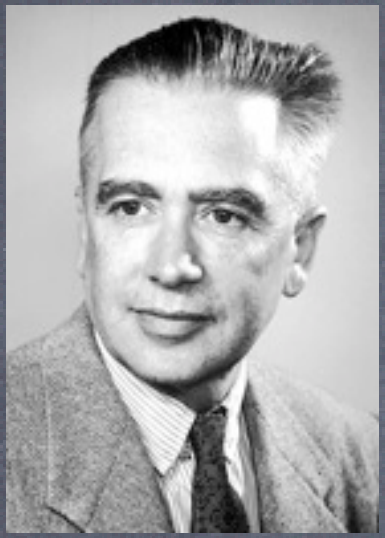
Antiproton nucleus collision at PANDA

Yue Ma,
Helmholtz Institute Mainz
y.ma@gsi.de

Outline

1. Introduction
2. Antiproton nucleus collision:
   - 2.1. generalized baryon-baryon interaction
   - 2.2. cold compressed hadron matter
   - 2.3. quark gluon matter(plasma?)
3. What PANDA can do?
4. Summary

1. Introduction: discovery of antiproton



E. Segrè

O. Chamberlain

Bevatron

- E. Segrè and O. Chamberlain in 1955.
- Bevatron: Billions of eV Synchrotron (GeV)

1. Introduction: discovery of antiproton

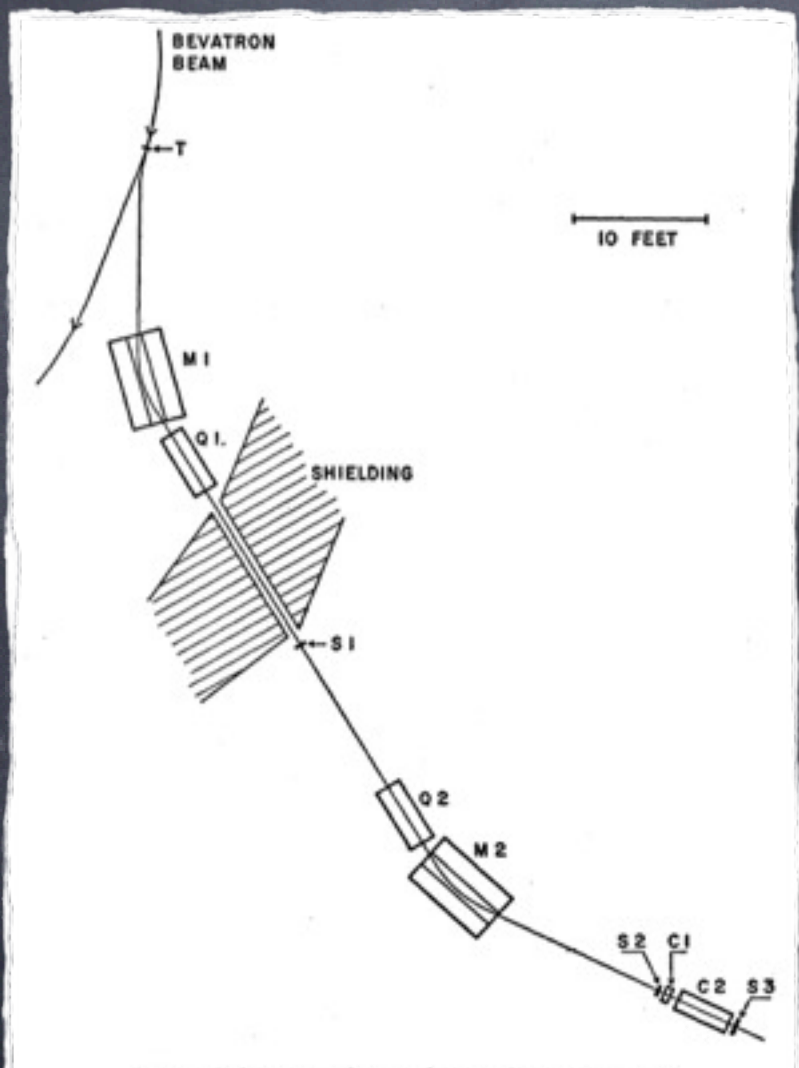


FIG. 1. Diagram of experimental arrangement. For details see Table I.

Beam: 5.6 GeV proton

Target: copper

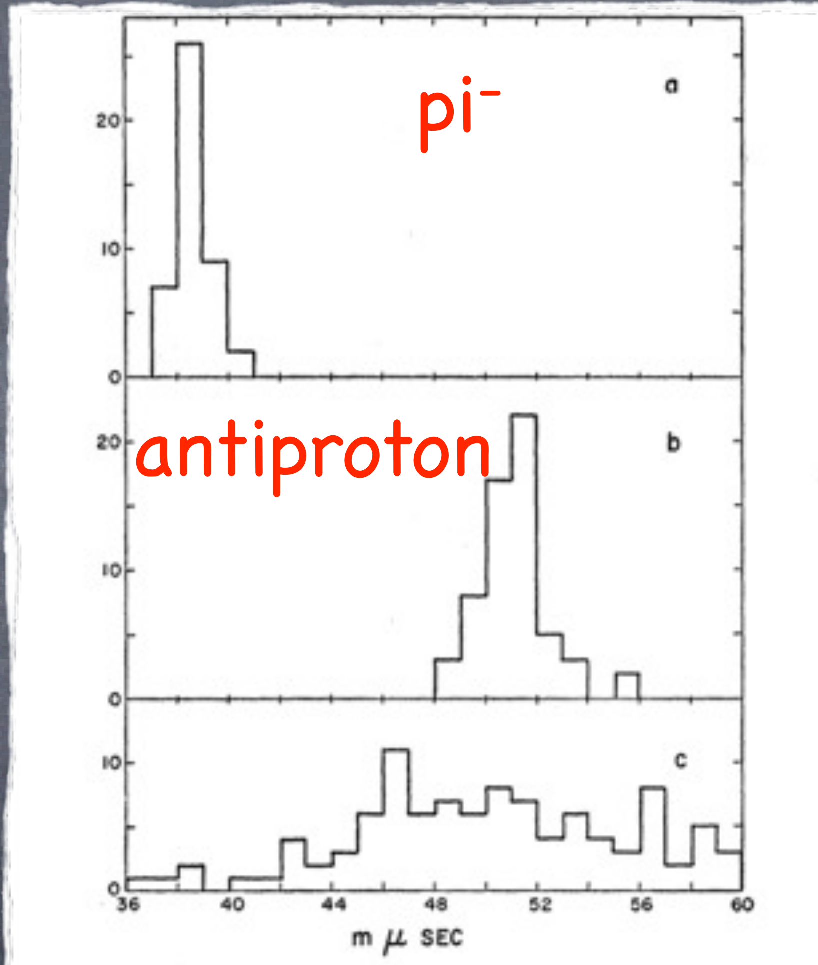


FIG. 3. (a) Histogram of meson flight times used for calibration. (b) Histogram of antiproton flight times. (c) Apparent flight times of a representative group of accidental coincidences. Times of flight are in units of 10^{-9} sec. The ordinates show the number of events in each 10^{-10}-sec intervals.

1. momentum selection

2. time of flight

1. Introduction: main facilities

- CERN:
  - Low Energy Antiproton Ring: 0.6 to 0.9 GeV/c
  - Antiproton decelerator: 0.1 GeV/c
- Fermilab:
  - Tevatron: 1.96 TeV/c
- FAIR:
  - PANDA: 1.5 to 15 GeV/c
  - FLAIR: 20 to 100 keV/c
- BNL & KEK ...

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Results from LEAR will be referred in this talk

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Results from LEAR will be referred in this talk

High luminosity($10^{32}/s{\cdot}cm^2$); almost 4 pi spectrometer

1. Introduction: physics results

- Antihydrogen production and CPT test
- Antiprotonic atom and x-ray spectroscopy
- Antiproton nucleon/nucleus scattering
- Antiproton nucleon annihilation spectroscopy

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optical potential;
pbar nucleus interaction

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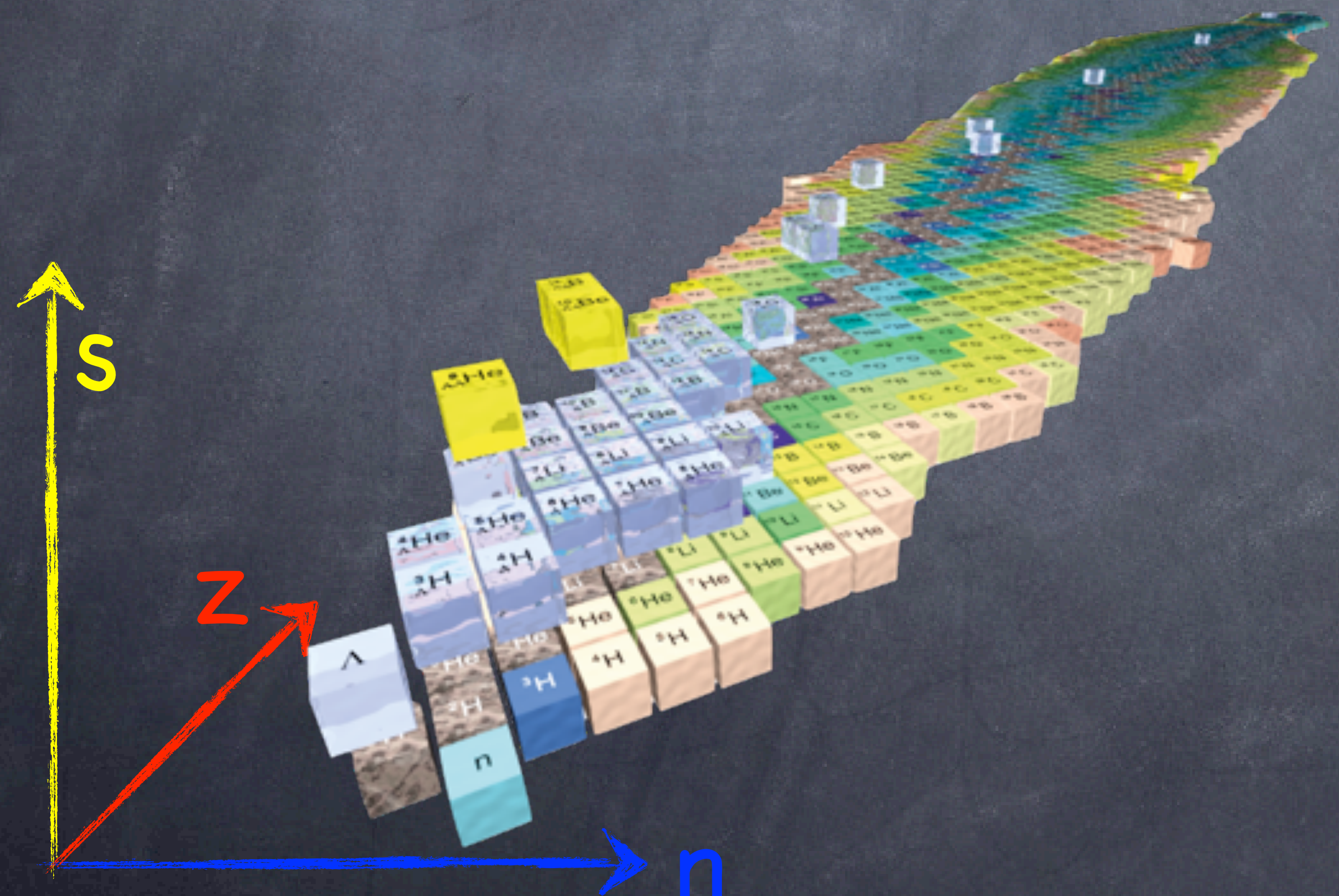
formation of quark gluon plasma?

optical potential;
pbar nucleus interaction

2.1. Generalized baryon-baryon Int.

- **Generalized baryon-baryon(BB) interaction**: how to incorporate antibaryon into baryon-baryon interaction



picture modified based on HypIX poster

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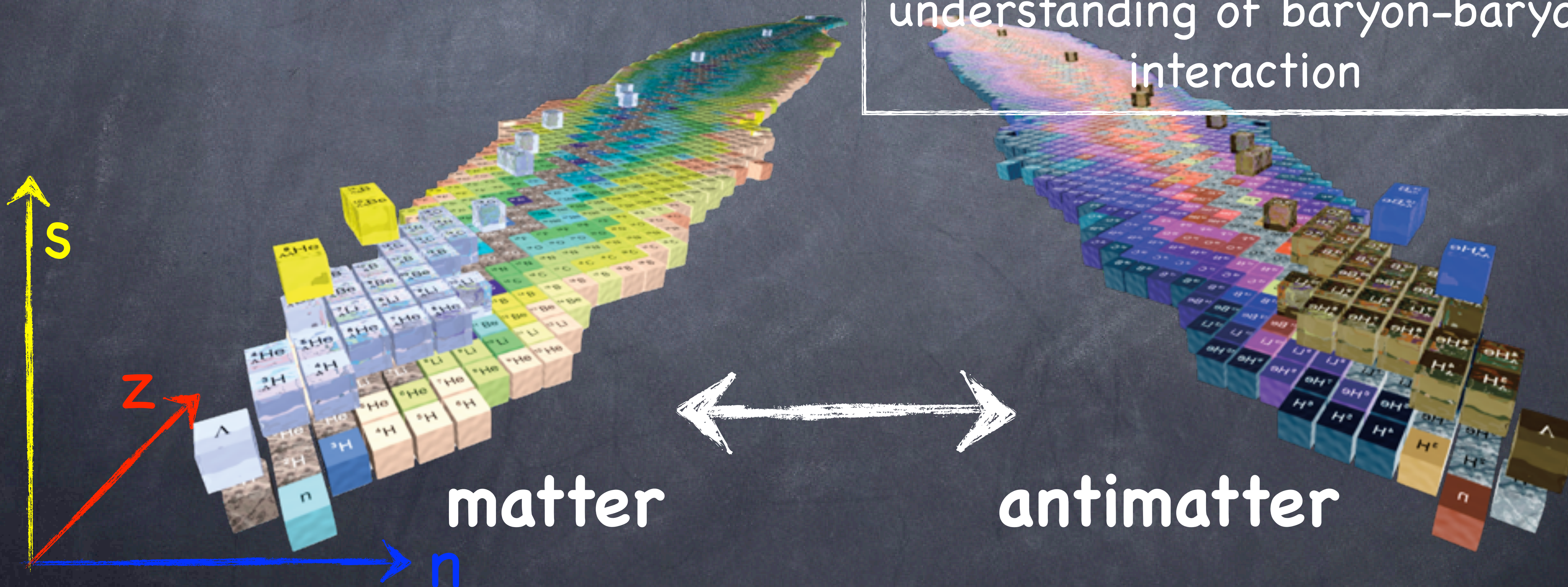
A unique way to improve our understanding of baryon-baryon interaction



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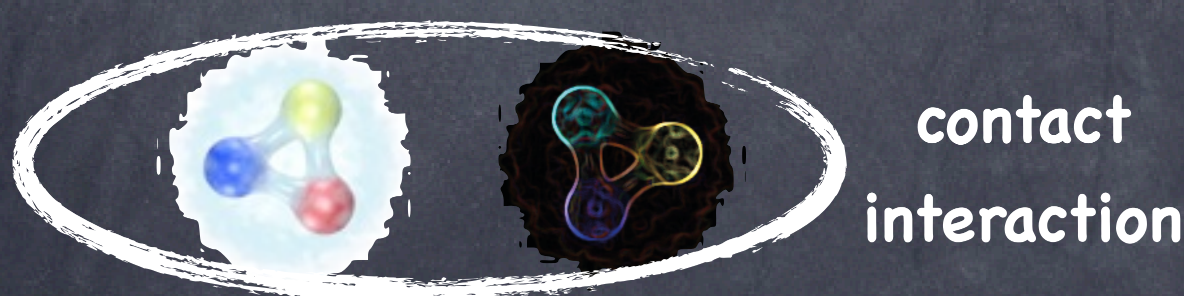
2.1. BB interaction: once upon a time

- It was believed that $V_0 > W_0$ and $R_R > R_I$.

$$V_{opt} \simeq -\frac{V_0}{exp(\frac{r-R_R}{a_R})+1} - \frac{iW_0}{exp(\frac{r-R_I}{a_I})+1}$$

V0: attraction due to meson exchange: R_R large



W0: annihilation and closer contact: R_I small

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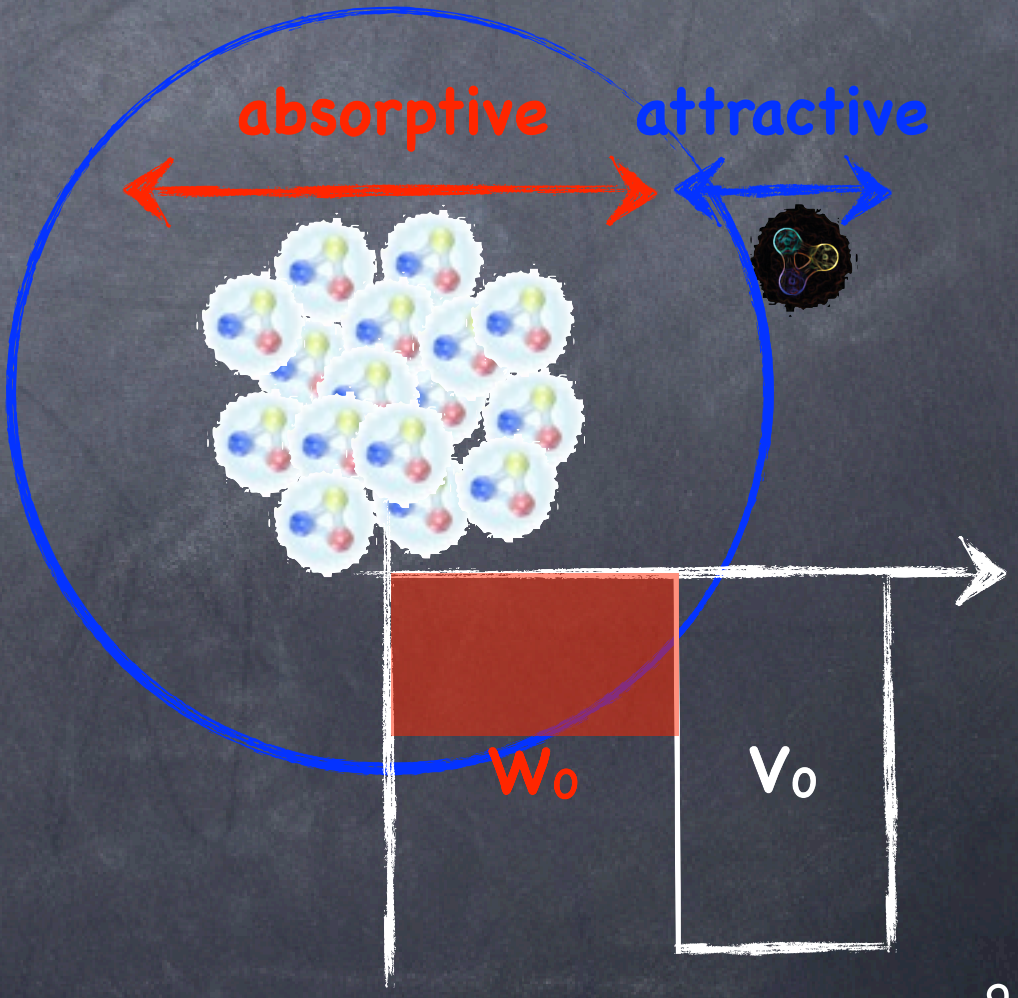
- If this is true: pocket attraction potential; orbiting states



E.H. Auerbach, et al., Phys. Rev. Lett. 46, p.702, (1981)

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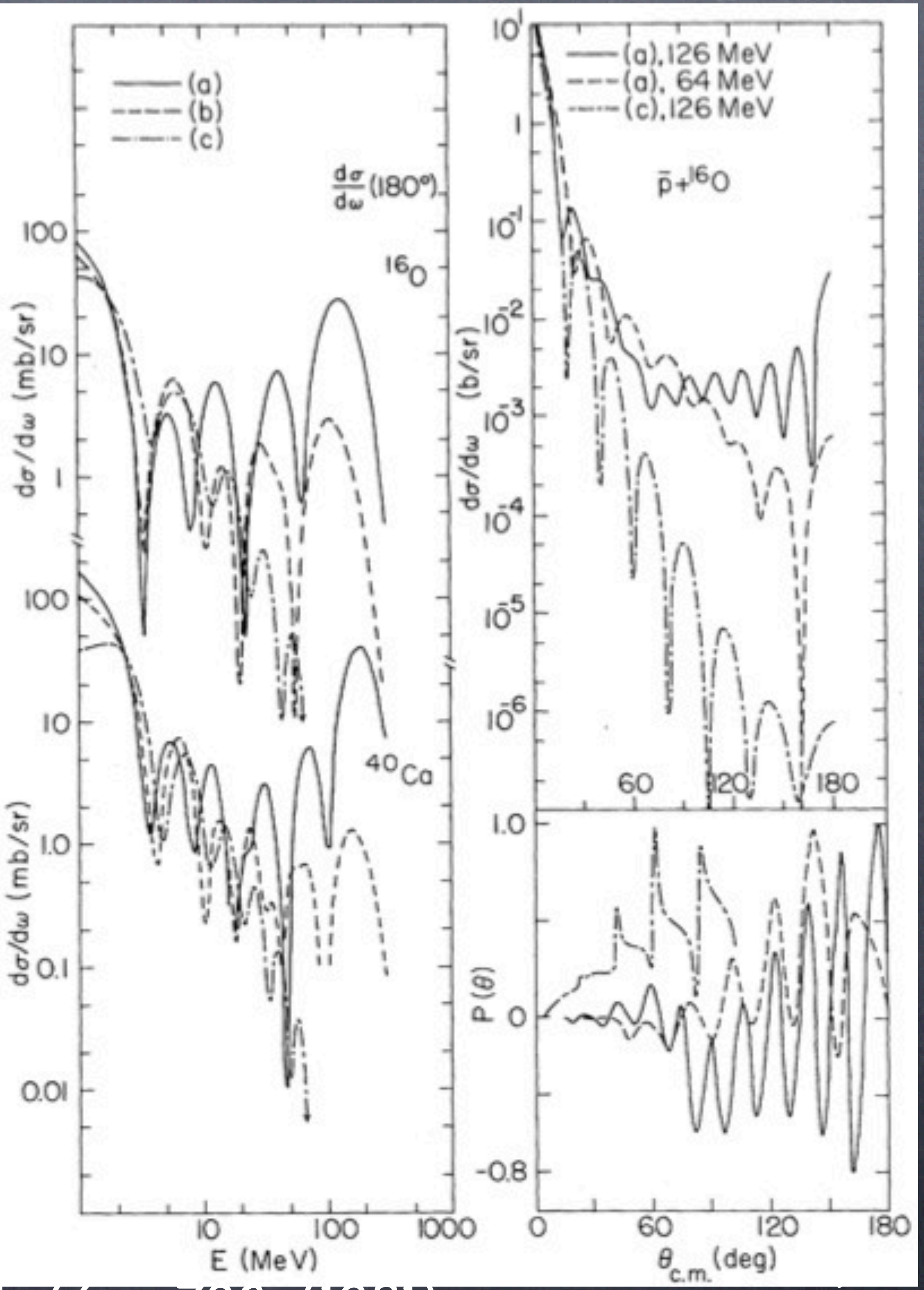
$$V_{opt} \simeq -\frac{V_0}{exp(\frac{r-R_R}{a_R})+1} -$$

- If this is true: pocket attraction potential; orbiting states

a.) V_0=300 MeV, W_0=100 MeV, R_R=1.3 fm, R_I=1.1 fm;
b.) V_0=300 MeV, W_0=100 MeV, R_R=R_I=1.2 fm;
c.) V_0=100 MeV, W_0=200 MeV, R_R=R_I=1.2 fm



