Recent results from STAR -focus on the p-Ω correlations

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“2nd EMMI Workshop: Anti-matter, hyper-matter and exotica production at the LHC”,
Nov. 6-10, 2017, Turin, Italy

Outline

☑ Introduction

☑ NΩ dibaryon

☑ Two-particle correlation function

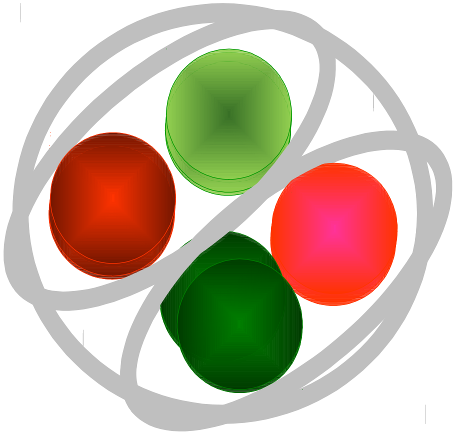
  – PΩ correlation function

☑ Summary and Outlook

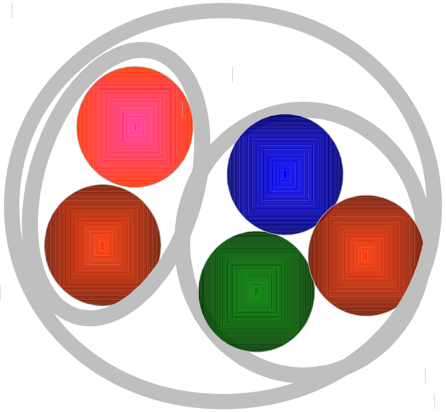
Introduction (1)

- ☑ **Standard Model: Baryons – 3 quarks and Mesons – pair of quark-antiquark**
- ☑ **1977: within Quark Bag Model, Jaffe predicted H-dibaryon made of six quarks (uuddss)** **(Phys. Rev. Lett. 38,195 (1977); 38, 617(E)(1977))**
- ☑ **Exotic hadrons – long standing challenge in hadron physics**

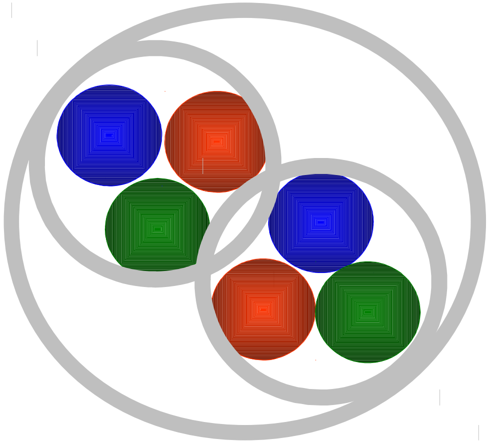
Tetraquark
Meson-Meson molecule



Pentaquark
Meson-Baryon molecule



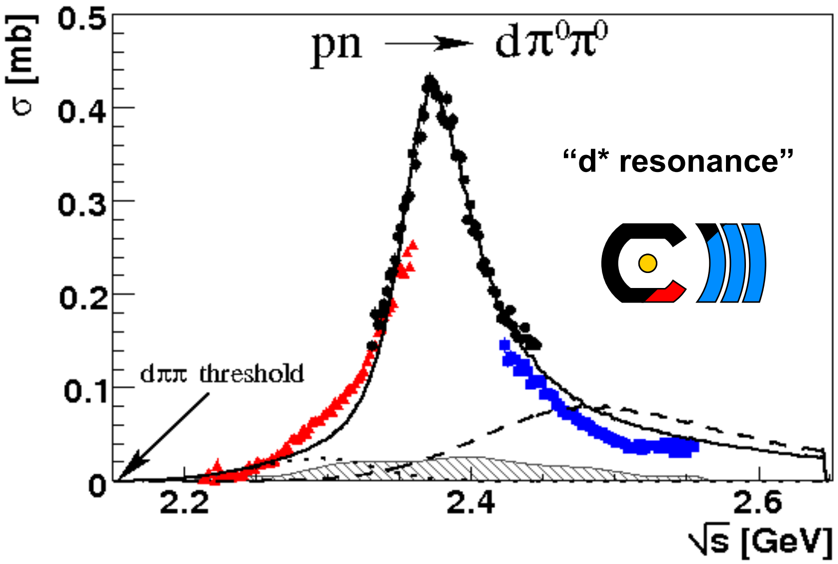
Hexaquark
Baryon-Baryon molecule



Introduction (2)

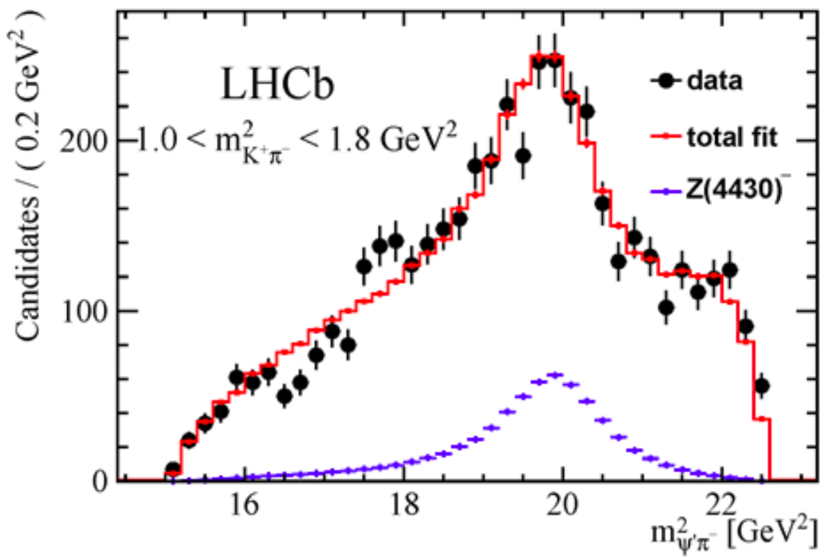
☑ **Observation of exotic states @ WASA-at-COSY, Belle, LHCb**

Phys. Rev. Lett. 106, 242302 (2011)

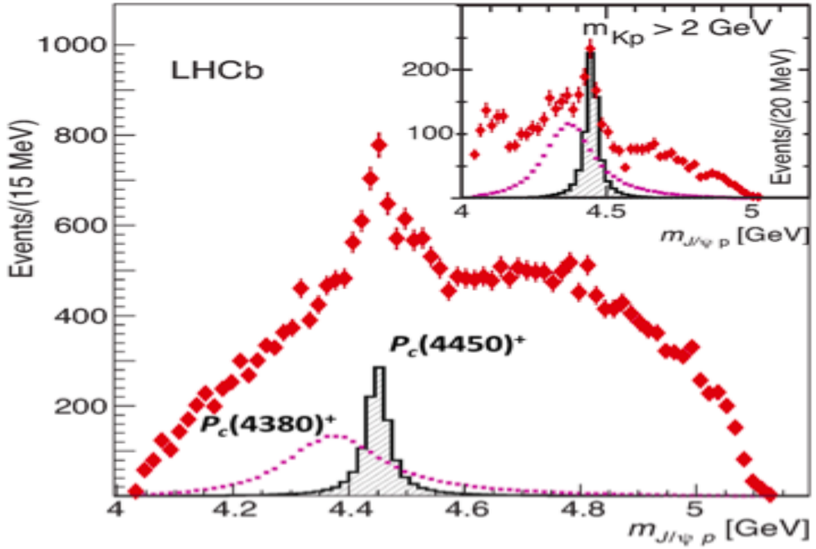


"d* resonance"

Phys. Rev. Lett. 115, 072001 (2015)



Phys. Rev. Lett. 112, 222002 (2014)



☑ Multi-quark states or molecular states?

Exotics in Strangeness Sector

Quark content, decay modes and mass of exotic states in strangeness sector:

Particle	Mass (MeV)	Quark composition	Decay mode
f_0	980	$q\bar{q}s\bar{s}$	$\pi\pi$
a_0	980	$q\bar{q}s\bar{s}$	$\pi\eta$
K(1460)	1460	$q\bar{q}q\bar{s}$	$\mathrm{K}\pi\pi$
$\Lambda(1405)$	1405	$\mathrm{qqqs}\bar{q}$	$\pi\Sigma$
$\Theta^+(1530)$	1530	$\mathrm{qqqq}\bar{s}$	KN
H	2245	uuddss	$\Lambda\Lambda$
$\mathrm{N}\Omega$	2573	qqqsss	$\Lambda\Xi$
$\Xi\Xi$	2627	qqssss	$\Lambda\Xi$
$\Omega\Omega$	3228	ssssss	$\Lambda\mathrm{K}^-+\Lambda\mathrm{K}^-$

