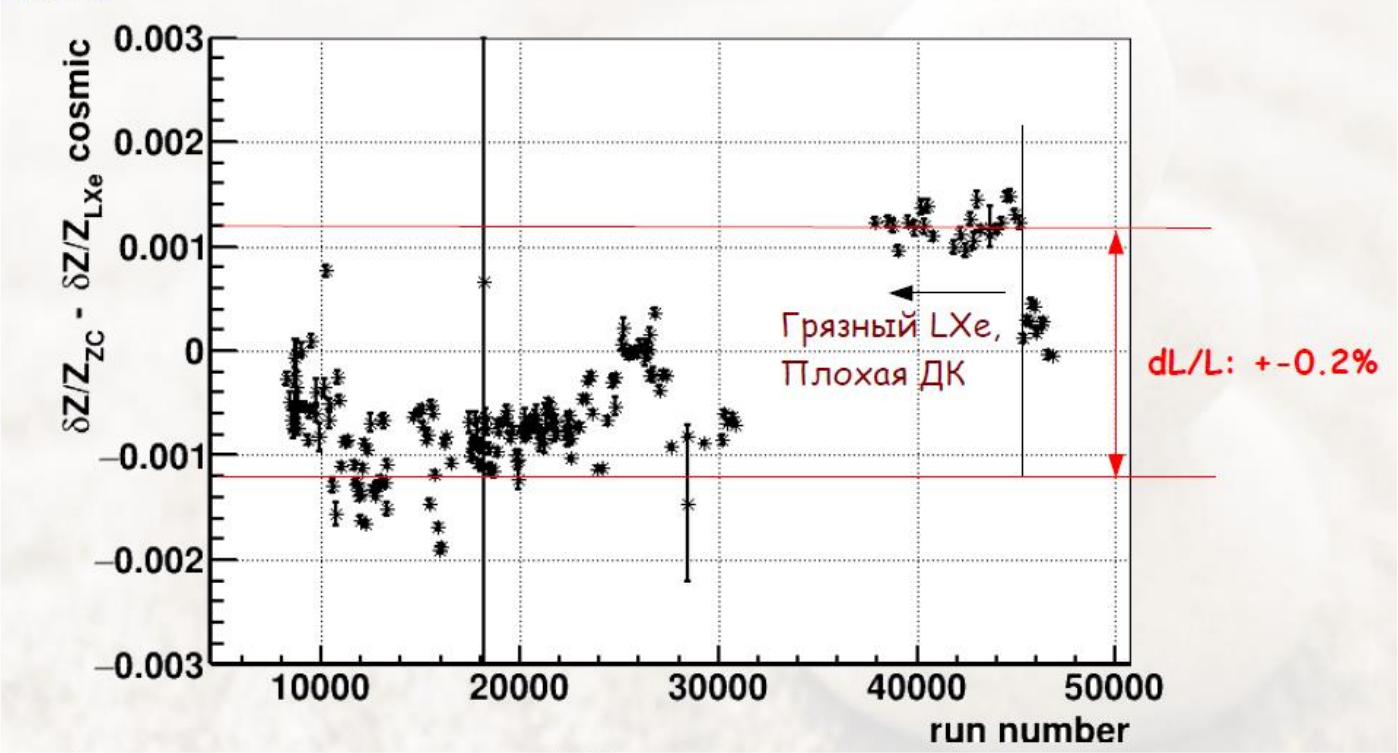
$\sigma(e^+e^- \to \mu^+\mu^-)$, exp/theory



Systematics	p-sep	E-sep
Rad.corr.	0.2%⊗(0-0.4)%	0.2%
$e/\mu/\pi$	0.6% - 0.2%(ρ) - 1.0%	O(1)%
Fiducial vol.	0.2%	
Beam energy	0.1%	
Nuclear int.	0.1%	
Pion decay	0.6% - 0.3%(ρ)	
Total	**0.9% - 0.6%(ρ) - 1.0%**	**not ready**

Fiducial volume

We have two independent systems, which can be used as the “standard ruler” for measurement of Θ of the track: Z-chamber and LXE-calorimeter.



Many internal checks: LXE vs Z, Z layer 1 vs layer 2, Bhabha vs cosmics,…
Systematical error due to fiducial volume <0.2%

Radiative corrections: unexpected surprise

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

Several MC generators available with 0.1-0.5% precision.

