Probing nuclear effects with transverse kinematic imbalance

Stephen Dolan

For the T2K Collaboration

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Overview

Thanks for voting for my poster!!!

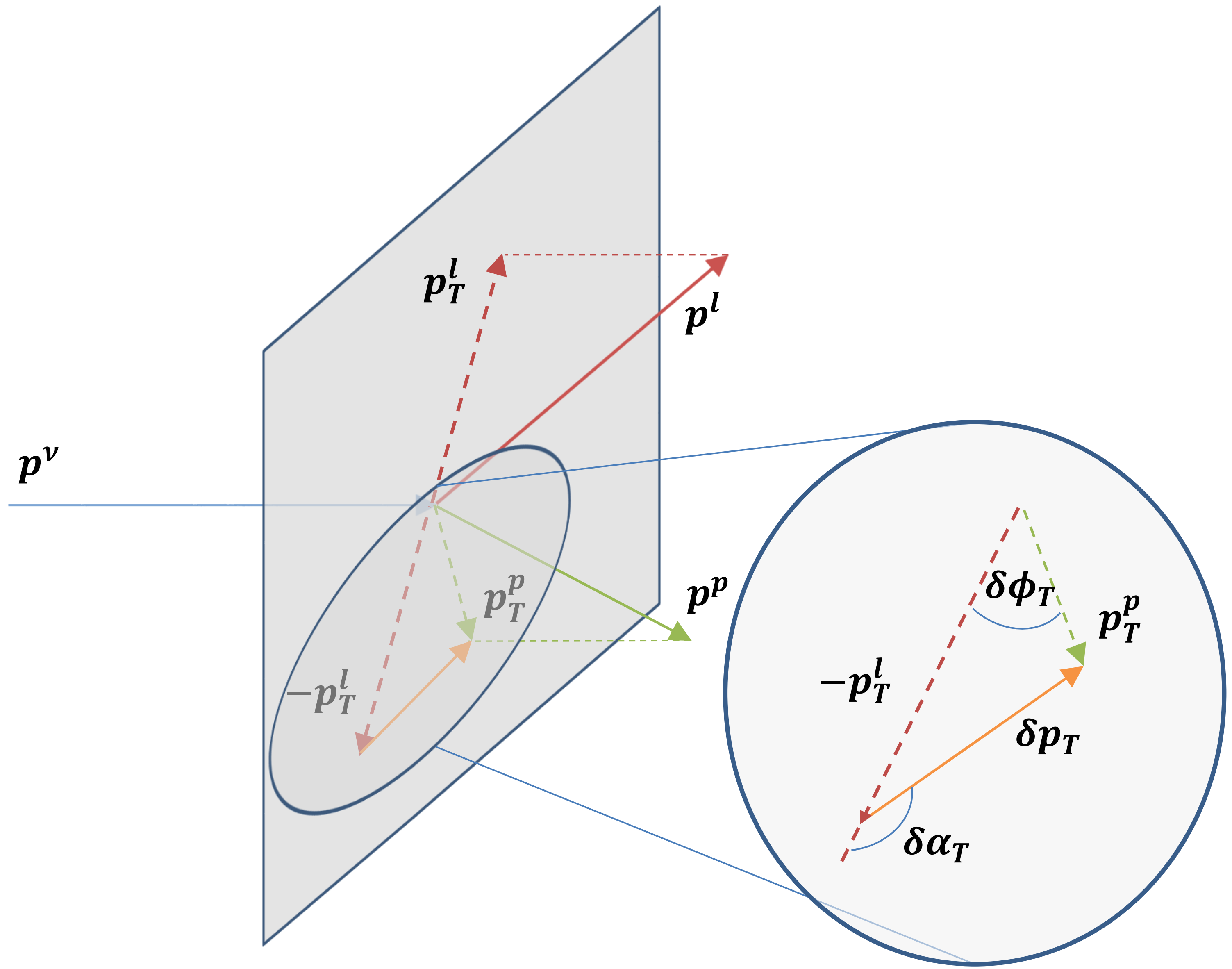
Described the measurement of a $\mathbf{CC0\pi + Np\ (N \geq 1)}$ cross section as a function of the **single transverse variables**

I presented the highlights of this analysis yesterday.

This talk will contain:

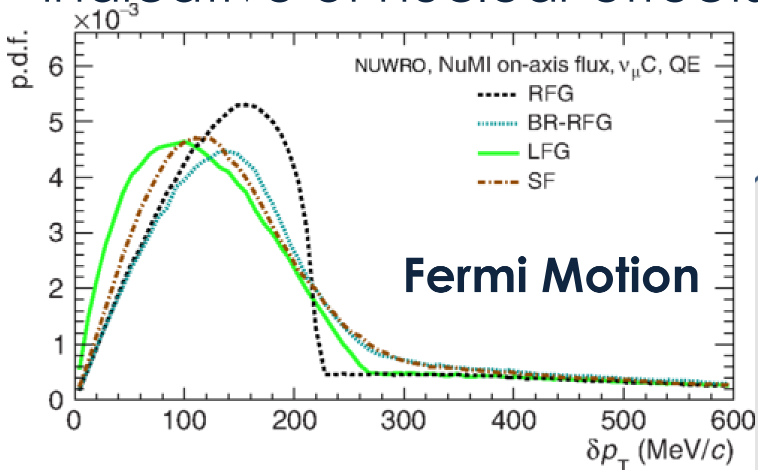
- A quick recap
- A closer look at the generator comparisons

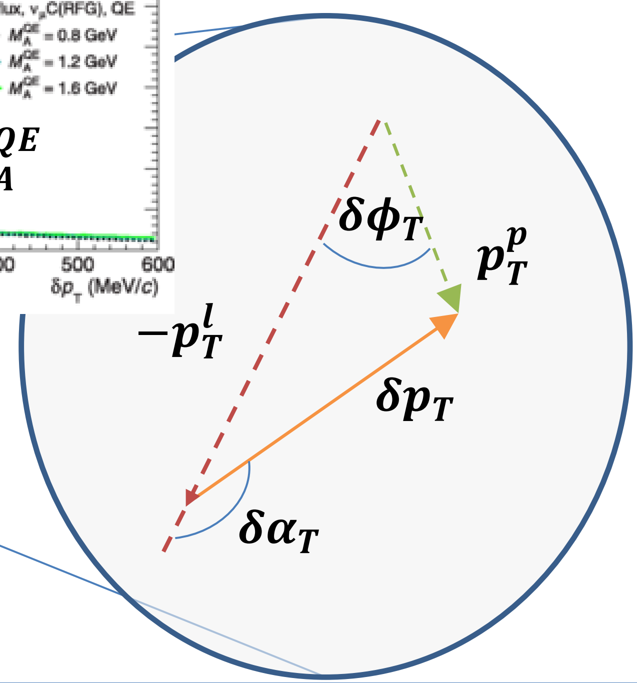
Single Transverse Variables

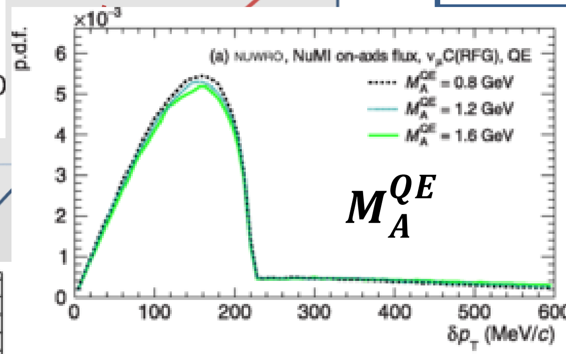


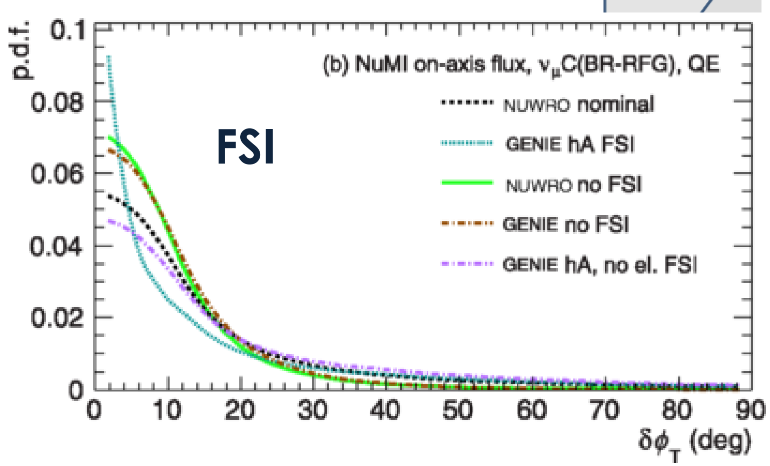
Single Transverse Variables

Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects









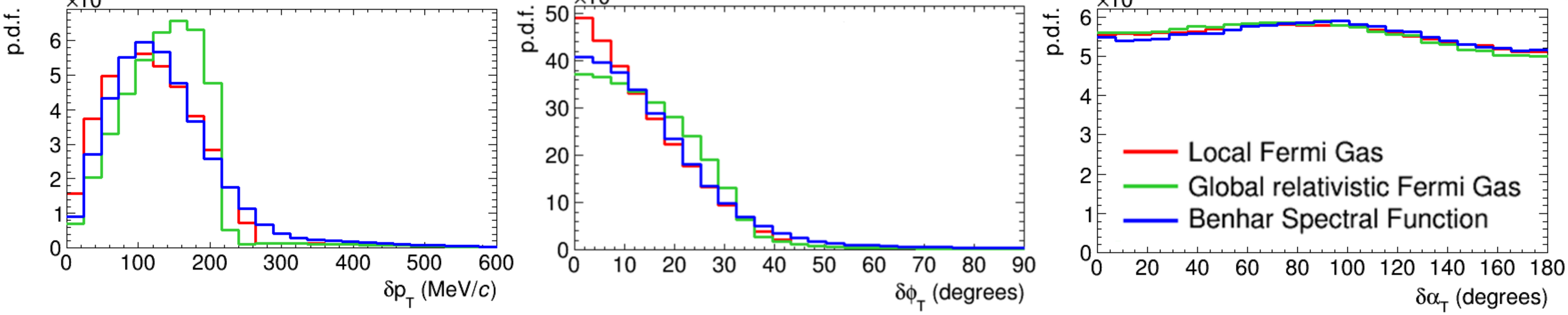
Phys. Rev. C **94**, 015503 (2016)