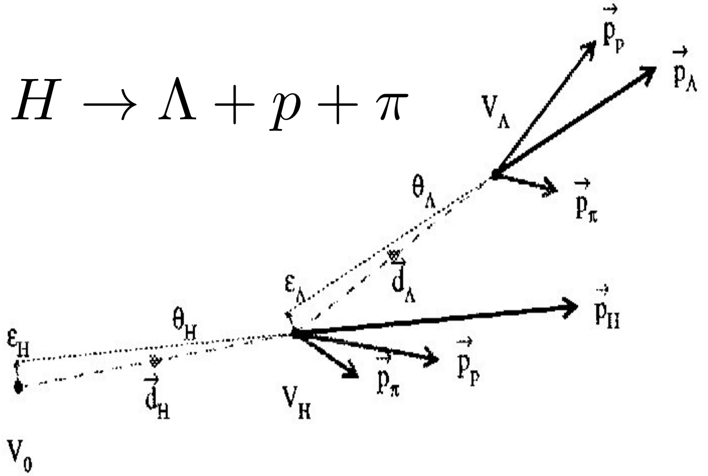
Phys. Rev. C 84, 064910 (2011), Phys. Rev. C 83, 015202 (2011)

☑ Recent results on H-dibaryon search:

- STAR Col., Phys. Rev. Lett. 114 (2015) 022301
- ALICE Col., Phys. Lett. B 752 (2016) 267

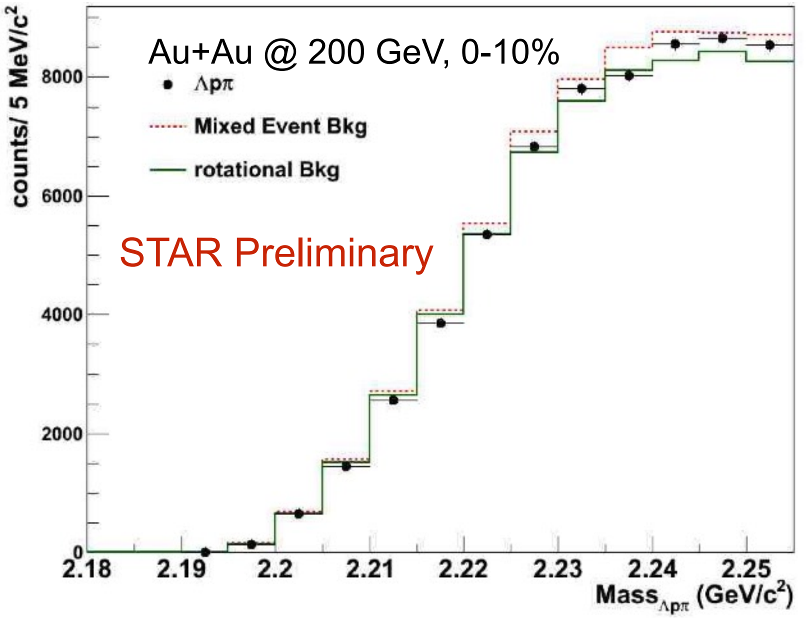
H-dibaryon Invariant Mass Distributions

☑ Topological reconstruction of $\Lambda p\pi$ to look of H
  - $2.2 < m_H < 2.231$ GeV/c^2
  - No visible signal in the data

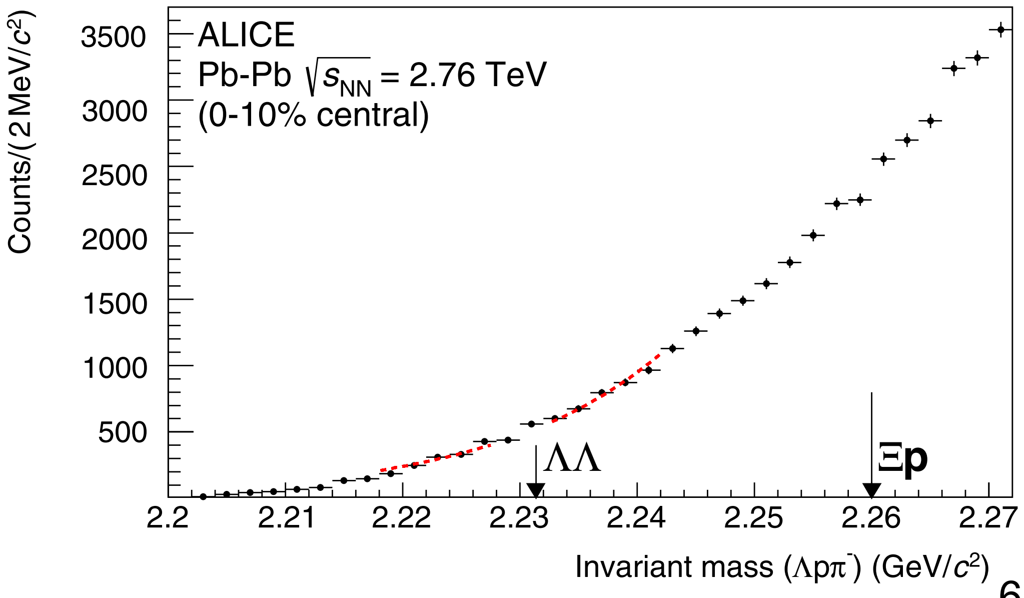


$$H \rightarrow \Lambda + p + \pi$$

N. Shah for STAR Col. Nucl. Phys. A 914 (2013) 410



ALICE Col. Phys. Lett. B 752 (2016) 267



NΩ Dibaryon Predictions

- **Nucleon-Ω(NΩ): a strangeness = -3 dibaron is stable against strong decay, from MIT bag and potential model calculation, E_B = 140-250 MeV**

"…there is no color-magnetic effect and the energies are dominated by modification to the single-quark wave function" Phys. Rev. Lett. 59 (1987) 627, Phys. Rev. C 69 (2004) 65207; 70 (2004) 35204

- **Lattice QCD calculation: E_B = 18.9 MeV, Nambu-Bethe-Salpeter wave function** Nucl. Phys. A 928 (2014) 89

- **Scattering length, effective range and binding energy of NΩ-dibaryon:**

	Scattering length (a_0) fm	Effective range (r_{eff}) fm	BE (sc) MeV	BE (cc) MeV
SU(2)	1.87	0.87	23.2	19.6
SU(3)	-4.23	2.1	ub	ub
QDCSM	2.58	0.9	8.1	7.3
HALQCD	$-1.28+0.13^{0.14}_{-0.15}$	$0.499+0.026^{0.029}_{-0.048}$	$18.9+5.0^{12.1}_{-1.8}$	

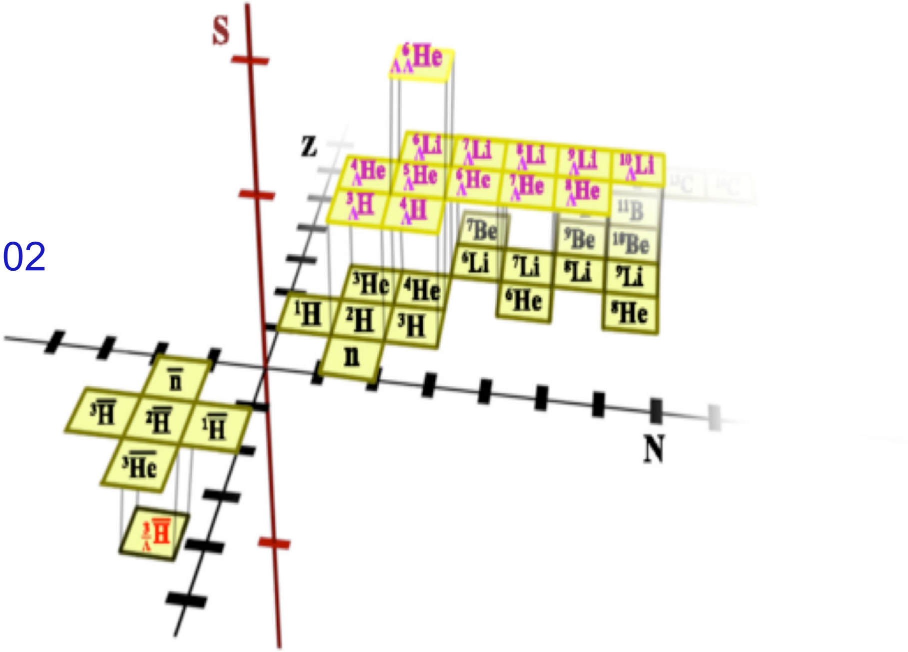
Phys. Rev. C 83 (2011) 015202, Nucl. Phys. A 928 (2014) 89

