Analysis Updates on the Λ Hadronization Studies (EG2 Dataset)

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Contents

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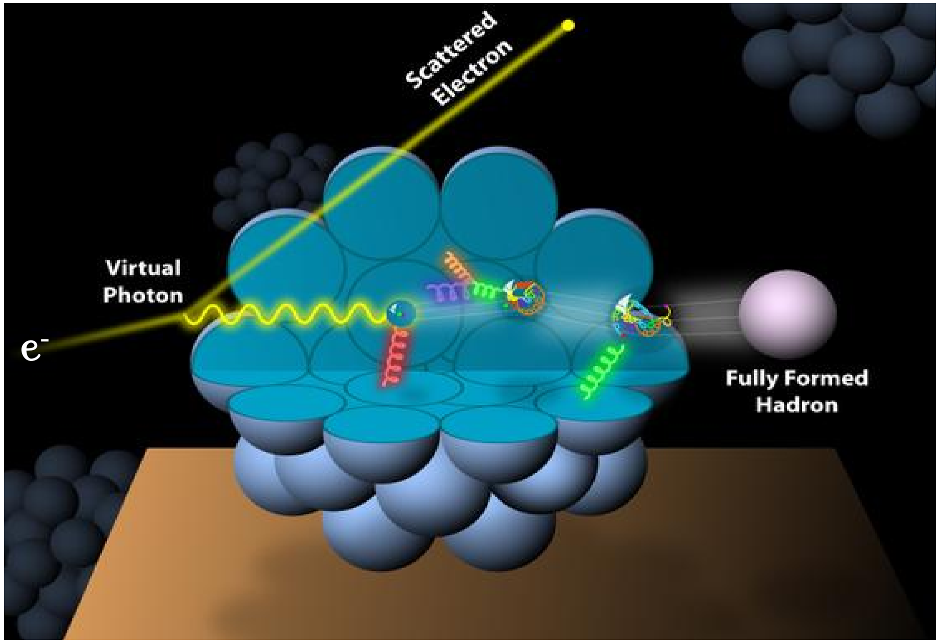
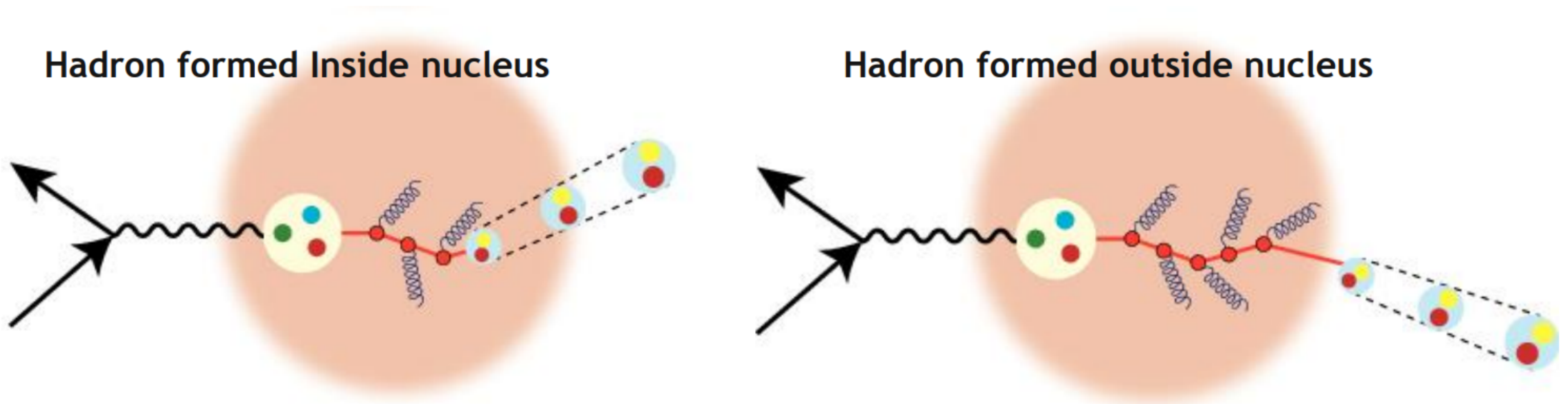
Jefferson Lab
11/14/2019

Probing QCD Dynamics

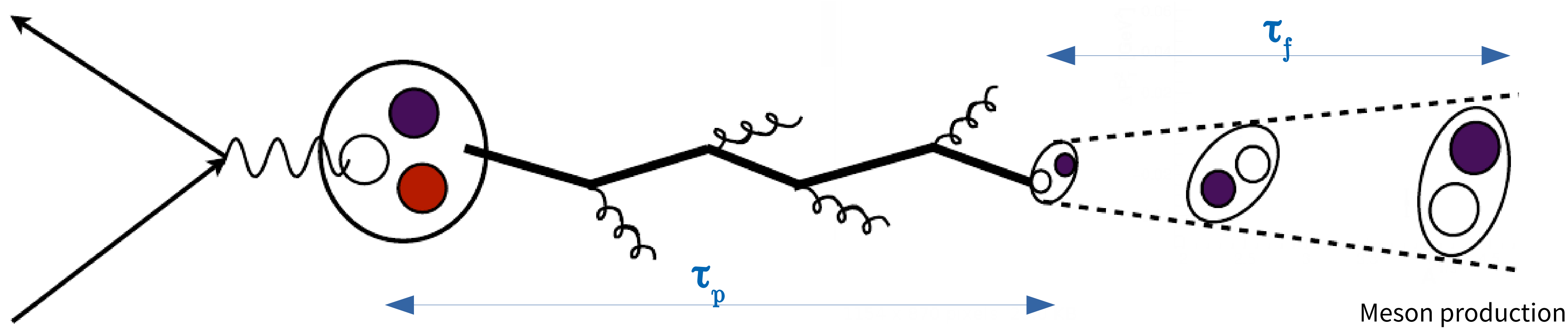
- **Hadronization process:**
  - Evolution of a colored bare quark into a fully dressed hadron.
  - A direct probe of the QCD confinement dynamics: quark propagation and fragmentation.





Depending on the size of nucleus and the energy of the probe, hadron formation can take place inside or outside the nucleus.

- Hadronization Timescales:
  - Production time, τ_p: Time spent by a deconfined quark to neutralize its color charge.
  - Formation time, τ_f: Time required to form a regular hadron.



- Hadronization studies:
  - Provide information on the dynamical scales of the process.
  - Constrain existing models that provide predictions of its time-characteristics.

Experimental Observables

- **Multiplicity ratio:**

$$R_{\mathrm{A}}^{h}\left(\nu, Q^2, z, p_T, \phi\right) = \frac{\left.\frac{N_h(\nu,Q^2,z,p_T,\phi)}{N_e(\nu,Q^2)|_{\mathrm{DIS}}}\right|_{\mathrm{A}}}{\left.\frac{N_h(\nu,Q^2,z,p_T,\phi)}{N_e(\nu,Q^2)|_{\mathrm{DIS}}}\right|_{\mathrm{D}}}$$

  - Normalization with the electron DIS events that permits cancellation of the initial state effects.

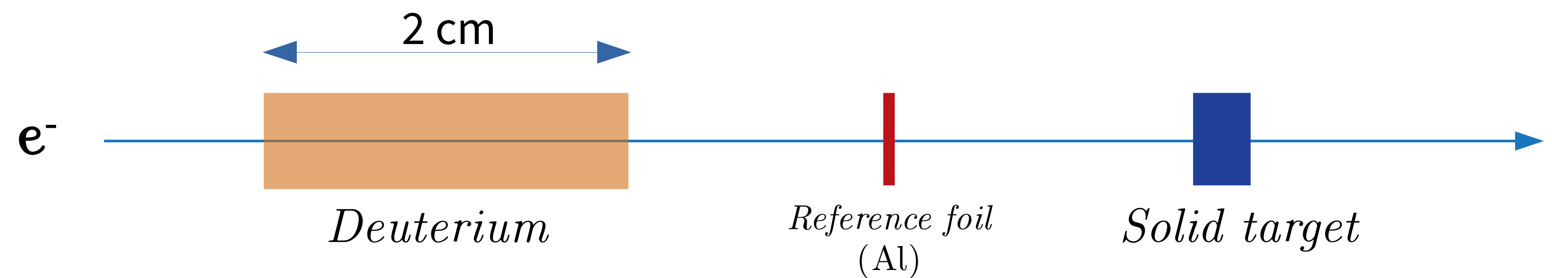
- **Transverse momentum broadening:**

D = loosely bound nuclei
A = Heavy Nuclei

$$\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$$

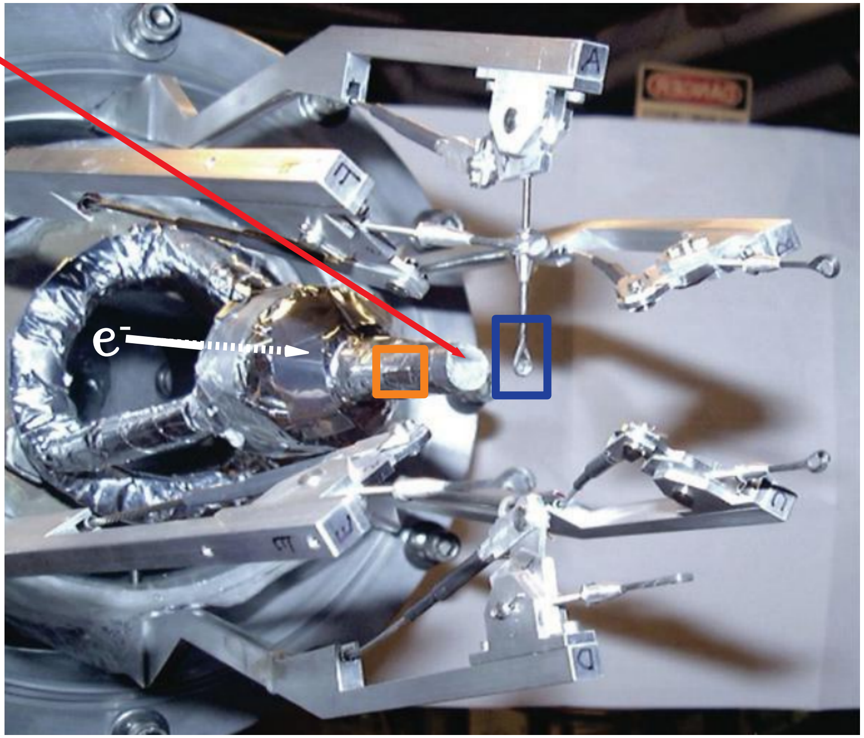
- **These observables provide insights about**
  - The hadronization timescales, i.e., production and formation times.
  - Parton energy loss (related to the p_T broadening).
  - Hadron attenuation (related to R_A^h).

- Targets: Deuterium, Carbon, Iron, Lead, Tin, Aluminum.
- Deuterium and solid target in beam simultaneously for reduced run-time systematics:



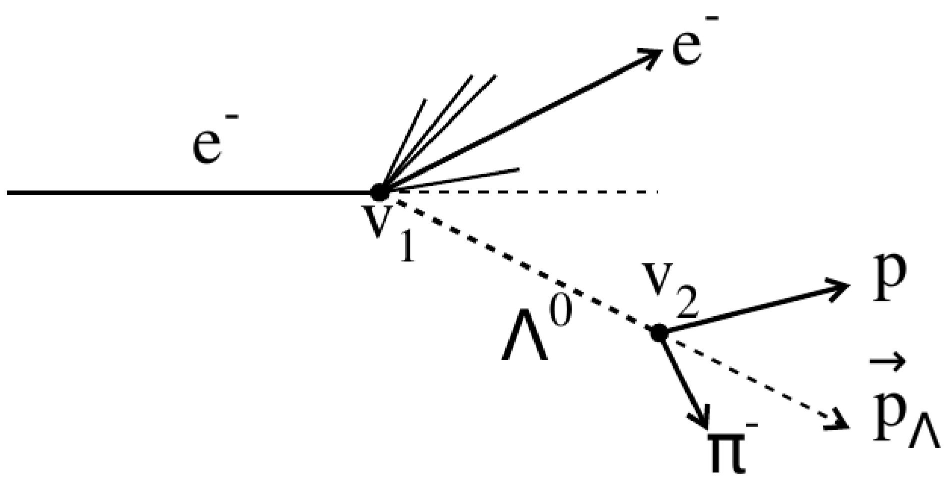
- Luminosity ~ 10^{34} s^{-1} cm^{-2}
- Beam energy: 5 GeV
- Target separation ~ 4 cm
- Solid Targets:

Targets	Fe	C	Al	Al	Pb	Sn
Radius (mm)	1.5	1.5	1.5	1.5	1.5	1.5
Thickness (mm)	0.4	1.72	0.58	1.5 E-03	0.14	0.3



Reaction Channel

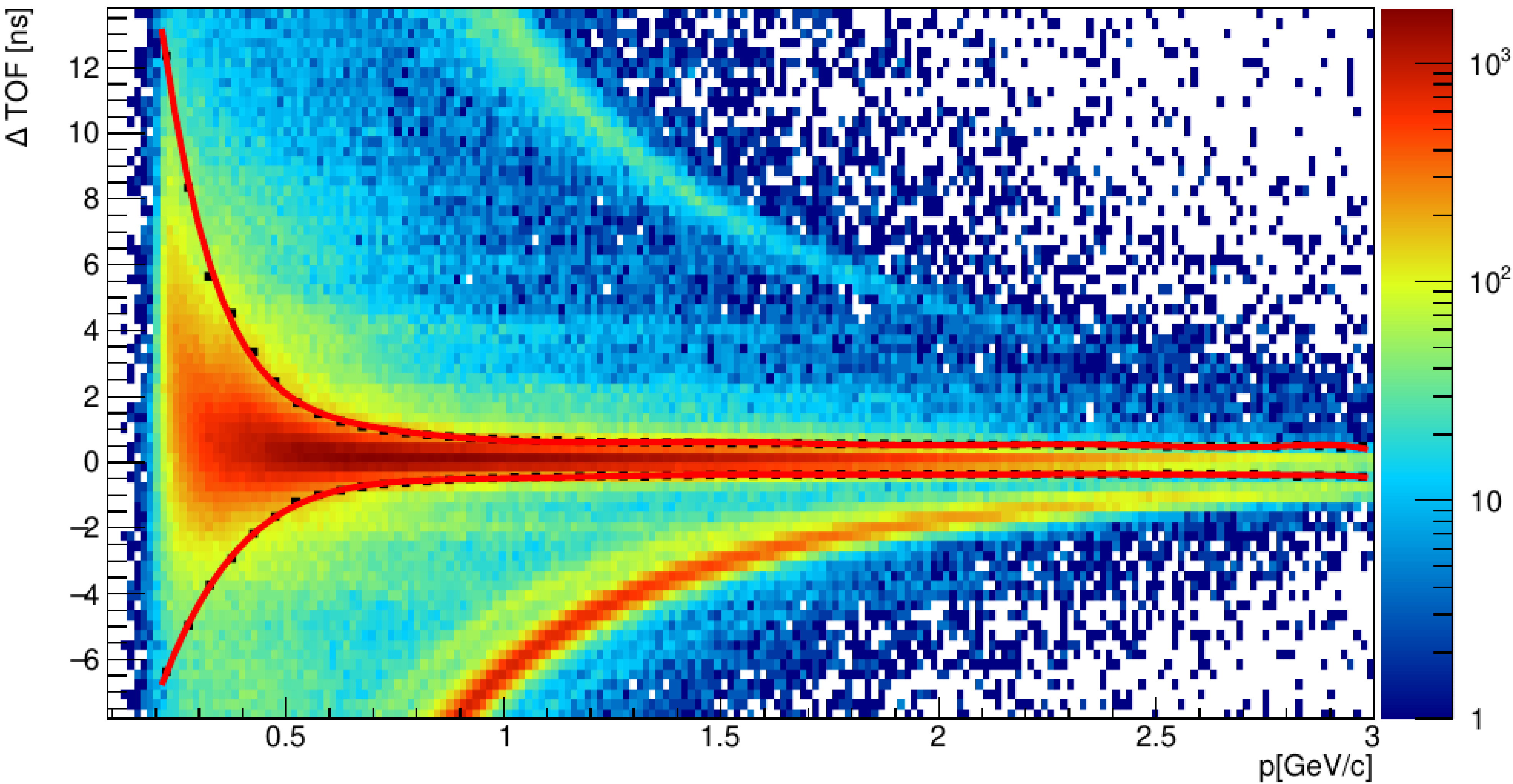
- **SIDIS**
  - $e + A \rightarrow e' + \Lambda$
  - Scattered electron and Lambda decay products detected.
- **$\Lambda \rightarrow \pi^- + p$**
  - ~64% branching ratio



- **e^- and π^- identification:**
  - Method:
    L. El Fassi (CLAS Collaboration),
    Physics Letters B 712 (2012) 326–330.
  - **e^-** : Positive response in the four CLAS subsystems, i.e. DC, CC, SC and EC.
  - **π^-** : Matching signal in drift chambers (DC) and scintillator counters (SC) to correlate the negatively charged particle's momentum and velocity and select the pion sample.

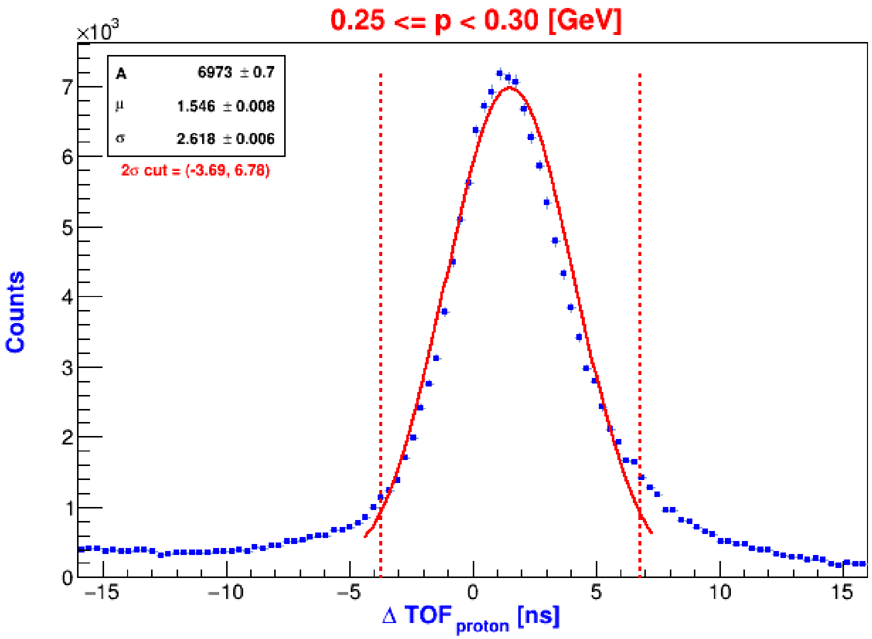
Proton Identification

- Matching signal in DC and SC.
- Timing versus momentum dependent study to select proton candidates – (Previously, a 9th order function was used to select proton events).



Proton Identification

- Matching signal in DC and SC.
- For different momentum slices, ΔTOF distributions are fit using a Gaussian function.



- Check out the animation here!

