Taiwan’s QCD Programs and Heavy Quarkonium Physics at STAR

Yi Yang

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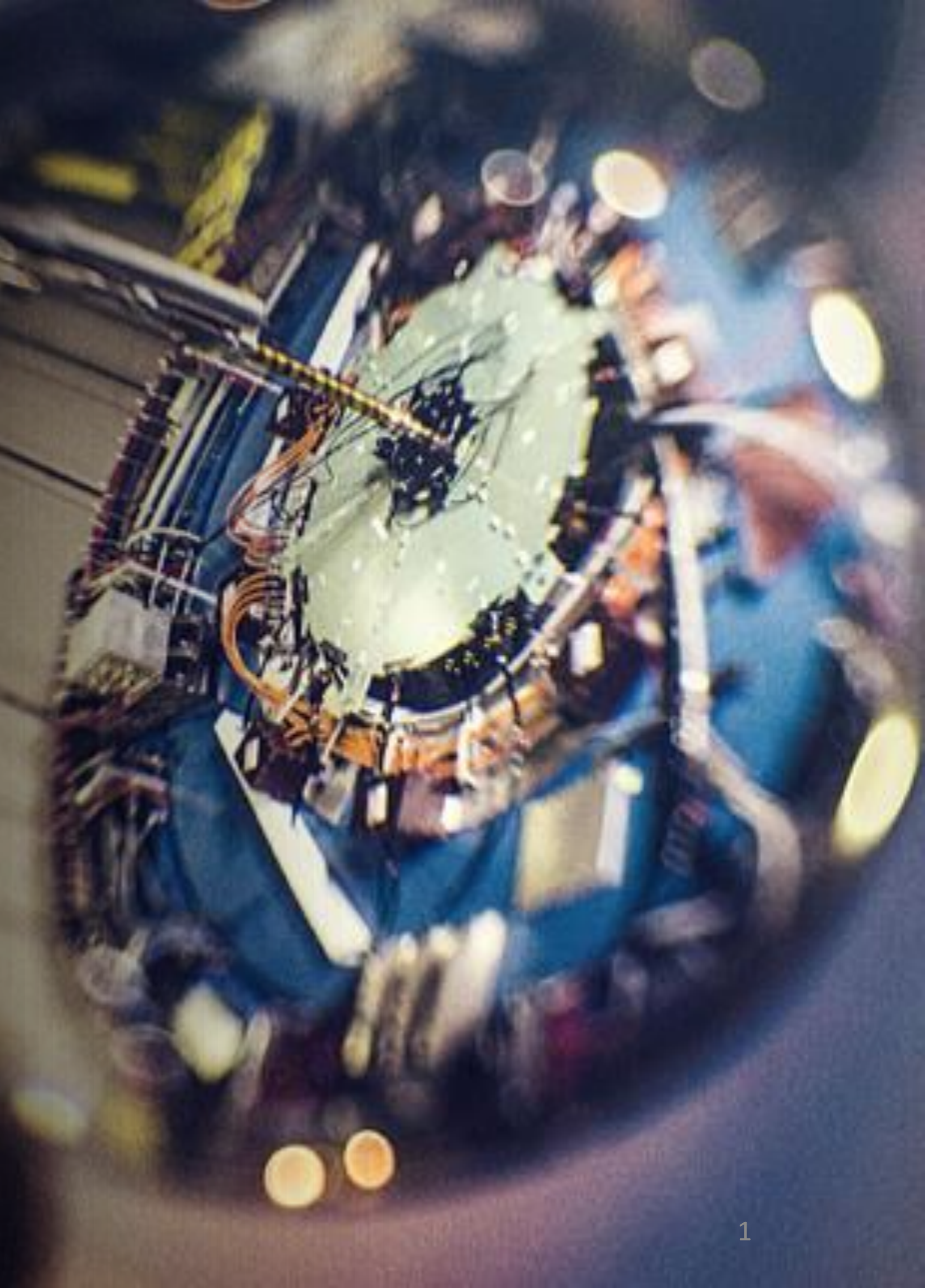
September 17, 2026 @ TK Workshop



Theoretical Groups

National Taiwan University (NTU)
Prof. Jiunn-Wei Chen
Prof. Ting-Wai Chiu

Academia Sinica (AS)
Prof. Hsiang-Nan Li
Prof. Di-Lun Yang

National Yang Ming Chiao Tung University (NYCU)
Prof. C.-J. David Lin

Chung Yuan Christian University (CYCU)
Prof. Chung-Wen Kao

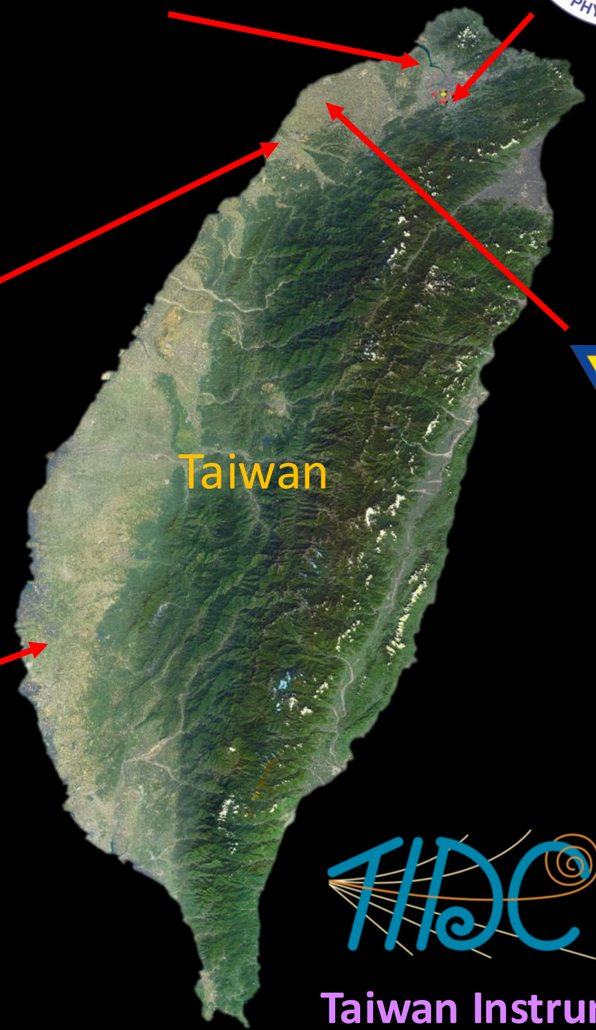
Physics interests:

- Nucleon/hadron physics with QCD effective theories & Lattice QCD
- Parton distribution functions
- Spin physics
- …

Experimental Groups

Academia Sinica (AS)
Prof. Wen-Chen Chang
Exps: COMPASS SPring-8 LEPS, LEPS2, FNAL E906, J-PARC E16, E50, ePIC
Prof. Yi Yang
Exps: STAR, ATLAS, Hall C, ePIC
Dr. Chih-Hsun Lin
Hardware expert

National Taiwan University (NTU)
Prof. Rong-Shyang Lu
Exps: sPHENIX, ePIC
Prof. Kai-Feng Jack Chen
Exp: ePIC



National Tsing Hua University (NTHU)
Prof. Pai-Hsien Jennifer Hsu
Exp: ePIC

National Central University (NCU)
Prof. Chia-Ming Kuo
Exps: CMS, sPHENIX, ePIC
Prof. Po-Ju Lin
Exps: COMPASS, Hall A/C, ePIC

National Cheng Kung University (NCKU)
Joint position: Prof. Yi Yang
Exps: STAR, ePIC

Taiwan Instrumentation and Detector Consortium (TIDC)
Director: Prof. Rong-Shyang Lu (NTU)

Physics Interests (Experimental)

- Photoproduction of $\phi, \omega, \eta, \eta'$ mesons and study their hadronic interactions with nucleons (SPring-8 LEPS, LEPS2)
- Measurement of nucleon sea quark asymmetry in most largest-x regime (E906)
- Orbital motion of valence quarks of protons (COMPASS)
- Partonic structure of pions (COMPASS)
- Evidence of chiral symmetry restoration in nuclear medium (E16)
- Novel study of proton tomography using pion beams (E50)
- Nucleon GPDs (Hall C)
- Heavy Flavor Physics, QGP (STAR, sPhenix, CMS, ATLAS)

About TIDC

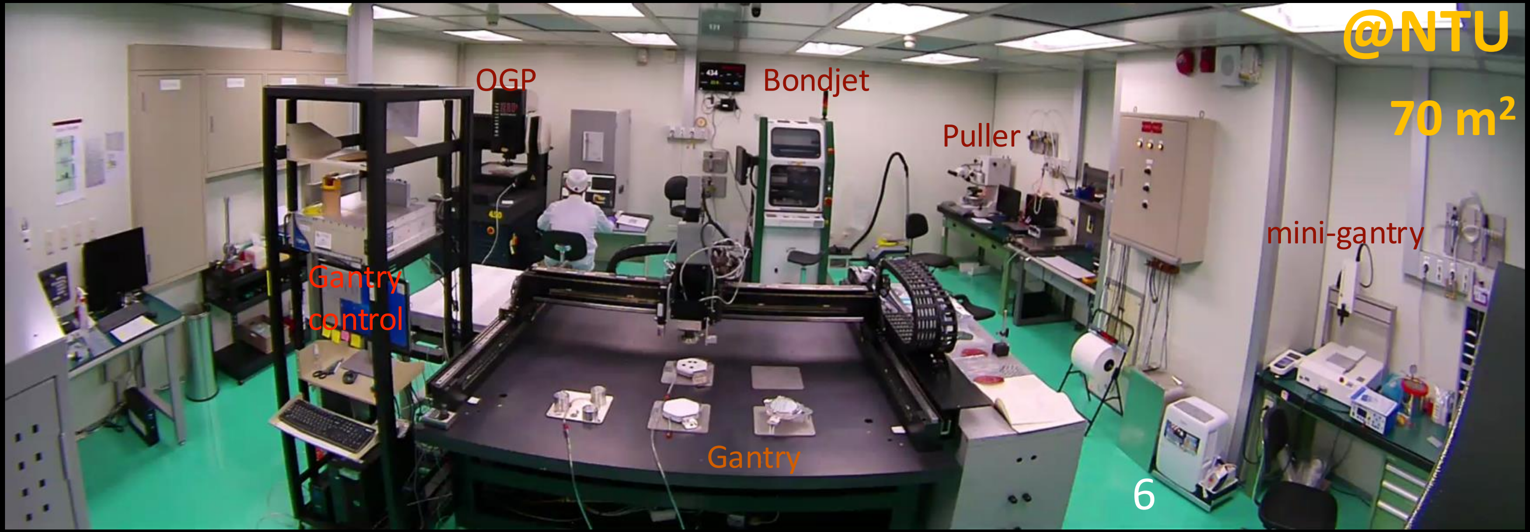
- **Taiwan Instrumentation and Detector Consortium (TIDC)** was established in 2019 by 5 institutes (AS, NCU, NTHU, NCKU, and NTU) in Taiwan supported by National Science and Technology Council in Taiwan

  ➔ Form a strong team to participate High Energy and High Nuclear Physics

https://tidc.phys.ntu.edu.tw/WordPress/

TIDC: Silicon Detector Facility

- Class 10,000, with temperature and humidity controlled at 23 °C and RH 50% all year round
- Fully operation with pressured dry-air supply and vacuum services
- Aerotech 1.25x1.25 m^2 robotic gantry with Labview control
- OGP optical 3D measurement
- Hesse BJ820 automatic Bondjet and DAGE 4000 Bondtester (puller)
- Manual probe station and picoprobes
- Glue dispensers, mini-gantry, microscope, degassing chamber, Keithley 2410 and tools …

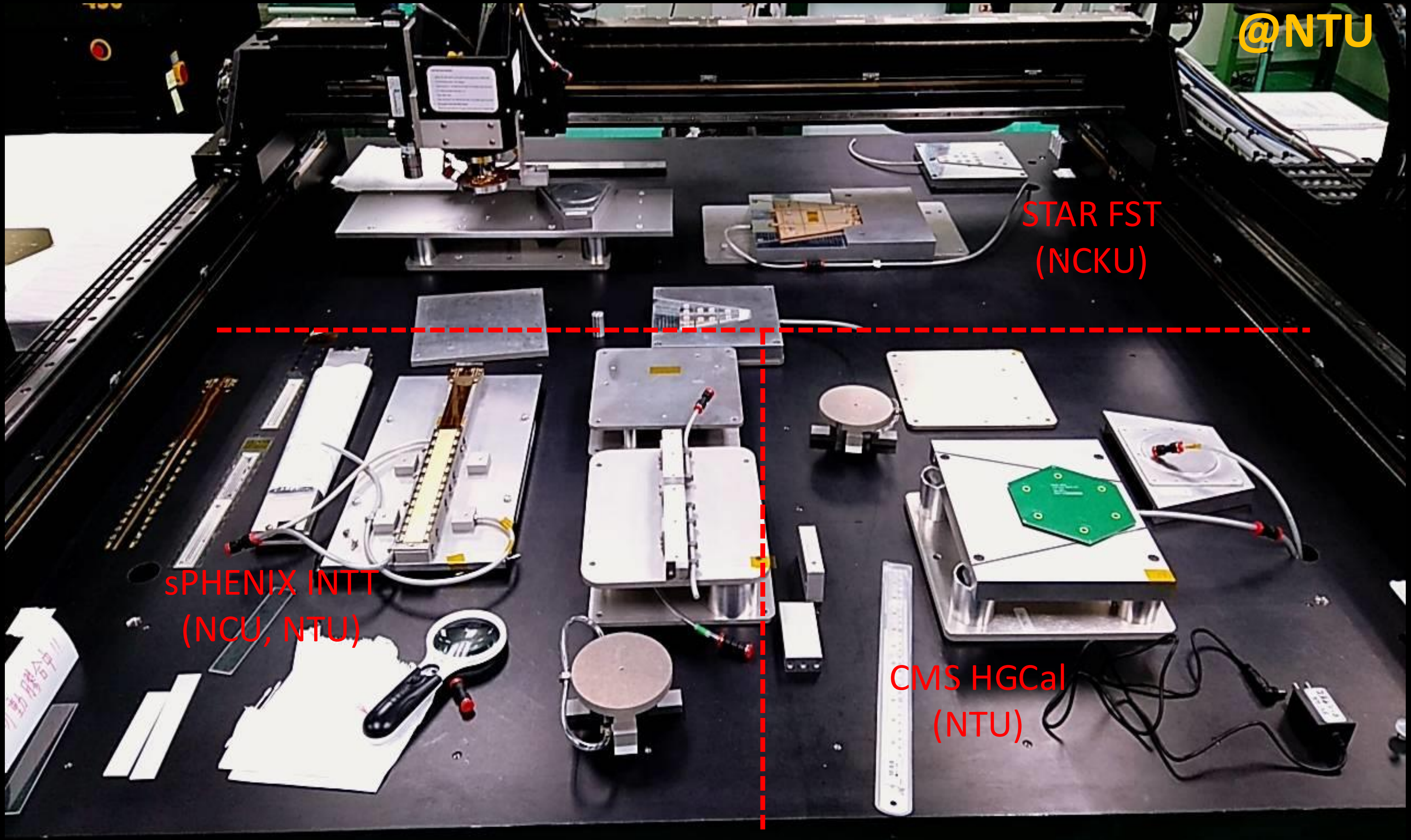


TIDC: Silicon Detector Facility

- Lab space for after-assembly testing and repair
- Equipped with workstations with tools and soldering iron
- Yamato Oven to cure epoxy and Hitachi Climate Chamber (-70 ^{o}C ~ 100 ^{o}C) for thermal stress tests
- Oscilloscopes, function generators, Keithley 2410, NIM crate and modules, NI PXIe crate and modules
- PCs and Mac's for LabVIEW and SolidWork

TIDC: Silicon Detector Facility

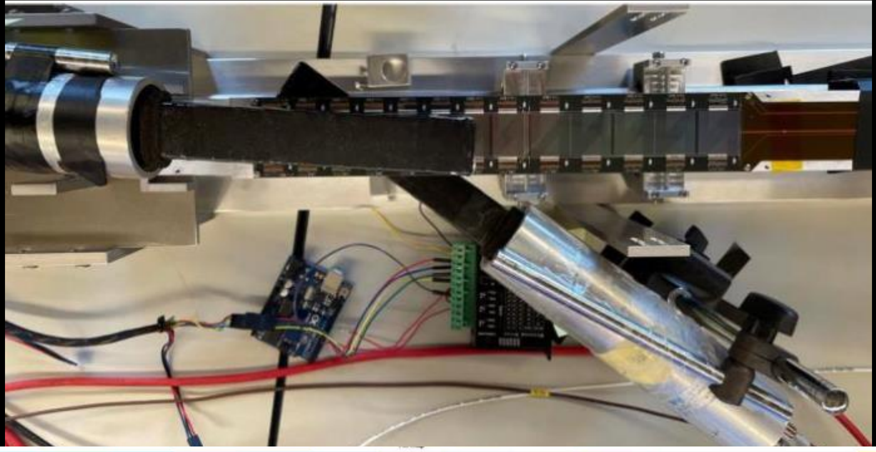
- Very productive period of TIDC (2019 – 2020,)

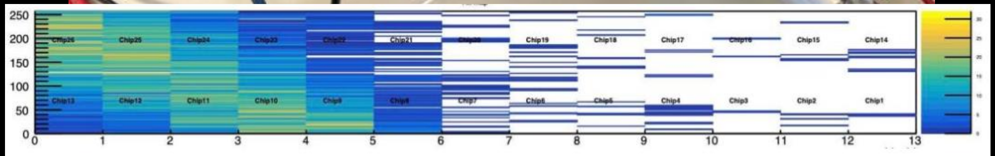


TIDC: Silicon Sensor Development Facility

@NCU

- 3 probe stations (1 for 8-inch and 2 for 6-inch silicon sensors)
- Capability to design the probe cards
- Perform the IV/CV measurements
- Silicon sensor R&D with the local semiconductor companies
- Silicon QC center for CMS HGCal and sPHENIX INTT
- Work with a local PCB company to produce high quality readout board for CMS HGCal

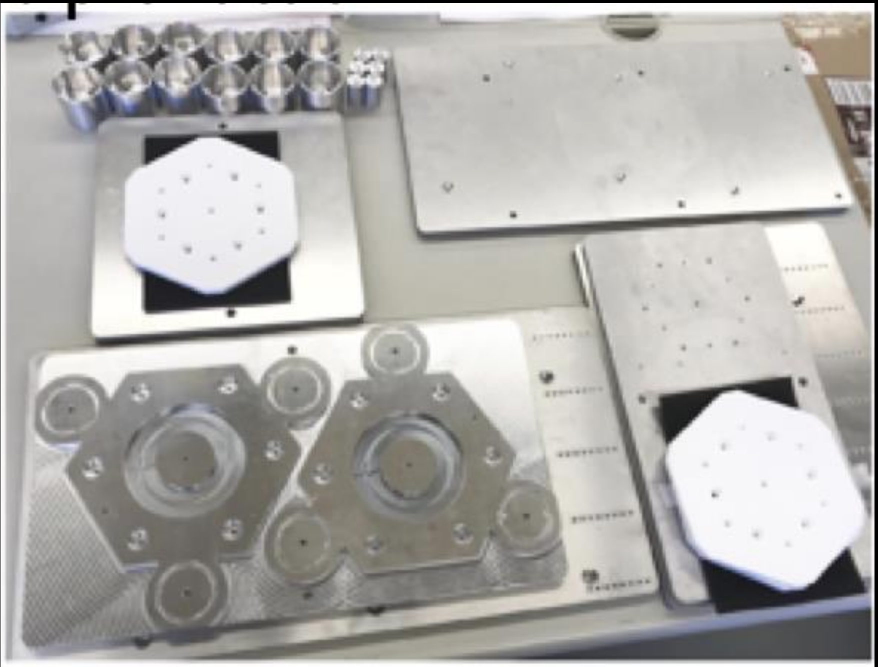


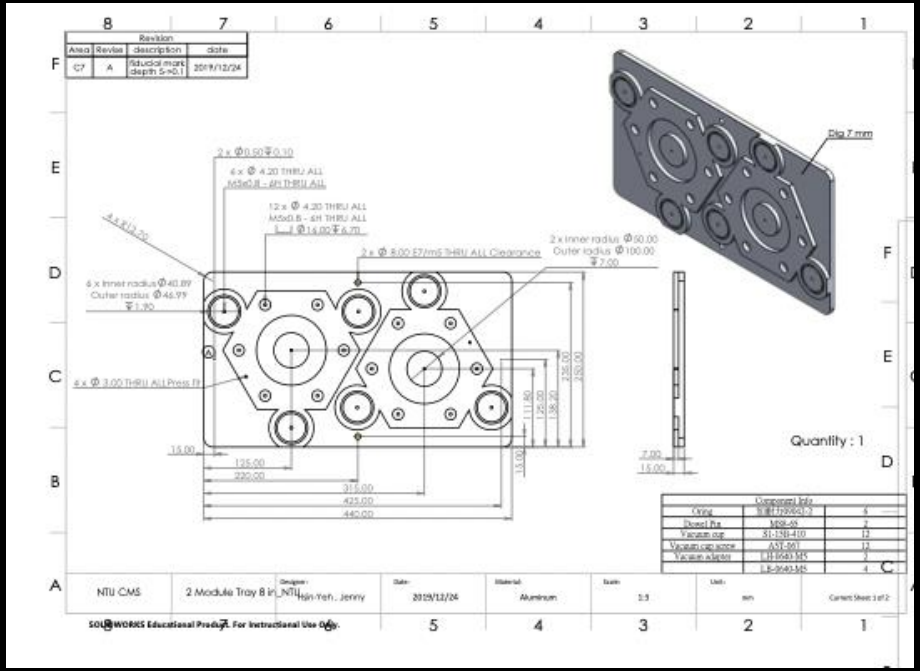


TIDC: High Precision Machine Shop

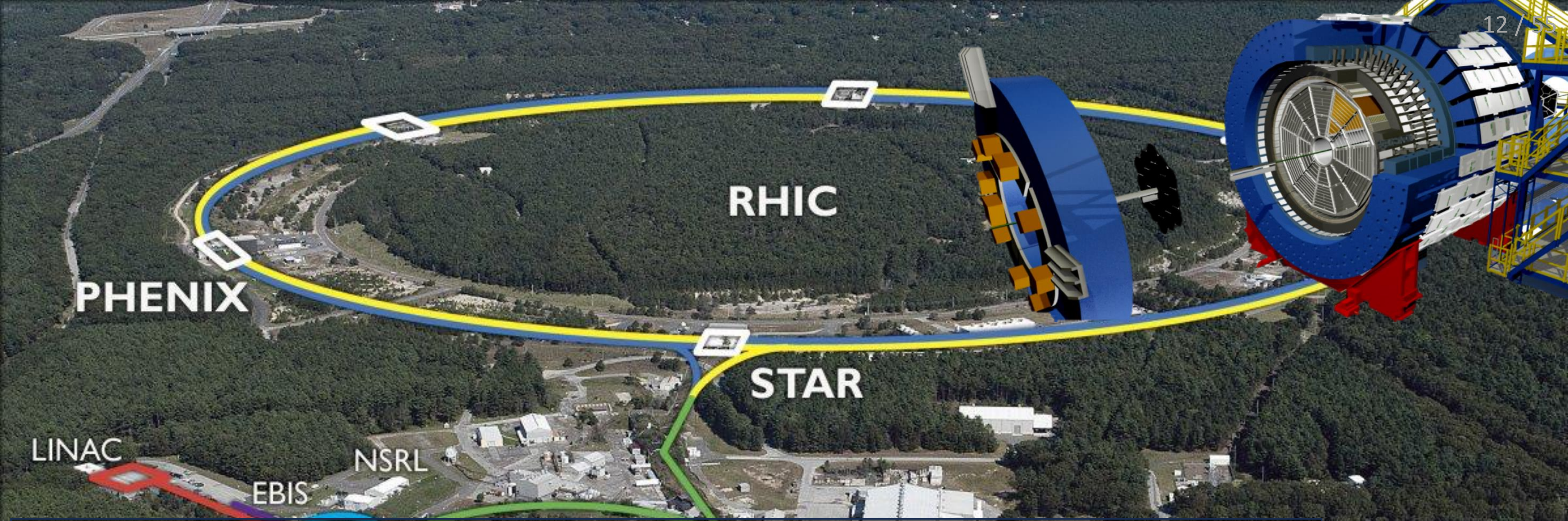
- Experienced engineers, effective production