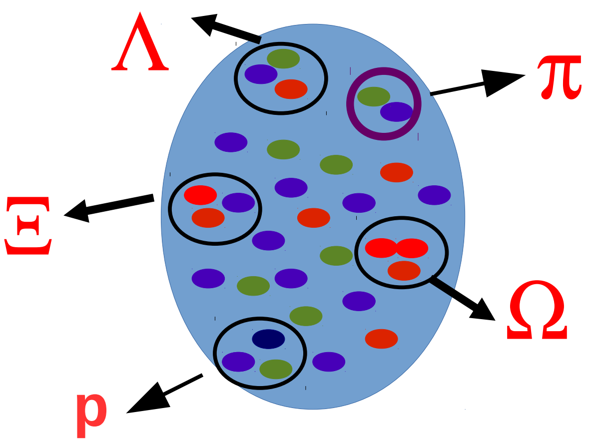
Venues for Dibaryon Search

☑ Systematic study of double strangeness systems

- The double hypernucleus, experiments at KEK,J-PARC

Phys. Rev. Lett. 87, 212502 (2001)
Prog. Theor. Exp. Phys. 2015, 033D02





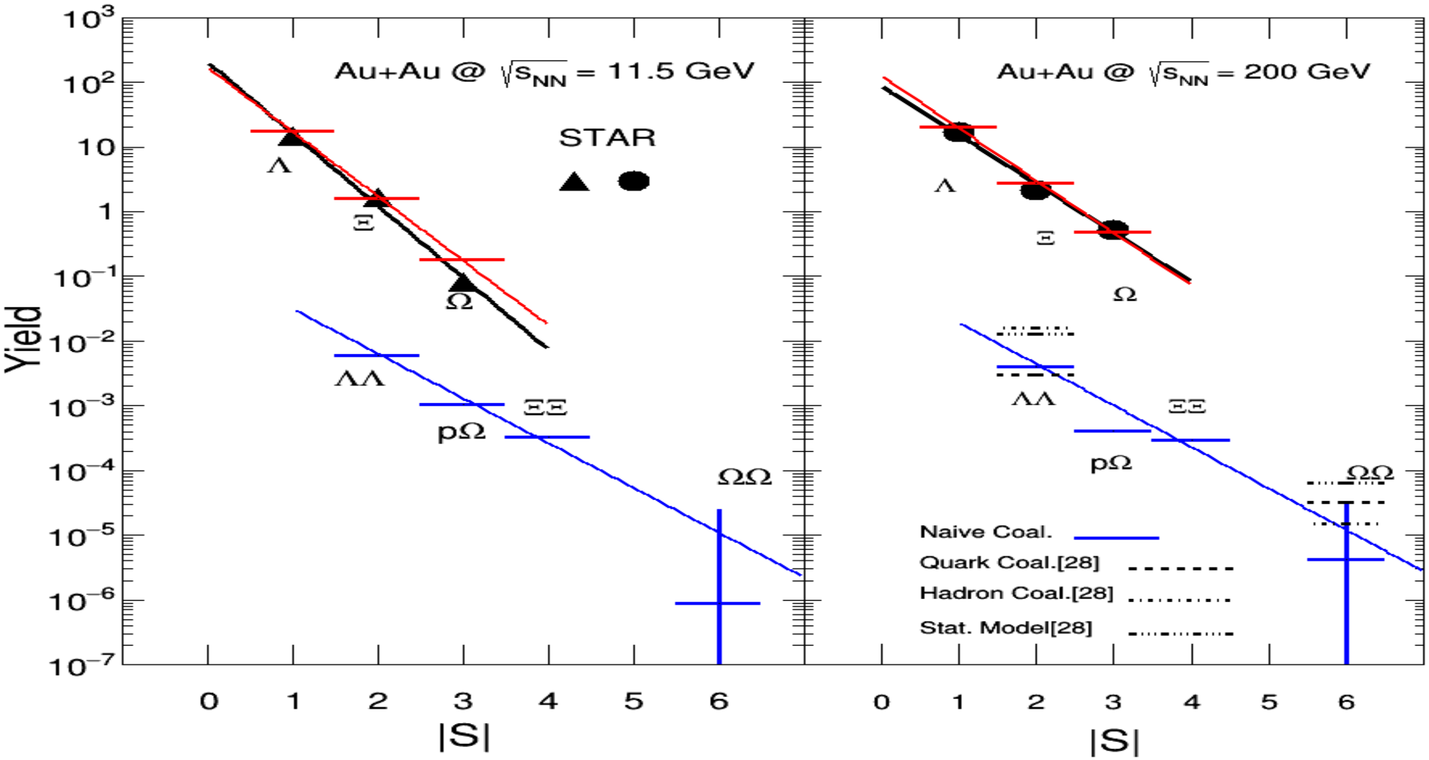
☑ Heavy Ion Collisions

- Hot and dense, strongly interacting partonic matter
- Environment suitable for production of exotic hadron
- We use $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions measured by STAR for this search

NΩ-dibaryon from Heavy-Ion Collisions

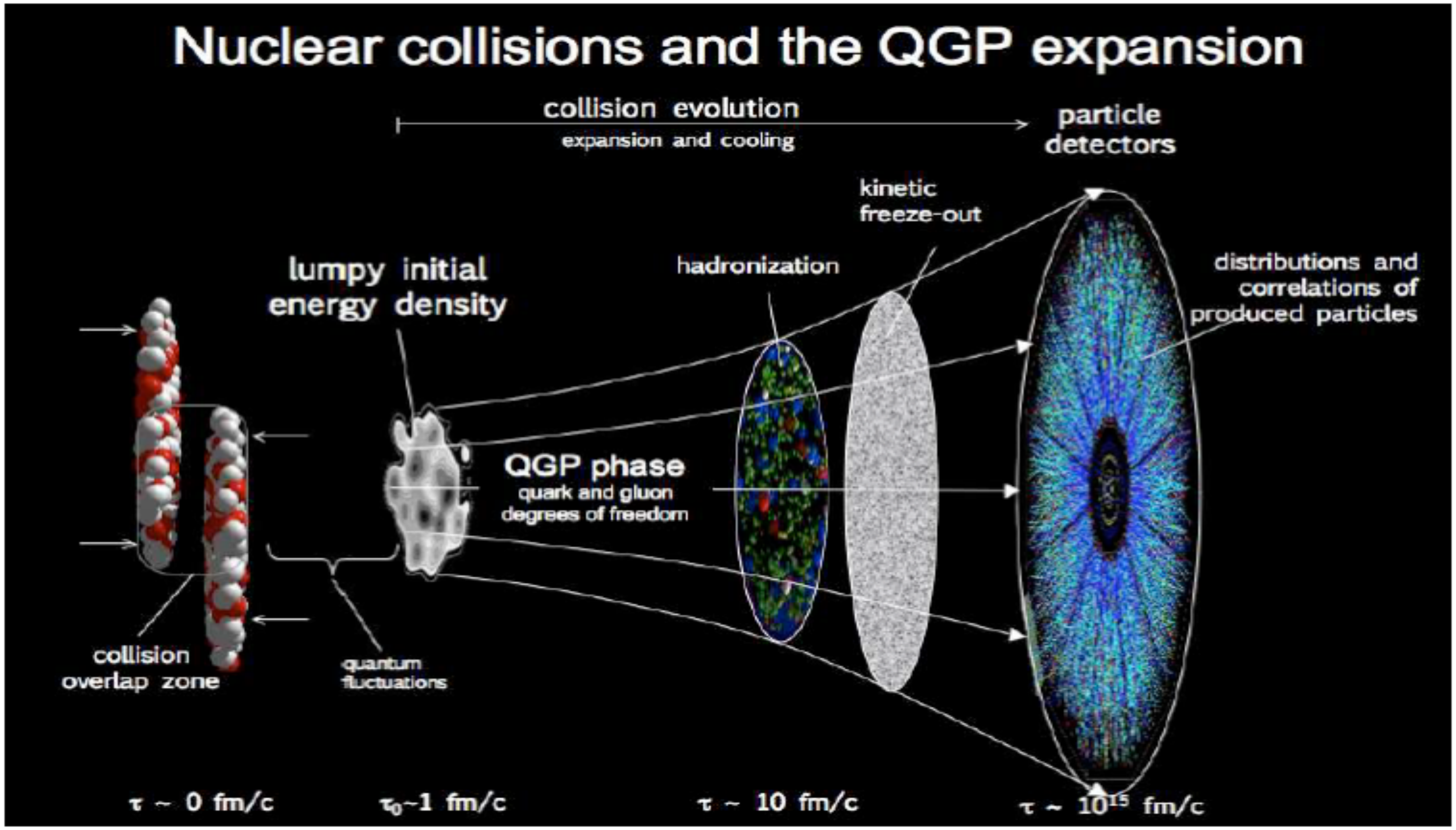
- ☑ NΩ-dibaryon is an isospin 1/2 doublet and has both pΩ and nΩ channels possible

Phys. Lett. B 754 (2016) 6



- ☑ In experiments, we can look at pΩ channel with two particle correlation analysis or invariant mass analysis (the J=2, S=-3 state weak decay is challenging)
  - – Invariant mass
    - Significant combinatorial background

Two Particle Correlation in HIC



☑ Baryon interaction via two particle momentum correlation

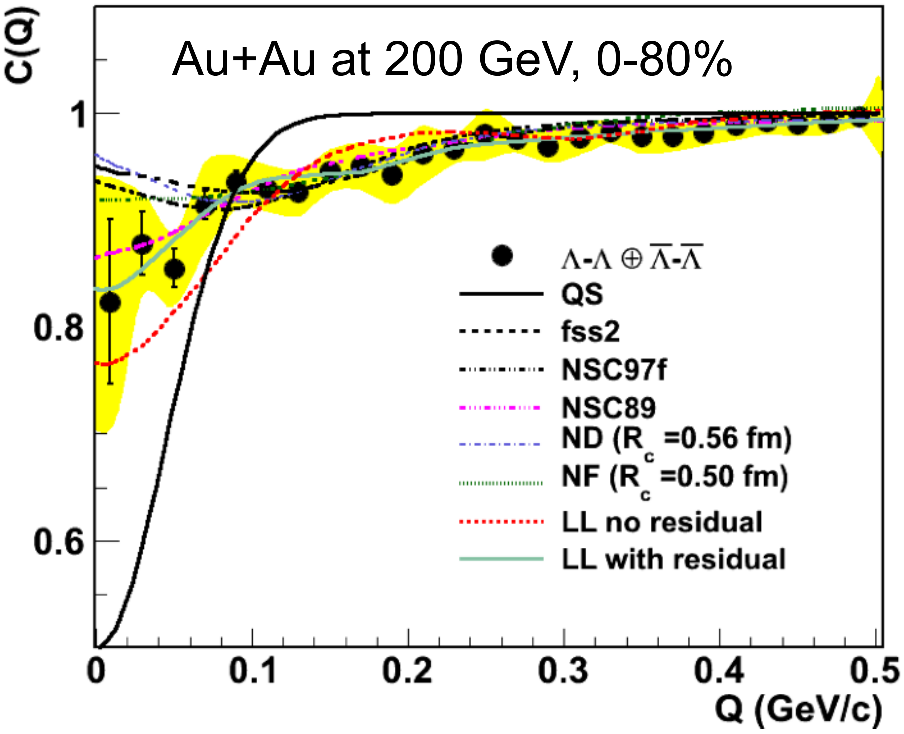
$$C(\boldsymbol{q}, \boldsymbol{P}) = \frac{E_1 E_2 dN_{12}/d\boldsymbol{p}_1 d\boldsymbol{p}_2}{(E_1 dN_1/d\boldsymbol{p}_1)(E_2 dN_2/d\boldsymbol{p}_2)} \,,$$

