JÜLICH
FORSCHUNGSZENTRUM

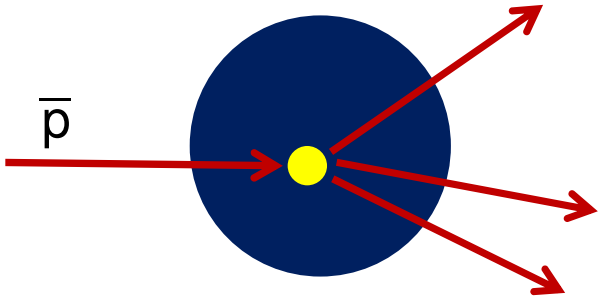
Antiproton Nucleus Collisions at $\overline{\text{P}}$ANDA

Oct 14, 2015 | Albrecht Gillitzer, IKP Forschungszentrum Jülich

EMMI Workshop „Cold Dense Nuclear Matter“, Darmstadt, October 13-17, 2015

Why to Study $\bar{p}$A Collisions at $\bar{P}$ANDA ?

- Access to a large number of 2-body states in $\bar{p}$N ‚annihilation'
- Sensitivity to nuclear potential of produced hadrons at low momentum
- Resonant formation of $c\bar{c}$ states with all fermion-antifermion quantum numbers
- $\bar{p}$ momentum range up to 15 GeV/c → large momentum transfer reactions



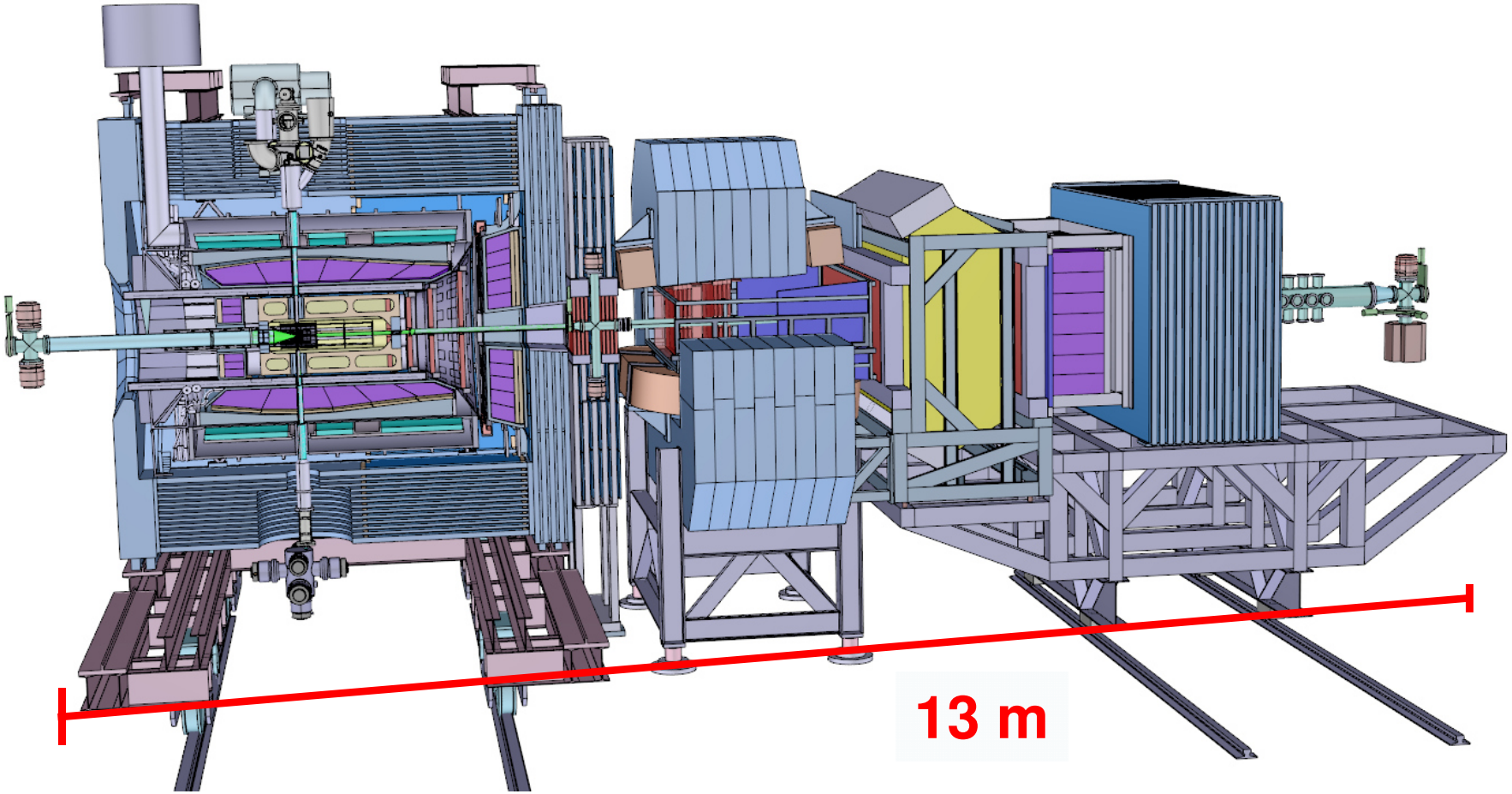
- Large detector acceptance, tracking and PID capability → allows studying large variety of final states

Comprehensive Physics Program

PANDA Physics Working Groups:

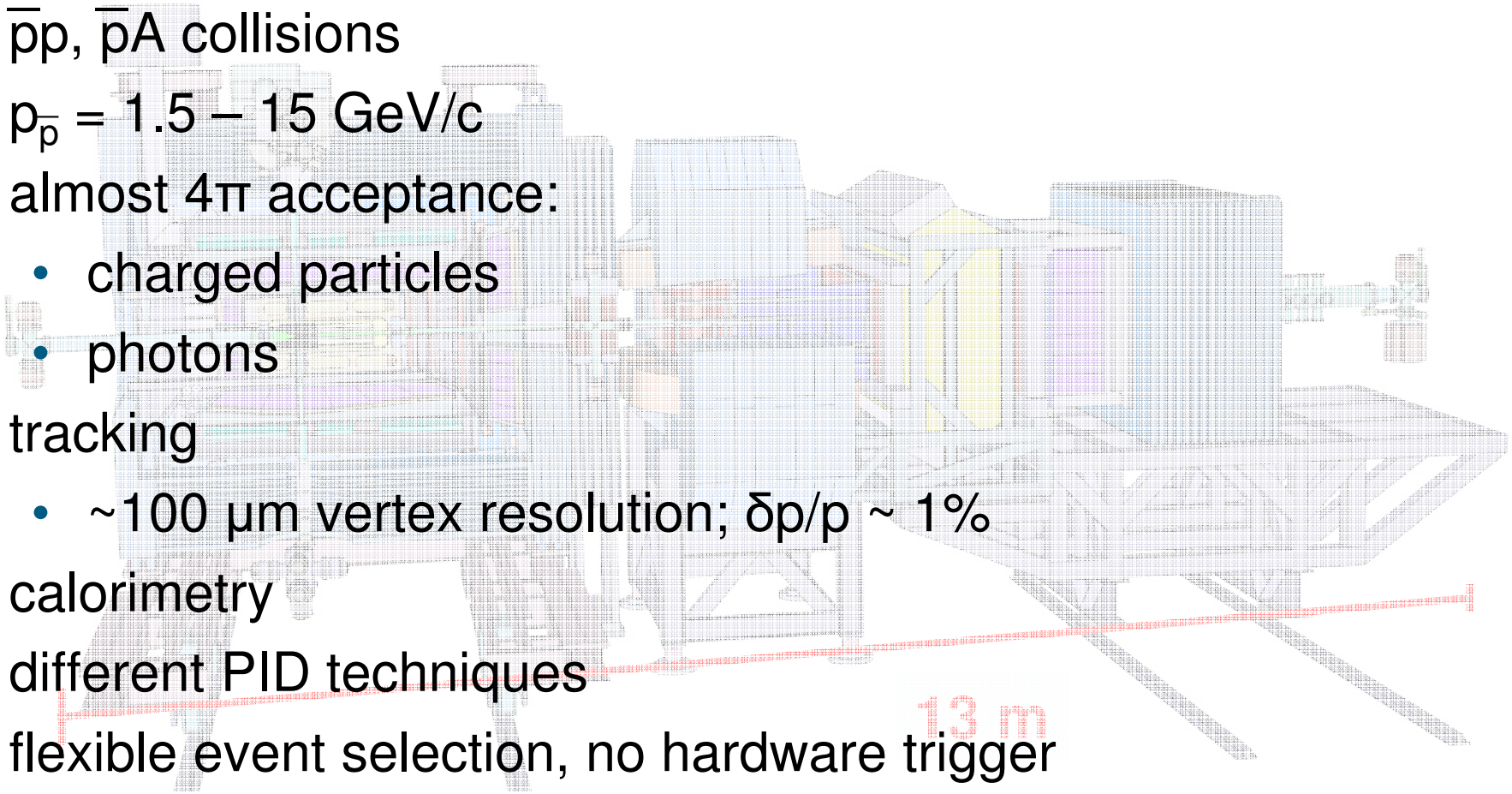
- Charmonium Spectroscopy
- Charmonium-like Exotics
- Heavy-Light Systems
- Light Meson Exotics
- Baryons
- QCD Dynamics
- Time-like Form Factors
- Hard Exclusive Processes
- Drell-Yan
- Electroweak Physics
- **Hadrons in Nuclei**
- Hypernuclear Physics

PANDA Detector & Parameters



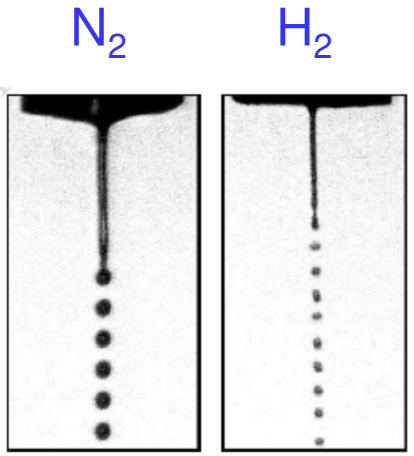
PANDA Detector & Parameters

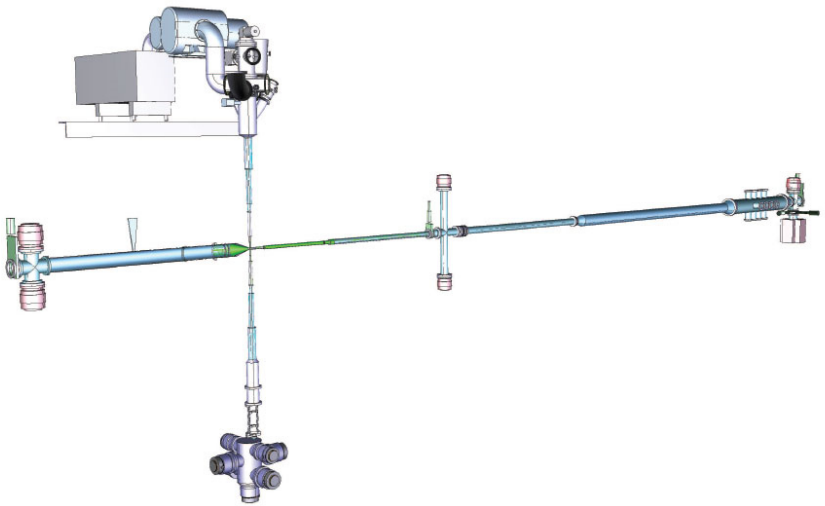
- $\bar{p}p$, $\bar{p}A$ collisions
  $p_{\bar{p}}$ = 1.5 – 15 GeV/c
- almost 4π acceptance:
  - charged particles
  - photons
- tracking
  - ~100 μm vertex resolution; δp/p ~ 1%
- calorimetry
- different PID techniques
- flexible event selection, no hardware trigger

