

Production of N^* resonances with hidden strangeness in various reactions

Bing-Song Zou

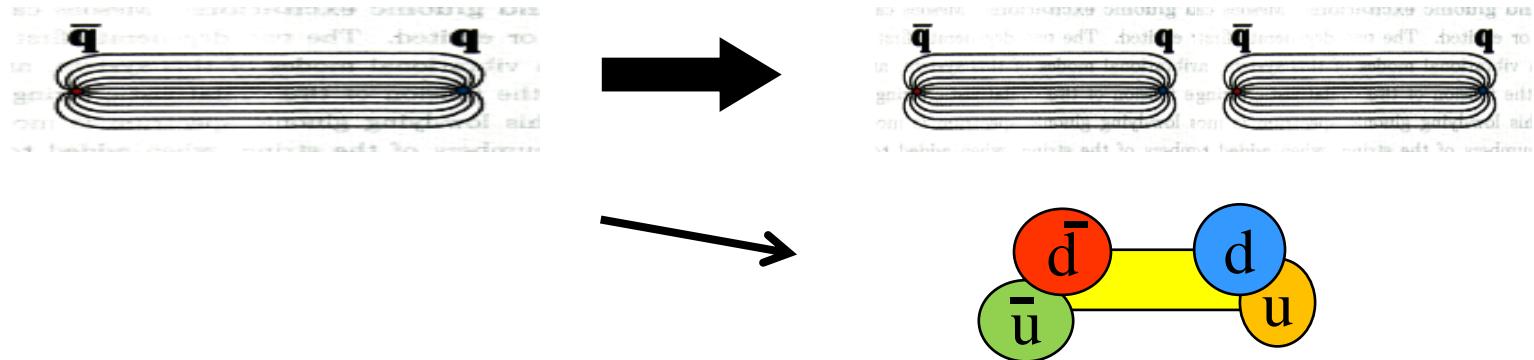
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Outline

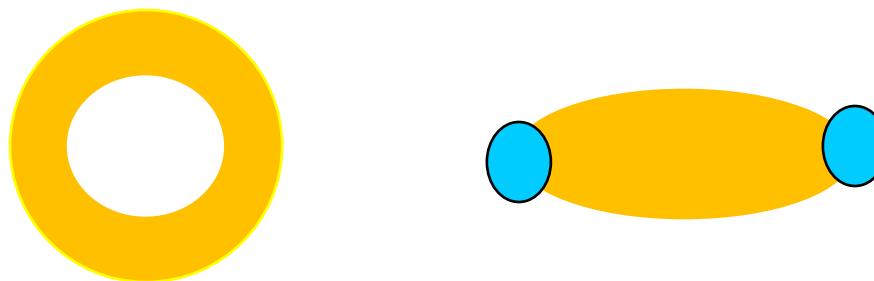
- General issues on hadron structure
- Quark-gluon structure of proton
- Pentaquark states from $\Lambda(1405)$ to P_c states
- N^* with hidden strangeness in various reactions
- Conclusions

1. General issues on hadron structure: how quarks & gluons construct hadrons?

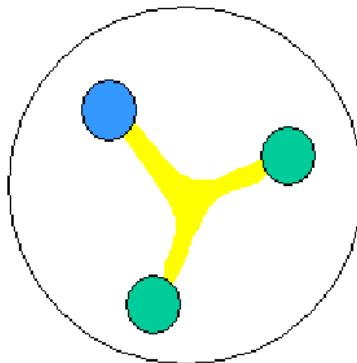
Key point for hadron structure & quark confinement
Unquenching dynamics: gluons $\rightarrow \bar{q}q$



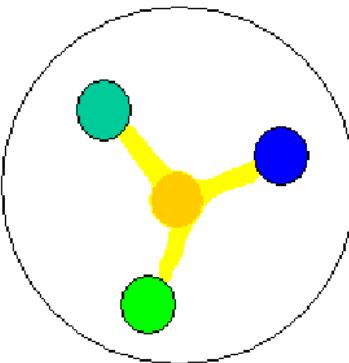
Mesons: $\bar{q}q$, tetraquarks, glueballs, $\bar{q}qg$ -hybrids?



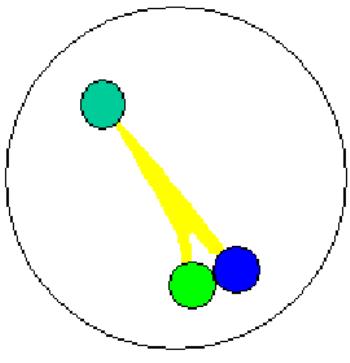
How about baryons?



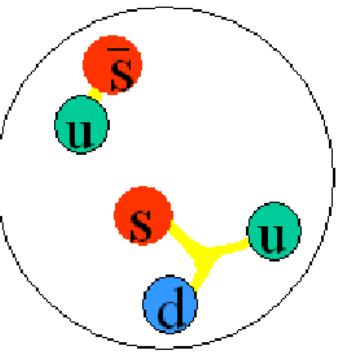
(a)



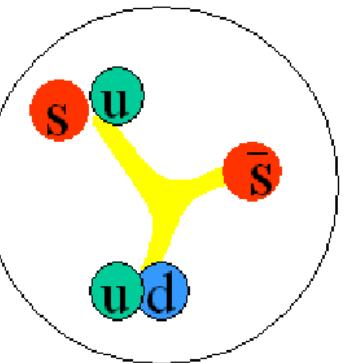
(b)



(c)



(d)



(e)

A. qqq

B. $qqqqg$

C. $q-q^2$

D-E. pentaquarks

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

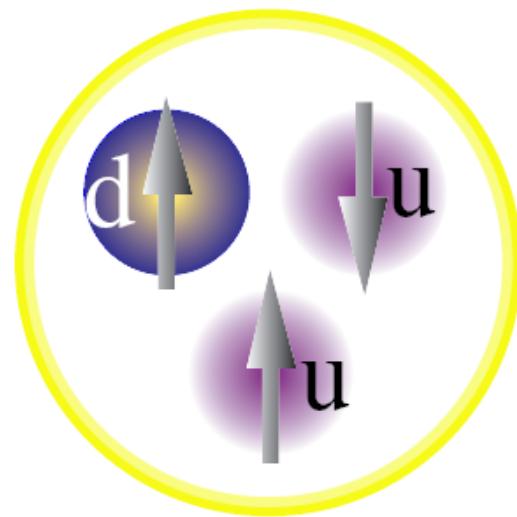
Number of observed N^* <A, “missing” ?

