

Lambda Hadronization Study using EG2 Dataset: Updates

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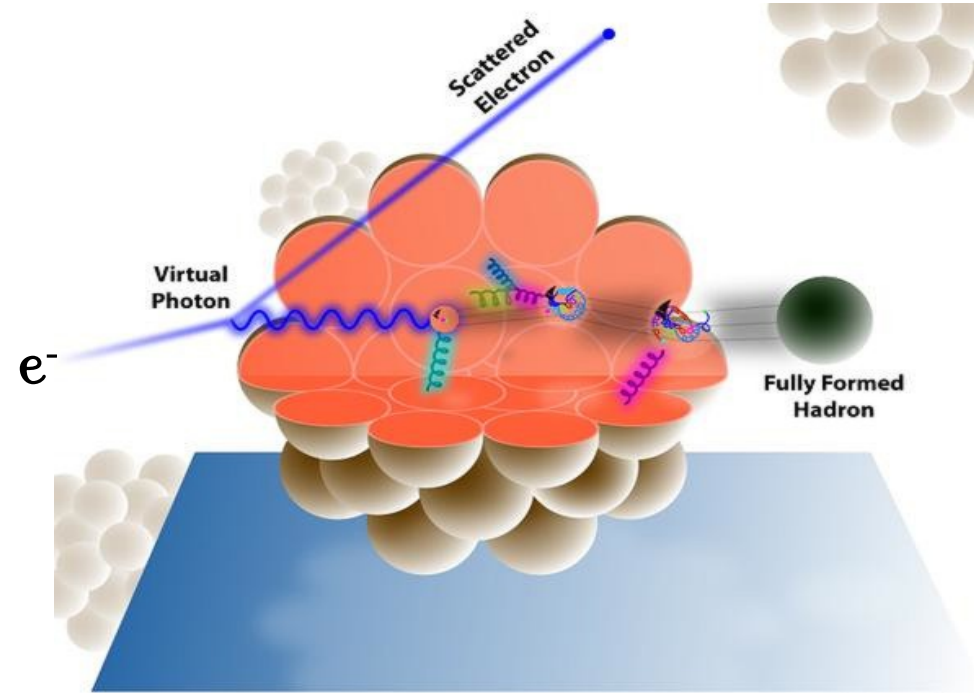
CLAS Collaboration Meeting
06/03/2021



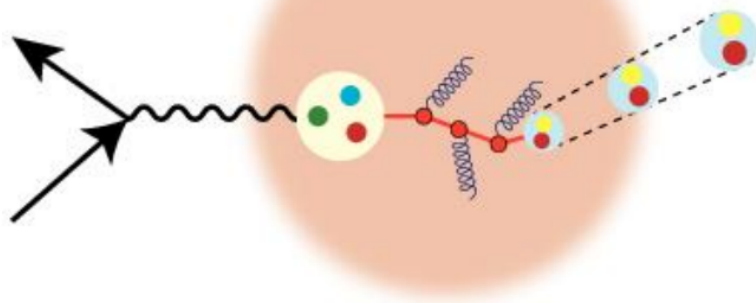
Probing QCD Dynamics

- Hadronization process:

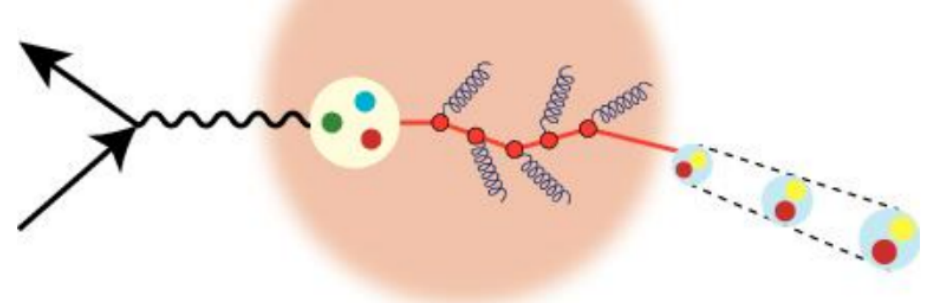
- ❖ Evolution of a colored bare quark into a fully dressed hadron.
- ❖ Quark propagation and Hadronization directly probe the QCD confinement dynamics.



Hadron formed inside nucleus



Hadron formed outside nucleus

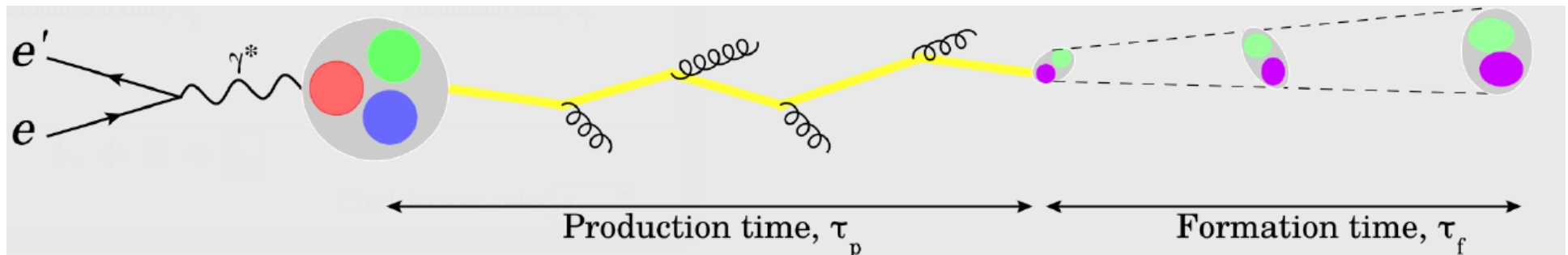


Depending on the size of nucleus, hadron formation can take place inside or outside the nucleus.

Probing QCD Dynamics

- **Hadronization Timescales:**

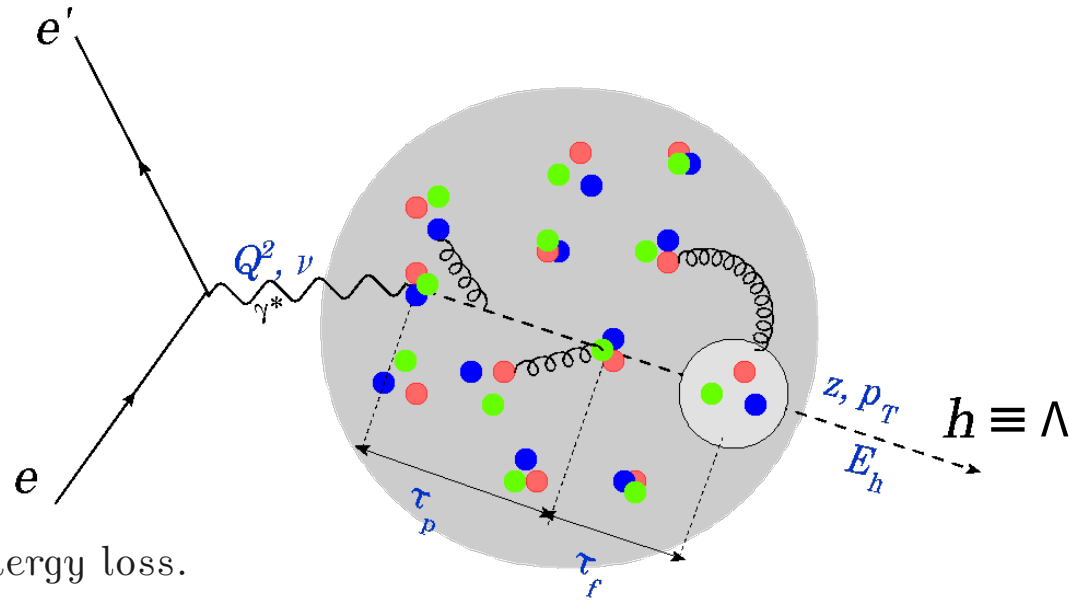
- ❖ Production time: Time spent by a deconfined quark to neutralize its color charge.
- ❖ Formation time: Time required to form a regular hadron.



- **Hadronization Studies:**

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

Λ SIDIS Kinematics



- ν : $E_e - E_{e'}$; Electron energy loss.
- Q^2 : Four-momentum transferred.
 - $Q^2 > 2 \text{ GeV}^2$ (to probe nucleon substructure).
- y : ν/E_e , electron energy fraction transferred to the struck quark.
 - $y < 0.85$ (to reduce the size of radiative effects).
- W : Total center of mass energy.
 - $W > 2 \text{ GeV}$ (to avoid contamination from resonance region).
- p_T : Hadron momentum transverse to the virtual photon direction.
- z : E_h/ν ; Fraction of the struck quark's initial energy carried by the formed hadron.
- x_F : $P_L^{\text{CM}} / P_L^{\text{max, CM}}$, Feynman variable, a fraction of the maximum longitudinal momentum carried by the observed hadron.

Experimental Observables

- Multiplicity ratio:

$$R_A^h(\nu, Q^2, z, p_T, \phi) = \frac{\left. \frac{N_h(\nu, Q^2, z, p_T, \phi)}{N_e(\nu, Q^2)|_{\text{DIS}}} \right|_A}{\left. \frac{N_h(\nu, Q^2, z, p_T, \phi)}{N_e(\nu, Q^2)|_{\text{DIS}}} \right|_D}$$

- Initial state effects are reduced/cancelled due to the normalization with the electron DIS events.

- Transverse momentum broadening (p_T broadening)

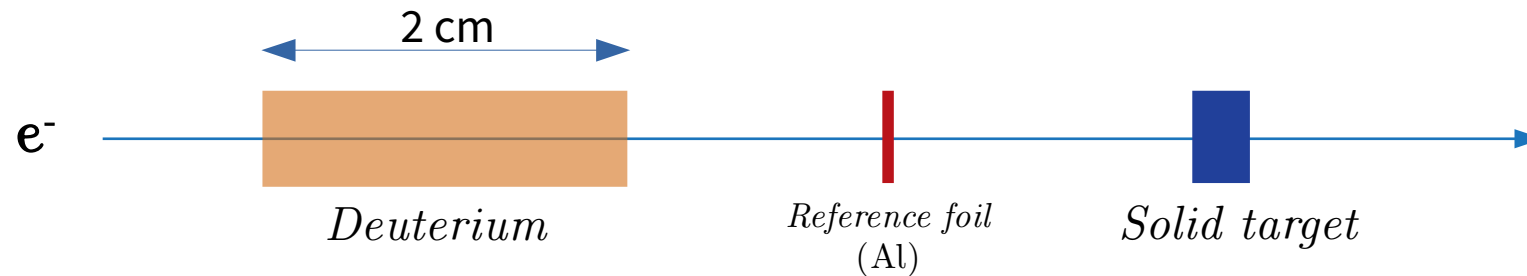
D = Deuterium
A = C, Fe, Pb

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

- 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).

