Search for ϕ-N Bound State in Jefferson Lab Hall B

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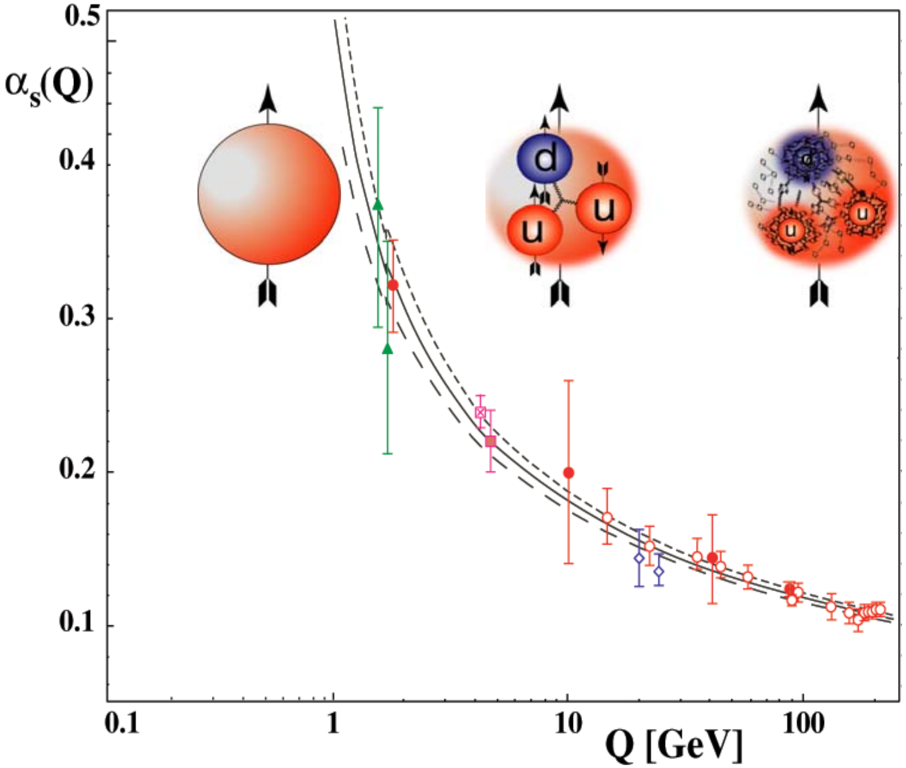
QCD: still unsolved in non-perturbative region

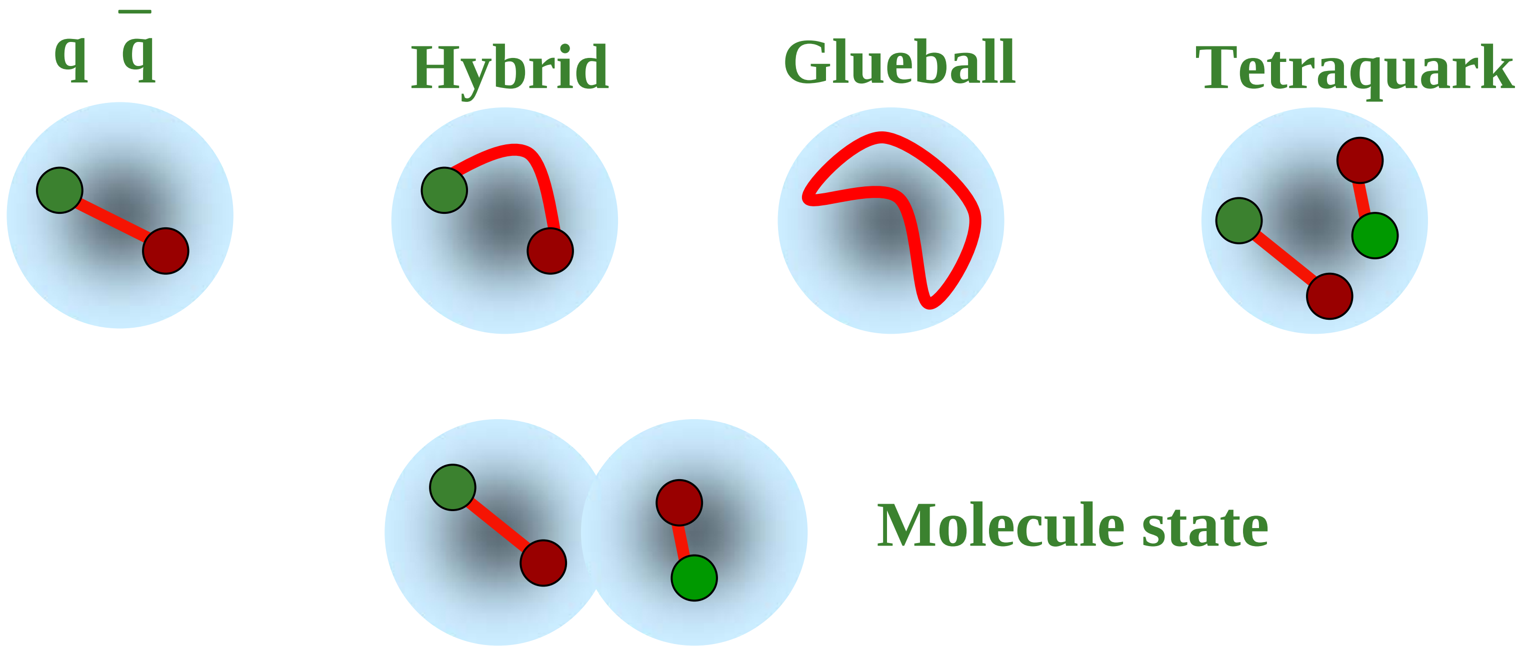


Gauge bosons: gluons (8)

- **2004 Nobel prize for ``asymptotic freedom''**
- **non-perturbative regime QCD ?????**
- **One of the top 10 challenges for physics!**

❑ Why care for QCD exotics?

QCD does not eliminate the existence of hadrons beyond simple ($q\bar{q}$) or (qqq) as a color-singlet system.



- **How confinement manifests itself at large distances?**
- **What leads to the chiral symmetry spontaneous breaking?**
- **What are the proper effective degrees of freedom for a hadron?**
- **… …**

Brief Recap on van der Waals Forces

1873: To explain deviations from ideal gas behavior, van der Waals proposed a modification to the gas law:

$$\left(\mathbf{P} + \frac{\mathbf{a}}{\mathbf{V}^2}\right)(\mathbf{V} - \mathbf{b}) = \mathbf{RT}$$

Reasoned out:

- Molecules have finite volume (accounted by "b")
- Attractive forces between the molecules (accounted by "a")

The relation predicted gas behavior across a larger pressure range

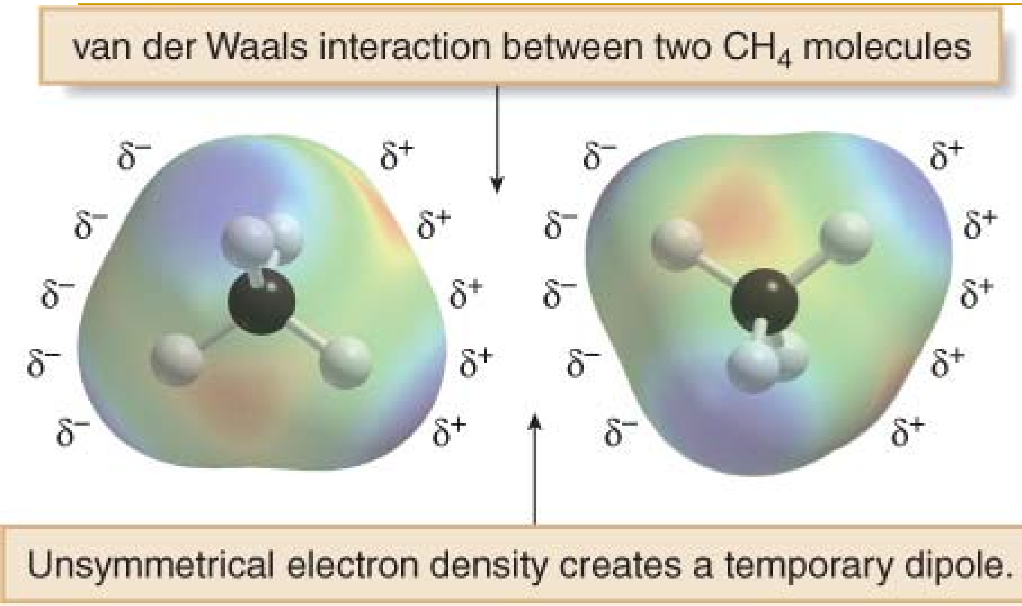
The attractive intermolecular forces between gas molecules is now known as " van der Waals forces "

van der Waals Forces

The three components that constitute van der Waals Forces

Interaction Component	Origin of Interactions	Equation
Keesom	Dipole-dipole	$w(r) = -\frac{u_1^2 u_2^2}{3(4\pi\varepsilon_o\varepsilon_r)^2 k_B T}\frac{1}{r^6}$
Debye	Dipole – induced dipole	$w(r) = -\frac{u^2\alpha_o}{(4\pi\varepsilon_o\varepsilon_r)^2}\frac{1}{r^6}$
London (Dispersion)	Induced Dipole – Induced Dipole	$w(r) = -\frac{3}{2}\frac{\alpha_{o1}\alpha_{o2}}{(4\pi\varepsilon_o)^2}\frac{I_1 I_2}{(I_1 + I_2)}\frac{1}{r^6}$

The London component is the most dominant.
n = 6 indicates van der Waals forces are short range



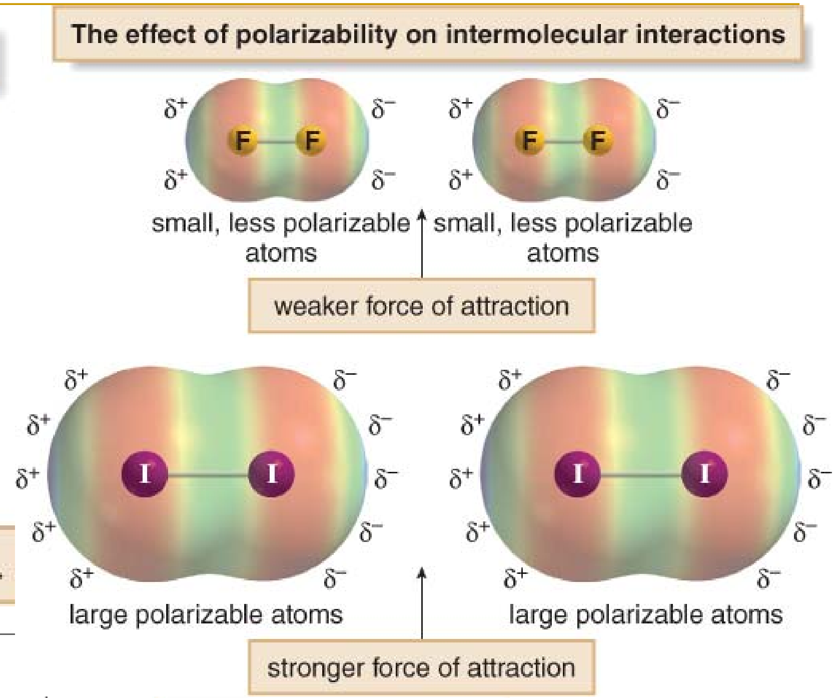
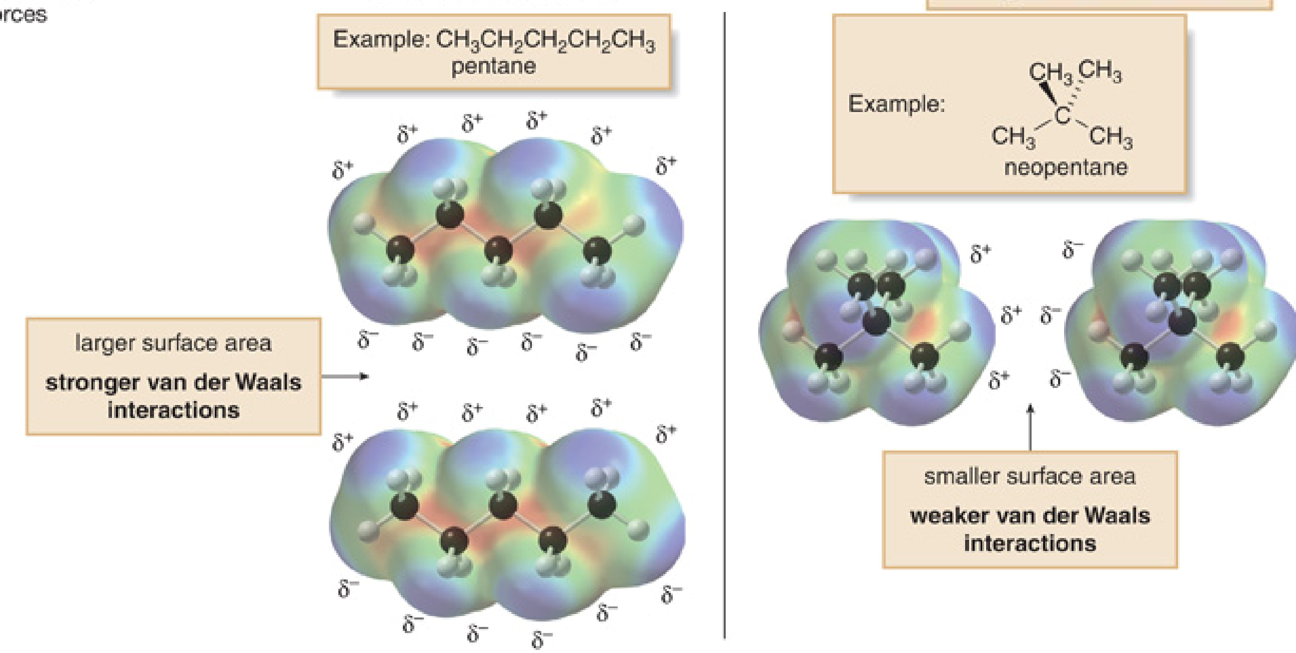


Figure 3.2 Surface area and van der Waals forces

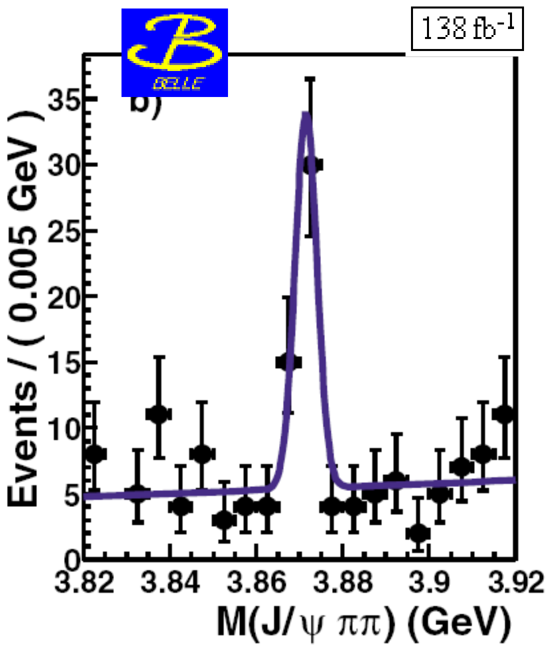


Question: are there any QCD molecular state?

