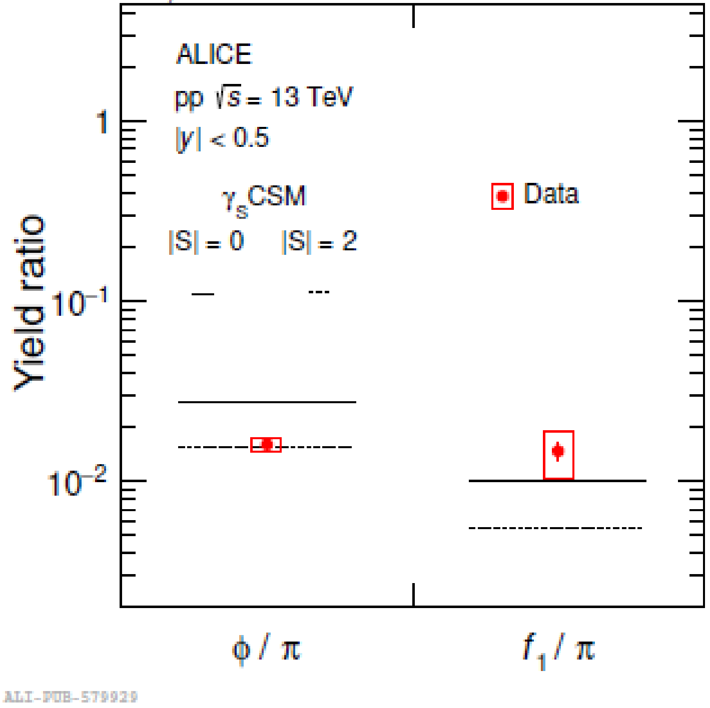
Post QM25
(ハドロン物理関係)

森野雄平(KEK-IPNS)

Exotic hadrons

$J^{PC} = 0^{++}$ mesonはquark modelで説明しづらい(exotic)
例えば
$q\bar{q}$ quark model :: $n\bar{n}$(I=0,I=1)< $n\bar{s}$, $s\bar{n}$ < $s\bar{s}$
現実 :: σ(I=0) < κ < f_0(I=0), a_0(I=1)
～500MeV ～700MeV ～980MeV

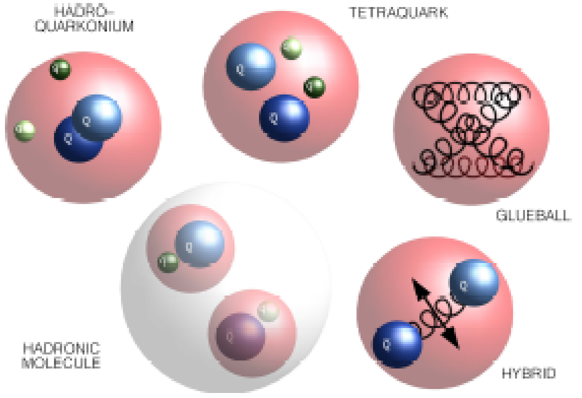
ALICE, arXiv:2409.11936



J.Kim(ALICE) oral

Internal structure of exotic hadrons still under debate

- Tetraquark: $(u\bar{u} + d\bar{d})s\bar{s}$
  PRD 103 (2021) 1, 014010, Mod.Phys.Lett. A2 (1987) 771
- Molecular state: $K\bar{K}$ ($f_0(980)$), $K\bar{K}^*$ ($f_1(1285)$)
  PRD 101 (2020) 9, 094034, PRD 42 (1990) 874
- Conventional meson: $u\bar{u} + d\bar{d}$
  PRD 67 (2003) 094011, PRD 96 (2017) 5, 054012

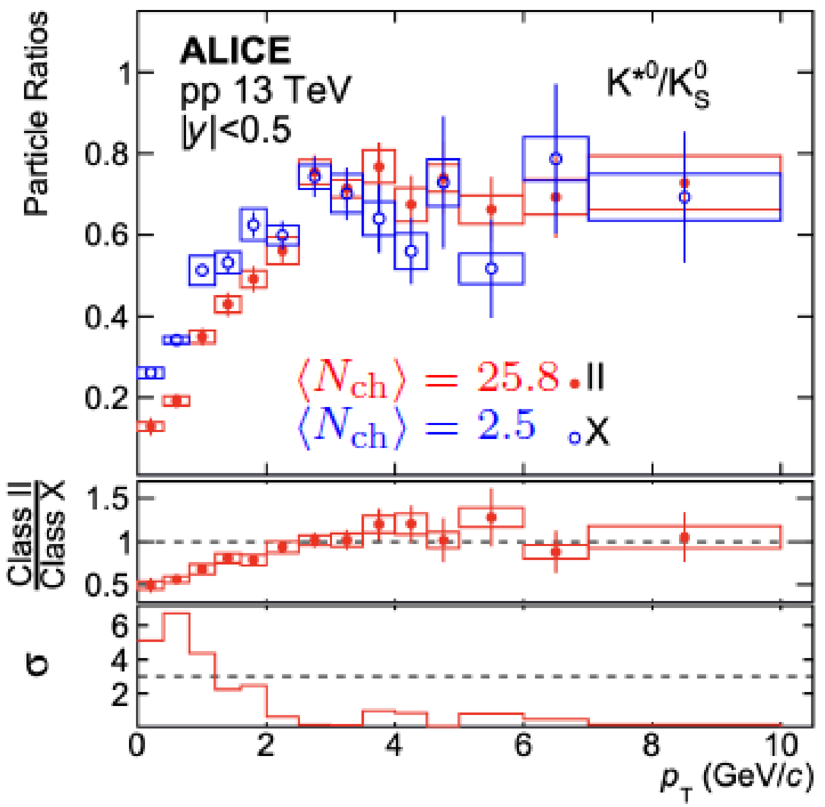


Comparison of particle yield ratios with thermal

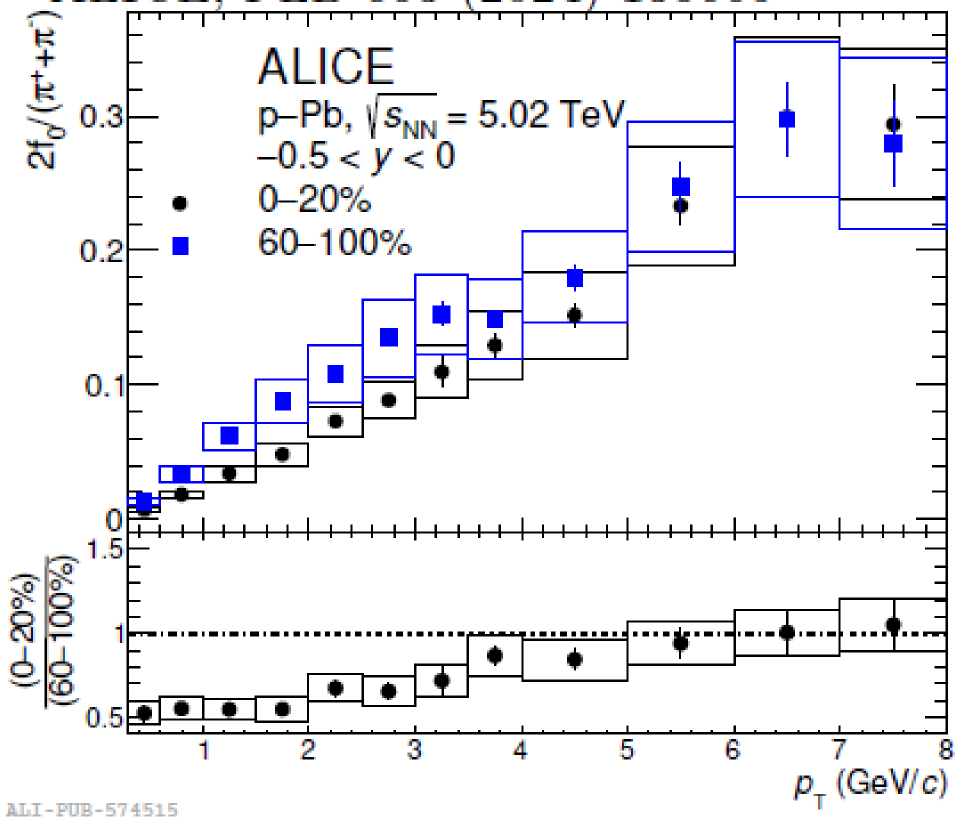
- Decreasing f_0/K^{*0} with $|S| = 0$ scenario
  → Measurement suggests both particles have no (anti-)strange quarks and probably are conventional mesons
- Alignment of particle yield ratio for $f_1(1285)$ with $|S| = 0$ scenario

J.Kim(ALICE) oral

ALICE, PLB 807 (2020) 135501



ALICE, PLB 853 (2024) 138665

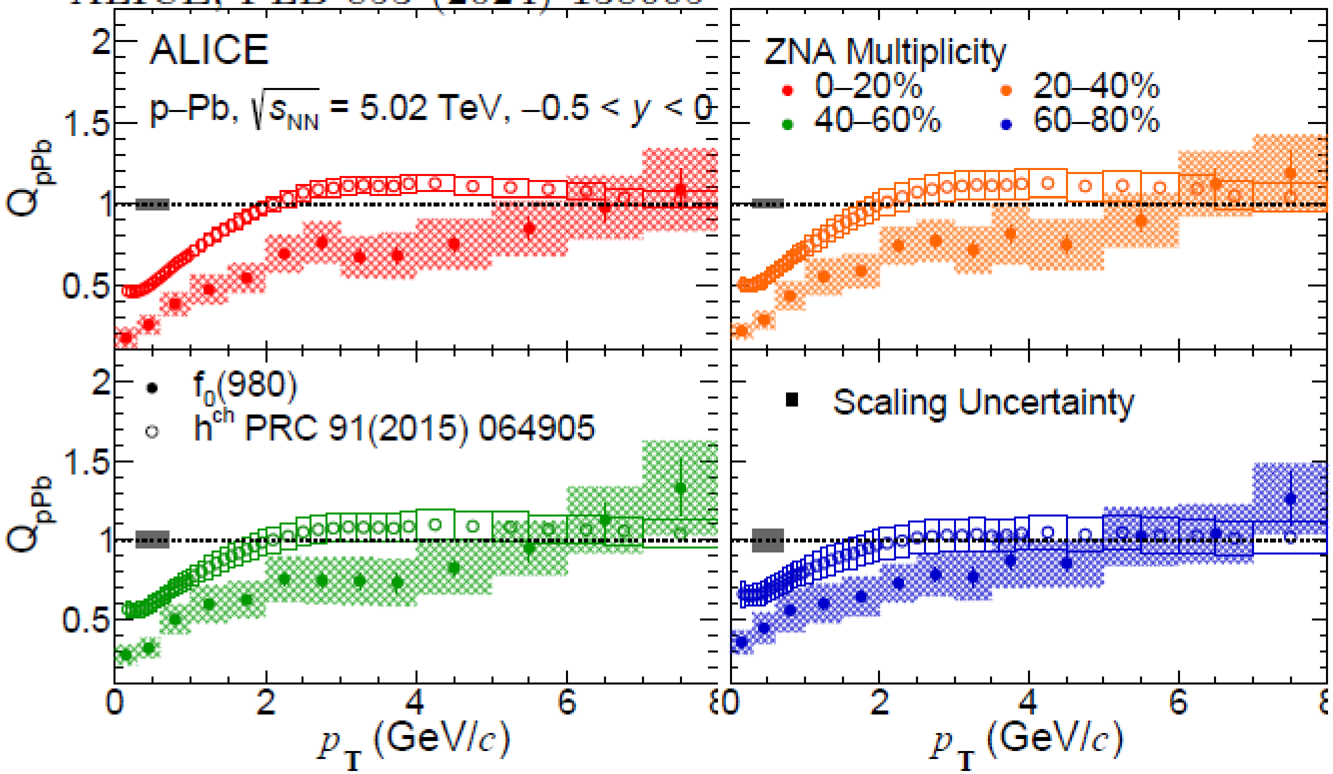


- $f_0(980)$ yields suppressed at low p_T in higher multiplicity events
  $\rightarrow$ $f_0(980)$ resonances significantly affected by **interactions with the hadron gas even in small collision system**

PLB 645 138

J.Kim(ALICE) oral

ALICE, PLB 853 (2024) 138665



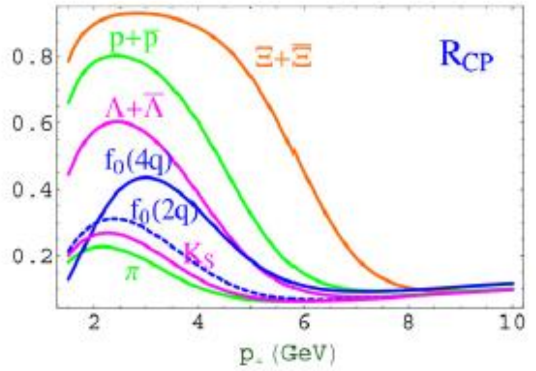


Fig. 6. R_{CP} for LHC using the same notation as in Fig. 5.