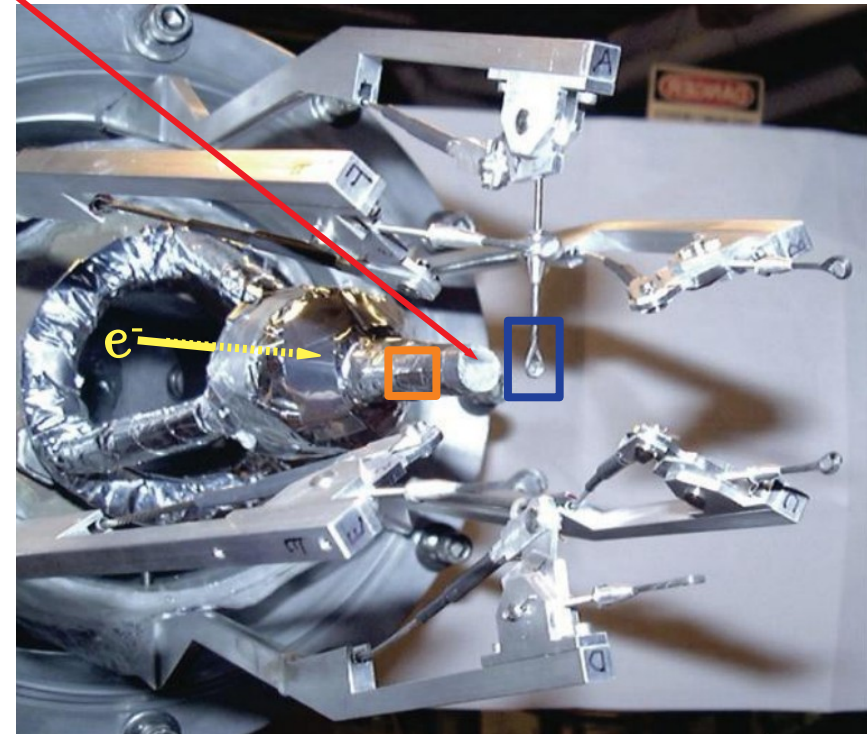
EG2 Run Conditions

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



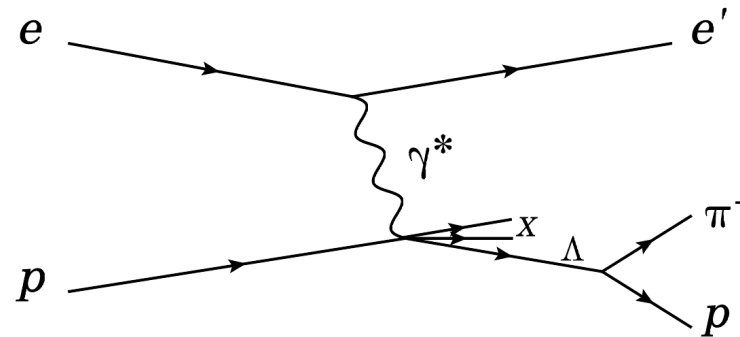
- Luminosity $\sim 10^{34} \text{ s}^{-1} \text{ cm}^{-2}$
- Beam energy: 5.014 GeV
- Target separation $\sim 4 \text{ cm}$
- Solid Targets:

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

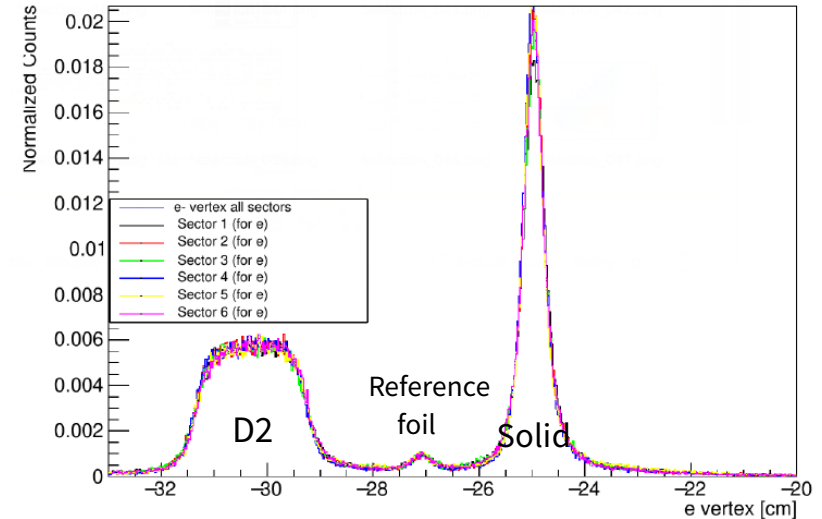


Cuts and Corrections

- Final state particles selected: one e ; at least one π^- and one p . Proton and pion mixture constitutes Lambda events.



- Electron ID: Positive response in DC, CC, SC and EC.
- Pion ID: Matching signal in DC and SC.
- Proton ID: Momentum dependent time analysis using ROOT's TSpline method.
- Vertex corrections applied.
- SIDIS cuts: $W > 2 \text{ GeV}$; $Q^2 > 1 \text{ GeV}^2$; $y < 0.85$.
- Corrections: Proton energy loss, electron momentum corrections applied.
- CLAS acceptance corrections.
- Endcap corrections (for multiplicity ratios).



Corrected e^- vertex distributions for six sectors of CLAS6 detector.

Acceptance Corrections

Variable	Range	# of Bins	Bin width
W [GeV]	2.0 – 2.8	2	0.4
ν	2.25 – 4.25	3	0.6
$\phi_{\pi^-}^*$ [deg]	0.0 – 360.0	2	180.0
$\Phi_{e'\Lambda}$ [deg]	0.0 – 360.0	3	120.0
p_Λ [GeV/c]	0.1 – 4.25	3	1.383
z	0.28 – 1.0	6	variable*

Total Bins = 648

- Generated 1B events using Pythia event generator for each target (Fe, C, Pb and D2).
- Six dimensional binning.
- *variable z-binning:

Bin #	1	2	3	4	5	6
z_{min}	0.28	0.38	0.44	0.51	0.60	0.75
z_{max}	0.38	0.44	0.51	0.60	0.75	1.00

- W: Total center of mass energy
- ν : Electron energy loss.
- ϕ_{π^-} : Decay angle of π^- in Λ rest frame.
- $\Phi_{e'\Lambda}$: Angle between leptonic and hadronic planes
- p_Λ : Momentum of Lambda
- z: Fraction of the struck quark's initial energy carried by the formed hadron.

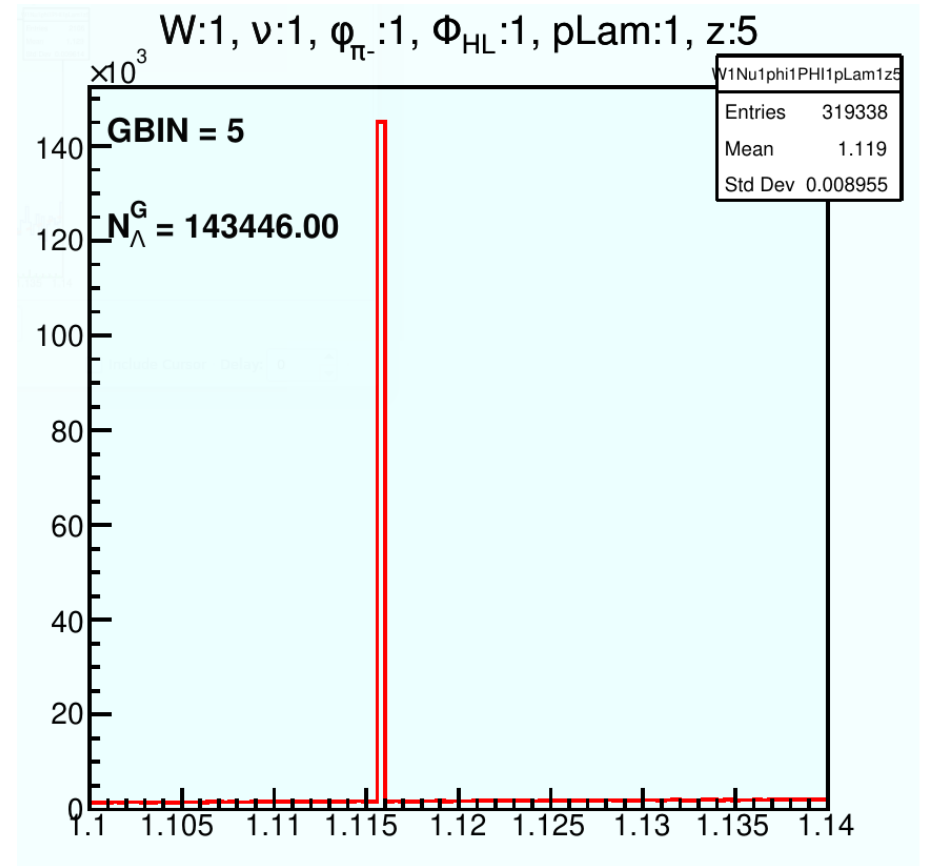
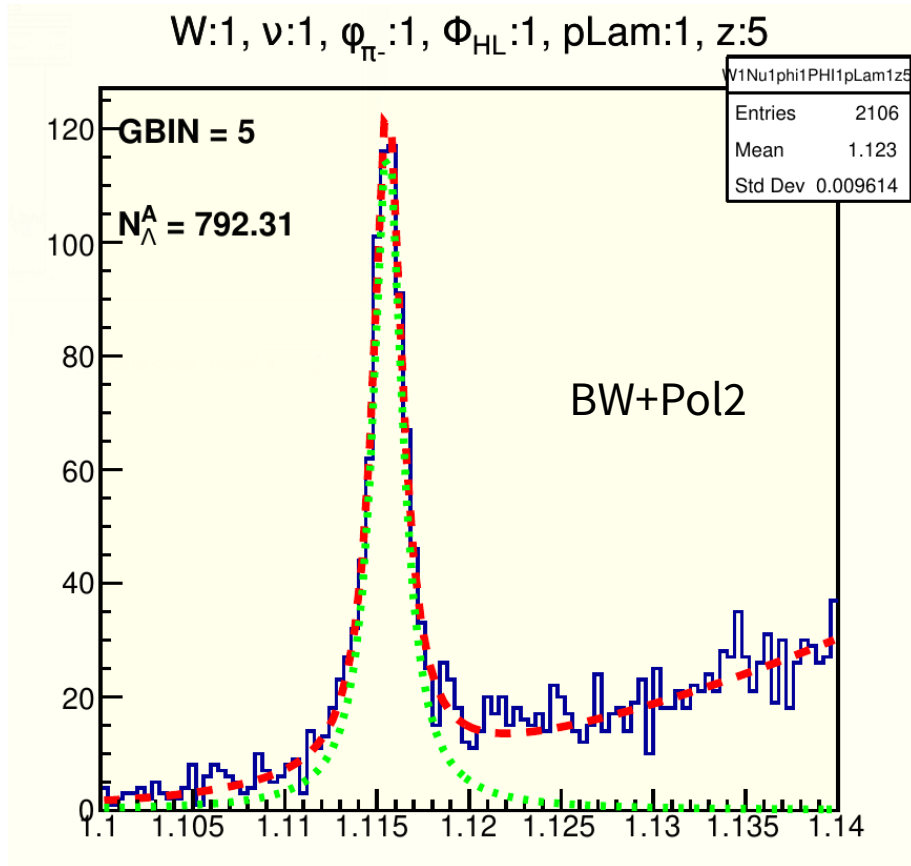
$$Bin, \quad k = (W, \nu, \theta_{\pi^-}^*, \phi_{\pi^-}^*, p_\Lambda, \Phi_{e'\Lambda}, z)$$

