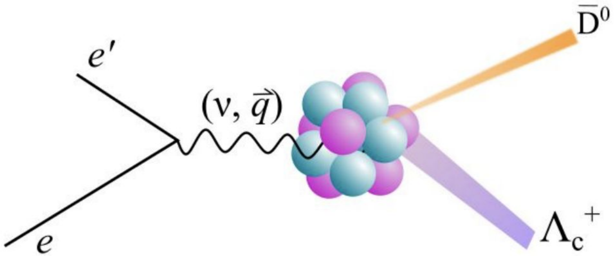
Open-charm production near threshold



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UC Riverside

11/15/2024

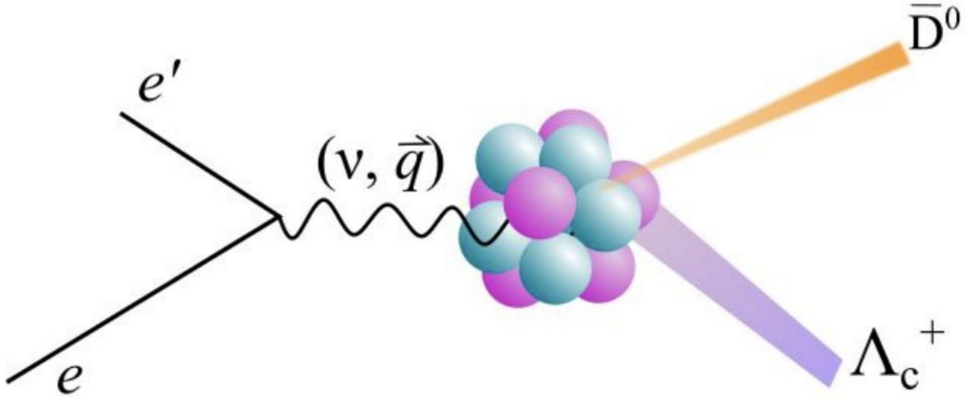
UC RIVERSIDE

CEBAF Large Acceptance Spectrometer

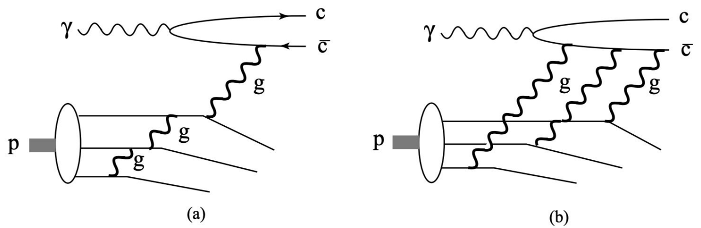
Motivation

- Open charm production is when c and $\bar{c}$ are produced and end up in different hadrons in the final state.
- The lightest open-charm final state that can be produced in γp (or γ*p) scattering is $\bar{D}^0\Lambda_c^+$.
    - Could take place in free or bound proton
- Measuring open-charm production in ep scattering near-threshold can reveal information about J/ψ (closed-charm) production
- This open-charm production mechanism can also be used to probe the diquark part of the proton wavefunction

