Search for a ϕ–N Bound State from ϕ Production in a Nuclear Medium (PR12-19-004)

2019/07/29

JLab PAC 47

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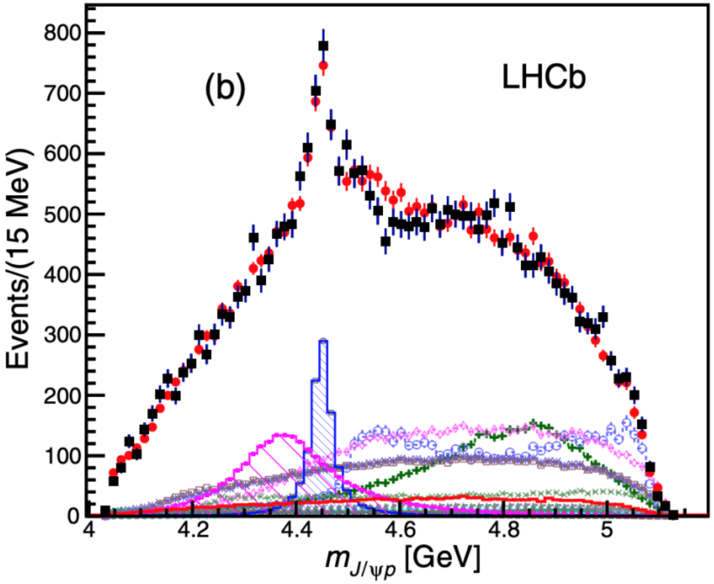
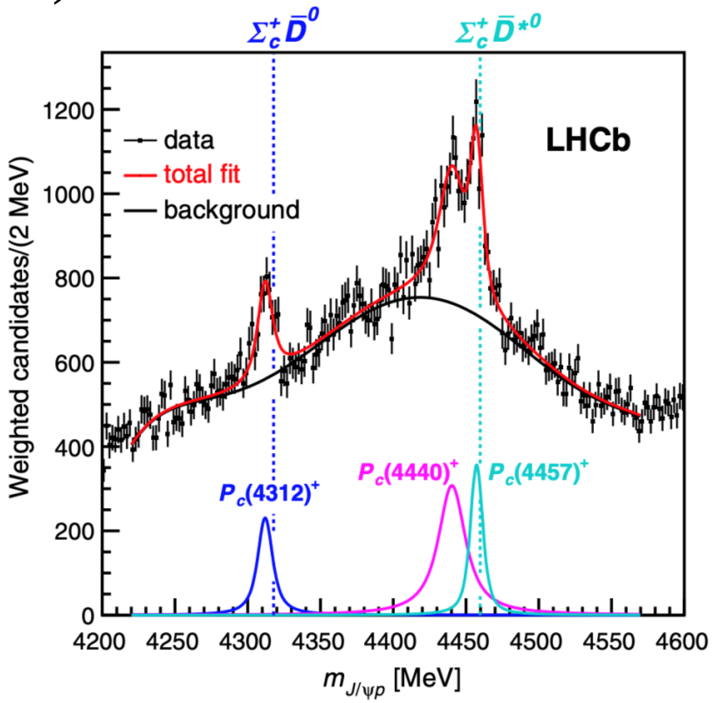
CLAS Collaboration

Introduction

- While most observed hadrons can be interpreted as three-quark (baryon) and quark-antiquark (meson) states, QCD does not prevent the existence of multiquark states.
- In 2015, LHCb reported hidden charm pentaquark candidates: $P_c(4450)^+$, $P_c(4380)^+$.
- New results from LHCb in 2019:
  - $P_c(4450)^+ \Longrightarrow P_c(4440)^+$ and $P_c(4457)^+$.
  - New resonance $P_c(4312)^+$.



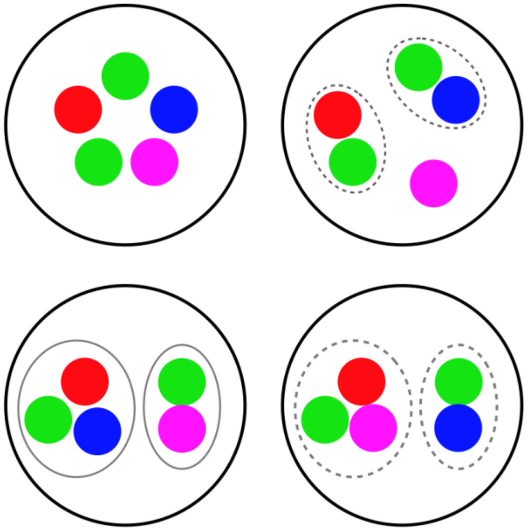
LHCb, PRL 115, 072001 (2015).



LHCb, PRL 122, 222001 (2019).

Introduction

- What are pentaquarks?
  - Tightly bound five quarks
  - Diquark-diquark-antiquark
  - Molecular state
  - Colored "baryon" and "meson"



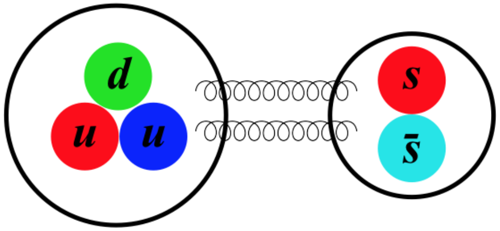
The study of multiquark states is a new approach to understand the dynamics of the strong interaction at the hadronic scale.

- Almost all observed multiquark candidates contain heavy quark constituent.

The experimental search for lighter pentaquark state, e.g., hidden strangeness pentaquark, is of unique importance to understand flavor dependent properties of the strong interaction.

ϕ-N Bound State

- QCD van der Waals force is expected to dominate the interaction between two hadrons when they have no common quarks.
  Brodsky, Schmidt, de Téramond, PRL 64, 1011 (1990).



- The force is enhanced at low relative velocities.
  Luke, Manohar, Savage, PLB 288, 355 (1992).

- *A ϕ-nucleon bound state is possible, if such attractive force is strong enough.*

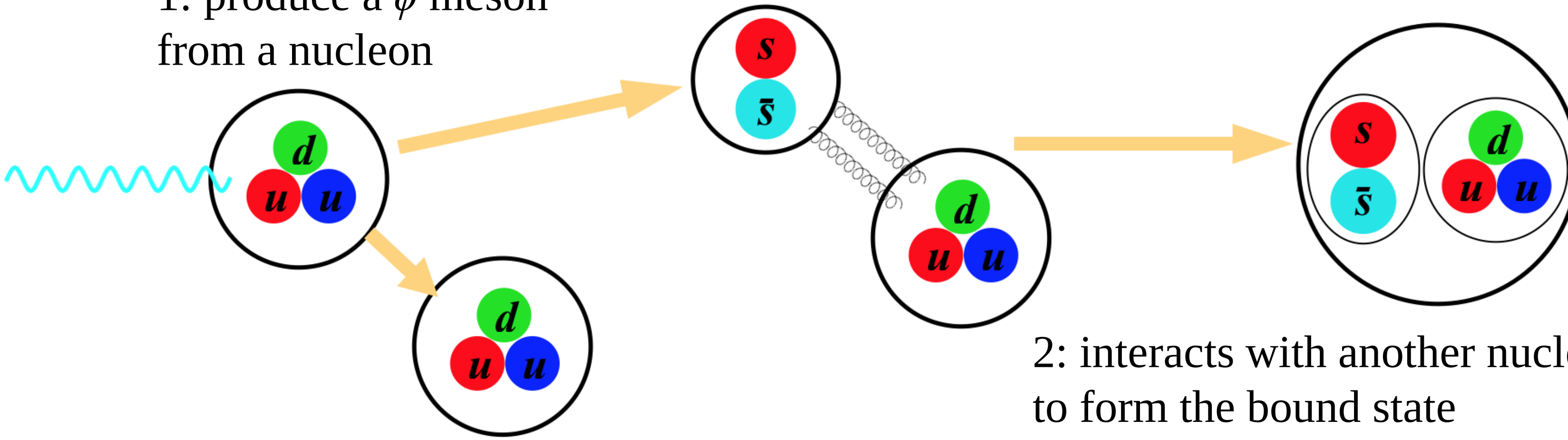
Theoretical predictions

- QCD van der Waals force, H. Gao *et al.*, PRC 63 022201 (2001).
- Chiral quark model, F. Huang *et al.*, PRC 73 025207 (2006).
- Lattice QCD, S.R. Beane *et al.*, PRD 91 114503 (2015).
- Quark delocalization color screen model, H. Gao et al., PRC 95 055202 (2017).
- Bethe-Salpeter equation, J. He *et al.*, PRD 98 094019 (2018).

ϕ-N Bound State Production

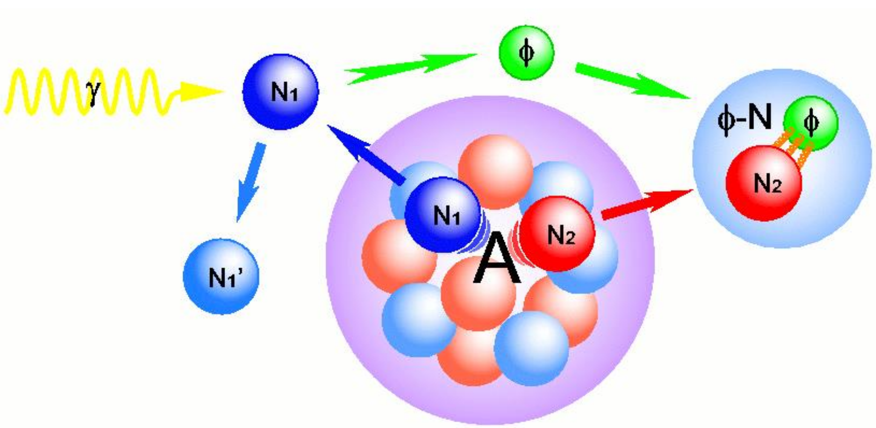
- A two-step production mechanism.

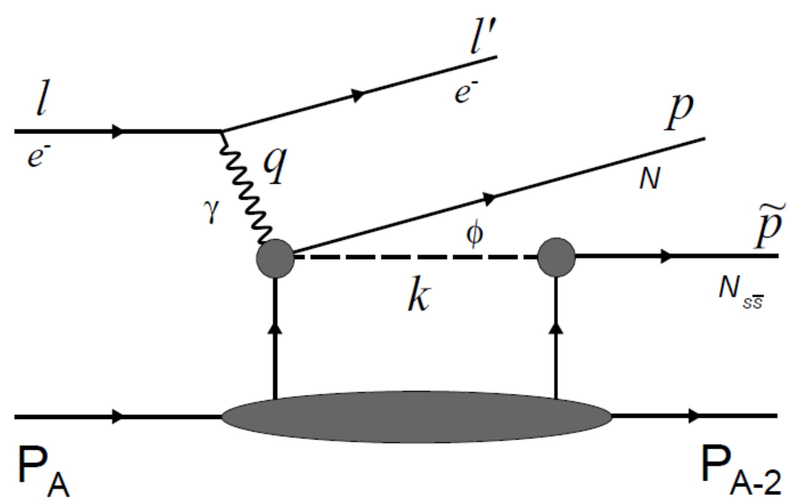
1: produce a ϕ meson from a nucleon



2: interacts with another nucleon to form the bound state

- sub- or near-threshold ϕ production from heavy nuclear target is preferred.



