Associated strangeness production and hyperon polarization

($pp \rightarrow pK\Lambda$)

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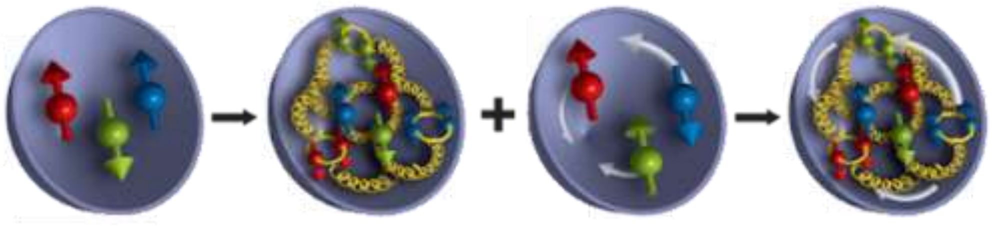
Spin in Particle Physics

1988 EMC experiment → "Spin crisis"

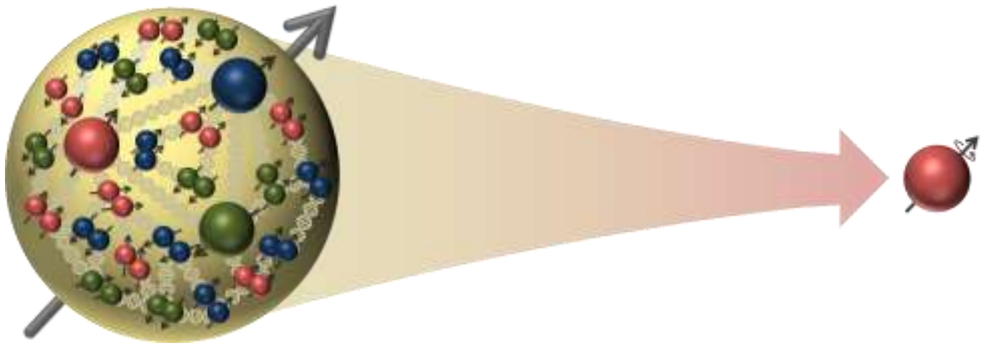


1970s 1980s/2000s Now

Spin decomposition:

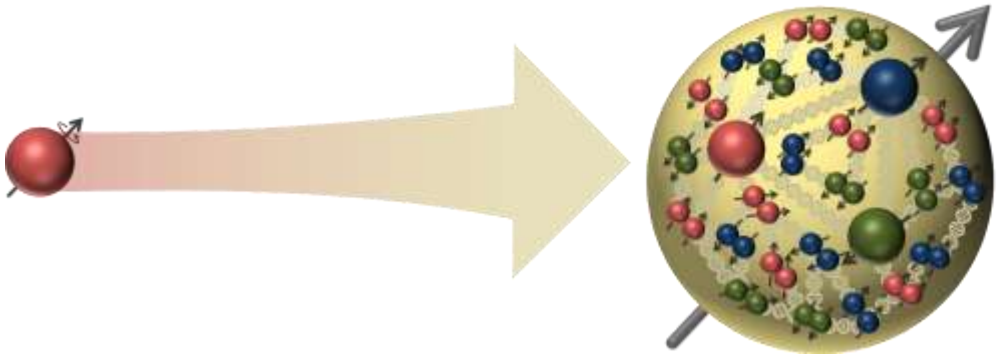
$$S_{tot} = \frac{1}{2} = \underbrace{\frac{1}{2}\Delta\boldsymbol{\Sigma}}_{\text{Quark spin}} + \underbrace{\Delta\boldsymbol{G}}_{\text{Gluon Spin}} + \underbrace{\boldsymbol{\mathcal{L}}_{q}}_{\text{Quark OAM}} + \underbrace{\boldsymbol{\mathcal{L}}_{g}}_{\text{Gluon OAM}}$$

Initial state



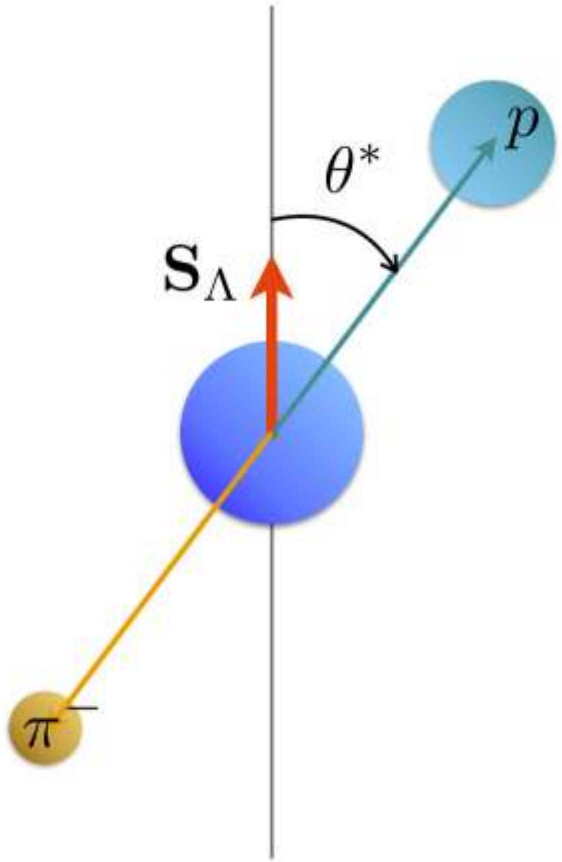
Nucleon

Hyperon



Final state

Spin in Particle Physics



Decay channel: $\Lambda \to p\pi^-$

branch ratio: $64.1 \pm 0.5\%$

parity violating weak decay

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} \propto \mathcal{A}\left(1 + \alpha_\Lambda P_\Lambda \cos\theta^*\right)$$

decay parameter: $\alpha_\Lambda = 0.748 \pm 0.007$

[Current PDG value]

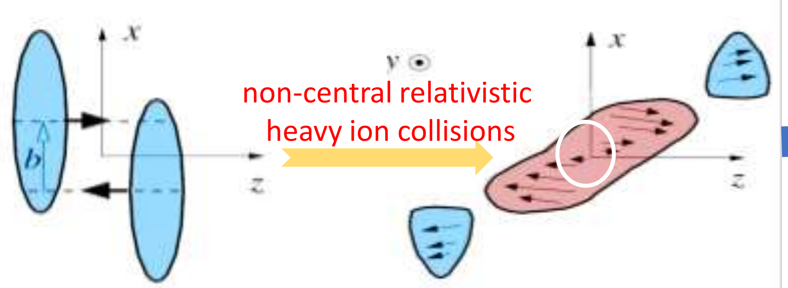
Allow to measure the spin (polarization) of the produced Λ

valence component: $|uds\rangle$

spin dominated by s quark

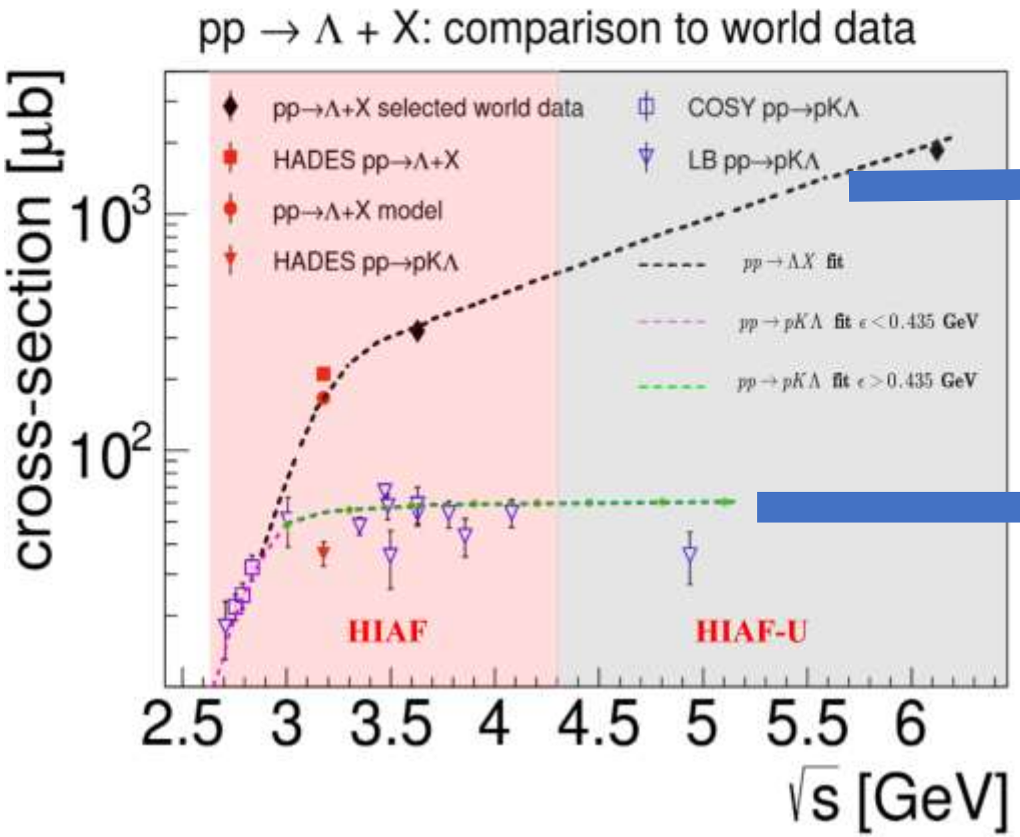
Sensitive to nucleon strange sea and its polarization

Lambda Physics at HIAF



① $AA \to \Lambda X$ **Global polarization**

Zuo-Tang Liang, Xin-Nian Wang, PRL 94,102301 (2005); PLB 629, 20 (2005).
Jian-Hua Gao, Shou-Wan Chen, Wei-tian Deng, Zuo-Tang Liang, Qun Wang, Xin-Nian Wang, PRC 77, 044902 (2008).



② $pp\,(A) \to \Lambda X$ **Λ "spontaneous" polarization puzzle**

Zuo-tang Liang, and C. Boros, Phys. Rev. Lett. 79, 3608 (1997); PRD 61, 117503 (2000).
H. Dong and Zuo-tang Liang, PRD 70, 014019 (2004); PRD 72, 033006 (2005).

③ $pp \to pK\,\Lambda$ **Λ polarization in exclusive processes**

Cross section

R. Machleidt, K. Holinde and C. Elster, Phys. Rept. 149, 1 (1987).
B. C. Liu, B. S. Zou, PRL 96, 042002 (2006).

Lambda Physics at HIAF

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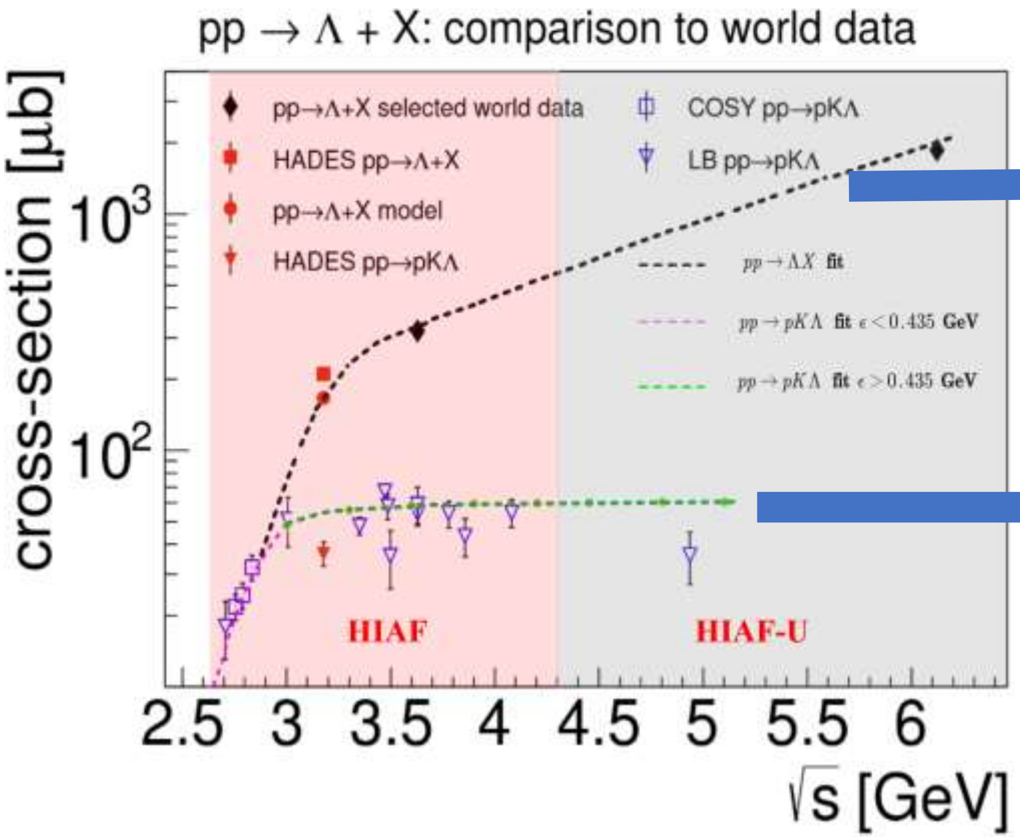

