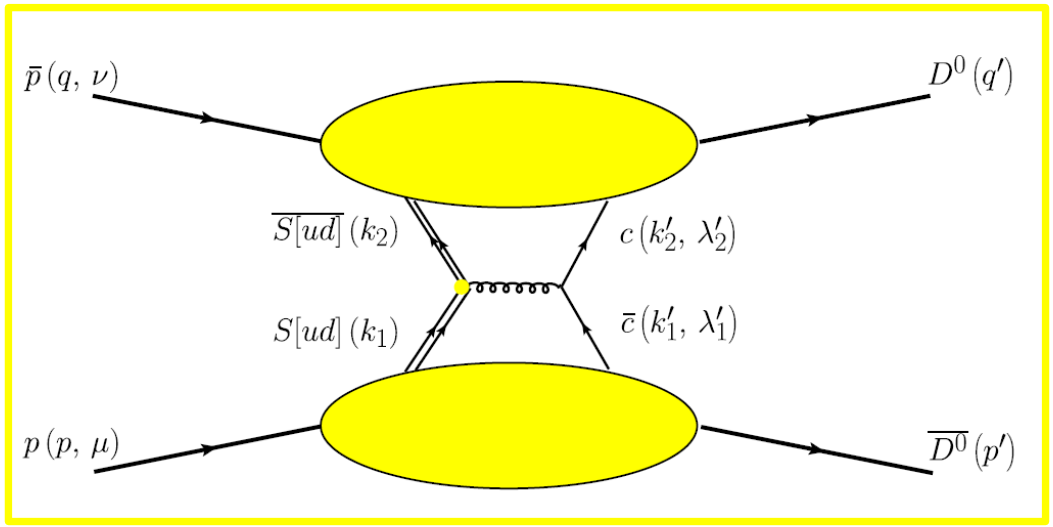
Strangeness and Charm Production by Antiprotons

H. Lenske

Institut für Theoretische Physik, JLU Gießen

Strangeness and Charm Production with Antiprotons on the Nucleon

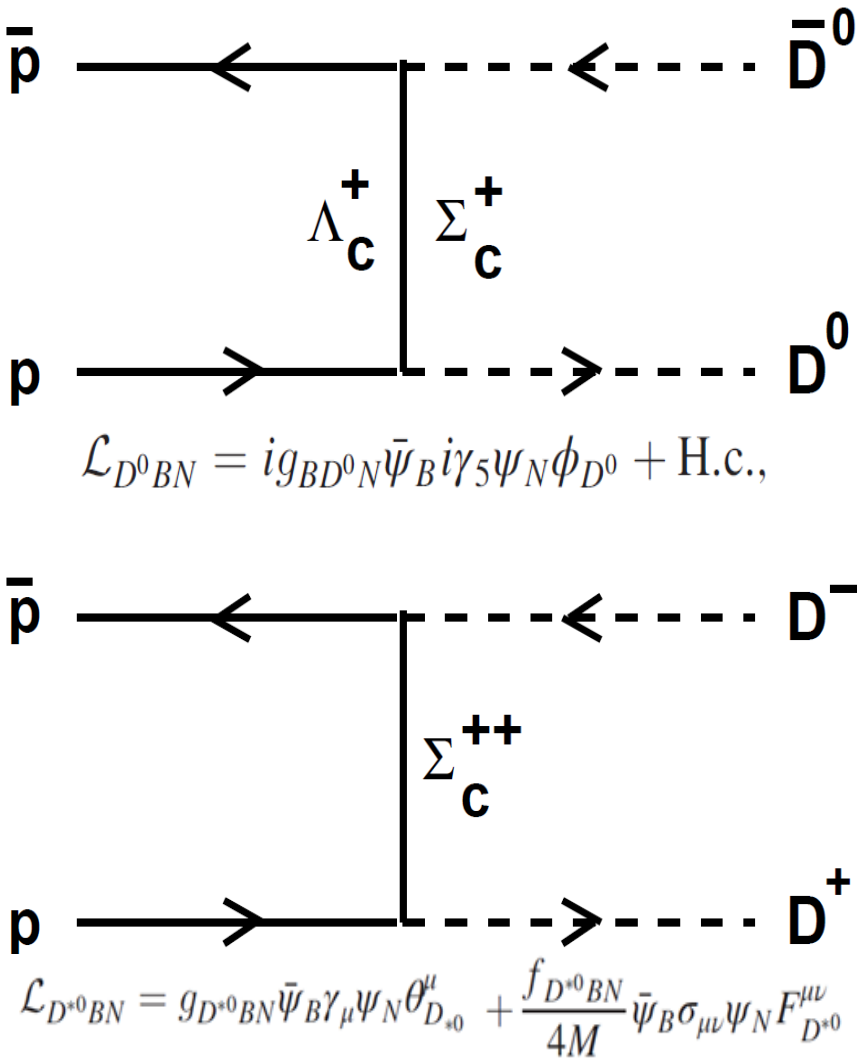
QCD Test Range:
D-Meson Production by Antiproton Annihilation



…e.g. Goritschnig et al., PRD 87 014017 (2013)

t-channel Baryon Exchange and s-Channel Resonance Production

(R. Shyam, H.L. Phys. Rev. D93 (2016) 034016)

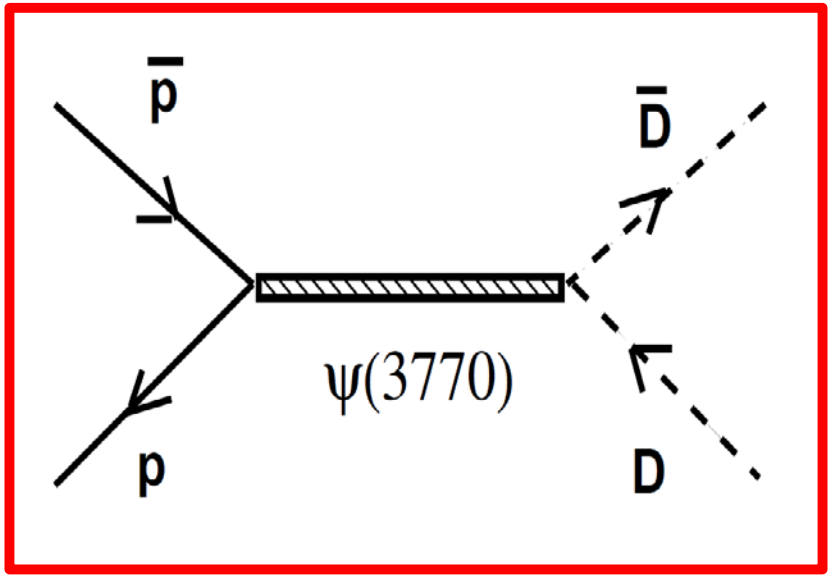


$$\mathcal{L}_{D^0BN} = ig_{BD^0N}\bar{\psi}_B i\gamma_5 \psi_N \phi_{D^0} + \text{H.c.},$$

$$\mathcal{L}_{D^{*0}BN} = g_{D^{*0}BN}\bar{\psi}_B \gamma_\mu \psi_N \theta^\mu_{D_{*0}} + \frac{f_{D^{*0}BN}}{4M}\bar{\psi}_B \sigma_{\mu\nu}\psi_N F^{\mu\nu}_{D^{*0}}$$

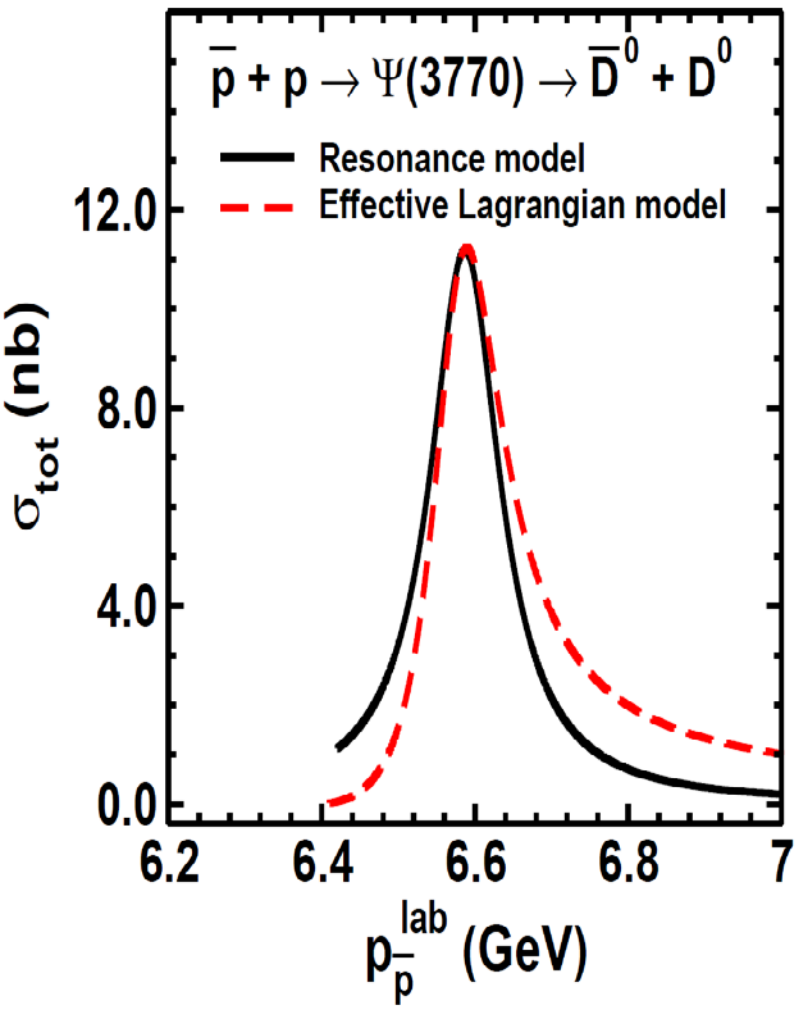
+

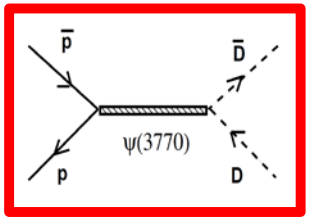
$$\mathcal{L}^{\Psi\bar{p}p}_\mu = g_{\Psi\bar{p}p}\left[\bar{\psi}_{\bar{p}}\left(\gamma_\mu + \frac{\kappa\Psi}{2M}\sigma_{\mu\nu}\partial^\nu \theta^\mu_\Psi\right)\psi_p\right]$$

