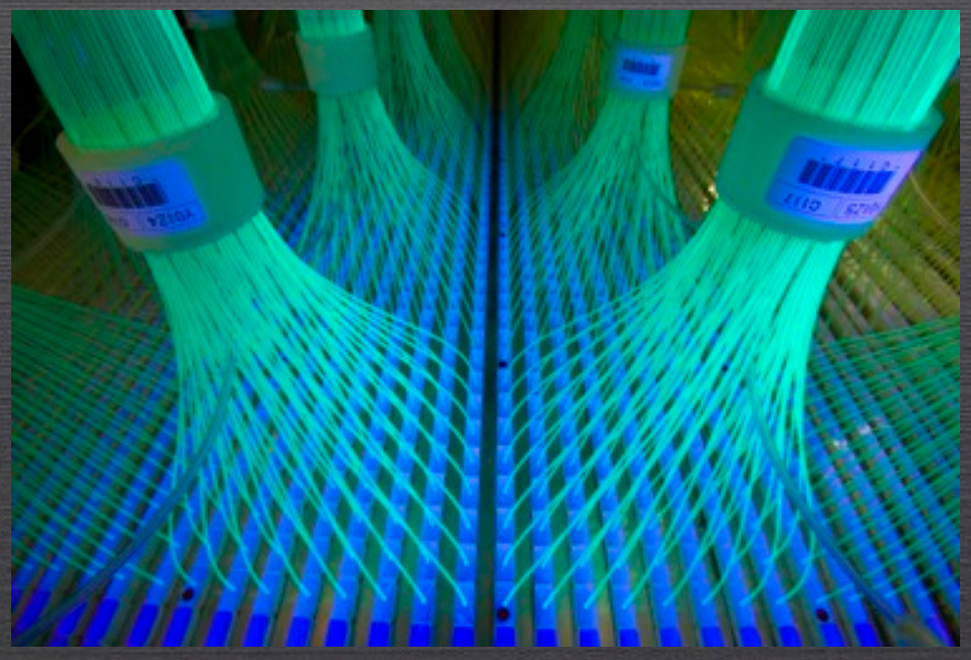
Neutrino Induced Pion Production at SciBooNE

Hide TANAKA
BNL



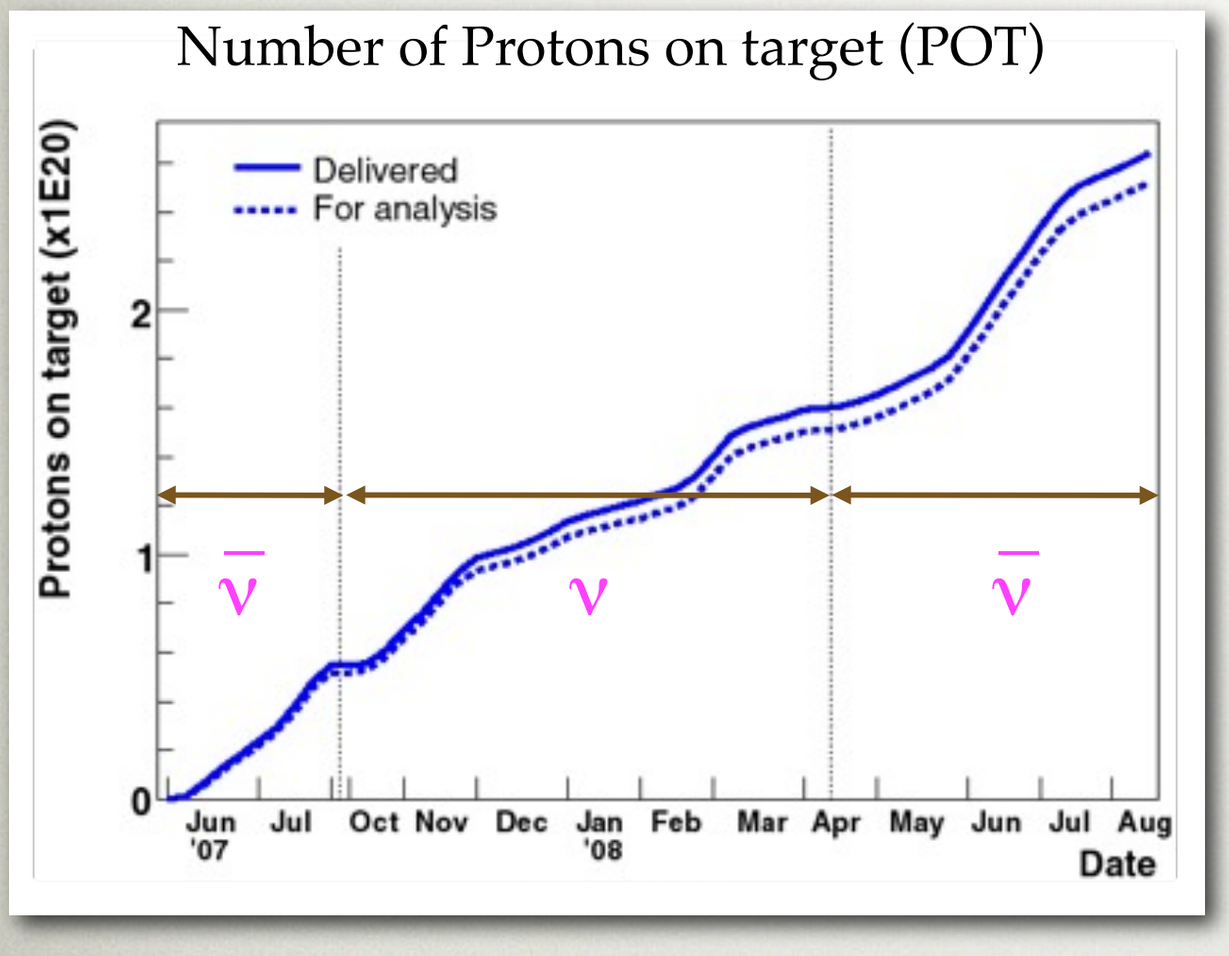
NuInt11 at Dehra Dun, India Mar. 8, 2011

Contents

- SciBooNE pion production measurements
  - ν CC coh-π^+: Phys.Rev.D78, 112004 (2008)
  - ν NC-π^0: Phys.Rev.D81, 033004 (2010)
  - ν NC coh-π^0: Phys.Rev.D81, 111102 (2011)
  - $\bar{\nu}$ CC coh-π^-: Preliminary results
  - ν CC-π^0: Preliminary results
- Summary

SciBooNE

SciBooNE Data



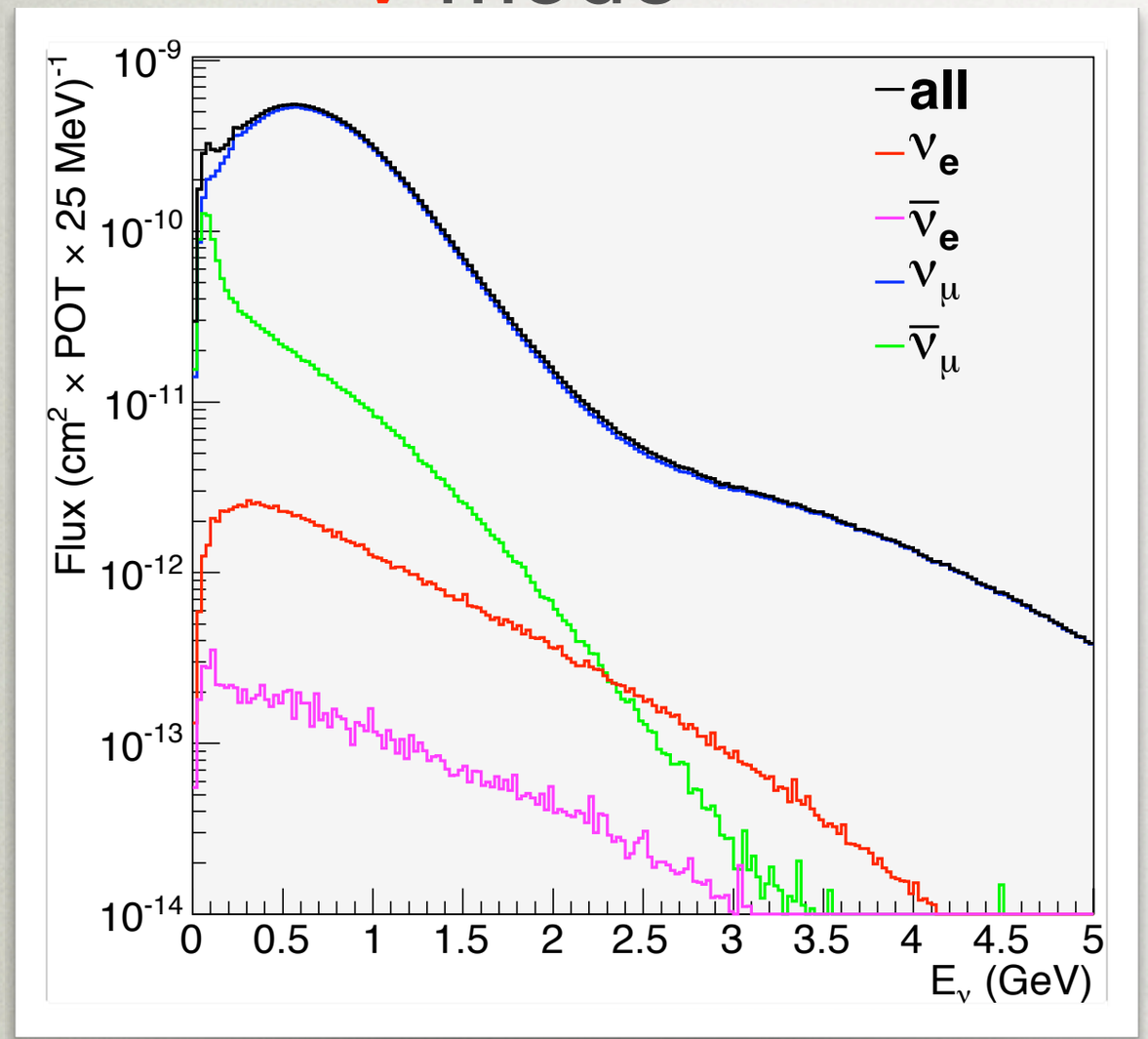
- 2.52×10^{20} POT in total
  - Neutrino: 0.99×10^{20} POT
  - Antineutrino: 1.53×10^{20} POT

- Data taking: Jun. 2007 - Aug. 2008

Results from full ν & $\bar{\nu}$ data set presented today

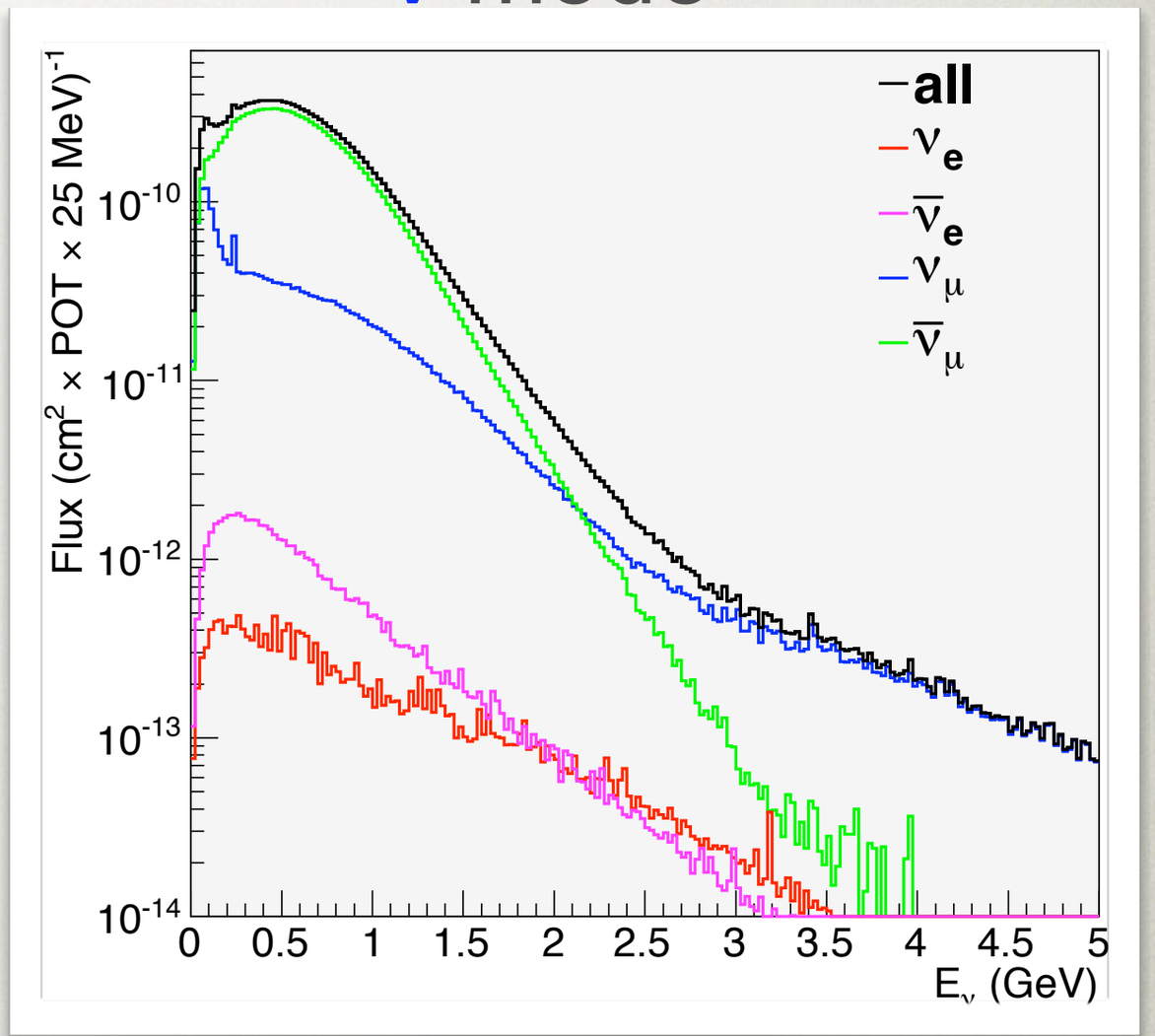
ν Flux Prediction

ν mode



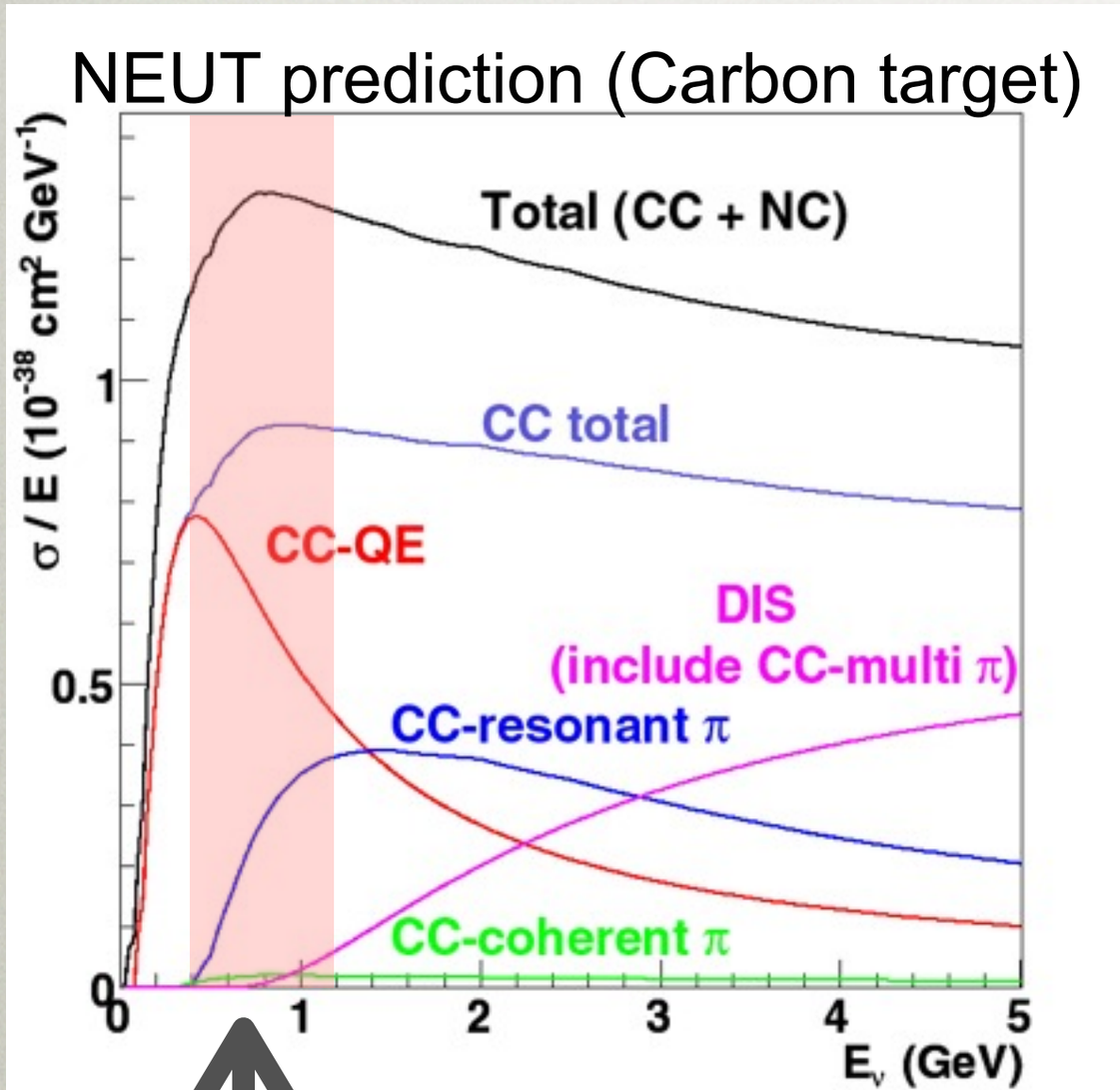
- <Ev> ~0.7 GeV
- 93% pure ν_μ beam
  - $\bar{\nu}_\mu$: ~6%
  - $\nu_e + \bar{\nu}_e$: < 0.1%

$\bar{\nu}$ mode



- <Ev> ~0.6 GeV
- 84% pure $\bar{\nu}_\mu$ beam
  - ν_μ: ~16%
  - $\nu_e + \bar{\nu}_e$: < 0.1%

Neutrino event generator (NEUT)



SciBooNE Energy

- QE
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2GeV/c^2
  - P_F=217MeV/c, E_B=27MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 GeV/c^2
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 GeV/c^2

CC/NC-π

- DIS
  - GRV98 PDF
  - Bodek-Yang correction
- Intra-nucleus interactions
  - Pion FSI & nucleon FSI (e.g. pion absorption)

Search for

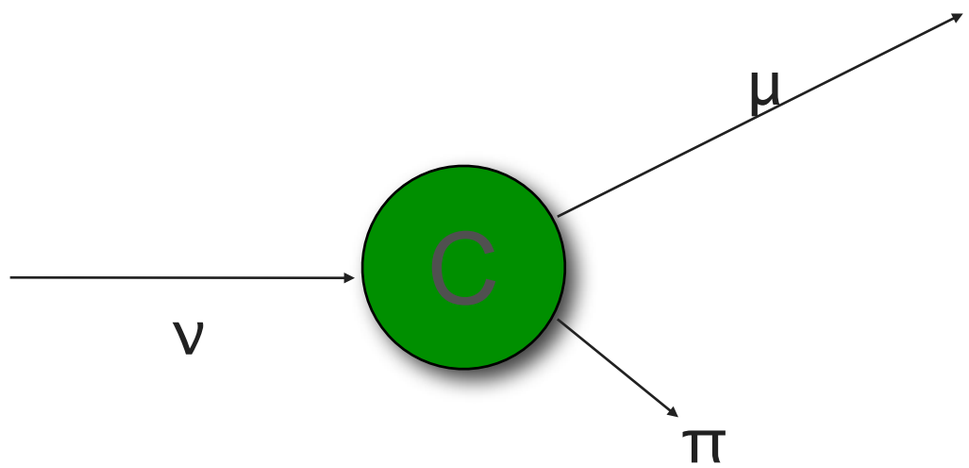
ν CC coherent π^+

Signal & Background

Signal

CC-coherent π

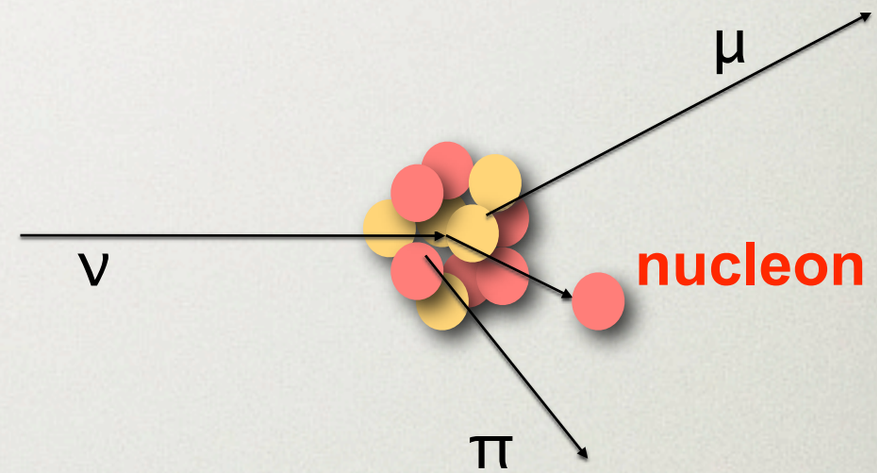
(ν+A→μ+A+π)



Background

CC-resonant π

(ν+p→μ+p+π)

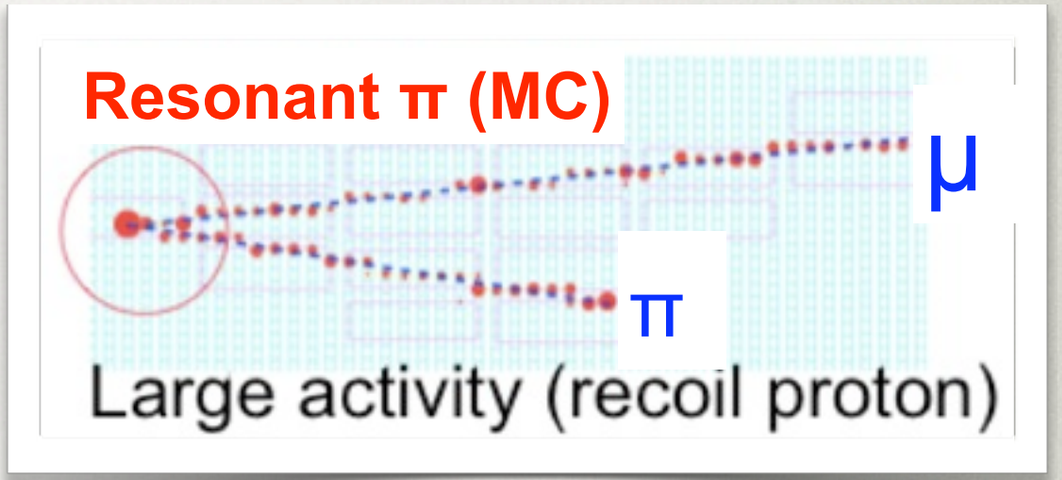


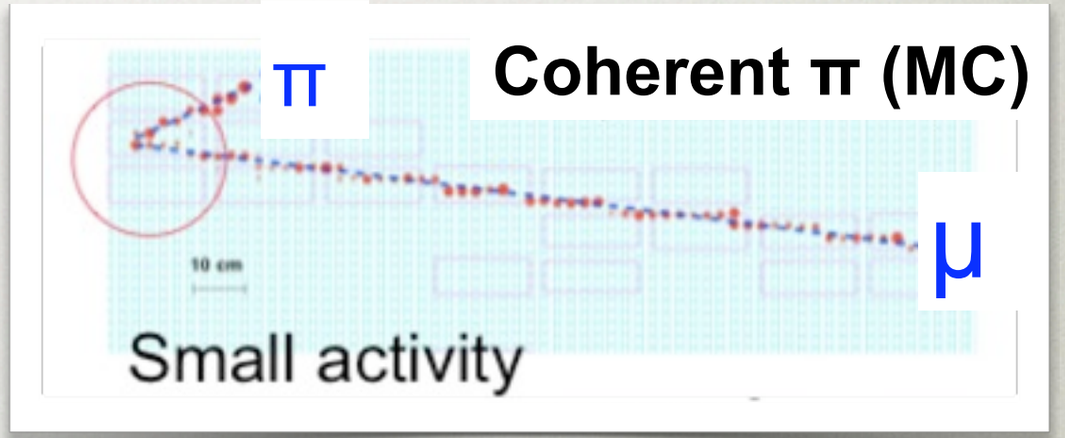
Predominant process in ~1GeV.
Mainly through Δ resonance.

Nucleon signature differ event-topology of resonant-π from coh-π.
Fine granularity of SciBar allows to separate coh-π and resonant π production event-by-event.

Technique to identify Coh-π

- Separate CC coherent-π from CC resonant-π:
  - Identify recoil proton
    - Resonant π has nucleon in final state
    - No recoiled-nucleon in coherent π
- Low energy proton make an energy deposit around the vertex = vertex activity





● : SciBar ADC hit (area∝energy deposit)

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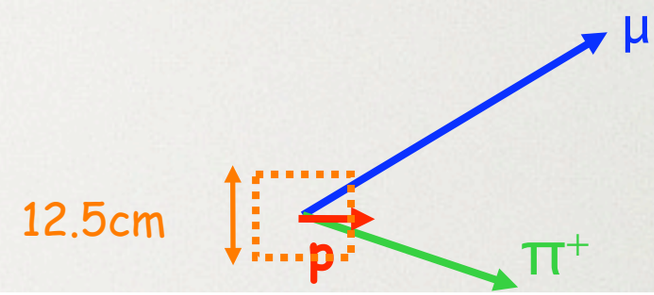

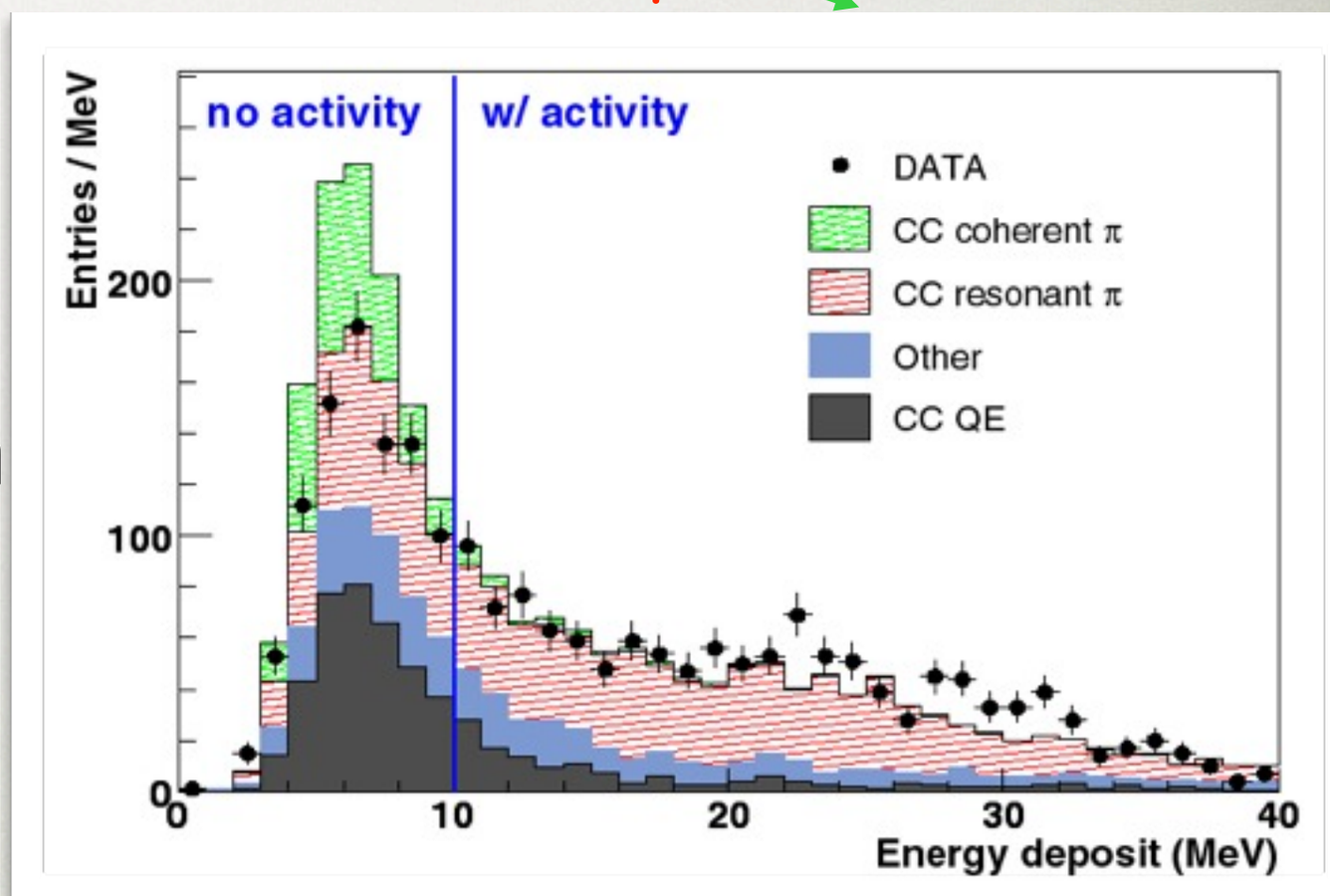

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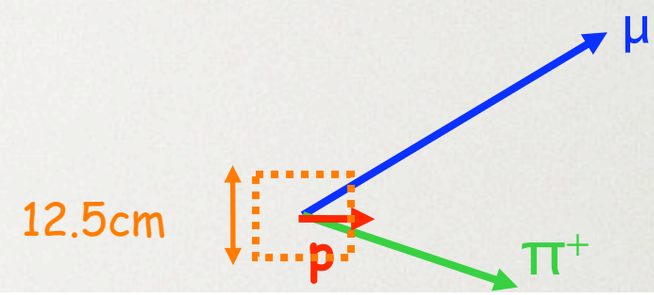
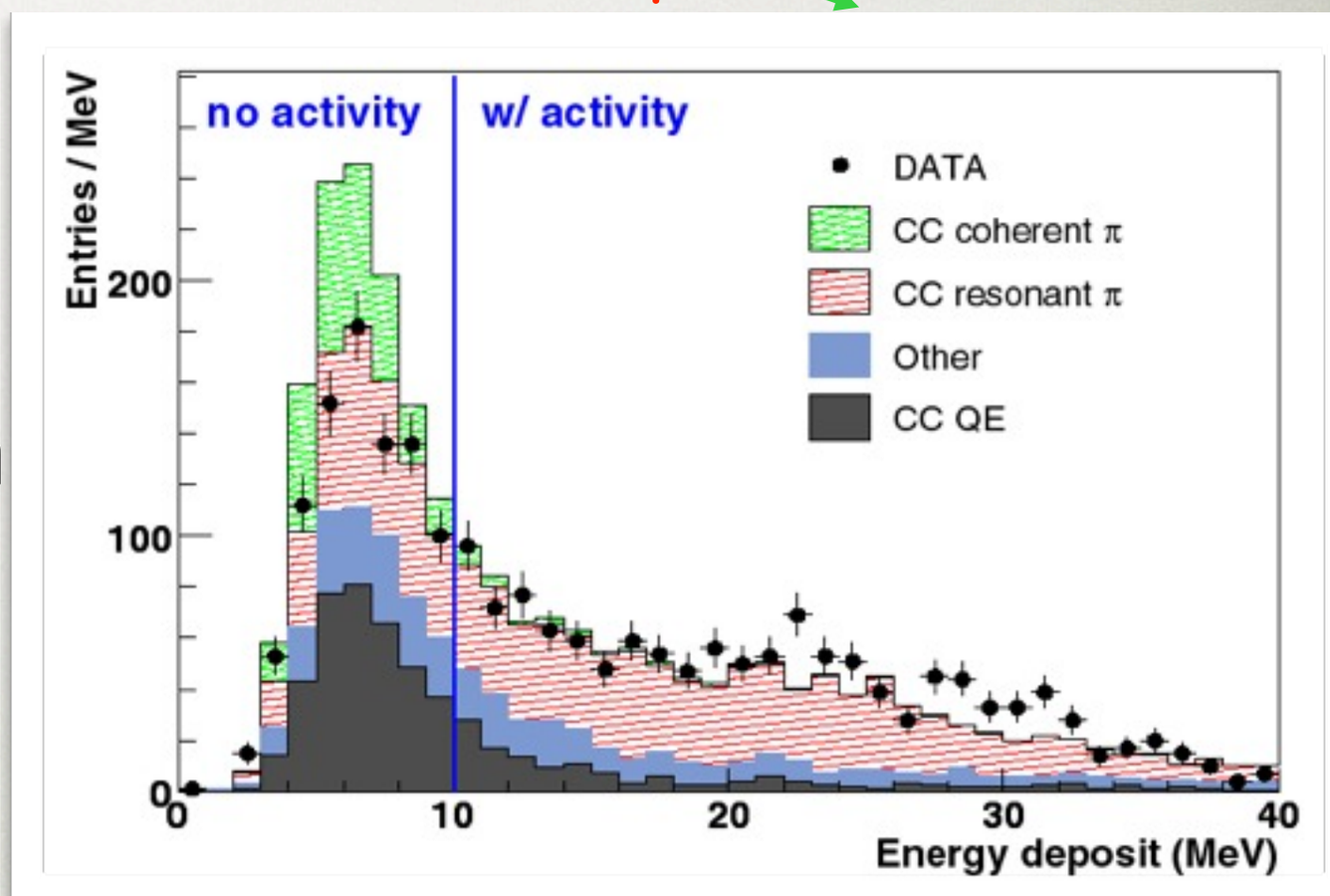