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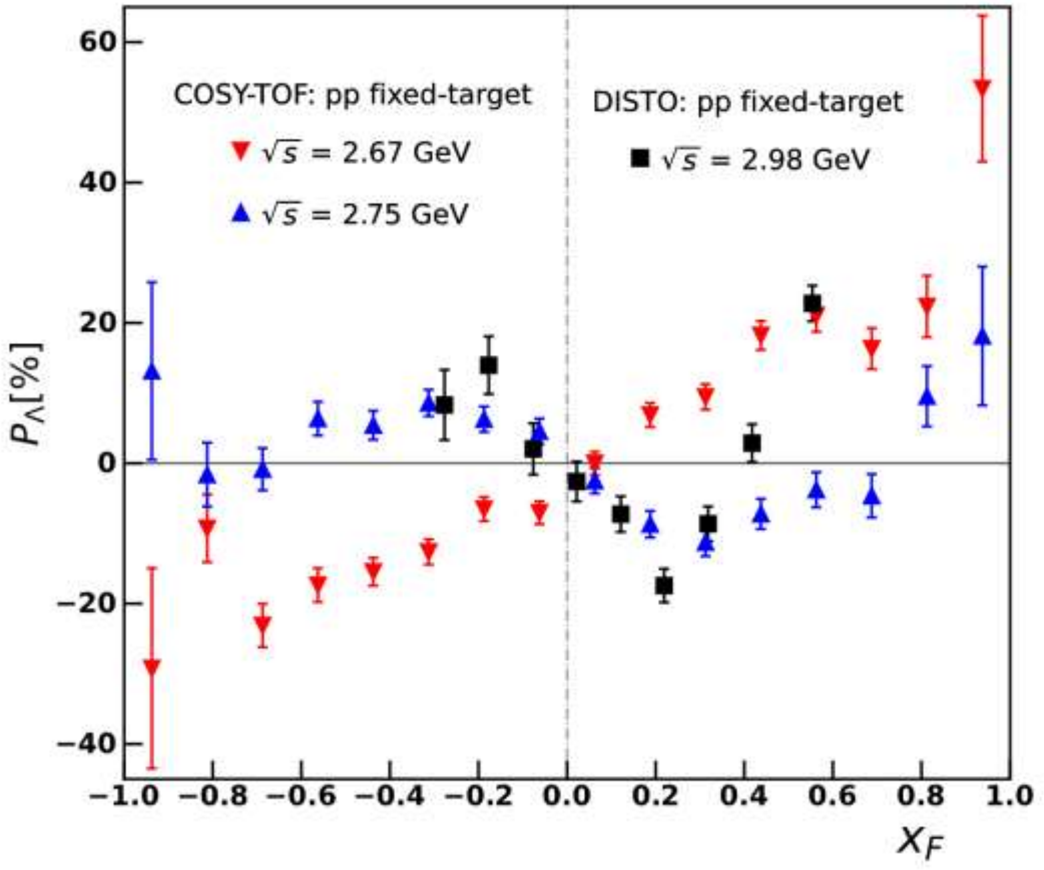
H. Dong and Zuo-tang Liang, PRD 70, 014019 (2004); PRD 72, 033006 (2005).

③ **H-NS white paper**

$pp \to pK\Lambda$ B. C. Liu, B. S. Zou, PRL 96, 042002 (2006).

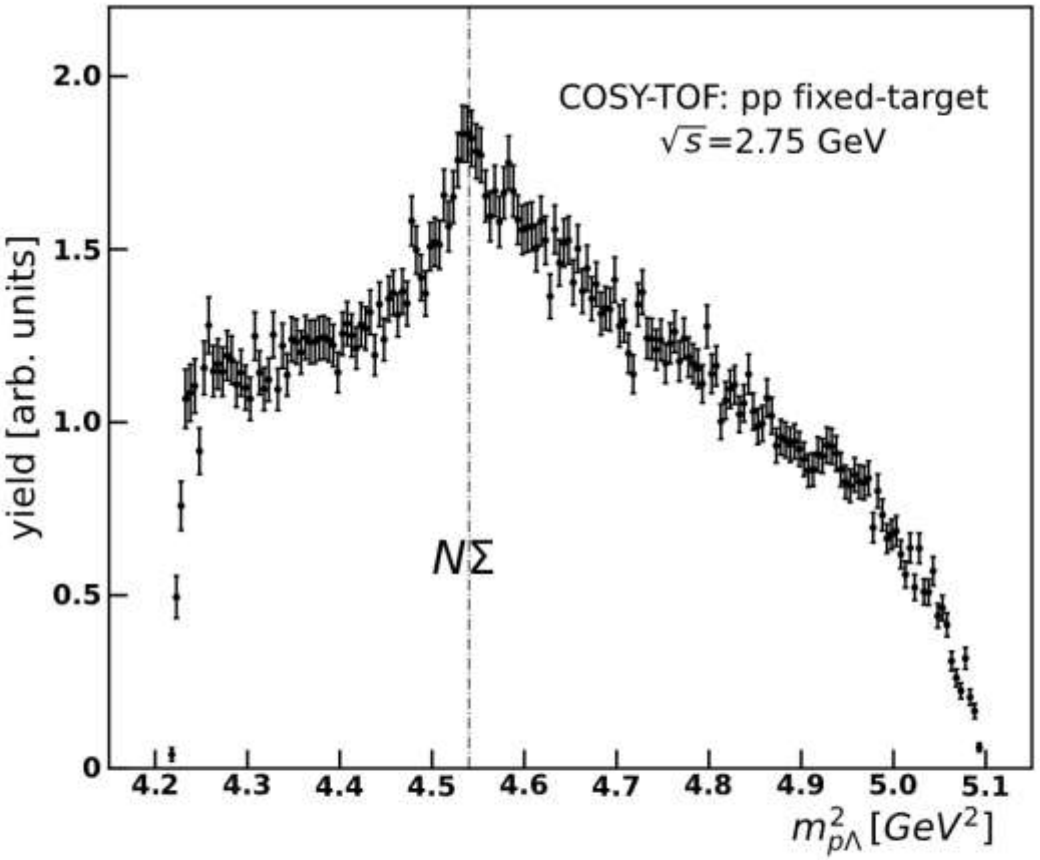
$pp \to pK\Lambda$ 过程的实验测量

Λ 极化



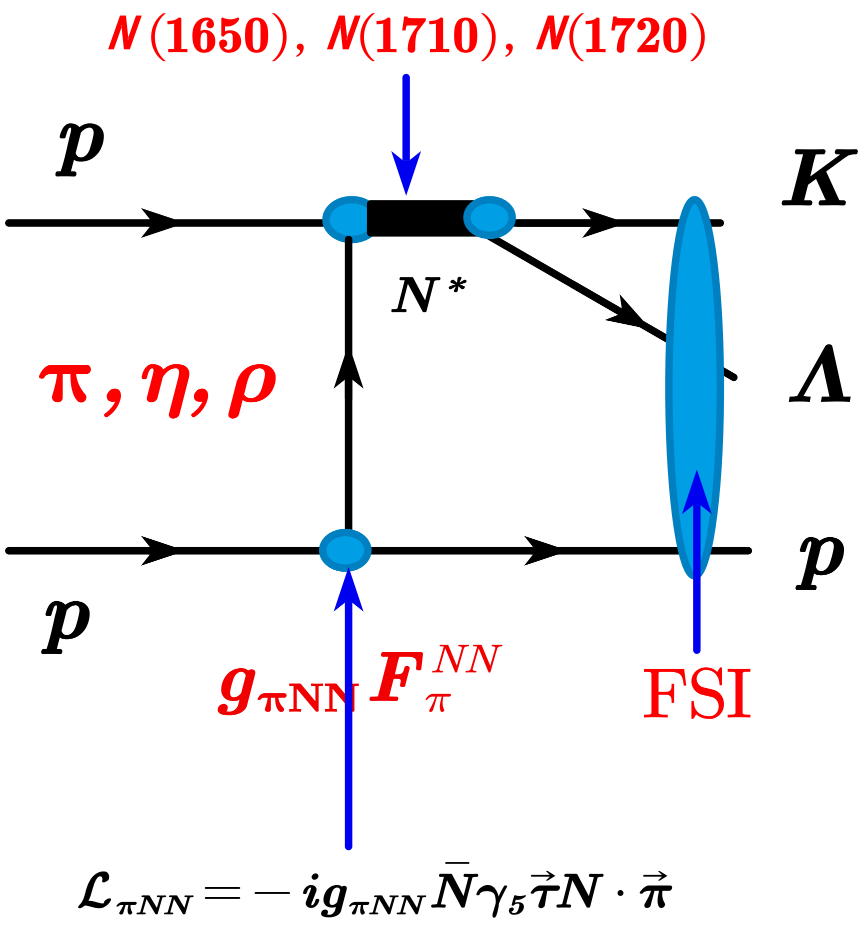
Λ 的极化有很强的能标依赖性！

产生截面随不变质量谱依赖



末态超子-核子之间存在很强的末态相互作用！

$pp \to pK\Lambda$ 过程的理论研究方案—介子交换模型



① **Exchanged meson**: π, η, ρ, ~~σ, ω~~

② **Resonance**: $N(1650)$, $N(1710)$, $N(1720)$,

~~$N(1675)$, $N(1895)$~~

③ **Coupling constants:** $g_{\pi NN}$, $g_{\pi \mathrm{NN}^*}$, $g_{N^*\Lambda\mathrm{K}}$

④ **Form factor:** F_π^{NN}, $F_\pi^{NN^*}$ 压低高动量转移贡献

⑤ **Off-shell form factors**: F_{N^*} 压低高离壳贡献

⑥ **Final State Interaction**: FSI

R. Machleidt, K. Holinde and C. Elster, Phys. Rept. 149, 1 (1987).
B. C. Liu, B. S. Zou, PRL 96, 042002 (2006).
Z. Ouyang, J. J. Xie, B. S. Zou, and H. S. Xu, Int. J. Mod. Phys. E 18, 281 (2009).

$pp \to pK\Lambda$ 过程的理论研究方案—N1535贡献

$N1535$ 衰变分支比

$N1535 \to N\pi$: (32-52)%

$N1535 \to N\eta$: (30-55)%

$N1535$ 传播子：Flatte-type

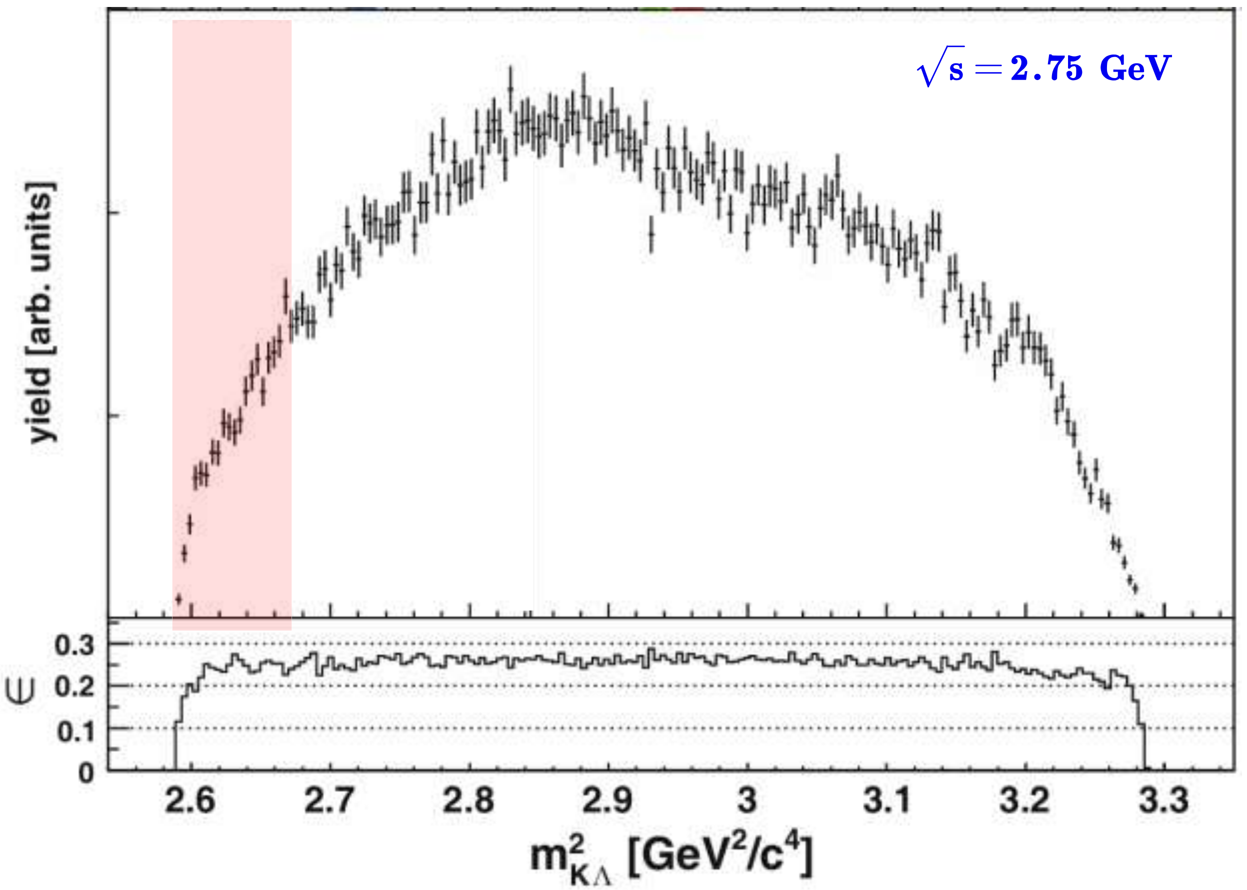
$$G_{N(1535)}(s) = \frac{1}{M_R^2 - s - iM_R\Gamma_{\pi N,\eta N}(s) - i\gamma_{K\Lambda}[\rho_{K\Lambda}(s) - \rho_{K\Lambda}(M_R^2)]}$$

$$\Gamma_{\pi N}(s) = \Gamma_R^0 \beta_{\pi N}\frac{\rho_{\pi N}(s)}{\rho_{\pi N}(M_R^2)}, \quad \Gamma_{\eta N}(s) = \Gamma_R^0 \beta_{\eta N}\frac{\rho_{\eta N}(s)}{\rho_{\eta N}(M_R^2)}$$

$$q_{M_B}(s) = \frac{\lambda^{1/2}(s, M_M^2, M_B^2)}{2\sqrt{s}}, \quad \rho_{MB}(s) = \frac{2q_{M_B}(s)}{\sqrt{s}}$$

$$\gamma_{K\Lambda} \simeq \frac{M_R g_{N^*K\Lambda}^2}{8\pi}[E_\Lambda(m_R) + m_\Lambda]$$