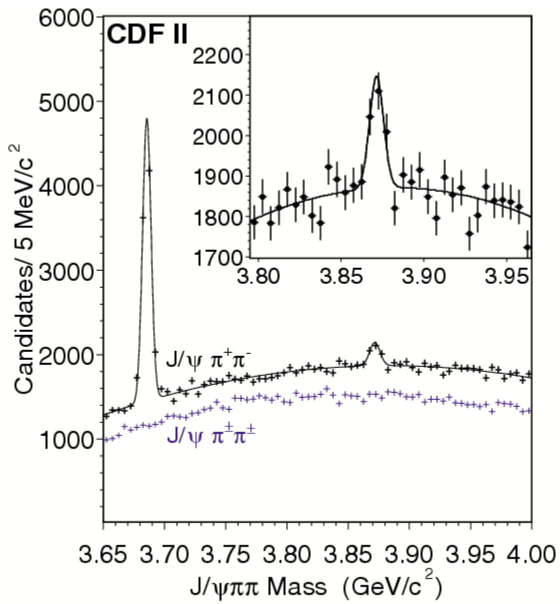
Answer: maybe

Discovery of the X(3872)

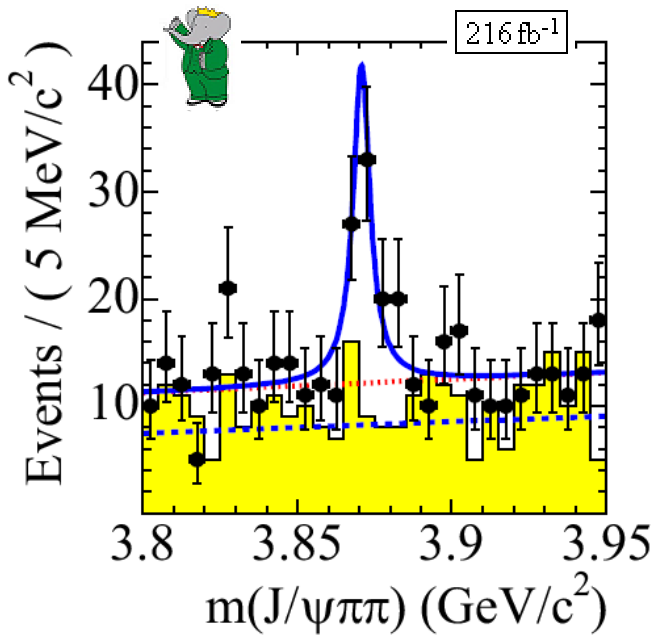
- In 2003, Belle discovered a new signal in $B^+ \rightarrow X K^+$, $X \rightarrow J/\psi \pi^+ \pi^-$
- Narrow (Γ<2.3MeV) particle with mass $m(X)=3871.2 +/- 0.6$ MeV/c^2



Phys. Rev. Lett. 91, 262001 (2003)



Phys. Rev. Lett. 93, 072001 (2004)
Phys. Rev. Lett. 93, 162002 (2004)



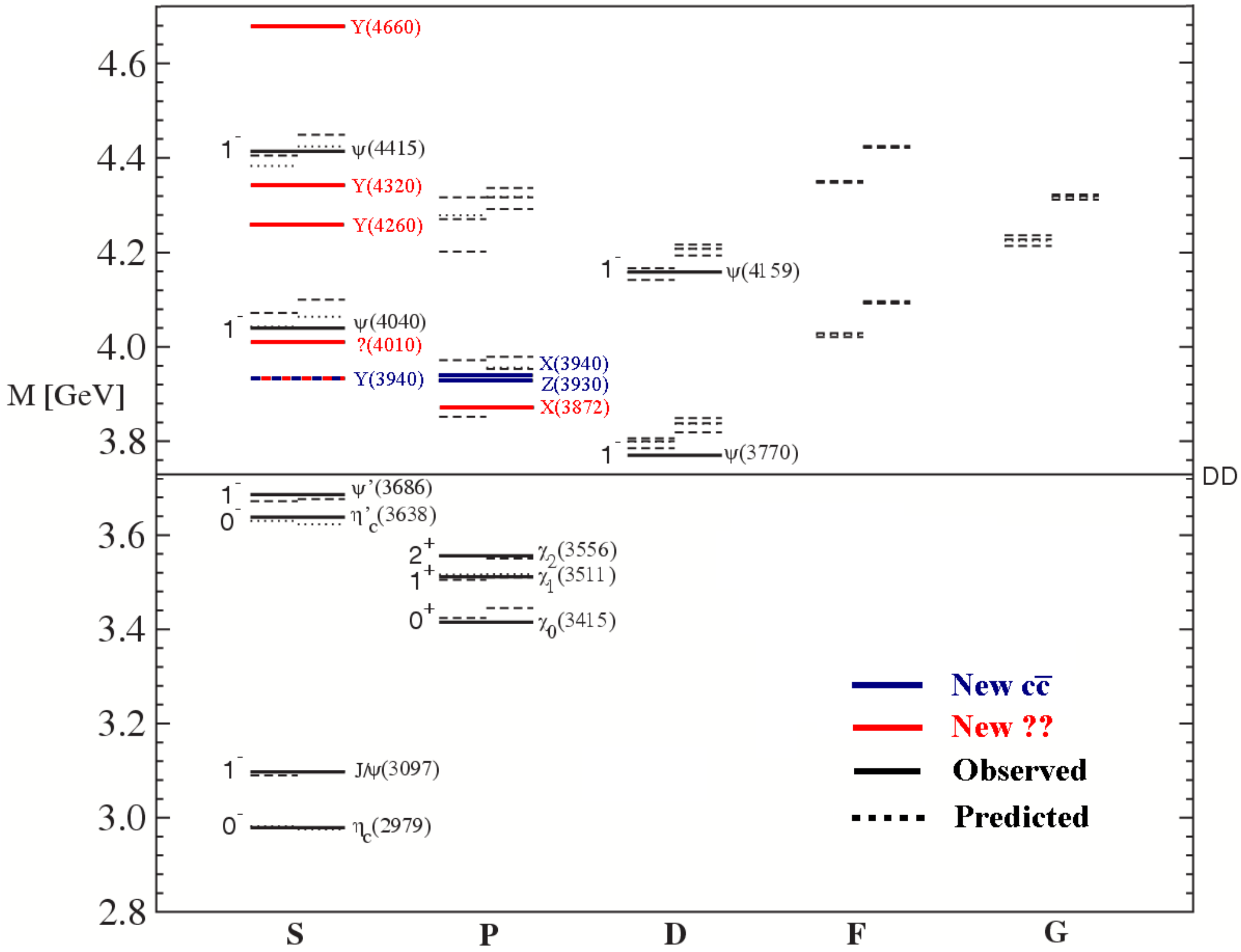
Phys. Rev. D 71, 071103 (2005)
Phys. Rev. D 73, 011101 (2006)

Confirmed by CDF, D0 and BaBar

X(3872) Interpretation

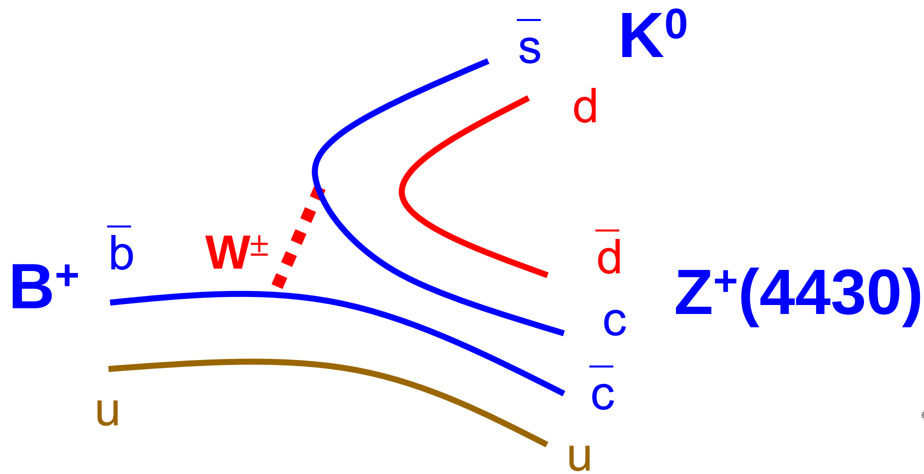
- X(3872) is puzzling
  - Similar to charmonium, ie: narrow state decaying to $J/\psi\pi^+\pi^-$
  - However, above DD threshold expect to be wide and X→DD dominant
  - Quantum numbers established: 1^{++}
  - It does not fit into the charmonium model
- Note: $m(X) \approx m(D) + m(\overline{D}^{*0})$
- Leading contender: a bound state of two D mesons
  - i.e.: a $D^0 D^{*0}$ molecule
  - Supported by predictions of mass, decay modes, J^{PC}, branching fractions
- Other exotic predictions:
  - “Tetraquark” 4-quark bound state
  - “Glueball” gluon bound state, charmonium-gluon hybrid

Charmonium Spectrum Revisited



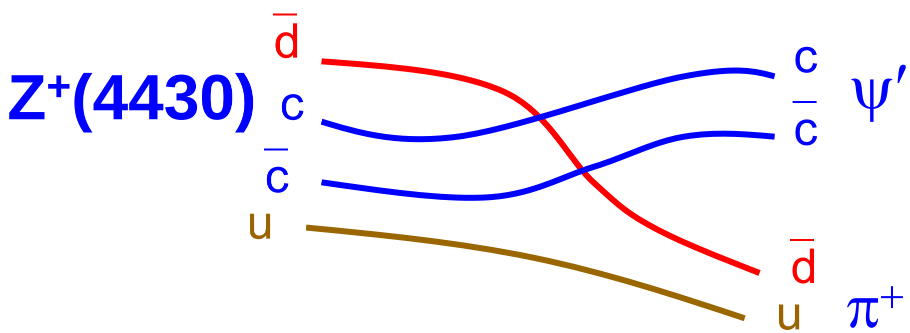
❑Belle results Z+(4430)

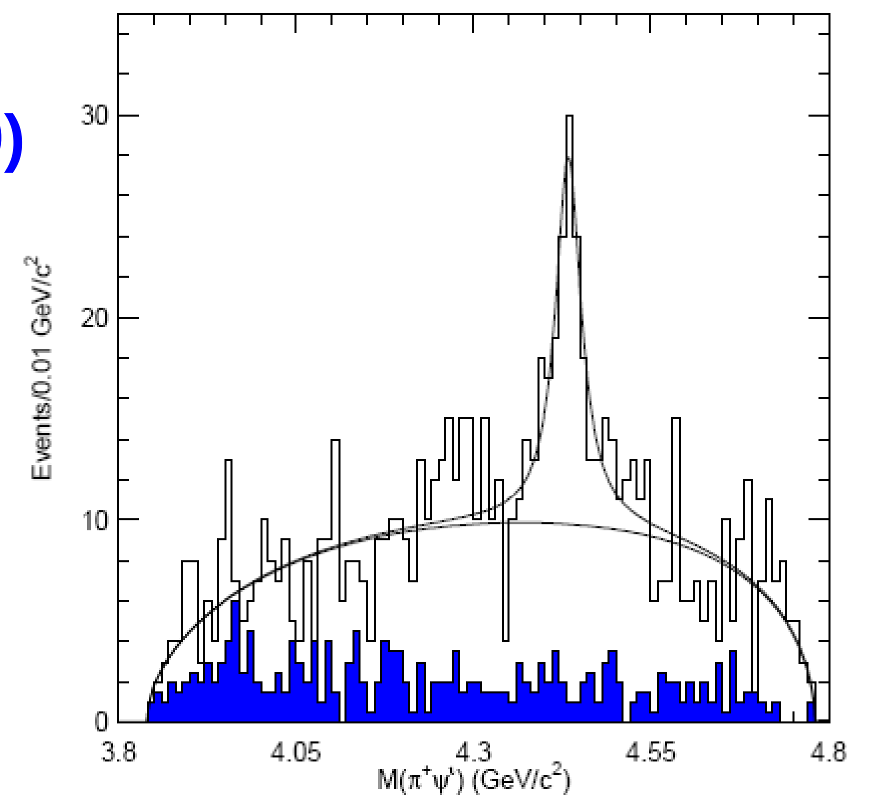
$$B \to K\pi^{\pm}\psi'$$



$$M = (4.433 \pm 0.004(\text{stat}) \pm 0.001(\text{syst}))\ \text{GeV}.$$

$$\Gamma = (0.044^{+0.017}_{-0.013}(\text{stat})^{+0.030}_{-0.011}(\text{syst}))\ \text{GeV},$$





Slide: Qiang Zhao

Belle Collaboration, PRL(2008); arXiv:0708.1790[hep-ex]

First charmonium with isospin I=1 !