- Demonstrates interesting sensitivity to nuclear effects for **exclusive interaction modes**

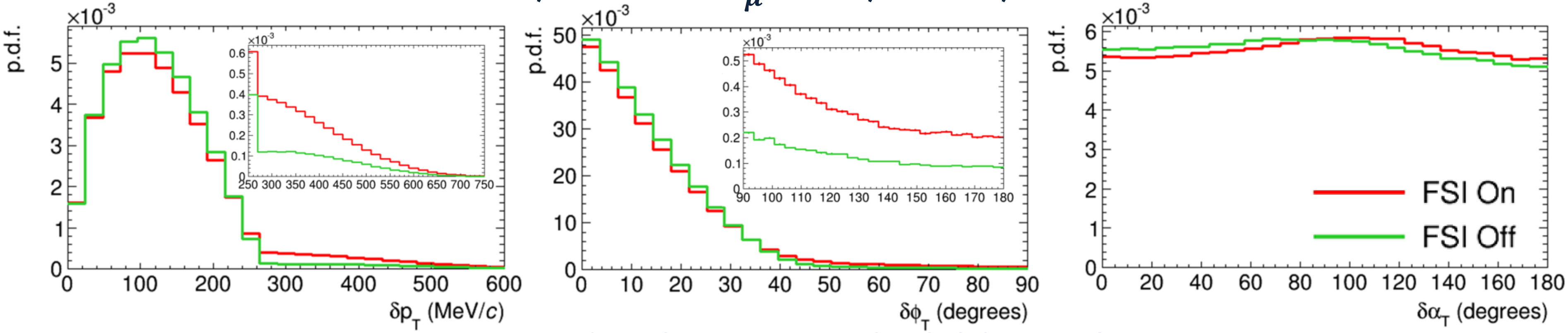
CC0π in STV - Fermi Motion and FSI

- Moving from CCQE→CC0Pi+Np, STV still a probe of nuclear effects

O. Benhar, *et al.*, Phys. Rev. D **72**, 053005 (2005)



NuWro, 0.6 GeV ν_μ on C, CC0π, FSI Off



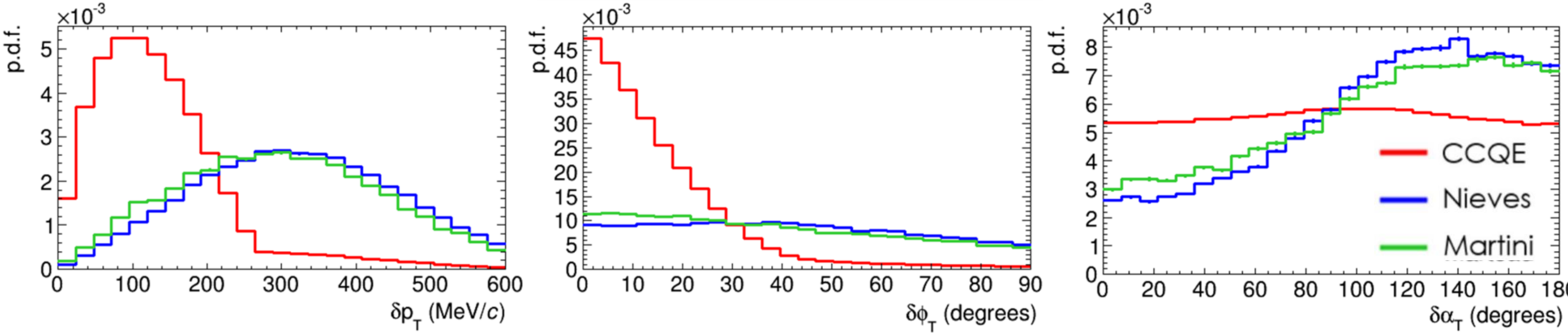
NuWro, 0.6 GeV ν_μ on C, CC0π, LFG

Quasi-real CC0Pi selection, keep events within rough ND280 acceptance :

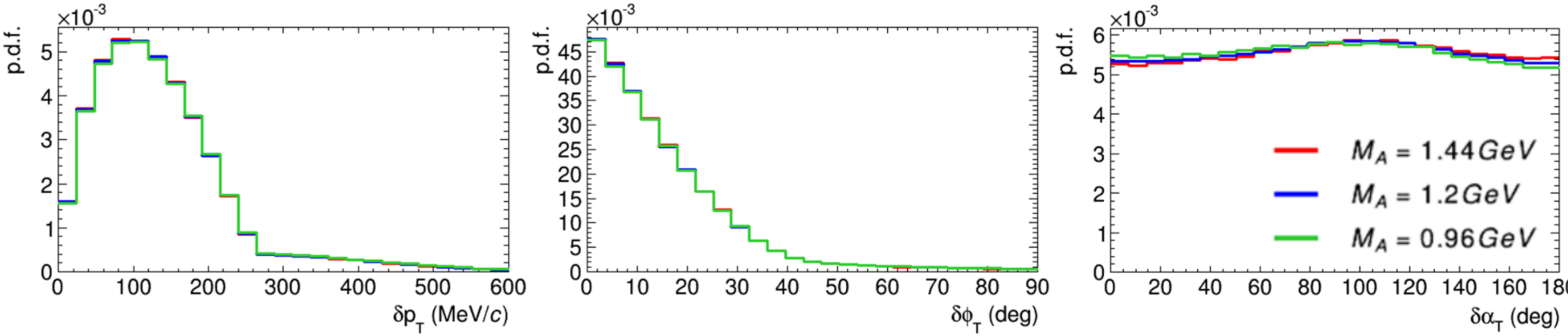
No Pions, 1 Muon, >0 Protons. $p_\mu > 250\ MeV, p_p > 450\ MeV, \cos(\theta_\mu) > -0.6, \cos(\theta_p) > 0.4$

CC0π in STV - 2p2h and M_A

M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **80**, 065501 (2009)   J. Nieves, I. R. Simo, and M. J. V. Vacas, Phys. Rev. C **83**, 045501 (2011)



NuWro, 0.6 GeV ν_μ on C, CC0π, FSI On, LFG



NuWro, 0.6 GeV ν_μ on C, CC0π, FSI On, LFG

- STV shape invariant with M_A
  - No ambiguity over M_A or nuclear effect contributions (MiniBooNE M_A puzzle)

