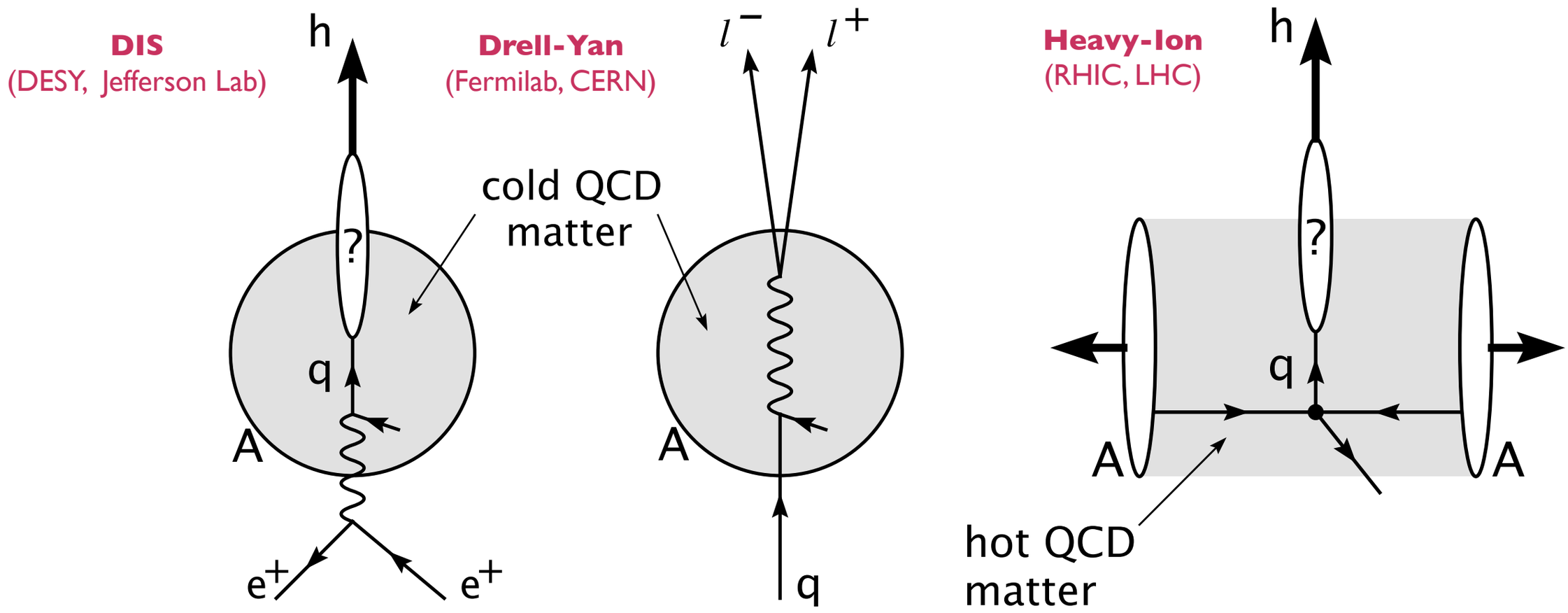
Medium modifications of quark propagation and hadron formation observables @ 22GeV

Science at the Luminosity Frontier:
Jefferson Lab at 22 GeV

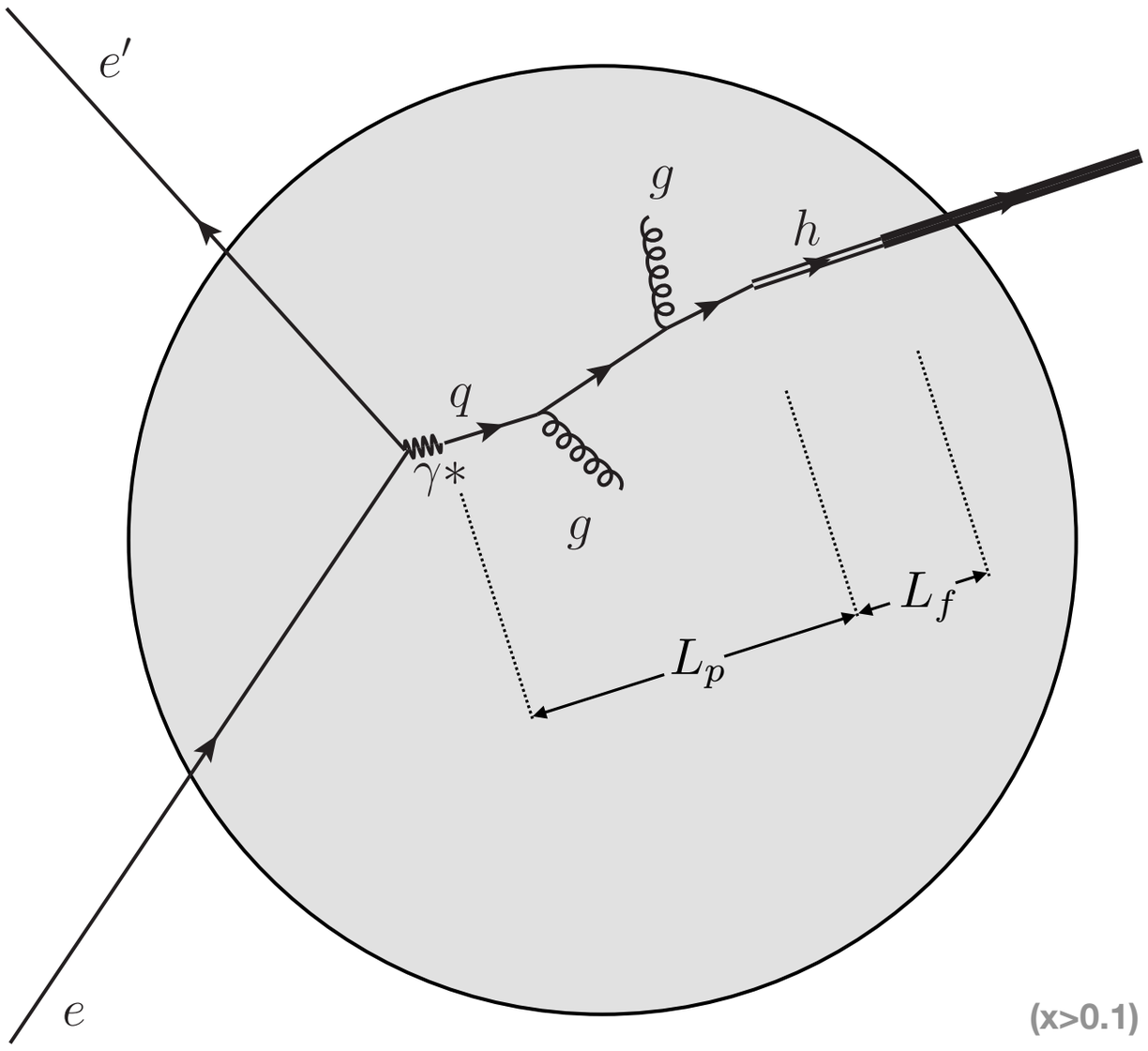
Taisiya Mineeva

Quark propagation and hadron formation



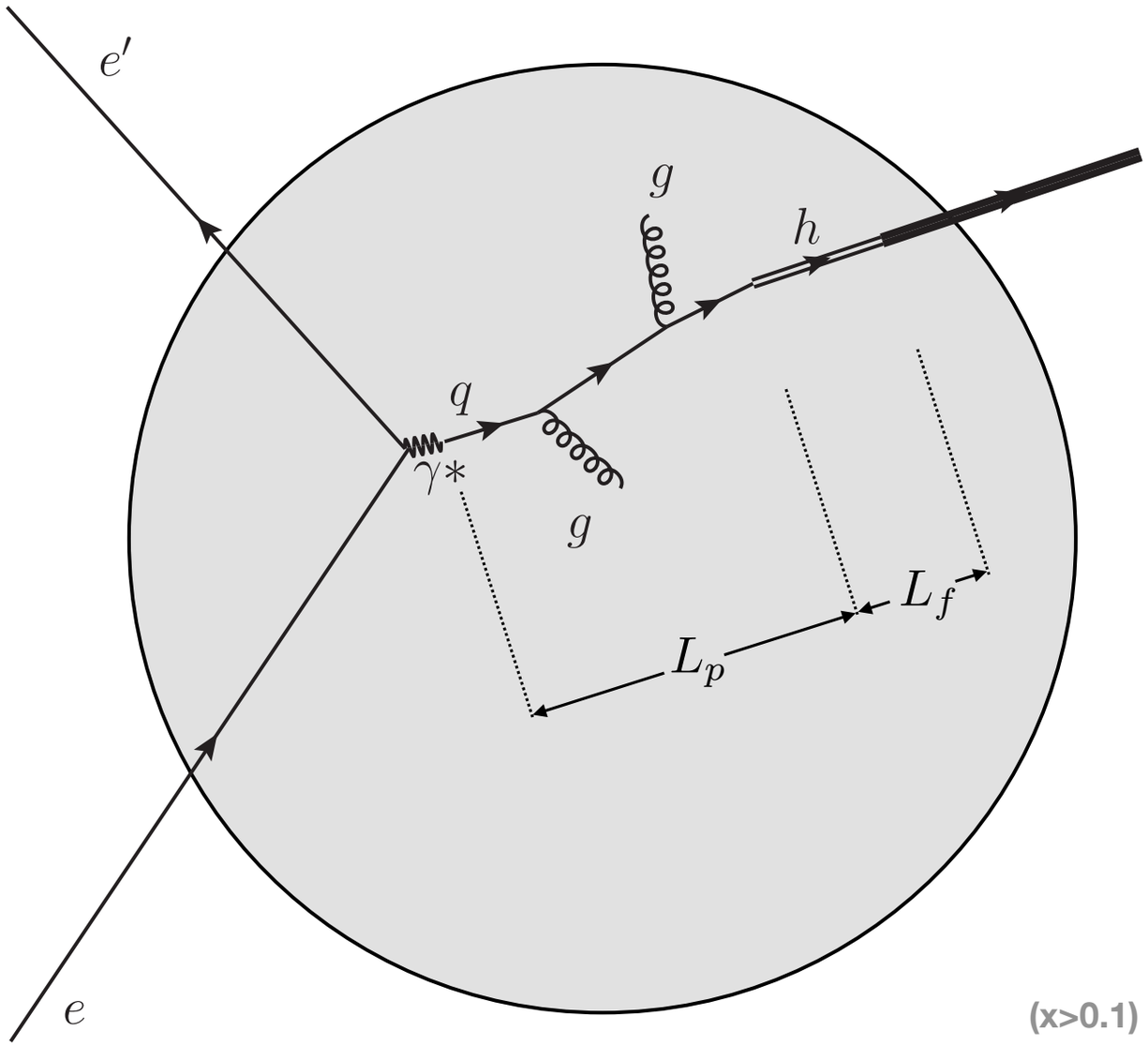
Accardi, Arleo, Brooks, d'Enterria, Muccifora Riv.Nuovo Cim.032:439553,2010 [arXiv:0907.3534]

Color Propagation and Hadron formation in Deep Inelastic Scattering (DIS)



(x>0.1)

Color Propagation and Hadron formation in Deep Inelastic Scattering (DIS)



(x>0.1)

Production length L_p relates to 'color lifetime' of quark following hard collision; it is the length required for colored system to neutralize its color

Formation length Lf is a distance over which a color neutral object pre-hadron evolves into observed hadron

e A : nuclei of increasing size act as space-time analyzer

Experimental observables

Hadronic Multiplicity ratio

$$R_{\mathrm{A}}^{h}\left(\nu, Q^{2}, z, p_{T}\right)=\left.\frac{\frac{N_{h}(\nu, Q^{2}, z, p_{T})}{N_{e}(\nu, Q^{2})|_{\mathrm{DIS}}}\right|_{\mathrm{A}}}{\left.\frac{N_{h}(\nu, Q^{2}, z, p_{T})}{N_{e}(\nu, Q^{2})|_{\mathrm{DIS}}}\right|_{\mathrm{D}}}$$

R_M =1 no effect due to the nucleus

R_M <1 we call it suppression

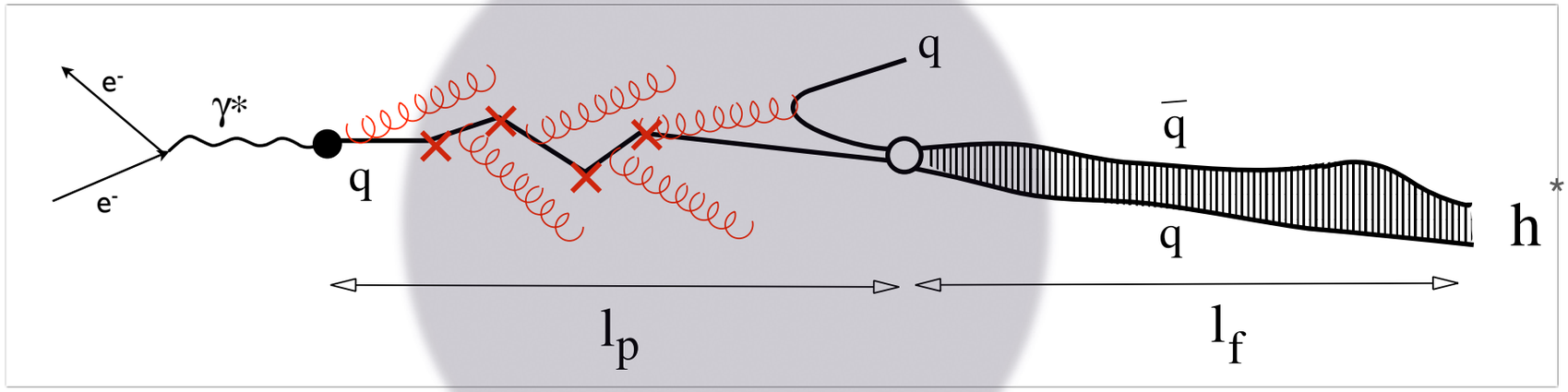
R_M >1 we call it enhancement

Transverse momentum broadening

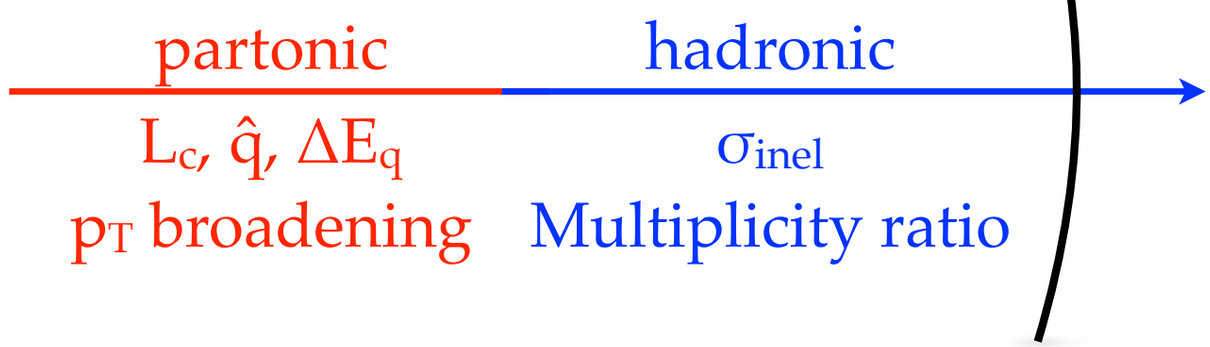
$$\Delta p_T^2(Q^2, \nu, z_h) \equiv \left\langle p_T^2(Q^2, \nu, z_h) \right\rangle |_A - \left\langle p_T^2(Q^2, \nu, z_h) \right\rangle |_D$$

Space-time view of hadronization in DIS

In medium *A*



Path of (struck) quark is divided into
"partonic phase" and "hadronic phase"



Partonic energy losses
Increase of transverse momentum

Hadron inelastic scattering
Decrease of the number of observed hadrons

Extraction of color lifetime Brooks-Lopez model

Physics Letters B 816 (2021) 136171

Contents lists available at ScienceDirect

Physics Letters B

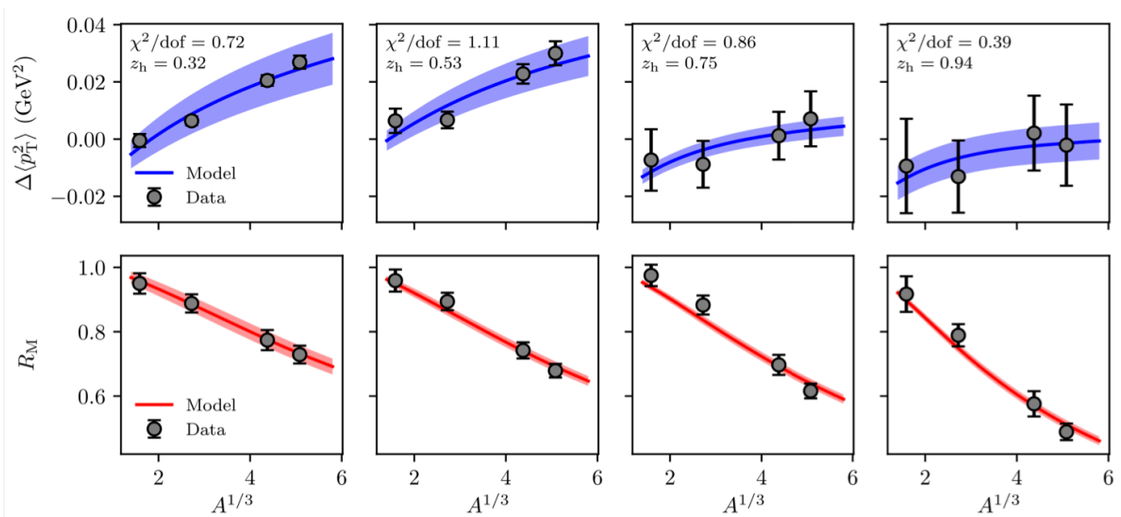
www.elsevier.com/locate/physletb

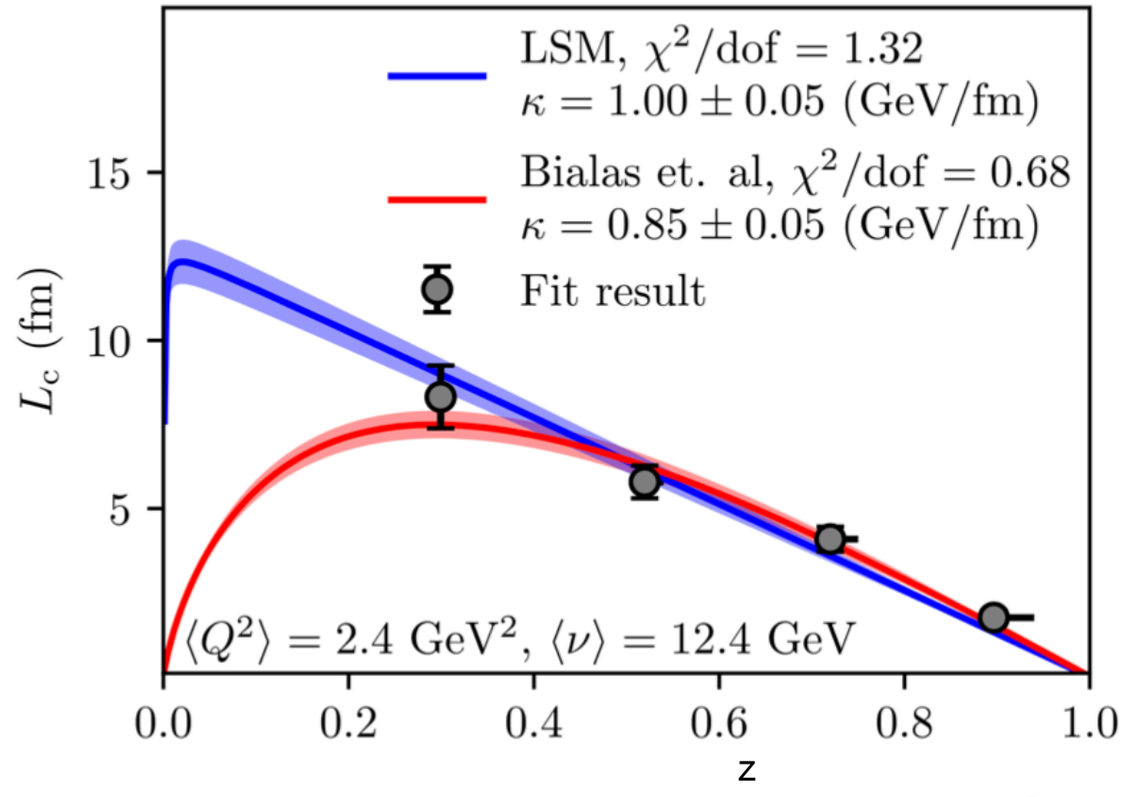
Estimating the color lifetime of energetic quarks

William K. Brooks [a,b,c,*], Jorge A. López [b,d]

- The **color lifetime** was estimated using simultaneous fit to two observables in the **HERMES** data with 3-parameter space-time model
- The answer depends on the kinematics and ranges from **2 to 8 fm/c**
- Independent determination of the string constant of the LSM!
- Measurement of transport coefficient

