WASA-AT-COSY

DIELECTRON PAIRS FROM η MESON DECAYS AT WASA DETECTOR

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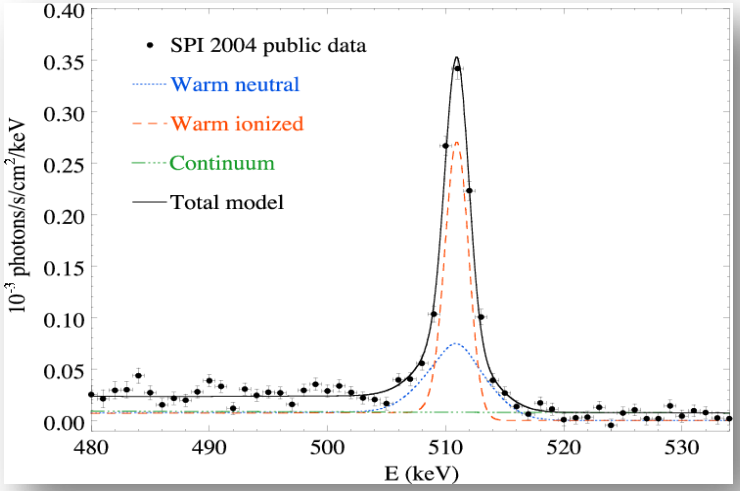
OUTLINE

- MOTIVATION FOR PHYSICS BEYOND THE STANDARD MODEL
- WASA-AT-COSY EXPERIMENT
- DARK BOSON SEARCH IN η MESON DALITZ DECAY
- η TRANSITION FORM FACTOR (TFF)
- RARE $\eta \rightarrow e^+e^-$ DECAY

MOTIVATION FOR PHYSICS BEYOND THE STANDARD MODEL : DARK MATTER

- NATURE OF DARK MATTER?
  - WIMPS
  - AXIONS
  - STERILE NEUTRINOS
  - …



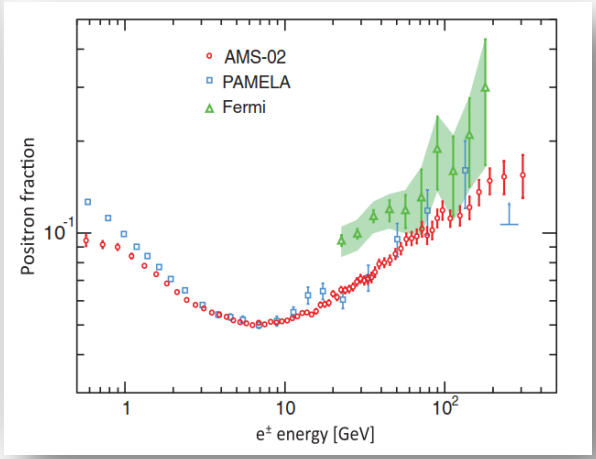
ArXiv: 1304.0833v8 [astro.ph-IM] April 24, 2018

- ASTROPHYSICAL ANOMALIES

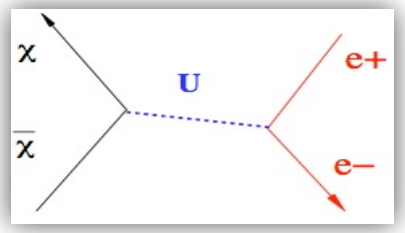
SPI/INTEGRAL, PAMELA, AMS, FERMI-LAT, HESS, ATIC

- MAGNITUDES AND ENERGY DISTRIBUTIONS OF e^+ AND e^-
- 511 keV PHOTONS FROM GALAXY CENTER
- HYPOTHESIS:

POSITRONS CREATED IN ANNIHILATIONS OF DARK PARTICLES INTO $e^+ e^-$, MEDIATED BY A HYPOTHETICAL NEW „LIGHT" BOSON



M Aguilar et al, PRL 110, 141102 (2013)



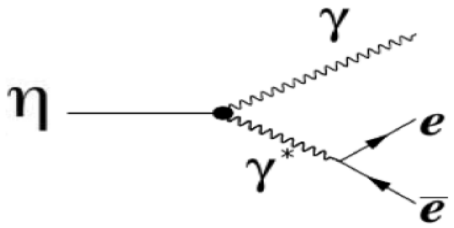
THE DARK PHOTON EXAMPLE

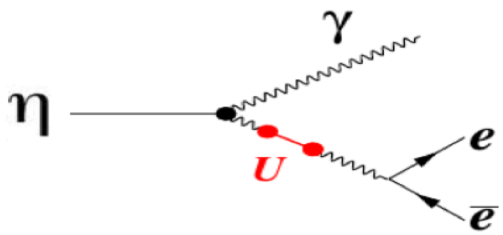
$\gamma_D = U$

- NEW „DARK” GAUGE SYMMETRY
- THE ASSOCIATED GAUGE BOSON U, WITH MASS M_U, COULD COUPLE TO SM THROUGH THE KINETIC SMALL MIXING TERM IN THE LAGRANGIAN:

$$L_{mix} = \frac{1}{2}\,\varepsilon\, F_{\mu\nu}^{QED}\, F^{\mu\nu}{}_{DARK}$$

- THIS DARK MEDIATOR IS ALSO CALLED THE DARK PHOTON γ_D SINCE IT CAN MIX WITH STANDARD PHOTONS IN ALL PROCESSES





$\varepsilon^2 = \alpha'/\alpha$

THE DARK PHOTON

- WE CAN SEARCH FOR ITS SIGNATURE IN DECAYS OF MESONS
- WASA-AT-COSY $\pi^0 \to e^+e^-\gamma$ ANALYSIS PUBLISHED
- NEW ANALYSIS IN $\eta \to e^+e^-\gamma$ CHANNEL: $M_\eta > M_\pi$
- MEAN LIFE-TIME:

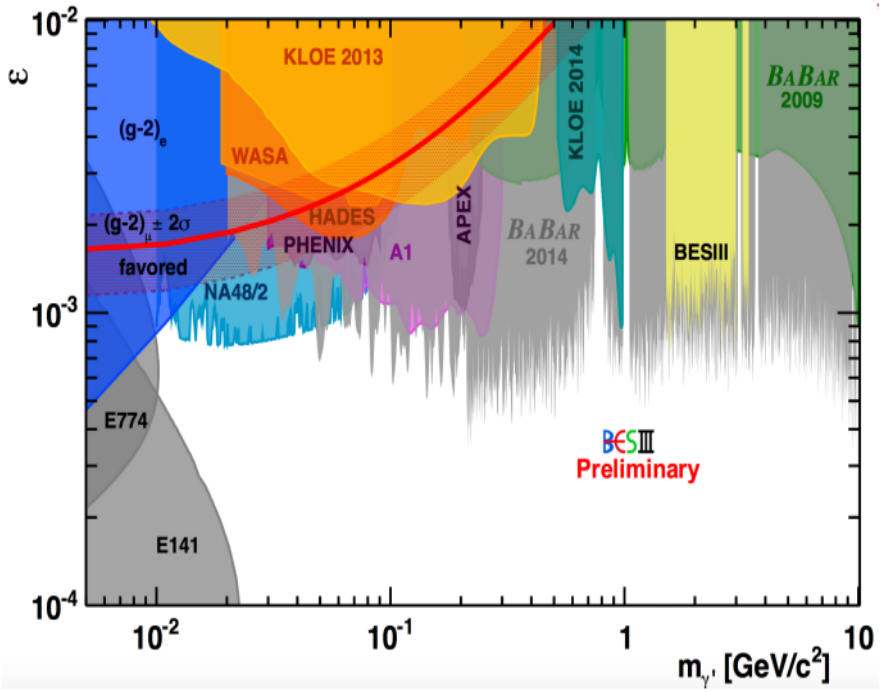
$$\tau_U \cong \frac{3}{\alpha \epsilon^2 M_U}$$ Fradette & al. arXiv:1407.0993

