FROM SPIN TO STRUCTURE

Beam Spin Asymmetry and the Strong Force

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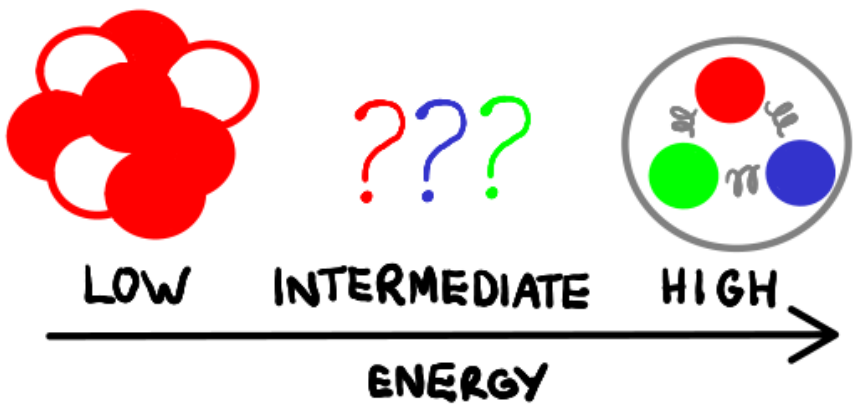
University of Regina

Motivation

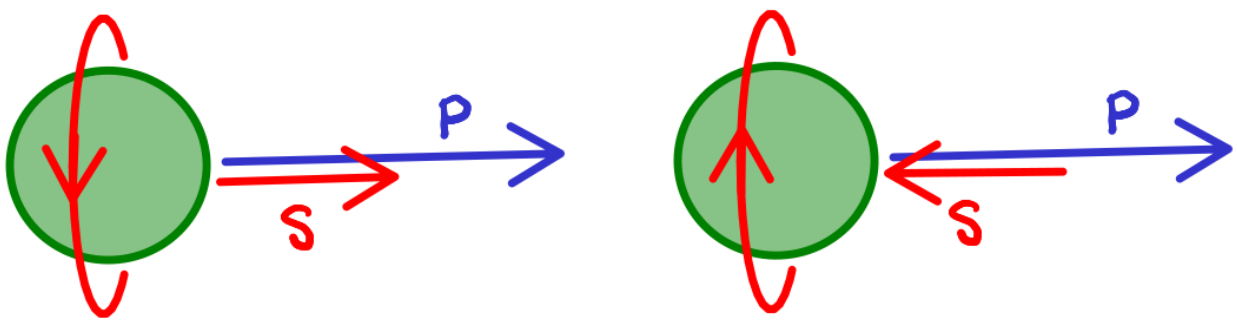
- Many unknowns in theory of **strong force**
- Meson electroproduction in Jefferson Lab Hall C probes **hadron structure**
- Use observables to study **non-perturbative QCD** in the **transition regime**



Beam Spin Asymmetry

$$BSA = \frac{1}{P}\left(\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right)$$

- Difference in cross-sections based on **helicity** (± 1) of the incident electron



A. Bacchetta et al. Phys. Rev. D 70, 117504 (2004).

Beam Spin Asymmetry

$$BSA = \frac{1}{P}\left(\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right) \propto \frac{\sigma_{LT'}}{\sigma_0}$$

- Difference in cross-sections based on **helicity** (± 1) of the incident electron
- Caused by interference between transversely and longitudinally polarized virtual photons

My research: BSA analysis of the reaction:

$$e^- + p \longrightarrow e^{-\prime} + \pi^+ + n$$

D. Drechsel & L. Tiator. J. Phys. G **18** 449 (1992).

The Goal

- Extract $\sigma_{LT'}/\sigma_0$ over a range of kinematics
- Compare with two types of models:

  Regge: considers **baryon** and **meson** degrees of freedom

  Generalized Parton Distribution (GPD): considers **quark** and **gluon** degrees of freedom

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  Regge: considers **baryon** and **meson** degrees of freedom

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The big question: Is $\sigma_{LT'}/\sigma_0$ better predicted by Regge or GPD-based models?

The Goal

- Extract $\sigma_{LT'}/\sigma_0$ over a range of kinematics
- Compare with two types of models:

  Regge: considers **baryon** and **meson** degrees of freedom

  Generalized Parton Distribution (GPD): considers **quark** and **gluon** degrees of freedom

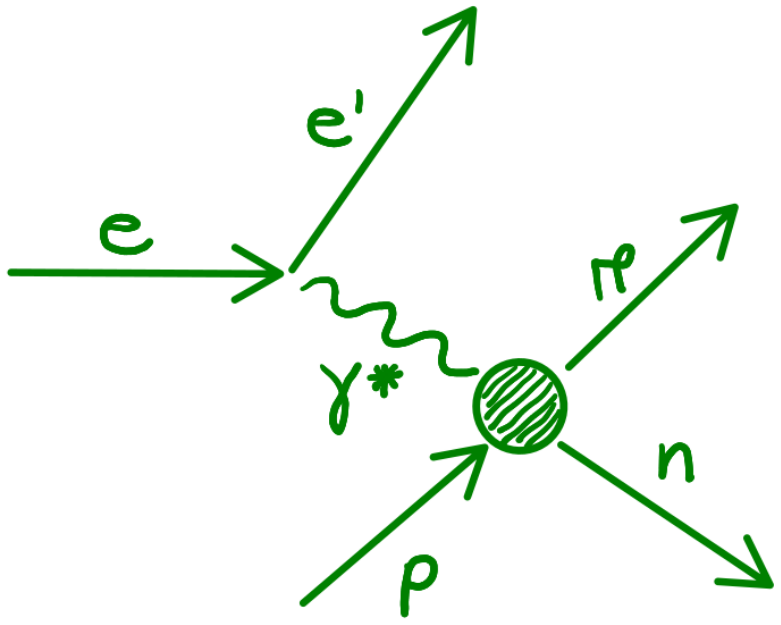
> **The bigger question:** *Which degrees of freedom apply to hadronic reactions in the transition regime?*

Some Definitions

Q^2: 4-momentum of γ^*

W: center of mass energy

-t: 4-momentum transfer from γ^* to meson



Some Definitions

Q^2: 4-momentum of γ^*

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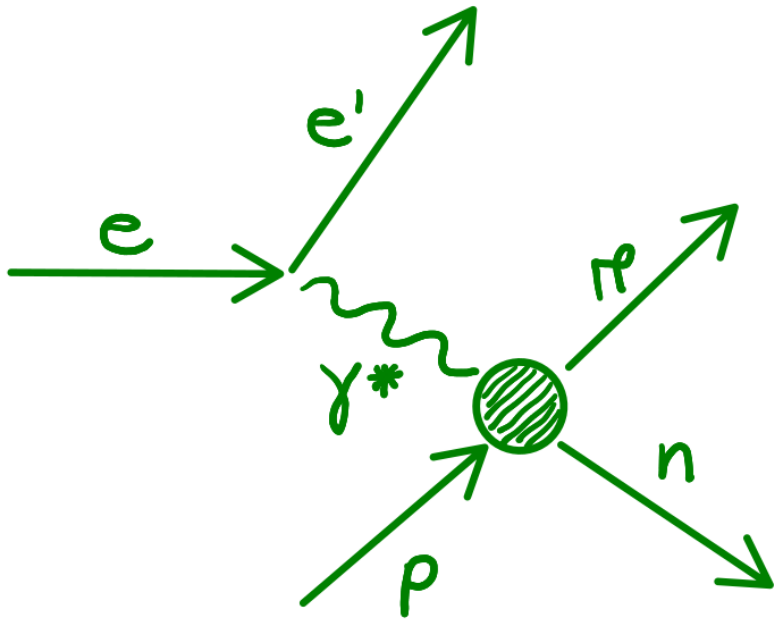

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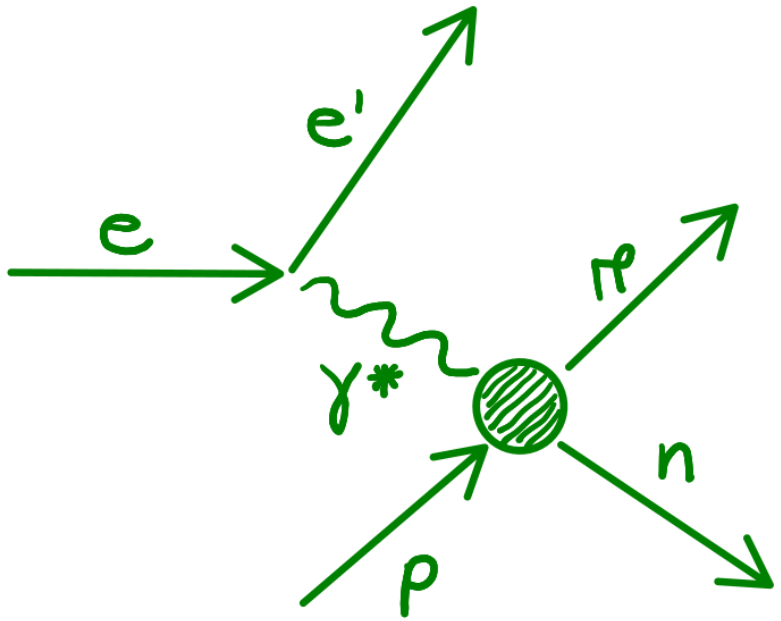

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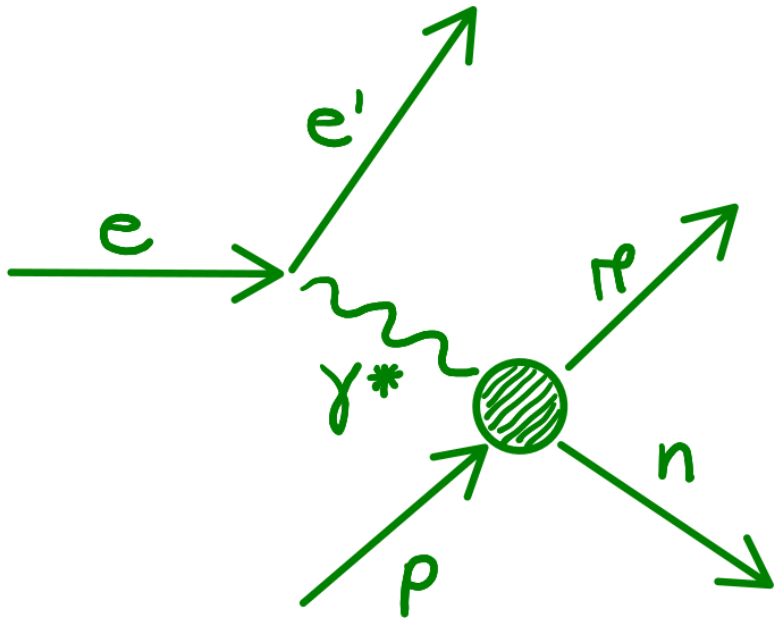

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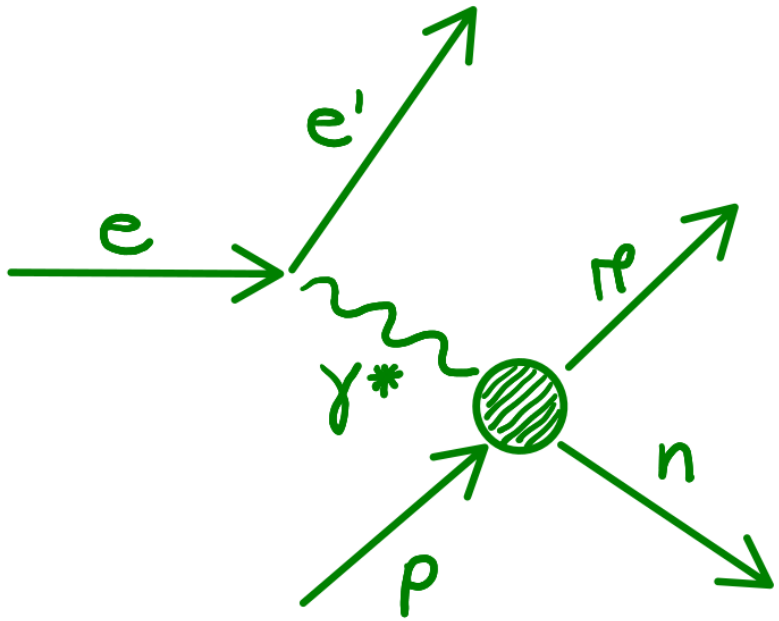

- Investigating transition regime: Q^2=1 to Q^2=5
- Above resonance region: W>2
- Data organized by (Q^2,W) $\rightarrow$ plot BSA in bins of -t

Getting Started

$$BSA = \frac{1}{\boldsymbol{P}} \left(\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \right)$$

- Beam polarization $\boldsymbol{P}$ measured at source $\longrightarrow$ calculate in our hall ($P = 89^{+1}_{-3}\%$)
- Accelerator flips beam helicity $\pm$ in a pseudo-random sequence $\longrightarrow$ events separated by helicity in data analysis
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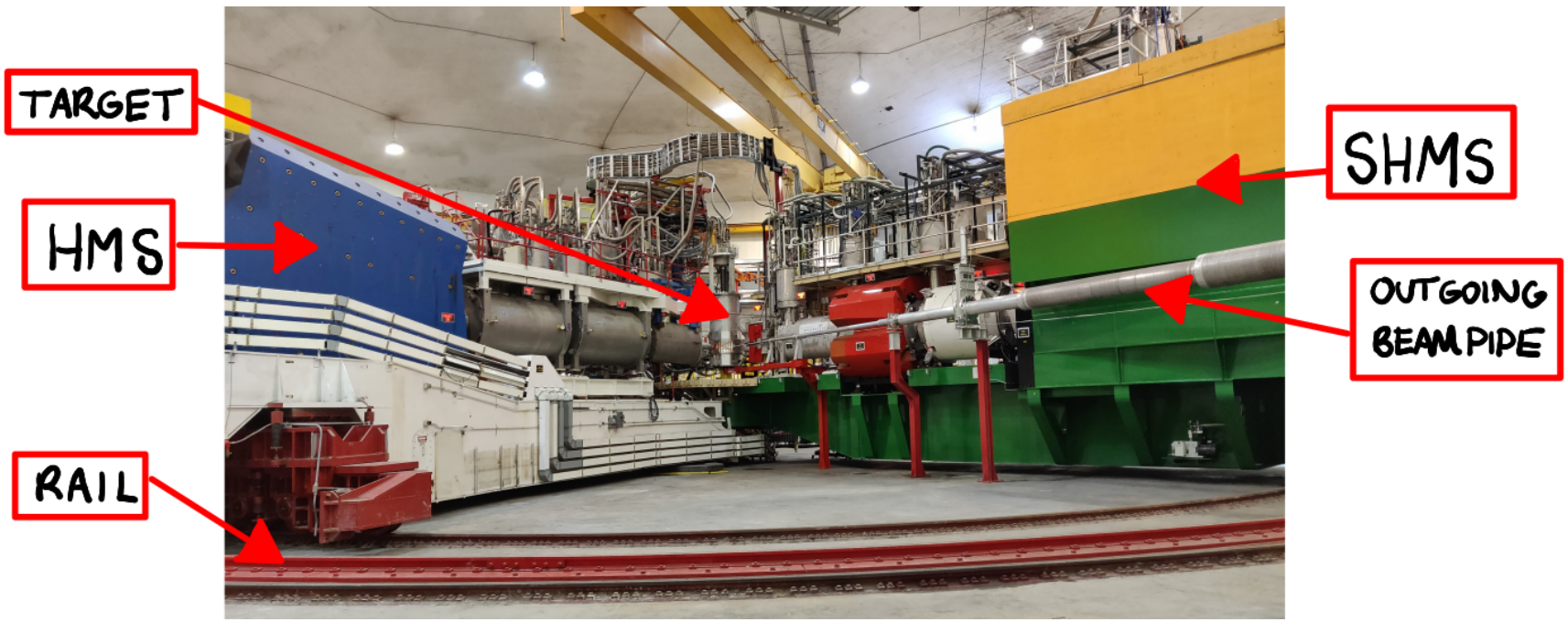
Welcome to Hall C!

