Search for NΩ bound state with the STAR detector at RHIC

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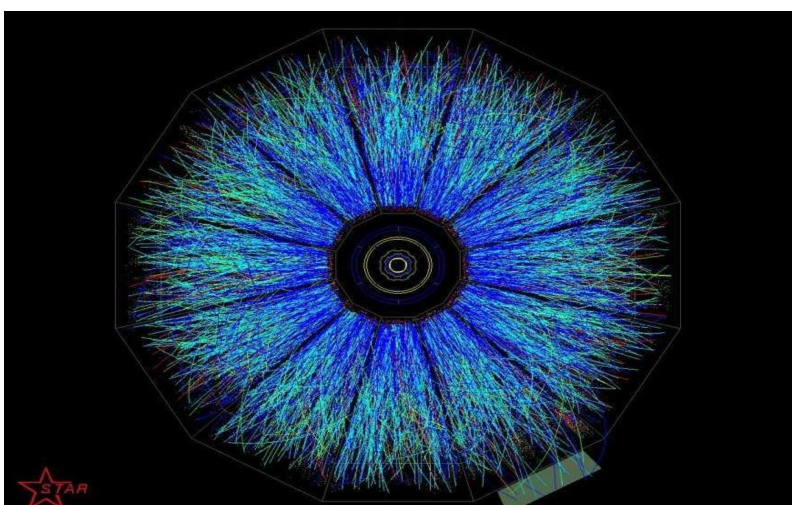


第十二届"QCD相变与相对论重离子物理"研讨会

The 12th workshop on QCD phase transitions and relativistic heavy ion collisions

西安 Xi'an, China 2017,07,21-23

Outline

- ✔ Introduction
- ✔ NΩ dibaryon
- ✔ Two-particle correlation function
  - ◆ Proton-Ω correlation function
- ✔ Summary

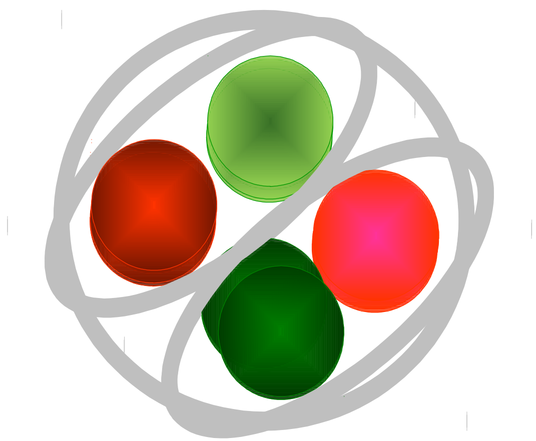
Introduction

- Standard Model: Baryons – 3 quarks and Mesons – pair of quark-antiquark

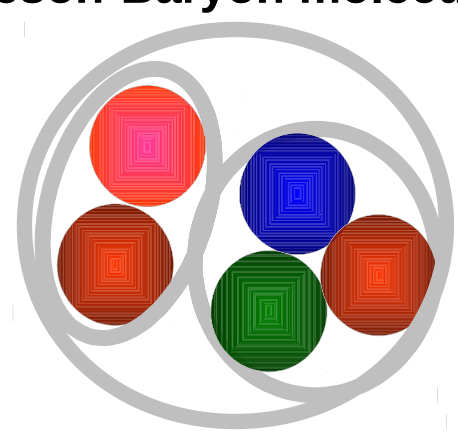
- 1977: within Quark Bag Model, Jaffe predicted H-dibaryon made of six quarks (uuddss) (R. Jaffe, Phys. Rev. Lett. 38,195 (1977); 38, 617(E)(1977))

