Updates on the η and ω Hadronization Analysis

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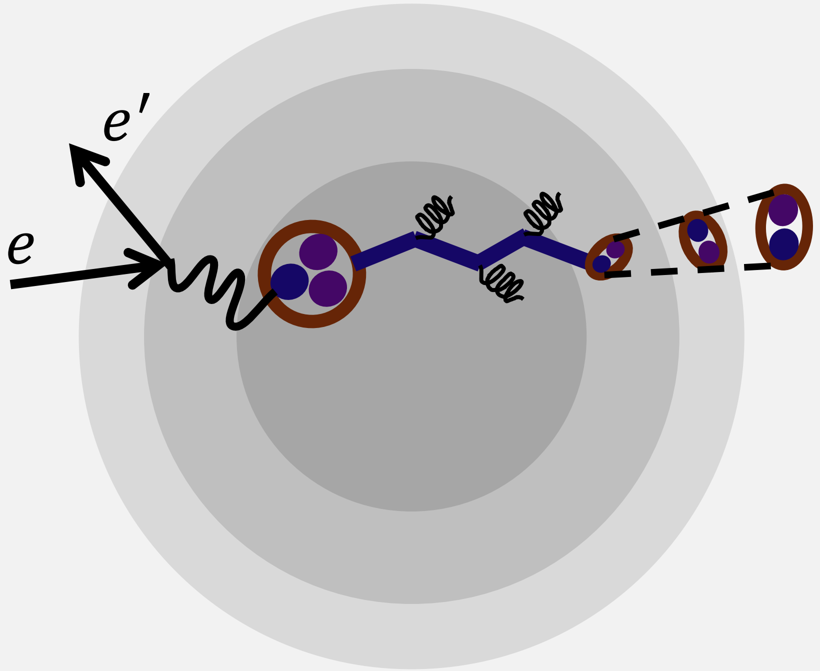
IV. Results and Discussion

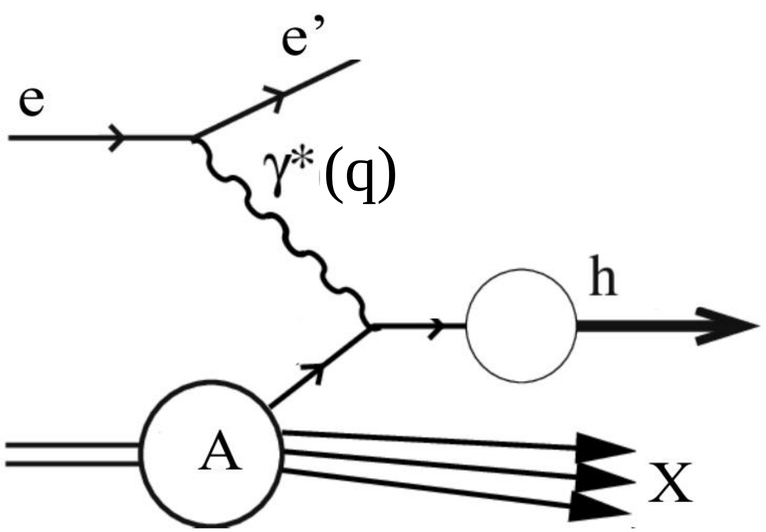
Hadronization is the formation of quarks and gluons into hadrons. **But how do nuclei of different sizes impact on this process?**



Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

Semi-Inclusive Deep-Inelastic Scattering (SIDIS) is the experimental process that allows to extract information about the quarks and gluons inside the proton.

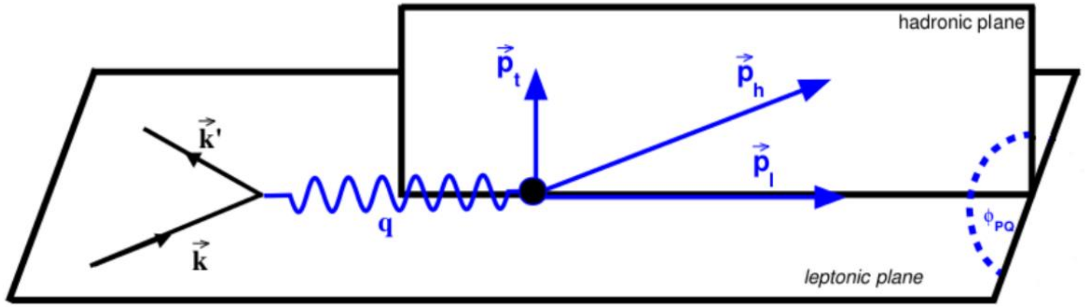
$$\boldsymbol{e(k)\, A(p) \;\rightarrow e'(k')\, h(p_h)\, X}$$



Electron variables:

- $Q^2 \equiv -q^2 \underset{lab}{\longrightarrow} 4\, E_b E' \sin^2(\theta/2)$: virtuality of the probe electron.
- $\nu = \frac{p \cdot q}{M} \underset{lab}{\longrightarrow} E_b - E'$: energy transferred from the electron to the target.

Hadron variables:



- $z_h = \frac{p \cdot p_h}{p \cdot q} \underset{lab}{\longrightarrow} \frac{E_h}{\nu}$: fraction of the virtual photon energy carried by the produced hadron.
- $p_T^2 = p_h^2\left(1 - \cos\theta_{PQ}\right)$: transversal momentum of the hadron w.r.t. the virtual photon direction.

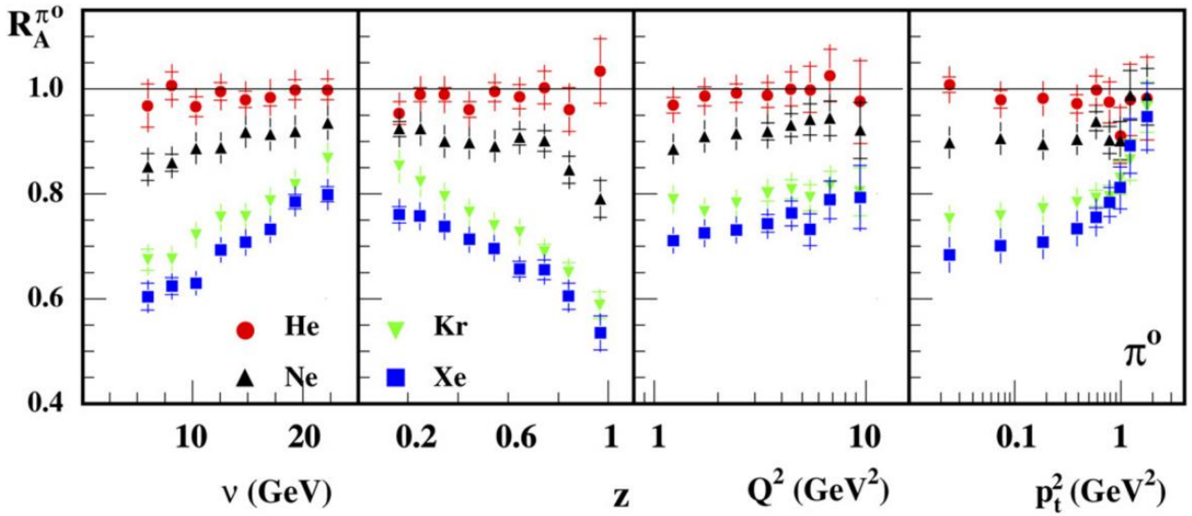
Multiplicity Ratio

The experimental **observable** to measure is the **Multiplicity Ratio** R_A^h observed in the scattering of a nucleus (A) to those on the deuteron (D):

$$R_A^h(Q^2,\nu,z_h,p_T^2) \equiv \frac{\left(\frac{N_h(Q^2,\nu,z_h,p_T^2)}{N_e^{DIS}(Q^2,\nu)}\right)_A}{\left(\frac{N_h(Q^2,\nu,z_h,p_T^2)}{N_e^{DIS}(Q^2,\nu)}\right)_D},$$

where:

- $\boldsymbol{N_h}$ is the number of semi-inclusive hadrons h in a given (Q^2,ν,z,p_T^2) bin.
- $\boldsymbol{N_e^{DIS}}$ the number of inclusive inclusive **DIS** electrons in the same (Q^2,ν) bin.

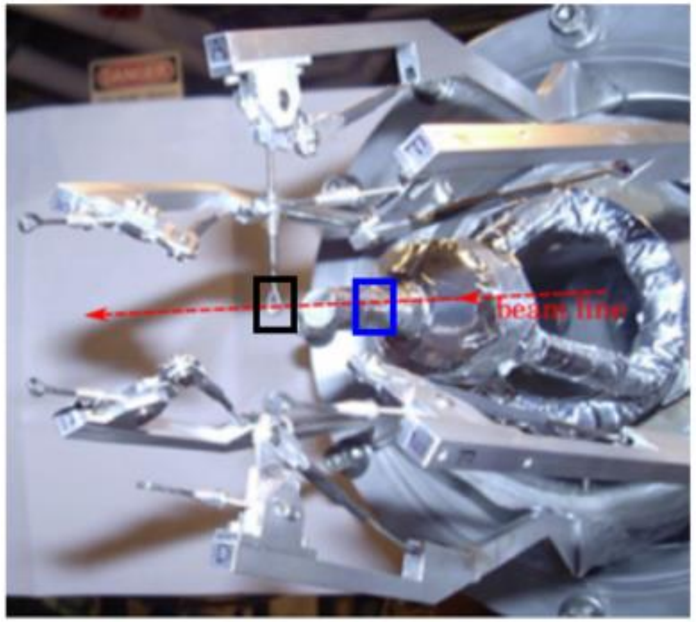


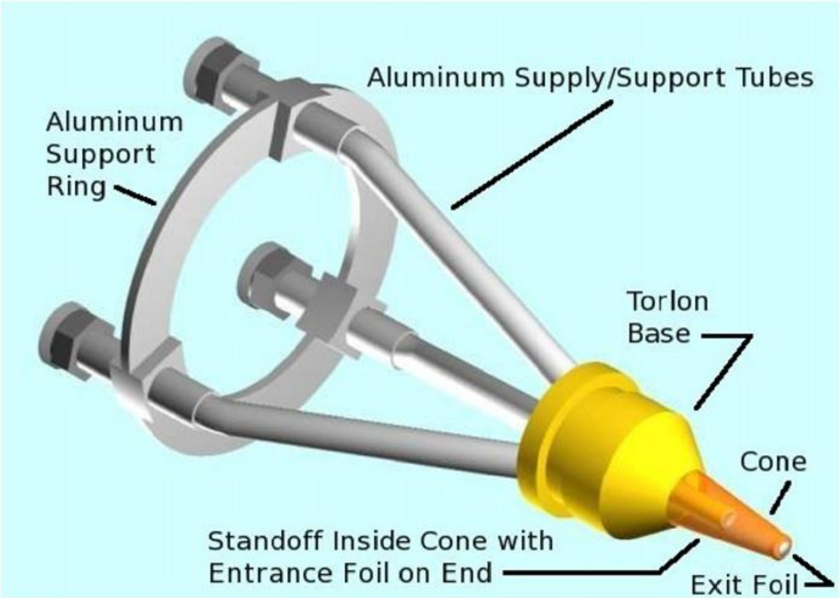
HERMES Collaboration. Nucl. Phys. B 780 (2007)

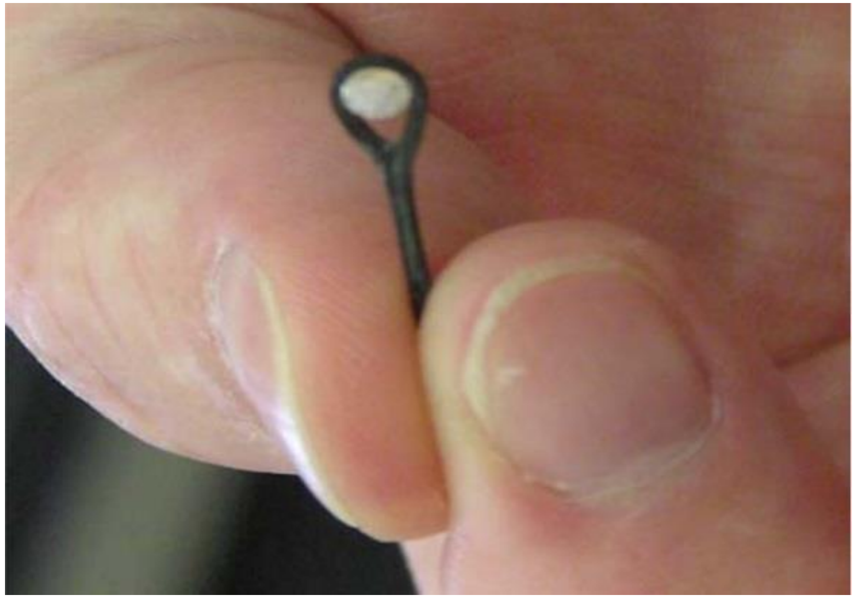
The EG2 Experiment

This experiment consisted of a 5 GeV electron beam incident on a double-target system where the beam passed through a **liquid target D (Deuterium)** and a **solid heavy target $A(C, Fe, Pb)$** simultaneously positioned in the **beam line**.

<u>Main features</u>: same luminosity for different nuclei, and reduction of systematic uncertainties.







The Program of the EG2 Experiment

DIS channels: *stable* hadrons, accessible with 11 GeV
JLab experiment PR12-06-117

Actively underway with existing 5 GeV data

	meson	cτ	mass	flavor content
3-dimensional MR	π^0	25 nm	0.13	$u\bar{u}d\bar{d}$
4-dimensional MR	π^+, π^-	7.8 m	0.14	$u\bar{d}, d\bar{u}$
1-dimensional MR	η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$
1-dimensional MR	ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$
	η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$
	ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$
	$f1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$
1-dimensional MR	K^0	27 mm	0.50	$d\bar{s}$
	K^+, K^-	3.7 m	0.49	$u\bar{s}, \bar{u}s$

baryon	cτ	mass	flavor content	
p	stable	0.94	ud	3-dimensional MR
$\bar{p}$	stable	0.94	$\overline{ud}$	
Λ	79 mm	1.1	uds	1-dimensional MR
$\Lambda(1520)$	13 fm	1.5	uds	
Σ^+	24 mm	1.2	us	
Σ^-	44 mm	1.2	ds	
Σ^0	22 pm	1.2	uds	
Ξ^0	87 mm	1.3	us	
Ξ^-	49 mm	1.3	ds	

Comparison of particles

Particle	π^0	η	ω
Charge	0	0	0
Type of meson	Pseudoscalar	Pseudoscalar	Vector
Mass	~ 0.135 GeV	~ 0.548 GeV	~ 0.782 GeV
Mean lifetime	$\sim 10^{-17}$ s	$\sim 10^{-19}$ s	$\sim 10^{-23}$ s
Quark content	$u\bar{u} - d\bar{d}$	$u\bar{u} + d\bar{d} - 2s\bar{s}$	$u\bar{u} + d\bar{d}$
Decay channels	$\pi^0 \to \gamma\gamma$ (99%)	$\boldsymbol{\eta \to \gamma\gamma}$ **(39%)** $\eta \to \pi^0\pi^0\pi^0$ (33%) $\eta \to \pi^+\pi^-\pi^0$ (23%)	$\boldsymbol{\omega \to \pi^+\pi^-\pi^0}$ **(89%)** $\omega \to \pi^0\gamma$ (8%)

This analysis corresponds to the world's first study on the hadronization of the η and ω meson.

Overview of cuts

Particle Identification

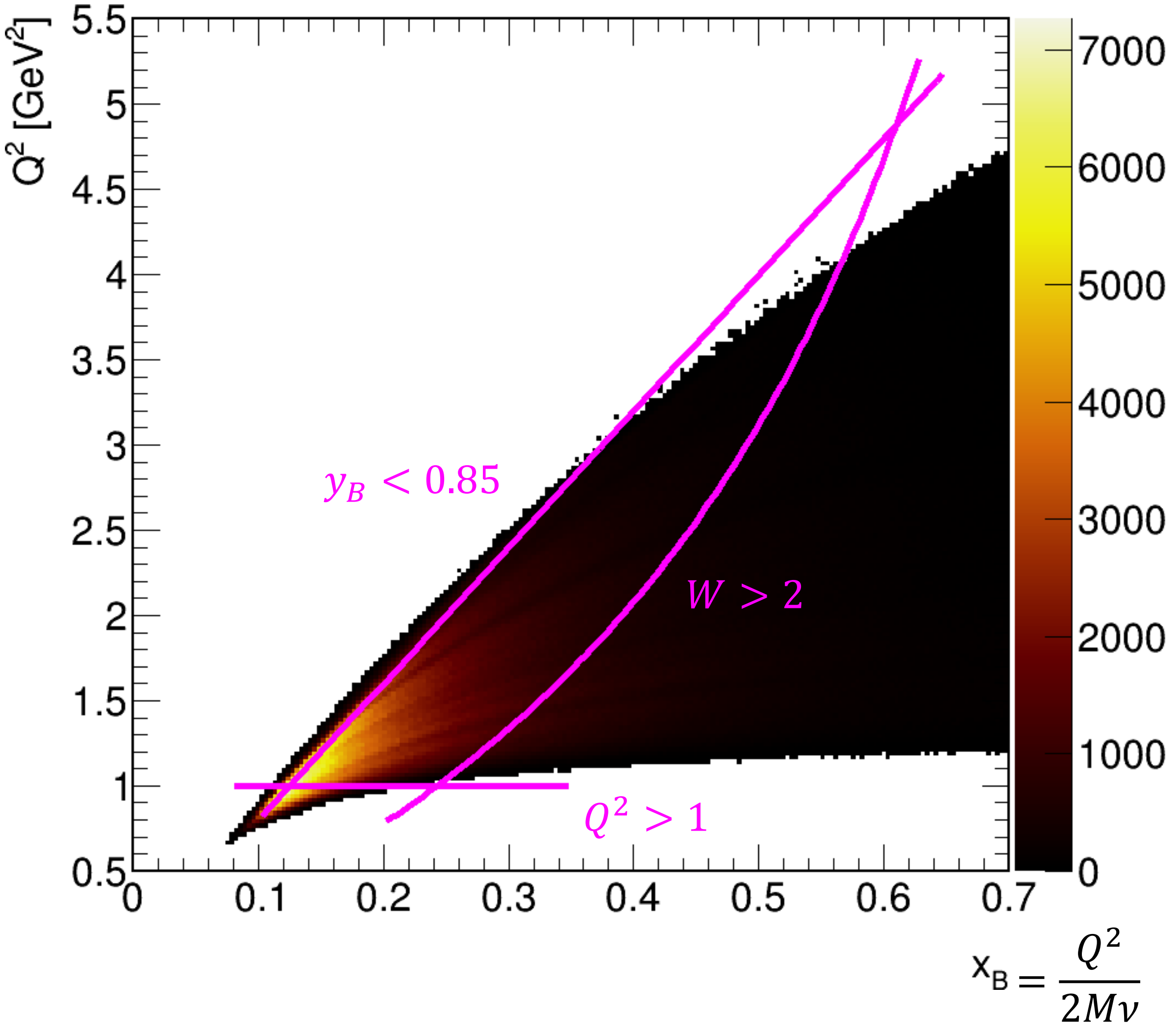
- Electrons, $\pi^+$and π^- ID are based on **S. Morán et al.** CLAS Analysis Note (2021)
- Photons ID is based on **T. Mineeva**. CLAS Analysis Note (2020)

Target Identification

Based on position of solid and liquid targets, done through electron vertex cuts.

Kinematical Region

- $Q^2 > 1\ \mathrm{GeV}^2$, necessary virtuality to probe nucleon substructure.
- $W > 2$ GeV, to avoid contamination from resonance region.
- $y_B = \nu/E_b < 0.85$, to reduce size of radiative effects.



Reconstruction of the η meson

Decay channel: $\eta \rightarrow \gamma\gamma$

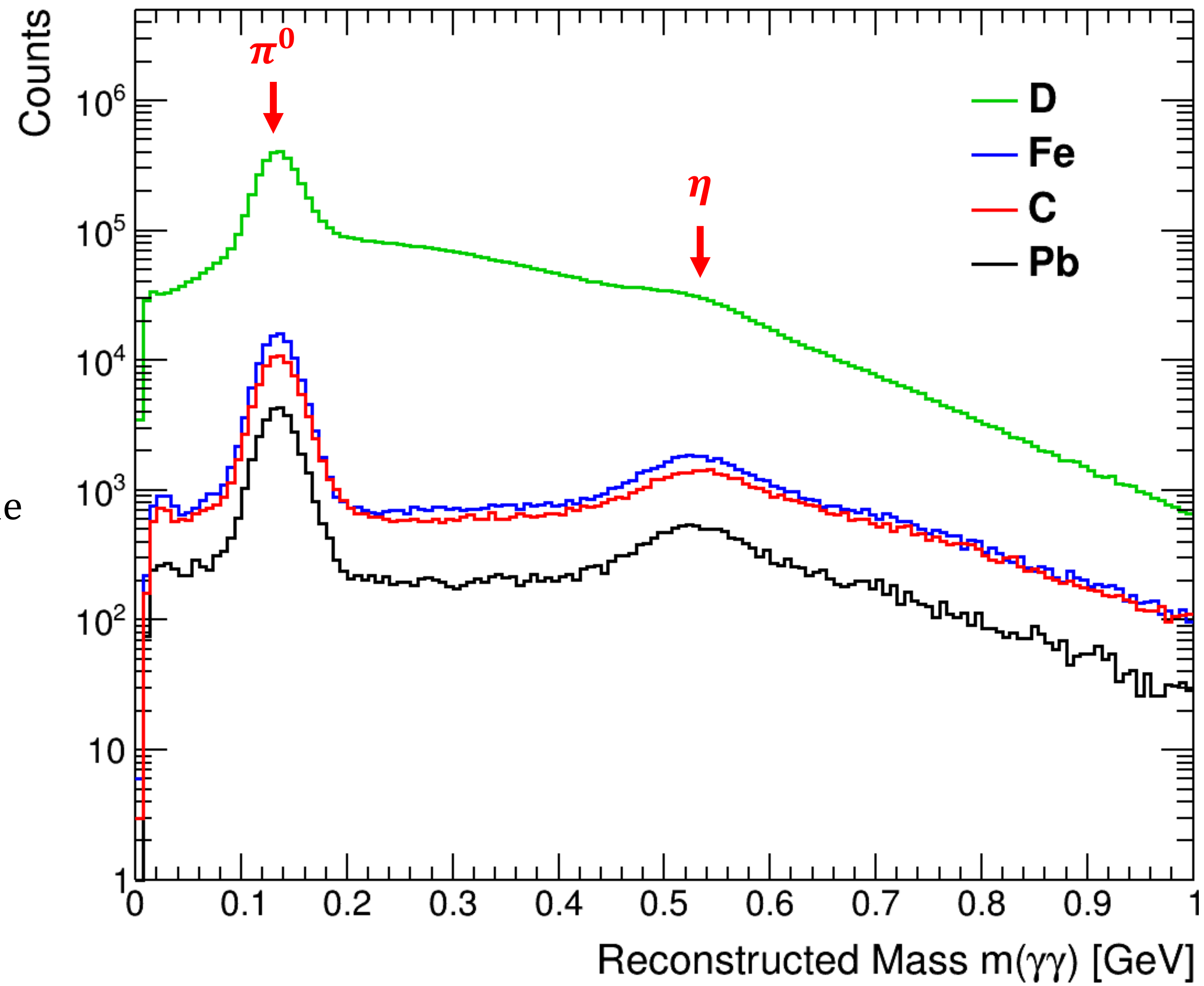
- Select all the events that have **at least 2γ** in their final state.
- Store all combinations **(η candidates).** The total number of ω candidates per event is given by

$$N_{\eta}^{comb} = \binom{N_{\gamma}}{2}$$

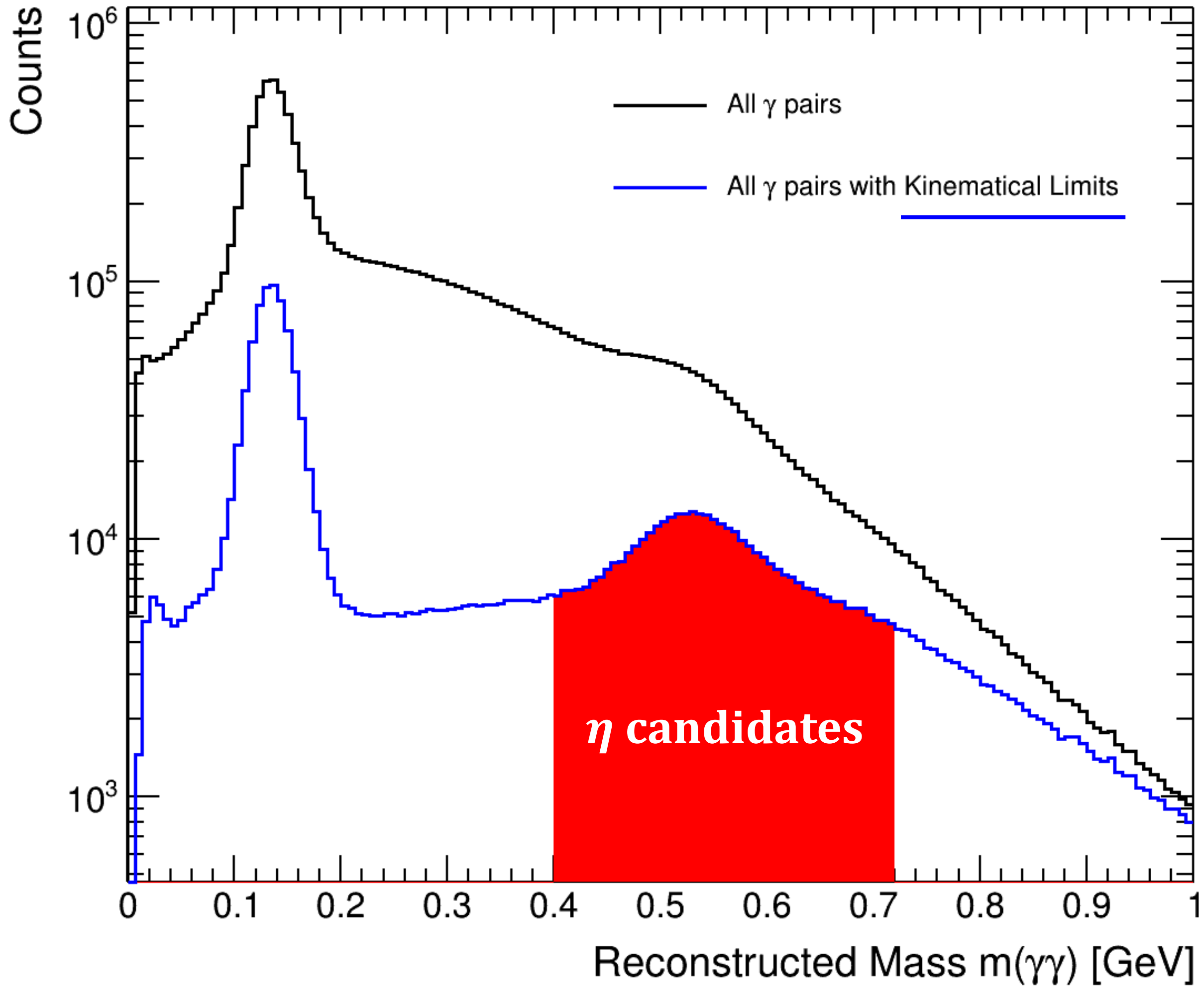
- Reconstruct the mass of the η meson as a 2-particle system,