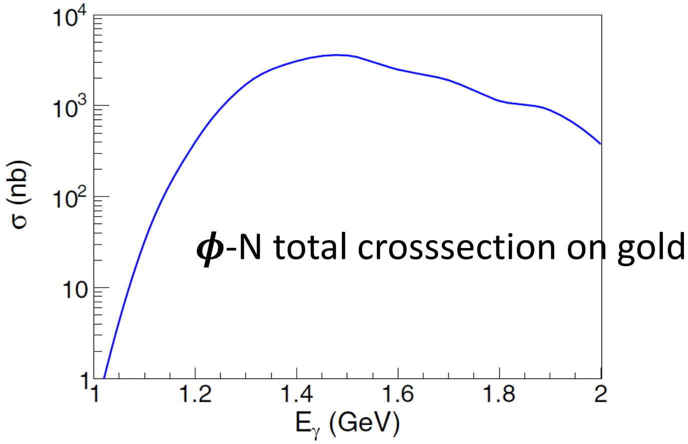


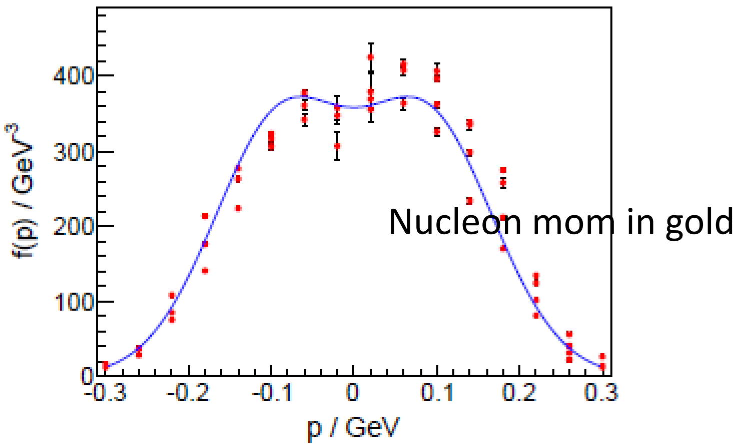
ϕ-N Bound State Production

H. Gao *et al.*, PRC 95 055202 (2017)

model prediction
ϕ-N (mass 1950 MeV, width 4 MeV)

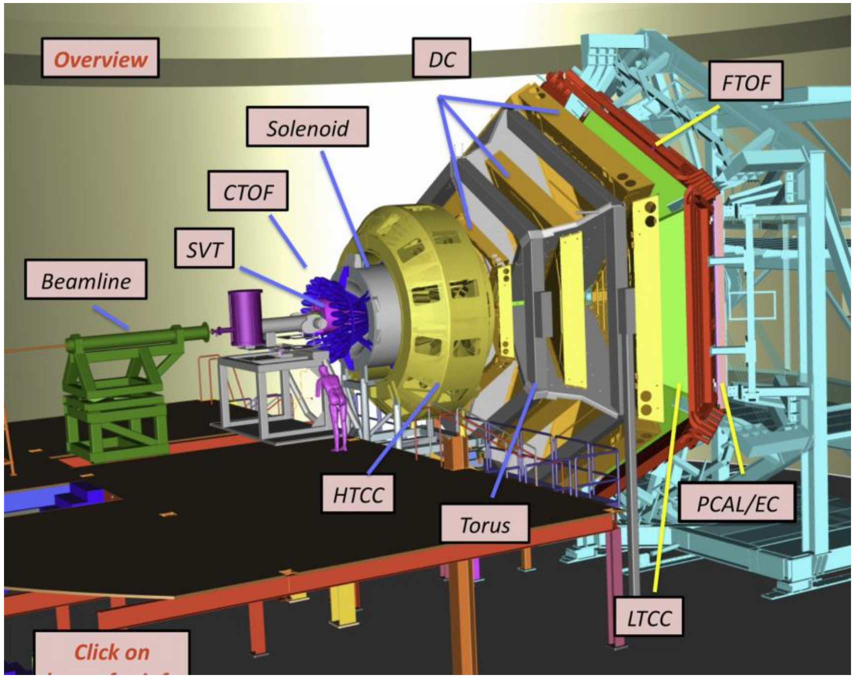
- Production with gold (Z=79 and A=197)
  - Sub-threshold and near-threshold production of ϕ from a proton or a neutron in gold nucleus
  - Then ϕ interacts with a nearby proton to form ϕ-p
  - ϕ-p can be reconstructed from its low momentum decay particles pK^+K^-

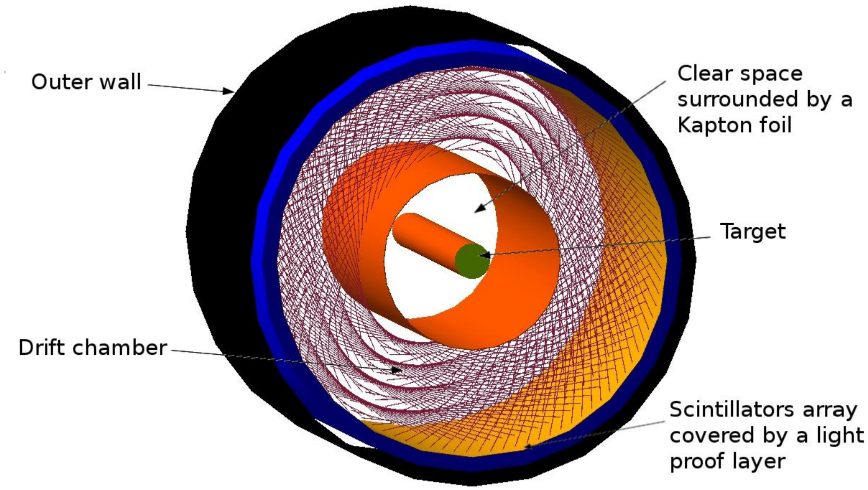




Note: the experimental detection does not rely on the particular production mechanism, while the rate estimation is based on this model calculation. The QCD van der Waals model has similar result.

CLAS12+ALERT





CLAS12 Forward Detector

- Detect charged particles from 5° to 35°

CLAS12 Forward Tagger

- Detect scattered electrons from 2.5° to 4.5°

ALERT

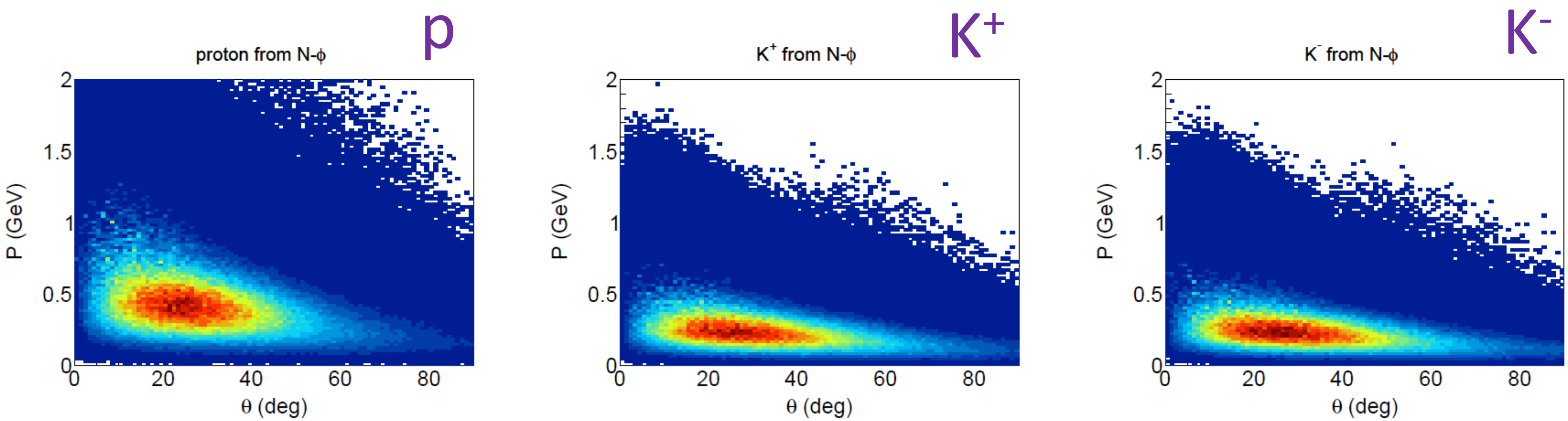
- Detect low momentum charged particles
- Inside 5T solenoid
- 30cm in length, ~12cm in radius
- Drift chamber for tracking and scintillator for TOF PID

Ideal for low momentum multiple particles final state detection

Generating ϕ-N Events

$$eAu \to e'N[\phi p]X \to e'NpK^+K^-X$$

- 4.4GeV 42nA electron beam on 0.1mm gold target (z=-15cm)
- Quasi-real photoproduction with scattered electrons (2.5-4.5deg, 1-4GeV)

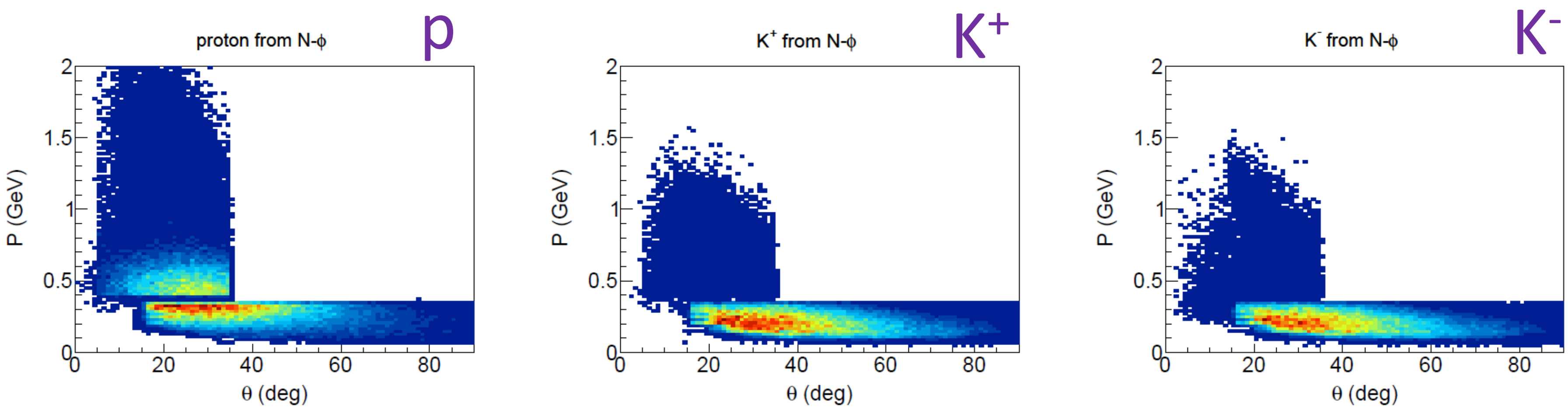


- Scattered electrons can be detected by Forward Tagger
- Crucial to detect triple coincidence of low mom pK^+K^- (100-800MeV) at forward angle
- Invariant mass of ϕ-N can be reconstructed

ϕ-N Detection with CLAS12+ALERT

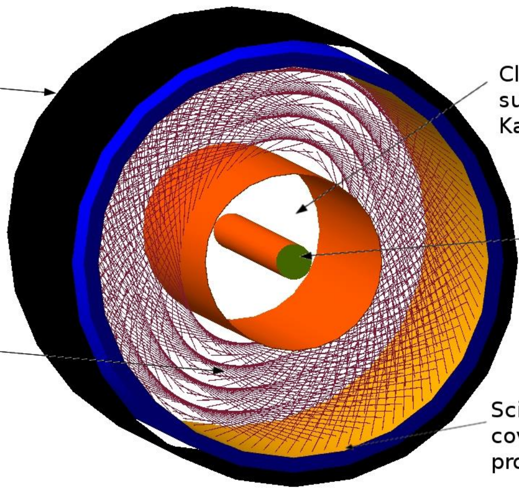
$$eAu \rightarrow e'N[\phi p]X \rightarrow e'NpK^+K^-X$$

- CLAS12 + ALERT acceptance and resolution applied to generated signal events



- pK^+K^- detected by ALERT (mostly) and by CLAS12 Forward Detector
- Majority of the production phase space is covered
- Detection is not dependent on any particular model

ALERT Detector



ALERT (E12-17-012) approved
- Detect protons and light ions
- 30cm long D2 and He4 gas target
- Prototyping ongoing
- Experimental Readiness Review scheduled in Fall 2019

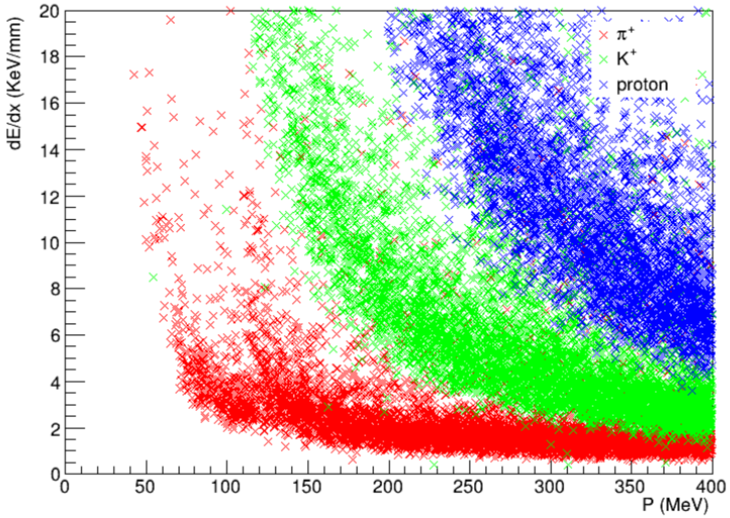
ALERT changes for this proposal:
1. Replace He4 with Ar in DC gas for better kaon detections
2. Replace gas target with 0.1mm gold foil at upstream entrance
3. Coincidence trigger with Forward Tagger