Tetraquark state? (Ebert et al; Rosner; Maiani et al; Lee)
Molecular state of $D^* \bar{D}1$? (Bugg; Liu et al)
Subthreshold effects due to $D^* \bar{D}1$? (Bugg; Chao et al)
Baryonium? (Qiao)
……
Why not seen in $J/\psi\ \pi$?
Can it couple to $\rho\eta_c$?
Where are its flavor partners?
……

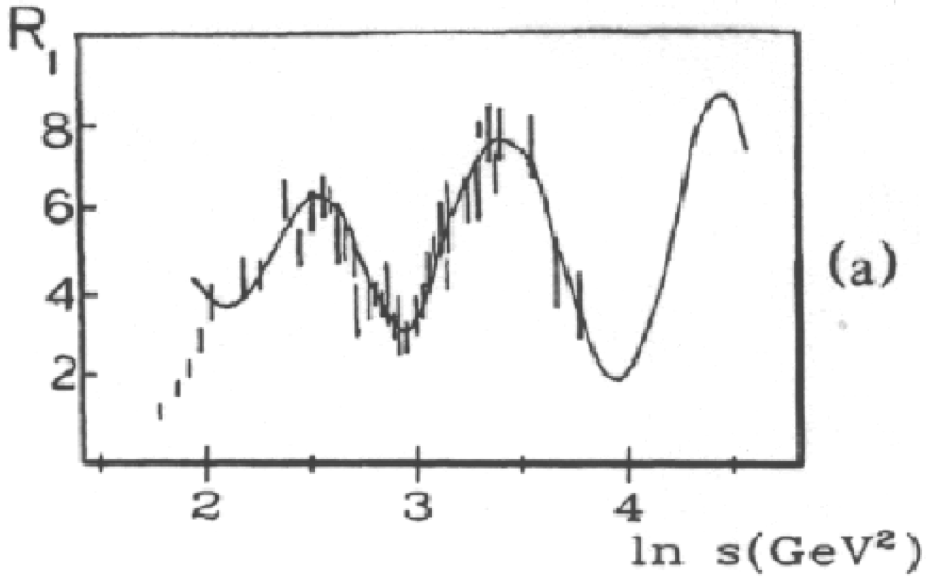
Strong coupling for $Z(4430)\to\psi'\pi$

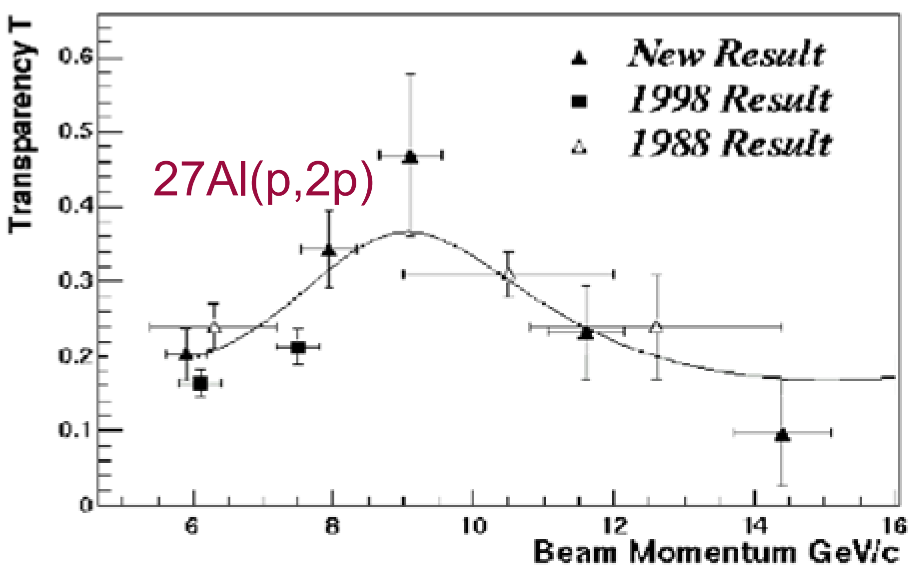
Slide: Qiang Zhao

Can meson-baryon form a molecule?

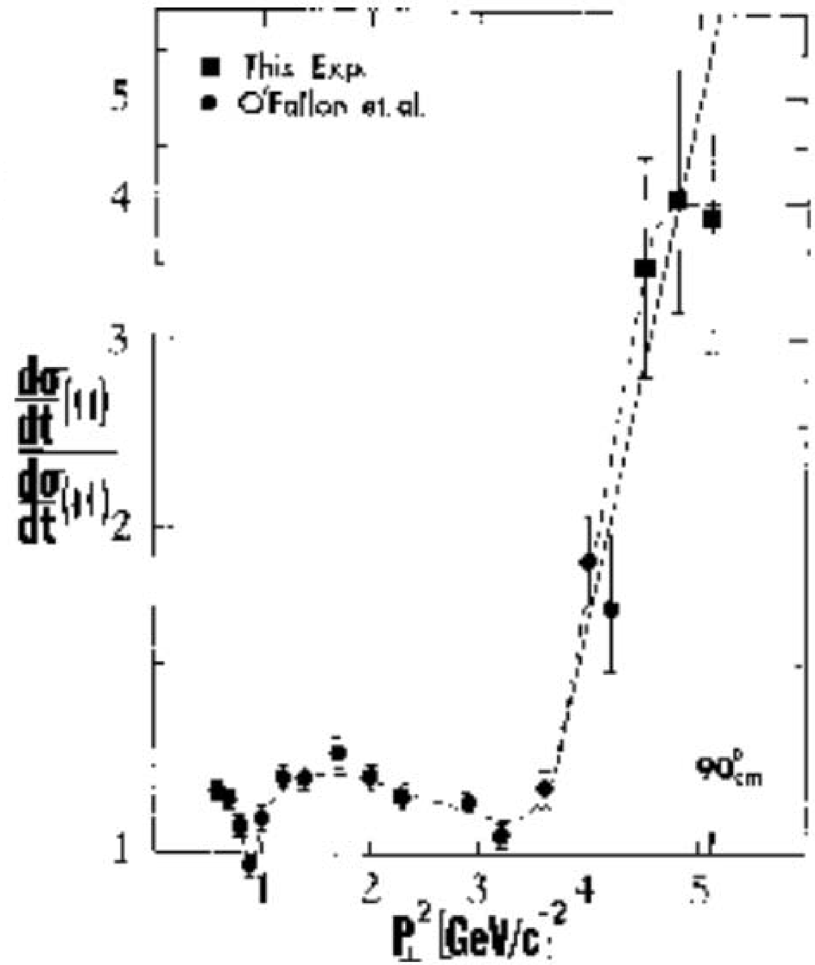
Nuclear-Bound Quarkonium

- **Proton-proton scattering:** intriguing behavior in spin correlation, nuclear transparency
- **QCD van der Walls interaction**, mediated by *multi-gluon exchanges*, is dominant when the two interacting color singlet hadrons have **no common quarks**. ***QCD analog*** of the attractive QED van der Waals potential
- No Pauli blocking, effective quarkonium-nuclear interaction will not have a short-range repulsion
- S. J. Brodsky, I. A. Schmidt, and G.F. de Teramond, Phys. Rev. Lett. **64**, 1011 (1990); Luke, Manohar and Savage
- Suggested a bound state of charm quarkonium to ^{3}He nucleus: η_c-^{3}He by studying proton capture on deuteron
- Binding energy ~ 20 MeV, width ~ tens of keV.
- D. A. Wasson, Phys. Rev. Lett. **67**, 2237 (1991).





PRL**61**,1698 (1988); PRL**81**, 5085 (1998), PRL**87**, 212301 (2001) (BNL experiments)



G.R. Court *et al*., Phys. Rev. Lett. **60**, 1924 (1988)

$$p + p \to \Lambda_c D p$$

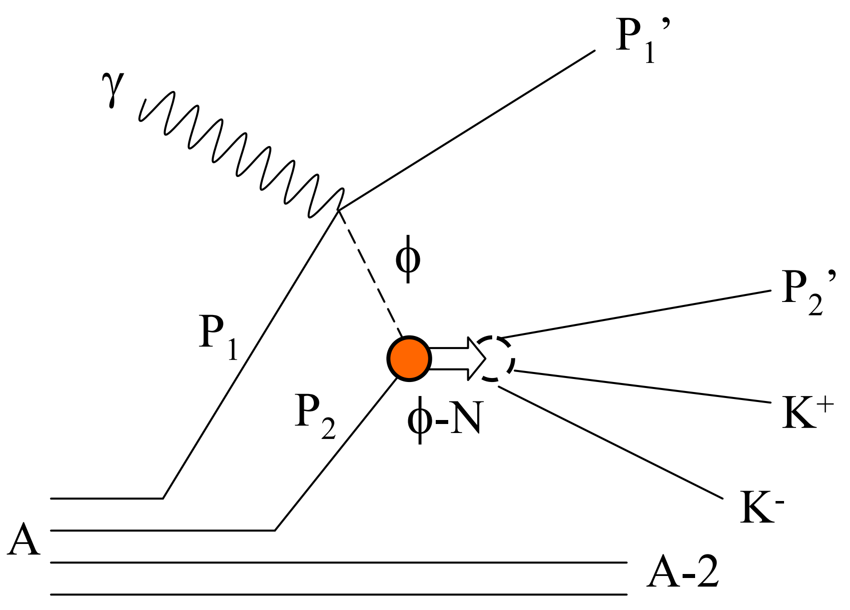
ϕ-N Bound State (suggested by Isgur)?

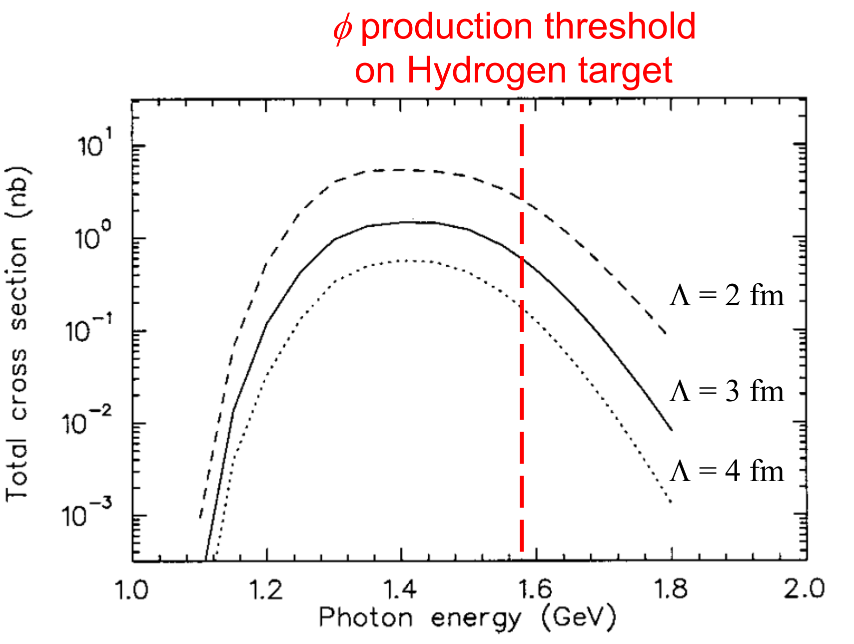
- H. Gao, T.-S. H. Lee, and V. Marinov, Phys. Rev. C **63**, 022201R (2001).
  - The interaction is expected to be enhanced by $(m_c/m_s)^3$, following Brodsky *et al.* PRL 64, 1011 (1990)
  - Varitional method with $V_{(q\bar{q})A} = -\frac{\alpha e^{-\mu r}}{r}, \ \alpha = 1.25, \ \mu = 0.6$
  - ***Binding energy ~ 2 MeV***
  - ϕ-N can be formed inside heavy nuclei through quasi-free ϕ photoproduction.

ϕ-N bound state in chiral quark model

- Huang, Zhang and Yu, Phys. Rev. C **73**, 025207 (2006)
- Chiral SU(3) quark model and the extended chiral SU(3) quark model solving the RGM equation
- Model parameters from previous work give good descriptions of
  - Baryon ground states
  - Deuteron binding energy
  - NN scattering phase shifts
- Extended chiral quark model plus channel coupling effect $\rightarrow$ ϕ-N quasi-bound state with several MeV of binding energy

Creation of ϕ-N Bound State in Heavy Nuclei





H. Gao, T.-S. H. Lee, and V. Marinov, Phys. Rev. C **63**, 022201 (2001)

- "Sub-threshold" generated ϕ is slow enough to bound with nucleon
- $\sigma^{tot} \sim 1.4$ nb on ^{12}C nucleus.

Possible Way to Detect ϕ-N

- "Sub-threshold" ϕ production in nuclei.
  - Can use real photon, electron or proton beam.
  - Need to tag energy of real/virtual photon.
- Detect all final states of ϕ-N bound state decay to reconstruct its invariant mass.
  - $\phi\text{-}N \rightarrow p_2'+K^+ + K^-$: triple coincidence
  - Other decay channels (see later)
- Jefferson Lab Hall B is a possible place to search for such particle:
  - Large acceptance detector and tagged photon beam.
  - Good particle identification.

Background Channels

- Four major background channels
  - Direct production:

$$\gamma + p_1 \rightarrow p_1' + K^+ + K^-$$

  - No Bound State:

$$\gamma + p_1 \rightarrow p_1' + \phi \rightarrow p_1' + K^+ + K^-$$

  - $\Lambda(1520)$ Production:

$$\gamma + p_1 \rightarrow \Lambda(1520) + K^+ \rightarrow p_1' + K^- + K^+$$

  - a_0/f_0 production

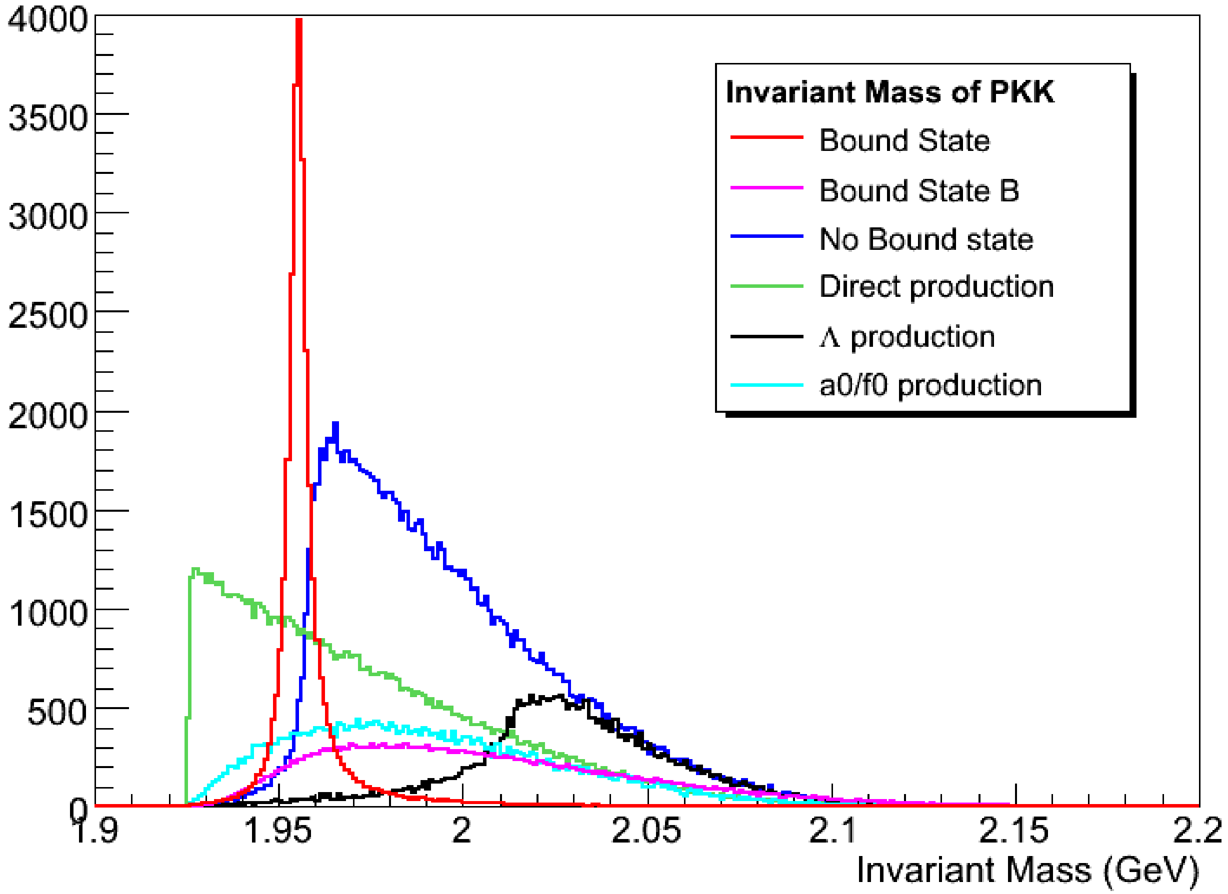
$$\gamma + p_1 \rightarrow p_1' + a_0 / f_0 \rightarrow p_1' + K^+ + K^-$$

- Bound state formed but K^+ K coincide with the recoil proton p_1'.