Open charm



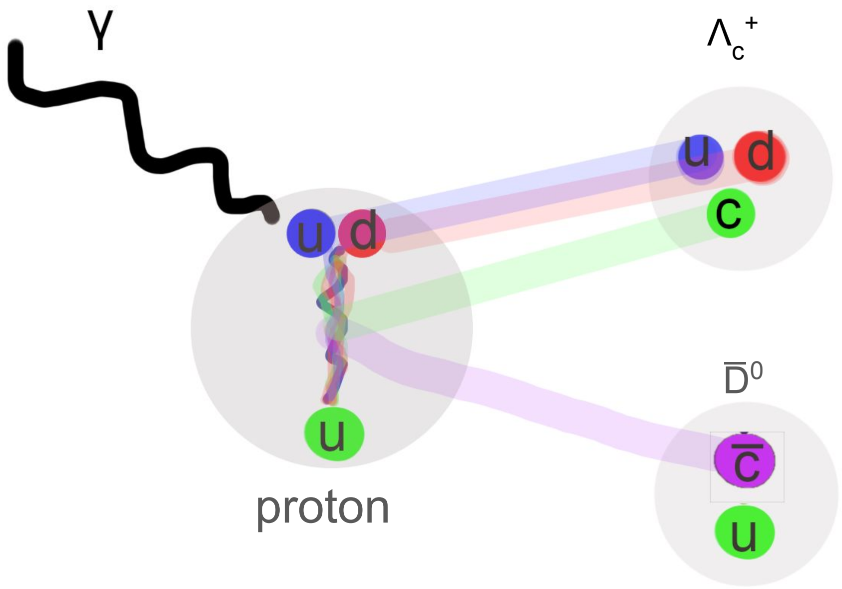
Closed charm*



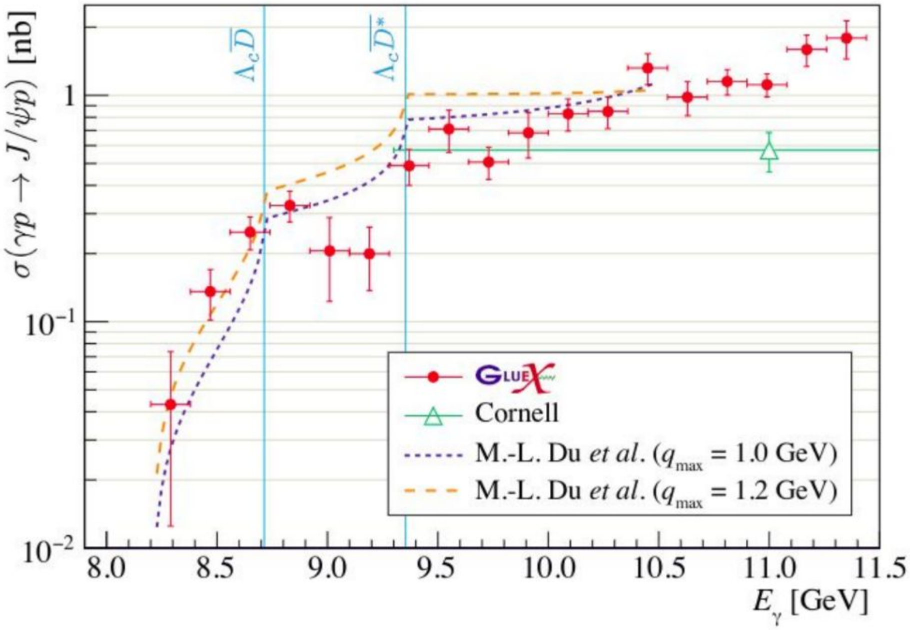
*Phys.Lett.B498:23-28,2001

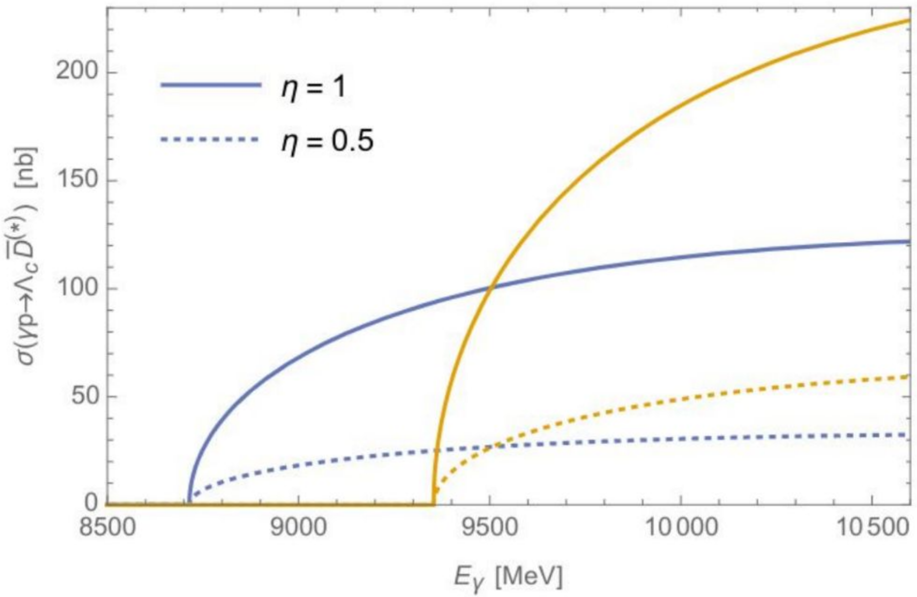
Enhanced cross-section due to di-quarks

- The presence of diquark+quark in a proton's wavefunction may enhance the cross-section of open charm production due to events where the γ strikes a diquark
- String breaking produces the $c\bar{c}$ pair.
- This ends up being a simpler process (fewer string breakings) than if a solitary quark (non-diquark state) is struck.

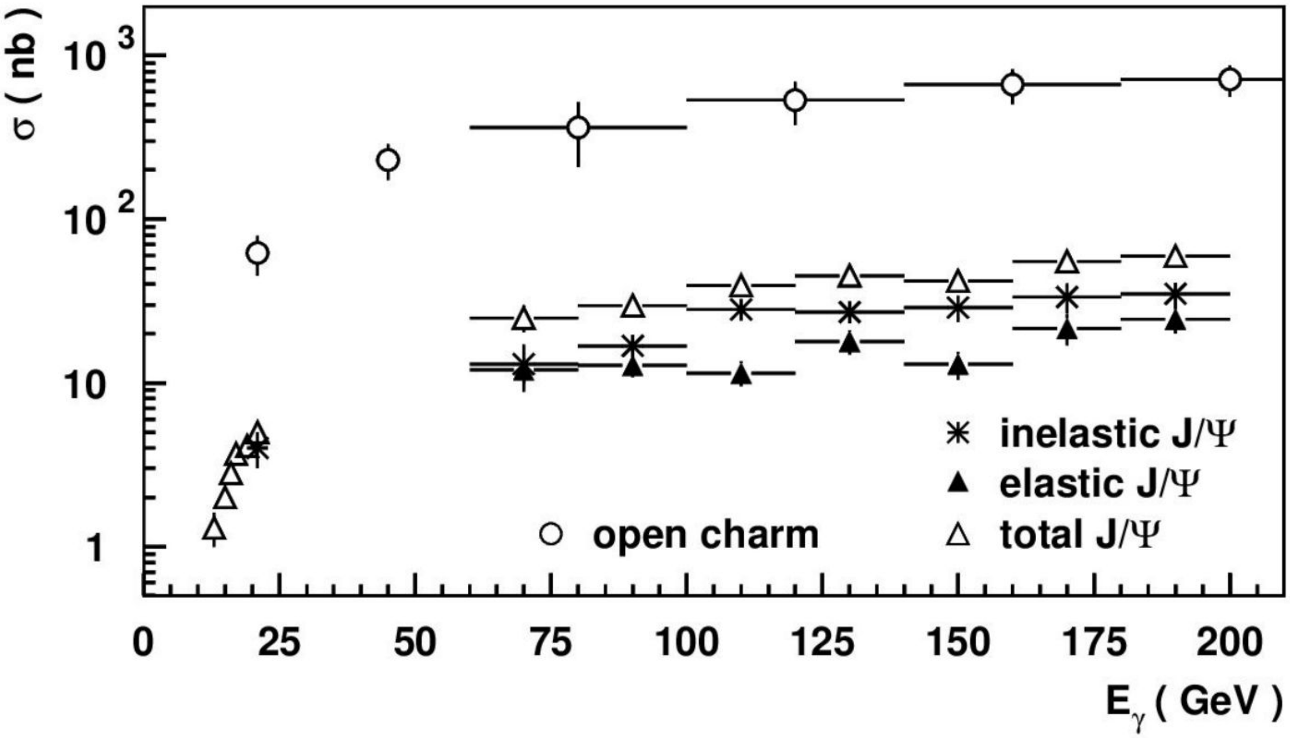


How is open-charm related to closed-charm (J/ψ)?





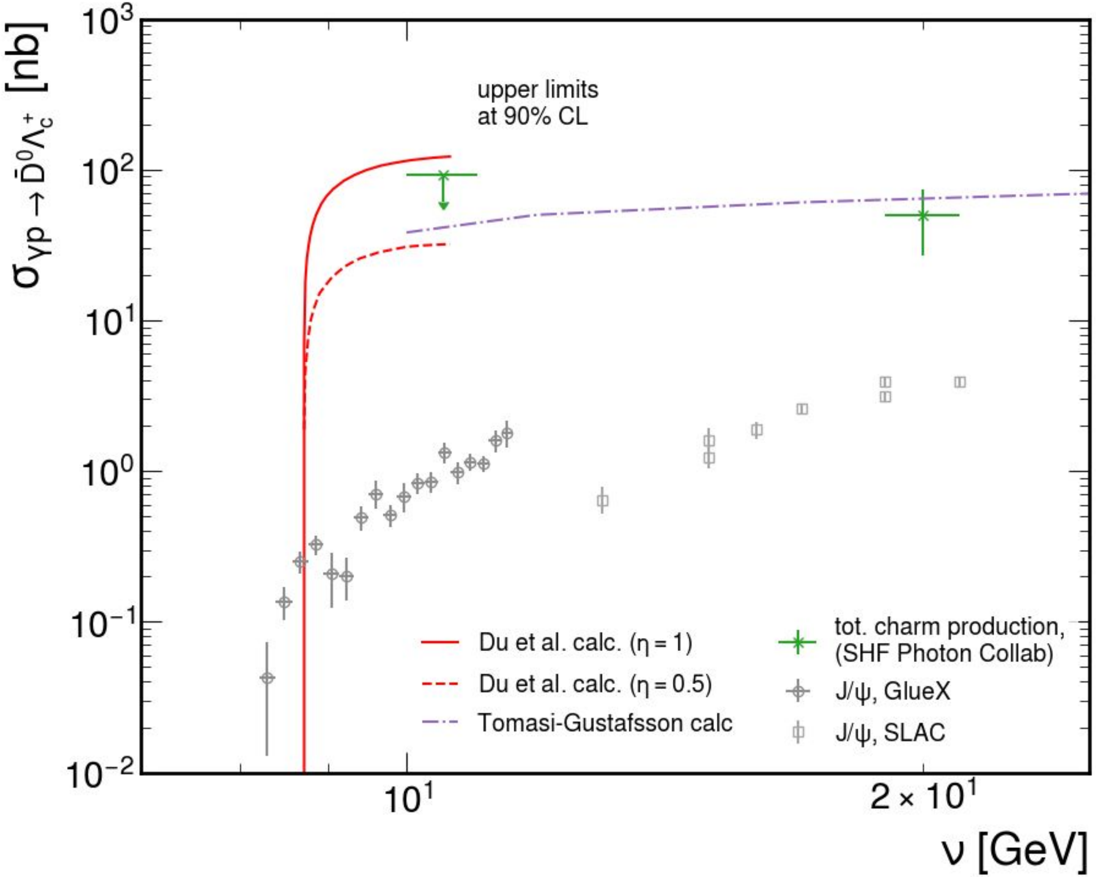
Open charm is expected to have larger cross section than J/ψ, based on measurements well above threshold



