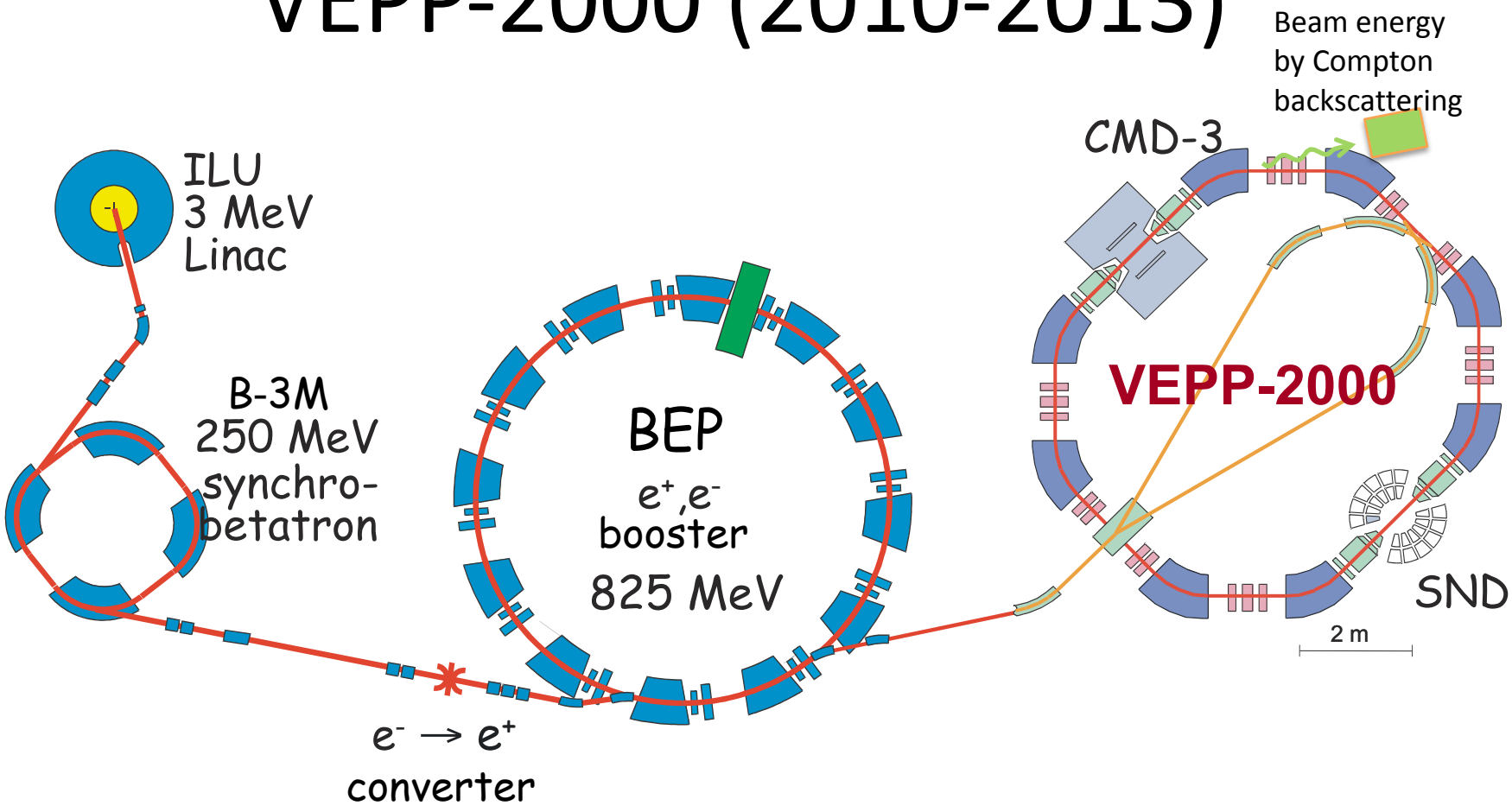
e^+e^- -> ppbar, nnbar, multihadrons at the NNbar threshold with VEPP-2000

E.Solodov

CMD-3 Collaboration

VEPP-2000 (2010-2013)



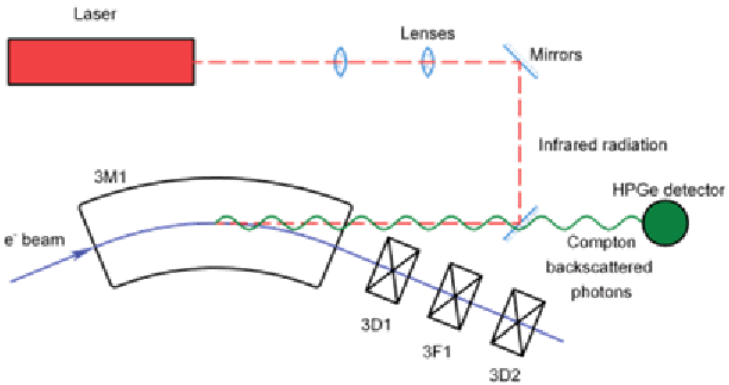
C.m. energy range is 0.32-2.0 GeV; unique optics – "round beams"

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

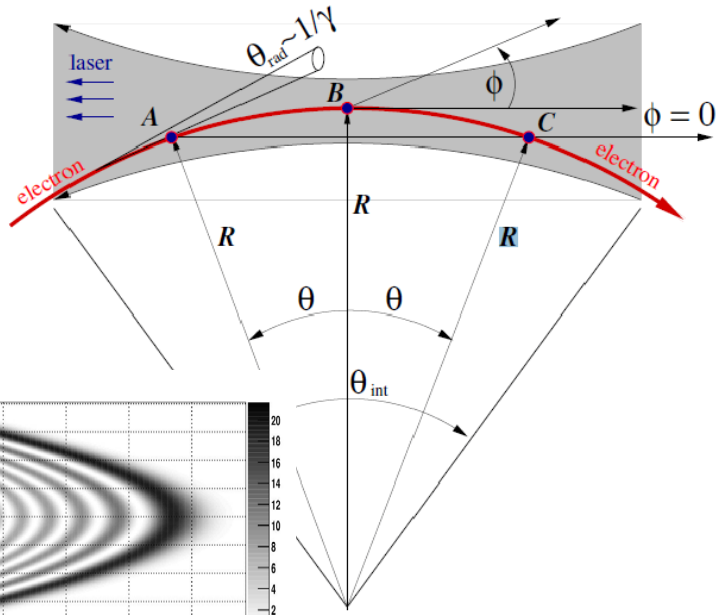
Experiments with two detectors, CMD-3 and SND, started by the end of 2010

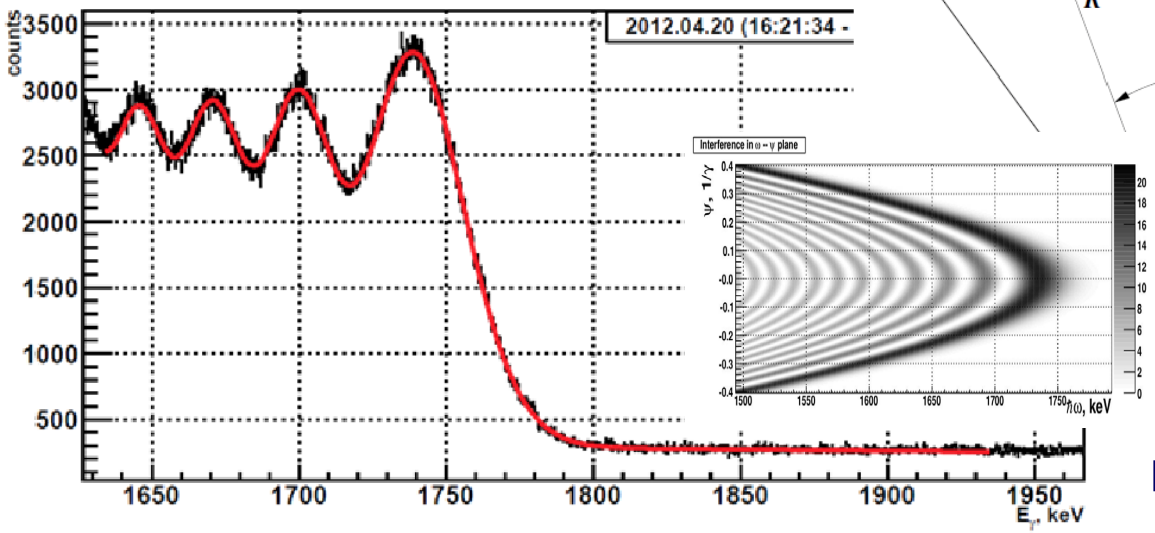
Energy measurement

Starting from 2012, energy is monitored continuously using Compton backscattering



Light from A and B interferes

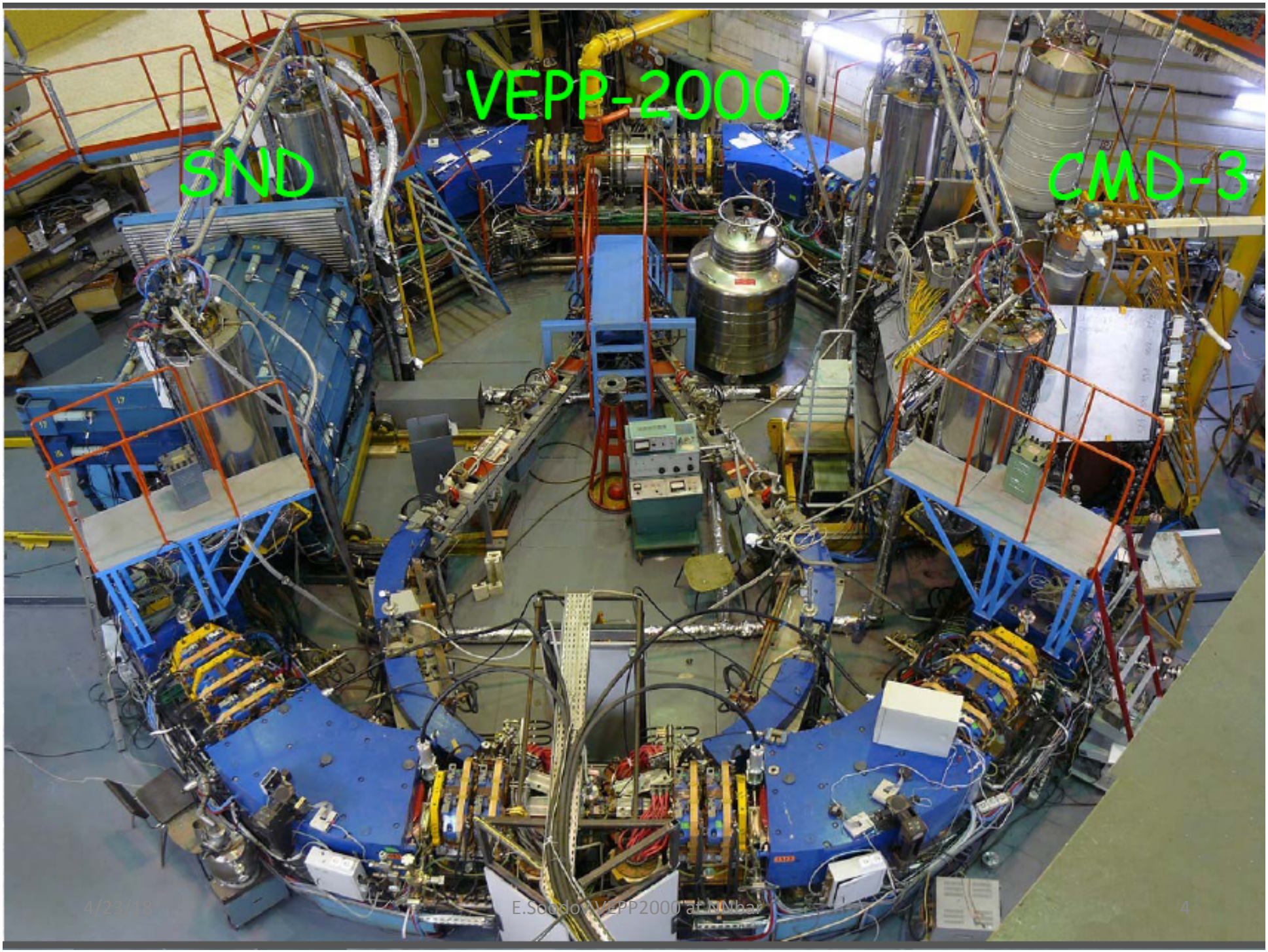




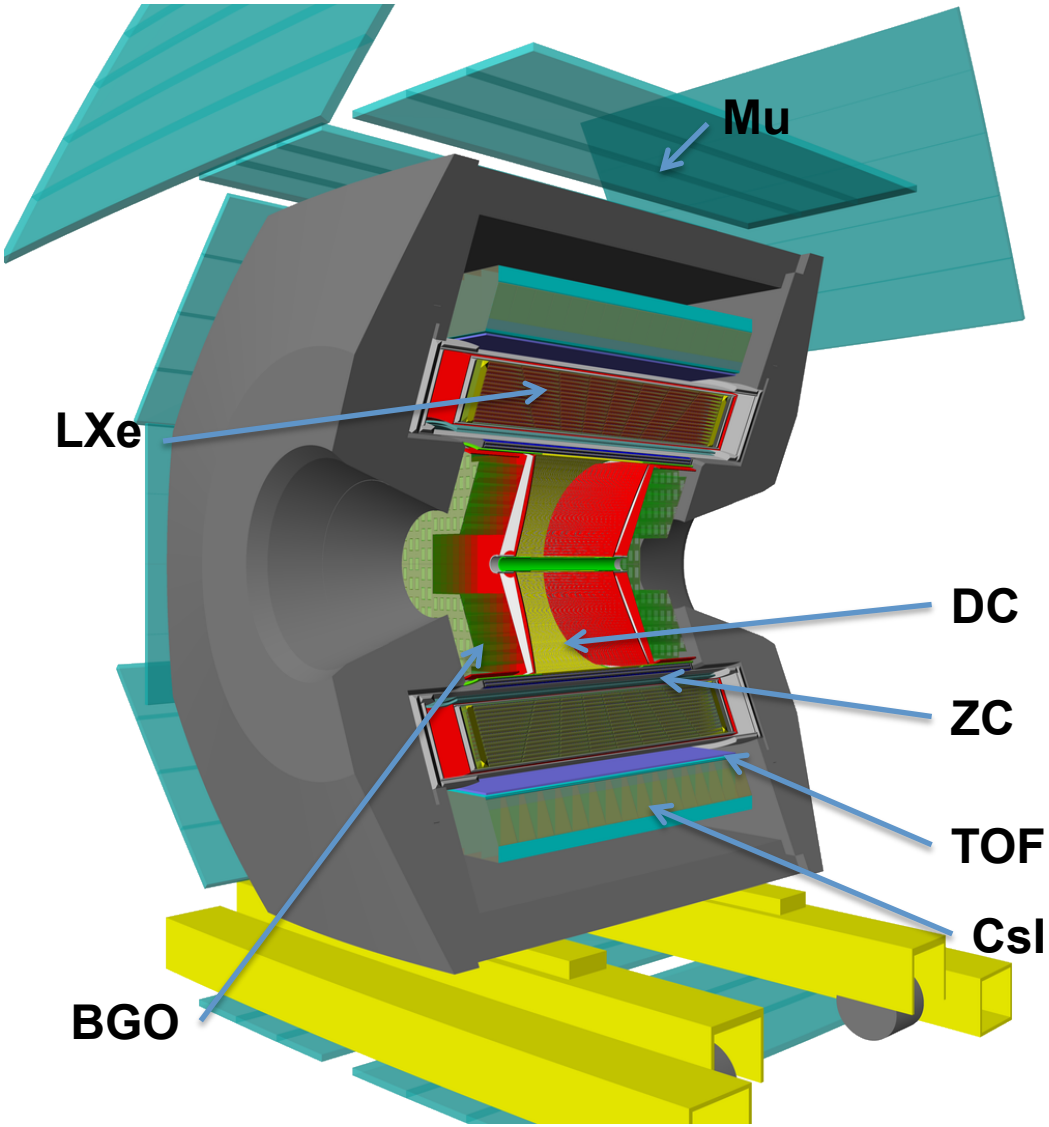
E = 993.662 ± 0.016 МэВ

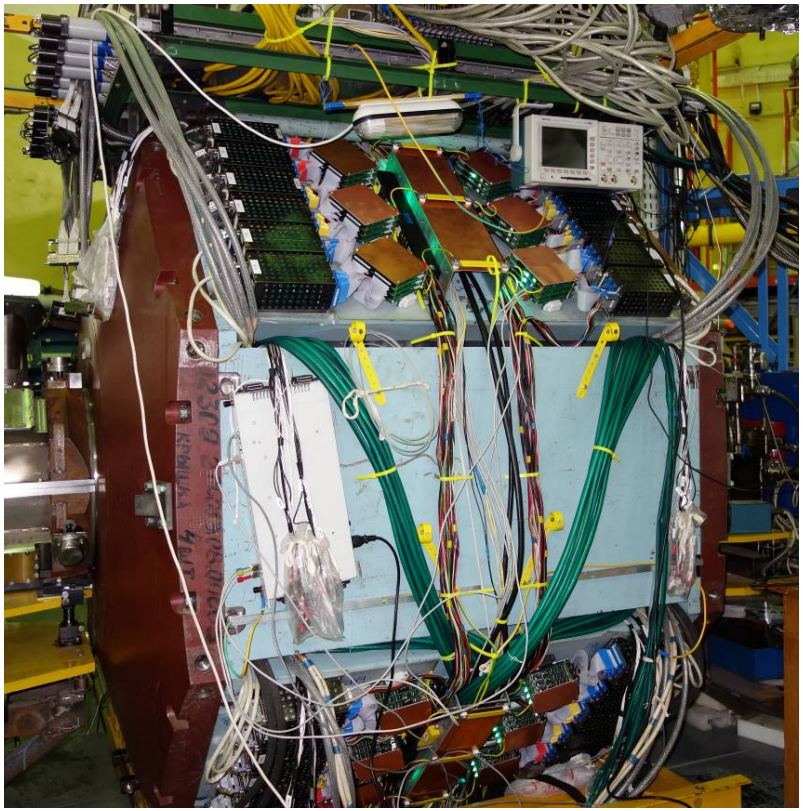
MeV

M.N. Achasov et al. arXiv:1211.0103v1 [physics.acc-ph] 1 Nov 2012

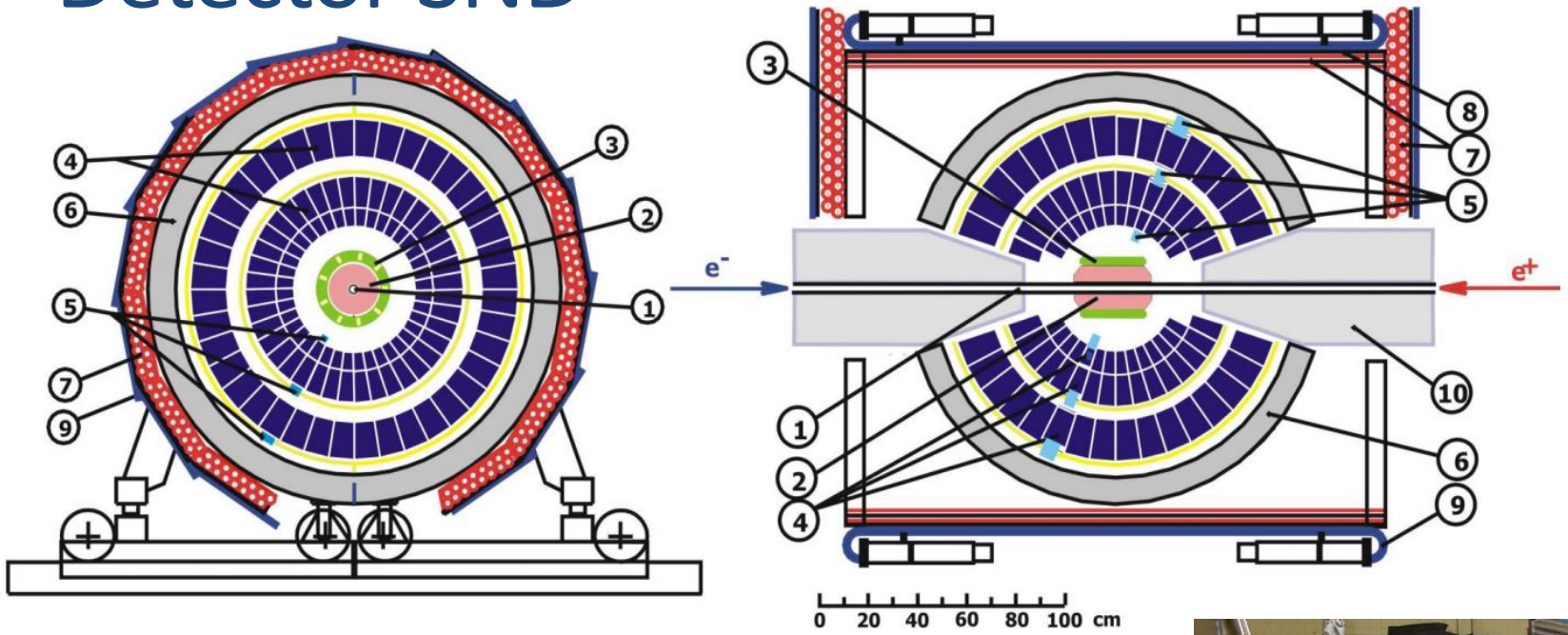

VEPP-2000
SND
CMD-3

Detector CMD-3



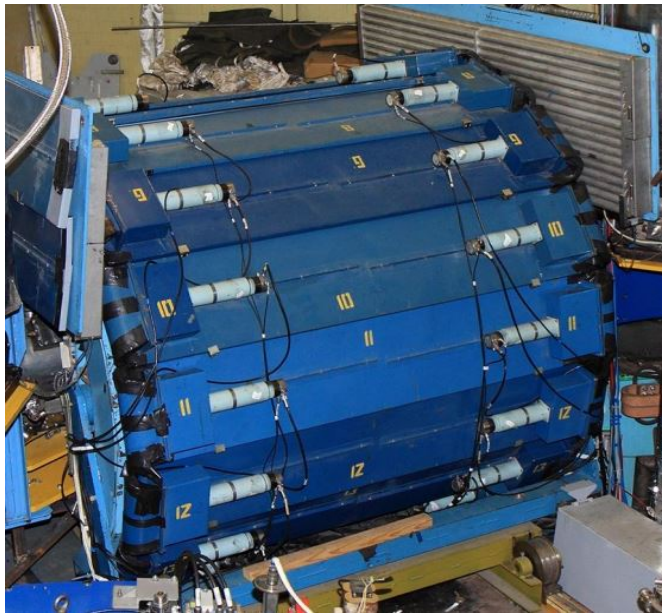


Detector SND

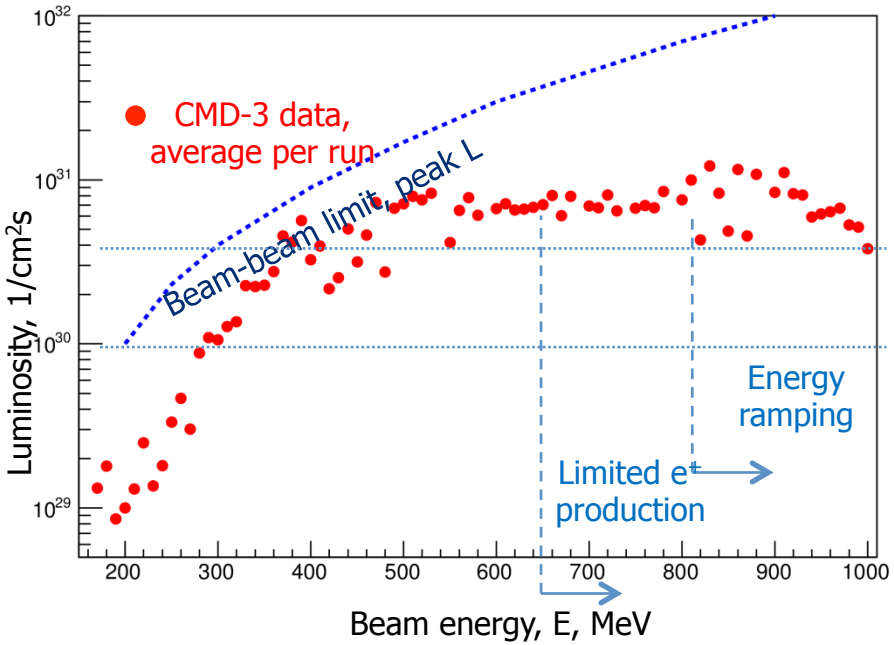


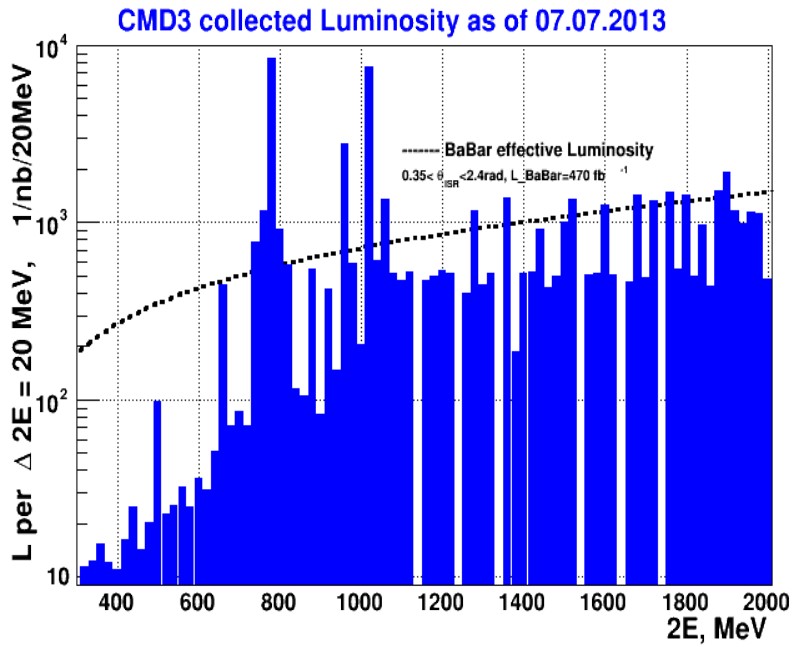
1 – vacuum chamber, 2 – tracking DC,
3 – aerogel n=1.13, 1.05 4 – NaI(Tl) crystals,
5 – phototriodes, 6 – absorber, 7–9 – muon detector, 10 – SC solenoids

High-resolution NaI calorimeter with excellent tracking and PID



Collected luminosity in 2011-2013





The luminosity was limited by a deficit of positrons and limited energy of the booster.