- Exotic hadrons – long standing challenge in hadron physics

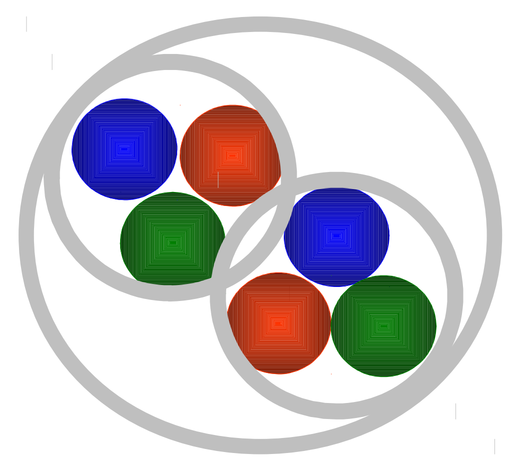
Tetraquark
Meson-Meson molecule



Pentaquark
Meson-Baryon molecule

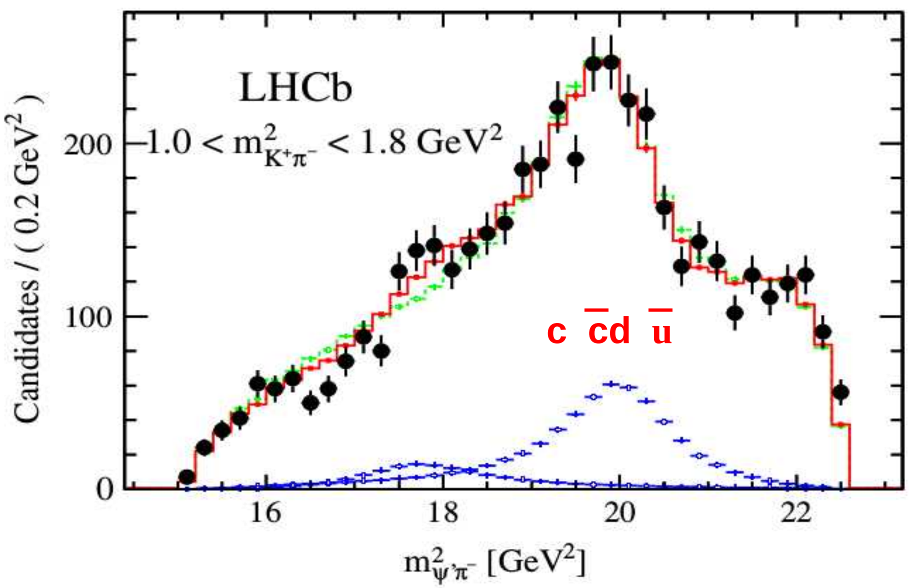


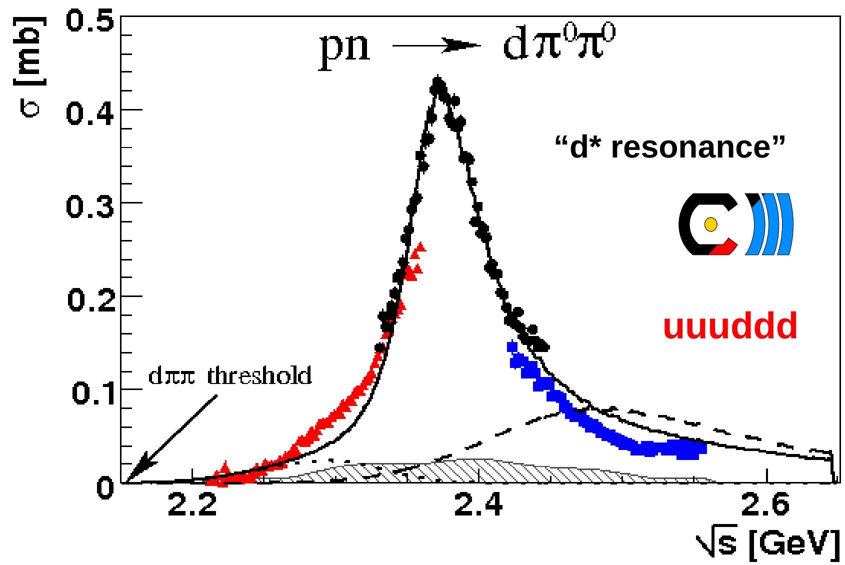
Hexaquark
Baryon-Baryon molecule

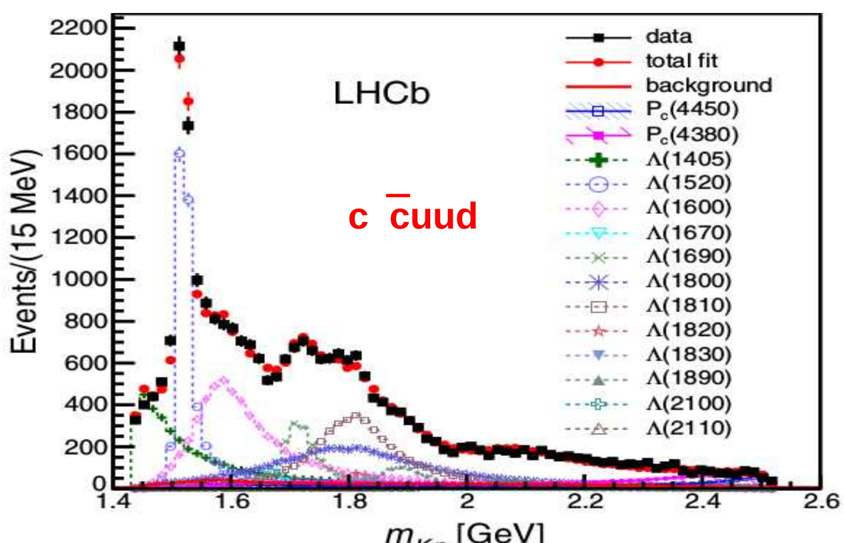


Introduction

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







Multi-quark states/molecular states?

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

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

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

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	$q\bar{q}q\bar{s}$	$K\pi\pi$
$\Lambda(1405)$	1405	$qqqs\bar{q}$	$\pi\Sigma$
$\Theta^+(1530)$	1530	$qqqq\bar{s}$	KN
H	2245	uuddss	$\Lambda\Lambda$
$N\Omega$	2573	qqqsss	$\Lambda\Xi$
$\Xi\Xi$	2627	qqssss	$\Lambda\Xi$
$\Omega\Omega$	3228	ssssss	$\Lambda K^- + \Lambda K^-$

ExHIC Collaboration, Phys. Rev. C 84 (2011) 064910, M. Chen et.al., Phys. Rev. C 83 (2011) 015202

Recent results on H-dibaryon search:

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

NΩ-dibaryon

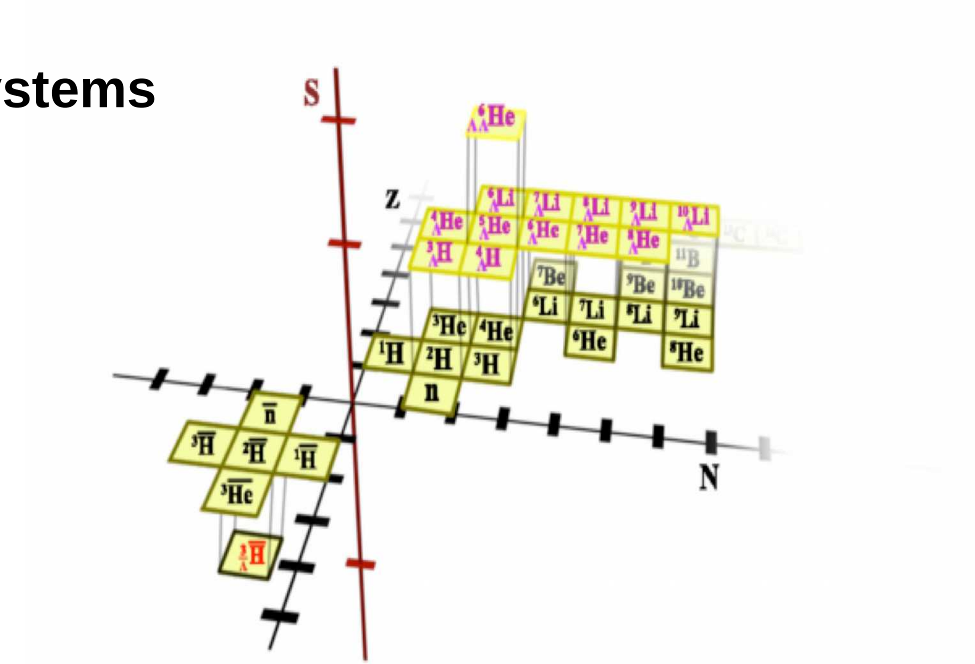
- **Nucleon-Ω (NΩ): A strangeness = -3 dibaryon is stable against strong decay**
  - **T. Goldman et al., Phys. Rev. Lett. 59 (1987) 627, H. Pang et al., Phys. Rev. C69 (2004) 065207, H. Pang et al., Phys. Rev. C70 (2004) 035204.**
- **Scattering length, effective range and binding energy (BE) of NΩ-dibaryon:**

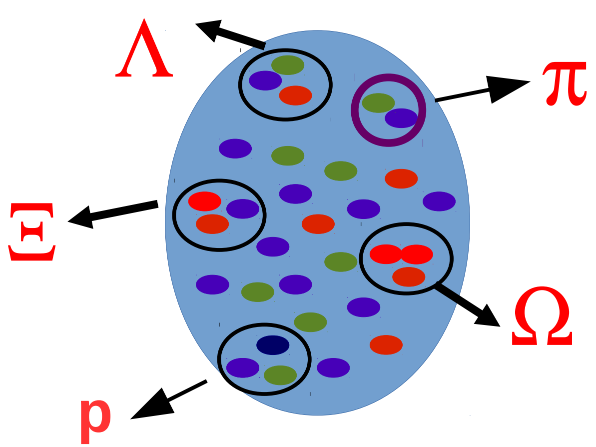
	Scattering length (a_0) fm	Effective range (r_{eff}) fm	BE (sc) MeV	BE (cc) MeV
SU(2)	1.87	0.87	23.2	19.6
SU(3)	-4.23	2.1	ub	ub
QDCSM	2.58	0.9	8.1	7.3
HALQCD	$-1.28+0.13^{0.14}_{-0.15}$	$0.499+0.026^{0.029}_{-0.048}$	$18.9+5.0^{12.1}_{-1.8}$	