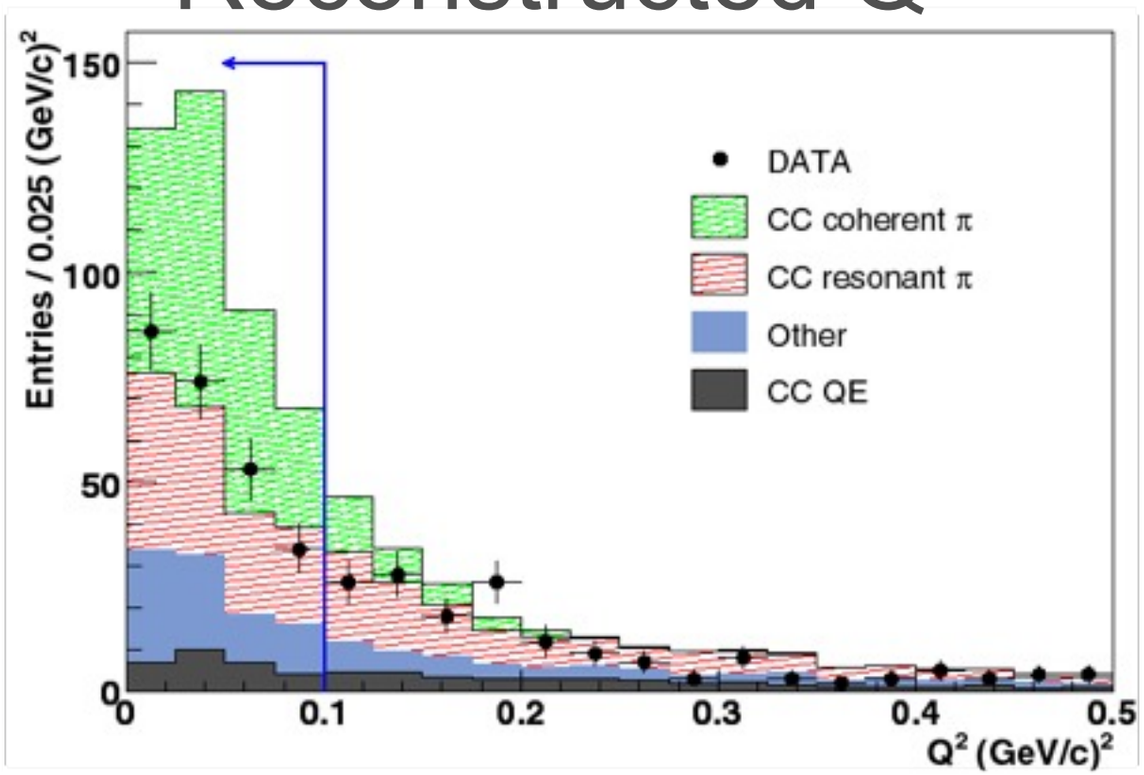
Data deficit in small vertex activity region.

CC coherent pion sample

K. Hiraide

<Eν>= 1.1 GeV

Reconstructed Q^2

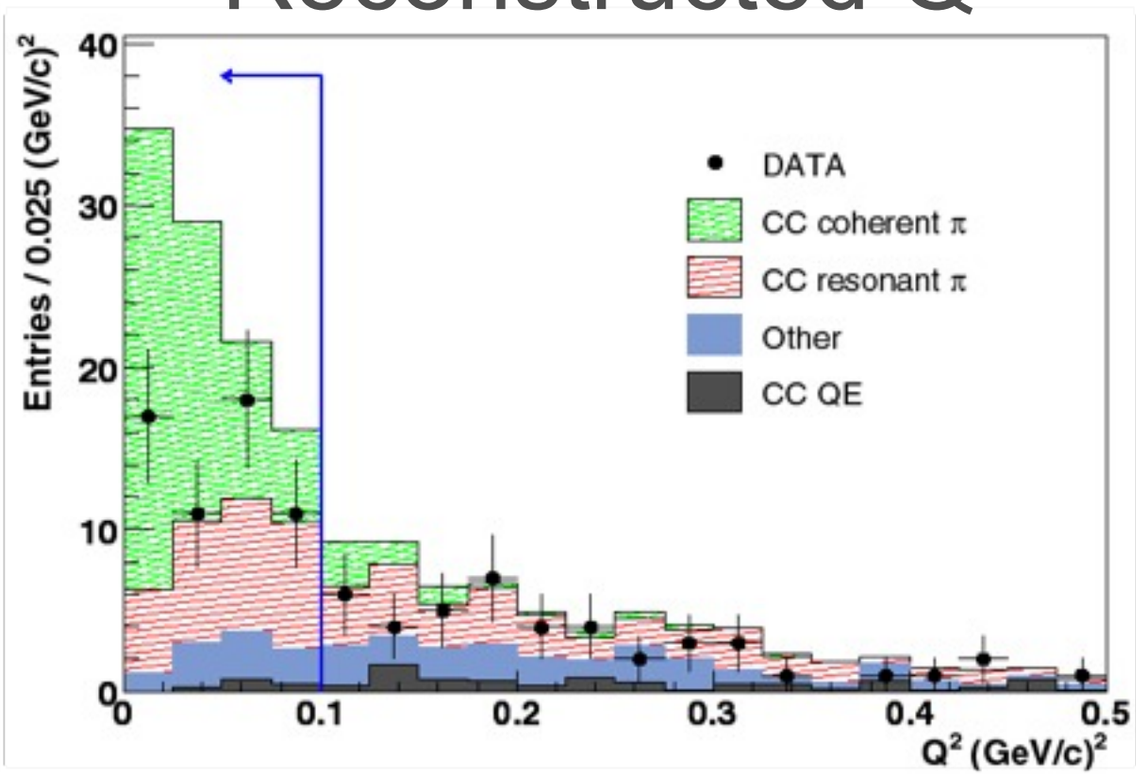


$$\sigma(\text{CC coherent}\,\pi)/\sigma(\text{CC})$$

$$= (0.16 \pm 0.17(stat)^{+0.30}_{-0.27}(sys)) \times 10^{-2}$$

<Eν>= 2.2 GeV

Reconstructed Q^2



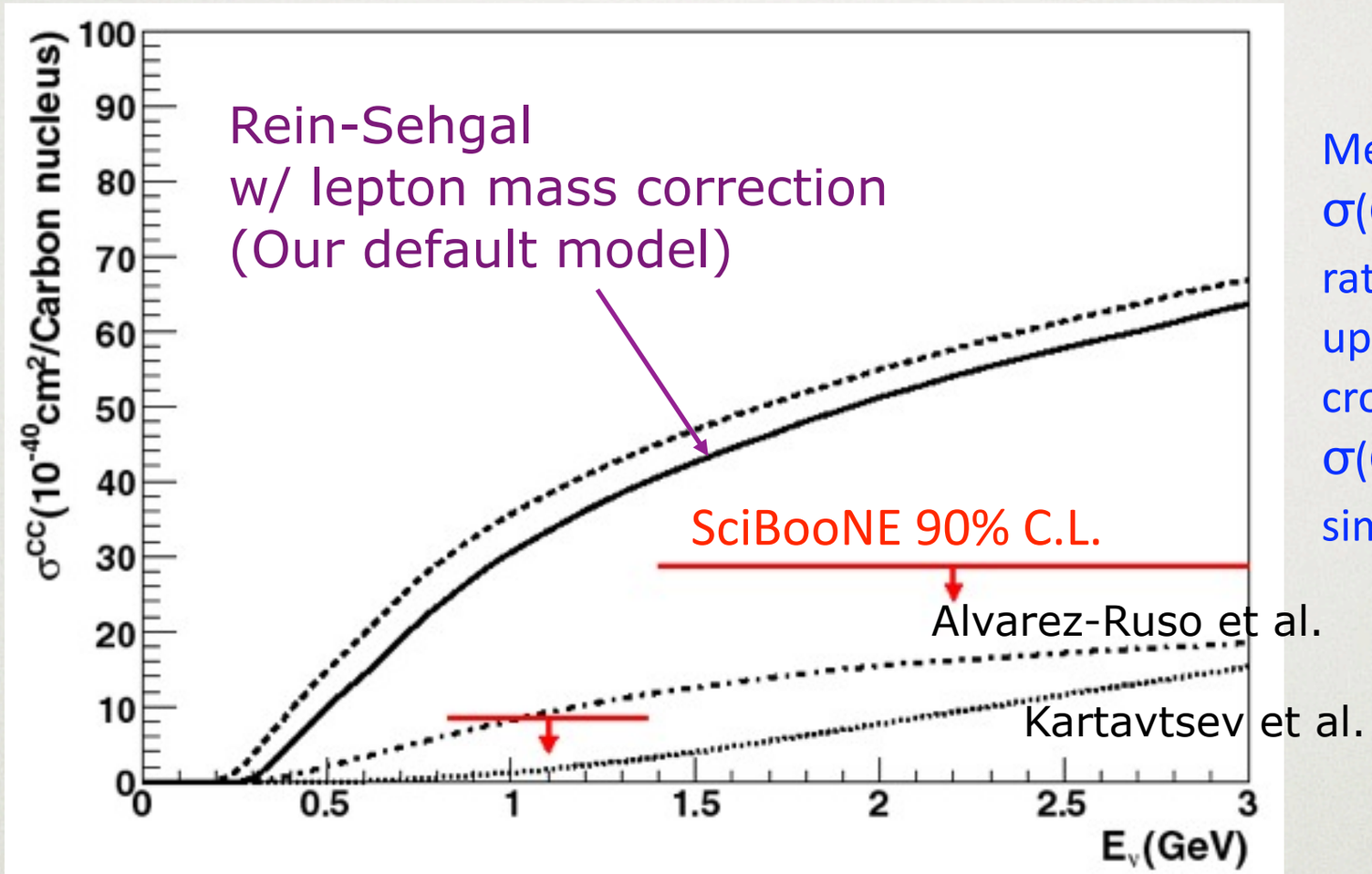
$$\sigma(\text{CC coherent}\,\pi)/\sigma(\text{CC})$$

$$= (0.68 \pm 0.32(stat)^{+0.39}_{-0.25}(sys)) \times 10^{-2}$$

No evidence of CC coherent pion production

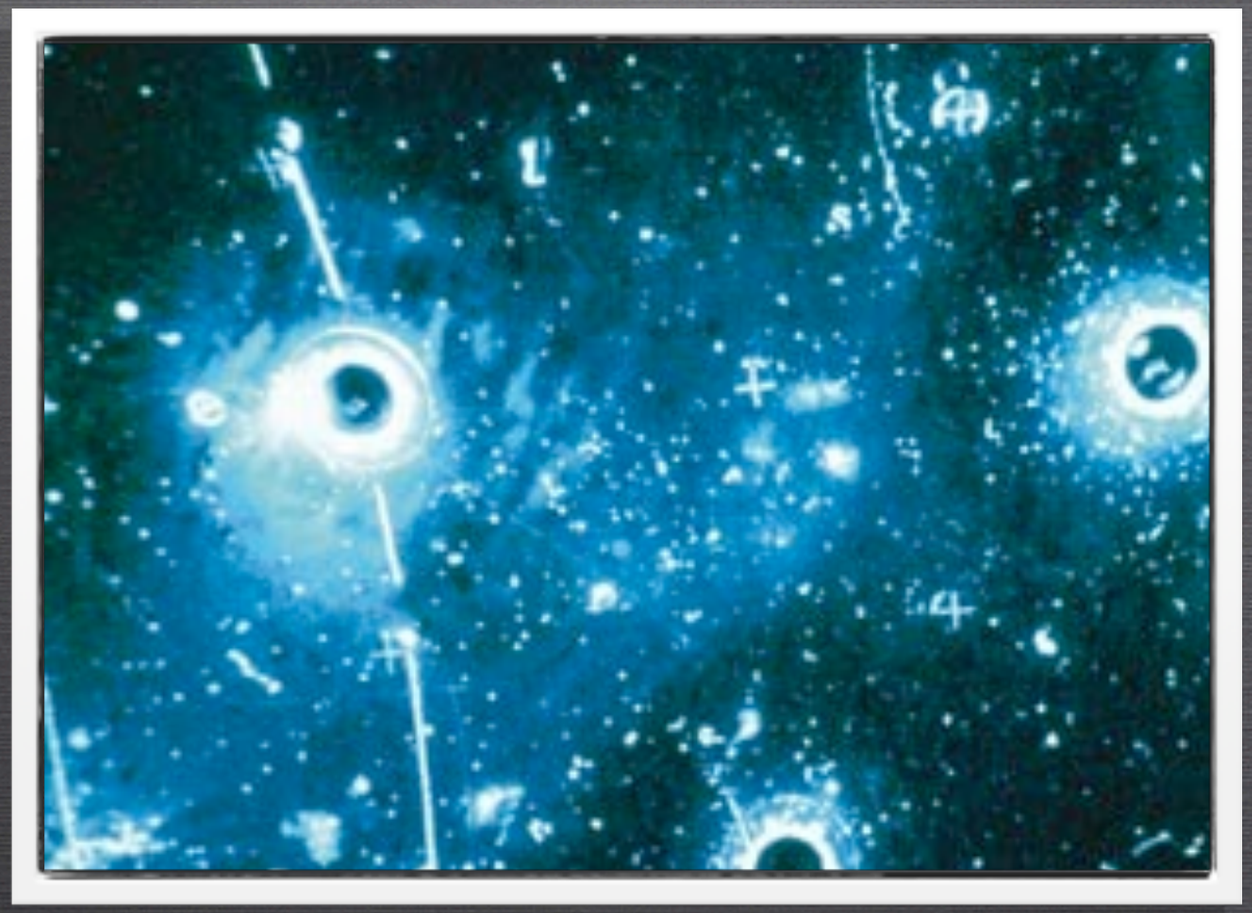
➜ set upper limit

Upper limit on cross section



Measured upper limits on σ(CC coherent π)/σ(CC) ratios are converted to upper limits on absolute cross sections by using σ(CC) predicted by MC simulation.

- SciBooNE's upper limit at ⟨Ev⟩ =1.1GeV corresponds to ~33% of R&S model prediction

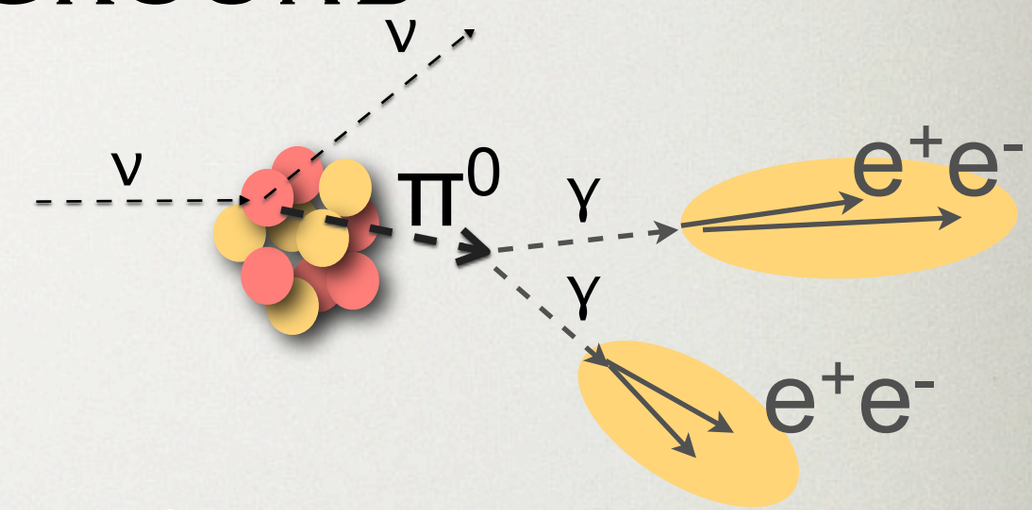


NC π^0 production

NC π^0 production

Signal & Background

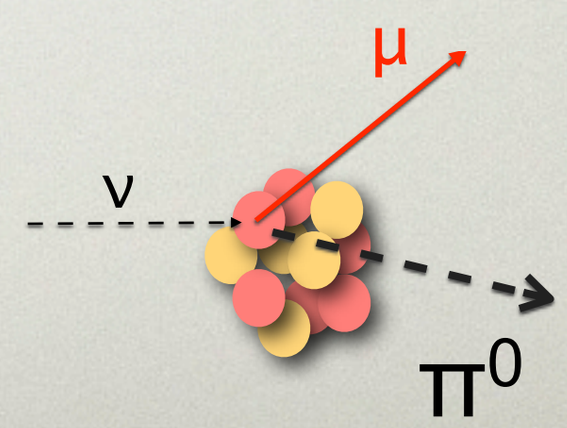
- Signal:
  - NC-π^0 production
    $\nu+C\rightarrow\nu+\pi^0+X$



- **NC-π^0** ≡ NC int. in which at least one π^0 in the final state
  - Two "shower-like" tracks (from π^0)
  - ~6% of total ν interactions (based on Rein-Sehgal model)

- Background:
  - CC-1π^0 production
  - External particles (e.g. n, γ)
    - Neutrino interaction outside detector ("Dirt event")

CC-1π^0: $\nu+C\rightarrow\mu+\pi^0+X$



NC π^0 production

Signal & Background

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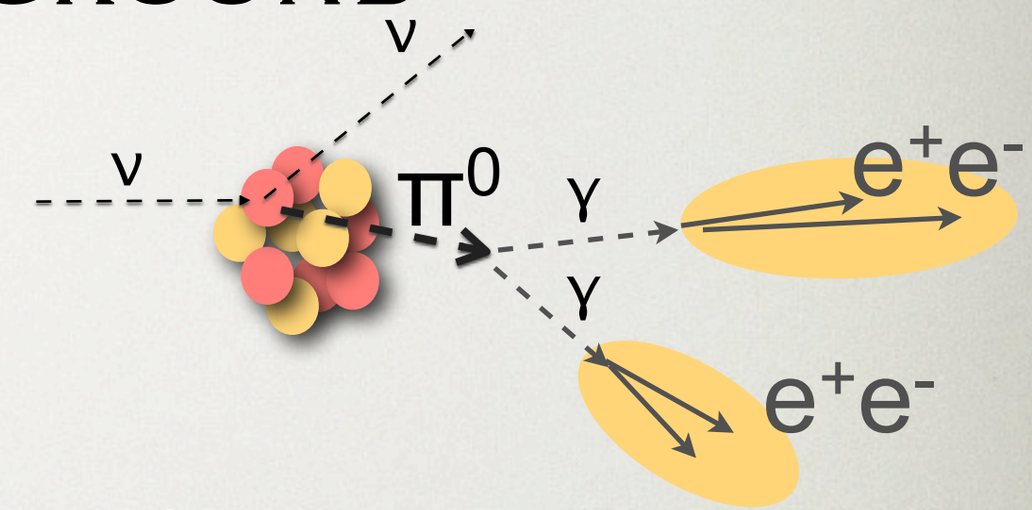
    $\nu + C \rightarrow \nu + \pi^0 + X$



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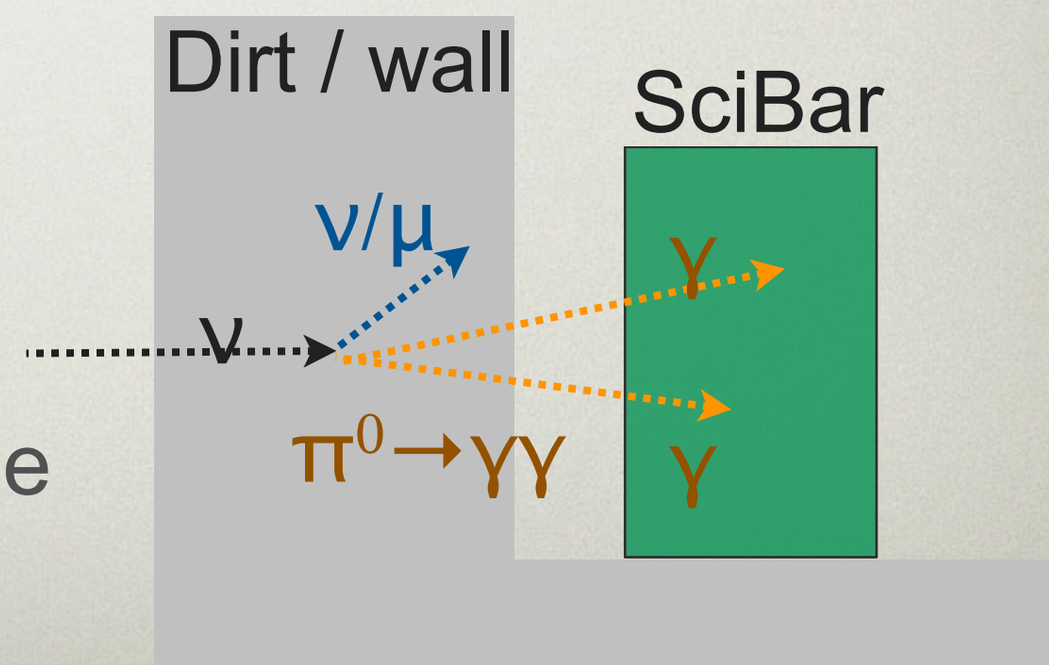
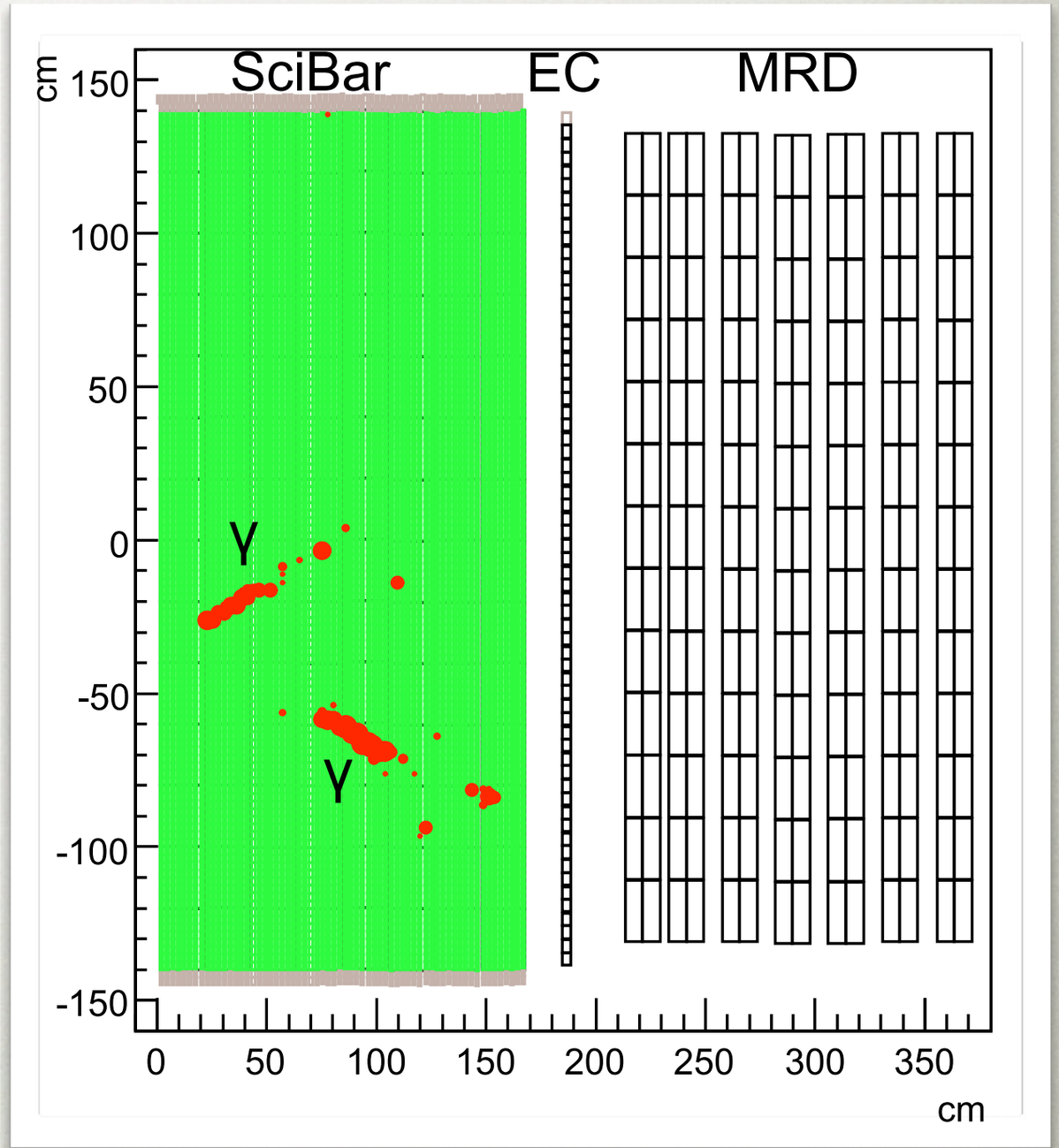


NC π^0 candidate

- Require at least two tracks contained in SciBar+EC.
  - No activity in MRD

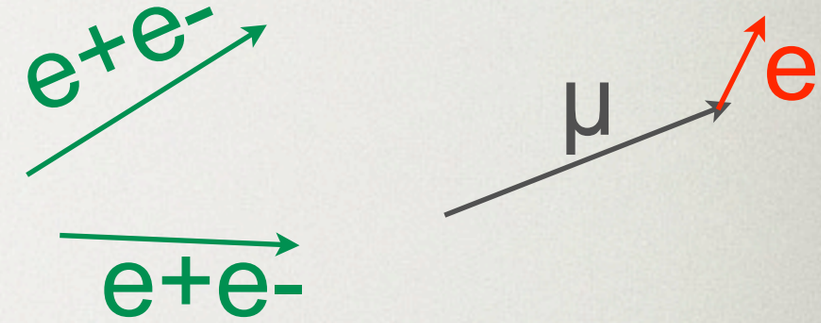
- Event selection cuts designed to find particles of converted photons with π^0 invariant mass

1. Internal BG rejection (CC events)
2. External BG rejection (particles from outside)

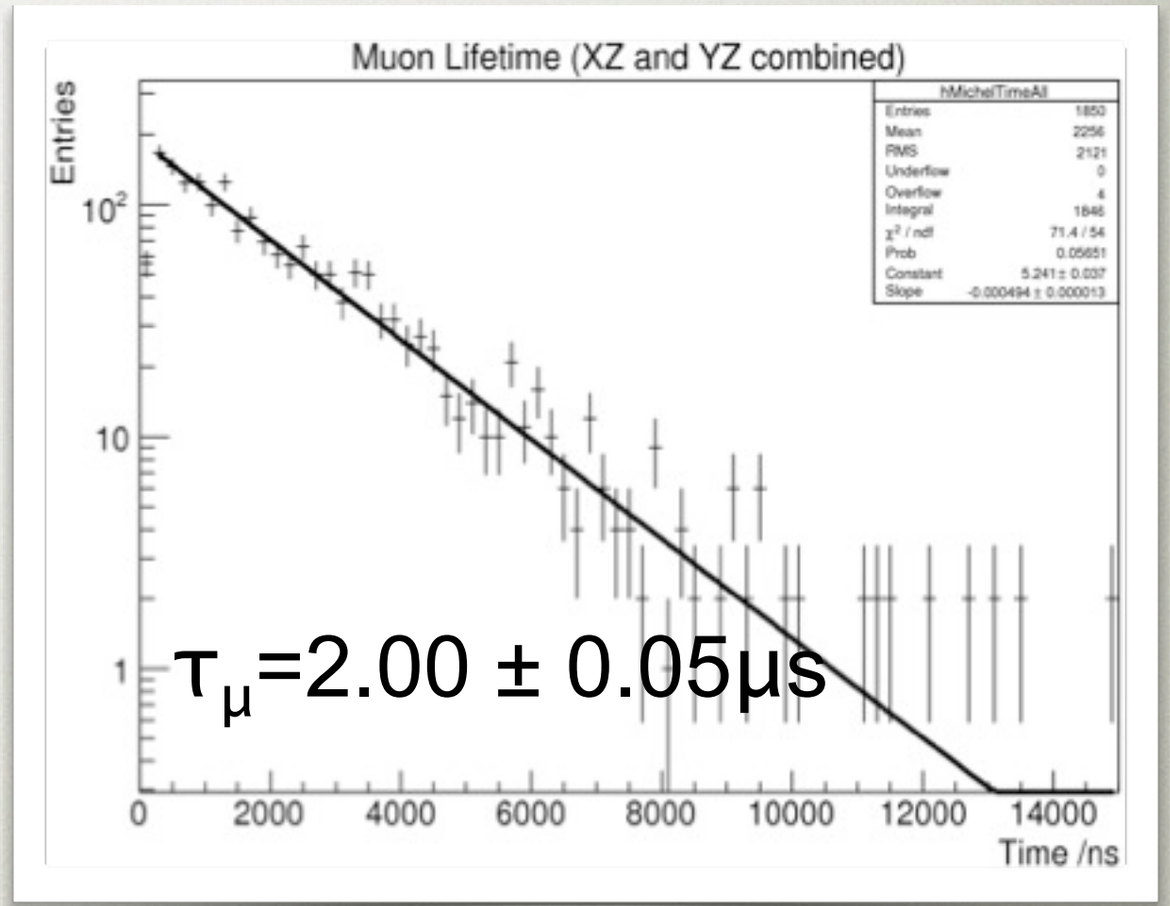


CC event rejection (1)