Poor knowledge on baryon spectroscopy
Lack effective reliable theoretical predictions

2. Quark gluon structure of proton

Classical picture of the proton

Constituent Quarks



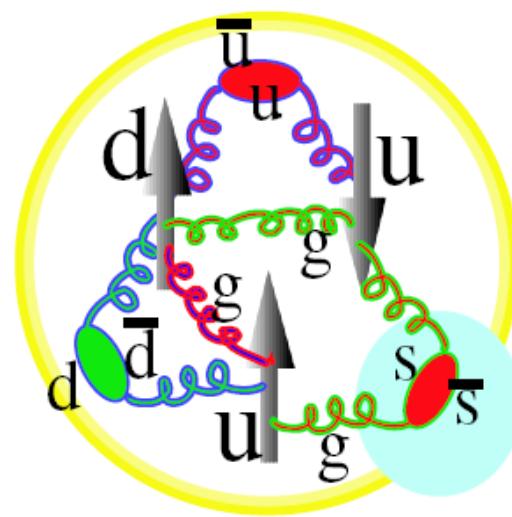
$$(Q^2 = 0 \text{ GeV}^2)$$

baryon octet

masses, magn. momenta

1964–1974

Parton Distributions



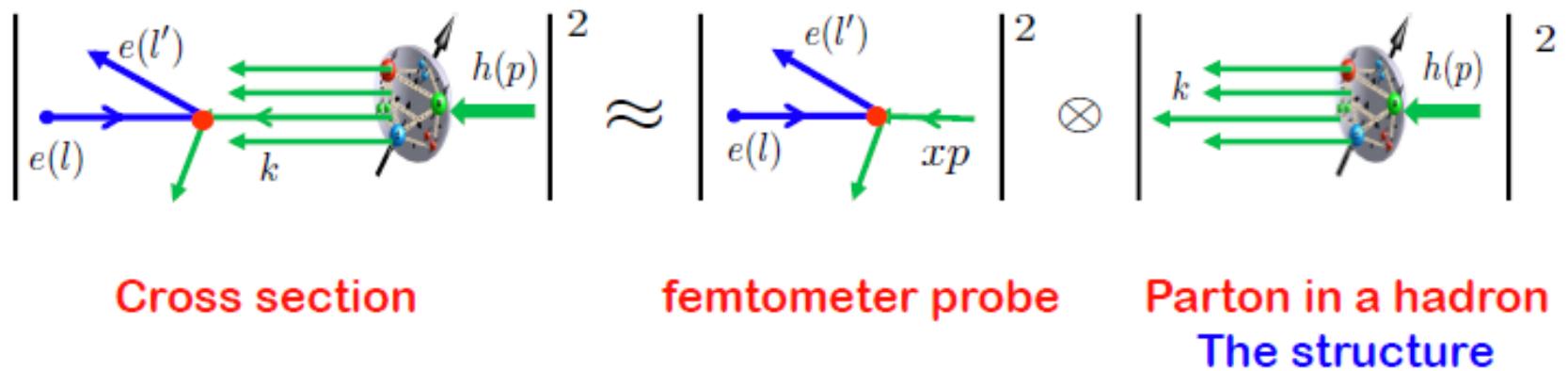
$$(Q^2 > 1 \text{ GeV}^2)$$

structure functions

momentum, spin

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

1974–1992



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

proton spin “crisis” , $\bar{d} - \bar{u} \sim 0.12$, $\bar{s}(x) \neq s(x)$, ...

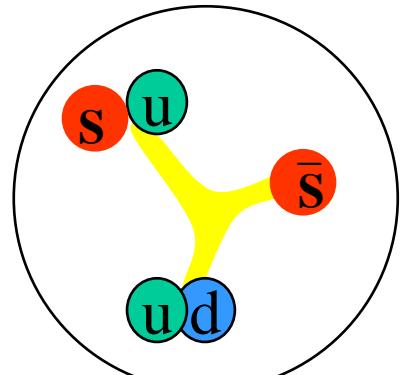
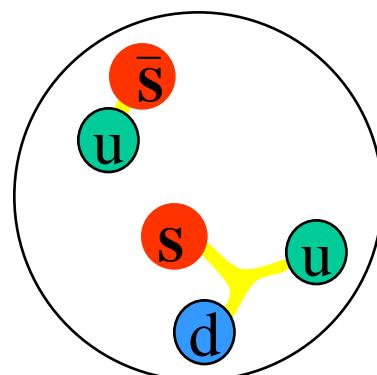
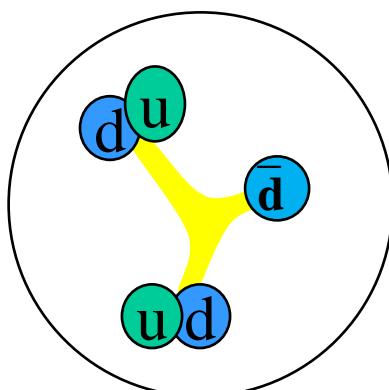
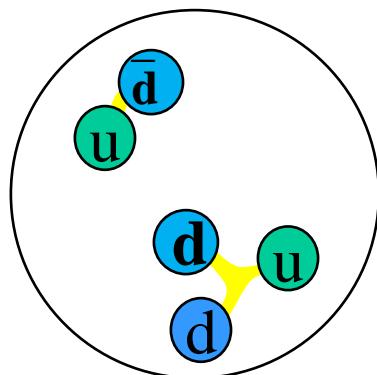
Spin “crisis”, $\bar{d} - \bar{u} \sim 0.12$, $\bar{s}(x) \neq s(x)$ puzzles \rightarrow
two possible solutions:

Meson clouds: Thomas, Speth, Weise, Oset, Brodsky, Ma, ...

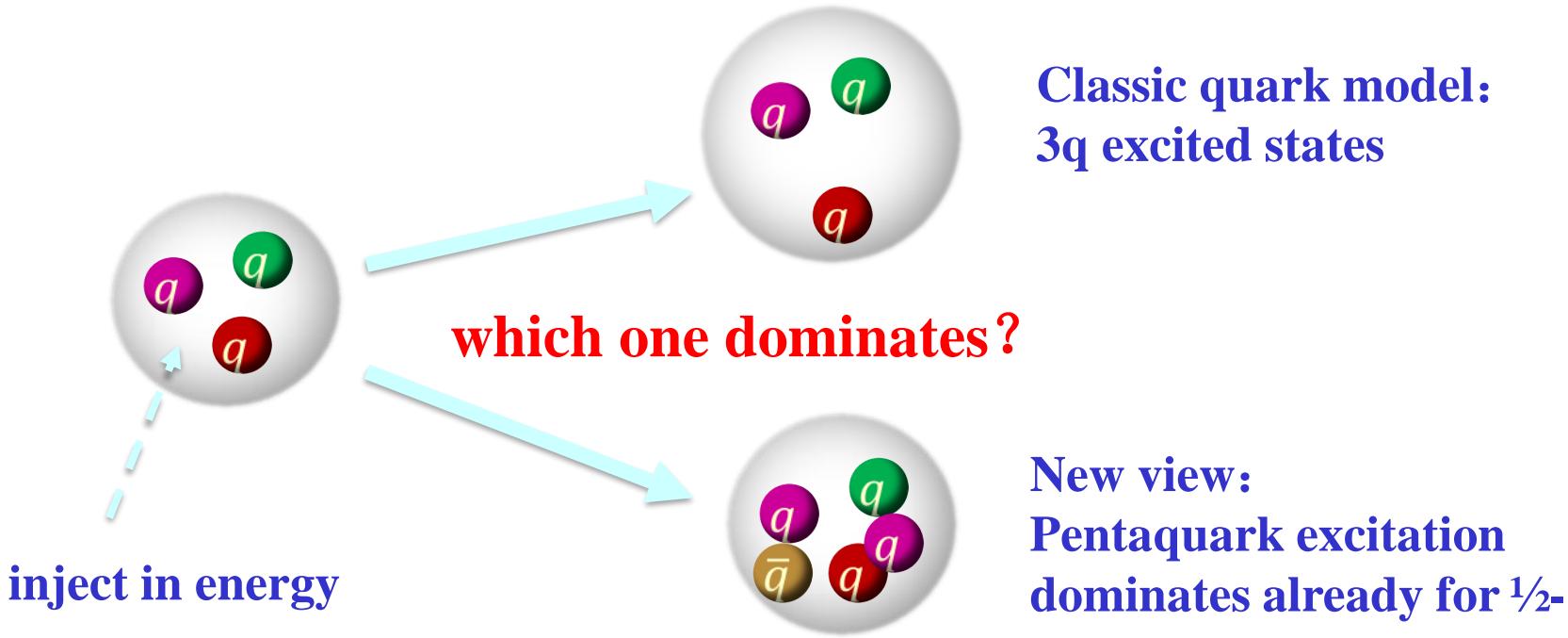
$$| p \rangle \sim | uud \rangle + \varepsilon_1 | n \text{ (udd)} \pi^+ (\bar{d}u) \rangle + \varepsilon_2 | \Delta^{++} (\text{uuu}) \pi^- (\bar{u}d) \rangle + \varepsilon' | \Lambda \text{ (uds)} K^+ (\bar{s}u) \rangle \dots$$

diquarks: Riska, Zou, Zhu, ...

