SIDIS Production in Nuclei

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Opportunities with JLab Energy and Luminosity Upgrade

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CENTRO CIENTÍFICO TECNOLÓGICO DE VALPARAÍSO

Outline

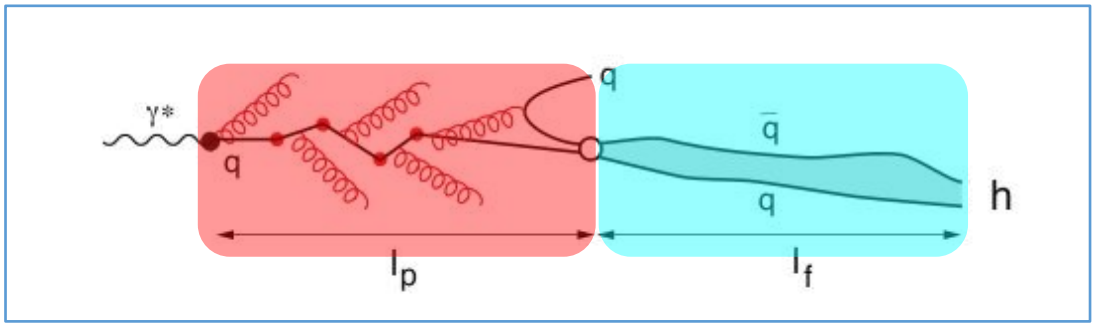
- Hadronization in cold nuclear matter
- Gluon polarization measurement

Hadronization Process I

Hadronization is the process responsible for transforming quarks produced from hard scattering reactions into hadrons. Its study is important because it helps to understand the properties of quark propagation and fragmentation.

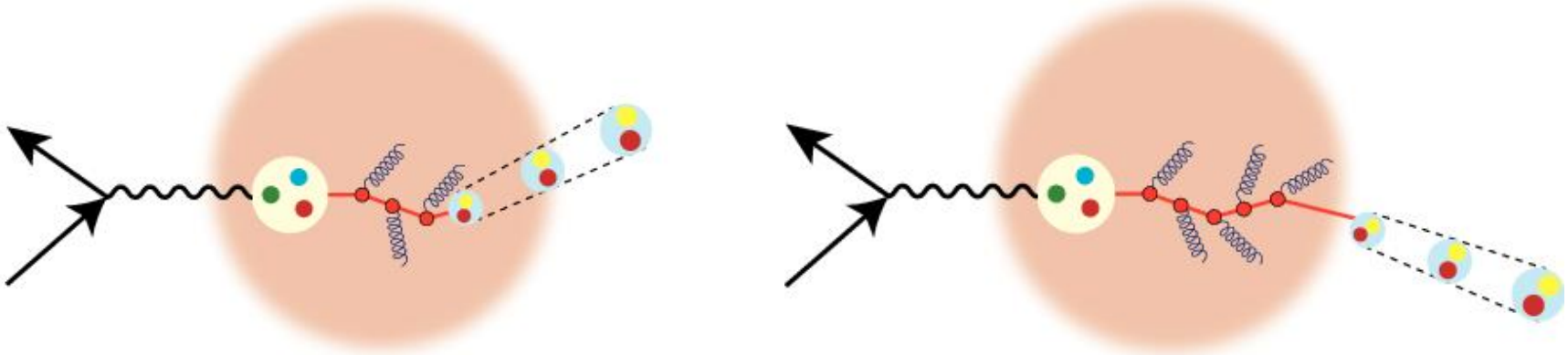
Hadronization is characterized by two mechanisms :

- **Quark energy loss** : related to the hadron production length (l_p) and can be accessed experimentally by measuring the transverse momentum of hadrons in various nuclei.
- **Hadron absorption** : related to the hadron formation length (l_f). It can be inferred from the ratio of number of hadrons produced in various nuclei.



Hadronization Process II

Depending on nucleus size, hadron formation can take place inside or outside the nucleus.



- Which process dominates? Parton energy loss or Hadron absorption?
- How long does it take to form the colorless object (prehadron) and the color field of a hadron ?
- Provides a test for the existing theoretical model
- fragmentation functions in the presence of nuclear medium?

Some Theoretical Models

- Quark Energy loss models Gluon radiation induced by multiple soft quark interactions with the medium is considered as the main source of quark energy loss. It can be evaluated from calculations based on pQCD.
- Twist-4 pQCD (X.-N. Wang, E. Wang, X. Guo, J. Osborne): Medium-induced gluon radiation only. Neglects hadron absorption because it assumes that hadron is formed outside the nucleus.
- Rescaling (A. Accardi, H. Pirner, V. Muccifora): Inspired by many deconfinement models originally developed to provide an explanation for the observed EMC effect. Introduce a scaling factor in the nuclear pdfs to account for the fact that the quark confinement scale in a bound nucleon is larger than the one in a free nucleon. Most of these models were extended to study the hadronization in nuclear environment by introducing a similar Q^2 rescaling factor in the medium-modified fragmentation functions.
- Quantitative Models shift in the quark energy (ΔE), introduced by the emission of gluons, results in a rescaling of the hadron energy fraction . In this context, the medium modified FF, is used to calculate the hadron multiplicity ratio. The calculations are used to provide a quantitative global fit to the quark energy loss.
- GIBUU (Gallmeister Boltzmann-Uehling- Uhlenbeck): MC generator that uses PYTHIA/JETSET to simulate the hard scattering and the production of hadrons. Interactions of the prehadron with the surrounding nuclear medium are included according to a semiclassical transport description which allows for elastic and inelastic rescattering through coupled-channel effects. This approach allows for hadron absorption as well as hadron recreation. Nuclear effects such as Fermi motion Pauli blocking and nuclear shadowing are taken into account.
- …

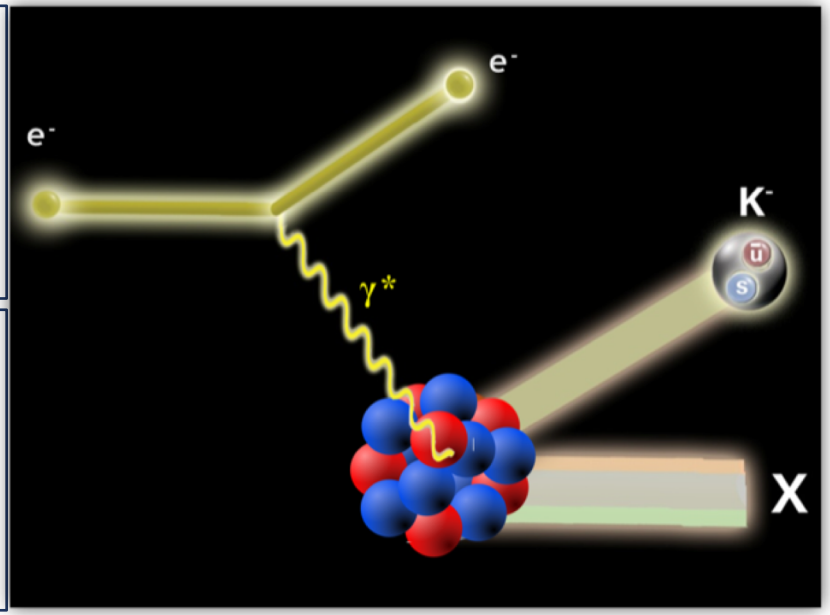
Experimental Observables

Single hadron Multiplicity Ratio:

$$R_A^h\left(x_B, Q^2, z, p_T^2, \varphi_{\gamma^* h}\right) = \frac{\left.\frac{N^h\left(x_B, Q^2, z, p_T^2, \varphi_{\gamma^* h}\right)}{N_{e-}\left(x_B, Q^2\right)}\right|_A}{\left.\frac{N^h\left(x_B, Q^2, z, p_T^2, \varphi_{\gamma^* h}\right)}{N_{e-}\left(x_B, Q^2\right)}\right|_D}$$

di-hadron Multiplicity Ratio:

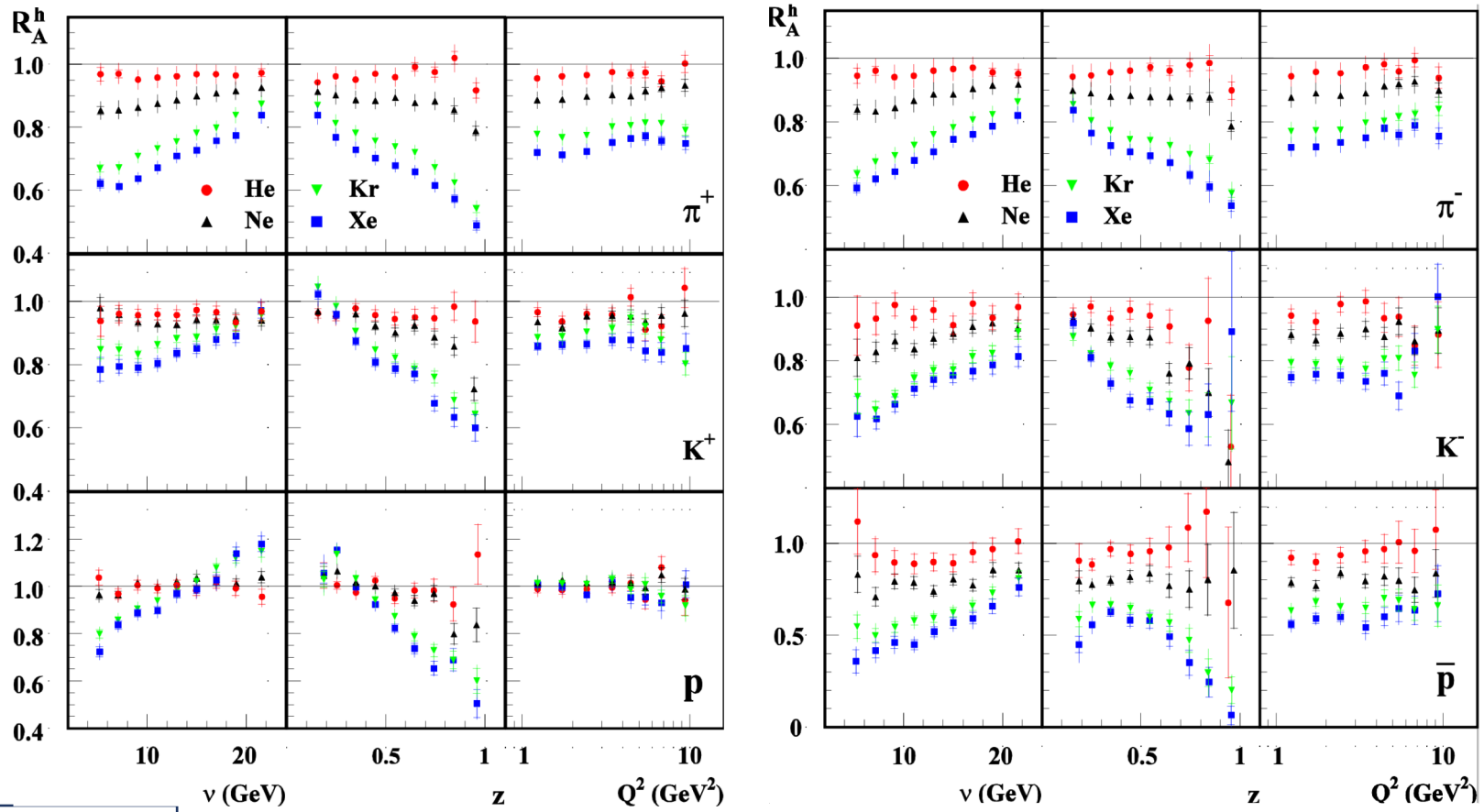
$$R_{2h}(x_B, Q^2, z_2) = \frac{\left.\frac{(dN^{z_1>0.5}(x_B, Q^2, z_2)/dz_2)}{N^{z_1>0.5}}\right|_A}{\left.\frac{(dN^{z_1>0.5}(x_B, Q^2, z_2)/dz_2)}{N^{z_1>0.5}}\right|_D}$$



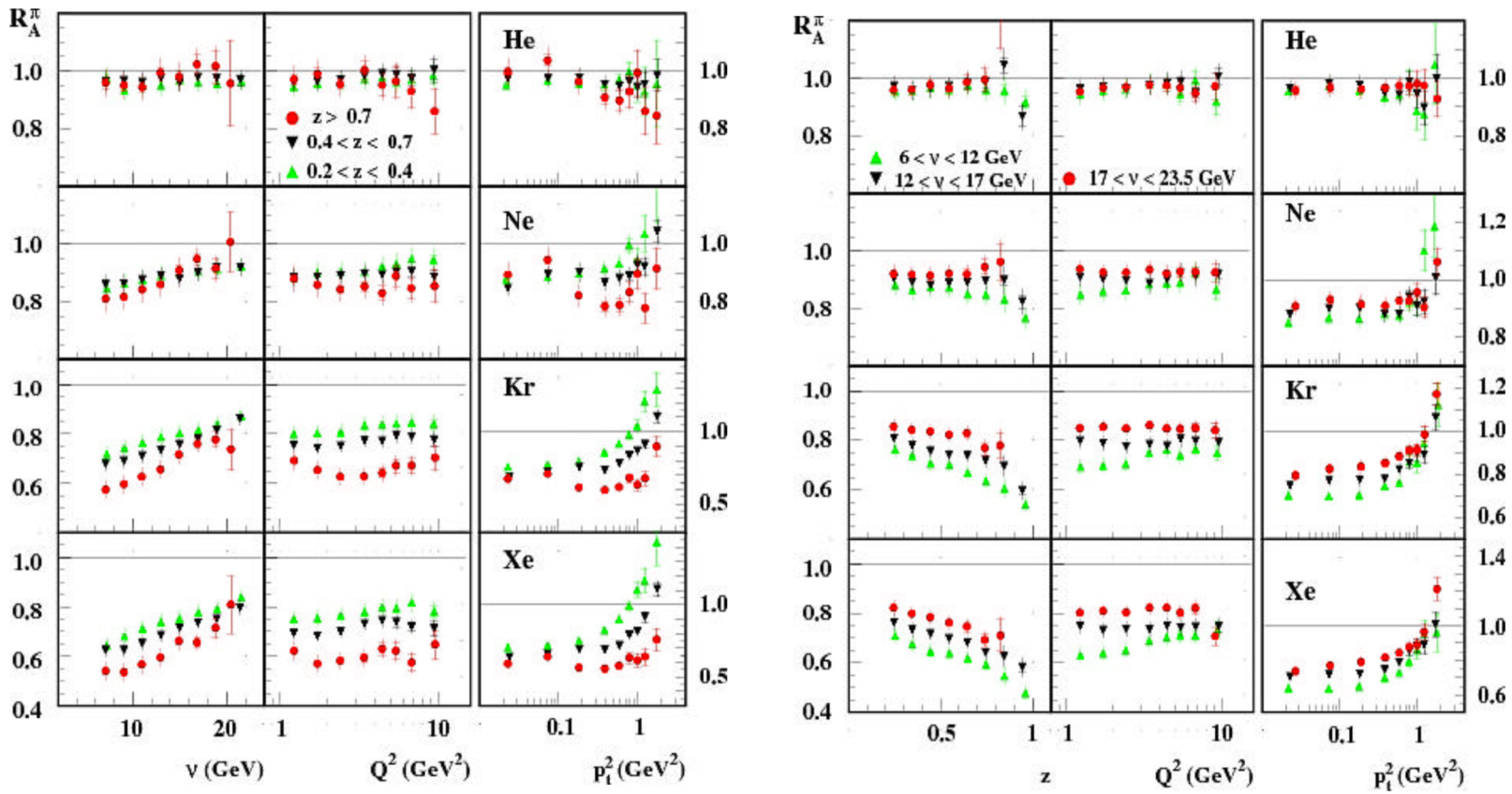
PT-Broadening:

$$\Delta P_T^2\left(x_B, Q^2, z, \varphi_{\gamma^* h}\right)\Big|_A^h = \left(\left\langle P_T^2\right\rangle_A^h - \left\langle P_T^2\right\rangle_D^h\right)\left(x_B, Q^2, z, \varphi_{\gamma^* h}\right)$$

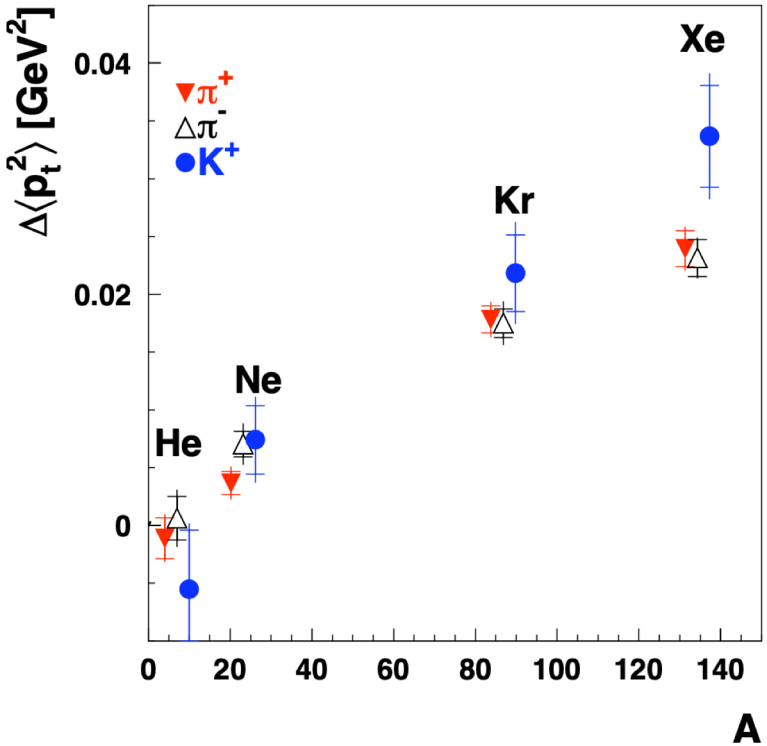
Multiplicity Ratio (HERMES)



2D MR Pions (HERMES)

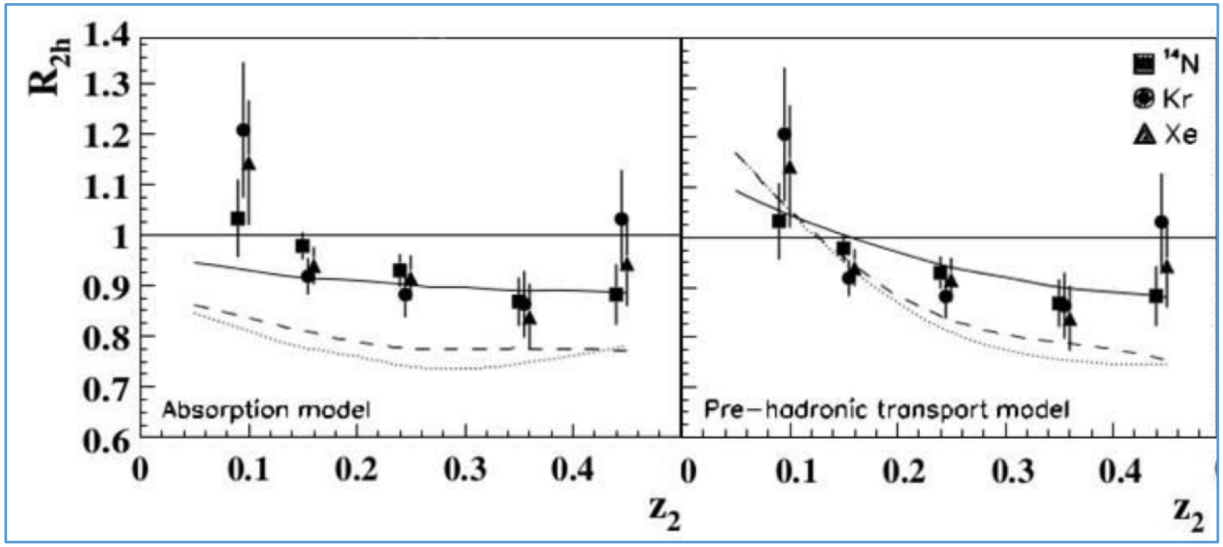


P_T-Broadening (HERMES)



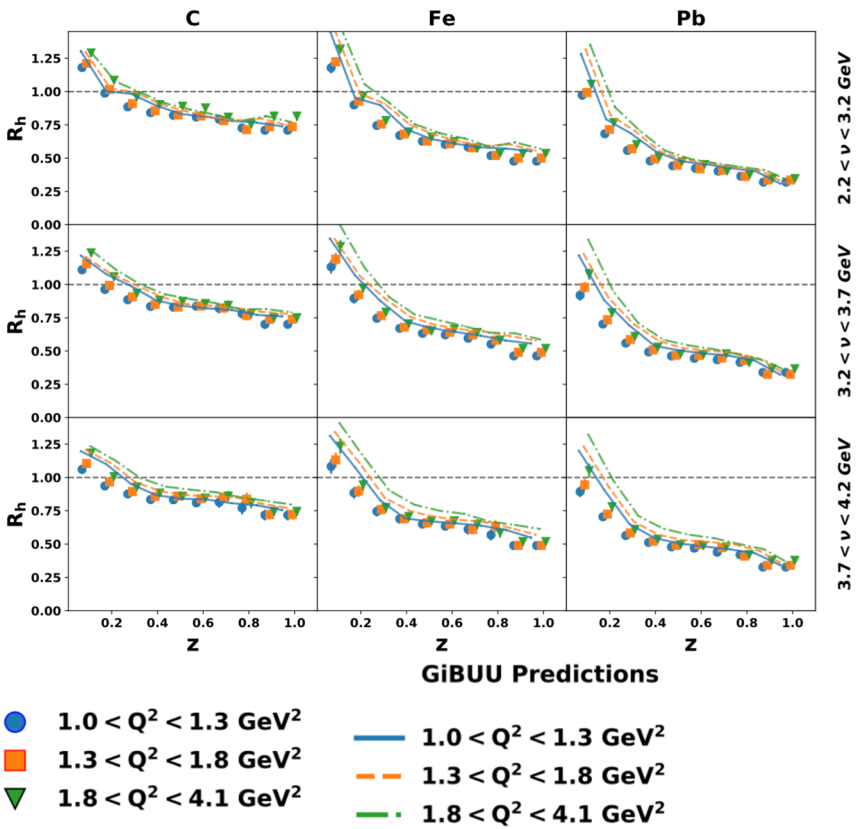
- Broadening increases with mass number A
- Similar effect for pions
- Broadening seems to be slightly different for K^+.

