Measurement of the $\omega \to \pi^+\pi^-\pi^0$ Dalitz plot distribution with WASA-at-COSY

Lena Heijkenskjöld
(JGU Mainz)

SFB 1044 School
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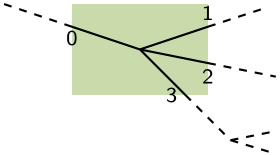
Presentation layout

- Introduction
  - What is a Dalitz plot?
  - Knowns/unknowns of $\omega \to \pi^+\pi^-\pi^0$ dynamic
  - Why study it?
- The experiment
  - The data sets and event selection
- Dalitz plot analysis
  - Creating and filling the Dalitz plot
  - Experiment - Theory comparison
  - Systematic checks
  - Results

What is a Dalitz plot?

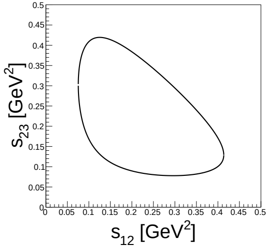
3-body decay



$\mathcal{M}$ given by two independent variables
$\rightarrow$ 2D representation, e.g. $\mathcal{M}(s_{12}, s_{23})$

$$\frac{d^2\Gamma}{ds_{12}ds_{23}} = \frac{1}{(2\pi)^3}\frac{1}{32m^3}|\mathcal{M}|^2$$

$$s_{ij} = |P_i + P_j|^2$$



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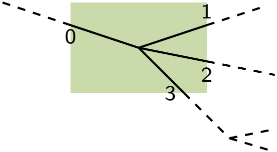

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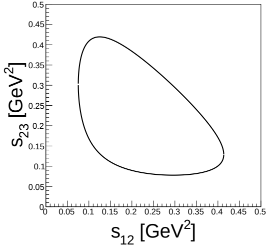

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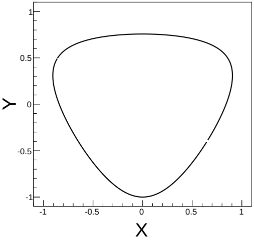
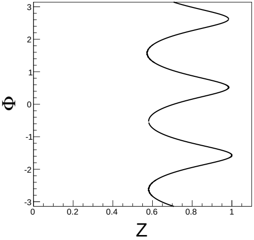
Common choice of variables when $m_1 = m_2 \approx m_3$



$$X = \sqrt{3}\frac{T_1^* - T_2^*}{Q_\omega}$$

$$Y = \frac{3T_3^*}{Q_\omega} - 1$$



$$X = \sqrt{Z}\cos\phi$$

$$Y = \sqrt{Z}\sin\phi$$

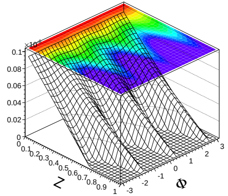
$\omega \to \pi^+\pi^-\pi^0$ dynamics

Dalitz plot density distribution $\sim |\mathcal{M}(s_{12}, s_{23})|^2$, $|\mathcal{M}|^2 = 1$: Phase space

Restrictions from quantum numbers

$\omega : I(J^P) = 0(1^-)$
$J_{3\pi} = 1$ and $J_{2\pi} = 1$

P - wave phase space
$|\mathcal{M}|^2 = \mathcal{P} \propto |\bar{\mathbf{p}}_i \times \bar{\mathbf{p}}_j|^2$



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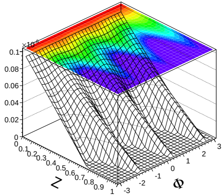
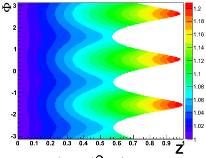


$\pi - \pi$ interactions

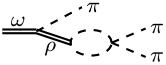
- Intermediate ρ
- $\pi - \pi$ rescattering



$|\mathcal{M}|^2 \ / \ \mathcal{P}$

Predictions of $|\mathcal{M}(s_{12}, s_{23})|^2$ by:

1. Lagrangian approach[1]



2. Dispersion approach[2,3]

$$\pi V \to \pi\pi$$
$$\downarrow$$
$$V \to \pi\pi\pi$$

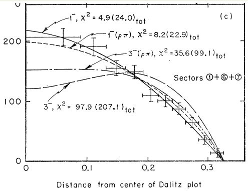
[1] [Uppsala] C. Terschlüsen, B. Strandberg, S. Leupold, F. Eichstädt Eur.Phys.J. A49 (2013) 116
[2] [Bonn] S.P. Schneider, et al., Eur.Phys.J. C72 (2014) 2012
[3] [JPAC] Danilkin, et al. Phys. Rev. D91 (2015) 094029

Why study $\omega \to \pi^+\pi^-\pi^0$ dynamics

Study importance of hadronic final state interactions

Largest previous statistics $\sim$ 4200 events.

Unable to distinguish ρ onset.



Phys. Rev. 145, 1050-1061 (1966)

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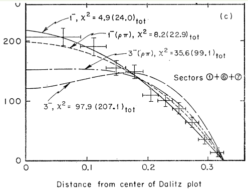

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Benchmark of/input to dispersion calculations of a_μ^{HLbL}

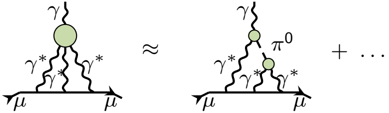
3-4σ discrepancy in $a_\mu^{SM} - a_\mu^{exp}$ — Data driven efforts to reduce theoretical error [4,5].

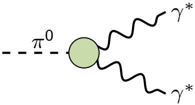
[4] *G. Colangelo, et al. Phys.Lett. B738 (2014) 6-12* [5] *V. Pauk, et al., Phys.Rev. D90 (2014) no.11, 113012*

Theory contribution	$a_\mu(\sigma_{a_\mu}) \times 10^{11}$
QED[6]	115965218.178(0.077)
EW[7]	153.6(1.0)
Strong[8]	
HVP	6793.6(41.4)
HLbL	103(29)

[6] *Aoyama, et al., Phys.Rev.Lett. 109 (2012) 111808*
[7] *Gnendiger, et al, Phys.Rev. D88 (2013) 053005*
[8] *Jegerlehner, arXiv:1705.00263 [hep-ph]*

Hadronic light-by-light scattering:





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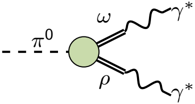
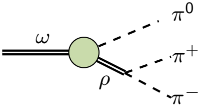
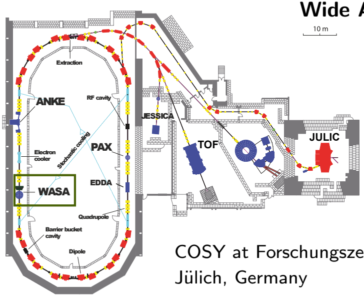


$\sim$

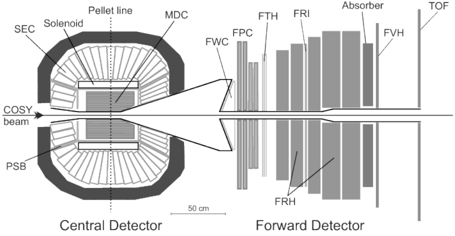


Experimental setup



COSY at Forschungszentrum Jülich, Germany

Wide Angle Shower Apparatus



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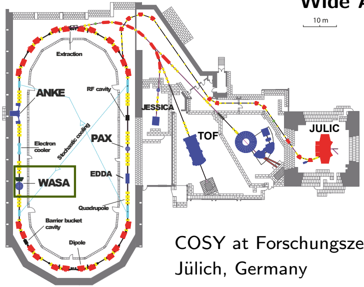

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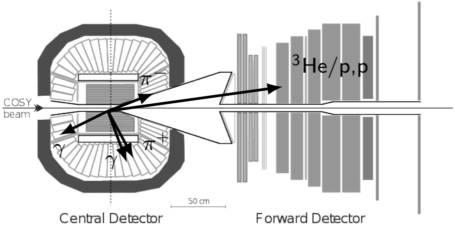