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



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



Pentaquark crucial for baryon spectroscopy and structure !

3. Pentaquark states from $\Lambda(1405) \rightarrow P_c$ 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.”

$1/2^-$ baryon nonet with strangeness

- Mass pattern : quenched or unquenched ?

uds (L=1) $1/2^-$	$\sim \Lambda^*(1670)$	$\sim [us][ds] \bar{s}$	$\bar{K}\Xi - \eta\Lambda$
uud (L=1) $1/2^-$	$\sim N^*(1535)$	$\sim [ud][us] \bar{s}$	$\bar{K}\Sigma - \bar{K}\Lambda - \eta N$
uds (L=1) $1/2^-$	$\sim \Lambda^*(1405)$	$\sim [ud][su] \bar{u}$	$\bar{K}N - \pi\Sigma$
uus (L=1) $1/2^-$	$\sim \Sigma^*(1390)$	$\sim [us][ud] \bar{d}$	$\bar{K}N - \pi\Sigma - \pi\Lambda$

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

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

$$J/\psi \rightarrow \bar{p}N^* \rightarrow \bar{p}(K\Lambda) / \bar{p}(p\eta) \rightarrow \text{large } g_{N^*K\Lambda}$$

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

$$\gamma p \rightarrow p\eta' \& pp \rightarrow pp\eta' \rightarrow \text{large } g_{N^*N\eta'}$$

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

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

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

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

narrower width (35MeV) than $\Lambda^*(1405)$



- prediction of three P_c pentaquark states $\rightarrow J/\psi\text{-}p$:
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

PRL 115, 072001 (2015)

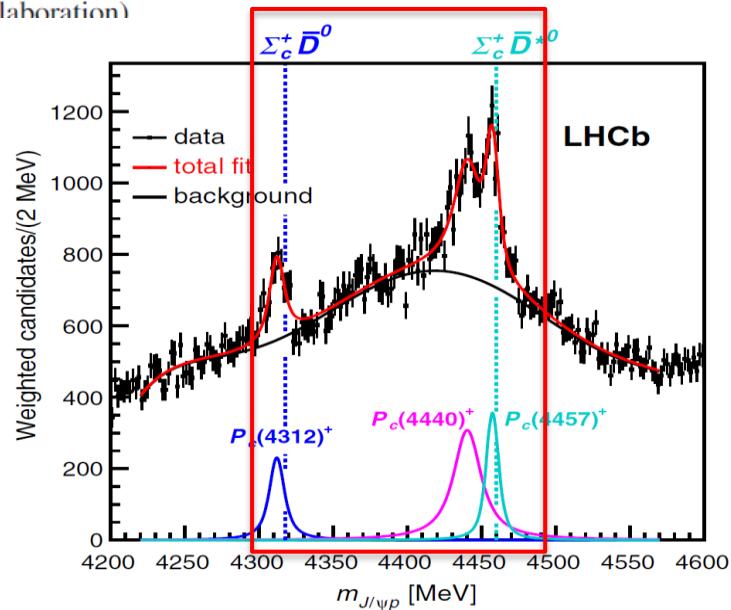
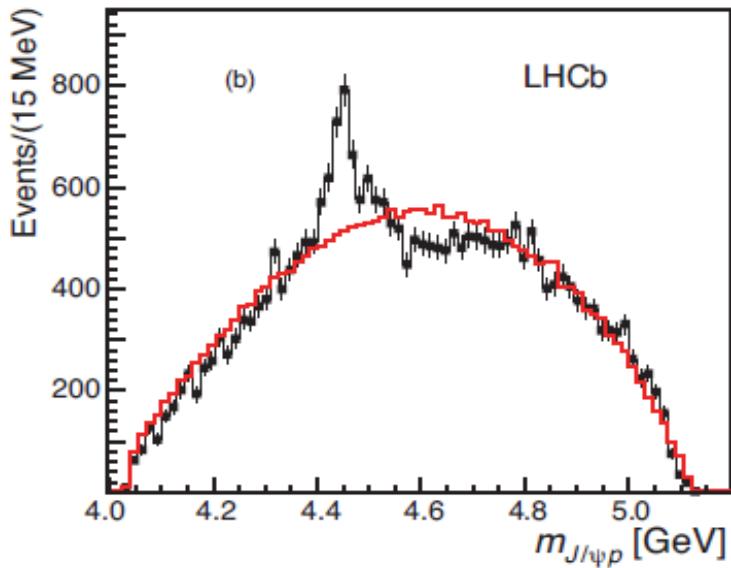
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
14 AUGUST 2015

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

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

PRL 122 (2019) 222001



A milestone for pentaquark search

P_c states: observation vs predictions

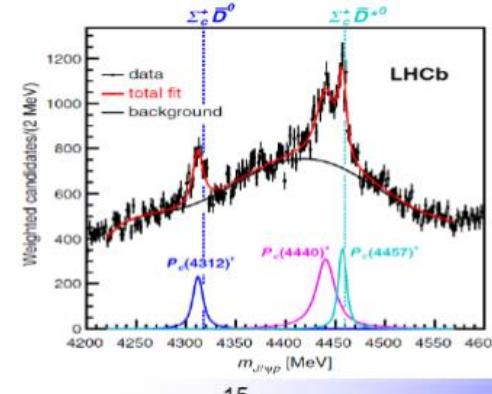
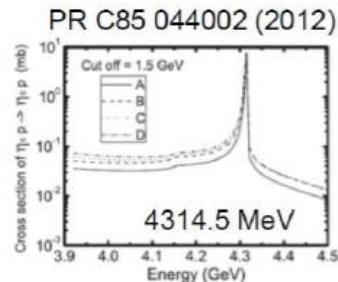
LHCb, PRL122 (2019) 222001



Moriond QCD, Tomasz Skwarnicki, Mar 26, 2019

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)



15

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	-	-	-	-	-
800	-	-	-	-	-
1200	4318.964 - 0.362i	1.826	4462.178 - 0.002i	0.002	
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	
<hr/>					
$J^P = \frac{3}{2}^-$					
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

Λ - cut off on exchanged meson mass.

$\Delta E(4440) = 19.5^{+4.9}_{-4.1}$ MeV

Multiquark states – crucial for hadron structure !