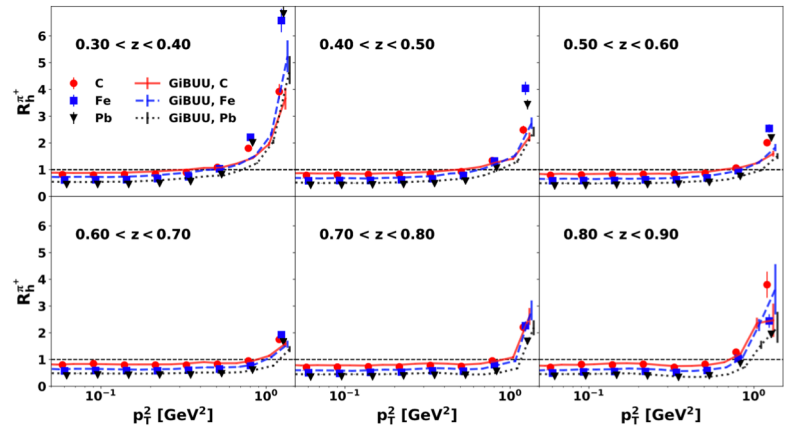
Di-hadron (HERMES)



- Di-hadron electroproduction offers an additional way to study hadronization.
- If partonic energy loss is the only mechanism involved, then, the absorption should not depend on the number of produced hadrons.
- Di-hadron to single hadron ratio vary slightly with A.

CLAS Results (EG2 experiment)





Results involving more hadron species, π^0, Λ, proton, di-hadrons to be pulished in the near future

Simulation

PYTHIA + RADGEN are used to generate SIDIS process.

- Tuned PYTHIA 6.4.28:

- The fragmentation functions parameter (a, b):

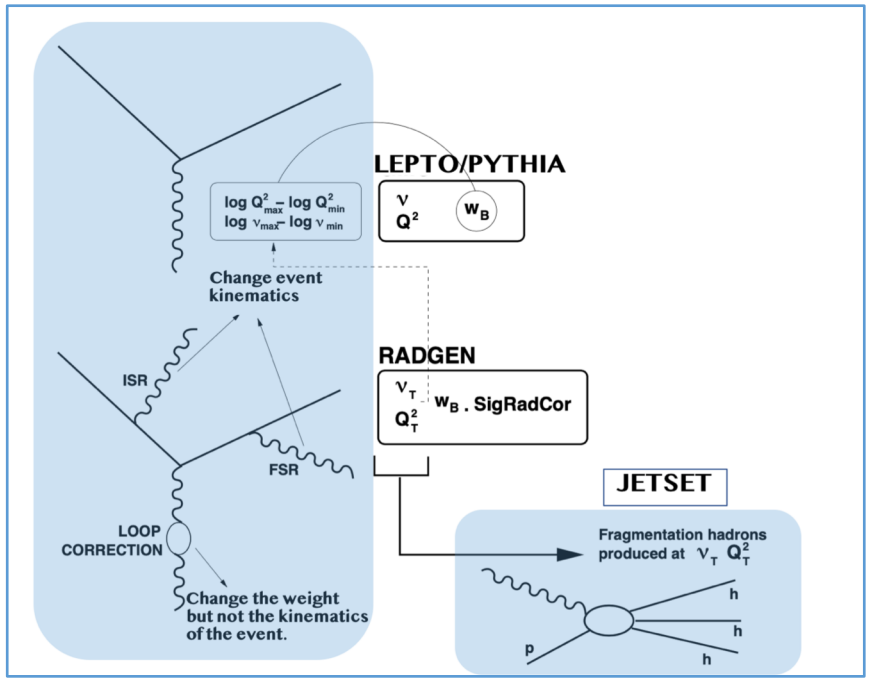
- $D(z) = z^{-1}(1-z)^{a}.e^{-\frac{bm_T^2}{z}}$

- The probability of producing/suppression of $q\bar{q}$ pair.

- Intrinsic k_T of partons.

- Fermi Motion: Parametrization of the nucleon momentum density (n(k)) obtained from C. Ciofi degli Atti paper, based on realistic many-body calculations.

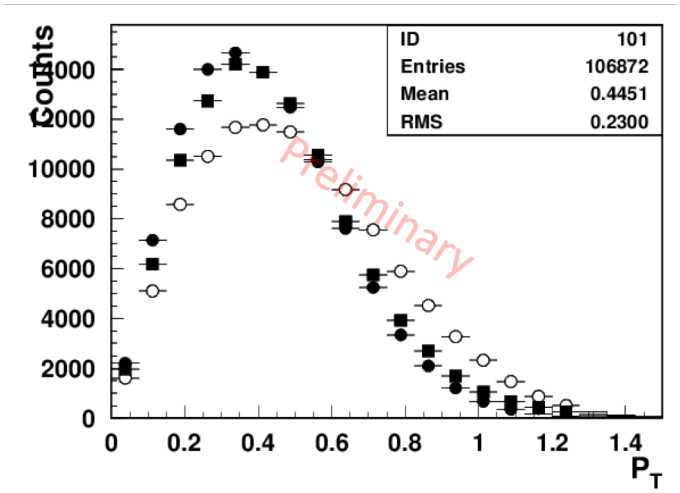
- Nuclear PDFs Parametrization LHAPDF 6.4.0



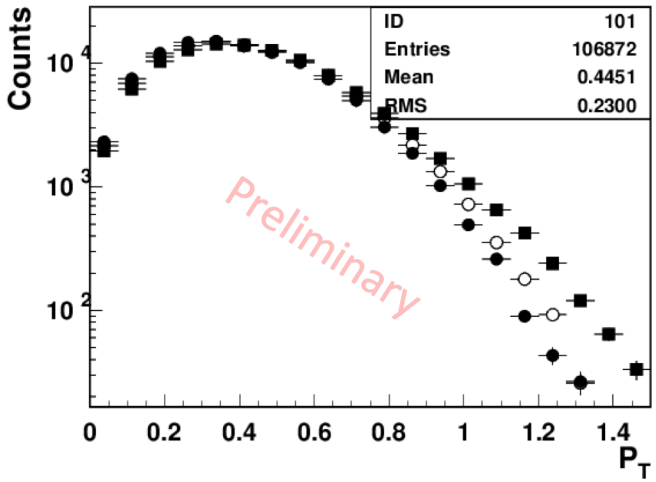
Pythia Tune

Parameter	Default	Tune 1	Tune 2	Tune 3	Tune 4	Tune 5
$q\bar{q}_{supp}$	0.10	0.10	0.02	0.03	0.025	0.029
q^s_{supp}	0.30	0.16	0.20	0.20625	0.120	0.283
$q^s q^s_{supp}$	0.40	0.40	0.40	0.25	0.25	0.40
$BM\bar{B}/B\bar{B}$	0.50	0.50	0.50	0.0	0.0	0.50
$s\bar{s}/BM\bar{B}$	0.50	0.50	0.50	0.0	0.0	0.50
$M_s/BM\bar{B}$	0.50	0.50	0.50	0.0	0.0	0.50
VM_{supp}	0.50	0.50	0.20	0.25	0.25	0.50
VM^s_{supp}	0.60	0.60	0.60	0.30	0.30	0.60
σ	0.36	0.33	0.37	0.382	0.382	0.381
f	0.01	0.01	0.03	0.03	0.03	0.01
P_T^f	2.00	2.00	2.50	2.50	2.50	2.00
E_0	0.80	0.80	0.80	0.20	0.20	0.80
a	0.30	0.89	1.74	1.1266	1.13	1.940
b	0.58	0.24	0.23	0.3672	0.37	0.544
a_{qq}	0.50	0.50	0.50	0.80	0.80	1.05