- Hall C: electron beam → fixed target → spectrometers



- Spectrometers are magnetic and moveable → choose charge, momentum, and angles to detect

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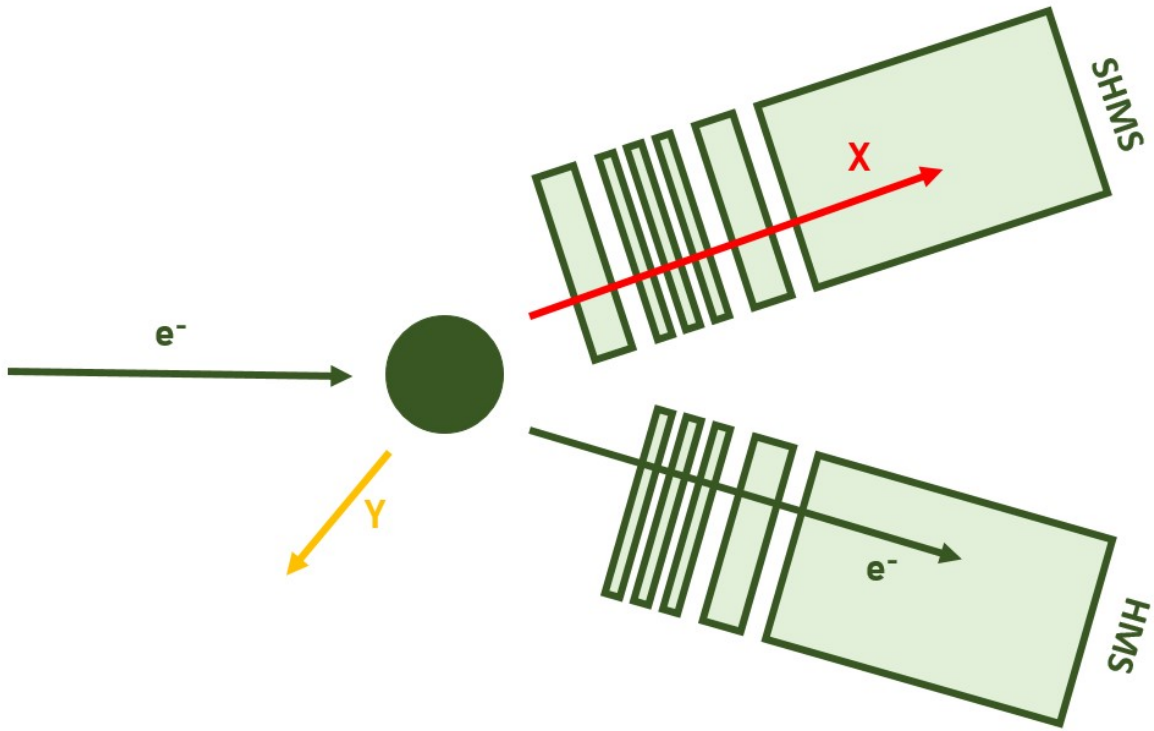

- Coincidence experiment: need simultaneous detection in **High Momentum Spectrometer** and **Super HMS**

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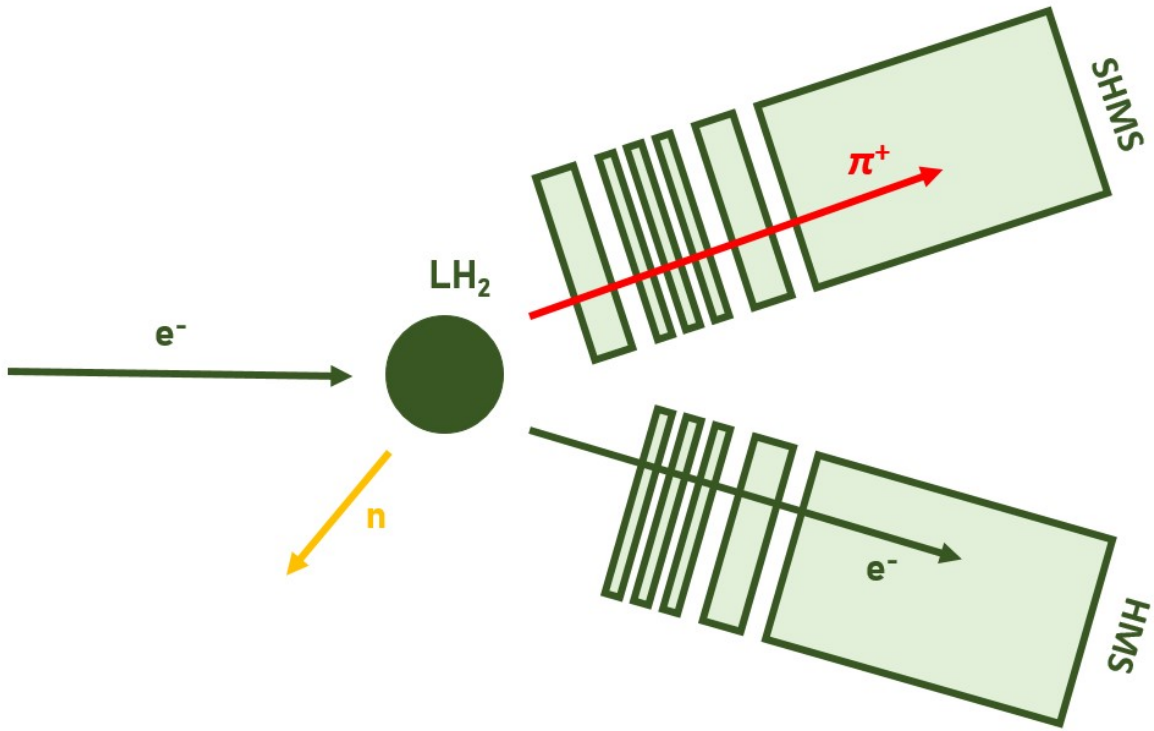

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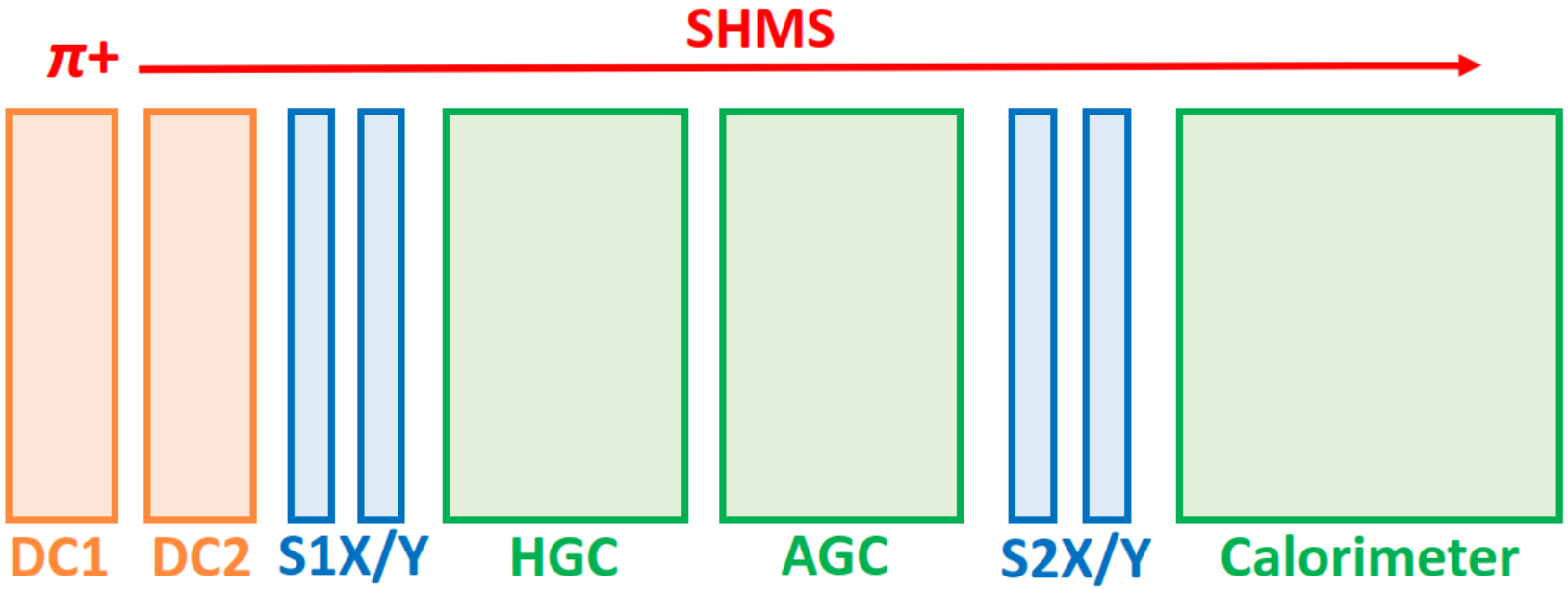
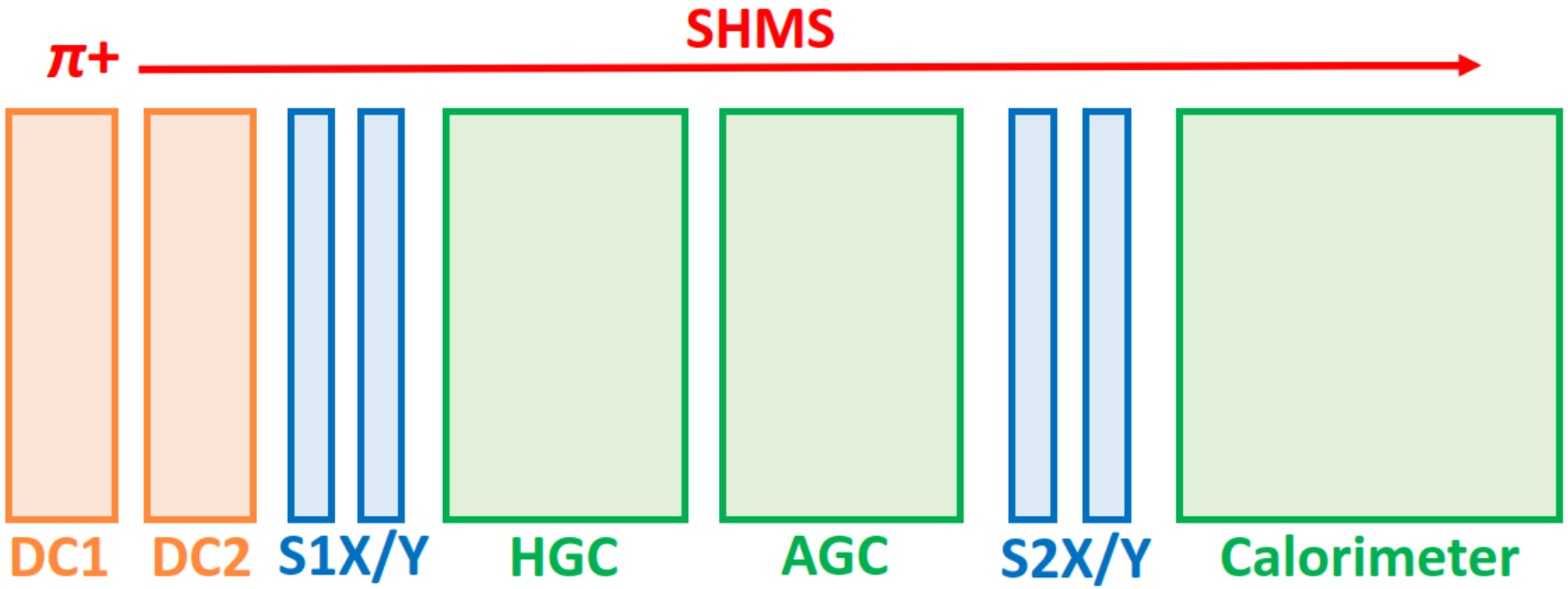
Particle Identification



- **SHMS** dipole magnet allows only **positive** particles
- Specialized detector stack for **tracking**, **trigger**, and **particle identification**
- π^+ will generate radiation in **both** threshold Čerenkovs

Particle Identification



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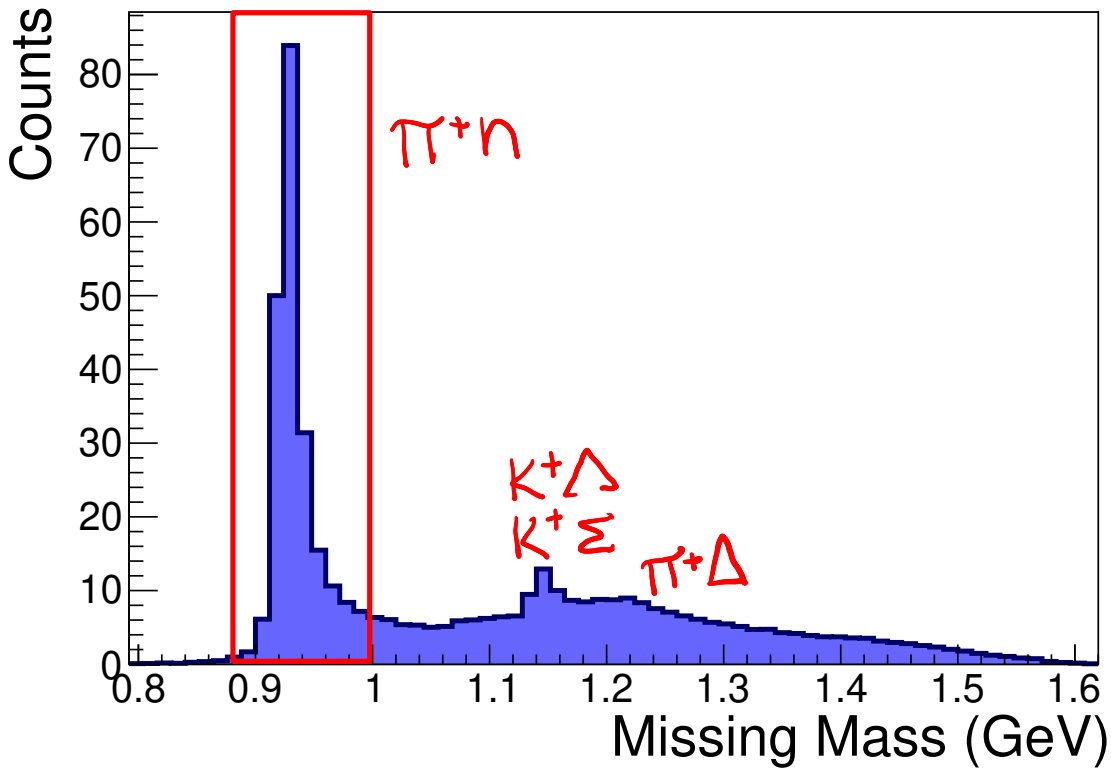
  $\rightarrow$ **HMS** is similar: negative particles, only one Čerenkov