X(3872)	→ top cited paper for Belle (2003)	2375 cites
Z _c (3900)	→ top cited paper for BES (2012)	1047 cites
P _c states	→ top cited paper for LHCb (2015)	1621 cites

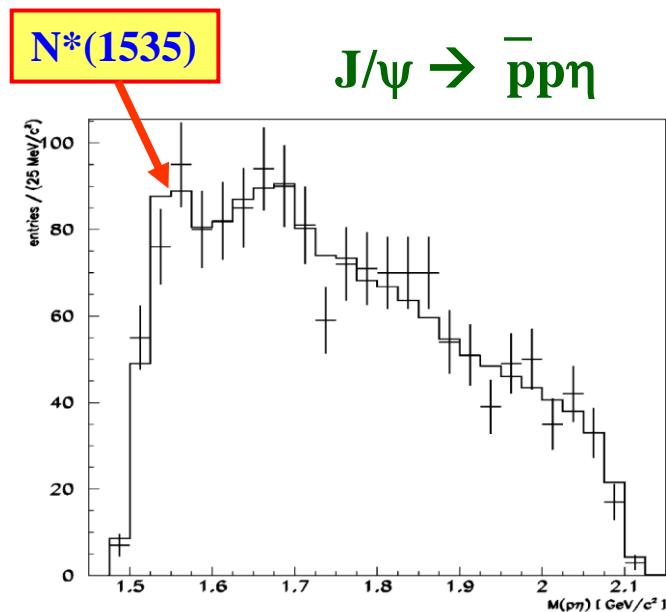
H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1:
“The hidden-charm pentaquark and tetraquark states” 996 cites

F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou,
Rev.Mod.Phys. 90 (2018)015004: “Hadronic molecules” 990 cites

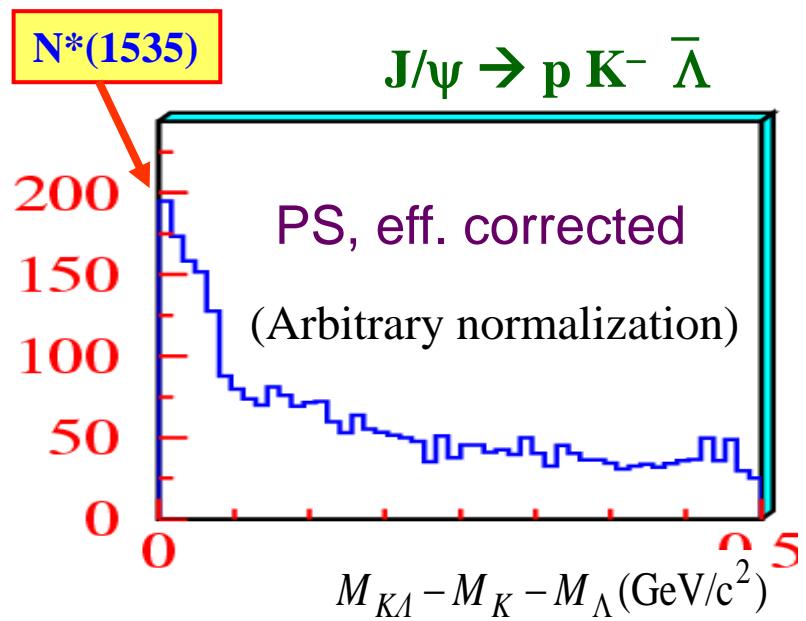
How about strange partners of P_c states ?

4. N* with hidden strangeness in various reactions

KΣ molecule - N*(1535) in J/ψ decays



BES, PLB510 (2001) 75



BESII, IJMPA20 (2005) 1985

B.C.Liu, B.S.Zou, PRL96 (2006) 042002 : **N*(1535) ~ $\bar{s} s u u d$!**

$K\Sigma^*$, $K^*\Sigma$, $K^*\Sigma^*$ molecules from charmonium decays at BES

$N^*(1875)$

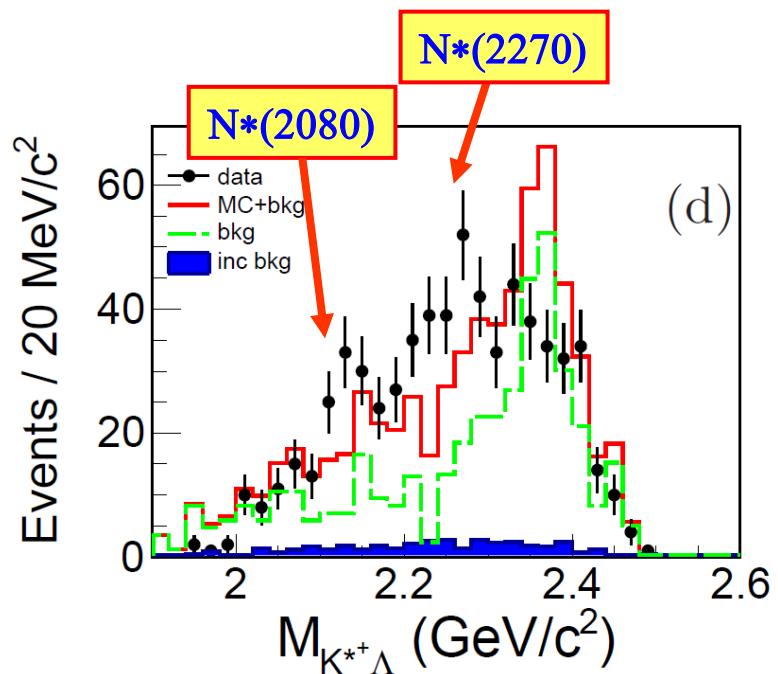
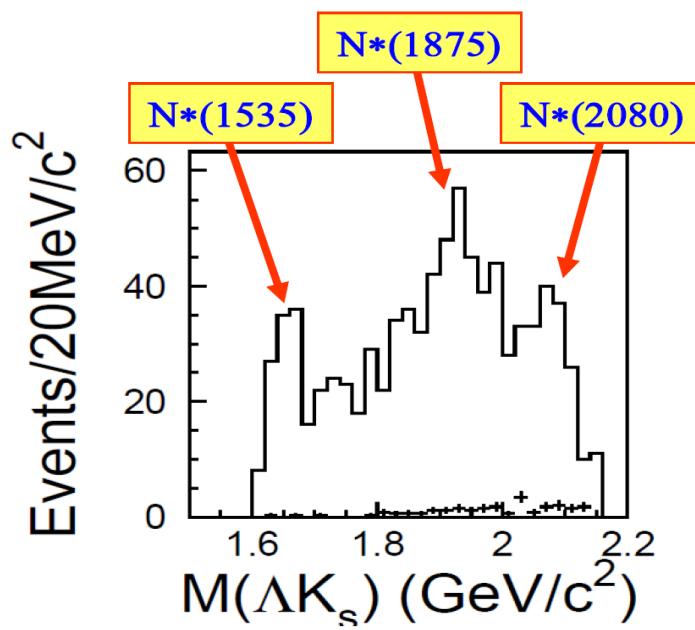
$K\Sigma^* \sim 1880$