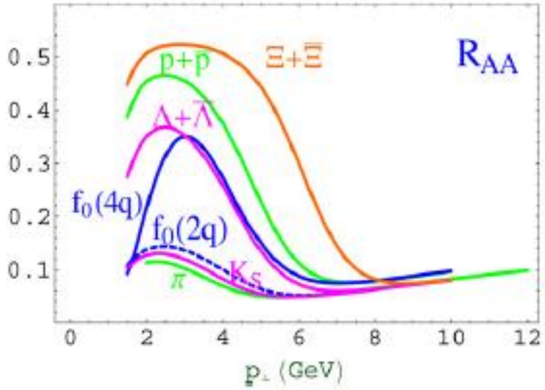
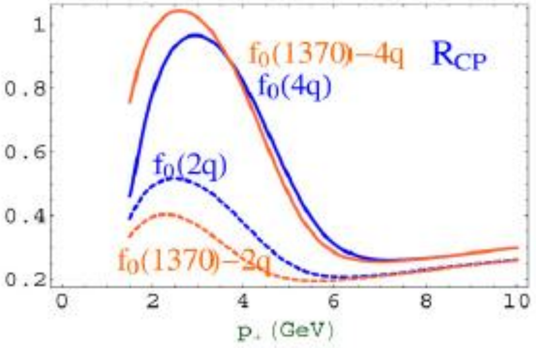


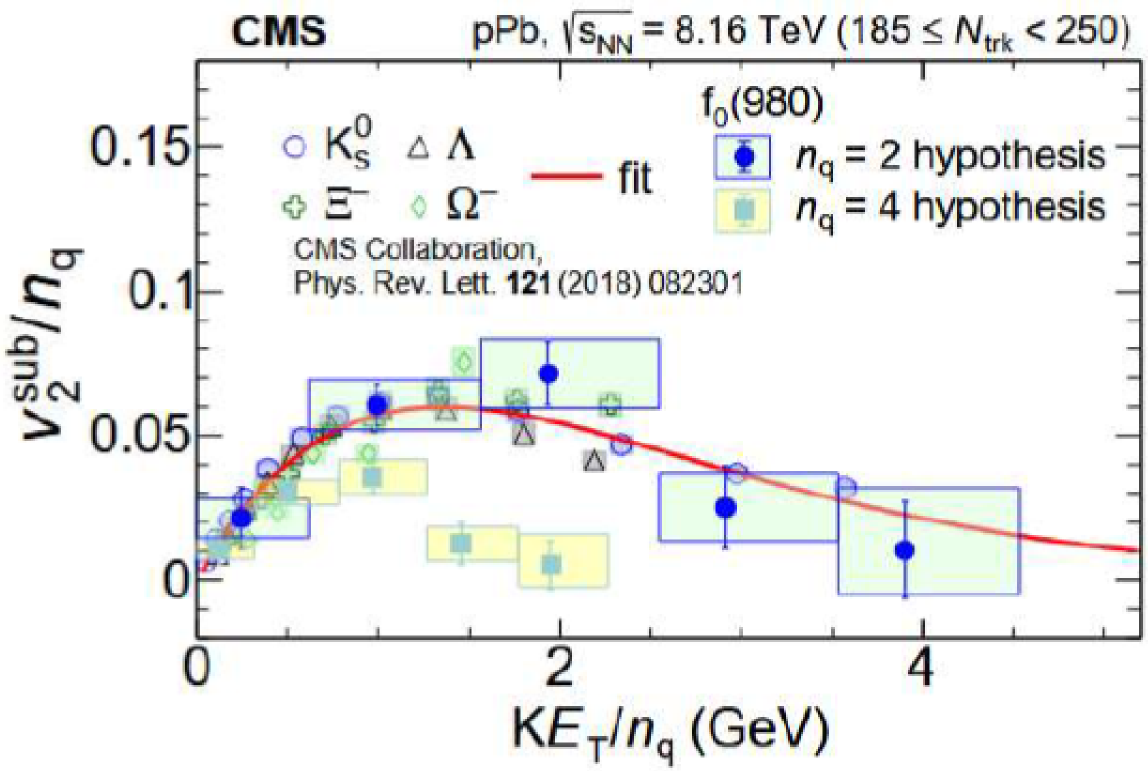
Fig. 7. R_{AA} for LHC using the same notation as in Fig. 5.



No Cronin-like enhancement in Q_{pPb}

- Internal structure to be a conventional meson (PLB 645 (2007) 138)

QM23 CMS & QM25 Y.Wang oral



- Assuming NCQ scaling, n_q of $f_0(980)$ is consistent with 2.
- $n_q = 4$ (tetra-quark state or $K\bar{K}$ molecule) exclude with 7.7σ.
- $n_q = 3$ ($q\bar{q}g$ hybrid) excluded with 3.5σ.

Favor $q\bar{q}$ normal meson state for $f_0(980)$

$\rightarrow$ conflict with the conclusion from hadron physics

Next:

- More rigorous coalescence calculations to support the $K\bar{K}$ molecular state for $f_0(980)$
- Explain why the scaling behavior breaks down at hadronic level

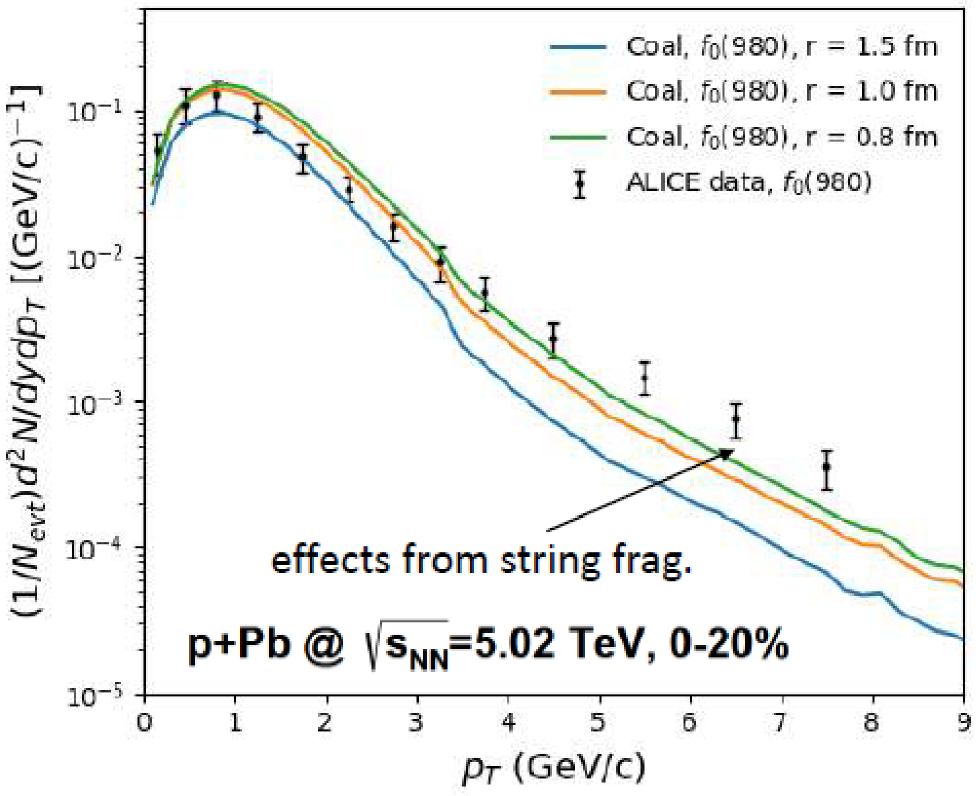
Y.Wang oral

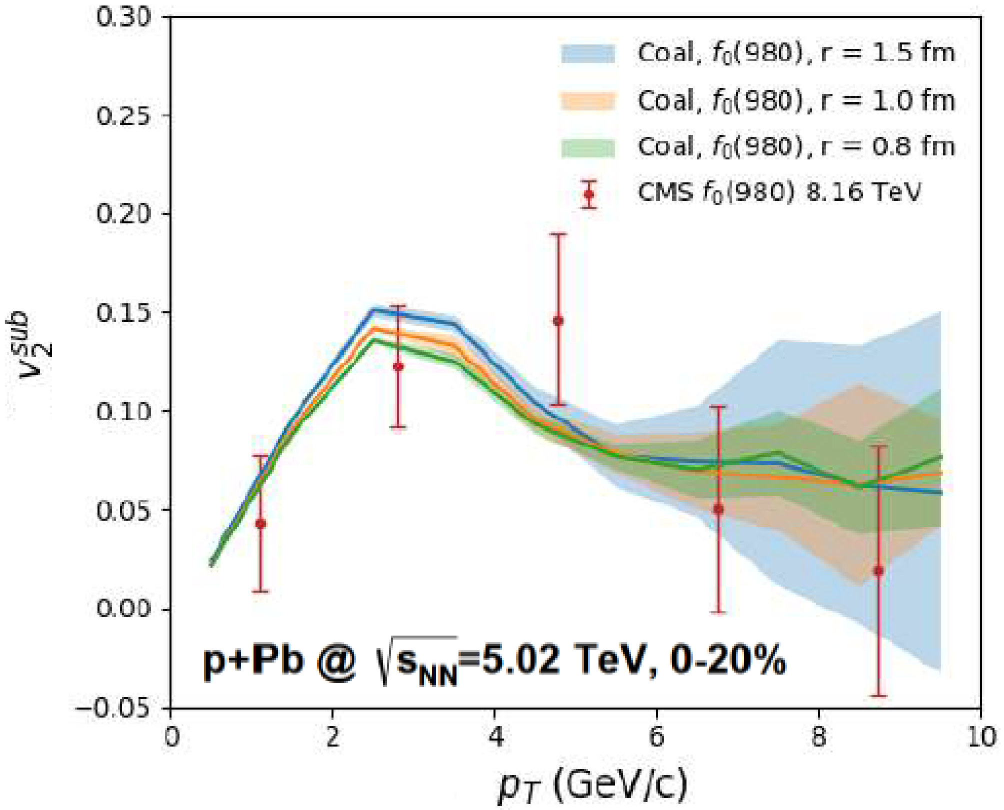
Coalescence calculation results for $f_0(980)$

- Use typical **molecular size estimation** method: $R \sim \frac{1}{\sqrt{2\mu E_B}}$ μ : reduced mass, E_B : binding energy

  Guo, F.-K., Hanhart, C., Meißner, U.-G., Wang, Q., & Zhao, Q. (2017). *Hadronic molecules*. arXiv:1705.00141.c

We consider the range from 1.0 fm to 1.5 fm as a reasonable interval for the RMS radius.





Y. Wang, W. Zhao, C. M. Ko, F. Guo, J. Xie, H. Song, in preparation.

Support for "molecular structure" for $f_0(980)$

Y.Wang oral

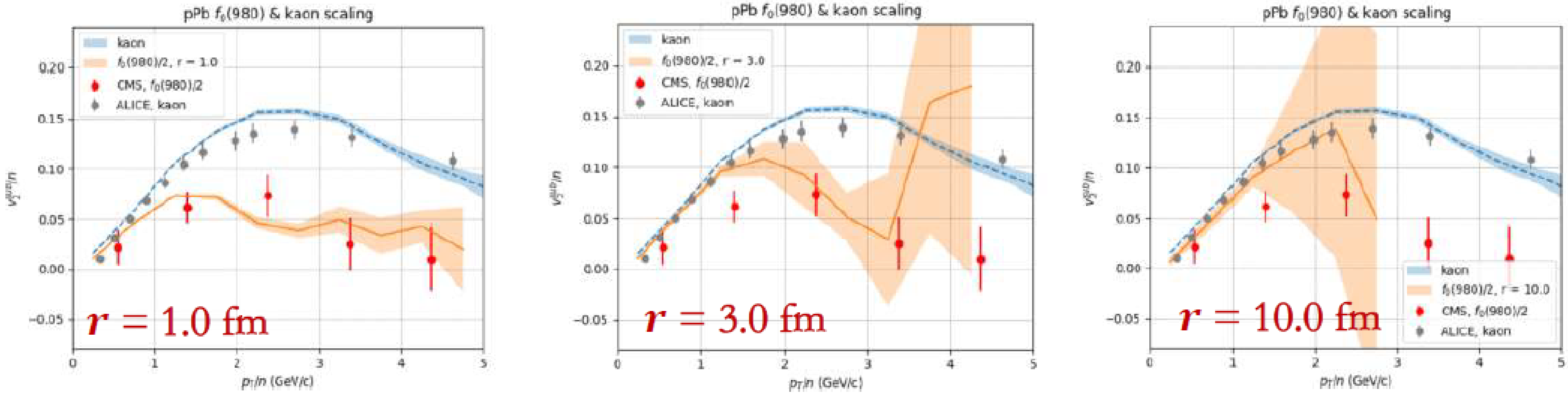
Violation of scaling behavior in hadronic level