Missing Mass Cut

- Isolate the reaction: $p(e, e'\pi^+)n$
- Neutron not detected $\rightarrow$ select neutron channel using:

$$M_{MISS} = \sqrt{(E_e + m_p - E_{e'} - E\pi+)^2 - (p_e - p_{e'} - p_{\pi+})^2}$$



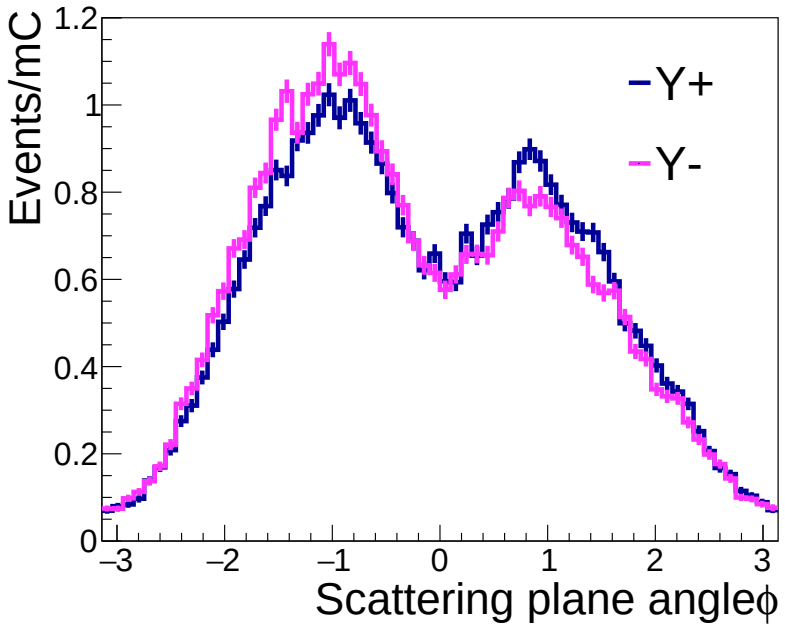
Yield Calculation

For **each helicity state**, do...

1. Particle identification
2. Missing mass cut
3. Prompt-random subtraction
4. Empty target subtraction

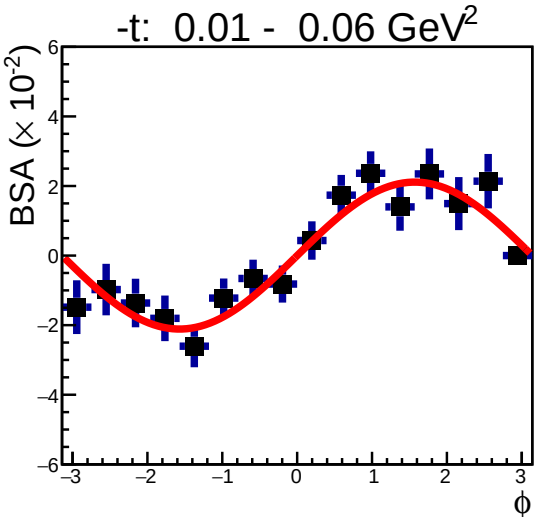
... to calculate yields Y^+ and Y^-

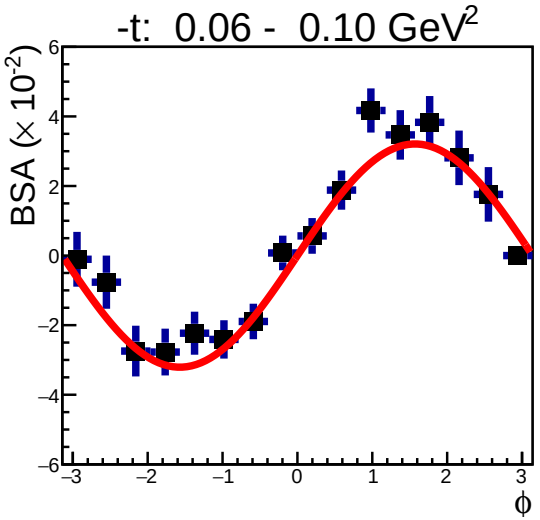
Yield: $Q^2 = 3,\ W = 2.32$

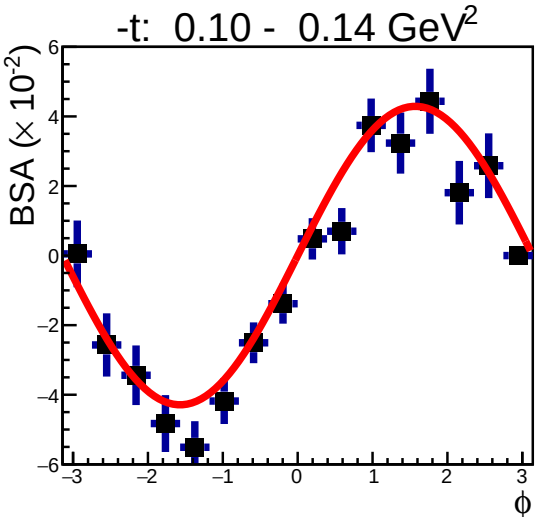


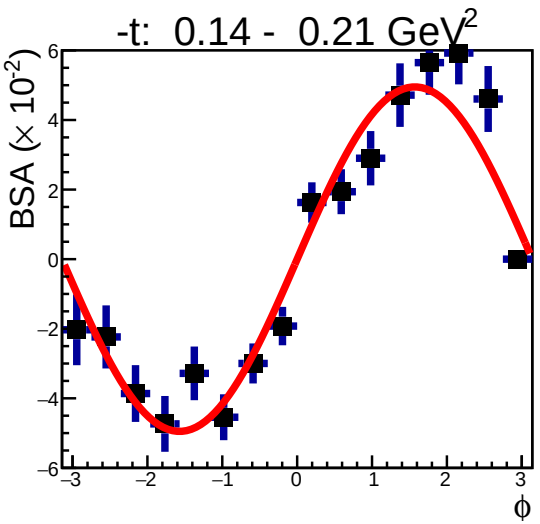
$$BSA = \frac{1}{P}\left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right)$$

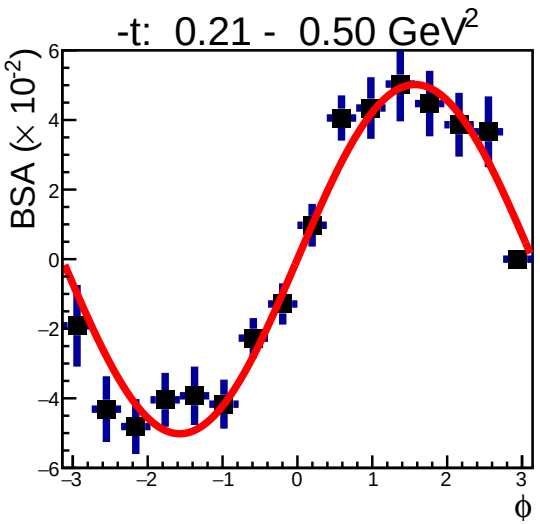
Asymmetry Q^2=2.115 GeV^2, W=2.95 GeV







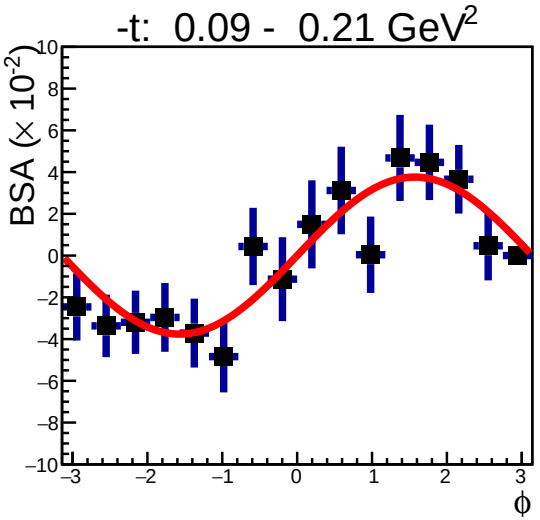


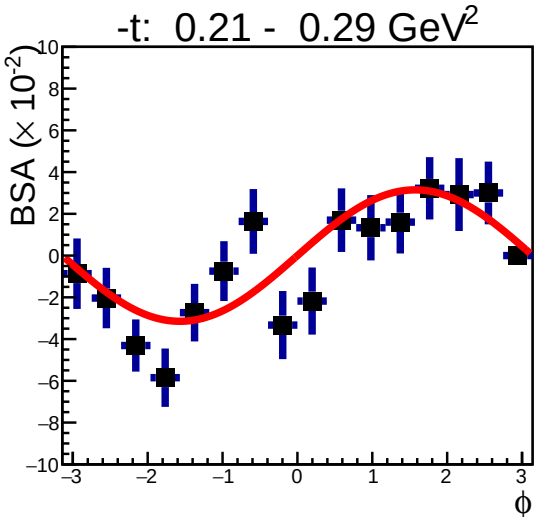


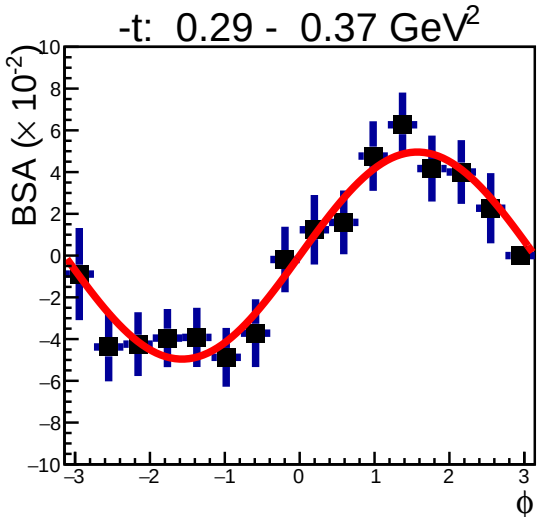
— $A\sin\phi$

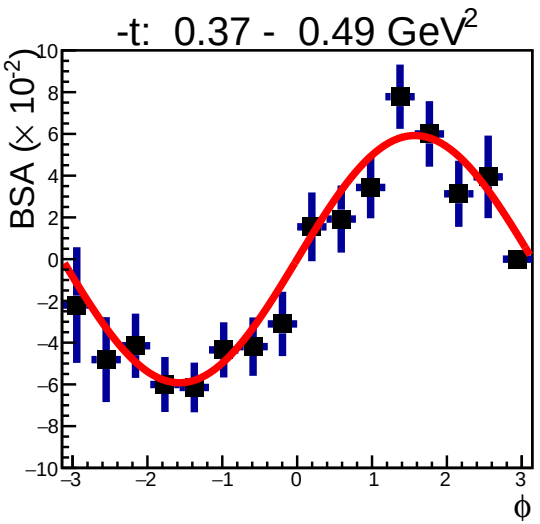
$$A \propto \frac{\sigma_{LT'}}{\sigma_0}$$

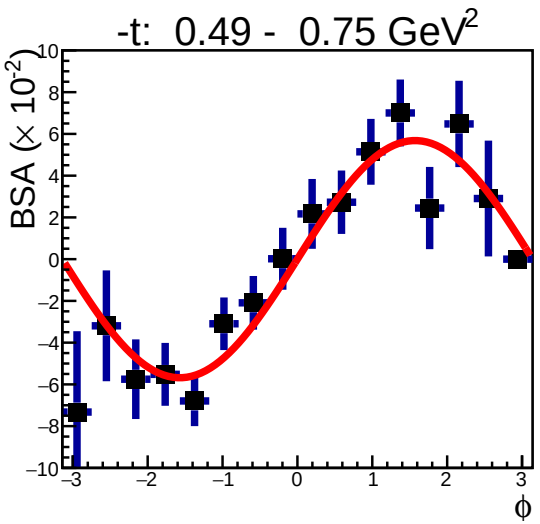
Asymmetry Q^2=3 GeV^2, W=2.32 GeV







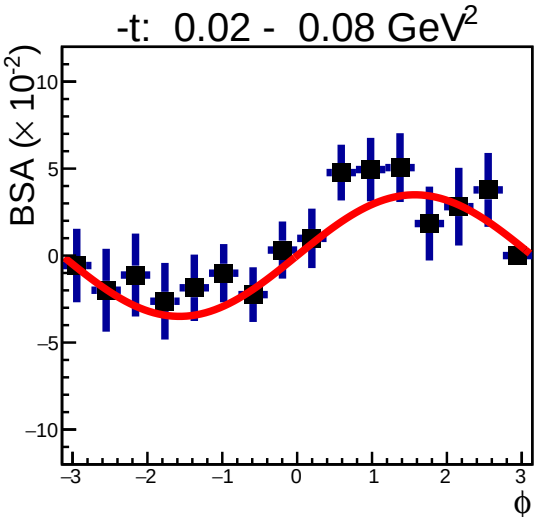


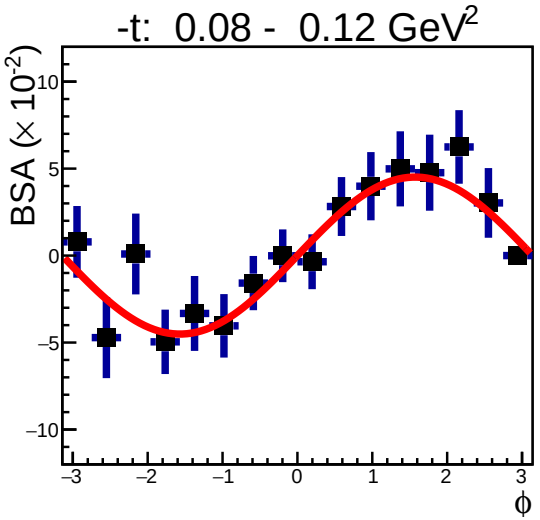


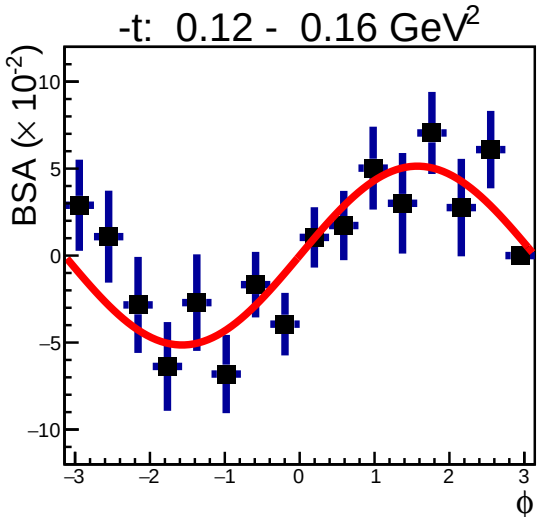
— $A\sin\phi$

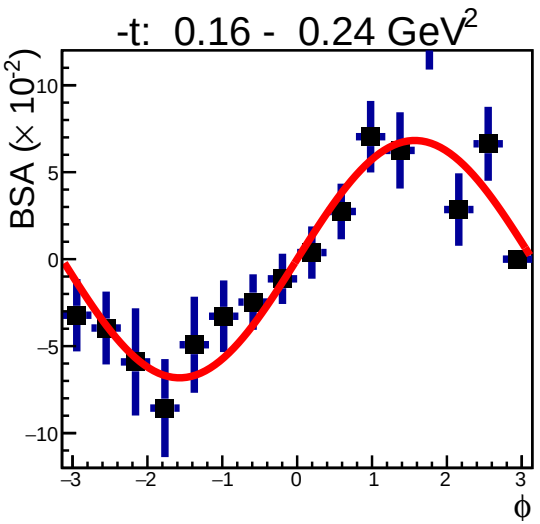
$$A \propto \frac{\sigma_{LT'}}{\sigma_0}$$