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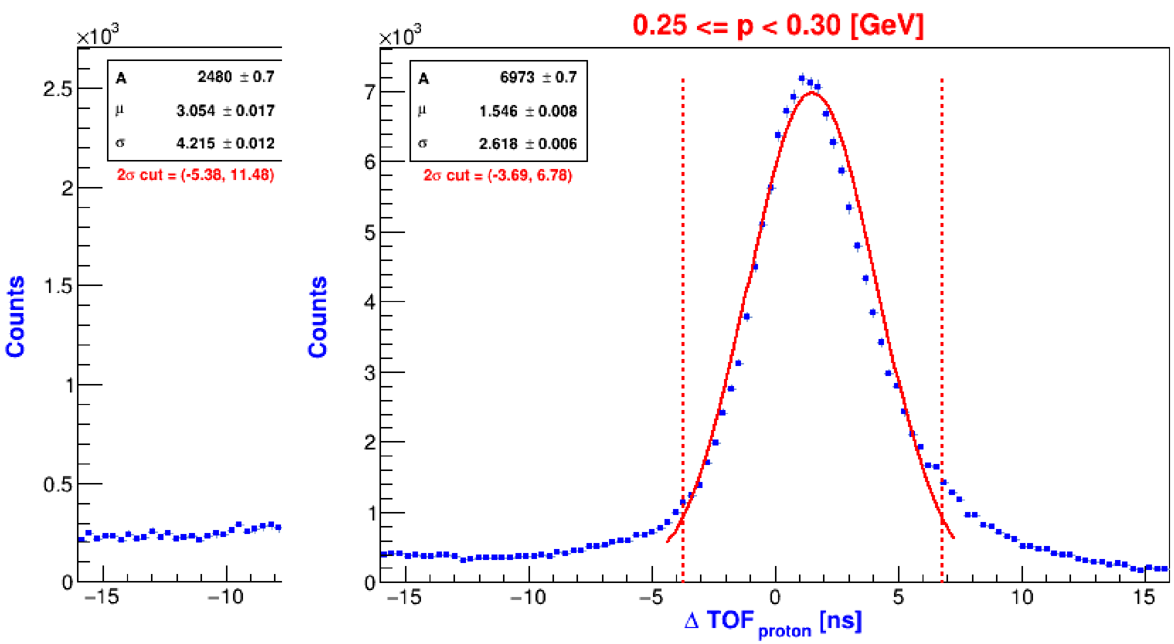

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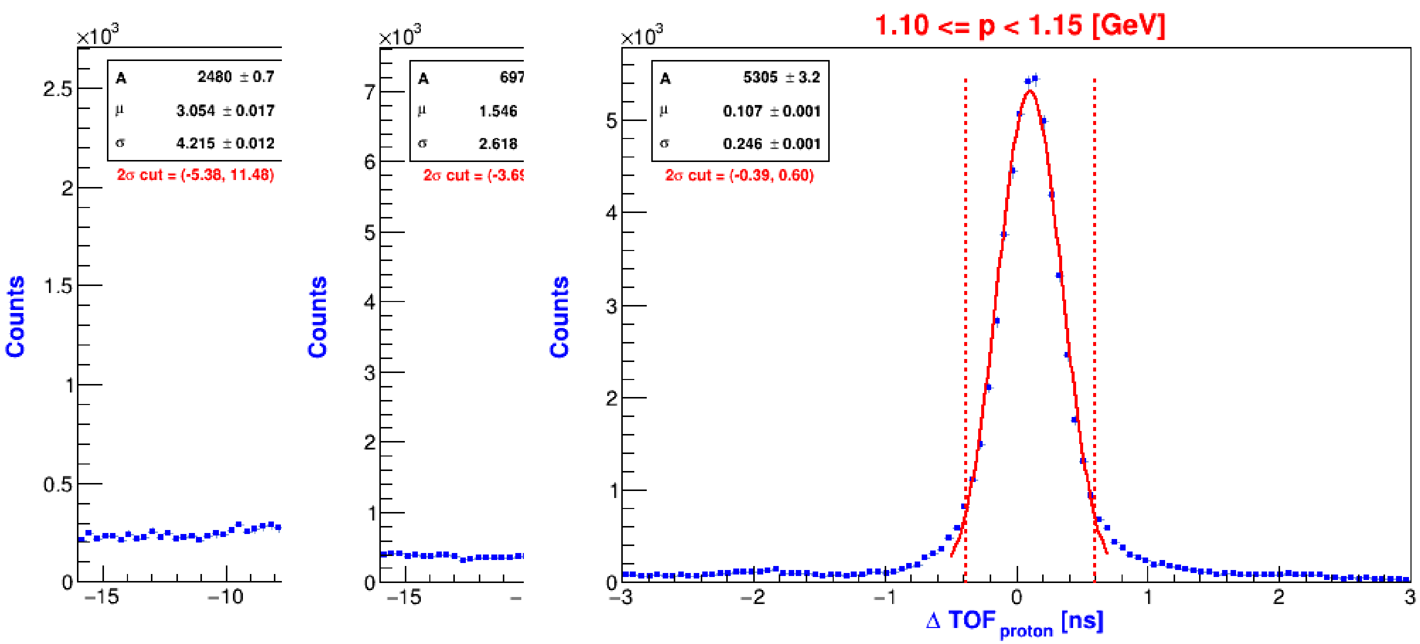
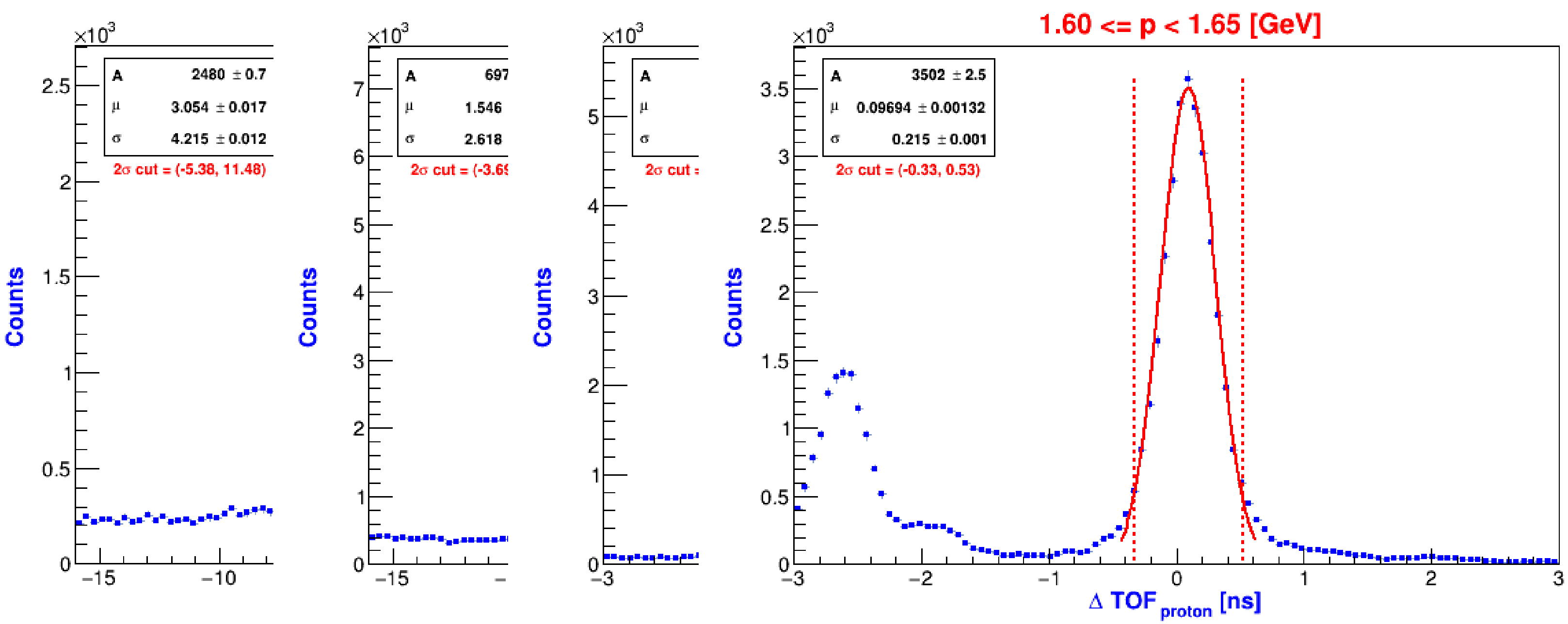


- Check out the animation here!

Proton Identification

- For different momentum slices, ΔTOF distributions are fit using a Gaussian function.
- At higher momenta, positive pions start to populate.



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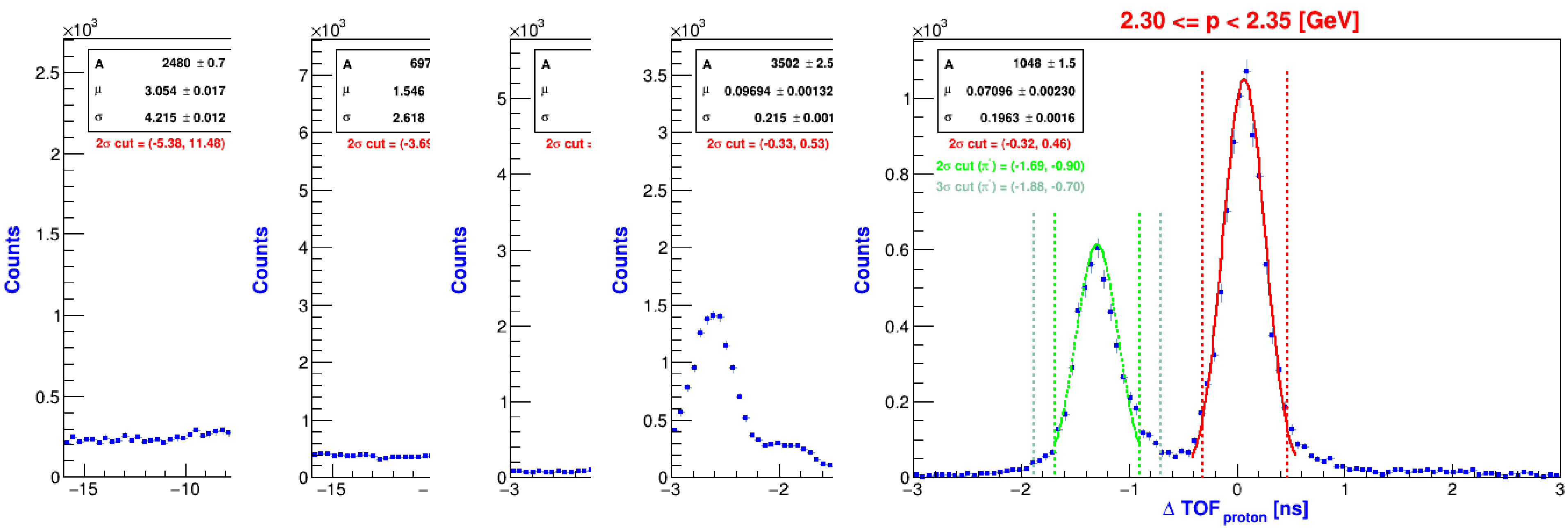
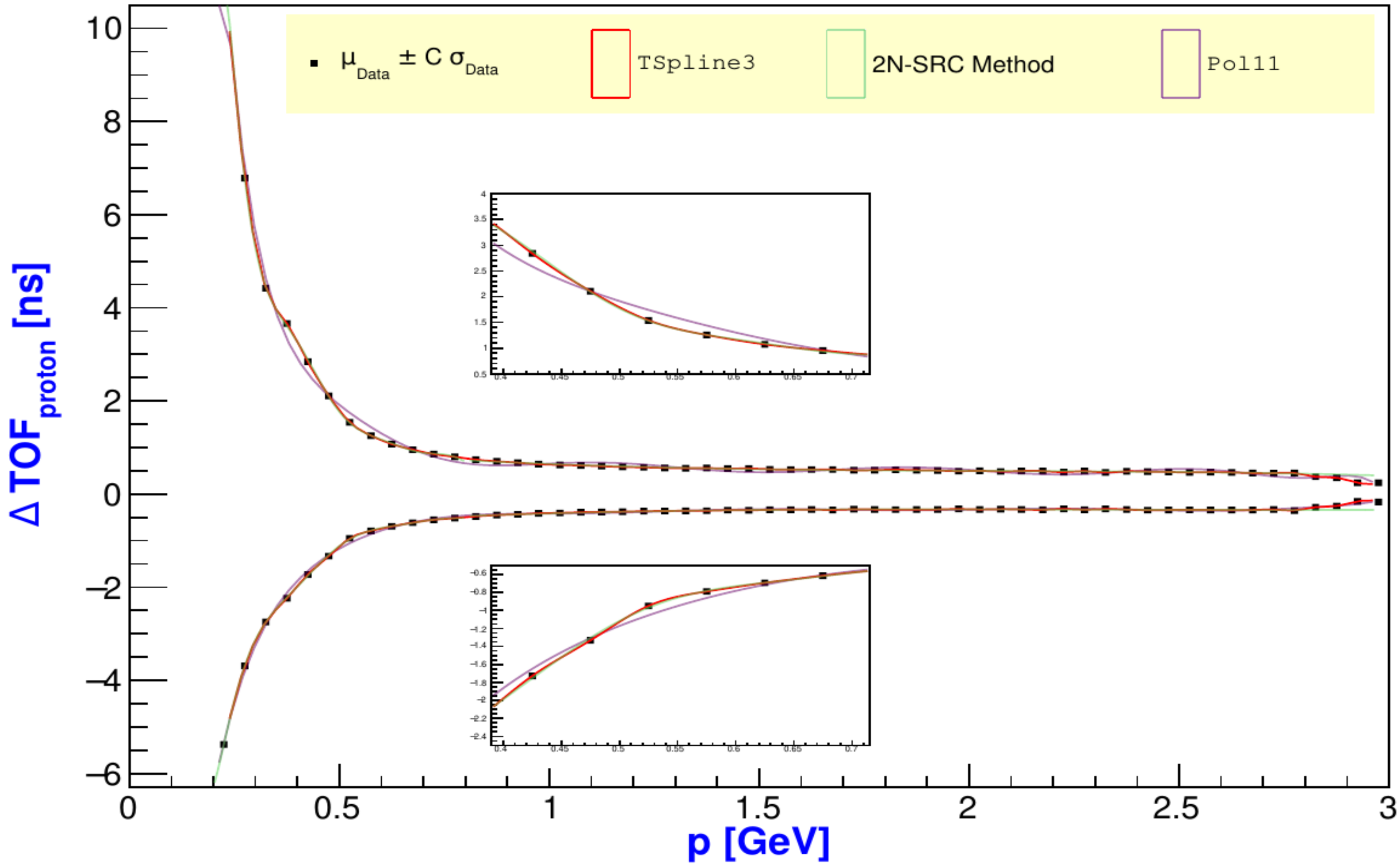


- Check out the animation [here](#)!

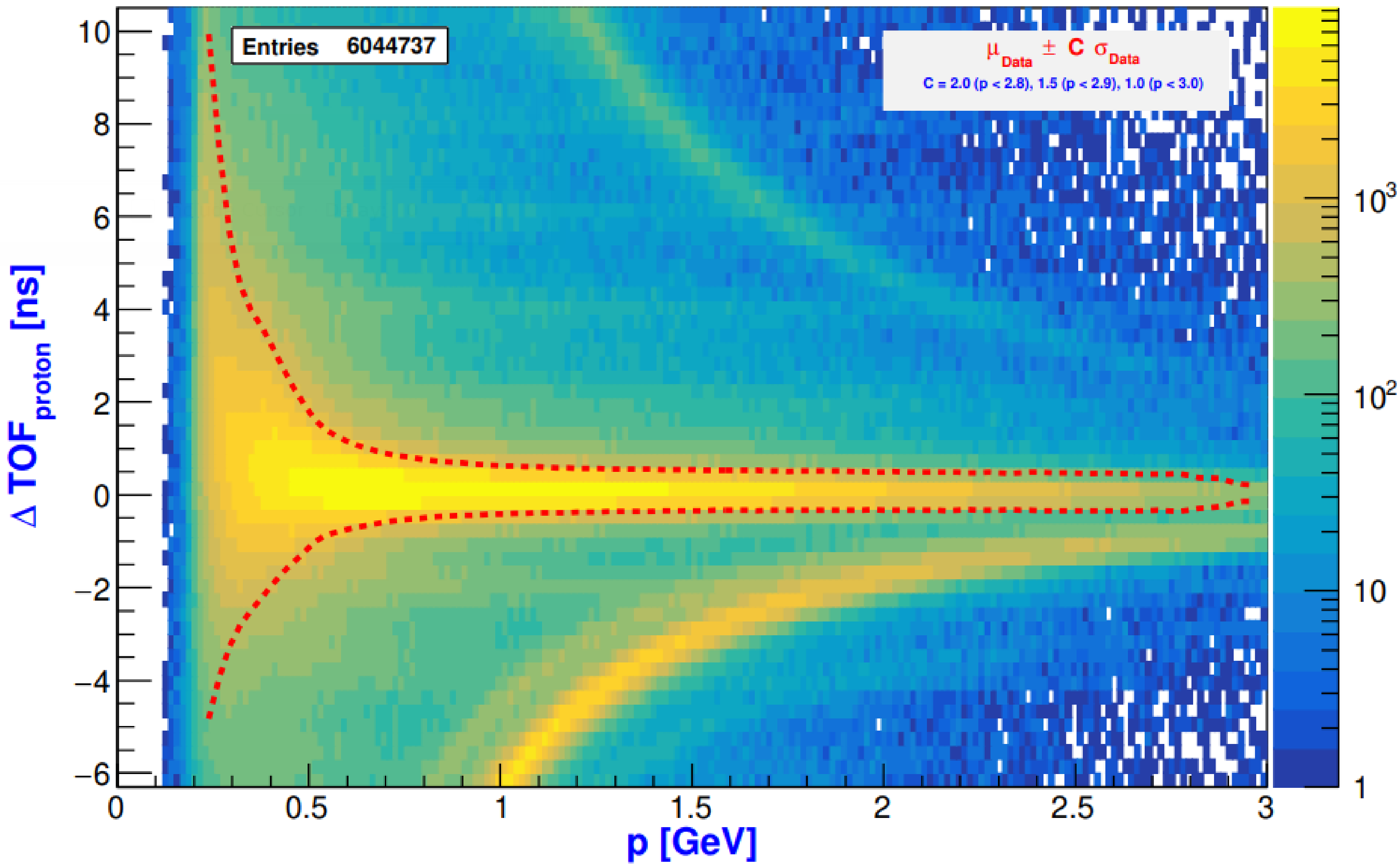
Proton Identification: Compared other methods

- The Gaussian mean and sigma are plotted.
- ROOT TSpline3 function is employed.
- Other methods are shown as comparison.

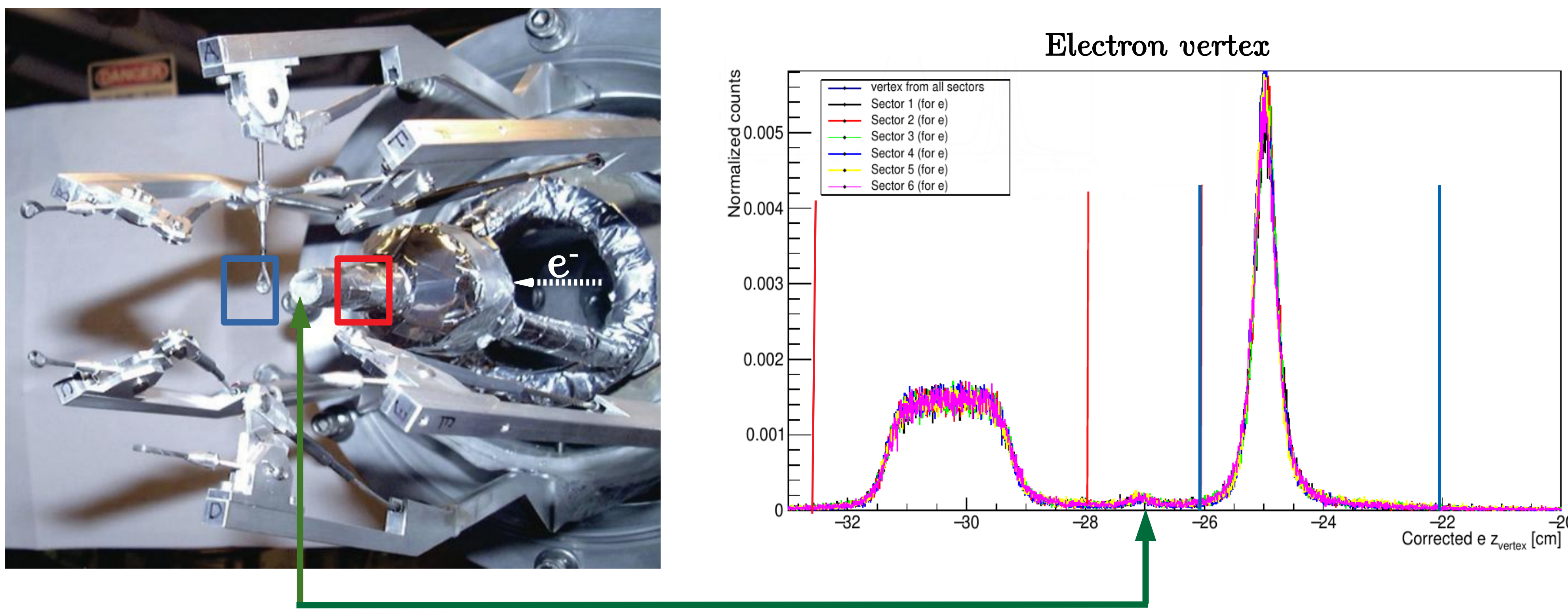


Proton Identification

- Matching signal in DC and SC.
- Timing versus momentum dependent study to select proton candidates using ROOT's spline interpolation function.