B. C. Liu, B. S. Zou, PRL 96, 042002 (2006).



核子-超子末态相互作用

超子-核子末态相互作用

$$\mathcal{M} \to \mathcal{M} \times \mathcal{A}_{FSI}$$

$$\mathcal{A}_{\Lambda p}(q) = N_0(m_\Lambda + m_N)\left[-\frac{1}{a} + \frac{rq^2}{2} - iq\right]^{-1}$$

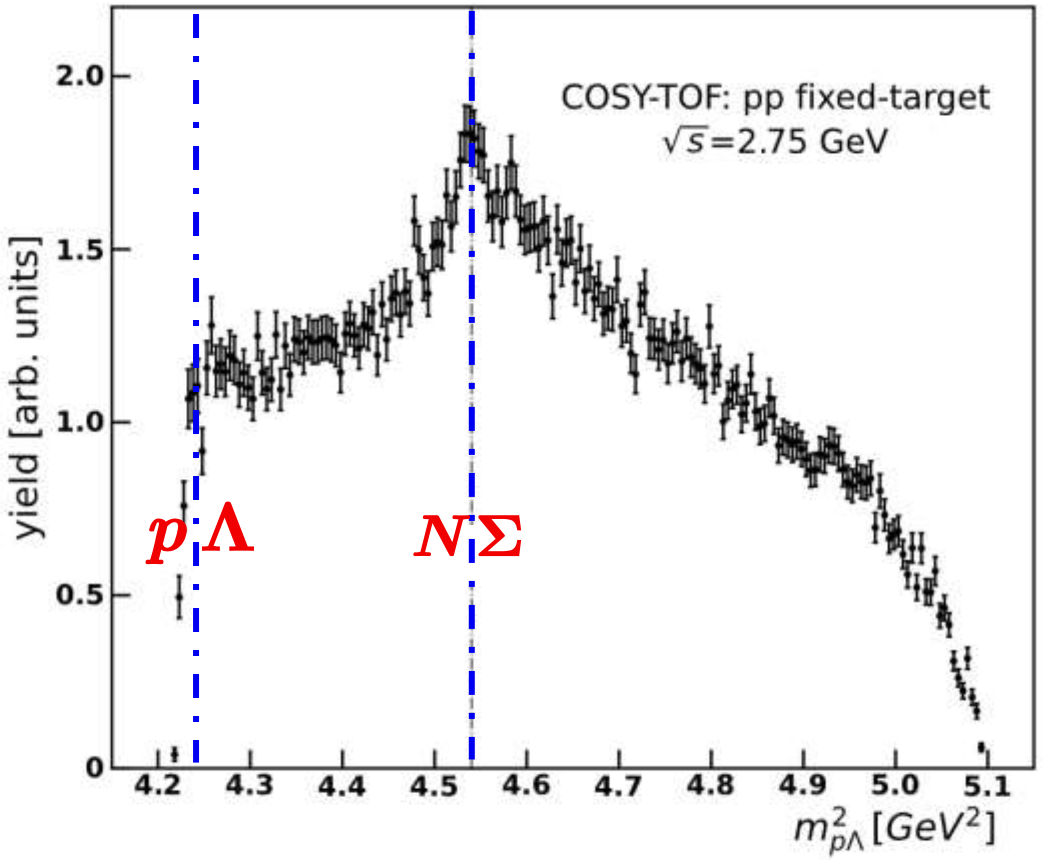
a: scattering length, r: effective range

K. M. Watson, Phys. Rev. 88, 1163 (1952).
A.B. Migdal, JETP 1, 2 (1955).

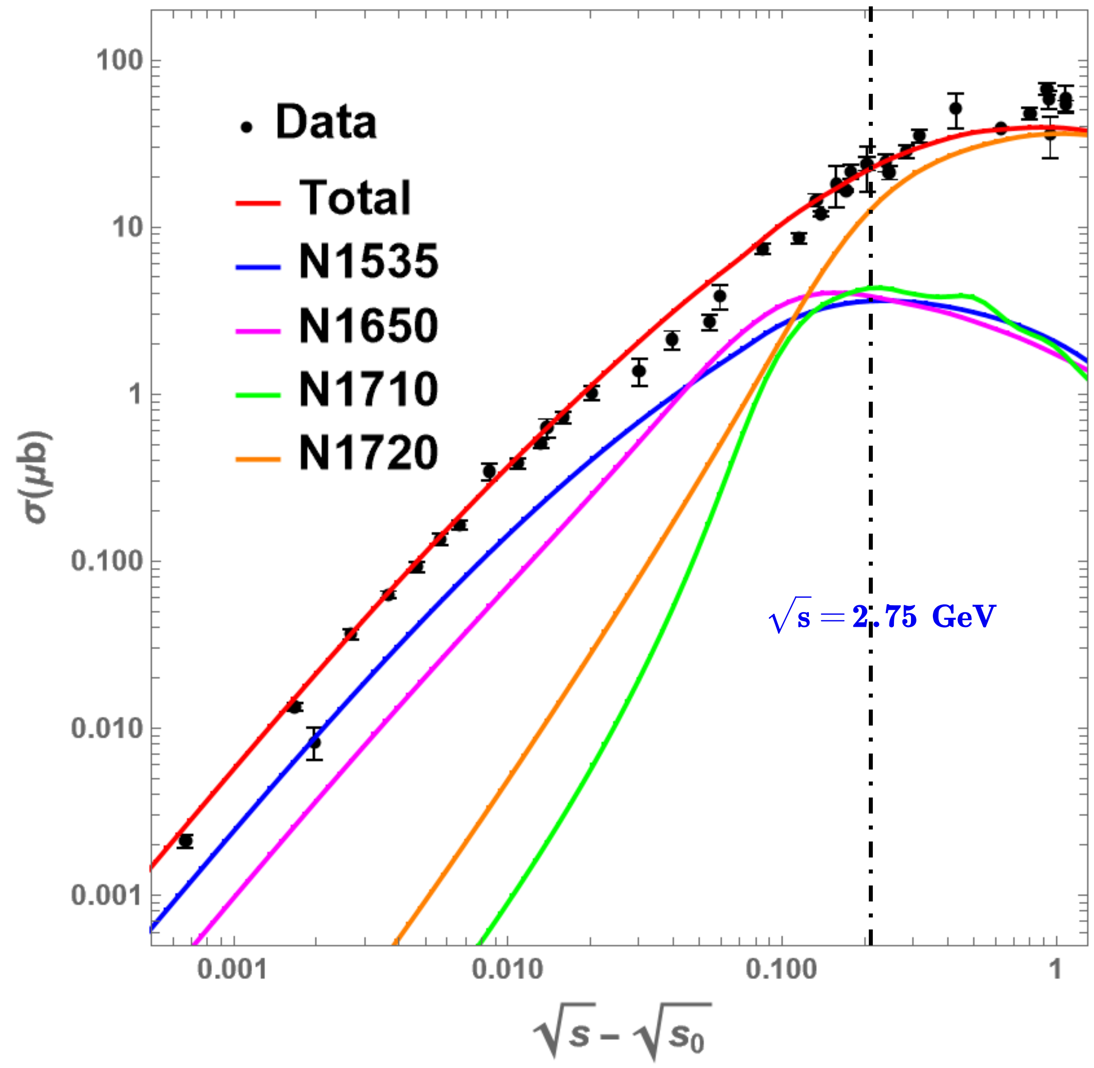
$$\mathcal{A}_{\Lambda p}(q) = \frac{q + i\beta}{q - i\alpha},$$

$$a = \frac{\alpha + \beta}{\alpha\beta}, \quad r = \frac{2}{\alpha + \beta}$$

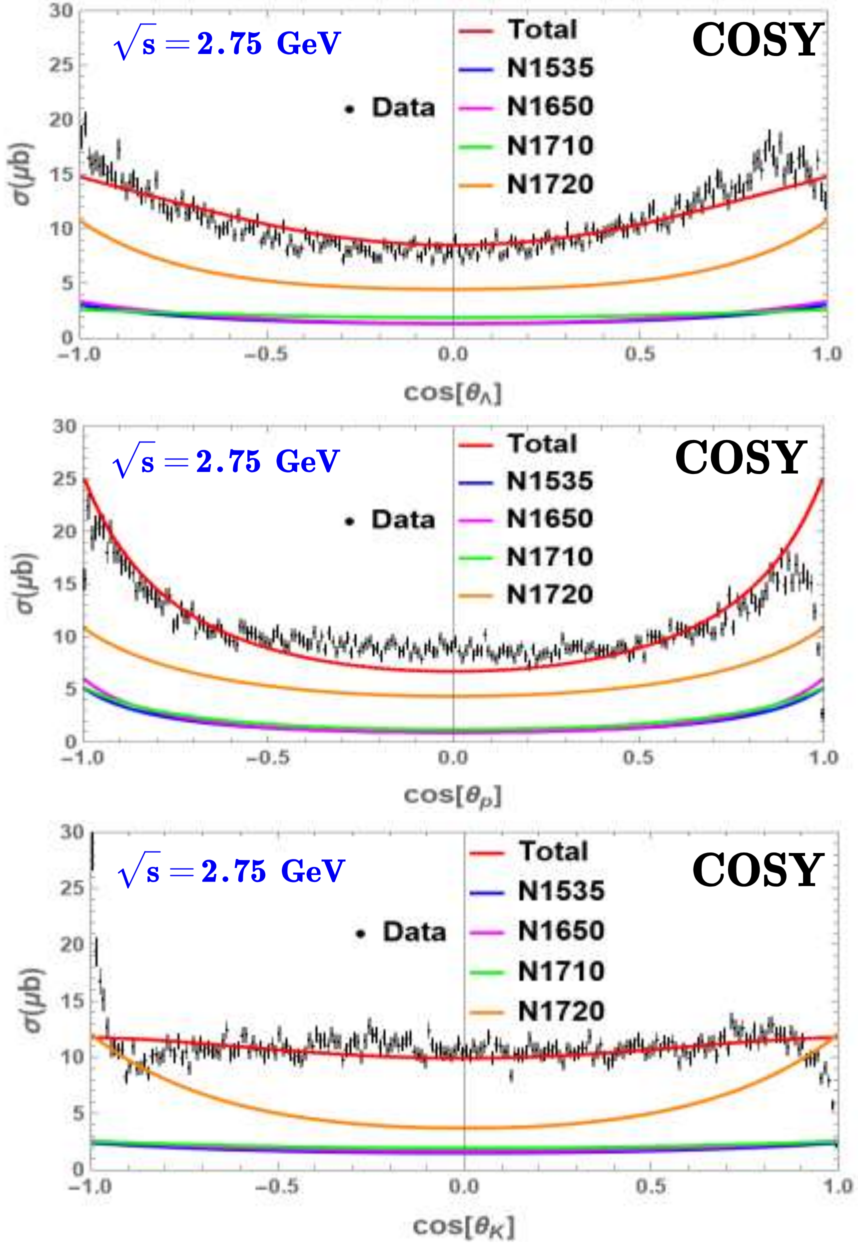
A. Gasparyan, J. Haidenbauer, C. Hanhart, PRC 72, 034006 (2005) .
A. Sibirtsev, J. Haidenbauer, H. W. Hammer, S. Krewald, EPJA 27, 269 (2006).