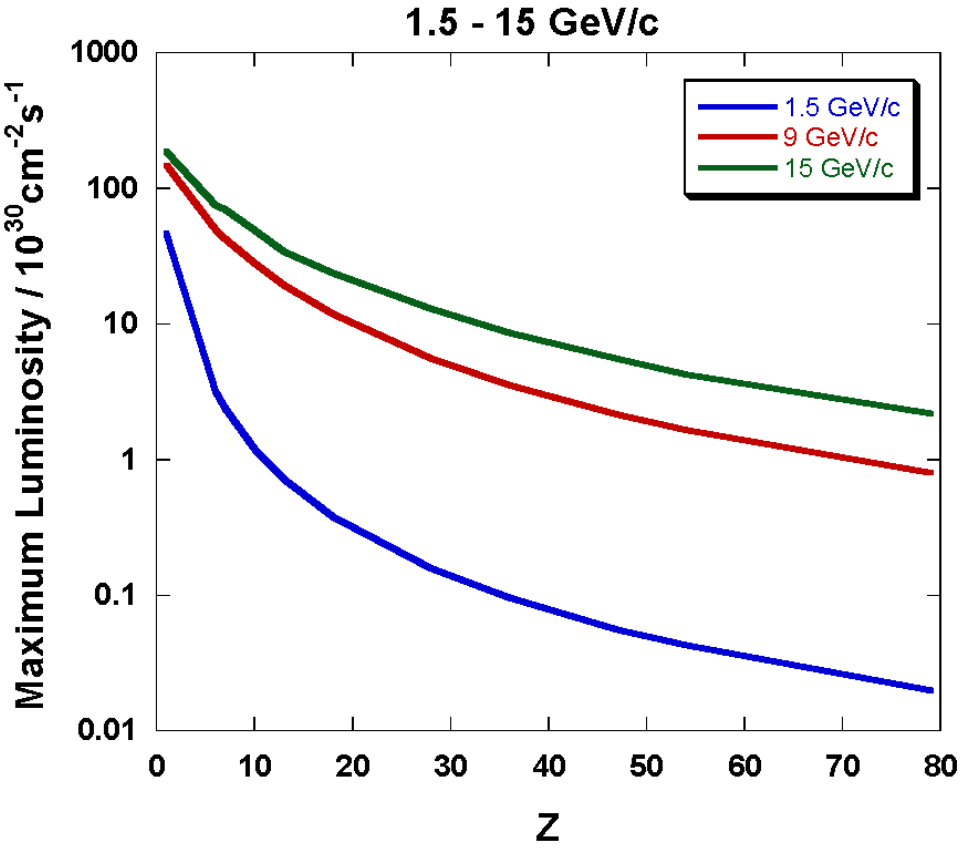


Nuclear Targets at PANDA

- Targets: cluster jet, pellet, solid
- cluster jet & pellet work for: D_2, N_2, Ne, Ar, Kr, Xe
- luminosity decreases with Z
- Au target: lose ~factor 10^3 at 1.5 GeV/c, ~10^2 at 15 GeV/c
- luminosity determination for for $\bar{p}A$





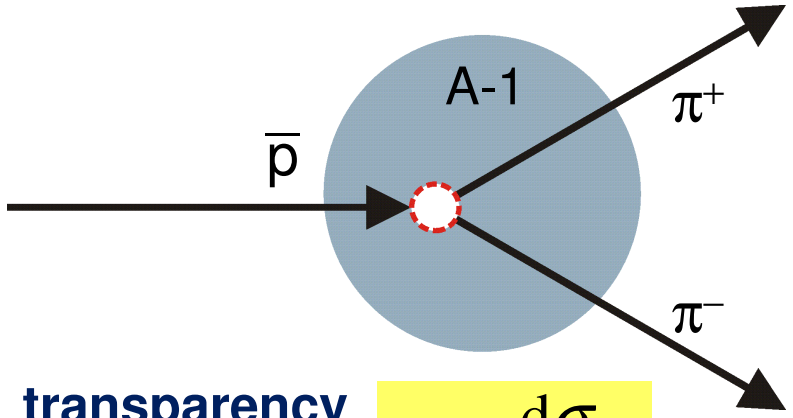


Topics in $\bar{p}$A Collisions

- Nuclear potential of hadrons (antibaryons, $\bar{K}$, …) (5)
- Charmonium nucleon interaction (4)
- Color transparency (1)
- Short range nucleon correlations (2)
- Non-nucleonic components (d, heavier nuclei) (3)

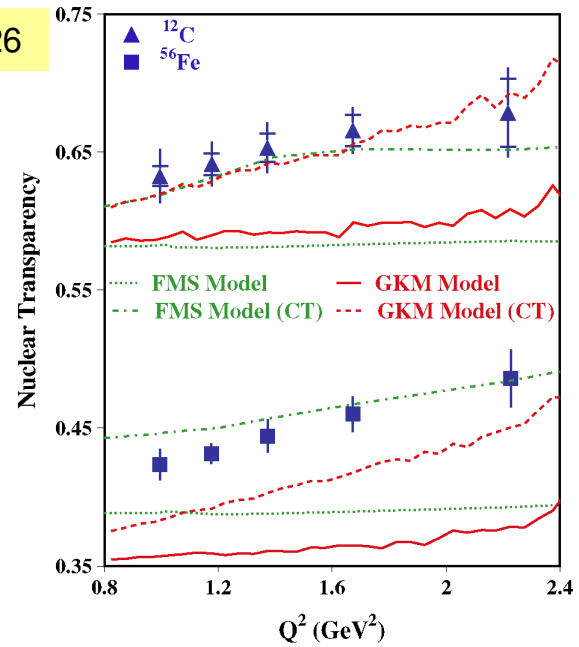
Color Transparency at PANDA

- small-size color-neutral objects have reduced cross section → should be seen at large momentum transfer
- CT established at high energies, evidence at intermediate energies:
  JLAB: (e,e'π^+) B. Clasie *et al.*, PRL 99 (2007) 242502
  and $\gamma^*A \rightarrow \rho^0 X$ L. El Fassi *et al.*, [CLAS] PLB 712 (2012) 326
- proposal: study CT with $\bar{p}$ at PANDA in two-body reactions, e.g. in $\pi^+\pi^-$ annihilation (B. Pire, M. Strikman, …)
- CT conditions should be achieved at momenta above 6 GeV/c

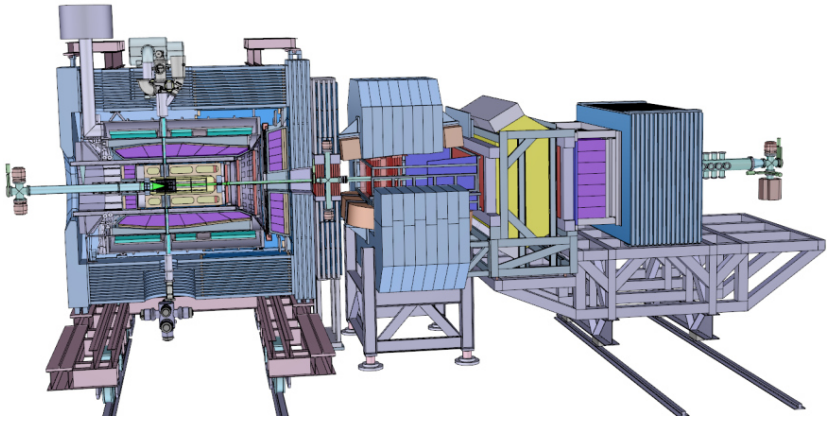


transparency ratio:

$$T = \frac{d\sigma_A}{A\, d\sigma_p}$$



Color Transparency at PANDA II

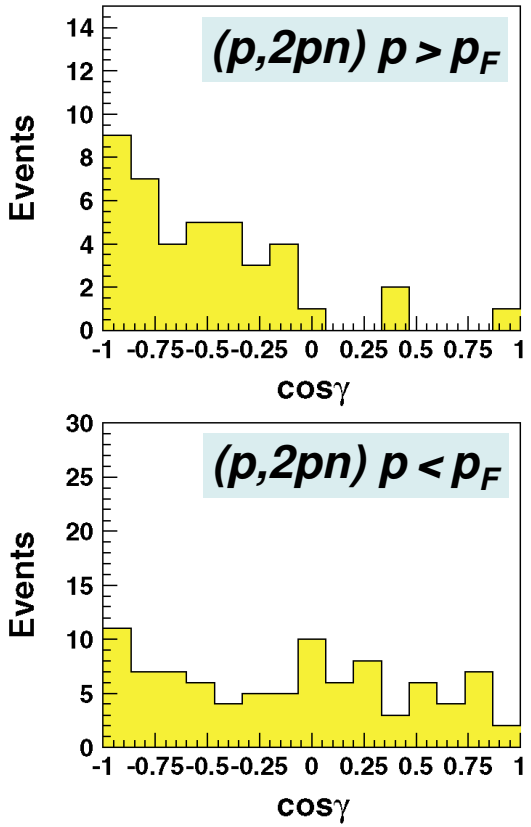


- comparably large rates in $\bar{p}$ induced reactions
- access to various 2-body final states in $\bar{p}p$ and $\bar{p}n$: $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^0\bar{\pi}^-$, $\rho^+\bar{\rho}^-$, $\rho^0\rho^0$, $\rho^0\rho^-$, $\eta\eta$, $\eta\eta'$, $\eta'\eta'$, $\phi\phi$, K^+K^-, K_sK^-, $p\bar{p}$, $\Delta^{++}\bar{\Delta}^{--}$, $\Delta^+\bar{\Delta}^-$, $\Delta^0\bar{\Delta}^0$, $\Delta^+\bar{\Delta}^{--}$, $\Delta^0\bar{\Delta}^-$
- sufficient acceptance for complex final states
- p_{max} = 15 GeV/c → $|t_{max}|$ ~ 14 GeV^2
- momentum resolution δp/p ~ 1% & veto condition on further particles should suppress high excitation energies of residual nuclei (to be proven quantitatively …)

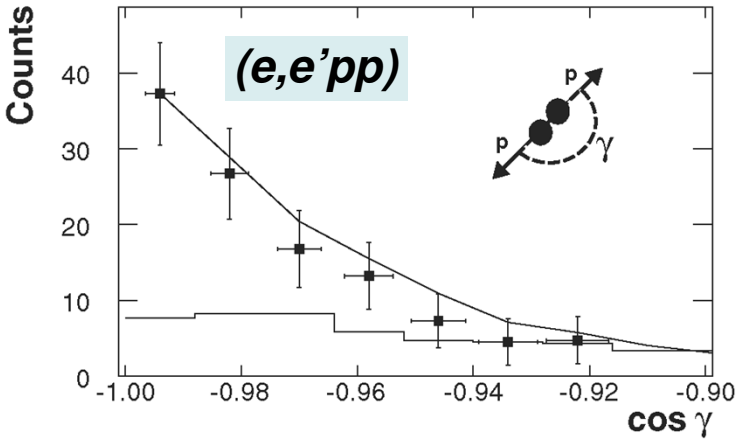
Short Range Correlations in Nuclei

- understanding of high momentum components / high density behavior of nuclear matter
- high momentum nucleons are paired
- recent observation at BNL and JLAB
- most nucleons with $p > p_F$ are paired
- most pairs are pn
- pp pairs are rare but particularly inter-esting since directly related to high density matter in neutron stars
- PANDA can observe both pp and pn correlations

