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η meson physics with WASA-at-COSY

Nils Hüsken
for the WASA-at-COSY Collaboration

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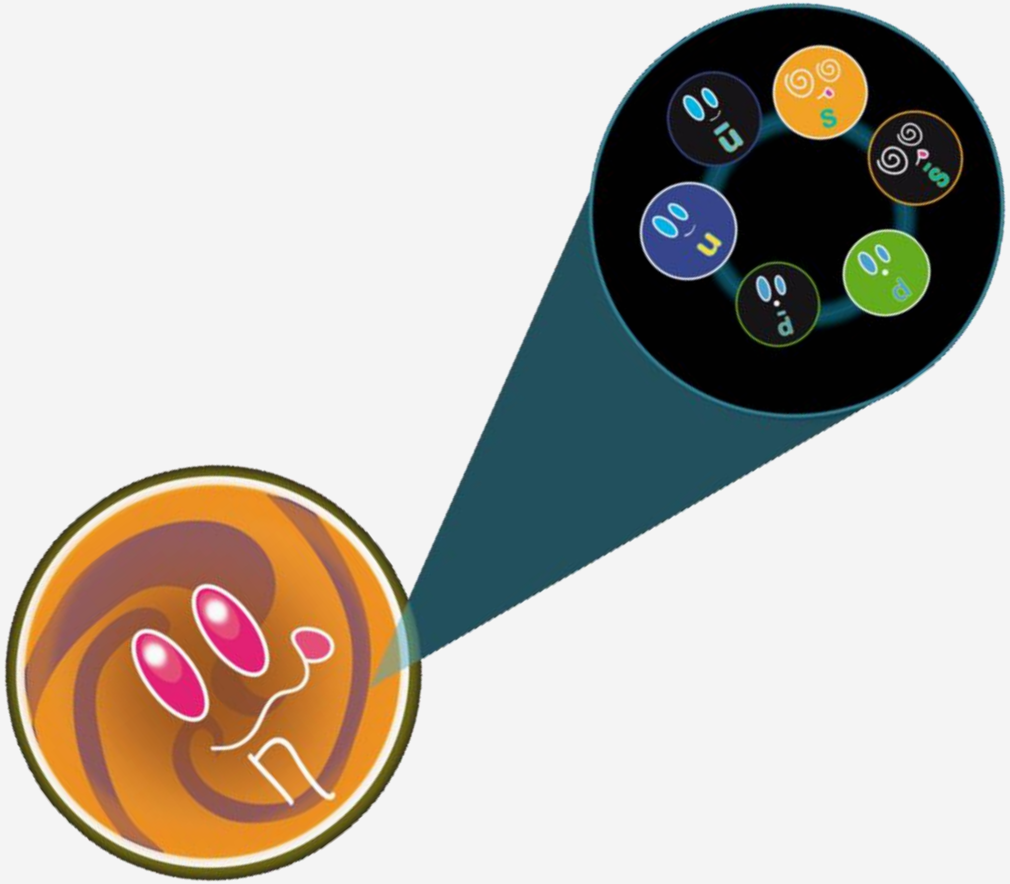
Outline

- The WASA-at-COSY experiment
- η production
  - analyzing power in $\vec{p}p \rightarrow pp\eta$
  - cross sections in $pd \rightarrow {}^3\mathrm{He}\eta$ away from threshold
- η decays
  - Dalitz and double-Dalitz decays
  - search for CP-violation in $\eta \rightarrow \pi^+\pi^-e^+e^-$
  - search for the C-violating decay $\eta \rightarrow \pi^0 e^+ e^-$



https://physicsandmore.deviantart.com/art/Eta-Meson-Structure-313364574

WASA-at-COSY

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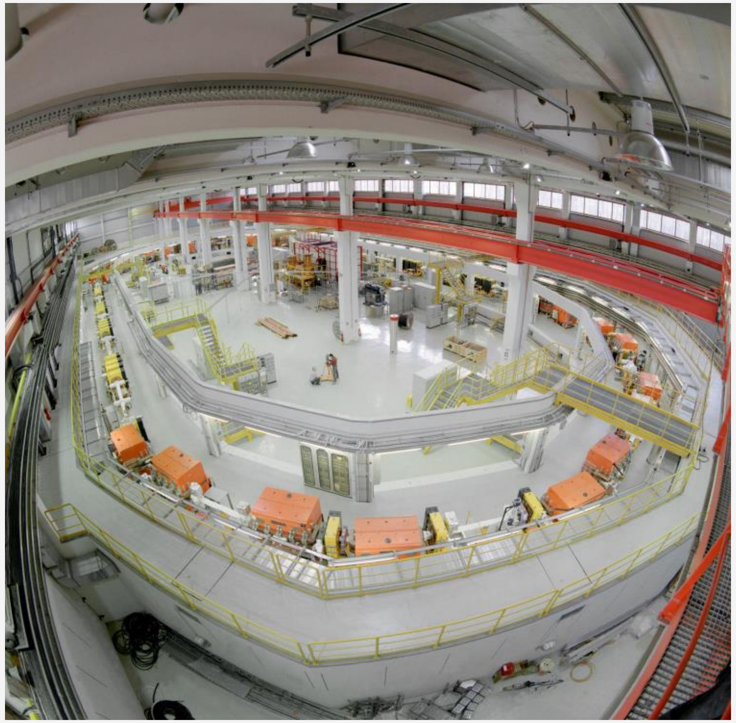
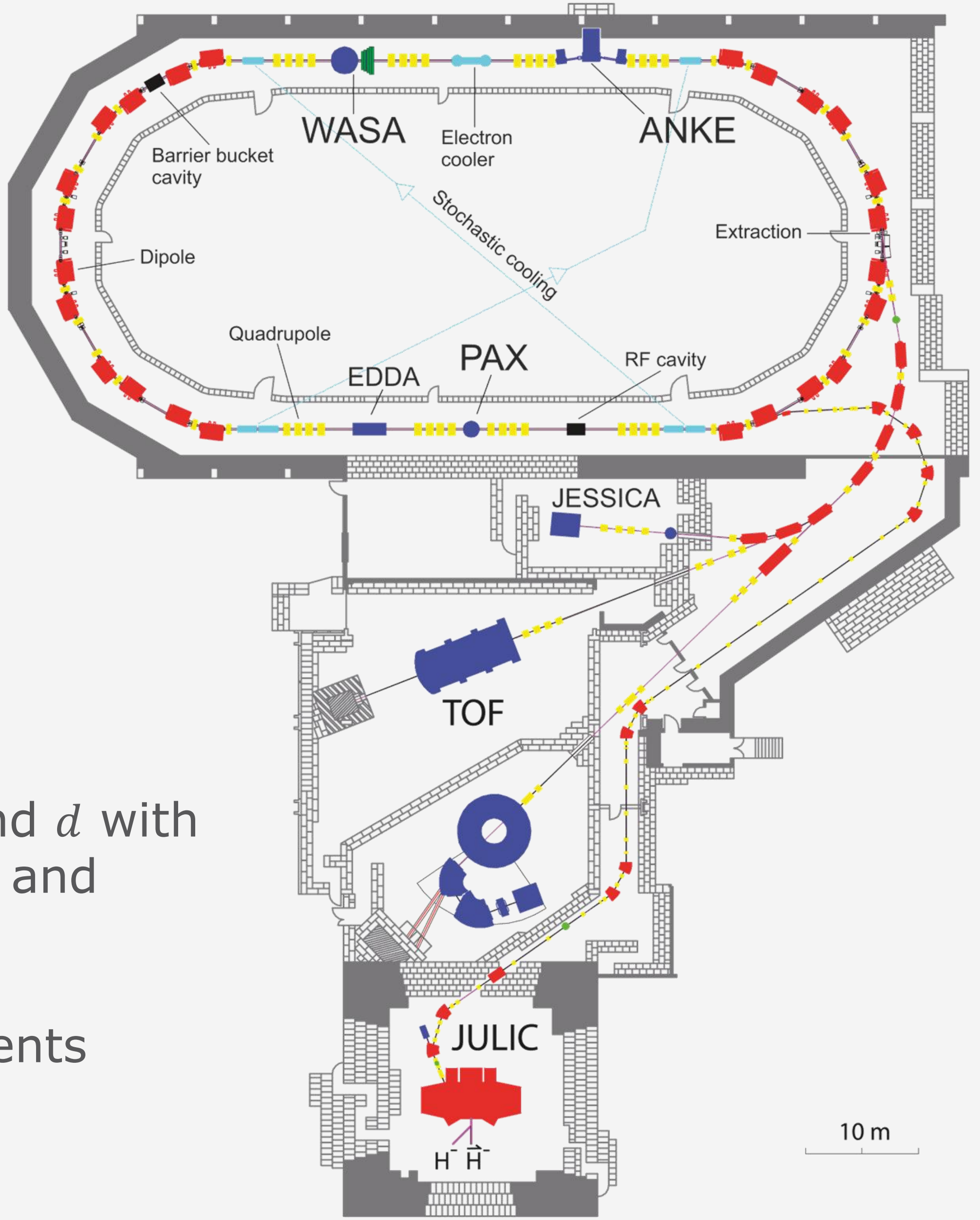
Cooler Synchrotron - COSY



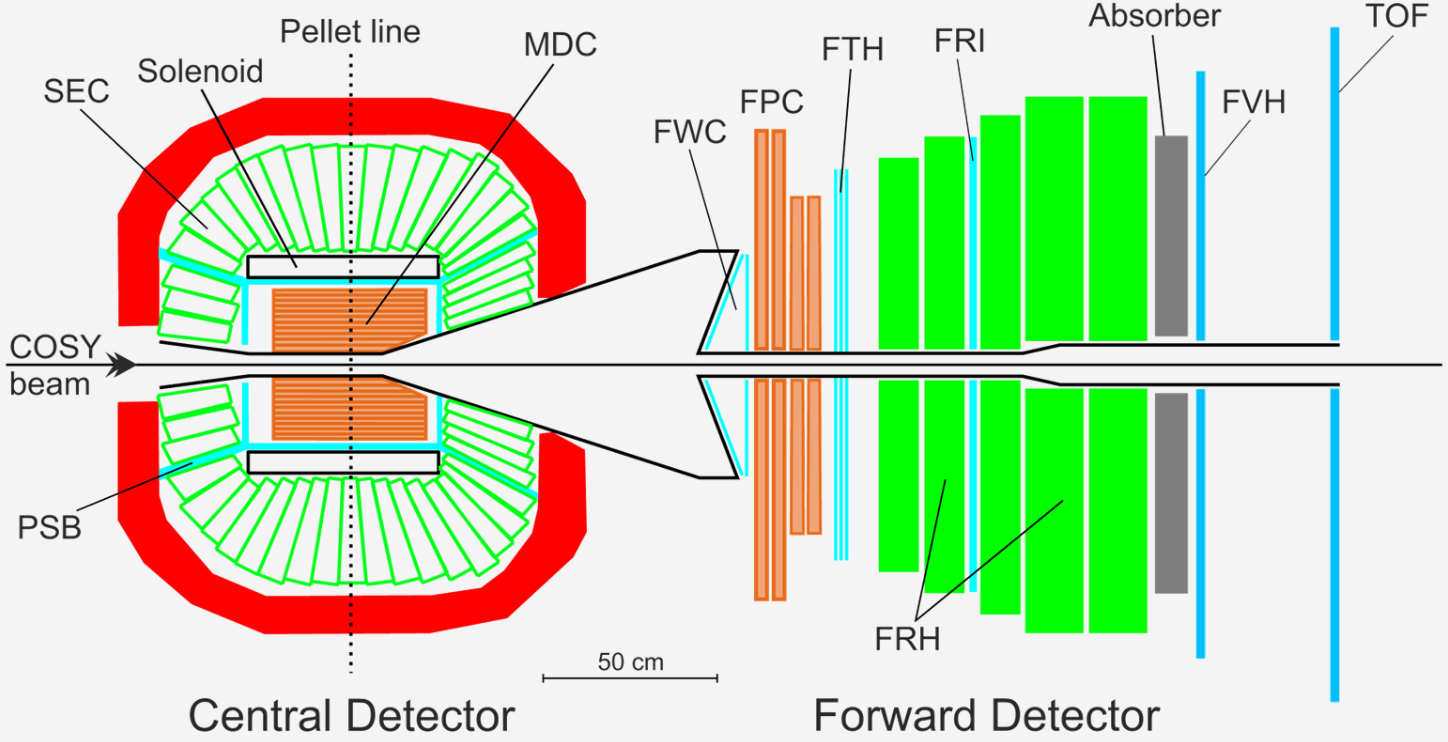
- named after its two cooling mechanisms
  - electron cooling
  - stochastic cooling