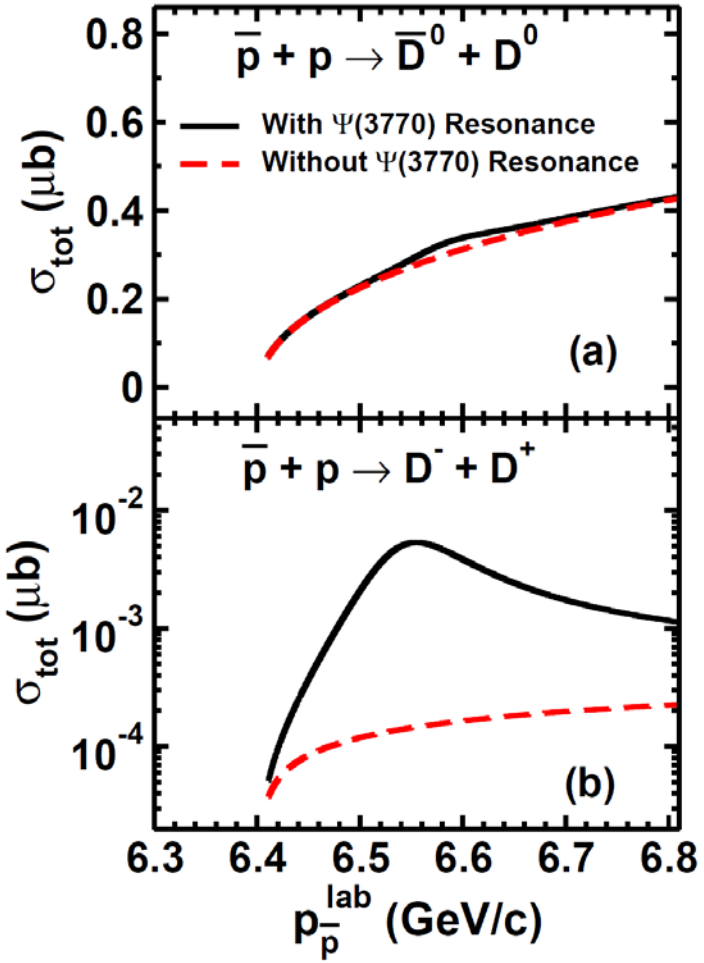


$$\mathcal{L}_{\Psi\bar{D}D} = g_{\Psi\bar{D}D}\left(\Phi_{\bar{D}}\,\partial_\mu\,\Phi_D\right)\theta^\mu_\Psi.$$

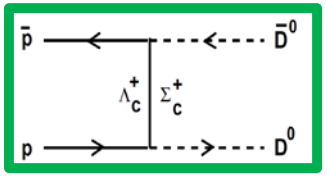
Open Charm Production through s-Channel Resonance Formation

