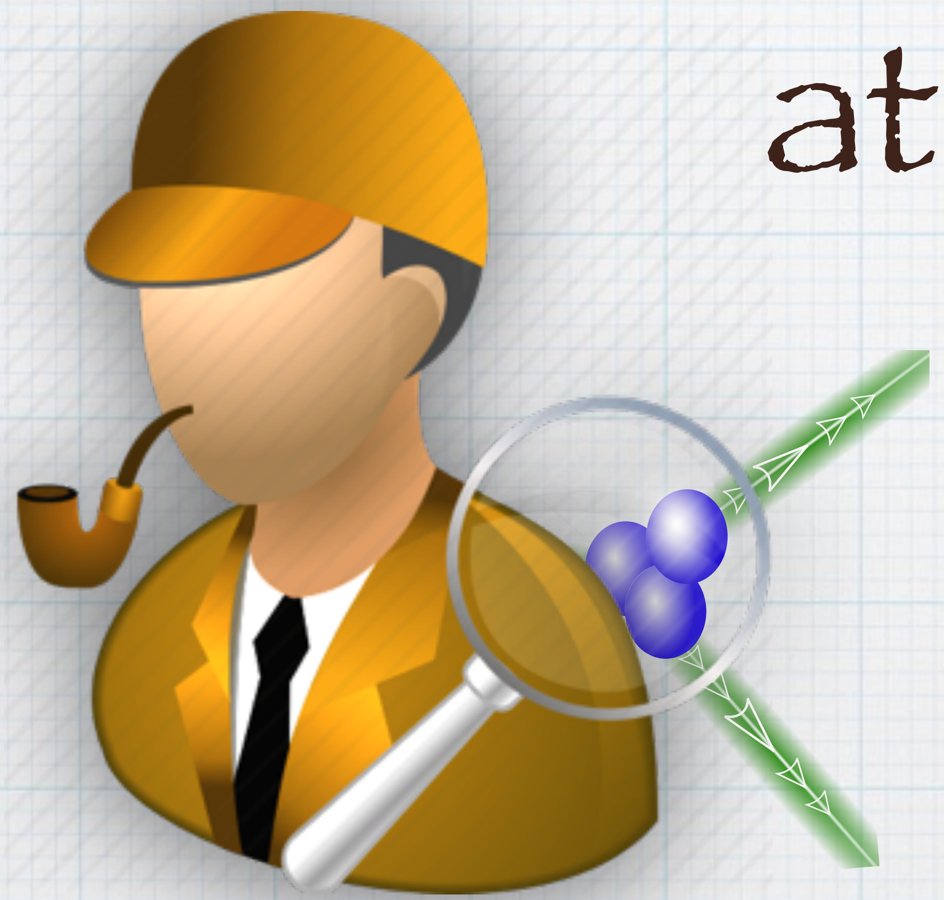
# A Search for ppp-SRC at EG2



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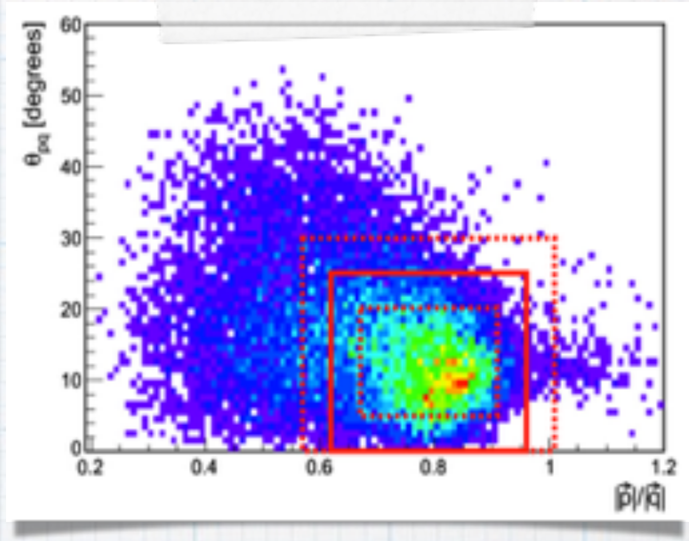
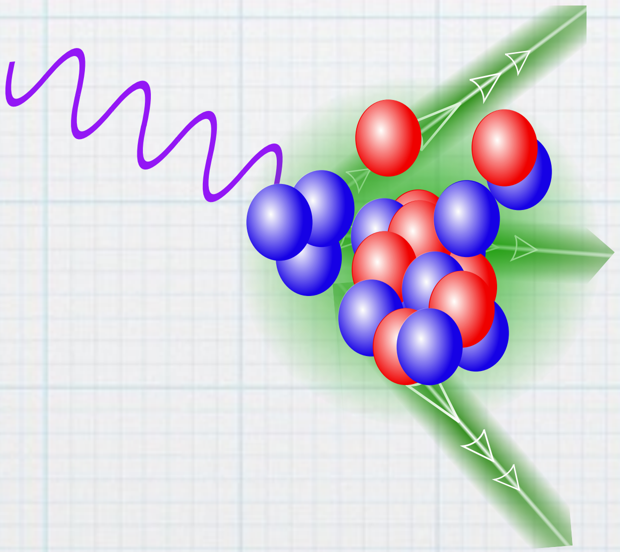
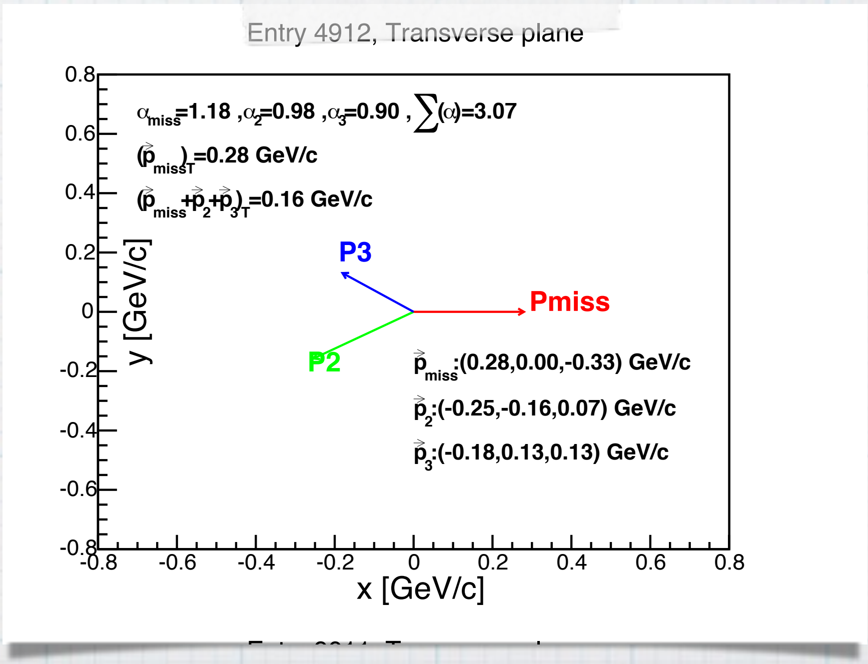
Int. Workshop on Exp. and Theo. topics in CLAS Data-Mining
Buffalo (NY), July-28, 2015

# Outline

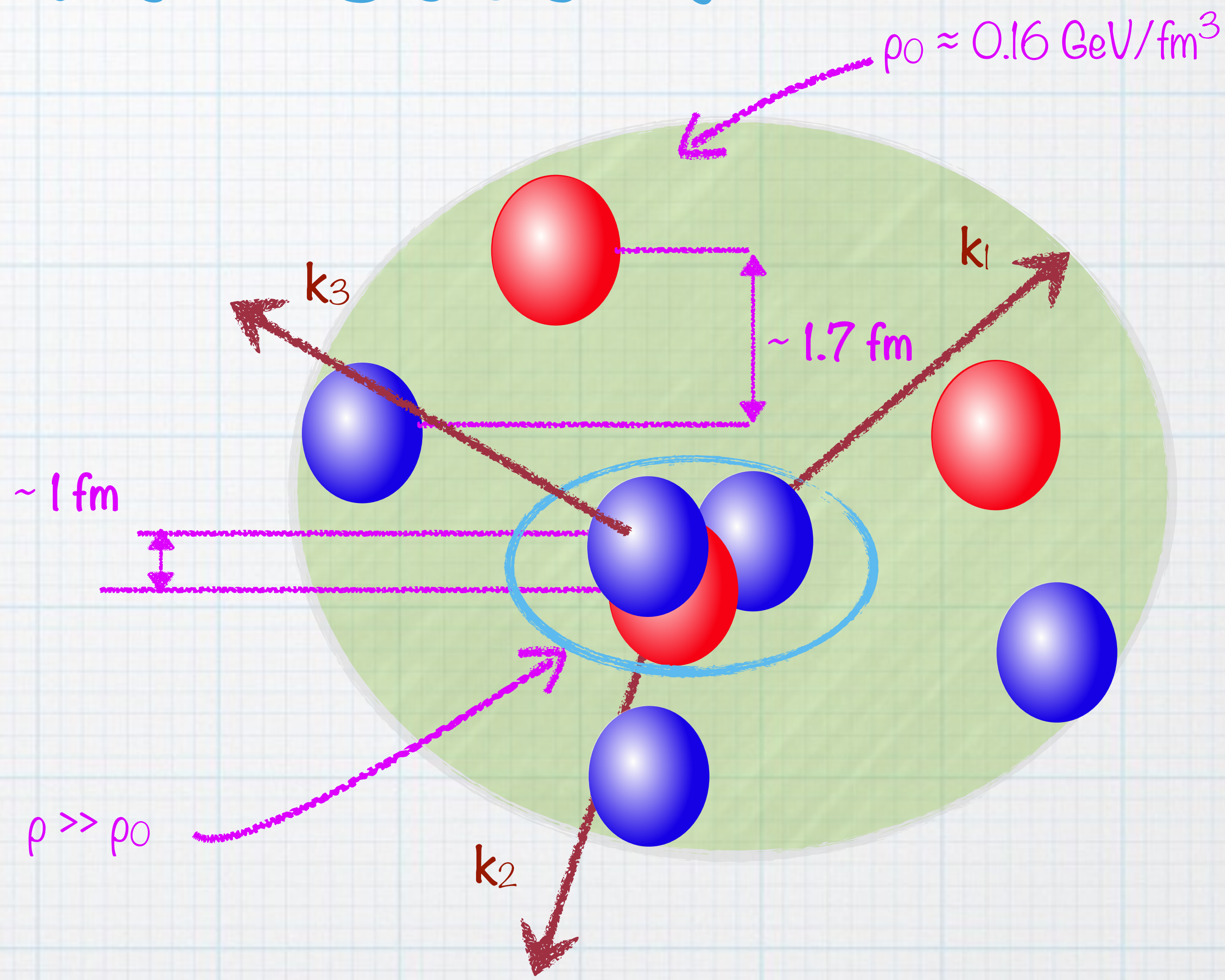



* What is 3N-SRC?
* Motivation, and estimating the expected number of ppp-SRC events.
* Search strategy
* Event selection
* Results
* Consequences
* Future plans





# What is 3N-SRC ?




* Large relative & small c.m. momentum (w.r.t Fermi)

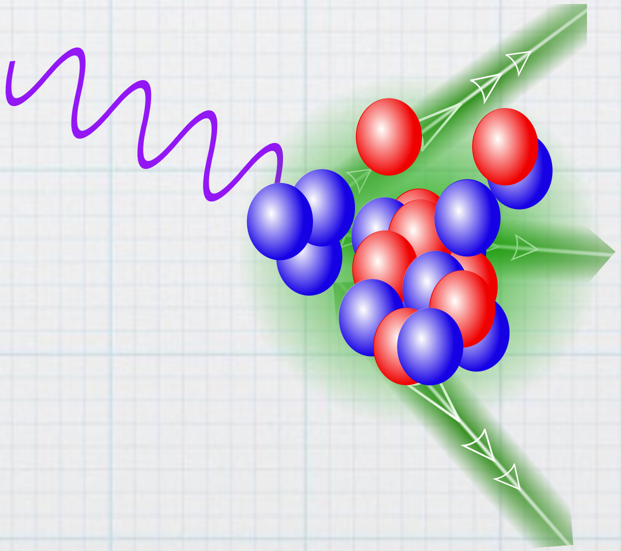
$$|\vec{k}_1 + \vec{k}_2 + \vec{k}_3| < k_F$$

$$|\vec{k}_1|, |\vec{k}_2|, |\vec{k}_3| > k_F$$

# Motivation

* We know Isospin and topological structure of 2N-SRC.

* Nothing is known experimentally on 3N-SRC



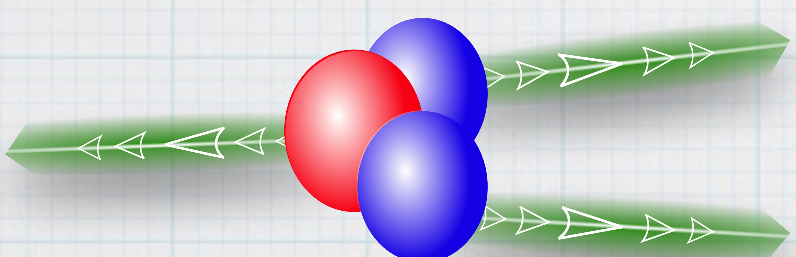
# 3N-SRC ?

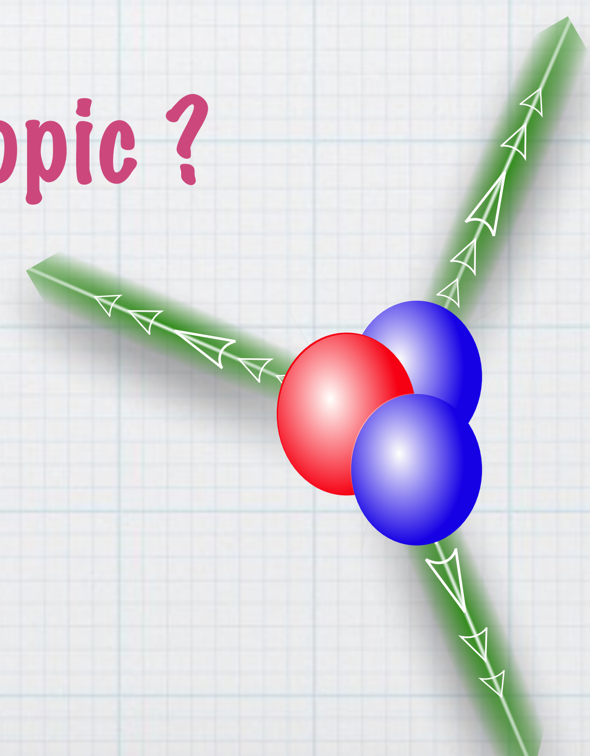
* Is there 3N-SRC? If so, how many?
* Isospin structure:

  fraction of nnn / ppp / nnp / npp ?

* Geometry

  Co-linear / Isotropic ?





# Estimate the expected fraction of 3N-SRC events ?

$$\frac{\sigma(3N\text{-}SRC)}{\sigma(e,e'p \text{ with large } p_{miss})} \sim 0.15\text{-}0.2$$

$$\frac{\sigma(np\text{-}SRC)}{\sigma(e,e'p \text{ with large } p_{miss})} \sim 96 \pm 22\%$$

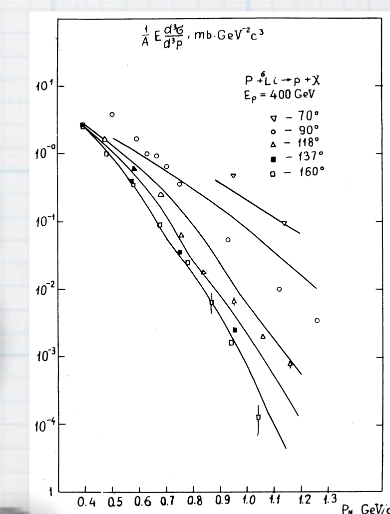
$$\frac{\sigma(np\text{-}SRC)}{\sigma(p,p'p \text{ with large } p_{miss})} \sim 92 \pm 18\%$$

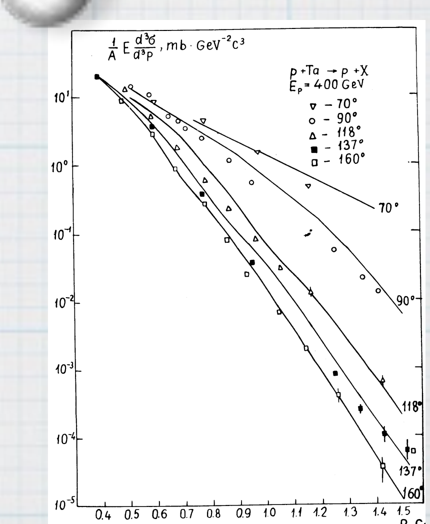
$$\frac{\sigma(pp\text{-}SRC)}{\sigma(e,e'p \text{ with large } p_{miss})} \sim 9.5 \pm 2\%$$

☞ $$\frac{\sigma(2N\text{-}SRC)}{\sigma(e,e'p \text{ with large } p_{miss})} > 80\%$$

☞ $$\frac{\sigma(3N\text{-}SRC)}{\sigma(e,e'p \text{ with large } p_{miss})} < 20\%$$

[M. Strikman priv. com. based on Phys.Rept. 76 (1981) 215-347]

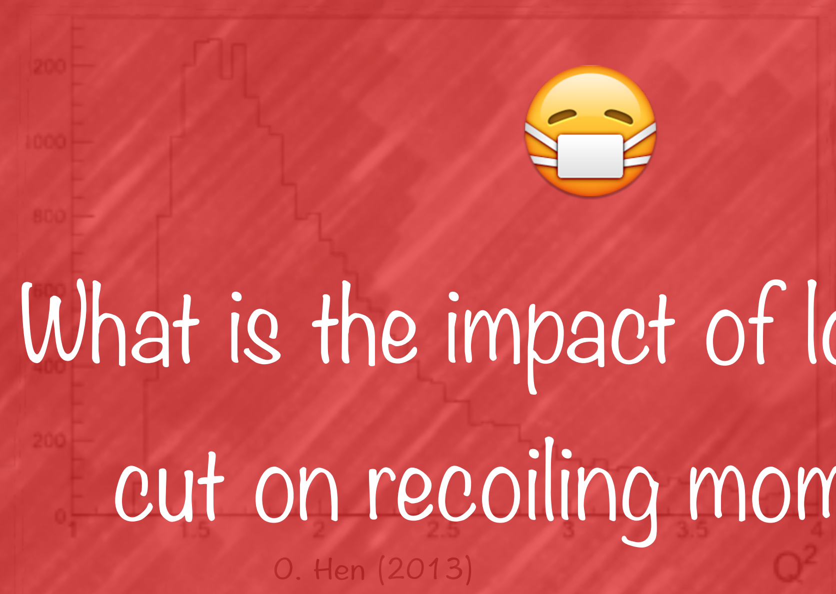


# Search Strategy

* Consider $^{12}C(e,e'p)X$ events with $x_B > 1.2$ as was done for pp-SRC search, and use kinematics and cuts which maximize SRC effect to
  - Identify ppp-SRC candidate events, and characterize them.
  - Constrain the relative probability of ppp-SRC to 3N-SRC.

# (e,e'p) SRC events selection




😷

Q: What is the impact of loosening the cut on recoiling momenta?