Simultaneous fit to two observables, *ΔpT2* and *R* for charged pions





Phys. Let. B 816 (2021) 136171 https://arxiv.org/abs/2004.07236

Brief overview of data

eA DIS: past, present, future

HERMES @27 GeV: $\sqrt{s}$ = 7.2 GeV

CLAS @ 5 GeV: $\sqrt{s}$ = 3.2 GeV

CLAS @11 GeV: $\sqrt{s}$ = 4.6 GeV

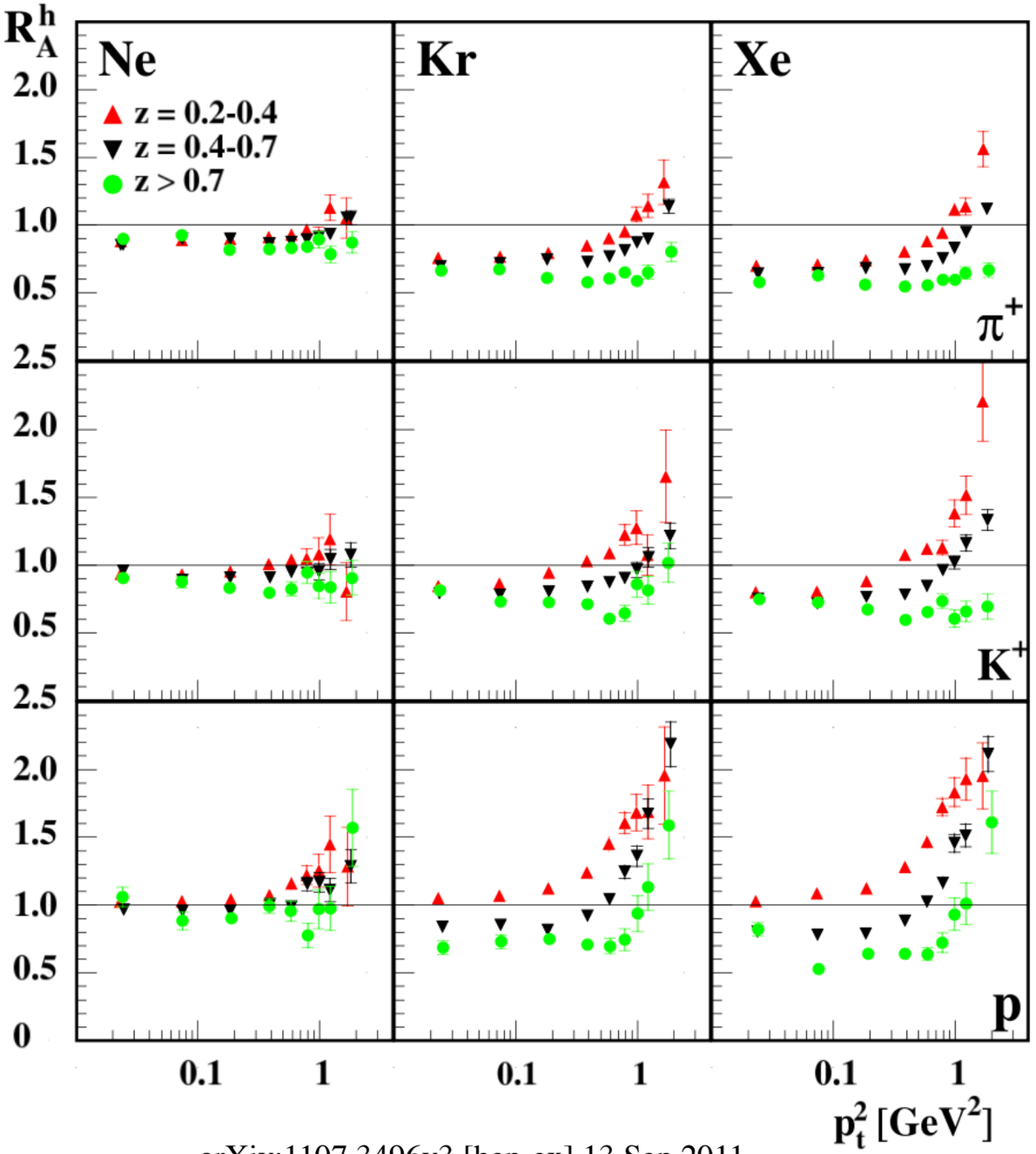
CLAS @ 22 GeV: $\sqrt{s}$ = 6.4 GeV

EicC: $\sqrt{s}$ = 11.9 - 16.7 GeV

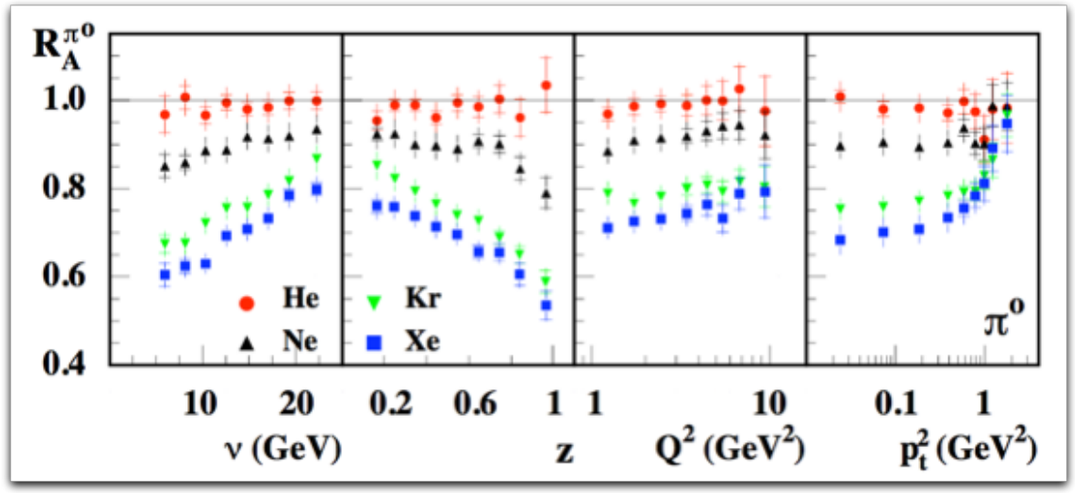
EIC eRHIC: $\sqrt{s}$ = 20 - 140 GeV

- *What are timescales of color neutralization and hadron formation?*
- *What are the differences in hadronization of light quarks vs heavy quarks*

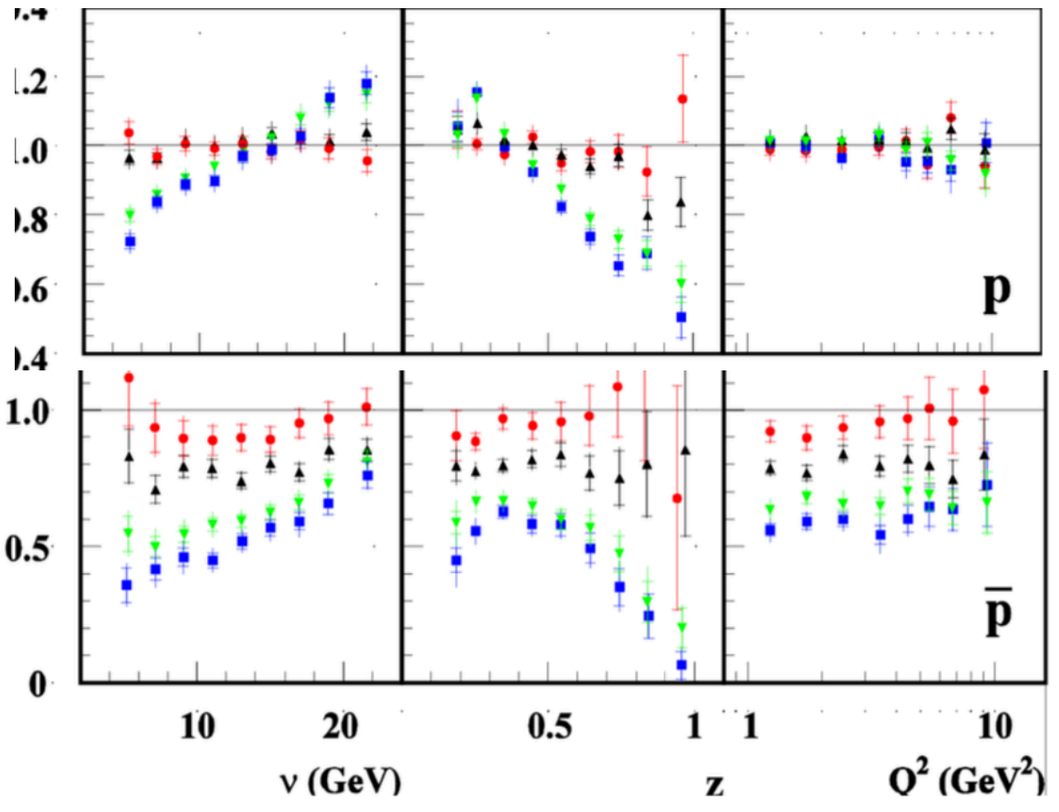
HERMES: 2D and 1D multiplicities



arXiv:1107.3496v3 [hep-ex] 13 Sep 2011
Eur. Phys. J. A47:113, 2011



HERMES Collaboration, A.Airapetian et. al., Nucl. Phys. B 780 (2007) 1–27

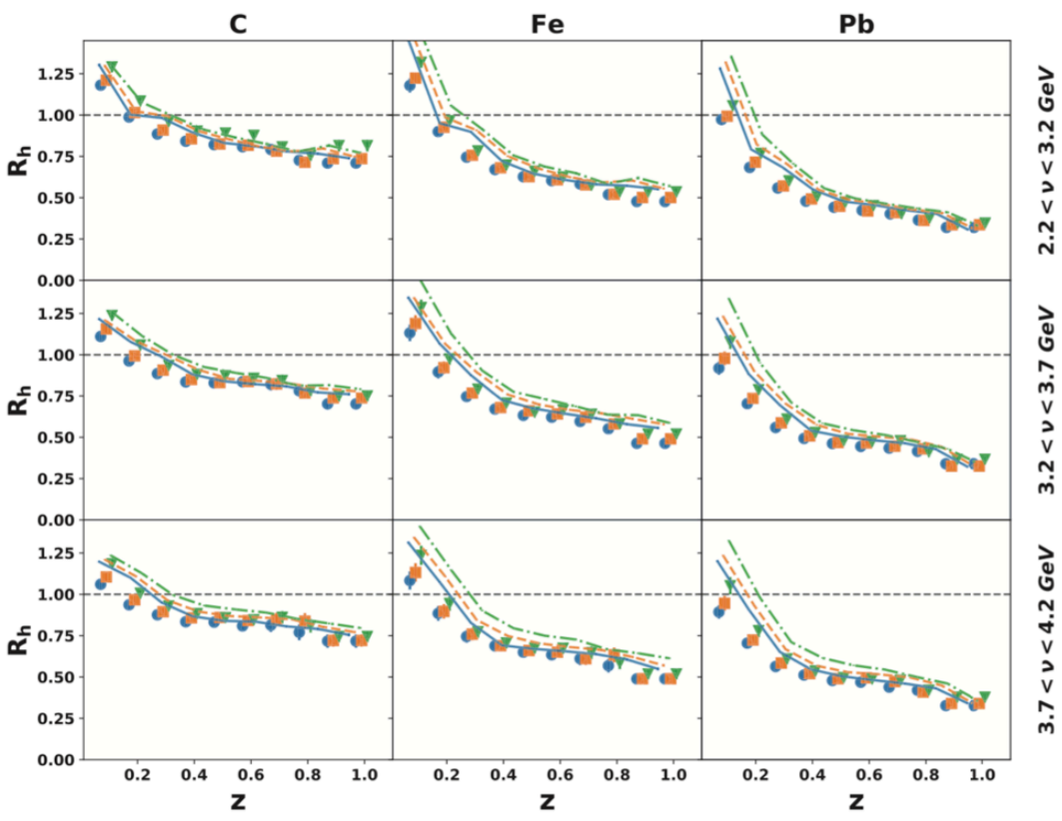


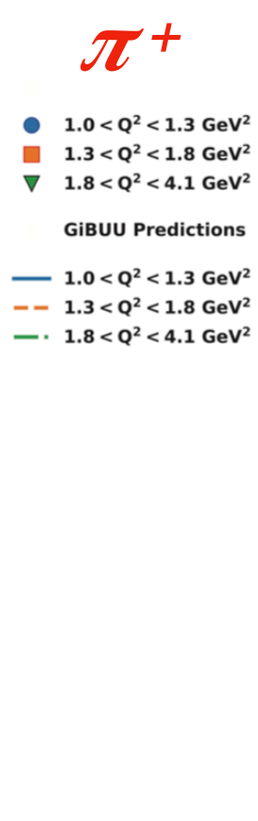
CLAS: 3D pion multiplicities

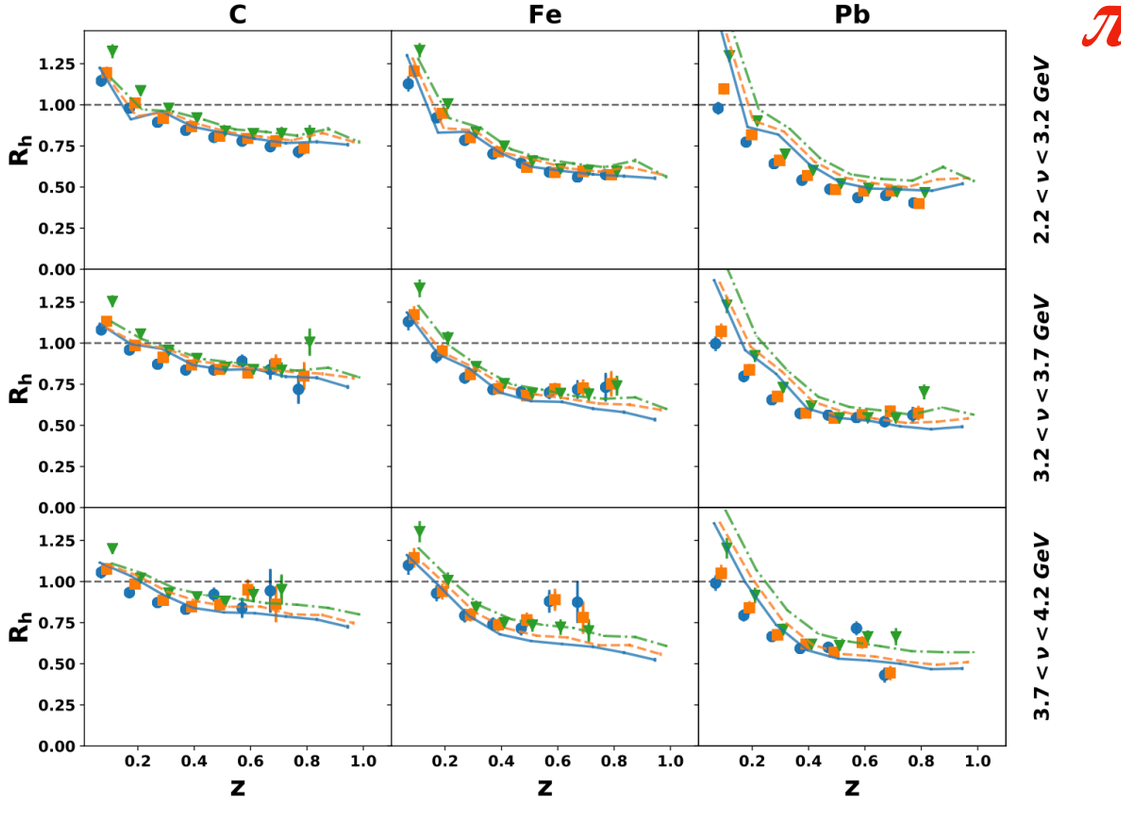
PHYSICAL REVIEW C **105**, 015201 (2022)

Measurement of charged-pion production in deep-inelastic scattering off nuclei with the CLAS detector

S. Morán,[1,3] R. Dupre,[2] H. Hakobyan,[1,52] M. Arratia,[3] W. K. Brooks,[1] A. Bórquez,[1] A. El Alaoui,[1] L. El Fassi,[4,5] K. Hafidi, R. Mendez,[1] T. Mineeva,[1] S. J. Paul,[3] M. J. Amaryan,[36] Giovanni Angelini,[19] Whitney R. Armstrong,[5] H. Atac,[43]