CMD-3: MCGPJ generator

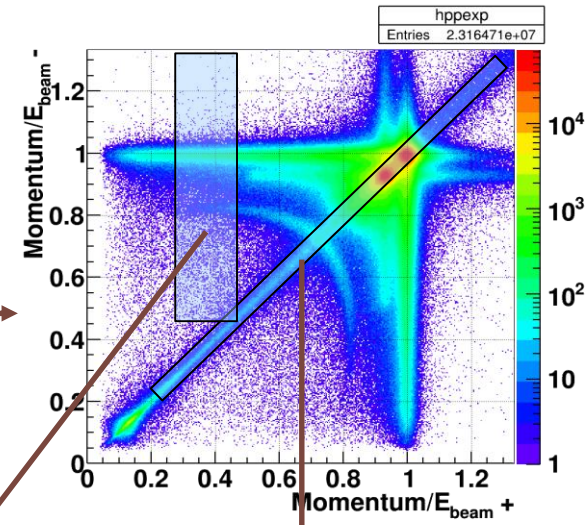
With high statistics we observed discrepancies in tails of e^+e^- experimental spectrum with theoretical prediction.

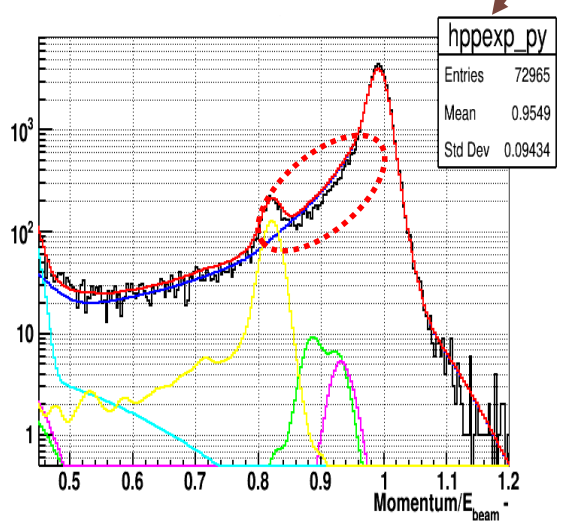
The corresponding changes in p.d.f.s $f_{ee}(p^+, p^-)$ produce percent-level systematic shift of $N(\pi^+\pi^-)$ for event separation by P

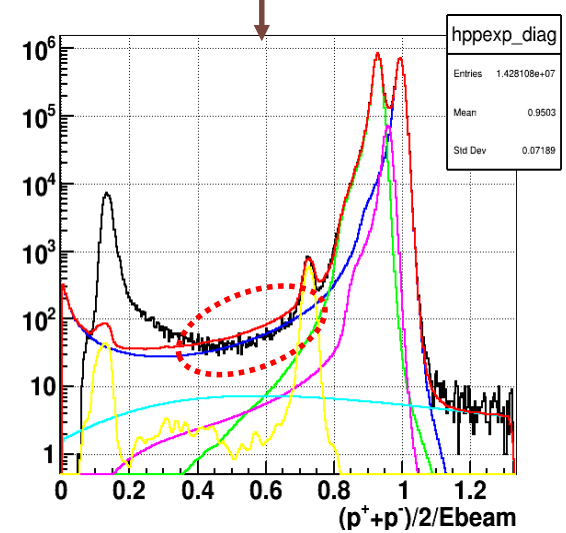
- For the integral (radiative correction) the effect is negligible

$$\frac{P^-}{E_b} \text{ vs } \frac{P^+}{E_b}$$

All 2013 data
$2 \cdot 10^7$ events







Radiative corrections: modified MCGPJ

The source of the problem is well understood:

- angular distribution of γ's in photon jets

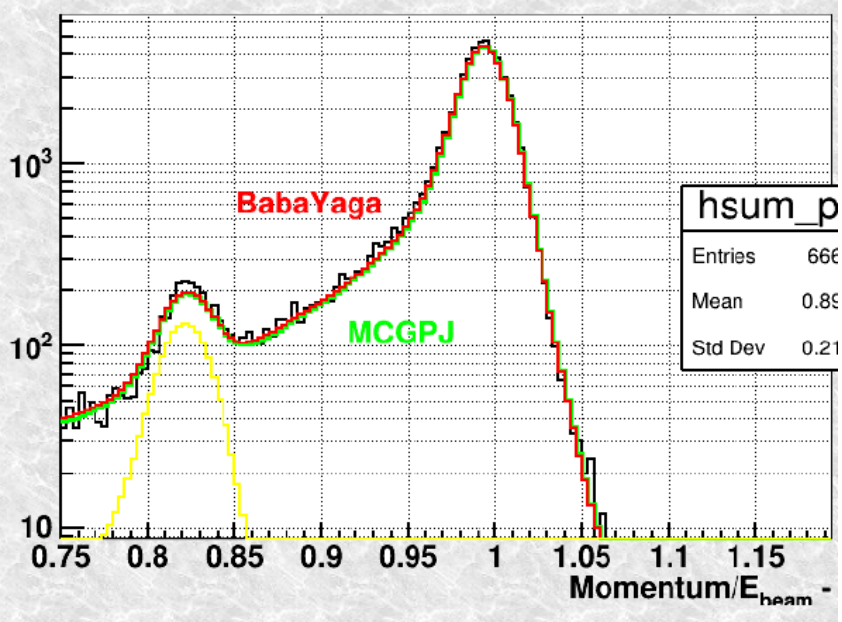
MCGPJ has been modified to include missing angular distribution

The modified MCGPJ shows factor x10 better agreement to the data

There are local discrepancies between modified MCGPJ and BabaYaga@NLO at 10% level (was x3)

Leads to cross-section systematical shift of (0-0.4)% for momentum-based separation

For precision <0.1% we need $e^+e^- \to e^+e^-(\gamma\gamma)$ NNLO generator

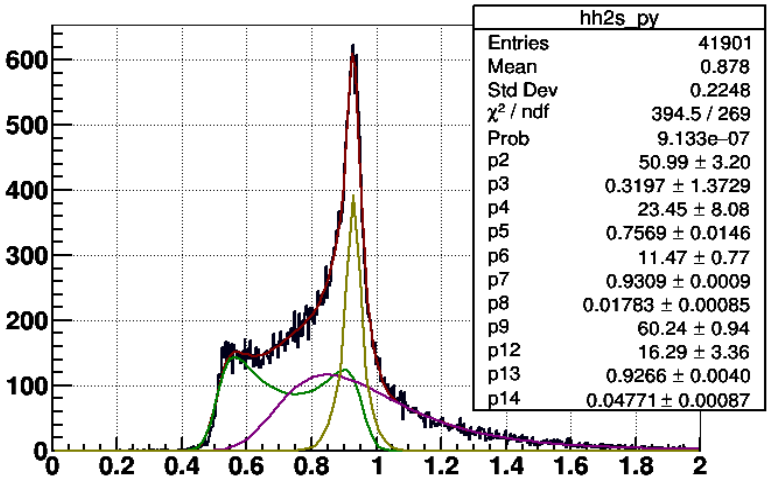


Pion decays in flight

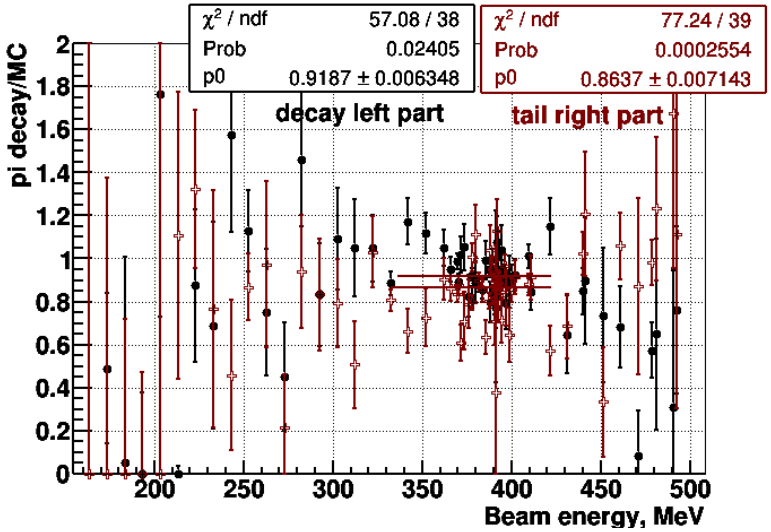
About 3% of pions decay in flight at ρ, some of them pass selection criteria.