Assumption of NCQ scaling

$$\rho^W_{f_0}(\boldsymbol{\rho}, \boldsymbol{p}_\rho) = 8\exp\left[-\frac{\boldsymbol{\rho}^2}{\sigma_\rho^2} - \boldsymbol{p}_\rho^2\sigma_\rho^2\right] \qquad \sigma_\rho = \frac{2}{\sqrt{3}}r, \qquad \boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{x}'_1 - \mathbf{x}'_2), \quad \mathbf{p}_\rho = \frac{1}{\sqrt{2}}(\mathbf{p}'_1 - \mathbf{p}'_2).$$

If σ_ρ is relatively large ➡ farther apart in coordinate space & closer in momentum space

- Consistent with the hadronic scaling of kaon ($\sim n_q = 4$ in NCQ scaling)



- No hadronic scaling, we need real coalescence calculation for $K\bar{K}$ component
- Coalescence calculation support for "molecular structure" for $f_0(980)$

Glueball candidates

$f_0(1370)$ $f_0(1500)$ $f_0(1710)$

Flavor symmetry assumption

$$(gb \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta') = 3:4:1:0:1$$

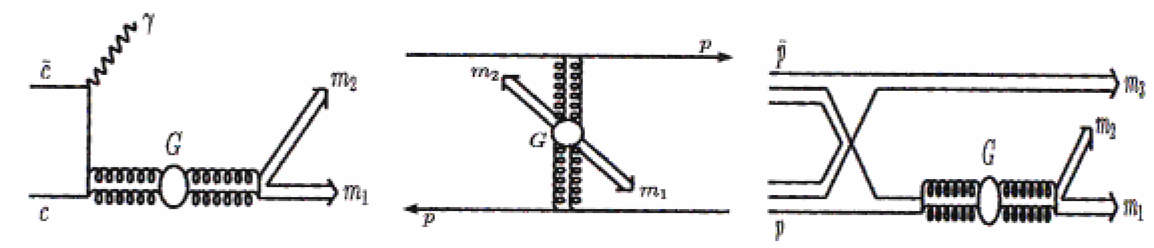
$f_0(1500)$ favor

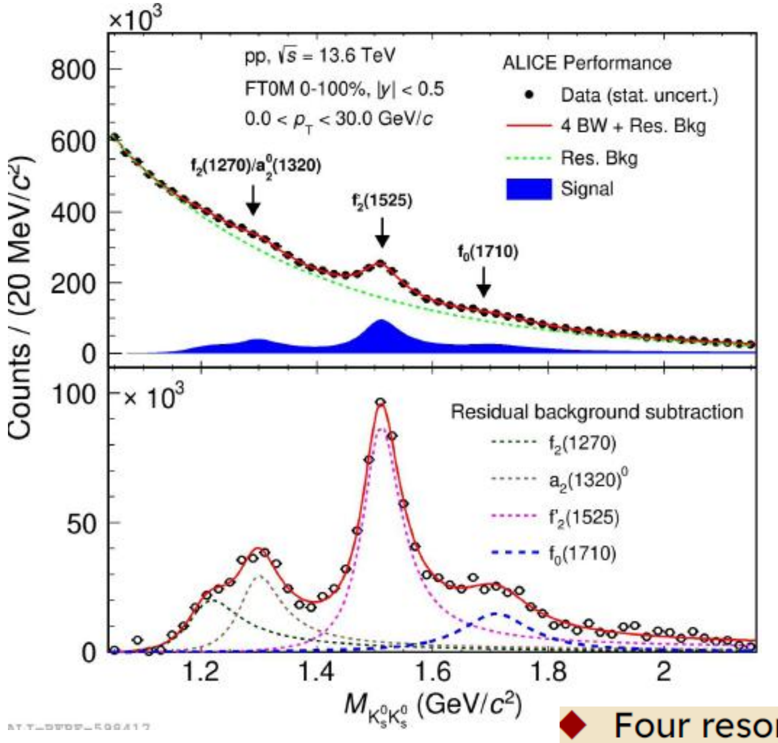
- $\gamma\gamma$ ↛ $f_0(1500)$
- $\gamma\gamma \to f_0(1710)$

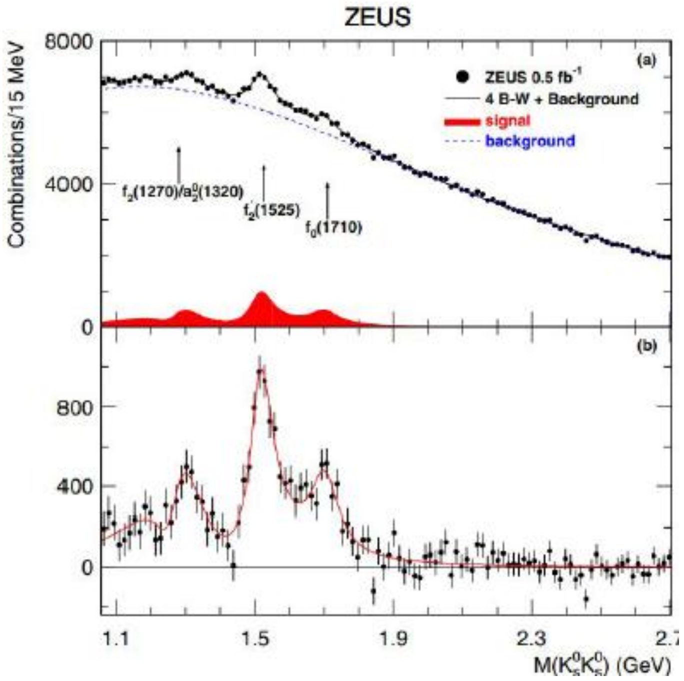
$f_0(1710)$ favor

- J/ψ radiative decay $f_0(1710) >> f_0(1500)$
- $f_0(1500) \to \eta\eta'$
- $f_0(1710)$ ↛ $\eta\eta'$

Glue rich processes







J.Kim(ALICE) oral & Sawan(ALICE) poster

- $f_0(1500)$は？
- 他の崩壊モードは？
- Pt分布、centrality依存性、異方性等々は？
- 今後に期待

◆ Four resonances are observed in the $K_S^0 K_S^0$ mass spectrum similar to the HERA experiment [5].

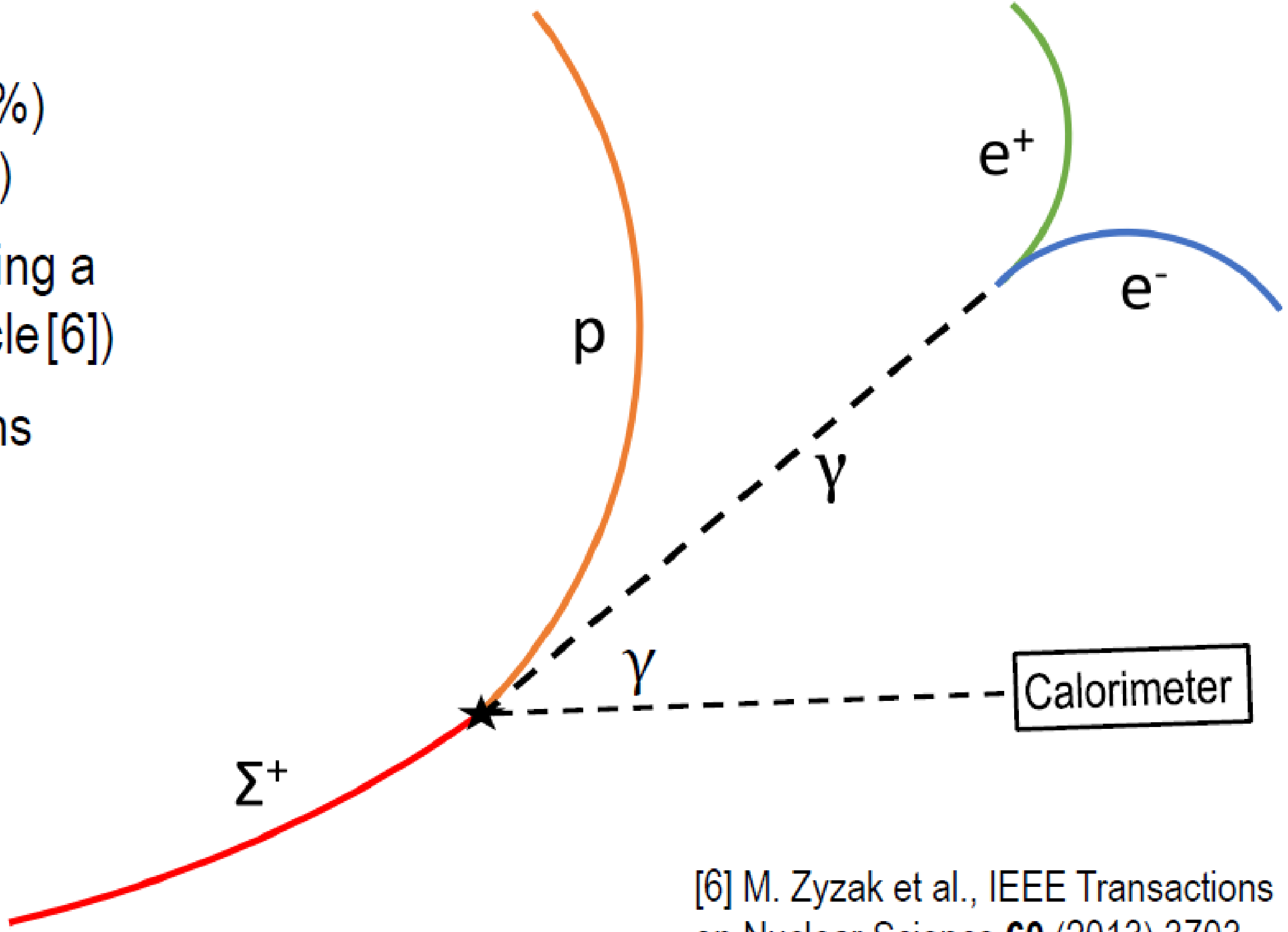
Σ^+ p correlation function

B.Heybeck(ALICE poster)

ALICE GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Σ^+ reconstruction in ALICE

- $\Sigma^+ \rightarrow \pi^0 + p$ (BR = 51.57%)
  $\pi^0 \rightarrow \gamma + \gamma$ (BR ≈ 100%)
- Reconstruct secondary vertex using a Kalman Filter approach (KFParticle[6])
- Measure photons with conversions and the calorimeters