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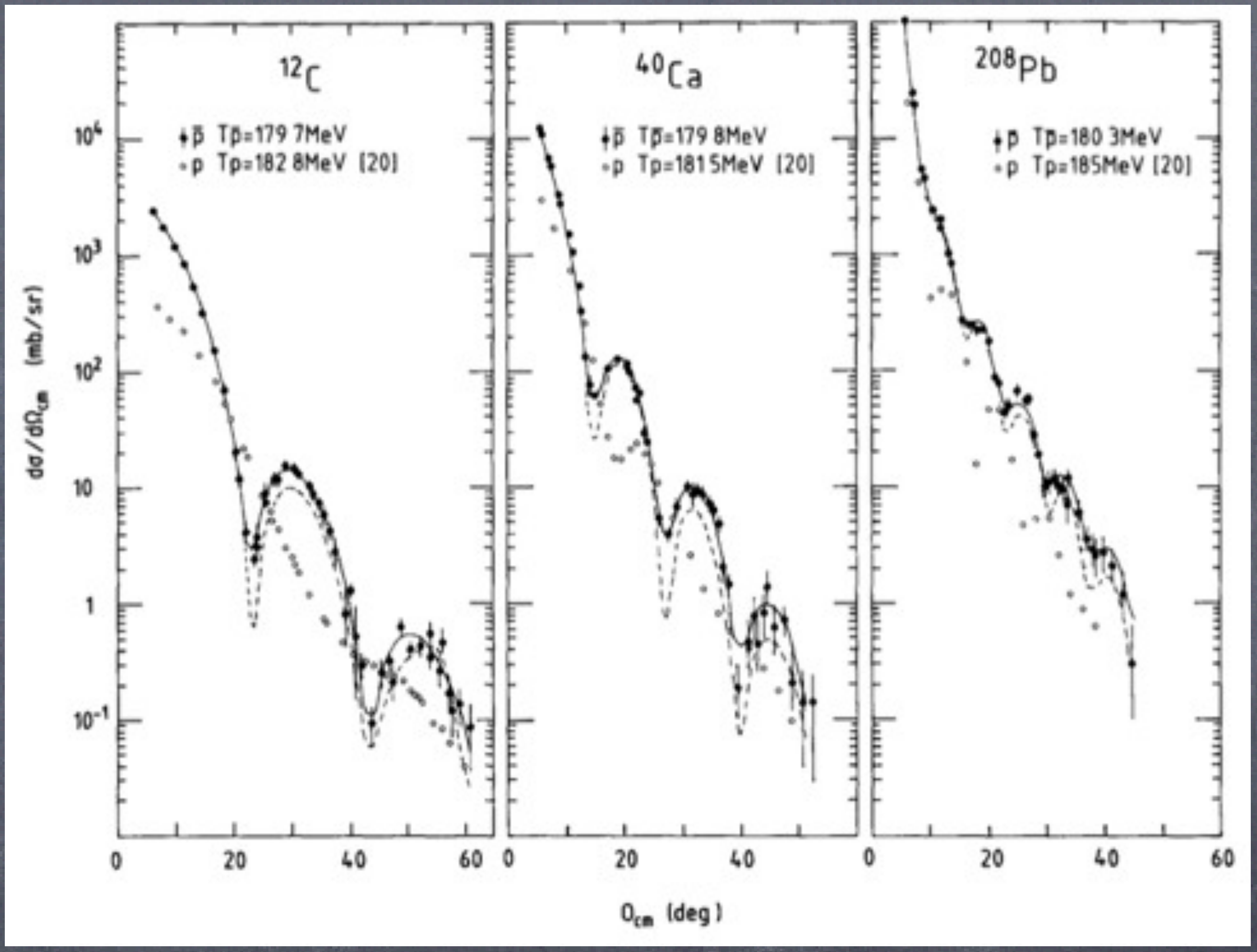
2.1. BB interaction: however ...

antiproton nucleus elastic scattering data



- Optical potential from elastic scattering:

$V_0 = 30 MeV$ **real term**

$W_0 = 118 \sim 172 MeV$ **imaginary term**

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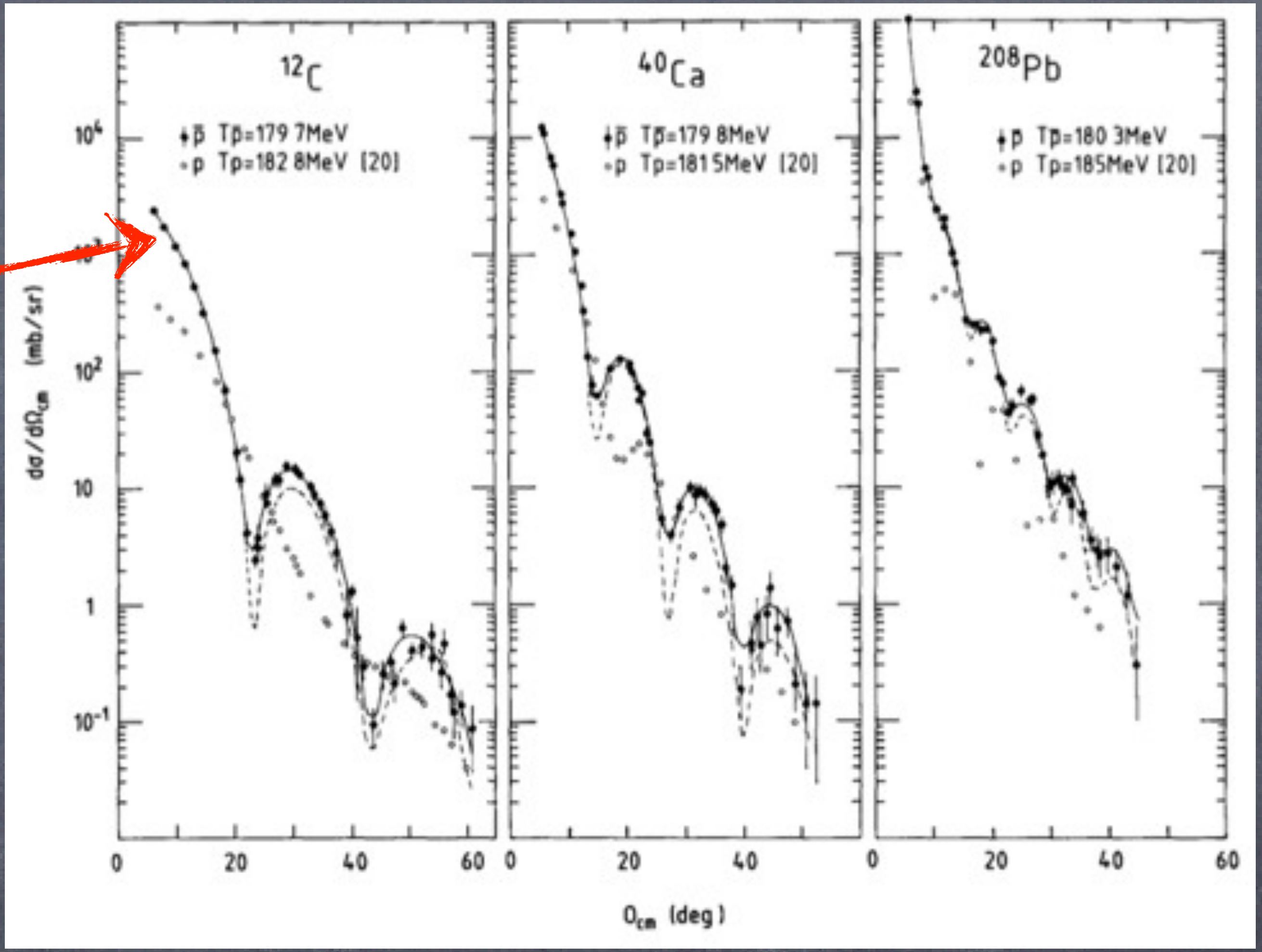
oscillation structure: absorption dominate



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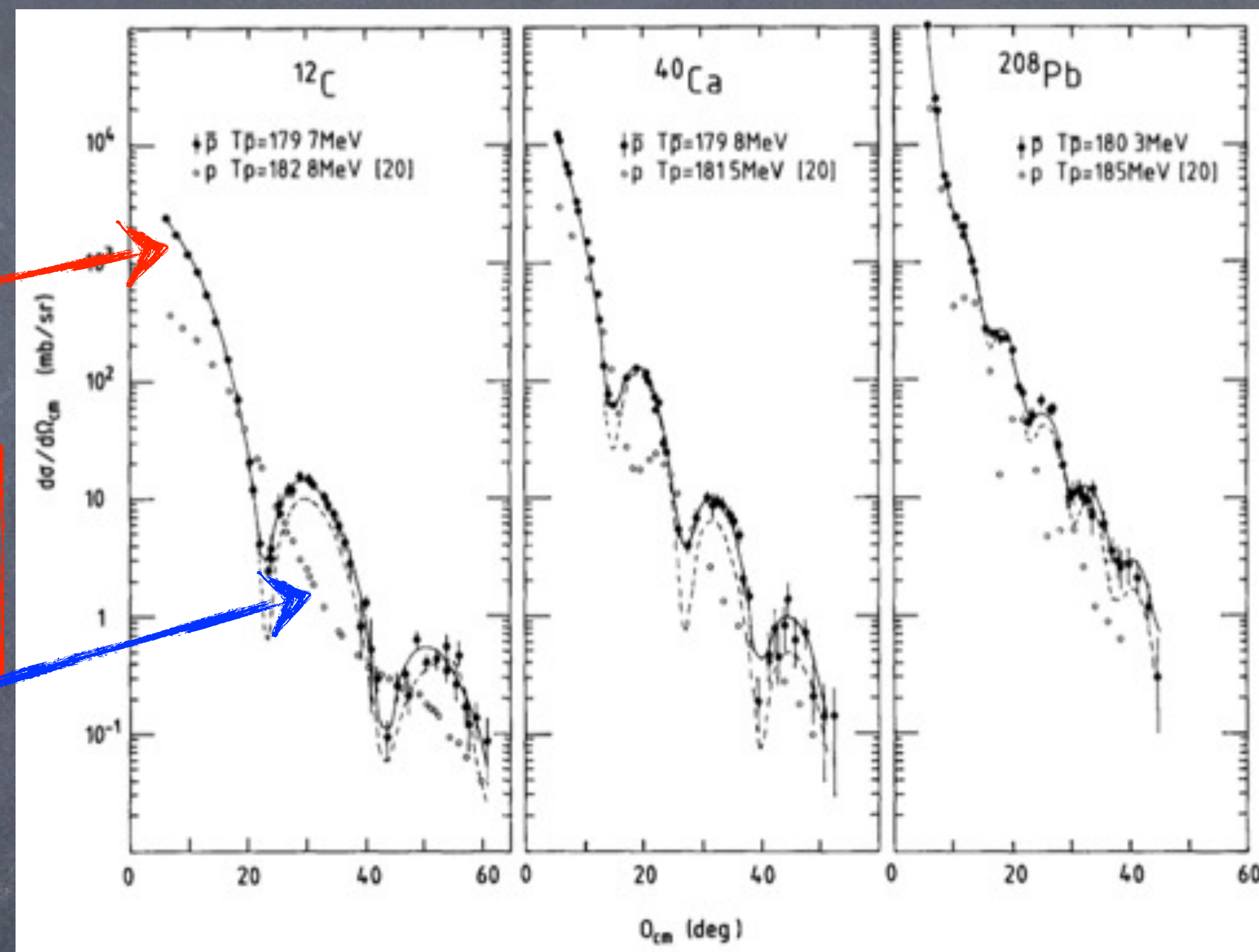

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2.1. BB interaction: at the same time

antiprotonic atom data

- x-ray peak shifted and broadened due to strong interaction
- Optical potential for antiproton in peripheral region (<3% of nuclear density)
- Extrapolated optical potential:

$V_0 = 110 MeV$ **real term**

$W_0 = 160 MeV$ **imaginary term**

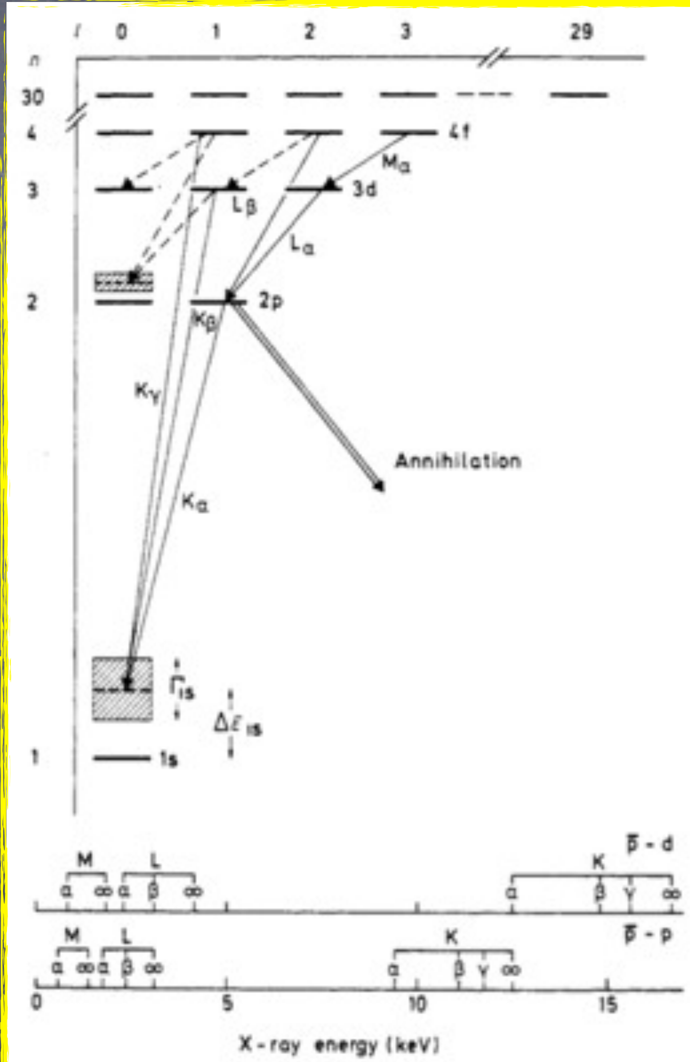

Figure 1. Level scheme for p̄-p and p̄-d atoms showing possible x-ray transitions and their electromagnetic energies.

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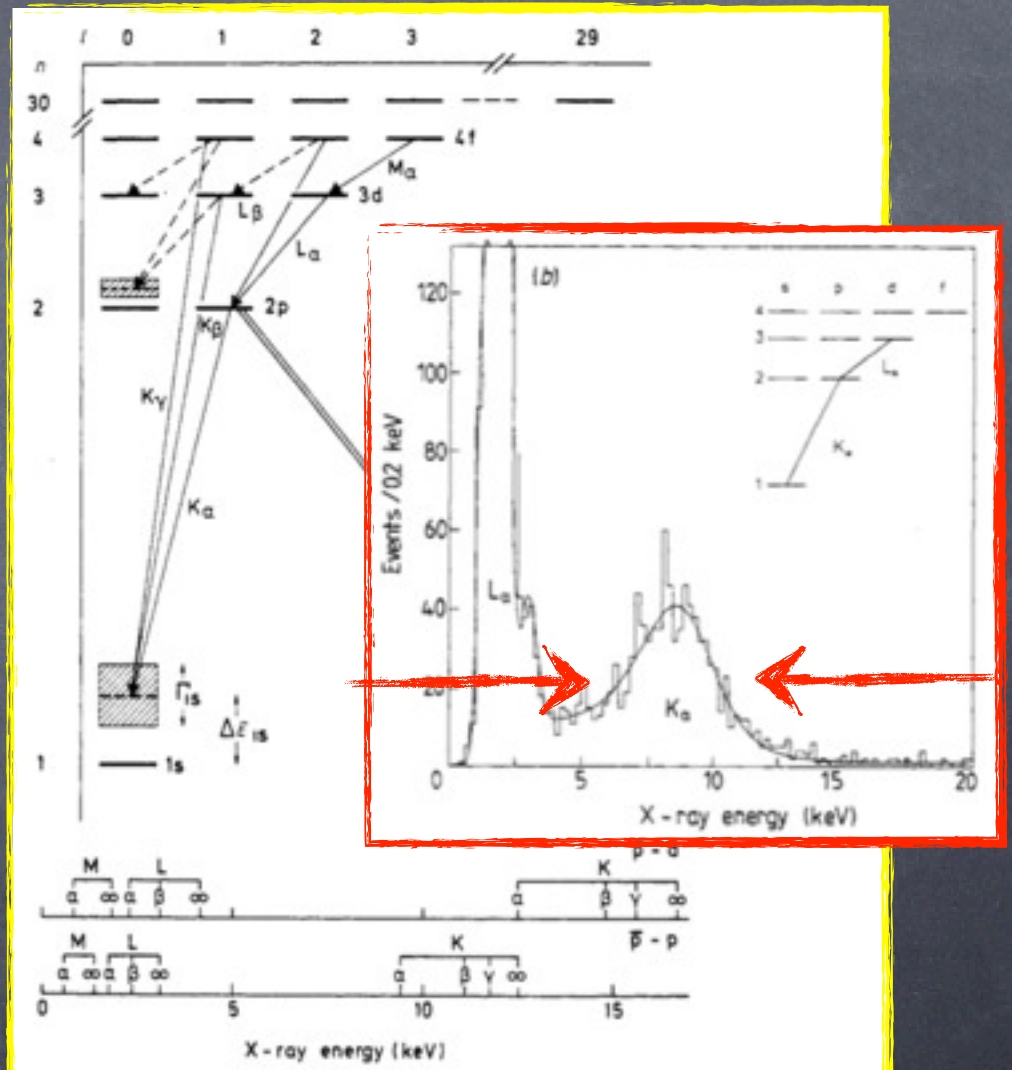

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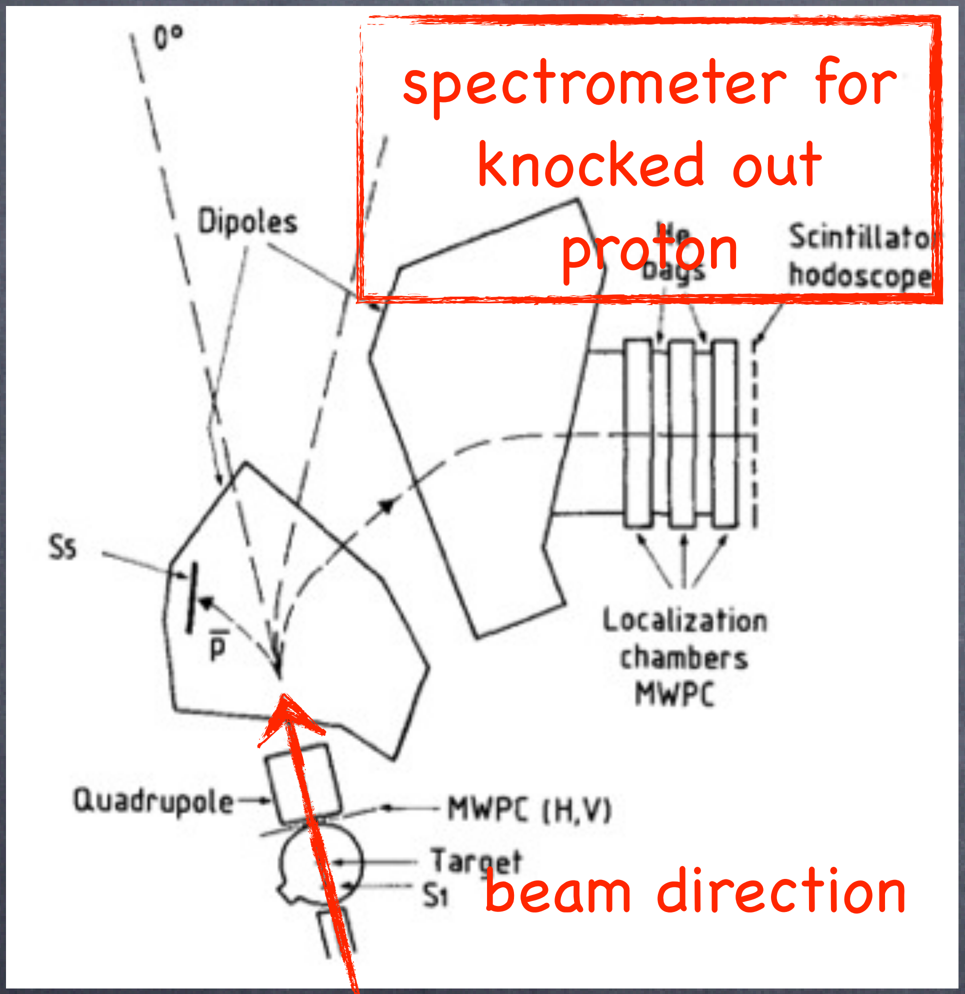
2.1. BB interaction: other approach

proton knock out experiment



LEAR experiment in 1980s:

$_{A}{}^{Z}T(\text{pbar, p})_{A-1}{}^{Z-2}T$

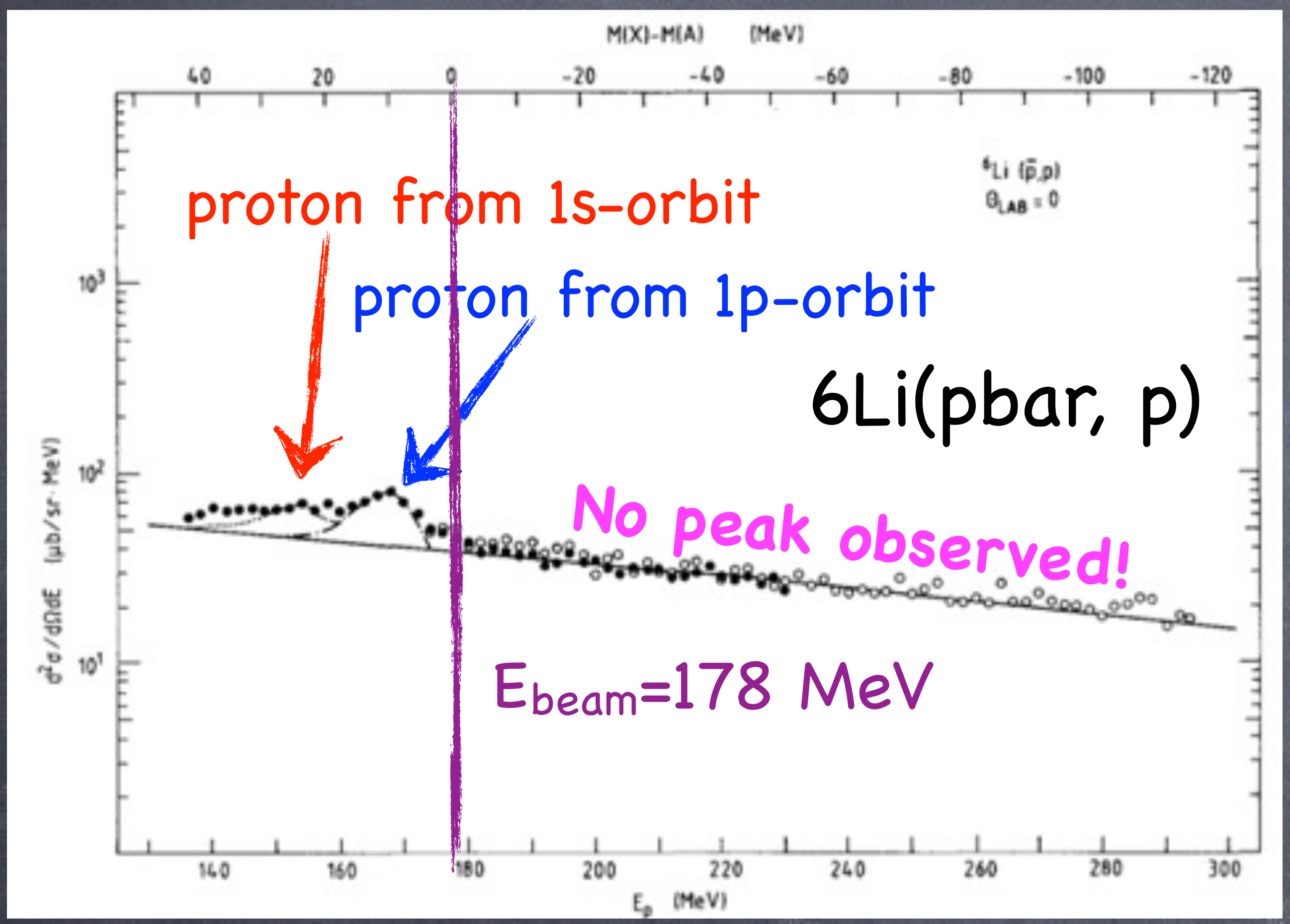
pbar beam(600 MeV/c) + ^{2}H, ^{6}Li, ^{12}C, ^{63}Cu, ^{208}Pb, ^{209}Bi