P_T Distribution RGC Data vs Pythia



Full square RGC data
Open circle pythia (Tune 1)
Full circle pythia (Tune 4)

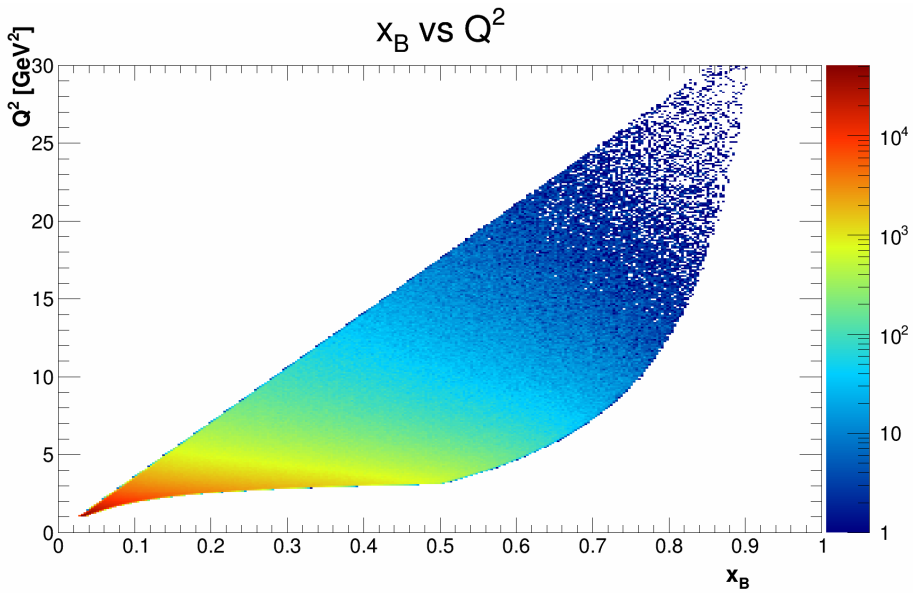


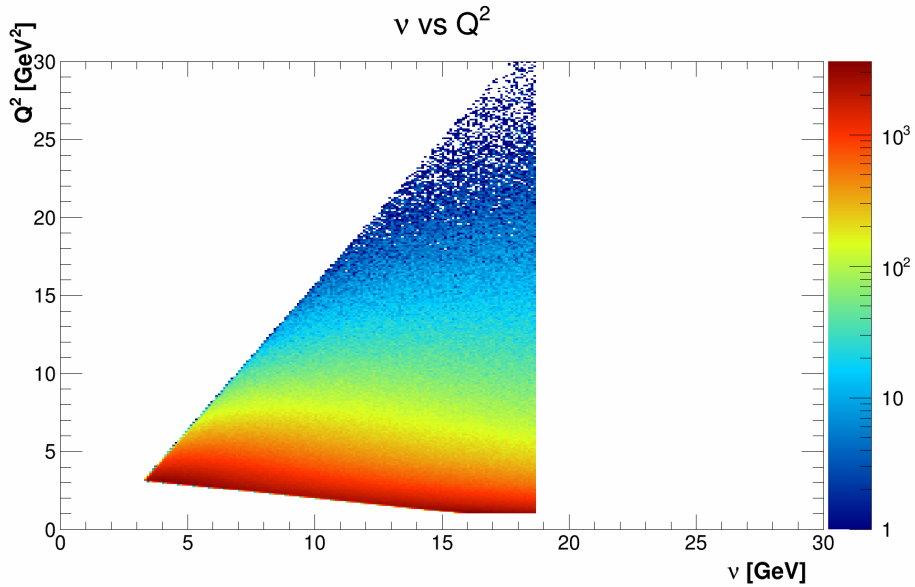
Full square RGC data
Full circle pythia (Tune 4)
Open circle pythia (Tune 5)

Count Rates @ 22 GeV (per 3M SIDIS Events)

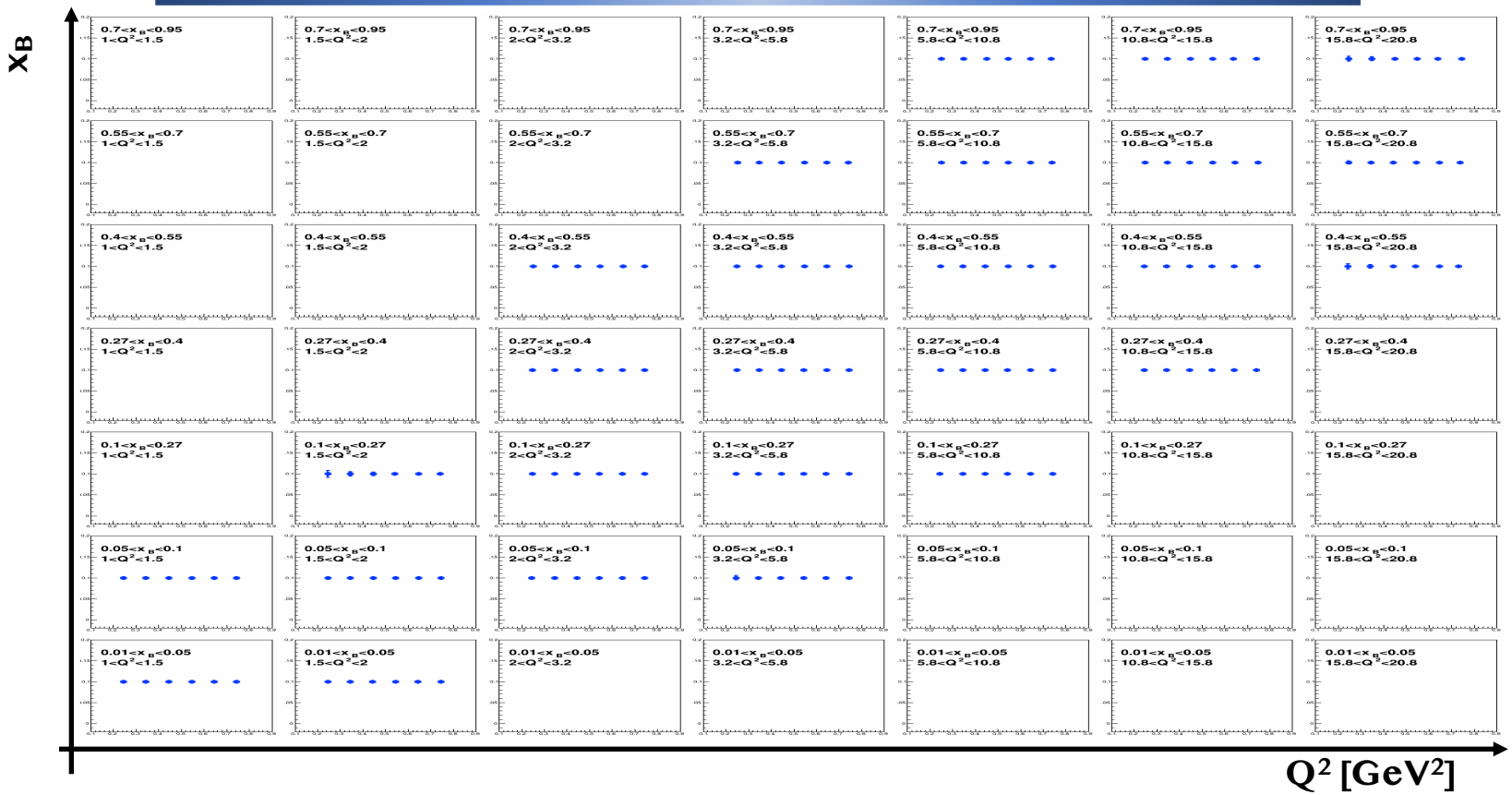
Particle	Decay mode/detection mode	Rates
π^+	direct	1,978,446
π^-	direct	1,283,912
K^+	direct	254754
K^-	direct	111,496
p	direct	1,666,891
π^0	2γ (98.82%)	2,696,633
K_s^0	$\pi^0\pi^0(30.7\%),\ \pi^+\pi^-(69.2\%)$	209,971
η	$2\gamma(39.41\%), 3\pi^0(32.7\%)$ $\pi^+\pi^-\pi^0(22.9\%), \pi^+\pi^-\gamma(4.22\%)$	145,739
ρ^0	$\pi^+\pi^-(\sim 100\%)$	671,091
ω	$\pi^+\pi^-\pi^0(89.3\%), \pi^0\gamma(8.4\%)$	851,882
Λ	$p\pi^-(63.9\%)$	35,198
ϕ	K^+K^- (49.2%)	15,606