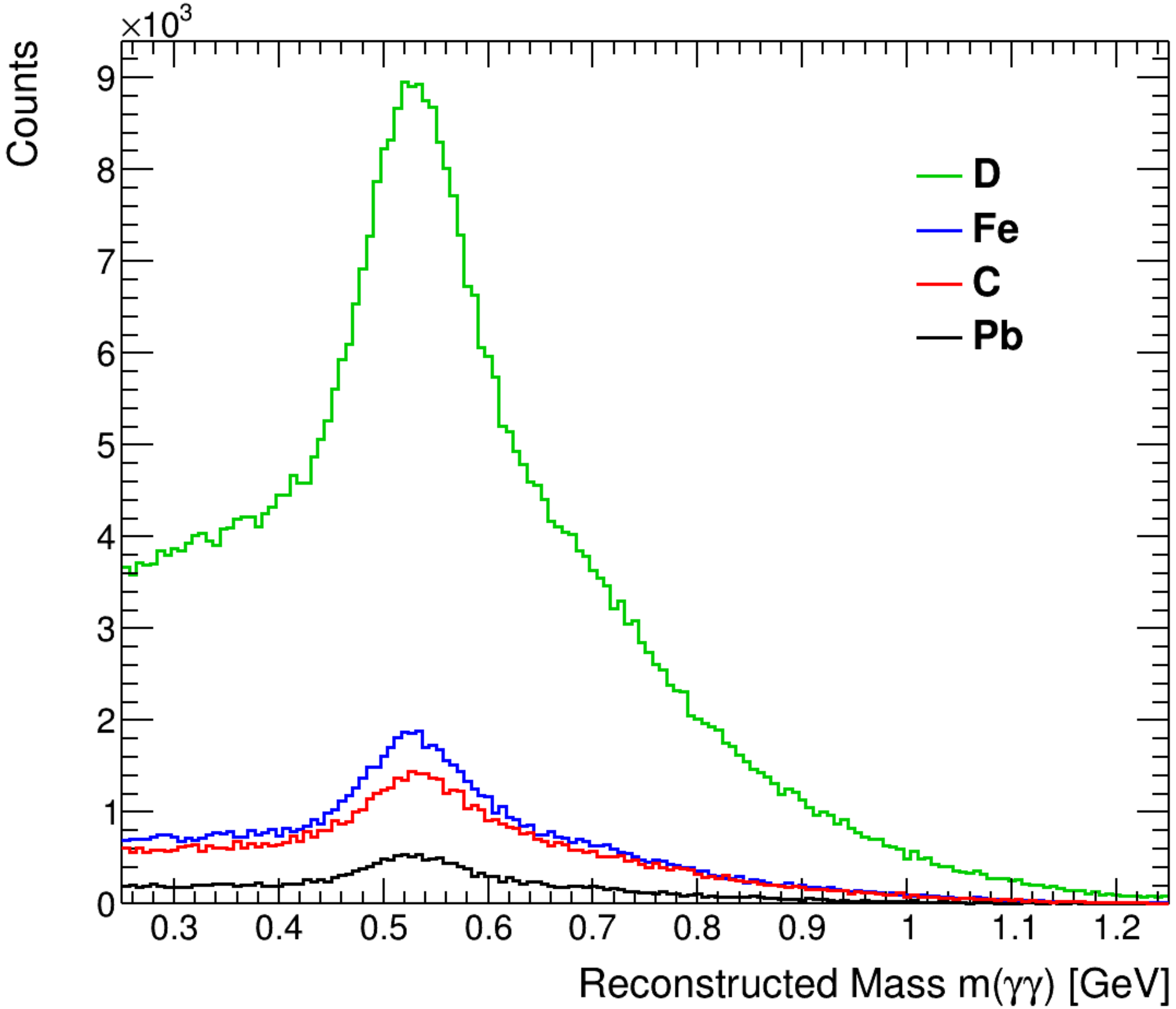
$$p_{\gamma\gamma} = p_{\gamma_1} + p_{\gamma_2}$$

$$\boldsymbol{m(\gamma\gamma) = \sqrt{E^2(\gamma\gamma) - |\vec{p}|^2(\gamma\gamma)}}$$



Reconstruction of the η meson (2)

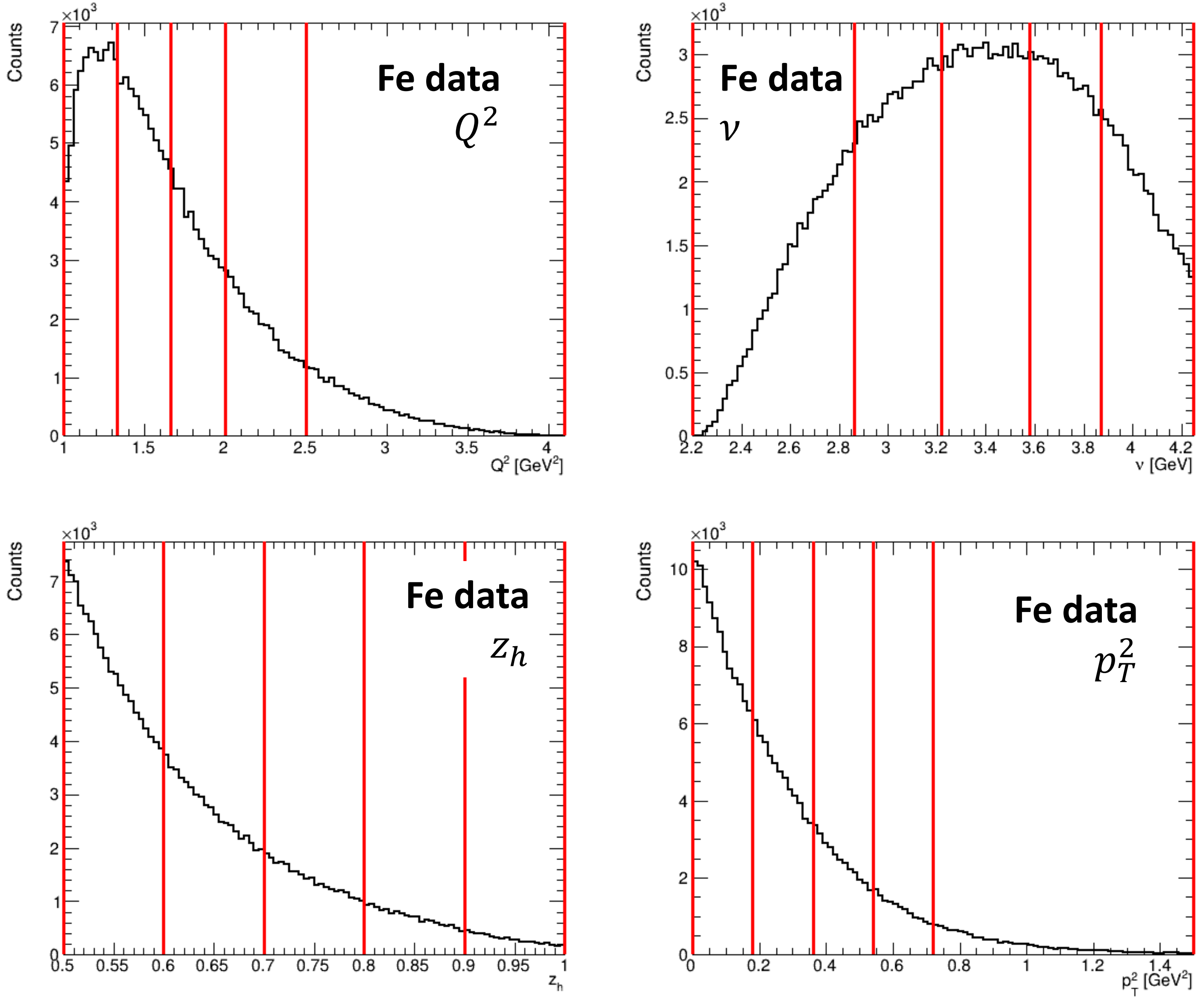




<u>Kinematical limits</u>:

$$1.0 < Q^2 < 4.1 \text{ GeV}$$
$$2.2 < \nu < 4.25 \text{ GeV}$$
$$0.5 < z_h < 1.0$$
$$0.0 < p_T^2 < 1.5 \text{ GeV}^2$$

Kinematic variable	**Bin edges**					
Q^2 (GeV^2)	1.0	1.33	1.66	2.0	2.5	4.1
ν (GeV)	2.2	2.86	3.22	3.58	3.87	4.25
z_h	0.5	0.6	0.7	0.8	0.9	1.0
p_T^2 (GeV^2)	0.0	0.18	0.36	0.54	0.72	1.5

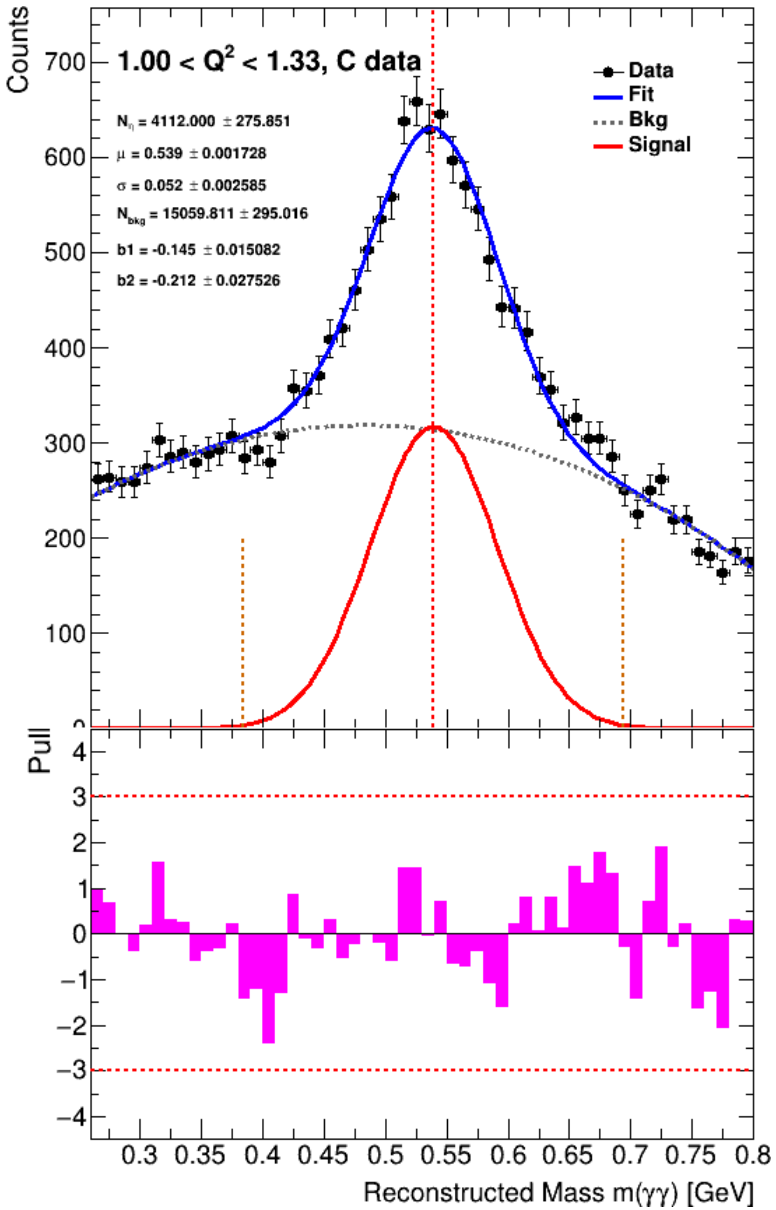


Background Subtraction: Background and Signal Fitting

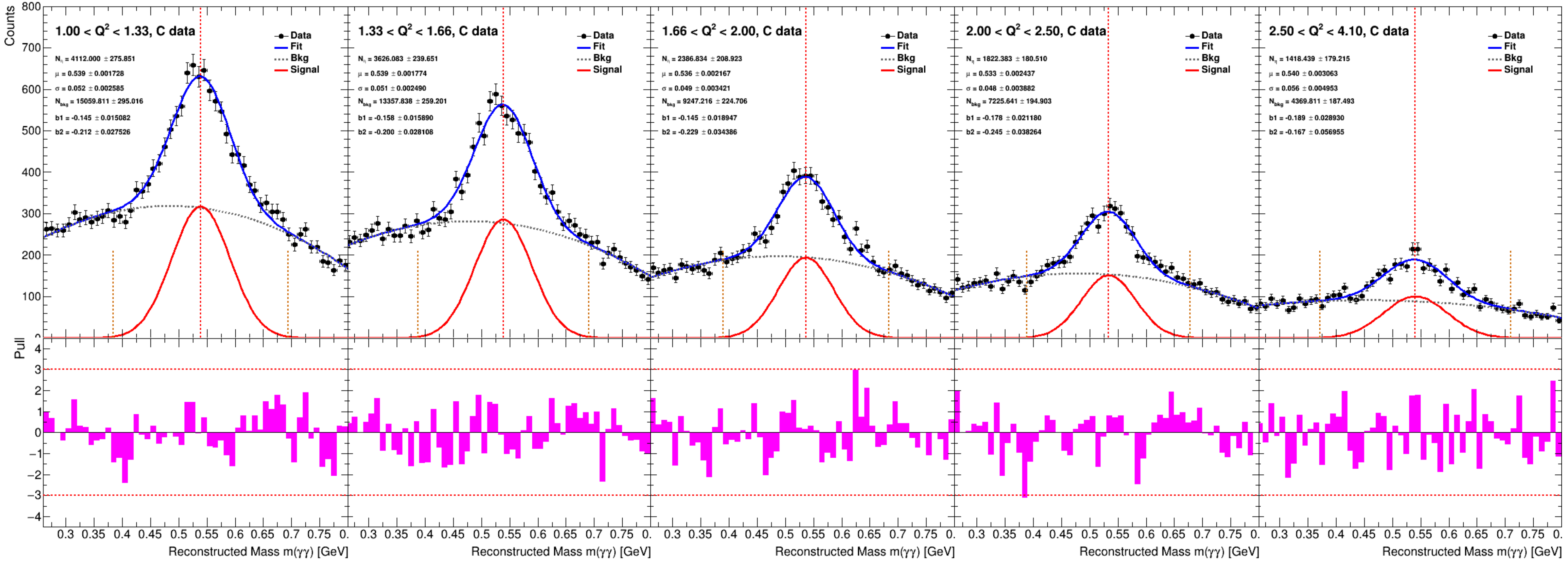
- Fit function:
  - $f(x) = N_\eta\, G(x; \mu, \sigma) + N_b\, p_2(x;\ b_1, b_2)$
  - Extended model: $N_\eta + N_b = N_{tot}$

- Count of hadrons by integrating signal component
- Primary tool: **ROOT's RooFit**

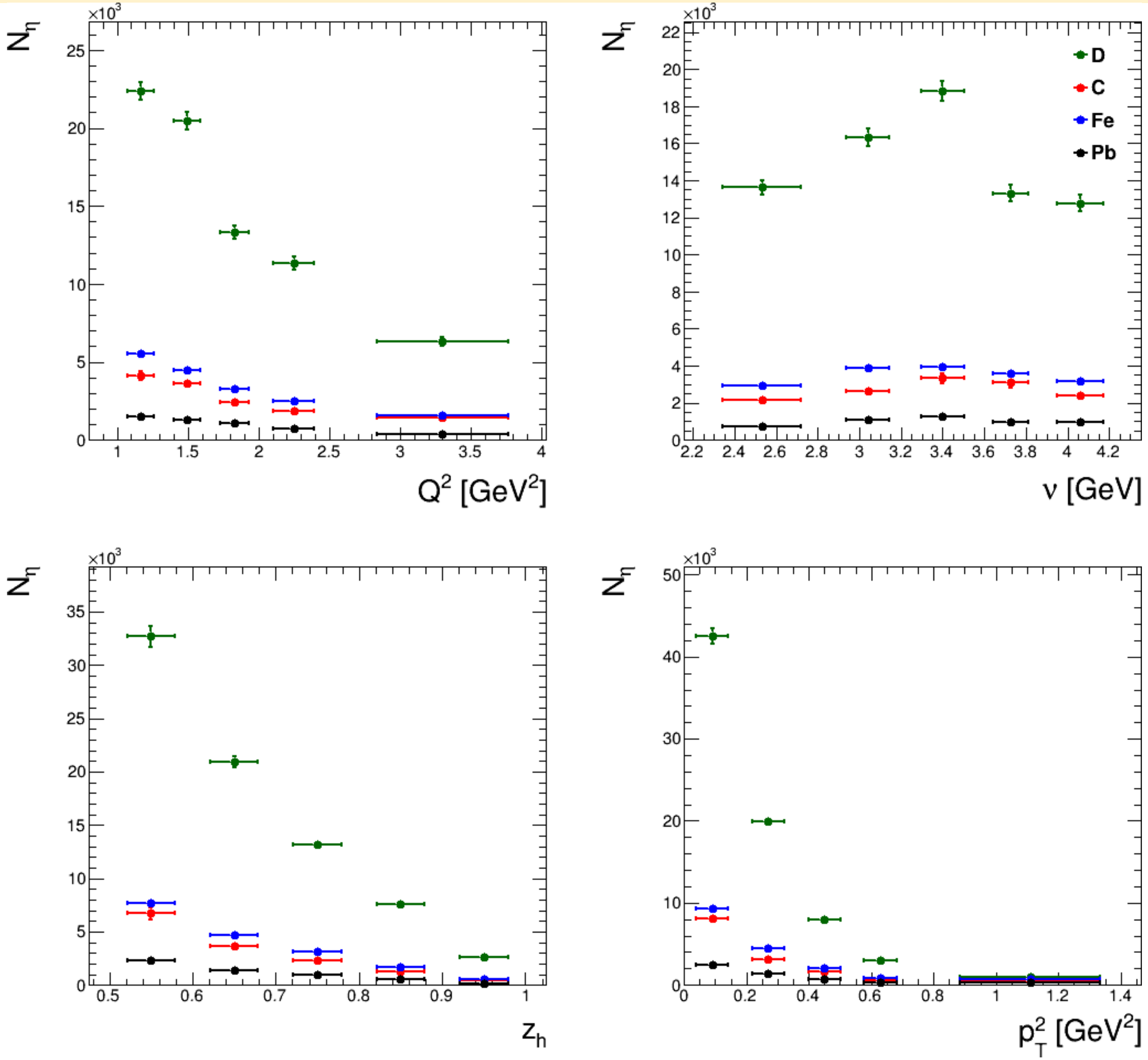
- Maximum likelihood fit
  - Event-by-event basis
  - Longer computation time than least squares method
  - Limitation: not known tests to measure goodness of fit.



Background and Signal Fitting



Extracted N_η



$\pi^0 \rightarrow \gamma\gamma$ Reconstruction

<u>**Decay channel**</u>: $\pi^0 \rightarrow \gamma\gamma$

$$p(\gamma\gamma) = p_{\gamma_1} + p_{\gamma_2}$$

$$\Longrightarrow m(\gamma\gamma) = 4\, E_{\gamma_1} E_{\gamma_2} \sin^2\left(\frac{\theta_{\gamma_1\gamma_2}}{2}\right)$$

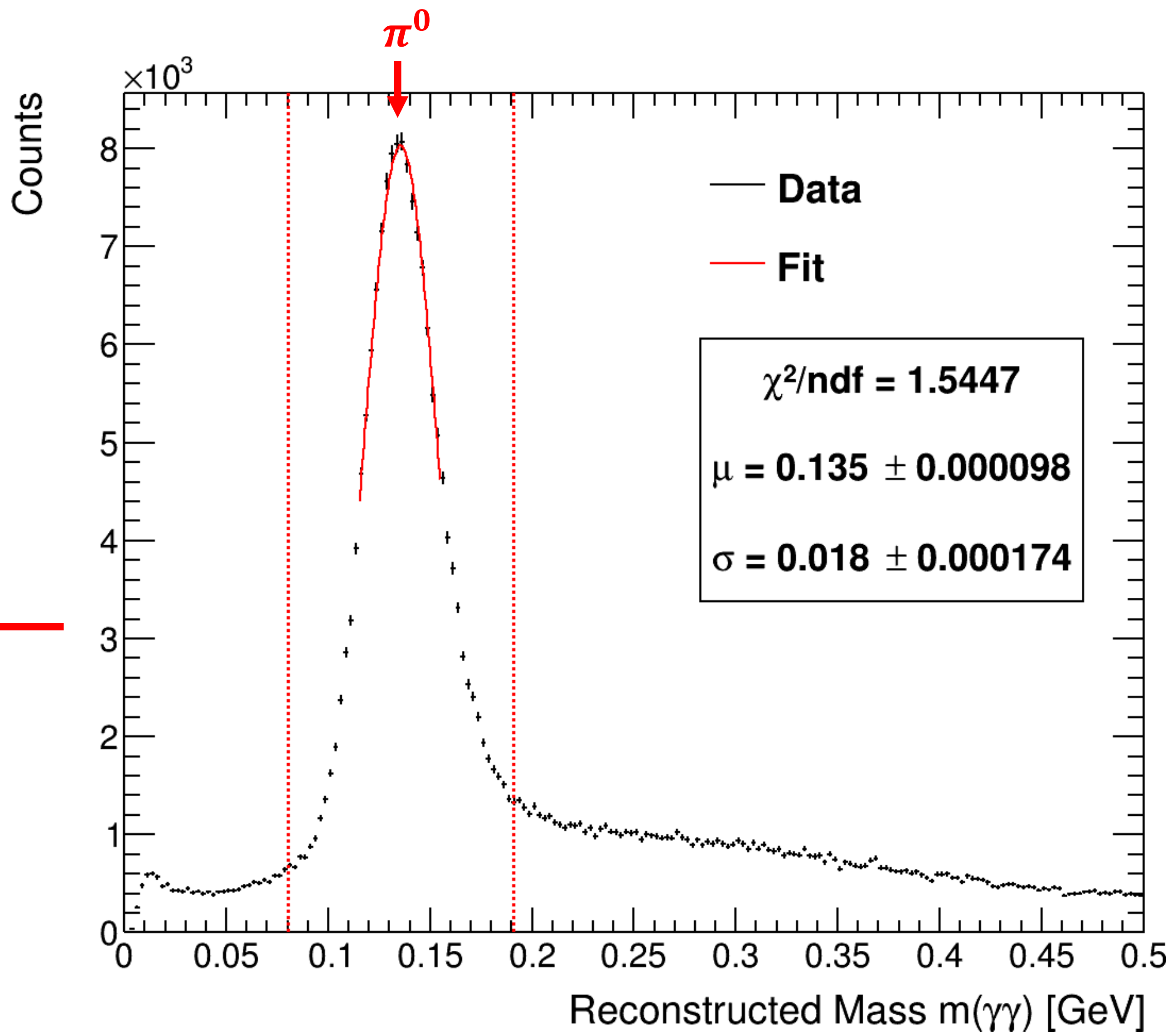
$\theta_{\gamma_1\,\gamma_2}$: angle between γ_1 and γ_2.

<u>**Procedure:**</u>

Gaussian fit around π^0 peak.
Horizontal lines represent $\mu \pm 3\sigma$ cut.