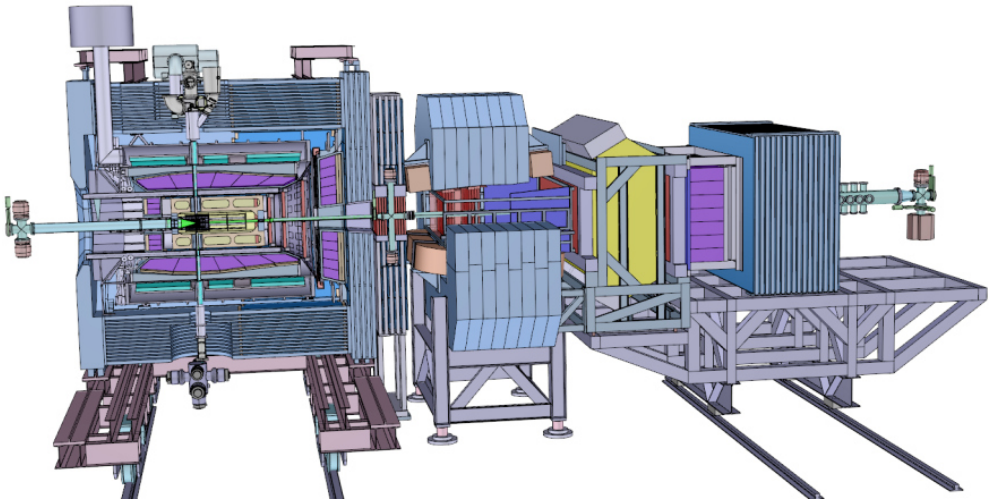
A. Tang *et al.*, PRL 90 (2003) 042301



R. Shneor *et al.*, PRL 99 (2007) 072501



SRC at PANDA

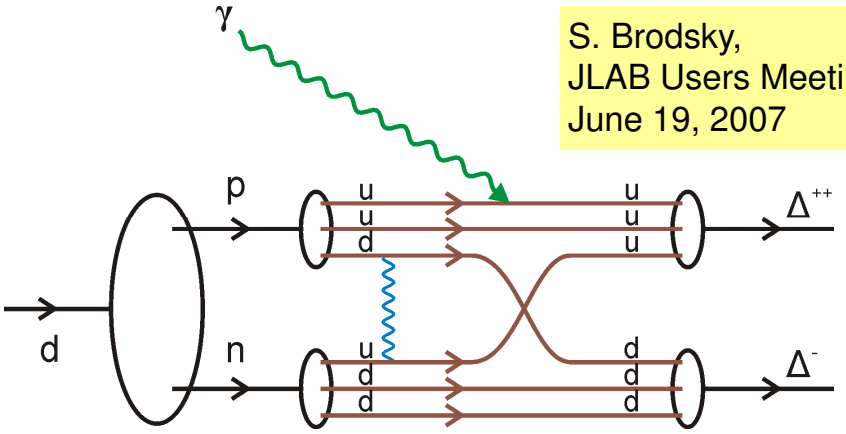


- large cross sections
- large acceptance
- complementarity to *p* and e^- induced reactions
- SRC can be probed both in nucleon knock-out *and* in annihilation-like 2-body reactions
- *pn* pairs can be identified without neutron detection, e.g. in a $(\bar{p},\pi^-\pi^0 p)$ reaction
- method can be extended to non-nucleonic components

Non-Nucleonic Component in the Deuteron

- ‚Hidden colors' of the deuteron
- ΔΔ component should be enhanced at short distances
- Experimental limit $G_{\Delta\Delta} < 0.4\%$

D. Allasia *et al.*, PLB 174 (1986) 450

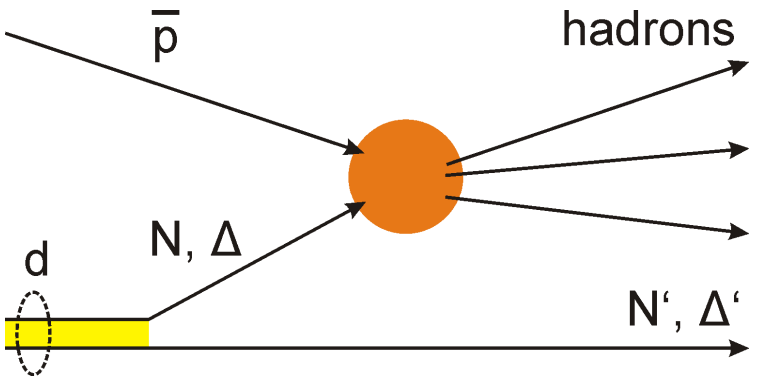


S. Brodsky,
JLAB Users Meeting
June 19, 2007

JLAB LOI 11-103

C. Granados, M. Sargsian, PRC 83 (2011) 054606

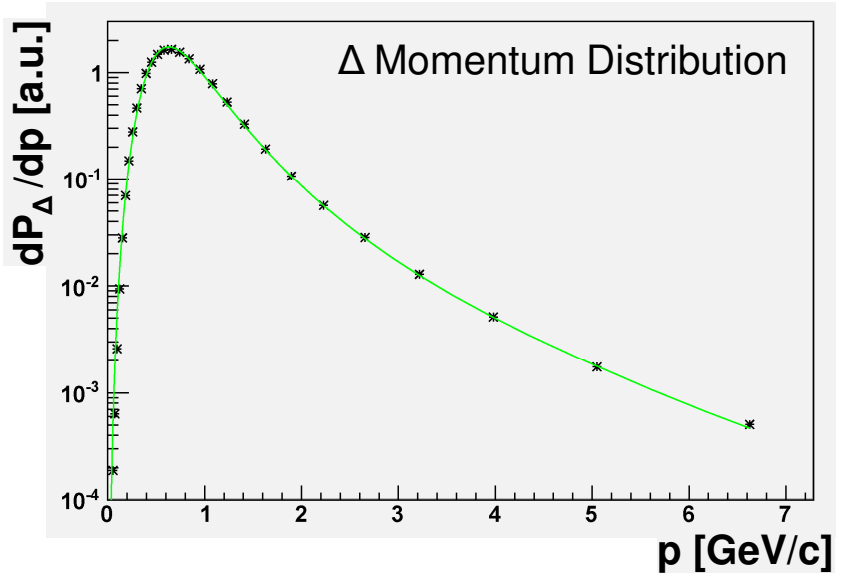
- Alternative to photo-disintegration: high momentum $\bar{p}d$ collisions
- Kinematical separation of the $\bar{p}\Delta$ and the recoiling Δ
- Reaction: $\bar{p}d_{\Delta^{++}\Delta^{-}} \rightarrow (p\pi^{+})(\pi^{-}\pi^{-})$

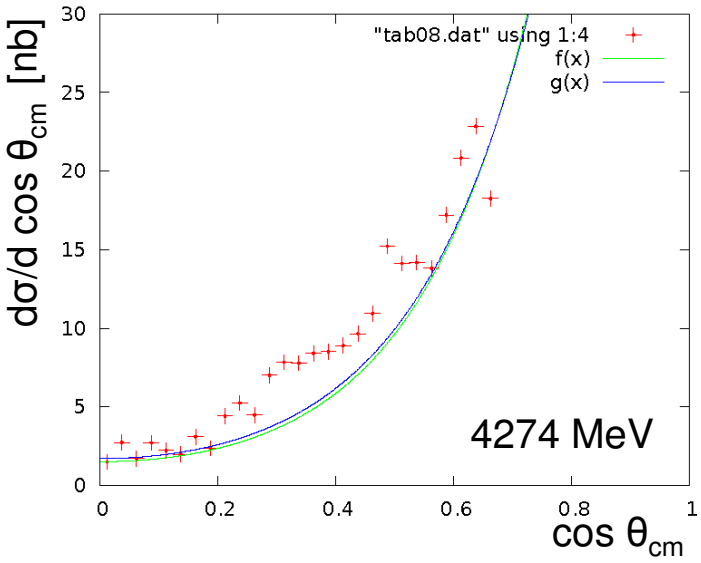


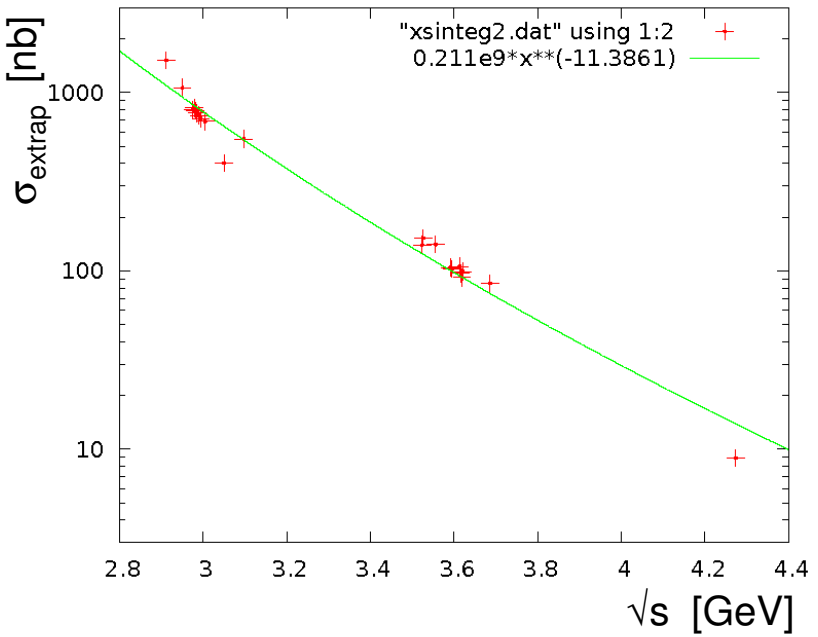
ΔΔ in the Deuteron: A Simple Model

- d Δ wave function by J. Haidenbauer
- $\sigma_{\mathrm{tot}}(\sqrt{s})$ and $\mathrm{d}\sigma/\mathrm{d}t$ parametrized according to Fermilab E 760 data on $\bar{p}p \to \pi^0\pi^0$ ($\sqrt{s}$~2.9 ... 4.3 GeV)
- $\sigma_{\mathrm{tot}} \propto s^{-5.7}$
- $\frac{\mathrm{d}\sigma}{\mathrm{d}z}(z) = A \cdot \left(e^{\beta z} + e^{-\beta z}\right)$,