M. Chen et al., Phys. Rev. C 83 (2011) 015202,
HAL QCD Collaboration, Nucl. Phys. A 928 (2014) 89

Venues for Dibaryon Search

- Systematic study of strangeness systems
  - ➢ Binding energies
    Experiments at J-PARC, KEK



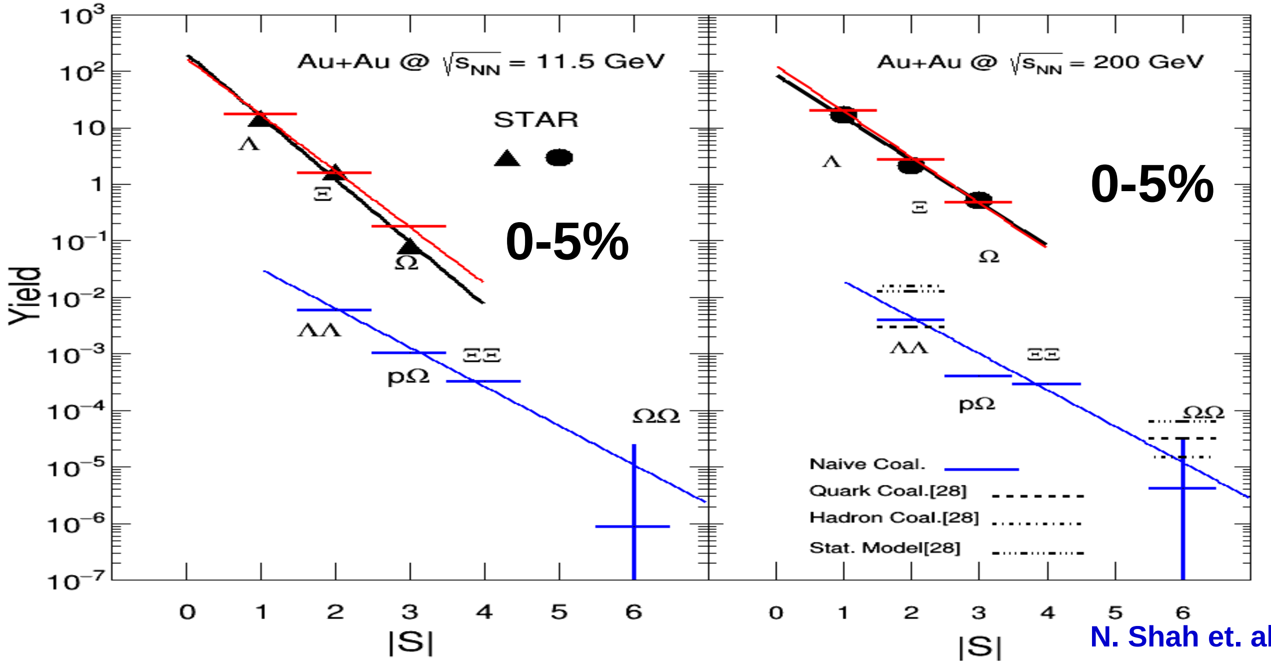


- Heavy-ion Collisions
  - ➢ Hot and dense, strongly interacting partonic matter
  - ➢ Environment is suitable for production of exotic hadrons

NΩ-dibaryon from Heavy-ion Collisions

- **Invariant mass**
  - ✔ **Significant combinatorial background in central Au+Au collisions makes exotic particle searches difficult**

- **Two-particle correlation functions**
  - ✔ **Information about Quantum Statistics (QS), Final State Interaction (FSI), exotic particles**



N. Shah et. al., Phys. Lett. B 754 (2016) 6

- **NΩ-dibaryon is an isospin 1⁄2 doublet and has both proton-Ω (PΩ) and neutron-Ω (nΩ) channels possible. Experimentally, STAR can study PΩ and nΩ channels via two-particle correlation function and invariant mass analyses, respectively.**

Two-particle Correlation Function

- Two-particle correlation function

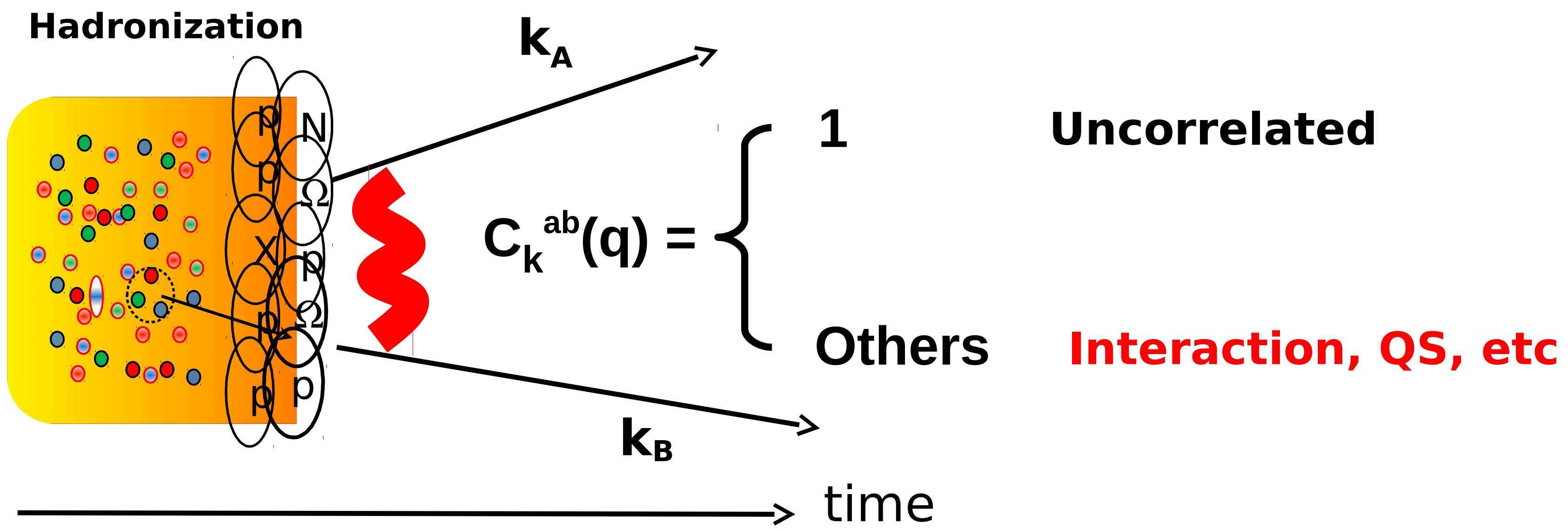
$$C^{ab}_{\vec{K}}(\vec{q}) = \frac{d^6N^{ab}/(dp_a^3 dp_b^3)}{(d^3N^a/dp_a^3)(d^3N^b/dp_b^3)} = \int d^3\vec{r'} \cdot S^{ab}_{\vec{K}}(\vec{r'}) \cdot |f(\vec{q},\vec{r'})|^2$$