- Identify muons
  - Find muon decay ($\mu \rightarrow e + 2\nu$)
    - Use SciBar TDC hits
    - Calculate time difference between track edges and late TDC hits
    - Require $\Delta t < 100$ ns



Muon lifetime



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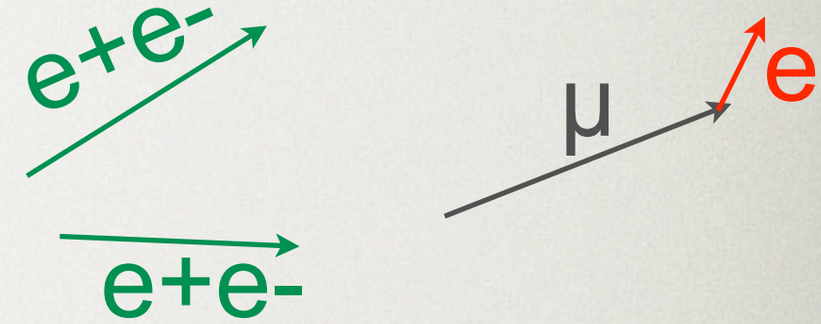
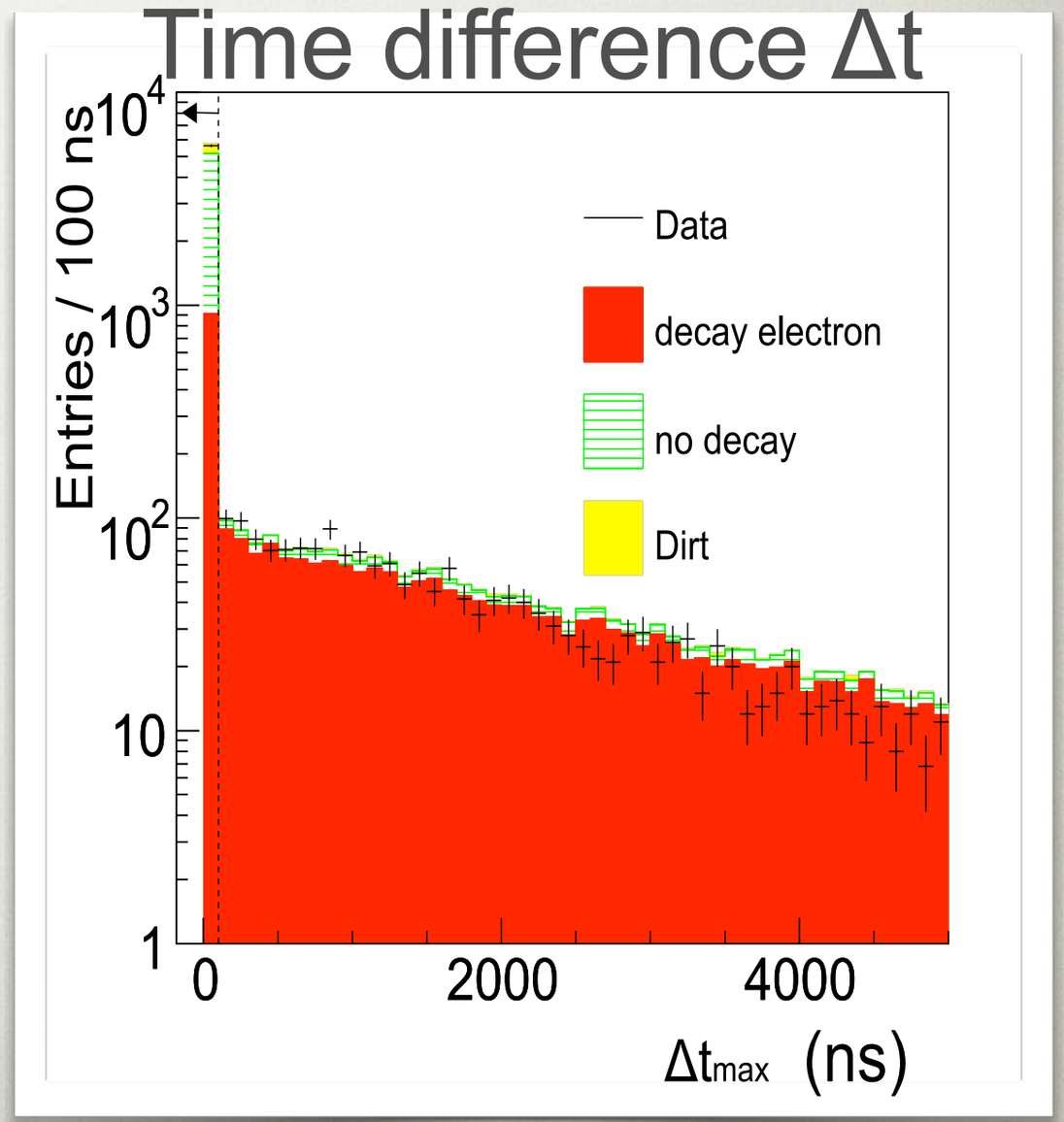
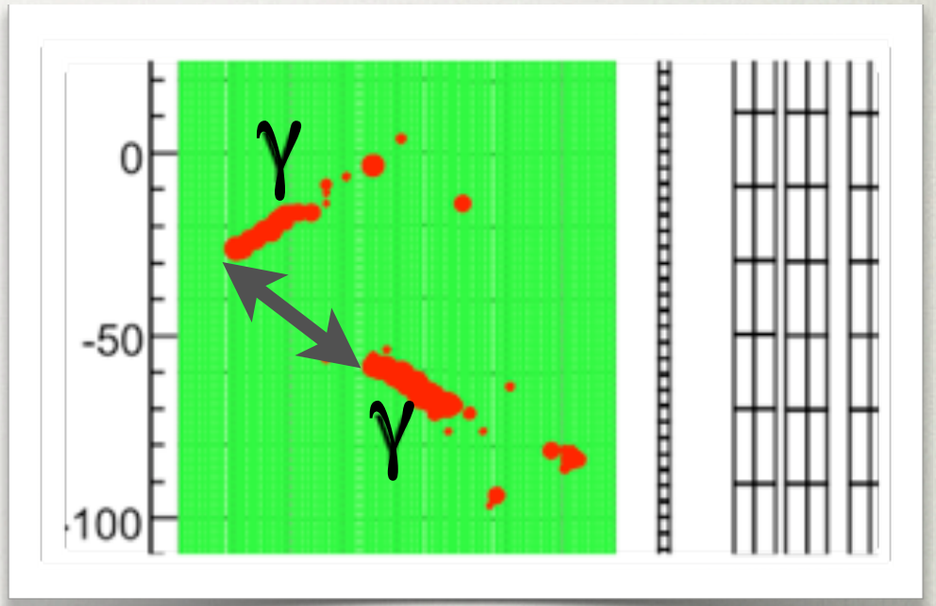




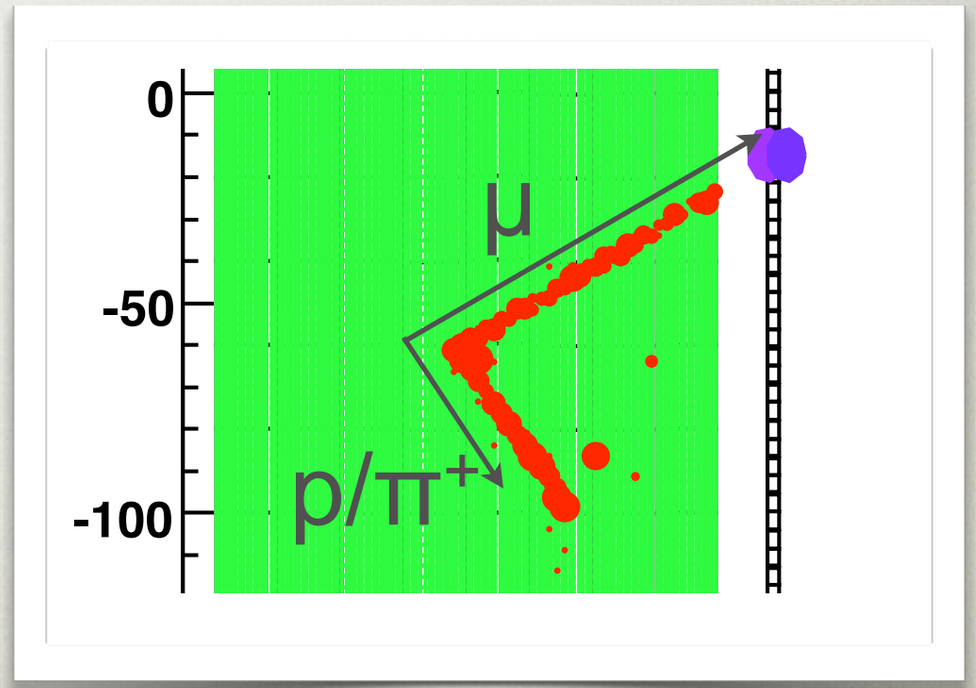
CC event rejection (2)

- Track separation
  - Photons have finite conversion distance
  - (CC events: μ and p/π^{+-} have common vertex)
  - Require tracks be at least 6 cm apart.
- ➜ ~80% of CC events rejected.

NC π^0 candidate



CC background



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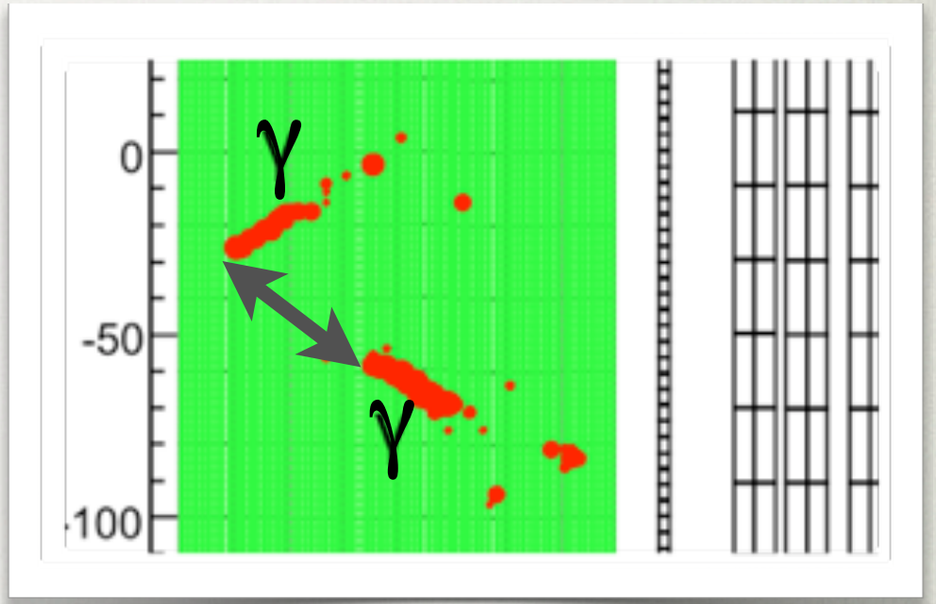
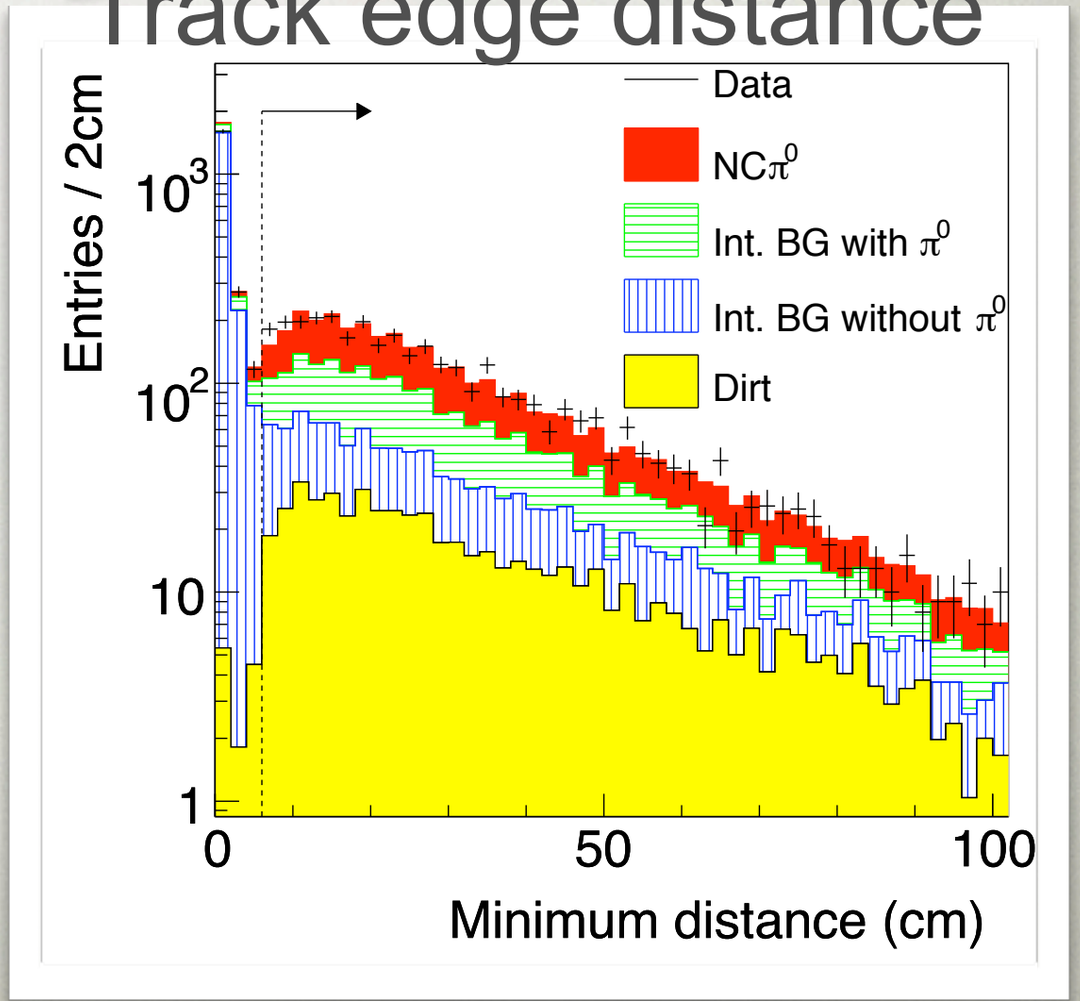
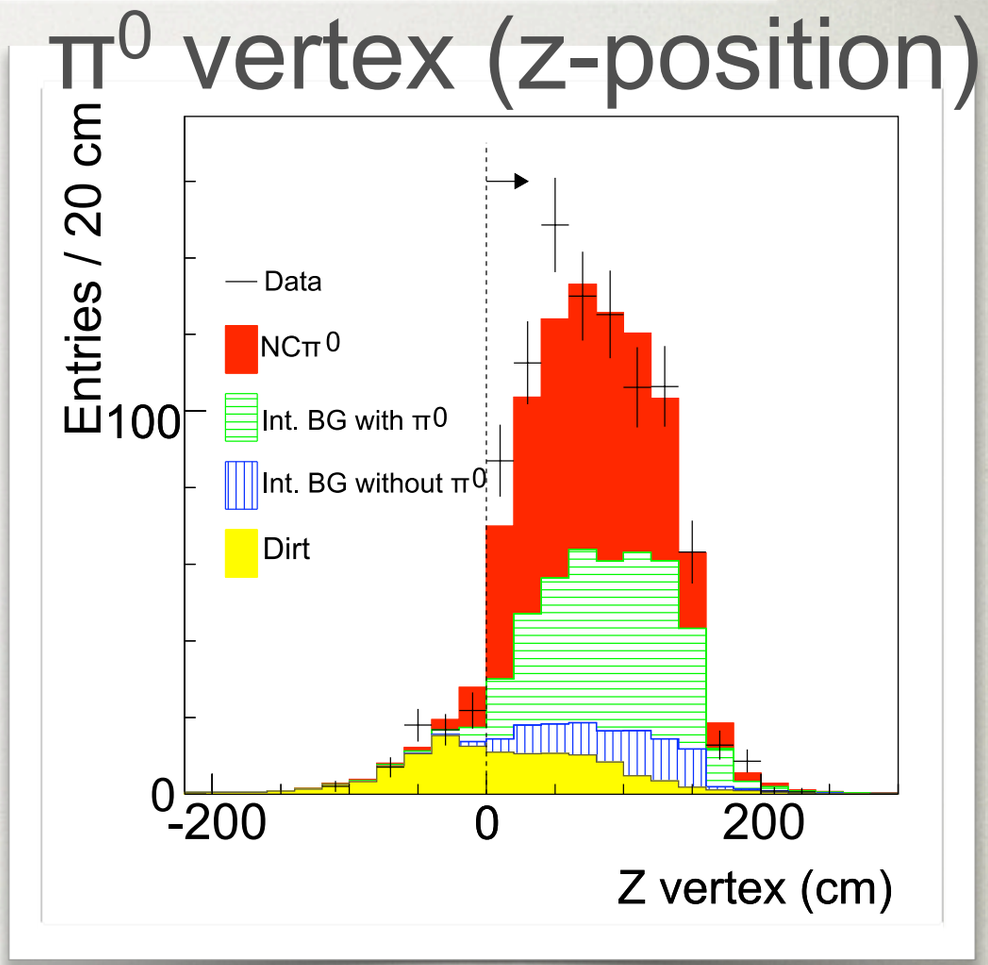


Track edge distance

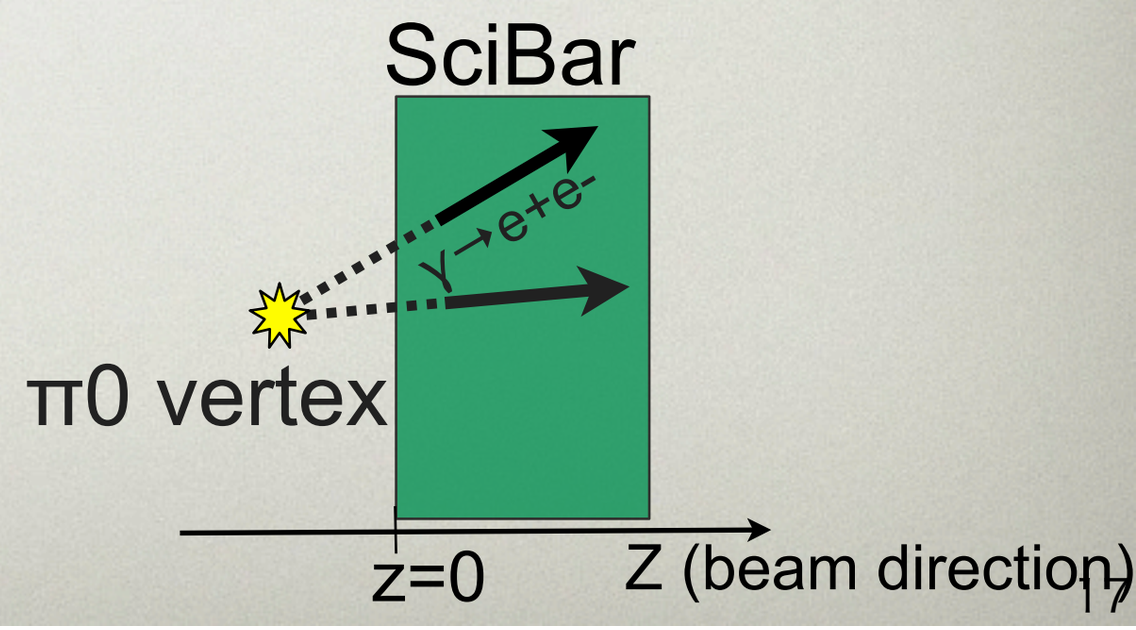


External BG Rejection

- Reconstruct π^0 vertex position
- Require photon tracks to point to a common vertex within SciBar.

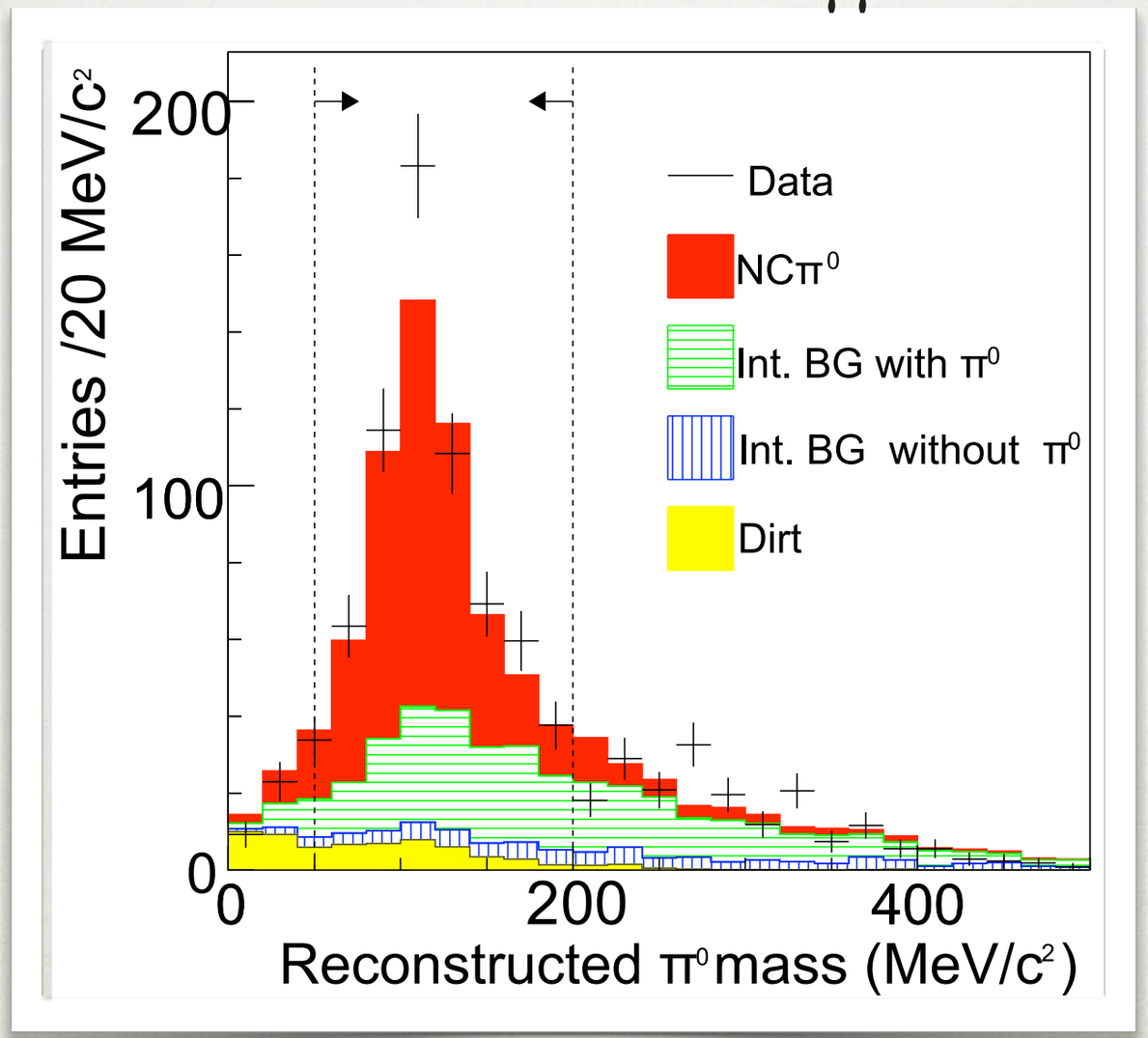


ex. Dirt event



NC π^0 production Cross-section

Reconstructed $M_{\gamma\gamma}$



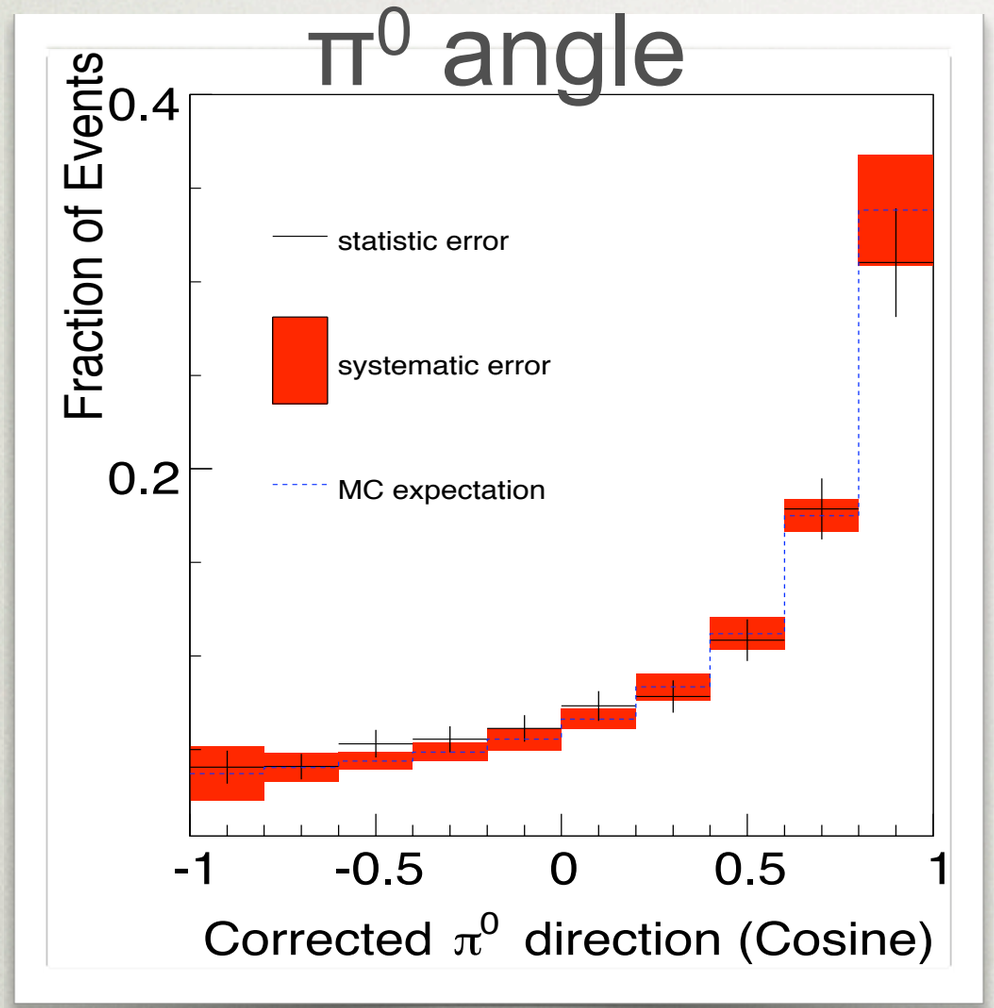
$$\frac{\sigma(\text{NC-}\pi^0)}{\sigma(\text{CC})} = [7.7 \pm 0.5(\text{stat.}) \pm 0.5\ (\text{sys.})] \times 10^{-2}$$

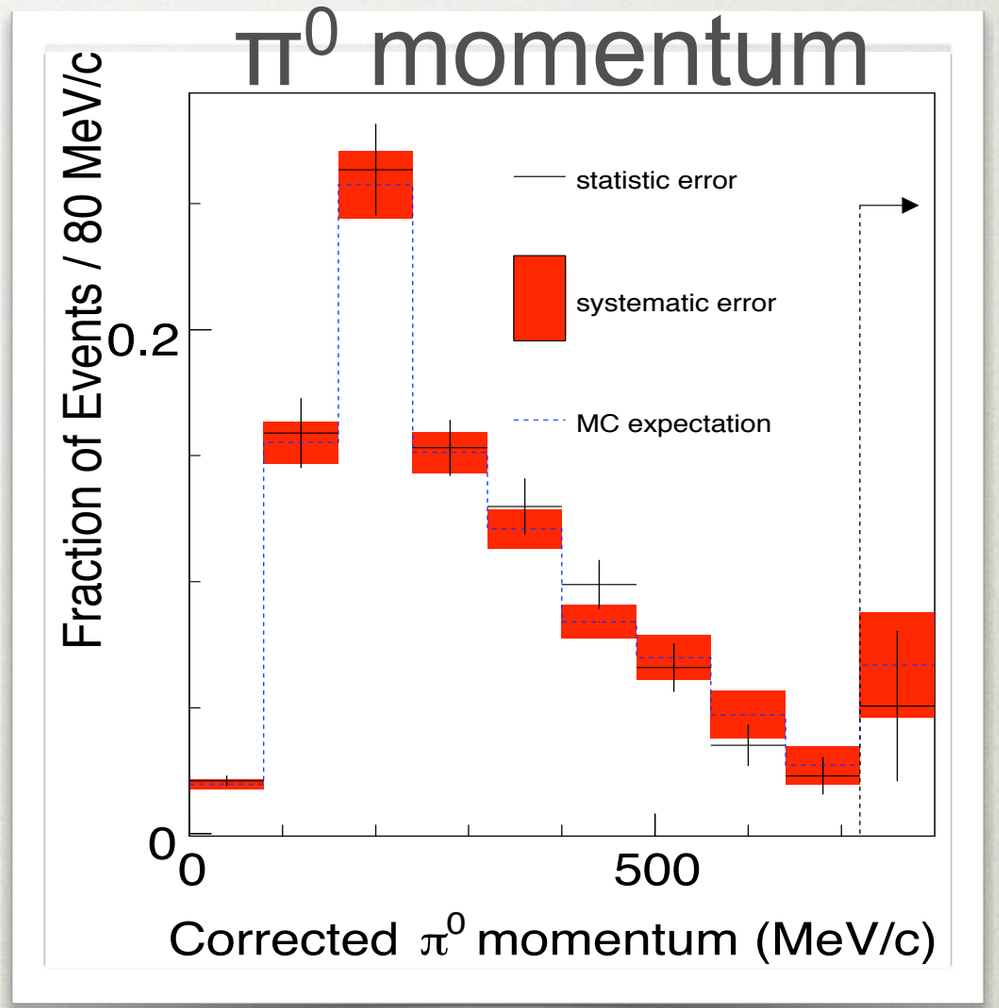
cf. MC prediction: $\frac{\sigma(\text{NC-}\pi^0)}{\sigma(\text{CC})} = 6.8 \times 10^{-2}$

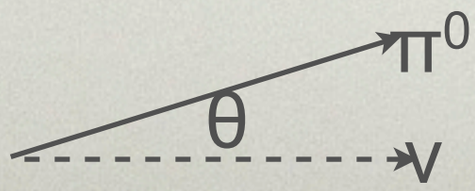
π^0 Kinematics

π^0 kinematics are important for BG evaluation of ν_e appearance search.