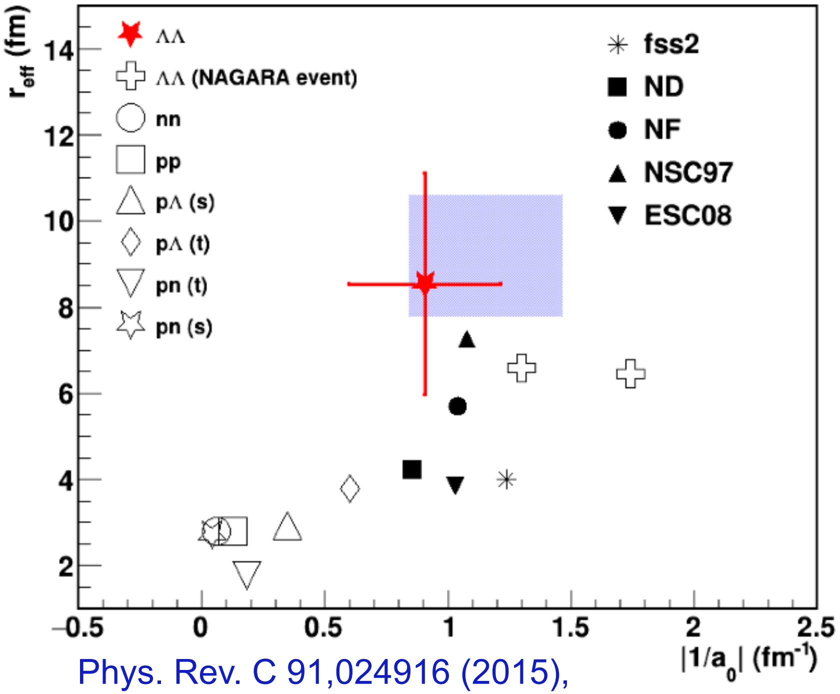
$$P \equiv p_1 + p_2 \,, \qquad q^\mu \equiv \frac{1}{2}\left[(p_1 - p_2)^\mu - \frac{(p_1 - p_2)\cdot P}{P^2} P^\mu\right] = \frac{E_2' p_1^\mu - E_1' p_2^\mu}{M_{\mathrm{inv}}} \,,$$

Lambda-Lambda Correlation Function

STAR Col. Phys. Rev. Lett. **114**, 022301 (2015)

$$|a_{\Lambda\Lambda}| < |a_{p\Lambda}| < |a_{NN}|$$



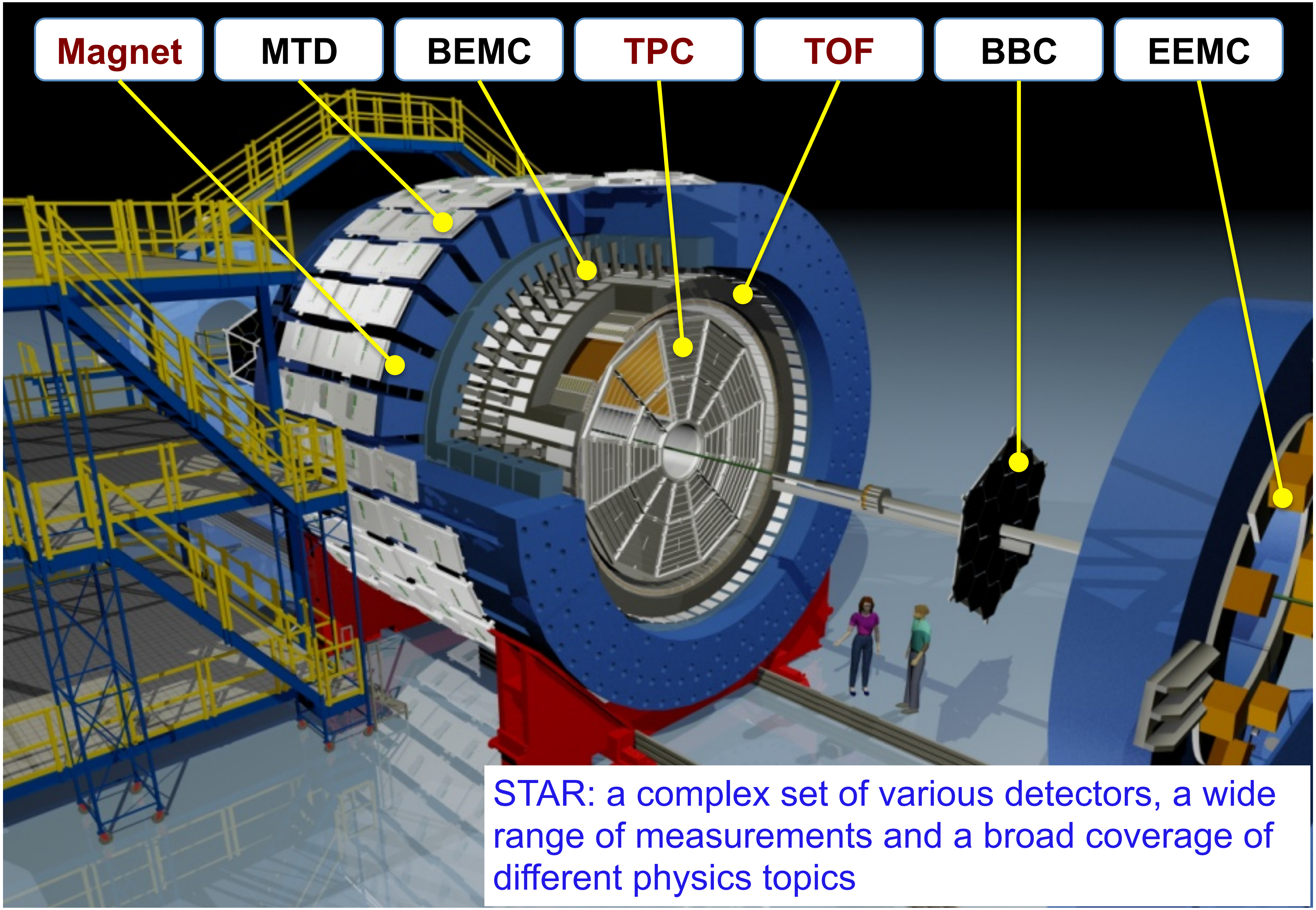


Phys. Rev. C 91,024916 (2015),
Prog. Part. Nucl. Phys. 95 (2017) 279

☑ All model fits to data suggest that a rather weak interaction is present between ΛΛ pairs

t → for triplet state
s → for singlet state
n-n → Phys. Lett. B, 80 (1979) 187
p-n → Phys. Rev. C 66, 047001 (2002)
p-p → Mod. Phys. 39 (1967) 584
p-Λ → Phys. Rev. Lett. 83, 3138 (1999)
ΛΛ → Phys. Rev. C 66, 024007(2002)
ΛΛ → Nucl. Phys. A 707 (2002) 491

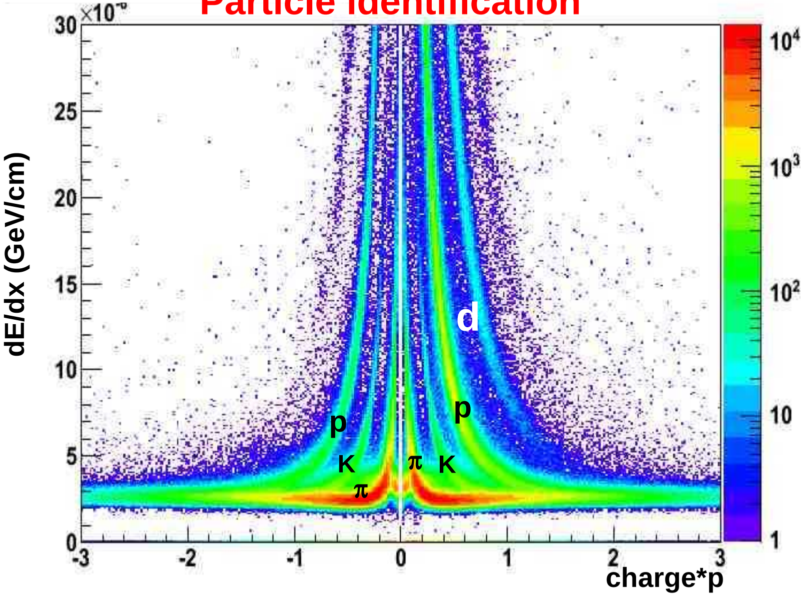
The STAR Detector at RHIC



STAR: a complex set of various detectors, a wide range of measurements and a broad coverage of different physics topics