- provides (un-)polarized p and d with momenta between $0.3\ \mathrm{GeV}/c$ and $3.7\ \mathrm{GeV}/c$

- internal & external experiments
  - WASA, ANKE & PAX
  - TOF



The WASA Experiment



- Pellet Target
  - provides frozen pellets of hydrogen or deuterium
- Central Detector
  - reconstruction of charged particles (e.g., $\pi^{\pm}, e^{\pm}, p$) in magnetic field
  - PID in scintillators
  - photons in electromagnetic calorimeter
- Forward Detector
  - heavier ejectiles ($p, d, {}^{3}\mathrm{He}$) are boosted in forward direction
  - scattering angles determined in proportional chamber
  - PID and energy measurement in various scintillators

Datasets

Production studies:

- $\vec{p}p \rightarrow pp\eta$: ~ 200.000 events/energy at 2 fixed energies
- $pd \rightarrow {}^3\mathrm{He}\eta$: ~ 250.000 events/energy at 15 fixed energies

Decay studies:

- $pd \rightarrow {}^3\mathrm{He}\eta$: 30×10^6 events
- $pp \rightarrow pp\eta$: 500×10^6 events

Search for η-mesic nuclei:

- $dd \rightarrow (\eta - {}^4\mathrm{He})$ in $dd \rightarrow {}^3\mathrm{He}\,\pi\,N$
- $pd \rightarrow (\eta - {}^3\mathrm{He})$ in $pd \rightarrow pp\,\pi\,N$ and $pd \rightarrow {}^3\mathrm{He}\,\gamma\gamma$

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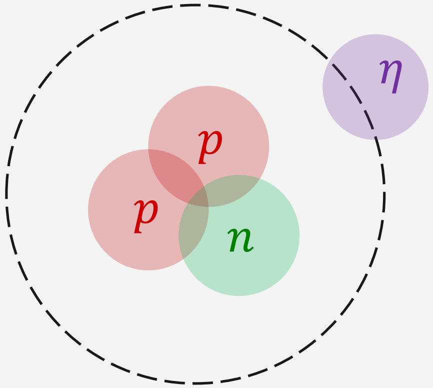
see: Talk by M. Skurzok, Tuesday, 9am
Poster by O. Rundel, Saturday, 2:30pm

η production

η production



- Haider & Liu (1985): ηN interaction is attractive
  - possible binding for $A \geq 12$

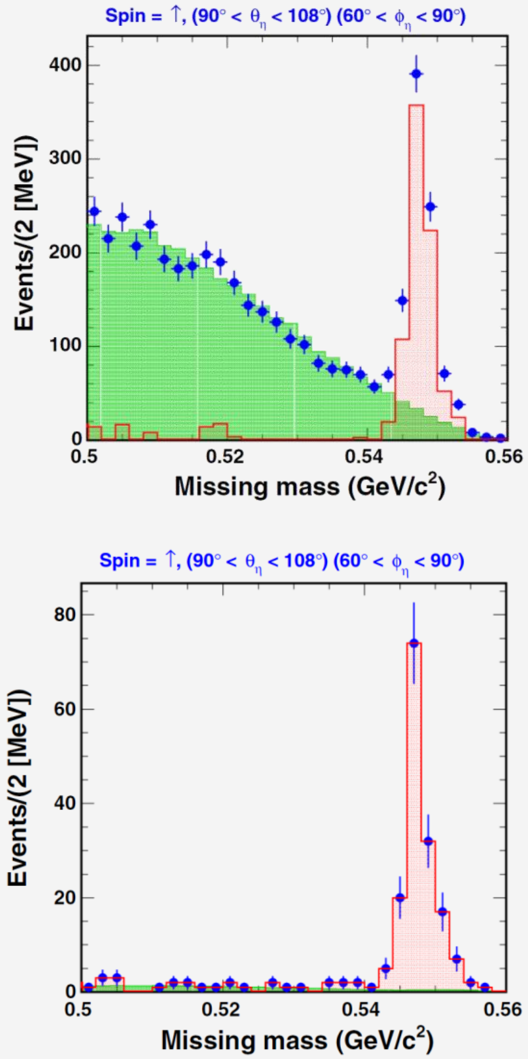
- η-production in NN- and NA-collisions has historically received a lot of interest
  - ηN and ηA interactions can only be studied in the final state
  - many reactions show signs of strong FSI (especially $pd \rightarrow {}^{3}\mathrm{He}\eta$)
  - multiple experiments search for η-mesic nuclei

- to study FSI, it is important to first understand the production mechanism

η production in $\vec{p}p \to pp\eta$

- new data published in 2018
- based on $200 \times$ larger statistics than previously available
- drastically reduced systematic uncertainties
  - symmetry and acceptance of WASA
  - WASA magnetic field switched off
  - measurement at two spin orientations
  - two decay modes ($\eta \to \gamma\gamma$ and $\eta \to \pi^0\pi^0\pi^0$)

- production models:
  - near threshold, S_{11} excitation via exchange of virtual mesons
  - strong isovector component
  - spin as a tool to gain further insight, both into exchanged mesons ($\pi, \eta, \rho, \omega, \sigma$) and nucleon resonances ($S_{11}(1535), D_{13}(1520), P_{11}(1440)$)



Phys. Rev. Lett. 120 (2018) 022002

η production in $\vec{p}p \rightarrow pp\eta$

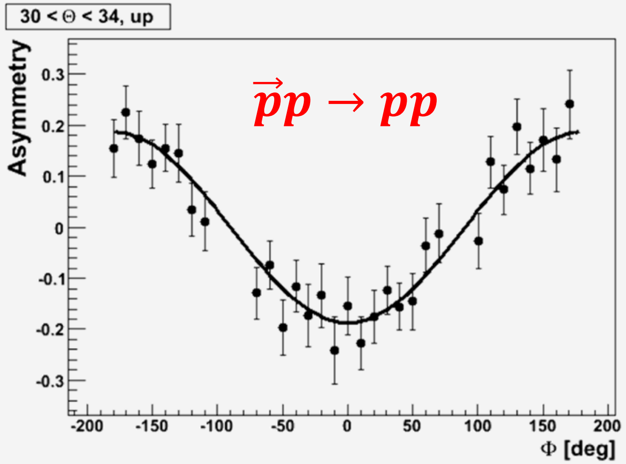
- measure asymmetry

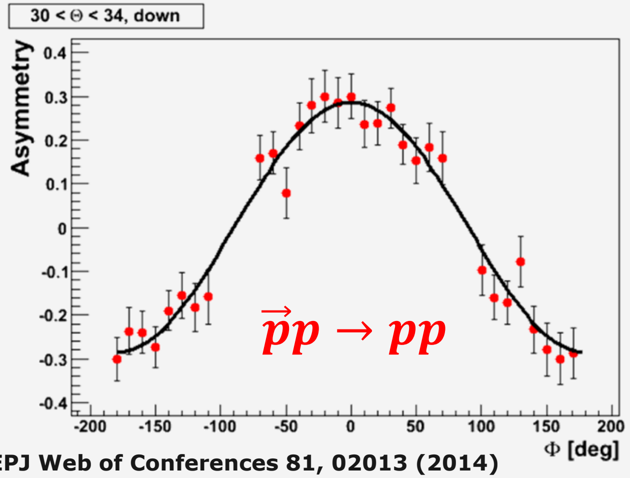
$$A(\theta_\eta, \phi_\eta) = \frac{N_\eta(\theta_\eta,\phi_\eta) - N_\eta(\theta_\eta,\phi_\eta+\pi)}{N_\eta(\theta_\eta,\phi_\eta) + N_\eta(\theta_\eta,\phi_\eta+\pi)}$$

- related to the analyzing power by

$$A(\theta_\eta, \phi_\eta) = P \cdot A_y(\theta_\eta)\cos(\phi_\eta)$$

- polarization P obtained from simultaneous measurement of $\vec{p}p \rightarrow pp$
  - using A_y previously measured by the EDDA experiment





EPJ Web of Conferences 81, 02013 (2014)

p_p / MeV/c	Spin mode	Polarization
2026	up down	0.793 ± 0.010 -0.577 ± 0.007
2188	up down	0.537 ± 0.009 -0.635 ± 0.011

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[1] K. Nakayama et al., Phys. Rev. C 68, 045201 (2003).
[2] G. Faldt and C. Wilkin, Phys. Scr. 64, 427 (2001).

