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Results on π^0 and η TFF from WASA-at-COSY

- Light meson TFF (from decays)
- WASA-at-COSY
- $\pi^0 \rightarrow e^+e^-\gamma$ / e^+e^-
- $\eta \rightarrow e^+e^-\gamma$ / $e^+e^-e^+e^-$ / e^+e^-
- Anomalous processes
 $\eta \rightarrow \pi^+\pi^-\gamma$, / $\pi^+\pi^-e^+e^-$; $\omega \rightarrow \pi^+\pi^-\pi^0$

Andrzej Kupść for WASA-at-COSY

Uppsala University

International Workshop on e^+e^- collisions from Φ to Ψ 2015

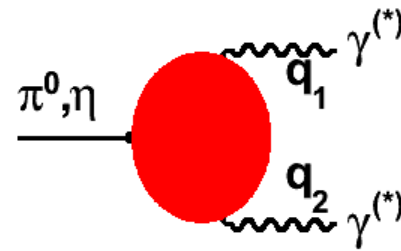
π^0, η Transition Form Factors (TFF)

Low energy QCD

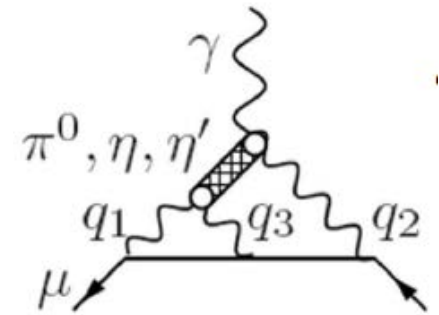
l^+l^- spectra for HI

dark photon (U boson)

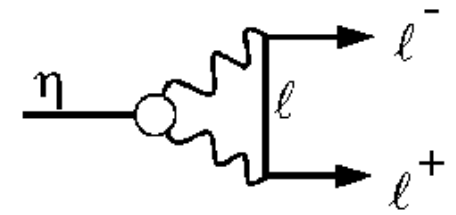
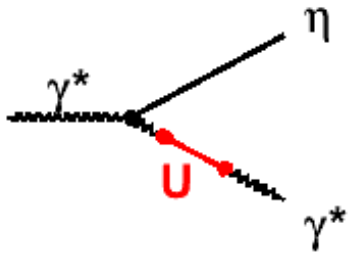
$$\Gamma(P \rightarrow \gamma\gamma)$$



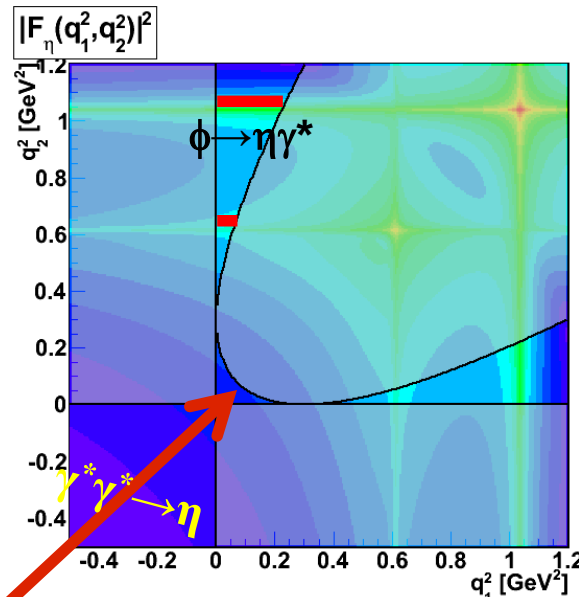
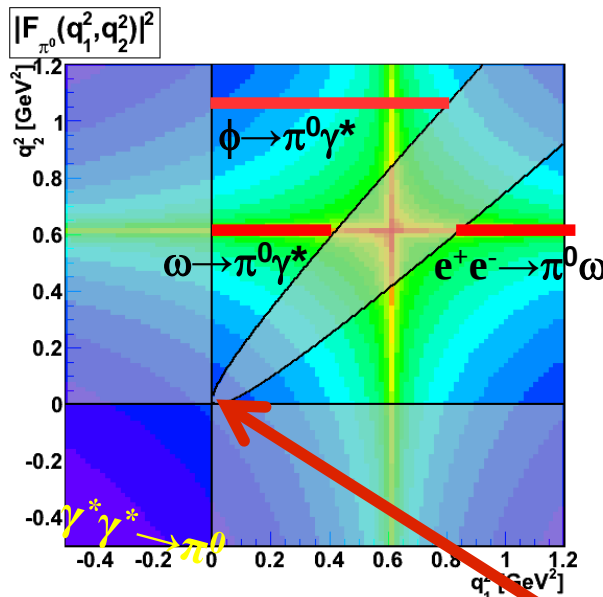
$$F_P(q_1^2, q_2^2)$$



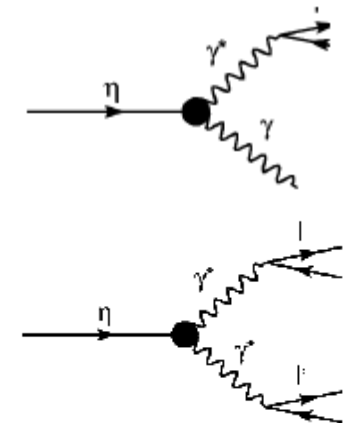
HLbL for a_μ



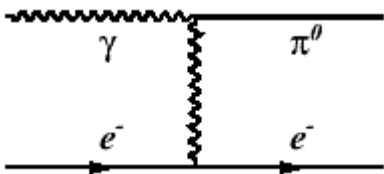
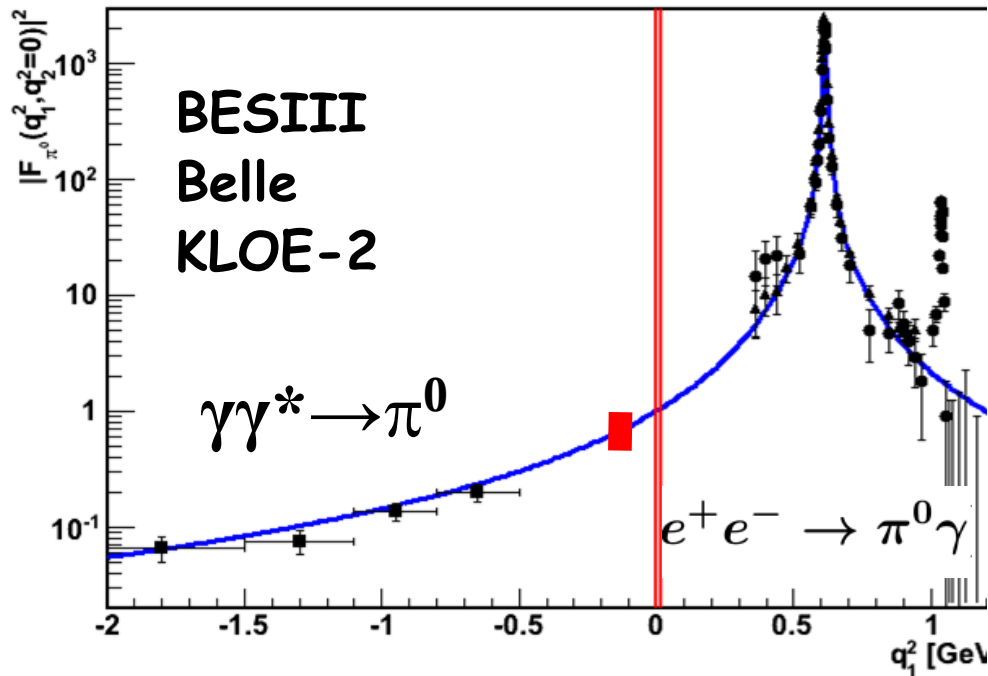
Access to $q^2 < 0$



$$P \rightarrow \gamma^* \gamma^*$$

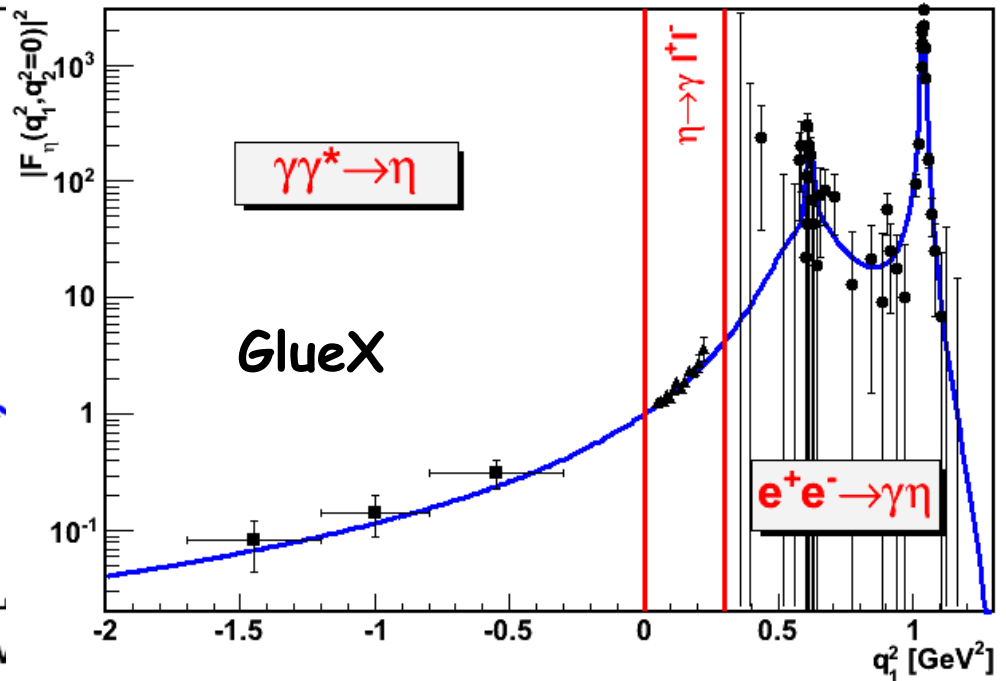


η, π^0 single off shell TFF



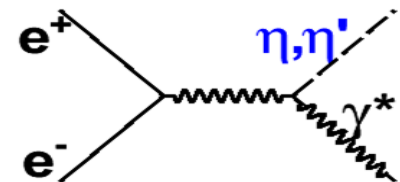
$$\frac{d\sigma}{dt}(e^- \gamma \rightarrow e^- P) = \frac{16}{3} \frac{\pi \alpha}{s m_P^3} \Gamma_{\gamma\gamma} |F_P(t, 0)|^2 \frac{s - m_P^2 + t}{t}$$

$P \rightarrow \gamma^* \gamma$
Dalitz decays:
KLOE, WASA, CBall, BESIII
CLAS, NA48



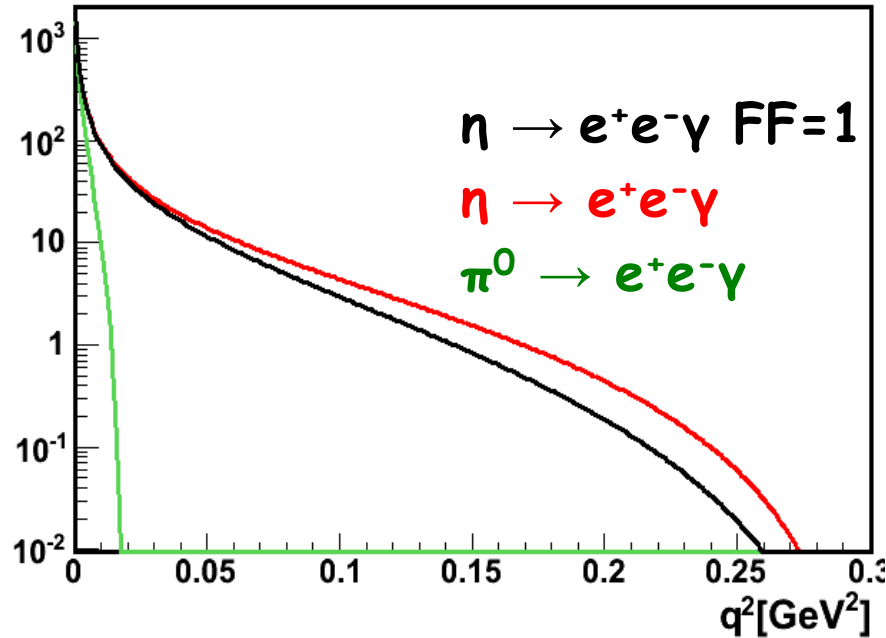
$\gamma^* \rightarrow P \gamma$
VEPP 2000 0.3-2 GeV
KLOE-2 ISR, BESIII

$$\sigma(e^+e^- \rightarrow P \gamma) = \frac{8}{3} \pi \alpha \Gamma_{\gamma\gamma} |F_P(s, 0)|^2 \left(\frac{s - m_P^2}{s m_P} \right)^3$$



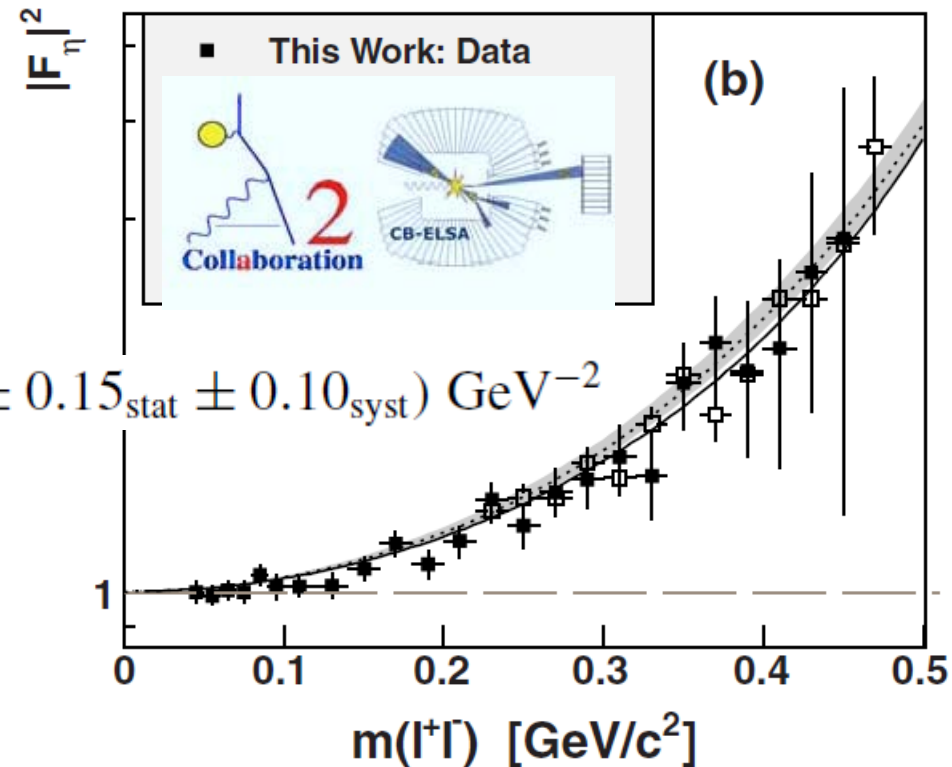
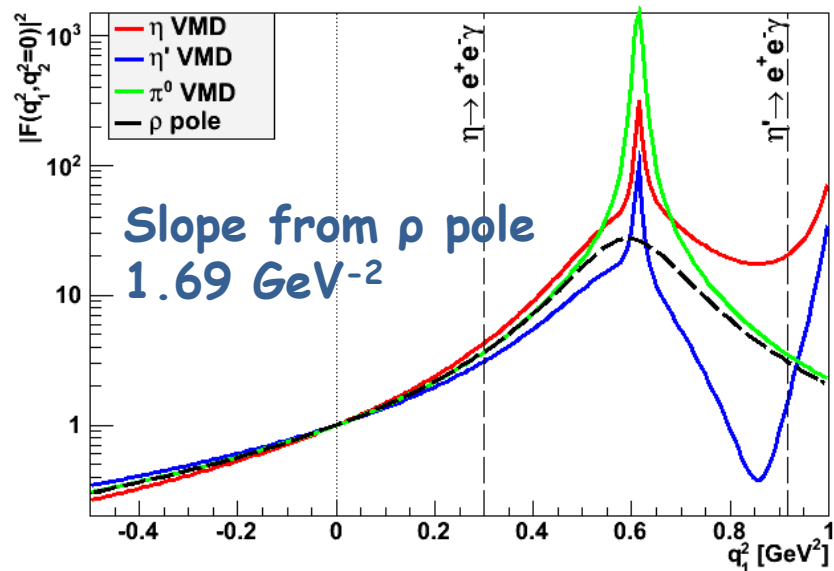
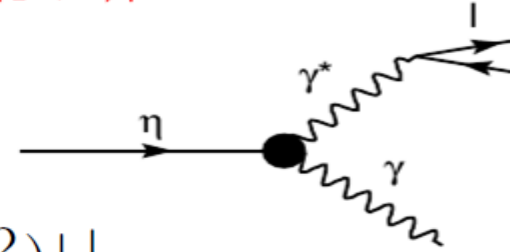
Single Dalitz decays

