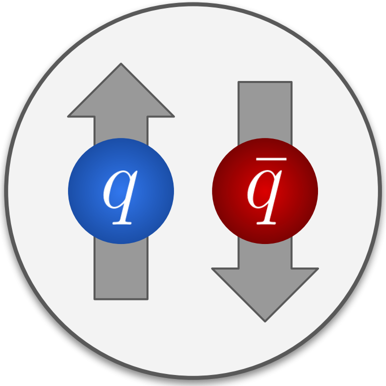
Meson Spectroscopy at Jefferson Lab

Charlie Velasquez (charlie.velasquez@york.ac.uk)

Meson Spectroscopy

Experimental Meson Spectrum

Meson	M (Exp)
$\pi^+[u\bar{d}]_{J^{PC}=0^{-+}}$	139.57039 ± 0.00018
$\pi^-[d\bar{u}]_{J^{PC}=0^{-+}}$	139.57039 ± 0.00018
$\pi^0[(u\bar{u} - d\bar{d})/\sqrt{2}]_{J^{PC}=0^{-+}}$	134.9768 ± 0.0005
$\rho^+[u\bar{d}]_{J^{PC}=1^{--}}$	775.4 ± 0.4
$\rho^-[d\bar{u}]_{J^{PC}=1^{--}}$	775.4 ± 0.4
$\rho^0[(u\bar{u} - d\bar{d})/\sqrt{2}]_{J^{PC}=1^{--}}$	775.26 ± 0.23
$\omega[(u\bar{u} + d\bar{d})/\sqrt{2}]_{J^{PC}=1^{--}}$	782.66 ± 0.13
$K^+[u\bar{s}]_{J^{PC}=0^{-+}}$	493.677 ± 0.016
$K^-[s\bar{u}]_{J^{PC}=0^{-+}}$	493.677 ± 0.016
$K^0[d\bar{s}]_{J^{PC}=0^{-+}}$	497.611 ± 0.013
$\overline{K}^0[s\bar{d}]_{J^{PC}=0^{-+}}$	497.611 ± 0.013
$K^{*+}[u\bar{s}]_{J^{PC}=1^{--}}$	891.67 ± 0.026
$K^{*-}[s\bar{u}]_{J^{PC}=1^{--}}$	891.67 ± 0.026
$K^{*0}[d\bar{s}]_{J^{PC}=1^{--}}$	896.00 ± 0.025
$\overline{K}^{*0}[s\bar{d}]_{J^{PC}=1^{--}}$	896.00 ± 0.025



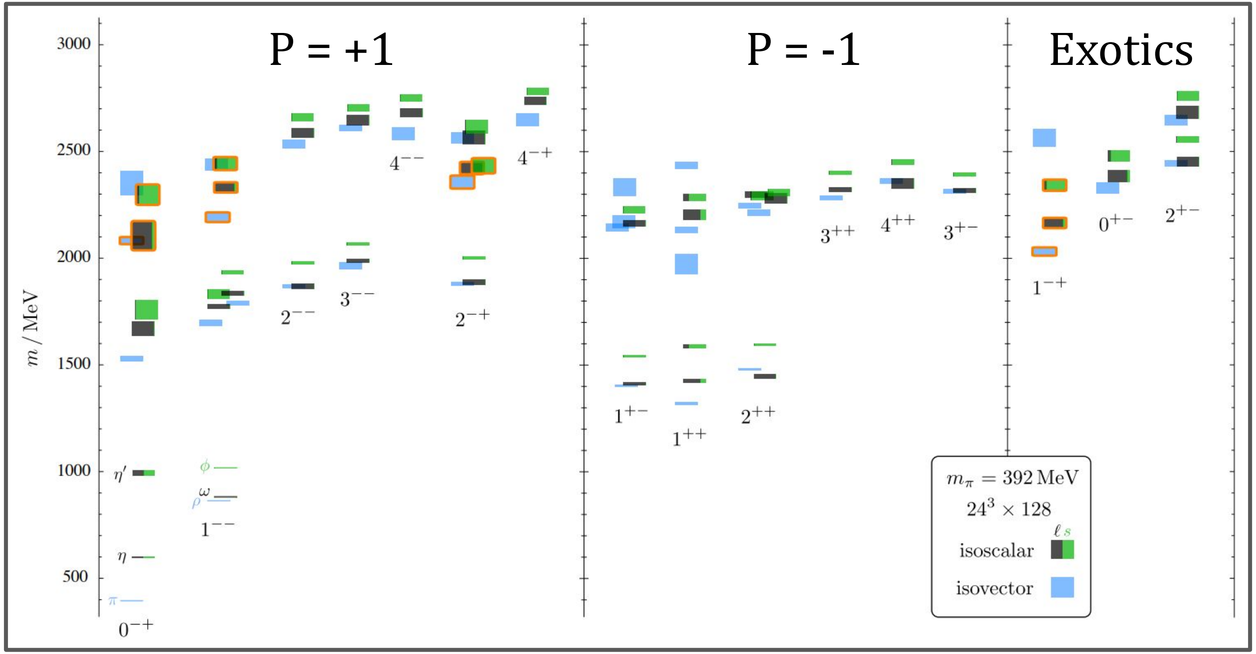
$$J = L + S$$

$$P = (-1)^{L+1}$$

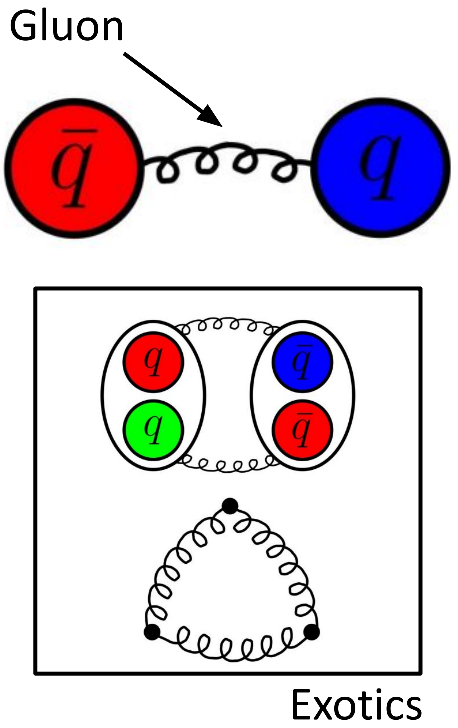
$$C = (-1)^{L+S}$$

Meson Spectroscopy

Lattice QCD Meson Spectrum



https://arxiv.org/pdf/1909.06366



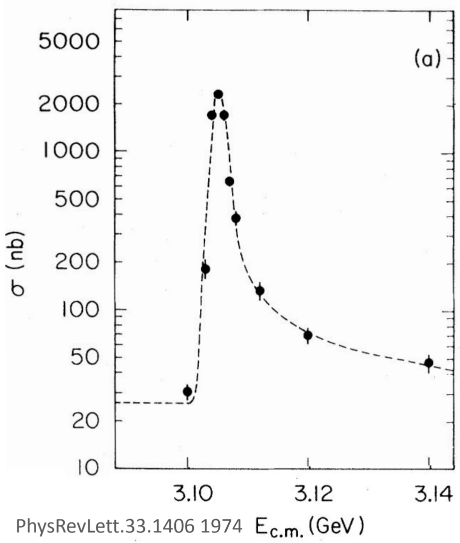
Meson Spectroscopy

Meson spectroscopy objectives:

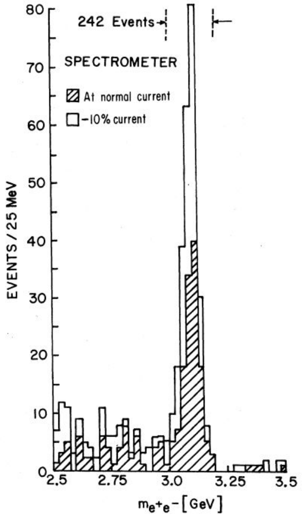
- Accurately determine properties of mesons
- Understand meson production and decay mechanisms
- Classify mesons
- Expand spectrum of known mesons
- Test predictions of lattice QCD
- Discover exotic mesons