η production in $\vec{p}p \rightarrow pp\eta$

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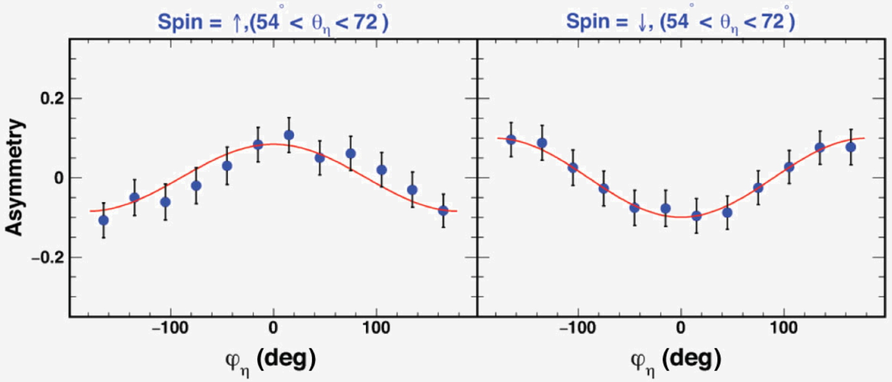
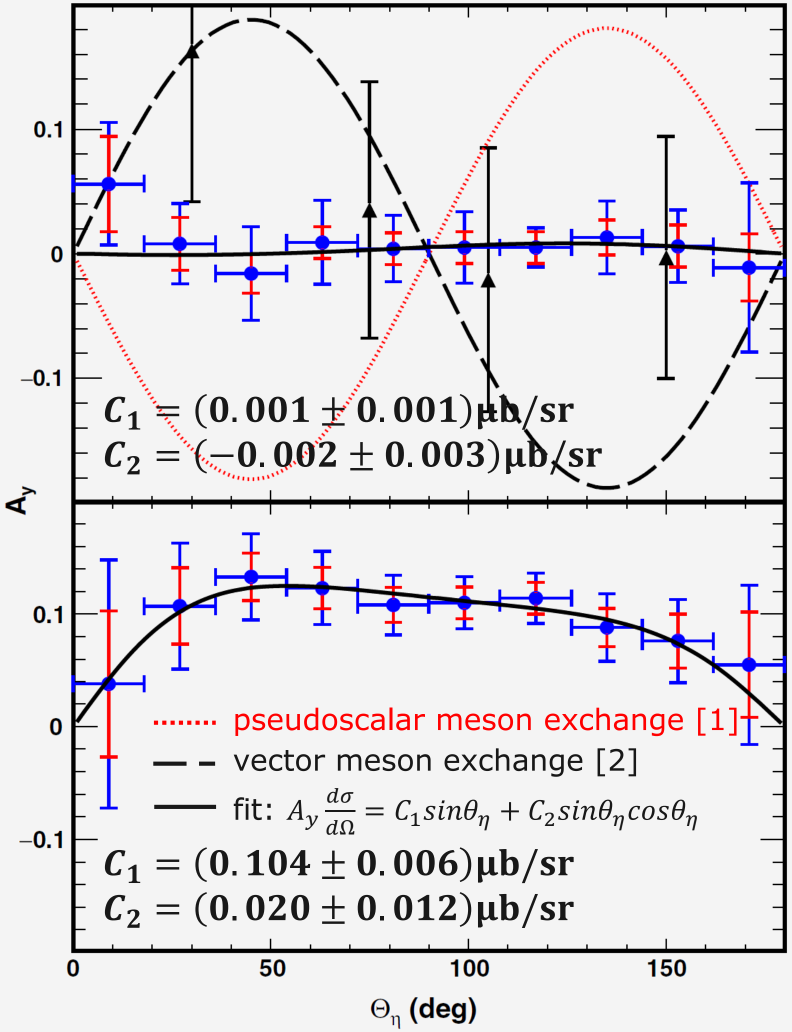


- combine asymmetry and polarization to extract information on A_y



Phys. Rev. Lett. 120 (2018) 022002

- data is consistent with s-wave production for $Q = 15\ \mathrm{MeV}$
    - contradicts predictions of single-meson (π or ρ) exchange
- evidence for higher partial waves at $Q = 72\ \mathrm{MeV}$

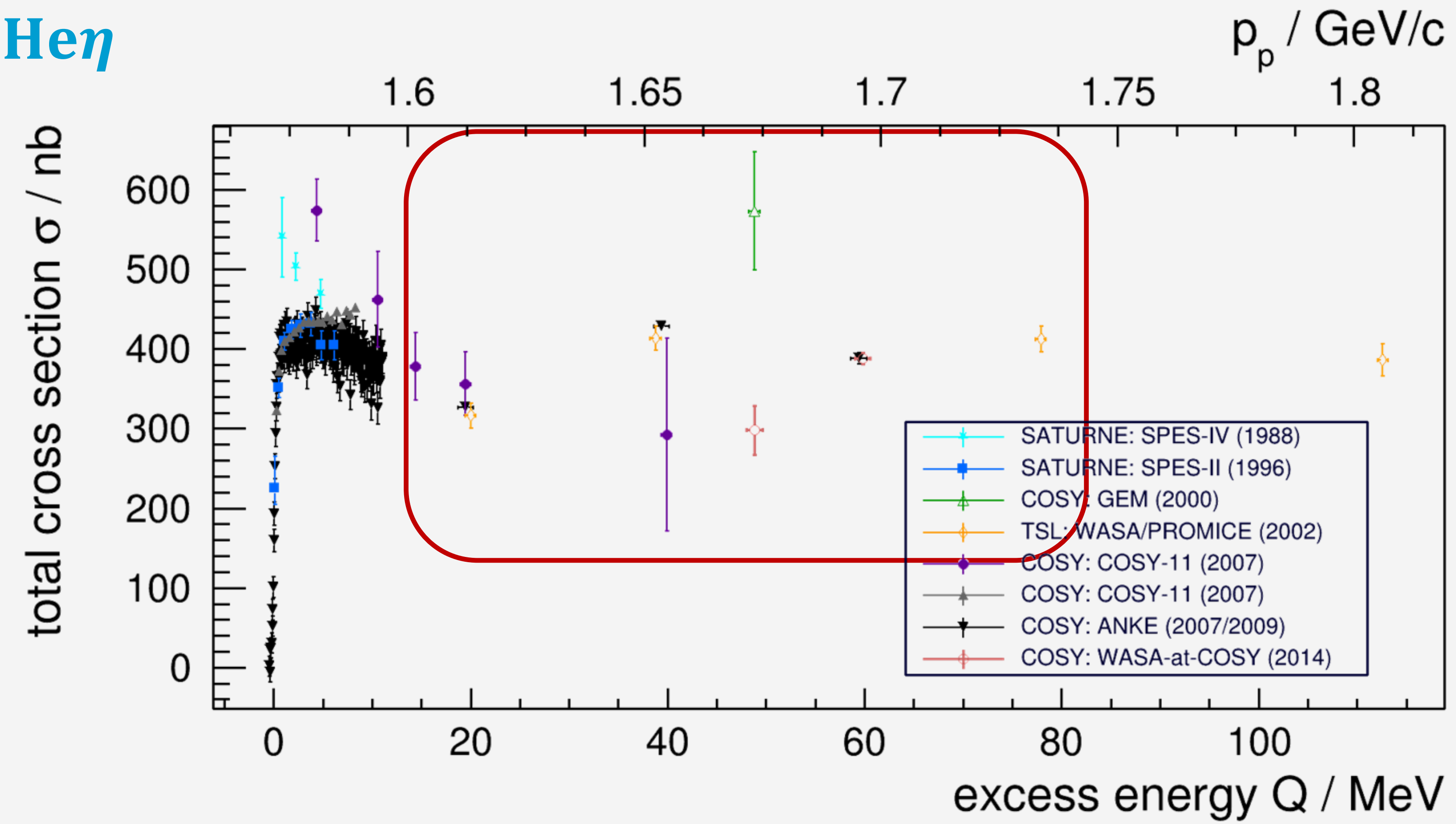
$$A_y(\theta_\eta)\frac{d\sigma}{d\Omega} = 2\pi\left(G_1^{y0} sin\theta_\eta + \left(H_1^{y0} + I_1^{y0}\right) sin2\theta_\eta\right)$$

(Ps^*Pp) $(Pp)^2$ (Ss^*Sd)

$$A_y(\theta_\eta)\frac{d\sigma}{d\Omega} = C_1 sin\theta_\eta + C_2 cos\theta_\eta sin\theta_\eta$$

η production in $pd \to {}^3\mathrm{He}\eta$

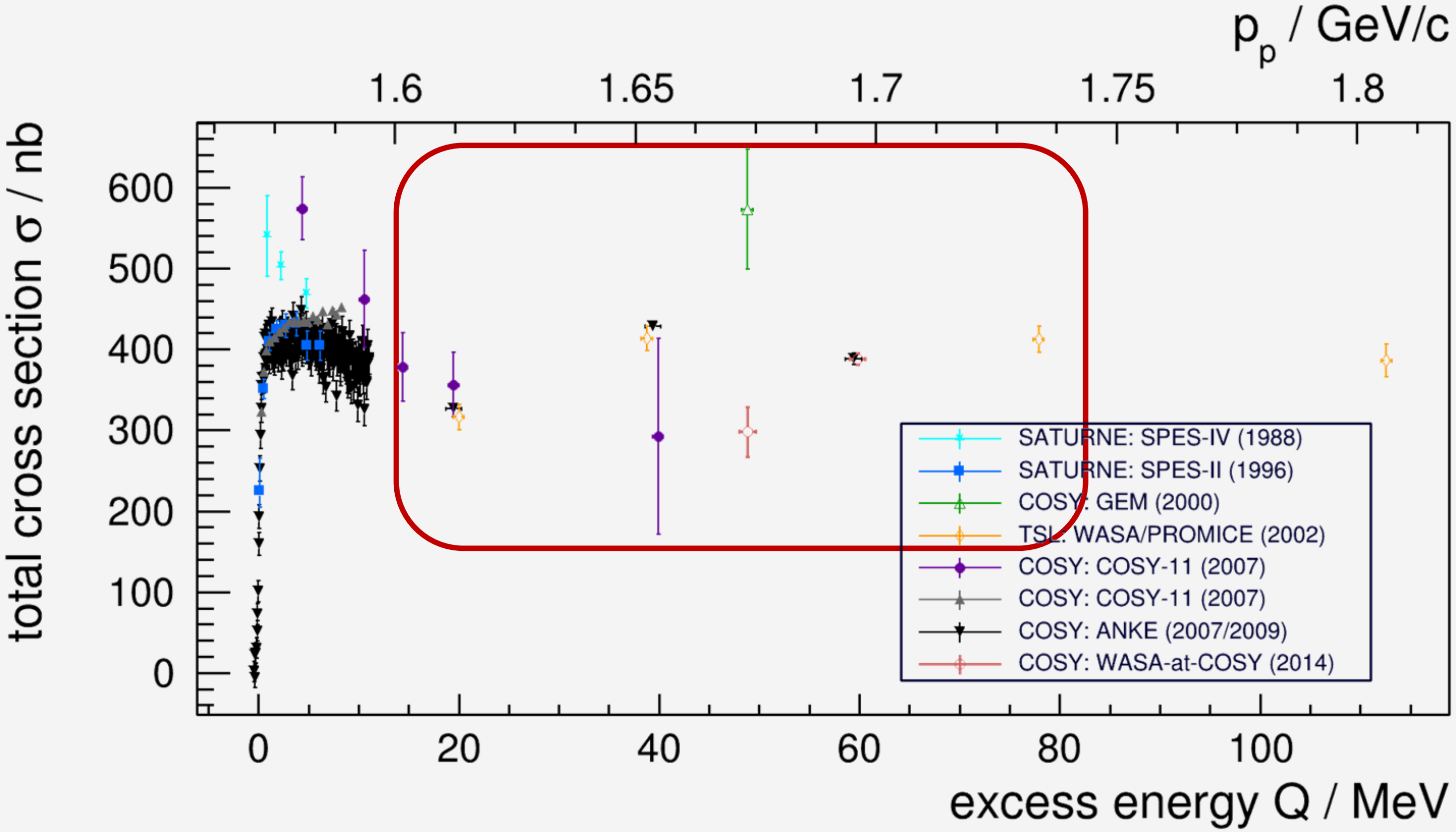
- strong rise at threshold
  - 0 to 400 nb within 1 MeV
  - highly unusual behavior
  - attributed to strong FSI
  - strong enough to support a bound state?
- higher excess energies much less explored
  - most data suggest a plateau
  - narrow variation at $Q \approx 50\ \mathrm{MeV}$ reported in 2014