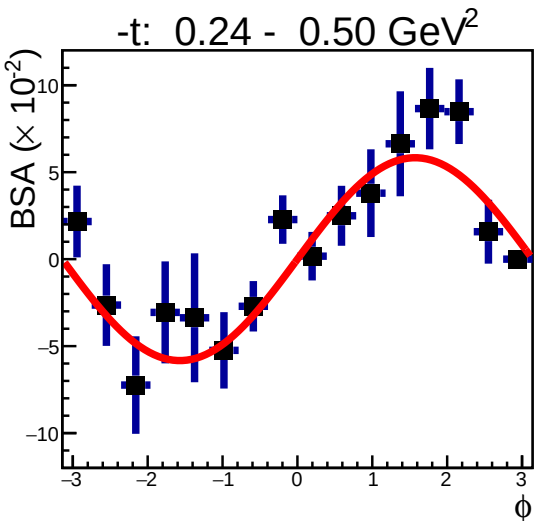
Asymmetry Q^2=3 GeV^2, W=3.14 GeV







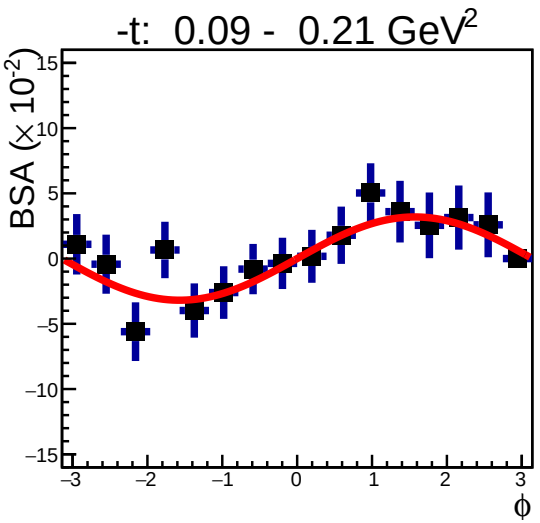


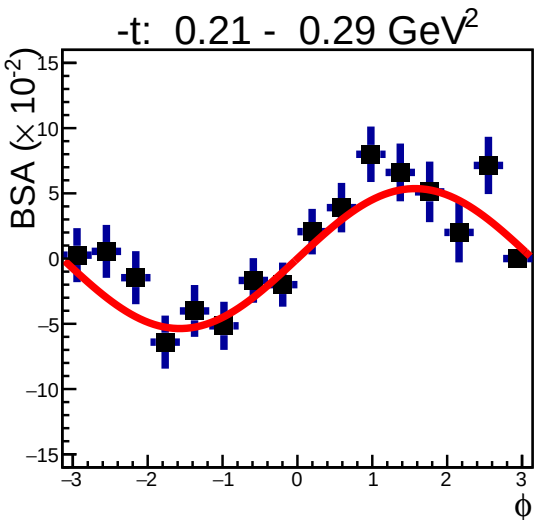


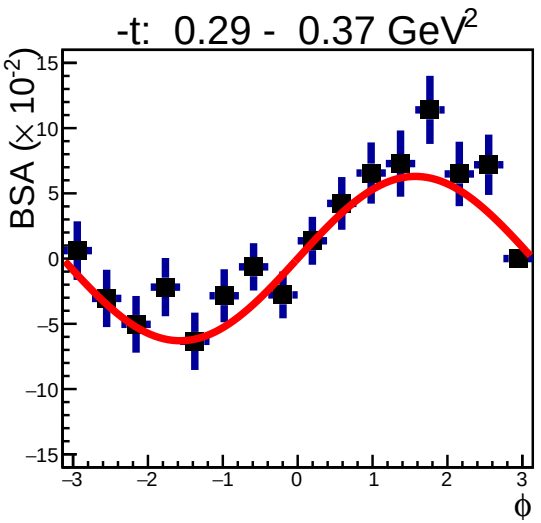
— $A\sin\phi$

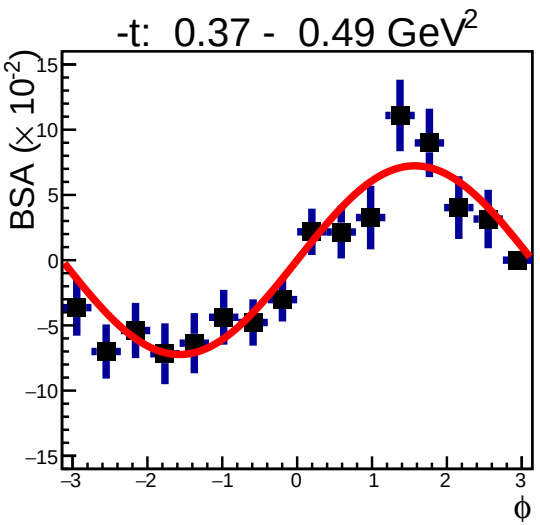
$$A \propto \frac{\sigma_{LT'}}{\sigma_0}$$

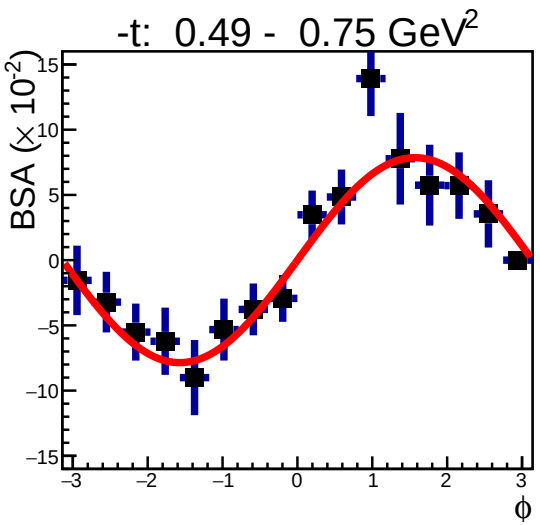
Asymmetry Q^2=4.4 GeV^2, W=2.74 GeV











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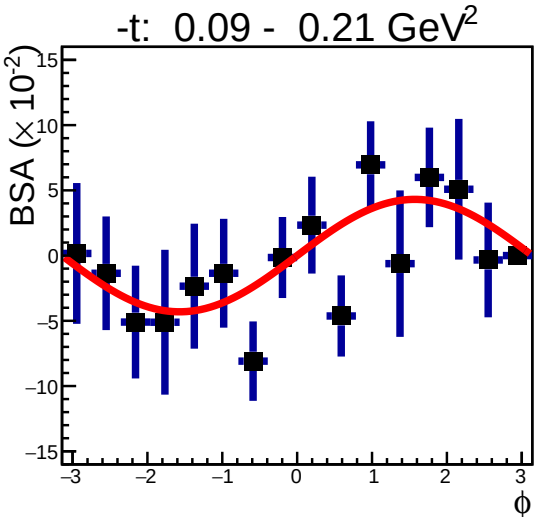
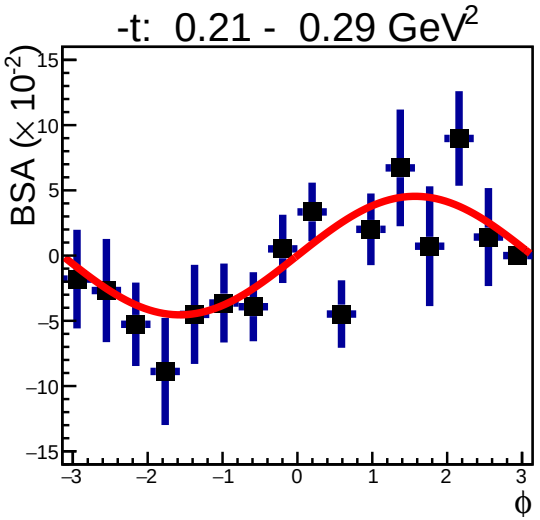
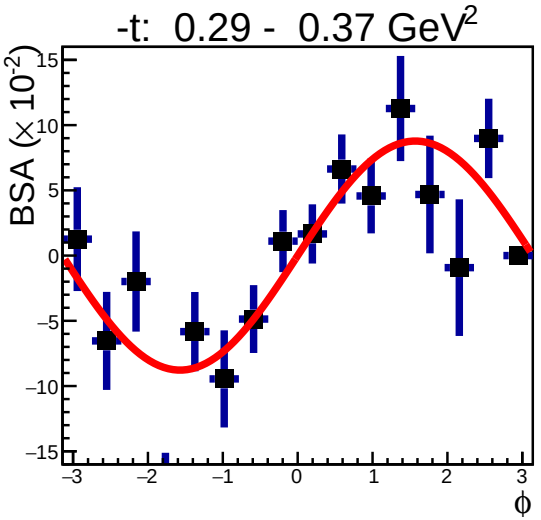
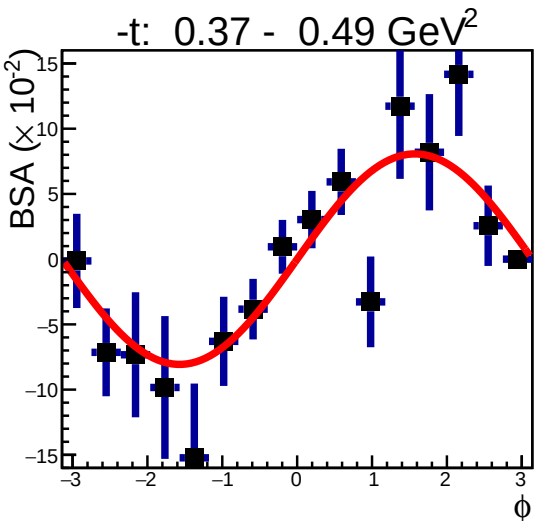
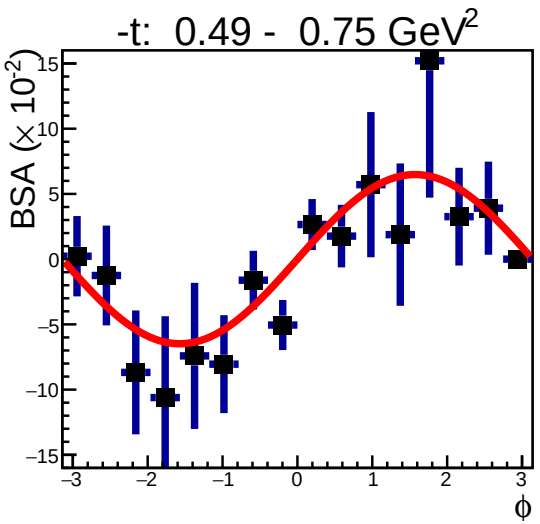
Asymmetry Q^2=5.5 GeV^2, W=3.02 GeV











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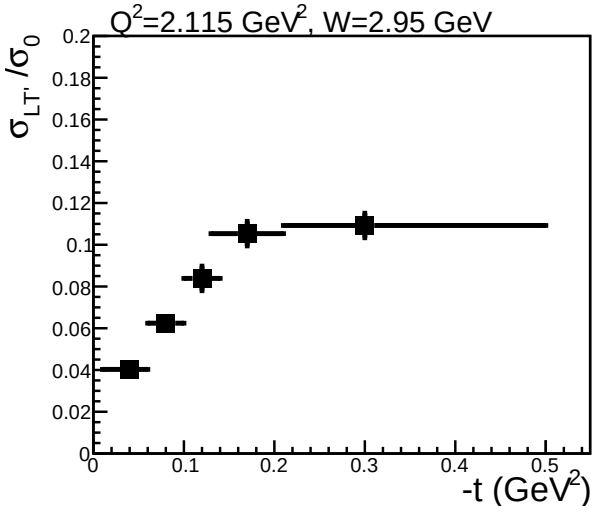
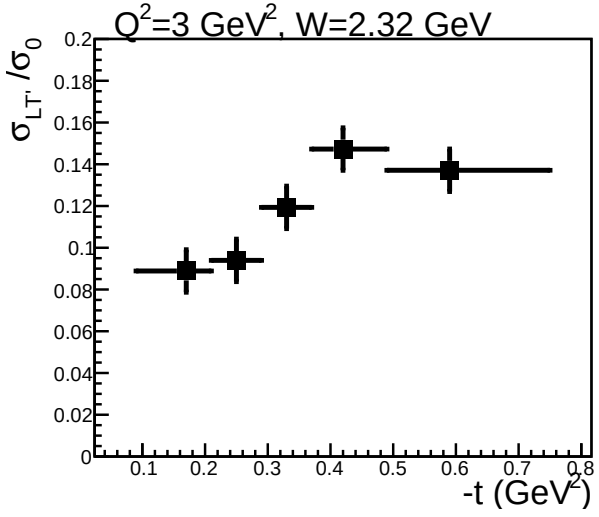
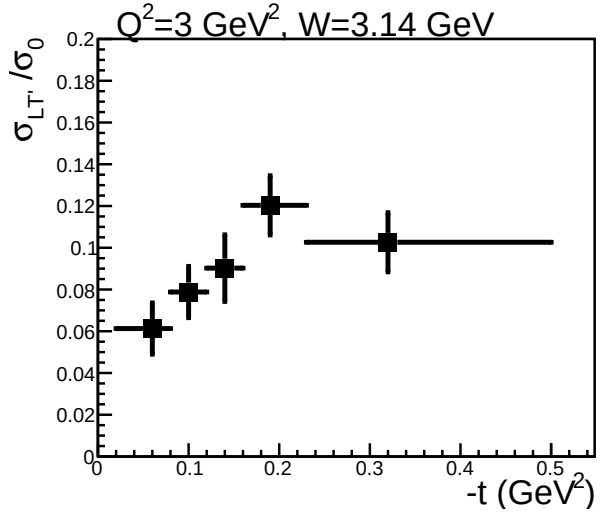
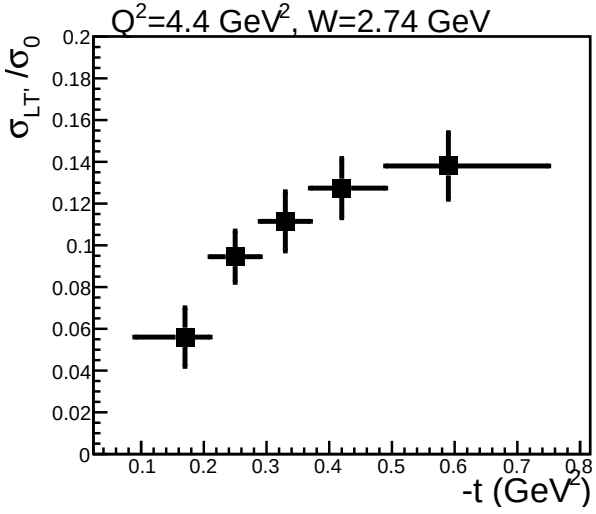
$$A \propto \frac{\sigma_{LT'}}{\sigma_0}$$