Collected data

$p + d \to {}^3He + \omega$

set A: $T_{beam} = 1.45$ GeV
set B: $T_{beam} = 1.50$ GeV

Analysed in my Ph.D. thesis

$p + p \to p + p + \omega$

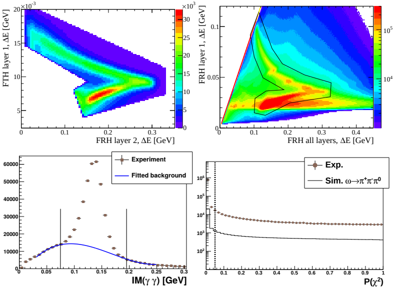
set C :$T_{beam} = 2.063$ GeV

Analysed in Ph.D. thesis of Siddhesh Sawant

Selected data events

Event selection

- ^{3}He/p,p candidate – $\Delta E \Delta E$ cuts
- $\pi^+\pi^-\gamma\gamma$ candidates
- π^0 candidates – IM($\gamma\gamma$) cut
- Kinematic fit – $P_{in} = P_{out}$, 4C-fit
  - Choose final track candidates
  - Test background hypothesis
  - Cut on P(χ^2) and improve kinematic resolution



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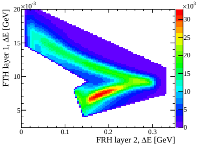
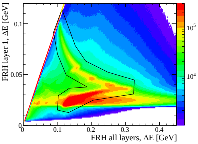
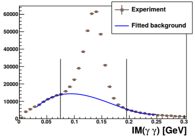
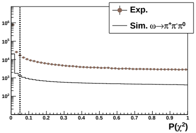


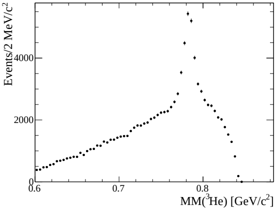






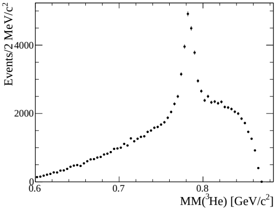
Selected data sample

set A



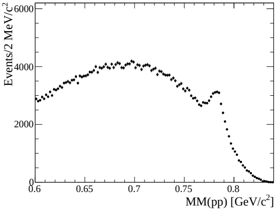
$N_\omega = 14600(200)$

set B



$N_\omega = 13500(200)$

set C



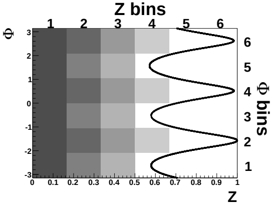
$N_\omega = 16000(300)$

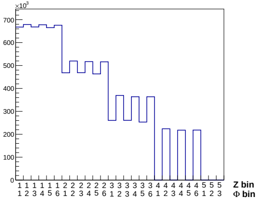
Creating the Dalitz plots

Bin size

$Z \in [0,1]$ and $\Phi \in [-\pi, \pi]$
6×6 bins

1D-representation for comparison





Creating the Dalitz plots

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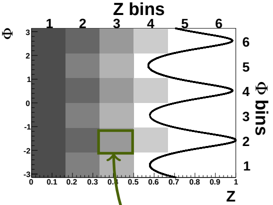
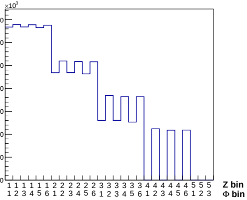
1D-representation for comparison



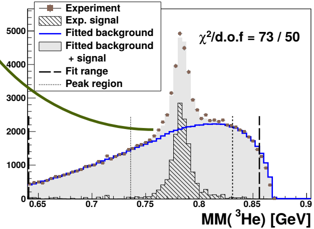


Extracting the ω events

Simulated distributions - $H_{\omega\to3\pi}$ and $H_{3\pi}$

$$\mathbf{F} = \Lambda H_{\omega\to3\pi} + \{a_1 + a_2x + a_3x^2\}H_{3\pi}$$

$$\Lambda = \frac{\lambda}{\int_{l_{min}}^{l_{max}} H_{\omega\to3\pi}} \qquad \lambda = \#\ \text{signal events}$$



