Production of strange and charmed baryons in pion-induced reactions

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- Kotaro Shirotori (RCNP)

Outline

Investigation of strange sector

Extension (Prediction) to charm sector

PRODUCTION of HADRONS

$$\pi^- p \rightarrow K^{*0}\Lambda$$
$$\pi^- p \rightarrow K^{*0}\Sigma^0$$
$$\pi^- p \rightarrow K^{*+}\Sigma^-$$

$$\pi^- p \rightarrow K^0\Lambda$$
$$\pi^- p \rightarrow K^0\Sigma^0$$
$$\pi^- p \rightarrow K^+\Sigma^-$$

$$\gamma p \rightarrow K^{*+}\Lambda$$
$$\gamma p \rightarrow K^{*+}\Sigma^0$$
$$\gamma p \rightarrow K^{*0}\Sigma^+$$

$$\gamma p \rightarrow K^+\Lambda$$
$$\gamma p \rightarrow K^+\Sigma^0$$
$$\gamma p \rightarrow K^0\Sigma^+$$

$$\pi^- p \rightarrow \phi n$$
$$\gamma p \rightarrow \phi p$$

O u t l i n e

PRODUCTION of HADRONS

Investigation of strange sector		Extension (Prediction) to charm sector
$\pi^- p \rightarrow K^{*0}\Lambda$		$\pi^- p \rightarrow D^{*-}\Lambda_c^+$
$\pi^- p \rightarrow K^{*0}\Sigma^0$		$\pi^- p \rightarrow D^{*-}\Sigma_c^+$
$\pi^- p \rightarrow K^{*+}\Sigma^-$		$\pi^- p \rightarrow \bar{D}^{*0}\Sigma_c^0$
$\pi^- p \rightarrow K^0\Lambda$		$\pi^- p \rightarrow D^-\Lambda_c^+$
$\pi^- p \rightarrow K^0\Sigma^0$		$\pi^- p \rightarrow D^-\Sigma_c^+$
$\pi^- p \rightarrow K^+\Sigma^-$	s → c	$\pi^- p \rightarrow \bar{D}^0\Sigma_c^0$
$\gamma p \rightarrow K^{*+}\Lambda$		$\gamma p \rightarrow \bar{D}^{*0}\Lambda_c^+$
$\gamma p \rightarrow K^{*+}\Sigma^0$		$\gamma p \rightarrow \bar{D}^{*0}\Sigma_c^+$
$\gamma p \rightarrow K^{*0}\Sigma^+$		$\gamma p \rightarrow D^{*-}\Sigma_c^{++}$
$\gamma p \rightarrow K^+\Lambda$		$\gamma p \rightarrow \bar{D}^0\Lambda_c^+$
$\gamma p \rightarrow K^+\Sigma^0$		$\gamma p \rightarrow \bar{D}^0\Sigma_c^+$
$\gamma p \rightarrow K^0\Sigma^+$		$\gamma p \rightarrow D^-\Sigma_c^{++}$
$\pi^- p \rightarrow \phi n$		$\pi^- p \rightarrow J/\Psi n$
$\gamma p \rightarrow \phi p$		$\gamma p \rightarrow J/\Psi p$

Outline

PRODUCTION of HADRONS

Investigation of strange sector		Extension (Prediction) to charm sector	
$\pi^- p \rightarrow K^{*0}\Lambda$		$\pi^- p \rightarrow D^{*-}\Lambda_c^+$	→ (O) PRD (2015) with J-PARC collaborators
$\pi^- p \rightarrow K^{*0}\Sigma^0$		$\pi^- p \rightarrow D^{*-}\Sigma_c^+$	
$\pi^- p \rightarrow K^{*+}\Sigma^-$		$\pi^- p \rightarrow \bar{D}^{*0}\Sigma_c^0$	
$\pi^- p \rightarrow K^0\Lambda$		$\pi^- p \rightarrow D^-\Lambda_c^+$	→ (O) Drafting
$\pi^- p \rightarrow K^0\Sigma^0$		$\pi^- p \rightarrow D^-\Sigma_c^+$	
$\pi^- p \rightarrow K^+\Sigma^-$		$\pi^- p \rightarrow \bar{D}^0\Sigma_c^0$	
	s → c		
$\gamma p \rightarrow K^{*+}\Lambda$		$\gamma p \rightarrow \bar{D}^{*0}\Lambda_c^+$	→ (O) Only strange sector
$\gamma p \rightarrow K^{*+}\Sigma^0$		$\gamma p \rightarrow \bar{D}^{*0}\Sigma_c^+$	
$\gamma p \rightarrow K^{*0}\Sigma^+$		$\gamma p \rightarrow D^{*-}\Sigma_c^{++}$	
$\gamma p \rightarrow K^+\Lambda$		$\gamma p \rightarrow \bar{D}^0\Lambda_c^+$	→ (Δ) Preliminary (strange sector) with LEPS collaborators
$\gamma p \rightarrow K^+\Sigma^0$		$\gamma p \rightarrow \bar{D}^0\Sigma_c^+$	
$\gamma p \rightarrow K^0\Sigma^+$		$\gamma p \rightarrow D^-\Sigma_c^{++}$	
			Pc(4380), Pc(4450) ?
$\pi^- p \rightarrow \phi n$		$\pi^- p \rightarrow \boxed{J/\Psi n}$	→ (Δ) Preliminary (charm sector)
$\gamma p \rightarrow \phi p$		$\gamma p \rightarrow \boxed{J/\Psi p}$	→ PRD92.034022(2015), Julich

Outline

PRODUCTION of HADRONS

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$\pi^- p \to K^{*0}\Lambda$	$\pi^- p \to D^{*-}\Lambda_c^+$
$\pi^- p \to K^{*0}\Sigma^0$	$\pi^- p \to D^{*-}\Sigma_c^+$
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$\pi^- p \to K^0\Lambda$	$\pi^- p \to D^-\Lambda_c^+$
$\pi^- p \to K^0\Sigma^0$	$\pi^- p \to D^-\Sigma_c^+$
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$\gamma p \to K^{*+}\Sigma^0$	$\gamma p \to \bar{D}^{*0}\Sigma_c^+$
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s → c

(O) PRD (2015) with J-PARC collaborators

(O) Drafting

(O) Only strange sector

(Δ) Preliminary (strange sector) with LEPS collaborators

Pc(4380), Pc(4450) ?

(Δ) Preliminary (charm sector)

PRD92.034022(2015), Julich

Outline

$\pi^- p \rightarrow K^{*0}\Lambda$ $\qquad$ $\pi^- p \rightarrow D^{*-}\Lambda_c^+$

$\pi^- p \rightarrow K^{0}\Lambda$ $\qquad$ $\pi^- p \rightarrow D^{-}\Lambda_c^+$

- Motivation
- Strategy
- Formalism
  (Effective Lagrangian & Regge model)
- Results : · total cross sections (σ)
  · differential cross sections
  (dσ/dΩ, dσ/dt)
- Summary & Future plan

I. Motivation

$$\boxed{\pi^- p \to K^{*0}\Lambda \qquad \pi^- p \to D^{*-}\Lambda_c^+}$$

1. Motivation

Baryons from PDG

q=u,d

◇ Light-flavor quark system

◇ Heavy + Light quark system

Light baryons

Charmed baryons

Bottom baryons

qqq

p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	**
$N(1895)$	$1/2^-$	[illegible]
$N(1900)$	$3/2^+$	***
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**

qqs

Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$		*
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	**
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$		**
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1770)$	$1/2^+$	*
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1840)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^-$	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

qss

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*

sss

Ω^-	$3/2^+$	****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

qqQ

qqc

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***

qsc

Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*

ssc

Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*

qqb, qsb, ssb

Λ_b^0	$1/2^+$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
Ω_b^-	$1/2^+$	***

1. Motivation

Baryons from PDG

◇ Charmed baryons are less known than light-flavor baryons.

◇ $\boxed{\text{Heavy + Light quark system}}$

• Recent research ($\underbrace{X, Y, Z,}_{q\bar{q}Q\bar{Q}}$ $\underbrace{P_c^+}_{qqqQ\bar{Q}}$,...) is a hot issue for the last decade

at the [Belle, Babar, Bes, LHCb,...] Collaborations.

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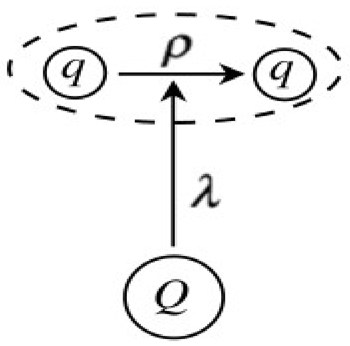
• A charmed baryon (qqQ) is one of the simplest among this system.

• It gives us a hint about a diquark.



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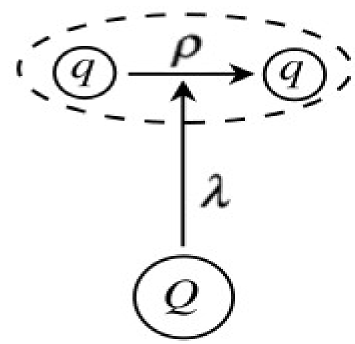

• LHCb, Belle, etc Collaborations are already producing charmed baryons.

Experiments

Limits on Charm Production in Hadronic Interactions near Threshold

Only an upper limit (7-nb) is estimated in 13-GeV/c pion energy.
PRL 55, 154 (1985) (BNL)

$$\pi^- p \rightarrow D^{*-} Y_c \, (Y_c = \Lambda_c^+, \Sigma_c^+, \ldots)$$

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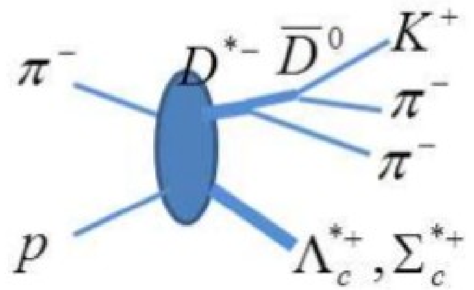
Proposal P50 is submitted at J-PARC

Charmed Baryon Spectroscopy via the (π, D^{*-}) reaction

$$\pi^- p \to D^{*-} Y_c$$



December 10, 2012

◇ The pion beam up to 20 GeV/c will be made.
◇ This energy can produce excited states of energies up to around 1 GeV excitation from the ground state.

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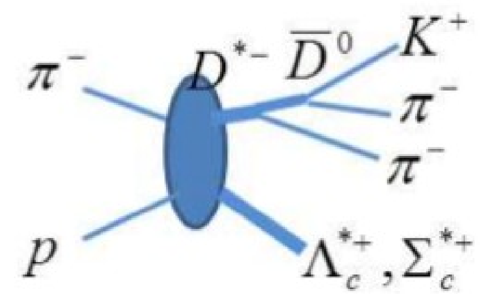


December 10, 2012

◇ The pion beam up to 20 GeV/c will be made.
◇ This energy can produce excited states of energies up to around 1 GeV excitation from the ground state.

A theoretical estimation of the production rate is important.
How to predict?

II. Strategy

$$\boxed{\pi^- p \;\to\; K^{*0}\Lambda \qquad\qquad \pi^- p \to D^{*-}\Lambda_c^+}$$

2. Strategy

We employ effective Lagrangian and Regge model.
How to determine **free parameters** ?

$$\boxed{\pi^- p \to D^{*-} \Lambda_c^+}$$

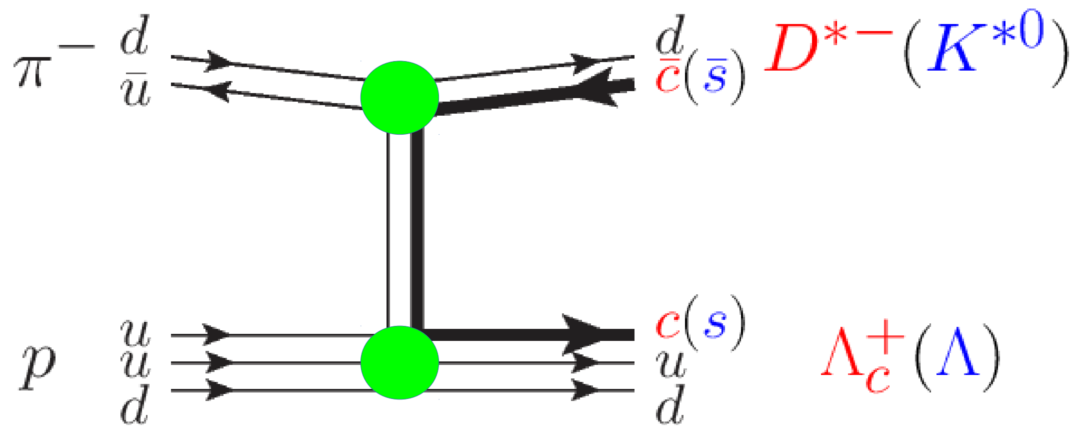
$d\bar{c}$ udc

2. Strategy

We employ effective Lagrangian and Regge model.
How to determine **free parameters** ?

$$\pi^- p \to D^{*-}\Lambda_c^+ \quad \xrightarrow[c \,\to\, s]{} \quad \pi^- p \to K^{*0}\Lambda$$

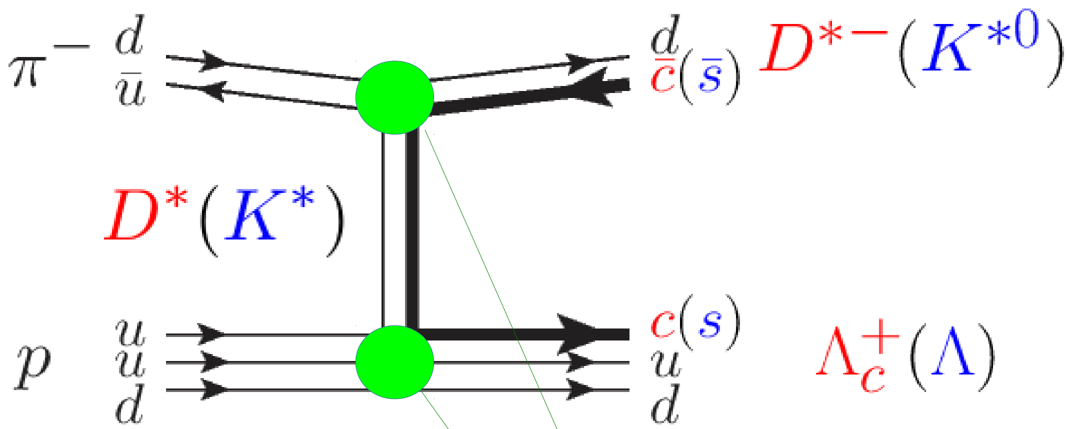
$d\bar{c}$ udc → $d\bar{s}$ uds



We employ effective Lagrangian and Regge model.
How to determine **free parameters** ?

$\pi^- p \to D^{*-}\Lambda_c^+$ $\xrightarrow{\quad c \longrightarrow s \quad}$ $\pi^- p \to K^{*0}\Lambda$

$d\bar{c}$ udc $\qquad$ $d\bar{s}$ uds

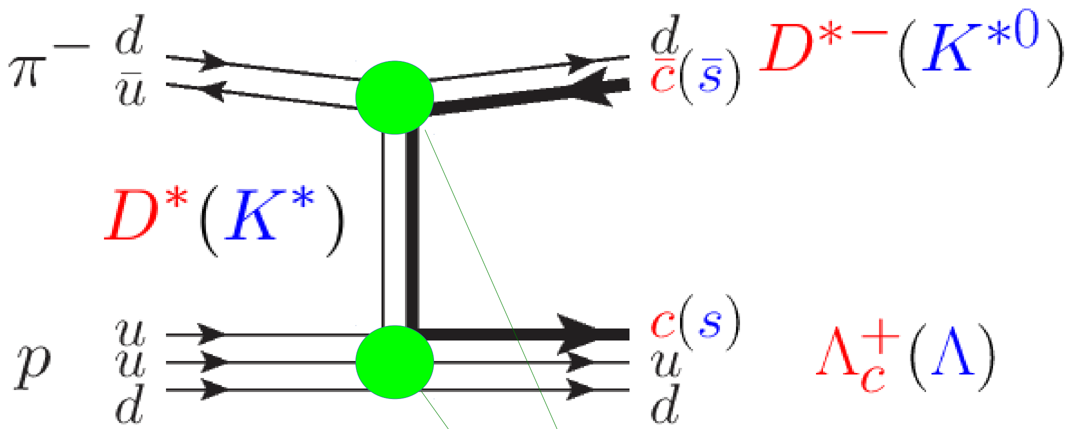


$g_{\pi K^* K^*}$ $\qquad$ $g_{\pi D^* D^*}$

$g_{K^* N \Lambda}$ **?** $g_{D^* N \Lambda_c}$

We employ effective Lagrangian and Regge model.
How to determine **free parameters** ?

$\pi^- p \to D^{*-}\Lambda_c^+$ (d$\bar{c}$ udc) $\xrightarrow{\;c\;\to\;s\;}$ $\pi^- p \to K^{*0}\Lambda$ (d$\bar{s}$ uds)



u,d ≪ s,c

$$g_{\pi K^* K^*} = g_{\pi D^* D^*}$$
$$g_{K^* N\Lambda} = g_{D^* N\Lambda_c}$$

The same **coupling constants** will be used for the corresponding vertices.

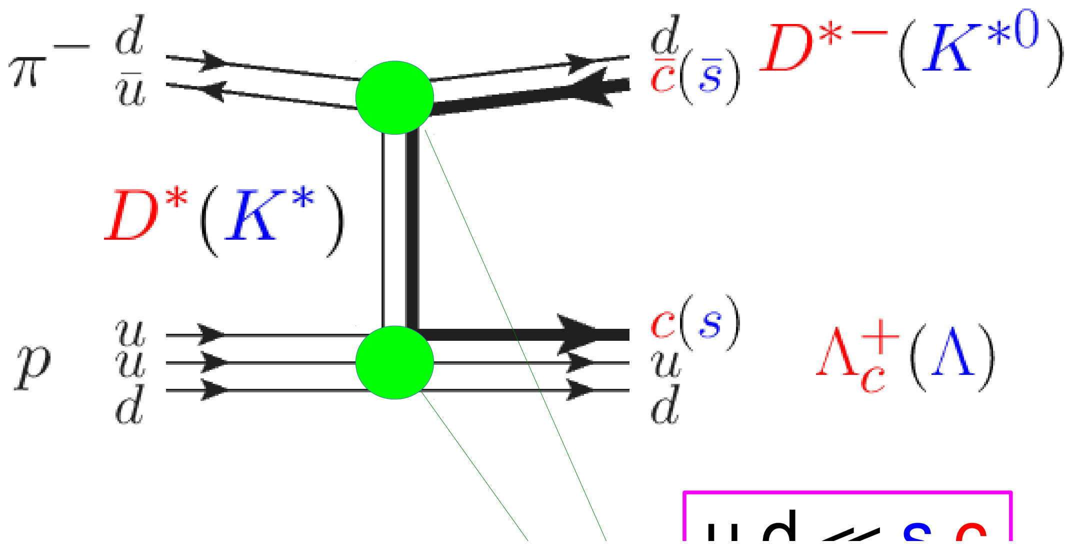
We rely on the strange sector for
the free parameters (**coupling constants** & **form factors**).

We employ effective Lagrangian and Regge model.
How to determine **free parameters** ?