FOR EXAMPLE, IF $\epsilon^2 > 10^{-6}$,

$M_U = 100$ MeV/c^2 THEN $\tau_u \sim 10^{-14}$ S AND

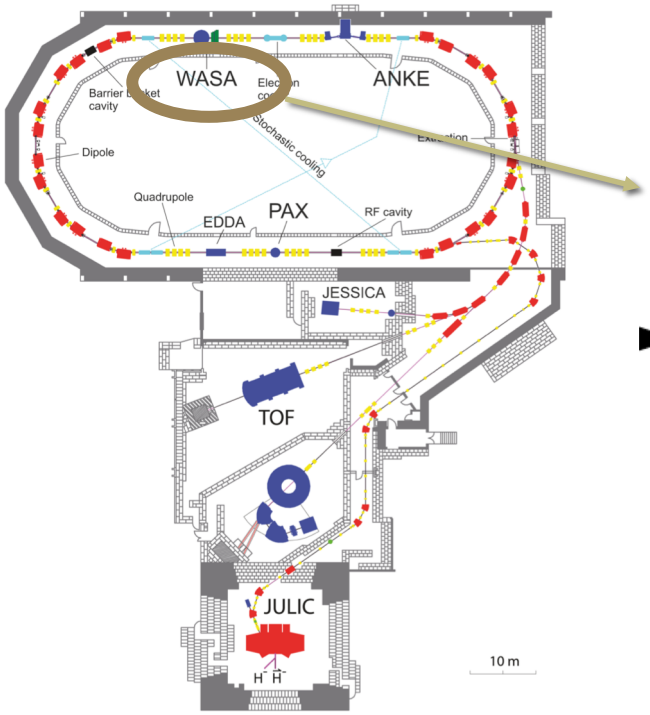
U MEAN FREE PATH LESS THAN 1 MM AND

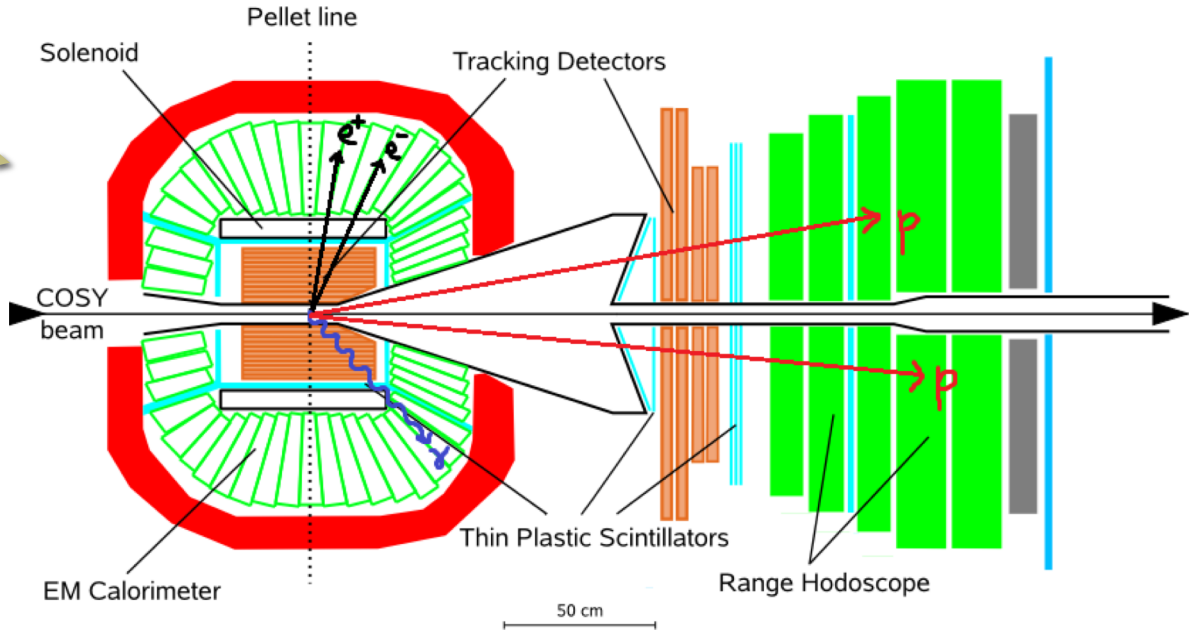
WIDTH < 1 eV



BESIII, Dayong Wang, *Int. J. Mod. Phys. Conf. Ser.*, **46**, 1860046 (2018)

WASA-AT-COSY EXPERIMENT





$\eta \to e^+e^-\gamma$ ANALYSIS

DARK PHOTON SEARCH

DATA SET

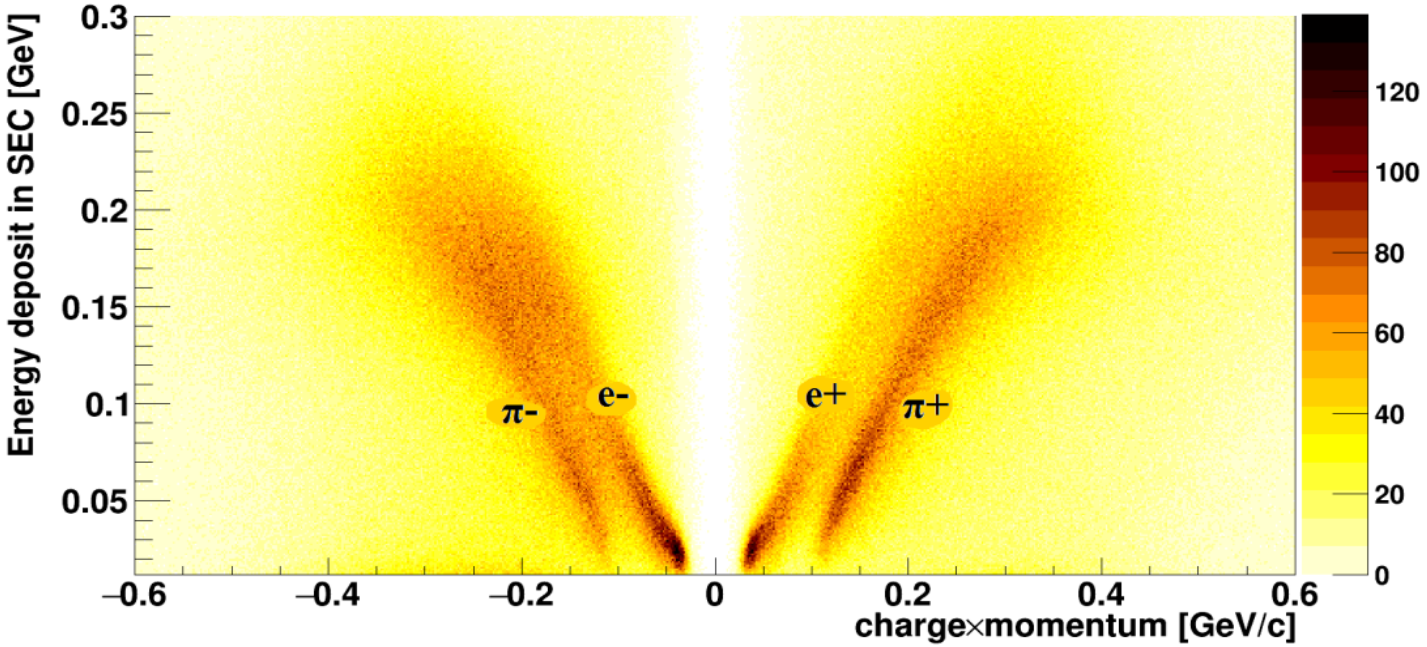
- p (COSY BEAM) p (FROZEN HYDORGEN PELLETS) @ 1.4 GeV KINETIC ENERGY
- 2012 FEB-APR (6-7 WEEKS OF DATA TAKING) ~100 TB OF DATA
- ~10^8 η MESONS (NEUTRAL AND CHARGED DECAYS)
- SPECIAL TRIGGER (TWO HIGH ENERGY TRAKCS IN CD AND TWO TRACKS IN FD)
- GLOBAL SELECTION OF DATA FOR ANALYSIS OF DIFFERENT DECAY MODES

SELECTION OF $\eta \rightarrow e^+e^-\gamma$ CHANNEL

- Time conditions:
  - tracks in forward detector (FDT) vs neutral/charged tracks in central detector (CDN/CDC)
- Energy conditions:
  - FDT energy deposits
  - CDN/CDC Energy deposits
- Missing Energy, missing momentum conditions
- Angular conditions:
  - (e^+e^-) vs γ in η rest frame (η reconstructed from missing momentum of pp)
  - η polar angle (w.r. to the beam direction)
- Invariant mass of $e^+e^-\gamma$
- Missing mass of pp
- ….

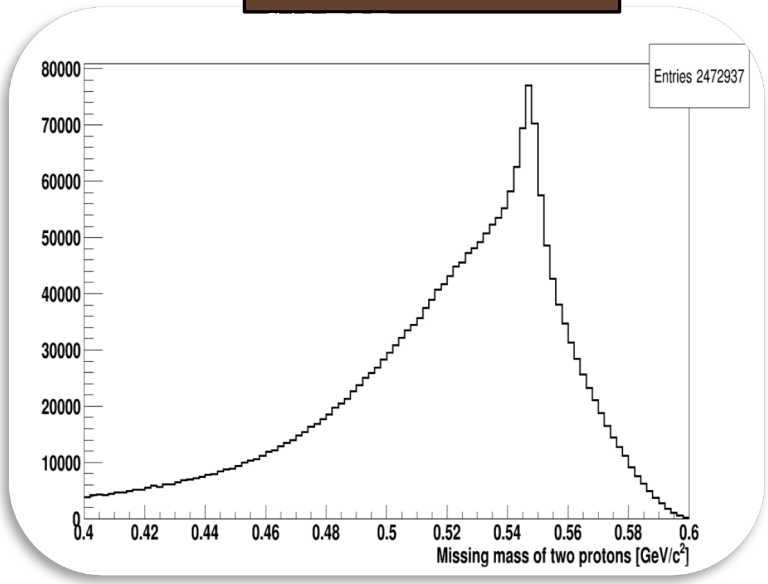
SELECTION OF $\eta \rightarrow e^+e^-\gamma$ CHANNEL

PARTICLE IDENTIFICATION (E_{DEP} VS CHARGE*MOMENTUM)