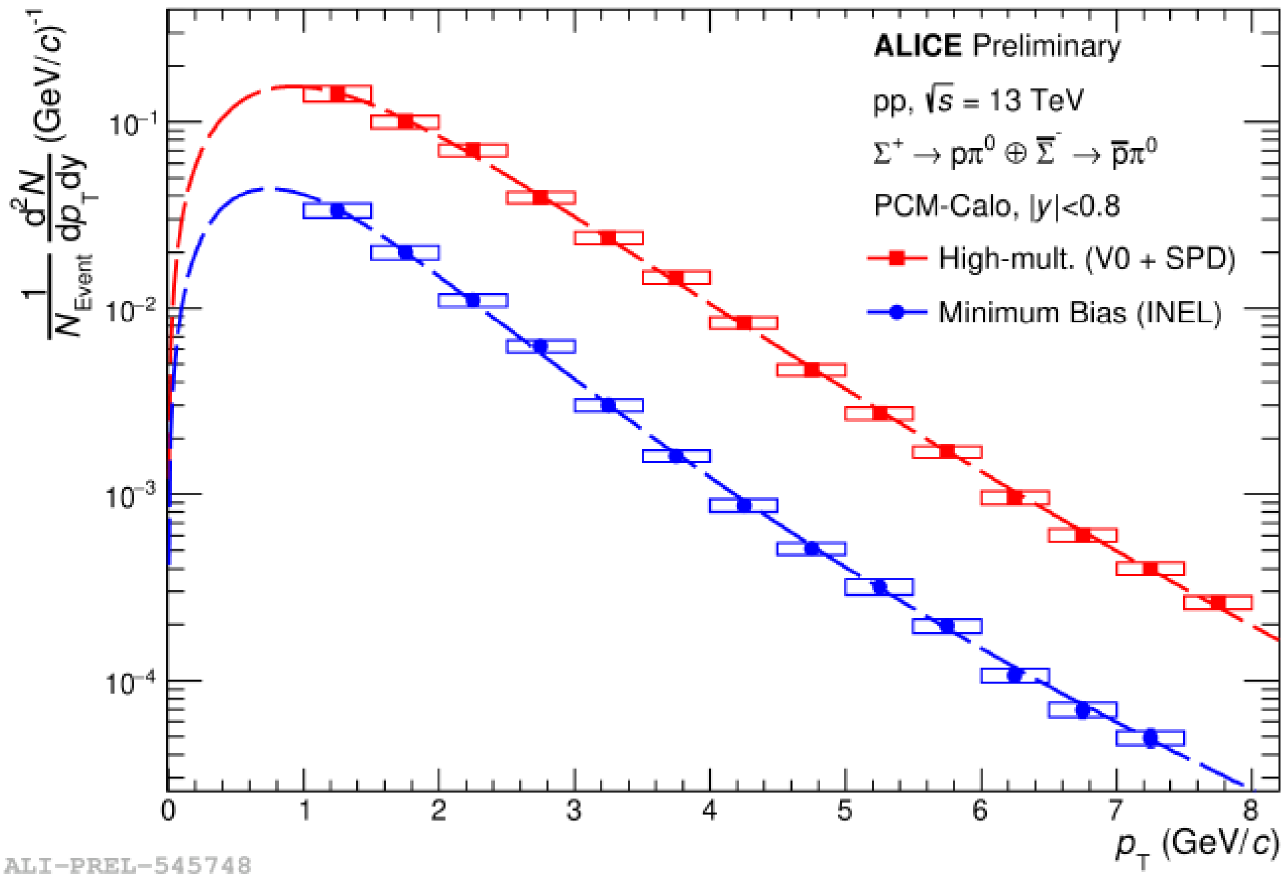


[6] M. Zyzak et al., IEEE Transactions on Nuclear Science **60** (2013) 3703

Σ^+ reconstruction in ALICE

- $\Sigma^+ \rightarrow \pi^0 + p$ (BR = 51.57%)
  $\pi^0 \rightarrow \gamma + \gamma$ (BR ≈ 100%)
- Reconstruct secondary vertex using a Kalman Filter approach (KFParticle)
- Measure photons with conversions and the calorimeters
  → First Σ^+ spectra at the LHC

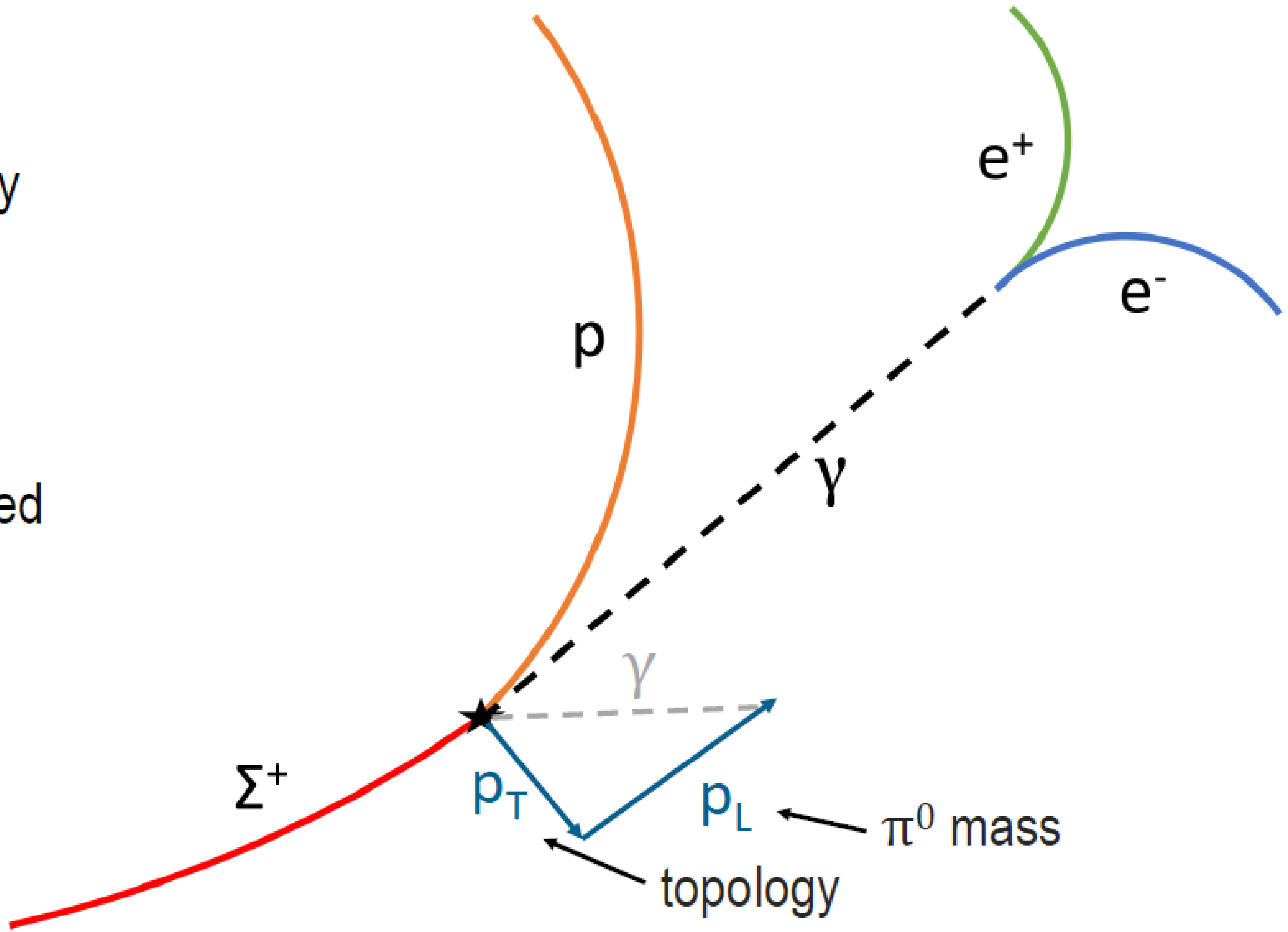
First measurement of Σ^+ at LHC energies!



Σ^+ reconstruction in ALICE

B.Heybeck(ALICE poster)

- Reconstruct only one photon to improve efficiency and calculate missing momentum from topology and π^0 mass
- Select particles using machine learning approach (XGBoost)
- Reconstruction efficiency improved by one order of magnitude
- Twofold improvement of purity

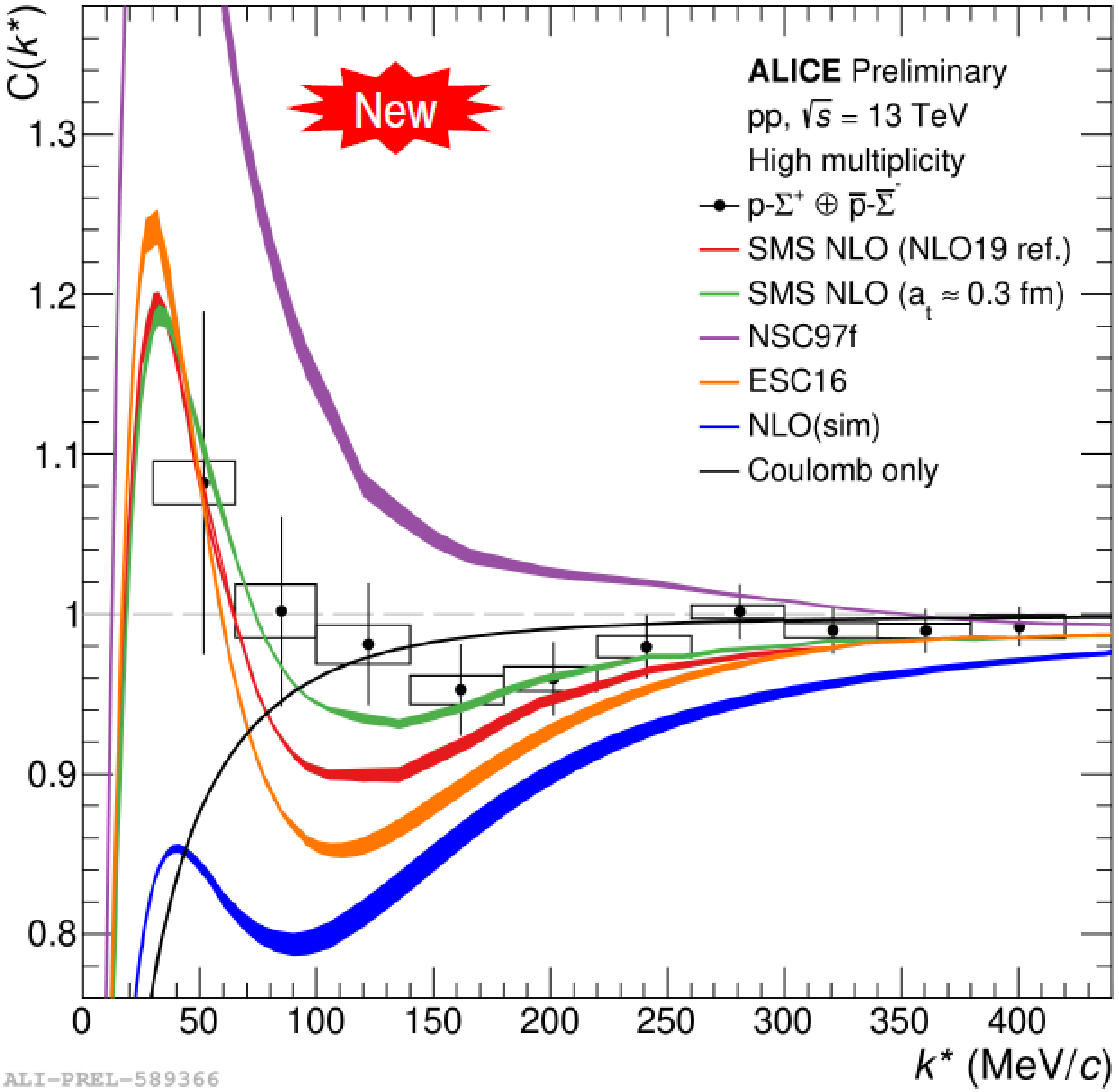


Comparison with data

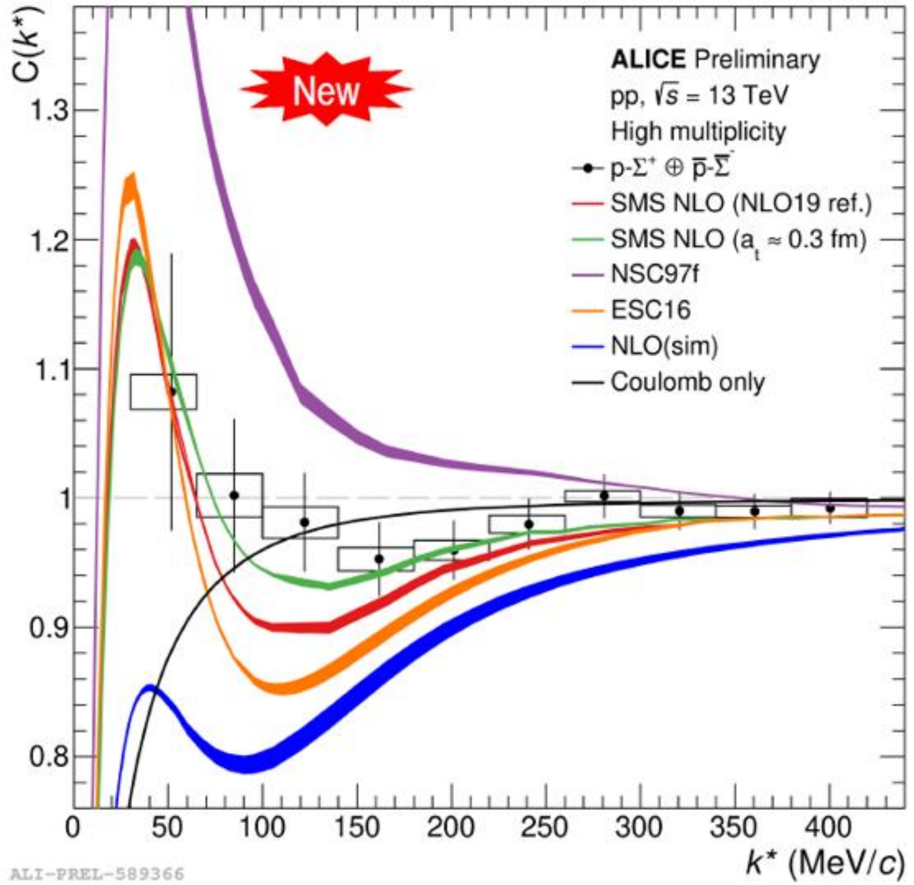
- Calculations weighted by λ-parameters to account for impurities in the data
- Error bands arise from uncertainty of the source size
- Large spread in model predictions
  → Data very constraining despite sizeable uncertainties