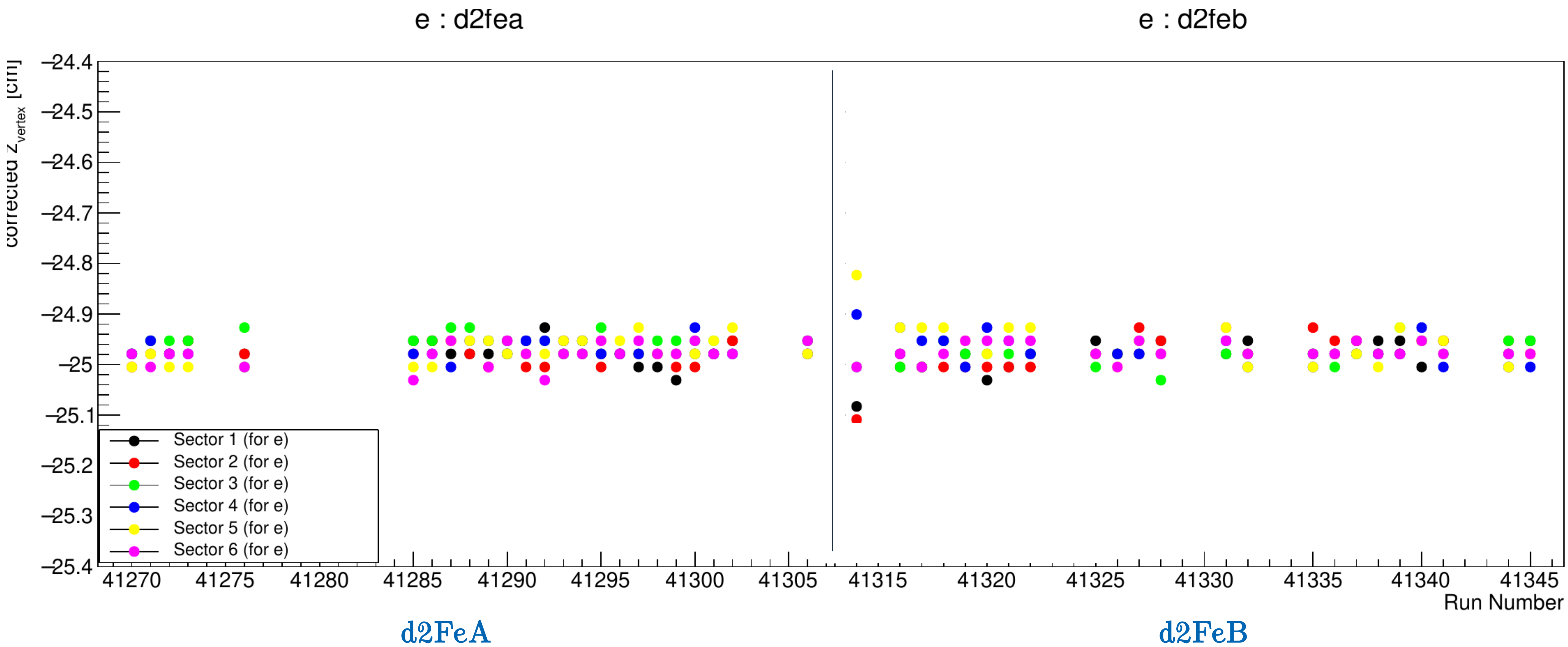
- Simultaneous targets: Necessary to correctly reconstruct the reaction vertex.



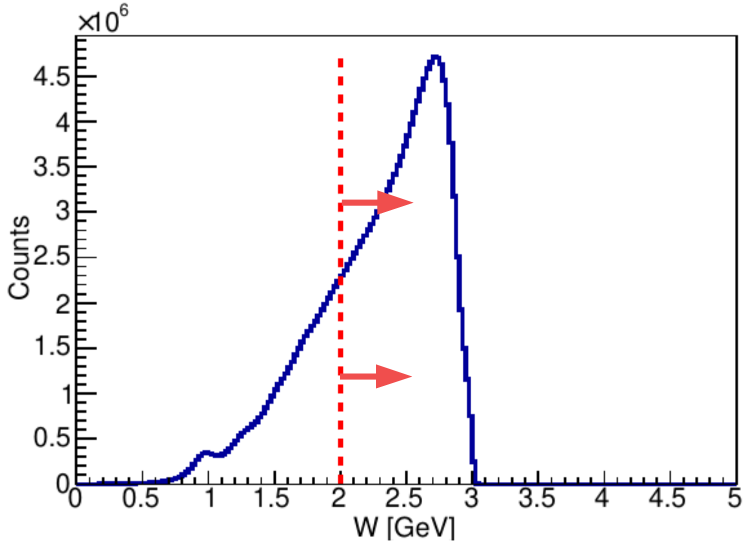
- All the identified particles underwent the vertex correction.

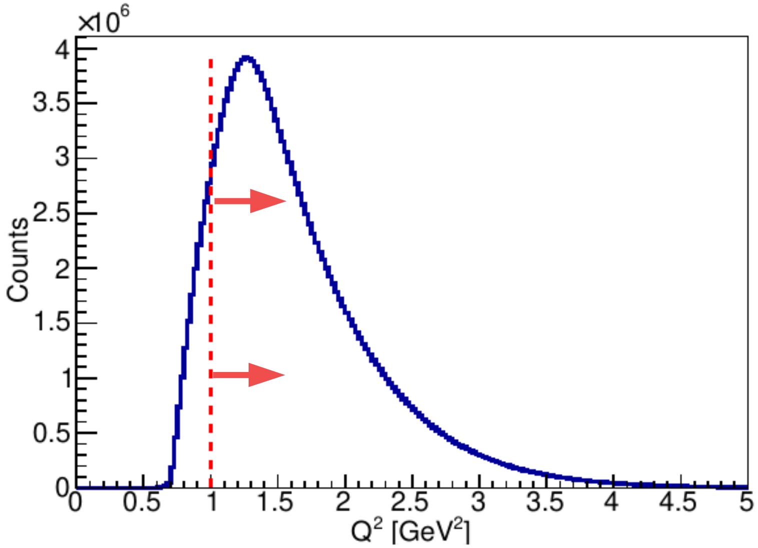
Vertex Correction: Consistency check

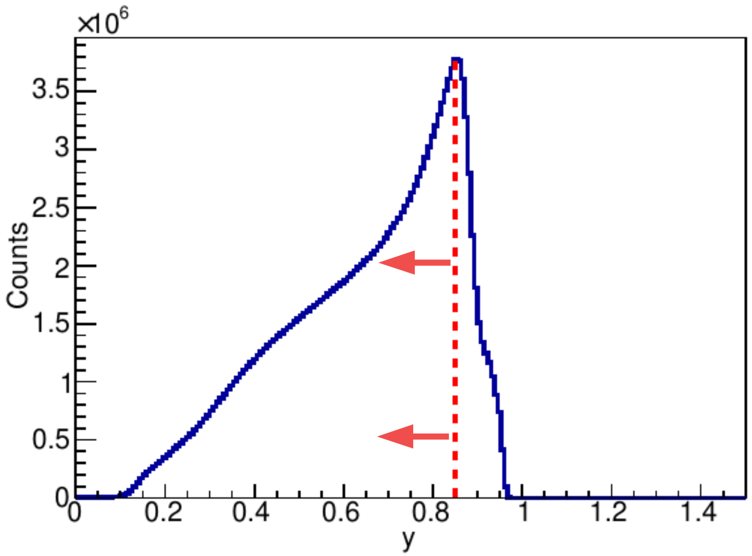
- Vertex corrections are applied appropriately. Consistent over entire run range.



Selection of SIDIS Events: Kinematic Cuts







$W > 2$ GeV

→ to avoid contamination from resonance region.

$Q^2 > 1$ GeV^2

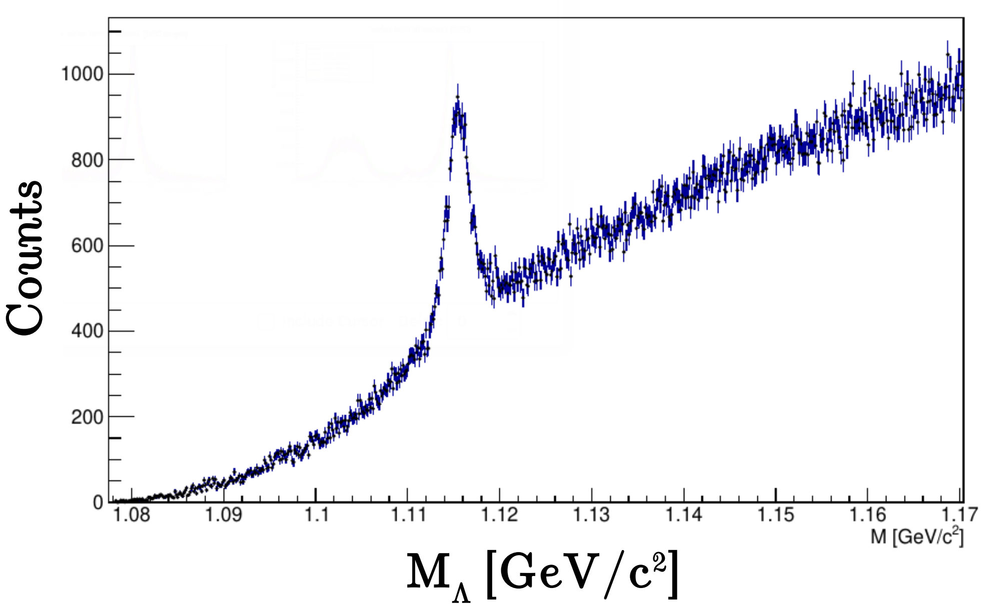
→ to probe nucleon substructure.

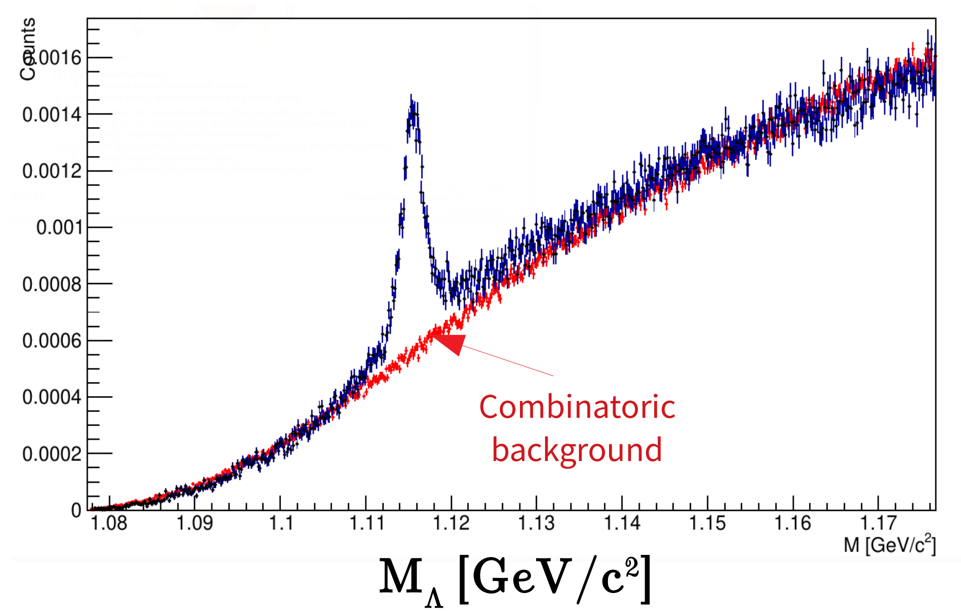
$y < 0.85$ (based on HERMES study)

→ to reduce the size of radiative effects.

Production Channel

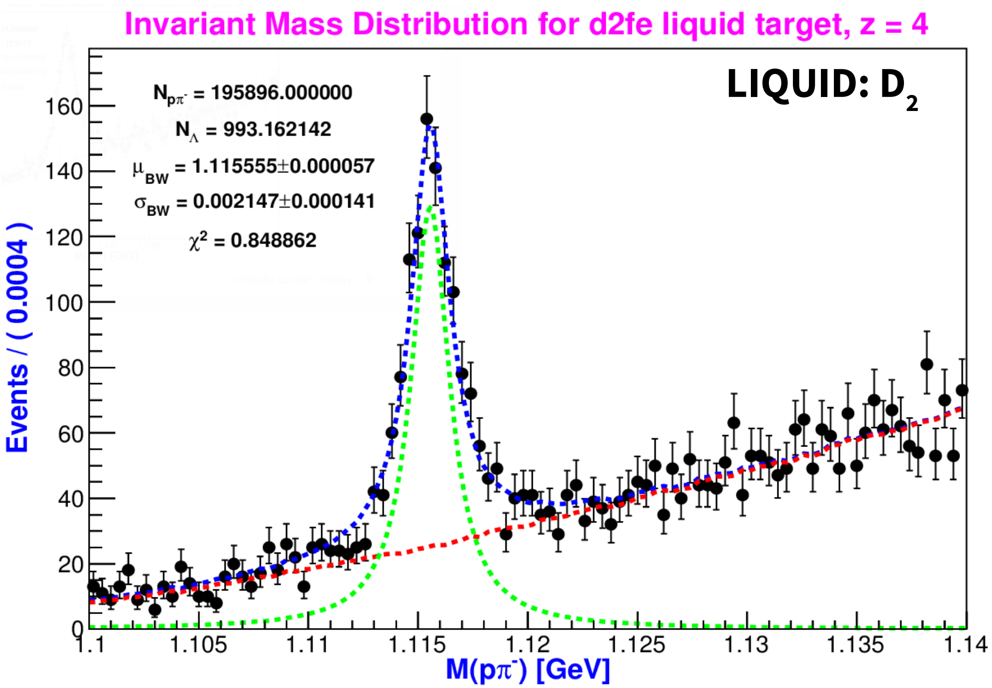
- Reconstruct Λ via its decay products π^- and p.
- Perform various sanity checks of the background subtraction and yield extraction techniques.
- Event mixing method is utilized to subtract the combinatoric background based on MINUIT minimization (RooFit).

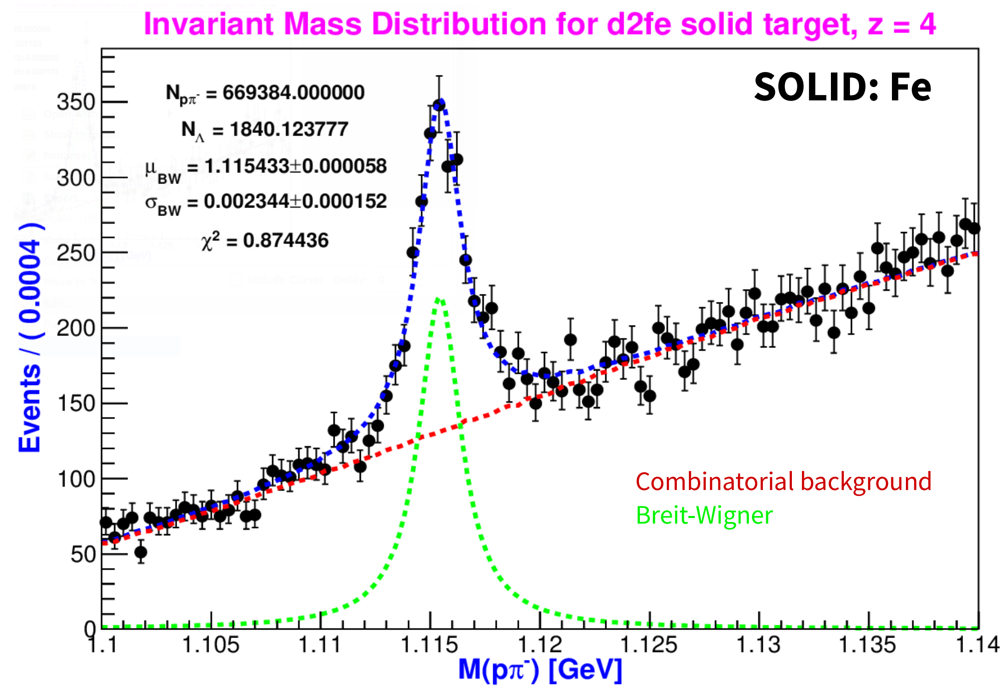




Λ Yield Extraction

- **A sample z-bin: Λ invariant mass distribution after the background subtraction using RooFit minimization (Breit-Wigner + combinatoric background).**
- z: fraction of the struck quark's initial energy carried by the formed hadron





z-bin	1	2	3	4	5	6	7	8	9
Range	[0.28, 0.36)	[0.36, 0.42)	[0.42, 0.48)	[0.48, 0.54)	[0.54, 0.6)	[0.6, 0.65)	[0.65, 0.7)	[0.7, 0.8)	[0.8, 0.9)

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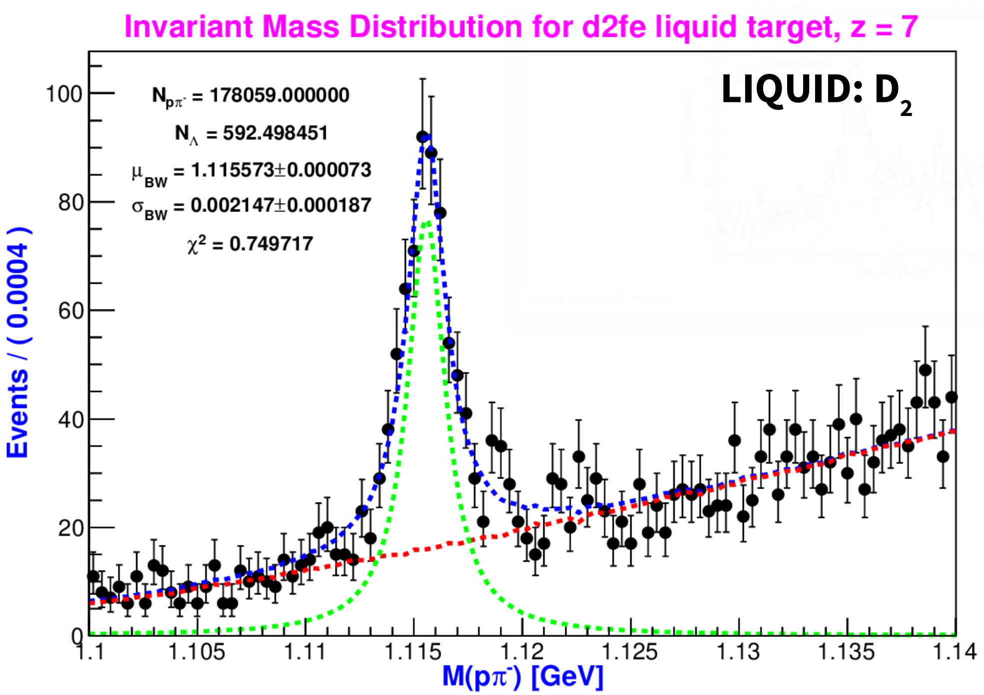