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



$$b_P = \left. \frac{d \ln |F_P(q^2)|}{dq^2} \right|_{q^2=0}$$

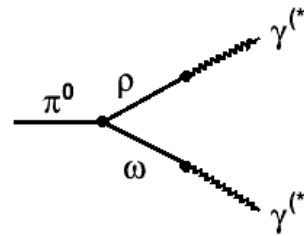
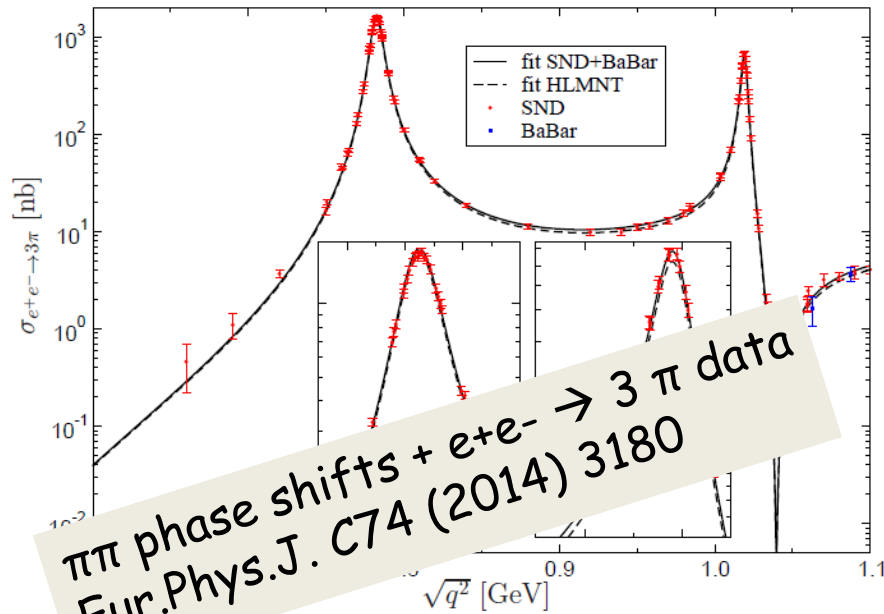
CB/TAPS: PRC89, 044608 (2014)



$$e^+e^- (V) \rightarrow \pi^+\pi^-\pi^0$$

$$\rightarrow \pi^+\pi^-\eta$$

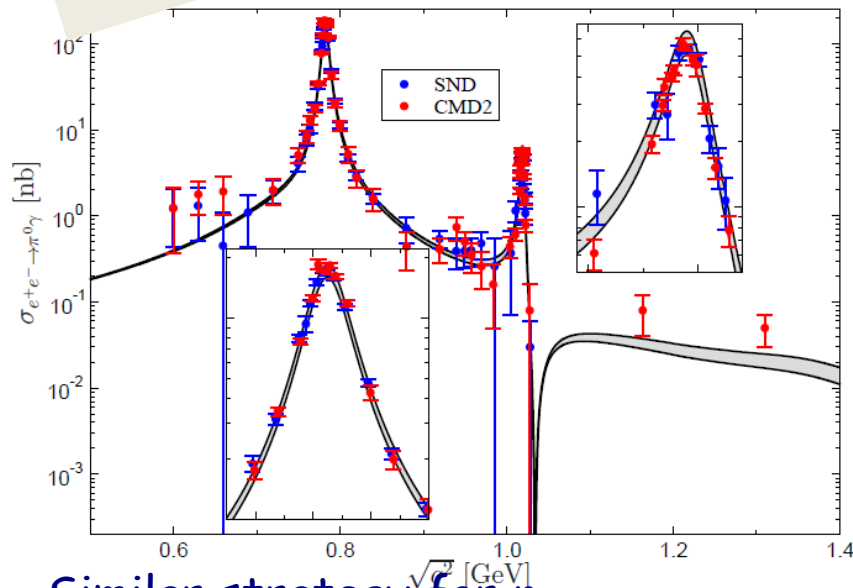
TFF



$$\eta \rightarrow e^+e^-\gamma \text{ from}$$

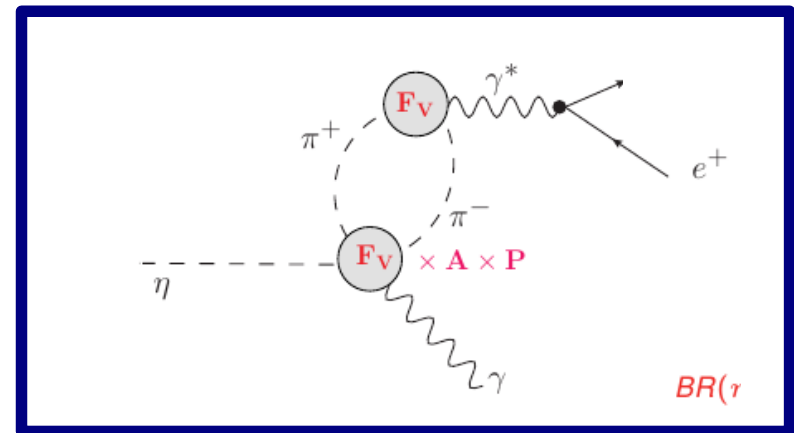
$$\eta \rightarrow \pi^+\pi^-\gamma$$

$$\sum_{V=\rho,\omega,\phi} \eta \rightarrow V \gamma^* \rightarrow e^+e^-\gamma$$



Similar strategy for η
From $e^+e^- \rightarrow \pi^+\pi^-\eta$ to η TFF

arXiv:1509.02194



$$A + \alpha \Rightarrow b\eta = 2.05^{+0.22}_{-0.10} \text{ GeV}^{-2}$$

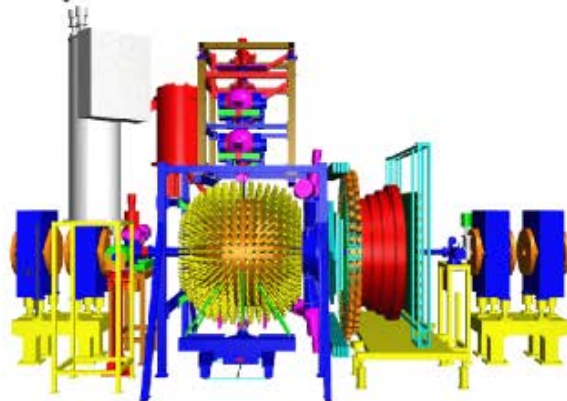
EPJC73(13)2668



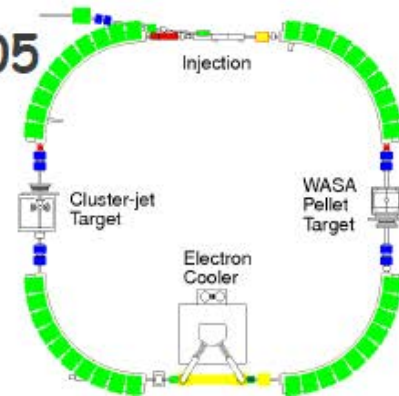
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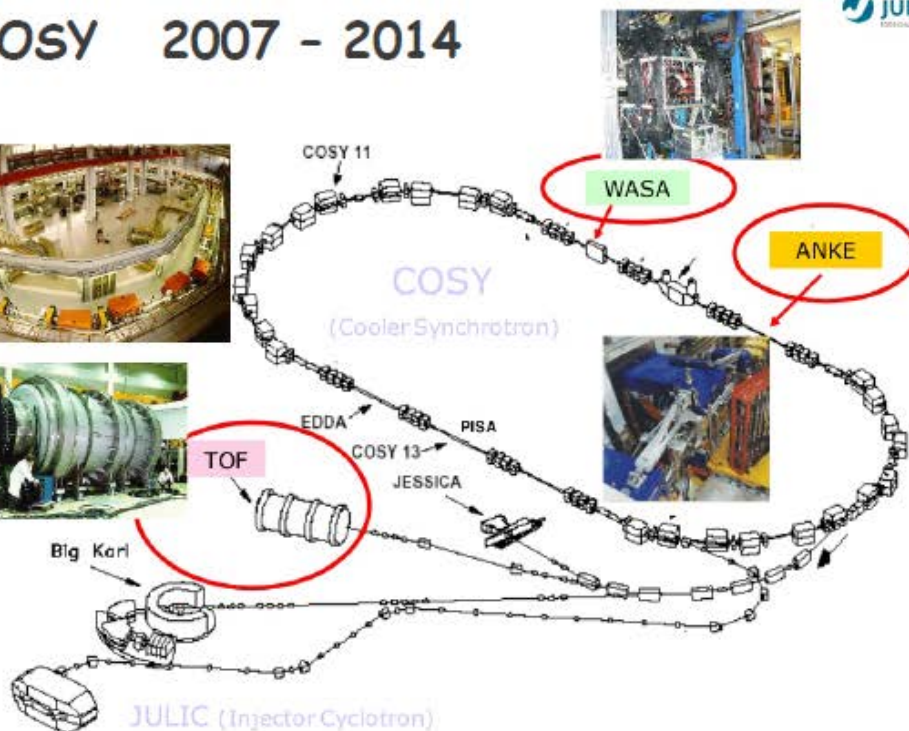
WASA Proposal 1987:
key experiments: $\pi^0, \eta \rightarrow e^+e^-$



CELSIUS < 2005

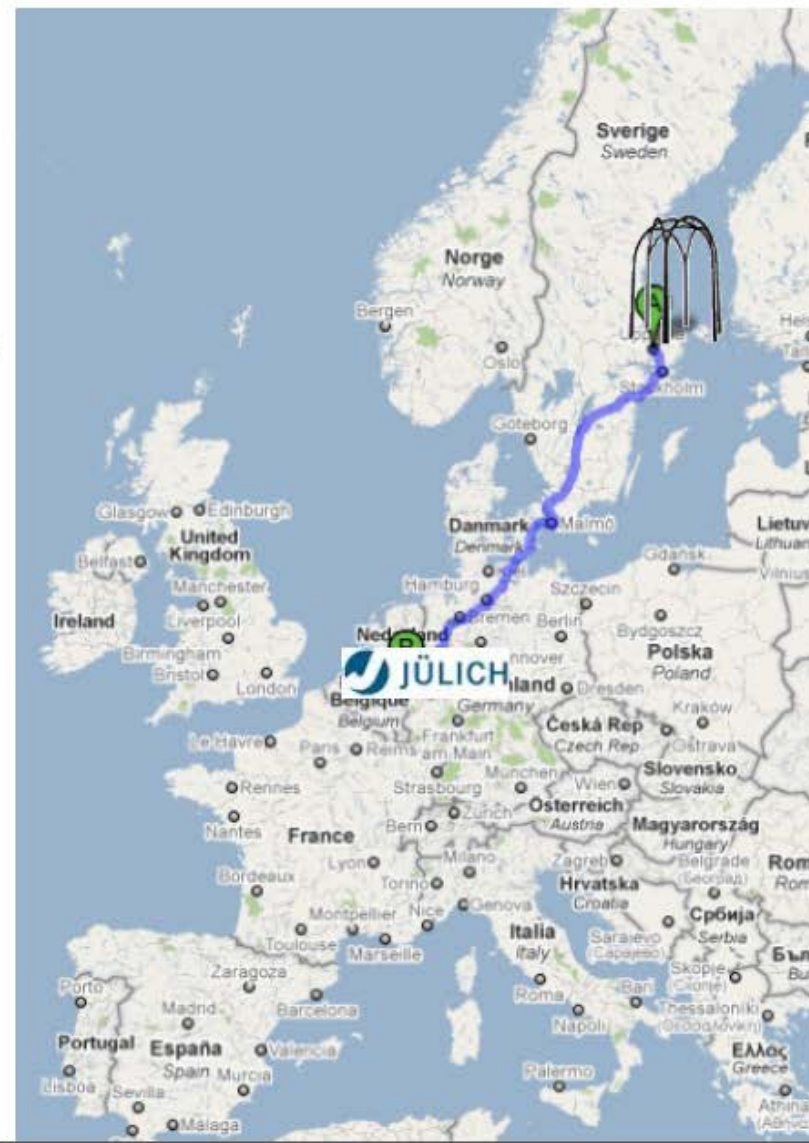


COSY 2007 - 2014



Schematic overview COSY Facility (FZ-Jülich)

Recent results from Experiments at COSY, HADRON2009, 4/12/09

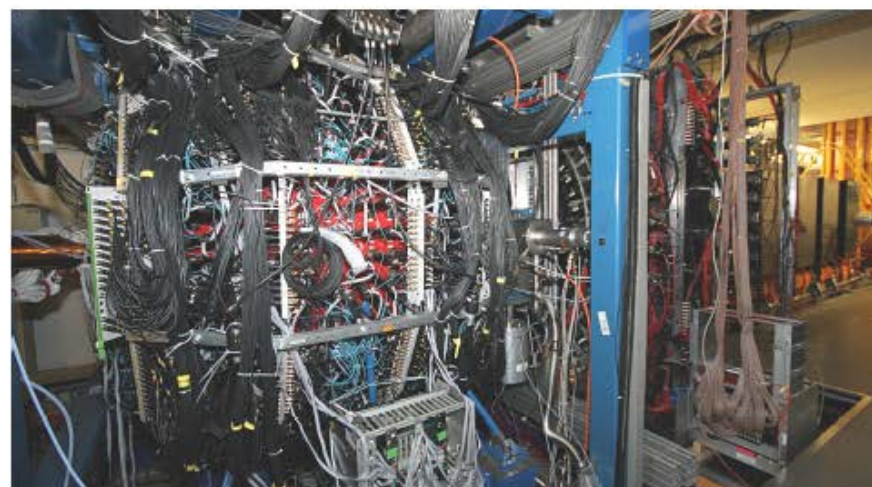
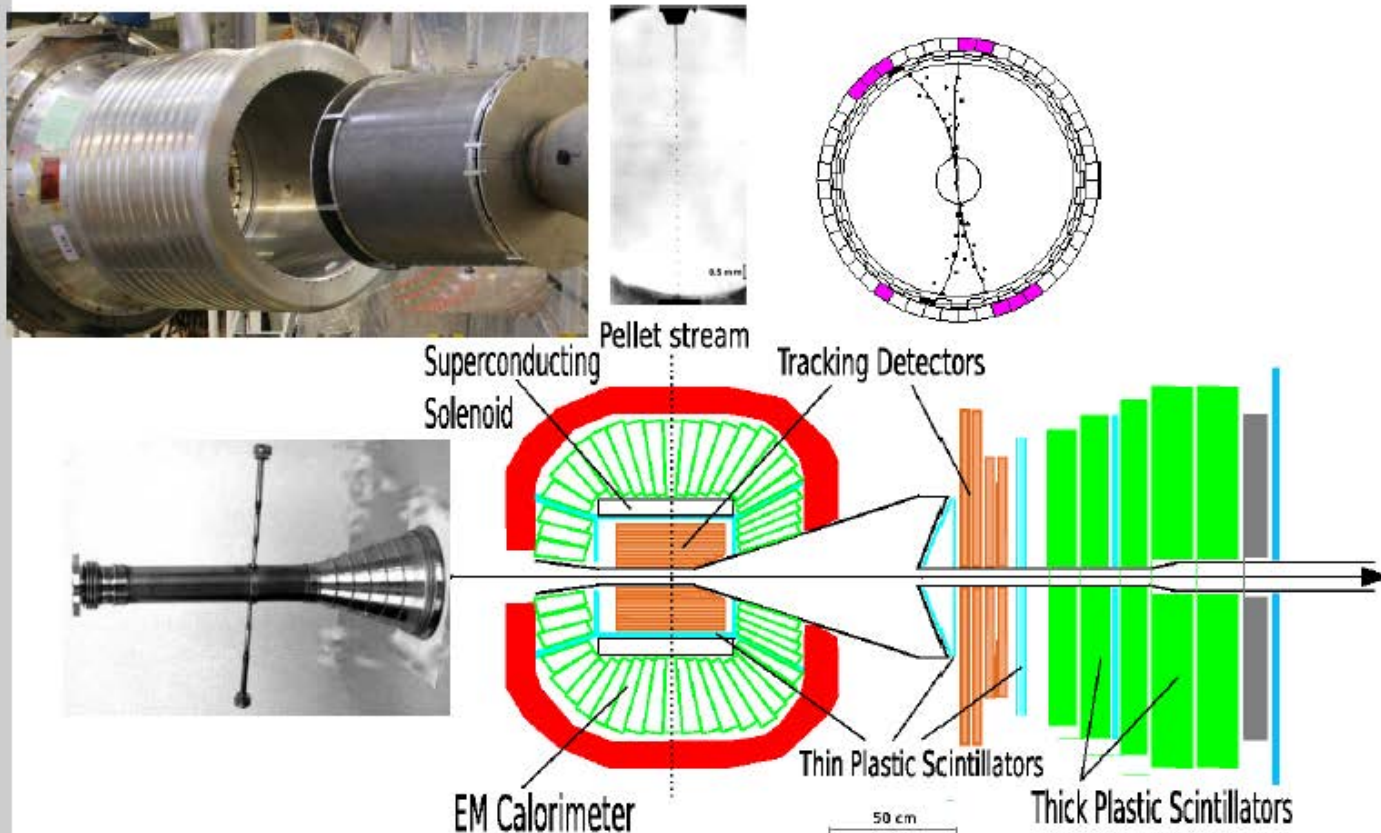




