Partial Wave Analysis of Strangeness Production at GeV Energies

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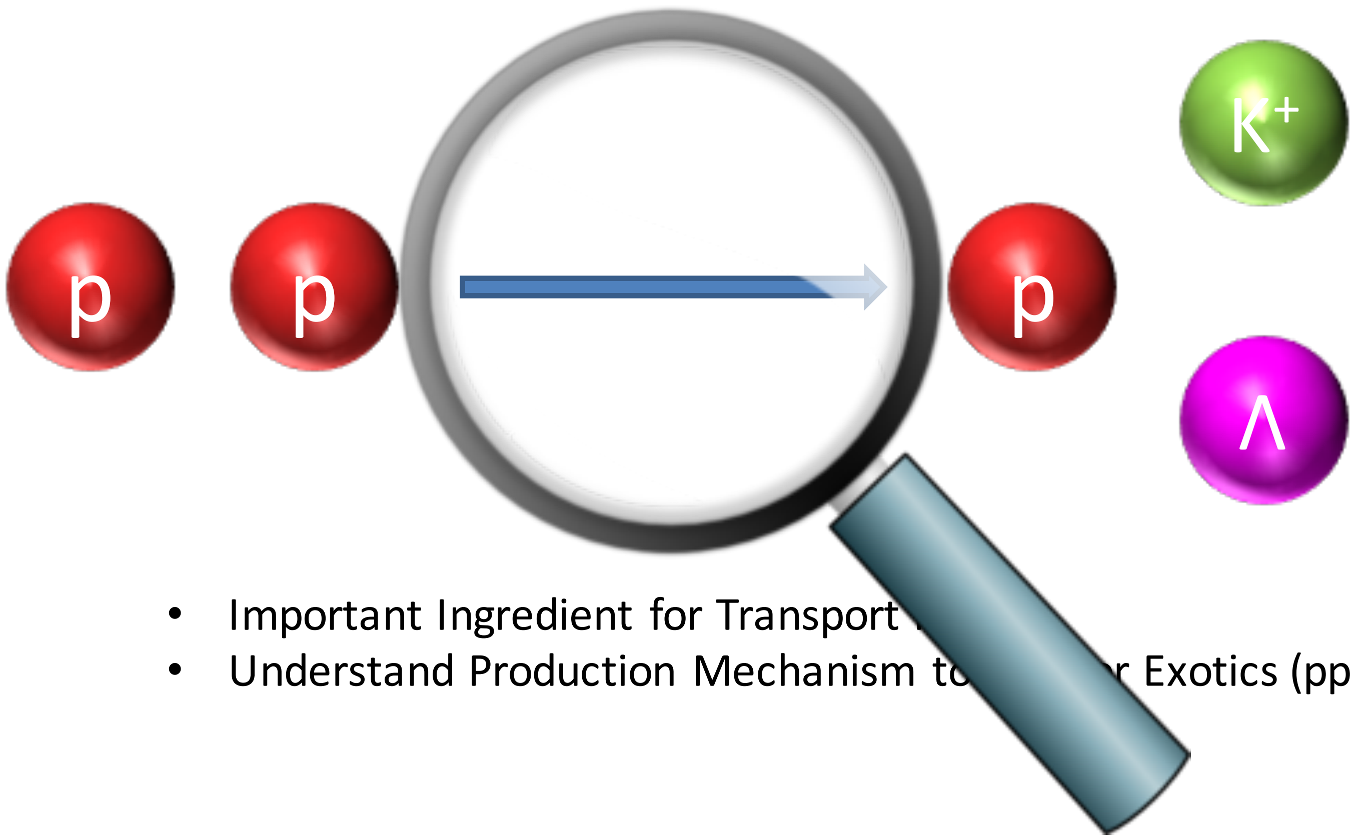
Excellence Cluster – Origin of the Universe

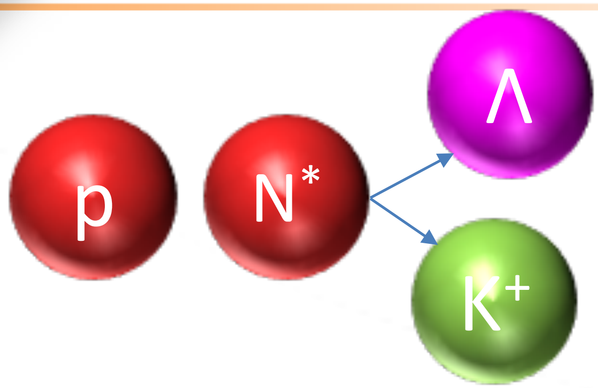
Petersburg Nuclear Physics Institute

Strangeness Production



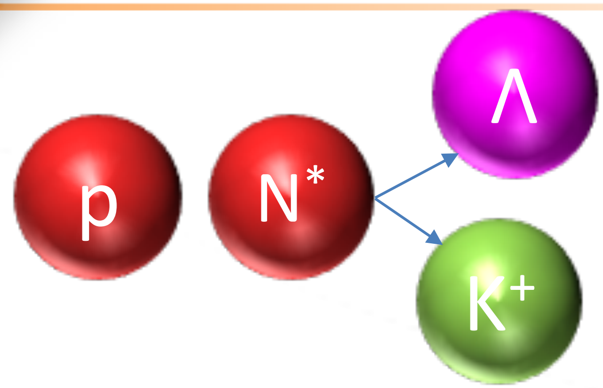
- Important Ingredient for Transport
- Understand Production Mechanism to … r Exotics (ppK^-)

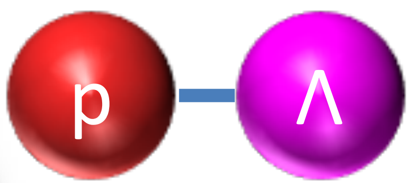
Strangeness Production



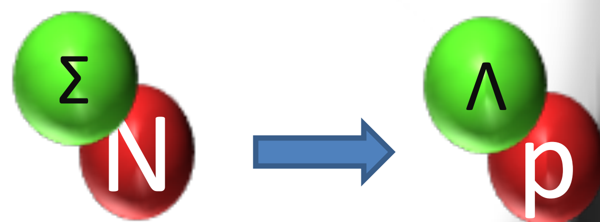
Resonance	J^P	Mass (GeV/c^2)	Γ (MeV/c^2)
N*(1650)	$1/2^-$	1.655	0.150
N*(1710)	$1/2^+$	1.710	0.100
N*(1720)	$3/2^+$	1.720	0.250
N*(1875)	$3/2^-$	1.875	0.220
N*(1880)	$1/2^+$	1.870	0.235
N*(1895)	$1/2^-$	2.090	0.090
N*(1900)	$3/2^+$	1.900	0.0250

Strangeness Production



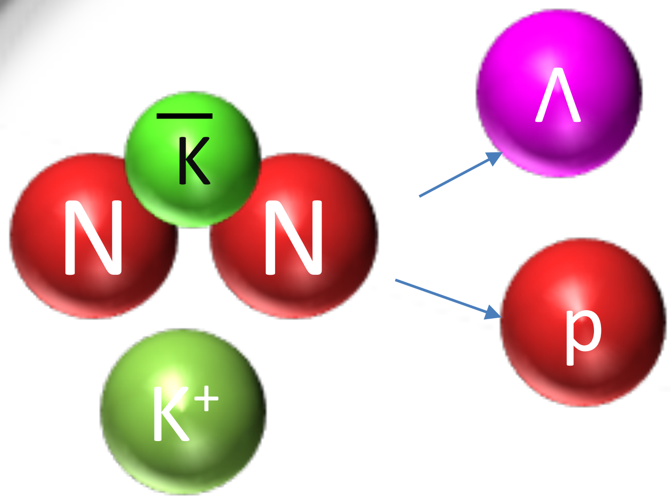


Final State Interaction
Aka: scattering length and effective range



Conversion Processes

Strangeness Production



Kaonic Bound States

Partial Wave Analysis

Bonn-Gatchina PWA Framework

A. Sarantsev et.al., Eur.Phys J A 25 2005

Cross-section Decomposition

$$d\sigma = \frac{(2\pi)^4|A|^2}{4|k|\sqrt{s}} d\phi(P, q_1, q_2, q_3), \qquad P = k_1 + k_2$$

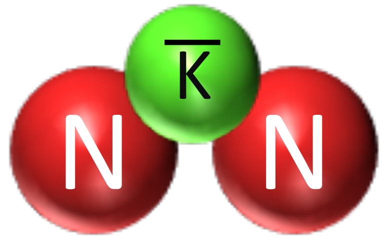
A : reaction amplitude A ∝ $A \propto A^{\alpha}_{tr}$ (s) (Transition amplitude of wave α)
k : 3-momentum of the initial particle in the CM
$s - P^2 : (k_1 + k_2)^2$
$d\phi(P, q_1, q_2, q_3)$: invariant three-particle phase space

Parameterization of the Transition

$$A^{\alpha}_{tr}(s) = (a^{\alpha}_1 + a^{\alpha}_3\sqrt{s})e^{a^{\alpha}_2}$$

a^{α}_1 Constant amplitude
a^{α}_2 Phase
a^{α}_3 Energy dependent amp.

Kaonic Cluster



Theoretical Predictions

	Chiral, energy dependent				
	var. [DHW09, DHW08]	Fad. [BO12b, BO12a]	var. [BGL12]	Fad. [IKS10]	Fad. [RS14]
BE	17–23	26–35	16	9–16	32
Γ_m	40–70	50	41	34–46	49
Γ_{nm}	4–12	30			
	Non-chiral, static calculations				
	var. [YA02, AY02]	Fad. [SGM07, SGMR07]	Fad. [IS07, IS09]	var. [WG09]	var. [FIK$^+$11]
BE	48	50–70	60–95	40–80	40
Γ_m	61	90–110	45–80	40–85	64–86
Γ_{nm}	12			∼20	∼21

Binding Energy (BE):

10-100 MeV

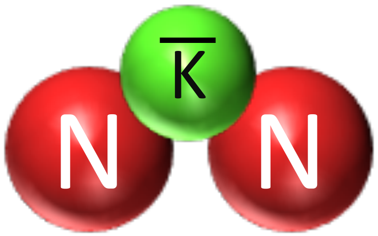
Mesonic Decay (Γ_m)

30-110 MeV

Non-Mesonic Decay (Γ_{nm})

4-30 MeV

Kaonic Cluster



$p + p \longrightarrow \underbrace{\Lambda(1405) + p}_{ppK^- } + K^+$

$ppK^- + K^+$

$\quad \hookrightarrow \Lambda + p$

Physical Background:

$p + p \longrightarrow \Lambda + p + K^+$

$p + p \longrightarrow N^{*+} + p$

$\quad \hookrightarrow \Lambda + K^+$

N^{*+} - Resonances

J. Beringer Phys.Rev. D86 (2012)

Resonance	J^P	Mass (GeV/c^2)	Γ (MeV/c^2)
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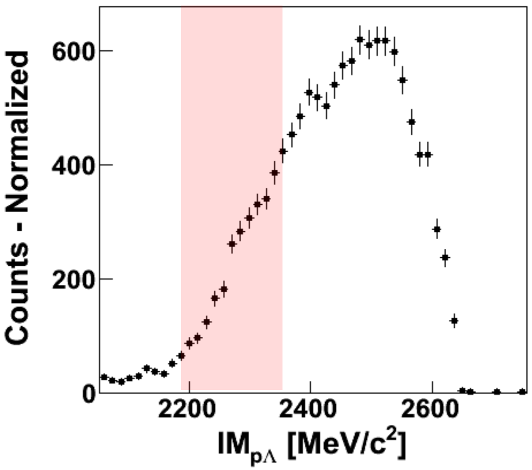
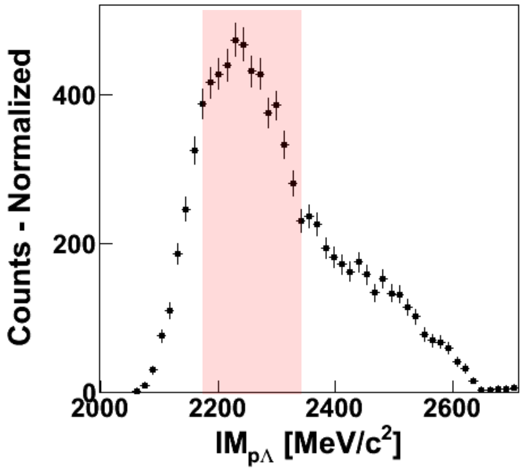
N*(1895)	$1/2^-$	2.090	0.090
N*(1900)	$3/2^+$	1.900	0.0250