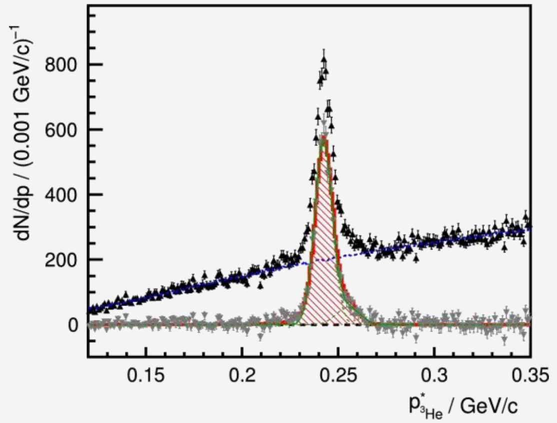
η production in $pd \to {}^{3}\mathrm{He}\eta$

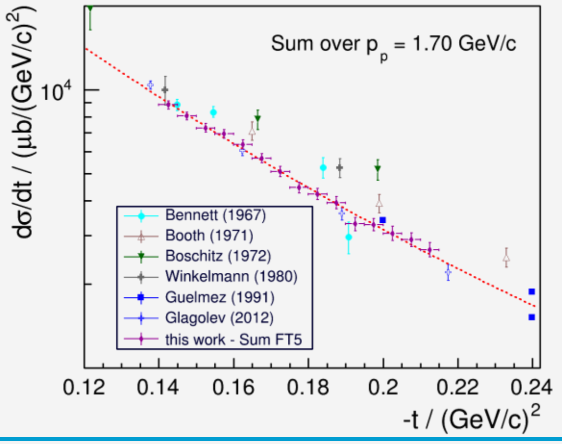
- in supercycle mode
  - 8 settings can be stored
  - beam momentum changes with each injection (every $90\ \mathrm{s}$)
  - minimum of systematic differences
- two such supercycles were used
  - 15 beam momenta in total
  - $p_p = 1.70\ \mathrm{GeV}/c$ measurement in both supercycles

SC 0: p / GeV/c	1.60	1.62	1.64	1.66	1.68	1.70	1.72	1.74
SC 1: p / GeV/c	1.61	1.63	1.65	1.67	1.69	1.70	1.71	1.73



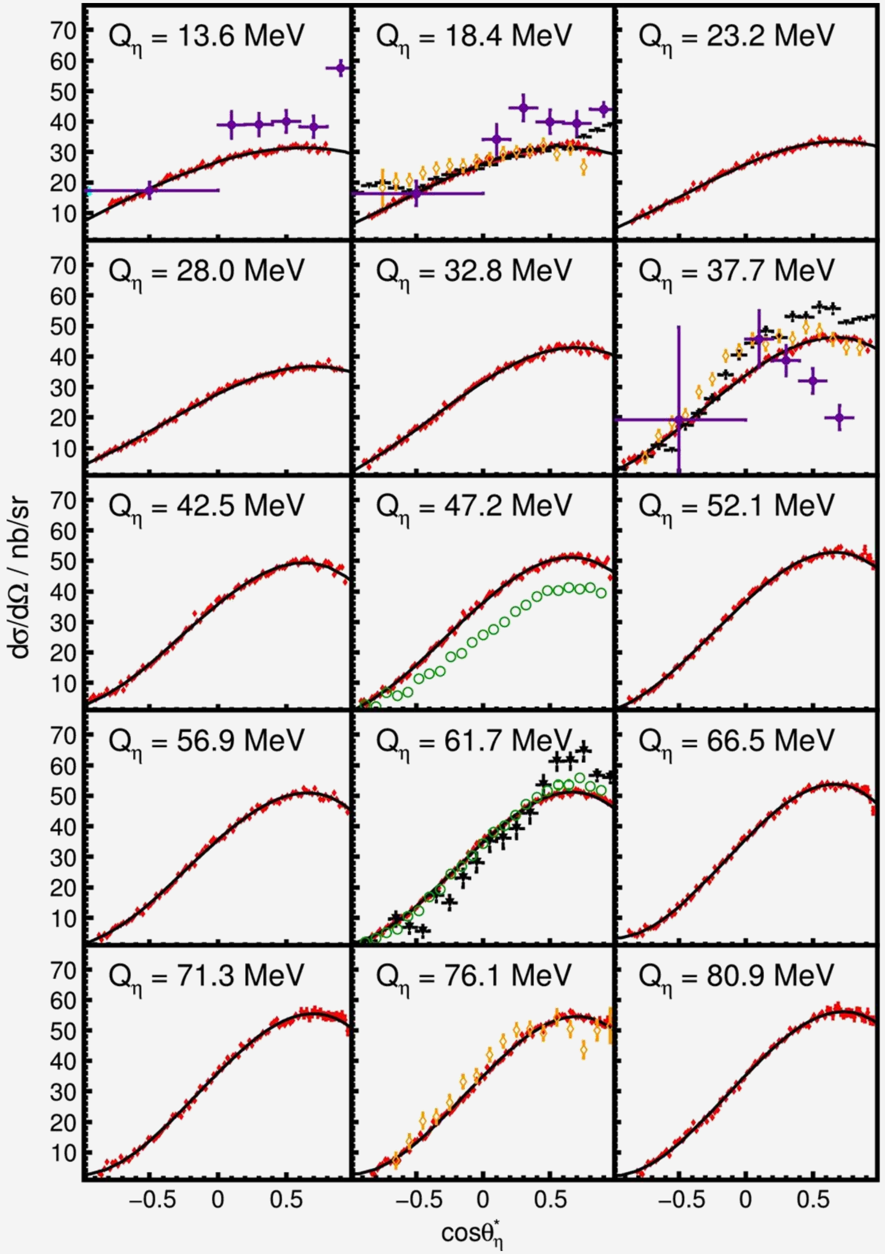
η production in $pd \to {}^3\text{He}\eta$





Physics Letters B 782 (2018) 297–304

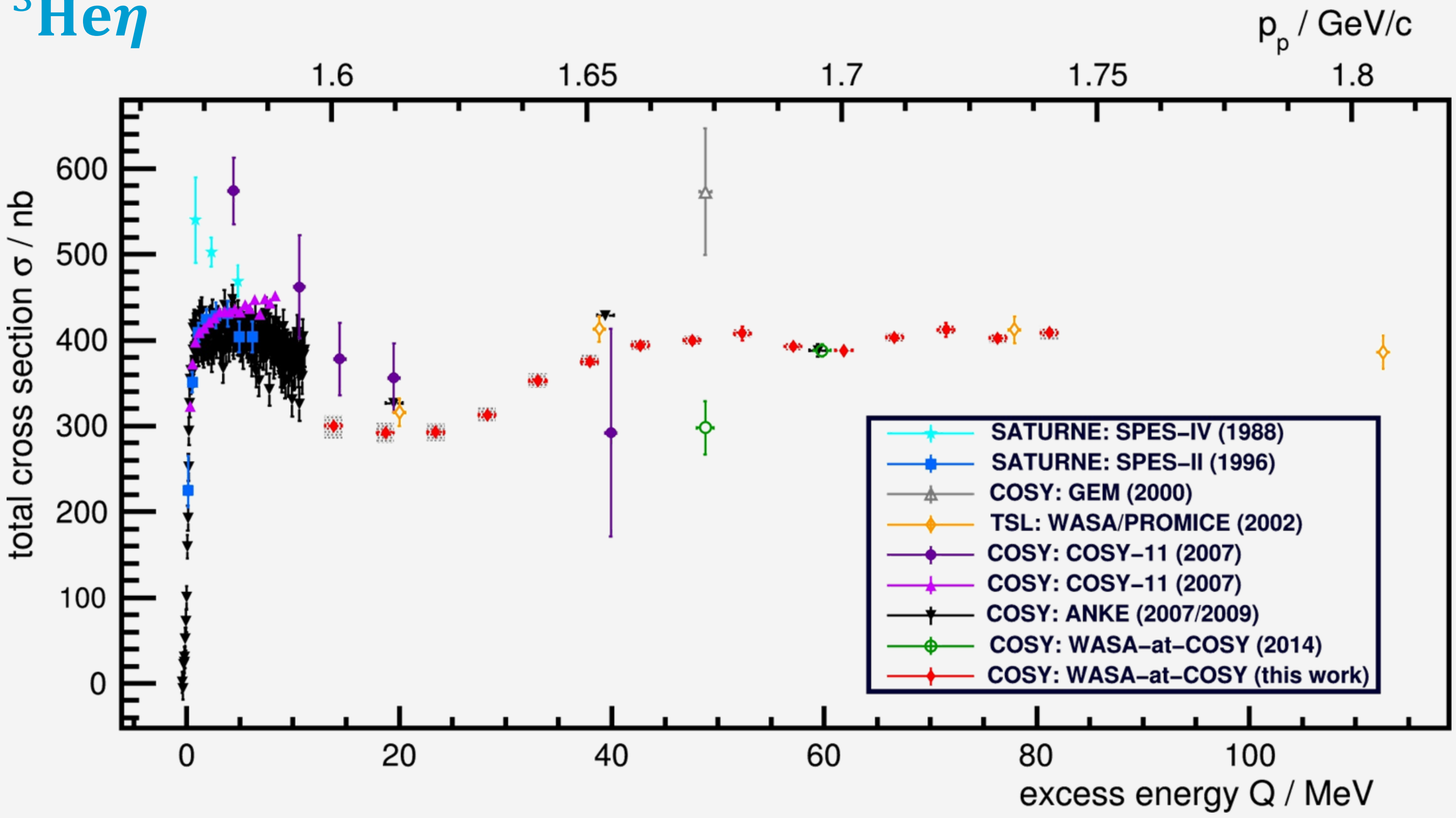
- missing mass analysis, no η reconstruction
- strong signal on top of background from $\text{pd} \to {}^3\text{He}(\pi\pi)^0$ and $\text{pd} \to {}^3\text{He}(\pi\pi\pi)^0$
- signal contribution extracted for 100 bins in $cos\theta^*_\eta$
- relative normalization performed using $pd \to pd$ scattering



Physics Letters B 782 (2018) 297–304

η production in $pd \to {}^3\mathrm{He}\eta$

- statistical precision:
  - 2.2 % point-to-point
  - 1.1 % chain-to-point
- systematic uncertainty:
  - normalization (16.3 %)
  - assumptions on elastic scattering distribution
  - rest-gas distribution
  - angle reconstruction
- variation around $Q \approx 50\ \mathrm{MeV}$ not confirmed:
  - caused by normalization using single-pion production