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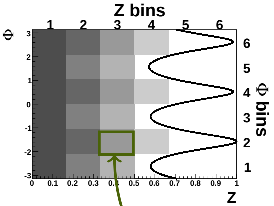

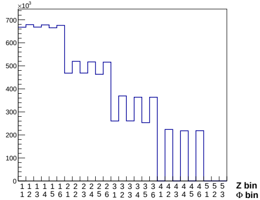

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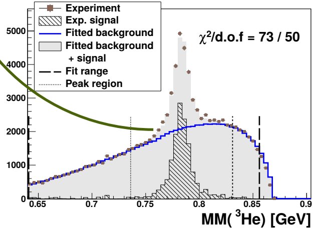
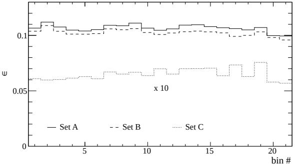


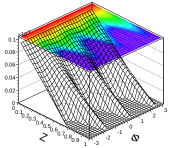
Efficiency correction



Using simulated signal data $\qquad \epsilon_i = \frac{N_i^{fit}}{N_i^{true}}$

Bin-wise efficiency correction $\qquad \tilde{N}_i = \frac{N_i}{\epsilon_i}$

Experiment - Theory comparison



Parametrisation

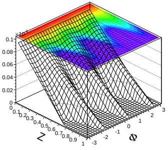
$$|\mathcal{M}|^2 \propto \mathcal{P}(Z,\phi) \cdot \mathcal{G}(Z,\phi)$$

P-wave phase space

$$1 + 2\boldsymbol{\alpha} Z + 2\boldsymbol{\beta} Z^{3/2}\sin(3\Phi) + \mathcal{O}(Z^2)$$

$\alpha,\ \beta, \ldots$ - Dalitz plot parameters

Experiment - Theory comparison



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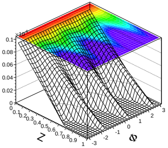
Fits to theory

- Lagrangian approach - Uppsala
- Dispersion approach - Bonn, JPAC

$\boldsymbol{\alpha}$ differ by $\sim$ factor 2

Experiment - Theory comparison



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Fits to data

Integral over bin area

$$\chi^2 = \chi^2_A + \chi^2_B + \chi^2_C \qquad \text{where} \qquad \chi^2_A = \sum_i \left(\frac{\tilde{N}_{iA} - \mathcal{N}_A \int_i (\mathcal{P} \cdot \mathcal{G}) dZ d\Phi}{\tilde{\sigma}_{iA}} \right)$$

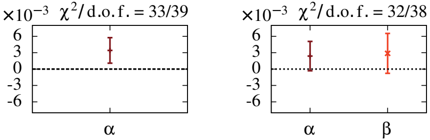
Sum over Dalitz plot bins

Check for systematic effects

Test of fit procedure

Fit to data simulated with P-wave only.

$\rightarrow$ No bias.



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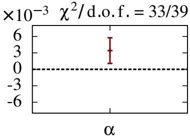
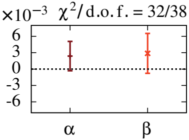
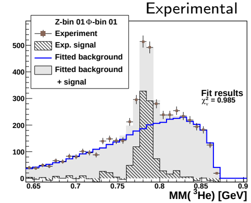




Test of signal extraction method



Simulated distributions - $H_{\omega\rightarrow 3\pi}$ (P-wave) and $H_{3\pi}$

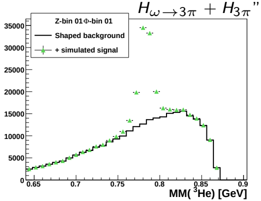
Reshape $H_{3\pi}$: $H_{3\pi}{}' = \{a_1 + a_2 x + a_3 x^2\} H_{3\pi}$

