Eta Decays with WASA-at-COSY

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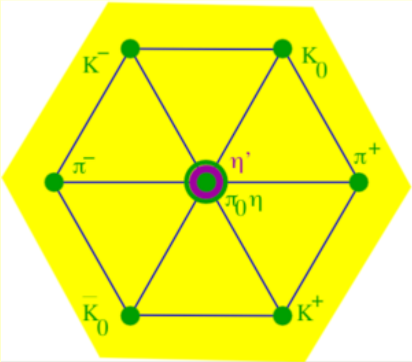
Outline

- Physics Motivation

Why the η is unique for symmetry tests of ChPT, C-violating and P-conserving new physics

- Charged radiative decays with WASA
- Why incident energy near thresholds was used
- Triggers, luminosity
- Main results from WASAat CELSIUS and WASAatCOSY
- COSY vs GSI advantages and disanvantages
- Summary and discussion

Why η is a unique probe



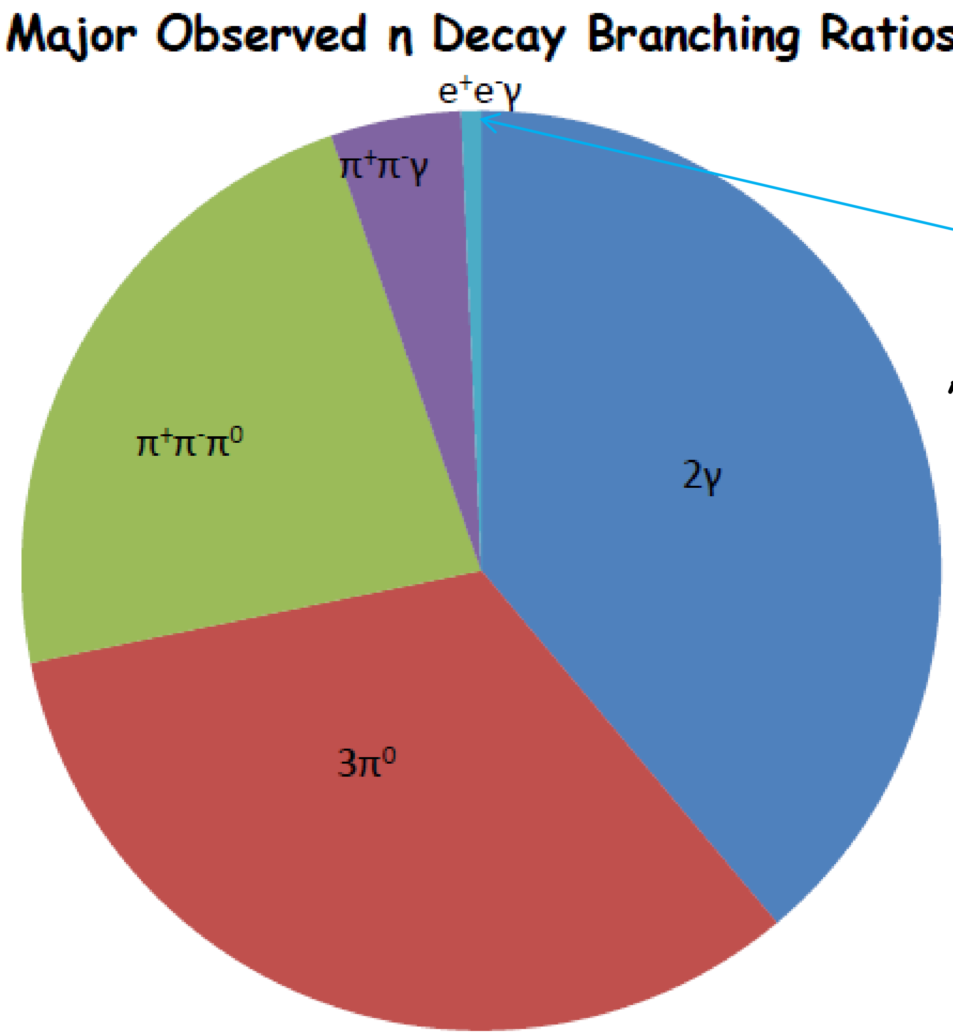
- A Goldstone boson due to spontaneous breaking of QCD chiral symmetry
  - ➡ η is one of key mesons bridging our understanding of low-energy hadron dynamics and underlying QCD

- η decay width Γ_η =1.3KeV is narrow
  - ➡ The lowest orders of η decays are filtered out, enhancing the contributions from higher orders.

- Eigenstate of P, C, CP, and G: $I^G J^{PC} = 0^+ 0^{-+}$
  - ➡ Study violations of discrete symmetries

- The η decays are flavor-conserving laboratories for new physics search.

The η Decay Modes



PDG 2016

The light blue sliver represents BR = 0.7%.

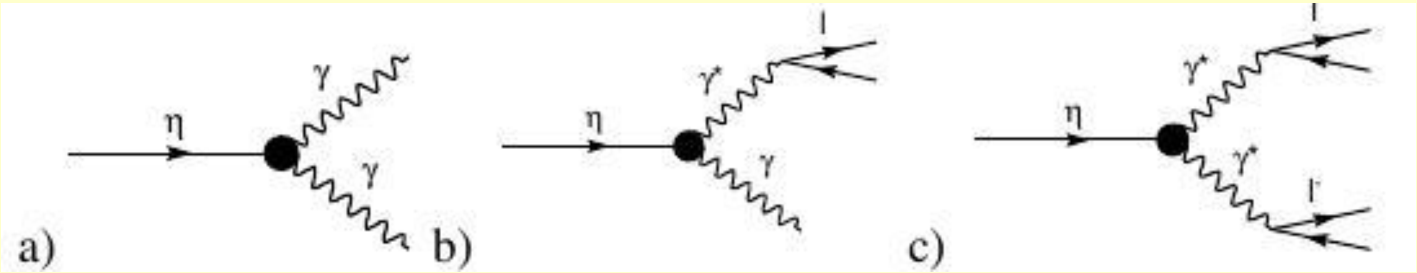
All other η rare decays would be invisible on this pie chart.

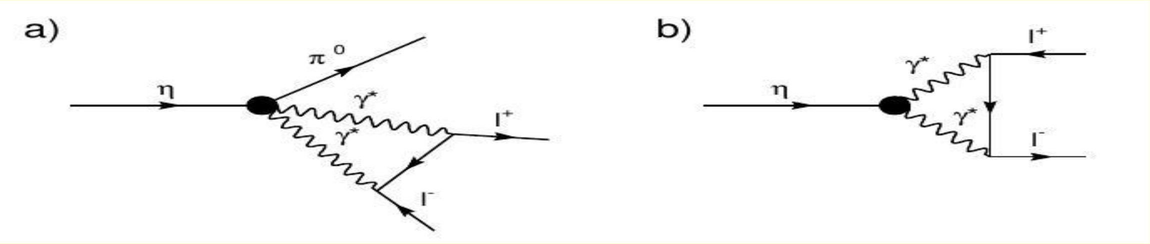
Eta charged modes

J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001

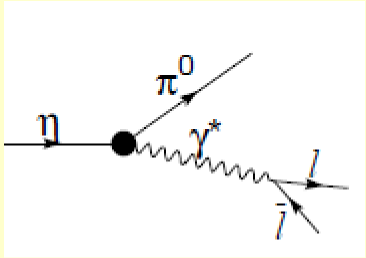
Mode		Fraction
$\pi^+\pi^-\pi^0$		(22.92 ± 0.28) %
$\pi^+\pi^-\gamma$		(4.22 ± 0.08) %
$e^+e^-\gamma$		$(6.9\pm0.4)\times10^{-3}$
$\mu^+\mu^-\gamma$		$(3.1\pm0.4)\times10^{-4}$
e^+e^-		$< 5.6\times10^{-6}$
$\mu^+\mu^-$		$(5.8\pm0.8)\times10^{-6}$
$2e^+2e^-$		$(2.40\pm0.22)\times10^{-5}$
$\pi^+\pi^-e^+e^-(\gamma)$		$(2.68\pm0.11)\times10^{-4}$
$e^+e^-\mu^+\mu^-$		$< 1.6\times10^{-4}$
$2\mu^+2\mu^-$		$< 3.6\times10^{-4}$
$\mu^+\mu^-\pi^+\pi^-$		$< 3.6\times10^{-4}$
$\pi^+e^-\overline{\nu}_e +$ c.c.		$< 1.7\times10^{-4}$
$\pi^+\pi^-2\gamma$		$< 2.1\times10^{-3}$
$\pi^+\pi^-\pi^0\gamma$		$< 5\times10^{-4}$
$\pi^0\mu^+\mu^-\gamma$		$< 3\times10^{-6}$
$\pi^+\pi^-$	P,CP	$< 1.3\times10^{-5}$
$\pi^0e^+e^-$	C	[f] $< 4\times10^{-5}$
$\pi^0\mu^+\mu^-$	C	[f] $< 5\times10^{-6}$
$\mu^+e^- + \mu^-e^+$	LF	$< 6\times10^{-6}$

Radiative eta decays studied with WASA
(both charged and neutral product measured in CD)





C and CP violating



$\eta \rightarrow e^+e^-$ and $\eta \rightarrow \pi^0 e^+e^-$ decays

Both decays are highly suppressed.

In SM can only proceed through a 2-photon intermediate state.