We know the cuts efficiencies for decay events to ~10% →
systematic error of 0.6% at lowest energies, 0.3% at ρ

Spectrum of decay “pions”



Data vs simulation

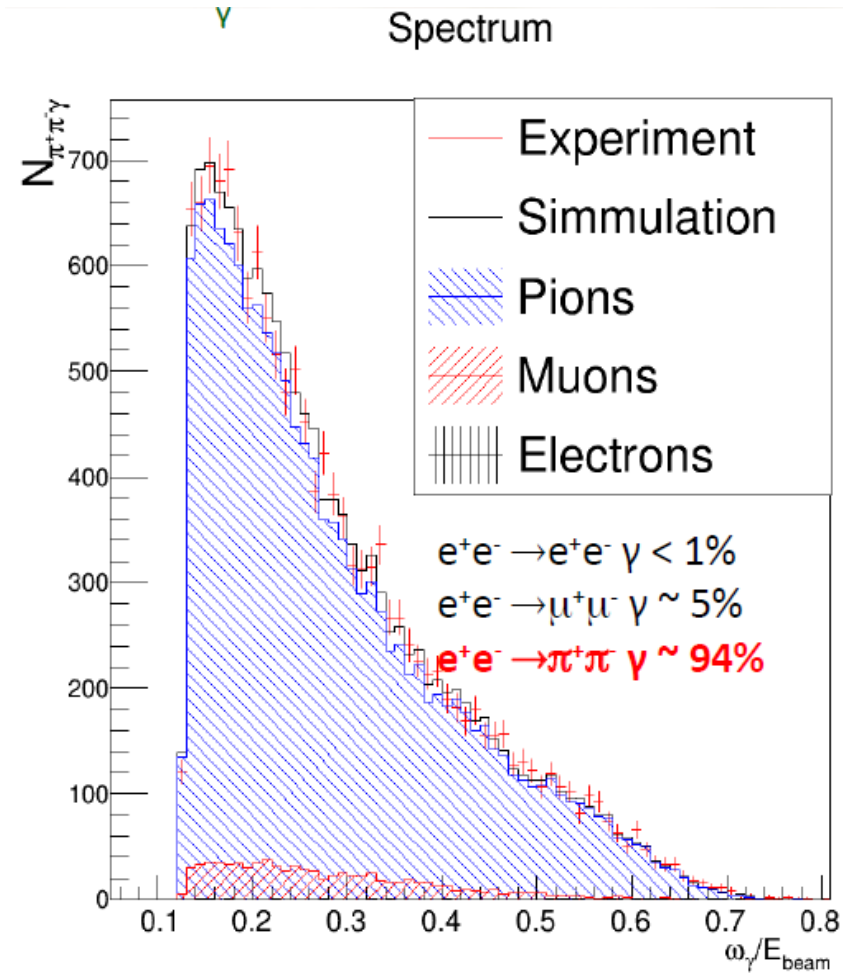


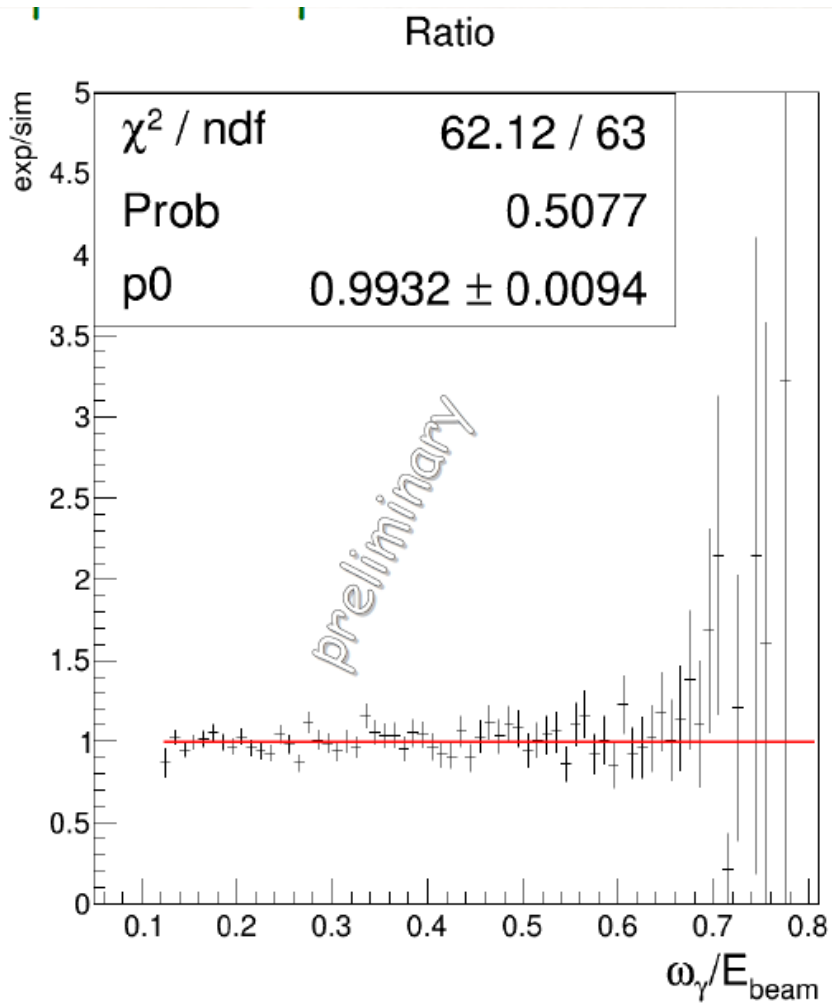
The number of decay events can be independently measured with fit of momentum distribution

We are working on more detailed DC simulation to improve agreement of data vs simulation. Factor of 2 improvement would be enough.