$$eff_k = \frac{N_{acc}(W, \nu, \theta_{\pi^-}^*, \phi_{\pi^-}^*, p_\Lambda, \Phi_{e'\Lambda}, z)}{N_{gen}(W, \nu, \theta_{\pi^-}^*, \phi_{\pi^-}^*, p_\Lambda, \Phi_{e'\Lambda}, z)}$$

$$\text{Weight, } w_k = \frac{1}{eff_k}$$

* represents rest frame of Λ .

Accepted and Generated Lambda Events



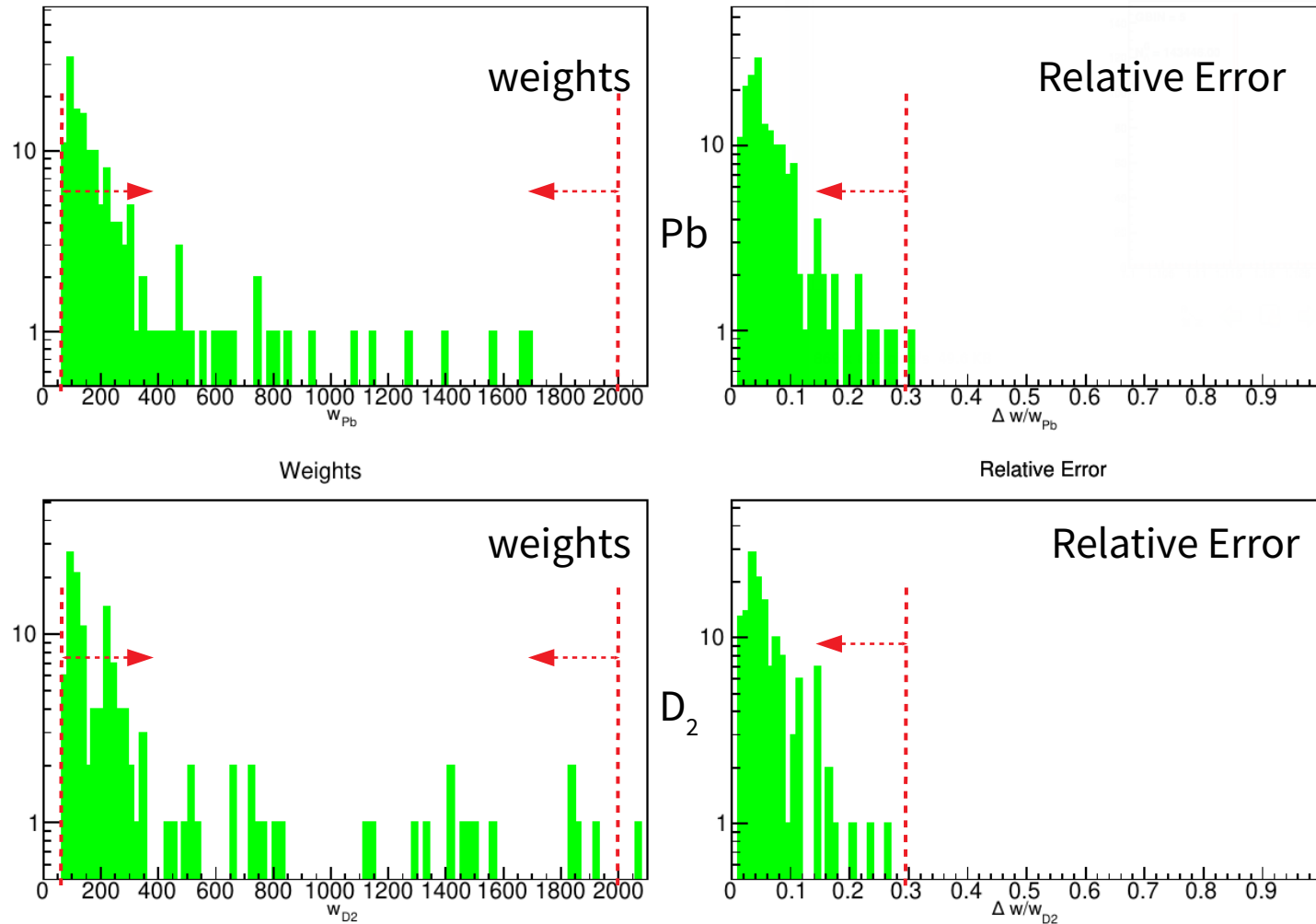
- Accepted Lambda events are extracted from the fit.
- Generated Lambda events are counted only from the peak.

$$eff_k = \frac{N_{acc}(W, \nu, \theta_{\pi^-}^*, \phi_{\pi^-}^*, p_{\Lambda}, \Phi_{e'\Lambda}, z)}{N_{gen}(W, \nu, \theta_{\pi^-}^*, \phi_{\pi^-}^*, p_{\Lambda}, \Phi_{e'\Lambda}, z)} = 0.00552$$