<u>Result</u>: $0.076 < m(\gamma\gamma) < 0.196$ GeV

[T. Mineeva. *Neutral Pion Multiplicity Ratios from SIDIS Lepton-nuclear Scattering*. CLAS Analysis Note (202)**]**



K^0 Exclusion

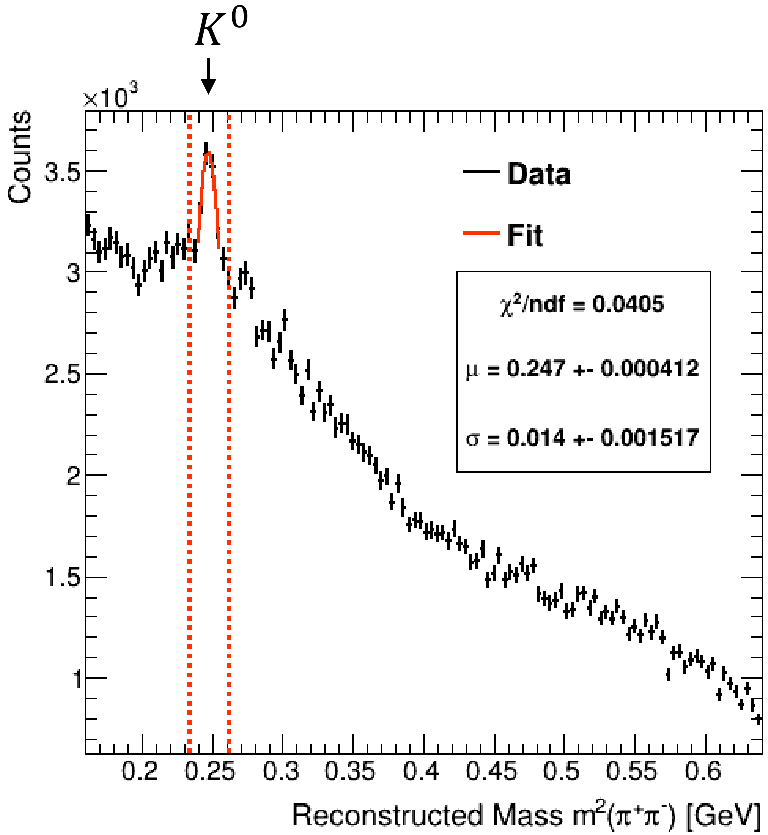
K_S^0 decays into a $\pi^+\pi^-$ pair, studied in a previous analysis. → **[A. Daniel**. Phys. Lett. B 706 (2011)**]**

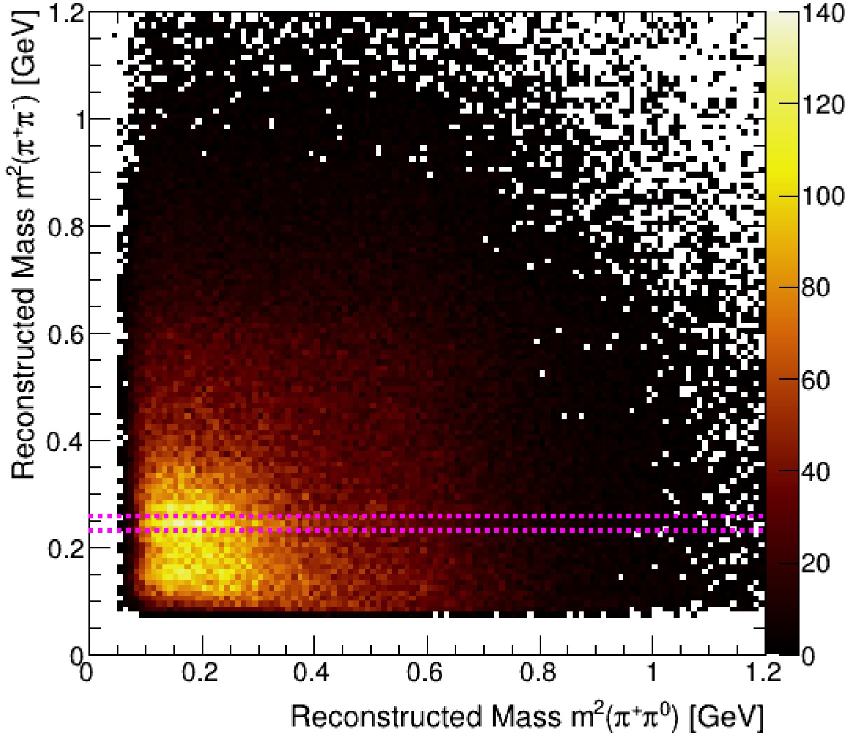
$$p(\pi^+\pi^-) = p_{\pi^+} + p_{\pi^-}$$

$$\Rightarrow m^2(\pi^+\pi^-) = 2M_{\pi^\pm} + 2E_{\pi^+}E_{\pi^-} - 2\left(p_x^{\pi^+}p_x^{\pi^-} + p_y^{\pi^+}p_y^{\pi^-} + p_z^{\pi^+}p_z^{\pi^-}\right), \qquad M_{\pi^\pm} = 0.139\ GeV$$

Gaussian fit around K^0 peak.
Horizontal lines represent $\mu \pm 1\sigma$ cut.

$m^2_{\pi^+\pi^-} < 0.232\ \mathrm{GeV}^2$
or
$m^2_{\pi^+\pi^-} > 0.262\ \mathrm{GeV}^2$





Reconstruction of the ω meson

Decay channel: $\omega \rightarrow \pi^+\pi^-\pi^0 \rightarrow \pi^+\pi^-\gamma\gamma$

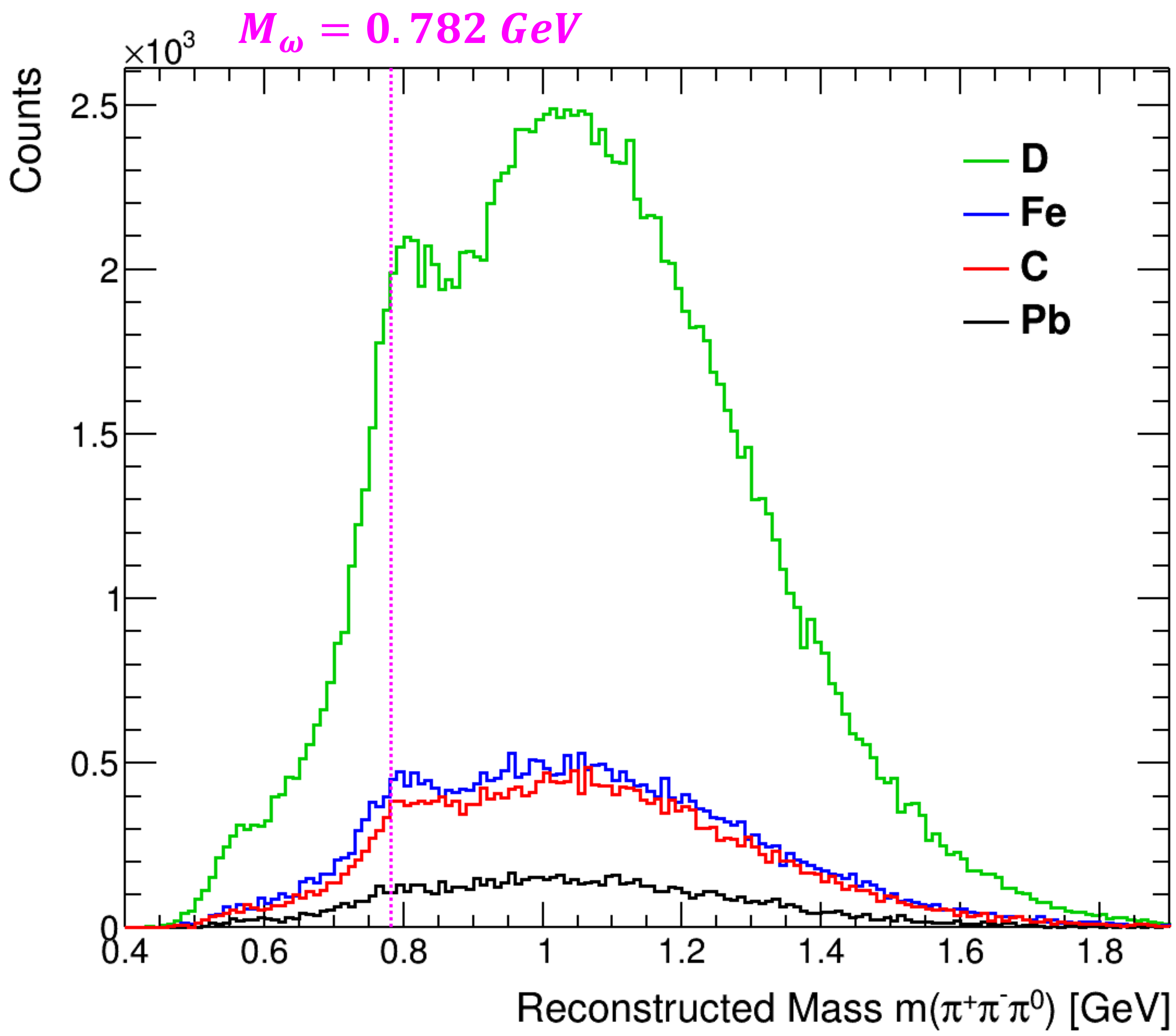
- Select all the events that have at least $1\pi^+$, $1\pi^-$ and 2γ in their final state.
- Store all combinations **(ω candidates).** The total number of ω candidates per event is given by

$$N_\omega^{comb} = \binom{N_{\pi^+}}{1}\binom{N_{\pi^-}}{1}\binom{N_\gamma}{2}$$

- Reconstruct the mass of the ω meson as a 3-particle system,

$$p_{\pi^+\pi^-\pi^0} = p_{\pi^+} + p_{\pi^-} + p_{\gamma\gamma}$$

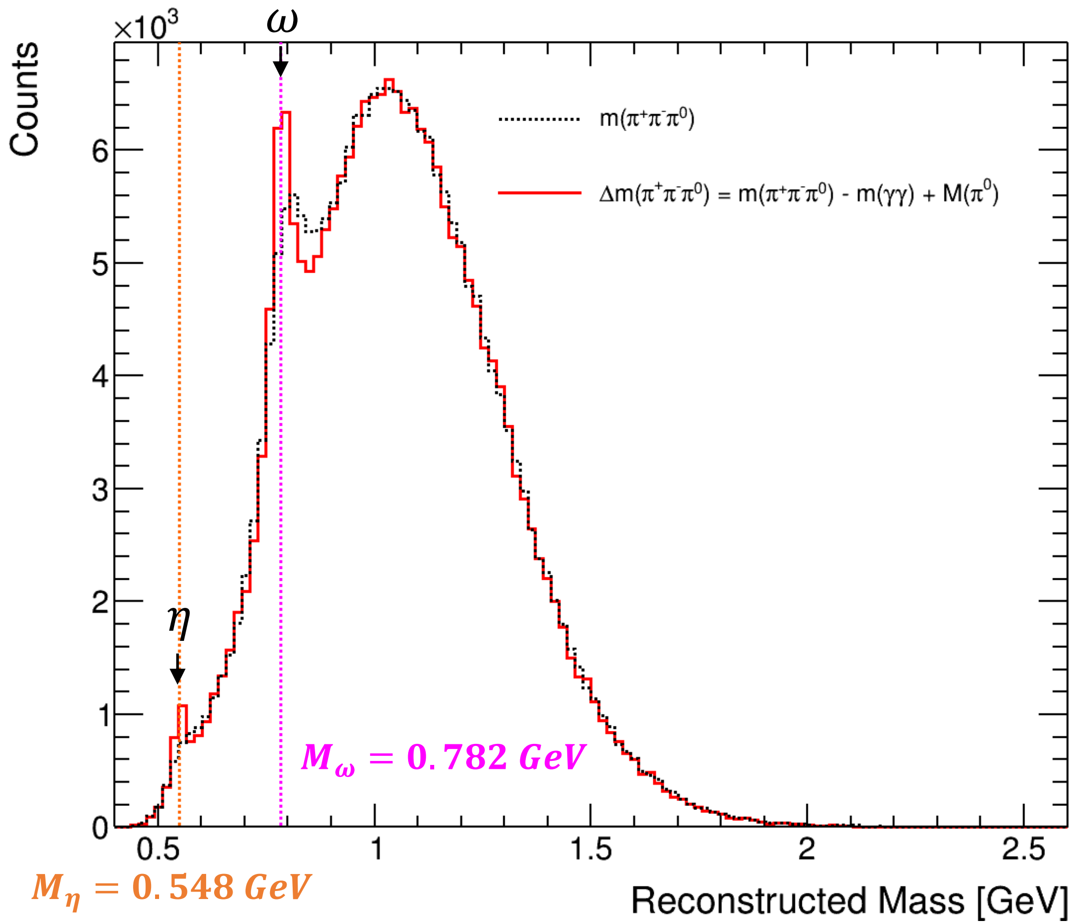
$$m(\pi^+\pi^-\pi^0) = \sqrt{E^2(\pi^+\pi^-\gamma\gamma) - |\vec{p}|^2(\pi^+\pi^-\gamma\gamma)}$$

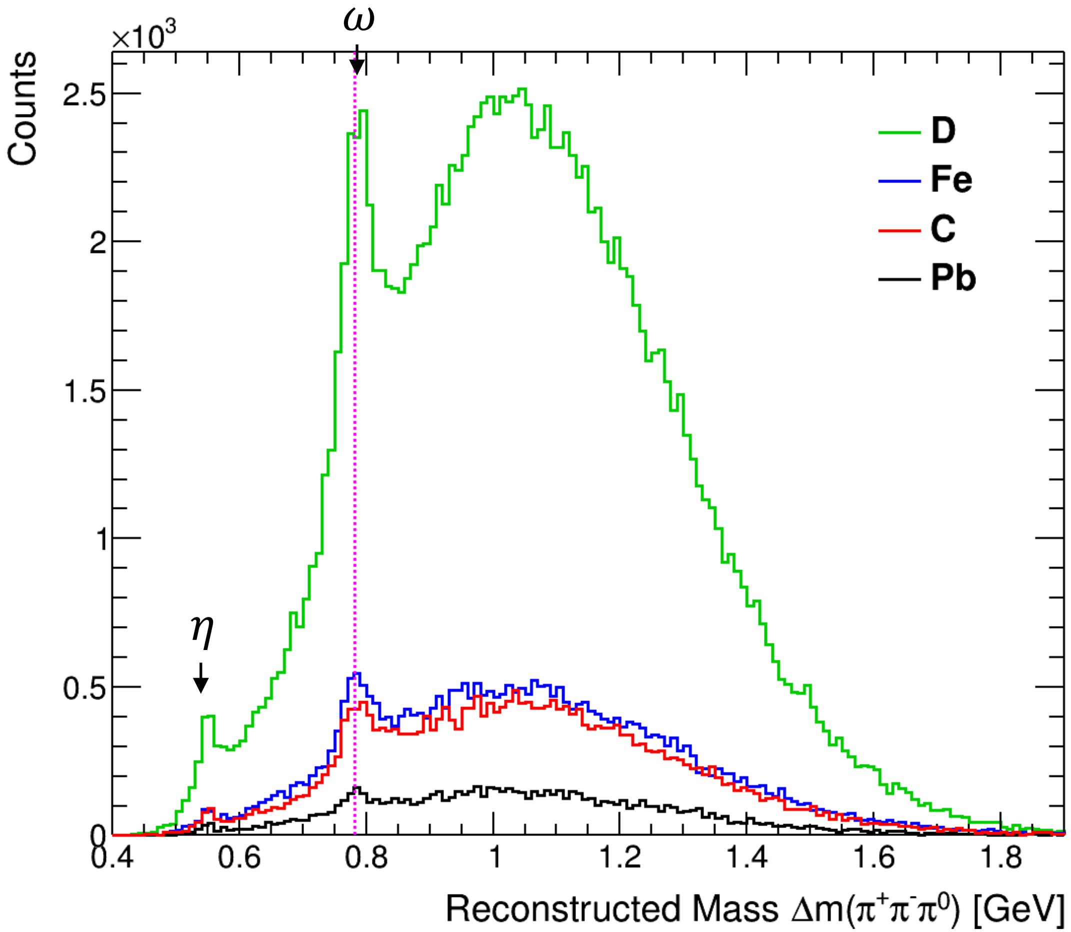


Reconstruction of the ω meson - III

An alternative mass expression is preferred: the **invariant mass difference**,

$$\Delta m(\pi^+\pi^-\pi^0) = m(\pi^+\pi^-\pi^0) - m(\gamma\gamma) + M_{\pi^0}$$

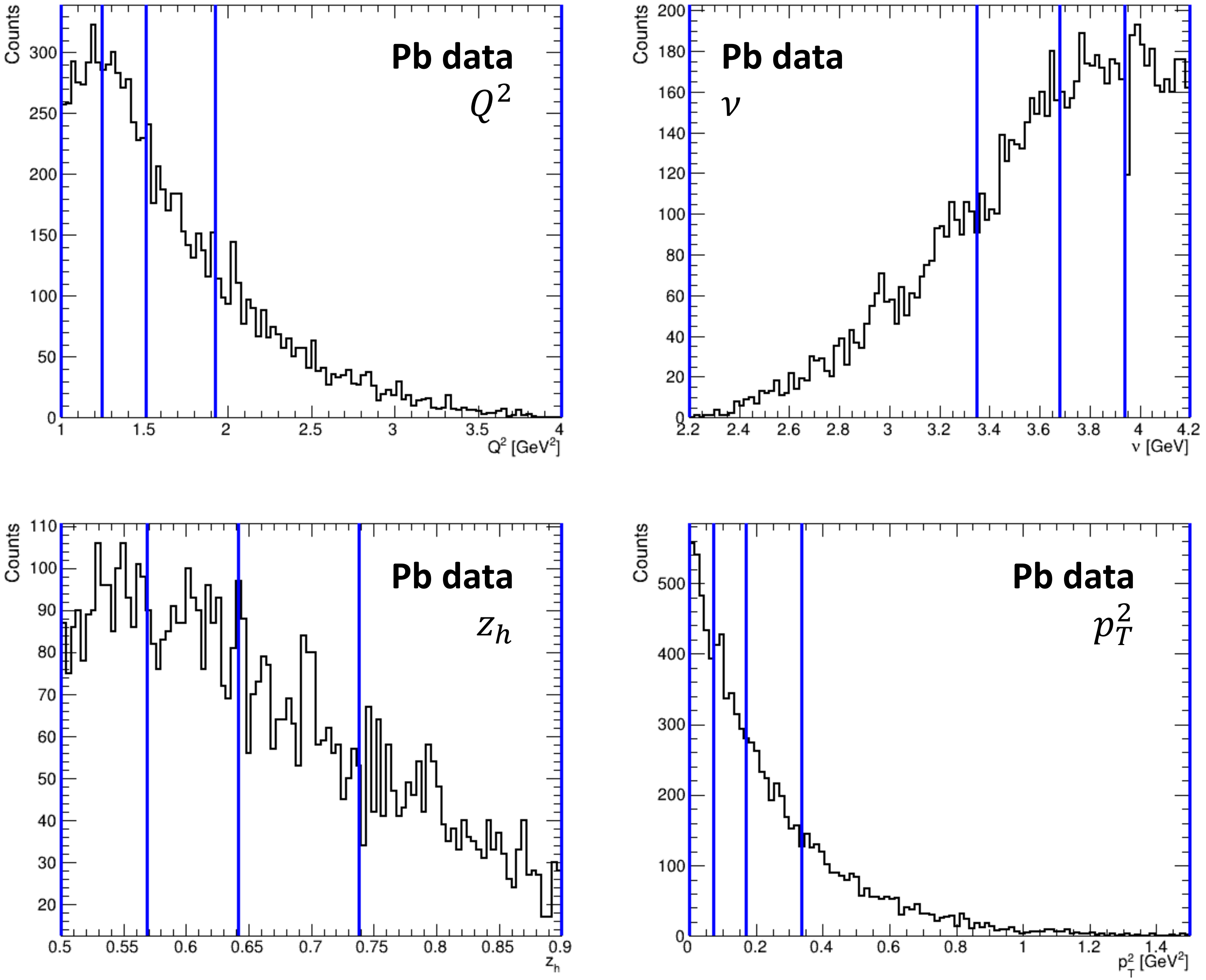




Binning

The binning to present the **multiplicity ratios** is one-dimensional and equally distributed.

Kinematic variable	**Bin edges**				
Q^2 (GeV^2)	1.0	1.25	1.51	1.92	4.0
ν (GeV)	2.2	3.35	3.68	3.94	4.2
z_h	0.5	0.57	0.64	0.74	0.9
p_T^2 (GeV^2)	0.0	0.07	0.17	0.34	1.5



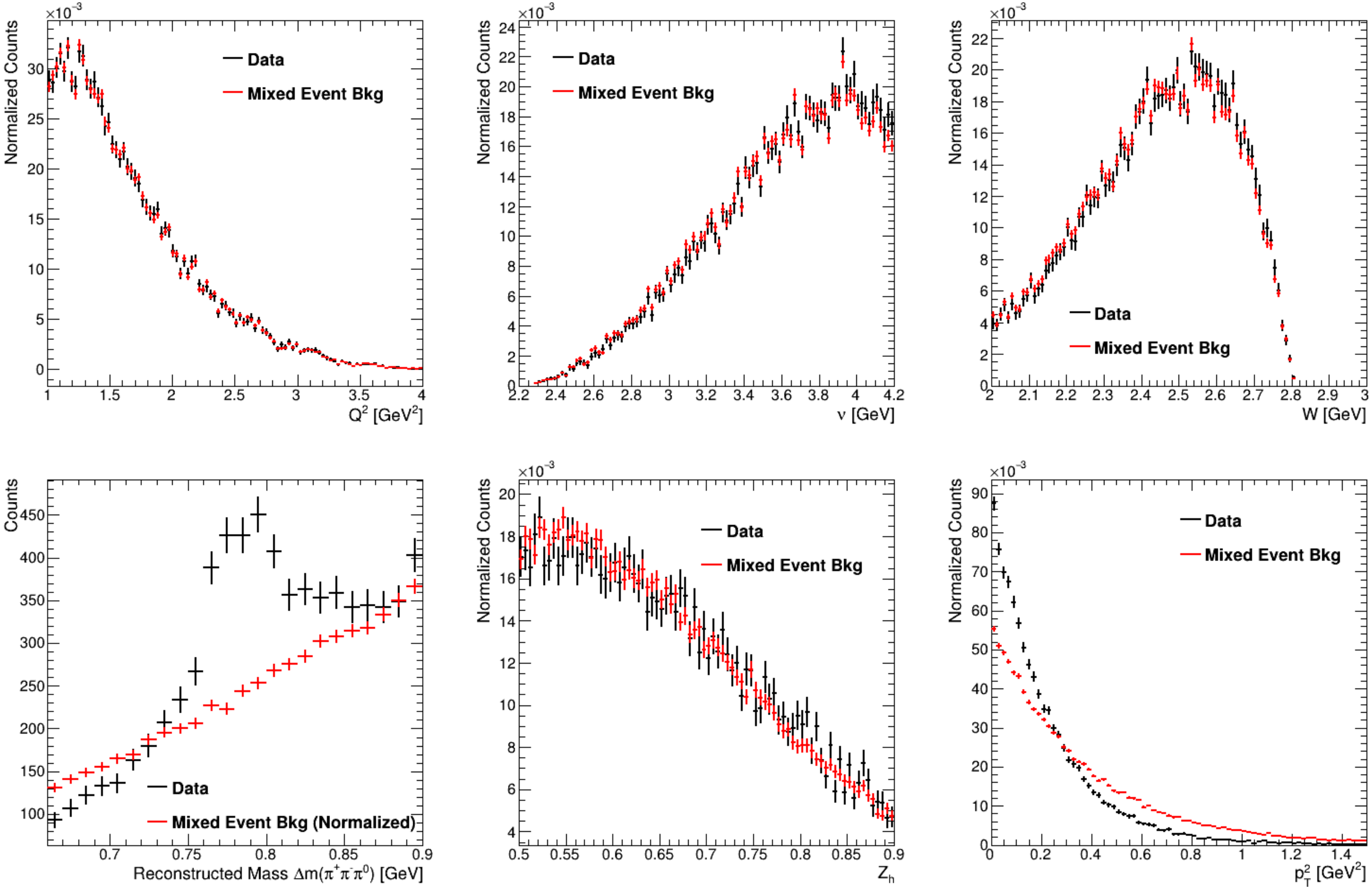
Event-Mixing Method:

The main idea is to describe the background shape of the ω invariant mass difference with pions that are **no longer correlated**, i.e., originating from different events.

- Keep all events with the minimum amount of final-state particles. (**"candidate event"**)
- Combine and form all the possible $\boldsymbol{\omega}$ candidates.
- For each formed $\boldsymbol{\omega}$ candidate,
    1. swap the $\boldsymbol{\pi}^+$ by a **random** $\boldsymbol{\pi}^+$ from **candidate events** from **same target**
    2. swap the $\boldsymbol{\pi}^-$ by a **random** $\boldsymbol{\pi}^-$
    3. swap the $\boldsymbol{\pi}^0$ by a **random** $\boldsymbol{\pi}^0$
    4. swap the three pions with **random** $\boldsymbol{\pi}^+, \boldsymbol{\pi}^-, \boldsymbol{\pi}^0$ (all from different events)
- Add the new 4 distributions.

[F. Jonas. M.Sc. Thesis (2018, University of Münster)**]**

Event-Mixing Method: Comparison with data



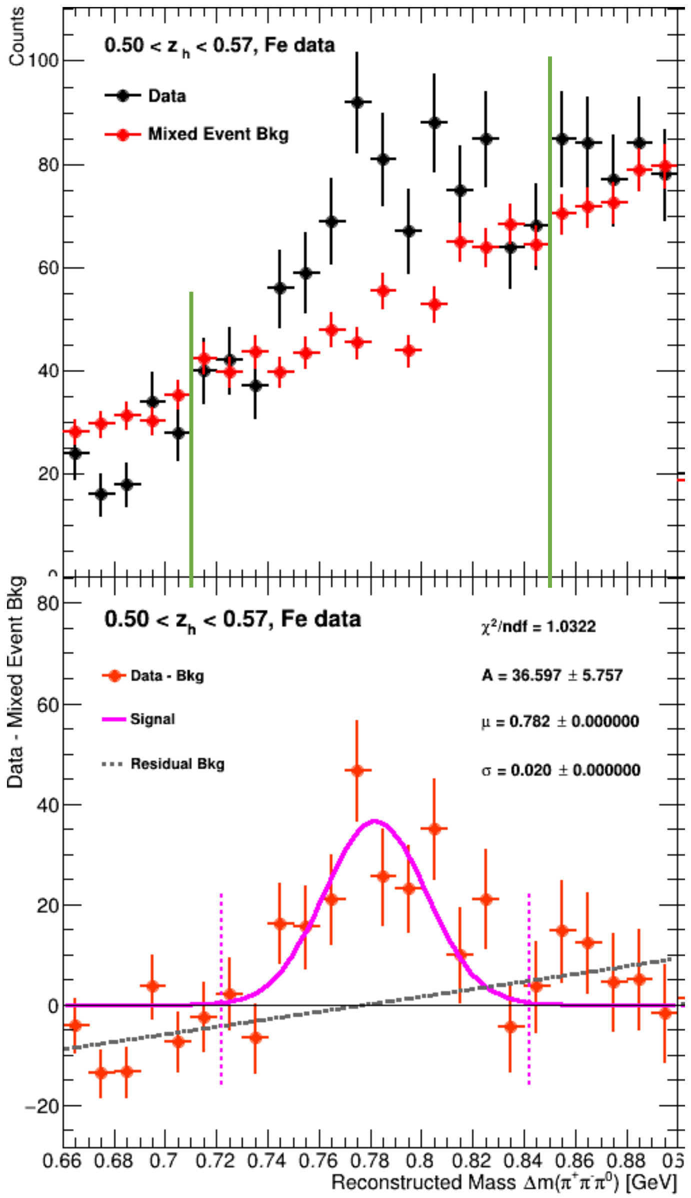
Event-Mixing Method: Normalization and extraction of N_ω

1.