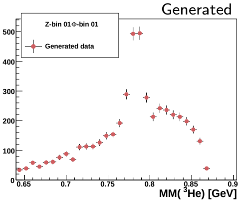
$$H_{3\pi}{}'' = H_{3\pi}{}' \times \frac{S_s/B_{s'}}{S_e/B_e}$$

Generate H_{Gen}, $\int H_{Gen} = \int H_{Exp}$

Extract signal events $\rightarrow$ Fill Dalitz plot

a_1, a_2, a_3 and S_e/B_e





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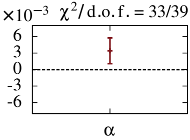
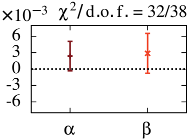
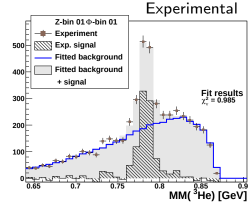




Test of signal extraction method



Simulated distributions - $H_{\omega\rightarrow 3\pi}$ (P-wave) and $H_{3\pi}$

Reshape $H_{3\pi}$: $\quad H_{3\pi}{}' = \{a_1 + a_2 x + a_3 x^2\} H_{3\pi}$

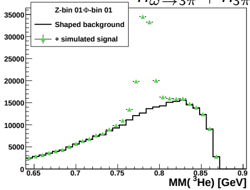
$$H_{3\pi}{}'' = H_{3\pi}{}' \times \frac{S_s/B_{s'}}{S_e/B_e}$$

Generate H_{Gen}, $\int H_{Gen} = \int H_{Exp}$

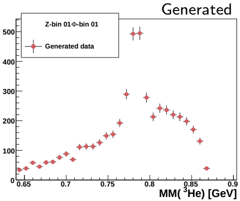
Extract signal events $\rightarrow$ Fill Dalitz plot

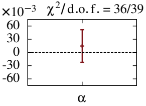
a_1, a_2, a_3 and S_e/B_e

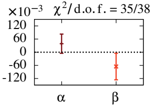
$H_{\omega\rightarrow 3\pi} + H_{3\pi}{}''$



$\longrightarrow$

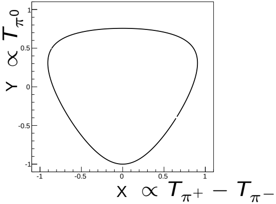






$\rightarrow$ No bias.

Check for systematic effects



Test efficiency correction

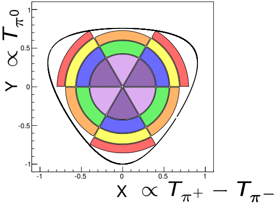
Fit the Dalitz plot including a X- or Y-term in ϵ:

$\epsilon_i \rightarrow \epsilon_i \left(1 + \xi^{ABC} \cdot X\right)$ or $\epsilon_i \rightarrow \epsilon_i \left(1 + \zeta^{ABC} \cdot Y\right)$

$\longrightarrow$ ζ^{ABC} and ξ^{A} consistent with zero
$\xi^{B} < 0$ and $\xi^{C} > 0$

Assuming charge symmetry, we applied correction to ϵ_i^{BC}.

Check for systematic effects



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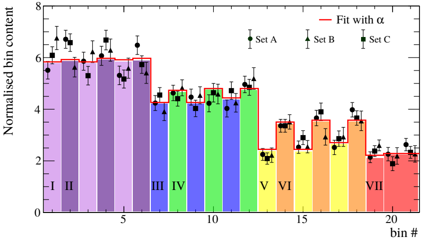
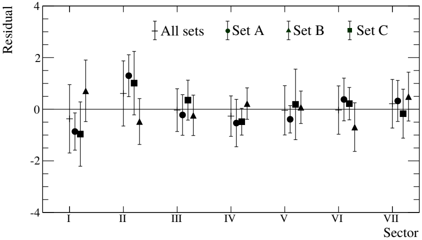
$\xi^{B} < 0$ and $\xi^{C} > 0$

Assuming charge symmetry, we applied correction to ϵ_i^{BC}.

Test data consistency

Compare residuals of data - α-fit within sectors.