Kinetic energy of knocked out proton reveals binding energy difference between pbar and proton

E. Aslanides et al, Nucl. Phys. A 470, p.445 (1987)

2.1. BB interaction: no peak?

Mass difference (MeV)



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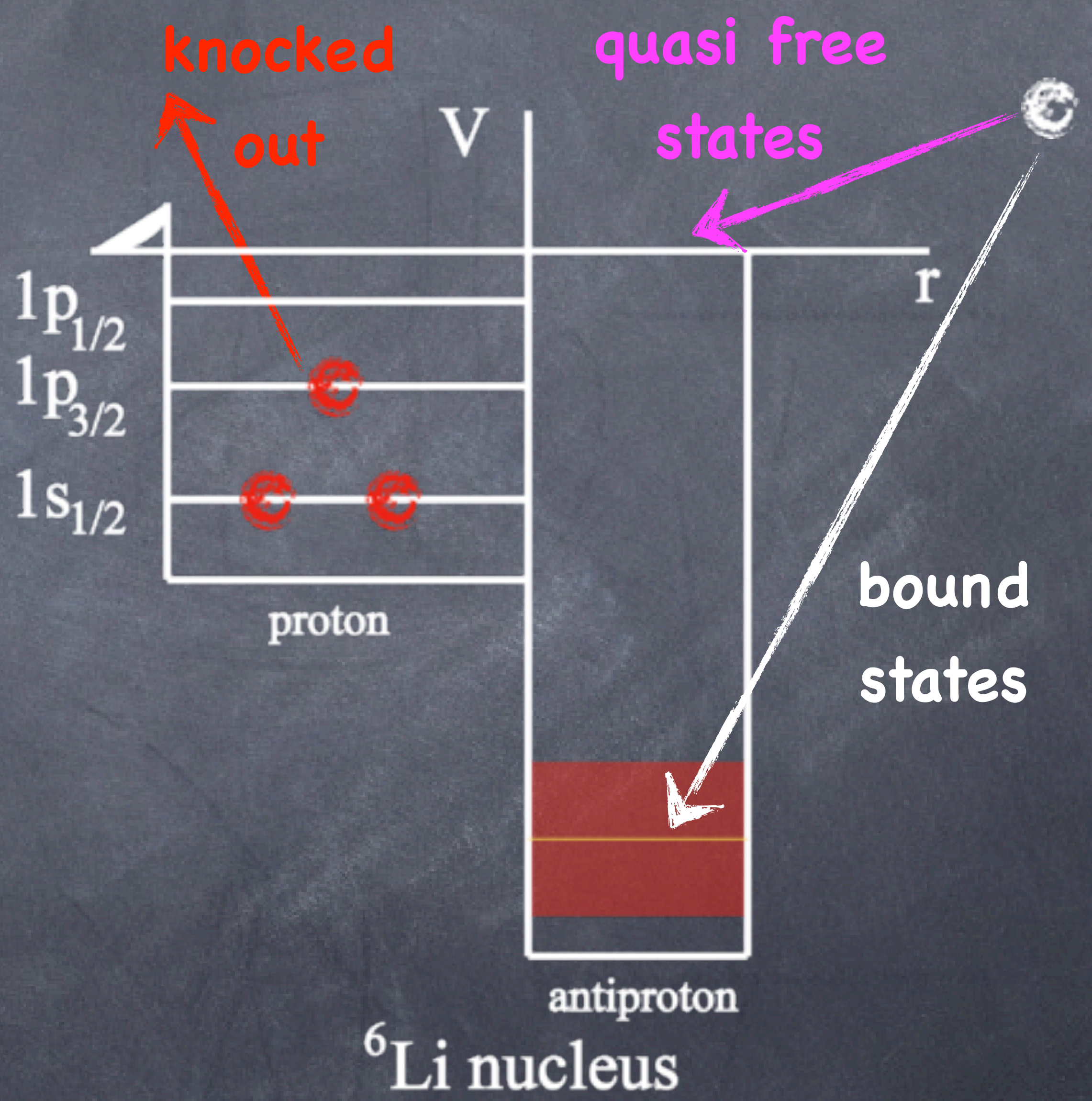

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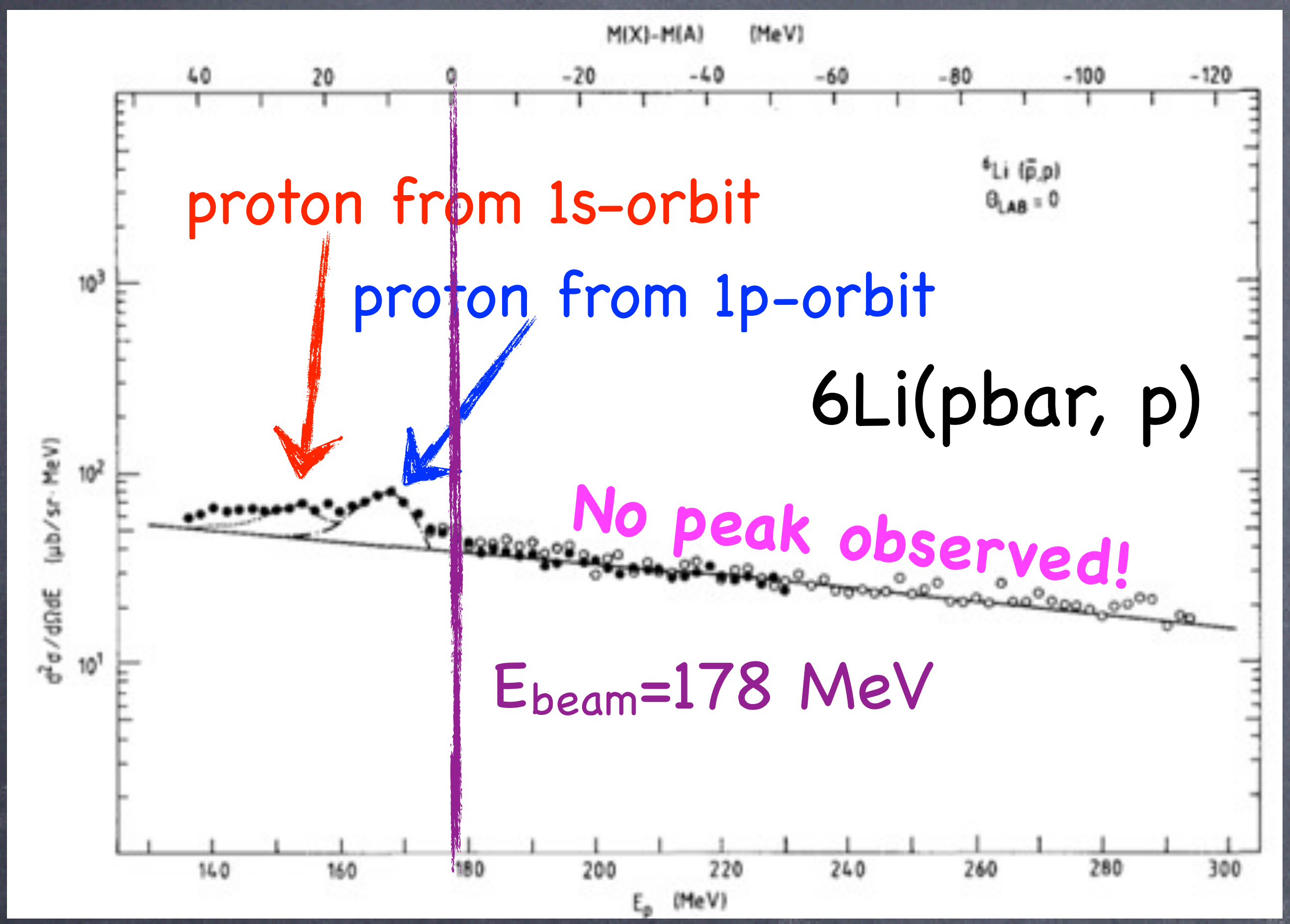

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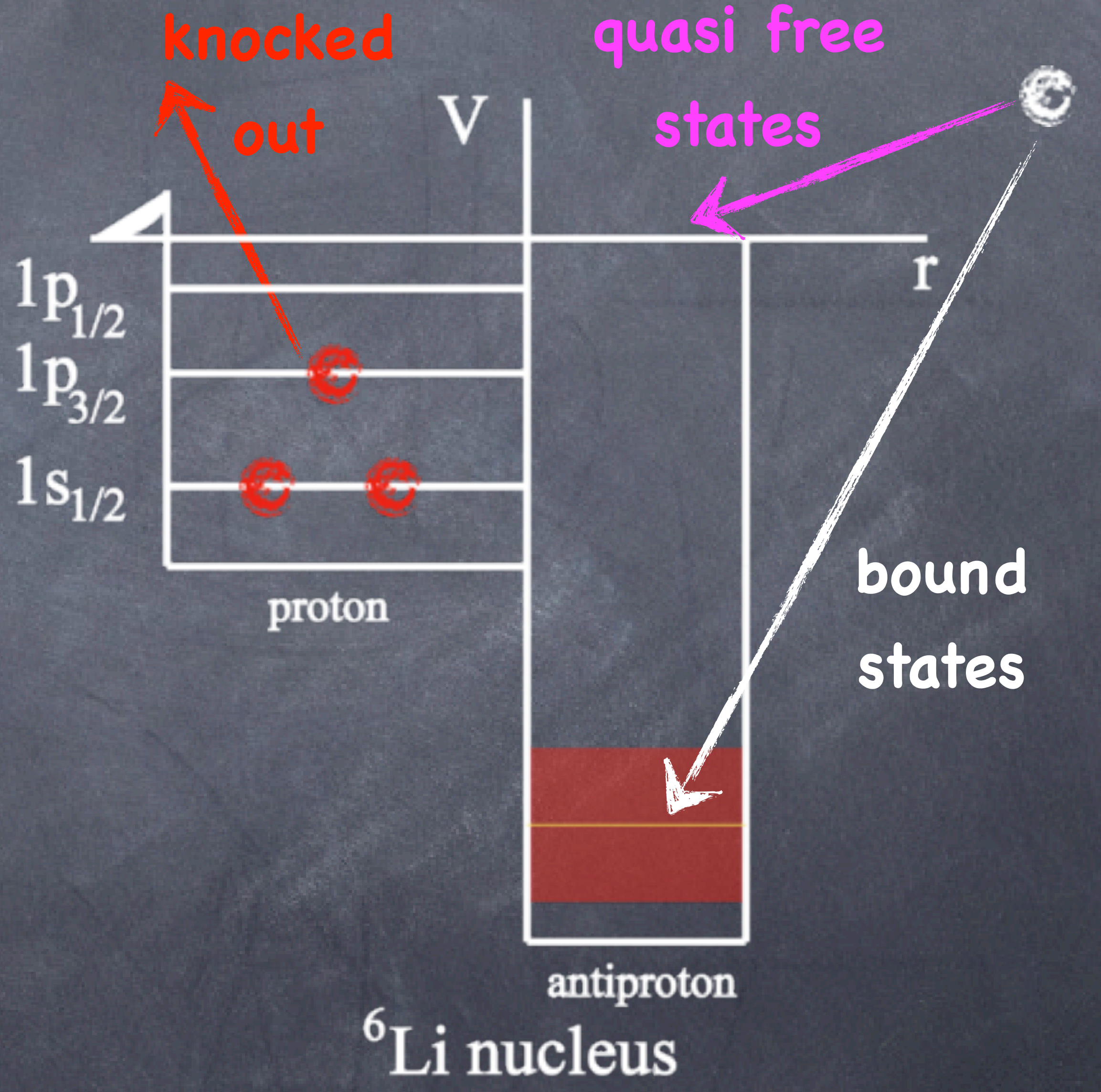
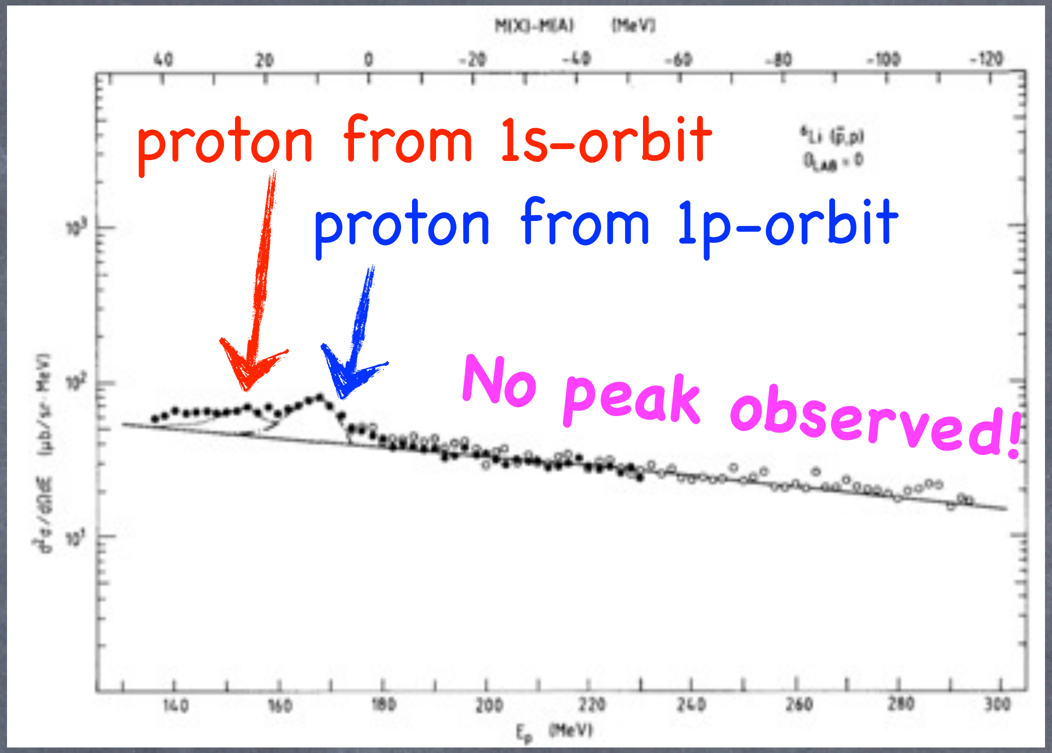


- **No peak observed** at higher kinetic energy: $E_p = E_{beam} + B_{pbar} - B_p$
- **pbar only goes to quasi free states?**

E. Aslanides et al, Nucl. Phys. A 470, p.445 (1987)

2.1. BB interaction: why no peak?



- $E_p = E_{beam} + B_{pbar} - B_p$ beyond the acceptance?
- pbar only stopped on surface of nucleus: not sensitive to nuclear potential(p_{pbar}=600MeV/c is too low)?
- Large virtual potential: bound state is too broad to be identified?

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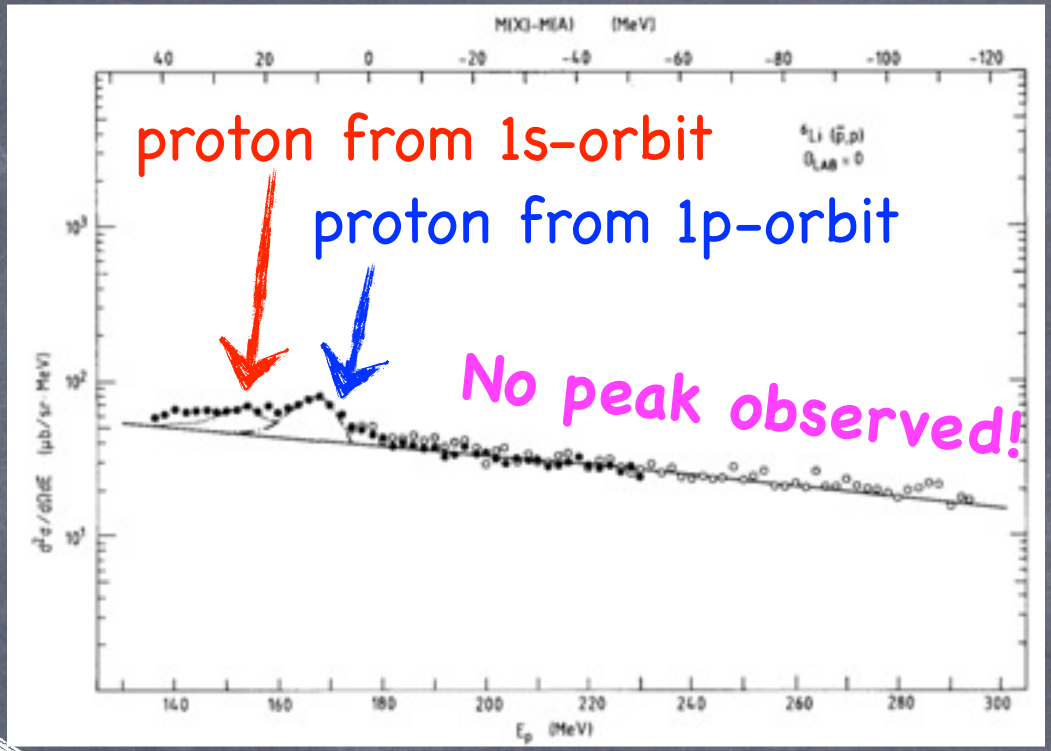

Too "lucky" to be true?

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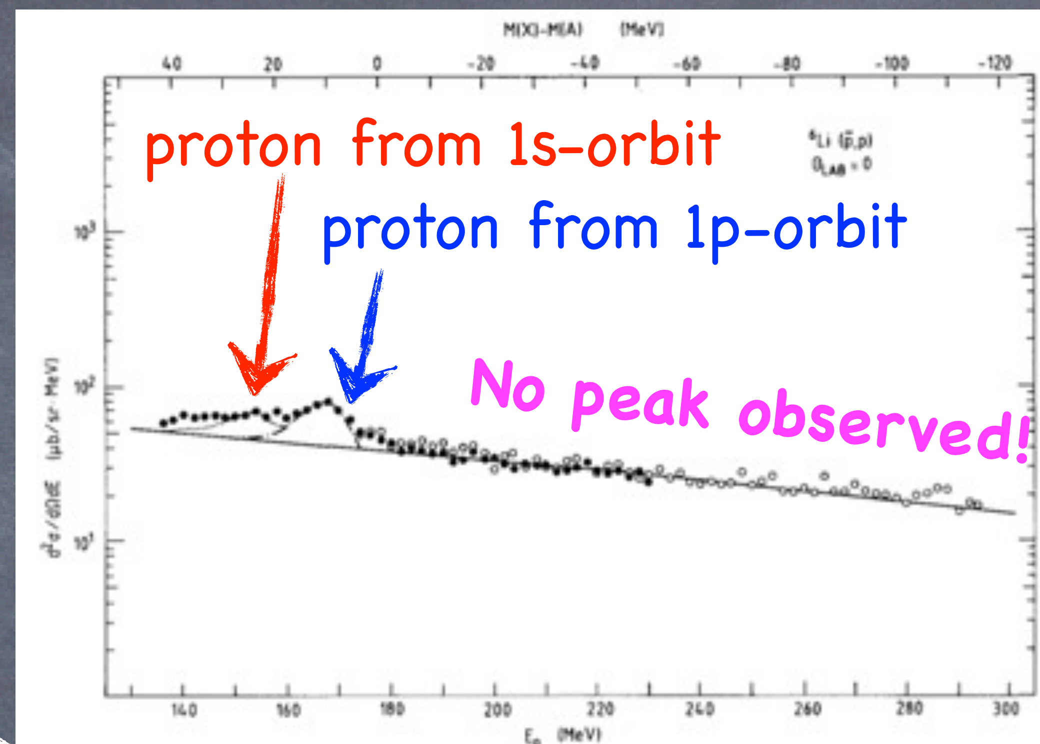

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We will cover this in more details

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2.1. BB interaction: theory says...

G-parity approach: sign of vector meson coupling constant flip

$$E_p = U_v + \sqrt{(M_0 - U_s)^2 + \mathbf{P_p}^2}$$

$$E_{\bar{p}} = -U_v + \sqrt{(M_0 - U_s)^2 + \mathbf{P_{\bar{p}}}^2}$$

- G-parity transformation: $V_0 \approx 700$MeV
- From absorption cross section: $V_0 = 150$MeV
- pbar production&dispersion relation: $V_0 = 100 \sim 200$MeV

A. Larionov, et al., Phys. Rev. C 80, p.021601, (2009)

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Maybe problematic if antiproton lost it identity

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2.1. BB interaction: where are we?

Approach	V_0 (MeV)	W_0 (MeV)
elastic scattering	30	100~200
antiprotonic atom	110	160
knock out reaction	?	?
RMF	150	use as input
G-parity	700	

To sum up:

- absorptive potential: probably strong
- attractive potential: exist? how large?

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To sum up:

We just don't know!

- absorptive potential: probably strong
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2.1 BB interaction: what can we do?