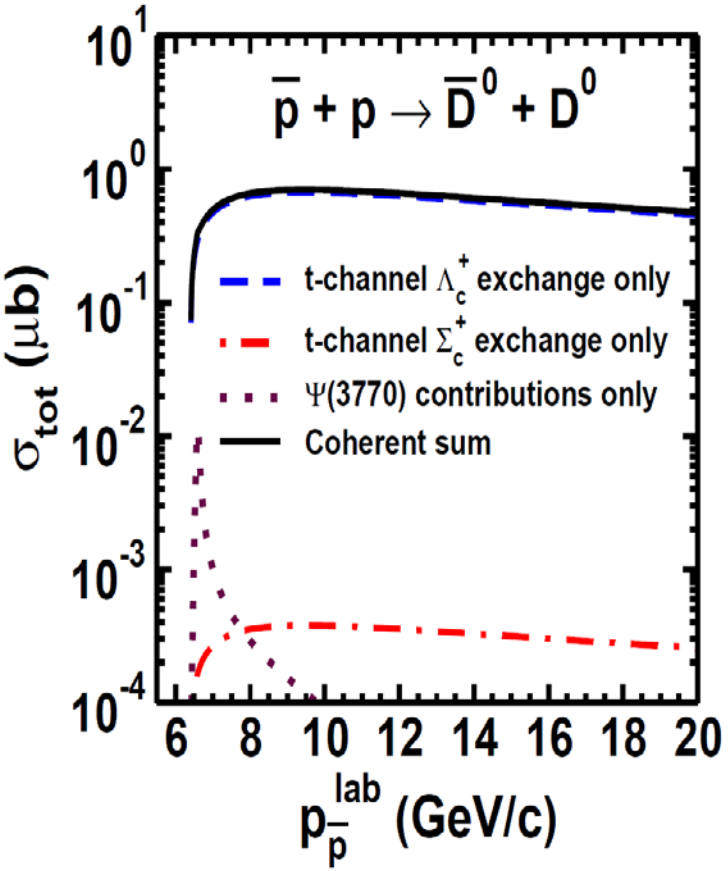


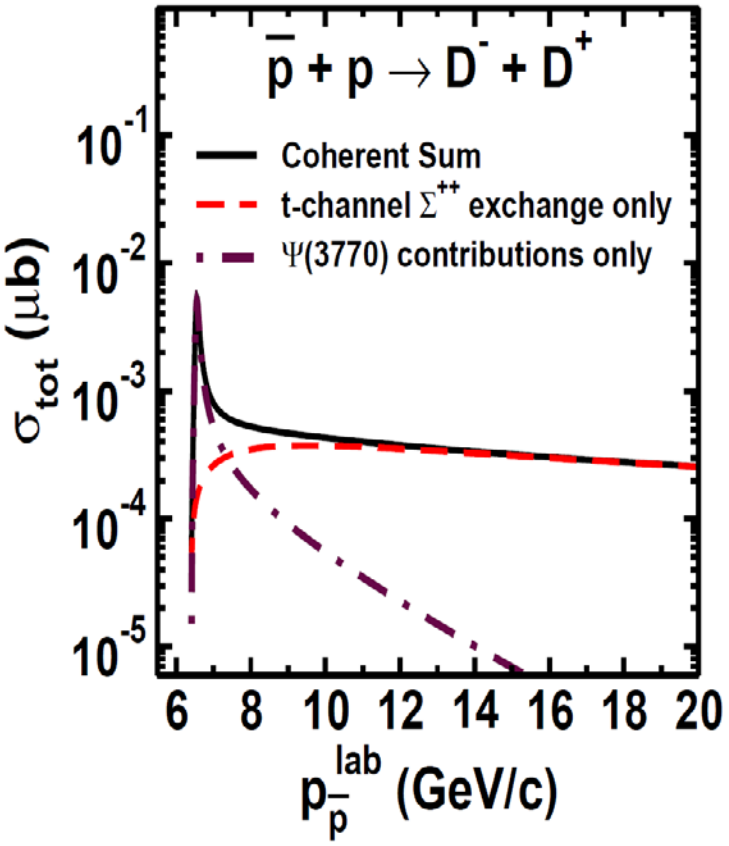




Open Charm Production through Baryon Exchange

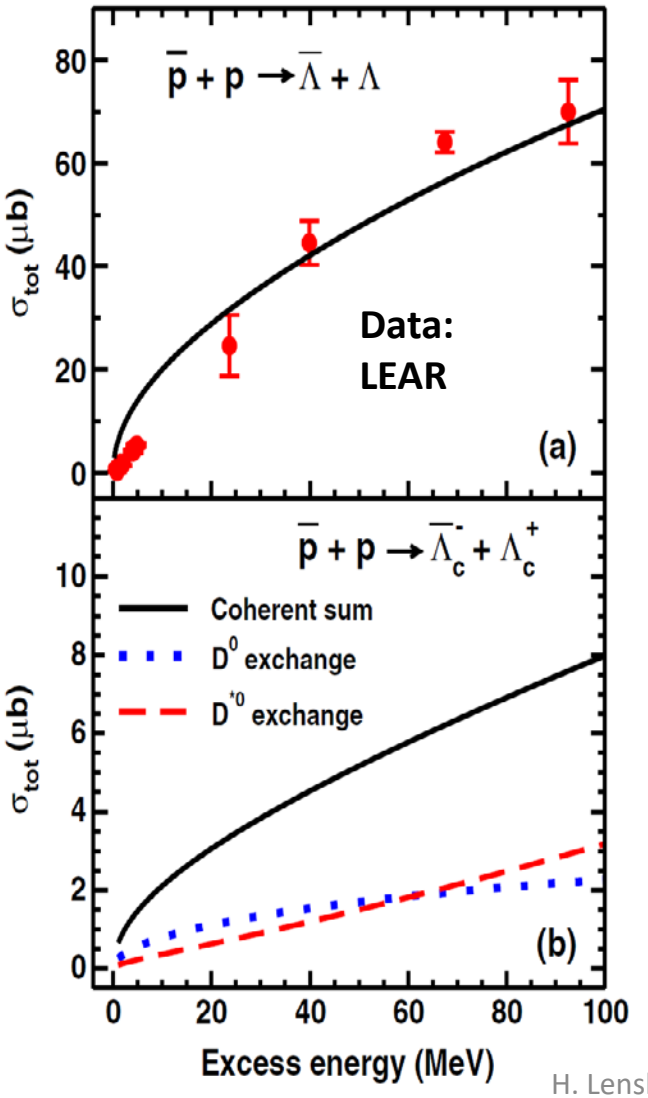


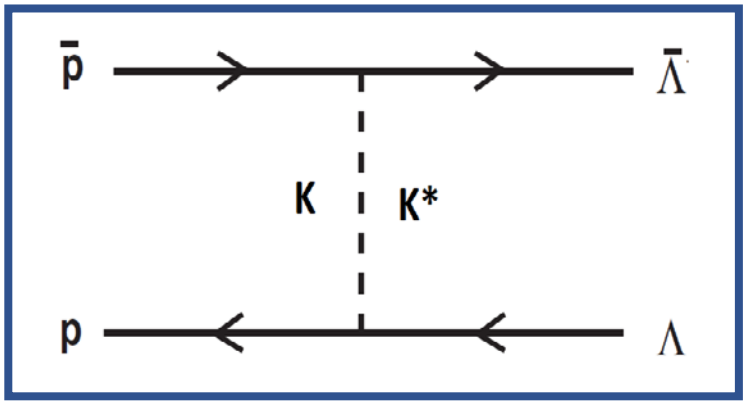


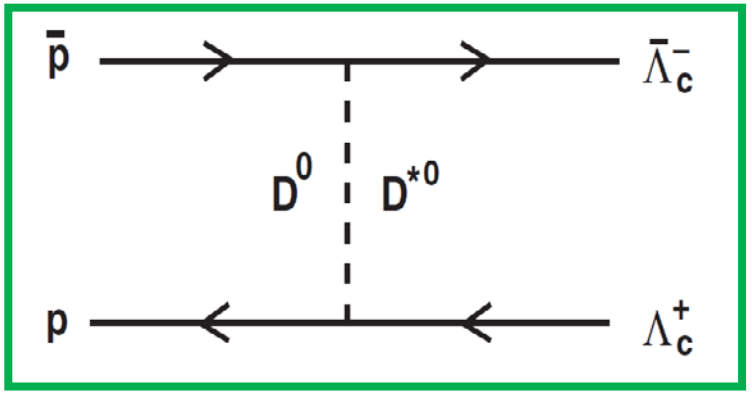


Antiproton-Proton Annihilation into Antibaryon-Baryon Pairs: The Hadronic Approach

(R. Sham, H.L., PRD 90 (2014) 014017 & PRD 93 (2016) 034016, A.Larionov, H.L., PLB 773 (2017) 470)





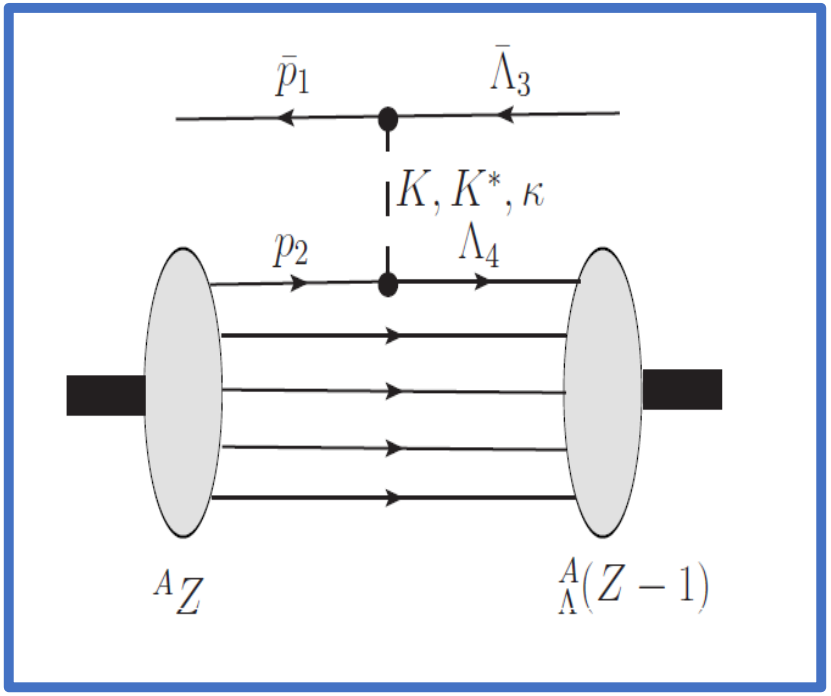


Agenda:

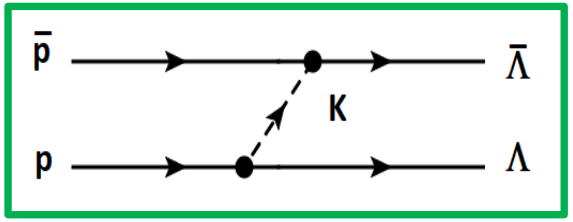
- **Hypernuclear production by coherent antiproton-nucleus reactions**
- **Covariant Lagrangian description of $(\bar{p}, \bar{\Lambda})$ reactions**
- **Probing $\Lambda(1405)$ meson-exchange in $(\bar{p}, \bar{\Lambda})$ hypernuclear production**
- **Hypernuclei from central antiproton-nucleus collisions**
- **Outlook**

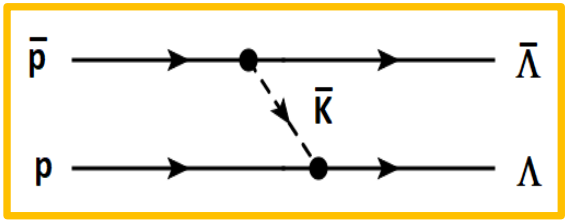
Antiprotonic Hypernuclear Production

Hadronic Scenario for Hypernuclear Production by Strangeness-Transfer

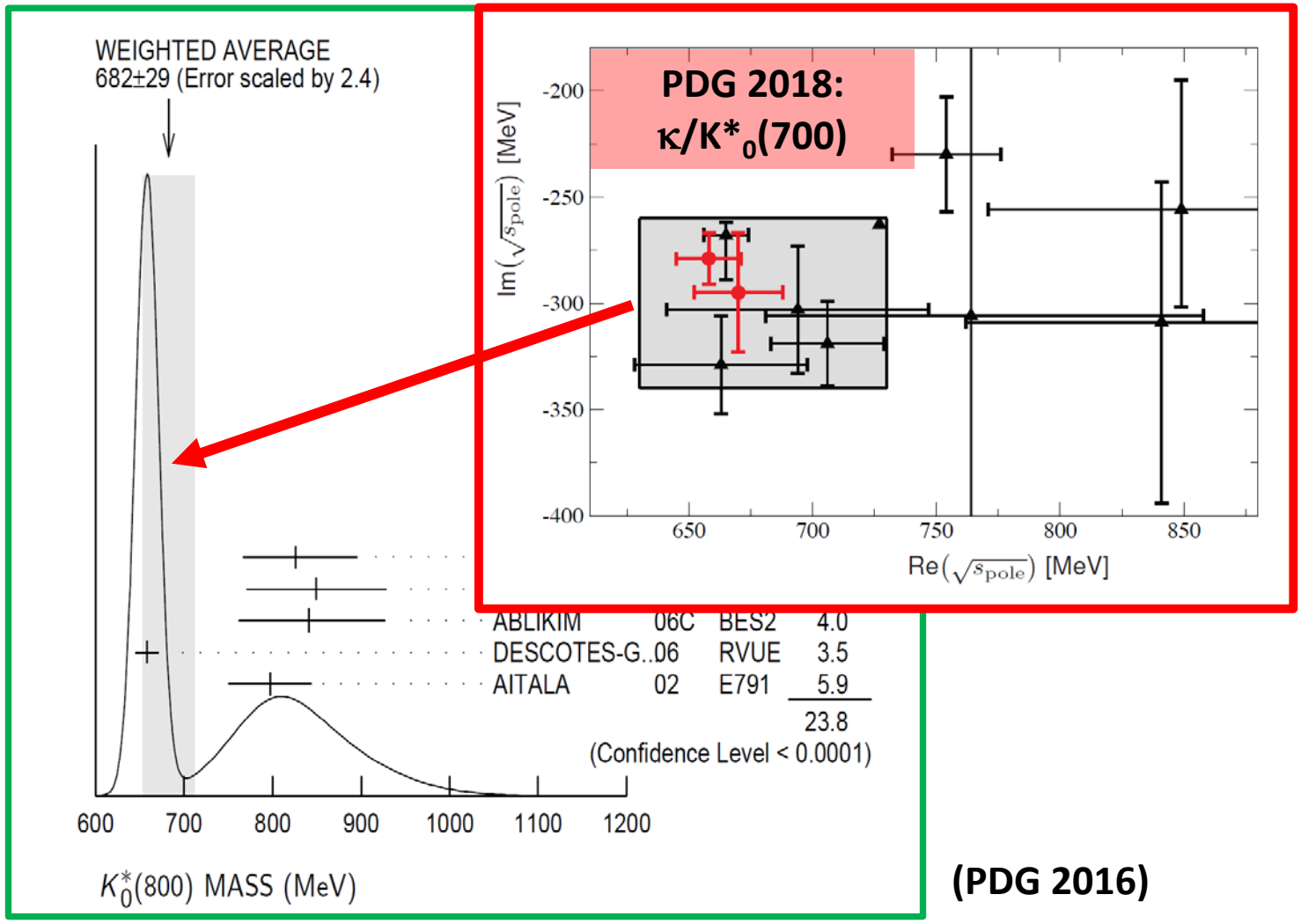


Feynman graph of the ${}^{A}Z(\bar{p},\bar{\Lambda}){}^{A}_{\Lambda}(Z-1)$ process.