$\pi^- p \to D^{*-}\Lambda_c^+$ — d$\bar{\text{c}}$ udc

c → s

$\pi^- p \to K^{*0}\Lambda$ — d$\bar{\text{s}}$ uds

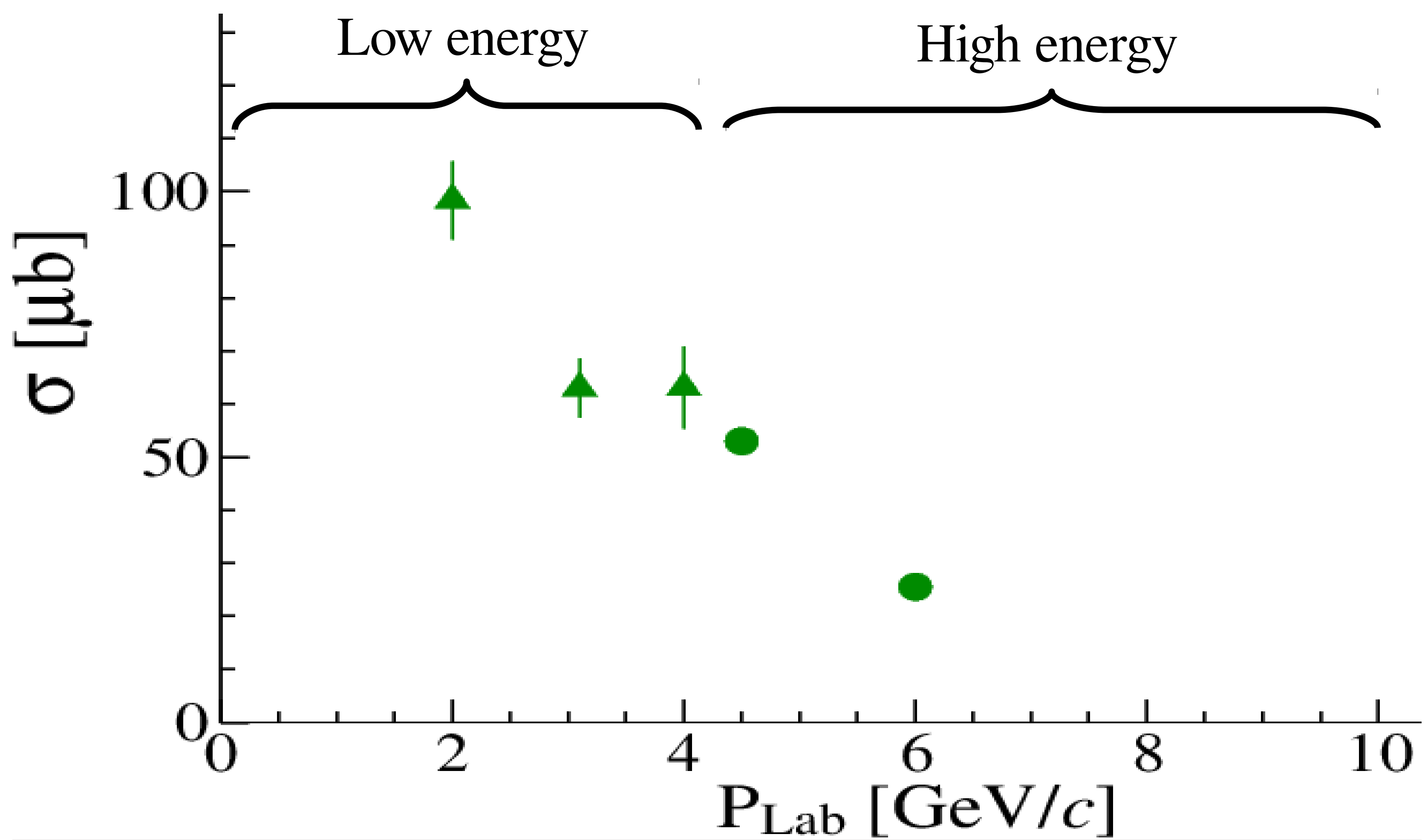


$g_{\pi K K^*}$	$g_{\pi K^* K^*}$	$g_{\pi NN}$	$g_{\pi \Sigma\Lambda}$	$g_{KN\Lambda}$	$g_{K^*N\Lambda}$	$\kappa_{K^*N\Lambda}$	$g_{K^*N\Sigma}$	$\kappa_{K^*N\Sigma}$
6.56	7.45 GeV^{-1}	13.3	11.9	-13.4	-4.26	2.91	-2.46	-0.529

Exp.   SU(3) relation   Nijmegen potential (NSC97a)

How do the two models differ from each other ?

$$\pi^- p \to K^{*0}\Lambda$$

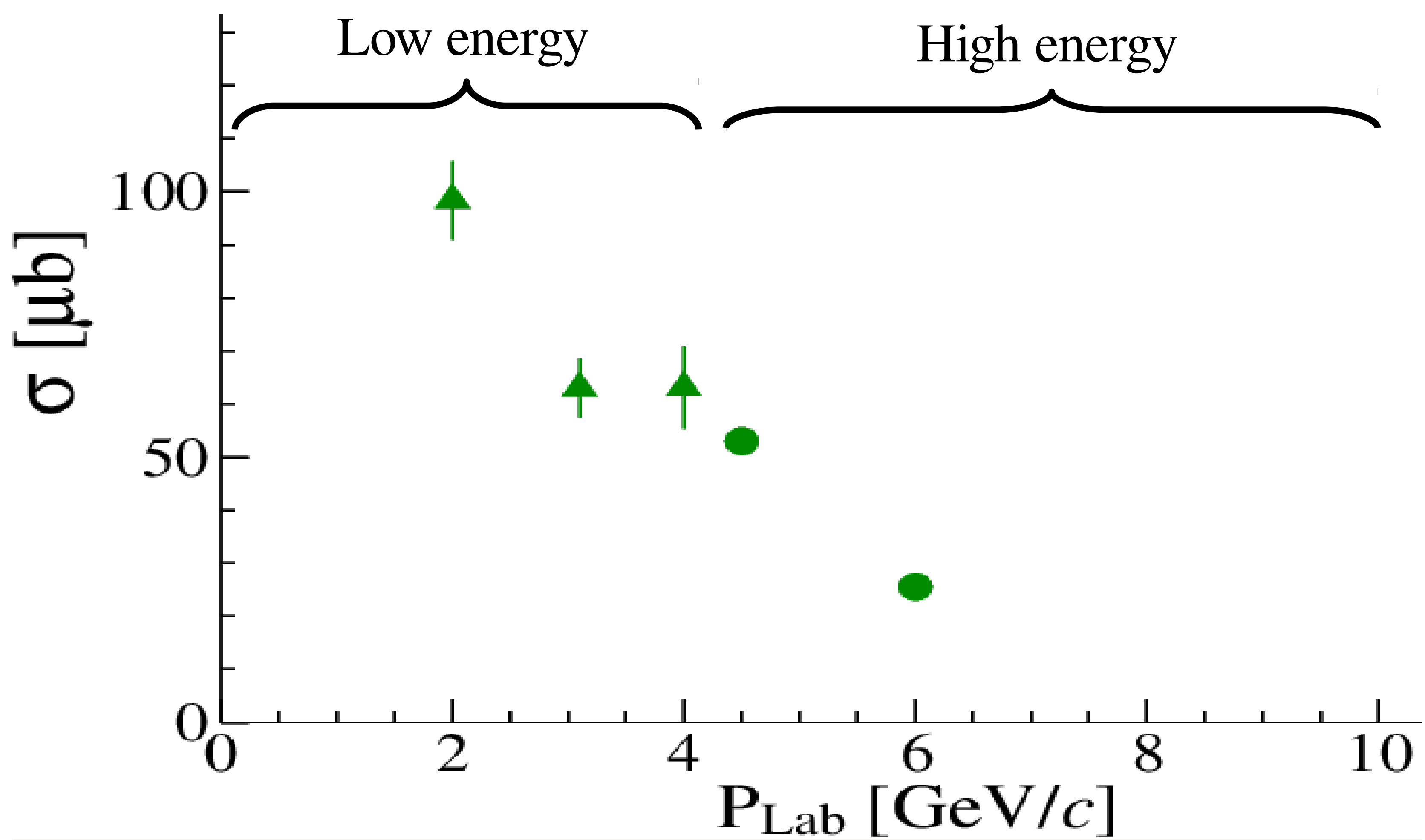


How do the two models differ from each other ?

$$\pi^- p \to K^{*0}\Lambda$$

Effective Lagrangians

Regge model



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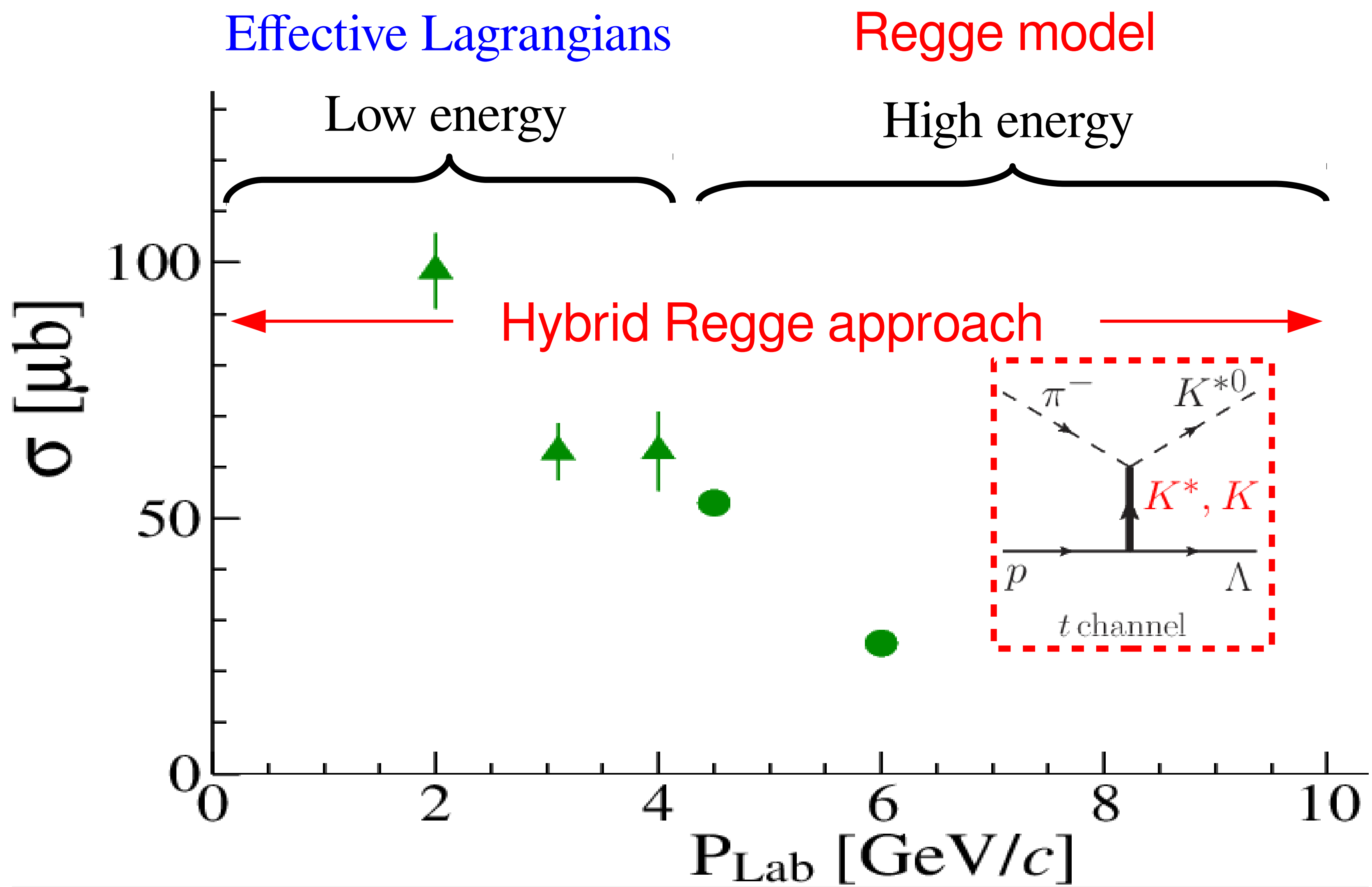
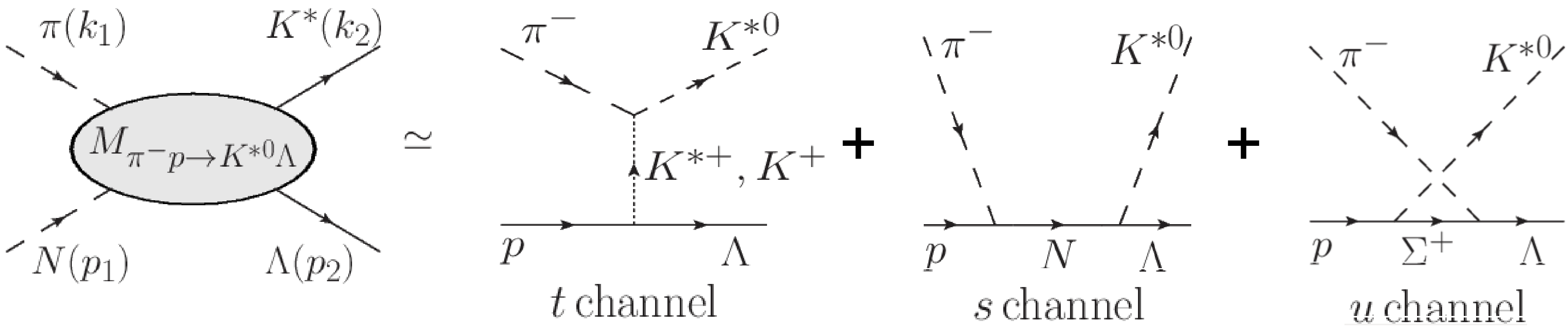


III. Formalism

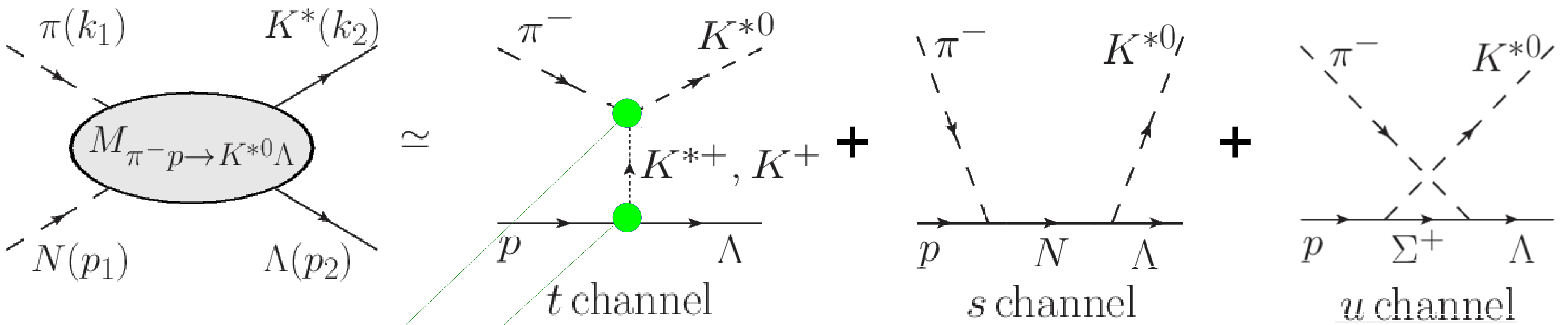
$$\pi^- p \to K^{*0}\Lambda \qquad \pi^- p \to D^{*-}\Lambda_c^+$$

Effective Lagrangians

Tree Level Diagrams



Tree Level Diagrams



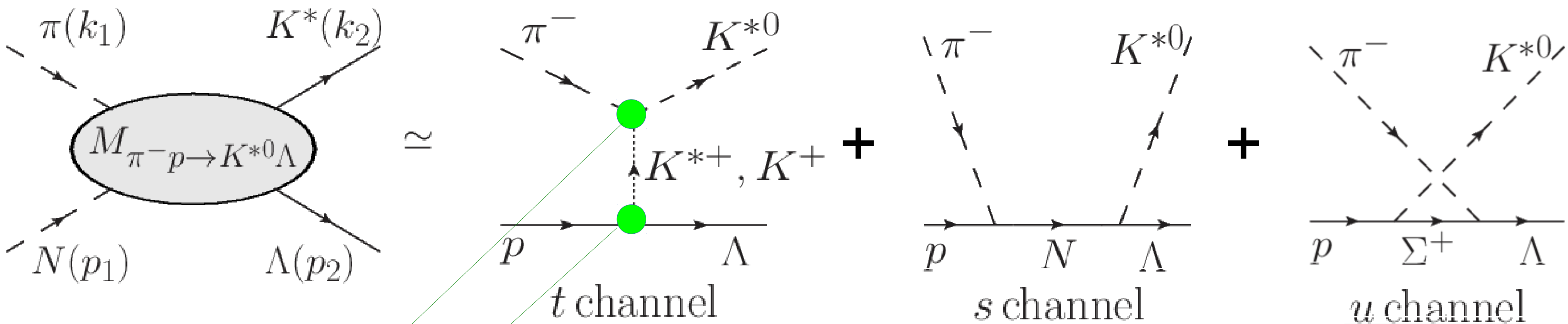
$$\mathcal{L}_{\pi K K^*} = -ig_{\pi K K^*}(\bar{K}\partial^\mu \boldsymbol{\tau}\cdot\boldsymbol{\pi} K^*_\mu - \bar{K}^*_\mu \partial^\mu \boldsymbol{\tau}\cdot\boldsymbol{\pi} K)$$

$$\mathcal{L}^{\mathrm{PV}}_{KN\Lambda} = \frac{g_{KN\Lambda}}{M_N + M_\Lambda}\bar{N}\gamma_\mu\gamma_5\Lambda\partial^\mu K + \mathrm{H.c.}$$

$$\mathcal{M}_K = I_K \frac{ig_{\pi K K^*}}{t - M_K^2}\varepsilon^*_\mu \bar{u}_\Lambda \frac{g_{KN\Lambda}}{M_N + M_\Lambda}\gamma^\nu\gamma_5 k_1^\mu (k_2 - k_1)_\nu u_N$$

Effective Lagrangians

Tree Level Diagrams



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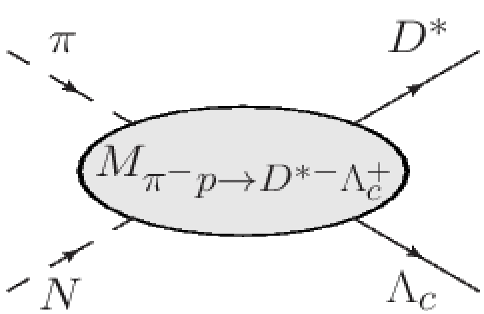


$$K \to D \quad K^* \to D^*$$

$$\Lambda \to \Lambda_c \quad \Sigma \to \Sigma_c$$

Feynman Amplitudes & Form Factors

Form factor : $F_{ex}(p^2) = \dfrac{\Lambda^4}{\Lambda^4 + (p^2 - M_{ex}^2)^2}$

$$\mathcal{M}_{\mathrm{Total}}[\pi^- p \to K^{*0}\Lambda(D^{*-}\Lambda_c^+)] = \mathcal{M}_{K(D)} \cdot F_{K(D)} + \mathcal{M}_{K^*(D^*)} \cdot F_{K^*(D^*)} + \mathcal{M}_{\Sigma(\Sigma_c)} \cdot F_{\Sigma(\Sigma_c)} + \mathcal{M}_N \cdot F_N$$

How to determine the cutoff masses, Λ ?

$\pi^- p \to K^{*0}\Lambda$

$\pi^- p \to D^{*-}\Lambda_c^+$

Determined by fitting to the experimental data. → The same values are used.

$$\Lambda_{K,K^*(D,D^*)} = 0.55\,\mathrm{GeV}$$

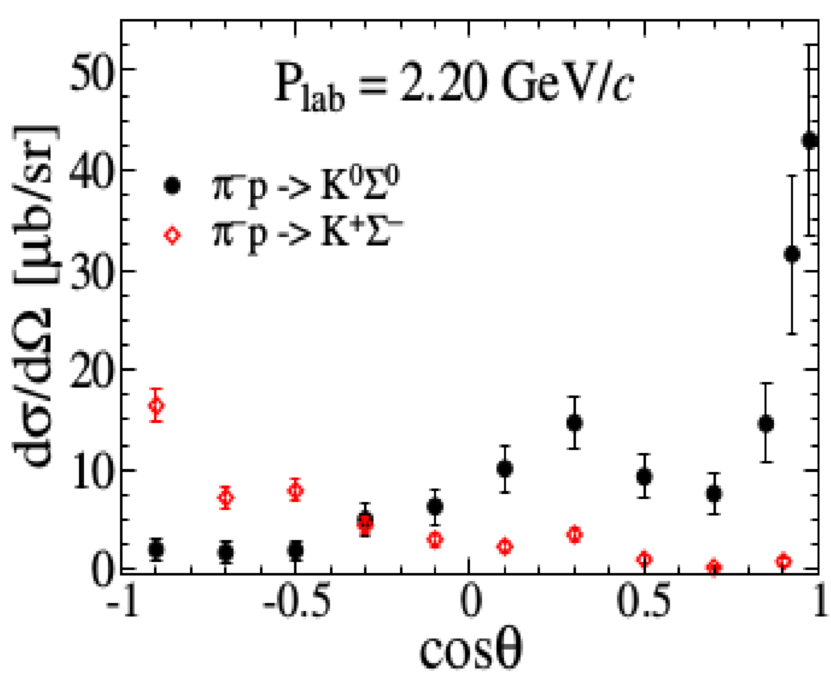
$$\Lambda_{N,\Sigma(N,\Sigma_c)} = 0.60\,\mathrm{GeV}$$

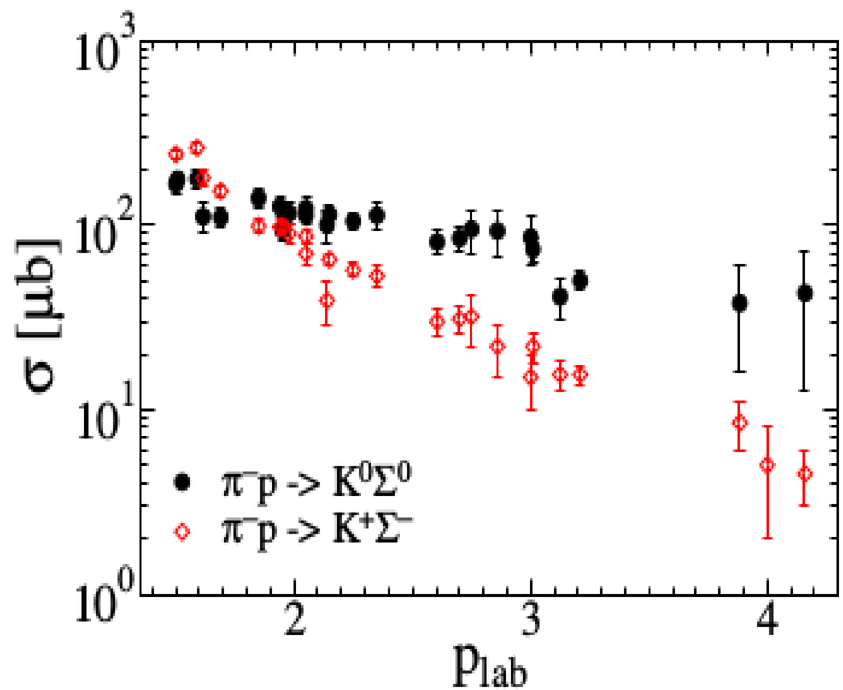
Regge model

General Idea

1. Most reactions have a tendency for a forward peak.
2. At high energies, t-channel exchange dominates.

=> A Regge method works.





Regge model

General Idea

1. Most reactions have a tendency for a forward peak.
2. At high energies, t-channel exchange dominates.

=> A Regge method works.

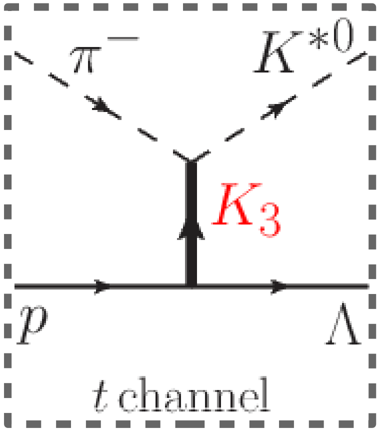
What is a Regge model?