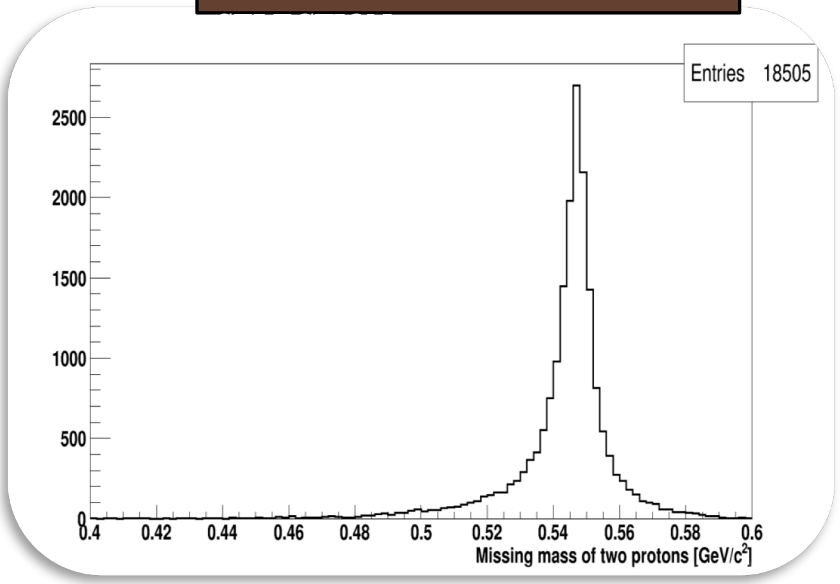


TAGGING OF η MESON IN WASA-AT-COSY

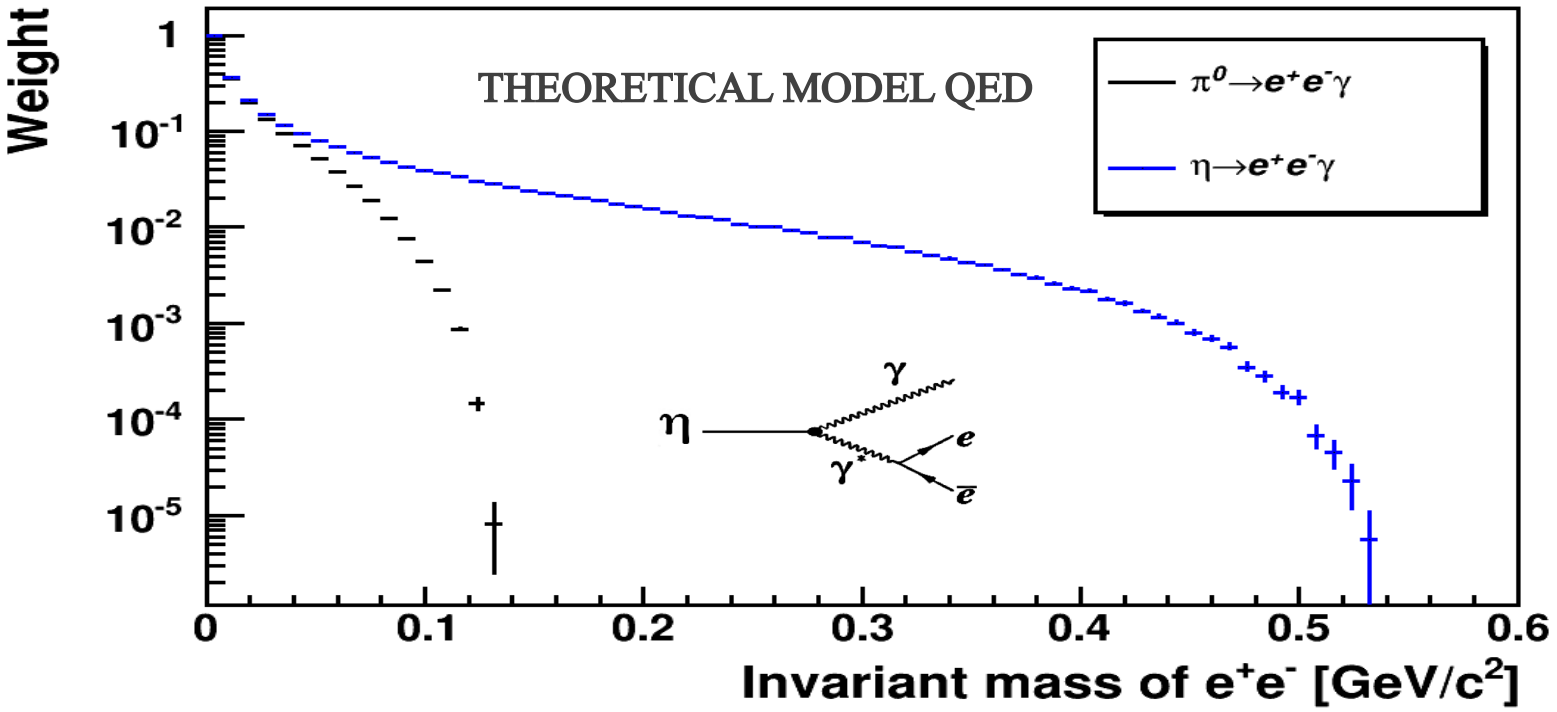
INITIAL DATA



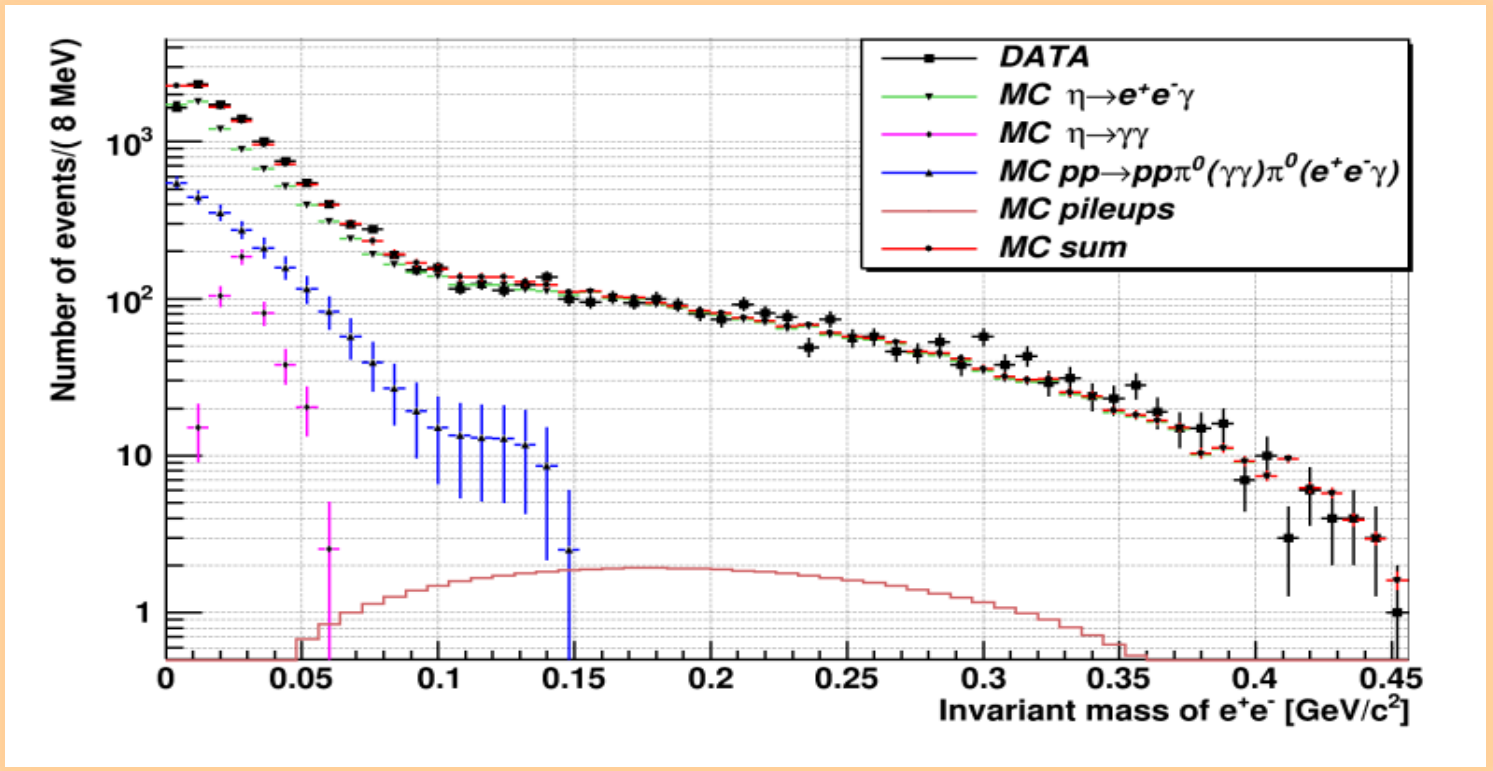
DATA SAMPLE AFTER



MESON DALITZ DECAYS $\pi^0/\eta \rightarrow e^+e^-\gamma$

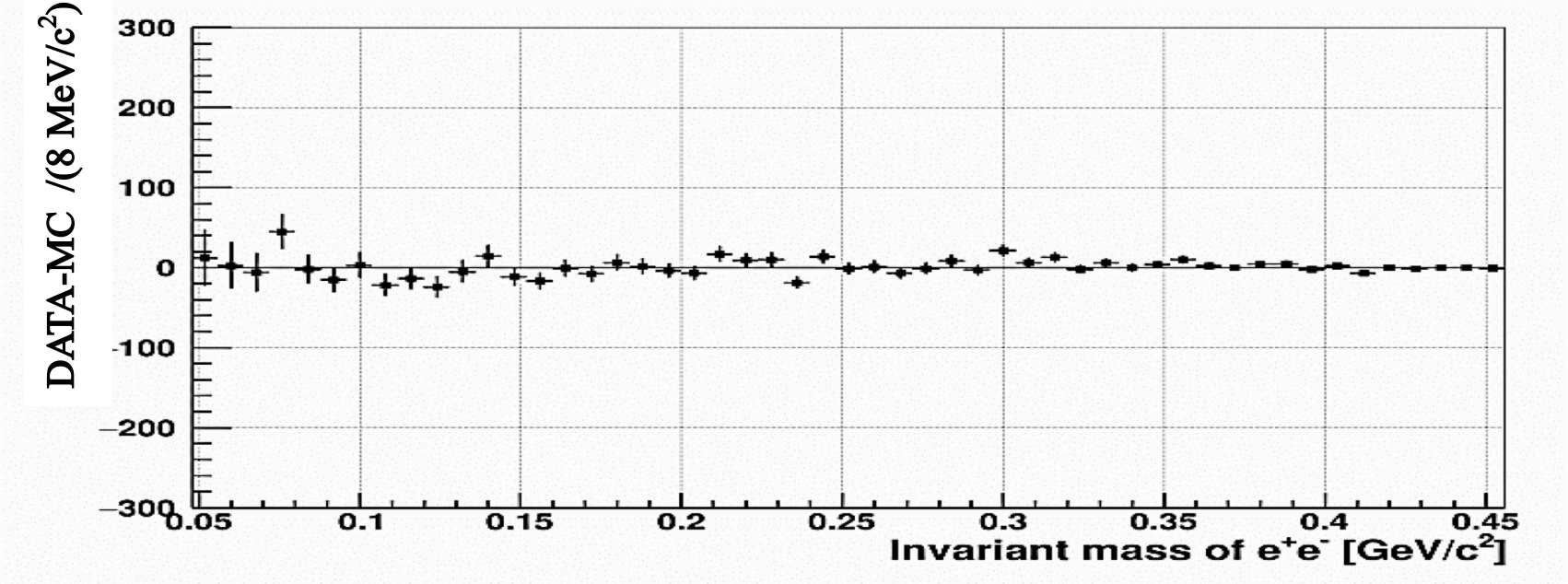


$\eta \rightarrow e^+e^-\gamma$ FINAL SAMPLE



SEARCH FOR A NARROW ENHANCEMENT:

DATA - SIMULATION



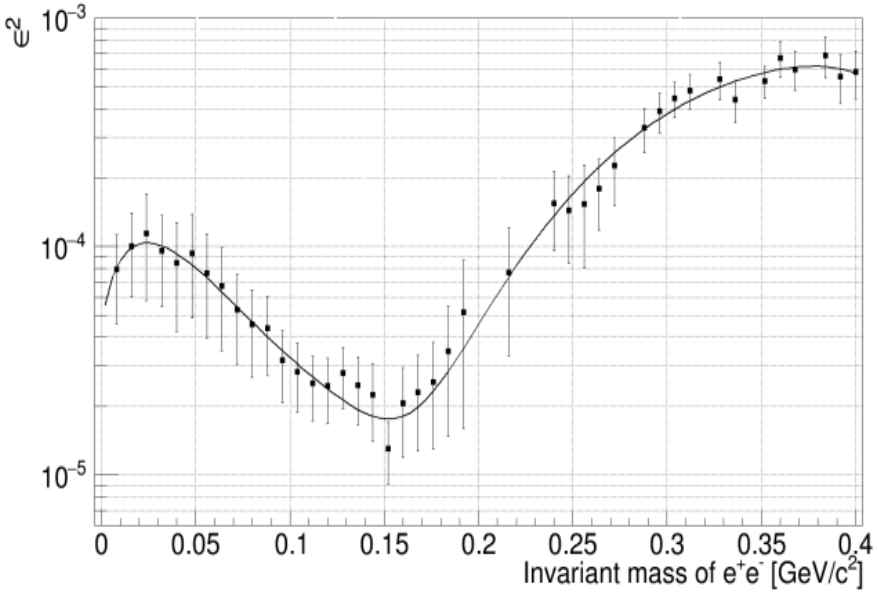
RESULT OF THE DARK PHOTON SEARCH IN $\eta \rightarrow e^+e^-\gamma$

WE DON'T SEE ANY STATISTICALLY SIGNIFICANT SIGNAL, THEREFORE WE CAN SET AN UPPER LIMIT ON $\beta = BR(\eta \rightarrow U\gamma)$

THE COUPLING PARAMETER ε IS A FUNCTION OF β AND OF THE DARK PHOTON MASS M_U.

$$\epsilon^2 = \frac{\beta}{2BR(\eta \to \gamma\gamma) \cdot BR(U \to e^+e^-)} \left(1 - \frac{M_U^2}{M_\eta^2}\right)^{-3} |F(M_U)|^{-2}$$

$\rightarrow$ UPPER LIMIT ON ε^2 @ 90% C.L.



TRANSITION FORM FACTOR

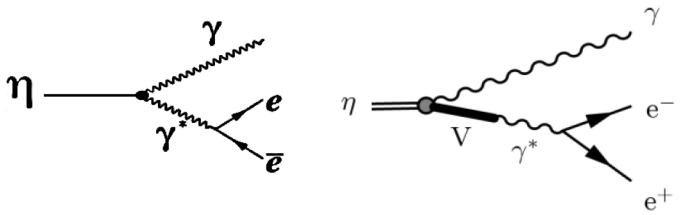
TRANSITION FORM FACTOR

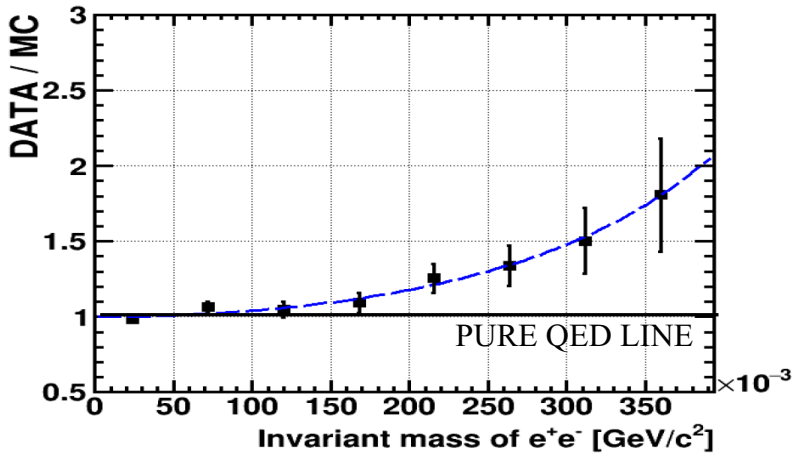
$$\frac{d\sigma}{dq^2} = \left|\frac{d\sigma}{dq^2}\right|_{QED} |F(q^2)|^2$$

TRANSITION FORM FACTOR

$$FF^2 = DATA/MC_{QED}$$

q^2 = VIRTUAL PHOTON MASS^2 = INVARIANT MASS^2 OF e^+e^-





VECTOR MESON DOMINANCE (J.J. SAKURAI PHYS.REV.LETT. 22 (1969) 981-984)

$$F(q^2) = \sum_V \frac{M_V^2}{M_V^2 - q^2 - iM_V\Gamma_V(q^2)} \cong \frac{1}{1 - \frac{q^2}{M_V^2}}$$

FIT FUNCTION WITH M_V

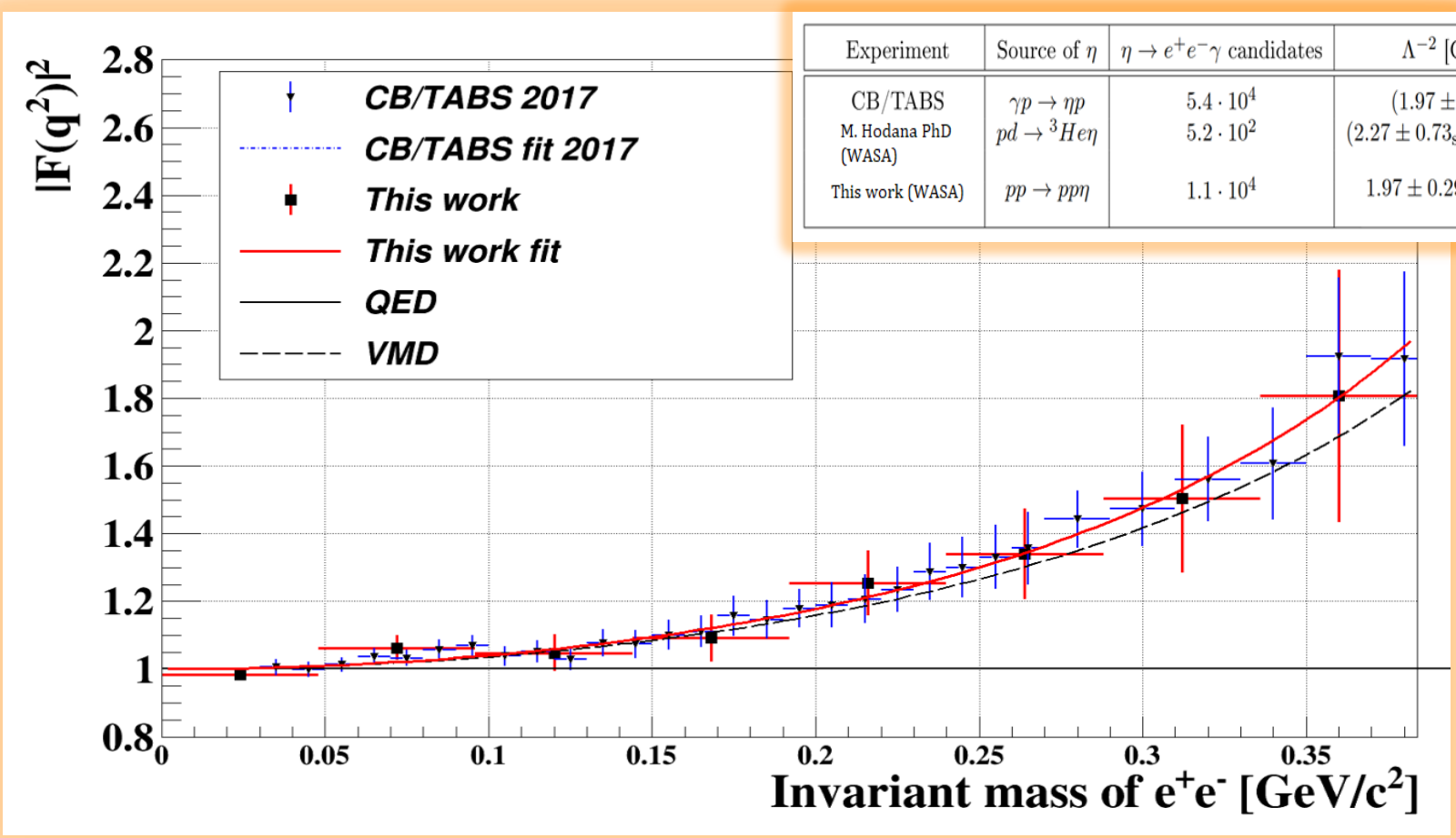
TAKEN AS FIT PARAMETER CALLED Λ

SEE ALSO L. HEIJKENSKJOLD TALK

PARALLEL SESSION B4 ON 8/6

TRANSITION FORM FACTOR

Experiment	Source of η	$\eta \to e^+e^-\gamma$ candidates	Λ^{-2} [GeV^{-2}]
CB/TABS	$\gamma p \to \eta p$	$5.4 \cdot 10^4$	$(1.97 \pm 0.11_{\text{tot}})$
M. Hodana PhD (WASA)	$pd \to {}^3He\eta$	$5.2 \cdot 10^2$	$(2.27 \pm 0.73_{\text{stat}} \pm 0.46_{\text{sys}})$
This work (WASA)	$pp \to pp\eta$	$1.1 \cdot 10^4$	$1.97 \pm 0.29_{\text{stat}}{}^{+0.13_{\text{sys}}}_{-0.23_{\text{sys}}}$