https://inspirehep.net/literature/553290

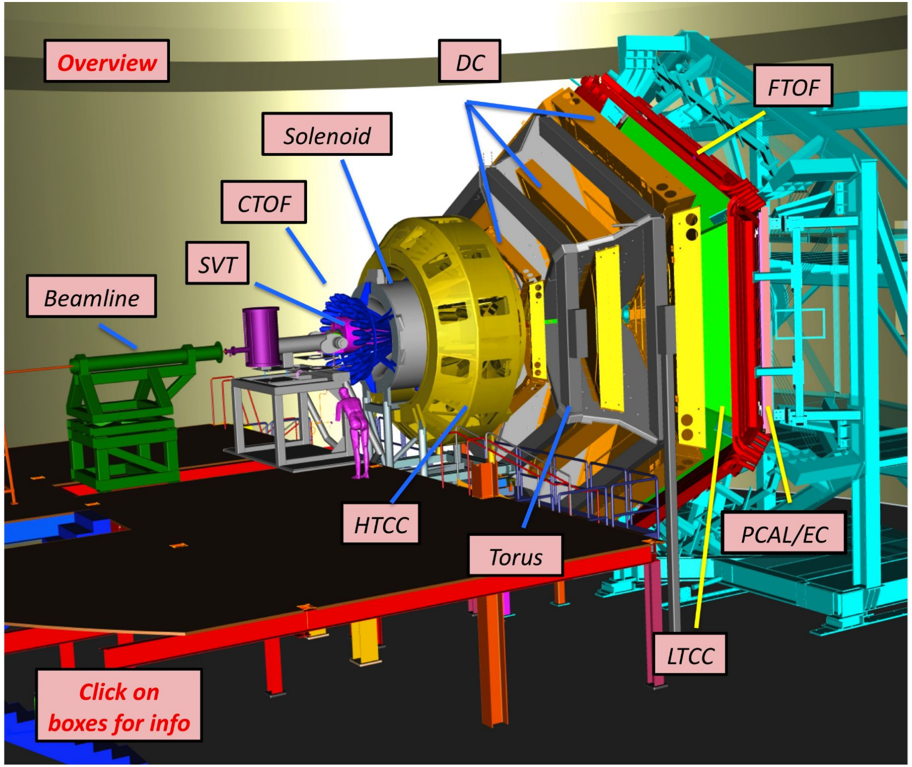
Existing measurements and predictions

- Upper limit set by SLAC measurement near threshold
- Closest non-zero measurement to threshold is at >2x the threshold
- Two independent predictions of σ=O(10-100) nb near threshold
- For comparison, J/ψ has been measured near threshold by GlueX at JLab.

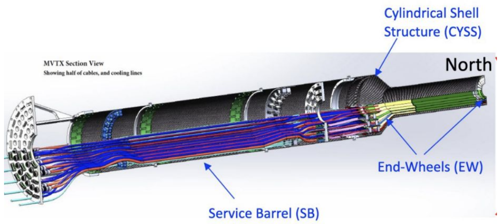


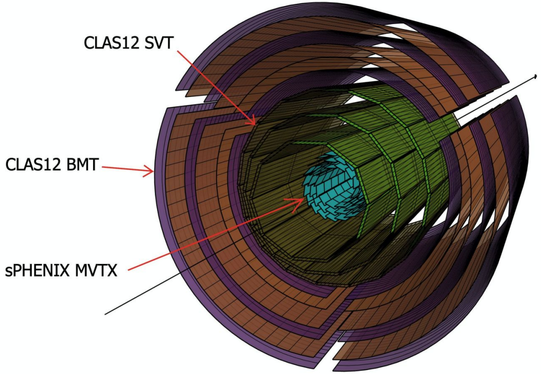
Possible measurement with CLAS12 detector

- 10.6 GeV e- beam
- Forward tagger can measure electrons as low as 0.5 GeV:
  - Energy transfer in quasi-real photoproduction up to 10.1 GeV, while threshold for $\gamma p \rightarrow \bar{D}^0 \Lambda_c^+$ is ν=8.7 GeV
- Detection strategies:
  - Either $\bar{D}^0$ or Λ_c^+ decay-product candidates can be detected, with the other charmed hadron inferred from missing mass (H target only)
  - Detect decay product candidates from both charmed hadrons
  - Displaced vertex search ($\bar{D}^0$ or Λ_c^+ decays downstream of a thin target)

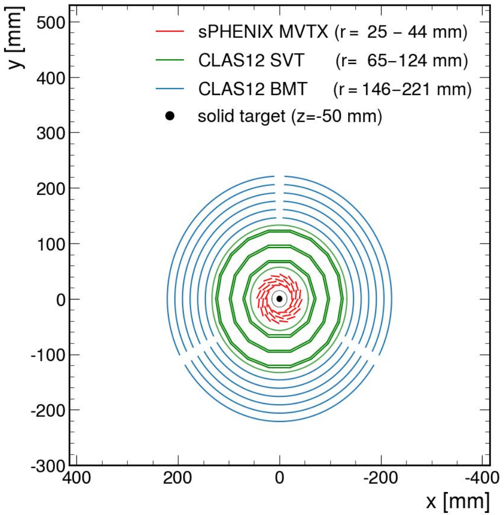


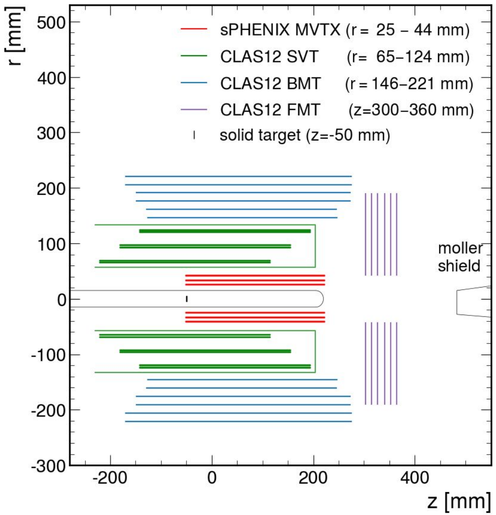
Open-Charm Production (continued)



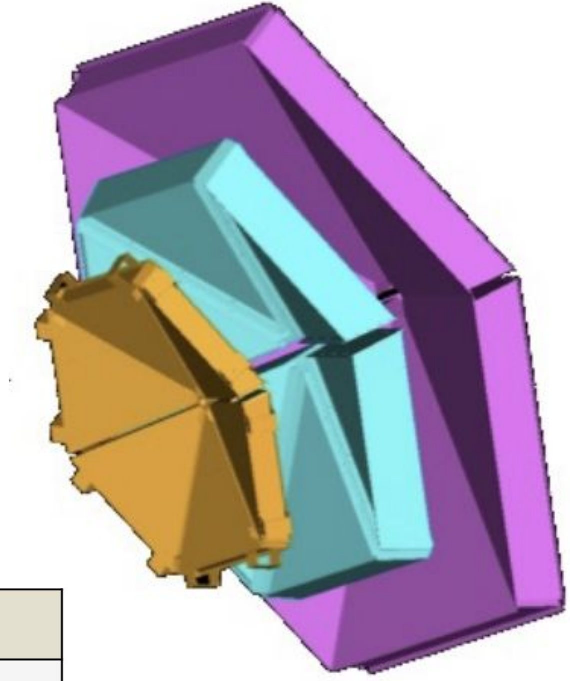


- To improve the vertex resolution, we wrote a letter of intent to borrow the MVTX detector from sPHENIX:
  - Pixel detector with pitch 27 μm
  - allows vertex resolution of ~5 μm.
  - Boosted lifetimes of charmed hadrons are O(100 μm)
  - Requiring one or more hadrons to have vertices >3σ downstream of target could reduce background by several orders of magnitude.
  - Acceptance as shown: 8.7º – 90º