@AS





Heavy Quarkonium at STAR



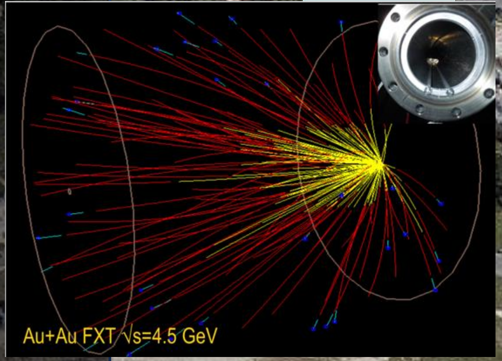
Relativistic Heavy-Ion Collider (RHIC)

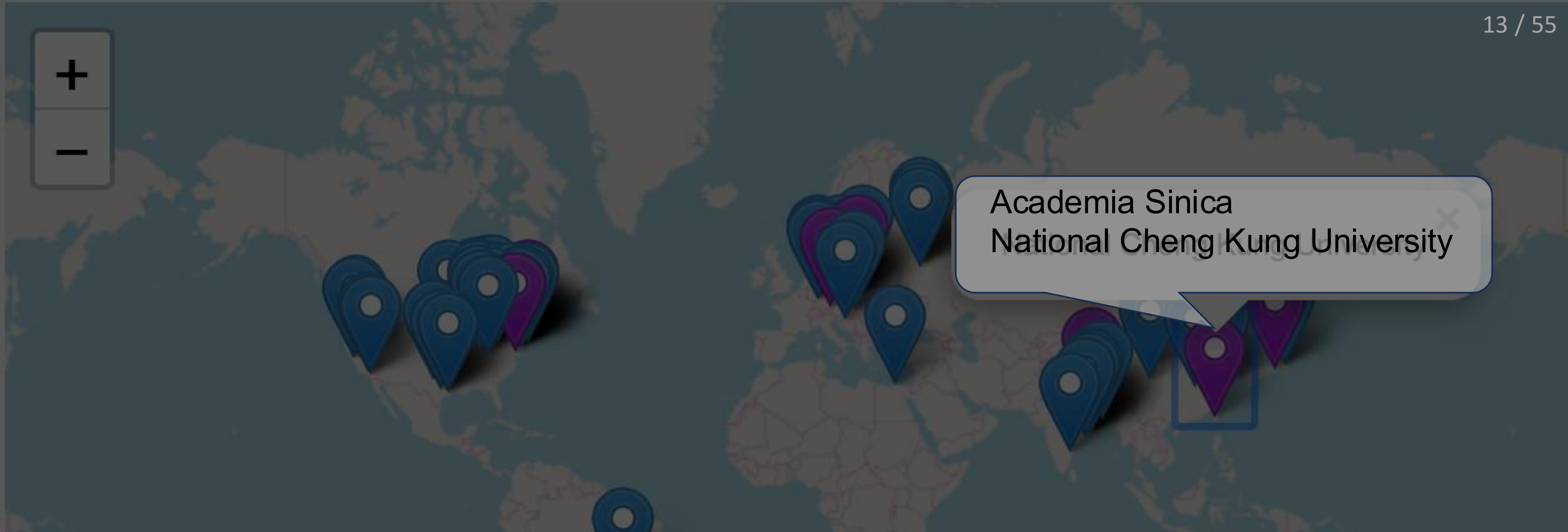
The most versatile collider in the world!

- The only **polarized proton** collider in the world
- Collision particles: p+p, p+Au, Au+Au, d+Au, U+U, Zr+Zr, …
- The collision energy for Au+Au collision: $\underbrace{3.5 - 7.7}_{\text{Fixed Target mode}}$ - 200 GeV

Fixed Target mode

Collider mode



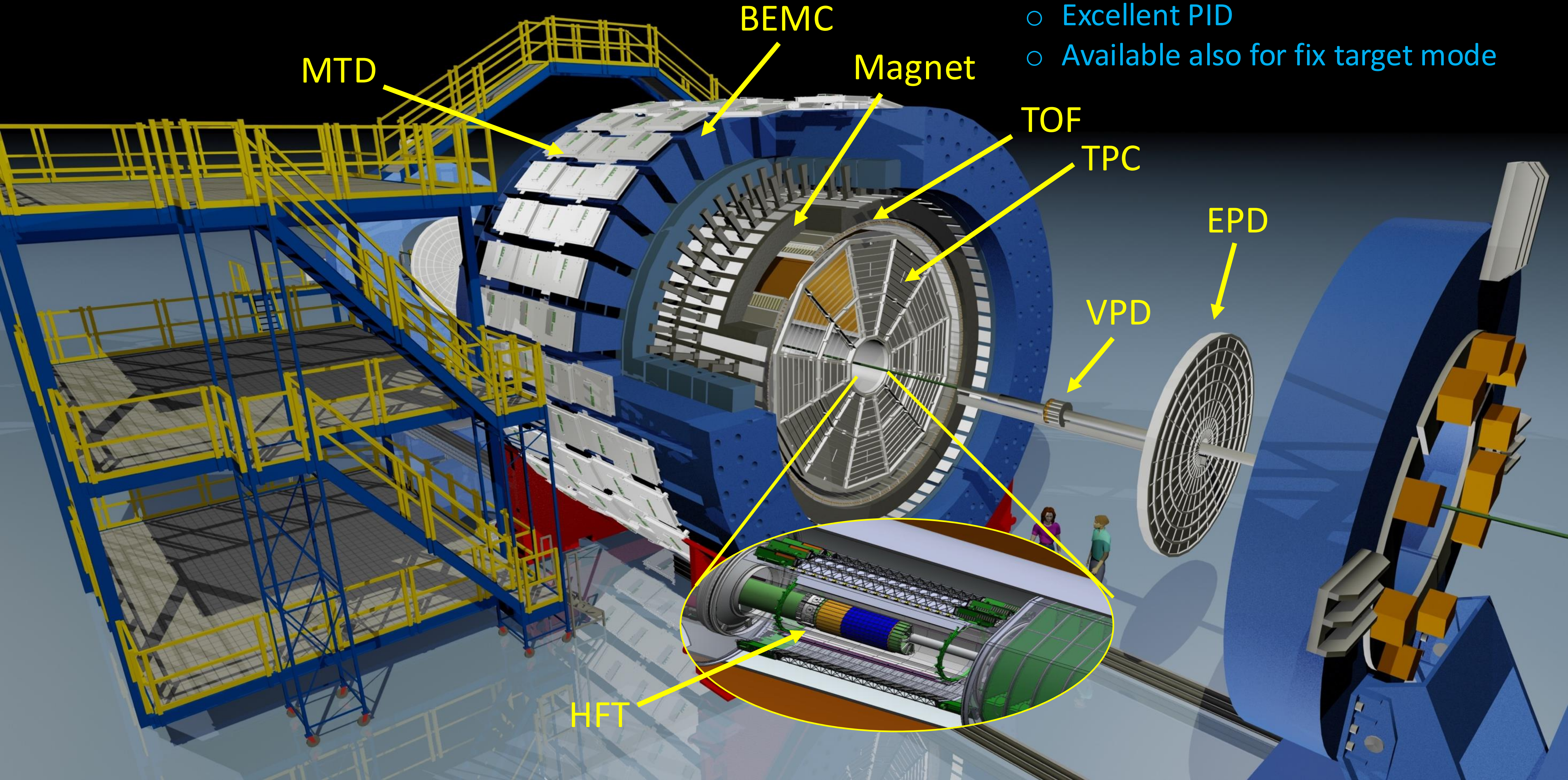


The STAR Collaboration

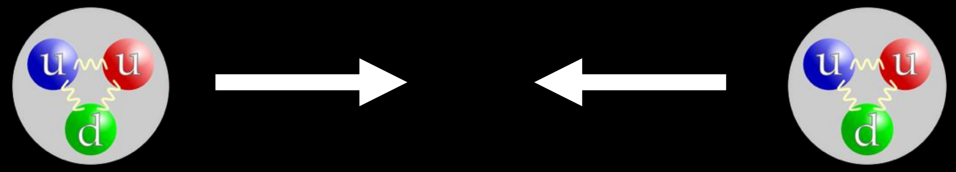
- STAR is composed of 67 institutes from 13 countries with a total of 693 collaborators
- AS/NCKU group mainly focuses on heavy flavor physics (quarkonium in pp, pA, and AA) and forward upgrades

The STAR Detector

- Large acceptance: $|\eta| < 1$, $0 < \phi < 2\pi$
- Excellent PID
- Available also for fix target mode



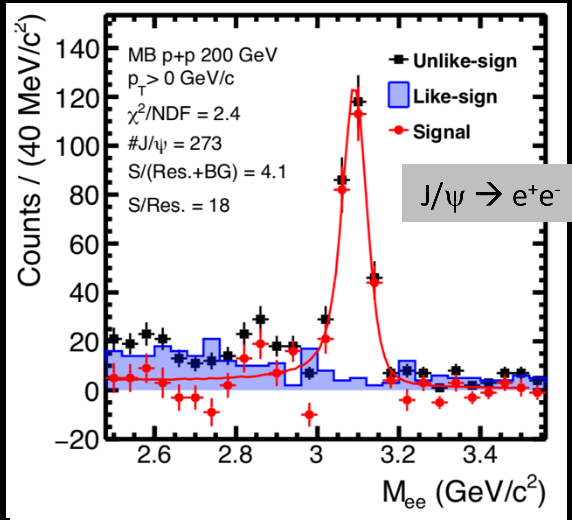
Hadron collisions

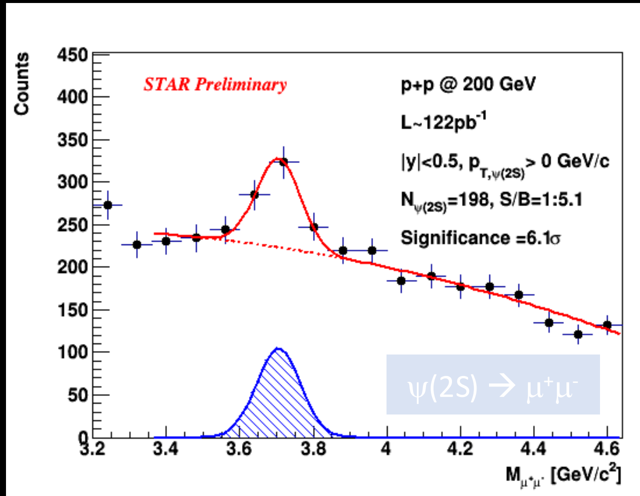


J/ψ & ψ(2S) in p+p @ 200 & 500 GeV

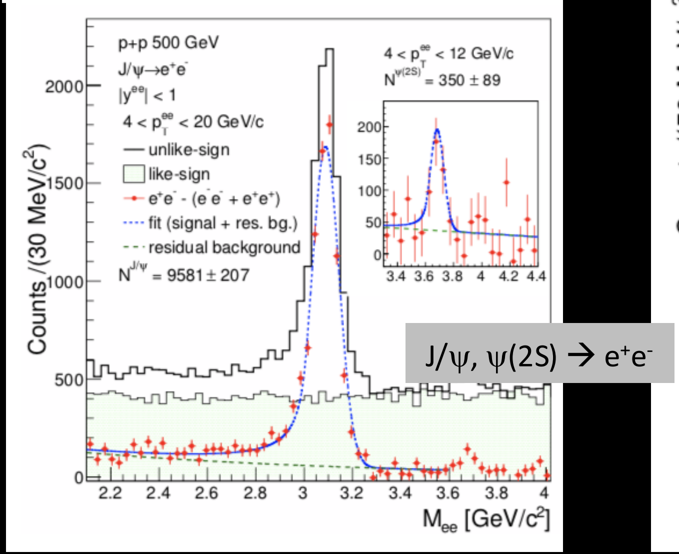
- J/ψ and ψ(2S) signals from the ***dielectron*** and ***dimuon*** channels

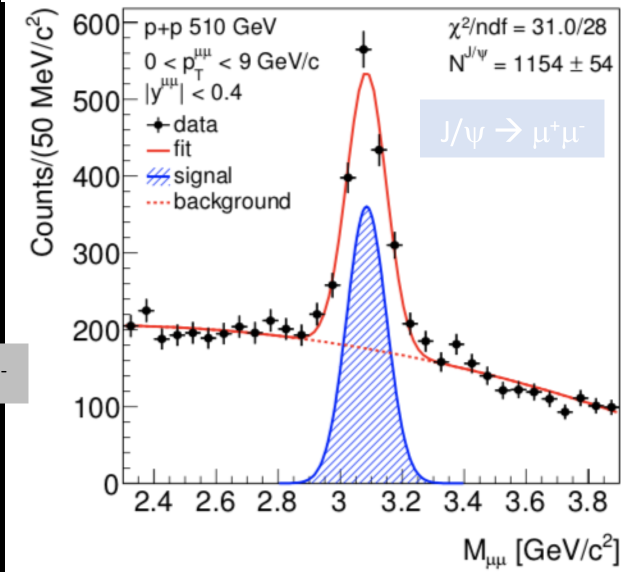
p+p @ 200 GeV





p+p @ 500 GeV

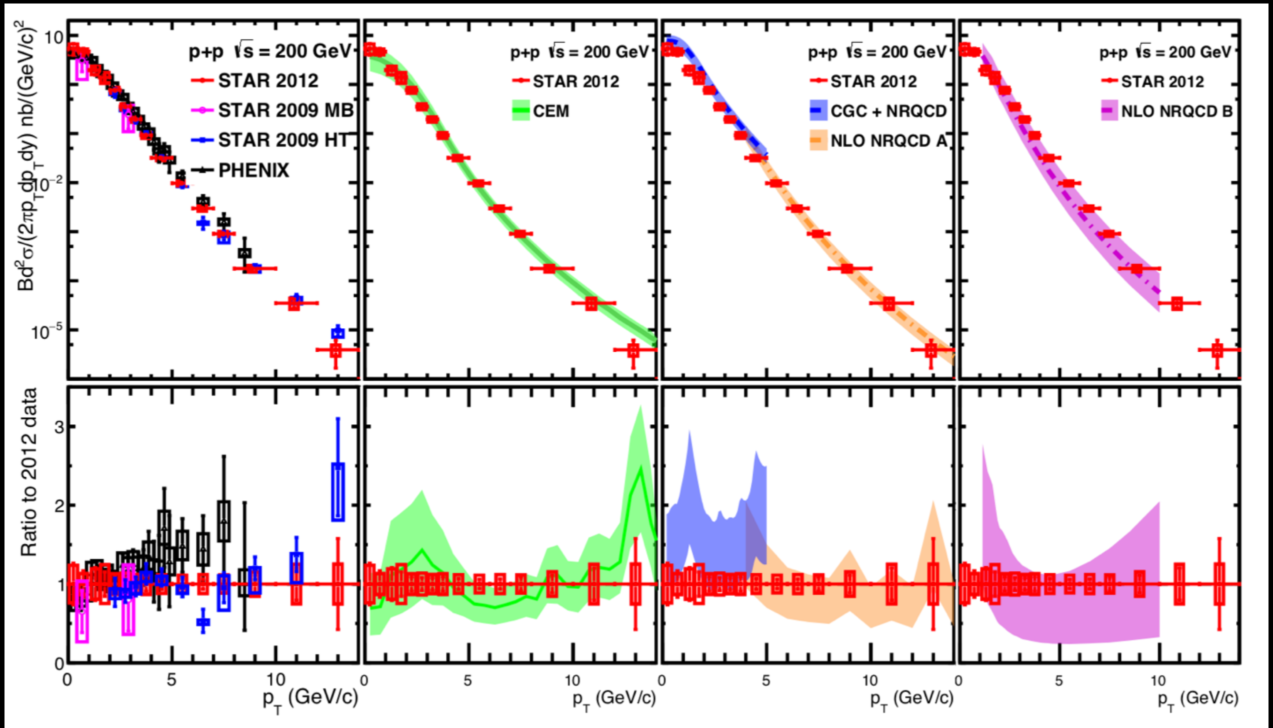




J/ψ Cross-Section in p+p Collisions @ 200 GeV

- Precision measurement of J/ψ production cross-section for $p_T^{J/\psi}$ from 0 to 14 GeV/c
- Consistent with CEM (direct J/ψ production only) and NLO NRQCD calculations (prompt J/ψ production)
- CGC+NRQCD seems to overestimate the data in the low p_T region

STAR 2012: PLB 786 (2018) 87-93
STAR 2009: PLB 722 (2013) 55; PRC 93 (2016) 064904
PHENIX: PRD 82 (2010) 012001
CEM: Phys. Rept. 462 (2008) 125; R. Vogt private communication (2009)
NLO+NRQCD A: PRD 84 (2011) 114001
CGC+NRQCD: PRL 113 (2014) 192301
NLO+NRQCD B: PRL 108 (2012) 172002



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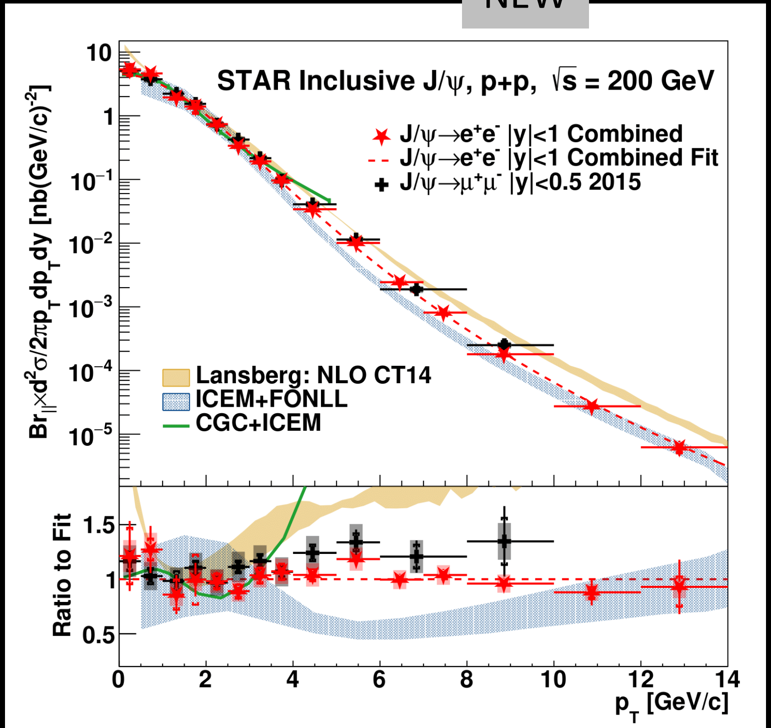
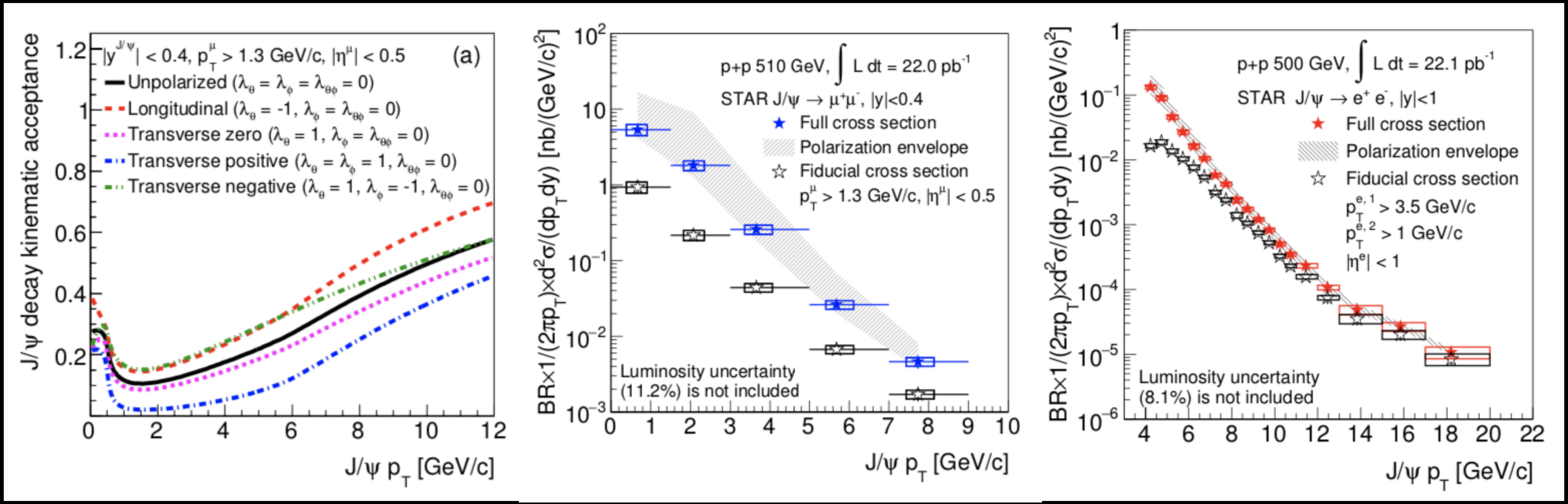


J/ψ Cross-Section in p+p Collisions @ 500 GeV

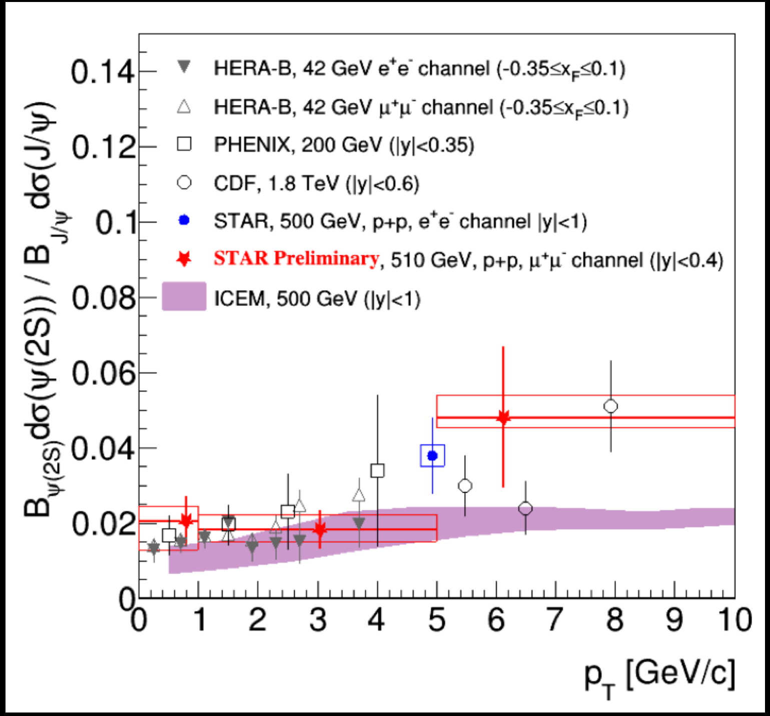
- Precision measurement of J/ψ production cross-section for $p_T^{J/\psi}$ from 0 to 20 GeV/c
- J/ψ kinematic acceptance strongly depends on the polarization assumption
  - **Fiducial cross-section**: restricted phase-space (no uncertainty from polarization)
  - **Full cross-section**: full phase-space (more models for comparison)