Total Data Set

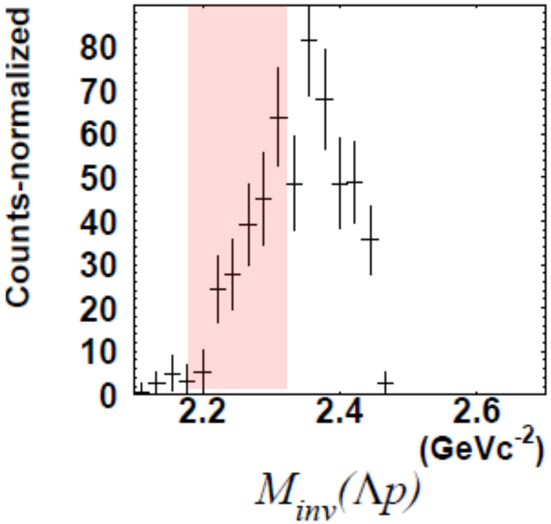
Hades Data E_{beam}=3.5 GeV



Had. Wall Data E_{beam}=3.5 GeV



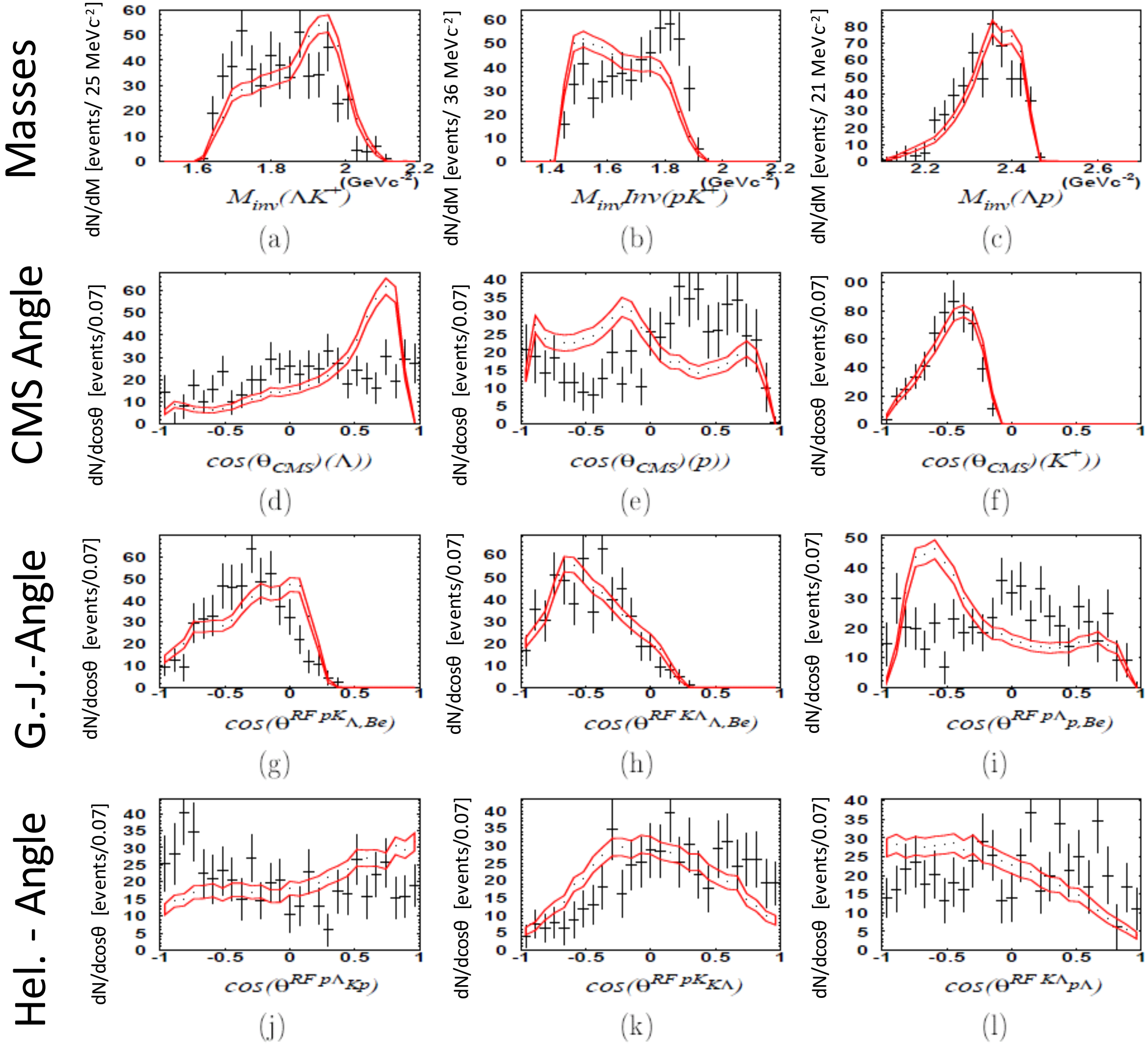
FOPI Data E_{beam}=3.1 GeV



No Peak Visible
No Signal?

