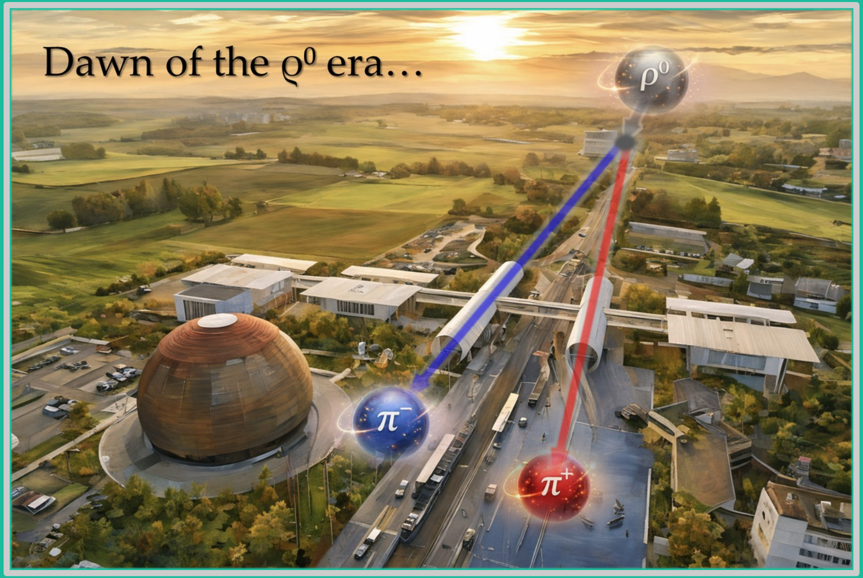


Vector Mesons in Collider Kinematics with PYTHIA

Christopher Dilks

EMMI Rapid Reaction Task Force

17 June 2026, CERN

Simulating Fragmentation: String + $^3P_0$ Model

- Fragmentation is handled by the Lund String Model
  - Spin effects in fragmentation are handled by the "$^3P_0$" model
  - Implemented in an event generator, "StringSpinner"

- PYTHIA handles PDFs
  - StringSpinner includes the quark transversity distribution

See Albi's talk (Monday) for details

String + $^3P_0$ Model

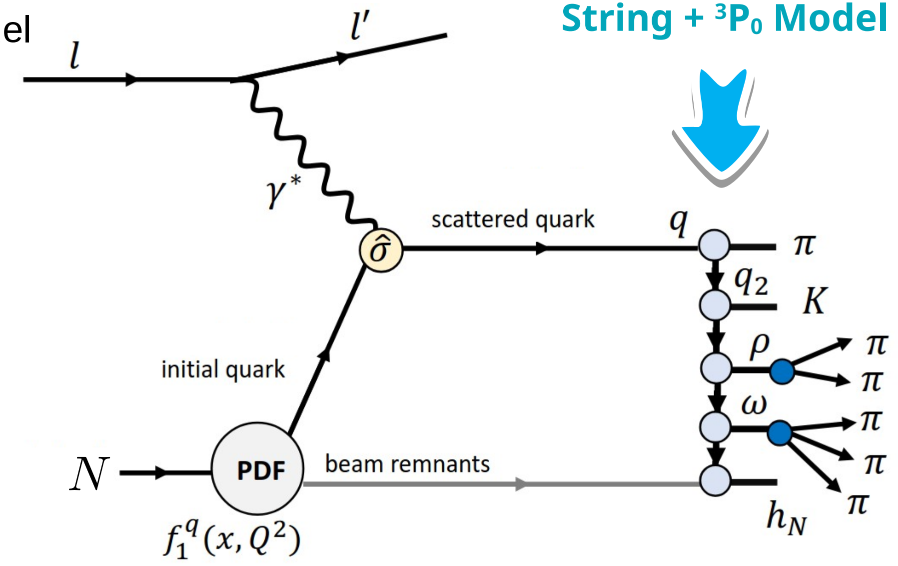
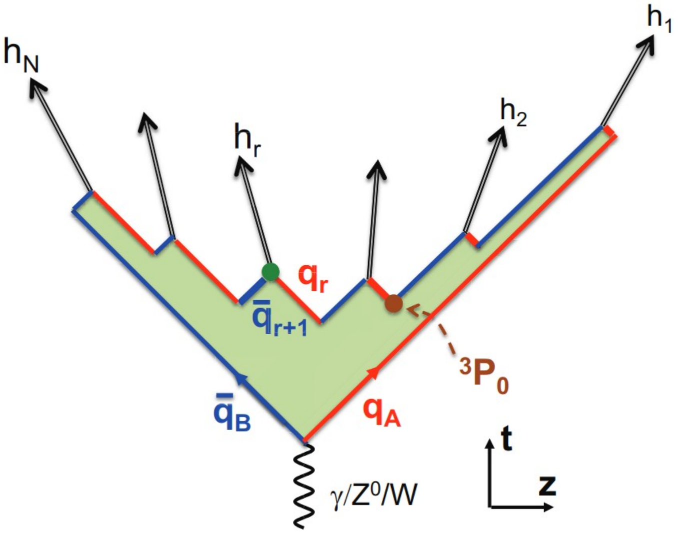


Figure adapted from A. Kerbizi, SPIN2023 presentation

String + $^3P_0$ Model

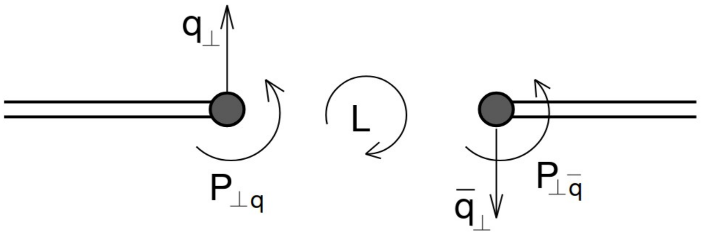
- Lund String Model for fragmentation
- Tunnelling of q-qbar pair in relative $^3P_0$ state



X. Artru, A. Kerbizi, JPS Conf.Proc. 37 (2022), 020101

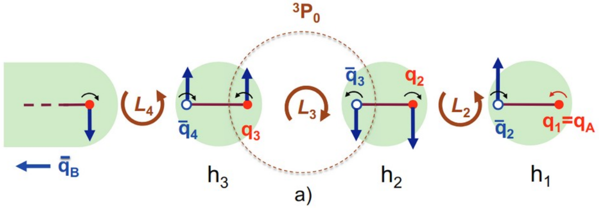
$^3P_0$ state

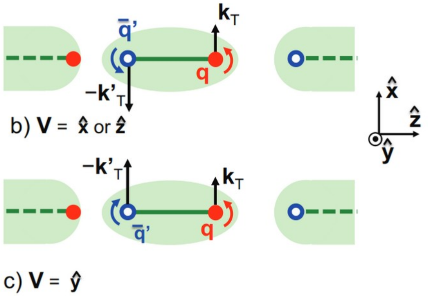
$^{2S+1}L_J \rightarrow S = 1 = -L \rightarrow J = 0$



X. Artru, J. Czyzewski, Acta Phys.Polon.B 29 (1998), 2115-2127

- Produce pseudoscalar mesons (a)
- Or vector mesons (b) & (c)





X. Artru, A. Kerbizi, JPS Conf.Proc. 37 (2022), 020101

StringSpinner Software

- **StringSpinner = Pythia 8 + String+$^3P_0$ model**
  - Uses Pythia's UserHooks to reweight unpolarized hadronization procedure according to the String+$^3P_0$ model
  - Angular momentum correlations with vector meson decay handled by Collins-Knowles recipe via Pythia's DecayHandler
  - Compatible with Pythia 8.3
- **Available on GitLab at** https://gitlab.com/albikerbizi/stringspinner/-/tree/master
  - Maintained by Albi Kerbizi, et al.
  - Allows anyone to use the String+$^3P_0$ model
- **For usage at CLAS, we have "clas-stringspinner"**
  - Available at https://github.com/JeffersonLab/clas-stringspinner
  - Consumer code
    - Runs Stringspinner+Pythia8, tuned for CLAS(12)
    - Outputs data formats compatible with CLAS12 simulation software

StringSpinner References:

- A. Kerbizi and L. Lönnblad, Comput.Phys.Commun. 272 (2022), 108234
- A. Kerbizi and L. Lönnblad, Comput.Phys.Commun. 292 (2023), 108886

Pythia 8.3:

- C. Bierlich, S. Chakraborty, N. Desai, L. Gellersen, I. Helenius, et al., SciPost Phys.Codeb. 2022 (2022), 8

Pythia 8 Tune for CLAS12

- Used Pythia 8.312 for tuning, but currently running 8.317
  - CLASDIS: well studied Pythia 6 event generator tuned for CLAS12 → starting point for tuning our Pythia 8
- NNPDF 2.3 PDFs (Pythia 8.3 default)
- SpaceShower:dipoleRecoil = off, since StringSpinner not handling multiple partons in showering process
- ISR, FSR, MPI = off
- Fragmentation Parameters: a = 1.2, b = 0.58 GeV^{-2}
- Ratio of Vector Meson to Pseudoscalar meson:
  - 0.7 for light quarks (ρ/π)
  - 0.75 for strange quarks (K^*/K)
    - Both larger than in Albi's presentation, but consistent with our Pythia 6 tune
- Quark transverse momenta:
  - p_T width: StringPT:sigma = 0.5 GeV
  - k_T width: 0.64 GeV → understood in CLASDIS, needs <u>more study</u> in Pythia 8

StringSpinner Parameters

- **Complex mass for the $^3P_0$ wave function**

$$\mu \in \mathbb{C} \qquad \begin{array}{ll} \mathrm{Re}\mu & \text{Longitudinal spin effects} \\ \mathrm{Im}\mu & \text{Transverse spin effects} \end{array}$$

$$\mu = 0.42 + 0.76i \ \mathrm{GeV}$$

from e^+e^- Collins from data comparisons

A. Kerbizi, X. Artru, Z. Belghobsi, F. Bradamante, A. Martin, Phys.Rev.D 97 (2018) 7, 074010

- **Fraction of longitudinally polarized vector mesons (VMs)**

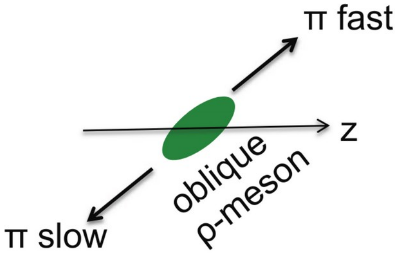
$$f_L := \frac{|G_L|^2}{2|G_T|^2 + |G_L|^2} \in [0, 1)$$

$$G_L, G_T \in \mathbb{C}$$

couplings of quarks to VMs with Longitudinal (L) or Transverse (T) polarization (w.r.t. string axis)

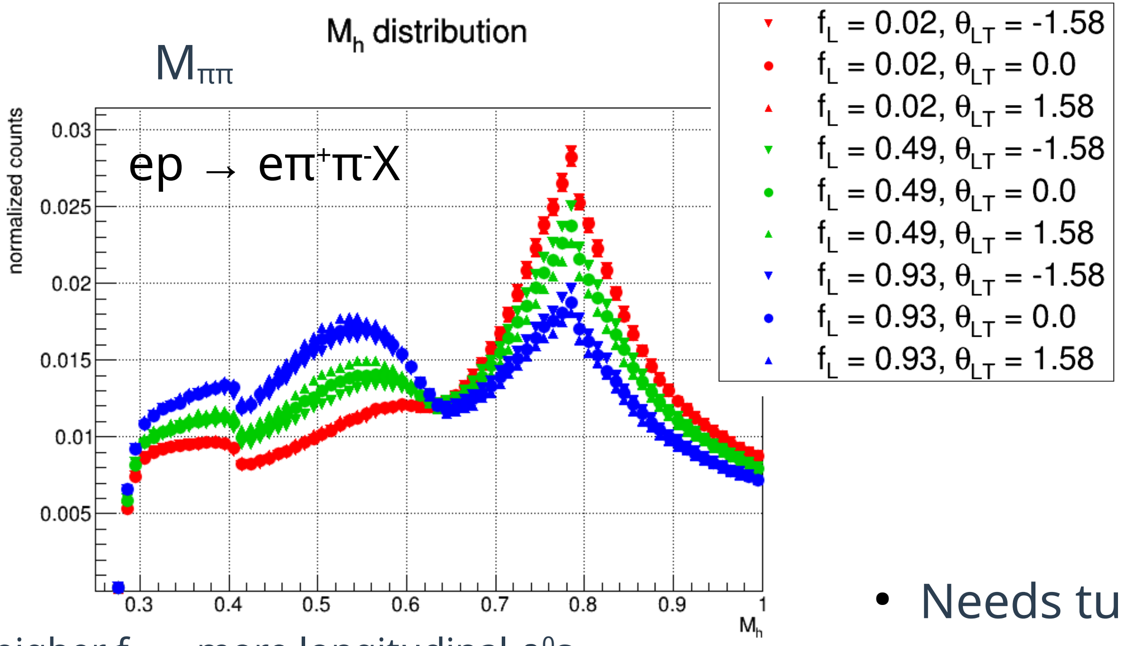
- **VM oblique polarization: interference between L and T polarization**

$$\theta_{LT} := \arg\left(\frac{G_L}{G_T}\right) \in [-\pi, \pi]$$

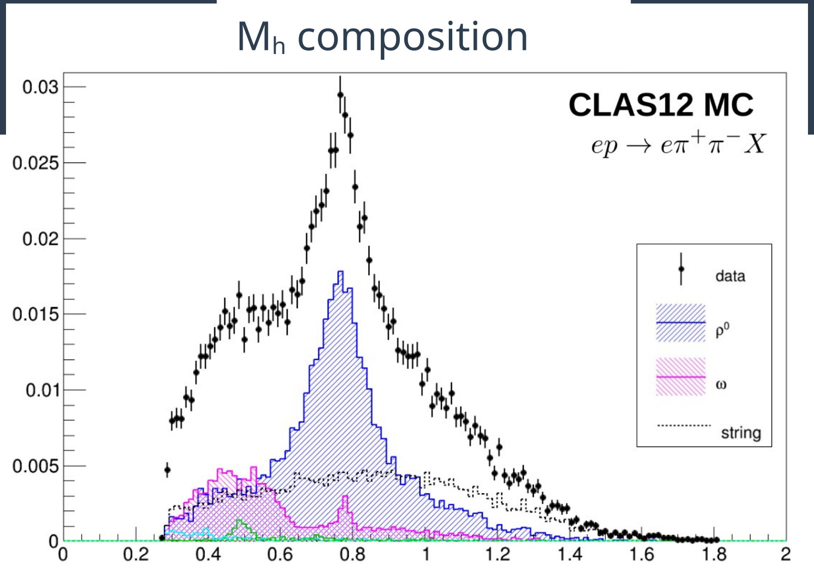


A. Kerbizi, X. Artru, A. Martin, Phys.Rev.D 104 (2021) 11, 114038
X. Artru, A. Kerbizi, JPS Conf.Proc. 37 (2022), 020101

StringSpinner Parameters



higher f_L → more longitudinal ρ^0s
→ less of them survive acceptance?