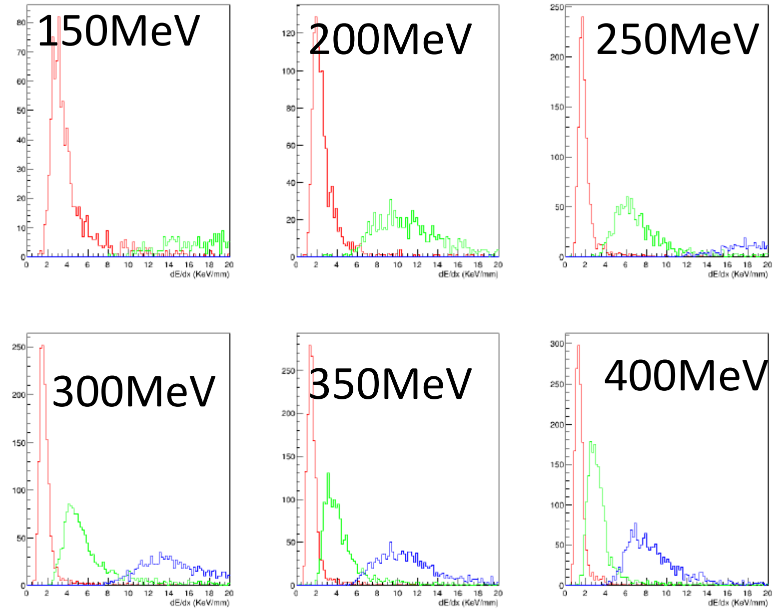
Need new beam time

ALERT DC

For P<350MeV, good separation between proton, kaon, pion

dE/dx VS P in DC gas





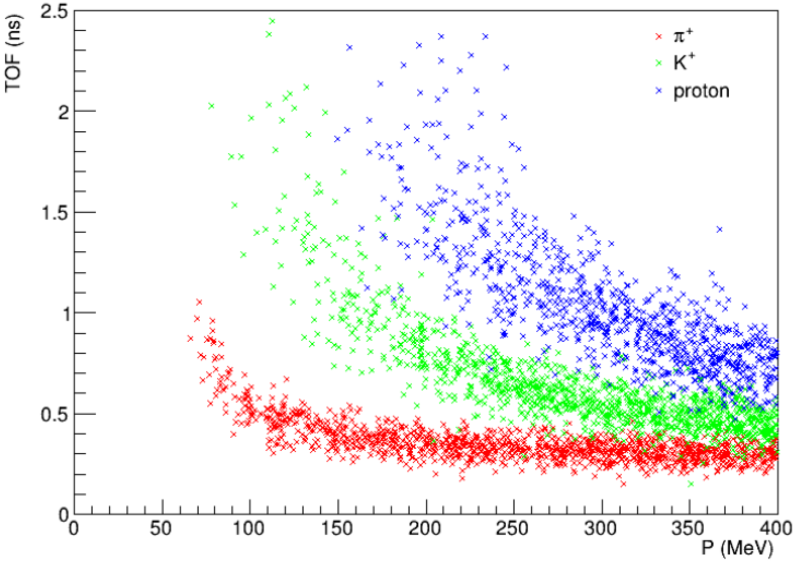
Projection in 100-400 MeV with 50MeV bin

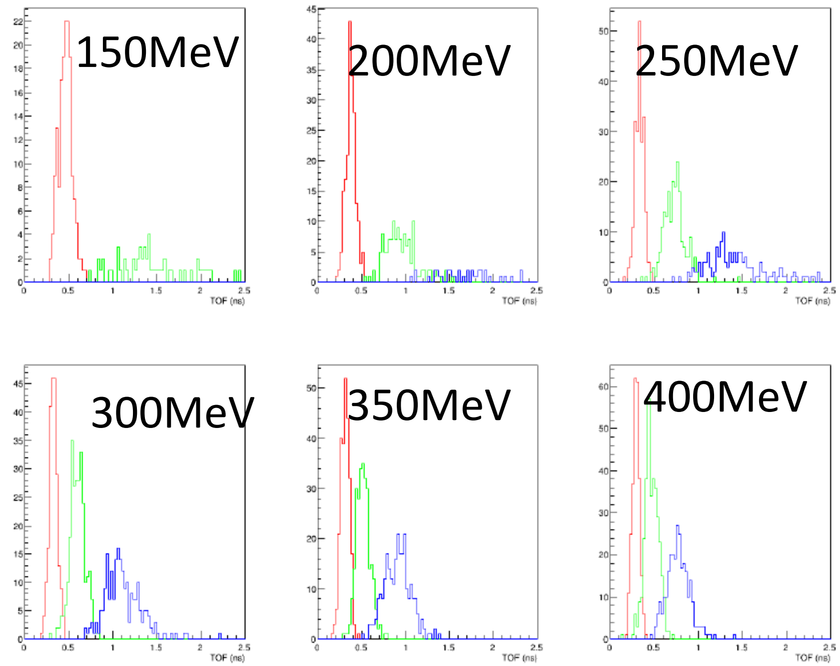
- Using Ar instead of He4 in DC gas
- The same numbers of all particle species are evenly distributed

ALERT TOF PID

For P<350MeV, proton and kaon efficiency >90% and pion rejection > 50

TOF with scintillators



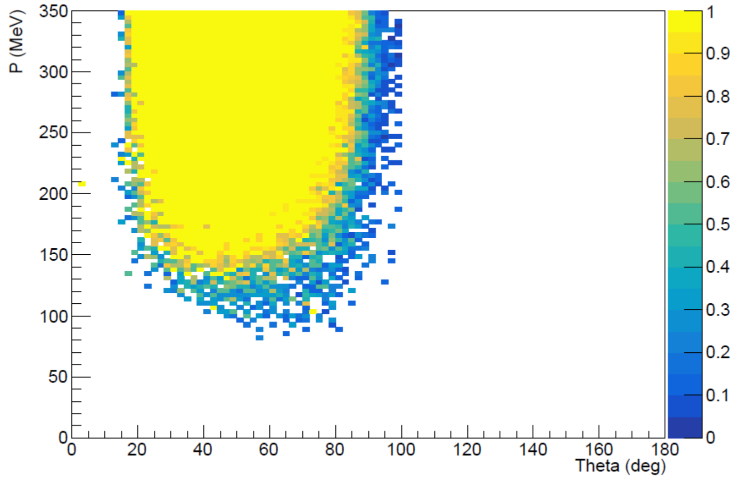


Projection in 100-400 MeV with 50MeV bin

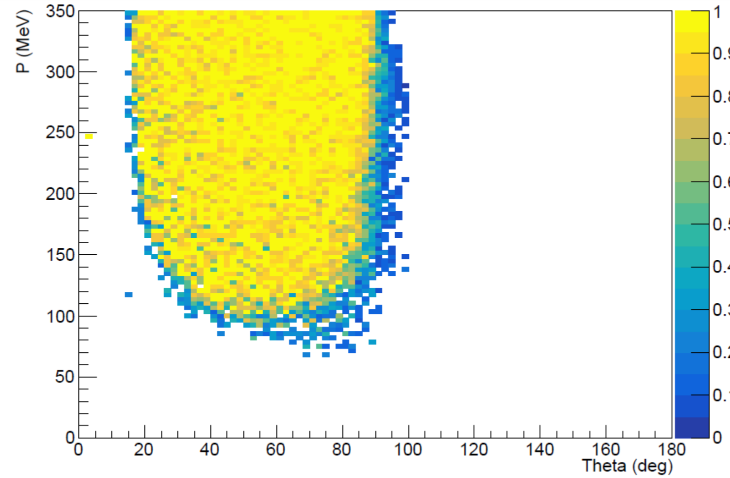
- Assume 150ps scintillator time resolution which could to improved to 50ps
- Plots show polar angle 75°-85° with shortest path length for worst case TOF PID
- The same numbers of all particle species are evenly distributed

ALERT Acceptance and Resolution

Acceptance: mom (130-350MeV for proton, 100-350MeV for kaon), polar angle (20^o-90^o), azimuthal (340^o)

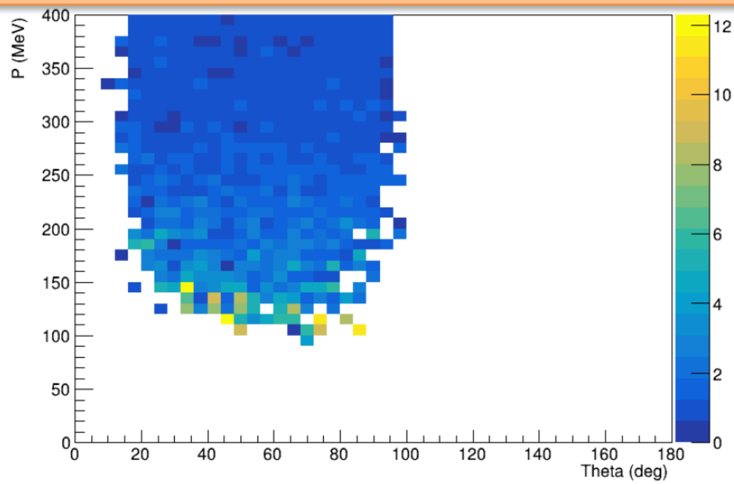


(a) Proton acceptance

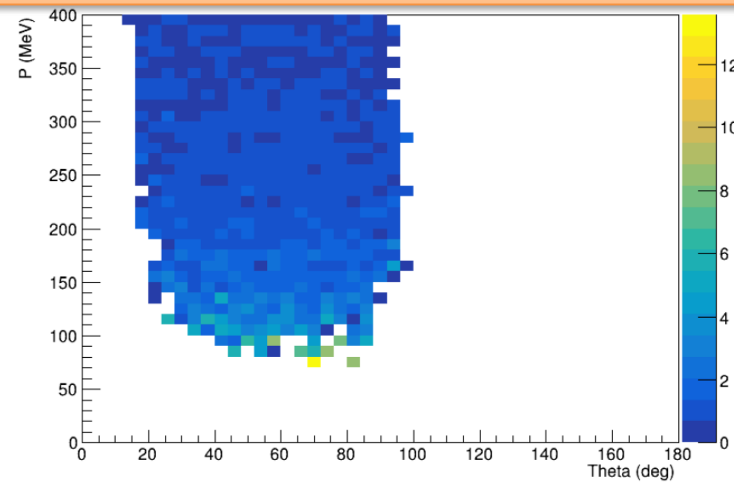


(b) K^+ acceptance

Resolution: mom ~2%, polar angle ~20mrad, azimuthal angle ~20mrad



(a) Proton momentum resolution in percentage



(b) K^+ momentum resolution in percentage

Background Simulation

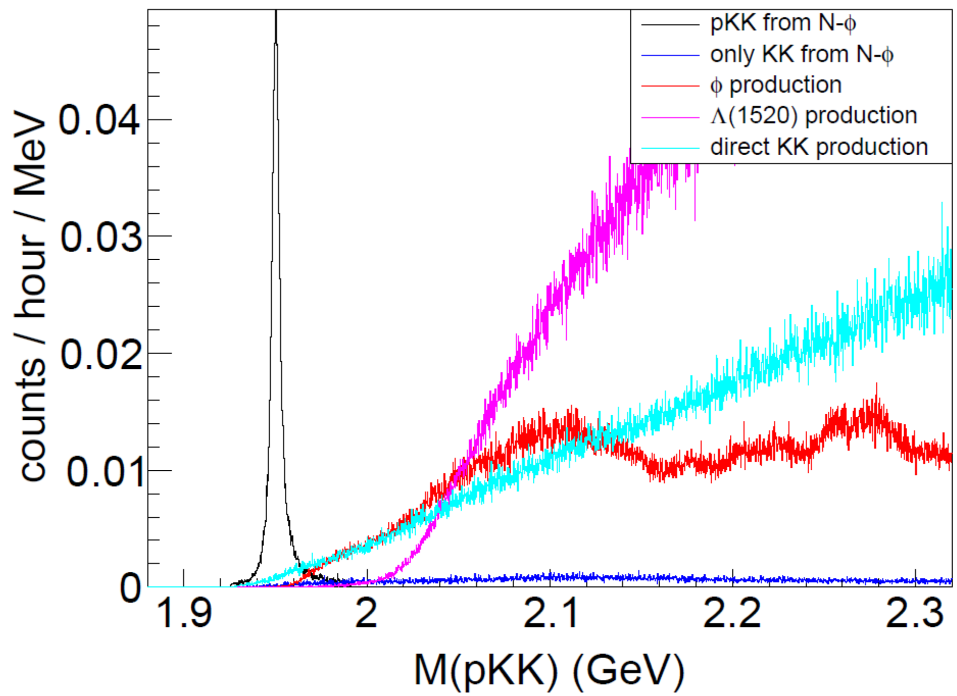
- Four background channels with the same final state
  - ϕ-N bound state production with ϕ production proton detected instead of the decay proton
  - ϕ production with no bound state:
    $$\gamma + p_1 \rightarrow p_1' + \phi \rightarrow p_1' + K^+ + K^-$$
  - Λ(1520) production:
    $$\gamma + p_1 \rightarrow \Lambda(1520) + K^+ \rightarrow p_1' + K^- + K^+$$
  - Direct double kaon production:
    $$\gamma + p_1 \rightarrow p_1' + K^+ + K^-$$

detected proton from those channels (correlated)
detected proton from spectators (uncorrelated)