A single particle exchange in the t-channel of spin J behaves as

$$\boxed{\sigma \sim s^{J-1}}$$

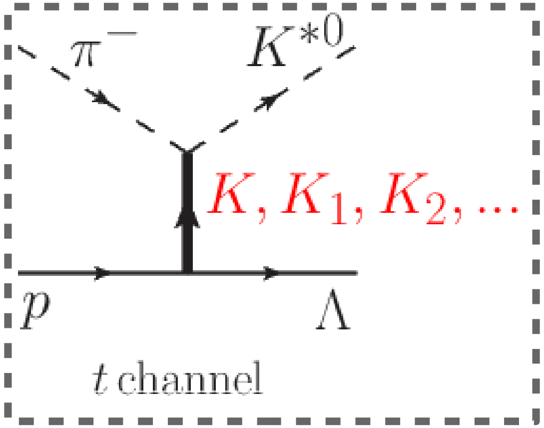
which violates unitarity for large J.

Froissart bound : $\sigma^{\mathrm{Tot}}(s) \leq \text{constant} \times \log^2(s/s_0)$



We need to sum up all meson exchanges of various J.

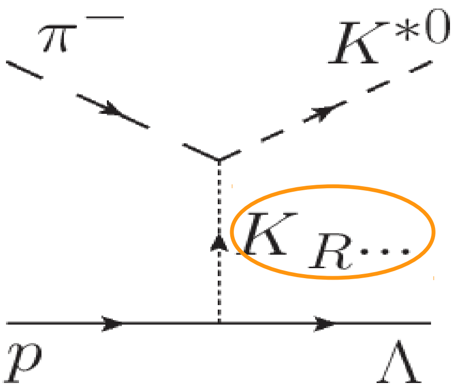
$$\boxed{\sigma \sim s^{\alpha(0)-1}}$$

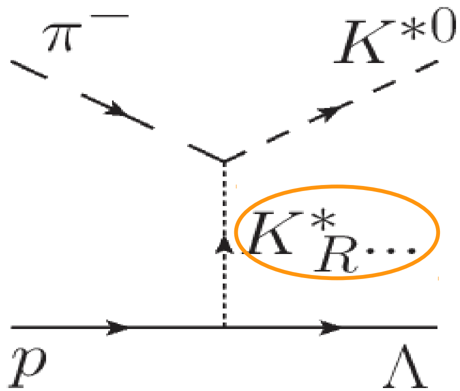


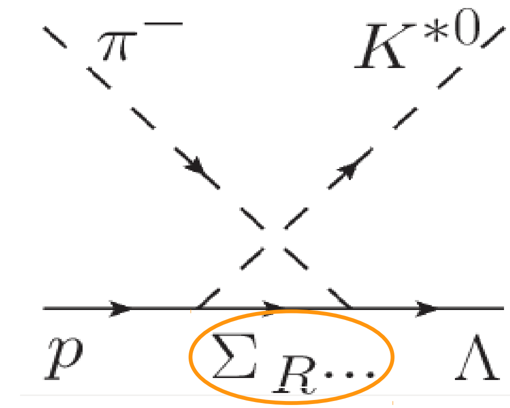
α(t) is called a Regge trajectory. α(t) = α(0) + α't

Regge model

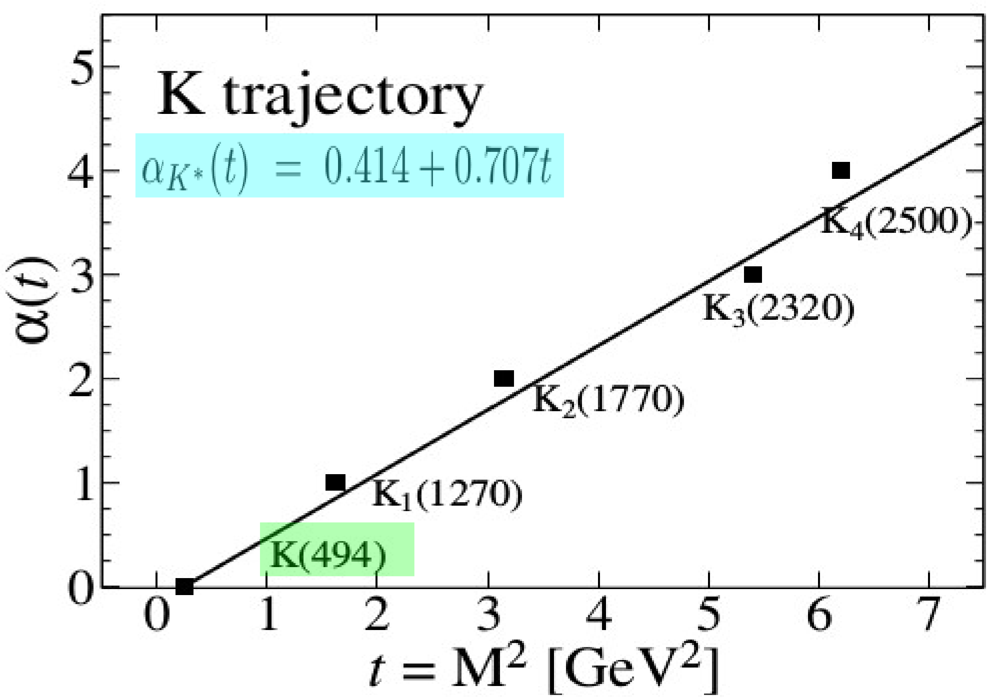
Regge Trajectories



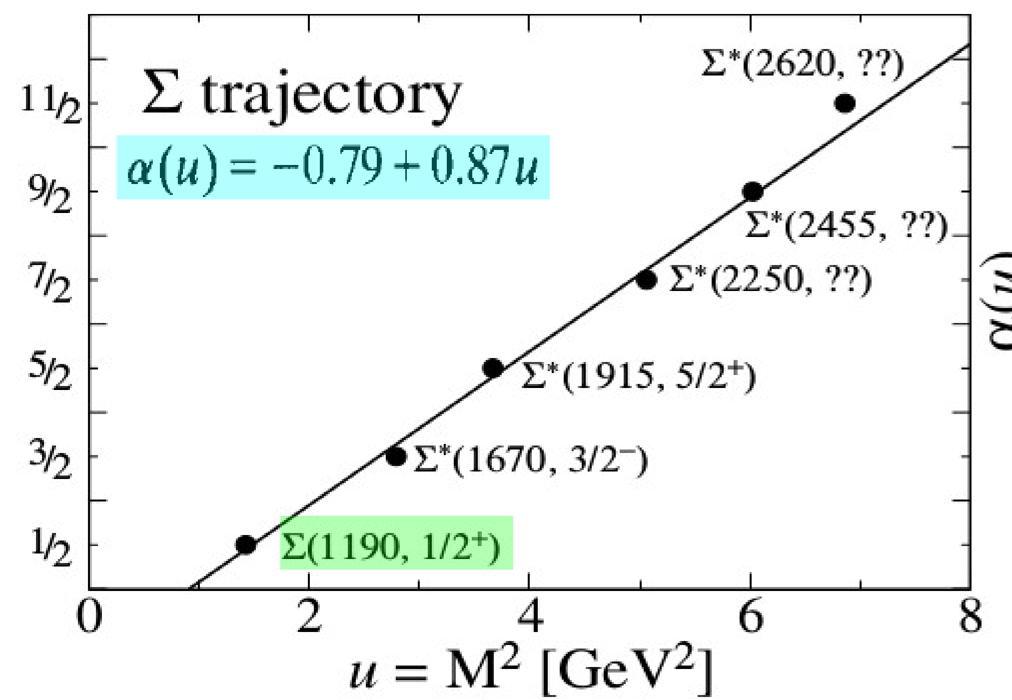




$$\boxed{\alpha(M^2) = J}$$



Brisudova et al, PRD 61.054013(2000)



J.K.Storrow, PhysRept. 103.317(1984)

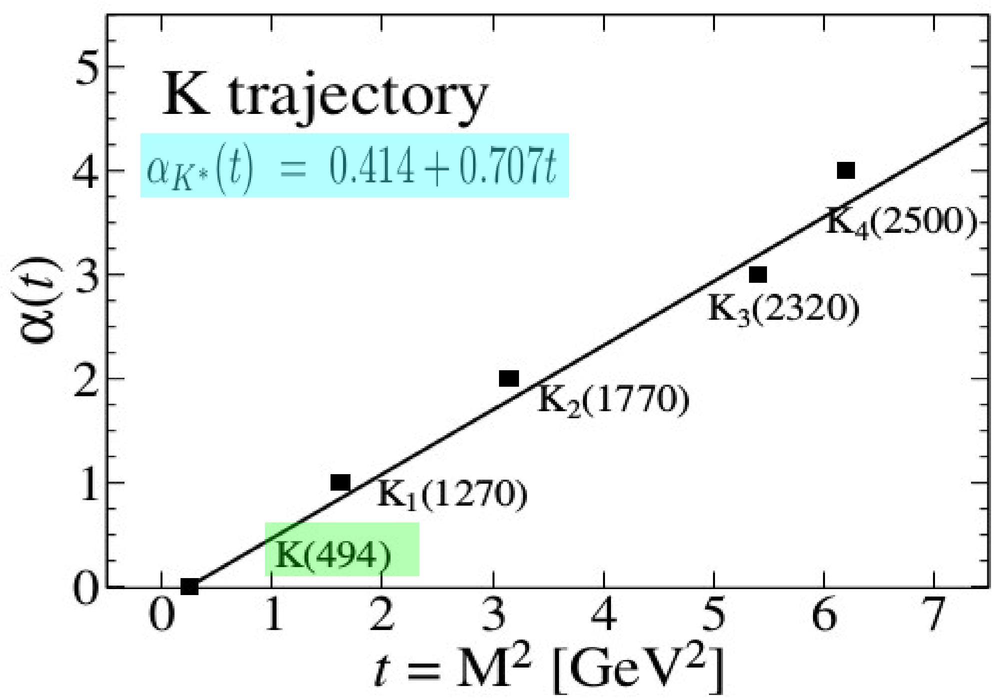
Regge model

Regge Trajectories

$\alpha(t)$ connect hadrons with their families
which have the same internal quantum number,
where **M** and **J** are the mass and the spin of a related hadrons.

For the charm Regge trajectories,
we rely on the quark-gluon string model (QGSM).

$$\boxed{\alpha(M^2) = J}$$



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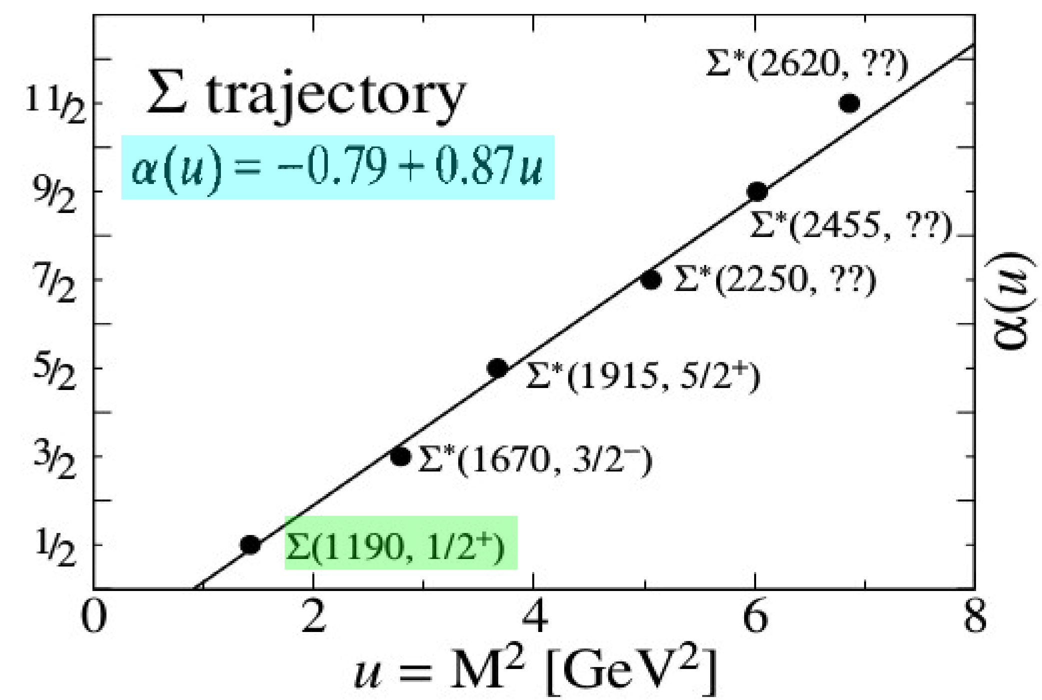


J.K.Storrow, PhysRept. 103.317(1984)

Regge Propagators & Amplitudes

$$P^{\mathrm{F}}_{K^*} = \frac{1}{t - M^2_{K^*}} \quad \Rightarrow \quad P^{\mathrm{R}}_{K^*}(s,t) = \left(\frac{s}{s_{K^*}}\right)^{\alpha_{K^*}(t)-1} \Gamma[1 - \alpha_{K^*}(t)]\alpha'_{K^*}$$

$$\mathcal{M}^{\mathrm{R}}_{K^*}(s,t) = \mathcal{M}^{\mathrm{F}}_{K^*}(s,t)\frac{P^{\mathrm{R}}_{K^*}(s,t)}{P^{\mathrm{F}}_{K^*}(t)}$$

The Regge propagators reduce to the Feynman propagators $1/(t-M^2)$ if one approaches the first pole on the trajectory (i.e. $t \to M^2$).

$$\Gamma[1 - \alpha(t)] = \frac{\Gamma[2-\alpha(t)]}{1-\alpha(t)} = \frac{\Gamma[1-(t-M^2_{K^*})\alpha']}{-(t-M^2_{K^*})\alpha'} \simeq \frac{-1}{\alpha'}\frac{1}{(t-M^2_{K^*})}$$

$$\alpha(t) = 1 + (t - M^2_{K^*})\alpha' \qquad t \to M^2_{K^*}$$

Asymptotic Behavior

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{1}{16\pi s^2}\frac{1}{2}\sum_{s_i,s_f,\lambda_f} |\mathcal{M}|^2$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(s\to\infty, t\to 0) \propto s^{2\alpha(t)-2}$$

$$\mathcal{M}_{K^*} \propto s^1$$

(We proved analytically.)

Regge model

Form factor : $C_{\rm ex}(p^2) = \dfrac{a}{(1 - p^2/\Lambda^2)^2}$

$$\mathcal{M}^{\rm R}_{\rm Total}[\pi^- p \to K^{*0}\Lambda(D^{*-}\Lambda_c^+)] = \mathcal{M}^{\rm R}_{K(D)} \cdot C_{K(D)} + \mathcal{M}^{\rm R}_{K^*(D^*)} \cdot C_{K^*(D^*)} + \mathcal{M}^{\rm R}_{\Sigma(\Sigma_c)} \cdot C_{\Sigma(\Sigma_c)}$$

$a_{K(D)}$	$a_{K^*(D^*)}$	$a_{\Sigma(\Sigma_c)}$
0.6	0.8	1.5

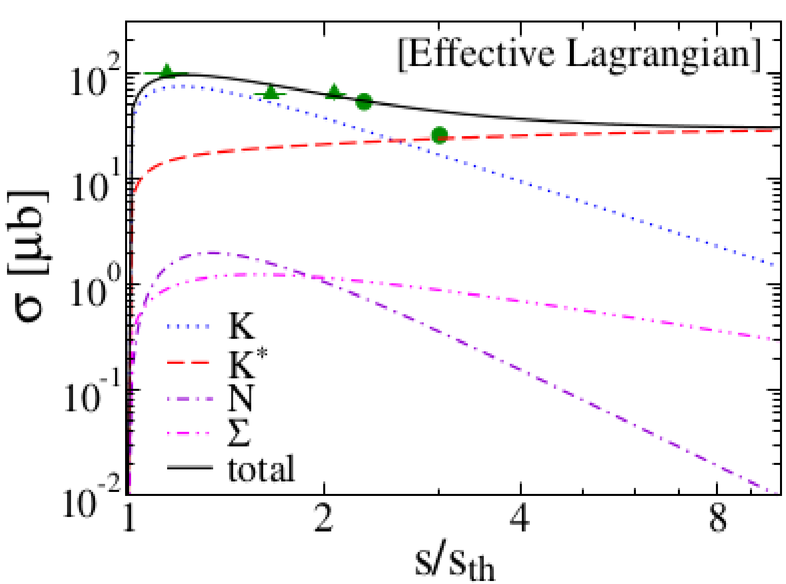
$\Lambda_{K,K^*,\Sigma\,(D,D^*,\Sigma_c)} = 1.0\,\mathrm{GeV}$

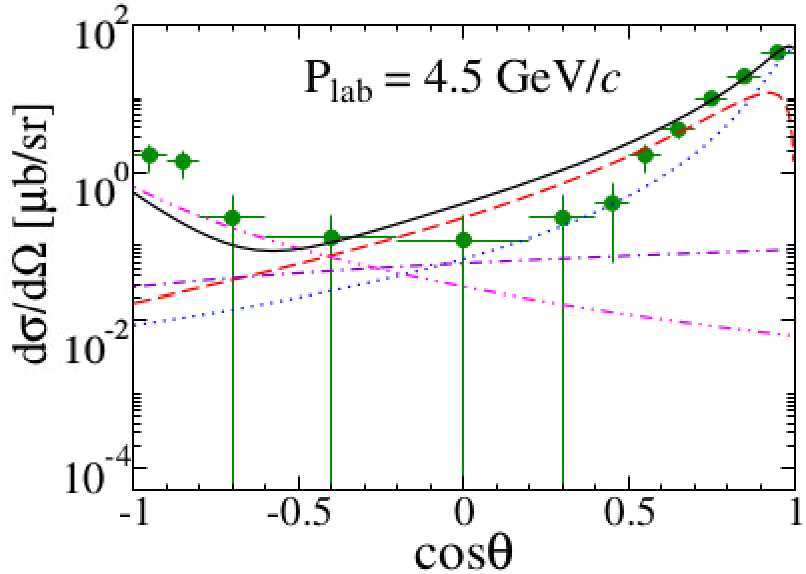
IV. Results

$\boxed{\pi^- p \rightarrow K^{*0}\Lambda \qquad \pi^- p \rightarrow D^{*-}\Lambda_c^+}$

4. Results : Total & Differential Cross Sections $\pi^- p \to K^{*0}\Lambda$

[Effective Lagrangians]





Exp. Data :

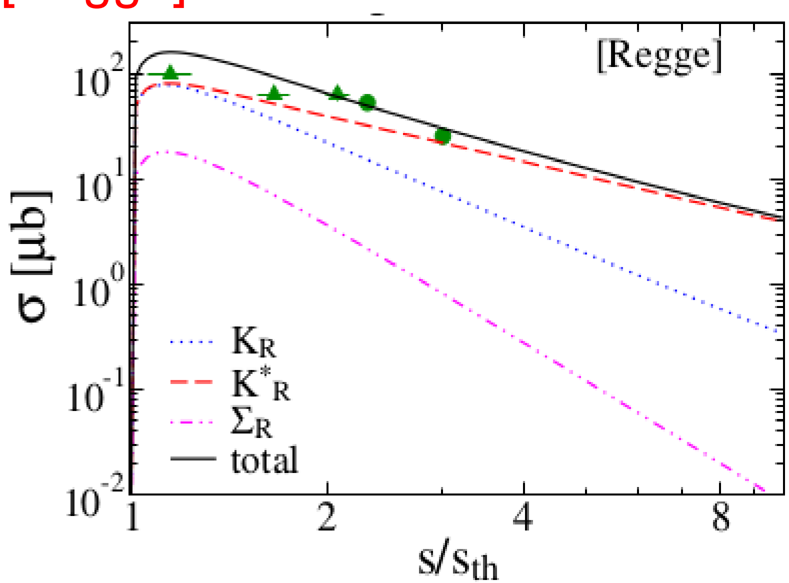
Dahl et al, PR163.1377(1967)

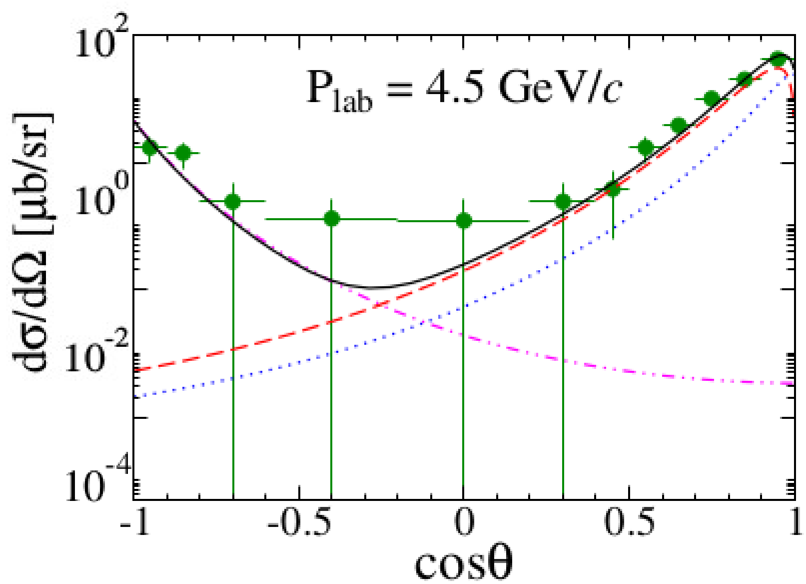
Crennell et al, PRD6.1220(1972)

$$\sigma \sim s^{J-1}$$

K (K*) exchange contributes mainly to the low (high)-energy region.