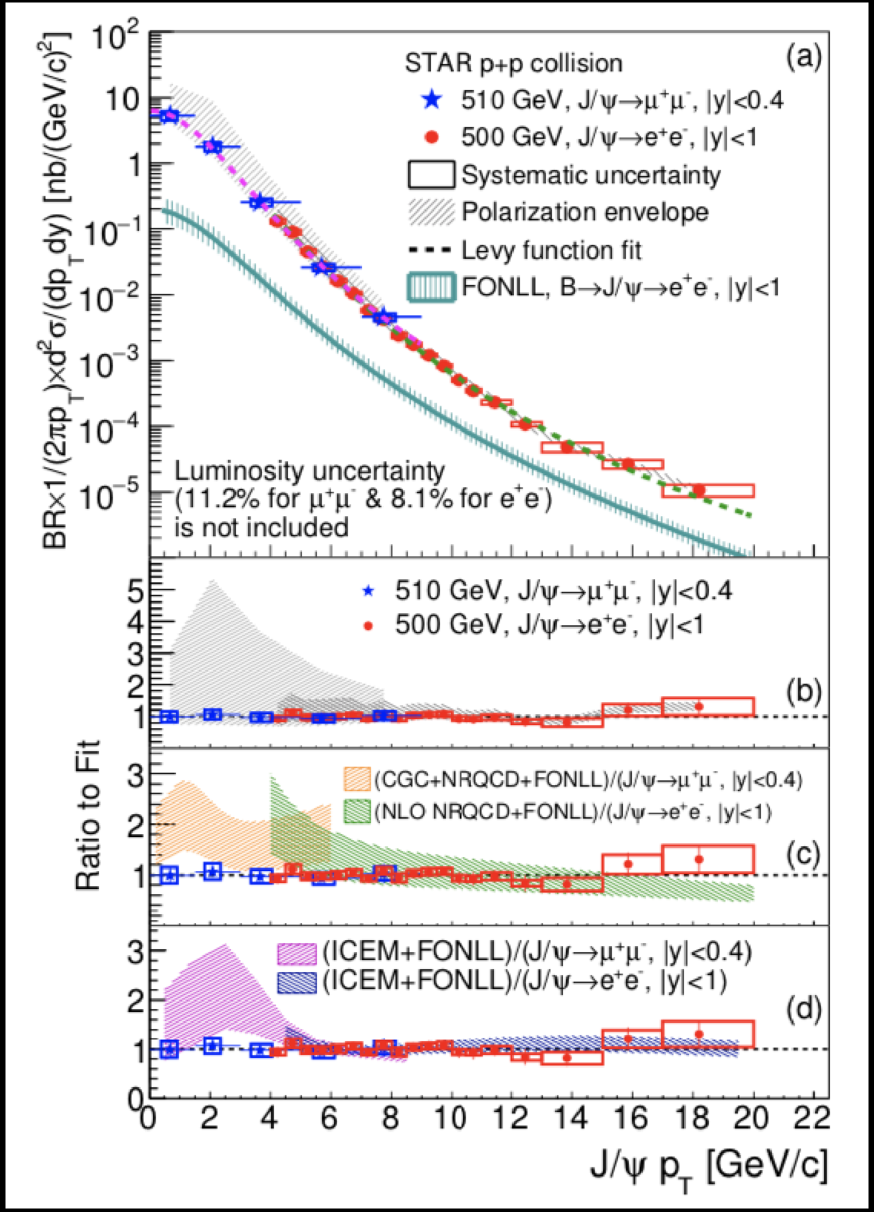
Phys. Rev. D 100, 052009, 2019



J/ψ Cross-Section in p+p Collisions @ 500 GeV

- Consistent with CGC+NRQCD, NLO NRQCD calculations and ICEM (prompt J/ψ)
- ψ(2S) to J/ψ ratio follows the world trend (adding 2017 data)

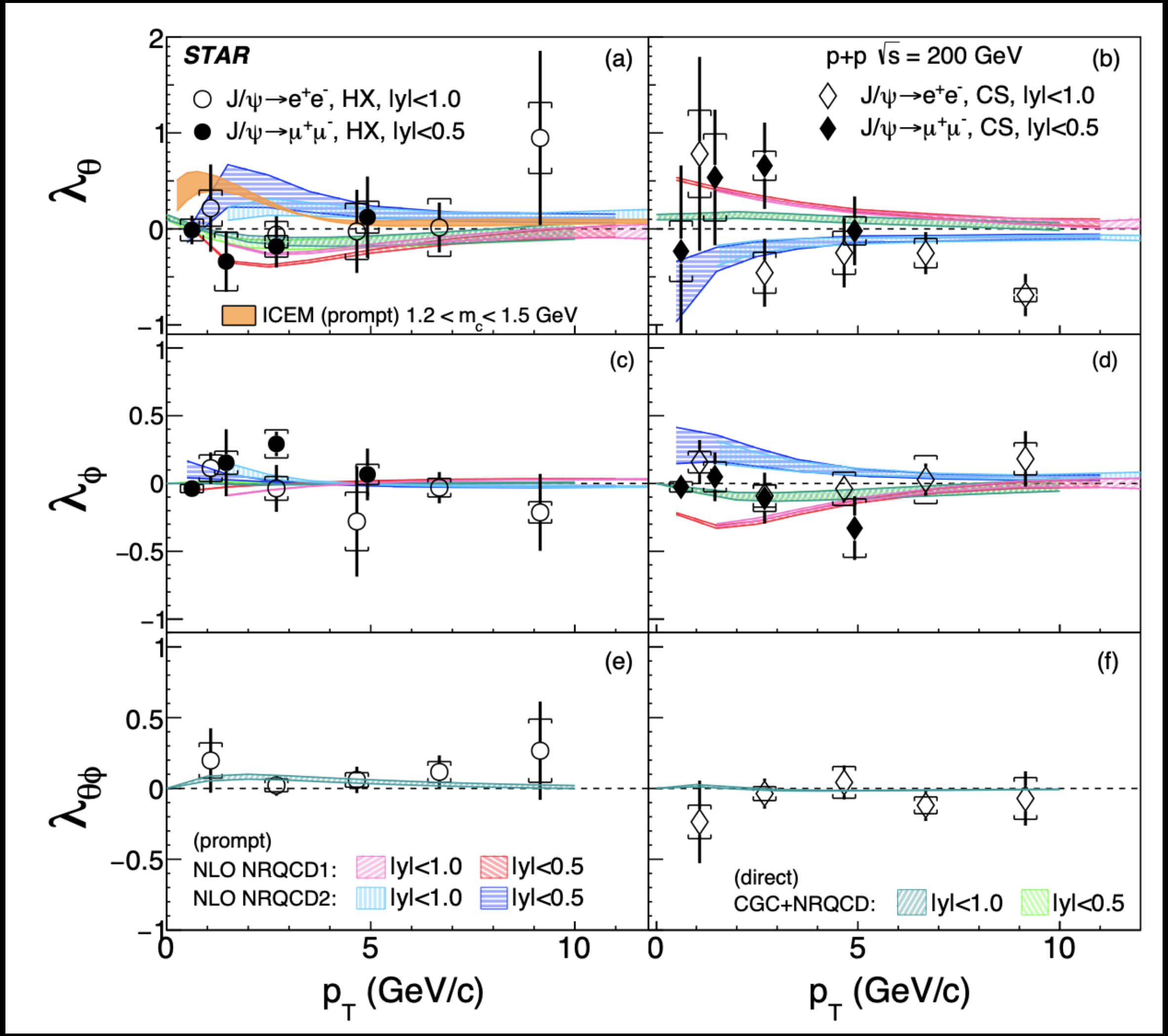




Phys. Rev. D 100, 052009, 2019

J/ψ Polarization Measurement

- First STAR J/ψ polarization measurements in Helicity (HX) and Collins-Soper (CS) frame from the ***dimuon*** channel in p+p collisions @ 200 GeV
- At this p_T range, it is sensitive to constraint NRQCD Long Distant Matrix Elements (LDMEs)
- λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$ are consistent with **ZERO** within uncertainties
- NRQCD and CGC+NRQCD predictions can both qualitatively describe data
- Possible to distinguish different NRQCD predictions with larger statistics at low p_T

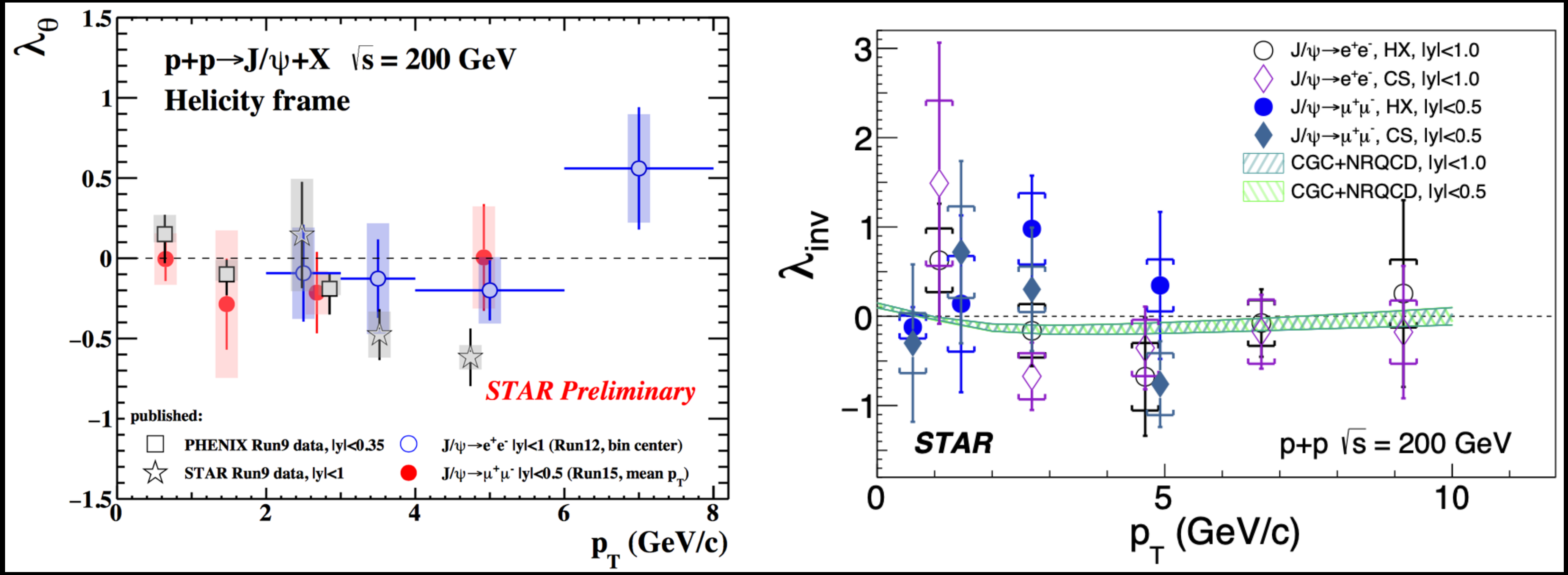


arXiv:2007.04732

NRQCD1: Phys. Rev. Lett 114 (2015) 092006
NRQCD2: Phys. Rev. Lett 110 (2013) 042002
CGC+NRQCD:JHEP12 (2018) 057

J/ψ Polarization Measurement

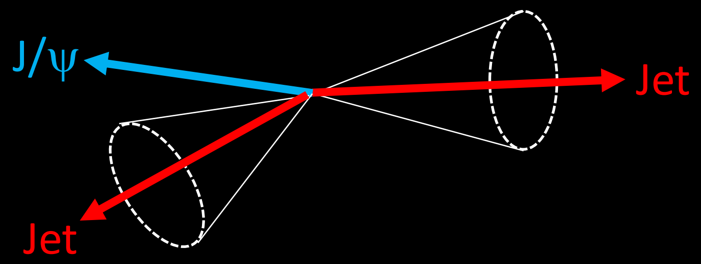
- Frame invariant quantity: $\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$
  - Good cross-check on measurements performed in different frames
- Consistent with the previous measurements from STAR and PHENIX

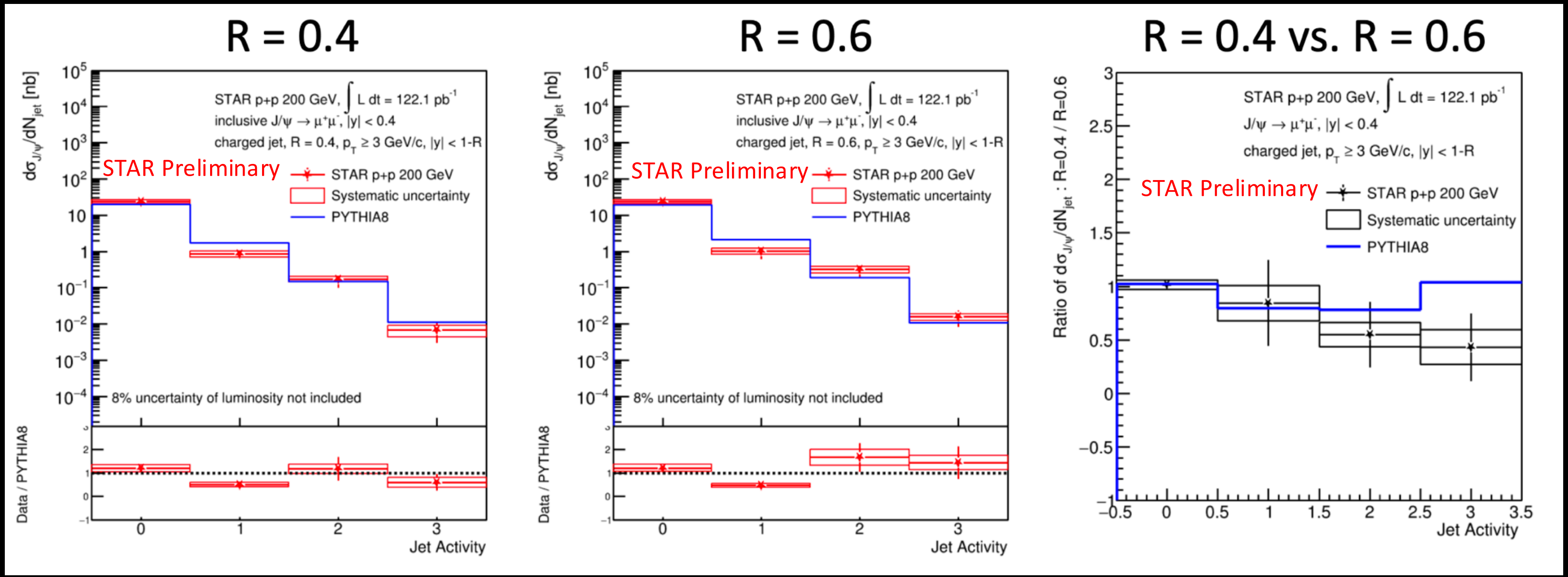


STAR Run 9: Phys. Lett. B739 (2014) 180–188
PHENIX: Phys. Rev. D **95**, 092003

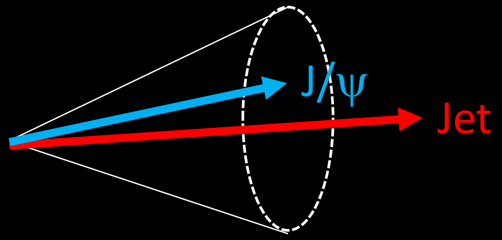
J/ψ Production with jet activity

- Study J/ψ production associated with jet activity could provide theorist a new variable to distinguish different models and have a better understanding of quarkonium production

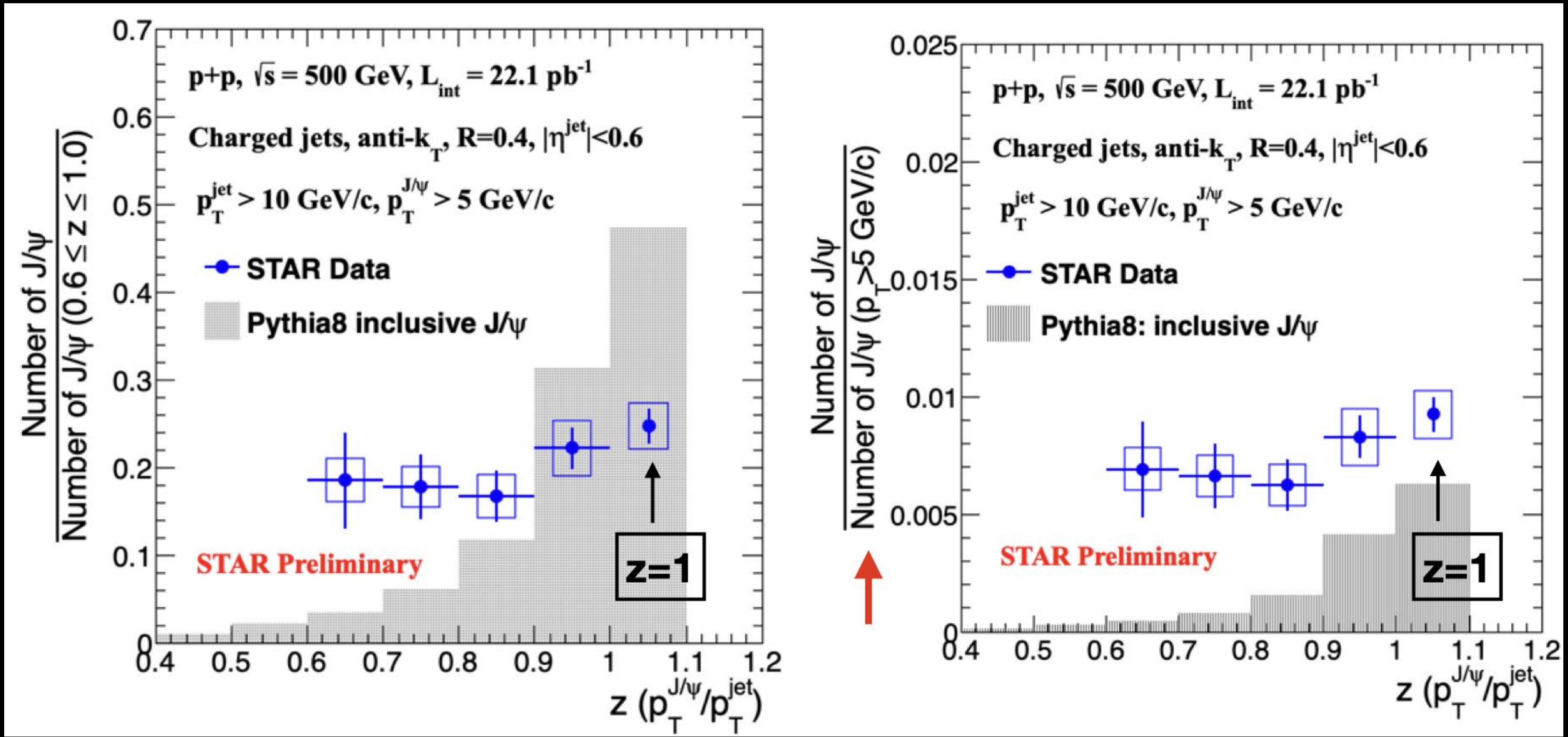




J/ψ Production in a jet

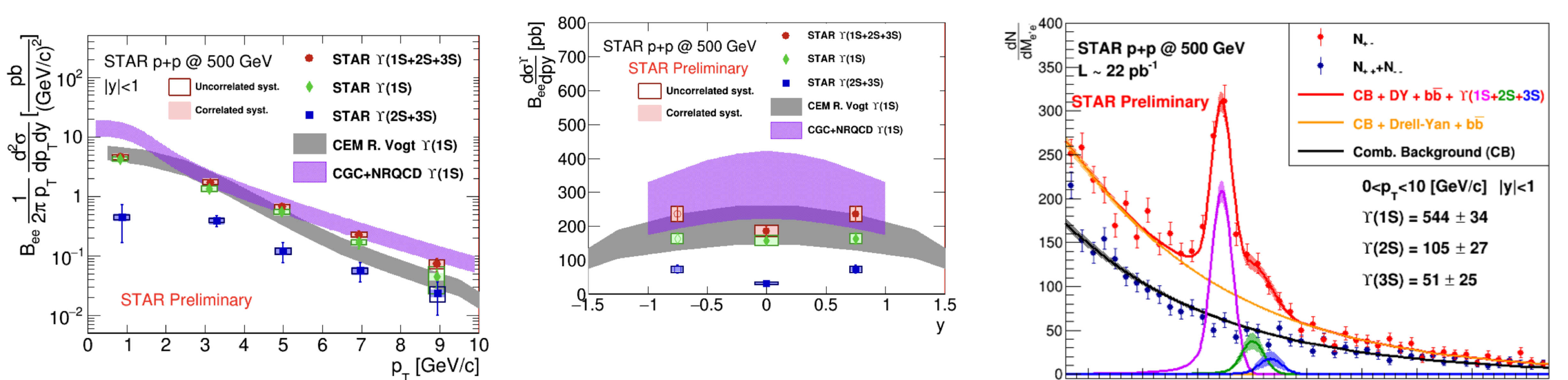


- Charged jet to J/ψ fragmentation function :
  No significant z dependence observed within uncertainties for z <1
- Different trend and probability of producing a J/ψ in charged jet for the measured kinematics range



Υ in p+p Collisions @ 500 GeV

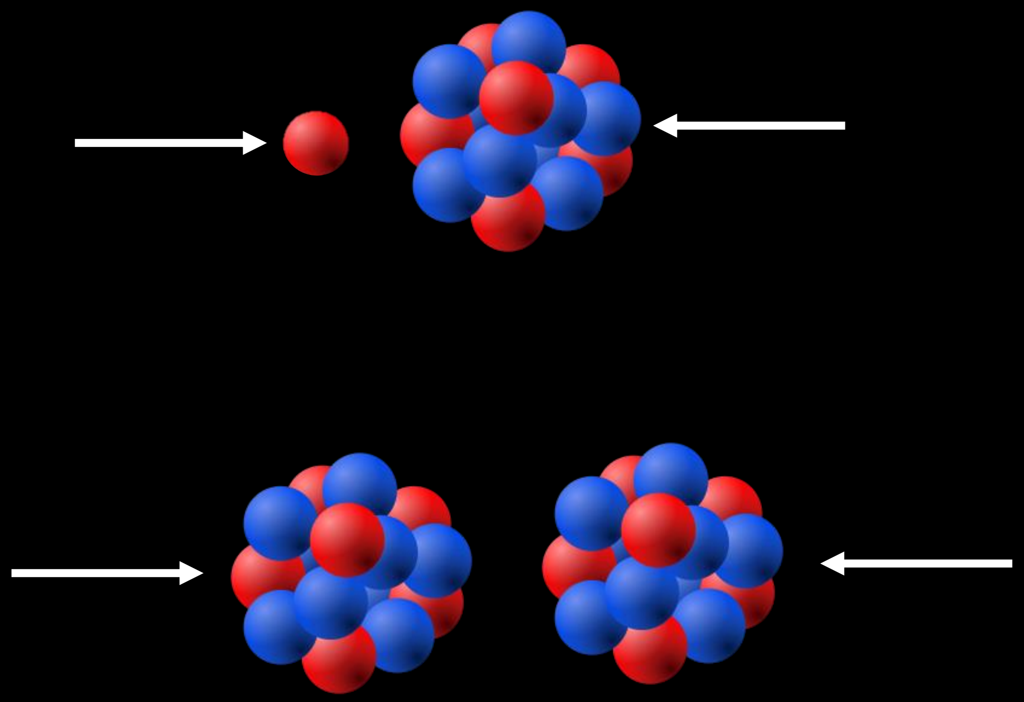
- The inclusive $\Upsilon(1S)$ production can be described by CEM predictions
- CGC+NRQCD calculation including only direct $\Upsilon(1S)$ overestimates the inclusive $\Upsilon(1S)$ measurement