To **normalize** the **mixed-event background** to the **data**, it is scaled by the following factor:

$$\frac{integral_{R1}^{data} + integral_{R2}^{data}}{integral_{R1}^{bkg} + integral_{R2}^{bkg}}$$

Where **R1** and **R2** stand for the left and right sidebands, respectively.



2.

The **normalized mixed event background** is subtracted from the **data**.

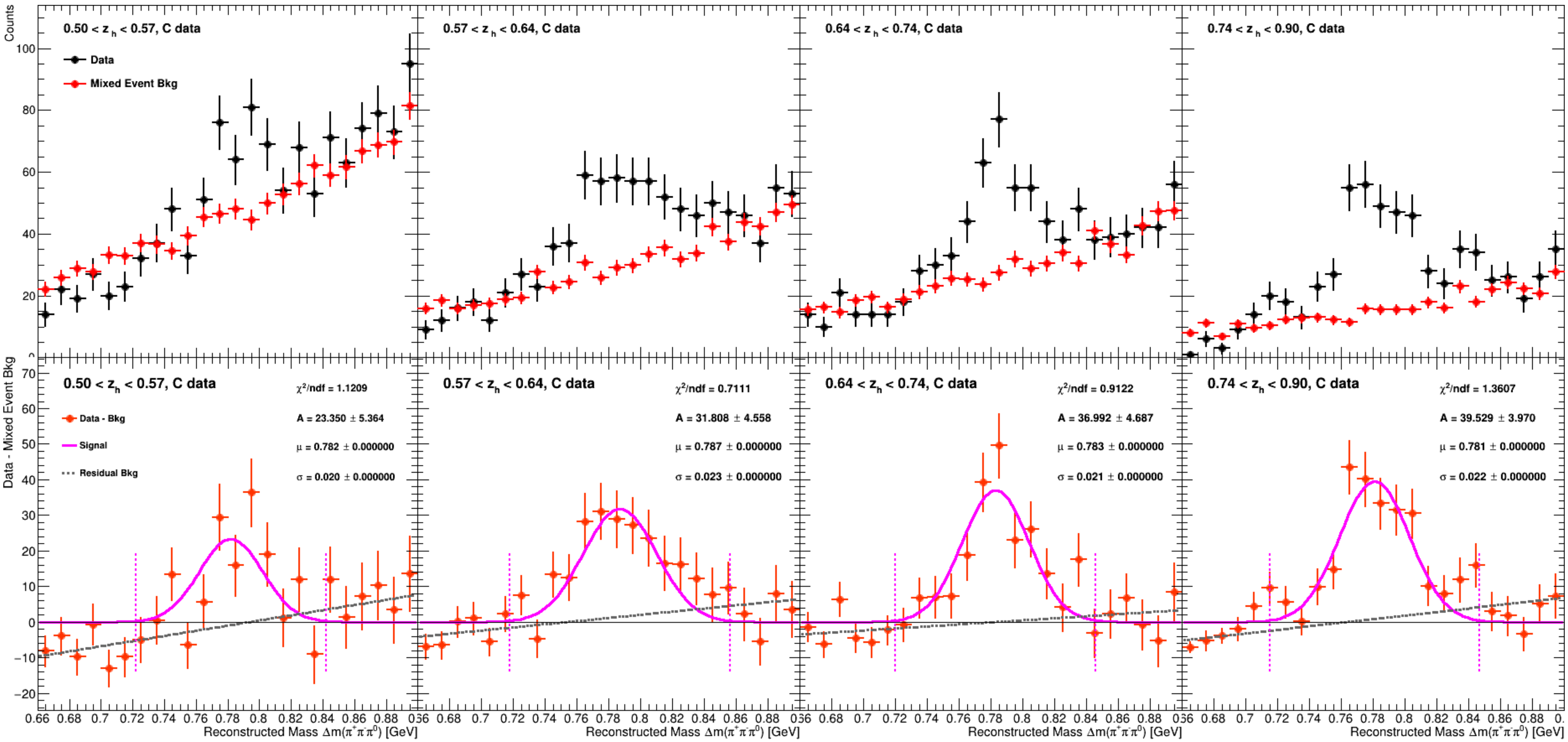
The **background-subtracted distribution** is fitted with a chi-square fit:

$$f(x) = G(x; A, \mu, \sigma) + p1(x; a1, a2)$$

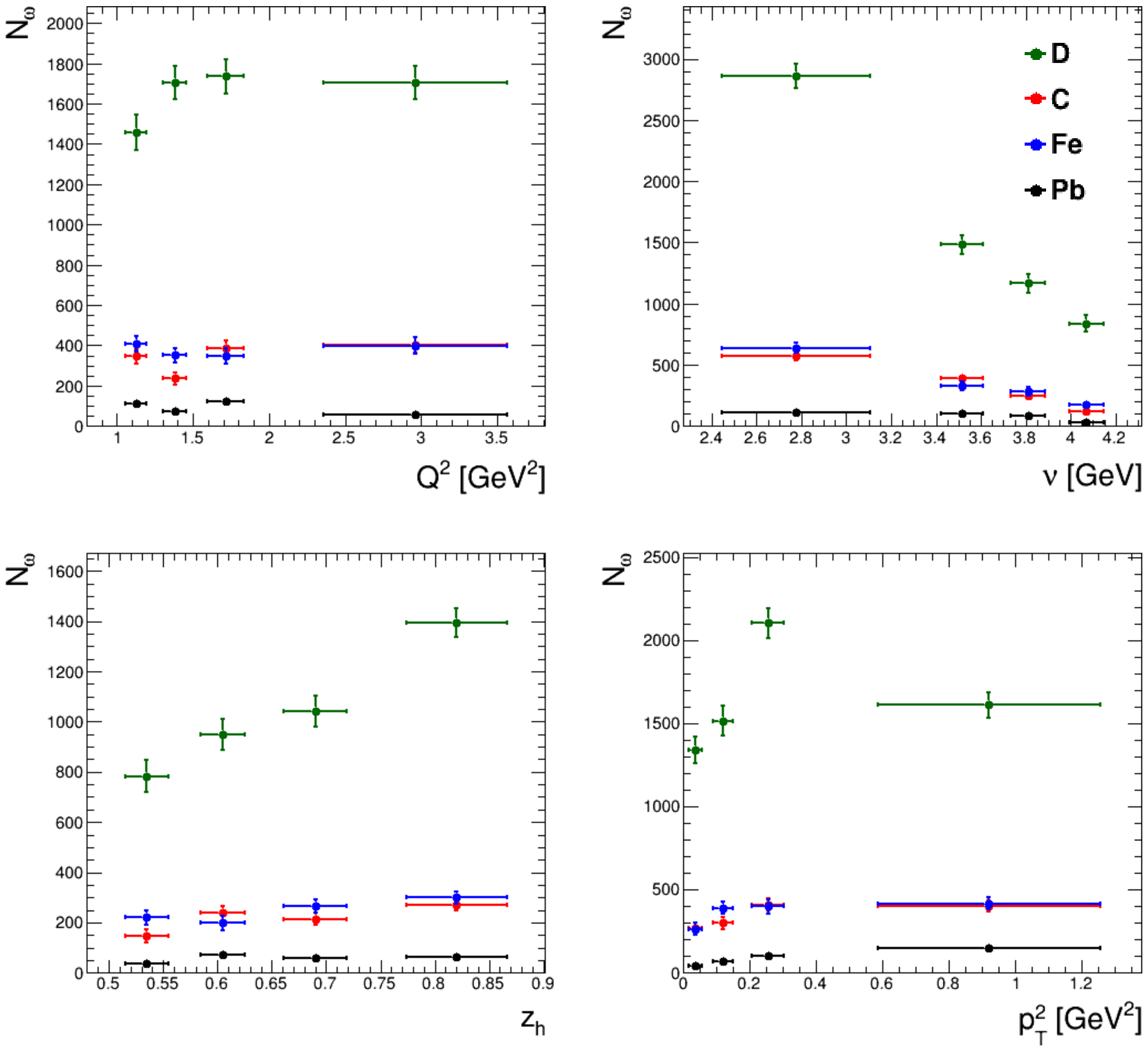
*μ and σ are **fixed** from preliminary fits on all data.

The number of ω mesons is calculated by integrating the **distribution** over the obtained $\mu \pm 3\sigma$ range.

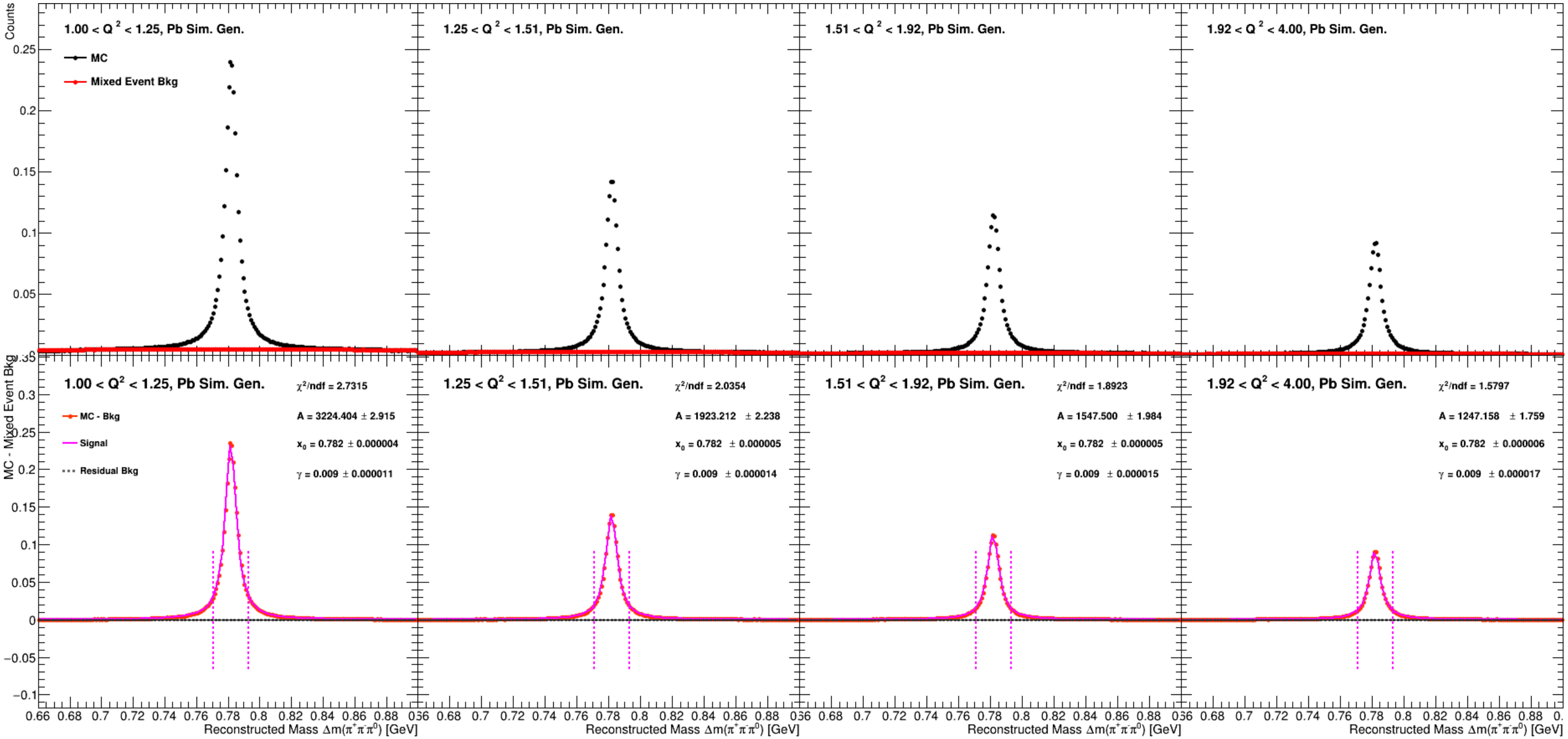
Event-Mixing Method: Application on Carbon data



Event-Mixing Method: Extracted N_ω

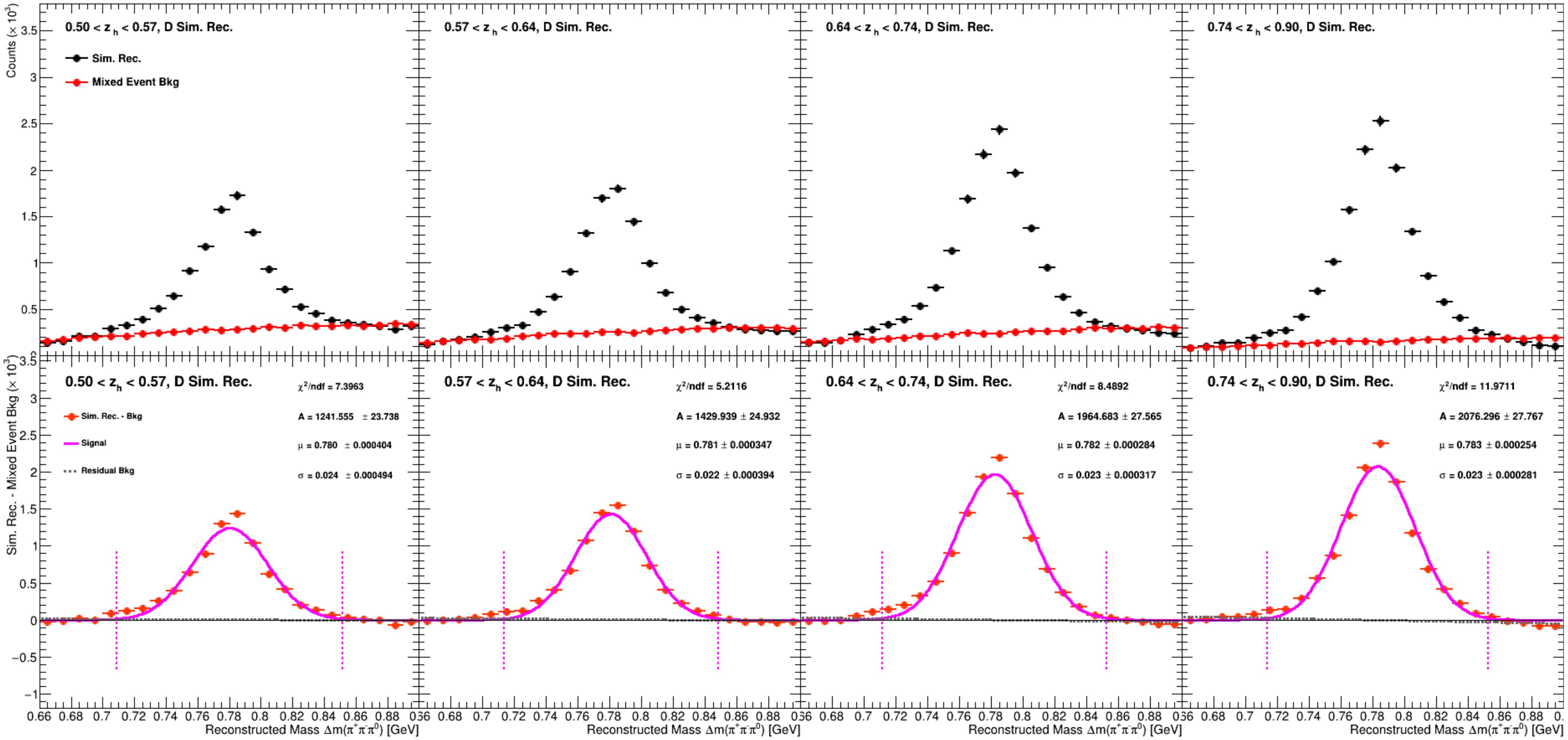


Generated Particles ID: Background Subtraction

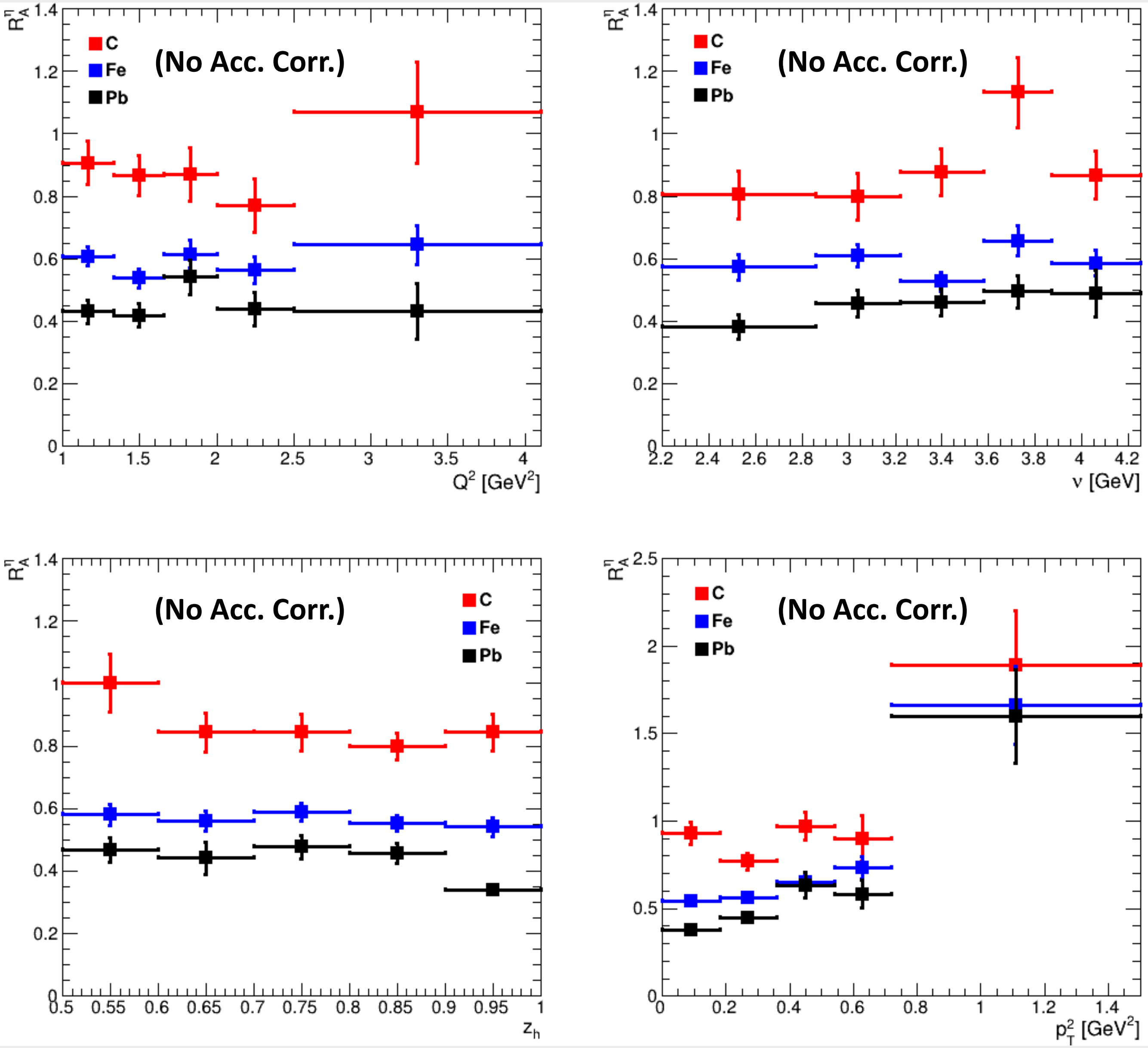


*In this case, a model composed of a **Breit-Wigner function** and a first-order polynomial is preferred to fit the ω peak.

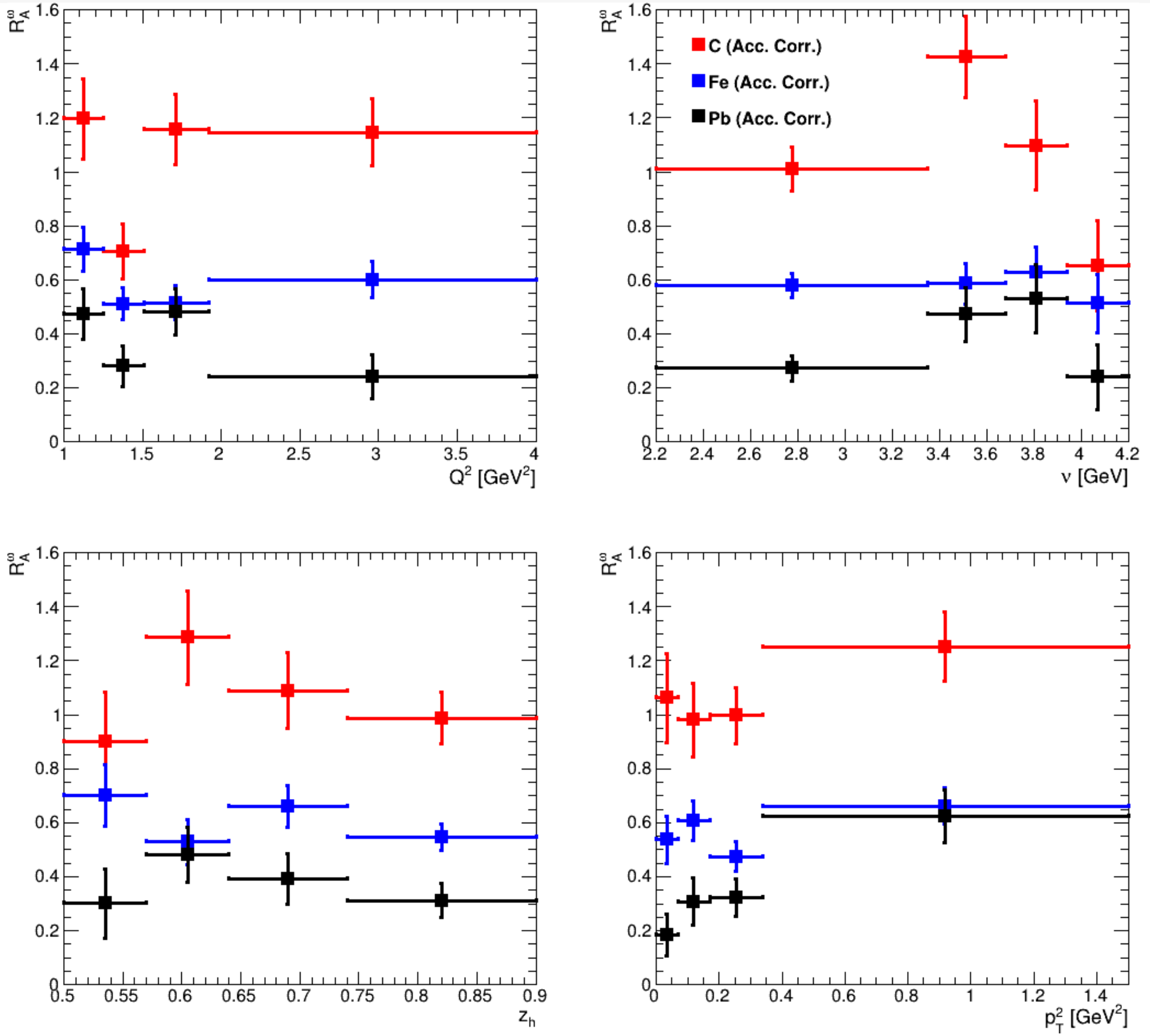
Reconstructed Particles ID: Background Subtraction



