Possible baryon spectroscopy with strangeness at HIAF

Bing-Song Zou

Institute of Theoretical Physics, CAS, Beijing

University of Chinese Academy of Sciences

Outline

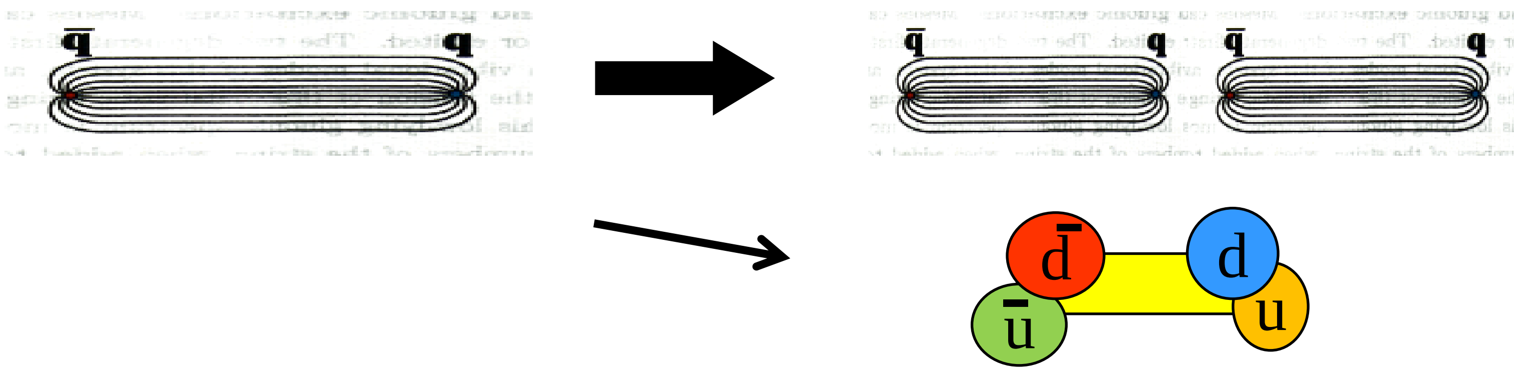
- **General issues on hadron structure**
- **Quark-gluon structure of proton**
- **Pentaquark states**
- **Possible baryon spectroscopy with strangeness at HIAF**

1. General issues on hadron structure:

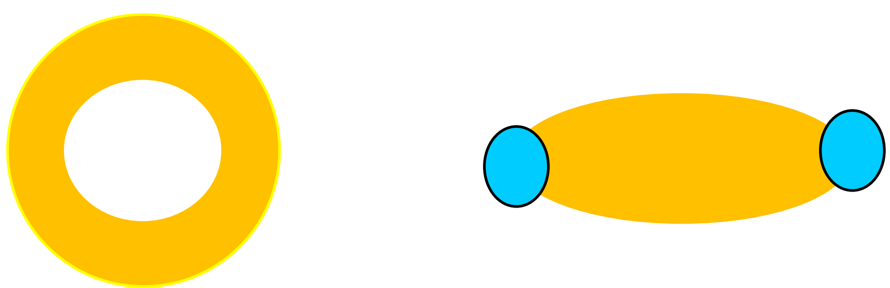
how quarks & gulons contruct hadrons?

Key point for hadron structure & quark confinement

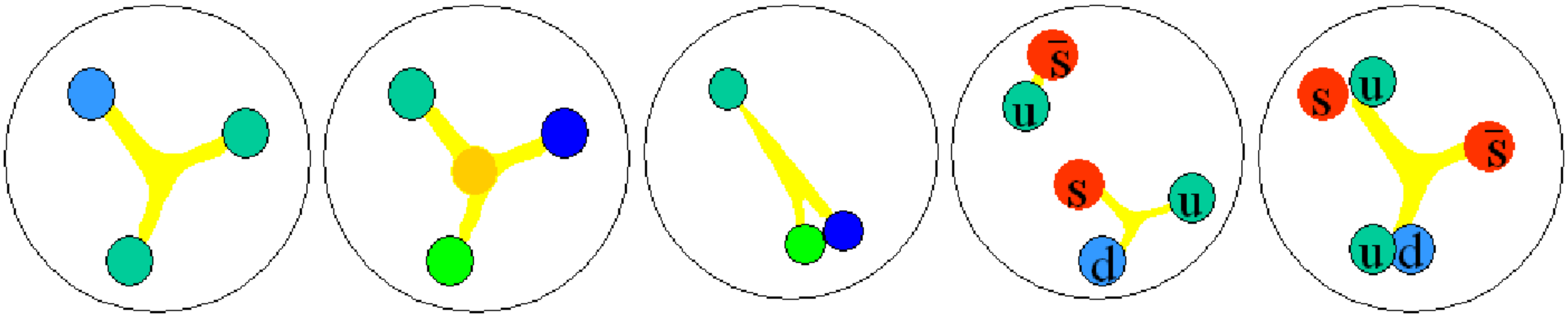
Unquenching dynamics: gluons → $\bar{q}q$



Mesons: $\bar{q}q$, tetraquarks, glueballs, $\bar{q}qg$-hybrids?



How about baryons?



(a) (b) (c) (d) (e)

A. qqq B. qqqg C. q-q^2 D-E. pentaquarks

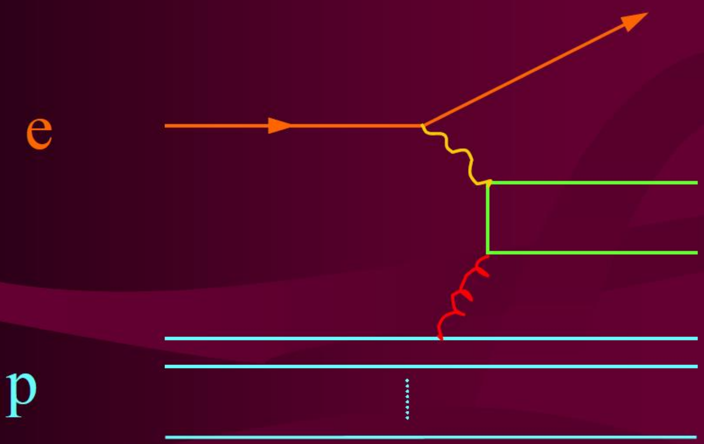
Number of predicted N*: D-E>B>A>C

Number of observed N* <A, "missing"?