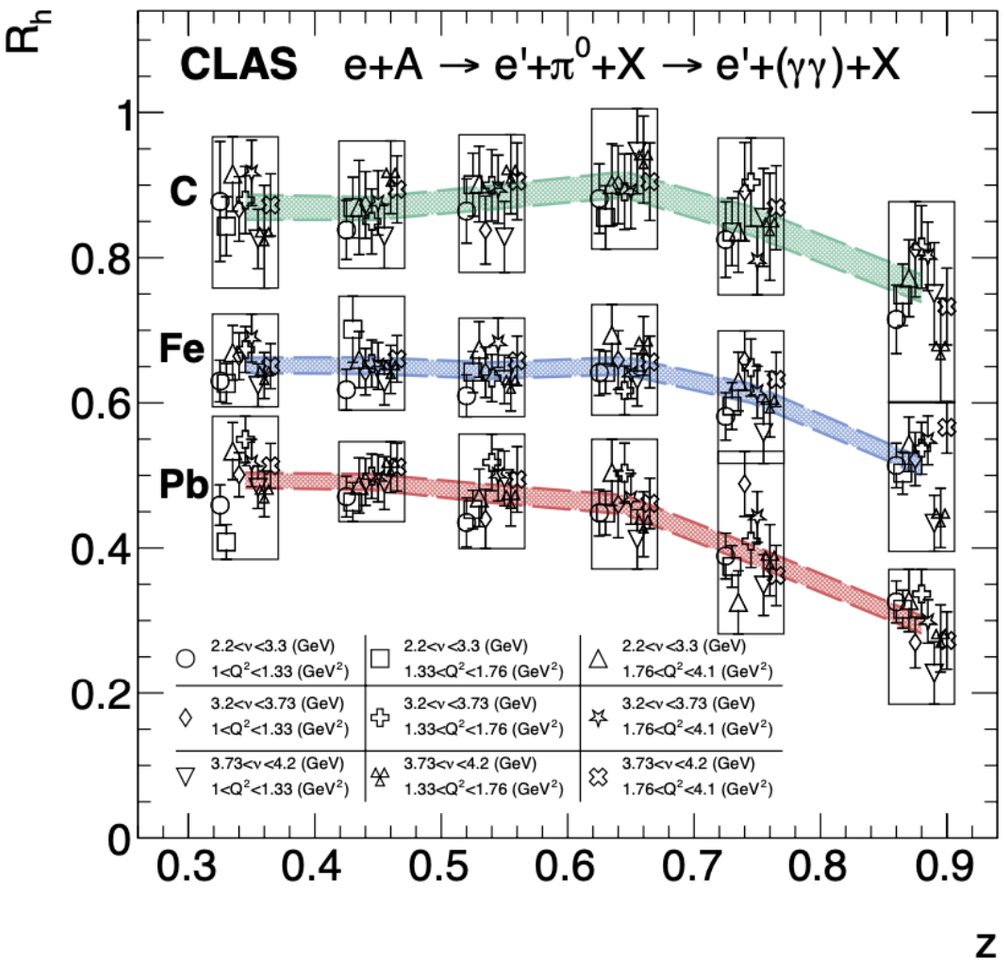




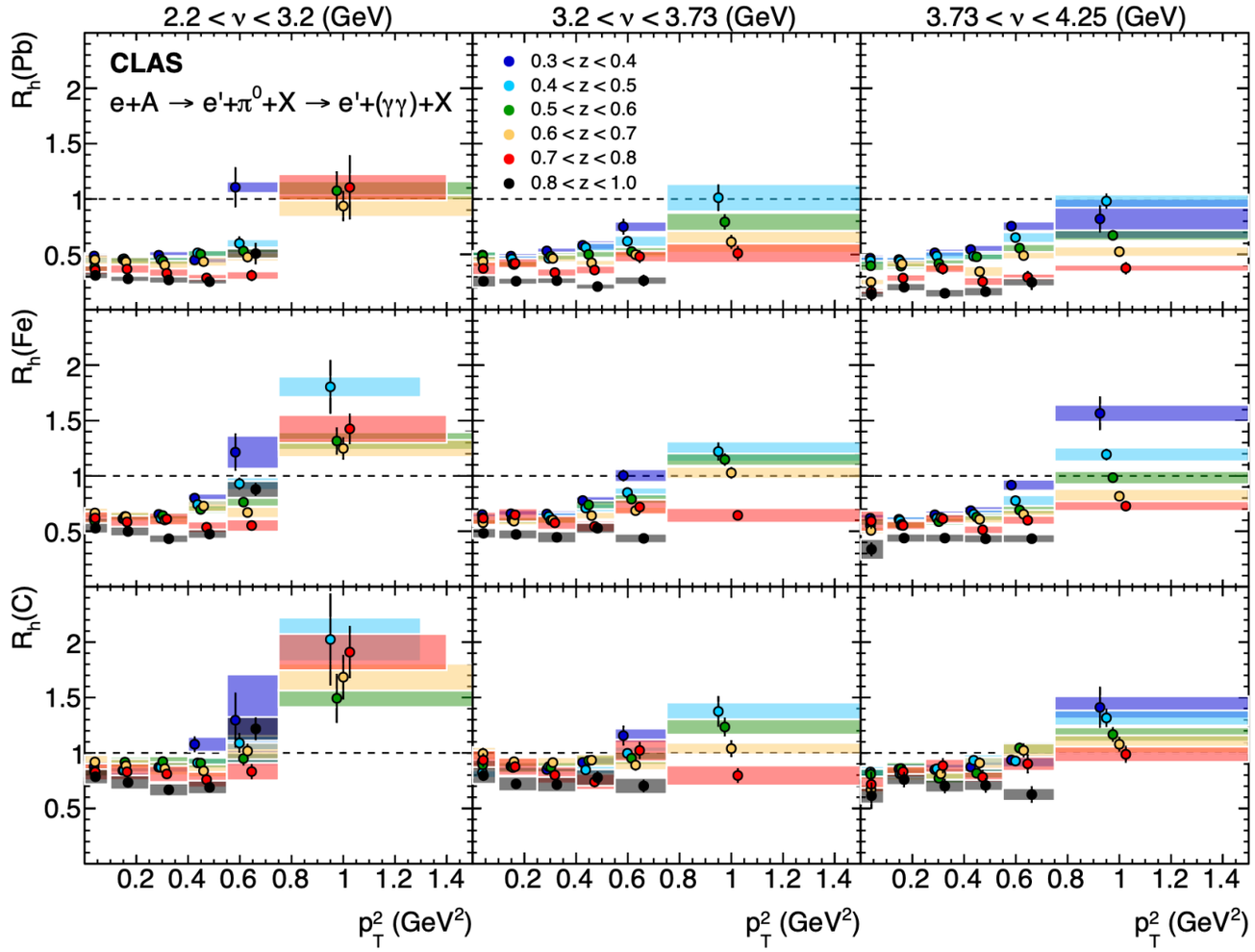
T.Mineeva

CLAS: 3D pion multiplicities

T.Mineeva et al. arXiv:2406.04513 to be submitted to PRC



π^0

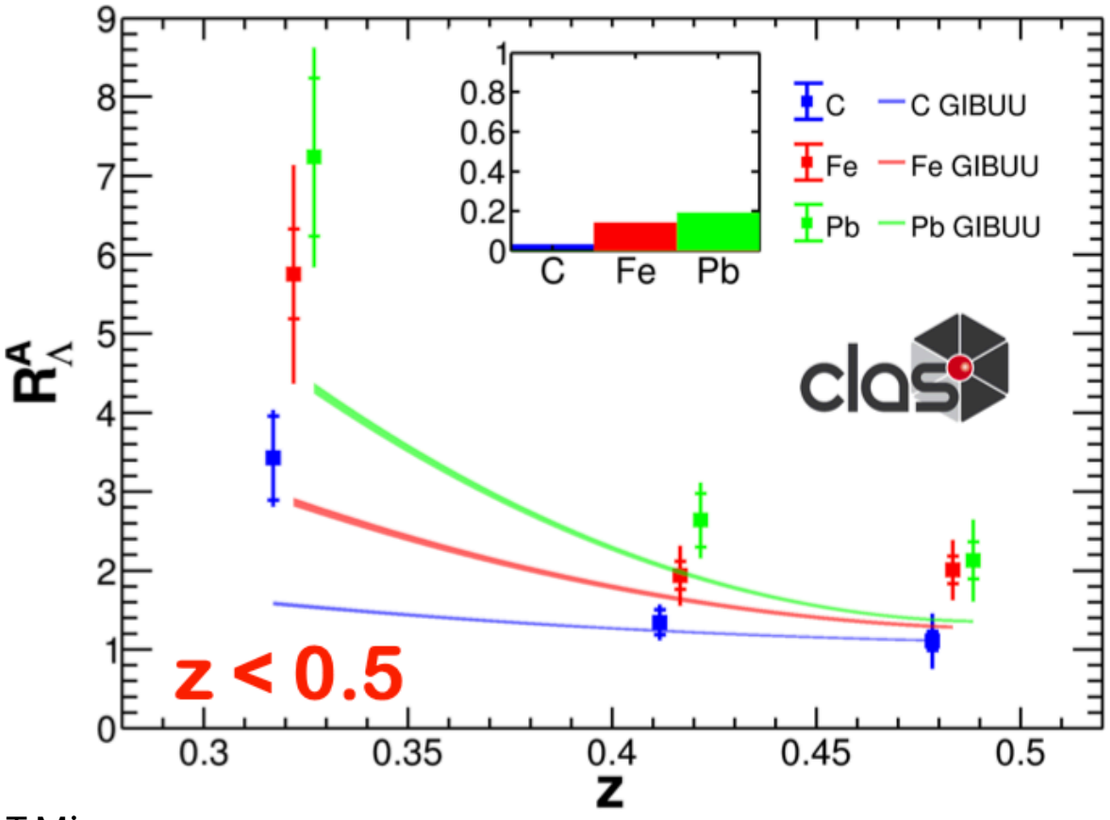


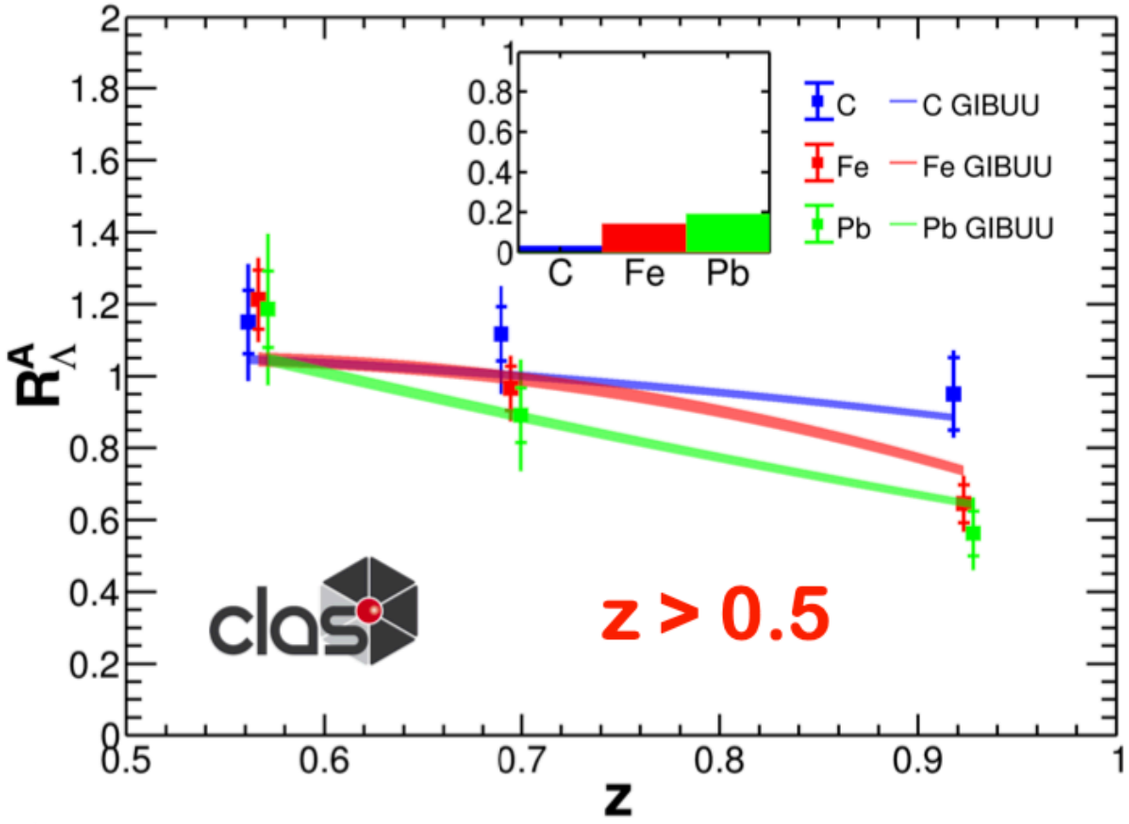
CLAS: Λ multiplicities

PHYSICAL REVIEW LETTERS **130,** 142301 (2023)

First Measurement of Λ Electroproduction off Nuclei in the Current and Target Fragmentation Regions

T. Chetry,[29,13] L. El Fassi,[29,*] W. K. Brooks,[44,45,46,43] R. Dupré,[23] A. El Alaoui,[44] K. Hafidi,[1] P. Achenbach,[43]





T.Mineeva

CLAS: Λ multiplicities

First lambda baryon
multiplicity ratio
1D now
2D in CLAS12
more in CLAS22

PHYSICAL REVIEW LETTERS **130,** 142301 (2023)

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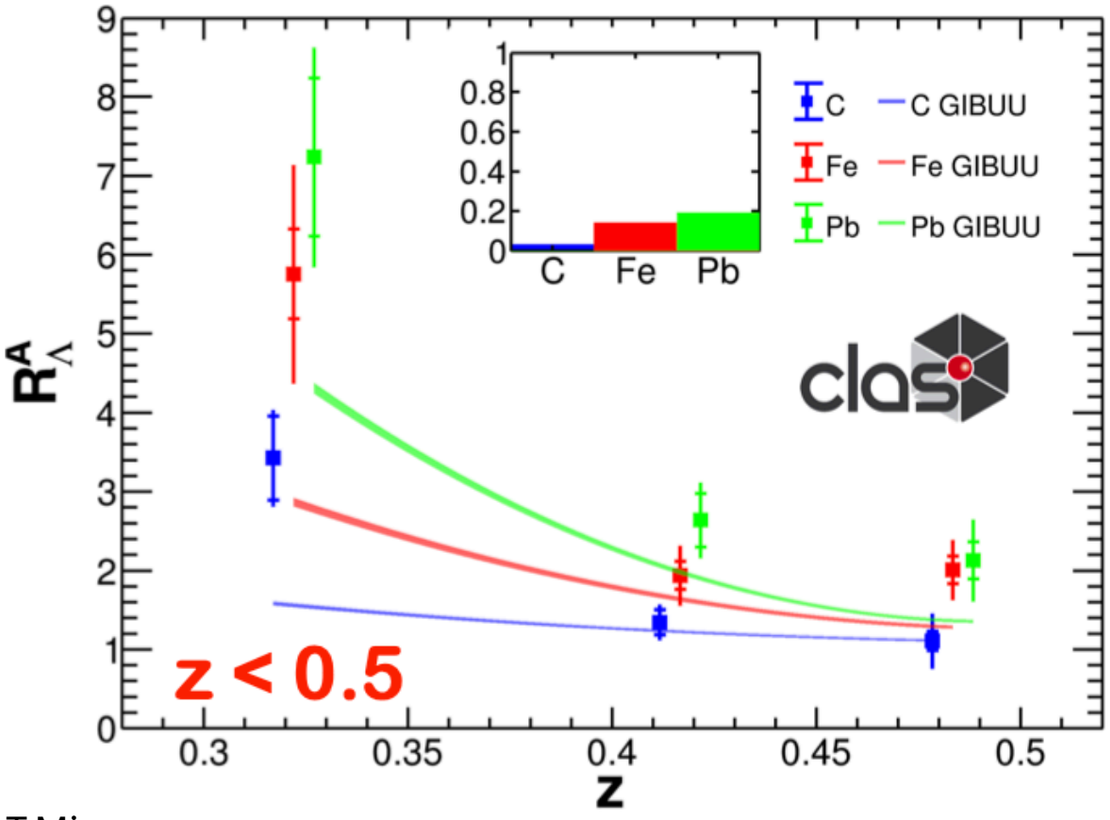
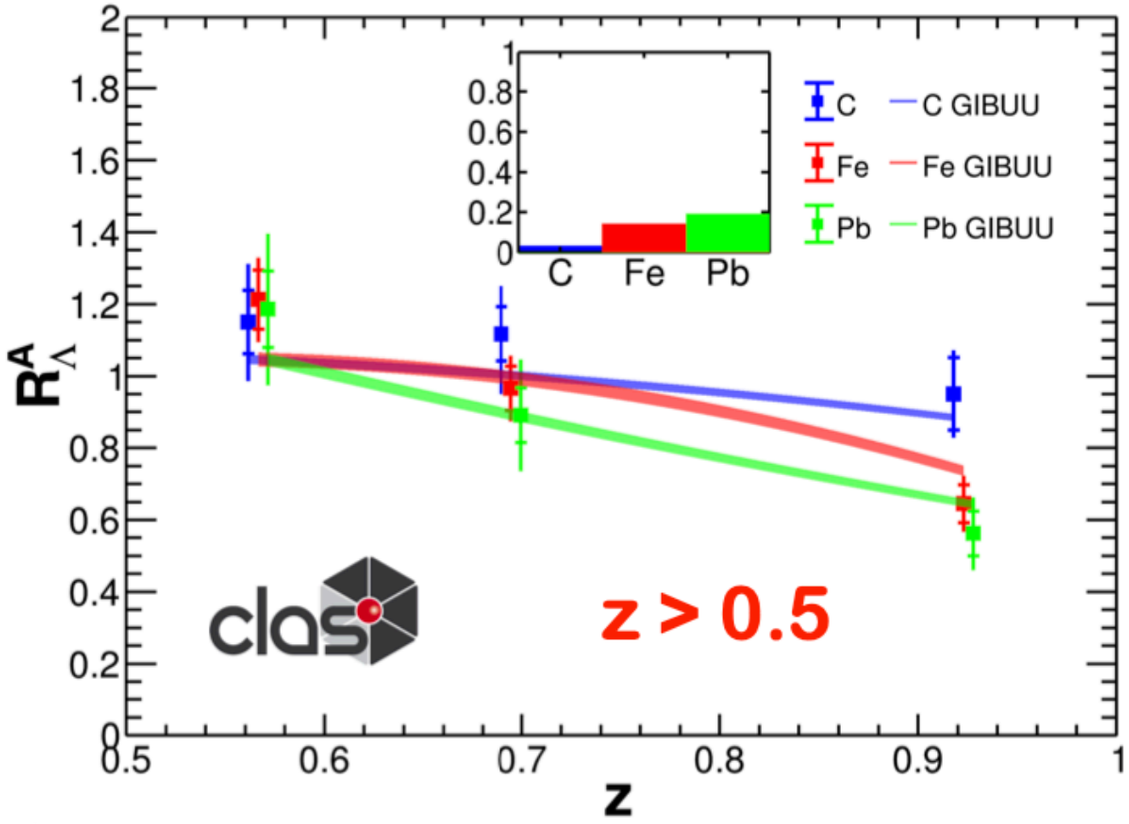
T. Chetry,[29,13] L. El Fassi,[29,*] W. K. Brooks,[44,45,46,43] R. Dupré,[23] A. El Alaoui,[44] K. Hafidi,[1] P. Achenbach,[43]

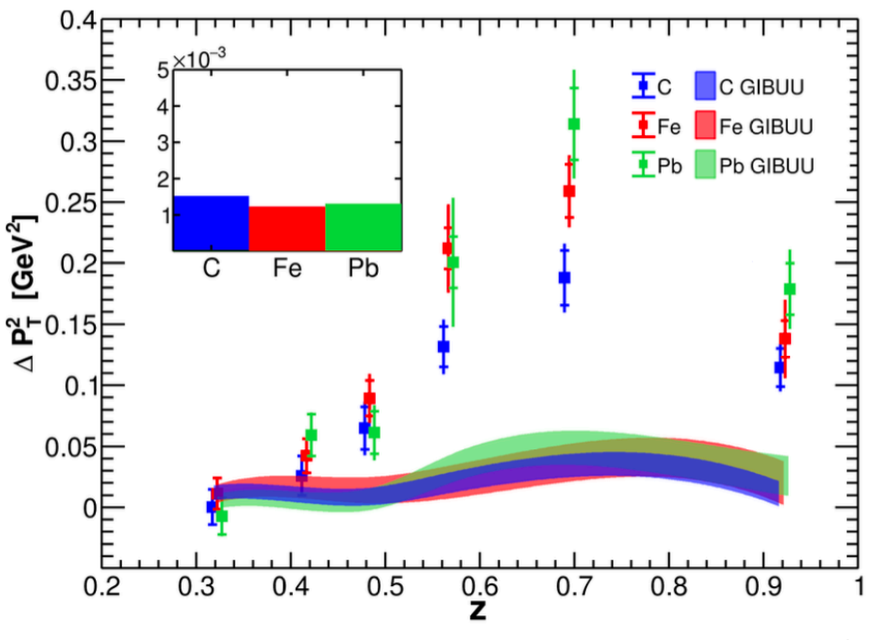


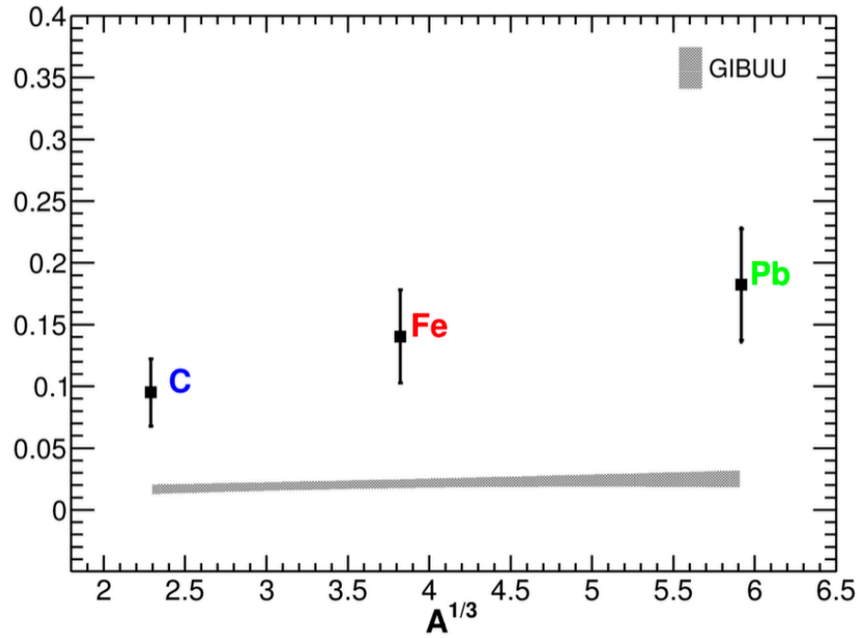


T.Mineeva

CLAS: Λ pT2 Broadening

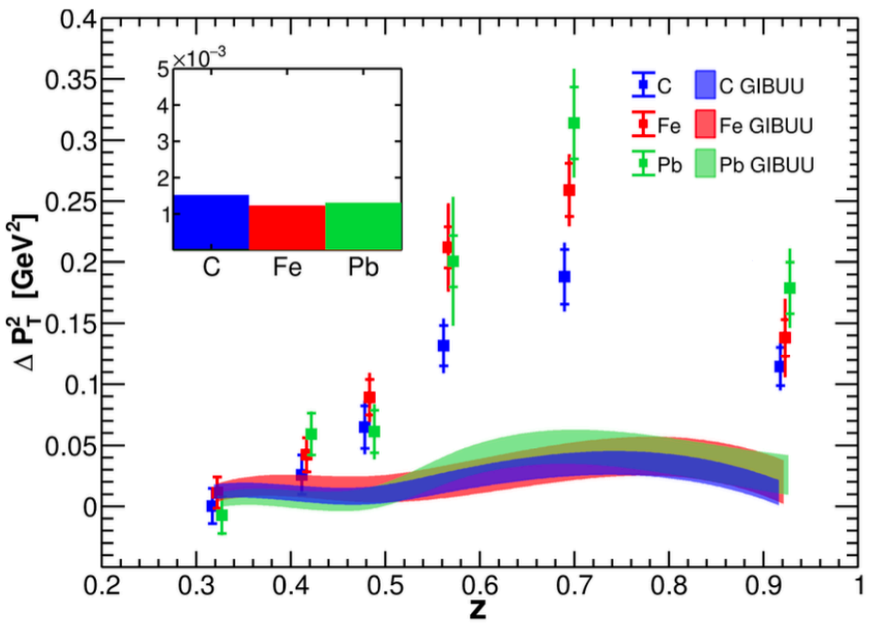
T. Chetry *et al* (CLAS Collaboration), Phys.Rev.Lett 130,