Behavior is consistent with results from
A. Kerbizi, X. Artru, A. Martin, Phys.Rev.D 104 (2021) 11, 114038

- Needs tuning!
  - PROFESSOR (see Albi's talk) with, e.g., CLAS12 dihadron A_{LU} (partial waves)
  - AI efforts from Duke?

CLAS12 MC-to-Data Comparison

CLAS12 Data

StringSpinner

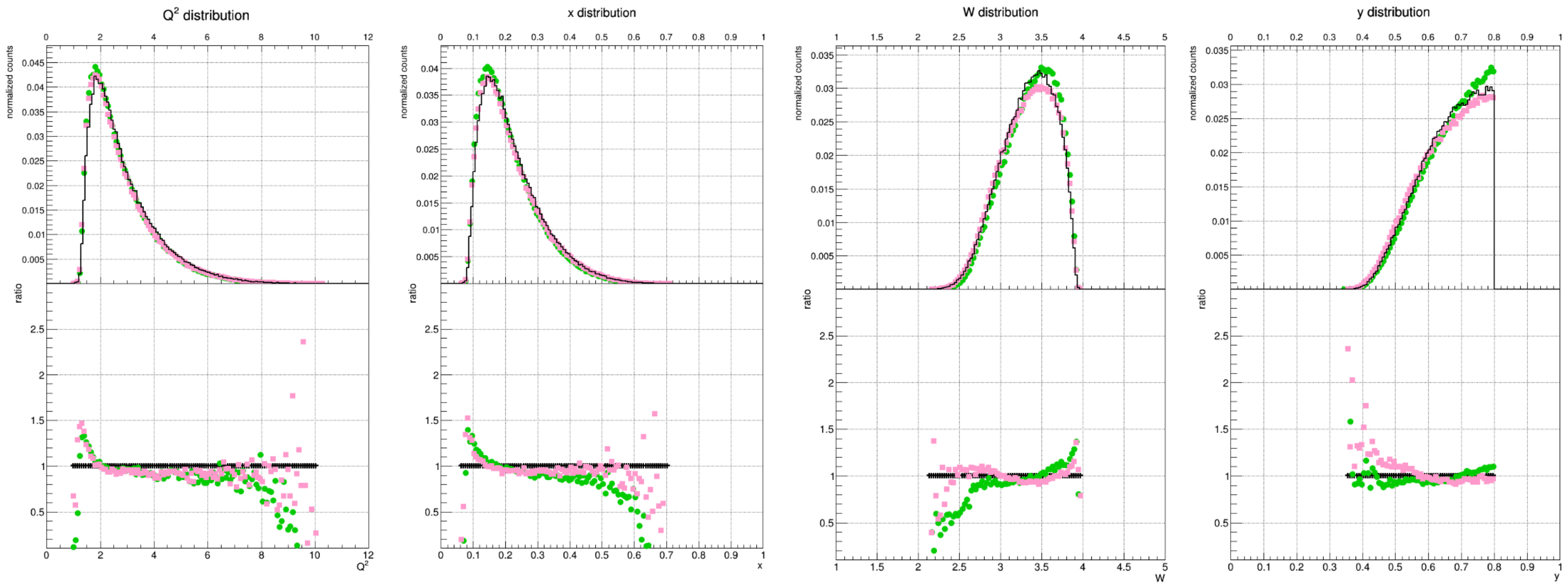
CLASDIS

Re μ = 0.42

Im μ = 0.76

$f_L = 0.5$

$\theta_{LT} = 0$



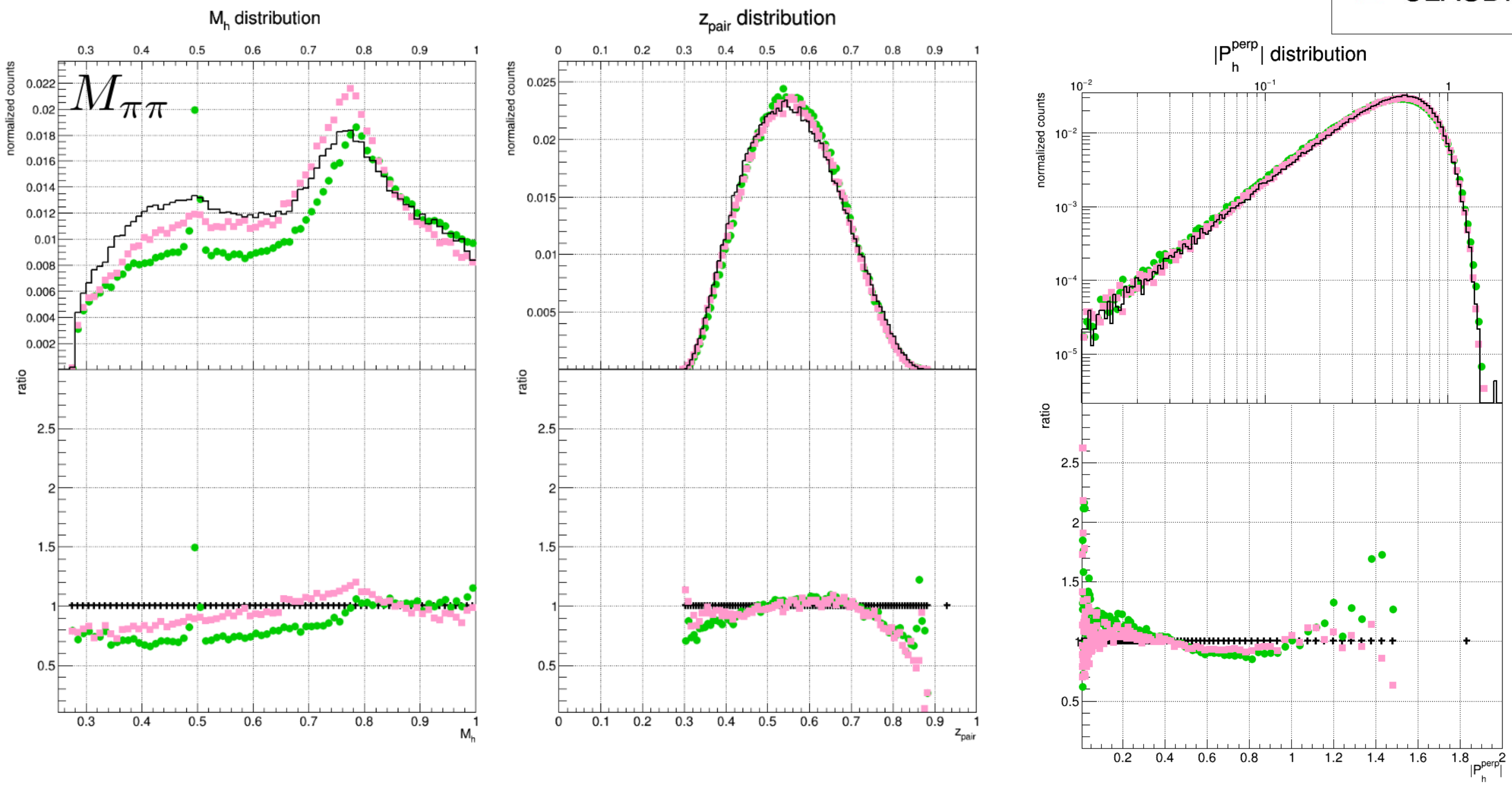
CLAS12 MC-to-Data Comparison

CLAS12 Data

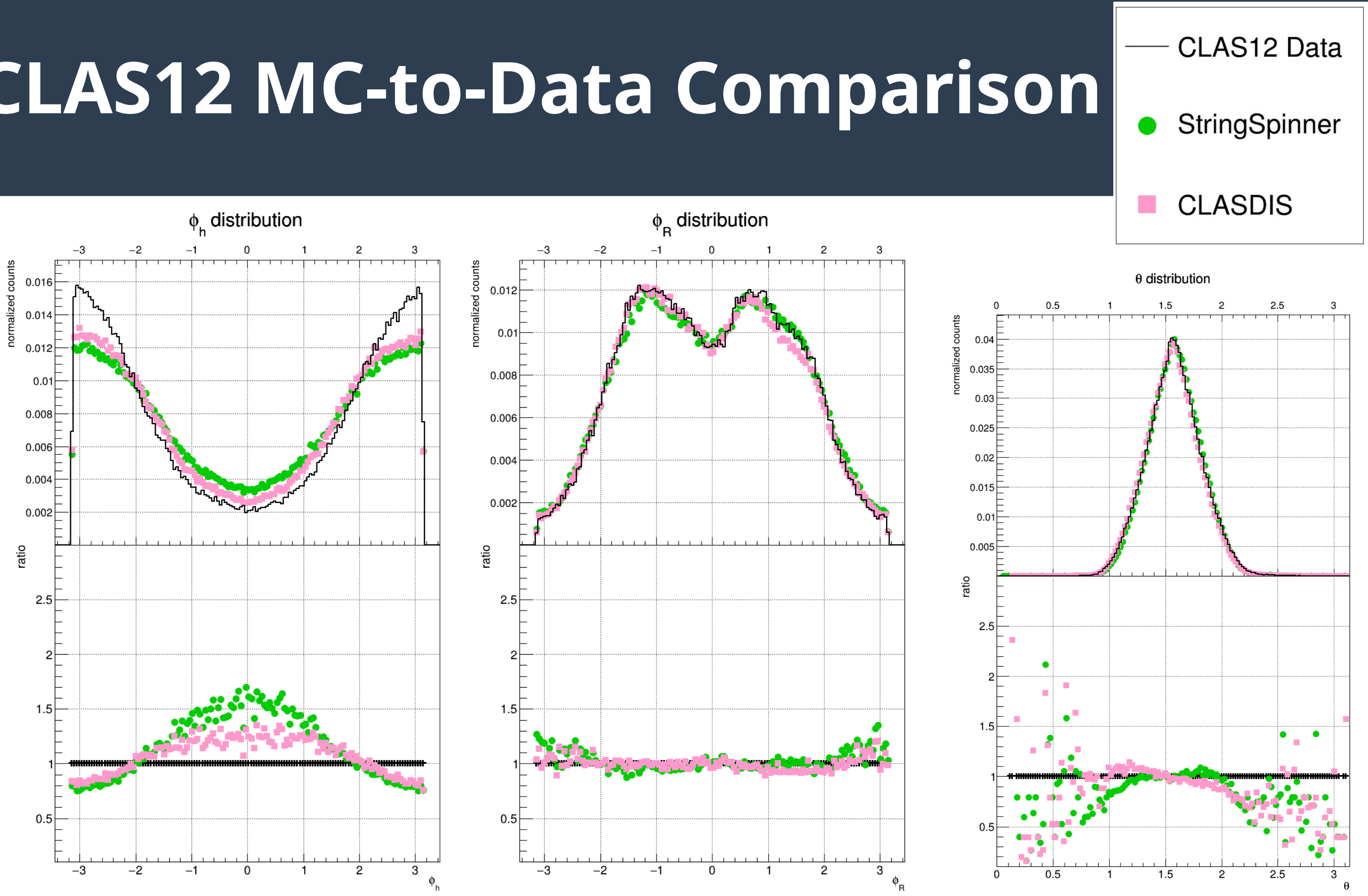
StringSpinner

CLASDIS

Re μ = 0.42
Im μ = 0.76
$f_L = 0.5$
$\theta_{LT} = 0$



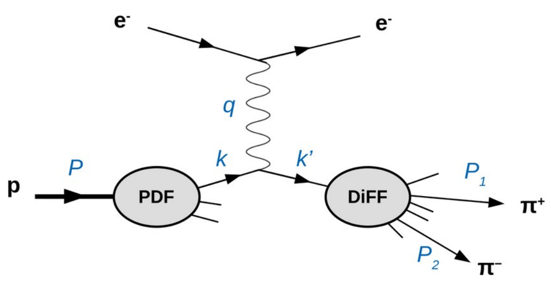
CLAS12 MC-to-Data Comparison

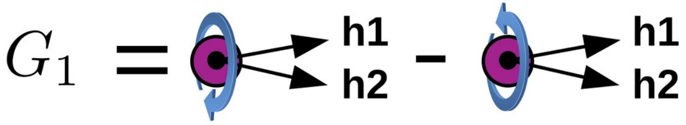


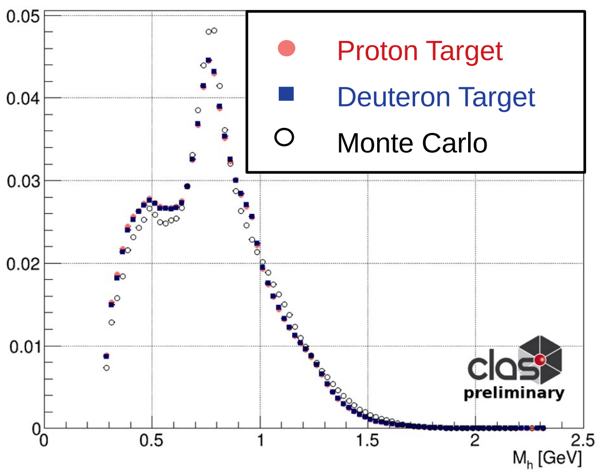
Re μ = 0.42
Im μ = 0.76
f_L = 0.5
θ_{LT} = 0