CC0π in STV - 2p2h and M_A

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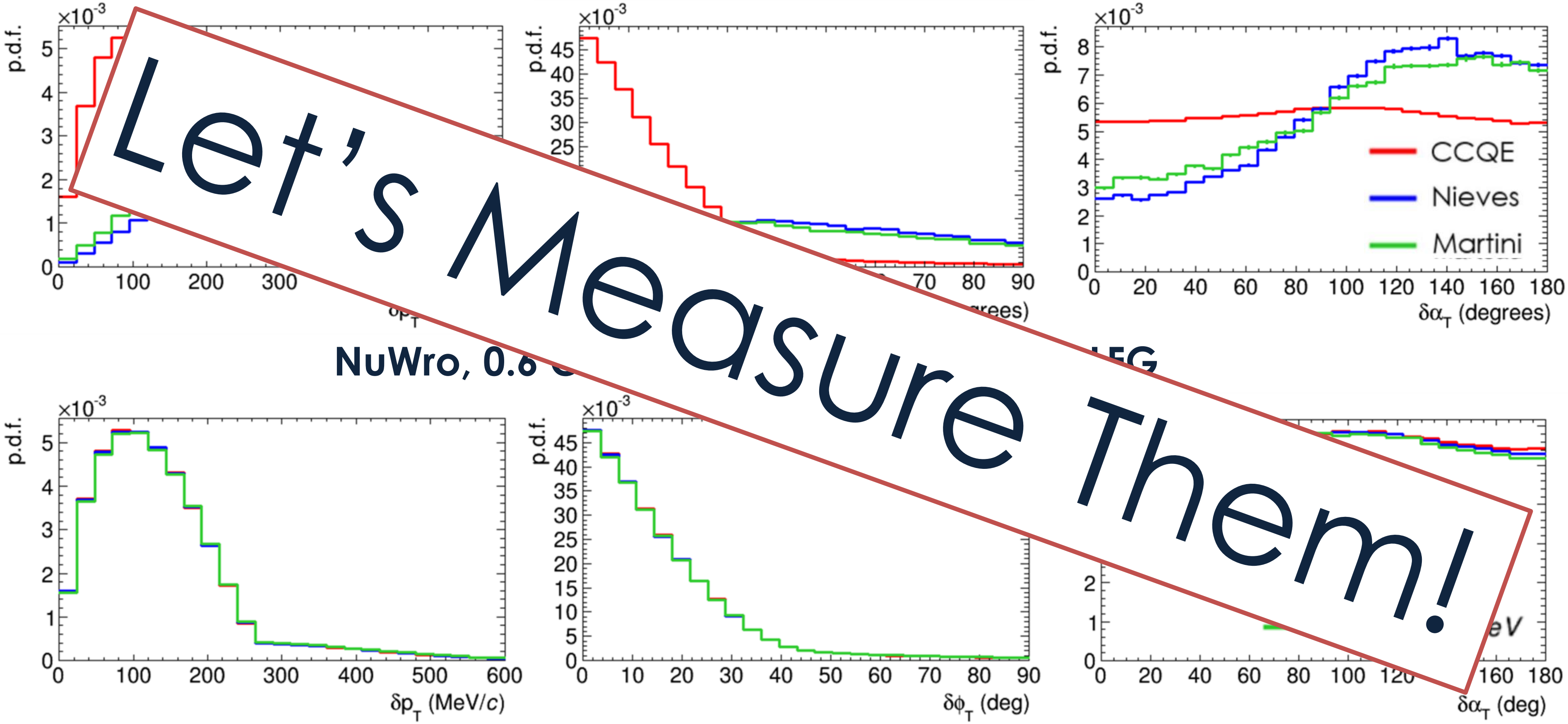
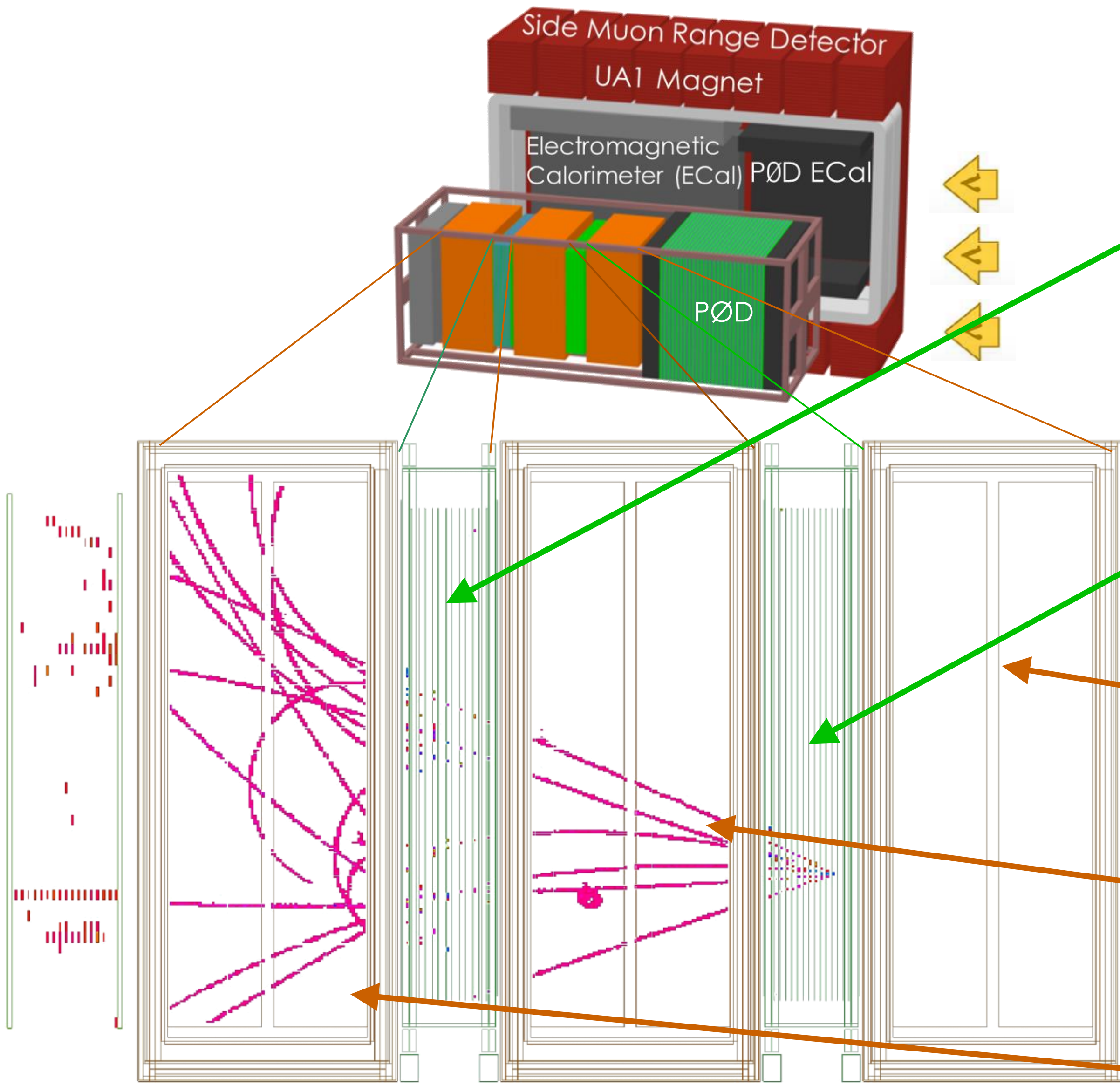


NuWro, 0.6 GeV ν_μ on C, CC0π, FSI On, LFG

- STV shape invariant with M_A
  - No ambiguity over M_A or nuclear effect contributions (MiniBooNE M_A puzzle)

ND280 (off axis near detector)



Muon neutrino beam
0.6 GeV peak energy

Fine-Grained Detectors (FGD 1 & 2):

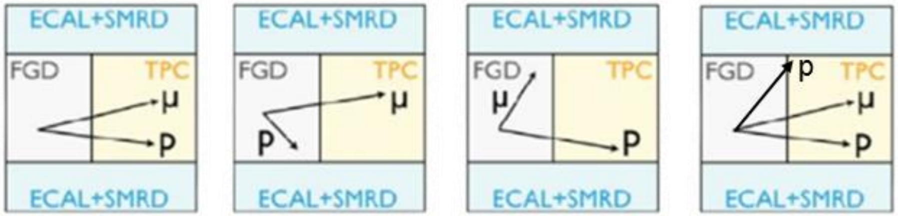
- CH scintillator tracker
- Target for ν
- FGD2 contains water

Time Projection Chambers (TPC):

- Excellent tracking
- High-res charged-particle momenta
- Accurate particle ID

Event Selection

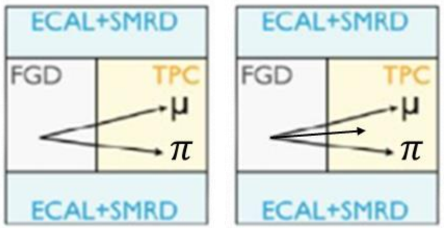
Signal



- Require one μ-like and p-like track(s) starting in FGD1 (CH target)
- Use a Michel electron tag and ECal EM shower veto to reject 1π backgrounds
- Use of many samples gives wide kinematic acceptance

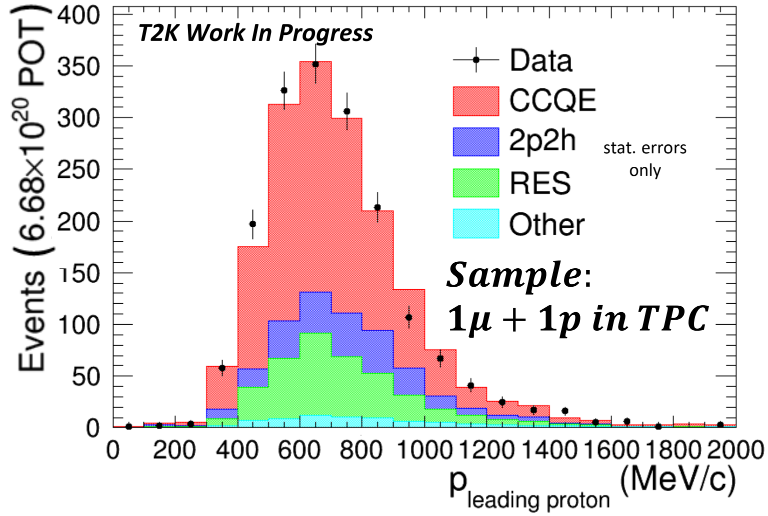
Sidebands

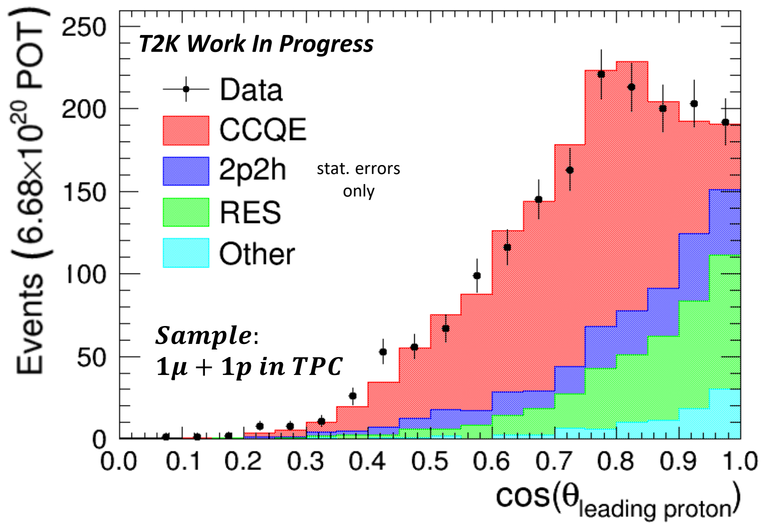
- Require extra π-like track(s)



CC1π CCOther

Reconstructed kinematics





NEUT 5.3.3.2; Benhar SF; $M_A = 1.21$;
Nieves et al. 2p2h; Area normalised to data

O. Benhar, *et al.*, Phys. Rev. D **72**, 053005 (2005)
J. Nieves, I. R. Simo, and M. J. V. Vacas, Phys. Rev. C **83**, 045501 (2011)

CC0π+Np in STV

Signal Definition

- One muon
- At least one proton
- Nothing else
- Adhere to fiducial constraints

- Measure **fiducial** flux-integrated **CC0$\boldsymbol{\pi + Np}$** cross section **in bins of STV**
- Restrict cross section to ND280 acceptance
  - *Essential to mitigate model-dependence of acceptance correction*

$$p_\mu > 250\ MeV/c$$
$$\cos(\theta_\mu) > -0.6$$
$$450\ MeV/c < p_p < 1\ GeV/c$$
$$\cos(\theta_p) > 0.4$$