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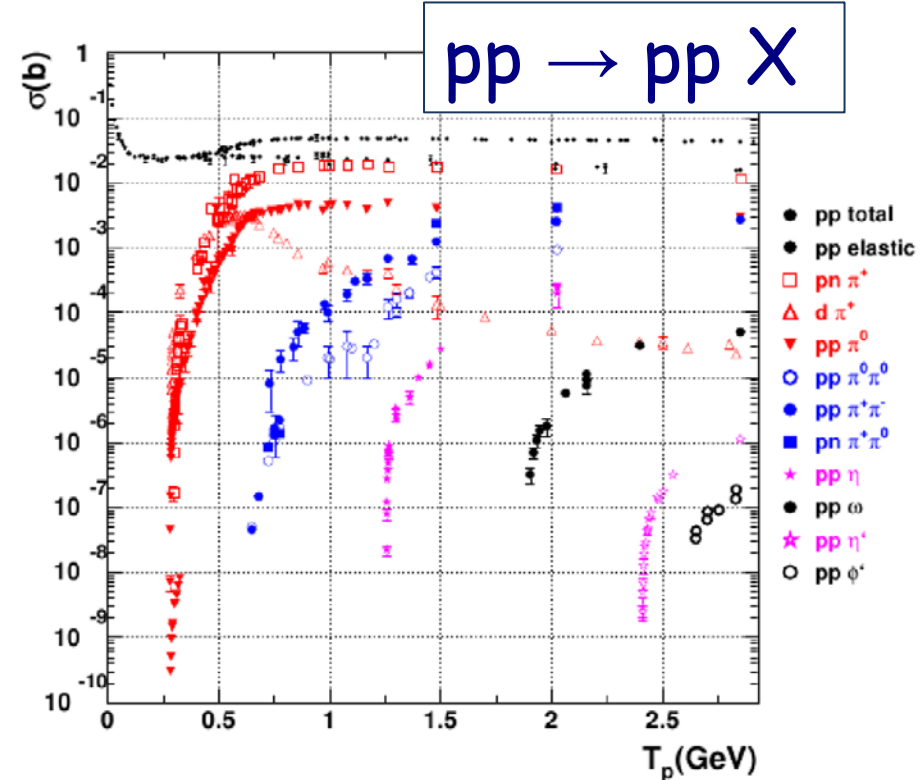
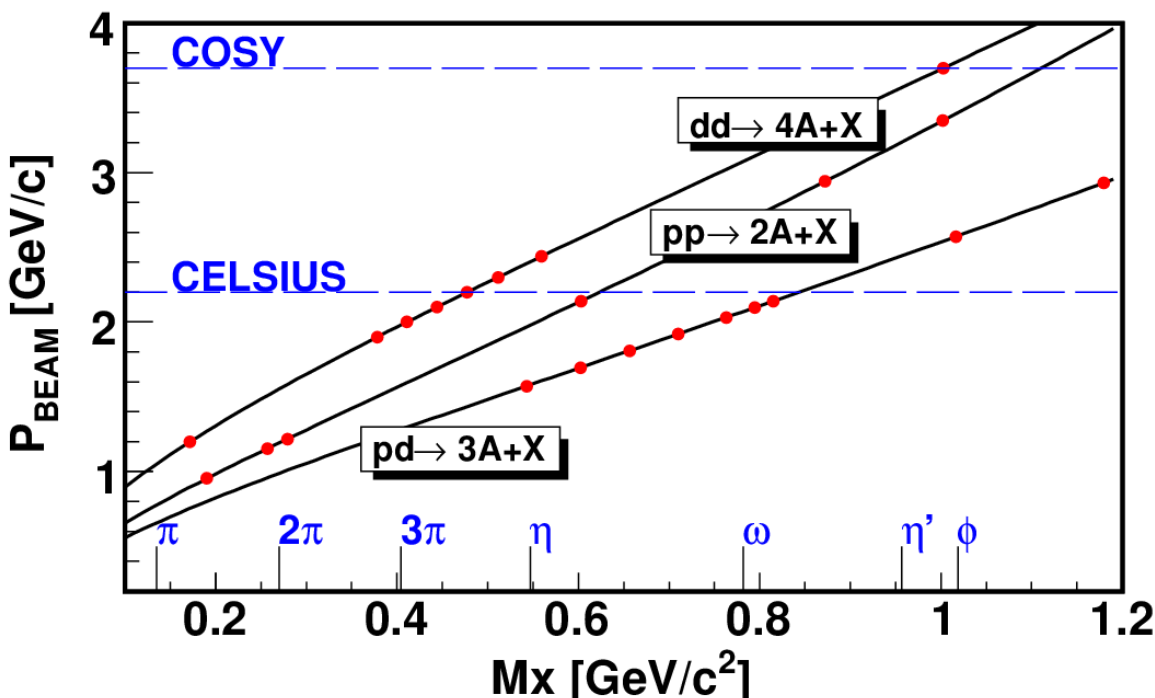
WASA detector



NIM A594,339

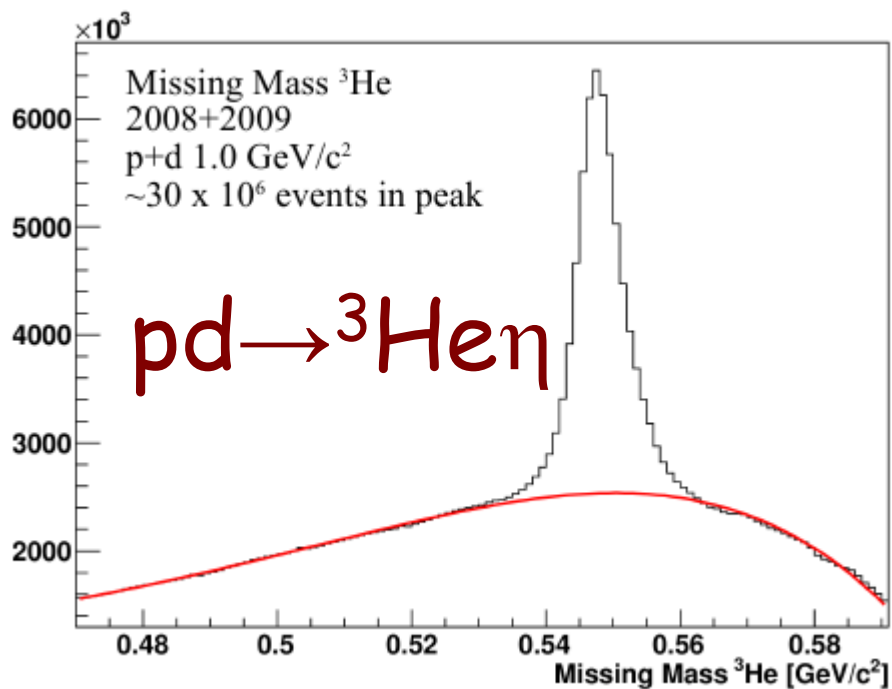
Hadro-production

	π^0	η	ω	η'
$pd \rightarrow 3HeX$	$O(\mu b)$	$0.4\mu b$	$85nb$	$0.6nb$
$pp \rightarrow pp X$	$1 mb$	$10\mu b$	$10\mu b$	$300nb$
$L < 10^{32} cm^{-2}s^{-1} = 0.1 nb/s$				

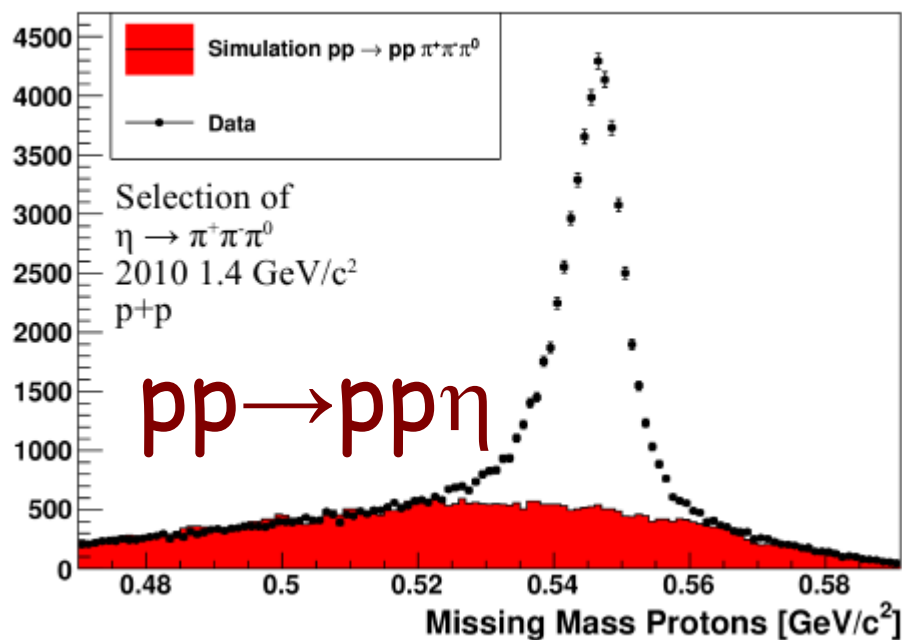




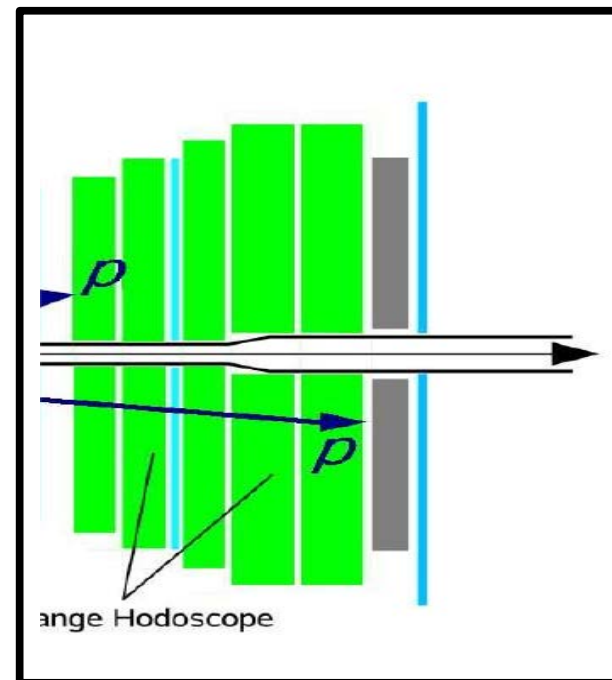
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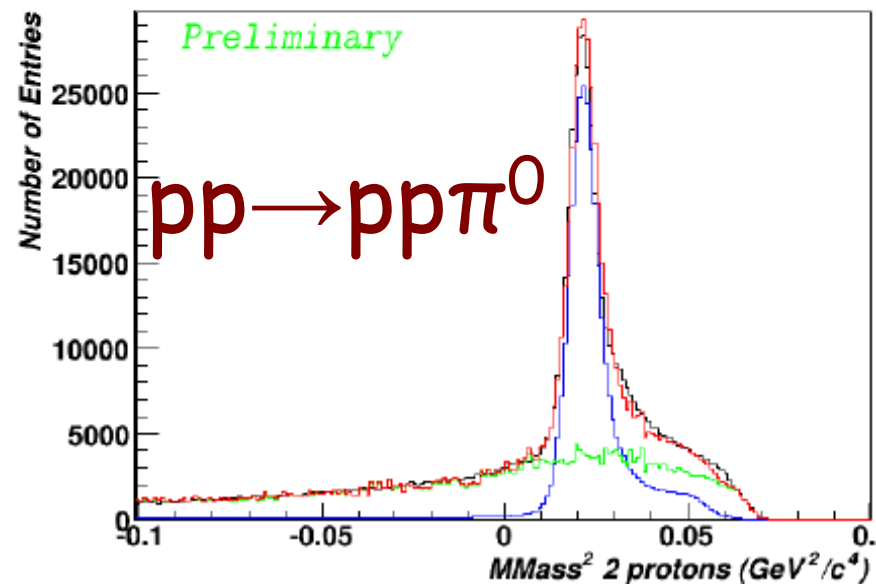
$$\text{Missing Mass} = \sqrt{(E_{\text{in}} - E_{\text{out}})^2 - (P_{\text{in}} - P_{\text{out}})^2}$$



Meson tagging



2 FD protons





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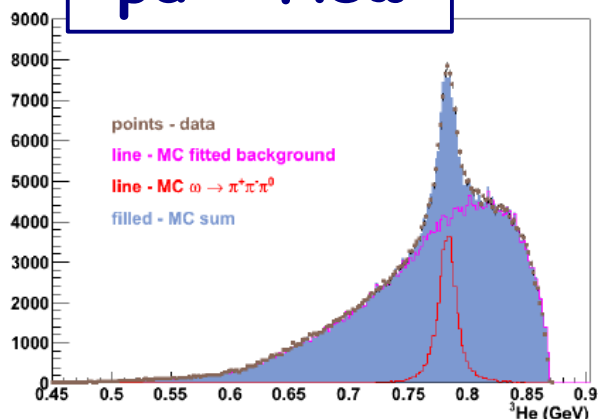


p + d, ~ 2 weeks,
P_{beam} 2.25 & 2.19 GeV/c

p + p, pilot run,
P_{beam} 2.851 & 3.350 GeV/c

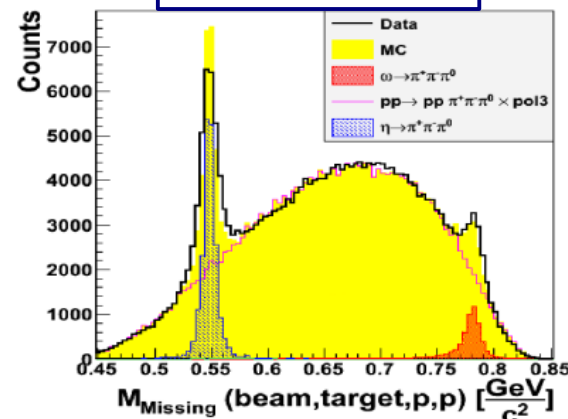
A glance at $\omega \rightarrow \pi^+ \pi^- \pi^0$

pd → ³He ω



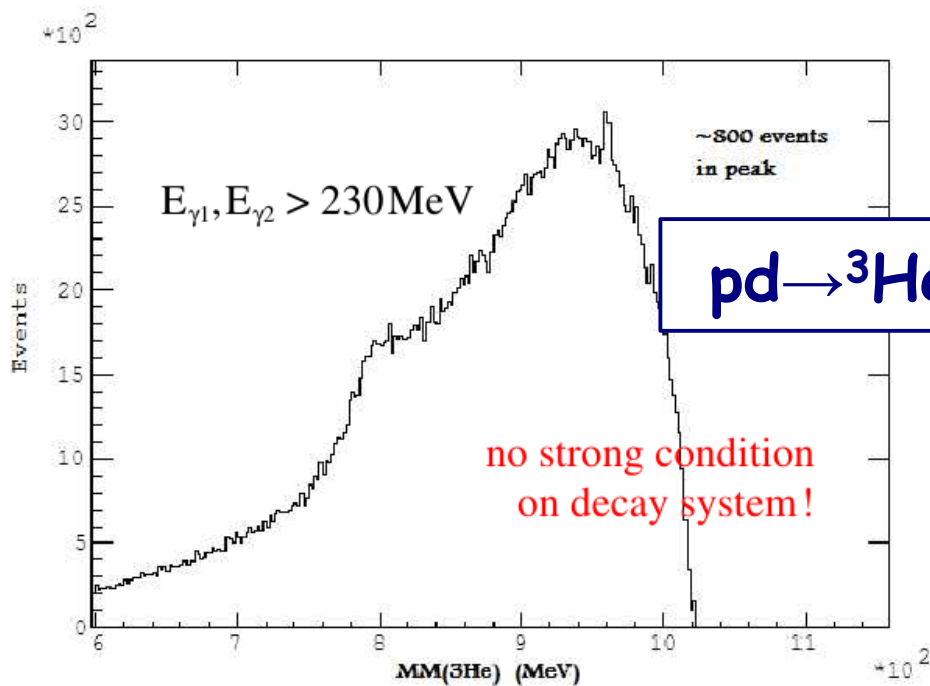
Cut based selection: 72 000 signal events

pp → pp ω



With kinematical fit: 5600 signal events
(1/3 of collected data)

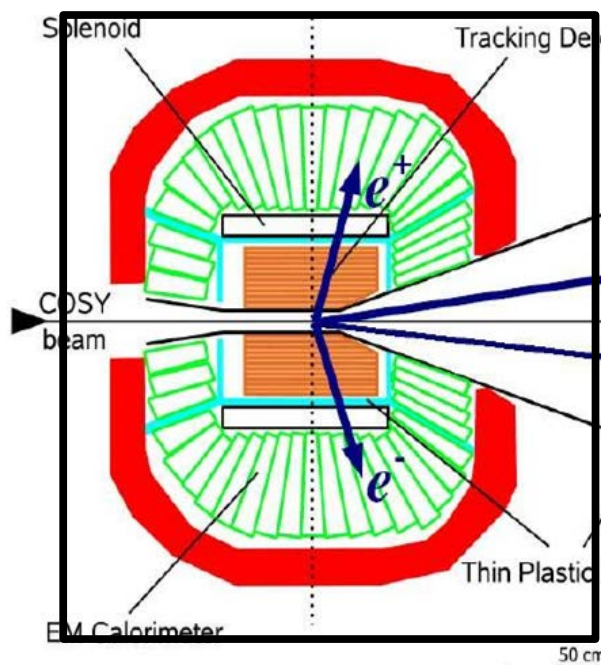
L. Heijkenkjöld, S. Sawant, F. Anjum Khan