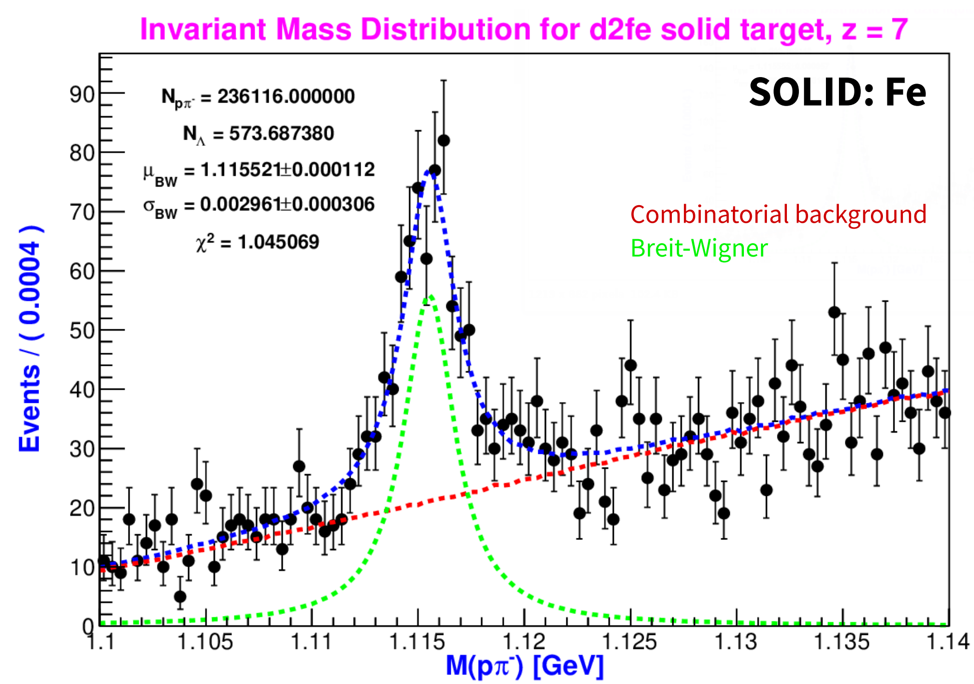

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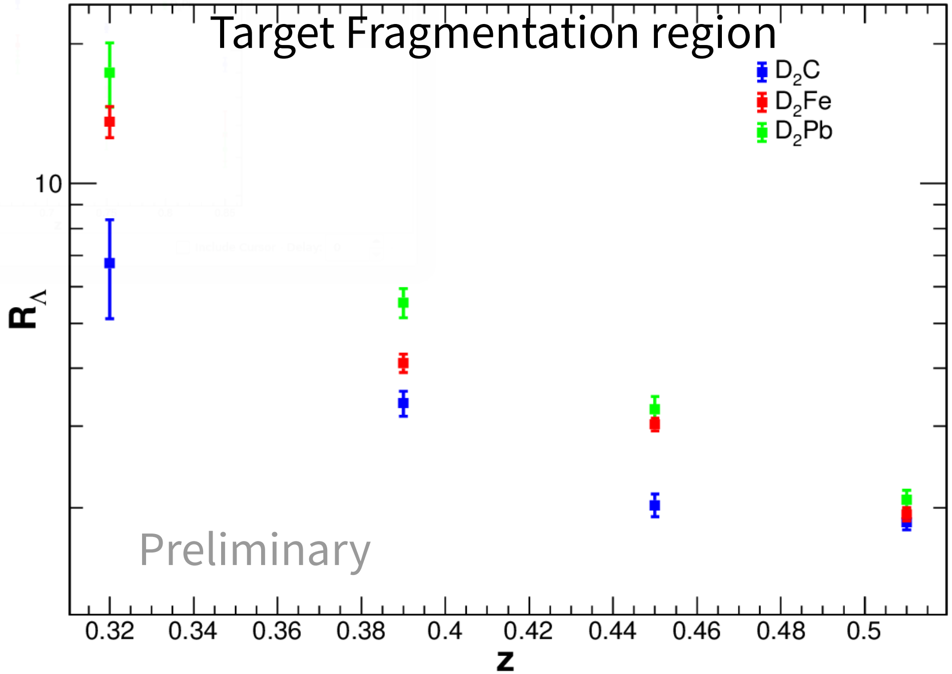
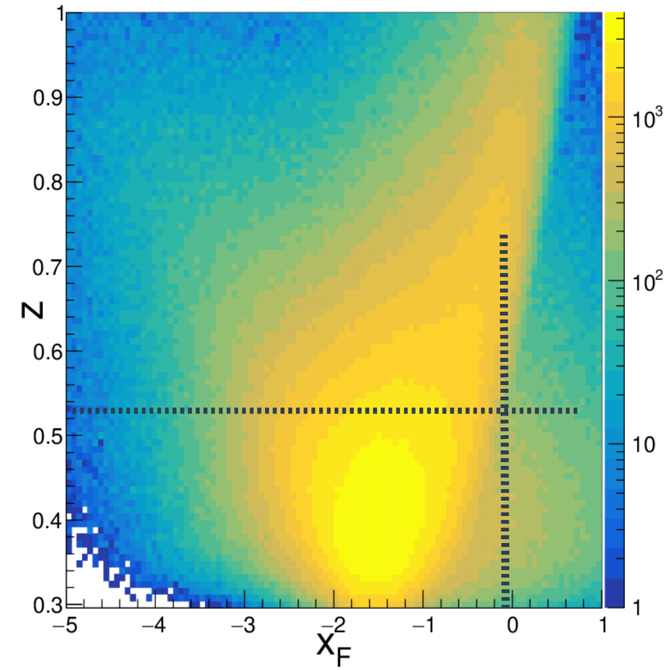
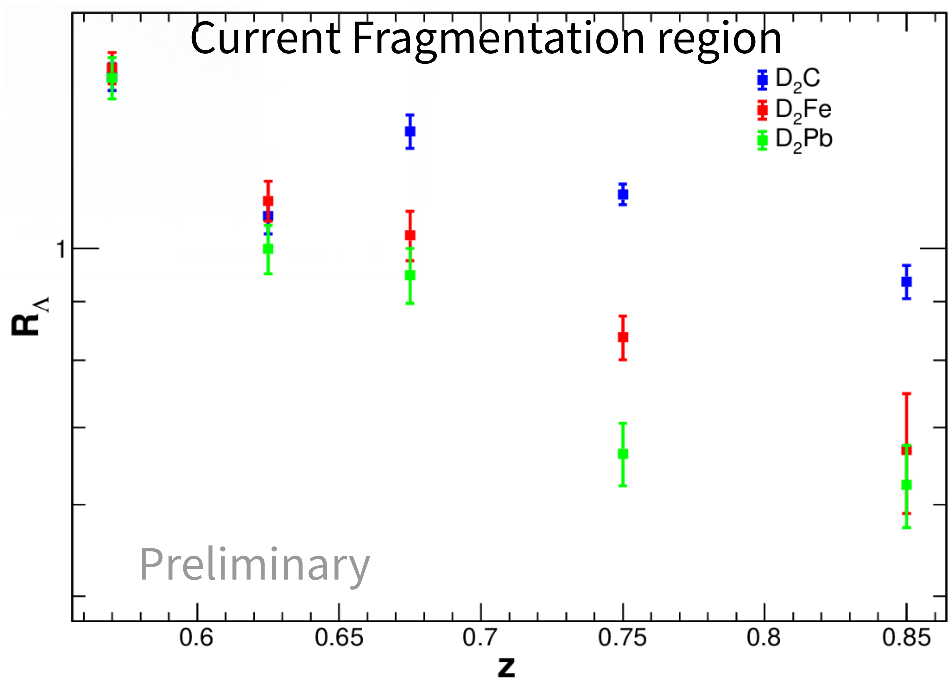






- $$R_A^h(z) = \frac{\left.\frac{N_h(z)}{N_e|_{DIS}}\right|_A}{\left.\frac{N_h(z)}{N_e|_{DIS}}\right|_D}$$

- First ever study of the hadronization process of Λ hyperon which probes the forward (current) and backward (target) fragmentation regions.

Transverse Momentum Broadening

- The pT-broadening is calculated as:

$$\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$$

where,

$$P_T^2 = |\vec{v_1}|^2 - \frac{(\vec{v_1}.\vec{v_2})^2}{|\vec{v_2}|^2}$$

$$\vec{v_1} = \vec{p}_{\pi^-} + \vec{p}_p \qquad \vec{v_2} = \vec{p}_e - \vec{p}_{e'}$$

- Error on the broadening is calculated as:

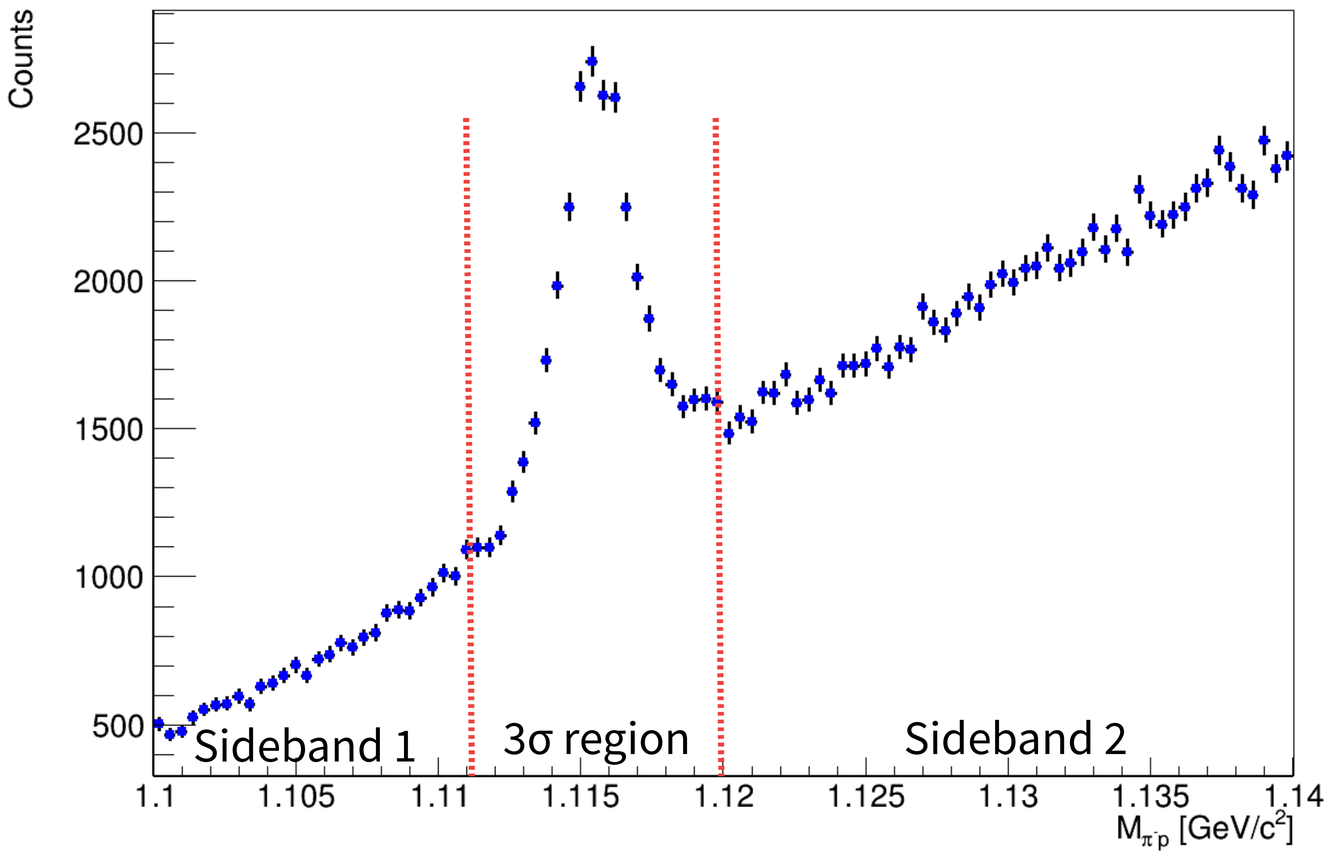
$$\sigma^2_{\Delta P_T^2} = \frac{(\langle P_T^4 \rangle - \langle P_T^2 \rangle^2)_A}{N_A^h} + \frac{(\langle P_T^4 \rangle - \langle P_T^2 \rangle^2)_D}{N_D^h}$$

- <> represents weighted average in the above equations.
- N^h = Number of hadrons coming from liquid (D) or solid (A) target.

Transverse Momentum Broadening

- We consider $1.1 \leq M_\Lambda < 1.14$ GeV for pT-broadening calculation.
- We also divide this mass range in three parts,
  - Sideband 1: $M_\Lambda \in [1.10, \mu - 3\sigma)$ GeV
  - 3σ region : $M_\Lambda \in [1.10, \mu + 3\sigma)$ GeV
  - Sideband 2: $M_\Lambda \in [\mu + 3\sigma, 1.14)$ GeV, as illustrated:

μ, σ: are extracted from Breit-Wigner fits (RooFit) for each z-bin considered



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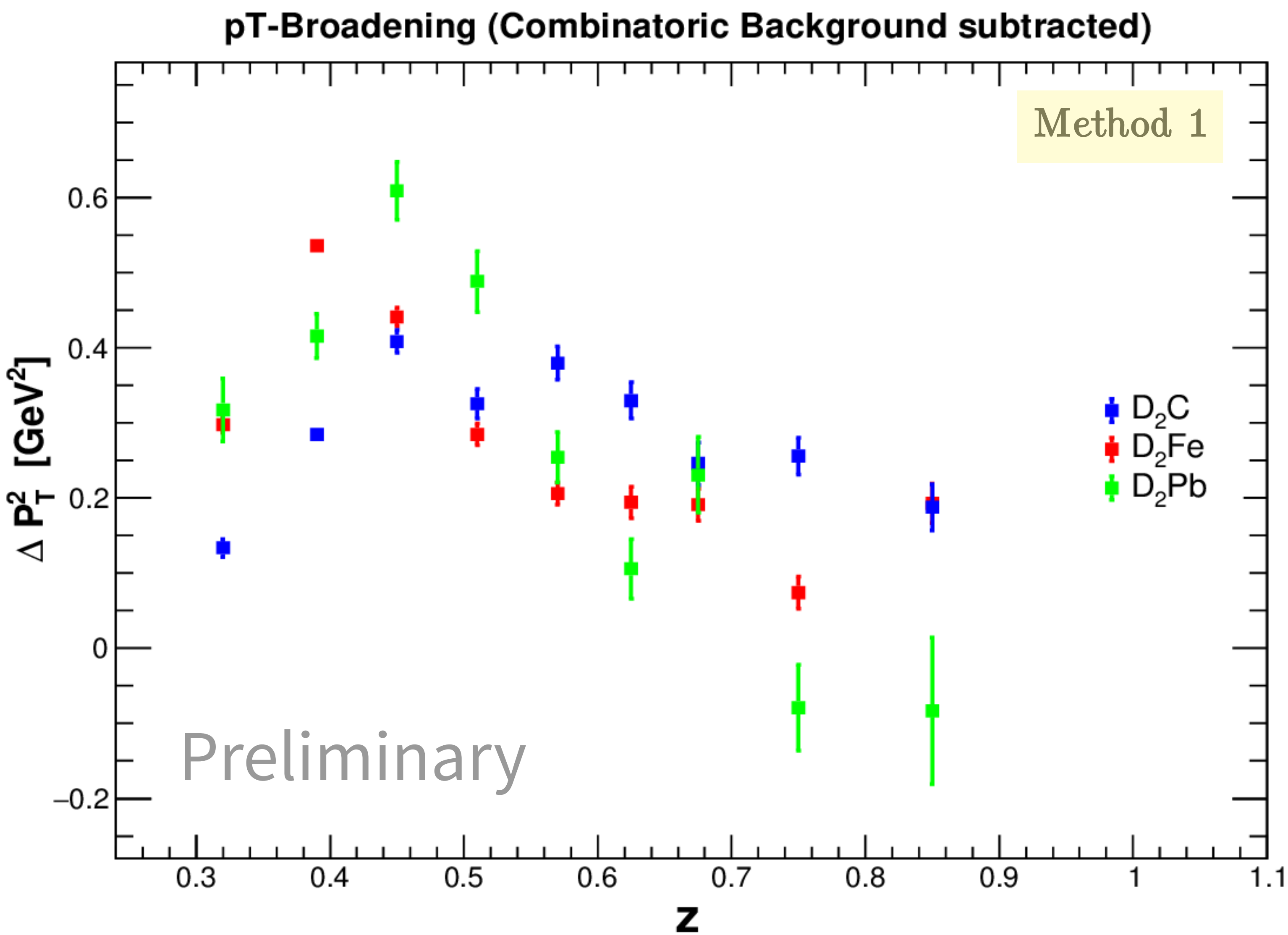
μ, σ: are extracted from Breit-Wigner fits (RooFit)

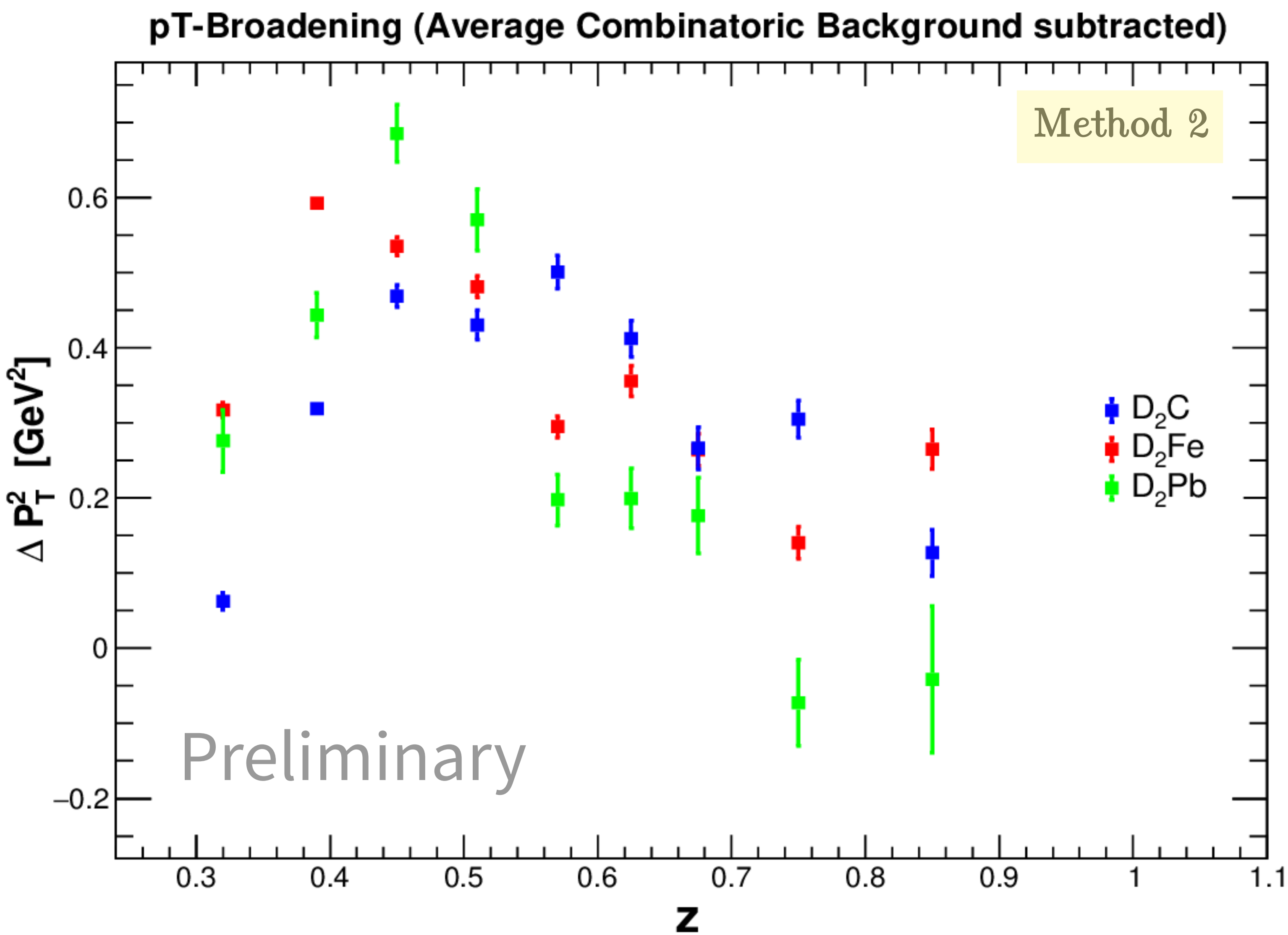
- We calculate pT broadening for the entire mass range for each target configuration. (A)
- We also calculate pT broadening from combinatoric background for entire mass range. (B)
- The average pT broadening from combinatoric background for each region is also calculated. (C)
- Method 1: A – B
- Method 2: A – C