$N^*(2080)$

$K^*\Sigma \sim 2086$

$N^*(2270)$

$K^*\Sigma^* \sim 2280$

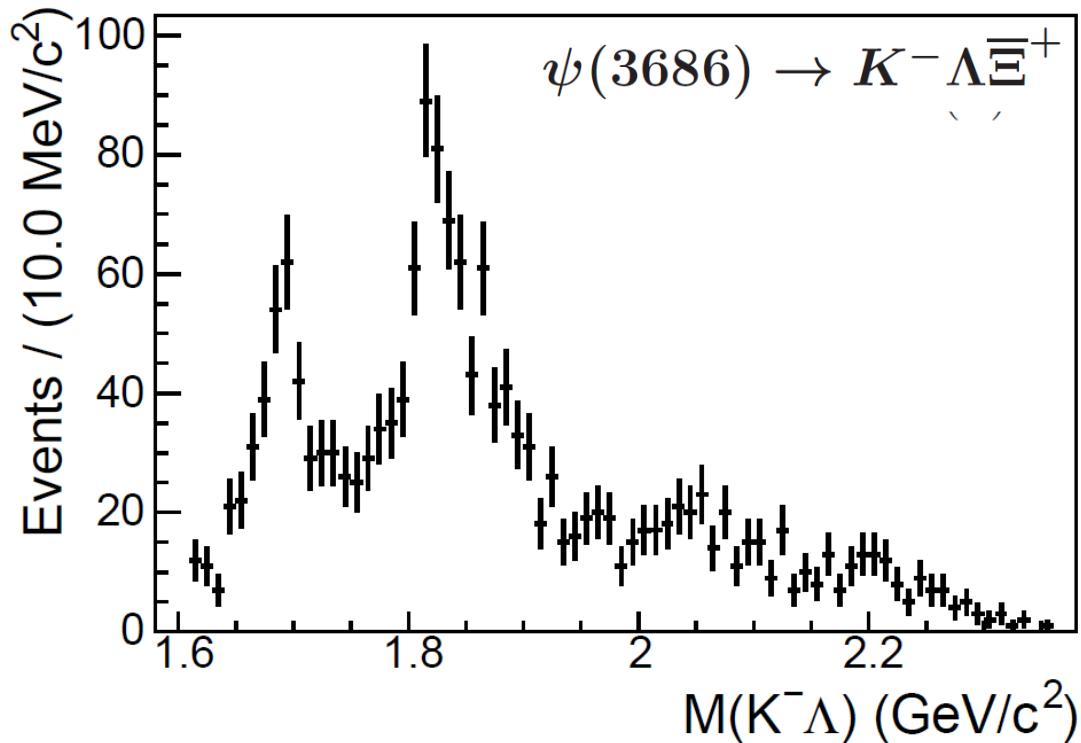


BESII, PLB659 (2008) 789



BESIII, PRD100(2019)052010

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



$\bar{K}\Sigma \sim \Xi(1680)$, $\bar{K}\Sigma^* \sim \Xi(1820)$, $\bar{K}^*\Sigma \sim \Xi(2080)$, $\bar{K}^*\Sigma^* \sim \Xi(2270)$