Any new physics beyond the SM can enhance the rates.

PDG 2016 90% CL

$\eta \rightarrow e^+e^- < 2.3\times10^{-6}$

$\eta \rightarrow \pi^0 e^+e^- < 4\times10^{-5}$

Trigger based on two protons in FD for pp->ppη
Trigger based on 3He in case of pd->3Heη reaction

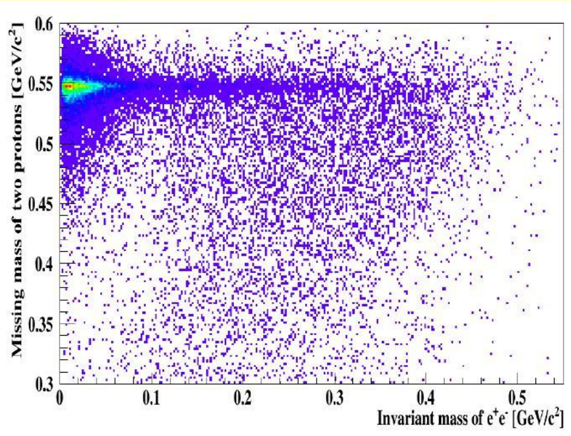
- At threshold :

tranversal momenta of primary product = 0

all primary particles emitted forward

trigger based on protons or the He.

Decay products emitted at large angles.



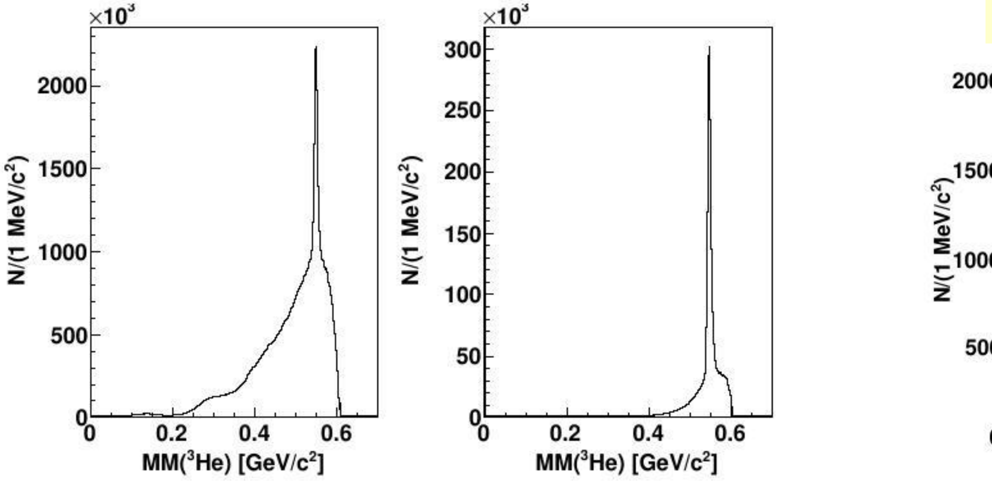


Figure 2: Distribution of ^{3}He missing mass for $pd \rightarrow {}^3\mathrm{He}X$ reaction at 1.0 GeV. The trigger w entirely on ^{3}He signal in FD without bias on the decay system. The plot shows all data collected in period. (left) data analysis bases only on the forward detector track – there is about 11×10^6 even peak at the η meson mass (right) in addition invariant mass of two photons $\geq$ 300 MeV/c^2.

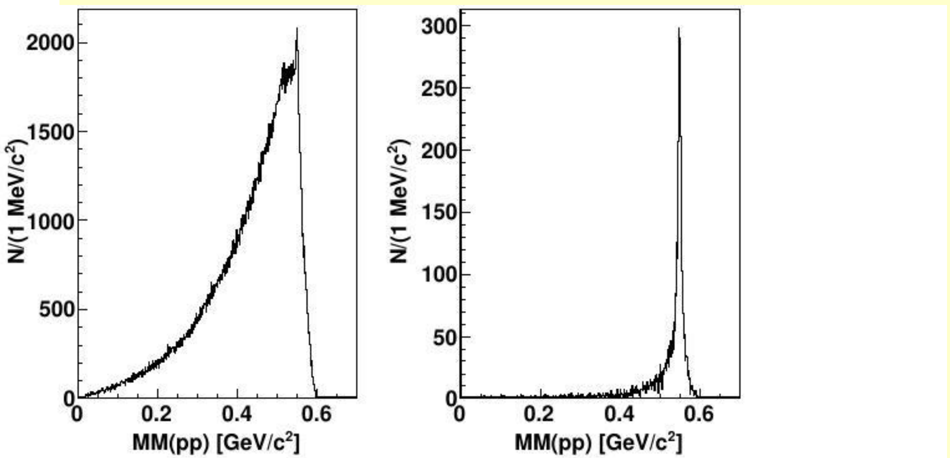
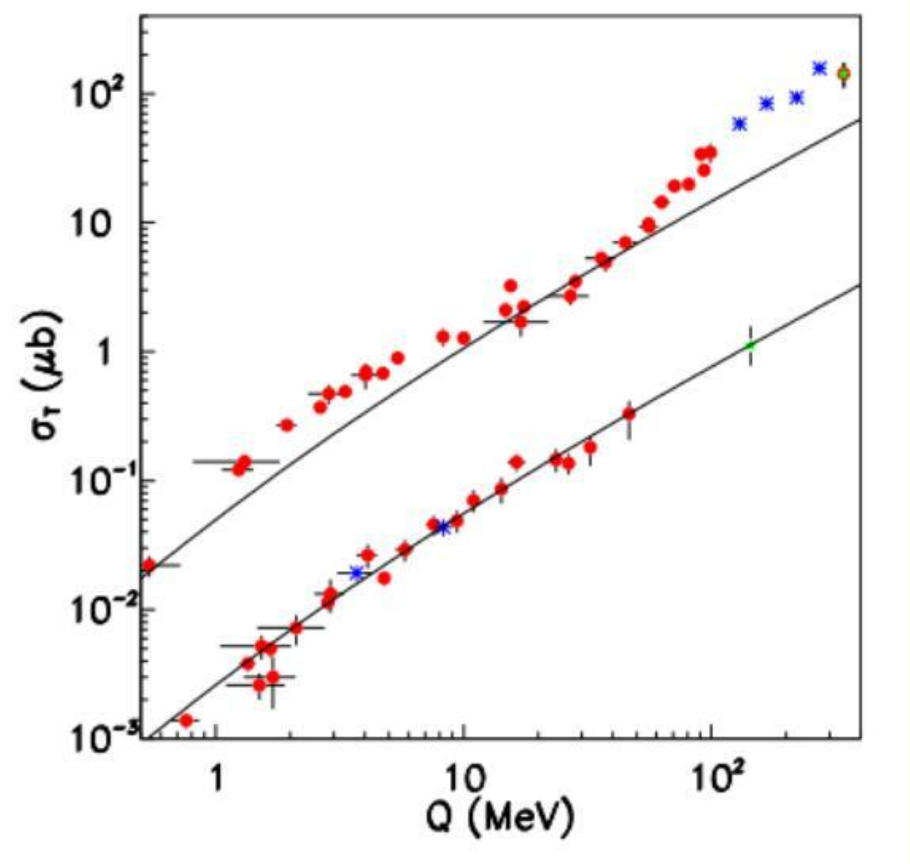


Figure 3: Proton–proton missing mass distributions in $pp \rightarrow ppX$ reaction at 1.4 GeV with trigger requiring two tracks from charged particles in FD and at least two clusters from neutral particles in the calorimeter.

Optimalization between the rise of cross section of η and η' with incident energy and efficiency of tagging in Forward Detectors.



Measurements of BR for rare radiative eta decays using WASA

- Phys.Rev.D77 (2008) 032004 WASAatCELSIUS

Decay mode	BR	BR limit 90% CL
1. $\eta \to e^+e^-e^+e^-$	$(2.7^{+2.1}_{-2.7\text{stat}} \pm 0.1_{\text{syst}}) \times 10^{-5}$	$<9.7 \times 10^{-5}$
2. $\eta \to \pi^+\pi^-\mu^+\mu^-$	—	$<3.6 \times 10^{-4}$
3. $\eta \to \mu^+\mu^-\mu^+\mu^-$	—	$<3.6 \times 10^{-4}$
4. $\eta \to e^+e^-$	—	$<2.7 \times 10^{-5}$
5. $\eta \to \pi^+\pi^-e^+e^-$	$(4.3^{+2.0}_{-1.6\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-4}$	—
6. $\eta \to e^+e^-\mu^+\mu^-$	—	$<1.6 \times 10^{-4}$
7. $\eta \to e^+e^-\gamma$	$(7.8 \pm 0.5_{\text{stat}} \pm 0.8_{\text{syst}}) \times 10^{-3}$	—

- Phys.Rev.C94 (2016) no6 , 065206 WASAatCOSY

Channel	Branching Ratio
$\eta \to \pi^+\pi^-\gamma$	$(4.67 \pm 0.07_{stat/fit} \pm 0.19_{sys}) \times 10^{-2}$
$\eta \to e^+e^-\gamma$	$(6.72 \pm 0.07_{stat/fit} \pm 0.31_{sys}) \times 10^{-3}$
$\eta \to \pi^+\pi^-e^+e^-$	$(2.7 \pm 0.2_{stat} \pm 0.2_{sys}) \times 10^{-4}$
$\eta \to e^+e^-e^+e^-$	$(3.2 \pm 0.9_{stat} \pm 0.5_{sys}) \times 10^{-5}$