The VEPP-2000 upgrade has started in 2013.

About 60 pb-1 collected per detector

$\omega(782)$	$8.3\ 1/pb$
$2E < 1$ GeV (except ω)	$9.4\ 1/pb$
$\varphi(1019)$	$8.4\ 1/pb$
$2E > 1.04$ GeV	$34.5\ 1/pb$

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

- At VEPP-2000 we do exclusive measurement of $\sigma(e^+e^- \to hadrons)$.

- 2 charged

$$e^+e^- \to \pi^+\pi^-, K^+K^-, K_S K_L, p\bar{p}$$

- 2 charged + γ's

$$e^+e^- \to \pi^+\pi^-\pi^0, \pi^+\pi^-\eta, K^+K^-\pi^0, K^+K^-\eta, K_S K_L \pi^0, \pi^+\pi^-\pi^0\eta,$$
$$\pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$$

- 4 charged

$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-, K_S K^*$$

- 4 charged + γ's

$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0, \pi^+\pi^-\eta, \pi^+\pi^-\omega, \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0, K^+K^-\eta, K^+K^-\omega$$

- 6 charged

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

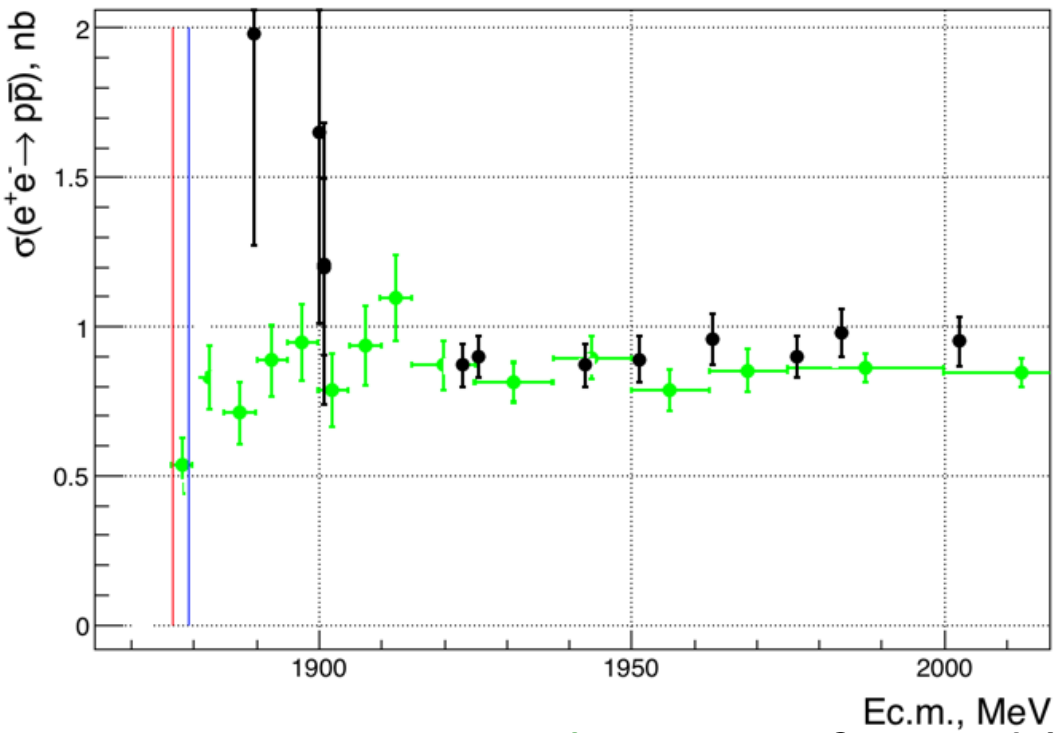
- γ's only

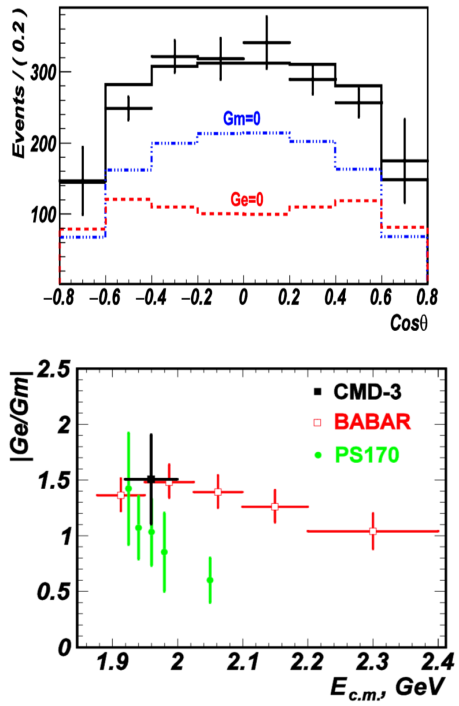
$$e^+e^- \to \pi^0\gamma, \eta\gamma, \pi^0\pi^0\gamma, \pi^0\eta\gamma, \pi^0\pi^0\pi^0\gamma, \pi^0\pi^0\eta\gamma$$

- other

$$e^+e^- \to n\bar{n}, \pi^0 e^+e^-, \eta e^+e^-$$

Cross section for e^+e^- -> ppbar



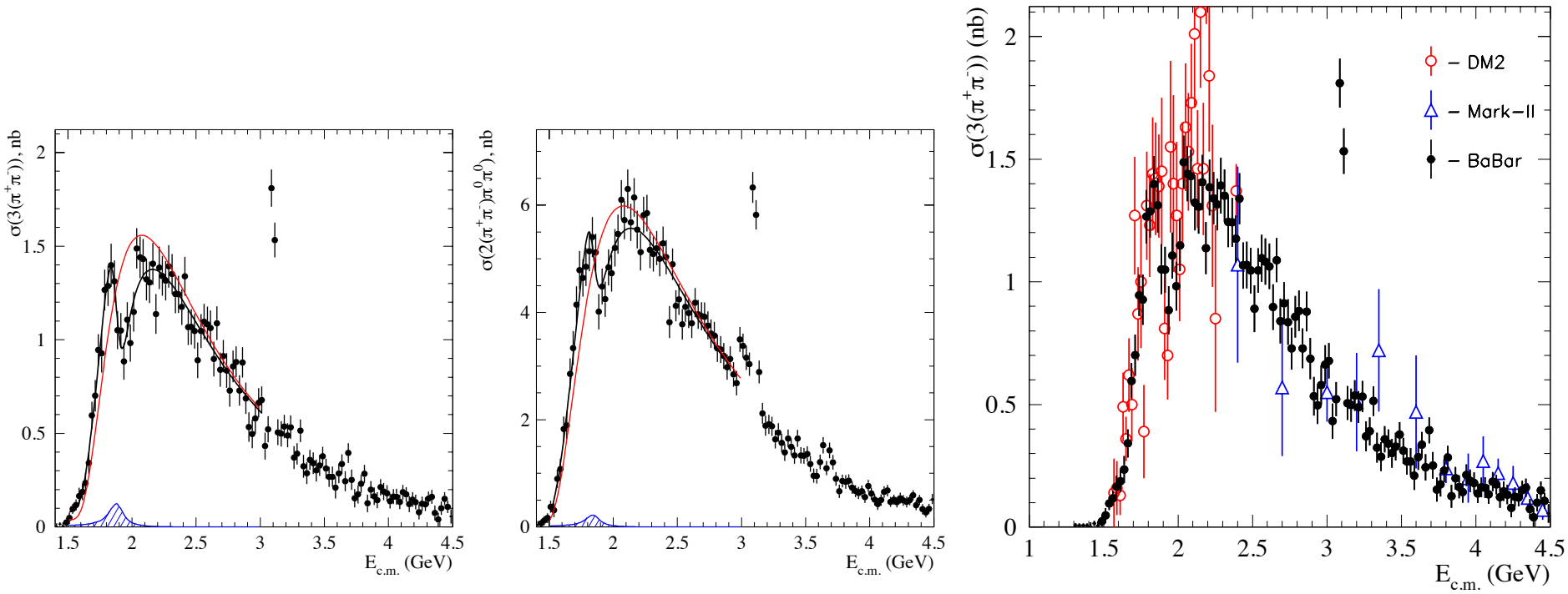


Nice BaBar data, confirmed by CMD-3 and BESIII demonstrate sharp rise cross section at threshold, but more detailed study is interesting

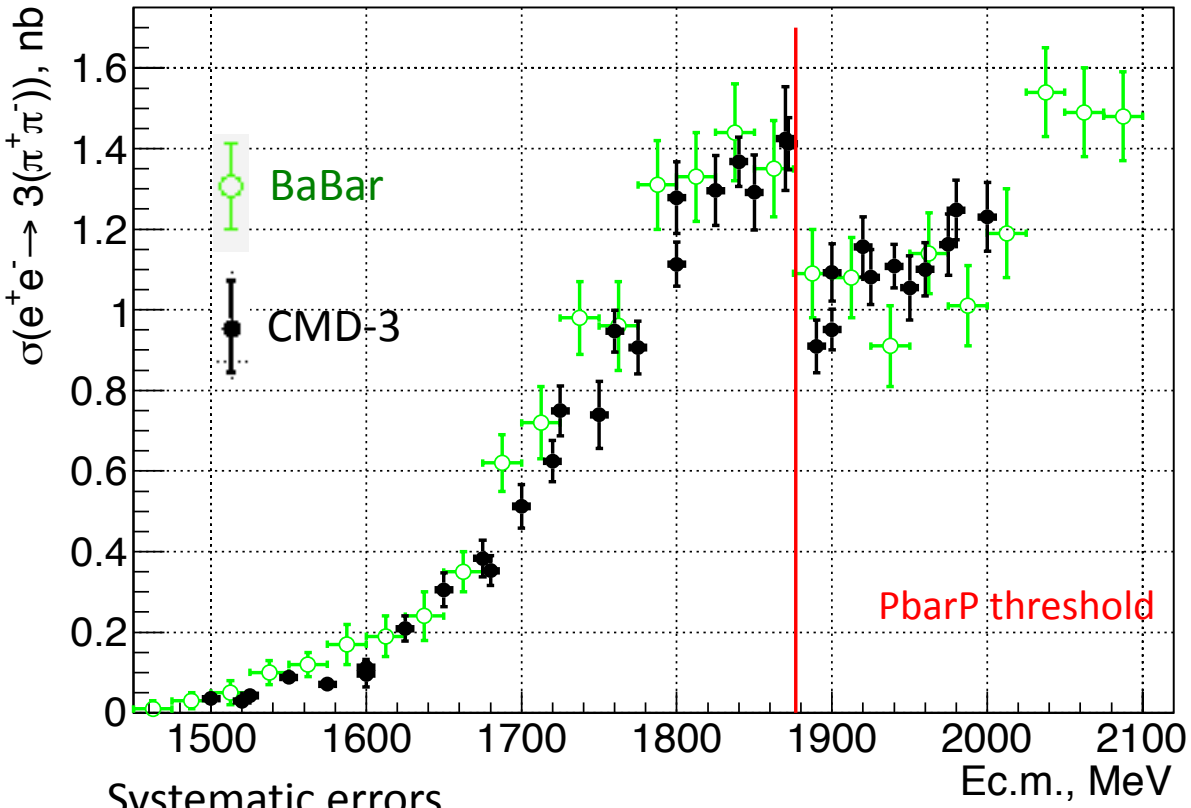
B. Aubert et al., (BaBar Collaboration), Phys. Rev. D 73, 092005 (2013).
R.R. Akhmetshin et al., (CMD-3 Collaboration), Phys. Lett. B759, 634 (2016).

e+e- → 6π before VEPP2000

- Interesting cross section behavior by DM-2, confirmed by BaBar
- NO other channels demonstrated it !
- Try to describe by resonance interference at the NNbar threshold



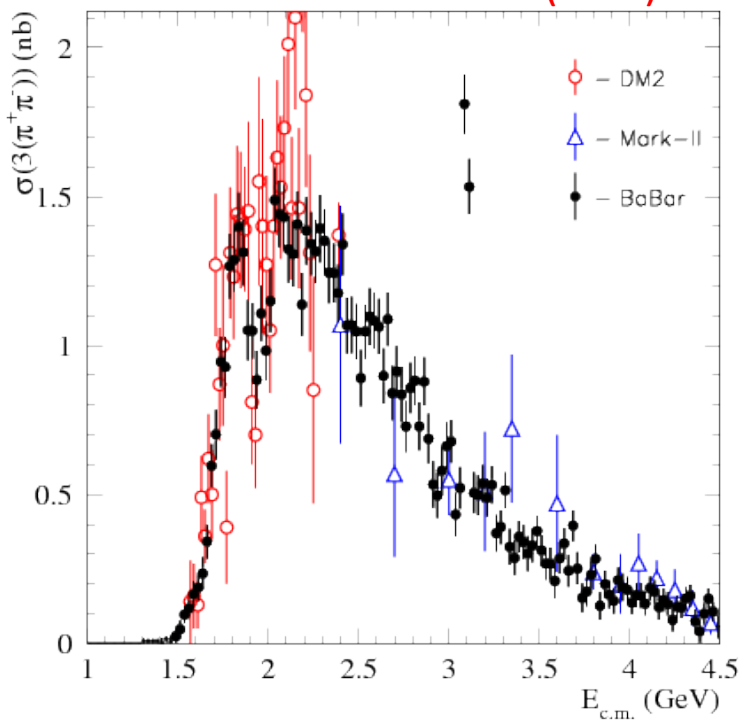
Cross section for $e^+e^- \to 3(\pi^+\pi^-)$



CMD-3 results from the 2011-2012 runs data
Phys. Lett. B 723 (2013) 73

It does not look like interference – too sharp < 10 MeV !?

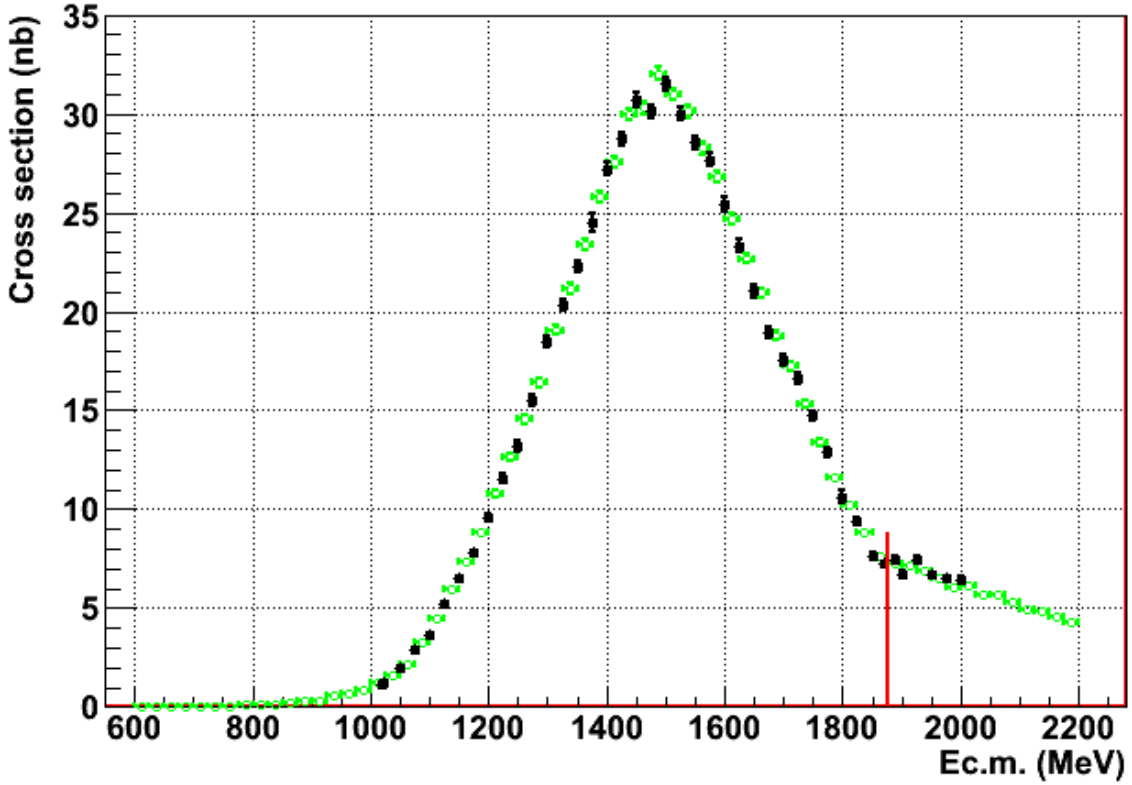
Other data for $e^+e^- \to 3(\pi^+\pi^-)$



Systematic errors

Model	- 4%
Event selection 5 tr.	- 3%
Event selection 6 tr.	- 1%
Luminosity	- 2%
Rad. correction	- 1%
Energy accuracy	- 1%
Total	- 6%

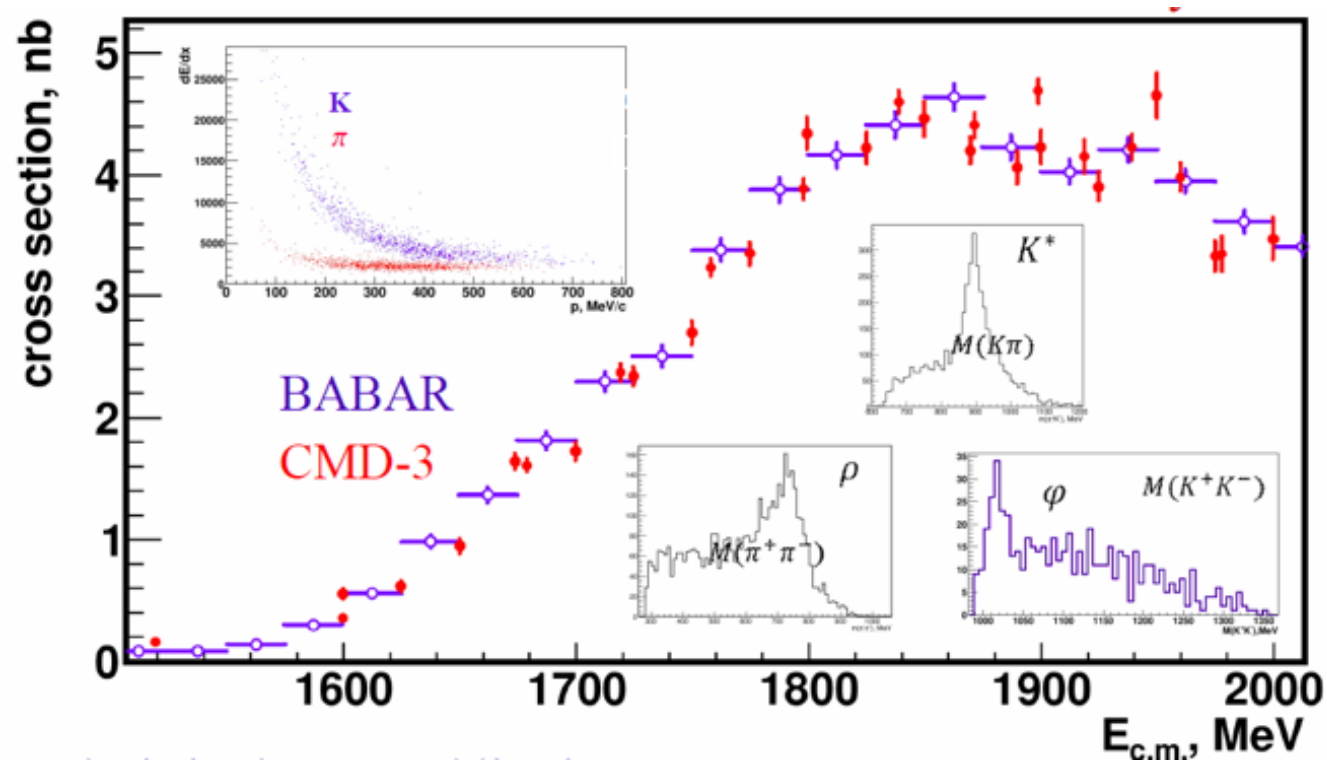
Nothing like that in $e^+e^- \to 2(\pi^+\pi^-)$!?



BaBar and preliminary CMD-3 data

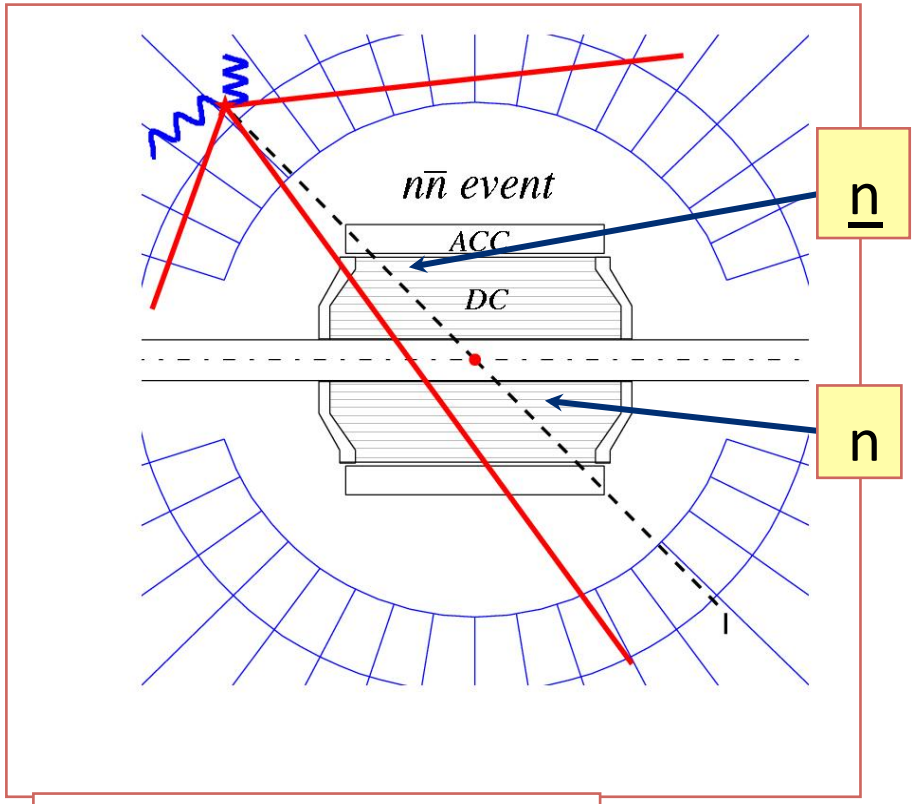
Are any other multi-hadron channels where we can see it?