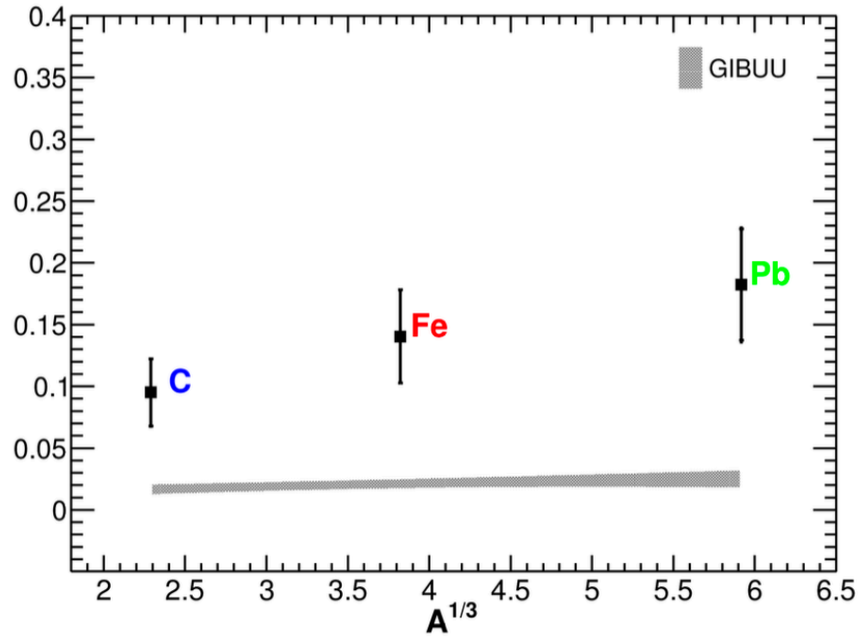




CLAS: Λ pT2 Broadening

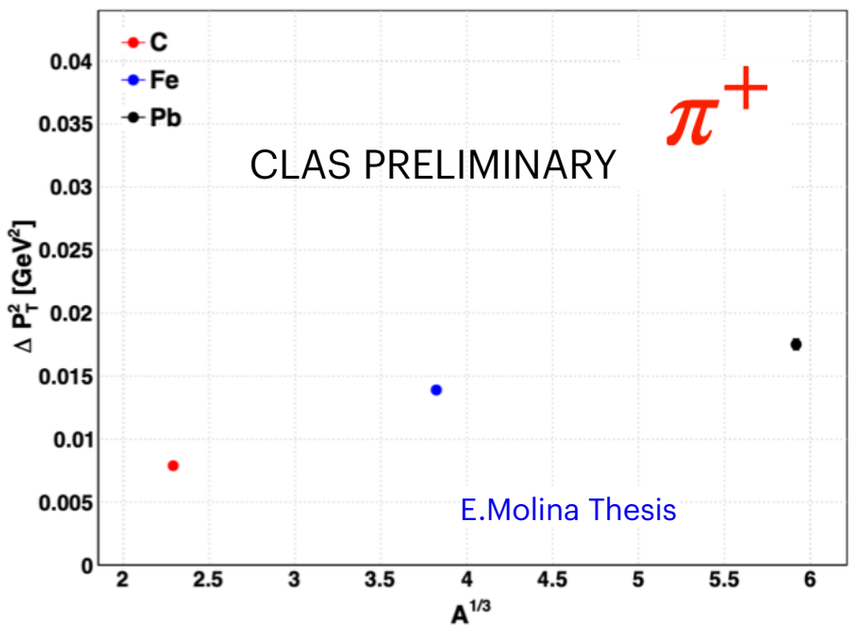
T. Chetry *et al* (CLAS Collaboration), Phys.Rev.Lett 130,





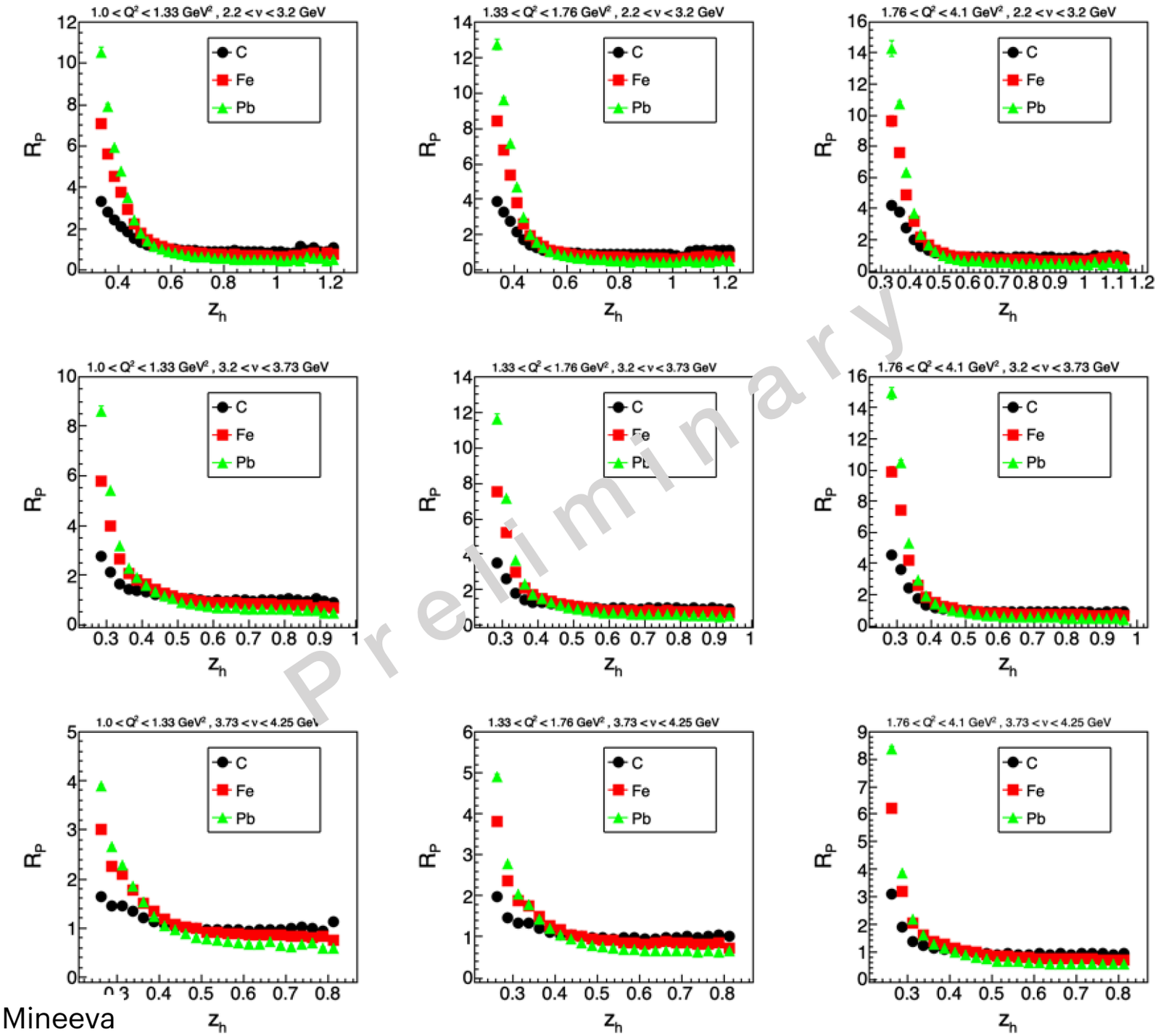
ΔpT2 on Λ is huge compared to pion:

0.3 vs 0.03 GeV^2



CLAS: 3D proton multiplicities

Mike Wood analysis in CLAS review



Proton multiplicity ratio:
3D now in Review
4D in CLAS12

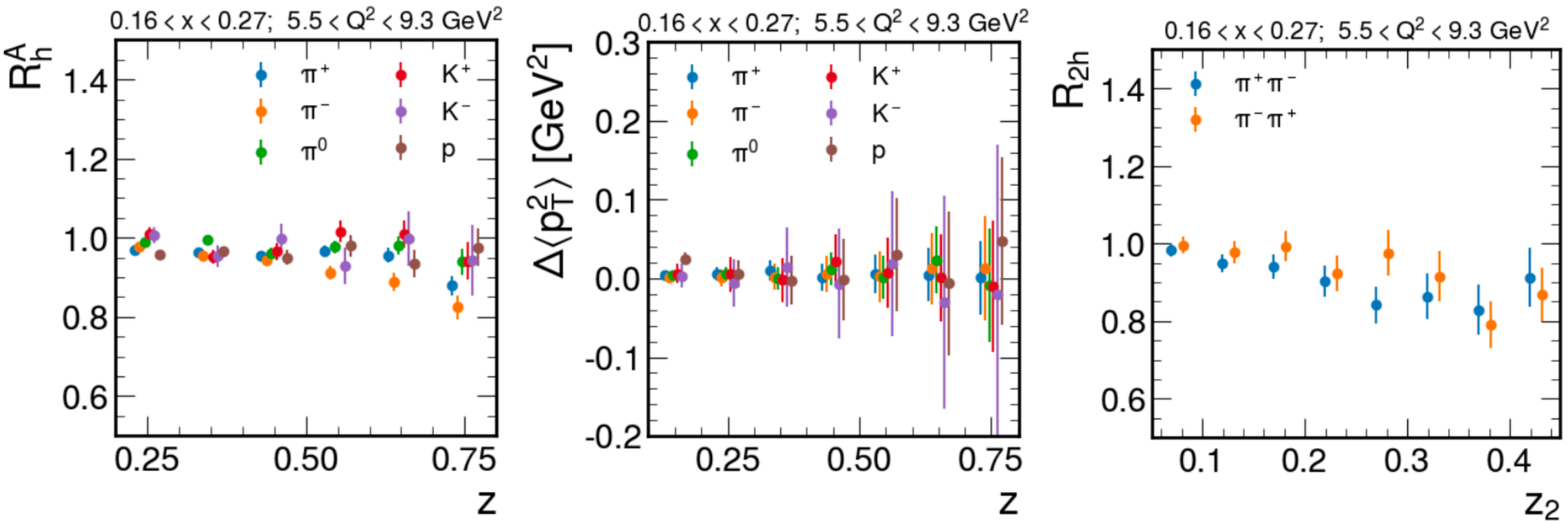
22 GeV Projections

Eur. Phys. J. A (2024) **60**: 173
https://doi.org/10.1140/epja/s10050-024-01282-x
Review

Strong interaction physics at the luminosity frontier with 22 GeV electrons at Jefferson Lab

7.3.6 Hadronization Studies in Nuclei

Ahmed El Alaoui



Three-fold projections from the *simulated sample using GiBUU event generator* assuming a per-nucleon luminosity of 10^{35} $cm^{-2}s^{-1}$ and 15 PAC days.

T.Mineeva

PyRad

PYTHIA + RADGEN are used to generate SIDIS process.

- Tuned PYTHIA 6.4.28:

- The fragmentation functions parameter (a, b):

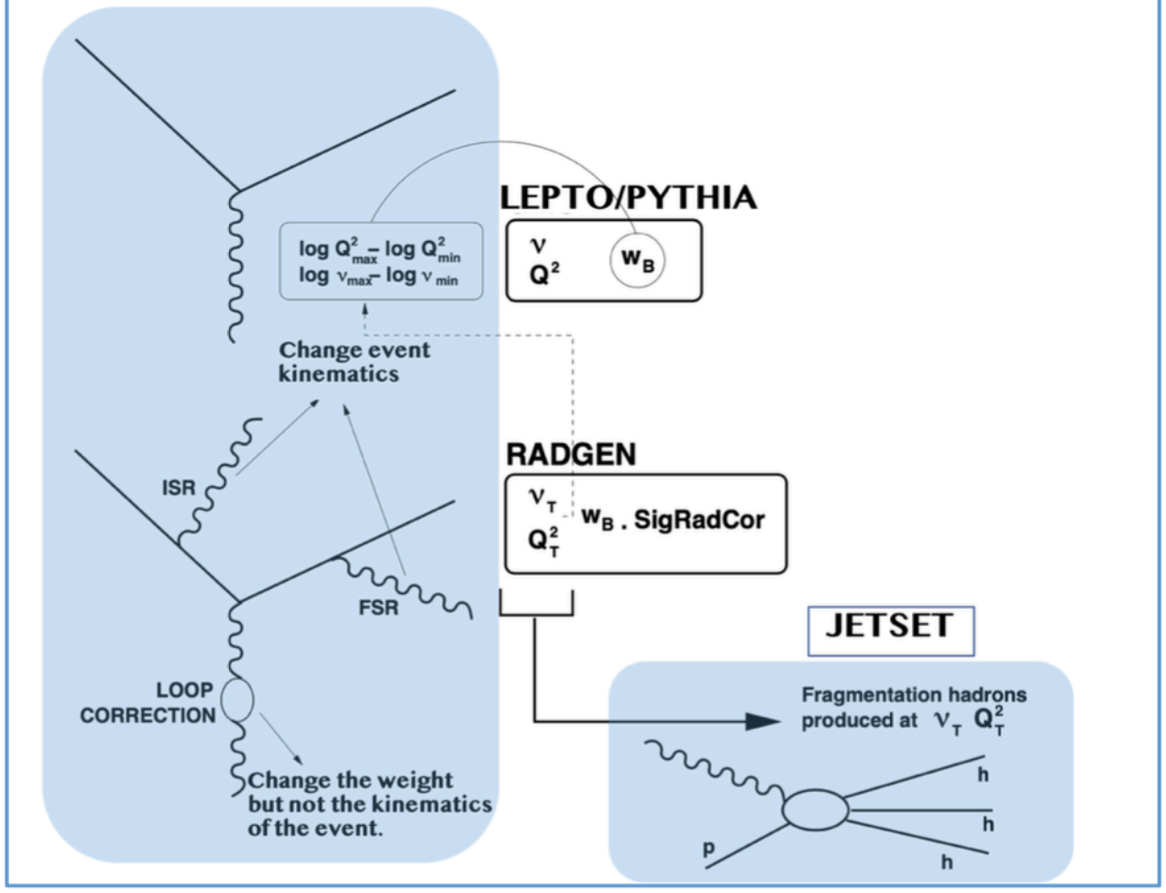
- $D(z) = z^{-1}(1-z)^{a}.e^{\frac{bm_T^2}{z}}$

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

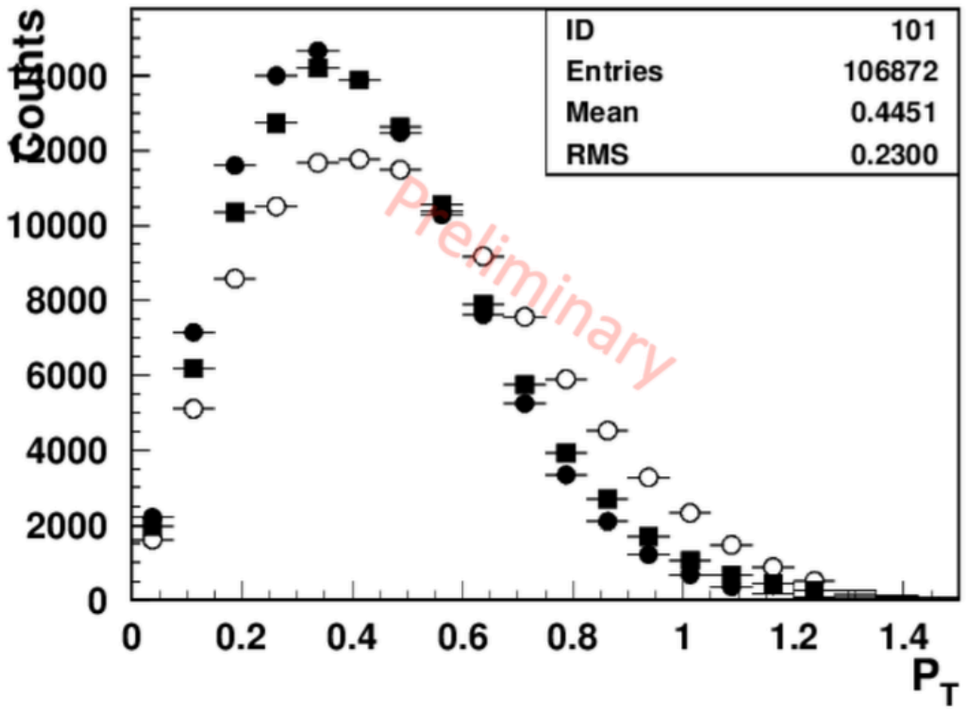
- Intrinsic k_T of partons.

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

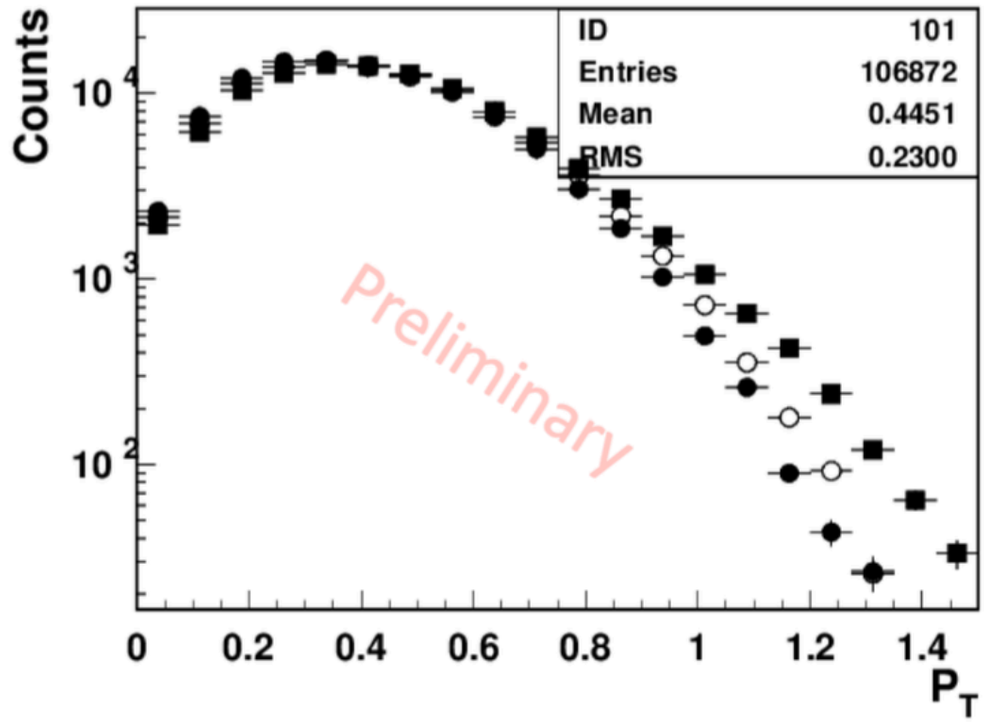
- Nuclear PDFs Parametrization LHAPDF 6.4.0



PyRad tuned to PGC data



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



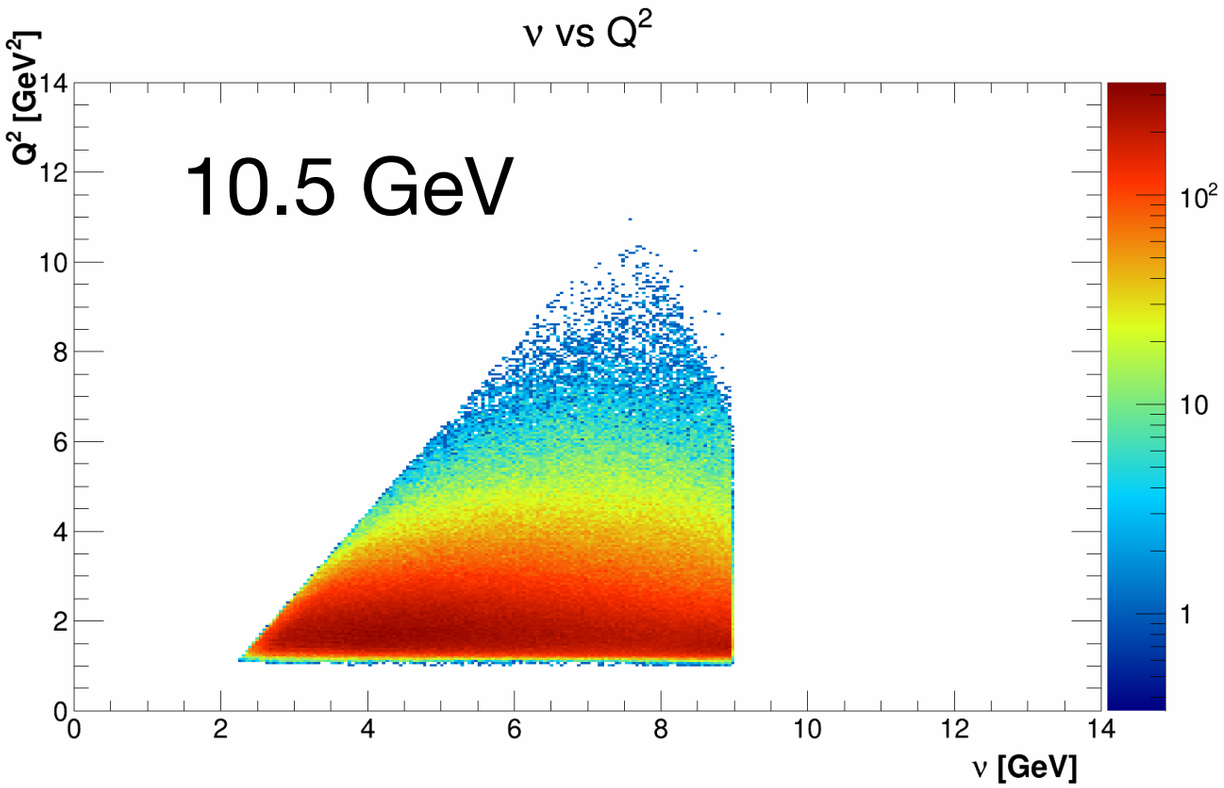
Full square RGC data
Full circle pythia (Tune 4)
Open circle pythia (Tune 5)