Physics Letters B 782 (2018) 297–304

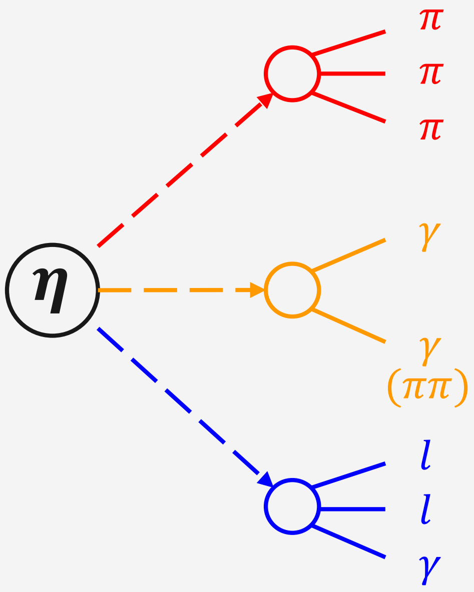
η decays

η meson decays as a laboratory

- η meson $((I^G)J^{PC} = (0^+)0^{-+})$ is an eigenstate to $\boldsymbol{P}$, $\boldsymbol{C}$, $\boldsymbol{G}$ and $\boldsymbol{CP}$
- all strong and electromagnetic decays forbidden to first order

➢ *long* lifetime of $\tau \approx 5 \times 10^{-19}\mathrm{s}$
➢ no dominating decay mode

➢ **ideal environment to search for rare or forbidden decays**



hadronic decays:
- isospin breaking
- $m_u - m_d$ difference

radiative decays:
- quantum anomalies
- $\pi\pi$-interaction

(semi-)leptonic decays:
- form factors
- beyond standard model physics

η meson decays as a laboratory

Decay	Branching Ratio	Topic to investigate
$\eta \to \pi^0\pi^0\pi^0$	$(32.68 \pm 0.23)\%$	Dalitz plot analysis
$\eta \to \pi^+\pi^-\pi^0$	$(22.92 \pm 0.28)\%$	Dalitz plot analysis
$\eta \to \pi^+\pi^-\gamma$	$(4.22 \pm 0.08)\%$	Box anomaly, $\pi^+\pi^-$ interaction
$\eta \to e^+e^-\gamma$	$(6.9 \pm 0.4) \times 10^{-3}$	Transition form factor
$\eta \to \pi^0\gamma\gamma$	$(2.56 \pm 0.22) \times 10^{-4}$	χPT
$\eta \to \pi^+\pi^-e^+e^-$	$(2.68 \pm 0.11) \times 10^{-4}$	Search for $\boldsymbol{CP}$ violation
$\eta \to e^+e^-e^+e^-$	$(2.40 \pm 0.22) \times 10^{-5}$	Transition form factor
$\eta \to \pi^0e^+e^-$	$< 4 \times 10^{-5}$	$\boldsymbol{C}$ violation, BSM physics
$\eta \to e^+e^-$	$< 2.3 \times 10^{-6}$	BSM physics

Chin. Phys. C, 40, 100001 (2016) and 2017 update

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see: Talk by D. Pszczel, Monday, 3:45pm

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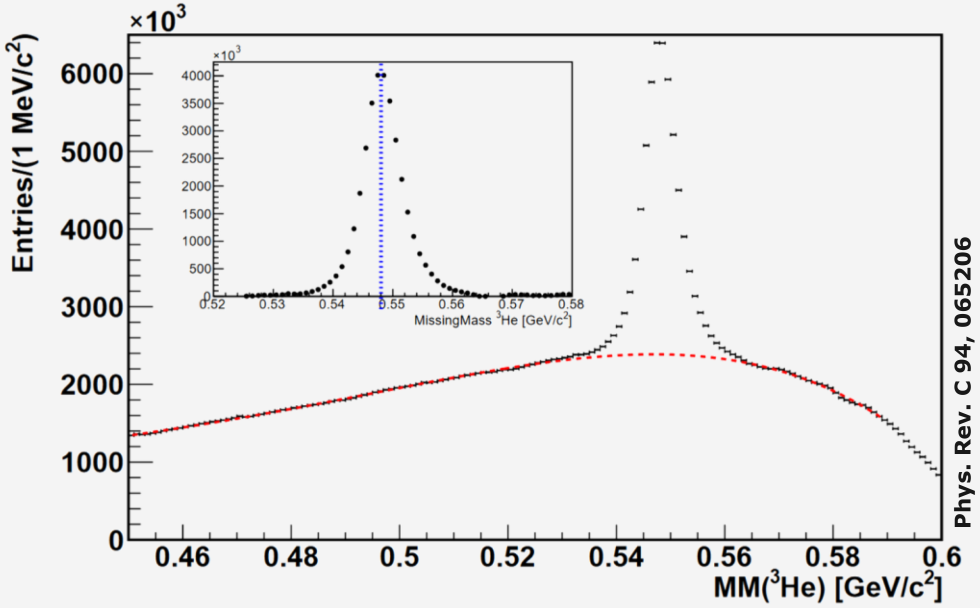
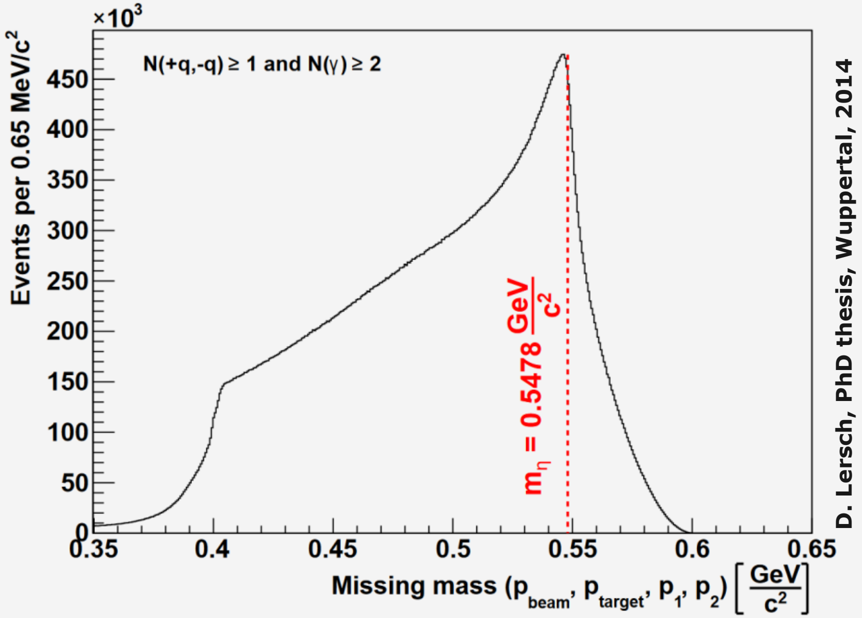
η meson decays as a laboratory



30×10^6 η events in $pd \to {}^3\mathrm{He}\eta$

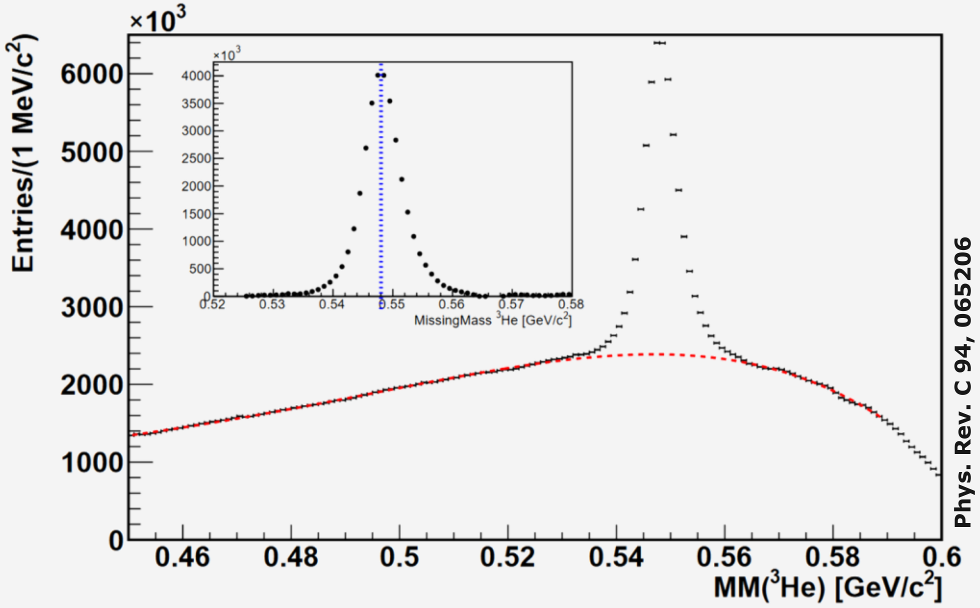
- ${}^3\mathrm{He}$ greatly aids in clean event selection
- good signal/background ratio

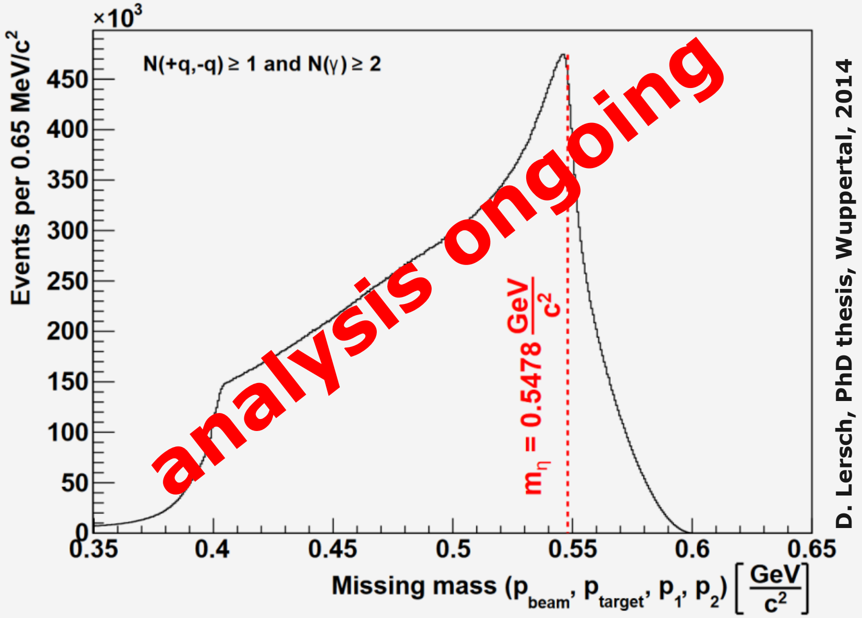


500×10^6 η events in $pp \to pp\eta$

- very large statistics
- worse signal/background ratio, smaller reconstruction efficiency