Measurement of the η → π+π−e+e− decay branching ratio, *Phys. Lett.* **B644** (2007) 299–303,

Measurement of the η → π+π−e+e− decay

Phys. Lett. **B644** (2007) 299–303

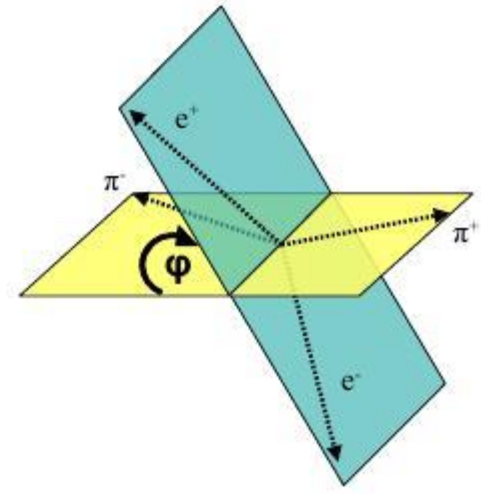


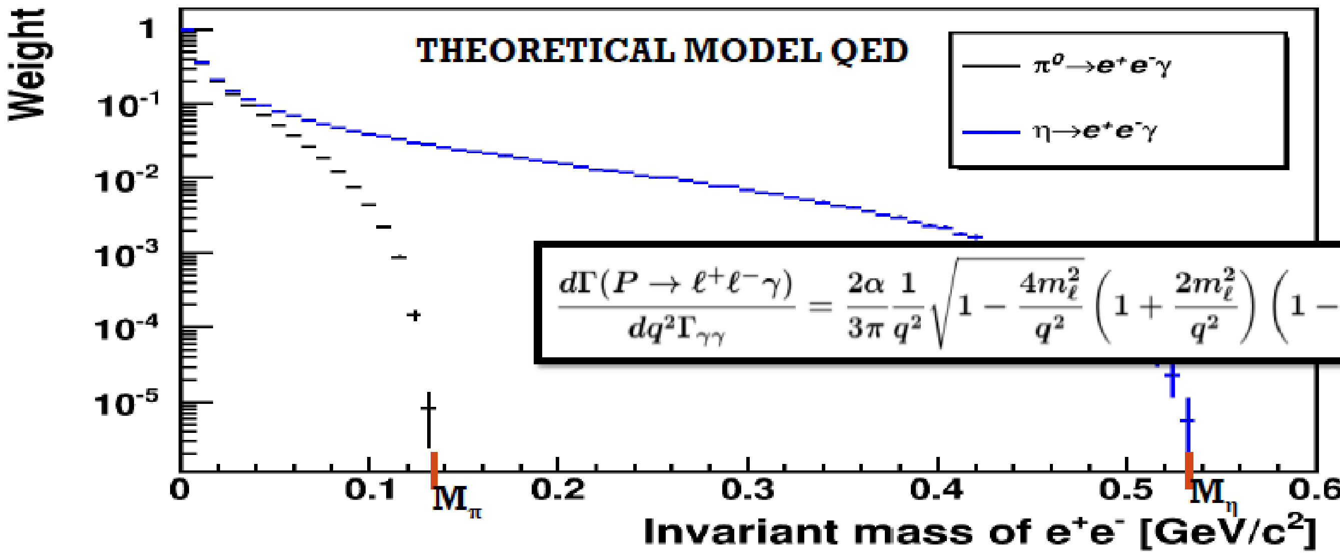
FIG. 11. (Color online) Definition of the dihedral angle ϕ for the $\eta \to \pi^+\pi^-e^+e^-$ decay in the η meson rest frame.

The measured dihedral angle asymmetry, A_ϕ for $\eta \to \pi^+\pi^-e^+e^-$ has been determined to be consistent with zero: $A_\phi = (-1.1 \pm 6.6_{stat} \pm 0.2_{sys}) \times 10^{-2}$.

INVARIANT MASS OF LEPTON PAIR

- $\eta \to e^+e^-\gamma$ larger mass range than $\pi^0 \to e^+e^-\gamma$
- Unfortunately – lower statistics ($\sigma_{pp\to pp\eta} << \sigma_{pp\to pp\pi}$)

  $\mu b << mb$



$$\frac{d\Gamma(P\to \ell^+\ell^-\gamma)}{dq^2\Gamma_{\gamma\gamma}} = \frac{2\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4m_\ell^2}{q^2}}\left(1+\frac{2m_\ell^2}{q^2}\right)\left(1-\frac{q^2}{M_P^2}\right)^3 |F_P(q^2,0)|^2$$

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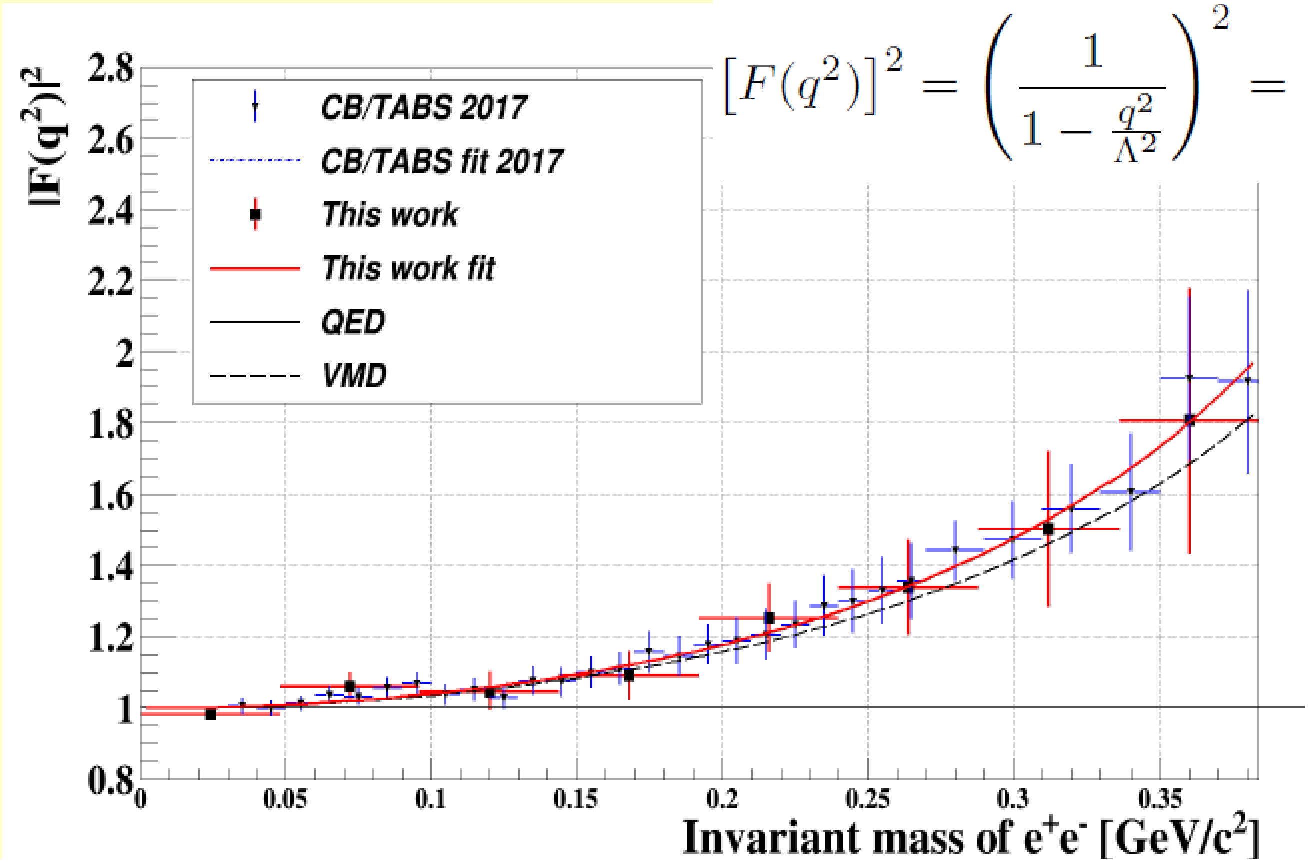
$$[F(q^2)]^2 = \left(\frac{1}{1-\frac{q^2}{\Lambda^2}}\right)^2 = \left(\frac{1}{1-b_\eta \cdot q^2}\right)^2$$

Eta transition form-factor parameter



$$[F(q^2)]^2 = \left(\frac{1}{1-\frac{q^2}{\Lambda^2}}\right)^2 = \left(\frac{1}{1-b_\eta \cdot q^2}\right)^2$$

Table 8.3: FF fits from various experiments

Experiment	Source of η	$\eta \to e^+e^-\gamma$ candidates	Λ^{-2} [GeV^{-2}]
CB/TABS	$\gamma p \to \eta p$	$5.4 \cdot 10^4$	$(1.97 \pm 0.11_{\text{tot}})$
WASA [68]	$pd \to {}^3He\eta$	$5.2 \cdot 10^2$	$(2.27 \pm 0.73_{\text{stat}} \pm 0.46_{\text{sys}})$
WASA [69]	$pp \to pp\eta$	$3.1 \cdot 10^3$	$(1.9 \pm 0.33_{\text{stat}})$
WASA this work	$pp \to pp\eta$	$1.1 \cdot 10^2$	$1.97 \pm 0.29_{\text{stat}}\,^{+0.14_{\text{sys}}}_{-0.22_{\text{sys}}}$

New possibility at FRS

Eta from nucleus-nucleus collisions ?