$\eta \to e^+e^-$ ANALYSIS

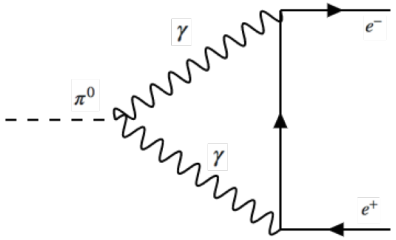
$\eta/\pi^0 \to e^+e^-$ DECAY CHANNELS

- HIGHLY SUPRESSED IN THE STANDARD MODEL:

  BR $(\eta \to e^+e^-) > 1.78 \cdot 10^{-9}$

- VERY SENSITIVE TO PHYSICS BEYOND THE SM

$$BR_{theo}[\eta \to e^+e^-] \sim BR[\eta \to \gamma\gamma] \cdot \alpha^2 \cdot (m_e/m_\eta)^2$$



- KTeV COLLABORATION MEASURED:

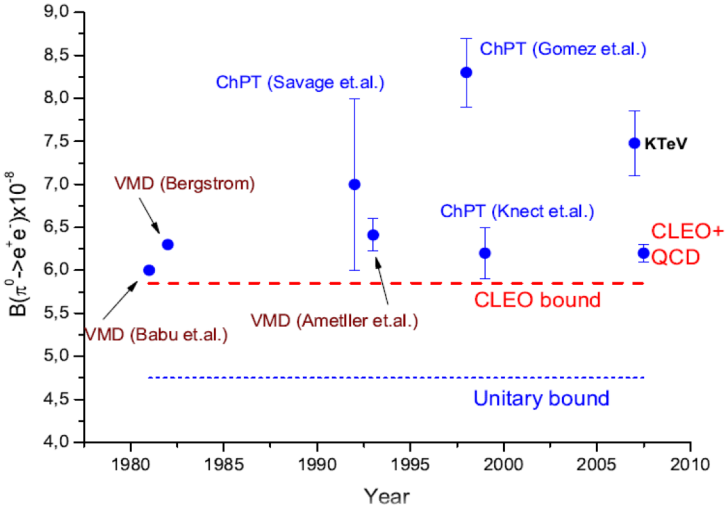
  BR $(\pi^0 \to e^+e^-) = (7.49 \pm 0.29 \pm 0.25) \cdot 10^{-8}$

  EXCEEDES THEORETICAL PREDICTIONS BY 3.1 σ

SEE DOROKHOV & AL [NUCL.PHYS.PROC.SUPPL. 225-227 (2012)]

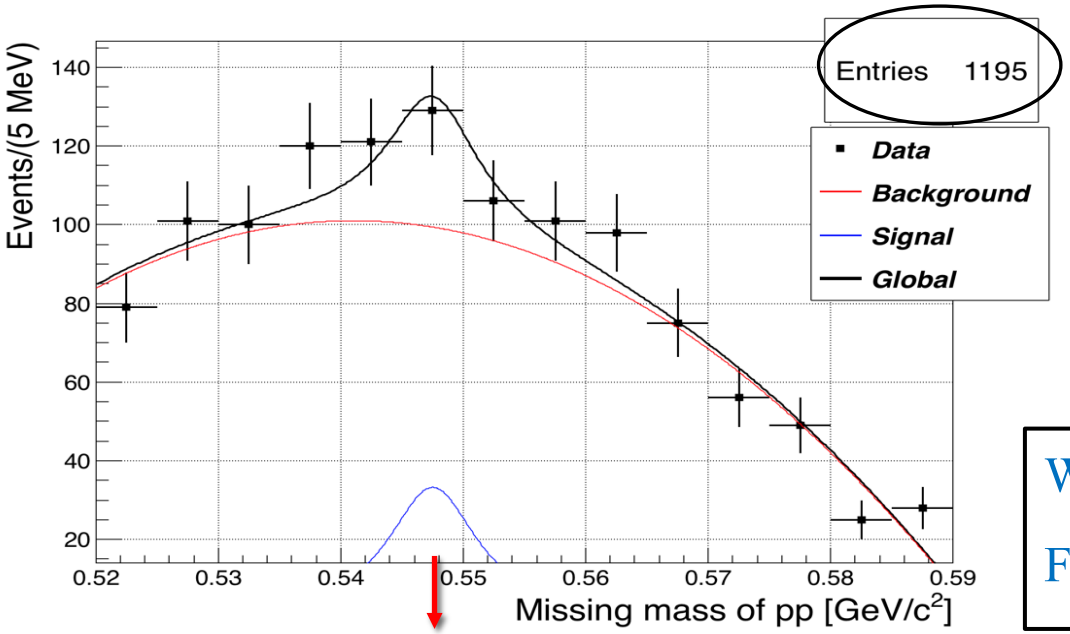
- AFTER MORE DETAILED CALCULATIONS (IMPROVED RADIATIVE CORRECTIONS) ~2 σ DISCREPANCY

SEE TALK BY T.HUSEK - B4 PARALLEL SESSION ON 8/6



$\eta \rightarrow e^+e^-$ ANALYSIS

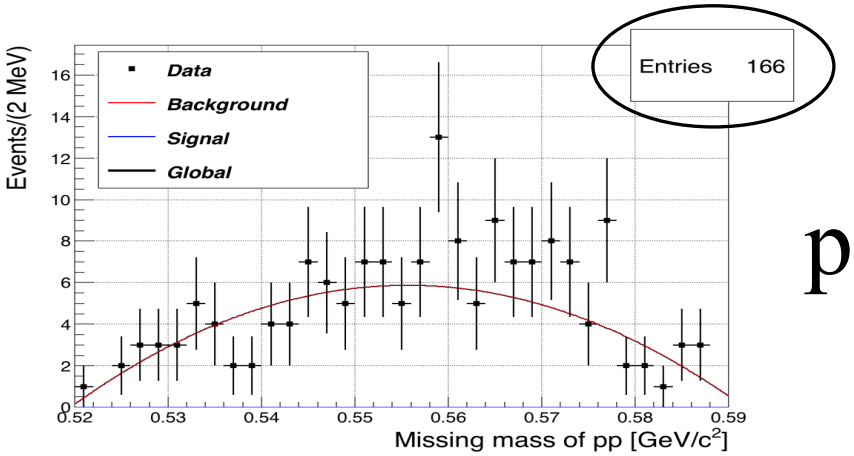
DATA FIT = CONTINOUS POLYNOMIAL BACKGROUND + SIGNAL REPRESENTED BY A LORENTZ FUNCTION (MEAN CLOSE TO η MASS, WIDTH EXCTRACTED FORM MC)