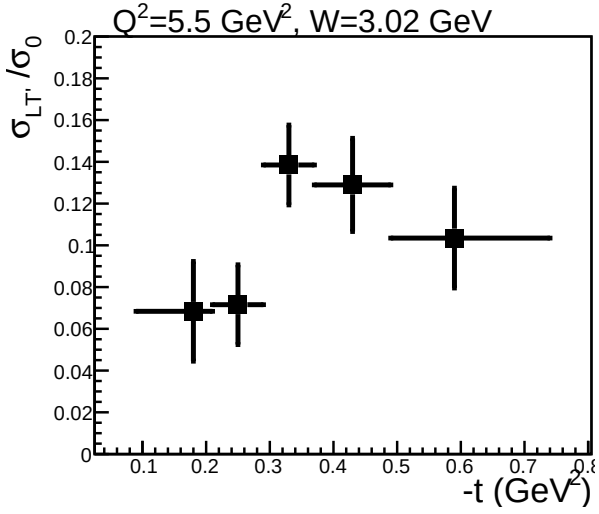
Results





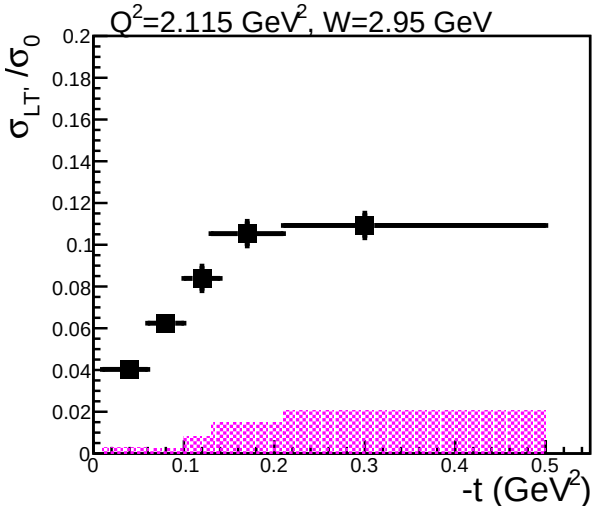


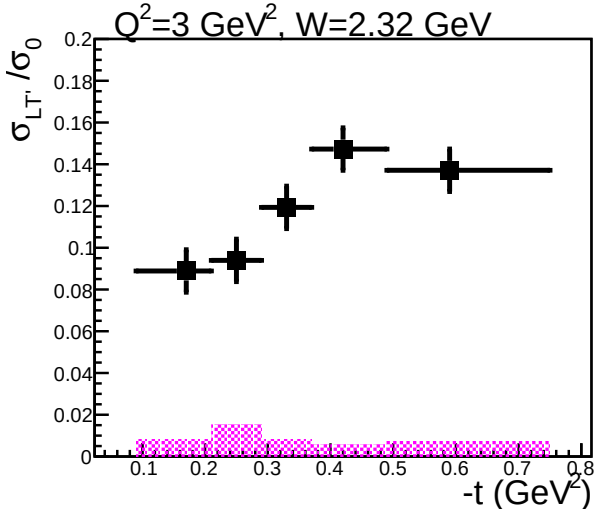


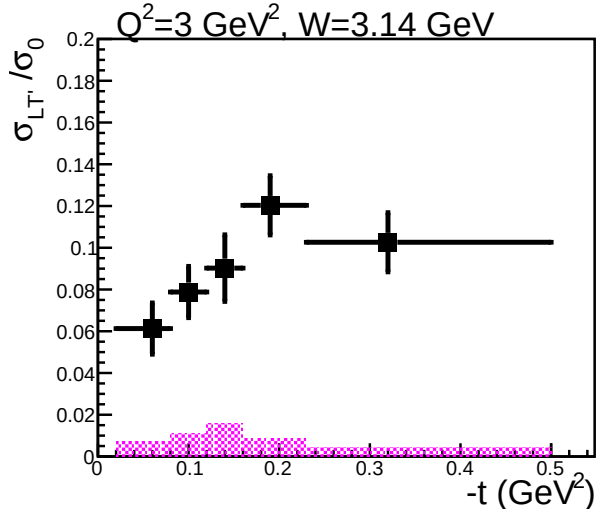


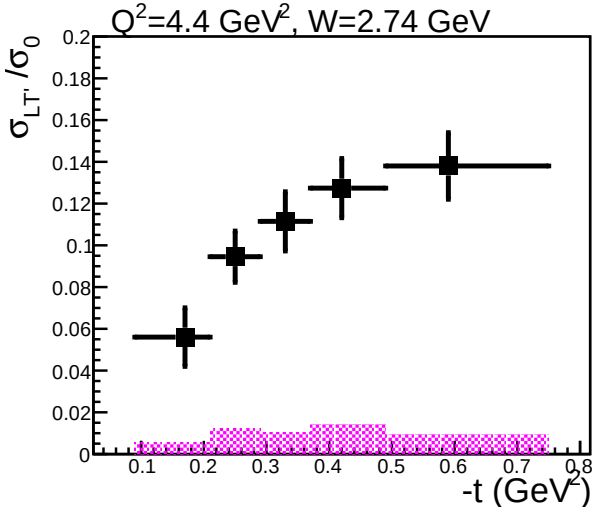
Data

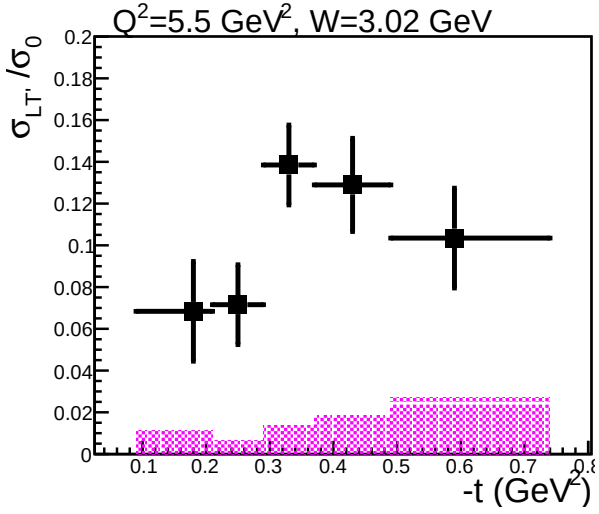
Results

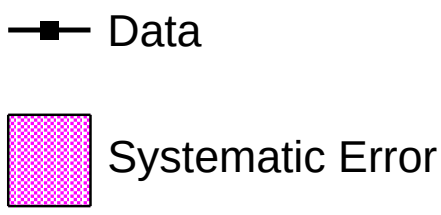






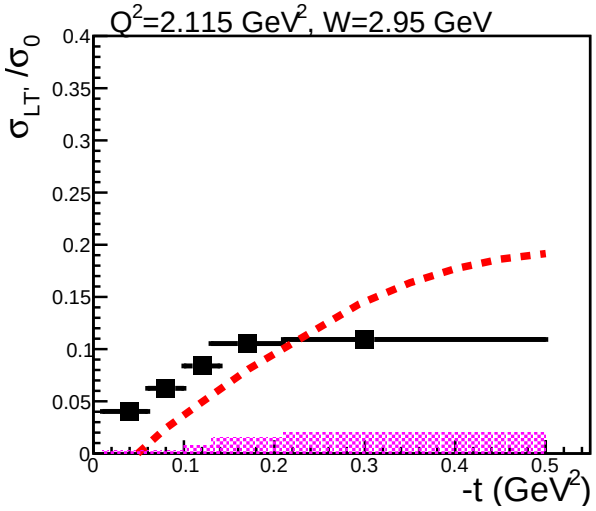


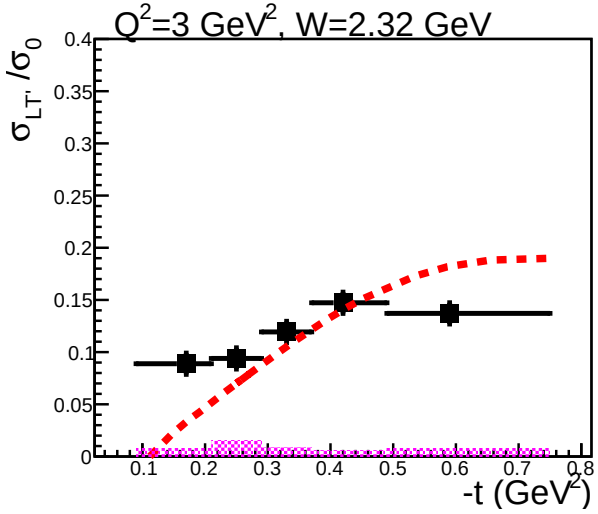


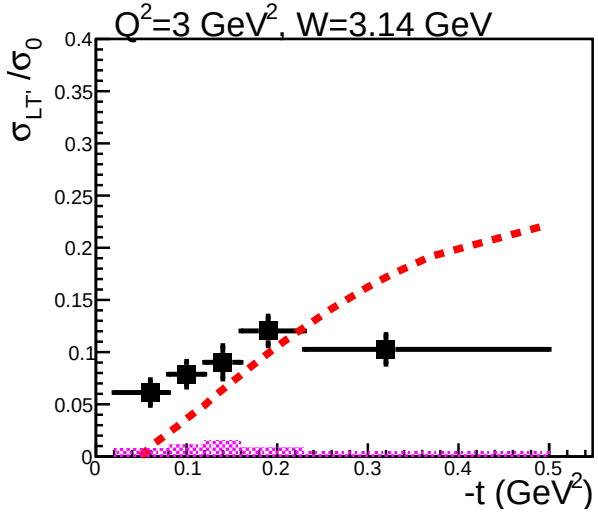


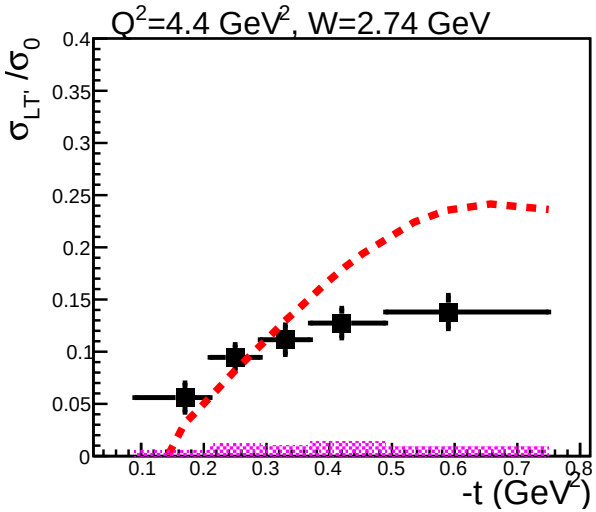
Systematics: beam polarization uncertainty, missing mass cut, coincidence time window

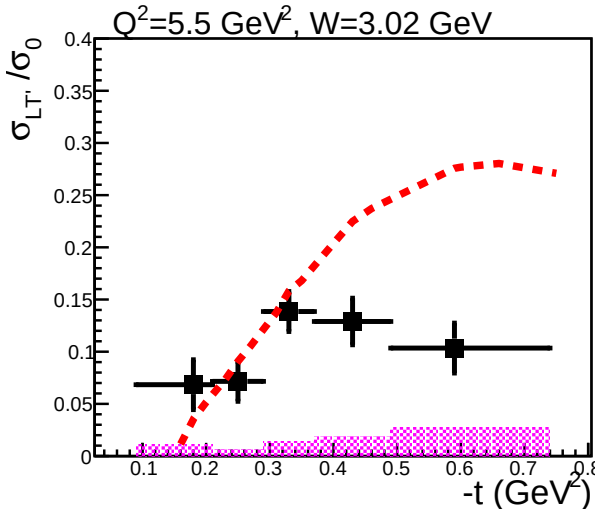
Results

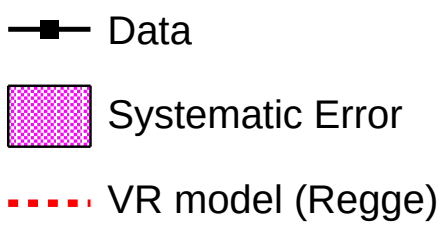








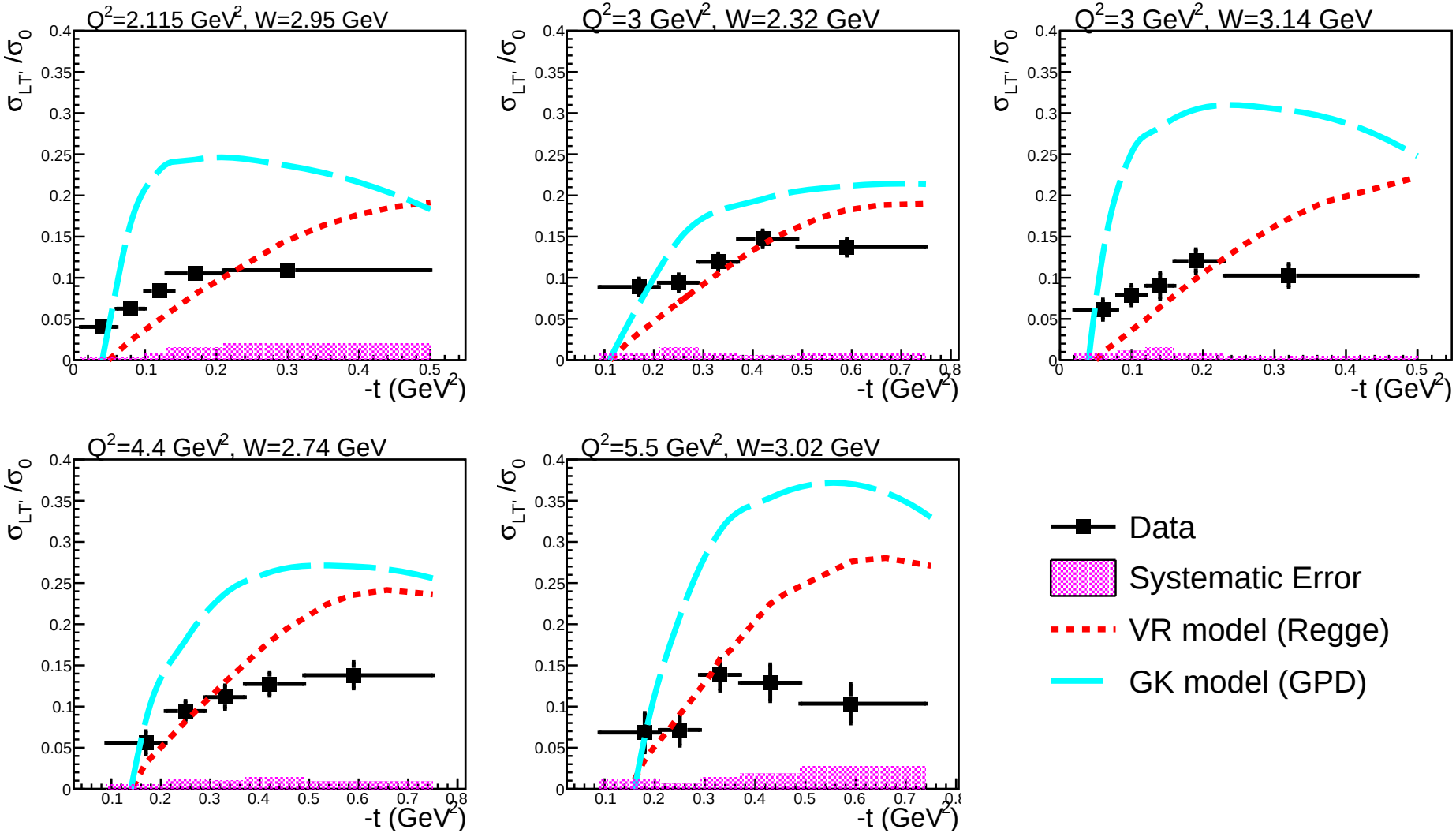




T. Vrancx, J. Ryckebusch & J. Nys, Phys. Rev C, **89** 065202 (2014).

http://rprmodel.ugent.be/calc/

Results



T. Vrancx, J. Ryckebusch & J. Nys, Phys. Rev C, **89** 065202 (2014). http://rprmodel.ugent.be/calc/

B. Berthou et al, Eur. Phys. J. C **78** 478 (2018). DOI: 10.1140/epjc/s10052-018-5948-0

S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010). DOI: 10.1140/epjc/s10052-009-1178-9