CEM: Phys.Rev.C 92 034909(2015)

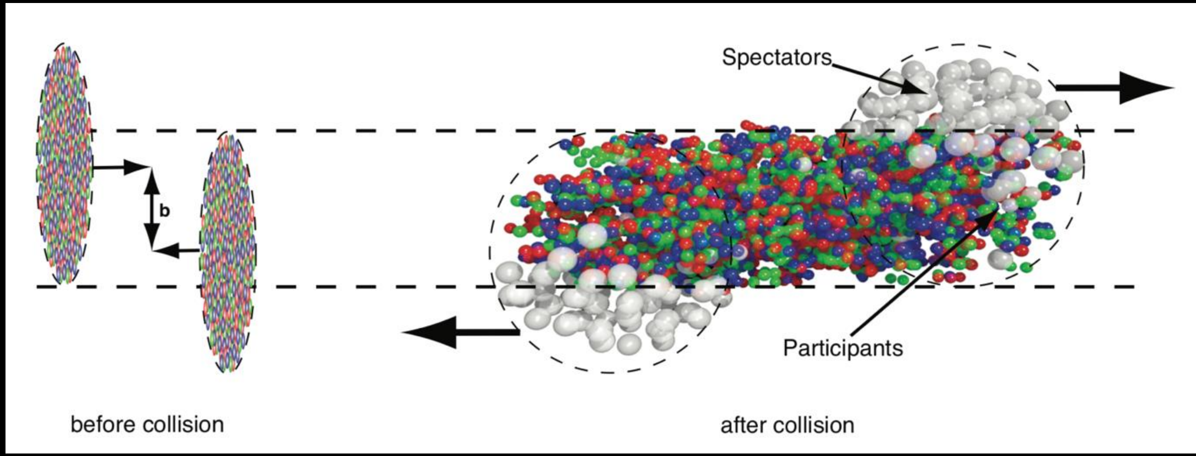
CGC+NRQCD: Phys.Rev.D 94, 014028(2016), Phys.Rev.Lett. 113, 192301(2014)

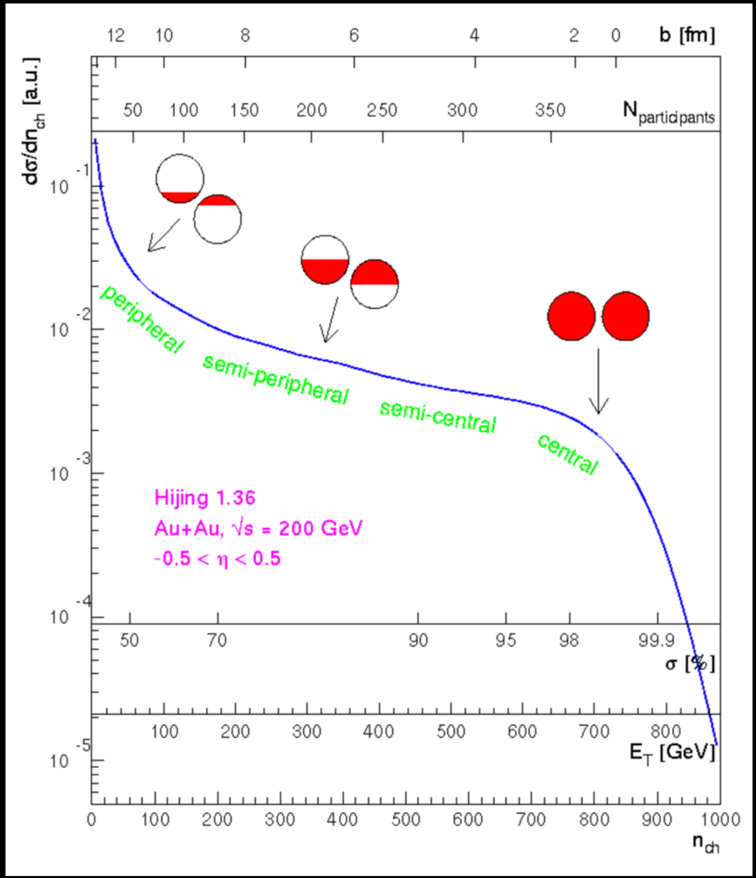
Heavy-Ion Collisions: p+A, A+A



Multiplicity and collision centrality

- The "**centrality**" is determined by the ***impact parameter b***
  - Small *b* (central collision):
    - Many nucleon-nucleon interactions (large N_{coll}), many particles produced (large multiplicity), **big system**
  - Large *b*: (peripheral collision):
    - Few nucleon-nucleon interactions (small N_{coll}), few particles produced (small multiplicity), **small system**





Nuclear Modification Factor (R_{AA})

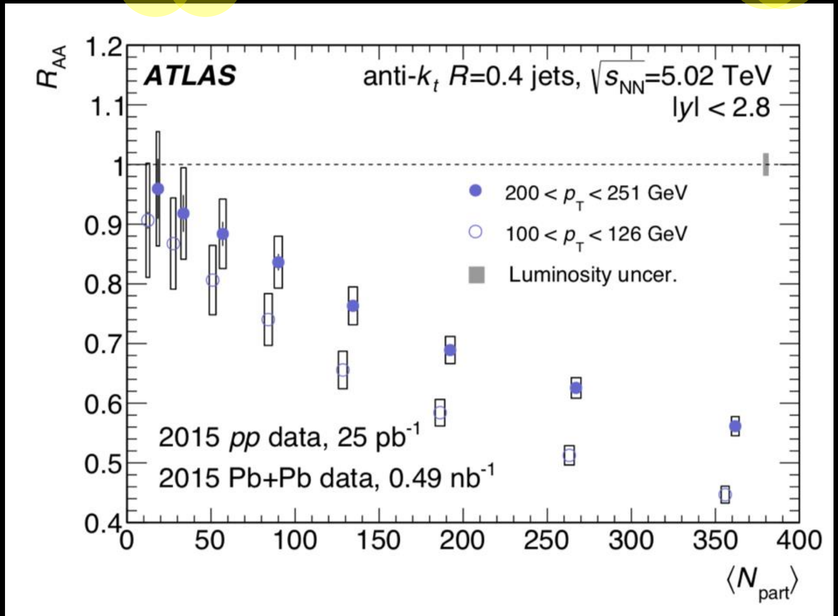
To quantify the effect of QGP:

$$R_{AA} = \frac{1}{T_{AA}} \frac{d^2N_{AA}/dp_T dy}{d^2\sigma_{pp}/dp_T dy}$$

- $d^2N_{AA}/dp_T dy$: the invariant yield of X in A+A collision
- $d^2\sigma_{pp}/dp_T dy$: the cross-section of X in p+p collision
- $T_{AA} = \langle N_{coll}\rangle/\sigma^{pp}_{inel}$

  N_{coll}: the average number of binary nucleon-nucleon collisions

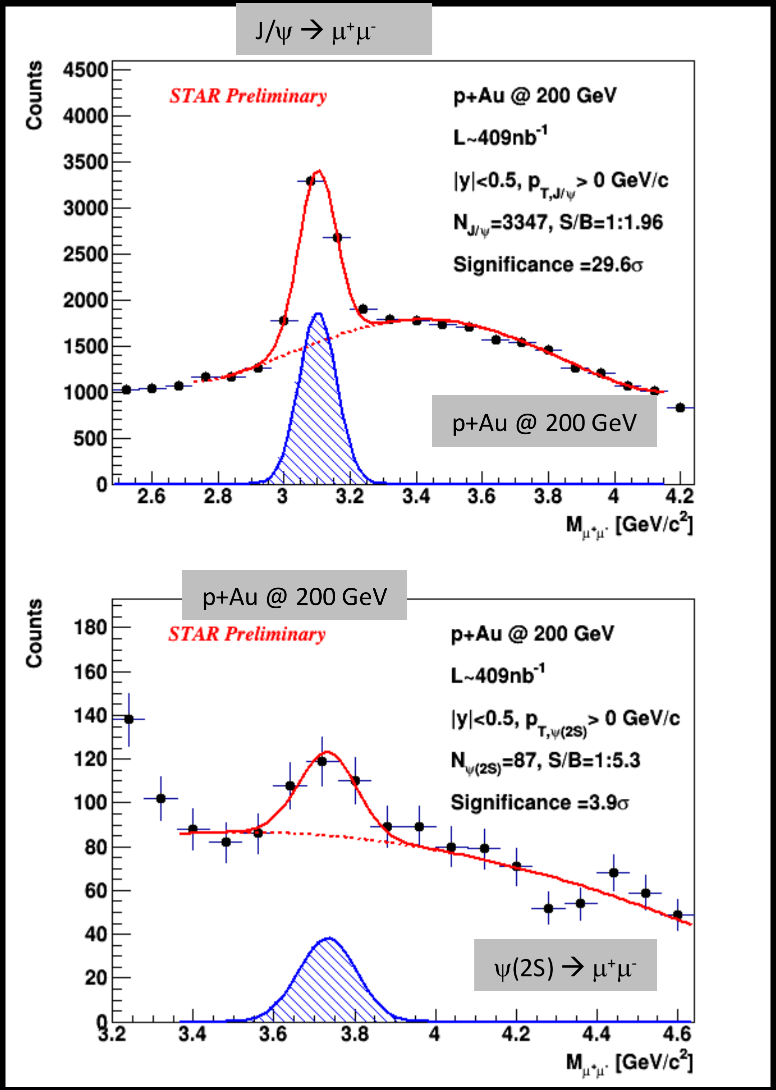
  σ^{pp}_{inel}: the inelastic nucleon-nucleon cross-section

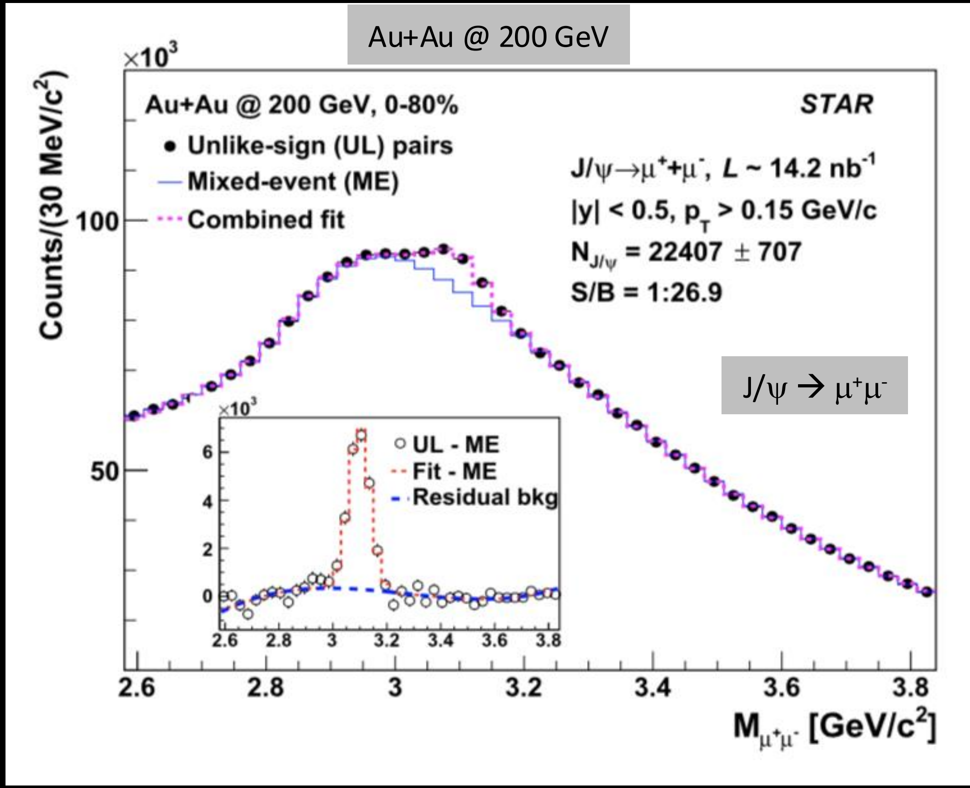


➔Significant suppression at central collisions and for the lower p_T jets

J/ψ & ψ(2S) in p+Au & Au+Au @ 200 GeV

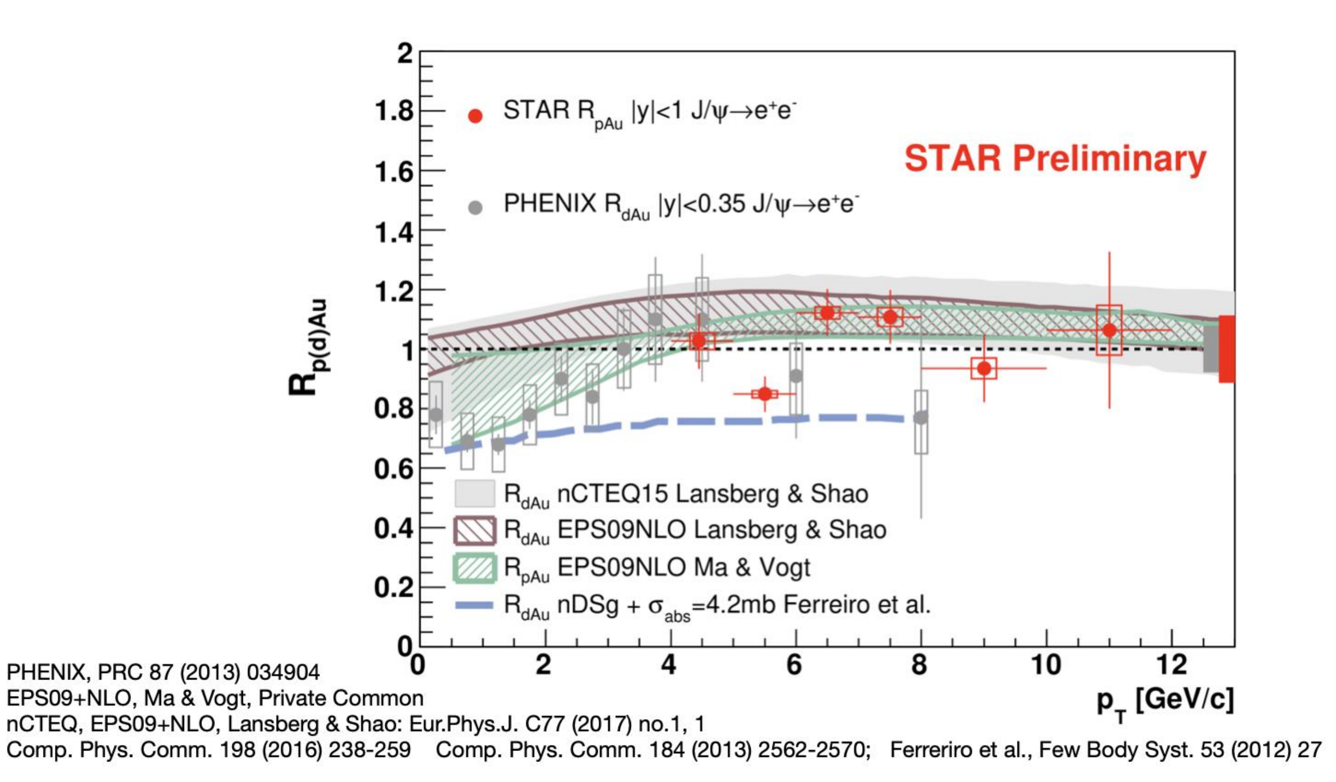
- Clear J/ψ and ψ(2S) signals in p+Au and Au+Au collisions

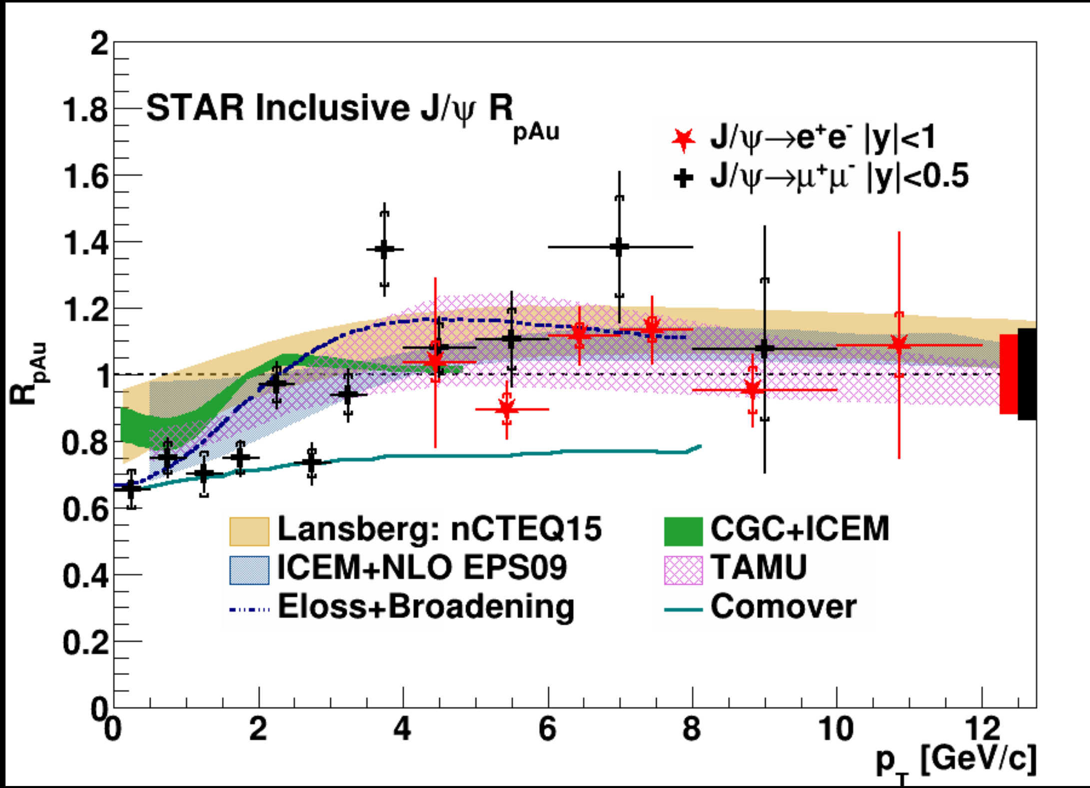




J/ψ R_{pAu} vs. p_T at 200 GeV

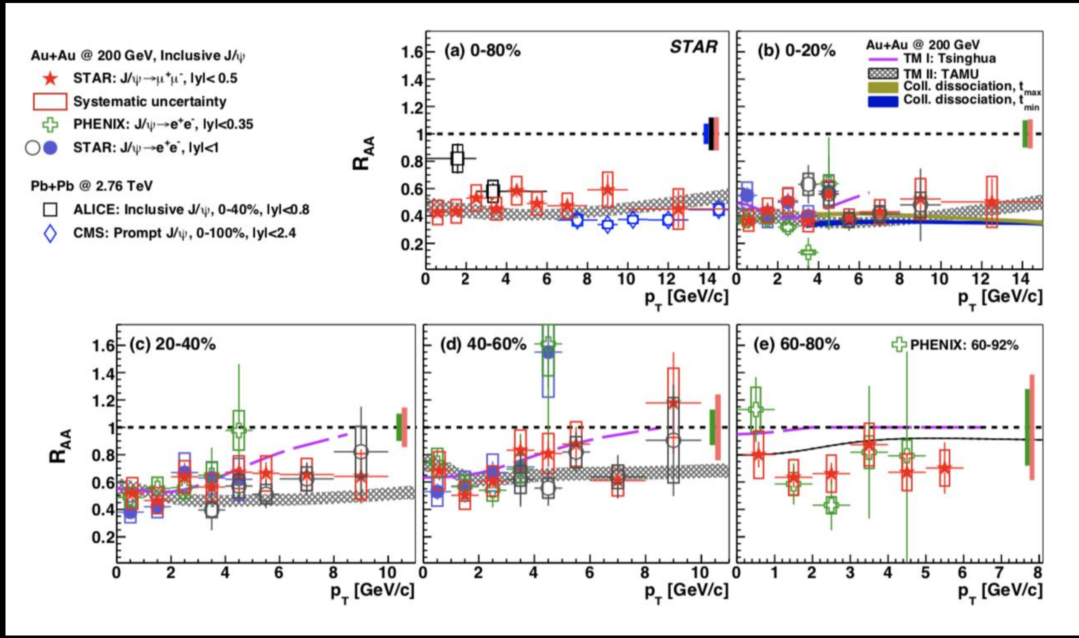
- R_{pAu} from STAR has similar trend as R_{dAu} from PHENIX
  - ➔ Similar CNM effects in p+Au and d+Au
- The model calculation with additional nuclear absorption on top of nuclear PDF effects can qualitatively describe the data

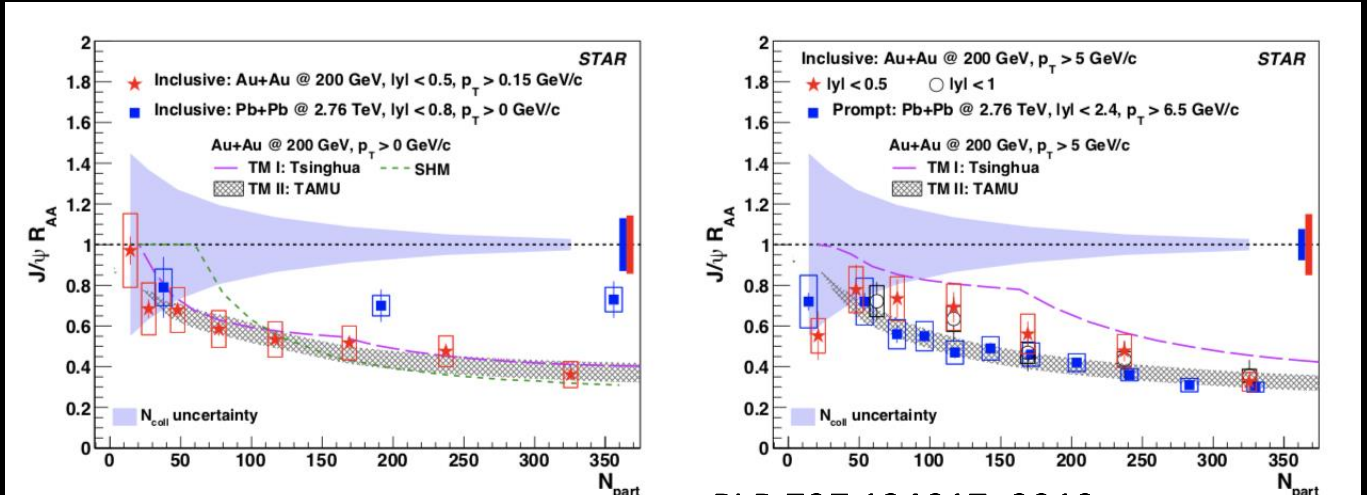




J/ψ R_{AA} vs. p_T at 200 GeV

- No obvious p_T dependence in R_{AA} in 0 - 20% centrality bin
- Suppression at low p_T: dissociation, Cold Nuclear Matter (CNM) effect, regeneration
- Strong suppression at high p_T in central collisions is a clear sign of dissociation
- RHIC vs. LHC
  - p_T > 0 GeV/c: larger contribution from regeneration at LHC
  - p_T > 5 GeV/c: larger dissociation rate at LHC