1/2⁻

3/2⁻

$K\Sigma^*$, $K^*\Sigma$, $K^*\Sigma^*$ molecules from γp reactions

$K\Sigma^* \sim 1880$

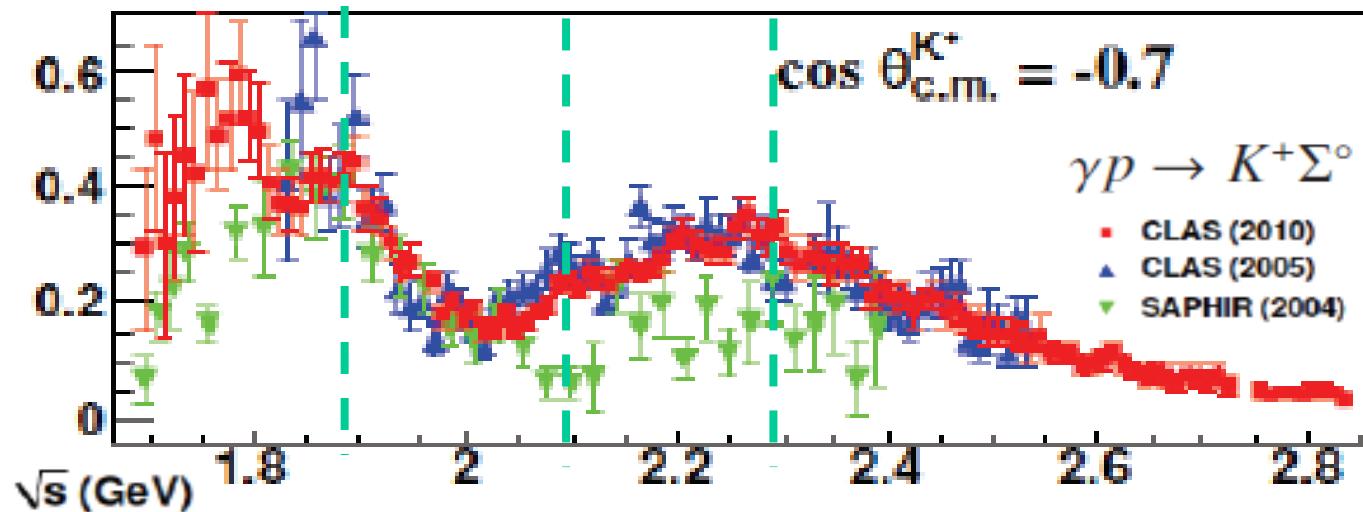
$N^*(1875)$

$K^*\Sigma \sim 2086$

$N^*(2080)$

$K^*\Sigma^* \sim 2280$

$N^*(2270)$



$K\Sigma \sim 1810$

$\Lambda(1/2^-)$

$K\Sigma^* \sim 2027$

$\Lambda(3/2^-)$

$K^*\Sigma \sim 2210$

$\Lambda(1/2^-, 3/2^-)$

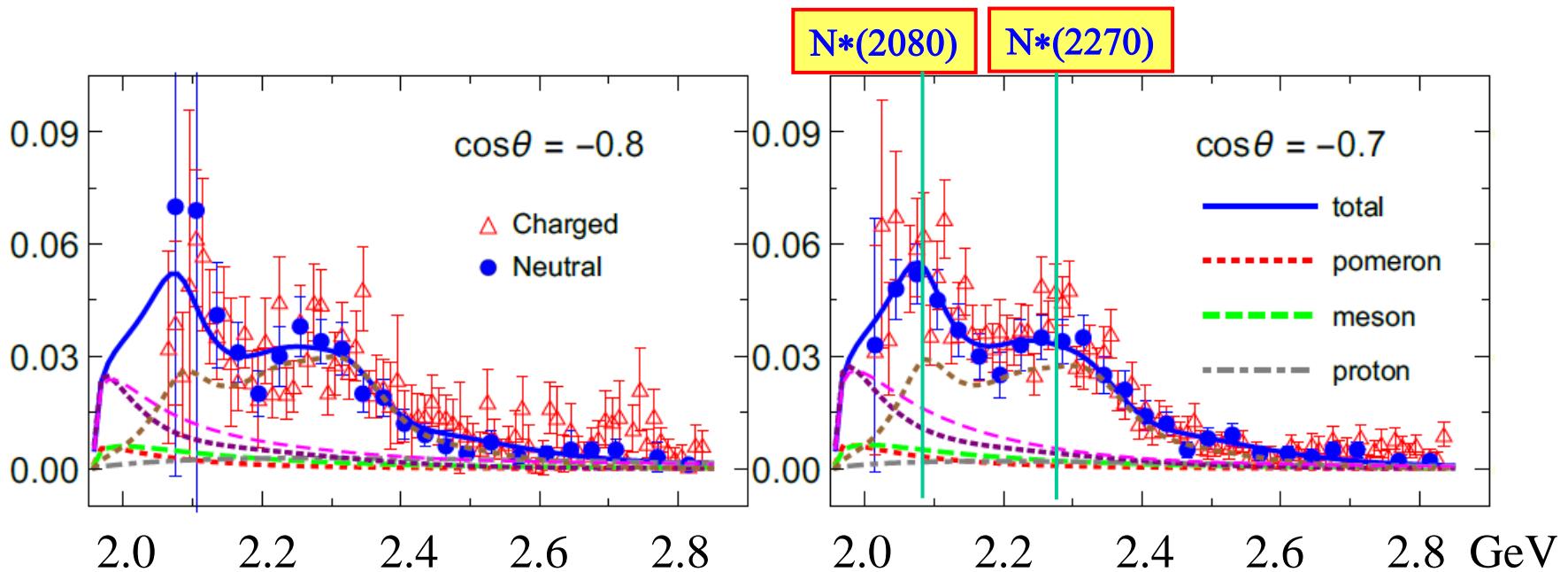
$K^*\Sigma^* \sim 2427$

$\Lambda(1/2^-, 3/2^-, 5/2^-)$

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

$\gamma p \rightarrow \phi p$

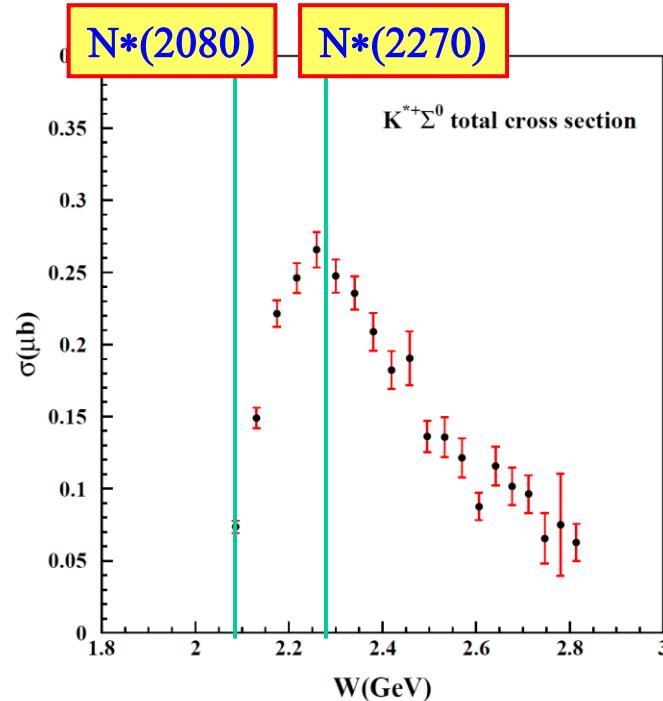
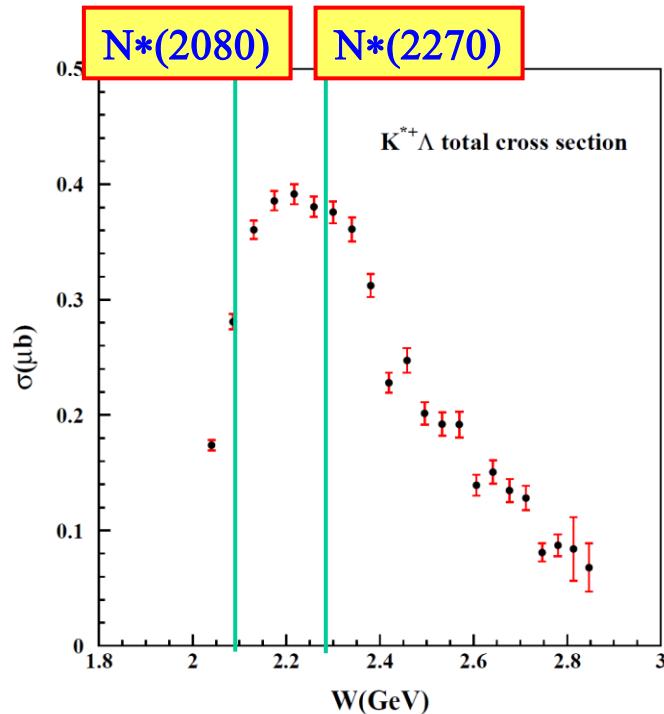
CLAS, PRC89(2014)019901



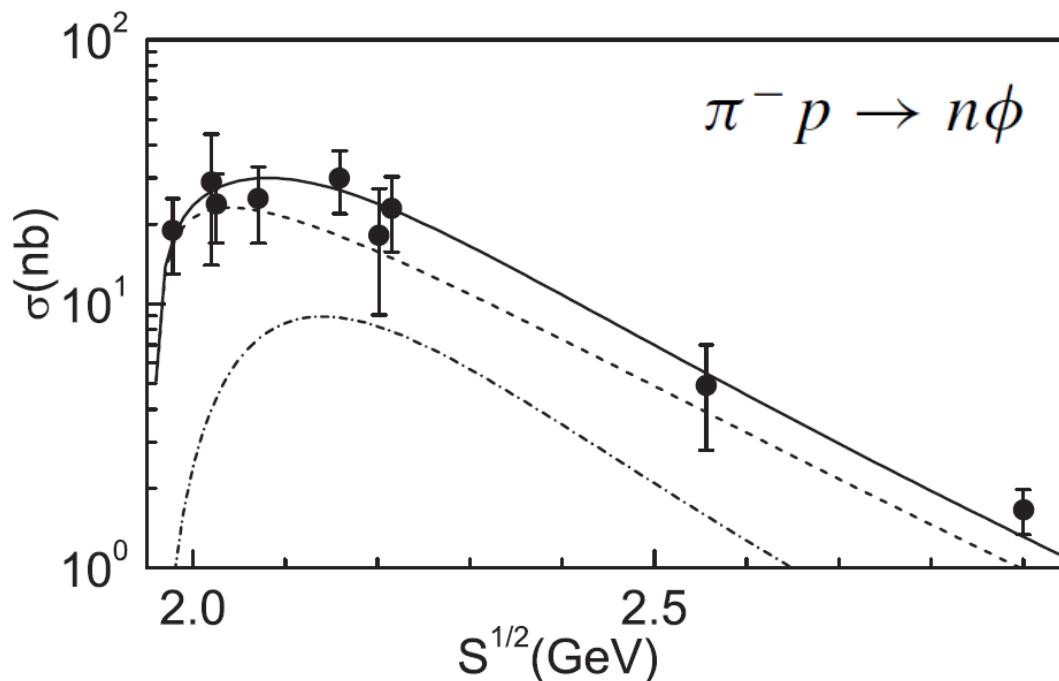
S.M.Wu, F.Wang, B.S.Zou, PRC108(2023)045201