[Regge]





$$\sigma \sim s^{\alpha(0)-1}$$

$$\alpha_K(0) = -0.151$$

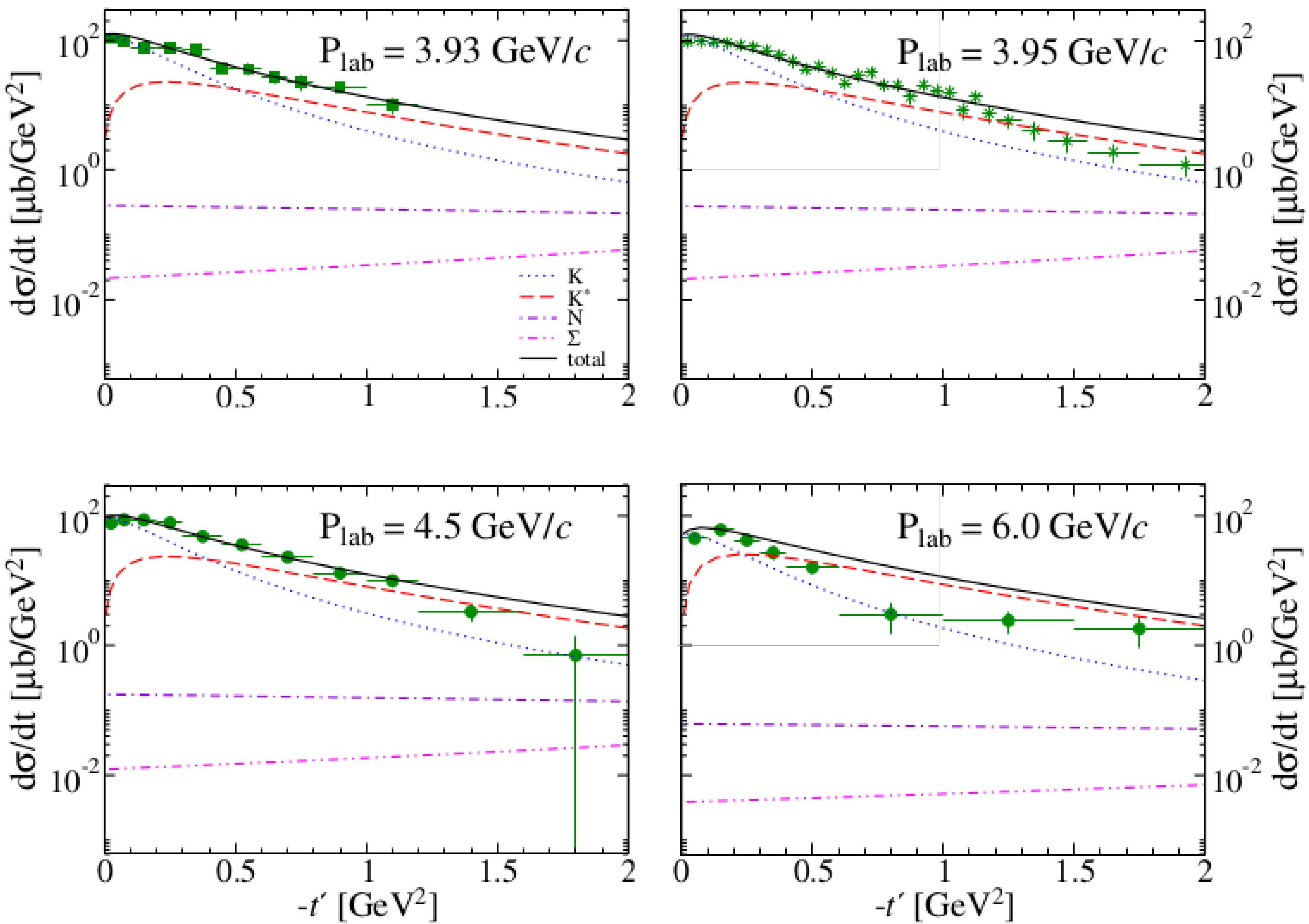
$$\alpha_{K^*}(0) = 0.414$$

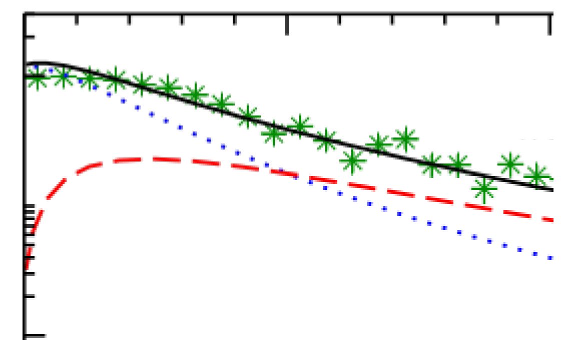
$$\alpha_\Sigma(0) = -0.79$$

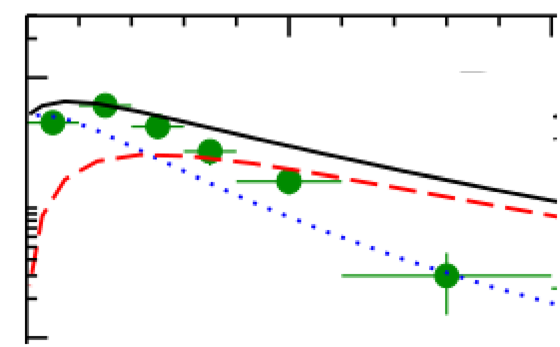
K* reggeon is dominant in the whole energy region.

4. Results : Differential Cross Sections $\pi^- p \to K^{*0}\Lambda$

[Effective Lagrangians]



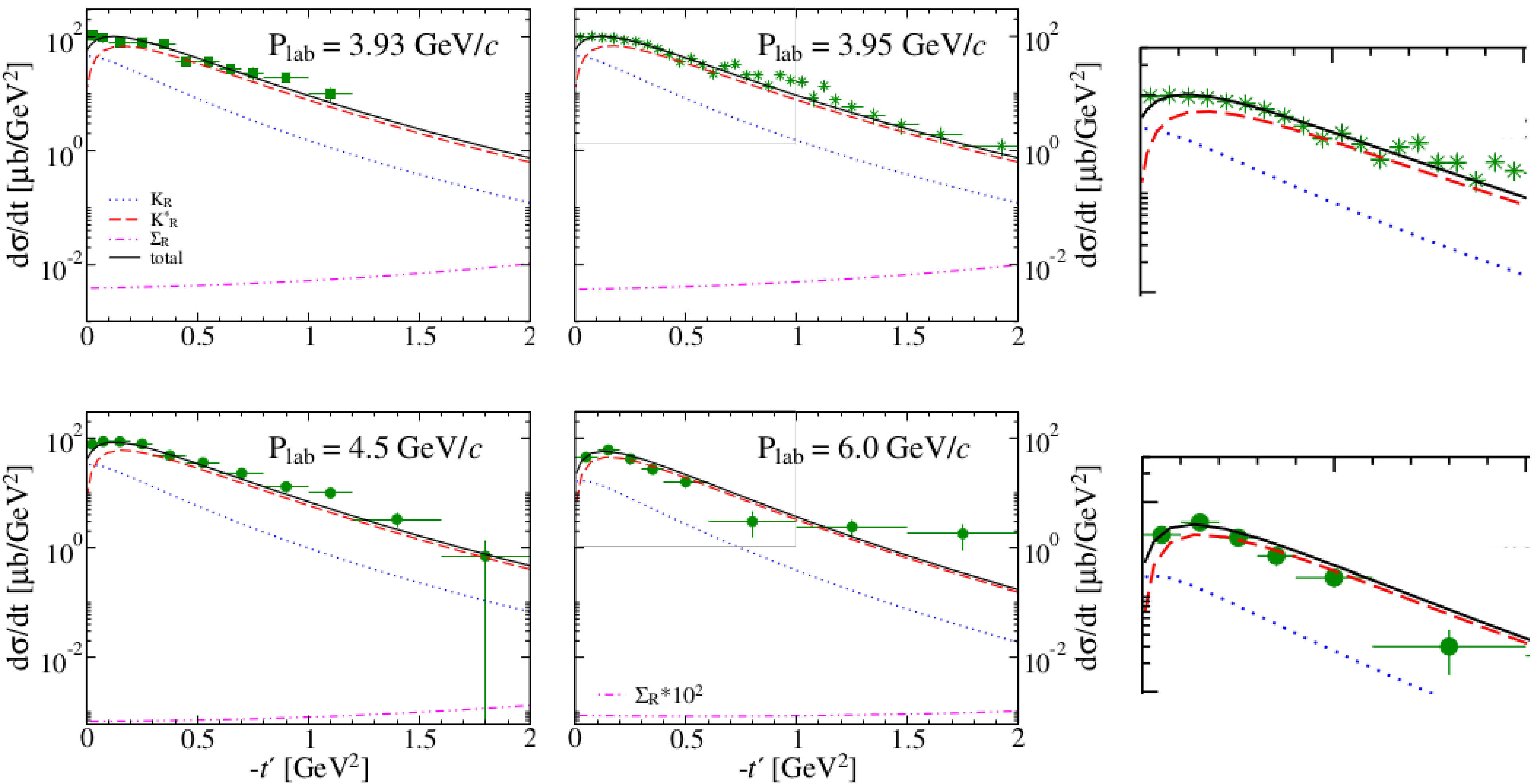




K exchange governs dσ/dt near $-t' \approx 0$, whereas
K^* exchange becomes dominant as $-t'$ increases.

4. Results : Differential Cross Sections $\pi^- p \to K^{*0}\Lambda$

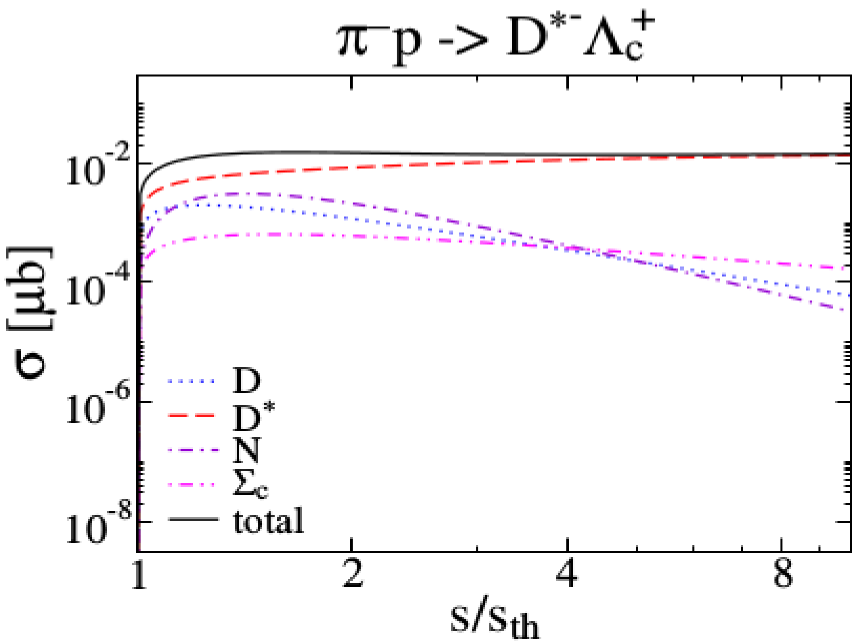
[Regge]

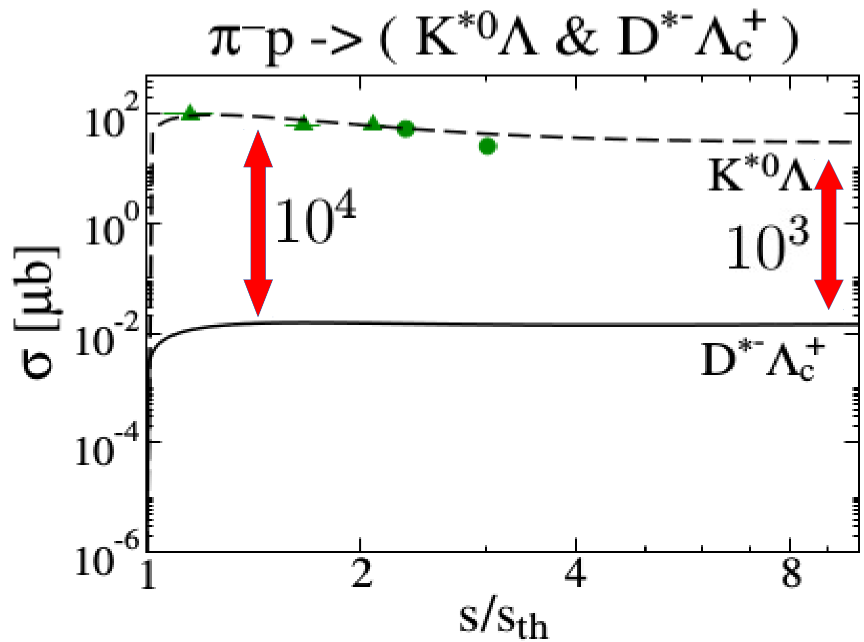


The slopes are faster than those of the effective Lagrangian method.
Regge approach explains the experimental data better at higher values of p_{lab}.

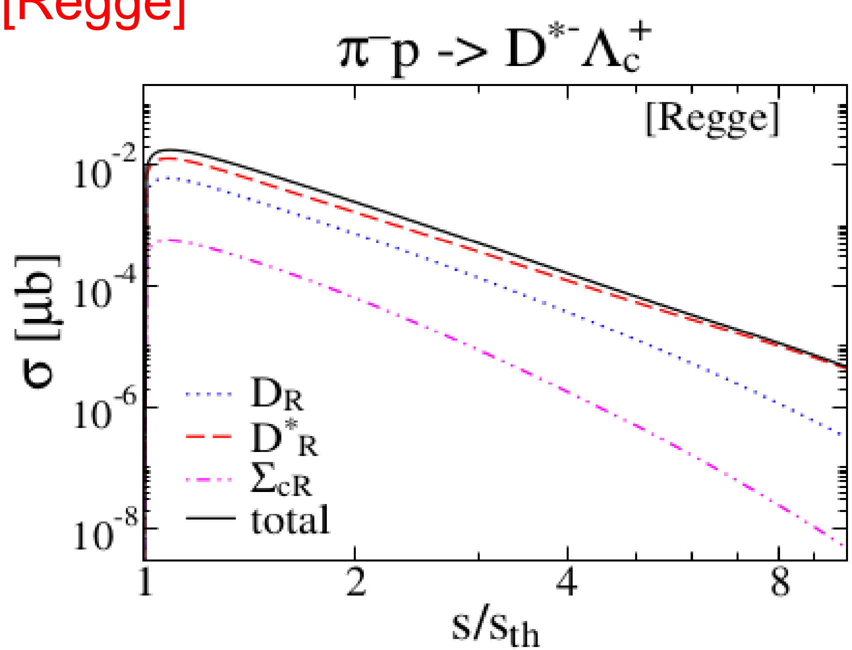
4. Results : Total Cross Sections

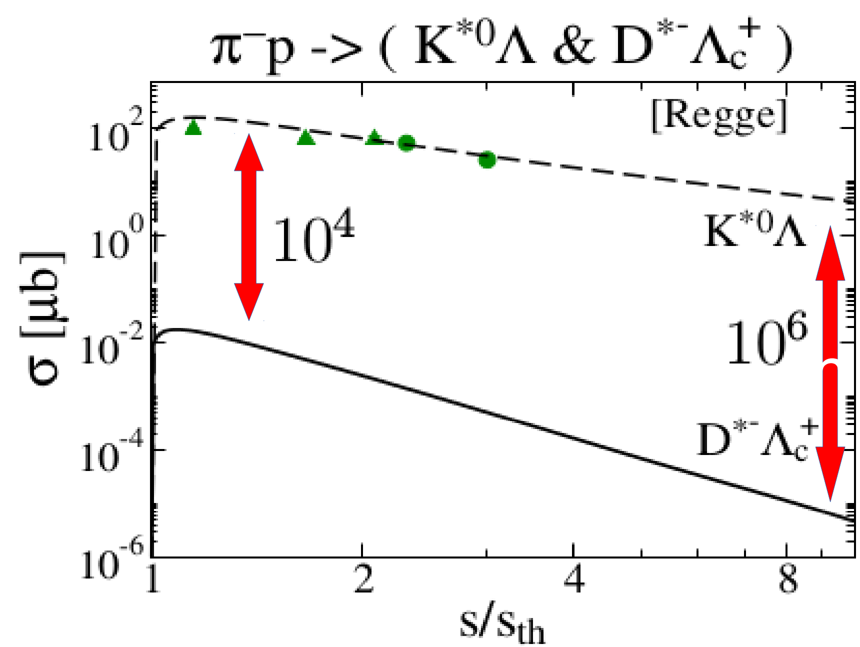
[Effective Lagrangians]





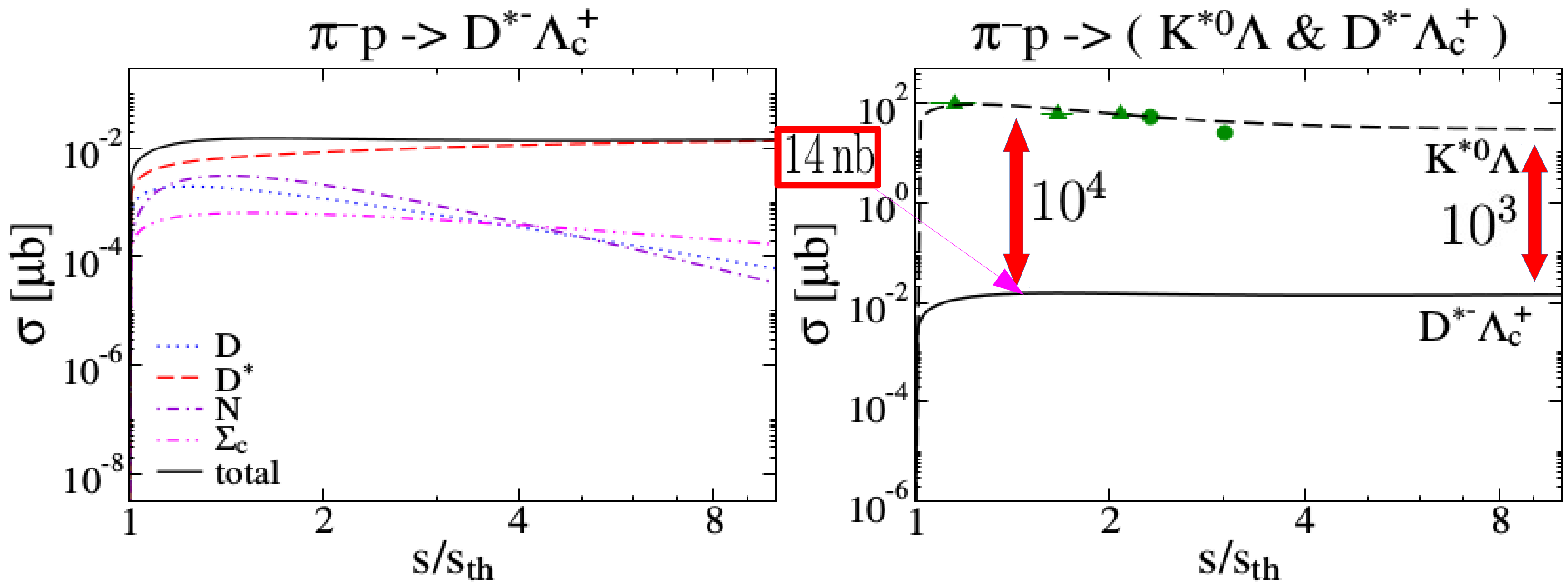
[Regge]



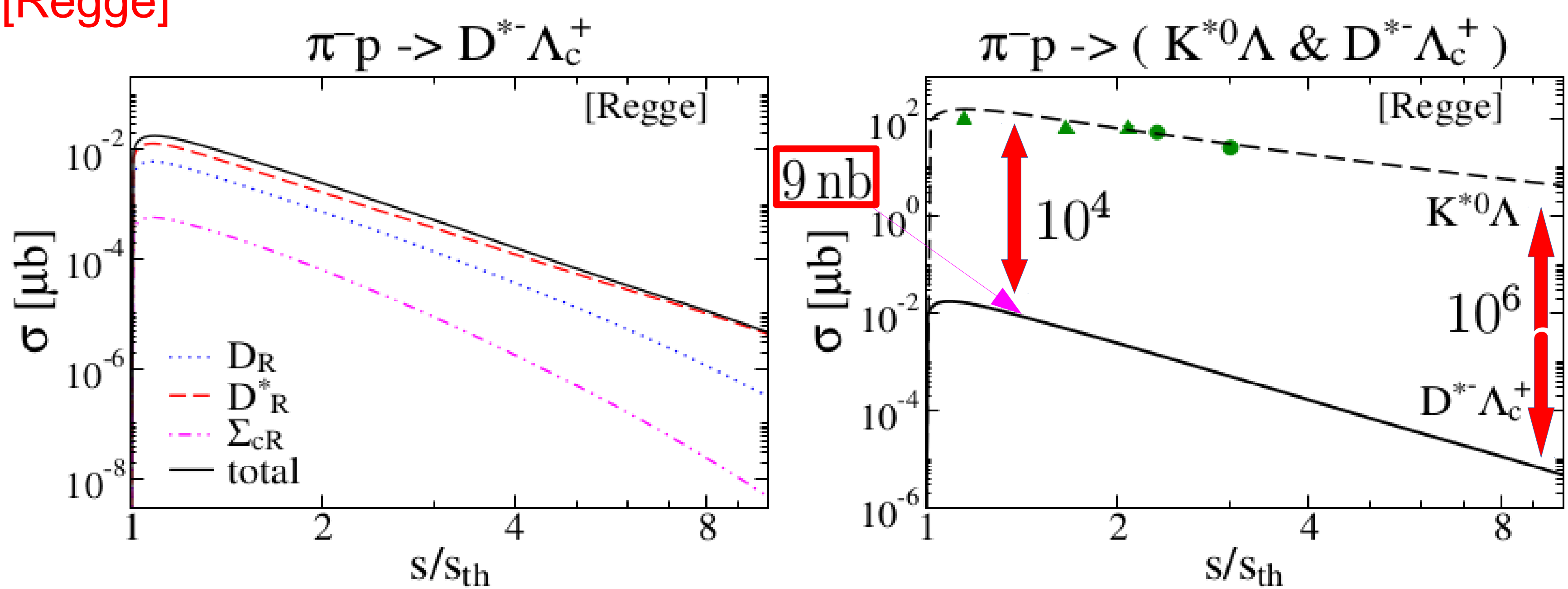


4. Results : Total Cross Sections

[Effective Lagrangians]