Phase Space Simulation

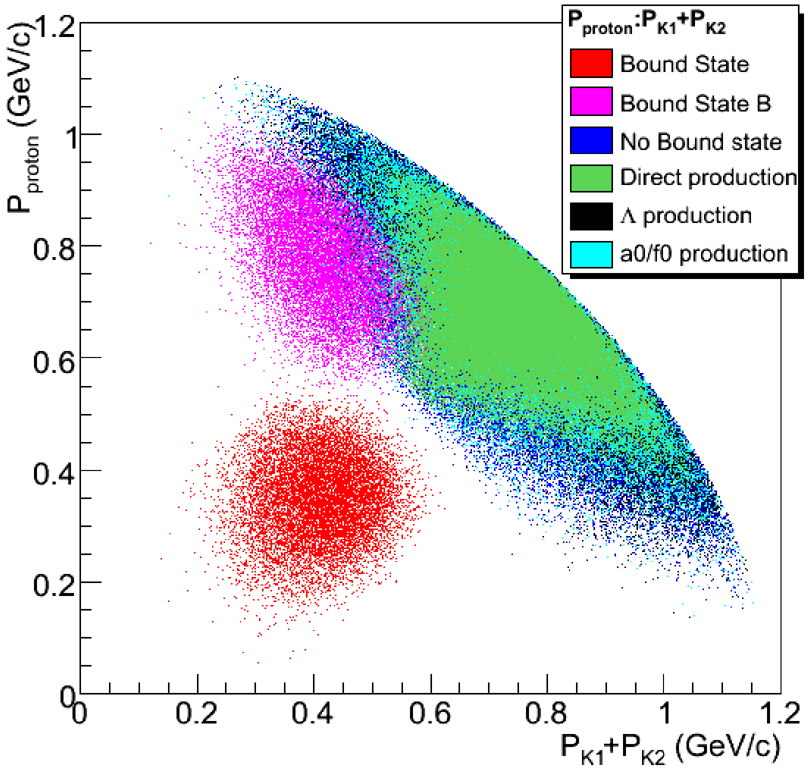
- Done by S. Liska and Y. Qiang.
- On four nuclear targets: ^{12}C, ^{56}Fe, ^{63}Cu and ^{197}Au.
- Fermi motion and missing energy distributions were taken into account in the simulation of quasi-free process.
- The following results were from ^{63}Cu target with photon energy $E\gamma = 1.35 \sim 1.55$ GeV
- Preliminary study with cross section weighting done by S. Liska (Duke senior thesis, 2008)

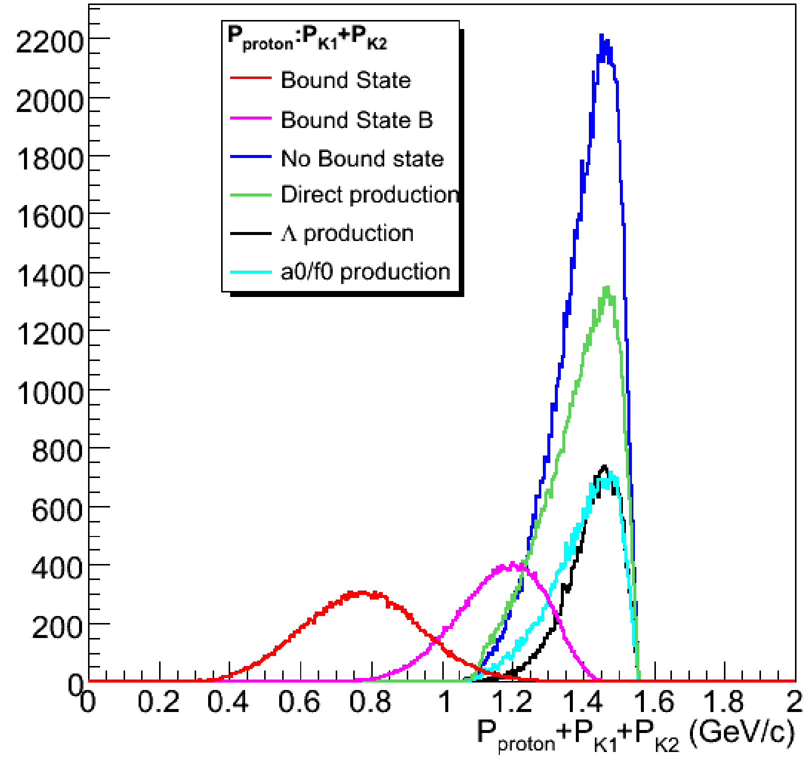
Invariant Mass of p K$^+$ K$^-$



- ϕ-N bound state (5 MeV width assumed) mixed with other channels.

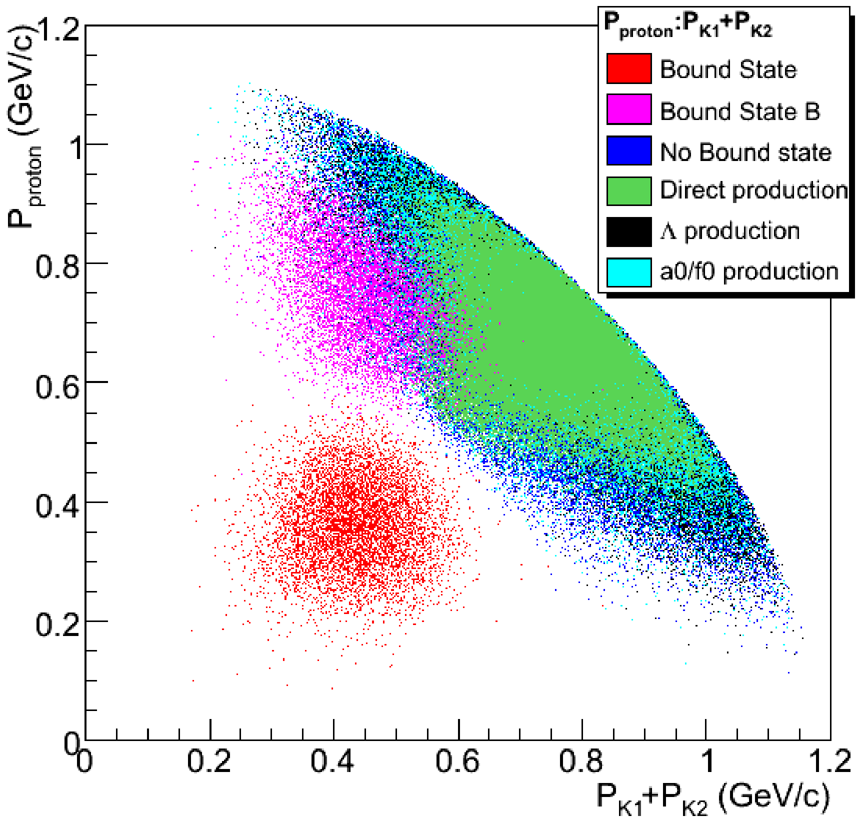
Momentum Distributions

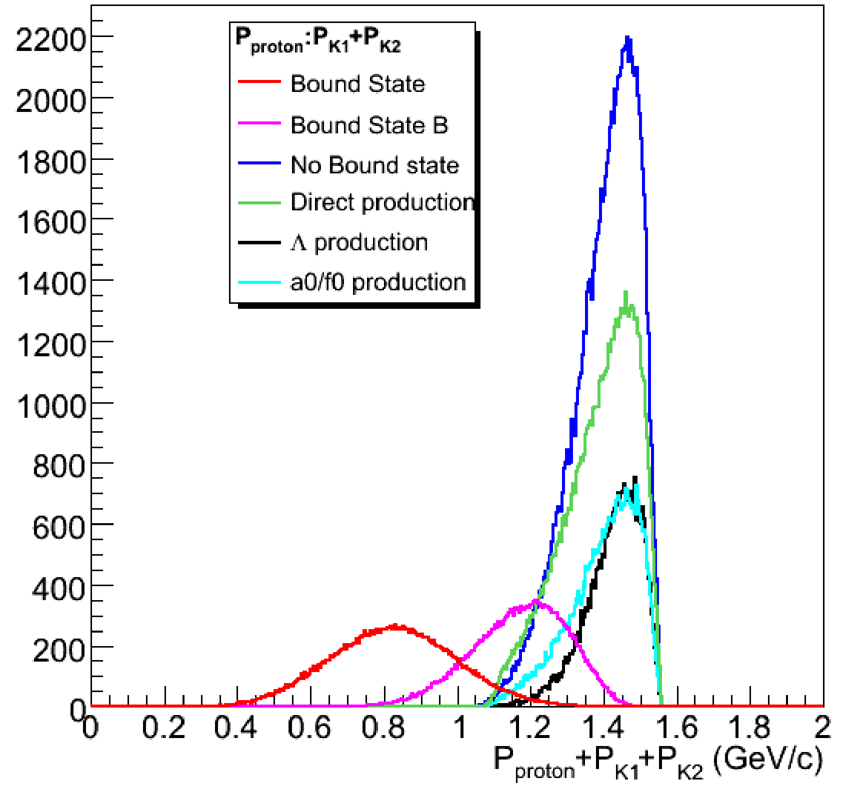




- ϕ-N bound state can be clearly identified (5 MeV width assumed).

Momentum Distributions

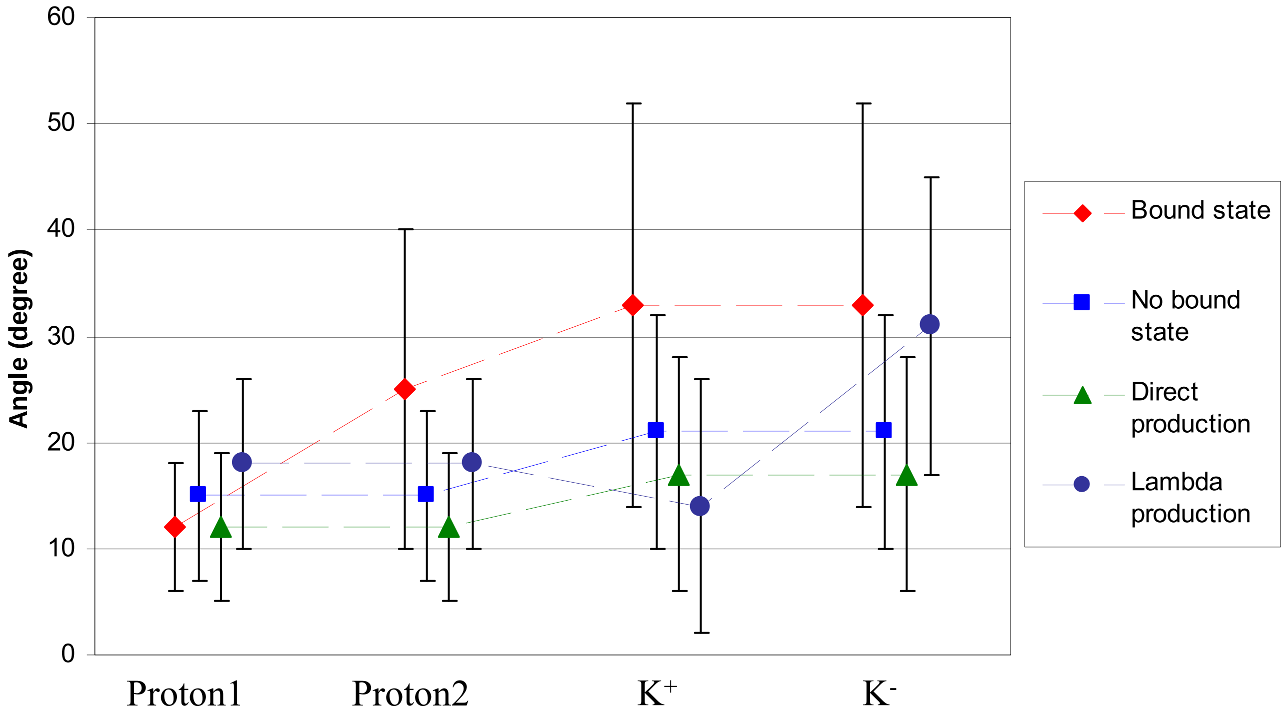




- ϕ-N bound state can be clearly identified (50 MeV width assumed).

Angles of Final States

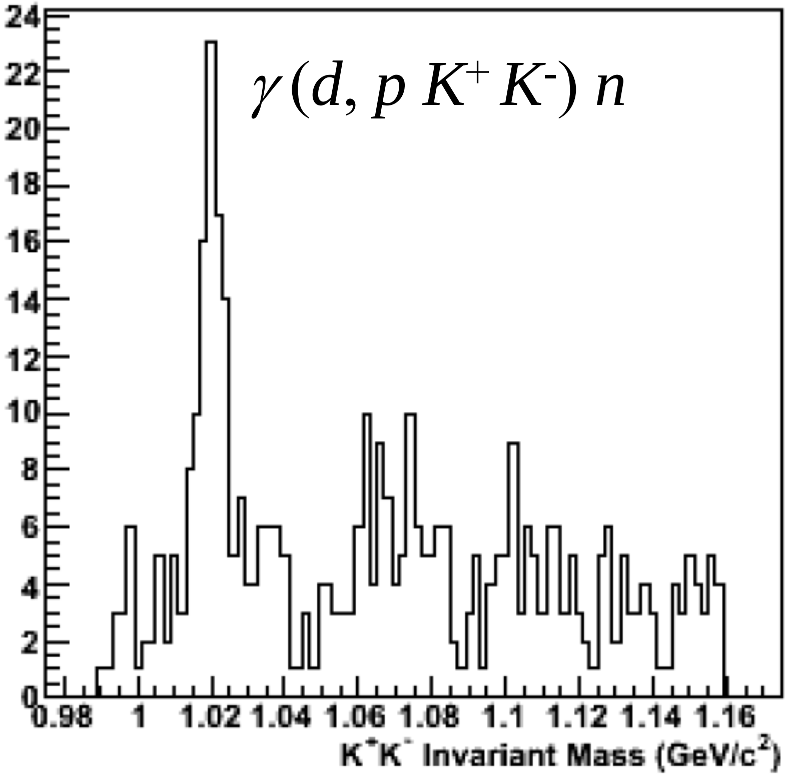
- All particles are produced forward while the final states of ϕ-N bound state have the largest angles.