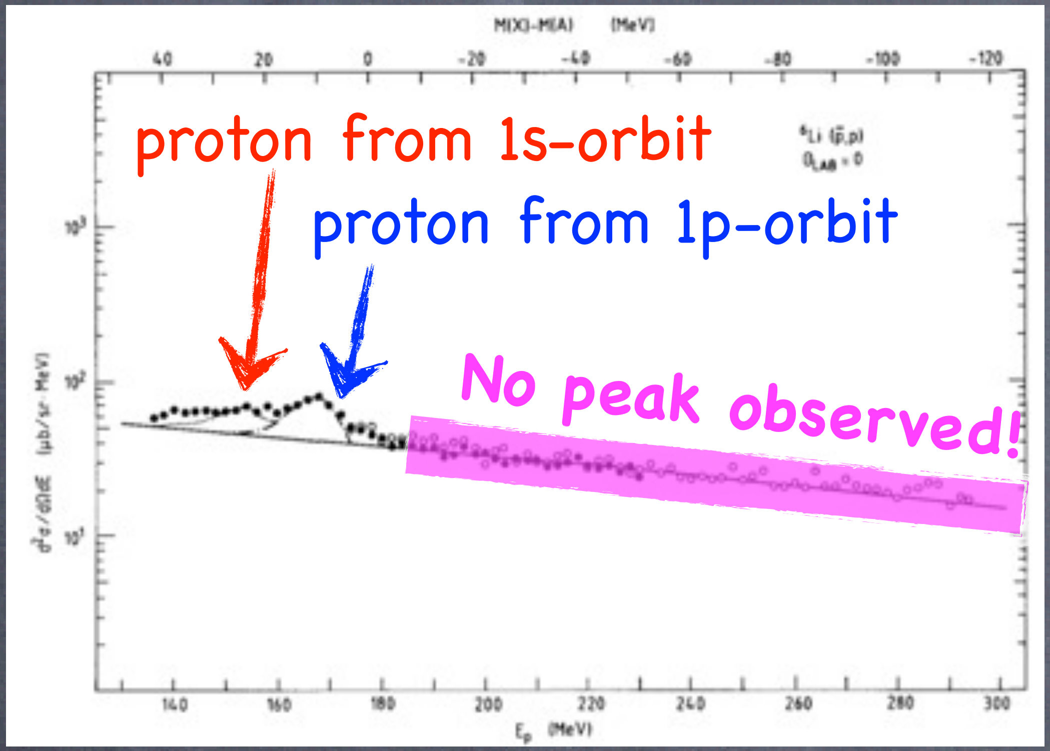
What's the difference PANDA can make:

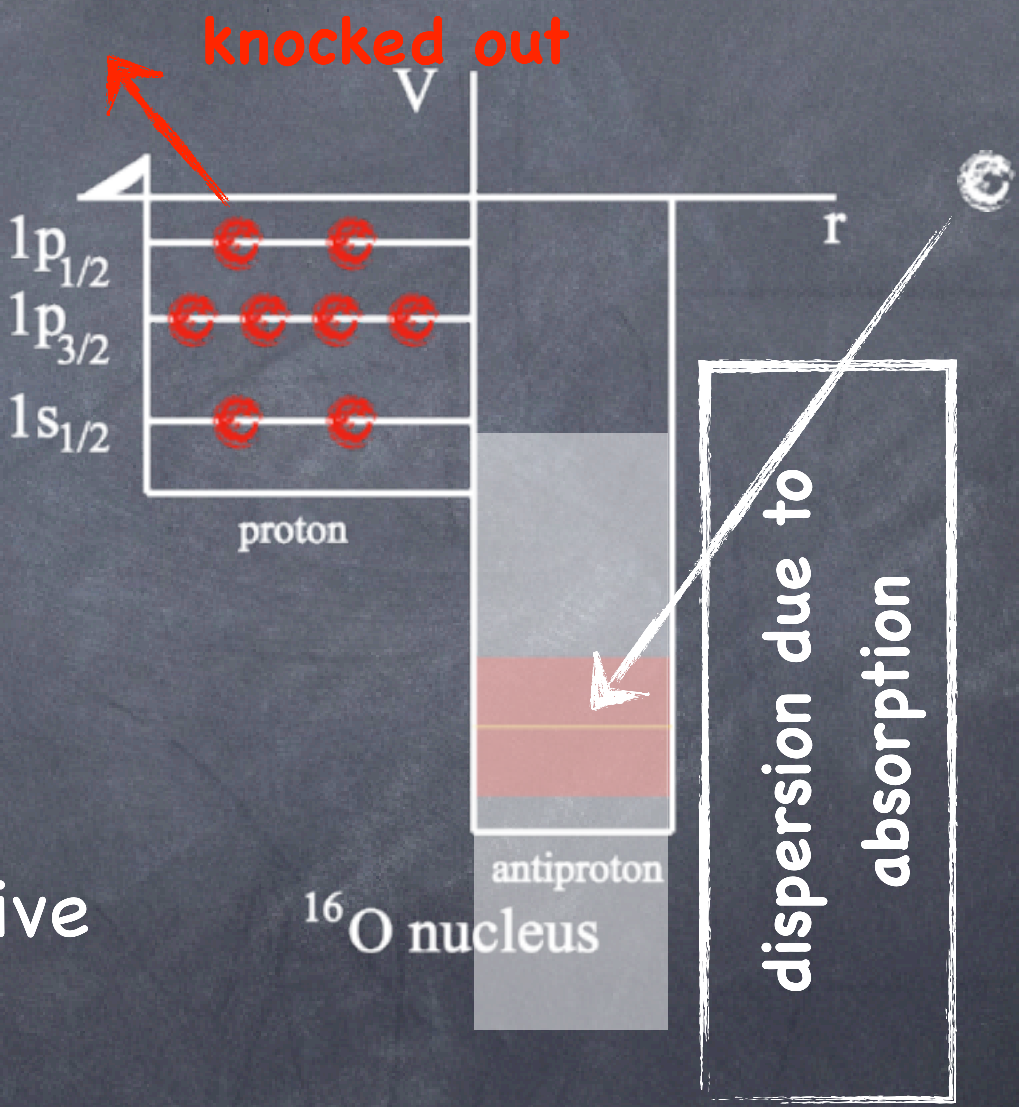
- Forward tracking & exclusive measurement of decay products
- Higher pbar momentum: penetrates into nucleus $\sigma^{\bar{p}p}_{ann} = C + \frac{D}{v_{rel}}$
- High luminosity for rare events

Two approaches:

1. measure the kinetic energy of the knocked out proton/pion at 0^o_{Lab}(revisit of knock out reaction experiment)
2. measure lepton pair invariant mass from in-flight annihilation(Free of FSI)

2.1 BB interaction: approach one





Didn't work due to smearing(absorptive potential) and large background;

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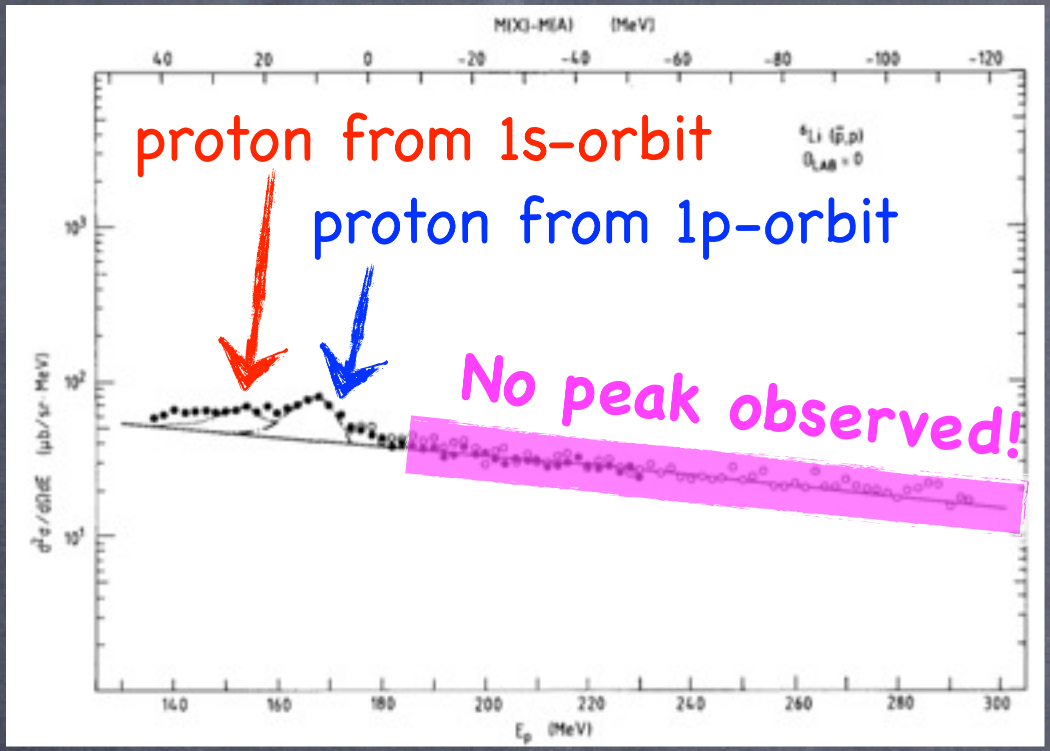

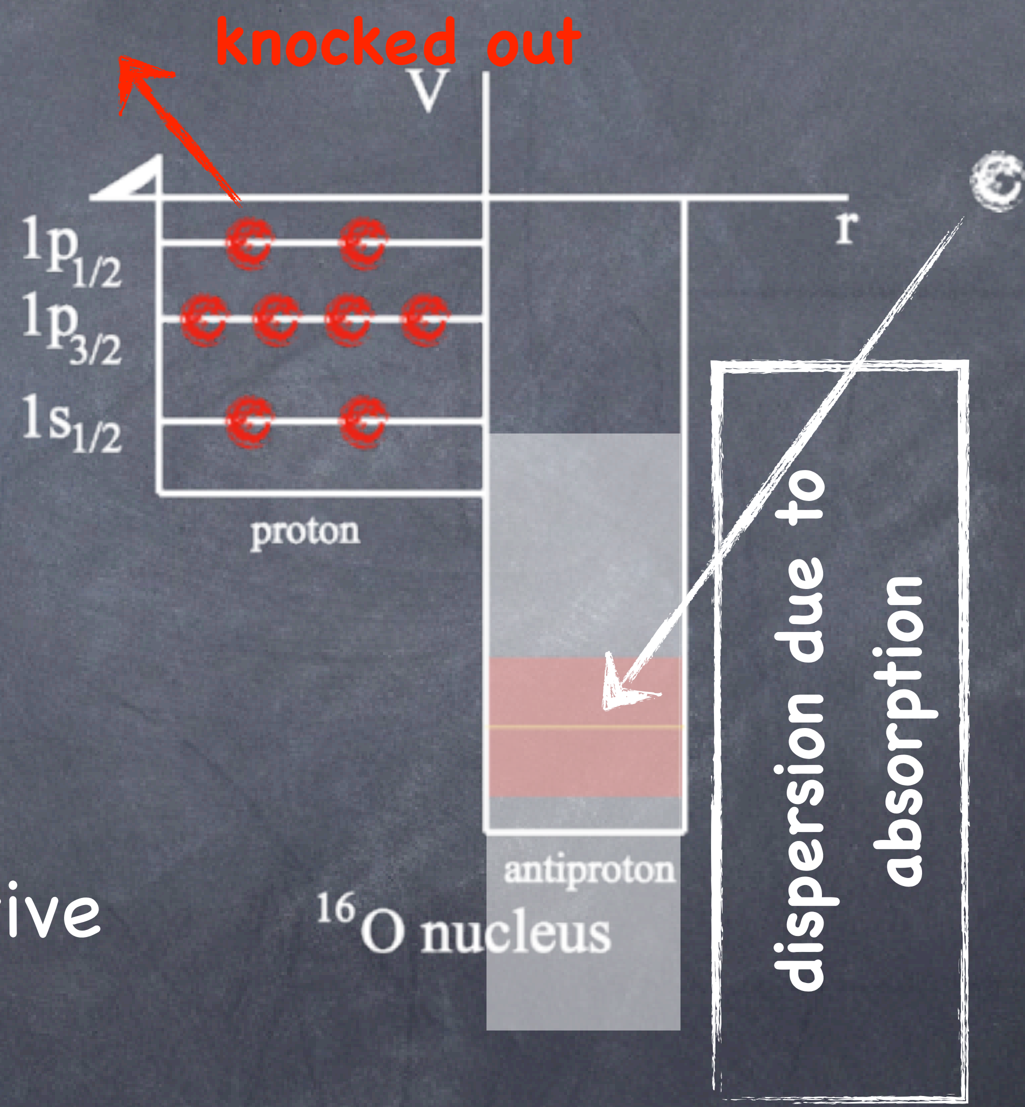

Didn't work due to smearing(absorptive potential) and large background;

Solution: measure the decay products

2.1 BB interaction: approach one

knocked proton with higher kinetic energy than the beam: where is the energy from?

1. from binding energy difference between proton and antiproton($E_p = E_{beam} + B_{pbar} - B_p$): symmetry in p_z of decayed pions
2. from light meson carrying large kinetic energy released from annihilation: asymmetry in p_z of decayed pions

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cutting condition

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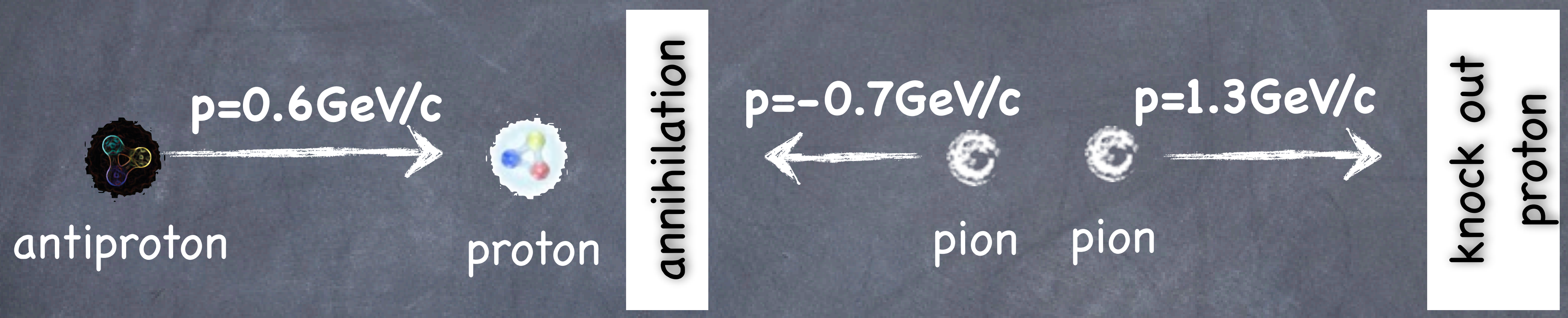

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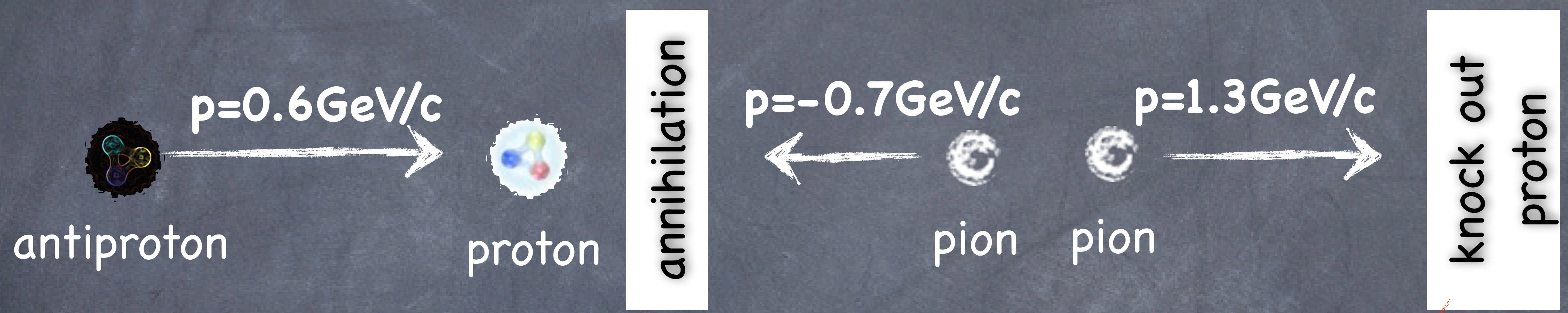

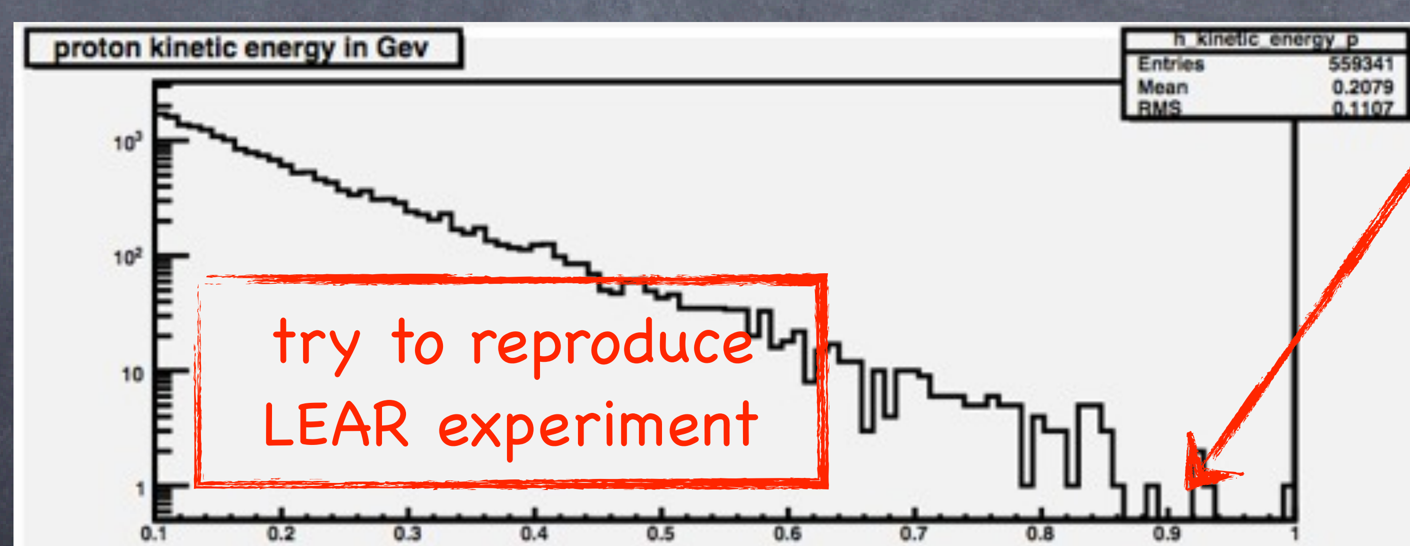

proton kinetic energy(Maximum E_k=0.95GeV)

Calculation with transport model(GiBUU)
beam=167MeV and ^{7}Li target

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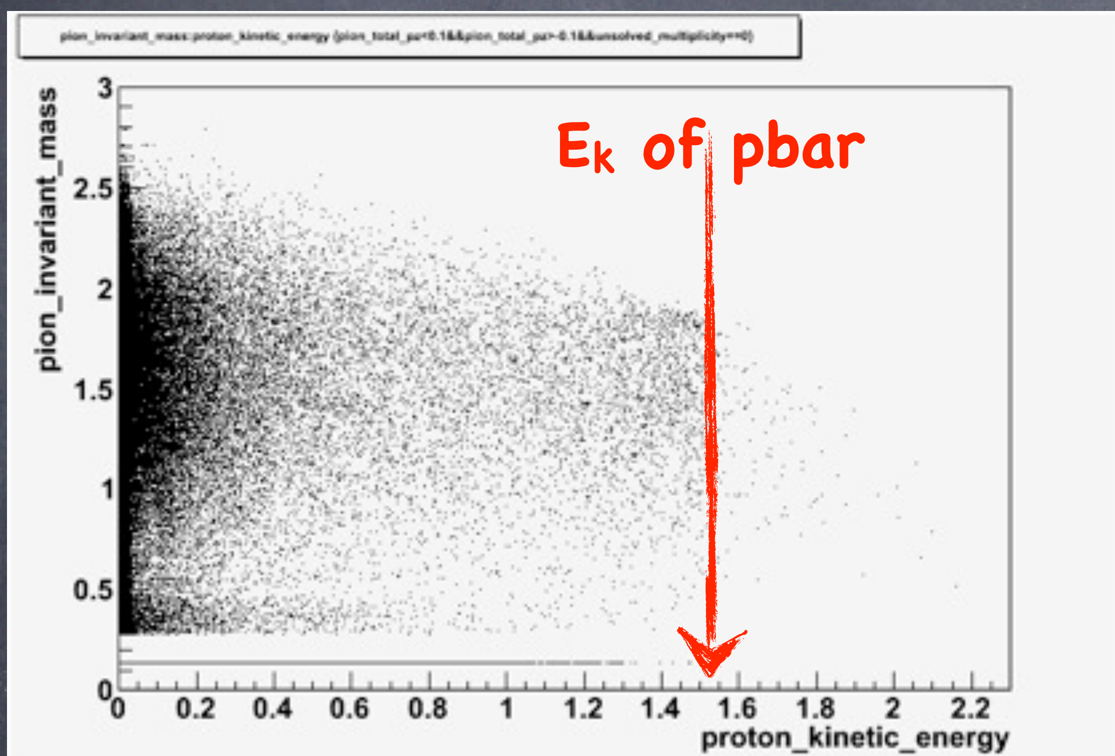
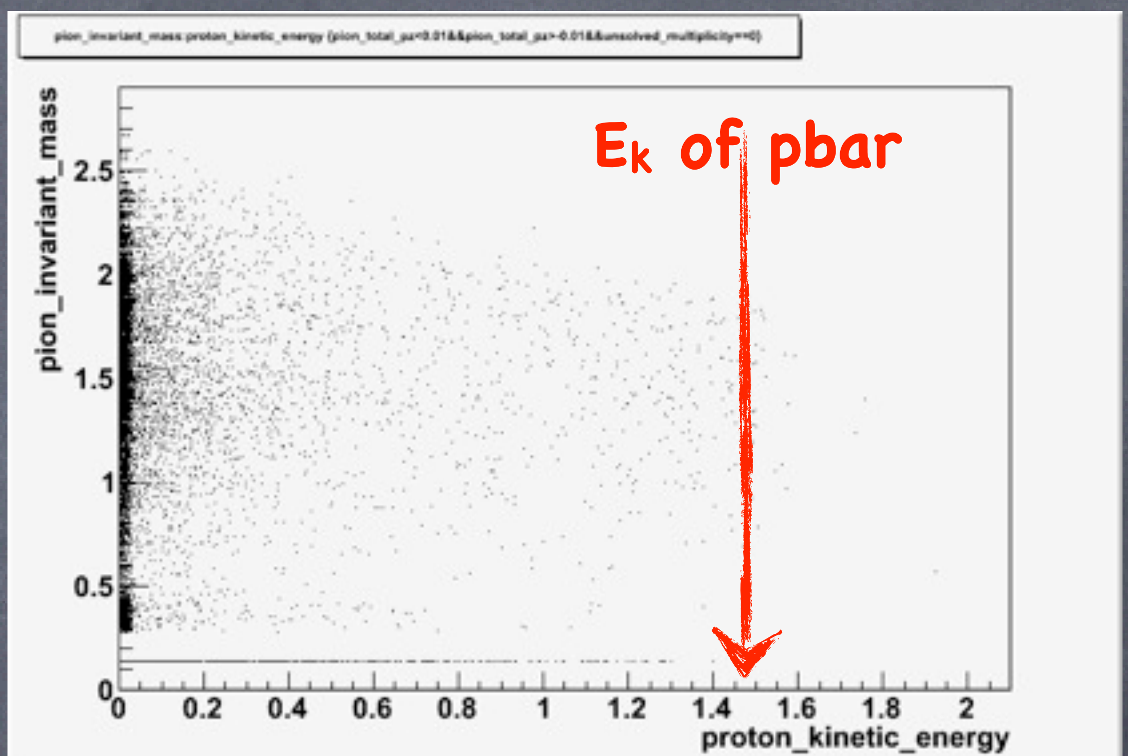


-100MeV/c<pz<100MeV/c



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Calculation with GiBUU for 5 Million events;
Beam=1.5 GeV, ^{16}O target
Main background: final state interaction(FSI)

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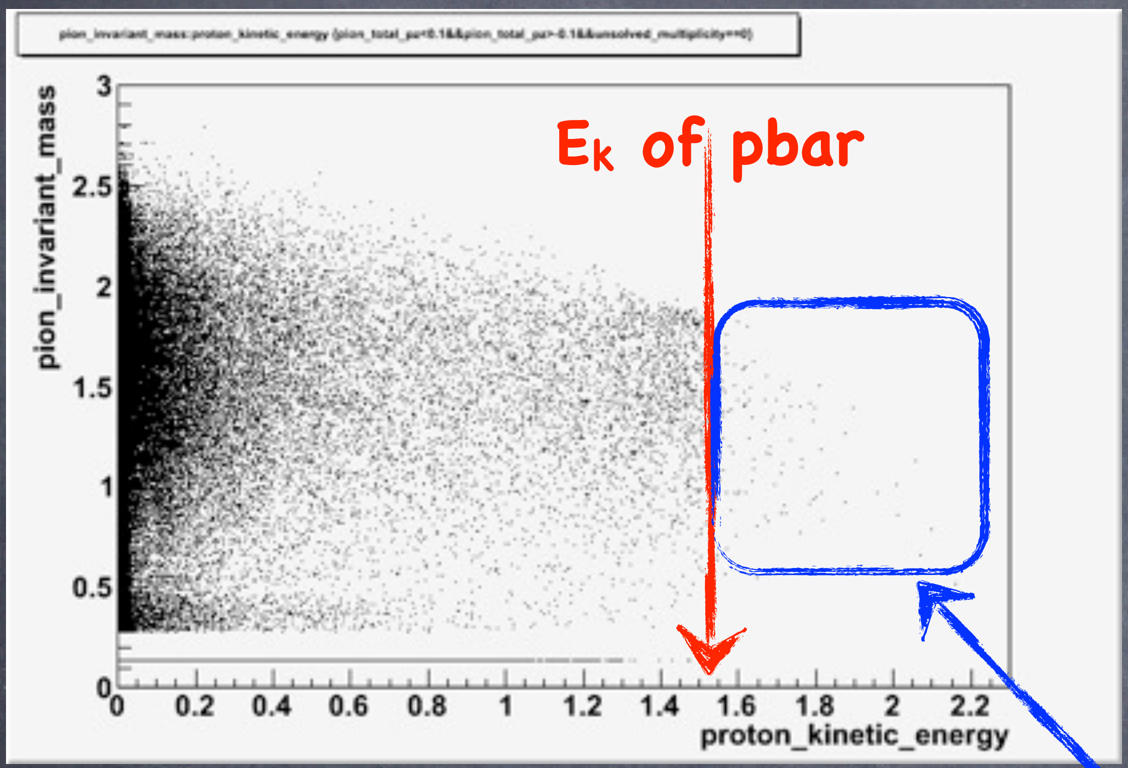