R. Münzer, PhD Thesis, TUM 2014
E. Epple, PhD Thesis, TUM 2014

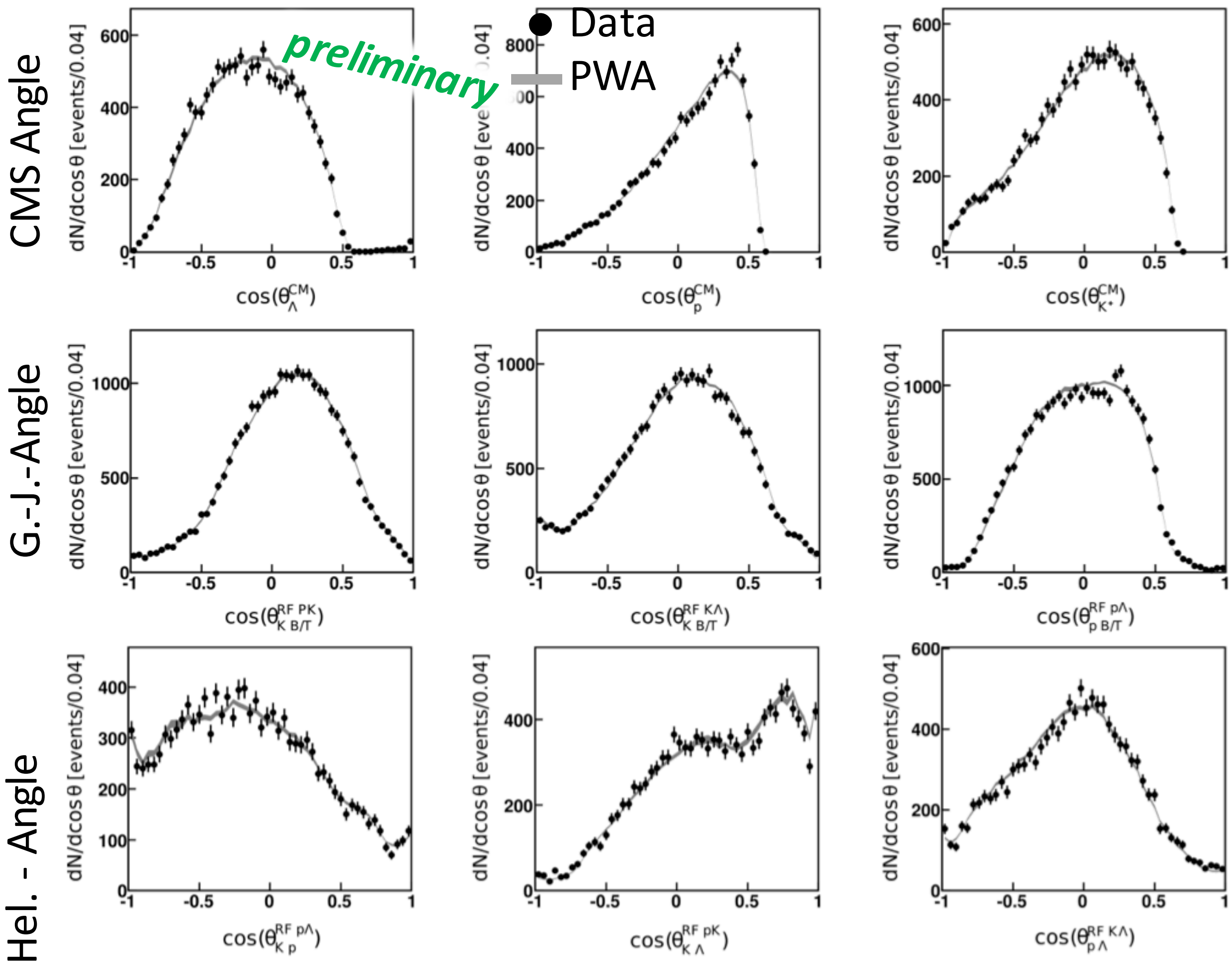
Phase Space Simulation



✚ Experimental Data

pp → p K⁺ Λ Phase Space

Four Best PWA Solutions

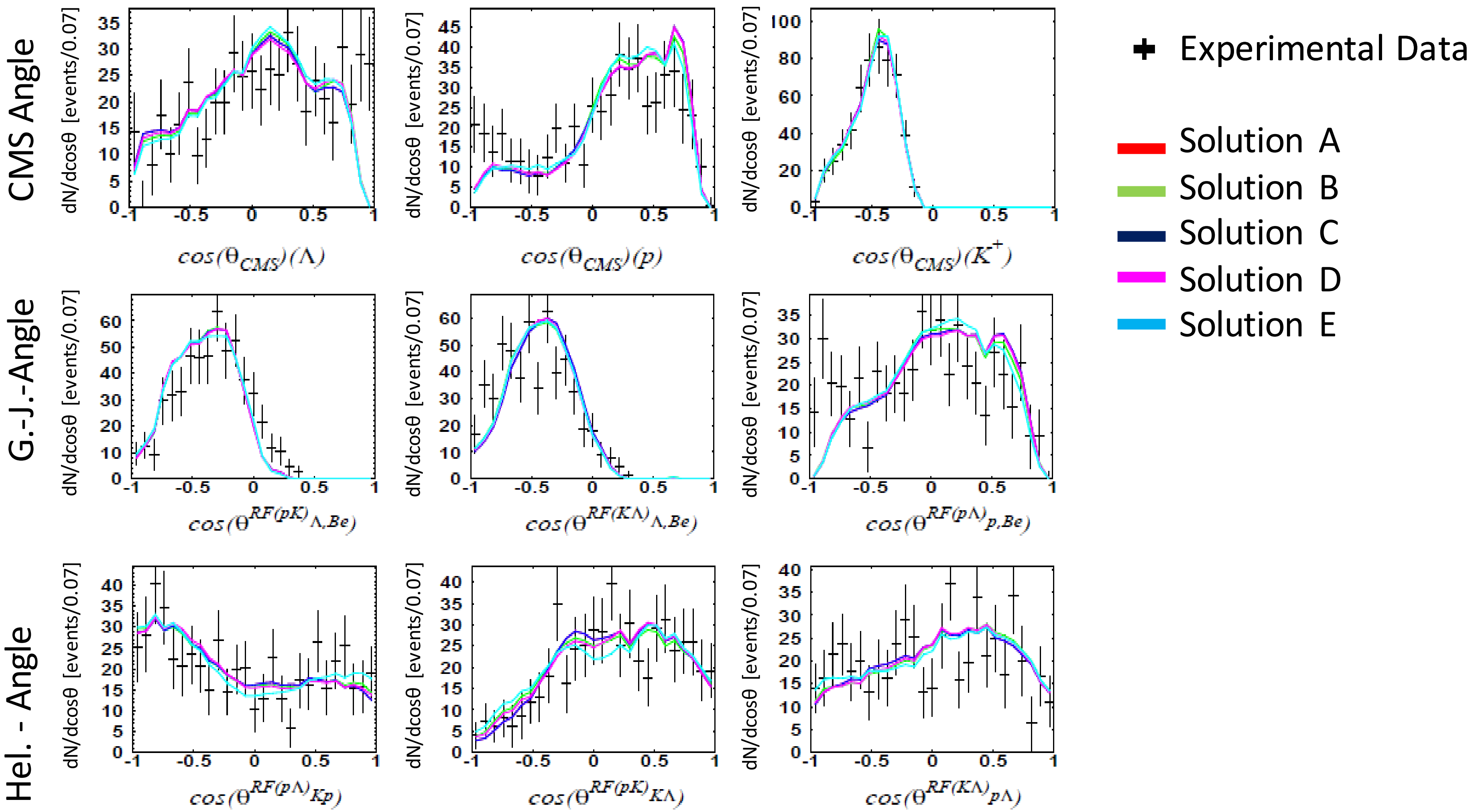


Inside HADES acceptance

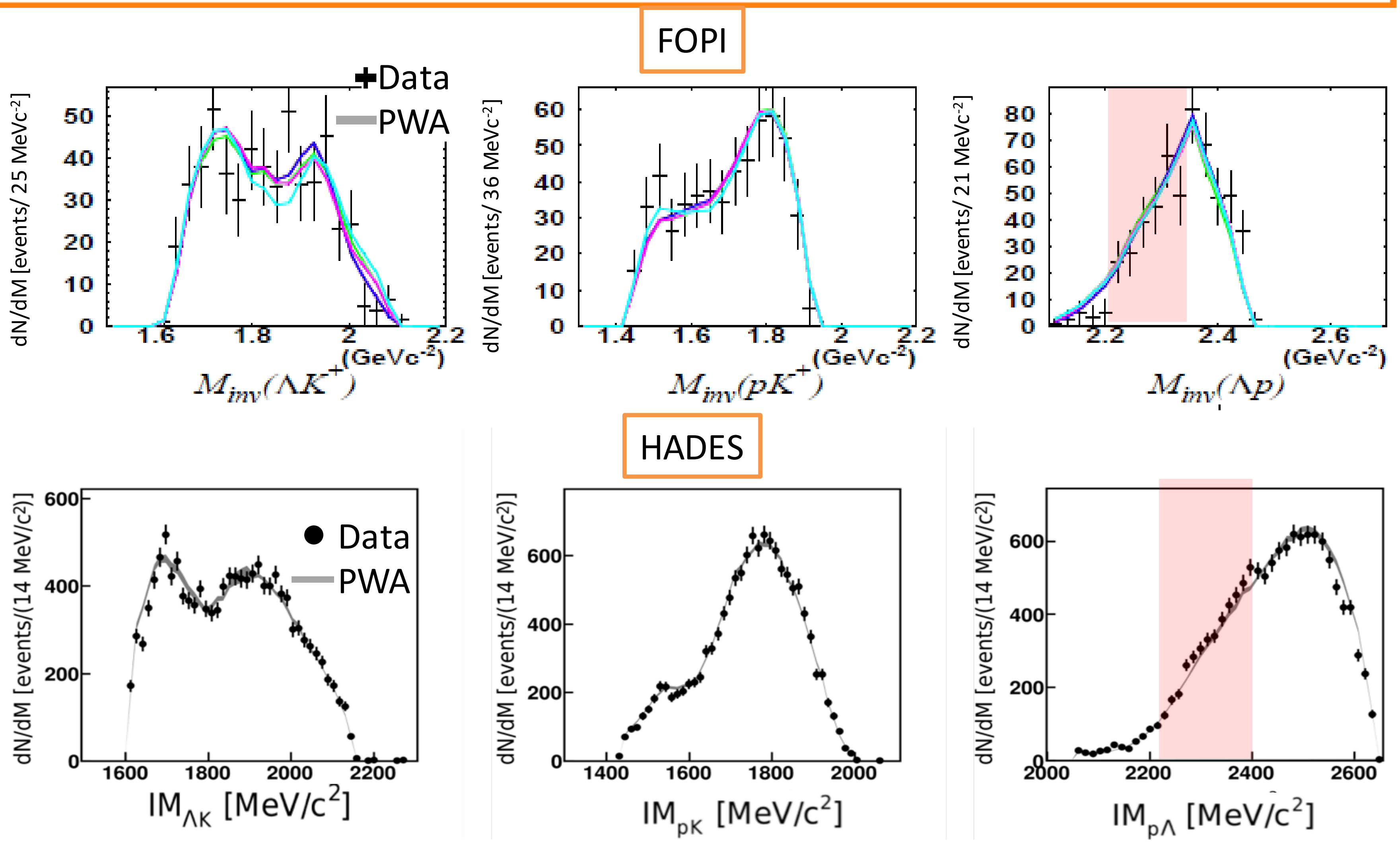
Measured Data

PWA solutions

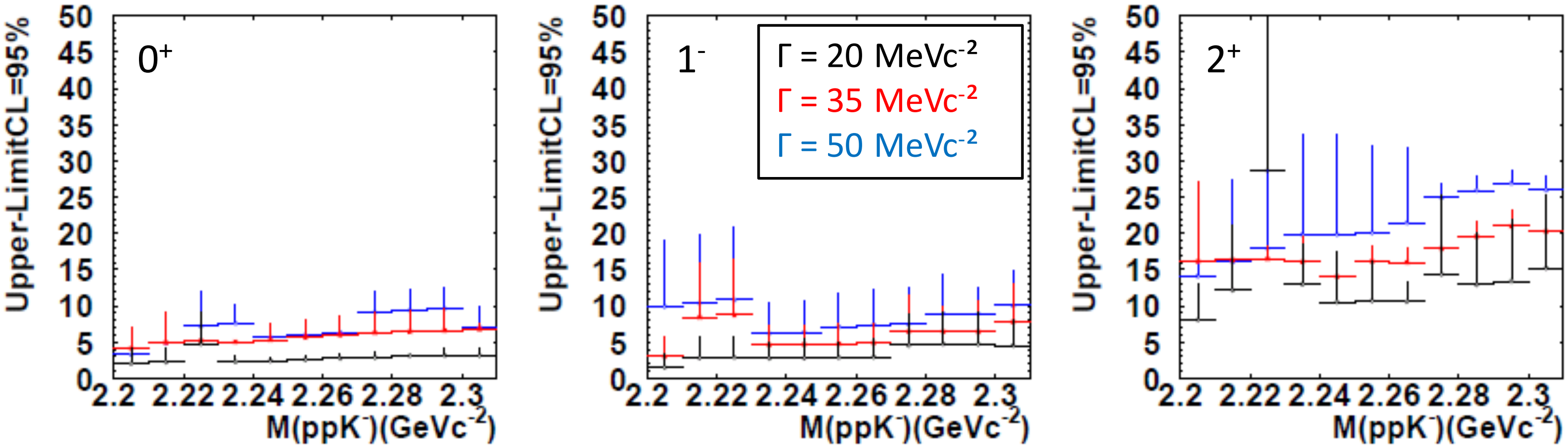
PWA Results


CMS Angle
G.-J.-Angle
Hel. - Angle
dN/dcosθ [events/0.07]
cos(Θ_CMS)(Λ)
cos(Θ_CMS)(p)
cos(Θ_CMS)(K+)
Experimental Data
Solution A
Solution B
Solution C
Solution D
Solution E

Four Best PWA Solutions



ppK⁻ Upper Limit Determination



p + p -> p + K⁺ + Λ
Total Cross Section

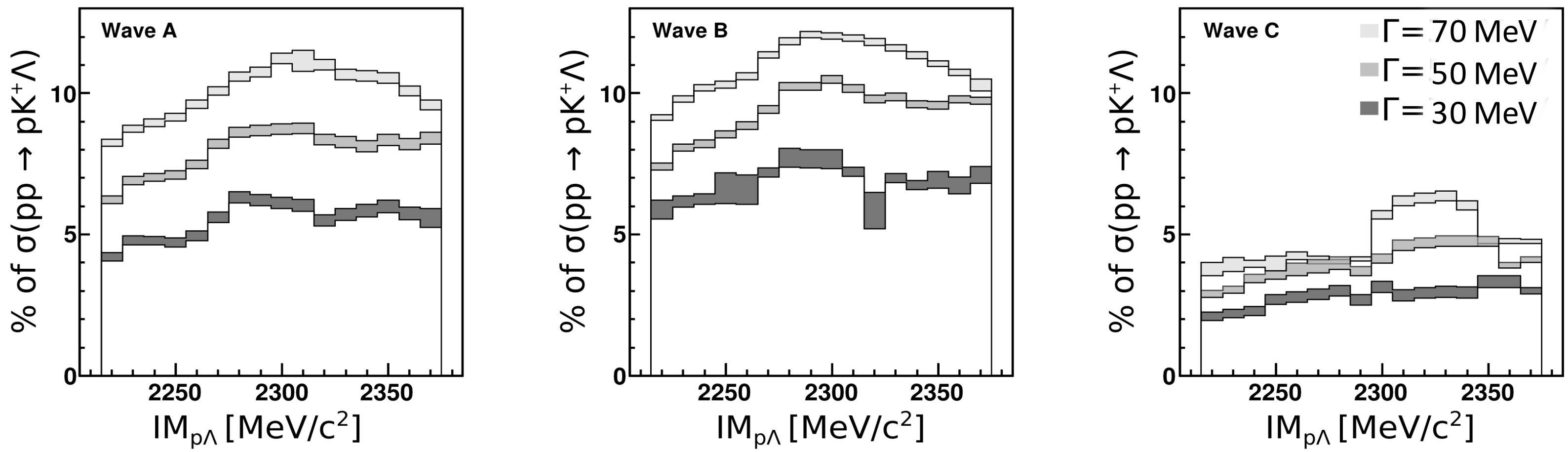
$$\sigma_{pK^+\Lambda} = 41.0 \pm 12.8 \mu b$$

Interpolated from literature

Upper Limit Cross Section

Γ (MeVc⁻²)	Cross Section (μb)
20	$7.6 \pm 1.2^{-3.5}$ - $22.4 \pm 3.6^{-10.7}$
35	$6.3 \pm 1.7^{-0.6}$ - $9.5 \pm 2.6^{-0.9}$
50	$10.2 \pm 1.8^{-4.5}$ - $11.6 \pm 3.4^{-0.6}$
60	$11.2 \pm 1.9^{-5.0}$ - $33.8 \pm 5.2^{-16.9}$
80	$11.4 \pm 2.7^{-3.8}$ - $35.9 \pm 5.7^{-17.4}$

Upper Limit



Measured total cross-section: $\sigma_{pK^{+}\Lambda} = 38.12 \pm 0.43^{+3.55}_{-2.83} \pm 2.67(p{+}p\text{-}error) - 2.9(background)\ \mu b$

Upper limit of ppK⁻ Cross Section:

Γ ($MeVc^{-2}$)	Cross Section (μb)
0^+	1.9 – 3.9
1^-	2.1 – 4.2
2^+	0.7 – 2.1

Production Cross Section Λ(1405)

$9.2 \pm 0.9 \pm 0.7\ ^{+3.3}_{-1.0}\ \mu b$

HADES coll. (G. Agakishiev et al.)
Phys. Lett. B742 (2015) 242-248.