Phase Space

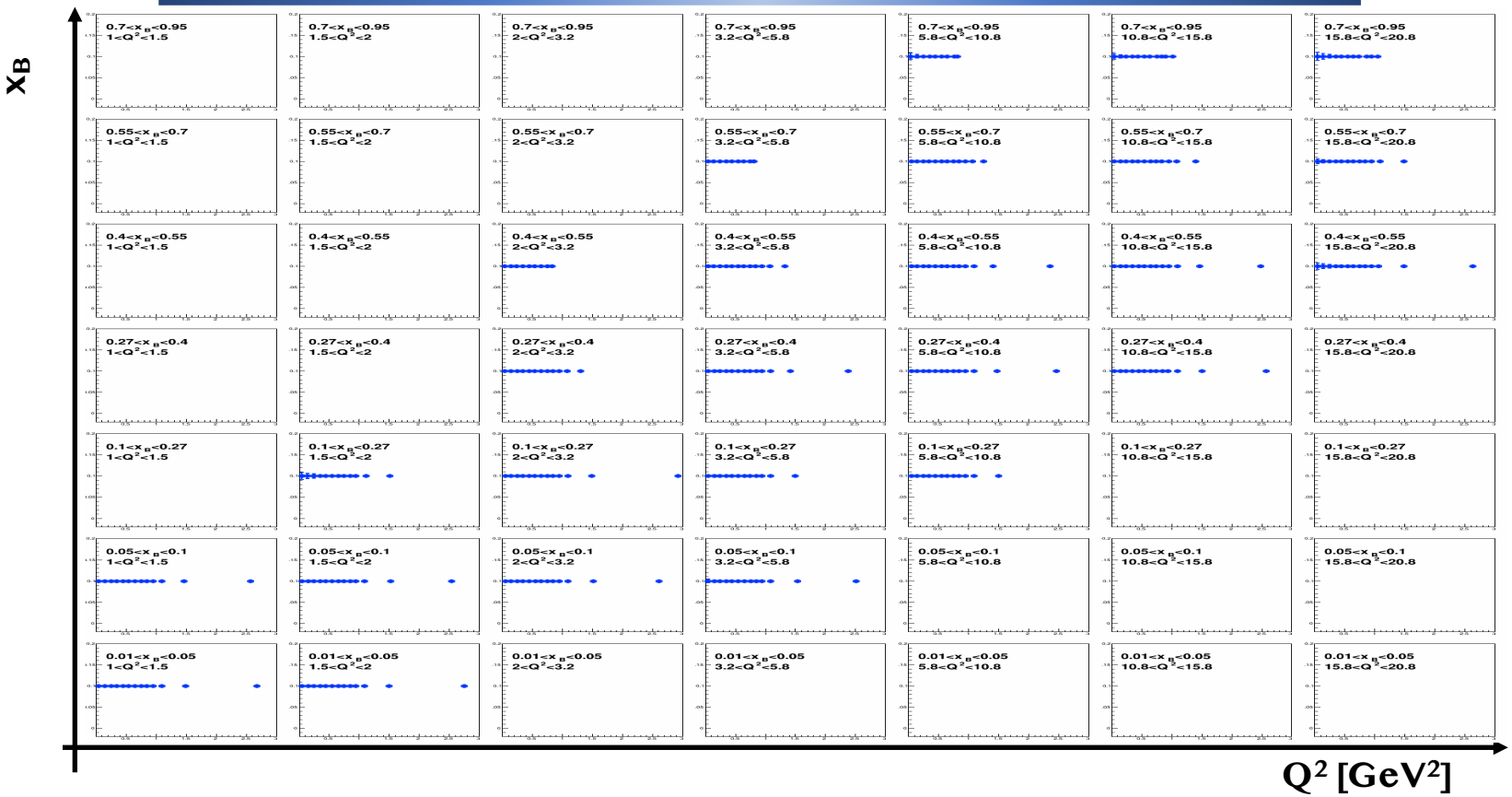




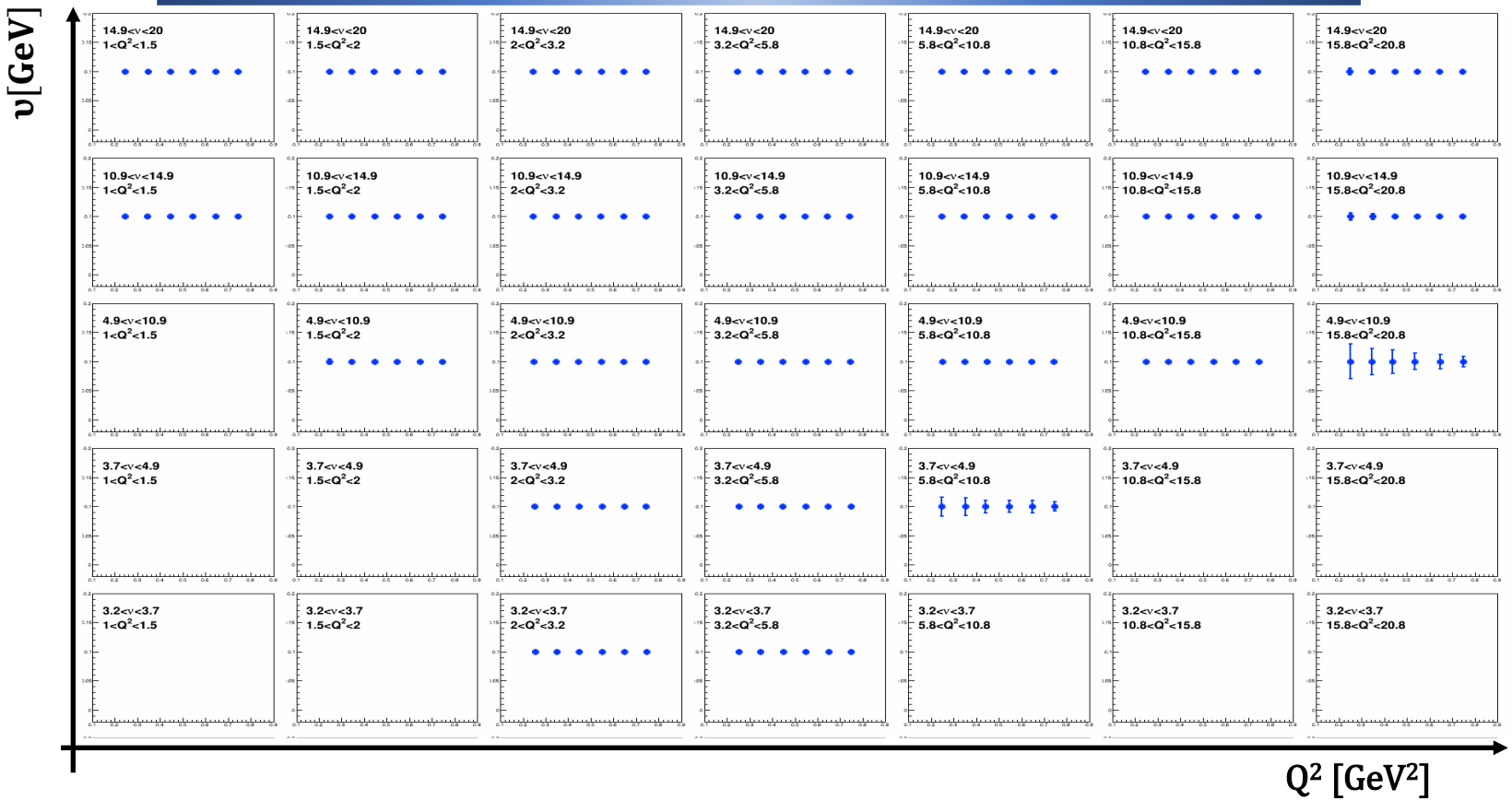
MR(x_B, Q^2, z) Projections, π^+, Carbon Target