Why not? Cross section is much larger.

But a lot of nuclei break up products. Peripheral collisions can be a solution.

Example:

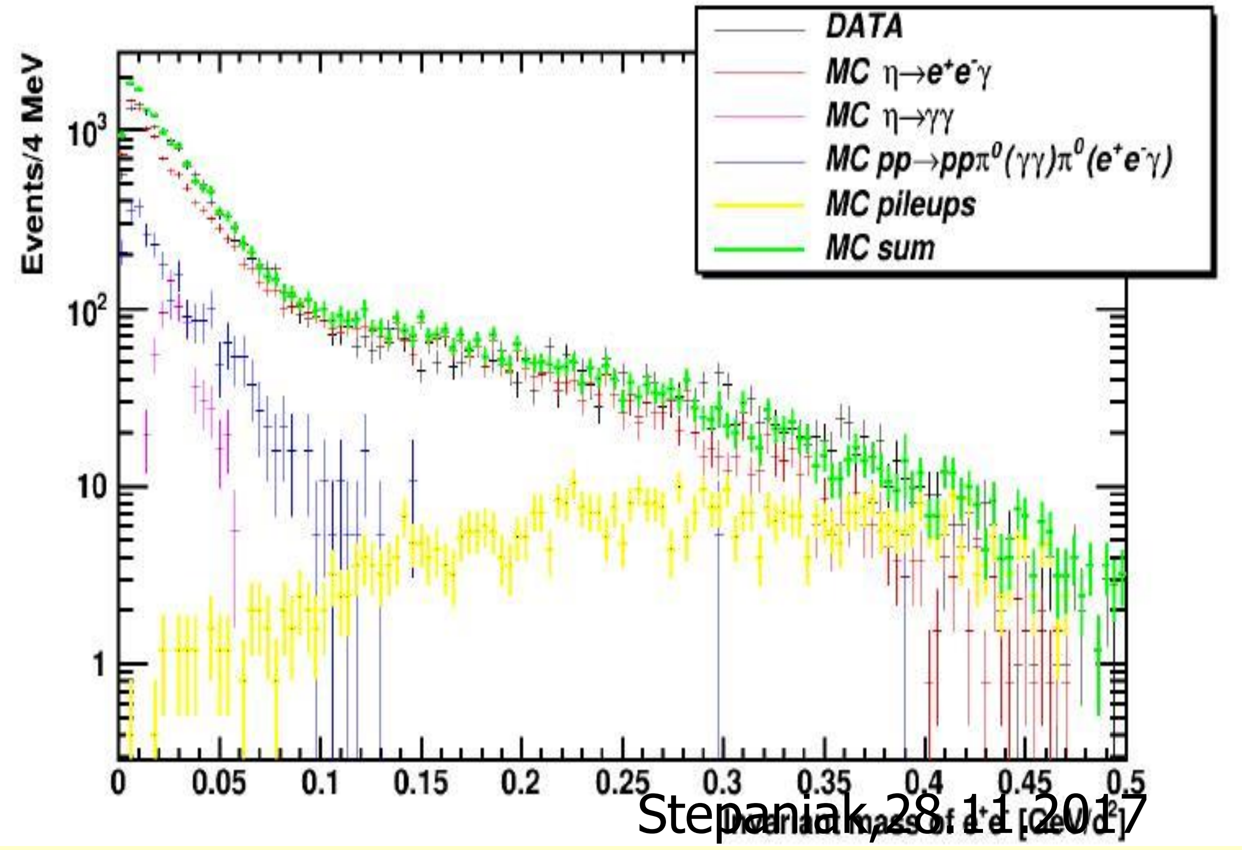
NA60 detected 9300 $\eta \to \mu^+\mu^-\gamma$ events

in peripheral In-In data. FF parameter extracted:

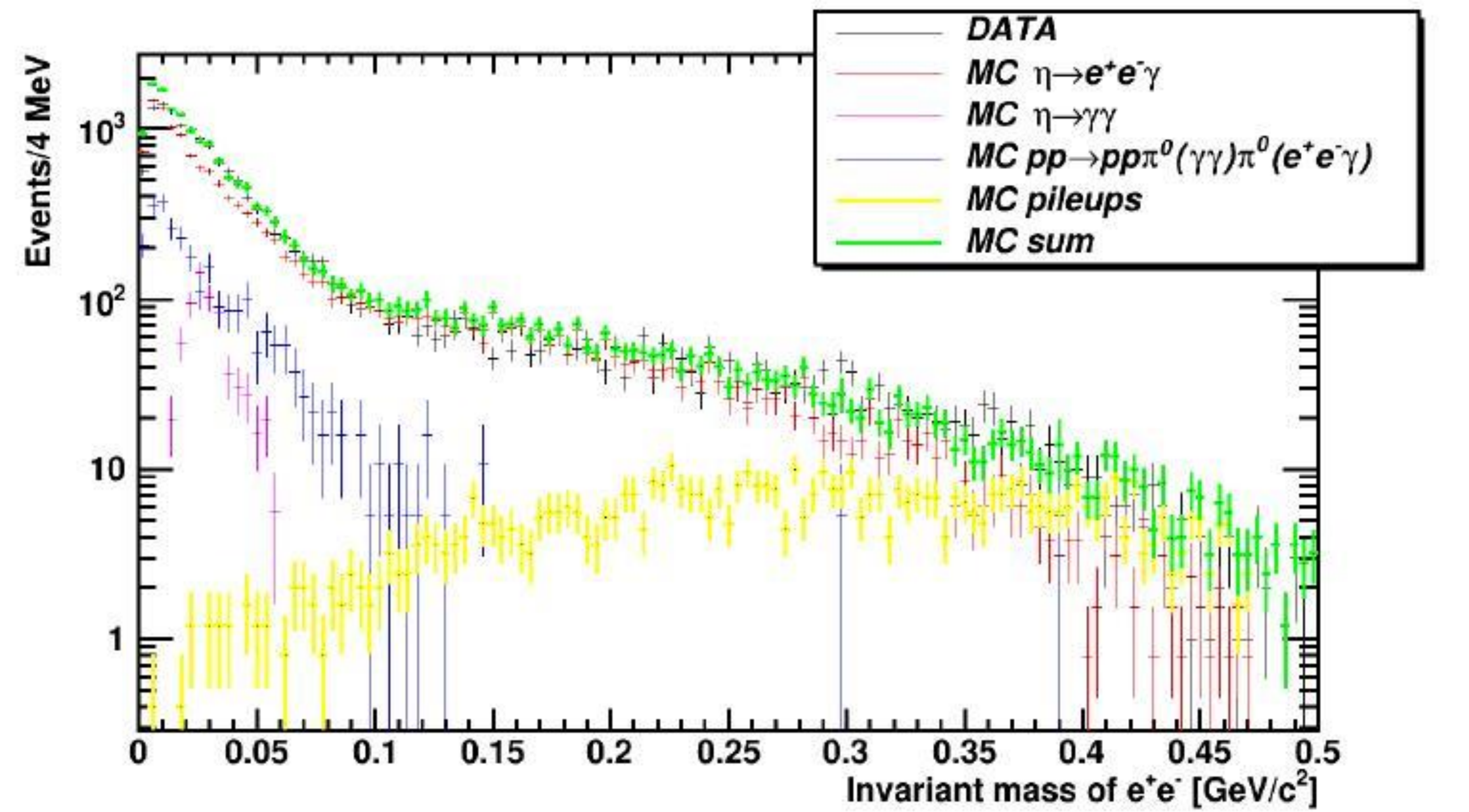
$\Lambda^{-2} = 1.95 \pm 0.17$ (0.05 sys)

DATA SET - $\eta \to e^+e^-\gamma$

- PP collision @ 1.4 GeV
- 2012 Feb-Apr (6-7 weeks of data taking) ~100 TB of data
- Initial selection („preselection"):
  - Trigger system based on clusters in Central Detector
  - Tracks in Forward Detector >= 2 (Energy, time and PID)
  - Hits in Drift Chamber >= 14 (at least two trakcs with signals from 7 MDC layers)
  - Charged clusters in CD thin plastic scintillators >= 2
- ~100 10^6 η



Invariant mass of e+e- pair from $\eta \rightarrow e^+e^-\gamma$
D.Pszczel PhD (2017), pp->ppη at 1.4 GeV