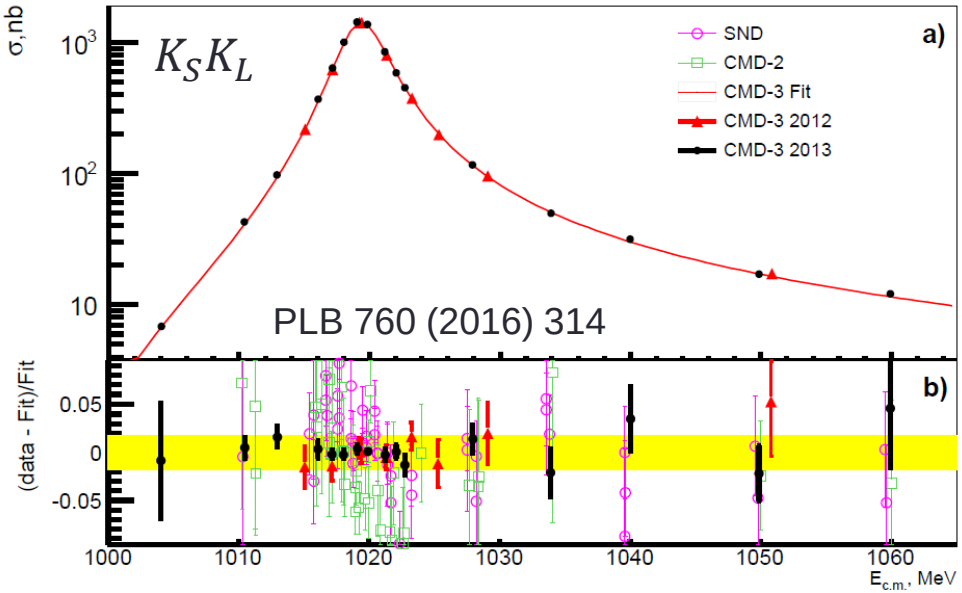
$e^+e^- \to \pi^+\pi^-\gamma$

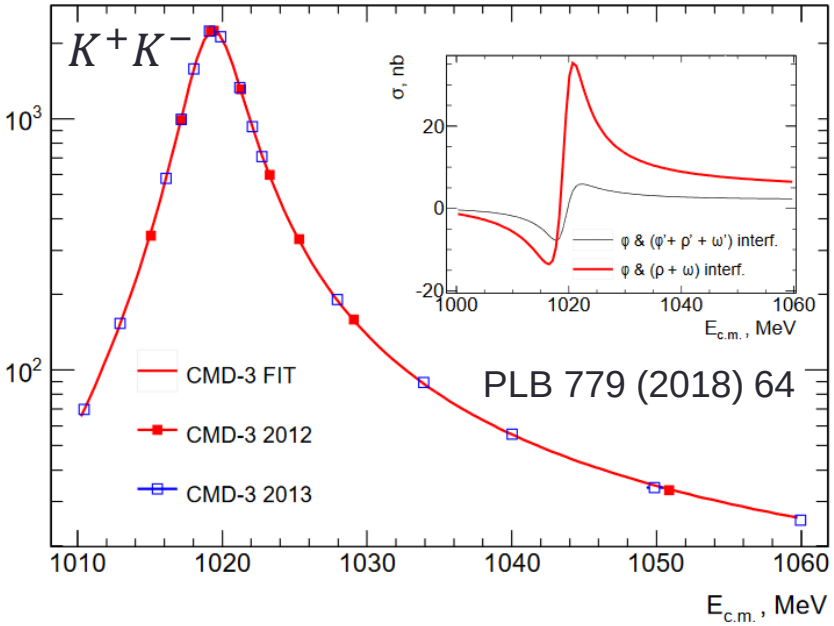
Comparison of measured and calculated γ energy spectrum for $\pi\pi\gamma$ events





$K_S K_L$ and K^+K^- @$\varphi(1020)$

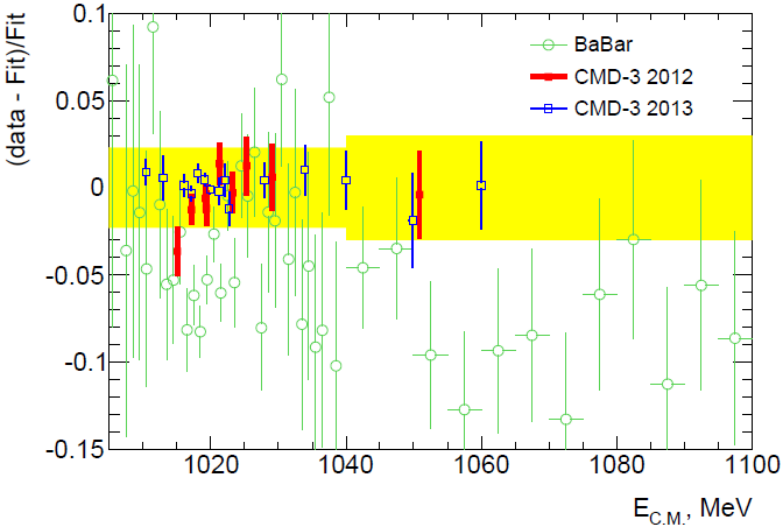