Multi-PWA

Data Sets

Experiment	E_B [GeV]	$pK^+\Lambda$ Statistics	Status
COSY-TOF	1.96	~160k	In Preparation (not used in the analysis)
DISTO	2.15	121 k	Available
COSY-TOF	2.16	43 k	Available
COSY-TOF	2.16	~90k	In Preparation (not used in the analysis)
DISTO	2.5	304 k	Available
DISTO	2.85	424 k	Available
FOPI	3.1	0.9 k	Single PWA
HADES	3.5	21 k	Single PWA

COSY-TOF Spectrometer

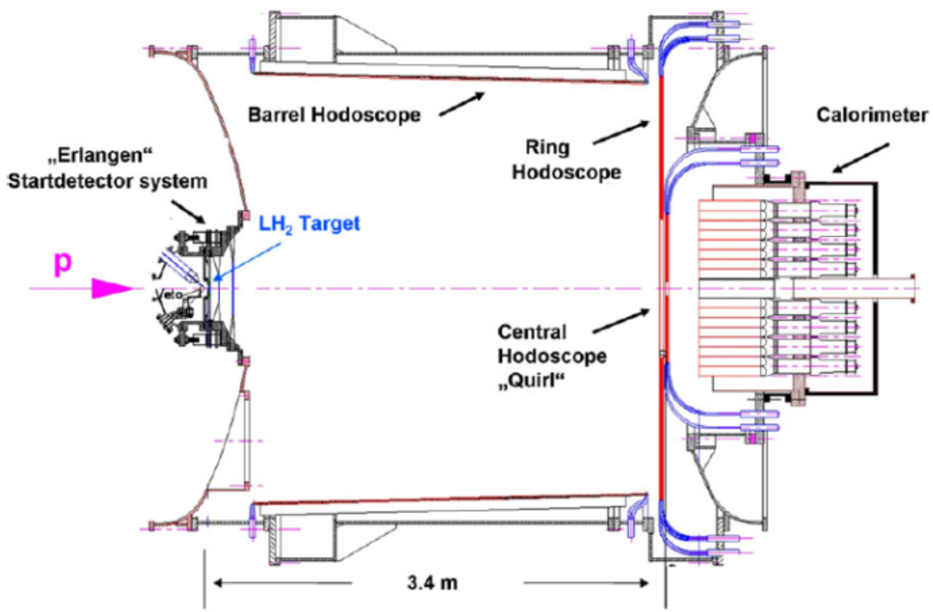
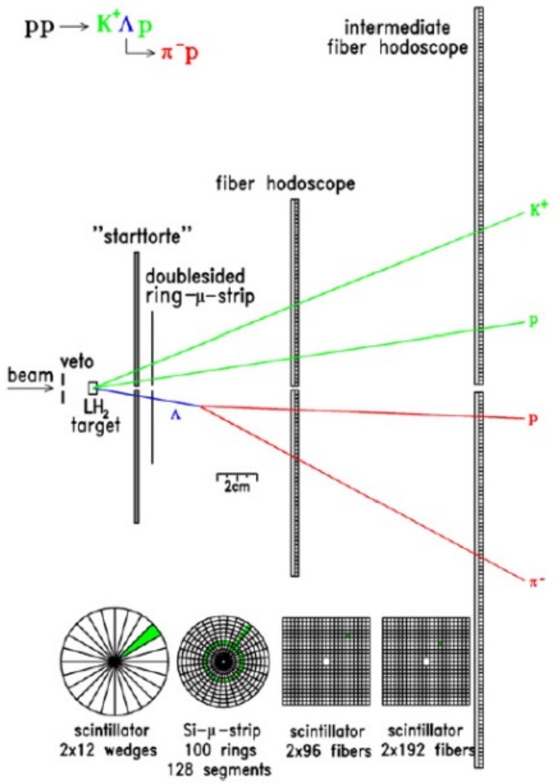


Fig. 1. Schematic view of the COSY-TOF detector.



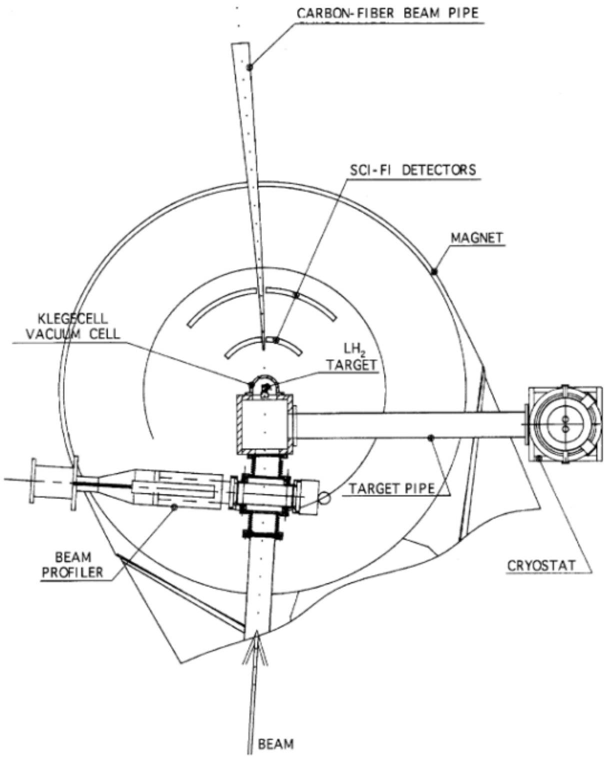
Acceptance: 1°-60° (polar), 2π (azimuthal)

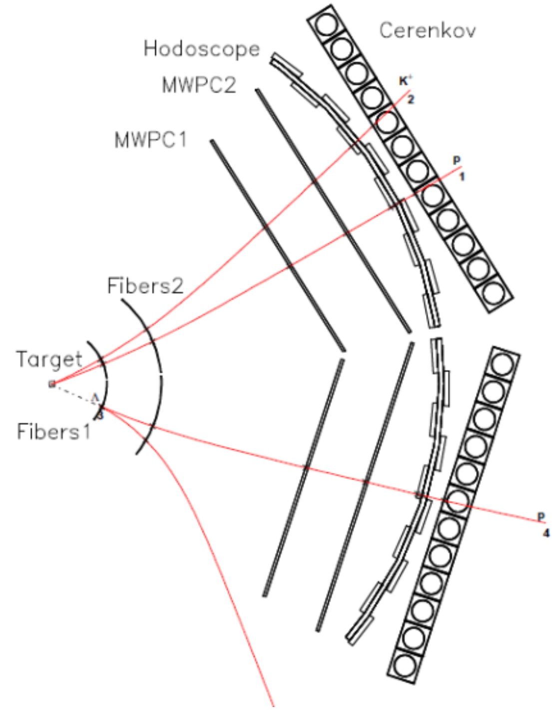
Sec. Vertex: $\sigma_{x,y} < 1mm, \sigma_z < 3mm$

$$\sigma_{TOF} = 300ps$$

$$\sigma_{MM(pK)} = 16\ MeV/c^2$$

DISTO Spectrometer





Acceptance: 23°-43° (polar), 2π (azimuthal)

$$\sigma_p = 5\%$$

$$\sigma_{MM(pK)} = 30\ MeV/c^2$$

Combined Analysis

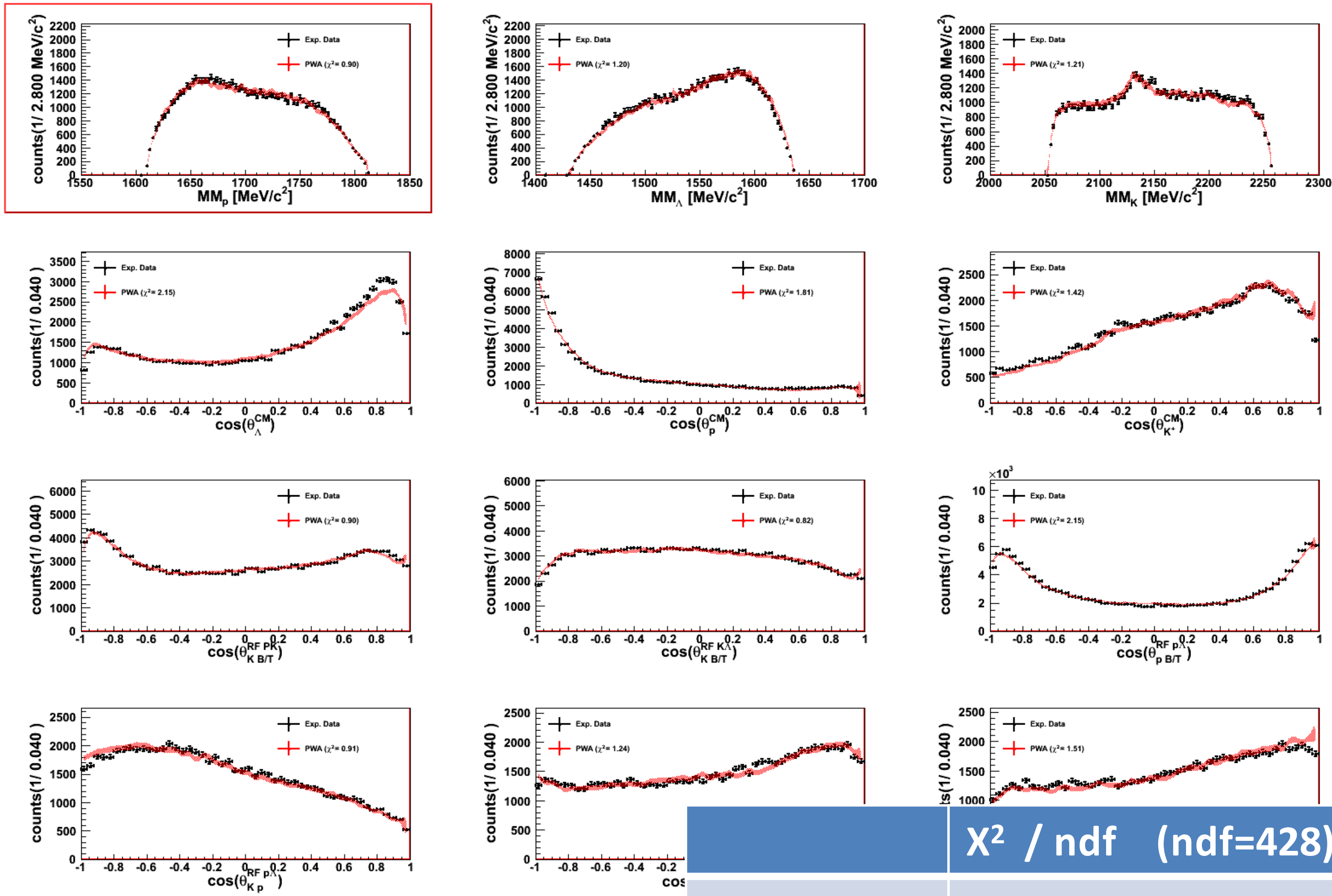
1. Solution for HADES+FOPI+DISTO25
   - Energy Range wide enough for energy dependence
   - High energy for higher N*-Resonances
   - Three datapoint to pin down set
   - Easier to make manual changes in parameter set
2. Include Stepwise further data sample
   1. Cosy216 / DISTO21 / DISTO28
   - Inclusion do not require further manual modification of data parameter set.