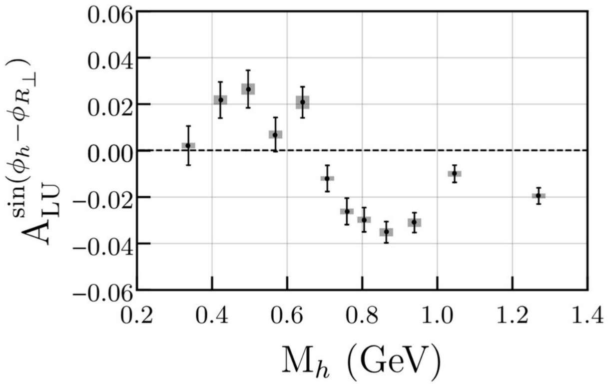
SIDIS π+π- and ρ^0s at CLAS12

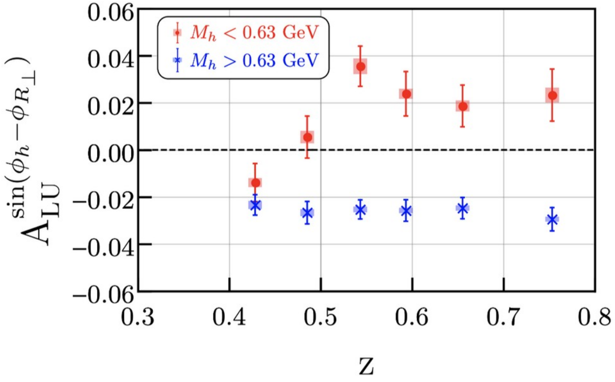
SIDIS π+π- Dihadron Spin Asymmetries







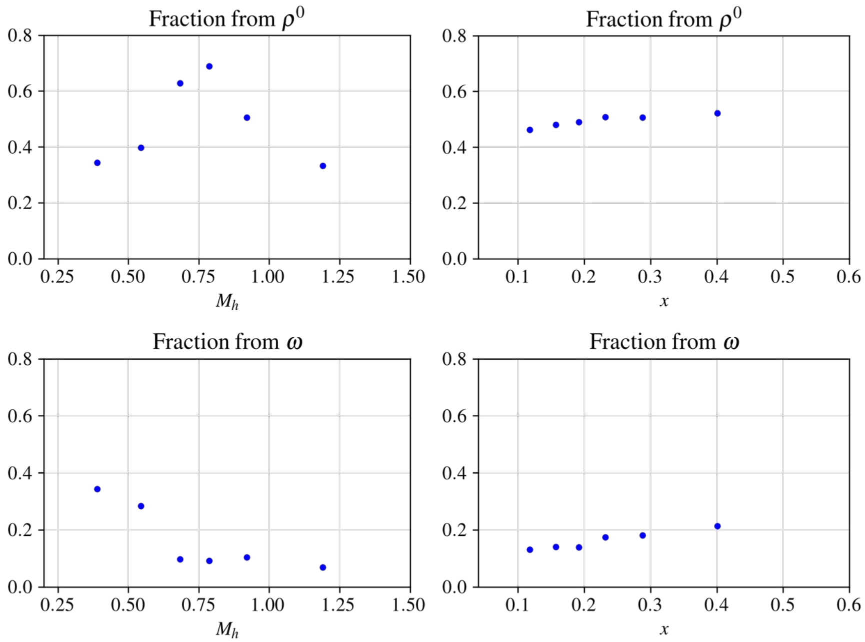


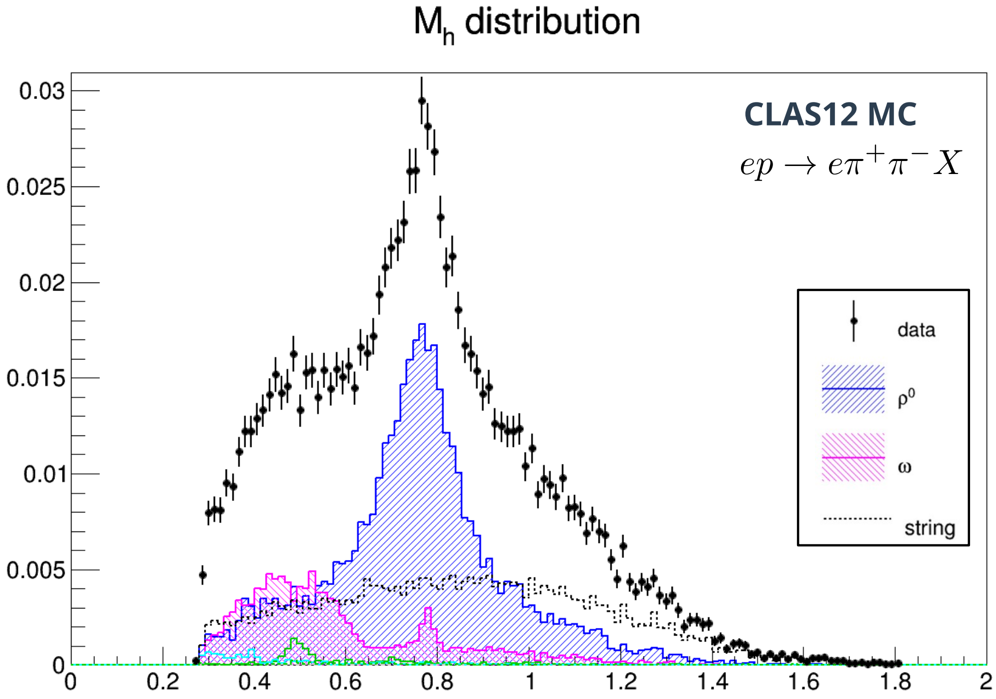


T.B. Hayward, CD, A. Vossen, *et al.* Phys.Rev.Lett. 126 (2021) 152501

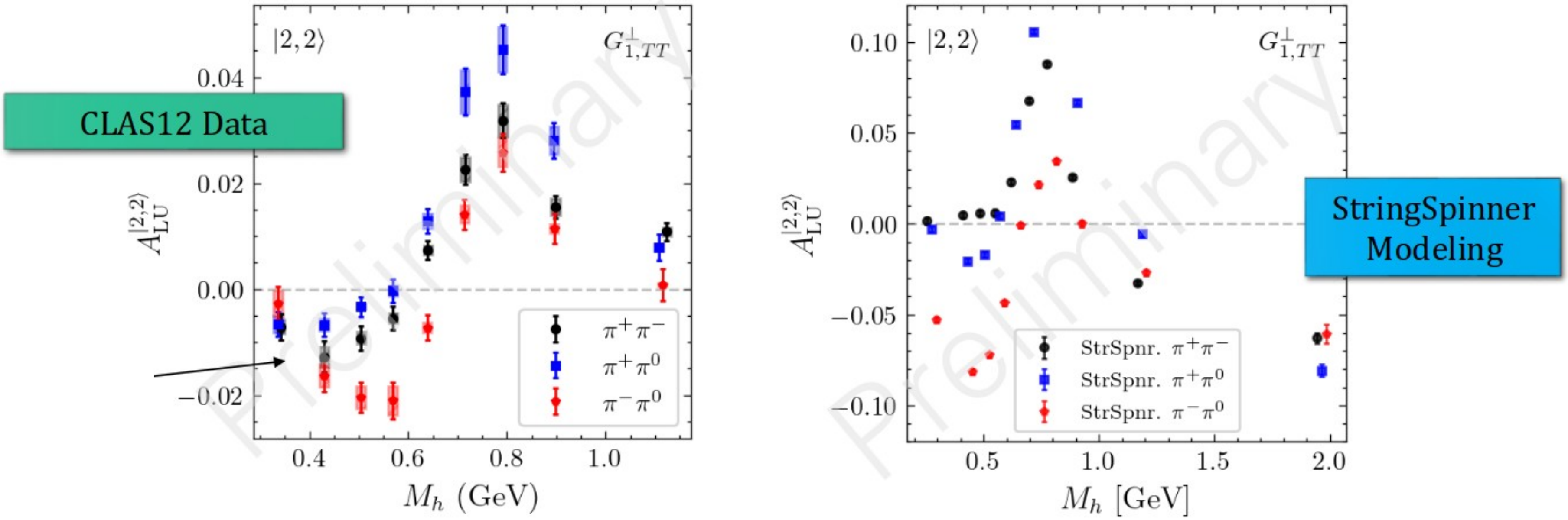
SIDIS π+π- and ρ⁰s at CLAS12

~1/2 the dihadrons come from ρ⁰s





ππ Dihadron A_{LU} Partial Waves & StringSpinner



$$F_{LU,T}^{P_{\ell,m}\sin(m(\phi_h-\phi_{R_\perp}))} = -\mathcal{I}\left[2\cos\left(m(\phi_h-\phi_p)\right) f_1 G_1^{|\ell,m\rangle}\right]$$

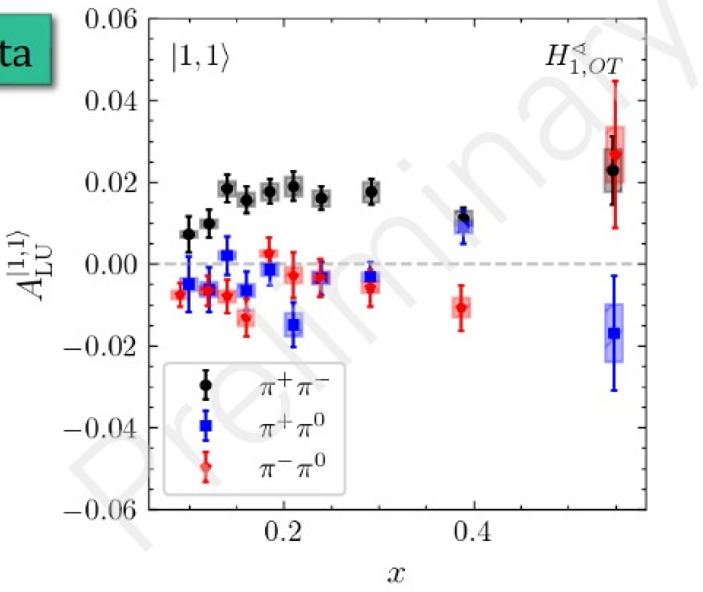
ℓ=2, m=2

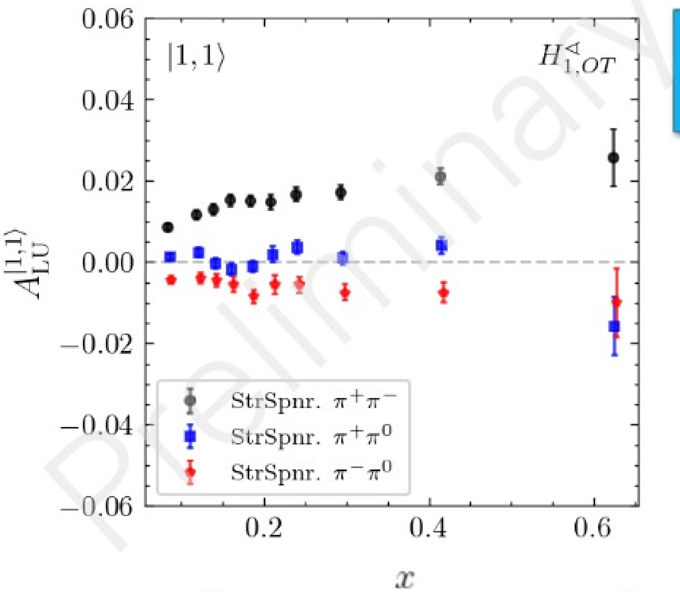
$$G_1^{|2,2\rangle} = G_1^{|2,-2\rangle} = -\frac{|\boldsymbol{p}_T|\,|\boldsymbol{R}|}{4M_h^2} G_{1,TT}^{\perp}$$

Gregory Matousek, IWHSS 2025 – QCD'N 2025
https://indico.cern.ch/event/1527657/

ππ Dihadron A_{LU} Partial Waves & StringSpinner

CLAS12 Data





StringSpinner Pseudodata

$$F_{LU}^{P_{\ell,m}\sin((1-m)\phi_h+m\phi_{R_\perp})} = \frac{2M}{Q}\mathcal{I}\left[-\frac{|\boldsymbol{p}_T|}{M_h}\cos\left((1-m)\left(\phi_p-\phi_h\right)\right)\left(xe\,H_1^{\perp|\ell,m\rangle}+\frac{M_h}{M}f_1\frac{\tilde{G}^{\perp|\ell,m\rangle}}{z}\right) + \ldots\right]$$

Gregory Matousek, IWHSS 2025 – QCD'N 2025

https://indico.cern.ch/event/1527657/

Some Ongoing Issues / Plans

- **StringSpinner parameter tuning**
  - Relative size of peaks in M_h distribution depends on these parameters
  - Use dihadron A_{LU} partial waves, combined with observables used in Albi's tuning

$$F_{LU,T}^{P_{\ell,m}\sin(m(\phi_h-\phi_{R_\perp}))} = -\mathcal{I}\left[2\cos\left(m(\phi_h-\phi_p)\right) f_1 G_1^{|\ell,m\rangle}\right]$$

$$F_{LU}^{P_{\ell,m}\sin((1-m)\phi_h+m\phi_{R_\perp})} = \frac{2M}{Q}\mathcal{I}\left[-\frac{|\boldsymbol{p}_T|}{M_h}\cos\left((1-m)\left(\phi_p-\phi_h\right)\right)\left(xe\,H_1^{\perp|\ell,m\rangle} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp|\ell,m\rangle}}{z}\right) + \ldots\right]$$

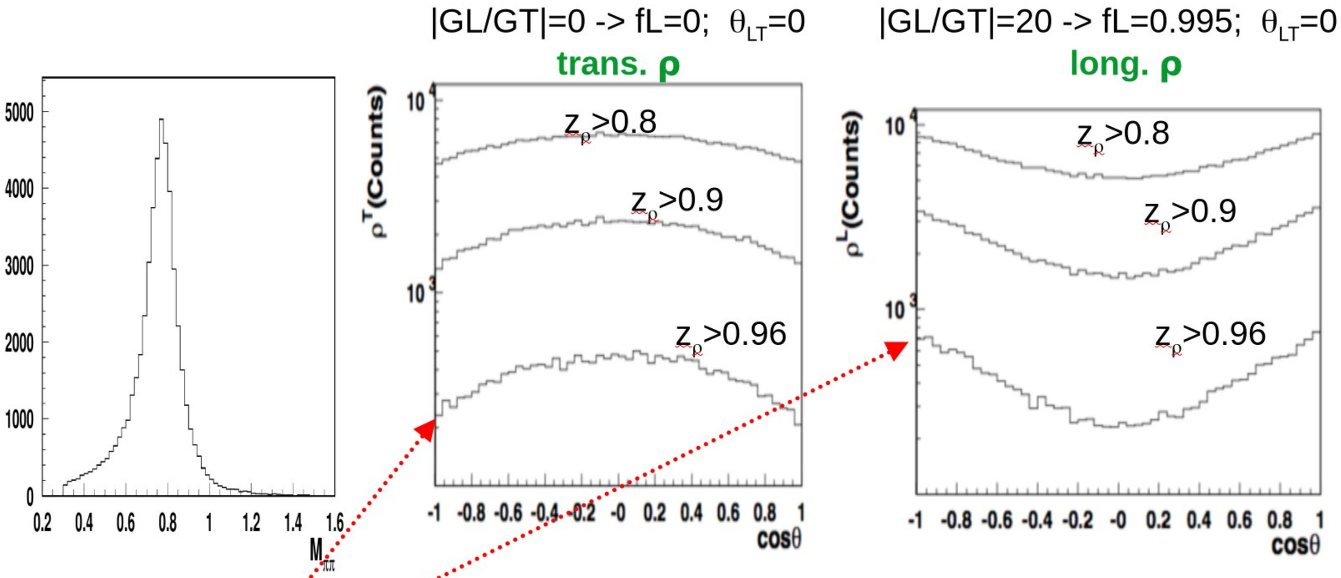
from Gliske, Bacchetta, Radici, Phys.Rev.D 90 (2014) 11, 114027

- **Test enabling diffractive physics in Pythia**
  - Need SDMEs (or amplitudes?)