- One background channel with misidentification
  - double pion production with pions misidentified as kaons
    - including direct double pion and resonance production
    - generator TWOPEG "CLAS12 Note 2017-001"

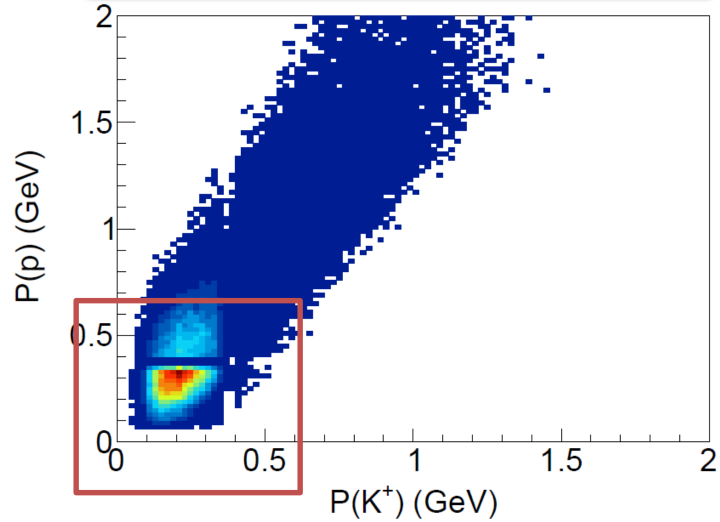
Background Suppression

- Signal and background channels are well separated in kinematic space
- We can apply cuts to suppress background

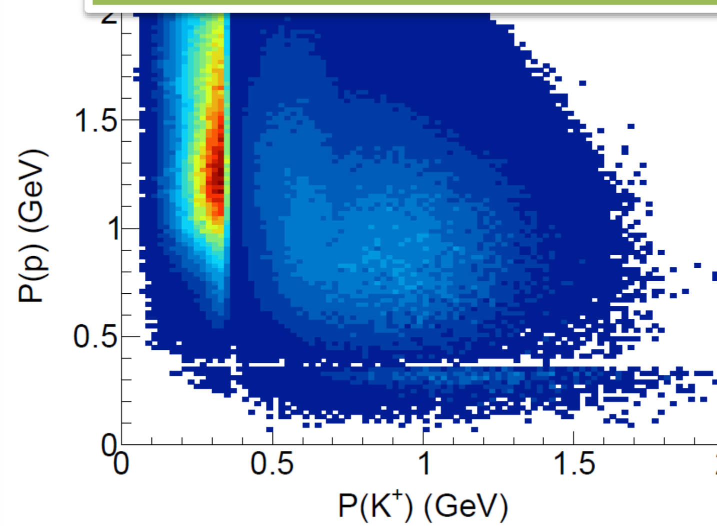


pK^+K^- invarains mass
of detected signal channel and four correlated background channels with same final state

ϕ production with bound state

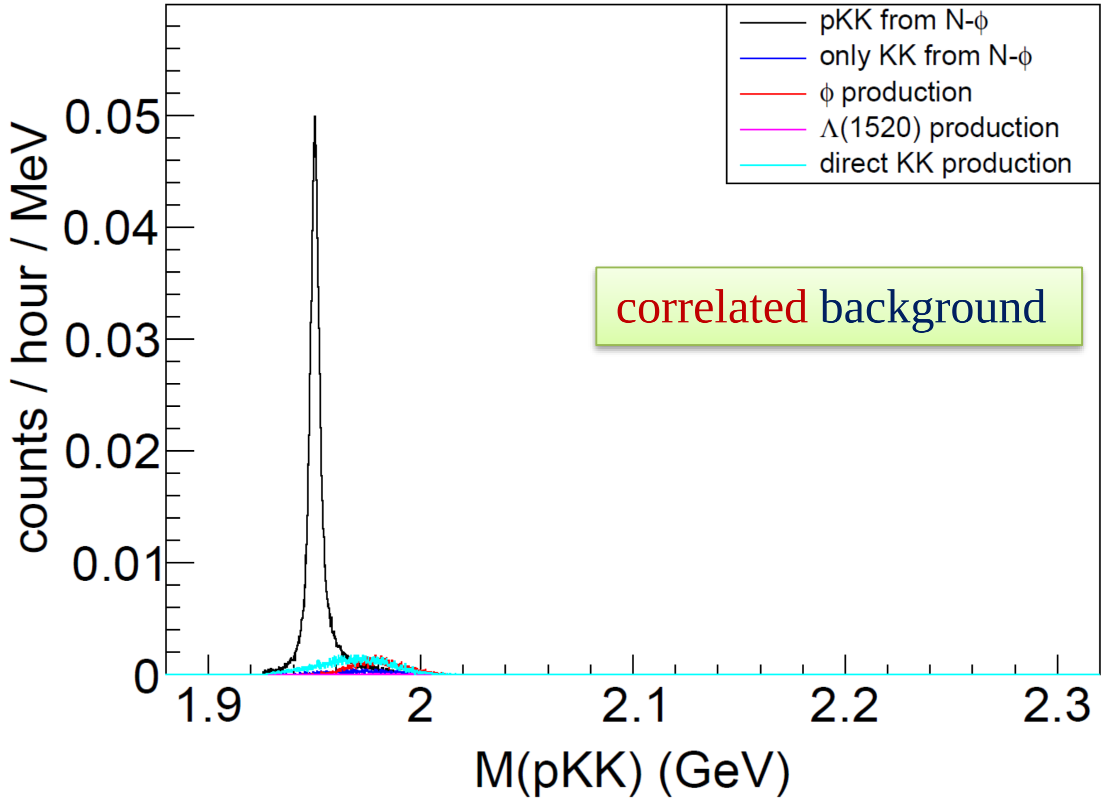


ϕ production without bound state



Invariant Mass of ϕ-N

ϕ-N signal is well separated from correlated background channels after kinematic cuts



Kinematic cuts:

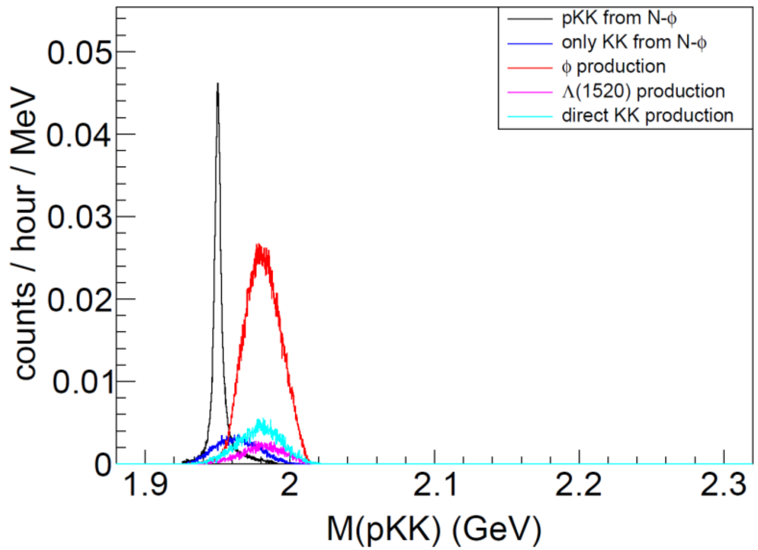
$$P(p) < 0.8 \text{ GeV}, \; P(K^{\pm}) < 0.5 \text{ GeV}$$

$$M(pK^{\pm}) < 1.48 \text{ GeV}, \text{ and } M(K^{+}K^{-}) < 1.04 \text{ GeV}.$$

Invariant Mass of ϕ-N

Other background channels are under control and could be improved with better timing

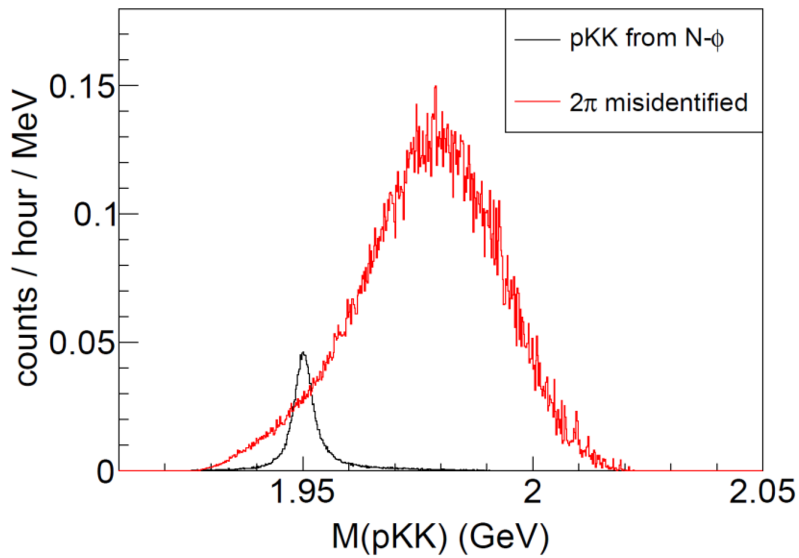
uncorrelated background



additional cut:

proton polar angle < 60°

double pion misidentified background



Single pion rejection factor 50

Projection and Beam Time Request

- 4.4 GeV 42 nA beam on 0.1mm gold foil target with nucleon luminosity 3e34/cm2/s (same as ALERT experiment)
- CLAS12+ALERT with 0.7 overall detection efficiency
- Apply all kinematic cuts
- Select 3σ of pK^+K^- invariant mass range from 1940MeV to 1960MeV
- Rate estimation
  - signal pK^+K^- from ϕ-p, 0.2/h
  - correlated background, negligible
  - uncorrelated background, 0.07/h (could be improved)
  - two pion misidentified background, 0.43/h (could be improved)
- 40 PAC days of data taking will provide 7.4σ detection

Beam time request: 45 days of beam time
40 days for production
5 days for commissioning

Summary

- This proposal will search for a ϕ−N bound state from ϕ production in a nuclear medium by using CLAS12 + ALERT detectors
- We need to use ALERT with different DC gas, gold foil target and coincidence trigger
- It could lead to a new direction of QCD study in the strangeness sector
- We request 45 days of beam time

A CLAS Collaboration Proposal to PAC47

Search for a $\phi - N$ Bound State from ϕ Production in a Nuclear Medium

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backup

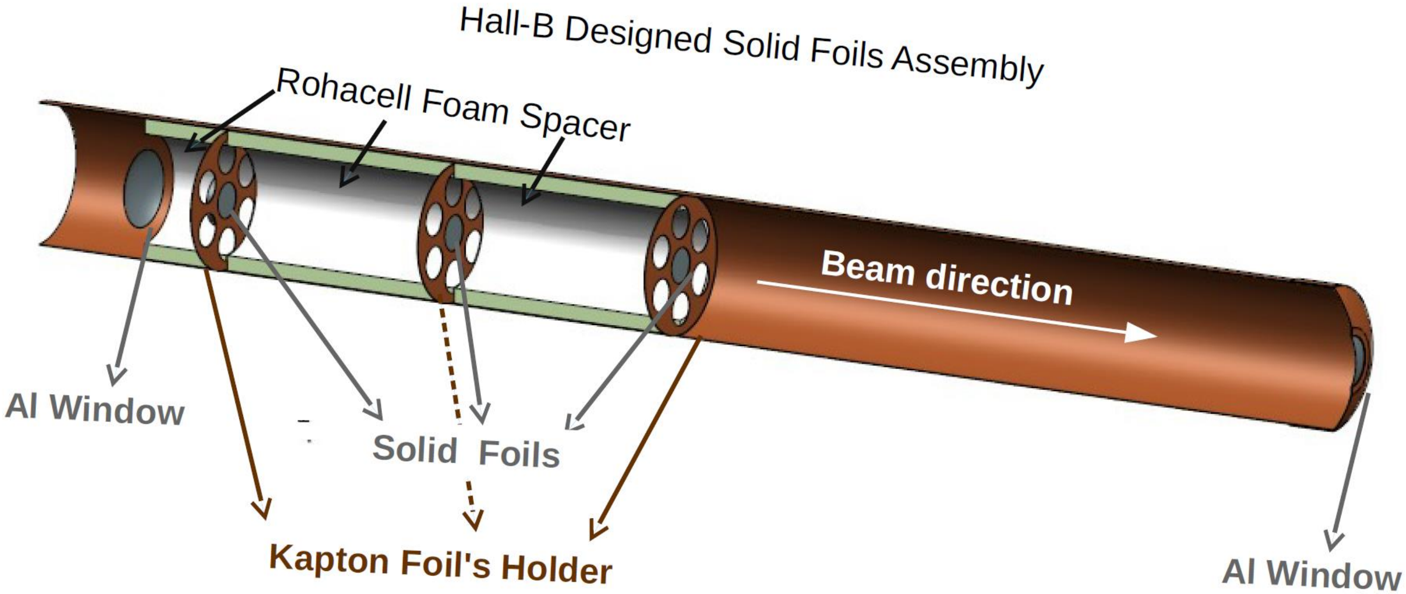
ALERT experiment

background rejection, while keeping the material budget as low as possible for low energy particle detection. ALERT will be installed inside the solenoid magnet instead of the CLAS12 Silicon Vertex Tracker and Micromegas tracker. We will use an 11 GeV longitudinally polarized electron beam (80% polarization) of up to 1000 nA on a gas target straw filled with deuterium or ^{4}He at 3 atm to obtain a luminosity up to 6×10^{34} nucleon cm^{-2}s^{-1}. In addition we will need to run hydrogen and ^{4}He targets at different beam energies for detector calibration. The following table summarizes our beam time request:

Configurations	**Proposals**	**Targets**	**Beam time request** days	**Beam current** nA	**Luminosity*** n/cm^2/s
Commissioning	All†	^{1}H, ^{4}He	5	Various	Various
A	Nuclear GPDs	^{4}He	10	1000	6×10^{34}
B	Tagged EMC & DVCS	^{2}H	20	500	3×10^{34}
C	All†	^{4}He	20	500	3×10^{34}
TOTAL			**55**		

Running Conditions: Updated Target Configuration

- Alternating the liquid deuterium (LD2) target with a set of three solid targets 5 cm apart:
  - ✔ Design already exists,
  - ✔ 5 cm guarantees a good vertex separation,
  - ✔ Solid foils are glued to a kapton disk, then to a foam cylinder, and mounted inside a 20 mm diameter Kapton cell (similar to the liquid target cell),
  - ✔ The cell will be purged with cold helium to dissipate heat from the beam interaction.



trigger rate estimation

- CLAS12 run 3048 has 70 kHz FT single-cluster trigger rate with
  - 6.4 GeV electron beams
  - 15 nA on 5cm long liquid hydrogen target with 2e34/cm2/s lumi
  - FCAL > 0.5 GeV
  - Q2_min = 0.006GeV^2
- This proposal
  - 4.4 GeV electron beam
  - 42nA on 0.1mm gold foil target with 3e34/cm2/s
  - 4GeV>FCAL>1GeV
  - Q2_min=0.008GeV^2

- Estimation for this proposal
  - Assume FT single-cluster rate is proportional to virtual photon flux (E'/Q^{2}E)
  - This proposal could have FT single-cluster trigger rate

    70 * (0.006/0.008)*(1/4.4)/(0.5/6.4)*(3e34/2e34) = 238 kHz
  - To have random coincidence trigger rate below CLAS12 limit 12kHz, assume 50ns time window, ALERT and CLAS12 forward angle detector need to provide a trigger below

    12/50/238 = 1MHz

Petiroc2A in the Trigger

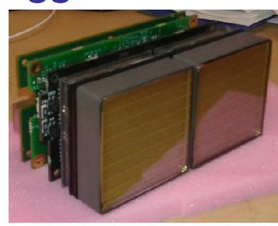
FPGA Readout board hasn't yet been used in the trigger, but supports it

- FPGA Readout to SSP optical link is bidirectional
  - SSP -> FPGA readout
    - 2.5Gbps
    - fixed latency clock, sync, & trigger
    - Register access commands
  - FPGA readout -> SSP
    - 2.5Gbps up to 6.25Gbps
    - 20% encoding overhead
    - 1Gbps for readout
    - 1Gbps for control
    - Up to 3Gbps for trigger

      Full 64bit channel pattern with 32ns timing resolution

      Timing can improved by grouping channels or by knowing dead-time due to shaping

34Gbps Optical link to CLAS12 Trigger Stage 2



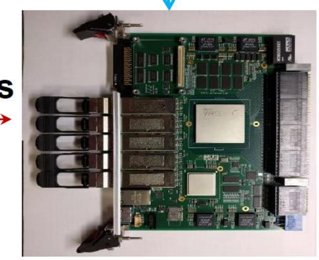
FPGA Readout (32 per SSP)

VXS Crate

SSP (up to 16)

20Gbps

x16



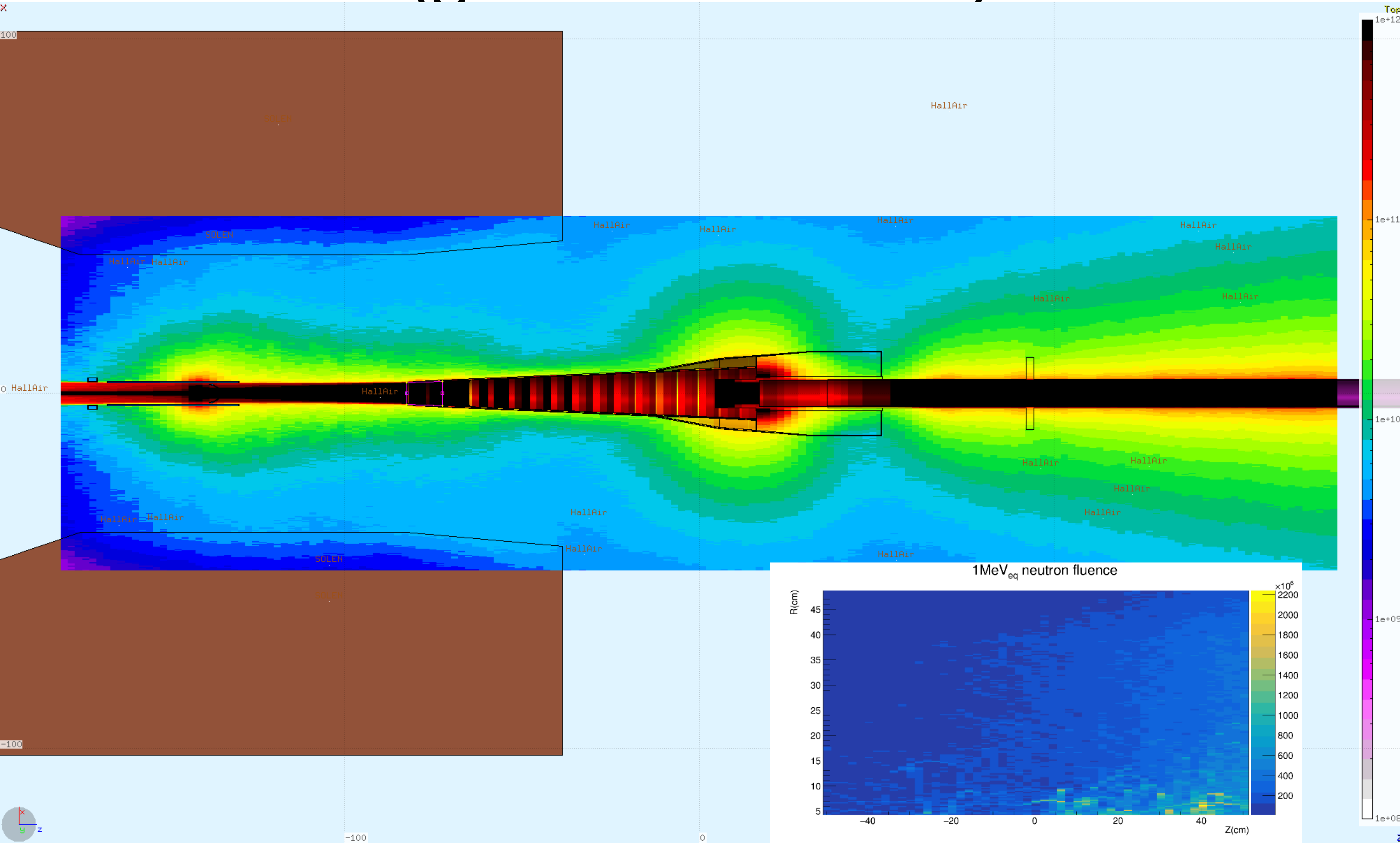
VTP

Trigger can be formed in SSP, VTP, or both using imformation from many channels

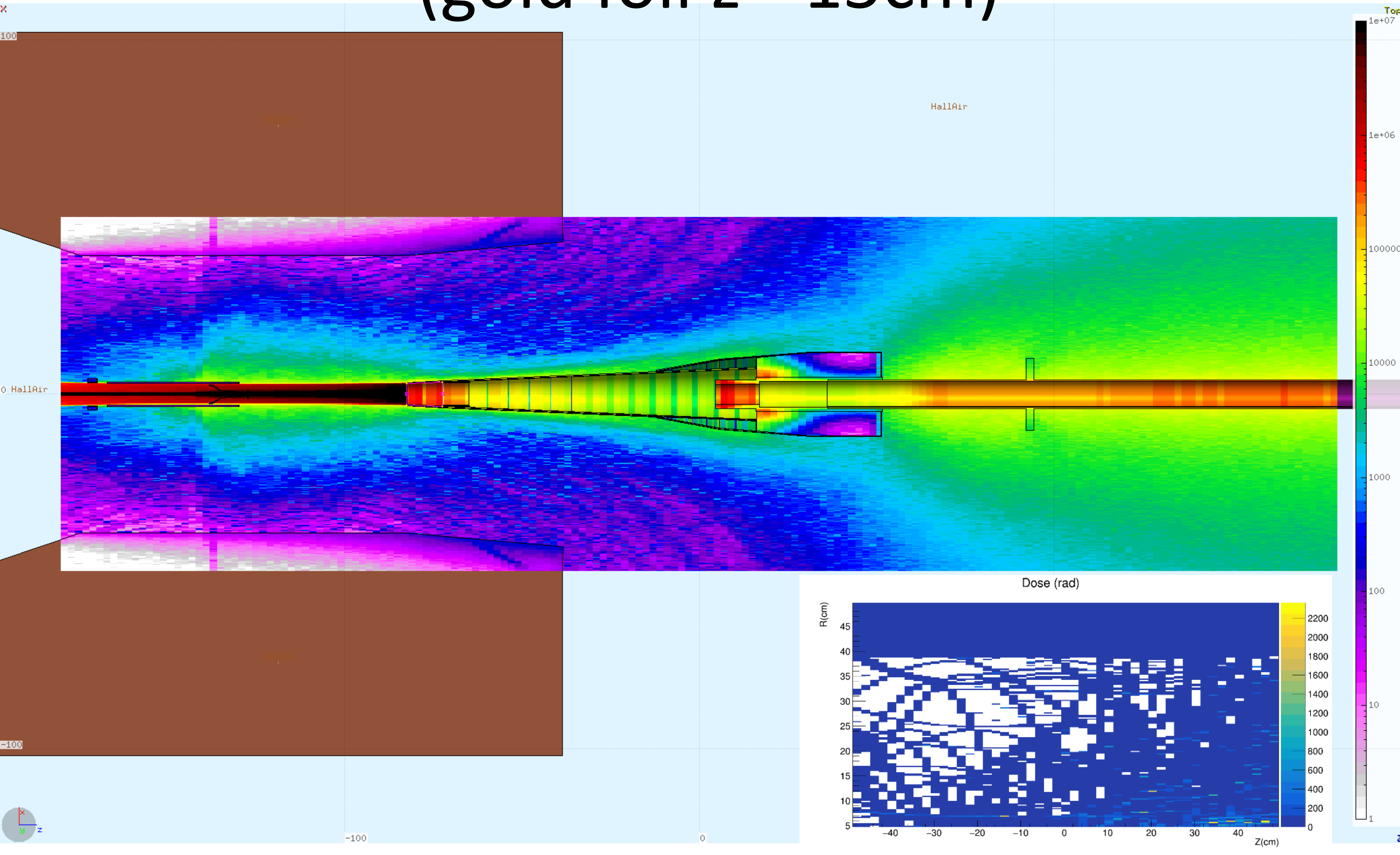
CLAS12 radiation background with gold foil target

- Fluka simulation by Lorenzo Zana
- Its geometry and materials include 0.1mm (3% RL) gold foil, Moller cone, 5T solenoid field and nothing else
  - The rest of the target is not there. I have changed the material of the USM target cell to air (that is the simulation that I have used). So, the border are there, but in reality is air as anywhere else.
  - The Moller cone is there, since it helps on shielding. It is the version with solid targets with Hall-B (same as run group M.)
- Simulation for 40 days at 40nA (8.64E17 electrons on target)
- For the rest for the simulation refer to https://userweb.jlab.org/~zana/Documents/Hall-B_USM/

1MeV equivalent neutron damage (gold foil z=-15cm)