$S^{ab}_{K}(r')$ – normalized separation distribution

$f(q,r')$ – two-particle wave function, $q = 2k^*$ (QS, FSI:Coulomb int., Strong interaction)

k^* is relative momentum of two particles in pair rest frame

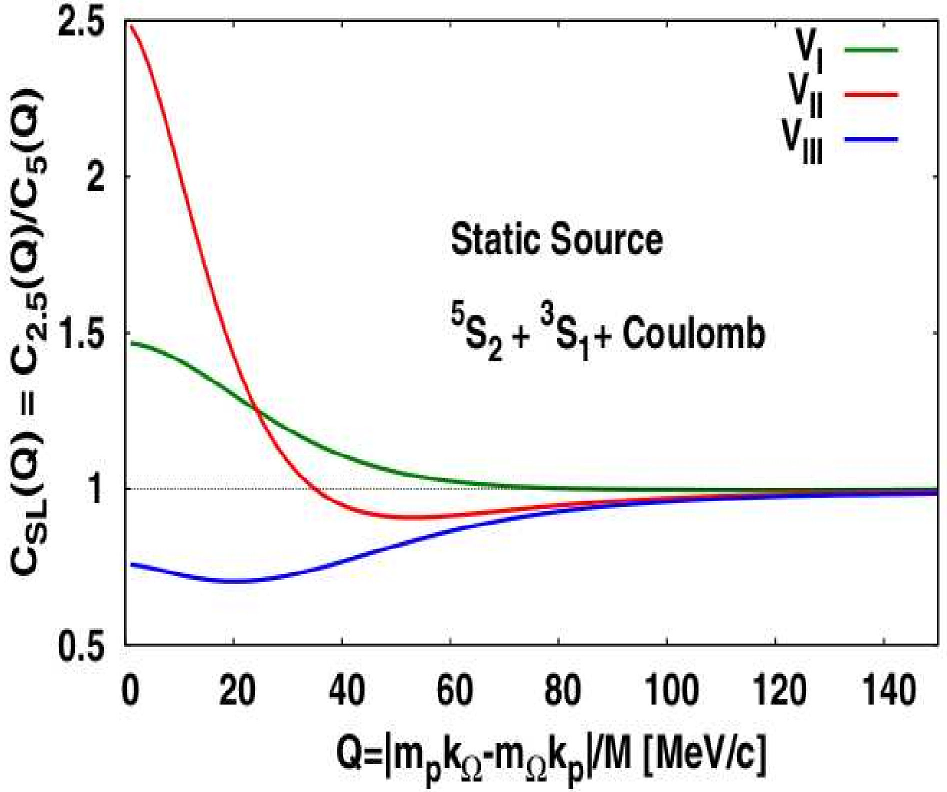
r' is the relative distance of two particles in pair rest frame.



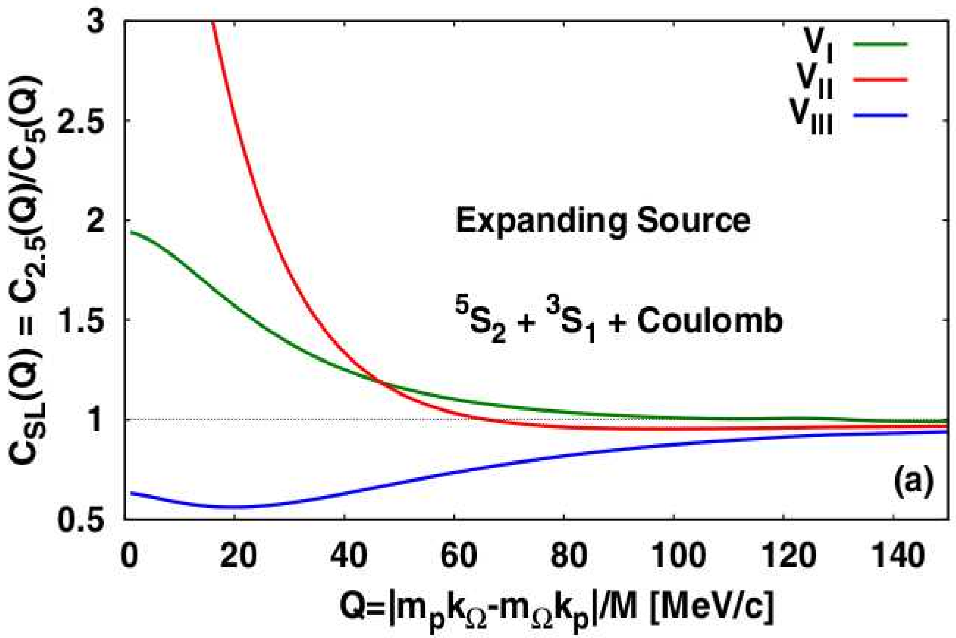
Two-particle Correlation Function

The ratio of correlation function between small and large collision systems to extract strong interactions between proton and Ω.