Not enough data in $e^+e^- \to K^+K^-\pi^+\pi^-$



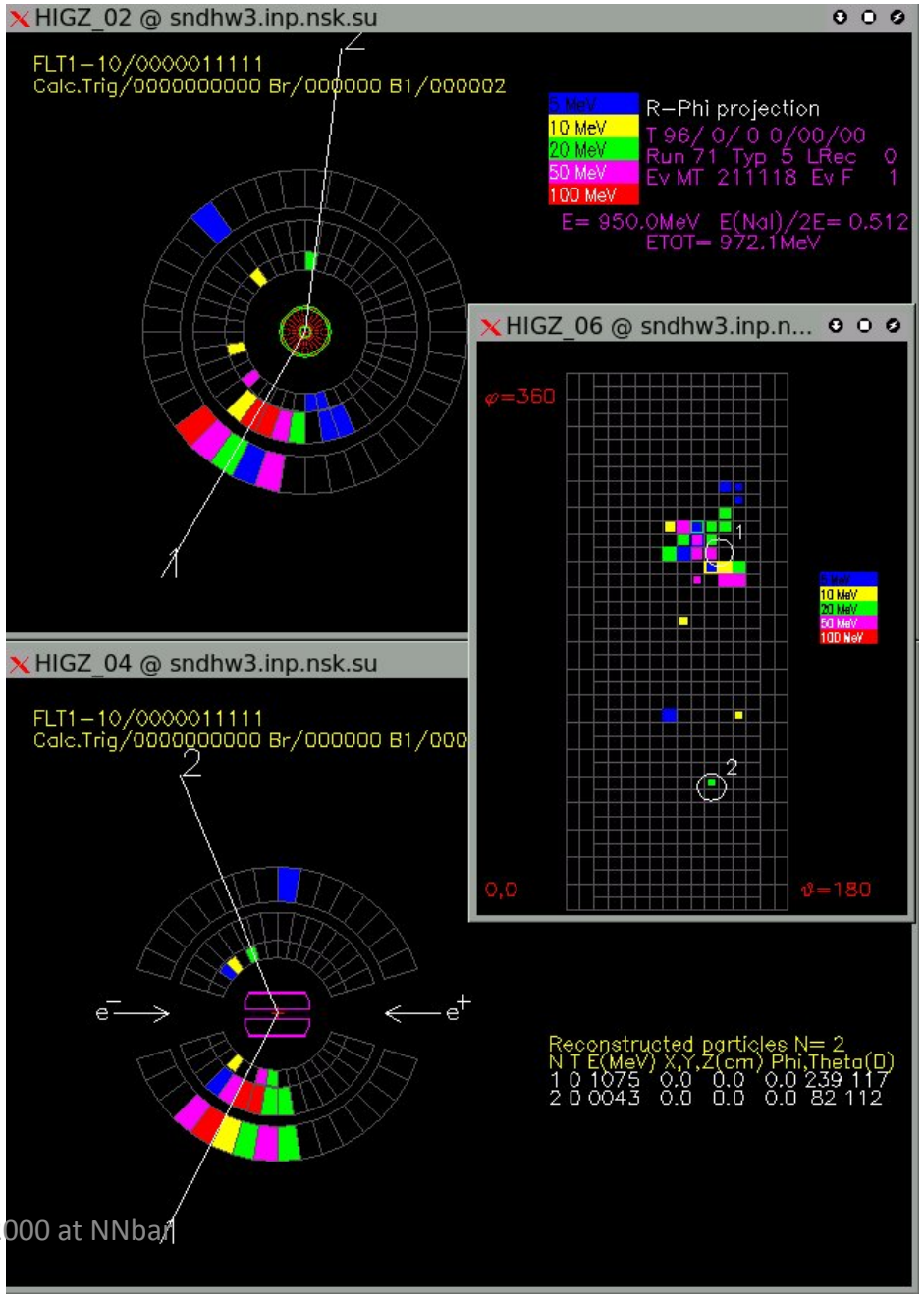
$e^+e^- \rightarrow n\bar{n}$

Event topology

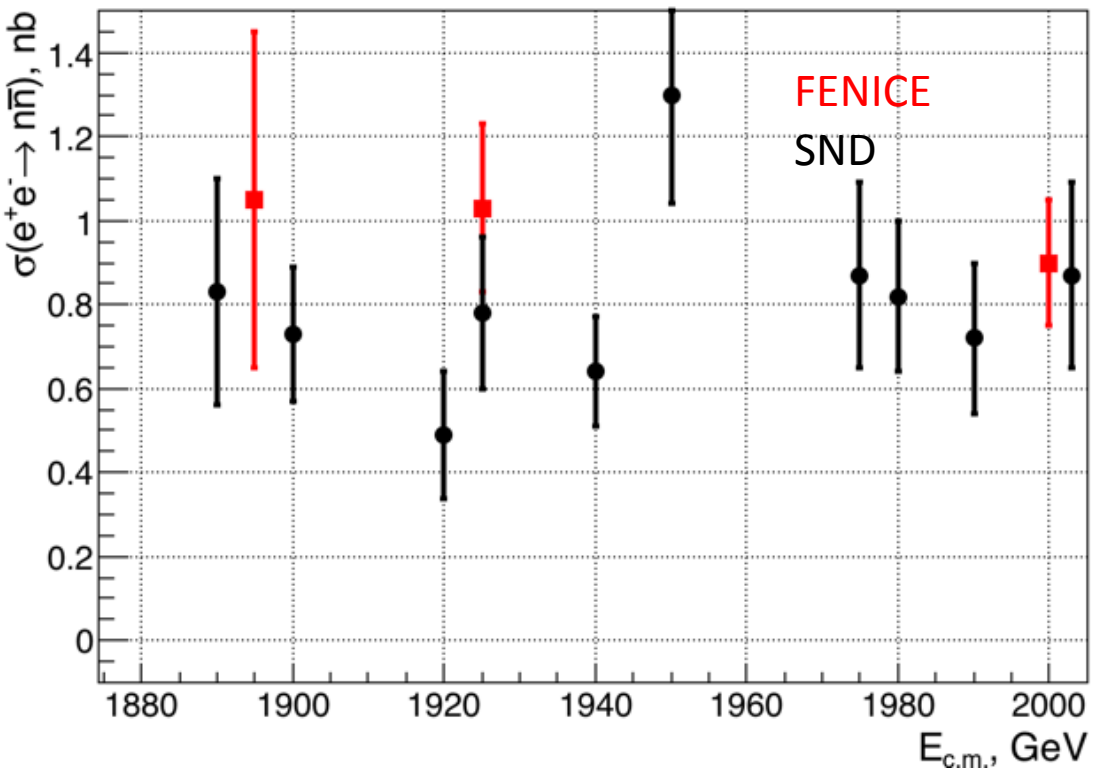


Even signature:

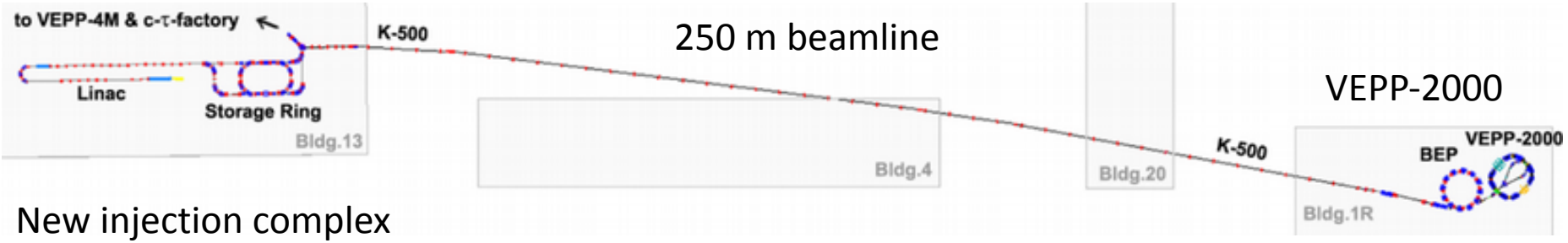
- no signal from neutron
- "star" from anti-neutron



New measurement after ~20 years



VEPP-2000 upgrade (2013-2016)



New injection complex

Collider upgrades:

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

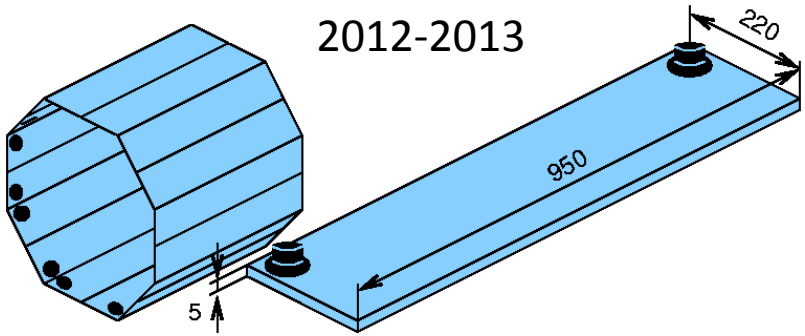
CMD-3 upgrades:

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

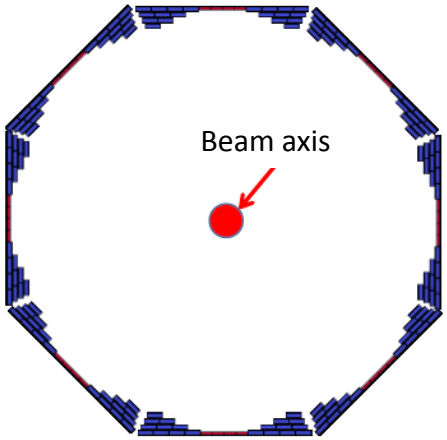
Detectors resumed data taking by the end of 2016

New TOF system

"Old" TOF
2012-2013

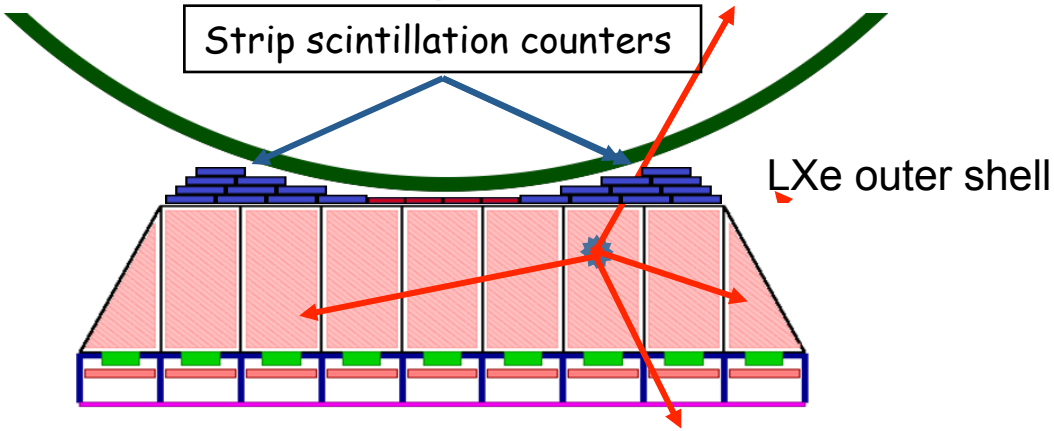


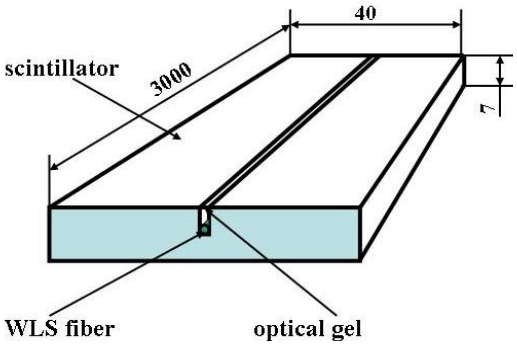
"New" TOF (2017-)



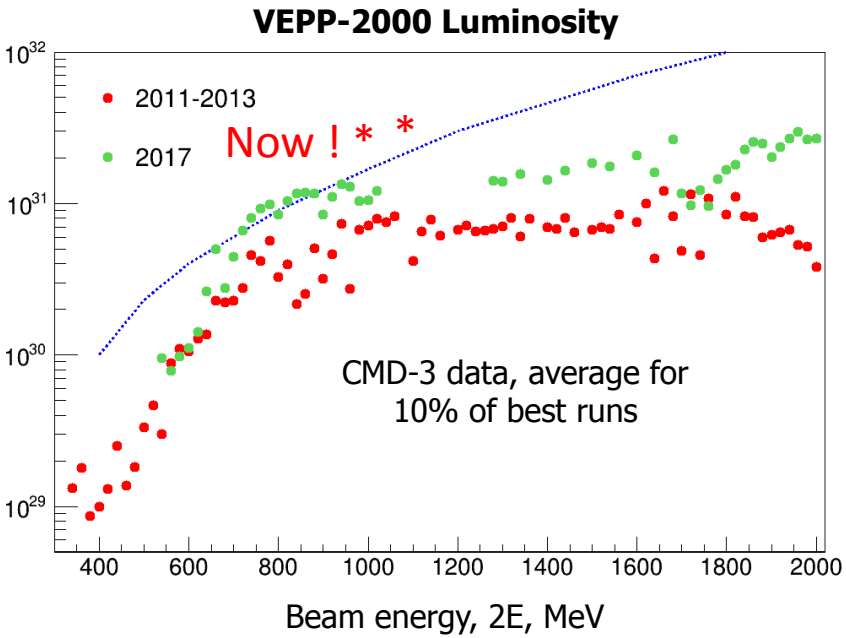
In 2013-2016 the TOF system was completely replaced

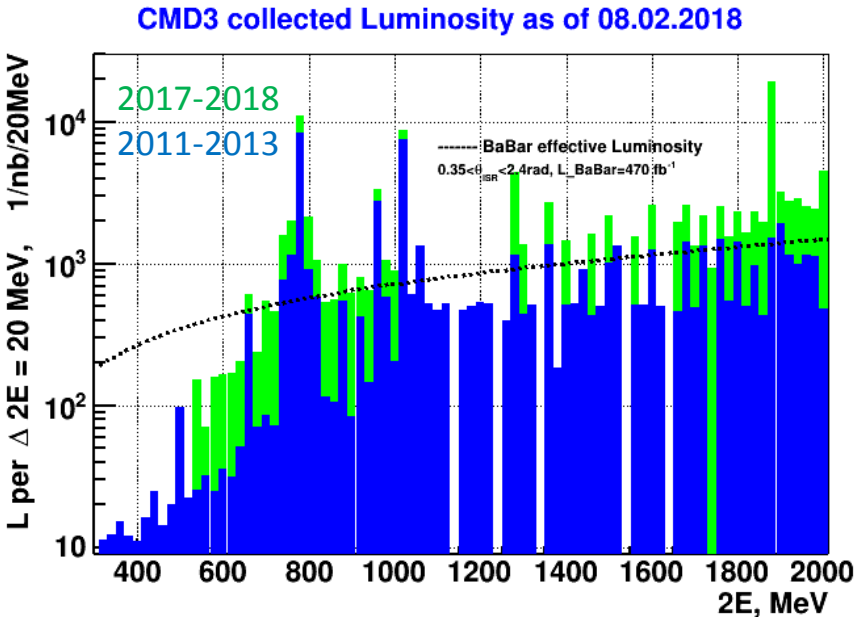
- More granulated (16 counters → 175 counters)
- 0.8 ns resolution per counter





2017-2018 data taking





In 2017: big improvement in luminosity, still way to go.

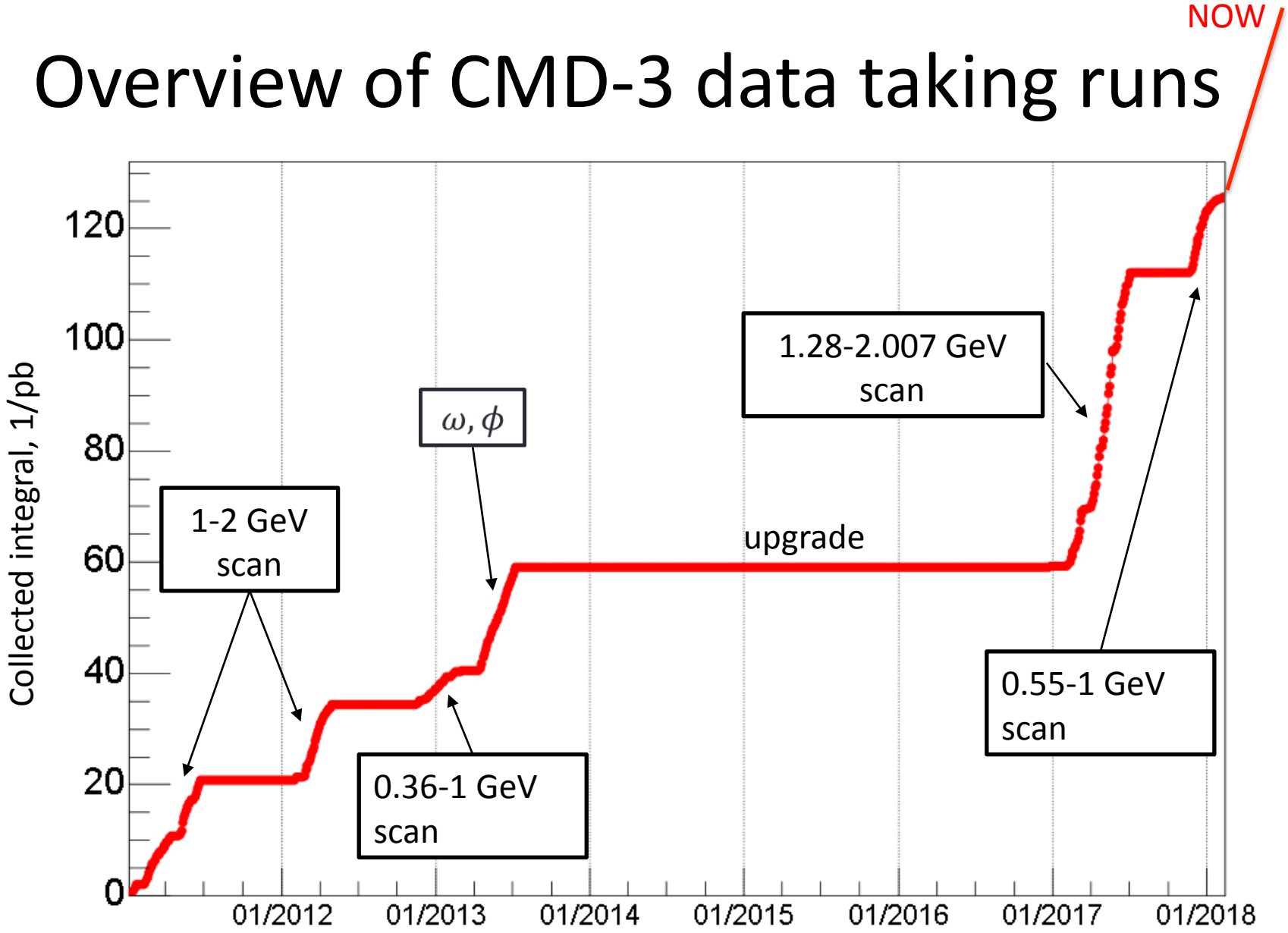
$4*10^{31}$ at E = 550 MeV has been achieved!

Below 1 GeV: ~40 pb^{-1} collected up to now and data taking is continuing

Above 1 GeV: ~50 pb^{-1} collected

2.007 GeV ($e^+e^- \to D^{0*}$)	4 $1/pb$
$p\bar{p}$ and $n\bar{n}$ threshold	14 $1/pb$
Overall:	
$1.28 - 2.007$ GeV	50 $1/pb$

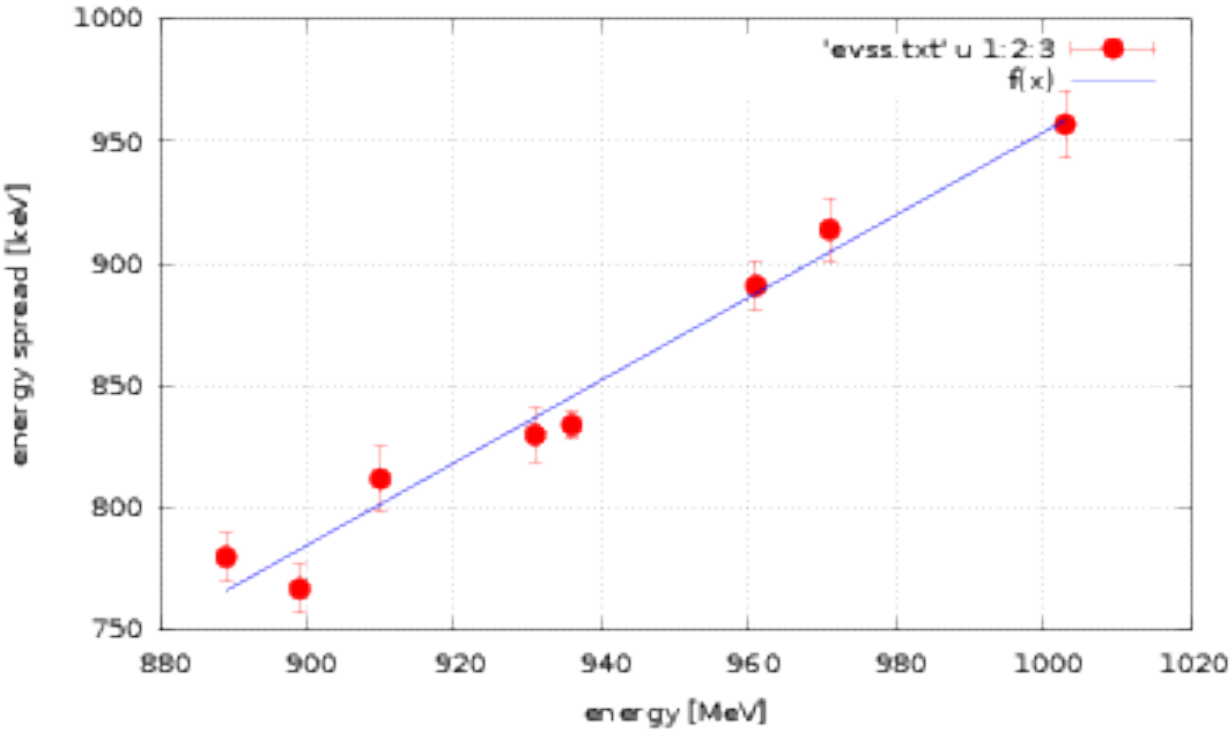
Overview of CMD-3 data taking runs



Today discussion – runs over NNbar threshold

In addition to general scan with 10-20 MeV step, data at eight points with 0.8 MeV step were recorded around NNbar threshold with 14 pb-1 integrated luminosity

Using back-scattering Compton signal, the beam energy spread was determined as ~1.2+-0.1 MeV for the center-of-mass energy .