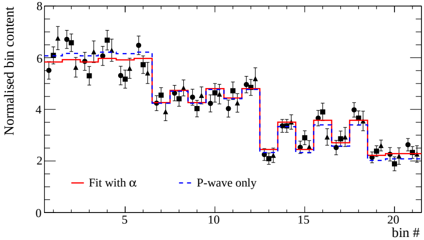




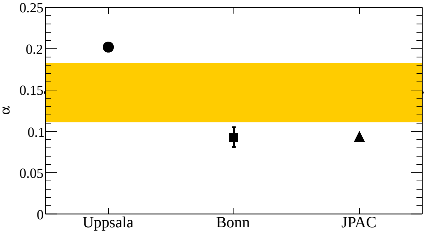
Arithmetic mean ~ 0 and rms ~ 1.

Results

$\alpha \times 10^3$	$\beta \times 10^3$	χ^2/d.o.f.
–	–	90.6 / 60
147(36)	–	71.5 / 59
133(41)	37(54)	71.0 / 58



First observation of deviation from P-wave: α



Article: P. Adlarson et al, Phys. Lett. B 770 (2017), 418-425

Summary and outlook

- $\omega \to \pi^+\pi^-\pi^0$ studied by WASA-at-COSY
  - First observation of deviation from P-wave phase space
  - Benchmark α from theory
- Higher statistics measurement
  - $\beta,\ \gamma, \ldots$
  - Increase precision for dispersive calculations

Summary and outlook

- $\omega \to \pi^+\pi^-\pi^0$ studied by WASA-at-COSY
  - First observation of deviation from P-wave phase space
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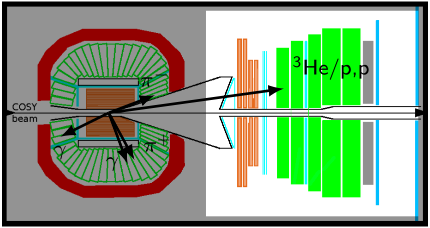
Thank you for your attention!

Backup slides – Theory parametrisation fit

	$\alpha \times 10^3$	$\beta \times 10^3$	$\gamma \times 10^3$	$\delta \times 10^3$
Uppsala	202	-	-	-
Bonn	84. . . 96	-	-	-
JPAC	94	-	-	-
Uppsala	190	54	-	-
Bonn	74. . . 84	24. . . 28	-	-
JPAC	84	28	-	-
Uppsala	172	43	50	-
Bonn	73. . . 81	24. . . 28	3. . . 6	-
JPAC	80	27	8	-
Uppsala	174	35	43	20
Bonn	74. . . 83	21. . . 24	0. . . 2	7. . . 8
JPAC	83	22	1	14

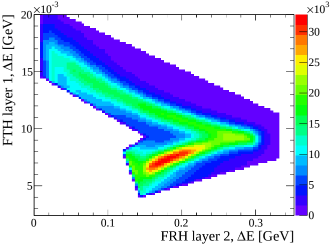
Phys. Rev. D 91, 094029 (2015)