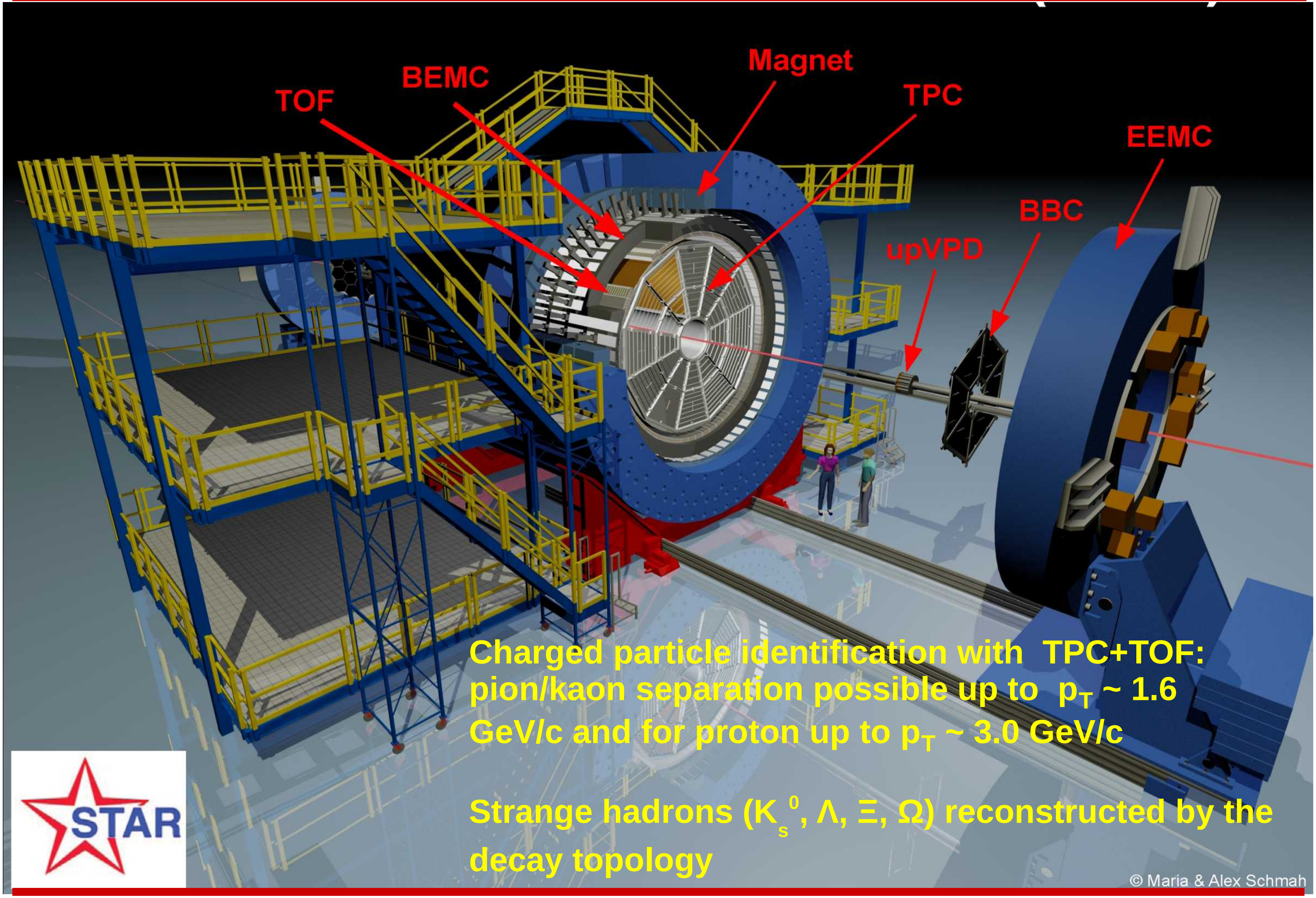
K. Morita et al., Phys. Rev. C 94, 031901 (2016)



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



Solenoid Tracker at RHIC (STAR)

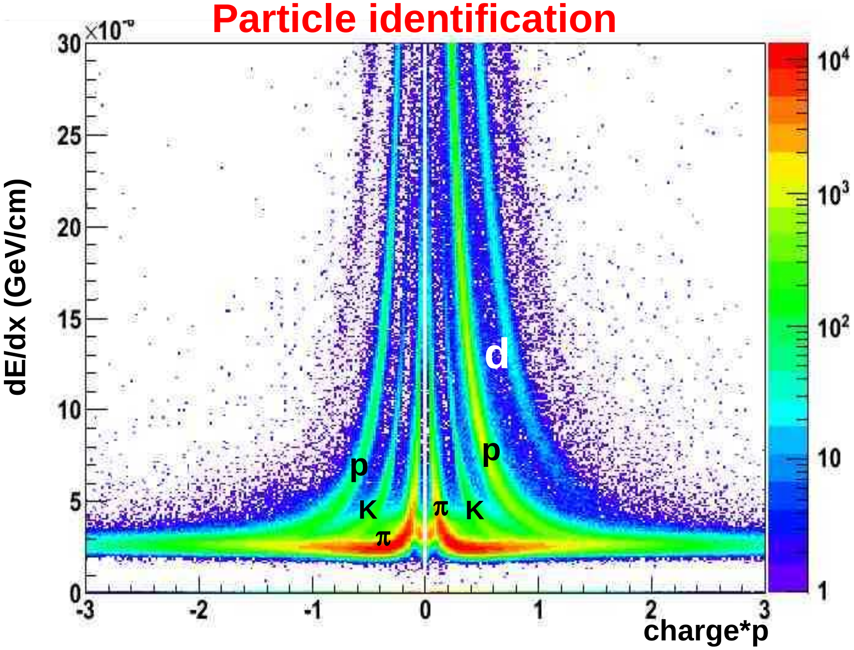


Charged particle identification with TPC+TOF: pion/kaon separation possible up to p_T ~ 1.6 GeV/c and for proton up to p_T ~ 3.0 GeV/c

Strange hadrons (K_s^0, Λ, Ξ, Ω) reconstructed by the decay topology

$\Omega^{-}+\overline{\Omega}^{+}$ Reconstruction

Particle identification



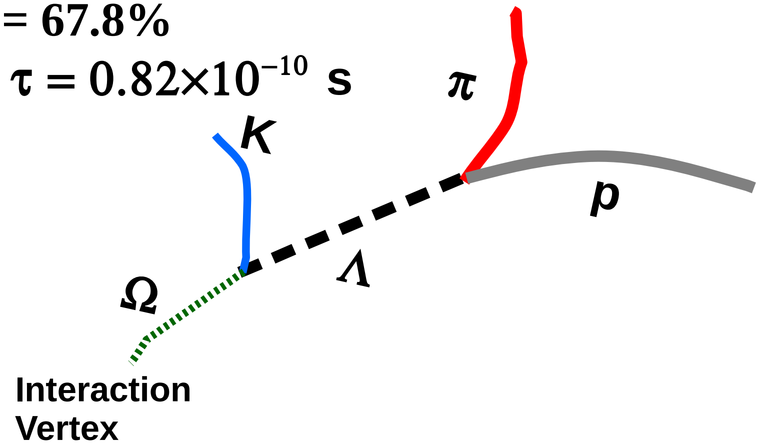
Au+Au $\sqrt{s}$ = 200 GeV (1.41 B events)