- **k_T tuning**
  - Evident in single-pion p_T distributions → our Pythia 6 tune produces p_T distributions that agree much better with CLAS12 data than what we get from our Pythia 8 tune

Initial Studies of cosθ

Event must have at least one $\pi^+\pi^-$ pair with $z_{pair}>0.8$

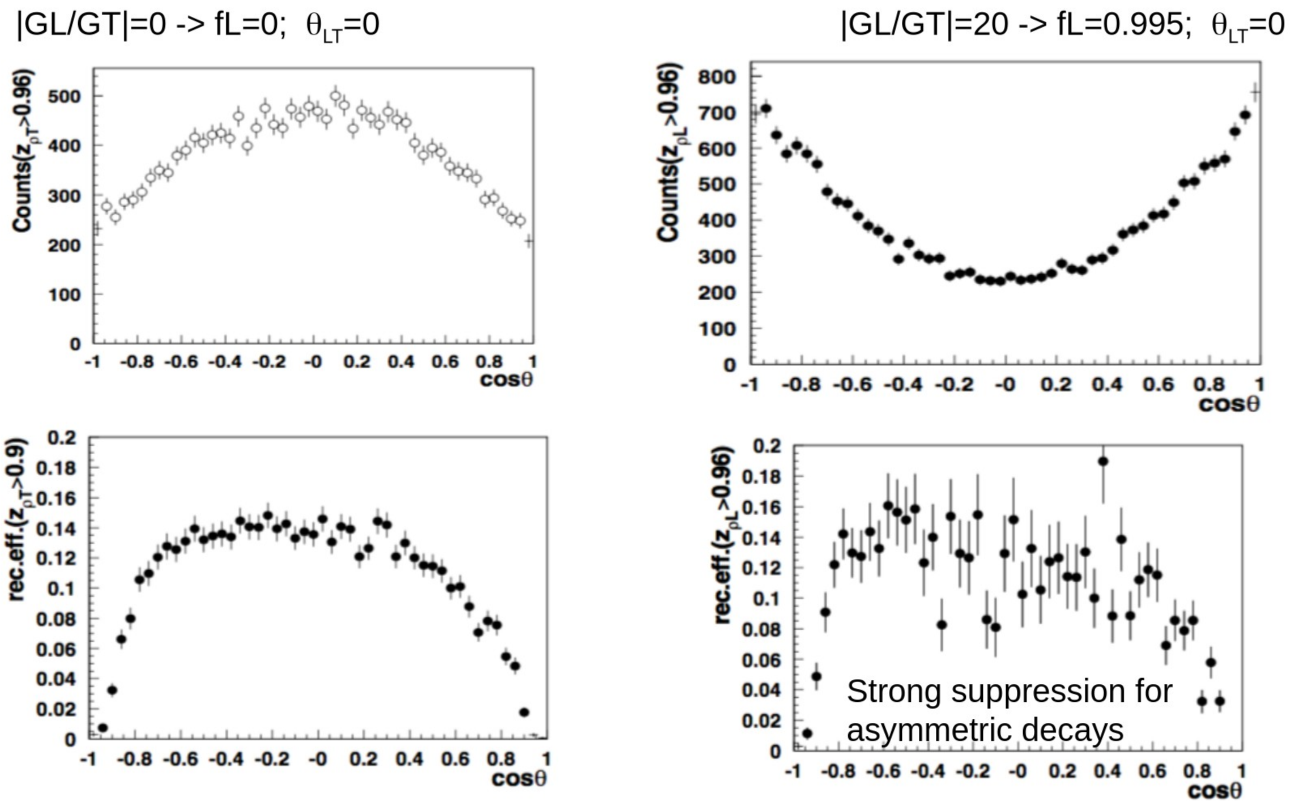


Includes cut on missing mass of the ρ to be a proton

from Harut

The pedestal in addition to $\cos^2\theta$ for longitudinal rho and $\sin^2\theta$ for transverse disappears for $z\to 1$. What exactly is that pedestal?

Initial Studies of cosθ



See Harut's talks (Monday & Tuesday)

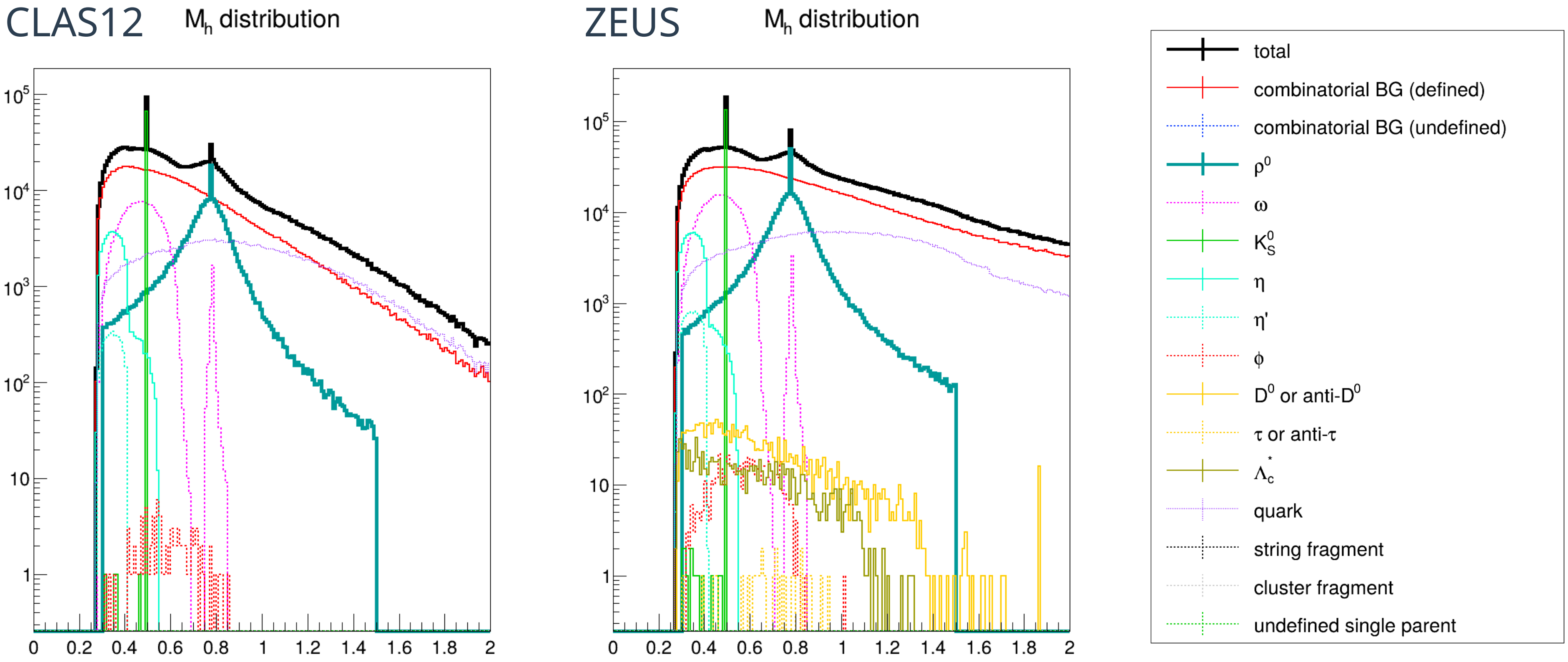
Generator Settings and Cuts

Updated $\cos\theta$ study for CLAS12 & ZEUS

- Unpolarized e^- and p beams
  - CLAS: 10.6 GeV e^- beam on fixed p target
  - ZEUS: 27.5 GeV e^- beam on 920 GeV p beam
- Final state includes e^-, π^+, π^-
- Less than 4 charged pions
- Scattered e^- with $2° < \theta < 60°$
- Q^2:
  - CLAS: $Q^2 > 1$ GeV^2
  - ZEUS: $1.5 < Q^2 < 200$ GeV^2
- StringSpinner
  - Trans. Pol. VMs: $|G_L/G_T|=0 \rightarrow f_L=0$
  - Long. Pol. VMs: $|G_L/G_T|=20 \rightarrow f_L=0.995$

- Pythia tuned for CLAS kinematics
  - **FIXME:** need ZEUS tuning!
- NOTE: Pythia's CoM energy lower limit for validity of the theoretical description is around 10 GeV, but CLAS12 has CoM ~ 4.5 GeV

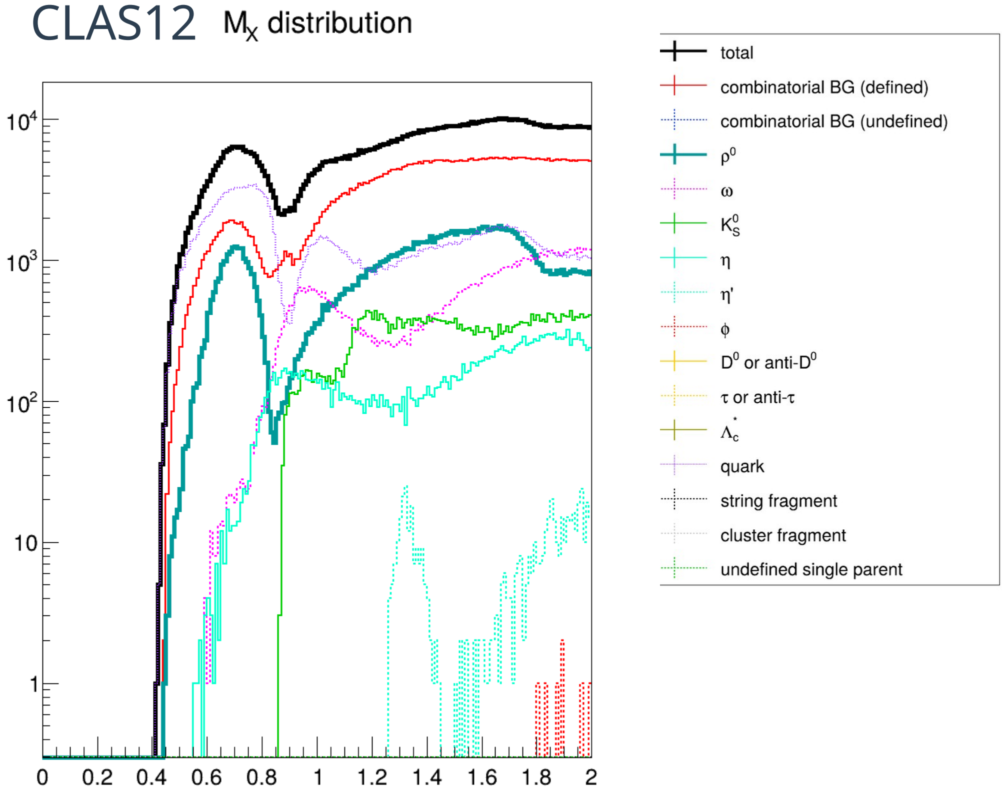
Invariant Mass $M_{\pi\pi}$ $ep \rightarrow e\pi^+\pi^- X$