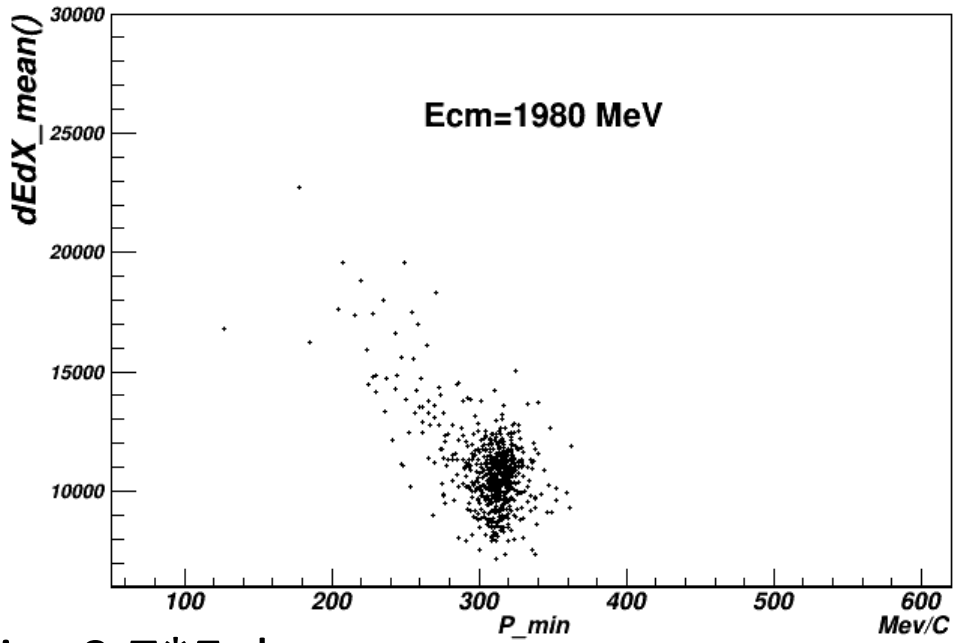
- Both detectors are analyzing data to extract e+e- -> ppbar, e+e- -> nnbar cross sections
- Both detectors are searching NNbar influence to the e+e- -> hadrons cross sections

Some analysis details: e+e- -> ppbar

Two classes of events:

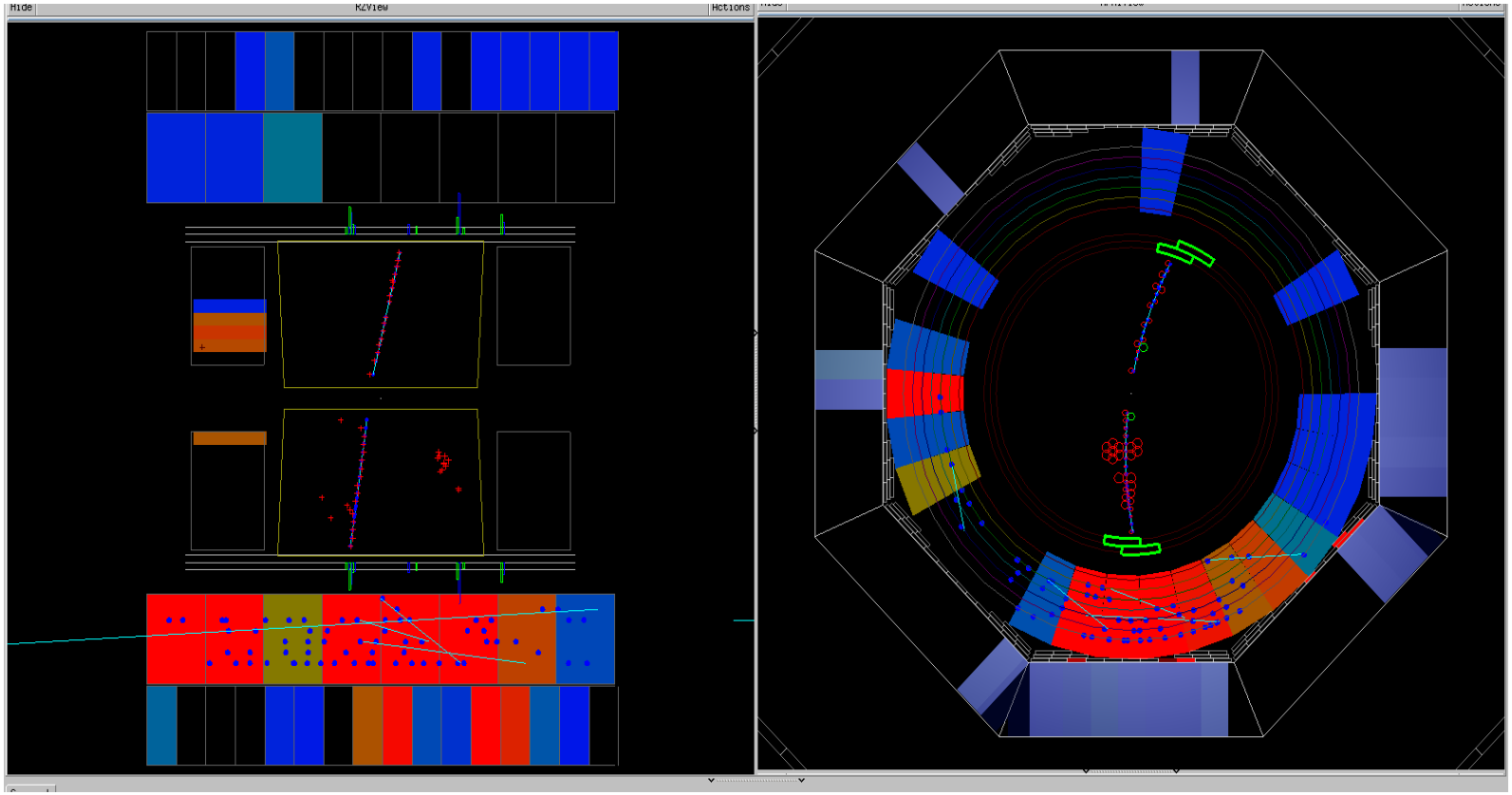
1. Above Ebeam = 950 MeV events are detected as two collinear tracks with large dE/dX

For collinear tracks:



1. N_trackCenter==2
2. δθ < 0.3 рад
3. Δϕ < 0.3 рад
4. Both tracks (dE/dX>6000)
5. E_plus<0.7*E_beam && E_min<0.7*E_beam
6. (P_plu-P_min)/(P_plu+P_min)<0.1
7. All hits in DC are in time

e+e- -> ppbar event display



4770 ppbar events with both tracks detected are found at five $E_{c.m.}$ energy points

Some analysis details: e+e- -> ppbar

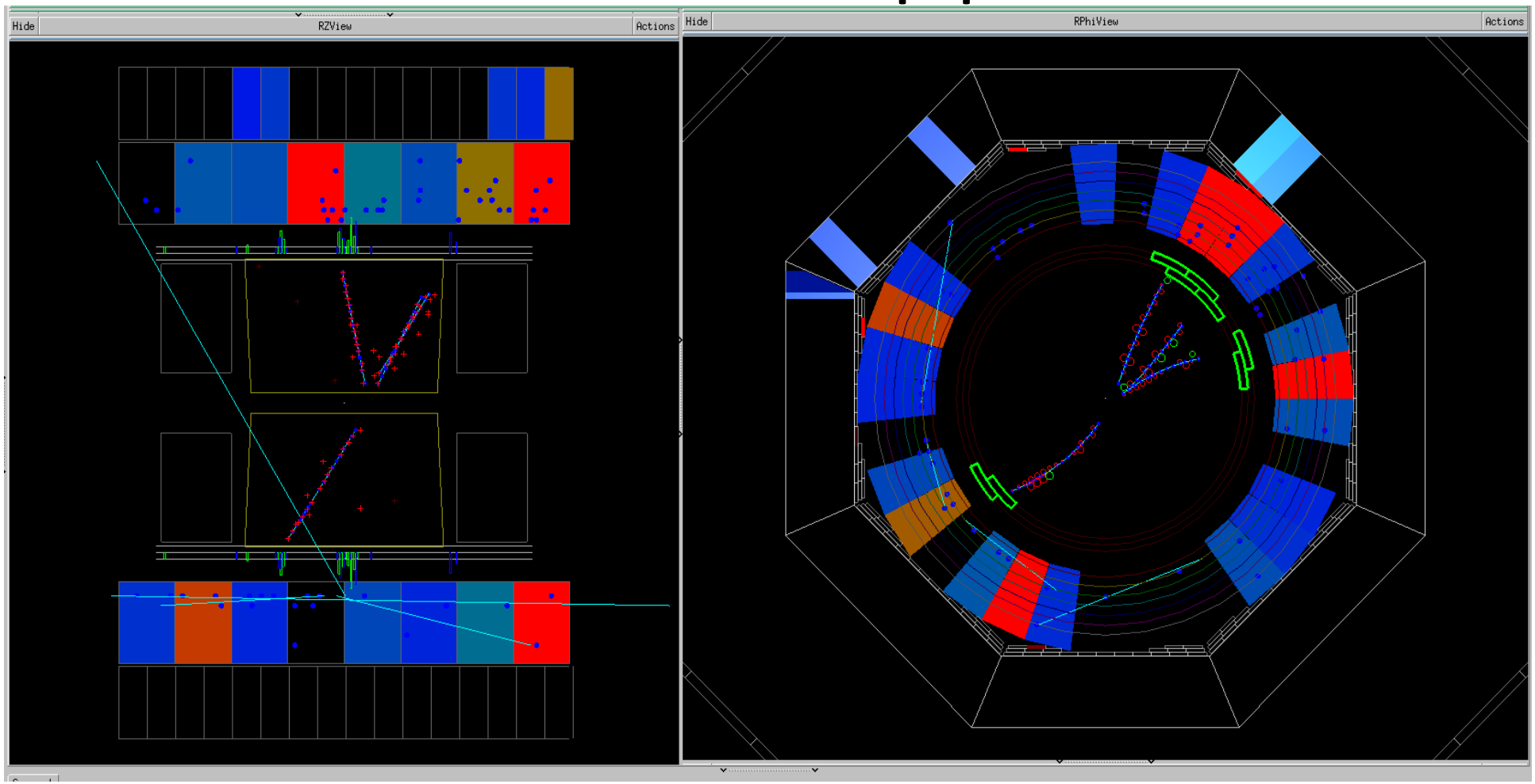
Two classes of events:

2. For E_{beam} < 950 MeV protons and anti-protons stop in the 0.5 mm aluminum beam pipe

We look for the annihilation star of anti-protons:

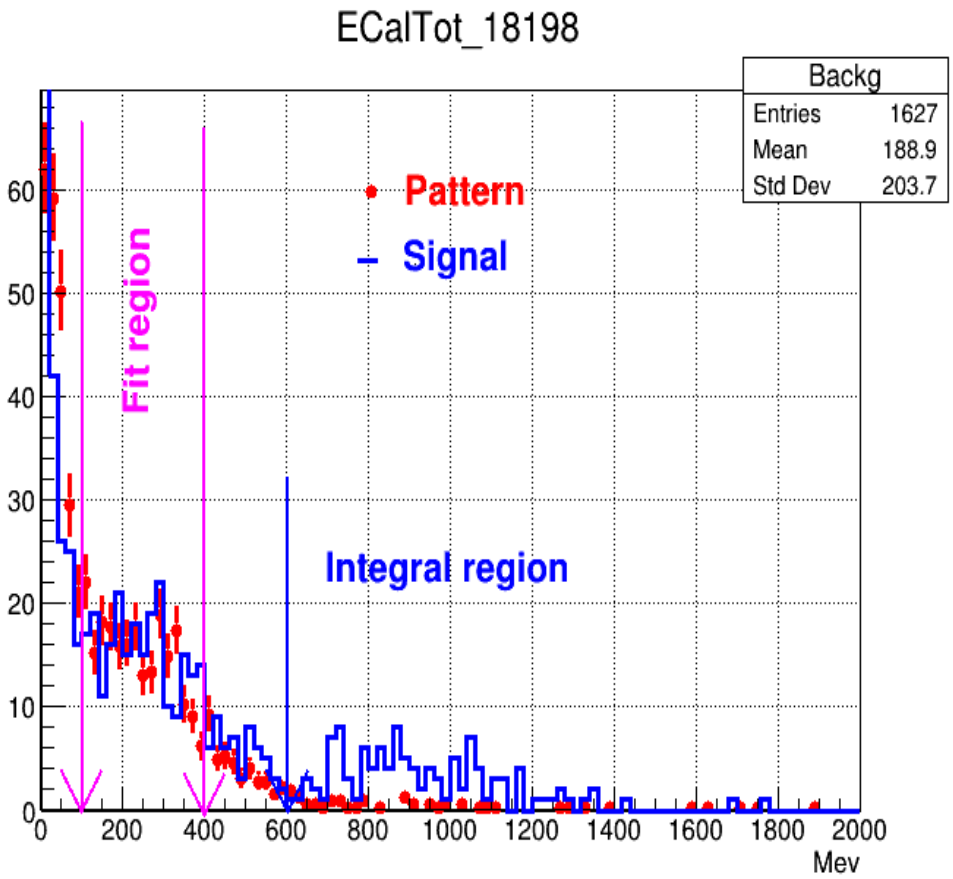
1. N_tracks >2
2. Tracks have common vertex at the beam pipe radius
3. All tracks are not protons (dE/dX<6000)
4. All hits in DC are in time

anti-proton annihilation in the beam pipe



Total energy deposition in calorimeter

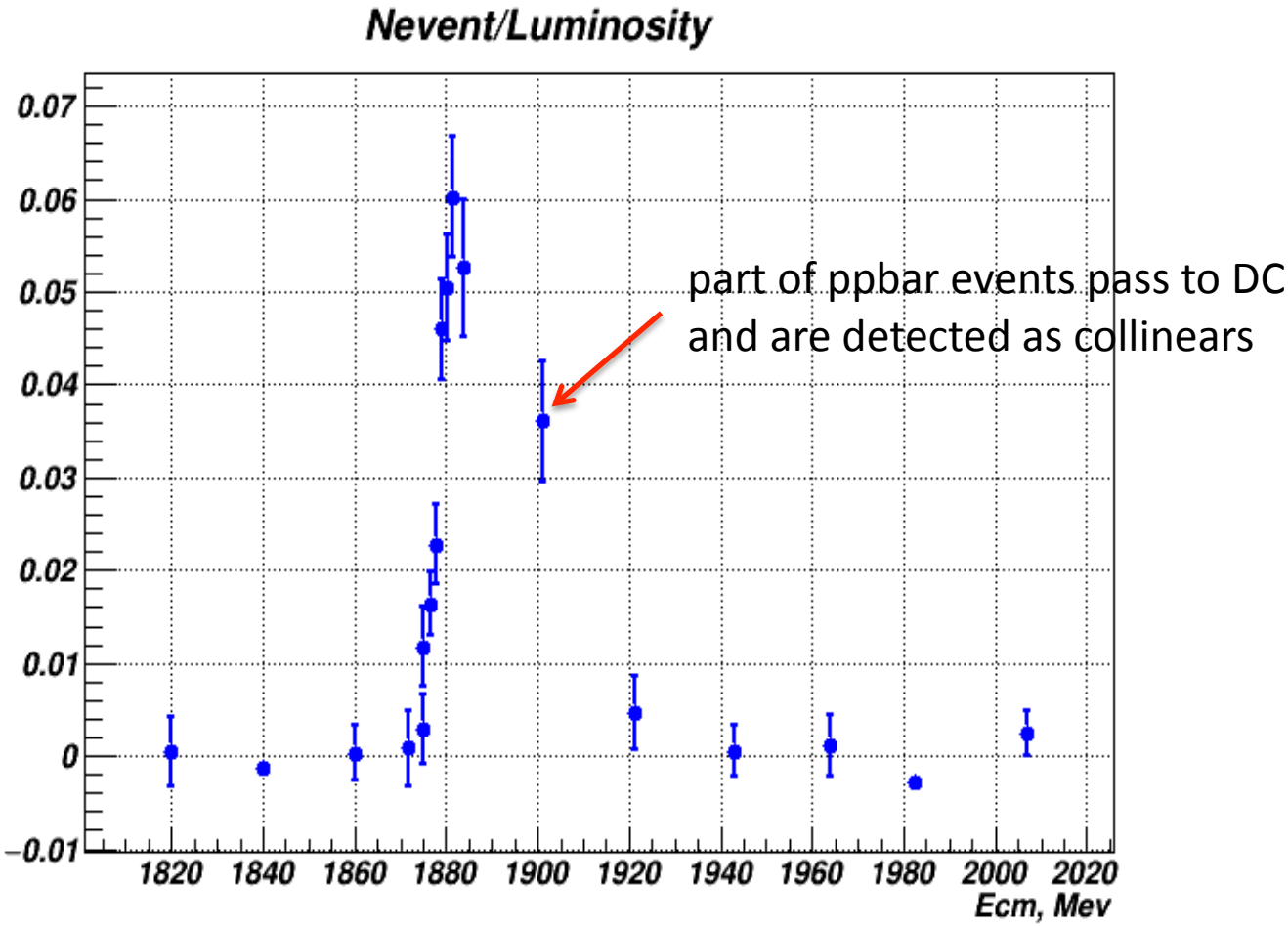
is used to select events with anti-proton annihilation:



RED – below NNbar threshold

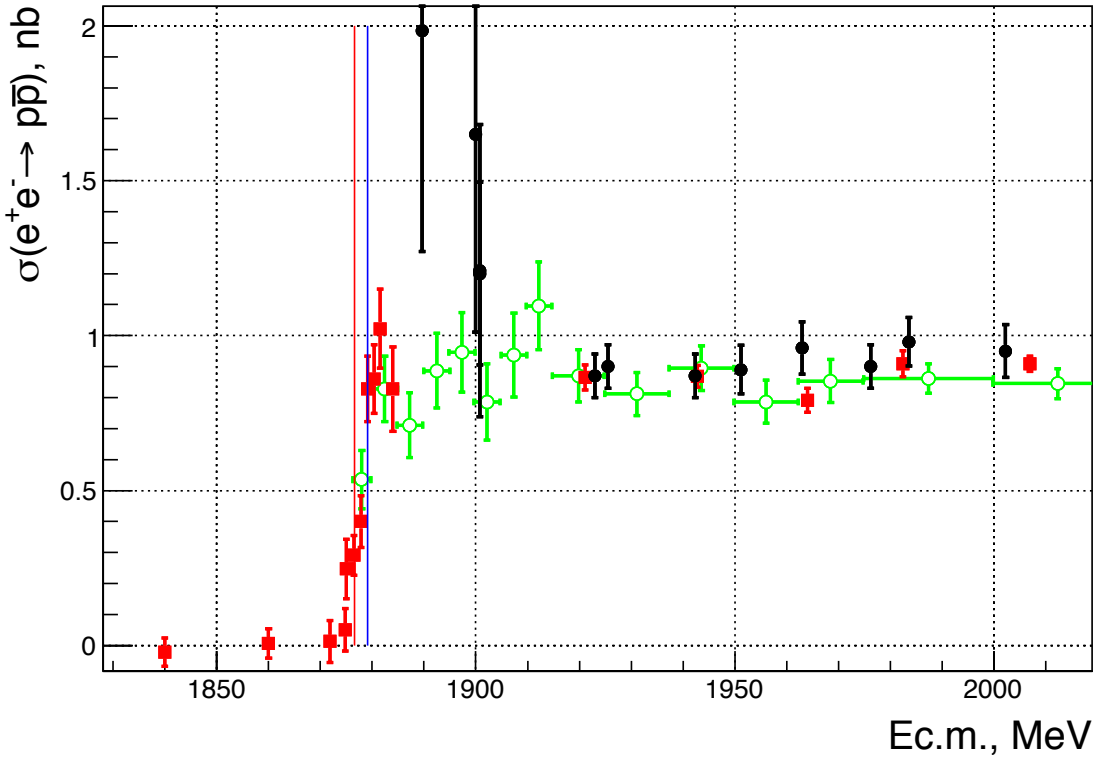
BLUE – above NNbar threshold

Number of ppbar events with annihilation in the pipe vs energy



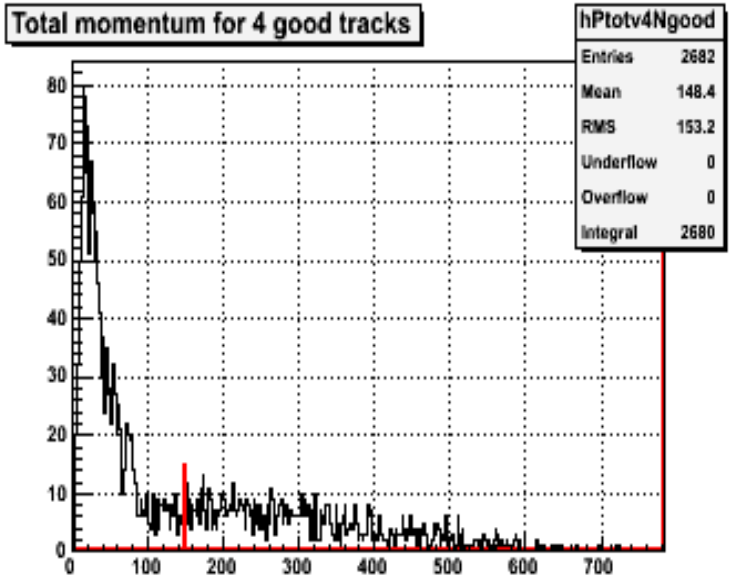
490 events have been found

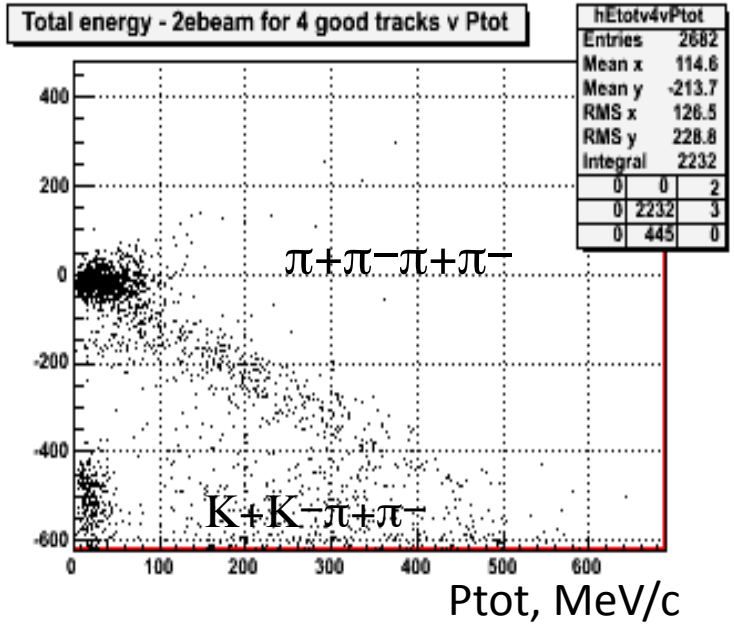
e+e- -> ppbar Born cross section



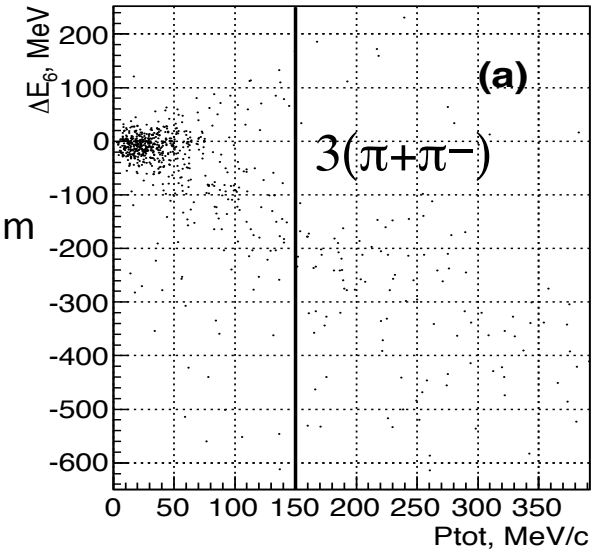
Our new 2017 data in comparison with BaBar and CMD-3 2011-2012 scans (R.R. Akhmetshin et al., (CMD-3 Collaboration), Phys. Lett. B759, 634 (2016).)