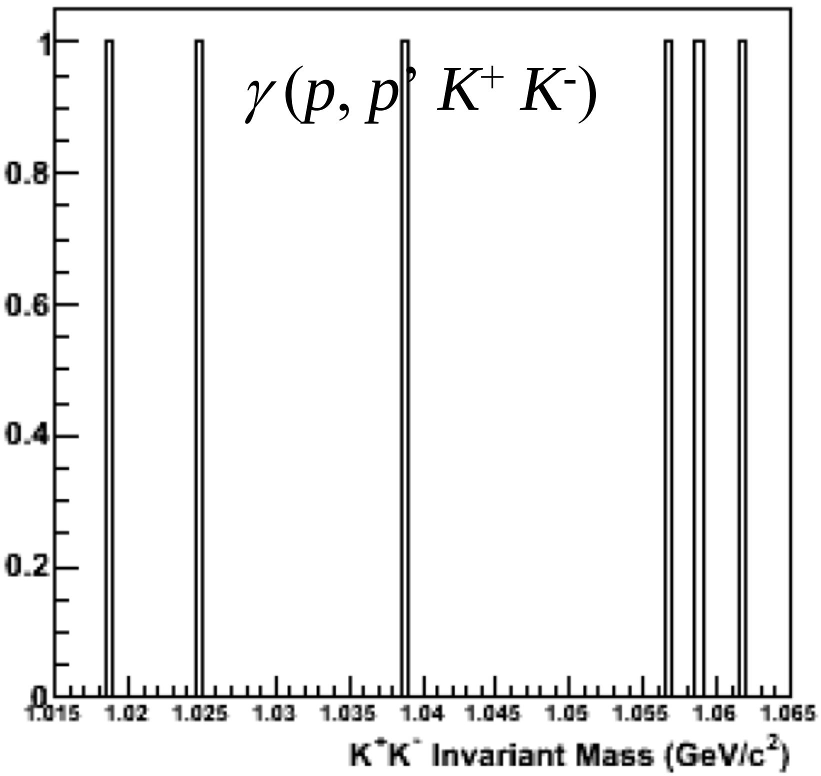


Summary of ϕ-N Final States

- $\phi\text{-}N \rightarrow p_2' + K^+ + K^-$
  - p_2' : 200 ~ 500 MeV/*c* $10^o \sim 40^o$
  - K^+ : 100 ~ 300 MeV/*c* $13^o \sim 52^o$
  - K^- : 100 ~ 300 MeV/*c* $13^o \sim 52^o$

Evidence of ϕ Production from Fermi Motion

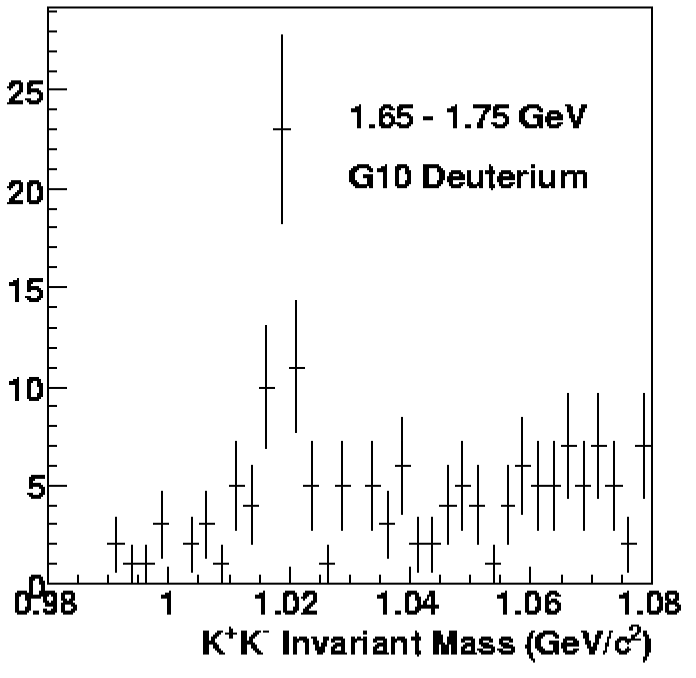


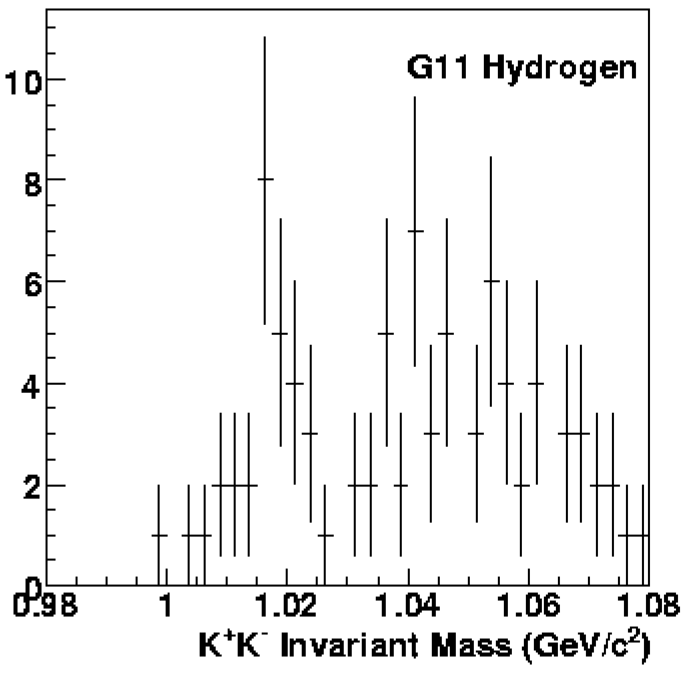


- X. Qian *et al*. CLAS g10 data, Eγ= 1.65~1.75 GeV (currently reviewed by CLAS ad hoc committee)

Evidence of φ Production from Fermi Motion

$\gamma(d, p\,K^+ K^-)\,n$ $\gamma(p, p'\,K^+ K^-)$

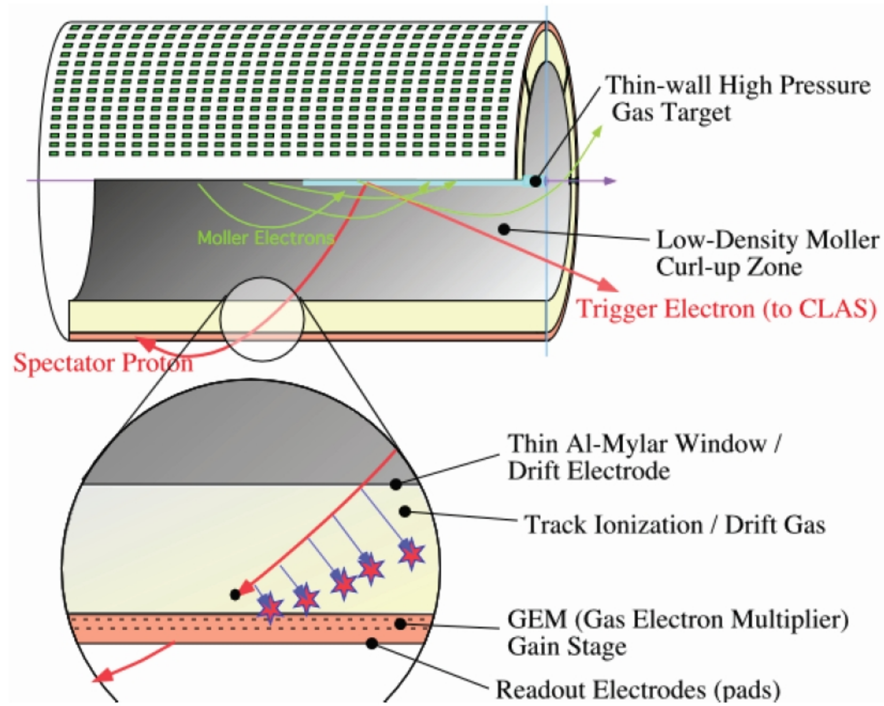




- X. Qian *et al*. CLAS g10 data, Eγ = 1.65~1.75 GeV (currently reviewed by CLAS ad hoc committee)

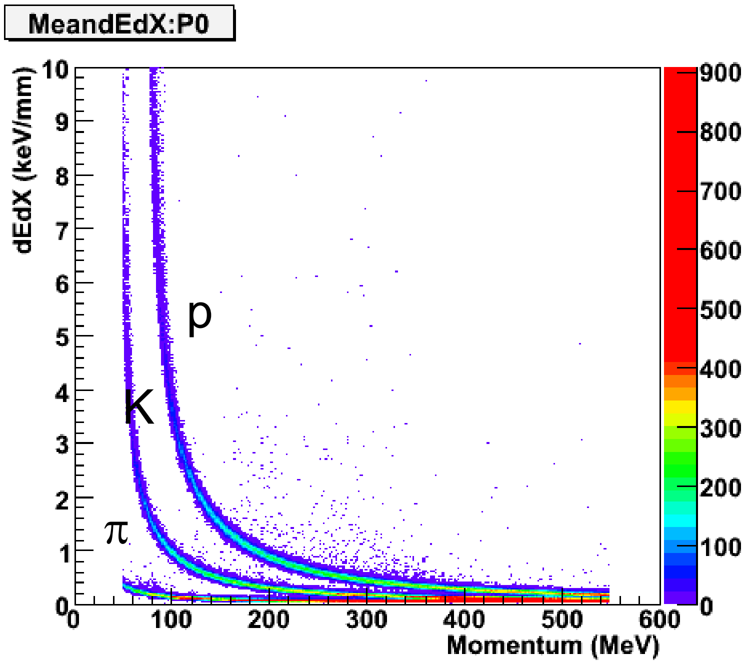
Study on BoNuS Detector

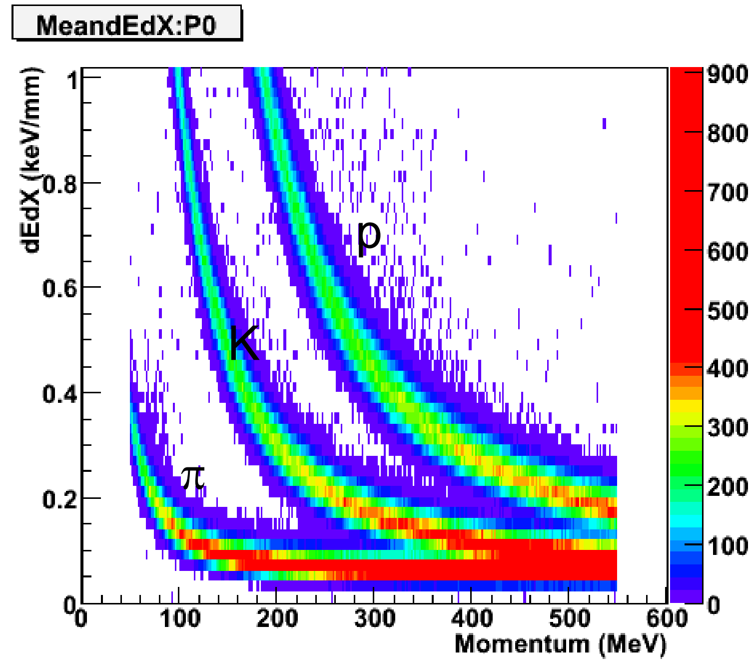
- Radial Time Projection Chamber (RTPC) using GEM foils.
- Active drifting volume: L=20 cm, R=3 cm.
- Longitudinal field is generated by Møller solenoid (2~7 T).



- Can be used to detected low momentum charged particles (< 250 MeV/*c*).
- GEANT4 simulation code by J. Zhang.

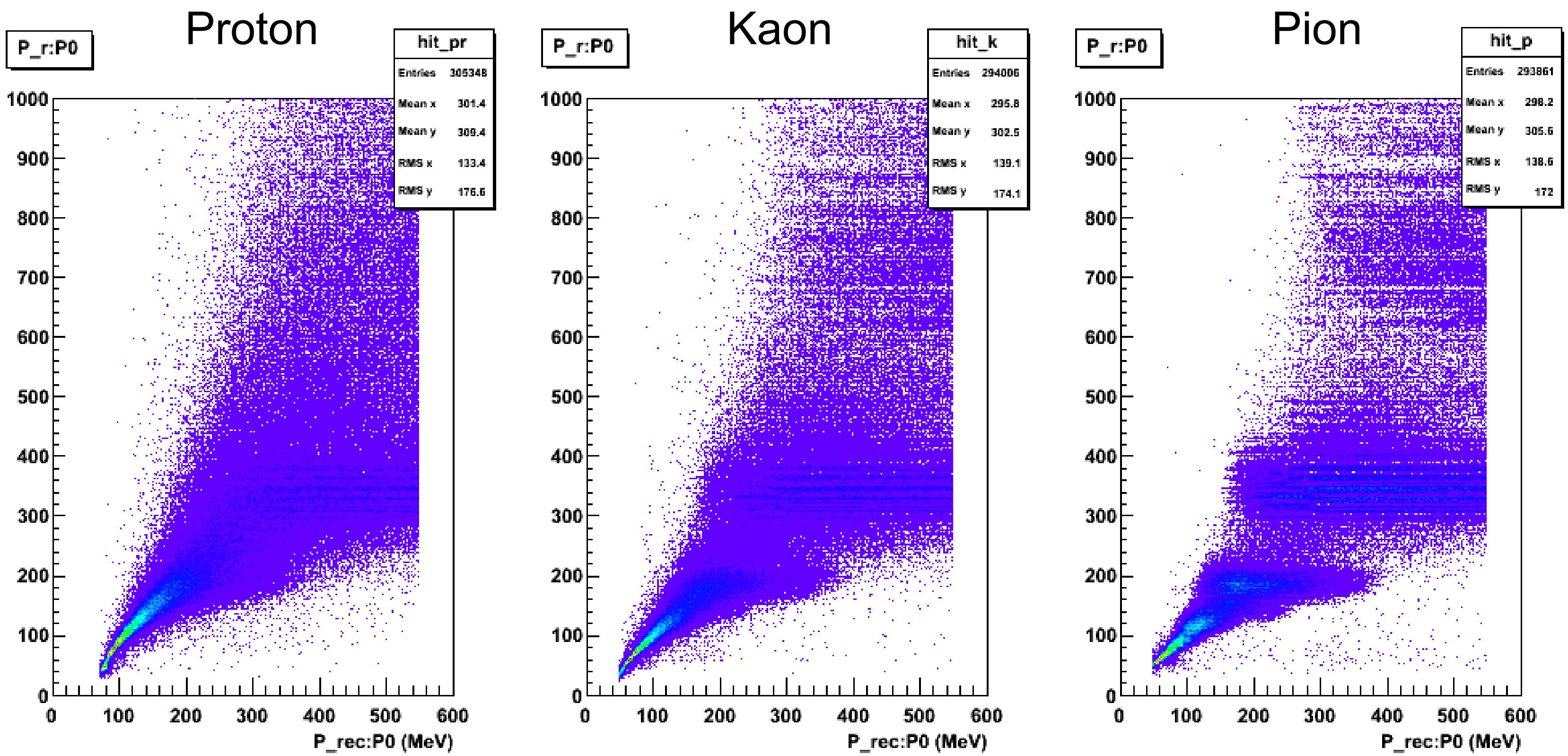
Average dE/dX in BoNuS





- BoNuS uses energy loss **dE/dX** and **momentum** reconstructed from measured curvature to identify charged particles.