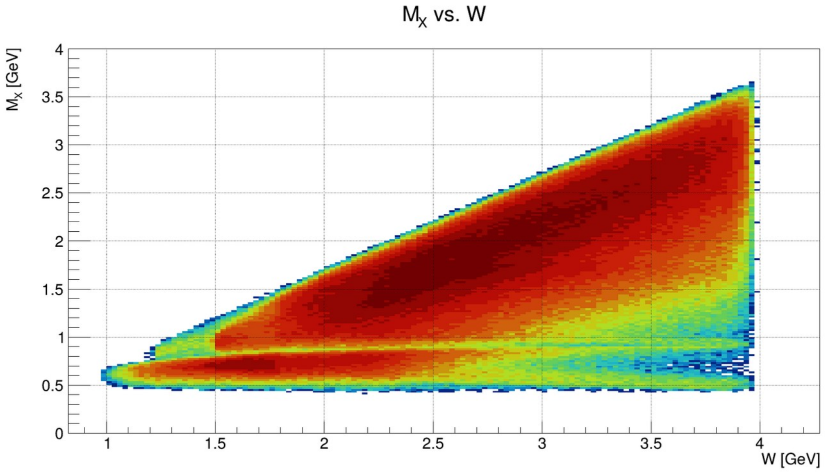


Missing Mass M_X from the Generator at CLAS12

$ep \rightarrow e\pi^+\pi^-X$

CLAS12



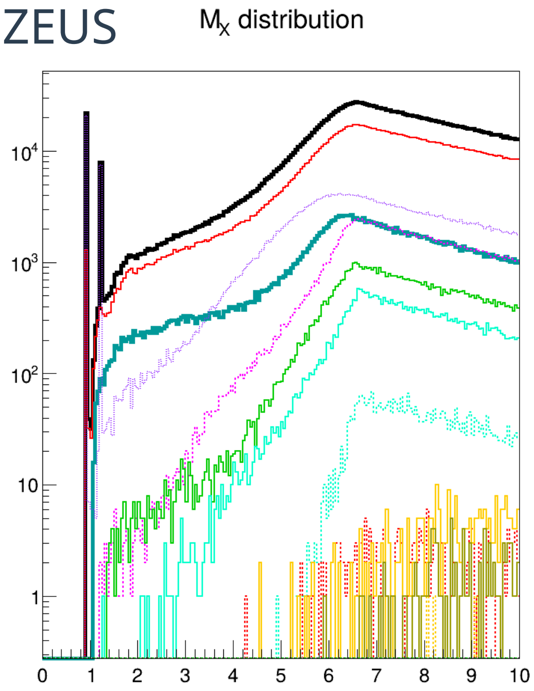


"Exclusive" peak at W < 2 GeV… no good for exclusive ρ studies

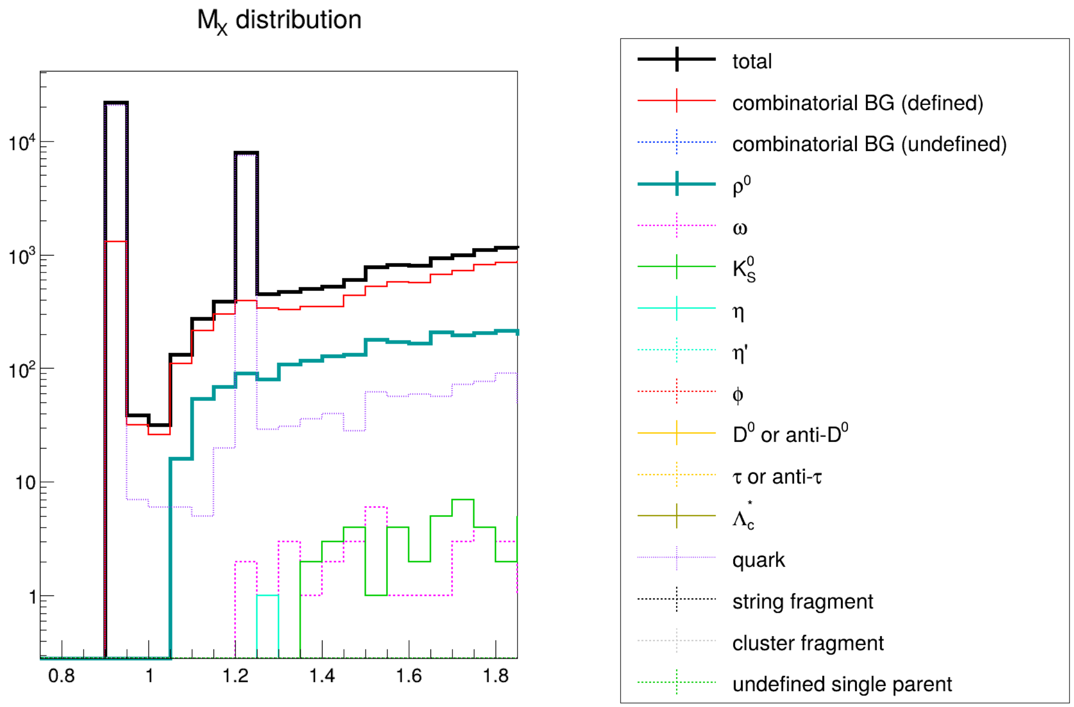
- Need to enable diffractive effects in Pythia
  - Requires VM SDMEs (or amplitudes?)

Missing Mass M_X from the Generator at ZEUS

$ep \to e\pi^+\pi^- X$



zoom

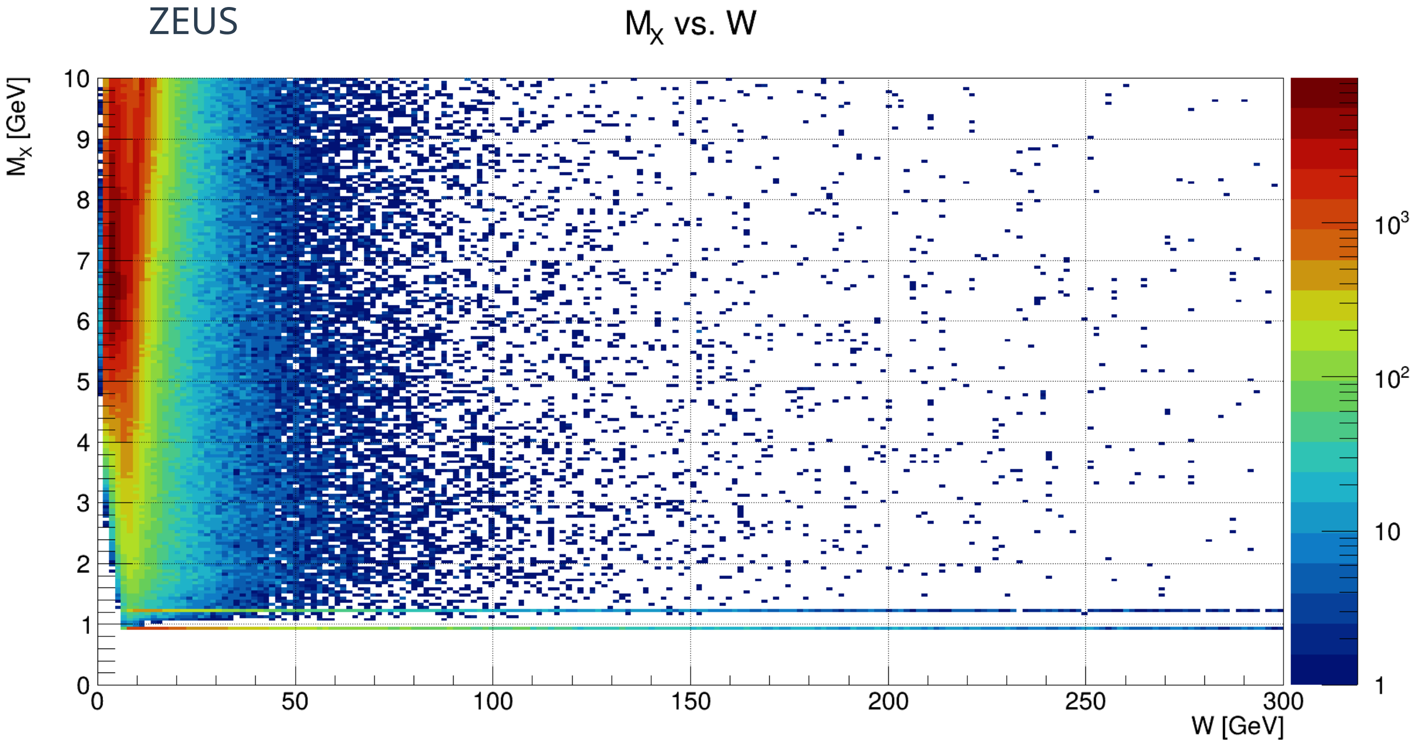


Exclusive peak composed of quark parents and combinatorial BG parents, no **VMs**