MR(x_B, Q^2, p_T^2) Projections, π^+, Carbon Target



MR(υ, Q^2, z) Projections, π^+, Carbon Target



MR(υ, Q^2, p_T^2) Projections, π^+, Carbon Target

Gluon Polarization Measurement

Gluon Polarization

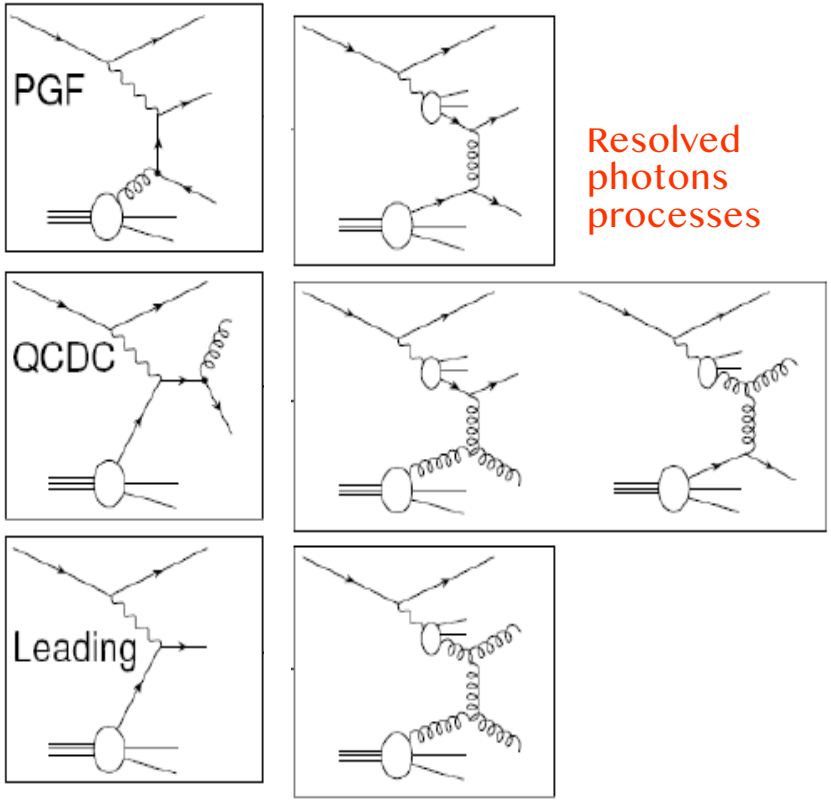
Indirect Measurement:

QCD analysis: fit to the nucleon spin structure function $g_1(x)$

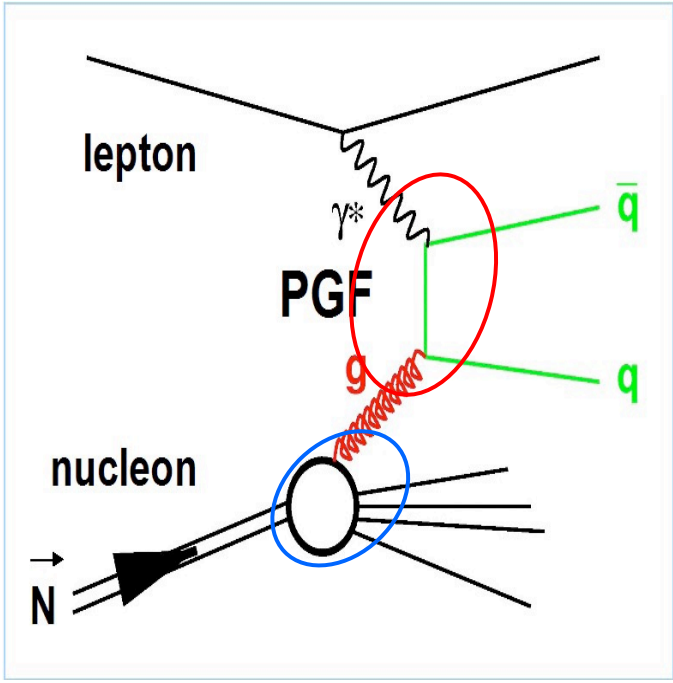
Direct Measurement:

$\Delta G/G$ can be accessed via Photon Gluon Fusion (PGF) process

- Open Charm
- High p_t hadron pairs production



PGF Process



Two approaches are used to tag PGF process

- q = c:
  - Open Charm D^0, D^* decay
  - Clean signal
  - Combinatorial background
  - Low statistics
- q = u, d, s:
  - High-p_t hadron Pairs
  - Physical background
  - High statistics