$$\text{Weight, } w_k = \frac{1}{eff_k} = 181.048$$

Relative error on weight, $\Delta w_k / w_k = 0.29$

Cuts on the Weights and Relative Error



$$60 \leq w < 2000$$

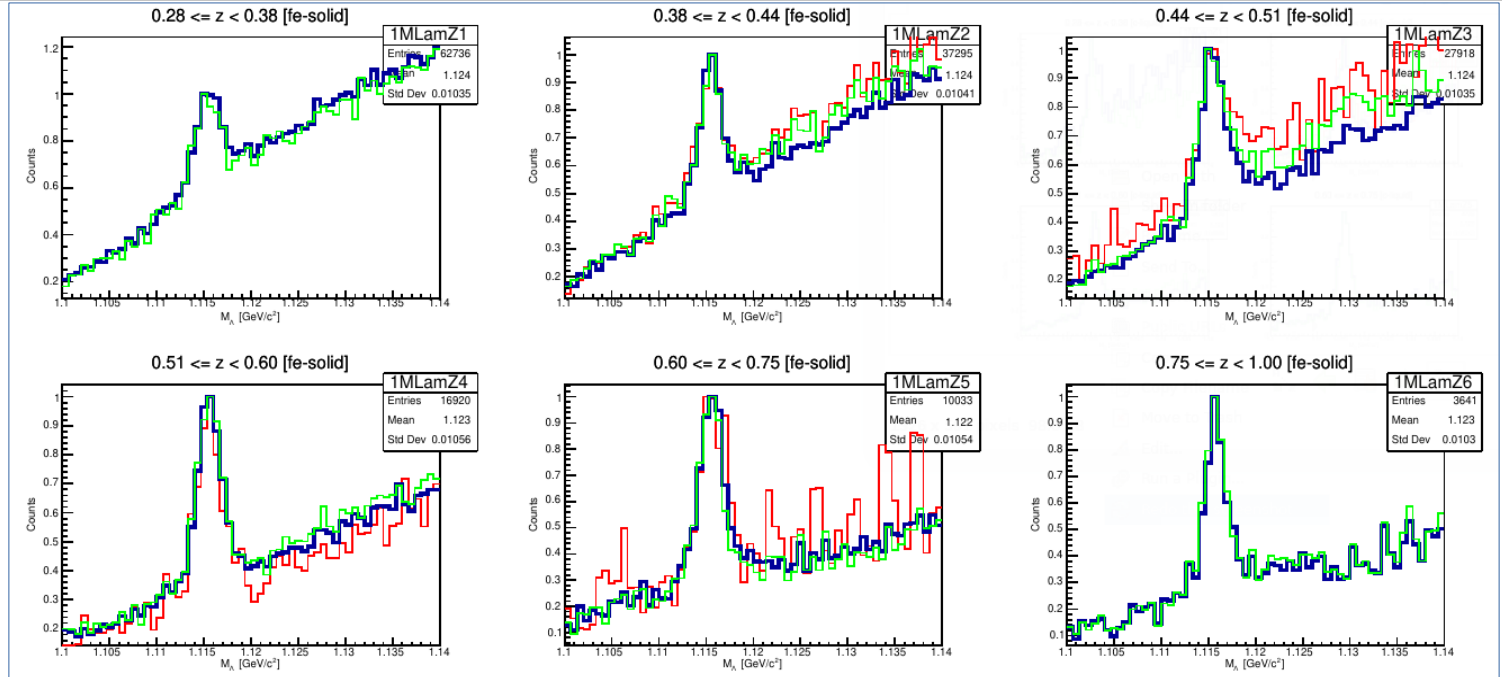
$$0.0 < \Delta w/w < 0.3$$

Other targets: Backup slides

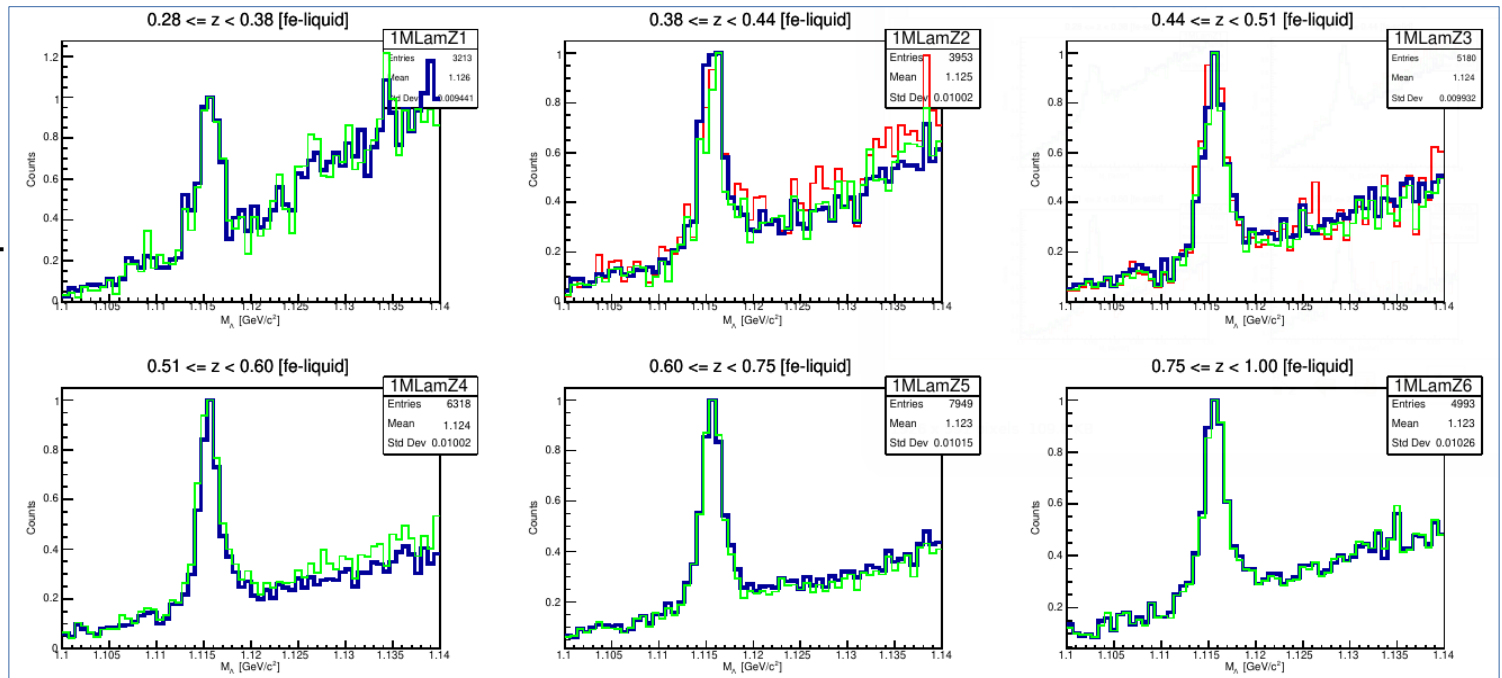
Effect of Weight Cuts on Λ Mass Distributions

- Uncorrected.
- Correction applied without weight cuts.
- Corrections applied with weight cuts.

D2Fe-Solid



D2Fe-Liquid



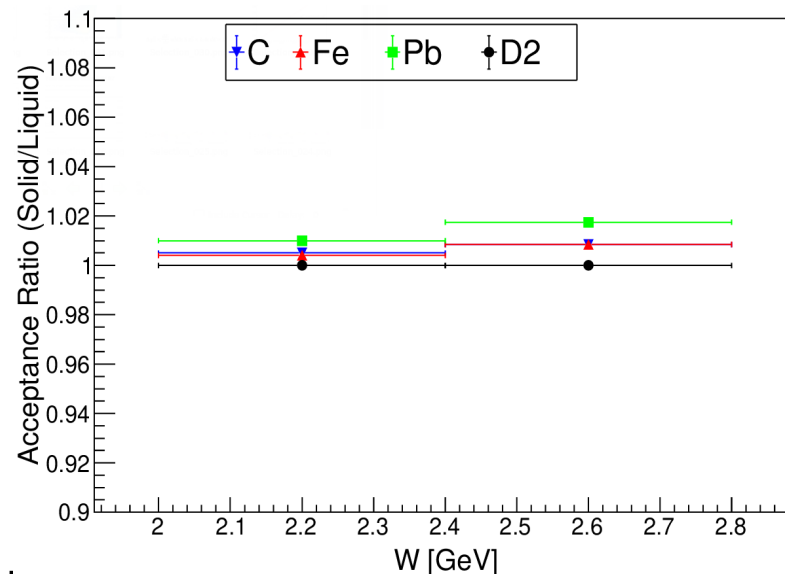
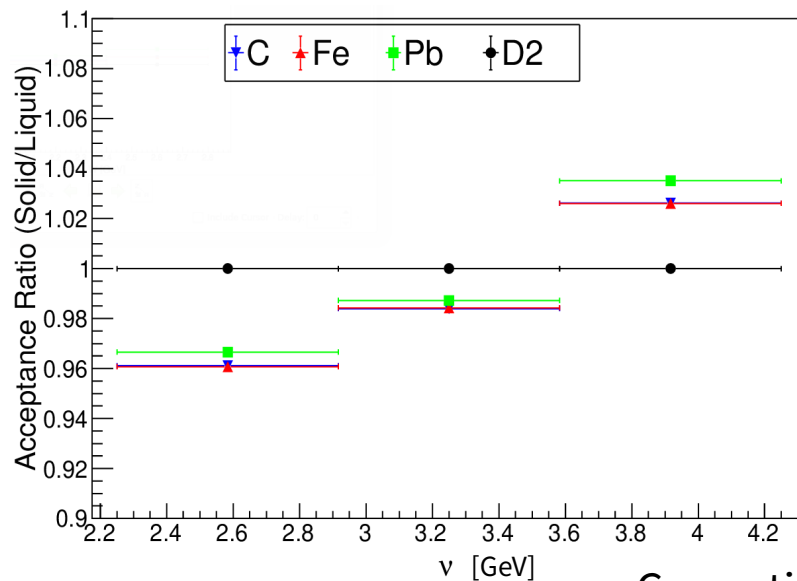
$$60 \leq w < 2000$$

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Other targets: Backup slides