Poor knowledge on baryon spectroscopy
Lack effective reliable theoretical predictions

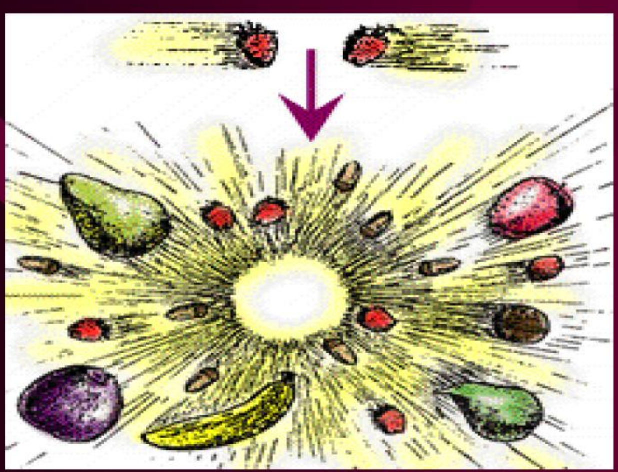
Two major methods for exploring baryon structure

1） lepton-proton scattering → parton distribution of proton



Problem： γ, g, $\bar{q}q$ transition，
intrinsic or extrinsic ？

2） hadrons, leptons, γ collisions → hadron spectroscopy



Atomic spectroscopy → Atomic Quantum Theory

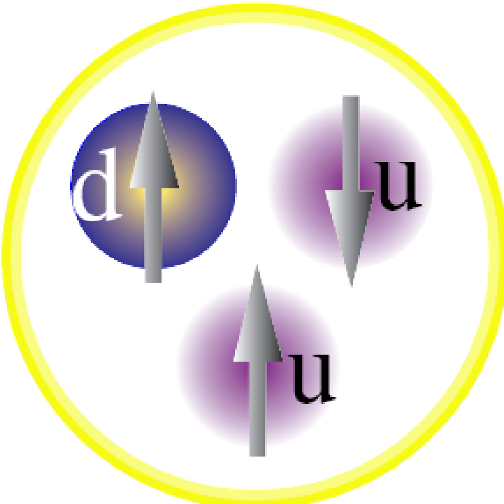
Nuclear spectroscopy → Shell Model &
Collective motion Model

Hadron spectroscopy → ?

2. Quark gluon structure of proton

Classical picture of the proton

Constituent Quarks



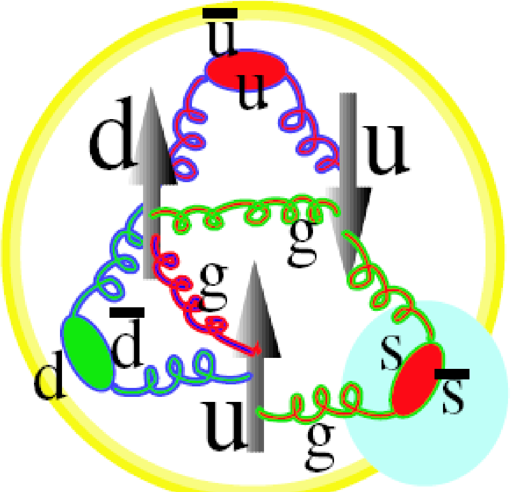
($Q^2 = 0$ GeV^2)

baryon octet

masses,magn. momenta

1964-1974

Parton Distributions



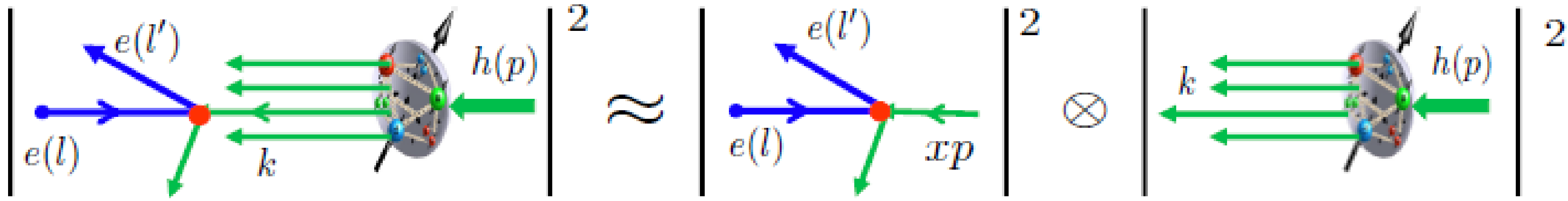
($Q^2 > 1$ GeV^2)

structure functions

momentum, spin

$$\bar{u}(x) = \bar{d}(x)\ , \quad \bar{s}(x) = s(x)$$

1974–1992



Cross section　　femtometer probe　　Parton in a hadron

The structure

QCD factorization → PDF (flavor, spin, momentum) of nucleon

proton spin "crisis" , $\bar{d} - \bar{u} \sim 0.12$, $\bar{s}(x) \neq s(x)$, …

Spin “crisis” , $\bar{d} - \bar{u} \sim 0.12$, $\bar{s}(x) \neq s(x)$ puzzles →

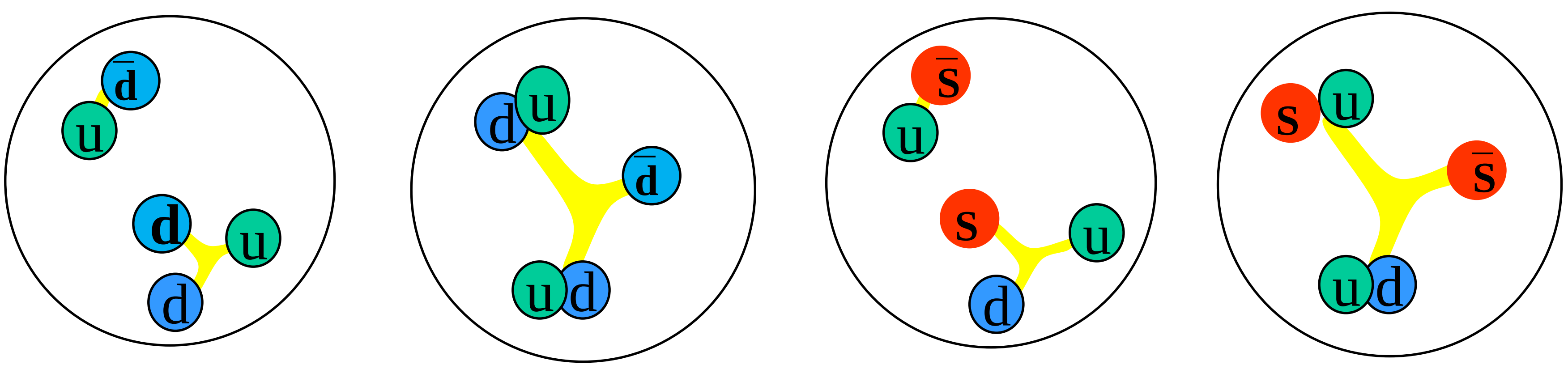
two possible solutions:

Meson clouds: **Thomas, Speth, Weise, Oset, Brodsky, Ma, …**

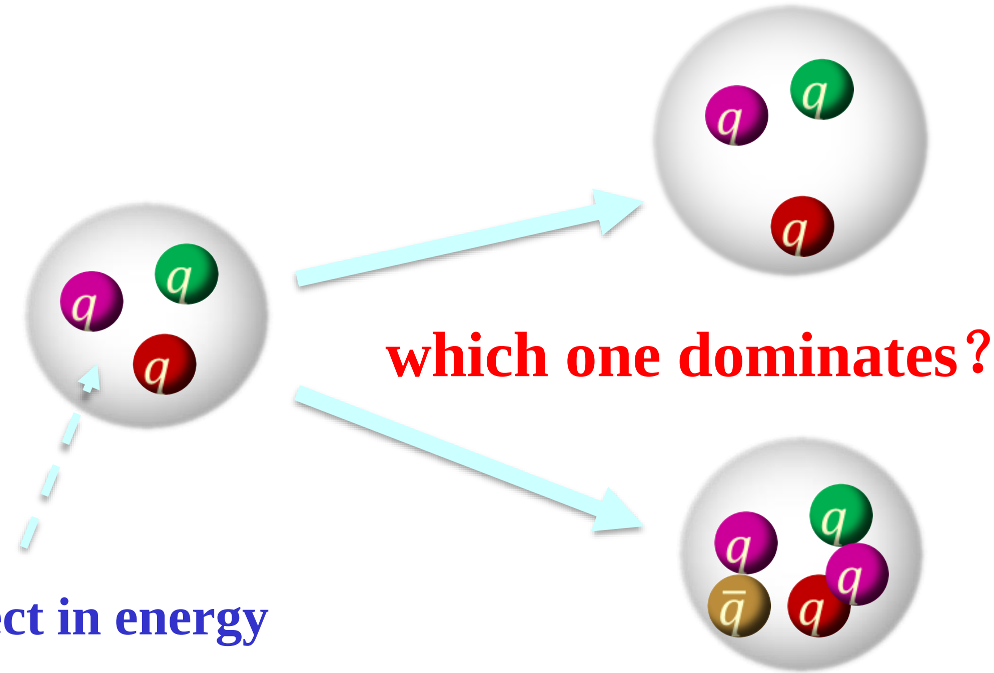
$$| p > \sim | uud > + \varepsilon_1 | n (udd) \pi^+ (\bar{d}u) > + \varepsilon_2 | \Delta^{++} (uuu) \pi^- (\bar{u}d) > + \varepsilon' | \Lambda (uds) K^+ (\bar{s}u) > \ldots$$

diquarks: **Riska, Zou, Zhu, …**

$$| p > \sim | uud > + \varepsilon_1 | [ud][ud] \bar{d} > + \varepsilon' | [ud][us] \bar{s} > + \ldots$$



~30% pentaquarks in proton → more in excited baryons !



Classic quark model:
3q excited states

New view:
Pentaquark excitation
dominates already for ½-

inject in energy

Pentaquark crucial for baryon spectroscopy and structure !

3. Pentaquark states

Fate of the first pentaquark predicted and observed:

1959: $\bar{K}N$ molecule predicted by Dalitz-Tuan, PRL2, 425

1961: $\Lambda(1405) \rightarrow \Sigma\pi$ observed by Alston et al., PRL6, 698

1964: Quark model (uds) for $\Lambda(1405)$

1995: $\bar{K}N$ dynamically generated -- Kaiser et al., NPA954, 325

2001: 2 pole structure by $\bar{K}N$-$\Sigma\pi$ -- Oller et al., PLB500, 263

PDG2010: "The clean Λ_c spectrum has in fact been taken to settle the decades-long discussion about the nature of the $\Lambda(1405)$ —true 3-quark state or mere $\bar{K}N$ threshold effect?— unambiguously in favor of the first interpretation."

Fate of the last famous fading pentaquark $\theta^+(1540)$:

1997: Z^+(1530) predicted by Diakonov et al., ZPA359, 305

2003: $\theta^+(1540) \rightarrow K^+n$ claimed by LEPS, PRL91, 012002

2003: $\bar{s}$ (ud)(ud) for θ(1540) by Jaffe&Wilczek, PRL91, 232003

2003: $\bar{s}$ ud)(ud) for θ(1540) by Karliner&Lipkin, PLB575, 249

2004: supported by 10 expts → θ(1540) well-established by PDG

2004: not supported by BESII, PRD70, 012004

2005: not supported by many high stats experiments

2006: removed from PDG

Note: $\theta^+(1540)$ is not supported by hadronic molecule model & chiral quark model by Huang, Zhang, Yu, Zou, PLB586(2004)69

$1/2^-$ baryon nonet with strangeness

- **Mass pattern : quenched or unquenched ?**

  uds (L=1) $1/2^-$ ~ $\Lambda^*(1670)$ ~ $[us][ds]\bar{s}$ $\bar{K}\Xi - \eta\Lambda$

  uud (L=1) $1/2^-$ ~ $N^*(1535)$ ~ $[ud][us]\bar{s}$ $\bar{K}\Sigma - \bar{K}\Lambda - \eta N$

  uds (L=1) $1/2^-$ ~ $\Lambda^*(1405)$ ~ $[ud][su]\bar{u}$ $\bar{K}N - \pi\Sigma$

  uus (L=1) $1/2^-$ ~ $\Sigma^*(1390)$ ~ $[us][ud]\bar{d}$ $\bar{K}N - \pi\Sigma - \pi\Lambda$

  Zou et al, NPA835 (2010) 199 ; CLAS, PRC87(2013)035206

- **Strange decays of N*(1535) :** PDG → large $g_{N^*N\eta}$

  $J/\psi \to \bar{p}N^* \to \bar{p}\,(K\Lambda)$ / $\bar{p}\,(p\eta)$ → large $g_{N^*K\Lambda}$

  Liu&Zou, PRL96 (2006) 042002; Geng,Oset,Zou&Doring, PRC79 (2009) 025203

  $\gamma p \to p\eta'$ & $pp \to pp\eta'$ → large $g_{N^*N\eta'}$

  M.Dugger et al., PRL96 (2006) 062001; Cao&Lee, PRC78(2008) 035207

  $\pi^- p \to n\phi$ & $pp \to pp\phi$ & $pn \to d\phi$ → large $g_{N^*N\phi}$

  Xie, Zou & Chiang, PRC77(2008)015206; Cao, Xie, Zou & Xu, PRC80(2009)025203

- **Strange decays of Λ*(1670) :** PDG → large $g_{\Lambda^*\Lambda\eta}$

  narrower width (35MeV) than Λ*(1405)

$\bar{s}suud \rightarrow \bar{c}cuud$

- prediction of three P_c pentaquark states → J/ψ-p :

  1 $\bar{D}\Sigma_c$ molecule + 2 $\bar{D}^*\Sigma_c$ molecules

  J.J.Wu, R.Molina, E.Oset, B.S.Zou, PRL 105 (2010) 232001

  W.L.Wang, F.Huang, Z.Y.Zhang, B.S.Zou, PRC 84 (2011) 015203

  J.J.Wu, T.H.Lee, B.S.Zou, PRC 85 (2012) 044002

- 4 more broader P_c states with $\Sigma_c \rightarrow \Sigma_c^*$:

  1 $\bar{D}\Sigma_c^*$ molecule + 3 $\bar{D}^*\Sigma_c^*$ molecules

  C.W.Xiao, J.Nieves, E.Oset, PRD 88 (2013) 056012

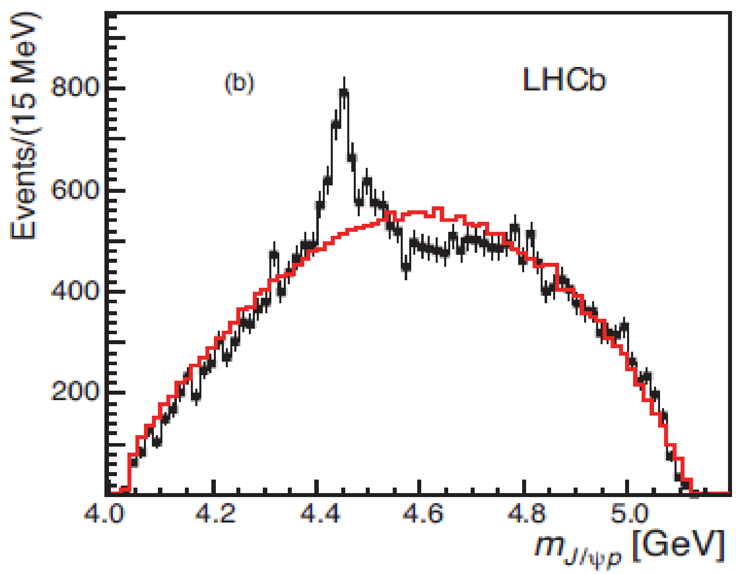
LHCb confirms our prediction of 3 narrow P_c states

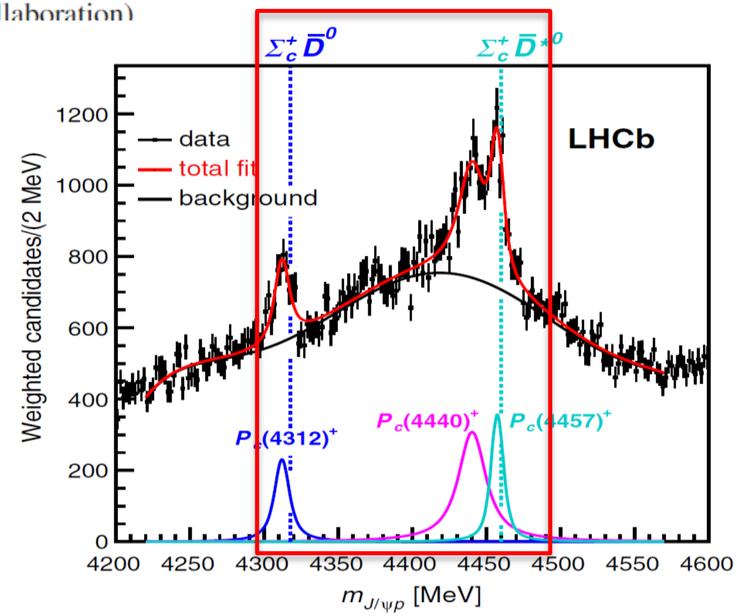
Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.**
(LHCb Collaboration)

PRL 122 (2019) 222001

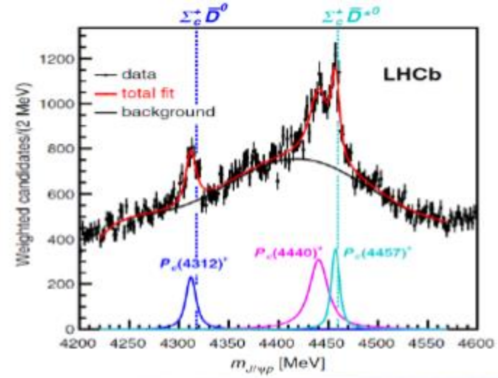




A milestone for pentaquark search

P_c states: observation vs predictions

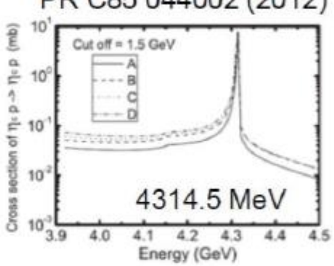
LHCb, PRL122 (2019) 222001



Comparison to numerical predictions

- Many theoretical predictions for $\Sigma_c^+\bar{D}^{(*)0}$ published before 2015, **some in quantitative agreement with the LHCb data**
  - Wu,Molina,Oset,Zou, PRL105, 232001 (2010),
  - **Wang,Huang,Zhang,Zou, PR C84, 015203 (2011),**
  - **Yang,Sun,He,Liu,Zhu, Chin. Phys. C36, 6 (2012),**
  - **Wu,Lee,Zou, PR C85 044002 (2012),**
  - Karliner,Rosner, PRL 115, 122001 (2015)

PR C85 044002 (2012)



ΔE – binding energy

Example:

Nucleon resonances with hidden charm in coupled-channels models

Jia-Jun Wu, T.-S. H. Lee, and B. S. Zou

Phys. Rev. C **85**, 044002 – Published 17 April 2012

arXiv:1202.1036

TABLE III: The pole position ($M - i\Gamma/2$) and "binding energy" ($\Delta E = E_{thr} - M$) for different cut-off parameter Λ and spin-parity J^P. The threshold E_{thr} is 4320.79 MeV of $\bar{D}\Sigma_c$ in PB system and 4462.18 MeV of $D^*\Sigma_c$ in VB system. The unit for the listed numbers is MeV.

		PB System		VB System	
$J^P = \frac{1}{2}^-$	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
	650	-	-	[illegible]	[illegible]
	800	-	-	$4462.178 - 0.002i$	0.002
	1200	$4318.964 - 0.362i$	1.826	$4459.513 - 0.417i$	2.667
	1500	$4314.531 - 1.448i$	6.259	$4454.088 - 1.662i$	8.092
	2000	$4301.115 - 5.835i$	19.68	$4438.277 - 7.115i$	23.90
$J^P = \frac{3}{2}^-$					
	650	-	-	-	-
	800	-	-	$4462.178 - 0.002i$	0.002
	1200	-	-	$4459.507 - 0.420i$	2.673
	1500	-	-	$4454.057 - 1.681i$	8.123
	2000	-	-	$4438.039 - 7.268i$	23.14

$\Delta E(4312) = 5.8^{+1.0}_{-6.8}$ MeV

$\Delta E(4457) = 2.5^{+4.3}_{-4.1}$ MeV

Λ - cut off on exchanged meson mass.

$\Delta E(4440) = 19.5^{+4.9}_{-4.3}$ MeV

Multiquark states – crucial for hadron structure !

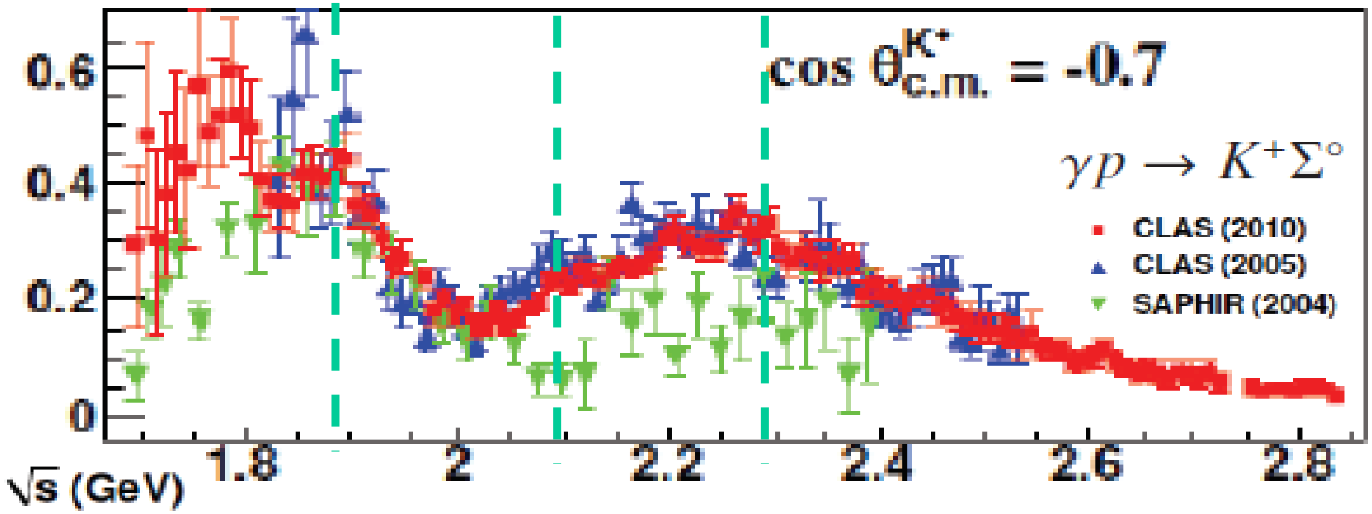
X(3872)	→	top cited paper for Belle (2003)	2328 cites
Zc(3900)	→	top cited paper for BES (2012)	1027 cites
Pc states	→	top cited paper for LHCb (2015)	1576 cites