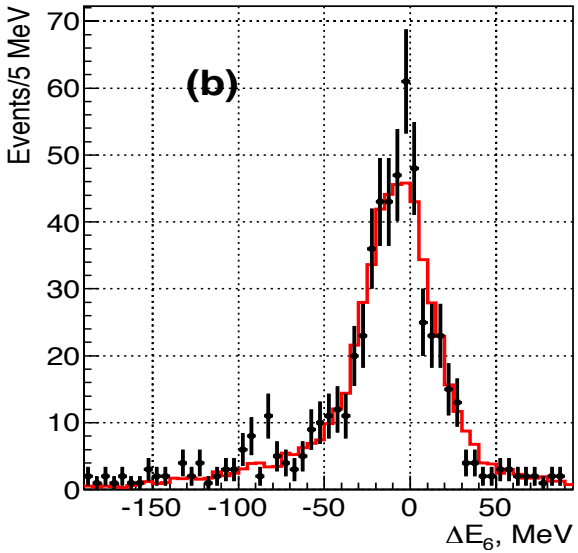
Clean sample of e+e- -> 4,6 charged



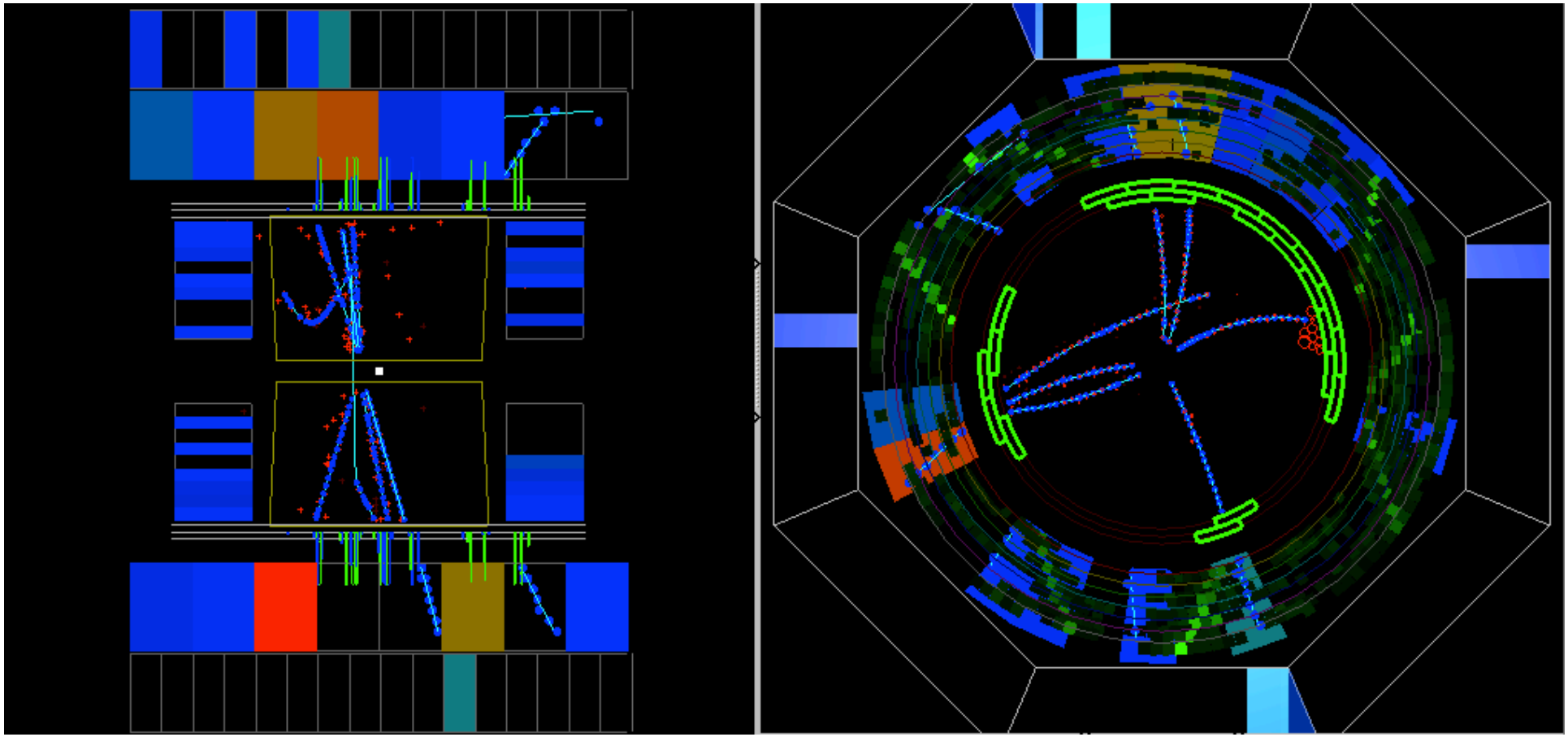


$$\Delta E_{4,6} = \Sigma_1^{4,6} E_\pi - 2 E_{beam}$$

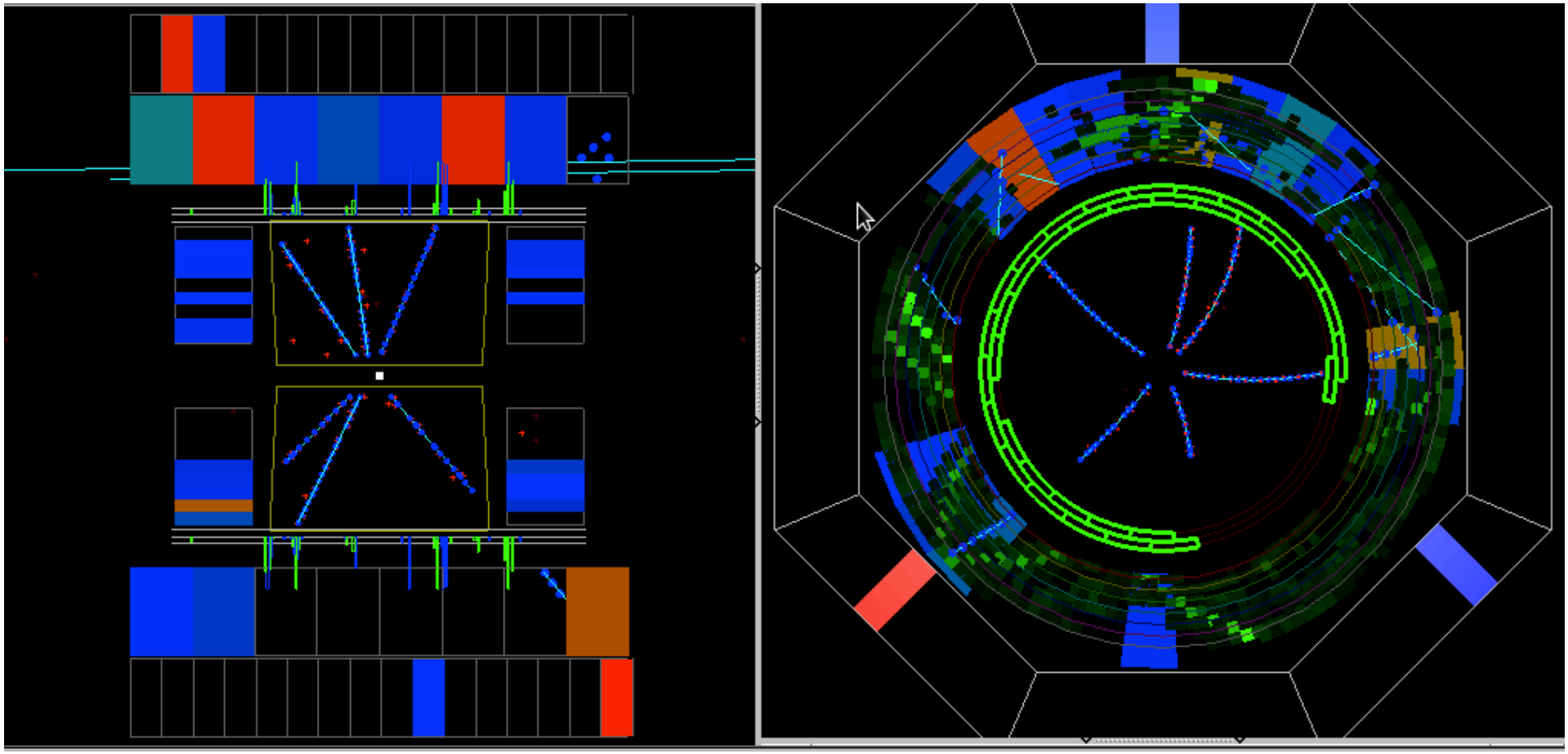




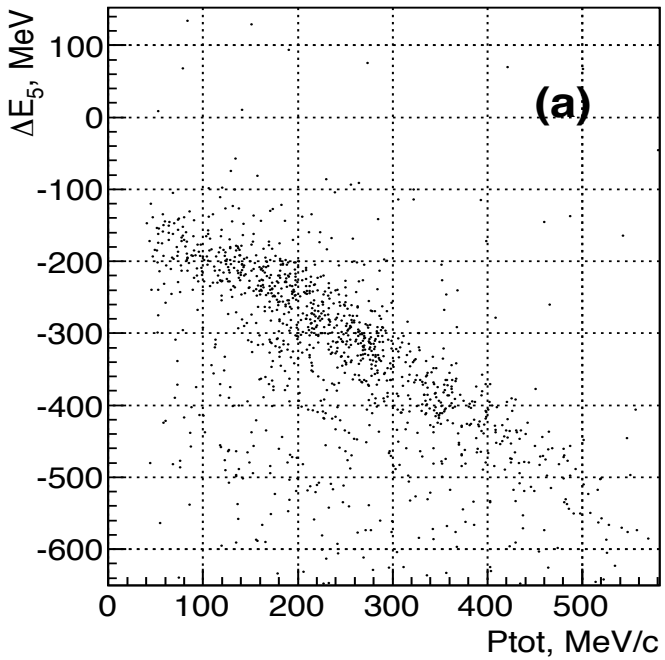
Example of $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ from CMD-3

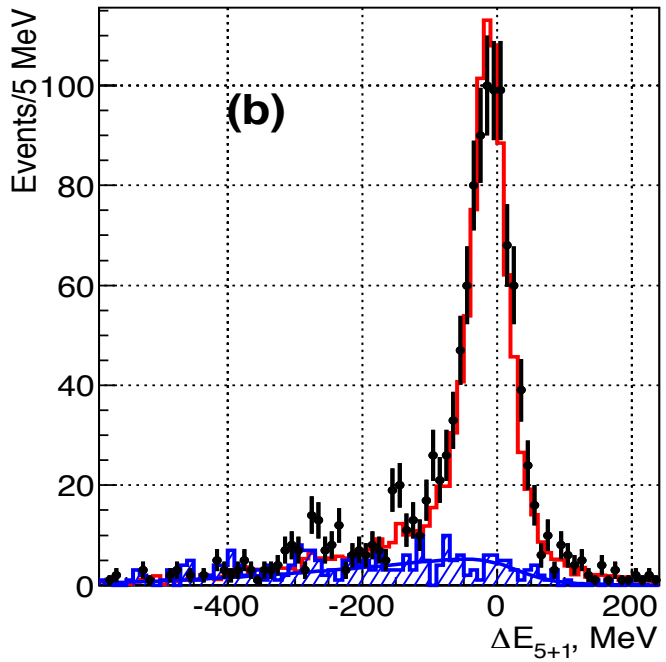


Example of $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ from CMD-3



Events with one missing track



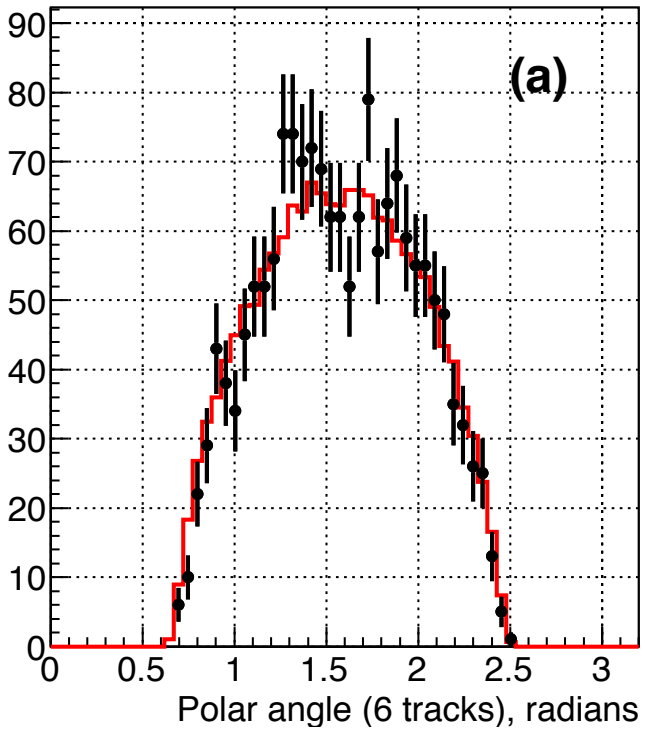


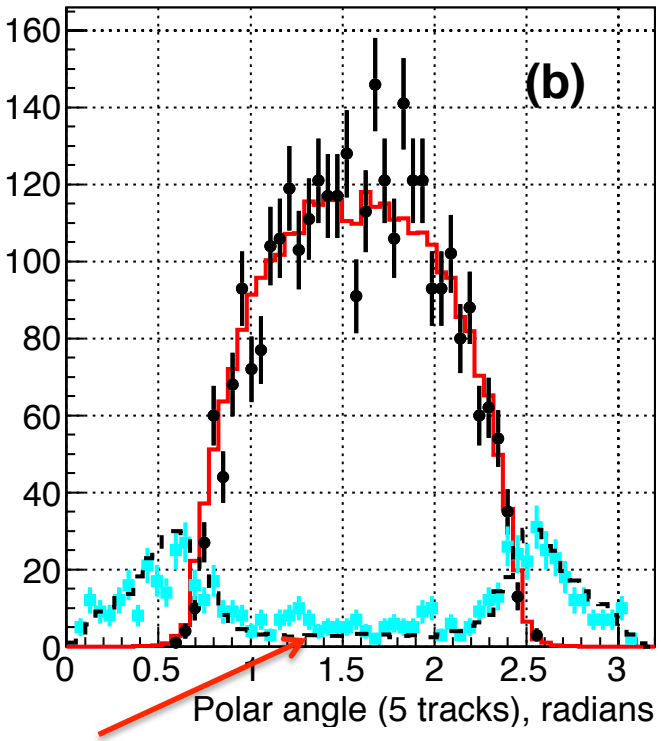
$$\Delta E_5 = \Sigma_1^5 E_\pi - 2 E_{beam}$$

$$\Delta E_{5+1} = \Sigma_1^5 E_\pi + E_{mis} - 2 E_{beam}$$

Also relatively clean sample – increase statistic by factor of two!

Angular distributions for $e^+e^- \to 3(\pi^+\pi^-)$ events





~ 15-17% events have track not reconstructed in DC:
DC efficiency relatively well simulated

DC acceptance is not 100% and ratio 5 tracks to 6 tracks events depends on production dynamics.

Angular distribution for $e^+e^- \to 3(\pi^+\pi^-)$ events(1)

Dynamic study: DC acceptance is not 100% and detection efficiency from MC depends on angular distribution of pions. We developed the Monte Carlo generators for few models, passed generated events through our detector simulation and compare with data.

We have tested : e+e- -> Phase Space,

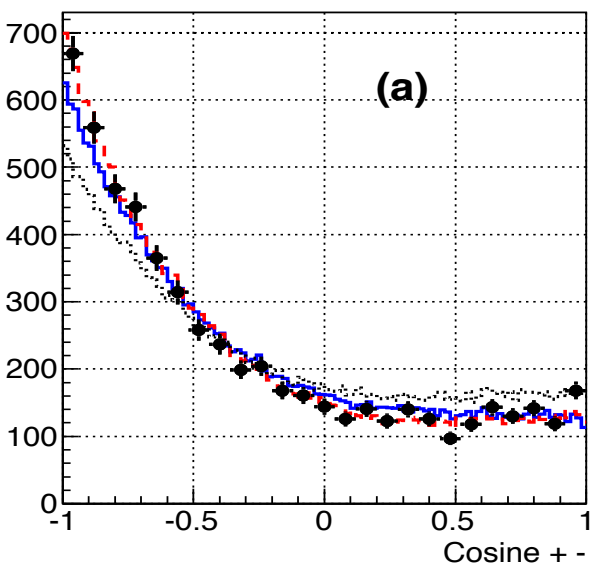
$\rho(1420,1700)f_0(600)$, ($\rho(1240,1700) \to a1(1260)\pi \to \rho(770)2\pi$)

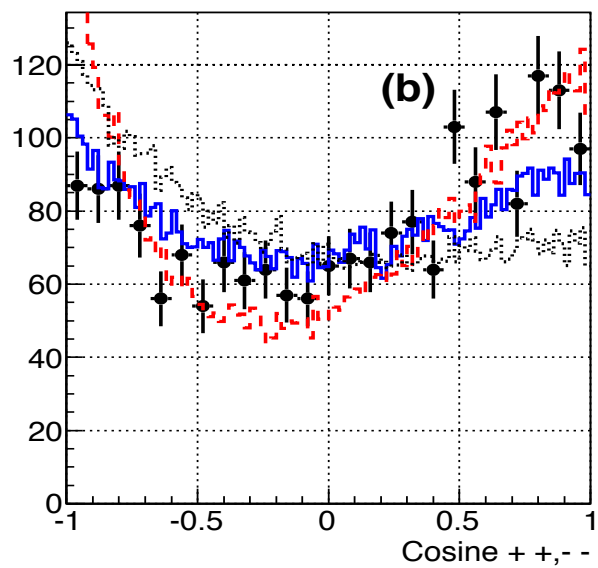
$\rho(770)2(\pi+\pi-)$,

$\rho(770)f_0(1370,1500)$, $f_0 \to 2(\pi+\pi-)$,

$\rho(770)f_2(1270)$, $f_2 \to 2(\pi+\pi-)$,

.....





Examples:

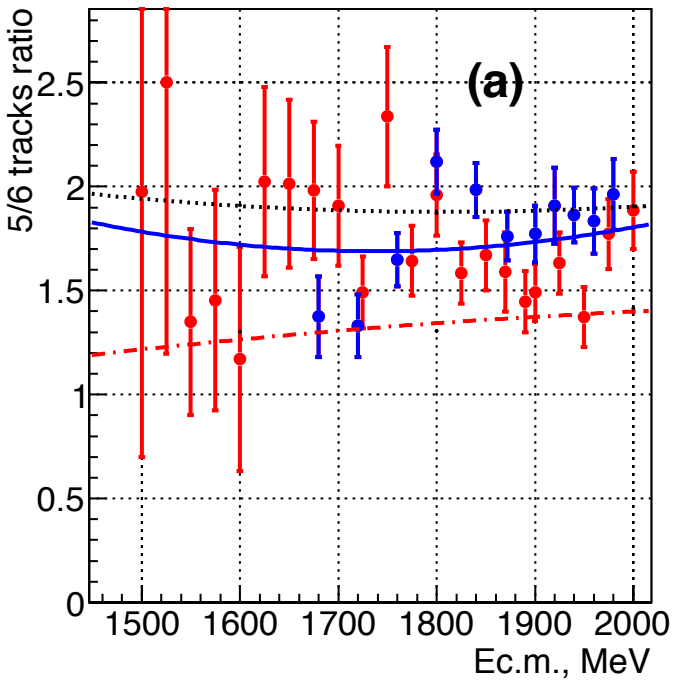
- ..... $\rho(1420,1700)f_0(600)$
- ——— $\rho(770)f_0(1370,1500)$
- - - - $\rho(770)f_2(1270)$

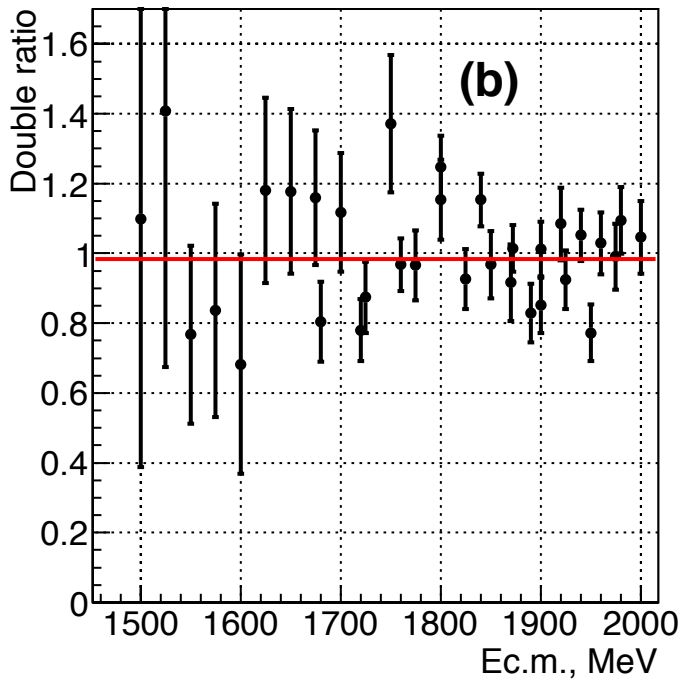
5/6 ration is used for model dependent error

Examples:

- ρ(1420,1700)f_0(600)
- ρ(770)f_0(1370,1500)
- ρ(770)f_2(1270)