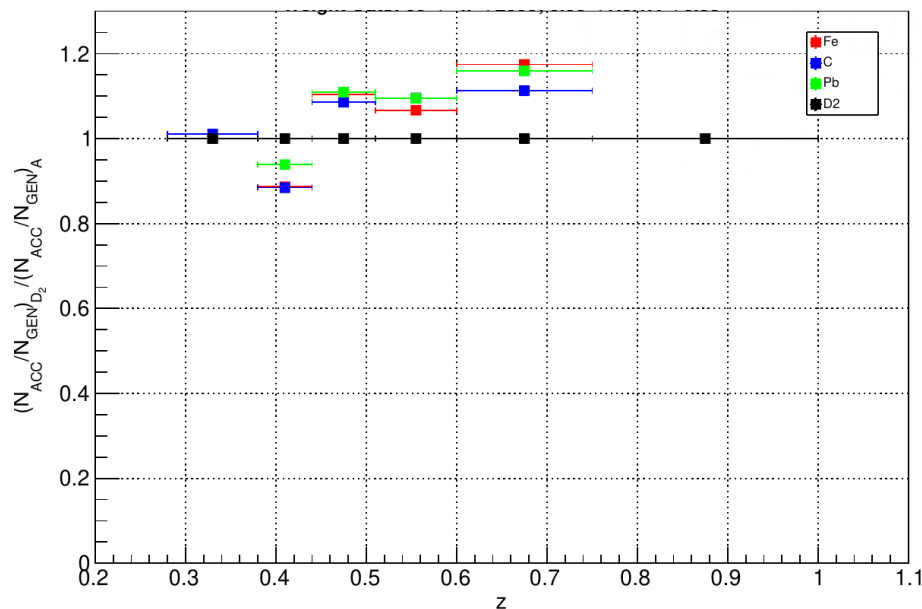
Acceptance Corrections

DIS electrons

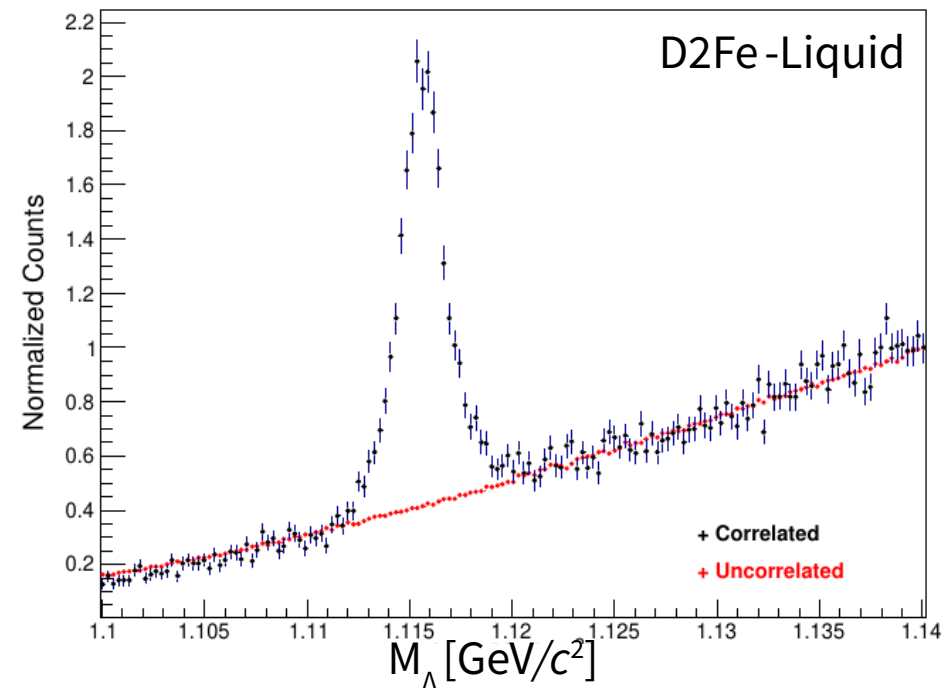
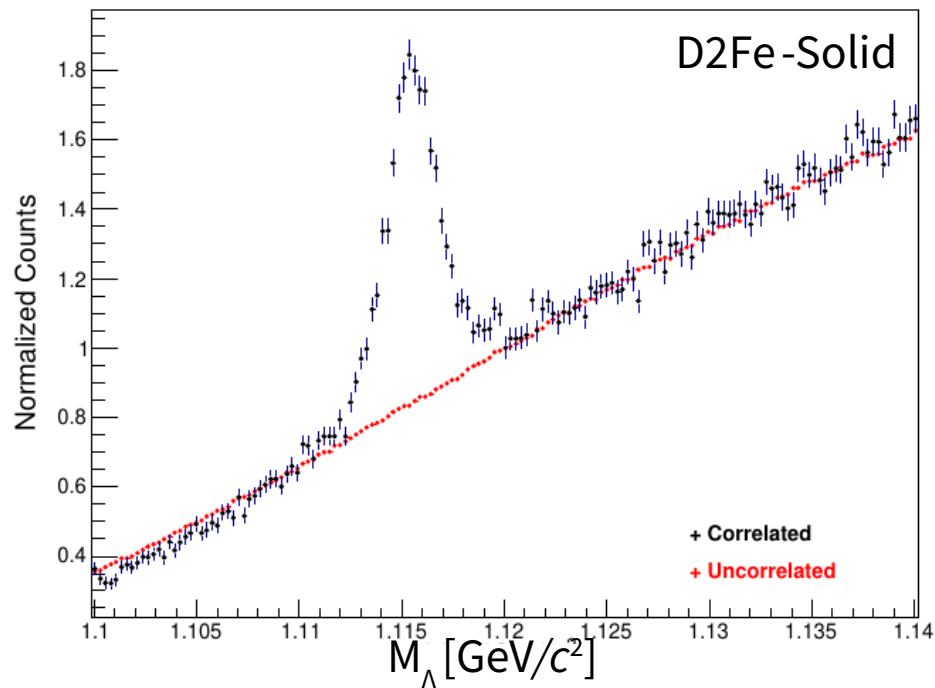


Correction is less than ~4%

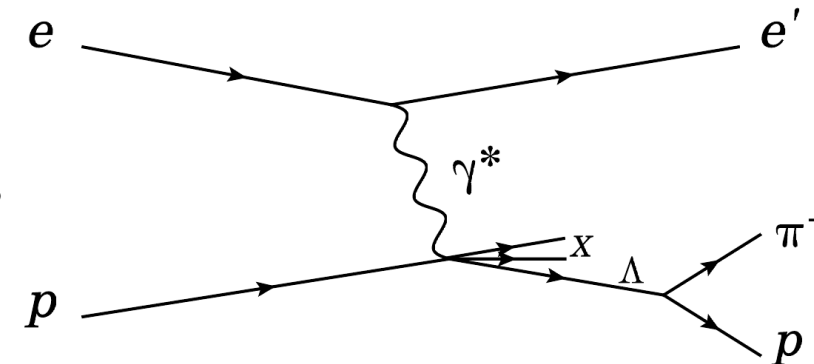
z-dependence



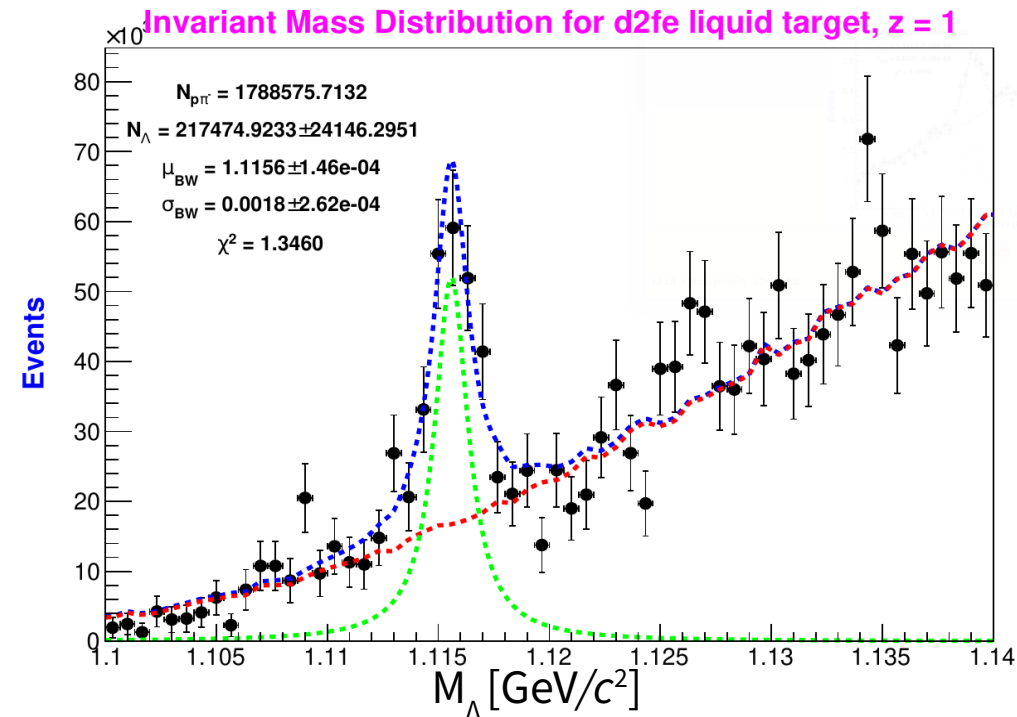
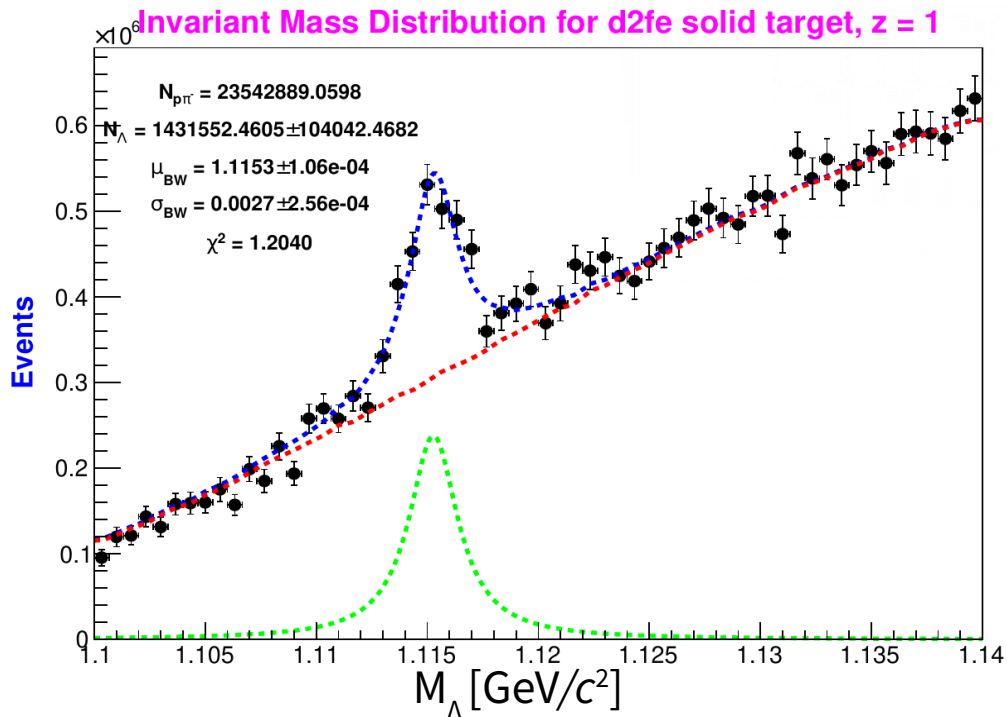
Global correction due to the weight cuts



- Correlated protons and pions mixture constitutes the Λ events with a peak at ~ 1.1156 GeV.
- Uncorrelated protons and pions mixture describes the background.
- Using RooFit (ROOT's fitting toolkit), the background subtracted Lambda-yield is extracted.

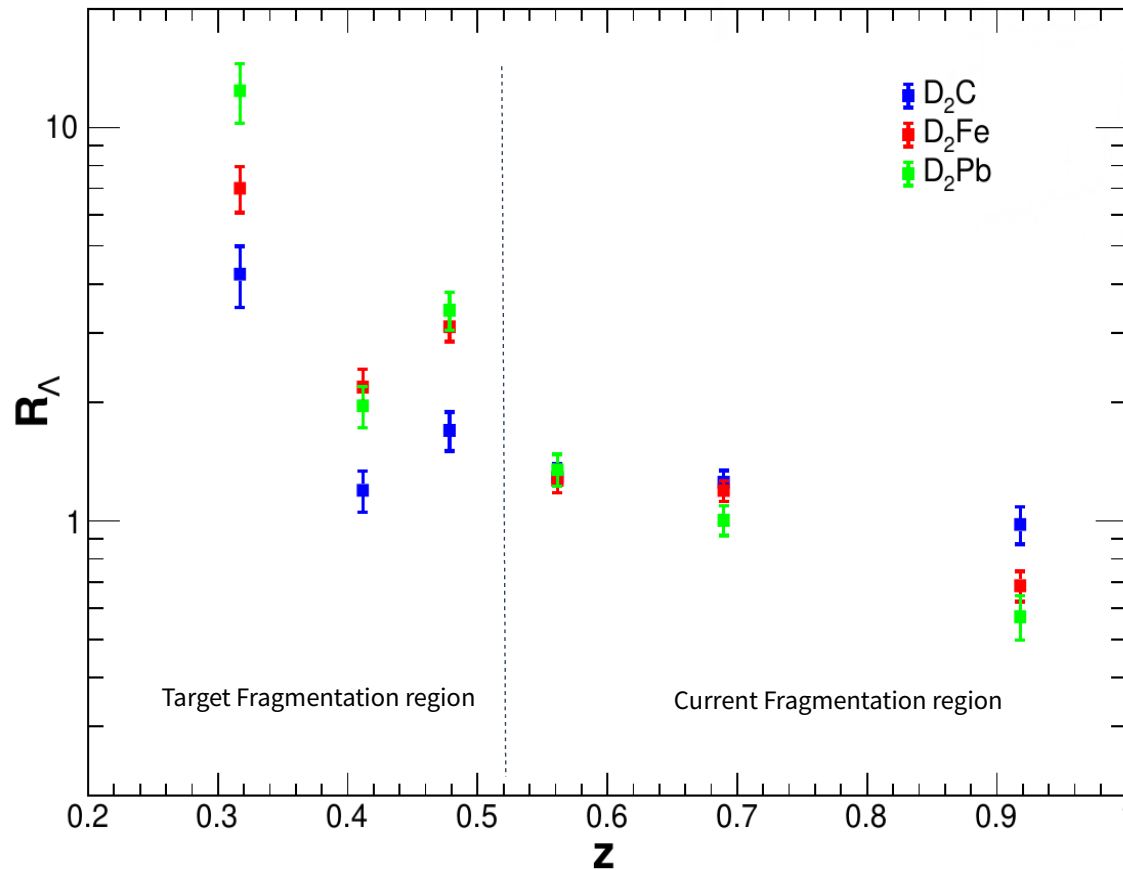


- A sample z-bin: Λ invariant mass distribution after the background subtraction using RooFit minimization (Breit-Wigner + combinatoric background).