$A_{PGF} = a_{LL}^{PGF} \times (\Delta G/G)$ factorization theorem

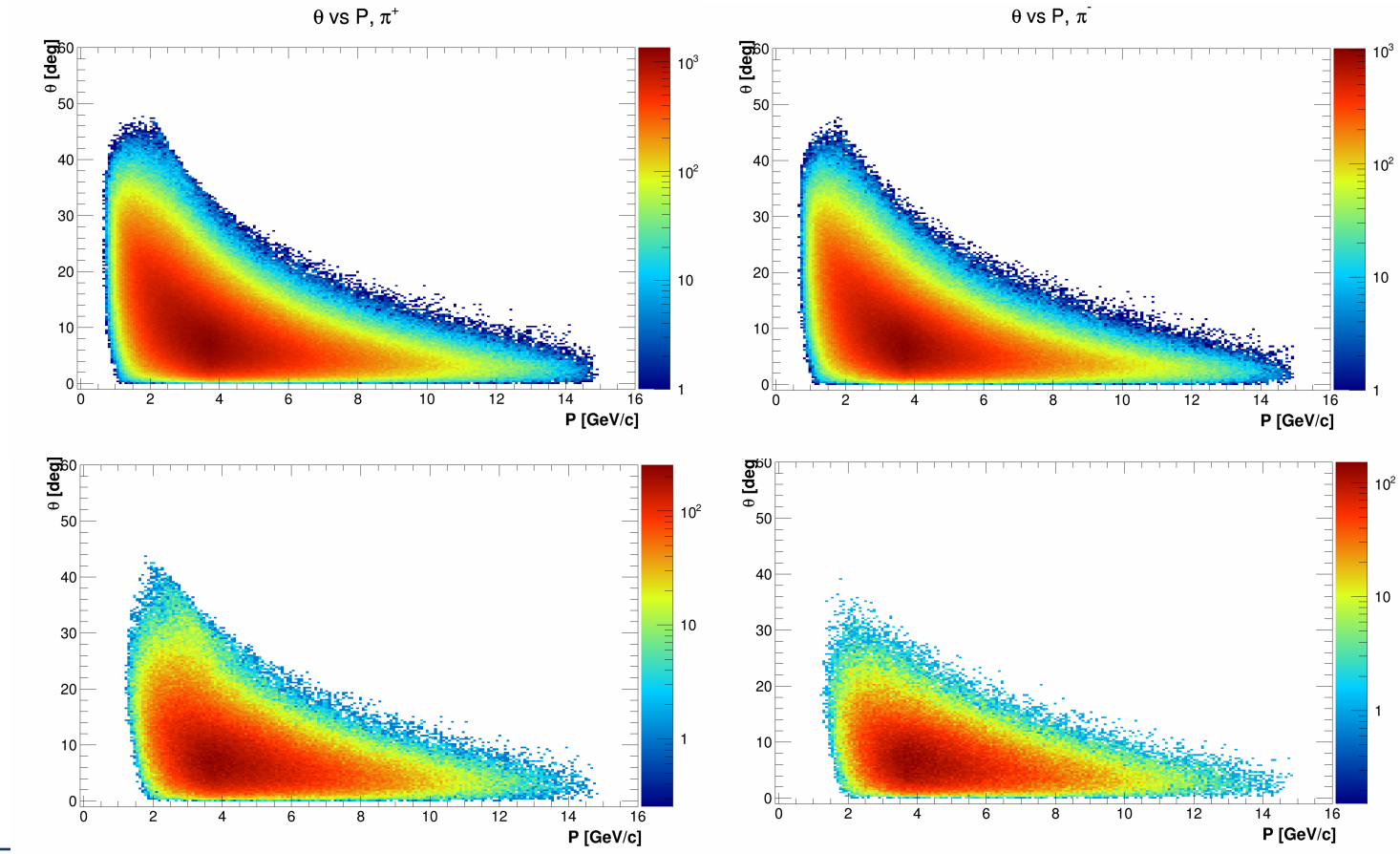
D meson Decay Mode

D meson	Mass (GeV)	Hadronic decay mode	BR
D^0	1.864	$K^-\pi^+$	3.9%
D^+	1.869	$K^-\pi^+\pi^+$	9.4%
D^-	1.869	$K^+\pi^-\pi^+$	9.4%
D^{*0}	2.007	$D^0\pi^0 \to K^-\pi^+\gamma\gamma$	62%
D^{*+}	2.010	$D^0\pi^+ \to K^-\pi^+\pi^+$ $D^+\pi^0 \to K^-\pi^+\pi^+\gamma\gamma$	67.7% 30.7%
D^{*-}	2.010	$D^0\pi^- \to K^-\pi^+\pi^-$ $D^-\pi^0 \to K^+\pi^-\pi^-\gamma\gamma$	67.7% 30.7%

Momentum and Angular distributions

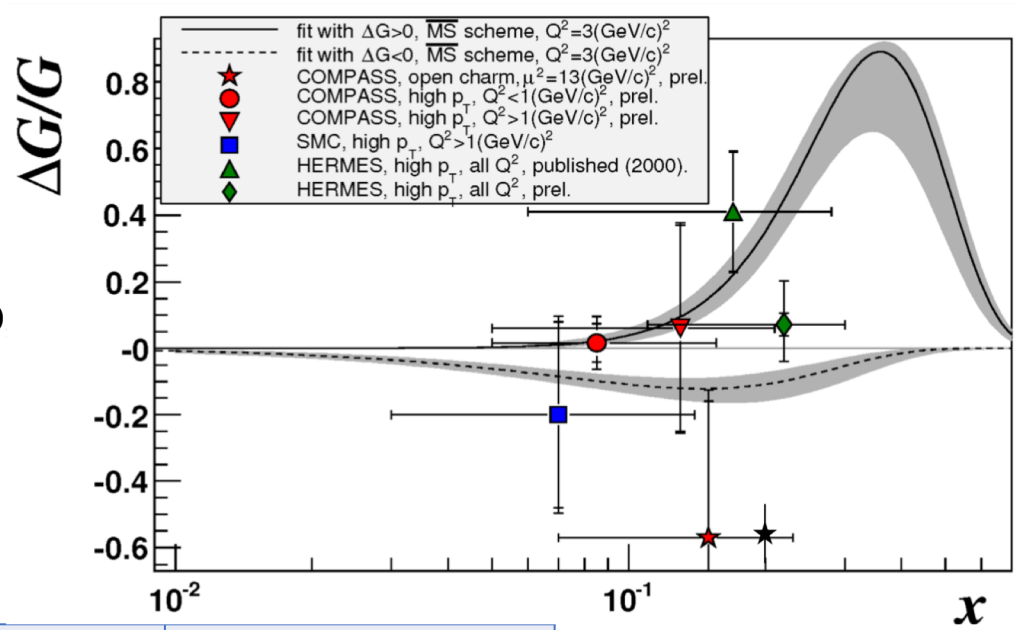
All pions

All kaons



Results

$L=10^{35}\ cm^{-2}s^{-1}$, $D=0.6$, $P_B=0.80$, $P_T = 0.80$
100 days of running



	N_D	$\delta A \approx \frac{1}{R_{PGF}} \frac{1}{D f P_B P_T} \frac{1}{\sqrt{N}}$	$\delta\left({}^{\Delta G}/_{G}\right) \approx \frac{1}{\langle a_{LL}^{PGF} \rangle} \delta A$
$\langle x_G \rangle = 0.21$	31200	0.052	0.11

Summary

- JLab @ 22 GeV will offer an opportunity to study hadronization process with a greater details.

- The high luminosity and beam energy will allow for a multidimentional analysis involving many hadron species.

- The data will provide a way to test several theoretical models and calculations.

- A possibility to measure the gluon polarization through the open charm channel.

HEP2023 Conference

8th International Conference on High Energy Physics in the LHC Era

9–13 Jan 2023
Universidad Técnica Federico Santa María
Chile/Continental timezone

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Contact
hep-chile@usm.cl

HEP2023 is the VIII international conference on High Energy Physics in the LHC Era. It will be held from the 9th to the 13th of January 2023 in the Universidad Técnica Federico Santa María (UTFSM), Valparaíso, Chile.

The scientific program of the Conference will address a broad range of topics covering the main areas of high-energy particle and nuclear physics such as: Higgs and EW Physics, Neutrino Physics, QCD, Beyond the SM Physics, Dark Matter particle searches, Astroparticles, Nuclear Physics, Heavy Ion collisions, Gravitational Waves measurements, Particle Detectors and Instrumentation, Future experimental facilities, and other topics.

We strongly encourage experimentalists and theoreticians from all around the world to participate to the conference to discuss the recent progress and latest development in high energy particle and nuclear physics.

We invite young researchers to participate also in the **HEP School**, taking place the week after the conference, more information about the lectures and the applications including important dates will be available soon on this page: https://indico.cern.ch/e/school2023