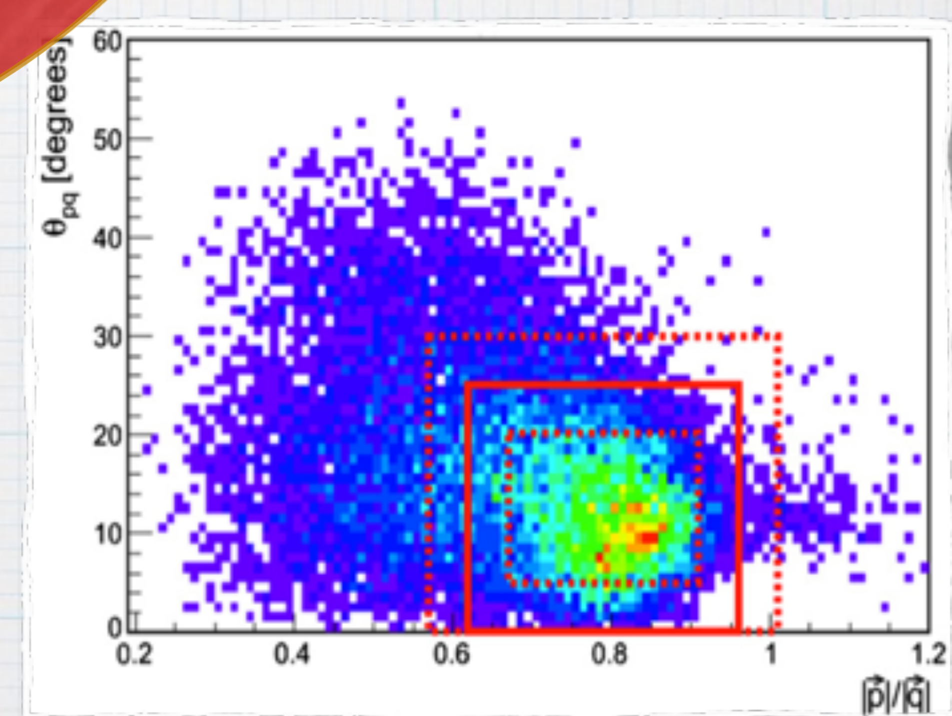
**Kinematics**

- $x_B > 1.2$
- $1 > |p_{miss}| > 0.3$ GeV/c

[ $Q^2 > 1.5\ (GeV/c)^2$ ]

**Leading proton**

- $\theta_{pq} < 25^0$
- $0.62 < |p|/|q| < 0.96$




**I loosened the cuts on:**

- $M_{miss} < 1.1\ GeV/c^2$
- $|p_2|,|p_3| > 0.35$ GeV/c

# LC fraction for $^{12}C(e,e'p/pp/ppp)$ events in SRC kinematics

**SRC Kinematics:**

**$1.2 < x_B$**

**$0.3 < |p_{miss}| < 1$ GeV/c**

**$\theta(\vec{p},\vec{q}) < 25^0$**

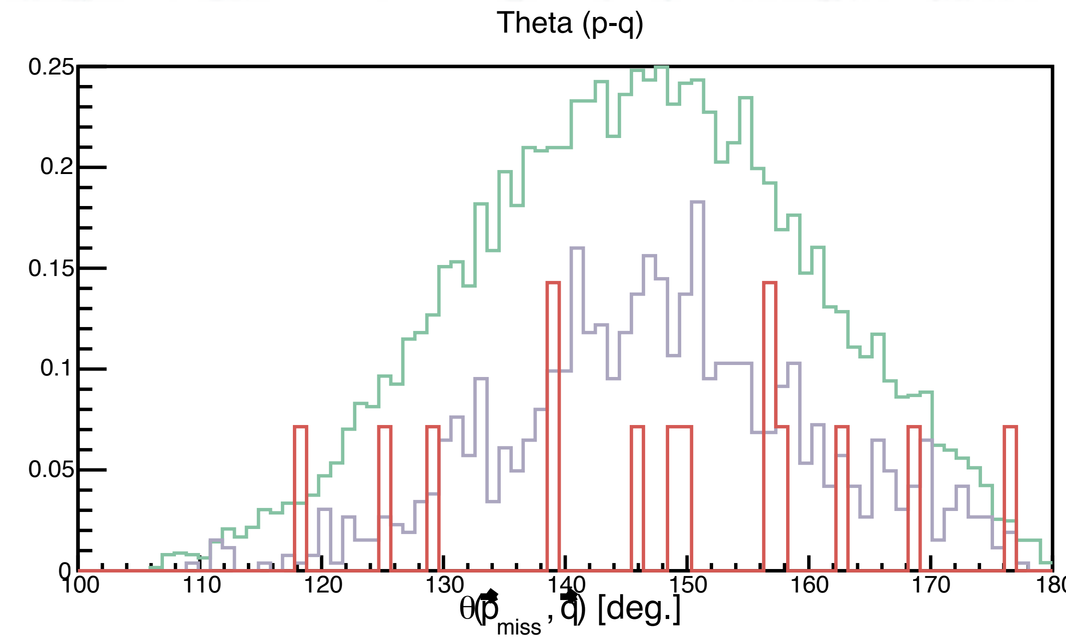
**$0.62 < |p_1|/|q| < 0.96$**

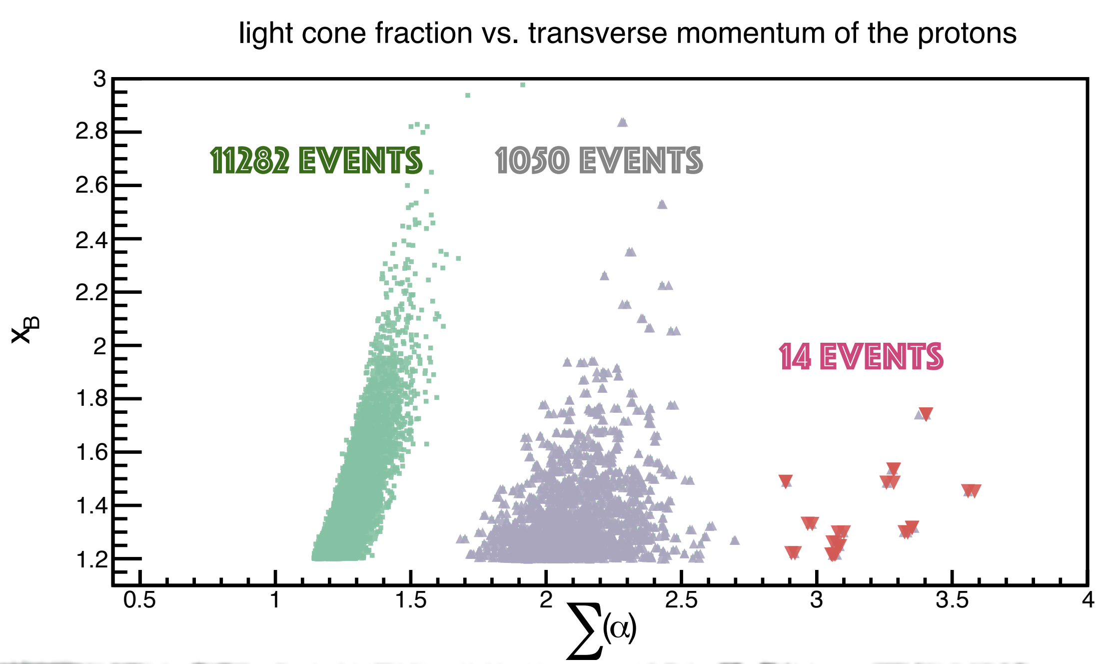
$$\alpha = A\frac{E_p - p_z}{m_A}$$

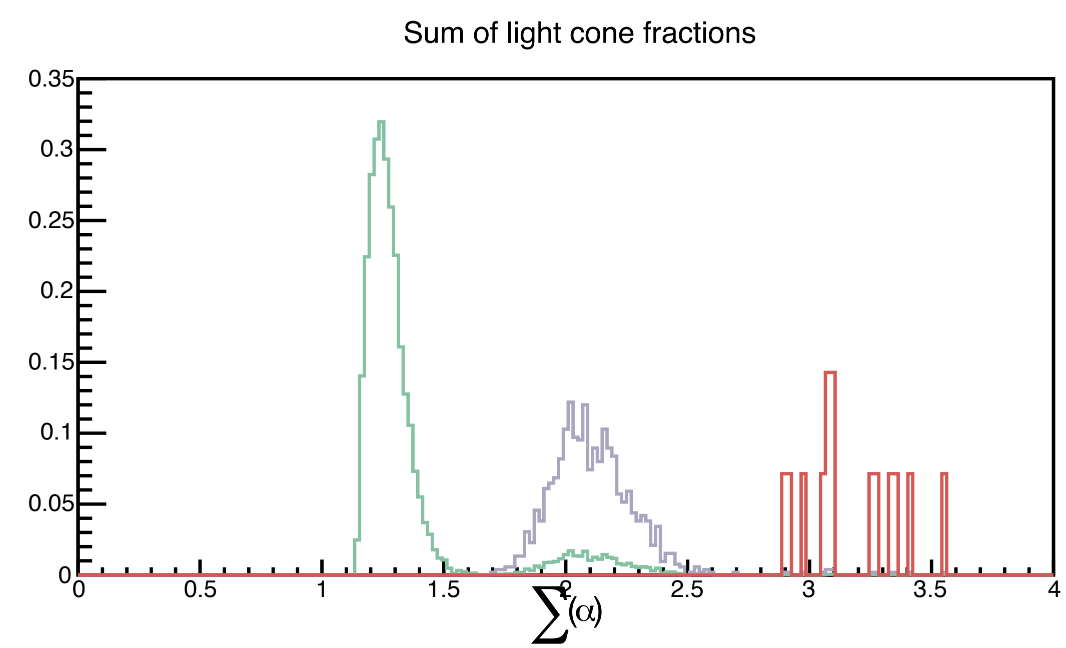
$^{12}C(e,e'p)$, 11282 events

$^{12}C(e,e'pp)$, 1050 events

$^{12}C(e,e'ppp)$, 14 events




$$\sum \alpha = \frac{A}{m_A}[(E_p^1 - p_z^1) - (\omega - q_z) + (E_p^2 - p_z^2) + (E_p^3 - p_z^3)]$$

# ppp-SRC / (e,e'p) with large $p_{miss}$

- First upper limit

  ppp-SRC / (e,e'p with large $p_{miss}$) ratio

  14/11282 ~ 0.12%

- Compare with predicted

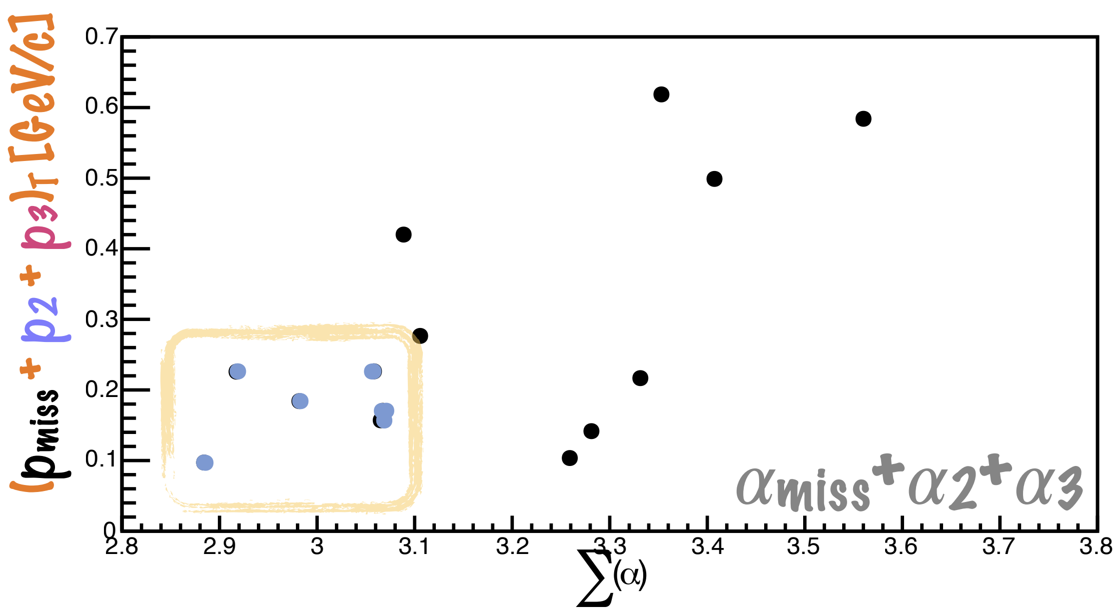
  3N-SRC/(e,e'p with large $p_{miss}$) ≲ 20%

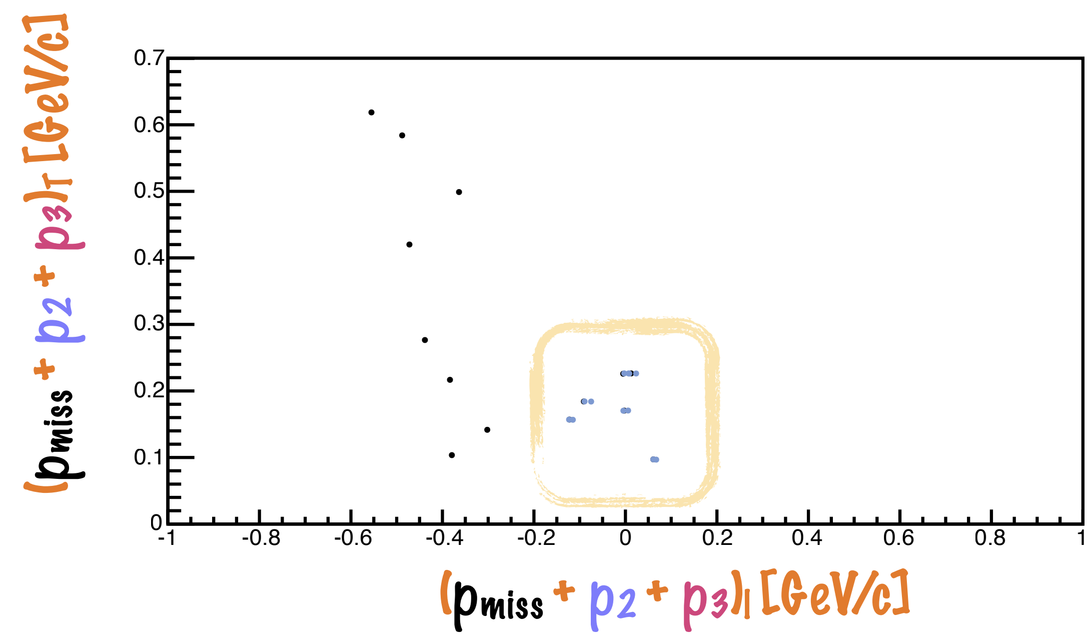
☞ **ppp-SRC / 3N-SRC ~ 6%**

Assuming the 3N estimation is right, this gives us a clear indication of Isospin 1/2 dominance in 3N-SRC: #nnp, #npp >> #ppp, #nnn

# We can improve the upper limit by imposing known properties of SRC.

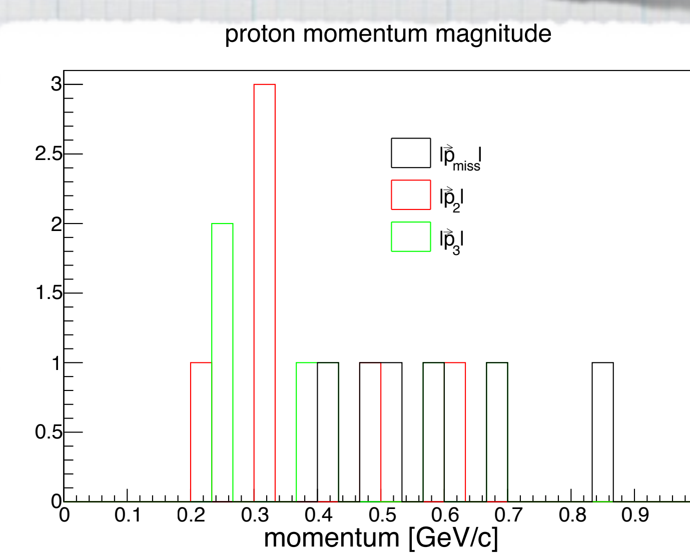
* Low P(c.m.) ☞ we request $|p_{c.m.}|<0.25$ GeV/c.



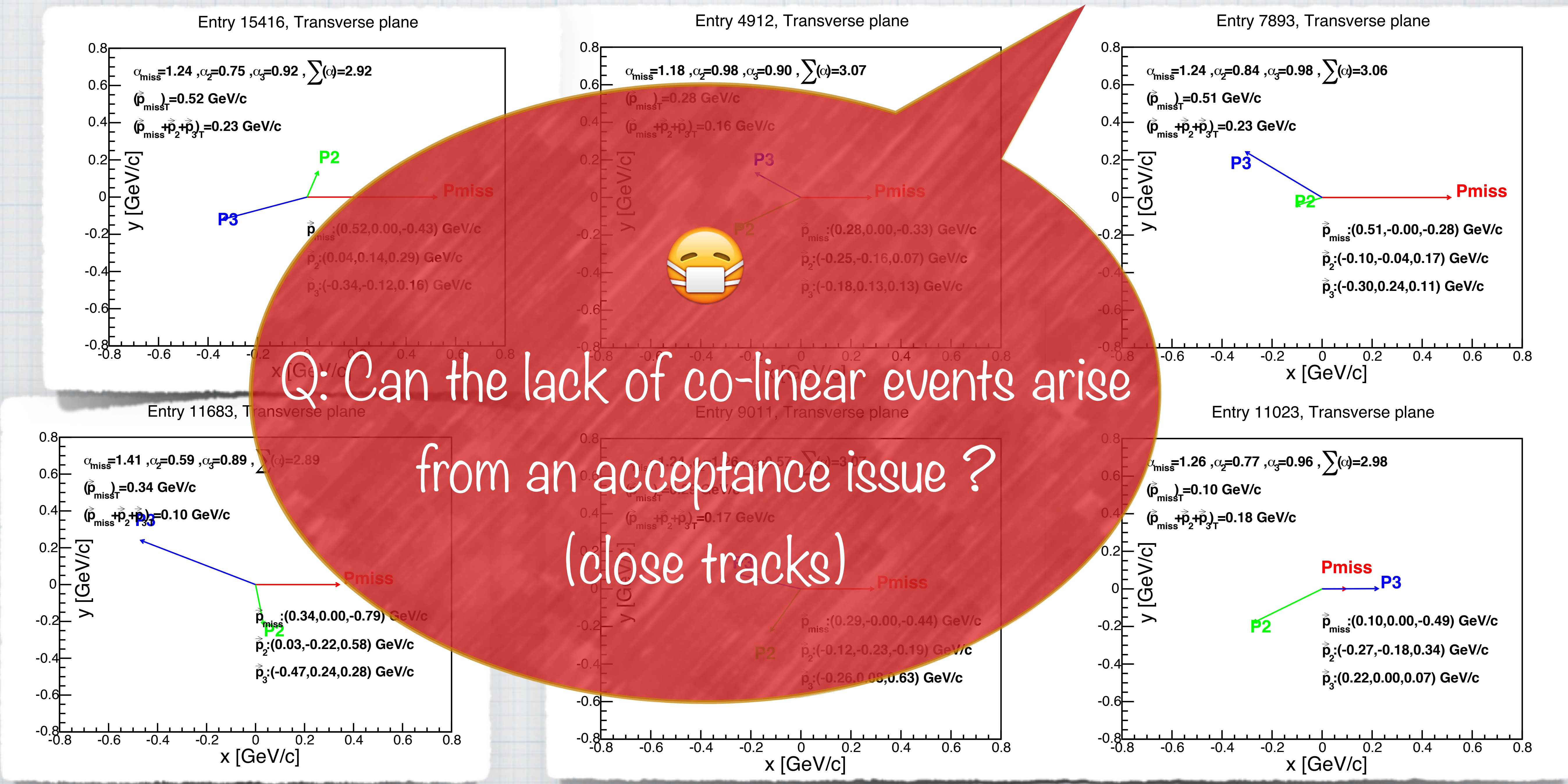

| event | $\vec{p}_{miss}$ | $\vec{p}_2$ | $\vec{p}_3$ | $(\vec{p}_{miss})_T$ | $(\vec{p}_{miss})_l$ | $(\vec{p}_{c.m.})_T$ | $(\vec{p}_{c.m})_l$ |
|---|---|---|---|---|---|---|---|
| - | $GeV/c$ | $GeV/c$ | $GeV/c$ | $GeV/c$ | $GeV/c$ | $GeV/c$ | $GeV/c$ |
| 4912 | (0.28,0.00,-0.33) | (-0.25,-0.16,0.07) | (-0.18,0.13,0.13) | 0.28 | -0.33 | 0.16 | -0.12 |
| 7893 | (0.51,-0.00,-0.28) | (-0.10,-0.04,0.17) | (-0.30,0.24,0.11) | 0.51 | -0.28 | 0.23 | 0.01 |
| 9011 | (0.29,-0.00,-0.44) | (-0.12,-0.23,-0.19) | (-0.26,0.08,0.63) | 0.29 | -0.44 | 0.17 | 0.01 |
| 11023 | (0.10,0.00,-0.49) | (-0.27,-0.18,0.34) | (0.22,0.00,0.07) | 0.10 | -0.49 | 0.18 | -0.07 |
| 11683 | (0.34,0.00,-0.79) | (0.03,-0.22,0.58) | (-0.47,0.24,0.28) | 0.34 | -0.79 | 0.10 | 0.07 |
| 15416 | (0.52,0.00,-0.43) | (0.04,0.14,0.29) | (-0.34,-0.12,0.16) | 0.52 | -0.43 | 0.23 | 0.02 |

| event | $\alpha_{miss}$ | $\alpha_2$ | $\alpha_3$ | $\sum(\alpha)$ |
|---|---|---|---|---|
| 4912 | 1.18 | 0.98 | 0.90 | 3.07 |
| 7893 | 1.24 | 0.84 | 0.98 | 3.06 |
| 9011 | 1.24 | 1.26 | 0.57 | 3.07 |
| 11023 | 1.26 | 0.77 | 0.96 | 2.98 |
| 11683 | 1.41 | 0.59 | 0.89 | 2.89 |
| 15416 | 1.24 | 0.75 | 0.92 | 2.92 |