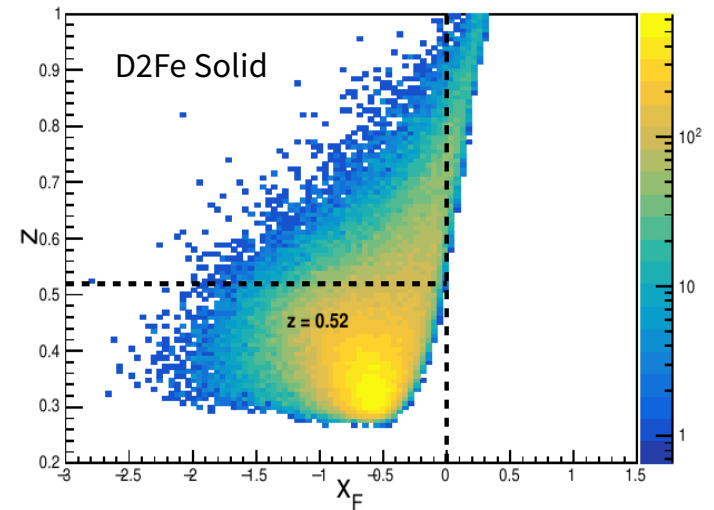


Bin #	1	2	3	4	5	6
z_{\min}	0.28	0.38	0.44	0.51	0.60	0.75
z_{\max}	0.38	0.44	0.51	0.60	0.75	1.00

* Radiative corrections
provided by A. El Alaoui

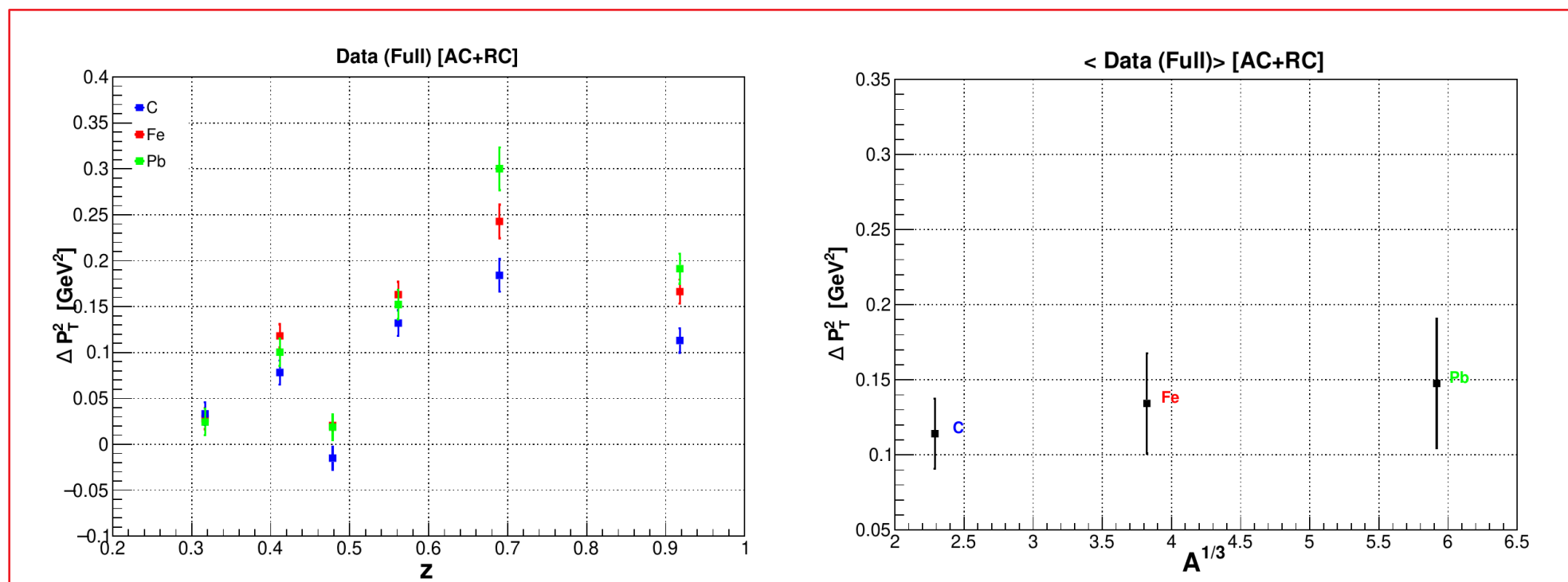
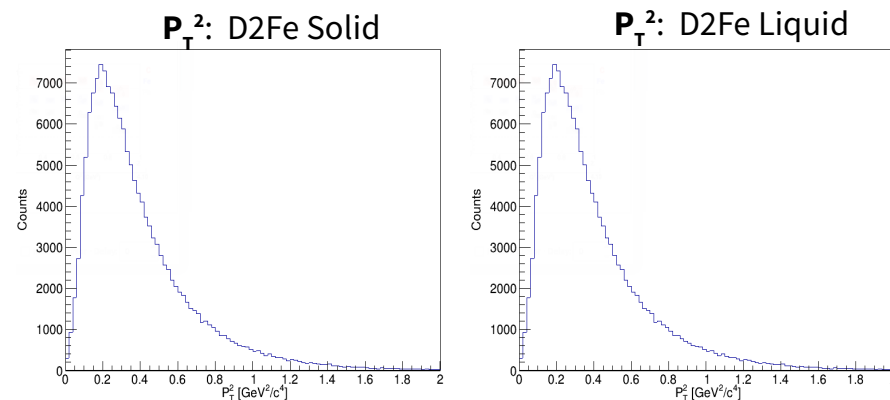


$$R_A^h(z) = \frac{\left. \frac{N_h(z)}{N_e|_{DIS}} \right|_A}{\left. \frac{N_h(z)}{N_e|_{DIS}} \right|_{D_2}}$$



- **Current fragmentation region:** struck quark initiates the hadronization process
- **Target fragmentation region:** The target remnant moves reciprocally with regard to the virtual photon direction undergoing a target fragmentation.
- An **attenuation flip** is observed at low z region for heavier nuclei.
- **First ever study** of the hadronization process of Λ hyperon which probes the forward (current) and backward (target) fragmentation regions.

- p_T^2 distributions recorded for Λ mass range:
 $1.1 \leq M_\Lambda < 1.14$ GeV (**Full**).
- $\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$



- More broadening at high z .
- More broadening observed in heavier nuclei.

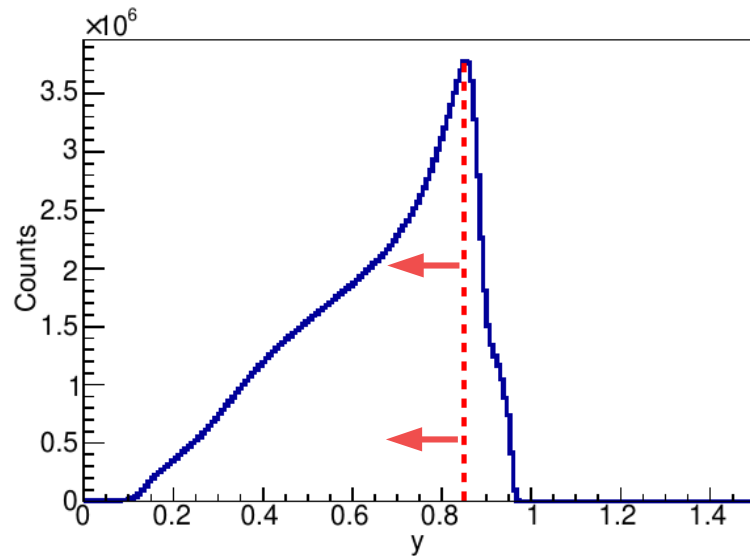
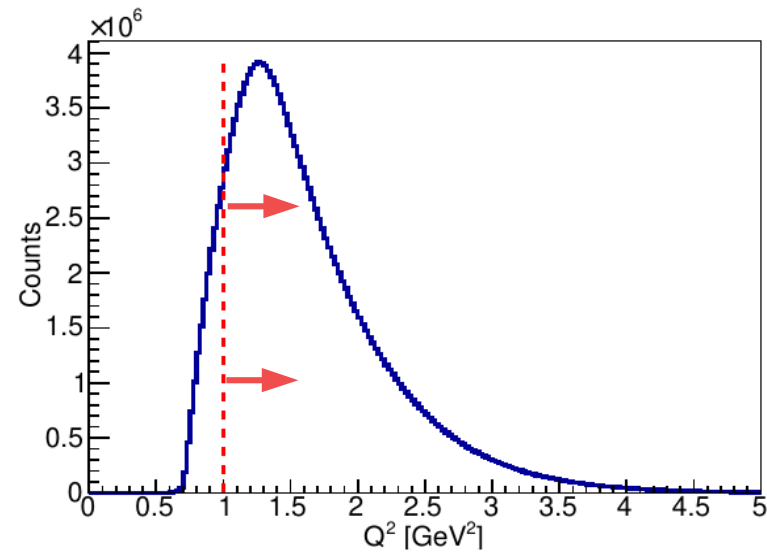
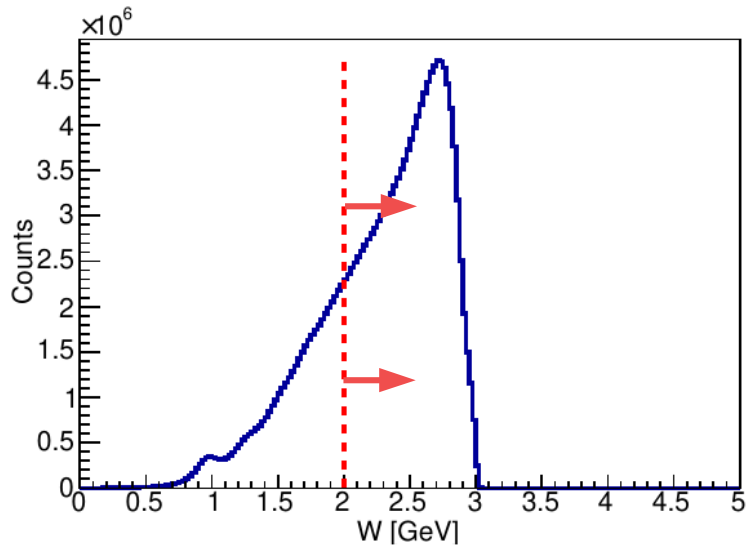
Summary and Outlook