CLAS12 momentum and angle resolutions



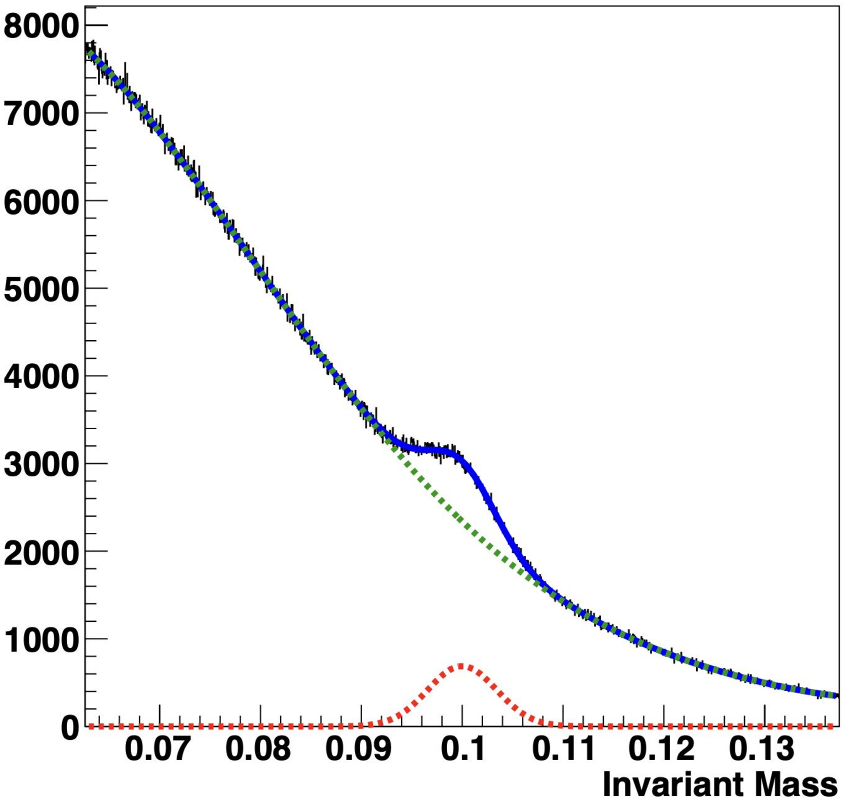
Most charged particles in CLAS12 have their momentum and angle determined by the drift chambers

These provide sufficient resolution for determining the invariant and missing mass of the charmed hadron's daughter particles.

DC – Tracking Specifications	
PARAMETER	**SPECIFICATION**
Angular coverage	$5^o – 40^o$ (50% ϕ-coverage at 5^o)
Momentum resolution	dp/p < 1%
θ Resolution	1 mrad
ϕ Resolution	1 mrad/sinθ
Luminosity	10^{35} cm^{-2} s^{-1}

Bump-hunting

- A standard practice to find a resonance signal on top of a background is to fit invariant mass distribution to a gaussian plus polynomial
- Yields or upper-limits can then be extracted from the fit.

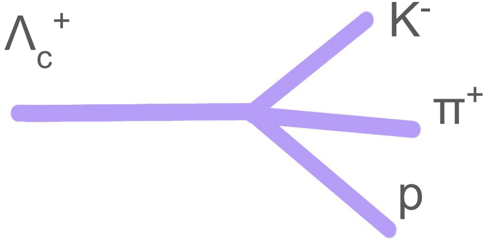


*S.J. Paul, PhD dissertation

Preferred decay channels:

- All daughters are charged
  - Optimizes mass resolution to improve bump-hunt
- Small number of daughter particles
- Relatively large branching ratio

3.95% BR



6.26% BR

Event generator studies

For each event, first determine the electron kinematics*, requiring $8.7<\nu<10.1$ GeV and $2.5^o<\theta<4.5^o$ **:

$$\frac{d\sigma}{dy\,d\theta} \propto \frac{1-y+y^2/2}{y\sin^2\frac{\theta}{2}} \times \sigma_{\gamma p}^{\text{calc}}(\nu)$$

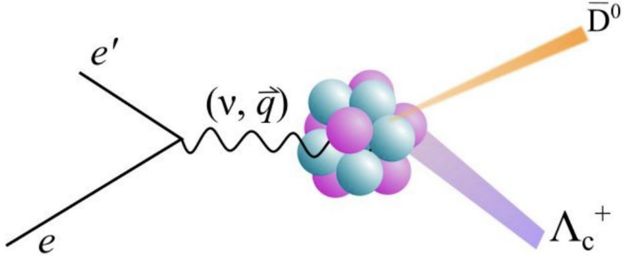
Next, assume that the γ^*p becomes a $\bar{D}^0$ and Λ_c^+ pair with uniform probability within the available phase space

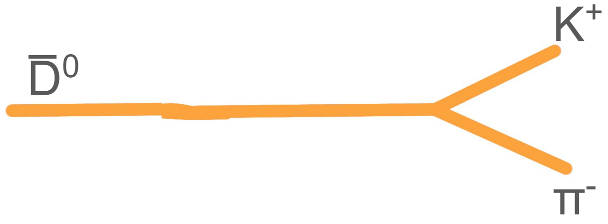
Finally, allow $\bar{D}^0$ to decay uniformly in phase space to $K^+\pi^-$ and the Λ_c^+ to decay to $K^-\pi^+p$

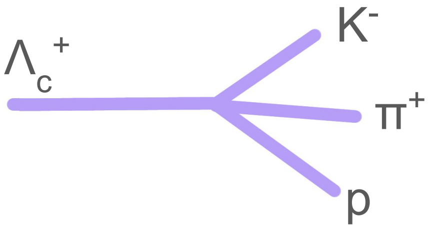
Position of the decays determined by exponential distribution with:

$$\ell = v\tau\gamma \equiv c\tau\beta\gamma \equiv \frac{c\tau}{m}P$$

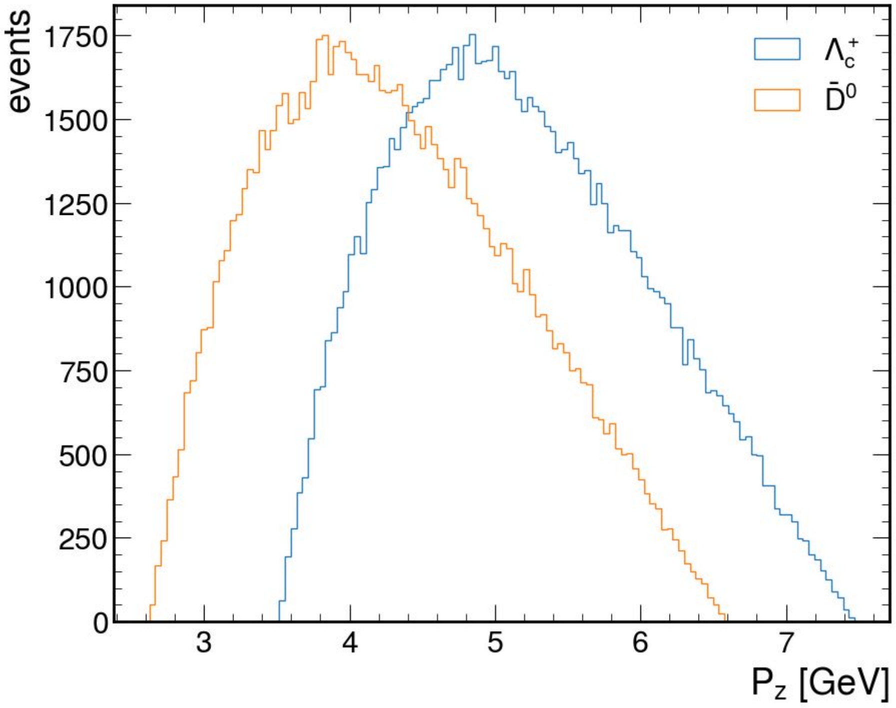
*derived from the conversion formula from quasi-photoproduction (Q^2~0) to real photoproduction formulas
**8.7 GeV threshold for the open charm production, the other limits due to CLAS12 Forward Tagger acceptance