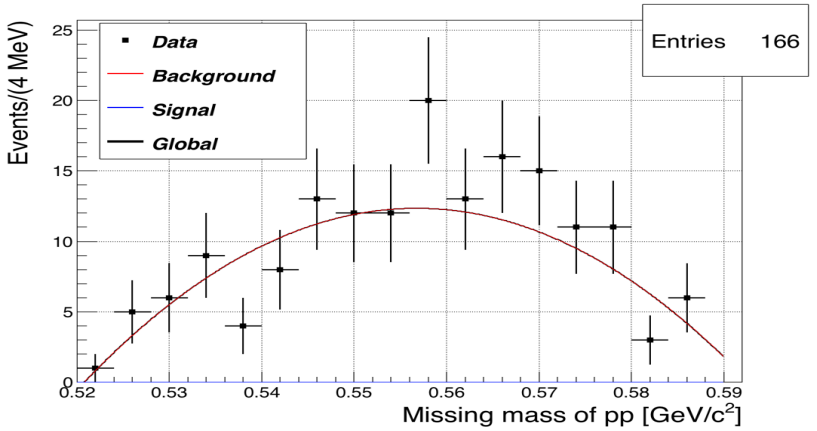
M_η=548 MeV/c^2

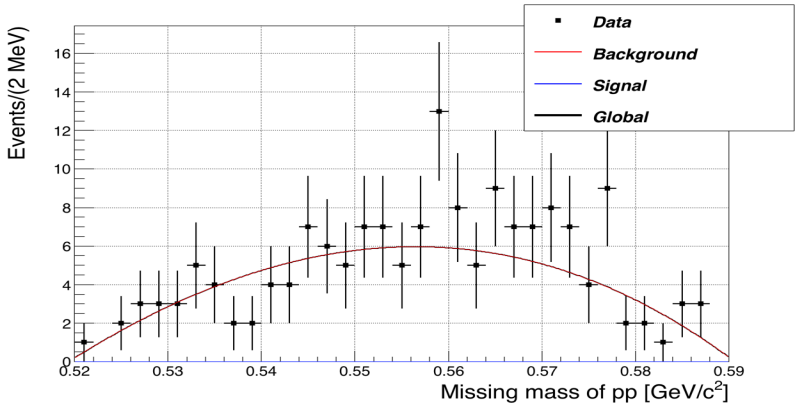
WITH BACKGROUND FROM η DECAYS

$\eta \rightarrow e^+e^-$ ANALYSIS: MORE CONSTRAINED SAMPLE

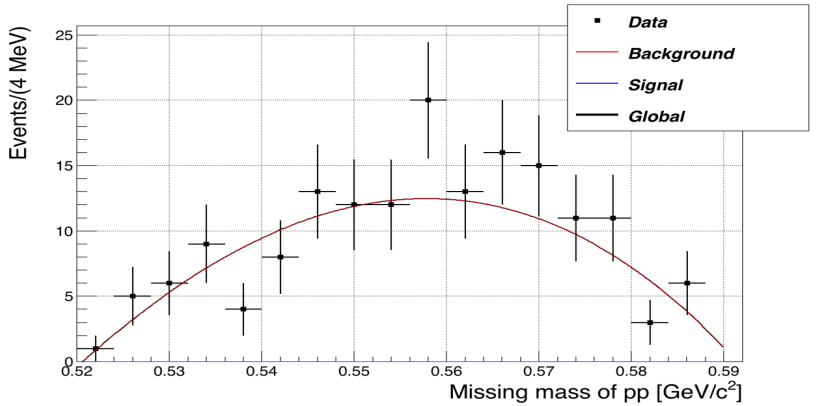


pol4





pol5



$\eta \rightarrow e^+e^-$ BR LIMIT

- TWO DIFFERENT RANGES: [520-590] AND [520-600] MeV/c^2
- THREE DIFFERENT BIN WIDTHS: 2, 4 AND 5 MeV/c^2
- TWO DIFFERENT BACKGROUND FUNCTIONS: 4th AND 5th ORDER POLYNOMIALS
- ONLY FITS WITH χ^2/NDF<2.5 TAKEN INTO ACCOUNT

$\longrightarrow$ **BR LIMIT = 4.14 • 10^{-6} @ 90% C.L.**

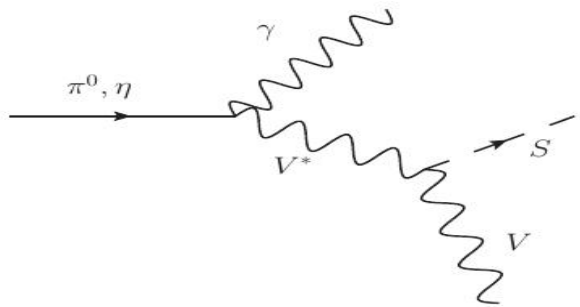
- PDG BEST RESULT BY HADES COLLABORATION 2.3• 10^{-6} @ 90% C.L.

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

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

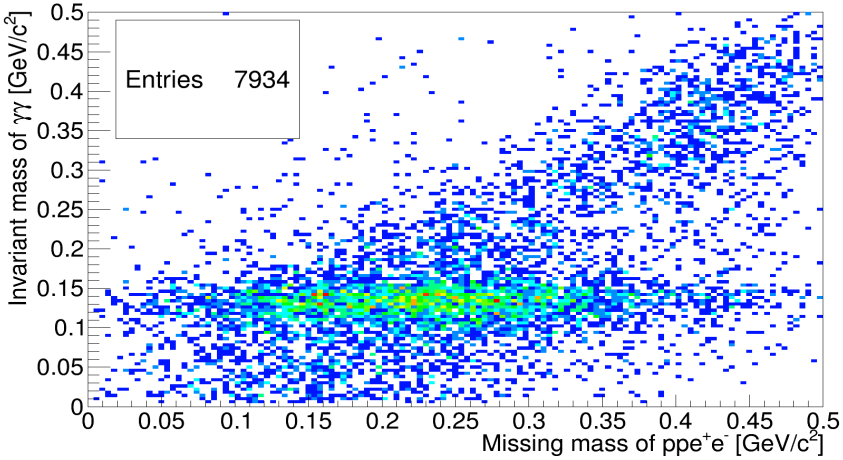
- THE "DARK" SECTOR IN MeV REGION CAN BE RICH. [SEE e.g. DARKSECTORS WORKSHOP arXiv:1608.08632]
- THE LEPTOPHILIC SCALAR MEDIATOR CAN BE CONSIDERED AS WELL. [SEE e.g. KNAPEN ET AL 2017]
- THE HIGGS-LIKE PARTICLE, IF EXISTS, CAN BE RESPONSIBLE FOR THE U MASS.
- THE ETA DECAYS INTO $e^+e^-\,\pi^0$ OR $e^+e^-\,\gamma\gamma$ IS A PERFECT PLACE TO SEARCH FOR A NEW LIGHT DARK SCALAR/PSEUDOSCALAR OBJECT WHICH DECAYS INTO e^+e^- SINCE $\eta \to \gamma^*\pi^0$ IS STRONGLY SUPPRESED (C VIOLATION). [SEE e.g. BERGSTROM PHYS.LETT.B232(1989)387]
- DARK HIGGS (S) PRODUCTION IN PSEUDOSCALAR MESON DECAYS [SEE e.g. arXiv:710.08430]

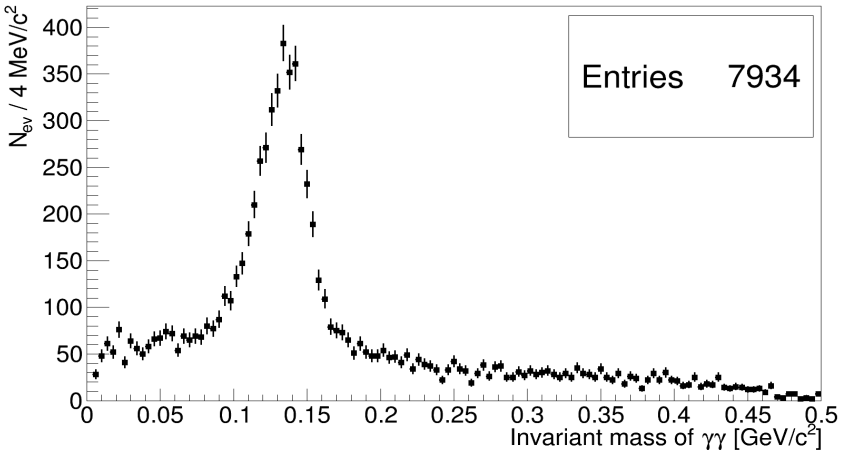
SEE ALSO N. HUSKEN TALK - 8/6 AT 11.30



$\eta \rightarrow \pi^0 e^+ e^-$ SAMPLE SELECTION

- POSITIVELY AND NEGATIVELY CHARGED TRACKS AND 2 NEUTRAL TRACKS
- ELECTRONS IDENTIFICATION
- REJECTION OF ELECTRON PAIRS FROM GAMMA CONVERSION AND SPLIT-OFFS
- CUTS ON TOTAL MISSING MASS AND MISSING ENERGY
- 288 EVENTS LEFT WITH MMpp IN (0.52-0.58) GeV INTERVAL AND WITH Mγγ IN THE π^0 MASS REGION (0.11-0.165) FOR FURTHER ANALYSIS



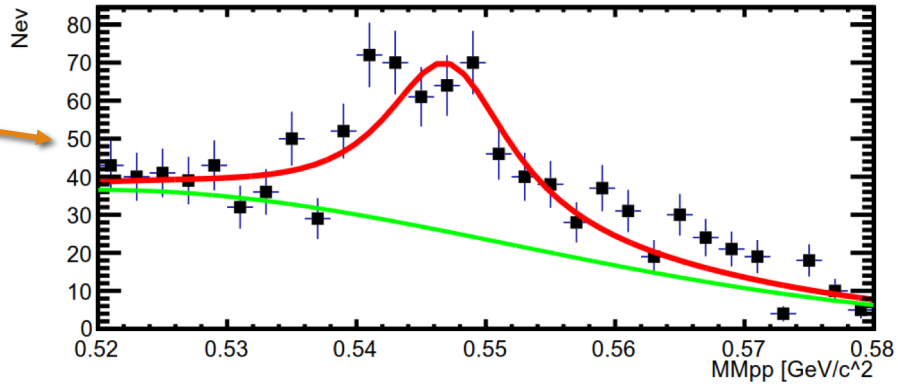


$\eta \rightarrow \pi^0 e^+ e^-$ BACKGROUNDS CHANNELS

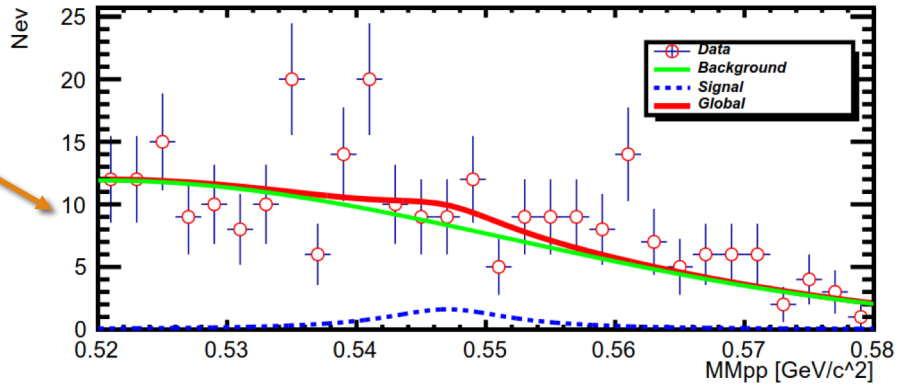
- MONTE CARLO SIMULATIONS WERE PERFORMED FOR SEVERAL ETA DECAY CHANNELS:
  - $\eta \rightarrow \pi^+ \pi^- \pi^0$
  - $\eta \rightarrow e^+ e^- \gamma$
  - $pp \rightarrow pp\ \pi^0(\rightarrow \gamma\gamma)\ \pi^0(\rightarrow e^+ e^- \gamma)$
    - WITH ONE PHOTON UNSEEN IN THE ACTIVE PART OF THE DETECTOR
    - NO η MESON PEAK IN MMpp EXPECTED FOR THIS REACTION

SEARCH FOR η SIGNAL IN MMpp FOR EVENT-CANDIDATES AFTER FINAL CUTS

- THE DISTRIBUTION BEFORE TOTAL MISSING MASS AND MISSING ENERGY CONDITION



- FINAL SAMPLE OF $\eta \rightarrow \pi^0 e^+ e^-$ CANDIDATES
- THE SUM OF ETA MMpp EXPERIMENTAL SHAPE AND BACKGROUND FROM $pp \rightarrow pp\pi^0\pi^0$ PRODUCTION WAS FITTED TO THE FINAL DISTRIBUTION OF 288 CANDIDATES FOR $\eta \rightarrow \pi^0 e^+ e^-$ DECAY.