Meson Spectroscopy

The November Revolution 1974



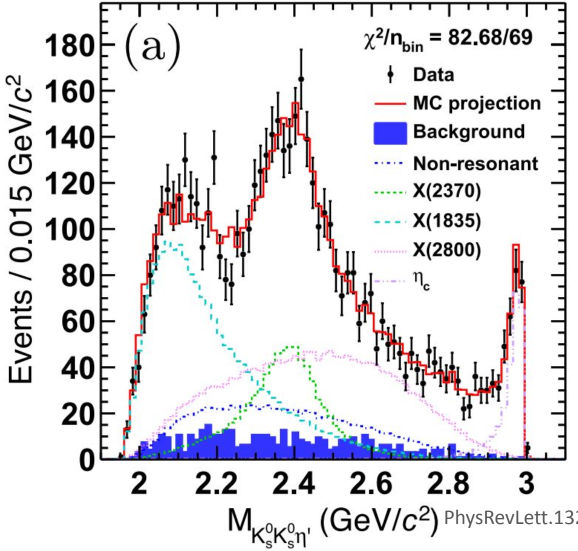
PhysRevLett.33.1406 1974



PhysRevLett.33.1404 1974

$$J/\psi \to e^- e^+$$

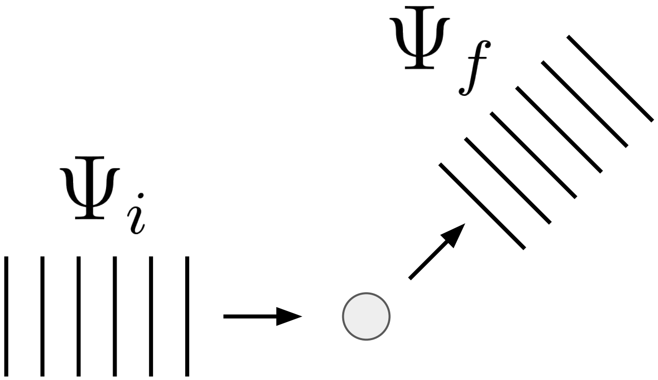
50 years on



PhysRevLett.132.181901 2024

$$X \to K_s^0 K_s^0 \eta'$$

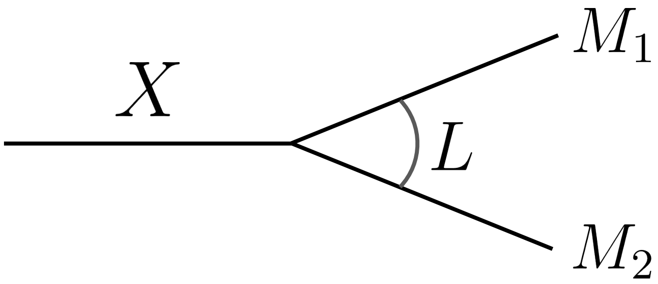
Partial Waves



$$\frac{d\sigma}{d\phi dcos\theta} = |\Psi_f - \Psi_i|^2$$
$$= \frac{1}{k^2} \left| \sum_{l=0}^{\infty} (2l+1) T_l P_l(cos\theta) \right|^2$$

T_l are the amplitudes which correspond to the proportion of eigenstate with angular momentum l in the final state, these amplitudes are known as the partial waves

Partial Waves



Allowed X states:

$$\hat{S}_1 = \hat{S}_2 = 0, L = 0, 1, 2, \ldots$$

$$J = L \quad P = C = -1^L$$

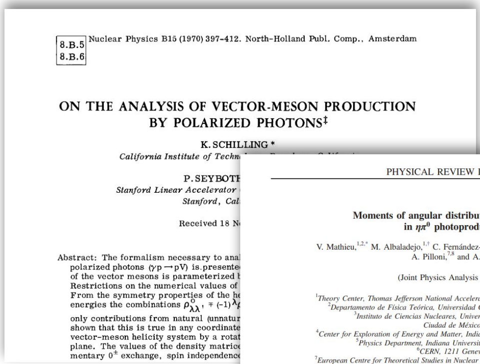
$$J^{PC} = 0^{++}, 1^{--}, 2^{++}, \ldots$$

For l = 2, the cross-section becomes,

$$\frac{d\sigma}{d\phi dcos\theta} \propto \boxed{T_0^2 P_0^2 + T_1^2 P_1^2 + T_2^2 P_2^2} + 2T_0T_1P_0P_1 + 2T_1T_2P_1P_2 + 2T_0T_2P_0P_2$$

Reaction of Interest

- Polarisation is a fundamental property of the photon
- Understand role of polarisation in meson photoproduction


8.B.5
8.B.6
Nuclear Physics B15 (1970) 397-412. North-Holland Publ. Comp., Amsterdam

ON THE ANALYSIS OF VECTOR-MESON PRODUCTION BY POLARIZED PHOTONS‡

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P. SEYBOTH
Stanford Linear Accelerator
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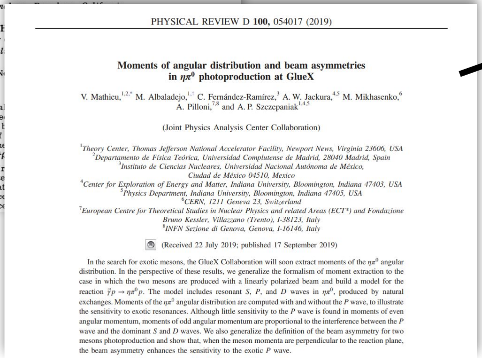
Received 18 N

Abstract: The formalism necessary to ana
polarized photons ($\gamma p \rightarrow pV$) is presente
of the vector mesons is parameterized
Restrictions on the numerical values of
From the symmetry properties of the
energies the combinations $\rho^0_{\lambda\lambda'} \mp (-1)^{\lambda}\rho$
only contributions from natural (unnatur
shown that this is true in any coordinate
vector-meson helicity system by a rota
plane. The values of the density matric
mentary $0^{\pm}$ exchange, spin independenc

Nuclear Physics BI5 (1970) 397-412


PHYSICAL REVIEW D **100**, 054017 (2019)

Moments of angular distribution and beam asymmetries in $\eta\pi^0$ photoproduction at GlueX

V. Mathieu,[1,2,*] M. Albaladejo,[1,†] C. Fernández-Ramírez,[3] A. W. Jackura,[4,5] M. Mikhasenko,[6] A. Pilloni,[7,8] and A. P. Szczepaniak[1,4,5]

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In the search for exotic mesons, the GlueX Collaboration will soon extract moments of the $\eta\pi^0$ angular distribution. In the perspective of these results, we generalize the formalism of moment extraction to the case in which the two mesons are produced with a linearly polarized beam and build a model for the reaction $\vec{\gamma}p \rightarrow \eta\pi^0 p$. The model includes resonant S, P, and D waves in $\eta\pi^0$, produced by natural exchanges. Moments of the $\eta\pi^0$ angular distribution are computed with and without the P wave, to illustrate the sensitivity to exotic resonances. Although little sensitivity to the P wave is found in moments of even angular momentum, moments of odd angular momentum are proportional to the interference between the P wave and the dominant S and D waves. We also generalize the definition of the beam asymmetry for two mesons photoproduction and show that, when the meson momenta are perpendicular to the reaction plane, the beam asymmetry enhances the sensitivity to the exotic P wave.

Phys. Rev. D 100, 054017

$$\frac{d\sigma}{dt\,dm_{KK}\,d\Omega\,d\Phi} \propto P_\gamma X \left| \sum_{l=0}^{l_{max}} T^l_m Y^m_l(\Omega) \right|^2$$

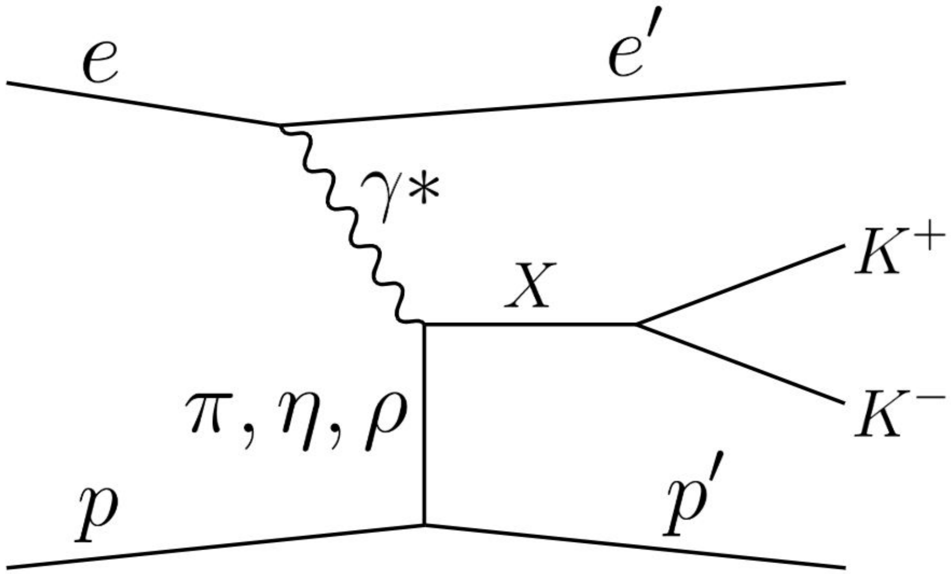
Photon linear polarization

$X = \cos(2\Phi),$
$\sin(2\Phi)$

Ω=(θ,ϕ) Gottfried-Jackson frame

Reaction of Interest

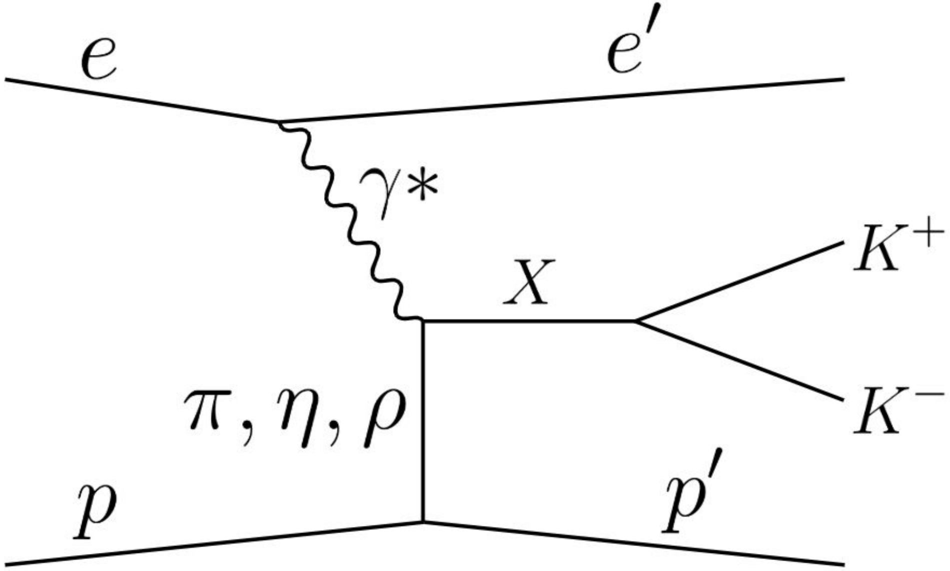
Reaction of interest: $ep \rightarrow ep' K^+ K^-$