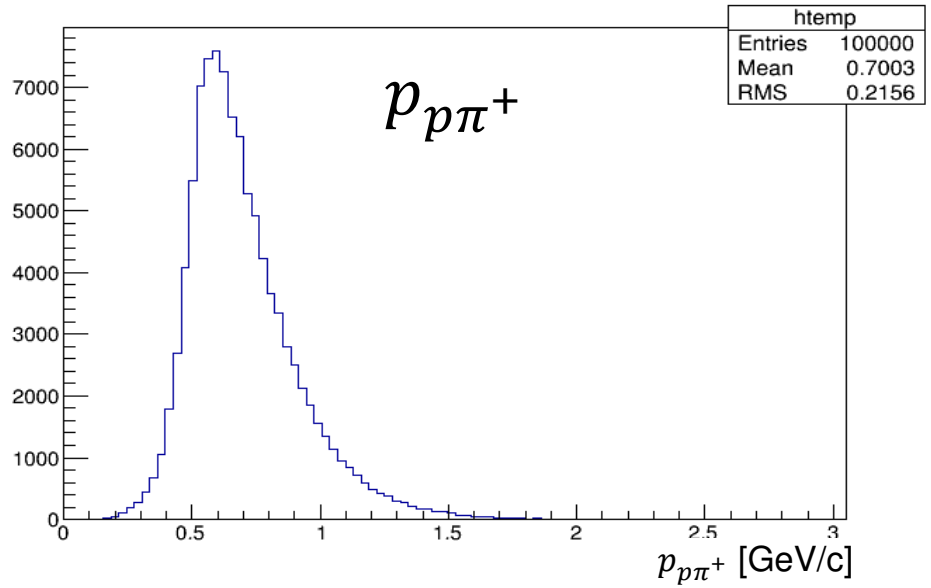
  $z = \cos\theta_{\mathrm{cm}}$

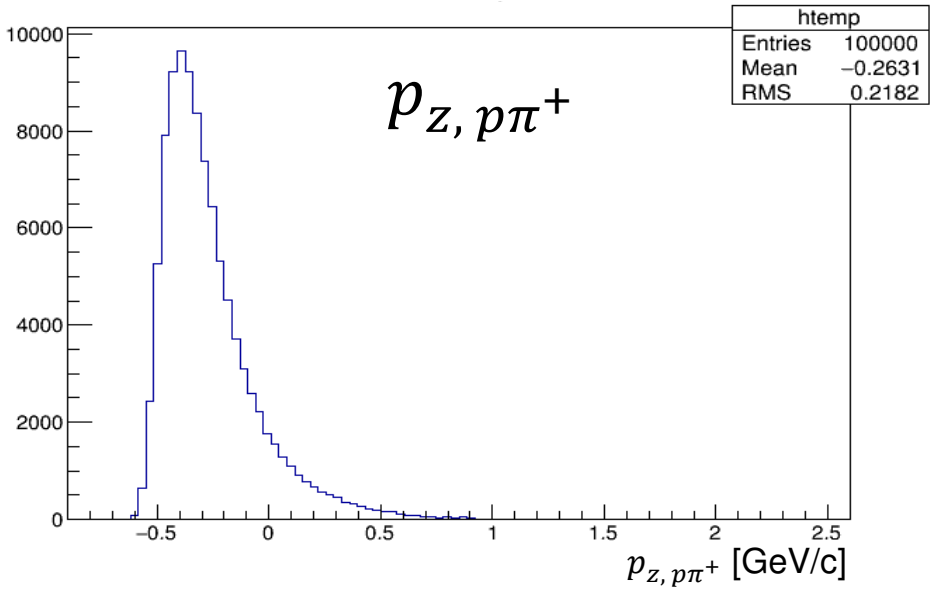


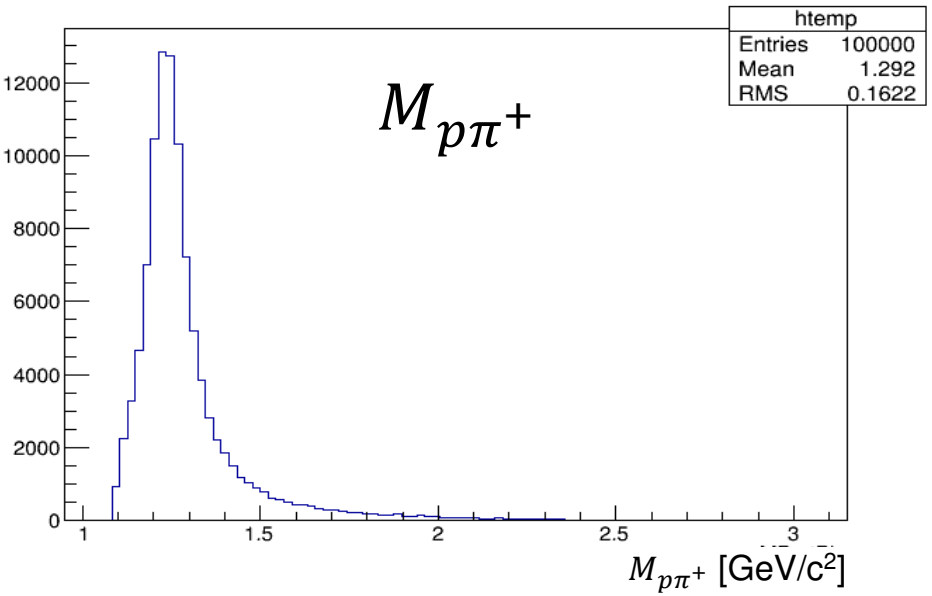




EvtGen: Generated Events

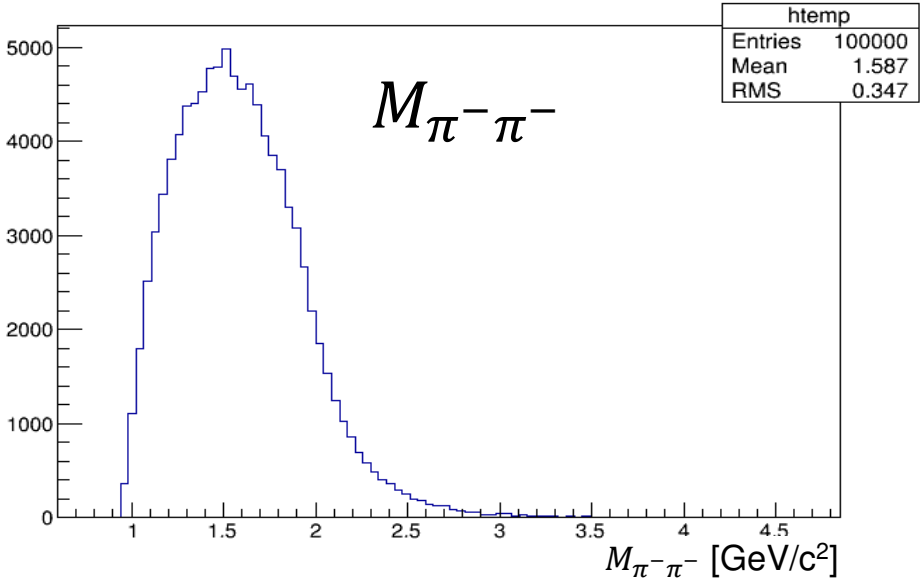


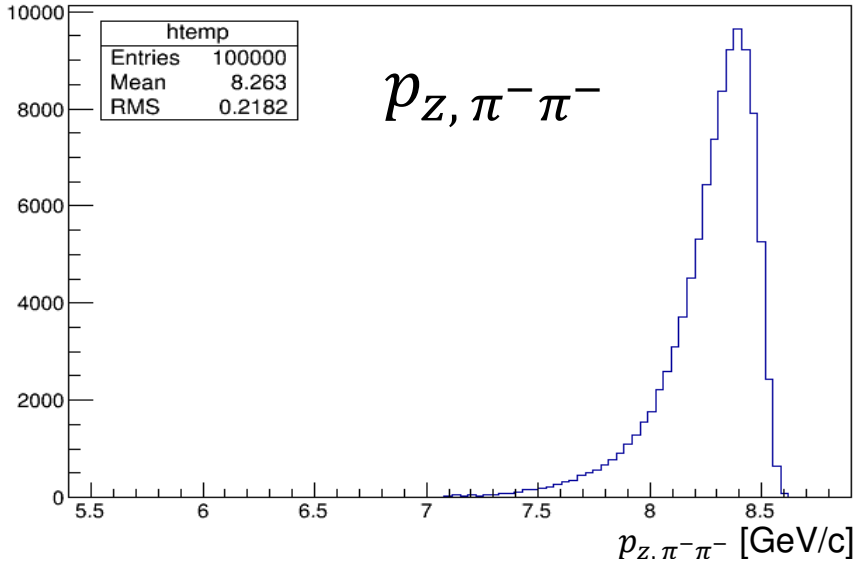


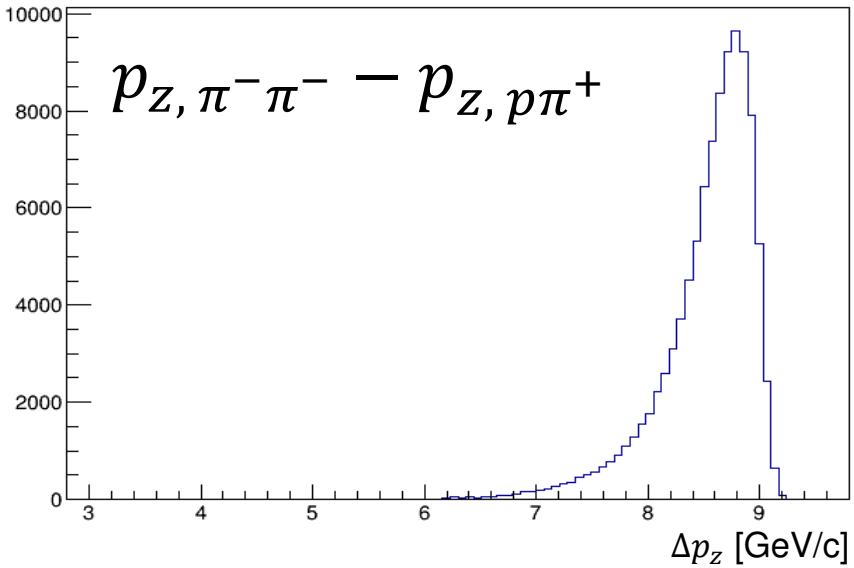


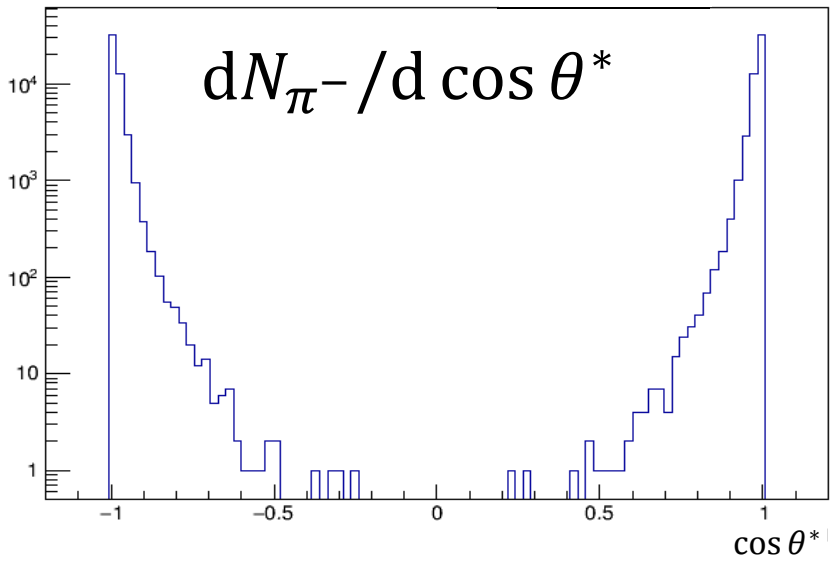
- $\bar{p}$ momentum = 8.0 GeV/c
- negative mean P_z of Δ^{++} due to energy dependence of cross section