Double ratio = $(N5/\varepsilon_{mc}5)/(N6/\varepsilon_{mc}6)$



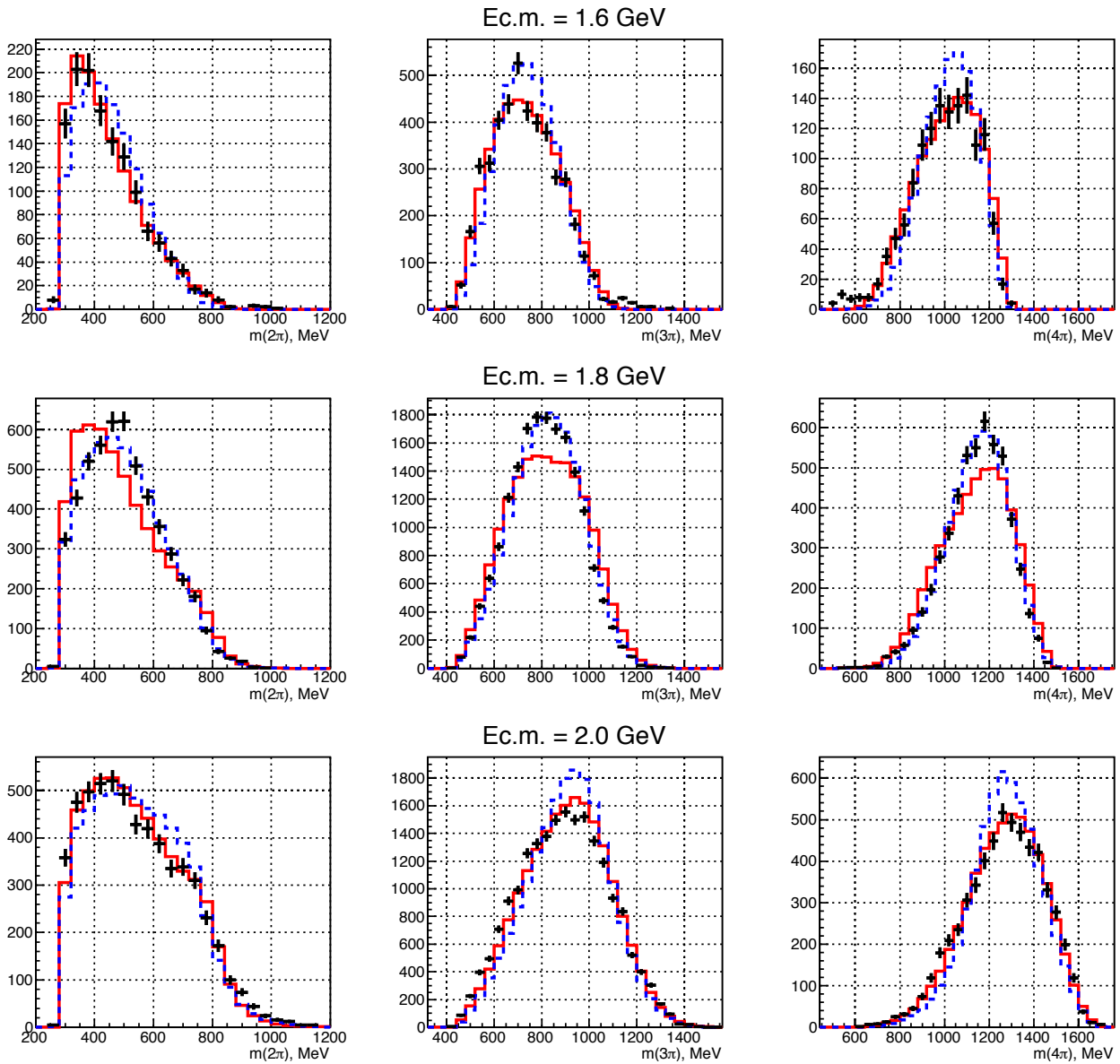


Fit: 0.984 +- 0.018

$\chi 2$ /n.d.f = 56/35

Dynamic study of the $e^+e^- \to 3(\pi^+\pi^-)$ process

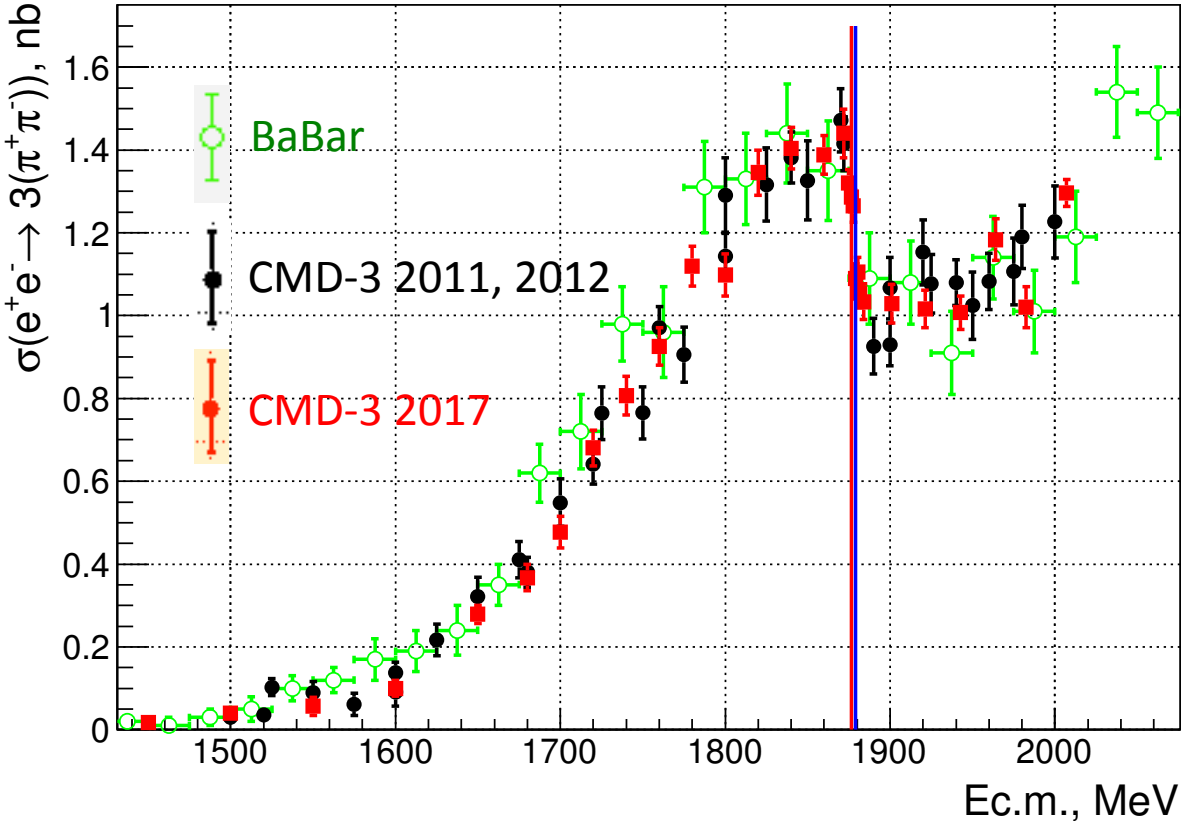
"Simple" $\rho(770)2(\pi+\pi-)$ or $\rho(770)f_0(1370,1500)$ both well describe angular distributions. But first describes mass distributions for Ec.m.=1.6+-0.1 and 2.0-0.1 GeV, and for 1.8+-0.1 GeV mass interval we need scalar resonance for 4 pions !!?



The production dynamic changes in the 1700-1900 MeV interval!

Preliminary study of 2017 data shows no changes just before and after NNbar threshold.

Cross section for $e^+e^- \to 3(\pi^+\pi^-)$



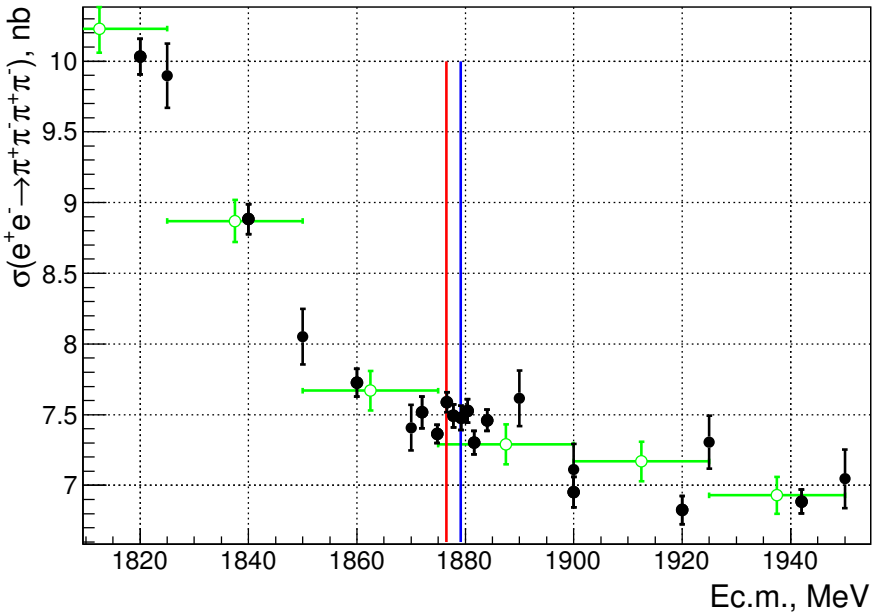
CMD-3 published results
2011-2012 r.r.
Phys. Lett. B 723 (2013) 73

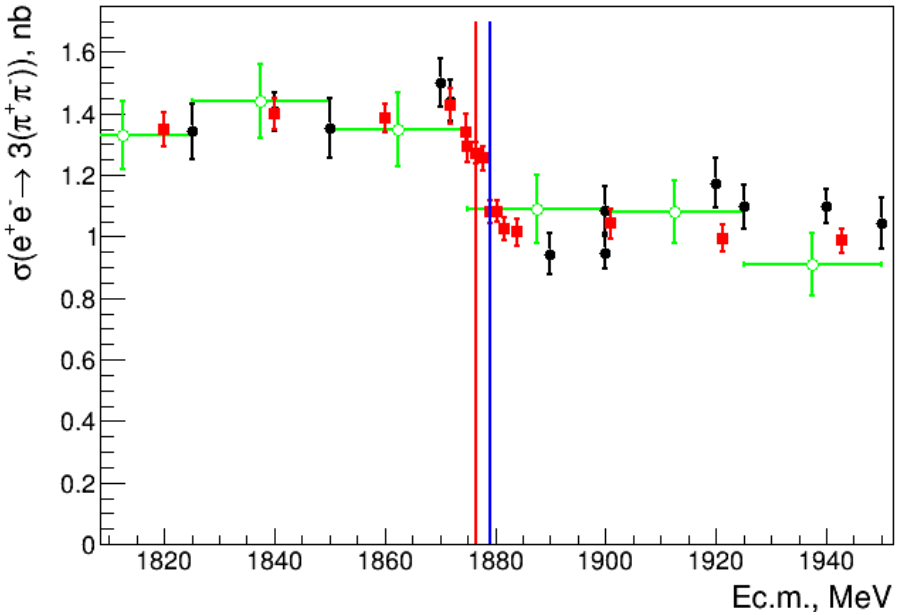
Preliminary 2017 scan data

Sharp jump has been confirmed

Systematic error is - 6%

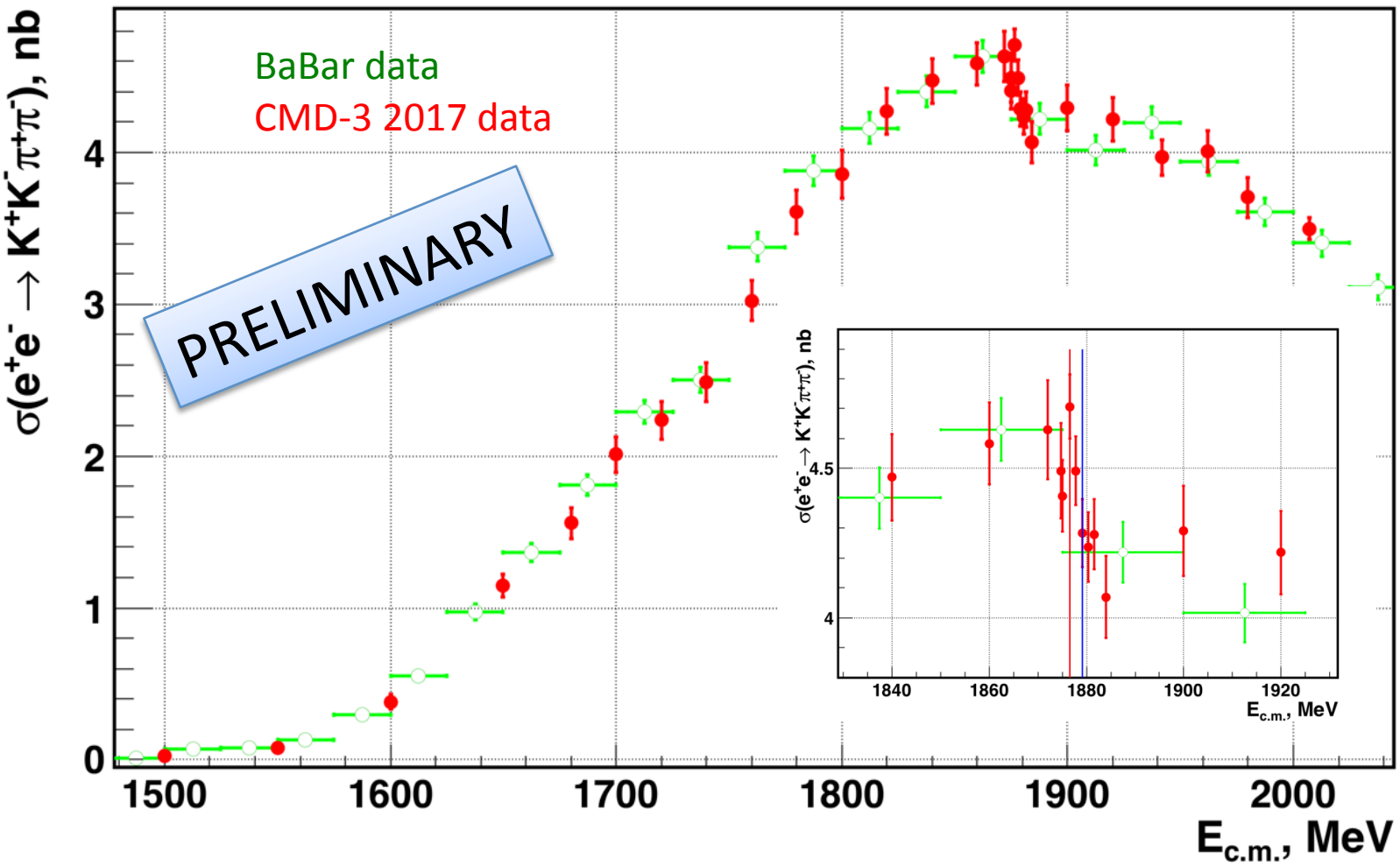
Cross sections around NN threshold





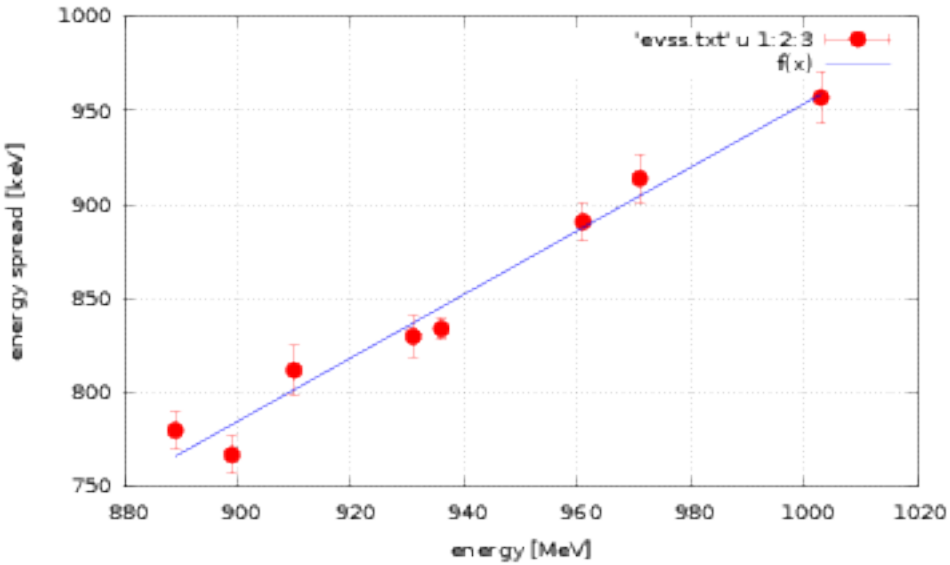
No structure (< 0.1 nb) is seen in $e^+e^- \to 2(\pi^+\pi^-)$ at the NN threshold !

NEW! Structure in $e^+e^- \to K^+K^-\pi^+\pi^-$



One more channel, where NN threshold structure has been observed!

At what energy and how fast?



If Born cross section is changing too fast, visible cross section is a convolution of Born cross section with beam energy spread and radiative effects.

Energy spread is directly measured by the back-scattering Compton photons and at the NN threshold is measured to be $\sigma_{E_{c.m.}}$ = 1.2 +- 0.1 МэВ - fixed

Visible cross section is a convolution of a “radiative” cross section and c.m. energy spread

$$\sigma_{\rm vis}(E_{\rm c.m.}) = \frac{1}{\sqrt{2\pi}\sigma_{E_{\rm c.m.}}} \int dE'_{\rm c.m.} \sigma_{f\gamma}(E'_{\rm c.m.}) \cdot \exp(-\frac{(E_{\rm c.m.} - E'_{\rm c.m.})^2}{2\sigma^2_{E_{\rm c.m.}}})$$

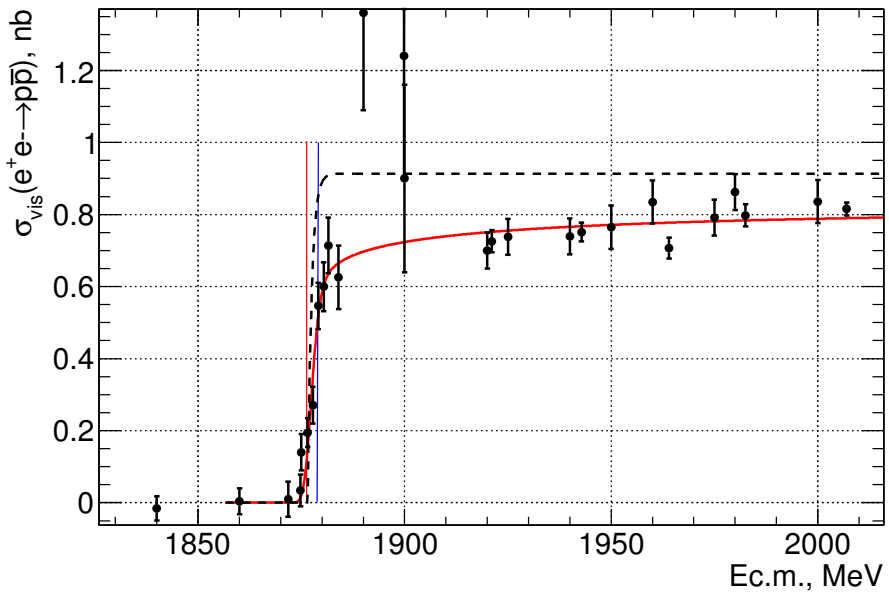
the “radiative” cross section is a convolution of Born cross section and radiative photon spectrum

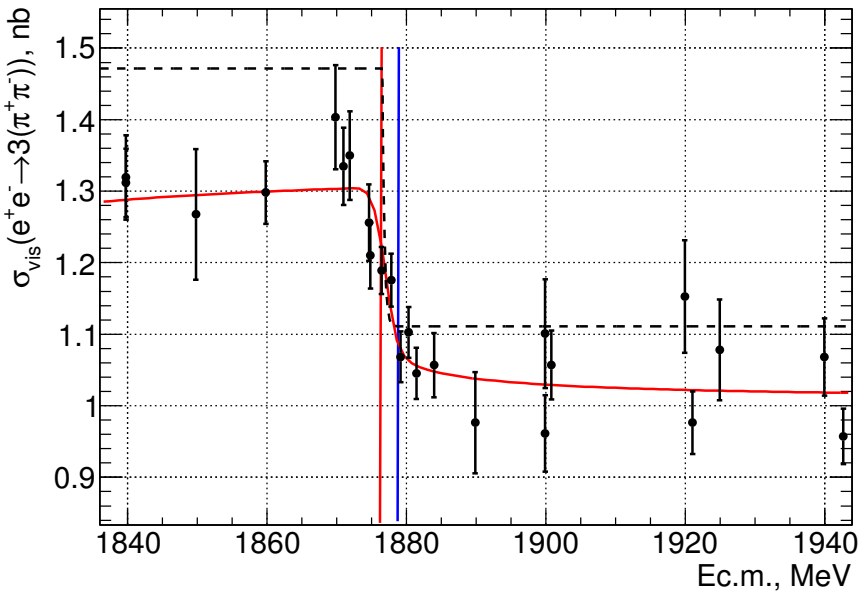
$$\sigma_{f\gamma}(E_{\rm c.m.}) = \int_0^{E_{\rm c.m.}} dE_\gamma \cdot \sigma_{\rm Born}(E_{\rm c.m.} - E_\gamma) \cdot F(E_{\rm c.m.}, E_\gamma).$$

Cross section changes very fast!

For a demonstration we fit observed (visible) cross sections with a exponentially rised Born cross section, changing from A to B at the threshold energy E_{thr}:

$$\sigma_{\mathrm{Born}}(\mathrm{E_{c.m.}}) = \mathrm{A} \pm \mathrm{B}(1 - \exp(-\frac{(\mathrm{E_{c.m.}} - \mathrm{E_{thr}})}{\sigma_{\mathrm{thr}}}))$$

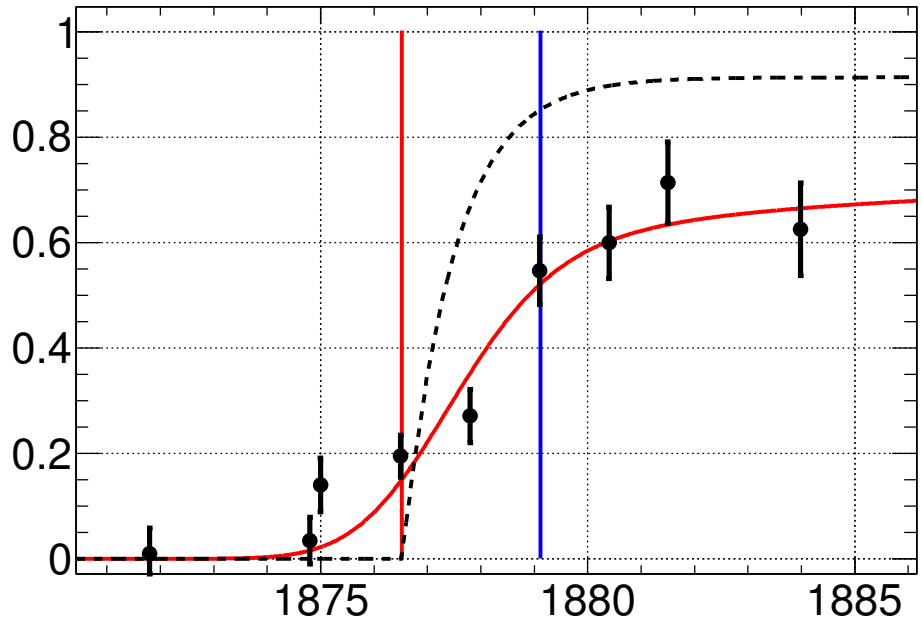


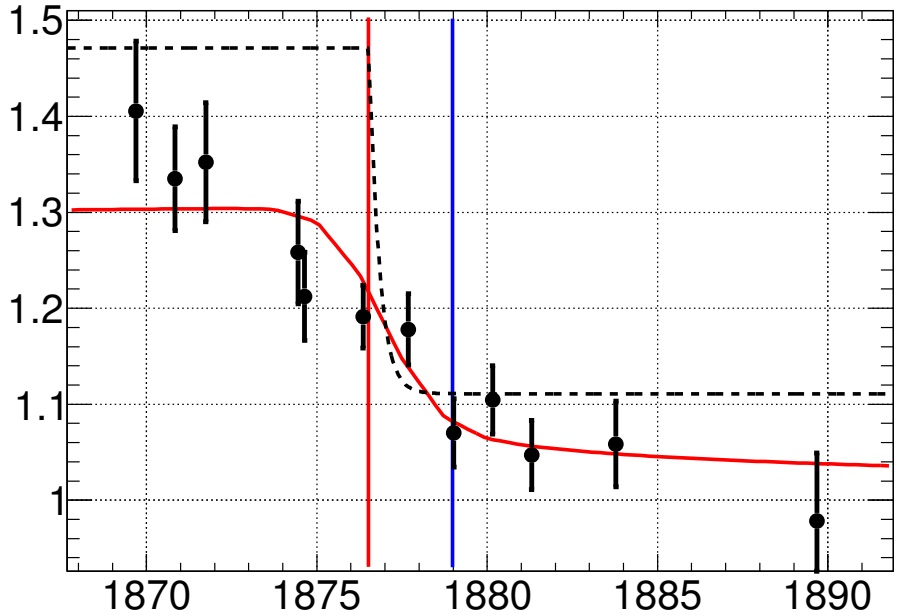


Very fast!

$$\sigma_{\mathrm{Born}}(\mathrm{E_{c.m.}}) = \mathrm{A} \pm \mathrm{B}(1 - \exp(-\frac{(\mathrm{E_{c.m.}} - \mathrm{E_{thr}})}{\sigma_{\mathrm{thr}}}))$$