$\eta \to \pi^0 e^+ e^-$ RESULTS

- PRELIMINARY 90% UPPER LIMIT FOR $\eta \to \pi^0 e^+ e^-$ FROM PP REACTION

$$BR = (2.4 \cdot \sigma_{SIG})/N_\eta/ACCEPTANCE = 5 \cdot 10^{-5}$$

WHERE THE σ_{SIG} WAS TAKEN FROM THE ERROR ON THE FIT PARAMETER.

- A MORE STRINGENT UPPER LIMIT WAS ALREADY OBTAINED BY WASA-AT-COSY FOR η'S PRODUCED IN PROTON-DEUTERON REACTION.

see arXiv:1802.08642 AND N. HUSKEN TALK - 8/6 AT 11.30

- THE UPPER LIMIT FOR $\eta \to e^+ e^- \gamma\gamma$ DECAY WHERE THE PHOTON PAIR DO NOT ORIGINATE FORM π^0 MESON DECAY, $BR = 2 \cdot 10^{-5}$, WAS FOUND FROM THE SAME PERIOD OF DATA TAKING.

SUMMARY

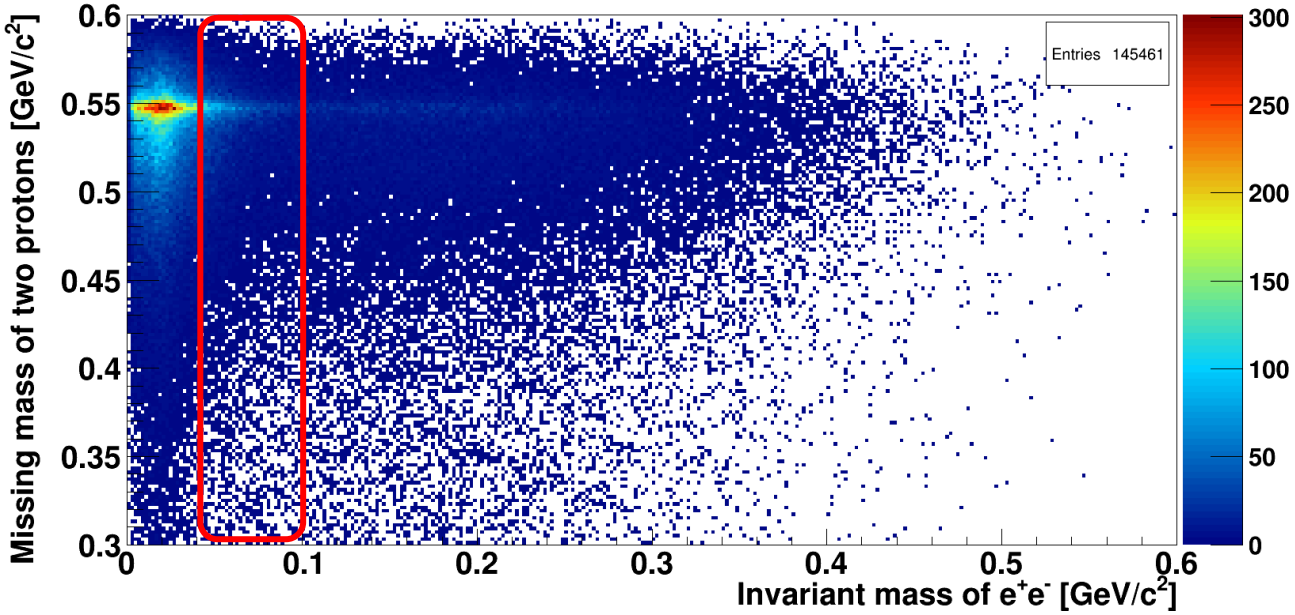
- COLLECTION OF A DATA SAMPLE FROM pp @ 1.4 GeV
  - $\eta \to e^+e^-\gamma$ SELECTION
    - U BOSON/DARK PHOTON SEARCH $\to$ UPPER LIMIT SET ON ε^2
    - η TRANSITION FORM FACTOR EXTRACTION
  - $\eta \to e^+e^-$ SELECTION
    - UPPER LIMIT SET ON $\eta \to e^+e^-$
  - $\eta \to \pi^0 e^+e^-/\gamma\gamma e^+e^-$ SELECTION
    - UPPER LIMIT SET ON $\eta \to \pi^0 e^+e^-/\gamma\gamma e^+e^-$