SMS NLO: J. Haidenbauer et al., Eur. Phys. J. A **56** (2020) 91
NSC97f: T. Rijken et al., Phys. Rev. C **59** (1999) 21
ESC16: M. Nagels et al., Phys. Rev. C **99** (2019) 044003
NLO(sim): J. Haidenbauer et al., Phys. Lett. B **829** (2022) 137074

B.Heybeck(ALICE poster)

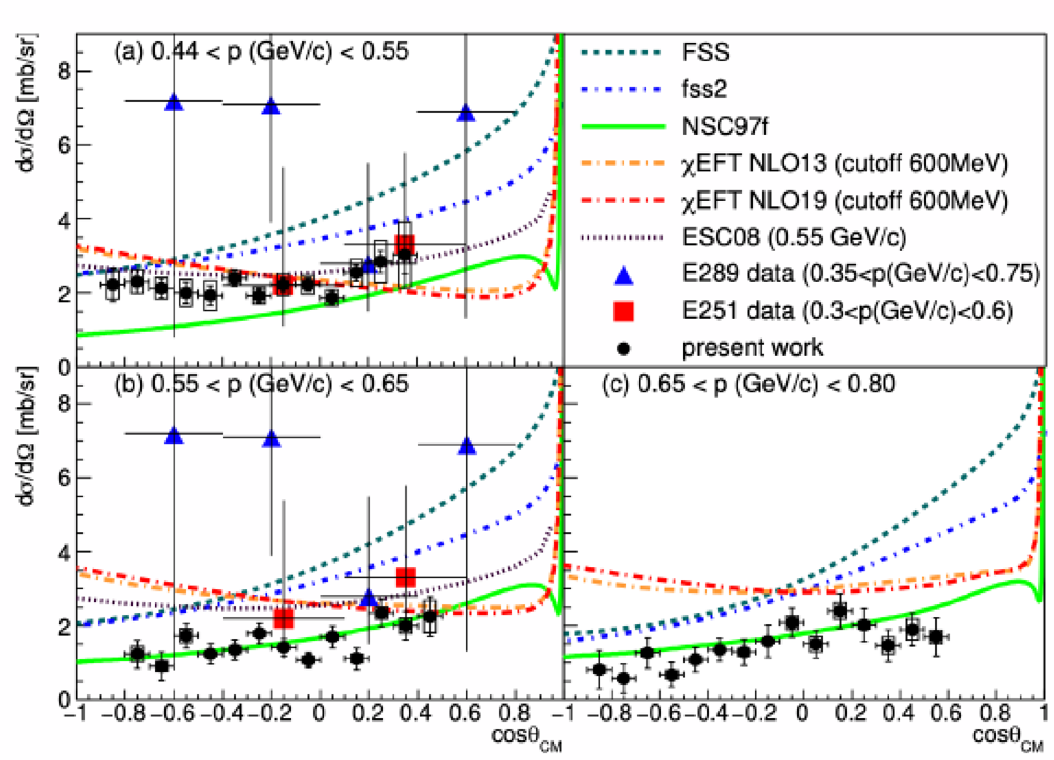


ALICE
Σ^+ p correlation function



J-PARC E40
Σ^+ p elastic scattering

T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01



NLO19はcorrelation function, elastic scattering(0.44<p<0.55)共にそれなりに一致。ただし、elastic scatteringの運動量依存性は再現しない。
NSC97(引力)はcorrelation functionを全く再現しないが、elastic scatteringに対しては、割と再現している。

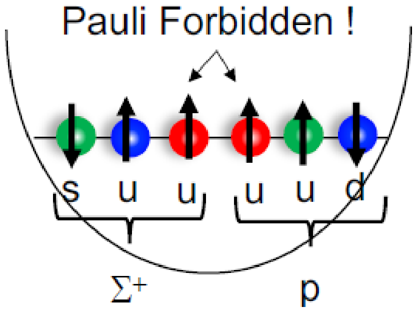
$^1S_0$ & $^3S_1$ channel

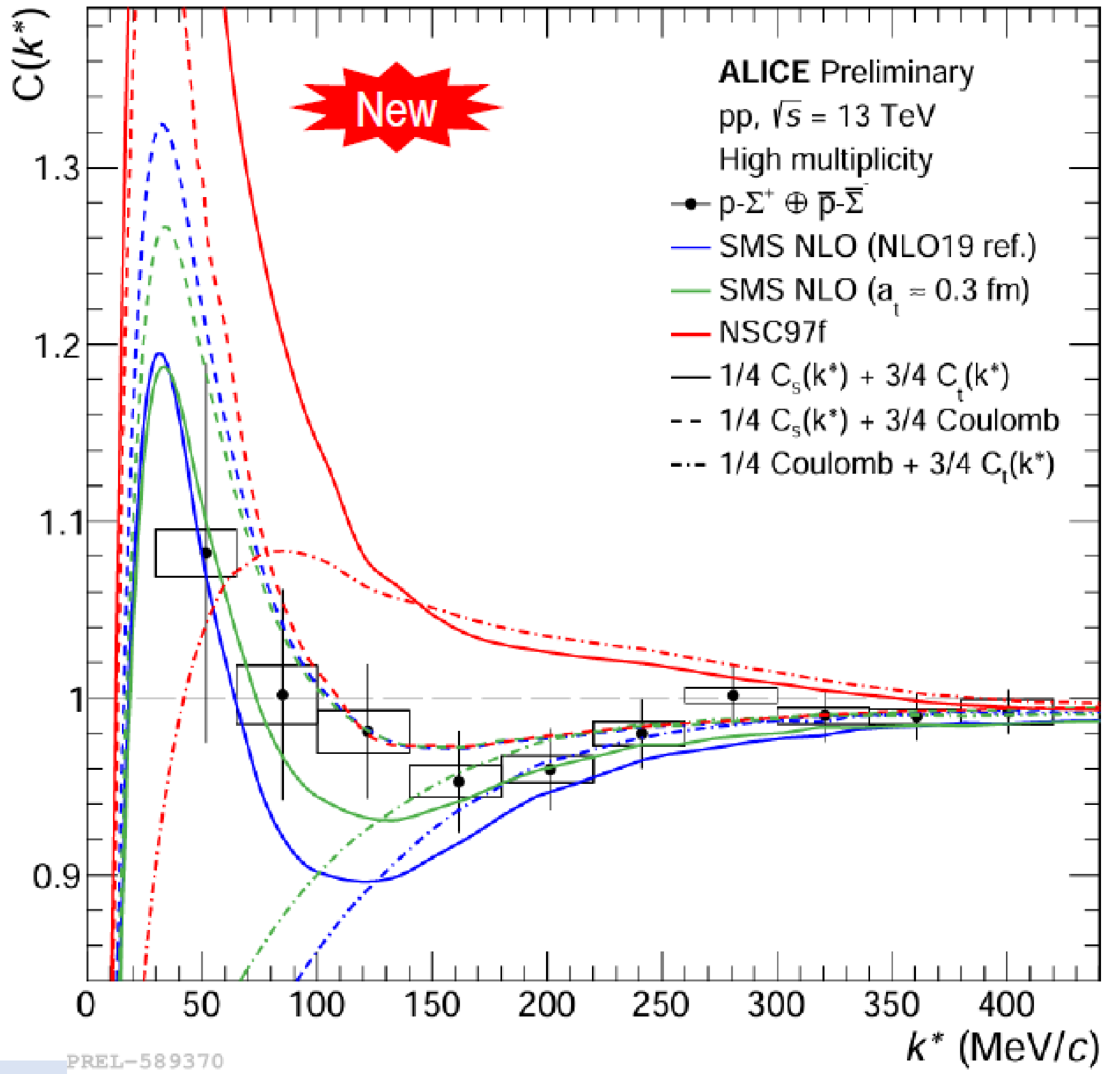
B.Heybeck(ALICE poster)

- Sensitivity to singlet strength only at very low k^* ($\lesssim$ 50 MeV/c)

channel			spin-parity	
baryon pair	strangeness	isospin	singlet-even/triplet-odd	triplet-even/singlet-odd
N–N	0	0	-	$(\overline{10})$
N–N	0	1	(27)	-
N–Λ	1	1/2	$\frac{1}{\sqrt{10}}[(8_s)+3(27)]$	$\frac{1}{\sqrt{2}}[-(8_a)+(\overline{10})]$
N–Σ	1	1/2	$\frac{1}{\sqrt{10}}[3(8_s)-(27)]$	$\frac{1}{\sqrt{2}}[(8_a)+(\overline{10})]$
N–Σ	1	3/2	(27)	(10)

- Correlation function very sensitive to triplet strength at higher k^*
- Good agreement with very shallow repulsion



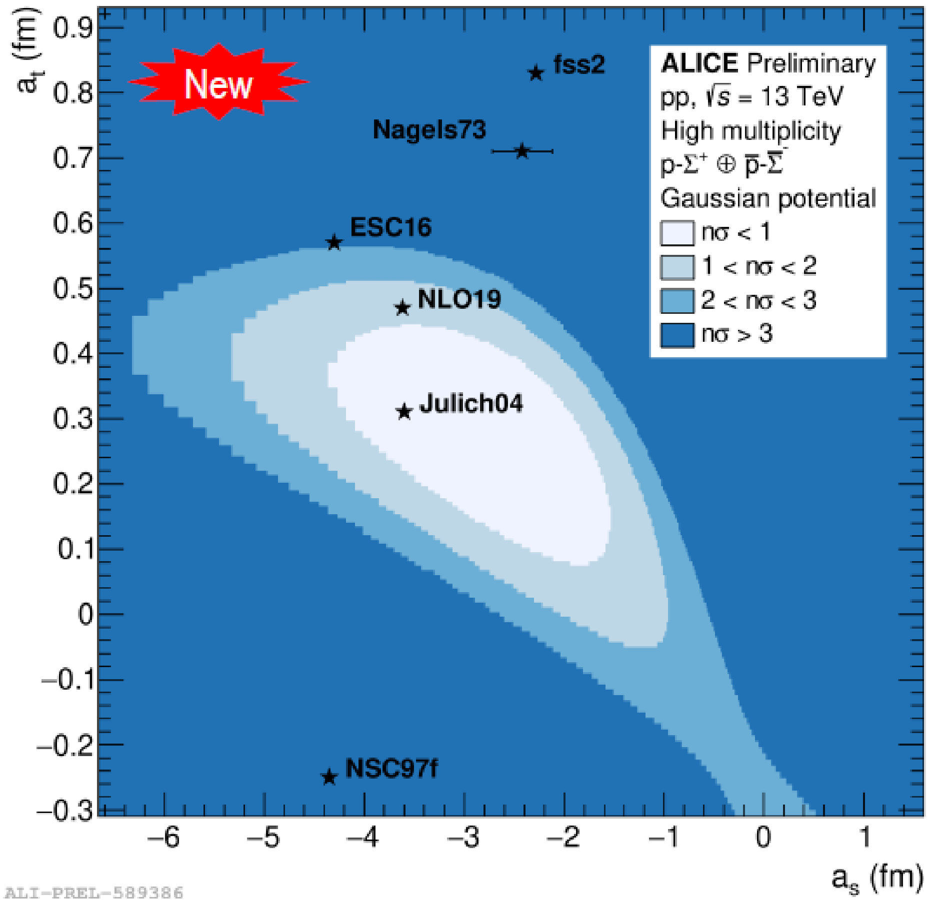


The more repulsive potential in $^3S_1$

→ The larger $d\sigma/d\Omega$ (like fss2)