Missing Mass M_X from the Generator at ZEUS

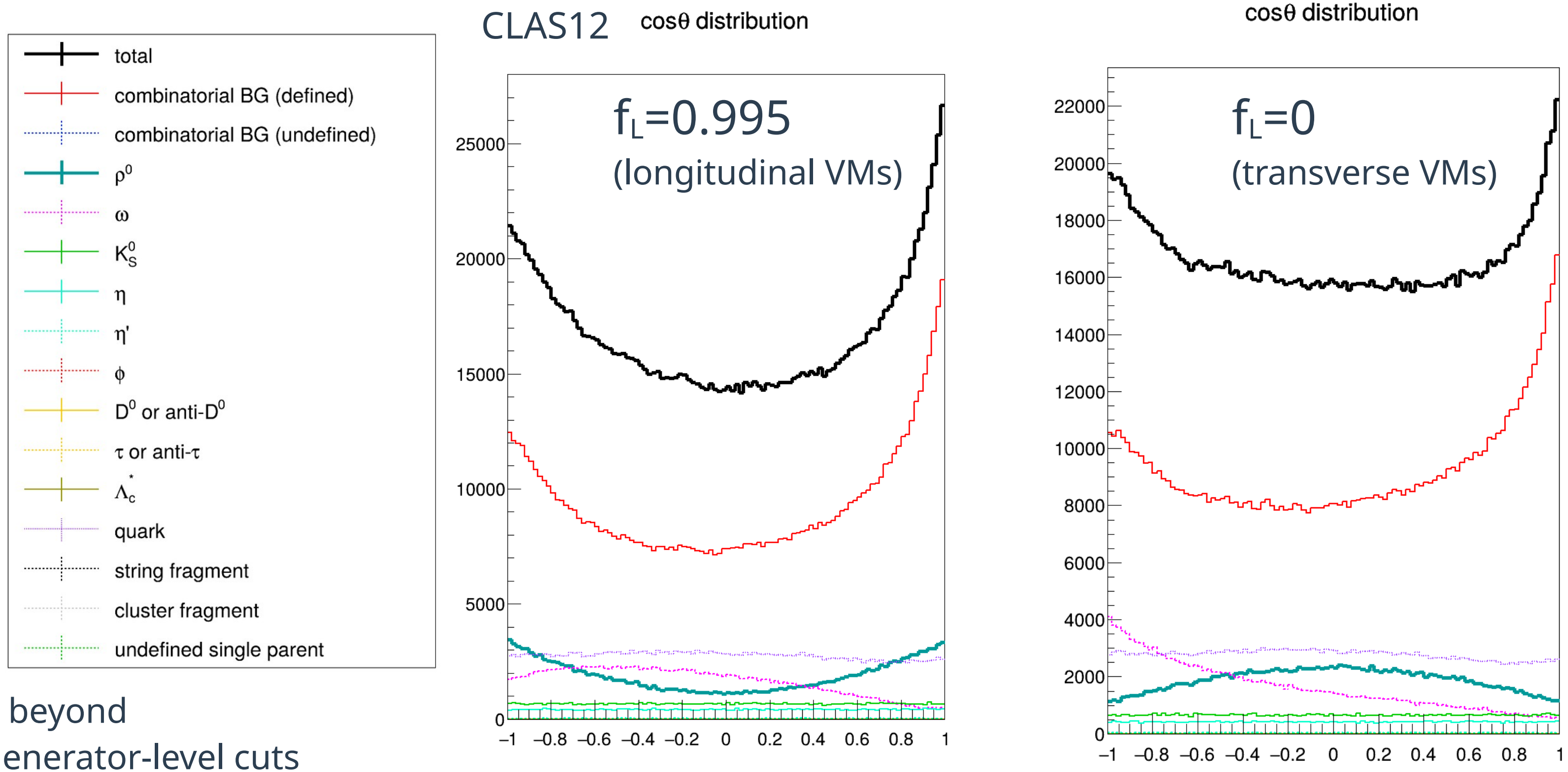
$ep \rightarrow e\pi^+\pi^- X$

ZEUS



Exclusive peaks persist across W range

cosθ from the Generator at CLAS12

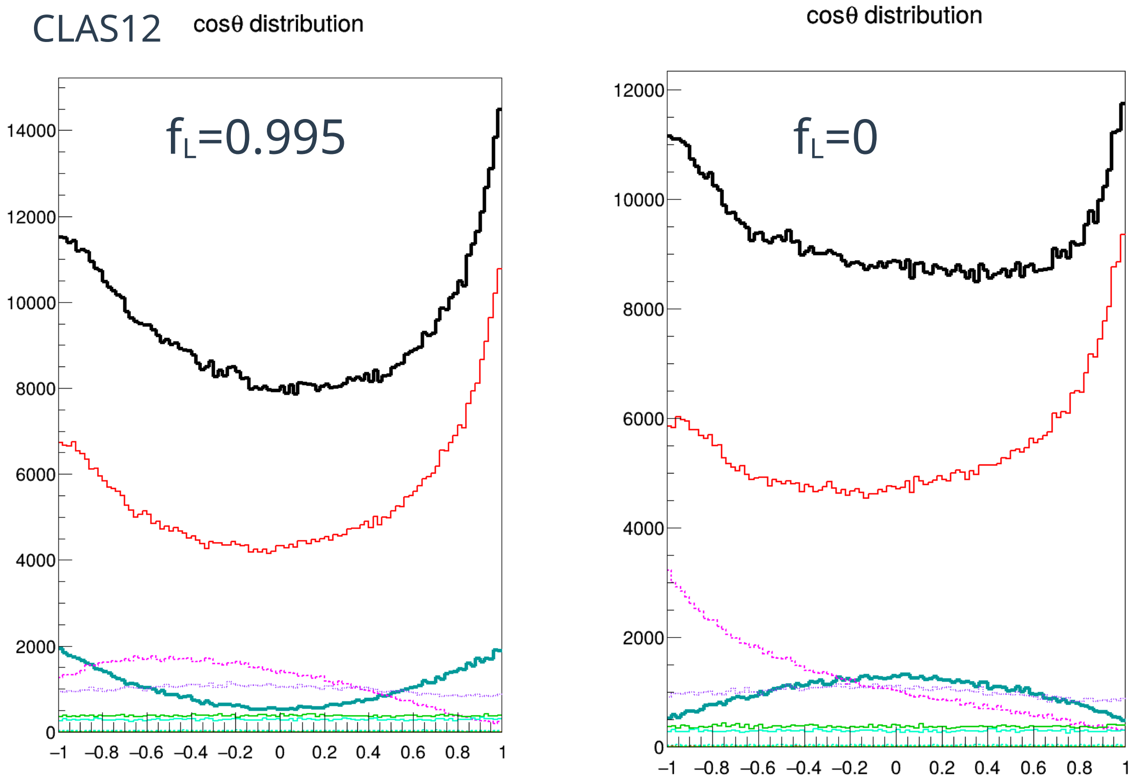


no additional cuts beyond
aforementioned generator-level cuts

Cosθ with CLAS12 SIDIS Analysis Cuts

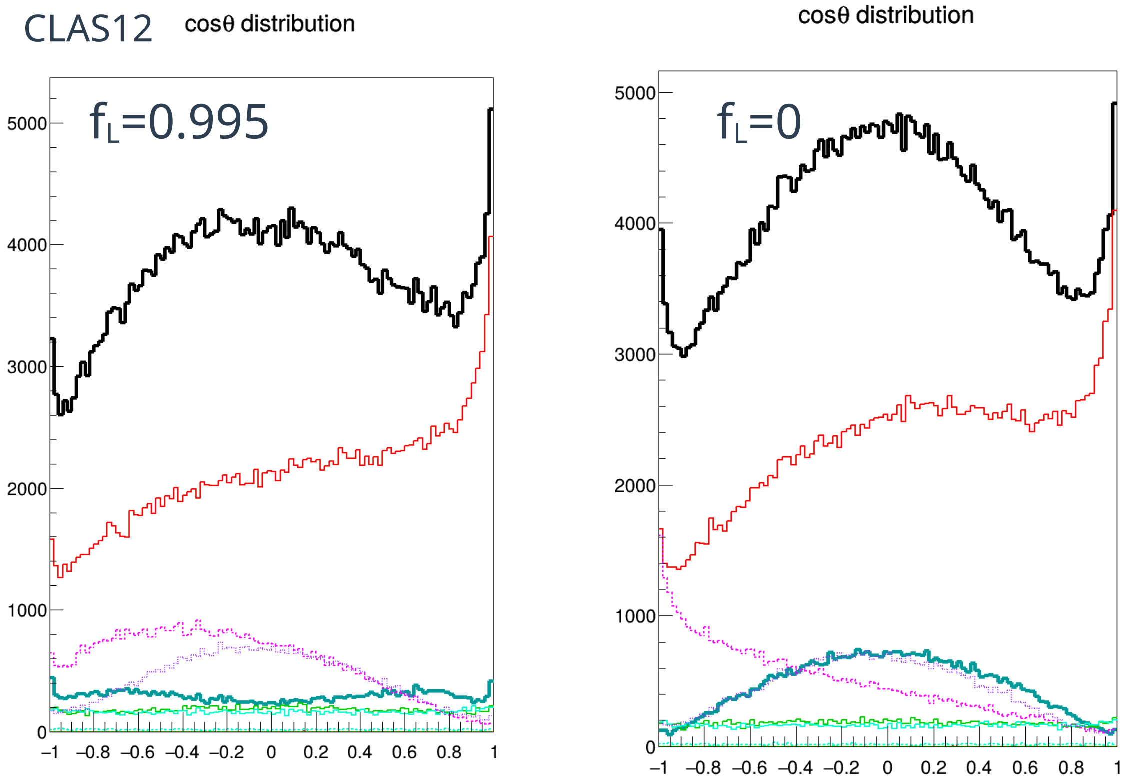
- **Inclusive cuts**
  - $Q^2 > 1$ GeV^2
  - $W > 2$ GeV
  - $y < 0.8$
- **Electron Momentum**
  - $5° < \theta < 35°$
  - $p > 2$ GeV
- **Pion Momentum**
  - ~~$5° < \theta < 35°$~~
  - ~~$p > 1.25$ GeV~~
- **Vertex**
  - $|v_z(e^-) - v_z(\pi)| < 20$ cm
- **Additional cuts**
  - $z_{\pi\pi} < 0.95$
  - $M_X(e\pi\pi) > 1.5$ GeV
  - ~~pion $x_F > 0$~~

cuts disabled



Cosθ with CLAS12 SIDIS Analysis Cuts

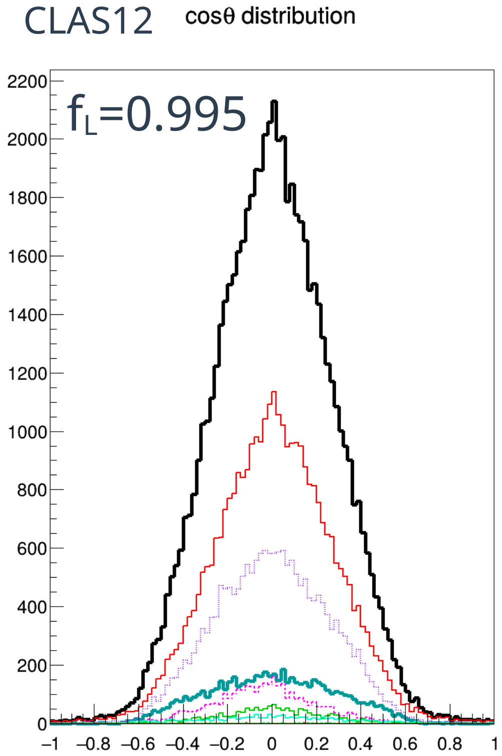
- **Inclusive cuts**
  - $Q^2 > 1\ \mathrm{GeV}^2$
  - $W > 2$ GeV
  - $y < 0.8$
- **Electron Momentum**
  - $5° < \theta < 35°$
  - $p > 2$ GeV
- **Pion Momentum**
  - $5° < \theta < 35°$ ← cut enabled
  - ~~p > 1.25 GeV~~
- **Vertex**
  - $|v_z(e^-) - v_z(\pi)| < 20$ cm
- **Additional cuts**
  - $z_{\pi\pi} < 0.95$
  - $M_X(e\pi\pi) > 1.5$ GeV
  - ~~pion $x_F > 0$~~

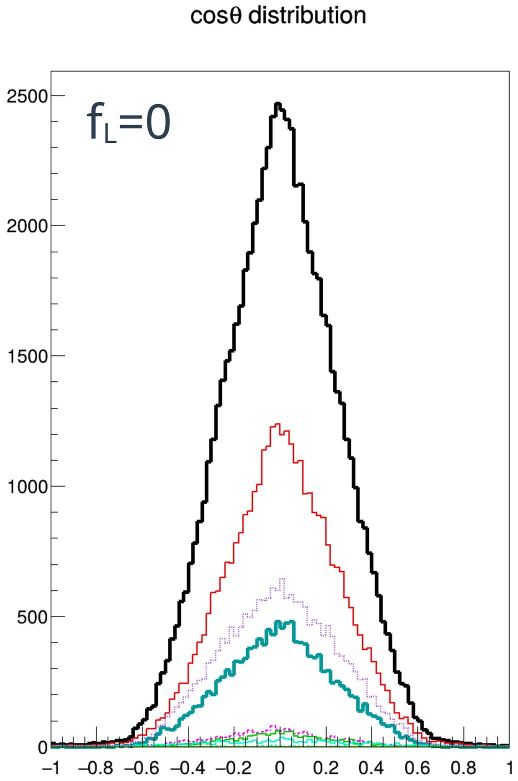


Cosθ with CLAS12 SIDIS Analysis Cuts

- **Inclusive cuts**
  - $Q^2 > 1\ GeV^2$
  - $W > 2$ GeV
  - $y < 0.8$
- **Electron Momentum**
  - $5° < \theta < 35°$
  - $p > 2$ GeV
- **Pion Momentum**
  - ~~5° < θ < 35°~~
  - $p > 1.25$ GeV
- **Vertex**
  - $|v_z(e^-) - v_z(\pi)| < 20$ cm
- **Additional cuts**
  - $z_{\pi\pi} < 0.95$
  - $M_X(e\pi\pi) > 1.5$ GeV
  - ~~pion $x_F > 0$~~

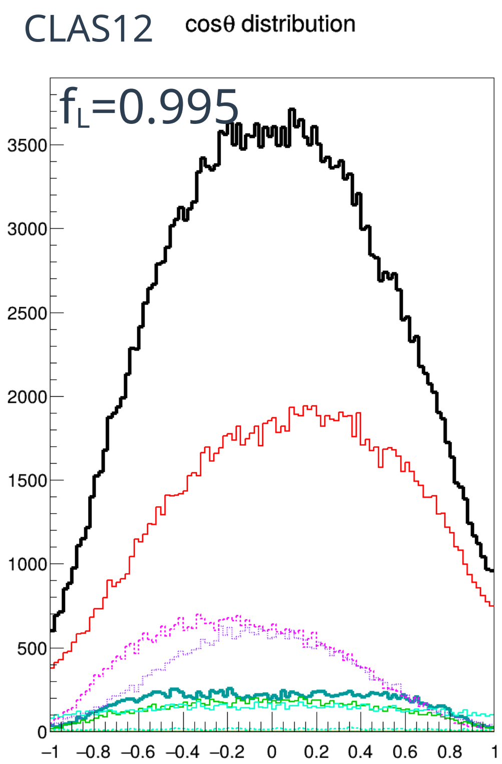
CLAS12

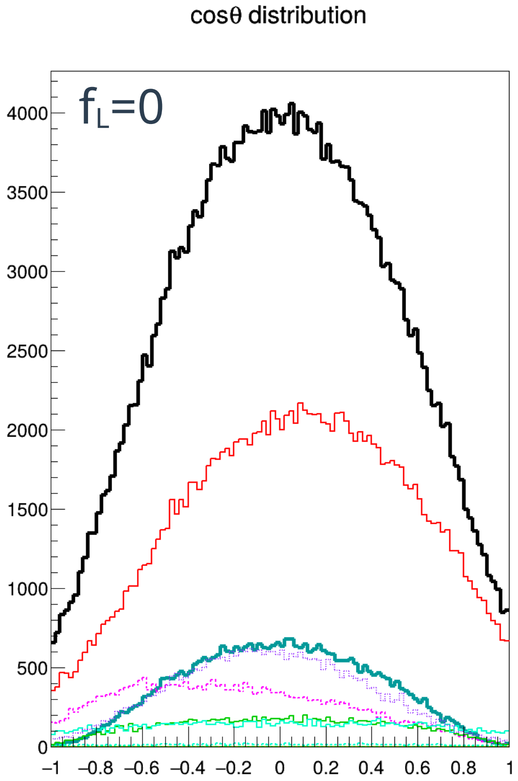




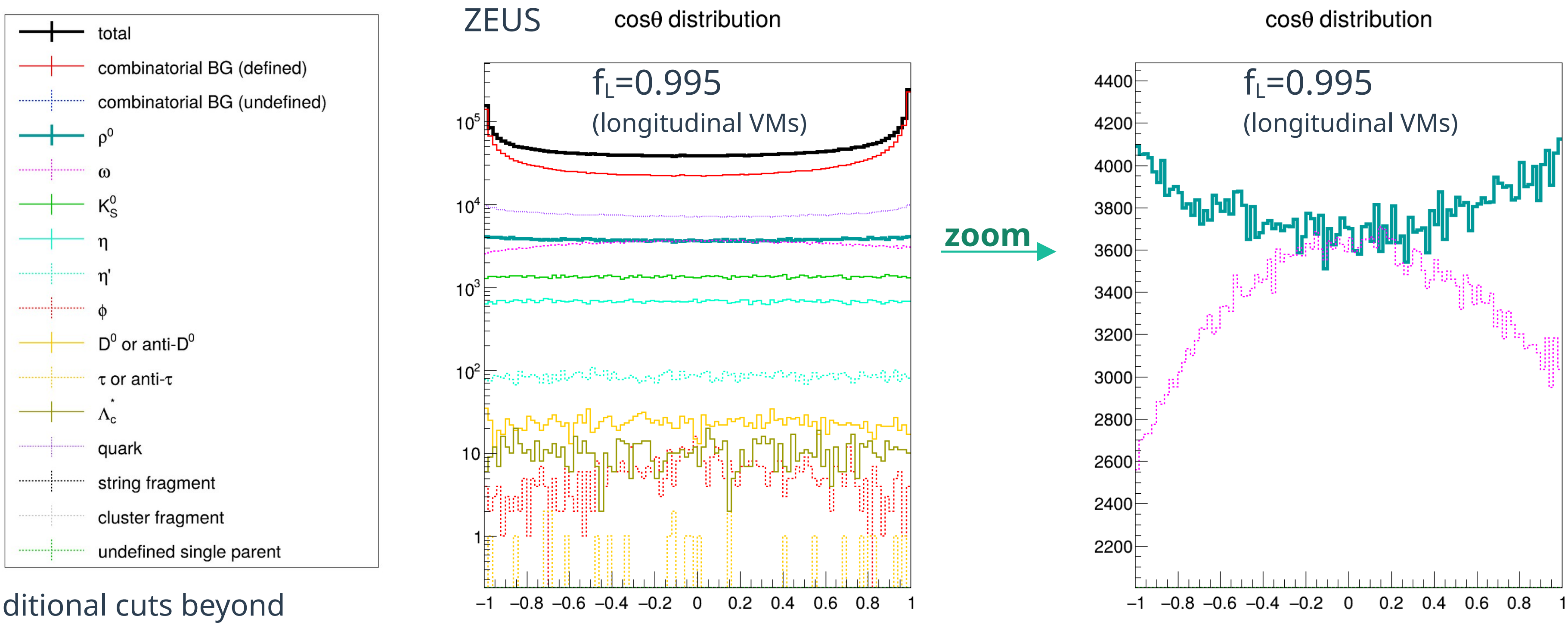
Cosθ with CLAS12 SIDIS Analysis Cuts

- **Inclusive cuts**
  - $Q^2 > 1\ \mathrm{GeV}^2$
  - $W > 2$ GeV
  - $y < 0.8$
- **Electron Momentum**
  - $5° < \theta < 35°$
  - $p > 2$ GeV
- **Pion Momentum**
  - ~~$5° < \theta < 35°$~~
  - ~~$p > 1.25$ GeV~~
- **Vertex**
  - $|v_z(e^-) - v_z(\pi)| < 20$ cm
- **Additional cuts**
  - $z_{\pi\pi} < 0.95$
  - $M_X(e\pi\pi) > 1.5$ GeV
  - pion $x_F > 0$