H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1:
"The hidden-charm pentaquark and tetraquark states" 960 cites

F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou,
Rev.Mod.Phys. 90 (2018)015004: "Hadronic molecules" 937 cites

Strange partners of P_c and P_{cs} states

$K\Sigma^*$ ~1880	$K^*\Sigma$ ~ 2086	$K^*\Sigma^*$ ~ 2280
N*(1875)	N*(2080)	N*(2270)



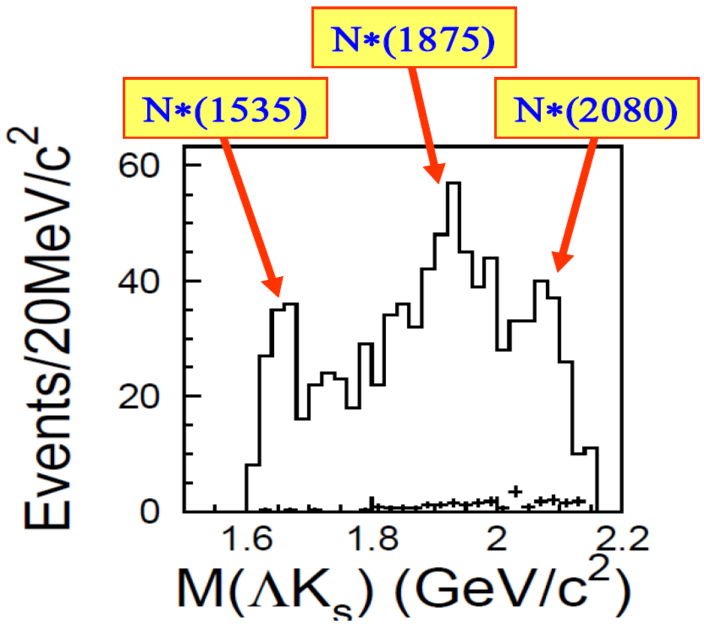
$K\Xi$ ~1810	$K\Xi^*$ ~ 2027	$K^*\Xi$ ~ 2210	$K^*\Xi^*$ ~ 2427
$\Lambda(1/2^-)$	$\Lambda(3/2^-)$	$\Lambda(1/2^-,3/2^-)$	$\Lambda(1/2^-,3/2^-,5/2^-)$

K^*N ~1833 : $\Lambda(1800)1/2^-$, $\Lambda(3/2^-)$

Strange partners of P_c states from charmonium decays at BES ?