ALICE

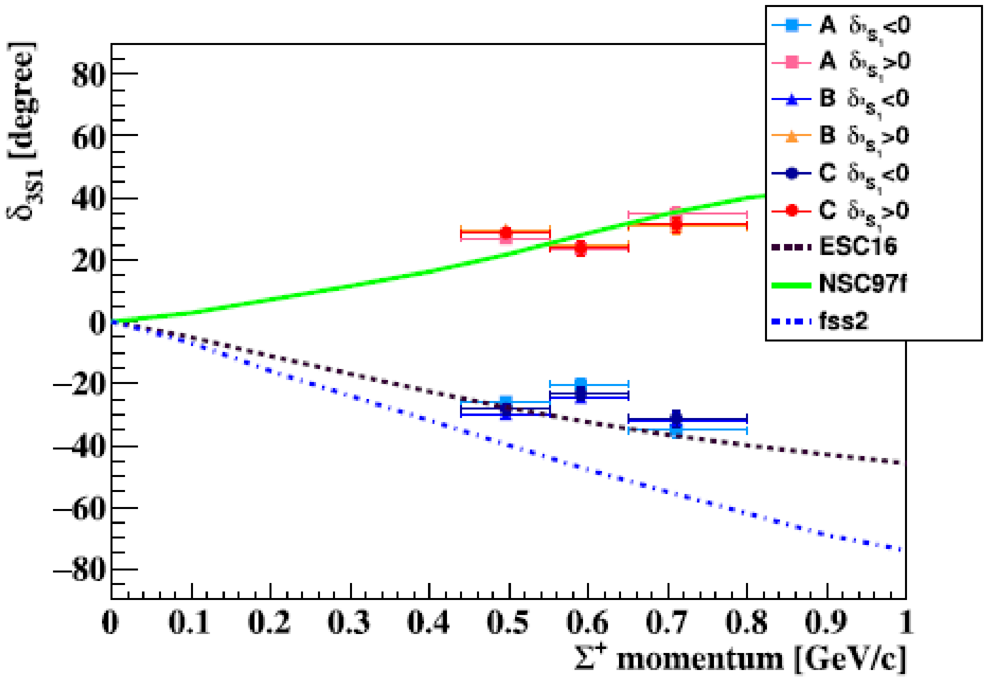
Σ^+ p correlation function



J-PARC E40

Σ^+ p elastic scattering

Phase shift of ^{3}S1

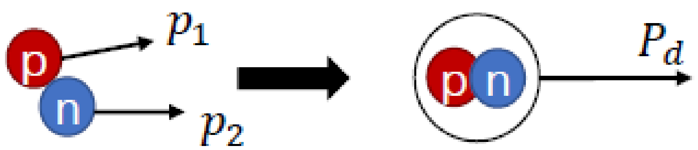


Correlation function→^{3}S1は弱い斥力、ESC16の半分程度

Elastic scattering→ ^{3}S1は、斥力と仮定すれば強くない斥力、ESC16と同程度

Back up

The Coalescence Model for light nuclei



p + n → deuteron

Phase space distributions of p/n (obtained from hydro)

$$\frac{dN_d}{d\boldsymbol{P}_d^3} = g_d \int d^3\boldsymbol{x}_1 d^3\boldsymbol{p}_1 d^3\boldsymbol{x}_2 d^3\boldsymbol{p}_2\, f_p(\boldsymbol{x}_1,\boldsymbol{p}_1) f_n(\boldsymbol{x}_2,\boldsymbol{p}_2) \times \rho_d^W(\boldsymbol{\rho},\boldsymbol{P}_\rho)\delta(\boldsymbol{P}_d - \boldsymbol{p}_1 - \boldsymbol{p}_2)$$

Wigner function of deuteron

$$\rho_d^W(\mathbf{r},\mathbf{k}) = \int \phi(\mathbf{r}+\frac{\mathbf{R}}{2})\phi^*(\mathbf{r}-\frac{\mathbf{R}}{2})\exp(-i\mathbf{k}\cdot\mathbf{R})d\mathbf{R}$$

wave function

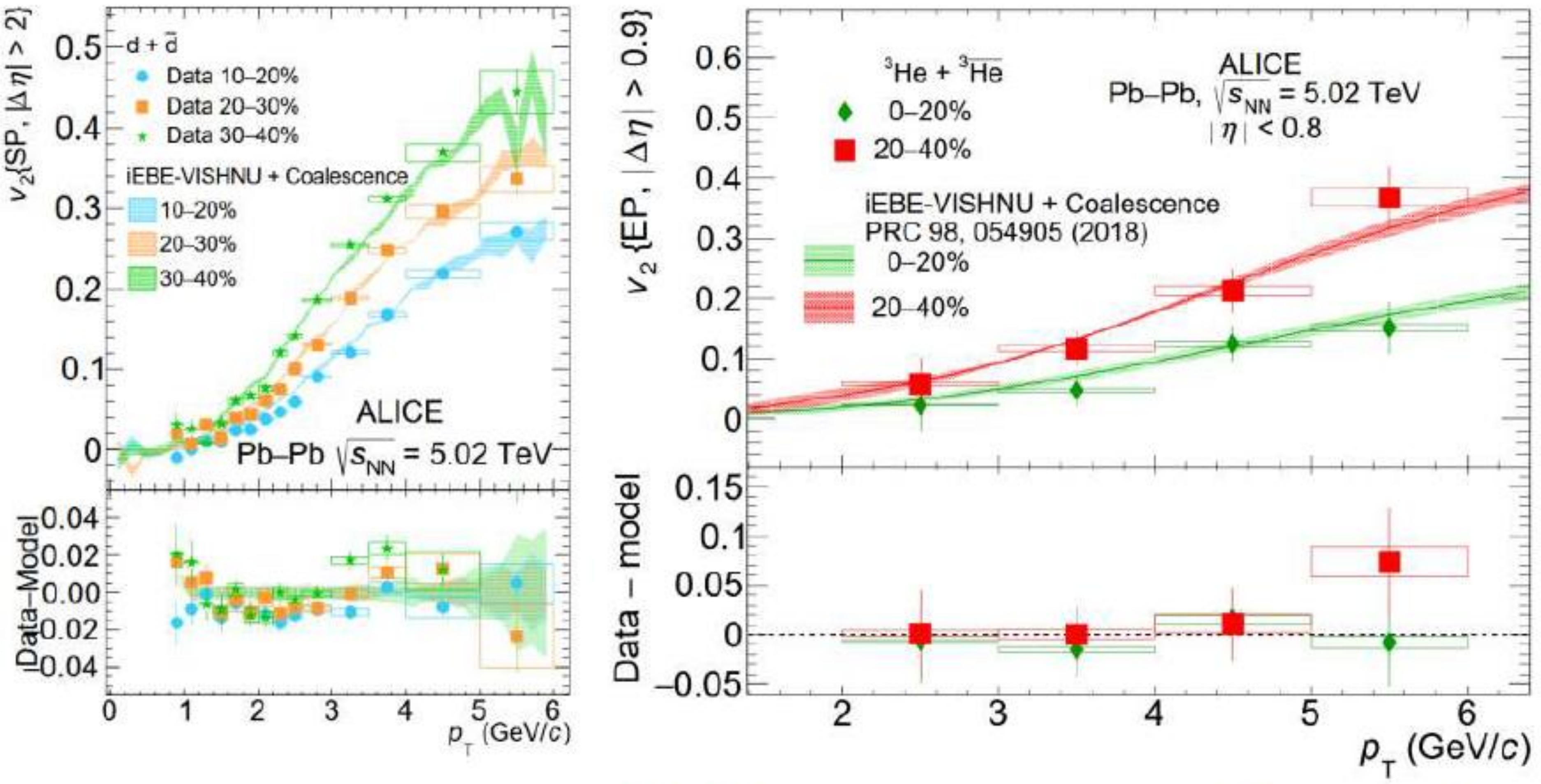
- If take the harmonic oscillator wave functions ϕ, then the Wigner function will be Gaussian.

$$\rho_d^W(\boldsymbol{\rho},\boldsymbol{p}_\rho) = 8\exp\left[-\frac{\boldsymbol{\rho}^2}{\sigma_d^2} - \boldsymbol{p}_\rho^2\sigma_d^2\right] \qquad \boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{x}_1' - \mathbf{x}_2'), \quad \mathbf{p}_\rho = \frac{1}{\sqrt{2}}(\mathbf{p}_1' - \mathbf{p}_2').$$

The parameter σ_d is related to the RMS radius of deuteron $\quad \sigma_d = \frac{2}{\sqrt{3}} r_d$

* Similar calculation for tritium, helium-3 …

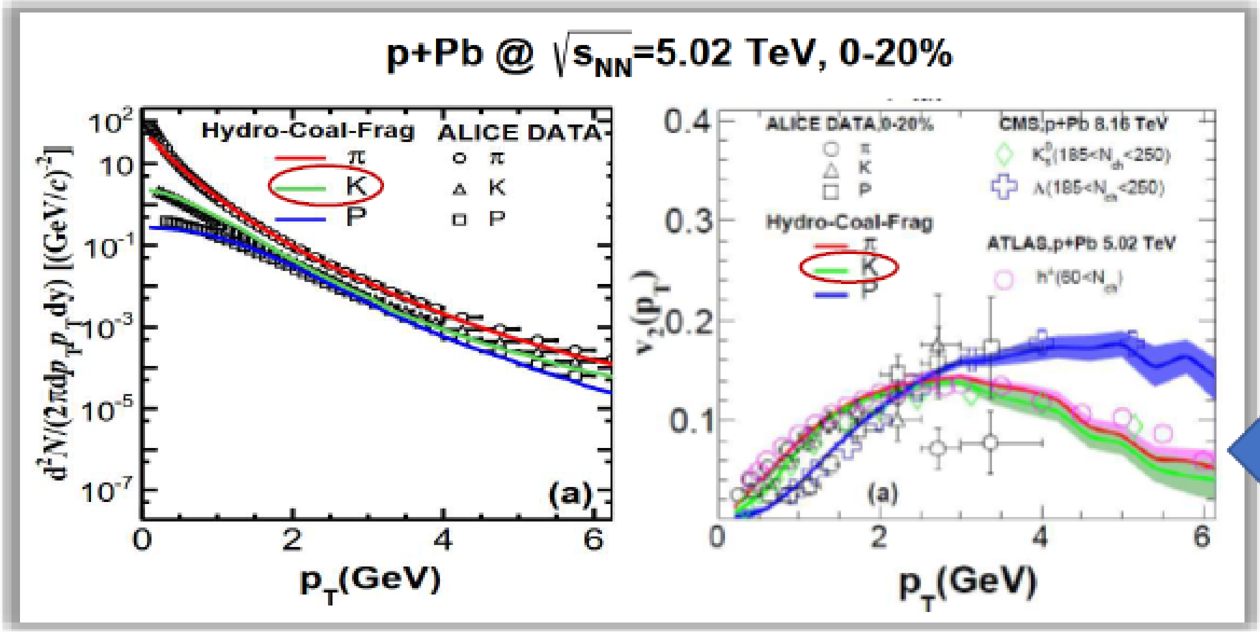
Elliptic flow for Light nuclei from Coalescence



- With coalescence model at hadronic level, we can describe the light nuclei (d ^{3}He …) well.

Experimental data: ALICE Collaboration. arXiv:2005.14639, Phys. Lett. B 805, 135414 (2020), arXiv:1910.09718
Theoretical calculation: W. Zhao, L. Zhu, H. Zheng, C. M. Ko, and H. Song, Phys. Rev. C98 (2018) 054905

Hadronic coalescence procedure for $f_0(980)$

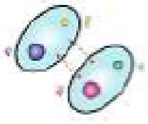


- kaons from early model calculation
- nicely describe the p_T spectra and elliptic flow from 0-6 GeV

Assumption: $f_0(980)$ is $K\bar{K}$ molecular

$$K + \bar{K} \rightarrow f_0(980)$$

$K\bar{K}$ component



$$\frac{dN_{f_0}}{d\boldsymbol{P}_{f_0}^3} = g_{f_0} \int d^3\boldsymbol{x}_1 d^3\boldsymbol{p}_1 d^3\boldsymbol{x}_2 d^3\boldsymbol{p}_2$$

$$\times f_K(\boldsymbol{x}_1,\boldsymbol{p}_1) f_{\bar{K}}(\boldsymbol{x}_2,\boldsymbol{p}_2)\, \rho_{f_0}^W(\boldsymbol{\rho},\boldsymbol{P}_\rho)\delta(\boldsymbol{P}_{f_0} - \boldsymbol{p}_1 - \boldsymbol{p}_2)$$

Phase space distributions of K and $\bar{K}$

Wigner function of $f_0(980)$

$$\rho_{f_0}^W(\boldsymbol{\rho},\boldsymbol{p}_\rho) = 8\exp\left[-\frac{\boldsymbol{\rho}^2}{\sigma_\rho^2} - \boldsymbol{p}_\rho^2\sigma_\rho^2\right]$$

$$\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{x}_1' - \mathbf{x}_2'), \quad \mathbf{p}_\rho = \frac{1}{\sqrt{2}}(\mathbf{p}_1' - \mathbf{p}_2').$$

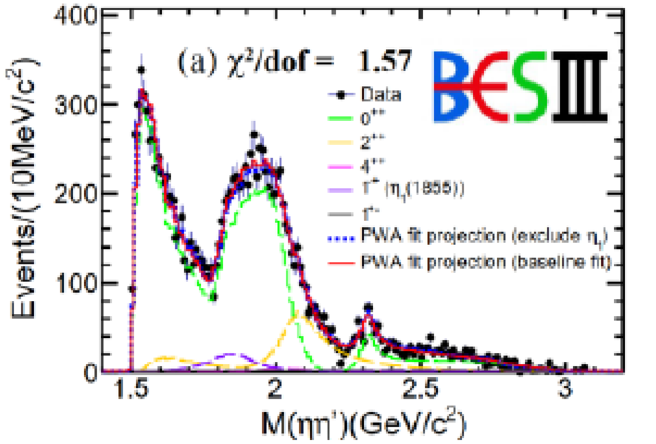
$$\sigma_\rho = \frac{2}{\sqrt{3}} r$$

Zhao, Ko, Liu, Qin & Song. Phys. Rev. Lett. 125 7 072301(2020)
ALICE Collaboration, arXiv:2411.09323, 2024.