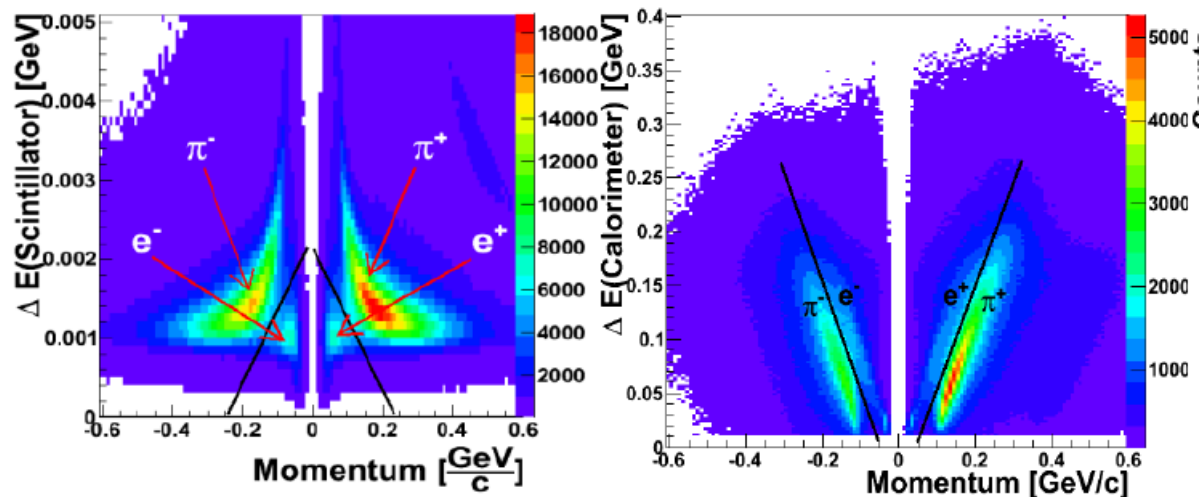
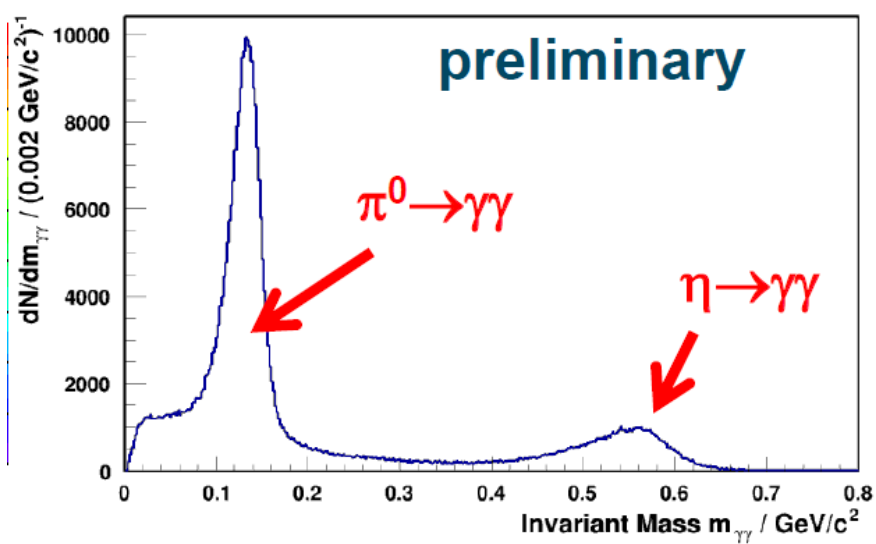
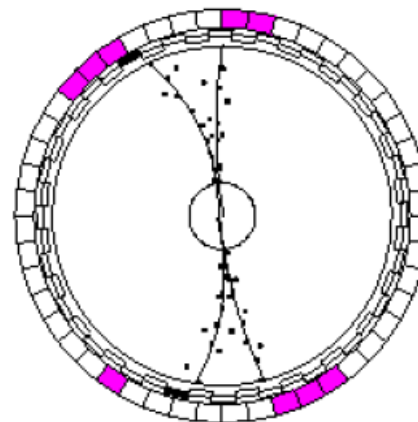
pd → ³He n'

no strong condition
on decay system!

J. Zlomanczuk



Decay products



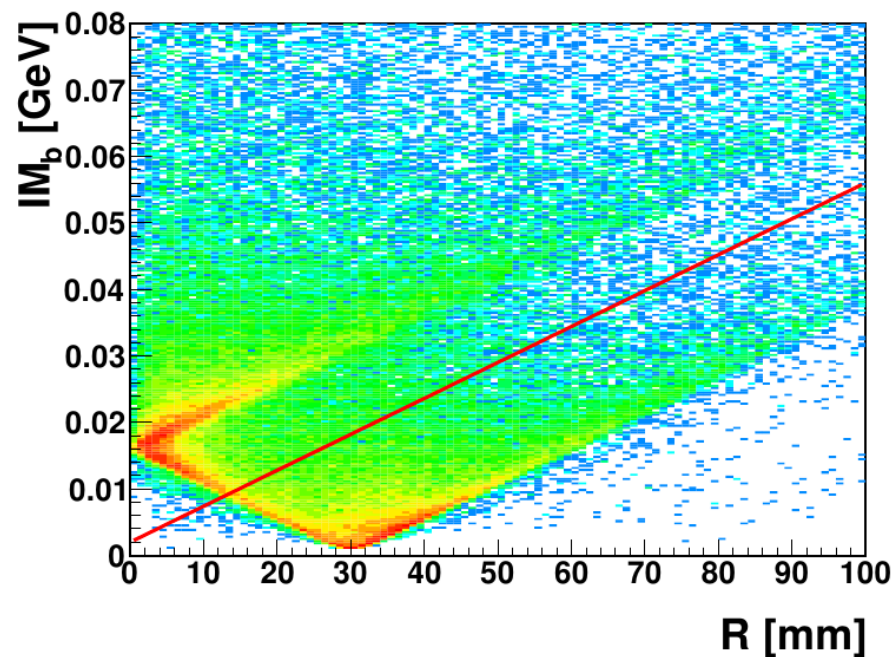
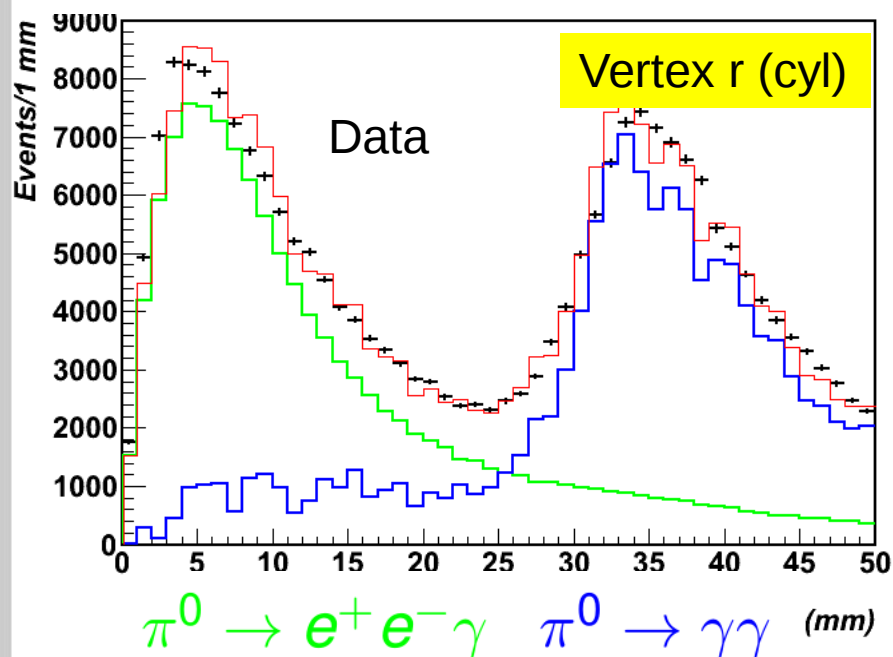
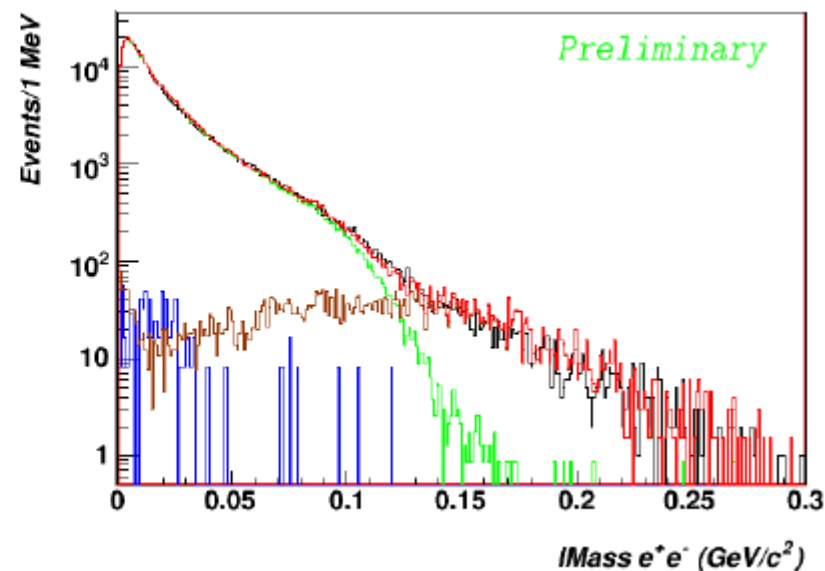
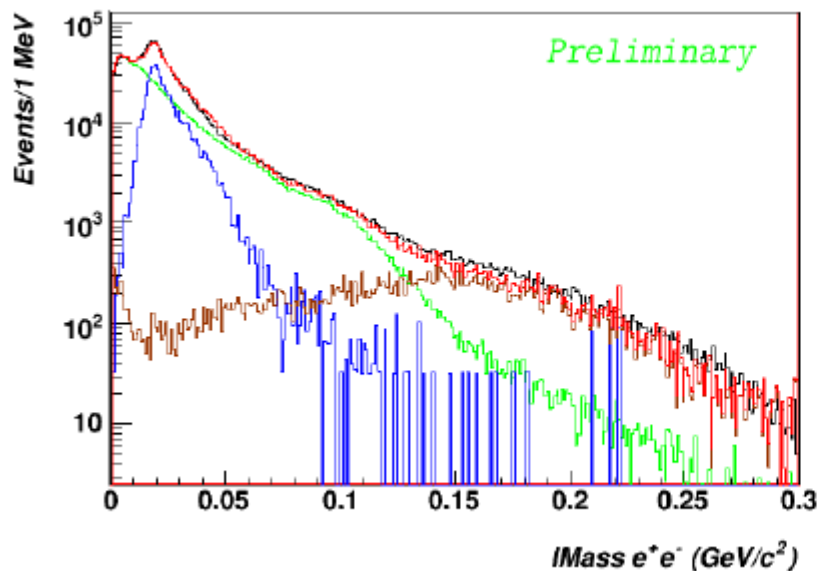


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Analysis: $\pi^0 \rightarrow \gamma e^+ e^-$

Vertex r 20 mm + PID



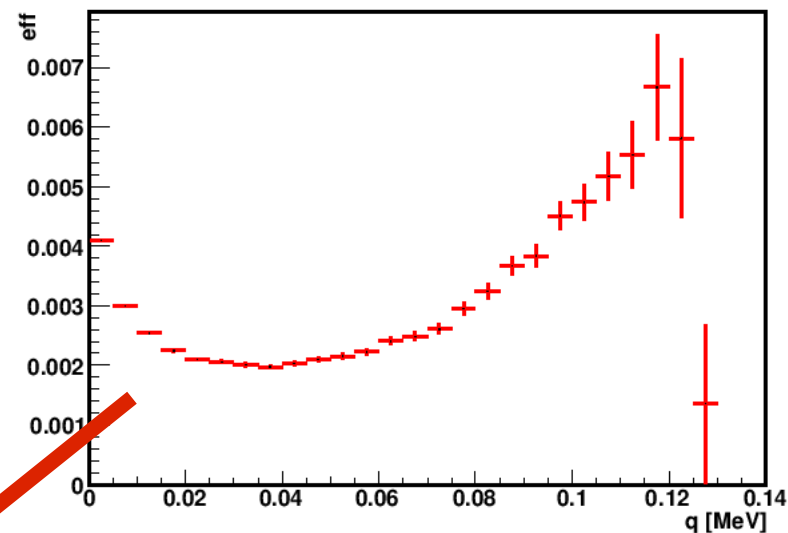
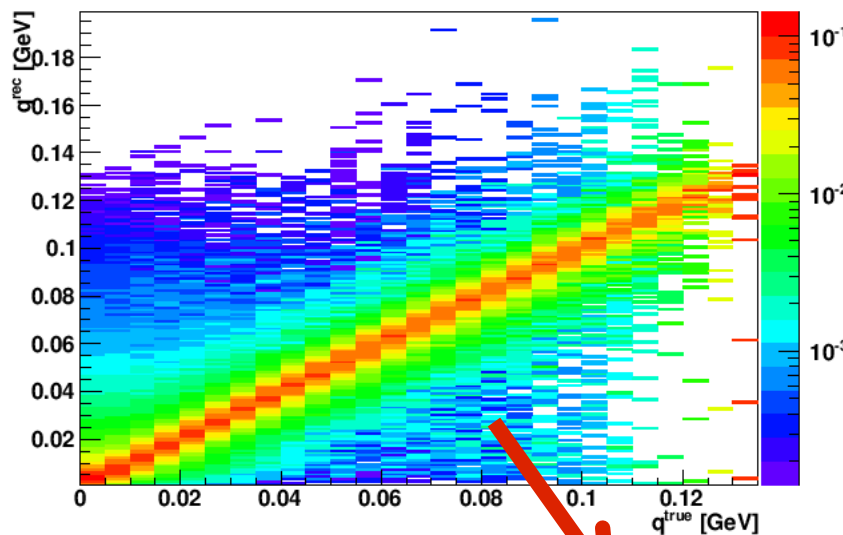


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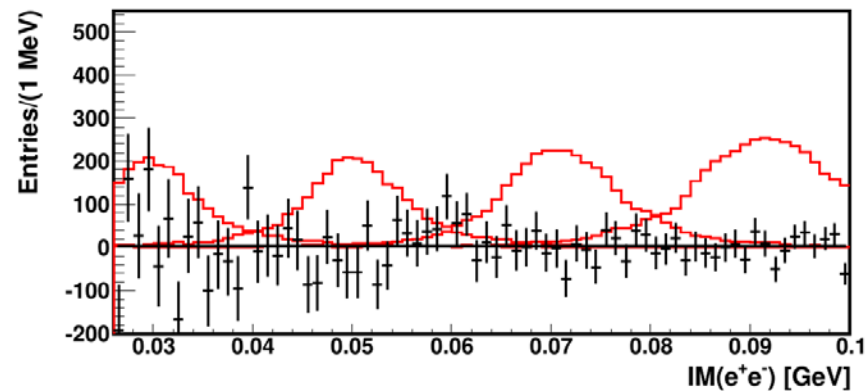
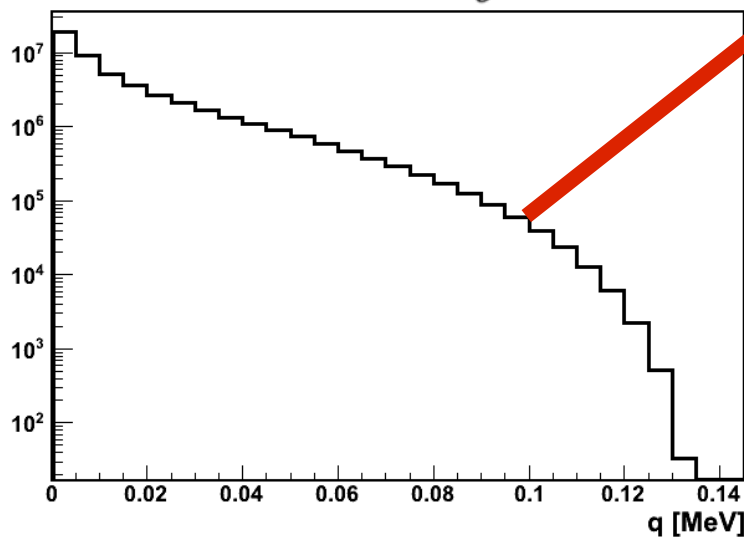
Extraction of: $\pi^0 \rightarrow \gamma U \rightarrow \gamma e^+ e^-$