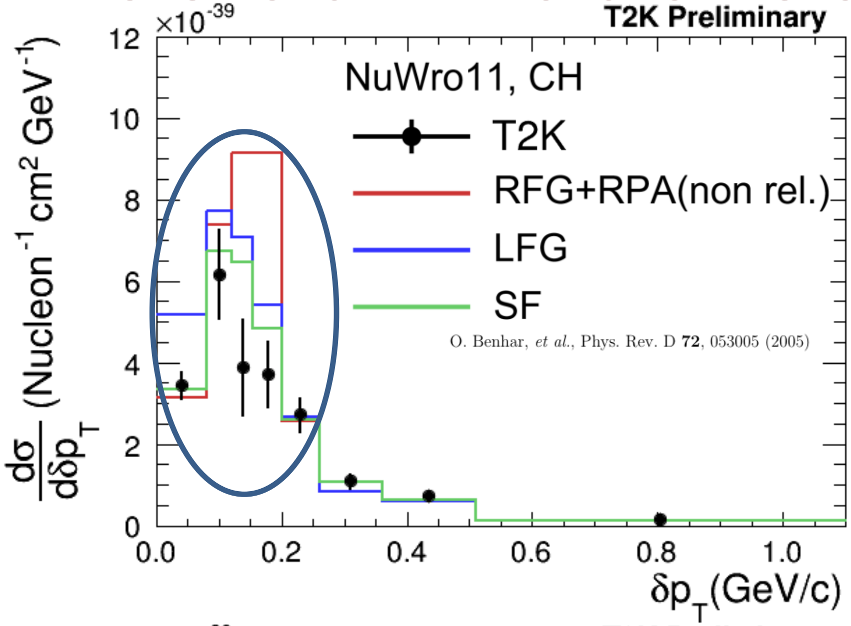
- Extract cross section using **a binned likelihood fit** with a **data driven** regularisation
- Compare results to predictions available from plethora of generators using NUISANCE

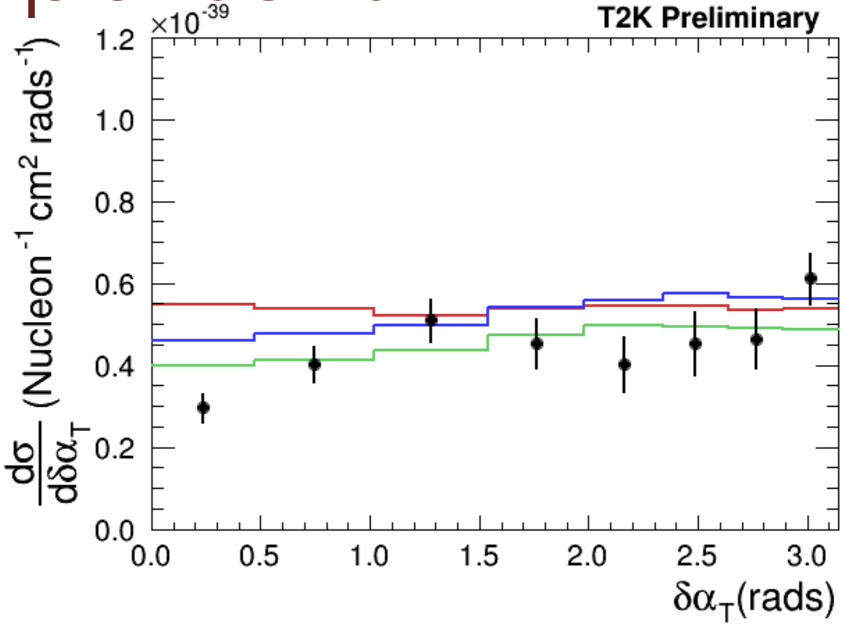
For details of unfolding and how model dependence is avoided:

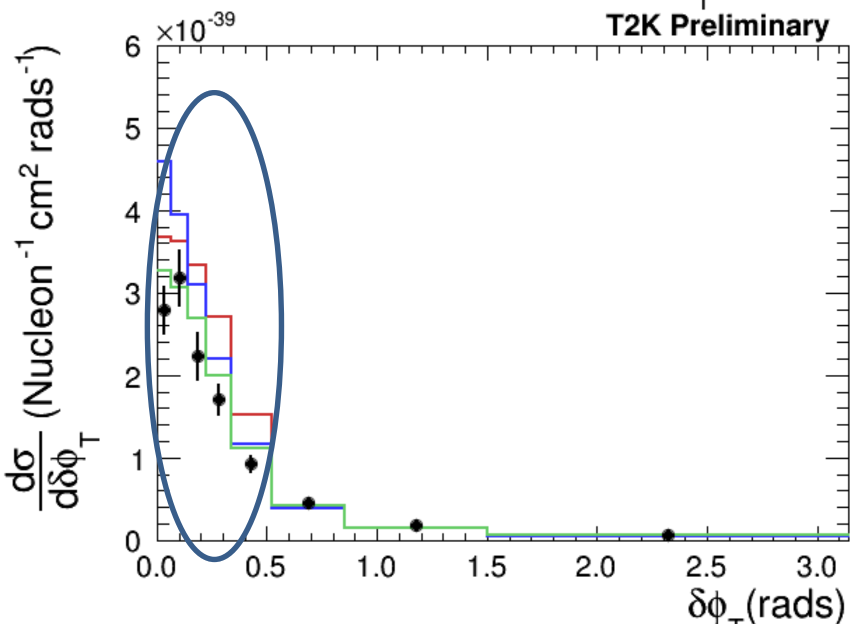
See slides from State of The Nu-tion

Detector: ND280 – FGD1 **Target:** CH **Signal:** CC0π+Np **Variables:** single-transverse **Status:** Paper in preparation