BG subtracted. Smearing & efficiency corrected.

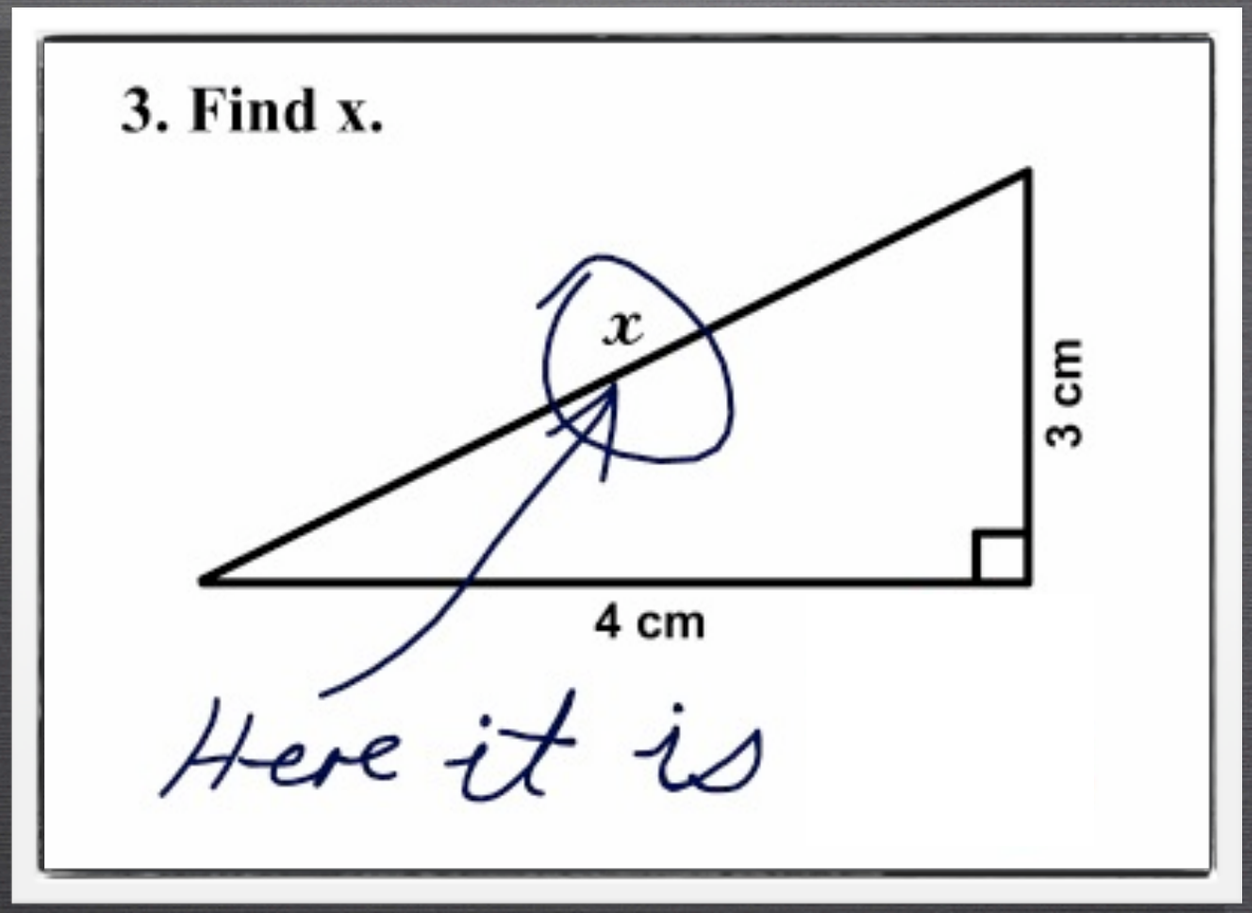






+ : Data with stat. error

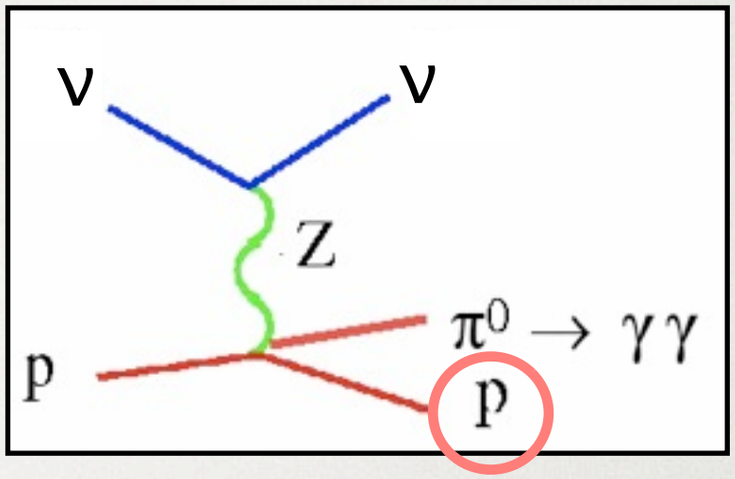
: MC with systematic error

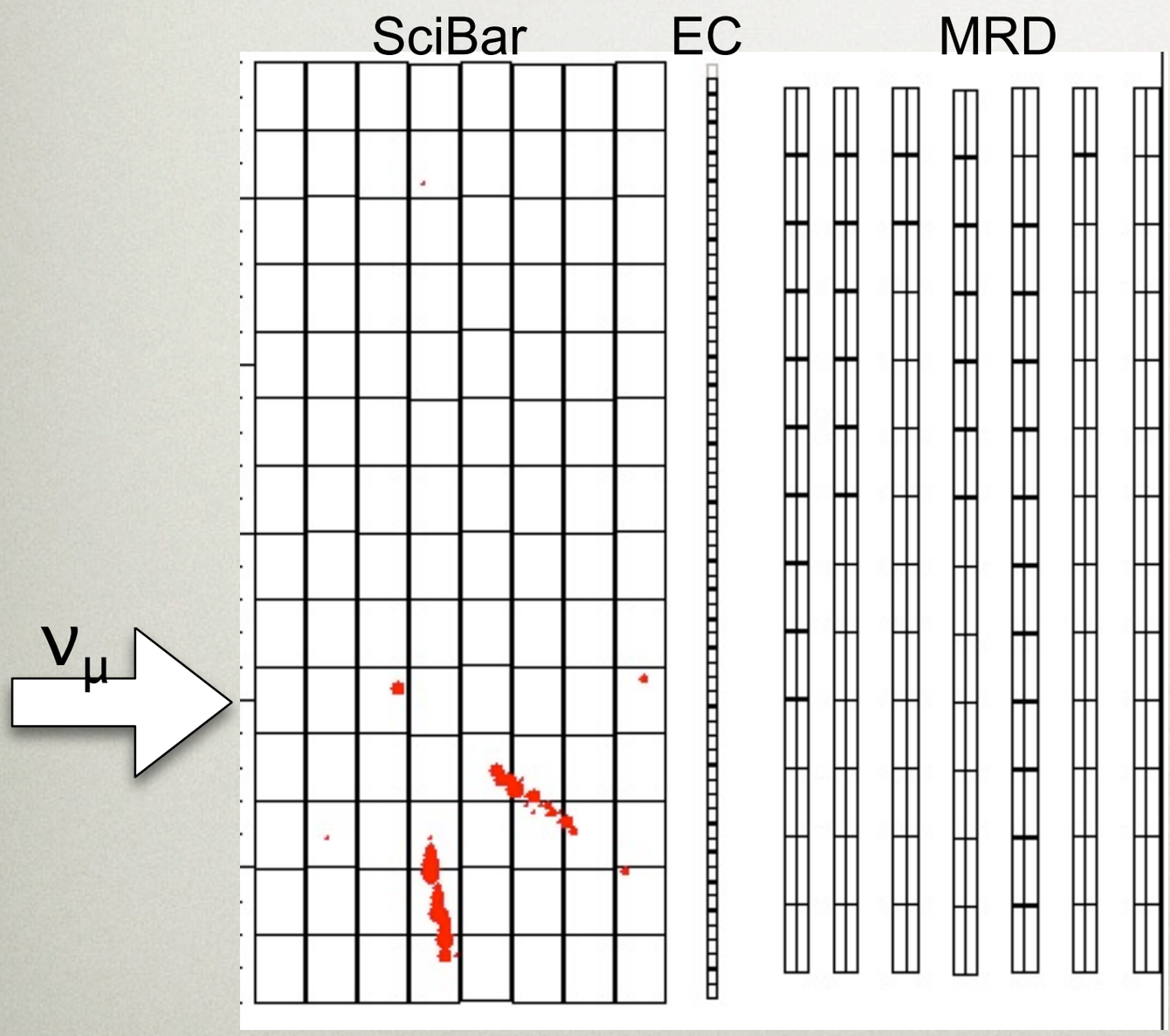


Search for NC coherent π^0

Extract NC coherent π^0

Neutral Current Resonant π^0
has nucleon in final state ➜
(no nucleon in coherent π)





● : SciBar hit, area∝energy deposit

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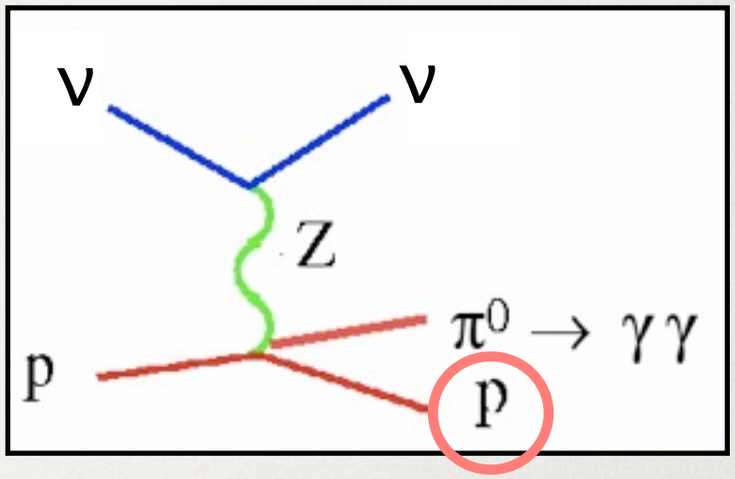

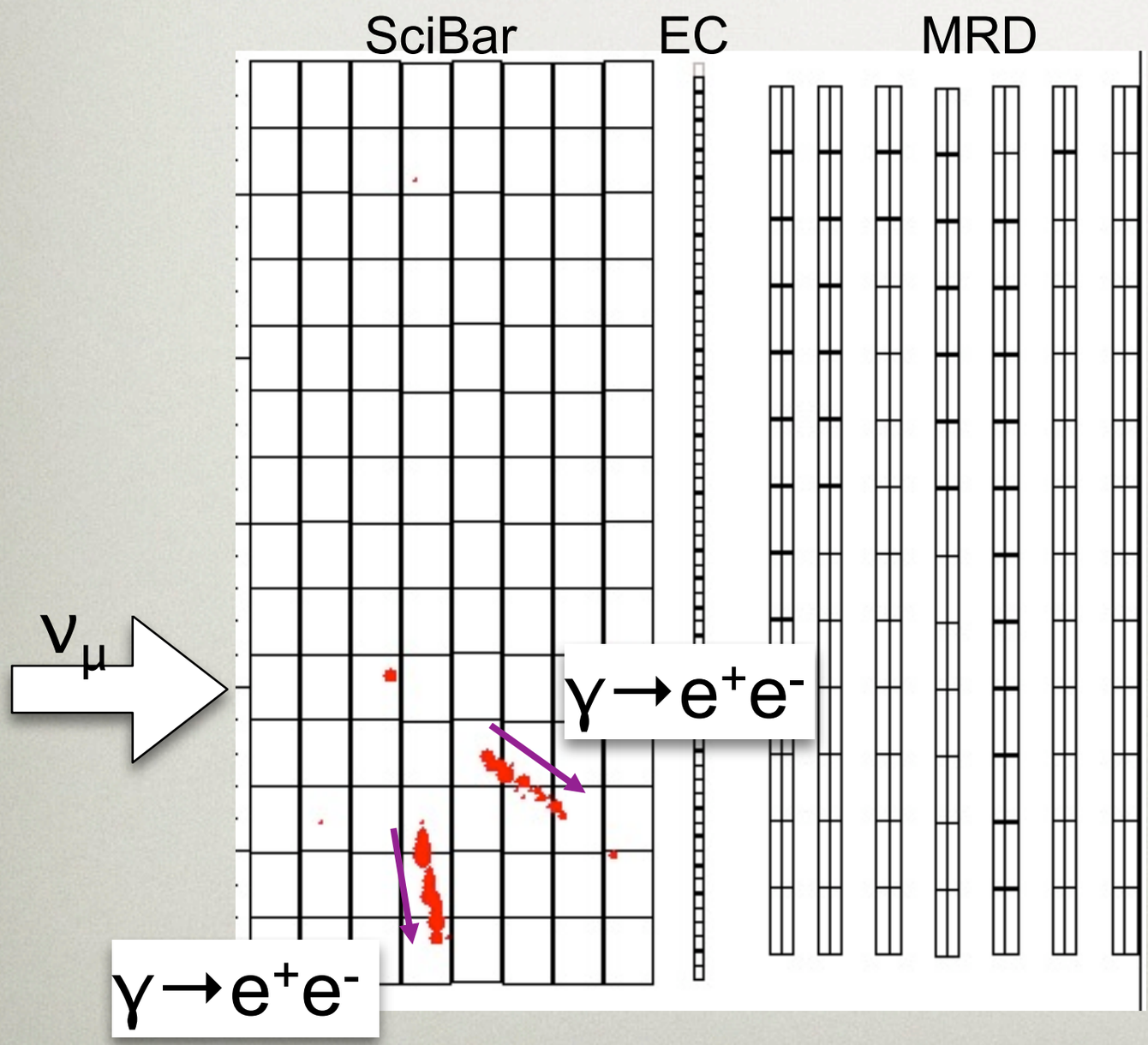

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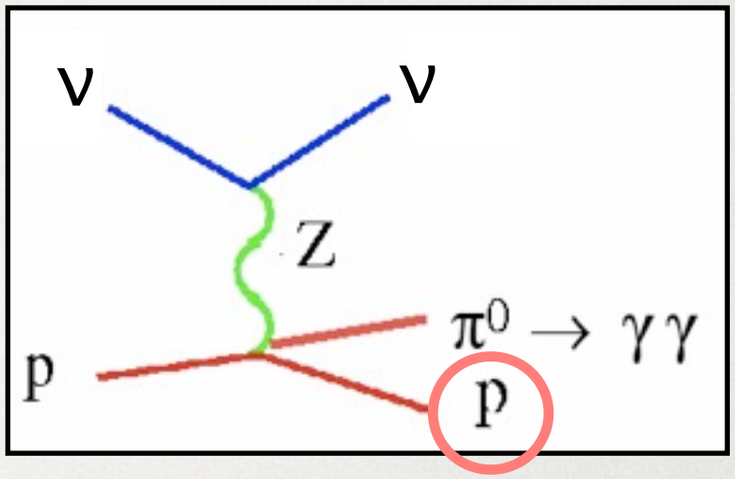

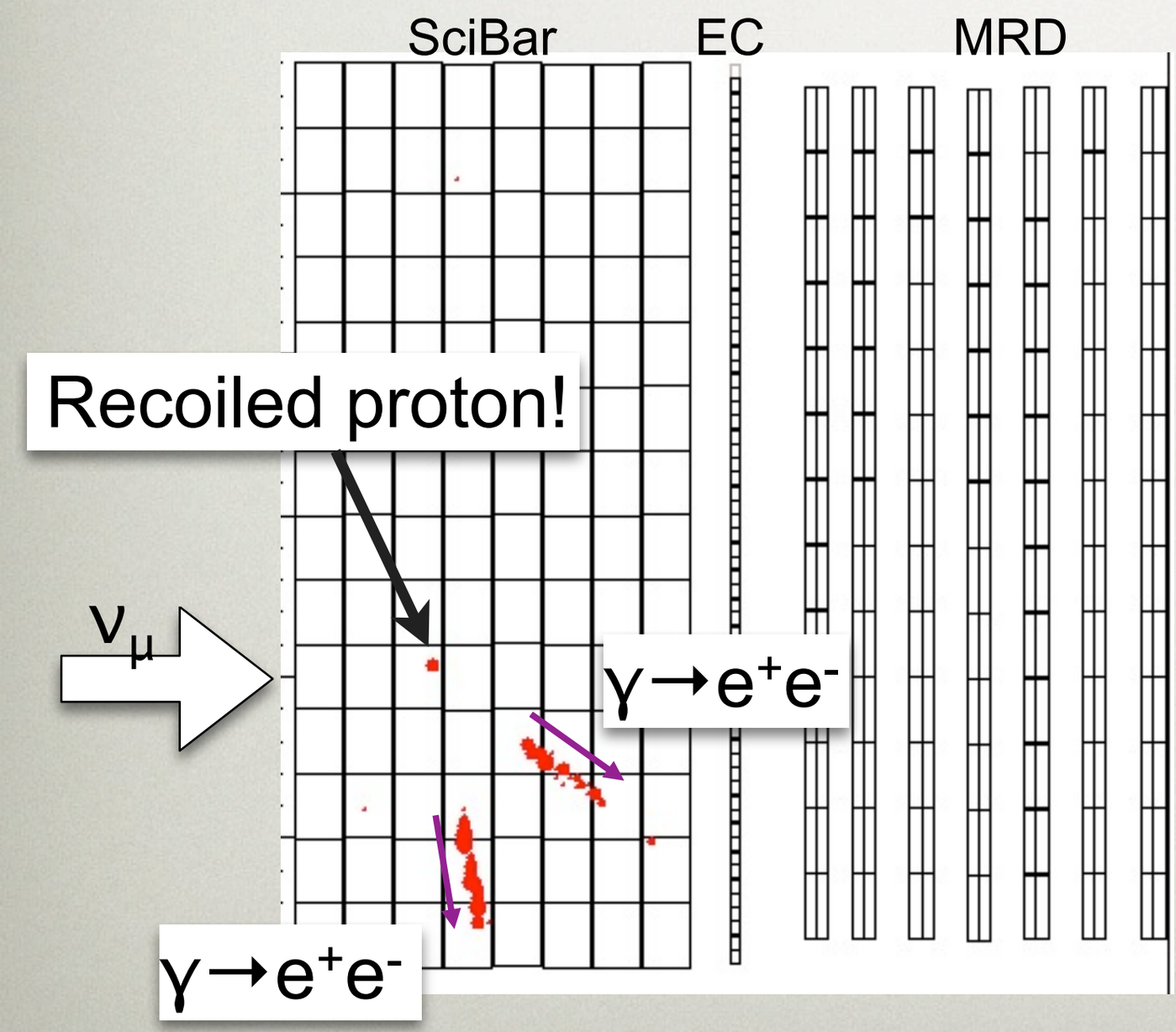

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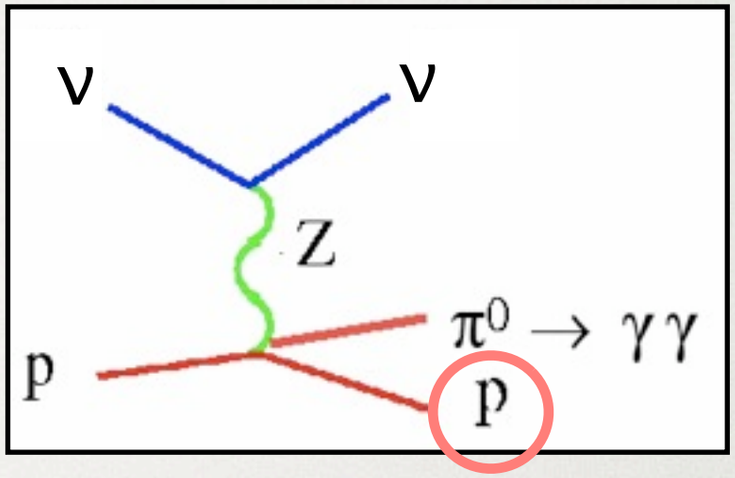

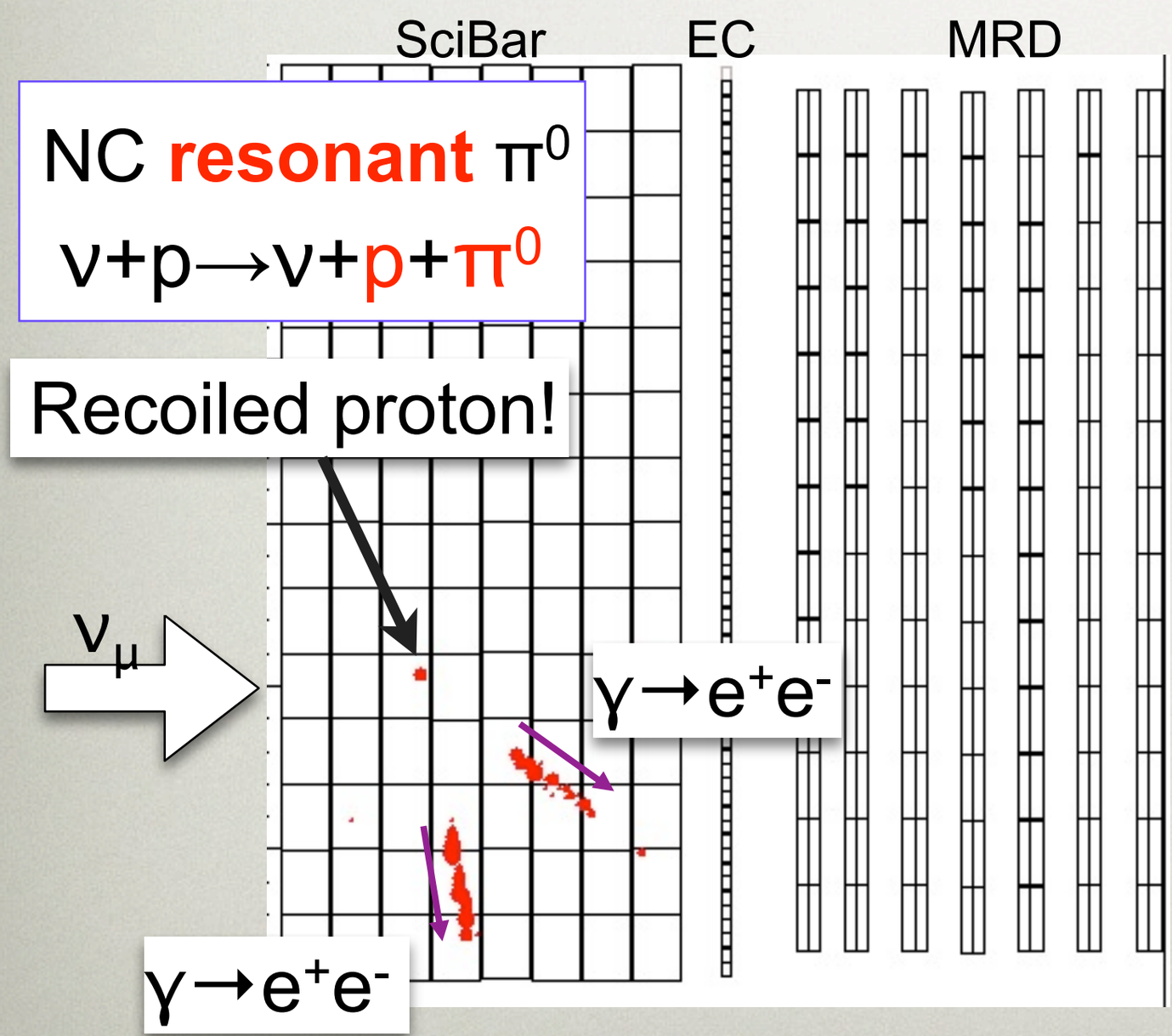

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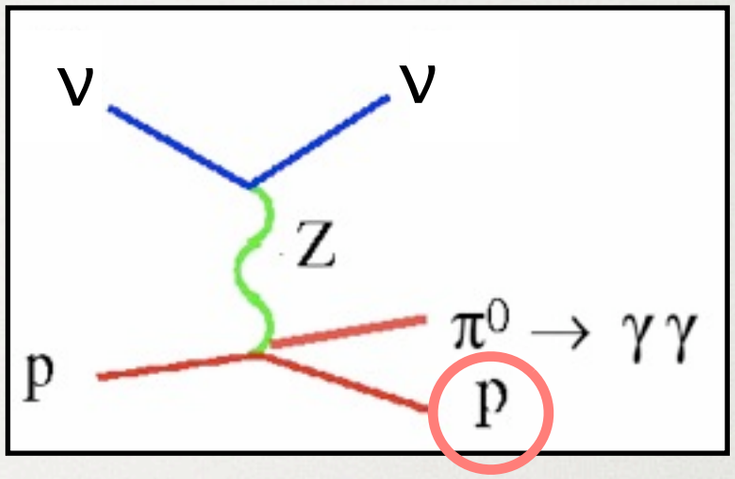
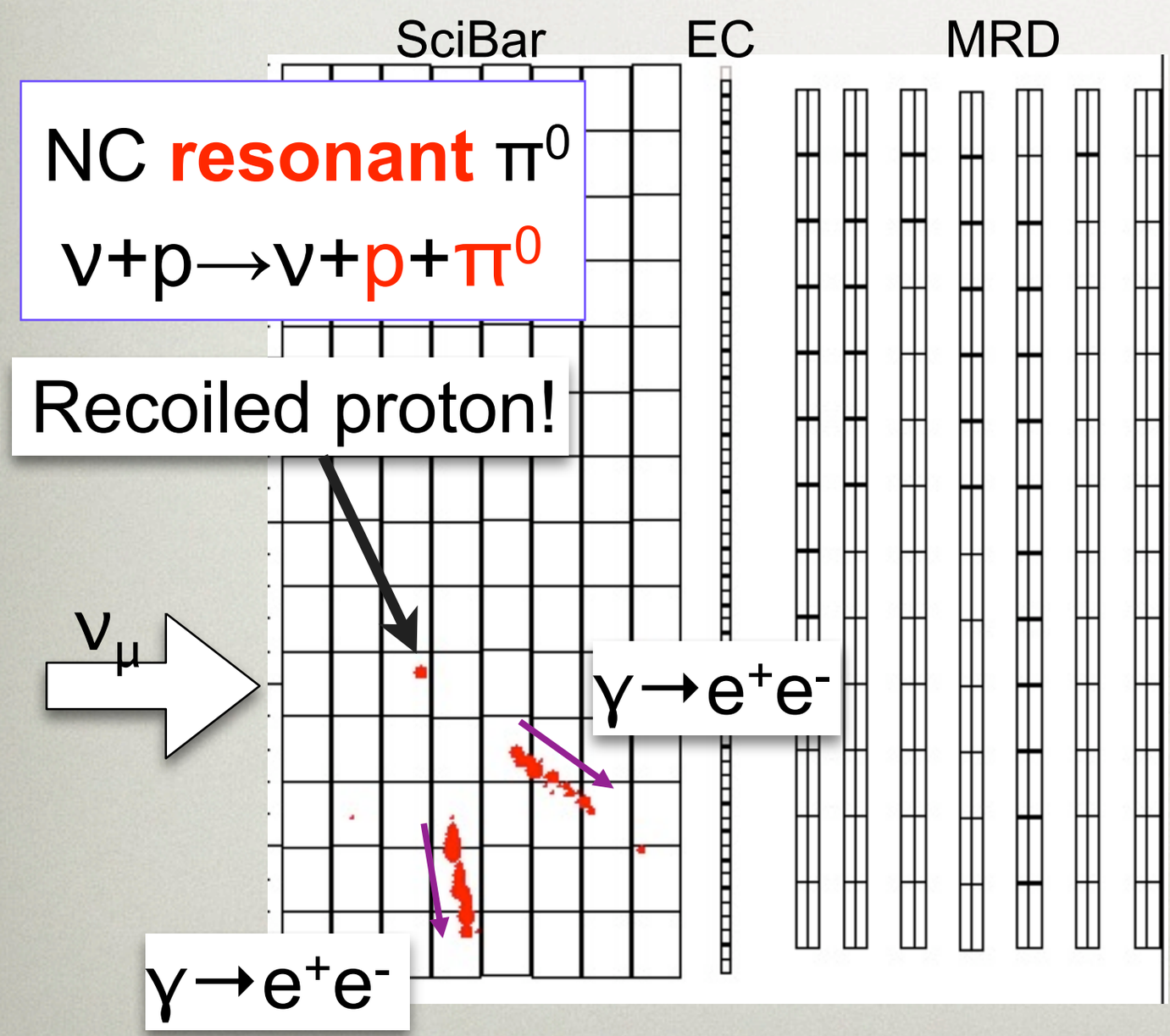
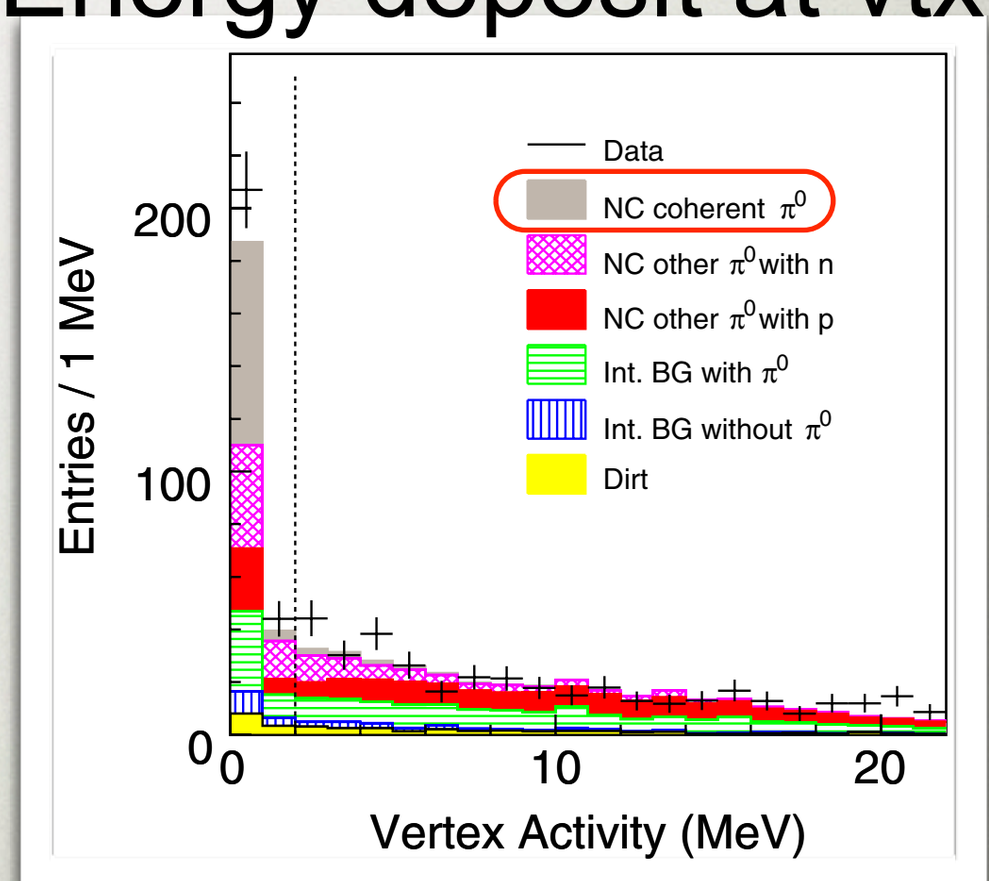
Neutral Current Resonant π^0
has nucleon in final state ➜
(no nucleon in coherent π)