Smearing matrix



$$N_i^d / N_{Tot} = \sum_j S_{ij} \varepsilon_j \nu_j (\pi^0 \rightarrow e^+ e^- \gamma) + S_{ik} \varepsilon_k \beta_k$$

PL B726 (2013) 187

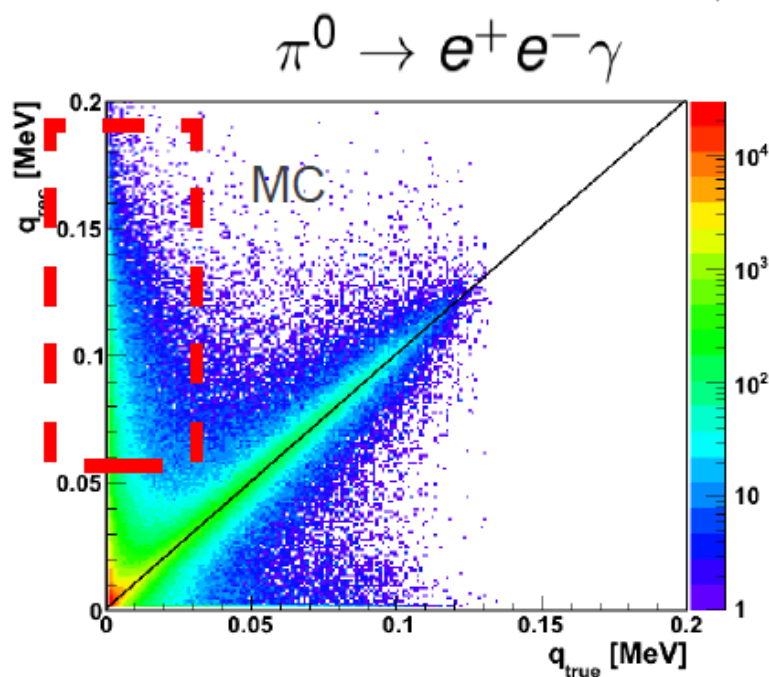
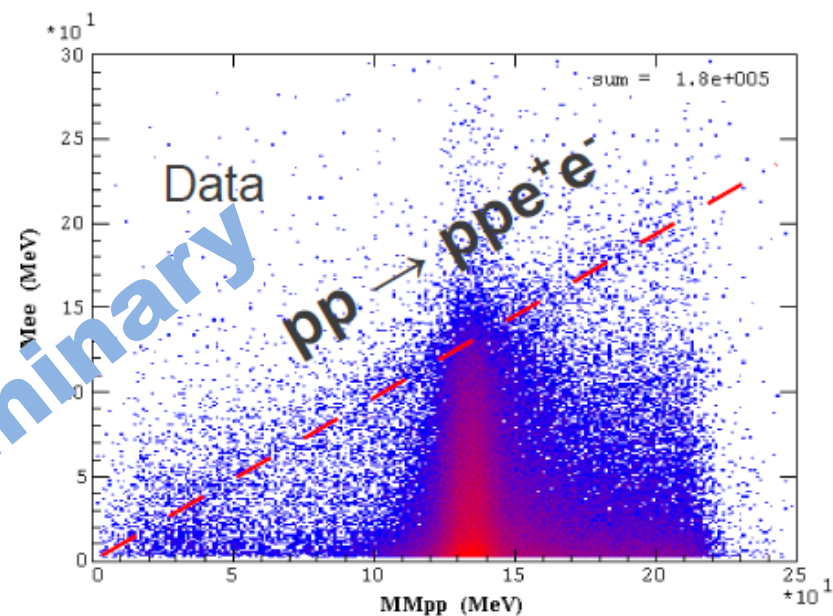
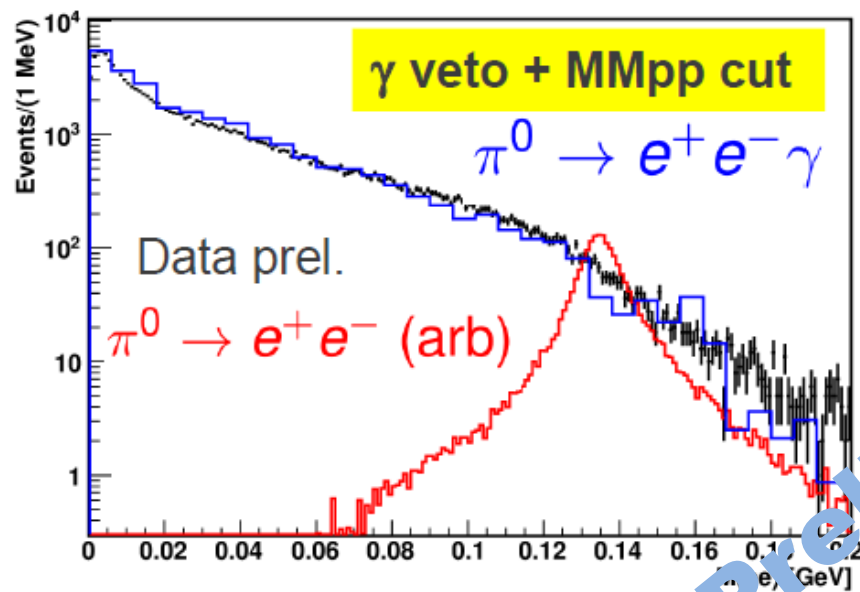




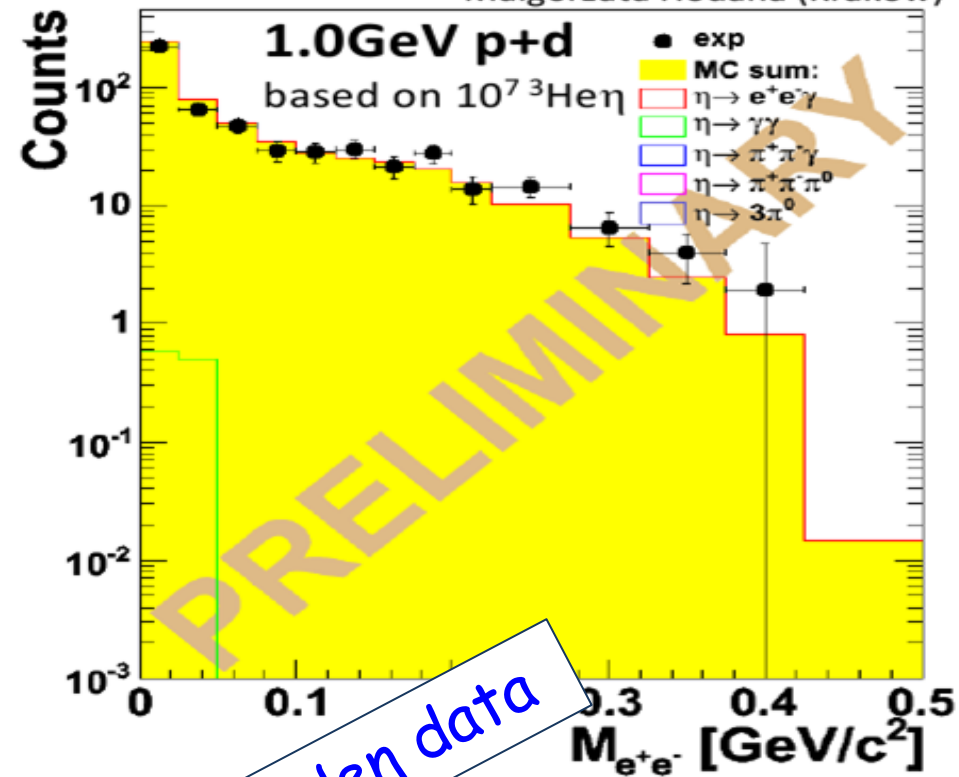
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Analysis: $\pi^0 \rightarrow e^+e^-$



Analysis: $\eta \rightarrow \gamma e^+ e^-$



pd $\rightarrow$ ^3He data

pd $\rightarrow$ $^3\text{He} \eta$

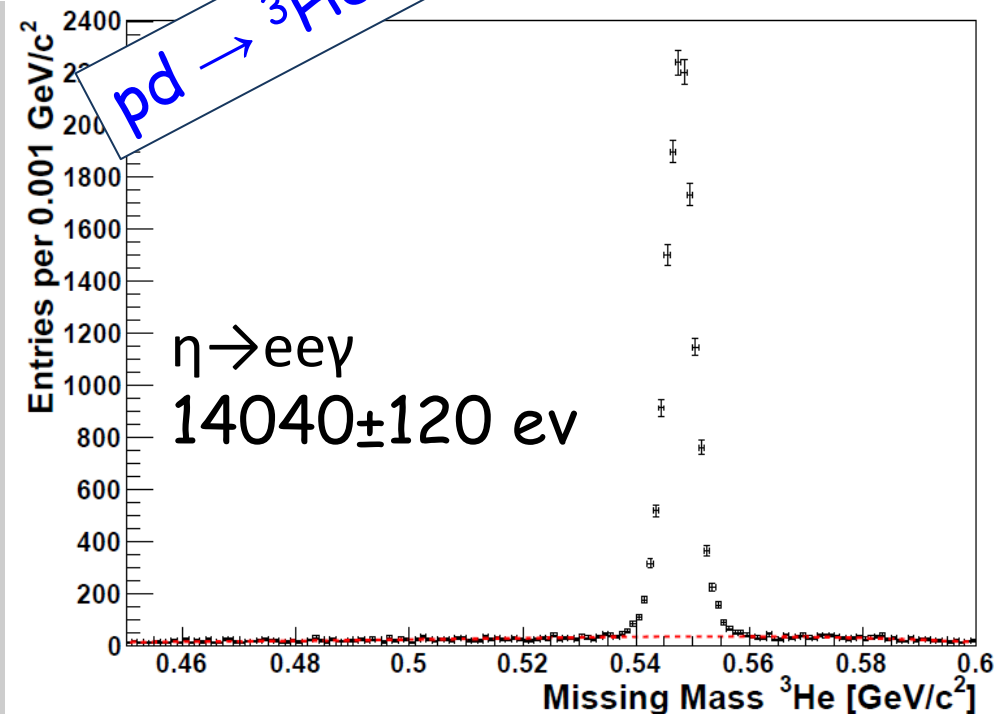
pp $\rightarrow$ pp η :

2010 data 8w

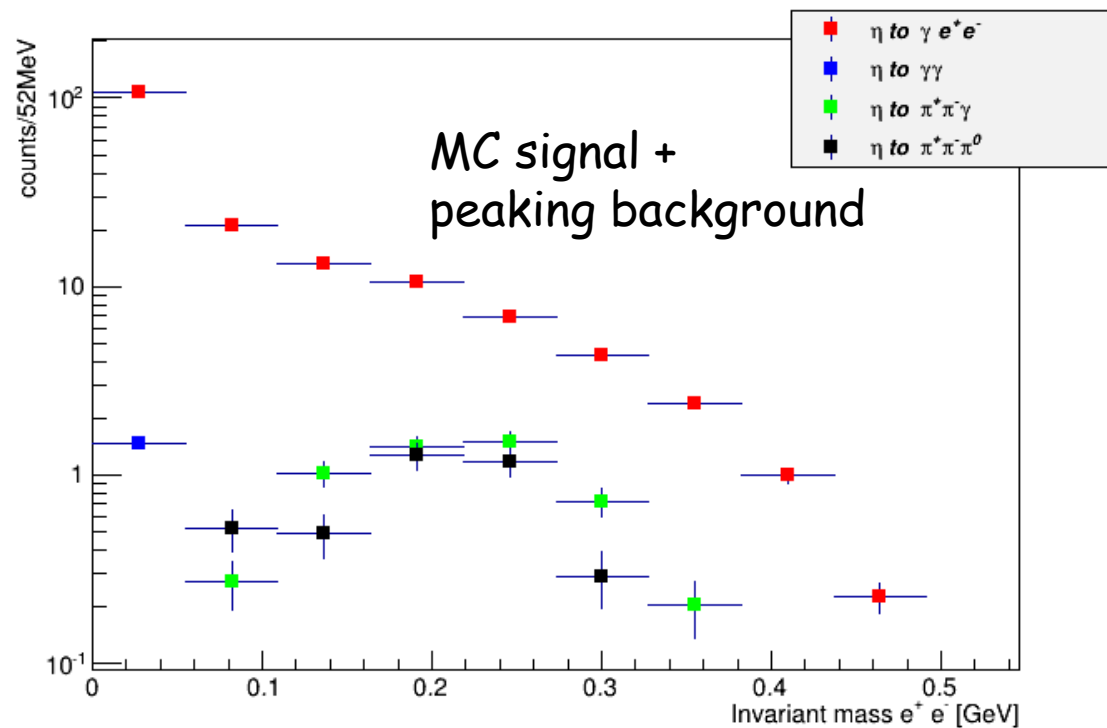
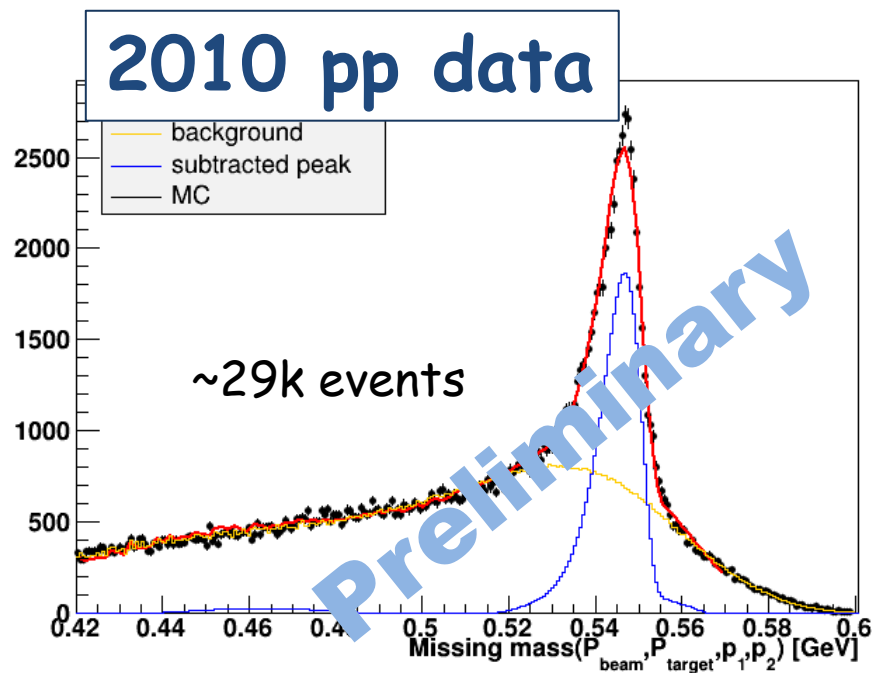
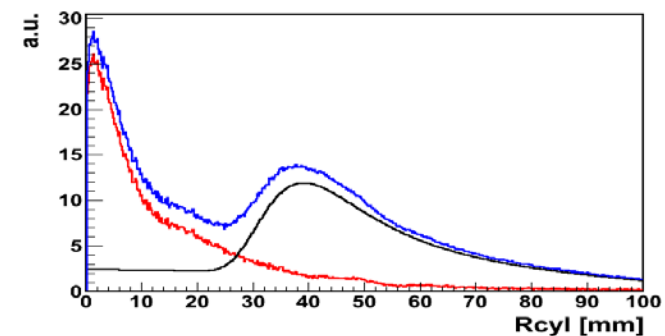
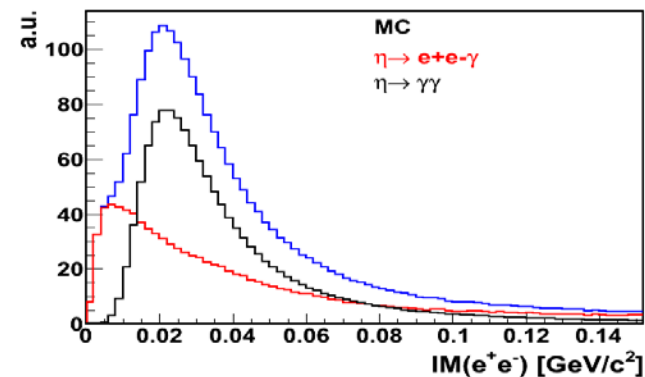
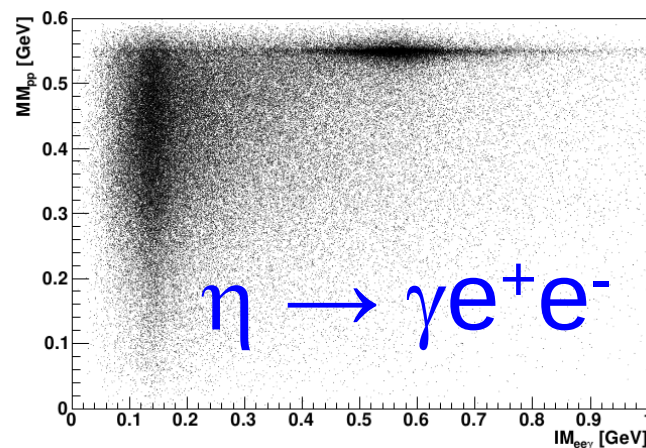
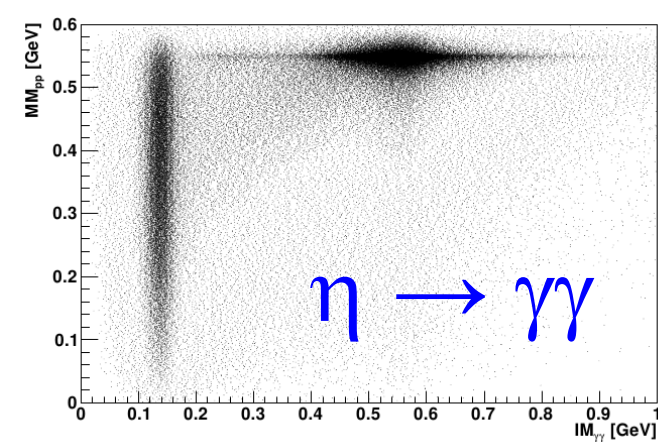
2012 data 8w