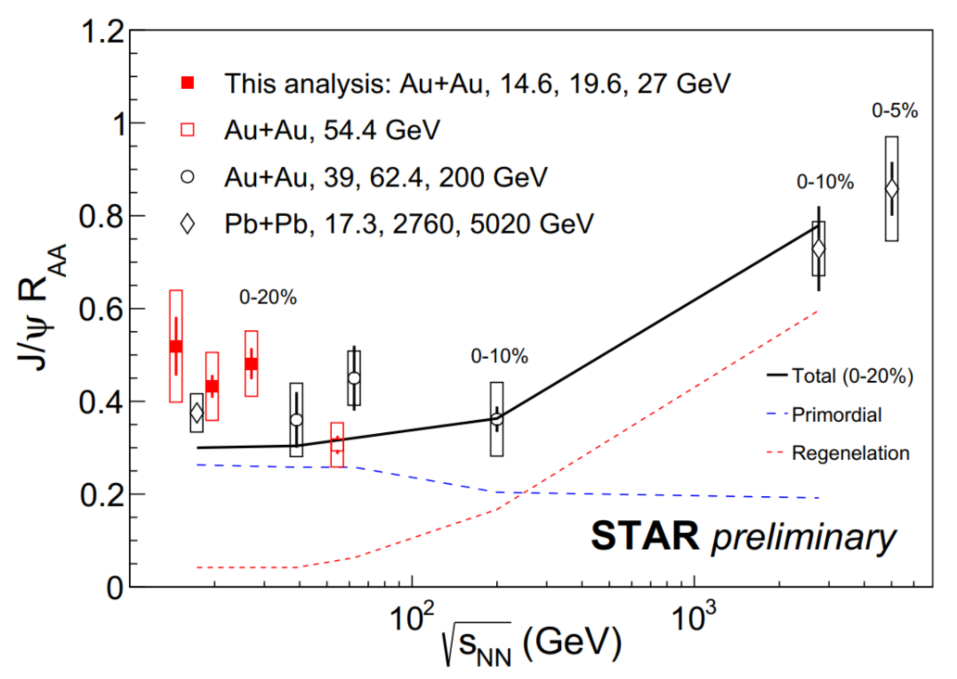


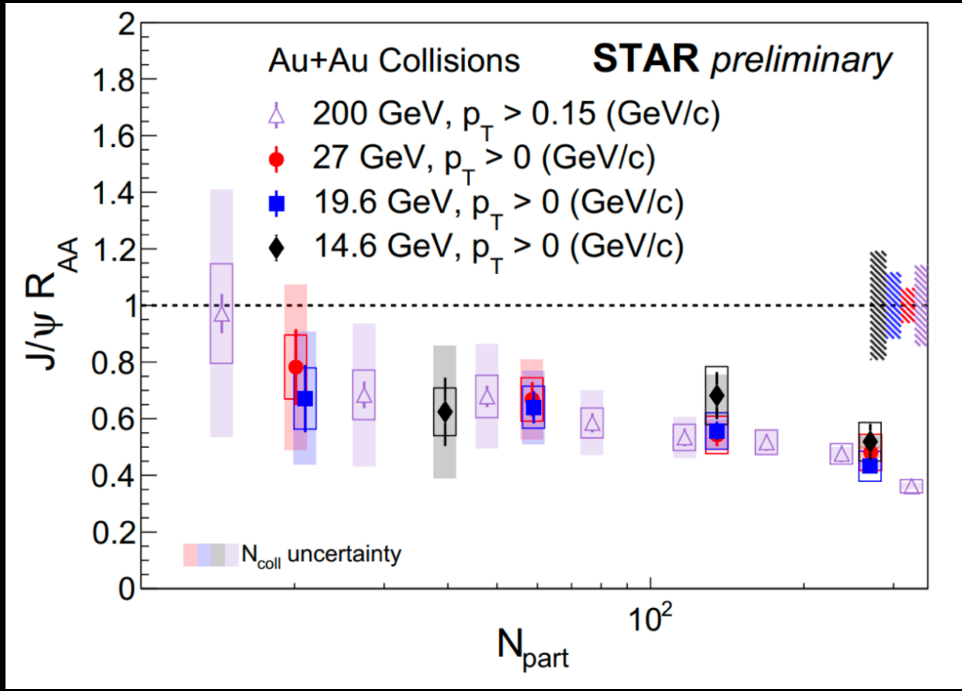


PLB 797 134917, 2019

Energy Dependence of J/ψ R_{AA}

- Data at $\sqrt{s_{NN}}$ = 14.6, 19.6 and 27 GeV follow global trend
- No significant energy dependence of J/ψ R_{AA} in central collisions is observed within uncertainties up to 200 GeV
- Regeneration dominates at LHC energies
- Model qualitatively describes the observed energy dependence
- R_{AA} shows no significant energy dependence at RHIC for similar <N_{part}>

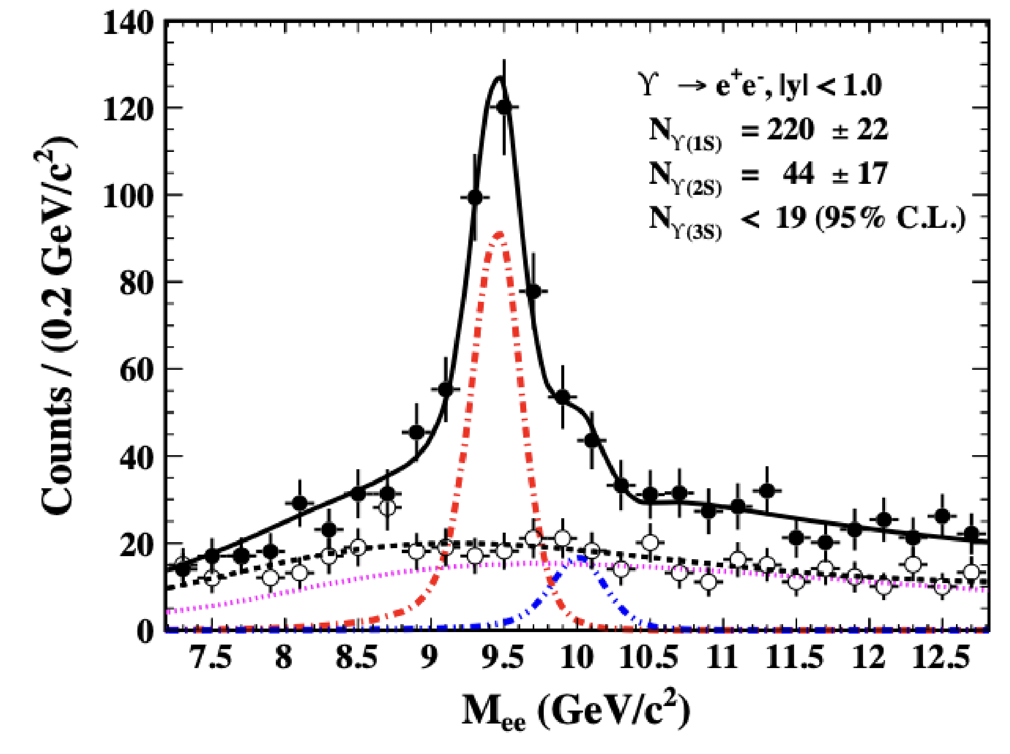




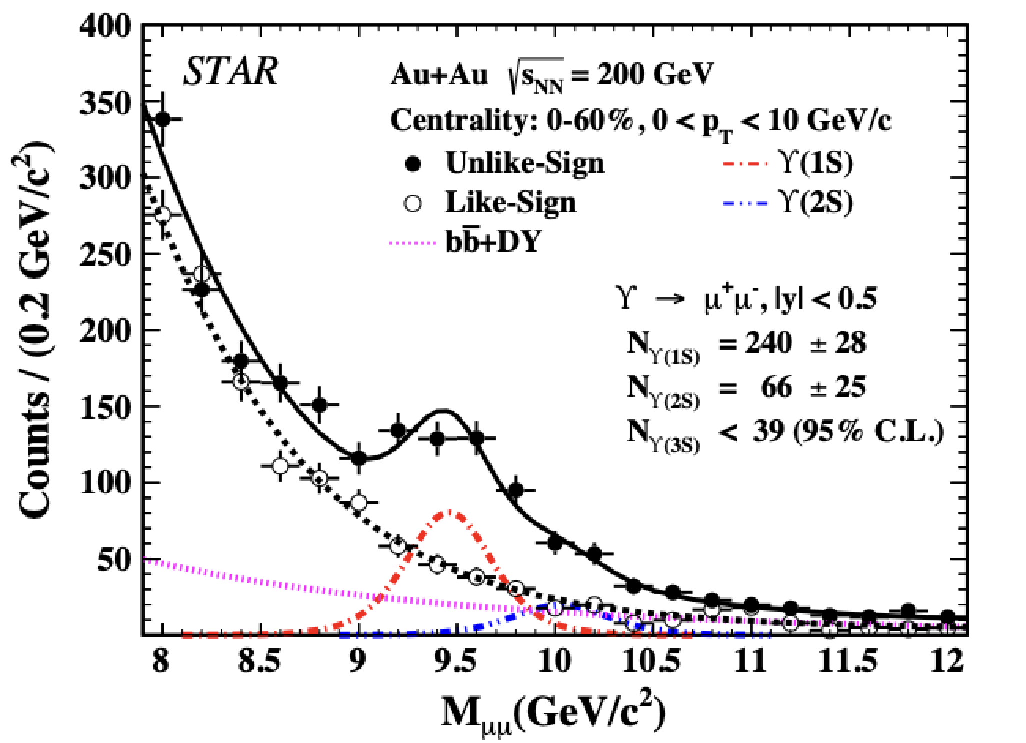
Υ in Au+Au Collisions @ 200 GeV

- Clear Υ(1S, 2S, 3S) signals in Au+Au collisions
  - ➔ First Υ(1S, 2S, 3S) → $\mu^+\mu^-$ measurement at STAR

$\Upsilon \rightarrow e^+e^-$



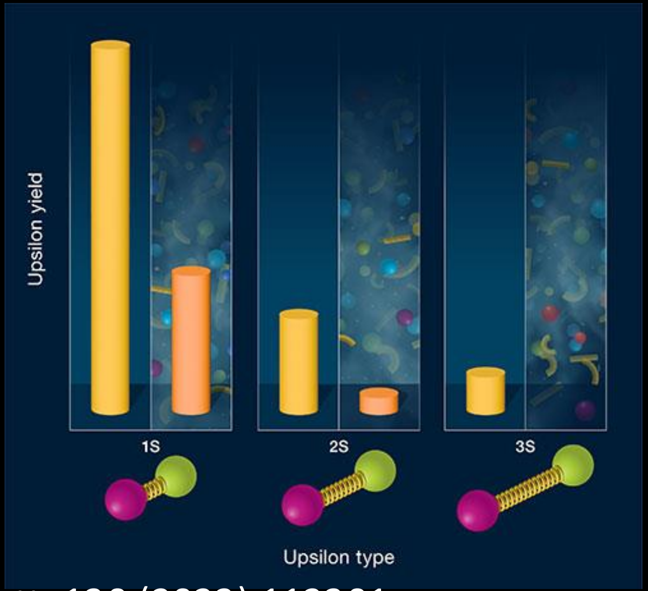
$\Upsilon \rightarrow \mu^+\mu^-$

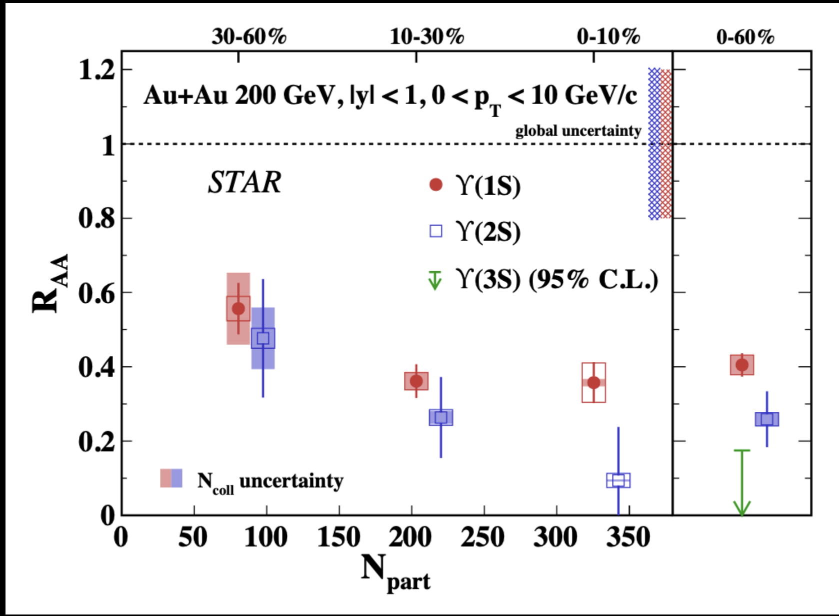


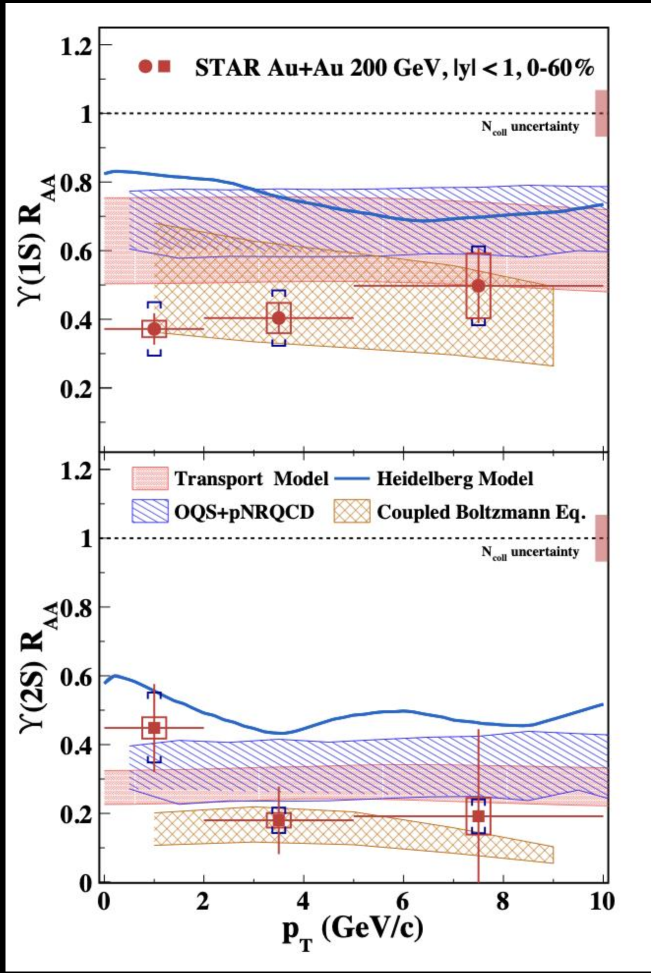
Υ R_{AA} vs. N_{part}

First time @ RHIC

- Suppression increasing with centrality
- Υ(2S+3S) is more suppressed than Υ(1S), in central collisions
  - ➔ **Sequential melting**
- RHIC vs. LHC:
  - Υ(1S): similar suppression as the CMS measurement
  - Υ(2S+3S): hint of less suppression at RHIC than at LHC





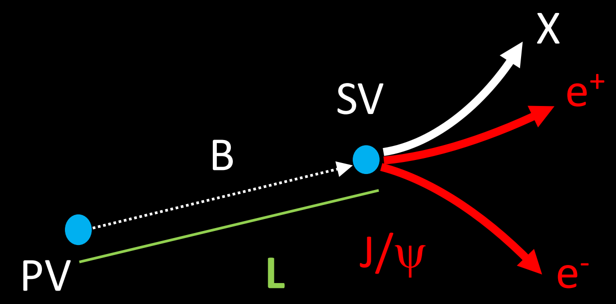


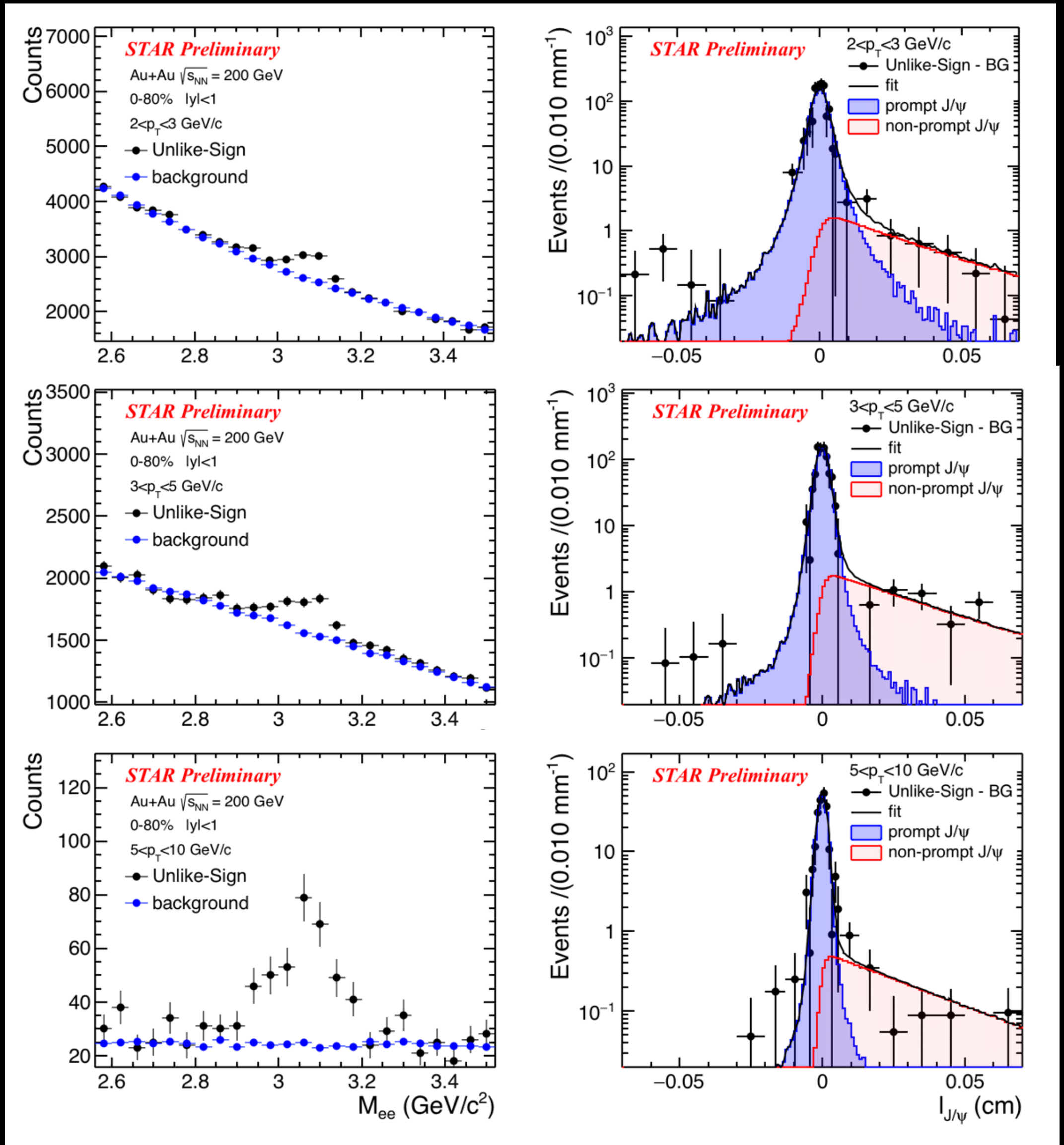
Phys. Rev. Lett. 130 (2023) 112301

Extract Non-prompt J/ψ Fraction

- Fit the distribution of the pseudo proper decay length with templates to extract non-prompt J/ψ fraction
- Pseudo proper decay length:

$$l_{J/\psi} = \frac{\vec{L}\cdot\hat{p}}{|\vec{p}|/c}\cdot M_{J/\psi}$$

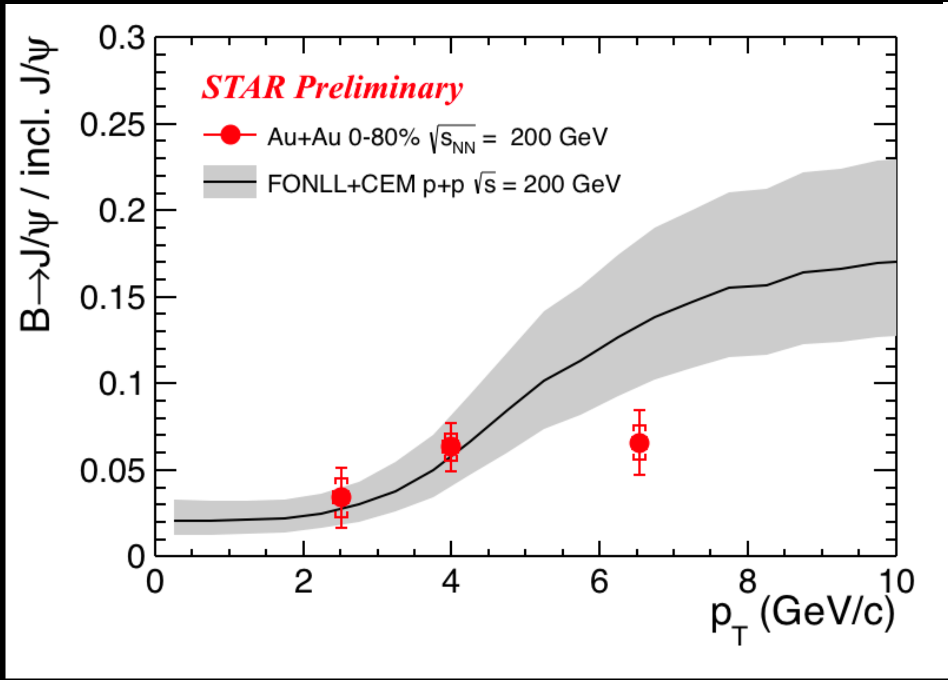


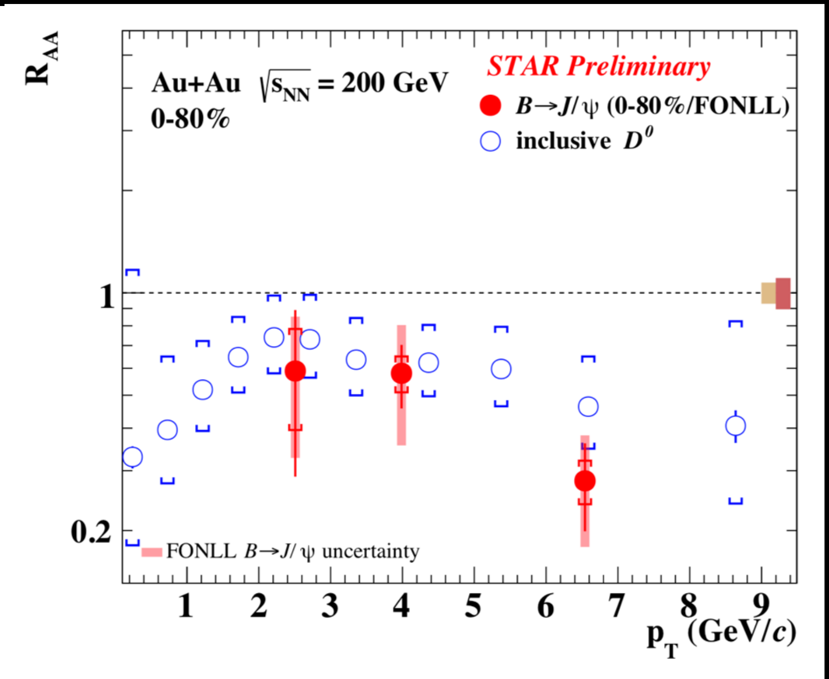


Non-prompt J/ψ Fraction and R_{AA}

- $R_{AA}^{B\rightarrow J/\psi} = \frac{f_{Au+Au}^{B\rightarrow J/\psi}(Data)}{f_{p+p}^{B\rightarrow J/\psi}(Theory)} R_{AA}^{inc.J/\psi}(Data)$