THANK YOU

BACKUP

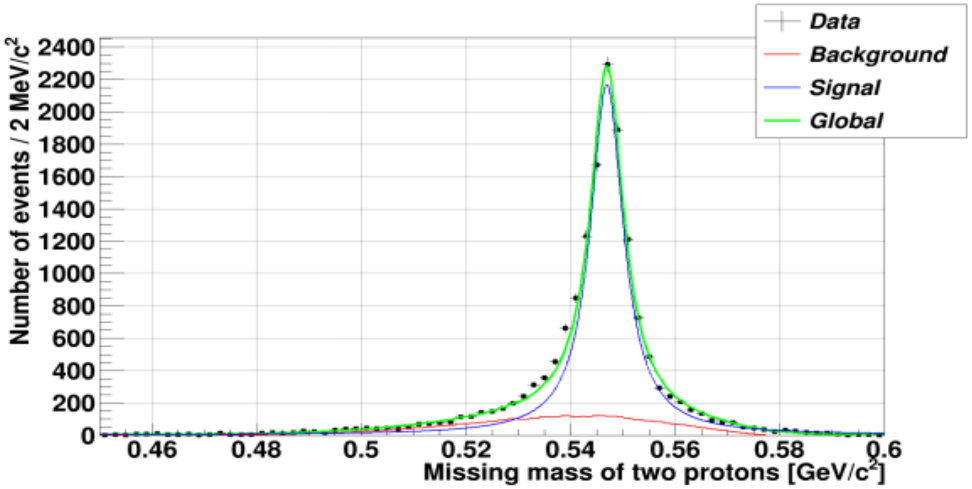
NON-η BACKGROUND REJECTION PROCEDURE

MMpp vs IMee



NON-η BACKGROUND REJECTION PROCEDURE

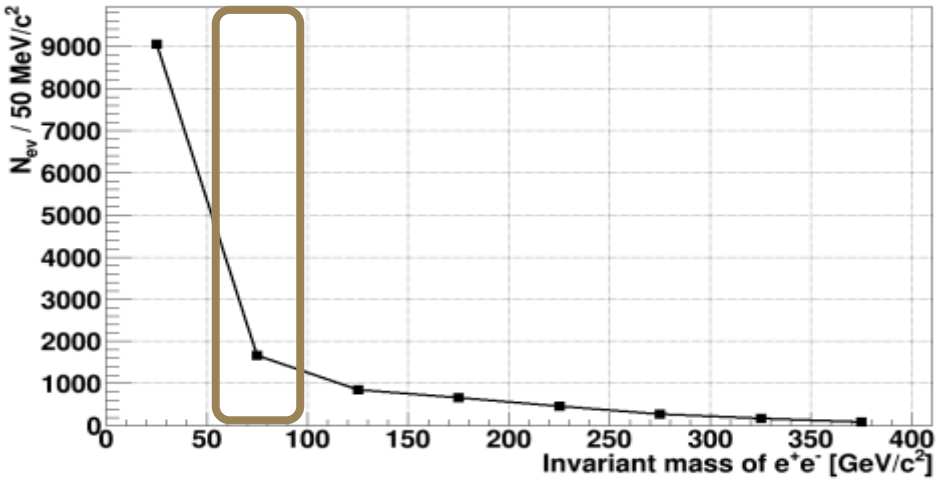
MMpp



DATA FIT = SIGNAL + BACKGROUND

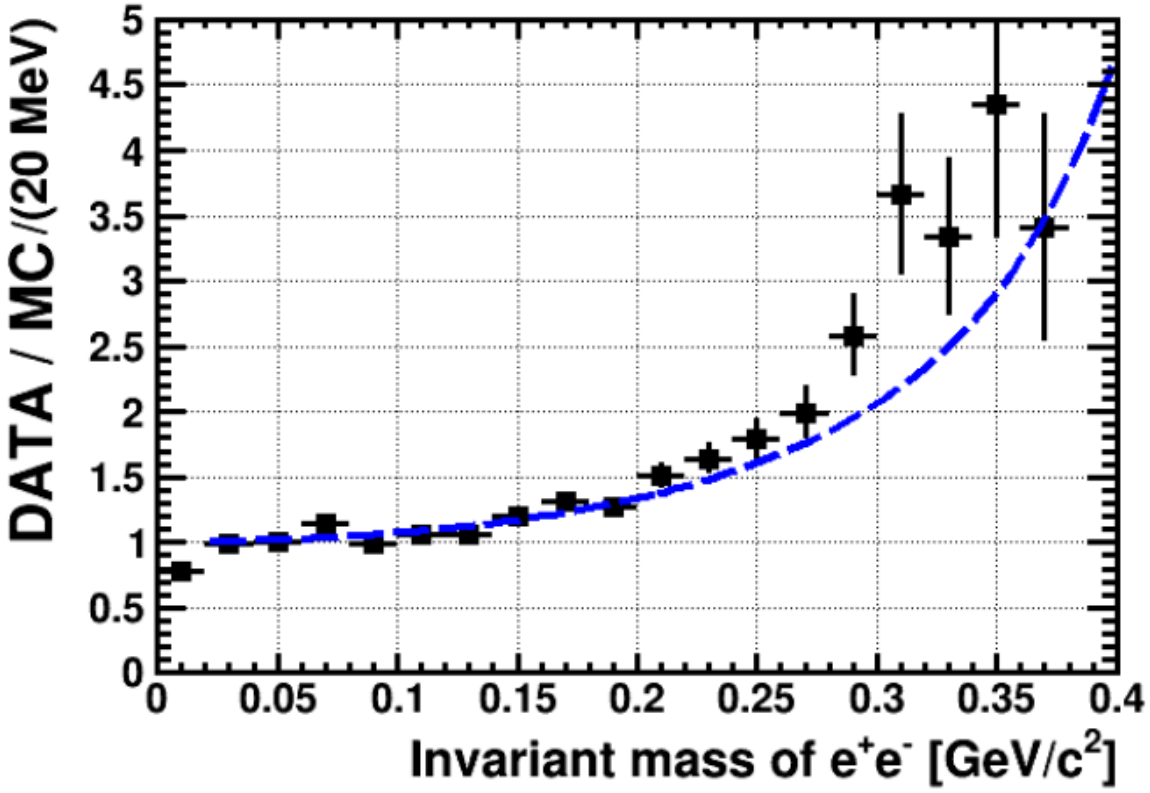
NON-η BACKGROUND REJECTION PROCEDURE

IMee



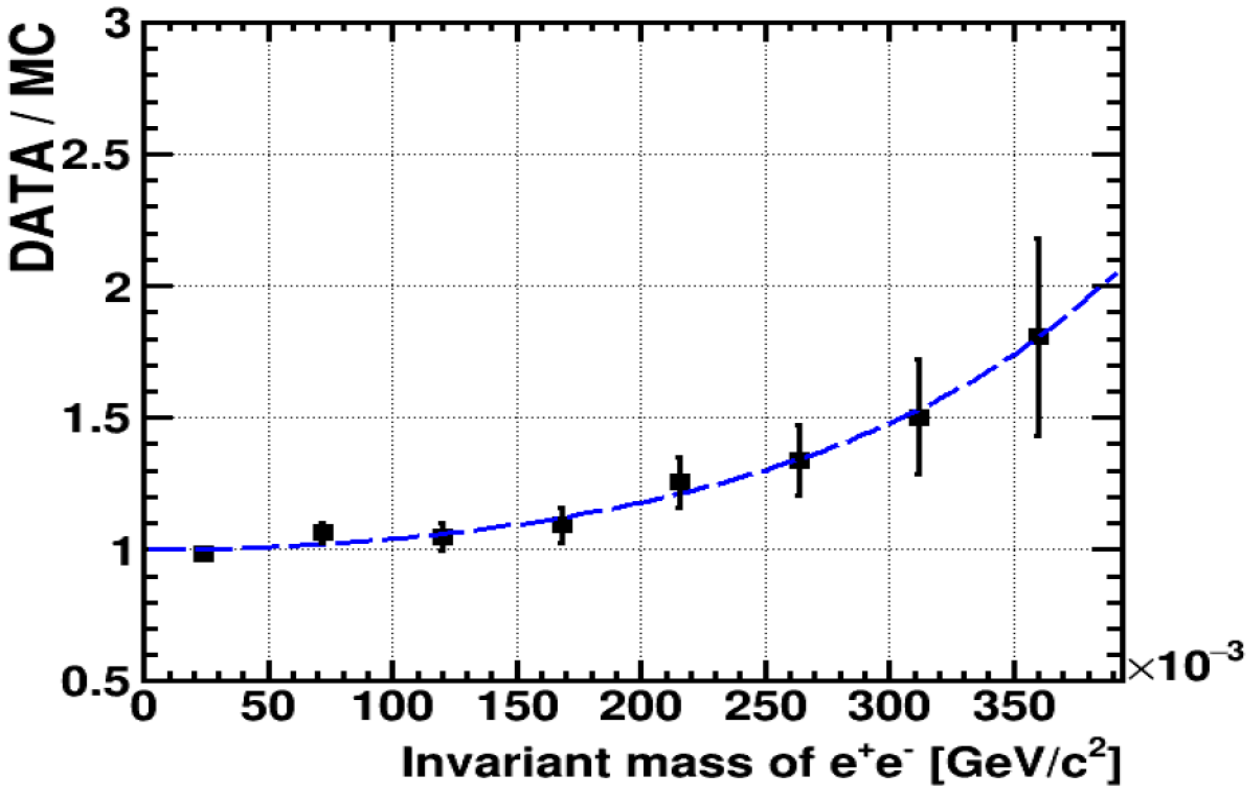
NON-η BACKGROUND REJECTION PROCEDURE

BEFORE



NON-η BACKGROUND REJECTION PROCEDURE

AFTER



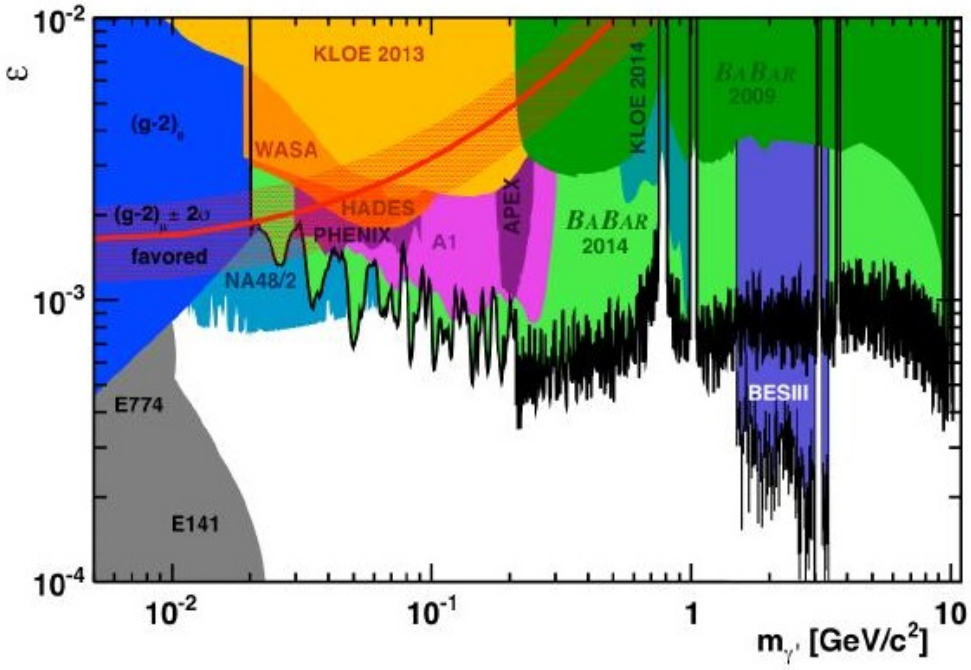
$\eta \rightarrow e^+e^-$ BR LIMIT

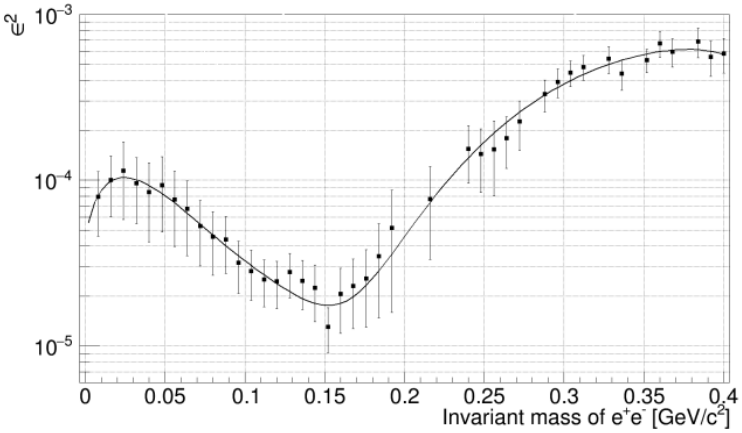
$$BR_{limit} = \frac{N_{sig} + \lambda\sigma_{sig}}{Acc \cdot N_{\eta}}$$

$$CL = \int_{-\infty}^{\mu+\lambda\sigma} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] dx = \frac{1}{2}\left[1 + erf\left(\frac{\lambda}{\sqrt{2}}\right)\right]$$

FELDMANN AND COUSINS, PHYS.REV. D57 (1998) 3873-3889

BACKUP


ε
10^-2
10^-3
10^-4
10^-2
10^-1
1
10
m_γ' [GeV/c^2]
KLOE 2013
KLOE 2014
BABAR 2009
BABAR 2014
(g-2)_e
WASA
(g-2)_μ ± 2σ
favored
HADES
PHENIX
A1
APEX
NA48/2
E774
E141
BESIII


ε^2
10^-3
10^-4
10^-5
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Invariant mass of e+e- [GeV/c^2]

BACKUP

Condition	Number of events
All events	$4{\cdot}10^6$
Trigger	$5.57{\cdot}10^5$ (13.9%)
$\geq$ 2 FD ch.tr. $\geq$ 10 MeV	$4.94{\cdot}10^5$ (12.35%)
$\geq$ 1 pair FD ch.tr. inside 10 ns time window	$4{\cdot}10^5$ (10%)
proton identification	$2.76{\cdot}10^5$ (6.9%)

- THOSE STATISTICS ARE FROM A TYPICAL DATA FILE
- WHOLE DATA SET x 3000
- ALL EVENTS IN DATA ~10^{10}