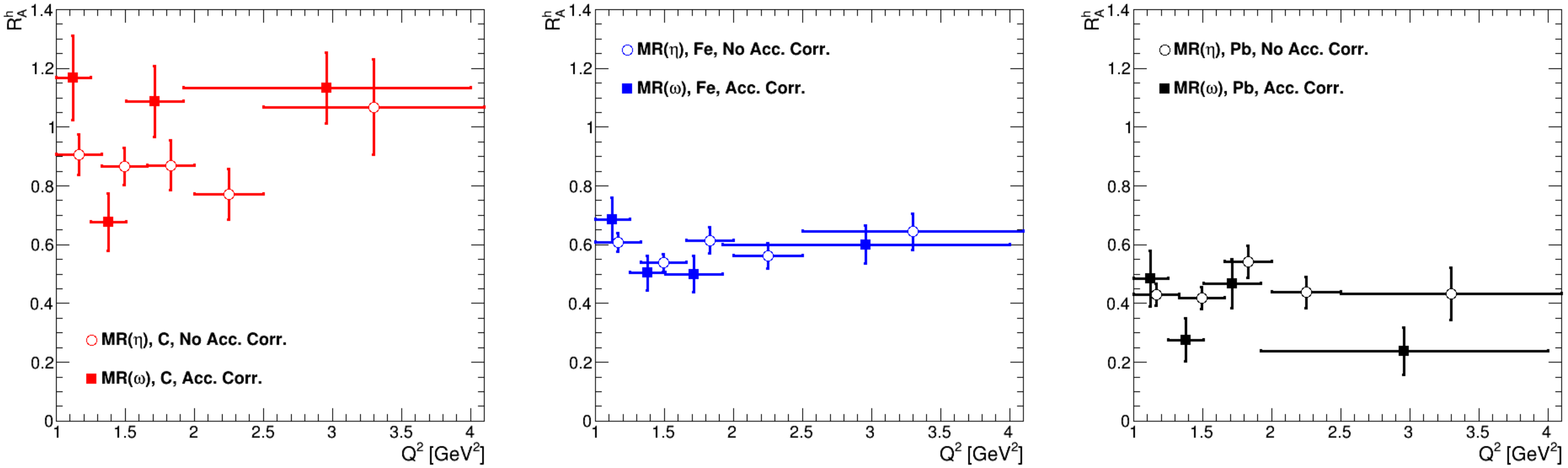
Multiplicity Ratios: η



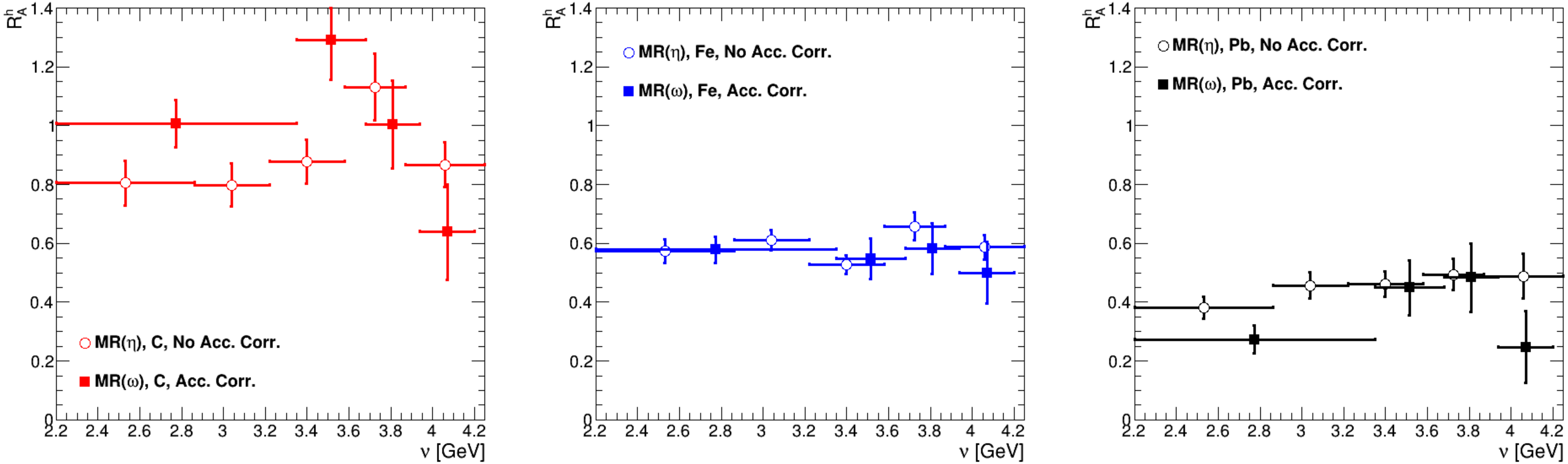
Multiplicity Ratios: ω



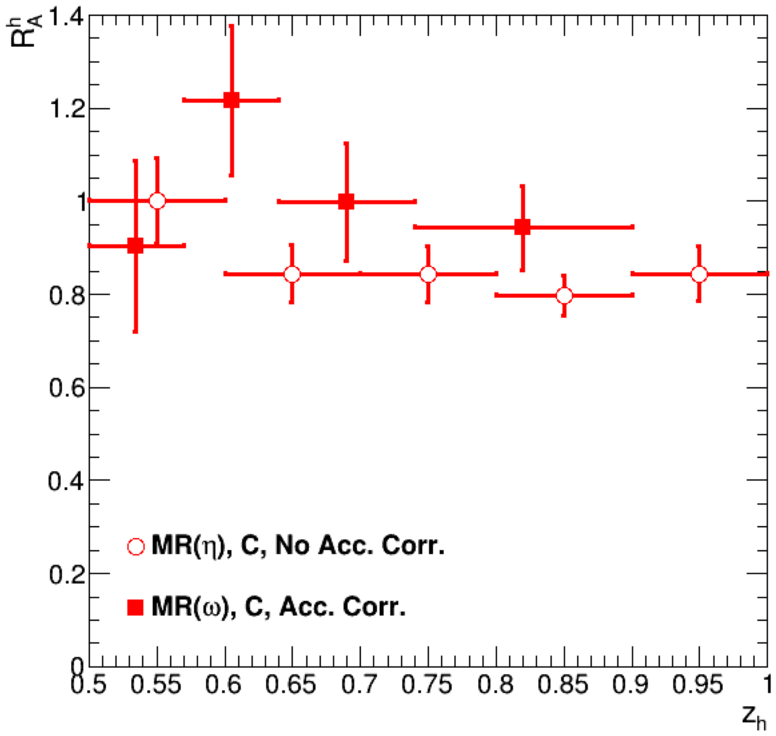
Multiplicity Ratio vs Q^2: Comparison between η and ω

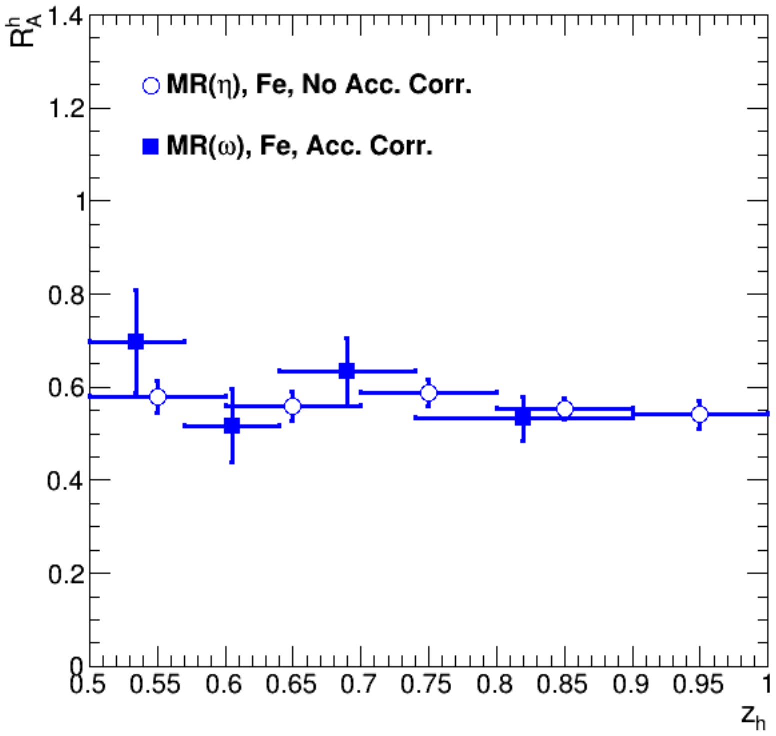


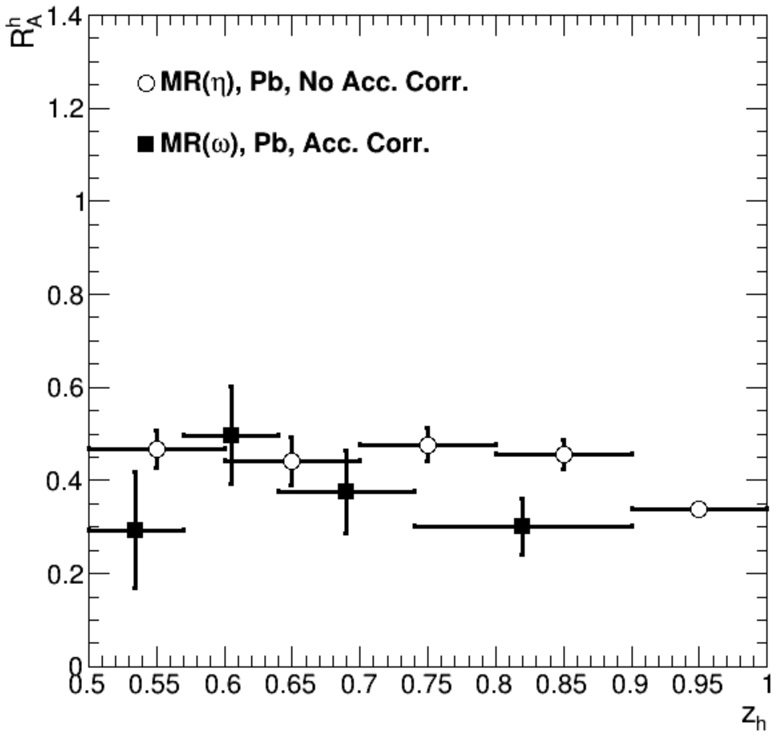
Multiplicity Ratio vs ν: Comparison between η and ω



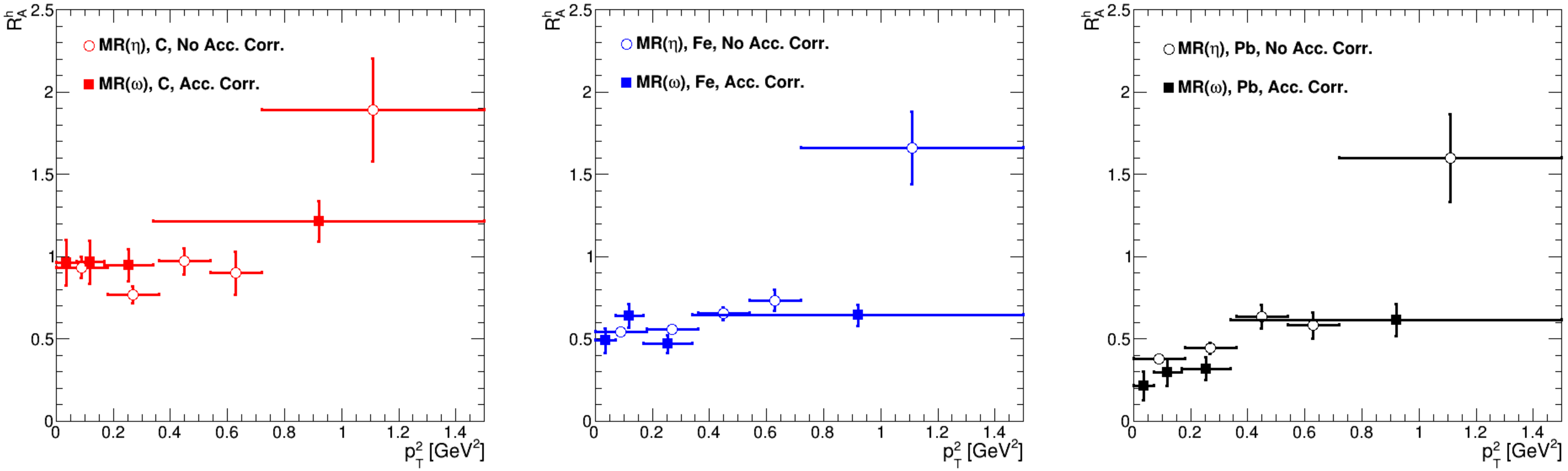
Multiplicity Ratio vs z_h: Comparison between η and ω





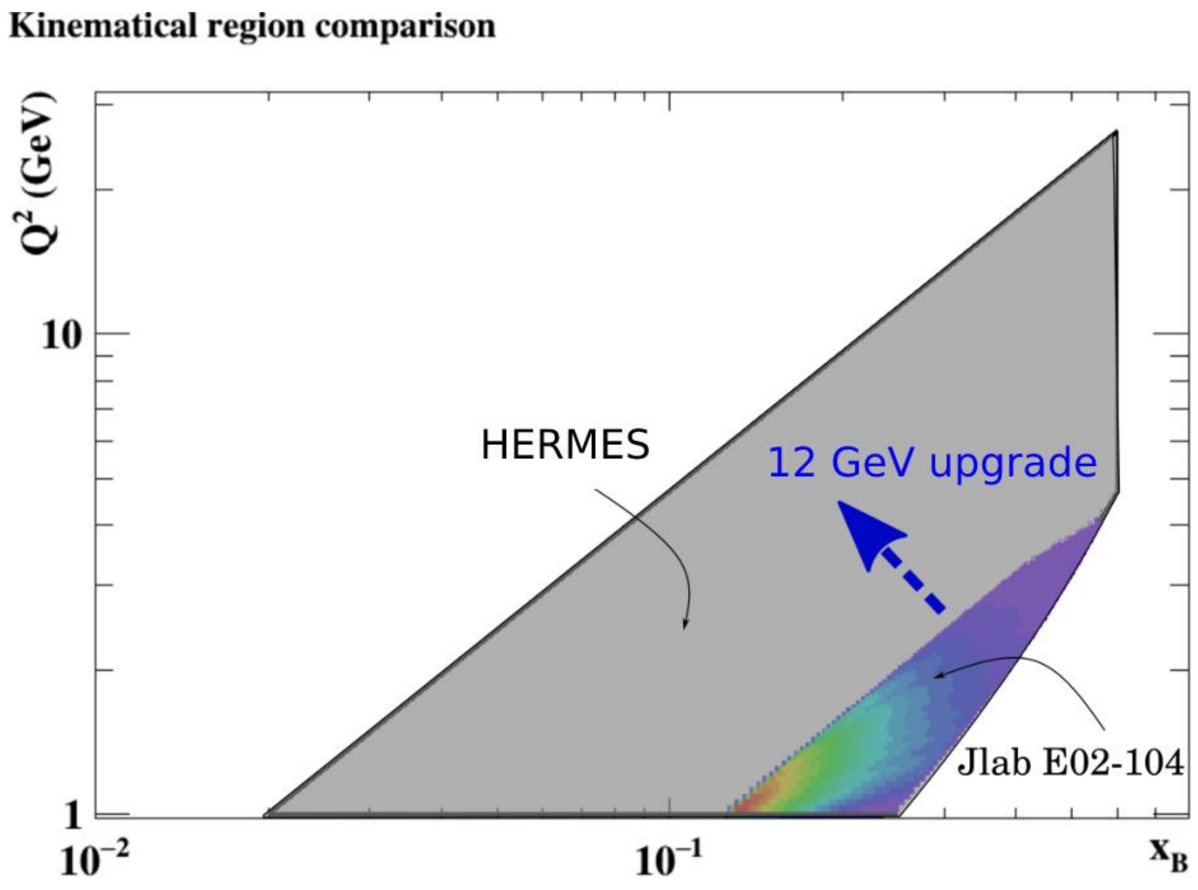


Multiplicity Ratio vs p_T^2: Comparison between η and ω



Next steps

- η Analysis
  - Background subtraction through event-mixing
  - Acceptance correction
- Radiative corrections
  - Externals
  - Coulomb Corrections
  - SIDIS Radiative Corrections
- Systematic uncertainties
  1. Particle ID
  2. Vertex cuts
  3. Background subtraction
  4. Acceptance correction
  5. Radiative corrections



Backup

Survival Probability: ω candidates

Survival Probability:

If a particle of mass M has a mean proper lifetime τ $(= 1/\Gamma)$ and has 4-momentum $(E, \boldsymbol{p})$, then the probability that it travels a distance x or greater is:

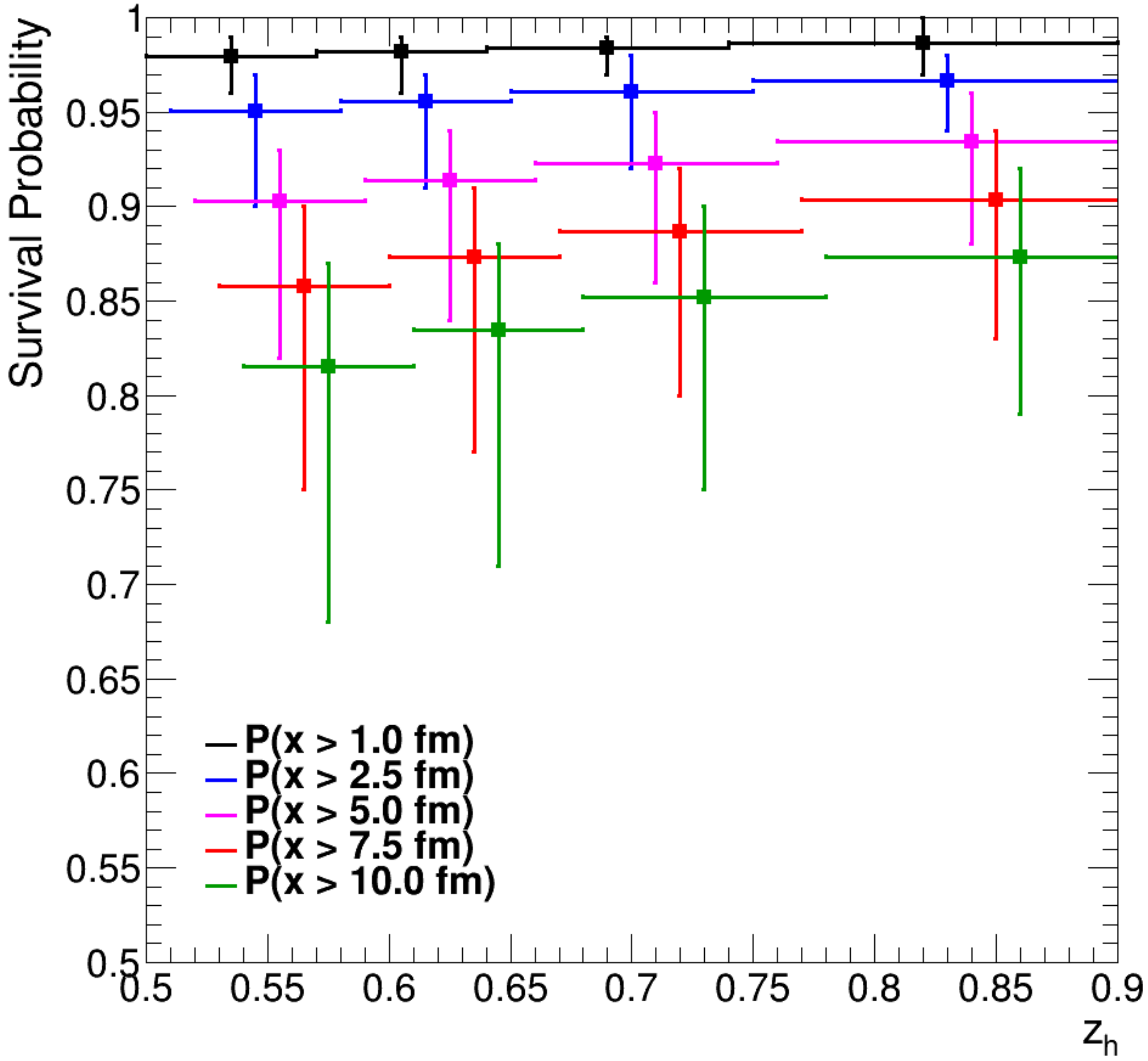
$$P(x) = e^{-M\,x\,\Gamma/|\mathbf{p}|}$$

In the case of ω, (in natural units)

- $M = 0.782$ GeV
- $\Gamma = 8.40 \times 10^{-3}$ GeV

* In the plot, x is translated from natural units to fm.

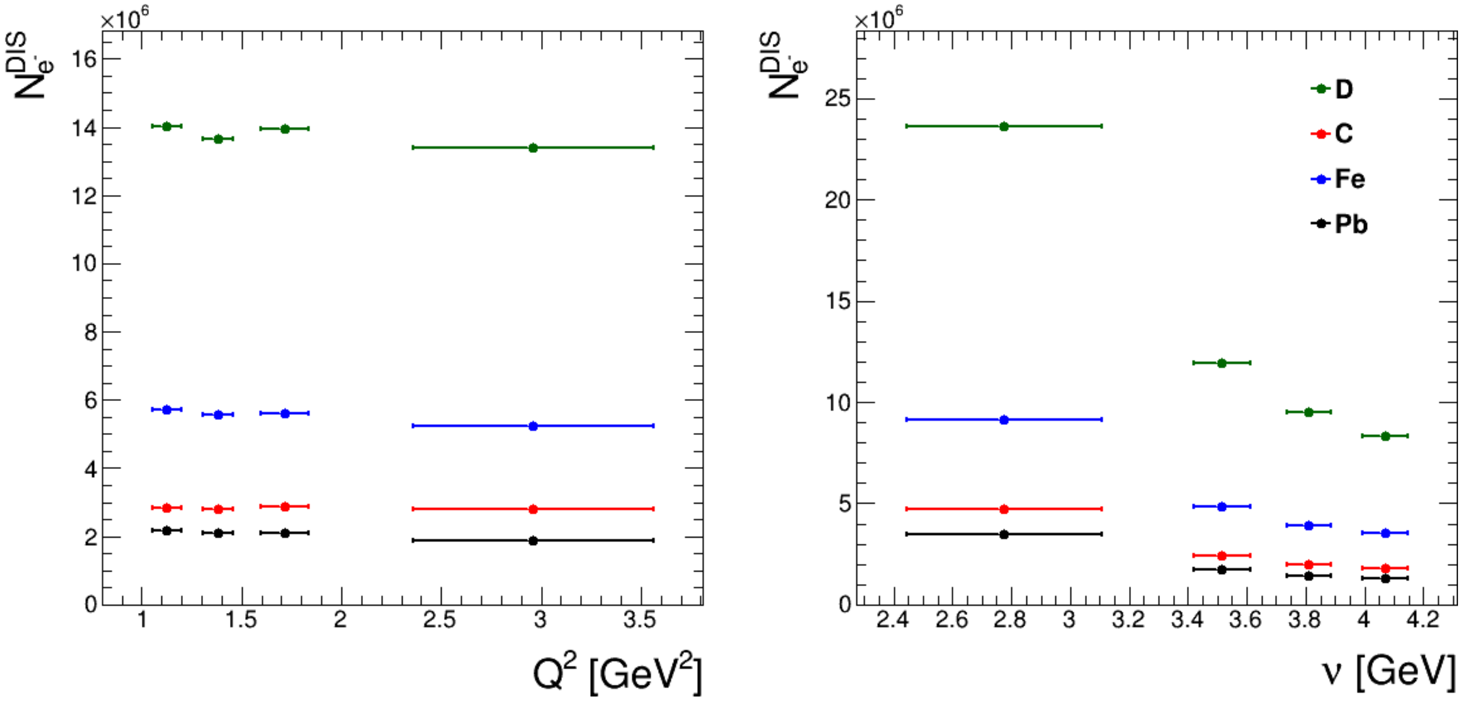
[Particle Data Group]



Electron Numbers

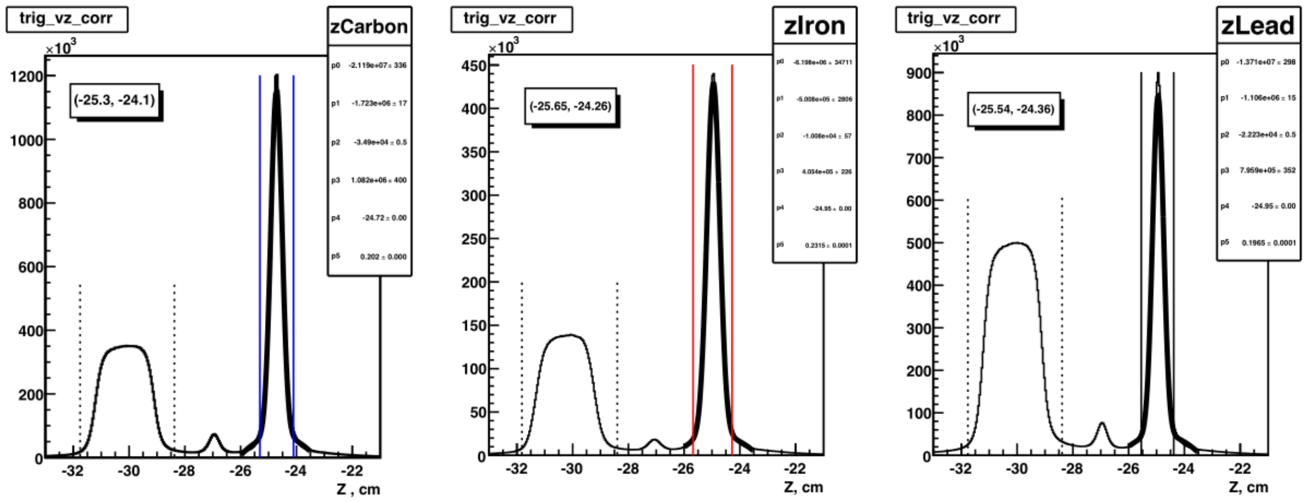
An important term in the definition of Multiplicity Ratio is the **number of DIS electrons** N_e^{DIS}.