Ω Reconstruction (1)

Particle identification



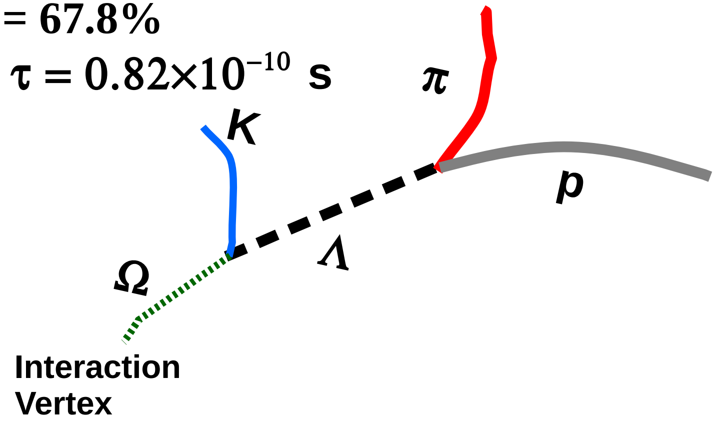
Au+Au $\sqrt{s}$ = 200 GeV (1.41 B events)

$\Omega \to \Lambda K$ (Mass = 1.672 GeV/c^2)

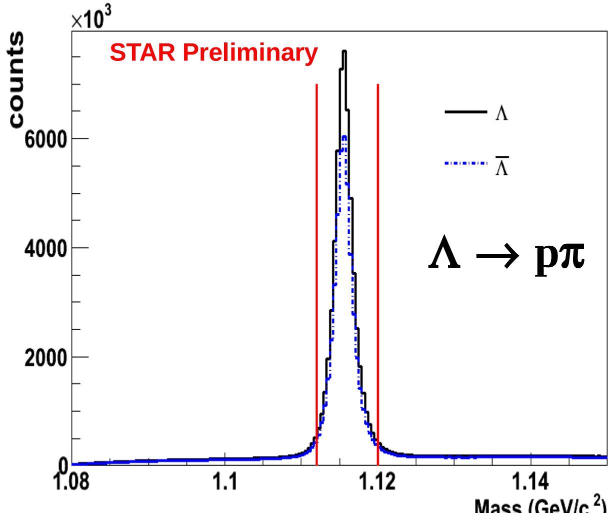
Branching ratio = 67.8%

Mean Life time: $\tau = 0.82\times10^{-10}$ s

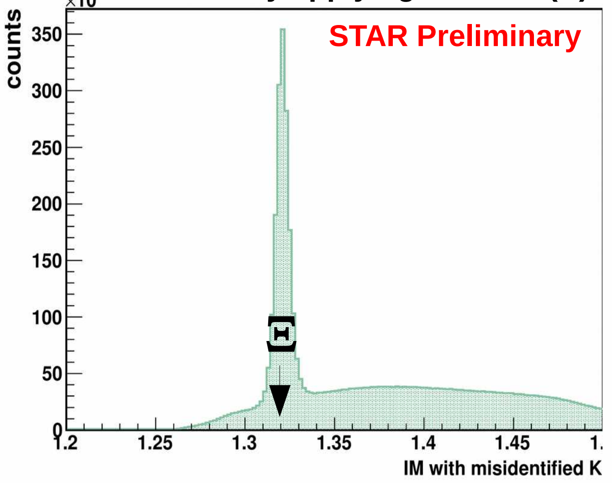
$c\tau$ = 2.46 cm



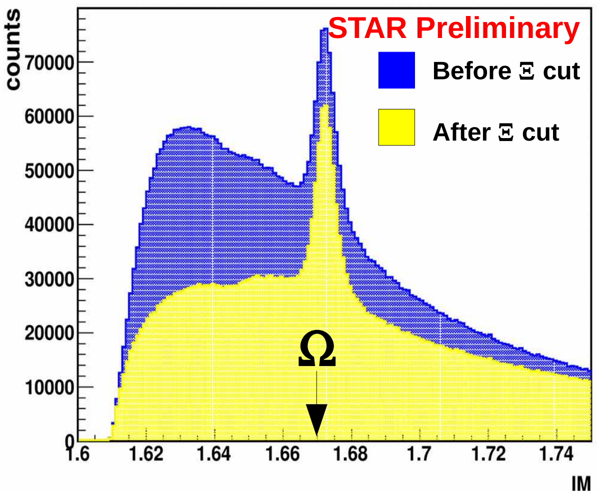
Reconstructed Λ



Background due to misidentified K removed by applying cut on M(Ξ)

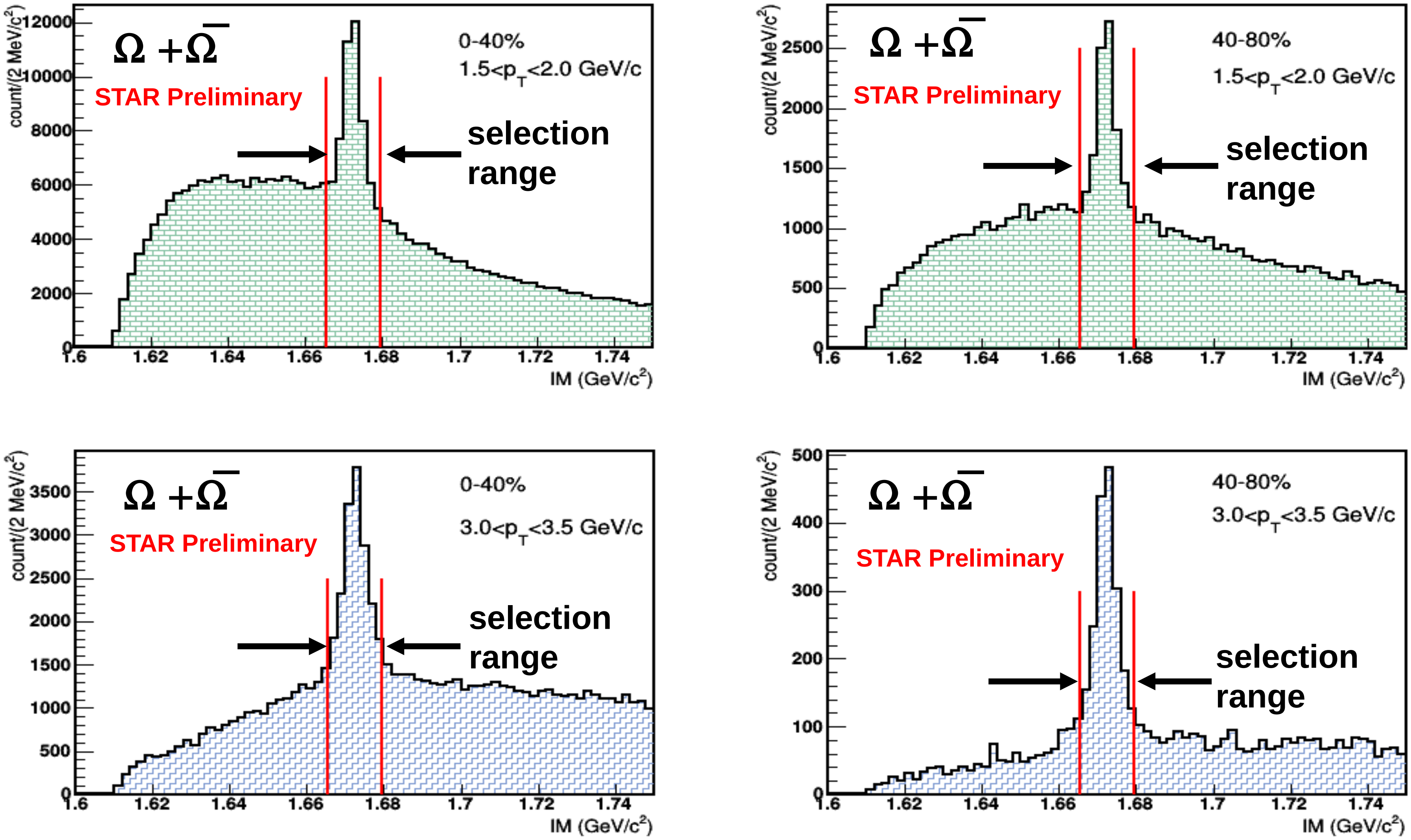


Reconstructed Ω



Ω Reconstruction (2)