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

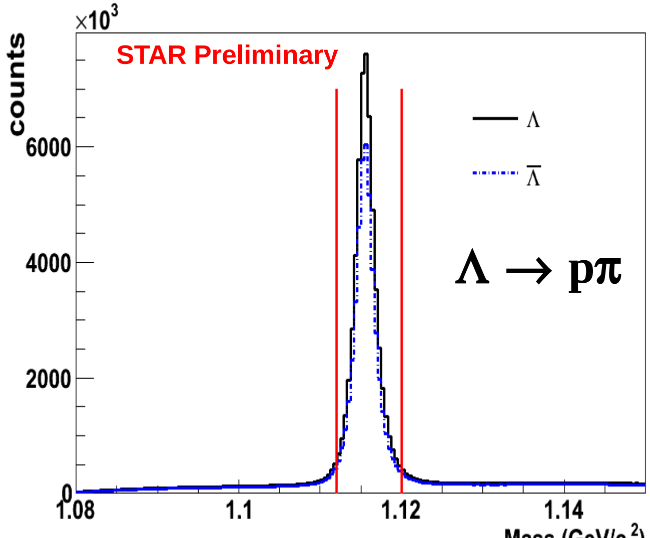
Branching ratio = 67.8%

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

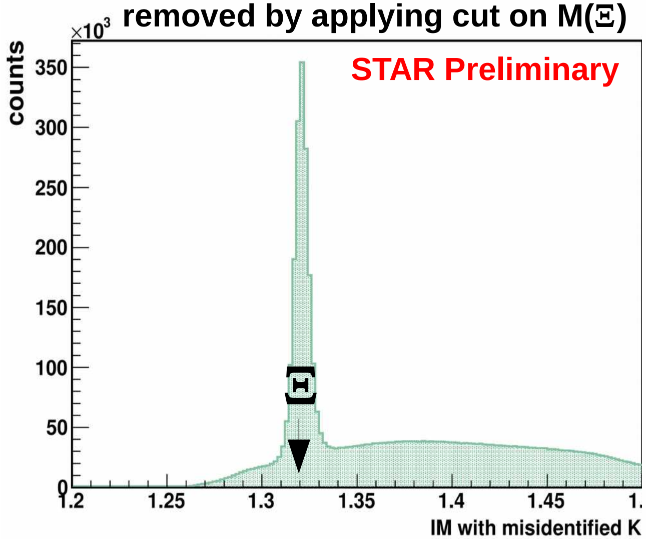
$c\tau$ = 2.46 cm



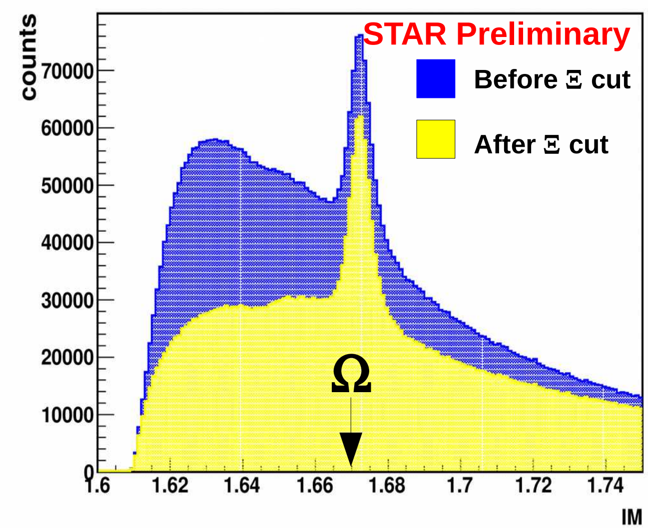
Reconstructed Λ



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

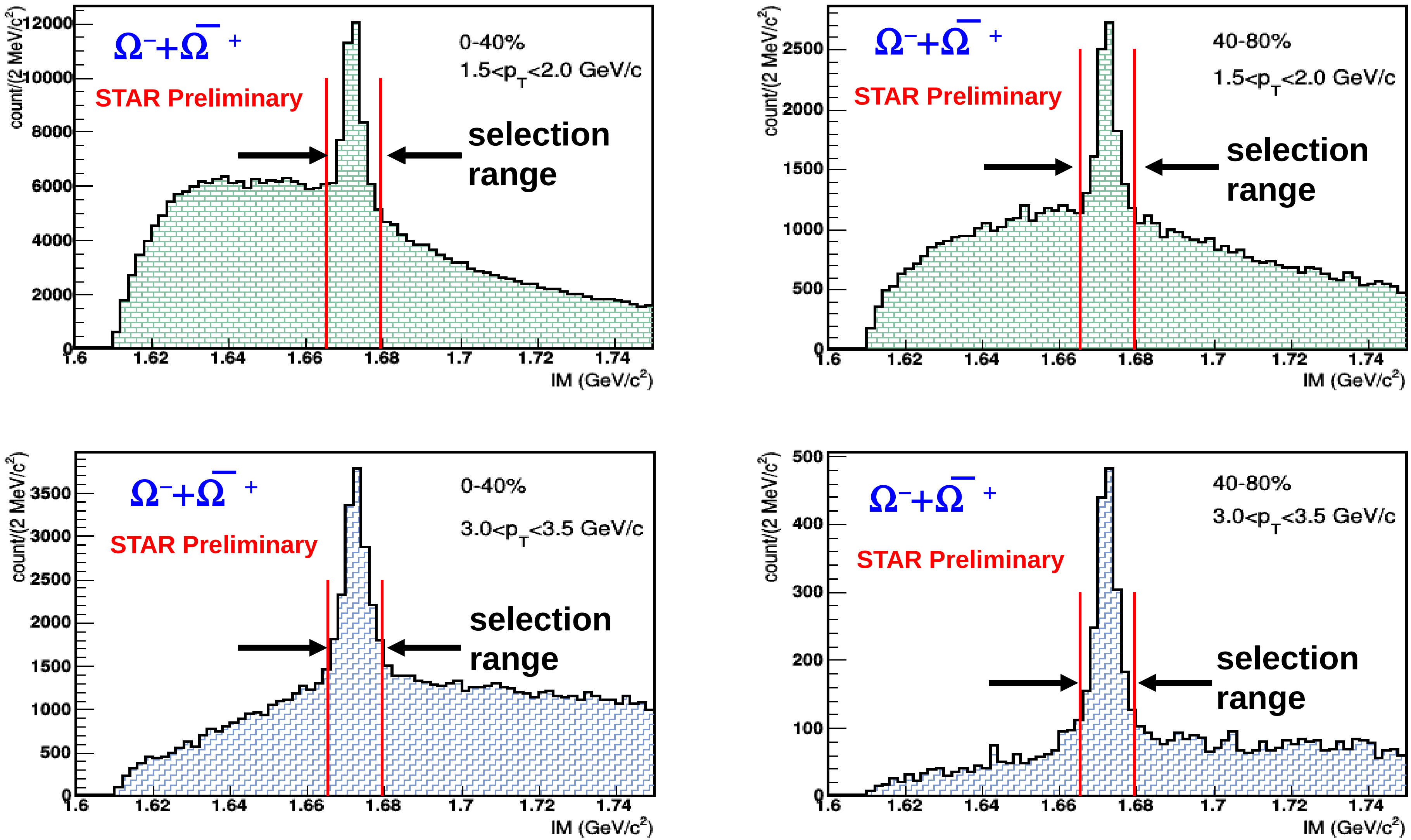


Reconstructed $\Omega^{-}+\overline{\Omega}^{+}$



$\Omega^- + \bar{\Omega}^+$ Reconstruction

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

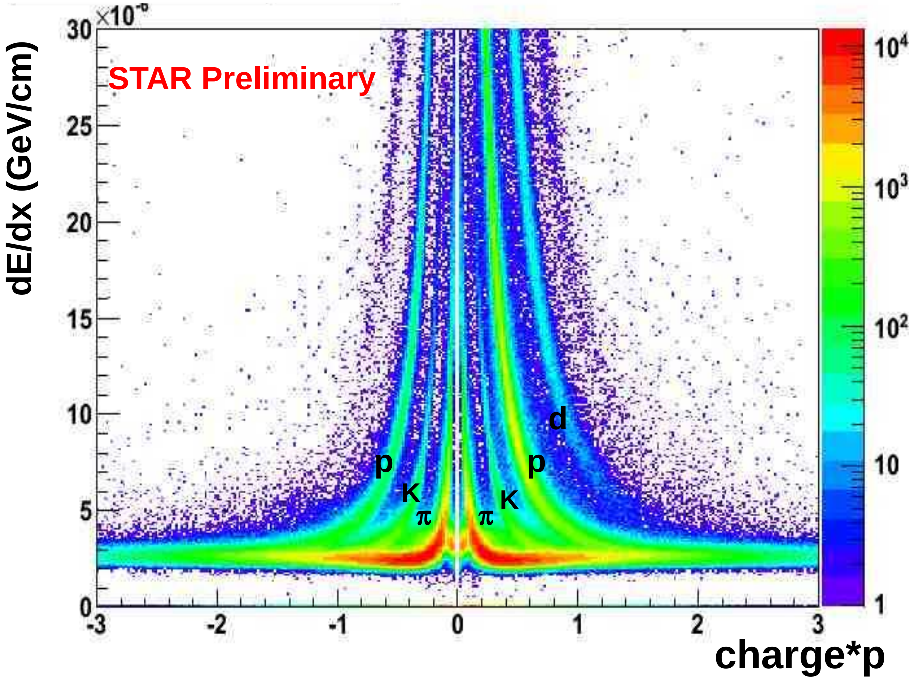


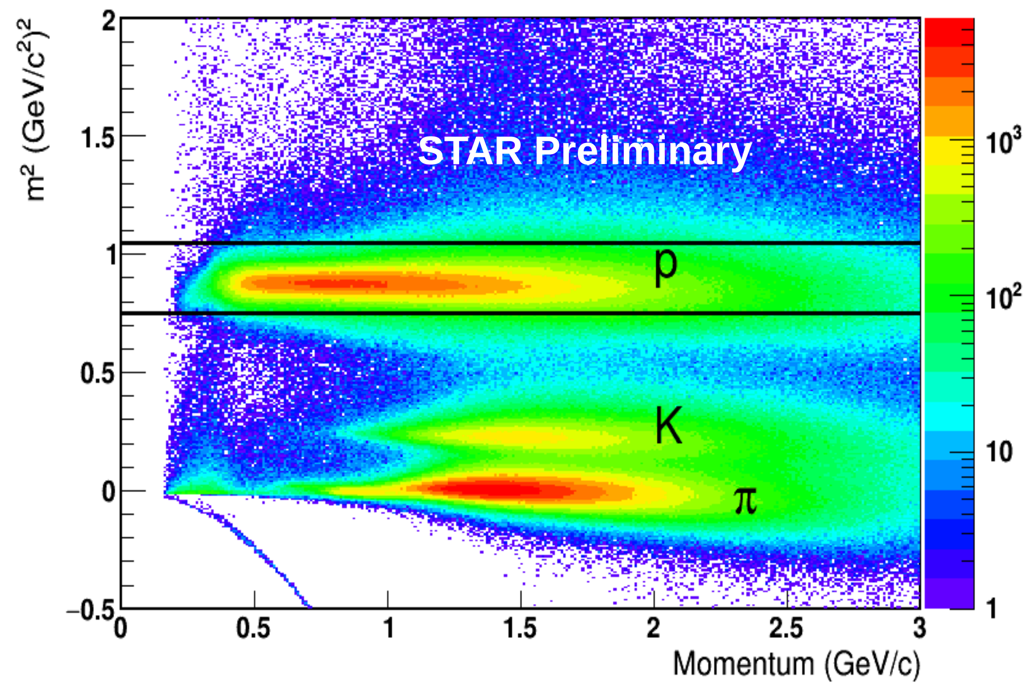