Correlated Scalar $[K,\pi]_{0+}$ Exchange: $\kappa/K^*_0(800)$ Spectral Function



(PDG 2016)

Covariant Lagrangian Approach

$$\mathcal{L}_{KN\Lambda} = -ig_{KN\Lambda}\bar{N}\gamma^5\Lambda K + \text{h.c.}\ ,$$

$$\mathcal{L}_{K^*N\Lambda} = \bar{N}\left(G_v\gamma^\mu - \frac{G_t}{m_N + m_\Lambda}\sigma^{\mu\nu}\partial_\nu^{K^*}\right)\Lambda K_\mu^* + \text{h.c.}$$

$$\mathcal{L}_{\kappa N\Lambda} = -g_{\kappa N\Lambda}\bar{N}\Lambda\kappa + \text{h.c.}\ .$$

SU(3)-based coupling constants:

$$g_{KN\Lambda} = -g_{\pi NN}\frac{3-2\alpha_{PS}}{\sqrt{3}}\ ,$$

$$G_{v,t} = -G_{v,t}^{\rho}\frac{3-2\alpha_{E,M}}{\sqrt{3}}\ ,$$

$$g_{\kappa N\Lambda} = -g_{\sigma NN}\frac{3-2\alpha_S}{3-4\alpha_S}\ ,$$

Elementary Reaction Amplitude and Cross Section

$$iM_K = -g^2_{KN\Lambda} F^2_K(q^2) \sqrt{\Omega}\, \bar{u}_{-p_1,-\lambda_1} \gamma^5 u_{-p_3,-\lambda_3} \frac{i}{q^2 - m_K^2} \bar{u}_{p_4\lambda_4} \gamma^5 u_{p_2\lambda_2} \ ,$$

$$iM_{K^*} = -F^2_{K^*}(q^2) \sqrt{\Omega}\, \bar{u}_{-p_1,-\lambda_1} \Gamma^\mu(-q) u_{-p_3,-\lambda_3} iG_{\mu\nu}(q) \bar{u}_{p_4\lambda_4} \Gamma^\nu(q) u_{p_2\lambda_2} \ ,$$

$$iM_\kappa = g^2_{\kappa N\Lambda} F^2_\kappa(q^2) \sqrt{\Omega}\, \bar{u}_{-p_1,-\lambda_1} u_{-p_3,-\lambda_3} \frac{i}{q^2 - m_\kappa^2 + i m_\kappa \Gamma_\kappa} \bar{u}_{p_4\lambda_4} u_{p_2\lambda_2} \ ,$$

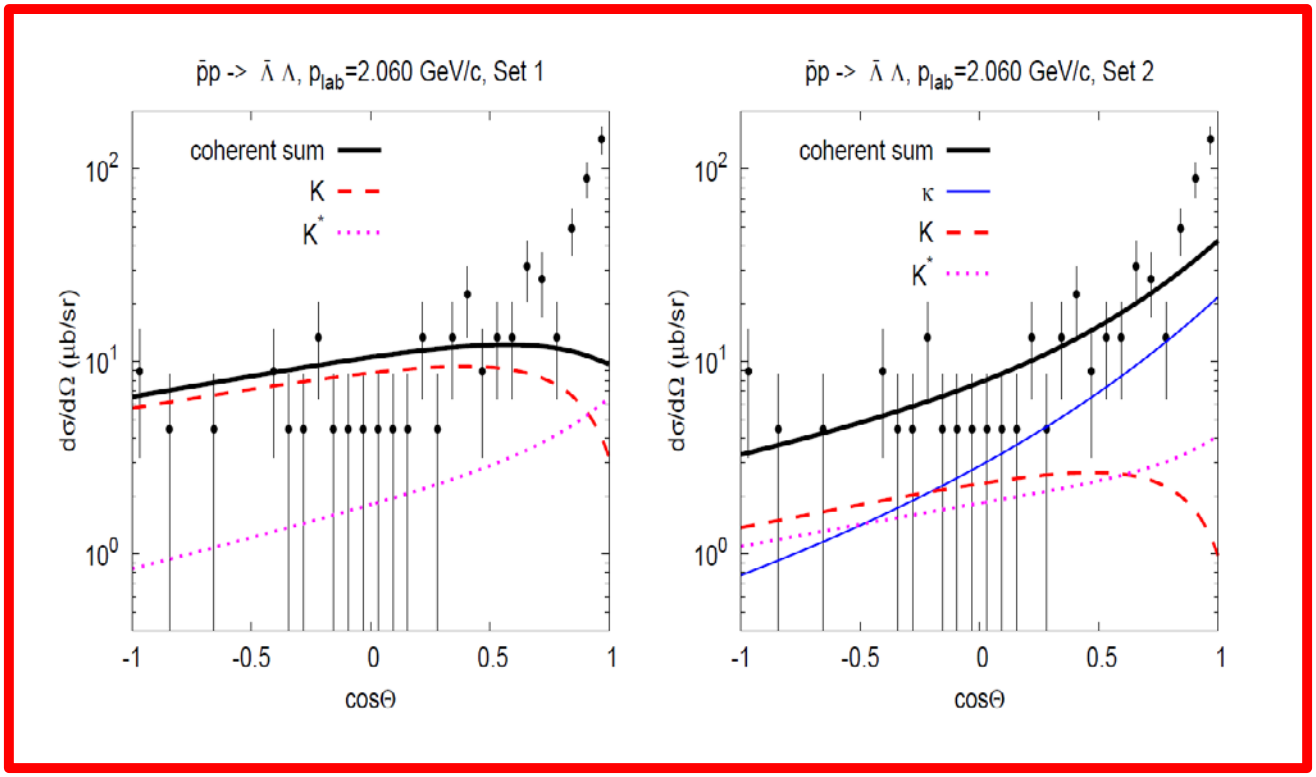
…including elementary annihilation channels by the attenuation factor

$$\Omega \sim e^{-\mathrm{Im}(U_B)} \sim e^{-\lambda \sigma_{reac}}$$

Elementary cross section:

$$\frac{d\sigma_{\bar{p}p\to\bar{\Lambda}\Lambda}}{d\Omega} = \frac{p_{\bar{\Lambda}\Lambda}}{256\pi^2 s p_{\bar{p}p}} \sum_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} |M_K + M_{K^*} + M_\kappa|^2$$

Elementary Reaction and Data
Differential Cross Sections



Without κ-exchange **With κ-exchange**

Evidence for κ/K*(800), i.e. correlated scalar [K,π], exchange!

Antiproton-Nucleus Reaction Amplitude

Including ISI and FSI Nuclear Interactions

$$i\mathcal{M}_K = -g^2_{KN\Lambda} F^2_K(q^2)\sqrt{\Omega}\,\bar{u}_{-p_1,-\lambda_1}\gamma^5 u_{-p_3,-\lambda_3}\frac{i}{q^2-m_K^2}\int d^3r e^{-iqr}\bar{\psi}_4(\boldsymbol{r})\gamma^5\psi_2(\boldsymbol{r})\,F_A(\boldsymbol{r})$$

$$i\mathcal{M}_{K^*} = -F^2_{K^*}(q^2)\sqrt{\Omega}\,\bar{u}_{-p_1,-\lambda_1}\Gamma^\mu(-q)u_{-p_3,-\lambda_3}iG_{\mu\nu}(q)\int d^3r e^{-iqr}\bar{\psi}_4(\boldsymbol{r})\Gamma^\nu(q)\psi_2(\boldsymbol{r})\,F_A(\boldsymbol{r})$$

$$i\mathcal{M}_\kappa = g^2_{\kappa N\Lambda} F^2_\kappa(q^2)\sqrt{\Omega}\,\bar{u}_{-p_1,-\lambda_1}u_{-p_3,-\lambda_3}\frac{i}{q^2-m_\kappa^2+im_\kappa\Gamma_\kappa}\int d^3r e^{-iqr}\bar{\psi}_4(\boldsymbol{r})\psi_2(\boldsymbol{r})\,F_A(\boldsymbol{r})$$

Including ISI and FSI Nuclear Interactions

$$F_A(r) = F_{\bar{p}}(r)F_{\bar{\Lambda}}(r)$$

Nuclear Reaction Coefficients in Glauber or Eikonal Approximation
…see A.Larionov, H.L., Nucl.Phys. A957 (2017) 450

Hypernuclear Production on ^{40}Ar

$$\bar{p} + {}^{40}Ar \rightarrow \bar{\Lambda} + {}^{40}_{\Lambda}Cl \;\; @ \; p_{Lab} = \; 2GeV/c$$