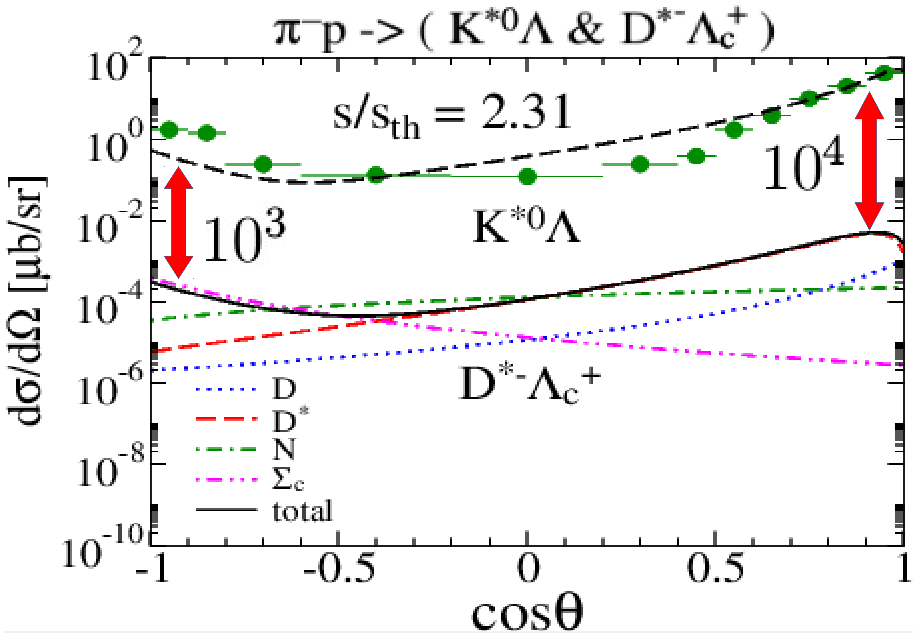
[Regge]



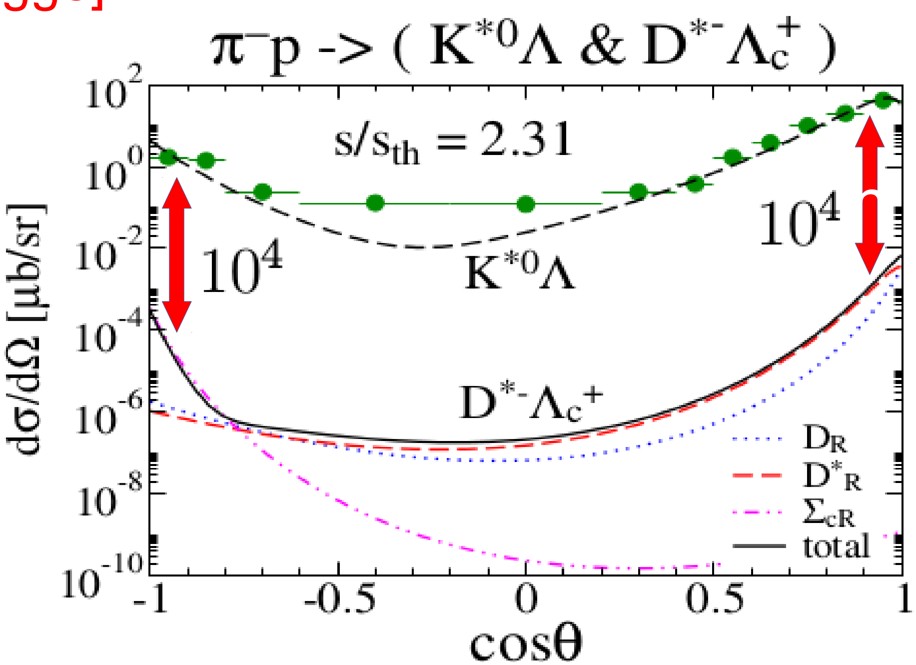
Upper limit:
7 nb at
13 GeV/c

4. Results : Differential Cross Sections

[Effective Lagrangians]



[Regge]

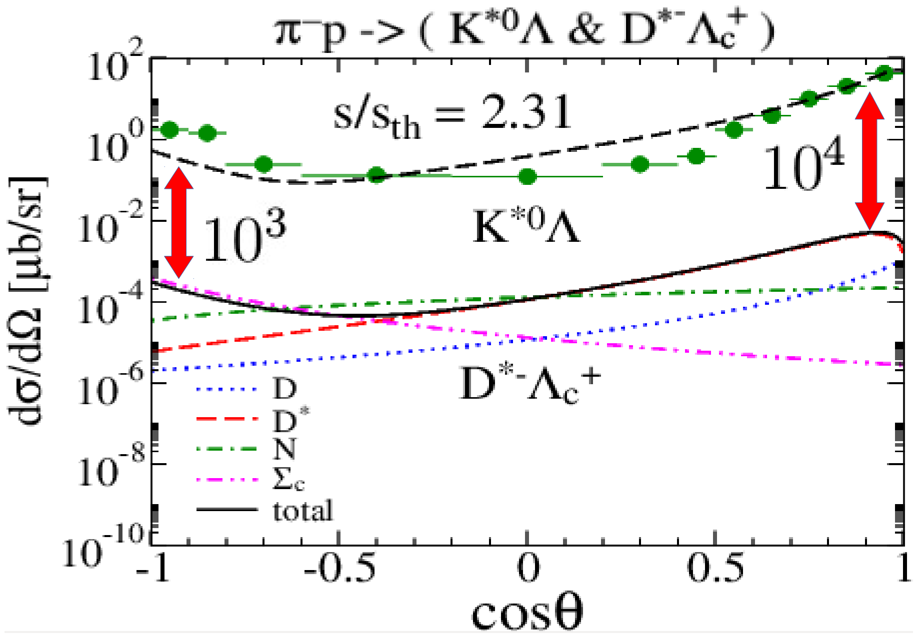


Where does this large gap come from?

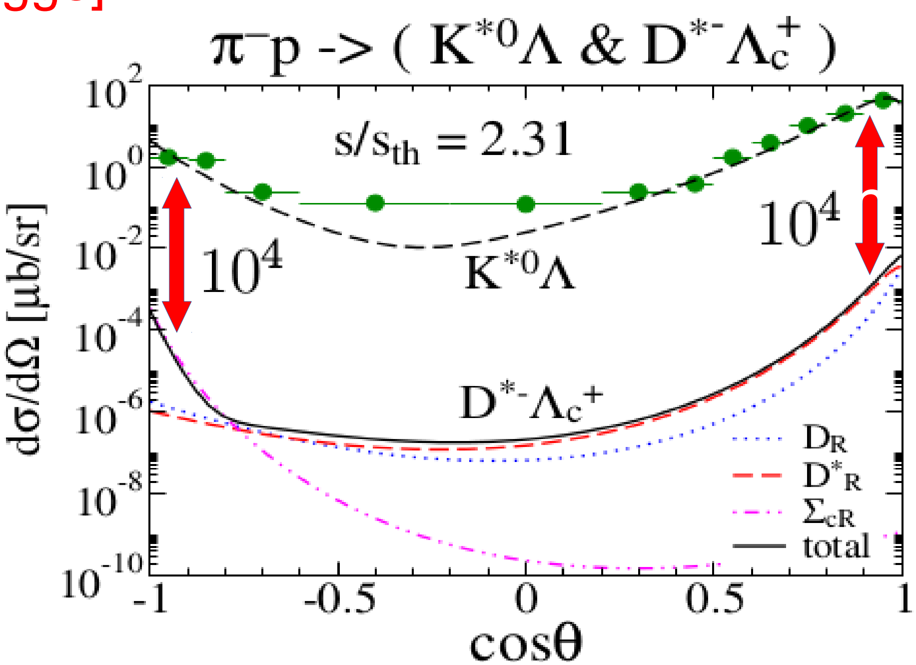
$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{CM}} = \frac{1}{64\pi^2 s}\frac{\mathbf{p}_{out}}{\mathbf{k}_{in}}\frac{1}{2}\sum|\mathcal{M}|^2$$

4. Results : Differential Cross Sections

[Effective Lagrangians]



[Regge]



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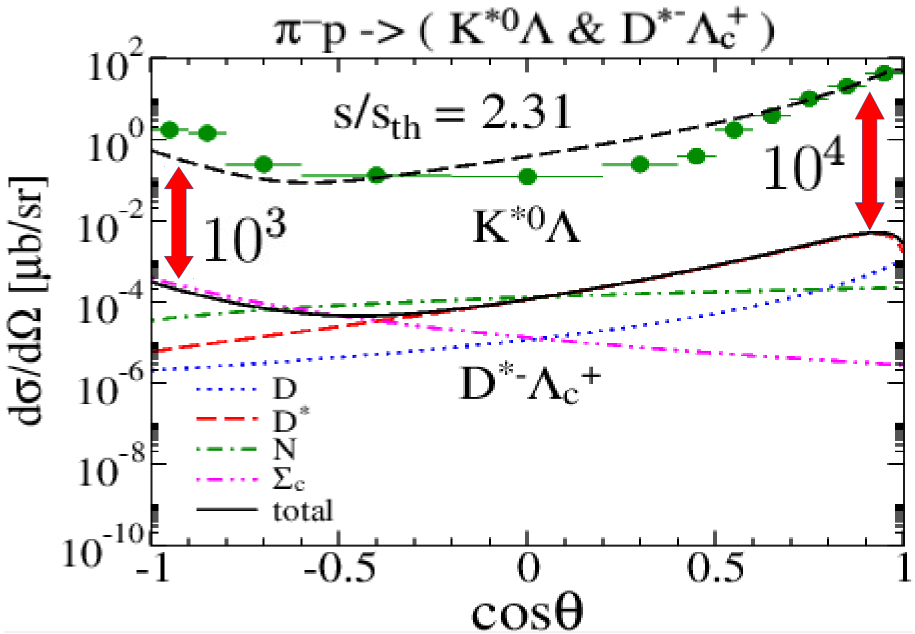
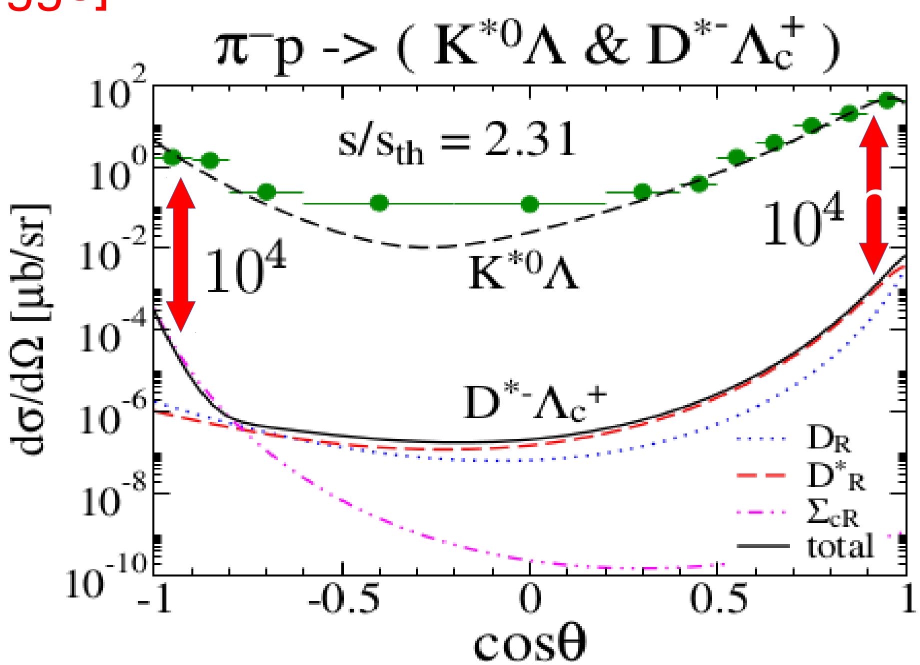
no effect, not main reason

4. Results : Differential Cross Sections

[Effective Lagrangians]



[Regge]



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no effect, not main reason

form factor

$$F_{ex}(p^2) = \frac{\Lambda^4}{\Lambda^4 + (p^2 - M_{ex}^2)^2}$$

energy scale parameter

$s_0(K) = 1.64,\ s_0(K^*) = 1.66$

$s_0(D) = 4.25,\ s_0(D^*) = 4.75$

$$P^{\mathrm{R}}_{K^*}(s,t) = \left(\frac{s}{s_{K^*}}\right)^{\alpha_{K^*}(t)-1}\Gamma[1-\alpha_{K^*}(t)]\alpha'_{K^*}$$

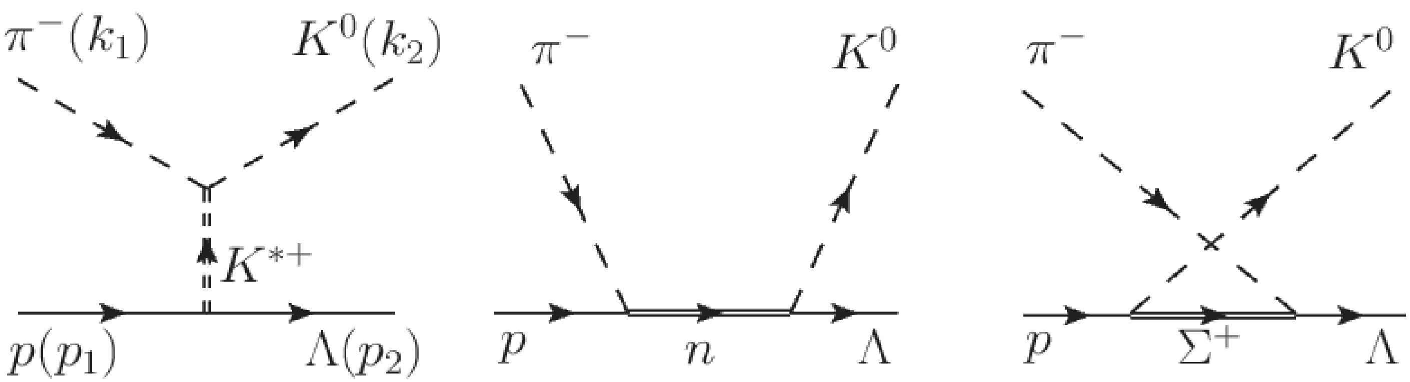
III. Formalism

$$\pi^- p \;\rightarrow\; K^0\Lambda \qquad\qquad \pi^- p \;\rightarrow\; D^-\Lambda_c^+$$

Tree Level Diagrams

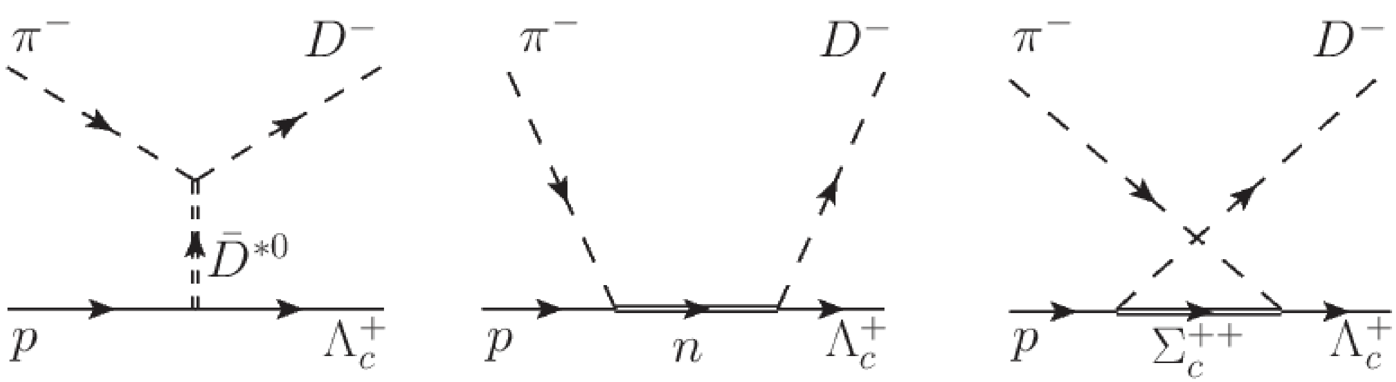
$$\boxed{\pi^- p \;\to\; K^0 \Lambda}$$

$d\bar{s}$ uds



$$\boxed{\pi^- p \;\to\; D^- \Lambda_c^+}$$

$d\bar{c}$ udc

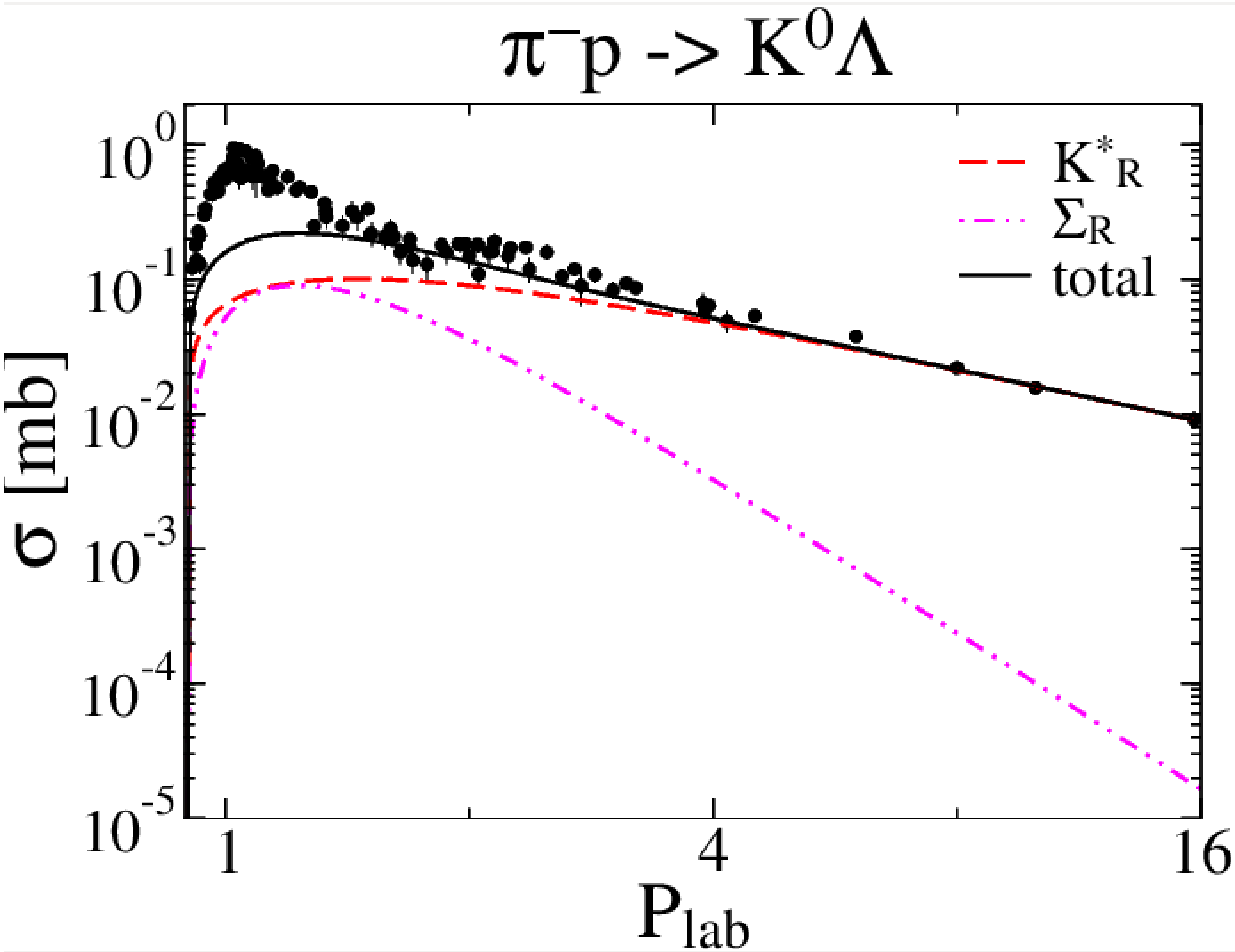


IV. Results

$$\boxed{\pi^- p \;\to\; K^0 \Lambda \qquad \pi^- p \;\to\; D^- \Lambda_c^+}$$

4. Results : Total Cross Sections

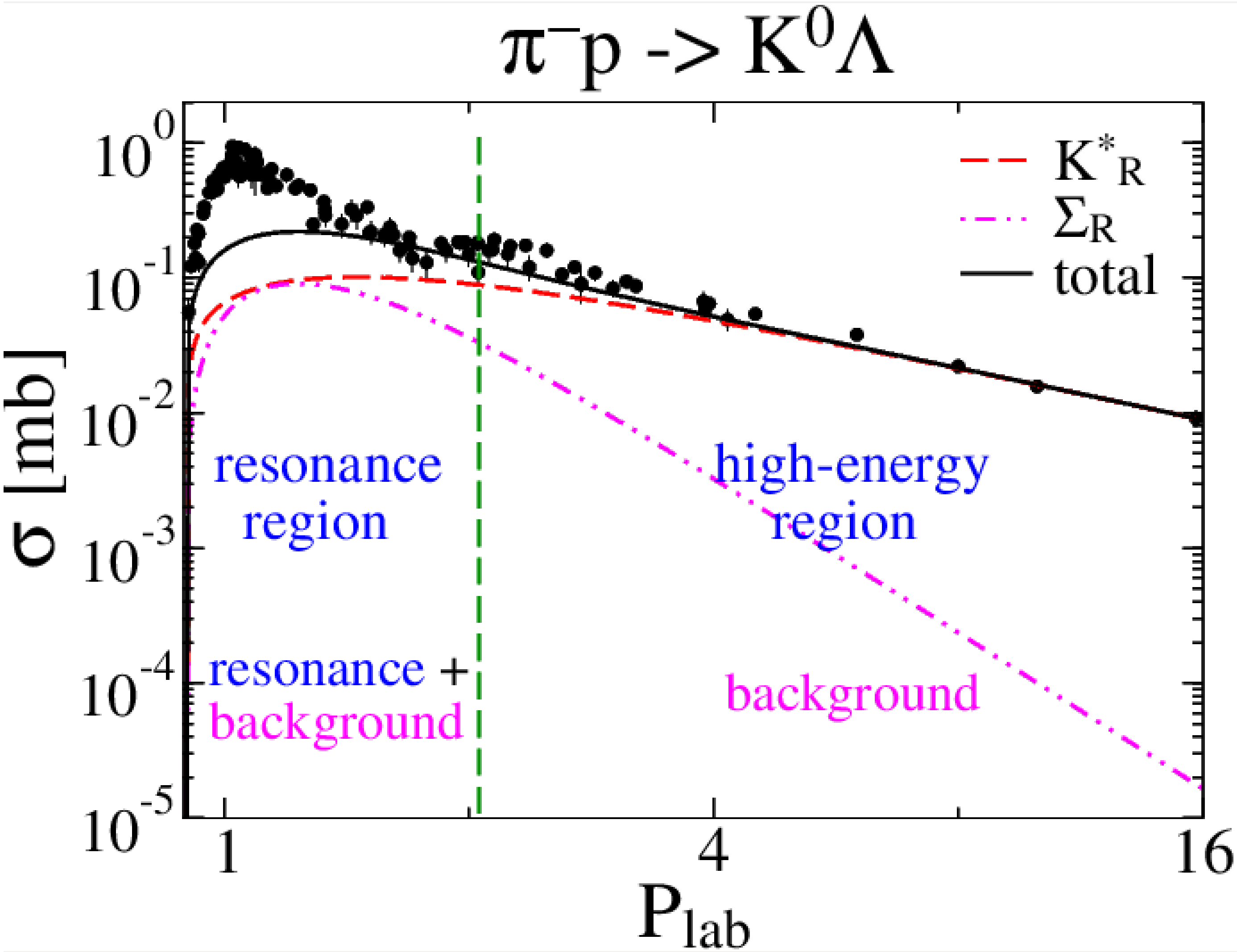
[Regge]