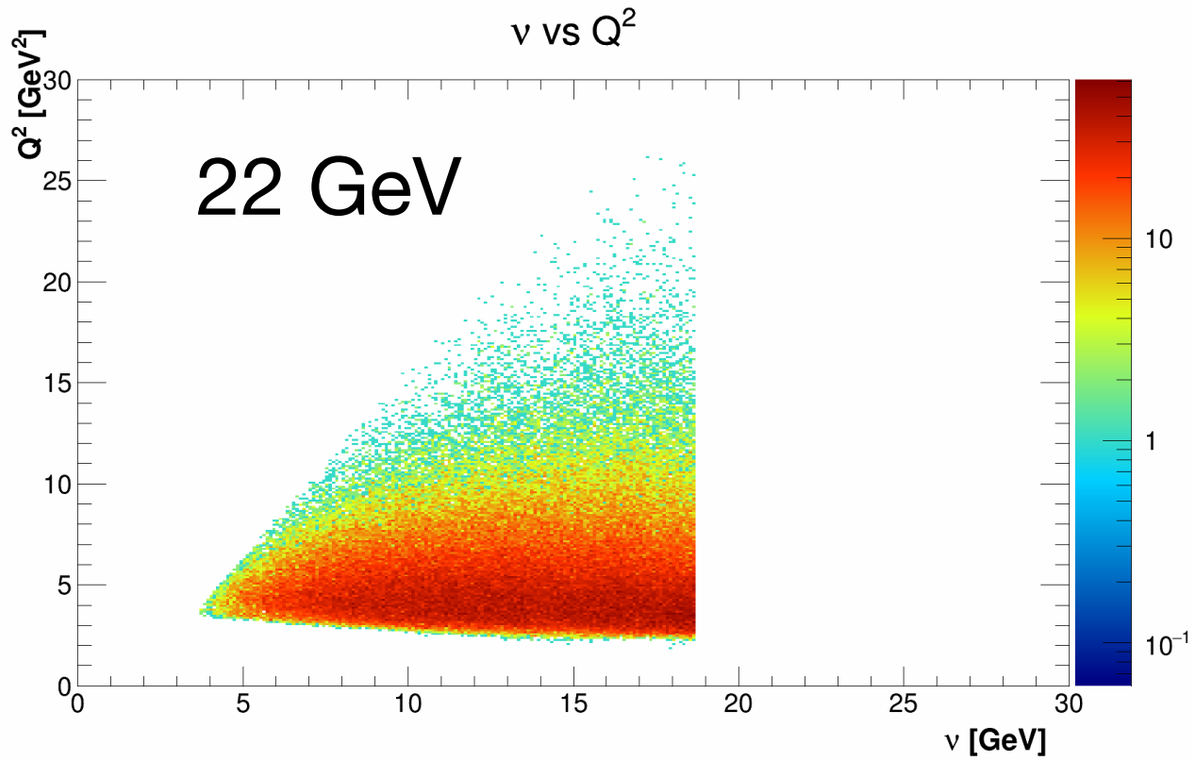
PyRad tuned parameters

Parameter Definition	Parameter Name	Default Value	Tune 1 Value	Tune 2 Value	Tune 3 Value	Tune 4 Value	Tune 5 Value	Tune 6 Value
$q\bar{q}_{supp}$	PARJ(1)	0.10	0.10	0.02	0.03	0.025	0.029	0.10
q^{s}_{supp}	PARJ(2)	0.30	0.16	0.20	0.20625	0.120	0.283	0.30
$q^{s}q^{s}_{supp}$	PARJ(3)	0.40	0.40	0.40	0.25	0.25	0.40	0.40
$BM\bar{B}/B\bar{B}$	PARJ(5)	0.50	0.50	0.50	0.0	0.0	0.50	0.50
$s\bar{s}/BM\bar{B}$	PARJ(6)	0.50	0.50	0.50	0.0	0.0	0.50	0.5
$M_{s}/BM\bar{B}$	PARJ(7)	0.50	0.50	0.50	0.0	0.0	0.50	0.5
VM_{supp}	PARJ(11)	0.50	0.50	0.20	0.25	0.25	0.50	0.7
VM^{s}_{supp}	PARJ(12)	0.60	0.60	0.60	0.30	0.30	0.60	0.75
σ of transverse momentum	PARJ(21)	0.36	0.33	0.37	0.382	0.382	0.381	0.60
f	PARJ(23)	0.01	0.01	0.03	0.03	0.03	0.01	0.01
P^{f}_{T}	PARJ(24)	2.00	2.00	2.50	2.50	2.50	2.00	2.0
remaining energy below which the fragmentation of a parton system is stopped	PARJ(33)	0.80	0.80	0.80	0.20	0.20	0.80	0.3
a	PARJ(41)	0.30	0.89	1.74	1.1266	1.13	1.940	1.2
b	PARJ(42)	0.58	0.24	0.23	0.3672	0.37	0.544	0.58
$a_{q\bar{q}}$	PARJ(45)	0.50	0.50	0.50	0.80	0.80	1.05	0.5

The table contains PARJ parameters only. Other parameters from PARU, MSTP, MSTU and MSTJ common blocks are also tuned but not included in the slide

Phase-space: Q2 vs ν

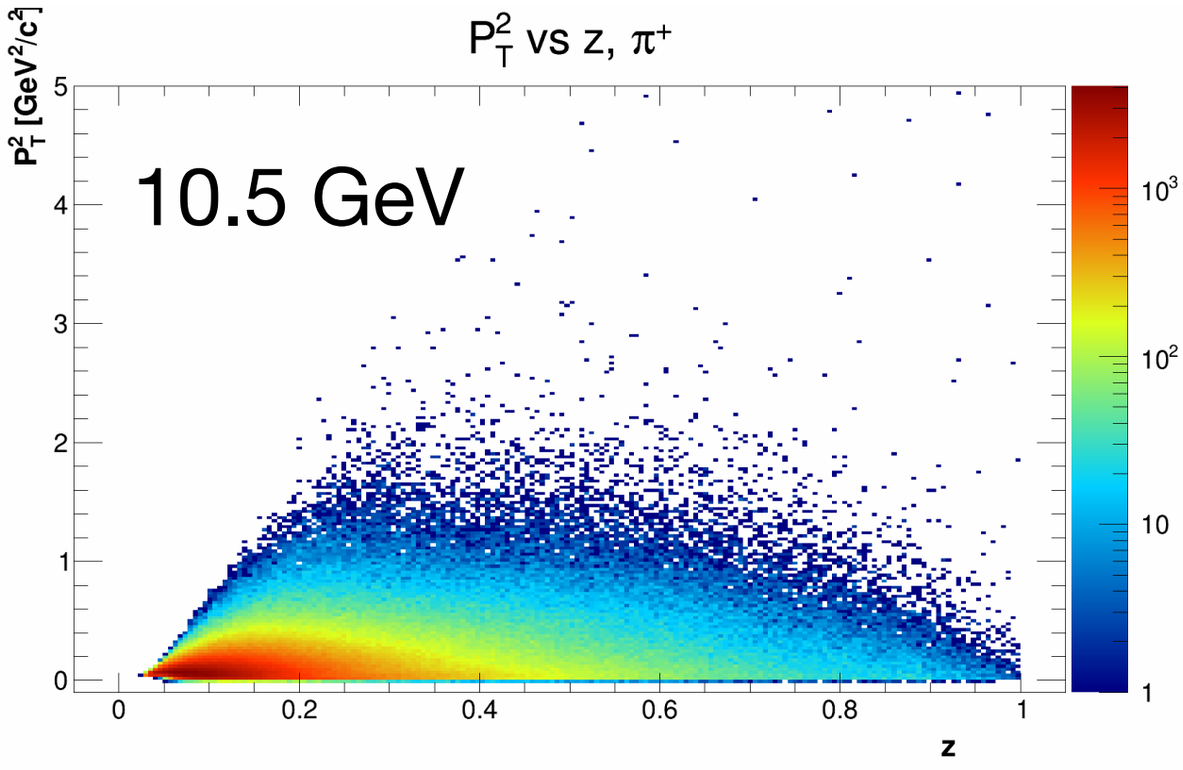


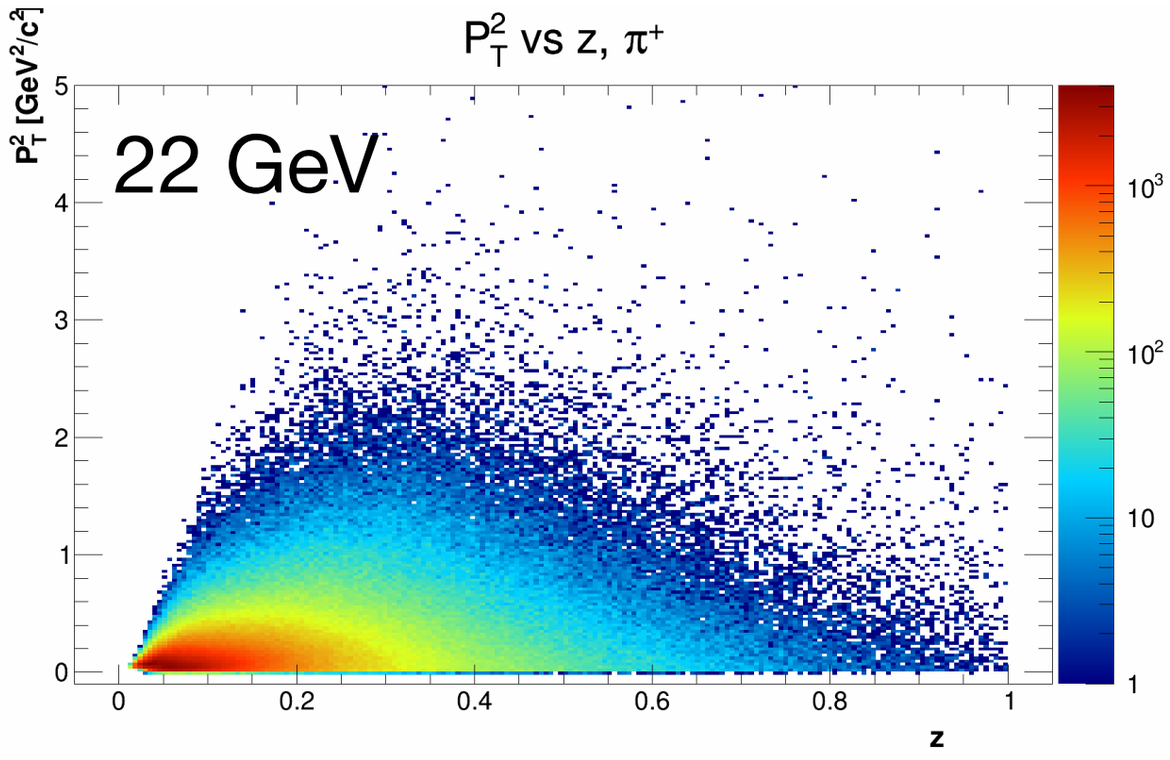


Cross section for q + γ* -> q @ 10.5 GeV is σ = 59.8 nB

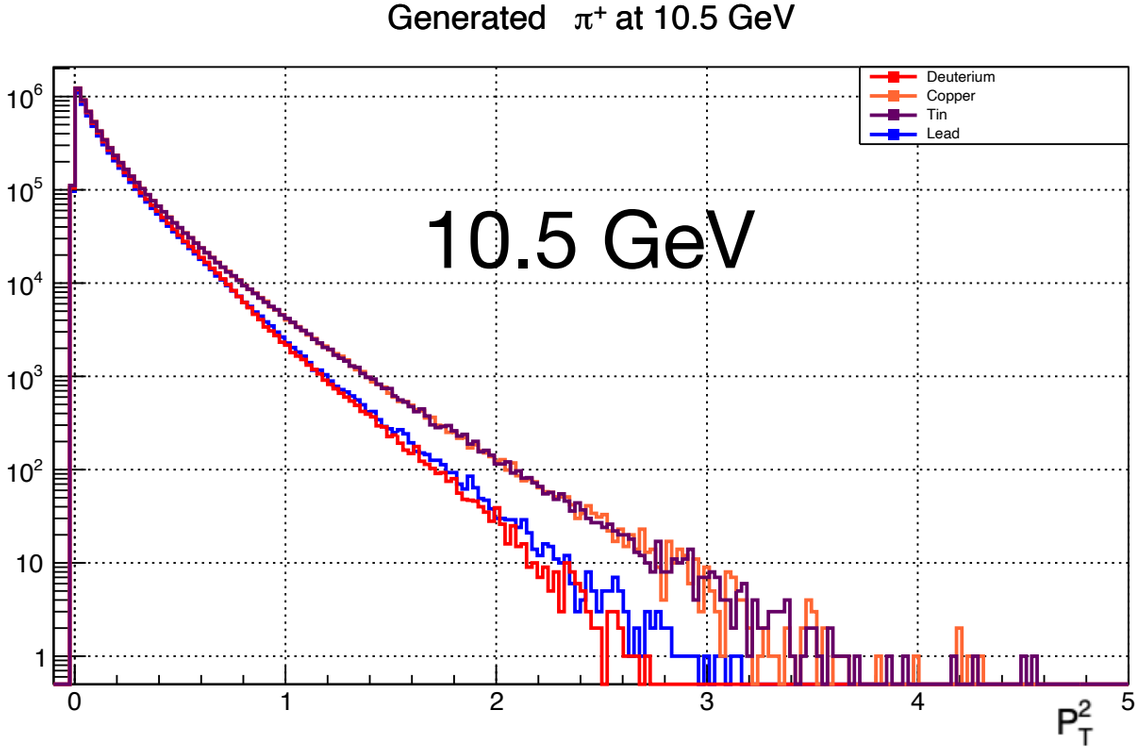
Cross section for q + γ* -> q @ 22 GeV is σ = 105 nB