• expect total

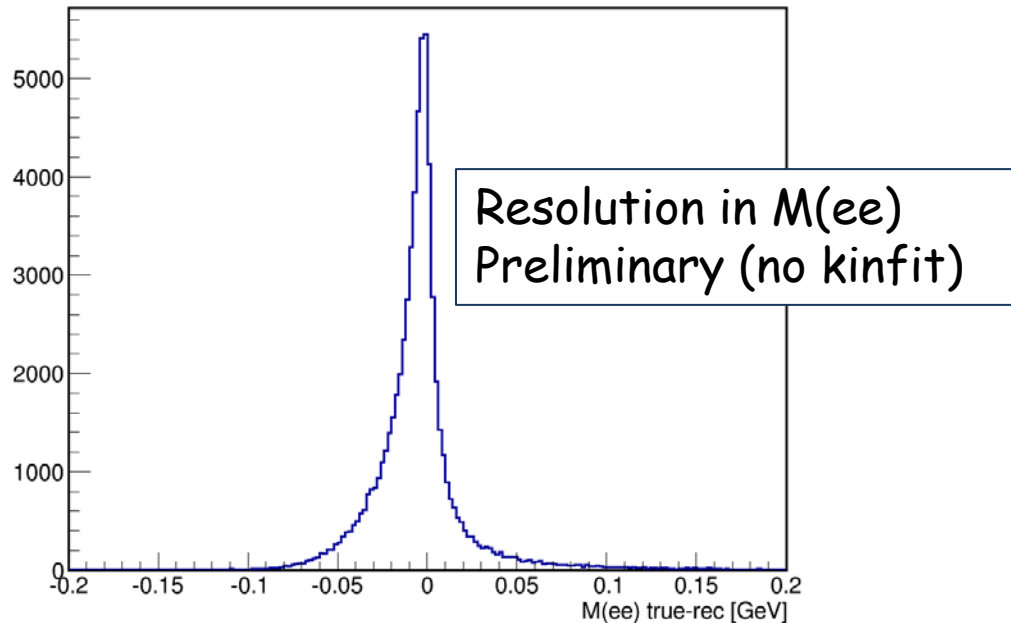
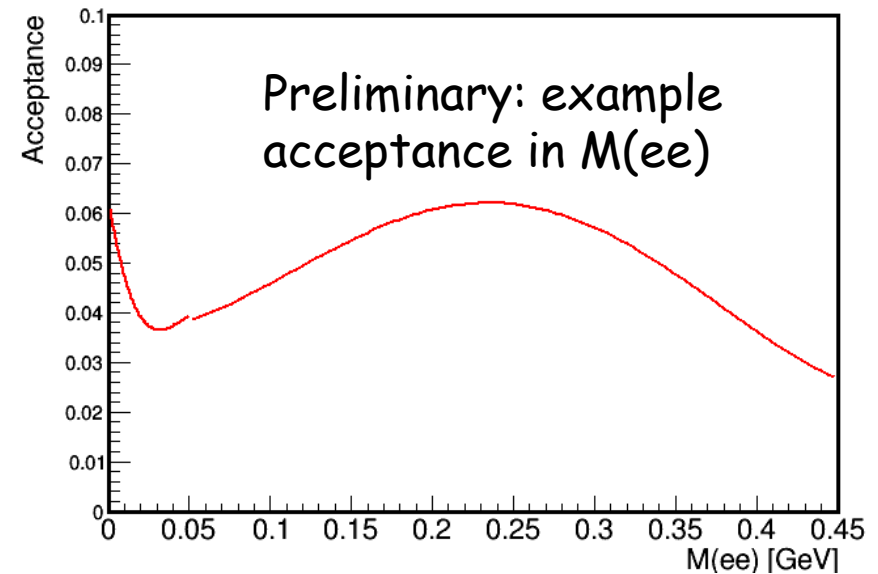
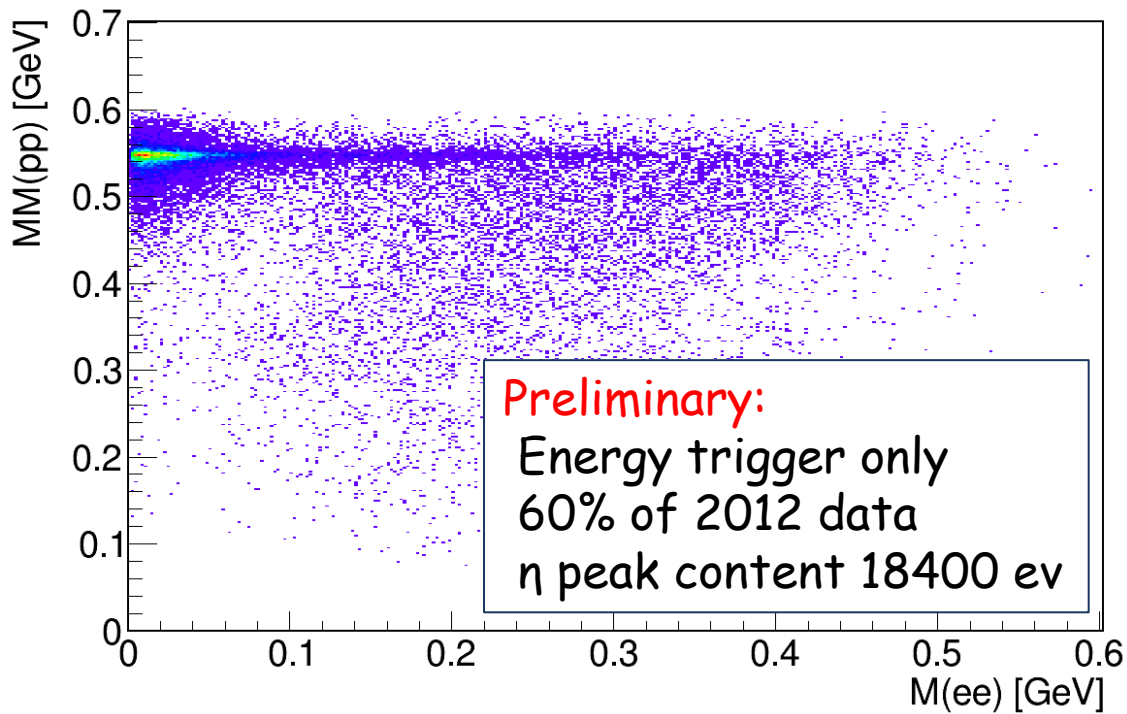
$\sim 75\text{k}$ $\eta \rightarrow e^+ e^- \gamma$



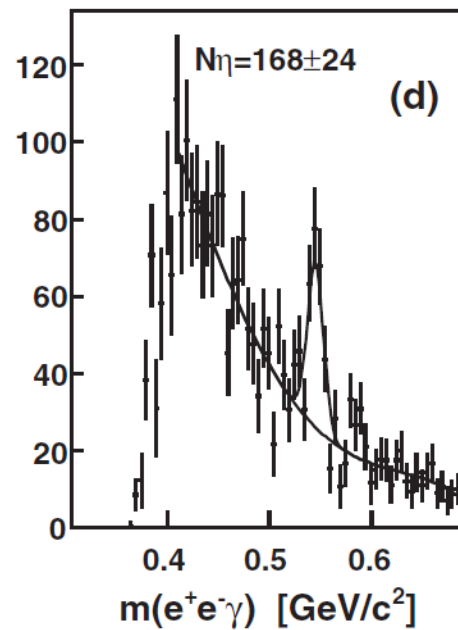
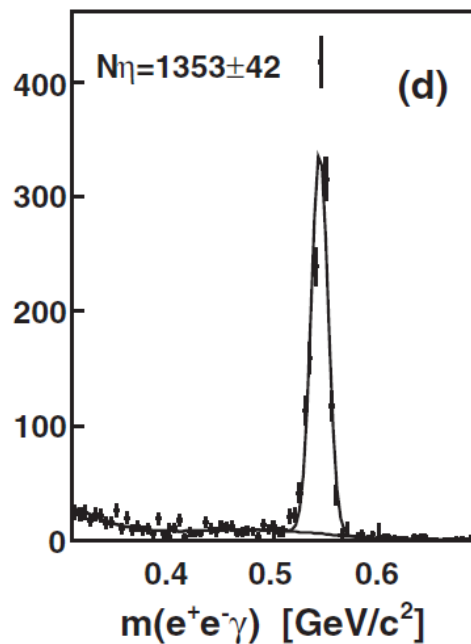
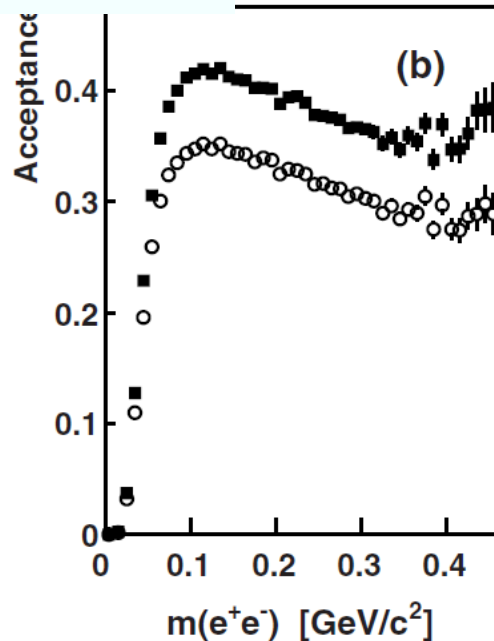
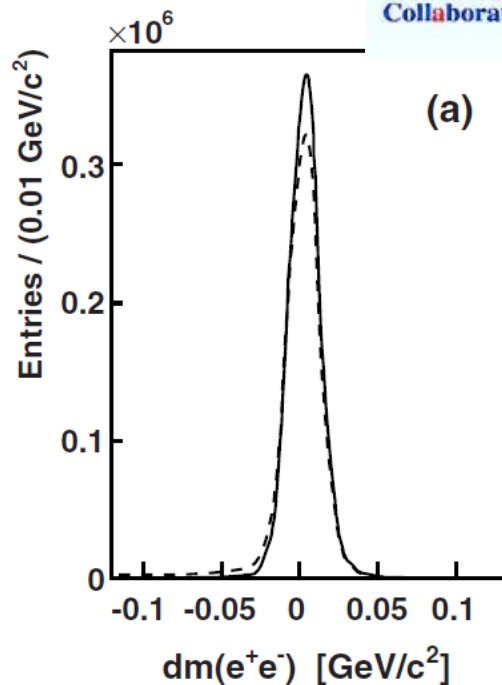
$\eta \rightarrow \gamma e^+ e^-$ from pp data



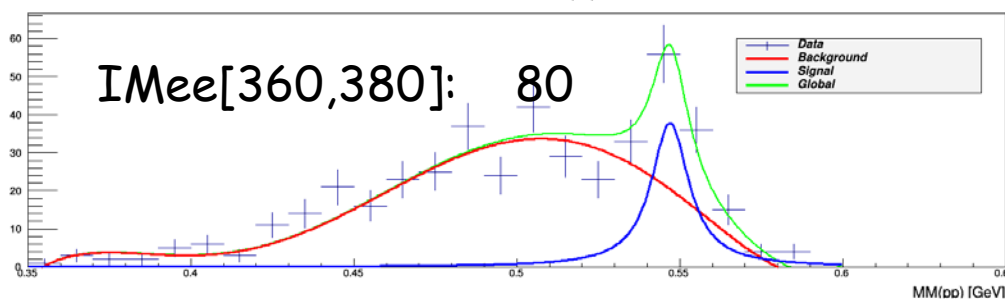
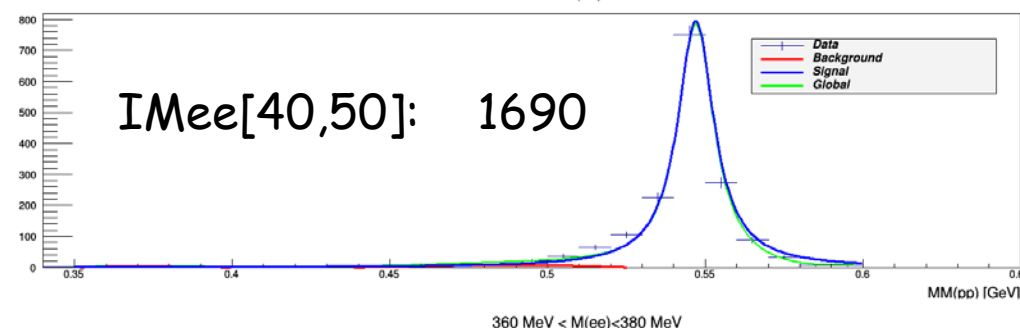
$\eta \rightarrow \gamma e^+ e^-$ from 2012 pp data



Full Range: 18400
 $IM_{ee}[40,50]$: 1690
 $IM_{ee}[360,380]$: 80
D. Pszczel NCBJ/UU



Preliminary:
Energy trigger only
60% of 2012 data



WASA-at-COSY expected
2010&2012 pp data:
Full Range: ~60k
IMee[40,50]: ~5k
IMee[360,380]: ~240
D. Pszczel & A. Goswami

CB/TAPS: PRC89, 044608 (2014)

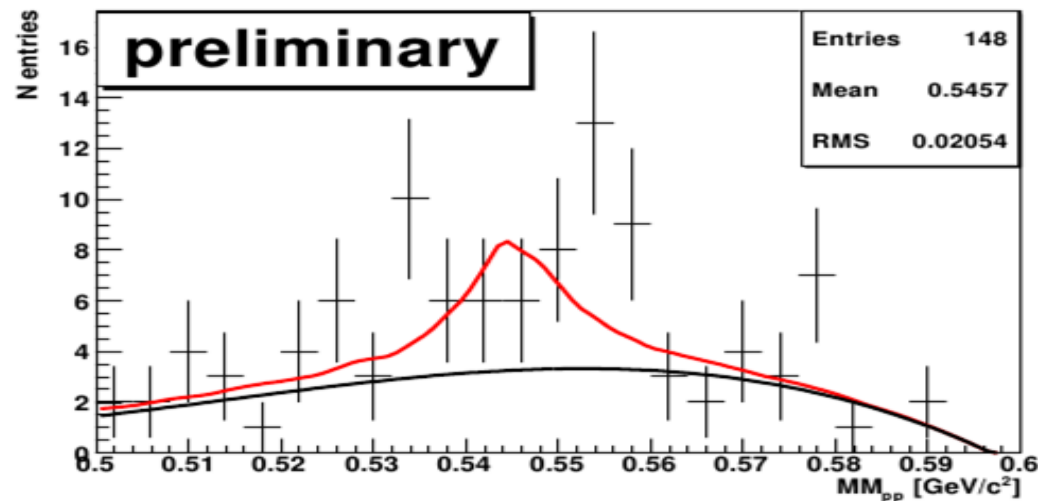
$$\eta \rightarrow e^+e^-$$

$$\Gamma(e^+e^-)/\Gamma_{\text{total}}$$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$<5.6 \times 10^{-6}$	90	¹ AGAKISHIEV	12A SPEC	$p p \rightarrow \eta + X$
* * * We do not use the following data for averages, fits, limits, etc. * * *				
$<2.7 \times 10^{-5}$	90	BERLOWSKI	08 WASA	$p d \rightarrow {}^3\text{He} \eta$
$<0.77 \times 10^{-4}$	90	BROWDER	97B CLE2	$e^+e^- \sim 10.5 \text{ GeV}$
$<2 \times 10^{-4}$	90	WHITE	96 SPEC	$p d \rightarrow \eta {}^3\text{He}$
$<3 \times 10^{-4}$	90	DAVIES	74 RVUE	Uses ESTEN 1967