- Photon (quasi-real) transfers momentum
- High degree of linear polarisation (P_γ>70%)
- Pomeron exchange, access to various X quantum numbers

Reaction of Interest

Reaction of interest: $ep \rightarrow ep'K^+K^-$



Cross-section:

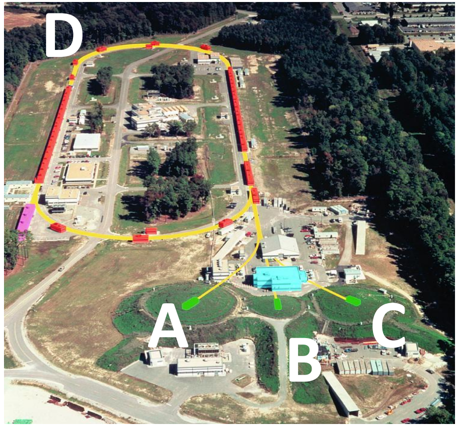
$$\frac{d\sigma}{dtdm_{KK}d\Omega d\Phi} \propto P_\gamma X \left| \sum_{l=0}^{l_{max}} T_m^l Y_l^m(\Omega) \right|^2$$

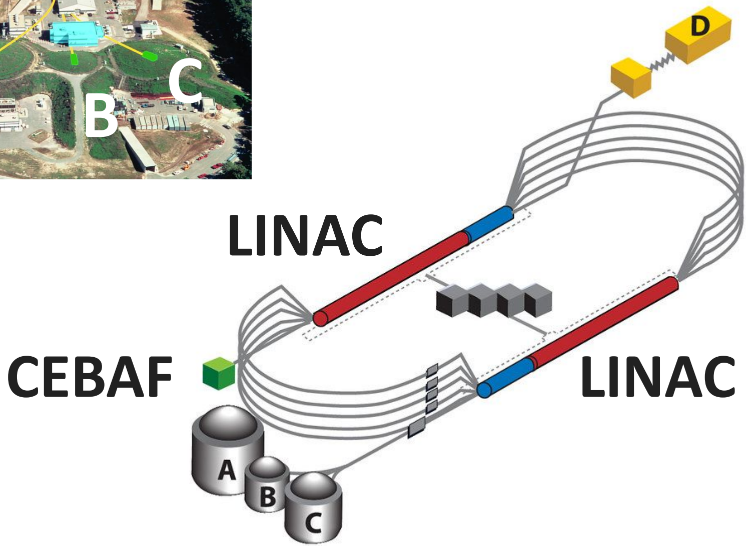
Allowed X states:

$$J^{PC} = 0^{++}, 1^{--}, 2^{++}, \ldots$$

Jefferson Laboratory

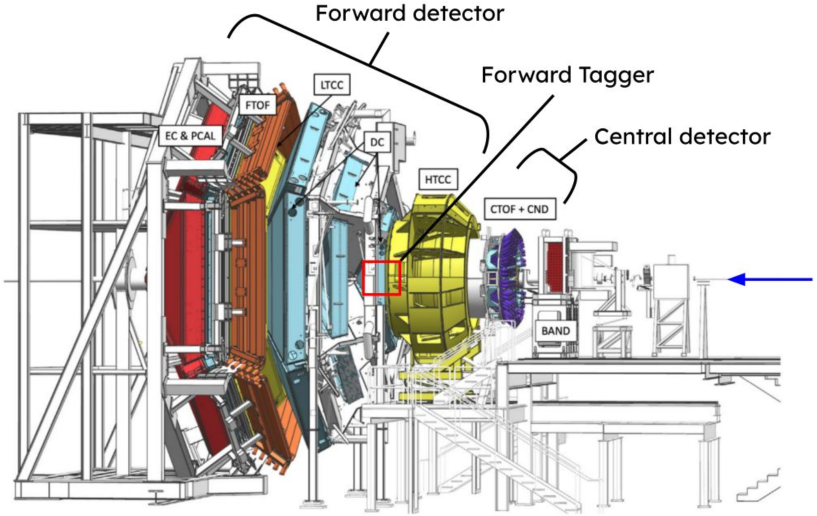
- Multi-GeV electron beam
- High luminosity beam
- Spin polarised beam
- Four experimental halls





CLAS12

- Located in hall B
- Determination of 4-momenta of particles
- 2.5° to 125° acceptance



Experimental Data

Data was obtained under the following conditions:

- 10.2 Gev per electron
- Liquid hydrogen target

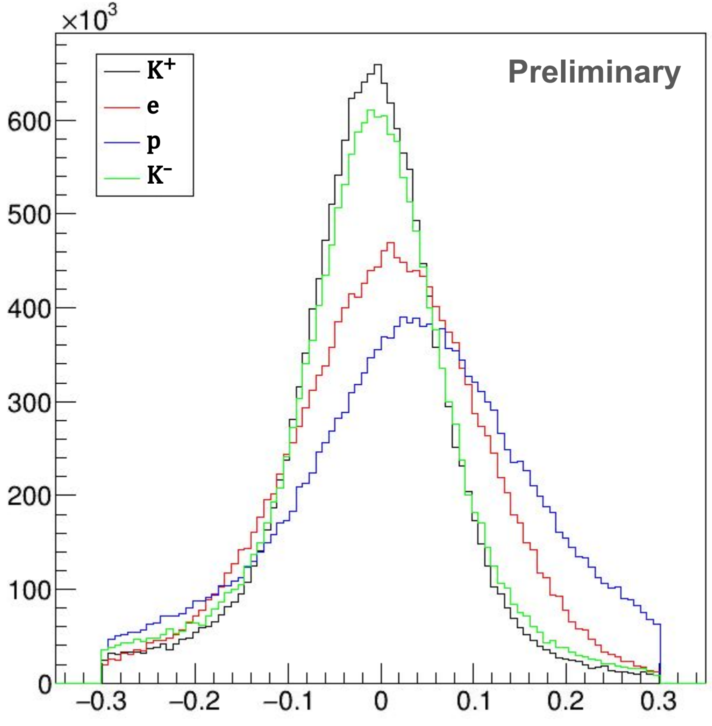
Obtaining events corresponding to the reaction of interest required:

- Event selection
- Reaction reconstruction

Event selection

Conditions:

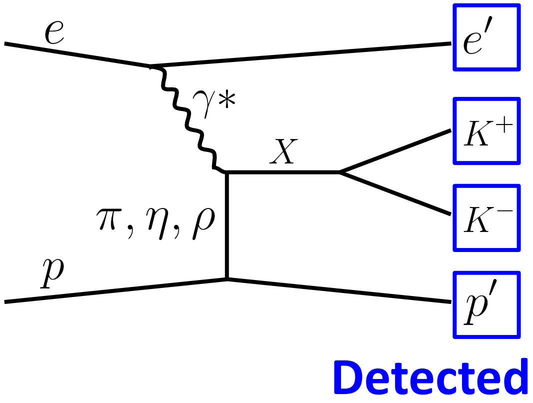
- Topology: epK^+K^-
- $\Delta t = |TOF_{FTOF} - TOF_{DC}| < 0.3$ ns
- Scattered electron:
    - Forward Tagger
    - $0.4 < E < 5$ GeV
- Kaons: Forward Detector