Parameter Scan

$pK\Lambda$ non resonant up to F wave *
Include different N* Resonances

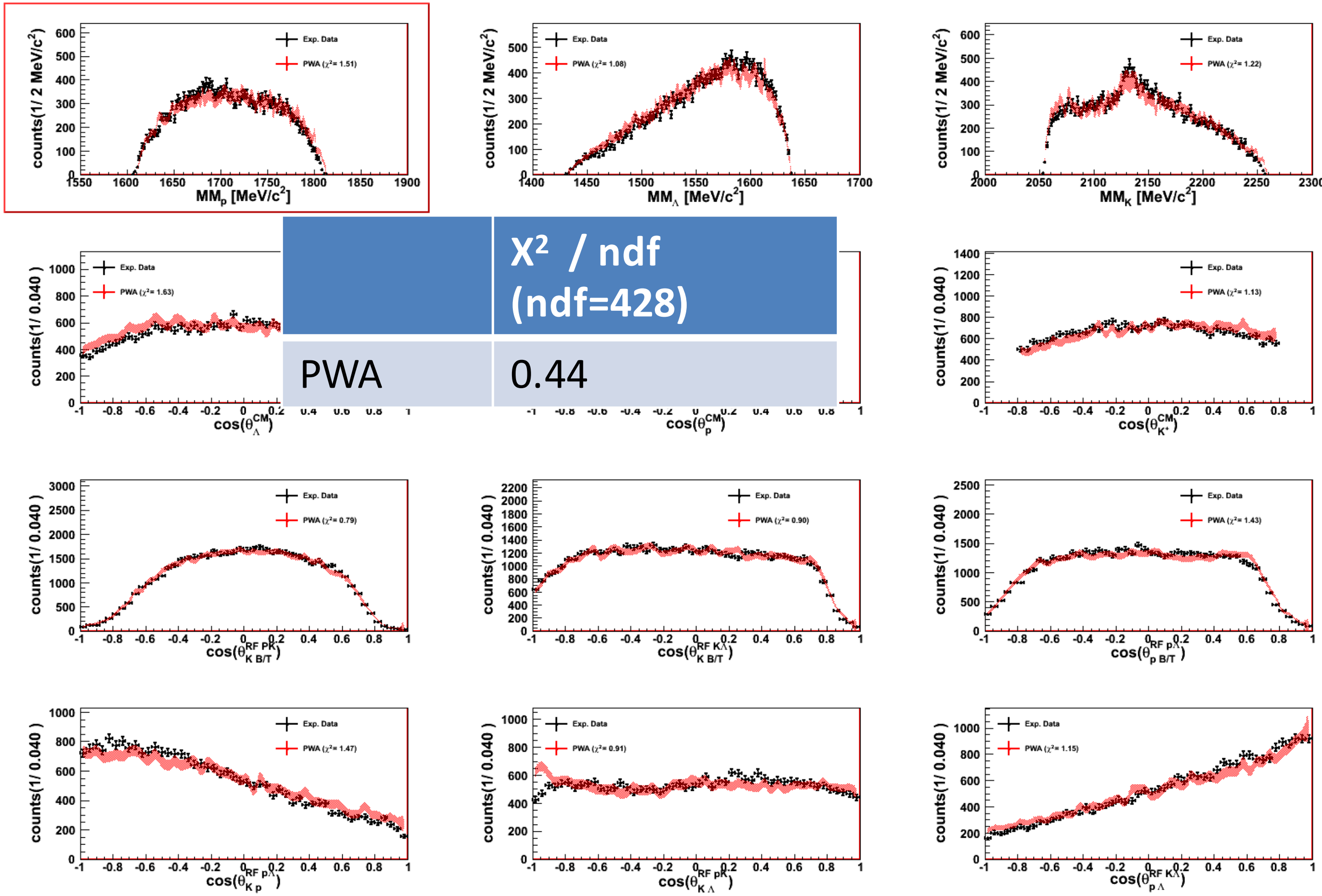
Solution	**A**	**B**	**C**	**D**	**E**
Loglike	-67142	-67018	-66878	-66504	-66405
$\frac{\chi^2}{ndf}(ndf = 4547)$	9,50	9,98	9,98	10,01	10,34
N*(1650)	+	+	+	+	+
N*(1710)	+	+	+	+	+
N*(1720)	+	+	+	+	-
N*(1875)	+	+	-	-	+
N*(1880)	+	+	+	+	+
N*(1895)	+	+	+	+	+
N*(1900)	-	+	+	-	+
$\Sigma N\ (0^+)$	+	+	+	+	+