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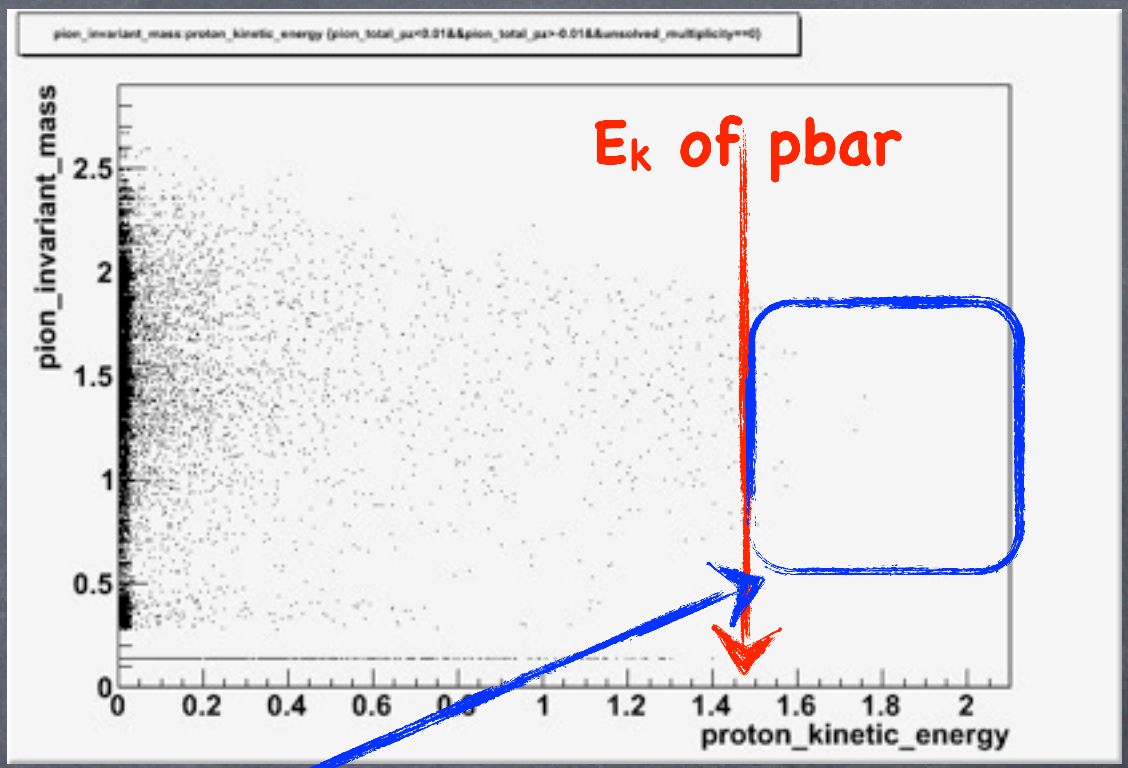

-10MeV/c<pz<10MeV/c

suppression of background

Calculation with GiBUU for 5 Million events;
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- Similar method can be applied to inelastic scattering: pbar+A->pbar+A+pion
- Measuring pion kinetic energy at 0^{o}_{Lab} and cutting on momentum(p_z) of decay products
- Employing the color transparency to reduce FSI of the knocked out pion(beam=15GeV/c)

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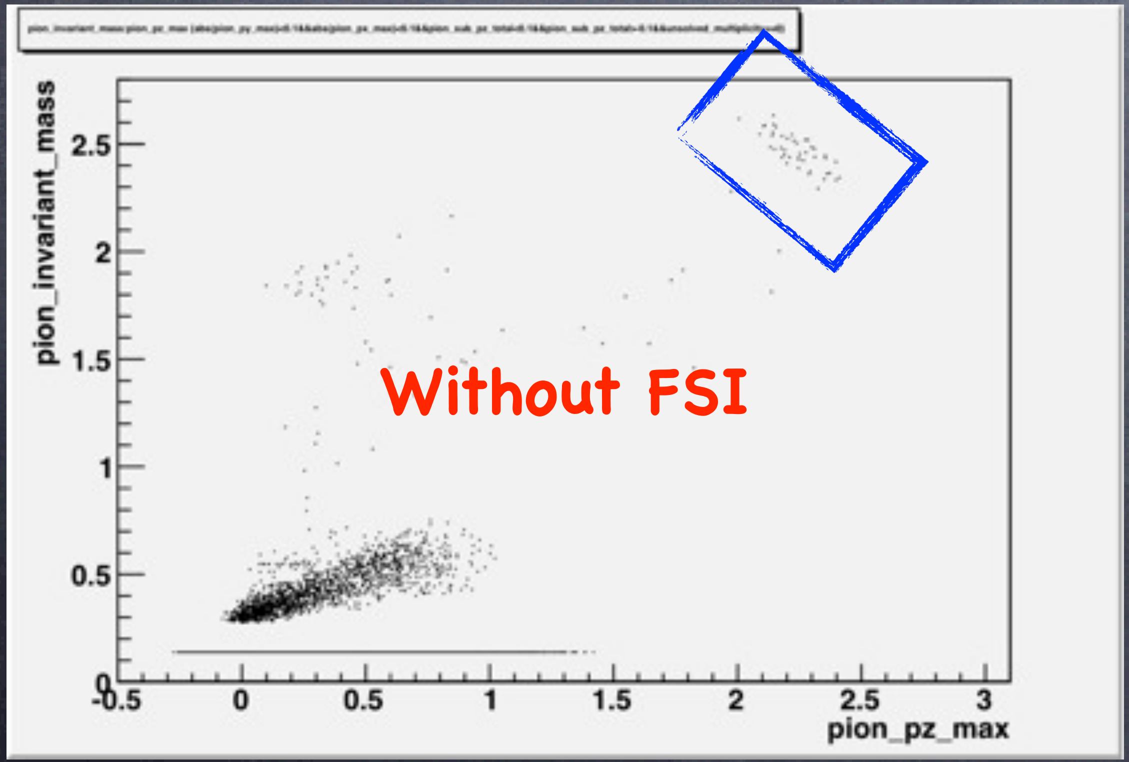

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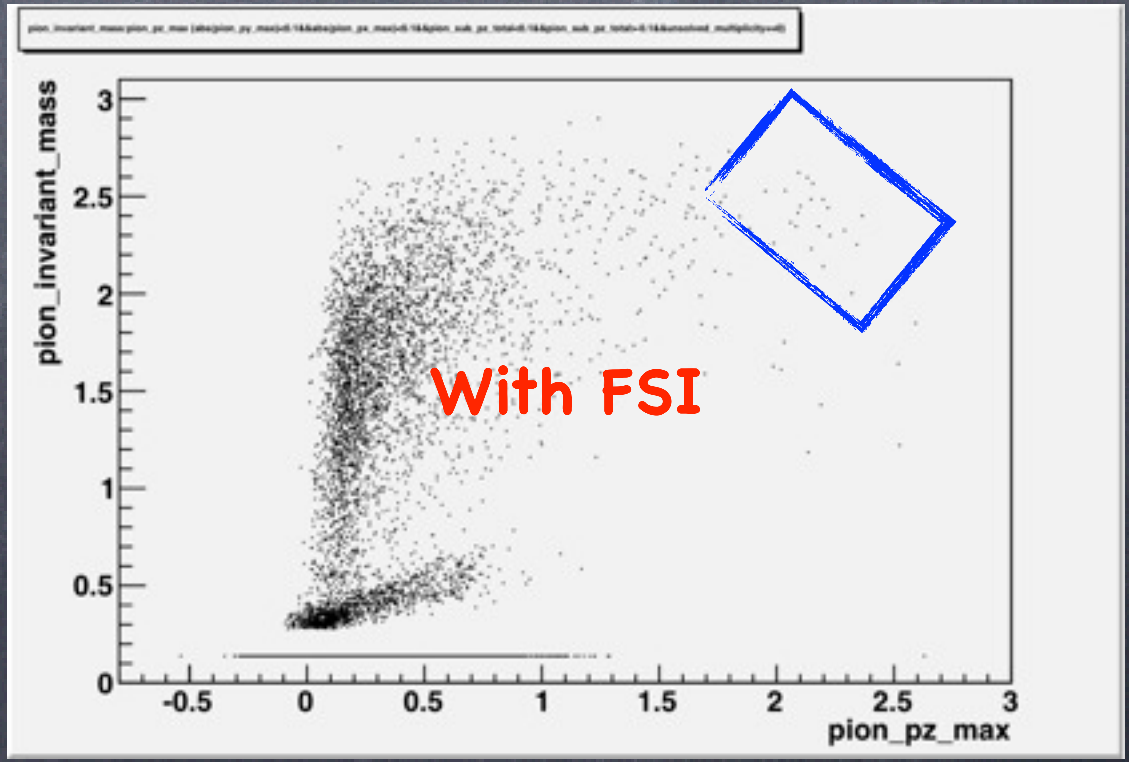

-100MeV/c<pz<100MeV/c

2.1 BB interaction: approach two

- beam condition: E_k=1.5GeV(p=2.25GeV/c)
- target (^{16}O): E_k=0GeV(p=0GeV/c)
- annihilation without potential:

$$M_{inv} = \sqrt{E_{total}^2 - P_{total}^2} = \sqrt{(E_k + M_0 + M_0)^2 - P_{total}^2}$$
$$= \sqrt{(1.5 + 0.938 + 0.938)^2 - (2.25)^2}$$
$$= 2.517GeV$$

- annihilation with potential(V=-150MeV):

$$E_{total} = E_{total}^{'} = E_k + \Delta E_k + M_0 + M_0 + V$$
$$E_k^{'} = E_k + \Delta E_k \quad (\Delta E_k = -V = 150MeV)$$

$$M_{inv}^{'} = \sqrt{E_{total}^{'2} - P_{total}^{'2}}$$
$$= \sqrt{(1.5 + 0.938 + 0.938)^2 - (2.41)^2}$$
$$= 2.36GeV$$

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invariant mass distribution reveals V_0 potential

- annihilation with potential:

$$M'_{inv} = \sqrt{E'^2_{total} - P'^2_{total}}$$
$$= \sqrt{(1.5 + 0.938 + 0.938)^2 - (2.41)^2}$$
$$= 2.36 GeV$$

2.1 BB interaction: approach two

- annihilation without potential:

$$M_{inv} = \sqrt{E_{total}^2 - P_{total}^2} = \sqrt{(E_k + M_0 + M_0)^2 - P_{total}^2}$$
$$= \sqrt{(1.5 + 0.938 + 0.938)^2 - (2.25)^2}$$
$$= 2.517 GeV$$

- annihilation with potential:

$$M'_{inv} = \sqrt{E'^2_{total} - P'^2_{total}}$$
$$= \sqrt{(1.5 + 0.938 + 0.938)^2 - (2.41)^2}$$
$$= 2.36 GeV$$

invariant mass distribution reveals V_0 potential

Background:

- off-shell of proton
- recoil of nucleon

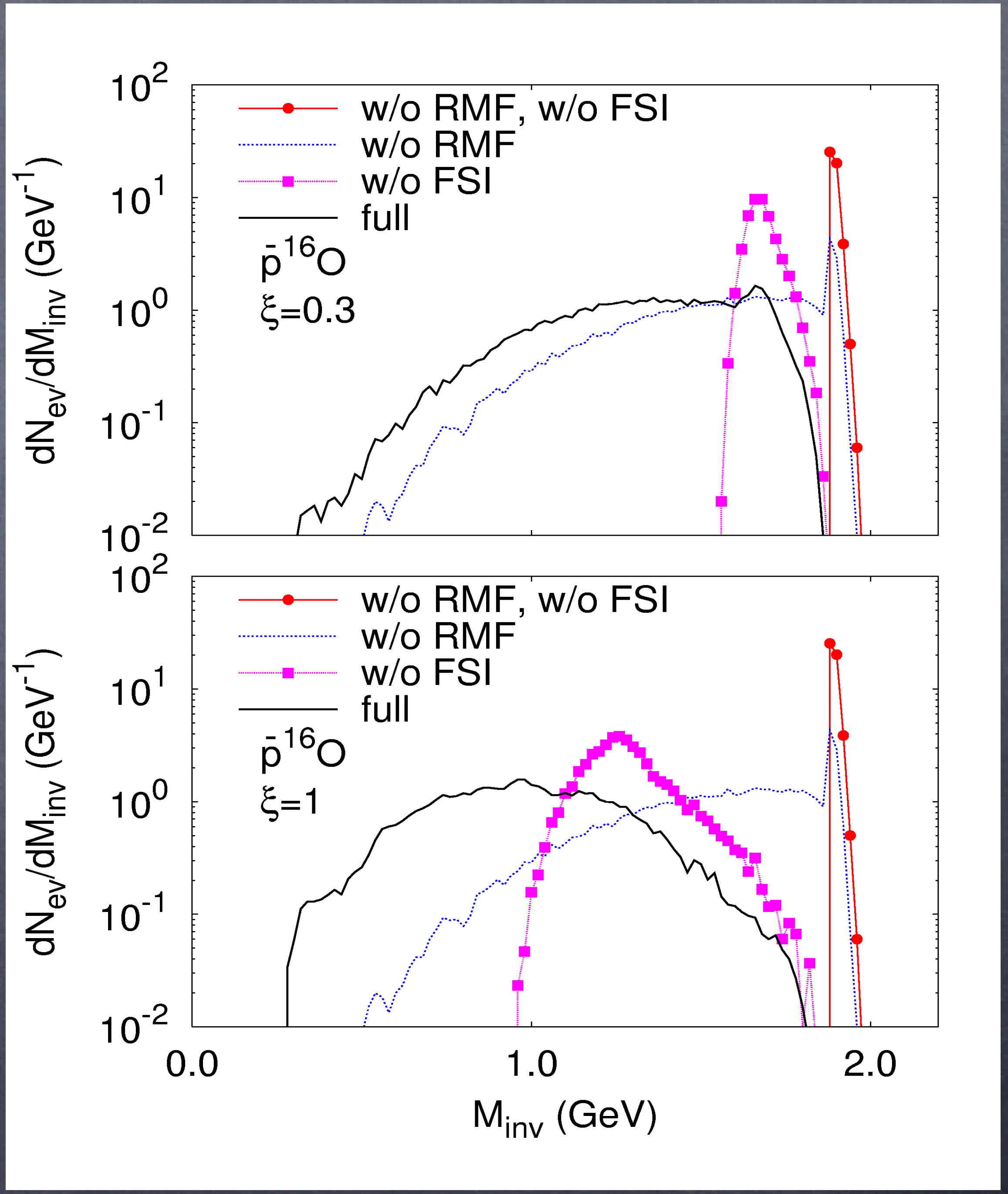
2.1 BB interaction: what if ...

Provided a large attractive potential of pbar+A:

- Invariant mass of stopped pbar annihilate into back-to-back pion pairs
- Possibility to extract in-medium hadron effective mass

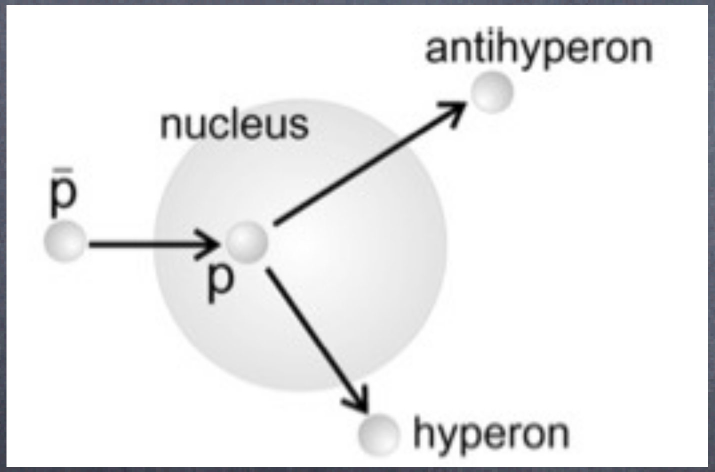
$$E_p = U_v + \sqrt{(M_0 - U_s)^2 + \mathbf{P_p}^2}$$

$$E_{\bar{p}} = -U_v + \sqrt{(M_0 - U_s)^2 + \mathbf{P_{\bar{p}}}^2}$$

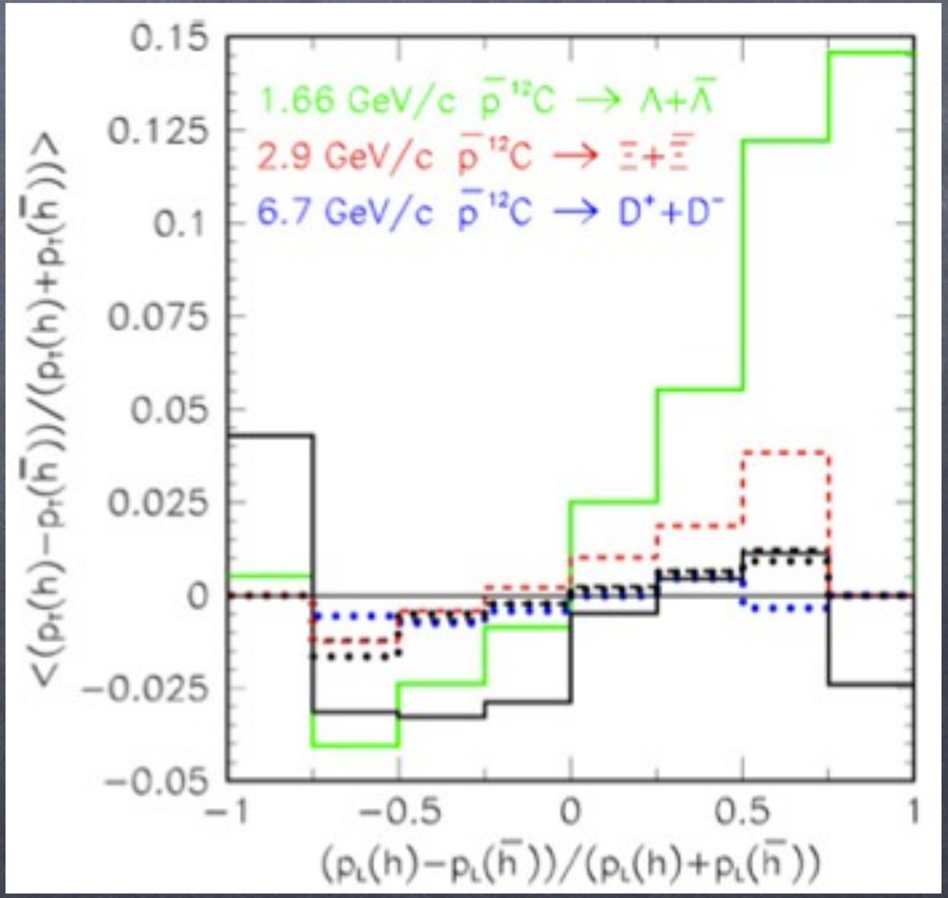


2.1 BB interaction: antihyperon

- Asymmetry of transverse momentum distribution between hyperon and antihyperon gives the information of antihyperon potential(J. Pochodzalla)



Minimum recoil momentum: 400 MeV/c



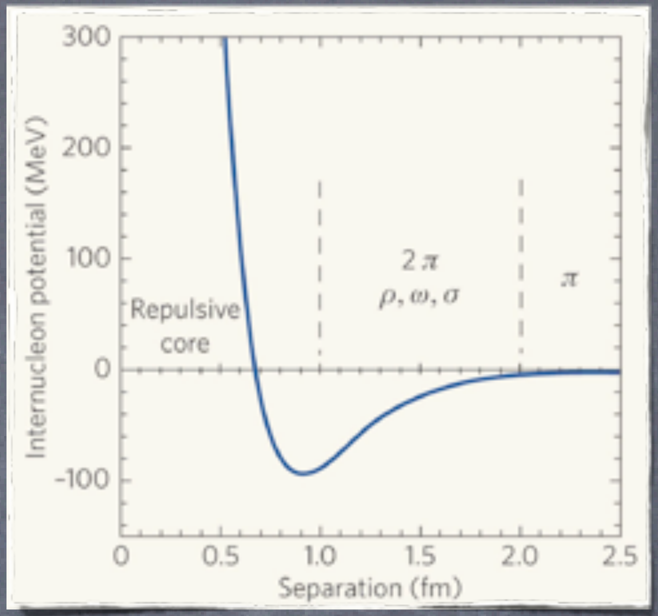
J. Pochodzalla, Phys. Lett. B 669, p.306 (2008)

2.2 Cold compressed matter

pictures from GSI, NASA and F. Wilczek

2.2 Cold compressed matter

- Constant density of nucleus: well established experimental fact



pictures from GSI, NASA and F. Wilczek

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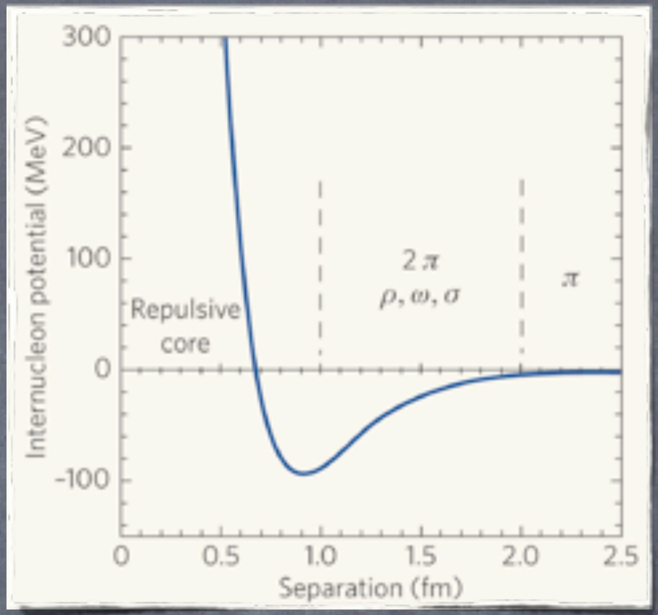
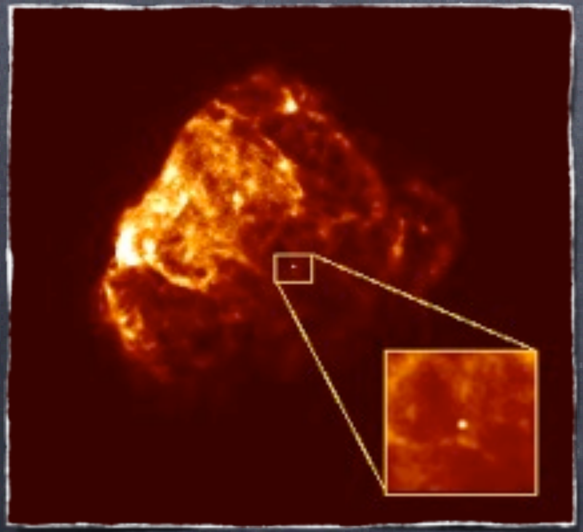


- Higher density is expected inside neutron star



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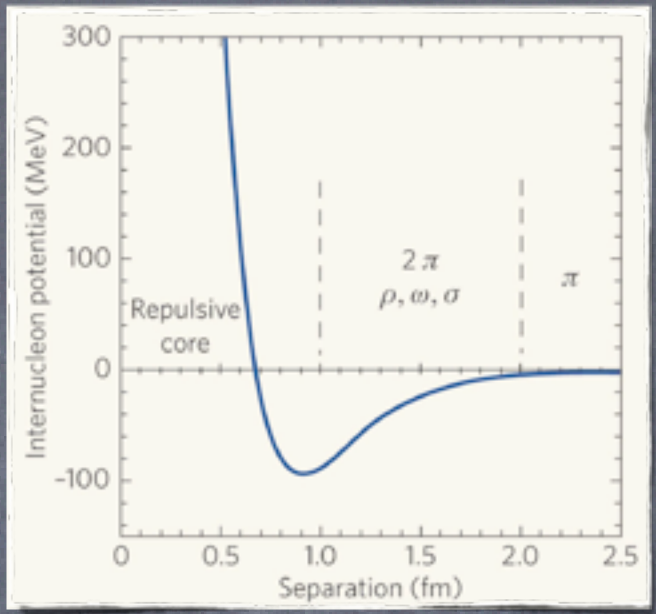

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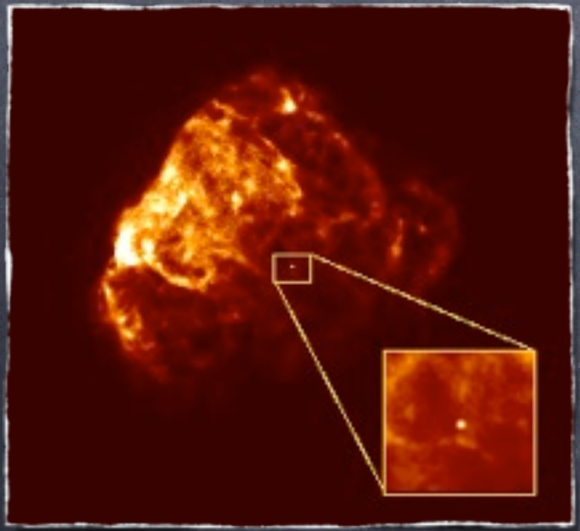
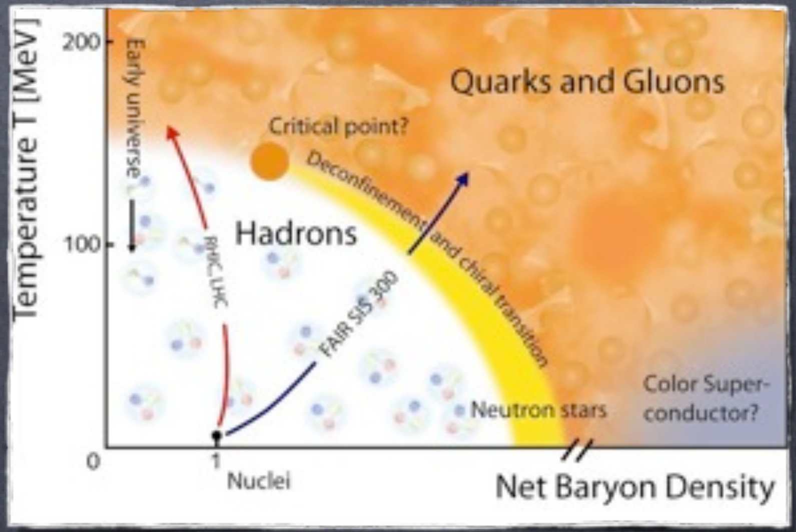


- How to produce such state inside laboratory?