$\Delta E_{pp\text{-}nn}$= 2.6 MeV

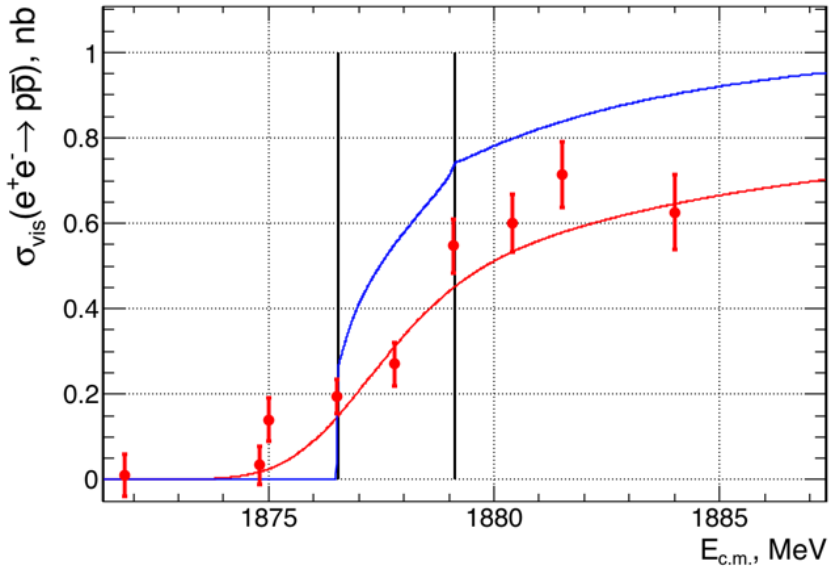


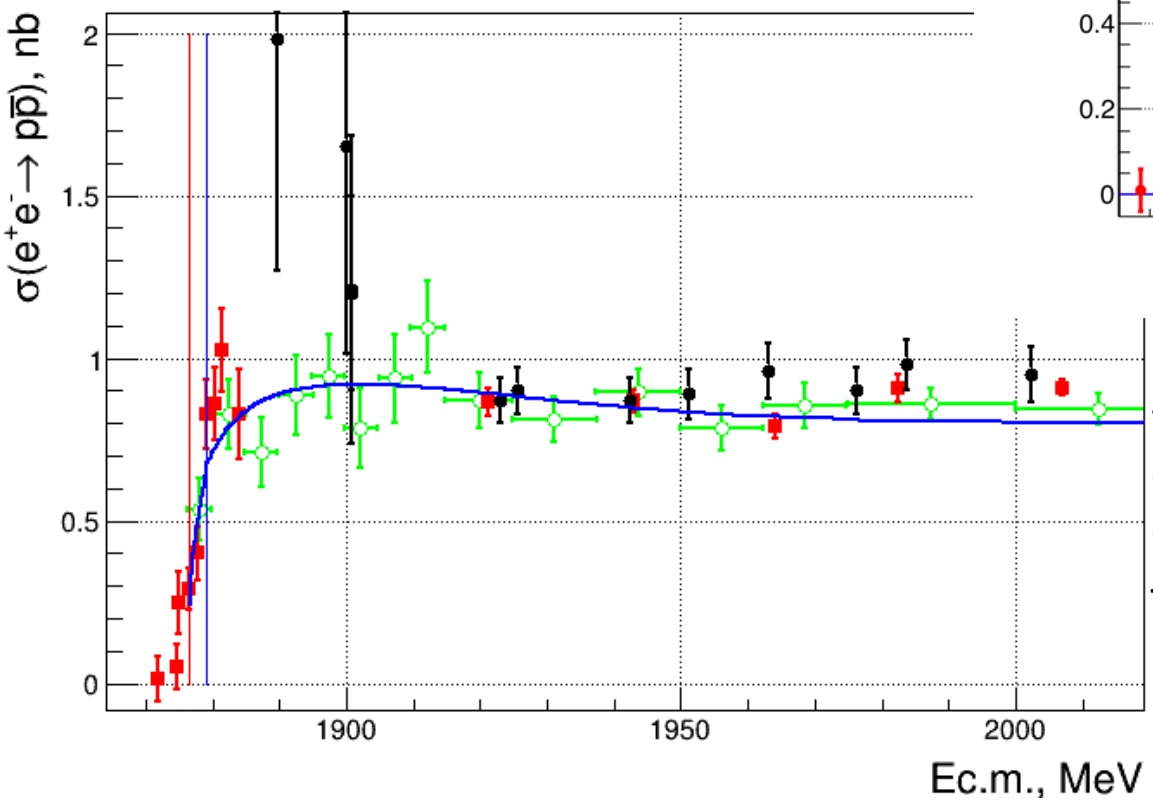


	A,nb	B, nb	E_{thr}, MeV	σ_{thr} , MeV	χ2/n.d.f.
p$\underline{p}$	0-fixed	0.91±0.01	1875.8±0.5	1.76±0.58	34/25
6π	1.49±0.02	-0.40±0.03	1873.7±0.6	3.1±0.9	17/20
p$\underline{p}$	0-fixed	0.914±0.011	1876.54-fixed	0.95±0.25	35/26
6π	1.47±0.03	-0.36±0.03	1876.54-fixed	0.29±0.73	22/21

Milstein-Salnikov prediction (fit?)

Theoretical calculation well describes the experimental data for ppbar production in e+e-

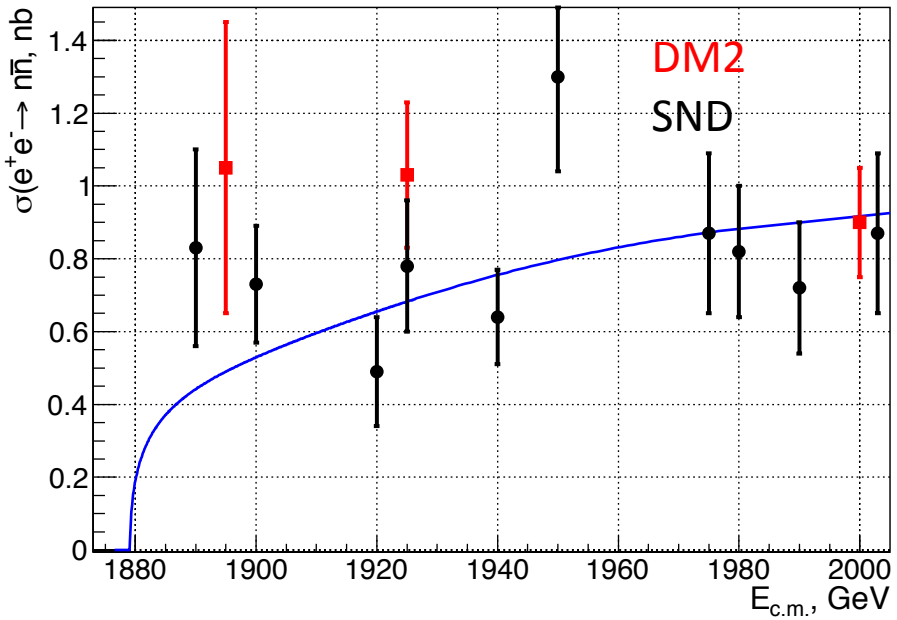




Using predicted shape convoluted with radiative effects and beam energy spread we fit visible XS:
Good agreement in shape
– theoretical prediction should be increased by 10% to fit our 2017 data
Note NON-ZERO XS at the threshold.

Milstein-Salnikov prediction (fit?)

Theoretical calculation not so well describes the experimental data for nnbar production in e+e-, but not in contradiction.

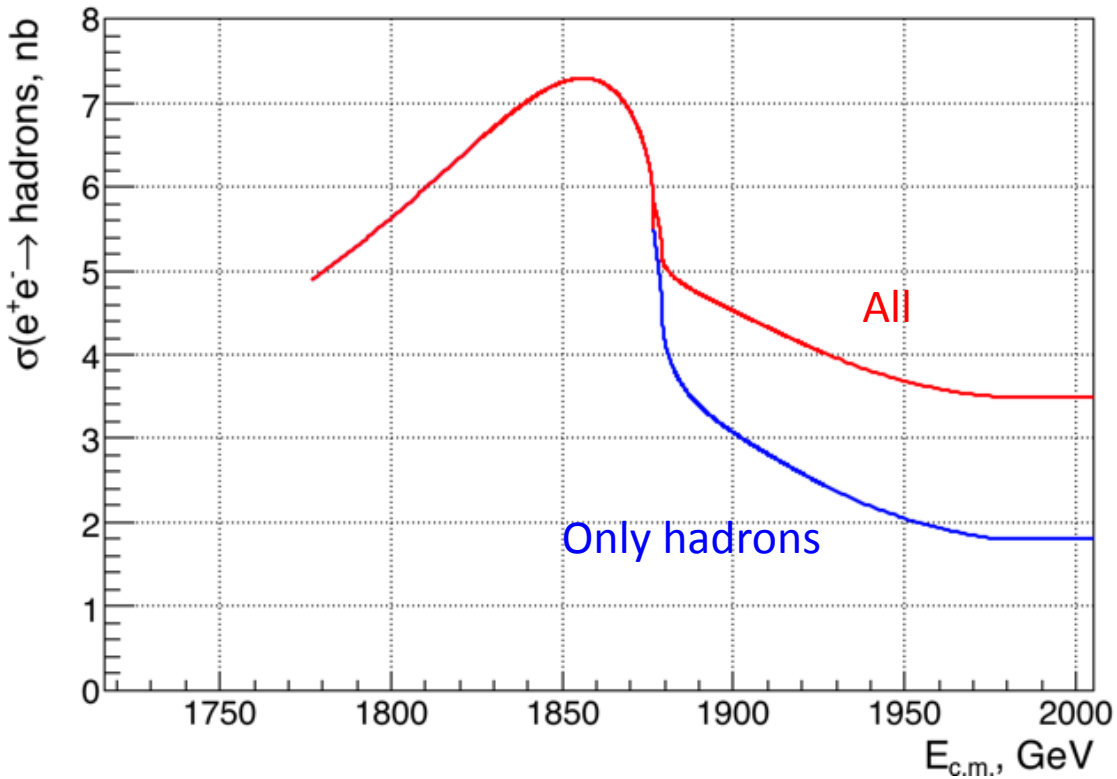


We are eagerly wait for the result of nnbar analysis from SND and CMD-3 at the threshold

Should be later this year.

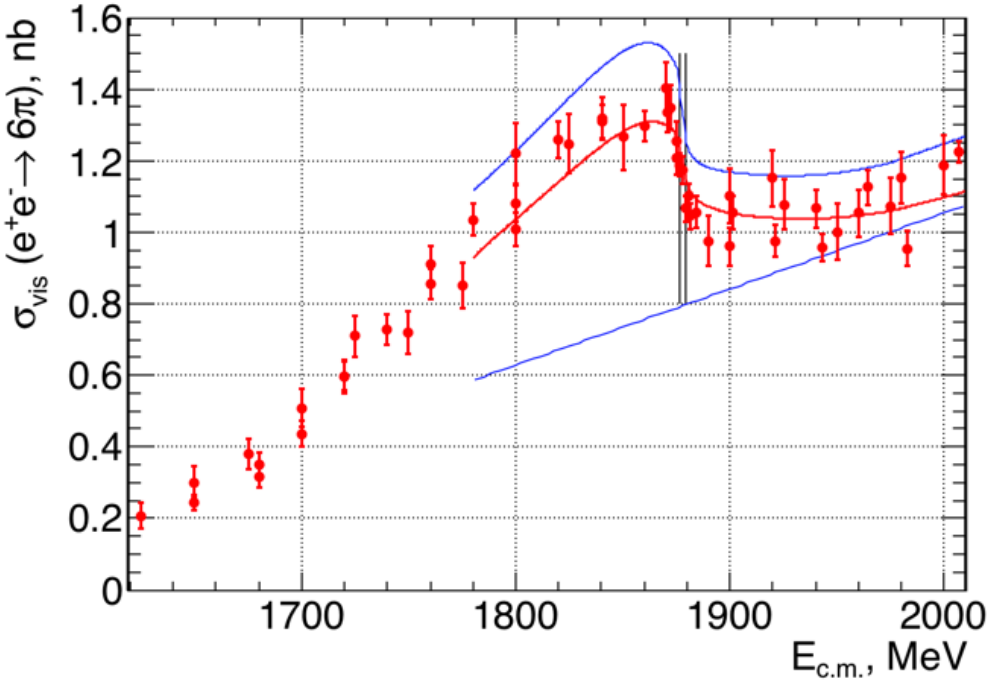
Milstein-Salnikov prediction

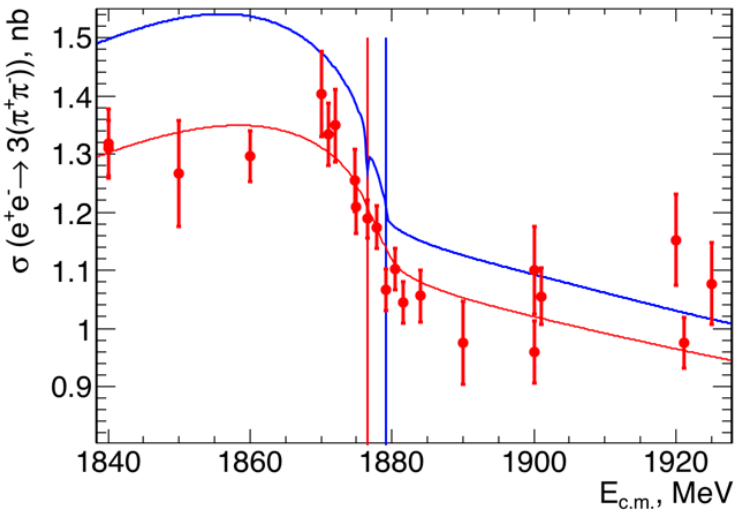
Large contribution to total hadronic cross section!!: 7 nb to ~40 nb total



Milstein-Salnikov prediction – fit 6π

Fit visible experimental XS with scaled theoretical function plus linear continuum
Large contribution to 6π hadronic cross section!!: ~50% at maximum!?



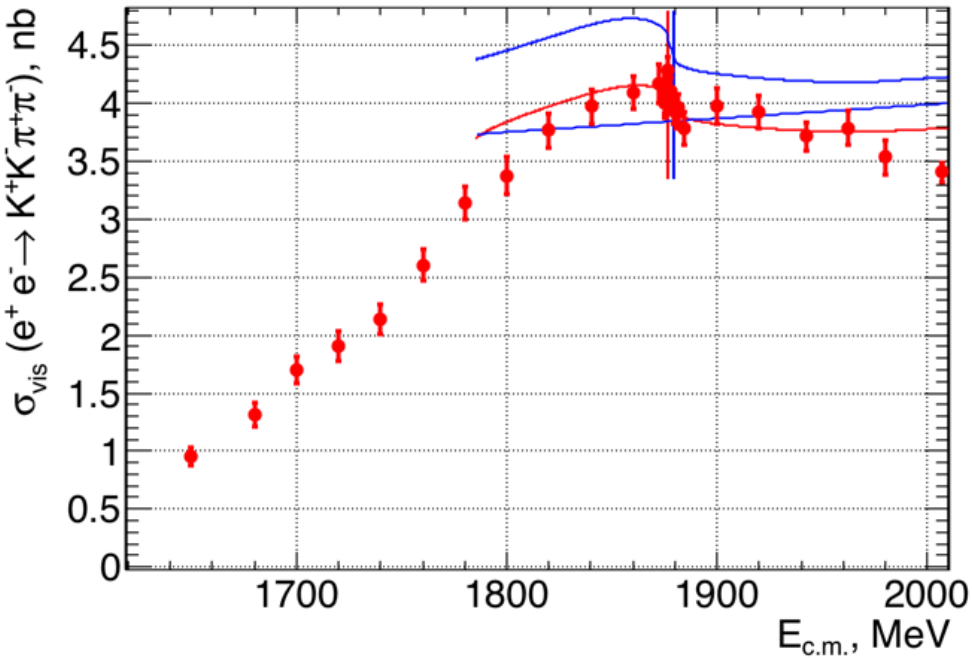


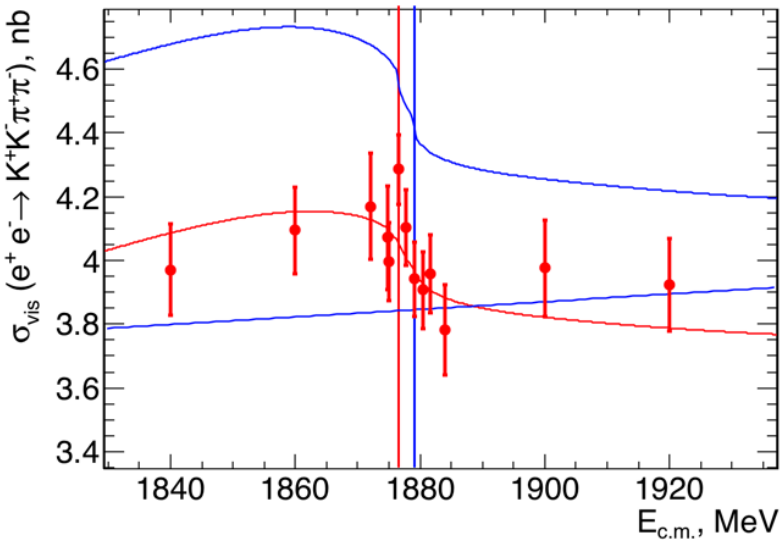
Theoretical function scaled by 0.106+-0.098

Experimental drop looks more sharp, but overall agreement is good

Milstein-Salnikov prediction – fit 2K2π

Fit visible experimental XS with scaled theoretical function plus linear continuum
Large contribution to 2K2π hadronic cross section!!: ~20% at maximum!?

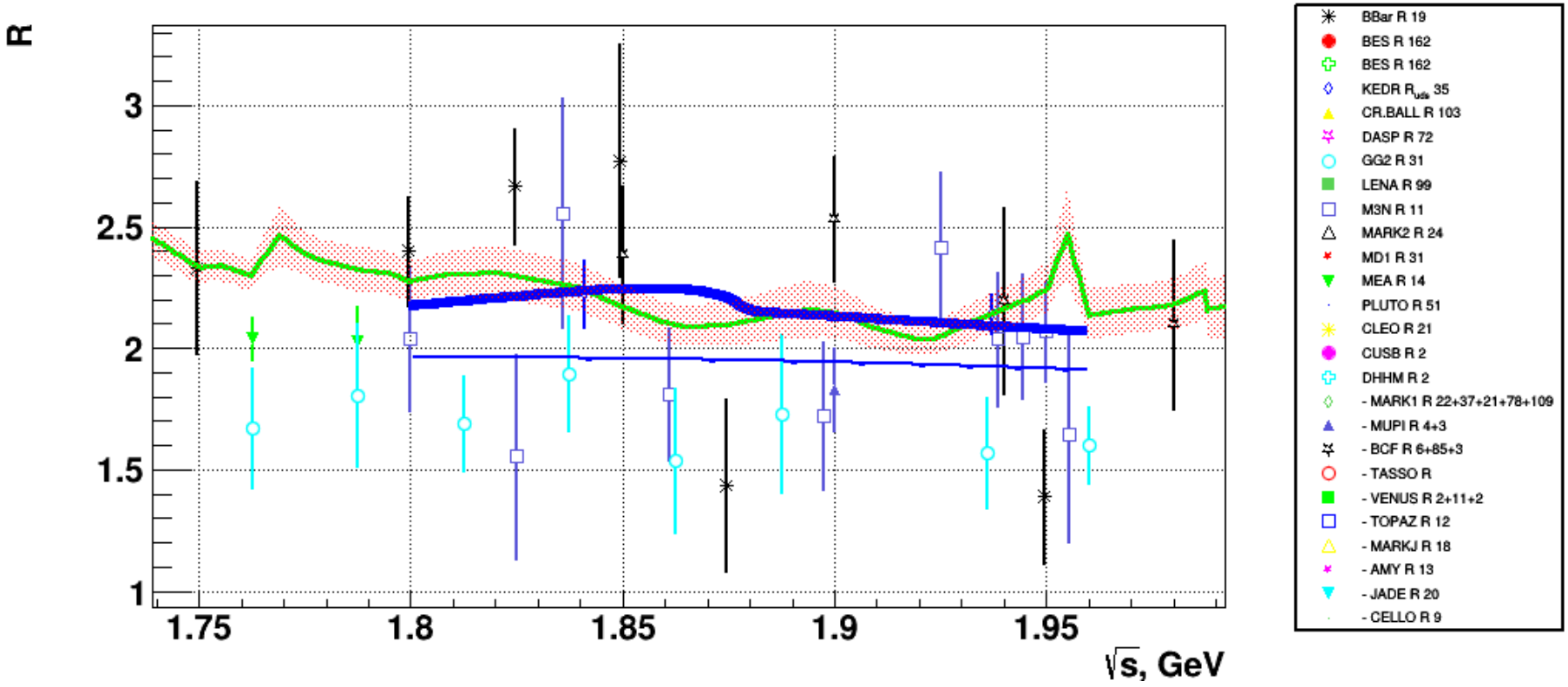




Theoretical function scaled by 0.18+-0.04

Agreement is good
Only ¼ of available data used –
events with one missing track add 3/4

Present accuracy in R is too poor

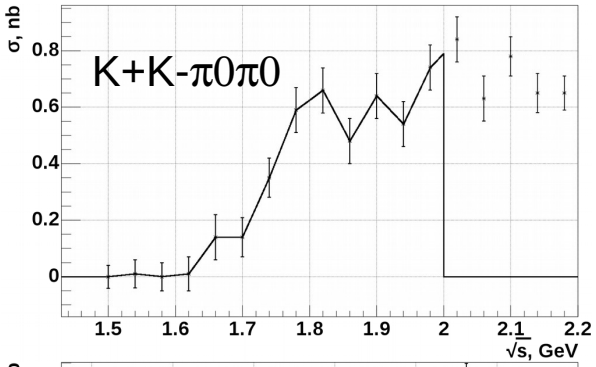


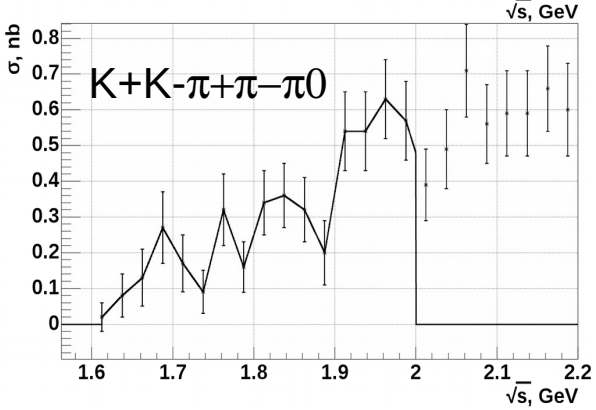
Green line and band – sum of exclusive channels

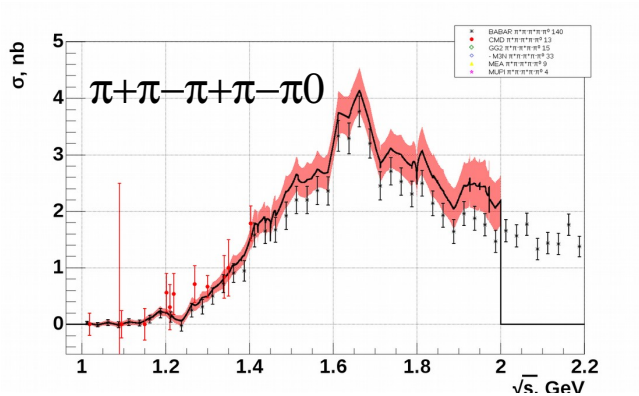
Points – inclusive measurements

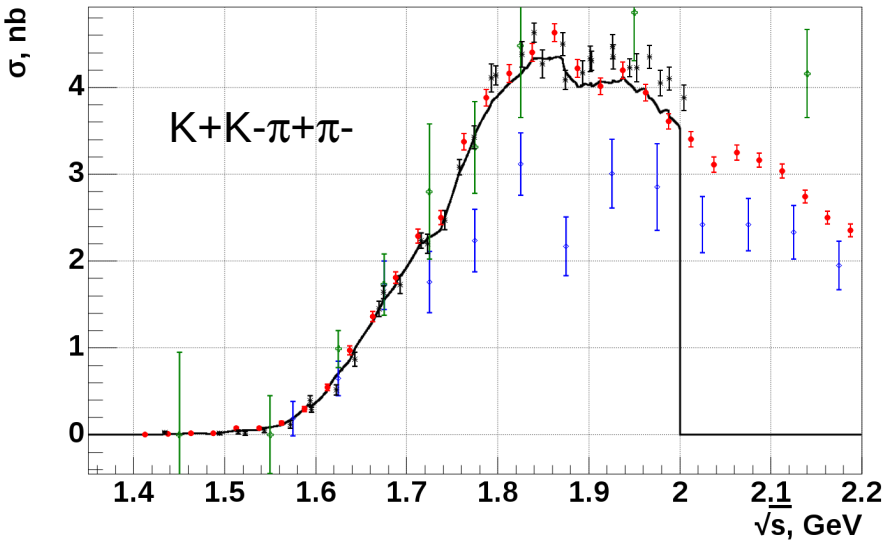
Blue line(s) – Milstein-Salnikov prediction – about 15% of total XS is due to NN interaction !?