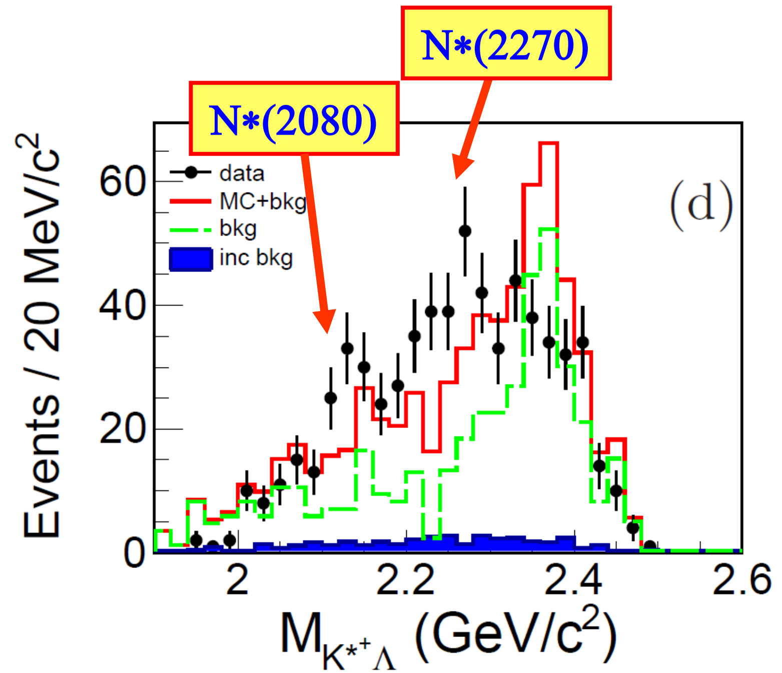
N*(1875) **N*(2080)** **N*(2270)**

$K\Sigma^*$ ~1880 $K^*\Sigma$ ~ 2086 $K^*\Sigma^*$ ~ 2280



$J/\psi \to nK_S^0\bar{\Lambda}$

BESII, PLB659 (2008) 789

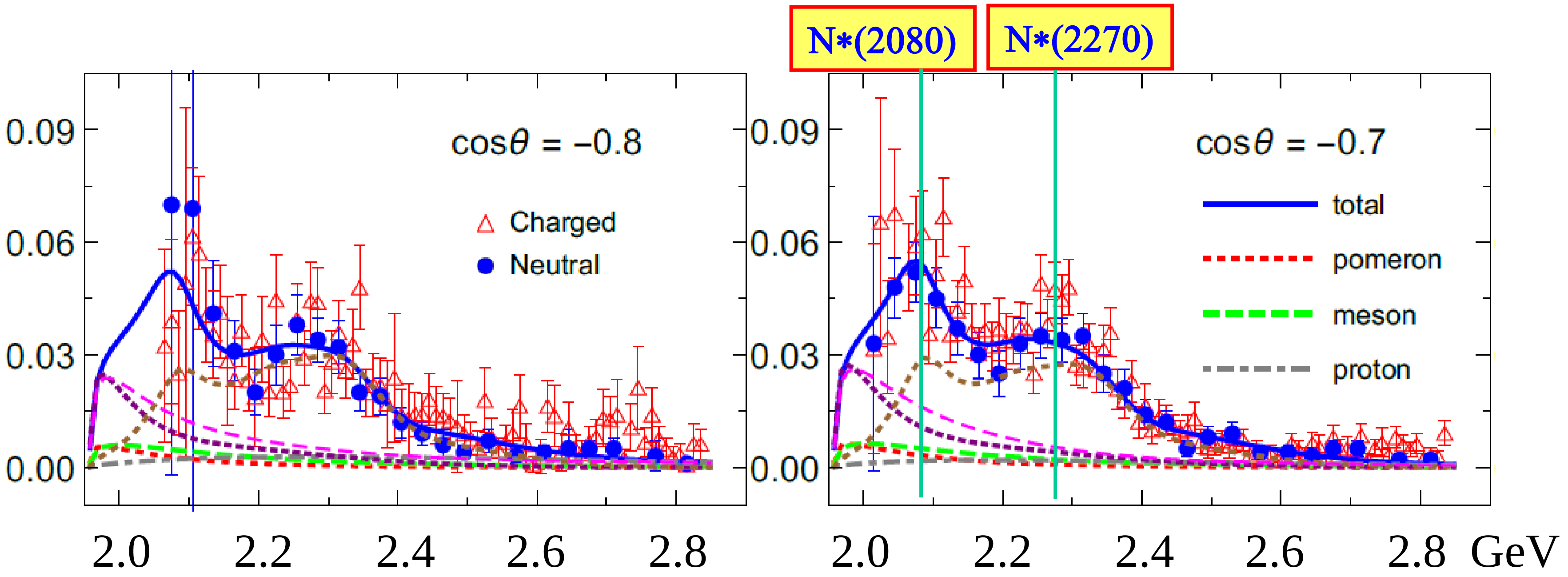


$\chi_{c0} \to \bar{p}K^{*+}\Lambda$ +c.c.

BESIII, PRD100(2019)052010

$\bar{K}\Sigma$ ~ $\Xi(1680)$, $\bar{K}\Sigma^*$ ~ $\Xi(1860)$, $\bar{K}^*\Sigma$ ~ $\Xi(2080)$, $\bar{K}^*\Sigma^*$ ~ $\Xi(2270)$

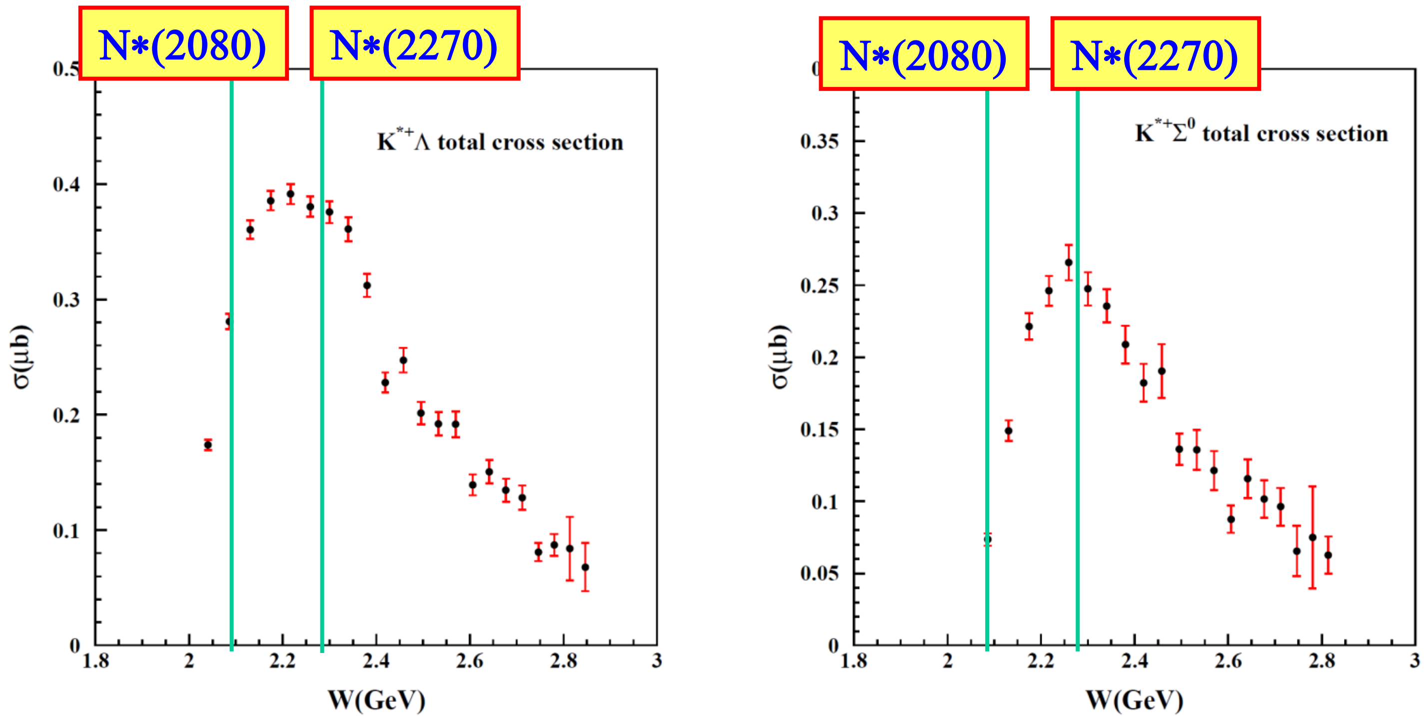
$\gamma p \to \phi p$ CLAS, PRC89(2014)019901



S.M.Wu, F.Wang, B.S.Zou, ArXiv: 2306.15385

Total cross sections of the reaction $\gamma p \to K^{*+}\Lambda$ (left) and $\gamma p \to K^{*+}\Sigma^0$ (right)