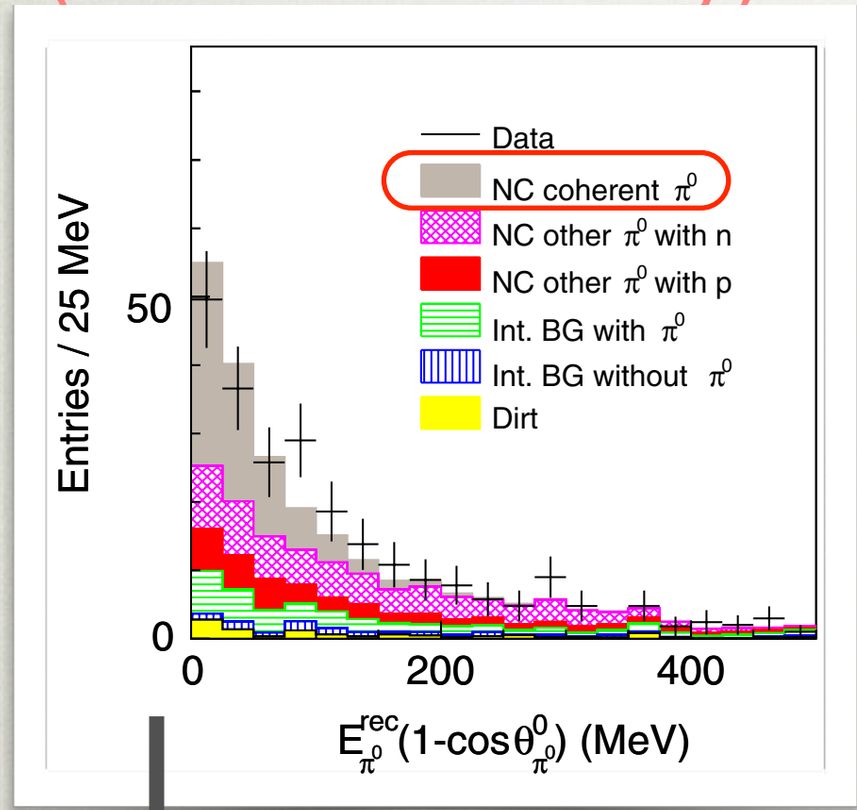
Energy deposit at vtx



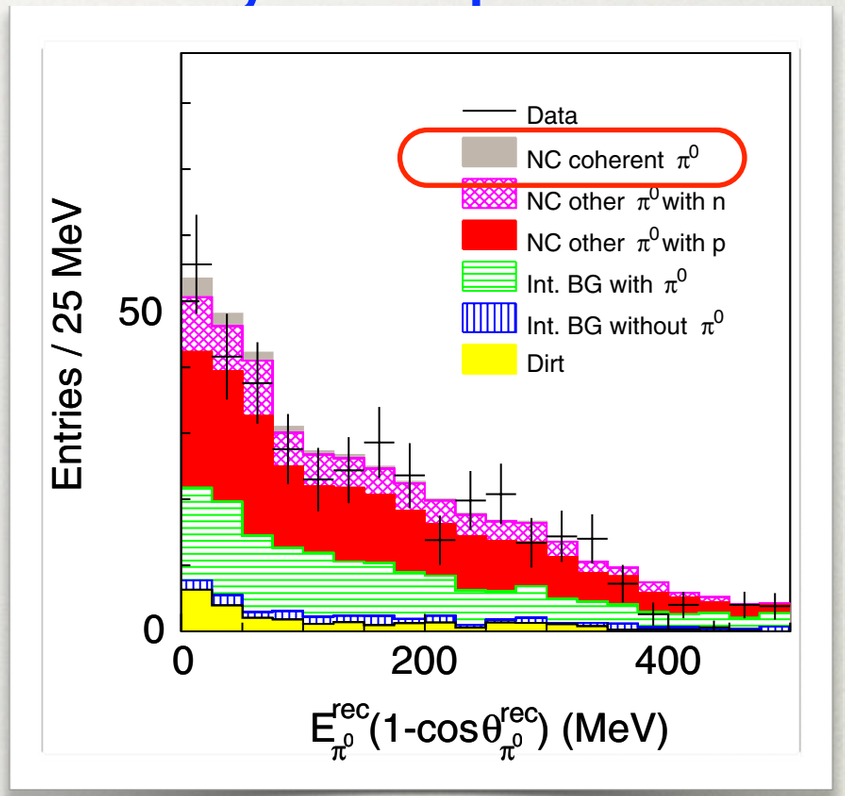
● : SciBar hit, area∝energy deposit

NC Coherent π^0 cross section

NC **coherent** π sample (no vertex activity)



NC π^0 with vertex activity sample



$$\frac{\sigma(\mathrm{NCcoh}\pi^0)}{\sigma(\mathrm{CC})} = (1.16 \pm 0.24) \times 10^{-2}$$

Clear evidence of NC coherent pion production.

cf. NEUT prediction based on Rein-Sehgal model:
$\sigma(\mathrm{NCcoh}\pi^0)/\sigma(\mathrm{CC}) = 1.21\times10^{-2}$

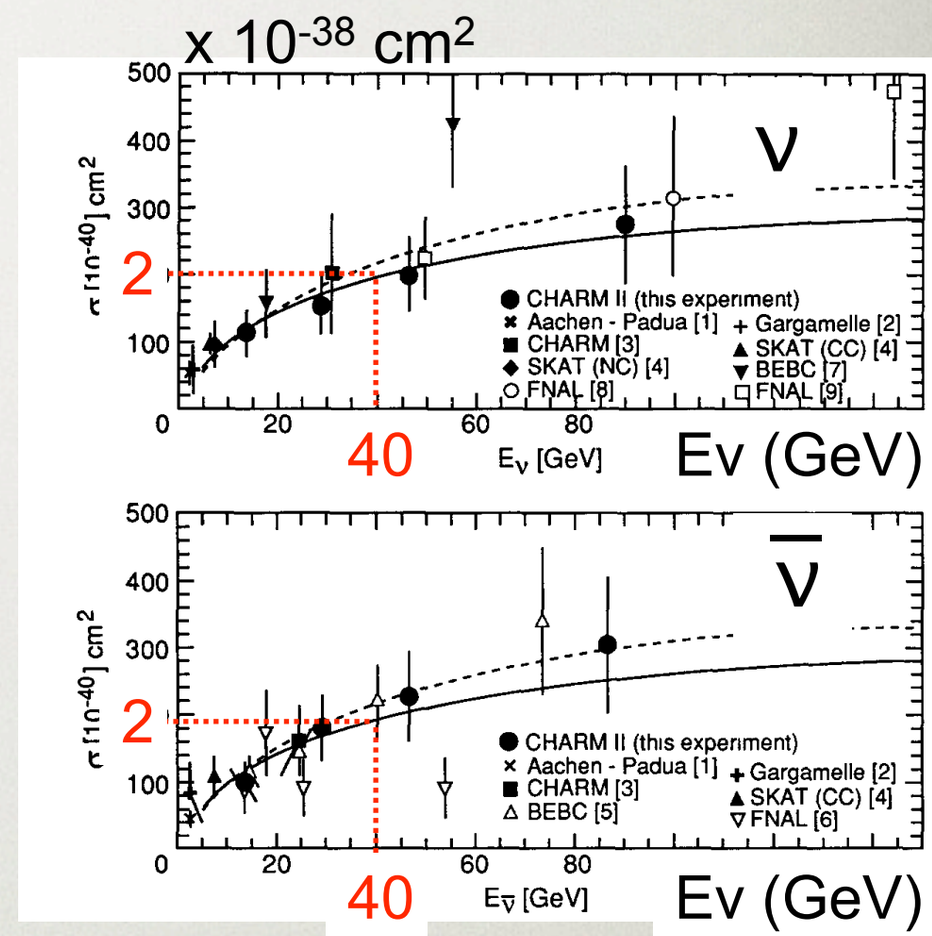
Search for

$\bar{\nu}$ CC coherent π

Preliminary results

$\bar{\nu}$ CC coherent π production

- $\bar{\nu}$ mode is more sensitive to CC coh-π events than ν mode
  - σ(ν coh-π) ~ σ($\bar{\nu}$ coh-π)
    while σ(νCC-bkg) > σ($\bar{\nu}$CC-bkg)
- Mirror analysis of SciBooNE's ν mode CC coh-π search
  - Same selection criteria, (almost) same method to evaluate background events
- Major difference: large fraction of Wong-Sign (WS) components in $\bar{\nu}$ mode beam.



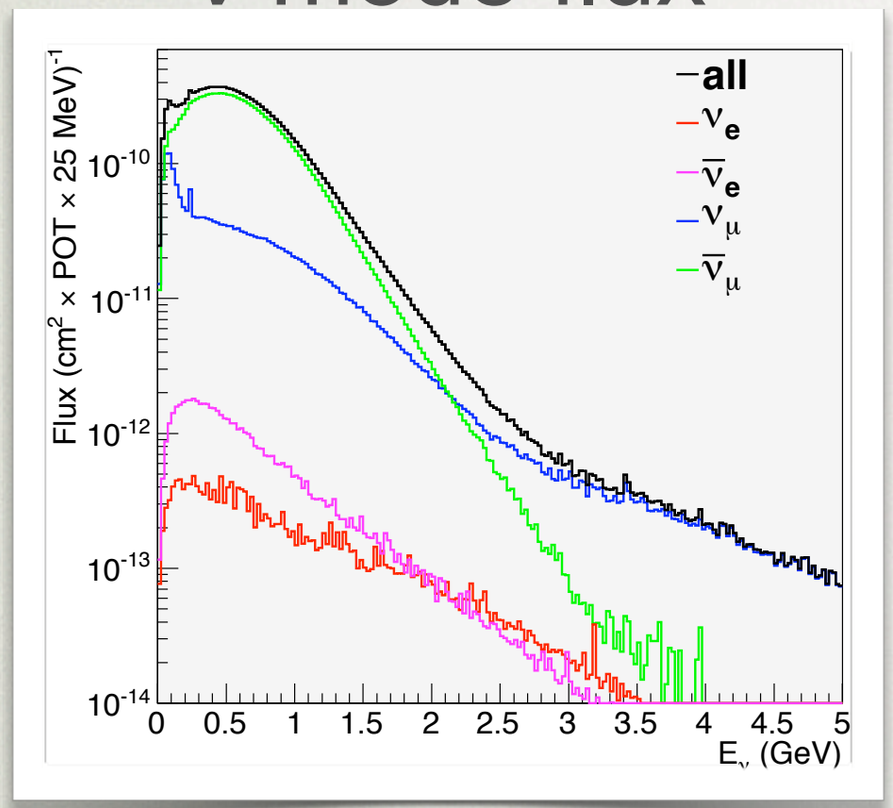
Plots from Phys.Lett. B313, 267-275 (1993)

Solid line: Rein-Sehgal model

Dotted line: Bel'kov-Kopeliovich

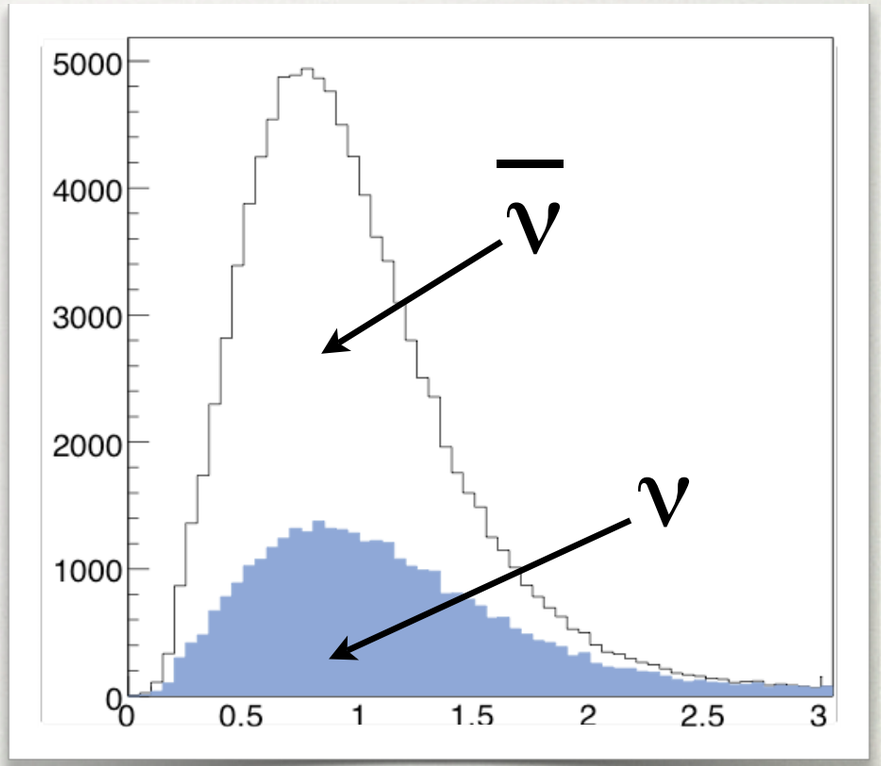
Wrong-Sign contribution

$\bar{\nu}$ mode flux



- $\bar{\nu}_\mu$ 84%
- ν_μ: ~16%

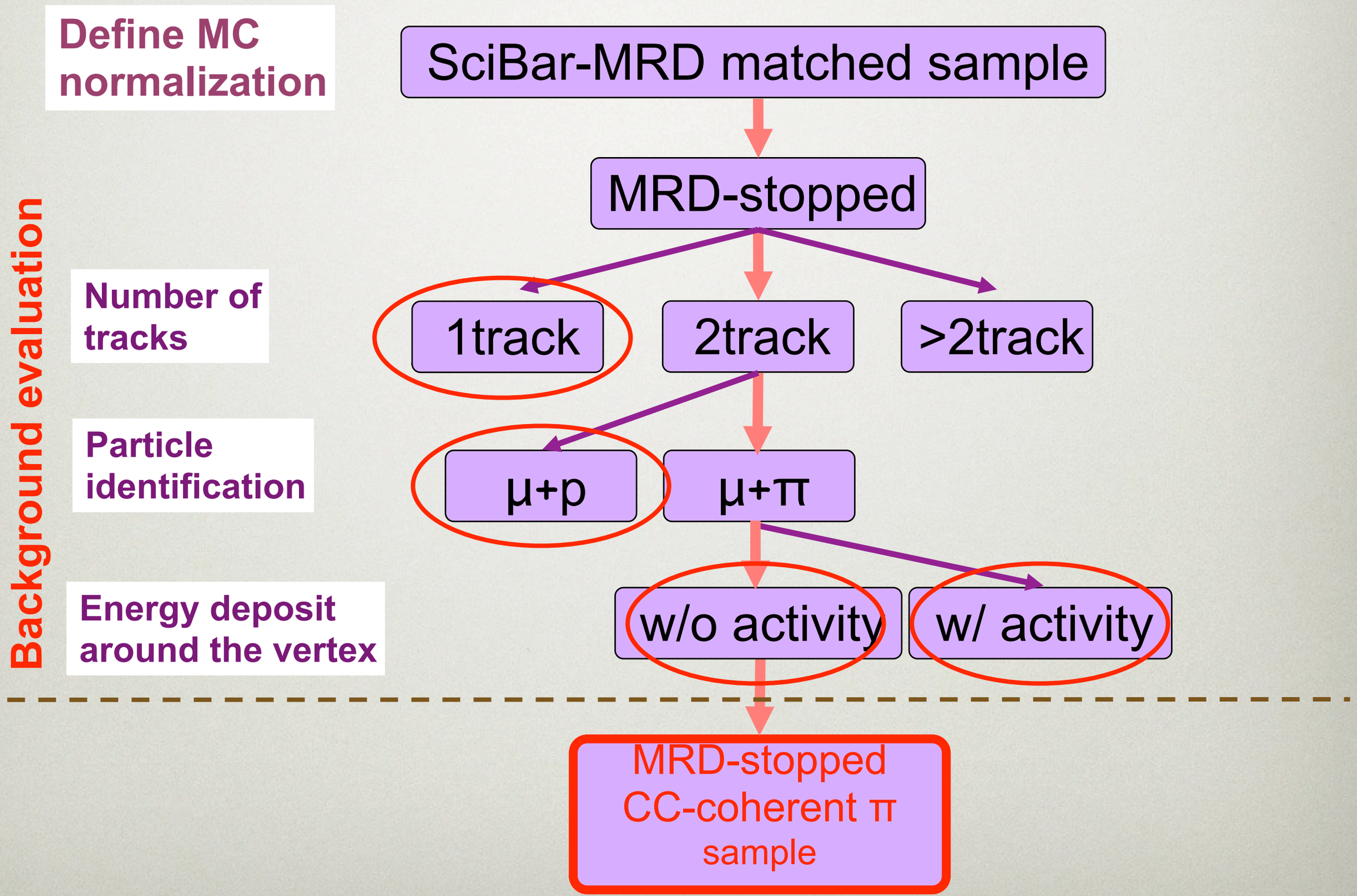
Rate: [flux] x [σ]



- $\bar{\nu}_\mu$:~63%
- ν_μ :~36%

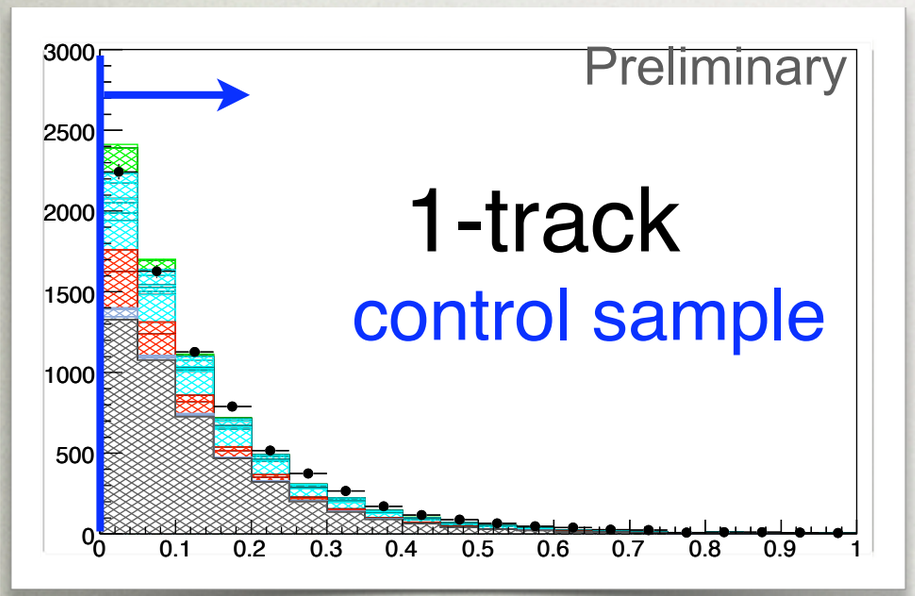
WS components contribute to both signal (CC coh-π) and background events

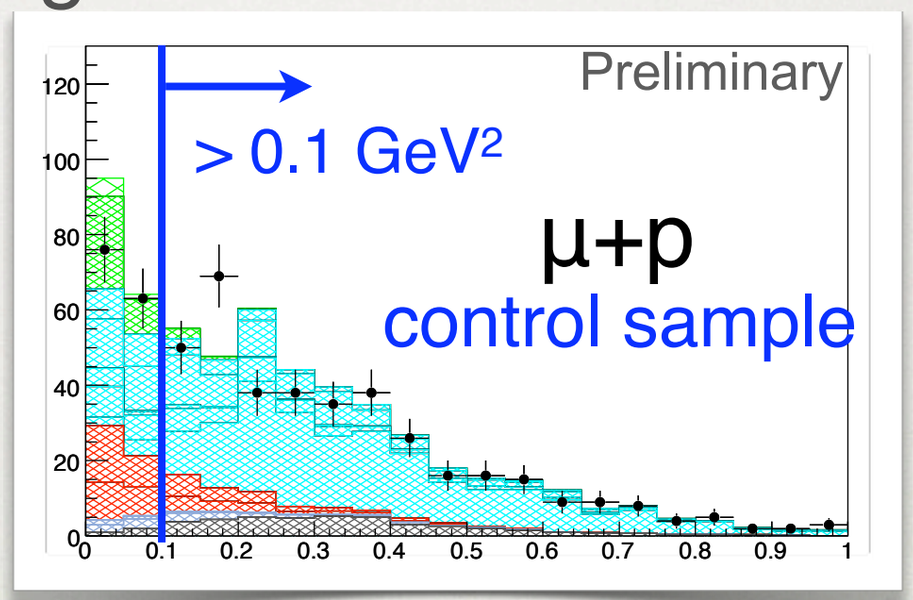
Event selection



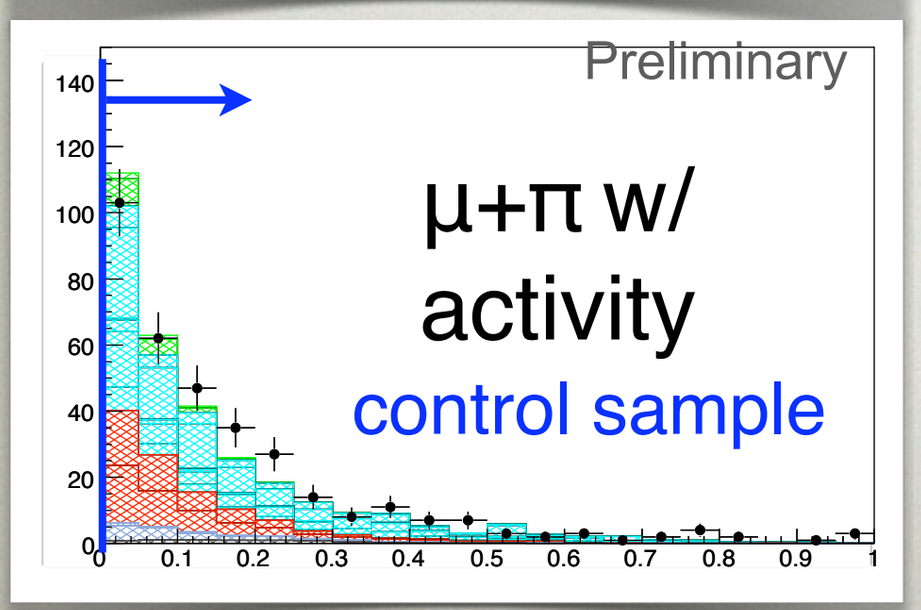
Background evaluation

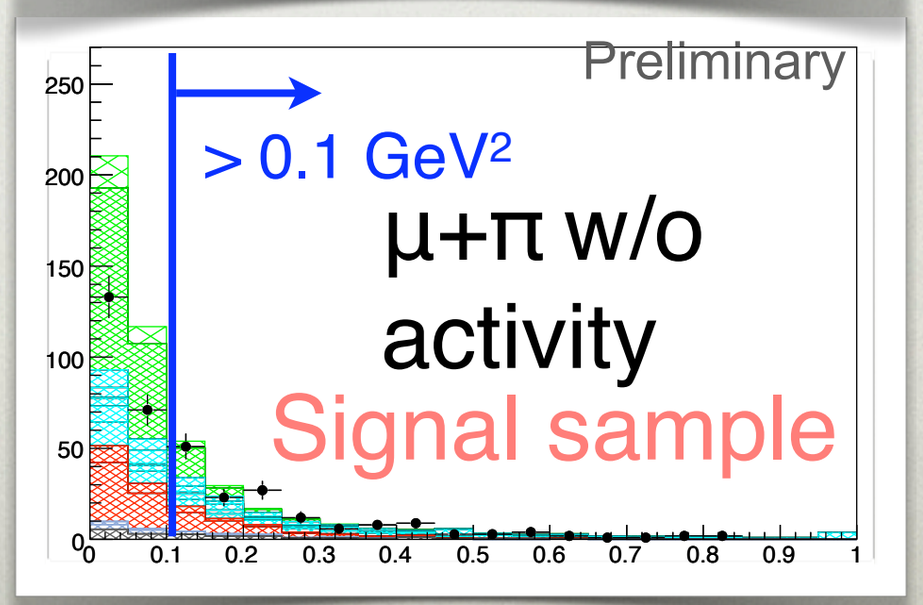
- Tune the MC, constraining systematic uncertainties due to ν interaction model, beam prediction and detector response.
- ➜ Evaluate background with the tuned MC

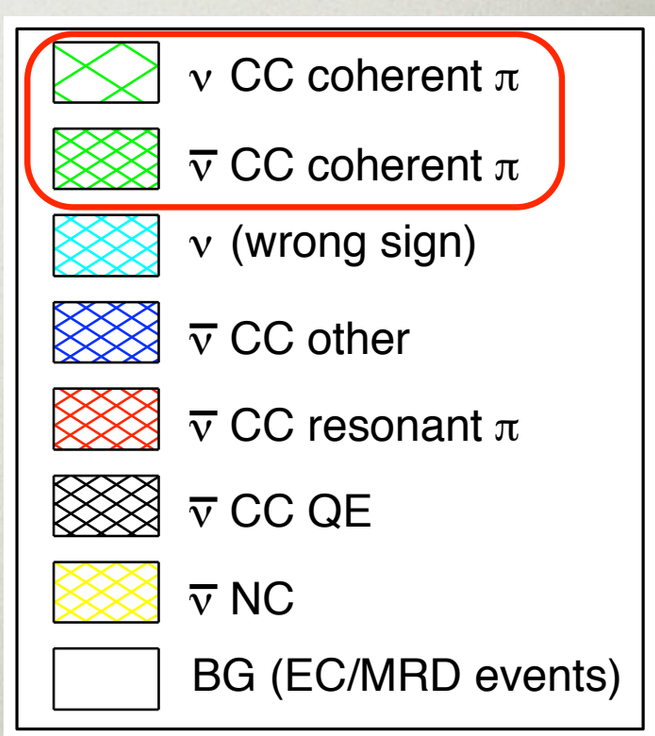




Q2 distributions







Fit Method & Fit Parameters

$$\chi^2 = \chi^2_{dist} + \chi^2_{sys} \qquad \chi^2_{dist} = 2\sum_{i,j}\left(N^{\rm exp}_{ij} - N^{\rm obs}_{ij} \times \ln\frac{N^{\rm obs}_{ij}}{N^{\rm exp}_{ij}}\right) \qquad \chi^2_{\rm sys} = (\boldsymbol{P_{sys}} - \boldsymbol{P_0})\boldsymbol{V}^{-1}(\boldsymbol{P_{sys}} - \boldsymbol{P_0})$$

$$N^{\rm exp}_{i,\ 1{\rm trk}} = R_{\rm norm} \cdot \left[n^{\rm QE}_{i,1{\rm trk}} + R_{\rm res} n^{\rm res}_{i,1{\rm trk}} + R_{\rm other} n^{\rm other}_{i,1{\rm trk}}\right]$$

$$N^{\rm exp}_{i,\ \mu p} = R_{\rm norm} \cdot R_{2{\rm trk}/1{\rm trk}} \cdot R_{p/\pi} \cdot \left[n^{\rm QE}_{i,\mu p} + R_{\rm res} n^{\rm res}_{i,\mu p} + R_{\rm other} n^{\rm other}_{i,\mu p}\right]$$

$$N^{\rm exp}_{i,\ \mu\pi{\rm H}} = R_{\rm norm} \cdot R_{2{\rm trk}/1{\rm trk}} \cdot \left[n^{\rm QE}_{i,\mu\pi{\rm H}} + R_{\rm res} n^{\rm res}_{i,\mu\pi{\rm H}} + R_{\rm other} n^{\rm other}_{i,\mu\pi{\rm H}}\right]$$

$$N^{\rm exp}_{i,\ \mu\pi{\rm L}} = R_{\rm norm} \cdot R_{2{\rm trk}/1{\rm trk}} \cdot R_{\rm act} \cdot \left[n^{\rm QE}_{i,\mu\pi{\rm L}} + R_{\rm res} n^{\rm res}_{i,\mu\pi{\rm L}} + R_{\rm other} n^{\rm other}_{i,\mu\pi{\rm L}}\right]$$

new

$$n^{\rm mode}_{i,{\rm sample}} \equiv \left(n^{\bar\nu-{\rm mode}}_{i,{\rm sample}} + R_{\rm WS} \cdot n^{\nu-{\rm mode}}_{i,{\rm sample}}\right)$$

new

- **R_{WS}**: scaling factor for Wrong-Sign (WS) events
- **$R_{2tr/1trk}$**: migration parameter between [1trk]-[2trk] samples
- **$R_{p/\pi}$**: migration param. between [μ+p]-[μ+π] samples
- **R_{act}**: migration param. between [with activity]-[w/o activity]
- **R_{res}**: scale factor for resonant-π
- **R_{other}**: scale factor for “other” (≡ multi-π, DIS, EC/MRD)
- **R_{pscale}**: momentum scale
- **R_{norm}**: overall normalization -- no constrained
- **kappa**: only for QE

Fit results

Preliminary

Param	Value	Error
R_{norm}	1.062	0.029
$R_{2trk/1trk}$	1.038	0.044
$R_{p\pi}$	0.901	0.057
R_{act}	1.038	0.104
R_{pscale}	1.022	0.002
R_{res}	1.11	0.099
R_{other}	1.023	0.096
Kappa	1.001	0.002
R_{WS}	0.948	0.057