EvtGen: Generated Events









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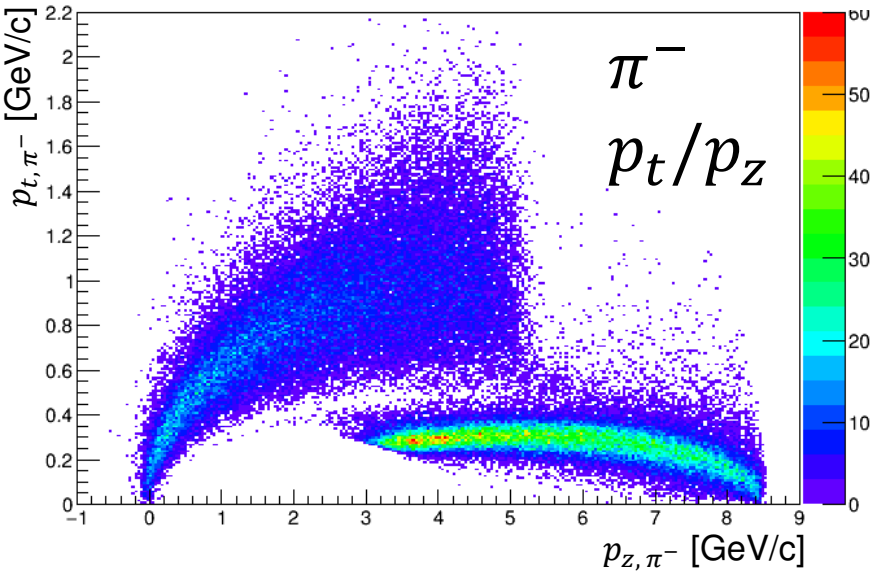
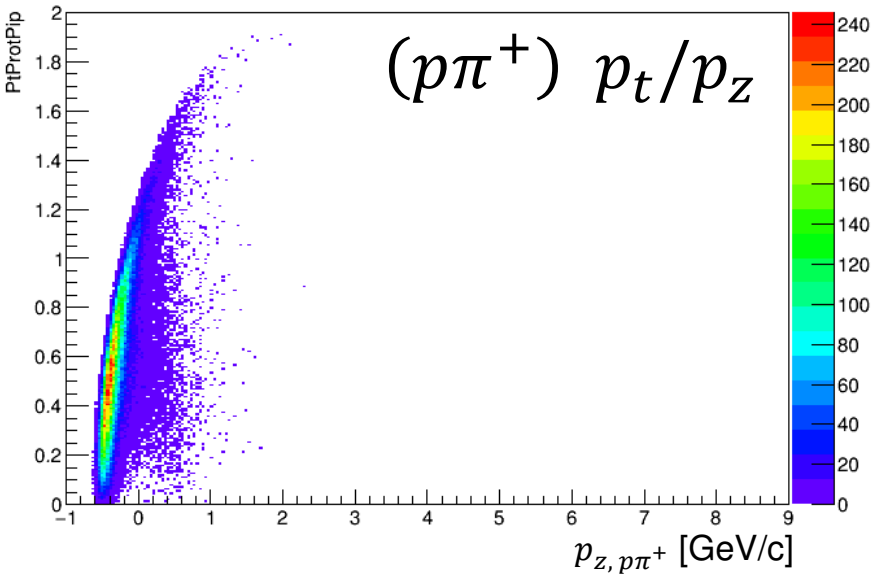
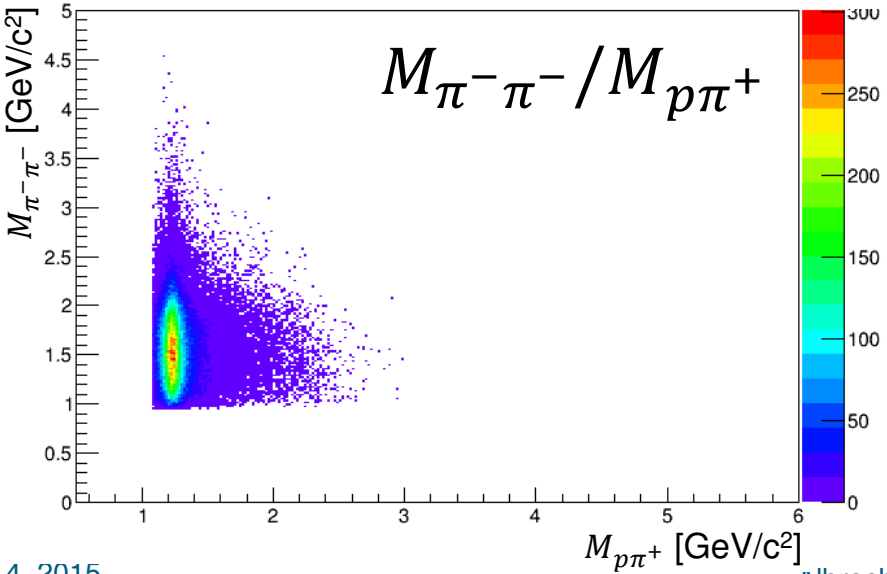
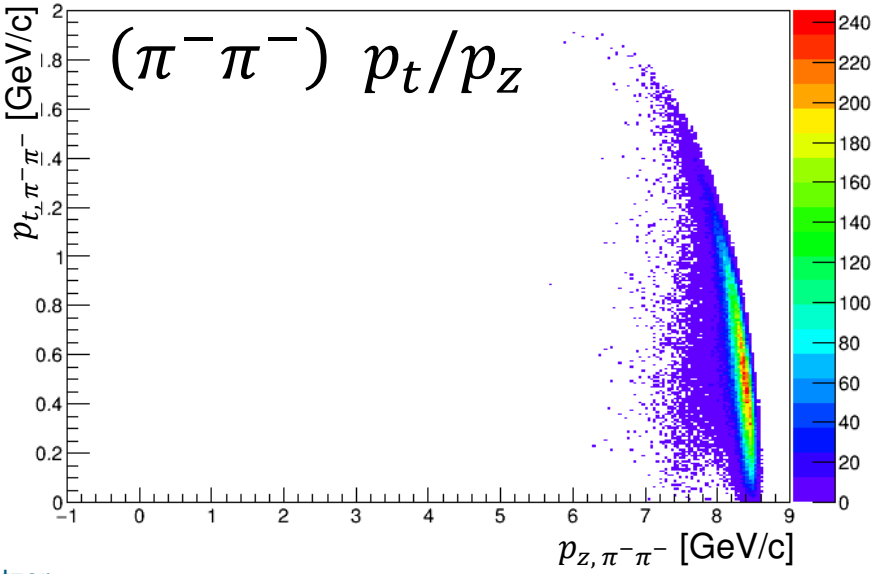






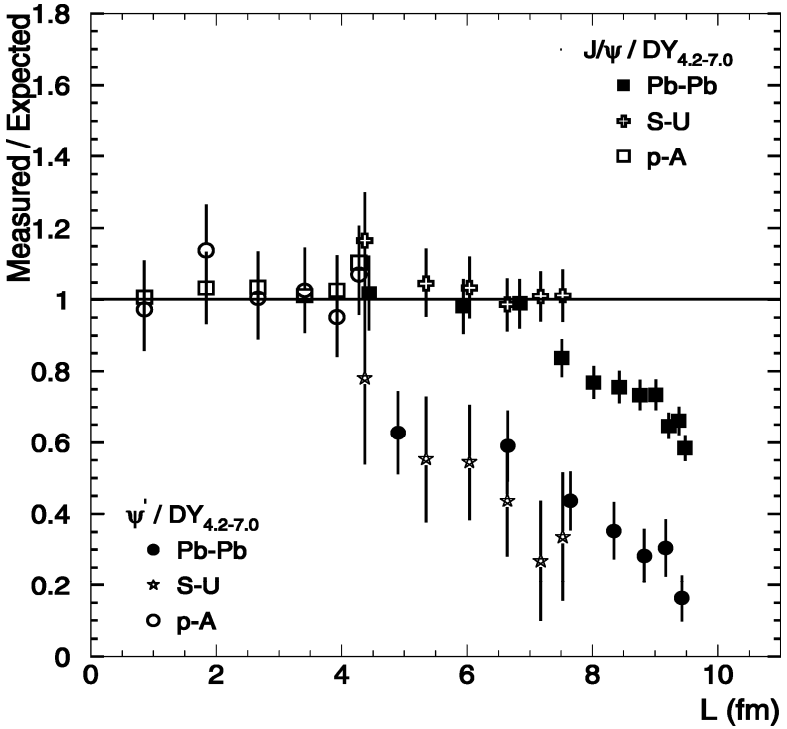


Which Signal and Background Rates to Expect?

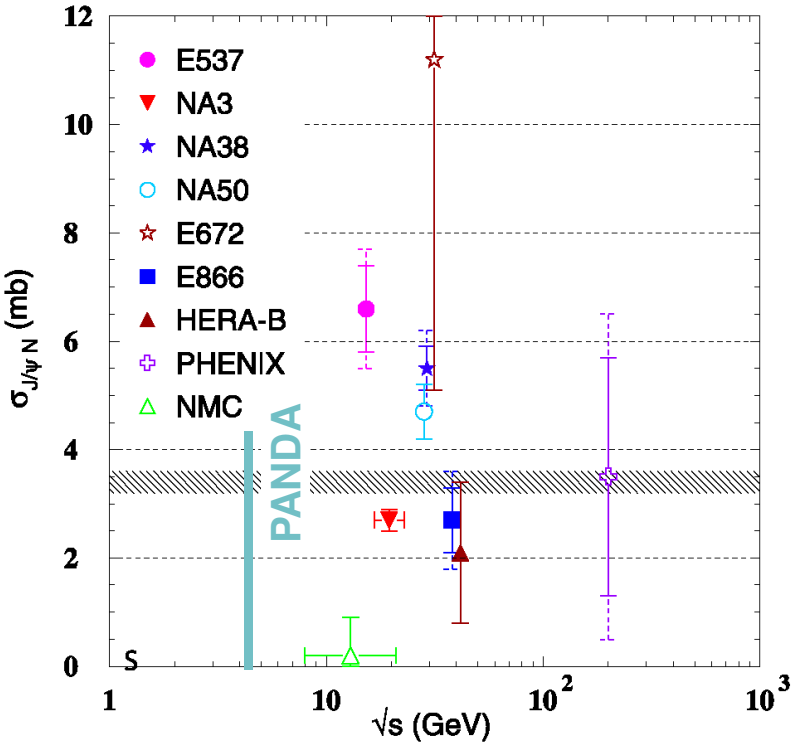
- signal rate estimate: $R_{\mathrm{sig}} \cong 1/s$ (produced) with:
  - $\sigma_{\bar{p}\Delta^- \to \pi^-\pi^-}(\sqrt{s} = 2\ \mathrm{GeV}) \cong 100\mu\mathrm{b} \cong 0.001 \cdot \sigma_{\mathrm{tot}}$
  - $\sigma_{\bar{p}\Delta^- \to \pi^-\pi^-}(\sqrt{s} = 1.5\ \mathrm{GeV}) \cong 2.7\mathrm{mb} \cong 0.027 \cdot \sigma_{\mathrm{tot}}$
  - $f(\Delta^{++}\Delta^-) = 10^{-3}$, $R_{\mathrm{tot}} = 10^6/s \leftrightarrow L = 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- background rate estimate: $R_{bg} \cong 500/s$ with:
  - $\sigma_{\bar{p}n \to \pi^+\pi^-\pi^-}(\sqrt{s} = 4\ \mathrm{GeV}) \cong 50\mu\mathrm{b}$
- so far only quasi-free background studied:
- 0 out of 250000 background events survive with appropriate cuts

J/ψ Nucleon Interaction – an Old Problem

NA50: A + A‘ → J/ψ(ψ‘) + X



B. Alessandro *et al.*, EPJC 39 (2005) 335



F. Arleo, EPJC 55 (2008) 449

→ evidence for QGP ?

- PANDA: $\sqrt{s}_{J/\psi N}$ = 4.5 GeV

J/ψ N Dissociation Cross Section with $\bar{p}$A

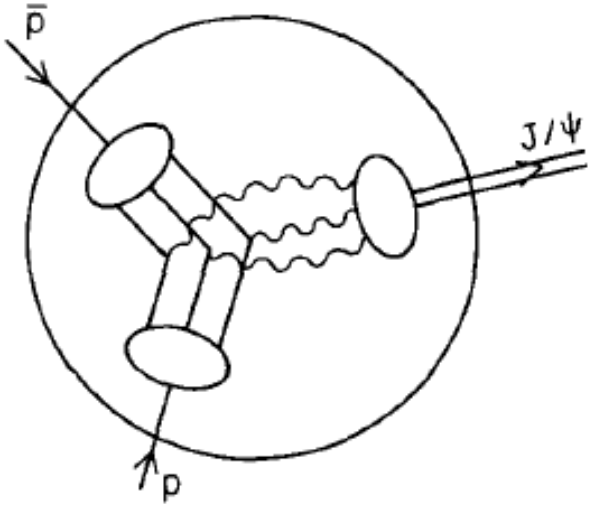


Fig. 2. The dominant mechanism for $p\bar{p}$ exclusive annihilation into J/ψ.