DISTO@2.14 GeV



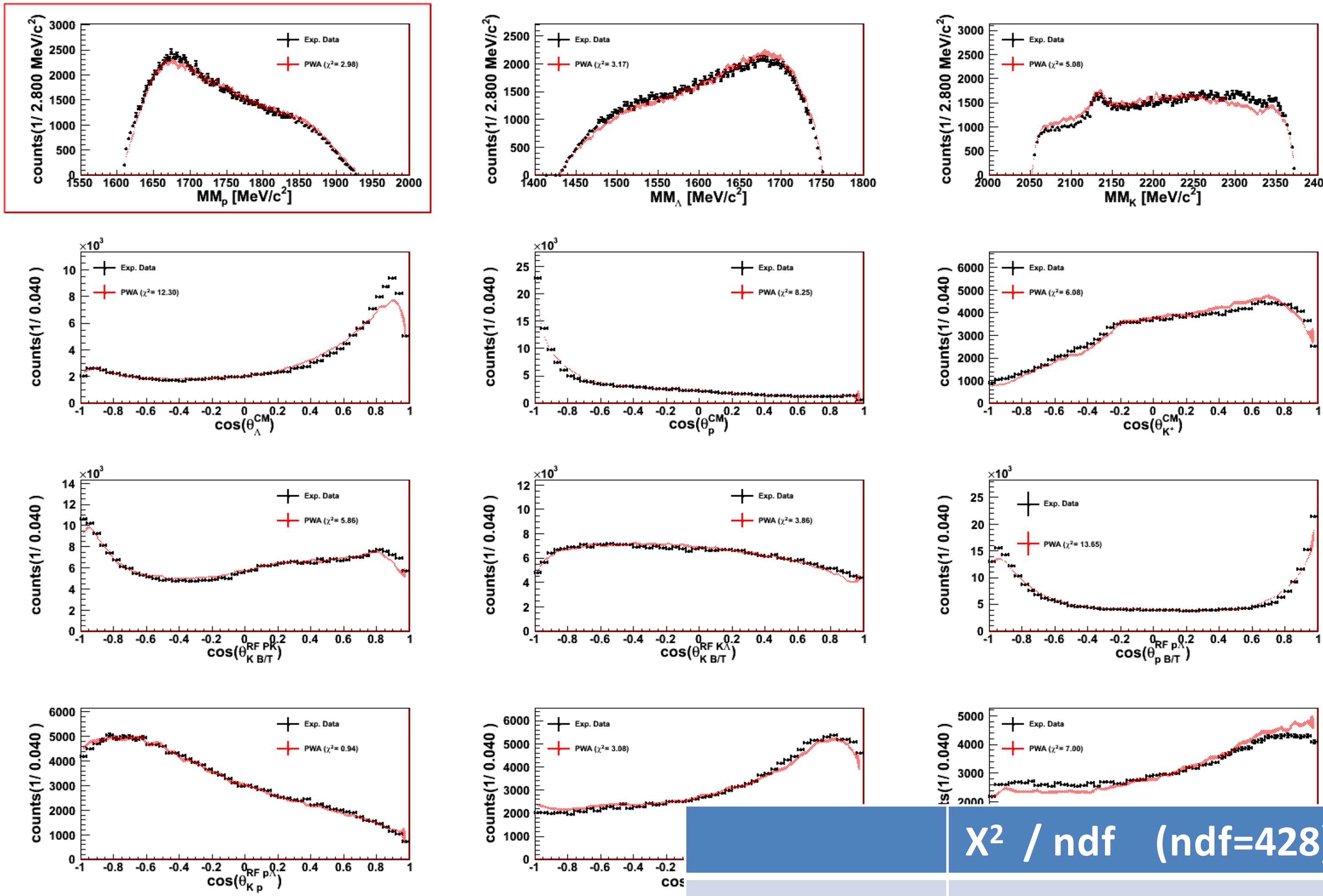
	X^2 / ndf (ndf=428)
PWA	1.52

COSY-TOF@2.16 GeV



	X^2 / ndf (ndf=428)
PWA	0.44

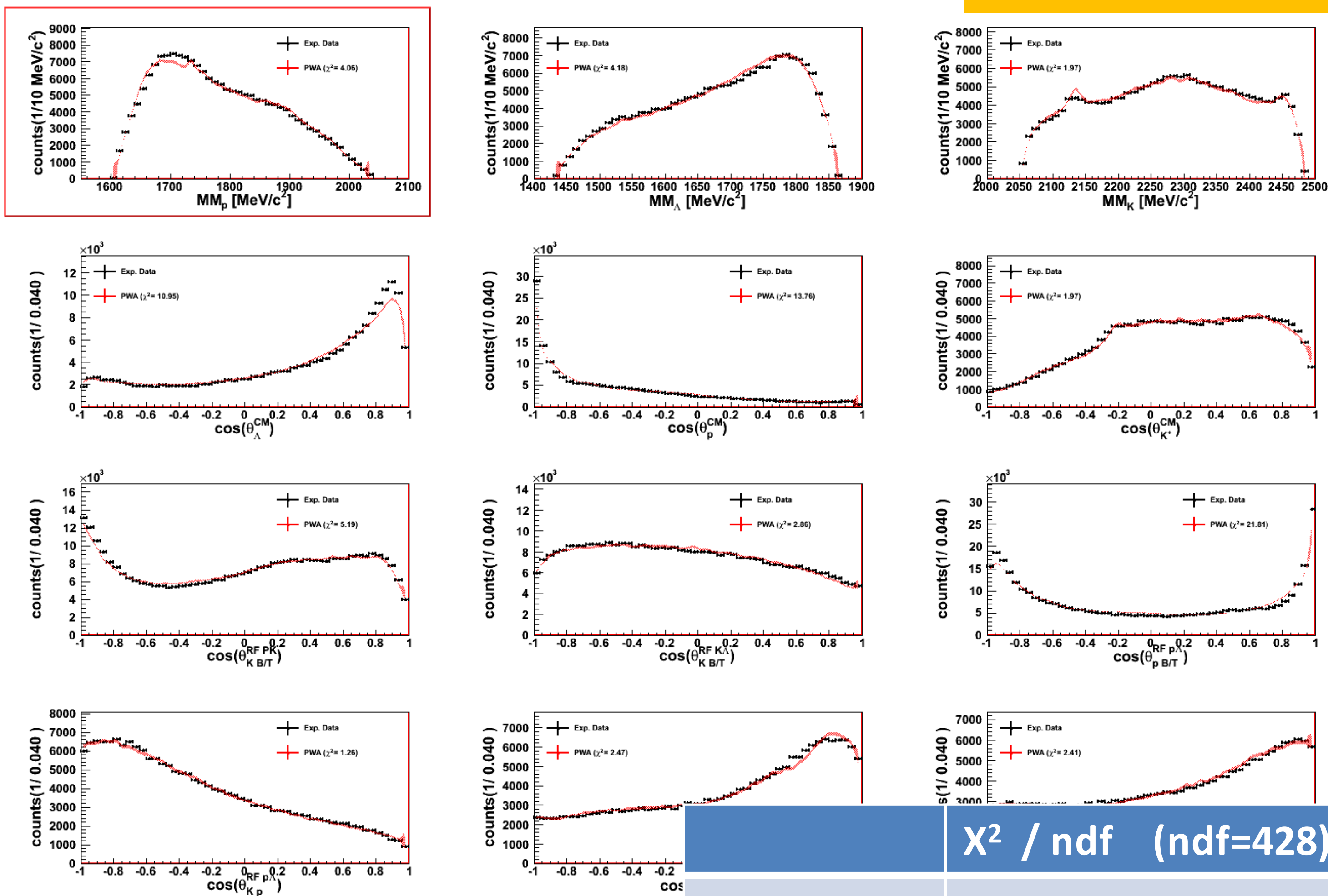
DISTO@2.5 GeV



	χ^2 / ndf (ndf=428)
PWA	2.56

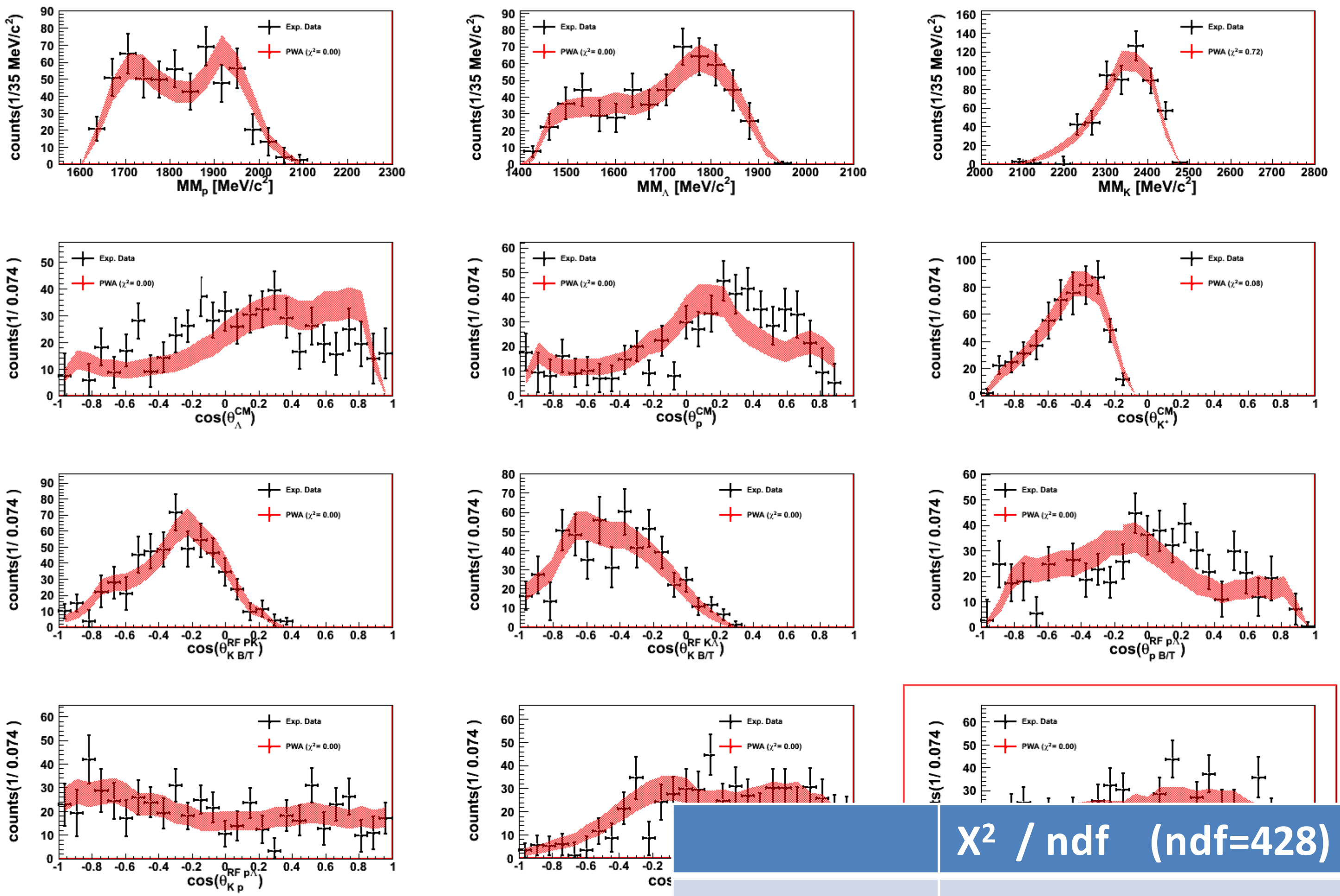
DISTO@2.85 GeV

No Kaonic Cluster included



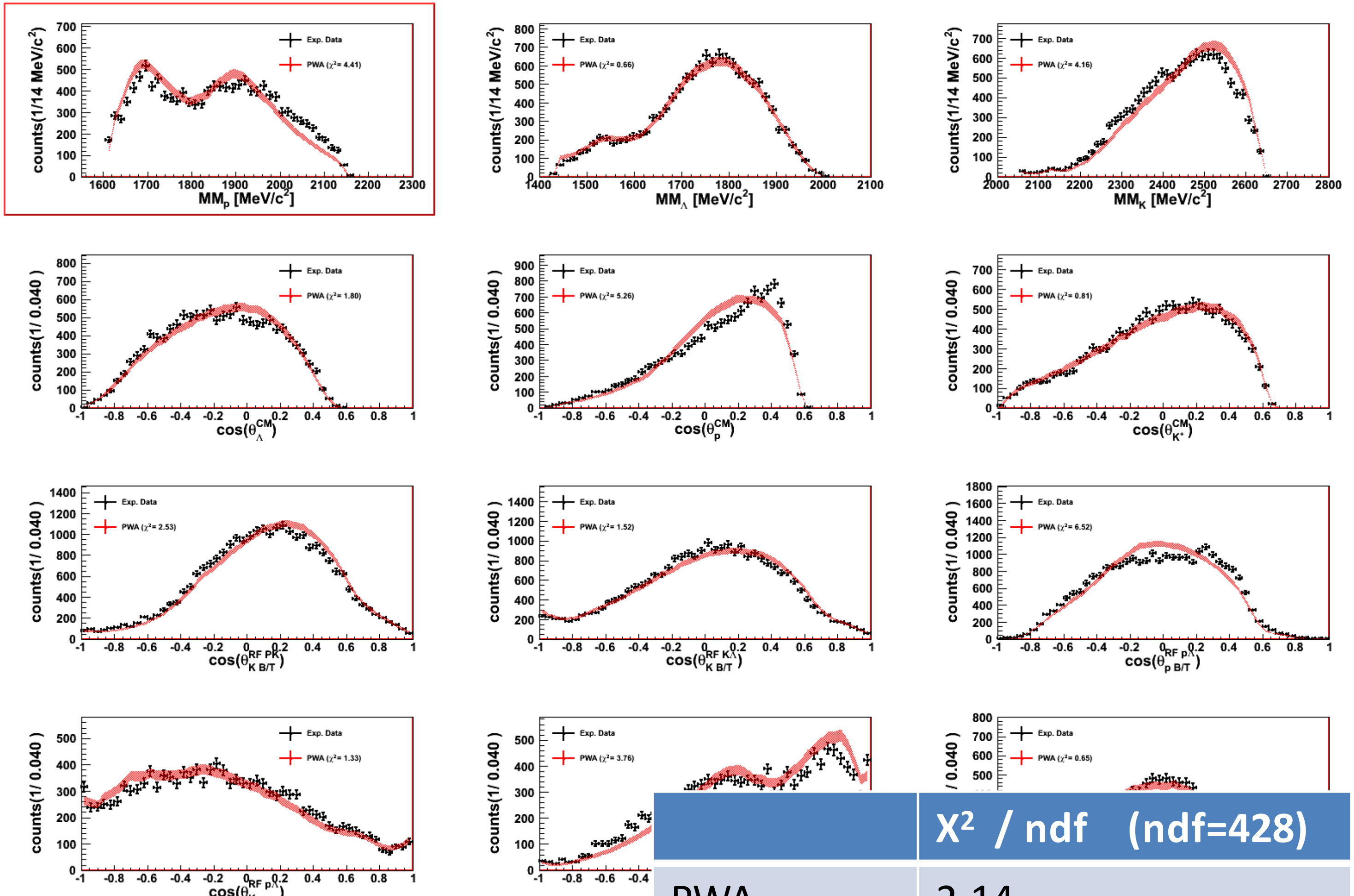
	X^2 / ndf (ndf=428)
PWA	3.55

FOPI



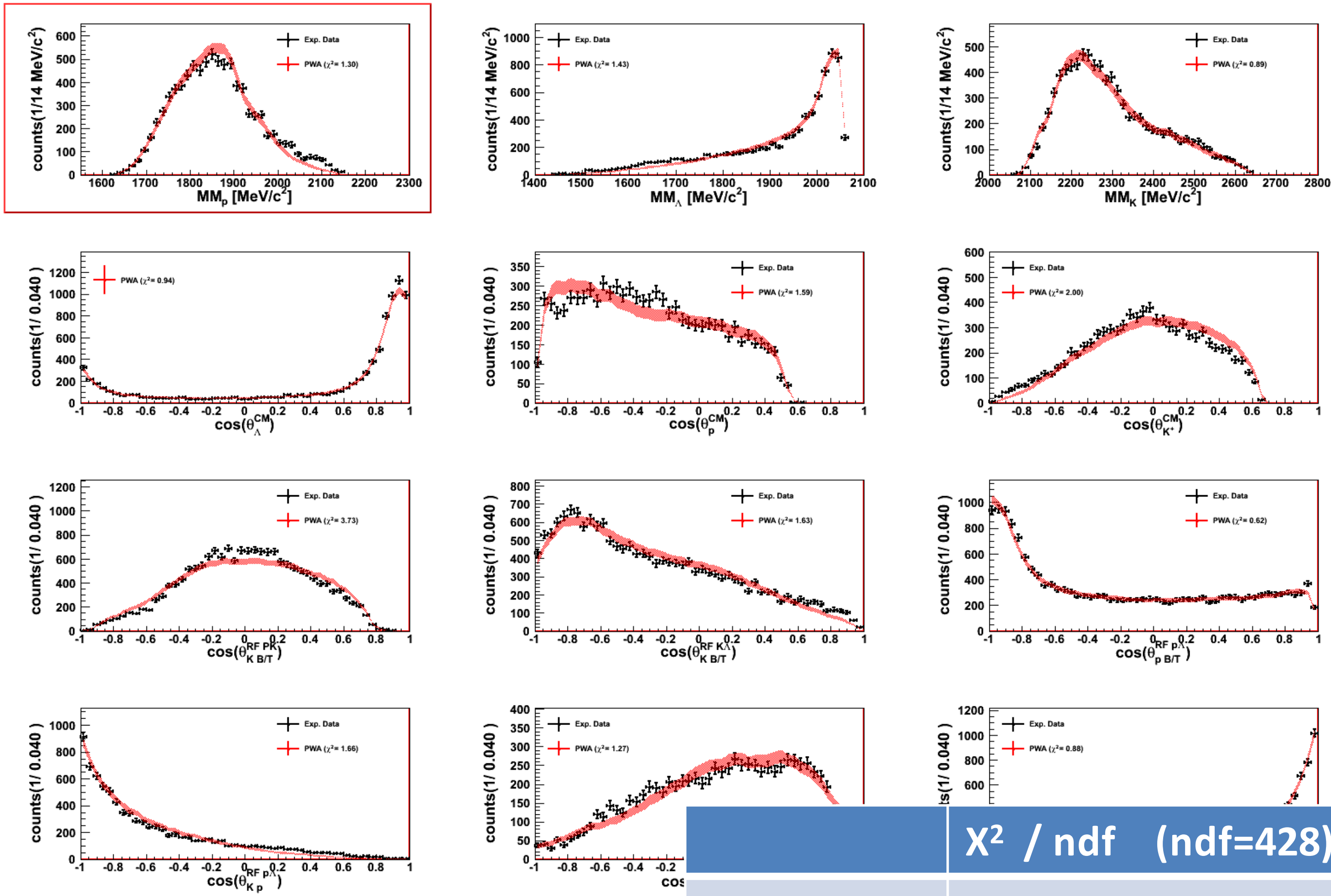
	X^2 / ndf (ndf=428)
PWA	0.91

HADES



	X^2 / ndf (ndf=428)
PWA	2.14

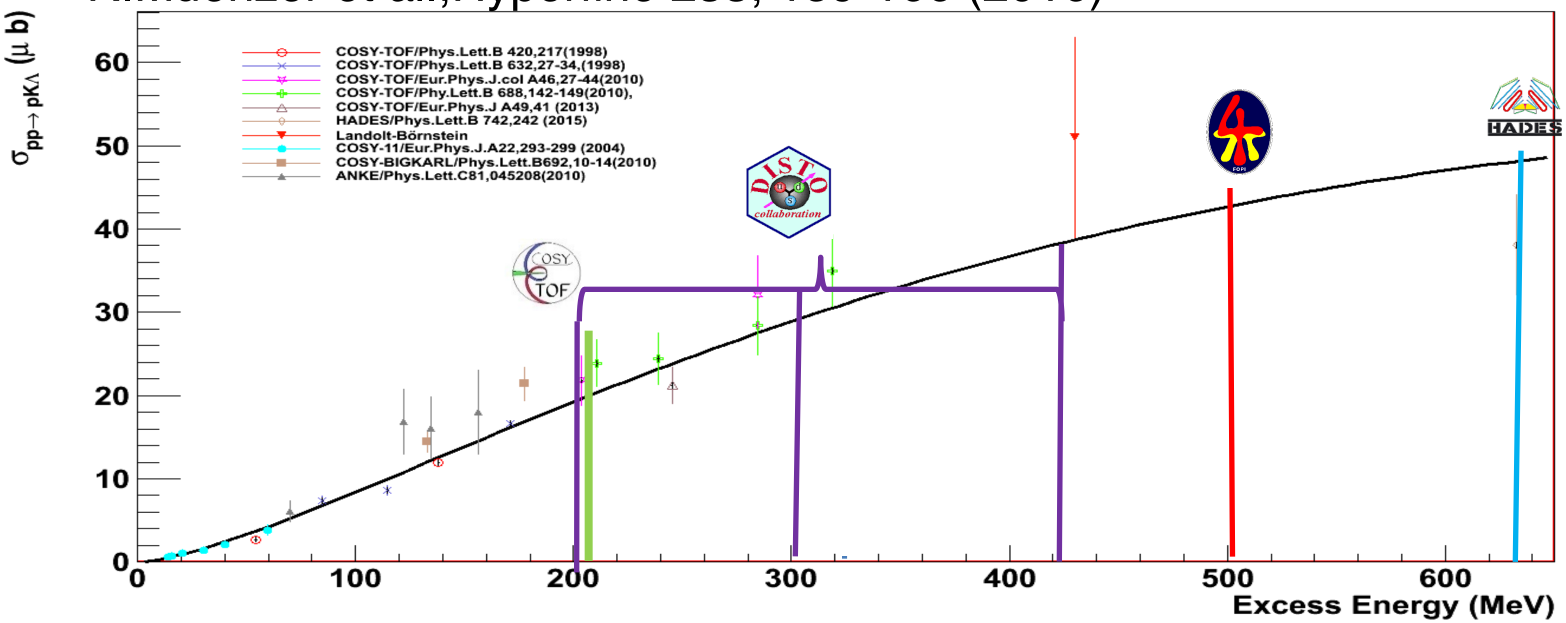
HADES - WALL



	X^2 / ndf (ndf=428)
PWA	1.86

Total Cross Section

R.Muenzer et al.,Hyperfine 233, 159-166 (2016)



$$\sigma_{pK\Lambda} = C_1\left(1 - \frac{s_0}{\left(\sqrt{s_0}+\epsilon\right)^2}\right)^{C_2}\left(\frac{s_0}{\left(\sqrt{s_0}+\epsilon\right)^2}\right)^{C_3}$$