# ppp-SRC candidates characteristics

Trios are generally divided isotropically

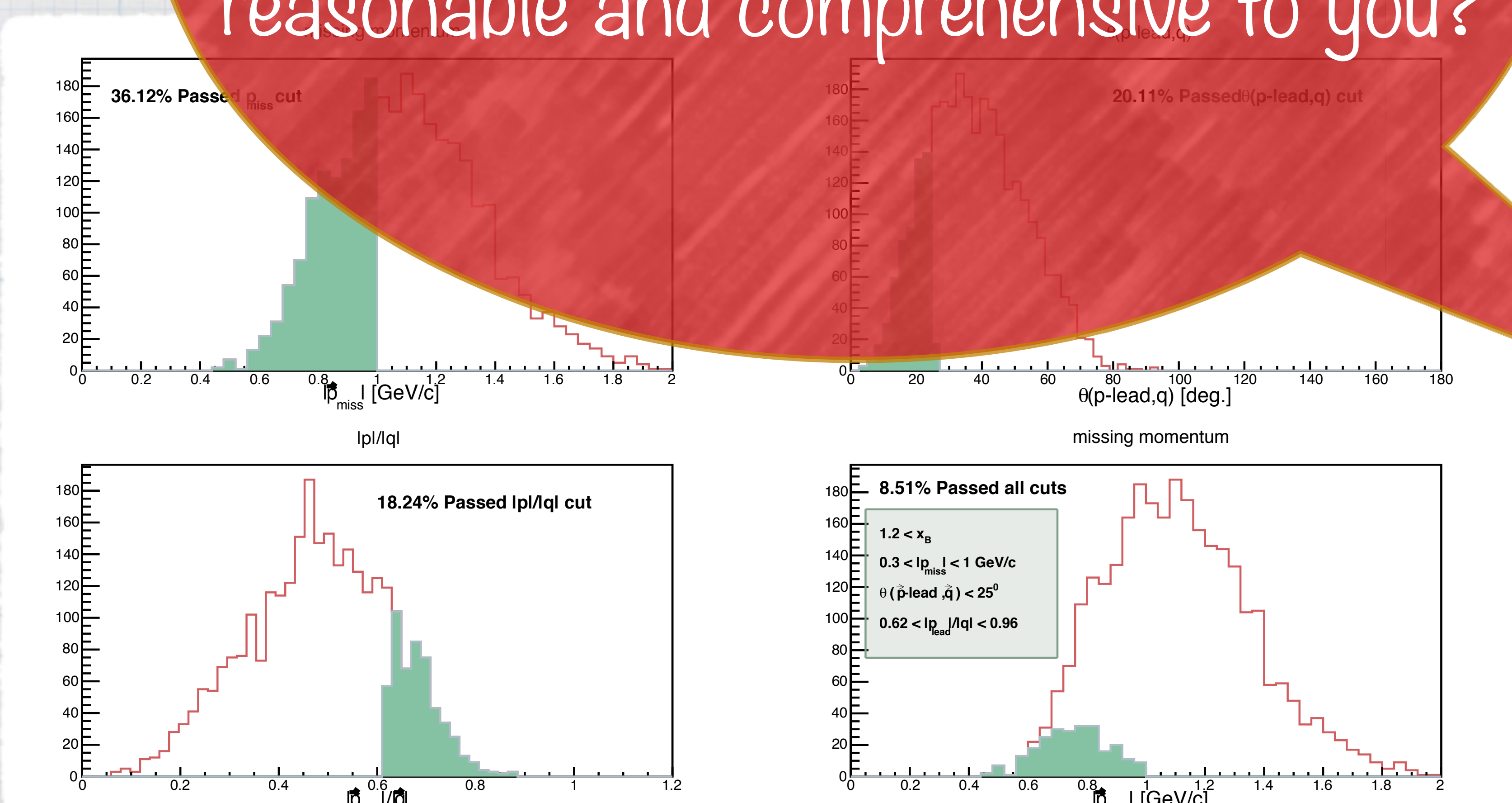


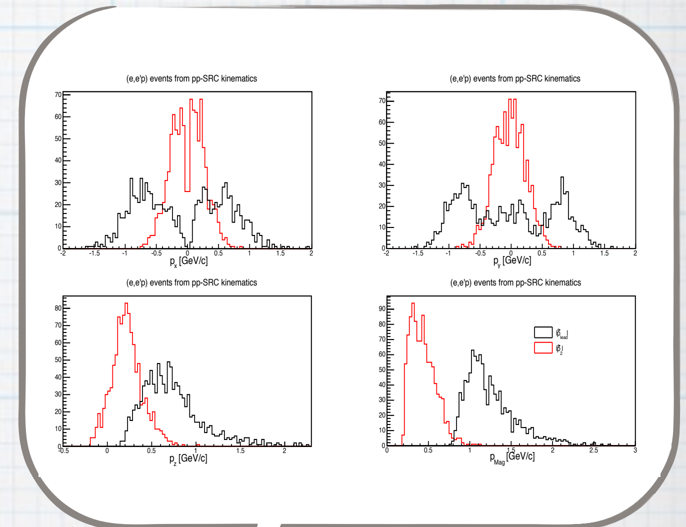
# We can improve the upper limit by enforcing known properties of the ppp-SRC:

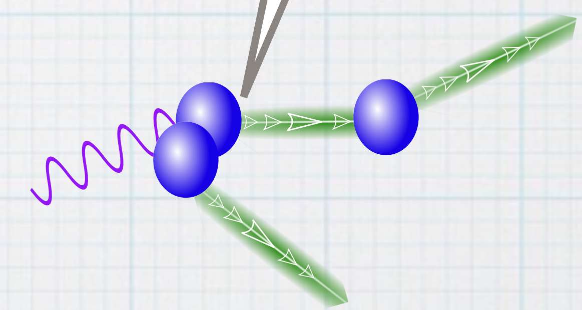
* based on our simple simulation

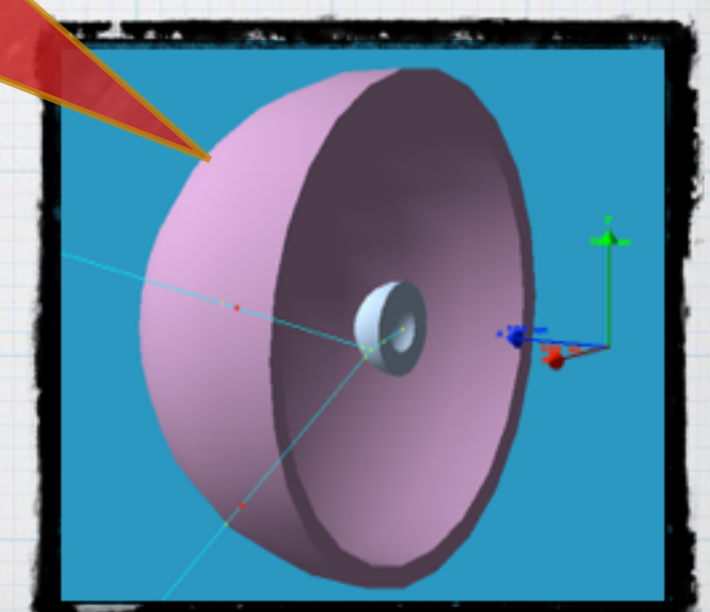
$|p_{miss}| < 0.6$ GeV/c.

Q: Does this simplified simulation seem reasonable and comprehensive to you?