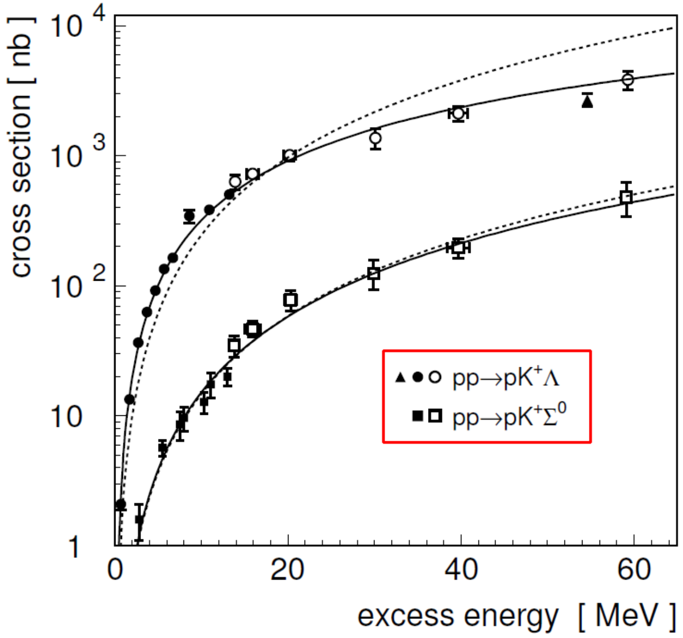
CLAS, PRC 87(2013)065204

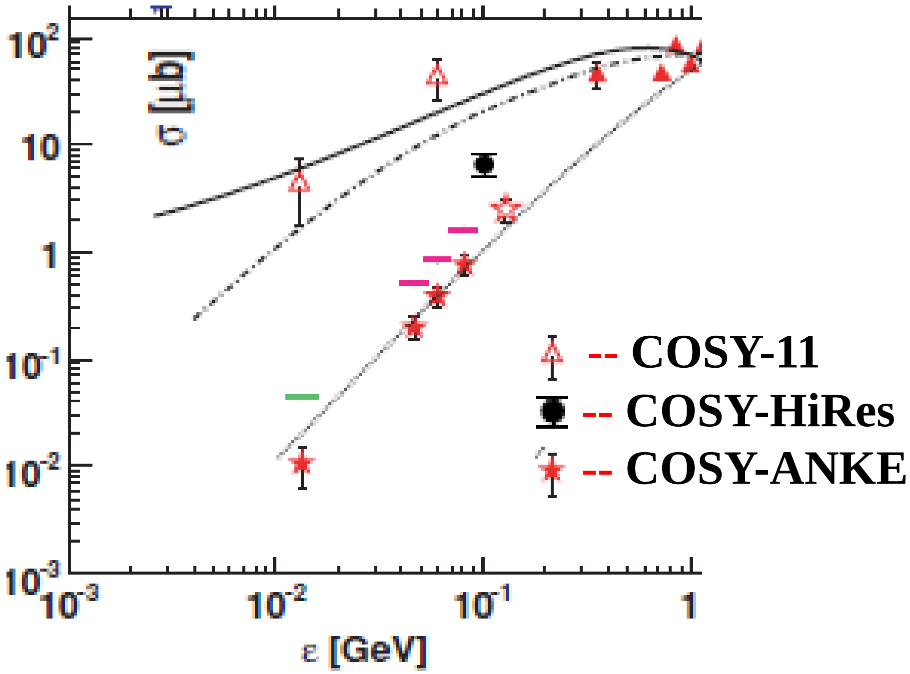


Di Ben, A.C.Wang, F.Huang, B.S.Zou, ArXiv: 2302.14308

4. Possible baryon spectroscopy with strangeness at HIAF

$p\, p \rightarrow p\, K^+ \Lambda$, $p\, K^+ \Sigma^0$, $n\, K^+ \Sigma^+$





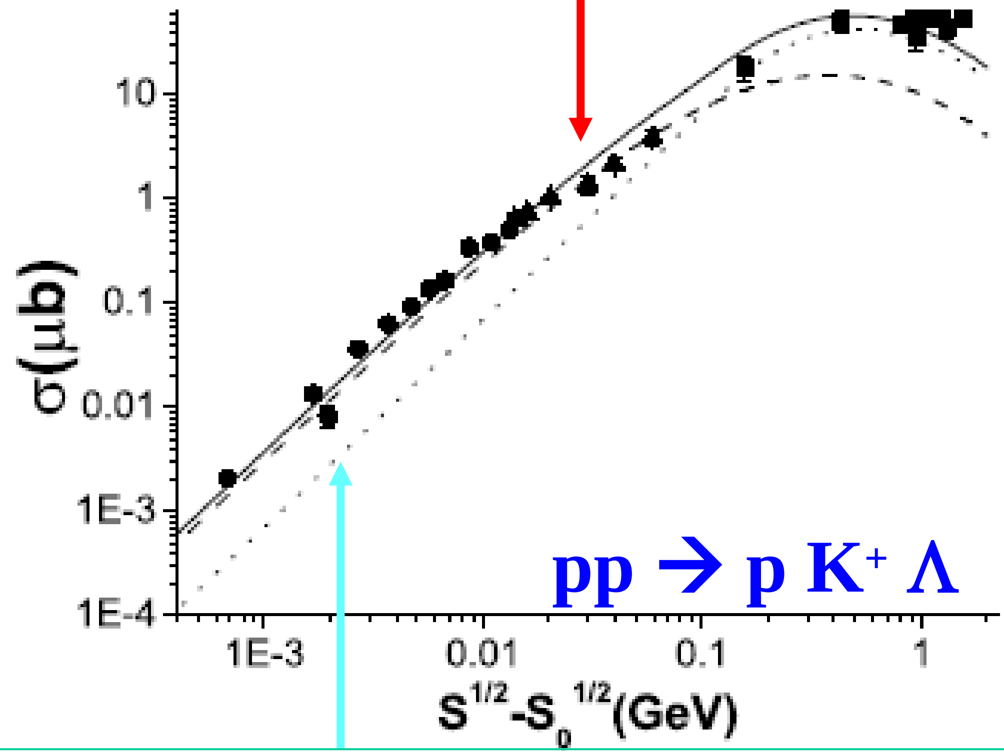
重离子碰撞奇异产生的基本过程，3个量级的不确定性！

COSY探测器局限性典型实例：3个探测器测量结果3个量级

Evidence for large $g_{N^*(1535)K\Lambda}$ from $pp \rightarrow p K^+ \Lambda$

Total cross section and theoretical results with N*(1535), N*(1650), N*(1710), N*(1720)