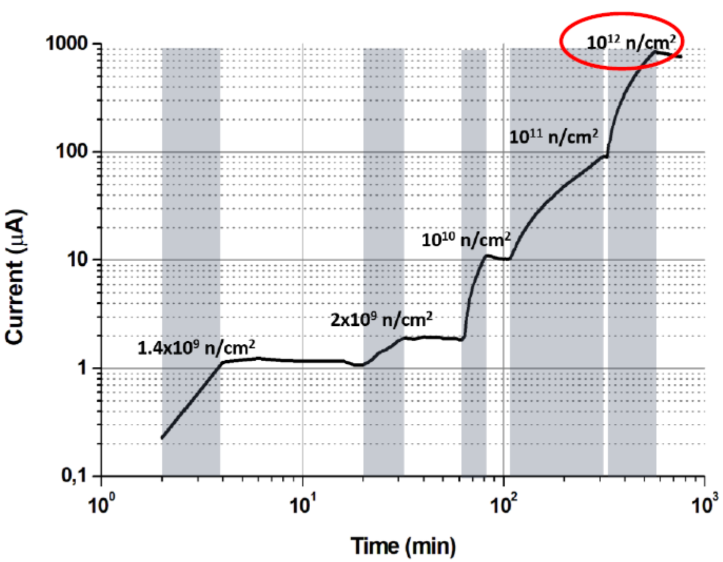


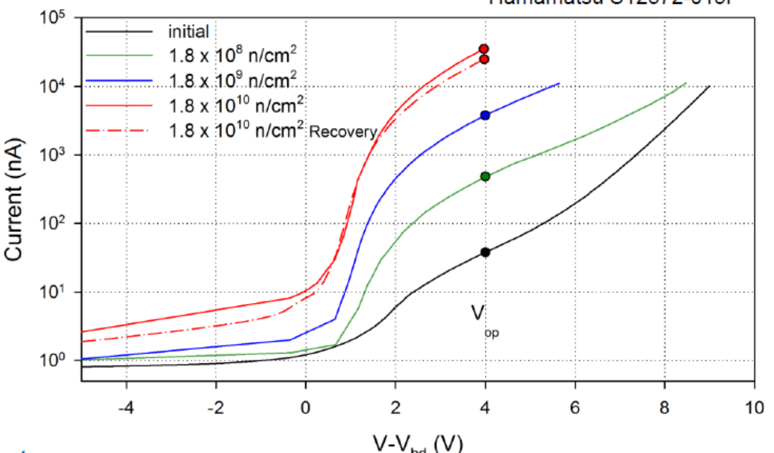
Dose in rad
(gold foil z=-15cm)



Neutron Irradiations

SiPMs irradiated with neutrons up to 10^{12} n/cm^2





Irradiations with neutrons up to ~ 17 MeV at the Atomki Cyclotron in Debrecen, Hungary

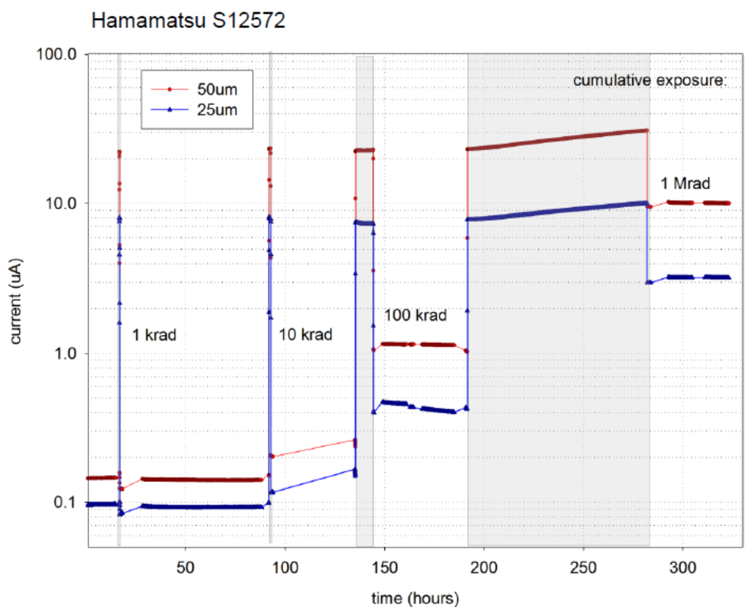
Effects

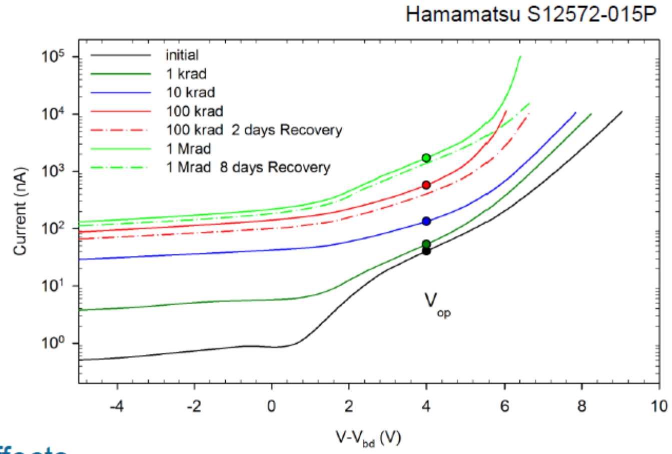
- Steady increase in current with dose
- Small increase in current below V_{op}
- Large increase at V_{op}
- Small, slow long term recovery at RT

arXiv:1809.04594.v4 (2019)
Results soon to appear in IEEE TNS

Gamma Ray Irradiations

SiPMs irradiated with ^{60}Co gamma rays to 1 Mrad





Effects

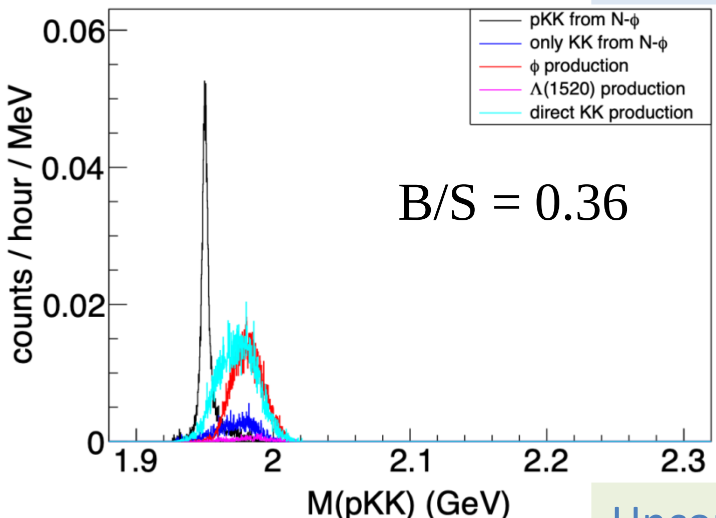
- Large current during irradiation due to direct ionization which disappears after source is removed
- Significant increase in current below V_{op}
- Moderate increase at V_{op}
- Small, slow long term recovery at RT

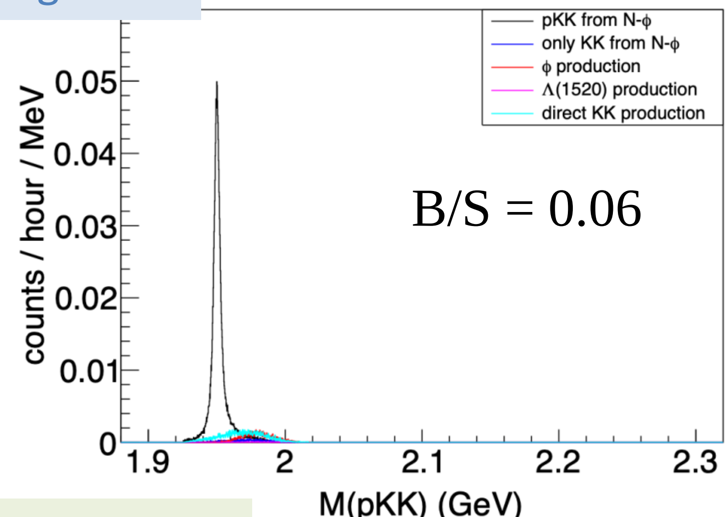
Comparison photoproduction (1.30 to 1.60GeV photon with 1e8/s rate) and electroproduction (4.4GeV e- with FT and 3e34/cm2/s lumi)

photoproduction

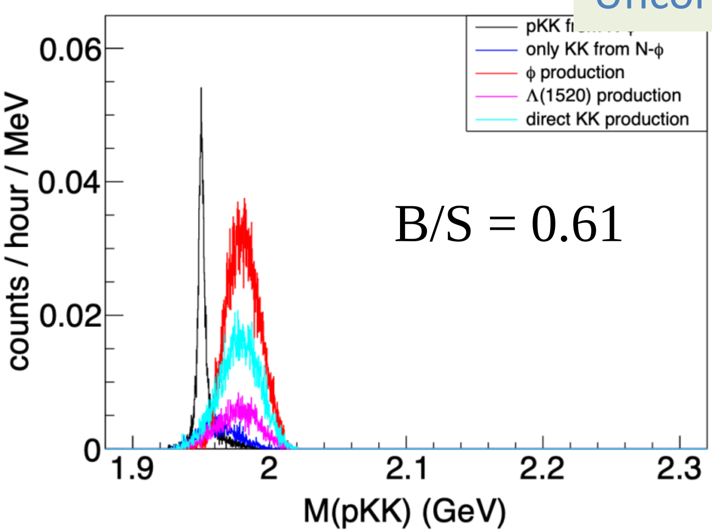
electroproduction

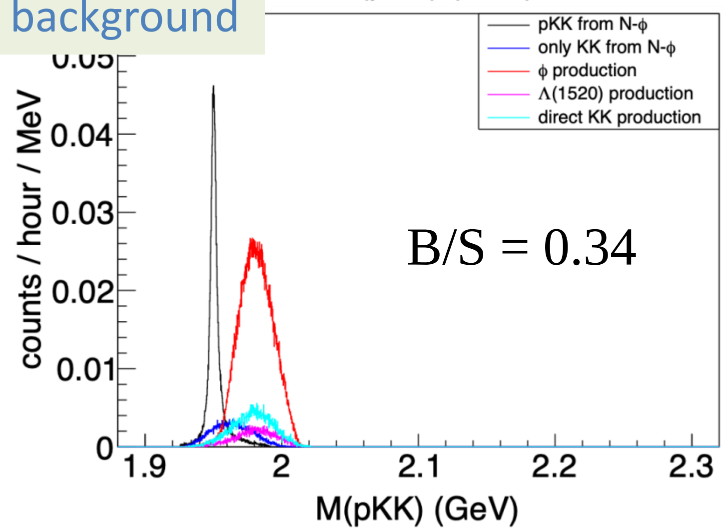
Correlated background





Uncorrelated background





ALERT DC occupancy

1e35/cm2/s lumi
200ns time window

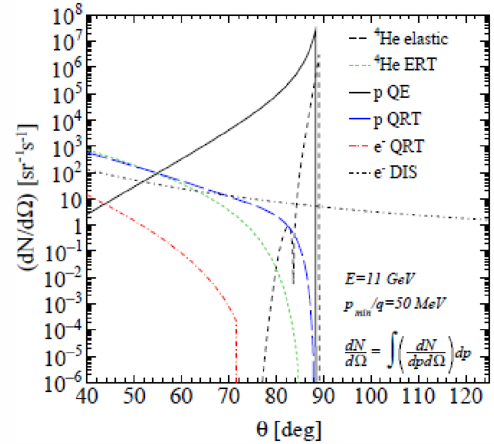
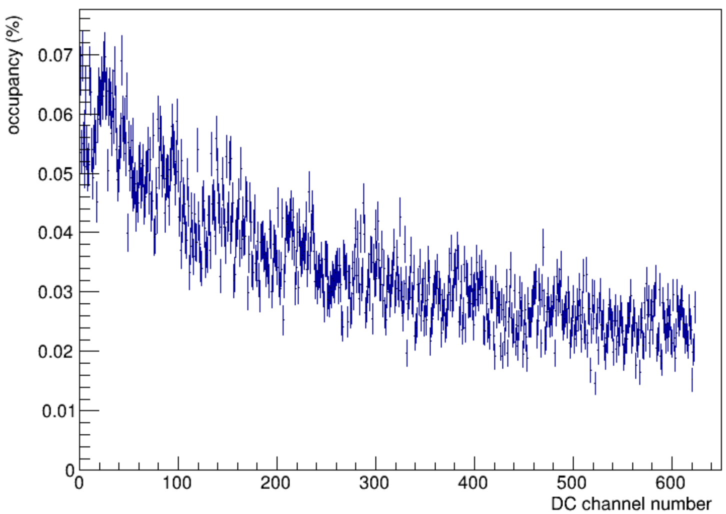
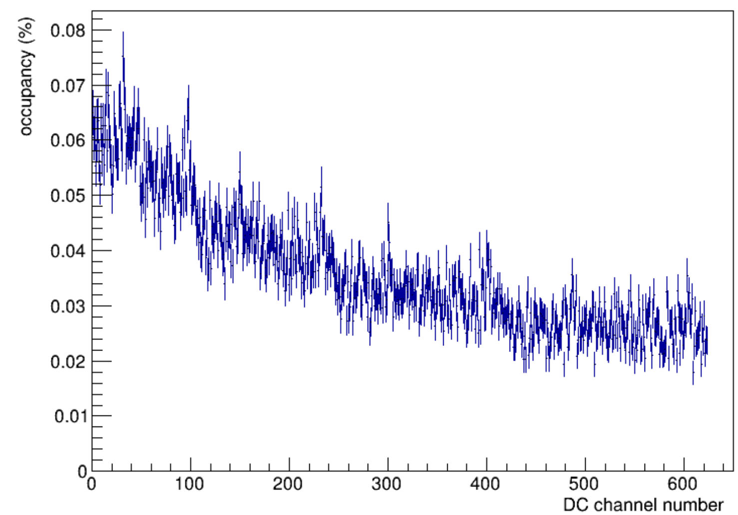


Figure 3.6: The rates for different processes as function of angle. The quasi-elastic radiative tails (QRT), ⁴He elastic radiative tail (ERT), and DIS contributions have been integrated over momenta starting at $p/q = 50$ MeV/c, where q is the electric charge of the particle detected.