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

CLAS, PRC 87(2013)065204



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

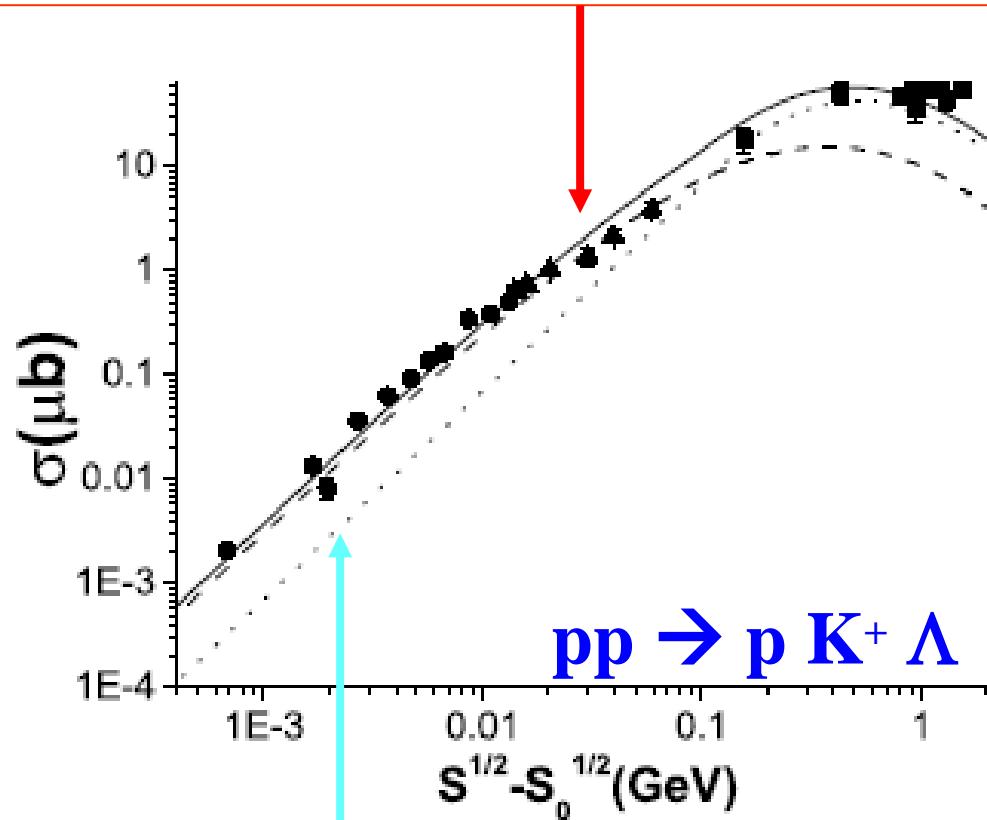


$N^*(1535) + N^*(1900) \frac{1}{2}+$ or $N^*(1875) + N^*(2080) + N^*(2270)$?

More data with angular distribution and polarization information are needed !

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 $pp \rightarrow p K^+ \Lambda$

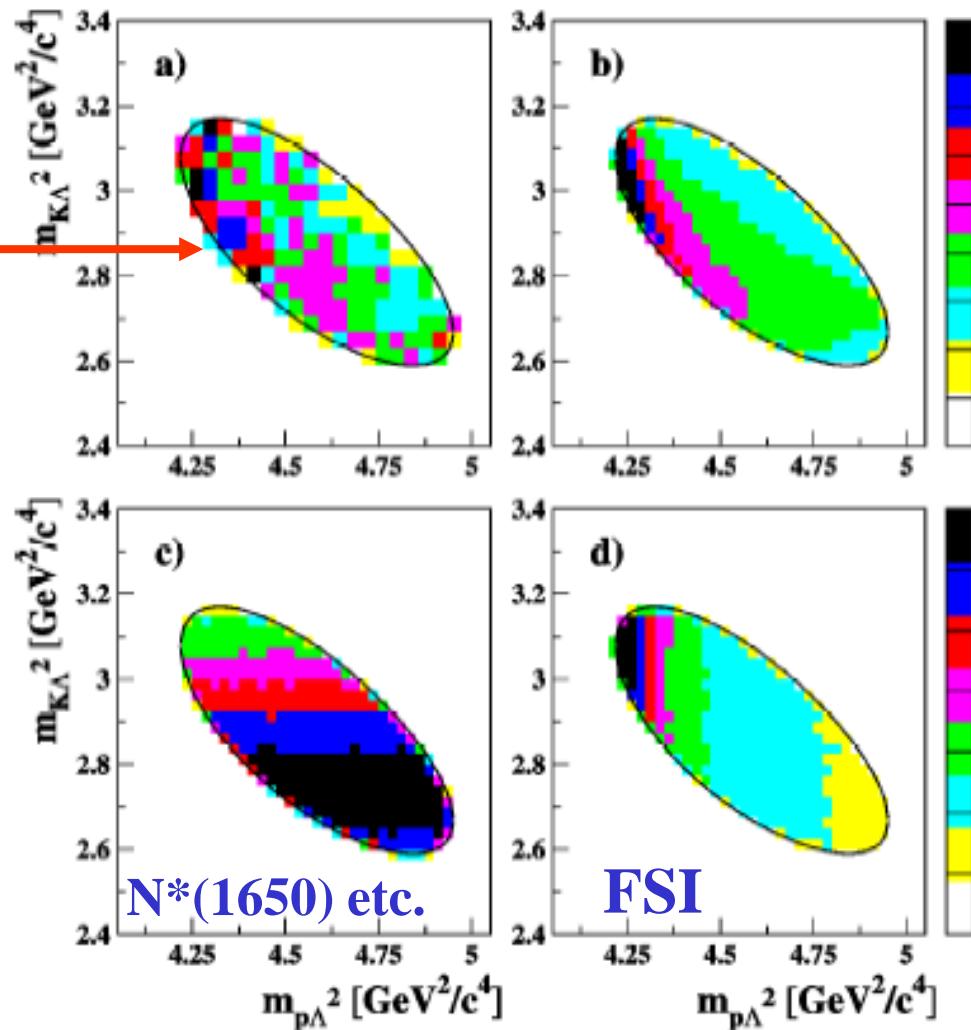
B.C.Liu & B.S.Zou, Phys. Rev. Lett. 98 (2007) 039102 (reply)

A.Sibirtsev et al., Phys. Rev. Lett. 98 (2007) 039101 (comment)

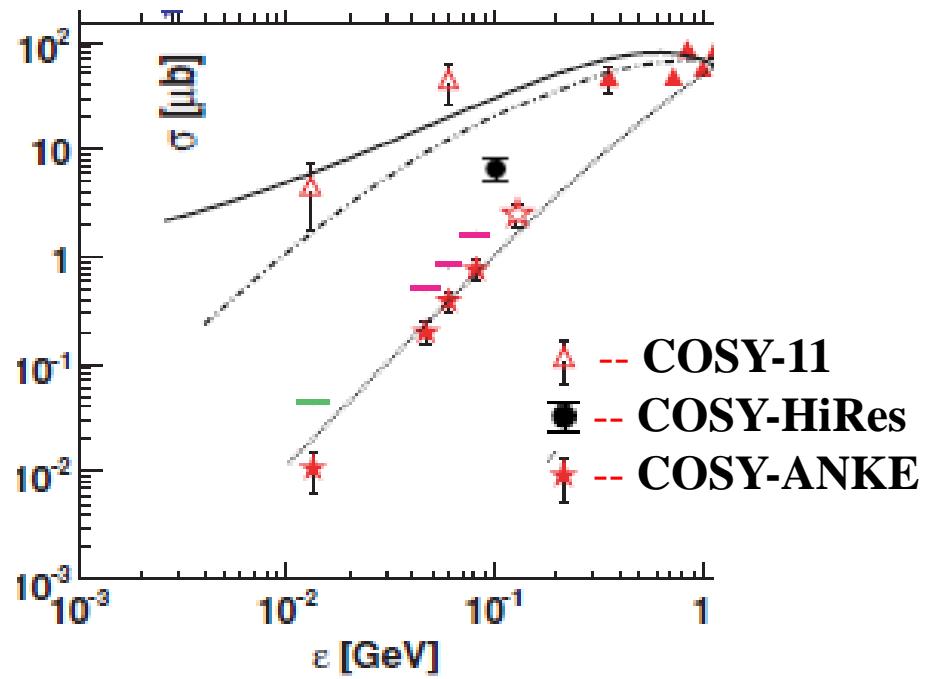
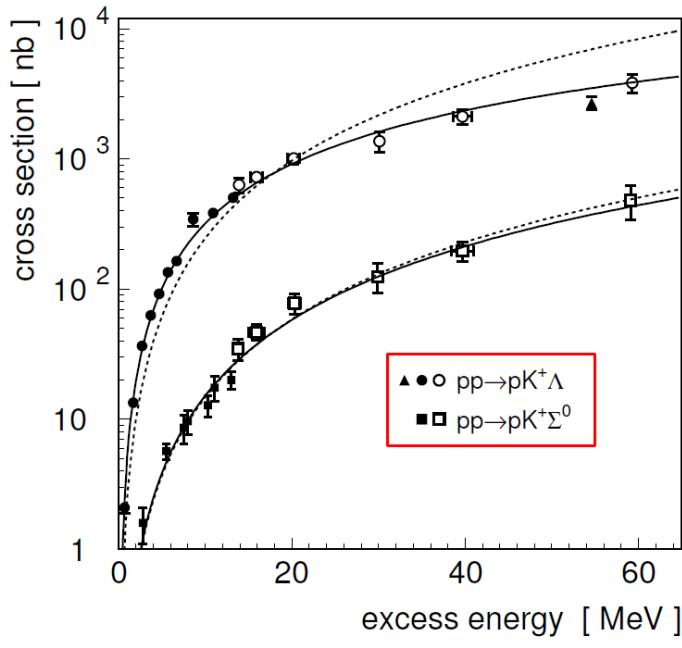
COSY-TOF data
S. Abdel-Samad *et al.*,
Phys.Lett.B632:27(2006)