Proton Identification with TPC+TOF

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
- ✔ $0.75 < m^2 < 1.1\ (GeV/c^2)^2$

Particle identification





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

Few Definitions and Corrections

Step-I Raw correlations

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

p – momentum of particles a and b
k* – relative momentum of a & b in pair rest frame

Step-II Purity correction

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

PP(k*) = P(Ω)×P(p) is pair purity.

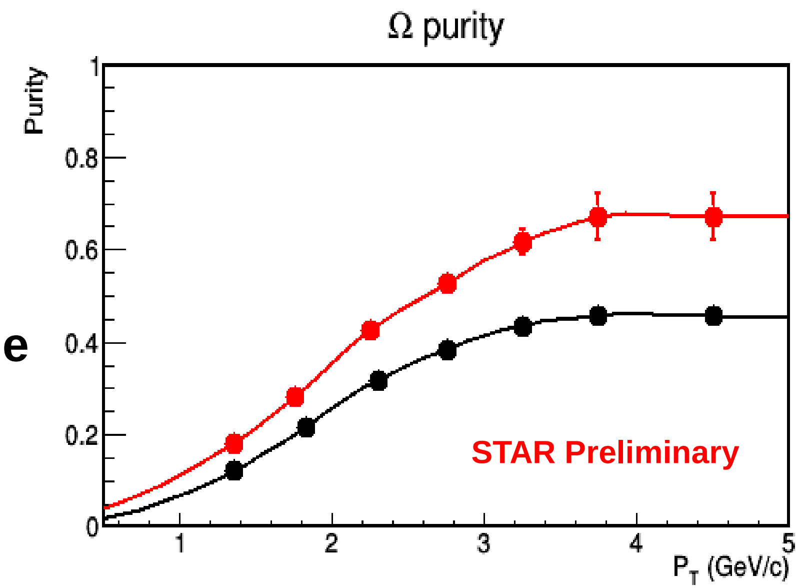
P(Ω) = S/(S+B)*Fr(Ω) and P(p) = S/(S+B)*Fr(p)
where Fr(x) is Fraction of primary particles