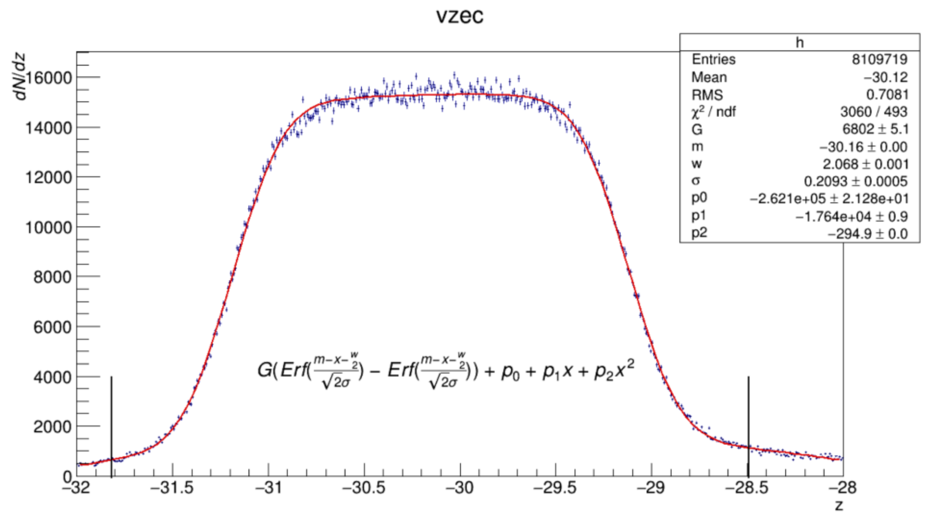
$$R_A^h \equiv \frac{\left(\dfrac{N_h(Q^2,\nu,z,p_T^2)}{\boxed{N_e^{DIS}(Q^2,\nu)}}\right)_A}{\left(\dfrac{N_h(Q^2,\nu,z,p_T^2)}{\boxed{N_e^{DIS}(Q^2,\nu)}}\right)_D}$$



Target	Number of inclusive DIS electrons
D	54,997,138
C	11,287,494
Fe	22,137,224
Pb	8,234,343

Target Determination: Electron Vertex Cuts





Fit to the electron z^{corr} vertex distributions for the deuterium target.

$$-31.80 < z_D^{corr} < -28.40 \text{ cm}$$

$$-25.65 < z_{Fe}^{corr} < -24.26 \text{ cm}$$

$$-25.33 < z_C^{corr} < -24.10 \text{ cm}$$

$$-25.54 < z_{Pb}^{corr} < -24.36 \text{ cm}$$

Usually, reconstruction of the y-position of the target can present background.

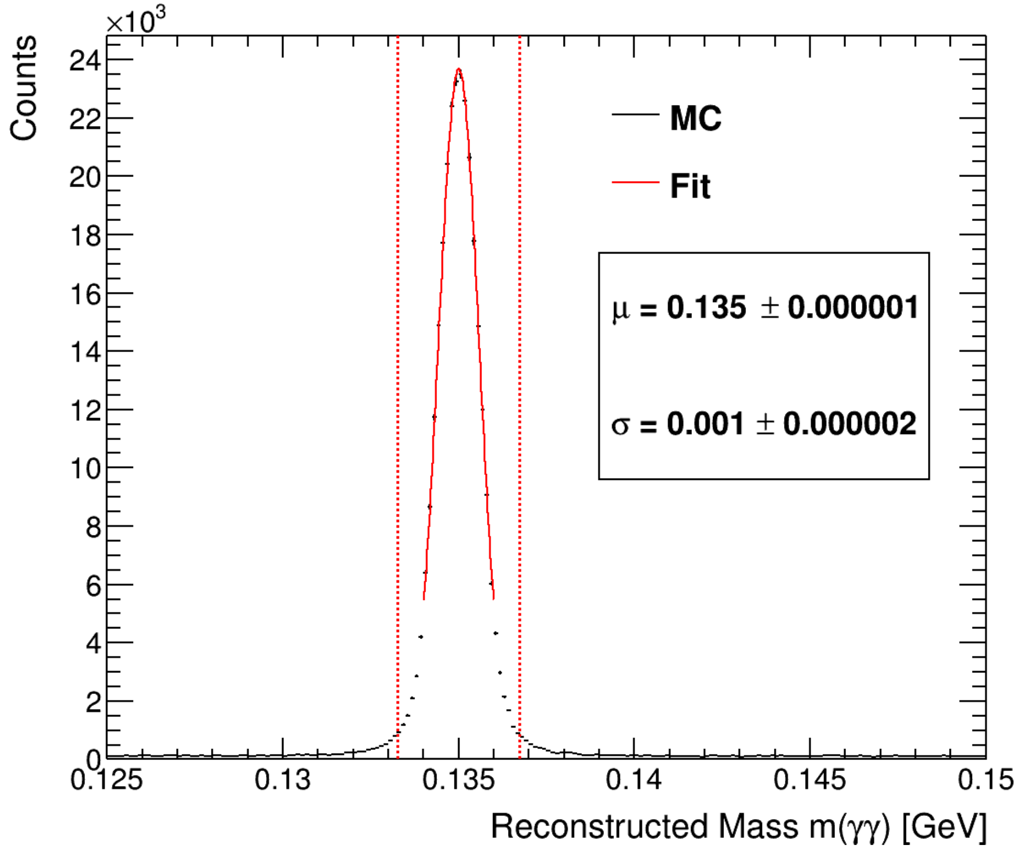
$\Longrightarrow$ A cut was also applied to the y^{corr}:

$$|y^{corr}| < 1.4\ cm$$

Generated Particles ID: Overview

To count how many ω mesons were generated, it is necessary to combine the final-state particles and form all possible ω candidates.

Neutral Pion Reconstruction



Overview of cuts

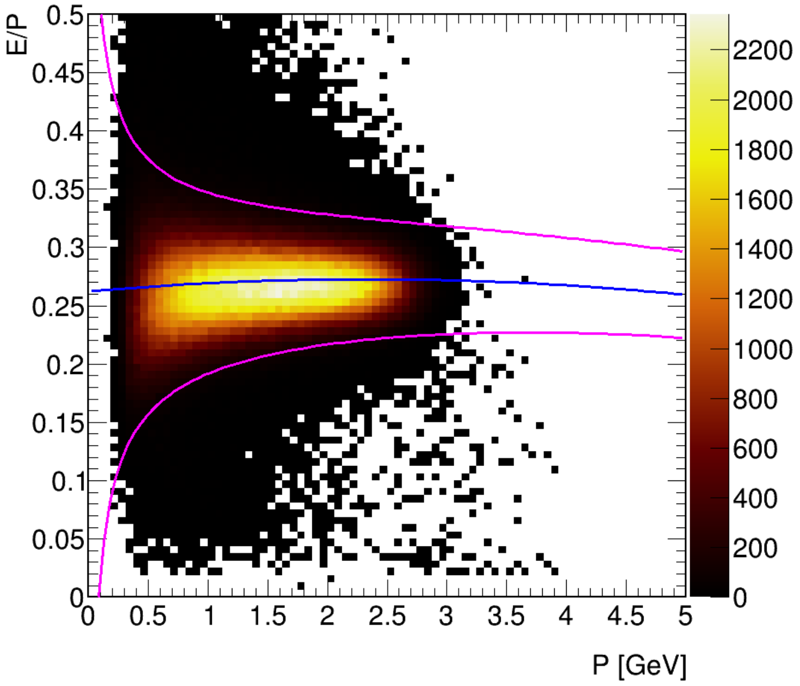
- There are no vertex cuts.
- DIS cuts are maintained for the scattered electrons.
- For consistency, the exact cut for exclusion of neutral kaons is maintained.

Reconstructed Particles ID

The particle identification criteria used to determine the type of **reconstructed** or **accepted** particles follows the procedures than data.

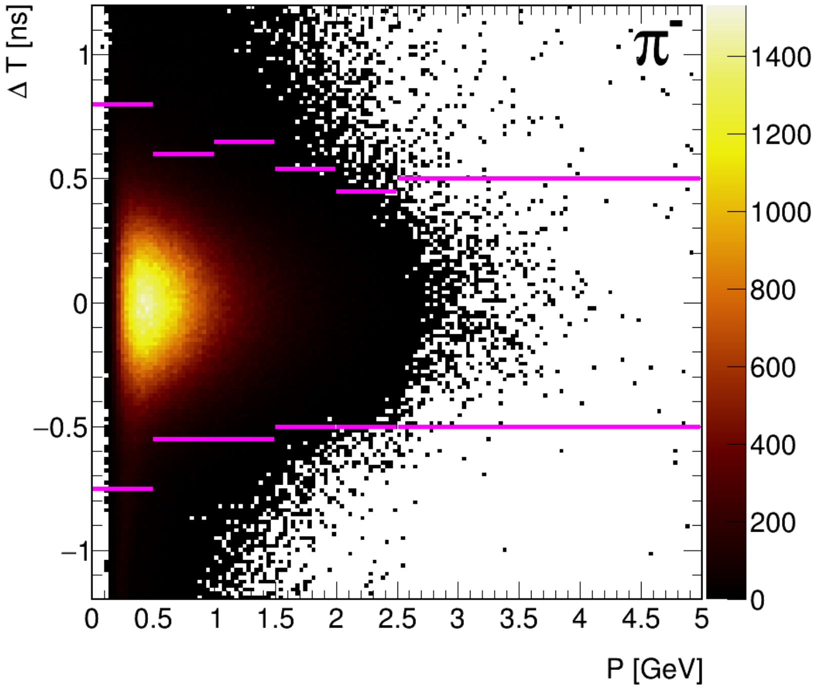
Electron ID

Same as data, except for the sampling fraction cut.



Charged Pions ID

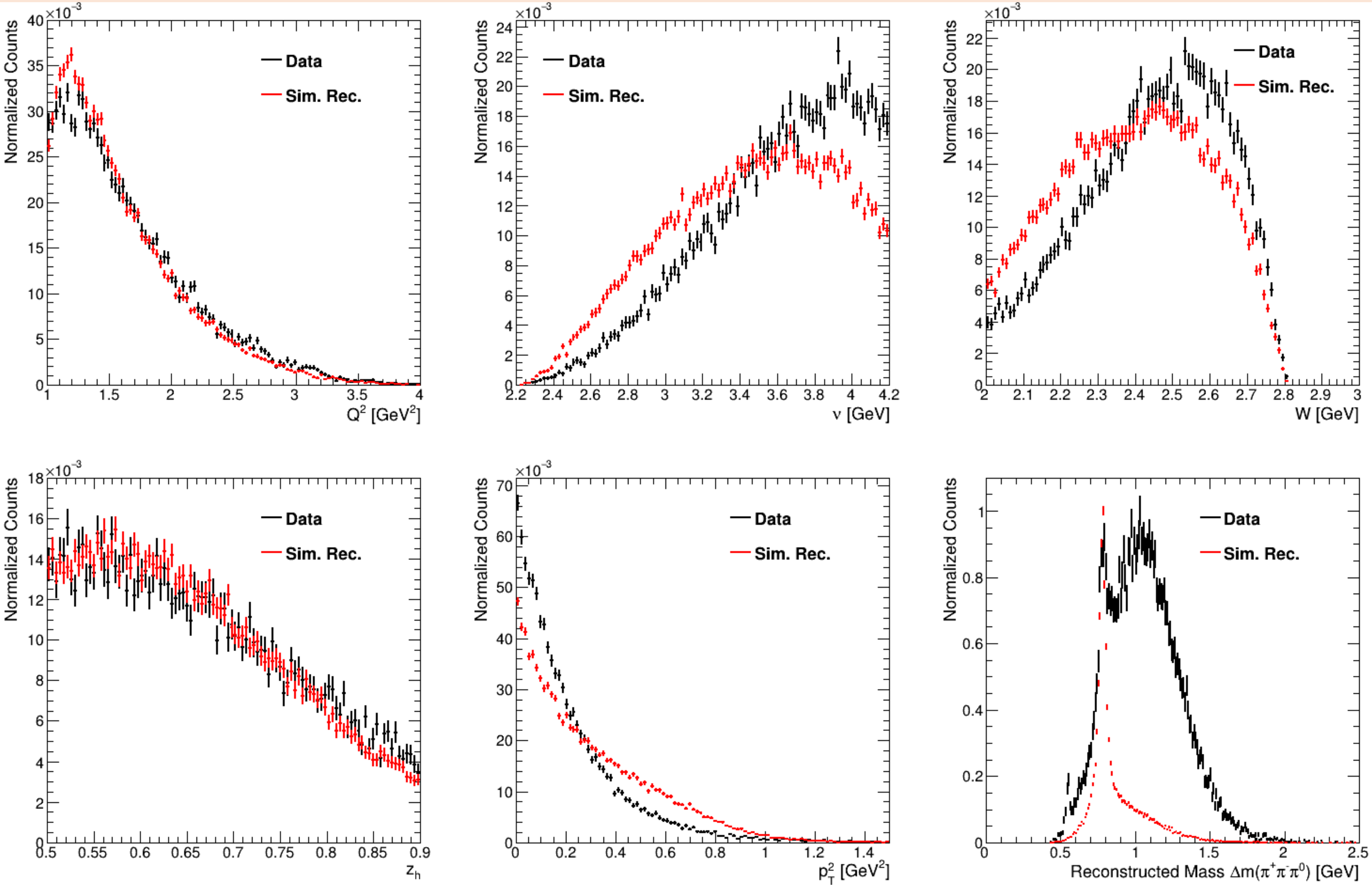
Same as data, except for the **TOF** cuts for π^-.



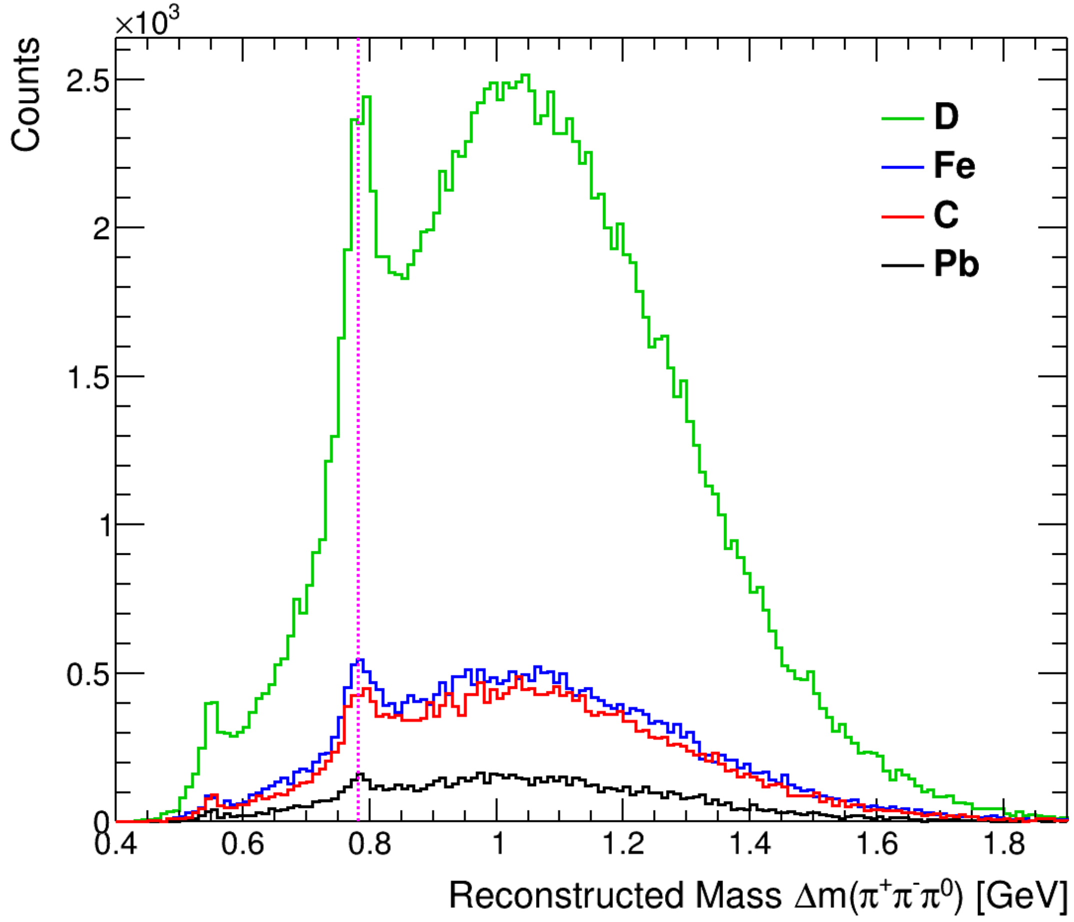
Overview of cuts

- Same Photons ID, except for the energy correction factors.
- No vertex cuts.
- DIS cuts.
- Same cut for exclusion of neutral kaons than data.
- Same cut for invariant mass of neutral pions.

Comparison between Data and Sim. Reconstructed



Background Subtraction



<u>How to count the number of measured ω mesons?</u>

Two methods for background subtraction were studied:

- Background and signal fitting
- Event-mixing technique

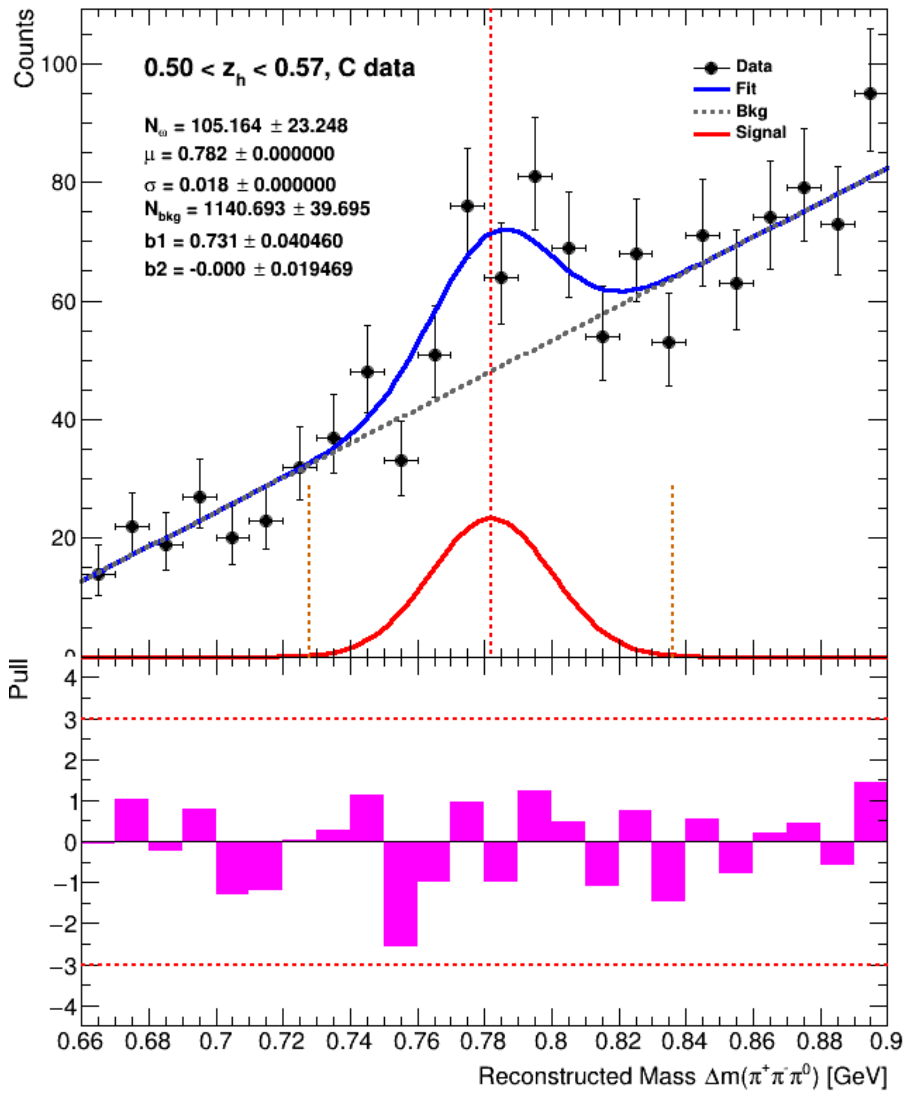
Background and Signal Fitting: Description

- Fit function:
  - $f(x) = N_\omega G(x; \mu, \sigma) + N_b\, p_2(x;\ b_1, b_2)$
  - Extended model: $N_\omega + N_b = N_{tot}$
- Parameters μ and σ are **fixed** from preliminary fits on all data.

- Count of hadrons by integrating signal component
- Primary tool: **ROOT's RooFit**

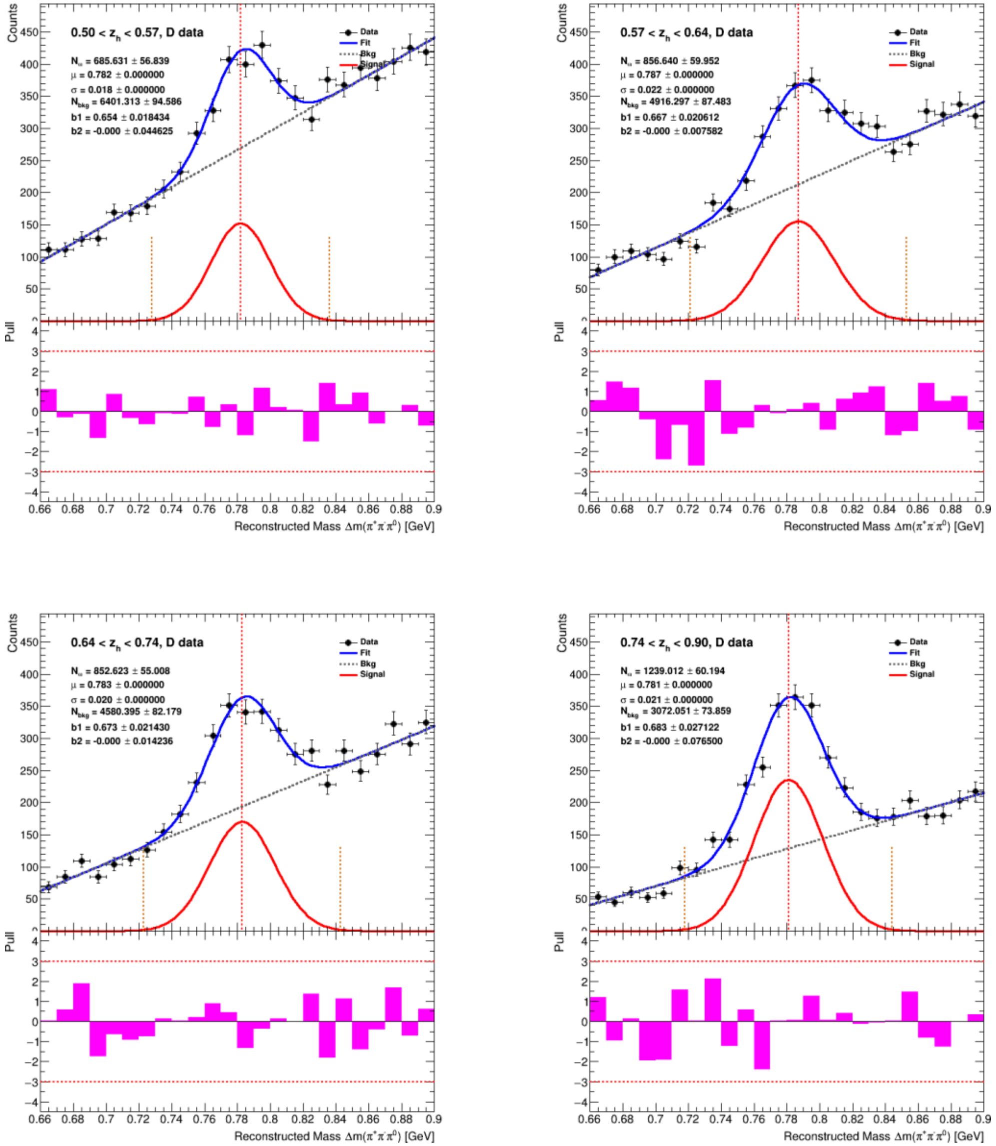
- Maximum likelihood fit
  - Event-by-event basis
  - Longer computation time than least squares method
  - Limitation: not known tests to measure goodness of fit.

$$\text{pull}(x_i) = \frac{\text{data}(x_i) - \text{model}(x_i)}{\text{data error}(x_i)}$$