Nuclear model comparisons

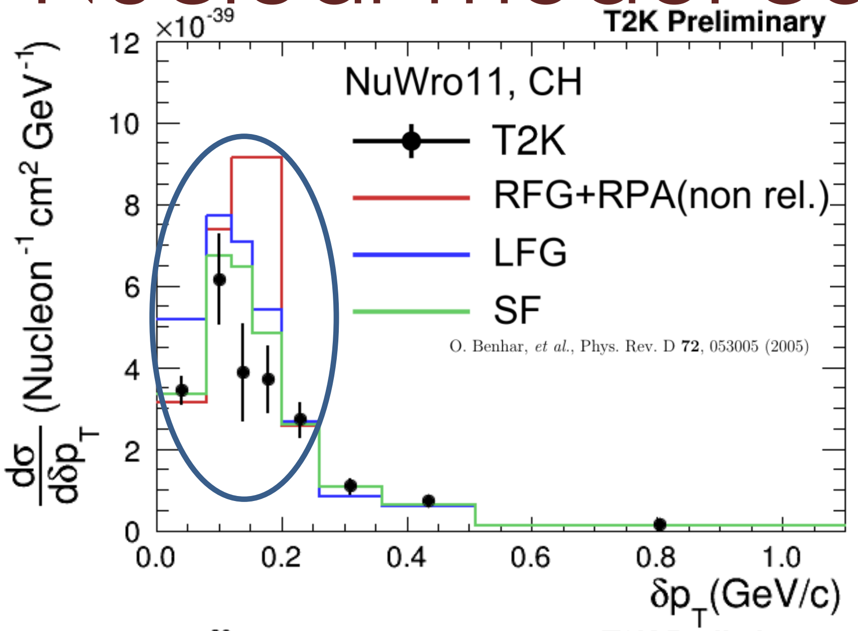


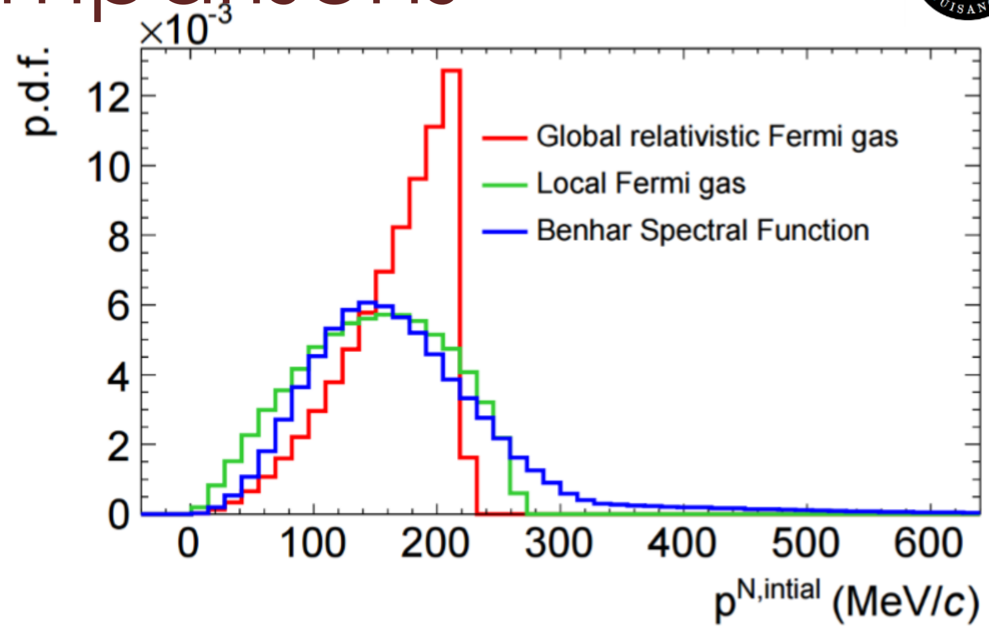


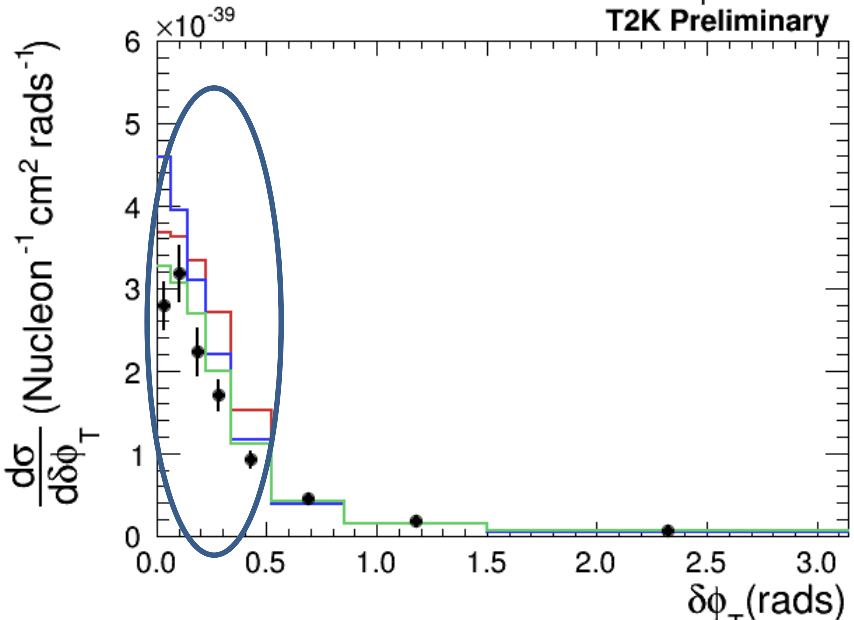


- The peak position and early bins in δp_T and $\delta \phi_T$ tell us about **Fermi Motion**.

Nuclear model comparisons

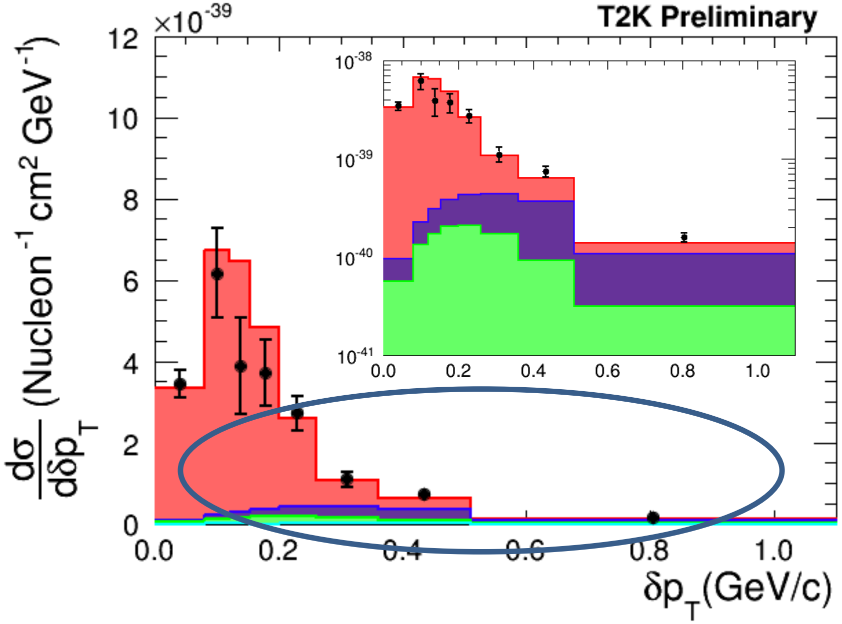


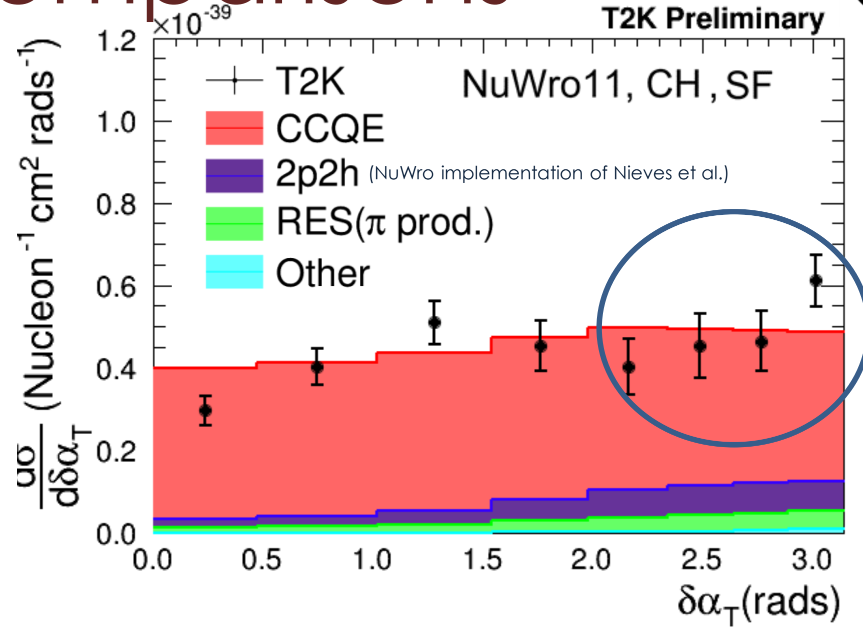


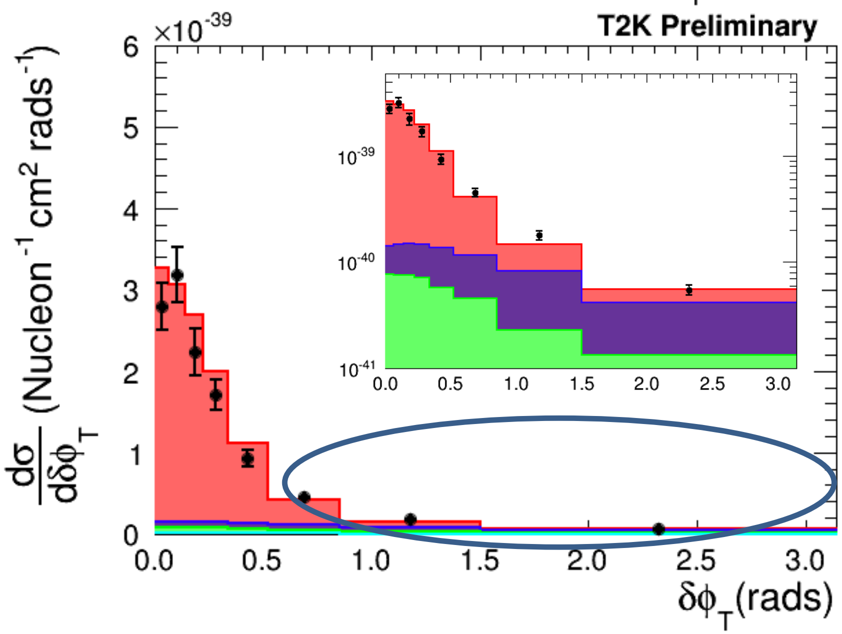


- The peak position and early bins in δp_T and $\delta\phi_T$ tell us about **Fermi Motion**.