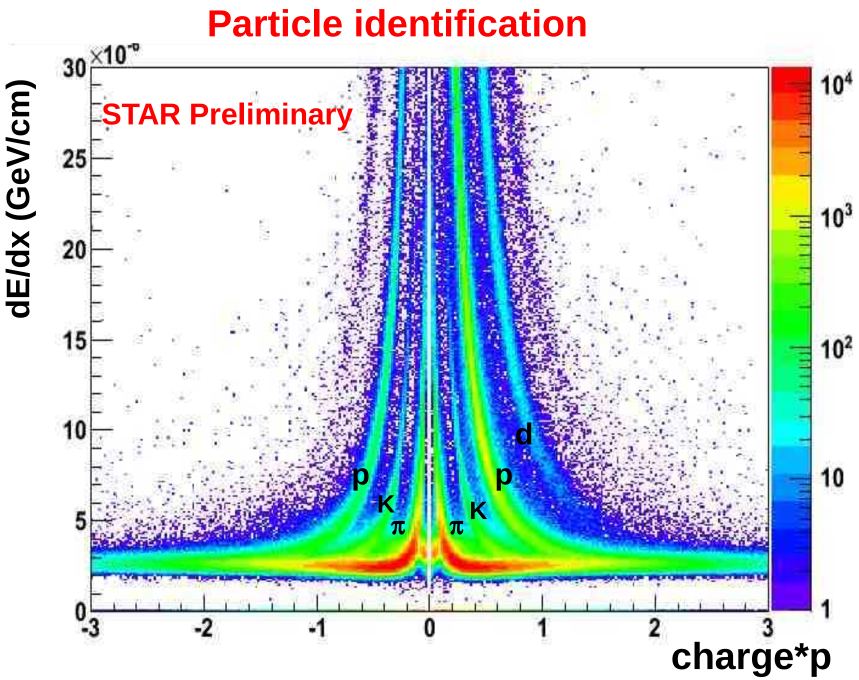
Reconstructed invariant mass of $\Omega+\bar{\Omega}$

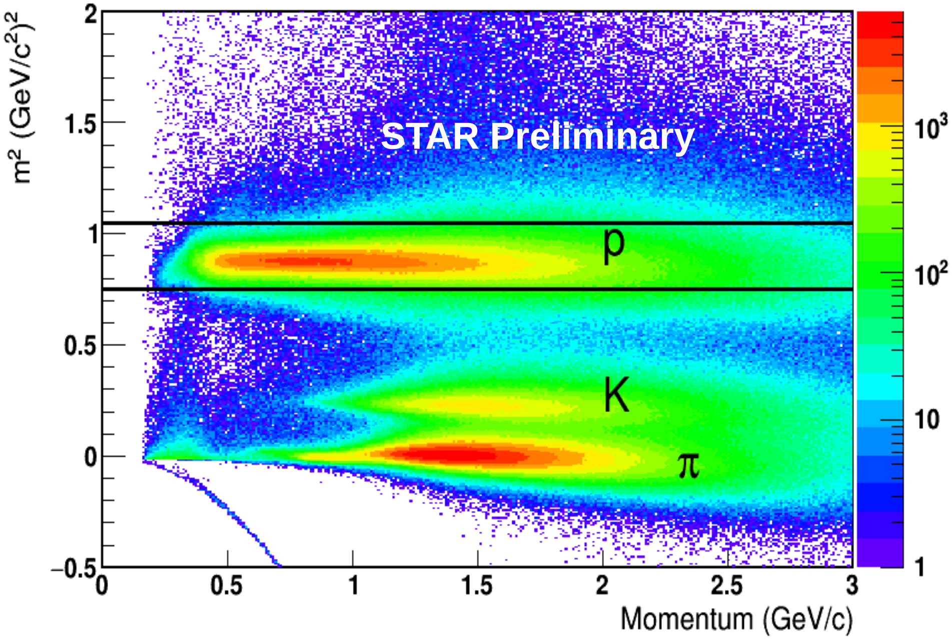


Proton Identification with TPC+TOF

Excellent PID with TPC+TOF

- ✔ Number of fit points > 15
- ✔ Ratio of fit points to possible points > 0.52
- ✔ p_T cut for proton tracks > 0.15 GeV/c
- DCA < 0.5 cm
- $0.75 < m^2 < 1.1\ (\mathrm{GeV}/c^2)^2$





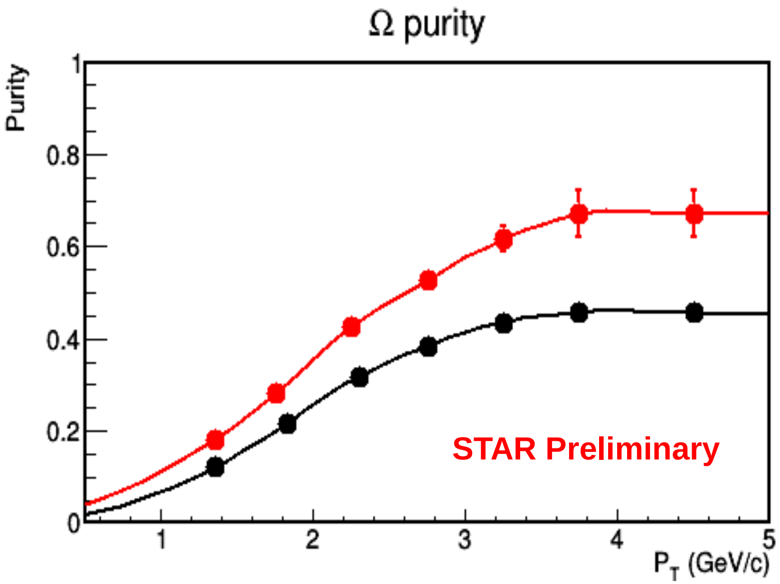
With proton and anti-proton S/(S+B) ~ 99%

Few Definitions and Corrections

Step-I Raw correlations

$$C(k^*) = \frac{P(p_a, p_b)}{P(p_a)P(p_b)} = \frac{real\ pairs}{mixed\ pairs}$$

p - momentum of particles a and b
k* - relative momentum



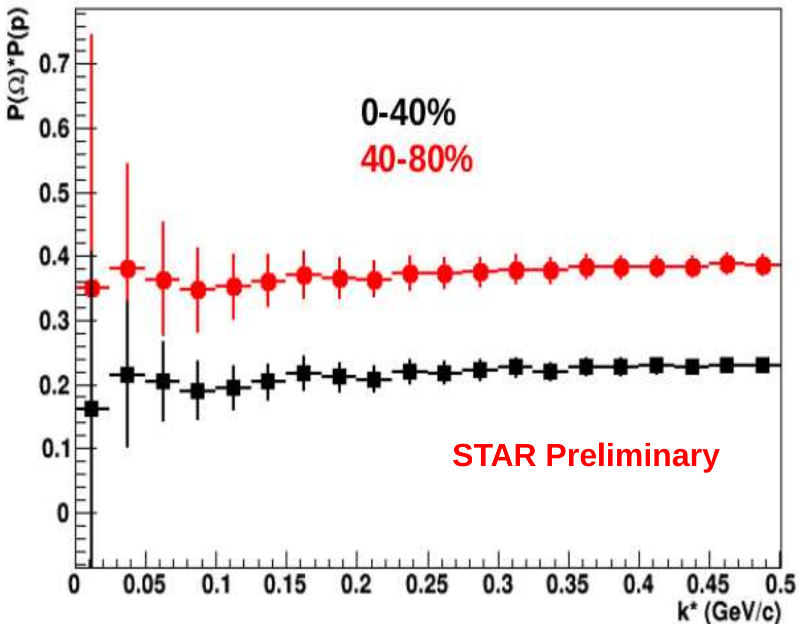
Step-II Purity correction

$$CF_{corrected}(k^*) = \frac{CF_{measured}(k^*) - 1}{PP(k^*)} + 1$$

PP(k*) = P(Ω)×P(p) is pair purity.

P(Ω) = S/(S+B)*Fr(Ω) and P(p) = S/(S+B)*Fr(p)
where Fr(x) is Fraction of primary particles