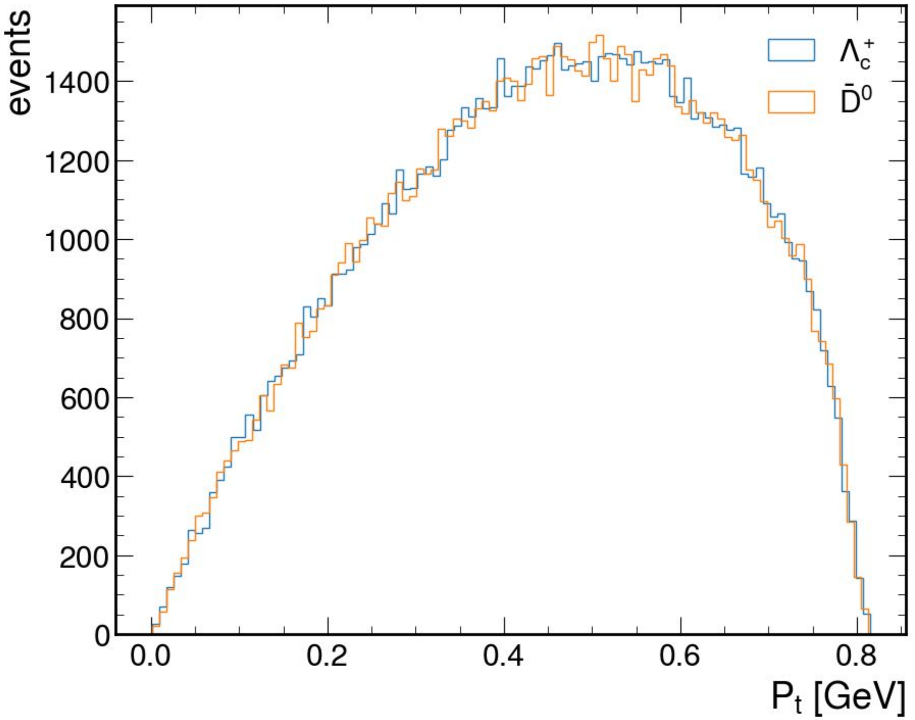




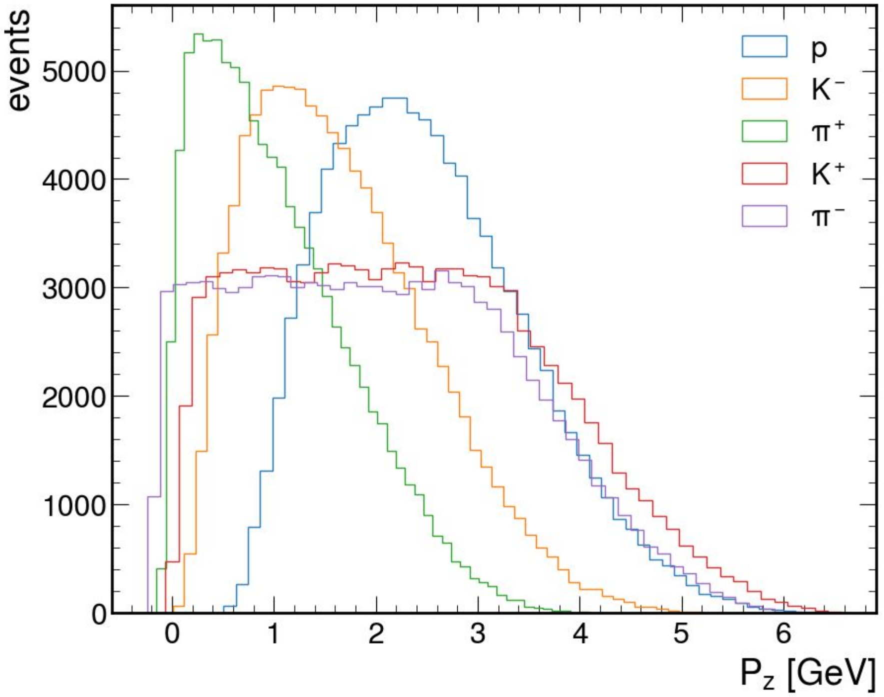


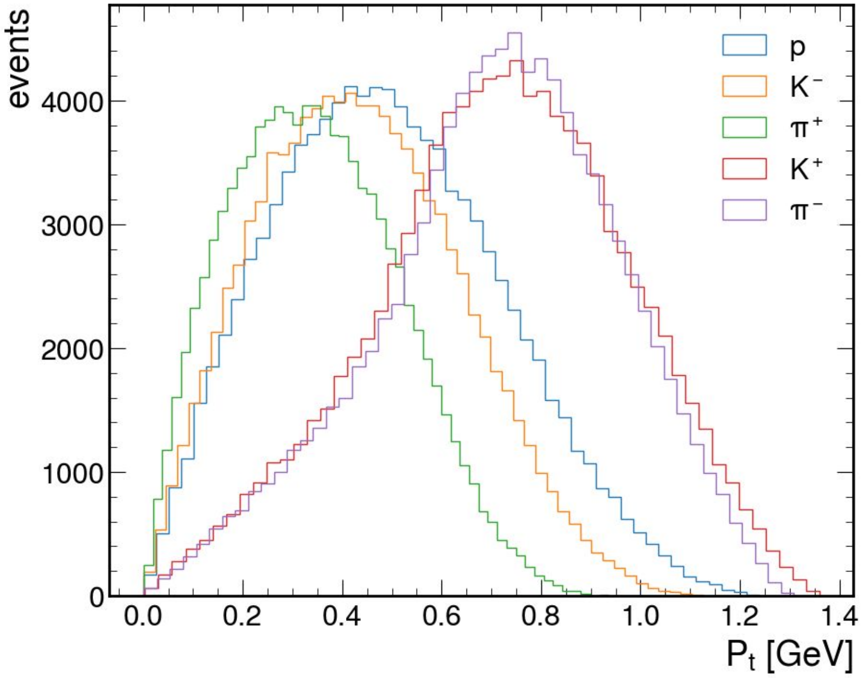
Momentum distributions



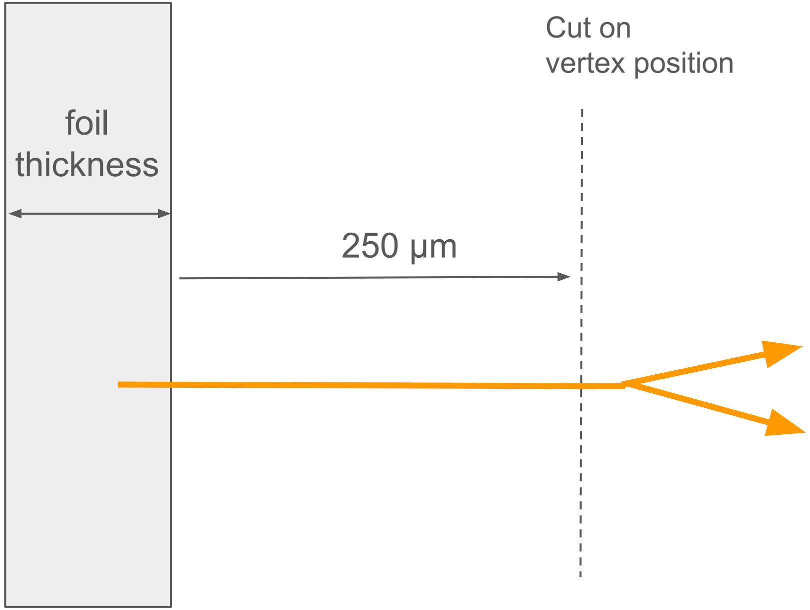


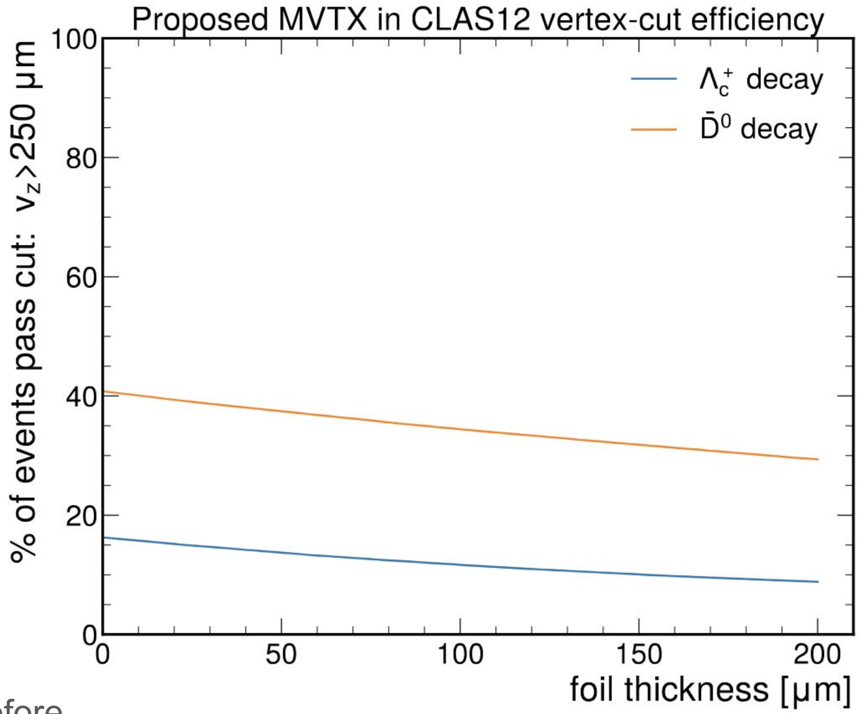