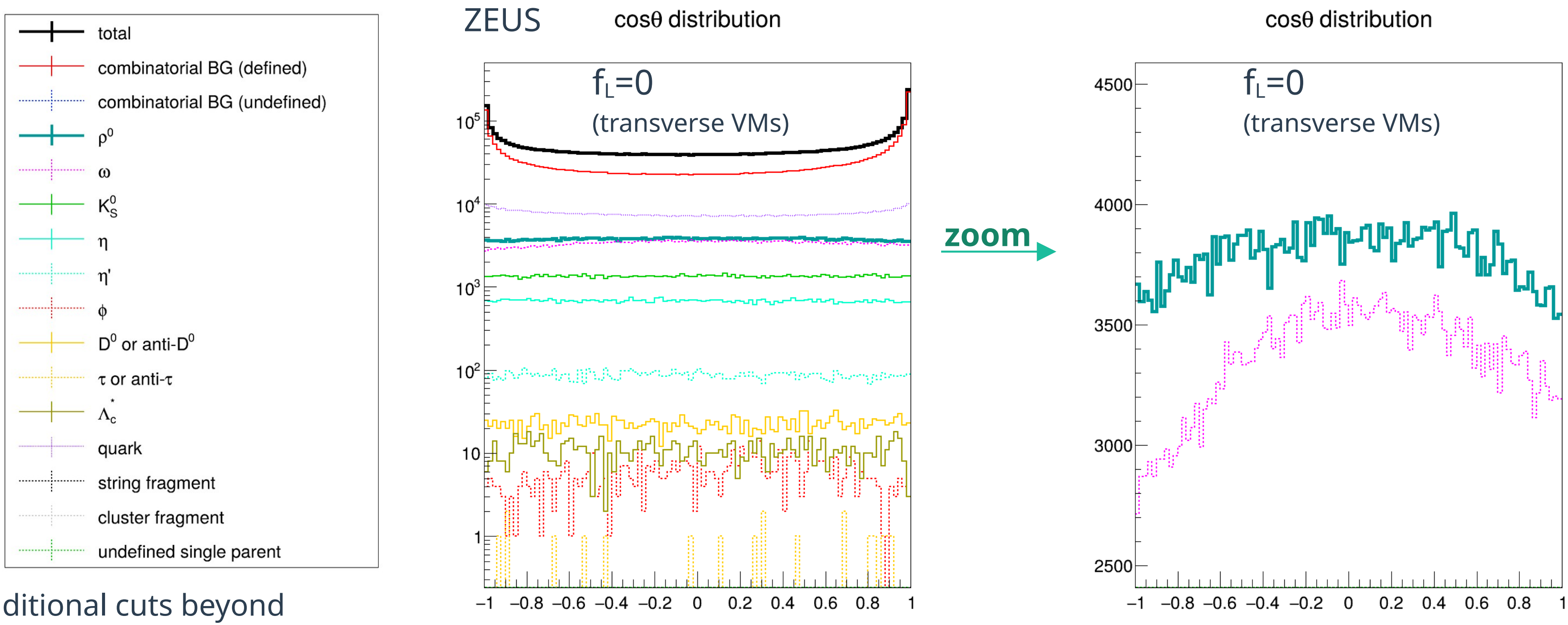


cosθ from the Generator at ZEUS



no additional cuts beyond aforementioned generator-level cuts

cosθ from the Generator at ZEUS



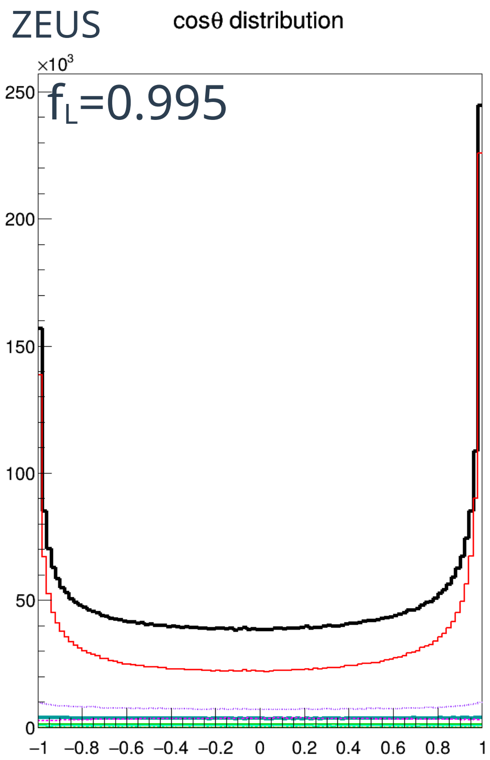
no additional cuts beyond aforementioned generator-level cuts

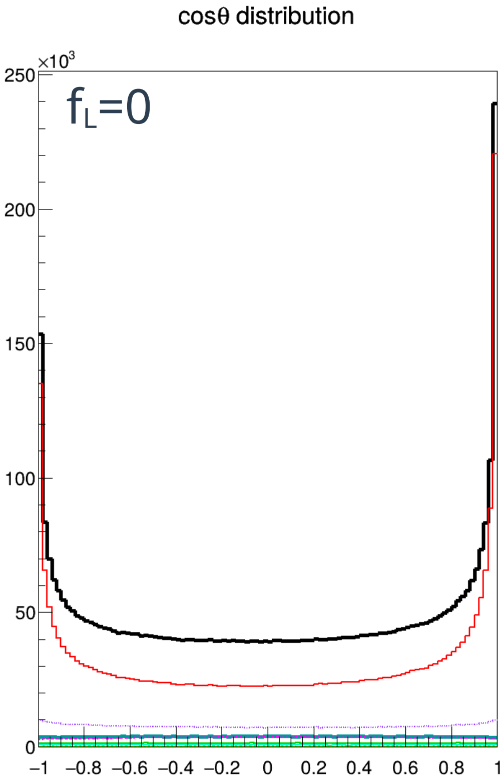
Cosθ with ZEUS Exclusive Analysis Cuts

- **Inclusive cuts**
  - ~~$2 < Q^2 > 160$ GeV^2~~
  - ~~$32 < W < 180$ GeV~~
- **Electron in RCAL**
  - ~~$3.5° < \theta < 51.9°$ (w.r.t. e beam)~~
  - ~~$E > 10$ GeV~~
- **Pions**
  - ~~$|\eta|<1.75$~~
  - ~~$p_T > 150$ MeV~~
- **Exclusivity**
  - ~~$0.65 < M_{\pi\pi} < 1.1$ GeV~~
  - ~~$|t| < 1$ GeV^2~~
- ~~$\delta = \Sigma(E-p_z)$ cut not applied (FIXME)~~

no cuts applied
(same plots as before)

Reference: DESY–07–118
August 2007





Cosθ with ZEUS Exclusive Analysis Cuts

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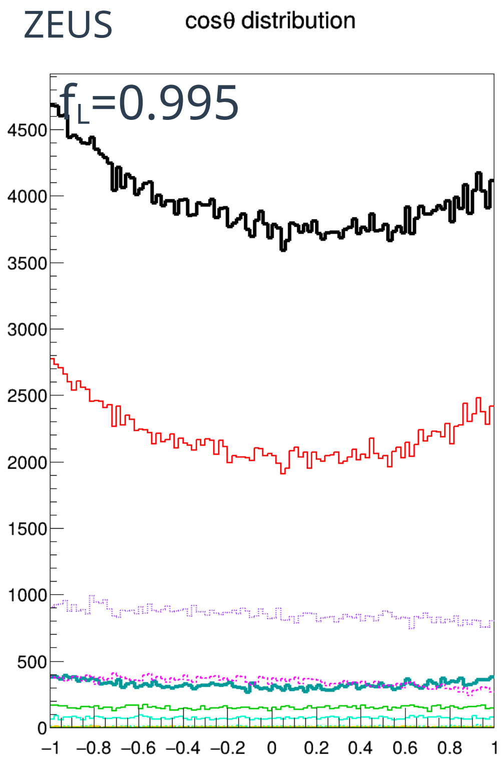
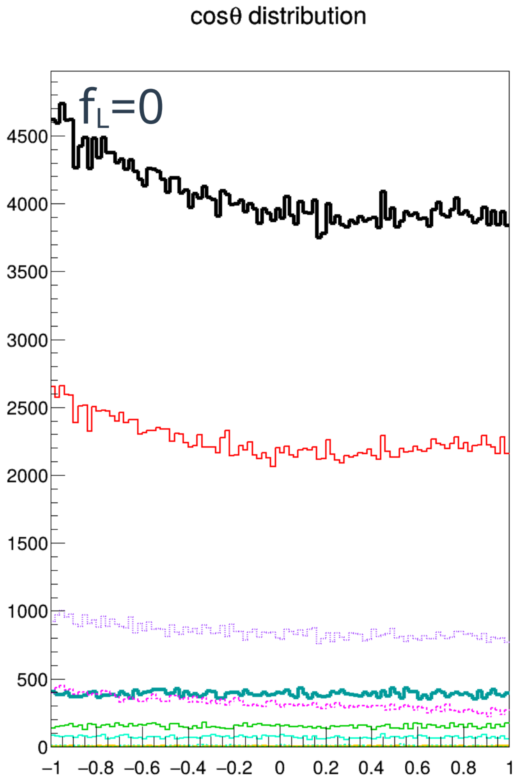
combinatorial
BG reduced

Reference: DESY–07–118
August 2007





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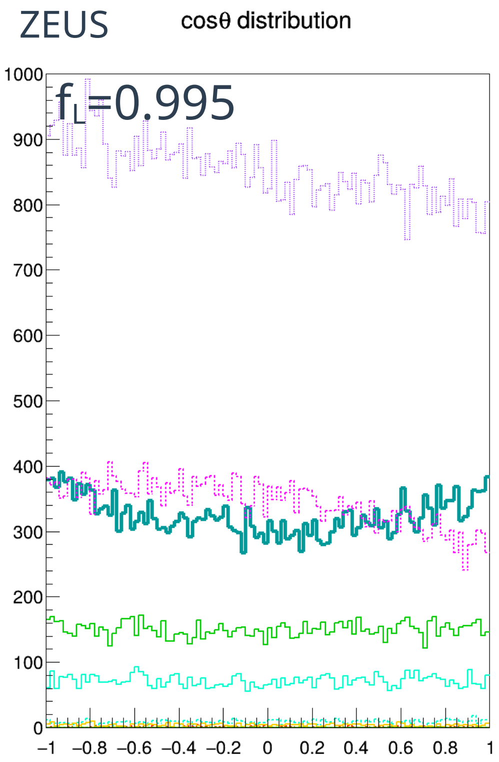
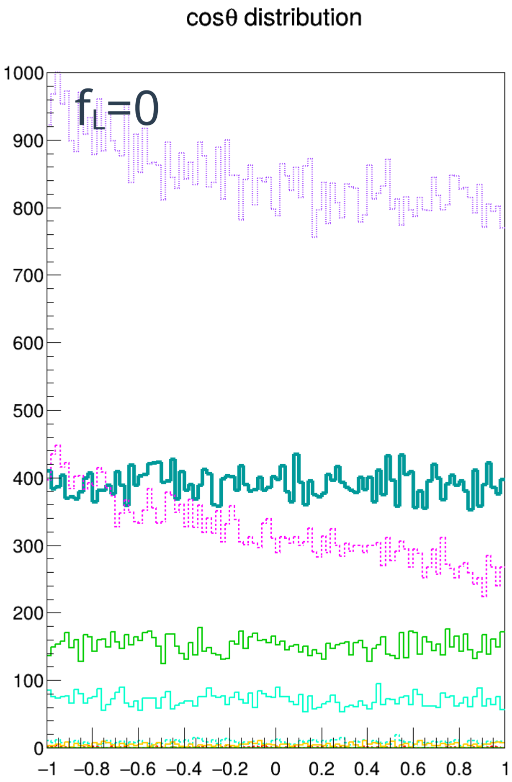
- ~~$\delta = \Sigma(E-p_z)$ cut not applied (FIXME)~~

combinatorial
BG reduced

zoomed to ρ

Reference: DESY–07–118
August 2007





Cosθ with ZEUS Exclusive Analysis Cuts

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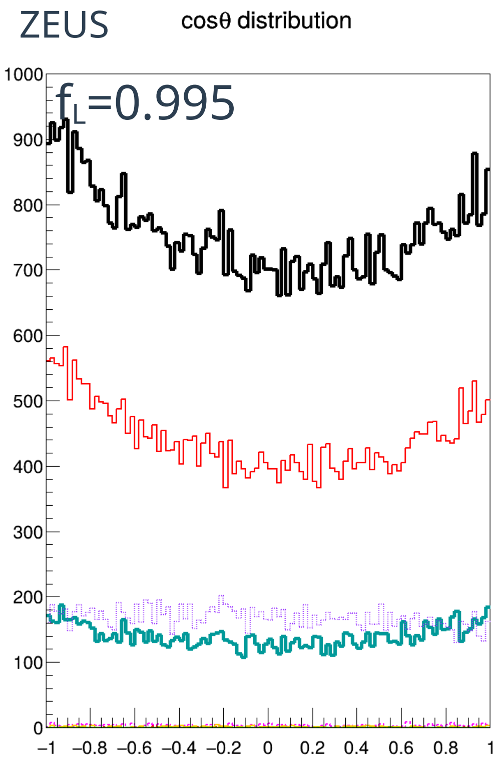