Interaction mode comparisons

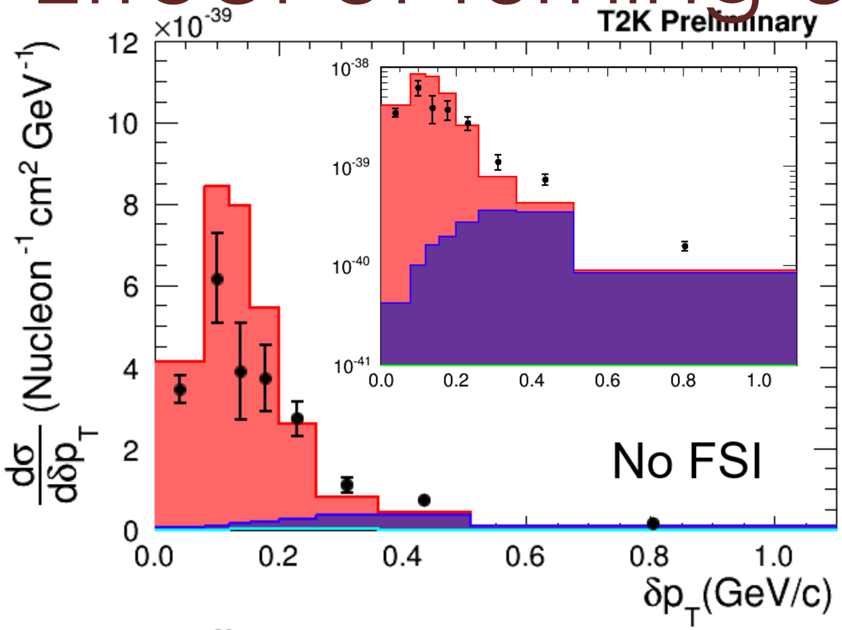


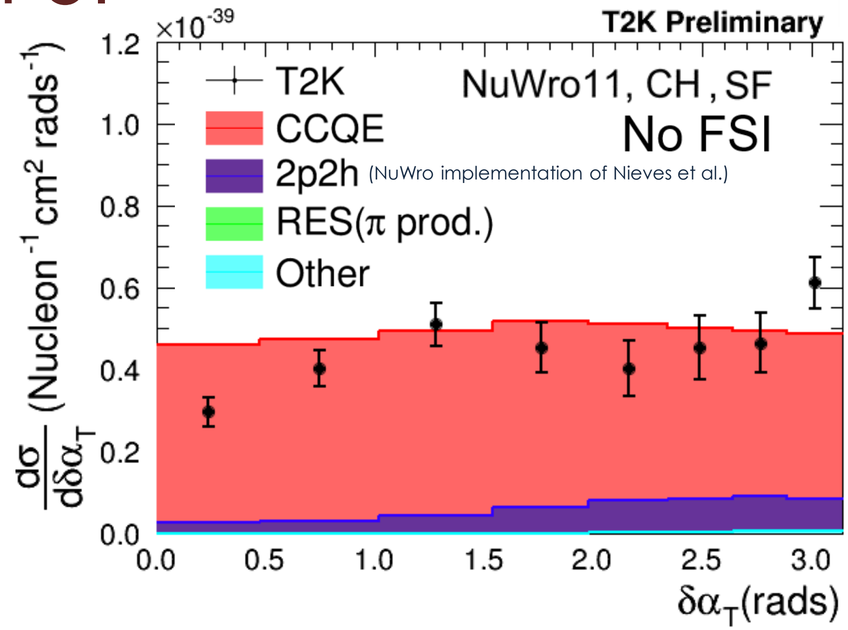


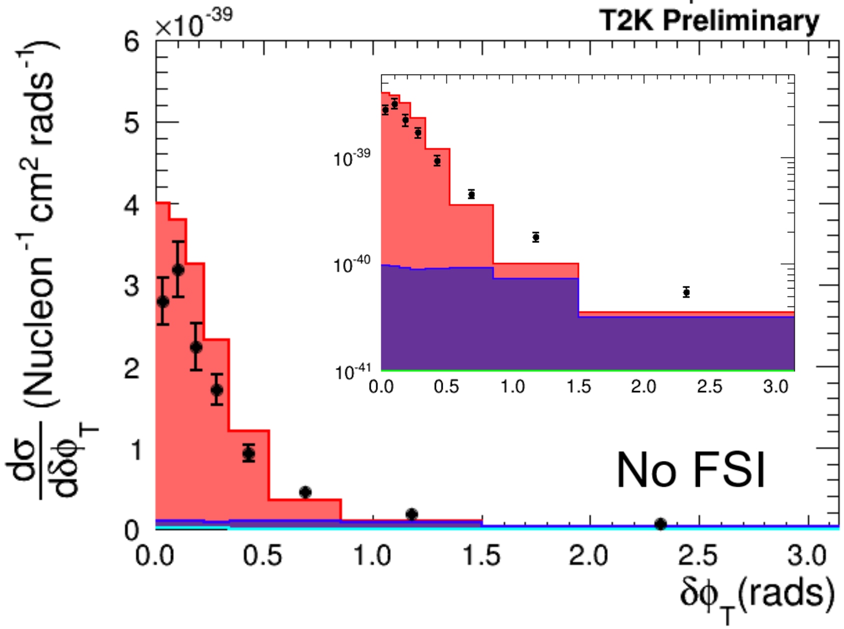


- The peak position and early bins in δp_T and $\delta\phi_T$ tell us about **Fermi Motion**.
- The tails in δp_T and $\delta\phi_T$ and the extent of the rise at large $\delta\alpha_T$ partially isolate the effects of Fermi Motion from **2p2h**.

Effect of turning off FSI

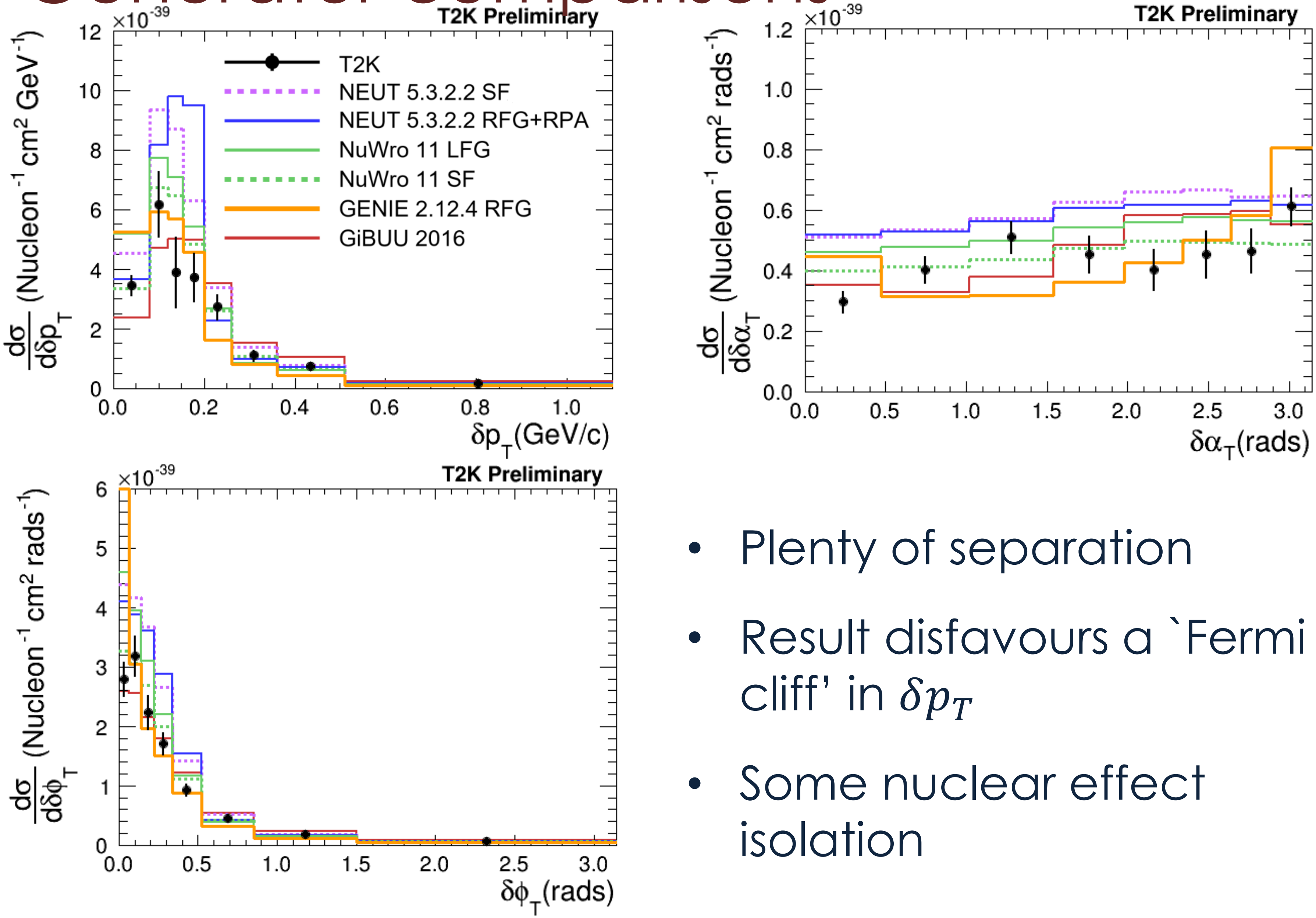






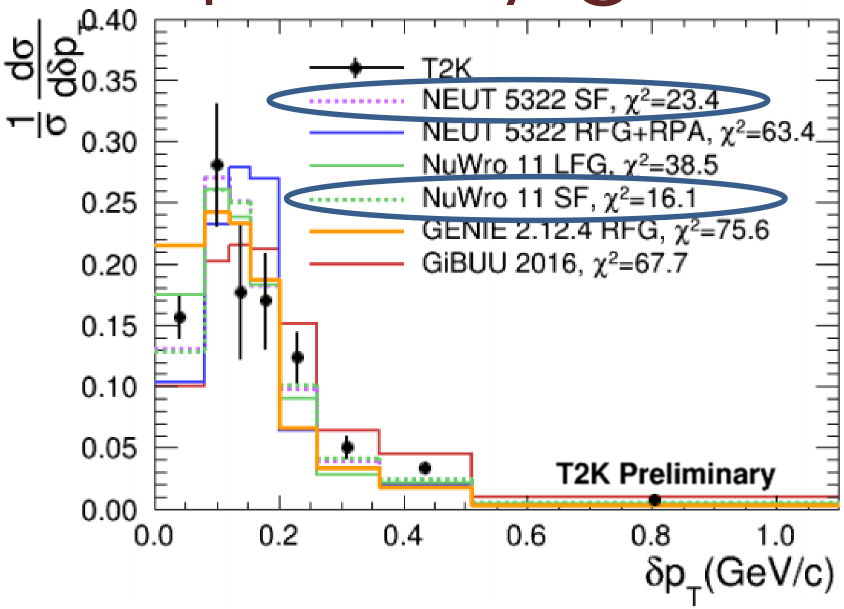
- The peak position and early bins in δp_T and $\delta\phi_T$ tell us about **Fermi Motion**.
- The tails in δp_T and $\delta\phi_T$ and the extent of the rise at large $\delta\alpha_T$ partially isolate the effects of Fermi Motion from **2p2h**.
- The removal of **FSI** causes a relative deficit of events in the tails, but an increased normalisation.