Theory Comparison

VR model (Regge)

- ✓ Reasonable agreement with **low -t** data
- × Does not predict **high -t** behaviour

GK model (GPD)

- ✓ Predicts overall **shape** of curve
- × Overestimates **magnitude** of asymmetry

Hoping to run 2 more models: **VGL (Regge)** & **Liutti (GPD)**

M. Vanderhaeghen, M. Guidal & J.-M. Laget, Phys. Rev. C, **57** 3 (1998).
http://lichen.phys.uregina.ca/ huberg/models/vgl_pion/

Summary and Conclusions

- Beam spin asymmetry calculated for $\boldsymbol{p(e, e'\pi^+)n}$
- Extracted $\boldsymbol{\sigma_{LT'}/\sigma_0}$ at different kinematics
- $-t$-dependence compared to theory

Kinematic variation of structure function $\sigma_{LT'}/\sigma_0$ used to probe the strong force in the transition regime!

Acknowledgements

My thanks to...

- Garth Huber
- Steve Wood and Peter Bosted
- KaonLT/PionLT Collaboration

NSERC CRSNG

CINP ICPN

Canadian Institute of Nuclear Physics

Institut canadien de physique nucléaire

JL

Hall C

This research was carried out at the University of Regina, on what is Treaty 4 land and the territories of the nêhiyawak, Anihšināpēk, Dakota, Lakota, Nakoda, and the Métis/Michif Nation.

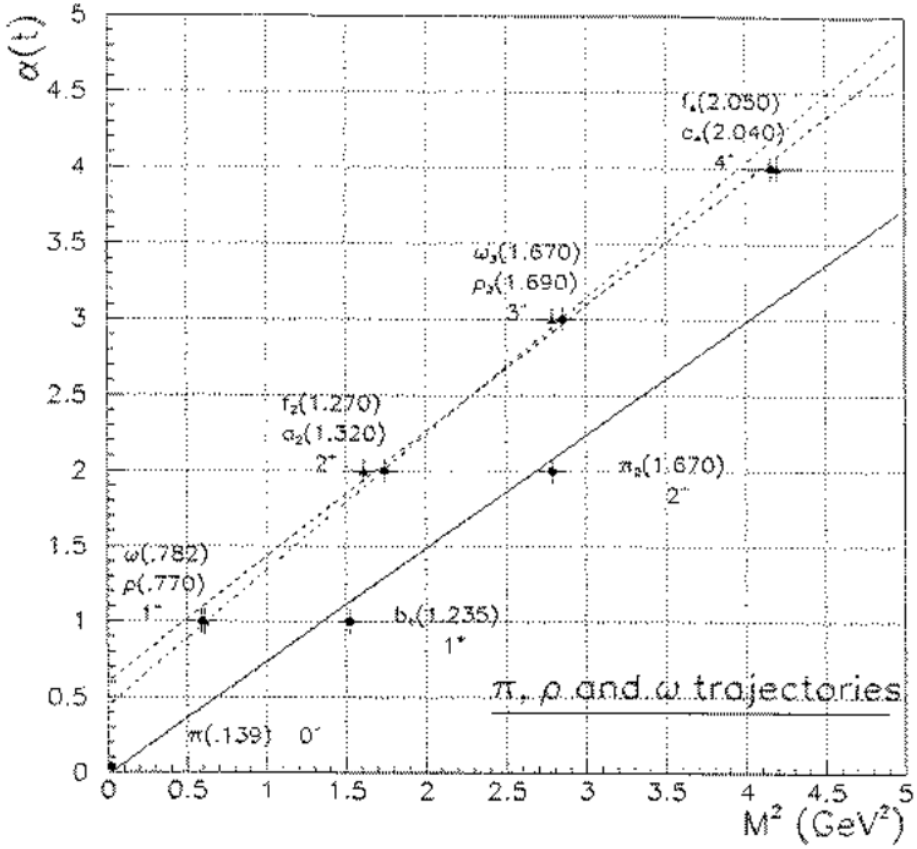
EXTRA SLIDES

Regge Models

- Regge trajectory: empirical relation between spin α and mass M^2
- Replace Feynmann propagator with Regge propagator

$\rightarrow$ Exchange of a series of particles along the Regge trajectory

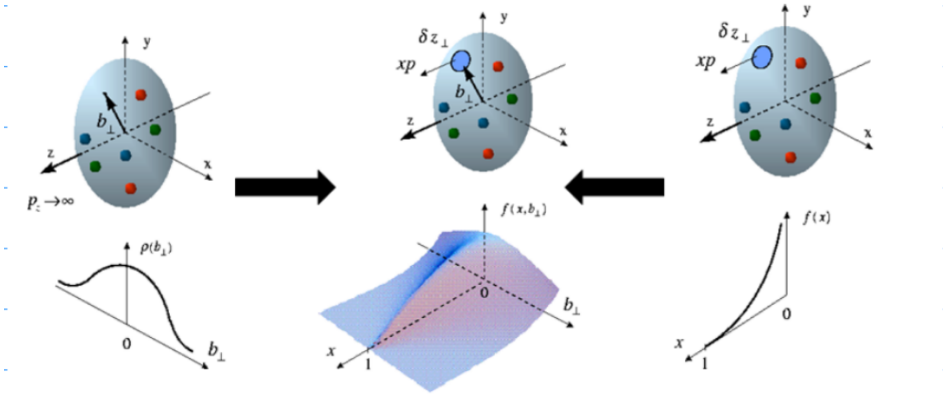
$\rightarrow$ Trajectory cutoff a free parameter in the model



J.M. Laget. Prog. Part. Nucl. Phys. **111** 103737 (2020).

Generalized Parton Distributions

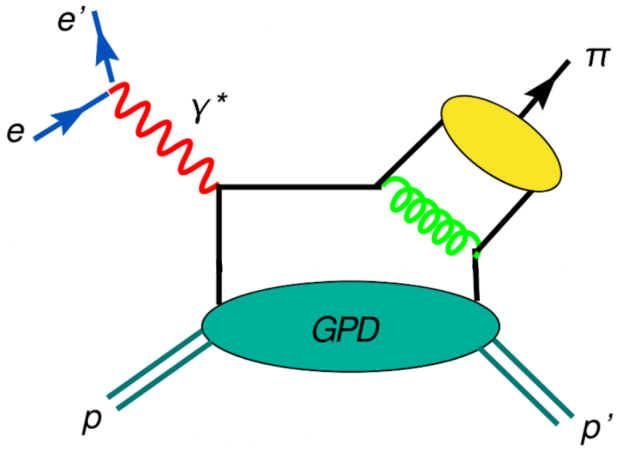
- 3D hadron structure in terms of quarks and gluons
- GPD describes non-perturbative part of the reaction



Form factors - Transverse charge and current densities

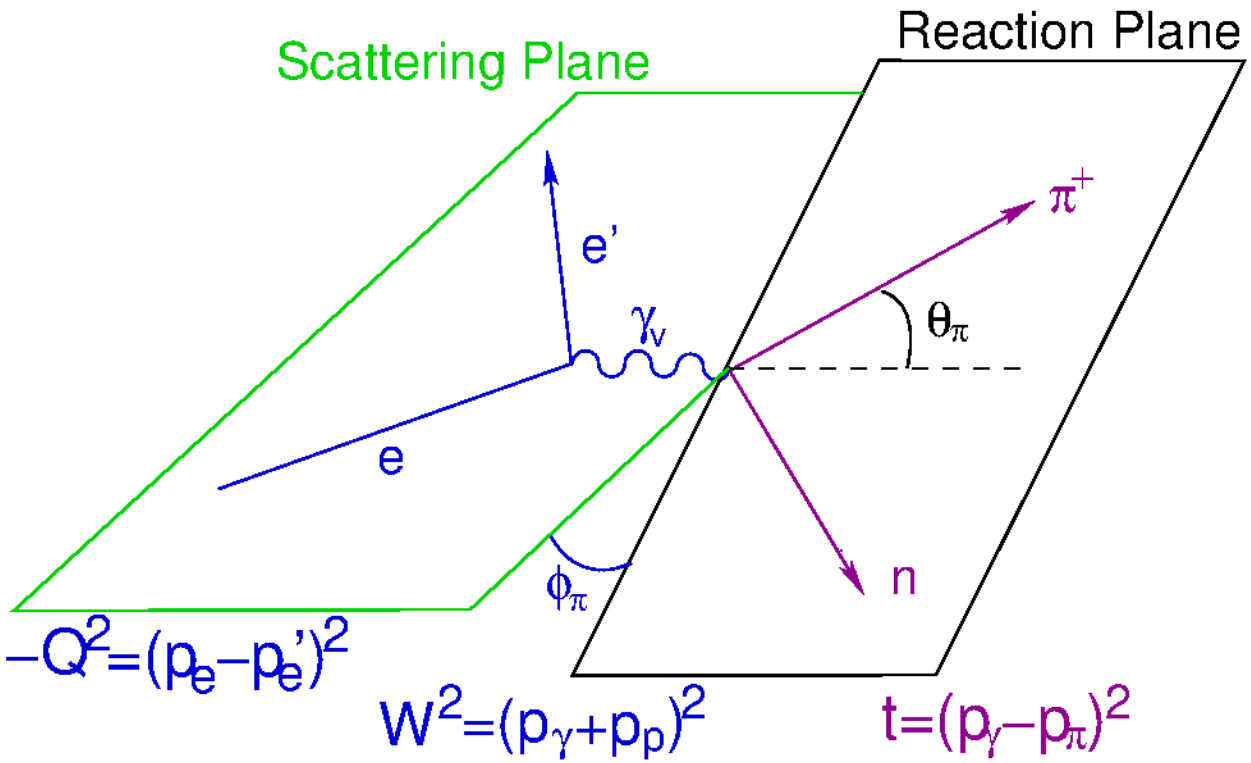
Generalised Parton Distributions - Correlated quark momentum and helicity distributions in transverse space

Parton Distribution Functions - Quark longitudinal helicity and momentum distributions



M. Diehl. Physics Reports **388** 41 – 277 (2003).

What is ϕ?


Scattering Plane
Reaction Plane
e'
γ_v
π^+
θ_π
e
ϕ_π
n
$-Q^2=(p_e-p_{e'})^2$
$W^2=(p_\gamma+p_p)^2$
$t=(p_\gamma-p_\pi)^2$

Another Fit

Data fits the functional form:

$$BSA = \frac{\boldsymbol{A}\sin(\phi)}{1 + B\cos(\phi) + C\cos(2\phi)}$$

Fit parameters depend on virtual photon polarization ϵ and ratios of cross-sections:

$$A = \sqrt{2\epsilon(1-\epsilon)}\frac{\boldsymbol{\sigma_{LT'}}}{\boldsymbol{\sigma_0}}$$

$$B = \sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}$$

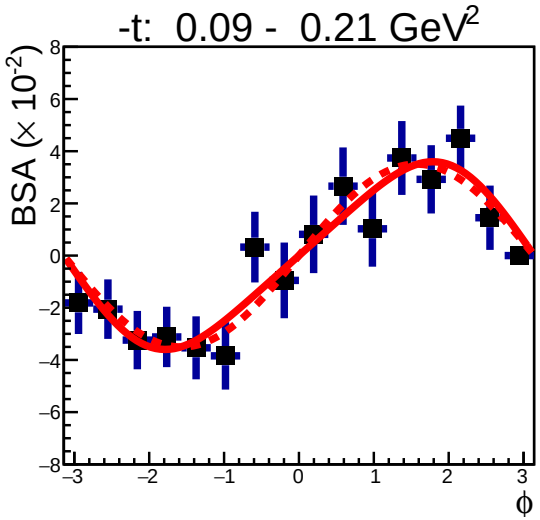
$$C = \epsilon\frac{\sigma_{TT}}{\sigma_0}$$

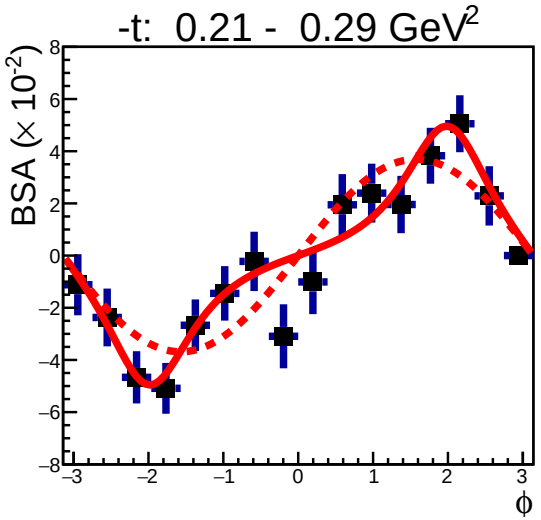
In this talk I use an approximated fit:

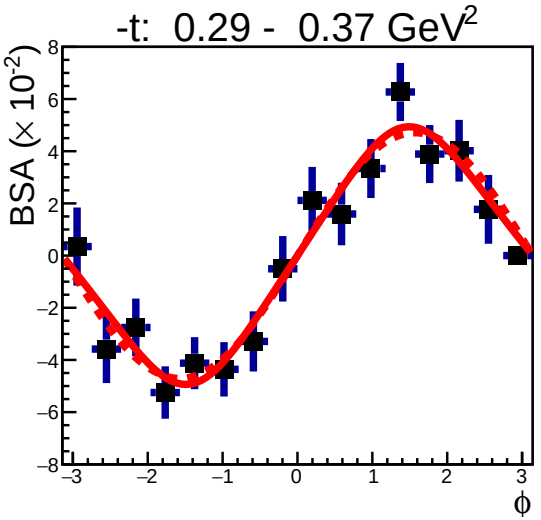
$$BSA = \boldsymbol{A}\sin(\phi)$$

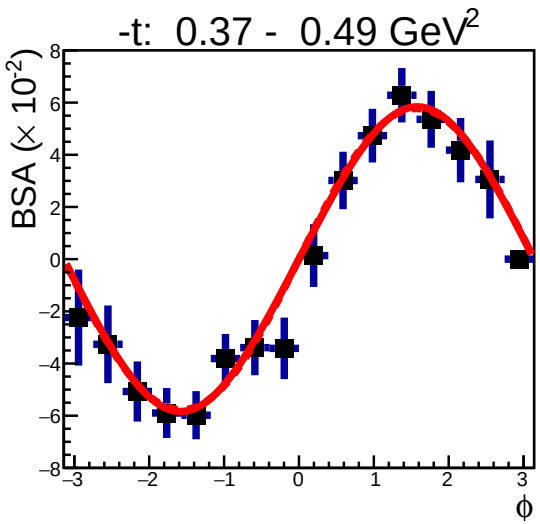
S. Diehl, SciPost Phys. Proc. **8** 066 (2022).