Ronchen et al (Julich),
EurPhysJA.49.44 (2013)
:Coupled channel analysis

4. Results : Total Cross Sections

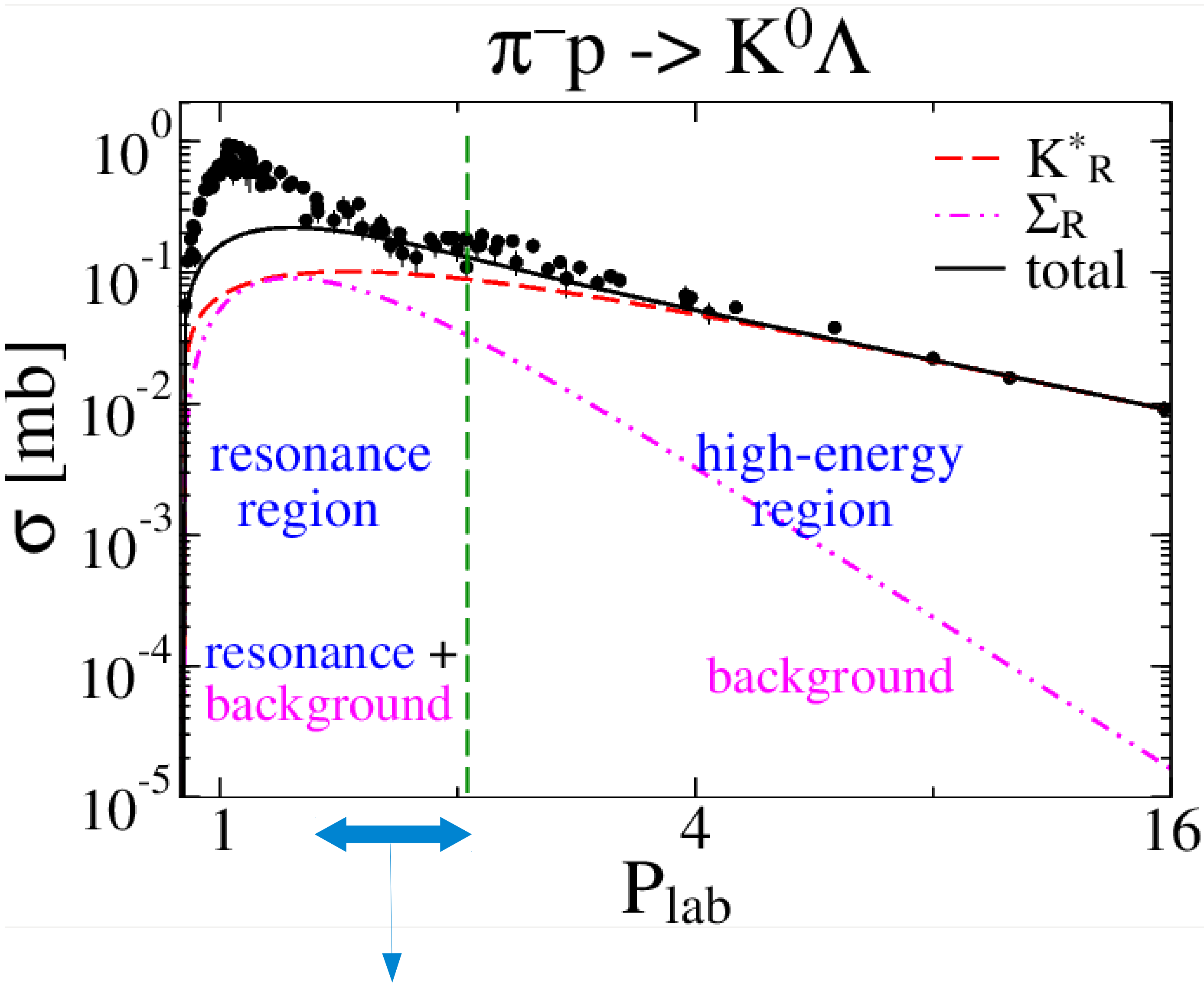
[Regge]



RPR (Regge plus Resonance) model is required.

4. Results : Total Cross Sections

[Regge]

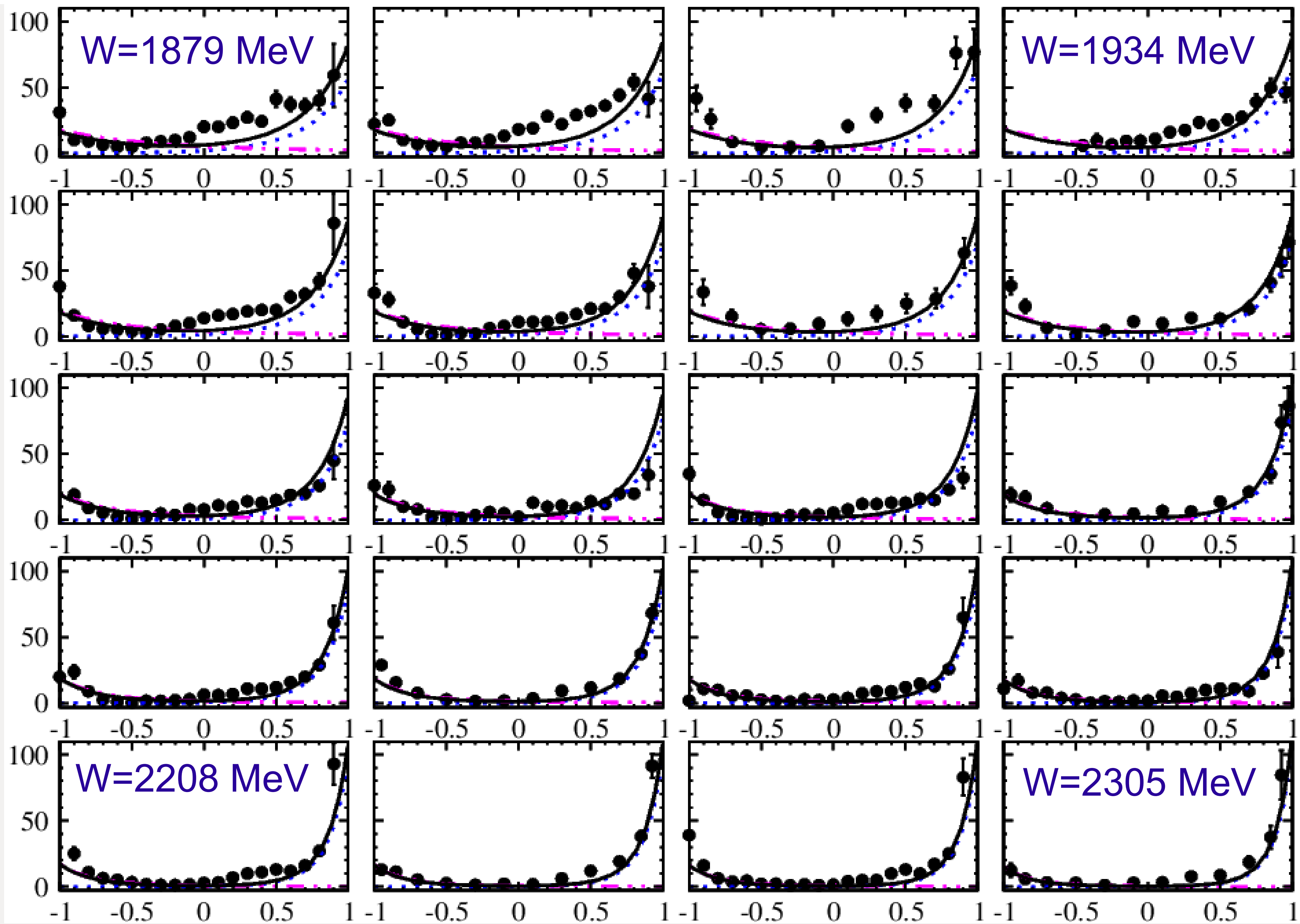


differential cross sections ?

4. Results : Differential Cross Sections

[Regge]

$$\pi^- p \rightarrow K^0 \Lambda$$



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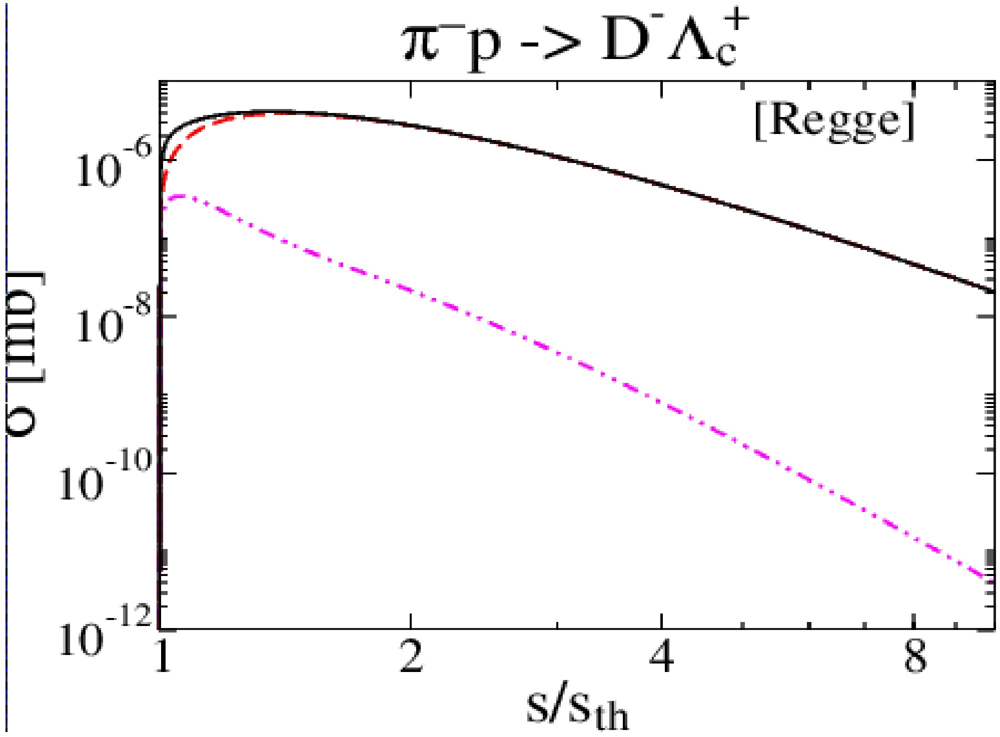

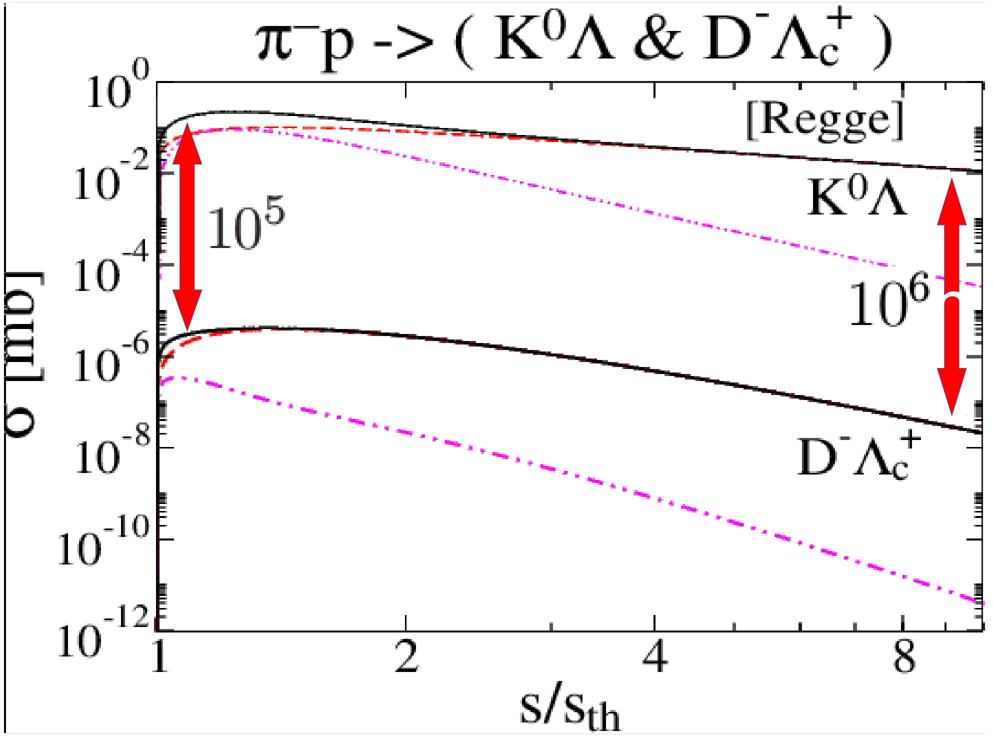

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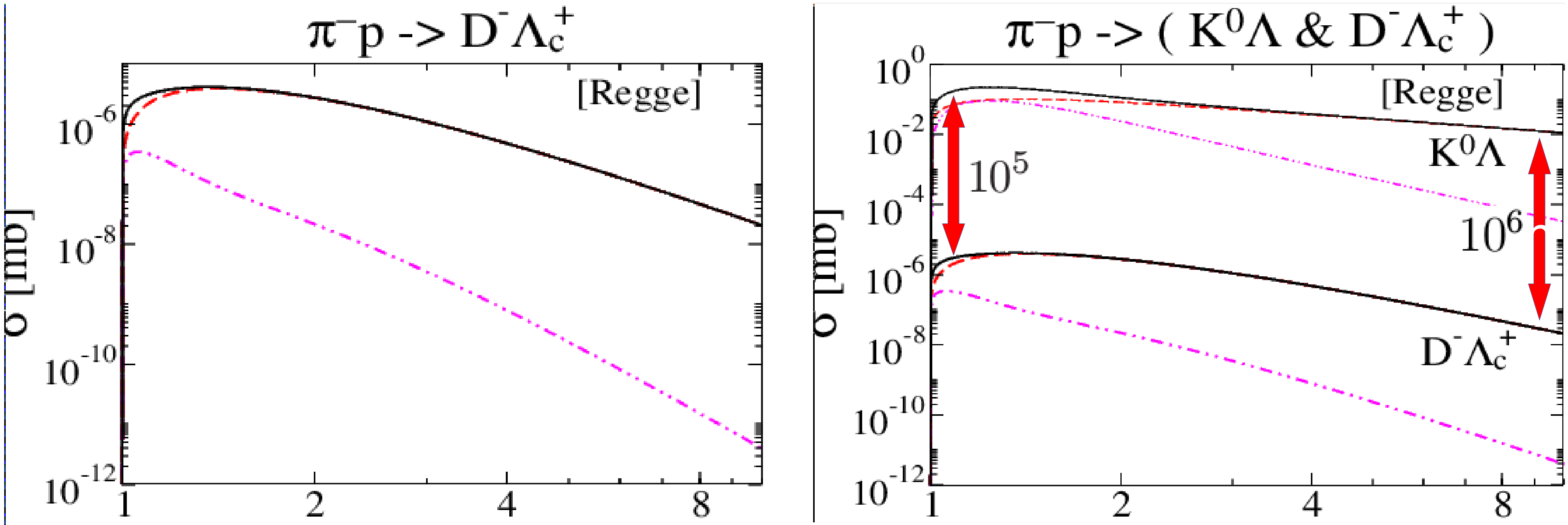

PHYSICAL REVIEW D **91,** 054027 (2015)

$\pi^- p \to D^- \Lambda_c^+$ within the generalized parton picture

Stefan Kofler,[1] Peter Kroll,[2] and Wolfgang Schweiger[1]

[1]*Institut für Physik, Universität Graz, 8010 Graz, Austria*

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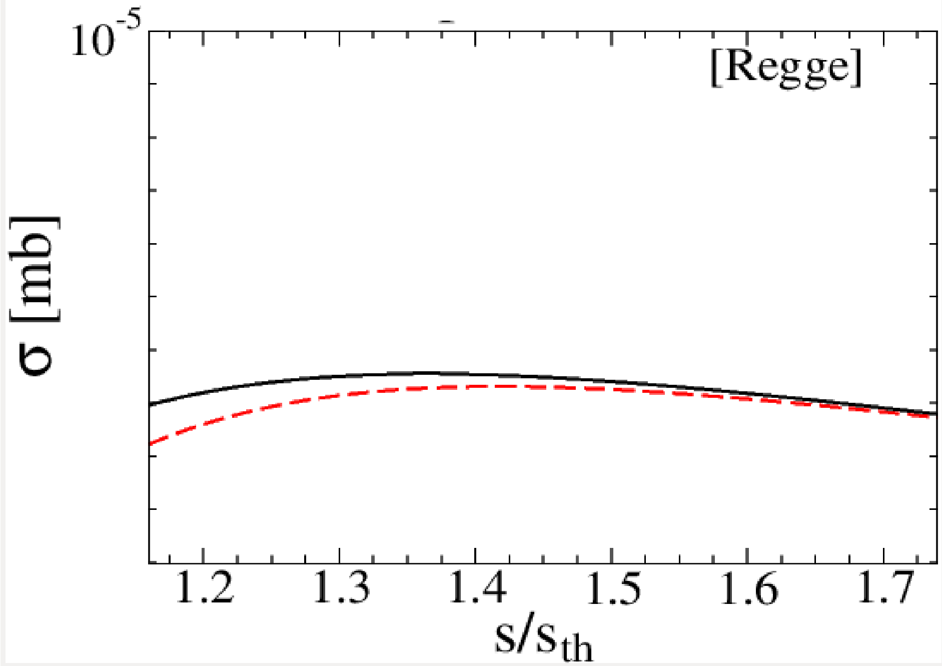
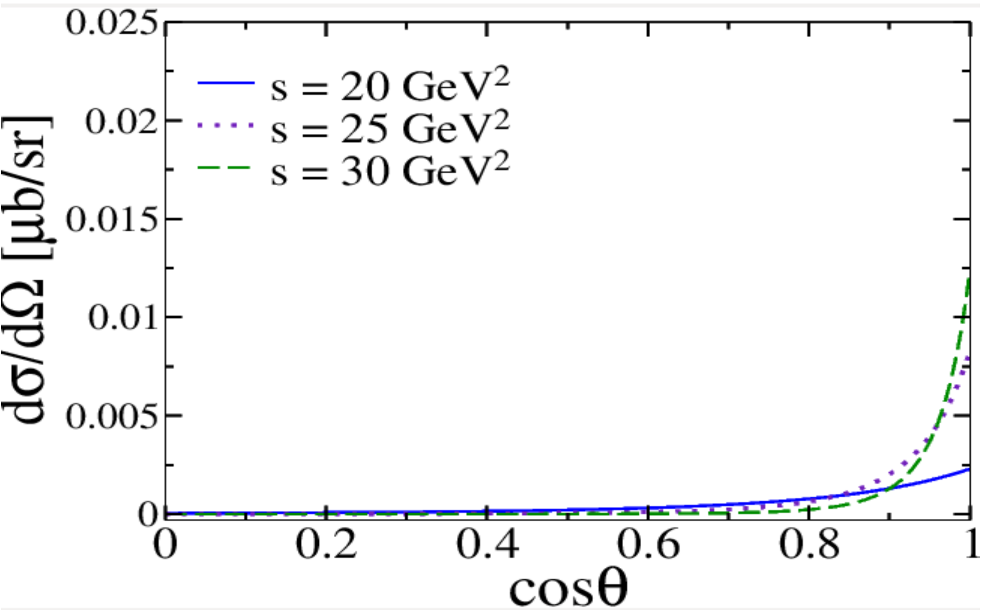
(Received 18 December 2014; published 23 March 2015)

We investigate the reaction $\pi^- p \to D^- \Lambda_c^+$ within the generalized parton picture. The process is described by a handbag-type mechanism with the charm-quark mass acting as the hard scale. As in the case of preceding work on $\overline{p}p \to \overline{\Lambda}_c^- \Lambda_c^+$ we assume that the process amplitude factorizes into one for the perturbatively calculable partonic subprocess $\overline{u}u \to \overline{c}c$ and hadronic matrix elements that can be parametrized in terms of generalized parton distributions. Modeling the generalized parton distributions by overlaps of (valence-quark) light-cone wave functions for the hadrons involved, we obtain numerical results for unpolarized differential and integrated cross sections as well as spin observables. Our approach works well above the production threshold ($s \gtrsim 20$ GeV^2) in the forward hemisphere and predicts unpolarized cross sections of the order of nb, a finding that could be of interest in view of plans to measure $\pi^- p \to D^- \Lambda_c^+$ at J-PARC.