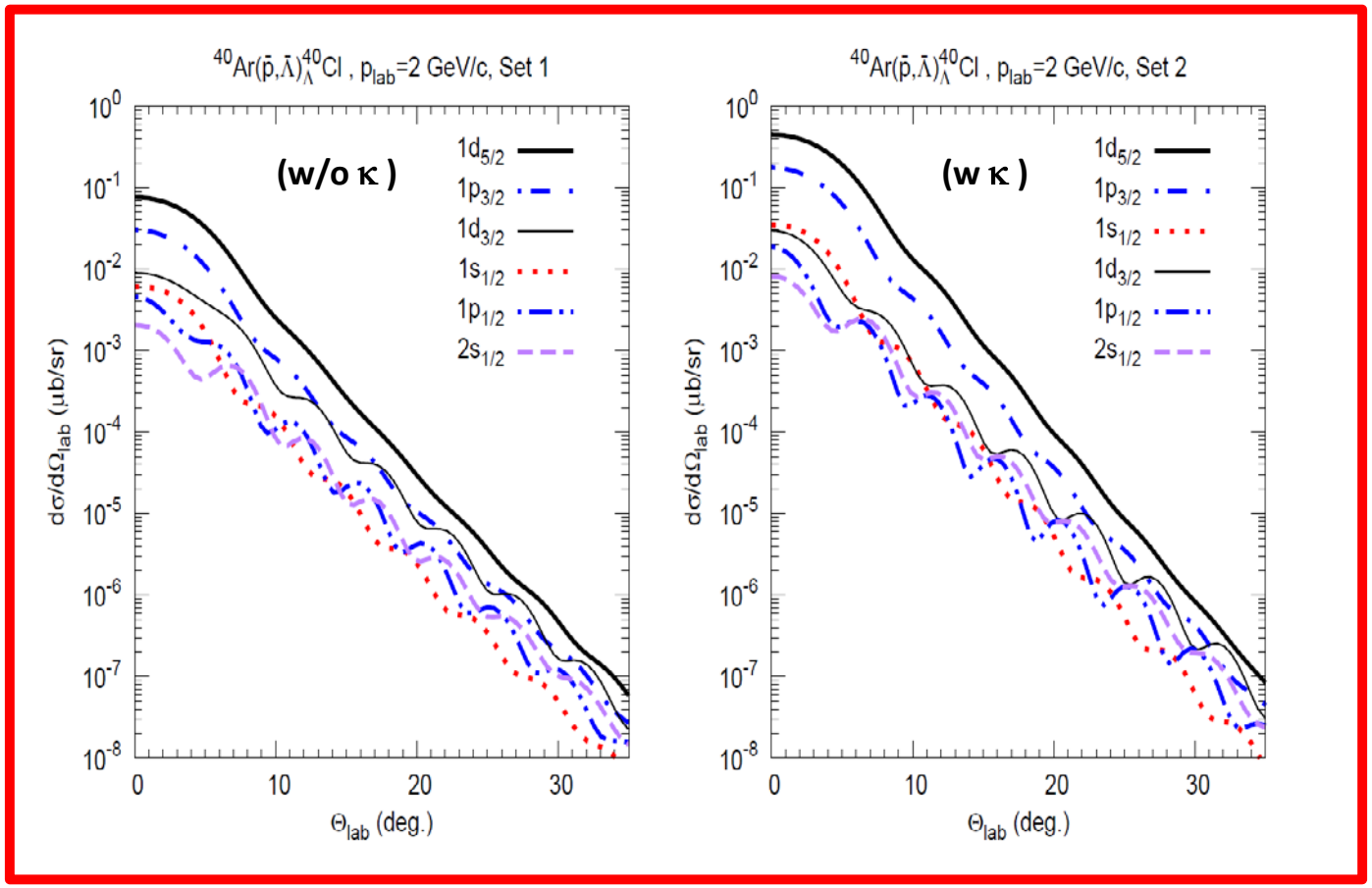
→ **PANDA @ FAIR**

$^{40}_{\Lambda}$Cl: RMF Λ single particle spectrum

Λ state	B_Λ [MeV]
$1s_{1/2}$	18.55 (18.7 ± 1.1)
$1p_{3/2}$	10.20 (9.9 ± 1.1)
$1p_{1/2}$	9.26 (9.9 ± 1.1)
$1d_{5/2}$	2.14 (1.5 ± 1.1)
$2s_{1/2}$	1.44
$1d_{3/2}$	0.84 (1.5 ± 1.1)

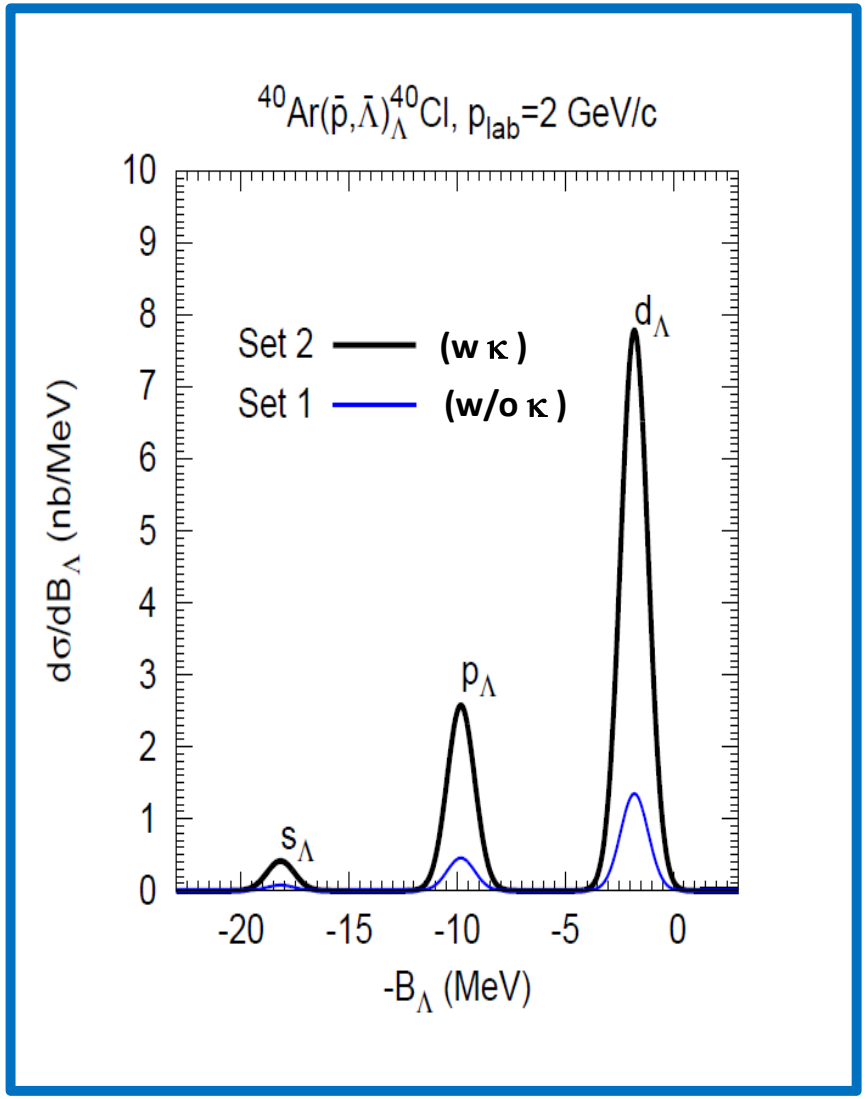
Binding energies of the Λ states in the $^{40}_{\Lambda}$Cl nucleus. Empirical Λ binding energies (spin-orbit splitting not resolved) for $^{40}_{\Lambda}$Ca are given in brackets.

Hypernuclear Production on ^{40}Ar
Differential Cross Sections for Λ Bound States



Without κ-exchange **With κ-exchange**

Hypernuclear Production
Spectral Distribution of Λ Bound States

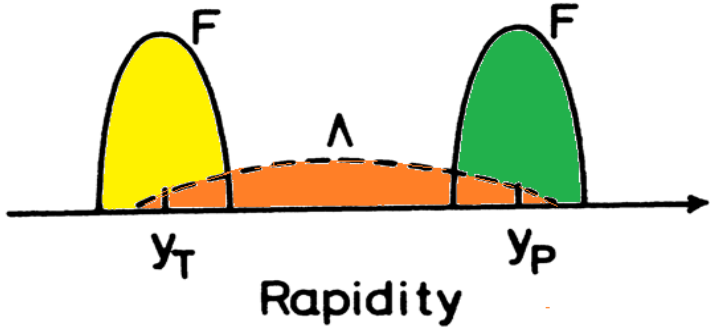


Multi-Strangeness Production by Antiproton Annihilation in Central $\bar{p}$A Collisions

…see H.L. et al., PPNP 98 (2018) 119

Transport Theory:
Formation of a Hypernucleus by Fragmentation and Hyperon Capturing

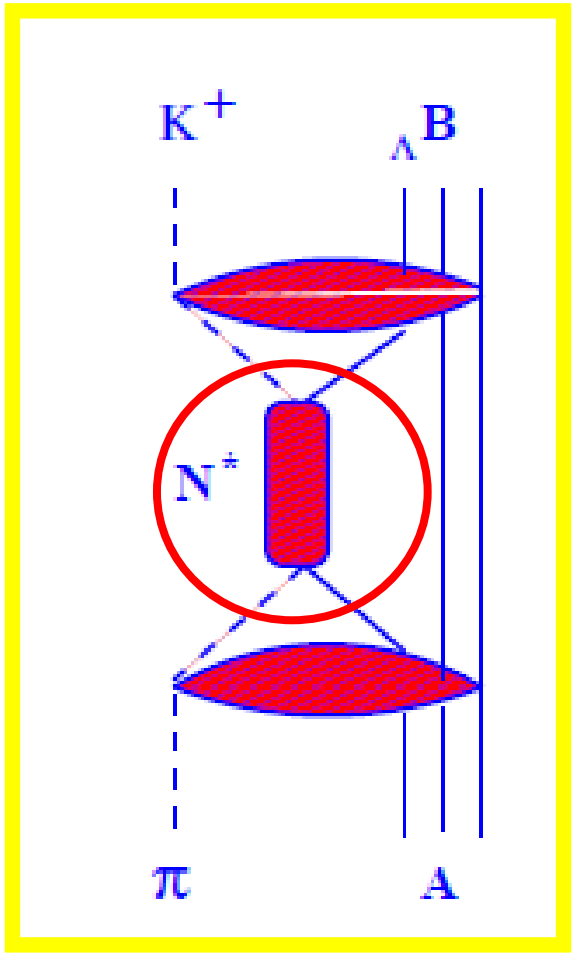
$$\frac{\gamma}{\sigma_r}\frac{d^3\sigma^{(\Lambda F)}}{dk_c^2} = \left[\frac{m_\Lambda + m_F}{m_\Lambda m_F}\right]^3 S_{\Lambda F}\left[\frac{\gamma}{\sigma_r}\frac{d^3\sigma^{(\Lambda)}}{dk_c^3}\right]\left[\frac{\gamma}{\sigma_r}\frac{d^3\sigma^{(F)}}{dk_c^3}\right]$$