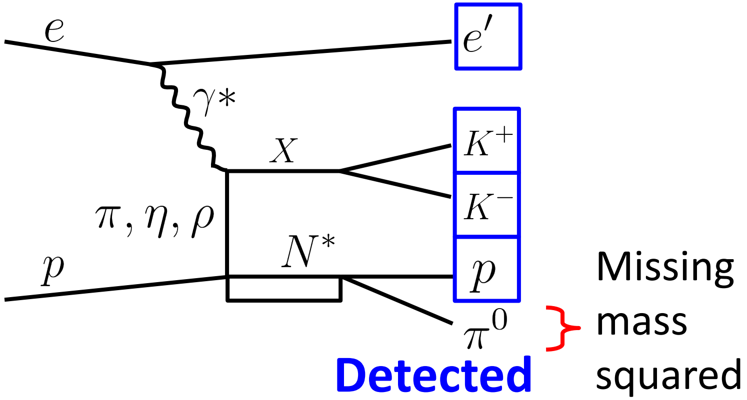


Reaction reconstruction

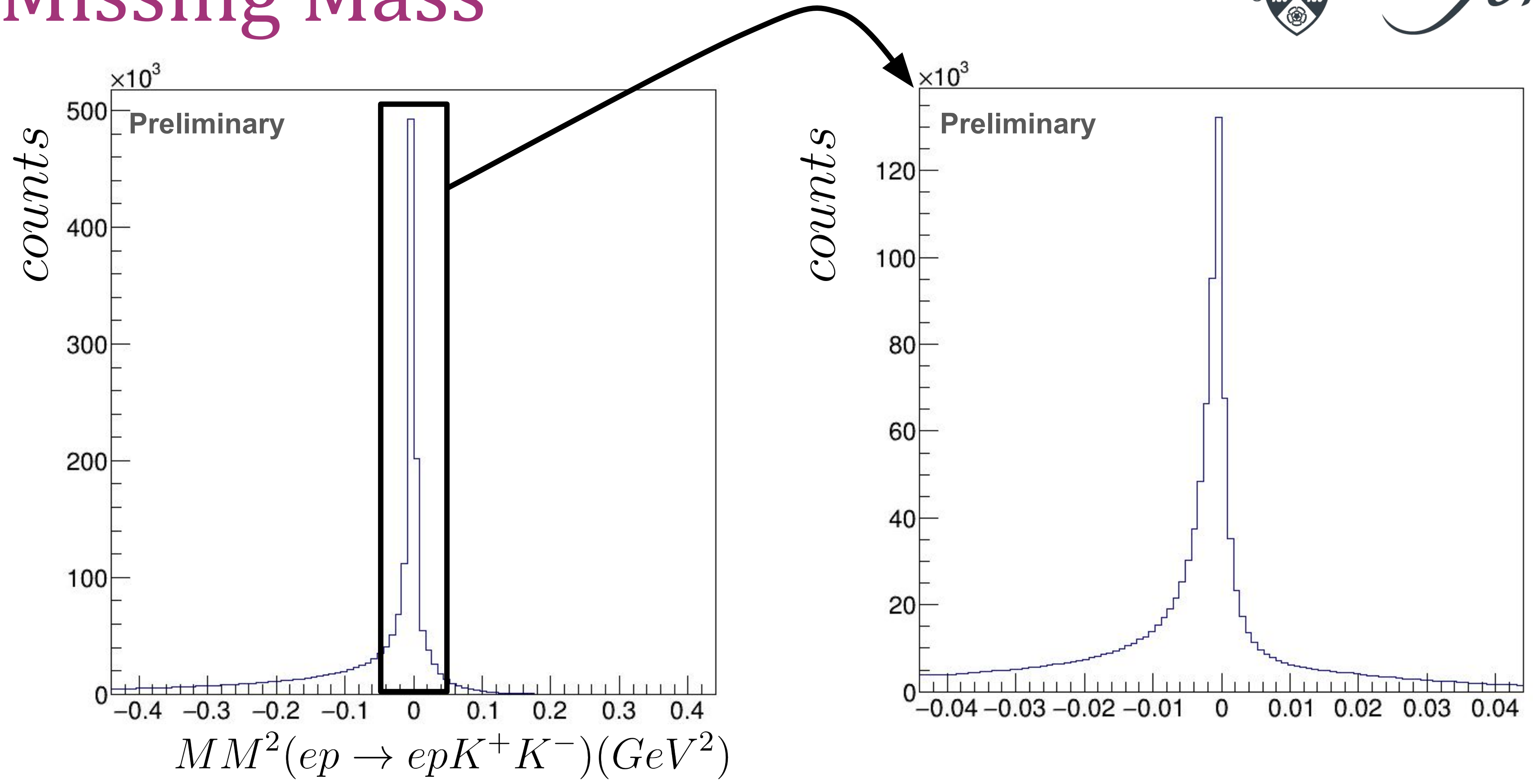
Missing mass squared of the event:

$$MM^2(ep \rightarrow e'pK^+K^-X) = |P_b + P_t|^2 - |P_{e'} + P_p + P_{K^+} + P_{K^-}|^2$$