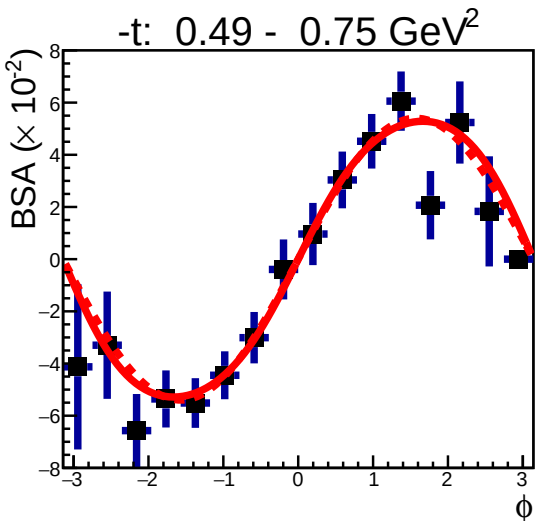
Asymmetry with Both Fits









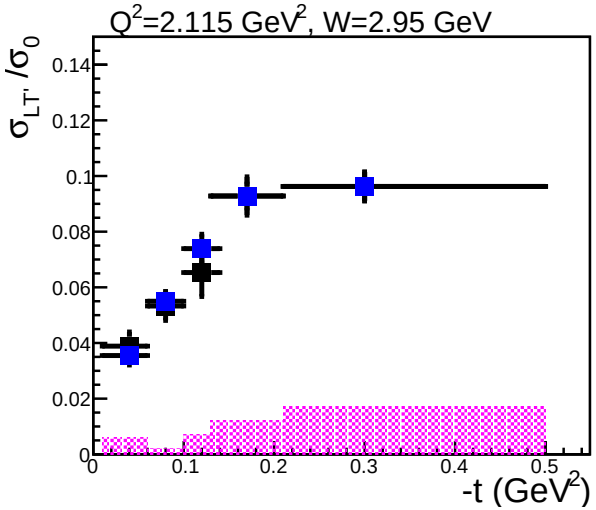


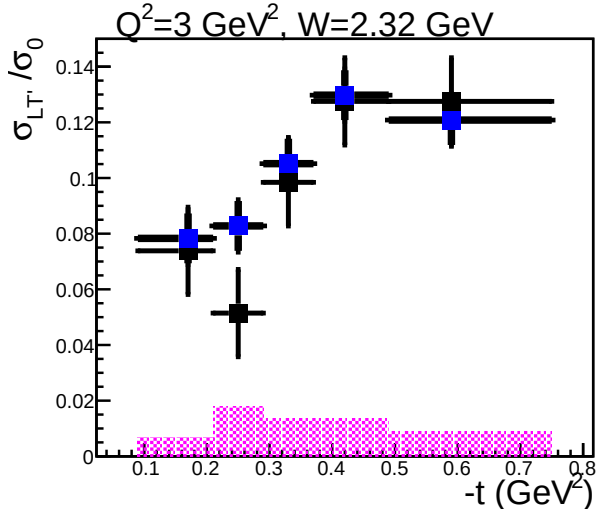
$A\sin\phi$

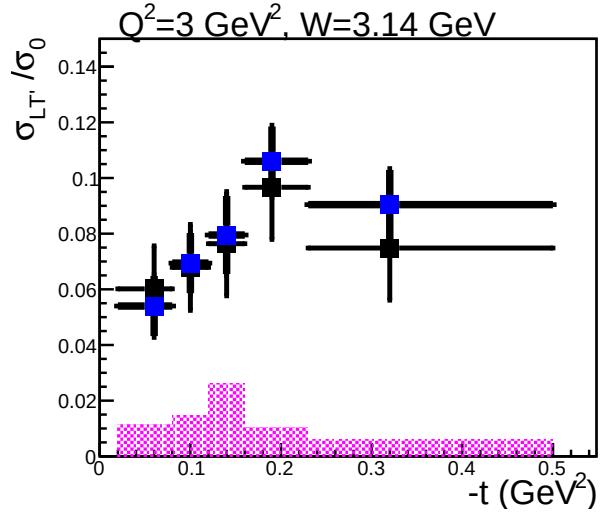
$$\frac{A\sin\phi}{1+B\cos\phi+C\cos 2\phi}$$

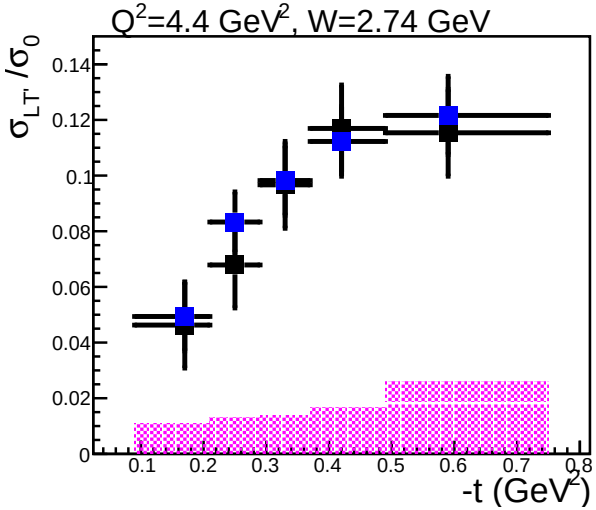
$$A \propto \frac{\sigma_{LT'}}{\sigma_0}$$