Daughter-particle momentum distributions





Longitudinal vertex-cut efficiency



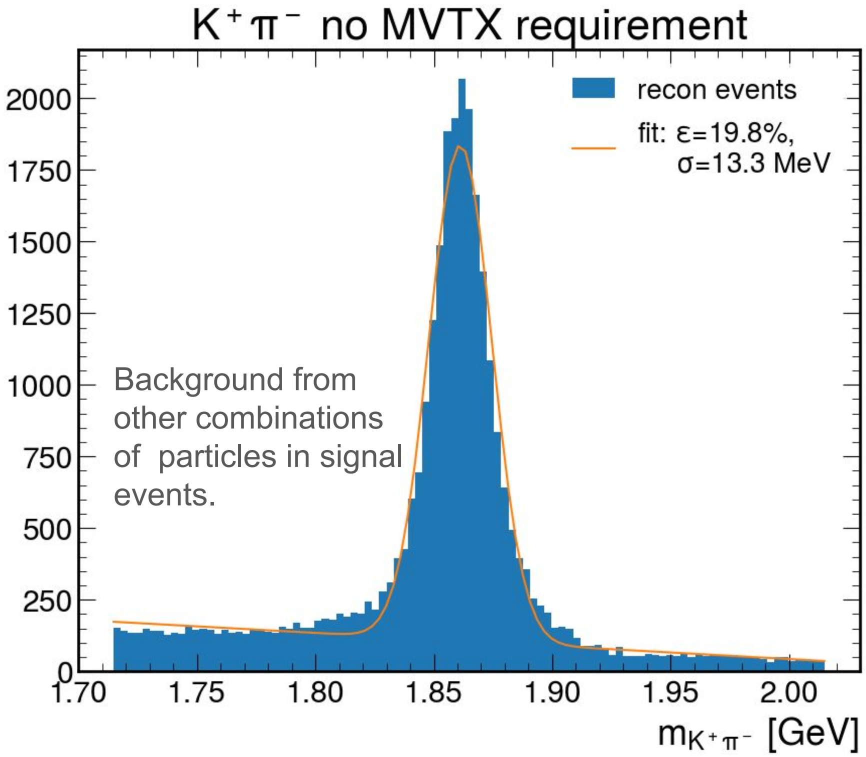


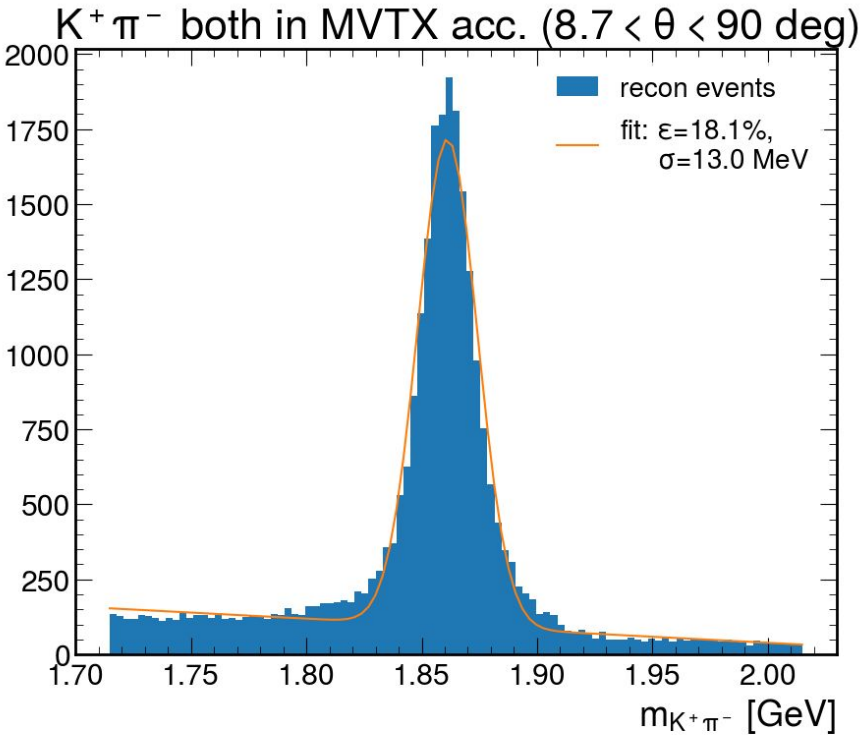
Fraction of events where charmed hadrons decay before cutoff was determined as a function of foil thickness