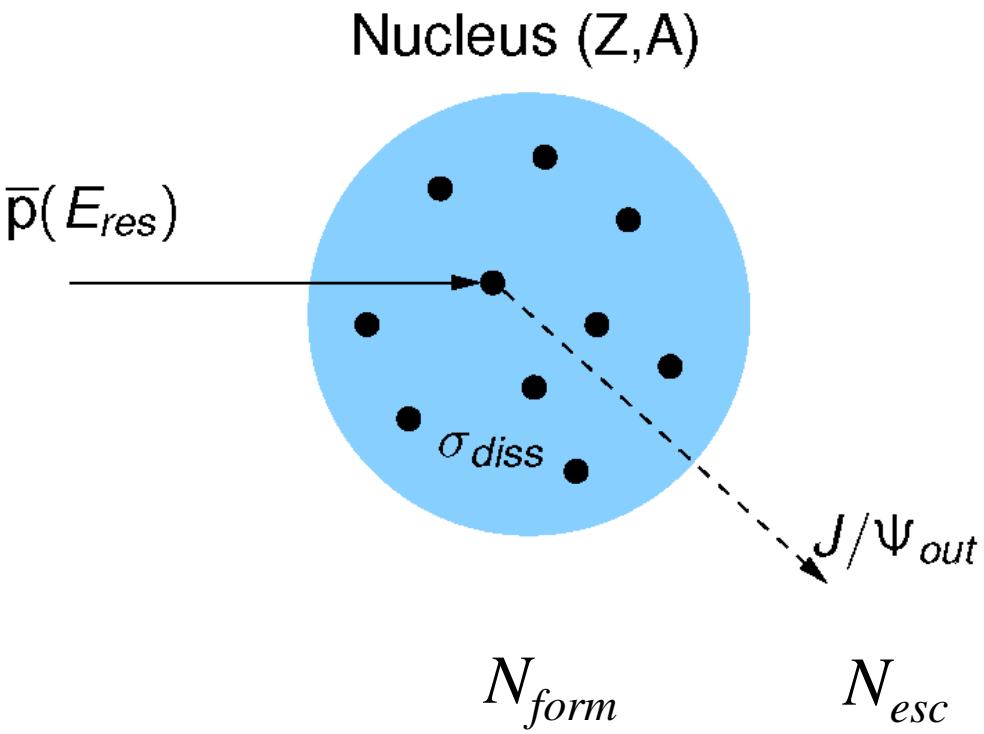
From S.J. Brodsky, A.H. Müller, PLB 206 (1988) 685

- **S.J. Brodsky, A.H. Müller, PLB 206 (1988) 685**
- G.R. Farrar et al., NPB 345 (1990) 125
- K. Seth, 629 (1998) 358

J/Ψ is formed inside the nucleus

Genuine J/Ψ N dissociation cross section can be studied !

J/ψ N Dissociation Cross Section with $\bar{p}$A



$$\sigma_{J/\psi N} = \frac{1}{\langle \rho L \rangle}\left(1 - \frac{N_{esc}}{N_{form}}\right)$$

- **S.J. Brodsky, A.H. Müller, PLB 206 (1988) 685**
- G.R. Farrar et al., NPB 345 (1990) 125
- K. Seth, 629 (1998) 358

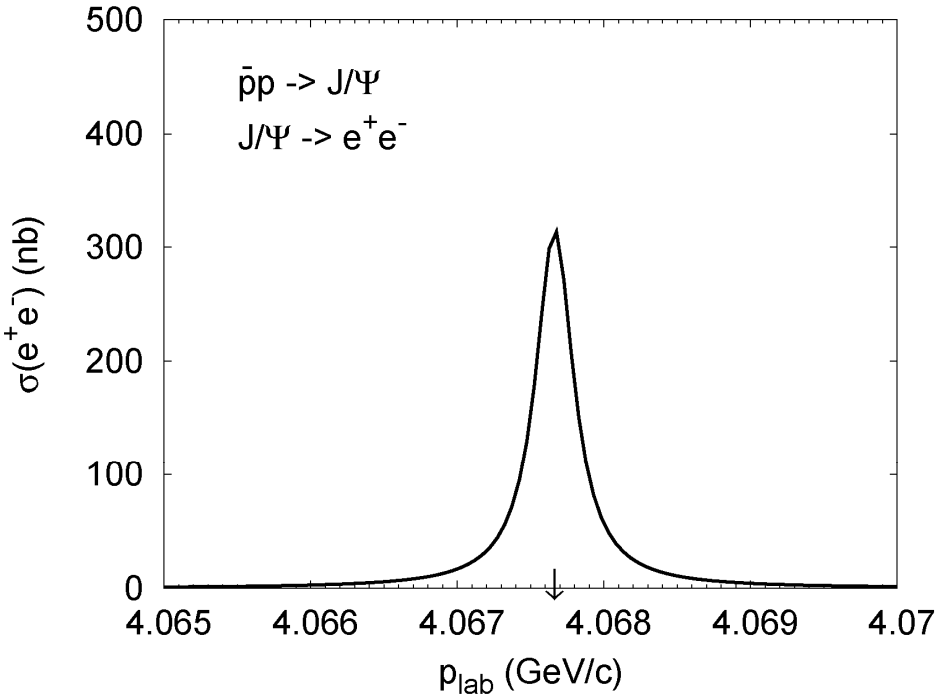
- well-defined conditions: exclusive resonant J/ψ formation on target proton at rest at 4.05 GeV/c
- no ambiguities due to feed-down, co-movers, …
- antiproton mean free path sufficiently known

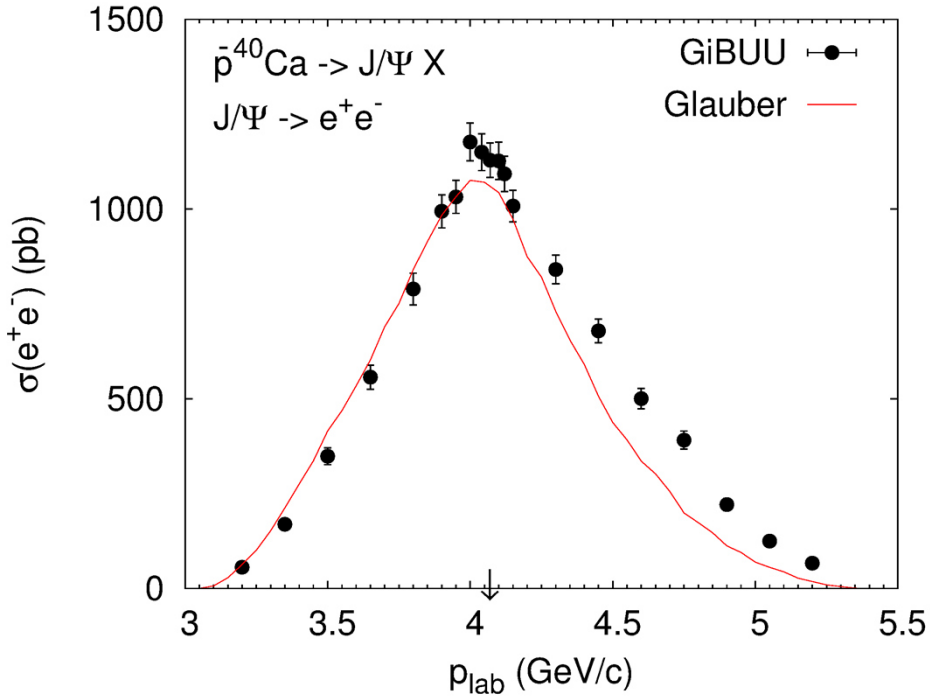
→ PANDA is unique !

$\bar{p}$ A → J/ψ X in GiBUU & Glauber Model

- resonant J/ψ formation implemented in GiBUU
- first results in comparison to Glauber model:
  - nuclear absorption effect visible ($\sigma_{J/\psi N}$ from A. Sibirtsev)
  - side-feeding not important

Alexei Larionov *et al.*,
PRC 87 (2013) 054608





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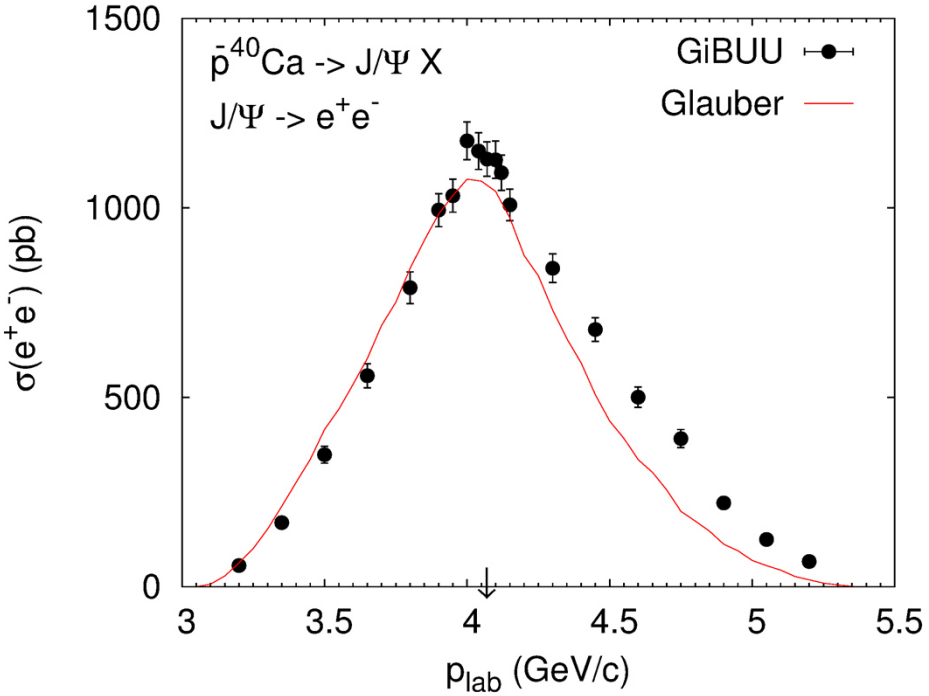
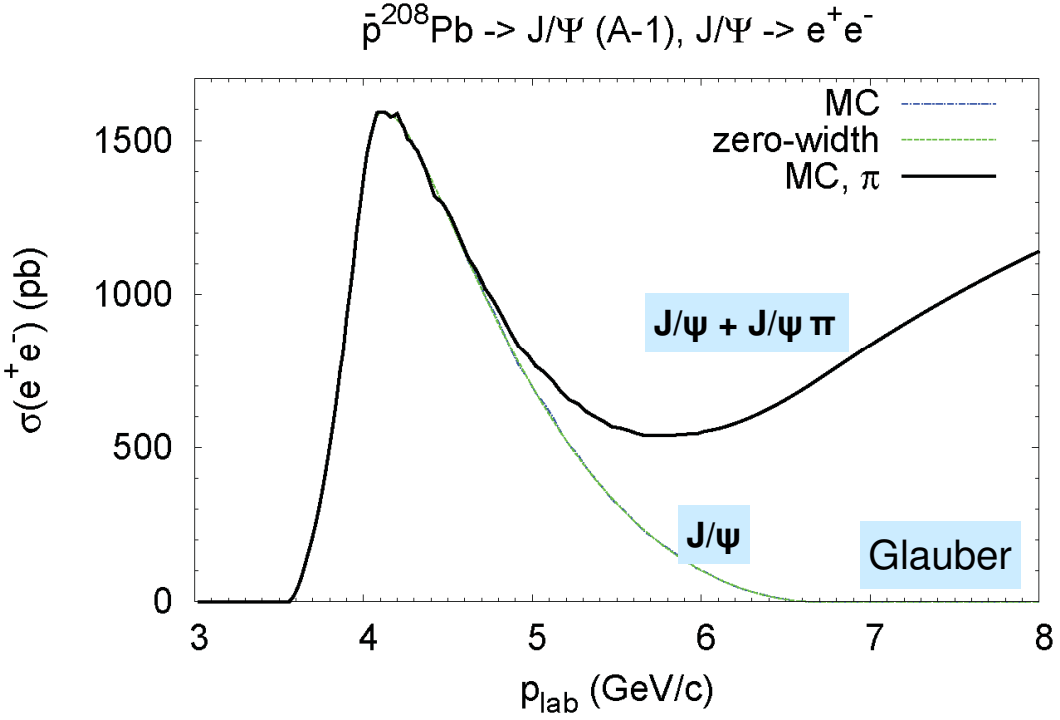