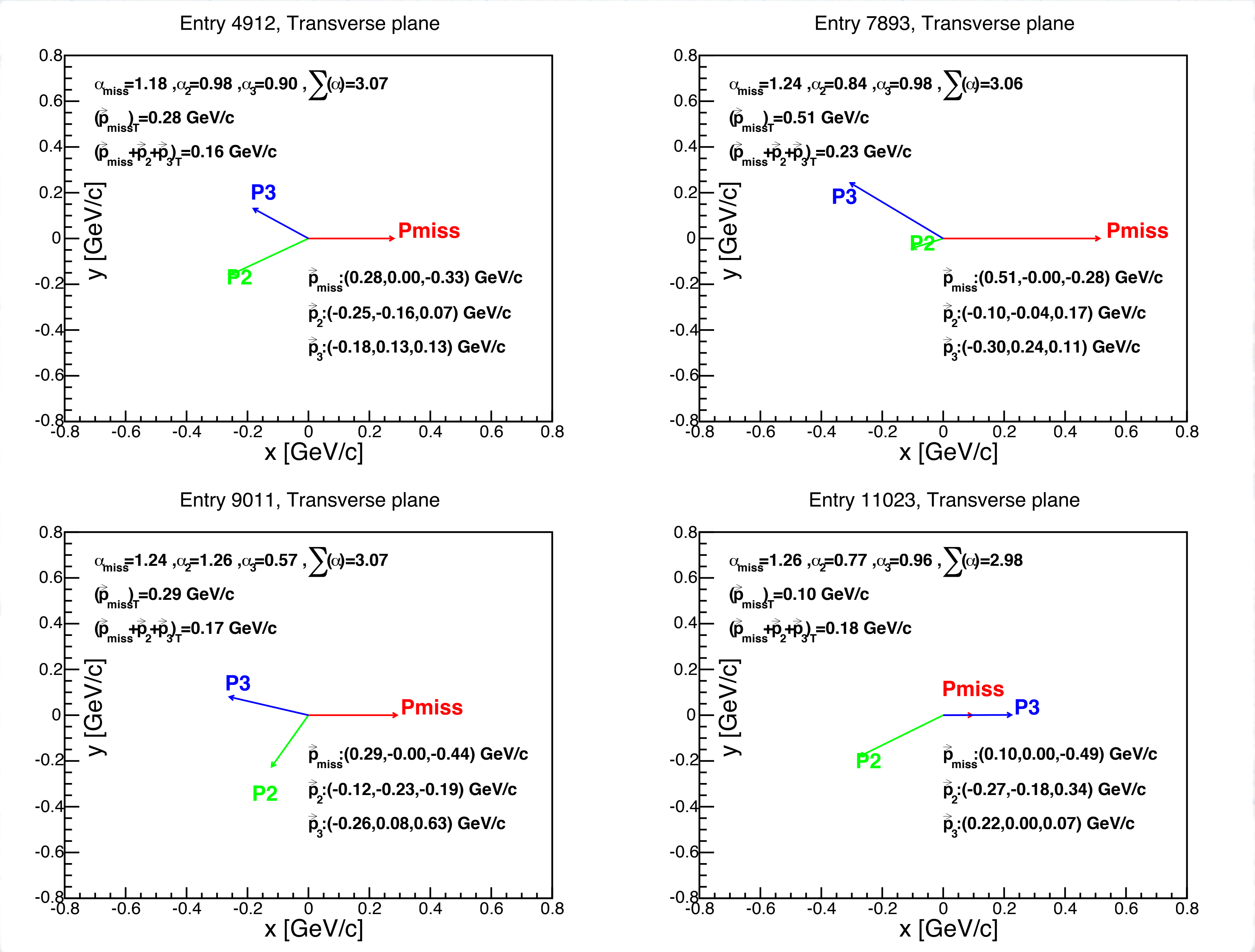


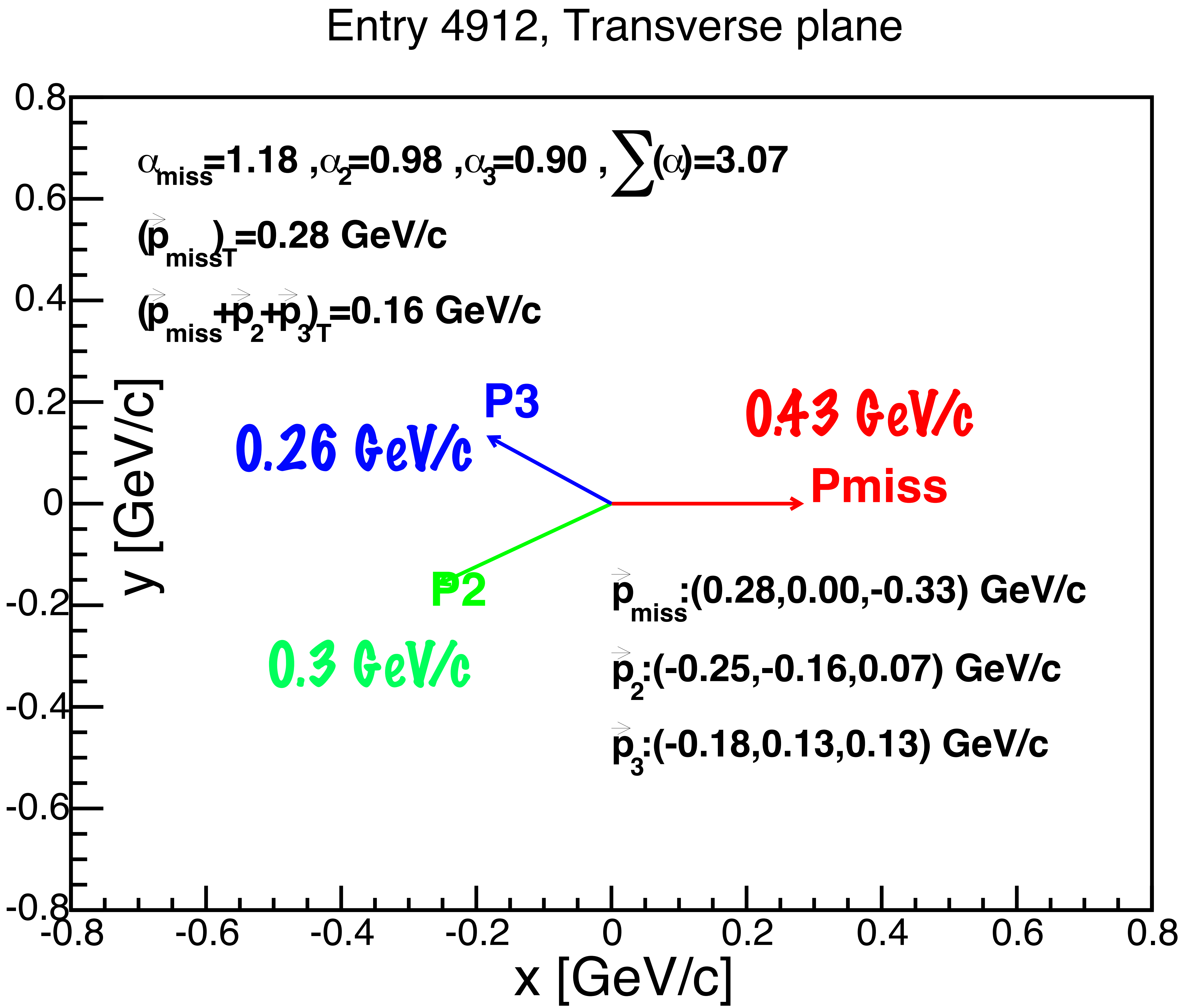





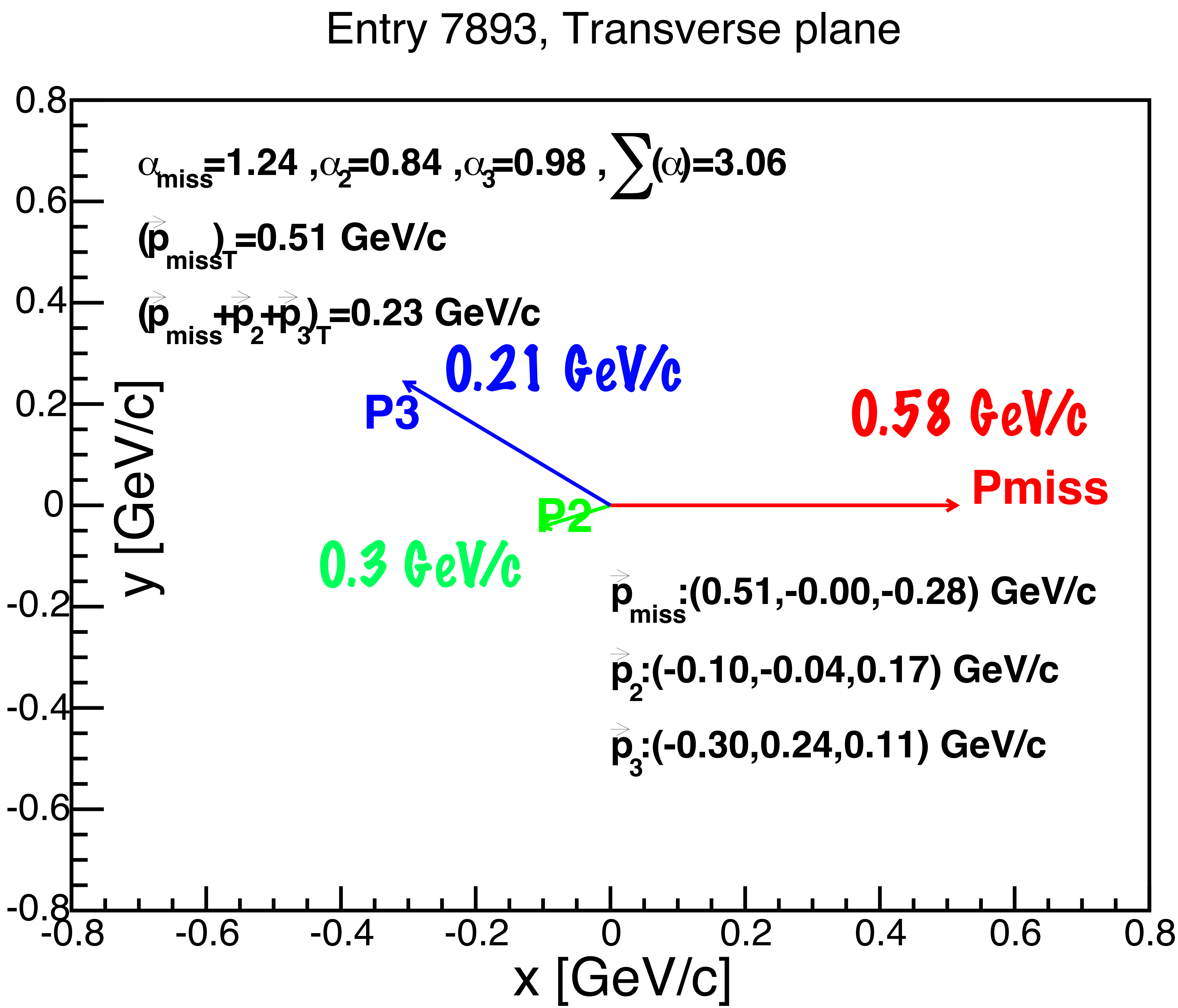


# 4 ppp-SRC candidates are left after |$p_{miss}$| < 0.6 GeV/c cut

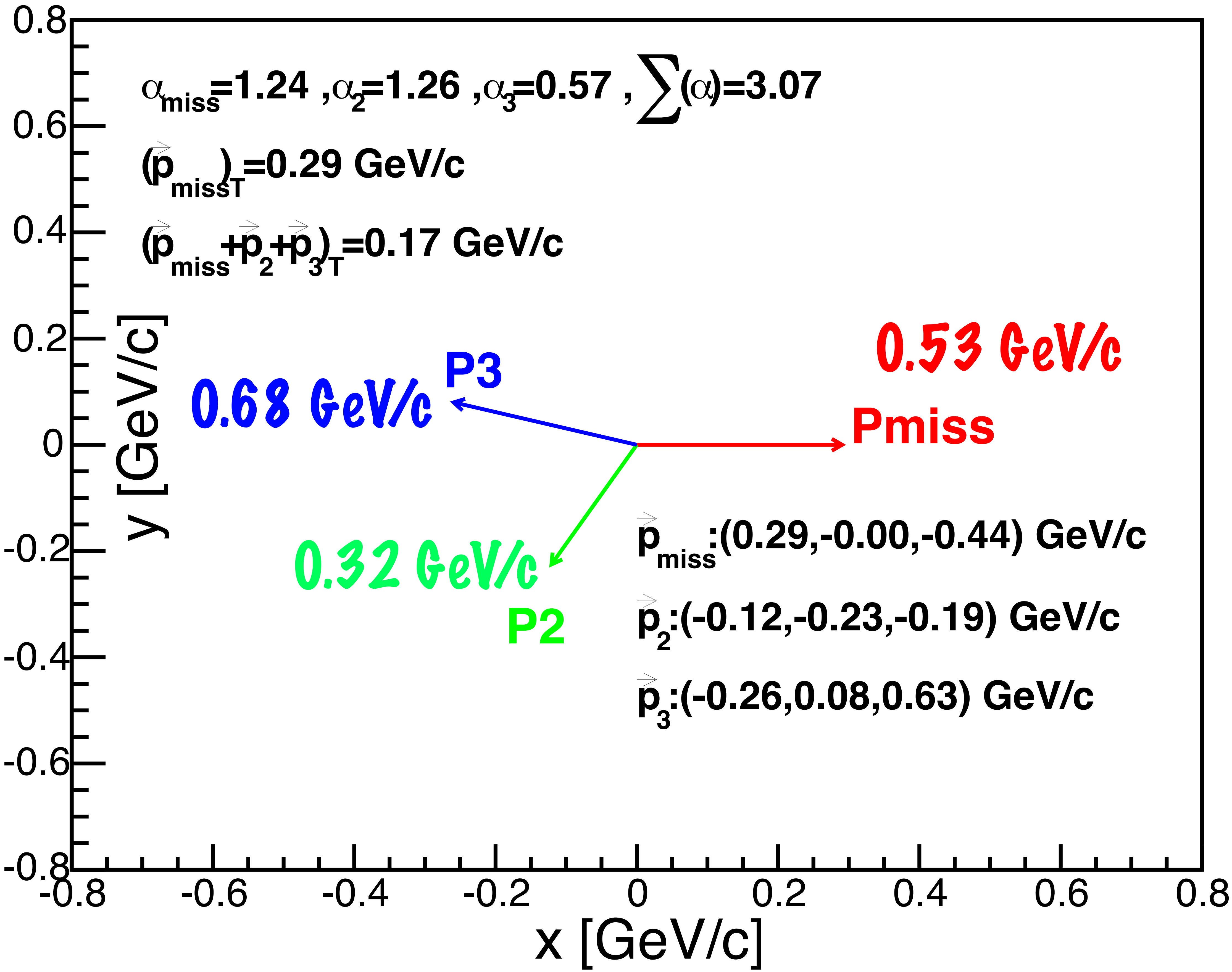


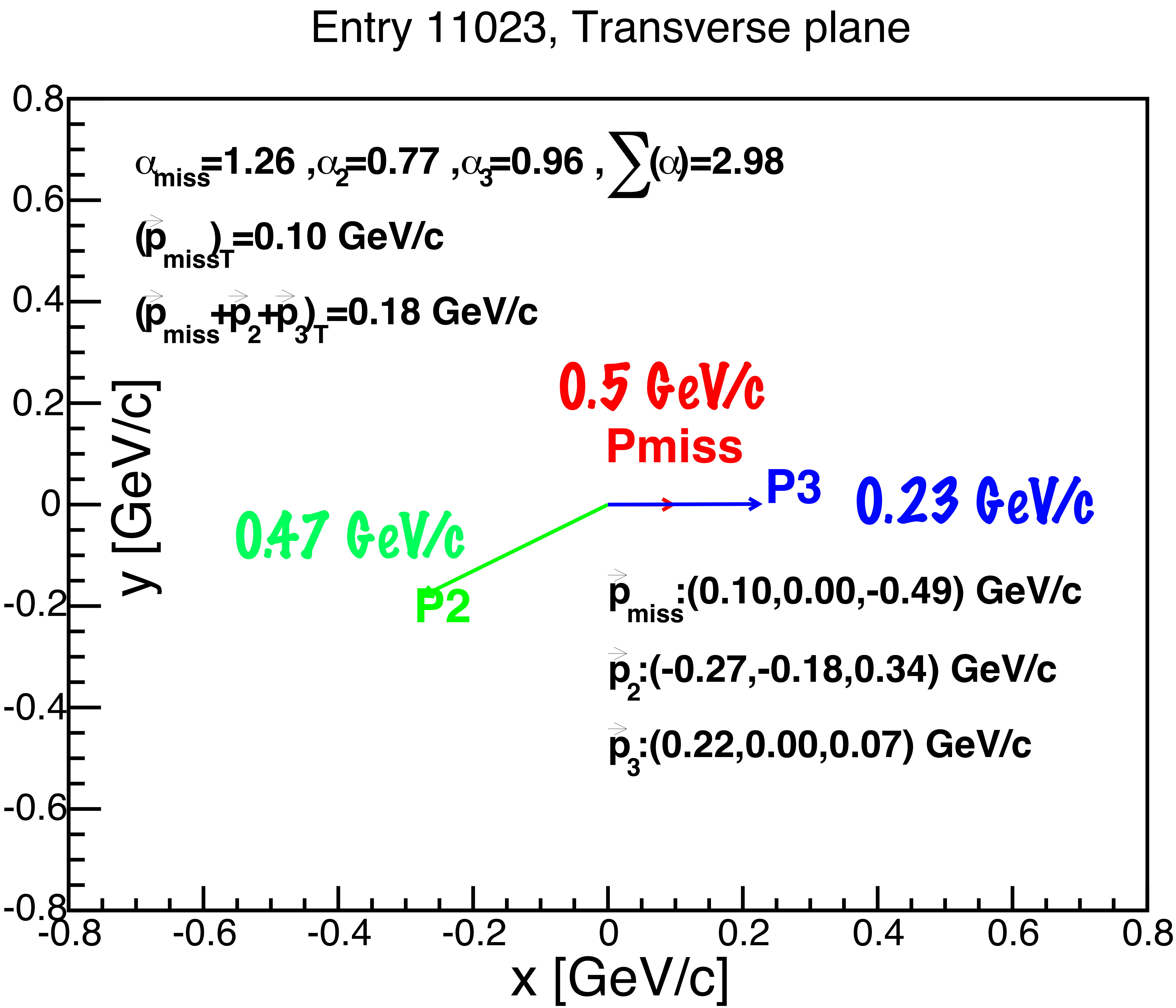


Entry 4912, Transverse plane
$\alpha_{miss}$=1.18 ,$\alpha_2$=0.98 ,$\alpha_3$=0.90 , $\sum(\alpha)$=3.07
$(\vec{p}_{miss})_T$=0.28 GeV/c
$(\vec{p}_{miss}+\vec{p}_2+\vec{p}_3)_T$=0.16 GeV/c
P3
0.26 GeV/c
0.43 GeV/c
Pmiss
P2
0.3 GeV/c
$\vec{p}_{miss}$:(0.28,0.00,-0.33) GeV/c
$\vec{p}_2$:(-0.25,-0.16,0.07) GeV/c
$\vec{p}_3$:(-0.18,0.13,0.13) GeV/c
y [GeV/c]
x [GeV/c]


Entry 7893, Transverse plane
$\alpha_{miss}$=1.24 ,$\alpha_2$=0.84 ,$\alpha_3$=0.98 , $\sum(\alpha)$=3.06
$(\vec{p}_{miss})_T$=0.51 GeV/c
$(\vec{p}_{miss}+\vec{p}_2+\vec{p}_3)_T$=0.23 GeV/c
0.21 GeV/c
P3
0.58 GeV/c
Pmiss
P2
0.3 GeV/c
$\vec{p}_{miss}$:(0.51,-0.00,-0.28) GeV/c
$\vec{p}_2$:(-0.10,-0.04,0.17) GeV/c
$\vec{p}_3$:(-0.30,0.24,0.11) GeV/c
y [GeV/c]
x [GeV/c]
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8

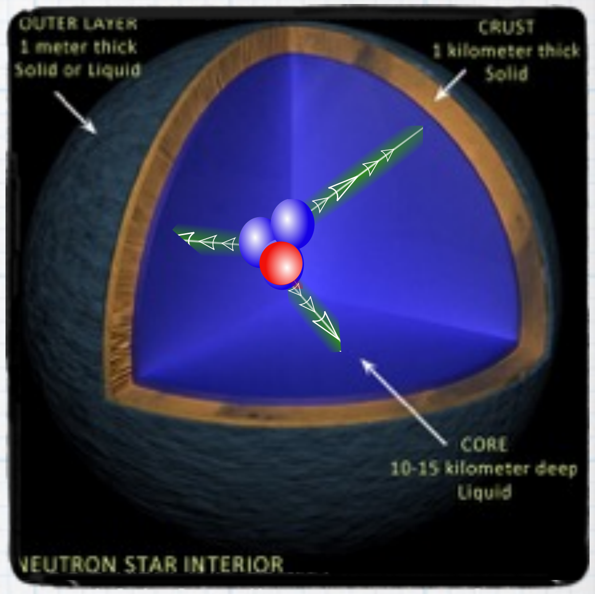
# Entry 9011, Transverse plane





Entry 11023, Transverse plane
$\alpha_{miss}$=1.26 ,$\alpha_2$=0.77 ,$\alpha_3$=0.96 , $\sum(\alpha)$=2.98
$(\vec{p}_{miss})_T$=0.10 GeV/c
$(\vec{p}_{miss}+\vec{p}_2+\vec{p}_3)_T$=0.18 GeV/c
0.5 GeV/c
Pmiss
P3
0.23 GeV/c
0.47 GeV/c
P2
$\vec{p}_{miss}$:(0.10,0.00,-0.49) GeV/c
$\vec{p}_2$:(-0.27,-0.18,0.34) GeV/c
$\vec{p}_3$:(0.22,0.00,0.07) GeV/c
y [GeV/c]
x [GeV/c]

# Consequences an Implications




* Different nucleons dominance / Isospin ½ dominance.

  (ppp & nnn are Isospin 3/2)

* The number of co-linear is small, and they generally Isotropic

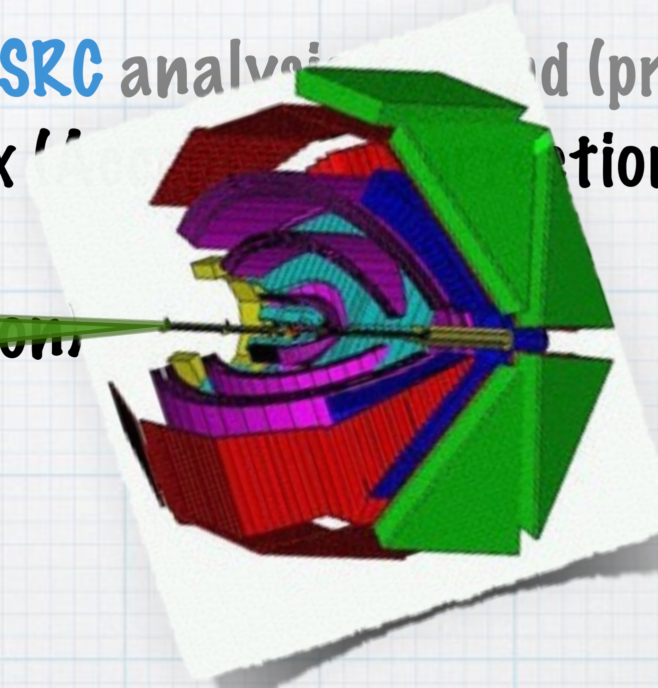
* Neutron star 3N-SRC dominance:

  - ~ 90% n, 10%p
  - Density >> nuclear density ☞ $\frac{\text{3N-SRC}}{\text{p with large } p_{miss}} > 0.15\text{-}0.2$
  - #nnn trios > #nnp trios
  - But due the Isospin structure of 3N-SRC, impact of nnp-SRC is large!

# Summary

* 2N-SRC Isospin structure is known, nothing is experimentally known for 3N-SRC so far.
* Selecting ppp-SRC candidates similar to previous 2N-SRC analysi... d (preliminary) ppp-SRC/(e,e'p with large $p_{miss}$) upper limit ~ 0.12% x (... tion).

Before acceptance correction



* Tighten th... x (Acceptance correction)
    - small p(c.m.)
    - [+ simple MC suggesting p(miss) < 0.6 GeV/c]

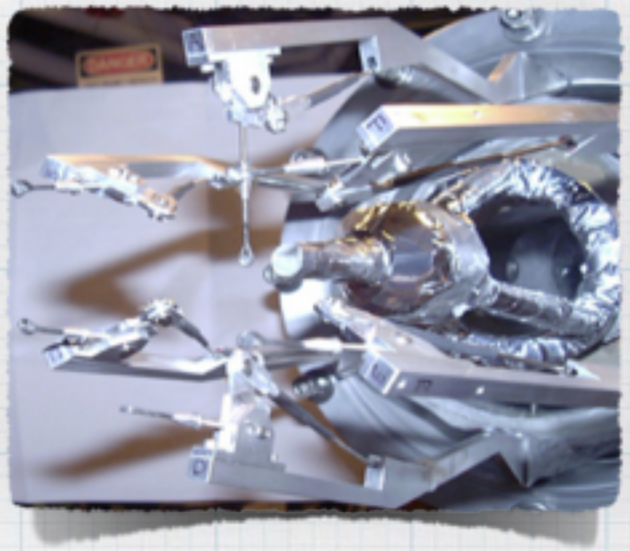
💡 **ppp-SRC/3N-SRC < 3%x (Acceptance correction)**

Experimental signature of 3N-SRC Isospin 1/2 dominance

(#nnp,npp-SRC > #ppp,nnn-SRC)

# Future plan

* Apply **Acceptance, Energy loss and Coulomb corrections.**
* Scan all **EG2 target nuclei.**



* Play the same game with **A(e,e′n)** events (combine **Meytal**′s analysis).
* Looking for **A(e,e′np)** and **A(e,e′npp)** events.

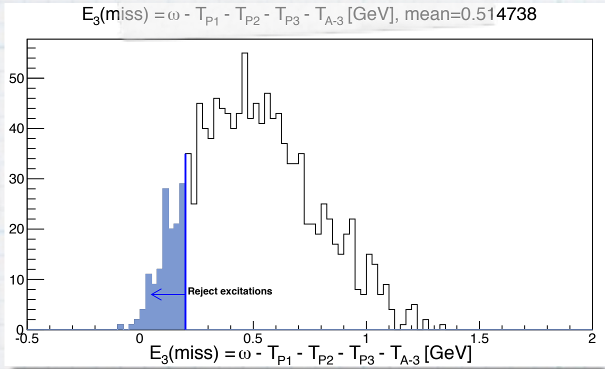
# Questions 😷

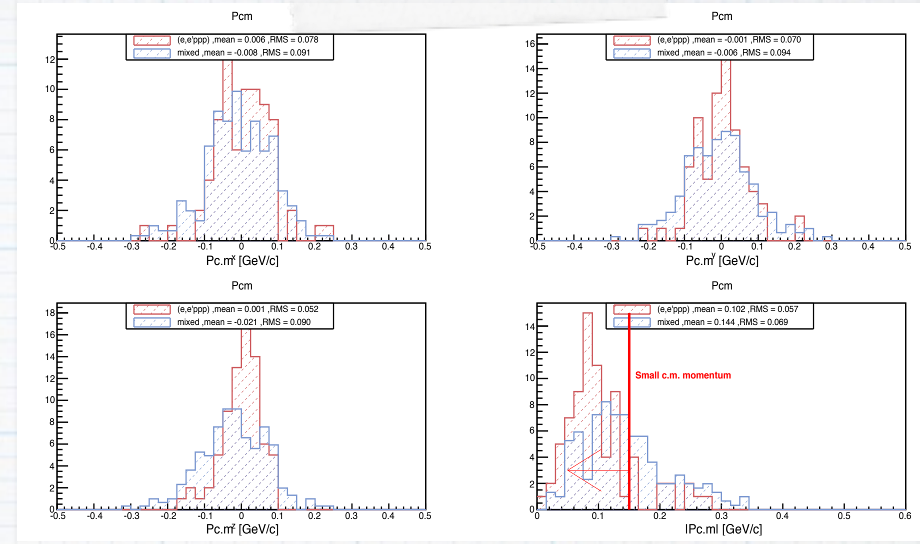
- What is the impact of loosening the cut on recoiling momenta ( $|p_2|, |p_3| > 0.35$ GeV/c )?
- Can the lack of co-linear events arise from an acceptance issue?
- Does my hadElastic simplified simulation seem reasonable and comprehensive to you?