Transverse Momentum Broadening (z-dependence)



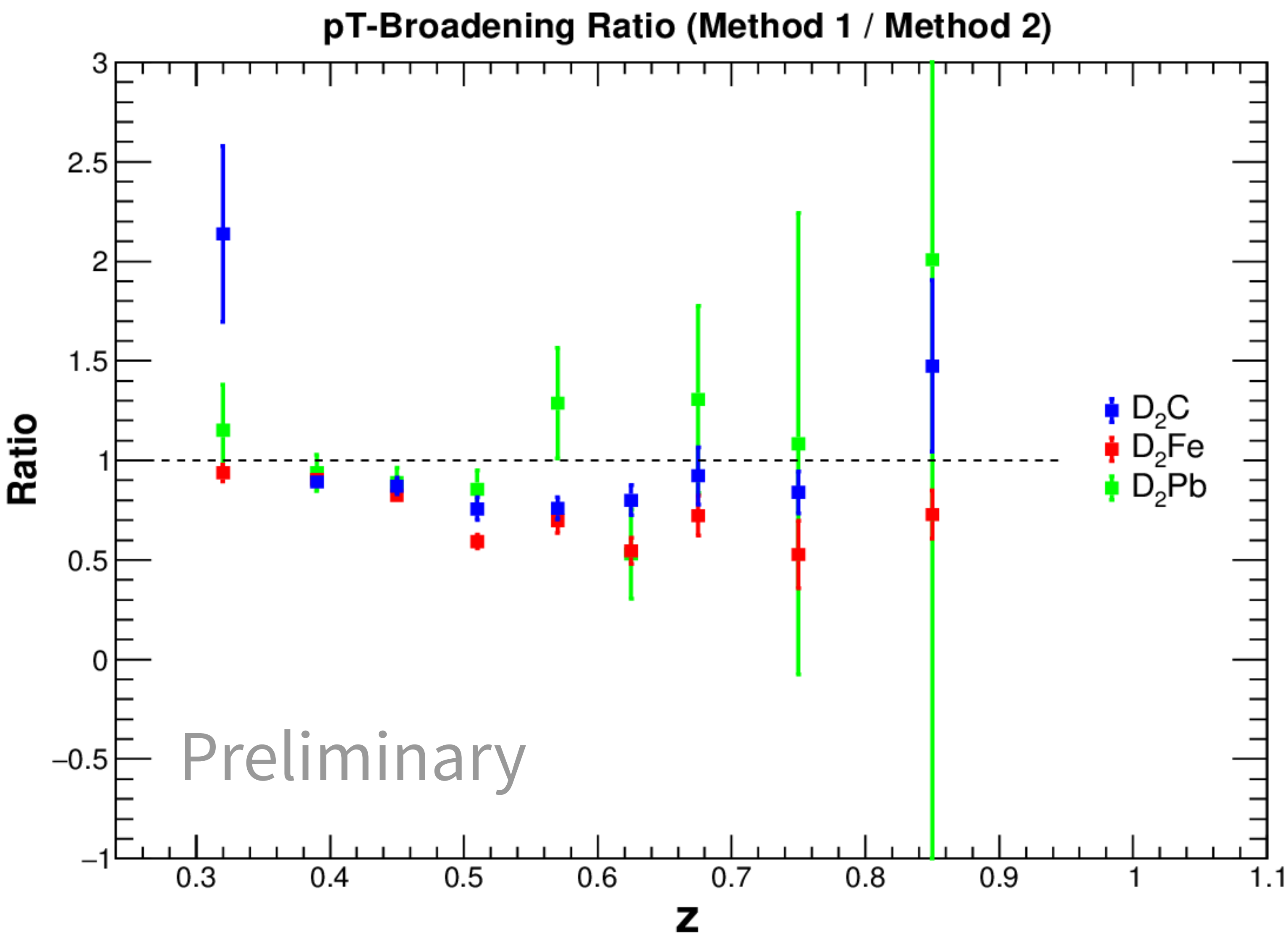
p_T broadening varies as a function of the fraction of the struck quark's initial energy carried by the formed hadron.

Transverse Momentum Broadening (z-dependence)



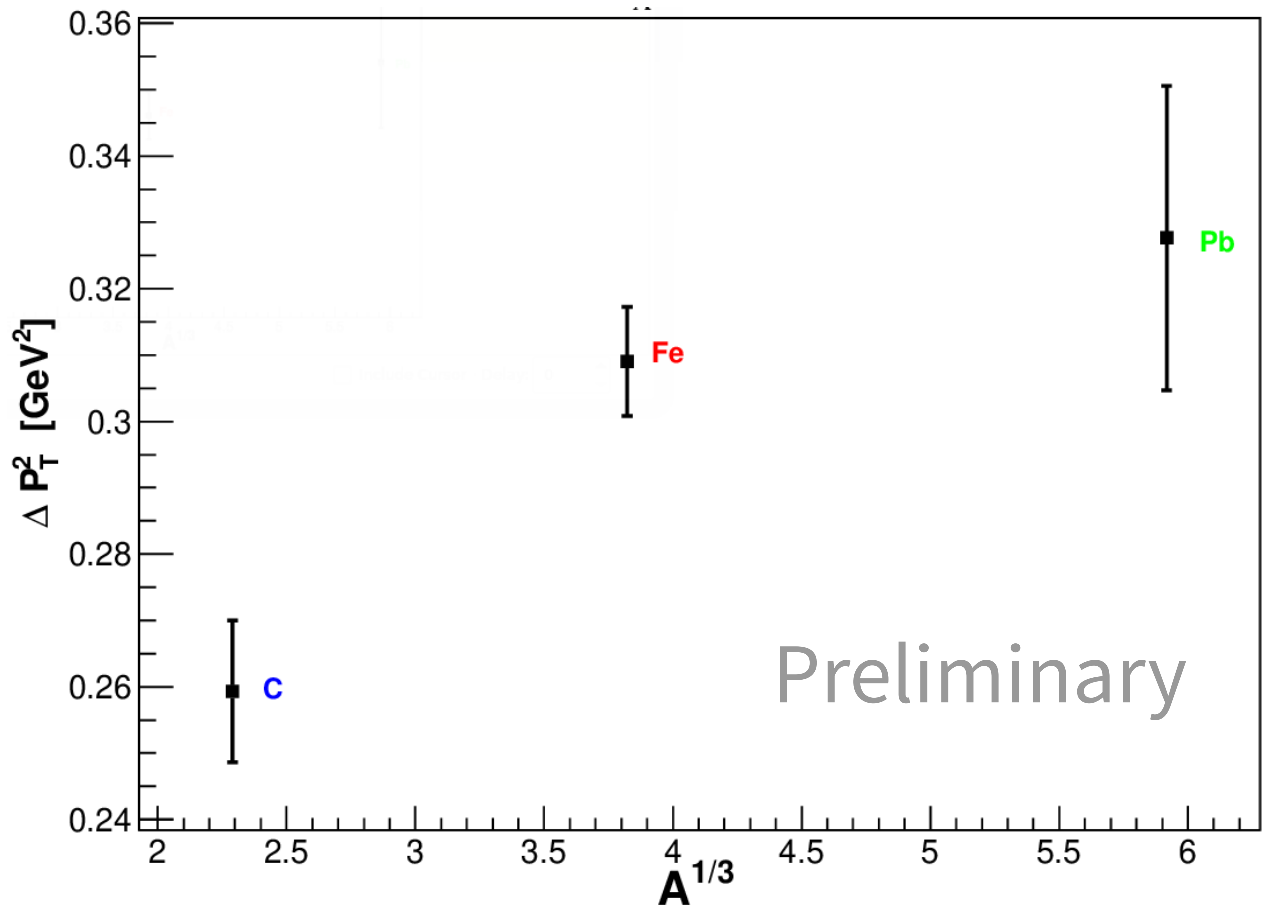
p_T broadening varies as a function of the fraction of the struck quark's initial energy carried by the formed hadron.

Transverse Momentum Broadening (Method 1 vs Method 2)



Comparison of the two methods of background subtraction.

Transverse Momentum Broadening (A-dependence)



p_T broadening is more enhanced for heavy nuclei as expected.

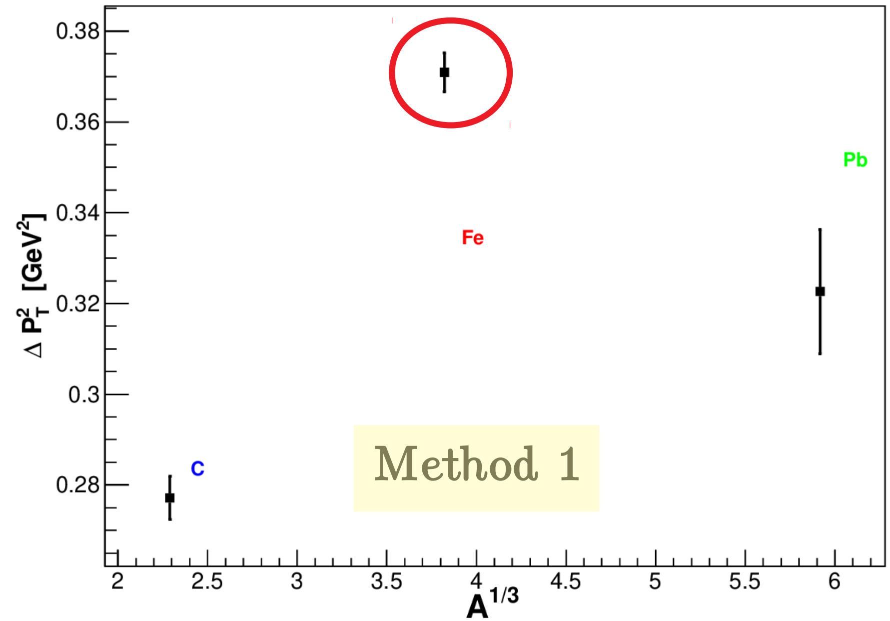
(Sideband is not subtracted!)

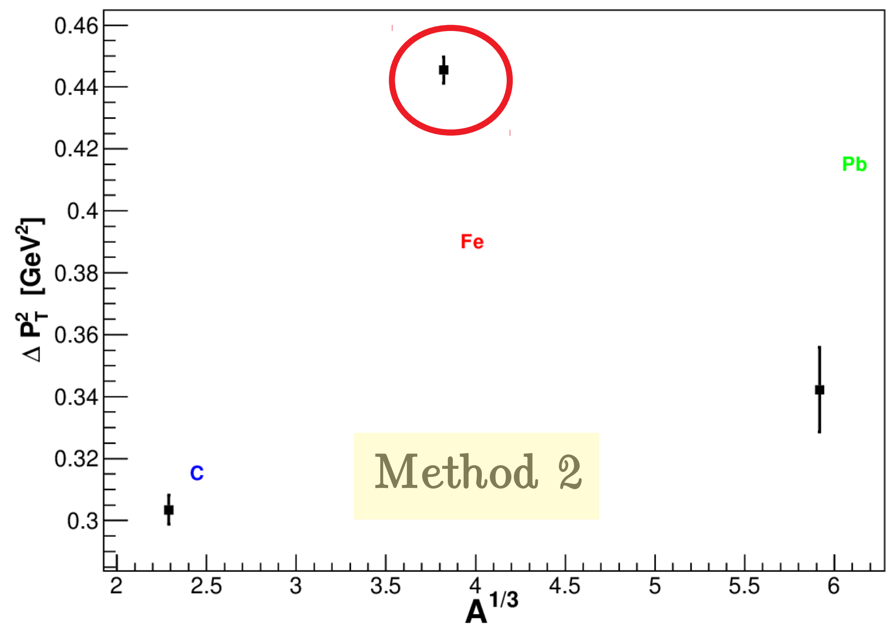
Broadening is enhanced for heavier nuclei.

Transverse Momentum Broadening (A-dependence)

A – dependence for p_T broadening extracted from the two methods (sideband subtracted).

Notice the odd behavior for the Fe.





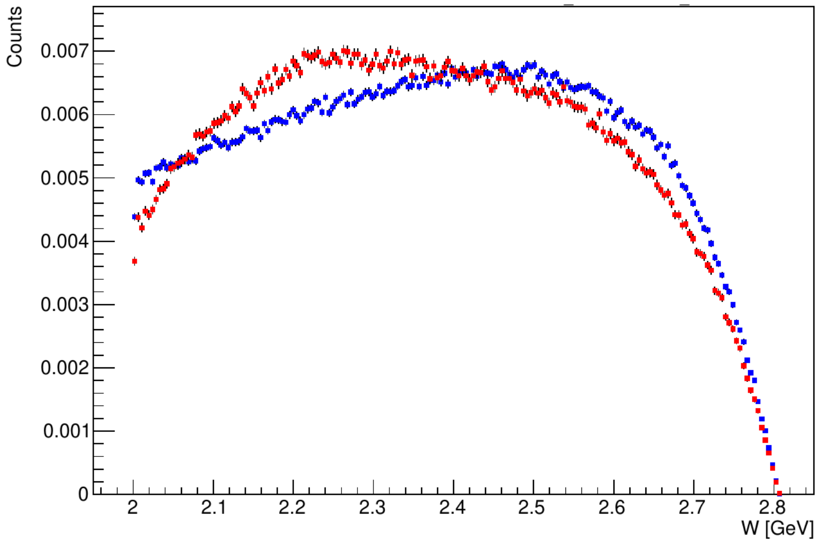
Acceptance Correction: General Steps

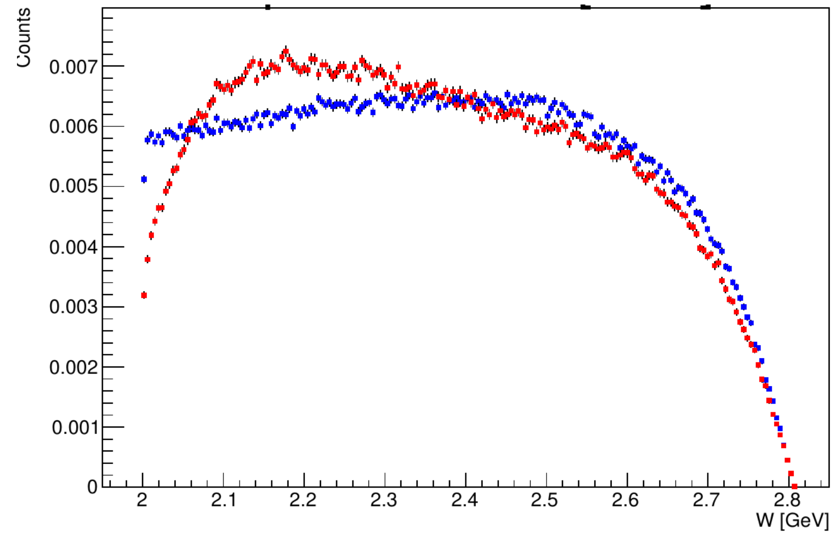
- **CLAS acceptance** → Detection, track reconstruction and event selection efficiencies.
  - The efficiency calculation is based on simulation.
- **PYTHIA generator is being used to simulate events of interest.**
  - Contains a model of non-perturbative (soft) and perturbative DIS processes.
  - Modified to incorporate the Fermi motion and nuclear parton distribution functions.

    (Package provided by Ahmed El Alaoui, Santa Maria University, Chile)
- **Apparatus simulation: Standard CLAS simulation package.**
  - Perform a comparison of several kinematic variables using real and simulated data.

Comparison (Experimental Data vs Simulation)