Λ Production X-section

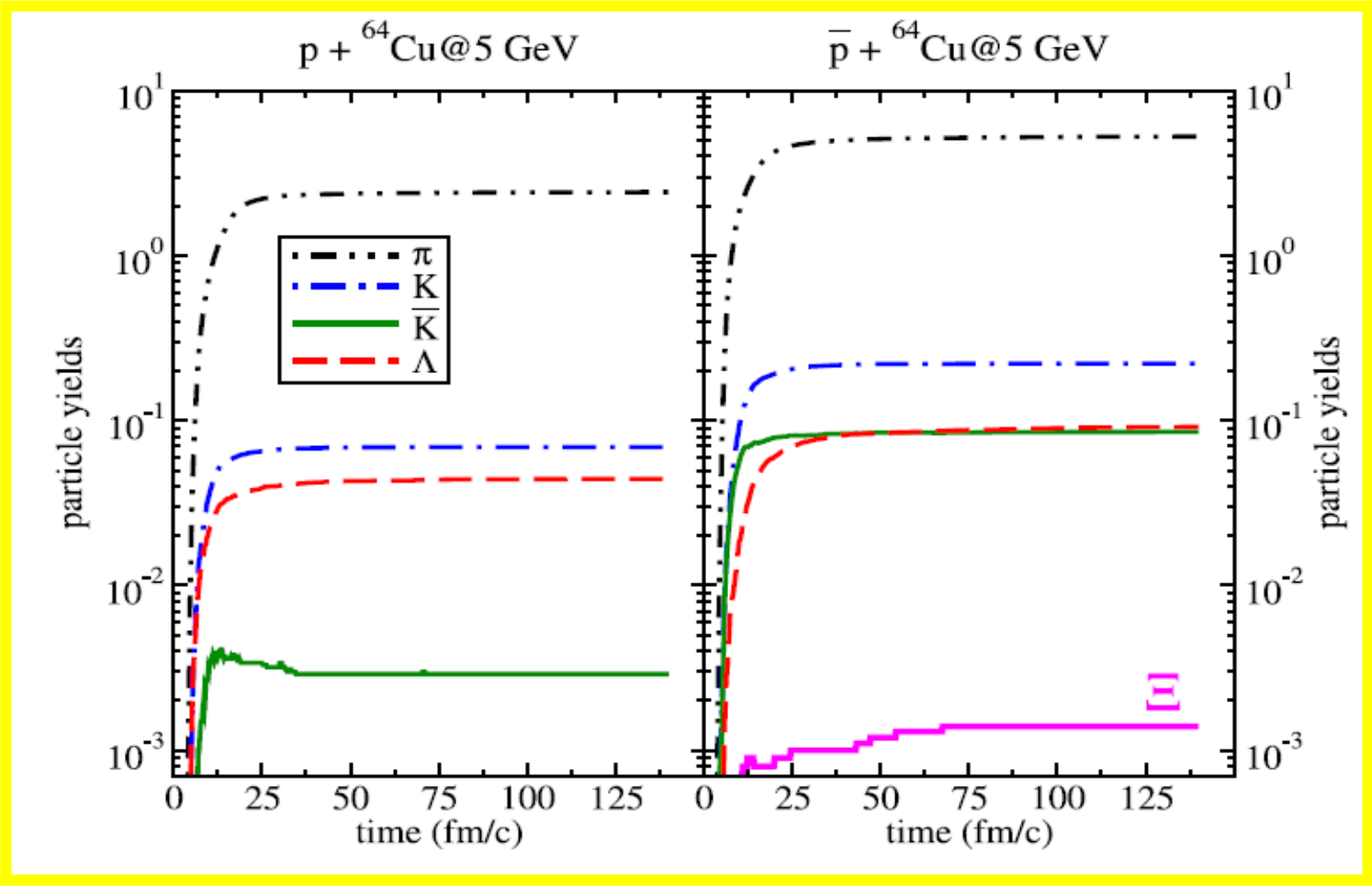
Fragment Production X-section

Antiproton Annihilation → Meson-rich Environment!

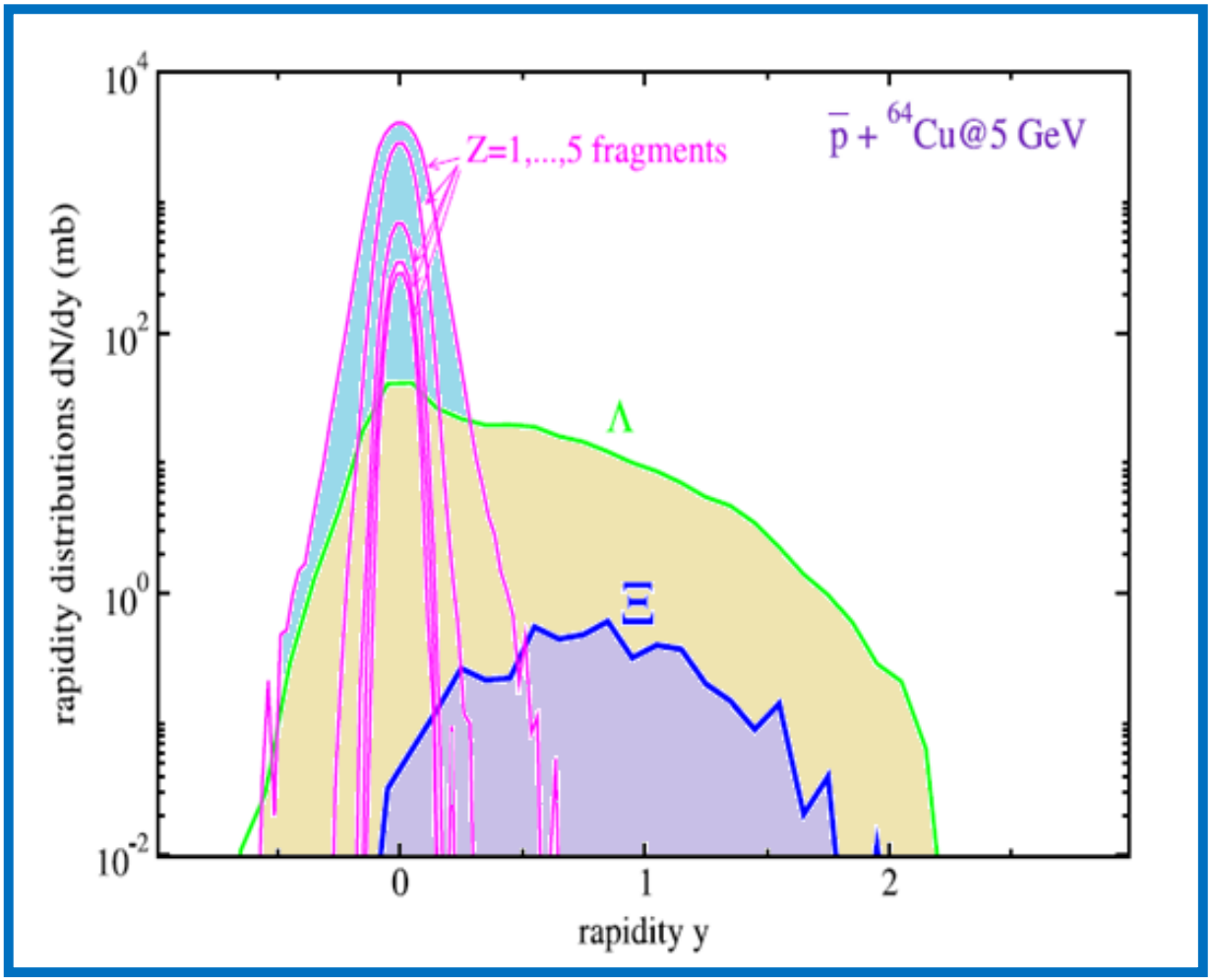


Important Secondary Process:
Strangeness Production through Resonances

Hadro-Production in Proton and Antiproton Collisions on Nuclei as a Function of Reaction Time