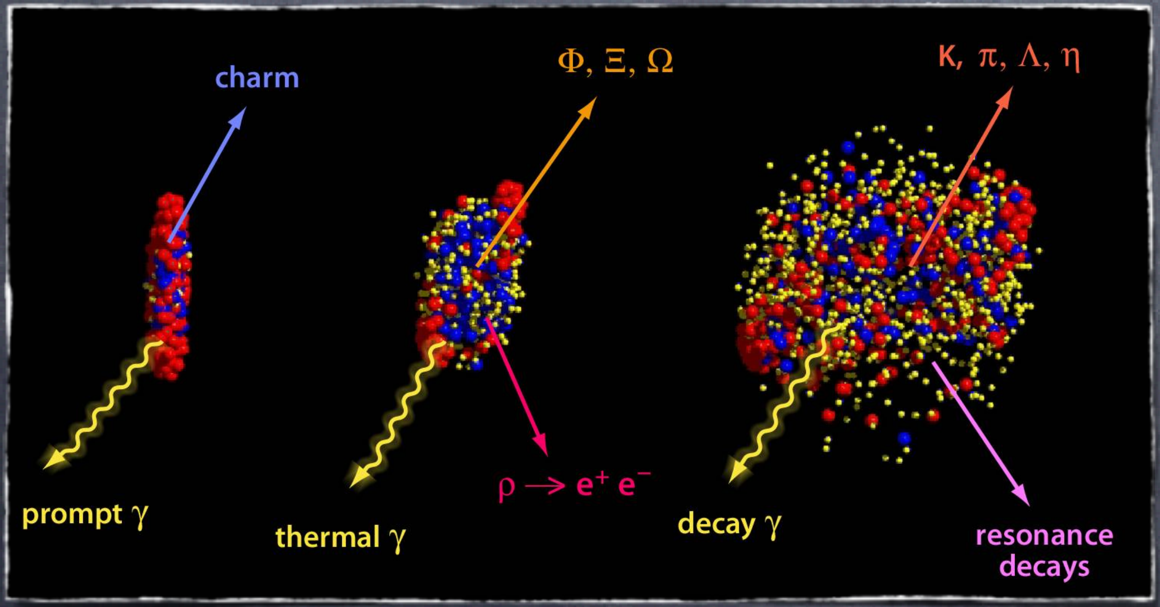


pictures from GSI, NASA and F. Wilczek

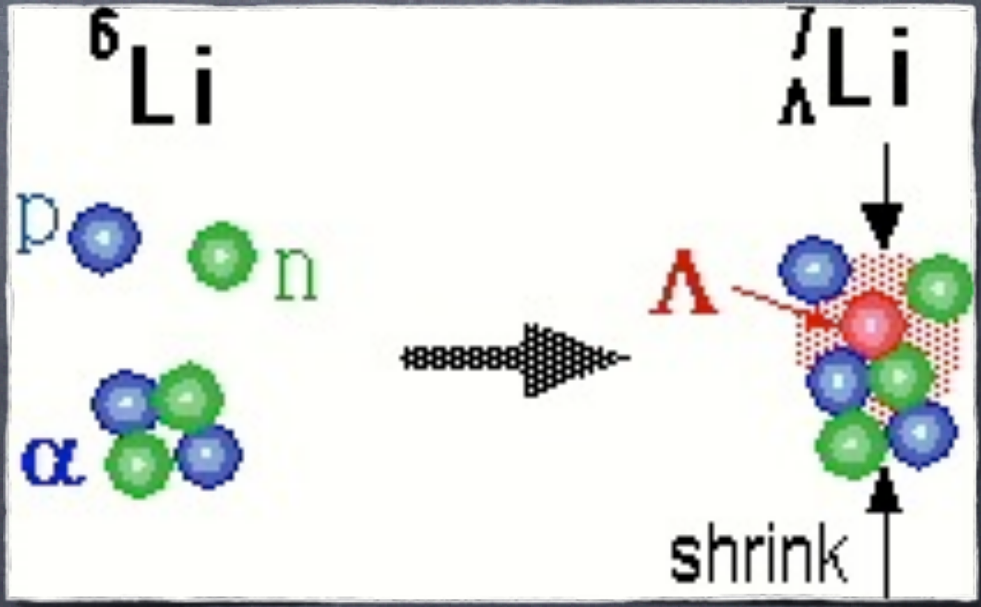
2.2 Cold compressed matter

How to compress nucleus in lab?

- Cold compression: Lambda hyperon + ^{6}Li (20% shrinkage)
- Hot compression: CBM@FAIR



Hot compression



Cold compression

K. Tanida et al., Phys. Rev. Lett. 86, p.1982 (2001)

2.2 Cold compressed matter

- Cold compression seems too “weak” (only 20% shrinkage) due to weakness of YN interaction(30 MeV).
- What if the pbarN potential measured to be >=150 MeV?
- To answer this question: RMF based study

Relativistic mean field (RMF) Lagrangian density:

$$\mathcal{L} = \sum_{j=N,\bar{N}} \bar{\psi}_j[\gamma(i\partial - g_{\omega j}\omega - g_{\rho j}\vec{\rho}\vec{\tau} - \frac{e}{2}(B_j + \tau^3)A) - m_N - g_{\sigma j}\sigma]\psi_j + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^2 - \frac{1}{4}\vec{\rho}_{\mu\nu}\vec{\rho}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^2 - \frac{1}{16\pi}A_{\mu\nu}A^{\mu\nu} ,$$

$$U(\sigma) = \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4 ,$$

$$G_{\mu\nu} \equiv \partial_\mu G_\nu - \partial_\nu G_\mu , \quad G = \omega,\ \vec{\rho},\ A .$$

G.A. Lalazissis et al., PRC 55, 540 (1997);
I.N. Mishustin et al., PRC 71, 035201 (2005);
A.L. et al., PRC 76, 044909 (2007).

Antibaryon-baryon collisions:
$\bar{B}B \to$ mesons — statistical annihilation model (I.A. Pshenichnov et al., 1992);
$\bar{B}B \to \bar{B}B$ (EL and CEX), $\bar{N}N \leftrightarrow \bar{N}\Delta(\bar{\Delta}N)$, $\bar{N}N \to \bar{\Lambda}\Lambda$, $\bar{N}(\bar{\Delta})N(\Delta) \to \bar{\Lambda}\Sigma(\bar{\Sigma}\Lambda)$, $\bar{N}(\bar{\Delta})N(\Delta) \to \bar{\Xi}\Xi$.
For $\sqrt{s} > 2.4$ GeV ($p_{lab} > 1.9$ GeV/c for $\bar{N}N$) : FRITIOF simulation of inelastic production $\bar{B}_1B_2 \to \bar{B}_3B_4 +$ mesons.

Baryon-baryon collisions:
$BB \to BB$ (EL and CEX), $NN \leftrightarrow NN\pi$, $NN \leftrightarrow \Delta\Delta$, $NN \leftrightarrow NR$, $N(\Delta,N^*)N(\Delta,N^*) \to N(\Delta)YK$, $YN \to YN$, $\Xi N \to \Lambda\Lambda$, $\Xi N \to \Lambda\Sigma$, $\Xi N \to \Xi N$.
For $\sqrt{s} > 2.4$ GeV : PYTHIA simulation of inelastic production $B_1B_2 \to B_3B_4 +$ mesons.

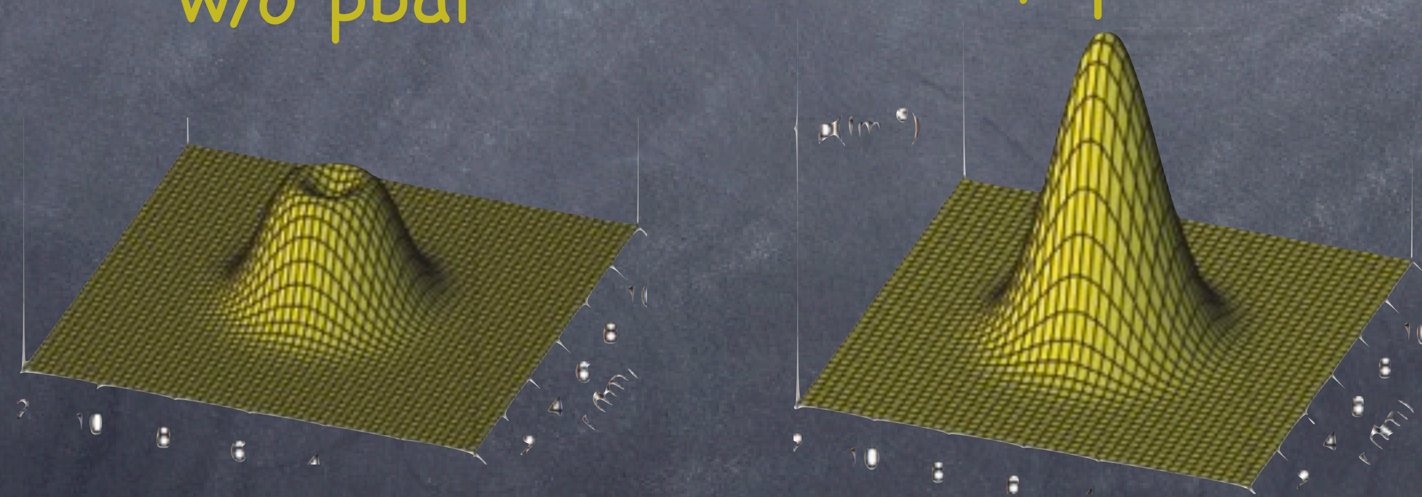
Meson-baryon collisions:
$\pi N \leftrightarrow R$, $\pi N \to K\bar{K}N$, $\pi(\eta,\rho,\omega)N \to YK$, $\bar{K}N \leftrightarrow Y^*$, $\bar{K}N \to \bar{K}N$, $\bar{K}N \leftrightarrow Y\pi$, $\bar{K}N \leftrightarrow Y^*\pi$, $\bar{K}N \to \Xi K$.
For $\sqrt{s} > 2.2$ GeV : PYTHIA simulation of MB collisions.

A. Larionov, et al., Phys. Rev. C 78, p.014604, (2008)

2.2 Cold compressed matter

- Possibility for the formation of cold compressed matter up to twice higher density
- Mainly depends on pbar lifetime inside nucleus
- Compressed nuclear matter: more interaction between decayed pions and surrounding nucleons

w/o pbar w/ pbar



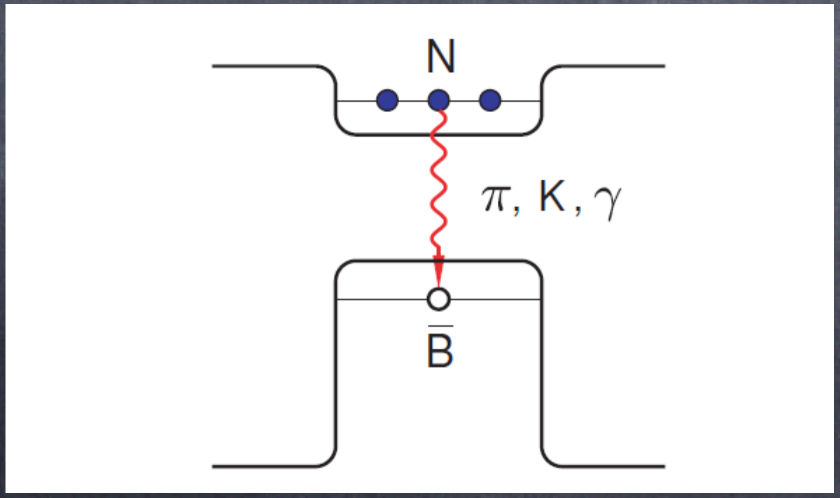
density distribution of ^{16}O

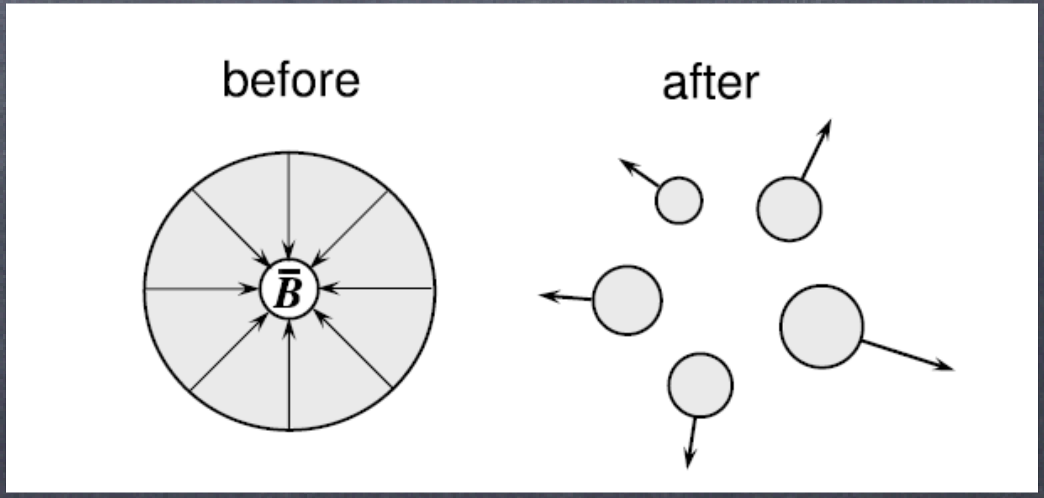
A. Larionov, et al., Phys. Rev. C 78, p.014604, (2008)

2.2 Cold compressed matter

Observables(up to a few 100 counts/s at PANDA):

- high energy proton or pion as trigger
- monoenergetic transition
- nuclear fragmentation signature
- pion multiplicity reduction due to smaller $\sqrt{s}$

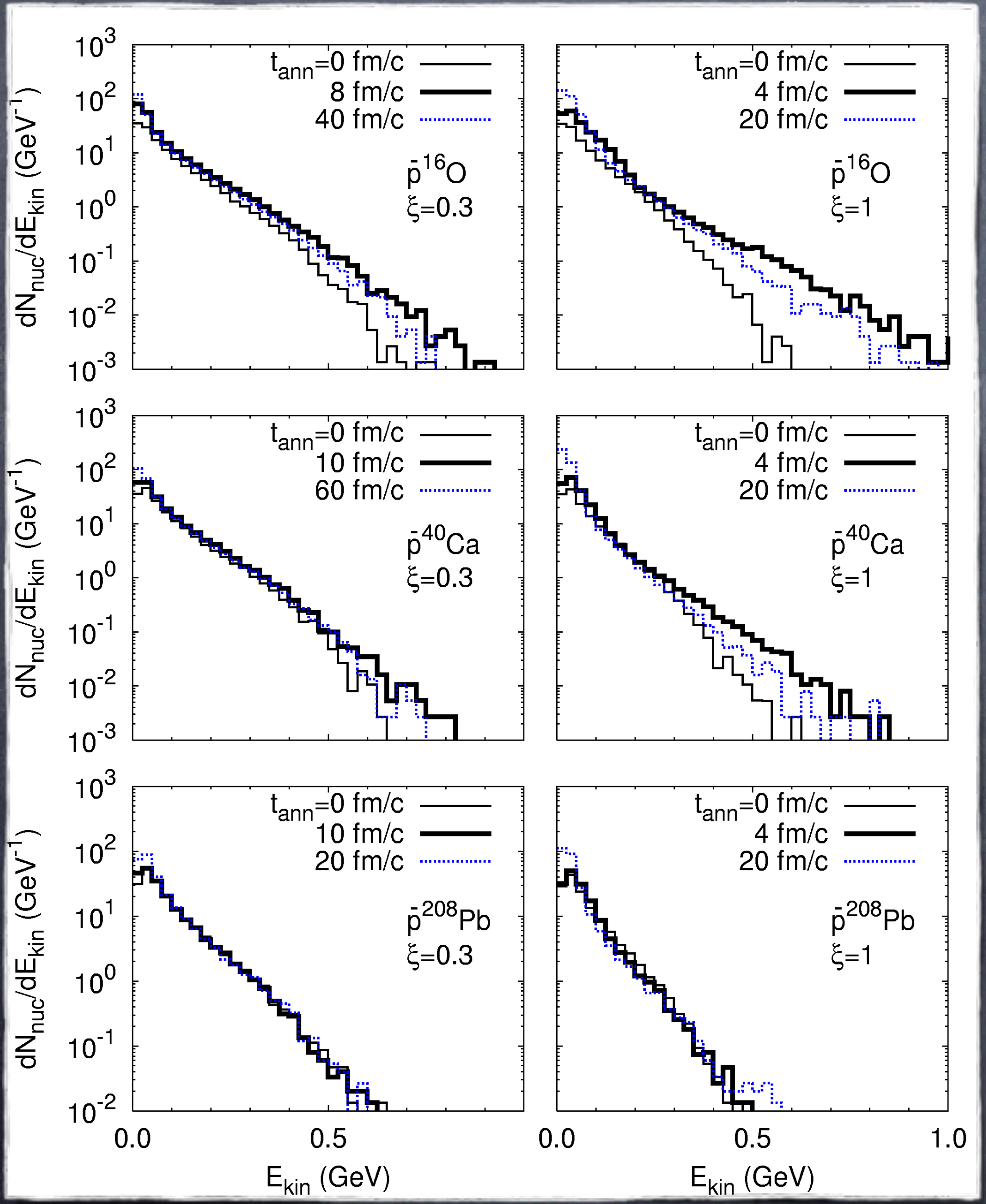


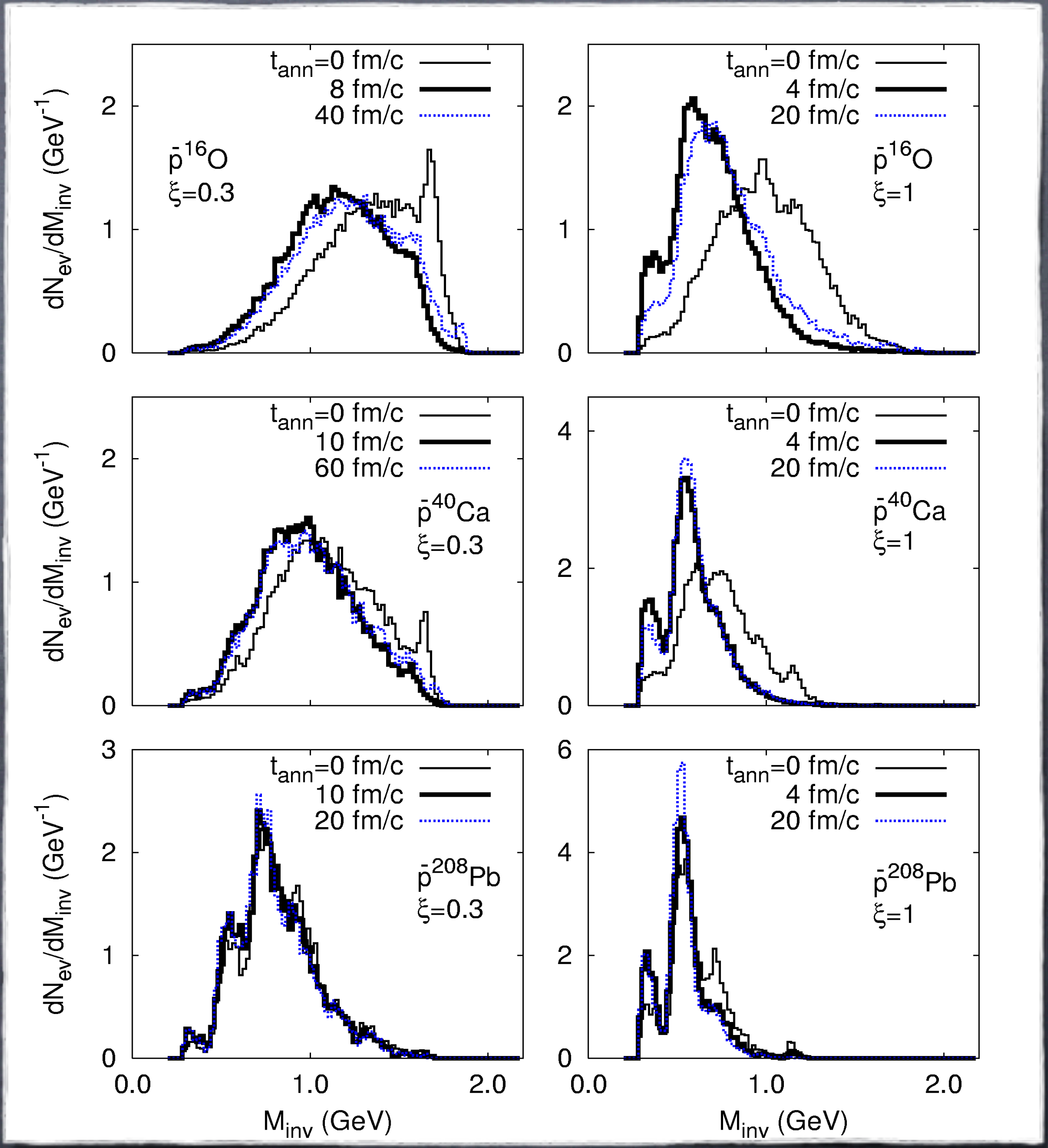


A. Larionov, et al., Phys. Rev. C 78, p.014604, (2008)

2.2 Cold compressed matter

Observable of compressed nuclear matter: more interaction between decayed pion and surrounding nucleon