CM energy, W

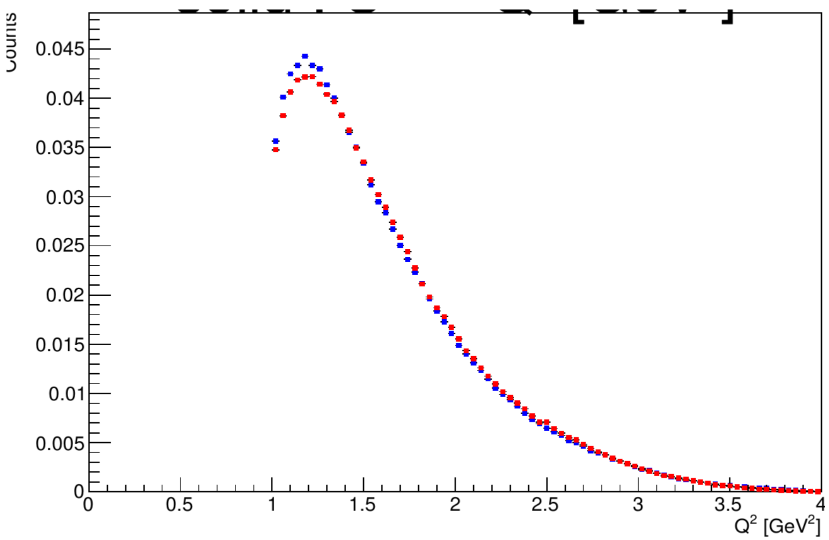


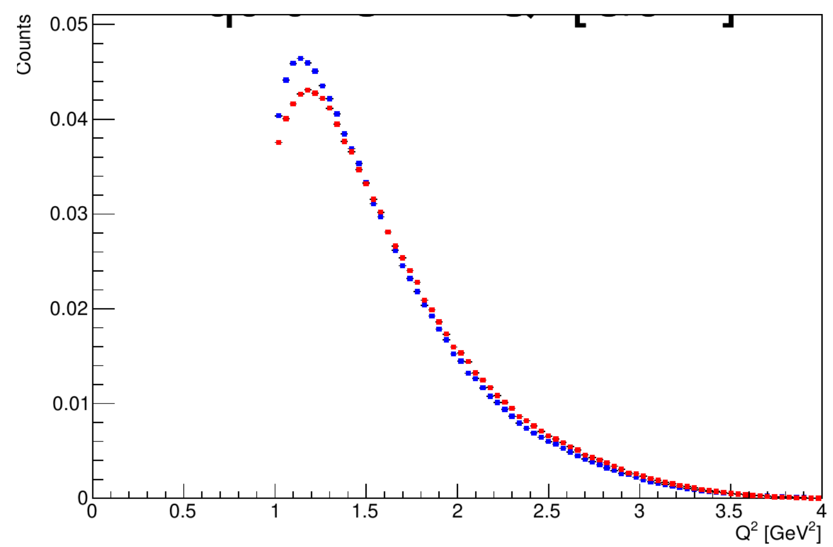


+ Data

+ MC

Q^2 distribution



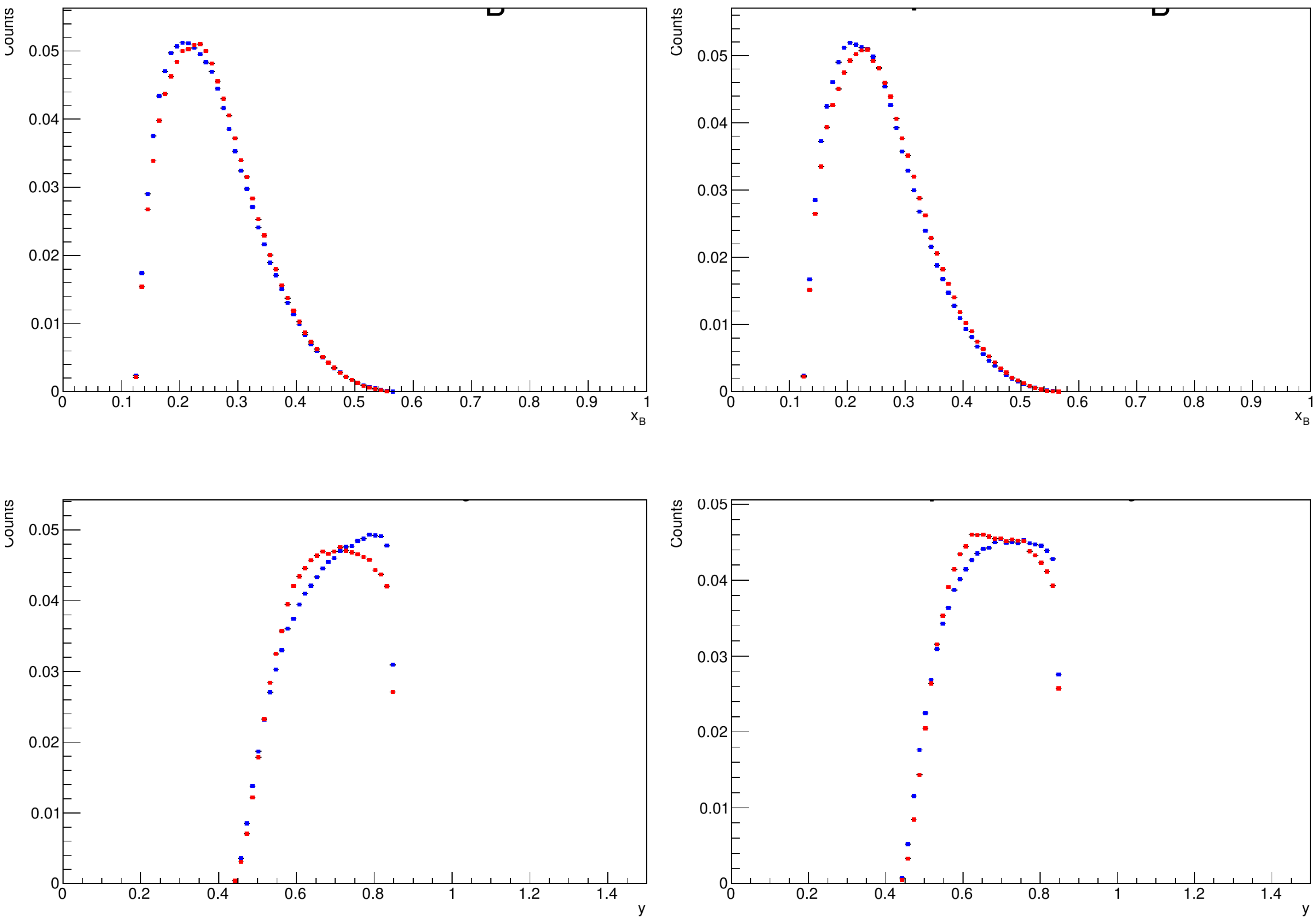


SOLID: C

LIQUID: D_2

Comparison (Experimental Data vs Simulation)

Bjorken x, x_B



+ Data

+ MC

y-distribution

SOLID: C

LIQUID: D_2

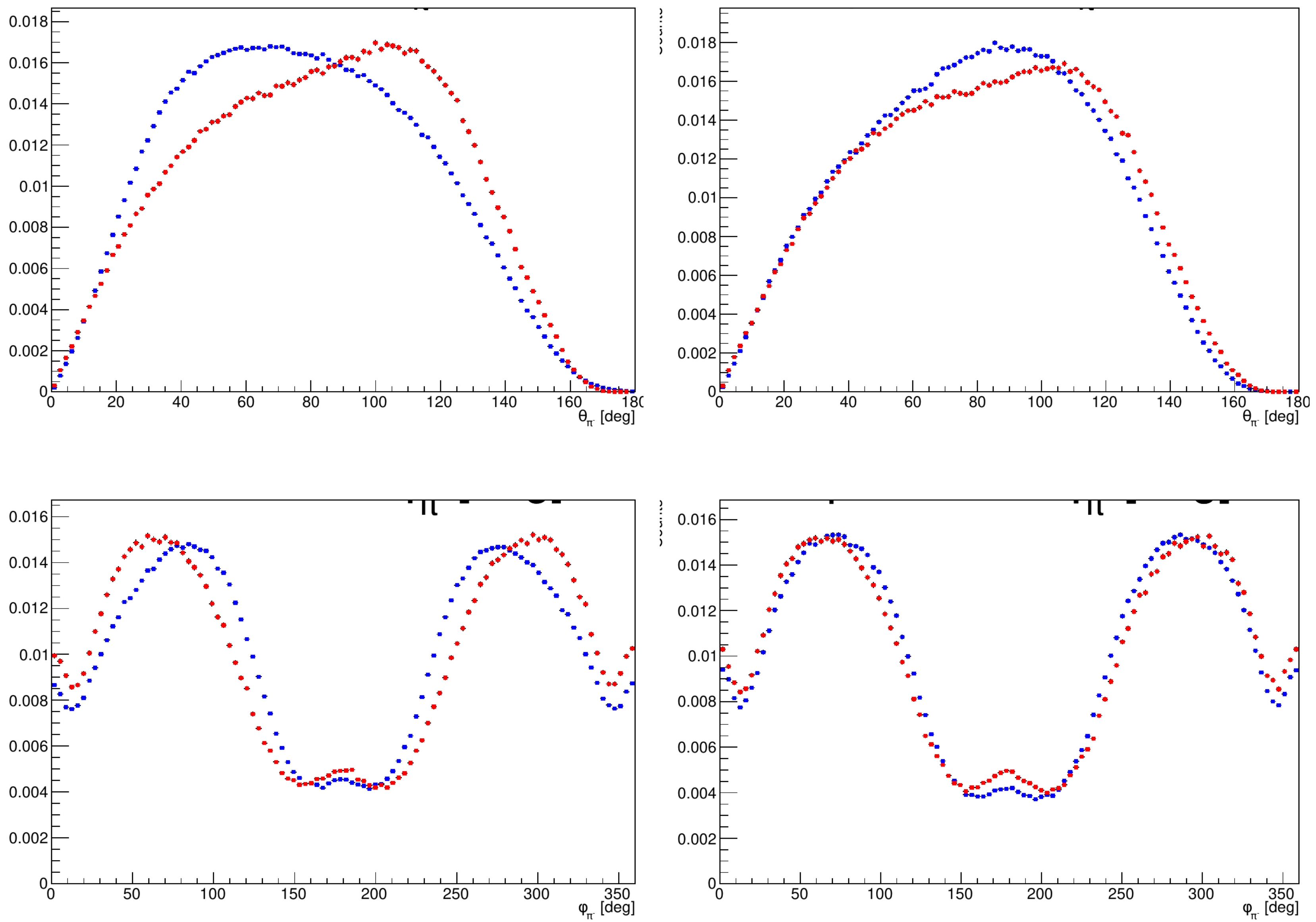
Comparison (Experimental Data vs Simulation)

Pion polar decay angle in Λ's rest frame, $\theta_{\pi-}$

Pion azimuthal decay angle in Λ's rest frame, $\phi_{\pi-}$

+ Data

+ MC



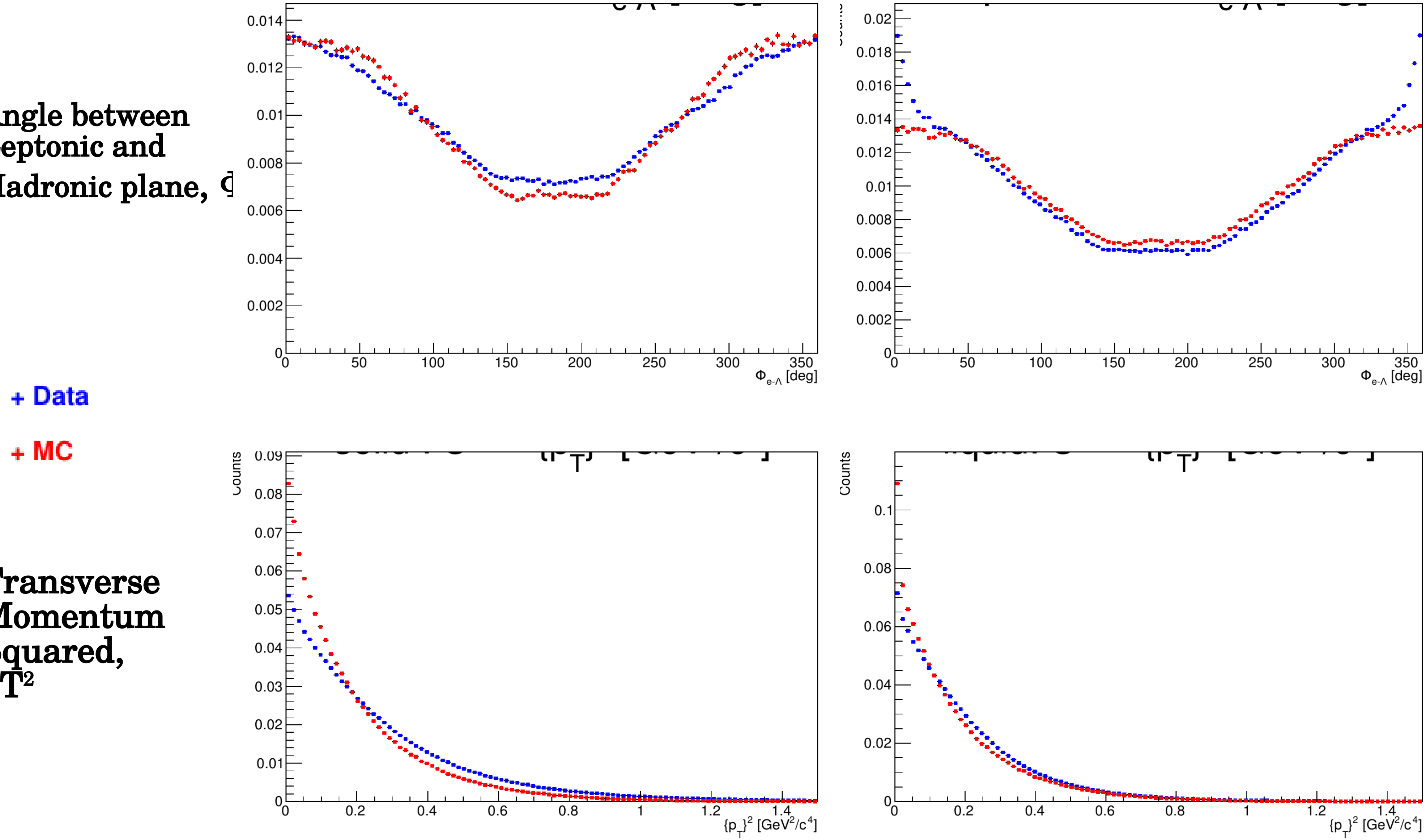
SOLID: C

LIQUID: D_2

Comparison (Experimental Data vs Simulation)

Angle between Leptonic and Hadronic plane, ɸ

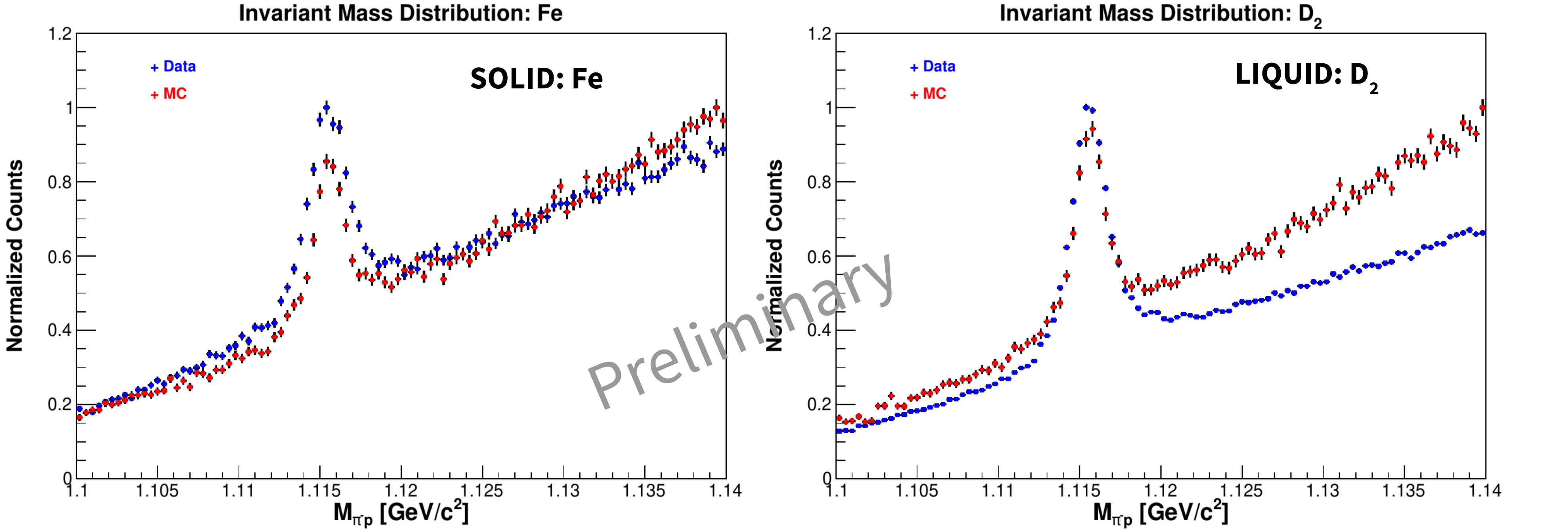
Transverse Momentum Squared, pT²



SOLID: C

LIQUID: D_2

Comparison (Experimental Data vs Simulation)



- We are actively working on the generator to improve the comparison between the real data and simulation. (Suggestions are welcome)
- Promising agreement between experimental data and simulation.
- Variables will be binned to perform multi-dimensional efficiency calculation:

$$\mathrm{Eff} = \frac{N_{acc}(Q^2, \theta_{\pi^-}, \ldots)}{N_{gen}(Q^2, \theta_{\pi^-}, \ldots)}$$

- Weights are then calculated as $1/\mathrm{Eff} \rightarrow$ apply to $R_A{}^h$, p_T broadening.

What's next?

- **Next steps would include:**
  - Optimization of event generator
  - Better comparison of Data with Simulation
  - Application of acceptance corrections, radiative corrections and perform systematic studies.
  - Study other dependencies of R_Λ on Q^2, ${P_T}^2$(Cronin effect).

Thank you for your attention!

Questions/Comments/Suggestions?

Thank you!!

Extras

Feynman x, x_F

- Feynman x expressions:

Raphael

$$x_F = 2\frac{zM_p\upsilon^2 - zQ^2\upsilon - (M_p + \upsilon)P.q}{\sqrt{\upsilon^2 + Q^2}(W^2 - M_h^2)}$$

Hayk

$$x_F = 2\frac{(\upsilon + M_p)\sqrt{p^2 - p_T^2} - z\upsilon\sqrt{Q^2 + \upsilon^2}}{\sqrt{(W^2 - M_n^2 - M_\pi^2)^2 - 4M_\pi^2 W^2}}$$

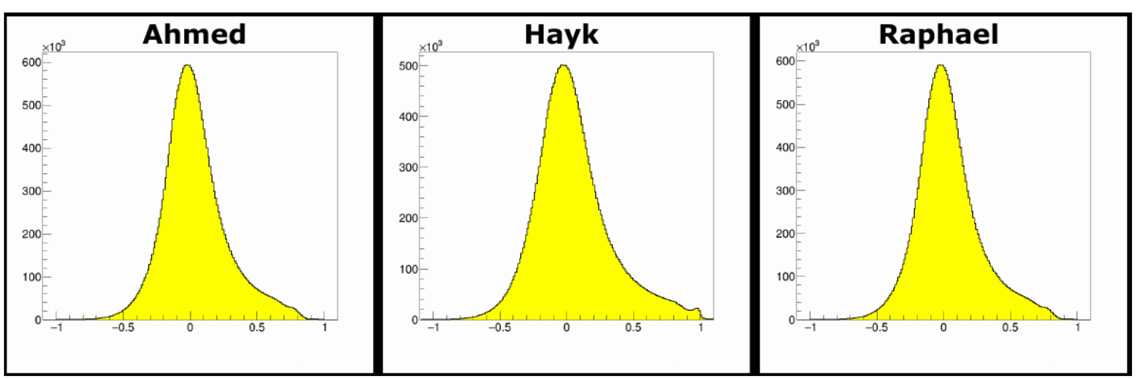
Ahmed

$$x_F = \frac{|\vec{p}_{||}|}{|\vec{q}|}$$

Expressed in the γ^*N CM frame

Modified expression (Hayk's)

$$x_F = 2\frac{(\nu + M_p)\sqrt{p^2 - p_T^2} - z\nu\sqrt{Q^2 + \nu^2}}{\sqrt{(W^2 - M_K^2 - M_\Lambda^2)^2 - 4M_\Lambda^2 W^2}}$$



Plot courtesy: Ahmed

Feynman x, x_F

Raphael

$$x_F = 2\frac{zM_p\upsilon^2 - zQ^2\upsilon - (M_p + \upsilon)P.q}{\sqrt{\upsilon^2 + Q^2}(W^2 - M_h^2)}$$

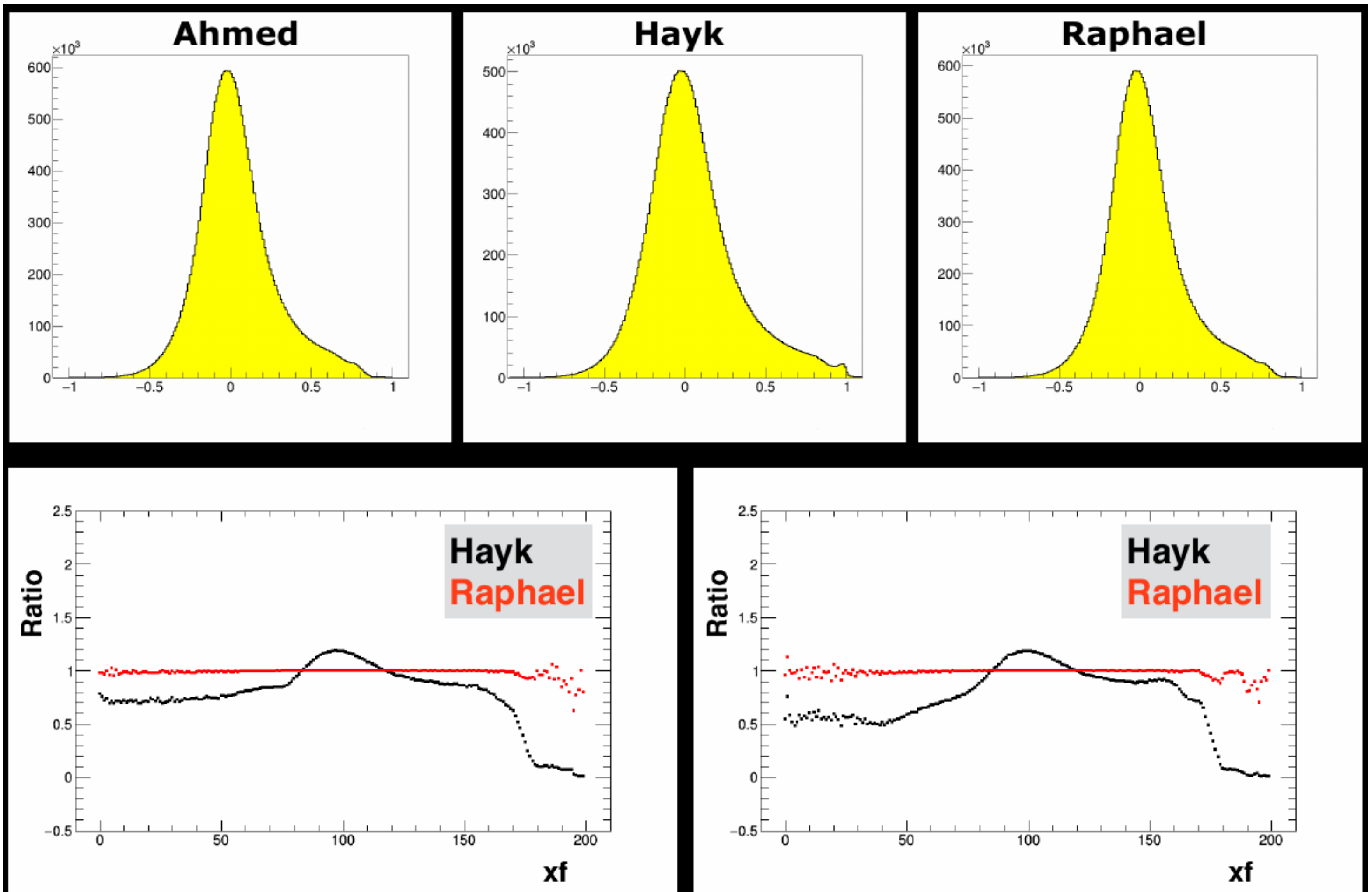
Hayk

$$x_F = 2\frac{(\upsilon + M_p)\sqrt{p^2 - p_T^2} - z\upsilon\sqrt{Q^2 + \upsilon^2}}{\sqrt{(W^2 - M_n^2 - M_\pi^2)^2 - 4M_\pi^2 W^2}}$$