After: $\chi 2/ndf = 83/66=1.25$

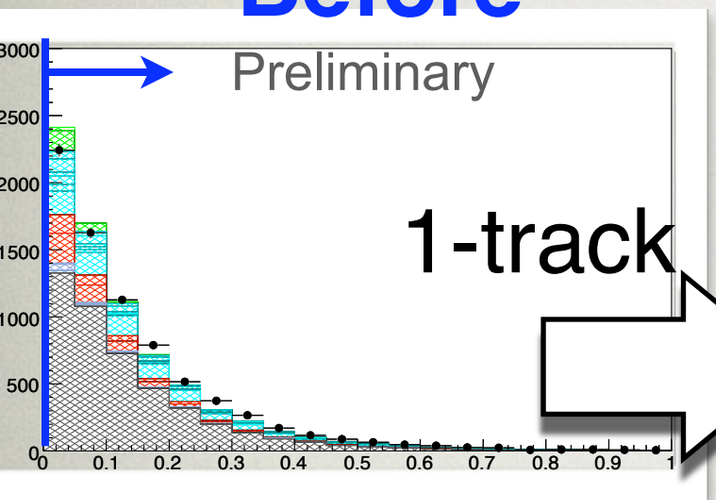
Preliminary

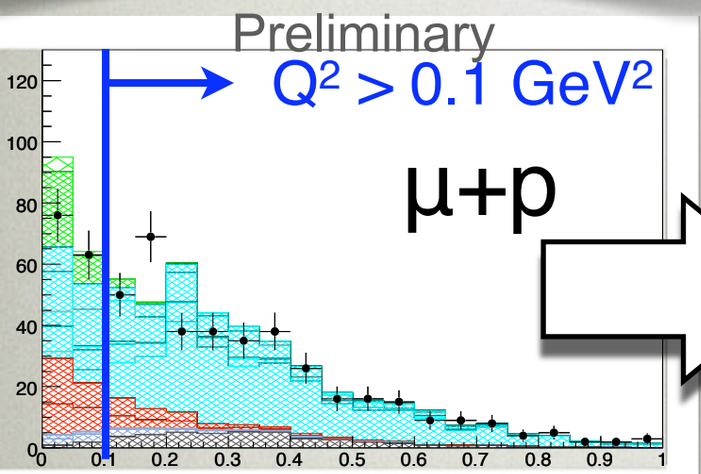
Before: $\chi 2/ndf = 162/75=2.16$

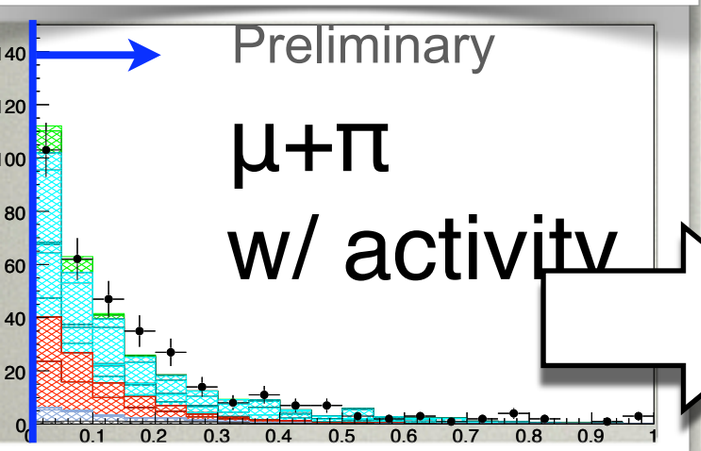
Fit results

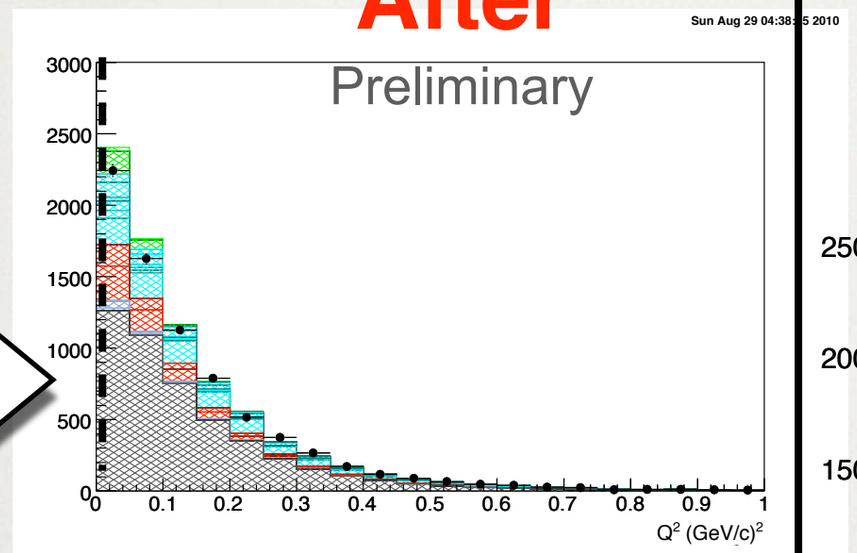
: $\bar{\nu}+\nu$ CC coherent π
: $\bar{\nu}$ CC resonant
: $\bar{\nu}$ Other (DIS, EC/MRD, NC)
: $\bar{\nu}$ CC QE
: Wrong-Sign

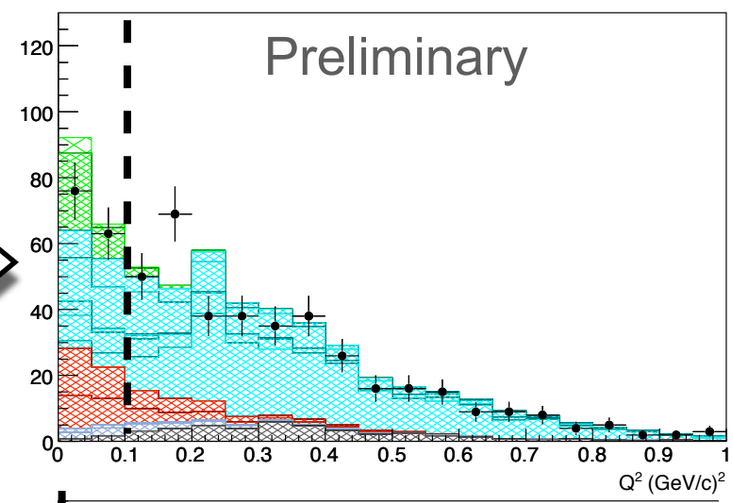
Before **After**

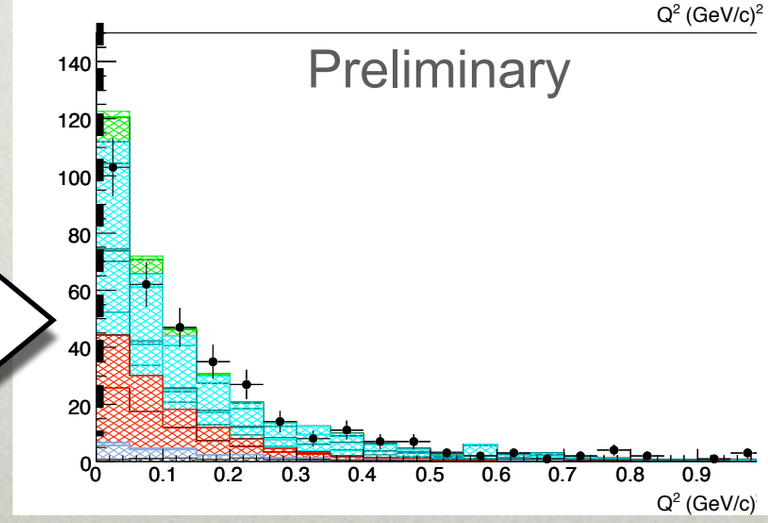




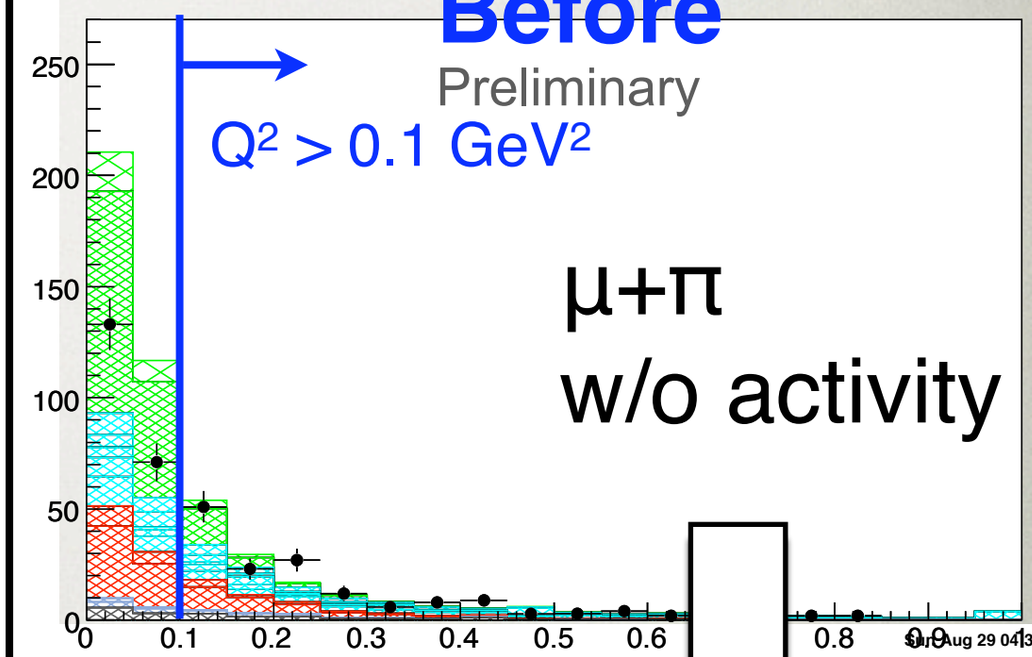




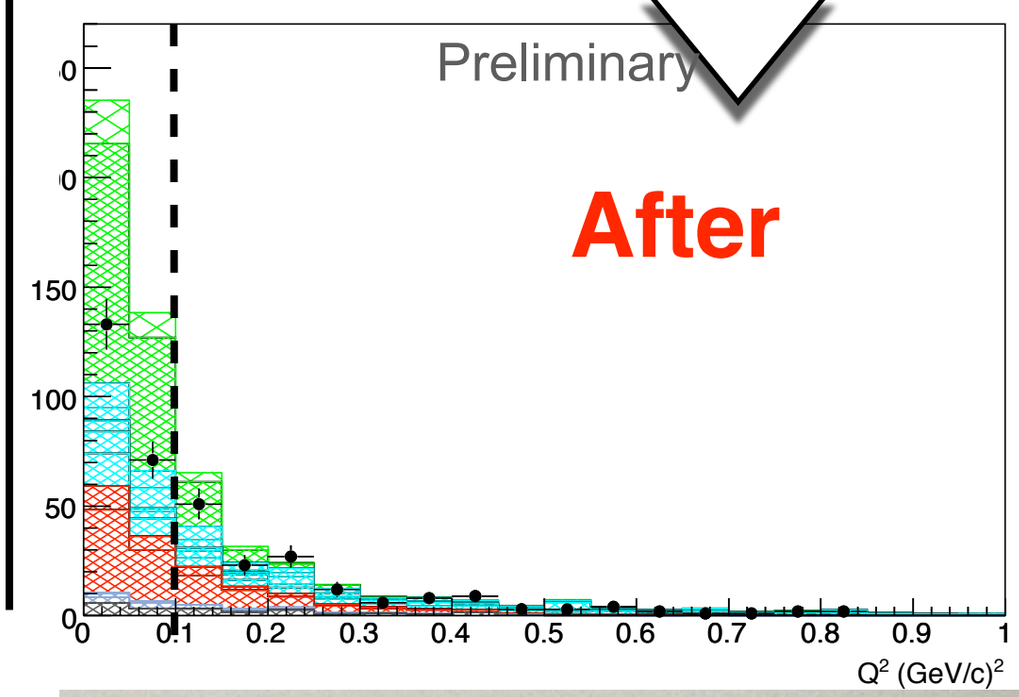




Before

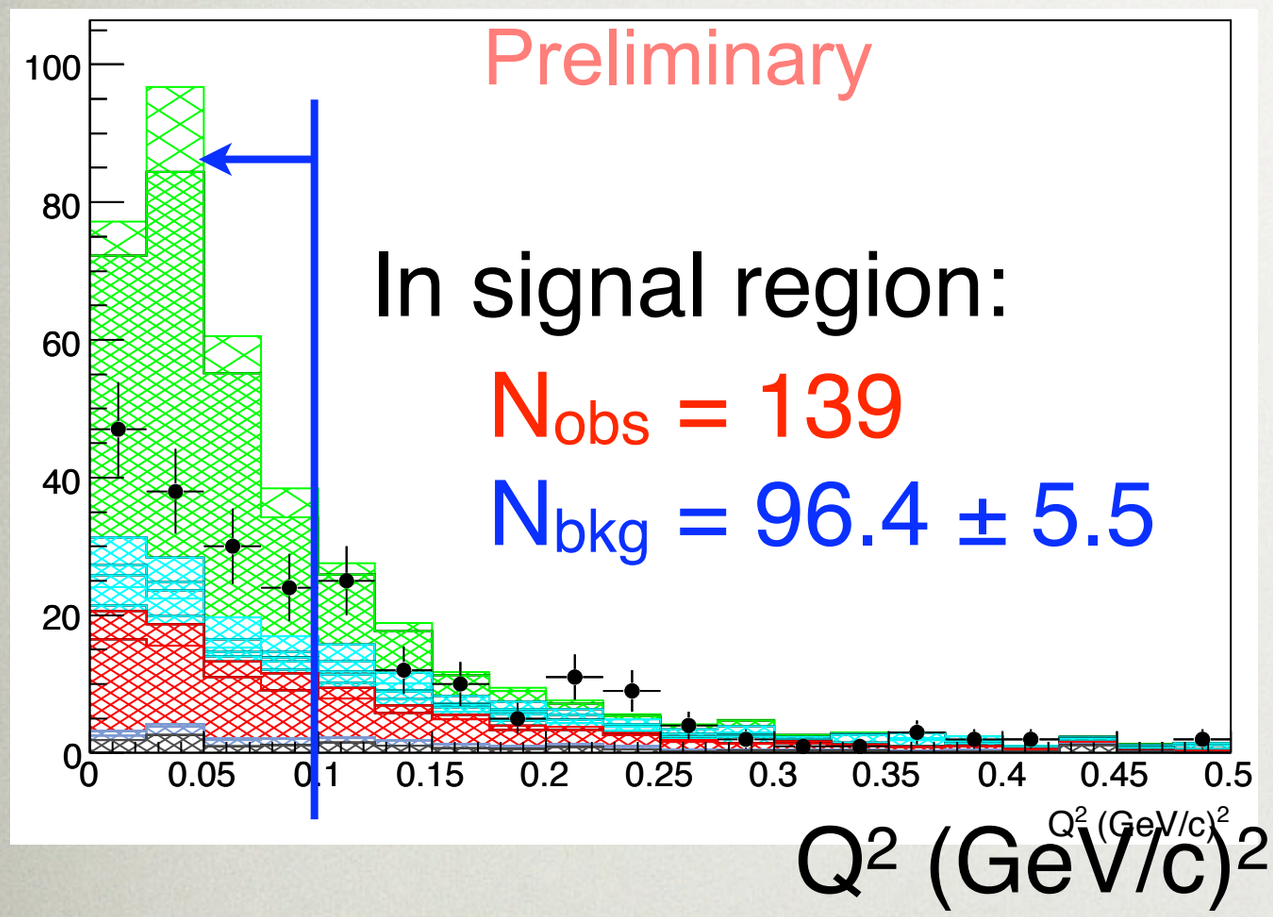


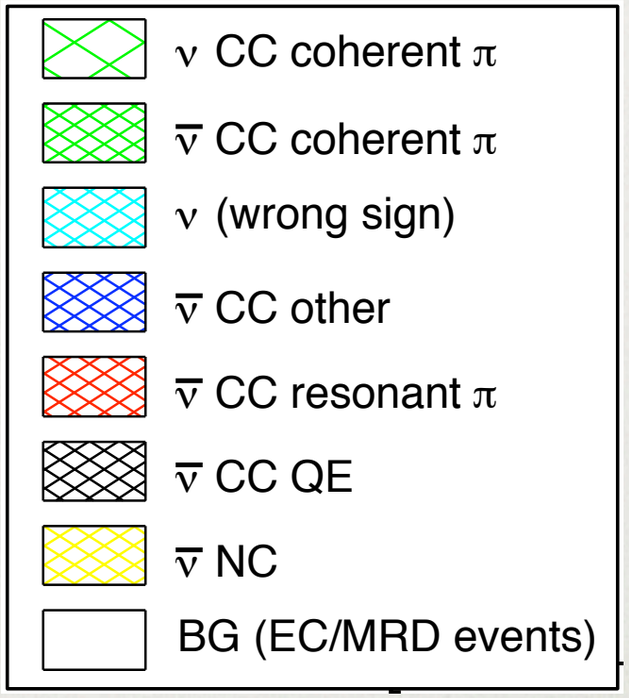
After



CC coh-π sample

Signal region ≡ $Q^2 < 0.1$ $(GeV/c)^2$





CC coh-π sample ≡
MRD-stop, 2-trk, μ+π, w/o vtx activity, non-QE, fwd-π

- The results corresponds to ~1/4 of R&S model
  - Based on number of events in $Q^2<0.1$
    - $N_{obs}-N_{bkg}$= 42.6
    - $N_{coh}(\nu+\bar{\nu})$ = 176.4 (NEUT, R&S)

Cross section ratio

~general formalism~

$$\#(\text{CC coh-}\pi) = \frac{N_{obs} - N_{bkg}}{e_{coh}} \qquad \#(\text{CC}) = \frac{N_{MRD} \times p_{cc}}{e_{cc}}$$

$$\boxed{R \equiv \frac{N_{obs} - N_{bkg}}{N_{MRD}} \times \frac{e_{cc}}{e_{coh} \times p_{cc}}}$$

- R: cross section ratio σ(CC coh-π) / σ(CC)
- N_{obs} ≡ # of observed events in CC coh-π sample (Q2<0.1)
- N_{bkg} ≡ # of expected Bkg events in CC coh-π sample (Q2<0.1)
- N_{MRD} ≡ # of observed MRD-match events
- e_{coh} ≡ CC coh-π selection efficiency
- e_{cc} ≡ CC selection efficiency
- p_{cc} ≡ CC purity

Cross section ratio

However $\bar{\nu}$ mode beam has ν (Wong-Sign) contamination. Data include both ν and $\bar{\nu}$ contributions, and the formula of **R** becomes complicated.

For example:

$$N_{bkg} = N^{\bar{\nu}}_{bkg} + N^{\nu}_{bkg}, \qquad N_{MRD} = N^{\bar{\nu}}_{MRD} + N^{\nu}_{MRD}$$

The cross section ratio **R**, we derive from data, will be formed like:

$$\mathbf{R} \equiv \frac{N_{obs} - N_{bkg}}{N_{MRD}} \times \frac{e_{cc}}{e_{coh} \times p_{cc}}$$

$$= \frac{\sigma(\bar{\nu}\ \mathrm{CC\ coh\text{-}}\pi) + r \cdot \sigma(\nu\ \mathrm{CC\ coh\text{-}}\pi)}{\sigma(\bar{\nu}\ \mathrm{CC}) + r \cdot \sigma(\nu\ \mathrm{CC})}$$

" r " is a ratio of $\bar{\nu}$ and ν fluxes in $\bar{\nu}$ mode beam:

$$r \equiv \int \Phi(\nu)\, dE \,/\, \int \Phi(\bar{\nu})\, dE = 0.19$$

Cross section ratio

- Cross section ratio with full systematic error
  - Mean neutrino energy: 1.0 GeV

$$\frac{\sigma(\bar{\nu}\ \text{CC coh-}\pi) + r\cdot\sigma(\nu\ \text{CC coh-}\pi)}{\sigma(\bar{\nu}\ \text{CC}) + r\cdot\sigma(\nu\ \text{CC})}$$

$$= (\ 1.13 \pm 0.34(\text{stat})\ ^{+0.31}_{-0.36}(\text{sys})\ )\ \text{x}\ 10^{-2}$$

Preliminary

- Cross section ratio ~2σ away from zero.

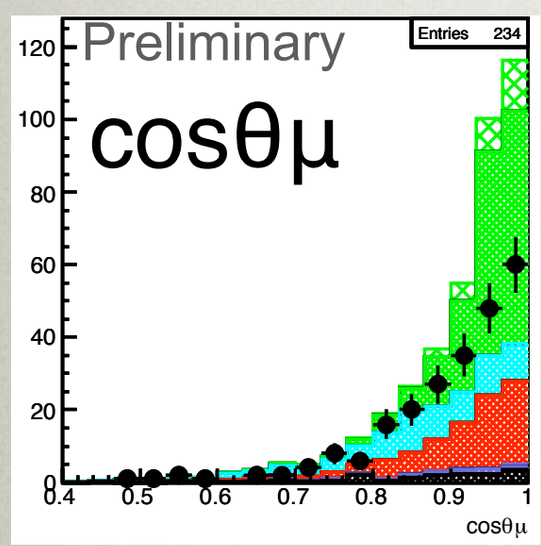
cf. ν mode CC coh-π result (MRD-stop sample, ⟨Eν⟩ = 1.1 GeV)

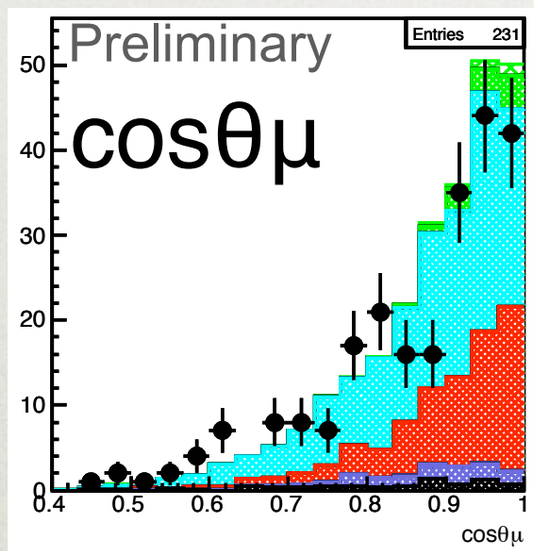
$$\frac{\sigma(\nu\ \text{CC coh-}\pi)}{\sigma(\nu\ \text{CC})} = (\ 0.16 \pm 0.17(\text{stat})\ ^{+0.30}_{-0.27}(\text{sys})\ )\ \text{x}\ 10^{-2}$$

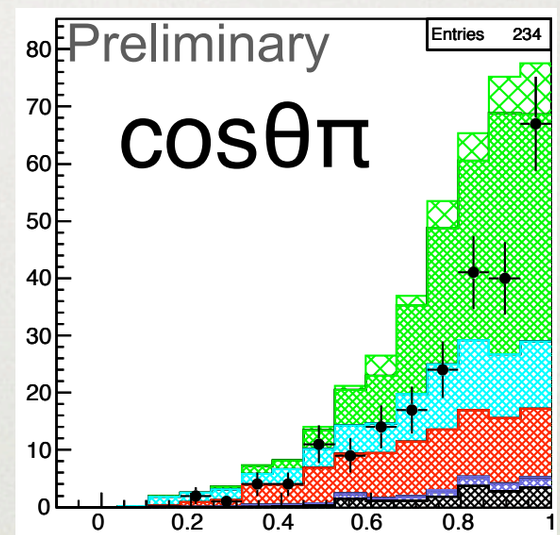
"NON-ZERO" CC COH-π SIGNATURE

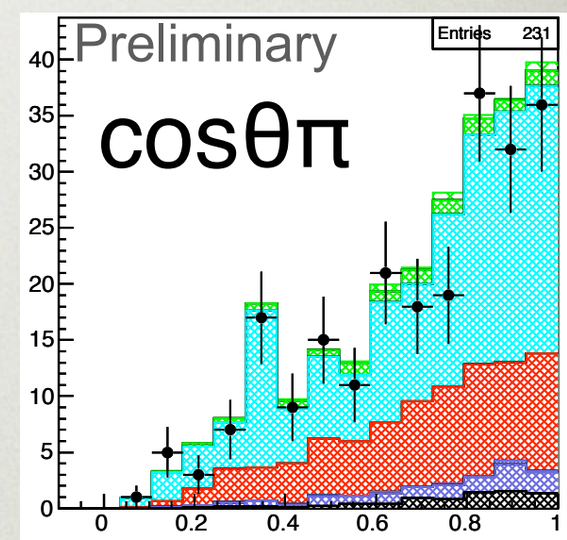
- Muon and pion angles
  - Coh-π sample ≡ w/o vtx activity
  - Counter sample ≡ w/ vtx activity

coh-π sample counter sample | coh-π sample counter sample

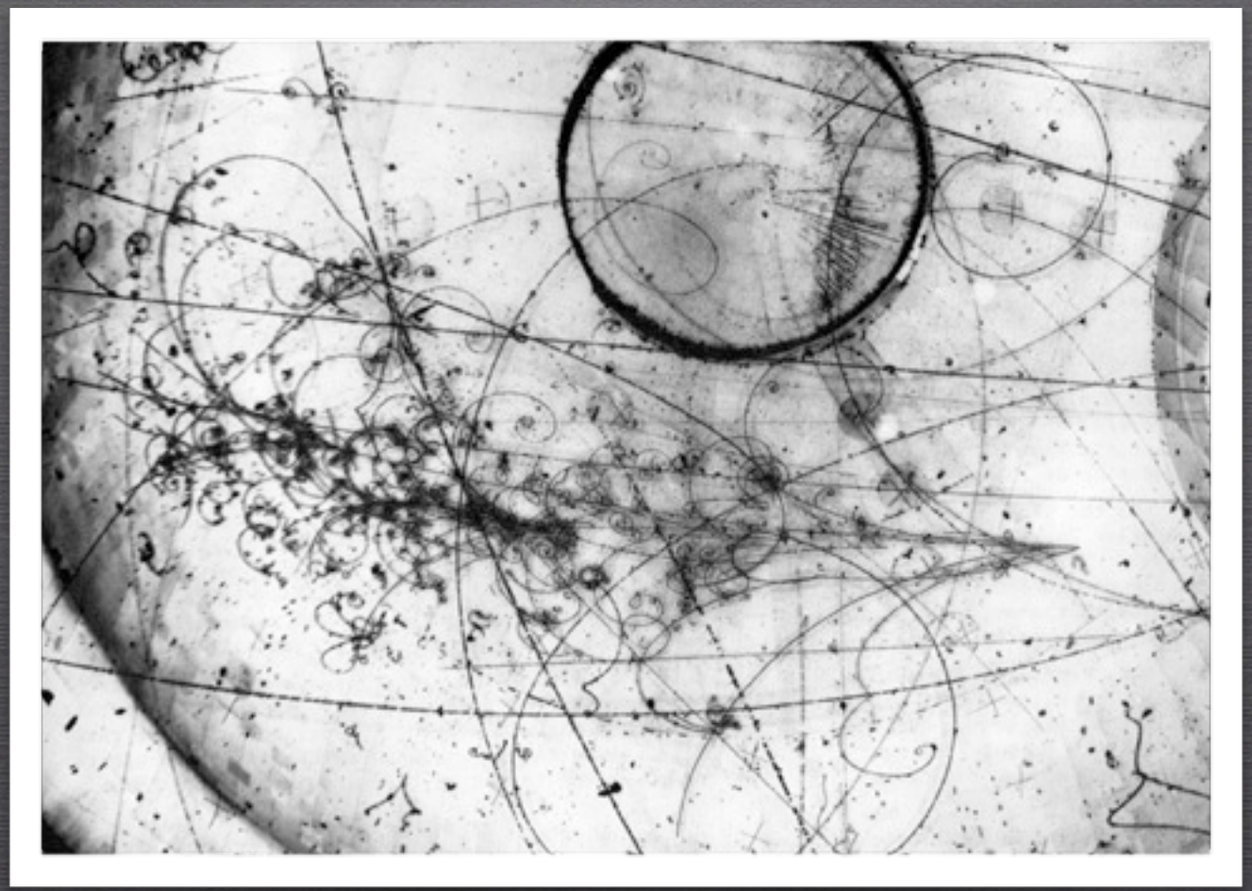








Data "excess" w.r.t. Bkg prediction concentrate in small angular region (forward region).