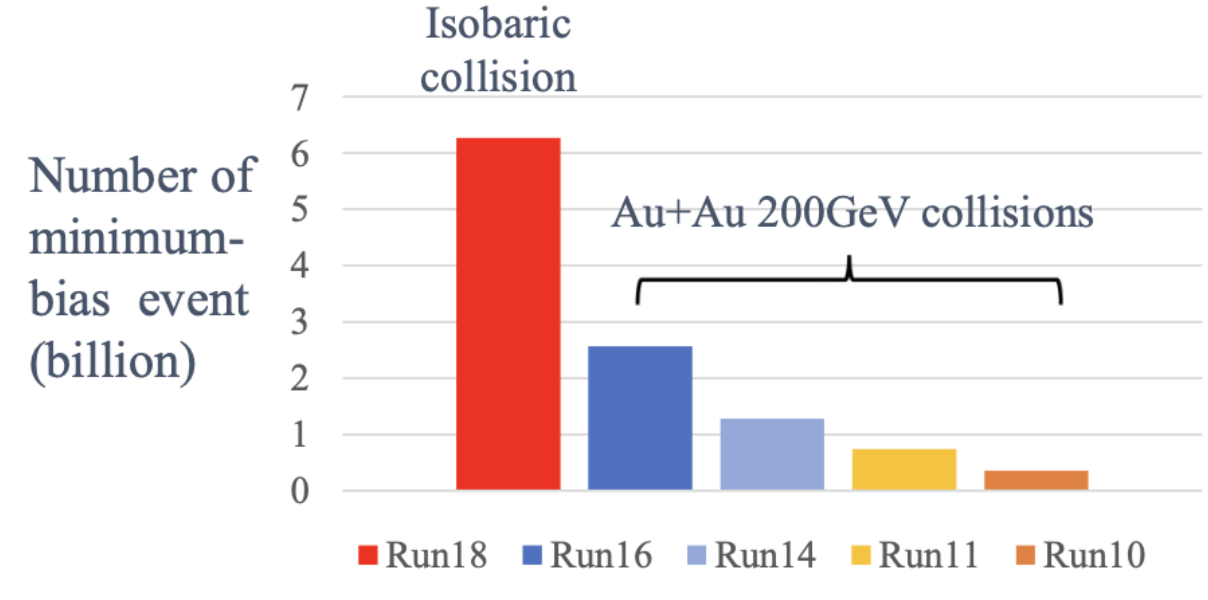
- Observe strong suppression of B → J/ψ at high p_T (> 5 GeV/c)
- Similar to inclusive D^0 R_{AA}

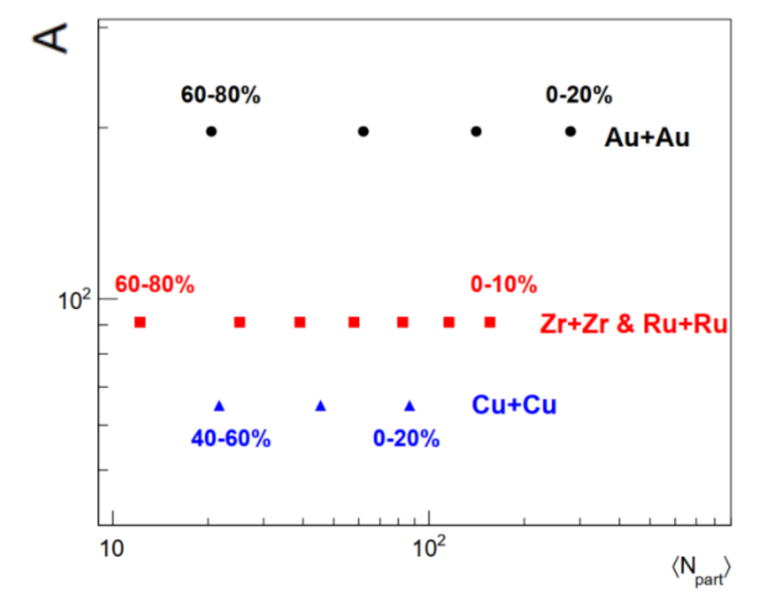




Zr+Zr & Ru+Ru Collisions at 200 GeV

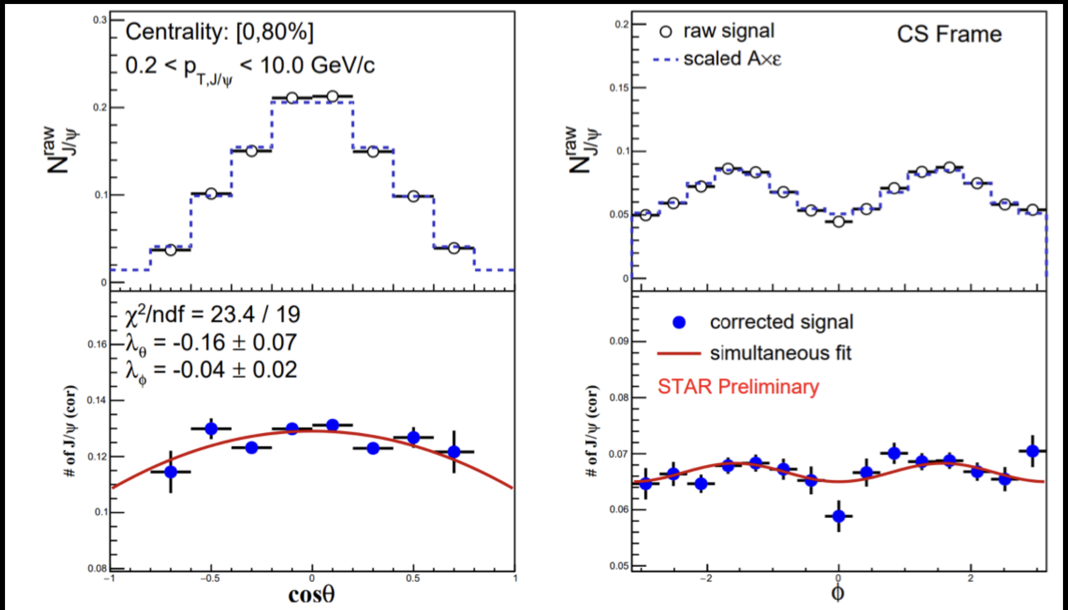
- High statistics enables measurements of:
  - J/ψ production with high precision
  - Sequential suppression of J/ψ, ψ(2S), Υ(1S), Υ(2S)
  - J/ψ polarization
- A moderate size collision system
  - Unique opportunity to study the system size dependence

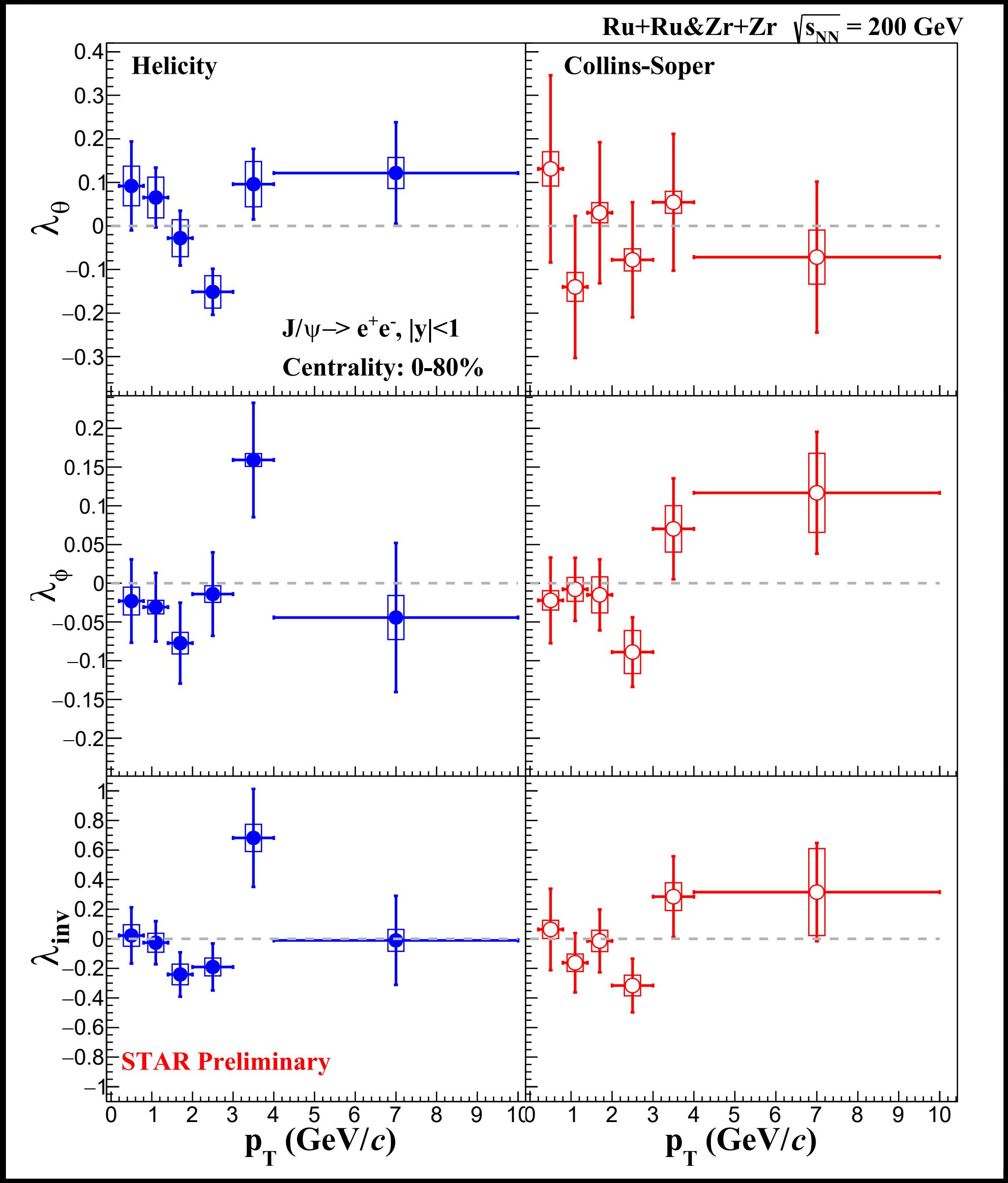




J/ψ Polarization in Zr+Zr & Ru+Ru Collisions

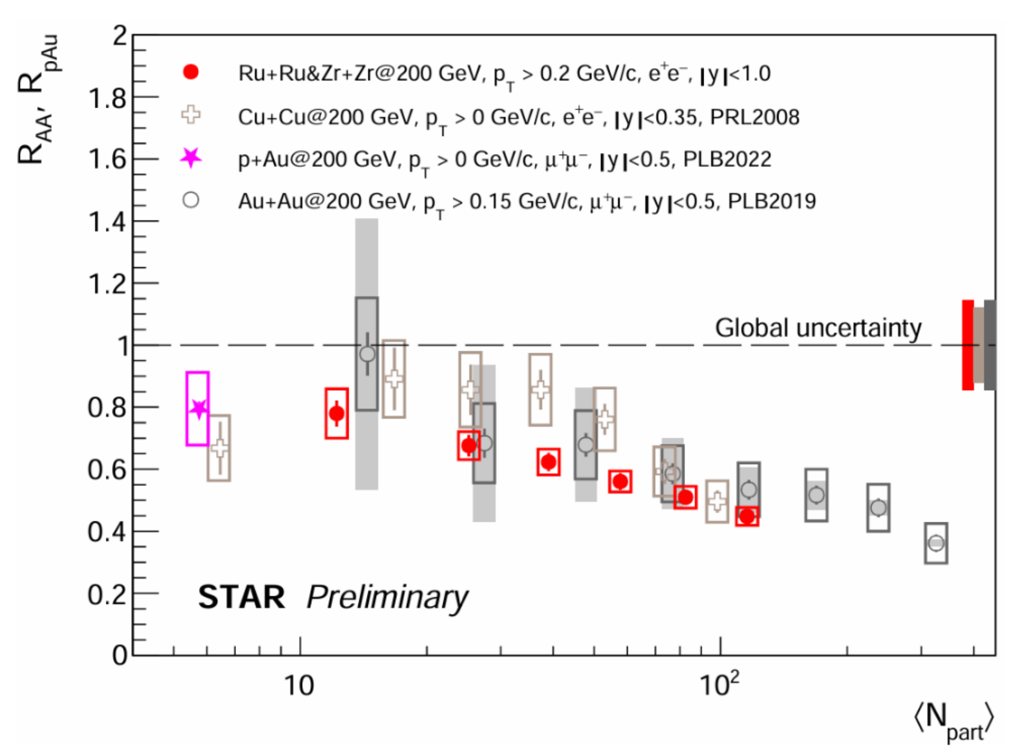
- First measurement of J/ψ polarization in heavy-ion collisions at RHIC
  - J/ψ : $0.2 < p_T < 10$ GeV/c, |y|<1
- J/ψ polarization vs p_T:
  - λ_θ, λ_ϕ consistent with zero in HX and CS frames
  - Hint of a non-trivial p_T dependence.

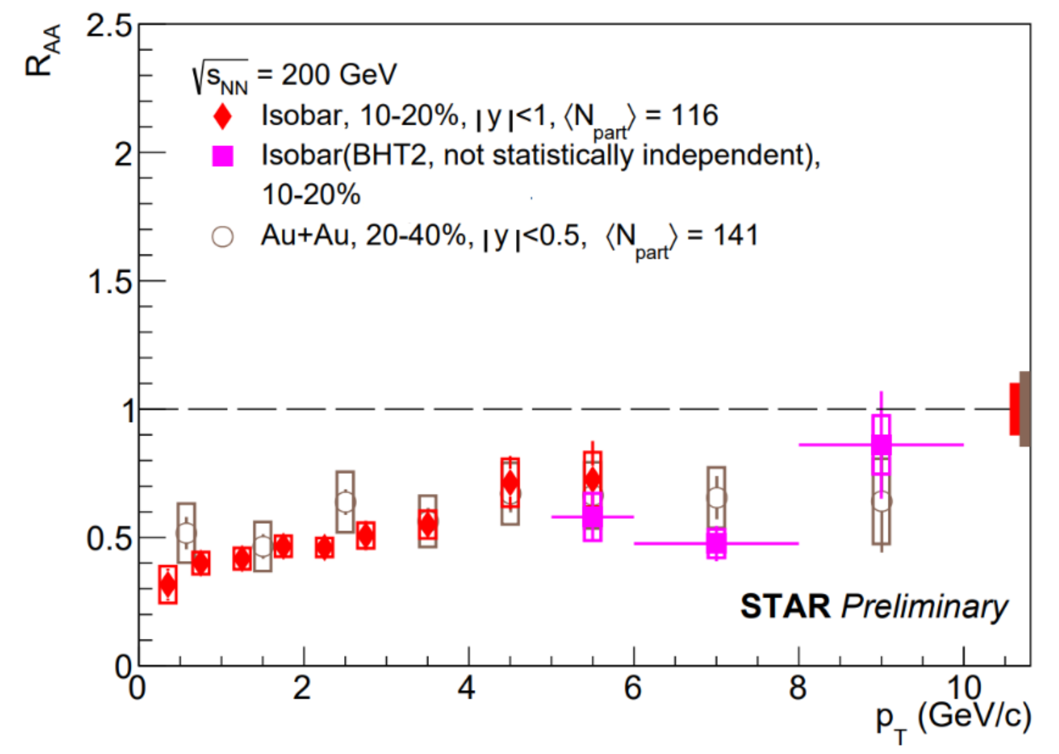




J/ψ R_{AA} in Zr+Zr & Ru+Ru Collisions

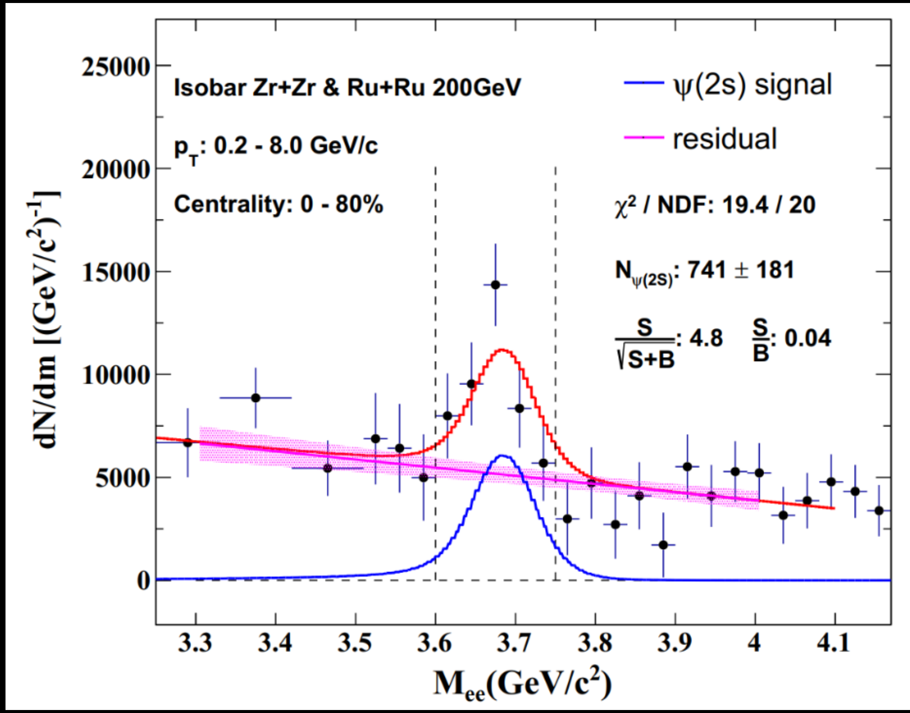
- Highest precision measurement at RHIC to date
- No significant collision system dependence observed at RHIC
  - ➔ Driven by overlap size rather than collision geometry
- Consistent with Au+Au results at similar N_{part} range

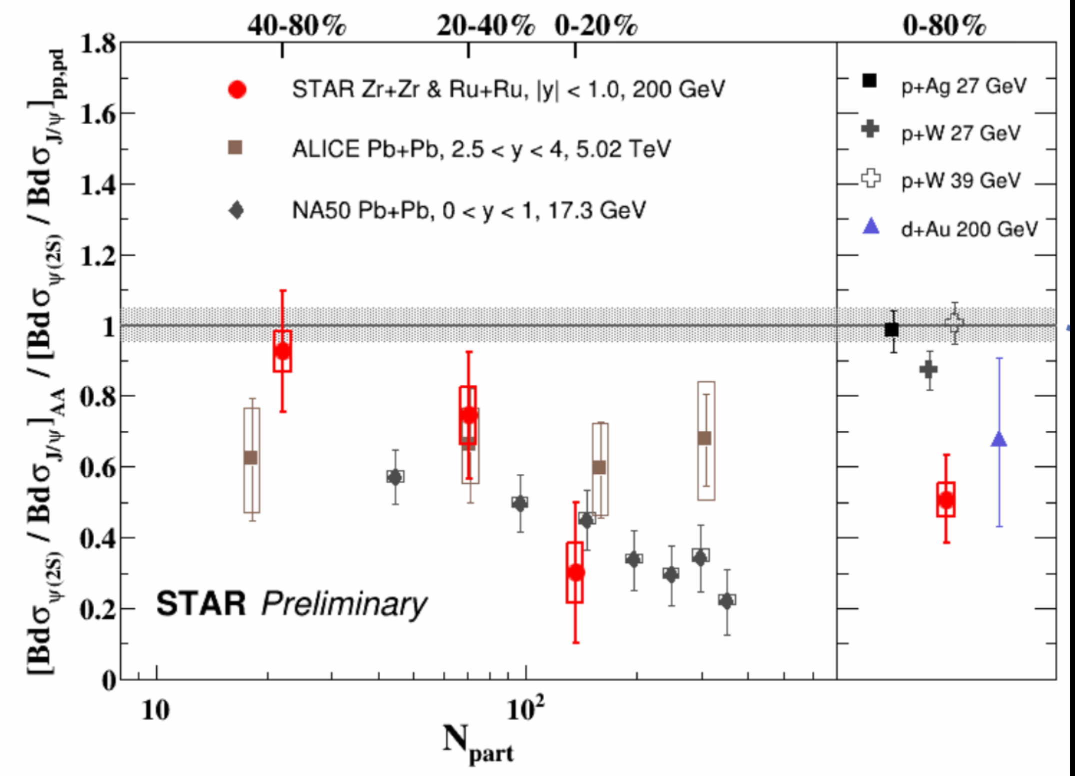




$\psi(2S)$ R_{AA} in Zr+Zr & Ru+Ru Collisions

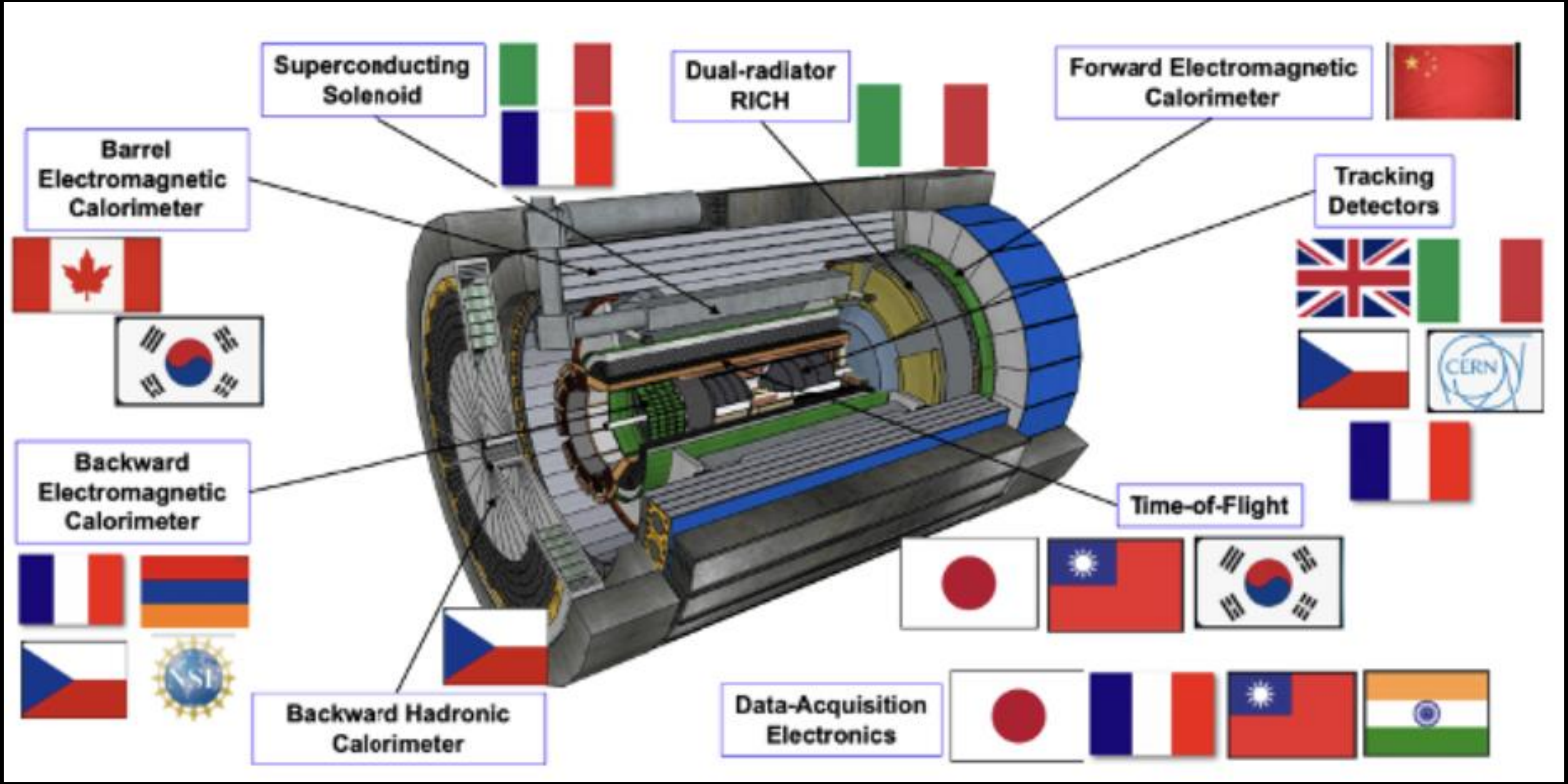
- First observation of charmonium sequential suppression in heavy-ion collisions at RHIC (3.5σ, 0-80%)
- $\psi(2S)$ over J/ψ double ratio is smaller than that in p+A collisions
- Centrality dependence trend seems to be more similar to that at SPS than at LHC