Ahmed

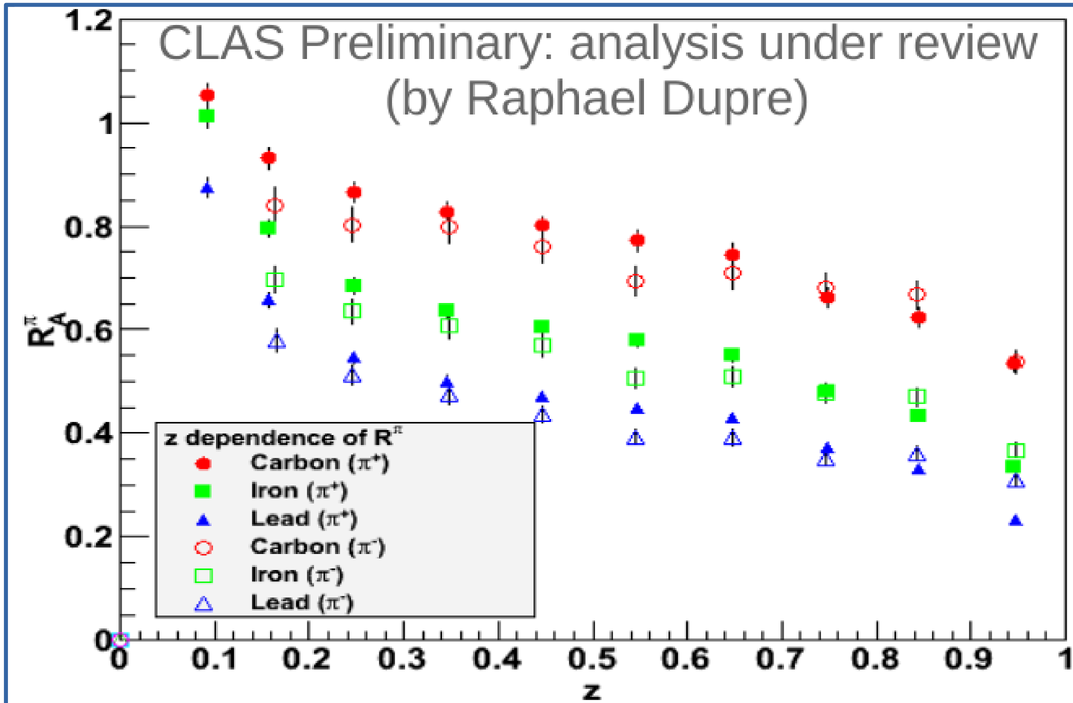
$$x_F = \frac{|\vec{p}_{||}|}{|\vec{q}|}$$

Expressed in the γ^*N CM frame



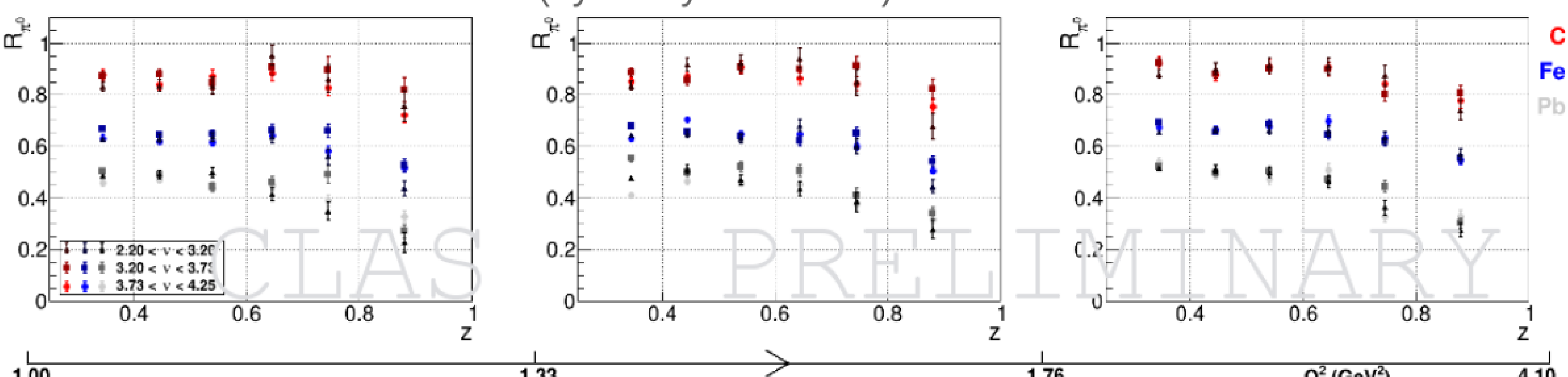
Plot courtesy: Ahmed

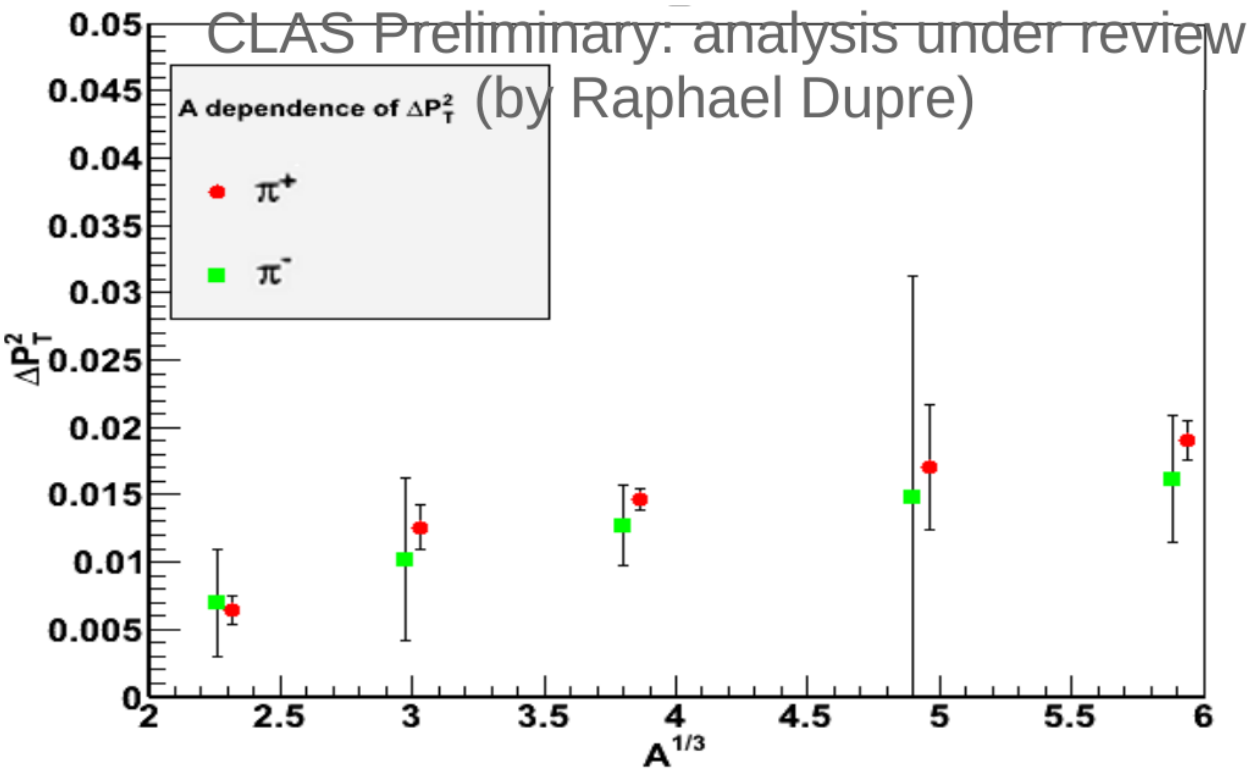
CLAS 6: Hadronization results on Meson channels



- 3-dimensional CLAS-6 multiplicity ratios in z x (Q^2, ν), fully corrected for radiative processes and acceptance, normalized to target thicknesses; C, Fe, Pb.
- Similar behavior for π^0 (Taisiya's thesis results; under review), π^+ (Hayk's thesis) and K^0 (A. Daniel, Ken Hicks *et al.*; published!)
- Consistent with Hermes results!

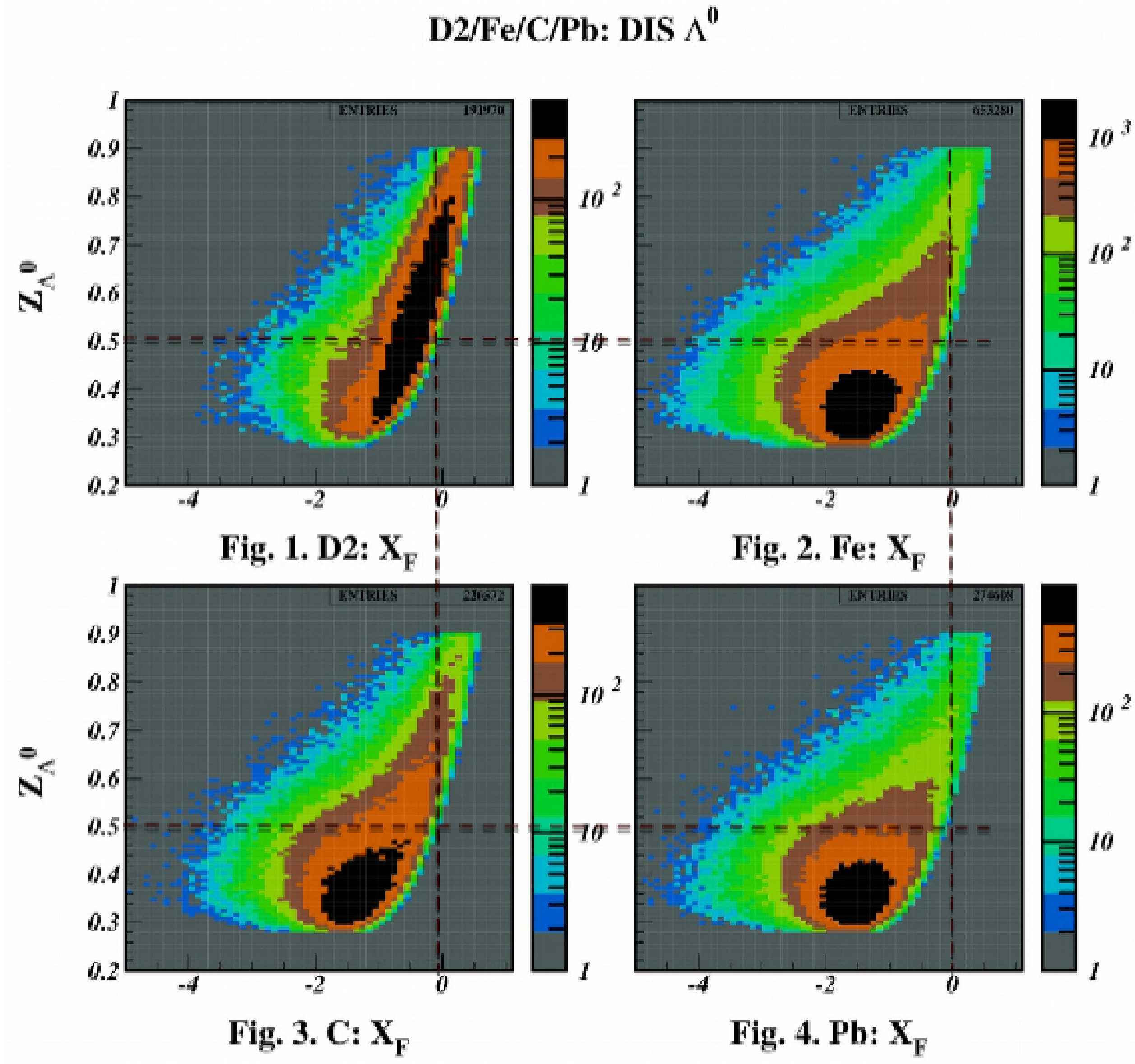
Example of 3-D π^0 multiplicity ratios
(by Taisiya Mineeva)





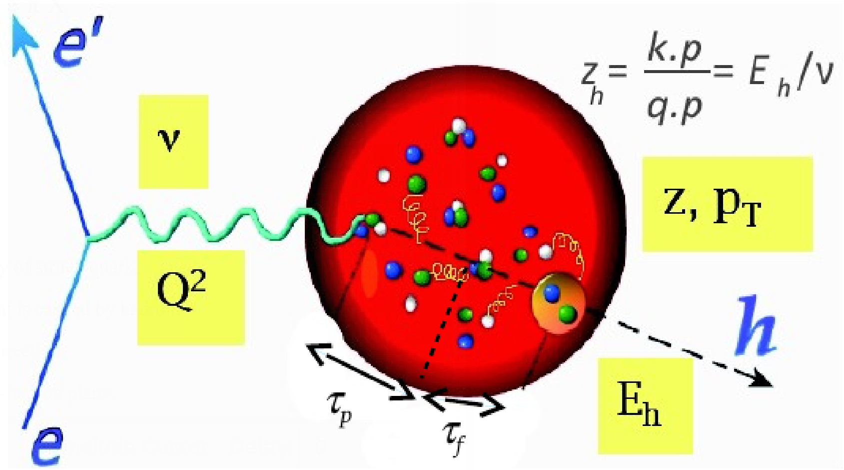
CLAS-6 transverse momentum broadening results for charged pions shows a similar behavior

- First time ever to study the hadronization process of Λ^0 hyperon and probe the forward (current) and backward (target) fragmentation regions.



SIDIS Production

Semi-Inclusive Deep Inelastic Scattering (SIDIS) is used to gain access to physical observables.



Kinematical variables:

ν : Electron energy loss,
≡ Initial energy of a struck quark

Q^2: Four-momentum transferred,
~ 1/(spatial resolution) of the probe

y : ν/E_{beam}, Electron energy fraction transferred to a struck quark,

$W : \sqrt{M_n^2 + 2\nu M_n - Q^2}$ *w/. M_n is a nucleon mass*, is the mass of the total hadronic final state,

z_h: Fraction of the struck quark's initial energy carried by the formed hadron ($0 < z_h < 1$)

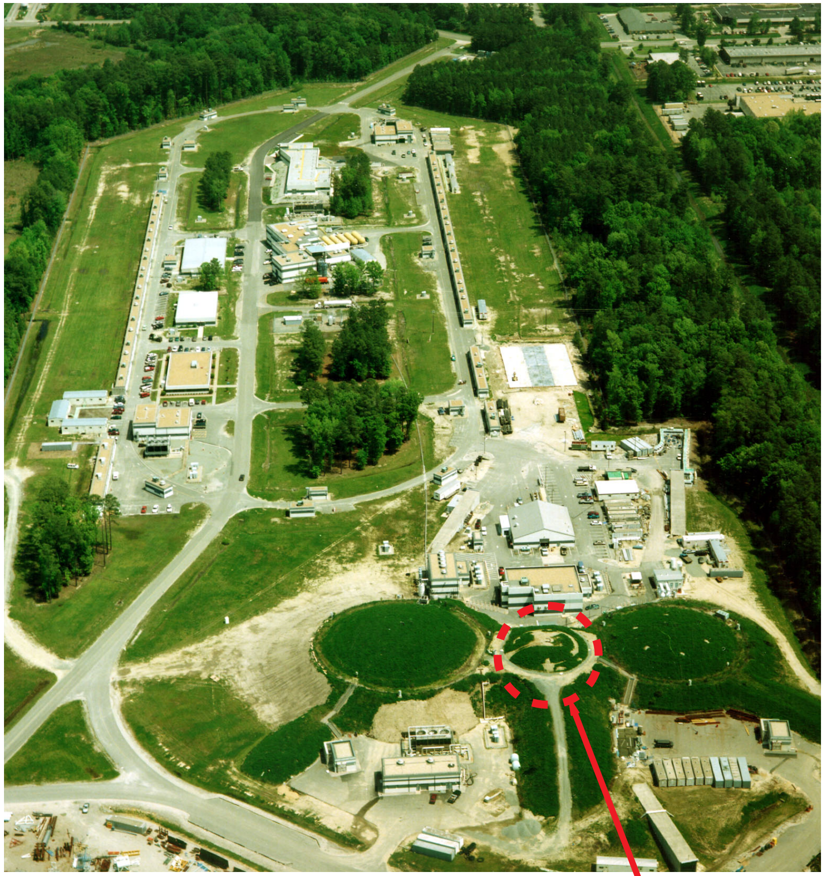
p_T: Hadron momentum transverse to a virtual photon direction.