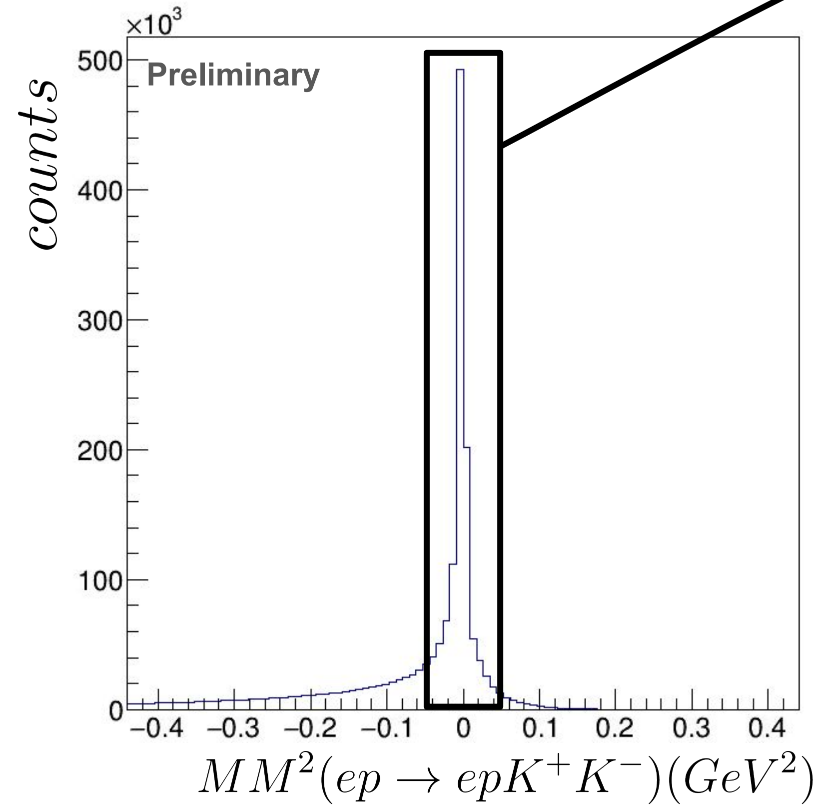


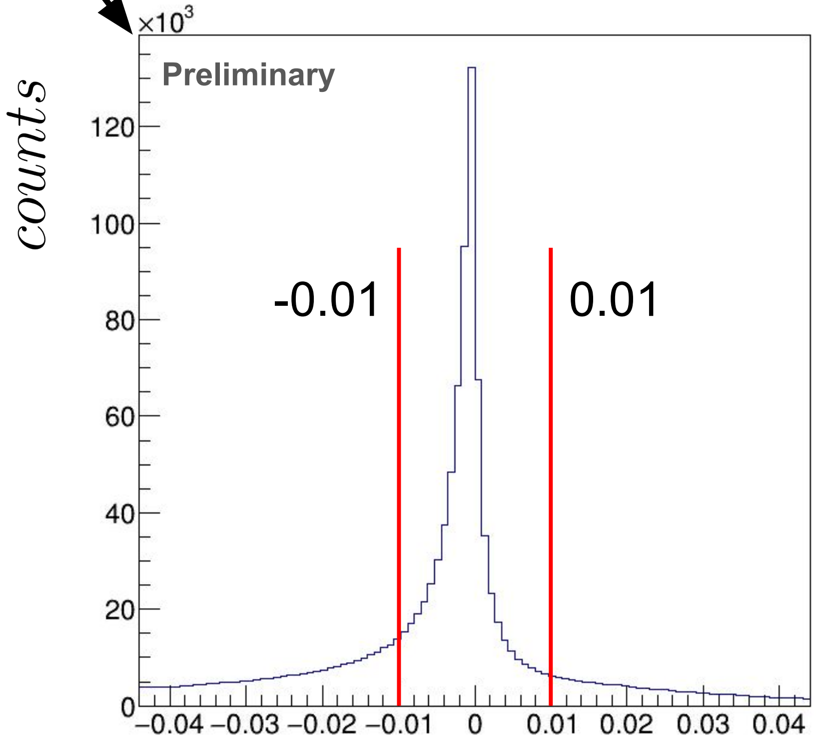


Missing Mass



Missing Mass

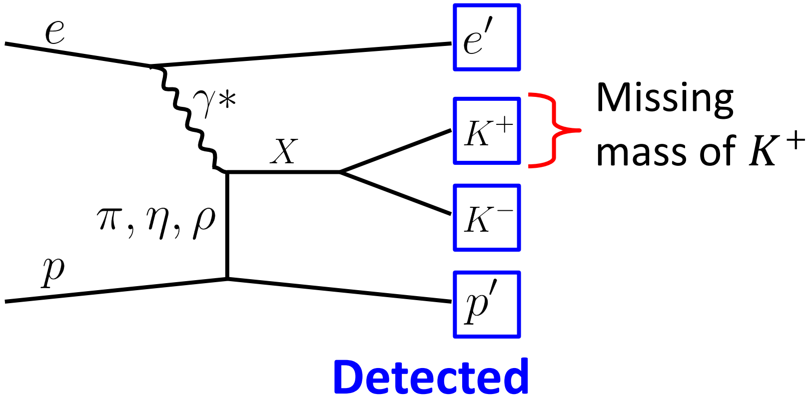


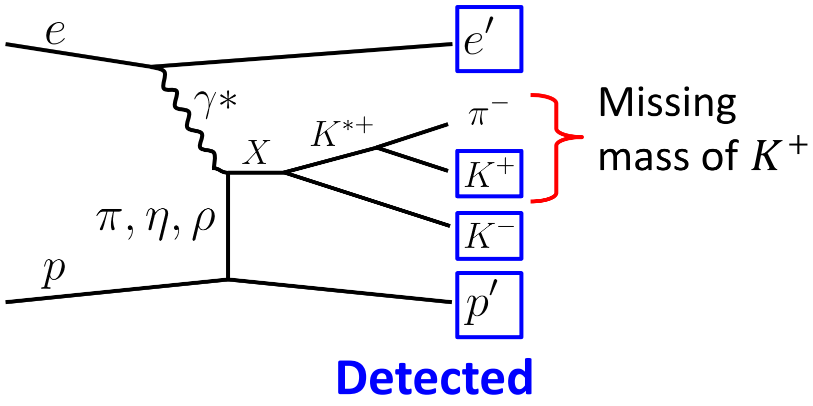


Reaction reconstruction

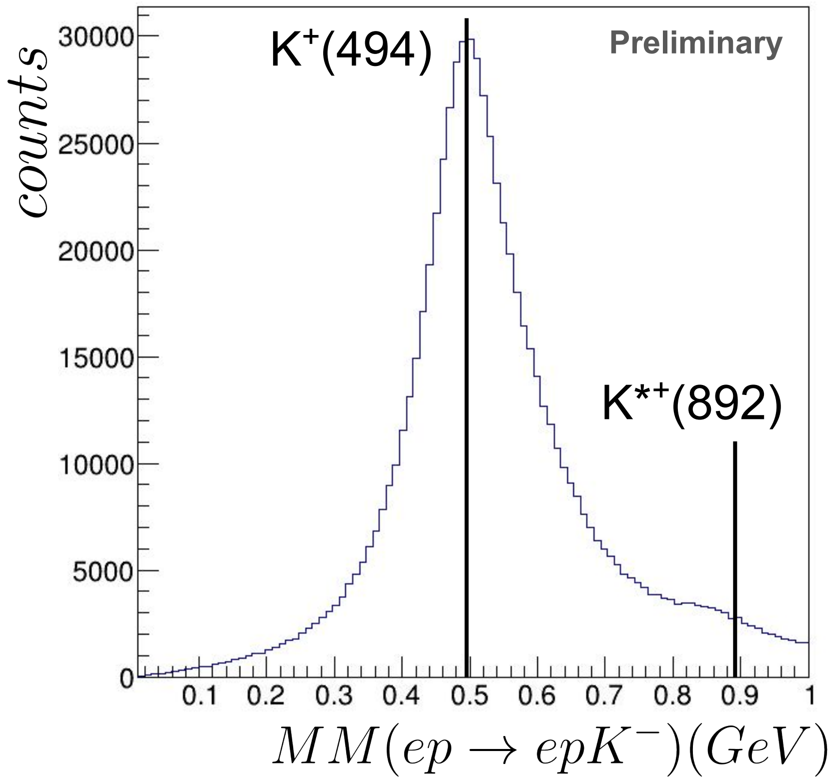
Missing mass of the kaons:

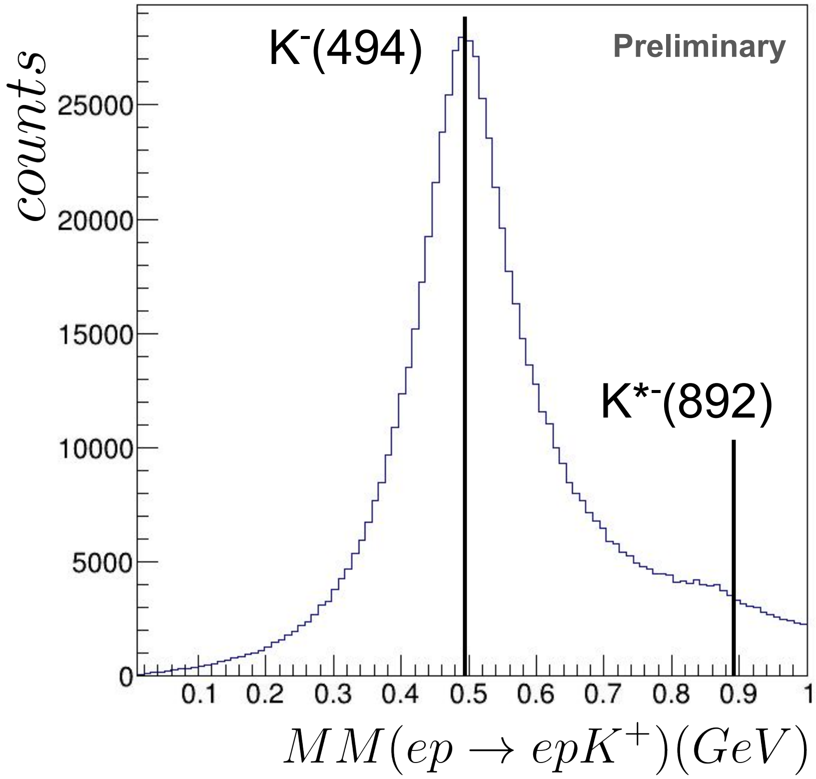
$$MM(ep \rightarrow e'pK^{\pm}X) = \sqrt{(|P_b + P_t|^2 - |P_{e'} + P_p + P_{K^{\pm}}|^2)}$$



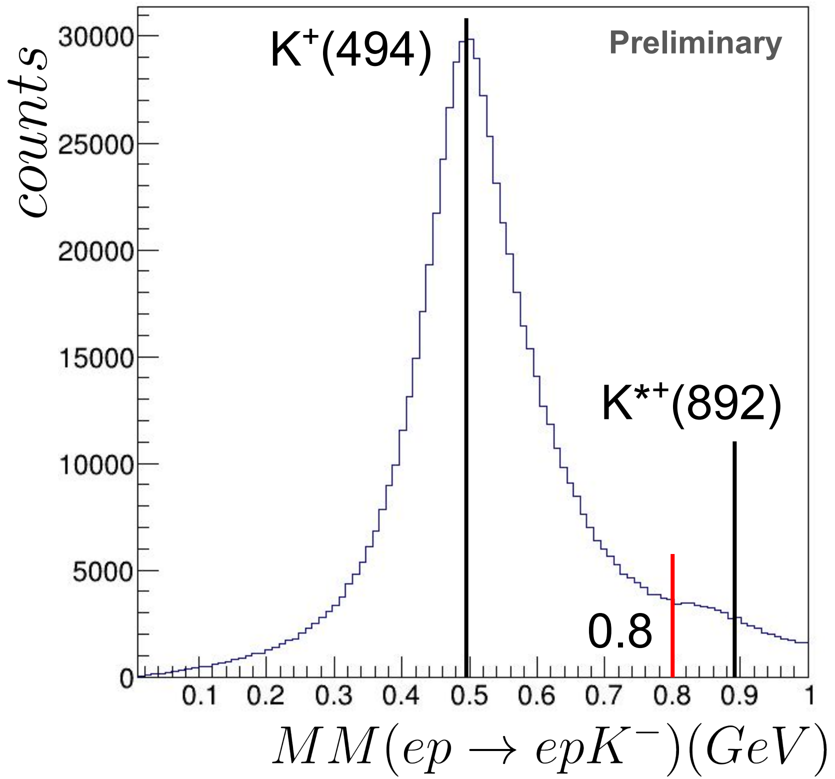


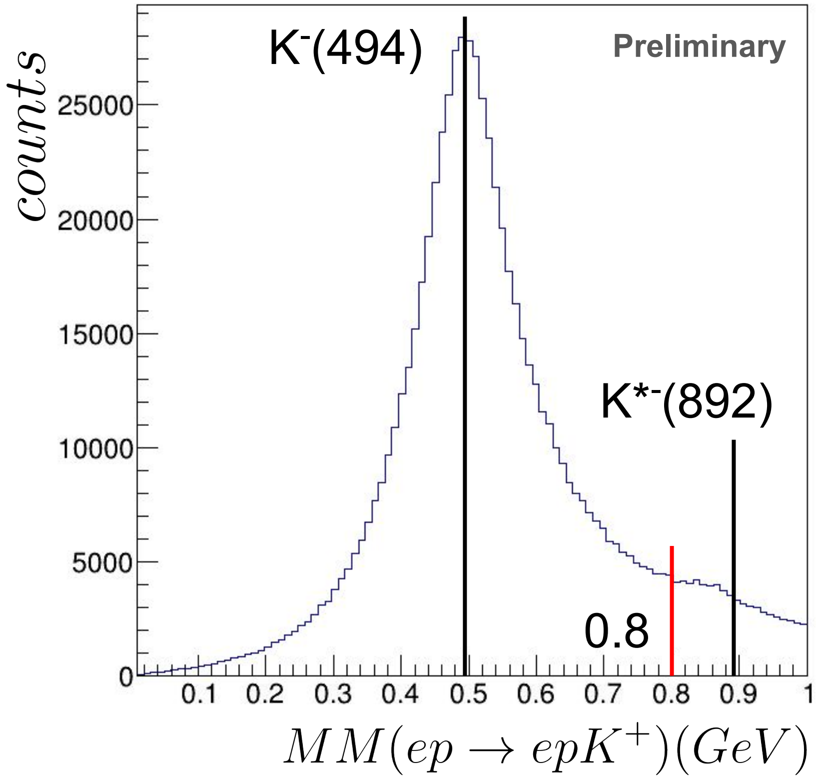
Missing Mass





Missing Mass

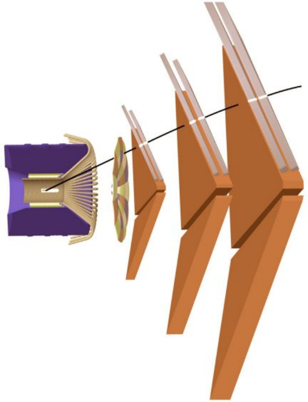




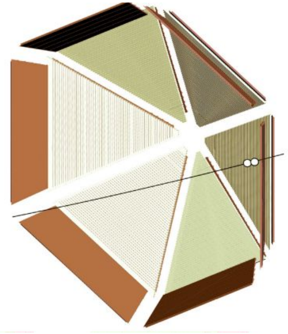
Simulations

Simulated data workflow:

- Created using Monte-Carlo event generator
- Passed through GEANT4 model of the detector
- Acceptances and efficiencies calculated
- Same event selection and reaction reconstruction was applied



Drift chambers

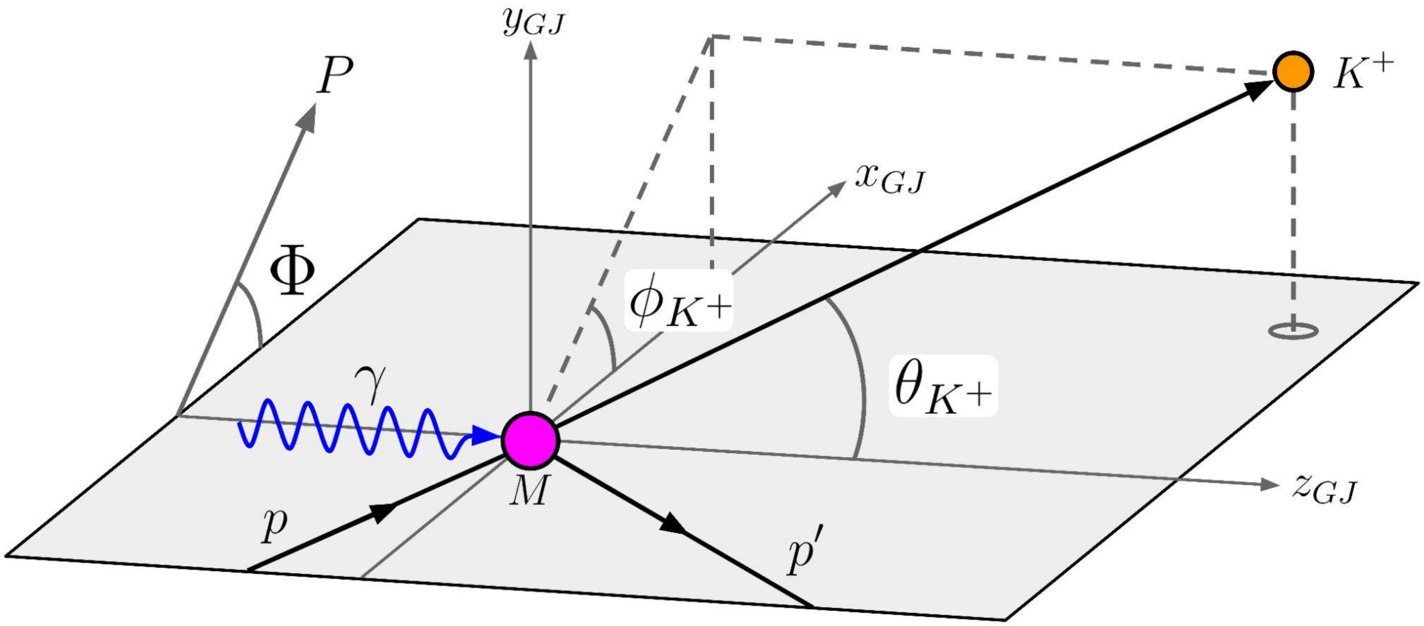


FTOF system

[The CLAS12 Geant4 simulation - ScienceDirect](j.nima.2020.163422)
j.nima.2020.163422

Angular distributions

Angular distributions in the Gottfried-Jackson frame were obtained.



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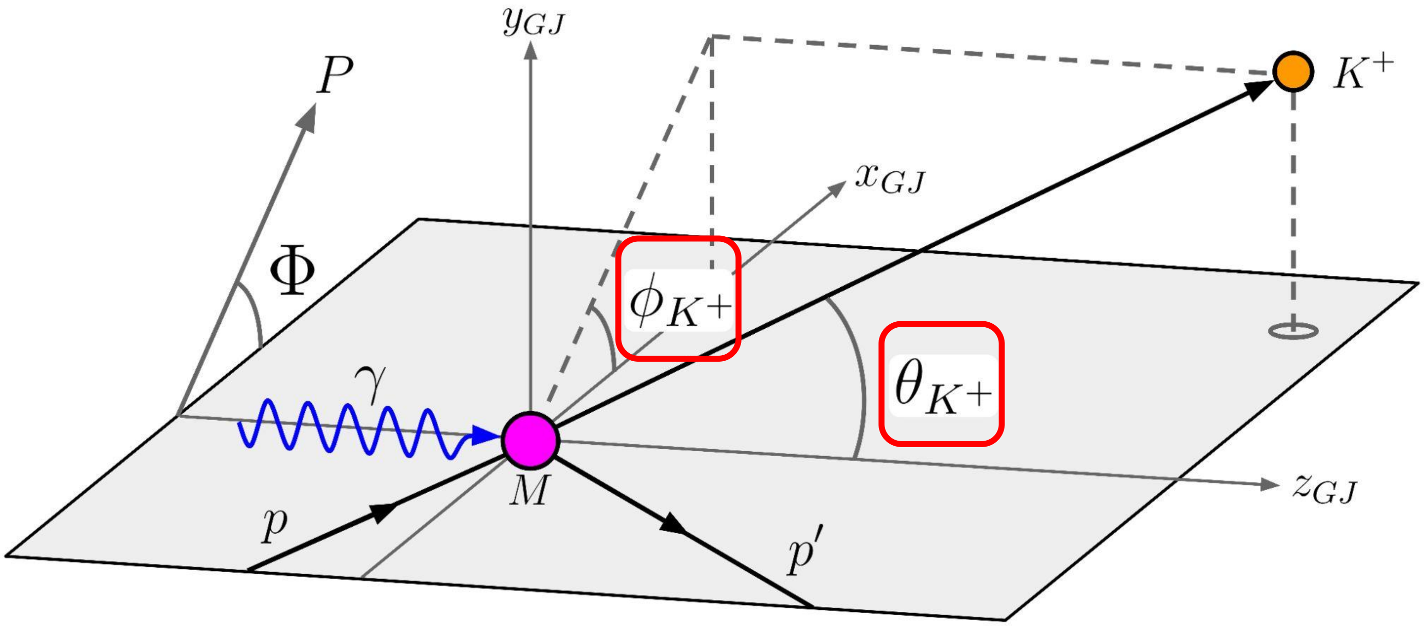
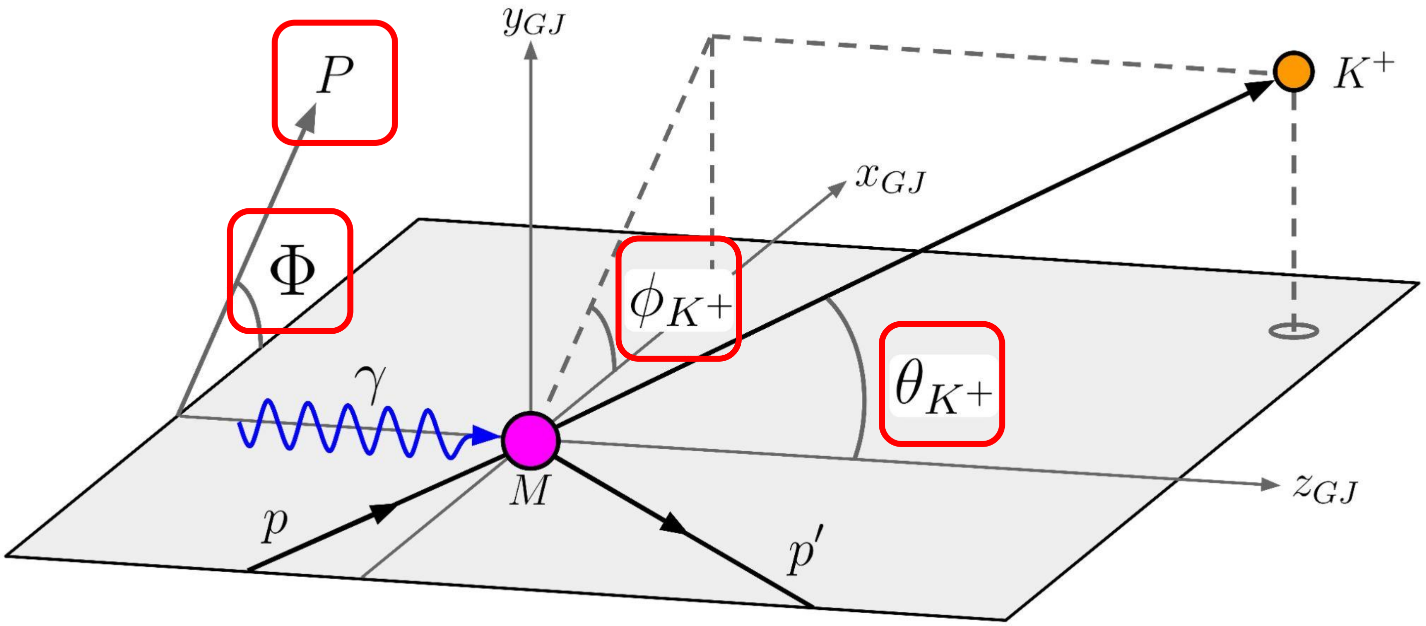