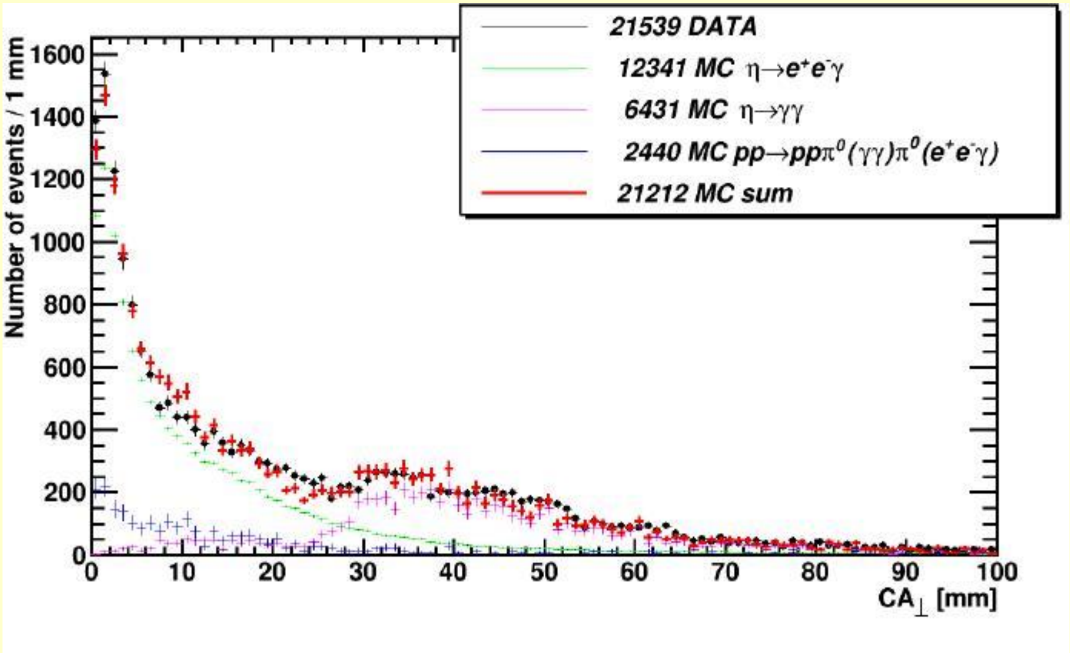


External photon conversion

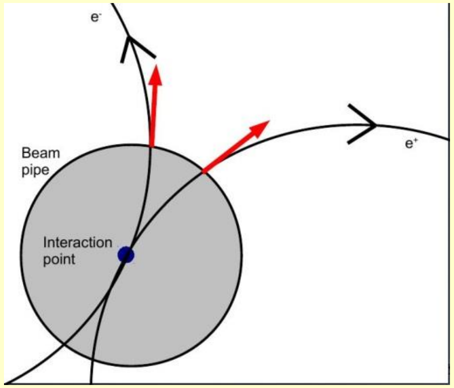
In 35 microns, windowless pellet target photon conversion is negligible.

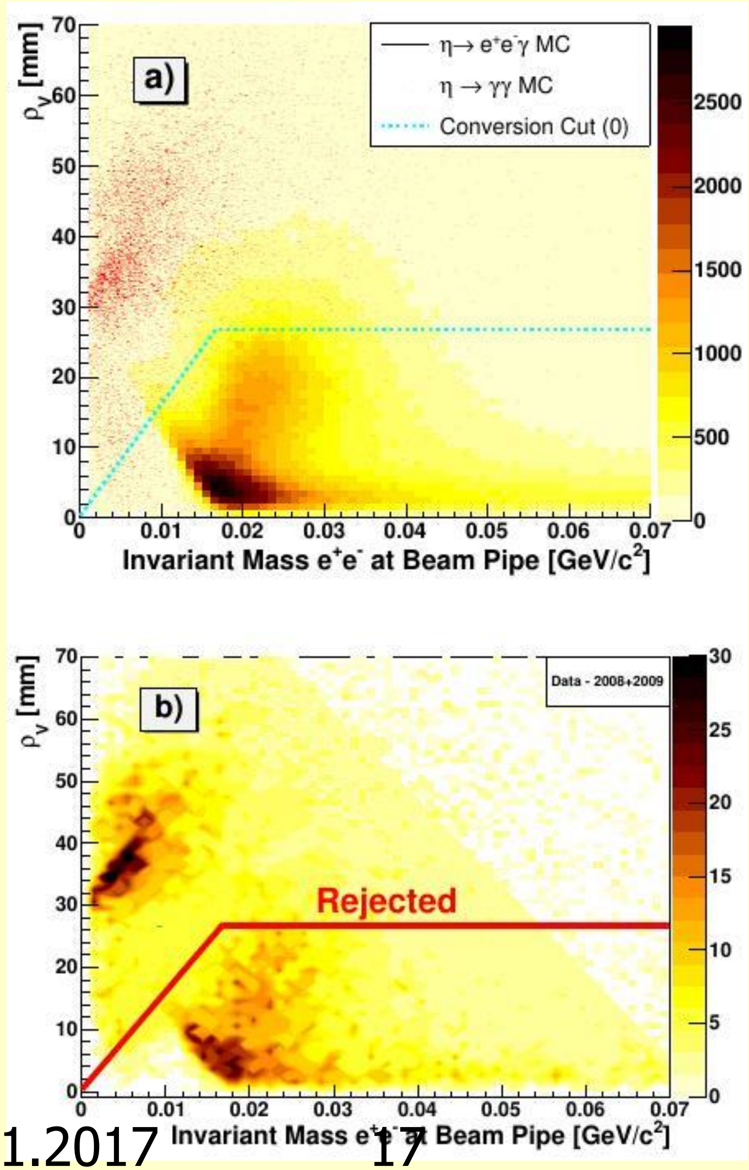
However we observed e+e- pairs from photon conversion in the 3mm thick berylium beam tube (30 mm radius).

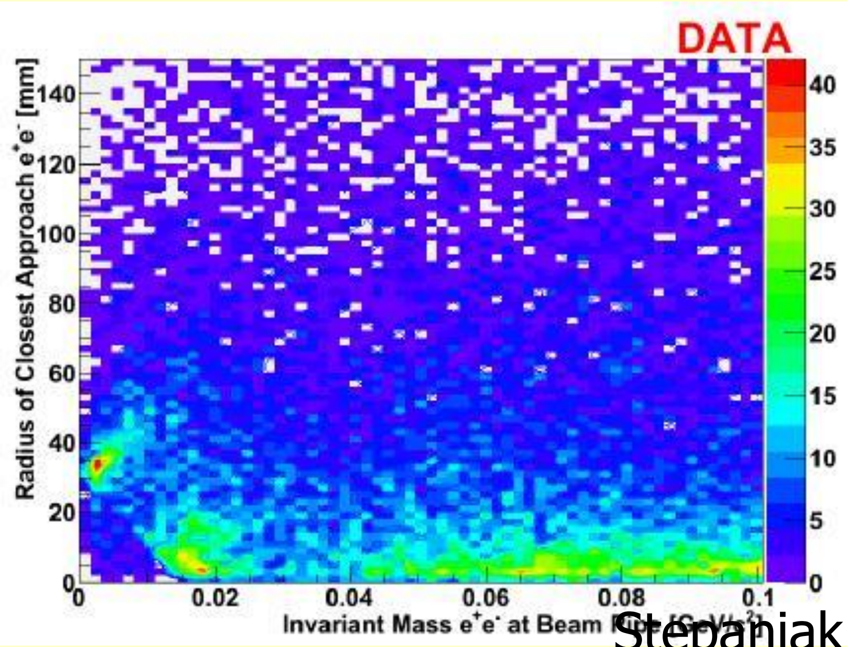
Transversal position of reconstracted vertex



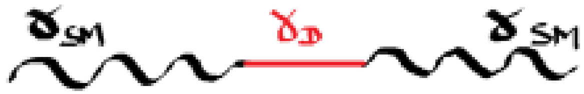
Rejection of external conversion of e+e- pairs







DARK PHOTON



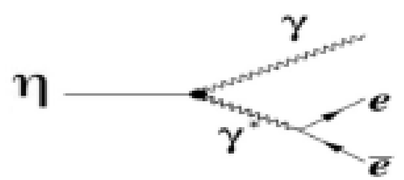
- New „Dark" gauge symmetry leaves the SM particles unchanged. The associated gauge boson U, with mass M_U, could couple to SM through the kinetic small mixing term in the Lagrangian:

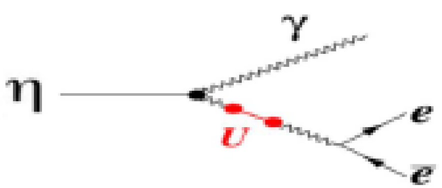
$$\mathbf{L}_{mix} = ½\ \varepsilon\ \mathbf{F}_{\mu\nu}^{QED}\ \mathbf{F}^{\mu\nu}_{DARK}$$

- The dark mediator is called the dark photon $\gamma_D = U = A'$

since it can mix with a photon in all processes (exemples fig.2 and fig.3)

- Phenomenological arguments suggest $\mathbf{M_U} < 2$ GeV and $10^{-2} < \varepsilon < 10^{-4}$