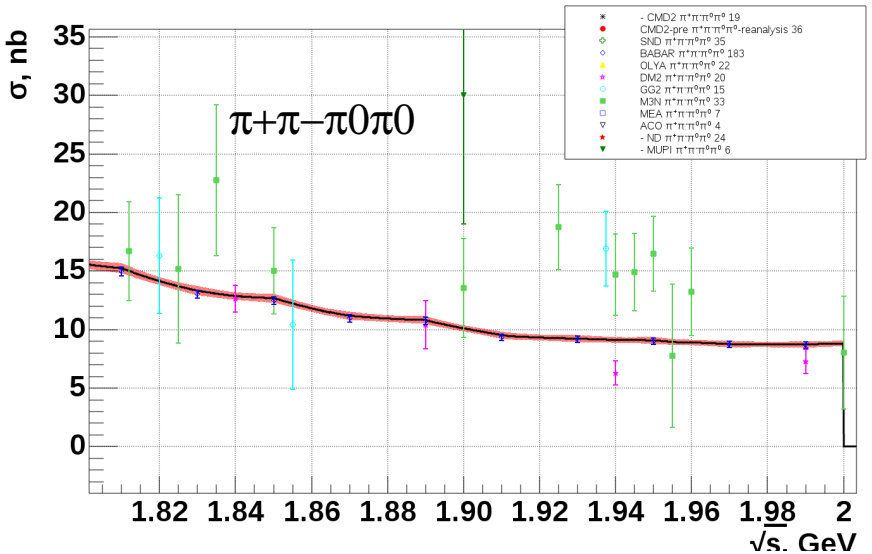
Cross sections data base











Open questions

- Why we do not see structure in 4π?
  - if it is a normal NNbar annihilation it should be 14%/6% larger, than for 6 pions
  - it looks like a complicated dynamics of virtual NN pair before annihilation?
  - in contrary – the NNbar annihilation to $K^+K^-\pi^+\pi^-$ is very low, but we see the structure
  - any other channels?
- Can we observe contribution to total cross section?
  - is changing in dynamics below threshold connected to NNbar contribution?
- Why there is no interference? Can we observe it with more data?
- Can we observe influence of two thresholds?

Summary

- In 2017 г. we have increase data at E>1 GeV by factor of 3 – Thanks to our machine people.
- We obtain preliminary results for the $e^+e^- \to p\bar{p}$, $3(\pi^+\pi^-)$, $2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$ cross sections in the 1.5 – 2.0 GeV energy range with the detailed scan at the NNbar threshold.
- We confirm sharp structure in $e^+e^- \to 3(\pi^+\pi^-)$ at the NNbar thresholds and found it in $K^+K^-\pi^+\pi^-$!
- Sharp structure is difficult to explain as interference of the resonance with continuum.
- With the small step scan we observe a "fine structure" of cross sections and for the $e^+e^- \to p\bar{p}$ cross section it is ~ 1 MeV !
- Unfortunately, still low statistic and energy spread do not allow to observe ultra-fine structure, the nnbar influence.
- Many other hadronic channels are under analysis – should be published soon
- Results for the $e^+e^- \to n\bar{n}$ will come out soon

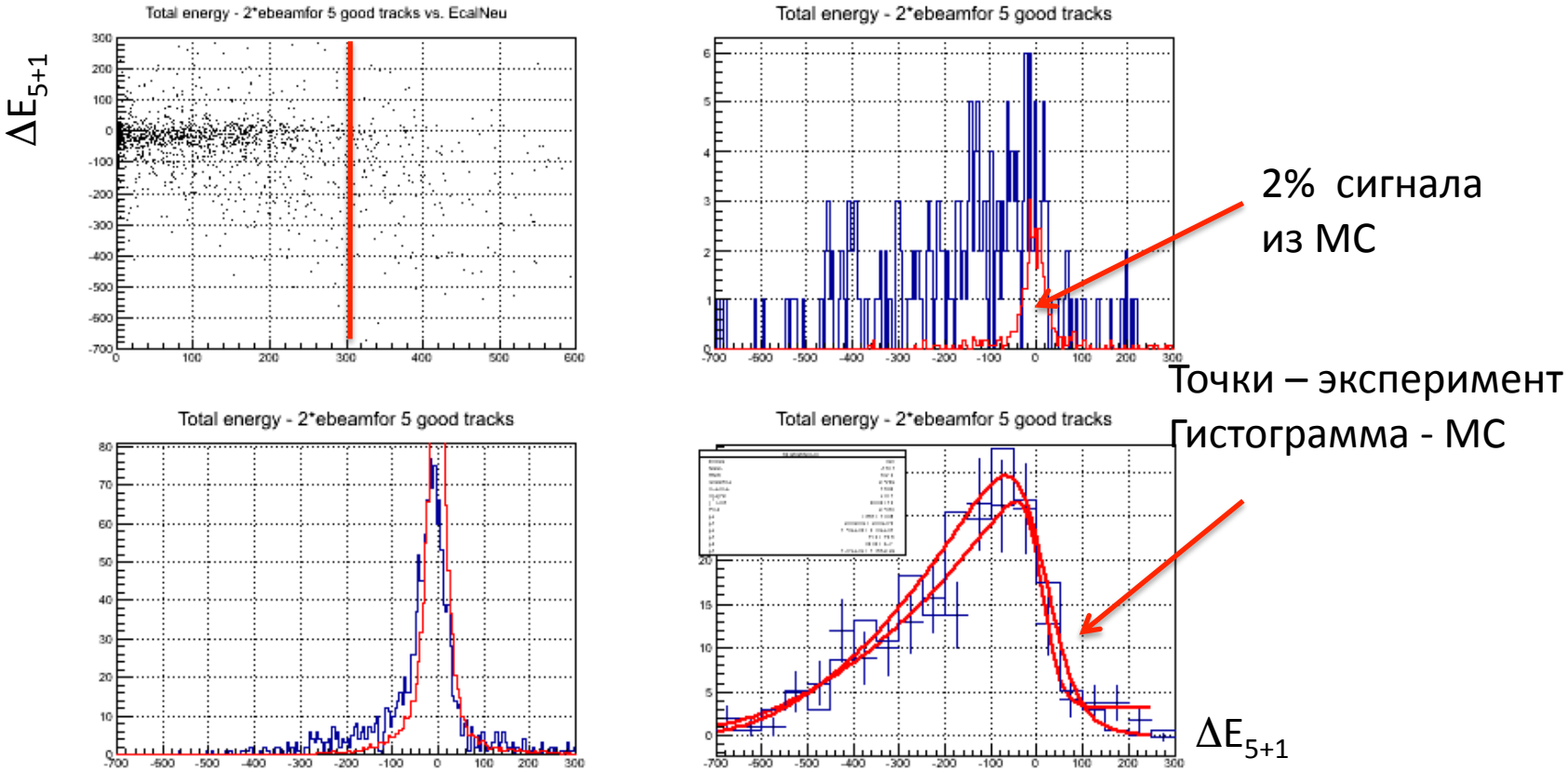
We plan to collect more data (X10) in next season

Thanks

Backup slides

Фон для событий с 5-ю треками (1)

Форма фона берется из моделирования фоновых процессов.
Основной вклад дают e+e- -> $2(\pi^+\pi^-)\pi^0\pi^0$, $2(\pi^+\pi^-)\pi^0$ с конверсией одного фотона
Для сравнения с экспериментом изучались события с $E_{neutral}$ > 300 MeV - - энергия в калориметре, не связанная с заряженными треками.

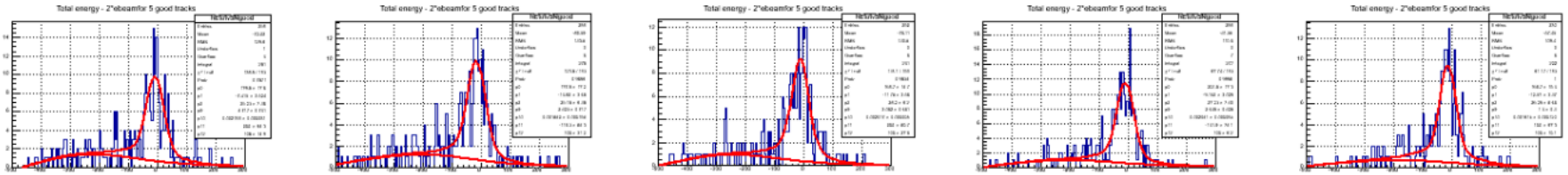


Фон аппроксимировался функцией Ферми умноженой на полином 3-й степени

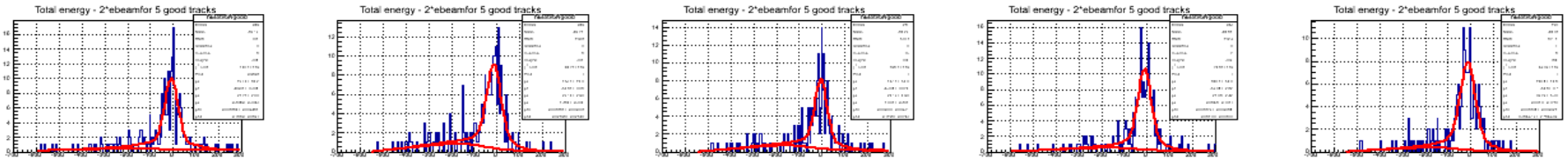
Фон для событий с 5-ю треками (2)

Проводилось определение числа событий с отбором $E_{neutral}$ < 300 MeV – и без него.
параметры Ферми фиксировались (и менялись от энергии)
– параметры полинома свободны

Нет отбора по $E_{neutral}$

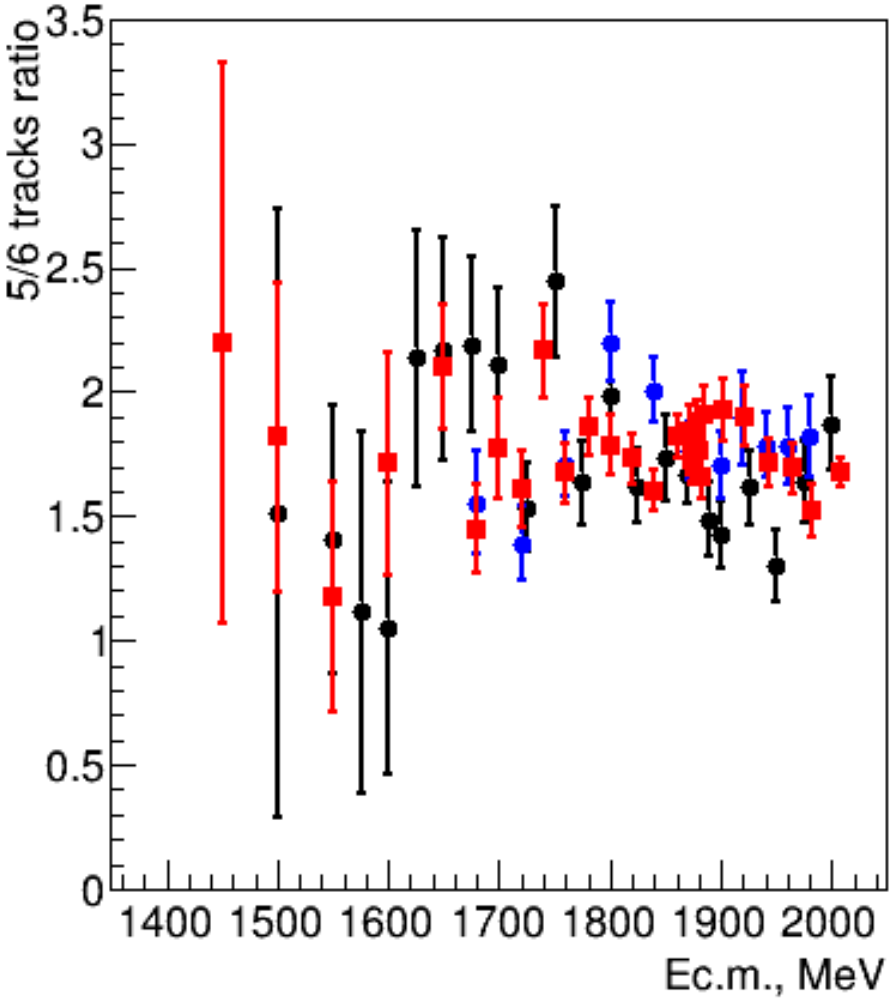


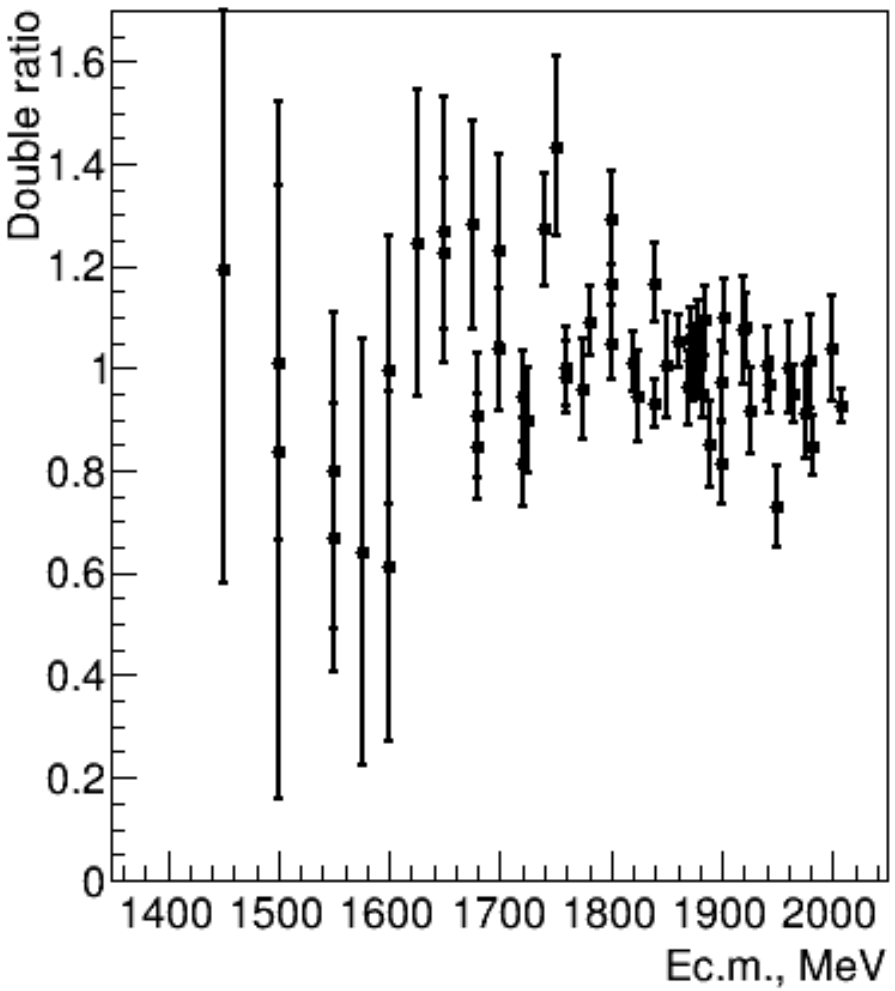
$E_{neutral}$ < 300 MeV



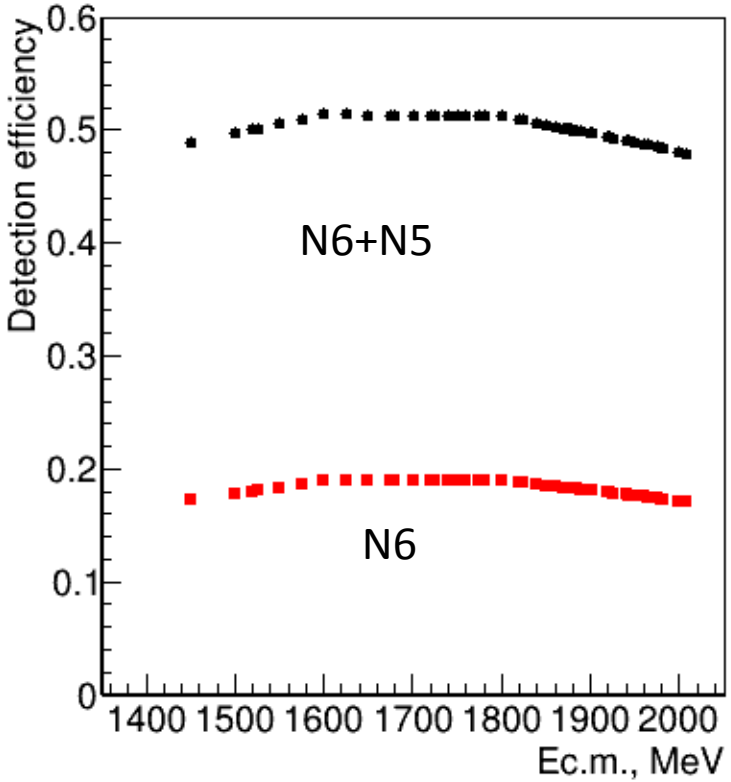
Интегрально число событий менялось не более,
чем на 3% - оценка систематической ошибки.
Статистически в каждой точке разница незаметна.

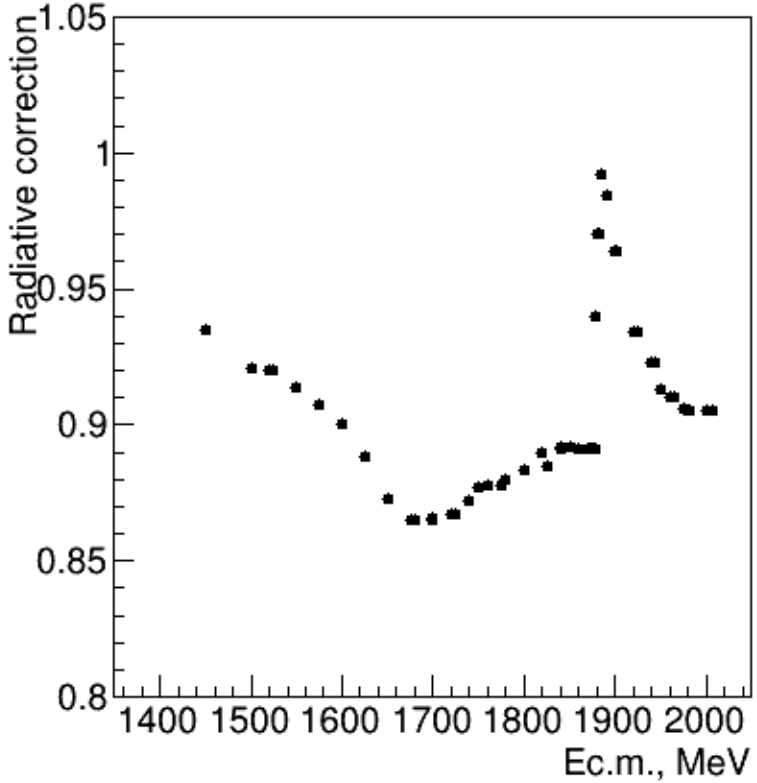
5/6 отношение – добавлены точки 2017 г.





Эффективность и рад. поправка



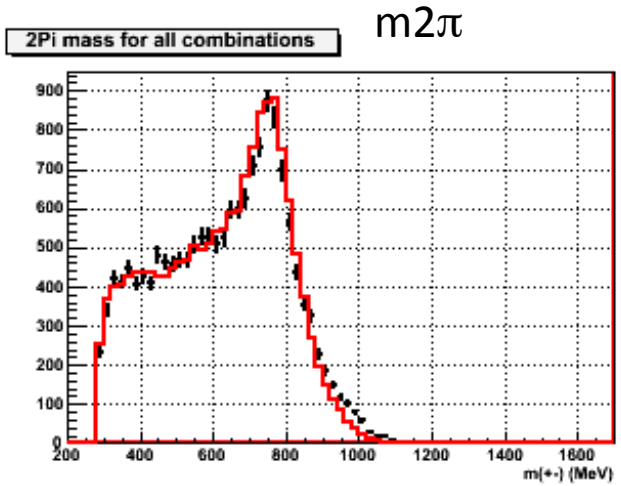


Для расчета сечений бралась сумма N6+N5

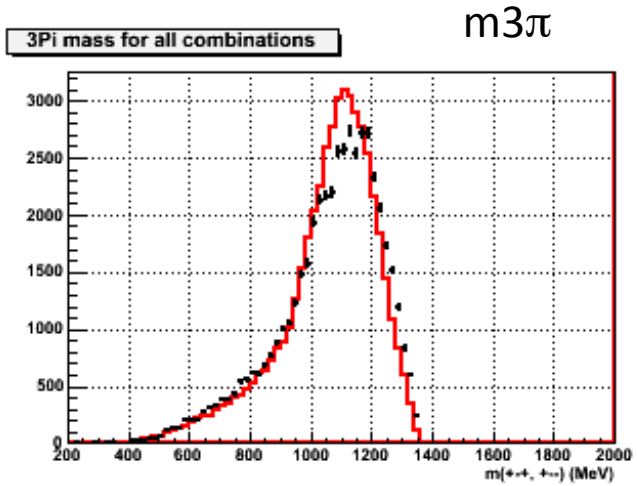
Рад. поправка расчитывалась итеррациями: Бралось сечение БаБар, потом подставлялось наше экспериментальное сечение.

Проблемы с пониманием динамики

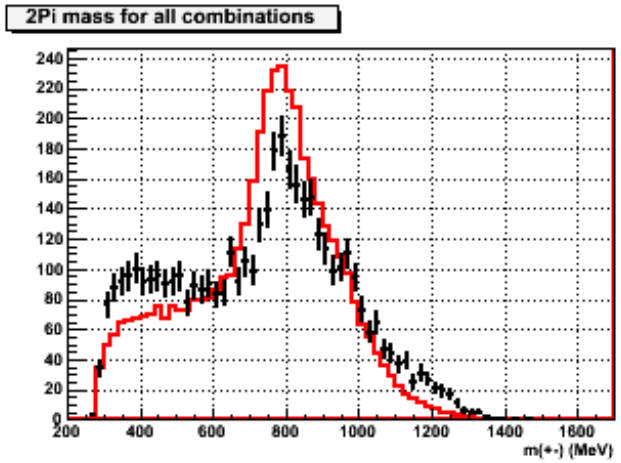
m2π

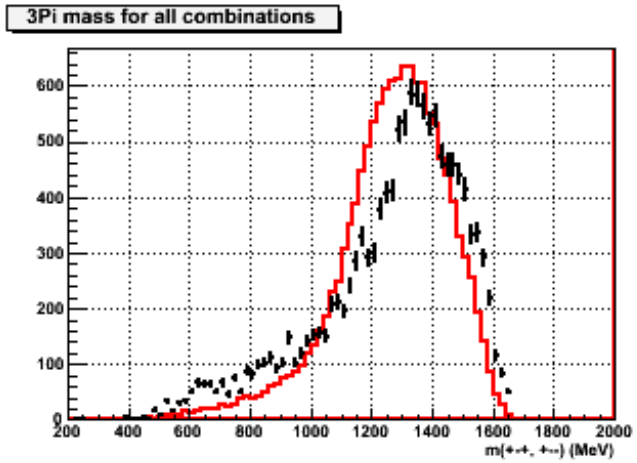


m3π



Ebeam = 750 MeV





Ebeam = 900 MeV

Модель $a_1\pi$ не описывает массовые расспределения выше 1.5 ГэВ

Мы не готовы оценить систематику в сечении $e^+e^- \to 2(\pi^+\pi^-)$