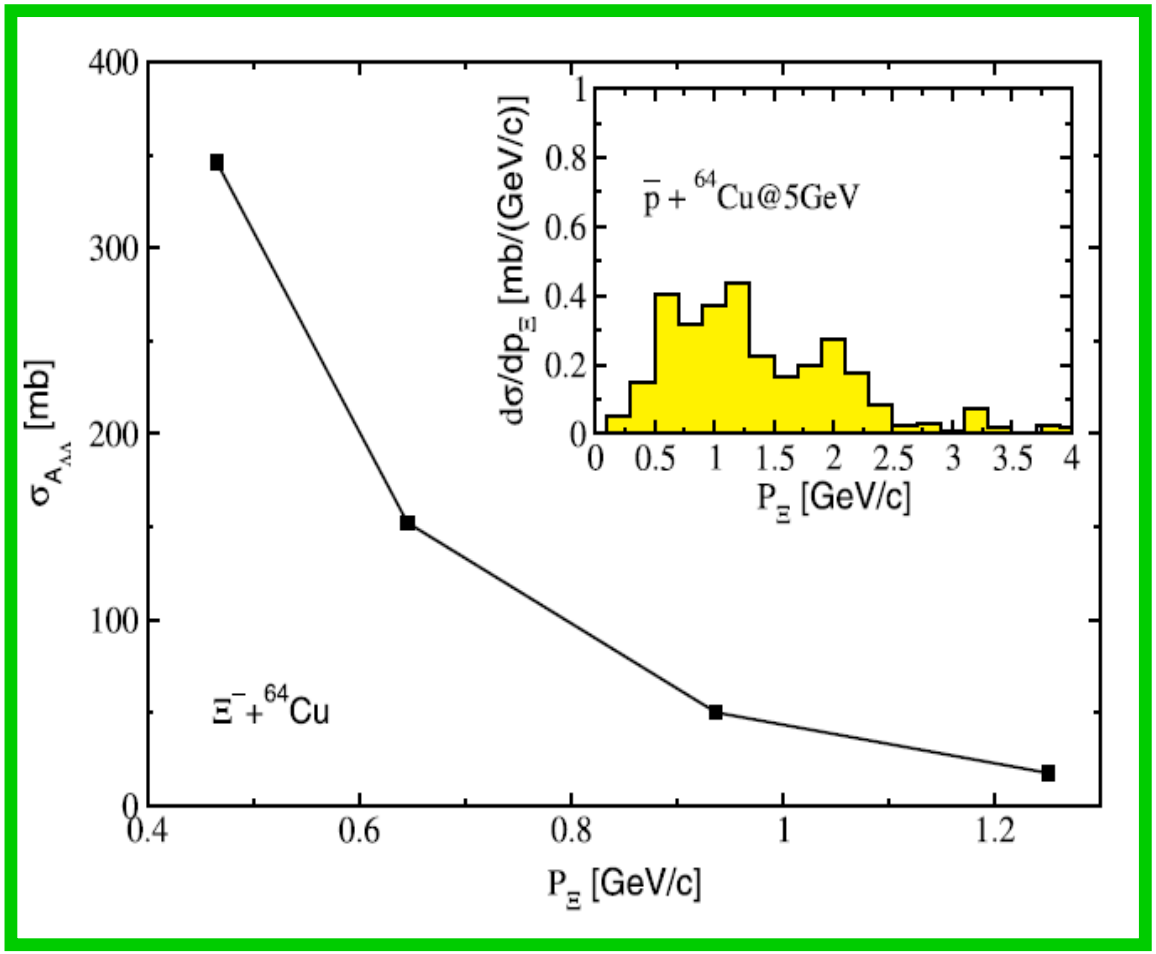


Rapidity Distribution of Fragments



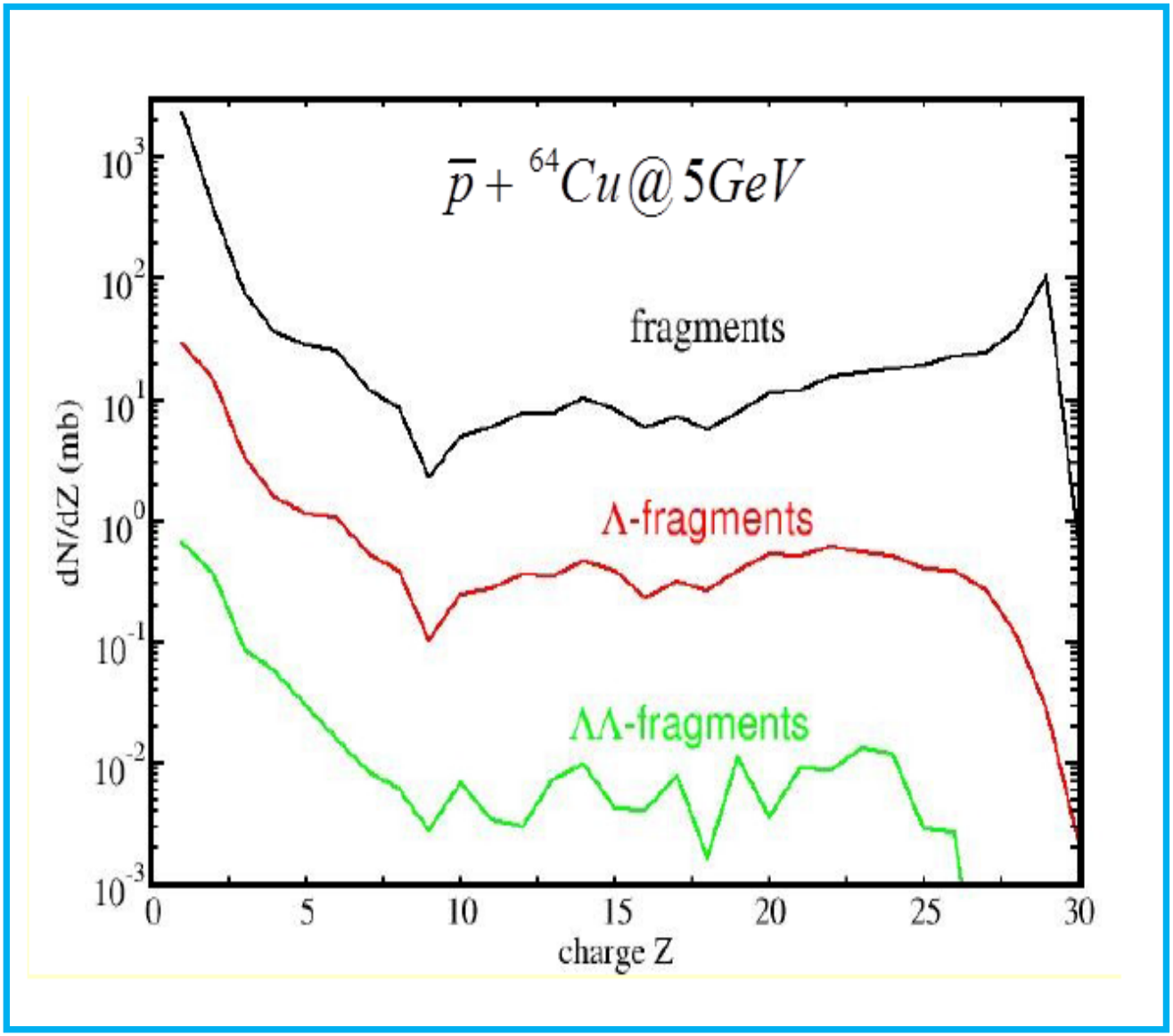
GiBUU + SMM calculations for the rapidity distributions of fragments with charge $Z = 1, \ldots, 5$ and hyperons with strangeness $S = -1$ (Λ) and $S = -2$ (Ξ), as indicated, for inclusive $\bar{p}$ + Cu@5 GeV reactions.

Preparation of Ξ Secondary Beam and ΛΛ Nuclei



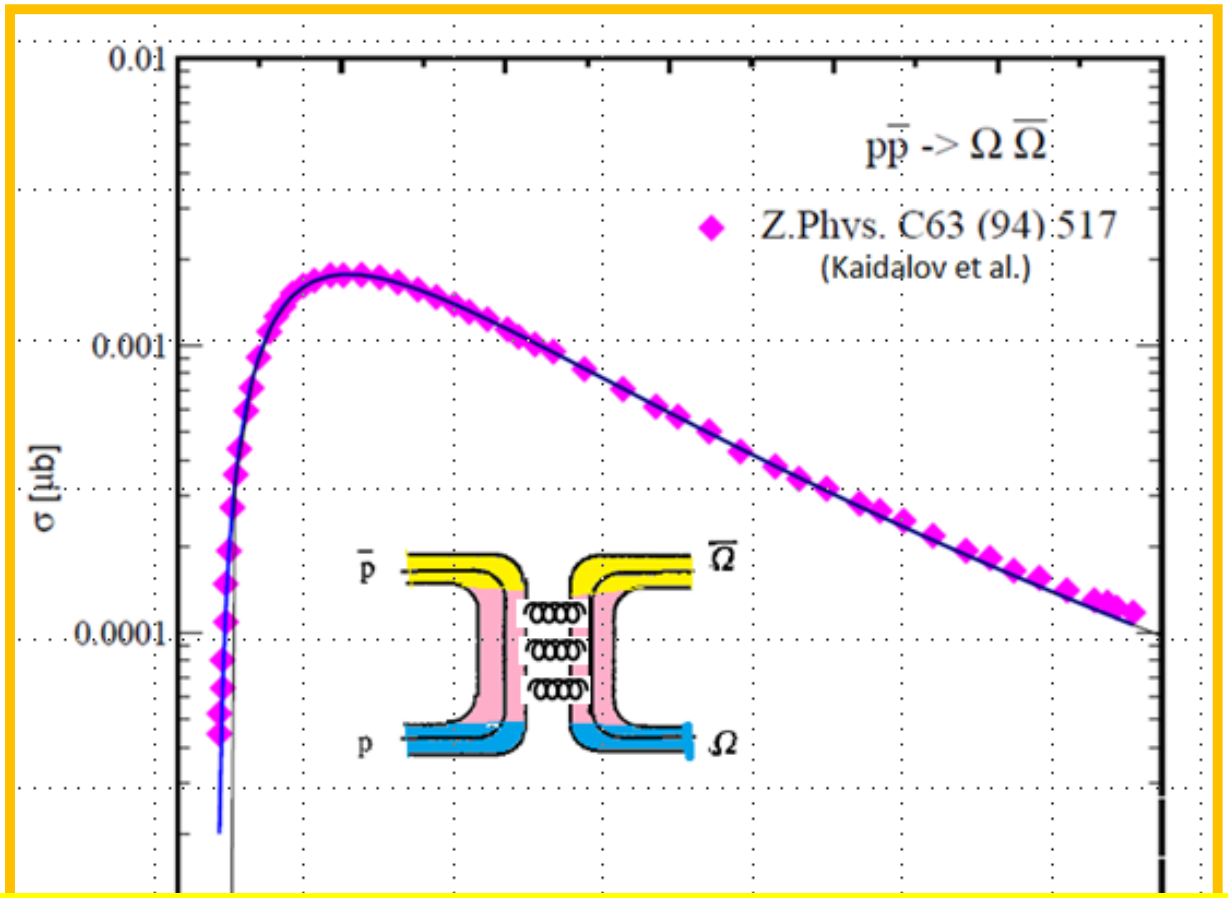
The insert panel shows now the Ξ-production cross section from $\bar{p}$-collisions on the first target, as indicated.