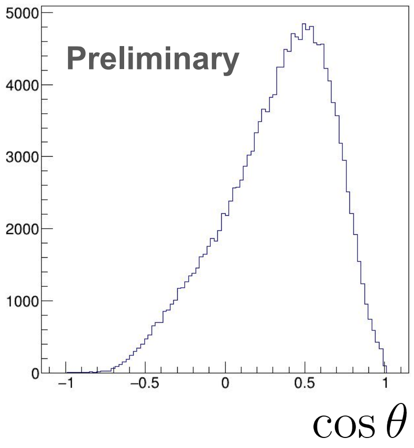
Angular distributions

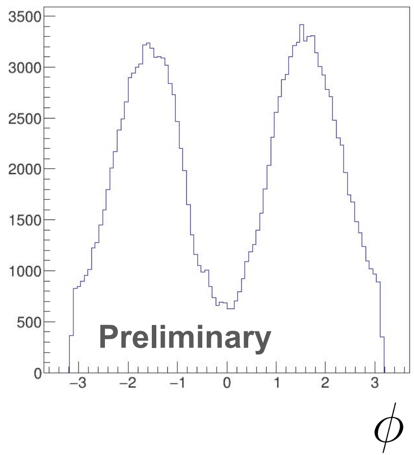
Angular distributions in the Gottfried-Jackson frame were obtained.

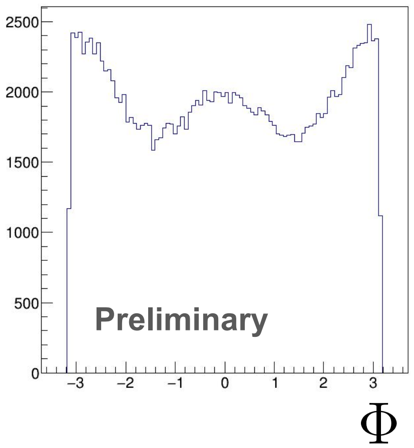


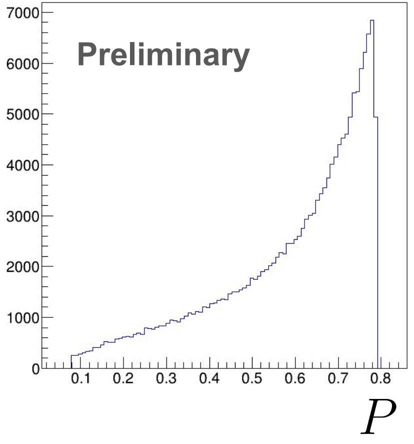
Angular distributions

Gottfried-Jackson angular distributions and polarisation for experimental data.





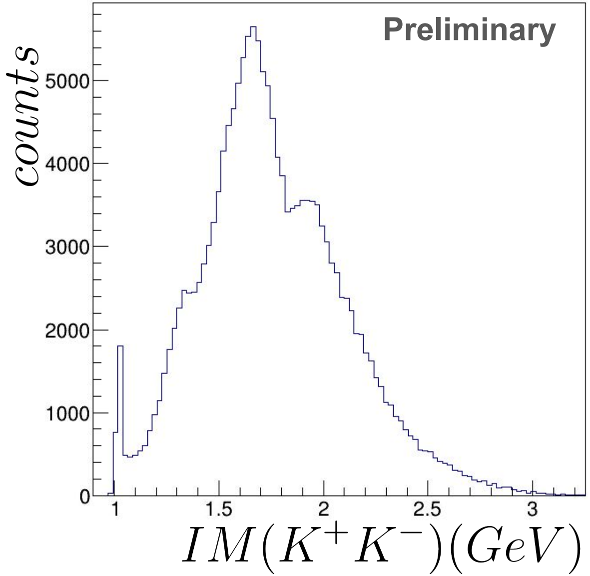




Extracting Partial Waves

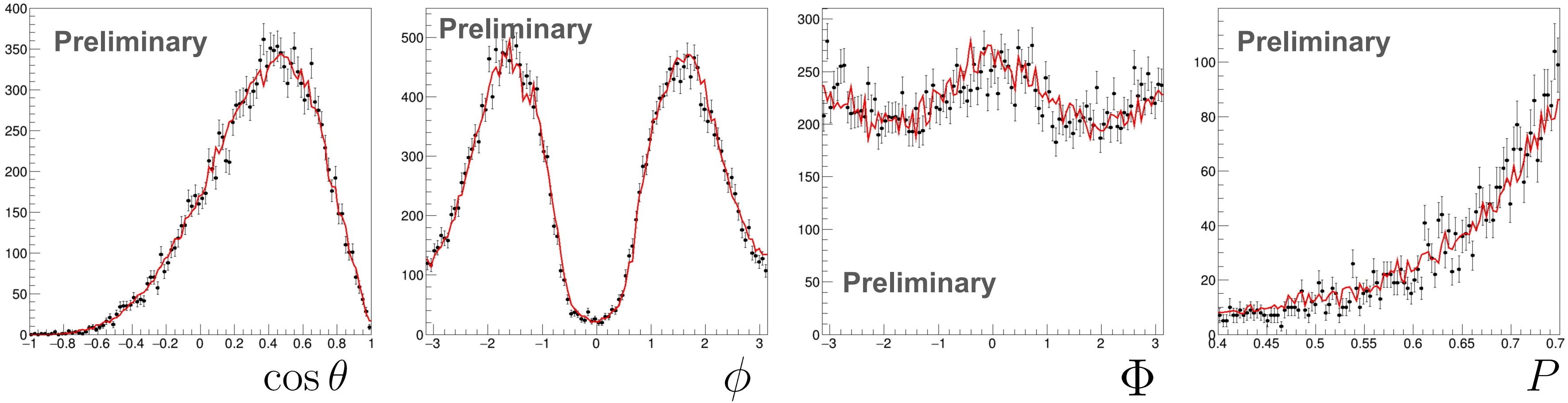
Partial waves were calculated using event-by-event maximum likelihood fitting and partial waves were acceptance- corrected.

Data were split into 40 K^+K^- invariant mass bins between 1.0 and 2.5 GeV. The partial waves were calculated independently in each bin.

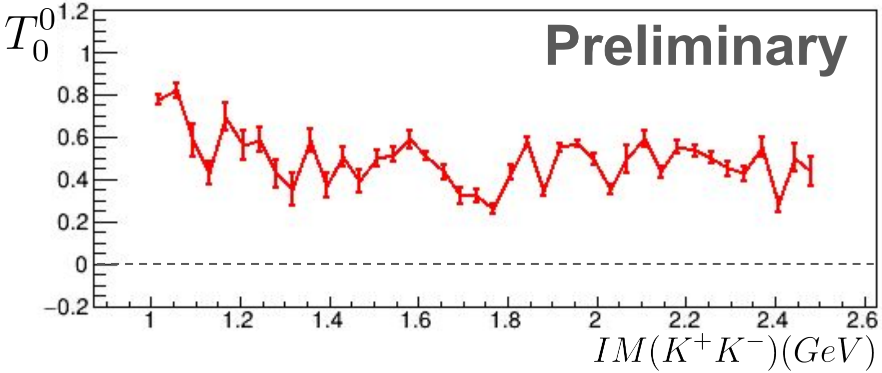


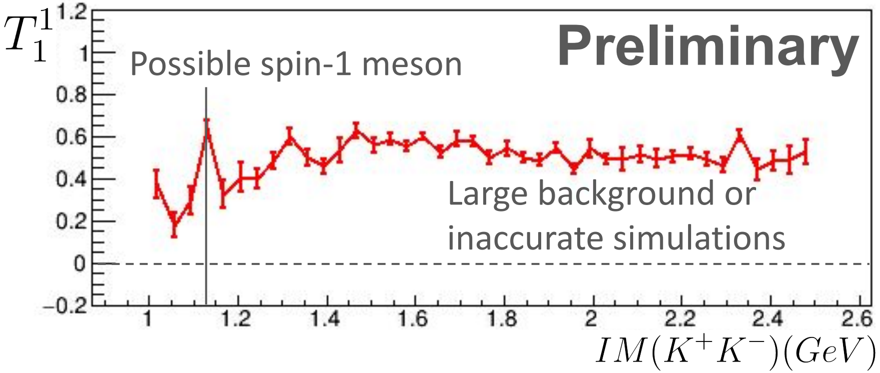
Extracting Partial Waves

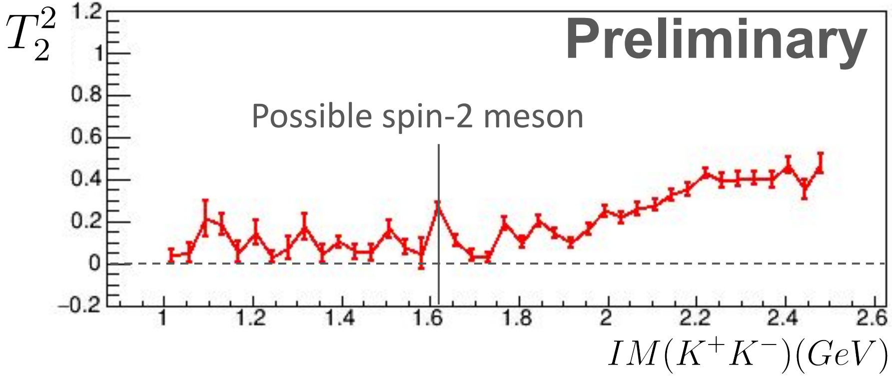
Polarisation and angular distributions for experimental (black) and projection of fit for each variable (red).