初步数值拟合结果—截面

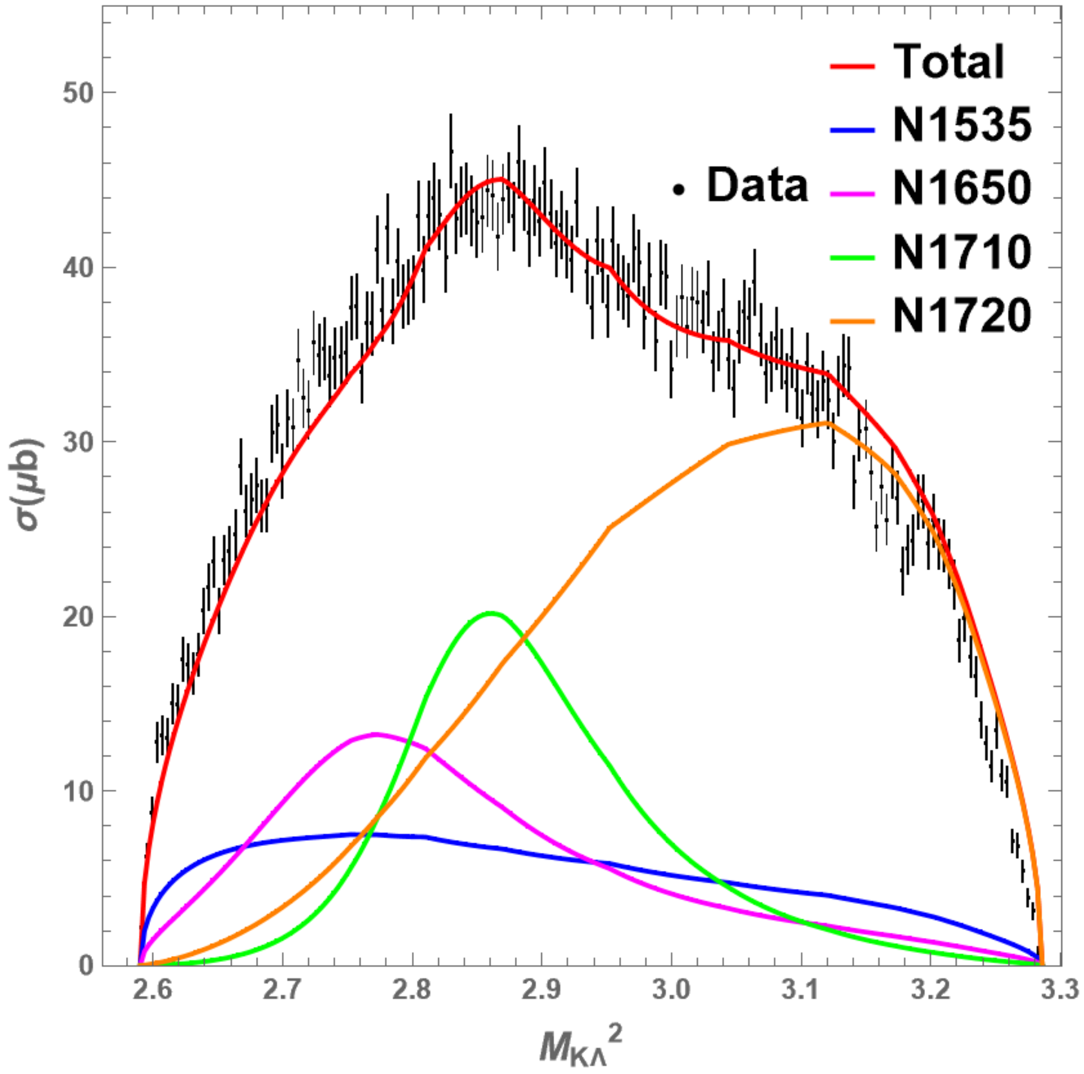


Data
Total
N1535
N1650
N1710
N1720
$\sqrt{s}=2.75$ GeV
$\sigma(\mu b)$
$\sqrt{s}-\sqrt{s_0}$

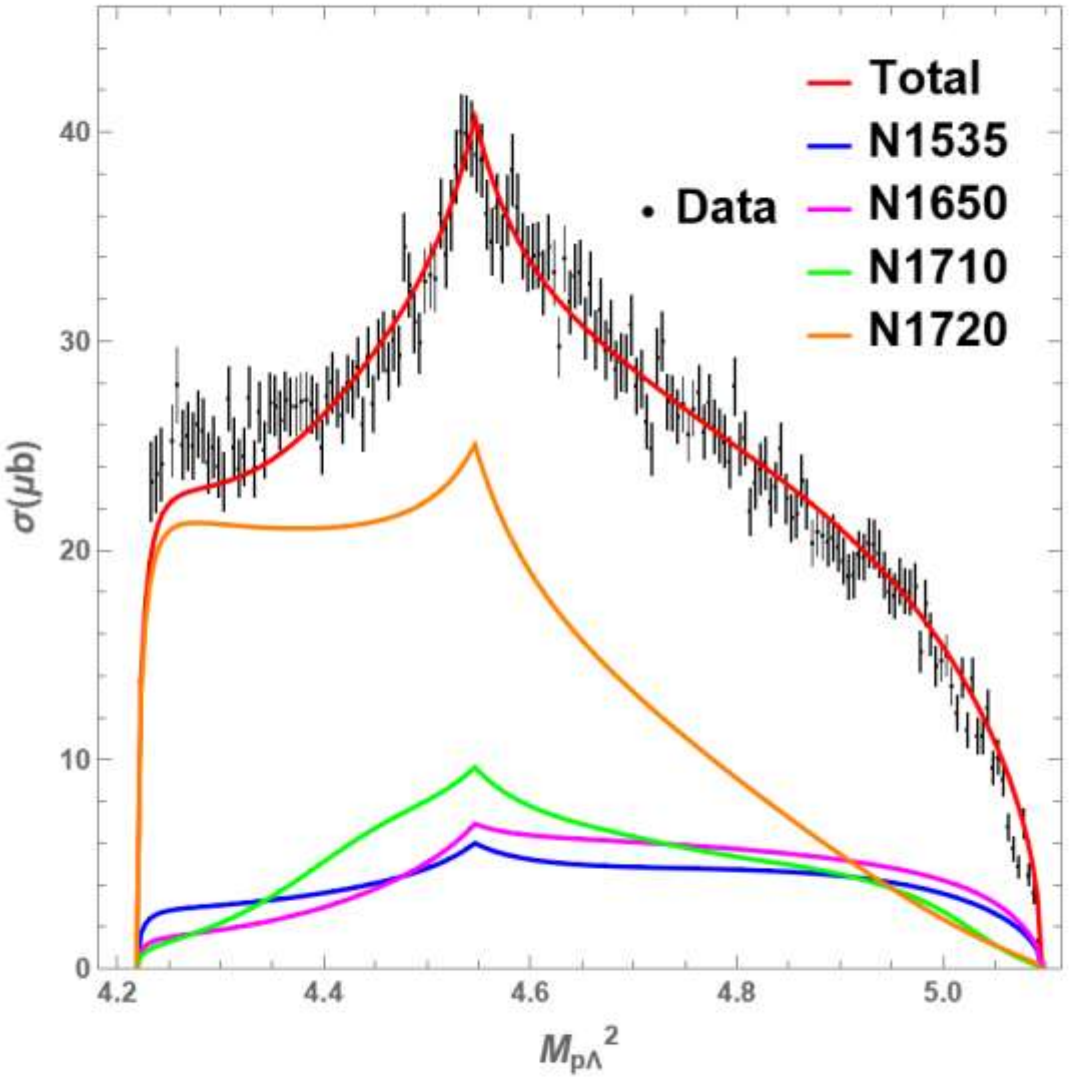


$\sqrt{s}=2.75$ GeV
COSY
Data
Total
N1535
N1650
N1710
N1720
$\sigma(\mu b)$
$\cos[\theta_\Lambda]$
$\cos[\theta_p]$
$\cos[\theta_K]$

初步数值拟合结果—截面

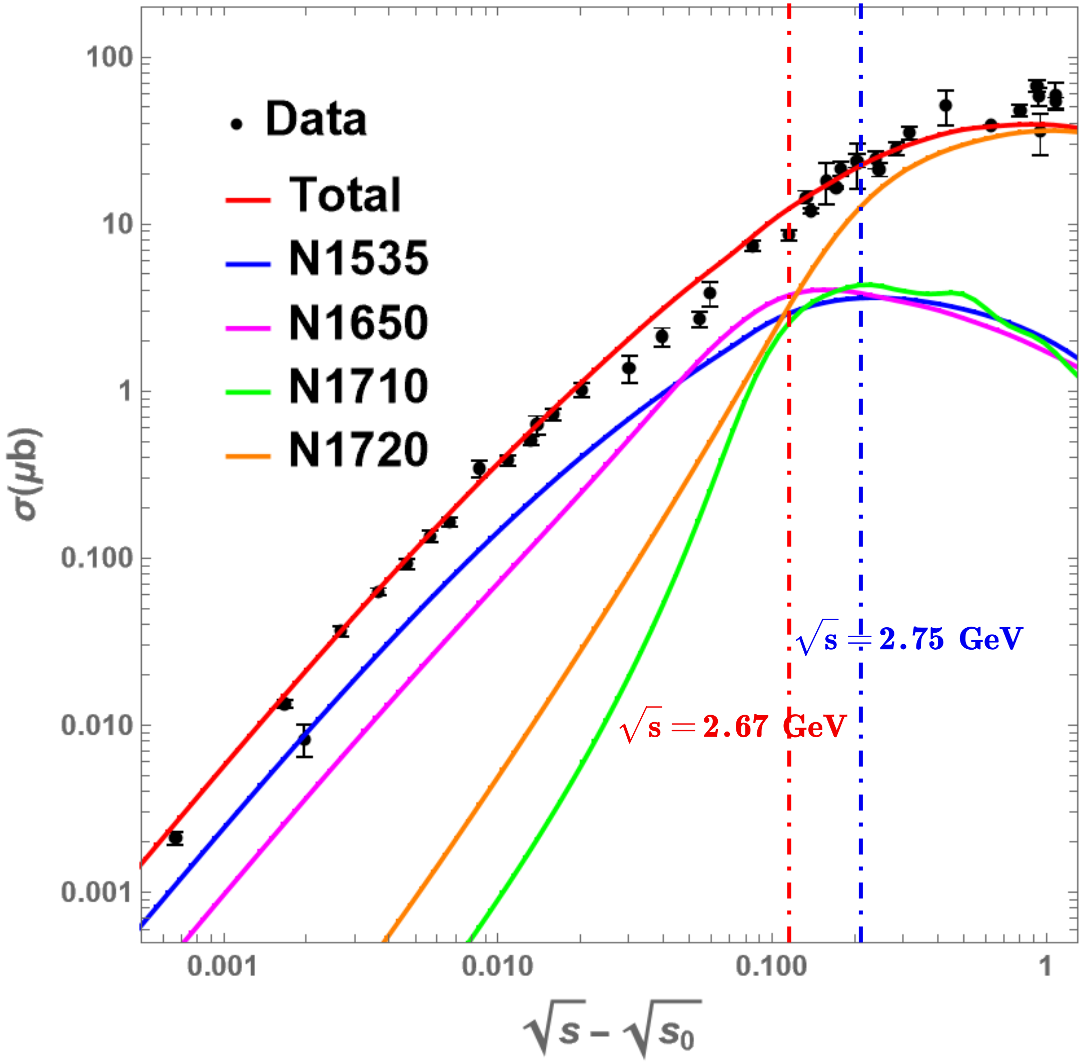


Total
N1535
Data
N1650
N1710
N1720
σ(μb)
50
40
30
20
10
0
2.6
2.7
2.8
2.9
3.0
3.1
3.2
3.3
$M_{K\Lambda}^2$

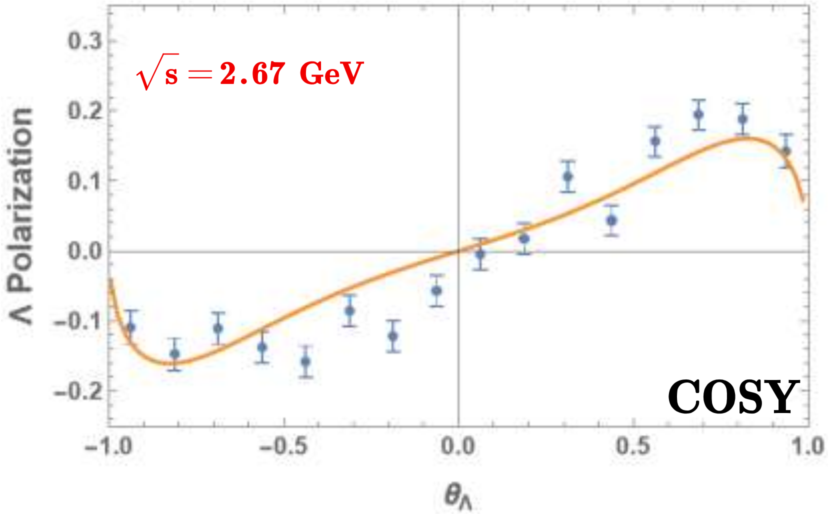


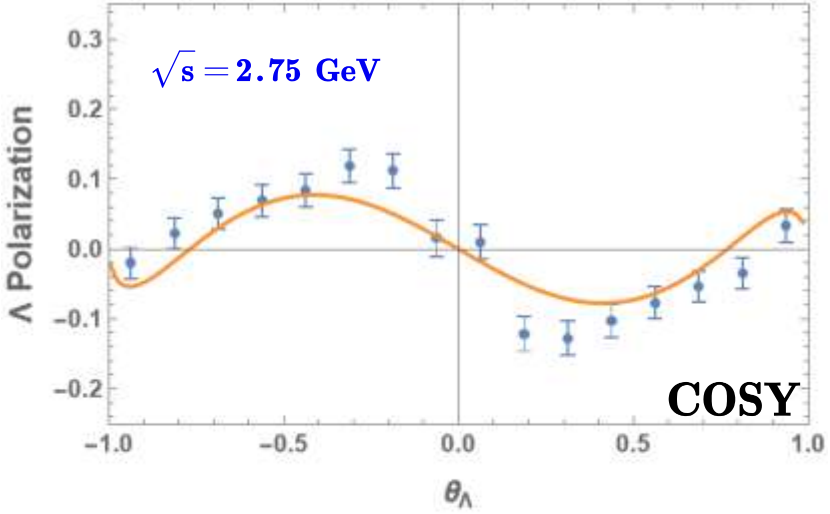
Total
N1535
Data
N1650
N1710
N1720
σ(μb)
40
30
20
10
0
4.2
4.4
4.6
4.8
5.0
$M_{p\Lambda}^2$