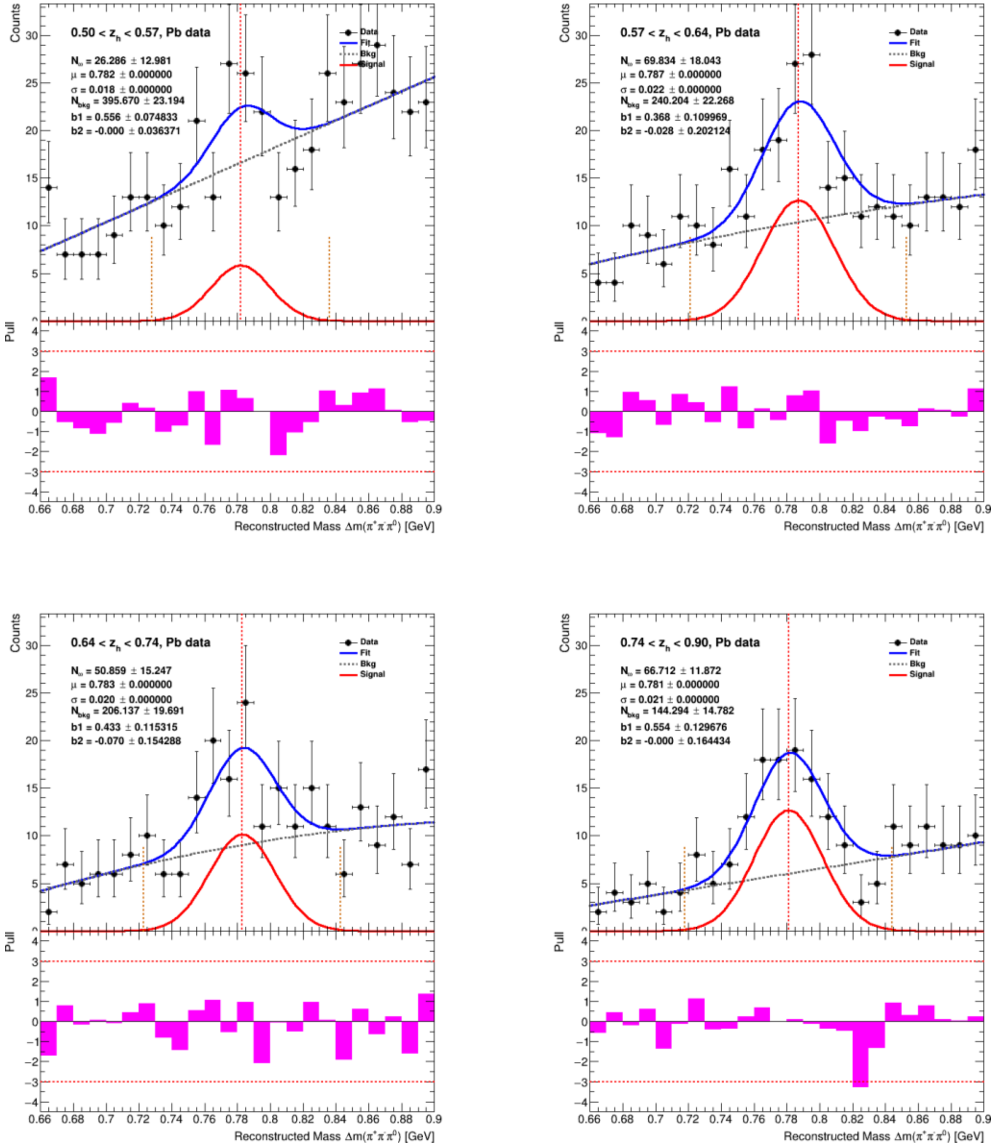


Background and Signal Fitting: Application

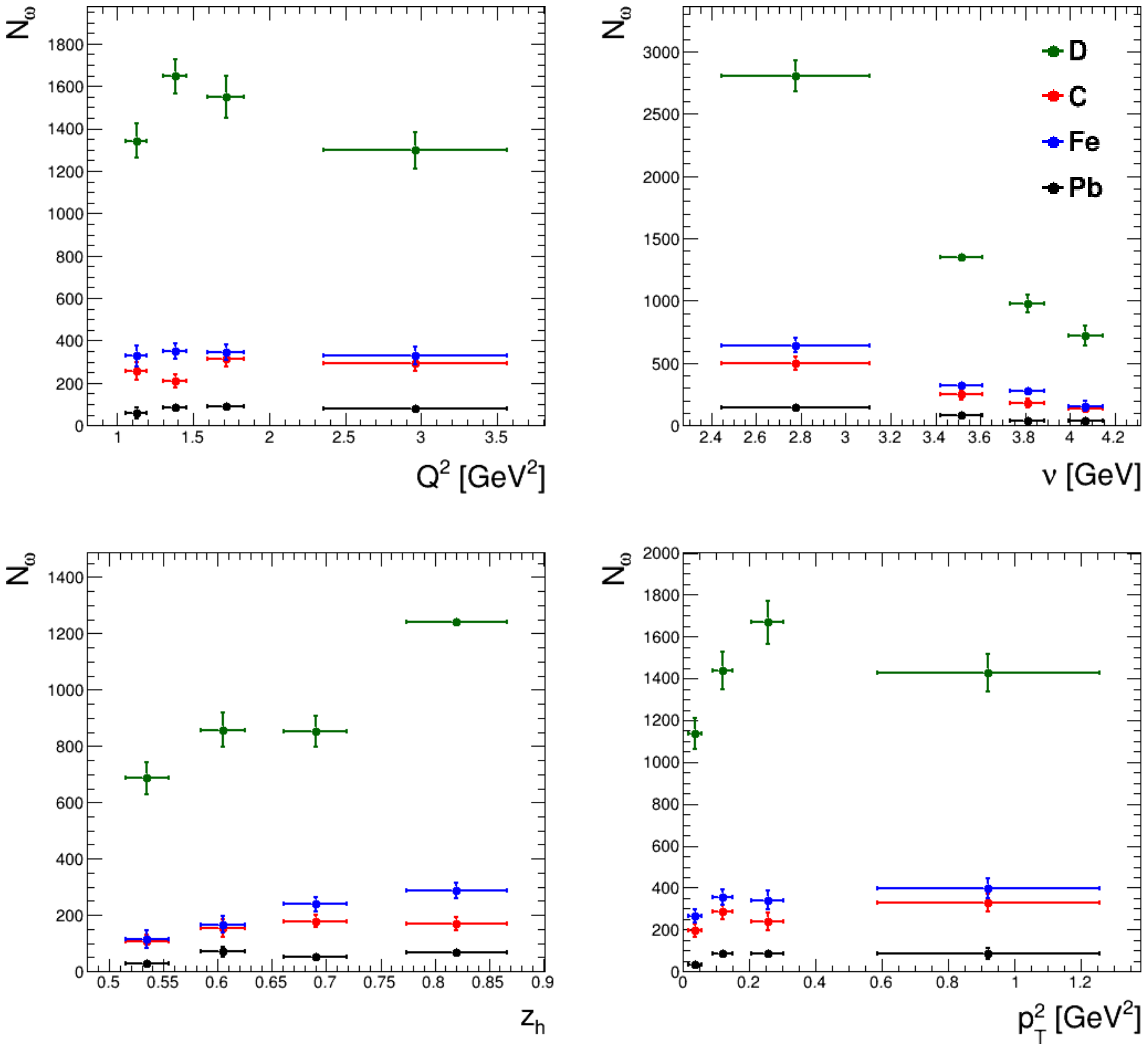
On Deuterium data



On Lead data

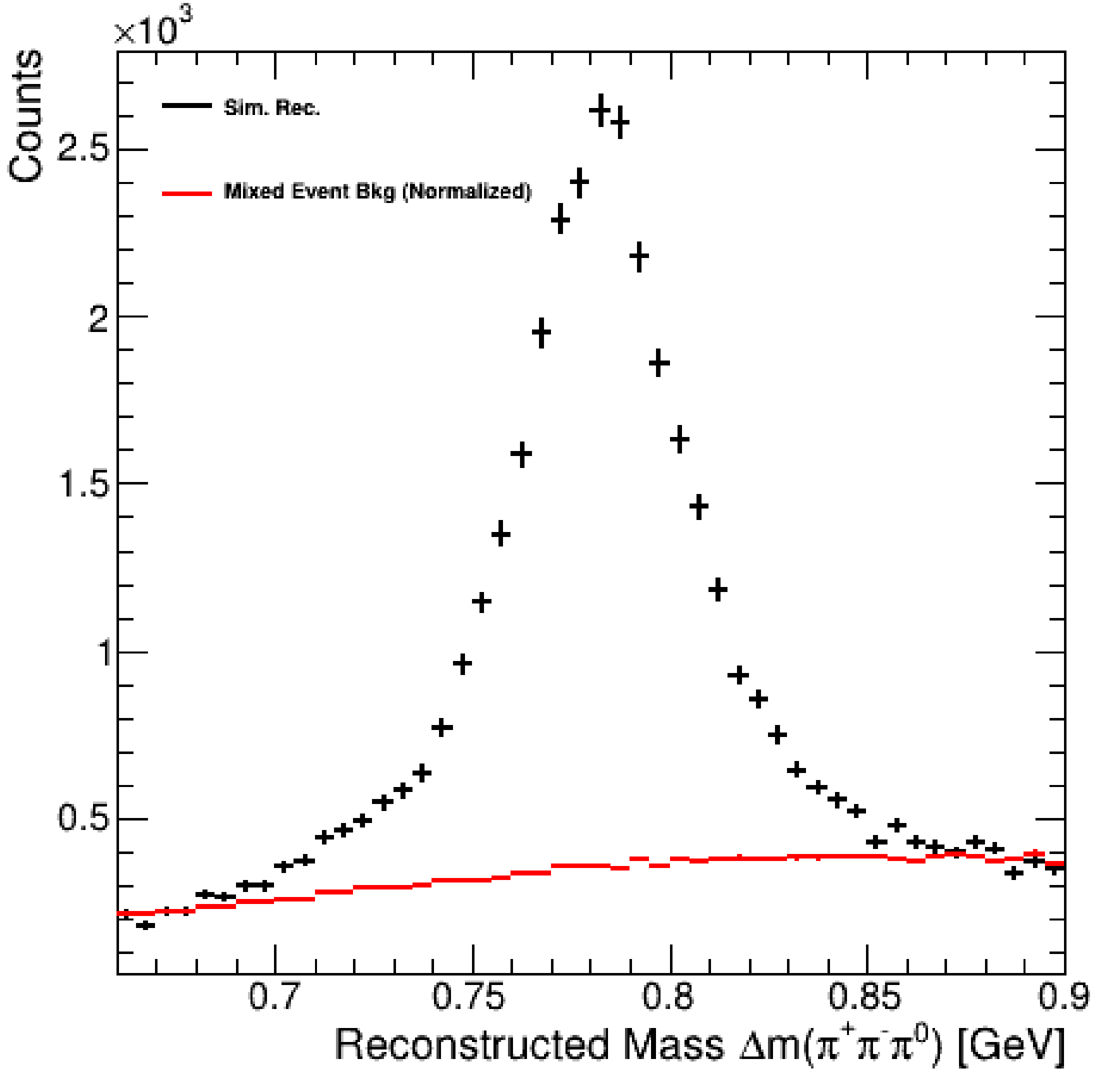


Background and Signal Fitting: Extracted N_ω



Reconstructed Particles ID: Event Mixing

Similarly to data and generated particles, one can subtract the combinatorial background by using **the event mixing method**.



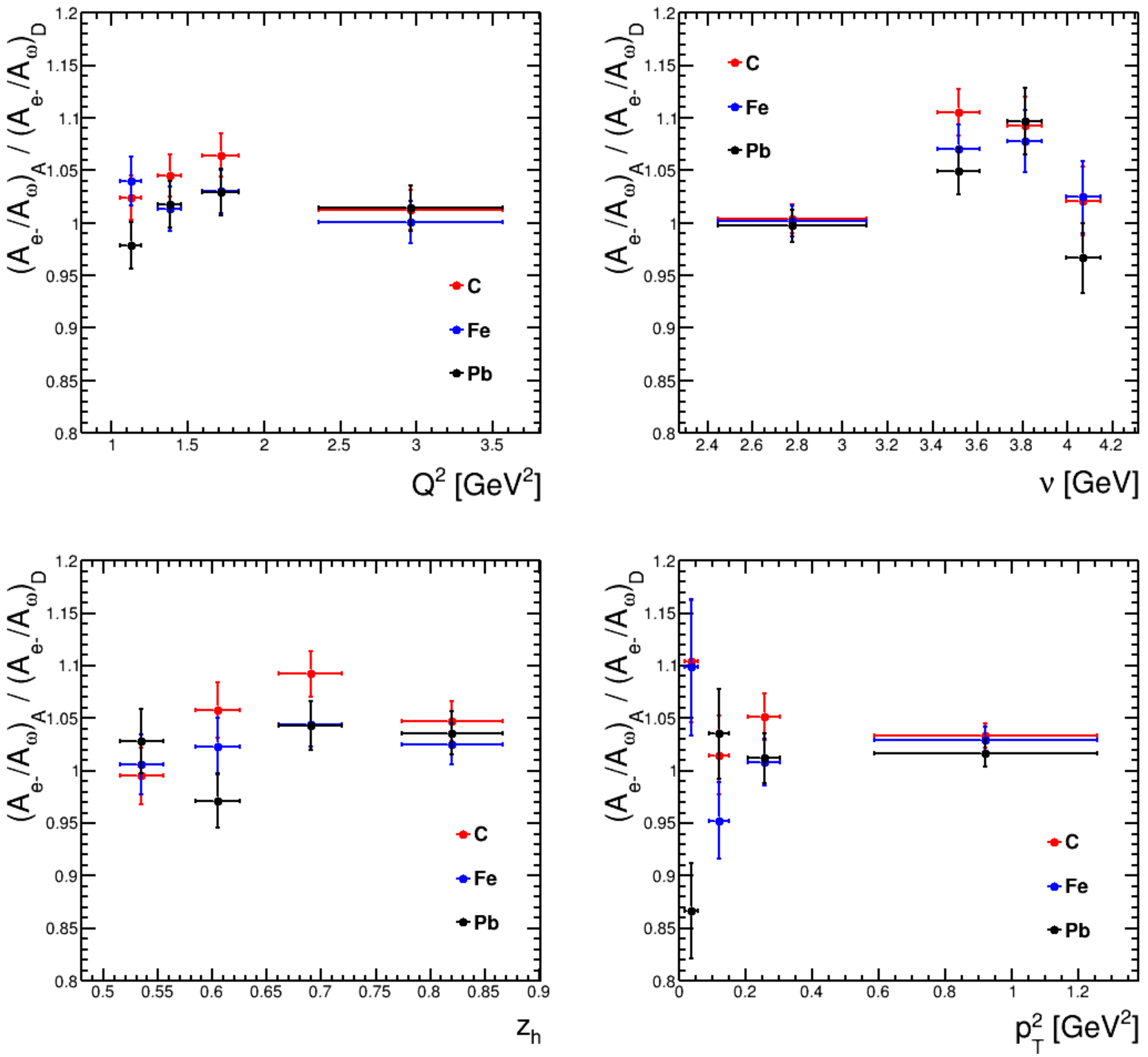
Acceptance Correction: Application

$$A_\omega = \frac{N_\omega^{rec}(Q^2, \nu, z_h, p_T^2)}{N_\omega^{gen}(Q^2, \nu, z_h, p_T^2)}$$

The Acceptance Correction Factor is applied to the number of detected particles on a bin-by-bin basis:

$$\longrightarrow N_\omega^{corr} = \frac{N_\omega}{A}$$

$$\Longrightarrow R'^h_A \equiv \frac{\left(\frac{N_h^{corr}(Q^2,\nu,z,p_T^2)}{N_e^{corr}(Q^2,\nu)}\right)_A}{\left(\frac{N_h^{corr}(Q^2,\nu,z,p_T^2)}{N_e^{corr}(Q^2,\nu)}\right)_D} = \frac{\left(\frac{A_e(Q^2,\nu)}{A_h(Q^2,\nu,z_h,p_T^2)}\right)}{\left(\frac{A_e(Q^2,\nu)}{A_h(Q^2,\nu,z_h,p_T^2)}\right)} R^h_A$$

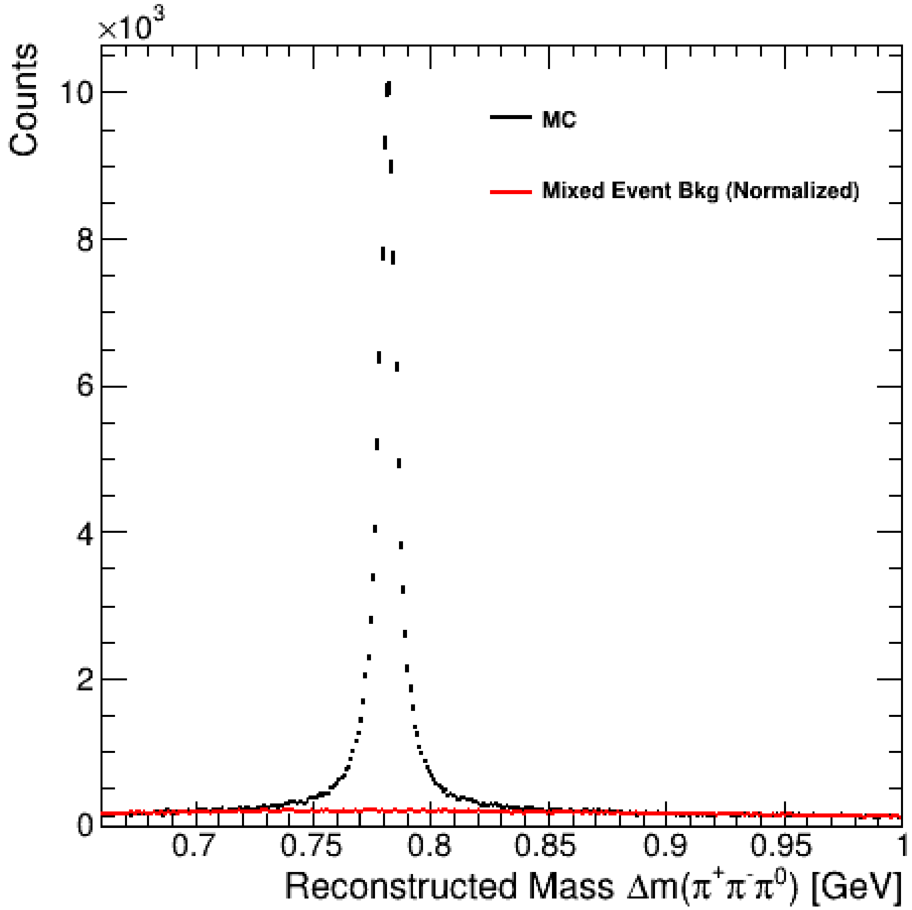


Generated Particles ID: Background Subtraction

Since there is **no parent particle information**, the only way to count the generated ω mesons is by reconstructing their invariant mass throug their three-pion decay.

However, one of the disadvantages of this method is that some combinatorial background will appear under the ω signal.

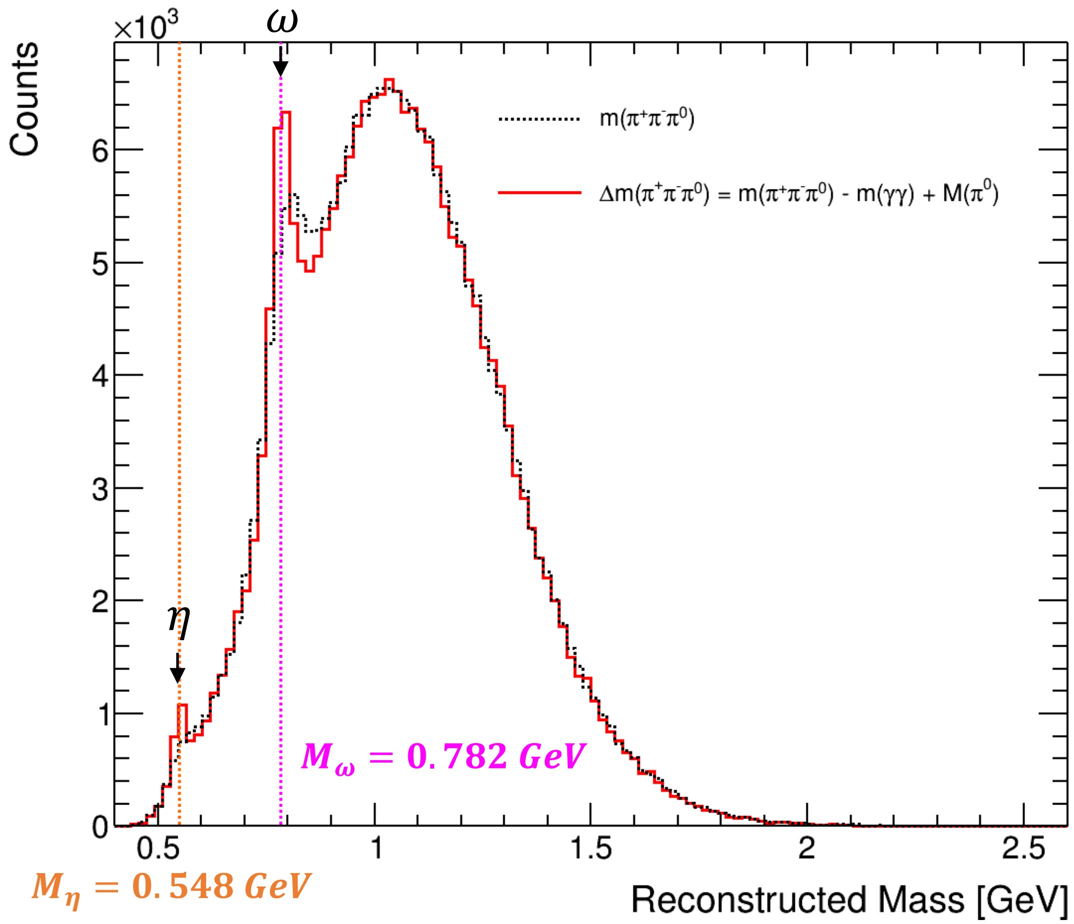
To subtract it, one can employ the same method used for data: **the event mixing**.



Reconstruction of the ω meson - II

An alternative mass expression is preferred: the **invariant mass difference**,

$$\Delta m(\pi^+\pi^-\pi^0) = m(\pi^+\pi^-\pi^0) - m(\gamma\gamma) + M_{\pi^0}, \qquad M_{\pi^0} = 0.135 \text{ GeV}$$

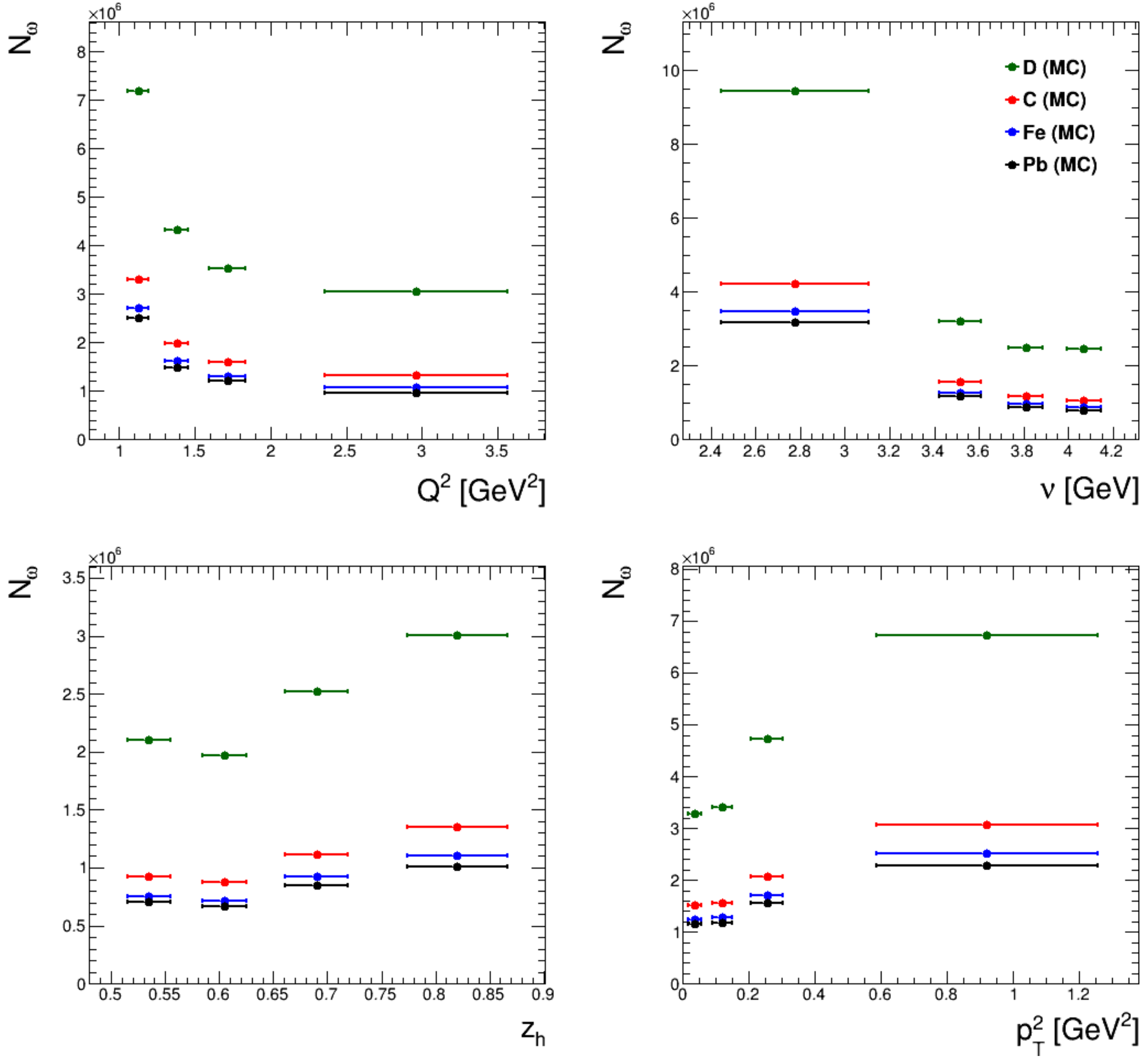


- Technique widely used by other experimental collaborations.
- The technique exploits the fact that two or more invariant masses can be defined due to two or more consecutive decays.