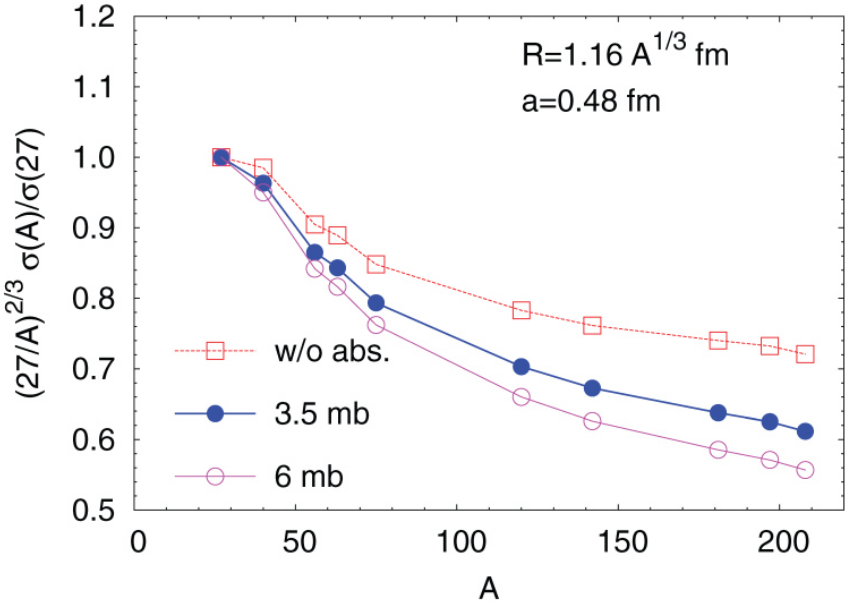


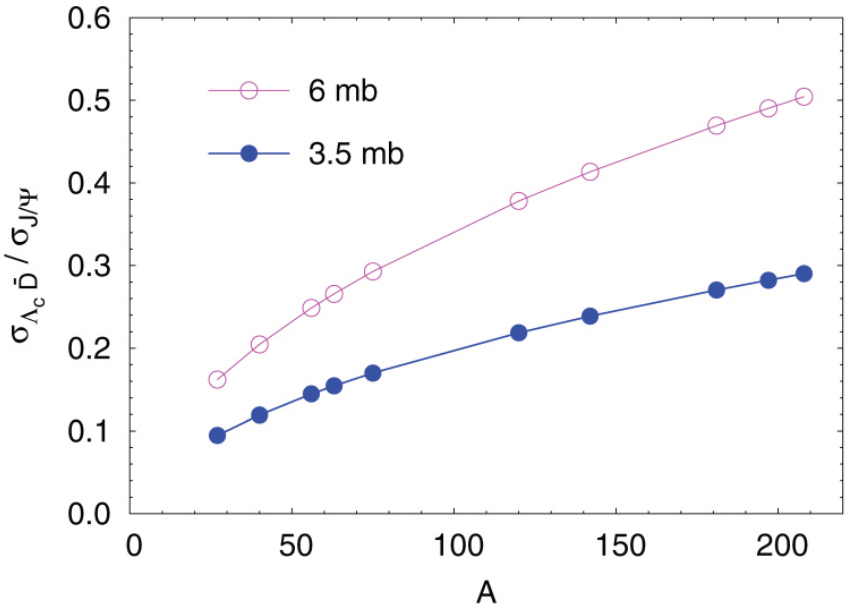
A. Larionov *et al.*, PRC 87 (2013) 054608

How to Deduce σ(J/ψN)

- Measure A dependence of J/ψ yield
- Measure D^+, D^0 yield in addition
- Exclusive measurement with d target: use Pontecorvo reaction:
  $\bar{p}d \rightarrow \bar{\Lambda}_c^+ D^0$ at $\sqrt{s} = M_{J/\psi}$
  $(\sigma \sim 20\, pb)$

A. Larionov, priv. comm. (2014)

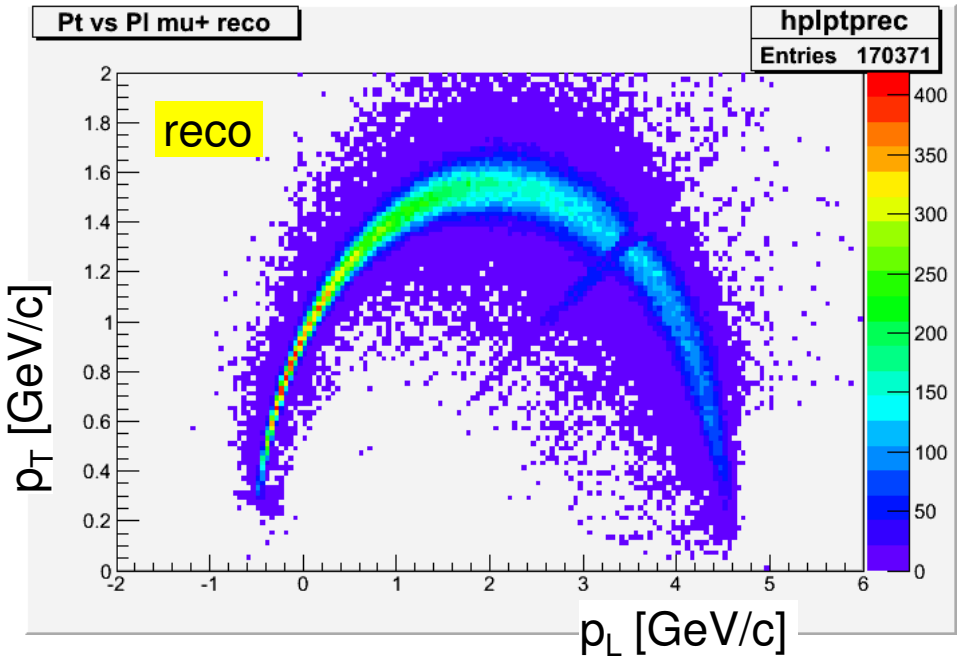




A. Larionov *et al.*, PRC 87 (2013) 054608

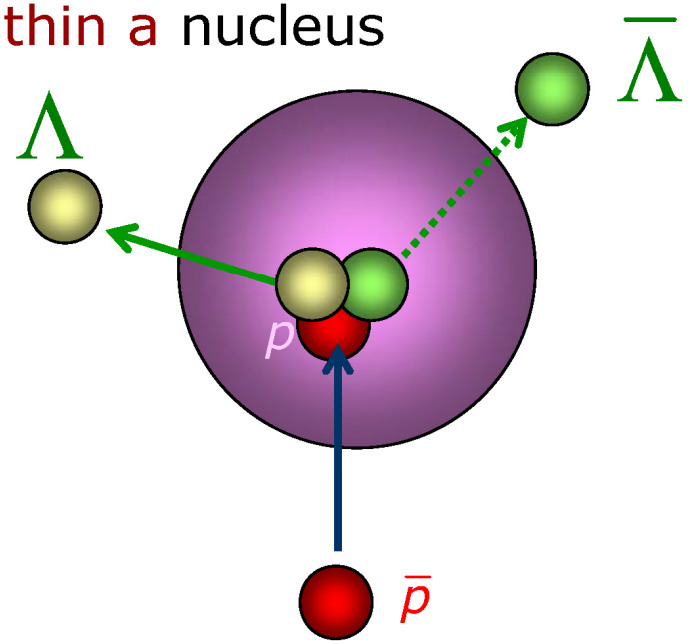
Nuclear J/ψ Absorption in PANDA: Status

- Signal and background studies with old framework for Physics Performance Report (Paul Bühler)
- GiBUU Event Generator for J/ψ (A. Larionov), interface to PandaRoot
- GiBUU 4.05 GeV/c $\bar{p}$ + ^{40}Ca: ~2×10^5 J/ψ, ~2×10^4 $\bar{D}\Lambda_c^+$
- PandaRoot simulation and analysis of J/ψ → e^+e^-, $\mu^+\mu^-$



Can we measure the potential for $\overline{Y}$?

- antiprotons are optimal for the production of mass without large momenta
- consider $p+\bar{p} \rightarrow Y+\overline{Y}$ close to threshold within a nucleus
- Λ and $\overline{\Lambda}$ that leave the nucleus will have different asymptotic momenta depending on the respective potential



- experimental complications
  - Avoid annihilation
  - Fermi motion of struck proton
  - Non-isotropic production
  - Density distribution U(ρ)
  - Exclusiveness
  - Momentum dependence of potential

need to look at average *transverse* momentum close to threshold of *coincident* $Y\overline{Y}$ pairs

J. Pochodzalla, PLB 669 (2008)306

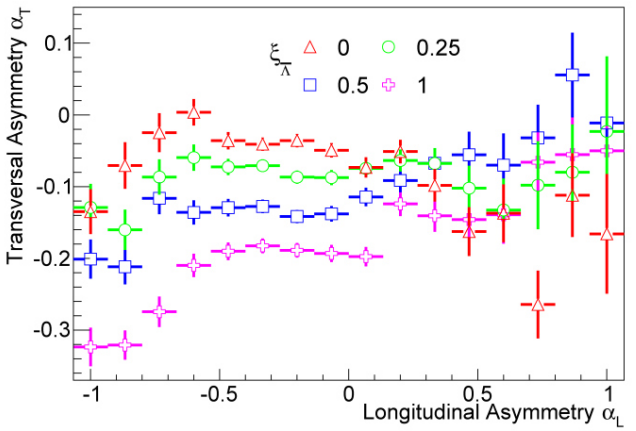
Study of $\bar{\Lambda}$ Potential with GiBUU

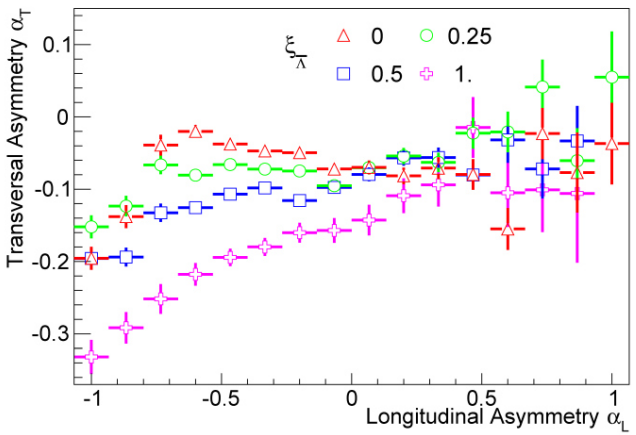
- $\bar{p}\,^{20}Ne \rightarrow \bar{\Lambda}\Lambda + X$ (E_{kin} = 0.85, 1 GeV)
- ~8000 $\bar{\Lambda}\Lambda$ each
- G parity transformation:
  $U_{\bar{\Lambda}} \cong -450$ MeV
- $\xi = 0 \ldots 1$ scaling factor

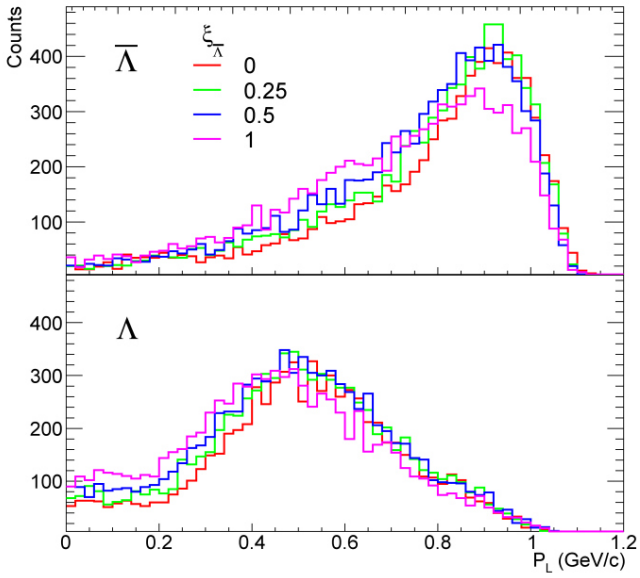
$$\alpha_T = \frac{p_T(\Lambda) - p_T(\bar{\Lambda})}{p_T(\Lambda) + p_T(\bar{\Lambda})}$$