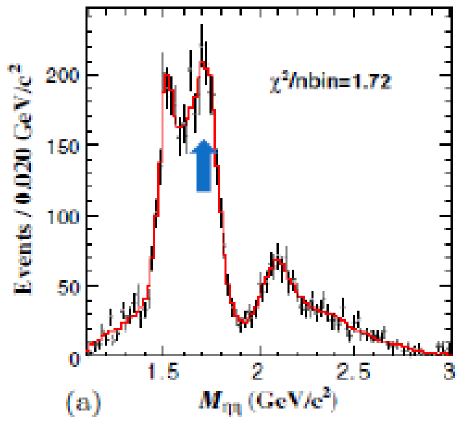
$f_0(1500)$ and $f_0(1710)$ at BESIII

- $J/\psi \to \gamma\eta\eta'$
  - $f_0(1500) \to \eta\eta'$: significant contribution
  - $f_0(1710) \to \eta\eta'$: not observed
- $J/\psi \to \gamma\eta'\eta'$, $J/\psi \to \gamma K_S K_S$, $J/\psi \to \gamma\pi^0\pi^0$
  - Large $f_0(1710)$ production (assuming $f_0(1810)$ is the same object)
- $f_0(1710)$ can have a large gluonic content or a sizeable overlap with the ground state scalar glueball

PRL**129** (2022), 192002
PRD**106** (2022), 072012

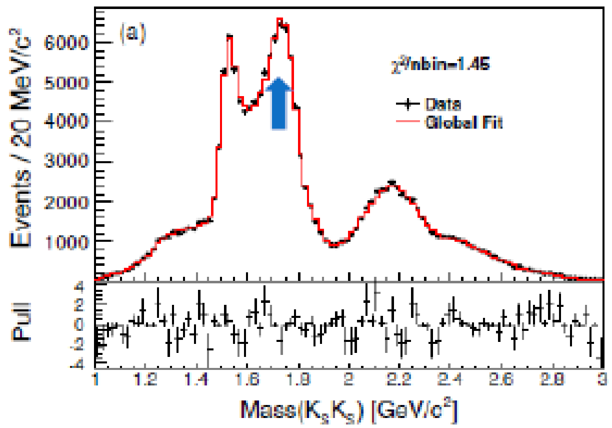


$J/\psi \to \gamma\eta\eta$



PRD87 (2013), 092009

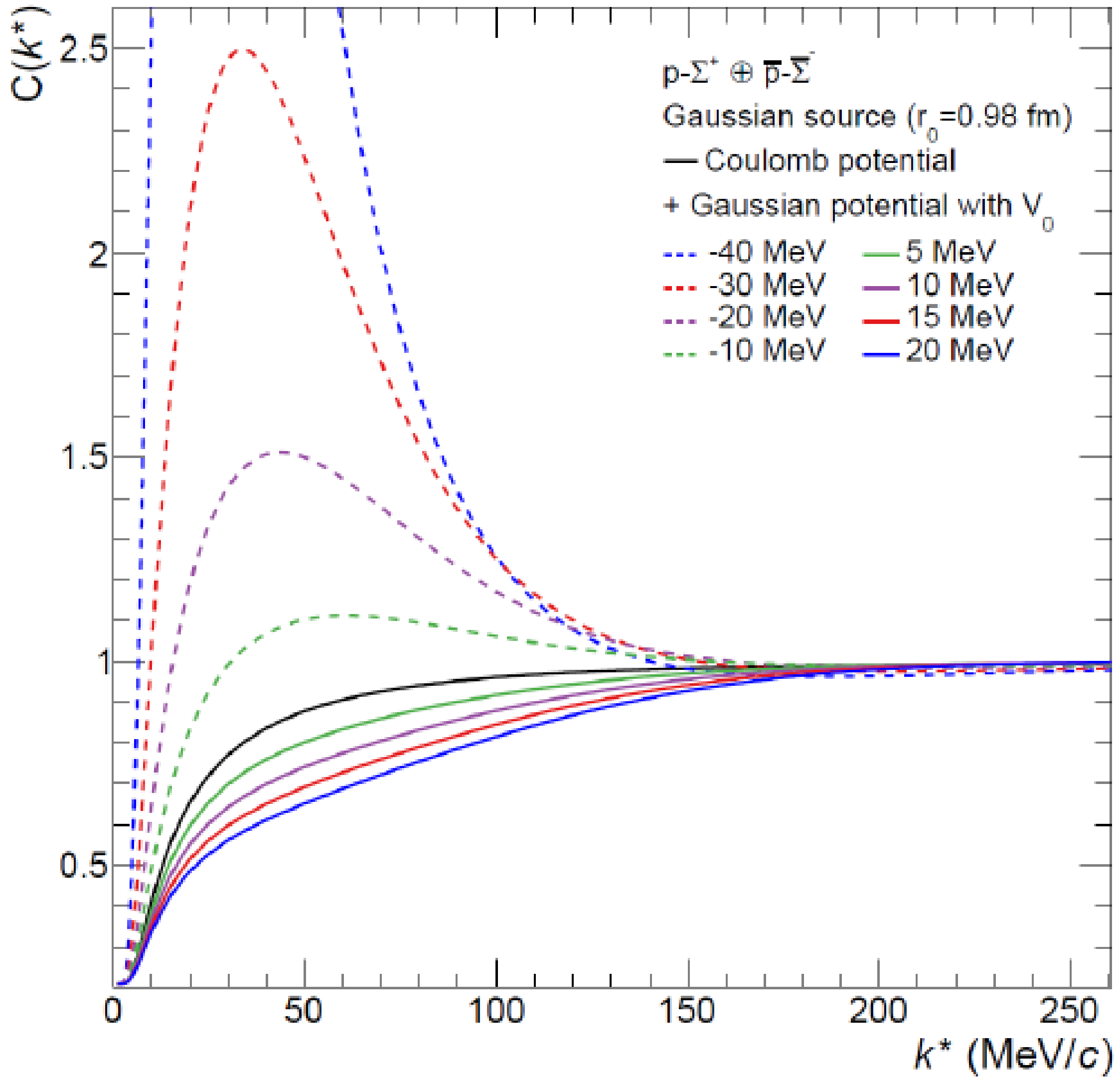
$J/\psi \to \gamma K_s K_s$

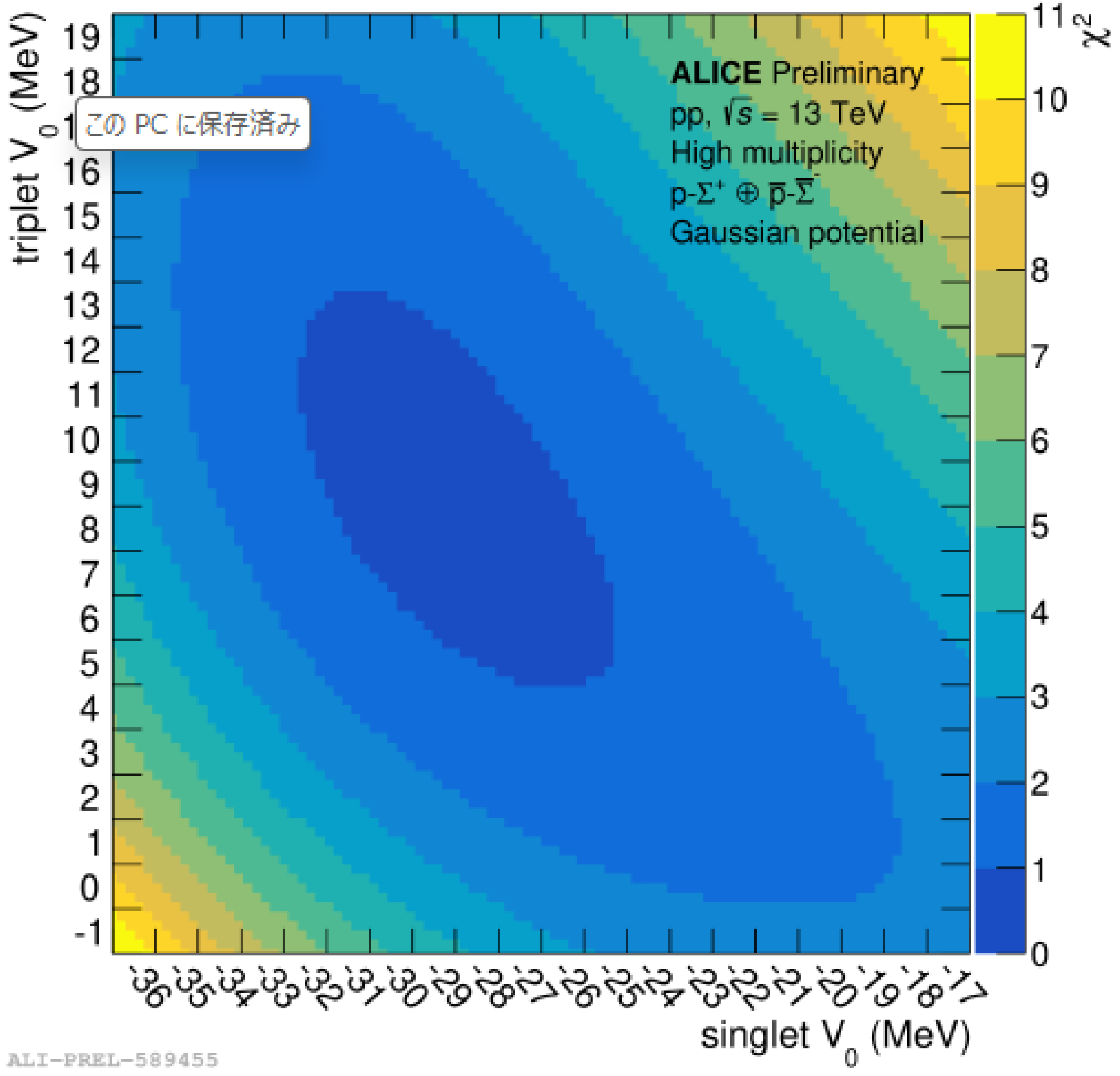


PRD98 (2018), 072003

Gaussian potential

➢ Obtain correlation functions from Gauss + Coulomb potential and compare to data





Phase shift analysis

T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01

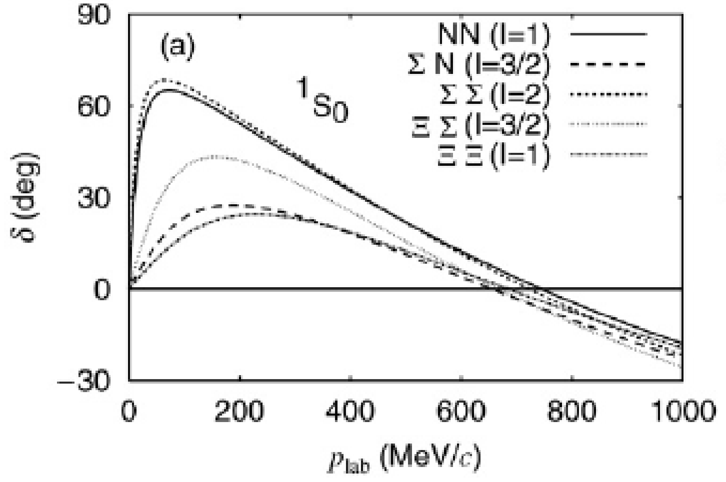
Phase shift analysis for Σ^+p $d\sigma/d\Omega$

- Two parameters : $\delta(^3S_1)$, $\delta(^1P_1)$
- Other phase shifts up to D wave :