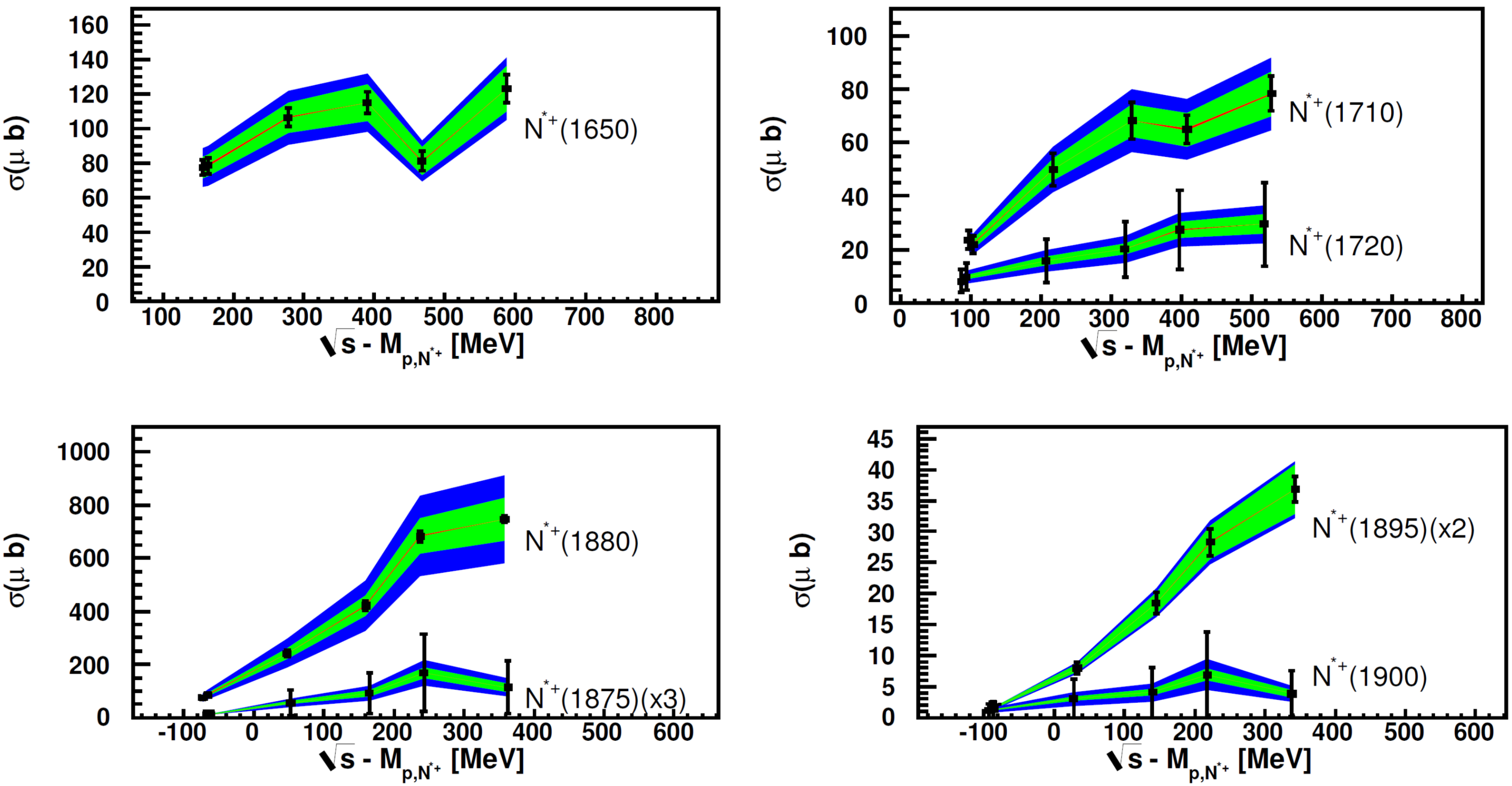
Value:

$$C_1 = 4.03 \pm 0.57\ 10^2$$
$$C_2 = 1.49 \pm 0.04$$
$$C_3 = 1.43 \pm 0.39$$

Branching Ratio

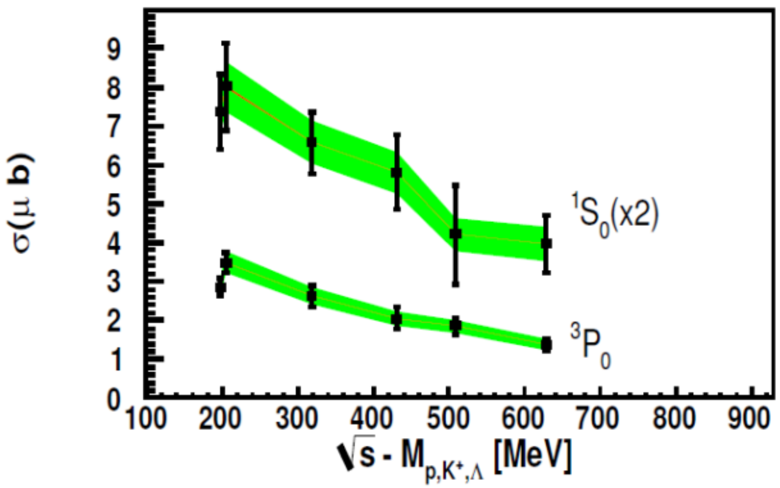
	Mass [GeV/c^2]	Width [GeV/c^2]	$\Gamma_{\Lambda K}/\Gamma_{All}$ %
N(1650)S_{11}	1.655	0.150	3-11
N(1710)P_{11}	1.710	0.200	5-25
N(1720)D_{13}	1.720	0.250	1-15
N(1875)D_{13}	1.875	0.220	4±2
N(1880)P_{11}	1.870	0.235	2±1
N(1895)S_{11}	1.895	0.090	18±5
N(1900)P_{13}	1.900	0.250	0-10

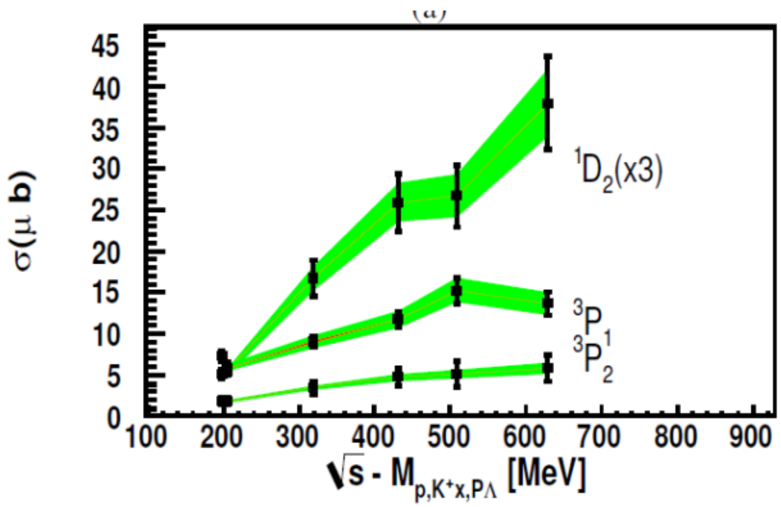
Cross Section

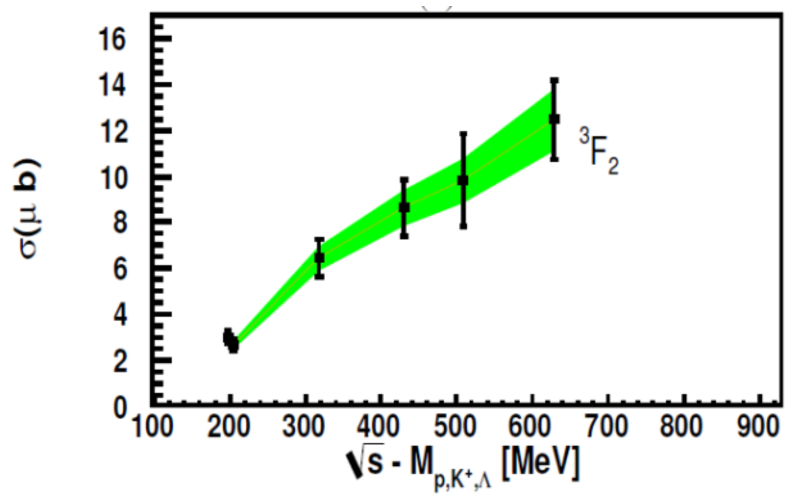


Non Resonant-Resonant: 20-80

Initial State







Final State Interaction in PWA

$$A_{2b}^{\beta} = \frac{\sqrt{s_i}}{1+\frac{1}{2} r^{\beta} q^2 a_{p\Lambda}^{\beta} + iq a_{p\Lambda}^{\beta} q^{2L}/F(q, r^{\beta}, L)}$$

$a_{p\Lambda}^{\beta}$ Scattering Length

r^{β} Effective Range of System

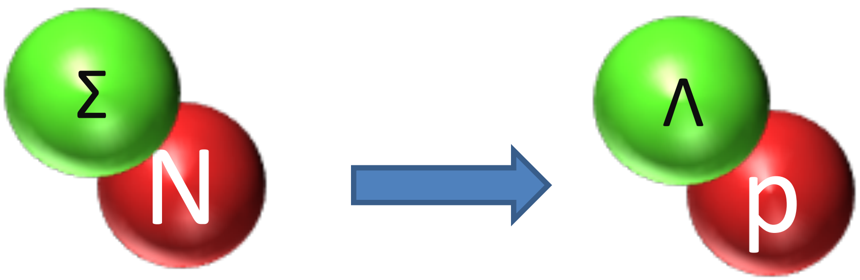
$$\alpha_s = -1.43 \pm 0.36 \pm 0{,}09\, fm \qquad \alpha_t = -1{,}88 \pm 0{,}38 \pm 0.10 fm$$
$$r_s = 1.31 \pm 0.24 \pm 0{,}16\, fm \qquad r_t = 1.04 \pm 0.78 \pm 0.15 fm$$