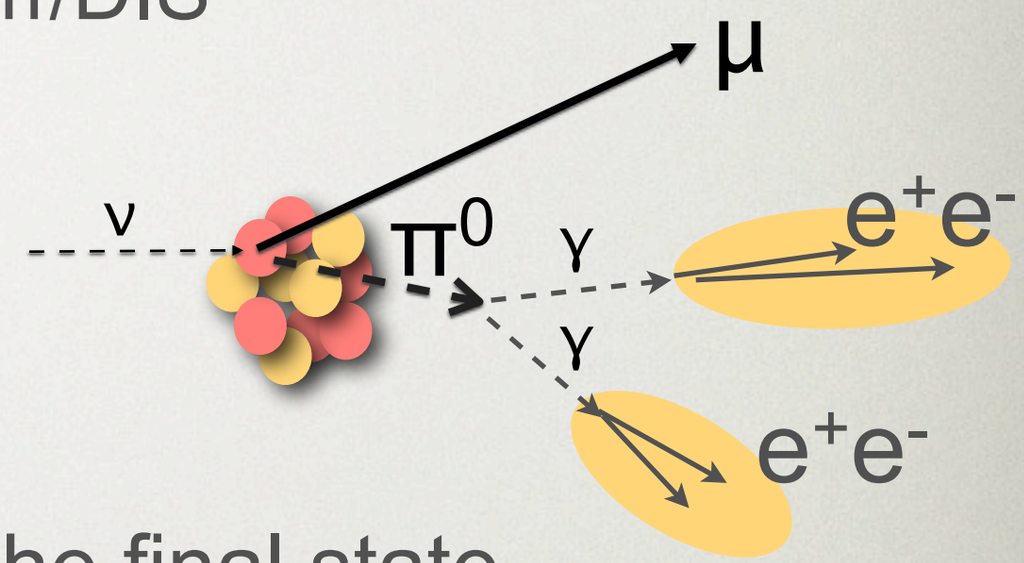
CC π^0 PRODUCTION

Preliminary results

CC π^0 production

CC π0 production: only incoherent-π contributions,
Sensitive to resonant-π & multi-π/DIS

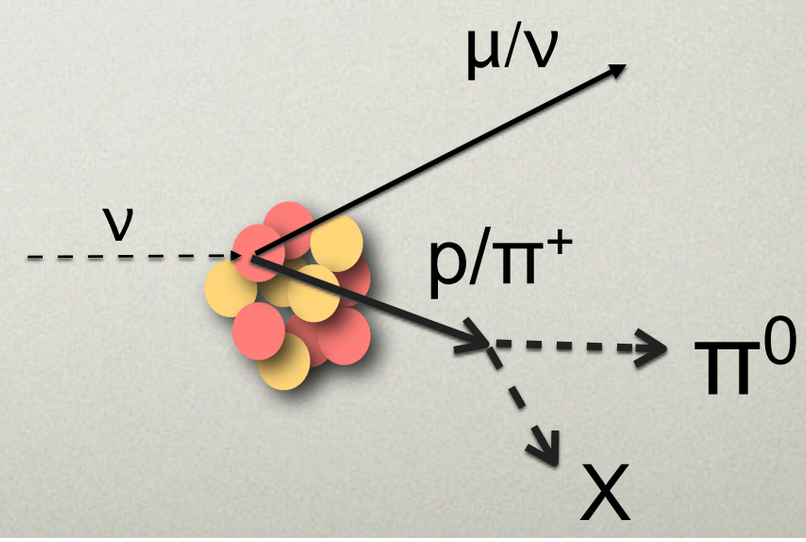
- Signal:
  - CC-π^0 production
    $\nu+C\rightarrow\mu+\pi^0+X$



- **CC-π^0** ≡ CC int. in which one π^0 in the final state
  (ex. one π^0 + one or more charged π events are also signal)

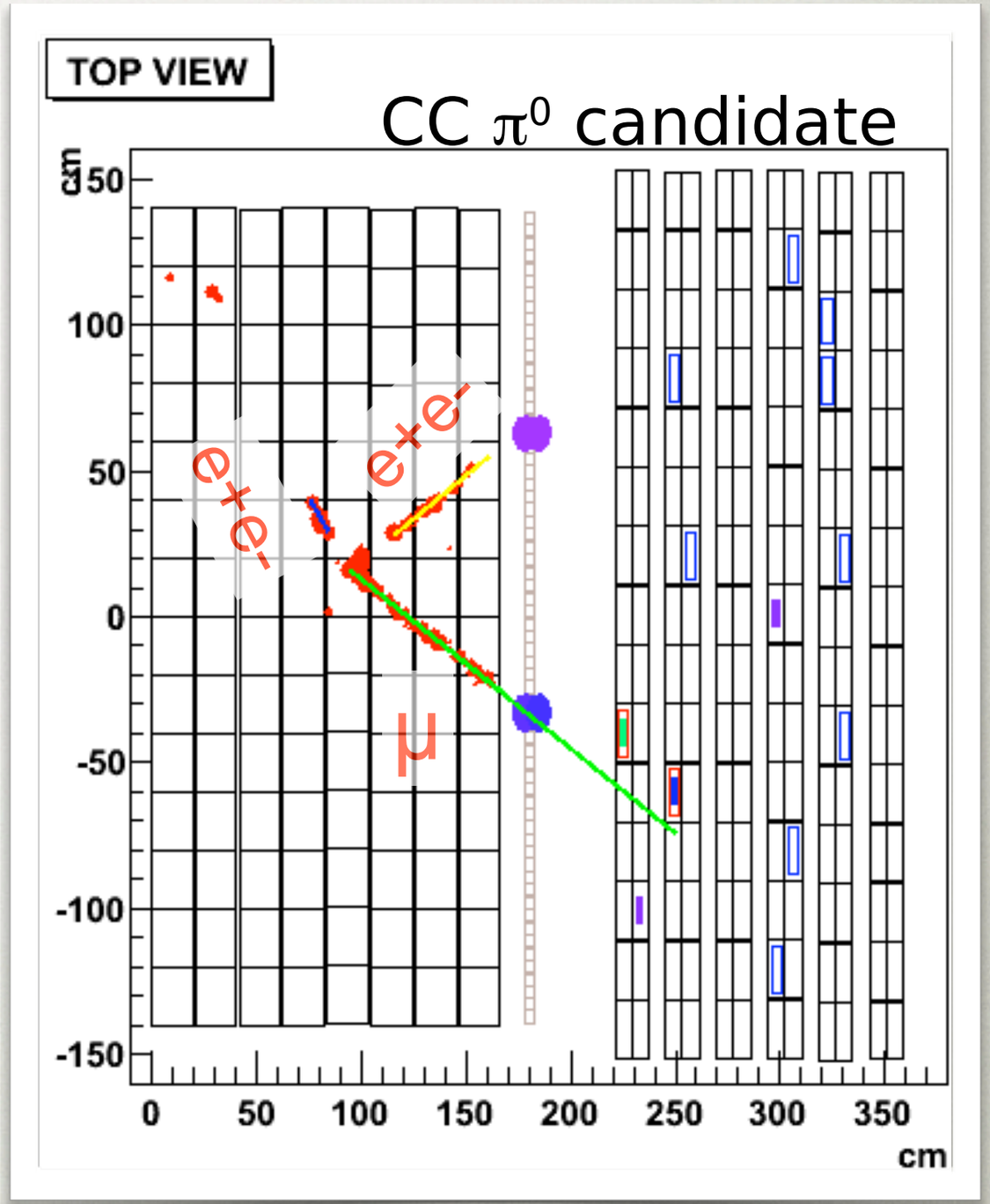
One muon + Two "shower-like" tracks (from π^0)

- Background:
  - ex. CC/NC events that produce π^0s in detector (outside the target nucleon)



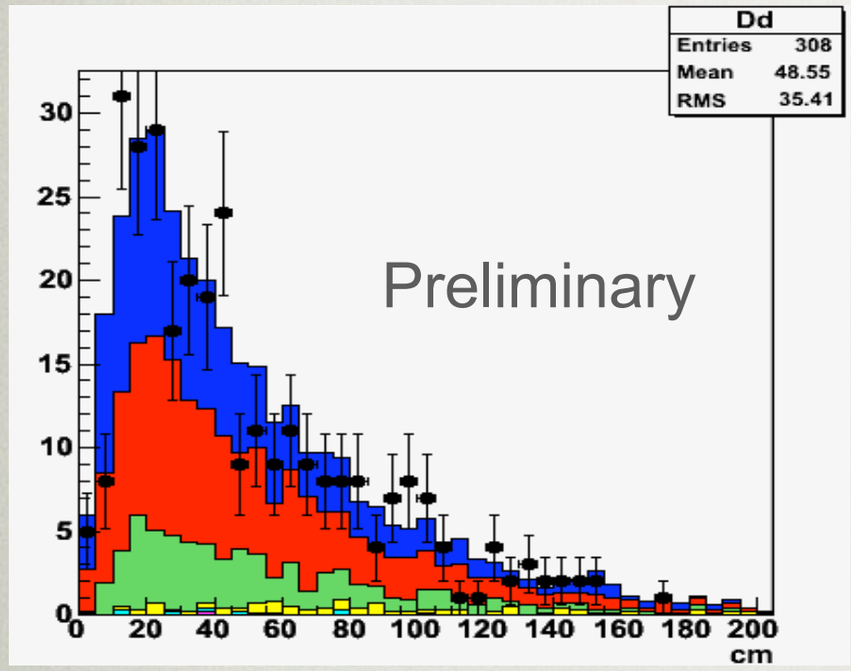
CC π^0 candidates

- Select events requiring:
  - One muon track: identify by MRD
  - Two shower-like tracks
    - non-proton like
    - tracks disconnected from event vertex



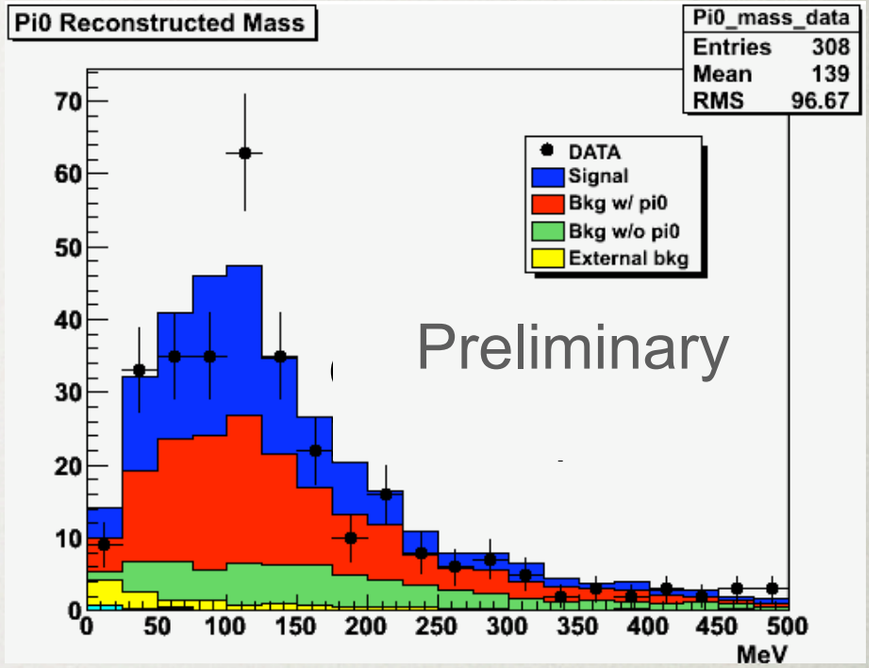
Selected CC-π^0 events

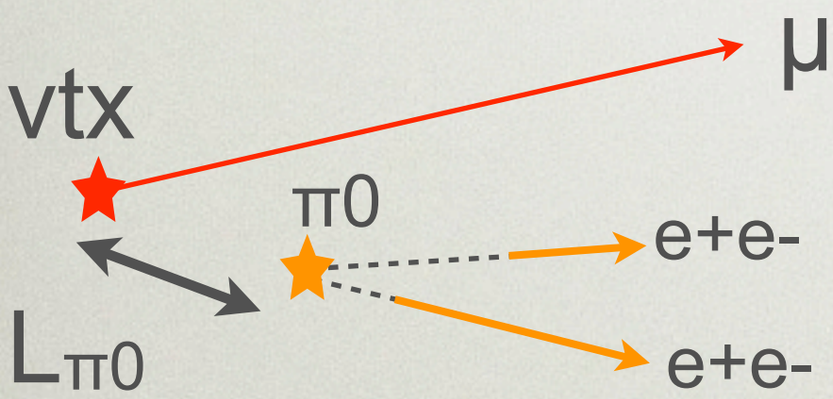
π^0 distance to vtx ($L_{\pi 0}$)



- : DATA
- : Signal
- : Bkg with π0
- : Bkg without π0
- : External bkg

π^0 mass ($M_{\pi 0}$)





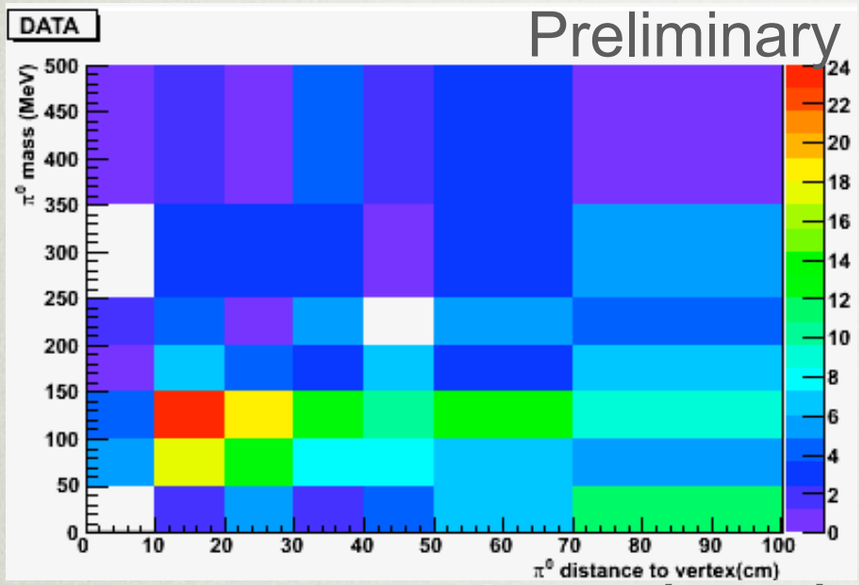
$L_{\pi 0}$ ≡ distance between ν vertex and reconstructed π0 vertex.

- Major background: π0 production in detector
- ➜ Bkg events have π0 vertex far away from neutrino vertex

Background evaluation

- Signal and Background events has different shape in $M_{\pi 0}$ and $L_{\pi 0}$ 2D distribution

DATA

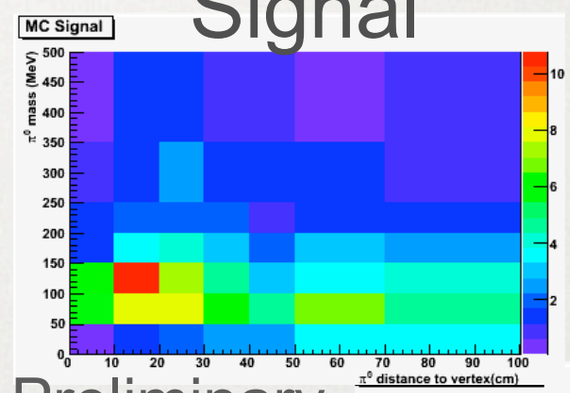


$M_{\pi 0}$ (MeV)

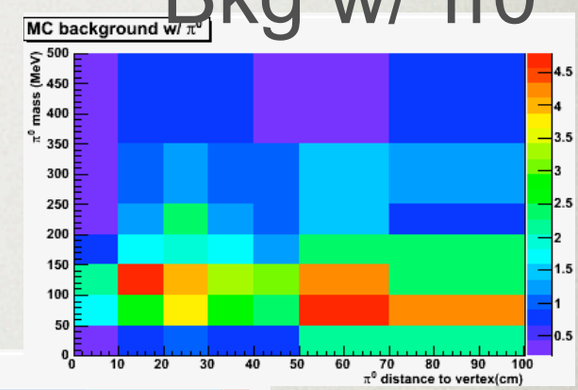
$L_{\pi 0}$ (cm)

MC templates

Signal

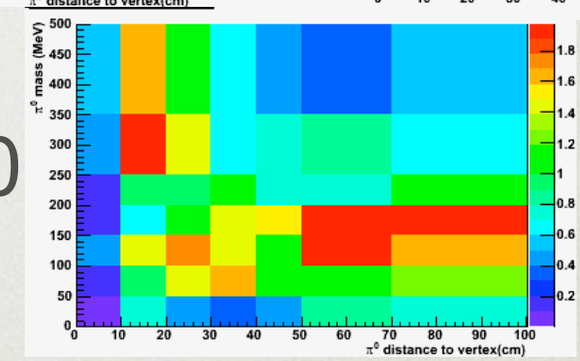


Bkg w/ π0



Preliminary

Bkg w/o π0



- ➜ MC template 2D ($M_{\pi 0}$, $L_{\pi 0}$) fit to data by re-weighting # of evts of Signal, Bkg w/ π0, Bkg w/o π0

$$Nobs = P_{sig} \cdot N(signal) + B_1 \cdot N(Bkg\ w/\ \pi 0) + B_2 \cdot N(Bkg\ w/o\ \pi 0) + N(external\ bkg)$$

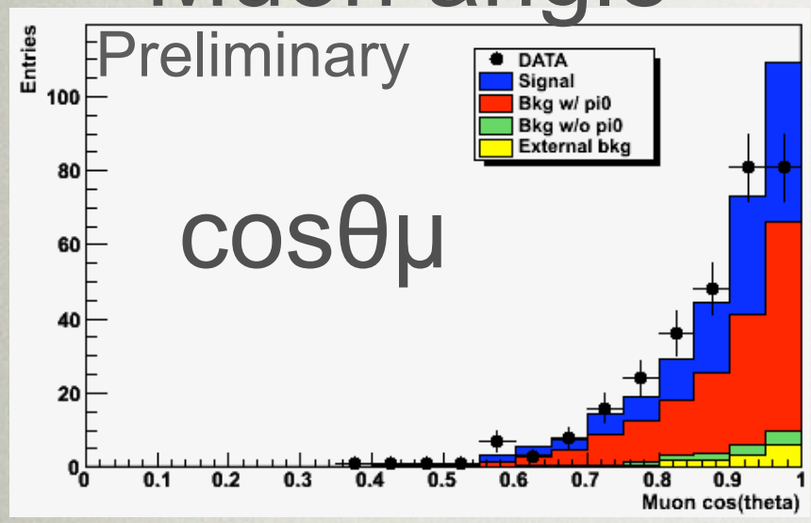
$$P_{sig} = 0.96 \pm 0.28,\ B_1 = 1.19 \pm 0.6,\ B_2 = 0.2 \pm 0.5$$

(Note: no systematic error included in the fit yet)

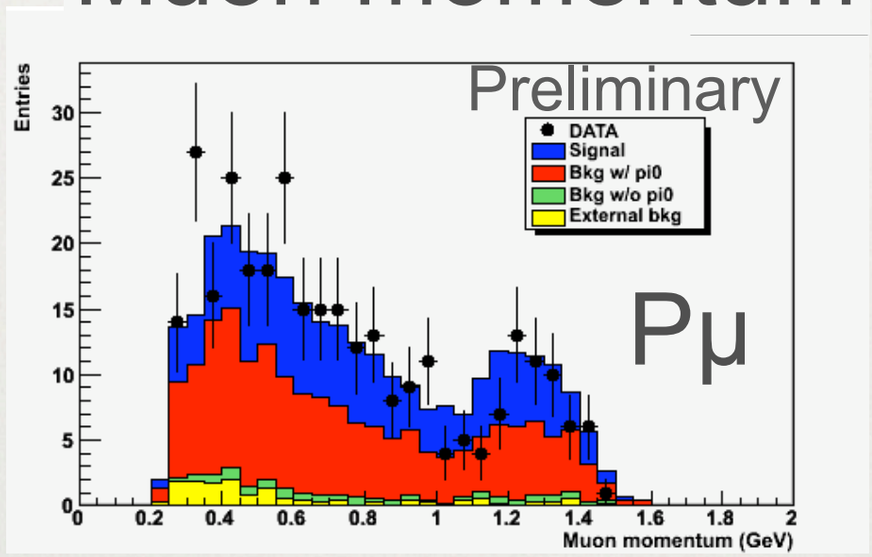
μ AND π^0 KINEMATICS

After fit
(MC absolutely normalized)

Muon angle

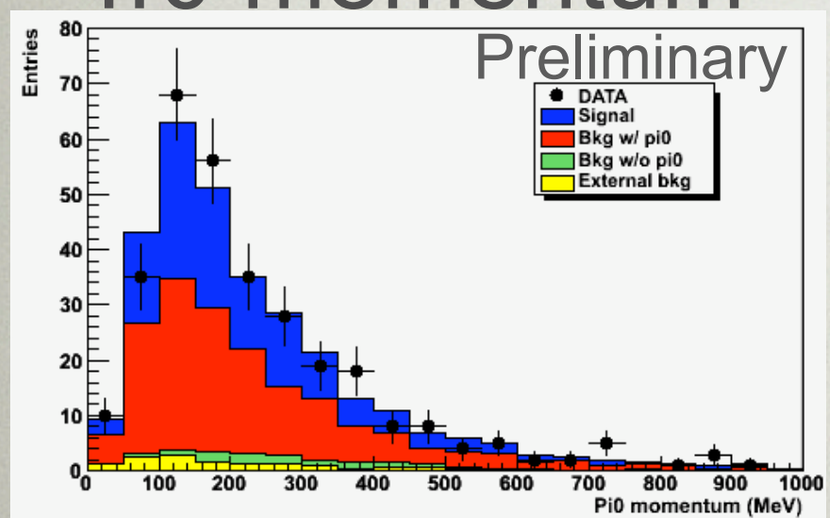


Muon momentum

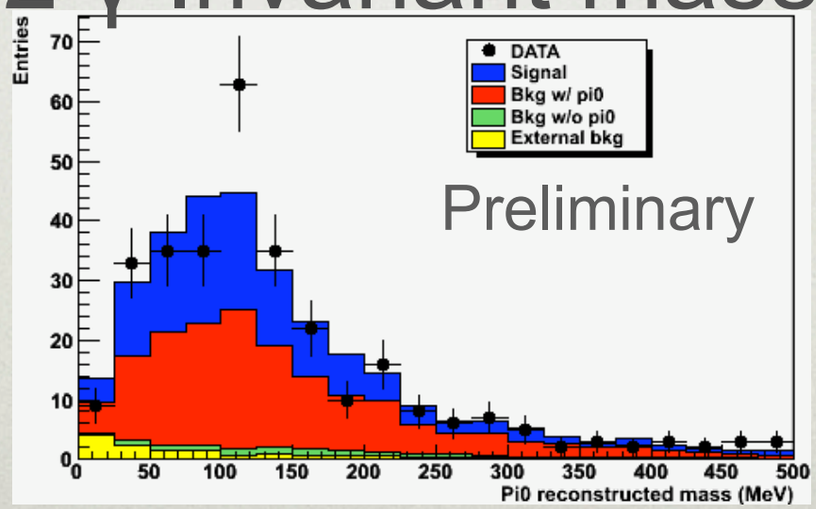


- ● : DATA
- : Signal
- : Bkg with π0
- : Bkg without π0
- : External bkg

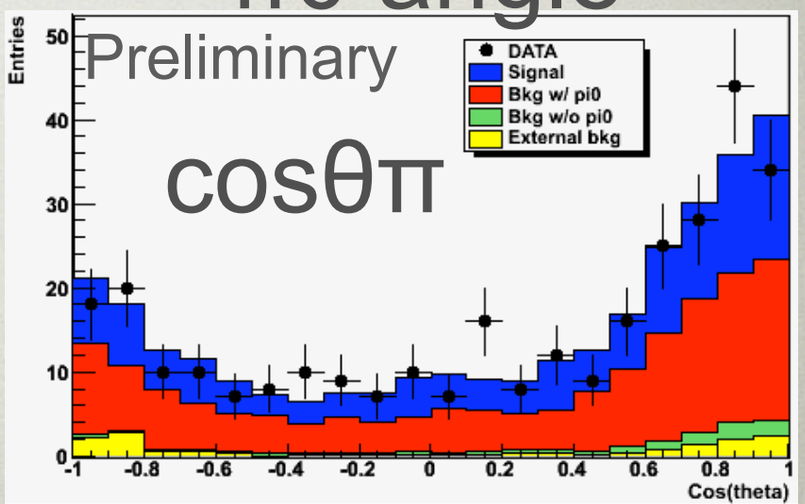
π0 momentum



2 γ Invariant mass



π0 angle



χ2 / DOF: 292.2 / 64 (before fit) → 78.8/61 (after fit)

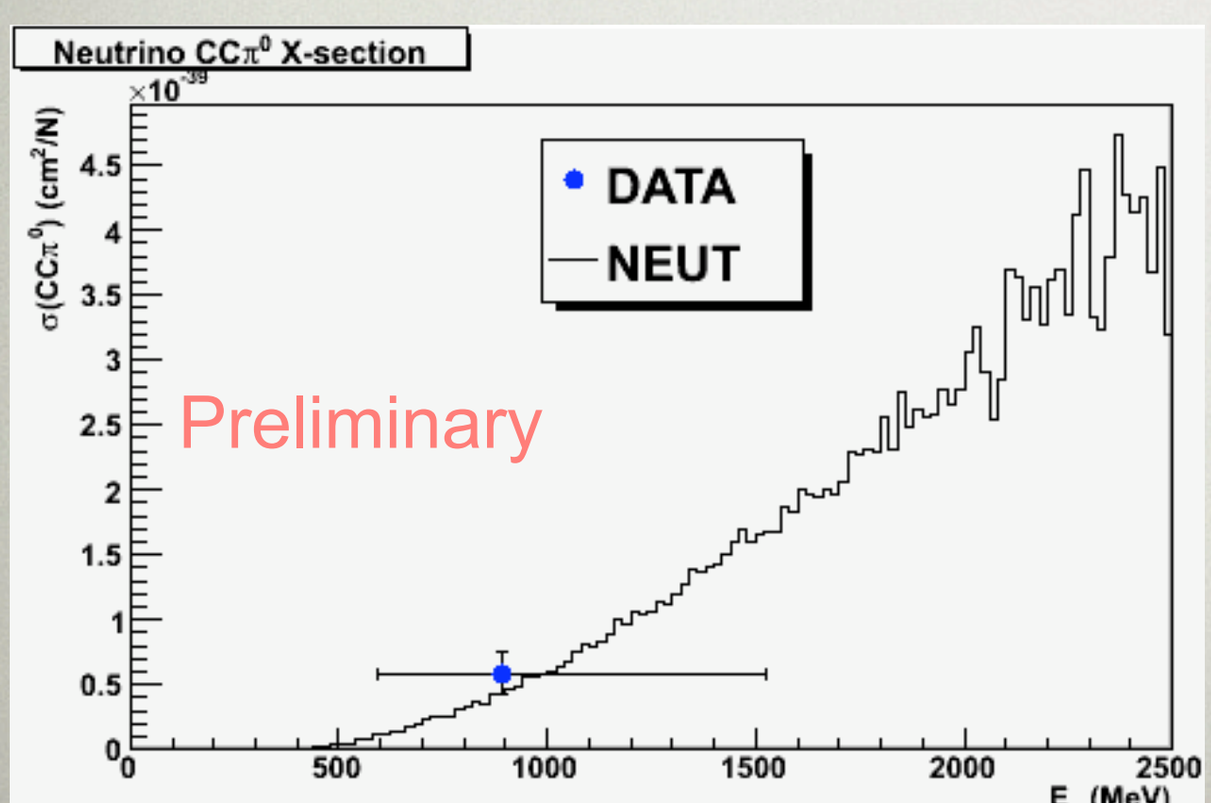
CC π^0 Cross section

- CC π^0 absolute cross section

$$\sigma(CC\pi^0) = [5.6 \pm 1.9(\text{stat})\ ] \times 10^{-40}\ \text{cm}^2/\text{nucleon}$$

$$\langle E\nu \rangle = 893.3^{+636.4}_{-303.3}\ \text{MeV}$$

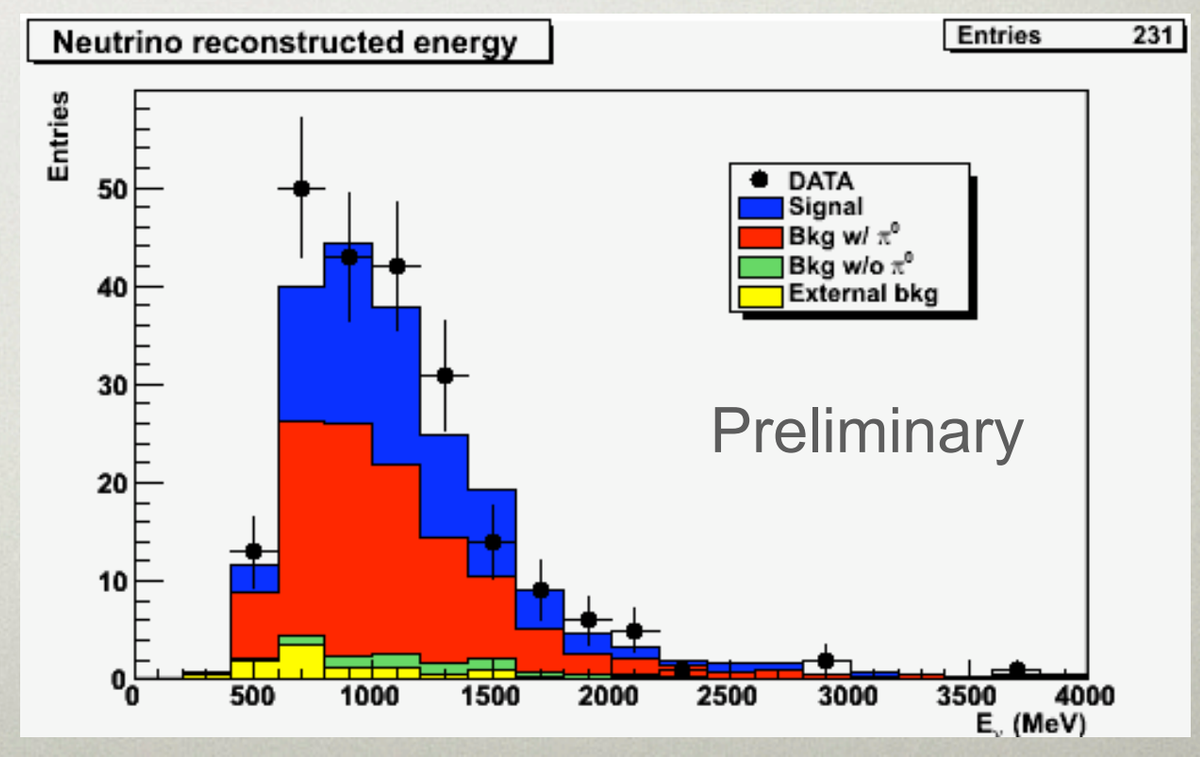
$\sigma(CC\pi^0)$: Data vs. MC



Ev reconstruction

$$E_\nu^{rec} = \frac{m_p^2 - m_n^2 - m_X^2 + 2 m_n E_X}{2\left(m_n - E_X + |p_X| \cos(\theta_{\nu X})\right)}$$

$$p_X \equiv p_\mu + p_{\gamma 1} + p_{\gamma 2}$$

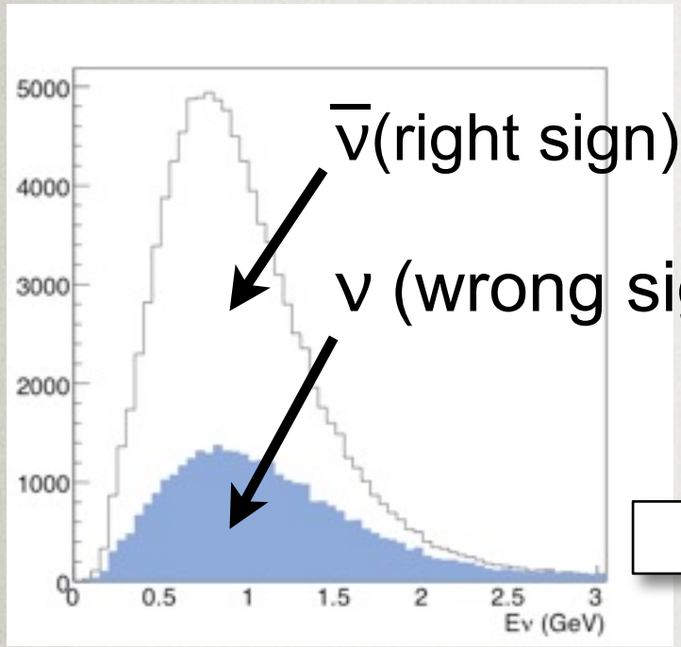


Summary

- ν CC coh-π: Phys.Rev.D78, 112004 (2008)
  - No evidence of CC coh-π
- ν NC-π0: Phys.Rev.D81, 033004 (2010)
  - Cross section and π0 kinematics, MC agree with data
- ν NC coh-π0: Phys.Rev.D81, 111102 (2011)
  - Clear evidence of coh-π, R-S model agrees with data
- $\bar{\nu}$ CC coh-π: preliminary results
  - Cross section ratio ~2σ away from zero
  - Data hint that non-zero CC coh-π events in very forward region (than R-S model)
- ν CC-π0: preliminary results
  - Absolute cross section, working on syst. uncertainties