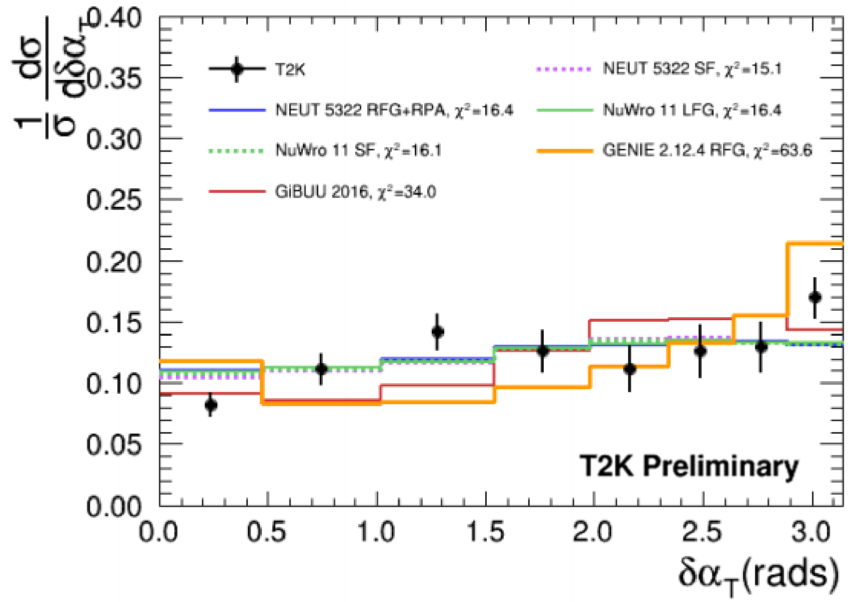
Generator comparisons

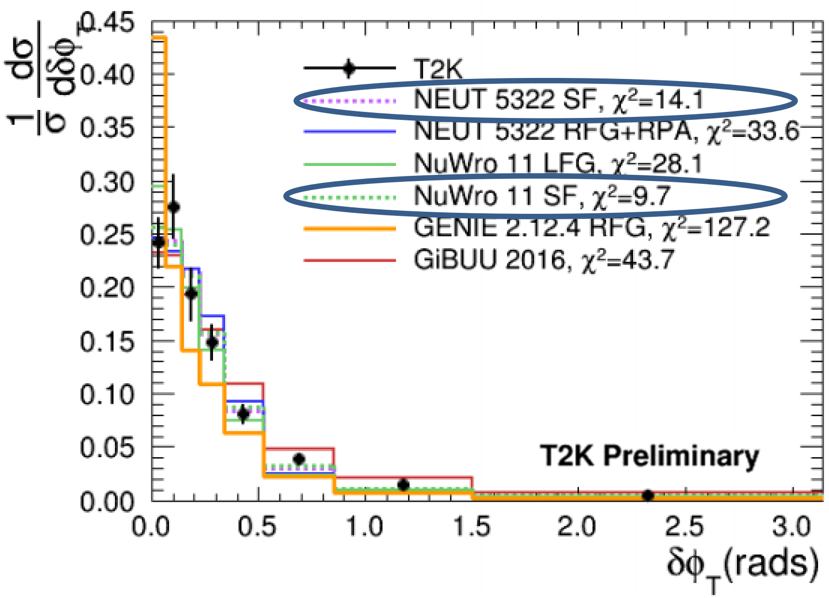


- Plenty of separation
- Result disfavours a `Fermi cliff' in δp_T
- Some nuclear effect isolation