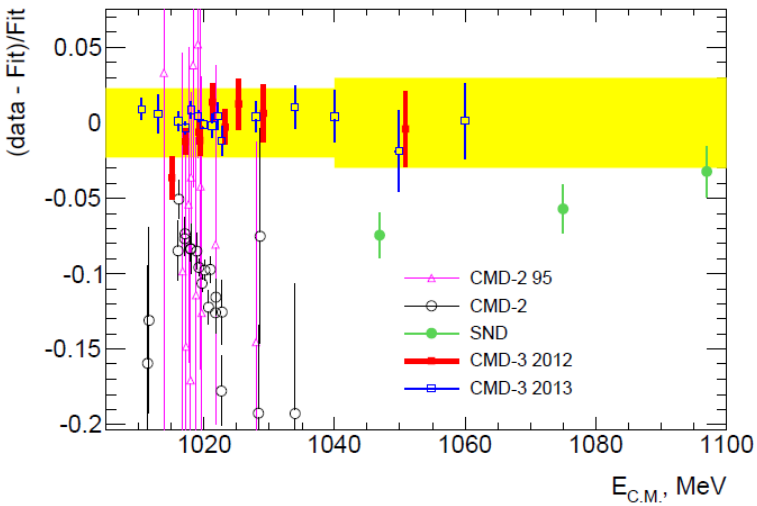


Recent result from CMD-3:

- $K_S K_L$ at φ, systematic precision 1.8%
- K^+K^- at φ, systematic precision 2.0% (2.8%)

K^+K^-: comparison with other measurements





$K_S K_L$ at φ is consistent between different experiments, but there is discrepancy in K^+K^- channel.