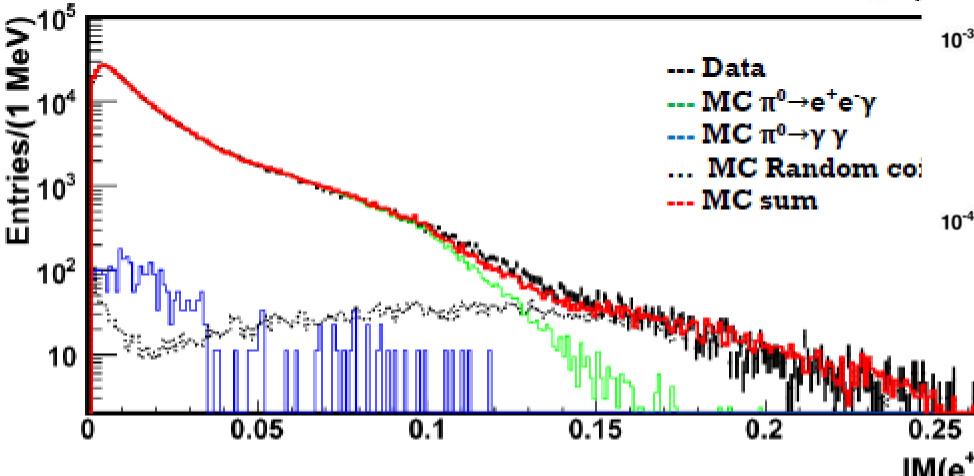
Wikipedia

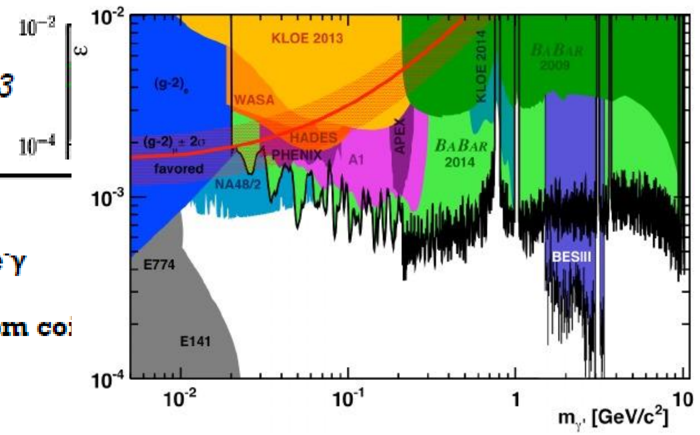
*The **dark photon** is a hypothetical elementary particle, proposed as an electromagnetic force carrier for dark matter. Dark photons would theoretically be detectable via their mixing with ordinary photons, and subsequent effect on the interactions of known particles (...) a dark photon is any spin-1 boson associated with a new U(1) gauge field. That is, any new force of nature that arises in a theoretical extension of the Standard Model and generally behaves like electromagnetism. Unlike ordinary photons, these models often feature a dark photon that is unstable or possesses non-zero mass, rapidly decaying into other particles such as electron-positron pairs. They may also interact directly with the known particles, like electrons or muons, if said particles are charged under the new force*

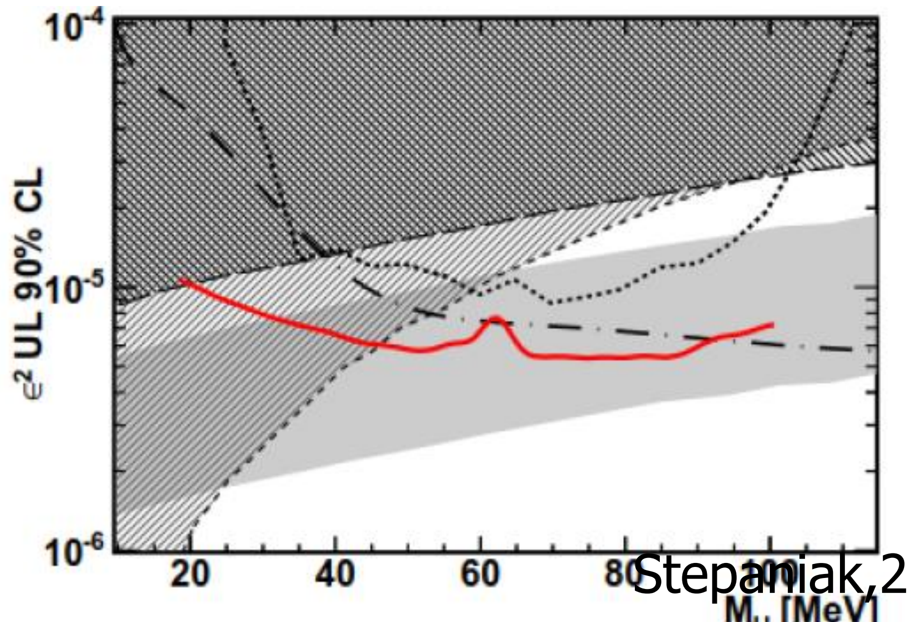
1

$\pi^0 \to e^+e^-\gamma$ CHANNEL γ_{dark} - γ_{sm} COUPLING PARAMETER UPPER LIMIT

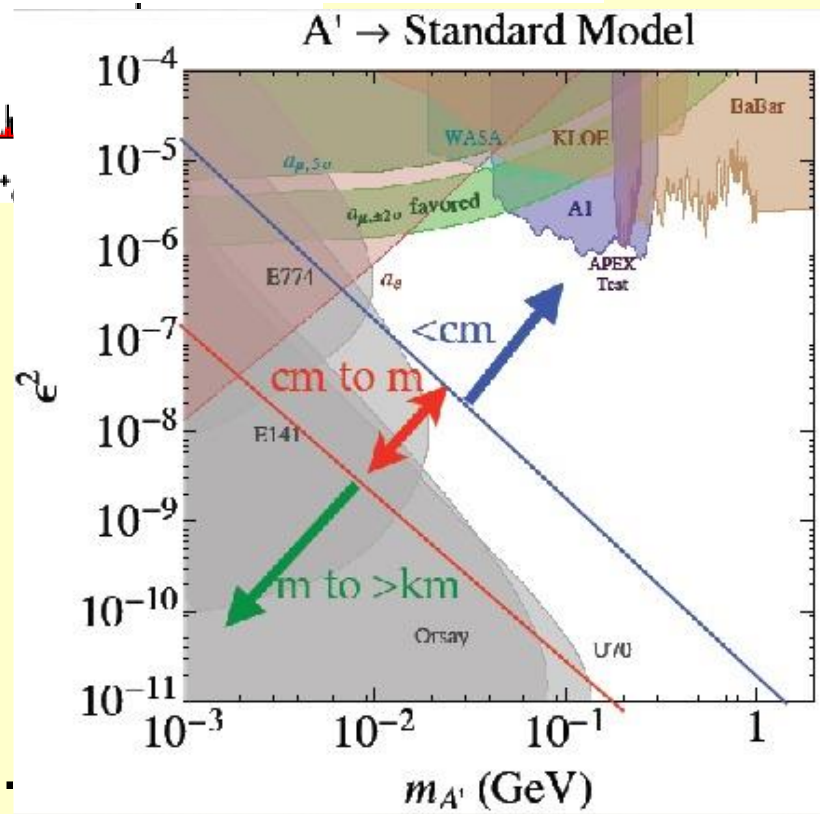
- $\pi^0 \to e^+e^-\gamma$ channel : *Phys.Lett. B726 (2013) 187-193*
- *MonteCarlo(Background + Signal) ≈ Data*







Stepaniak,28.11.



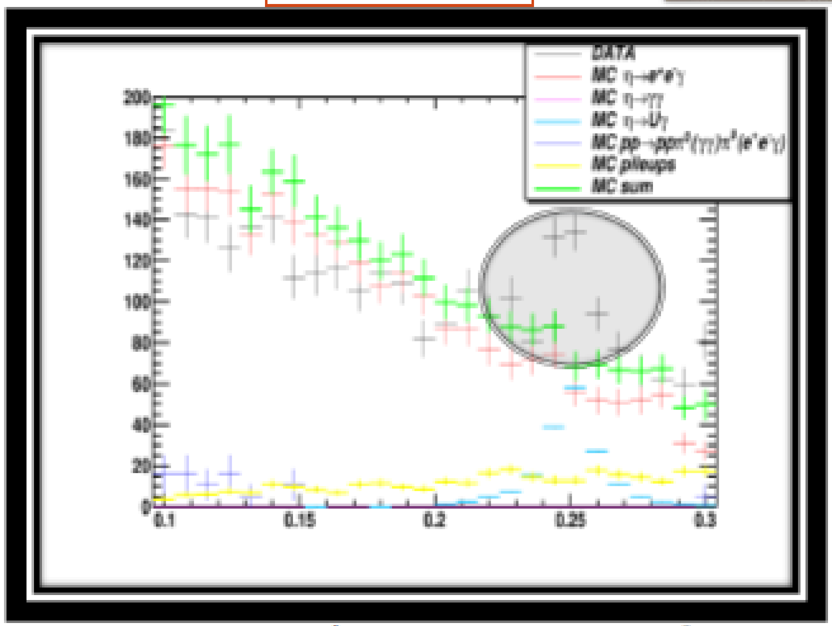
D.Pszczel , EPS Conf. Venice 2017

SIMULATION OF SIGNAL SIGNATURE

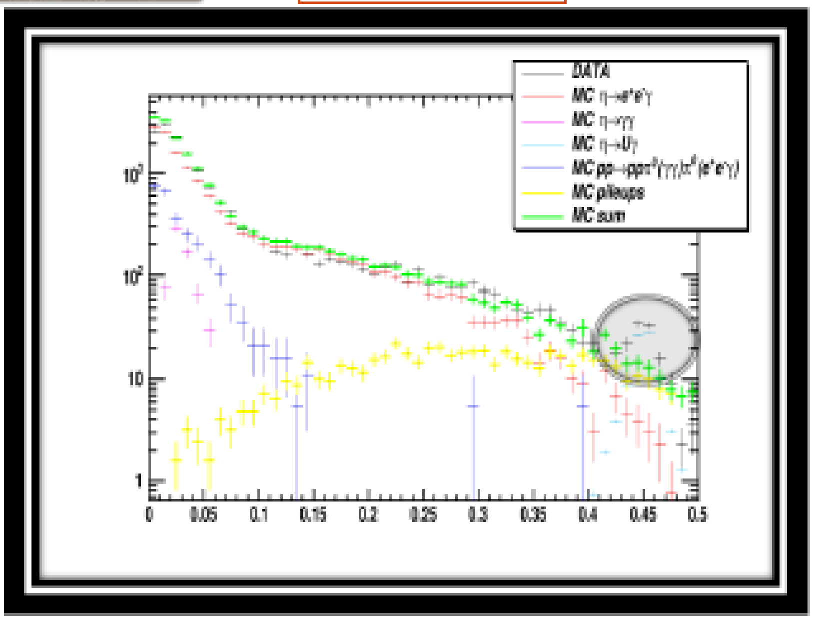
BR = 10^{-4}
M = 250 MeV/c^2

$\eta \to \gamma\, U[e^+e^-]$

BR = 10^{-5}
M = 450 MeV/c^2



Invariant mass of e^+e^- [GeV/c^2]