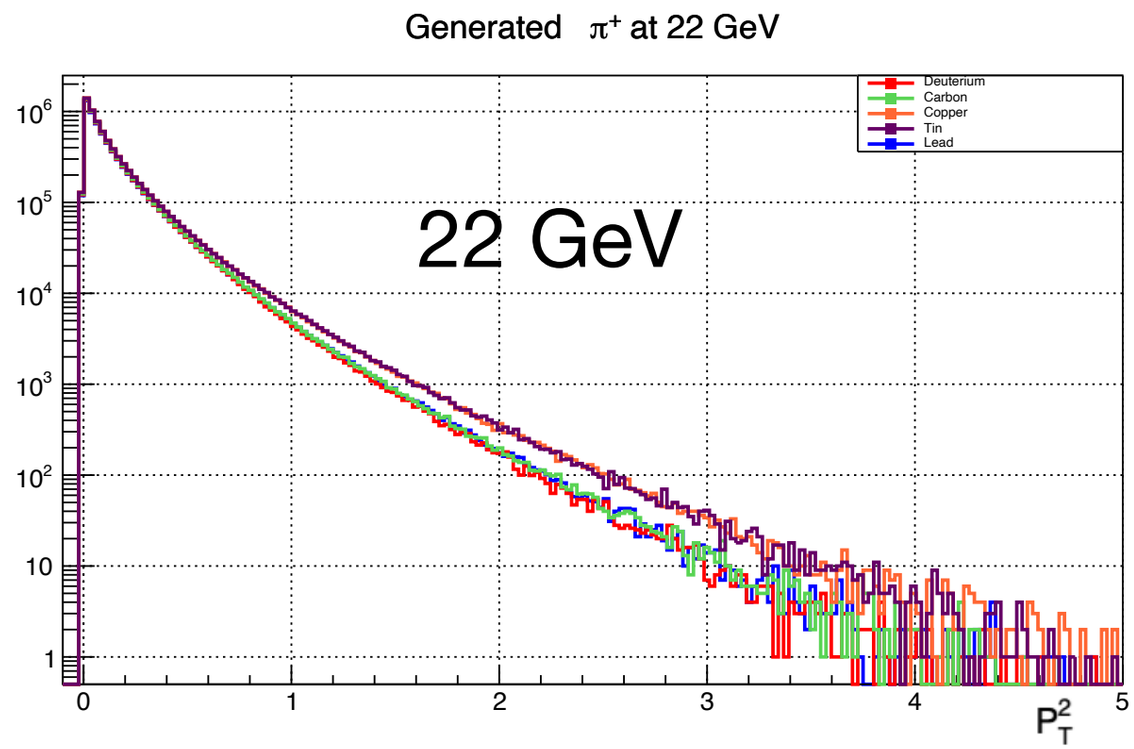
Phase-space: pT2 vs z

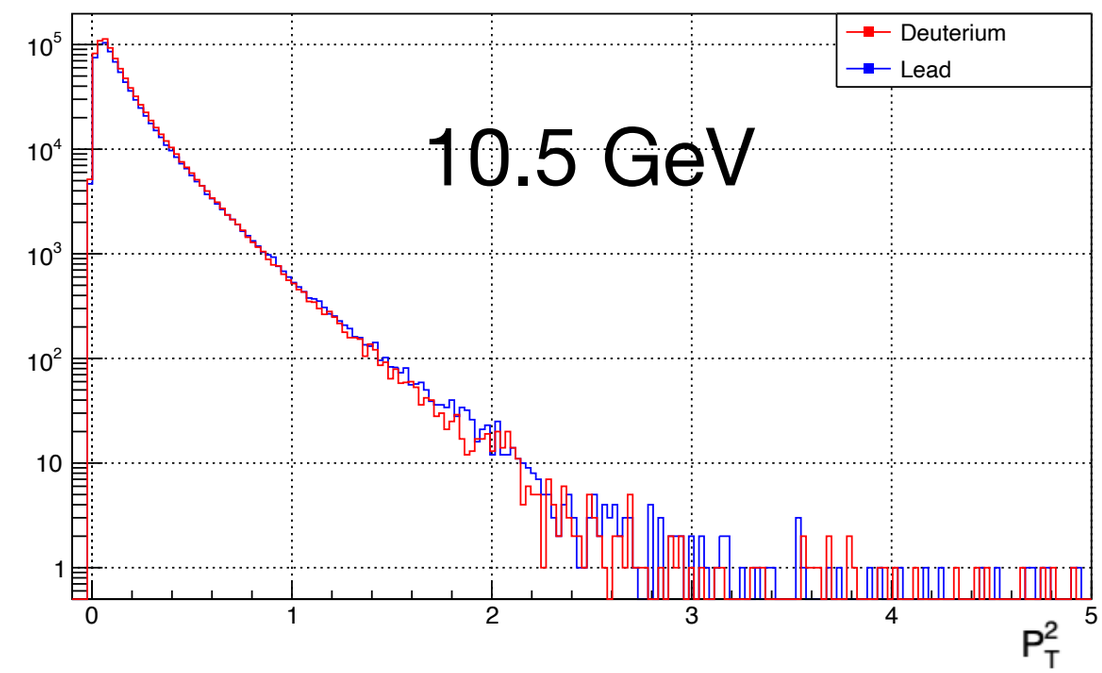


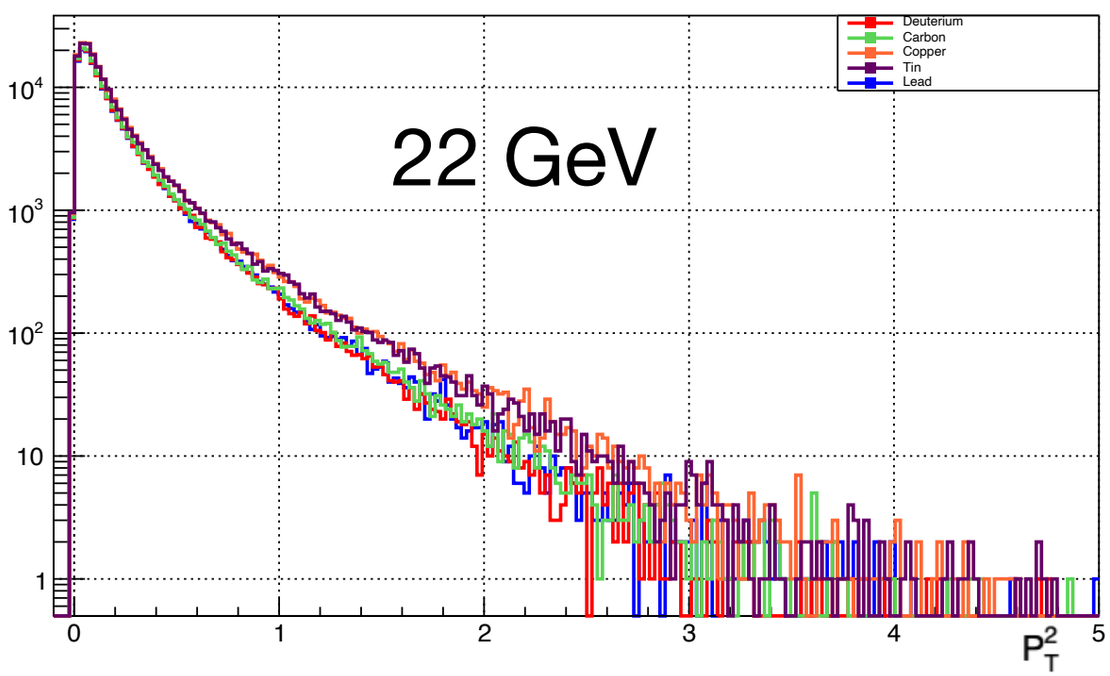


Nuclear effects: Fermi motion + nPDF

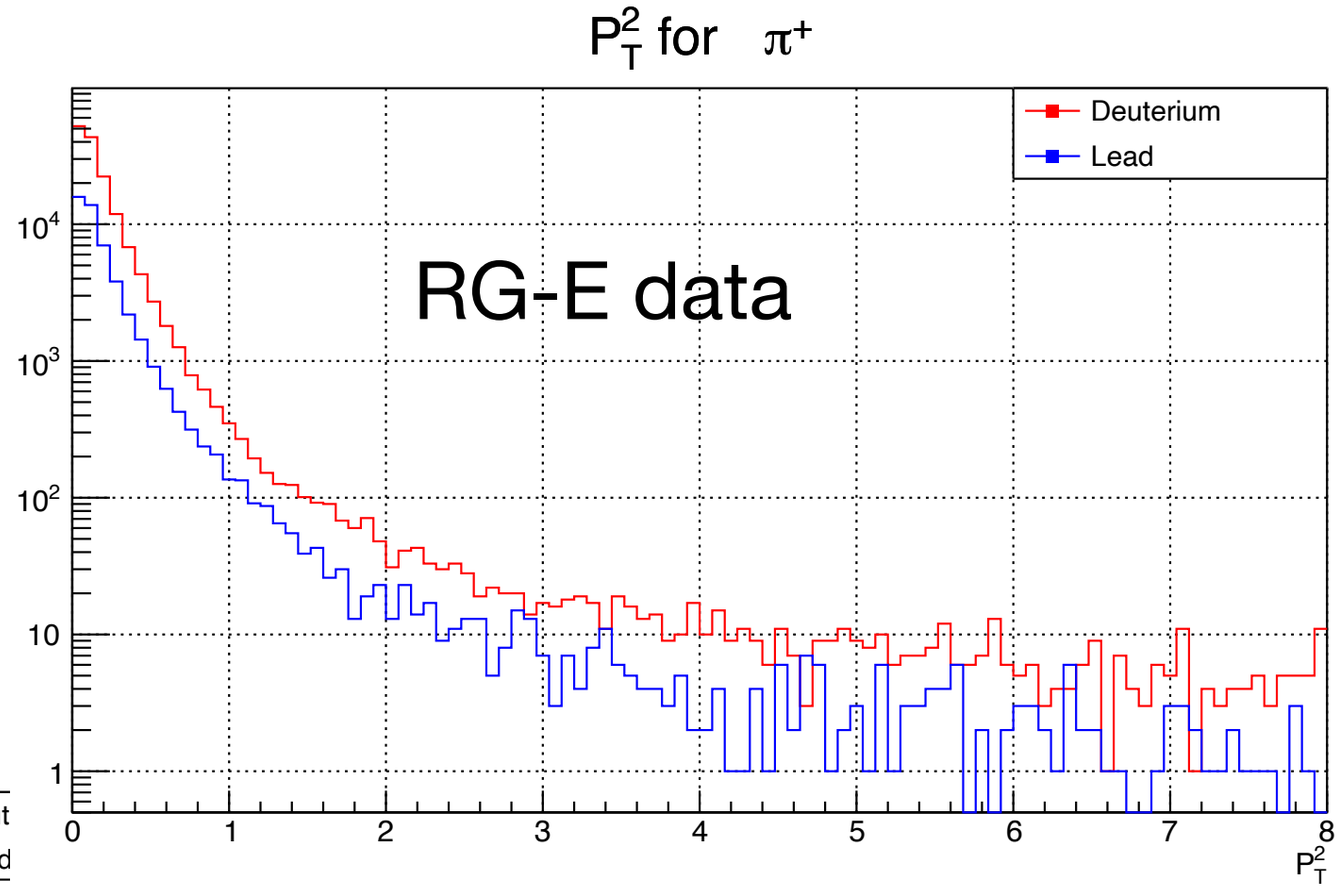


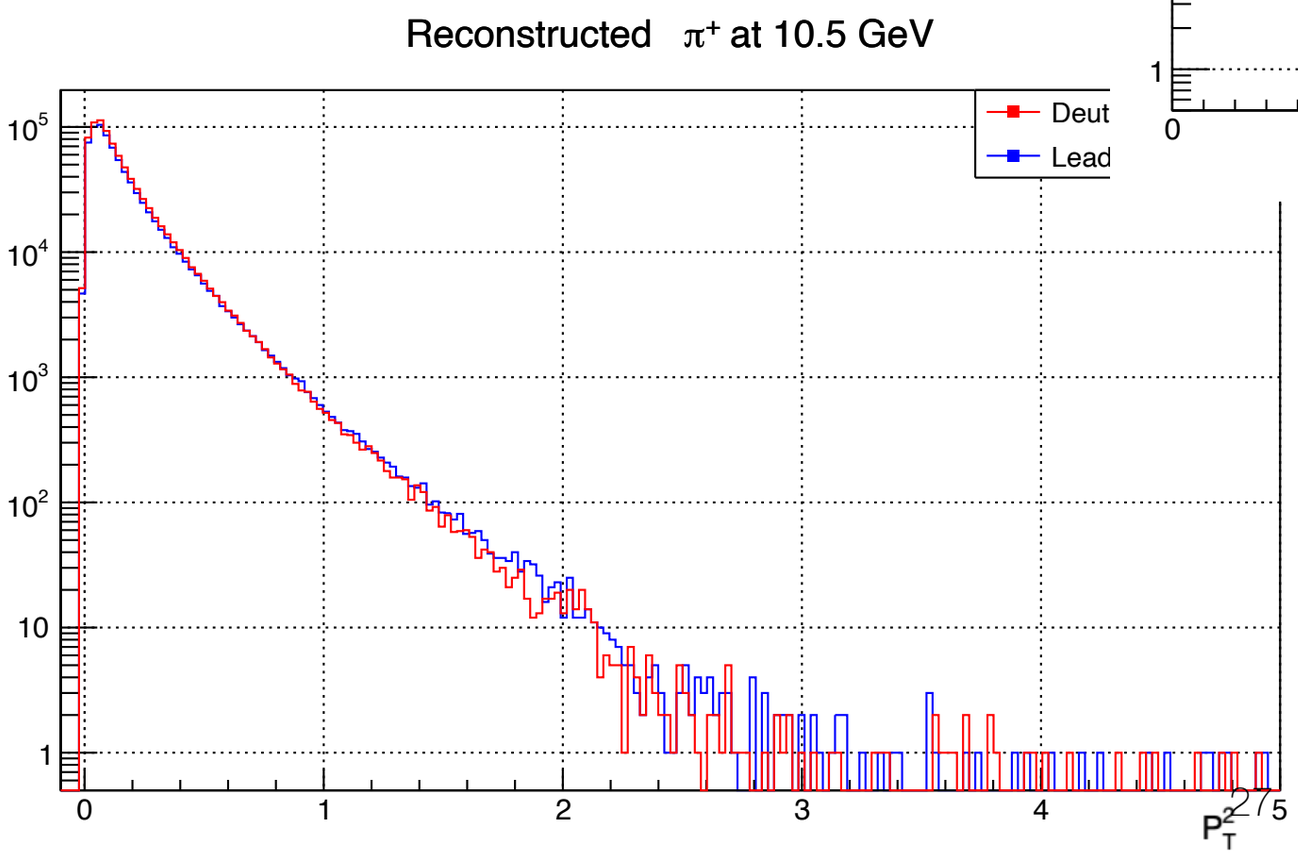




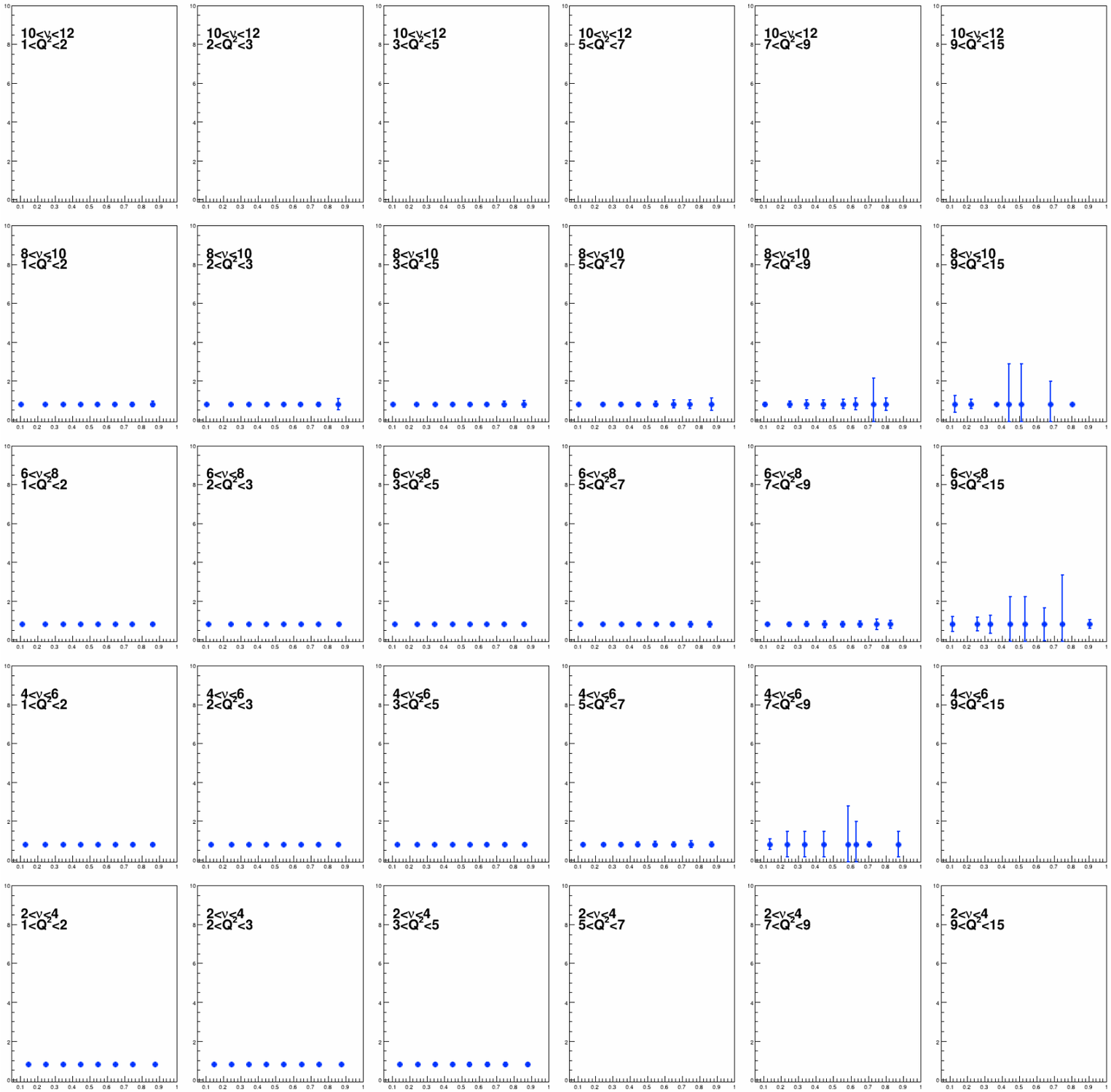


Nuclear effects: Fermi motion + nPDF



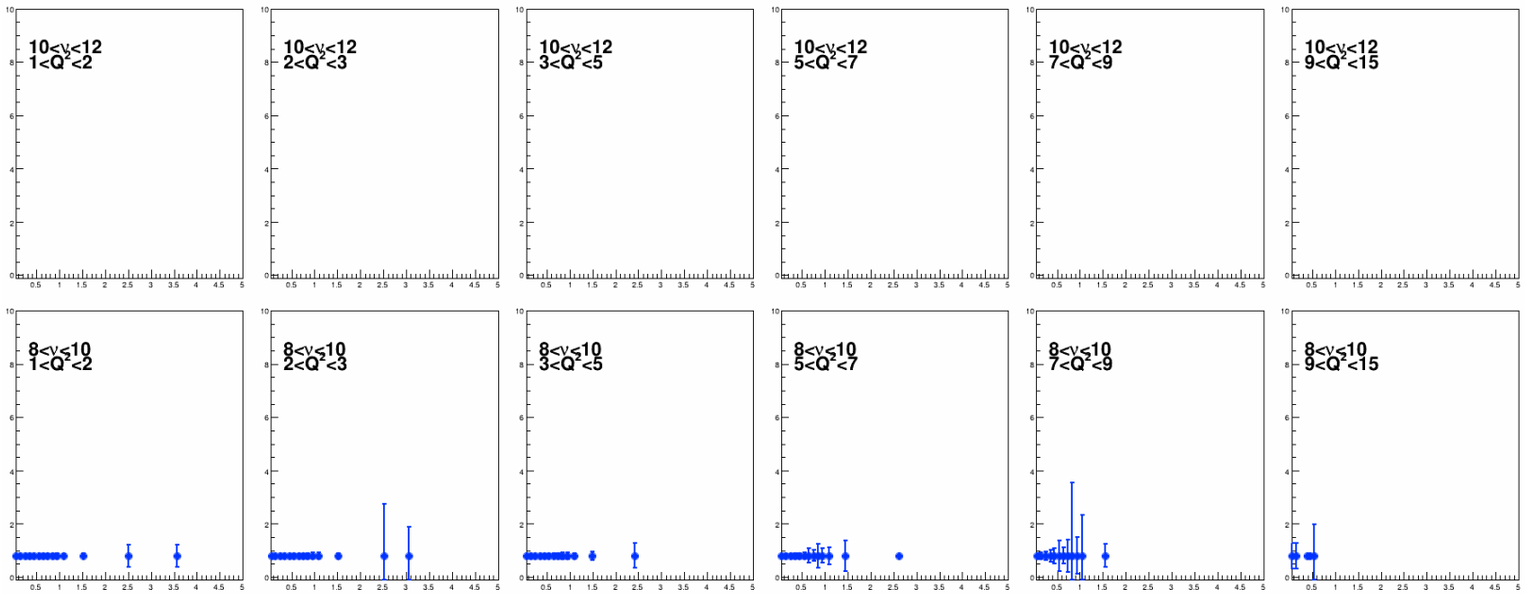


Projected multiplicity ratios: 10.5 GeV (Q2, nu, z)



Projected multiplicity ratios: 22 GeV (Q2, nu, z)

Projected multiplicity ratios: 10.5 GeV (nu, z, pT2)



Projected multiplicity ratios: 22 GeV (nu, z, pT2)

CLAS6

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	uūdd̄	5.7% (sys)
π^+, π^-	7.8 m	0.14	ud̄, dū	3.2% (sys)
η	170 pm	0.55	uūdd̄ss̄	6.2% (sys)
ω	23 fm	0.78	uūdd̄ss̄	6.7% (sys)
η'	0.98 pm	0.96	uūdd̄ss̄	8.5% (sys)
ϕ	44 fm	1	uūdd̄ss̄	5.0% (stat)*
f1	8 fm	1.3	uūddss̄	-
K^0	27 mm	0.5	ds̄	4.7% (sys)
K^+, K^-	3.7 m	0.49	us̄, ūs	4.4% (sys)
p	stable	0.94	uud	3.2% (sys)
$\bar{p}$	stable	0.94	ūūd̄	5.9% (stat)**
Λ	79 mm	1.1	uds	4.1% (sys)
$\Lambda(1520)$	13 fm	1.5	uds	8.8% (sys)
Σ^+	24 mm	1.2	uus	6.6% (sys)
Σ^-	44 mm	1.2	dds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	uss	16% (stat)*
Ξ^-	49 mm	1.3	dss	7.8% (stat)*

Published / in review from CLAS6

CLAS12

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	uūdd̄	5.7% (sys)
π^+, π^-	7.8 m	0.14	ud̄, dū	3.2% (sys)
η	170 pm	0.55	uūdd̄ss̄	6.2% (sys)
ω	23 fm	0.78	uūdd̄ss̄	6.7% (sys)
η'	0.98 pm	0.96	uūdd̄ss̄	8.5% (sys)
ϕ	44 fm	1	uūdd̄ss̄	5.0% (stat)*
f1	8 fm	1.3	uūdd̄ss̄	-
K^0	27 mm	0.5	ds̄	4.7% (sys)
K^+, K^-	3.7 m	0.49	us̄, ūs	4.4% (sys)
p	stable	0.94	uud	3.2% (sys)
$\bar{p}$	stable	0.94	ūūd̄	5.9% (stat)**
Λ	79 mm	1.1	uds	4.1% (sys)
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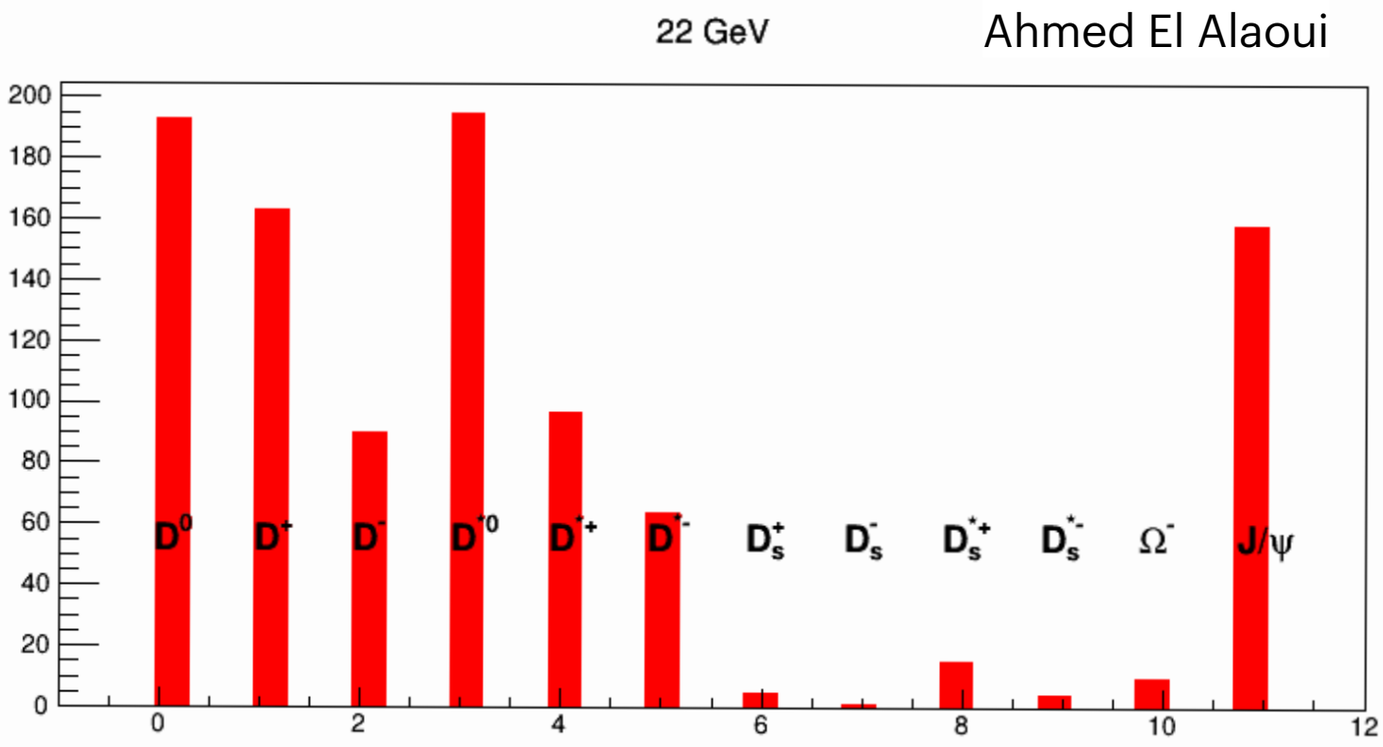
Σ^+	24 mm	1.2	uus	6.6% (sys)
Σ^-	44 mm	1.2	dds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	usc	16% (stat)*
Ξ^-	49 mm	1.3	dsc	7.8% (stat)*

Anticipated from CLAS12

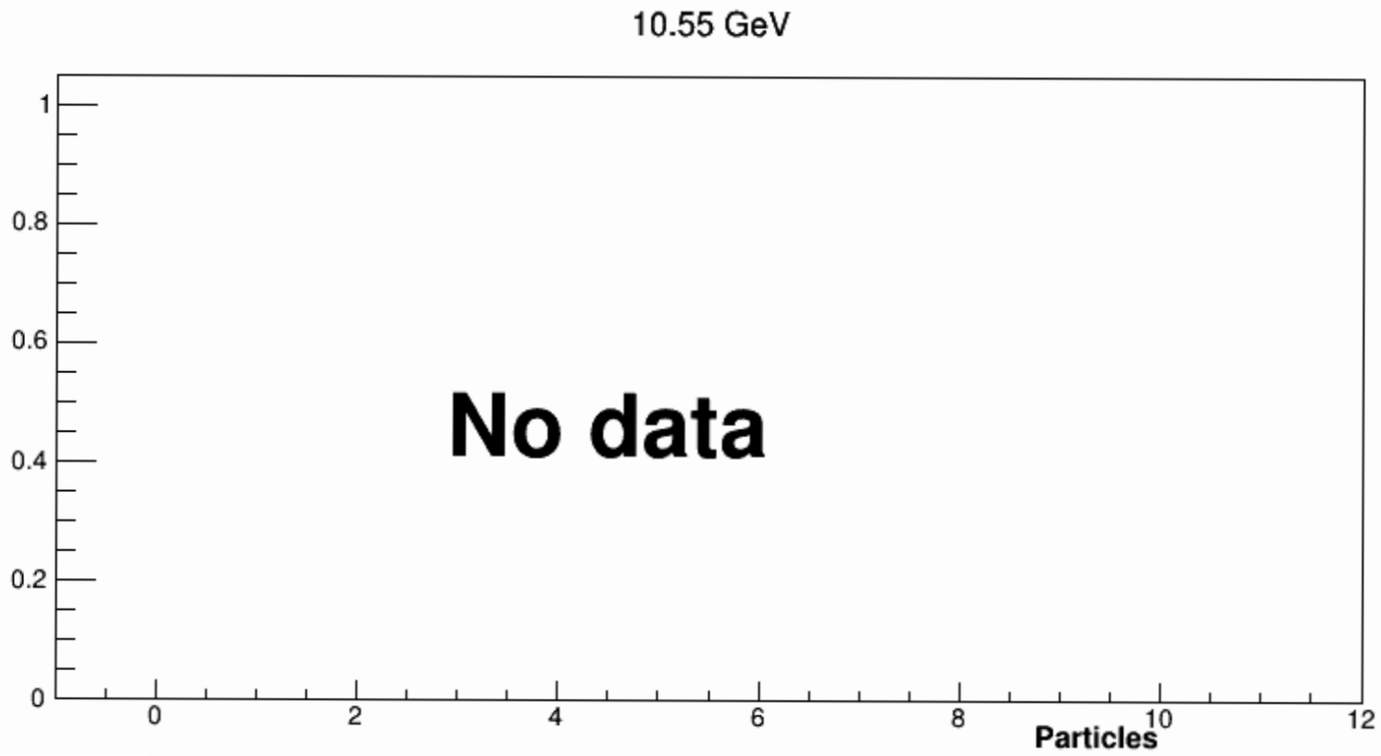
Can study rare and complex cases of hadrons probing mass, strangeness and rank dependence of hadron formation and color propagation