初步数值拟合结果—超子极化

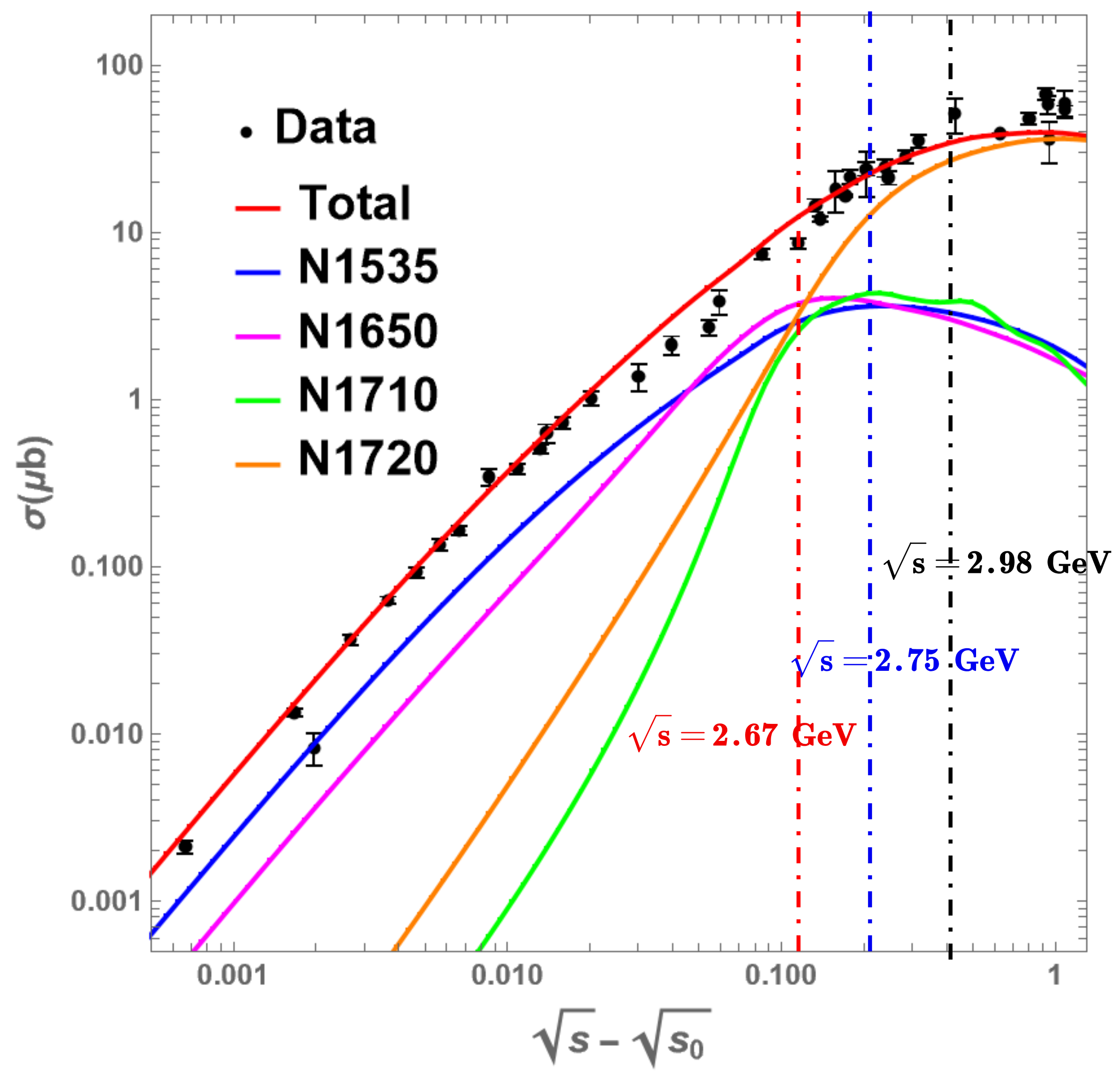


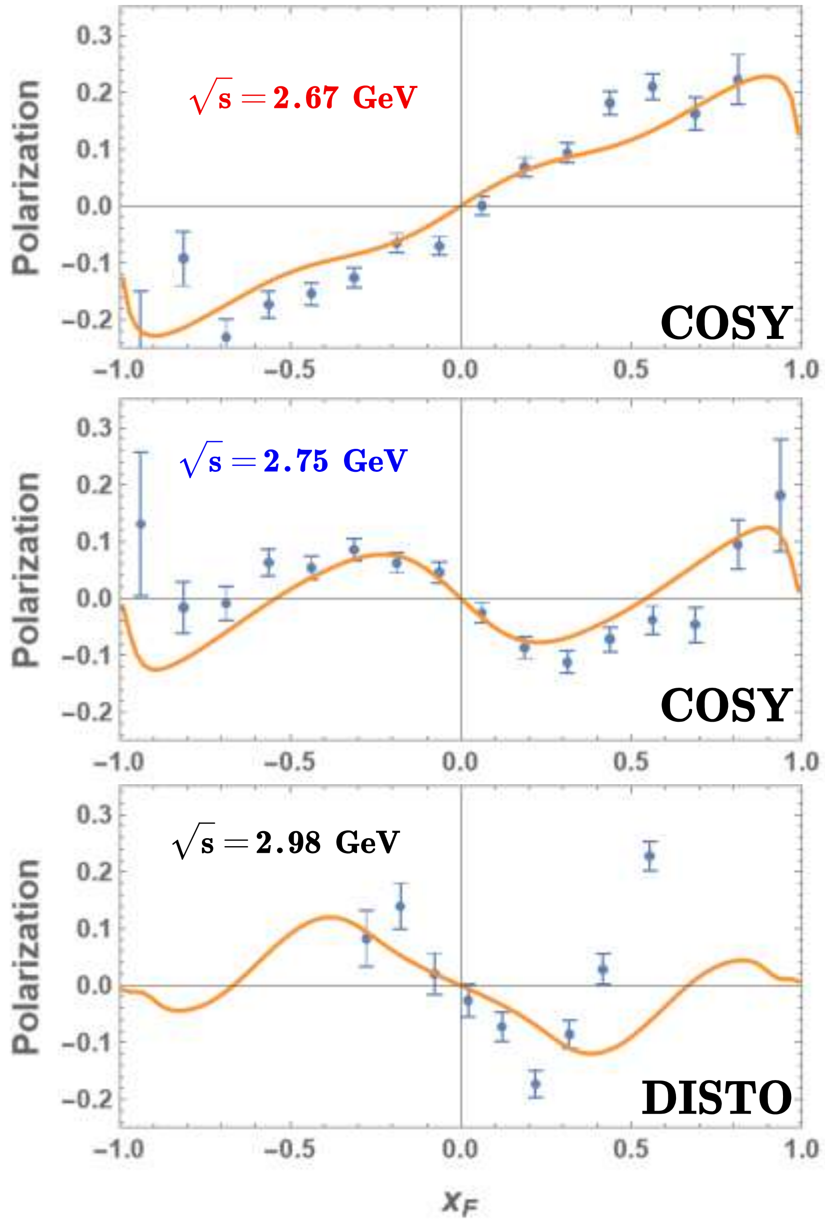
$$\mathcal{M}=\mathcal{M}_{\mathrm{N(1535)}}+e^{i\phi_1}\mathcal{M}_{\mathrm{N(1650)}}+e^{i\phi_2}\mathcal{M}_{\mathrm{N(1710)}}+e^{i\phi_3}\mathcal{M}_{\mathrm{N(1720)}}$$