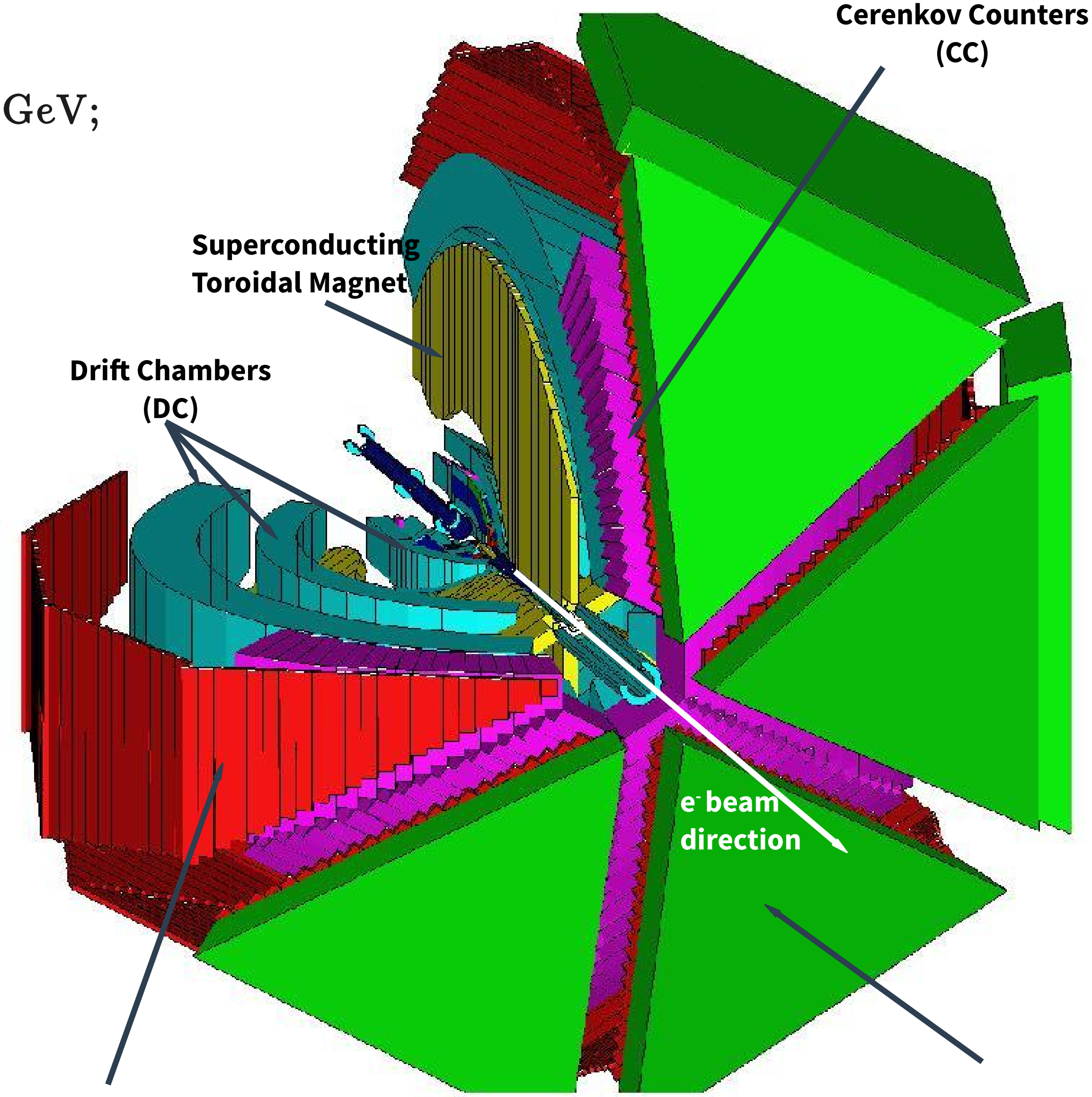
x_F: $\frac{P_L}{P_L^{max}}$, *Feynman variable*, a fraction of the maximum longitudinal momentum carried by the observed hadron.

CLAS @ JLab before the upgrade

- Jefferson Lab: Newport News, VA;
- CEBAF: accelerated electrons up to 6 GeV;
- Experimental Halls: A, B, C

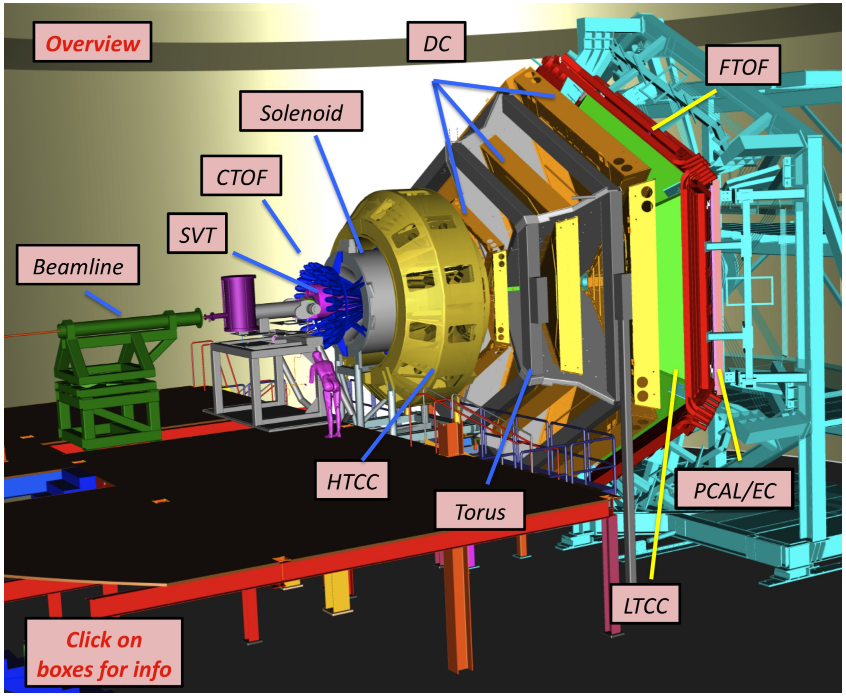
  (and D, 12 GeV upgrade);
- Hall B: electron or photon beam;





Hadronization Studies with CLAS12 @ JLab

With 12 GeV upgrade of the CEBAF: accelerate electrons up to 11 GeV in Hall B.



Actively underway with existing 5 GeV data

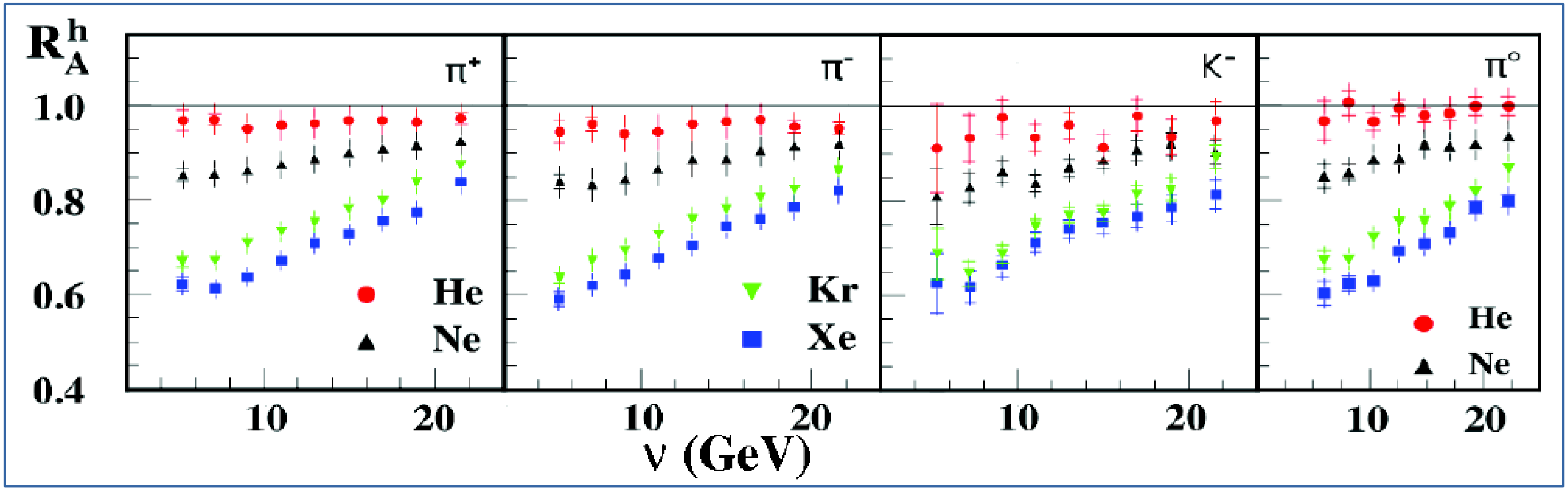
meson	cτ	mass	flavor content	*baryon*	cτ	mass	flavor content
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	p	stable	0.94	ud
π^+, π^-	7.8 m	0.14	$u\bar{d}, d\bar{u}$	$\bar{p}$	stable	0.94	$\overline{ud}$
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	Λ	79 mm	1.1	uds
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\Lambda(1520)$	13 fm	1.5	uds
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	Σ^+	24 mm	1.2	us
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	Σ^-	44 mm	1.2	ds
$f1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	Σ^0	22 pm	1.2	uds
K^0	27 mm	0.50	$d\bar{s}$	Ξ^0	87 mm	1.3	us
K^+, K^-	3.7 m	0.49	$u\bar{s}, \bar{u}s$	Ξ^-	49 mm	1.3	ds

DIS channels: stable hadrons accessible with the CLAS12 detector

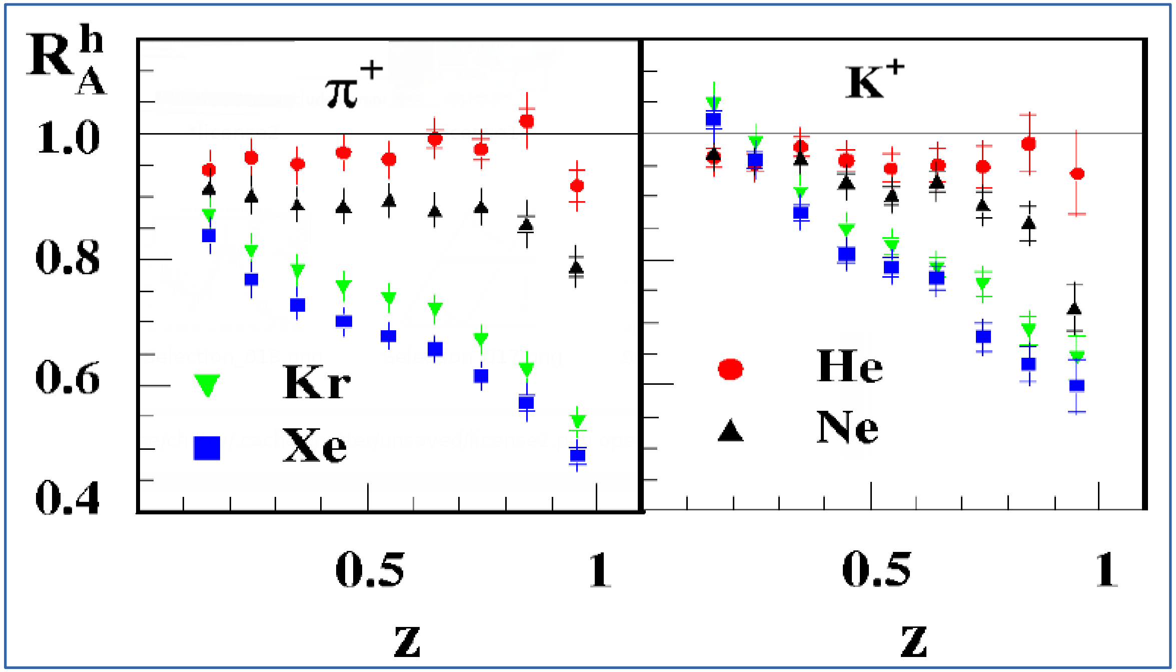
- Span a wider range of nuclei masses → Better understanding of A dependence;
- Study of various hadrons production → Improve our understanding of hadron's formation mechanism.
- Higher statistical precision → Multi-dimensional study of physics observables dependencies for a comprehensive extraction of the production and formation time scales.

Positron beam, E_{beam} = 27 GeV

A. Airapetian et al.
Nucl. Phys. vol. B780, pages 1–27, 2007

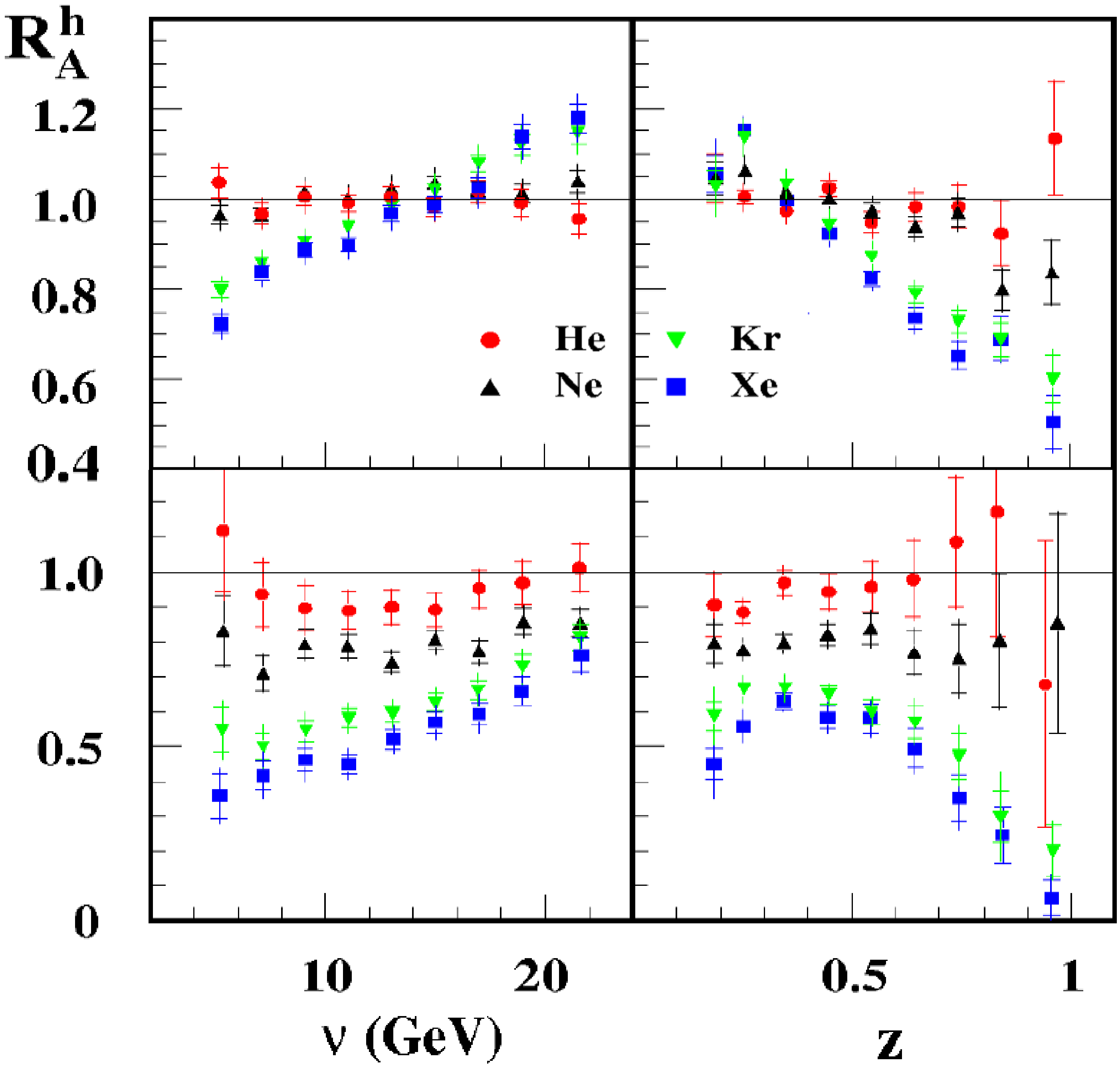


$$z \equiv \frac{E_{hadron}}{\nu}$$



- All pion flavors and K^- experience similar attenuation.
- K^+ is less attenuated compared to π^+ most likely due to a contamination from $\pi + p \rightarrow \Lambda + K$ (B. Kopeliovich *et al.*) from the target fragmentation.

A. Airapetian et al.
Nucl. Phys. vol. B780, pages 1–27, 2007



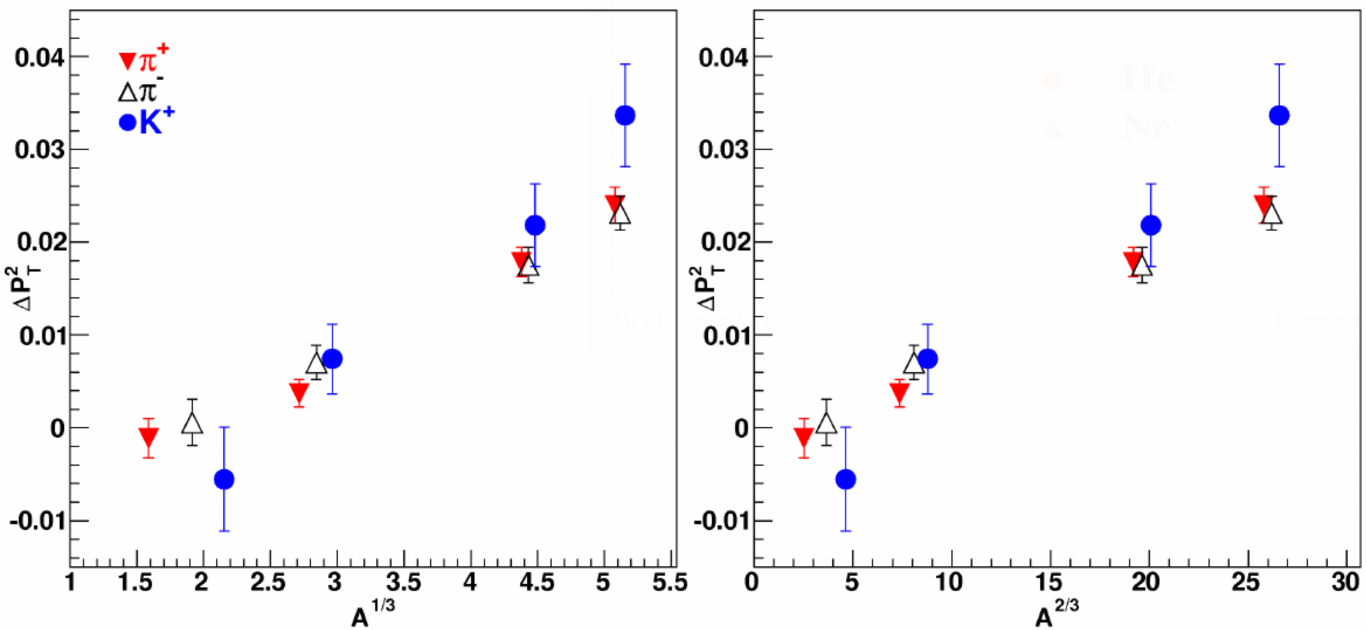
proton

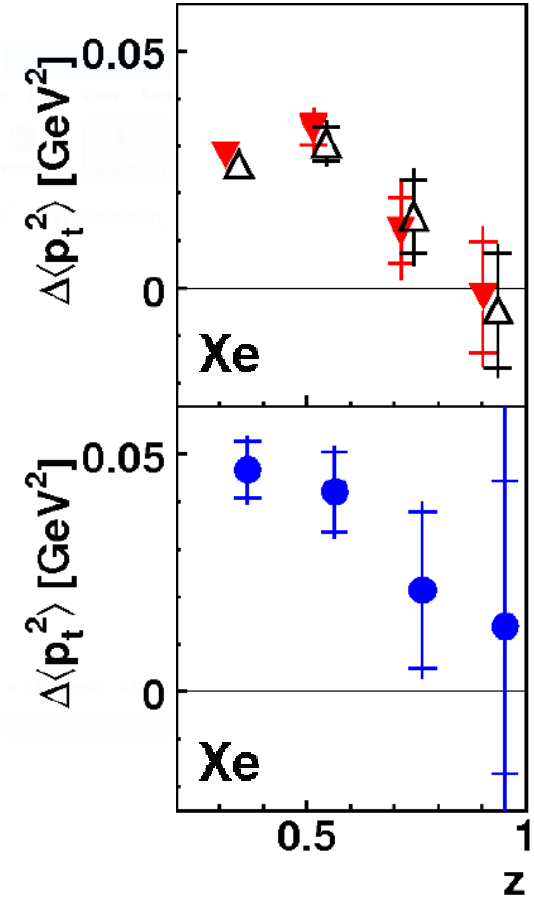
anti-proton

Positron beam, E_{beam} = 27 GeV

HERMES Transverse Momentum Broadening

Positron beam, E_{beam} = 27 GeV





- Reduced broadening at high z favors no prehadron interaction.
- K^+ p_T broadening is different compared to that of pions $\rightarrow$ Flavor dependence?
- Similar effect for nuclear size dependencies, $A^{1/3}(\propto r)$ and $A^{2/3}(\propto r^2)$ $\rightarrow$ Calls for more data?