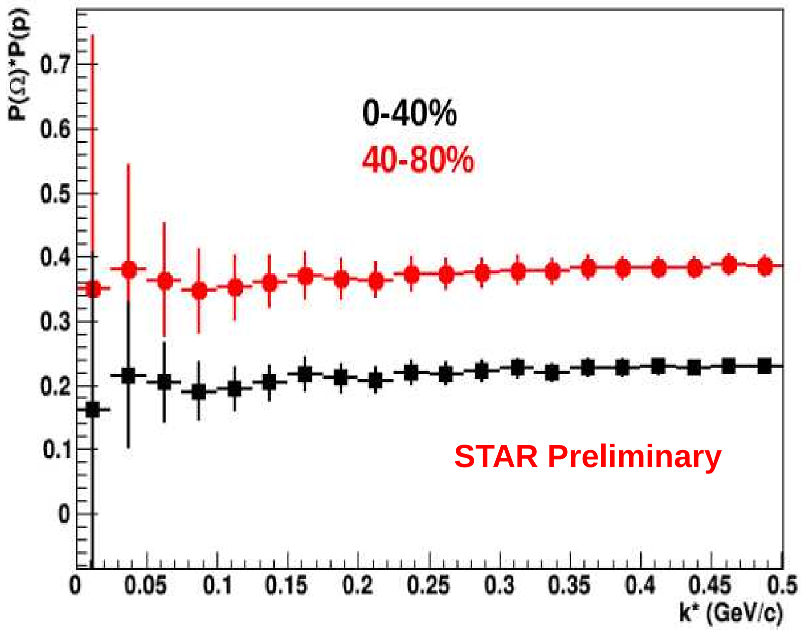
Fr(Ω) = 1 and Fr(p) = 0.52 ± 0.04

Step-III Momentum smearing

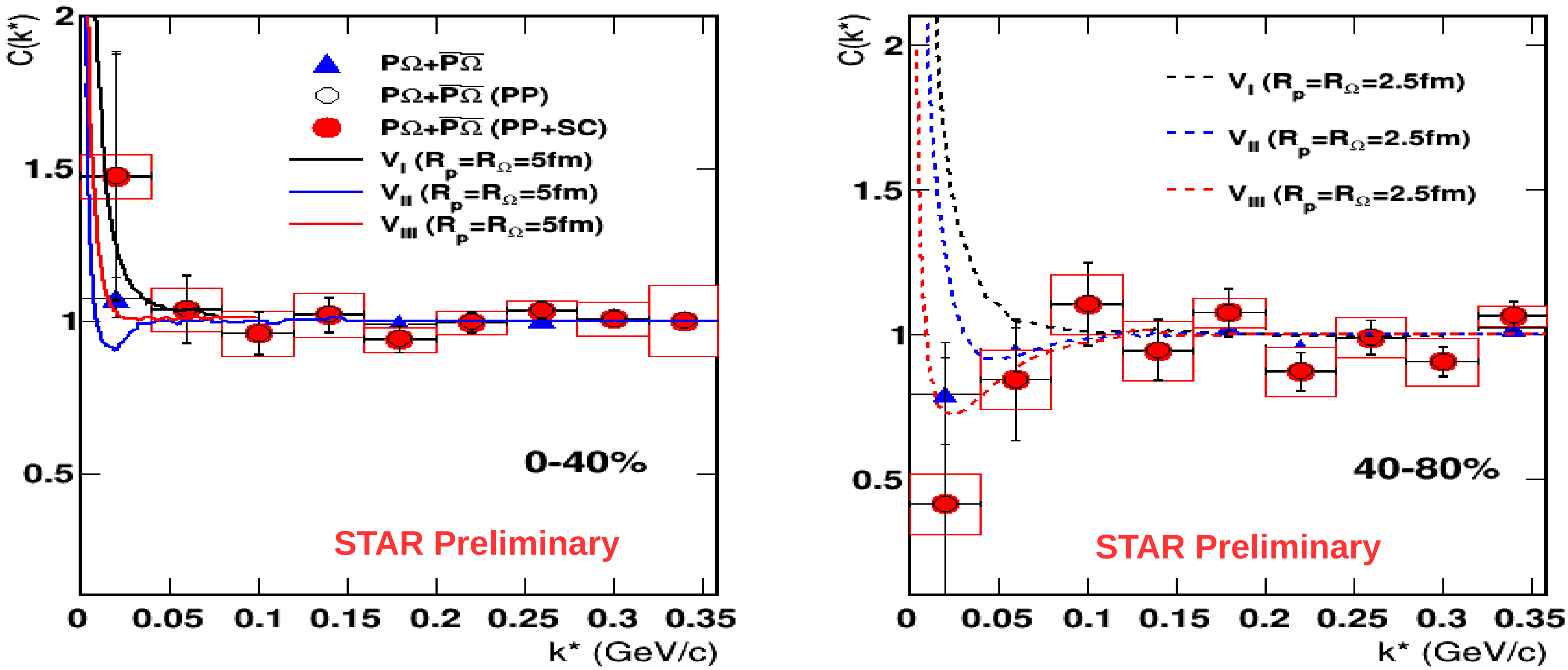
$$CF(k^*) = CF(k^*)\frac{CF_{nosmearing}}{CF_{smearing}}$$

Smearing correction factor is 0.99 ± 0.02





PΩ Correlations



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}.

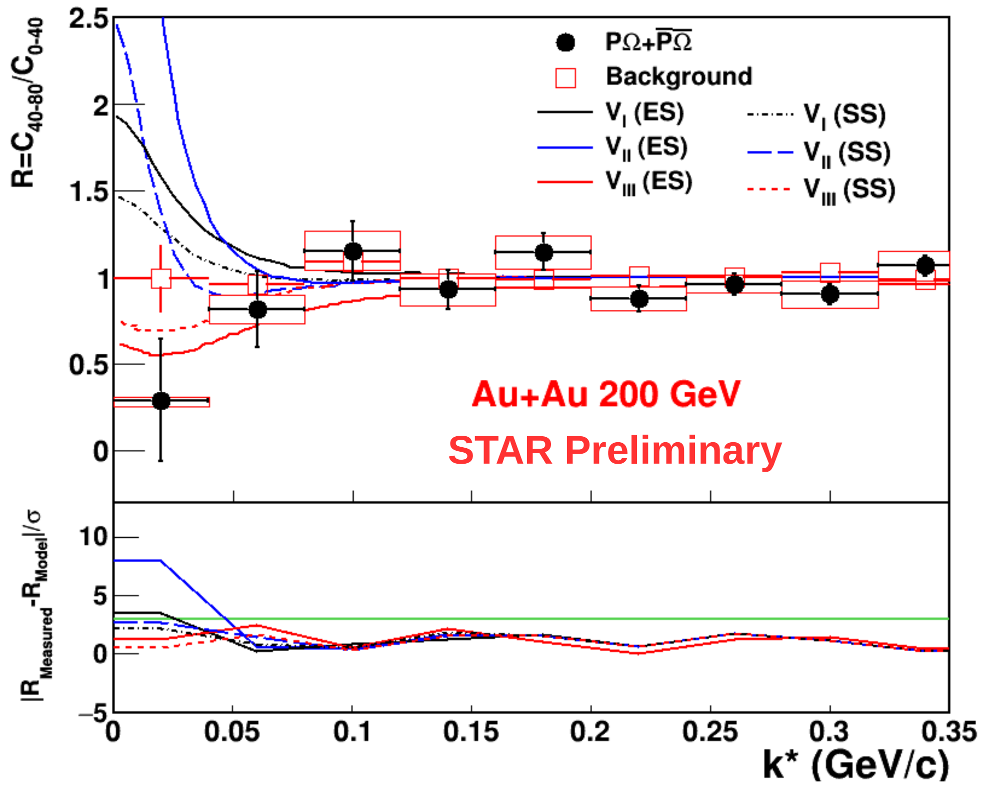
Spin-2 PΩ potentials	V_I	V_{II}	V_{III}
Binding energy E_B (MeV)	-	6.3	26.9
Scattering length a_0 (fm)	-1.12	5.79	1.29
Effective range r_{eff} (fm)	1.16	0.96	0.65

K. Morita et al., Phys. Rev. C 94, 031901 (2016)

PΩ Correlations

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

K. Morita et al., Phys. Rev. C 94, 031901 (2016)

Summary:

✔ The first measurement of correlation function for PΩ from Au+Au collisions @ 200 GeV is presented.

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

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

Thank you!