New baryon structure information to reveal diquark degrees of freedom for n, p and Λ

CLAS22

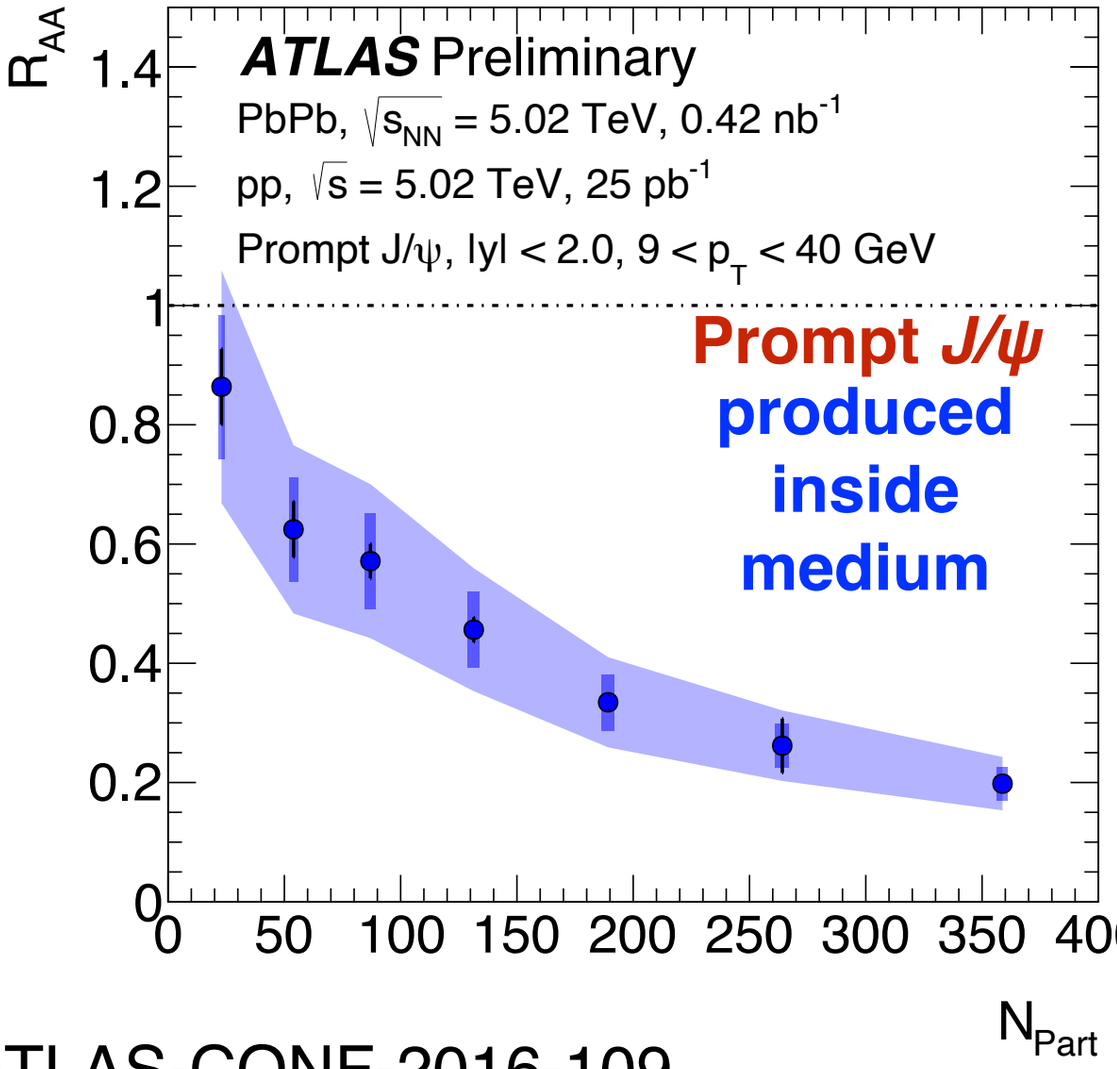


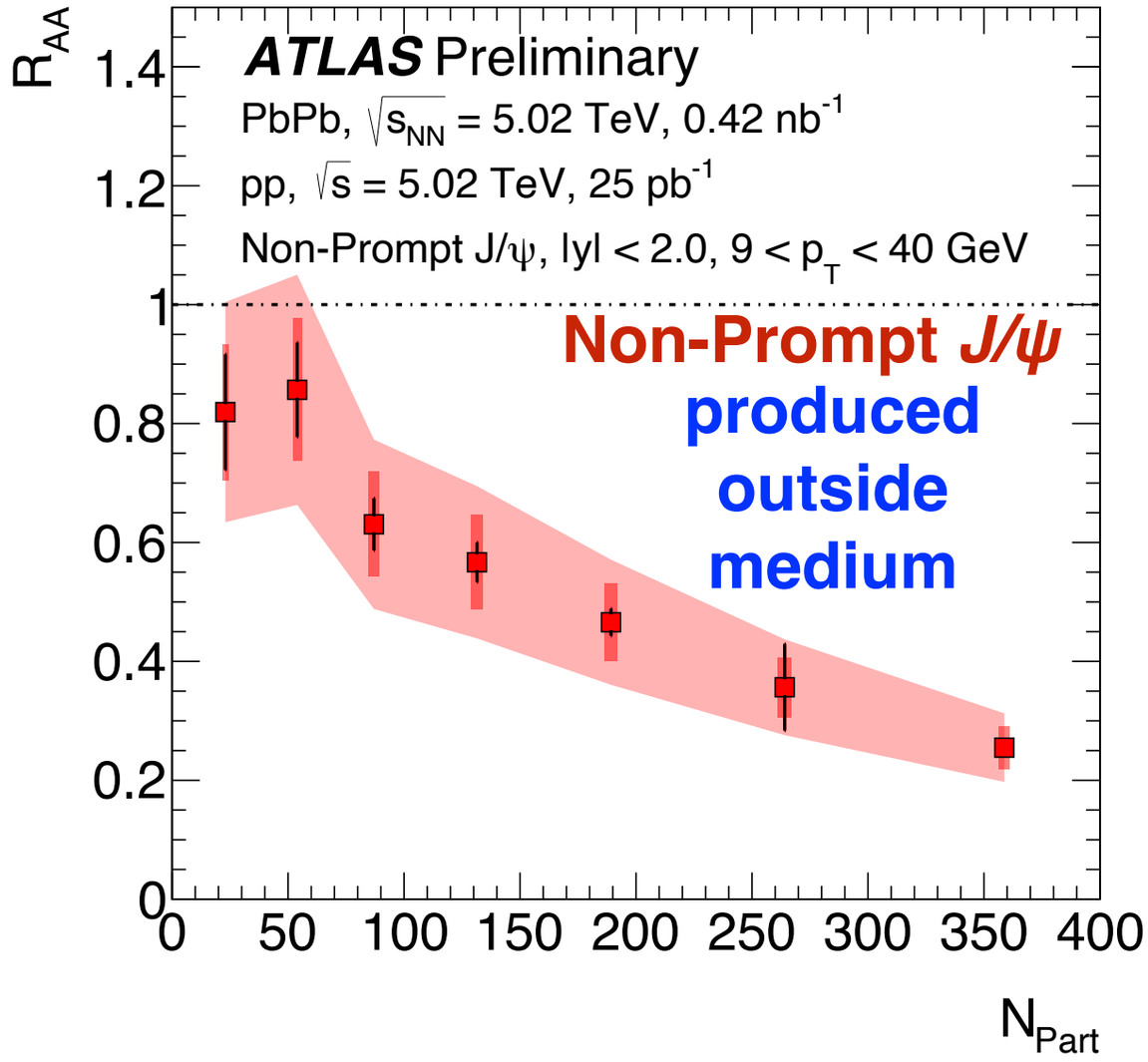
Ahmed El Alaoui



T.Mineeva

J/ψ nuclear modification factor R_{AA}

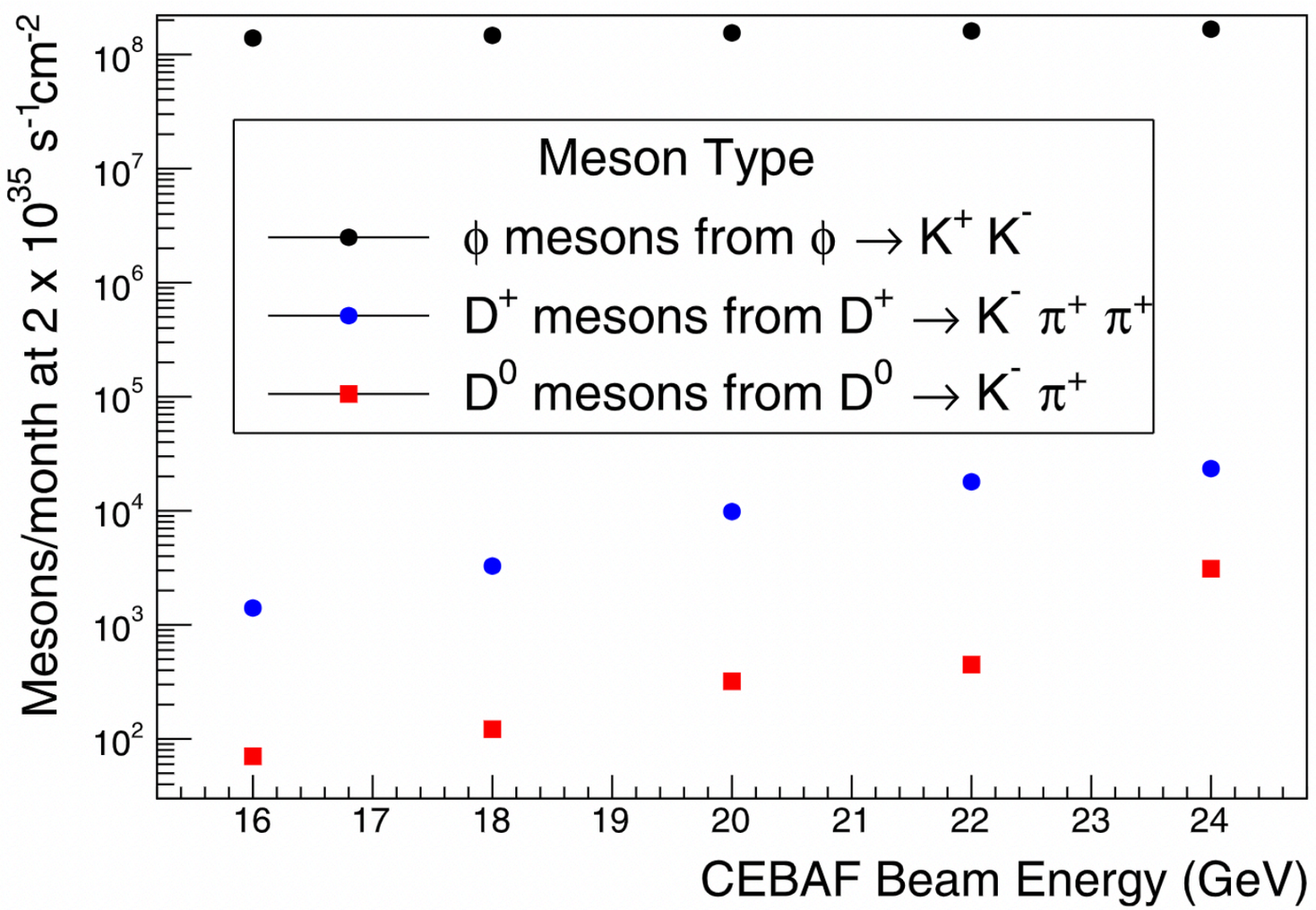




ATLAS-CONF-2016-109

- **R_{AA} strongly dependent on collision centrality.**
- **Suppression pattern and magnitude are very similar for both production mechanisms.**

Multidimensional hadronization analysis of **heavy flavor meson** production from nuclei at 24 GeV in CLAS



- Two and three dimensional analysis of phi meson hadronization! (1D at 12 GeV)
- One and two dimensional analysis of D mesons

J. Arrington, M. Battaglieri, A. Boehnlein et al.
Progress in Particle and Nuclear Physics 2022 (in press)

Potential measurements:
Λ polarization

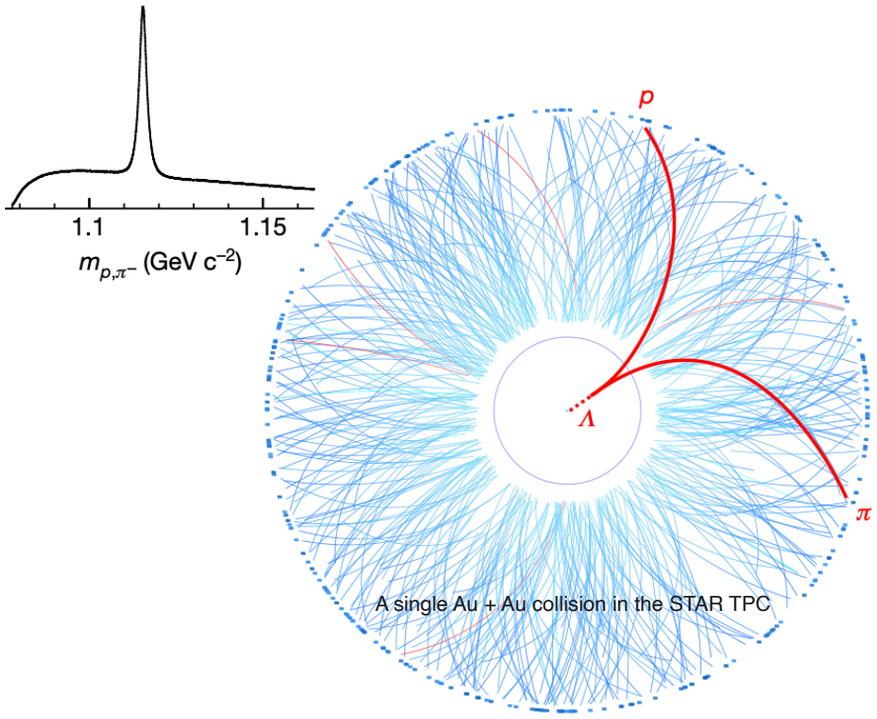
LETTER

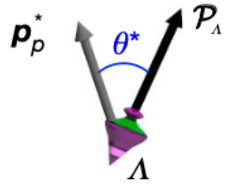
doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

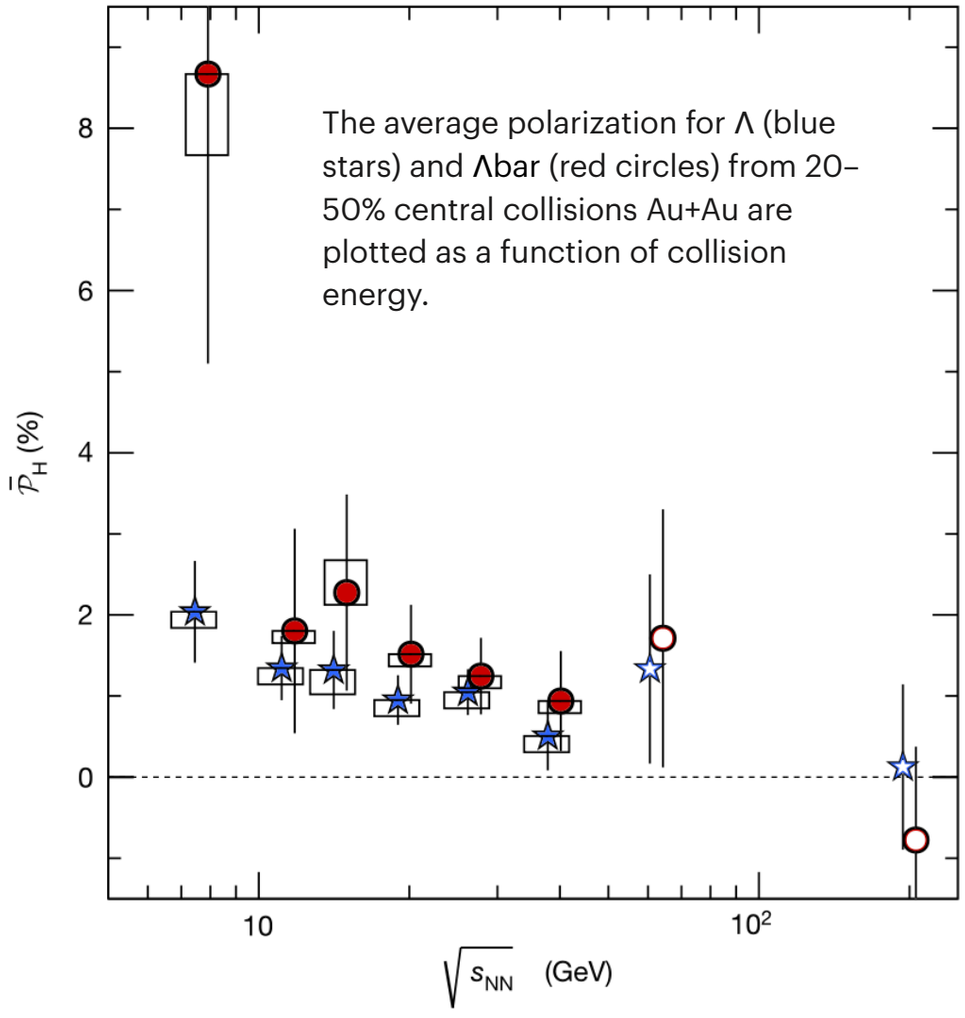
The STAR Collaboration*

3 August 2017 | VOL 548 | NATURE | 63





$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \alpha_H |\mathcal{P}_H| \cos\theta^*)$$



The average polarization for Λ (blue stars) and Λbar (red circles) from 20–50% central collisions Au+Au are plotted as a function of collision energy.

The proton tends to be emitted along the spin direction of the parent Λ

HI collisions are expected to produce intense magnetic fields; coupling between the field and the μ of the particle may induce larger polarization. Consistency check with hydrodynamic models!

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics B (Proc. Suppl.) 210–211 (2011) 111–114
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
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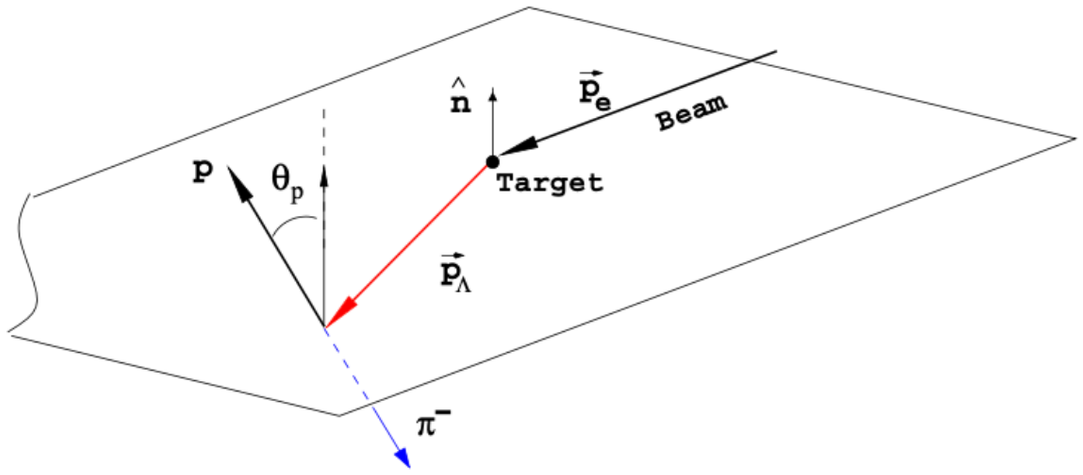
Lambda polarization at HERMES

S. Belostotski[a], Yu. Naryshkin[a] * and D. Veretennikov[a]
(on behalf of the HERMES collaboration)

$$\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p}(1 + \alpha P_n^{\Lambda} \cdot cos\theta_p)$$



θ_p is the angle between the proton momentum and the Λ-polarization direction in the Λ rest frame, i.e the angle between decay proton with respect to the normal n^ to the scattering plane

P_n^ is the transverse polarization of the Λ

α = 0.642 ± 0.013 is the analyzing power of the parity-violating weak decay.