New CMD-3 K^+K^- cross-section is above CMD-2 and BaBar, but is consistent with isospin symmetry:

$$R = \frac{g_{\varphi K^+K^-}}{g_{\varphi K_S K_L}\sqrt{Z(m_\varphi)}} = 0.990 \pm 0.017$$

- $R_{SND} = 0.92 \pm 0.03 (2.6\sigma)$
- $R_{CMD-2} = 0.943 \pm 0.013 (4.4\sigma)$
- $R_{BaBar} = 0.972 \pm 0.017 (1.5\sigma)$

$K_S K_L$ and K^+K^-: $\rho - \varphi$ interference

$\rho - \varphi$ interference can be directly observed:

$$R_{c/n} = \sigma(e^+e^- \to K^+K^-) \times \frac{p^3_{K^0}(s)}{p^3_{K^\pm}(s)} \times \frac{1}{Z(s)} - \delta \times \sigma(e^+e^- \to K_S K_L)$$

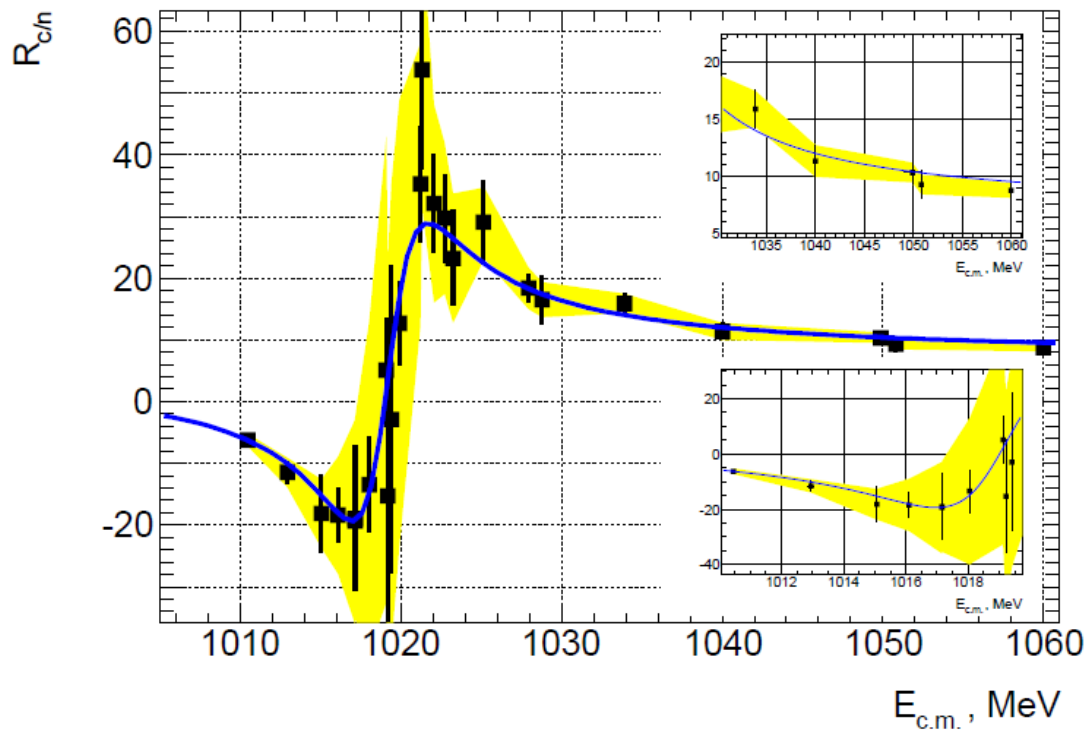
- $r_{\rho,\omega} = 0.91 \pm 0.04$

  deviation of SU(3) relations

  $g_{\omega K^+K^-} = g_{\rho K^+K^-} = -g_{\varphi K^+K^-}/\sqrt{2}$

- $\delta = 0.989 \pm 0.003$

  test of systematic errors



$R(s)$ at $N\bar{N}$ threshold

VEPP-2000: unique ability for detailed scan of $p\bar{p}$ and $n\bar{n}$ threshold.