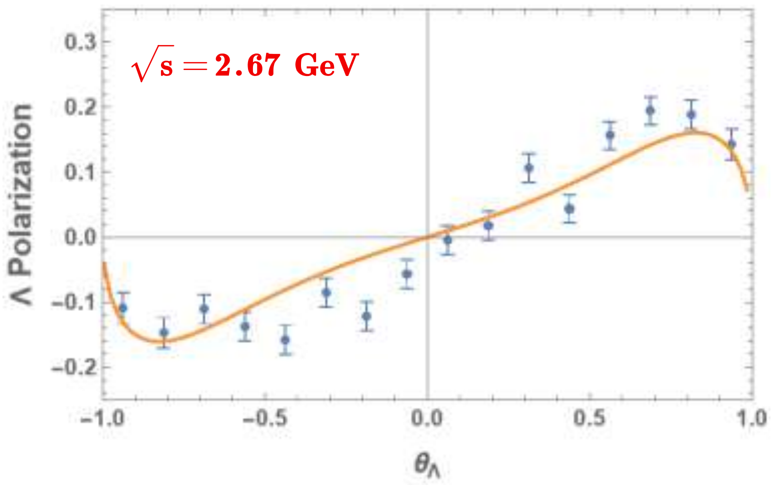
初步数值拟合结果—超子极化

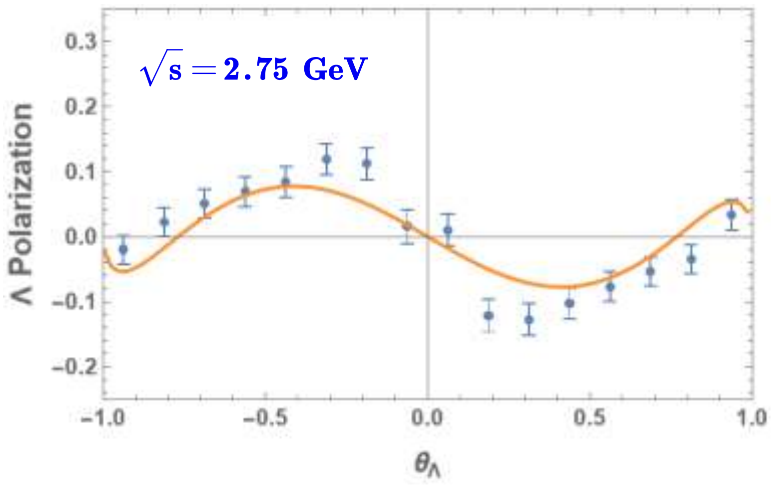




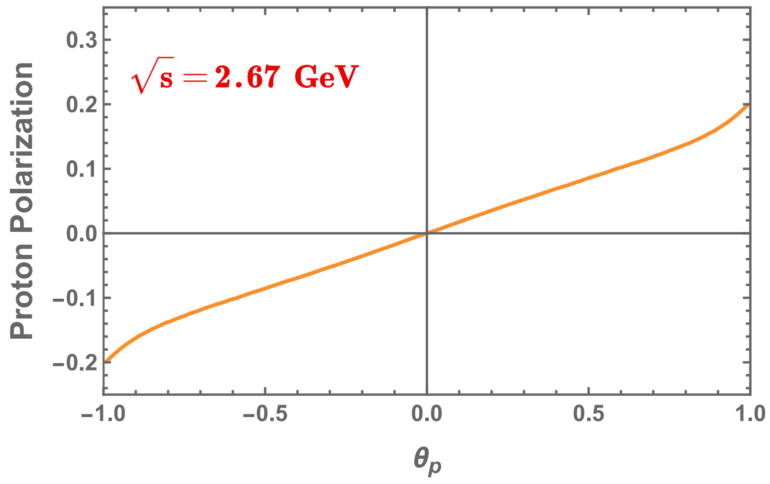
极化预言—核子极化

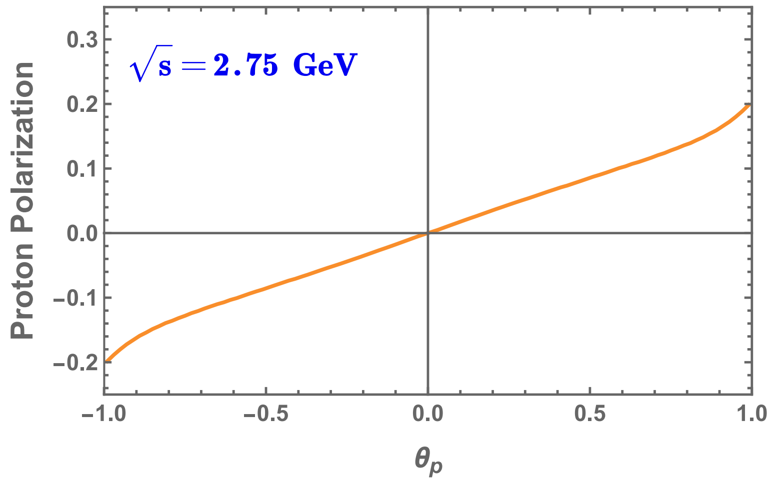
Λ 极化



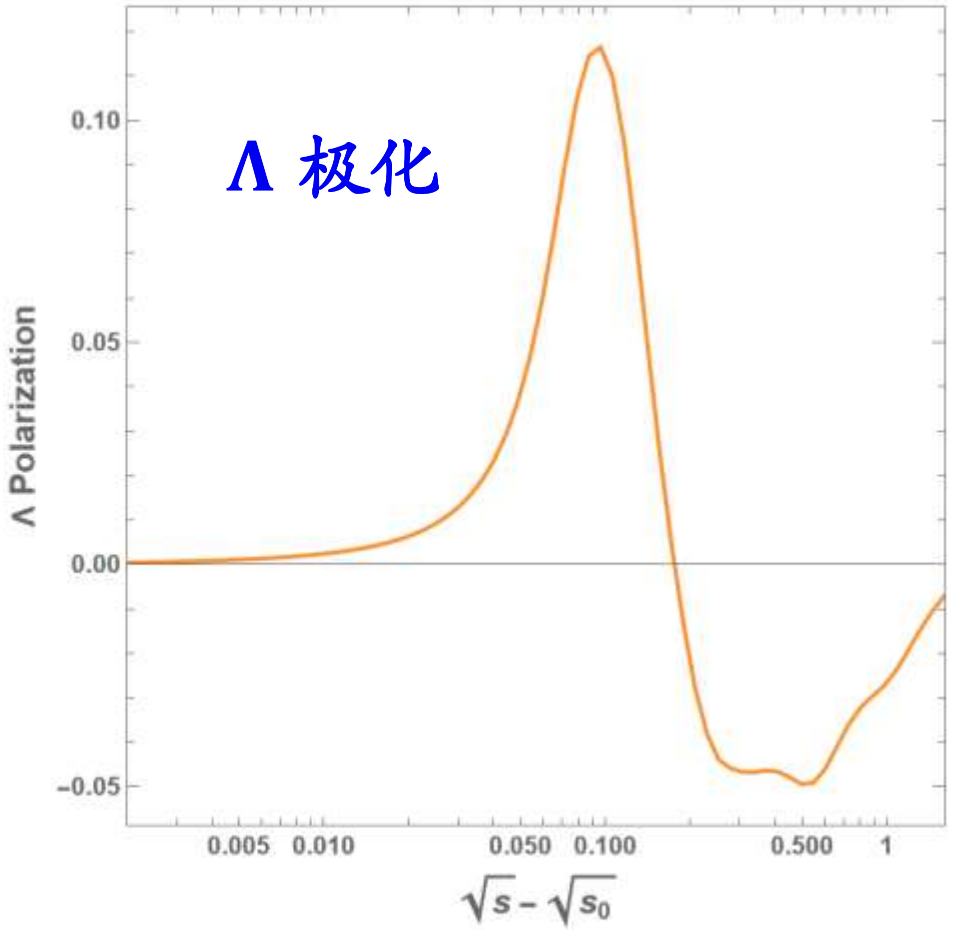


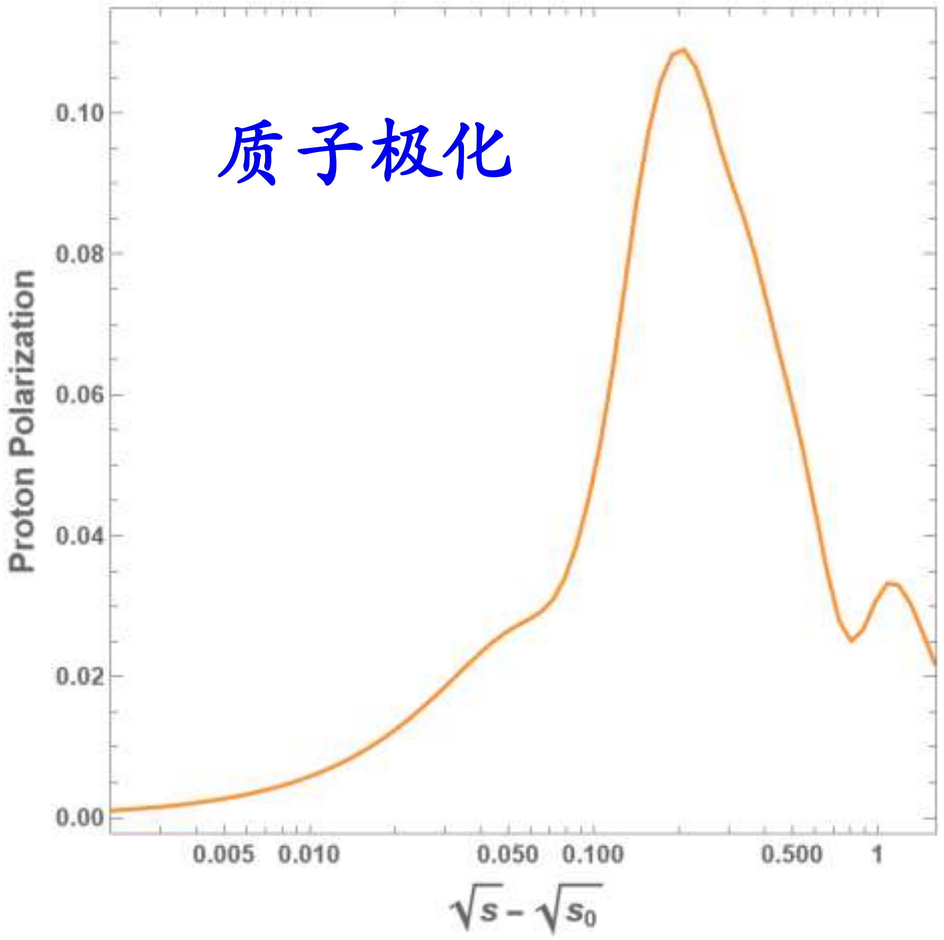
质子极化





极化预言—极化的质心能依赖





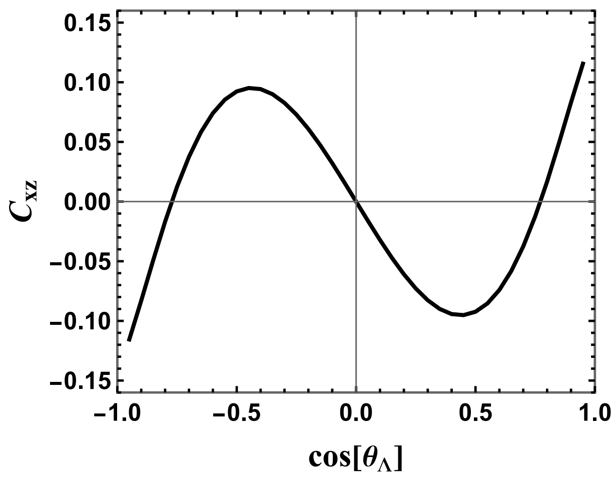
极化预言—超子-核子极化关联

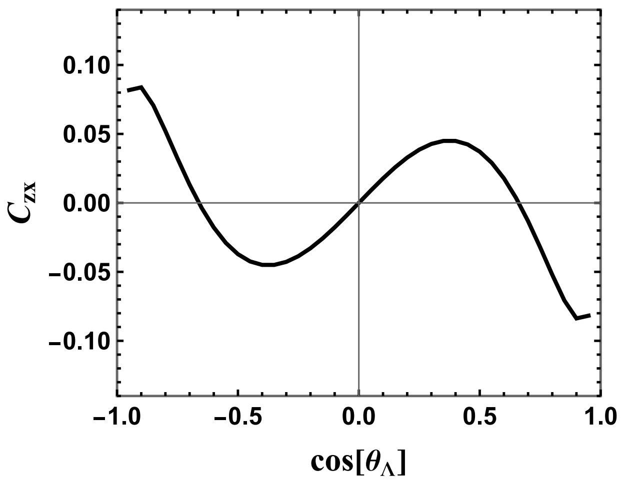
超子-核子的极化关联

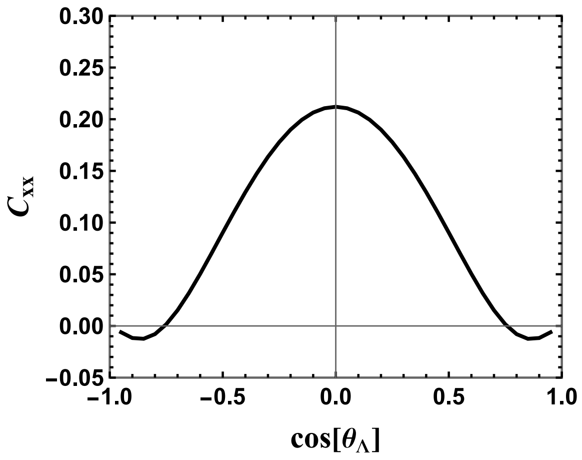
$$\boldsymbol{\rho} = \frac{1}{4}\left(\mathbf{1}_4 + \boldsymbol{B}_{\mathrm{i}}^{p}\boldsymbol{\sigma}^{\mathrm{i}} \otimes \mathbf{1}_2 + \boldsymbol{B}_{\mathrm{j}}^{\Lambda}\mathbf{1}_2 \otimes \boldsymbol{\sigma}^{\mathrm{j}} + \boldsymbol{C}_{\mathrm{ij}}\boldsymbol{\sigma}^{\mathrm{i}} \otimes \boldsymbol{\sigma}^{\mathrm{j}}\right)$$

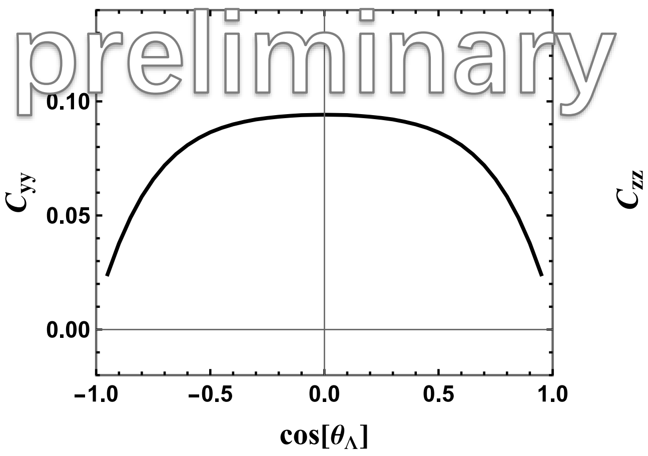
$$\boldsymbol{B}_{\mathrm{i}}^{p} = (0, P_y^{p}, 0), \qquad \boldsymbol{B}_{\mathrm{i}}^{p} = (0, P_y^{\Lambda}, 0)$$

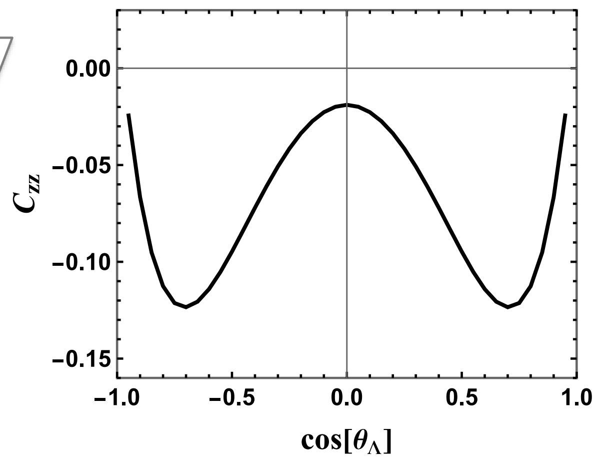
$$\boldsymbol{C}_{\mathrm{ij}} = \begin{pmatrix} C_{xx} & 0 & C_{xz} \\ 0 & C_{yy} & 0 \\ C_{zx} & 0 & C_{zz} \end{pmatrix}$$











Collaborate with Xu Cao, BoChao Liu Tianbo Liu,
Jiajun Wu, Yuxiang Zhao, BingSong Zou…