# Thank you for your time…

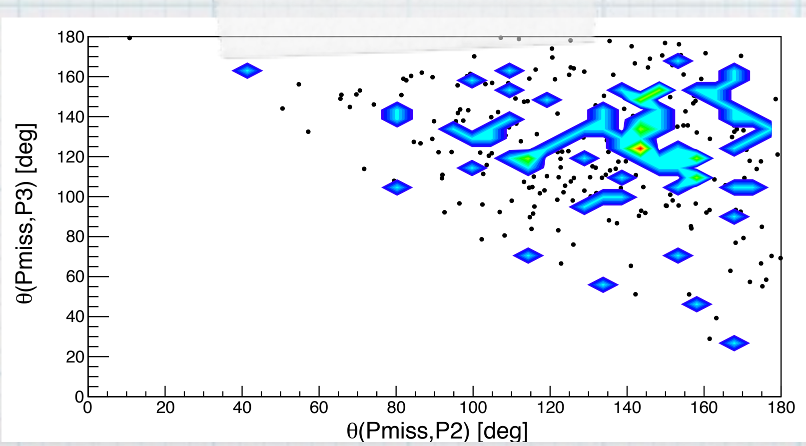
Comments/Suggestions/Questions:
cohen.erez7@gmail.com

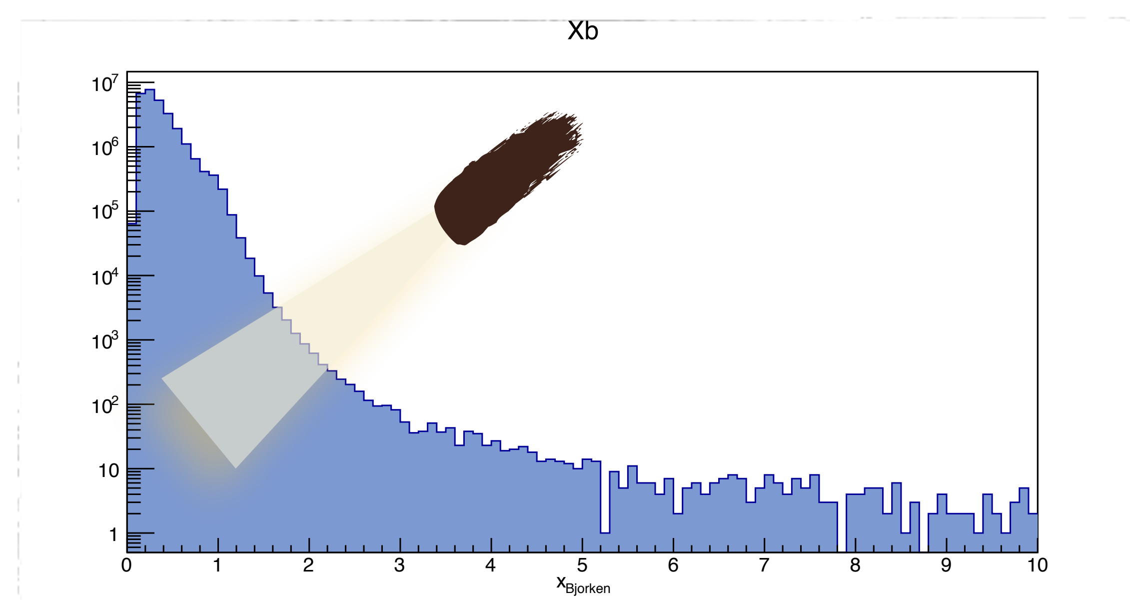
# Backup slides



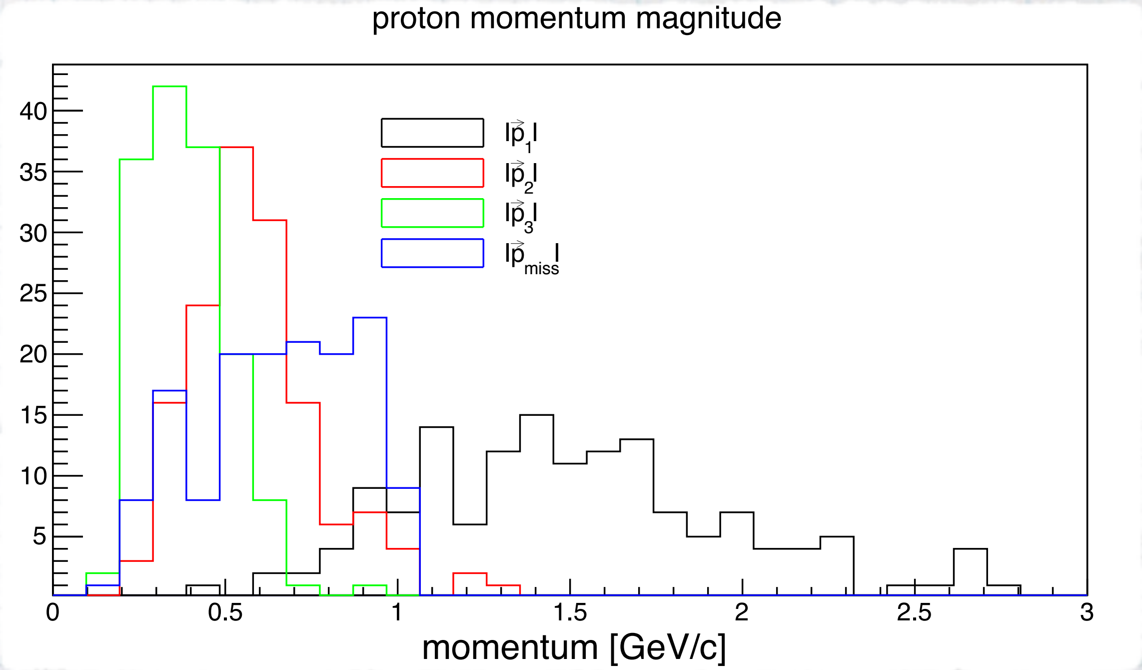

# Initial search - consider events with $x_B < 1$

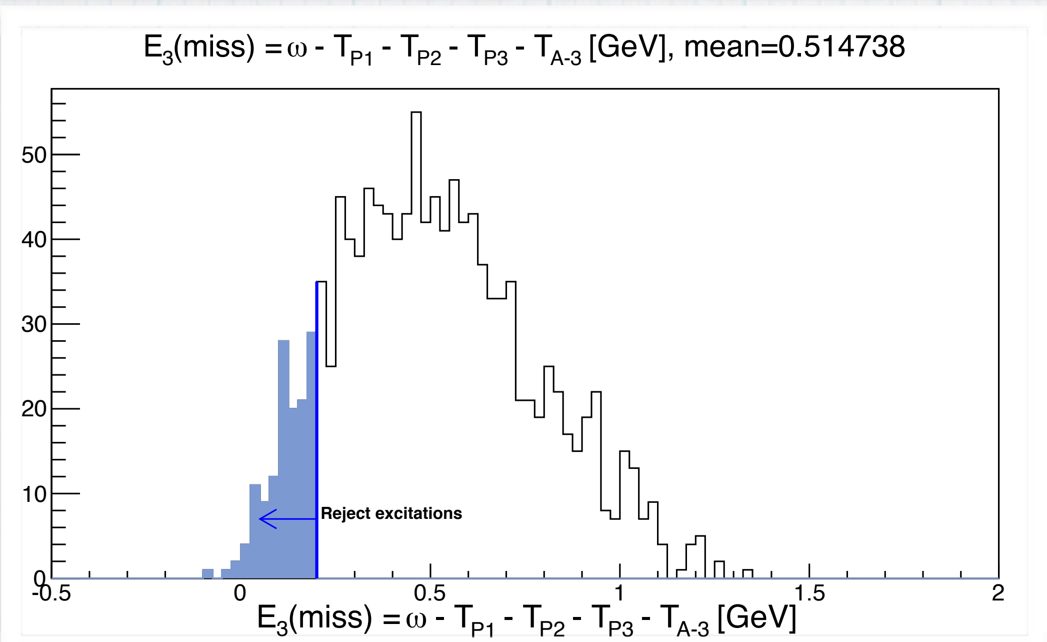


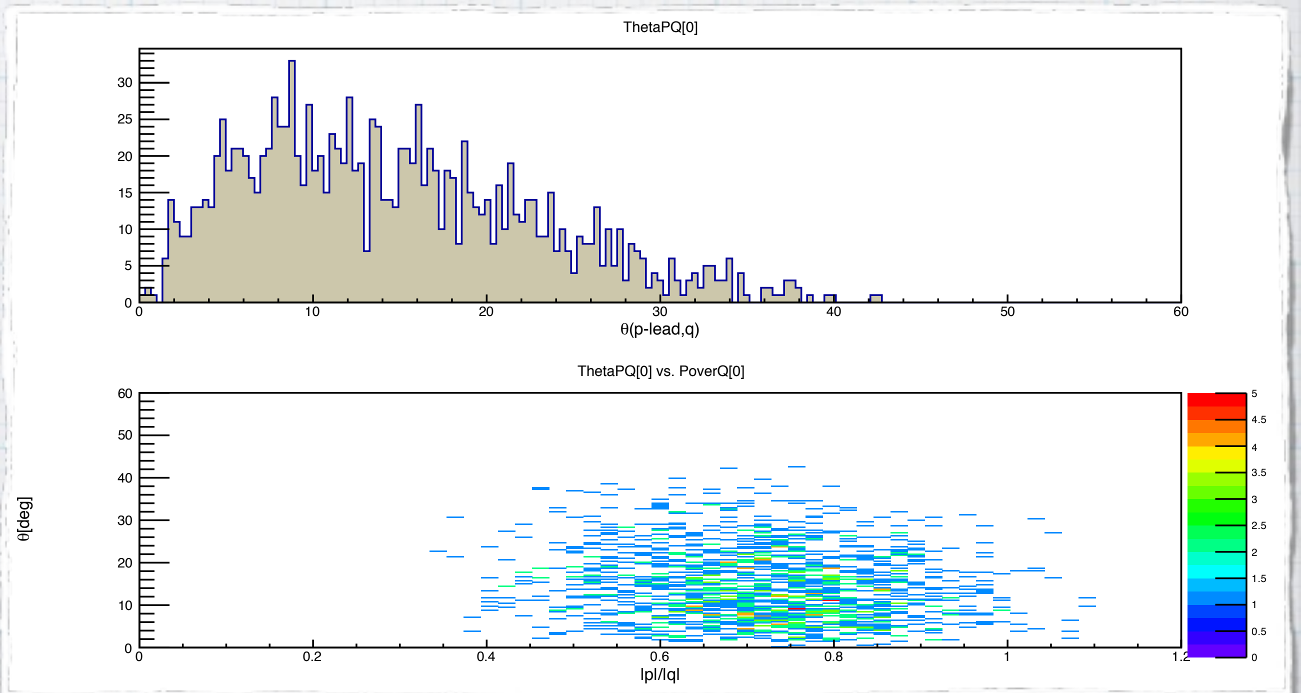



# Event selection

- EG2 data
- $^{12}C(e,e'ppp)$ events with
  - $|p_{miss}| < 1$ GeV/c
  - $0 < E_{miss3} < 200$ MeV

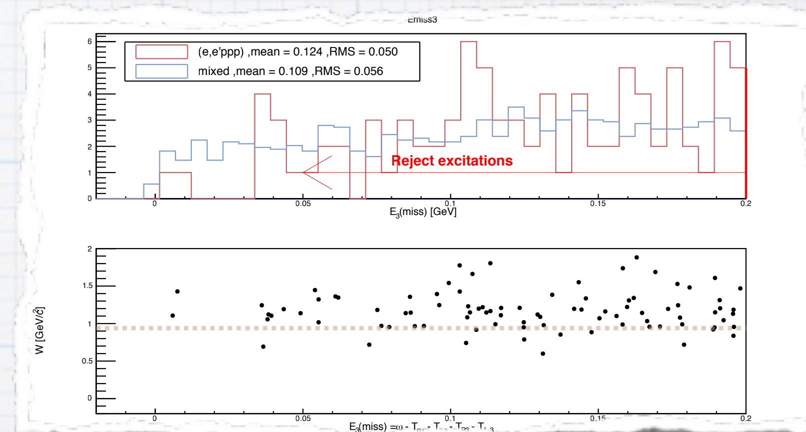


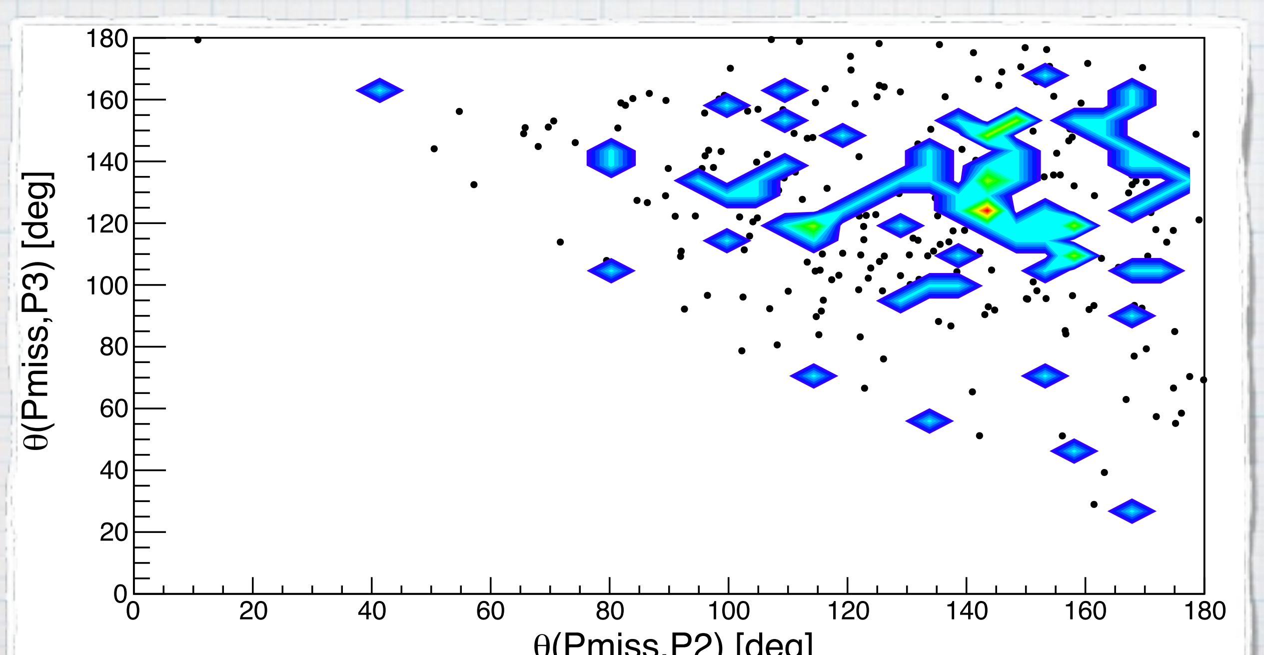



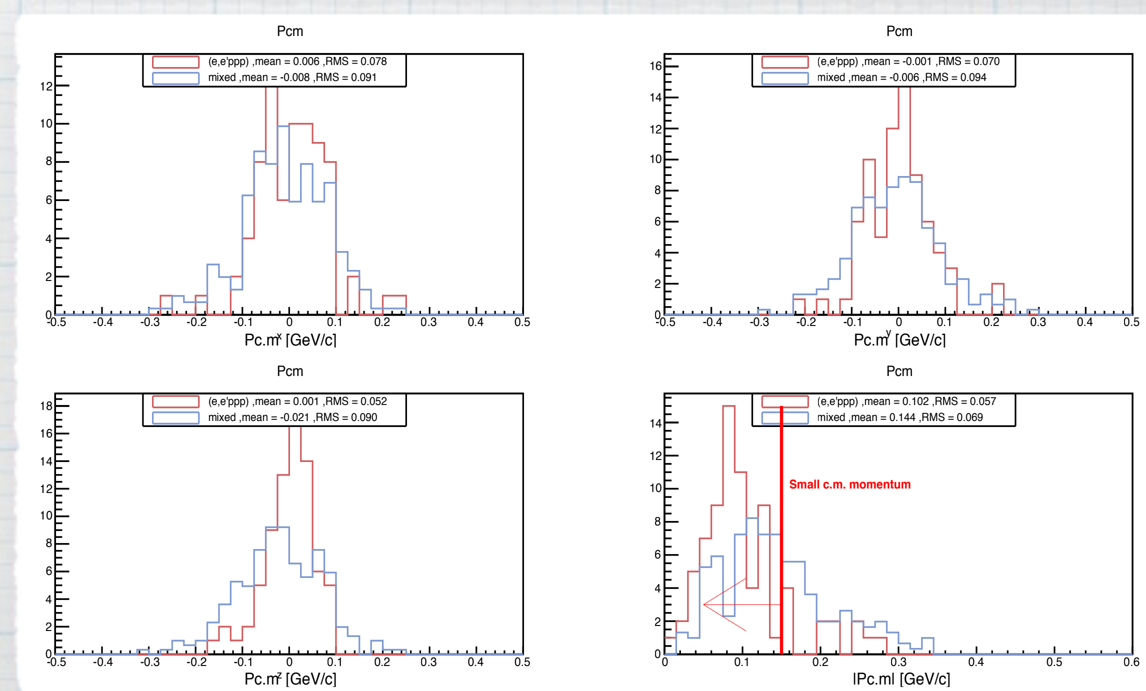
# Strategy

* Calculate as many kinematical variables as possible.




* Build **mixed events** tree.
* Compare data (**Signal**) to mixed events (**Background**)



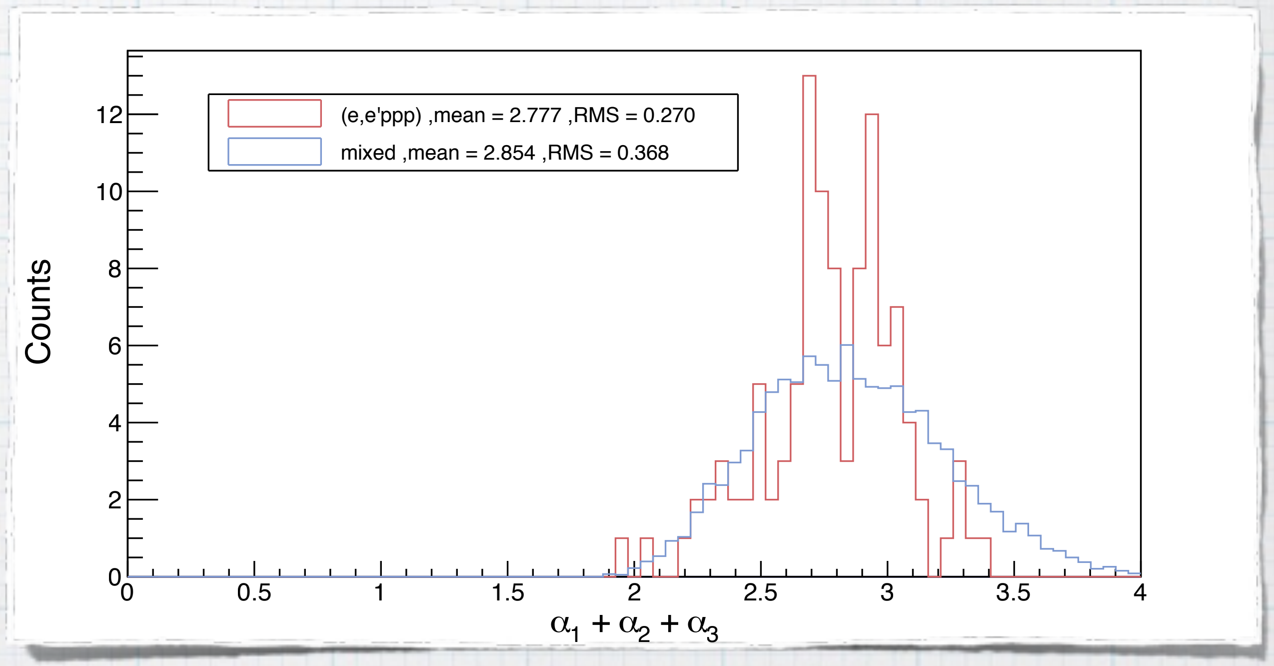



# Studying the LC fraction in the relativistic regime

* $\alpha_j$ is similar to $x_B$ for inelastic scattering.

$$\alpha = A\frac{E_p - p_z}{m_A}$$

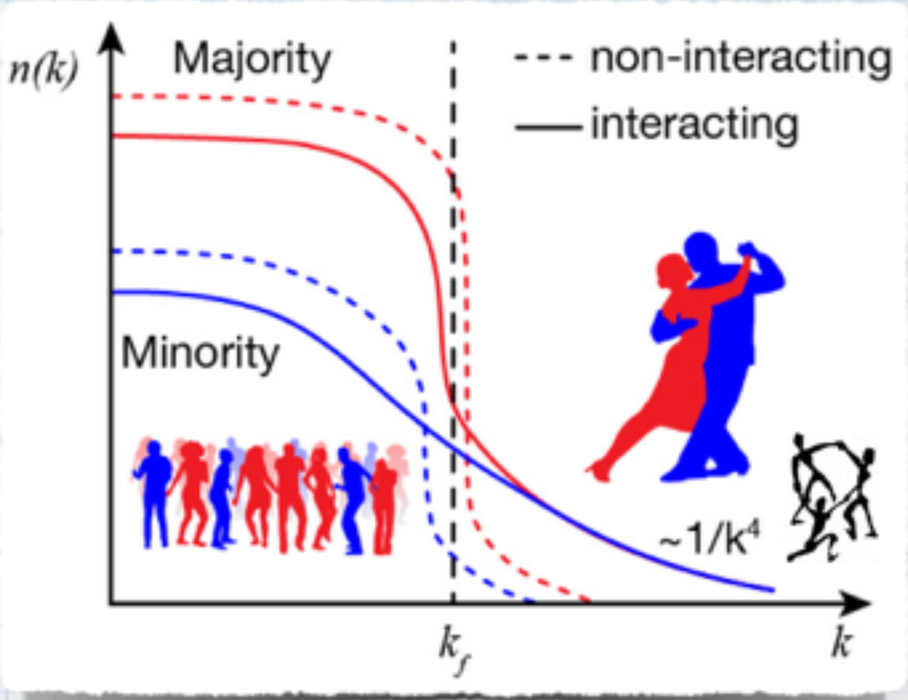
- $\Sigma\alpha_j > 2$ requires at least 2 nucleons involved.
- $\Sigma\alpha_j$ can distinguish 2N-SRC from 3N-SRC.