Invariant mass of e^+e^- [GeV/c^2]

11

Search for U->ee coupling parameter ε to SM photon in eta→e+e-γ

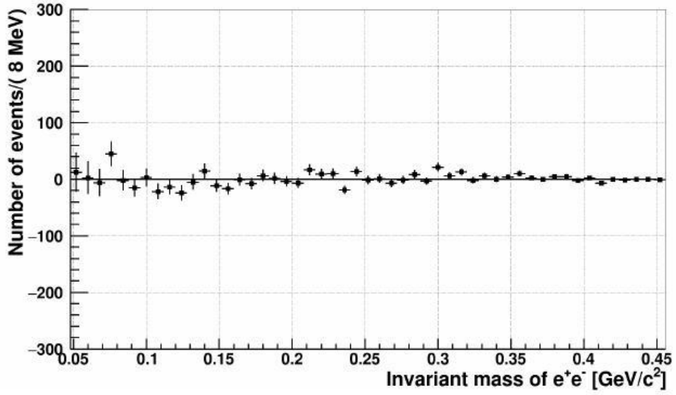


FIGURE 8.13: Invariant mass of e^+e^- - difference between data and sum of background Monte Carlo simulations.

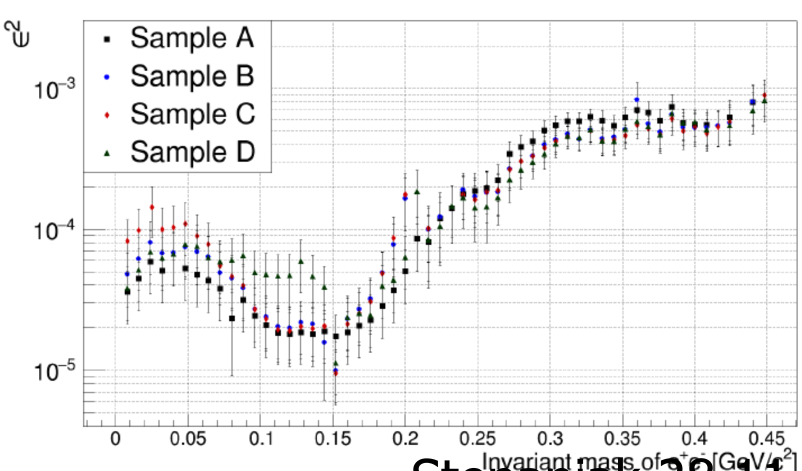
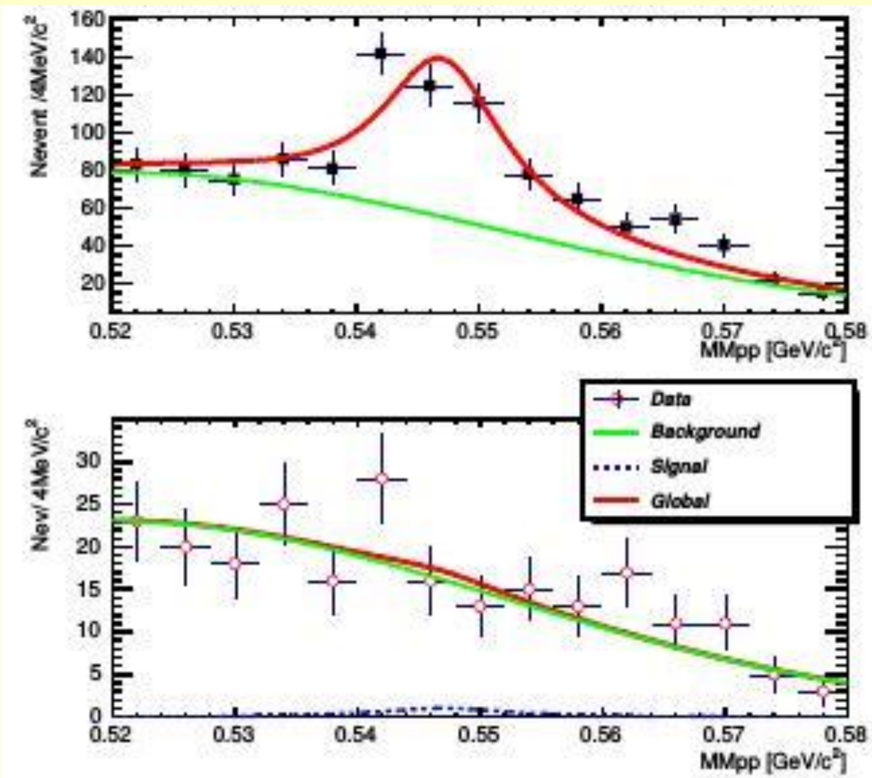


FIGURE 8.18: Upper limit on ϵ^2 as a function of e^+e^- invariant mass (U boson mass).

The 2012 run pp 1.4 GeV . MMpp distributions after final selection (particle identification and several cleaning cuts) Aditional rejection of non-eta events. Fit to sum of the eta signal and direct multiple pion production.

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

$\eta \to e+e-$



Distribution of pp missing mass for $\eta \to \pi^0 e^+ e^-$ candidates from 2012 run. The best fits to the sum of the signal an[illegible] are shown for first (a) and second (b) selection step.