$$BR_{\eta \rightarrow e^+e^-} < 2.5 \times 10^{-6}$$

HADES, PLB731 (2014) 265

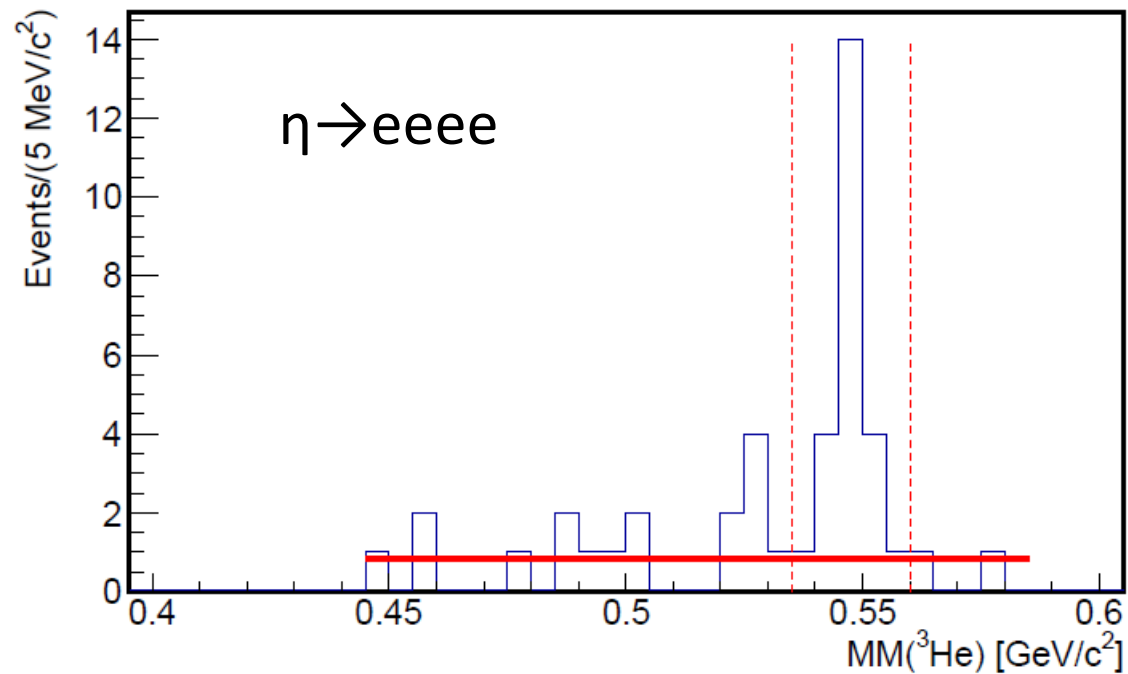
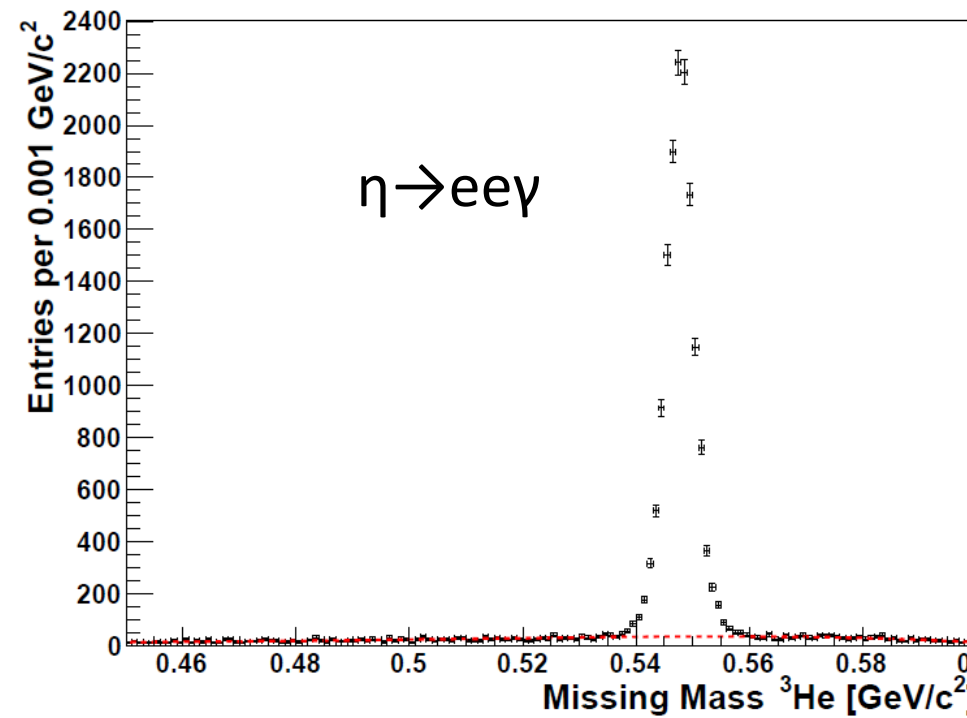
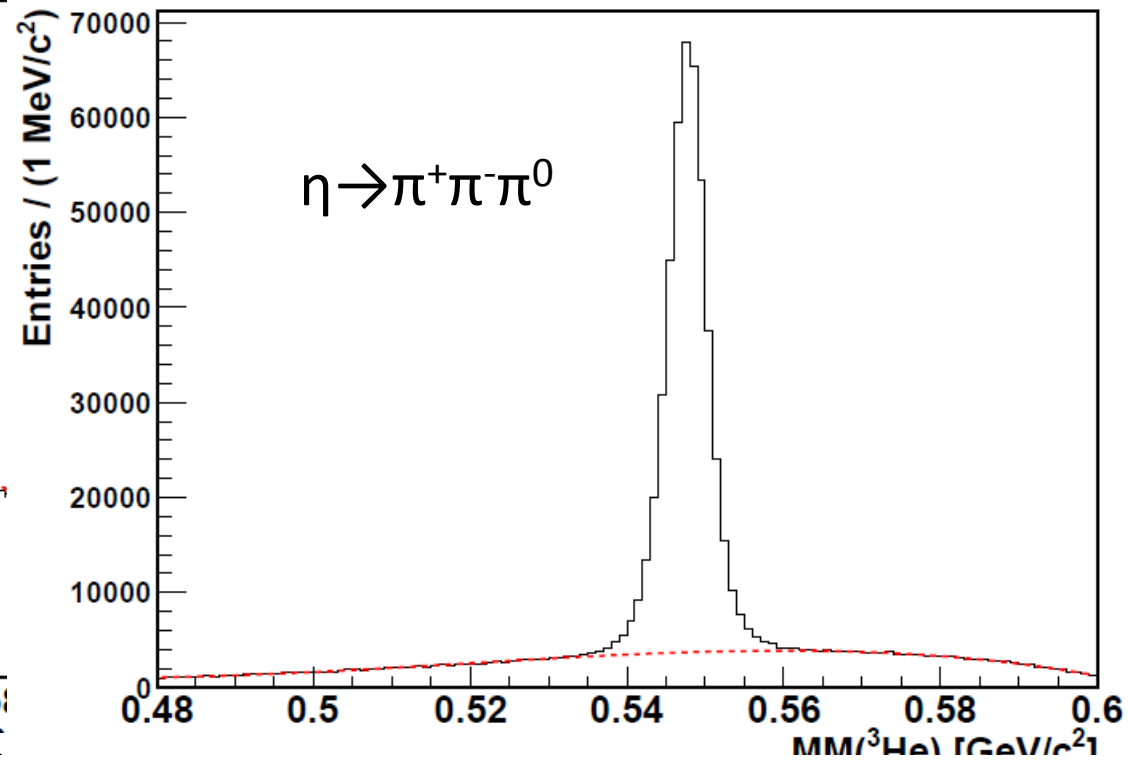
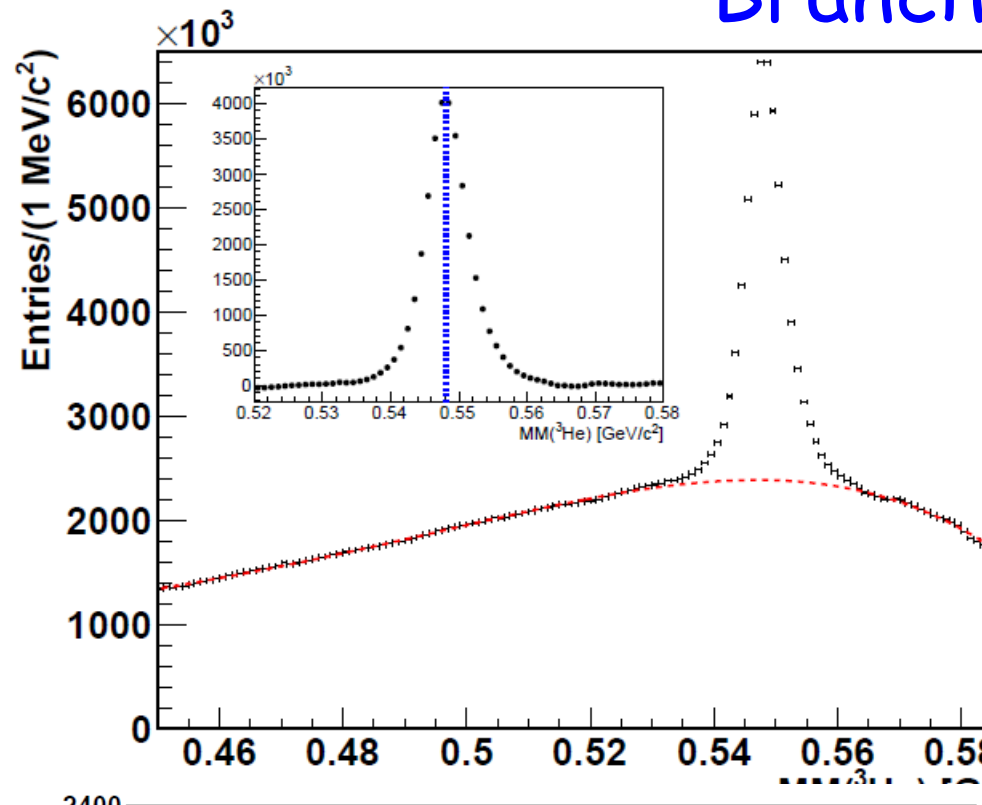


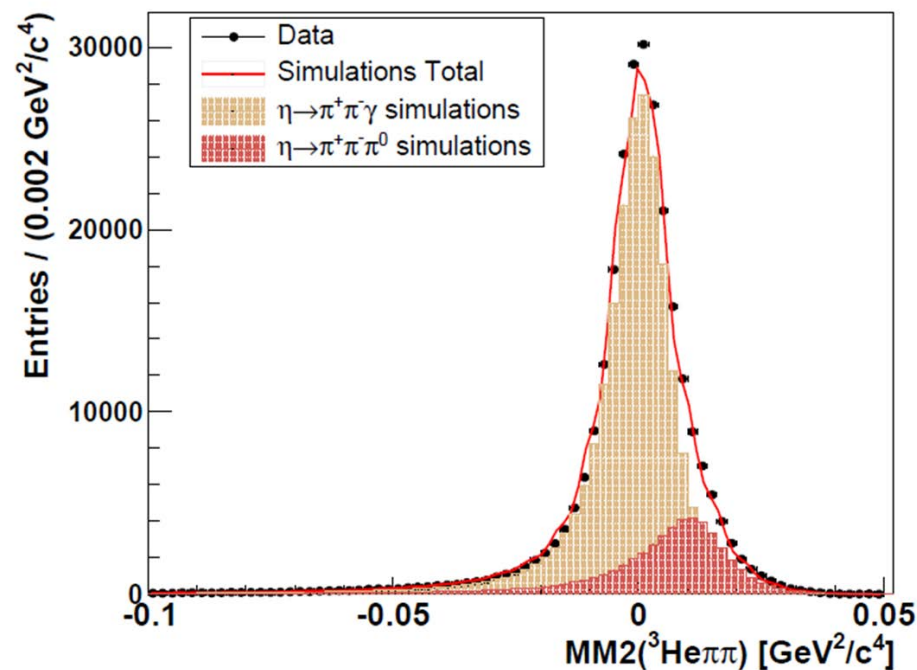
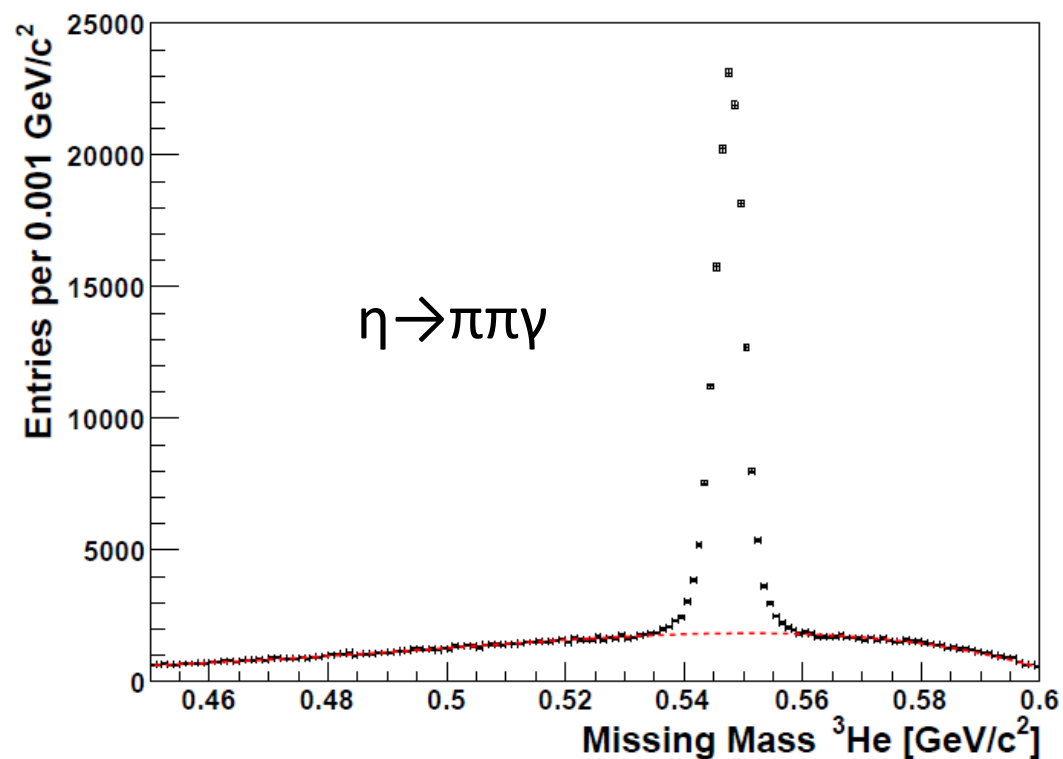
WASA-at-COSY (2013)

- $pd \rightarrow {}^3\text{He} \eta$ (all data)
- $<6 \times 10^{-6}$ 90% CL (prel)

- $pp \rightarrow pp \eta$ (1/9 data)
- $<4.6 \times 10^{-6}$ 90%CL (prel)

Branching ratios from pd data





$$\Gamma(\eta \rightarrow \pi^+ \pi^- \gamma) / \Gamma(\eta \rightarrow \pi^+ \pi^- \pi^0)$$