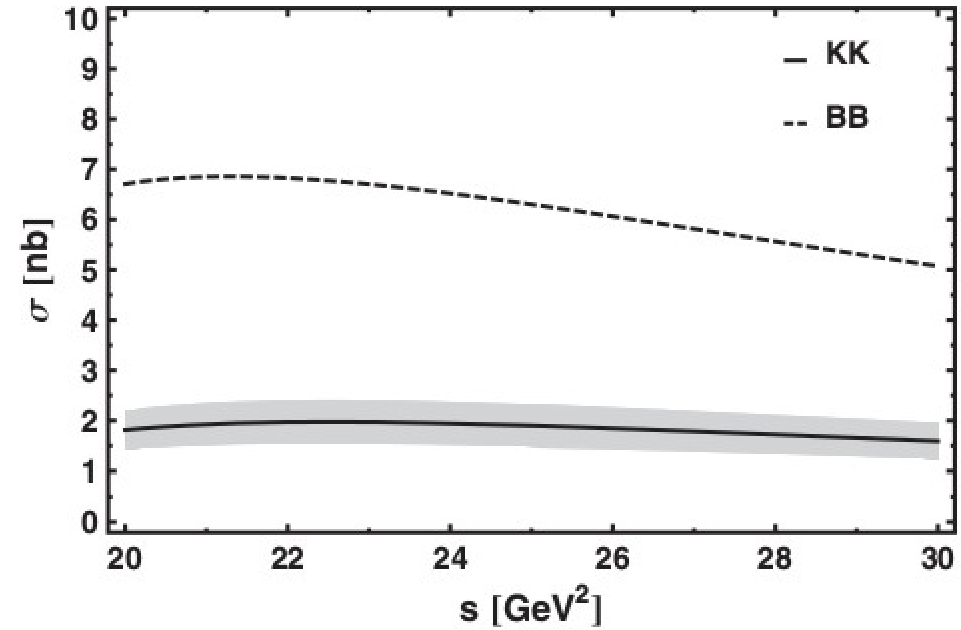
4. Results : Total & Differential Cross Sections

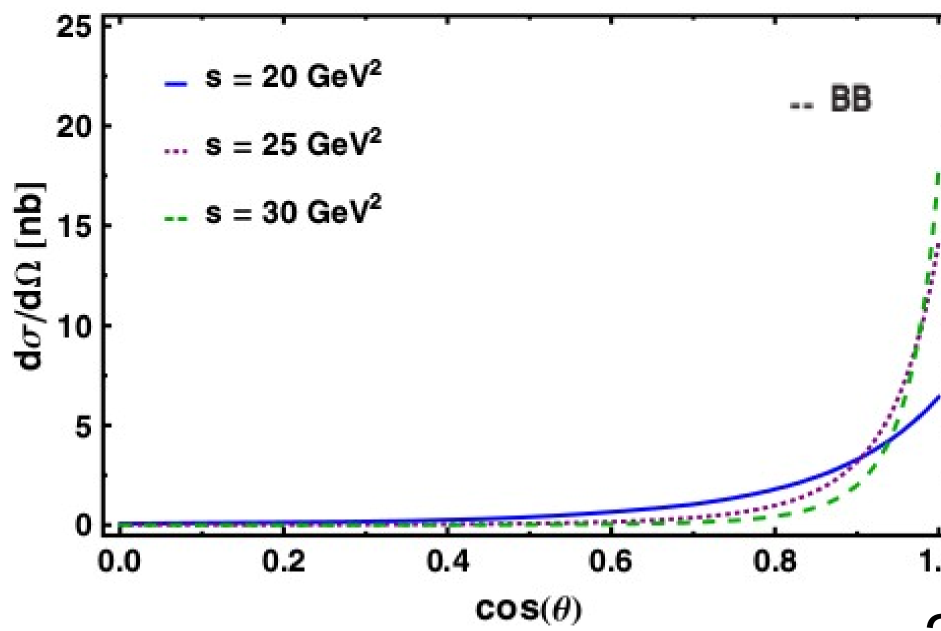
My results





Kofler et al





V. Summary & Future plan

5. Summary & Future plan

◇ The production rates of the ($\pi^- p \to K^* \Lambda$, $\pi^- p \to D^* \Lambda_c$) are calculated.

◇ In effective Lagrangians , we take into account the contributions

of $K(D)$, $K^*(D^*)$, N, and $\Sigma(\Sigma_c)$ exchanges.

In a Regge model, $K(D)$, $K^*(D^*)$, and $\Sigma(\Sigma_c)$ reggeon exchanges are considered.

◇ In general, vector meson exchanges (K^*,D^*) govern our reaction processes.

◇ σ ($\pi^- p \to K^* \Lambda$) **>** σ ($\pi^- p \to D^* \Lambda_c$), $10^4 \sim 10^3$ ($10^4 \sim 10^6$) times

for the effective Lagrangians (Regge model).

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◇ $\sigma(\pi^- p \rightarrow K^* \Lambda) > \sigma(\pi^- p \rightarrow D^* \Lambda_c)$, $10^4 \sim 10^3$ ($10^4 \sim 10^6$) times for the effective Lagrangians (Regge model).

◇ In the case of the ($\pi^- p \rightarrow K \Lambda$, $\pi^- p \rightarrow D \Lambda_c$),

$K^*(D^*)$ and $\Sigma(\Sigma_c)$ reggeon exchanges are considered with a Regge model.

◇ (K^*,D^*) reggeon exchanges govern our reaction processes.

◇ $\sigma(\pi^- p \rightarrow K \Lambda) > \sigma(\pi^- p \rightarrow D \Lambda_c)$, $10^5 \sim 10^6$ times for the Regge model.

---

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◇ σ ($\pi^- p \rightarrow K \Lambda$) **>** σ ($\pi^- p \rightarrow D \Lambda c$), $10^5 \sim 10^6$ times for the Regge model.

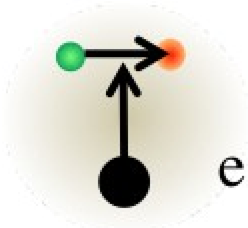
- Coupled-channel analysis

Thank you very much

Backup

Wave function

By T. Yoshida (Tokyo tech.)

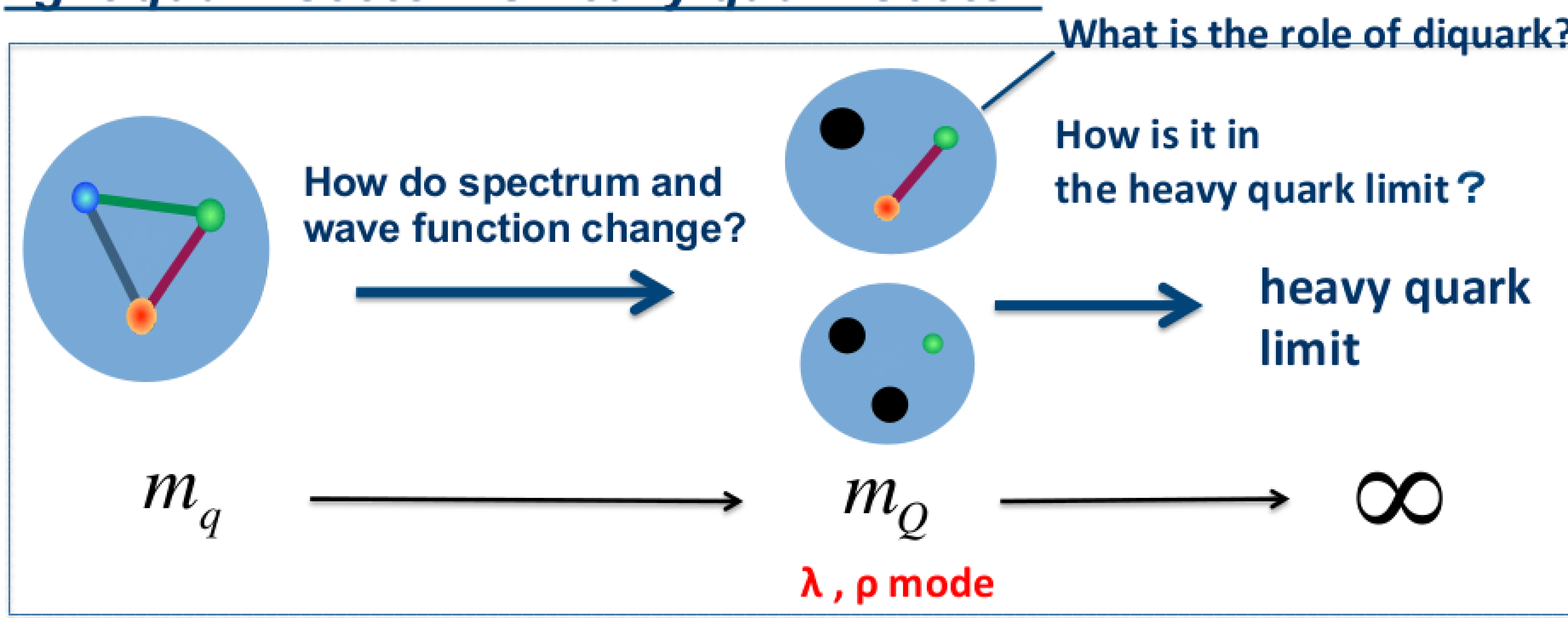


Mixing of $\Lambda(\text{phys}) = c_\lambda \Lambda({}^2\lambda) + c_\rho \Lambda({}^2\rho)$

e.g. λ-mode dominant state: How much the other mode mixes?

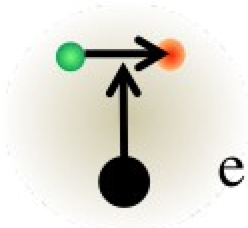
Charmed baryon spectroscopy in a quark model

light quark sector vs heavy quark sector



Wave function

By T. Yoshida (Tokyo tech.)



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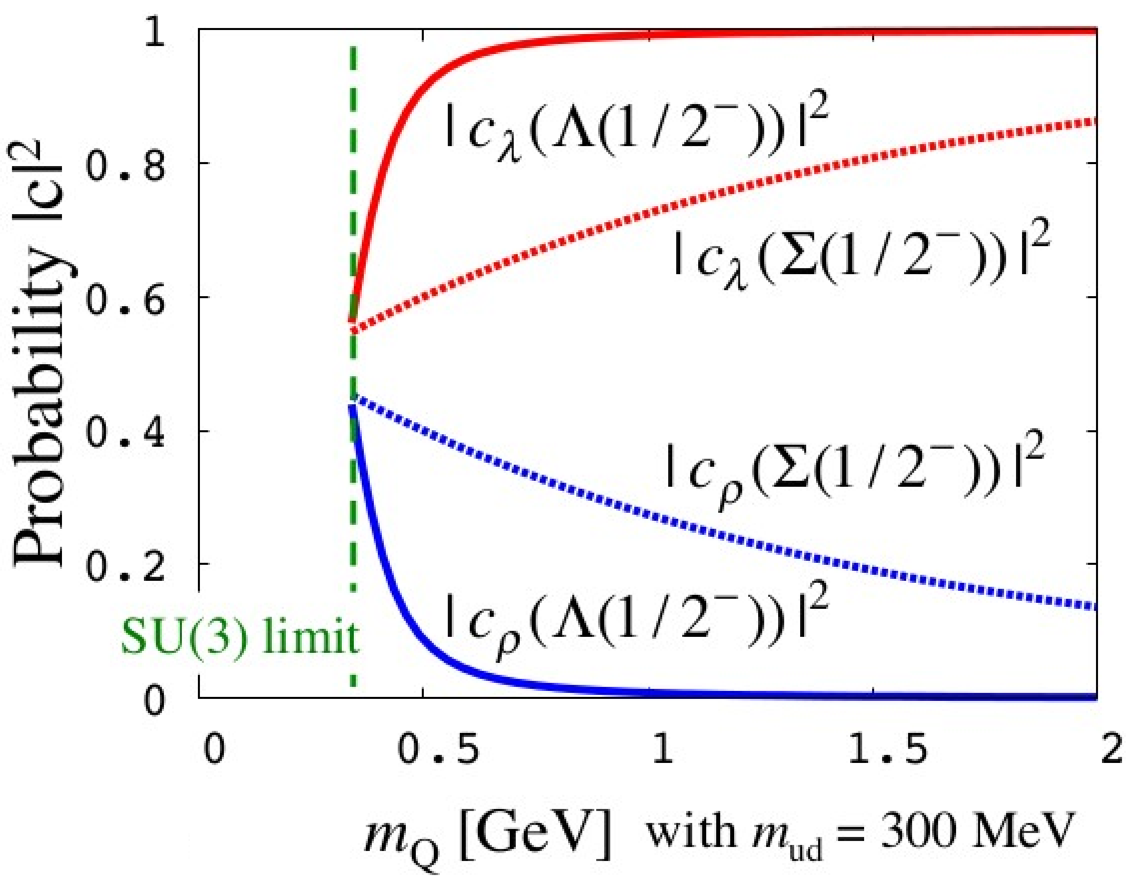


Effective Lagrangians

Effective Lagrangians

$$
\begin{aligned}
\mathcal{L}_{\pi K K^*} &= -i g_{\pi K K^*}(\bar{K}\partial^\mu \boldsymbol{\tau}\cdot\boldsymbol{\pi} K^*_\mu - \bar{K}^*_\mu \partial^\mu \boldsymbol{\tau}\cdot\boldsymbol{\pi} K) \\
\mathcal{L}_{\pi K^* K^*} &= -g_{\pi K^* K^*}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu \bar{K}^*_\nu \boldsymbol{\tau}\cdot\boldsymbol{\pi}\partial_\alpha K^*_\beta
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\pi NN} &= \frac{g_{\pi NN}}{2M_N}\bar{N}\gamma_\mu\gamma_5\partial^\mu \boldsymbol{\tau}\cdot\boldsymbol{\pi} N, \\
\mathcal{L}_{\pi\Sigma\Lambda} &= \frac{g_{\pi\Sigma\Lambda}}{M_\Lambda + M_\Sigma}\bar{\Lambda}\gamma_\mu\gamma_5\partial^\mu \boldsymbol{\pi}\cdot\boldsymbol{\Sigma} + \mathrm{H.c.} \\
\mathcal{L}_{KN\Lambda} &= \frac{g_{KN\Lambda}}{M_N + M_\Lambda}\bar{N}\gamma_\mu\gamma_5\Lambda\partial^\mu K + \mathrm{H.c.}
\end{aligned}
$$

$$
\mathcal{L}_{K^*NY} = -g_{K^*NY}\bar{N}\left[\gamma_\mu Y - \frac{\kappa_{K^*NY}}{2M_N}\sigma_{\mu\nu} Y \partial^\nu\right] K^{*\mu} + \mathrm{H.c.}
$$

Coupling Constants

$g_{\pi K K^*}$	$g_{\pi K^* K^*}$	$g_{\pi NN}$	$g_{\pi\Sigma\Lambda}$	$g_{KN\Lambda}$	$g_{K^*N\Lambda}$	$\kappa_{K^*N\Lambda}$	$g_{K^*N\Sigma}$	$\kappa_{K^*N\Sigma}$
6.56	7.45 GeV^{-1}	13.3	11.9	-13.4	-4.26	2.91	-2.46	-0.529

Exp.

SU(3) relation

Nijmegen potential (NSC97a)

3. Formalism

Coupling Constants

$g_{\pi K K^*}$	$g_{\pi K^* K^*}$	$g_{\pi NN}$	$g_{\pi \Sigma\Lambda}$	$g_{KN\Lambda}$	$g_{K^*N\Lambda}$	$\kappa_{K^*N\Lambda}$	$g_{K^*N\Sigma}$	$\kappa_{K^*N\Sigma}$
6.56	7.45 GeV^{-1}	13.3	11.9	-13.4	-4.26	2.91	-2.46	-0.529

Exp.

SU(3) relation

Nijmegen potential (NSC97a)

Nijmegen potential (NSC97f)

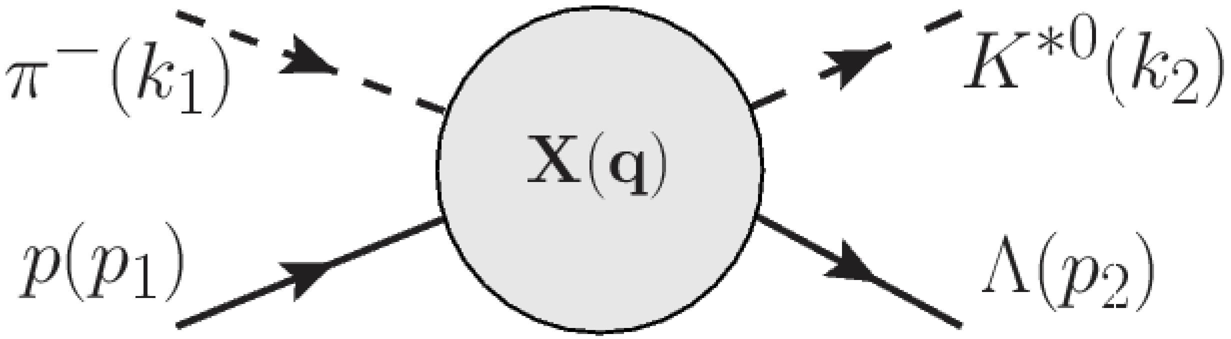
$g_{\pi K K^*}$	$g_{\pi K^* K^*}$	$g_{\pi NN}$	$g_{\pi \Sigma\Lambda}$	$g_{KN\Lambda}$	$g_{K^*N\Lambda}$	$\kappa_{K^*N\Lambda}$	$g_{K^*N\Sigma}$	$\kappa_{K^*N\Sigma}$
6.56	7.45 GeV^{-1}	13.3	11.9	-17.5	-6.11	2.66	-3.52	-1.29

g(f)/g(a) $\rightarrow$ 1.31 1.43 1.43

$a_{K(D)}$	$a_{K^*(D^*)}$	$a_{\Sigma(\Sigma_c)}$
0.6	0.9	1.6

3. Formalism

Feynman Amplitudes

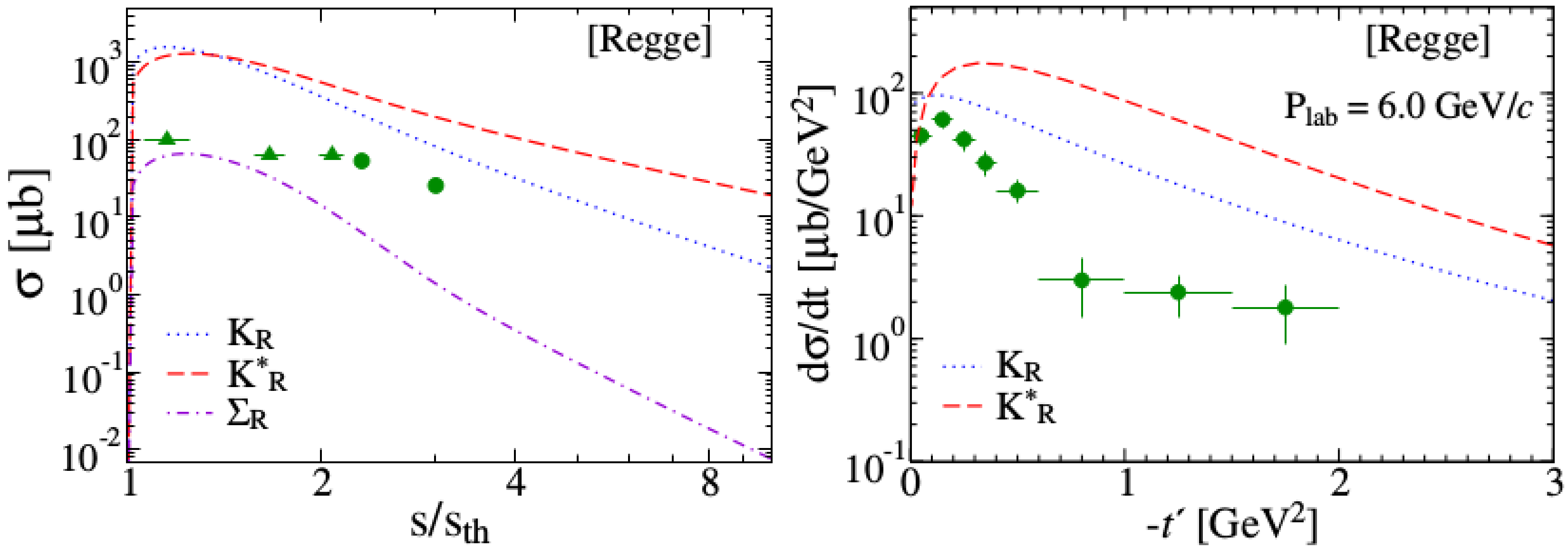


$$\mathcal{M} = \varepsilon^*_\mu \bar{u}_\Lambda \mathcal{M}^\mu \ u_N$$

$$\begin{aligned}
\mathcal{M}^\mu_K &= I_K \frac{i g_{\pi K K^*}}{t - M_K^2} \frac{g_{KN\Lambda}}{M_N + M_\Lambda} \gamma^\nu \gamma_5 k_1^\mu (k_2 - k_1)_\nu, \\
\mathcal{M}^\mu_{K^*} &= I_{K^*} \frac{g_{\pi K^* K^*} g_{K^* N\Lambda}}{t - M_{K^*}^2} \epsilon^{\mu\nu\alpha\beta} \left[\gamma_\nu - \frac{i\kappa_{K^* N\Lambda}}{M_N + M_\Lambda} \sigma_{\nu\lambda} (k_2 - k_1)^\lambda \right] k_{2\alpha} k_{1\beta}, \\
\mathcal{M}^\mu_N &= I_N \frac{i g_{K^* N\Lambda}}{s - M_N^2} \frac{g_{\pi NN}}{2M_N} \left[\gamma^\mu - \frac{i\kappa_{K^* N\Lambda}}{M_N + M_\Lambda} \sigma^{\mu\nu} k_{2\nu} \right] (\not{k}_1 + \not{p}_1 + M_N) \gamma^\alpha \gamma_5 k_{1\alpha}, \\
\mathcal{M}^\mu_\Sigma &= I_\Sigma \frac{i g_{K^* N\Sigma}}{u - M_\Sigma^2} \frac{g_{\pi\Sigma\Lambda}}{M_\Sigma + M_\Lambda} \gamma^\alpha \gamma_5 (\not{p}_2 - \not{k}_1 + M_\Sigma) \left[\gamma^\mu - \frac{i\kappa_{K^* N\Sigma}}{M_N + M_\Sigma} \sigma^{\mu\nu} k_{2\nu} \right] k_{1\alpha}.
\end{aligned}$$

Regge model

Cross sections without form factors



➪ K^* reggeon exchange may be more dominant than K reggeon one.