Fr(Ω) = 1 and Fr(p) = 0.52

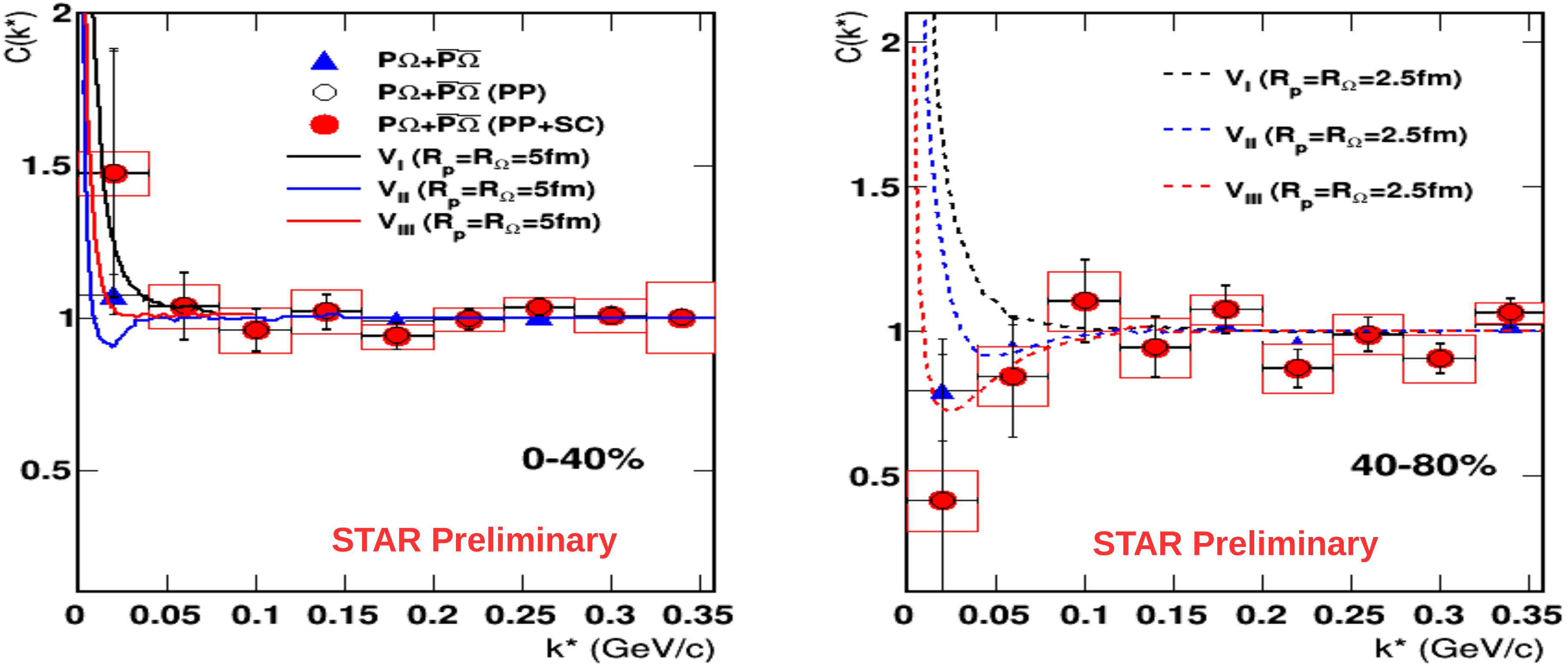


Step-III Momentum smearing

$$CF(k^*) = CF(k^*)\frac{CF_{nosmearing}}{CF_{smearing}}$$

Smearing correction factor is 0.99

PΩ Correlation Function



PP → Pair Purity Correction
PP+SC → Pair Purity + Mom. Smearing Correction
R → Emission source size
Boxes → systematic uncertainty

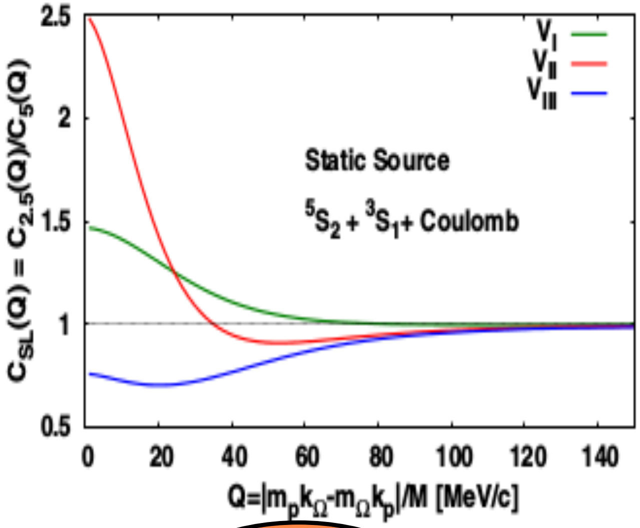
Comparison of measured PΩ correlation function from 0-40 and 40-80% centrality with the predictions for PΩ interaction potentials V_I, V_{II} and V_{III}.

Spin-2 pΩ potentials	V_I	V_{II}	V_{III}
Binding energy E_B (MeV)	-	6.3	26.9
Scattering length a_0 (fm)	-1.12	5.79	1.29
Effective range r_{eff} (fm)	1.16	0.96	0.65

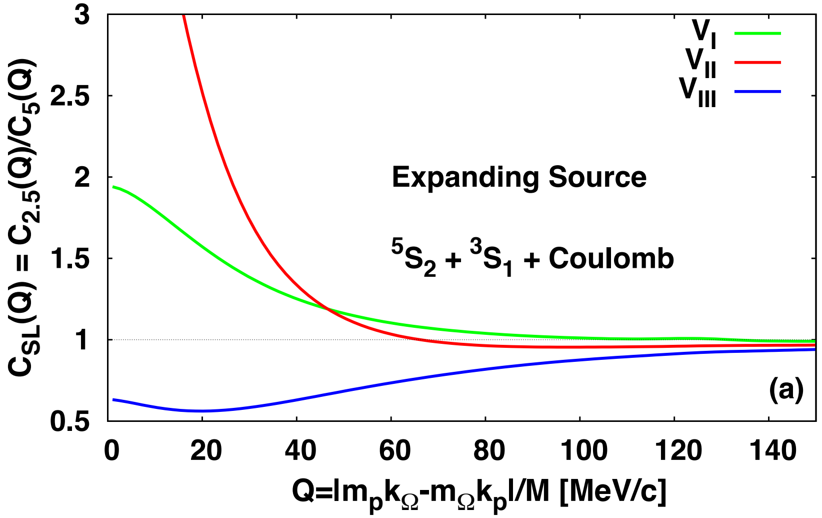
Phys. Rev. C 94, 031901 (2016)

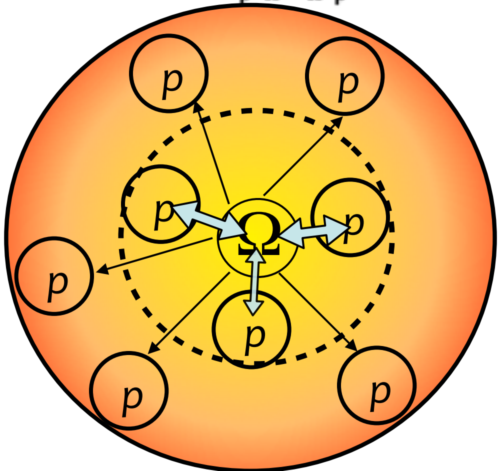
Proposal on Source Size Dependence Analysis

☑ The ratio of the correlation function between the small and large collision system is insensitive to the Coulomb interaction and also to the source model of the emission, thus it provides a useful measure to extract the strong interaction part of the pΩ attraction from experiments at RHIC/LHC



Phys. Rev. C 94, 031901 (2016)





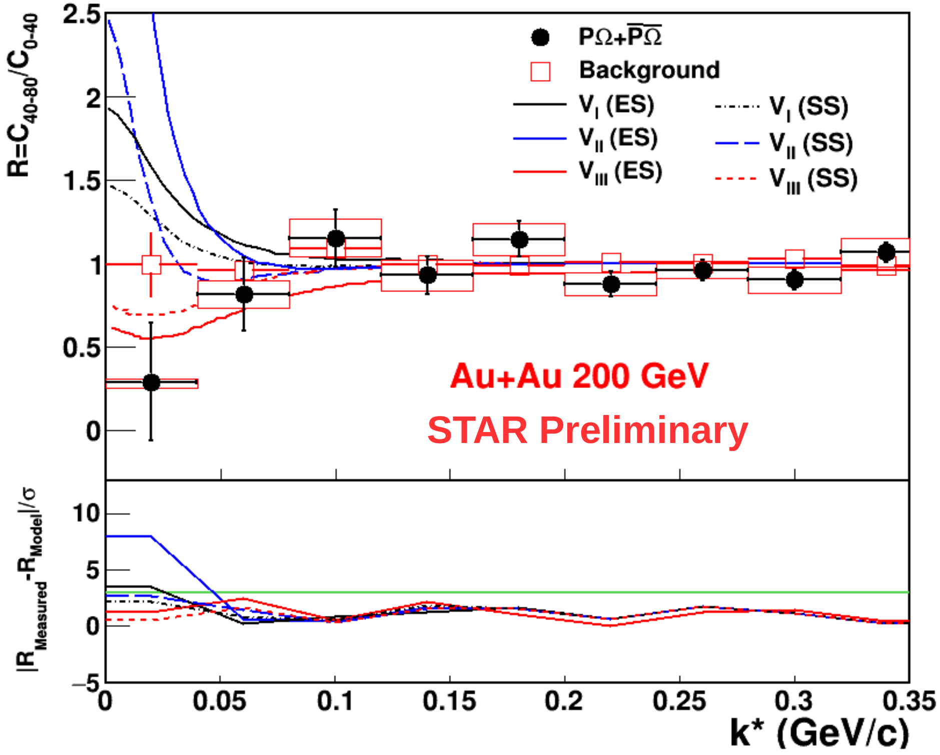
Ratio of C(Q): small/large system:

- Loose : Enhancement at low Q
- Tight : C(Q) < 1
- No Bound: Slightly above 1

Source Size Analysis on PΩ Correlation Function

The ratio of correlation function between small and large collision systems for the background is unity within uncertainties.

The ratio of correlation function between small and large collision systems at low k* is lower than background.