Results







UNIVERSITY of York

Outlook

Topics of future research:

- Improve accuracy of simulated data
- Systematic studies on all reaction reconstruction conditions
- Implementation of background removal
- Study of other reactions such as $ep \rightarrow ep'K^+K^-\pi^0$

Thank you for listening

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Reaction of Interest

Amplitude

Polarisation matrix

$$I(\Omega,\Phi) \equiv \frac{d\sigma}{dt\,dm_{KK}\,d\Omega\,d\Phi} = \kappa \sum A(\Omega)\rho^{\gamma}(\Phi)A^{*}(\Omega)$$

Polarisation

$$= I^{0}(\Omega) - P_{\gamma} I^{1}(\Omega)\cos 2\Phi - P_{\gamma} I^{2}(\Omega)\sin 2\Phi$$

$$I^{n}(\Omega) \propto \sum A(\Omega)A^{*}(\Omega)$$

$$A(\Omega) = \sum T_{m}^{l} Y_{l}^{m}(\Omega)$$

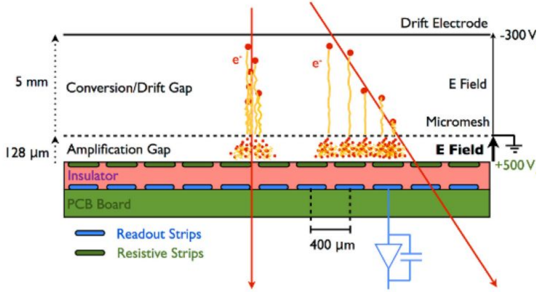
$$\frac{d\sigma}{dt\,dm_{KK}\,d\Omega\,d\Phi} \propto P_{\gamma}\left|\sum_{l=0}^{l_{max}} T_{m}^{l} Y_{l}^{m}(\Omega)\right|^{2}$$

Partial waves

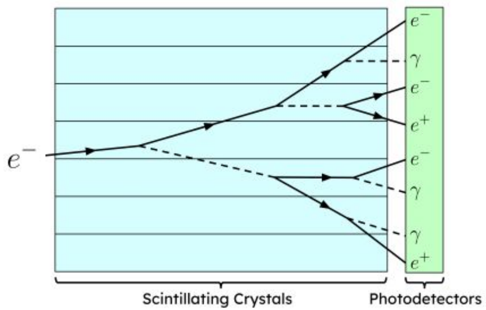
Phys. Rev. D 100, 054017

CLAS12

Micromegas gas tracker - determines vertex, momentum



Calorimeter - determines energy



$$M^2 = p_p^2 \cdot \frac{1. - \beta^2}{\beta^2}$$

$$\beta = \frac{P_L}{t_p c}$$

p_p - particle momentum

P_L - particle path length

t_p - flight time over P_L

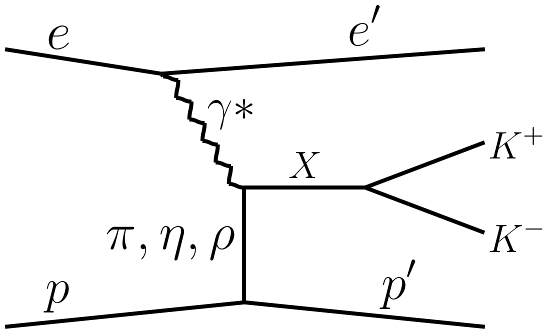
Missing mass

The missing mass squared of the reaction is given by:

$$MM^2(ep \rightarrow e'pK^+K^-X) = |P_b + P_t|^2 - |P_{e'} + P_p + P_{K^+} + P_{K^-}|^2$$

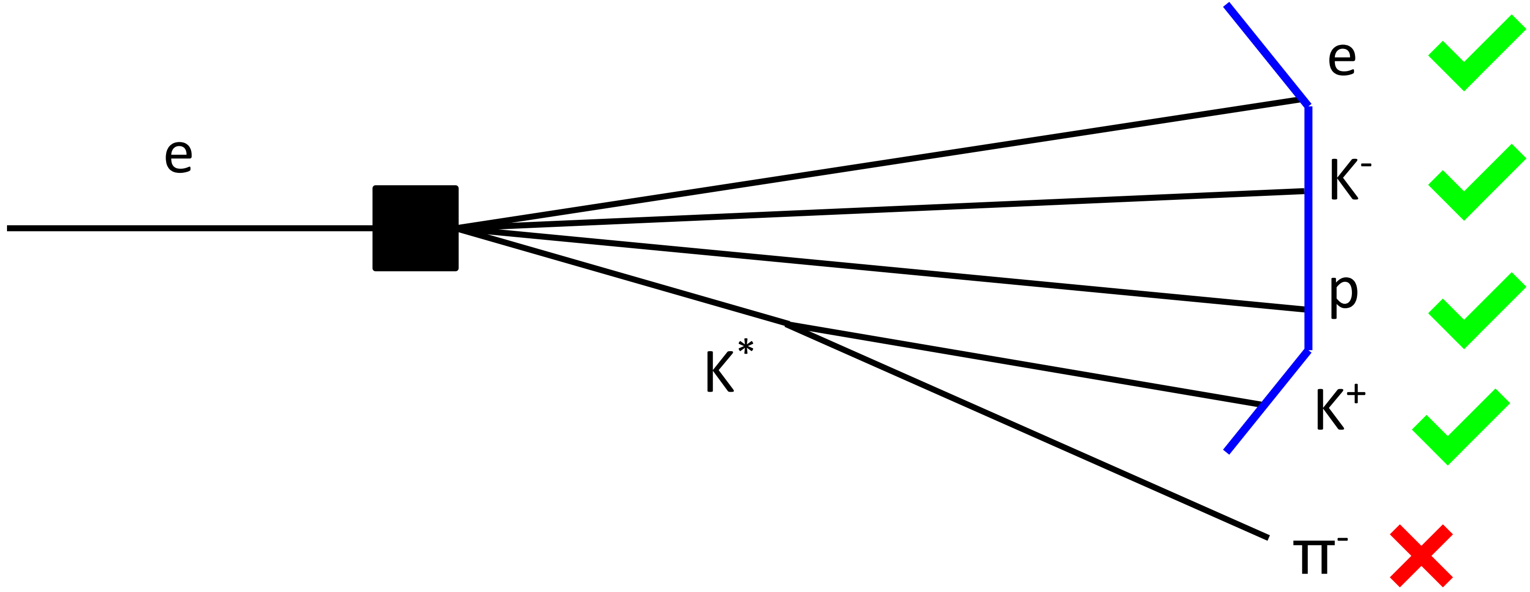
$$= (E_b + m_t - E_{e'} - E_p - E_{K^+} - E_{K^-})^2$$

$$- |\bar{p}_b + \bar{p}'_e - \bar{p}_p - \bar{p}_{K^+} - \bar{p}_{K^-}|^2$$



Missing mass

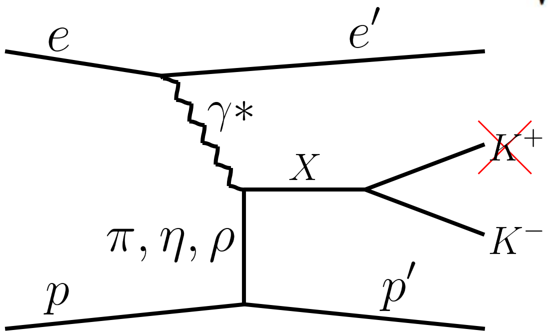
An example:



Missing mass

The K^+ missing mass is given by:

$$MM(ep \to e' p K^- X) = \sqrt{|P_b + P_t|^2 - |P_{e'} + P_p + P_{K^-}|^2}$$
$$= \sqrt{(E_b + m_t - E_{e'} - E_p \ - E_{K^-})^2 \ - |\bar{p}_b + \bar{p}_{e'} - \bar{p}_p - \bar{p}_{K^-}|^2}$$



Angular distributions

Angular distributions in the Gottfried-jackson frame were obtained.

$$P = [1 + 2\frac{Q^2 + v^2}{Q^2}\tan^2(\frac{\theta_{e'}}{2})]^{-1}$$

$$Q^2 = 4E_b E_{e'} \sin^2(\frac{\theta_{e'}}{2})$$