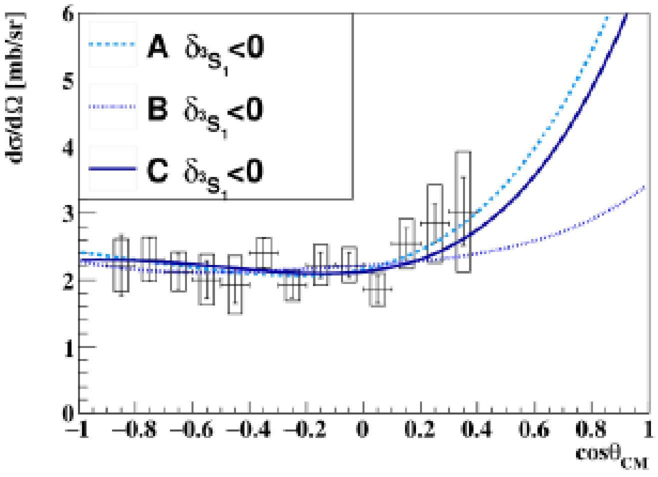
  fixed on NSC97f, ESC16, pp scat

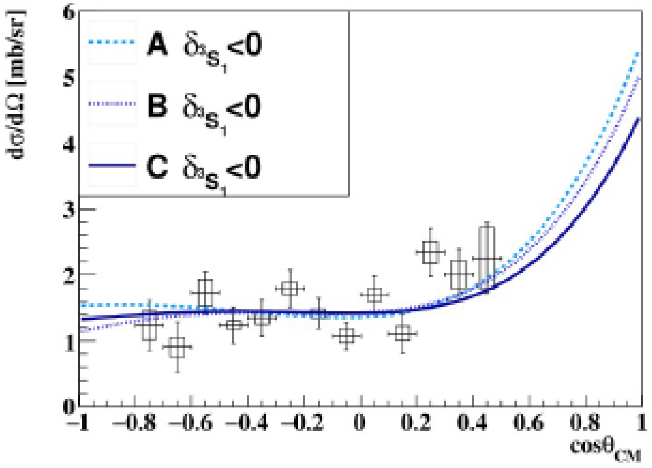
strangeness	BB channel (I)	^{1}Even or ^{3}Odd	^{3}Even or ^{1}Odd
0	$NN(I=0)$	–	(**10***)
	$NN(I=1)$	(**27**)	–
	$\Sigma N(I=\frac{3}{2})$	(**27**)	(**10**)

- Constrained from NN (I=1) channel
- Smaller uncertainty



Fitting $d\sigma/d\Omega$ with sum of partial waves





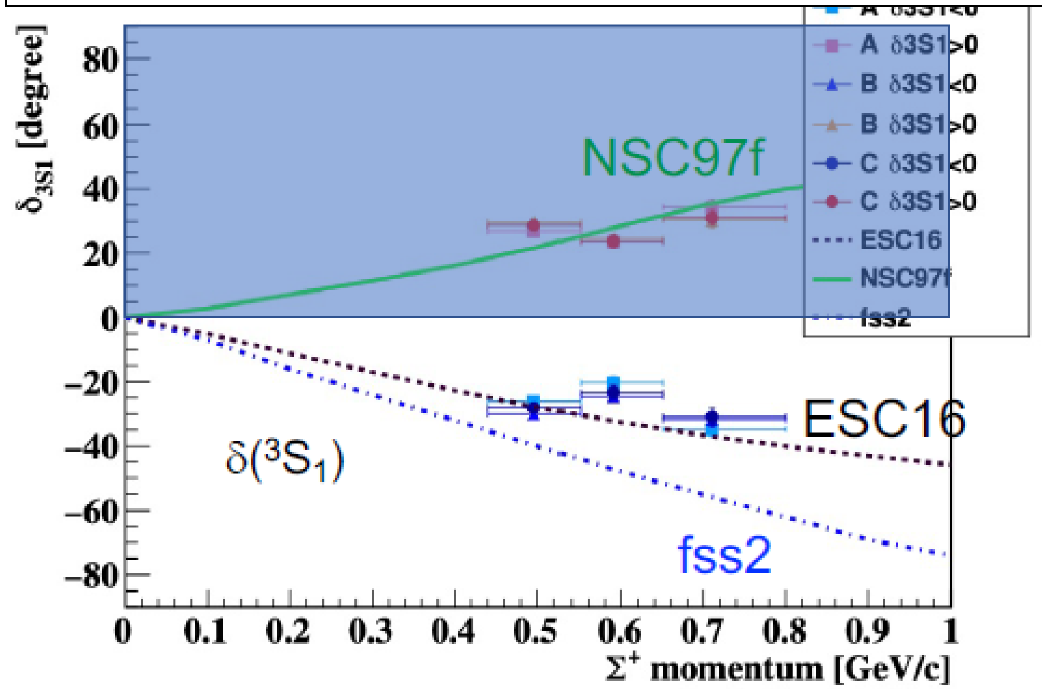
Phase shift analysis

T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01

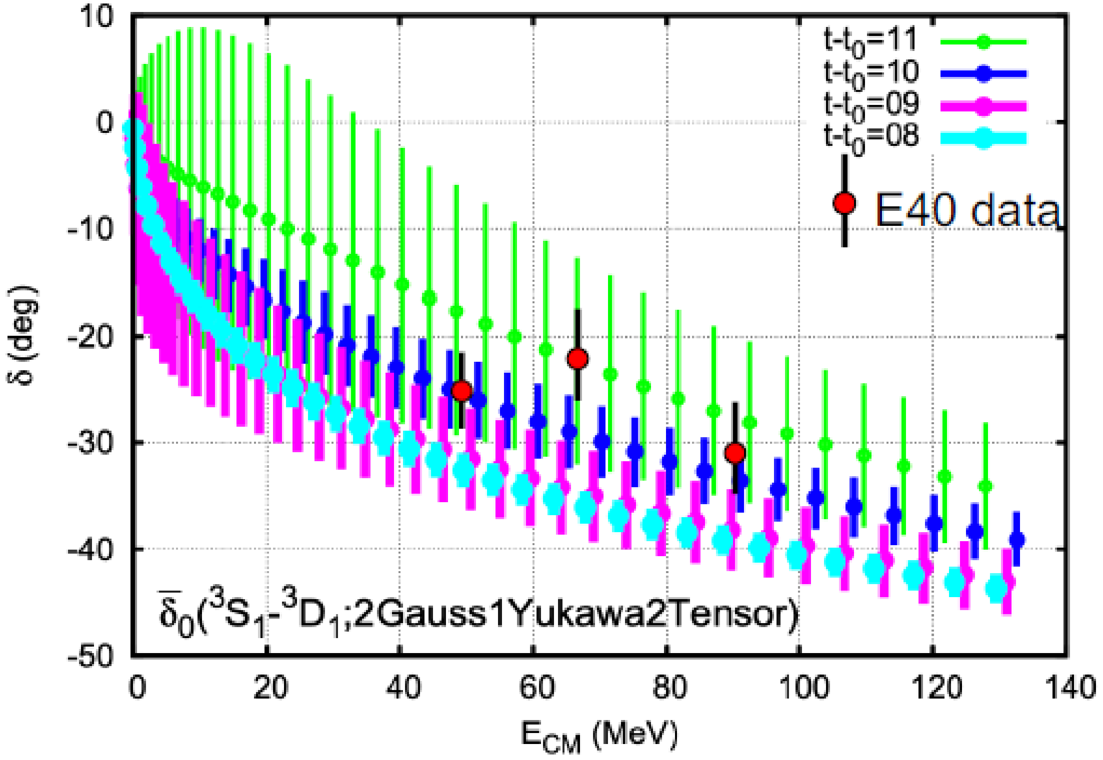
Phase shift analysis for Σ^+p $d\sigma/d\Omega$

- Two parameters : $\delta(^3S_1)$, $\delta(^1P_1)$
- Other phase shifts up to D wave : fixed on NSC97f, ESC16, pp scat

First experimental derivation of phase shift of $^3S_1$



Comparison with HAL QCD ΣN potential



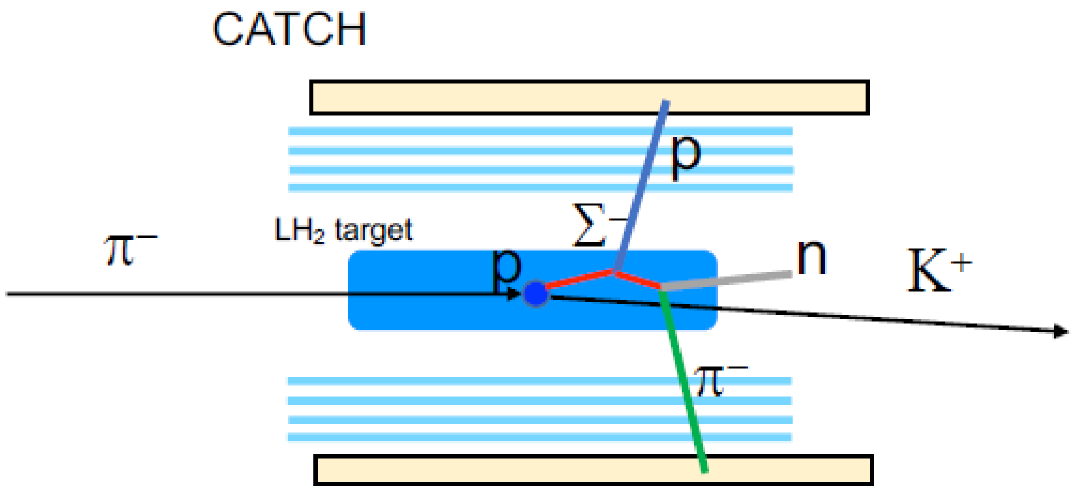
H. Nemura et al., EPJ Web of Conf., 175, 05030 (2018)

Derived phase shift suggest that **the $^3S_1$ interaction is moderately repulsive**.

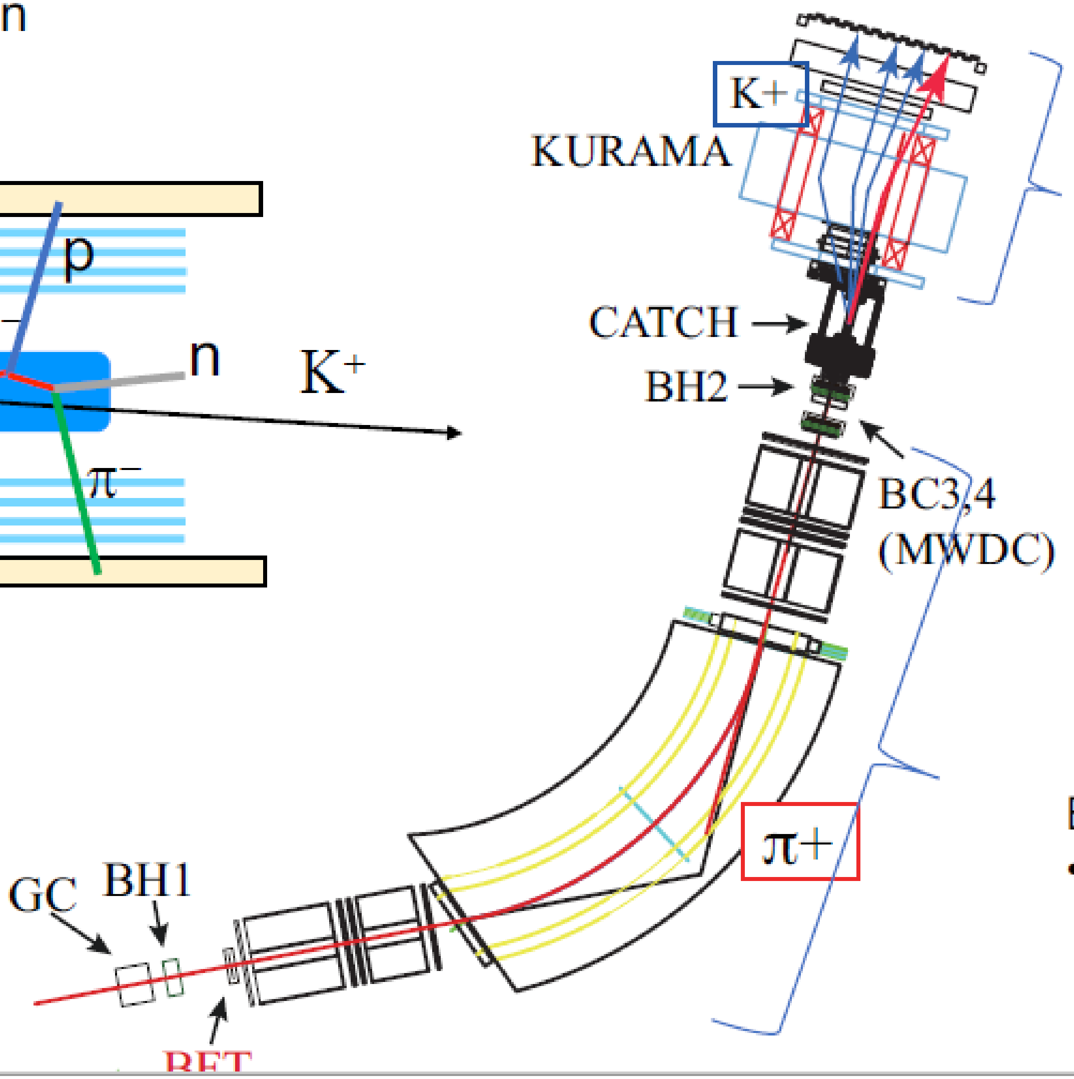
J-PARC E40 experimental setup

Two successive two-body reactions

- Σ production by πp→K⁺Σ reaction
- Σp scattering reaction



@ J-PARC K1.8 beam line



KURAMA spectrometer

- Identification of K⁺
- Momentum analysis

Momentum tagging of Σ beam

Beam-line spectrometer

- Momentum analysis of π beam