B.C.Liu, B.S.Zou, Phys. Rev. Lett. 96 (2006) 042002

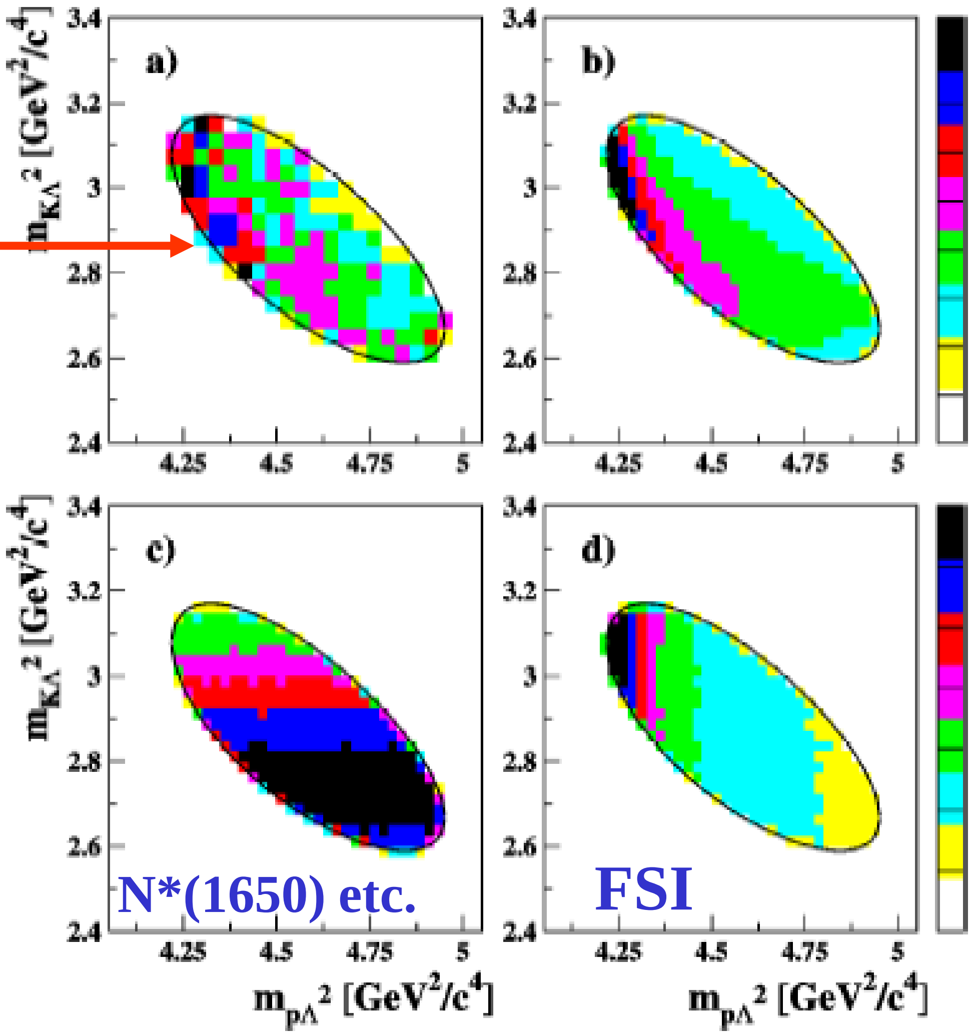


Tsushima,Sibirtsev,Thomas, PRC59 (1999) 369, without including N*(1535)

FSI vs N*(1535) contribution in pp → p K^+ Λ

B.C.Liu & B.S.Zou, Phys. Rev. Lett. 98 (2007) 039102 (reply)
A.Sibirtsev et al., Phys. Rev. Lett. 98 (2007) 039101 (comment)

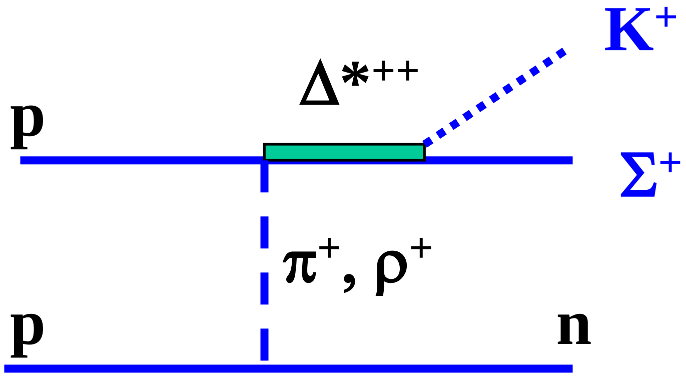
COSY-TOF data
S. Abdel-Samad *et al.*,
Phys.Lett.B632:27(2006)



Both FSI & N*(1535) are needed !

$pp \rightarrow nK^+\Sigma^+$: the best place for $\rho^+ p \rightarrow \Delta^{*++}$ (uuu)

J.J.Xie & B.S.Zou, Phys. Lett. B649 (2007) 405



Δ^{*++} (uuu) -- the most accessible system with 3 identical valence quarks

-- our present knowledge from $\pi^+ p$ data is still very poor

-- accessible at COSY and CSR

Our calculation for $pp \rightarrow nK^+\Sigma^+$

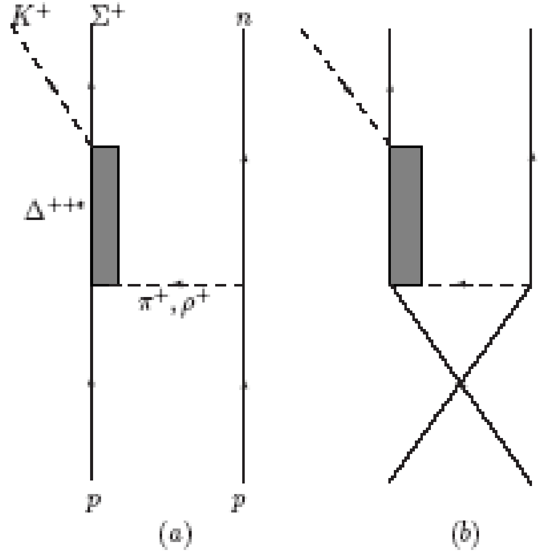
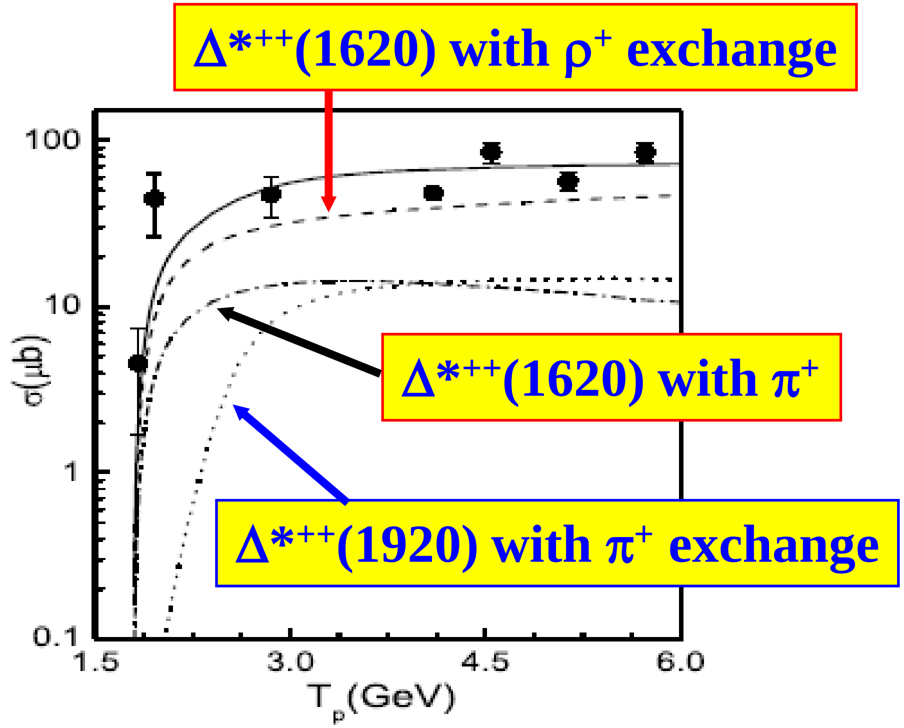


Figure 1: Feynman diagrams for $pp \to nK^+\Sigma^+$ reaction.



t-channel ρ-exchange plays important role !

COSY能区、亮度及多个探测器，都有局限性。
HIAF + CEE 在能区、亮度和探测器等方面全方位超过COSY，在重子谱研究方面大有可为。

pp → $pK^+\Lambda$, $nK^+\Sigma^+$, $pK^+\Sigma^0$, $Ks\Sigma^+p$, $pp\phi$, $pp\eta$, $pp\eta'$, ppK^+K^-, pnK^+Ks, $p\Lambda Ks\,\pi^+$, $p\Lambda K^+\eta$, $p\Lambda K^+\phi$, $p\Xi^-K^+K^+$, ……

→ strange partners of P_c and P_{cs} states

+ more reliable input for studying K production in HIC

另外 pp → $n\,K^+\,\Sigma^+$ 为寻找与ρ^+p及 $K^+\Sigma^+$耦合强的“失踪”的Δ^{*++}重子激发态，完善(uuu) 重子谱，可起到国际上独一无二的作用.

目前Δ^{*++}(uuu) 重子谱只有7~10个确立的成员

Thanks !