**Both FSI & N*(1535)
are needed !**



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



Basic strangeness production processes suffer large uncertainty!

$p\ p$ with $E_{cm} \sim 5\text{GeV}$ at HIAF may play an important role here

**Due to limitation of energy range, luminosity and detectors at COSY,
not much observations on N^* with hidden strangeness from pp yet.**

HIAF + CEE @ Huizhou may play a important role

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

→ strange partners of P_c and P_{cs} states

+ more reliable input for studying K production in HIC

How about pp at JPARC ?

Conclusions

- strange partners of P_c states are expected to exist
- strong evidence for their existence in $\bar{c}c$ decays, γp and $p p$
- more experiments with higher statistics are needed
- $\pi p @ JPARC, EIC \& EicC$ may play a important role here:

$\pi^- p \rightarrow n\phi, K\Lambda, K\Sigma, K^*\Lambda, K^*\Sigma, K\Sigma^*, \dots$

$\gamma^{(*)} p \rightarrow p\phi, K^+\Lambda, K\Sigma, K^{*+}\Lambda, K^*\Sigma, K\Sigma^*, \dots$

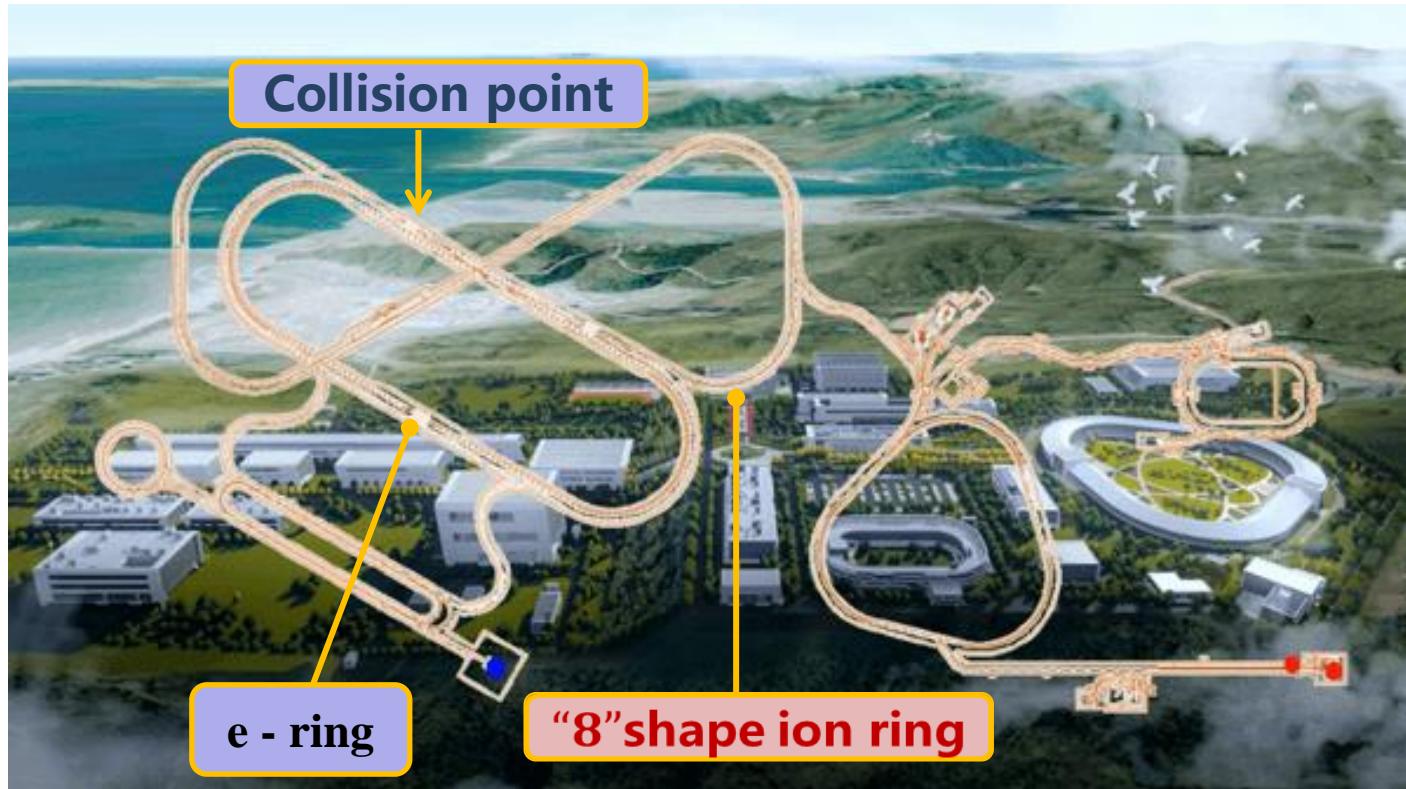
Thank you for your attention !



2023.05.04



EicC@HIAF



Complementary to CBM and PANDA at FAIR etc.



SCNT

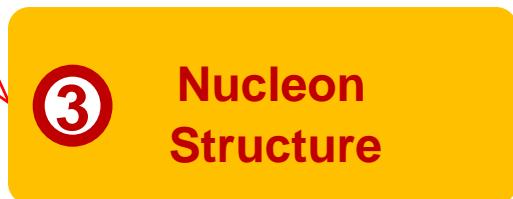
- 1) INT, Seattle, US
- 2) ECT*, Trento, Italy
- 3) FIAS, Frankfurt, Germany
- 4) YITP, Kyoto, Japan
- 5) ...



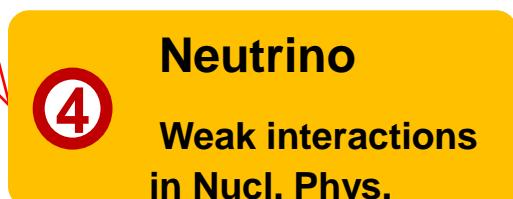
- Super Heavy Element
- New Isotopes
- Collision Dynamics
- Nuclear-astrophysics



- QCD phase boundary, critical point
- Hyper-nuclear production
- EOS at high baryon density
- CEE, CBM, NICA, STAR



- Hadron spectroscopy
- 3D Imaging
- Origin of mass and spin
- EicC, EIC, BESIII, PANDA



- Dirac or Majorana?
- Beyond SM physics
- Nuclear structure with neutrino
- $\text{N}\nu\text{DE}$, NEXT

You are welcome to SCNT to participate its activities!