η meson decays as a laboratory





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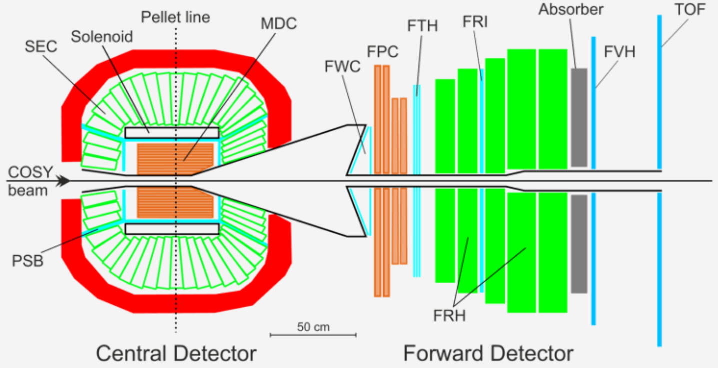
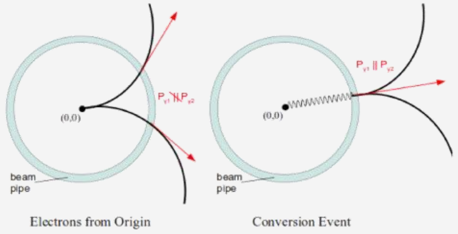
η meson decays as a laboratory

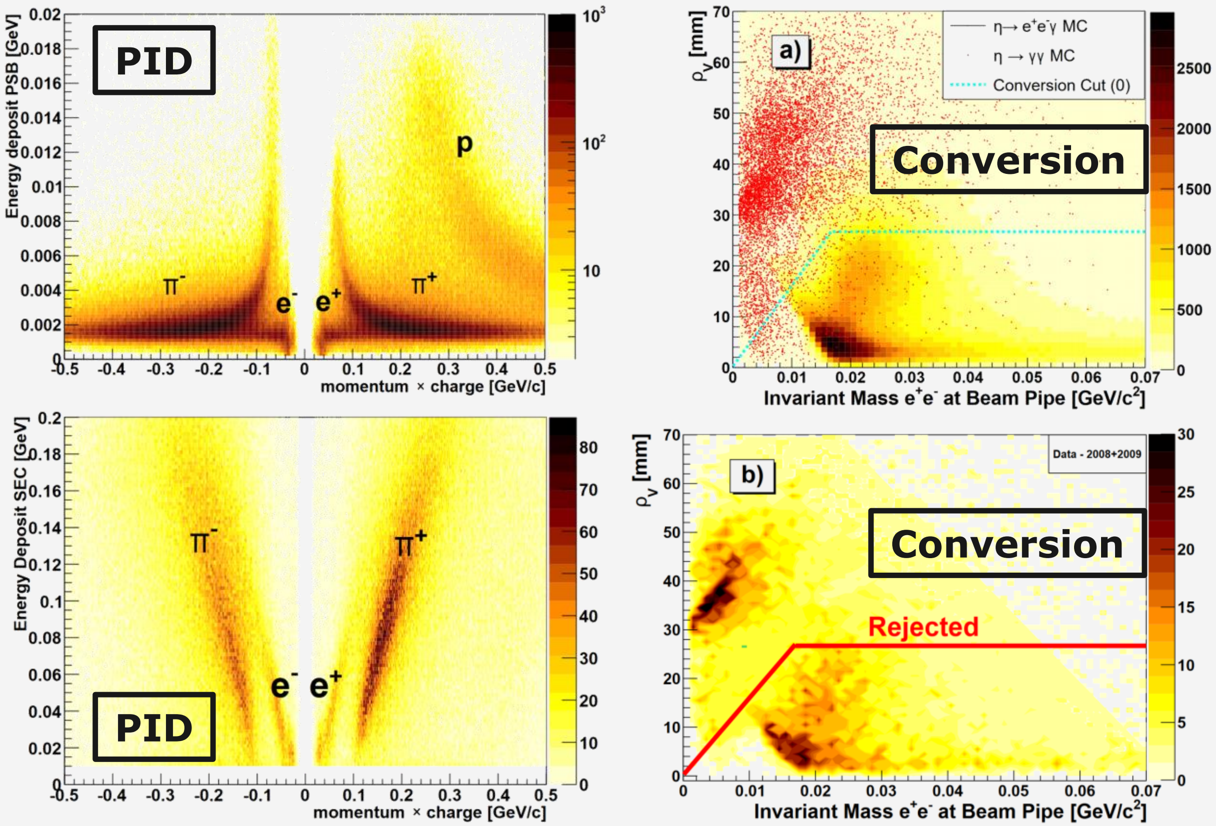
- PID: $e^{\pm}, \pi^{\pm}, p$ separated by ΔE vs $q \cdot p$



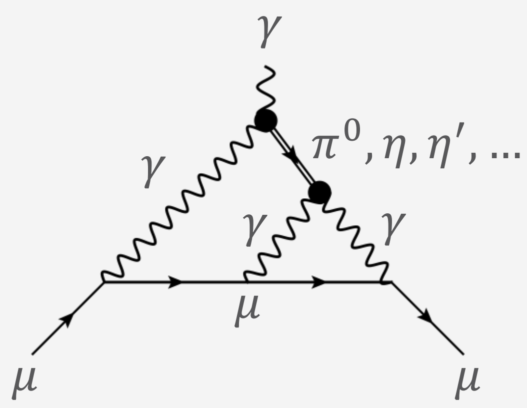
- exclude $e^{+}e^{-}$ pairs from conversion on detector material (e.g., on the beampipe)

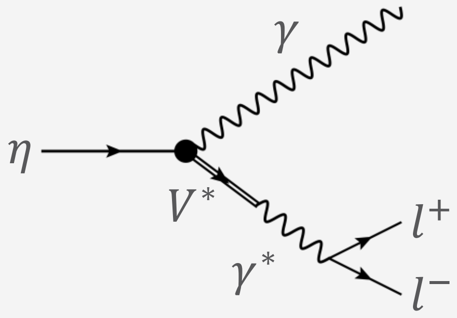


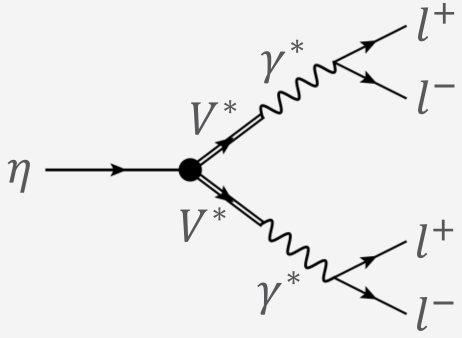
Phys. Rev. C 94, 065206



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







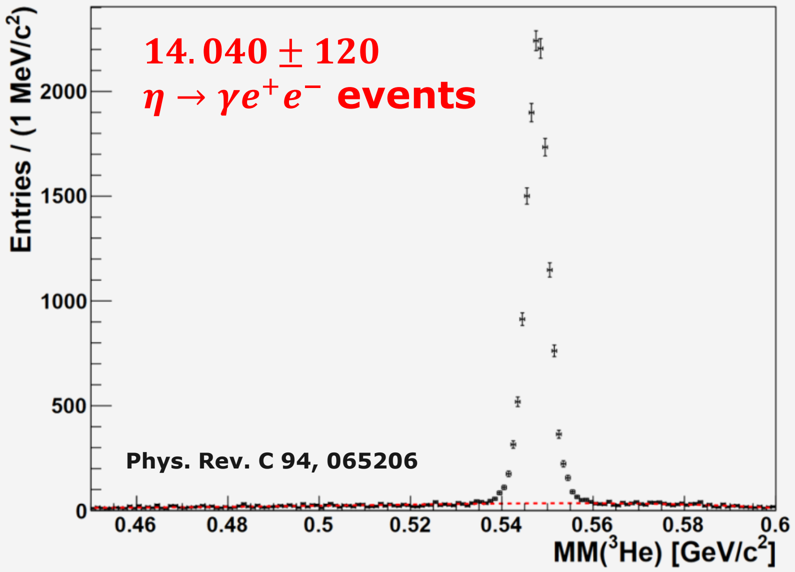
Muon $g_\mu - 2$: Hadronic light-by-light

- one of the largest uncertainties in the theoretical calculation of $g_\mu - 2$
- depends on meson form factor $F(q_1^2, q_2^2)$
- (double-)Dalitz decays help in determining $F(q_1^2, q_2^2)$ for $q_1^2 > 0, q_2^2 = 0$ and $q_1^2 > 0, q_2^2 > 0$

Form factor:

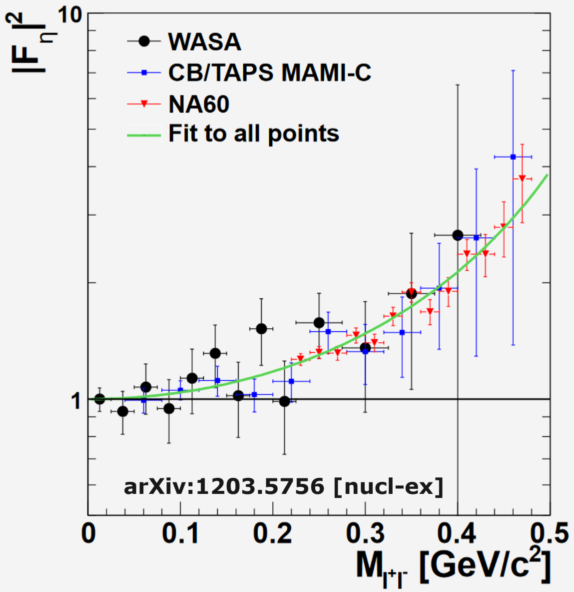
- Dalitz decay: $\frac{d\Gamma}{dq^2} = \left(\frac{d\Gamma}{dq^2}\right)_{QED} \times |F(q^2)|^2$
  - ➢ measure $BR(\eta \to \gamma e^+ e^-)$ & $IM(e^+ e^-)$
  - ➢ PDG: $BR(\eta \to \gamma e^+ e^-) = (6.9 \pm 0.4) \times 10^{-3}$
- double-Dalitz decay:
  - ➢ measure $BR(\eta \to e^+ e^- e^+ e^-)$
  - ➢ PDG: $BR(\eta \to e^+ e^- e^+ e^-) = (2.4 \pm 0.2 \pm 0.1) \times 10^{-5}$

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



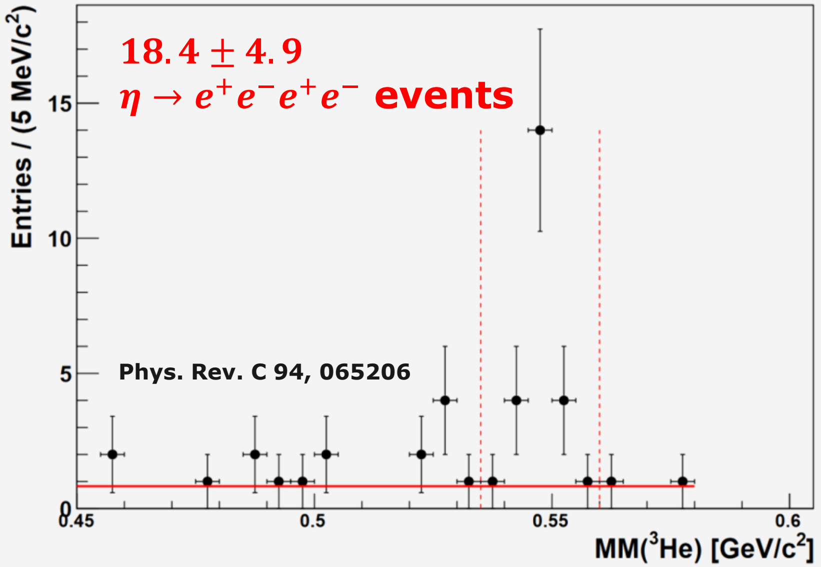
Resulting Branching ratio:

- $\frac{\Gamma(\eta\to\gamma e^+e^-)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)} = (2.97 \pm 0.03 \pm 0.13) \times 10^{-2}$
- $BR(\eta \to \gamma e^+e^-) = (6.72 \pm 0.07 \pm 0.31) \times 10^{-3}$
- PDG: $BR(\eta \to \gamma e^+e^-) = (6.9 \pm 0.4) \times 10^{-3}$



Form factor:

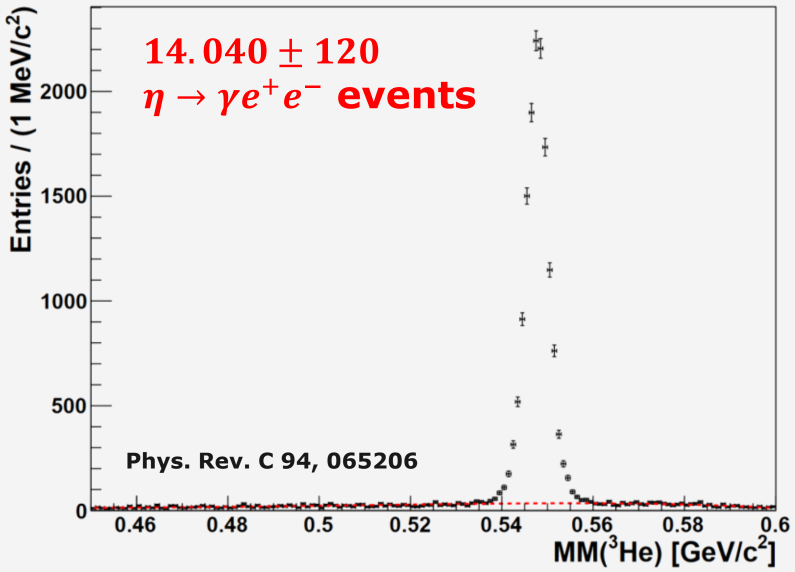
- consistent with other works

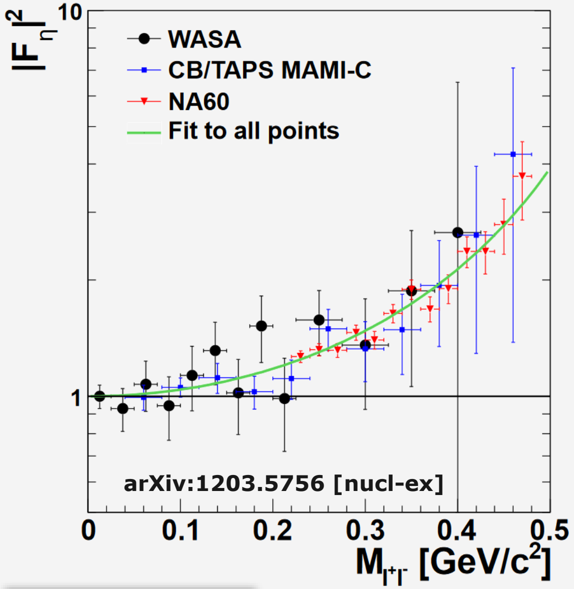


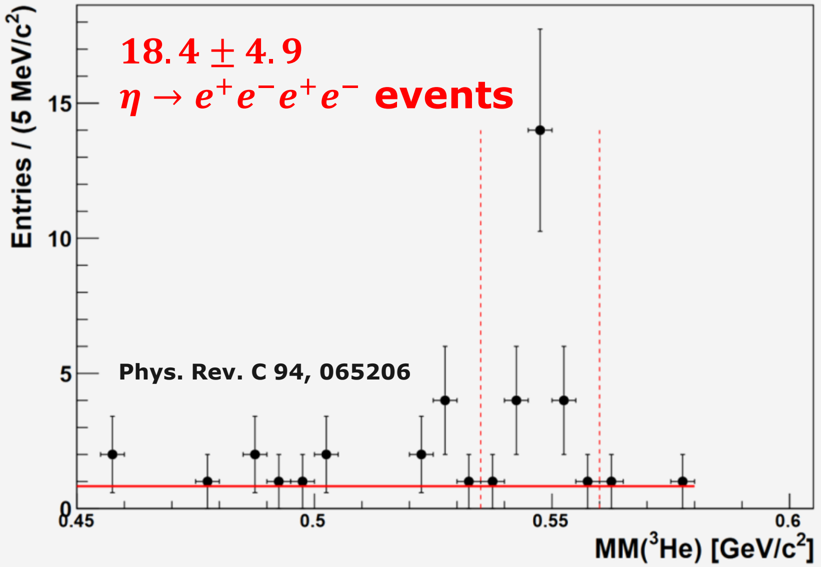
Resulting Branching ratio:

- $\frac{\Gamma(\eta\to e^+e^-e^+e^-)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)} = (1.4 \pm 0.4 \pm 0.2) \times 10^{-4}$
- $BR(\eta \to e^+e^-e^+e^-) = (3.2 \pm 0.9 \pm 0.5) \times 10^{-5}$
- PDG: $BR = (2.4 \pm 0.2 \pm 0.1) \times 10^{-5}$

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







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- PDG: $BR(\eta \to \gamma e^+ e^-) = (6.9 \pm 0.4) \times 10^{-3}$

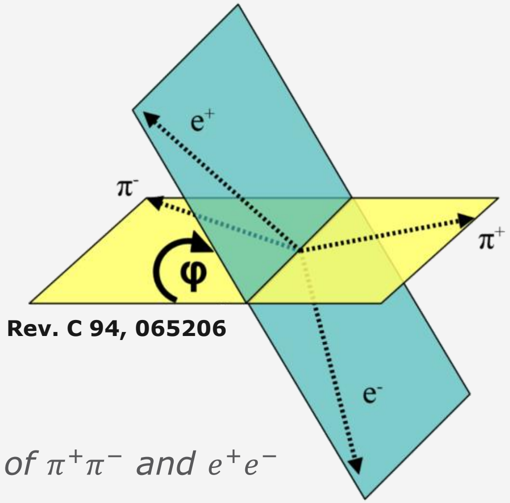
Outlook:

- based on the $pd \to {}^3\mathrm{He}\eta$ dataset
- $16 \times$ the statistics available in $pp \to pp\eta$
- currently being analyzed (see Talk by D. Pszczel)

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

$\eta \to \pi^+\pi^-\gamma$:

- CP-conserving for $M1$ and $E2$ transitions
- CP-violating for $E1$ transitions
- would have to measure γ polarization



Phys. Rev. C 94, 065206

dihedral angle ϕ:
angle between decay planes of $\pi^+\pi^-$ and e^+e^-

➢ **Idea:**
measure $\eta \to \pi^+\pi^-[\gamma^* \to e^+e^-]$ instead

- study asymmetry

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

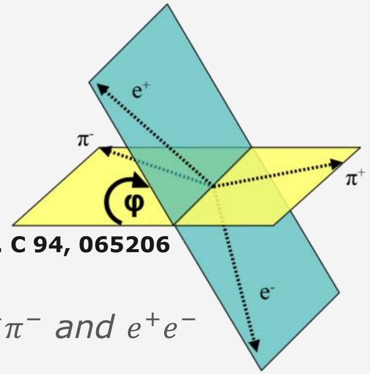
- PDG:

  $BR(\eta \to \pi^+\pi^-e^+e^-) = (2.68 \pm 0.11) \times 10^{-4}$

  $A_\phi = (-0.6 \pm 2.5 \pm 1.8) \times 10^{-2}$

- Theory: $A_\phi < 1\%$

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



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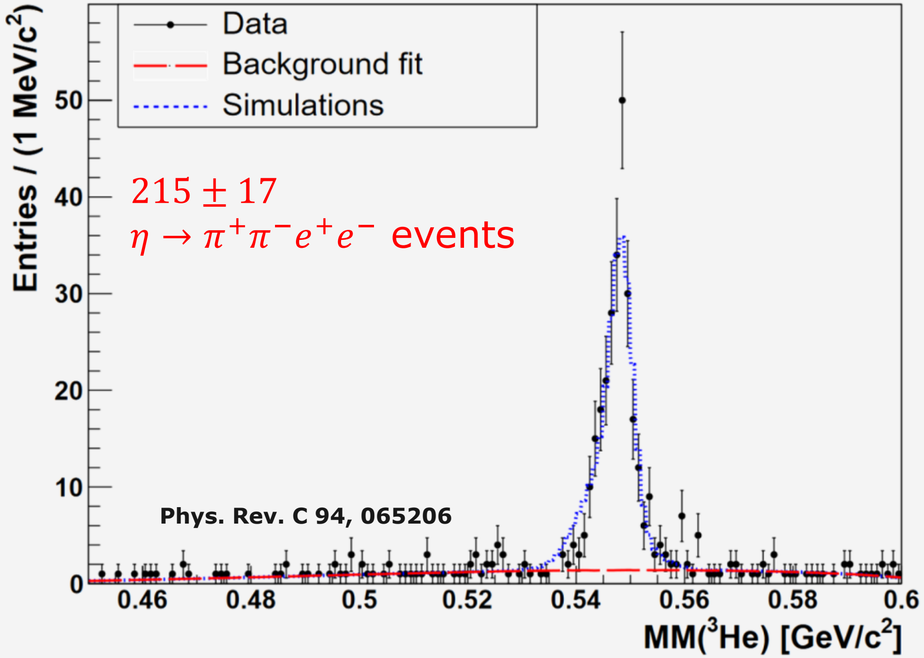
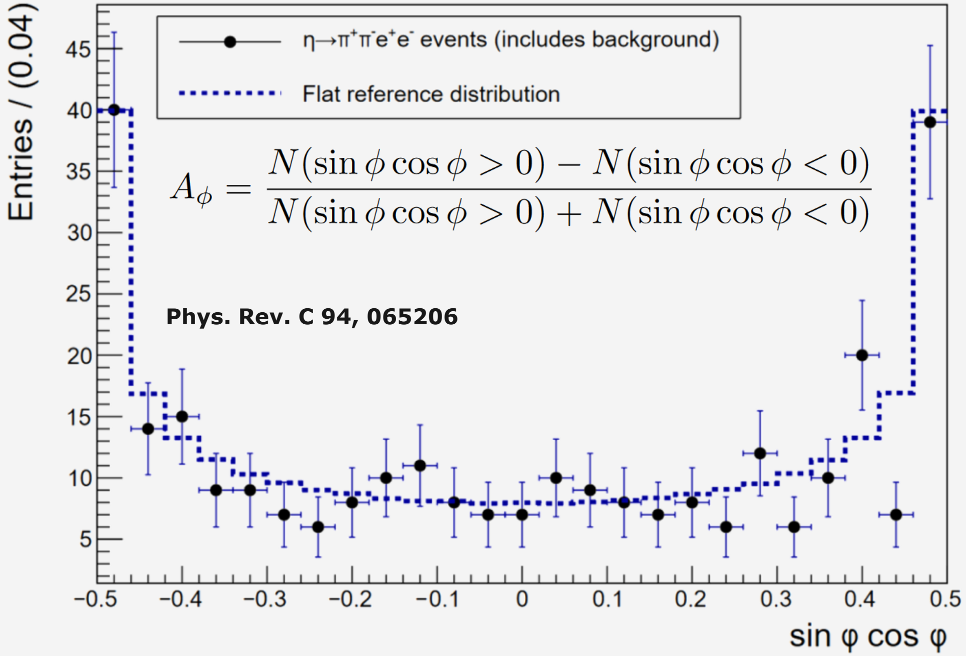
dihedral angle ϕ:
angle between decay planes of $\pi^+\pi^-$ and e^+e^-