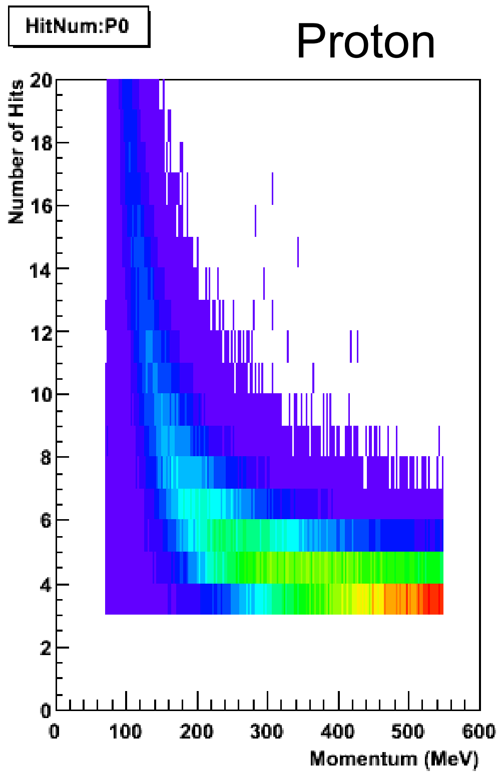
Momentum Reconstruction

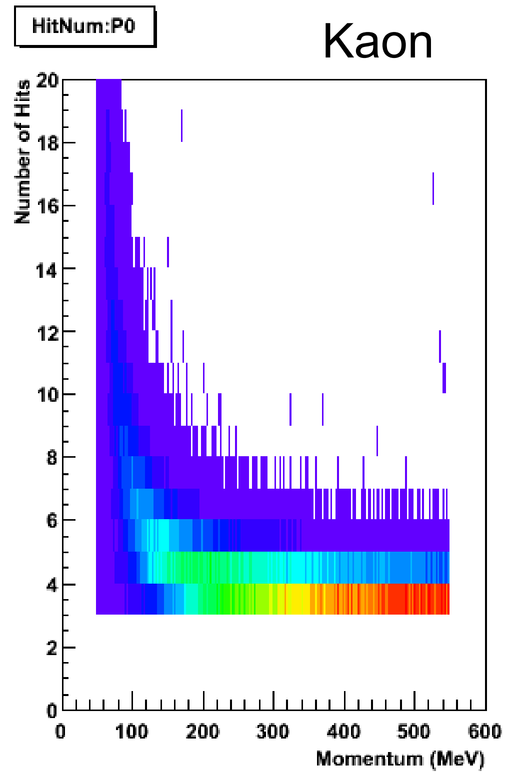


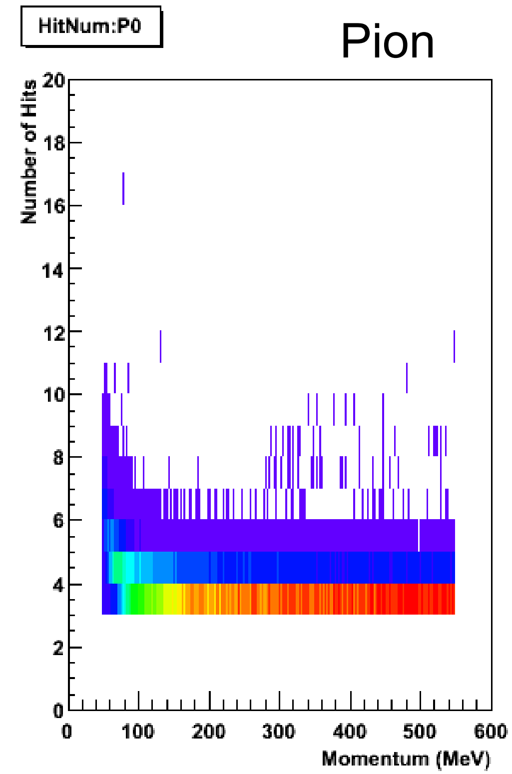
- Only low momentum (<200MeV/*c*) could be reconstructed correctly.

Number of Hits

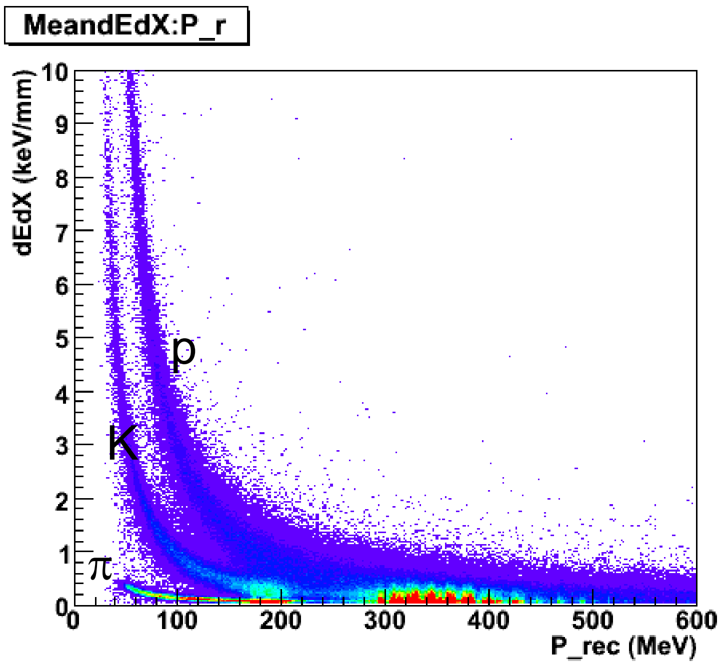
- More than 3 hits are required to define a track:

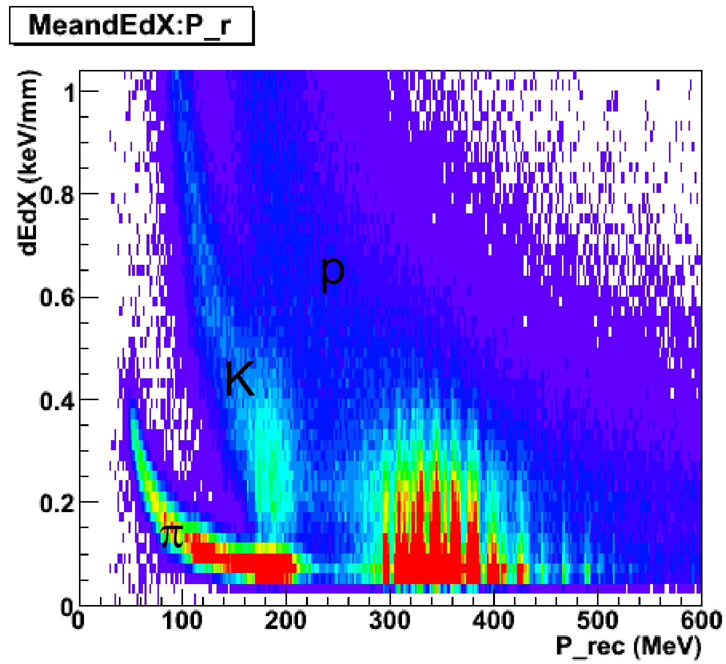






dE/dX vs. Reconstructed Momentum





- The BoNuS RTPC can identify charged particles with momentum below 200 MeV/*c*.
- The use of CLAS seems to be necessary.

Other decay channels of phi-N?

- Two channels have larger phase spaces
  - Decay into Lambda and kaon:

$$\phi - N \rightarrow \Lambda^0 + K^+ \rightarrow p + \pi^- + K^+$$

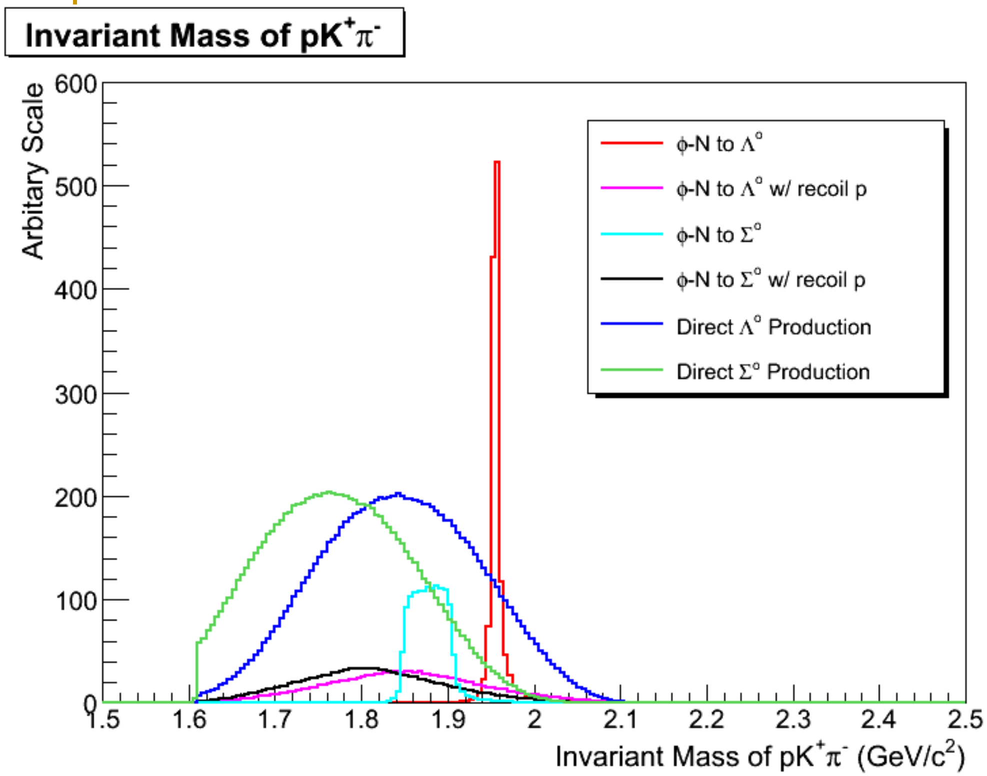
  - Decay into Sigma and kaon:

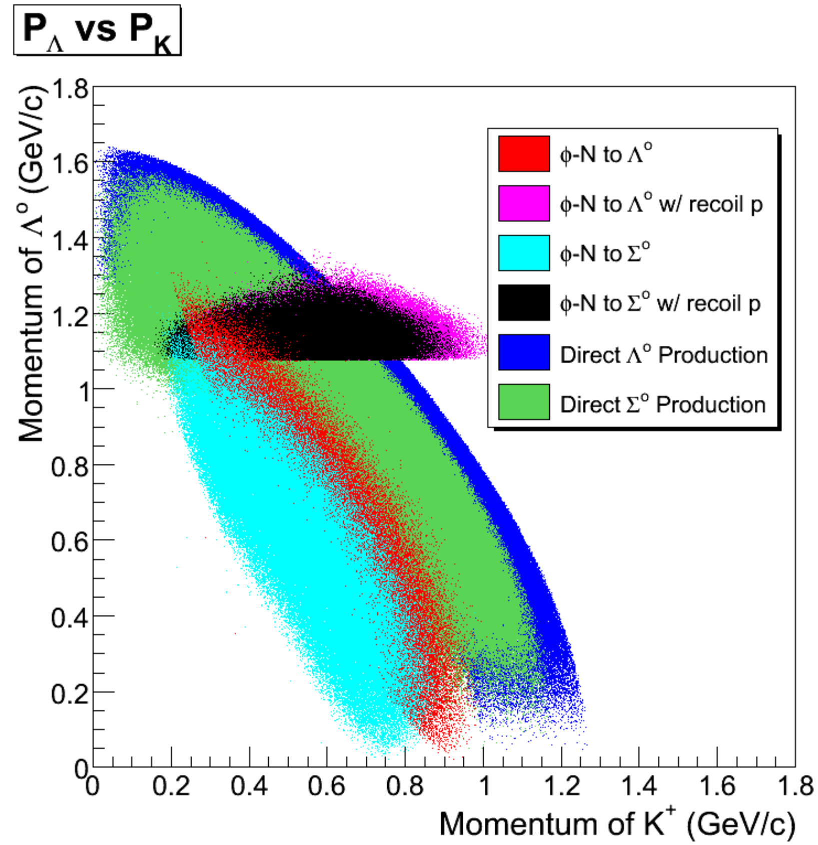
$$\phi - N \rightarrow \Sigma^0 + K^+ \rightarrow \Lambda^0 + \gamma + K^+ \rightarrow p + \pi^- + \gamma + K^+$$

- Simulations carried for these two decay channels (see next slides)