Acceptance studies with GEMC

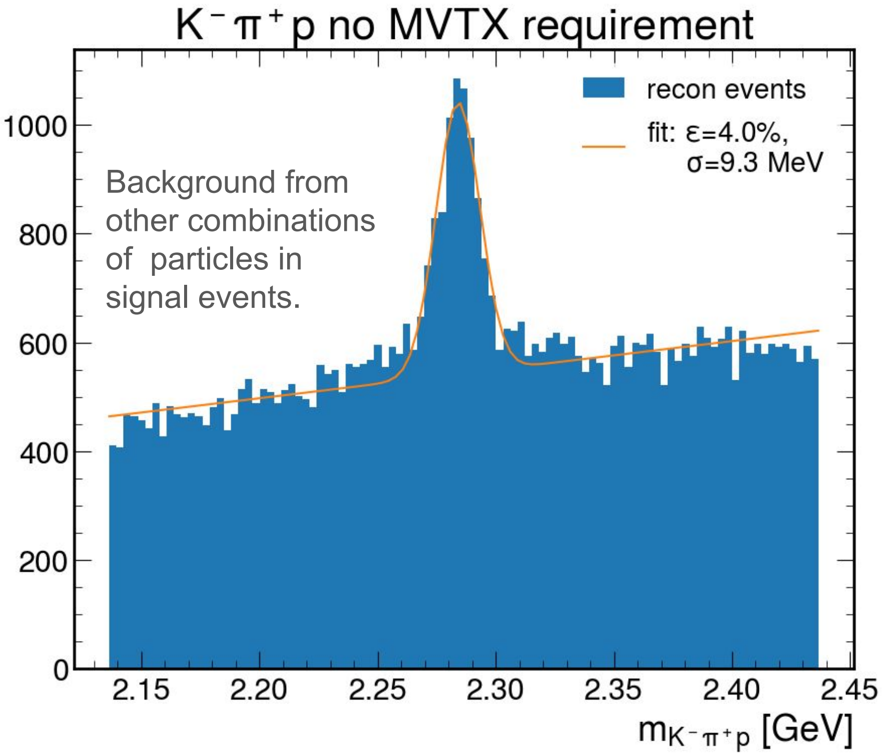
- Generated 96k events with Λ_c^+ and $\overline{D}^0$ decaying into $K^-\pi^+p$ and $K^+\pi^-$.
- Run events through GEMC with CLAS12 detector
- Reconstructed the electron in the FT and charged hadrons with the DC.
- Find combinations of charged hadrons
  - Two hadrons with opposite charge, reconstruct invariant mass as if it is $K^+\pi^-$
  - Three hadrons, with one negative charge, and the other two positive. Reconstruct mass as if it's $K^-\pi^+p$
- Fit invariant mass distributions as gauss+poly
  - Efficiency (including acceptance) = (Integral of gaussian)/(number of generated events)
  - Mass resolution = sigma of gaussian.

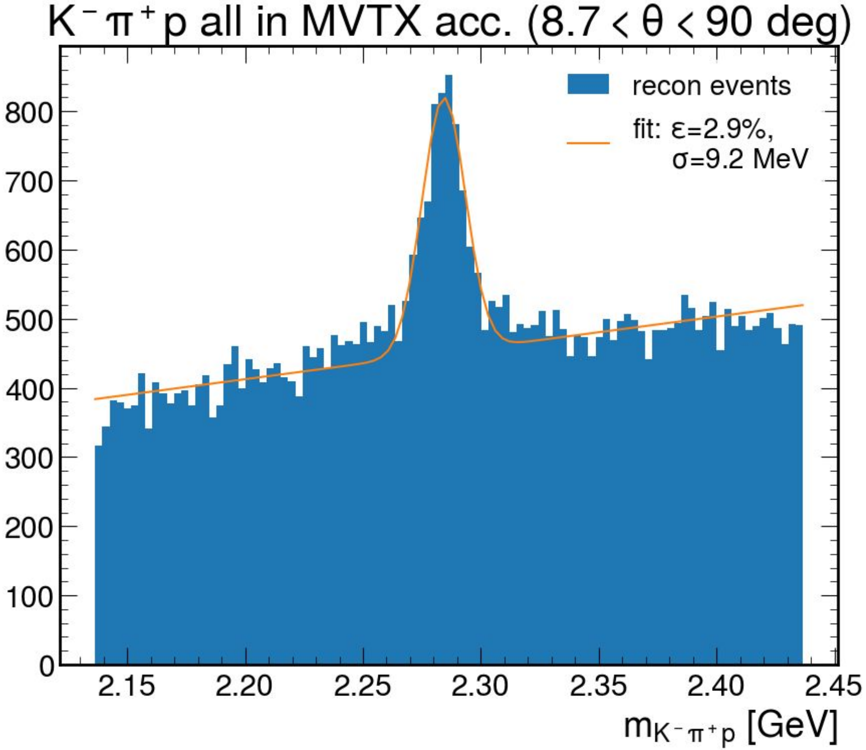
$\overline{D}^0$ candidates





Λ_c^+ candidates





Expected yields

Quantity	K-π+p	K+π-	units	notes
Free proton xs (lower limit)	0.0082	0.0082	nb	σ_γp calculated by Du et al, evaluated at η=0.5, converted to σ_ep [Eur. Phys. J. C 80, 1053 (2020)]
Free proton xs (upper limit)	0.0328	0.0328		same, evaluated at η=1.0
Z/A	0.44	0.44		evaluated for 9Be
Tot luminosity	1.30E+08	1.30E+08	nb^-1	100 days, 50% PAC eff. 3e34 cm-2s-1, with 5-foil 100 μm Be target at 85 nA, per nucleon
Branching ratio	6.26%	3.88%		PDG
CLAS12 efficiency including geometric acceptance	3.9%	19.8%		GEMC
MVTX geometric acceptance	74.4%	91.4%		add cut: 8.7<θ<90 deg
MVTX efficiency (not including acceptance)	51%	64%		assuming 80% reconstruction efficiency per daughter particle
Vertex cut efficiency	12%	34%		assuming 100 μm per foil 250 μm cut
Expected signal events	**52 - 208**	**717 - 2867**		product of the above factors

Updated since the LOI
To be refined with future studies
expected yields

$$\sigma_{ep} = \int_{y_{\min}}^{y_{\max}} \frac{\alpha}{\pi y} \sigma_{\gamma p}(\nu) \left((1 - y + 1/2y^2) \log \left(\frac{Q^2_{\max}}{Q^2_{\min}} \right) + m_e^2 y^2 (Q^{-2}_{\max} - Q^{-2}_{\min}) \right)$$