- First ever study of the hadronization process of Λ -hyperon probing the current- and target-fragmentation regions.
- Results from the baryon and meson channels using the same EG2 dataset are consistent.
- Next steps would include:
 - Finalize the analysis review and work on the paper draft.
 - Outlook: Study other dependencies of R_Λ on Q^2 , P_T^2 (Cronin effect).

Thank you!

Extras

Selection of SIDIS Events: Kinematic Cuts



$$W > 2 \text{ GeV}$$

→ to avoid contamination from resonance region.

$$Q^2 > 1 \text{ GeV}^2$$

→ to probe nucleon substructure.

$$y < 0.85 \text{ (based on HERMES study)}$$

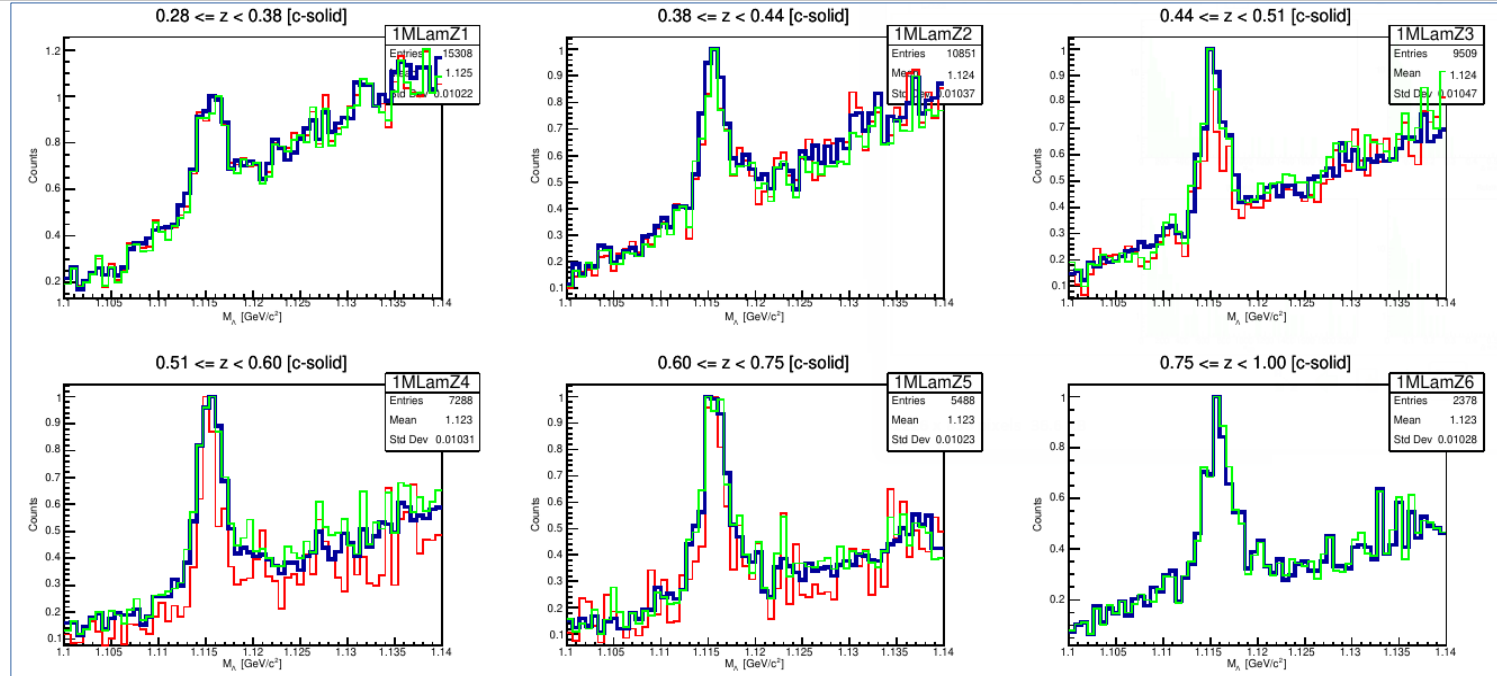
→ to reduce the size of radiative effects.

Effect on Λ Mass Distributions

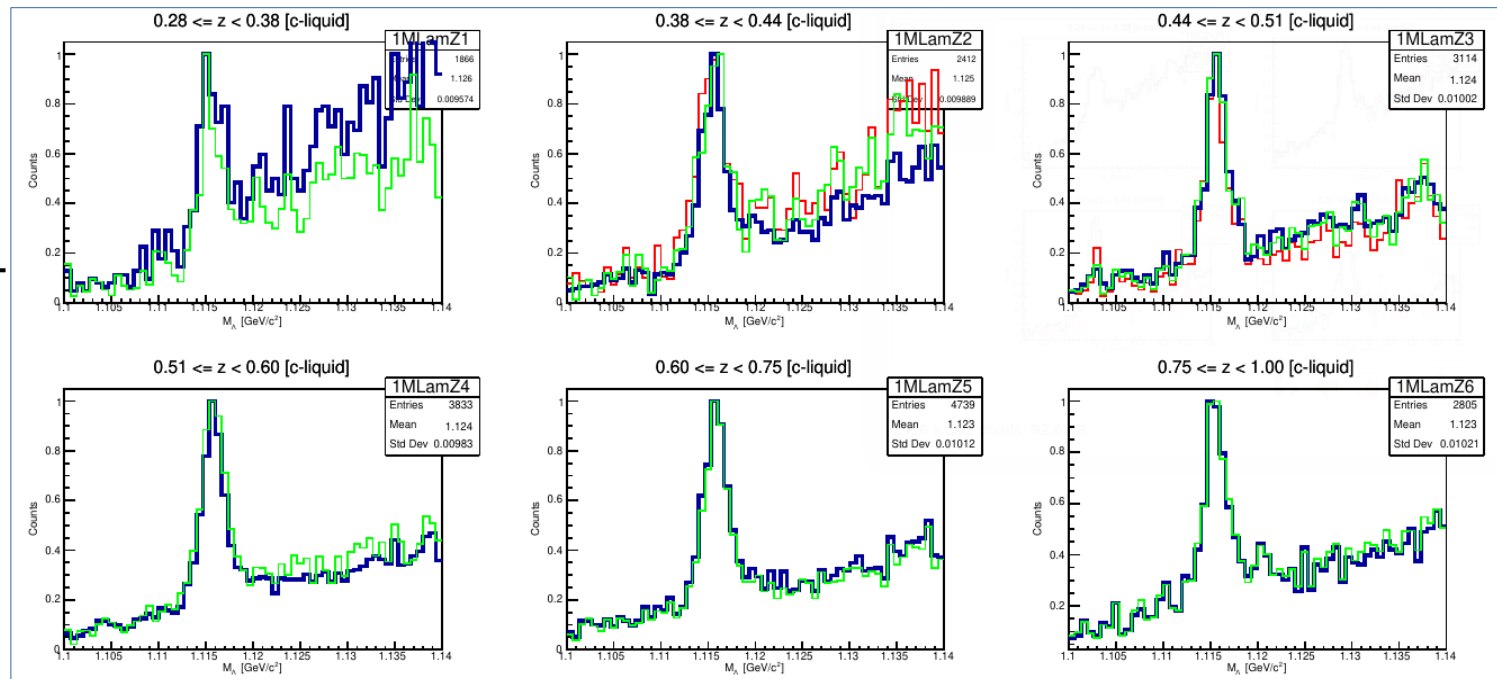
Preliminary

- Uncorrected.
- Correction applied without weight cuts.
- Corrections applied with weight cuts.