$0.1856 \pm 0.0005 \pm 0.0028$

200k

BABUSCI

2013

KLOE

$0.175 \pm 0.007 \pm 0.006$

859

LOPEZ

2007

CLEO

*** We do not use the following data for averages, fits, limits, etc ***

0.209 ± 0.004

18k

THALER

1973

ASPK

0.201 ± 0.006

7250

GORMLEY

1970

ASPK

0.28 ± 0.04

BALTAY

1967R

0.25 ± 0.035

MIT

0.30 ± 0.06

MIT

0.196 ± 0.041

FOSTER

1966

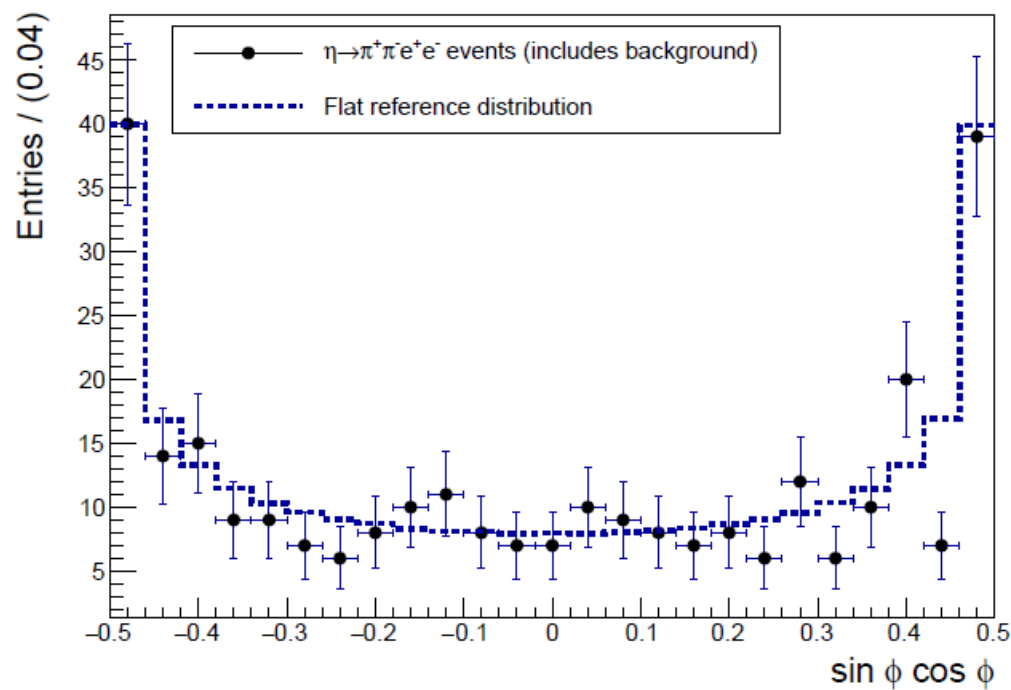
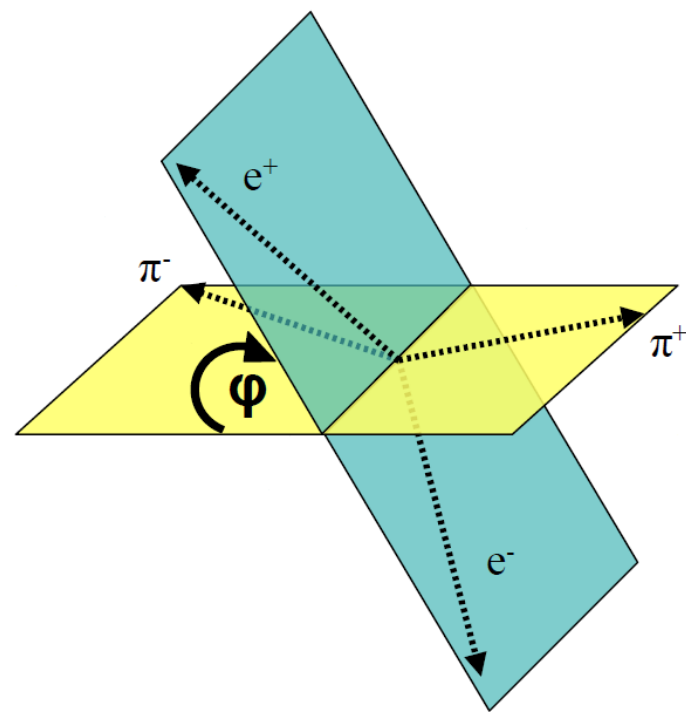
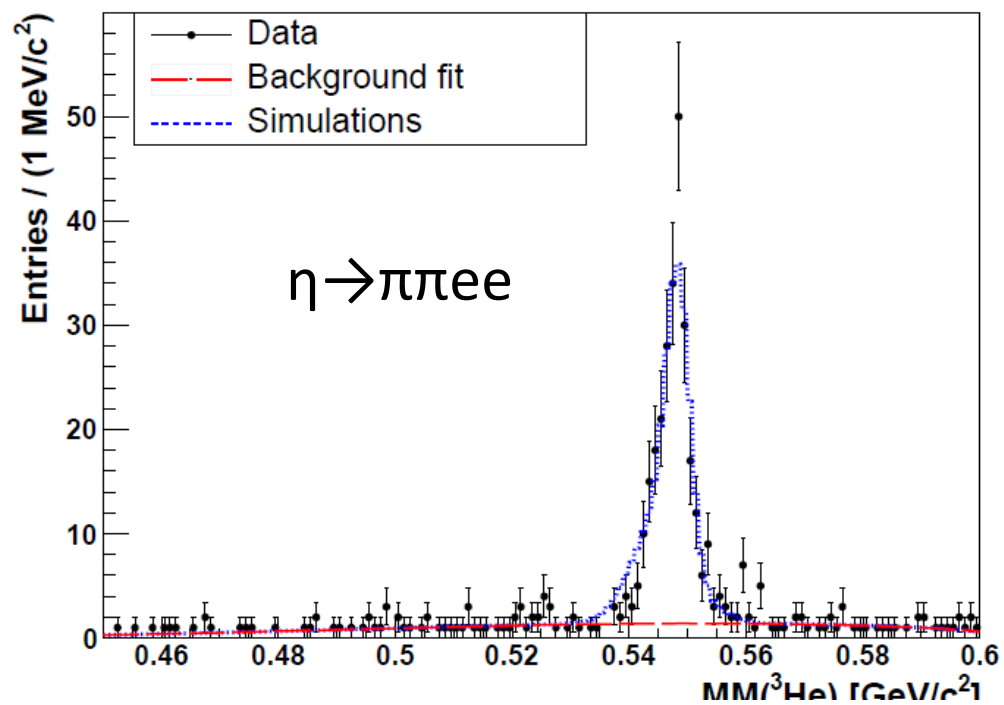
HBC

1965C

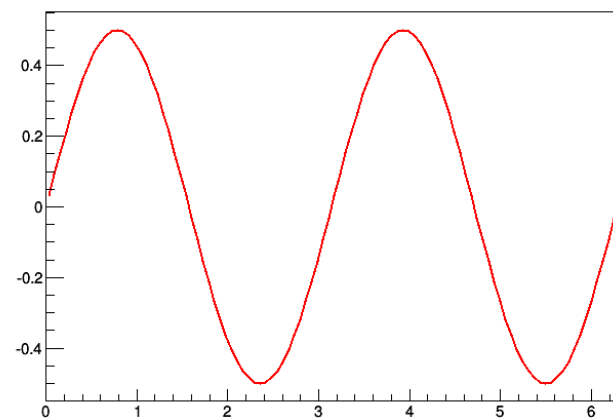
HBC

2.6 and 2.5 σ above
CLEO , KLOE

WASA-at-COSY: $0.208 \pm 0.003_{(stat/fit)} \pm 0.008_{sys}$

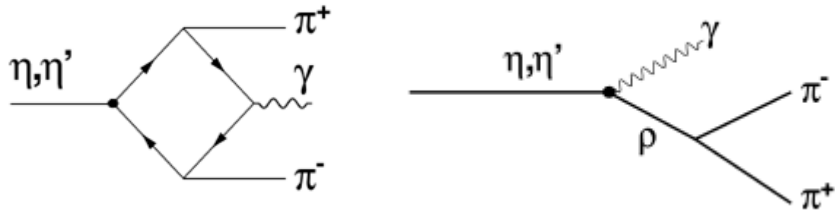


$$A_\phi = \frac{N(\sin \phi \cos \phi > 0) - N(\sin \phi \cos \phi < 0)}{N(\sin \phi \cos \phi > 0) + N(\sin \phi \cos \phi < 0)}$$



$$A_\phi = (-1.1 \pm 6.6_{stat} \pm 0.2_{sys}) \times 10^{-2}$$

$$\eta \rightarrow \pi^+ \pi^- \gamma$$

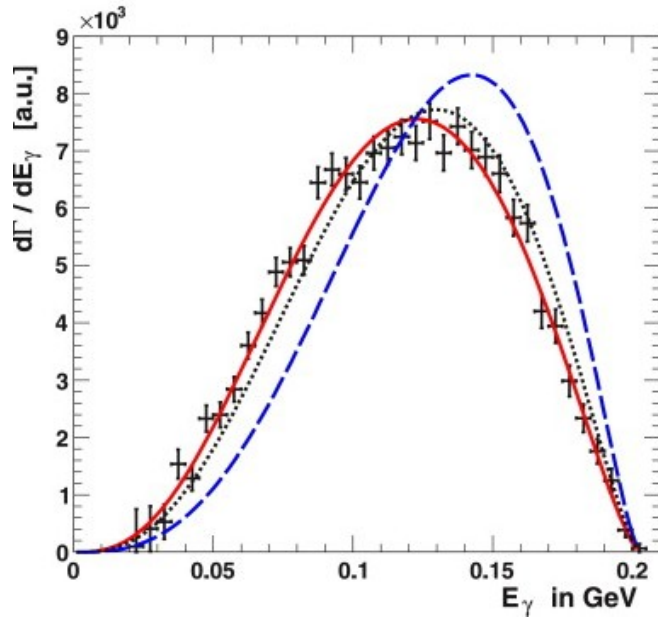


$$\frac{d\Gamma_{\eta(\eta')}}{ds_{\pi\pi}} \propto \left| \mathcal{C} + \frac{1}{s_{\pi\pi} - m_\rho^2 - im_\rho \Gamma_\rho} \right|^2$$

$$\frac{d\Gamma}{ds} = |\mathcal{A}(1 + \alpha s + \dots) F_V(s)|^2 K_P(s)$$

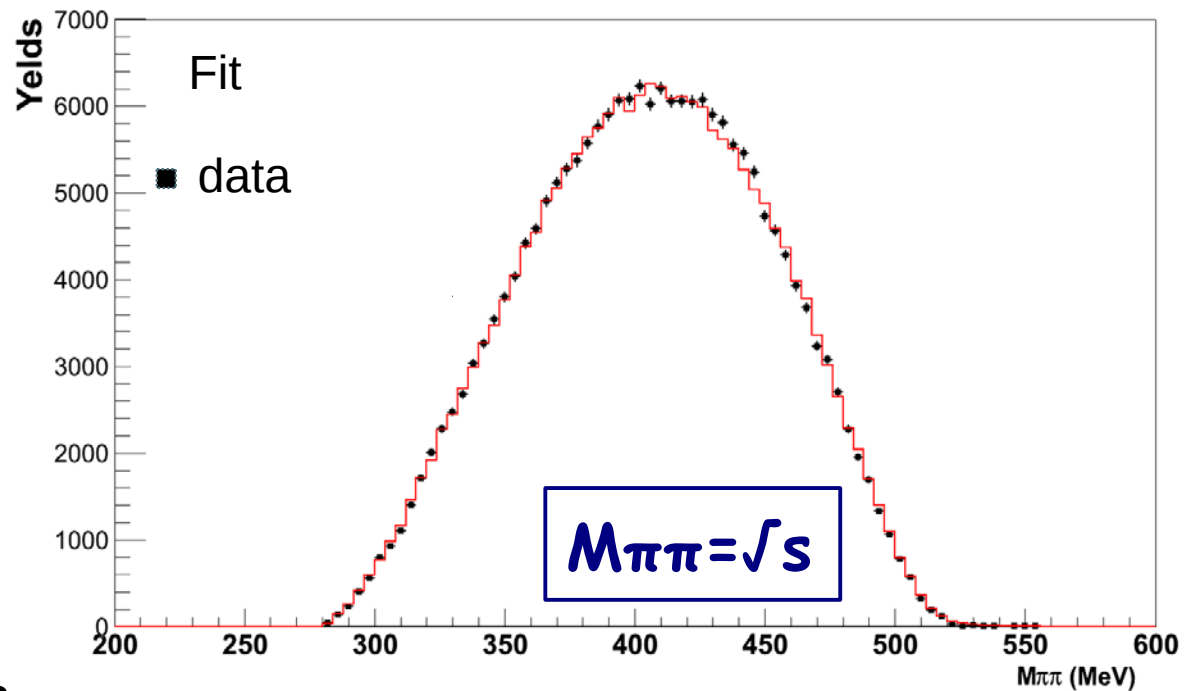
PLB707 (2012) 184

$$e^+e^- \rightarrow \pi^+\pi^-$$



$$\alpha = 1.89 \pm 0.25_{\text{stat}} \pm 0.59_{\text{syst}} \text{ GeV}^{-2}$$

[WASA PLB707 (2012) 243]

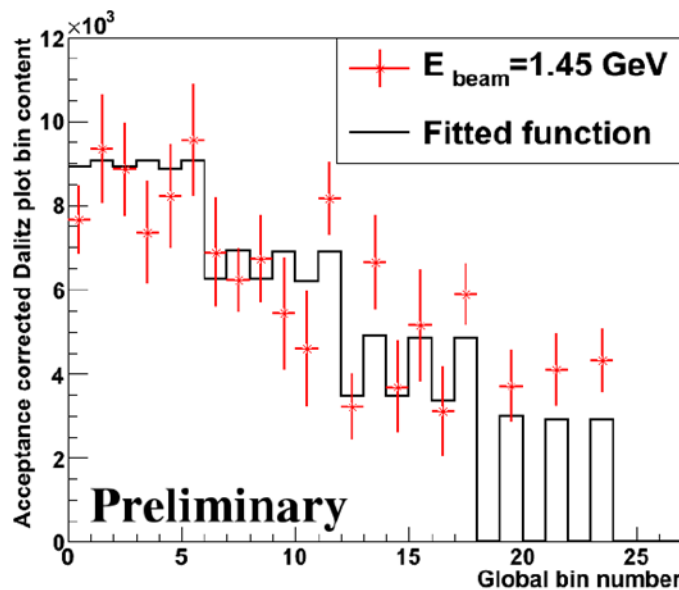
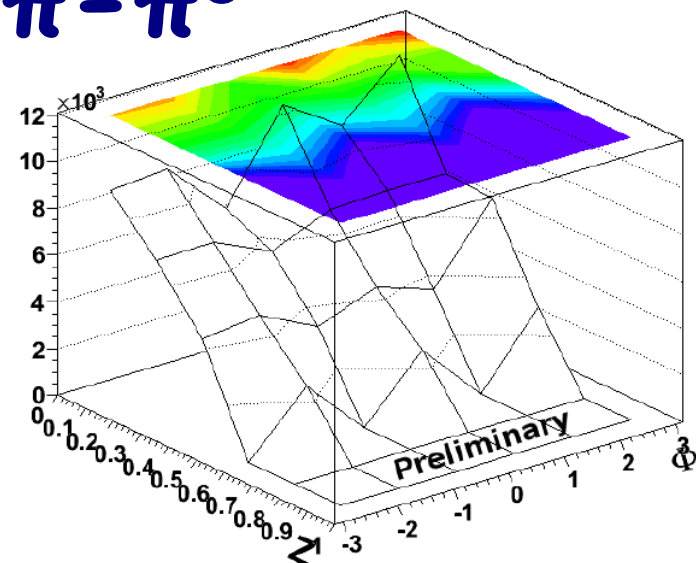
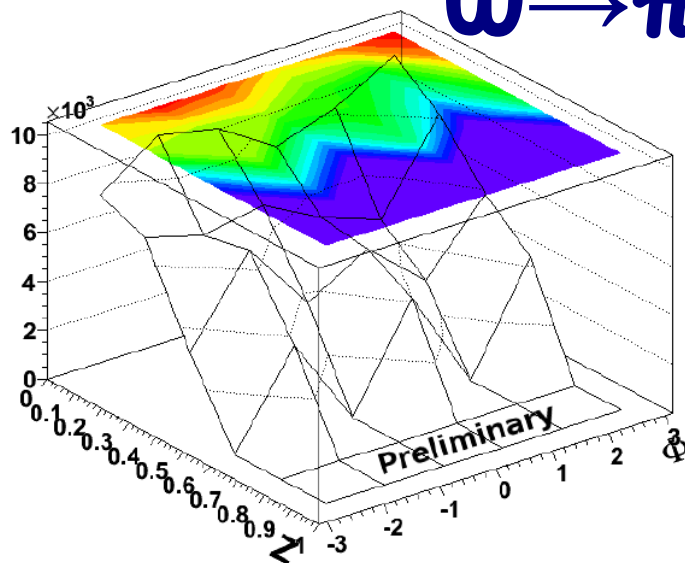


$$\alpha = 1.31 \pm 0.08_{\text{stat}} \pm 0.40_{\text{syst}} \text{ GeV}^{-2}$$

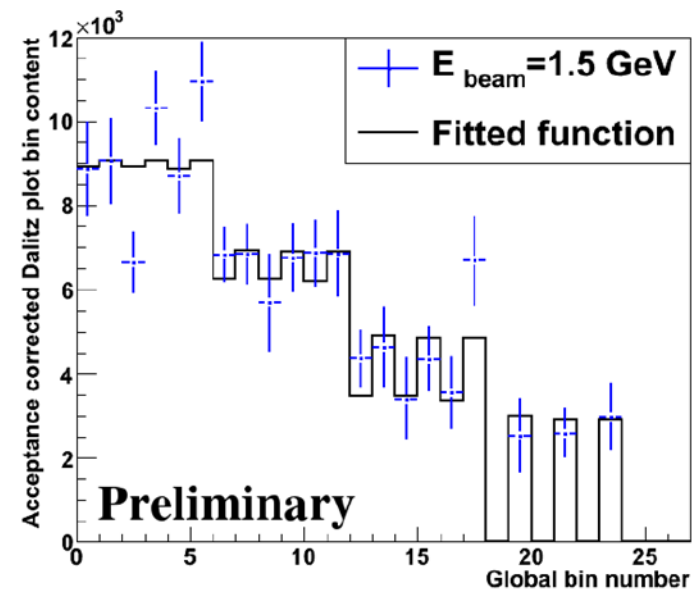
[KLOE PLB718 (2013) 910]



$$\omega \rightarrow \pi^+ \pi^- \pi^0$$



(a) $T_{\text{beam}} = 1.45$ GeV



(b) $T_{\text{beam}} = 1.5$ GeV

$$F(Z, \Phi) = \mathcal{P} \cdot \left\{ 1 + 2\alpha Z + 2\beta Z^{3/2} \sin 3\Phi + 2\gamma Z^2 + \mathcal{O}(Z^{5/2}) \right\},$$



Conclusions/Outlook

- WASA-at-COSY experiments finished 2014
- Data samples π^0, η :
- $>5 \times 10^7 \pi^0 \rightarrow e^+e^-\gamma$
- 50k - 100k $\eta \rightarrow e^+e^-\gamma$
- Many PhD projects will end 2016
- Branching ratios from pd data final results
arXiv: 1509.06588 (today):

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