Phase Space Simulation

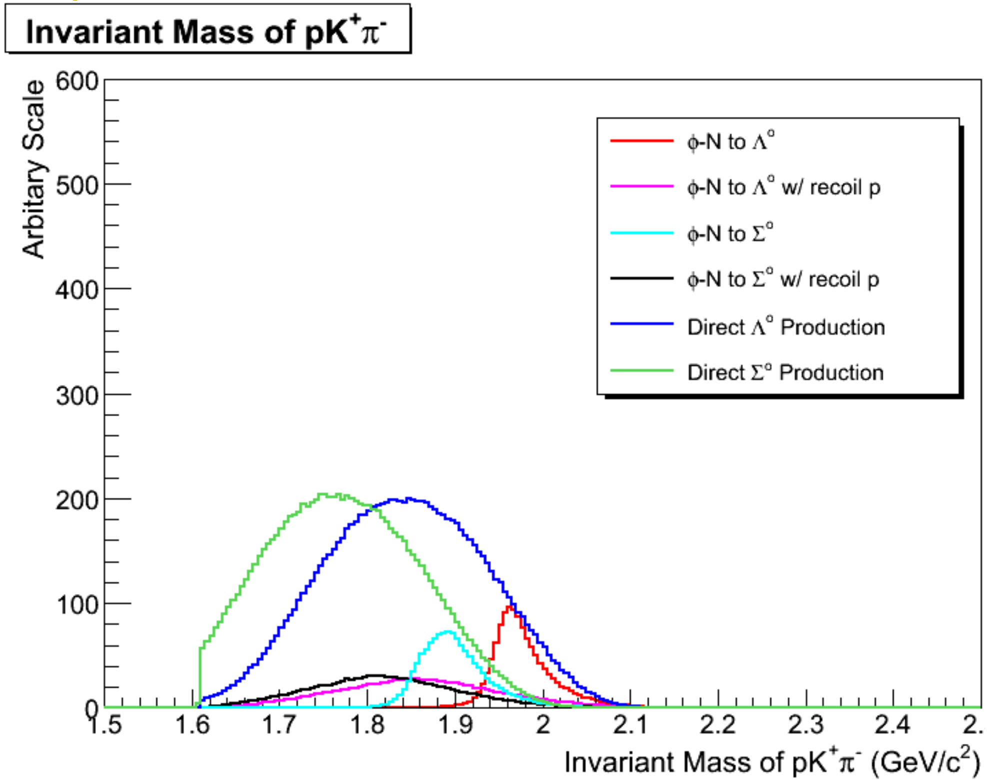
- Performed by Y. Qiang.
- One nuclear target as a test case: ^{63}Cu.
- Fermi motion and missing energy distributions were taken into account in the simulation of quasi-free process.
- Simulations also taken into account two phi-N state widths: 5 MeV and 50 MeV
- The following results were from ^{63}Cu target with photon energy $E\gamma = 1.35 \sim 1.55$ GeV.

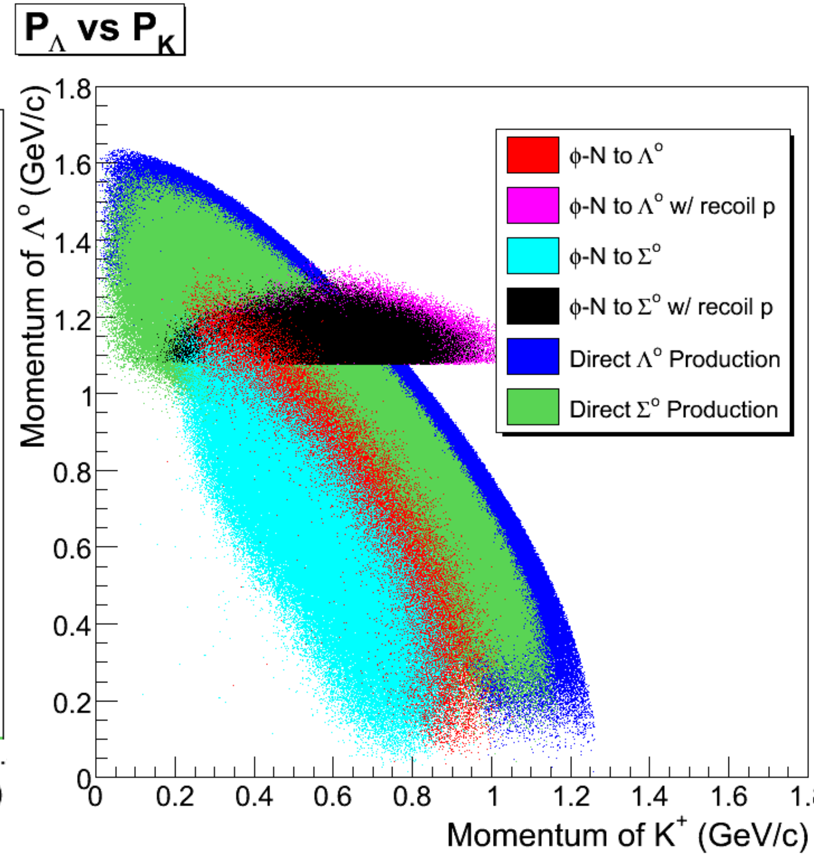




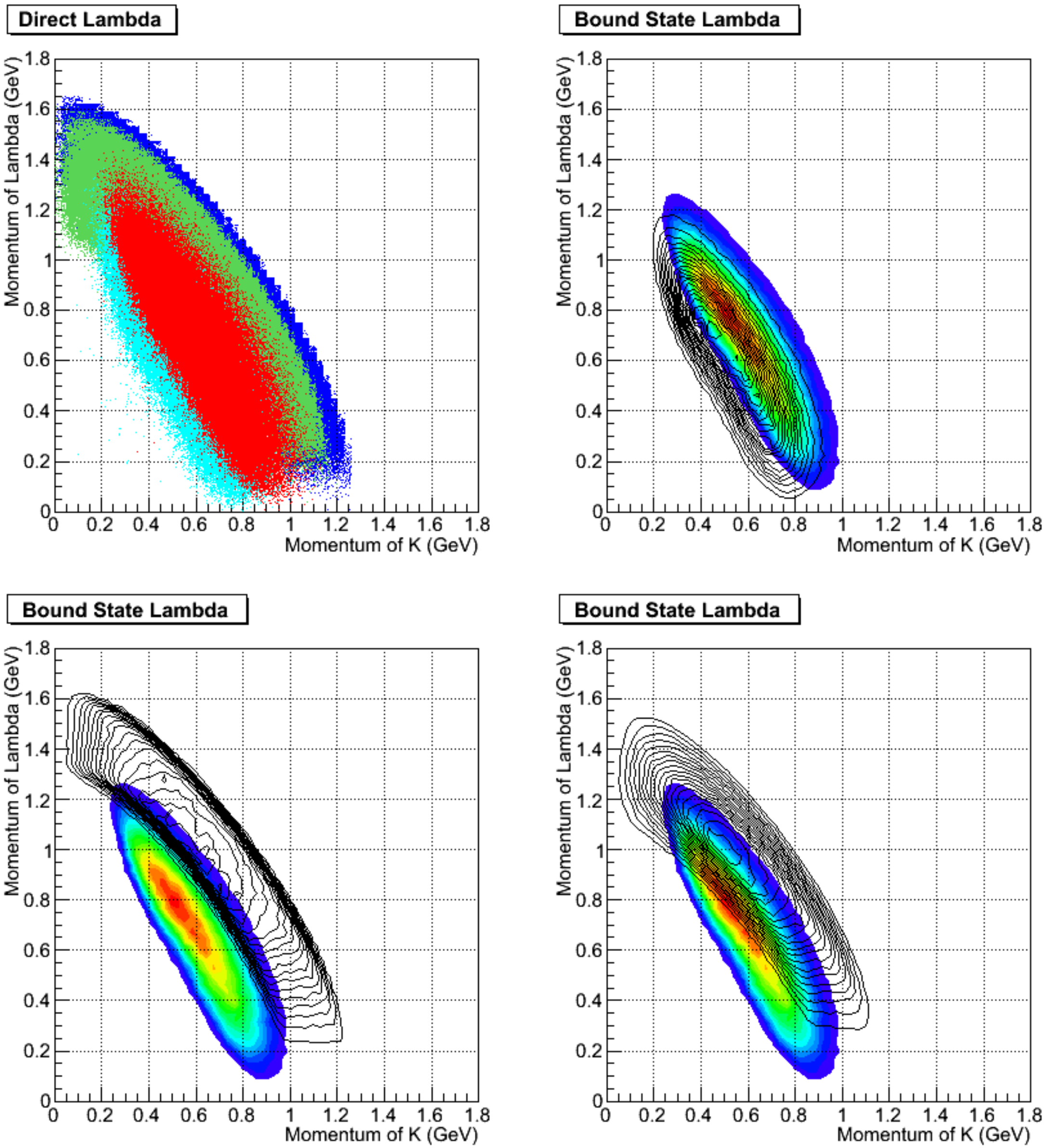
- ϕ-N bound state with 5 MeV width, separation possible by detecting the original recoiling proton and the decaying kaon and pion, **can not reconstruct the invariant mass of the bound state**
- Development of cuts needed to separate the signal from the background

(Poy Torngern, Duke undergraduate)





- ϕ-N bound state with 50 MeV width, separation possible by detecting the original recoiling proton and the decaying kaon and pion, can not reconstruct the invariant mass of the bound state
- Development of cuts needed to separate the signal from the background



Upper left panel:

Blue: direct Lambda

Green: direct Sigma

Red: bound Lambda decay

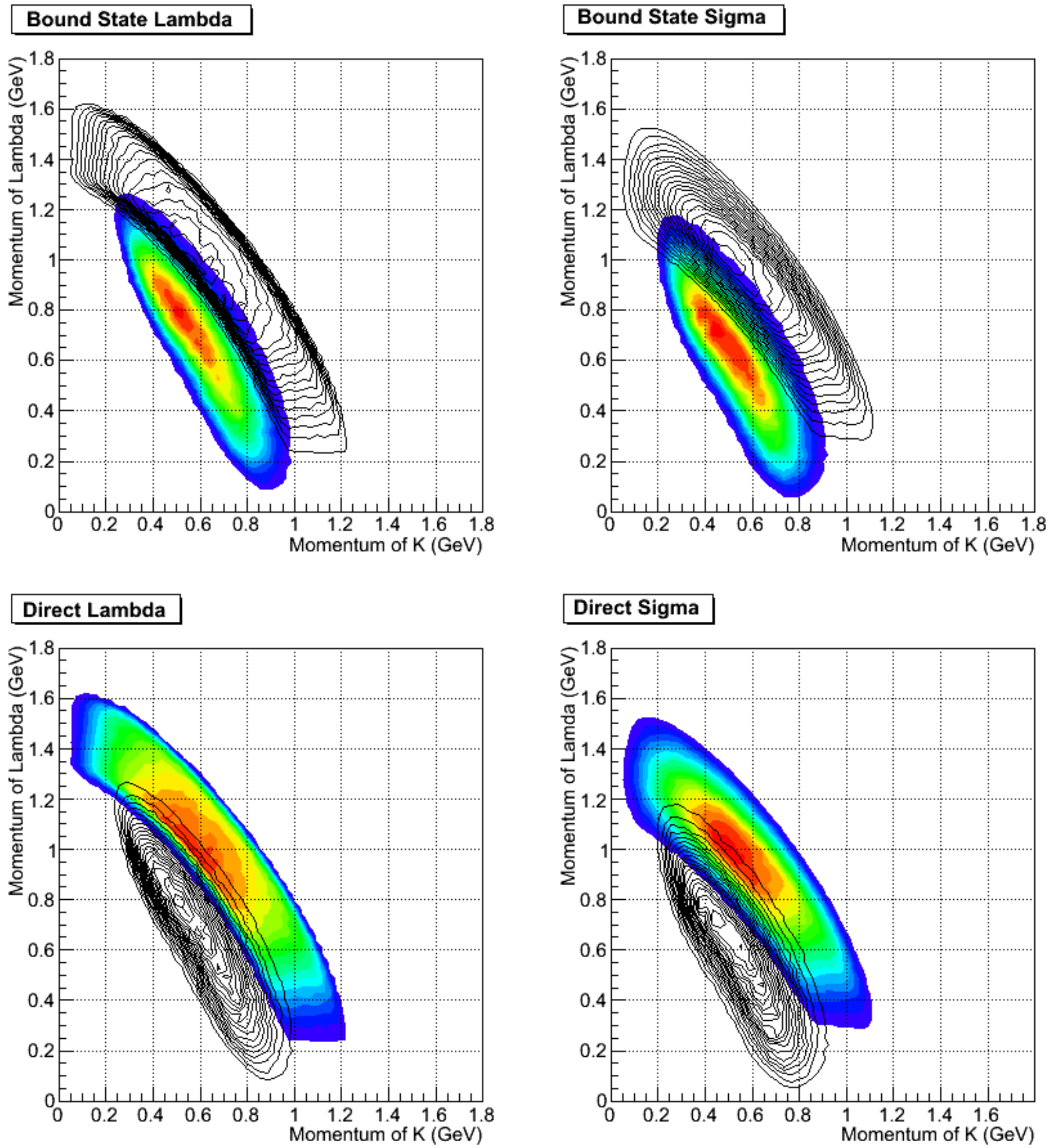
Light blue: bound Sigma decay

Lower panel:

Left black: direct Lambda

Right black: direct Sigma

color: bound Lambda decay



Upper panel:

Left black: direct Lambda

Right black: direct Sigma

color: bound sigma decay

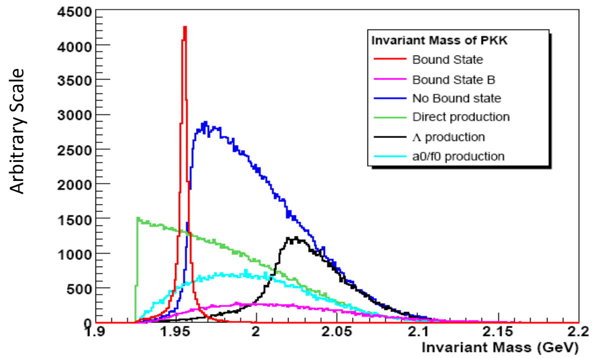
Lower panel: color code Switched

Sigma decay has better Separation, not able to Reconstruct the mass of The bound state

[Refer to A Letter-Of-Intent to Jefferson Lab PAC-33 by Y. Qiang et al.]