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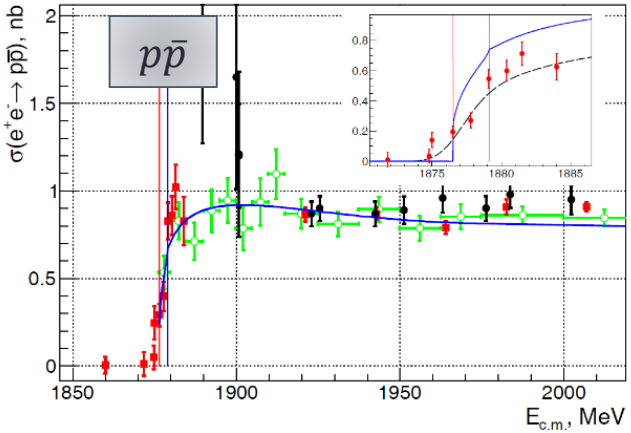
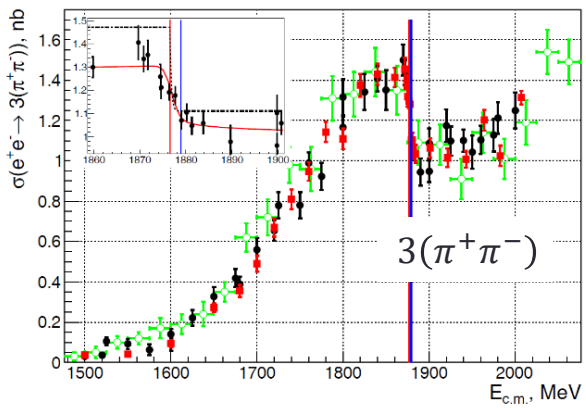
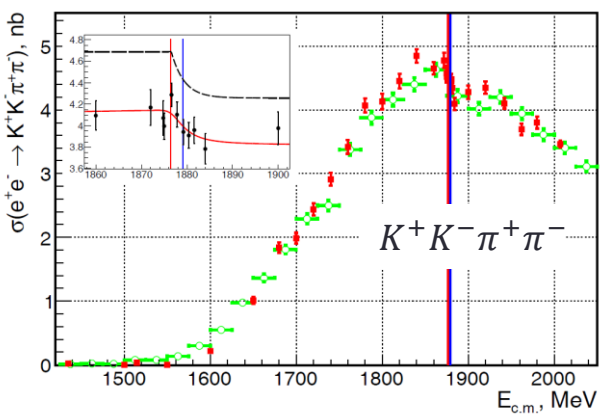
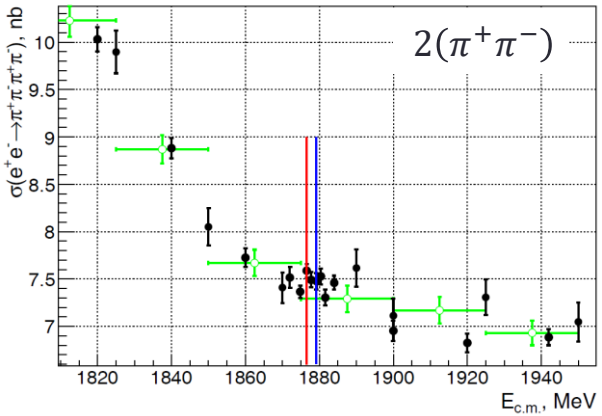






- observed the sharp change of $e^+e^- \to p\bar{p}$, $3(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$
- width is ~1 MeV – consistent with energy resolution
- puzzle – why there is no change in $e^+e^- \to 2(\pi^+\pi^-)$?

Plan to do comprehensive study of this energy range.



Conclusion

- CMD-3 has collected 250 1/pb in the whole energy range $0.32 \leq \sqrt{s} \leq 2.0$ GeV, available at VEPP-2000, with the goal to collect total of 0.5-1 1/fb
- Data analysis of exclusive modes of $e^+e^- \to hadrons$ is in progress. Many results have been published.
- The analysis of $e^+e^- \to \pi^+\pi^-$ is at the final stages