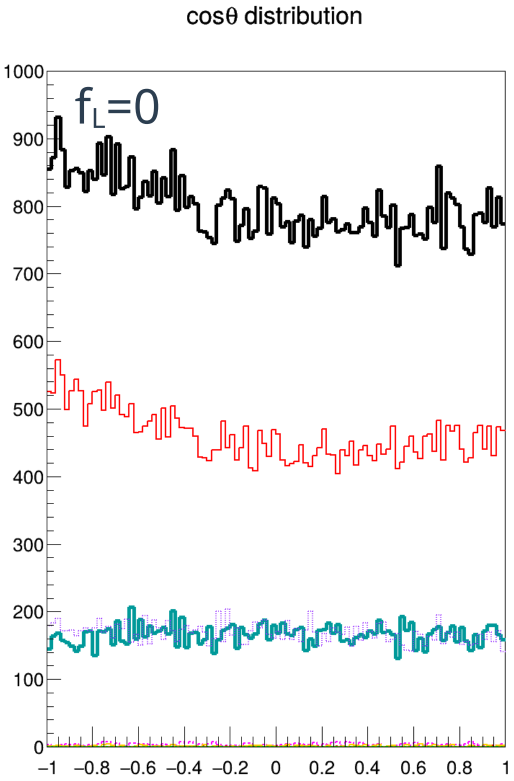

Cosθ with ZEUS Exclusive Analysis Cuts

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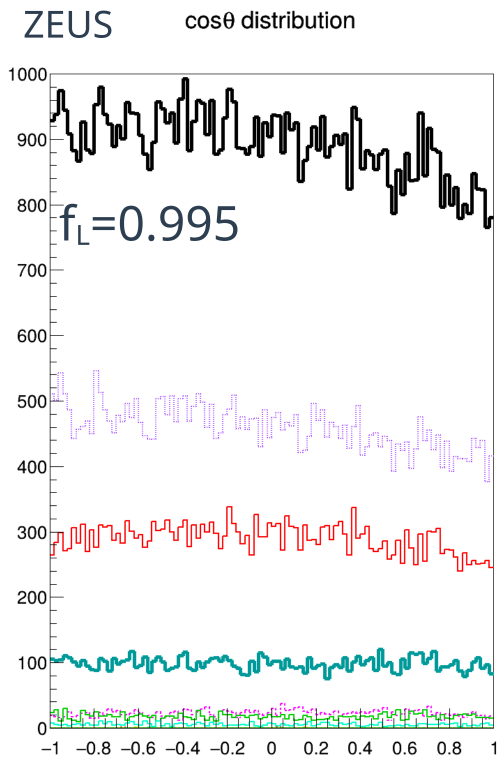
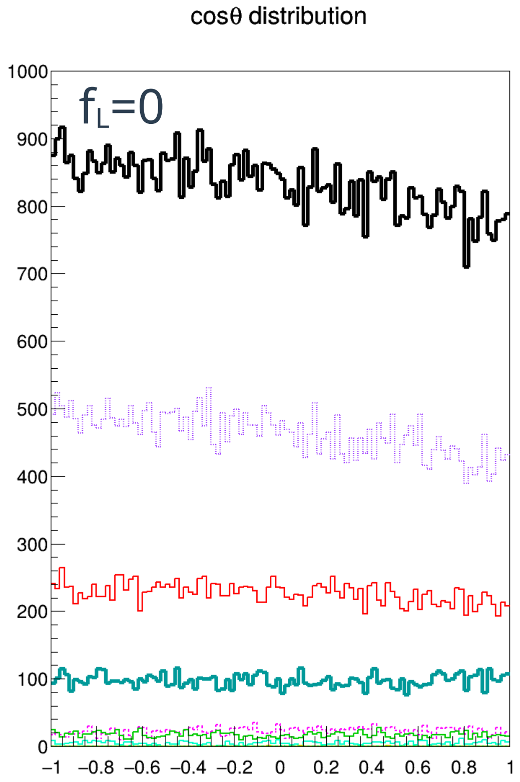
- ~~$\delta = \Sigma(E-p_z)$ cut not applied (FIXME)~~

test |t| cut in isolation, since cuts a large fraction

Reference: DESY–07–118
August 2007





Cosθ with ZEUS Exclusive Analysis Cuts

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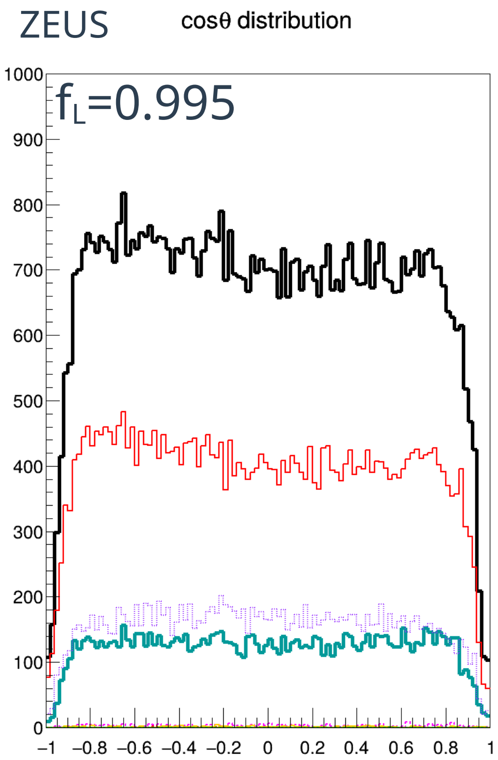
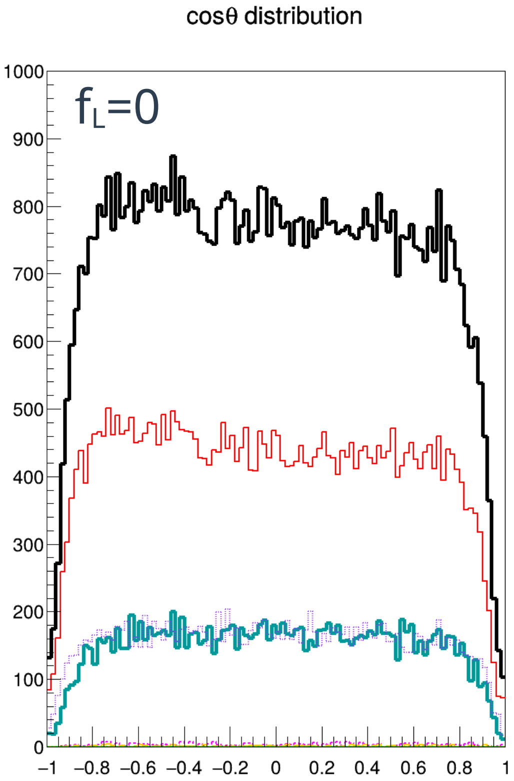
$|\cos\theta|$~1 cut away by p_T cut, which excludes regions of poor recon. eff. and p res.

Reference: DESY–07–118
August 2007





Summary

- **Pythia8 + StringSpinner**
  - Tuned to CLAS12
  - Promising for reproducing dihadron beam spin asymmetries
- **Cosθ / acceptance studies**
- **I can rapidly produce additional plots to facilitate discussion**

Semi-Inclusive vs. Exclusive

Semi-Inclusive

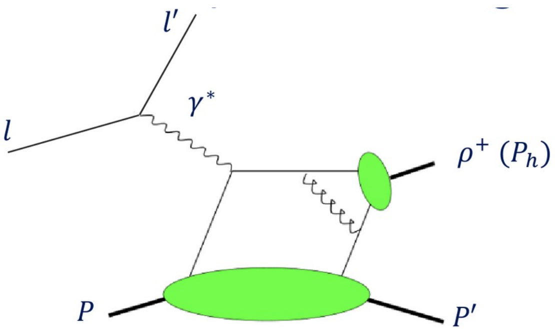
- Longitudinal photon contributions are leading twist
- Contaminated by exclusive VMs

Exclusive

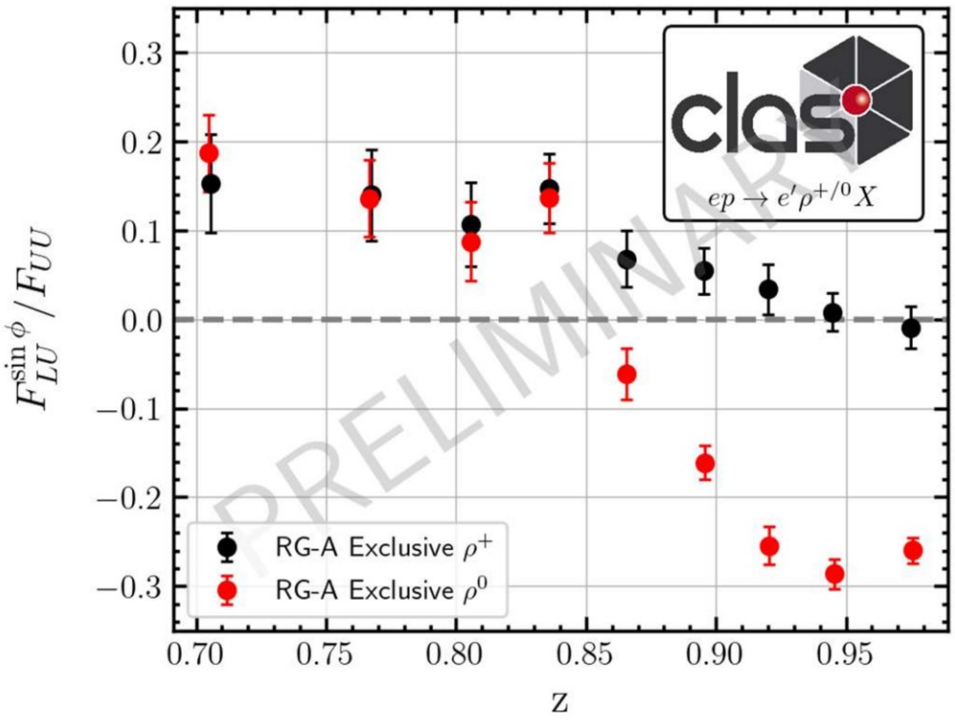
- Transverse photon contributions are leading twist

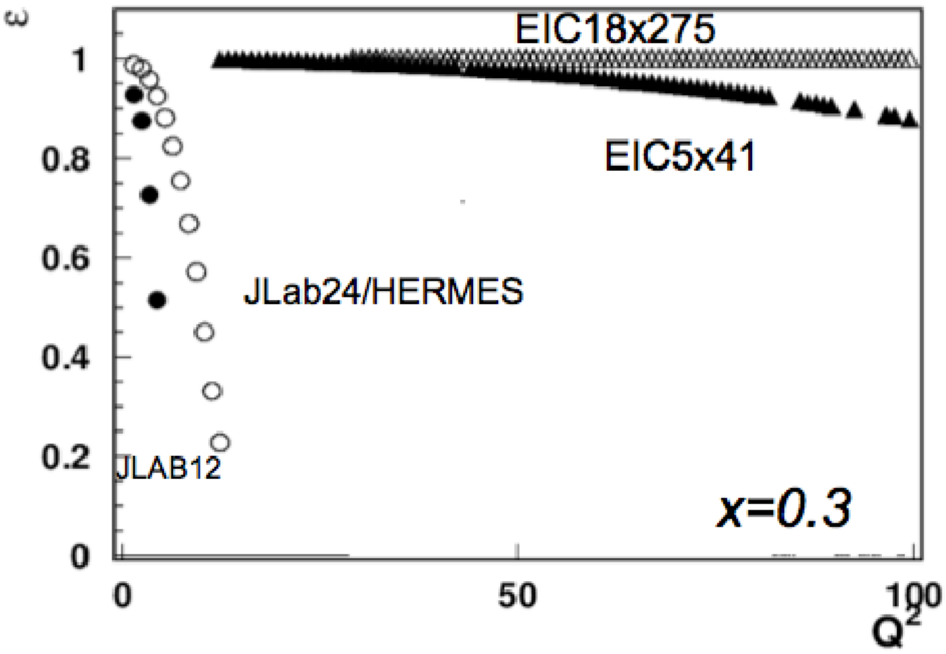
Select ρ Studies at CLAS12

Exclusive ρ Spin Asymmetries



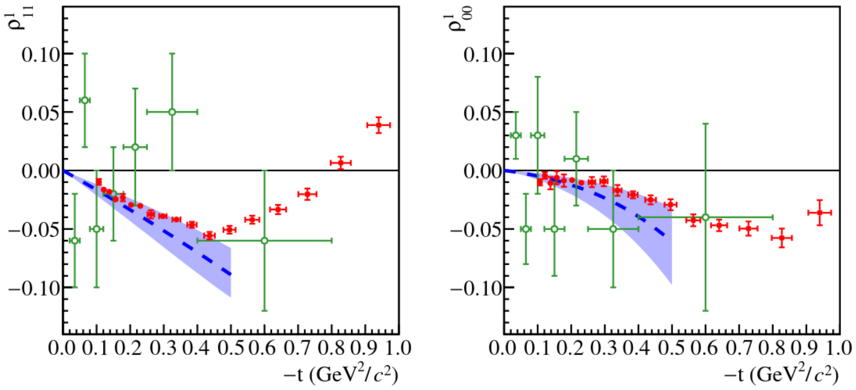
G.Matousek (Duke) & N.Trotta (UCONN)



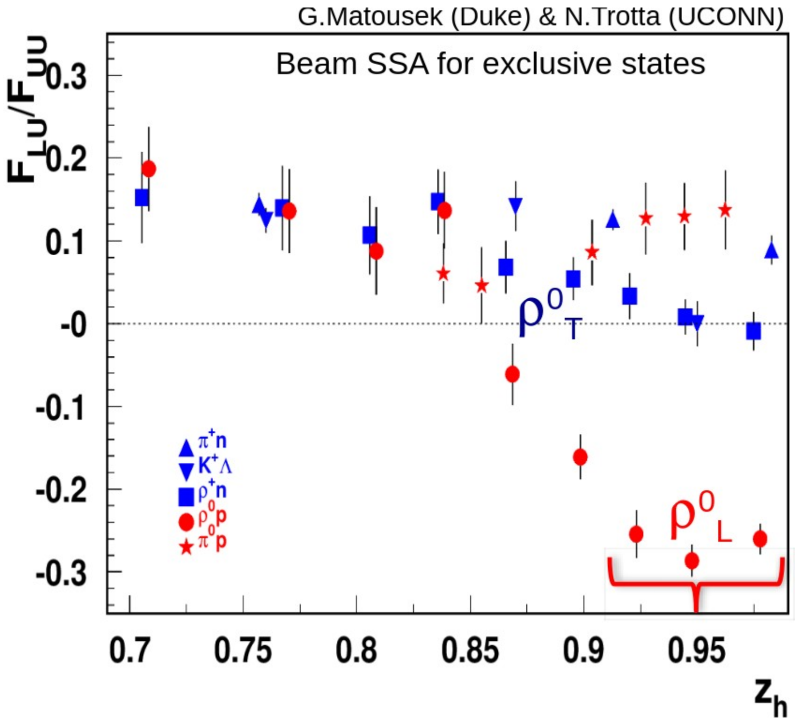

ε
1
0.8
0.6
0.4
0.2
0
0
50
100
Q^2
EIC18x275
EIC5x41
JLab24/HERMES
JLAB12
x=0.3

ρ Photoproduction

JLab/GlueX, S. Adhikari et al, Phys.Rev.C 108 (2023), 055204: ArXiv:2305.09047



While at small t (dominant part of the statistics) the transverse rhos dominate, at large t the contribution from transverse photons going to longitudinal rho becomes more significant



Large z → small t

At small t, transverse rhos dominate