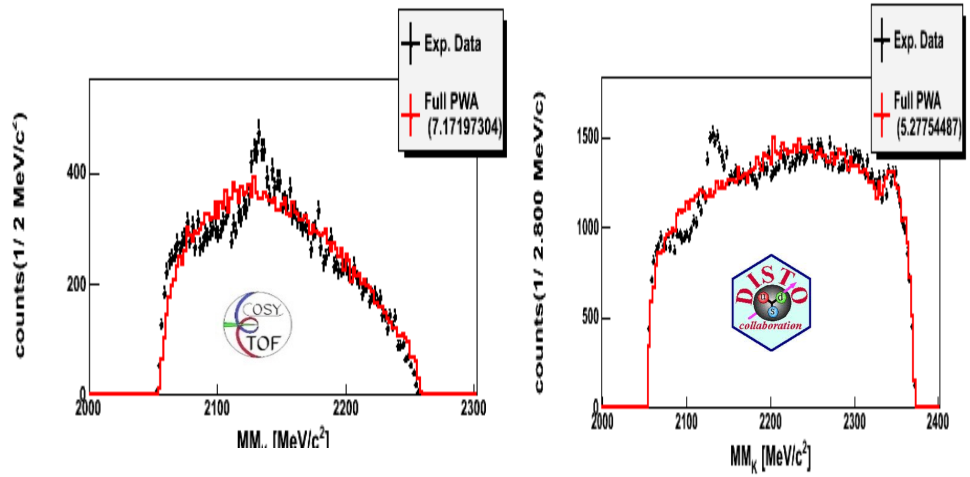
Source	${}^1S_0\ a_{\Lambda-p}$ [fm]	${}^1S_0\ r_{\Lambda-p}$ [fm]	${}^3S_1\ a_{\Lambda-p}$ [fm]	${}^3S_1\ r_{\Lambda-p}$ [fm]	$< a_{\Lambda-p} >$ [fm]
This work	$-1.43 \pm 0.36 \pm 0.09$	$1.31 \pm 0.24 \pm 0.16$	$1.88 \pm 0.38 \pm 0.10$	$1.04 \pm 0.78 \pm 0.15$	
NLO[2] [15]	-2.91	2.78	-1.54	2.72	-1.88[3]
LO[2] [15]	-1.91	1.40	-1.23	2.13	-1.4[3]
[16]	$-1.8^{+2.3}_{-4.2}$	-	$-1.6^{+1.1}_{-0.8}$	-	-
[17]	-	-	-	-	$-1.25 \pm 0.08 \pm 0.03$
[18]	-	-	$-1.31^{0.32}_{-0.49} \pm 0.3 \pm 0.16$	-	$-1.233 \pm 0.014 \pm 0.3 \pm 0.12$

[15] Haidenbauer et al.Nuclear Physics A,915,24-58 (2013)
[16] G. Alexander et a., Phys. Rev. 173,1452 (1968).
[17] M.Roeder et al., Eur. Phys. J. A49, 157 (2013)
[18] Hauenstein 2014

The ΣN Cusp Effect

Coupled Channel:





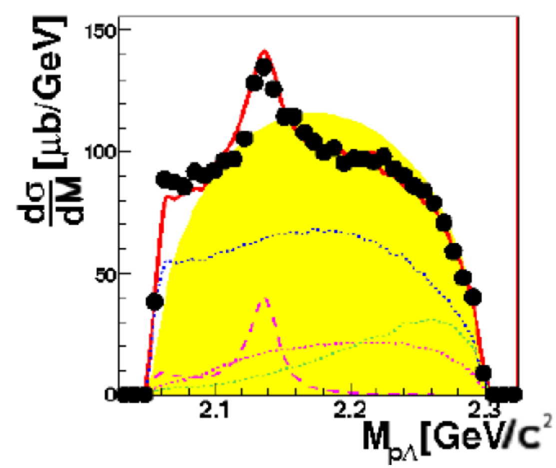
At Threshold : 2130 $MeVc^{-2}$

Quantum Number of Cusp: 0^+ / 1^+ (L=0,2)

Spectral Function:

Breit Wigner

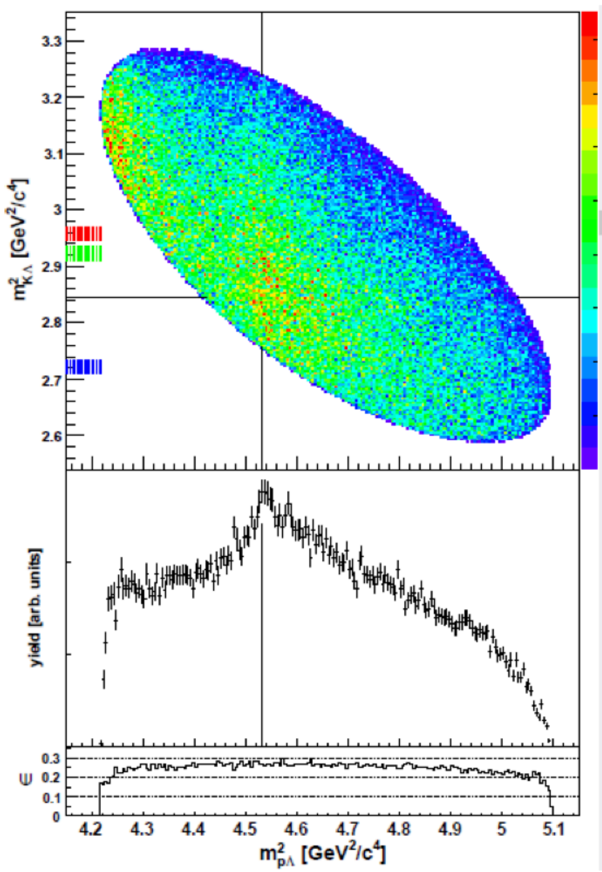
Flatté



S.Abd El-Samad, Eur.Phys.J A49(2013)

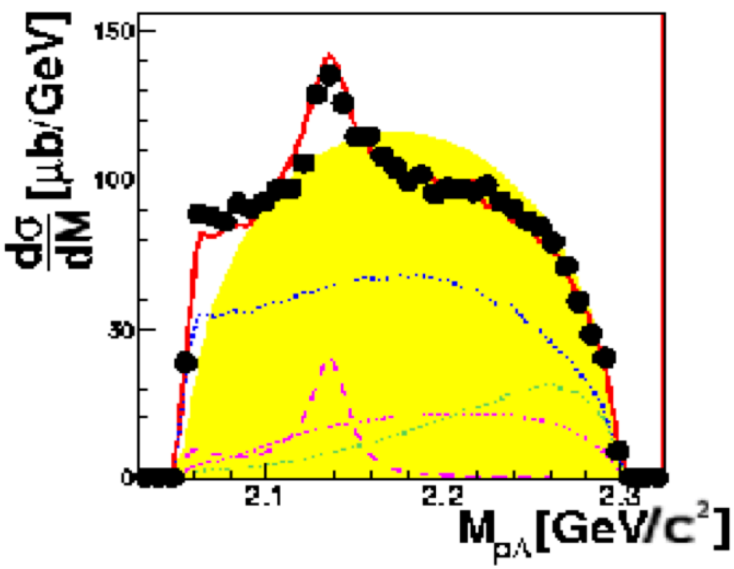
Previous Observations

- Experimental Observation:



- Cosy-TOF Analysis:

S.Abd El-Samad, Eur.Phys.J A49(2013)



Solid line: Full MC simulation

Shaded areas: phase-space distributions

Cusp Spectral Function

The Breit-Wigner:

$$\frac{d\sigma_{p\Lambda}}{dm_{p\Lambda}} \approx \frac{1}{\left|m_R^2 - m_{p\Lambda}^2 - i\, m_{p\Lambda}\Gamma\right|^2}$$

$Mass\ M_{cusp} = 2.13\text{GeV}$, $With\ \Gamma = 0.02\text{GeV}$

$g_{p\Sigma} \ll g_{p\Lambda}$ *Symmetric*

$g_{p\Sigma} \gg g_{p\Lambda}$ *Antisymmetric*

The Flatté parametrization:

$$\frac{d\sigma_{p\Lambda}}{dm_{p\Lambda}} \approx \frac{\Gamma_{p\Lambda}}{\left|m_R^2 - m_{p\Lambda}^2 - i\, m_{p\Lambda}(\Gamma_{p\Lambda} + \Gamma_{p\Sigma})\right|^2}$$

$\Gamma_{p\Lambda} = g_{p\Lambda} * q_{p\Lambda}$ $\qquad \Gamma_{p\Sigma} = g_{p\Sigma} * q_{p\Sigma}$

Above the threshold

$$q_{p\Sigma} = \frac{\sqrt{(m_{p\Sigma}^2 - (m_\Sigma + m_p)^2) * (m_{p\Sigma}^2 - (m_p - m_\Sigma)^2)}}{2\, m_{p\Sigma}}$$

Below the threshold

$$q_{p\Sigma} = i * \frac{\sqrt{((m_\Sigma + m_p)^2 - m_{p\Sigma}^2) * (m_{p\Sigma}^2 - (m_p - m_\Sigma)^2)}}{2\, m_{p\Sigma}}$$

Data Set

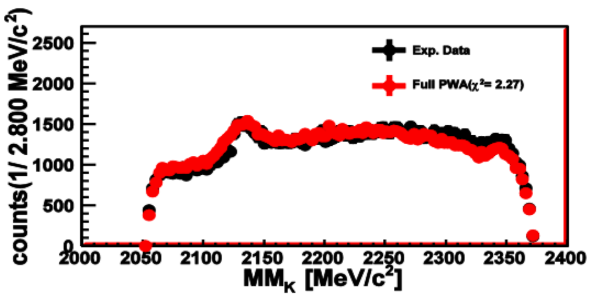
- Combined data analysis

Experiment	E_{beam}(GeV)	Sqrt(S)(GeV)	Statistics	Polar.
DISTO[12][13]	2.14	2.75	76982	Y
DISTO[12][13]	2.5	2.85	80000	Y
DISTO[11][12][13]	2.85	2.98	182597	Y
COSY-TOF[14]	2.16	2.75	43662	Y

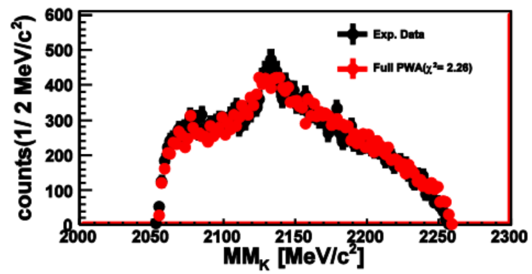
- The data samples are fitted parallel in BG-Framework.
- The parameters are optimized to explained all data samples
- The parallel fitting assure, that different detector acceptance and efficiency for different spectrometers and beam energies are not mixed.

Results

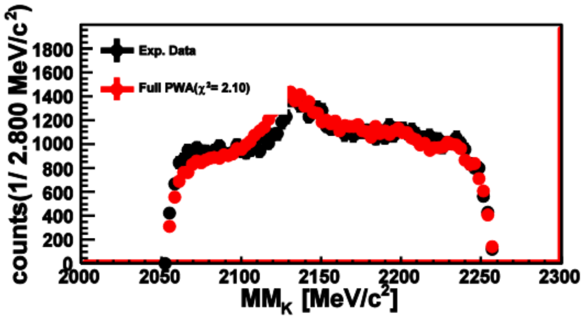
- DISTO 2.5GEV



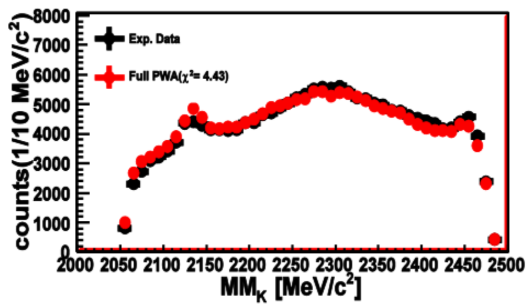
- COSY-TOF 2.16GEV



- DISTO 2.14GEV



- DISTO 2.85GEV



- **Final coupling constants:** $g_{N\Sigma}$=1.55±0.08x10^{-2} , $g_{p\Lambda}$ = 0.30±0.03x10^{-2}
- **Threhold mass value from the fit:** m_R=2.13±0.006 GeV/c^2

Summary and Outlook

- Combined Analysis for COSY & DISTO & HADES & FOPI completed
- Systematical Analysis performed
- Excitation Function for N* and pKL extracted
- Scattering Length p-Λ separate for Singlet and Triplet
- Cusp Wave included too (not discussed here)
- Common upper limit for Kaonic Bound states to come soon