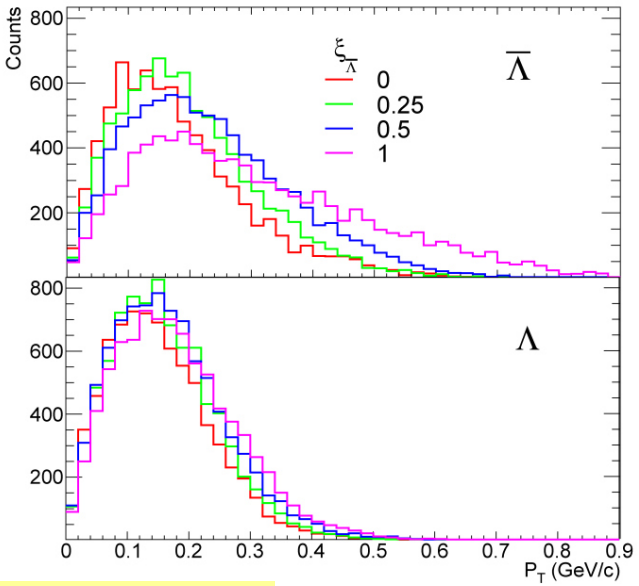
$$\alpha_L = \frac{p_L(\Lambda) - p_L(\bar{\Lambda})}{p_L(\Lambda) + p_L(\bar{\Lambda})}$$

- plot α_T vs. α_L









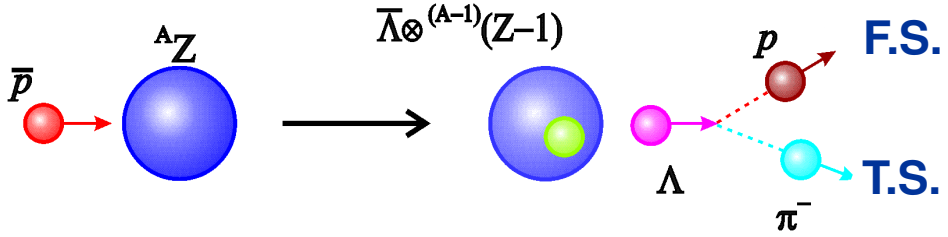
A. Sanchez Lorente *et al.*, PLB 749 (2015) 421

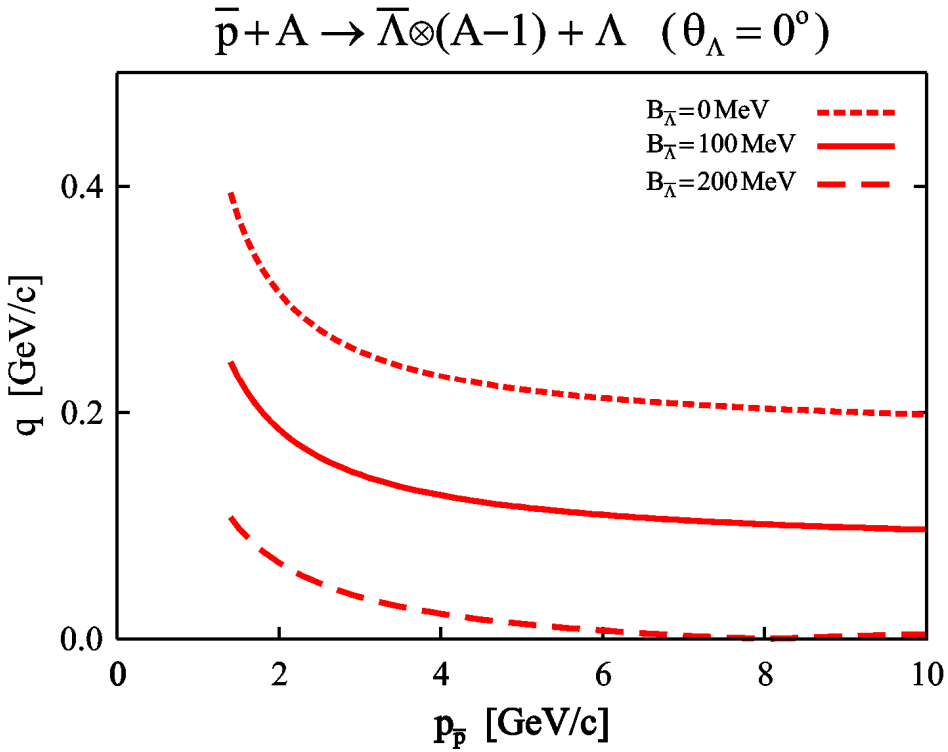
$\overline{\Lambda}$ Nuclear Potential from Recoilfree Reaction

- use $\bar{p}p \rightarrow \overline{\Lambda}\Lambda$ at $\theta_\Lambda \sim 0^o$ with nuclear proton
- detect $p\pi^-$ in Forward Spec.
- small momentum transfer
- $\left(\frac{d\sigma}{d\Omega}\right)_{\bar{p}p \rightarrow \overline{\Lambda}\Lambda,\, \theta_\Lambda \sim 0^o} \cong 2\,\mu b/sr$ at p = 1.77 GeV/c

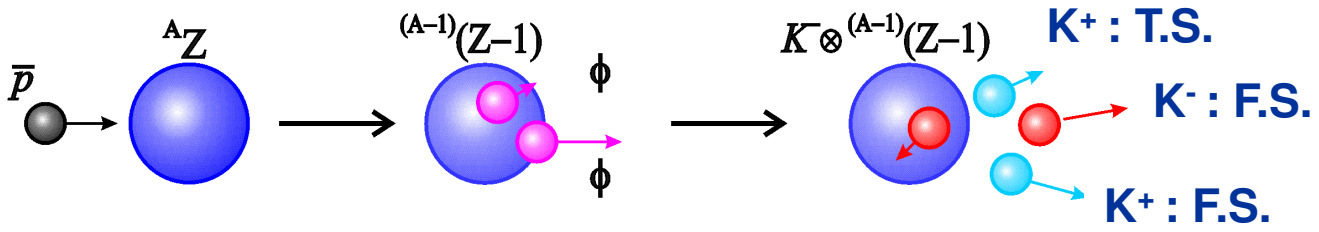
  P.D. Barnes *et al.* (LEAR-PS185), PRC 54 (1996) 2831

- residual system: $\overline{\Lambda}N \rightarrow \overline{K} + n\pi$



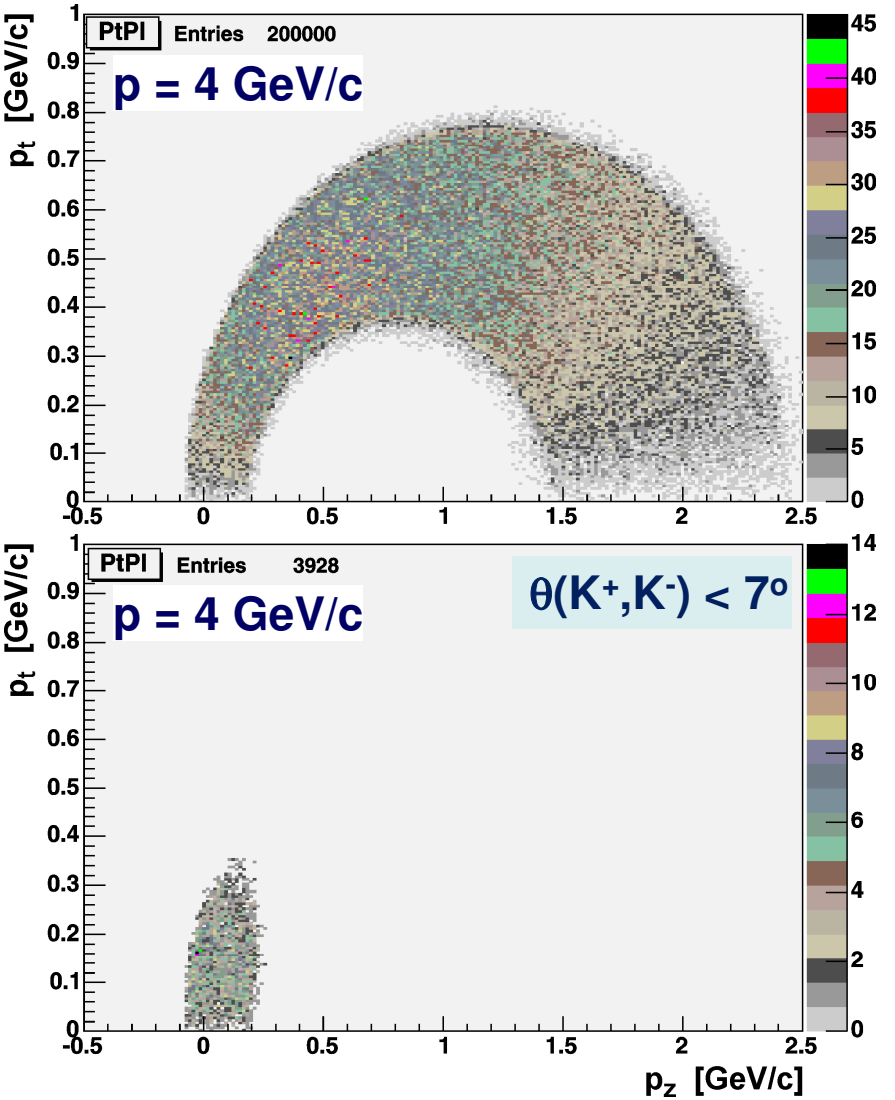


Anti-Kaons

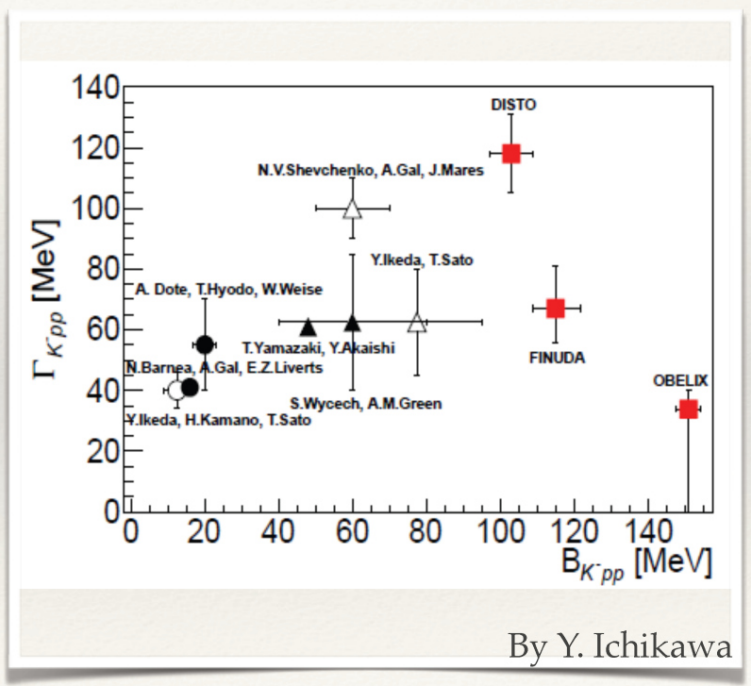


- nuclear potential of $\bar{K}$ still controversially discussed
- use $\bar{p}p \rightarrow \phi\phi$ at $\theta = 0^{o}$ to produce slow K^{-} in nuclei
- $\sigma_{\bar{p}p\rightarrow\phi\phi} \approx 4\ \mu b$ at $p = 1.4$ GeV/c

  JETSET: PLB 345 (1995) 325
- K^{-} captured in attractive potential
- measure ϕK^{+} missing mass
- challenge: detect and identify slow K^{+}



Bound $\bar{K}$NN System?



- theoretical contraversy
- experimental claims (FINUDA, DISTO)
- other studies performed or planned: HADES, FOPI, COSY-TOF, AMADEUS, J-PARC E15, E27
- PANDA: use elementary process $\bar{p}p \rightarrow \bar{\Lambda}\Lambda(1405)$ on nuclear proton (any nucleus A)
- for $\bar{K}NN$: use $\bar{p}d \rightarrow \bar{\Lambda}\,[\bar{K}NN]^0$
- detectable decays: $[\bar{K}NN]^0 \rightarrow \Lambda p\pi^-, \Sigma^0 p\pi^-$

Summary

- PANDA offers a worldwide unique combination
  - antiproton-nucleus collisions
  - momentum range 1.5 – 15 GeV/c
  - detection capability
- $\bar{p}$A collisions allow to study
  - properties of hadrons inside the nuclear environment
  - the properties of the nuclear medium itself
  - the time scale of hard reactions
- new perspectives & complementarity
- *new members are welcome to join the $\bar{p}$A physics in PANDA !*