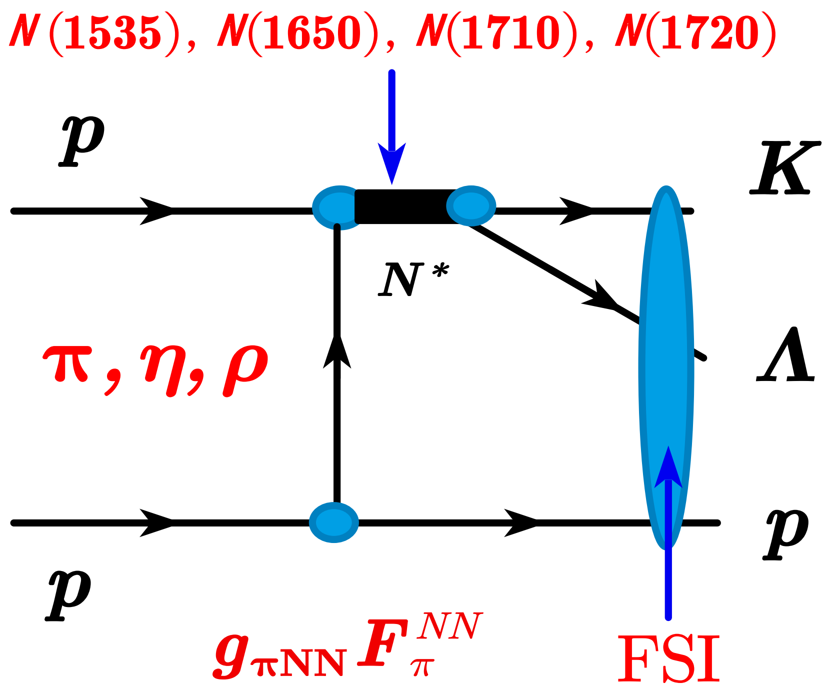
Summary and Outlook

1. 遍举超子产生过程是HIAF和H-NS的重要物理研究课题。

2. 我们在介子交换模型下，给出了现有实验数据的理论解释。

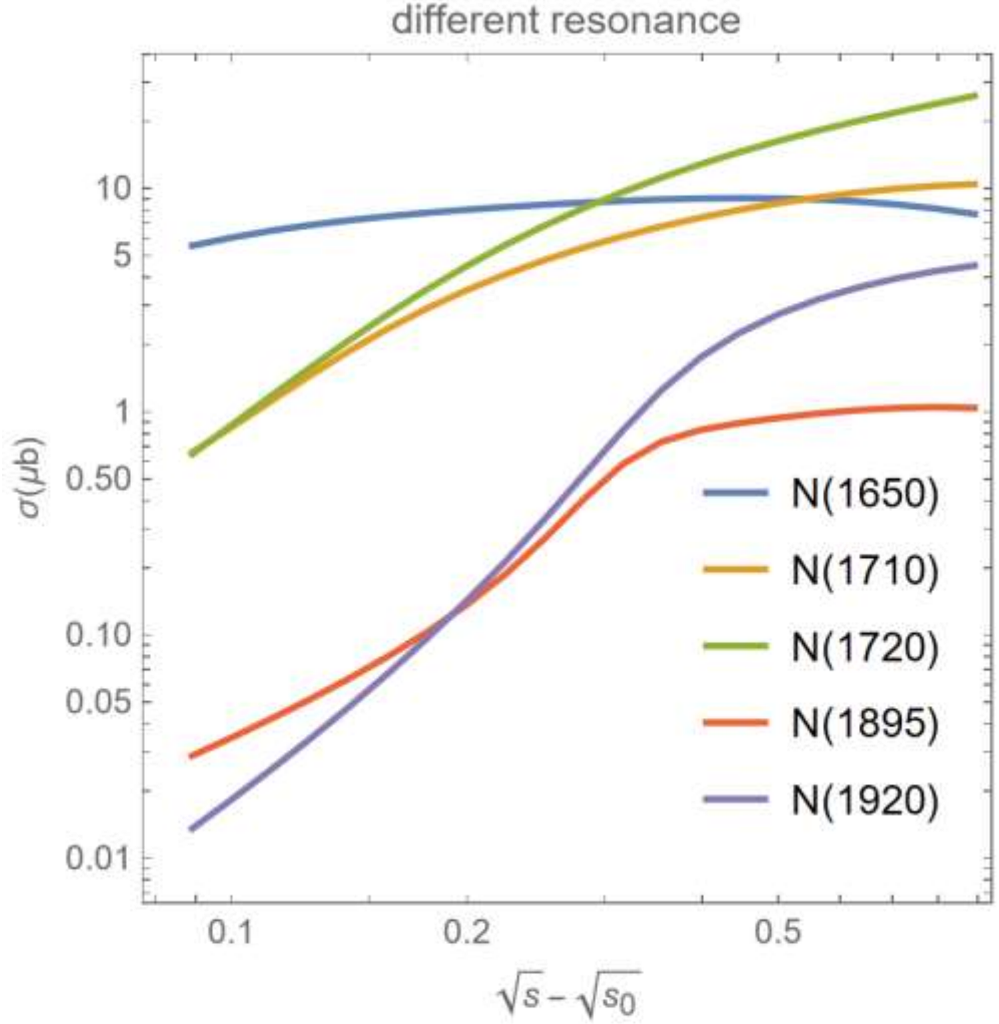
3. 我们核子极化以及核子-超子极化关联给出了理论预言。

4. $pp \to pK\Lambda$ 反应道有望成为理解强子性质，核子-超子相互作用，极化产生机制等物理课题的重要窗口。



Back up

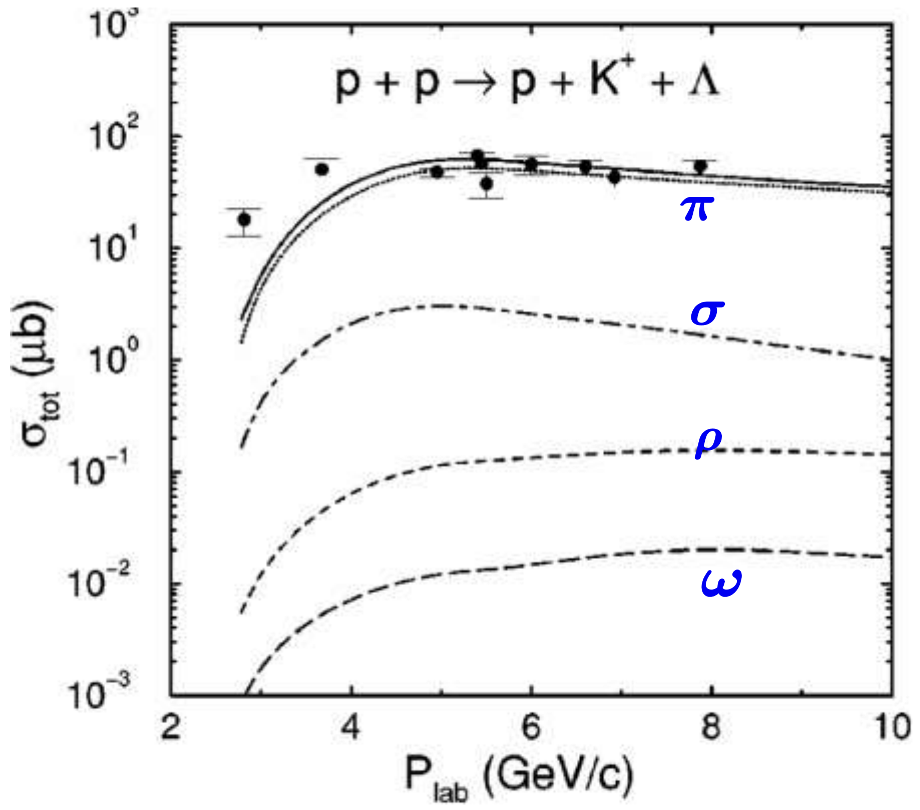
Cross Section



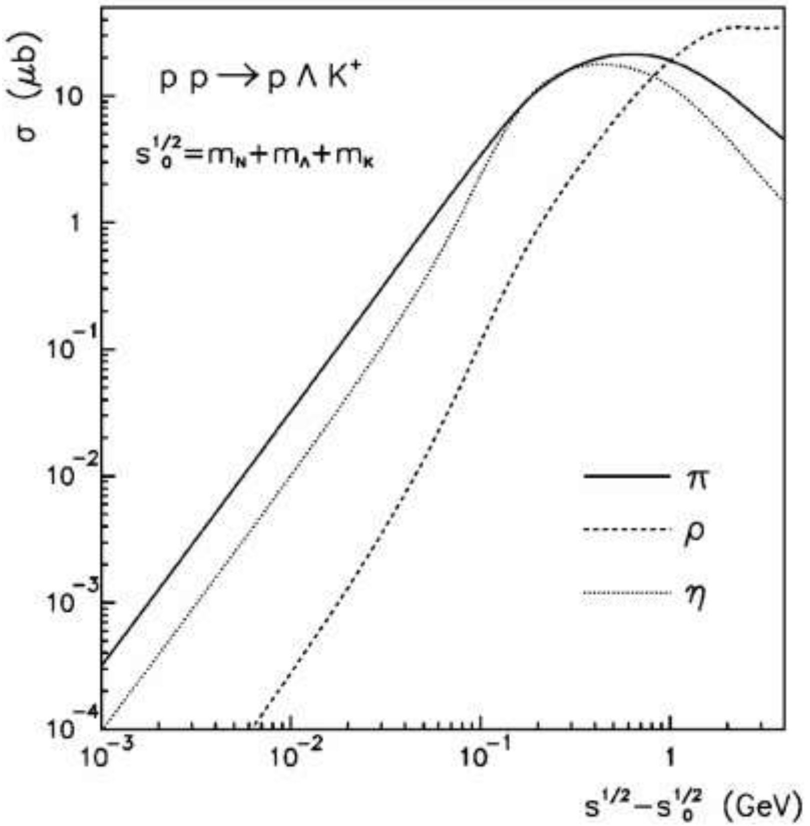
Meson Exchange Model

$$F_M^{NN}(k_M^2) = \left(\frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - k_M^2}\right)^n,$$

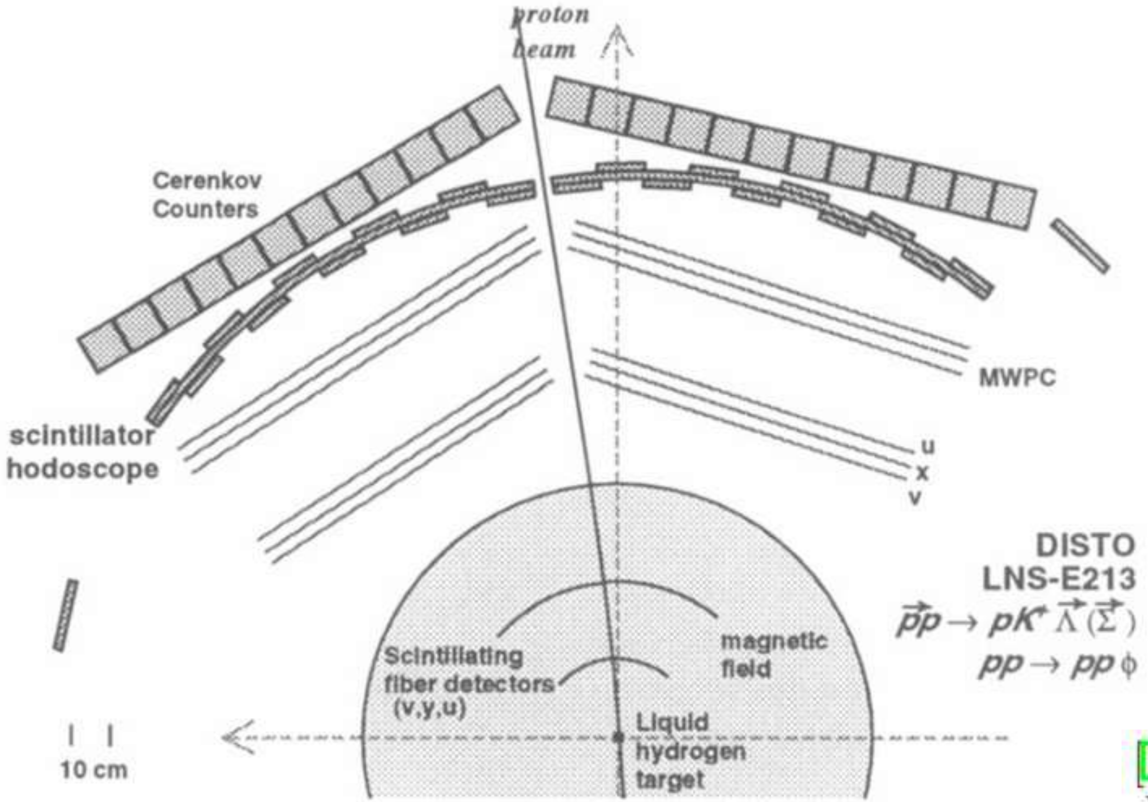
$$F_M(\vec{q}) = \left(\frac{\Lambda_M^2}{\Lambda_M^2 + \vec{q}^{\,2}}\right)^n,$$