Production of S=-1 and S=-2 Hypernuclei



The S=-3 Sector: Ω^- Production

Elementary Ω^- Production by Antiproton-Proton Annihilation

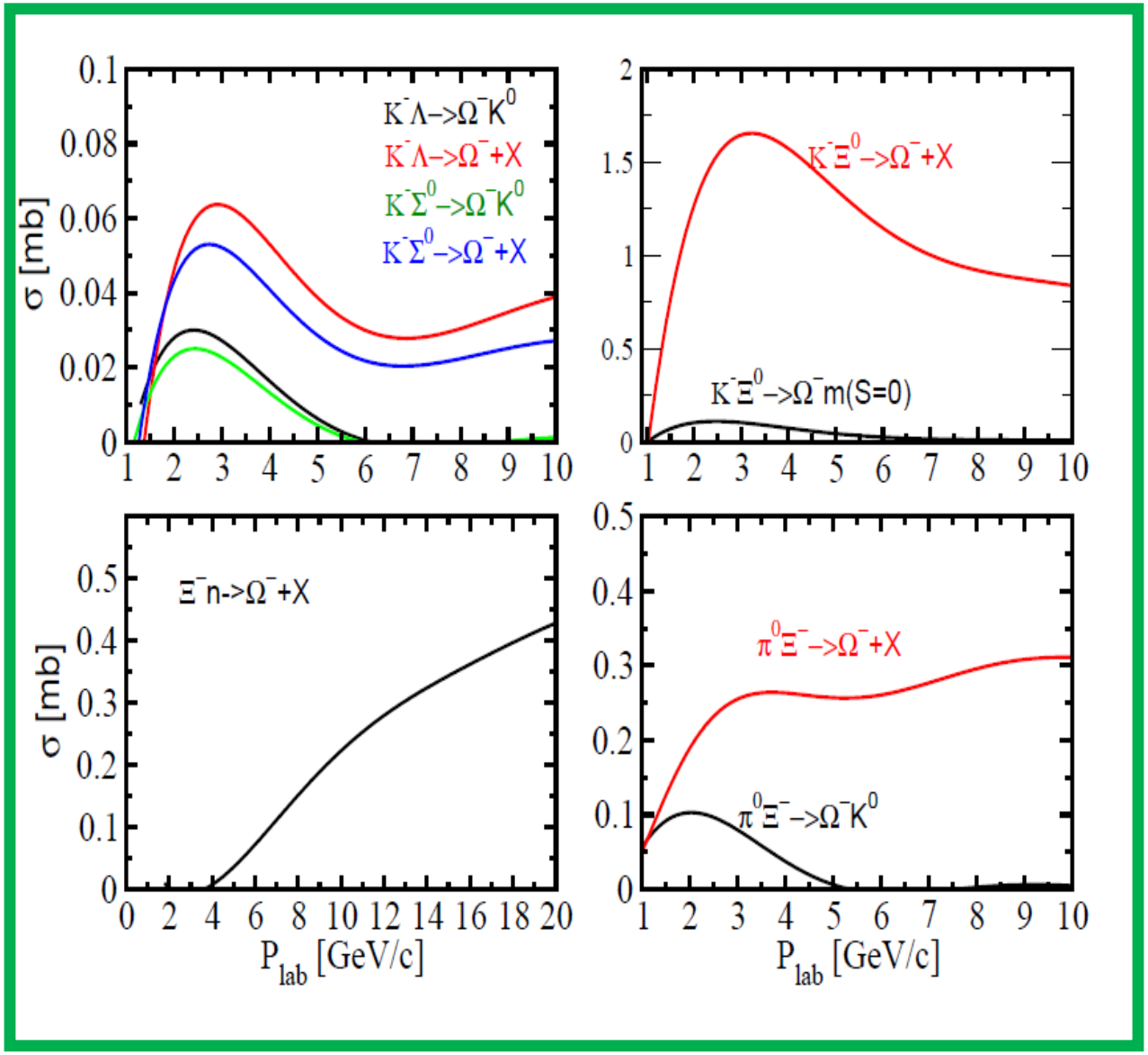


OZI-Rule:

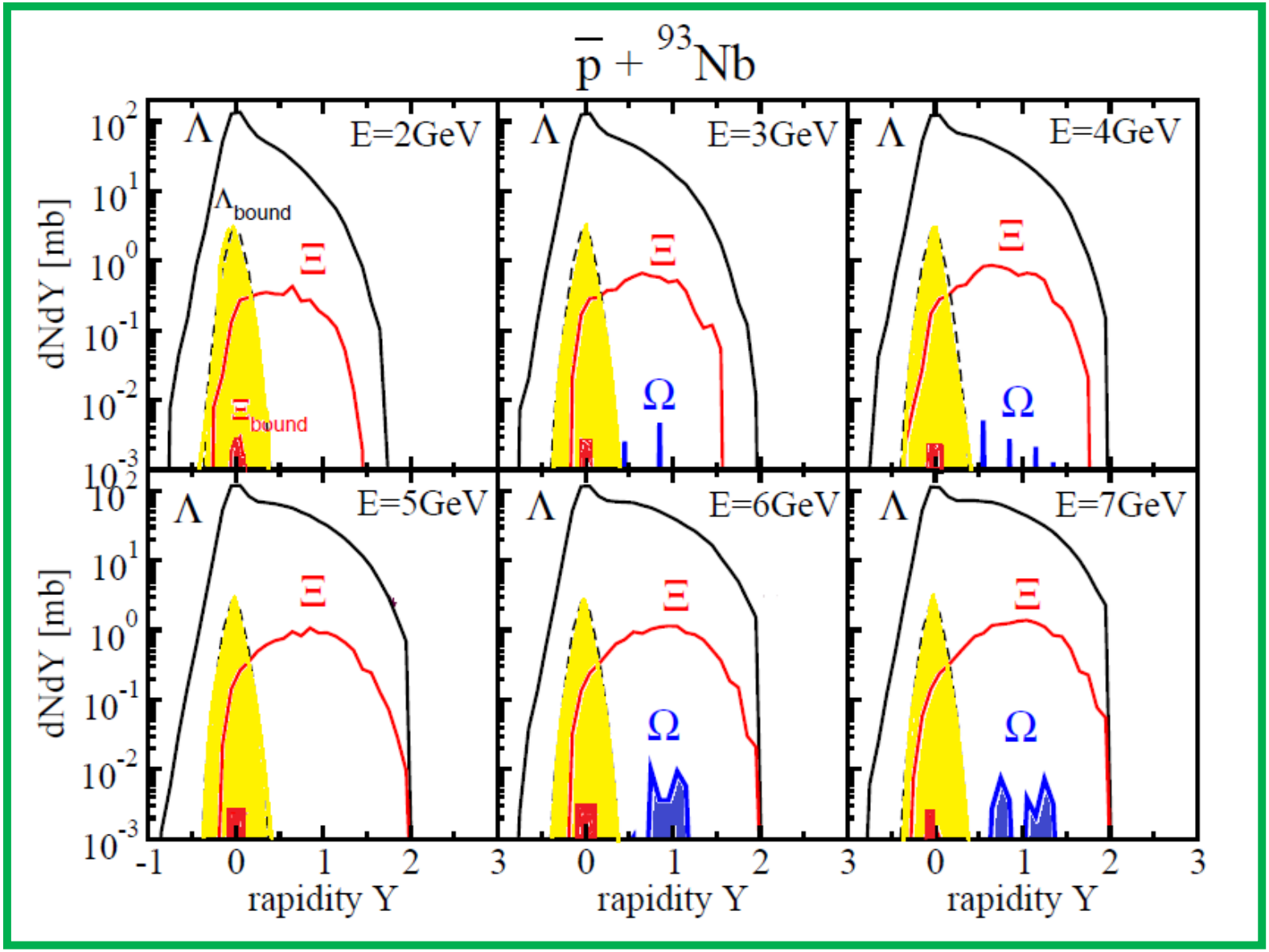
Diagrams which can be split only by cutting gluon lines are suppressed

(Okuba, Zweig, Iizuka)

Solution: In-Medium Ω^- Production by Secondary Reactions



Λ, Ξ, Ω⁻ Production in Antiproton-Nucleus Collisions



Summary and Outlook

- **Covariant description of hadron production in antiproton-proton reactions**
- **Strangeness and charm production in elementary reactions**
- **Hypernuclear production by quasi-elastic strangeness exchange**
- **Correlated $[K,\pi]_{0+}$ exchange by $\kappa/K^*_0(700)$ meson exchange**
- **Mulit-Strangeness production in central antiproton-nucleus collisions**
- ***Continuum dynamics of Λ-A and Σ–A systems***
- ***Dymamical description of the „κ"=π+K channel***
- ***Charmed hypernuclei?***

…with most essential contributions by
Theo Gaitanos, Alexei Larionov, and Radhey Shyam!

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