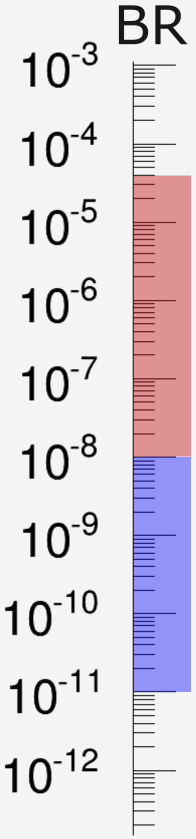
$BR(\eta \to \pi^+\pi^-e^+e^-) = (2.7 \pm 0.2 \pm 0.2) \times 10^{-4}$

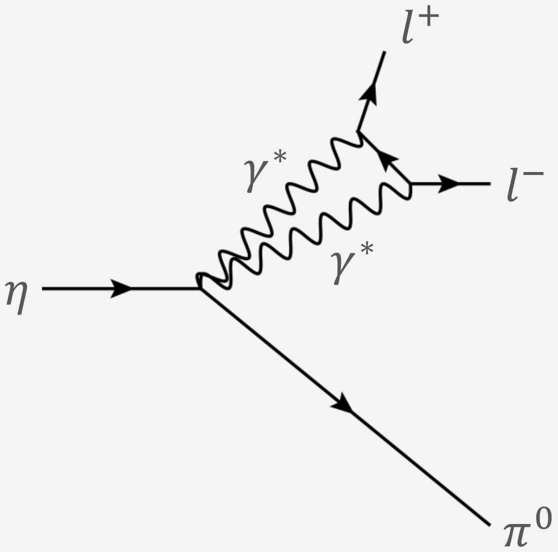
PDG: $BR(\eta \to \pi^+\pi^-e^+e^-) = (2.68 \pm 0.11) \times 10^{-4}$

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

PDG: $A_\phi = (-0.6 \pm 2.5 \pm 1.8) \times 10^{-2}$

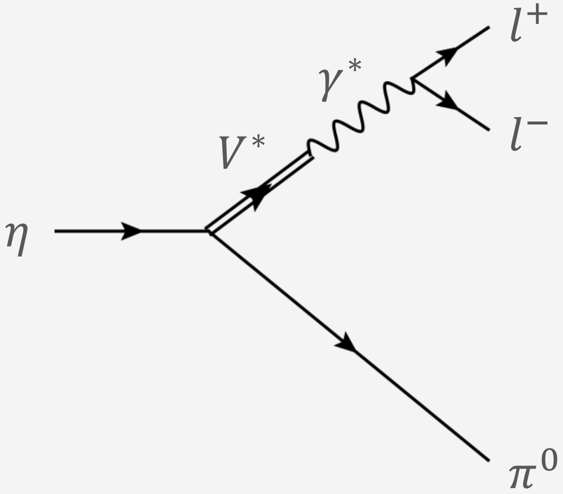
$\eta \rightarrow \pi^0 e^+ e^-$

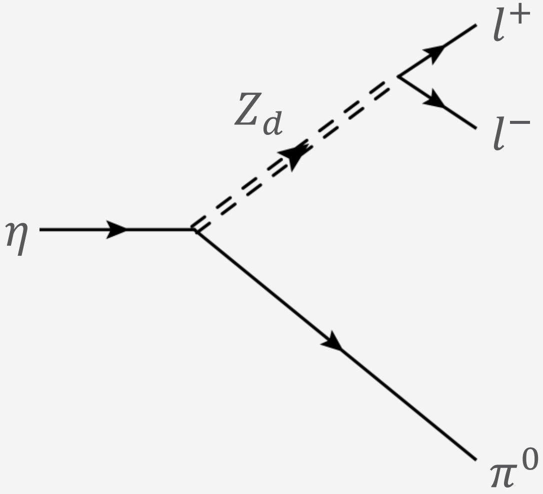




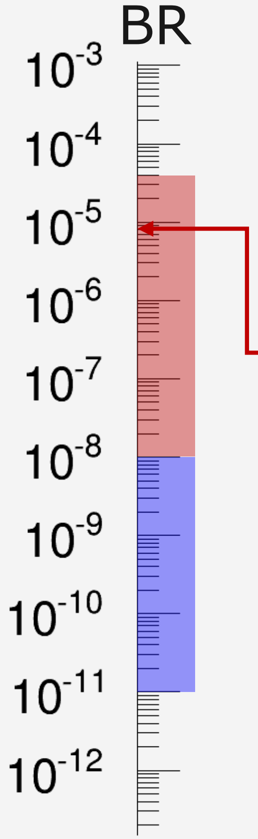
- single γ^* decay violates C-parity
- allowed standard model decay via $\gamma^*\gamma^*$ predicted $BR \approx 10^{-8} \dots 10^{-11}$

- search for C-parity violation in standard model decay
- search for beyond standard model decays via dark bosons
- ➢ 3 orders of magnitude between best upper limit and highest standard model prediction





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



- no signal found in $pd \to {}^3\mathrm{He}\eta$

➢ new upper limit:

$$BR_{\text{virtual}}(\eta \to \pi^0 e^+ e^-) < 7.5 \times 10^{-6}$$

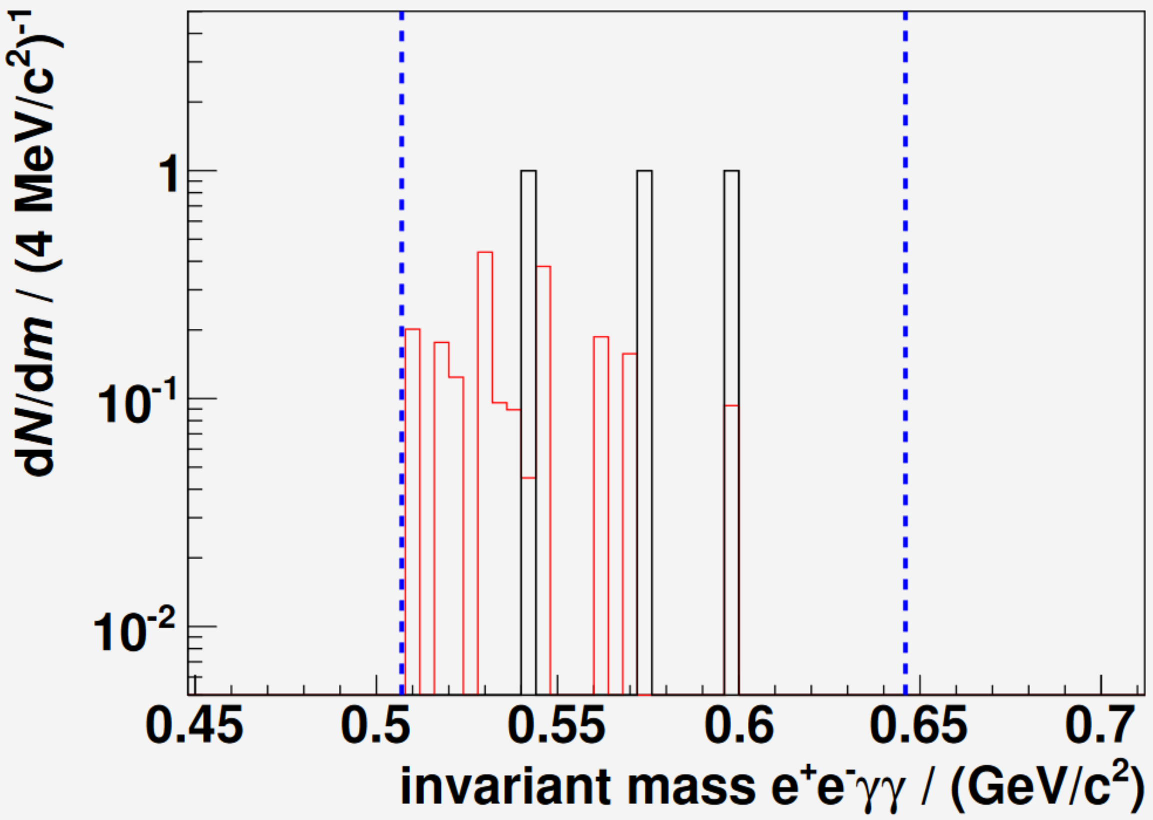
$$BR_{\text{phase}}(\eta \to \pi^0 e^+ e^-) < 9.5 \times 10^{-6}$$

PDG: $\mathrm{BR} < 4 \times 10^{-5}$

➢ still ways to go to reach the standard model predictions

➢ an order of magnitude more data in $pp \to pp\eta$

arXiv:1802.08642 [hep-ex], submitted to PLB



Summary

η-production:

- new results for A_y in $\vec{p}p \to pp\eta$
  - more precise by an order of magnitude
  - data suggests pure s-wave production at $Q = 15\ \mathrm{MeV}$
  - evidence for higher partial waves at $Q = 72\ \mathrm{MeV}$
  - provides stringent limits on existing and future theoretical models
- new results for $\sigma(Q)$ and $d\sigma/d\Omega$ in $pd \to {}^3\mathrm{He}\eta$
  - first time a continuous, high statistics dataset is available away from the production threshold
  - unveils a prominent structure in $\sigma(Q)$
  - detailed $d\sigma/d\Omega$ serve as benchmark for future models

η-decays:

- large datasamples
  - $30 \times 10^6\ \eta$ in $pd \to {}^3\mathrm{He}\eta$
  - $500 \times 10^6\ \eta$ in $pp \to pp\eta$
  - allows to search for rare and forbidden decays
- published results in $pd \to {}^3\mathrm{He}\eta$
  - $\eta \to \pi^+\pi^-\pi^0$
  - $\eta \to \pi^+\pi^-\gamma$
  - $\eta \to \pi^+\pi^-e^+e^-$
  - $\eta \to e^+e^-\gamma$
  - $\eta \to e^+e^-e^+e^-$
  - $\eta \to \pi^0e^+e^-$
- analyses of the larger $pp \to pp\eta$ sample ongoing

WWU
MÜNSTER

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