I. Triple Coincidence of K^+K^-N

$$\gamma\, p_1 p_2 \rightarrow \phi\, p_1' p_2 \rightarrow (\phi\, p_2)\, p_1' \rightarrow K^+ K^- p_1' p_2'$$



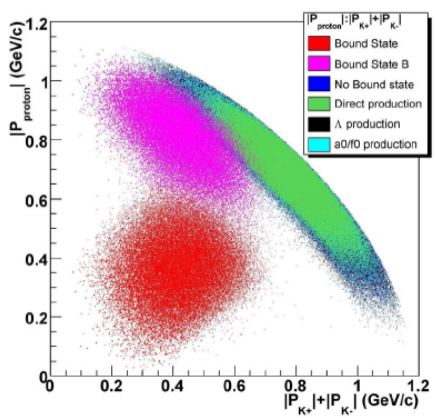
Easier experimental configuration: ϕ-N → ϕp

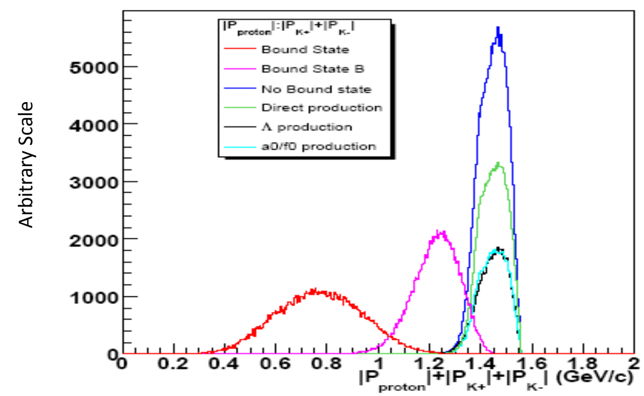
Need a clear separation of bound state (red) channel from the backgrounds

Identification of the ϕ-N bound state from other background channels was achieved by investigating their kinematics correlations through a phase space simulation.

[S. Liska et al, Phys. Rev. C75, 058201 (2007)]

$$\left|\vec{P}_{proton}\right| + \left|\vec{P}_{K^+}\right| + \left|\vec{P}_{K^-}\right|$$



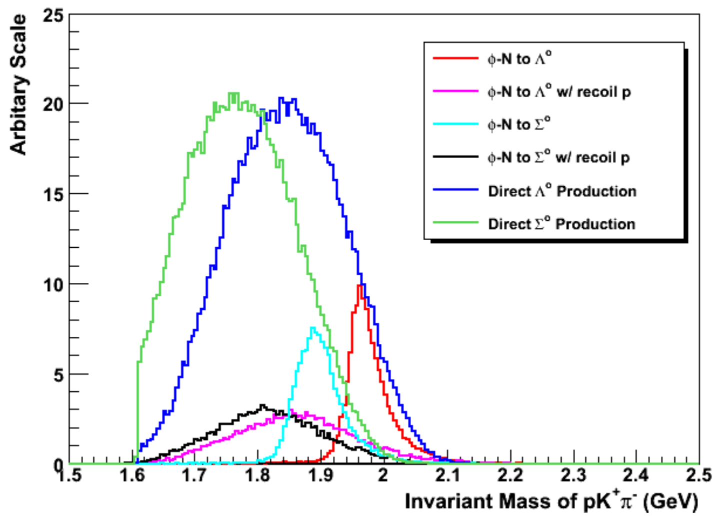


2D Momentum Separation between proton and the kaon system

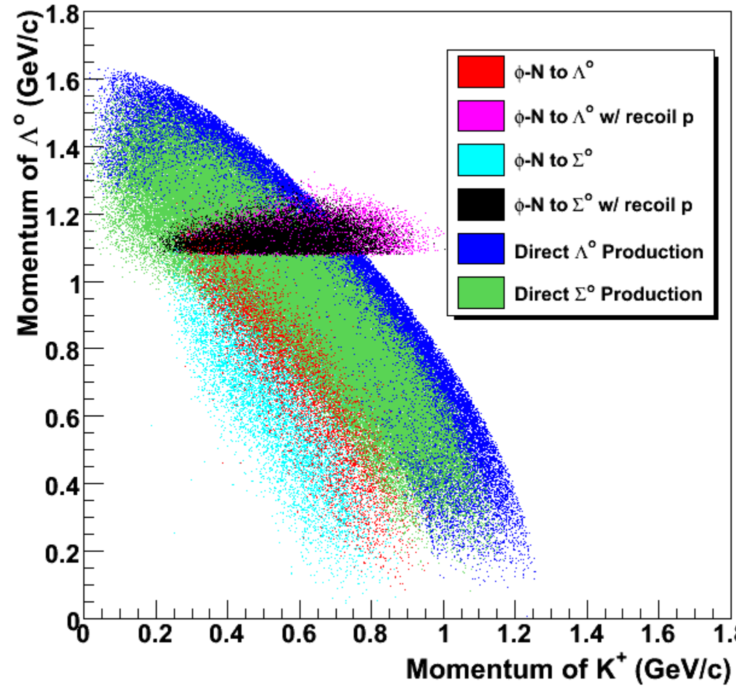
II. KΛ and KΣ decay

$$\phi p \to \Lambda(1116)K^{+} \to p'\pi^{-}K^{+}$$

$$\phi p \to \Sigma^{0}(1193)K^{+} \to \Lambda\gamma K^{+} \to p'\pi^{-}\gamma K^{+}$$



Desired bound states are ϕ-N to Λ^0 (red) and ϕ-N to Σ^0 (blue)



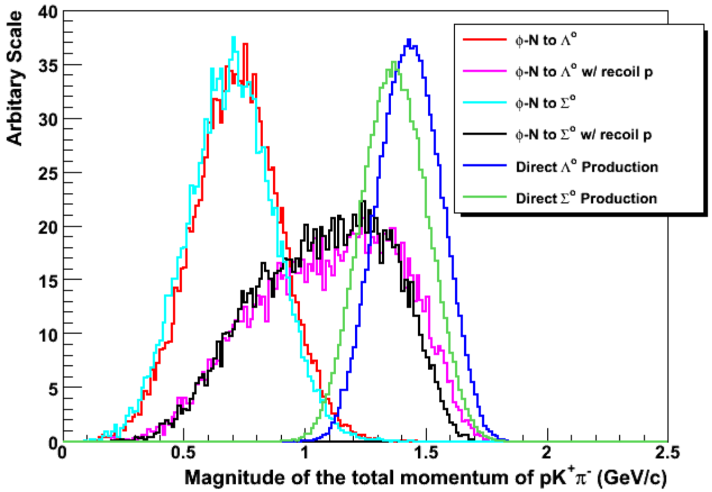
Best momentum separation suggests possibility of identifying bound state channels (red and blue)

Any kinematic relationship to identify such bound state channels?

Absolute sum of momentum

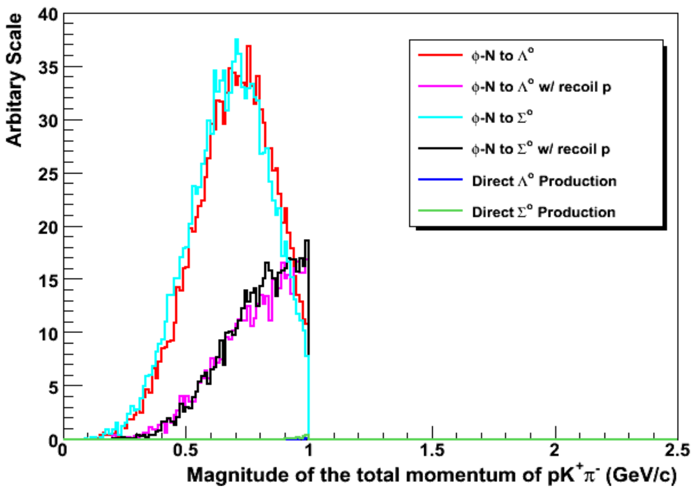
$$\left|\vec{P}_p + \vec{P}_{K^+} + \vec{P}_{\pi^-}\right|$$

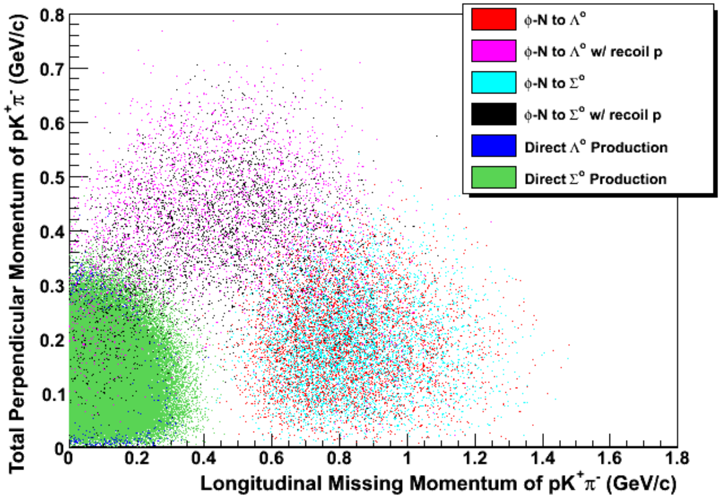
0.5% resolution



Apply a cut

$$\left|\vec{P}_p + \vec{P}_{K^+} + \vec{P}_{\pi^-}\right| < 1 \quad \text{GeV/c}$$





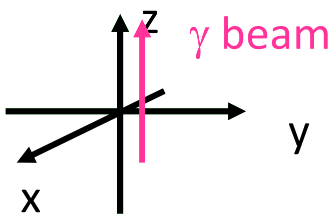
Longitudinal Missing Momentum

$$E_\gamma - \left(|\vec{P}_{p_z}| + |\vec{P}_{K_z^+}| + |\vec{P}_{\pi_z^-}| \right)$$

vs

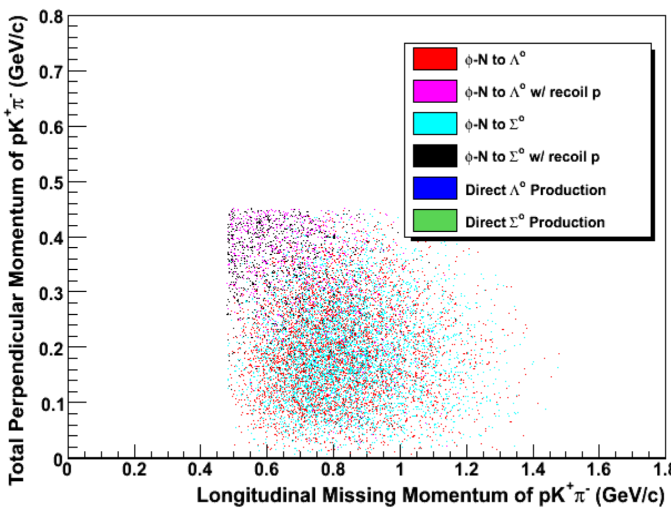
Total perpendicular momentum

$$\left| (\vec{P}_p + \vec{P}_{K^+} + \vec{P}_{\pi^-})_\perp \right|$$



Coordinate system

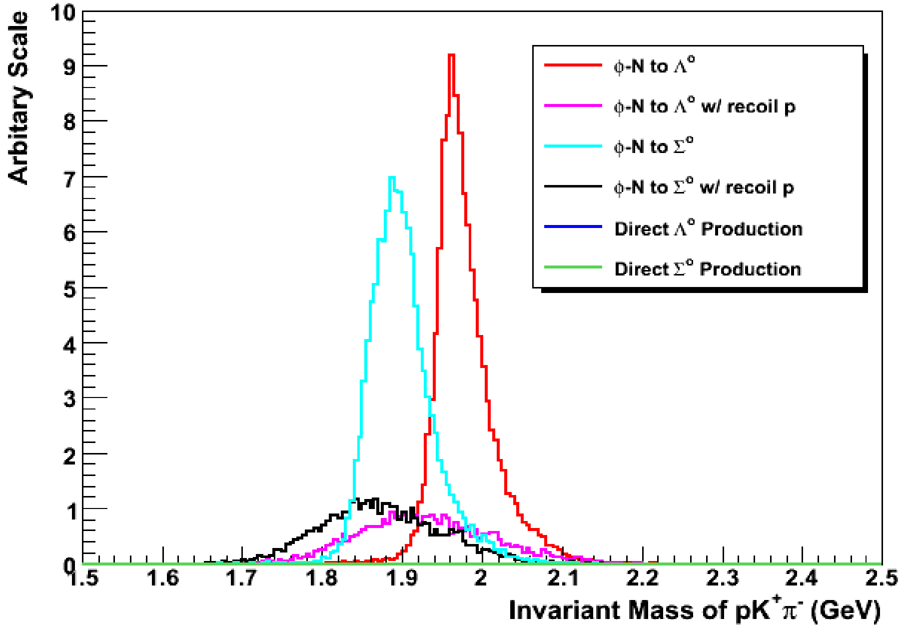
Apply a cut



$$E_\gamma - \left(|\vec{P}_{p_z}| + |\vec{P}_{K_z^+}| + |\vec{P}_{\pi_z^-}| \right) > 0.48$$ GeV/c

and

$$\left| (\vec{P}_p + \vec{P}_{K^+} + \vec{P}_{\pi^-})_\perp \right| < 0.45$$ GeV/c



Identification of the ϕ-N bound state channels in KΛ and KΣ decay was achieved by applying three cuts. The first cut is to remove all events of absolute sum of the final product's momenta that is greater than 1 GeV/c. The second cut is accepting all events of longitudinal missing momentum of the final product that is greater than 0.48 GeV/c. The last cut is eliminating all events of total perpendicular momentum that is greater than 0.45 GeV/c. The final result, in the invariant mass distribution, demonstrates a clear separation of the bound state as shown.

Experimental strategy

- Detect all three charged particle final states with two positively charged particles and one negative charged particle including proton, kaons and pions
- More simulations including cross sections necessary
- Particle identification and large acceptance are crucial for the search

Proposal: LOI-08-004
Title: First Search for ϕ-N Bound State
Spokespersons: Yi Qiang, Haiyan Gao

PAC Comments

Recent observations of similar charmed molecular states at electron-positron colliders indicate that ***this may be a very interesting experiment***. It has long been thought that the scalar mesons, a0, f0(980), may well be molecular in nature with hidden strangeness. ***Clear observations in recent years of several possibly molecular states with hidden charm have strengthened this idea.***
It is then natural to study whether baryons with such hidden strangeness exist and serve to motivate this proposal.

However, one possible concern is the ***effect of the interaction of such a molecular state with other nucleons in a nucleus.***
It would be very useful if the theory could be further developed before a submission of a full proposal to a future PAC.

Theoretical issues and help needed

- Final state interaction of the bound state with other nucleons inside the nucleus (PAC comment)
- Theoretical investigation of the width and the decay branching ratio of the bound state
- More theoretical study of the production cross-section
- Can one observe such a state on the lattice (private communications with K.F. Liu)?

Summary

- The search of ϕ-N bound state (QCD molecular state) is important and exciting
- ϕ-N bound state predicted to have moderate cross section in sub-threshold ϕ photo-production
- Potential decay channels of KK, KLambda, and KSigma investigated, promising for identifying the bound state
- Jefferson Lab Hall B - a good place to carry out the search
  - Our study on the BoNuS RTPC has been done
  - Study on CLAS detector is still underway
- CLAS12 will be better

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