Backup slides – Event selection

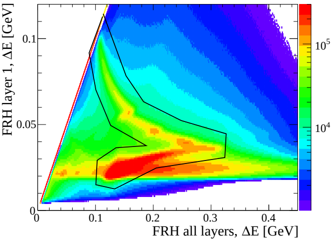


- ^{3}He/p,p candidate

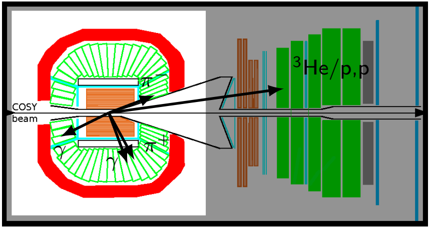
^{3}He



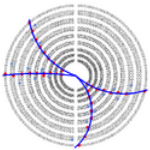
p,p



Backup slides – Event selection

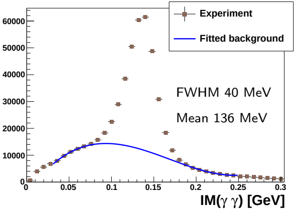


- ^{3}He/p,p candidate
- $\pi^+\pi^-\gamma\gamma$ candidates



Charged tracks PID using
drift chamber and solenoid $\sim$ 1 T

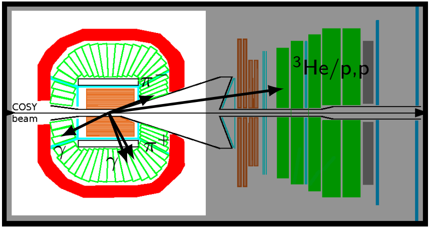
$\geq$ 2 oppositely charged



γ reconstruction
in calorimeter

$\geq$ 2 neutral

Backup slides – Event selection



- ^{3}He/p,p candidate
- $\pi^+\pi^-\gamma\gamma$ candidates
- π^0 candidates

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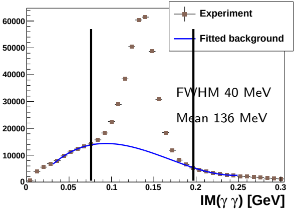

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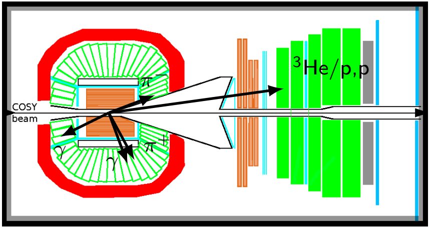
Backup slides – Event selection



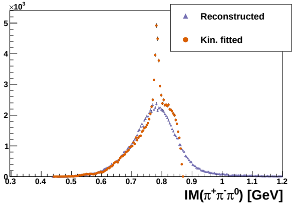
- ^{3}He/p,p candidate
- $\pi^+\pi^-\gamma\gamma$ candidates
- π^0 candidates
- Kinematic fit

Constraint: $P_{in} = P_{out}$,

Hypothesis: $$\begin{aligned} pd &\to {}^3\mathrm{He}\pi^+\pi^-\gamma\gamma \\ pp &\to pp\pi^+\pi^-\gamma\gamma \end{aligned}$$

- Choose final track candidates
- Test $\begin{aligned} pd &\to {}^3\mathrm{He}\pi^+\pi^- \\ pp &\to pp\pi^+\pi^- \end{aligned}$ hypothesis
- Cut on P(χ^2)>0.05

Improve resolution for $X^{Rec} = T,\ \theta,\ \phi$



Fit method

$$\text{Parametrisation } \mathcal{P} \ \cdot \ \mathcal{G}(Z,\Phi)$$

$$\mathcal{G}(Z,\Phi) = 1 + 2\alpha Z + 2\beta Z^{3/2}\sin(3\Phi) + 2\gamma Z^2 + 2\delta Z^{5/2}\sin(3\Phi) + \mathcal{O}(Z^3)$$

$$\chi^2 = \sum_{a=1}^{3}\sum_{ij}\left(\frac{\tilde{N}^a_{ij} - \mathcal{N}^a(H^{(i)}_{ij} + \alpha H^{(ii)}_{ij} + \beta H^{(iii)}_{ij} + \ldots)}{\tilde{\sigma}_{N^a_{ij}}}\right)^2$$

$$H^{(i)}_{ij} = \int_{bin^{min}_{ij}}^{bin^{max}_{ij}} P(Z,\Phi)dZd\Phi$$

$$H^{(ii)}_{ij} = \int_{bin^{min}_{ij}}^{bin^{max}_{ij}} 2ZP(Z,\Phi)dZd\Phi$$

$$H^{(iii)}_{ij} = \int_{bin^{min}_{ij}}^{bin^{max}_{ij}} 2Z^{3/2}\sin(3\Phi)P(Z,\Phi)dZd\Phi$$

$$H^{(iv)}_{ij} = \int_{bin^{min}_{ij}}^{bin^{max}_{ij}} 2Z^2P(Z,\Phi)dZd\Phi$$