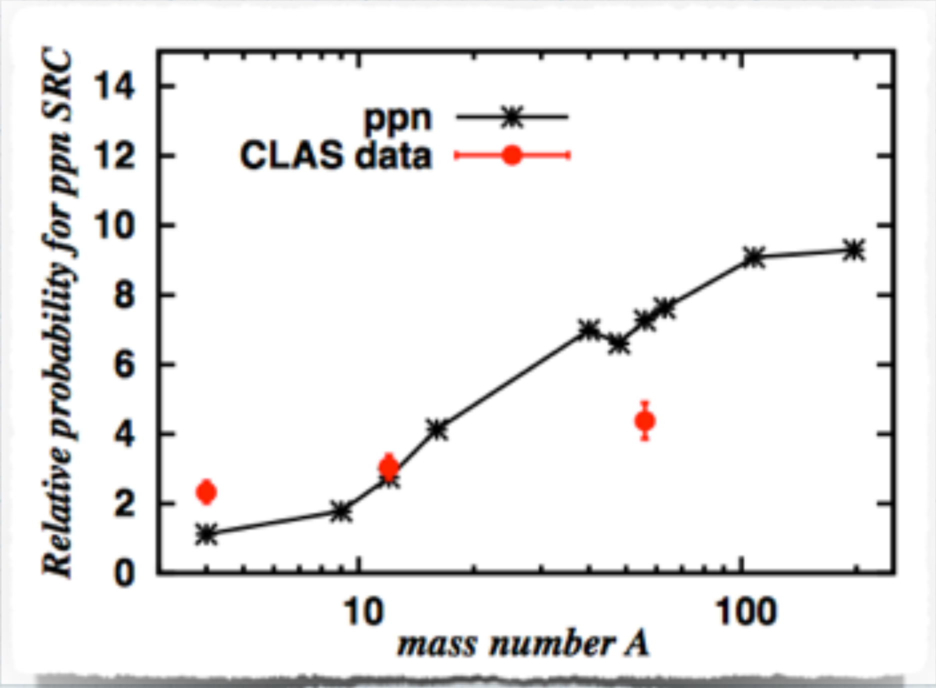



$$\sum\alpha = \frac{A}{m_A}[(E_p^1 - p_z^1) - (\omega - q_z) + (E_p^2 - p_z^2) + (E_p^3 - p_z^3)]$$

# The advantage of $x_B > 1$

- Wish to suppress multi-step processes off low momentum nucleons in the simplest way.
- $x_B < 1$ would require getting rid of inelastic processes which perhaps is possible but more tricky.
- Use Or Hen' observation that 2p-SRC is well seen for $x_B > 1.2$ .
- Since this sample is clean we can use relative normalization to see how much ppp is suppressed as compared to pp.




Vanhalst et. al. arXiv:1206.5151v2

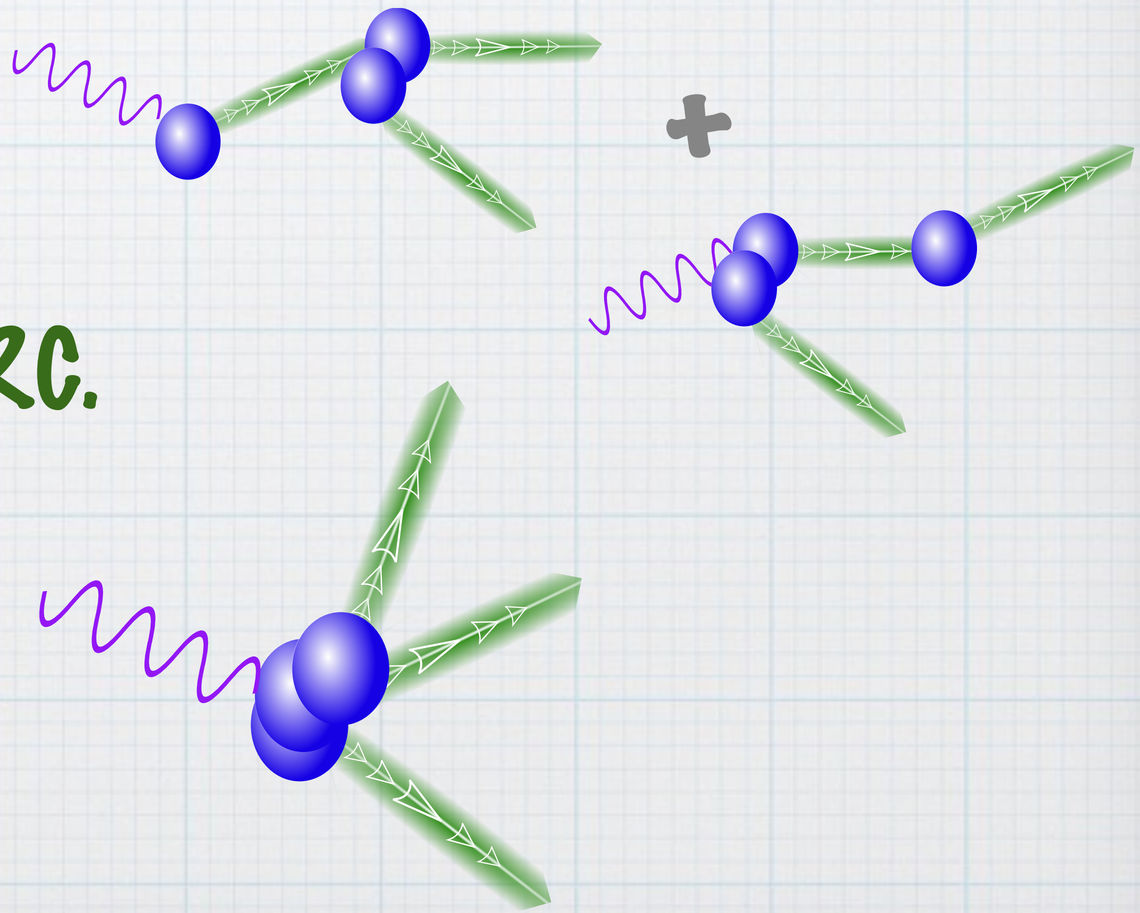
# Backup slides

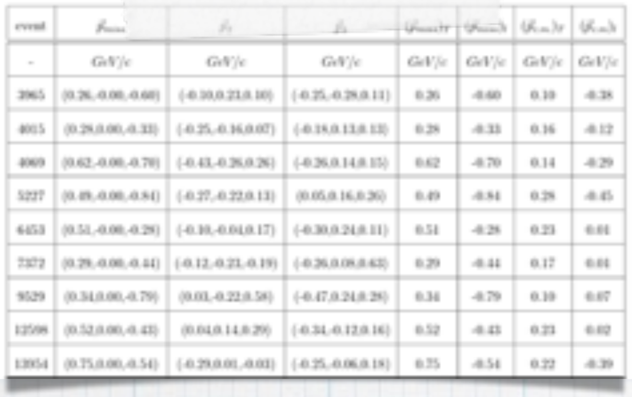
# 3p in the final state

* Two possible mechanisms produce (e,e′ppp) event:

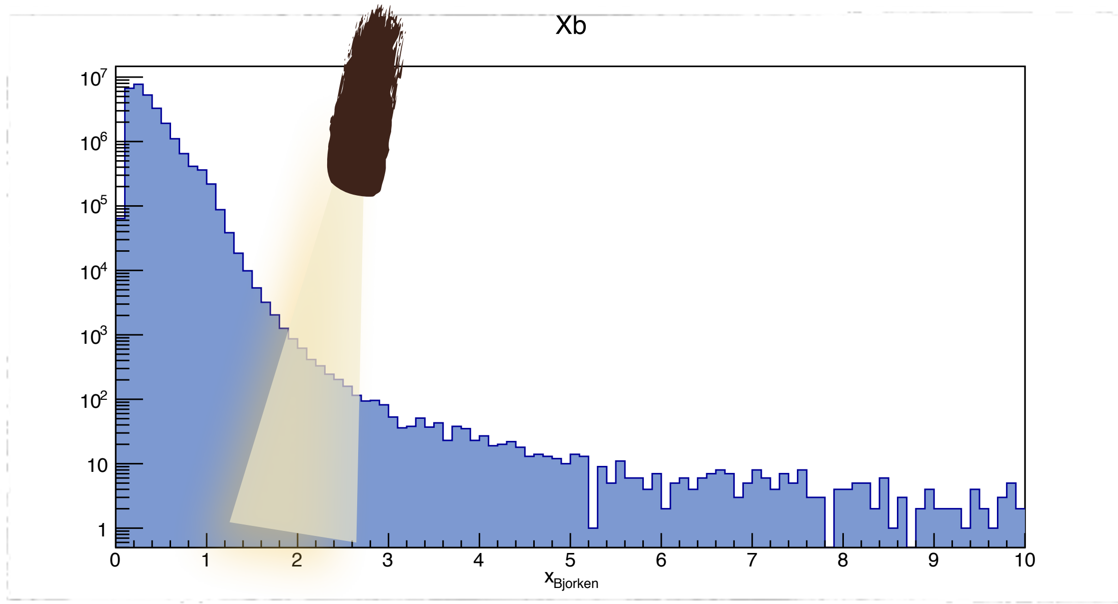
e Interacts with p + pp-SRC.

e Interacts with p from 3p-SRC.

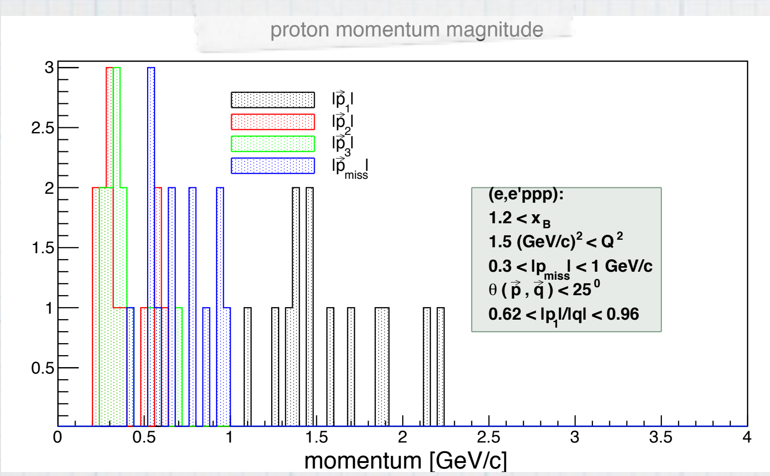


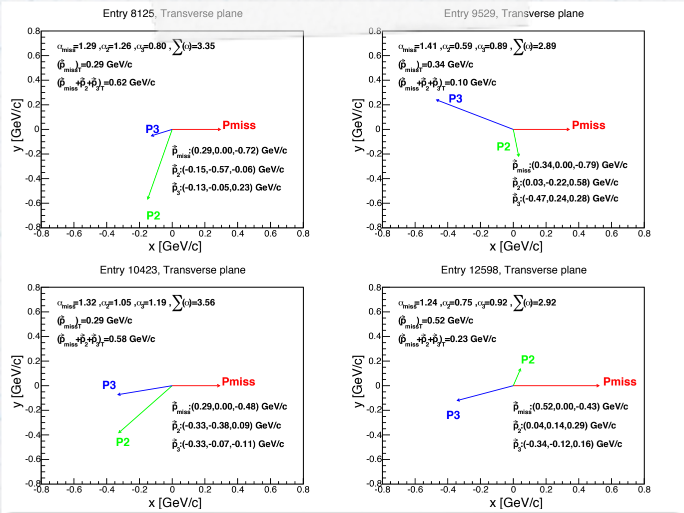


| event | $\vec{p}_{miss}$ | $\vec{p}_2$ | $\vec{p}_3$ | $(\vec{p}_{miss})_x$ | $(\vec{p}_{miss})_z$ | $(\vec{p}_{c.m.})_x$ | $(\vec{p}_{c.m.})_z$ |
|---|---|---|---|---|---|---|---|
| - | GeV/c | GeV/c | GeV/c | GeV/c | GeV/c | GeV/c | GeV/c |
| 3965 | (0.26,-0.00,-0.60) | (-0.10,0.23,0.10) | (-0.25,-0.28,0.11) | 0.26 | -0.60 | 0.10 | -0.38 |
| 4015 | (0.28,0.00,-0.33) | (-0.25,-0.16,0.07) | (-0.18,0.13,0.13) | 0.28 | -0.33 | 0.16 | -0.12 |
| 4069 | (0.62,-0.00,-0.70) | (-0.43,-0.26,0.26) | (-0.26,0.14,0.15) | 0.62 | -0.70 | 0.14 | -0.29 |
| 5227 | (0.49,-0.00,-0.84) | (-0.27,-0.22,0.13) | (0.05,0.16,0.26) | 0.49 | -0.84 | 0.28 | -0.45 |
| 6453 | (0.51,-0.00,-0.28) | (-0.10,-0.04,0.17) | (-0.30,0.24,0.11) | 0.51 | -0.28 | 0.23 | 0.01 |
| 7372 | (0.29,-0.00,-0.44) | (-0.12,-0.21,-0.19) | (-0.26,0.08,0.63) | 0.29 | -0.44 | 0.17 | 0.01 |
| 9529 | (0.34,0.00,-0.79) | (0.03,-0.22,0.58) | (-0.47,0.24,0.28) | 0.34 | -0.79 | 0.10 | 0.07 |
| 12598 | (0.52,0.00,-0.43) | (0.04,0.14,0.29) | (-0.34,-0.12,0.16) | 0.52 | -0.43 | 0.23 | 0.02 |
| 13954 | (0.75,0.00,-0.54) | (-0.29,0.01,-0.03) | (-0.25,-0.06,0.18) | 0.75 | -0.54 | 0.22 | -0.39 |