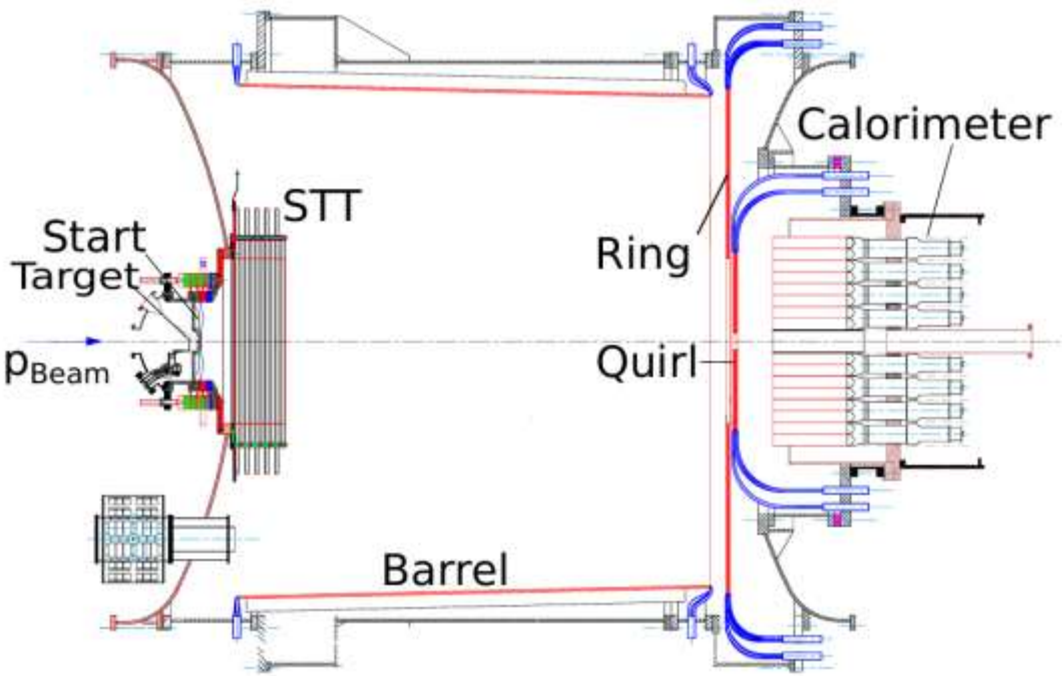


R. Shame, PRC 60, 055213 (1999).



K. Tsushima, A. Sibirtsev, A.W. Thomas, G.Q. Li, PRC 59, 369 (1999).





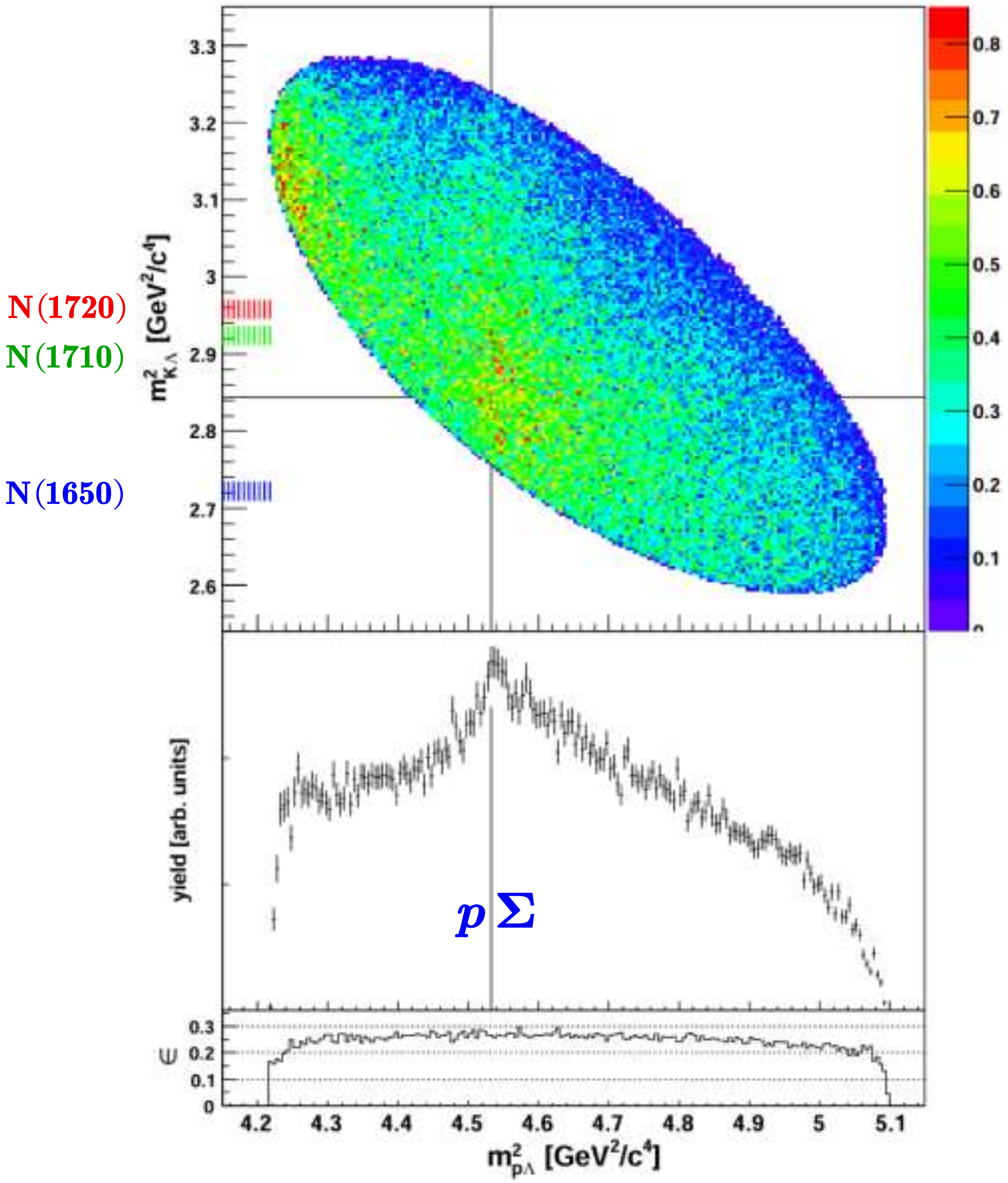
[1]. Due to the nearly 4π acceptance of the COSY-TOF detector for this reaction it is possible to measure the Λ polarization, the analyzing power determined with the final state particles, and the Λ spin transfer coefficient for

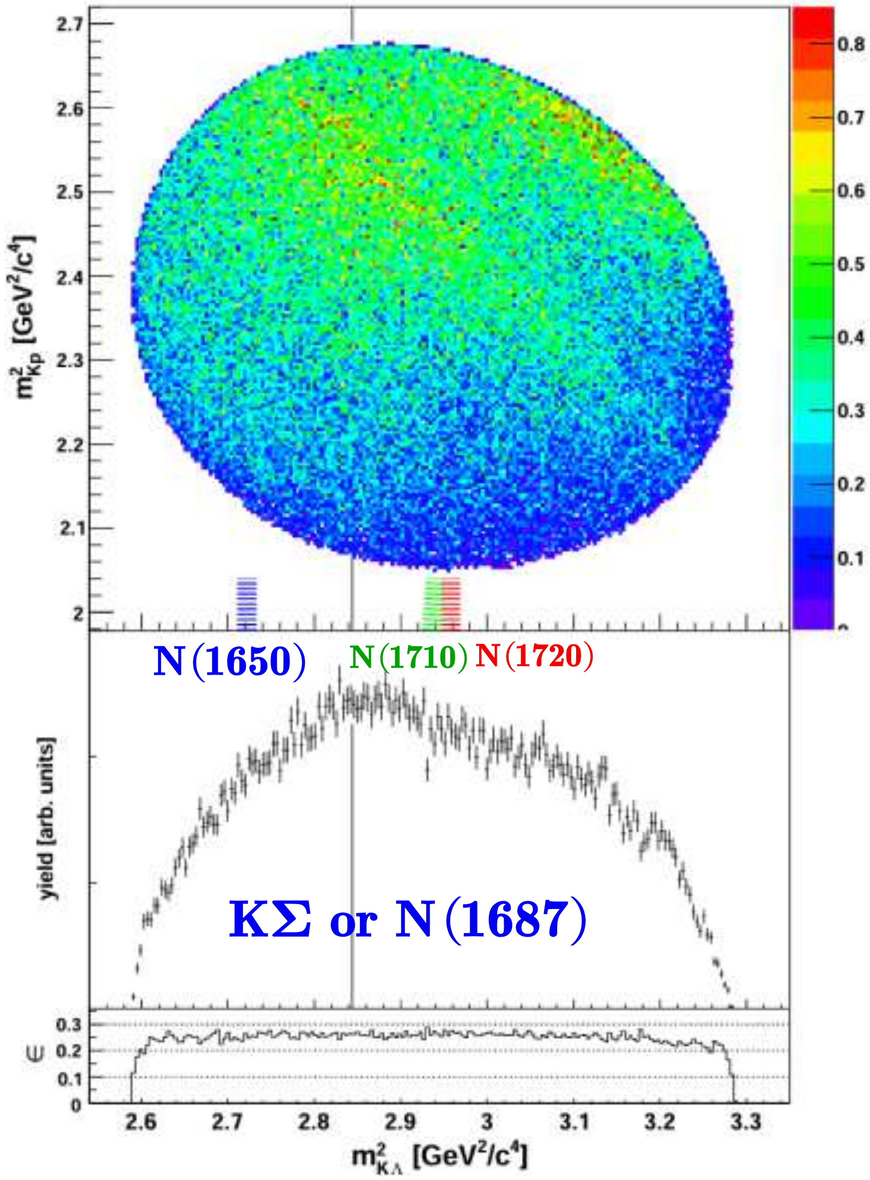
The innermost detectors are two sets of plastic scintillating fibers inside the magnet at the radii of 20 cm and 40 cm. Each set comprises three planes (v, y and u) of fibers. The active area covers 45° horizontally and ±15.5° vertically with respect to the beam, except for a central hole of 1.5° half angle for the exit beam pipe. Outside of the magnet, there are two sets of planar multi-wire proportional chambers, each containing three planes (v, x and u) of wires. Behind the MWPC's, there is a scintillator hodoscope, composed

$\vec{p}p$ collisions at three incident proton momenta: 3.67, 3.31 and 2.94 GeV/c. Detection of all charged particles in the final state allows exclusive measurements for hyperons, while the use of polarized beam makes it possible to measure analyzing powers A_y and the spin transfer coefficient D_{NN}, in addition to the polarization of the outgoing hyperon. An outline of the physics motivation and a brief description of the experimental setup is given. Some preliminary results from the data taken at 3.67 GeV/c are presented.

try are existing for all three distributions: At backward angles there is a surplus of events, which is mainly due to the pK($\Sigma^0 \to \Lambda\gamma$) background. At extreme forward angles ($\cos\vartheta^{cm} \geq 0.95$) of the proton and kaon distributions a deficit of events is found. The affected range corresponds to scattering angles in the lab system of smaller than 5°–6° degrees. It is supposed that the deficit of events is caused by an efficiency drop in the cones of the start counter, which cannot be exactly described by the Monte Carlo program.

Invariant Mass Distribution





Resonance Mass and Width

1635 to 1665 ($\approx$ 1650)	OUR ESTIMATE		
1657 $\pm$6		GOLOVATCH	2019
1666 $\pm$3	[1]	HUNT	2019
1634 $\pm$5		KASHEVAROV	2017
1654 $\pm$6		SOKHOYAN	2015A
1665 $\pm$2	[1]	SHKLYAR	2013
1634.7 $\pm$1.1	[1]	ARNDT	2006

100 to 150 ($\approx$ 125)	OUR ESTIMATE		
154 $\pm$28		GOLOVATCH	2019
133 $\pm$7	[1]	HUNT	2019
128 $\pm$16		KASHEVAROV	2017
102 $\pm$8		SOKHOYAN	2015A
147 $\pm$14	[1]	SHKLYAR	2013
115.4 $\pm$2.8	[1]	ARNDT	2006

Lambda Production for Exclusive Process

$$M_{\pi N1650} = -ig_{\pi NN}g_{\pi NN(1650)}g_{K\Lambda N(1650)}F_K^{\Lambda N^*}\left(p_K^2\right)F_\pi^{NN^*}\left(q_\pi^2\right)F_\pi^{NN}\left(q_\pi^2\right)\bar{u}_\Lambda\left(p_\Lambda,\lambda_\Lambda\right)G_2\left(1650\right)u_p\left(p_2,\lambda_2\right)$$
$$\times G_\pi\left(q_\pi\right)\bar{u}\left(p_n,\lambda_n\right)\gamma_5 u_p\left(p_1,\lambda_1\right)-\left(p_1\leftrightarrow p_2;\lambda_1\leftrightarrow\lambda_2\right),$$

交换介子 的种类	介子质量 $m_\alpha(MeV)$	Bonn势 $g_\alpha^2/4\pi$	(A) $\Lambda_\alpha(GeV)$
π	138.03	14.7	1.3
η	548.8	4	1.5
ρ	769	0.86	1.95
ω	782.6	25	1.35
δ	983	1.3	2.0
σ	550	8.8	2.0

$$\Gamma[N(1650)\to N\pi] = 3\frac{g_{\pi NN(1650)}^2}{4\pi}\frac{(E_N+m_N)}{m_{N(1650)}}|\vec{p}_N|,$$

$$\Gamma[N(1650)\to N\eta] = \frac{g_{\eta NN(1650)}^2}{4\pi}\frac{(E_N+m_N)}{m_{N(1650)}}|\vec{p}_N|,$$

$$\Gamma[N(1650)\to \Lambda K] = \frac{g_{\Lambda KN(1650)}^2}{4\pi}\frac{(E_\Lambda+m_\Lambda)}{m_{N(1650)}}|\vec{p}_\Lambda|,$$

resonance	mass (MeV)	width (MeV)	decay channel	branching ratio
$N1650$ $(1/2^-)$	1635-1665	100-150	$N\pi$ $N\eta$ $N\rho$ ΛK	(50-70)% (15-35)% (12-22)% (5-15)%
$N1710$ $(1/2^+)$	1680-1740	80-200	$N\pi$ $N\eta$ $N\rho$ ΛK	(5-20)% (10-50)% (11-23)% (5-25)%
$N1720$ $(3/2^+)$	1680-1750	150-400	$N\pi$ $N\eta$ $N\rho$ ΛK	(8-14)% (1-5)% (1-2)% (4-19)%