Backup

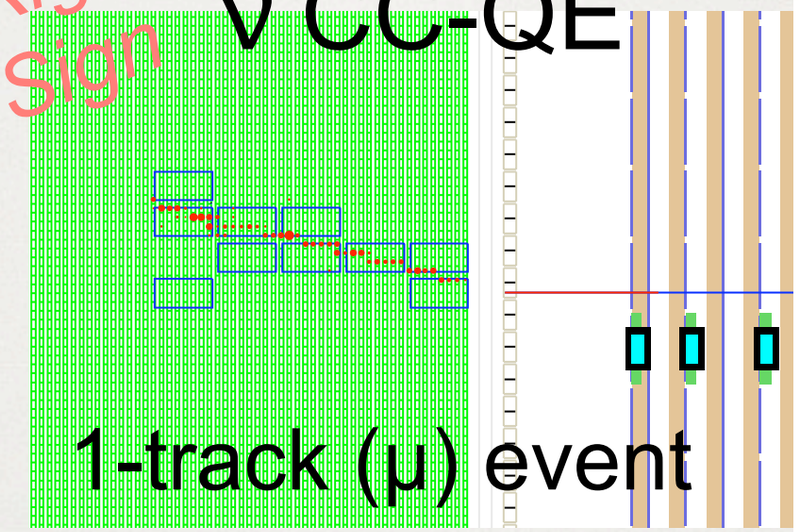
$\bar{\nu}$ and ν samples



ν (wrong sign) ~30% background in MRD stopped sample

Right Sign

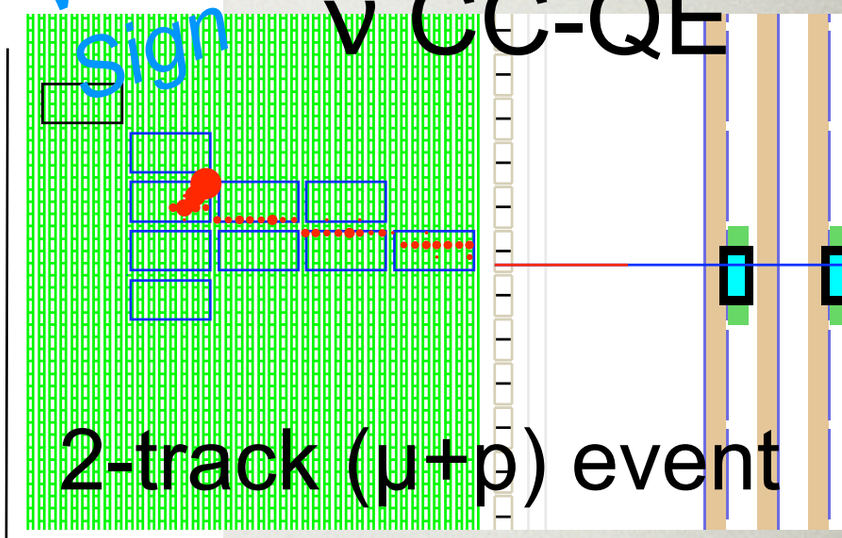
$\bar{\nu}$ CC-QE



1-track (μ) event

Wrong Sign

ν CC-QE



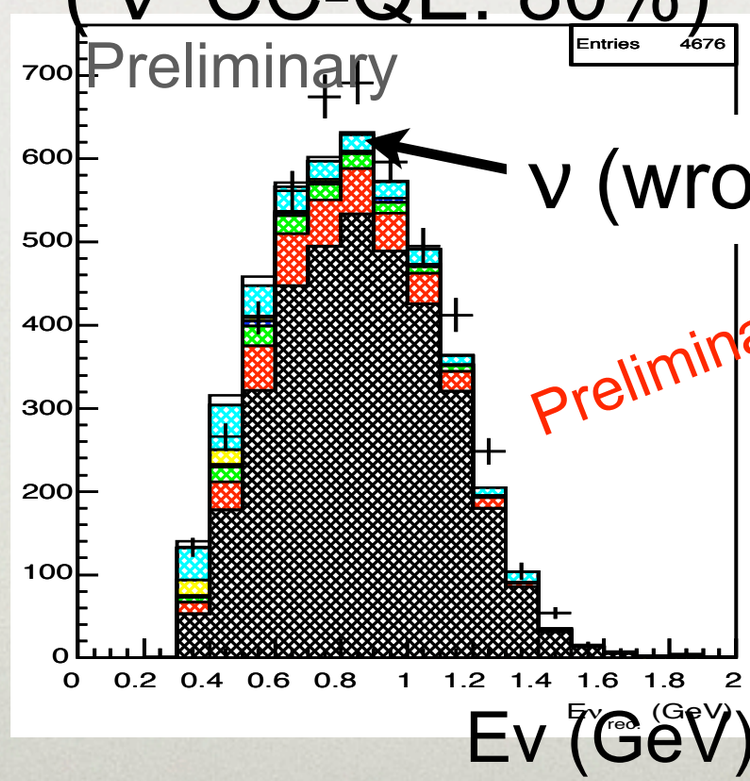
2-track (μ+p) event

~90% $\bar{\nu}$ purity

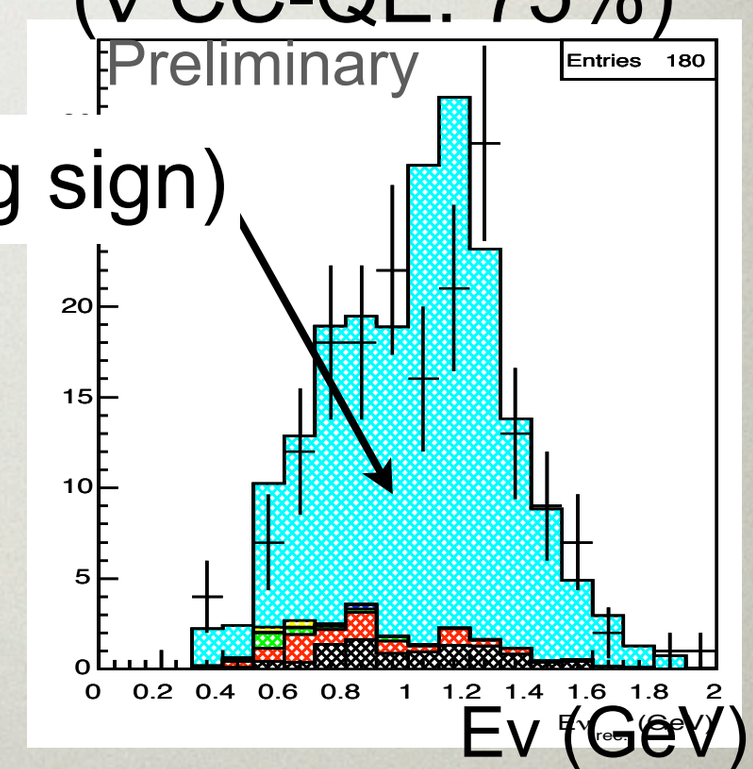
($\bar{\nu}$ CC-QE: 80%)

~90% ν purity

(ν CC-QE: 75%)



1-track w/o activity sample



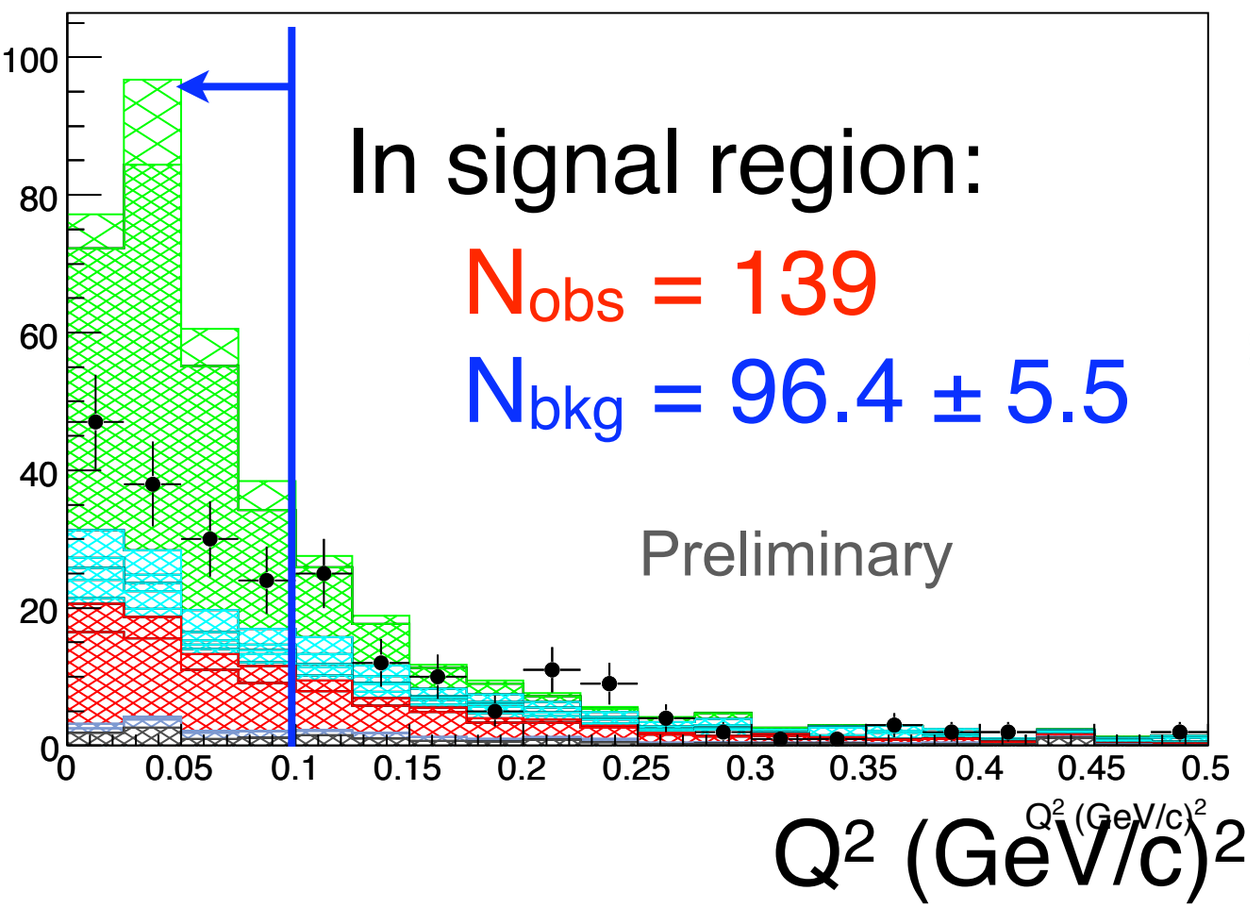
2-track QE-like sample

Number of events in coherent-π sample

After fit

CC coh-π sample ≡
MRD-stop, 2-trk, μ+π, w/o
vtx activity non-QE, fwd-π

Signal region ≡ $Q^2 < 0.1$ $(GeV/c)^2$



- : $\bar{\nu}+\nu$ CC coherent π
- : $\bar{\nu}$ CC resonant
- : $\bar{\nu}$ Other (DIS, EC/MRD, NC)
- : $\bar{\nu}$ CC QE
- : Wrong-Sign

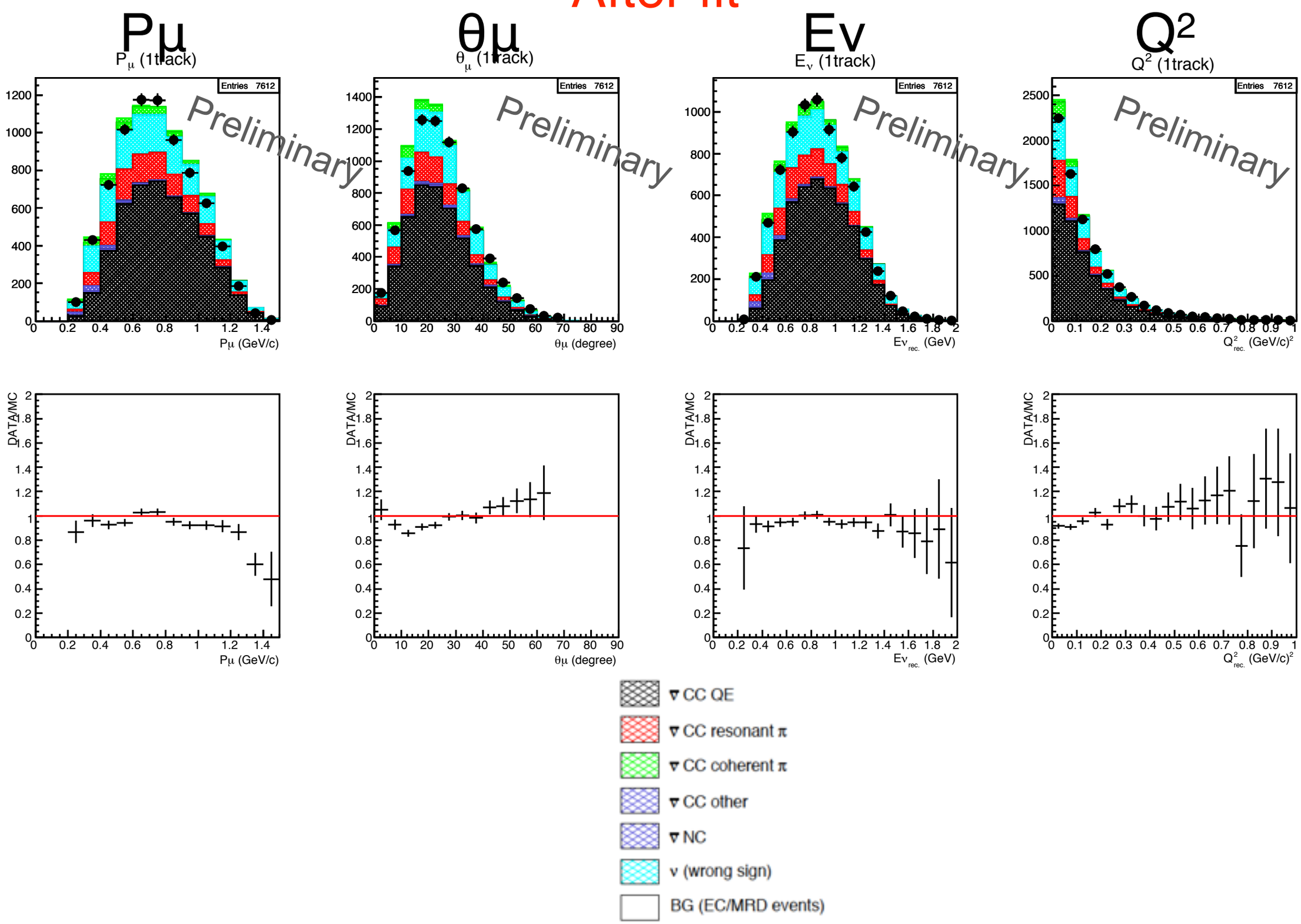
- # of events (MC prediction)

Signal
- $\bar{\nu}$ CC coh-π: 173.8 (44%)
- ν CC coh-π: 31.4 (8%)

Background
- Wrong-Sign + EC/MRD: 31.4 (8%)
- $\bar{\nu}$ NC: 1.7 (0.4%)
- $\bar{\nu}$ CC res-π: 85.2 (22%)
- $\bar{\nu}$ CC multiπ/DIS: 7.8 (2%)
- $\bar{\nu}$ CCQE: 16.0 (4%)

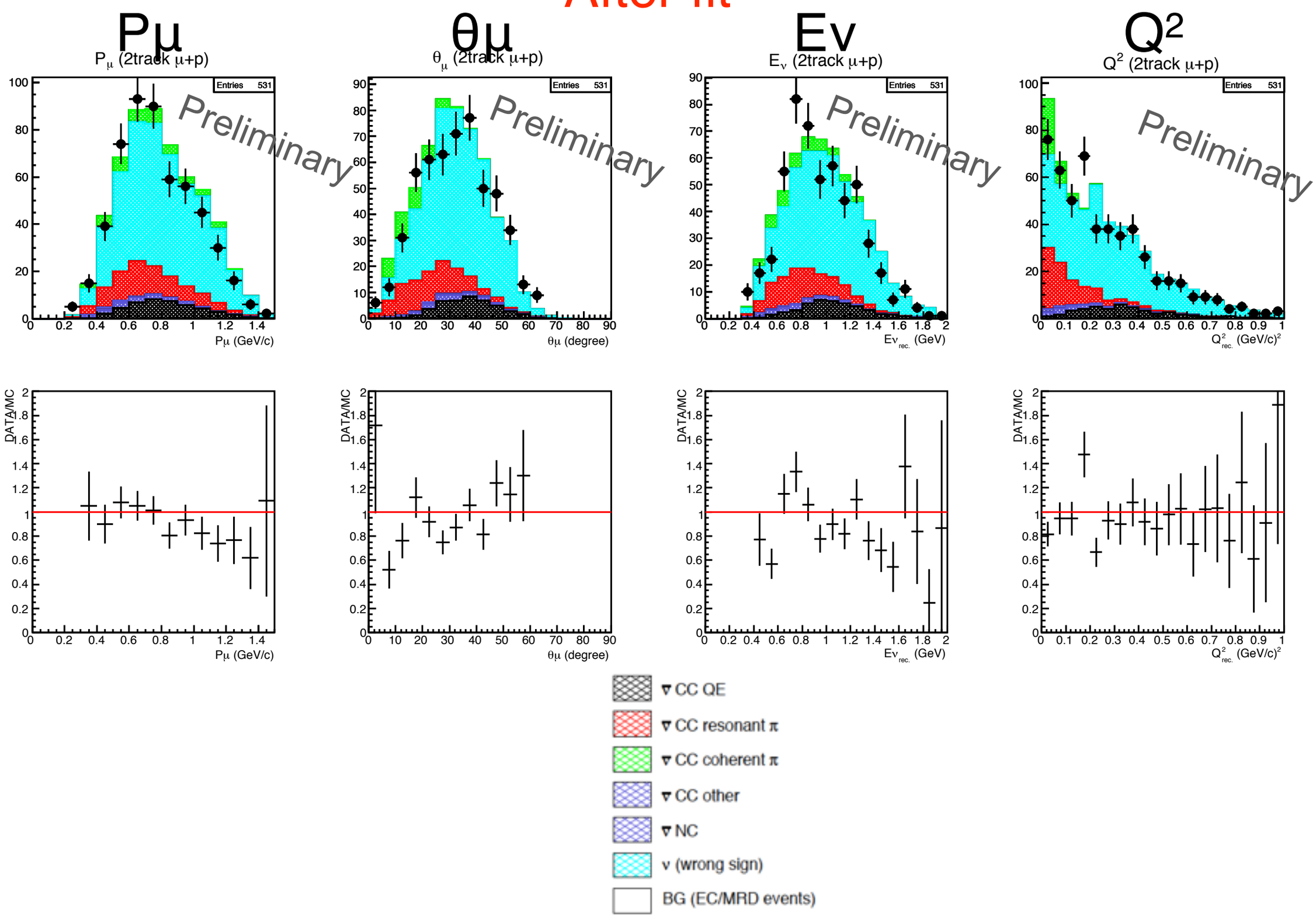
μ distribution: 1-trk sample

After fit

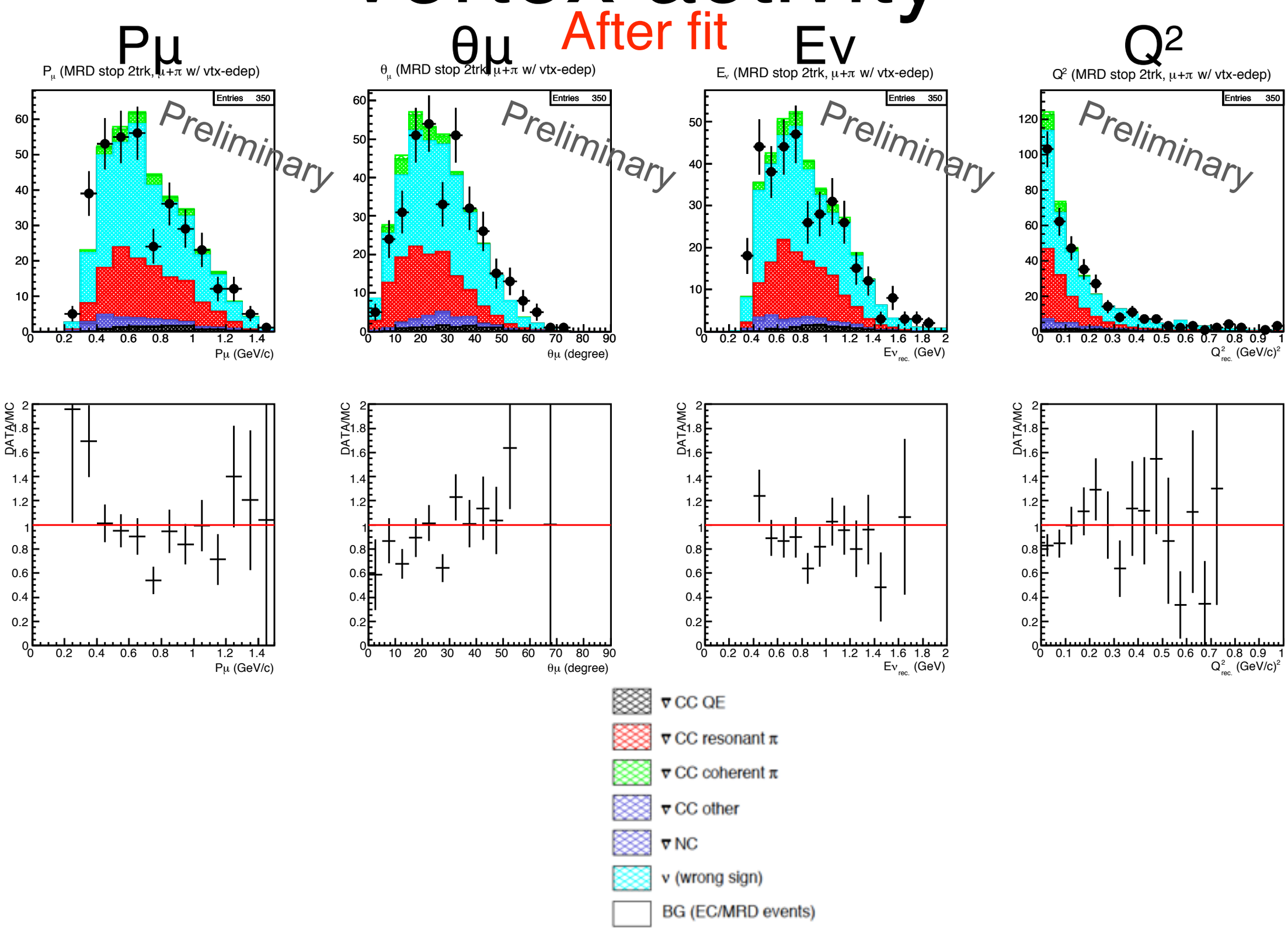


μ distribution: μ+p sample

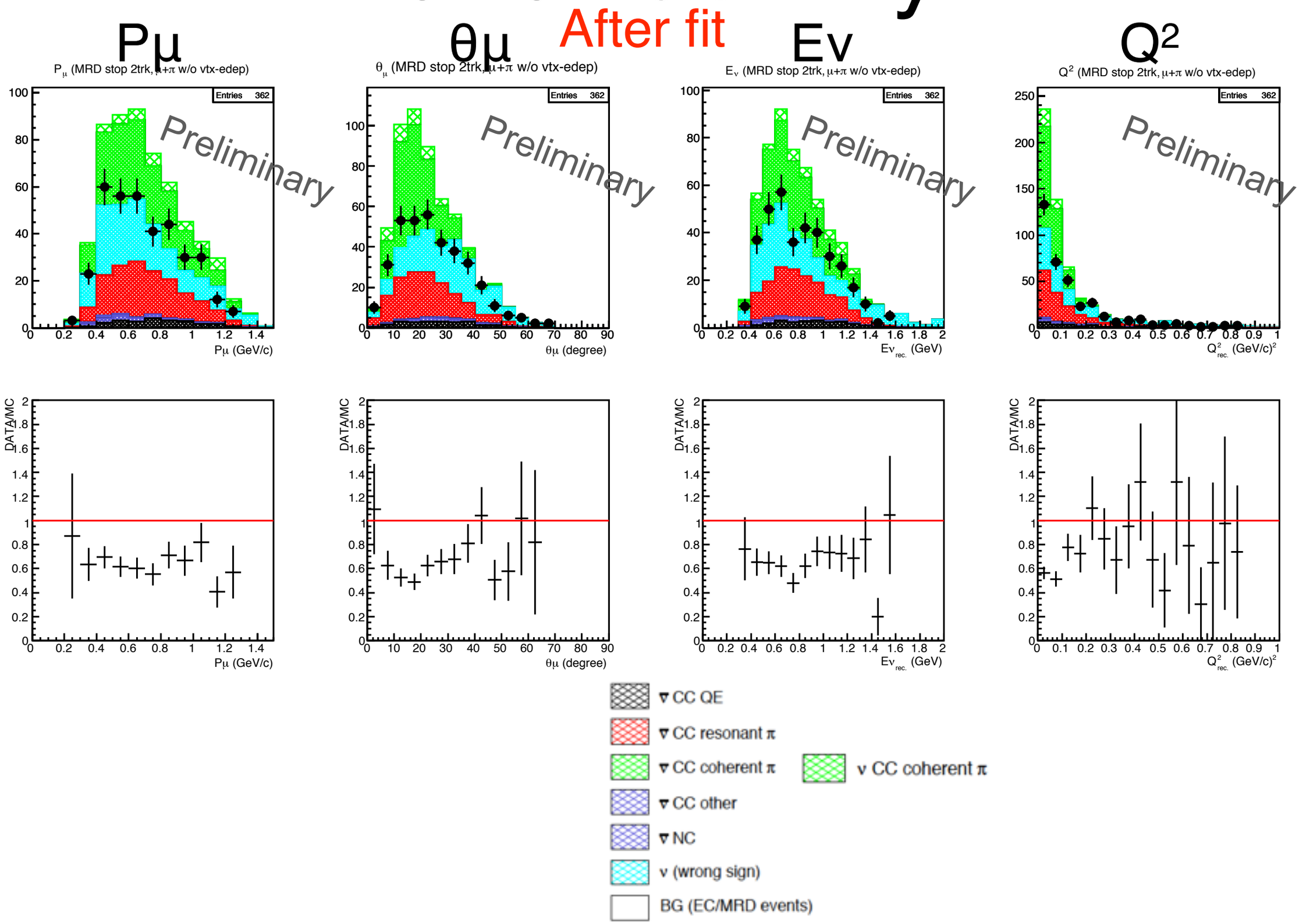
After fit



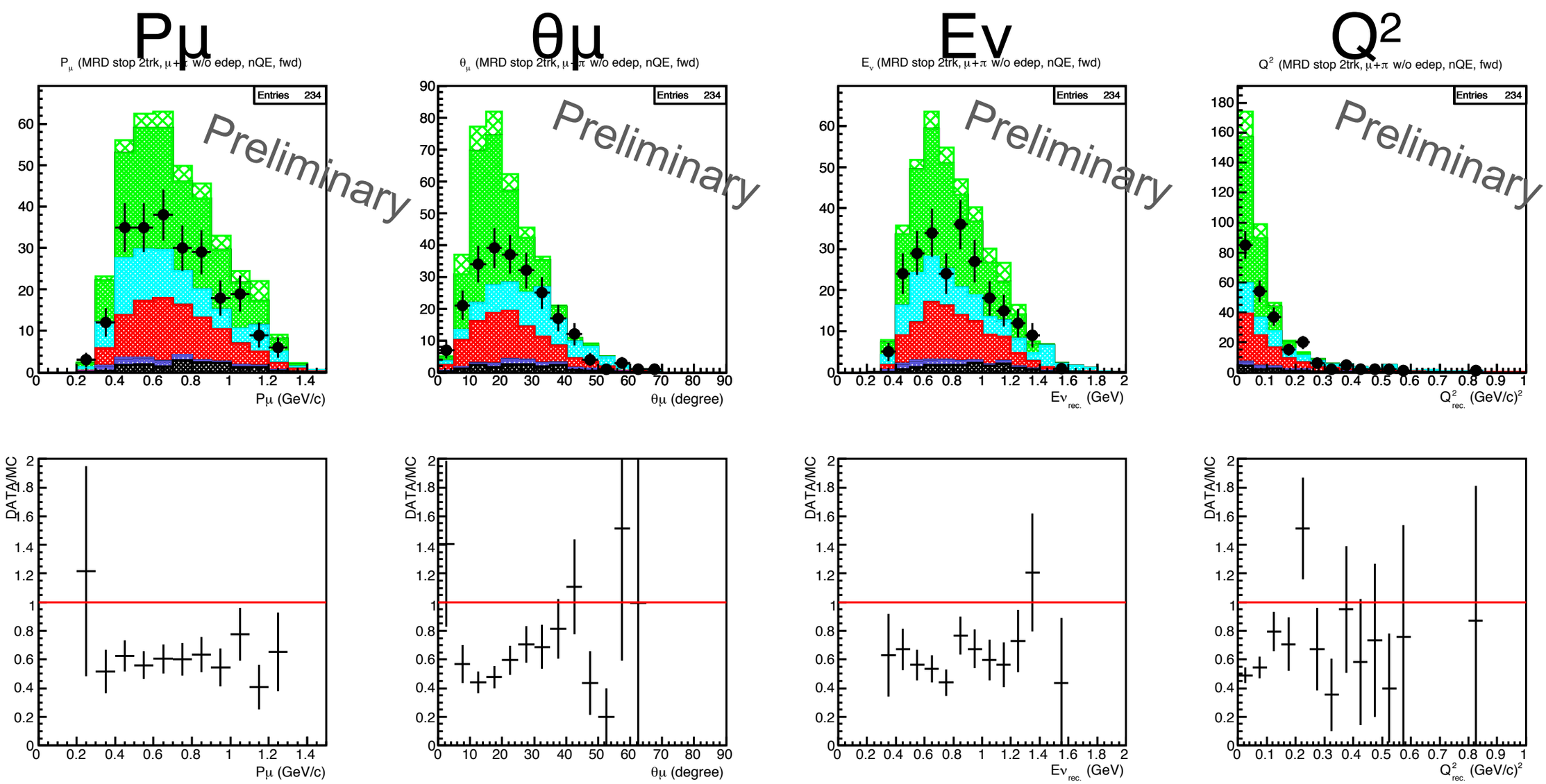
μ distribution: μ+π w/ vertex activity



μ distribution: μ+π w/o vertex activity



μ distribution: coh-π sample

After fit

coh-π sample ≡ MRD-stop, 2-trk, μ+π, w/o vtx activity non-QE, fwd-π