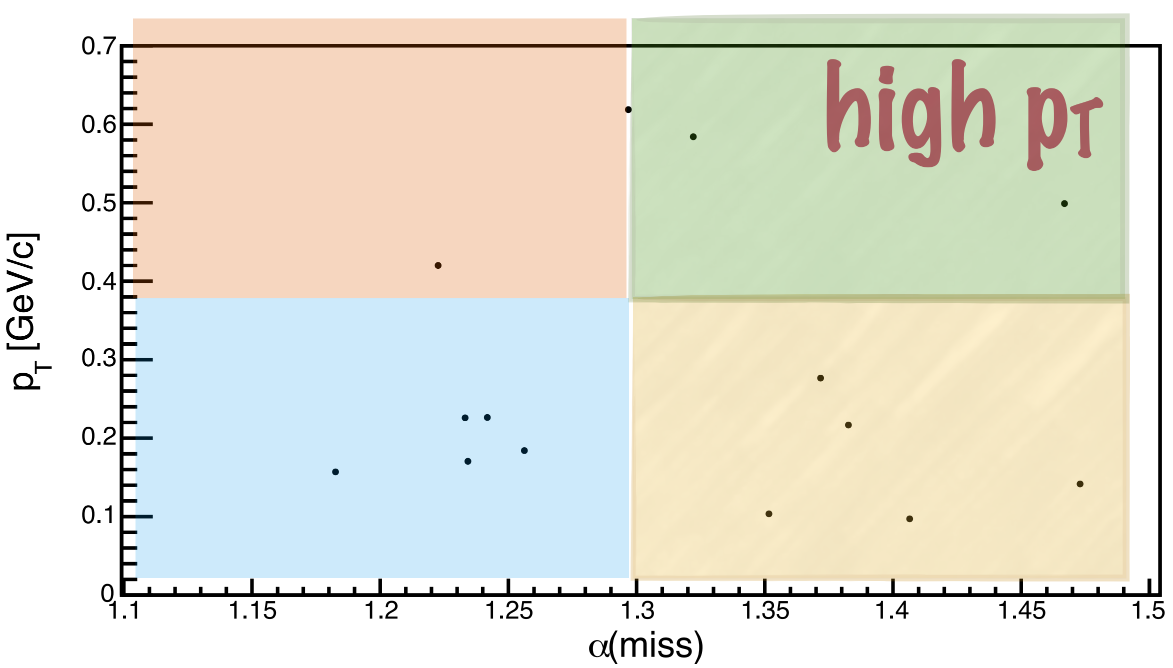


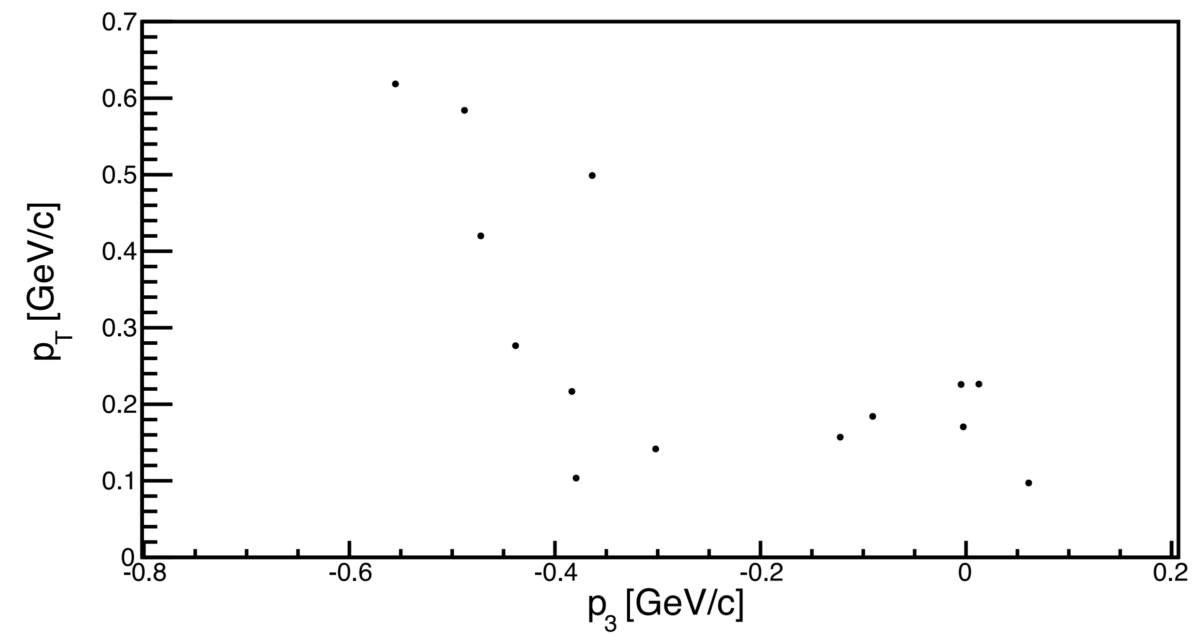

# Changing approach - cleaning events to SRC kinematics

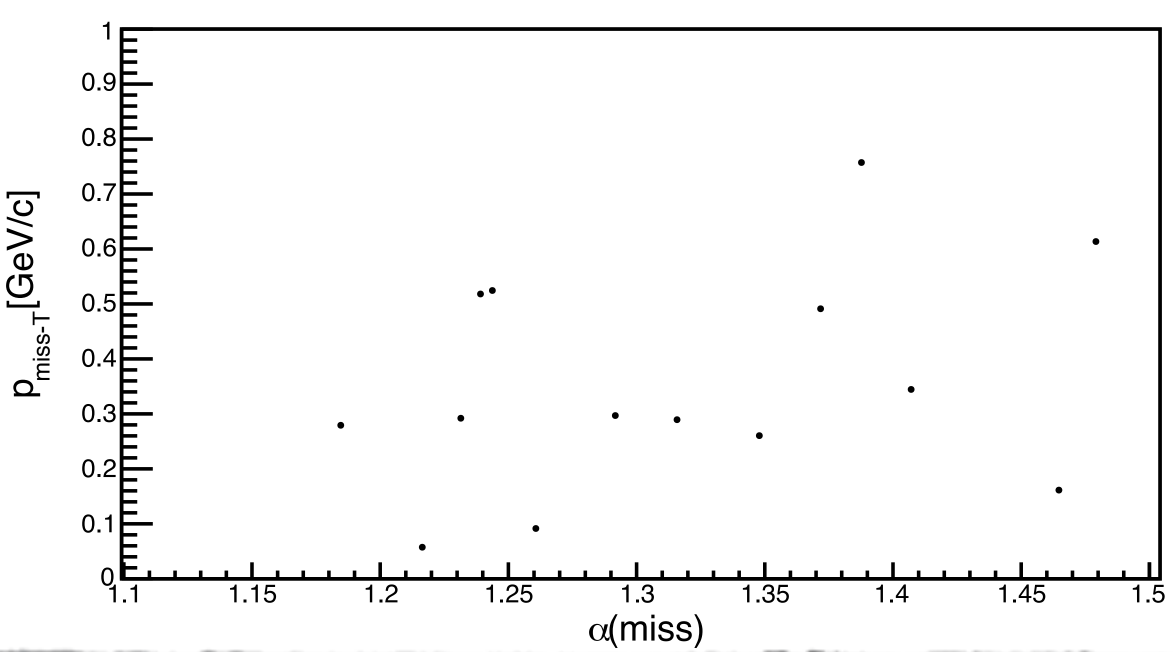


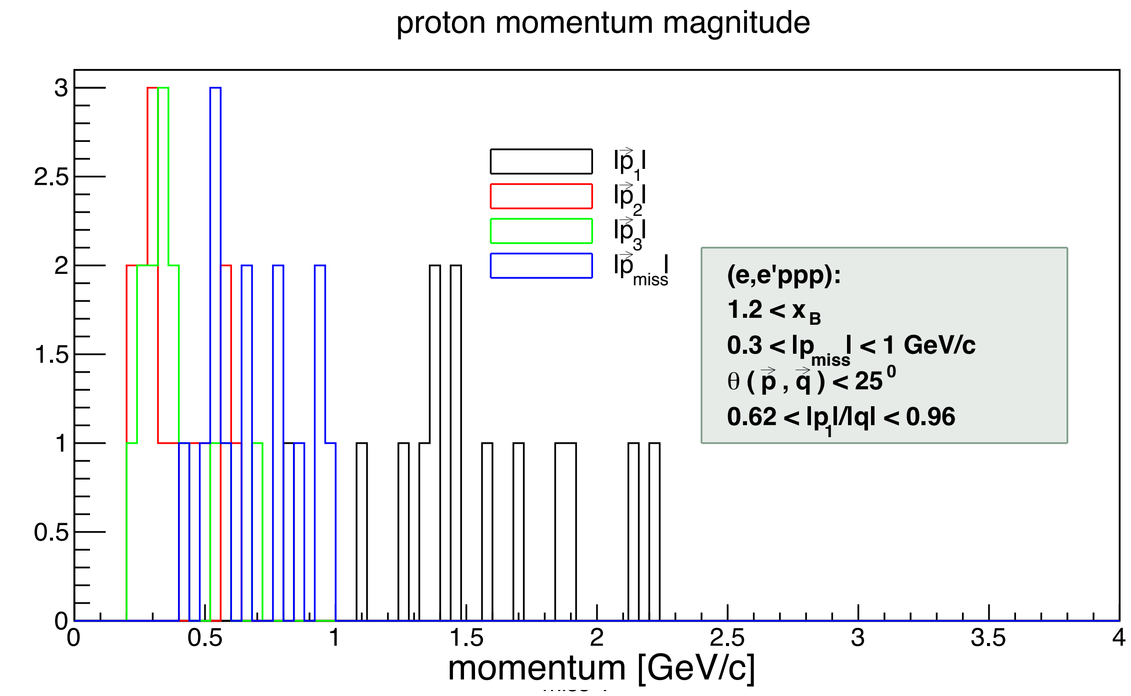



# 14 $^{12}$C(e,e'ppp) events in SRC kinematics - characteristics

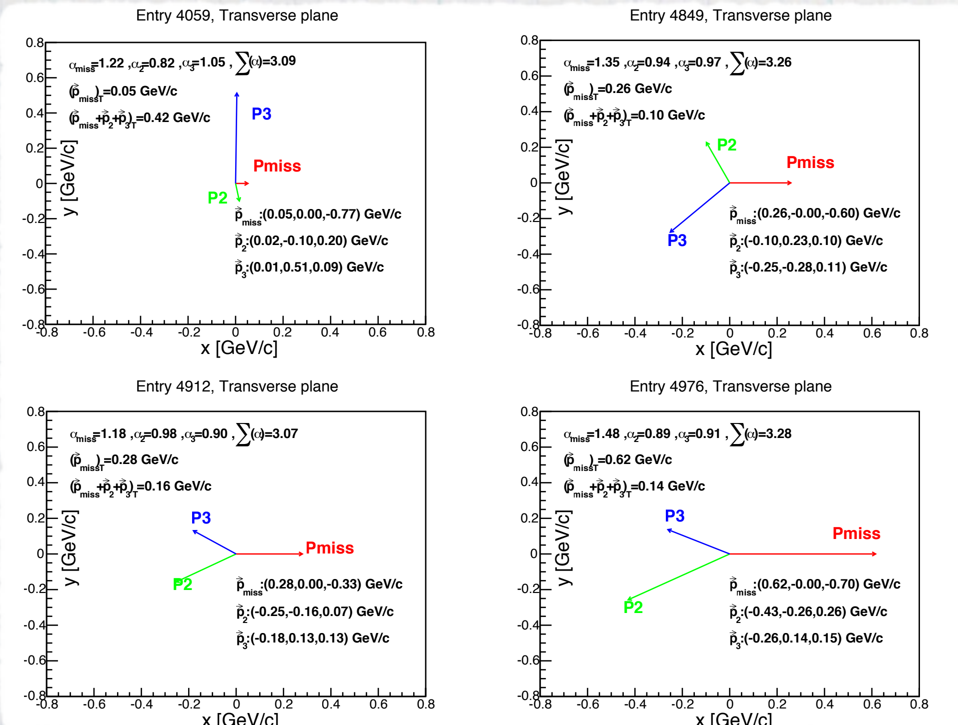


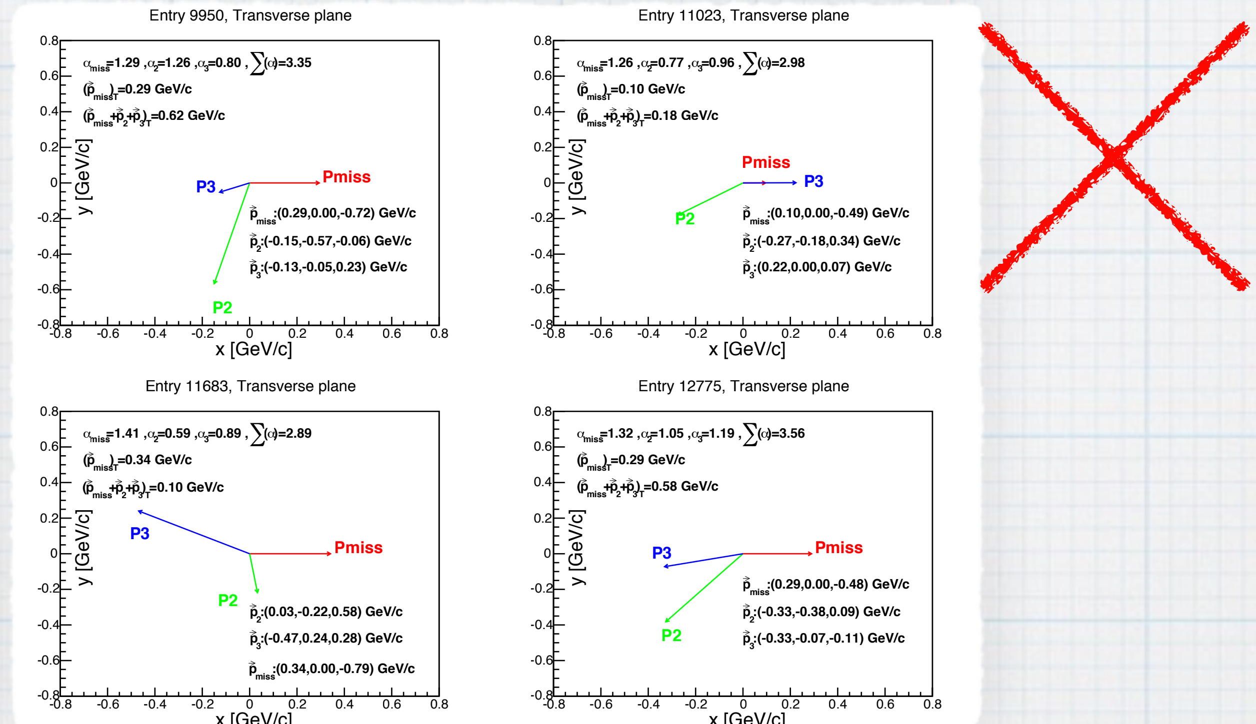



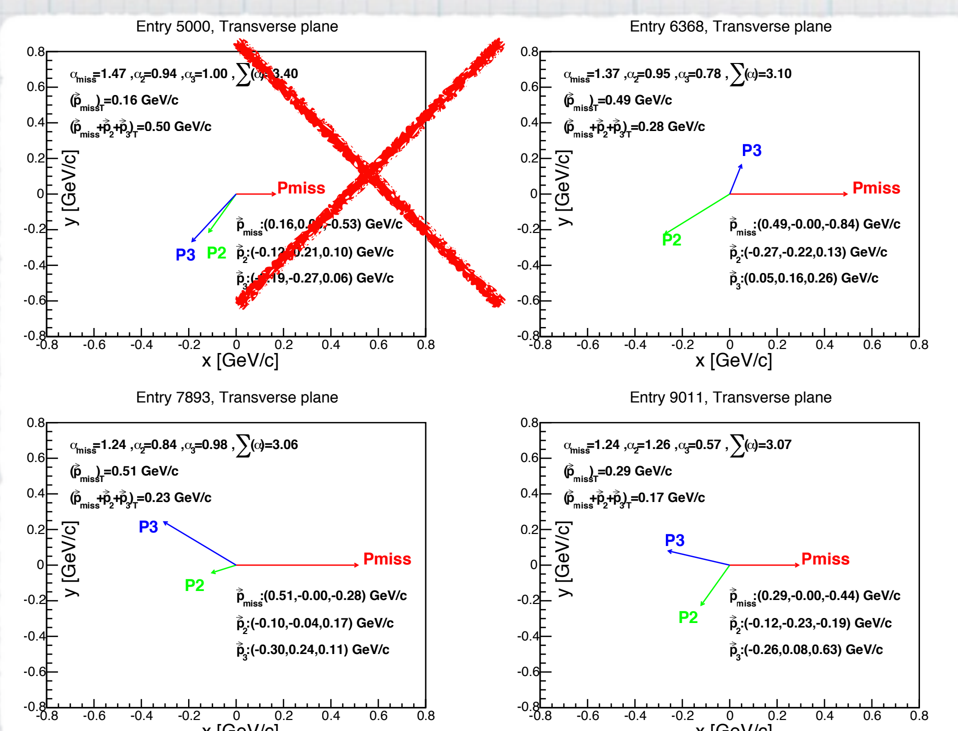



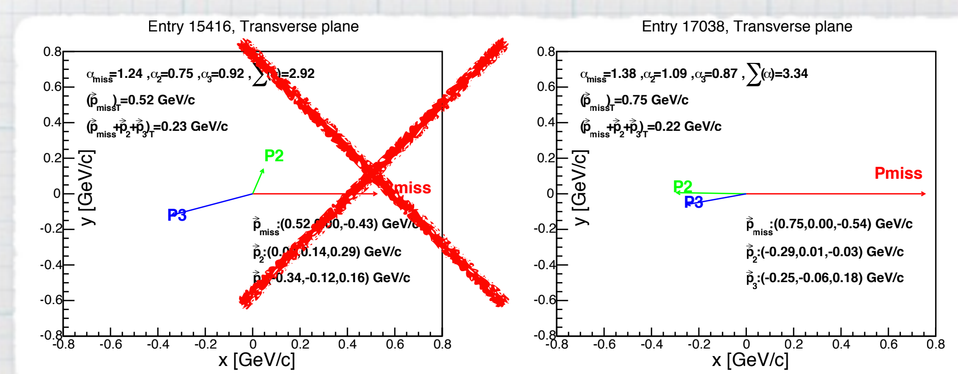



# Transverse plane projection



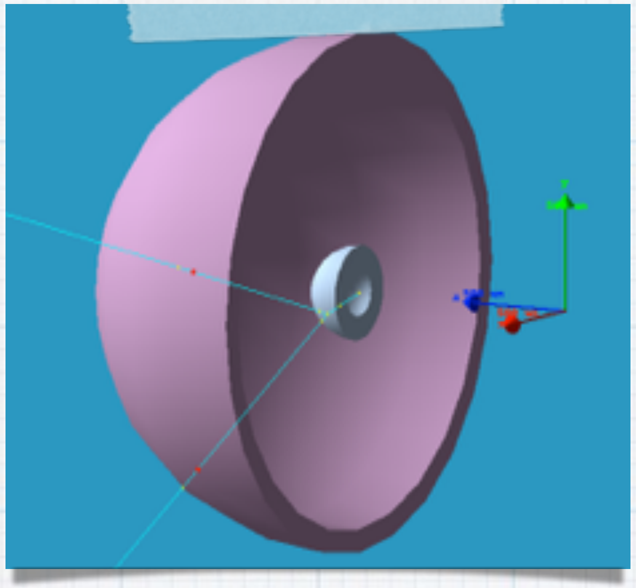



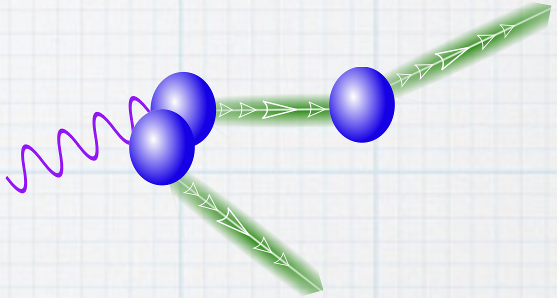




9 ARE BALANCED

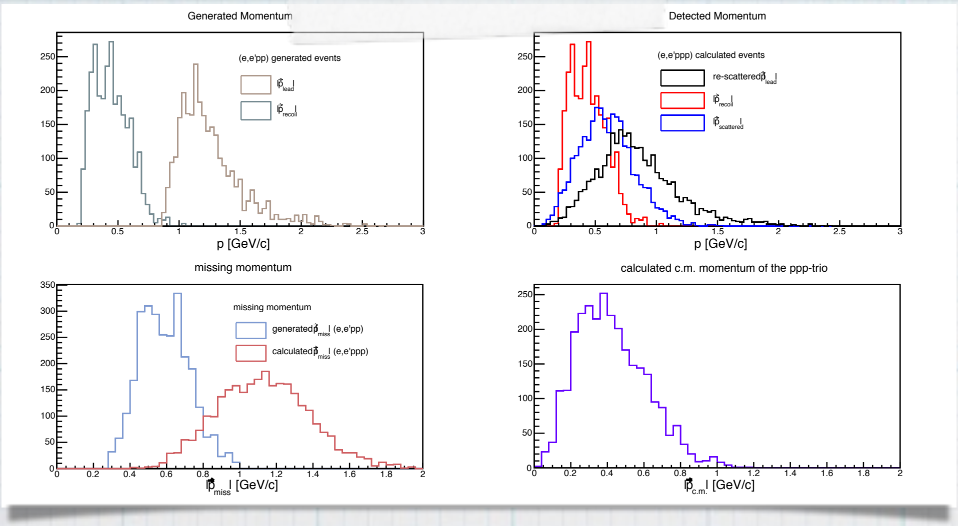
# Further information on the 3p-SRC candidates

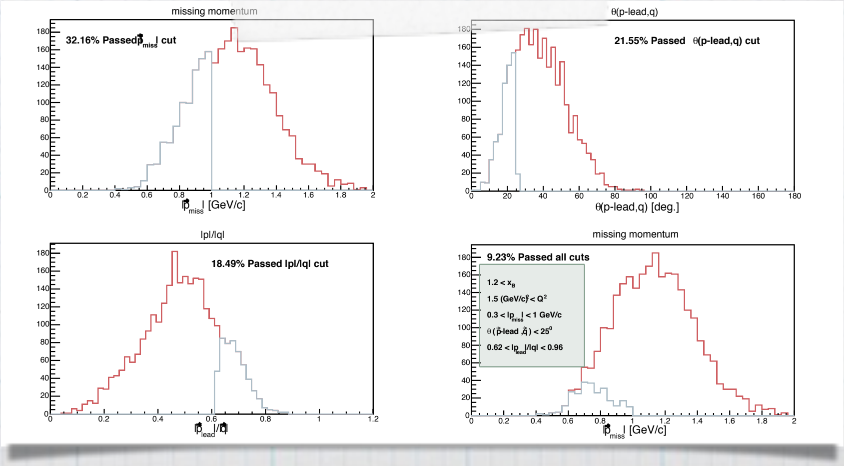
| event | $\vec{p}_{miss}$ | $\vec{p}_2$ | $\vec{p}_3$ | $(\vec{p}_{miss})_T$ | $(\vec{p}_{miss})_l$ | $(\vec{p}_{c.m.})_T$ | $(\vec{p}_{c.m})_l$ | $\alpha_{miss}$ | $\alpha_2$ | $\alpha_3$ | $\sum(\alpha)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| - | $GeV/c$ | $GeV/c$ | $GeV/c$ | $GeV/c$ | $GeV/c$ | $GeV/c$ | $GeV/c$ | | | | |
| 4849 | (0.26,-0.00,-0.60) | (-0.10,0.23,0.10) | (-0.25,-0.28,0.11) | 0.26 | -0.60 | 0.10 | -0.38 | 1.35 | 0.94 | 0.97 | 3.26 |
| 4912 | (0.28,0.00,-0.33) | (-0.25,-0.16,0.07) | (-0.18,0.13,0.13) | 0.28 | -0.33 | 0.16 | -0.12 | 1.18 | 0.98 | 0.90 | 3.07 |
| 4976 | (0.62,-0.00,-0.70) | (-0.43,-0.26,0.26) | (-0.26,0.14,0.15) | 0.62 | -0.70 | 0.14 | -0.29 | 1.48 | 0.89 | 0.91 | 3.28 |
| 6368 | (0.49,-0.00,-0.84) | (-0.27,-0.22,0.13) | (0.05,0.16,0.26) | 0.49 | -0.84 | 0.28 | -0.45 | 1.37 | 0.95 | 0.78 | 3.10 |
| 7893 | (0.51,-0.00,-0.28) | (-0.10,-0.04,0.17) | (-0.30,0.24,0.11) | 0.51 | -0.28 | 0.23 | 0.01 | 1.24 | 0.84 | 0.98 | 3.06 |
| 9011 | (0.29,-0.00,-0.44) | (-0.12,-0.23,-0.19) | (-0.26,0.08,0.63) | 0.29 | -0.44 | 0.17 | 0.01 | 1.24 | 1.26 | 0.57 | 3.07 |
| 11683 | (0.34,0.00,-0.79) | (0.03,-0.22,0.58) | (-0.47,0.24,0.28) | 0.34 | -0.79 | 0.10 | 0.07 | 1.41 | 0.59 | 0.89 | 2.89 |
| 15416 | (0.52,0.00,-0.43) | (0.04,0.14,0.29) | (-0.34,-0.12,0.16) | 0.52 | -0.43 | 0.23 | 0.02 | 1.24 | 0.75 | 0.92 | 2.92 |
| 17038 | (0.75,0.00,-0.54) | (-0.29,0.01,-0.03) | (-0.25,-0.06,0.18) | 0.75 | -0.54 | 0.22 | -0.39 | 1.38 | 1.09 | 0.87 | 3.34 |





# Background contribution

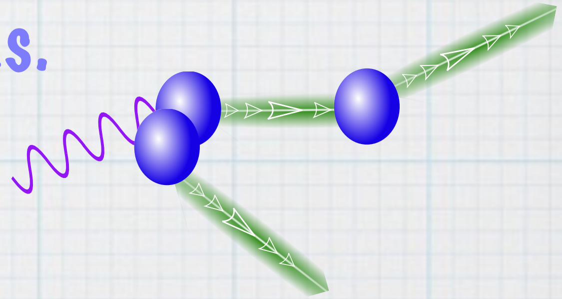


# Characterizing background contribution

* 3N correlations without distortions should have
    * $(p_{miss} + p_2 + p_3)_T < 0.2\text{-}0.3$ GeV/c
    * $\Sigma\alpha - 3 < 0.2\text{-}0.3$

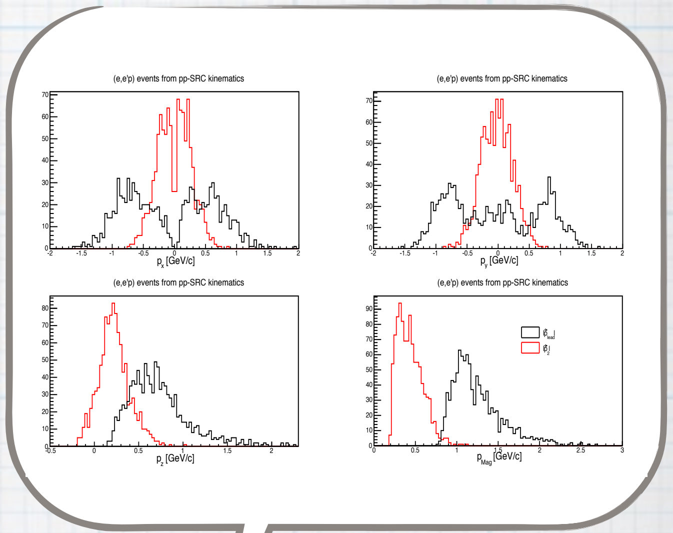
* Larger values are likely:
    * pnpp correlations in which all goes through pn interactions.
    * Re-scattering

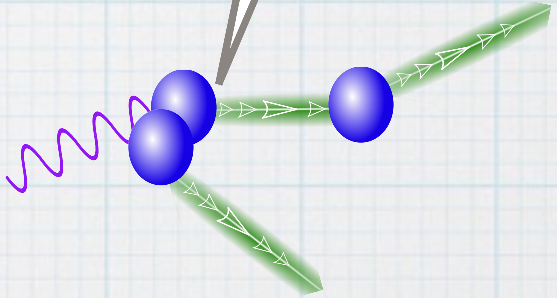


* Its important to have an idea where do the 4 events with $|p_{miss}| \sim 0.8\text{-}1$ GeV/c come from.
* Such a large suppression of ppp- to pp-SRC requires us to look for rare processes which mimic 3p-SRC.