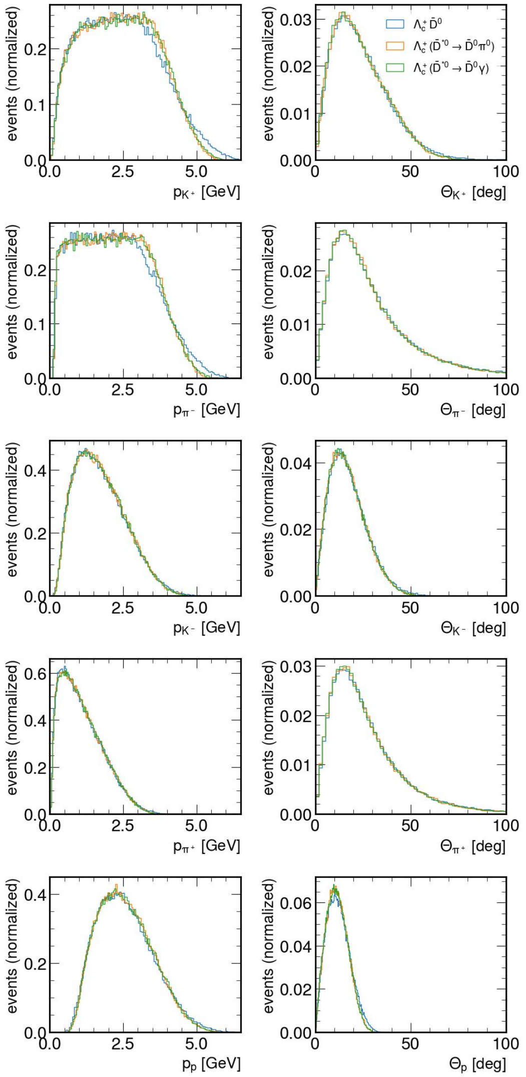
Conclusions

- Only an upper limit has been measured for open-charm production near threshold, unlike closed-charm (J/ψ) production
  - May reveal insights regarding J/ψ production processes.
- Open-charm near-threshold cross sections may be enhanced by diquark configurations in proton, and therefore serve as a useful probe for diquark.
- CLAS12 detector at JLab may be well suited for measuring open-charm production
  - Monte-Carlo with GEMC show that the efficiency (including acceptance) is O(20%) for the $\bar{D}^0 \to K^+\pi^-$ channel
  - Further work:
    - Incorporate MVTX into GEMC, and determine its efficiency and vertex resolution

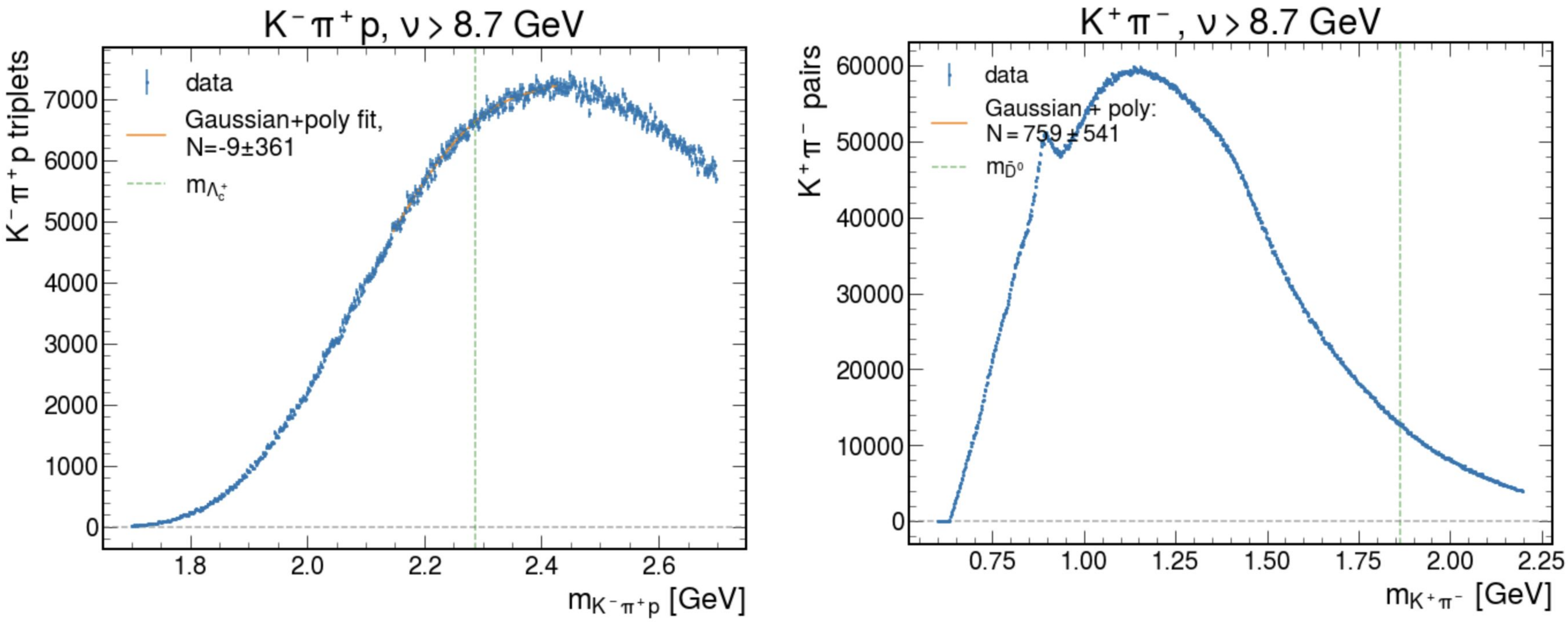
Backup slides

D0 versus D0*

Kinematics of events in which D0 bar is produced directly (rather than through the decay of a D0* bar) have similar kinematics to those in which a D0* bar is produced



Estimates of background from existing CLAS12 data (RGA)

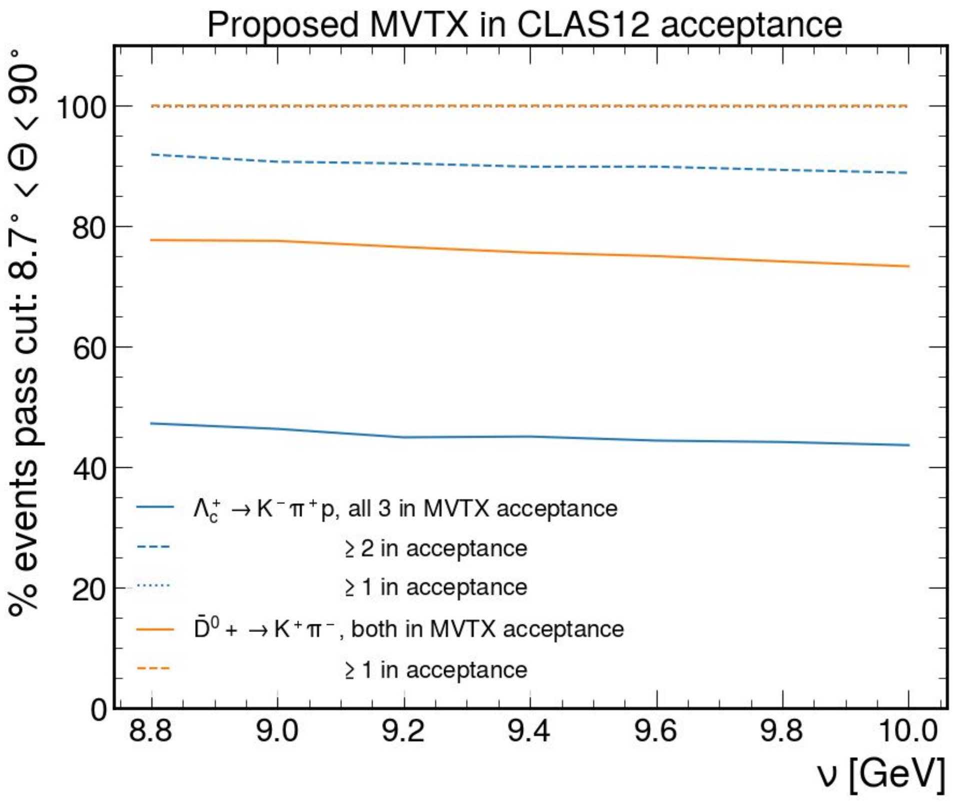


*Note: no cut was made on the missing mass, since missing-mass distribution will be smeared when using a foil (nuclear) target.

Useful for estimating background rates for the experiment with MVTX

Geometric acceptance of the MVTX

- Requiring all three Λ_c^+ decay products to be detected by MVTX reduces acceptance by factor of ~2
- Requiring at least 2 decay products (of either particle) to be in MVTX has less of an acceptance loss
- Requiring at least 1 particle in MVTX has almost no acceptance loss.



With missing mass cut (RGA)