HERMES (2011): https://www.sciencedirect.com/science/article/pii/S0920563210004925

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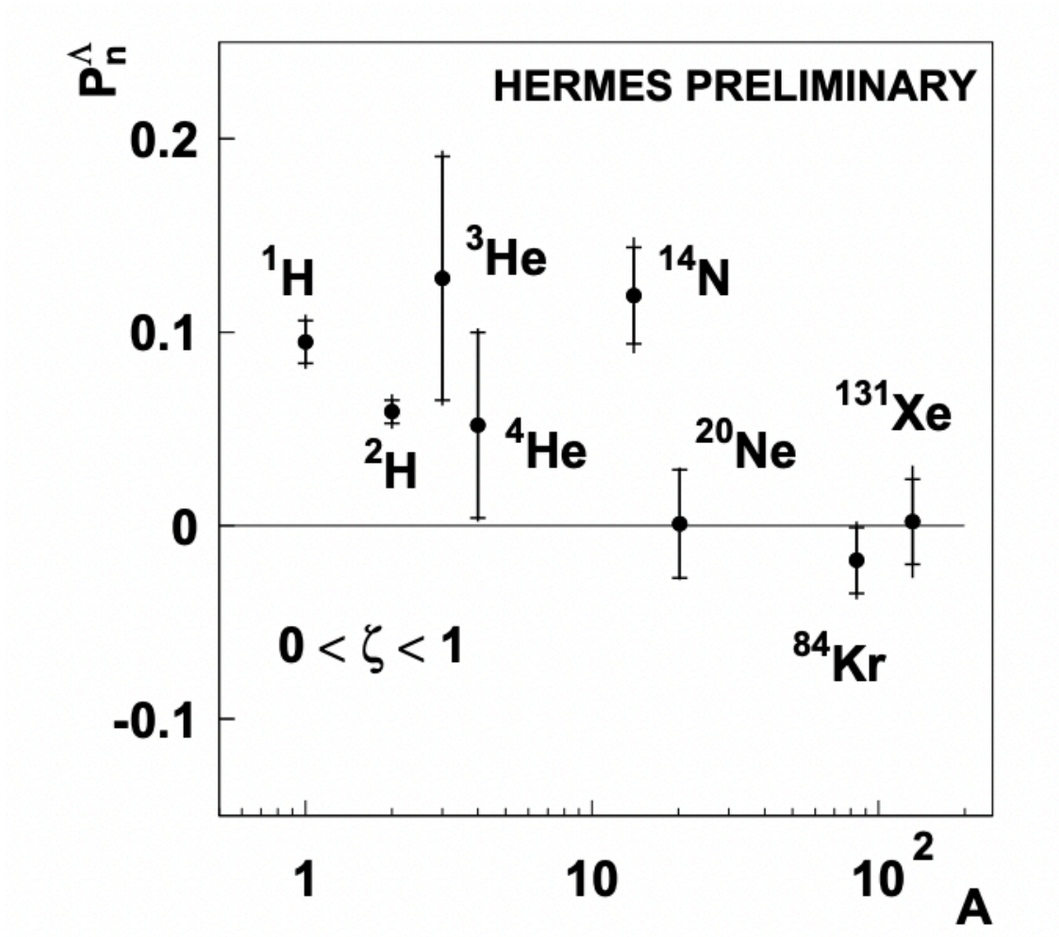
Transverse Λ polarization vs A



HERMES: 27.6 GeV longitudinally polarized positron beam on 2H, 3He, 4He, N, Ne, Kr and Xe

Averaged over the experimental kinematics, the net transverse Λ polarization is:

$P_n^\Lambda = 0.078 \pm 0.006(\text{stat}) \pm 0.012(\text{syst})$

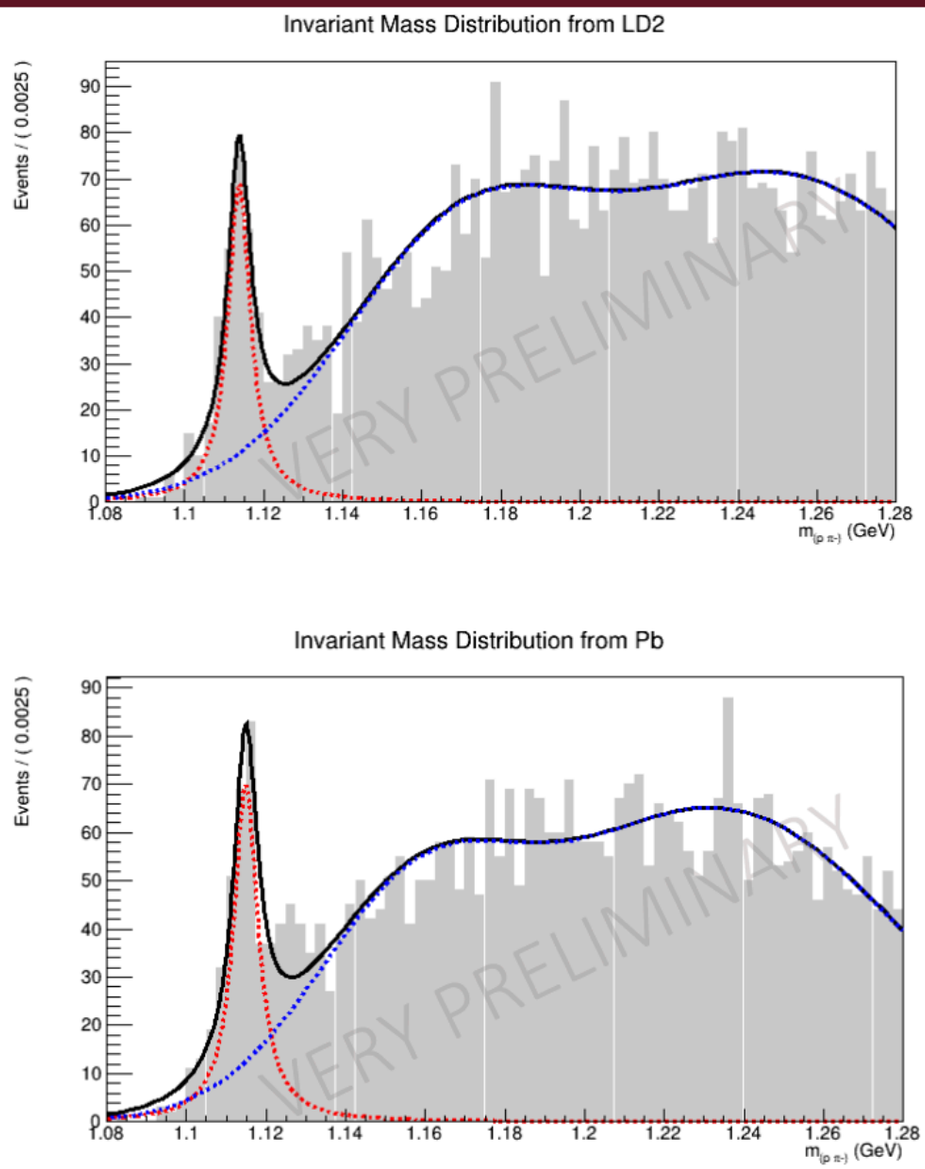
$P_n^{\bar{\Lambda}} = -0.025 \pm 0.015(\text{stat}) \pm 0.018(\text{syst})$

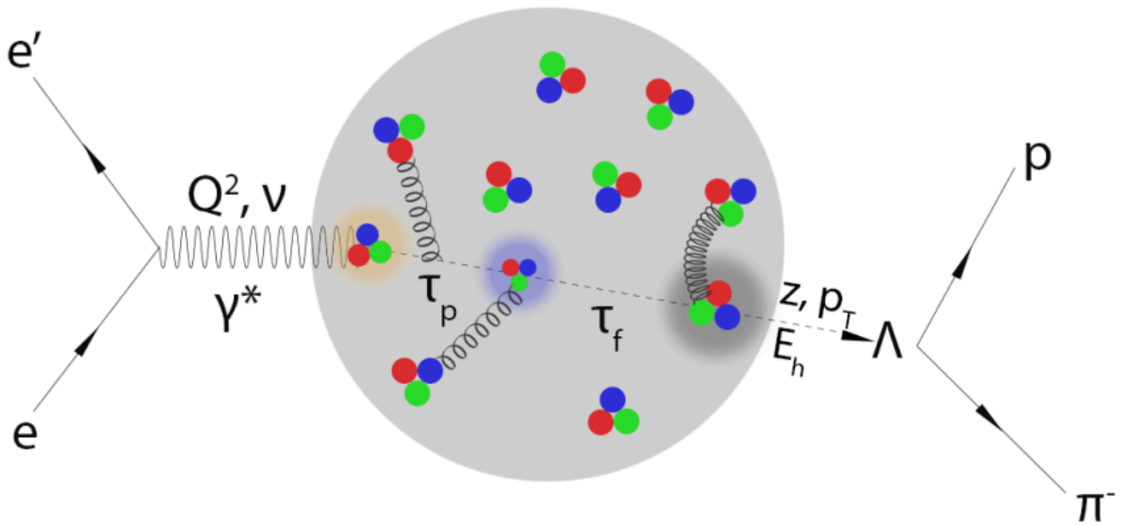
HERMES (2011): https://www.sciencedirect.com/science/article/pii/S0920563210004925

Lambda from CLAS 12

Lambda Production Channel

- Our channel of interest is Lambda SIDIS production off nuclei
- Lambda is identified through its decay daughter particles, proton and π-, detected in coincidence with the scattered electron
- Cuts applied on secondary vertex to refine the Lambda signal
  - Distance between the electron and secondary Lambda vertex
  - Opening angle between protons and π⁻s

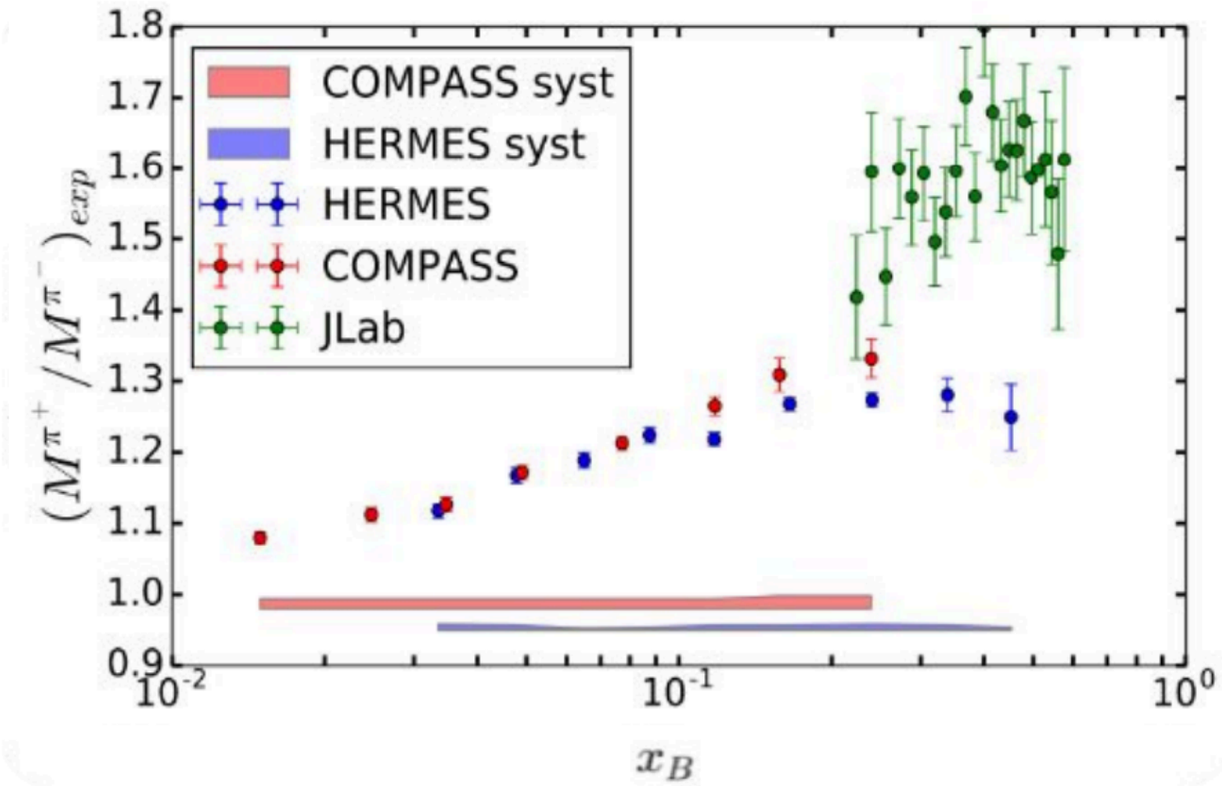




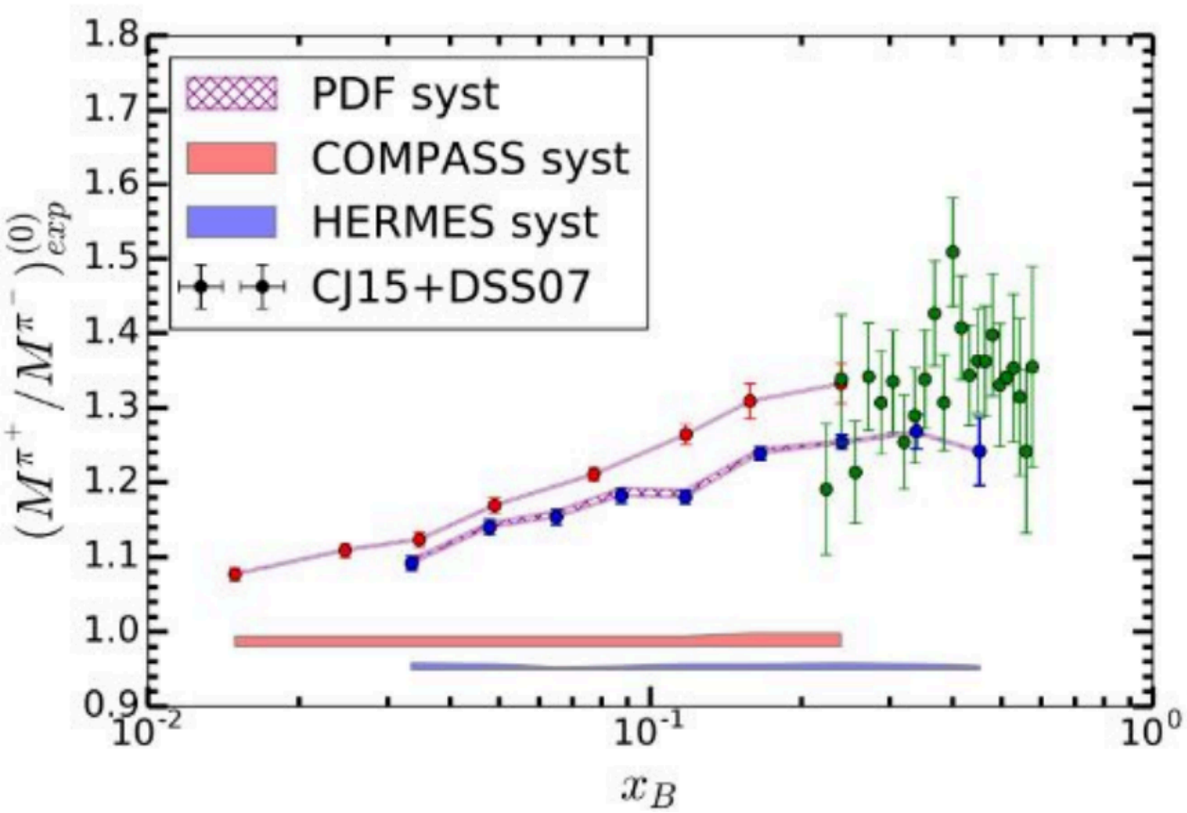
Potential measurements:
Hadron Mass Correction

Pions (integrated over z, Q^2)

Experimental data



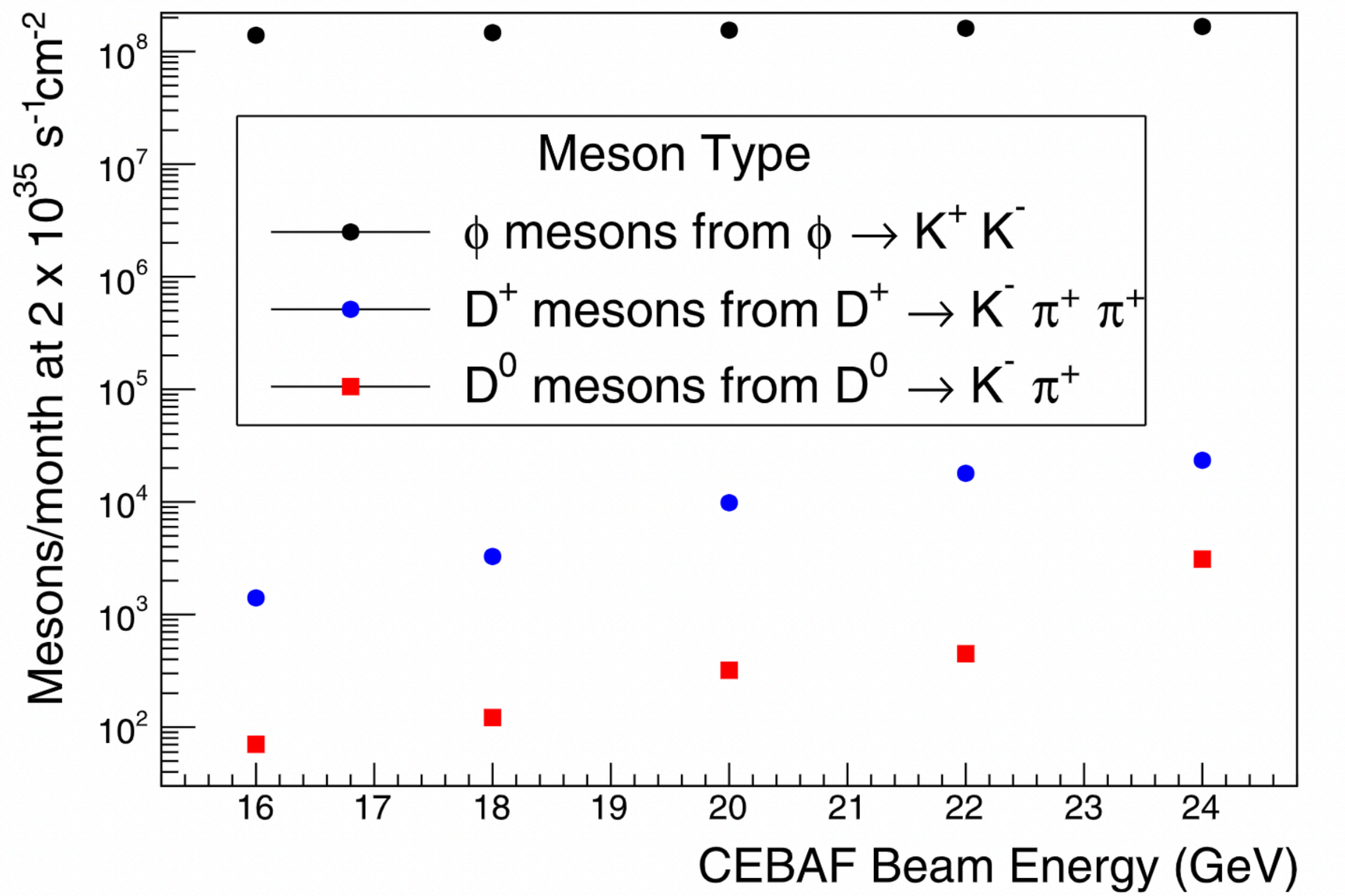
HMCs removed



From Alberto Accardi talk

https://arxiv.org/pdf/1711.04346

Multidimensional hadronization analysis of **heavy flavor meson** production from nuclei at 24 GeV in CLAS



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Summary

- Transverse momentum broadening and hadronic multiplicity ratio observables provide insights on the lifetime of ‘free’ quark and time scale for the formation of hadrons

- CLAS at 6 GeV high luminosity data on ^{2}H, ^{12}C, ^{56}Fe, ^{207}Pb:
  - Published results on: 3D π^+ / π^- and π^0 multiplicities;
    Λ multiplicity ratios and $\Delta pT2$; di-hadron production
  - In process: p multiplicities, $\Delta pT2$ for π^+ (E.Molina), $\Delta pT2$ for double pion production, π^+ azimuthal dependencies, Bose-Einstein correlations

- Successful realization of CLAS12 experiment (E12-06-117) at 11 GeV. Access to 4D multiplicities and large spectrum of hadrons

- JLab @ 22 GeV: larger kinematical coverage, access to rare mesons and baryons, 4D MR