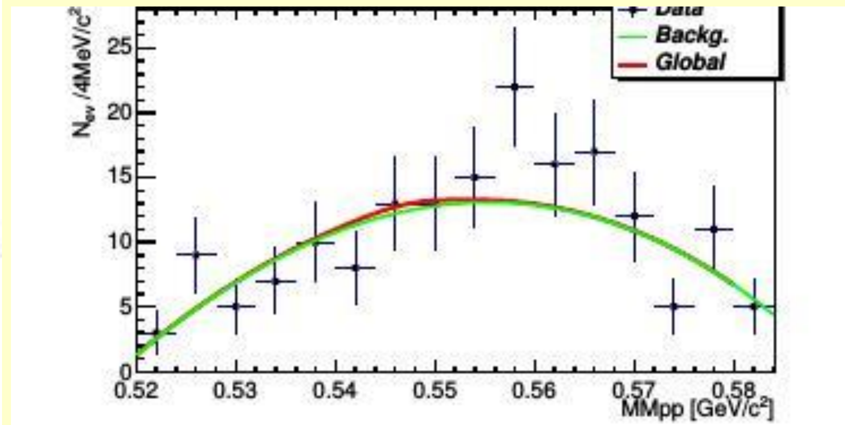
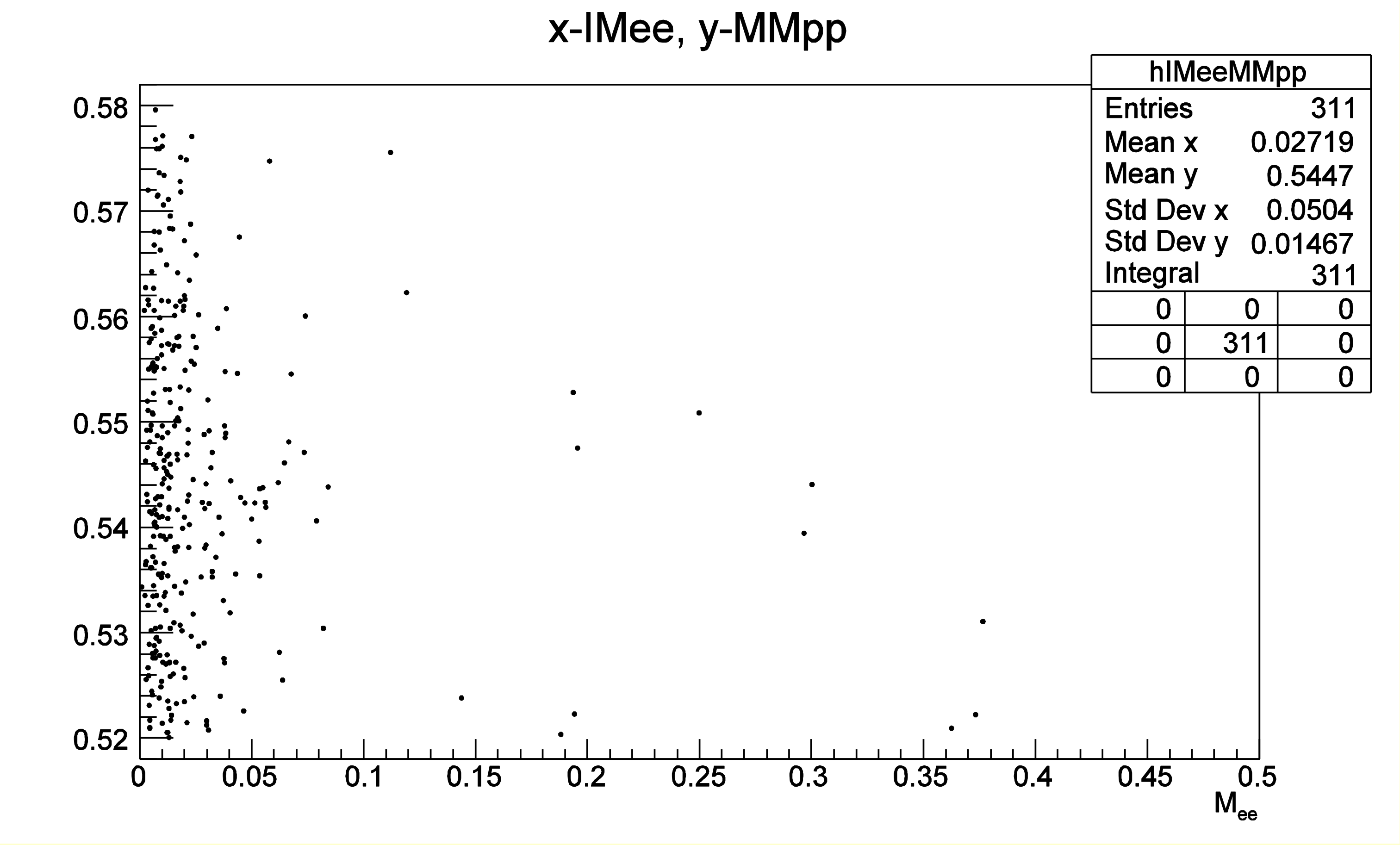
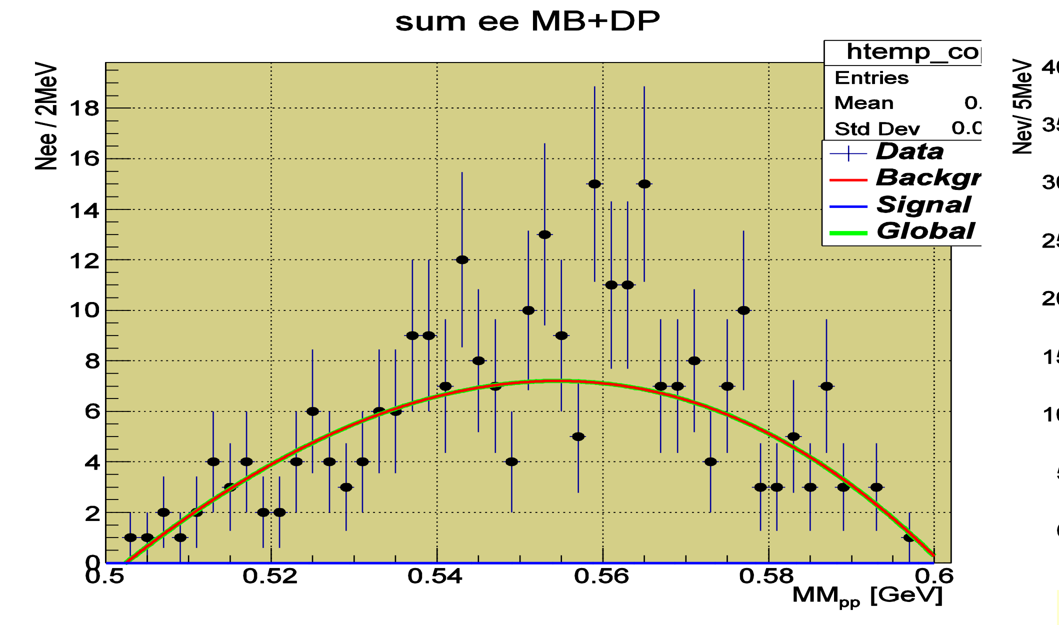


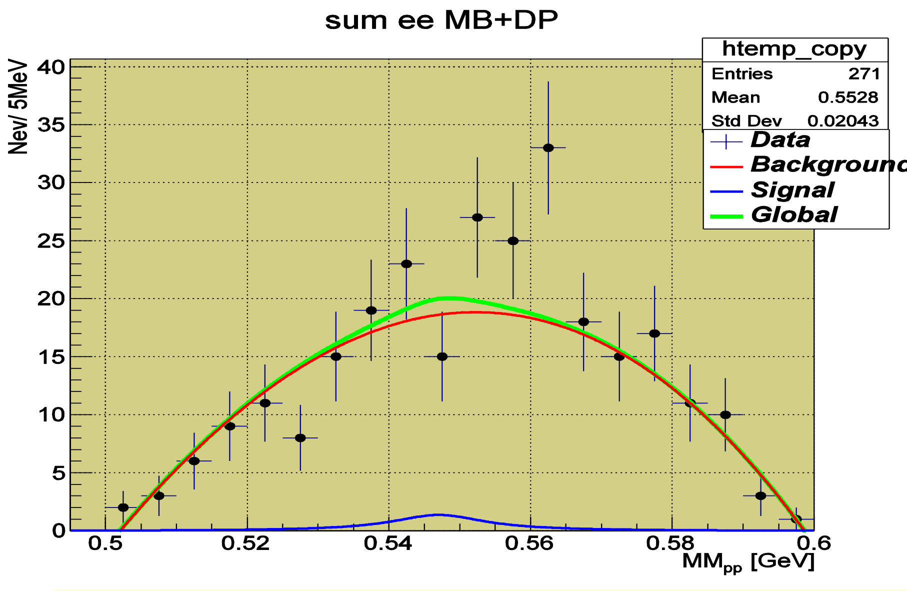
Fig. 3: Distribution of pp missing mass for $\eta \to e^+e^-$ candidates in 2012 data set .

Event candidates for $\eta \rightarrow \pi^{\circ} ee$ decay channel run 2012



$\eta \rightarrow e^+e^-$ two runs (2008 and 2012)





Main background from pp->pp pi+pi- reaction after final rejection cuts (61 ev in 2008 and 211 in 2012).

No visible maximum in MMpp distribution. Fit to the sum of Lorentzian fuction and polinomial background gives 0+-1ev with 2 MeV binning and 7+- 13 ev for 5 MeV bins (upper and lower figs).

Optimistic preliminary upper limit for e+e- for 0 events and 0.6 % average acceptance without systematic error:

$2.3/ (146*10^6)/0.006 = 2.69 \ 10^{-6}$

Can we measure rare radiative decays at FRS ?

➢ WASA at COSY

- Reactions : pp, pd
- cross section pp->ppη ~10μb at 1.4 GeV,
- pd->3Heη~ 50-150nb
- Triggers pp, 3He near threshold
- Background from external gamma conversion:

  Negligible in the windowless pellet target.

• WASA at FRS

- Reactions e.g Cp, pC. CC ?
- cross section for eta at least ten times larger ($\sigma_{pn} > \sigma_{pp}$ and $\sim A^{2/3}$)
- Triggers ?
- e.g. three forward going He in the case of carbon beam near threshold. Should be tested.
- Larger background from external gamma conversion in the target -> much larger amount of combinatorial e+e- pairs .

How to tag eta at FRS?

Two possible configuration

1. Carbon target. Proton on (virtual pn) in nucleus?

   Eta tagging on 3He possible but not so clean as for pd on free deuteron.

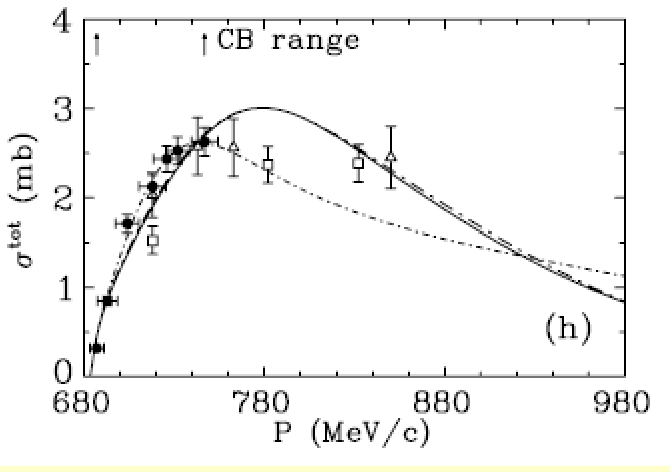
2. Carbon beam on thin Carbon target.

   Much larger cross section but larger background. Tag eta by two alphas in FD?

- The best upper limits on BR for very rare eta decays in nucleon-nucleon reaction was not better than about 10^{-6}because of large background from direct 2 and 3 pion production and pile-ups.

  For example in pp at 1.4 GeV $\sigma(\eta)/\sigma(\pi^\circ\pi^\circ) \cong 1/30$

- It would be much better to use pion beam.
- It appeared that luminosity greater than about $5*10^{31}$ does not lead to larger number of useful events – due to pile-ups.



The End

Thank you!