SS → Static source
ES → Expanding source
Background → Ω sideband is used
Boxes → systematic uncertainty

Spin-2 pΩ potentials	V_I	V_{II}	V_{III}
Binding energy E_B (MeV)	-	6.3	26.9
Scattering length a_0 (fm)	-1.12	5.79	1.29
Effective range r_{eff} (fm)	1.16	0.96	0.65

Phys. Rev. C 94, 031901 (2016)

Summary

☑ Present the measurement of correlation function for PΩ from Au+Au collisions @ 200 GeV

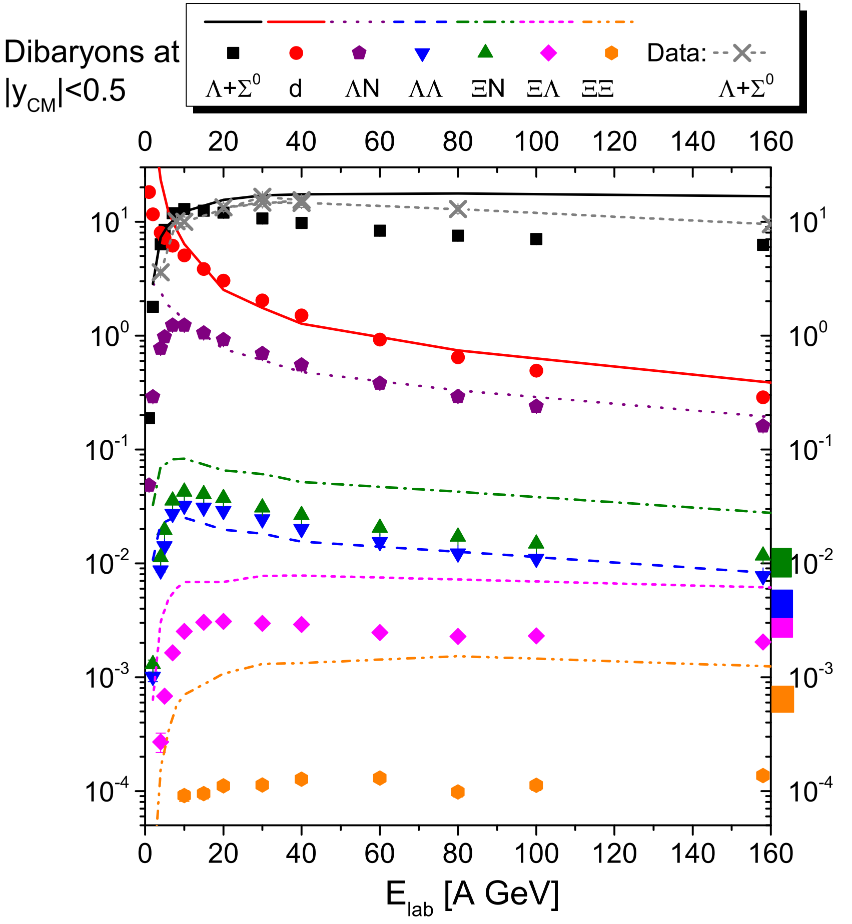
☑ The ratio of correlation function for the small (peripheral collisions) to the large (central collisions) system is smaller than unity at low k* with large uncertainties

☑ The measured ratio of correlation function from peripheral to central collisions is compared with predictions based on the PΩ interaction potentials derived from lattice QCD simulations

Beam Energy Scan Phase II

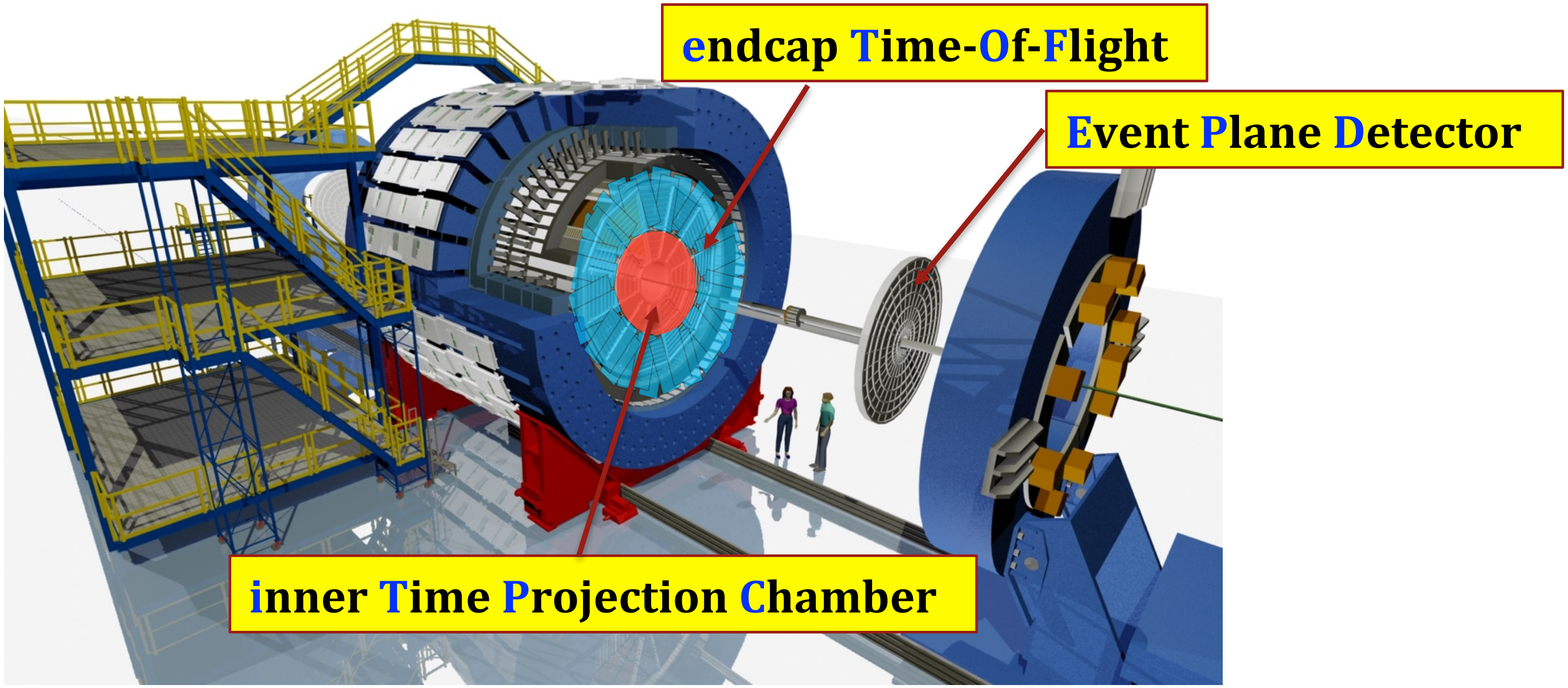
- ☑ STAR BES-II at 2019 and 2020
  - – detector upgrades
  - – low energy electron cooling
  - – rich hyperon production

Collision Energies	Proposed Event	BES-I Event
7.7	100	4
9.1	160	N/A
11.5	230	12
14.5	300	20
19.6	400	36



Phys. Lett. B 714 (2012) 85

STAR Major Upgrades before 2020



iTPC upgrade	**EPD upgrade**	**eTOF upgrade**
Continuous pad rows Replace all inner TPC sectors	**Replace Beam Beam Counter**	**Add CBM TOF modules and electronics (FAIR Phase 0)**
$\|\eta\|<1.5$	**$2.1<\|\eta\|<5.1$**	**$-1.6<\eta<-1.1$**
p_T >60 MeV/c	Better trigger & b/g reduction	Extend forward PID capability
Better dE/dx resolution Better momentum resolution	Greatly improved Event Plane info (esp. 1st-order EP)	Allows higher energy range of Fixed Target program
Fully operational in 2019	**Fully operational in 2018**	**Fully operational in 2019**

Thank you for your attention!

Proposal on source size dependence analysis

The ratio of correlation function between small and large collision systems to extract strong p-Omega interaction w/o much contamination from Coulomb interaction.

Morita etc. arXiv:1605.06765

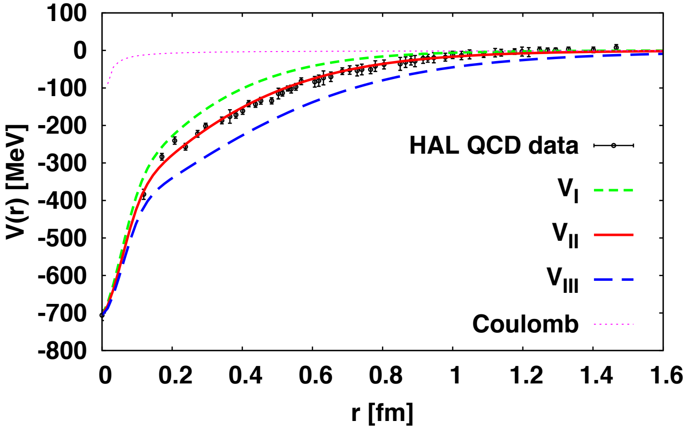


TABLE I: The binding energy (E_B), the scattering length (a_0) and the effective range ($r_{\rm eff}$) with and without the Coulomb attraction in the $p\Omega$ system. Physical masses of the proton and Ω are used.

Spin-2 $N\Omega$ Potentials		$V_{\rm I}$	$V_{\rm II}$	$V_{\rm III}$
without Coulomb	E_B [MeV]	–	0.05	24.8
	a_0 [fm]	−1.0	23.1	1.60
	$r_{\rm eff}$ [fm]	1.15	0.95	0.65
with Coulomb	E_B [MeV]	–	6.3	26.9
	a_0 [fm]	−1.12	5.79	1.29
	$r_{\rm eff}$ [fm]	1.16	0.96	0.65