Form factor : $C_{\text{ex}}(p^2) = \dfrac{a}{(1-p^2/\Lambda^2)^2}$

$$\boxed{\begin{aligned}\mathcal{M}^{\rm R}_{\rm Total}[\pi^- p \to K^{*0}\Lambda(D^{*-}\Lambda_c^+)] = {} & \mathcal{M}^{\rm R}_{K(D)}\cdot C_{K(D)} + \\ & \mathcal{M}^{\rm R}_{K^*(D^*)}\cdot C_{K^*(D^*)} + \mathcal{M}^{\rm R}_{\Sigma(\Sigma_c)}\cdot C_{\Sigma(\Sigma_c)}\end{aligned}}$$

$a_{K(D)}$	$a_{K^*(D^*)}$	$a_{\Sigma(\Sigma_c)}$
0.6	0.8	1.5

$\Lambda_{K,K^*,\Sigma\,(D,D^*,\Sigma_c)} = 1.0\,\text{GeV}$

Regge Parameters

(a) The intercept and the slope of the trajectory for the nondiagonal transition are related to the corresponding parameters for the diagonal transitions :

$$\alpha(t) = \alpha(0) + \alpha' t$$?

$$\boxed{2\alpha_{ij} = \alpha_{\bar{i}i}(0) + \alpha_{\bar{j}j}(0) \qquad 2/\alpha'_{ij} = 1/\alpha'_{\bar{i}i} + 1/\alpha'_{\bar{j}j}}$$

$$\pi^- p \to K^{*0}\Lambda$$

$$\begin{aligned} \alpha_{\bar{u}u}(t) = \alpha_\pi(t) &= -0.0118 + 0.647t \\ \alpha_{\bar{s}s}(t) = \alpha_{\eta_s}(t) &= -0.291 + 0.606t \\ \alpha_{us}(t) = \alpha_K(t) &= -0.151 + 0.617t \end{aligned}$$

$$\begin{aligned} \alpha_{\bar{u}u}(t) = \alpha_\rho(t) &= 0.55 + 0.742t \\ \alpha_{\bar{s}s}(t) = \alpha_\phi(t) &= 0.27 + 0.675t \\ \alpha_{us}(t) = \alpha_{K^*}(t) &= 0.414 + 0.707t \end{aligned}$$

$$\pi^- p \to D^{*-}\Lambda_c^+$$

$$\begin{aligned} \alpha_{\bar{u}u}(t) = \alpha_\pi(t) &= -0.0118 + 0.647t \\ \alpha_{\bar{c}c}(t) = \alpha_{\eta_c}(t) &= -3.2103 + 0.332t \\ \alpha_{uc}(t) = \alpha_D(t) &= -1.6115 + 0.439t \end{aligned}$$

$$\begin{aligned} \alpha_{\bar{u}u}(t) = \alpha_\rho(t) &= 0.55 + 0.742t \\ \alpha_{\bar{c}c}(t) = \alpha_{J/\Phi}(t) &= -2.60 + 0.340t \\ \alpha_{uc}(t) = \alpha_{D^*}(t) &= -1.02 + 0.467t \end{aligned}$$

Brisudova et al, PRD 61.054013(2000)

Regge Parameters

(b) The energy scale parameter is related to the corresponding parameters for the diagonal transitions :

$$\pi^- p \to K^{*0}\Lambda$$

$$\boxed{s_0^{\pi N\to K^*\Lambda} = \left(s_0^{\pi N}\right)^{\frac{\alpha_\rho(0)-1}{2(\alpha_{K^*}(0)-1)}}\left(s_0^{K^*\Lambda}\right)^{\frac{\alpha_\phi(0)-1}{2(\alpha_{K^*}(0)-1)}}}$$

$$\alpha(t)=\alpha(0)+\alpha' t$$

$$m_u\approx 0.5, m_c\approx 1.6\ [\mathrm{GeV}]$$

$$s_0^{\pi N}\approx 1.5, s_0^{K\Lambda}\approx 1.76\ [\mathrm{GeV}^2]$$

$$\underline{s_0(K)=1.64, s_0(K^*)=1.66}$$

$$\pi^- p \to D^{*-}\Lambda_c^+$$

$$\boxed{s_0^{\pi N\to D^*\Lambda_c} = \left(s_0^{\pi N}\right)^{\frac{\alpha_\rho(0)-1}{2(\alpha_{D^*}(0)-1)}}\left(s_0^{D^*\Lambda_c}\right)^{\frac{\alpha_{J/\Psi}(0)-1}{2(\alpha_{D^*}(0)-1)}}}$$

$$\alpha(t)=\alpha(0)+\alpha' t$$

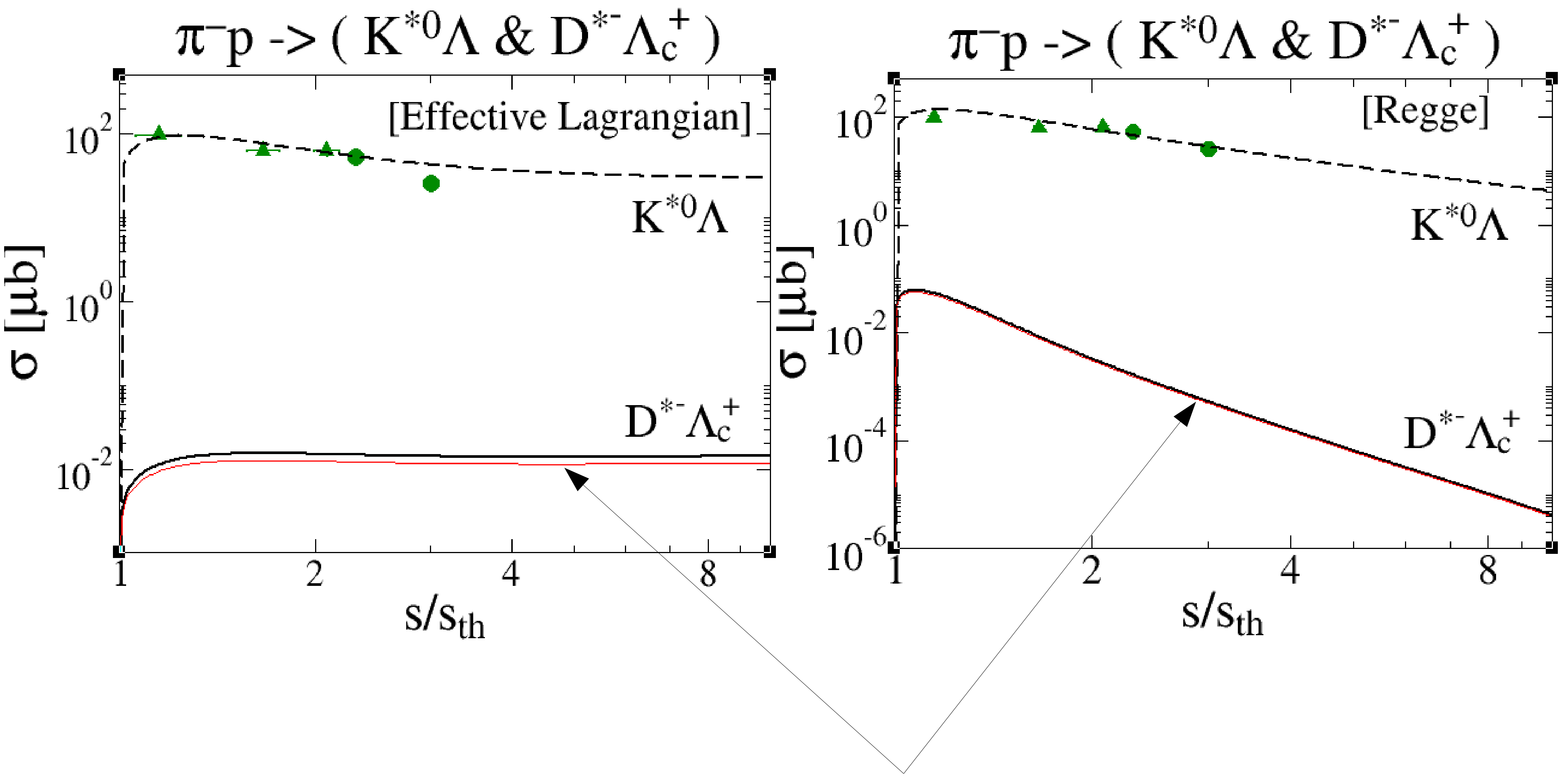
$$m_u\approx 0.5, m_s\approx 0.6\ [\mathrm{GeV}]$$

$$s_0^{\pi N}\approx 1.5, s_0^{D\Lambda_c}\approx 5.46\ [\mathrm{GeV}^2]$$

$$\underline{s_0(D)=4.25, s_0(D^*)=4.75}$$

Brisudova et al, PRD 61.054013(2000)

4. Results : Total Cross Sections

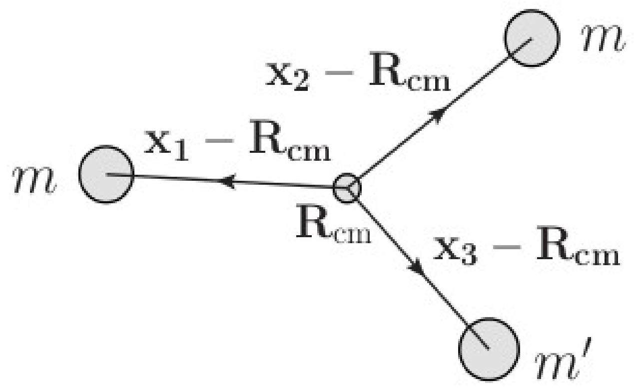


$$0.55\,\mathrm{GeV} \Longrightarrow 0.537\,\mathrm{GeV}$$
$$0.60\,\mathrm{GeV} \Longrightarrow 0.586\,\mathrm{GeV}$$

s c

4. Results

Form factors & Size of baryons



$$\boxed{\begin{aligned}\langle R^2\rangle &= \frac{1}{3}\sum_{i=1}^{3}(\boldsymbol{x}_i - \boldsymbol{R}_{\rm cm})^2 \\ &= \left[\frac{m'^2+2m^2}{(2m+m')^2}\frac{1}{\alpha_\lambda^2}+\frac{1}{4\alpha_\rho^2}\right]\end{aligned}}$$

$$\alpha_\rho^2 = \sqrt{3m_\rho K} = \sqrt{3mK}$$

$$\alpha_\lambda^2 = \sqrt{3m_\lambda K} = 3\sqrt{\frac{mm'K}{2m+m'}}$$

the nucleon

$m' = m \simeq 0.35\,\mathrm{GeV}$

$$\langle R^2\rangle = \frac{1}{3\alpha_\lambda^2}+\frac{1}{4\alpha_\rho^2} = \frac{7}{12}\frac{1}{\sqrt{3mK}} = (0.5\,fm)^2 = (2.5\,\mathrm{GeV}^{-1})^2$$

$$\Longrightarrow \quad K = 0.0083\,\mathrm{GeV}^3$$

charmed baryon

$m' = m_Q \simeq 1.5\,\mathrm{GeV}$

$$\langle R^2\rangle = (2.56\,\mathrm{GeV}^{-1})^2 = (0.512\,fm)^2$$

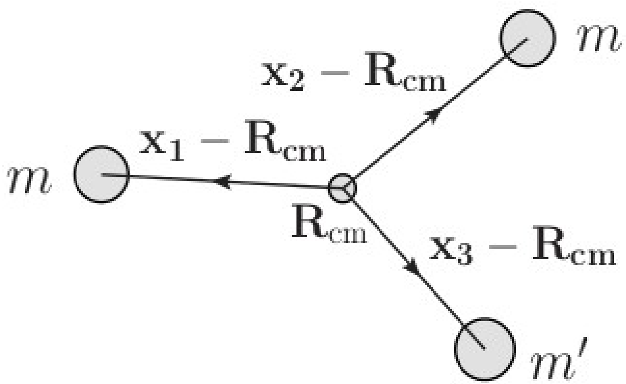
$$\Lambda \propto 1/\text{Size of a Baryon}$$

$$0.55\,\mathrm{GeV} \Longrightarrow 0.537\,\mathrm{GeV}$$

$$0.60\,\mathrm{GeV} \Longrightarrow 0.586\,\mathrm{GeV}$$

s c

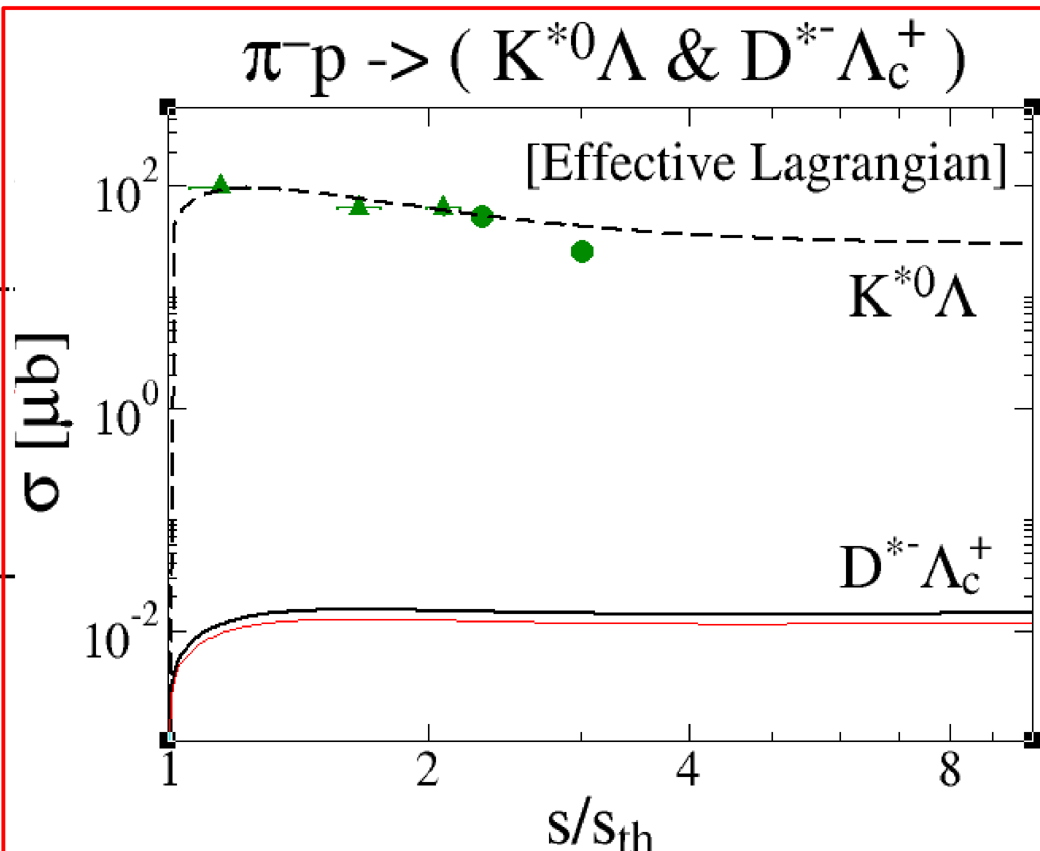
Form factors & Size of baryons



$$\langle R^2 \rangle = \frac{1}{3}\sum_{i=1}^{3}(\boldsymbol{x}_i - \boldsymbol{R}_{\rm cm})^2$$
$$= \left[\frac{m'^2 + 2m^2}{(2m+m')^2}\frac{1}{\alpha_\lambda^2} + \frac{1}{4\alpha_\rho^2}\right]$$

$$\alpha_\rho^2 = \sqrt{3m_\rho K} = \sqrt{3mK}$$

$$\alpha_\lambda^2 = \sqrt{3m_\lambda K} = 3\sqrt{\frac{mm'K}{2m+m'}}$$



$$= \frac{7}{12}\frac{1}{\sqrt{3mK}} = (0.5\,fm)^2 = (2.5\ {\rm GeV}^{-1})^2$$

$$K = 0.0083\ {\rm GeV}^3$$

$$)^2 = (0.512\,fm)^2$$

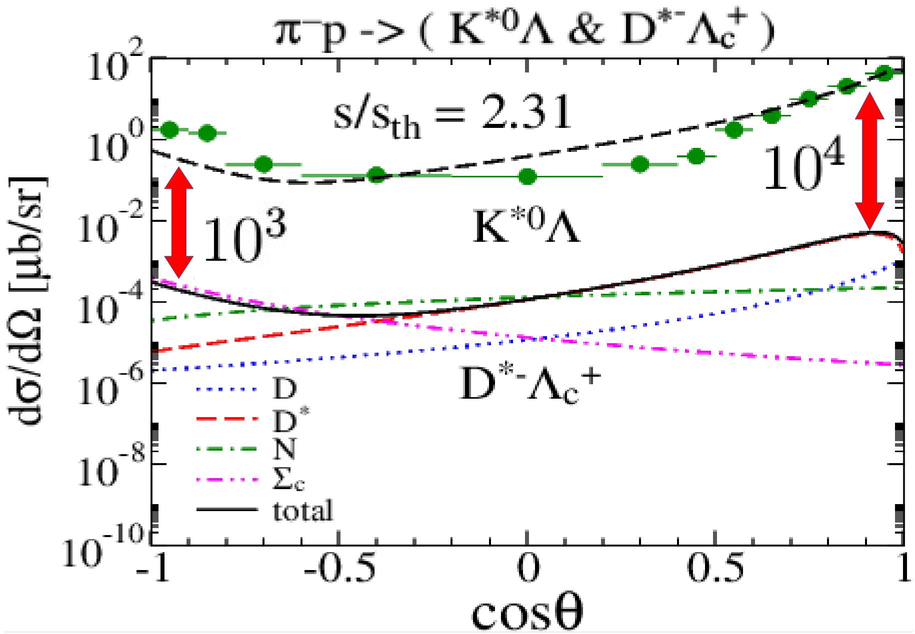
$$0.55\ {\rm GeV} \Longrightarrow 0.537\ {\rm GeV}$$

$$0.60\ {\rm GeV} \Longrightarrow 0.586\ {\rm GeV}$$

s c

4. Results : Differential Cross Sections

[Effective Lagrangians]

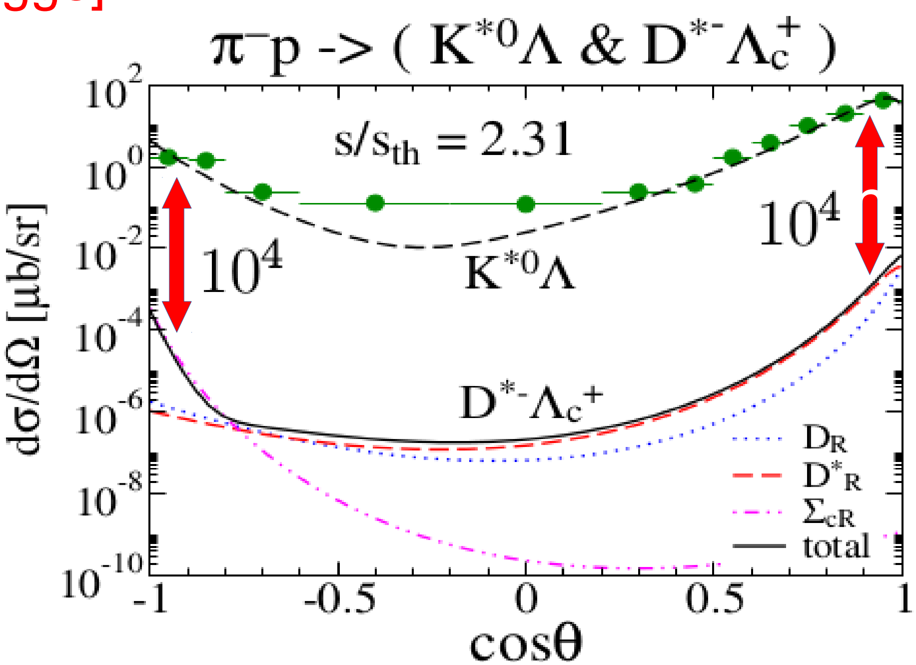


Where does this large gap come from?

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm CM} = \frac{1}{64\pi^2 s}\frac{\mathbf{p}_{out}}{\mathbf{k}_{in}}\frac{1}{2}\sum|\mathcal{M}|^2$$

no effect, not main reason

[Regge]



Assumptions
1: couplings (s) = couplings (c)
2: cutoff masses (s) = cutoff masses (c)

These assumptions are reasonable?

END