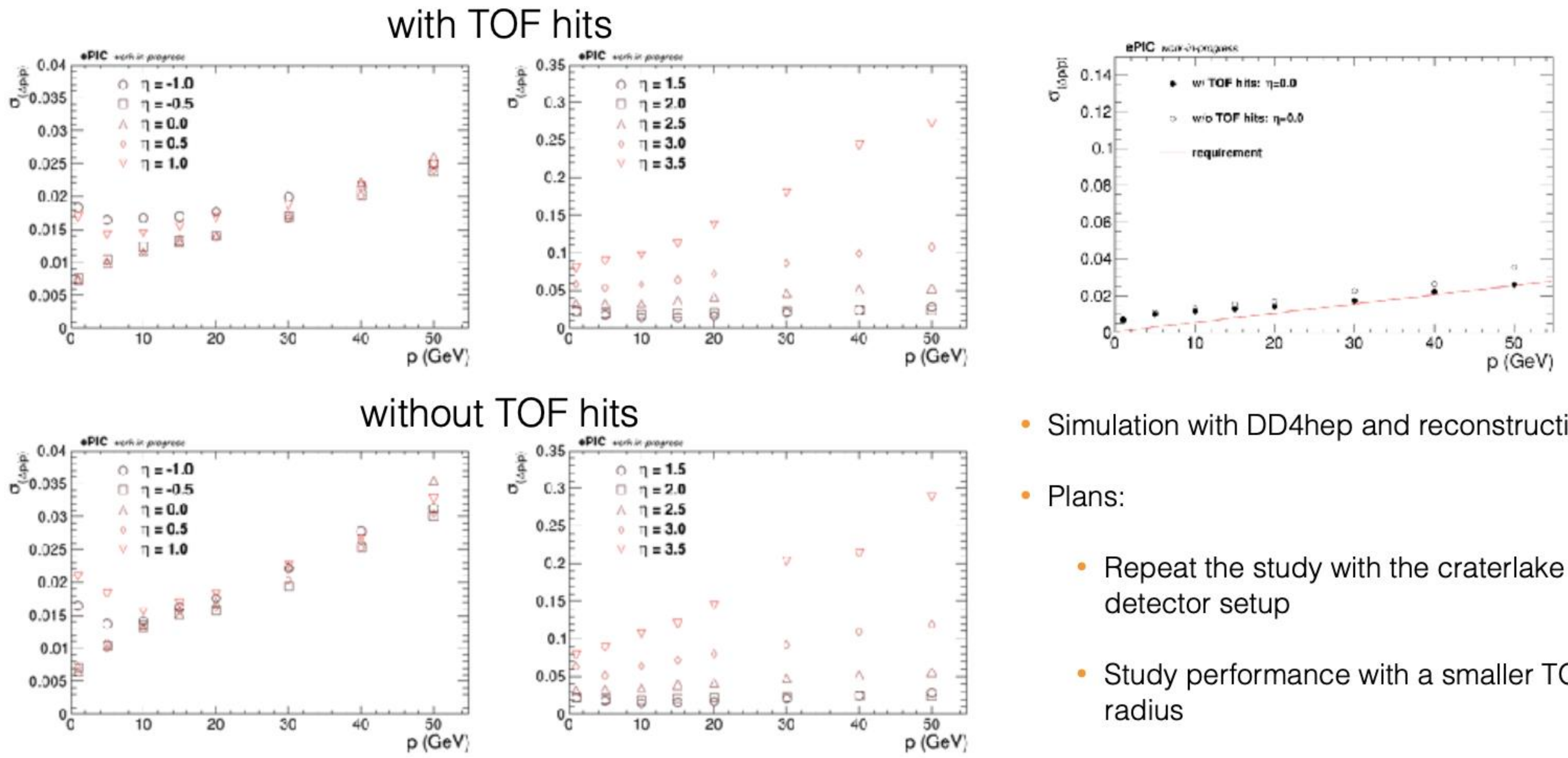
EIC/ePIC Activities in Taiwan

TOF Participation



TOF Performance Study

- Started to study the impact of AC-LGAD on the momentum resolution at ePIC
- Goal: optimize the pad size of the AC-LGAD sensors if it's needed



- Simulation with DD4hep and reconstruction
- Plans:
  - Repeat the study with the craterlake detector setup
  - Study performance with a smaller TOF radius

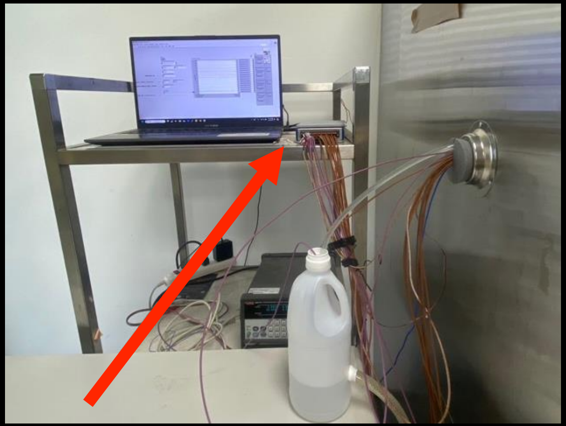
AS-NCKU-Purdue Team

- **Yi Yang (NCKU), Wen-Chen Chang (AS) & Po-Ju Lin (NCU): design, simulation, testing**
  - Experiences with the AMS-02 UTTPS radiator and lead the project of the mechanical structure of STAR FST
  - Excellent machine shop

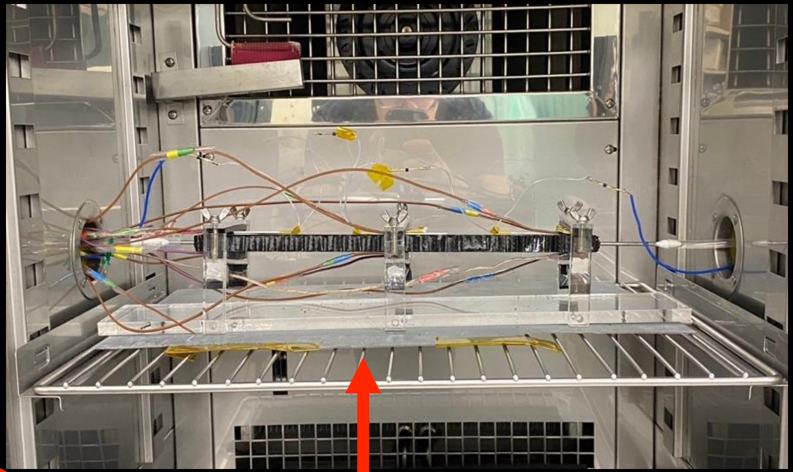
- **Andreas Jung (Purdue): design, simulation, prototype**
  - Experienced in R&D for low mass support structures.
  - Working on the light-weight composite tracker support structures for CMS

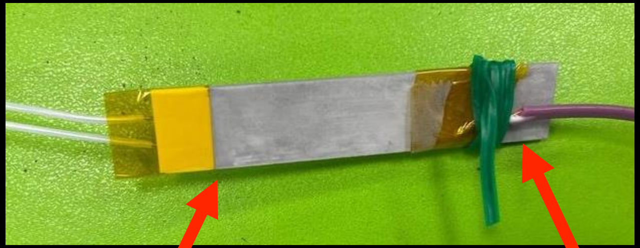
Yu-Tang Wang (NCKU)

Thermal Test Setup @ NCKU



NI 9213 DAQ
- 16 channels
- Accuracy:
  - High-resolution mode : <0.02 ˚C
  - High-speed mode : <0.25 ˚C





Environmental chamber
- Inner dimensions: 40 x 50 x 60 cm^3
- Temperature: -40 ˚C ~ 100 ˚C (± 0.2 ˚C)
- Humidity: 10% ~ 98% (± 2.5%)

Flow meter
- 20 – 300 cc/min

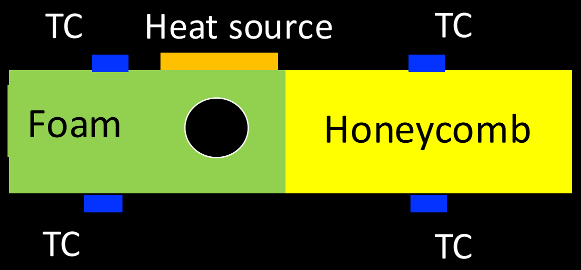
Heat source (x 9)
- Ceramic plate (5Ω): ~500˚C

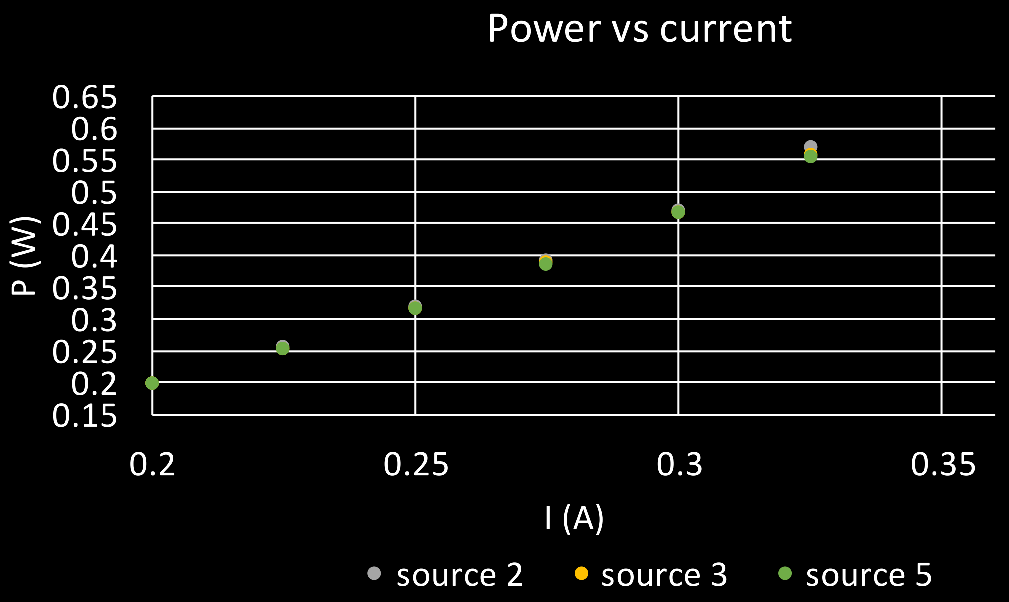
Thermocouple (x 16)
- Type E: -250˚C ~ 900˚C