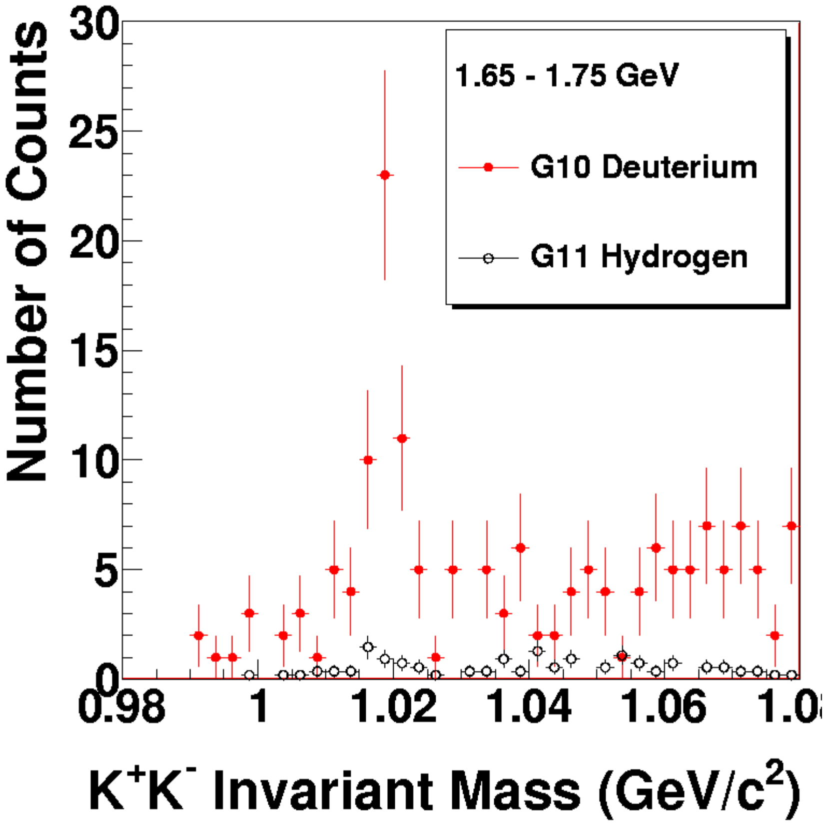
ALERT exp with gas of He4(90%)CO2(10%)

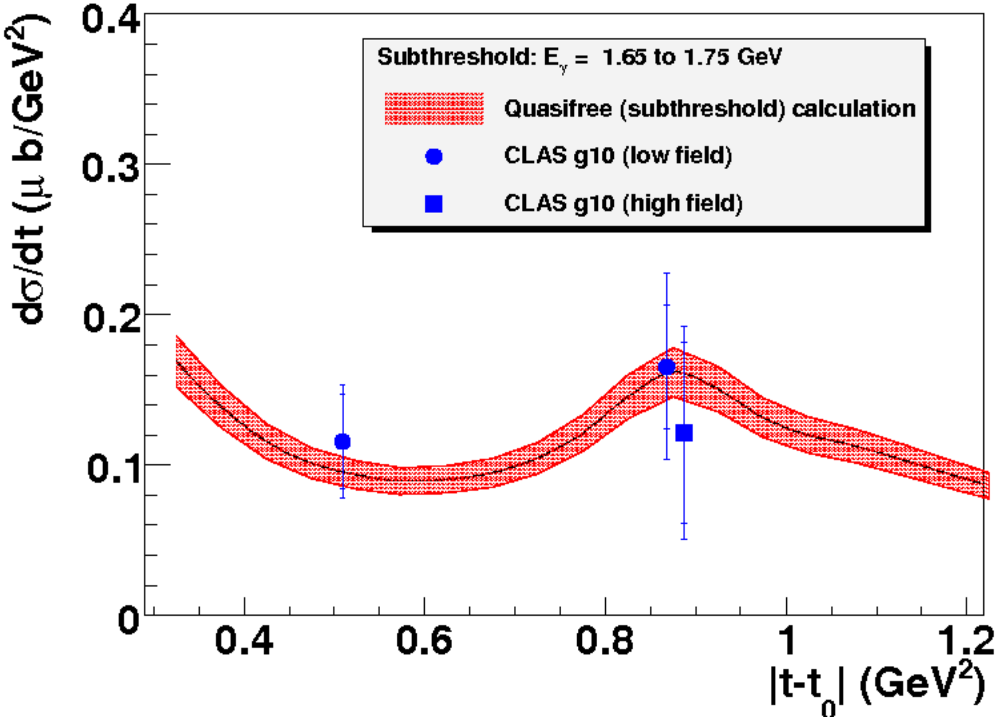
This exp with gas of Ar(80%)CO2(20%)





CLAS g10 results: Φ Production on Deuteron below CLAS threshold



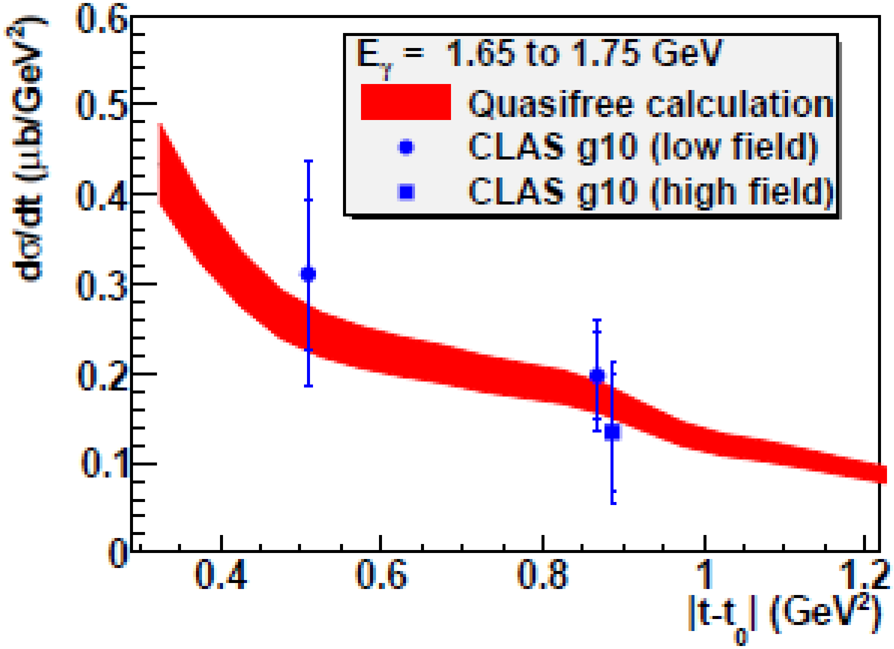


Introduce E_γ^{boost} > 1.75 GeV cut to ensure subthreshold

E_γ^{boost} is photon energy in the proton-at-rest frame

Conclusion

- See "near-threshold" events,
  - Validity of phi-N bound state search technique, which is to generate a slow phi using fermi momentum of nucleon.
- Differential cross section is consistent with simple quasi-free calculation.
  - Did not rule out any exotic behavior since data is limited by statistics.
  - Good for future design of experiment.



Near threshold results

without $E_\gamma^{boost} > 1.75$ GeV cut

X. Qian et al, PLB 696, 338 (2011)

T. Sekihara, et al., arXiv:1008.4422

Results different from W.C. Chang et al. PLB684(2010)6, though different kinematics

CLAS12 detector

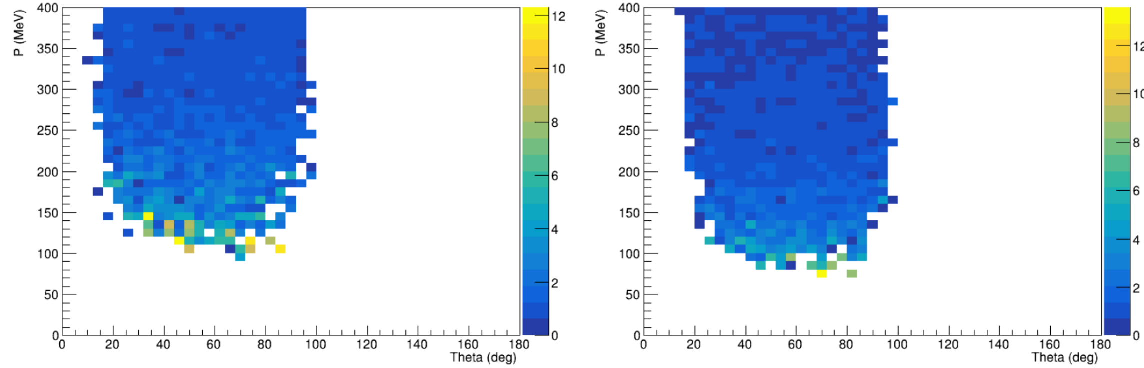
Parameters	Forward Detector	Central Detector	Forward Tagger
Charged Particles:			
Polar Angular Range (θ)	5° to 35°	35° to 125°	2.5° to 4.5°
Resolution:			
Polar Angle ($\delta\theta$)	< 1 mrad	< 10 mrad to 20 mrad	$< 1.5\%$
Azimuthal Angle ($\delta\phi$)	< 4 mrad	< 5 mrad	$< 2^\circ$
Momentum (δp/p)	$< 1\%$ at 5 GeV/c	$< 5\%$ at 1.5 GeV/c	$< 0.02/\sqrt{(E)}$
Neutral Particles:			
Polar Angular Range (θ)	5° to 40°	40° to 125° (neutrons)	
Resolution:			
Polar angle ($\delta\theta$)	< 4 mrad	< 10 mrad	
Energy	$< 0.1/\sqrt{(E)}$	$< 5\%$	
PID:			
e/π	full momentum range	N/A	full momentum range
π/p	full momentum range	< 1.25 GeV/c	
K/π	< 3 GeV/c	< 0.65 GeV/c	
K/p	< 4 GeV/c	< 1 GeV/c	

Experimental Setup

- CLAS12+ALERT
  - 4.4GeV 42nA electron beam, 0.1mm gold foil target, 3e34/cm2/s nucleon luminosity
  - Forward Tagger (2.5-4.5deg, 1-4GeV) detect scattered e-
  - ALERT detects $pK^{+}K^{-}$ with $100<P<350$ MeV
  - CLAS12 forward angle detects $pK^{+}K^{-}$ depending on torus field

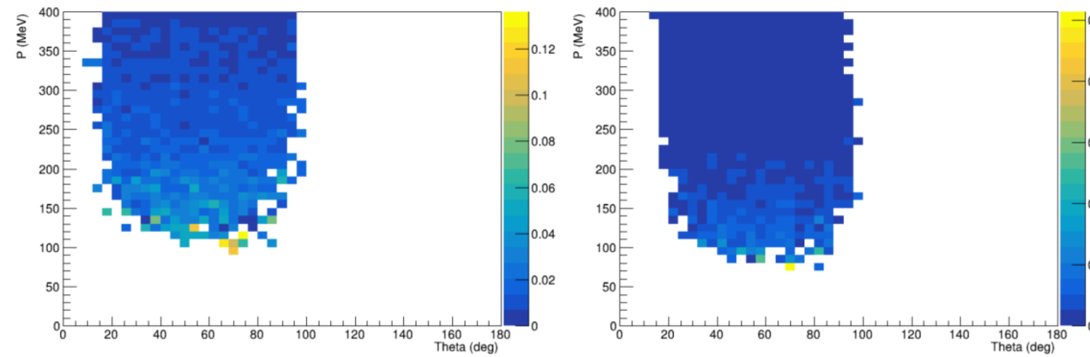
ALERT resolution

mom 2%

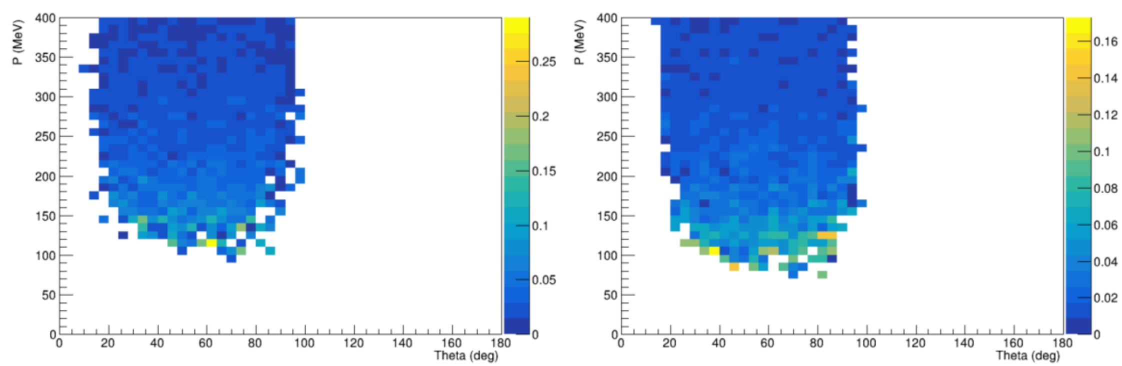


(a) Proton momentum resolution in percentage (b) K^+ momentum resolution in percentage