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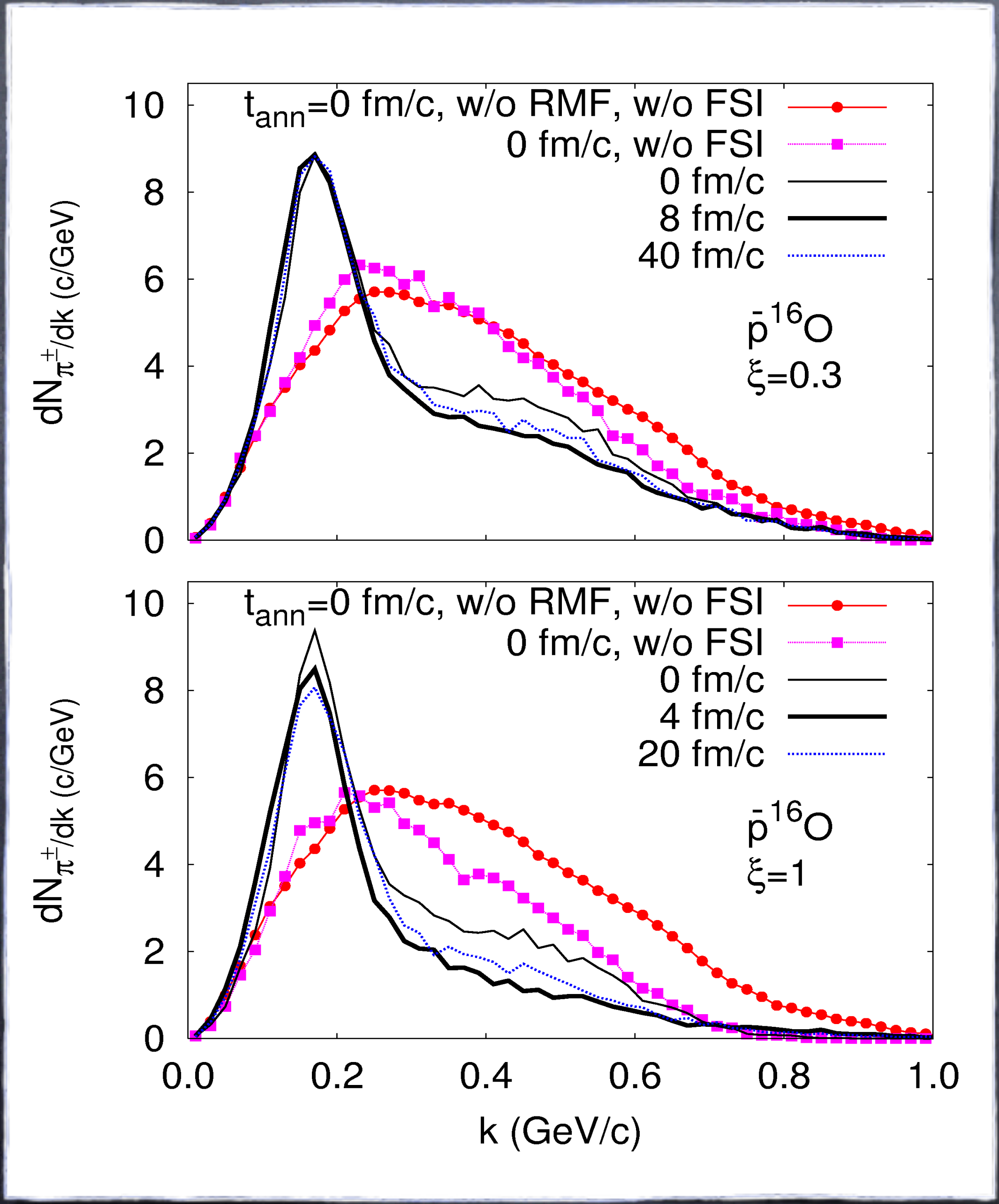

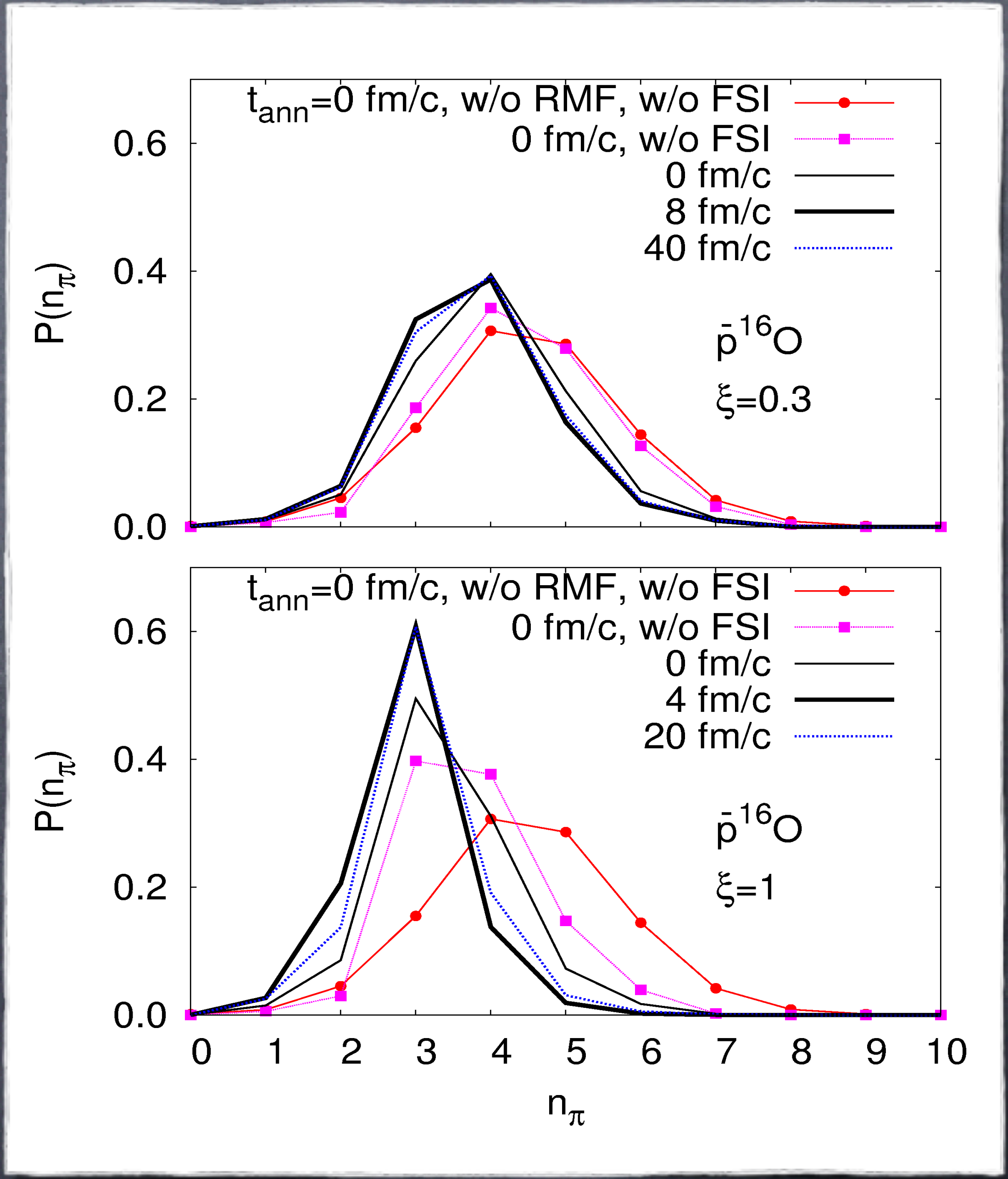

2.2 Quark gluon matter/plasma

- If cold compression is achieved, density will be a few times higher than normal nuclear density.
- Possibility of quark gluon matter/plasma?

I.N. Mishustin, et al., Phys. Rev. C 71, p.035201, (2005)

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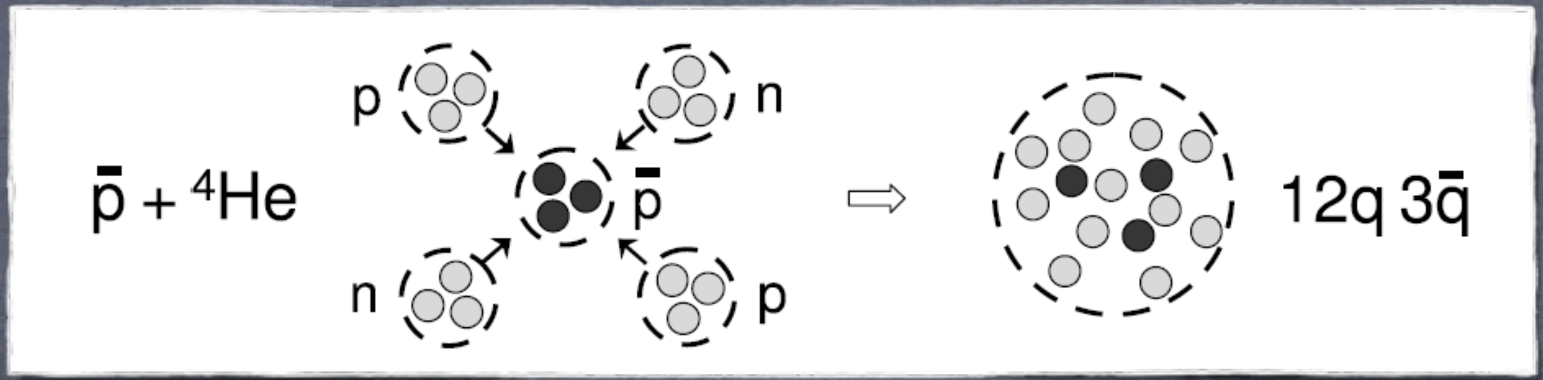


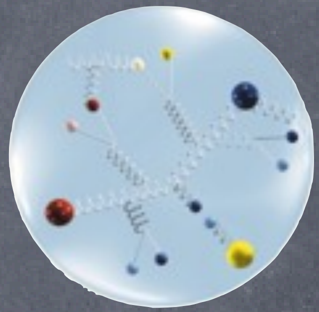
Combined effects of high density and B=-1

Refer such a state as "quark gluon matter(QGM)" to distinguish the hot quark gluon plasma(QGP).

I.N. Mishustin, et al., Phys. Rev. C 71, p.035201, (2005)

2.2 Quark gluon matter(QGM)

- Fire ball/hadron gas picture of pbar+N annihilation
- Possibility to distinguish hadronic int. and QGM?
- What is nucleon, nucleus and nuclear matter?
- "Effective interaction" vs. degree of freedom



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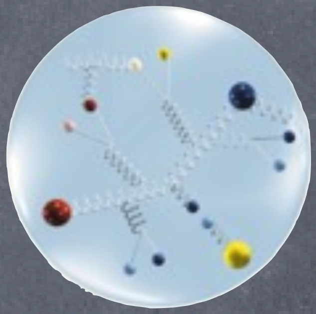
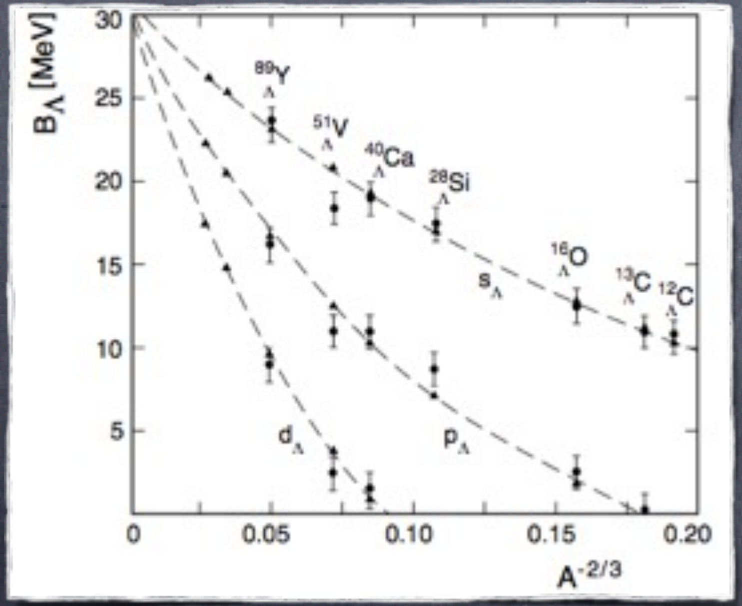
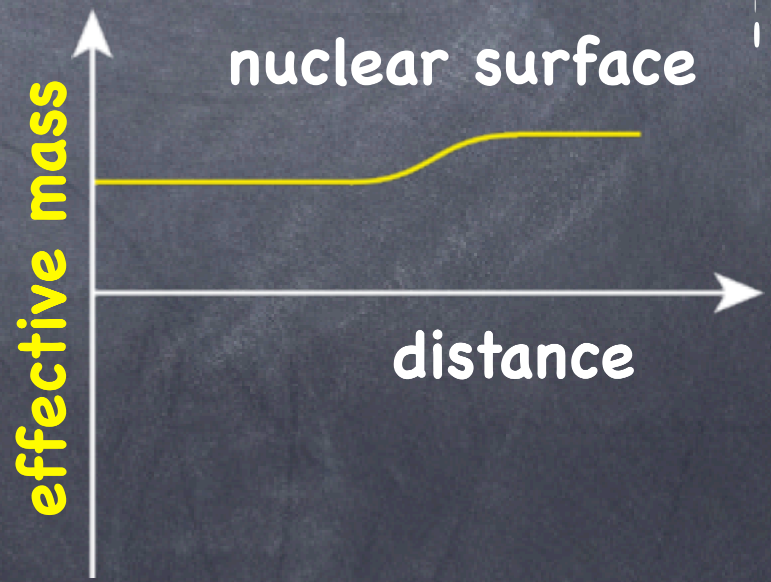


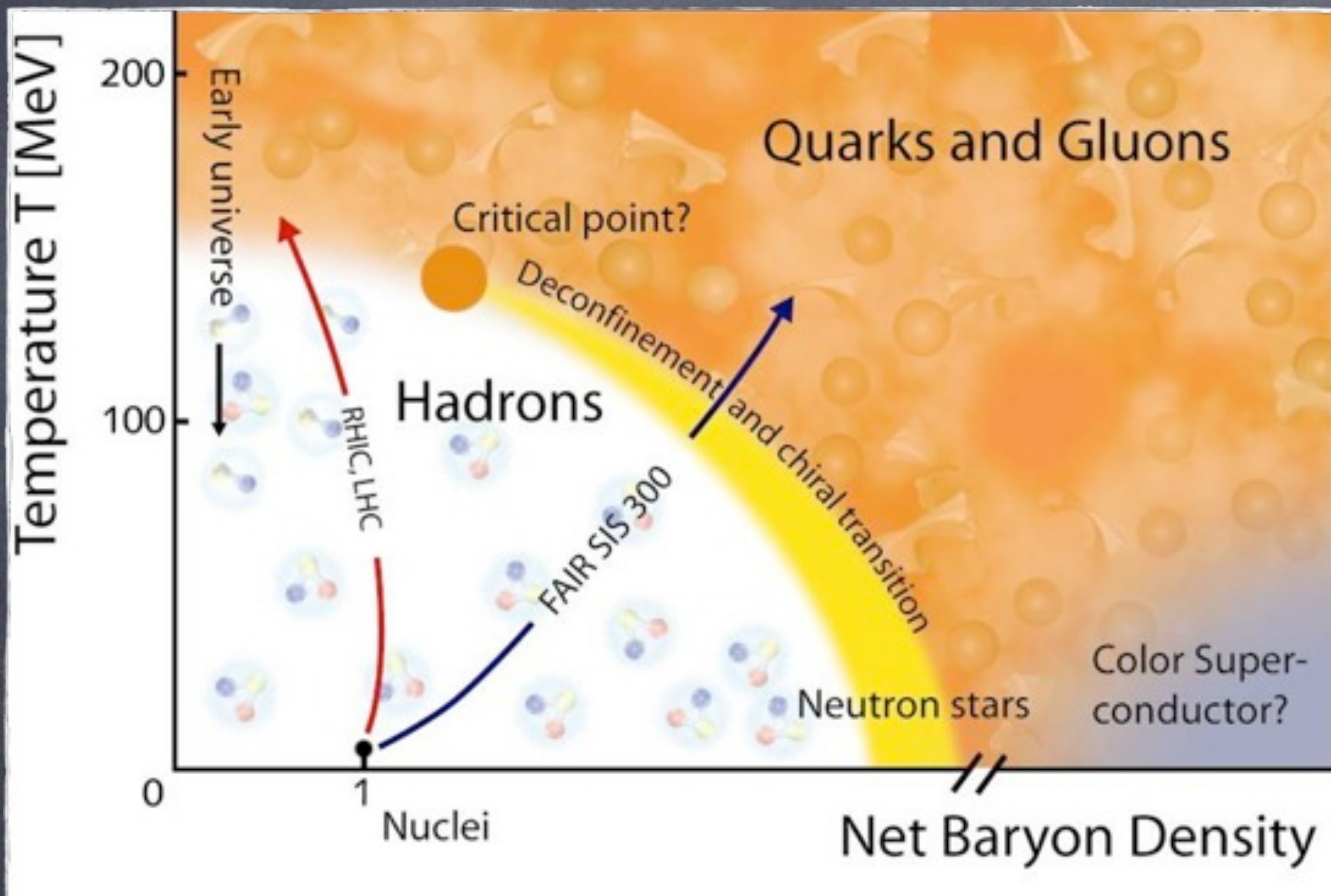


Lambda Hyperon level energy fitted by Woods-saxon shape potential



Nucleon effective mass based on relativistic mean field theory

2.3 QGM: hybrid of QGP and baryon



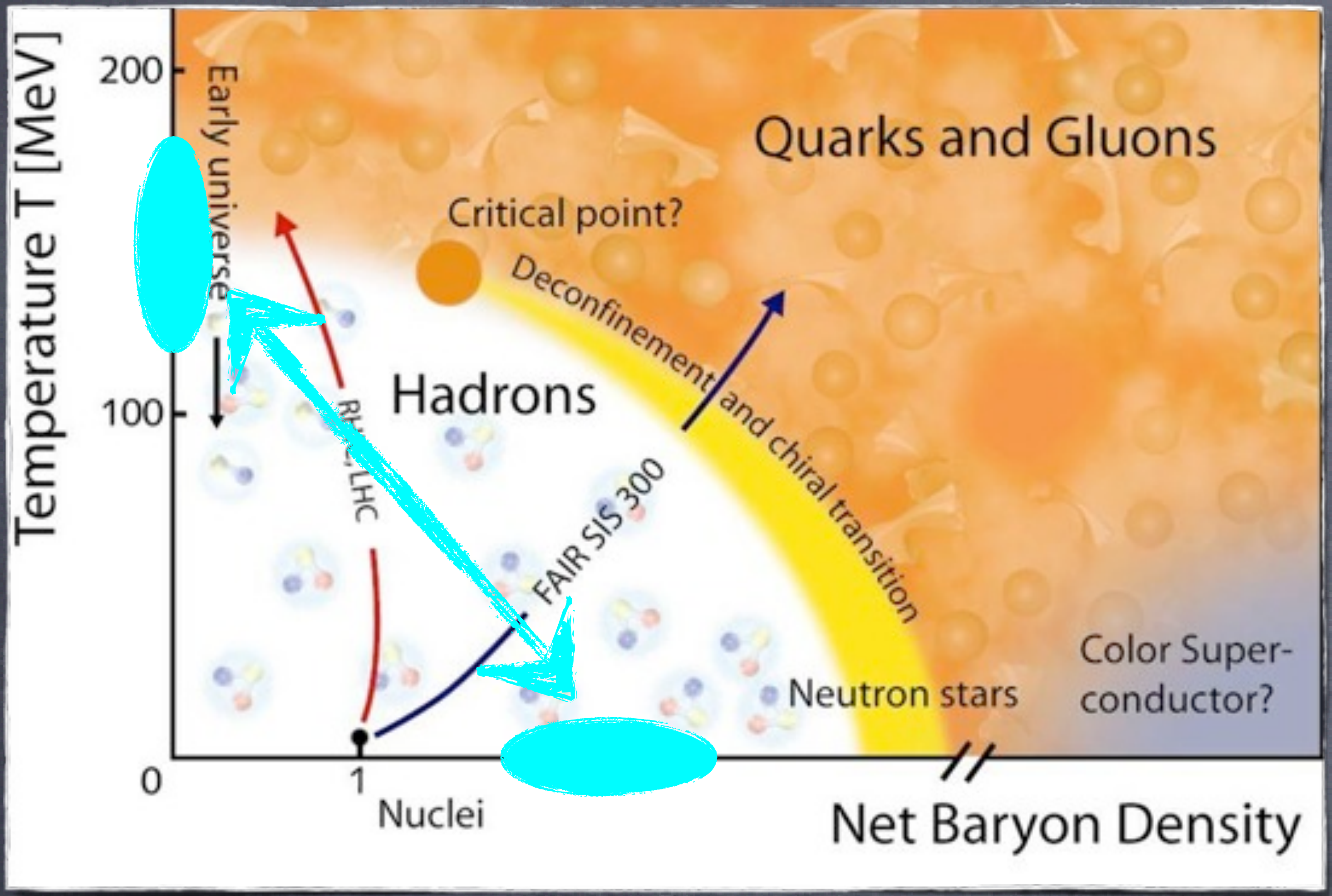
A drop of QGP + compressed nuclear matter

More fundamental interaction than hadronic multi-nucleon annihilation?