D2C-Solid



D2C-Liquid



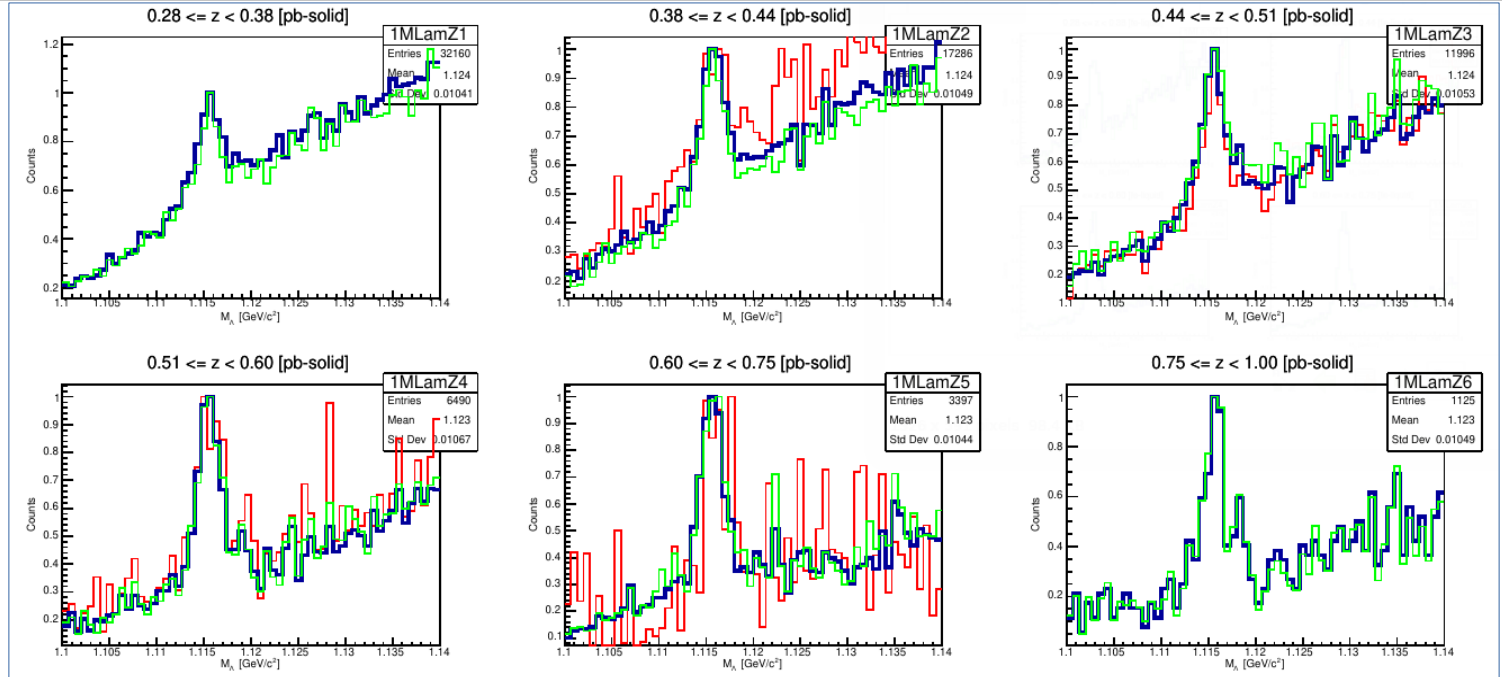
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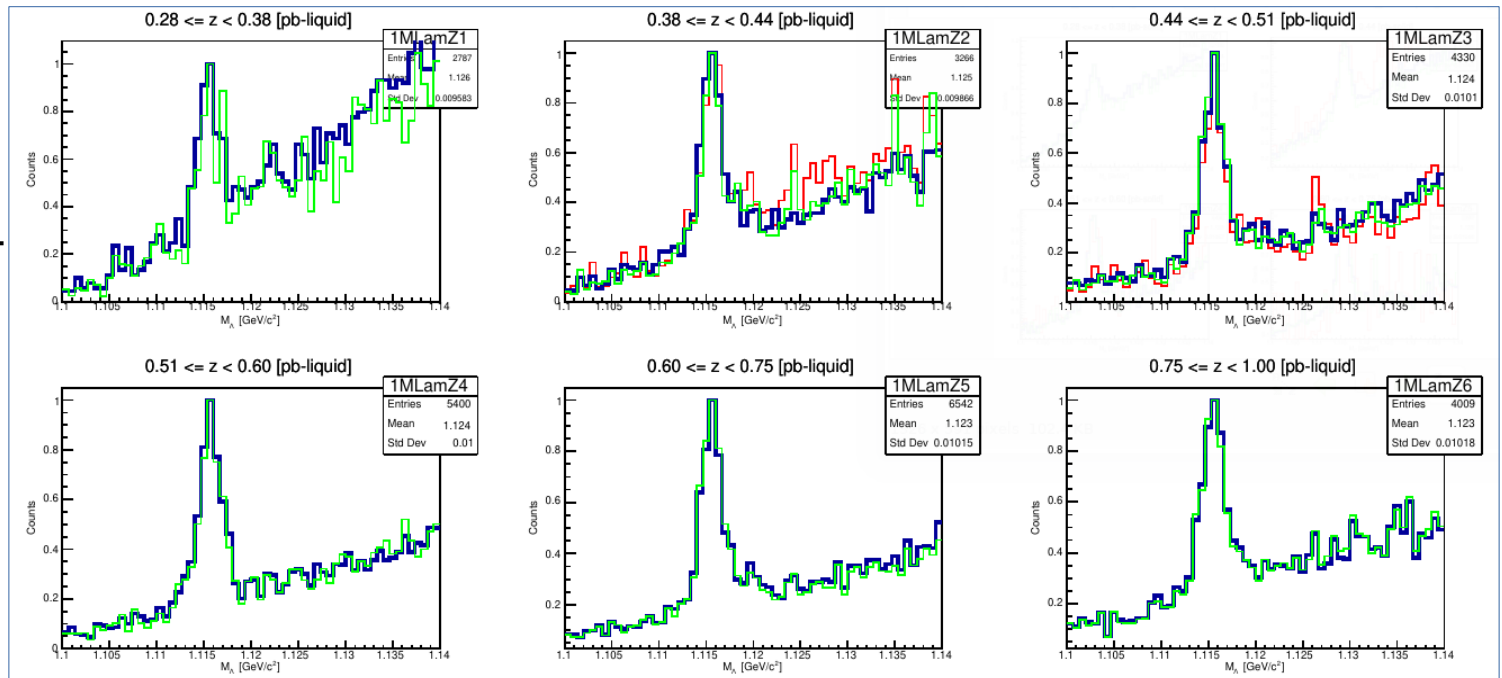
Effect of Weight Cuts on Λ Mass Distributions

- Uncorrected.
- Correction applied without weight cuts.
- Corrections applied with weight cuts.

D2Pb-Solid



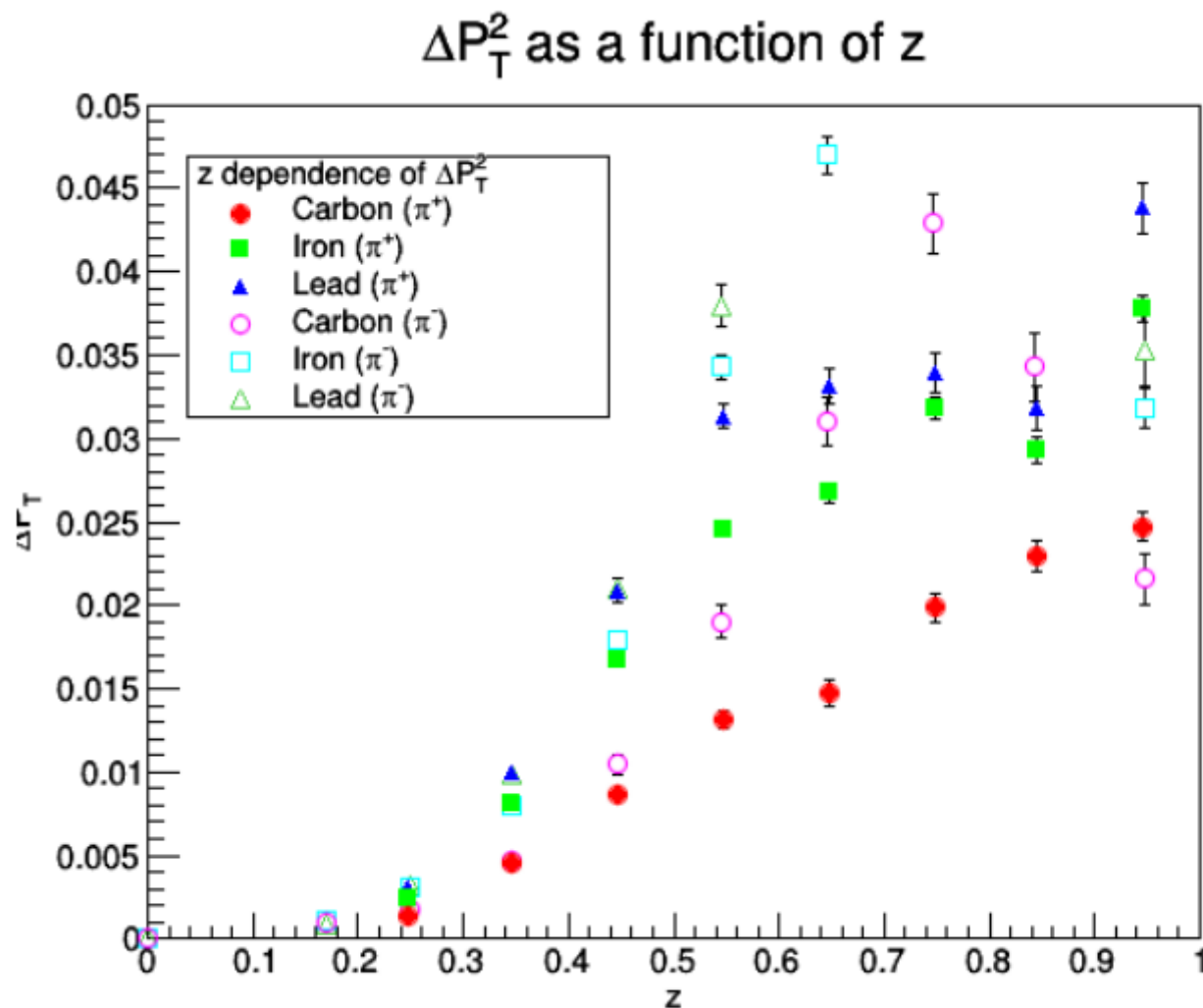
D2Pb-Liquid



$$60 \leq w < 2000$$

$$0.0 < \Delta w/w < 0.3$$

Transverse Momentum Broadening: Mesons



Study of the hadronization of charged pions
(Undergoing CLAS review)
-R. Dupre

- Proton PID (1-3%)
- Vertex Correction (1-2%)
- Combinatorial background subtraction: (1-2%)
- Acceptance correction:
 - Weight cut (1-5%)
- Signal fitting:
 - Relativistic Breit-Wigner ($\sim 4\%$)
 - Ross-Stodolosky equation ($\sim 6\%$)
 - Soding parametrization ($\sim 5\%$)
- Effect of the variation of the invariant mass range, radiative effect, end-cap corrections are currently ongoing.

Total of systematic effects $\sim 10 - 15\%$