Cooling system
- Temperature: 3 ˚C ~ 32 ˚C

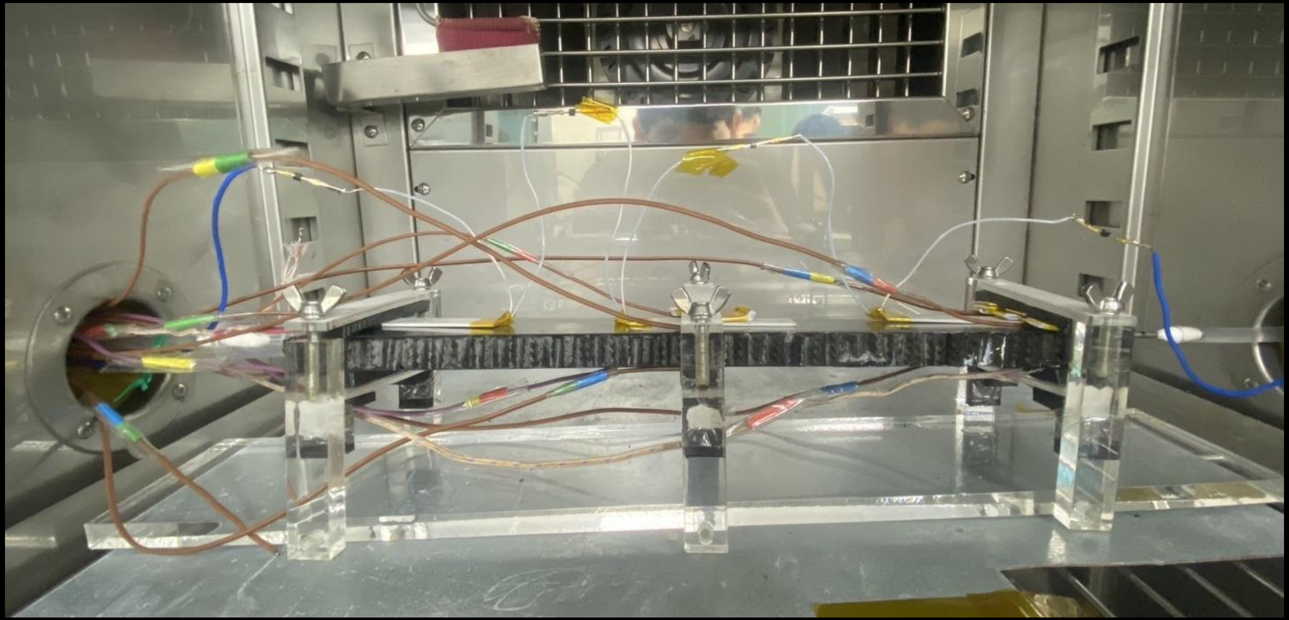
Thermal Test Setup @ NCKU

3D-printed holder



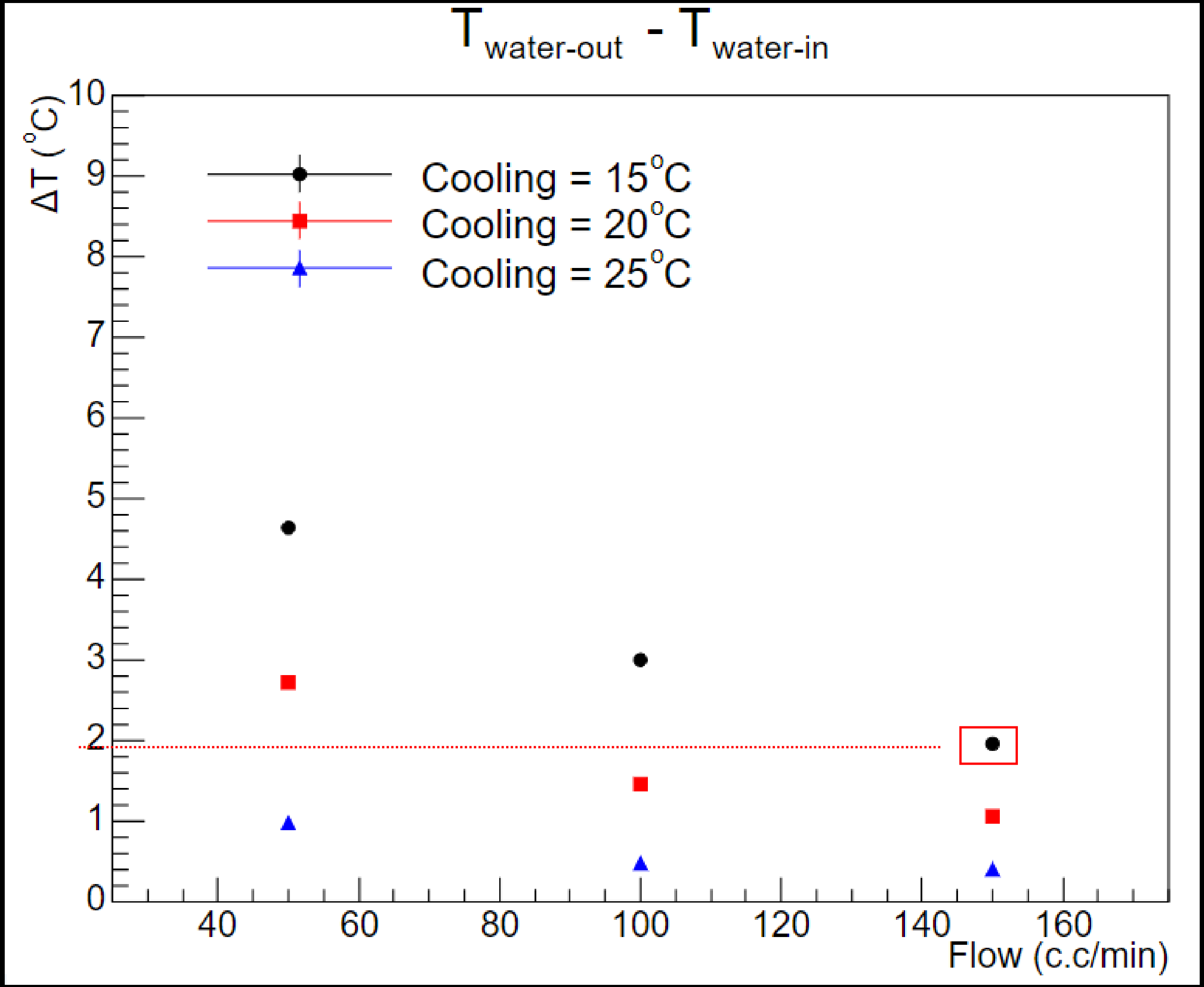


Water out



Water in

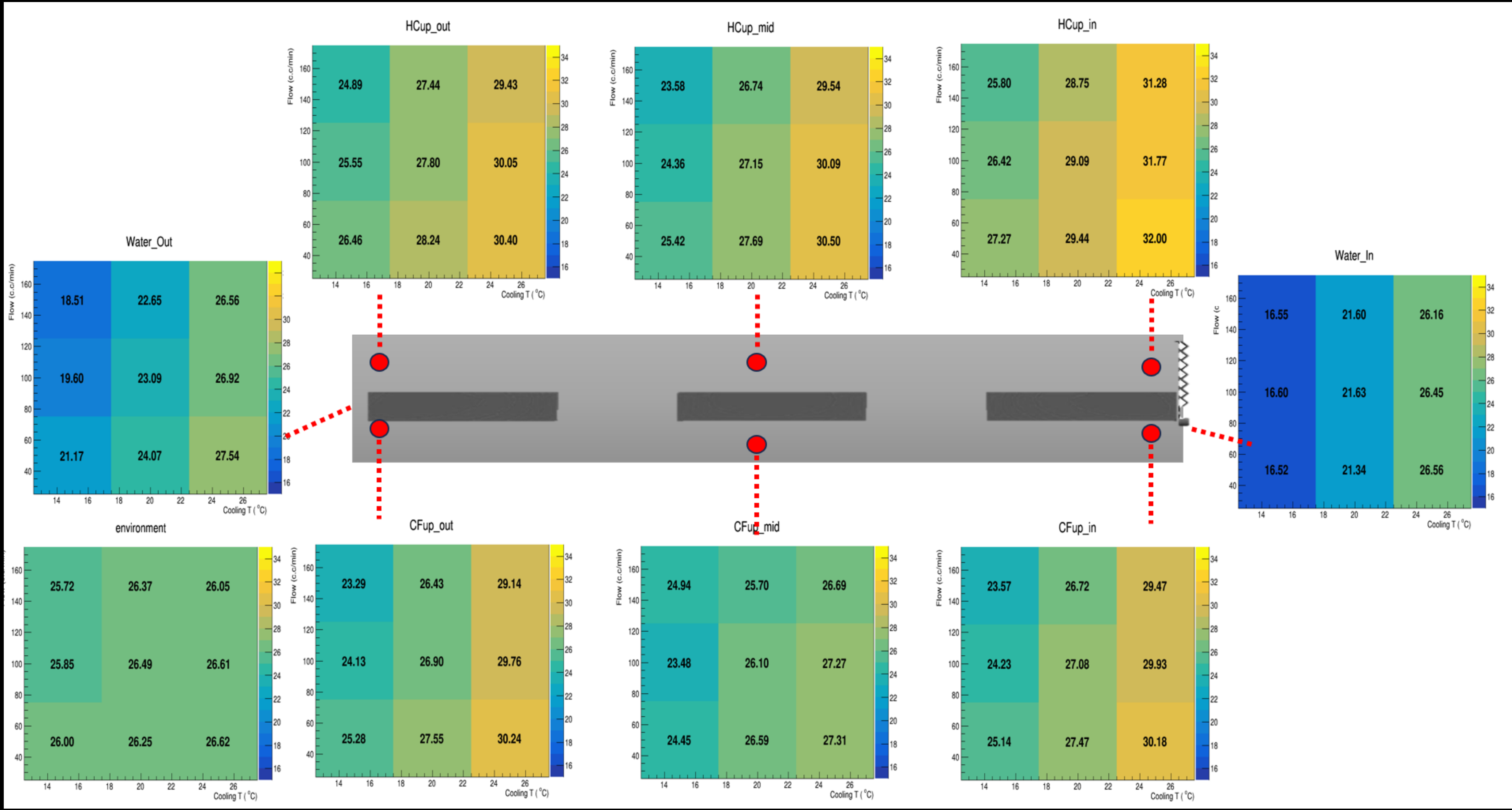
ΔT between Water-in and -out



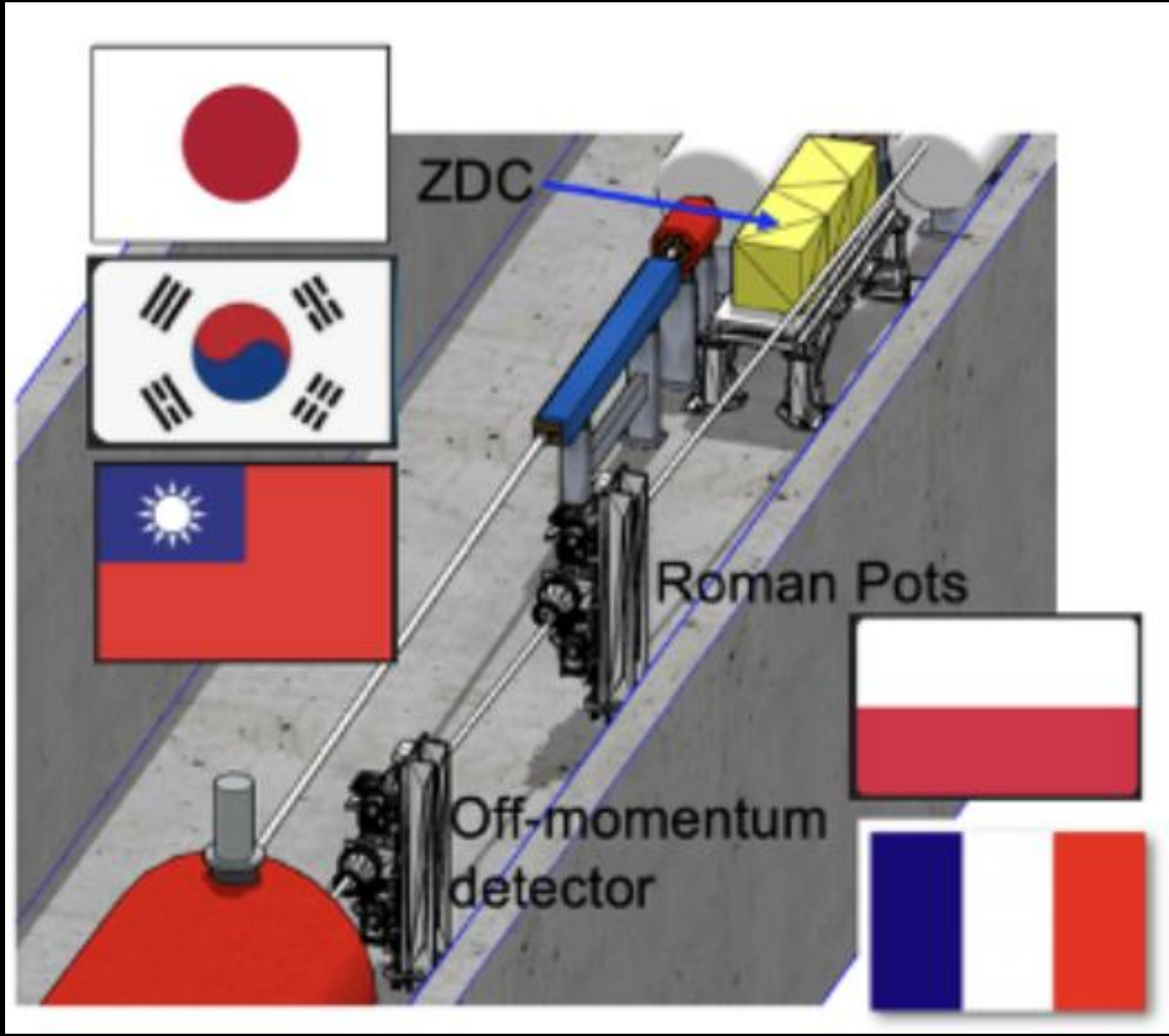
1.96

Temperature in different Flow Rate and Cooling Temperature

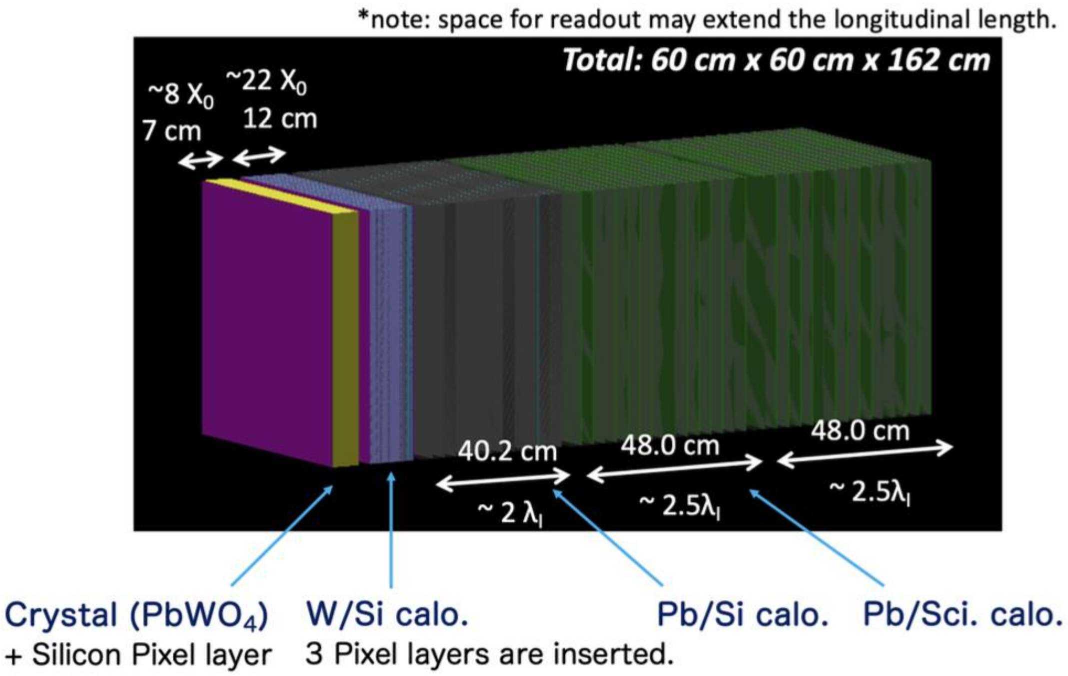
Power: 6 W, top



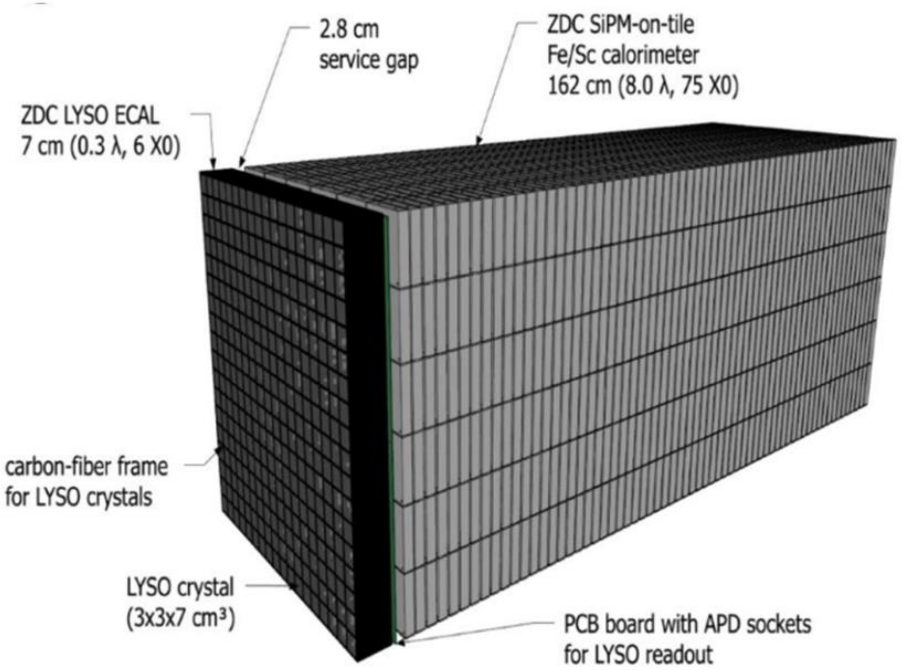
ZDC Participation



ZDC Design

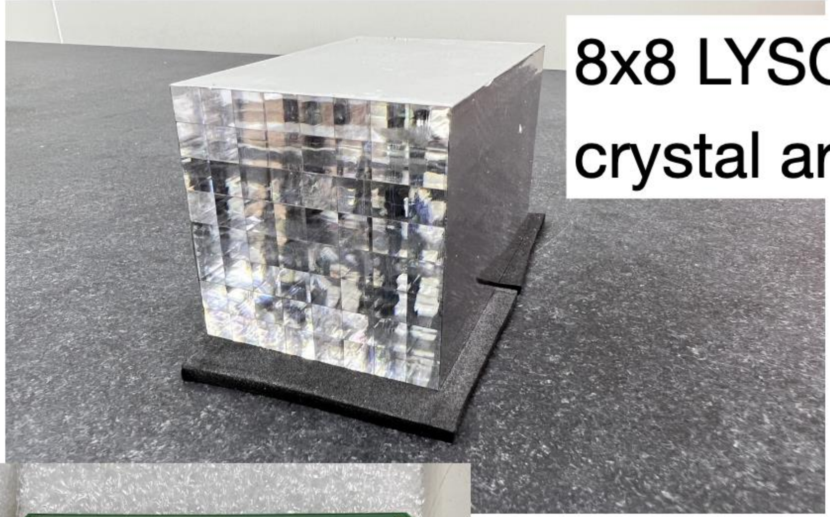


Originally proposed ZDC

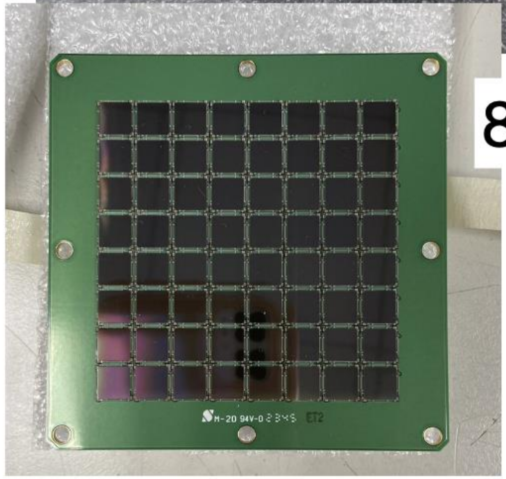


Recently proposed ZDC

ZDC ECAL Prototype with LYSO Crystals

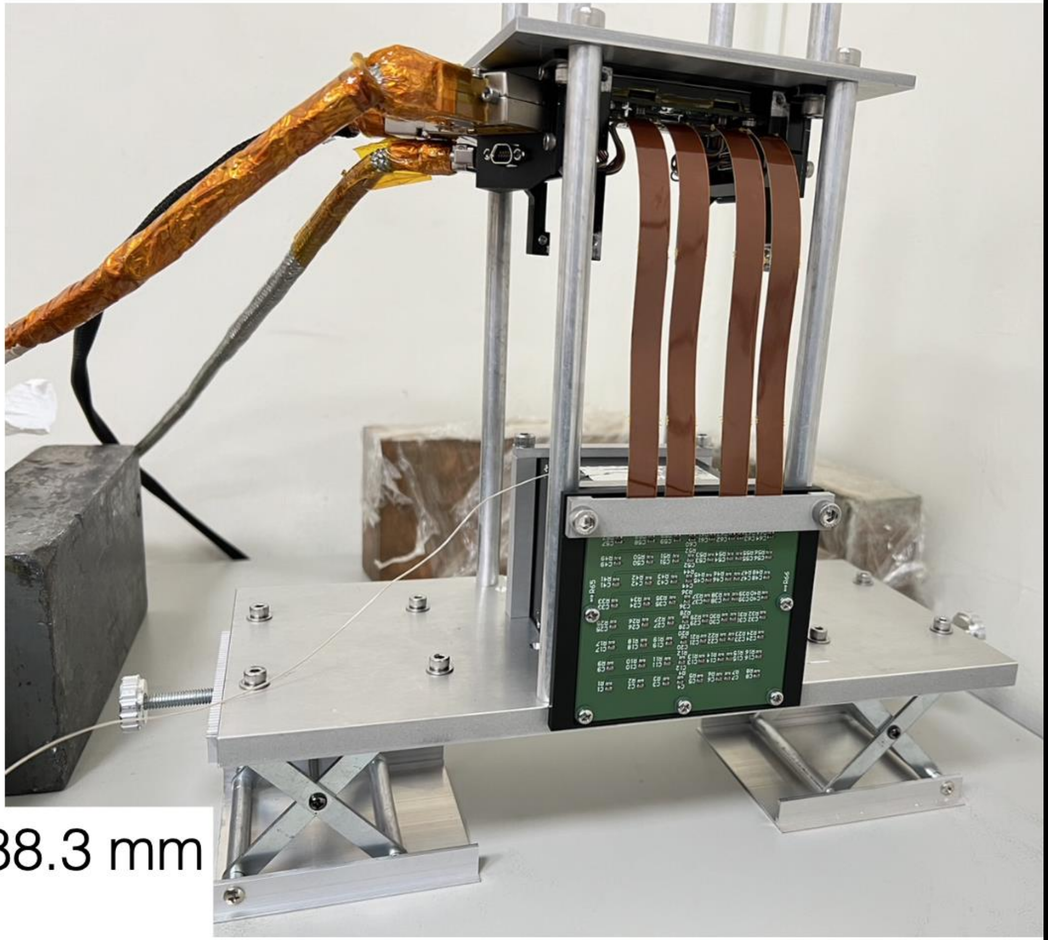


8x8 LYSO crystal array



8x8 SiPM array

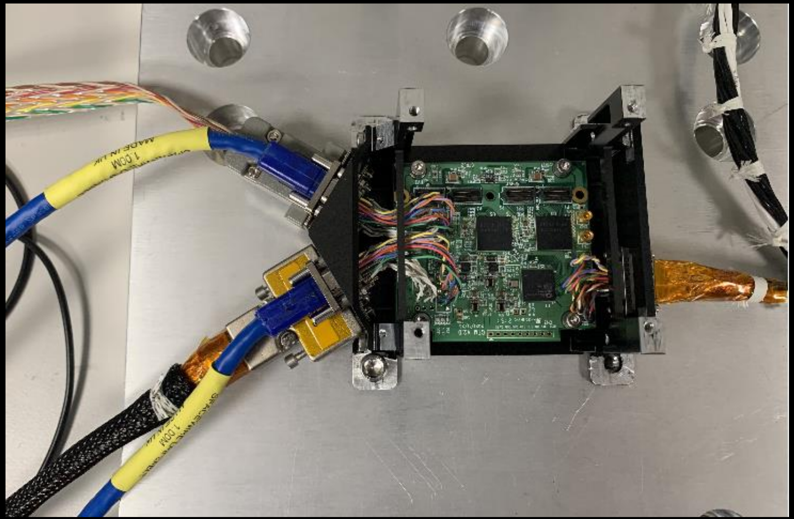
LYSO calorimeter prototype



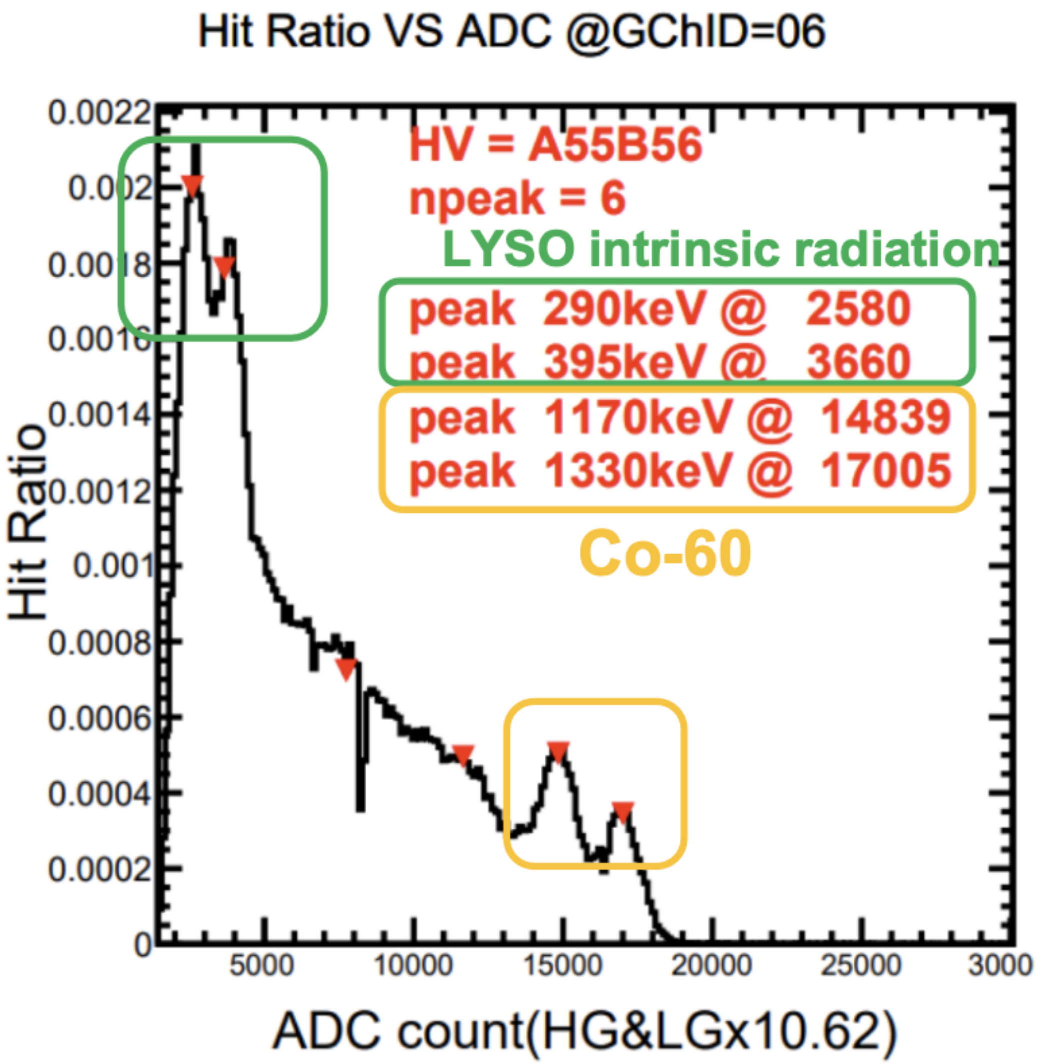
One crystal: 7.12 mm x 7.12 mm x 88.3 mm
8x8 array: 56.96 mm x 56.96 mm

Readout for the ZDC ECAL Prototype with LYSO

- Designed by Chih-Hsun Lin of Academia Sinica
- 64 channels
- Trigger:
  - Self-triggered
  - Can accept external timing signal ➔ needs to be studied
  - May accept external trigger ➔ needs to be studied



Tests with Co-60



We use Co-60 and LYSO intrinsic radiation to calibrate the detector.

- **@HV = 27.00V**

➔ 1.330 MeV @ 17005 digit

➔ 1.330 MeV / 17005 digit ~ 7.8e-5 MeV / digit

Saturated digit = 11, 0000 digit

➔ 11,0000 digit * 0.1268MeV = 8.6MeV

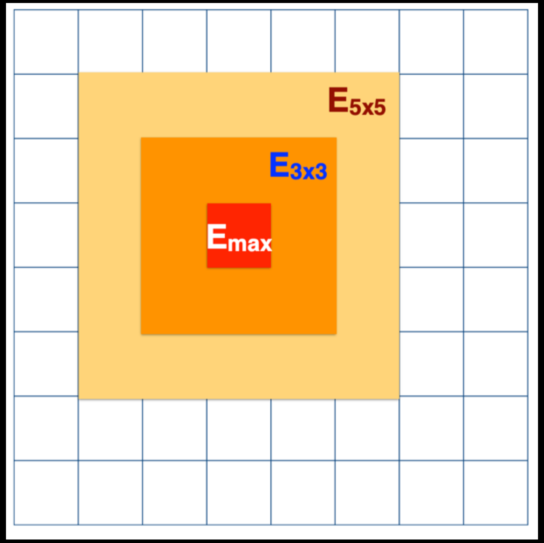
➔ **Saturated at 8.6MeV**

This HV/gain is too high for our beam test condition.

- HV setting range = 24.7V to 28.2V

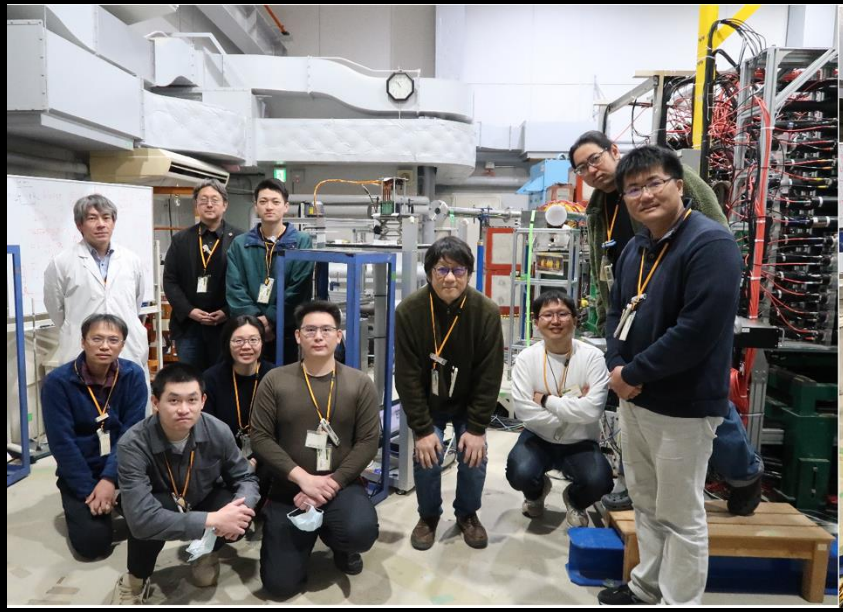
Beam Test @ ELPH

- A beam test with positrons was conducted at the ELPH, Tohoku University, between **15 and 21 February 2024**
- Beam time: ~36 hours (**19 and 21 February 2024**)
- Beam energy: 47.18 MeV up to 823.26 MeV
- Rate: 1,000 - 3,000 Hz
- Participants: RIKEN, Tsukuba University, Tsukuba University of Technology, Sejong University, EIC-Taiwan



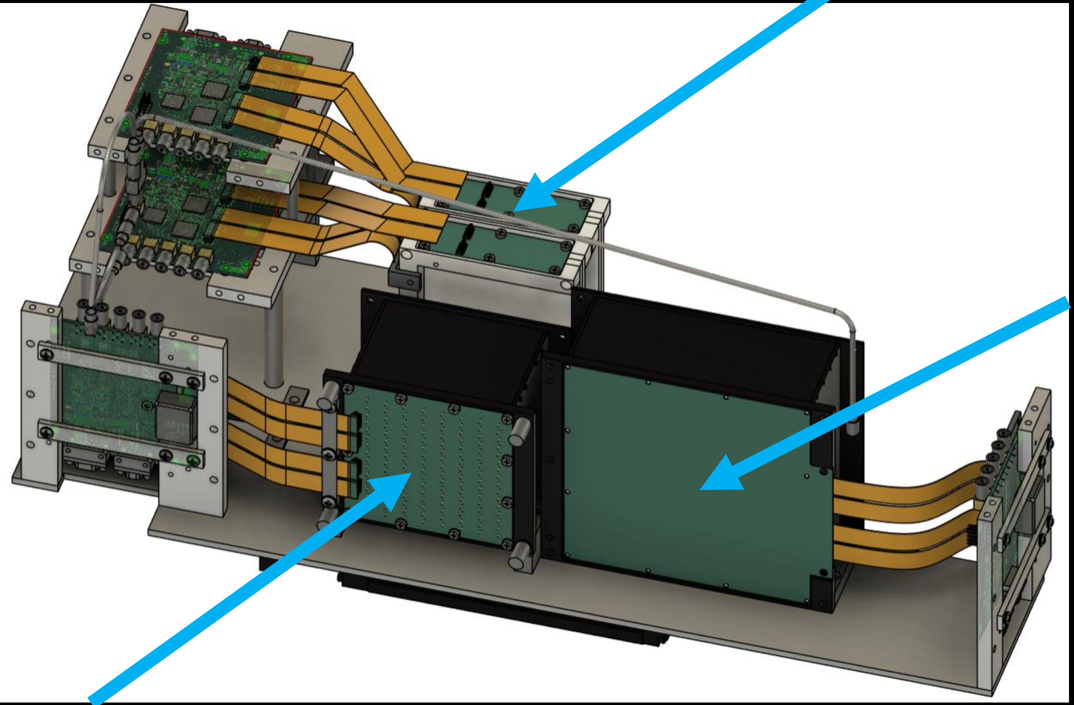
Goals:

- Detector performance
- Comparison between data and simulation
- E_{max} vs E_{beam} at different SiPM HVs
- Hit multiplicity
- Energy spectra (E_{max}, E_{3x3}, E_{5x5})
- Shower shapes (E_{max}/E_{5x5}, E_{3x3}/E_{5x5}, $Emax/E_{3x3}$, E_{2x5}/E_{5x5}, σ_x, σ_y, …)
- Beam profile
- Energy resolution as a function of beam energy



2nd beam test @ RARIS

Beam telescope:
Plastic scintillators + SiPMs



Calorimeter:
$PbWO_4$ crystals + SiPMs

Calorimeter: LYSO crystals + APDs

Lots of theoretical and experimental activities on QCD in Taiwan and many more interesting results on quarkonia from STAR are coming in future!