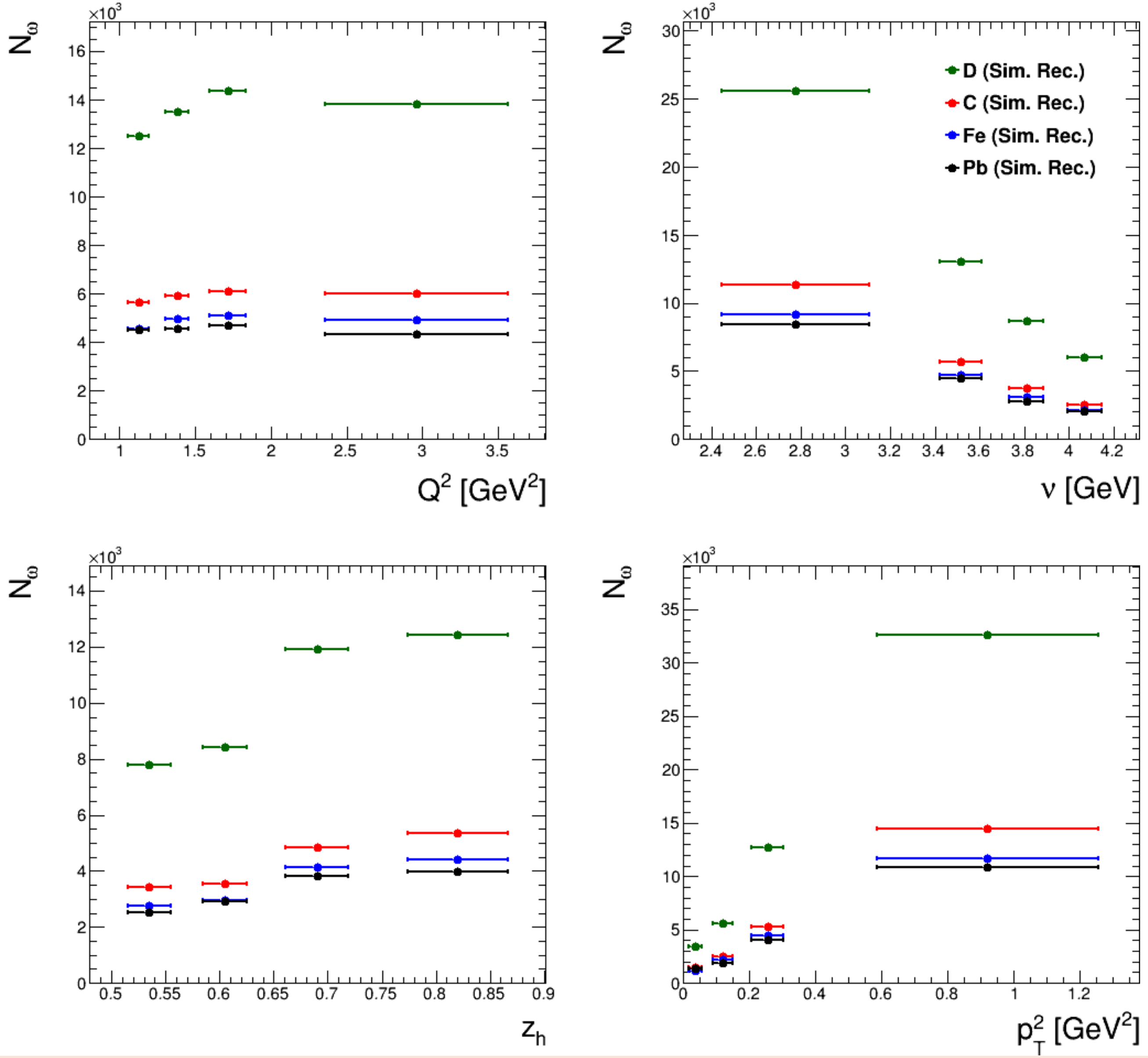
Benefits:

1. The ω and η peaks gets narrower and higher
2. The overall background shape does not change

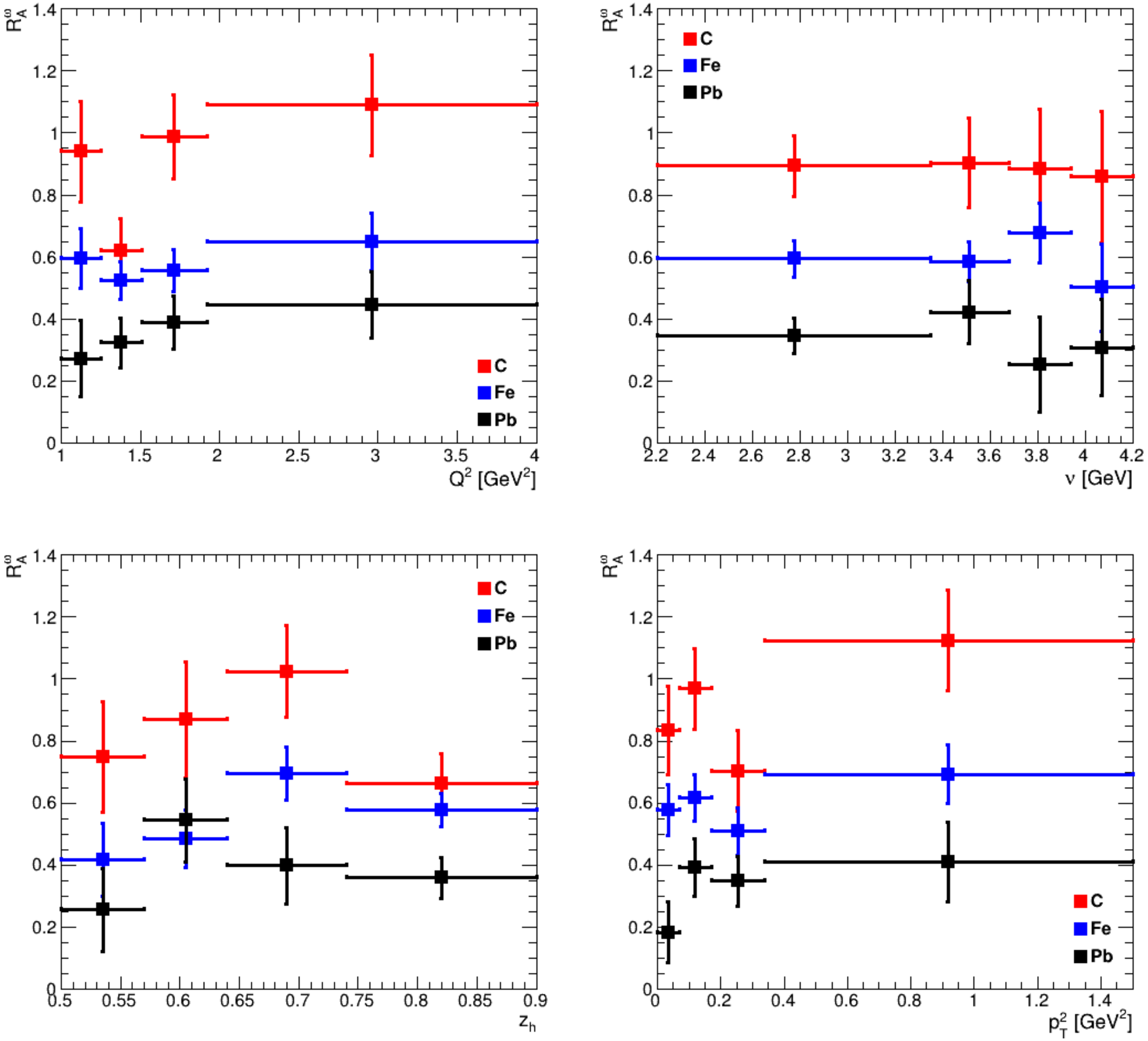
Generated Particles ID: Extracted N_ω



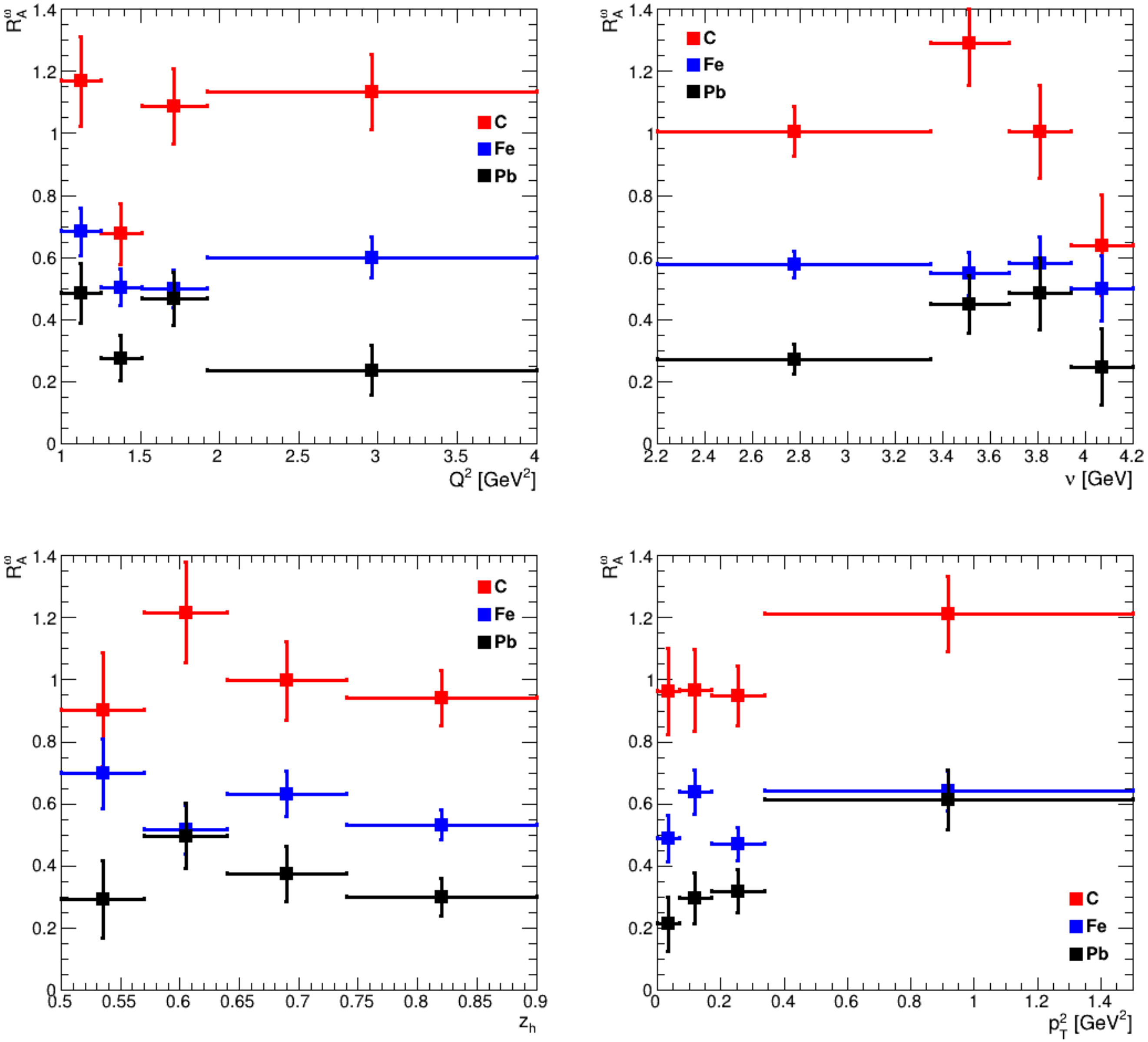
Reconstructed Particles ID: Extracted N_ω



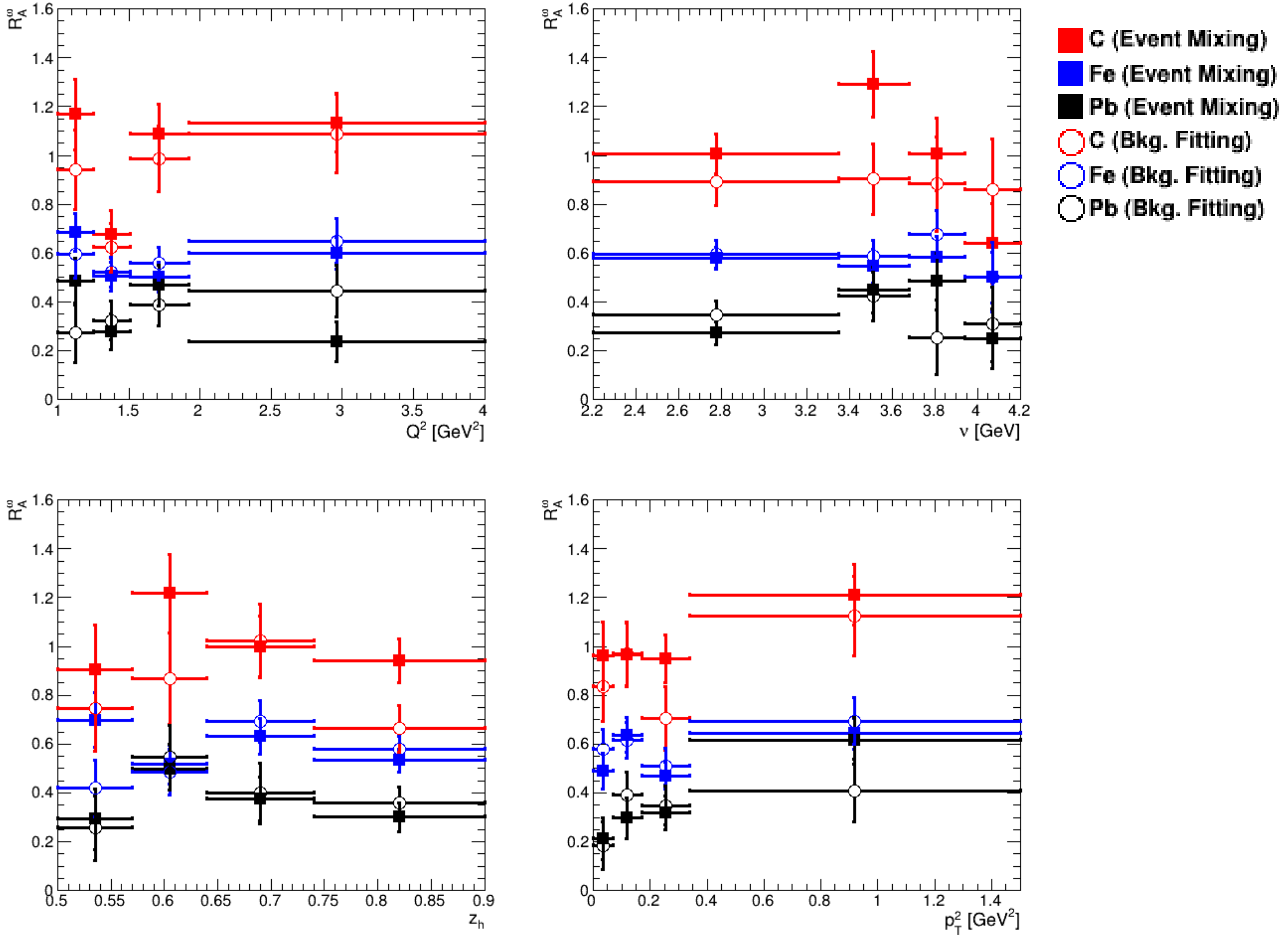
Results: 1-D MR of the ω meson – Method: Bkg Fitting



Results: 1-D MR of the ω meson – Method: Event Mixing

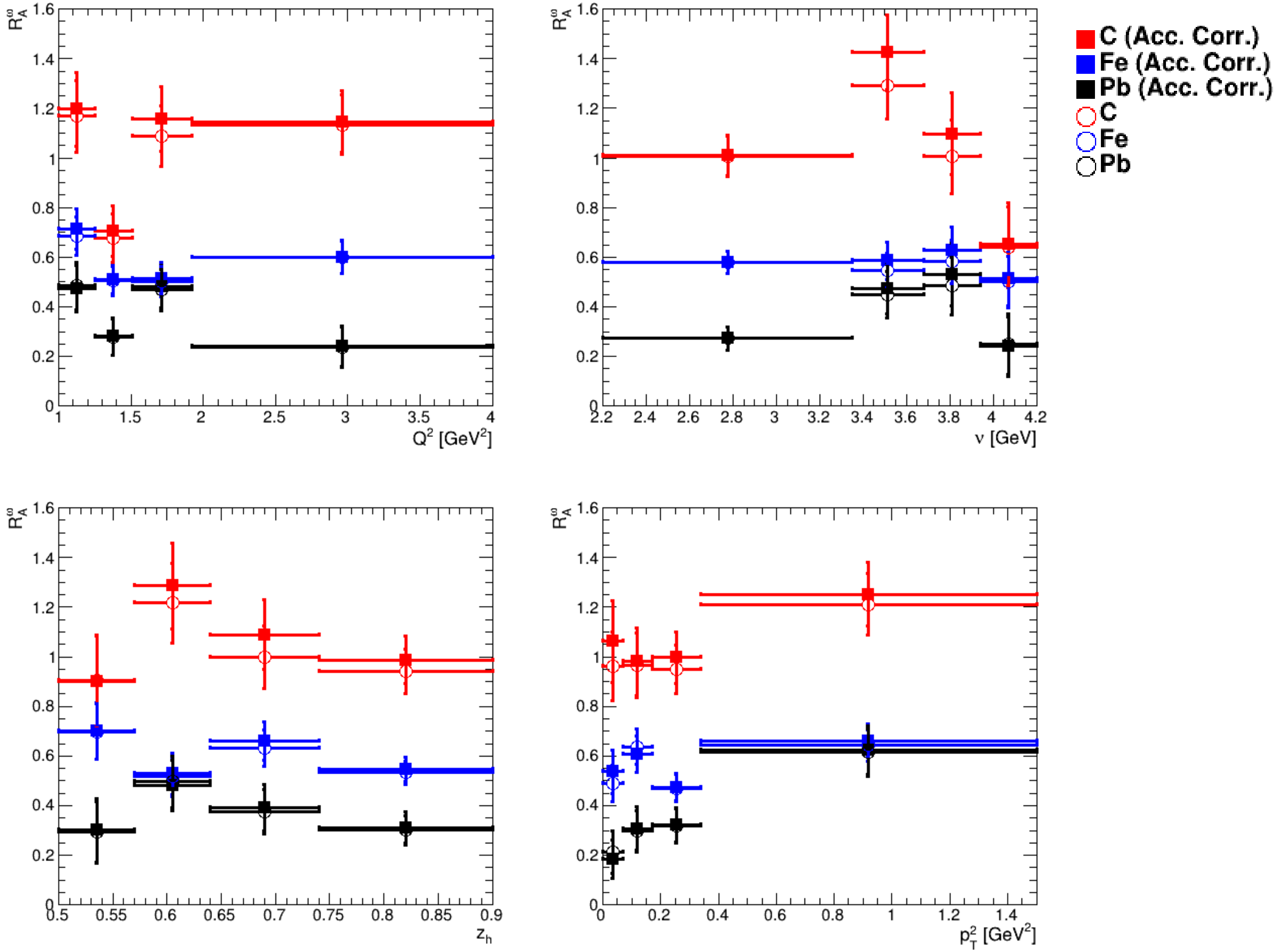


Results: 1-D MR of the ω meson – Comparison between methods



Results: 1-D MR of the ω meson – Acceptance Corrected vs Uncorrected

Background subtraction method: event-mixing.



Conclusions: 1-D MR of the ω meson

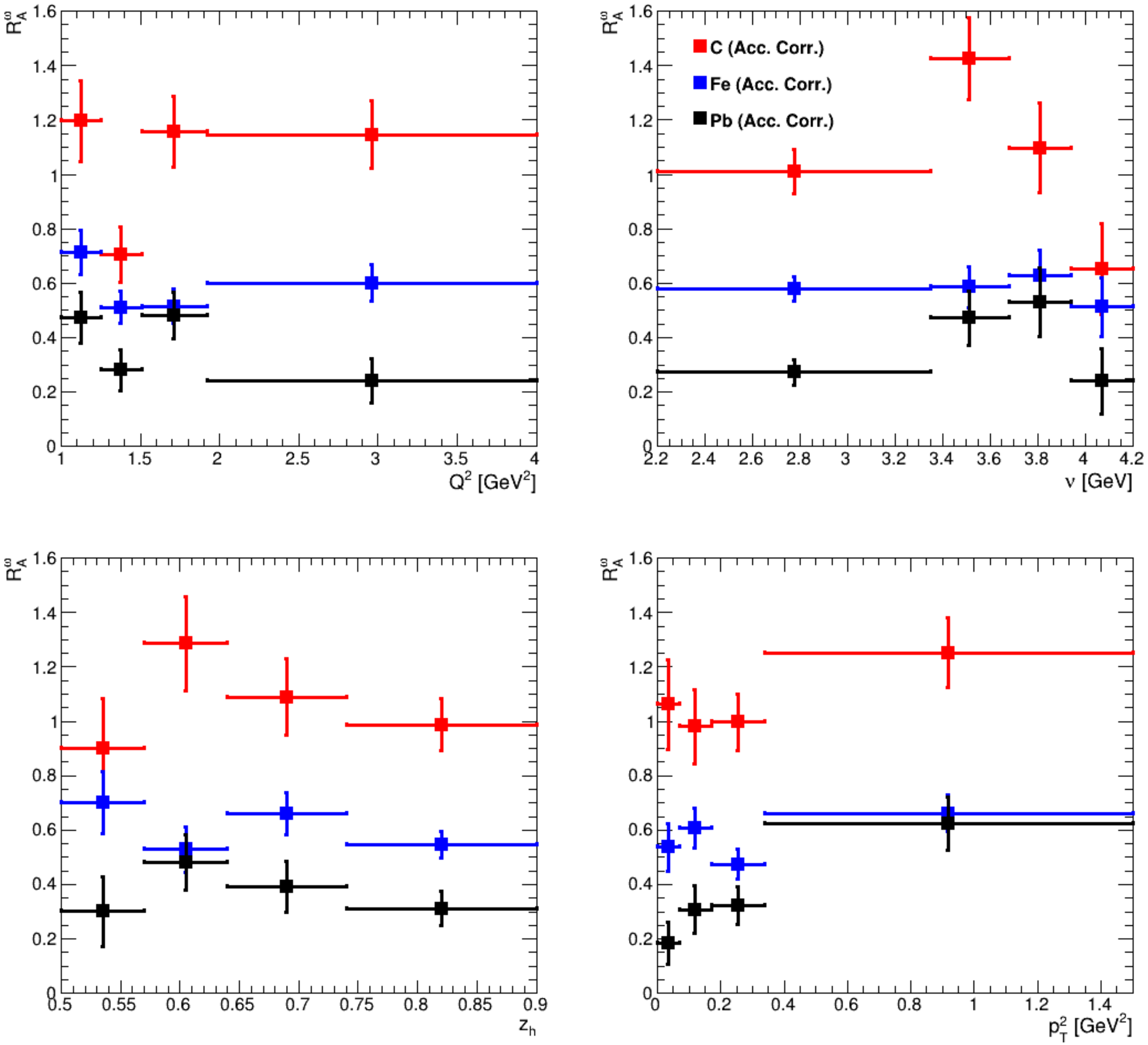
<u>In all plots:</u>
The nuclear environment attenuates the production of the ω meson.

In MR vs Q^2:

- Almost no dependence on Q^2.
- Expected from previous analyses.

In MR vs z_h:

- MR decreases when z_h increases.
- Expected from previous analyses.



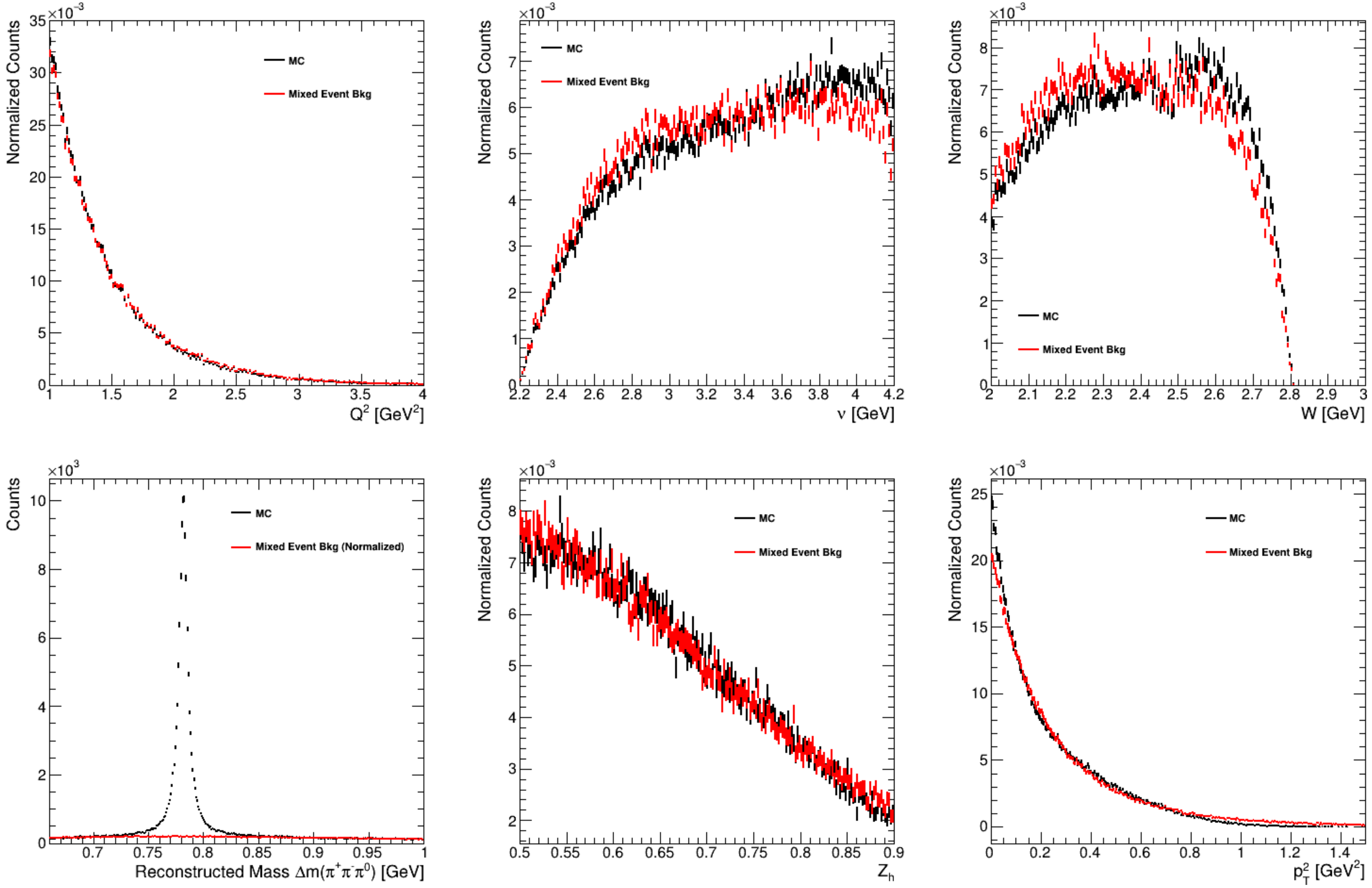
In MR vs ν:

- MR slightly decreases when ν increases.
- **Unexpected** from previous analyses.

In MR vs p_T^2:

- MR increases when p_T^2 increases.
- Expected from previous analyses.
- **Cronin effect** holds.

Generated Particles ID: Comparison with Event-Mixing



Reconstructed Particles ID: Comparison with Event-Mixing