Polar angle
20mrad



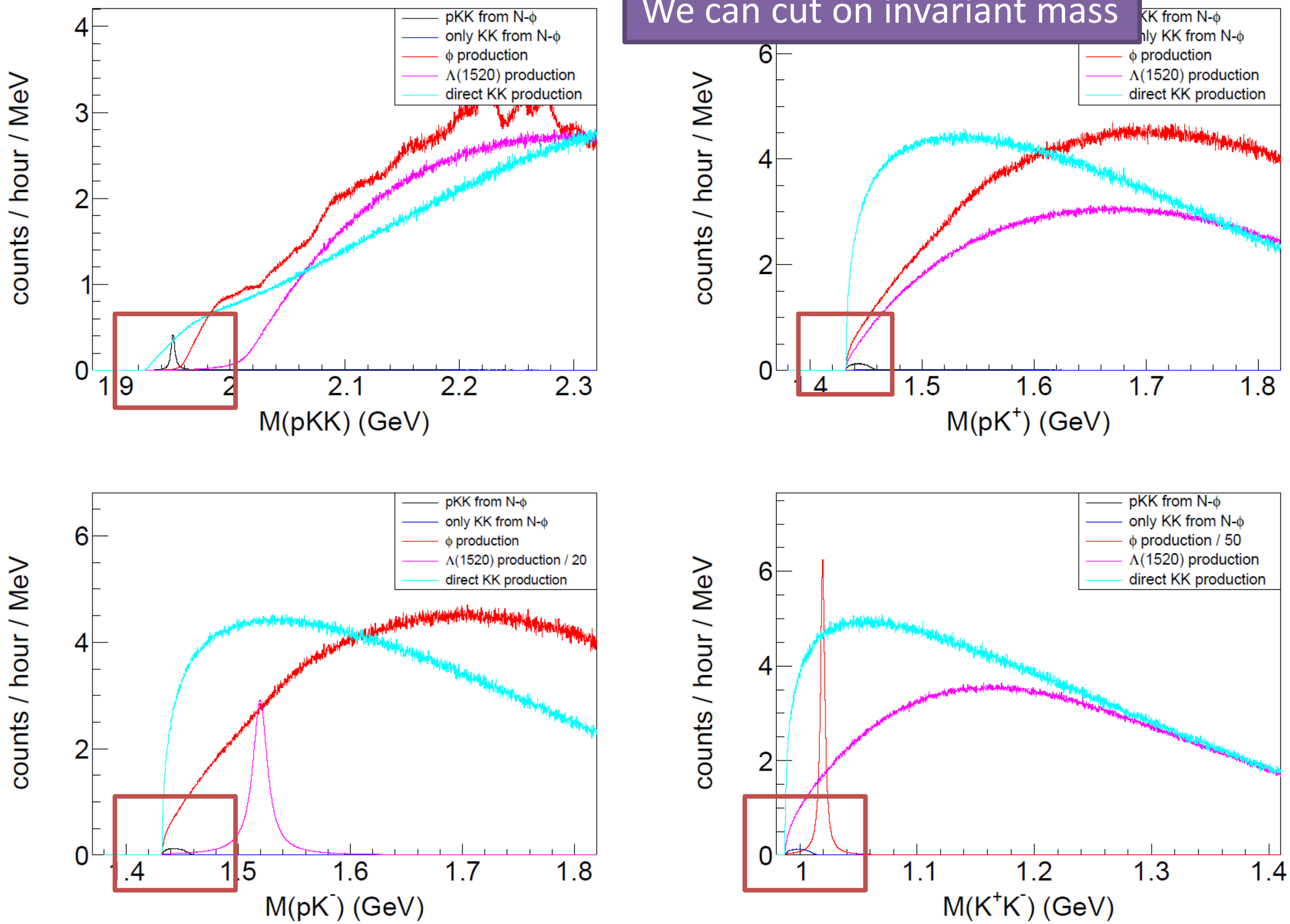
Azimuthal angle
20mrad



(a) Proton azimuthal angle resolution in rad (b) K^+ azimuthal angle resolution in rad

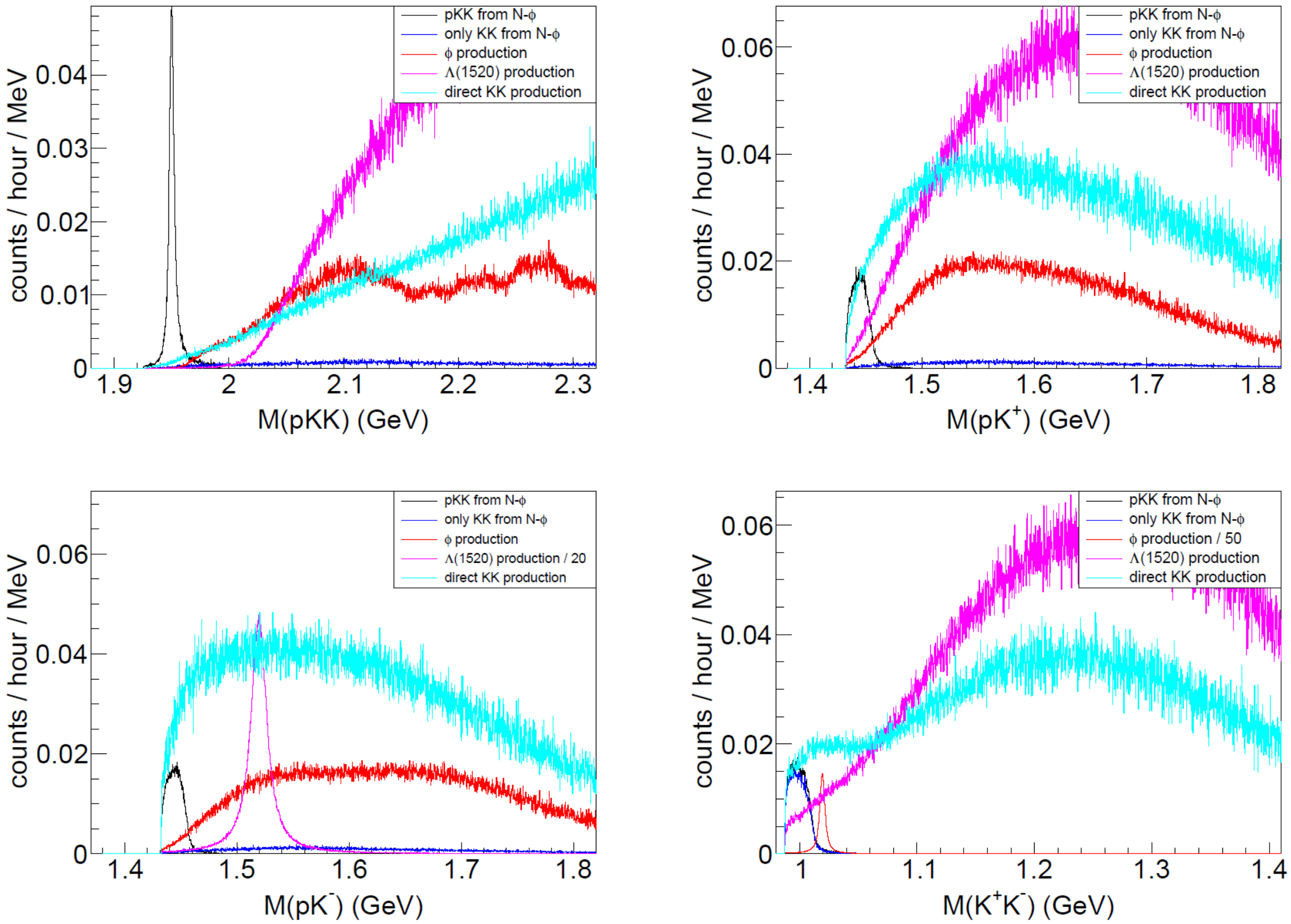
Four background channels with same final state (generated)

We can cut on invariant mass



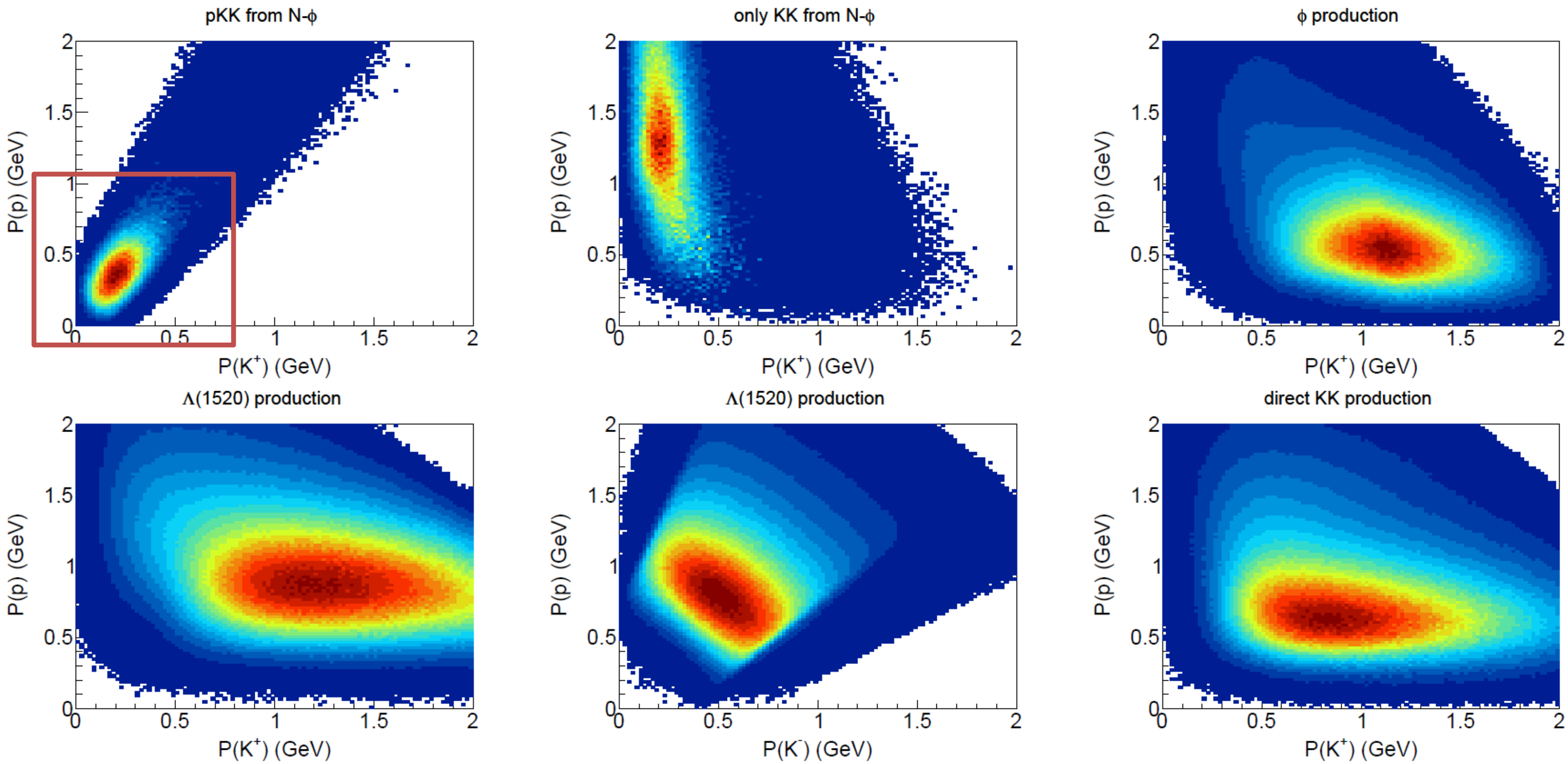
Four background channels with same final state (detected)

We can cut on invariant mass



Four background channels with same final state (generated)

We can cut on mom



Four background channels with same final state (detected)

We can cut on mom