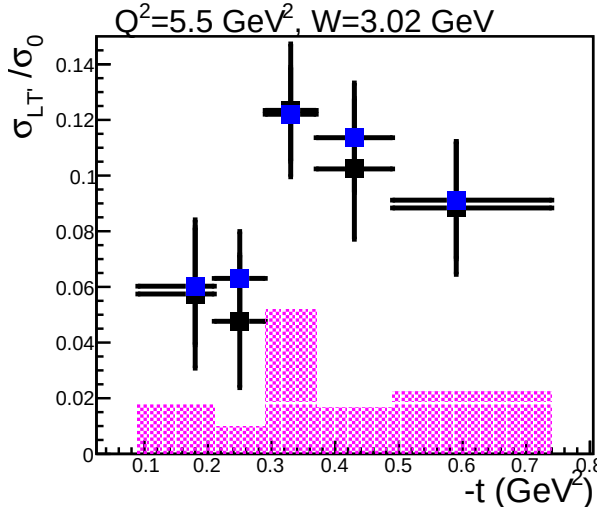
Systematics with Both Fits

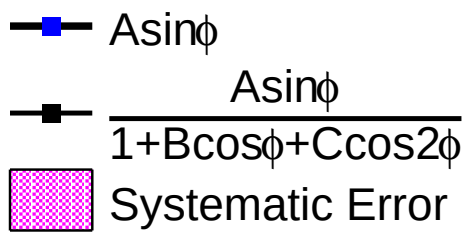




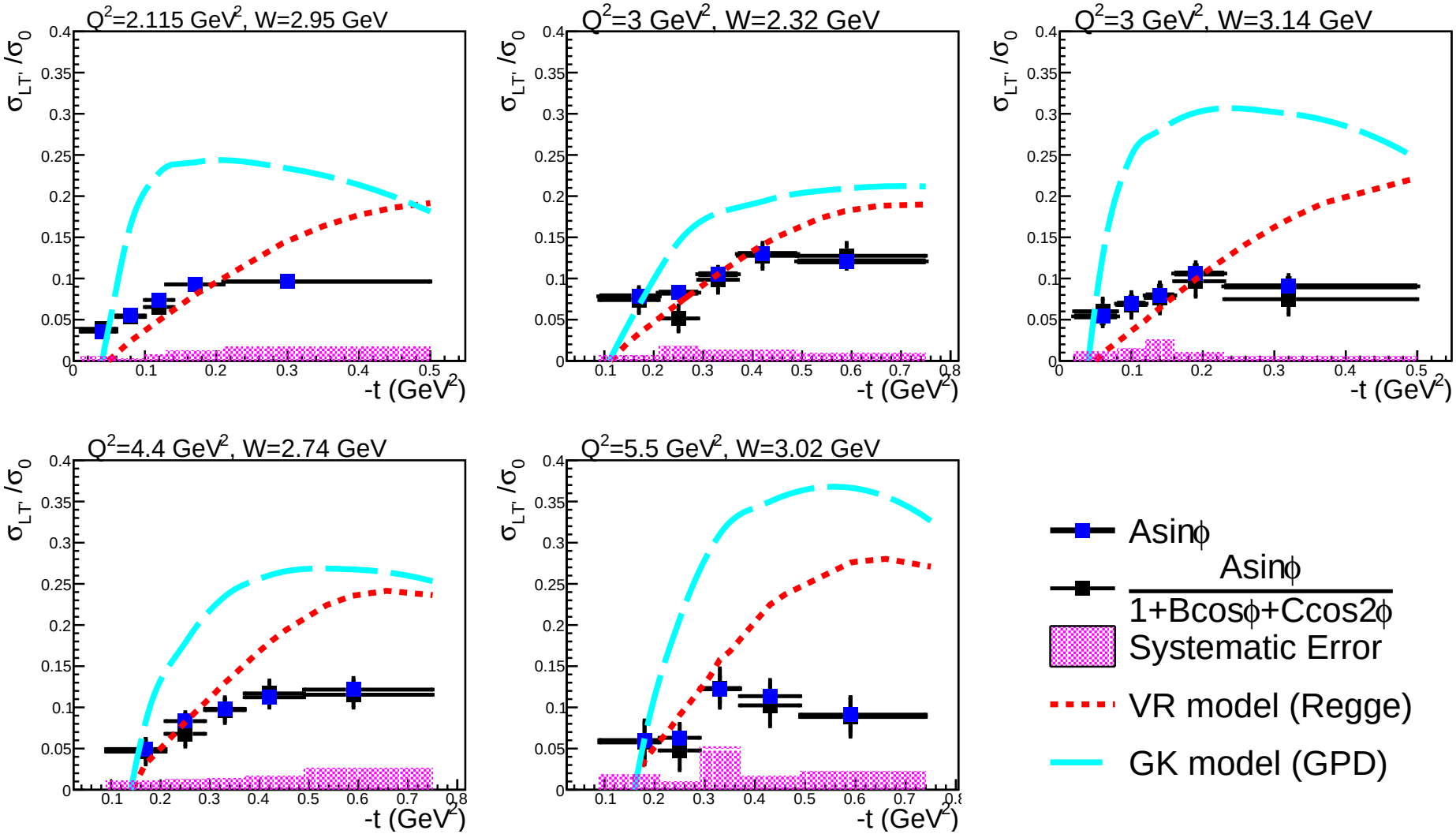




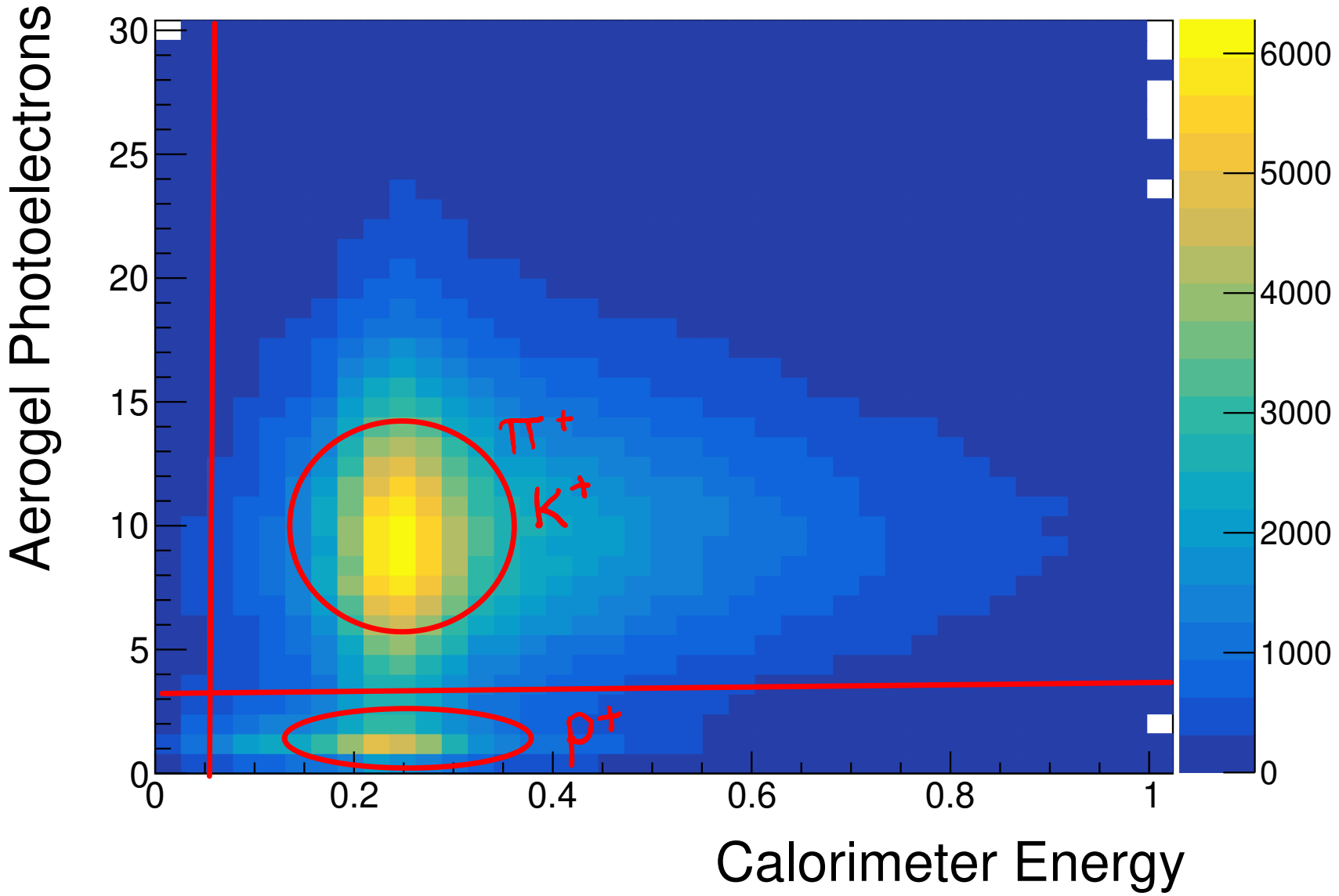




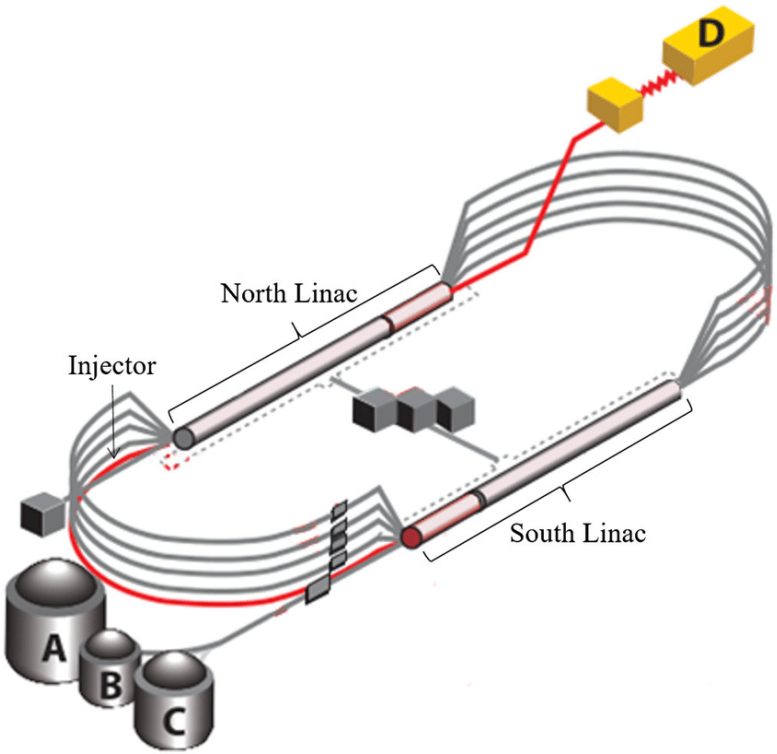
Results with Both Fits



Particle Identification



CEBAF



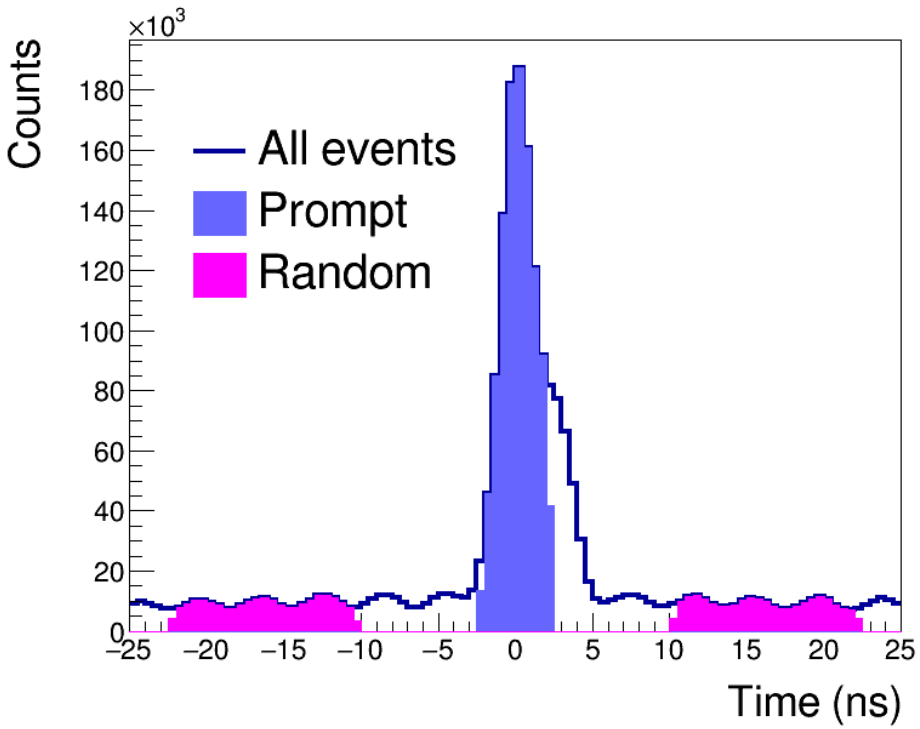
- Continuous Electron Beam Accelerator Facility — the Jefferson Lab accelerator
- Up to 12 GeV beam energy
- Polarized beam, control over helicity of e^-
- Can deliver beam to all 4 experimental halls simultaneously

C. Tennant et al. Phys. Rev. Accel. Beams **23** 114601 (2020).

Prompt vs Random

$$t_{COIN} = t_{SHMS} - t_{HMS}$$

- **Prompt** events: true coincidence event
- **Random** events: false coincidence triggered

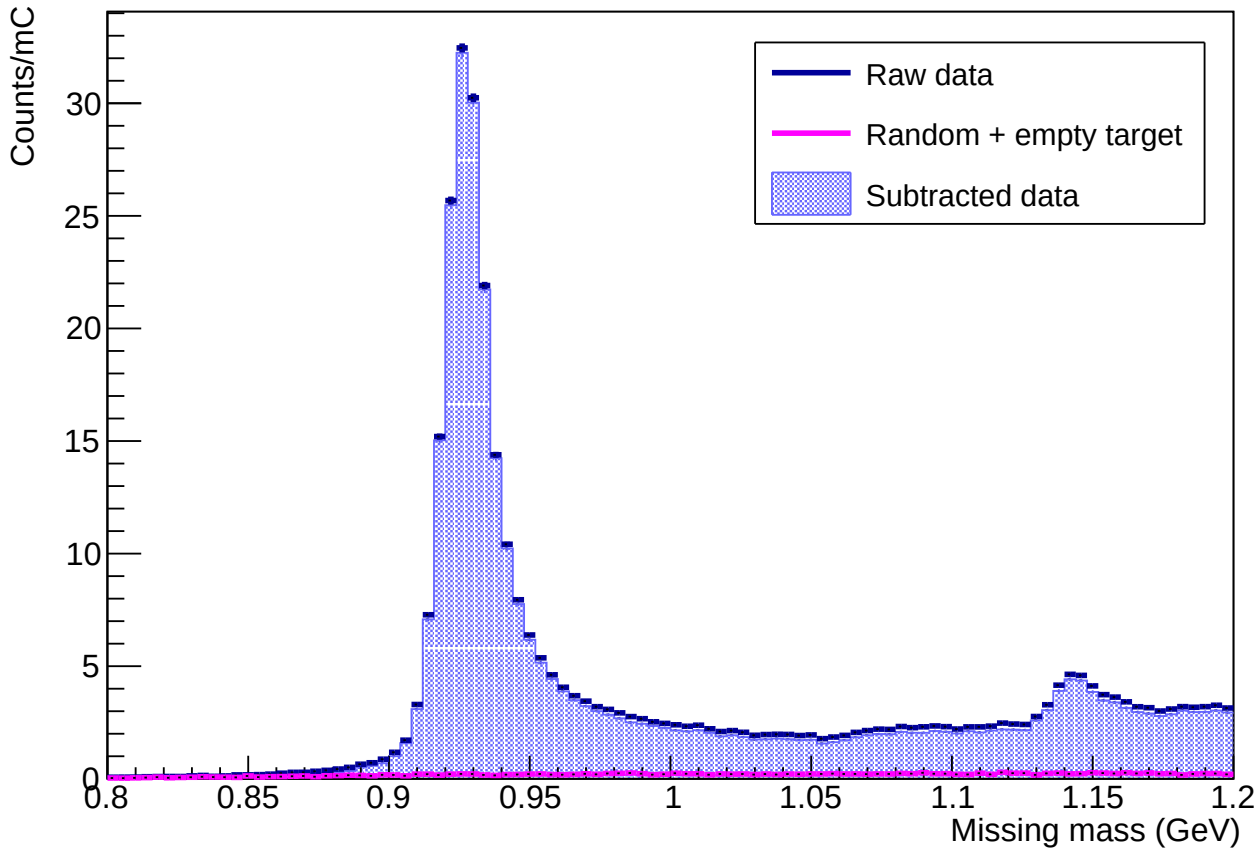


Subtract average over N random windows to eliminate background:

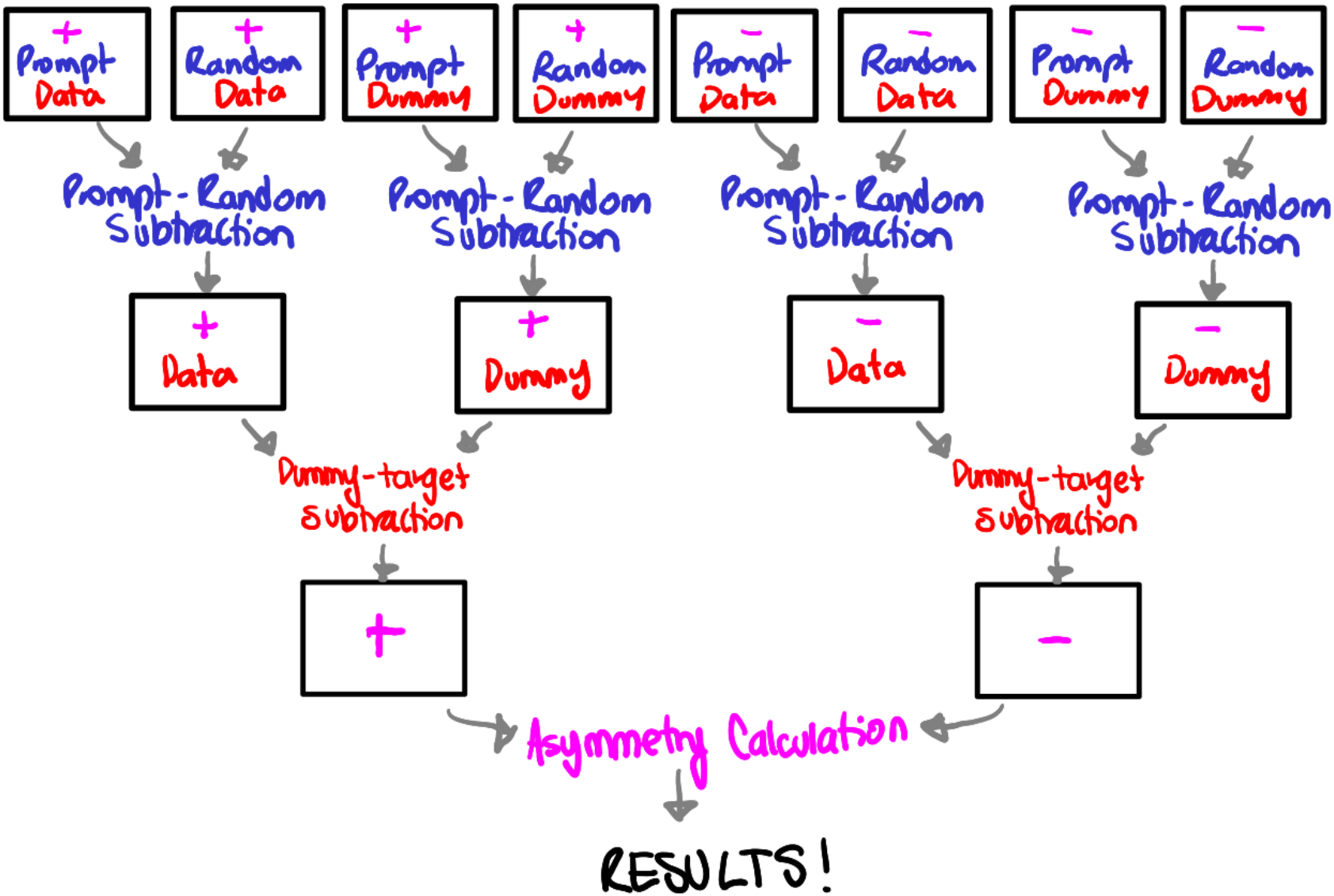
$$Y = Y_{PROMPT} - Y_{RANDOM}/N$$

Subtractions

- Subtract for events occuring at random times
- Events occuring at target walls - subtract empty target data sample

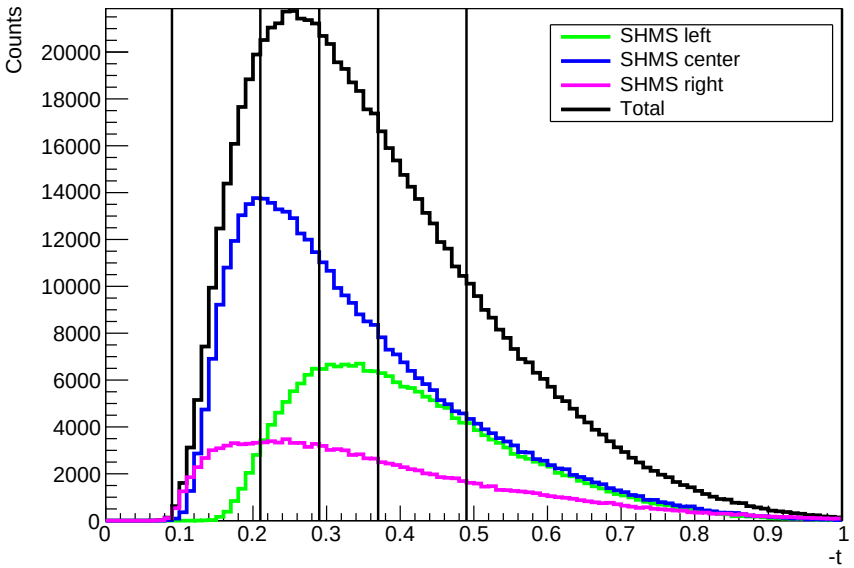


Analysis Flowchart



-t Binning

- Sum all events at one (Q^2,W) and separate $-t$ into bins with similar numbers of events:



Low	High	Width	Events
0.09	0.21	0.12	107457
0.21	0.29	0.08	147586
0.29	0.37	0.08	177052
0.37	0.49	0.12	168172
0.49	1	0.51	172644

Statistical Errors

Assumes independent errors and follows general rules for error propagation:

Initial bin error: $\sigma = \sqrt{N}$

Prompt-random subtraction:

$$\sigma = \sqrt{\sigma^2_{PROMPT} + (\sigma_{RANDOM}/N_{WINDOWS})^2}$$

Empty target subtraction:

$$\sigma = \sqrt{(\sigma_{LH2}/Q_{LH2})^2 + (\sigma_{MT}/(Q_{MT}t_{MT}))^2}$$

Asymmetry calculation:

$$\sigma = \sqrt{\left(\frac{\sqrt{\sigma_+^2 + \sigma_-^2}}{N_+ + N_-}\right)^2 + \left(\frac{\sqrt{\sigma_+^2 + \sigma_-^2}(N_+ - N_-)}{(N_+ + N_-)^2}\right)^2}$$

Systematic Errors

- Beam polarization uncertainty
- Cut dependence of missing mass window
- Cut dependence of coincidence timing window