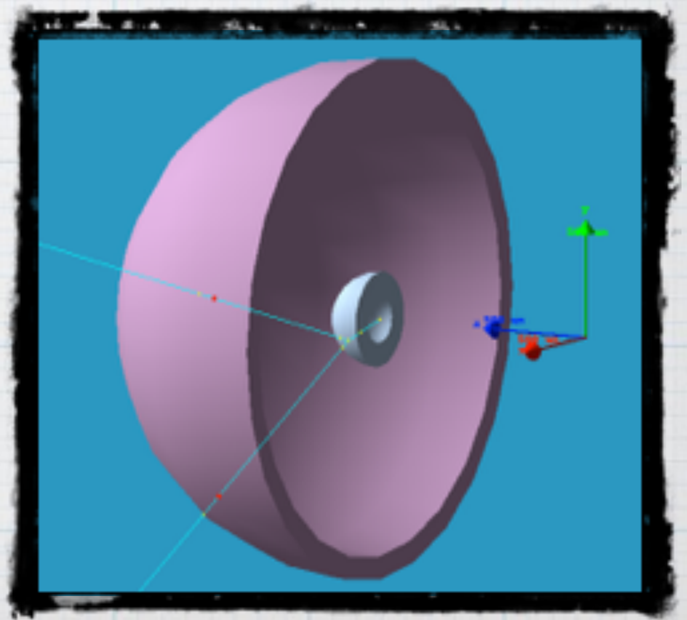
# Studying contribution to Re-scattering

* Consider elastic re-scattering of pp-SRC ($p_{lead}$), off a proton ($p_3$) when leaving the nucleus.

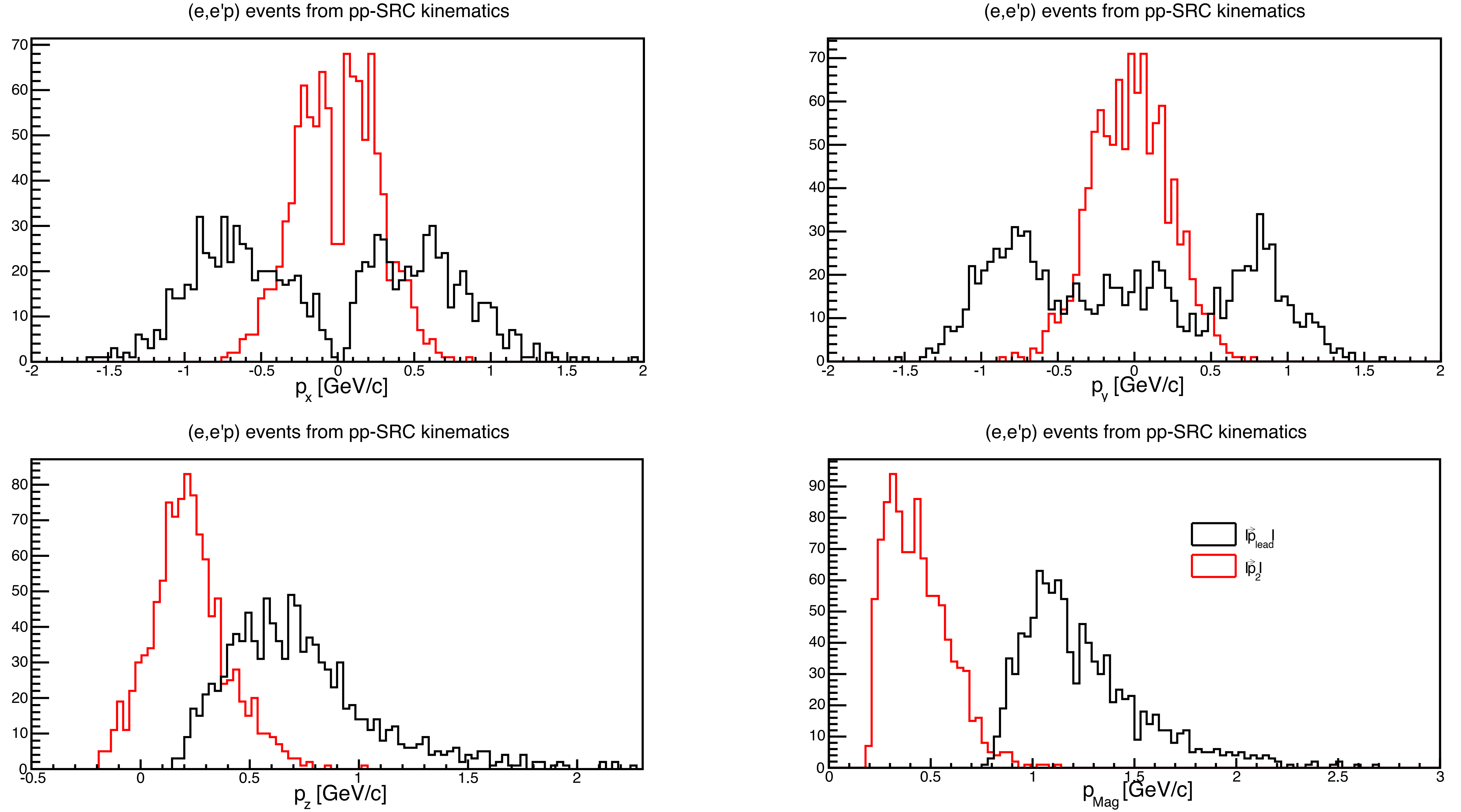




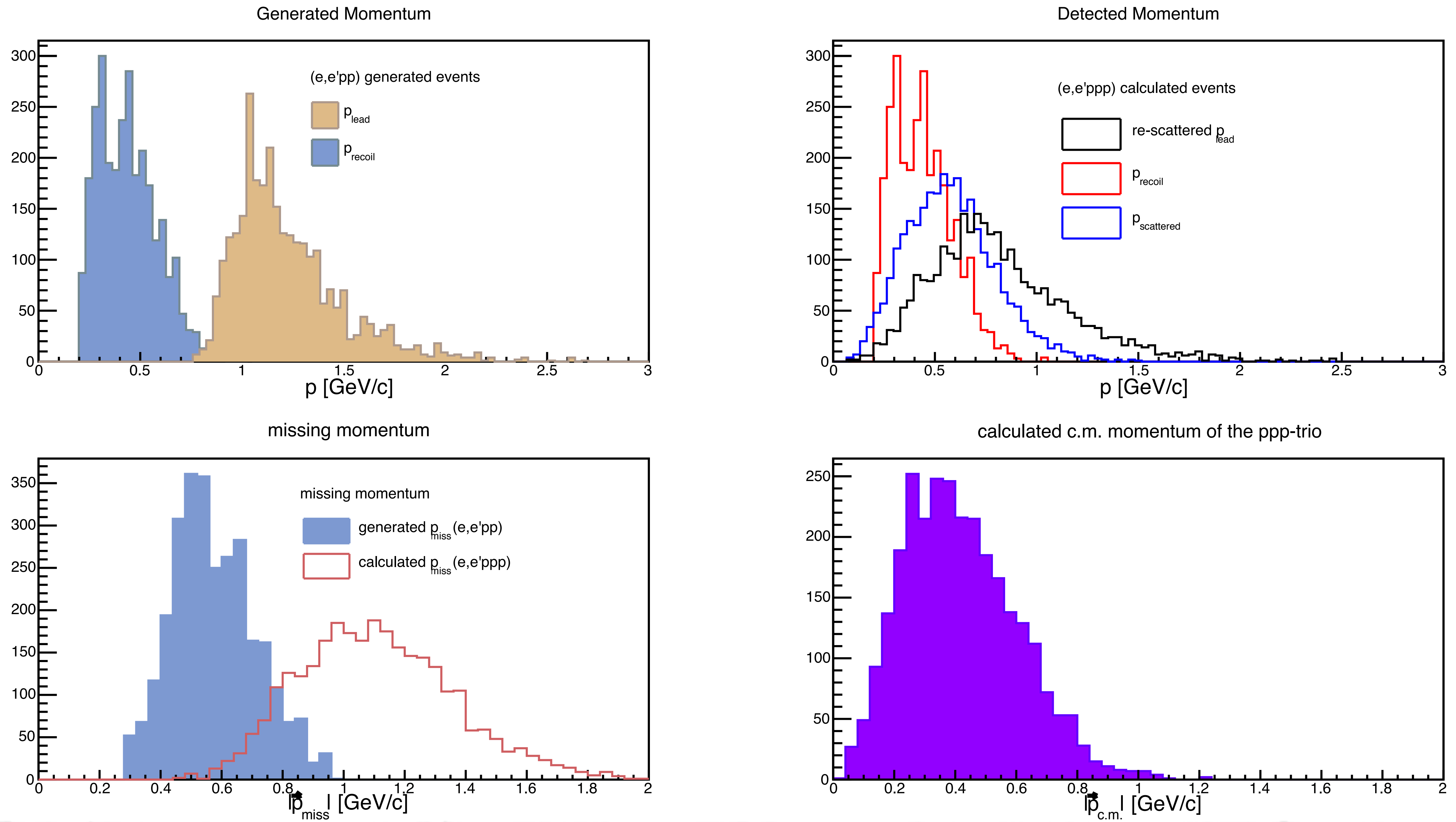
* Model using Geant4 simulation:
  - Both $p_{lead}$ & $p_{recoil}$ from pp-SRC (e,e'pp) data were injected into the simulation,
  - $p_{lead}$ was allowed to re-scatter elastically off $p_3$ at rest.



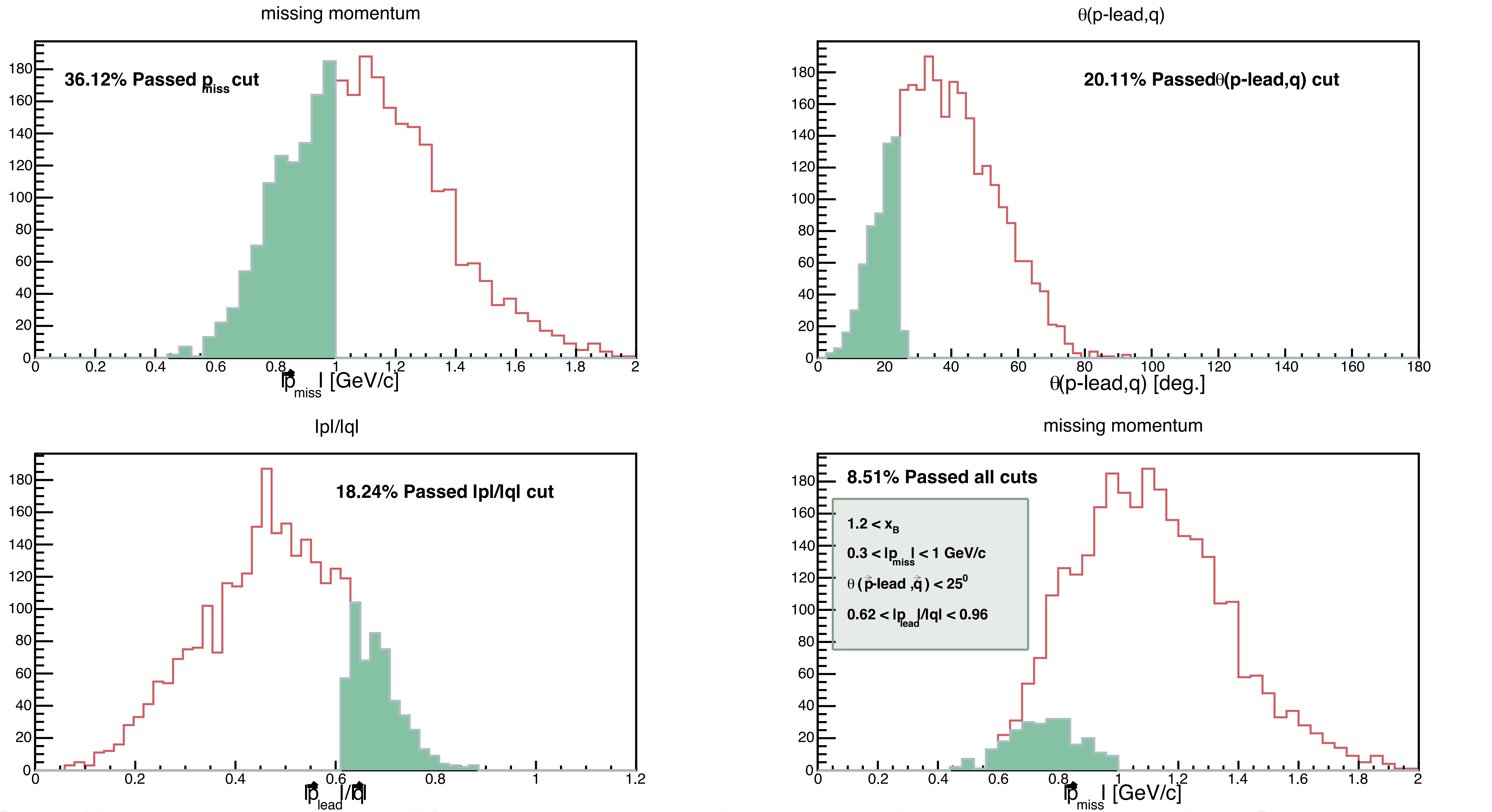
# Data - simulation input



# Simulation results



# Simulation results



# Simulation results

* About 8.5% of the pp-SRC re-scattering events contribute to ppp-SRC candidates.
* This contribution comes with high missing momentum, may explain high $|p_{miss}|$ 3p-SRC candidates.
* Normalization needs to be figured out:

1050 pp events X 8.5% X 0.4 (p/N) $\sim$

35 (e,e'ppp) events

# Work under way

* pp-SRC re-scattering background contribution:
  * How much a **scattering off a bound nucleon** could be different?
  * Improving the model by allowing $p_3$ to move (**Fermi motion**).
* The residual system (3p+6n) is highly excited (~**47 MeV**). What effects does this introduce?

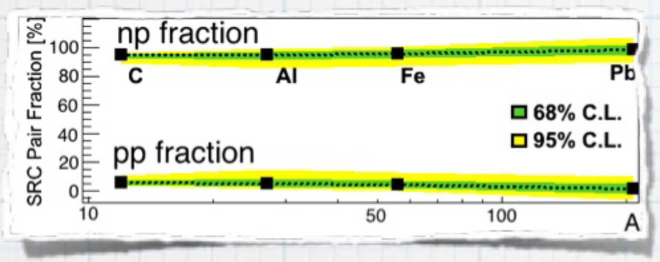
| Nuclide | Z | N | Mass excess (keV) | Binding energy (keV) | Mass (mu) | Origin |
|---|---|---|---|---|---|---|
| $^{12}$C | 6 | 6 | 0.0 ± 0.0 | 92161.753 ± 0.014 | 12 000000.0 ± 0.0 | |
| $^{9}$Li | 3 | 6 | 24953.903 ± 1.946 | 45340.942 ± 1.946 | 9 026789.122 ± 2.089 | |

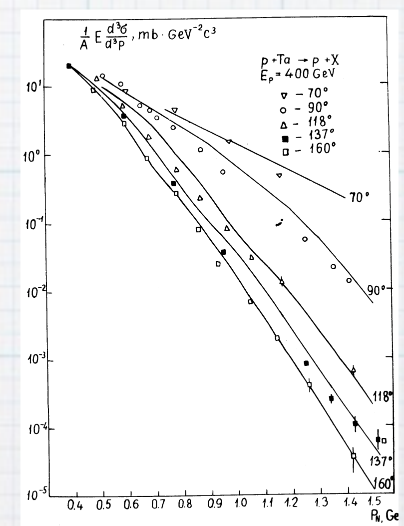
# Estimate the expected number of ppp-SRC events

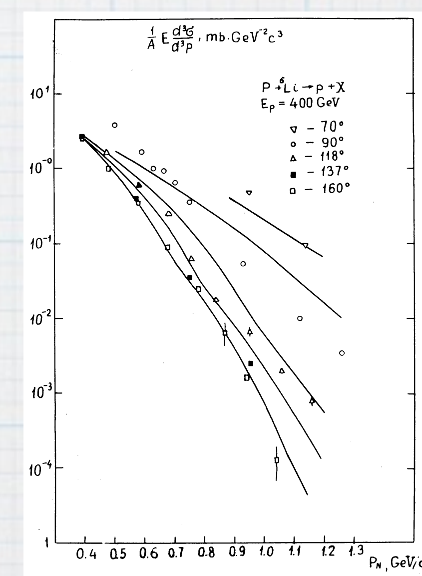
$$\frac{\sigma(pp\text{-}SRC)}{\sigma(2N\text{-}SRC)} \sim 0.1 = \lambda \qquad \frac{\sigma(3N\text{-}SRC)}{\sigma(2N\text{-}SRC)} \sim 0.15\text{-}0.2 \qquad \frac{\sigma(ppp\text{-}SRC)}{\sigma(3N\text{-}SRC)} \sim \lambda^2$$

[Science, 346:614 (2014)]

[M. Strikman priv. com. based on Phys.Rept. 76 (1981) 215-347]



$$\#ppp\text{-}SRC = \frac{\sigma(ppp\text{-}SRC)}{\sigma(pp\text{-}SRC)} \#pp\text{-}SRC$$

$$= \frac{\sigma(ppp\text{-}SRC)}{\sigma(3N\text{-}SRC)} \frac{\sigma(3N\text{-}SRC)}{\sigma(2N\text{-}SRC)} \frac{\sigma(2N\text{-}SRC)}{\sigma(pp\text{-}SRC)} \#pp\text{-}SRC$$

$$= 0.15\text{-}0.2\lambda \ \#pp\text{-}SRC$$

$$= 1.5\text{-}2\% \ \#pp\text{-}SRC$$

$\lambda^2$

$\lambda$

0.15-0.2

For ~ 1000 pp-SRC events, we expect 15-20 ppp-SRC