Quark and gluon directly involved? **Signature?**

From CBM@FAIR

2.3 QGM: hybrid of QGP and baryon



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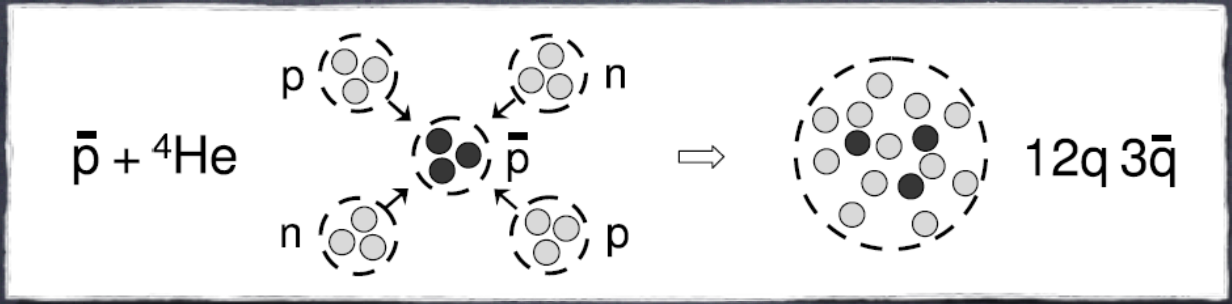
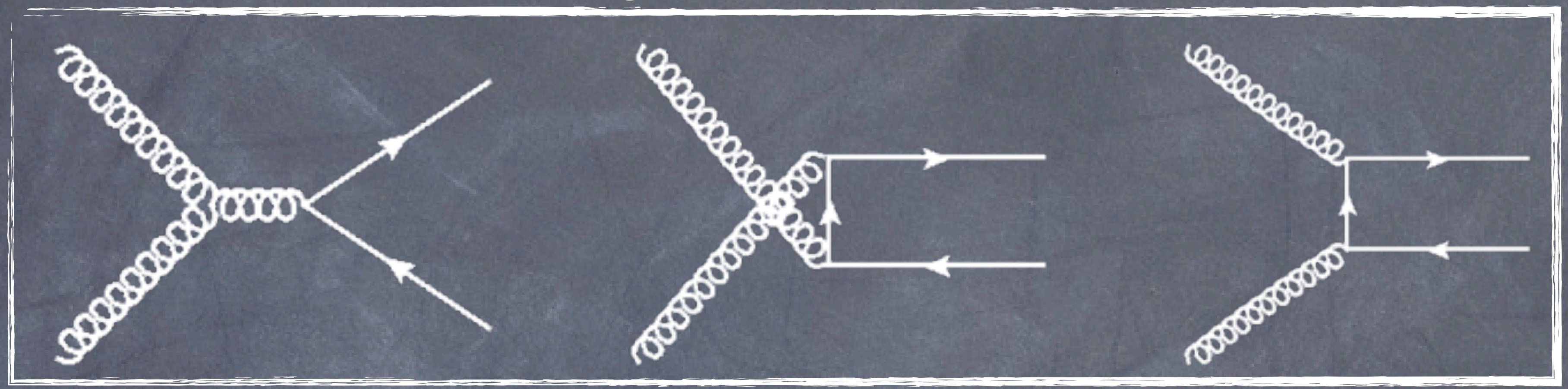
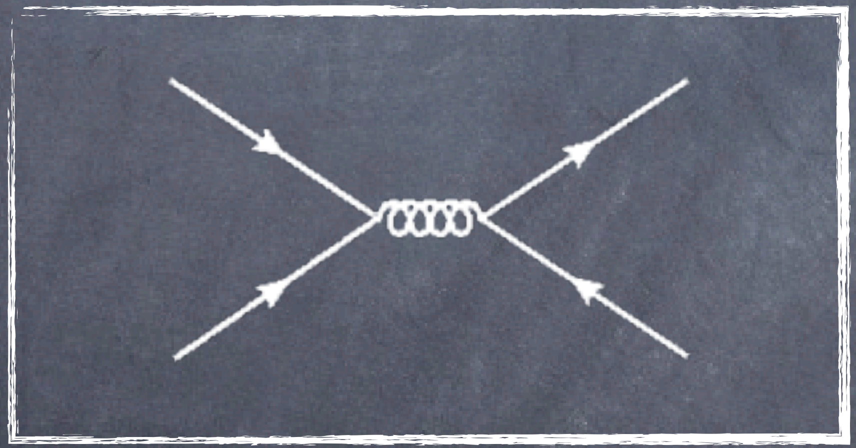


From CBM@FAIR

2.3 QGM: signature

gluon channel





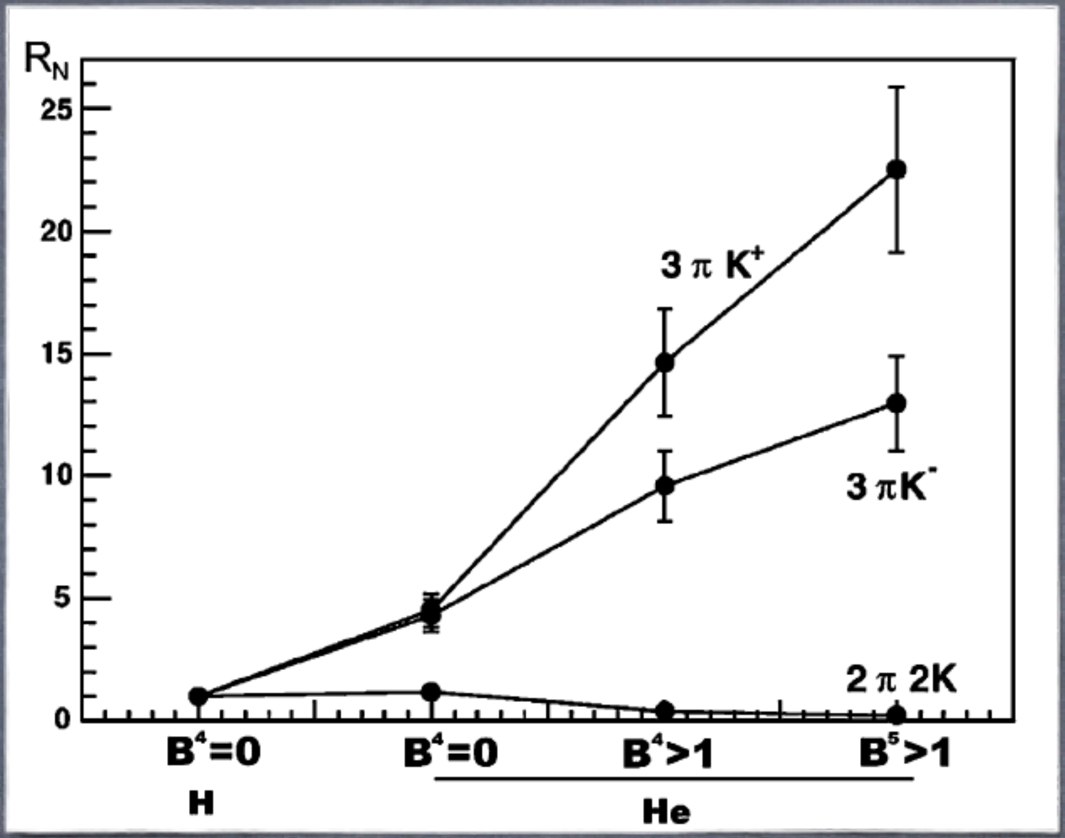
quark channel

90% of strangeness comes from gluon production;

Enhanced strangeness production as signature of formation of GQP

J. Rafelski, Nucl. Phys. A, 418, p.215c, (1984)

2.3 QGM: by antiproton?



OBELIX collaboration@ LEAR

pbar+^{4}He annihilation at rest:

multi-nucleon annihilation enhance strangeness production by a factor of 22.

C. Bendiscioli, et al., Nucl. Phys. A 815, p.67, (2009)

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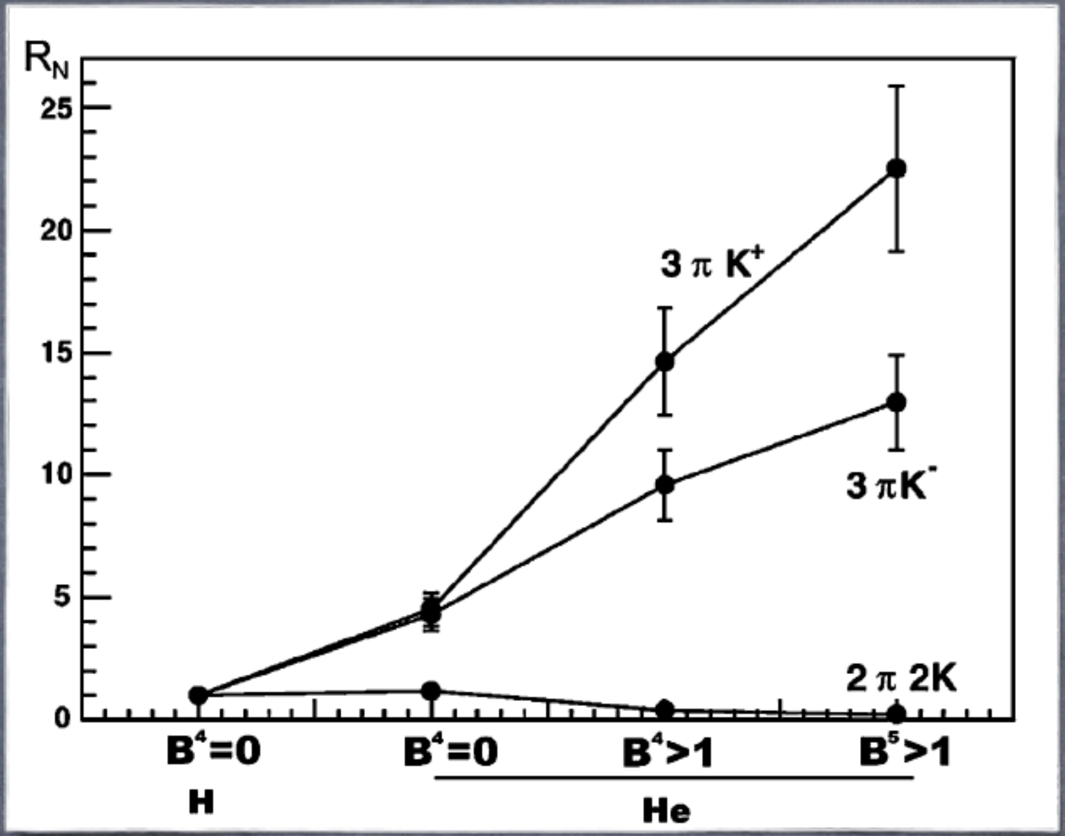

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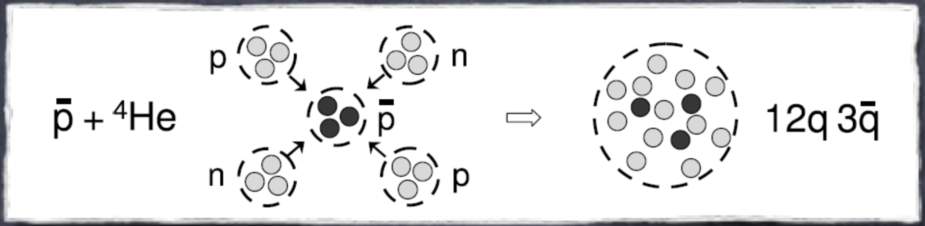


C. Bendiscioli, et al., Nucl. Phys. A 815, p.67, (2009)

3. What can PANDA do?

- Antimatter potential inside matter: **additional forward spectrometer**(higher momentum than beam)
- Investigate cold compression: **nuclear fragmentation measurement**(nuclear phase transition)
- QGM/isospin dependent interaction study by **knock out** experiment(more trackable prongs)

3. Start off experiments

pbar + ^{2}H:

- precise binding energy measurement
- isospin dependence of interaction
- x-ray from magnetic transition

pbar + ^{3}He:

- quark gluon matter/multi-nucleon annihilation

pbar + ^{16}O:

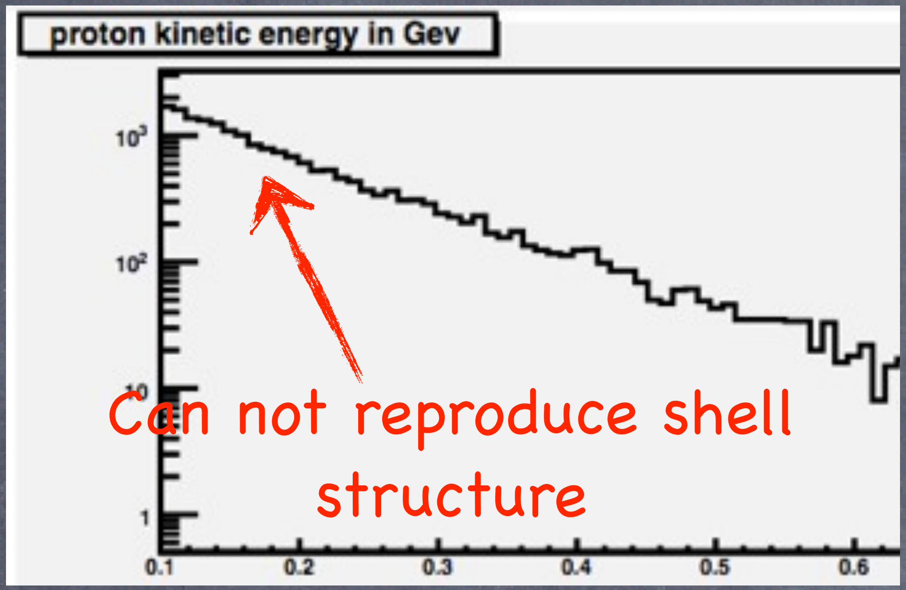
- pbar/antihyperon potential
- compressed matter

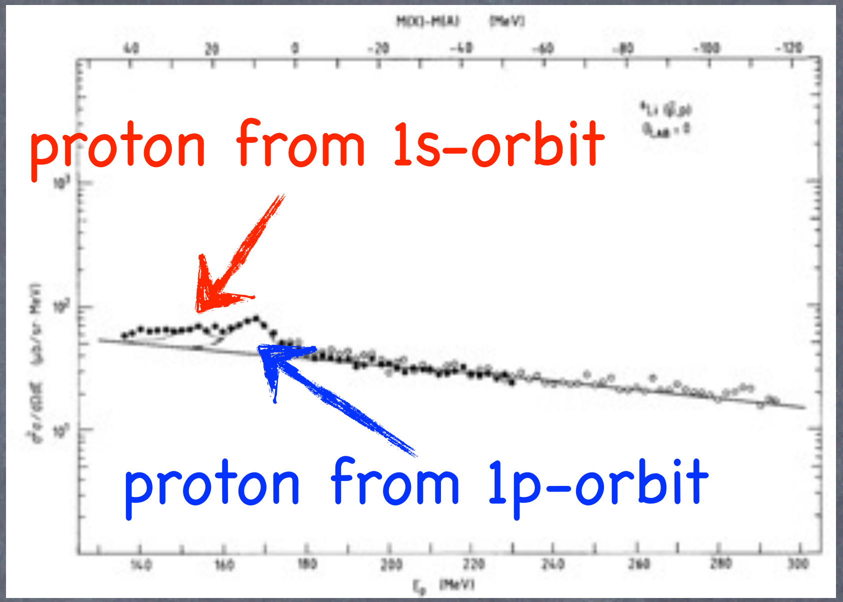
$$\bar{p} + p \rightarrow p + \bar{p}$$

$$\bar{p} + p \rightarrow n + \bar{n}$$

$$\bar{p} + n \rightarrow n + \bar{p}$$

3. Challenges





- Theoretical support needed: current transportation model can not reproduce shell structure
- Simulation vs. data taking : 1 event/core·s (impact_parameter=R+4fm); 1000 cores x 3 h == 1 second of data taking

GiBUU supported by A. Larionov of Gissen Uni.

3. Challenges

- Can we extract physical observables from effects of FSI and Fermi motion?
- Can we reconstruct tracks correctly(primary pions together with nuclear fragments)?
- Is the PANDA still functional with charge more than 2 particles?
- Forward tracking for 0^o particles with higher momentum than beam
- Target fragmentation measurement: fiber barrel detector with QDC and replace MVD?

4. Summary

A revisit of pbar nucleus collision with modern detector (PANDA) could tell us

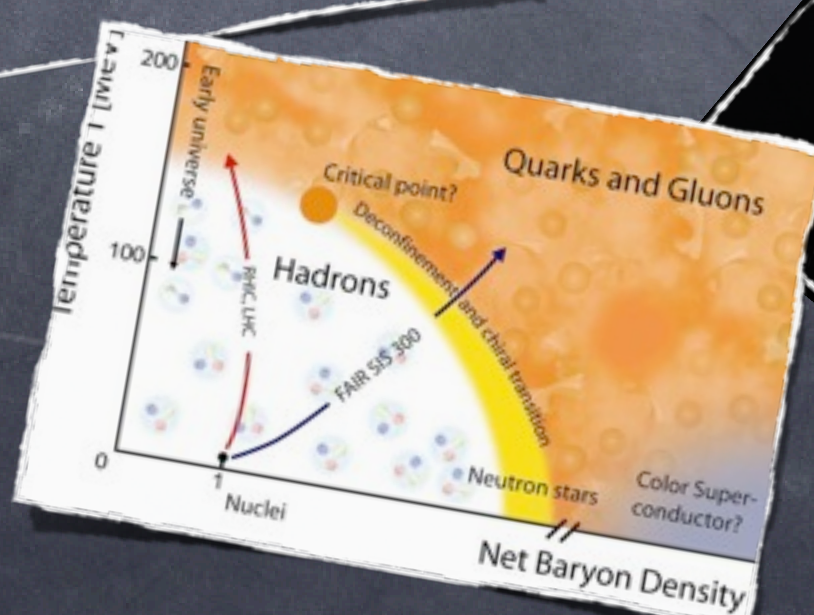
- antimatter potential inside matter
- possibility to form cold compressed matter
- direct gluon degree of freedom(QGM)

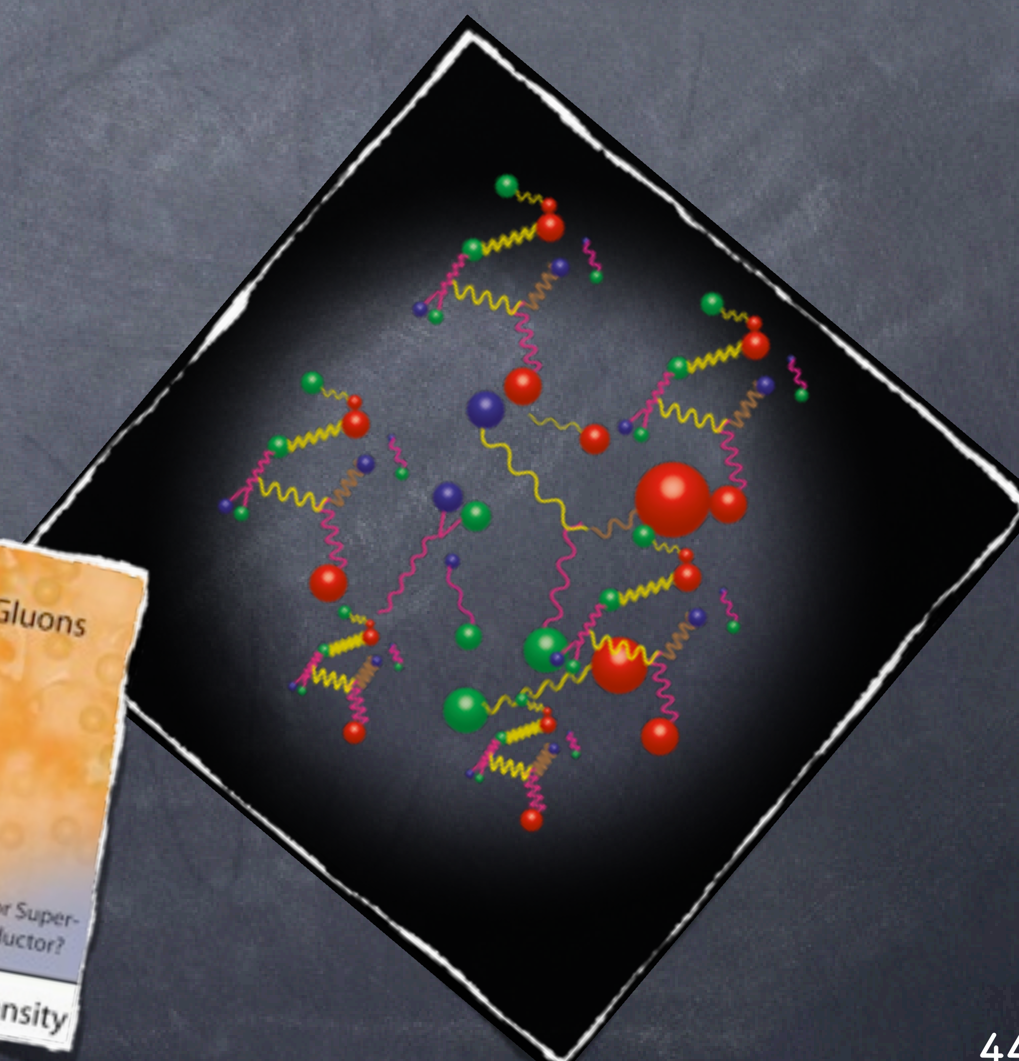
To realize it

- simulation with new event generator and analysis algorithm
- hardware R&D
- driving force from community

Acknowledgement

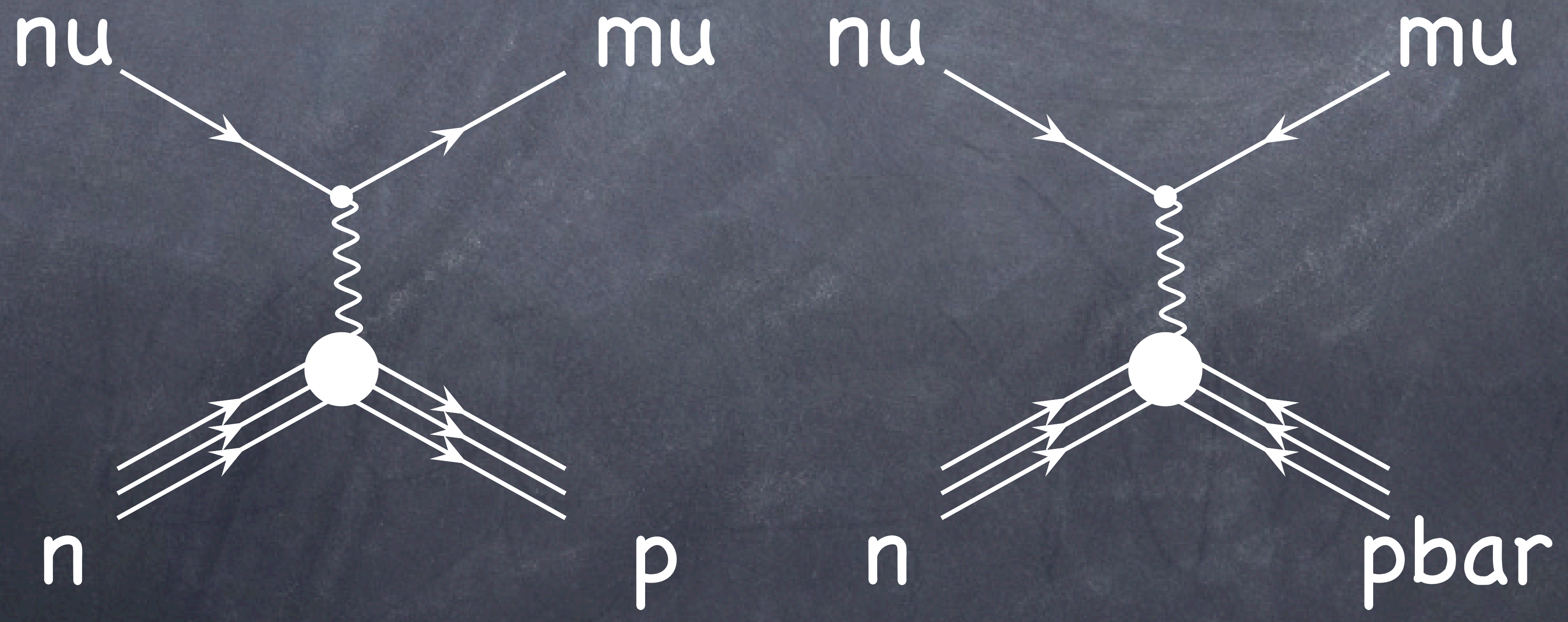
Thanks for the encouraging discussion
with F. Maas, A. Larionov and A. Gillitzer!





Addendum

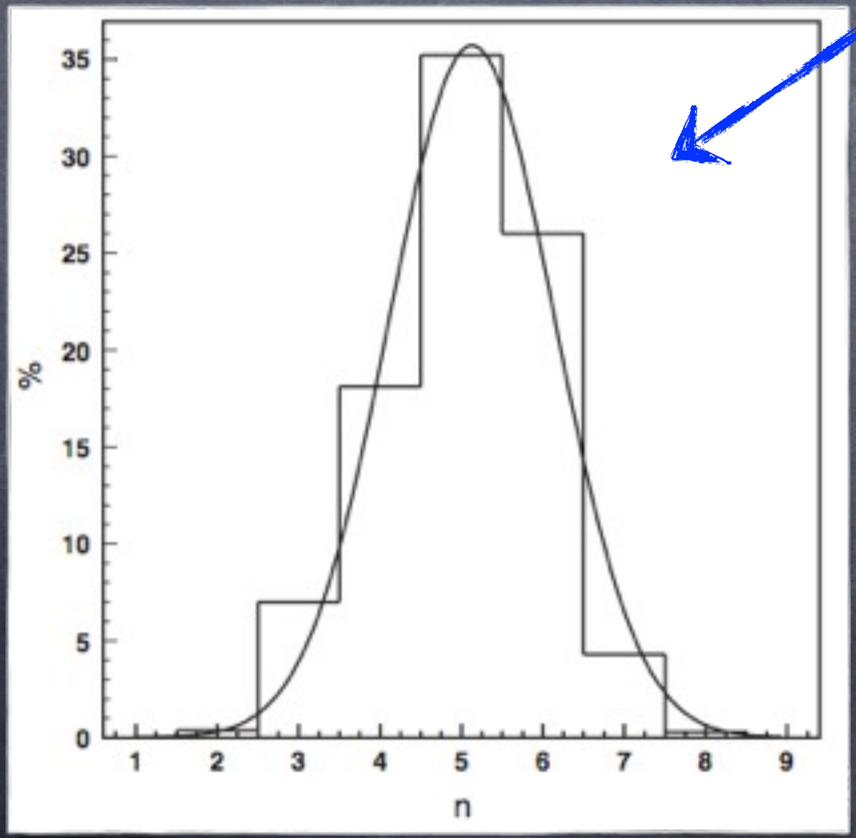
- Time-like weak charge distribution at PANDA?
- External target setup necessary
- Challenge on event selection



Addendum

- production of pion gas?
- challenge the limit?

pion multiplicity distribution
fitted by Gaissian:
mean = 5.03
σ = 1.13



pbar+p -> 13 pions maximum
from the fitted Gaussian:
P(10 pi) = 2.2e-5
P(11 pi) = 3.1e-7
P(12 pi) = 1.9e-9
P(13 pi) = 5e-12

E. Klempt, et al. Phys. Rep. 413, p.197, (2005)

Addendum

Related topics but not covered:

- pbar + A -> pbar + A + lepton pair(F. Maas)
- Color transparency
- D, J/Psi meson medium effects