Shape only generator comparisons

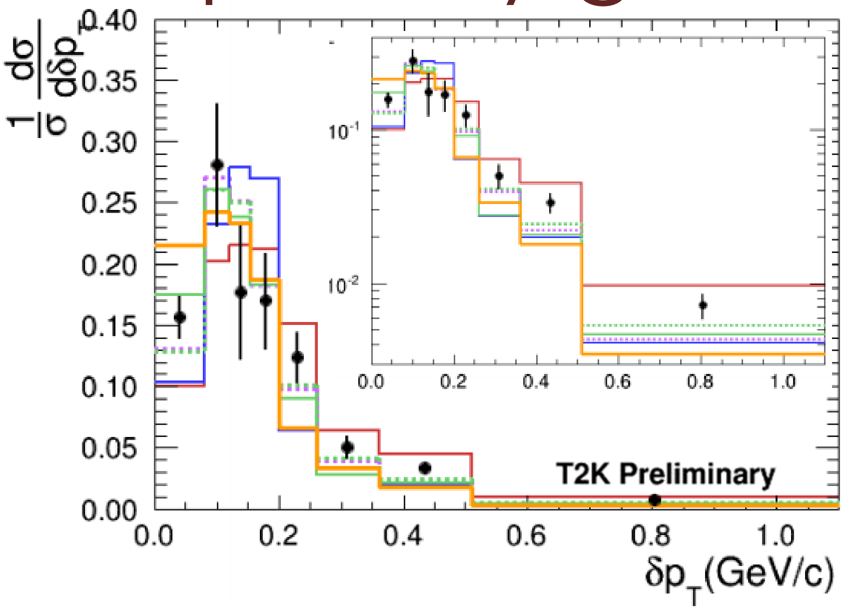


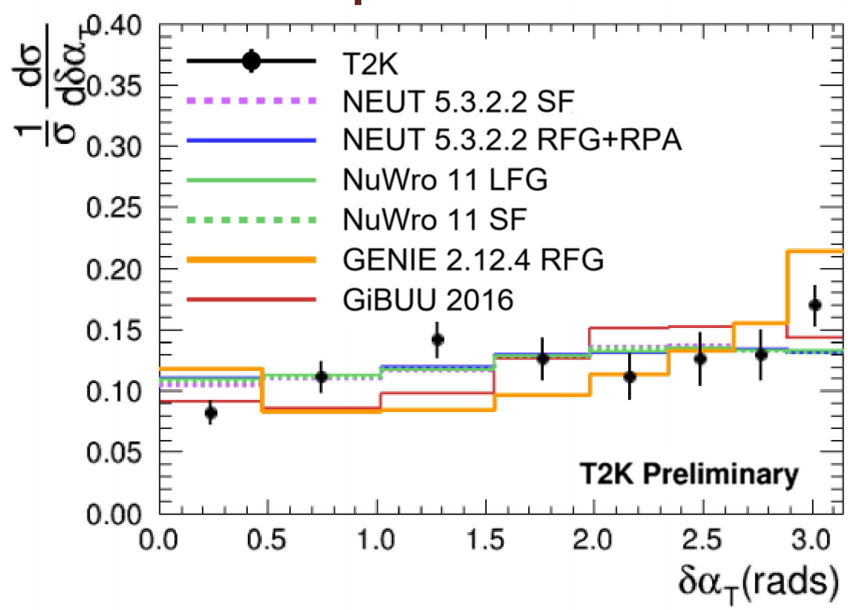


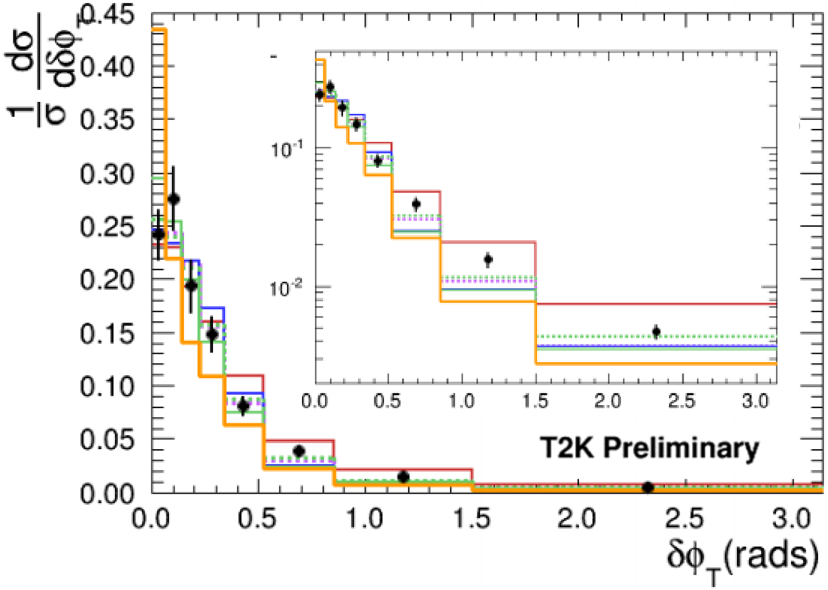


- Preference for a SF + 2p2h franken-model

Shape only generator comparisons

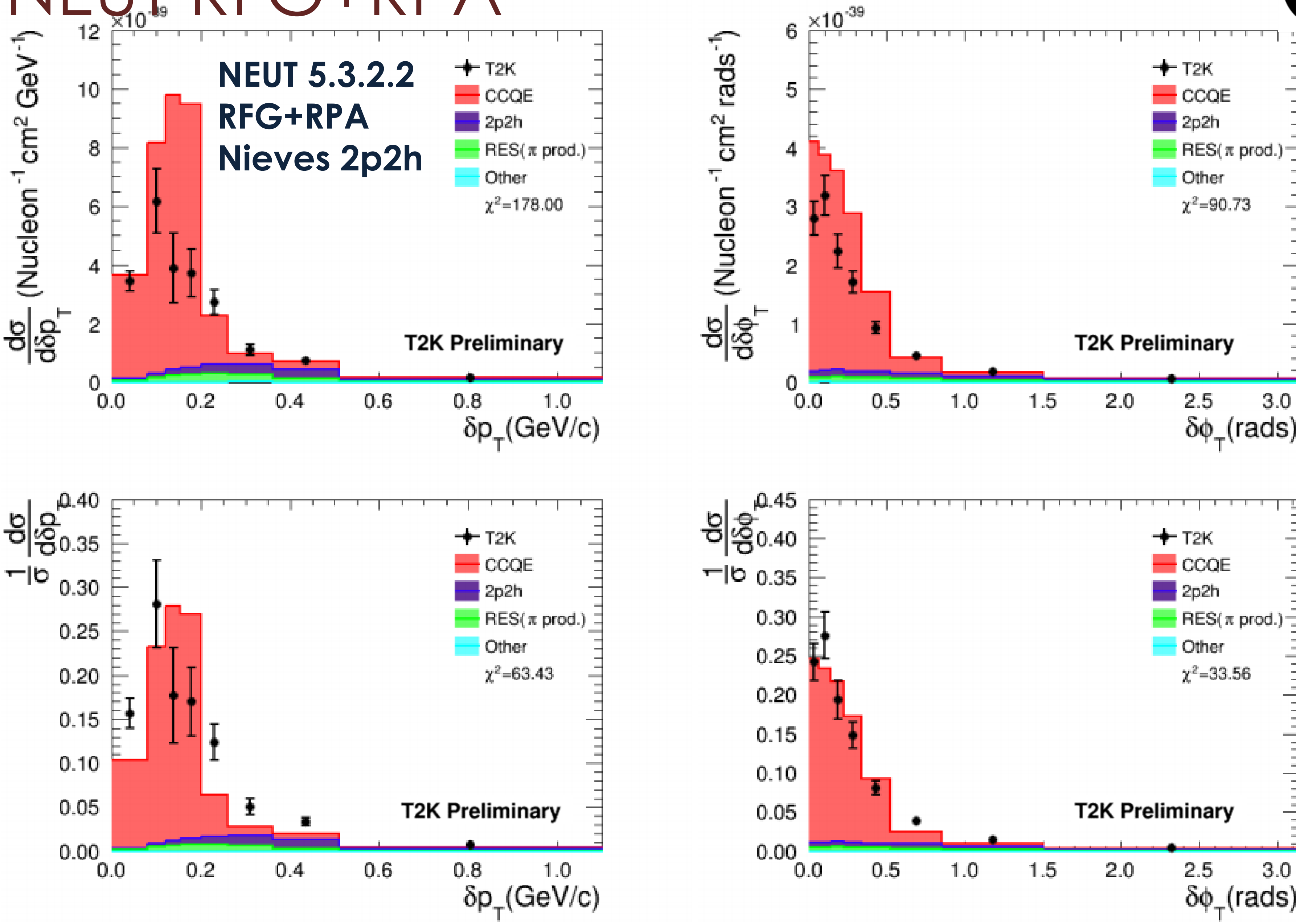




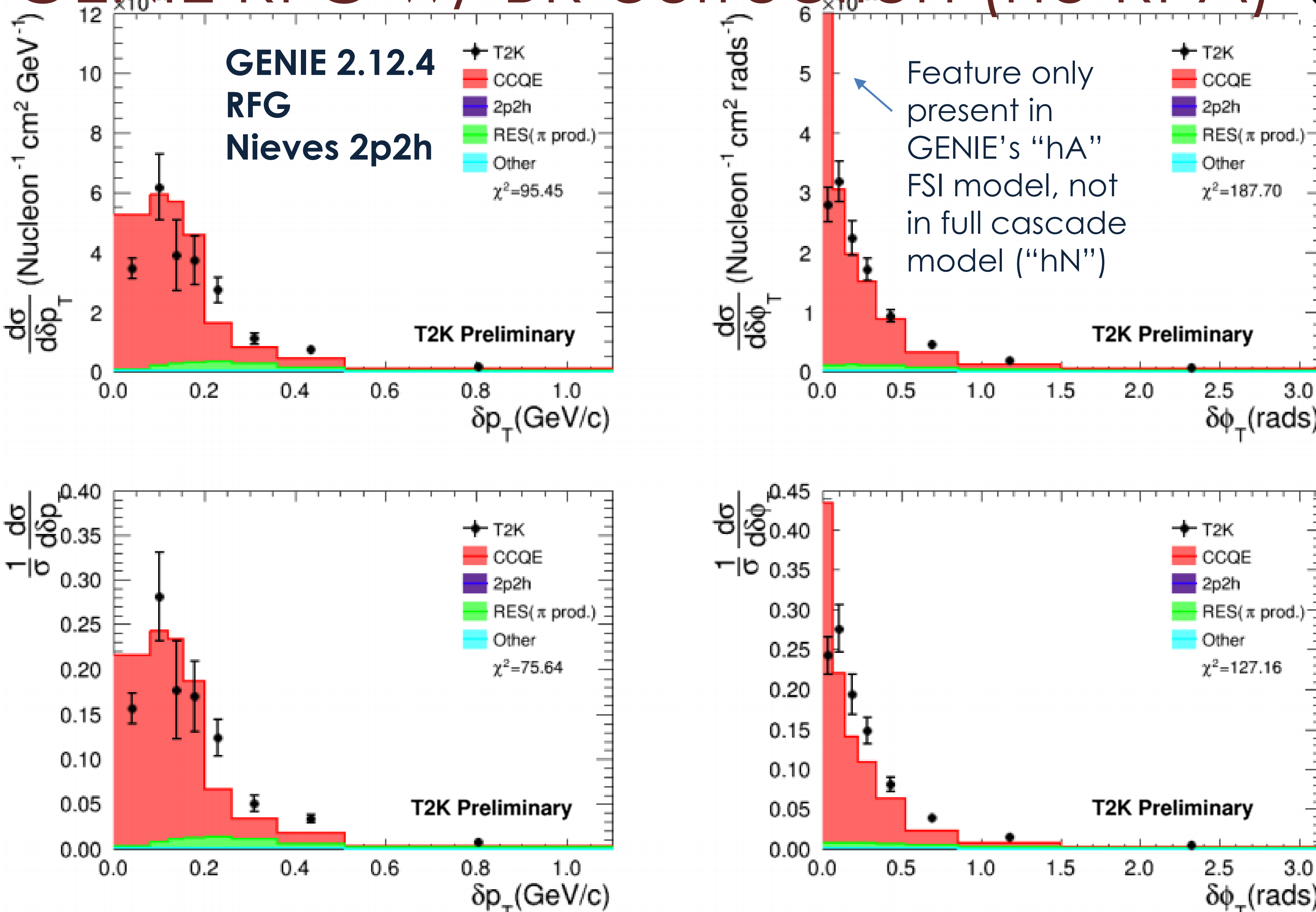


- Preference for a SF + 2p2h franken-model
- Relative excess in the 2p2h enhanced region (for all but GiBUU)

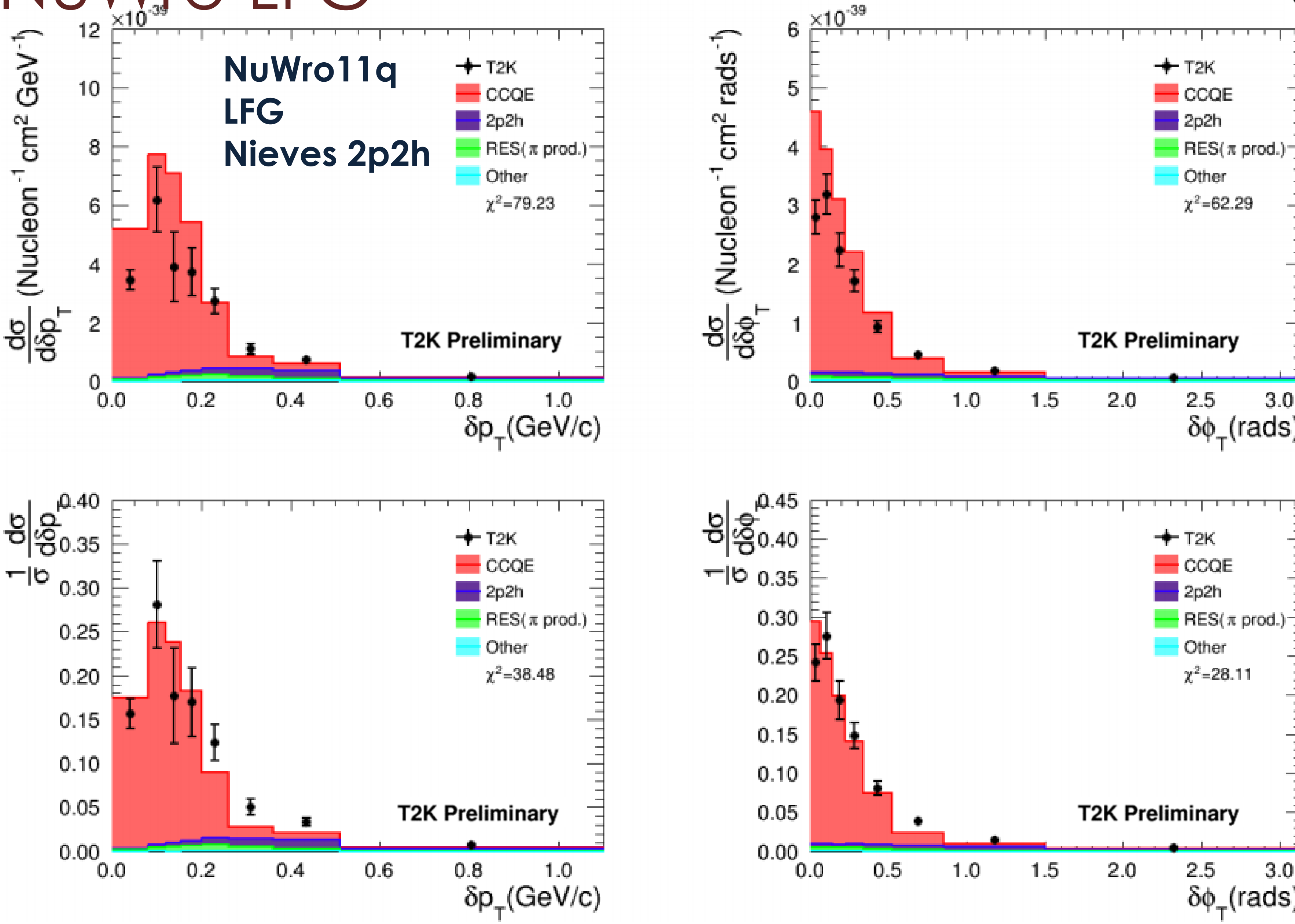
NEUT RFG+RPA


NEUT 5.3.2.2
RFG+RPA
Nieves 2p2h
T2K
CCQE
2p2h
RES(π prod.)
Other
χ²=178.00
χ²=90.73
χ²=63.43
χ²=33.56
T2K Preliminary
×10⁻³⁹
dσ/dδp_T (Nucleon⁻¹ cm² GeV⁻¹)
dσ/dδφ_T (Nucleon⁻¹ cm² rads⁻¹)
1/σ dσ/dδp_T
1/σ dσ/dδφ_T
δp_T(GeV/c)
δφ_T(rads)
0.0
0.2
0.4
0.6
0.8
1.0
0.5
1.5
2.0
2.5
3.0

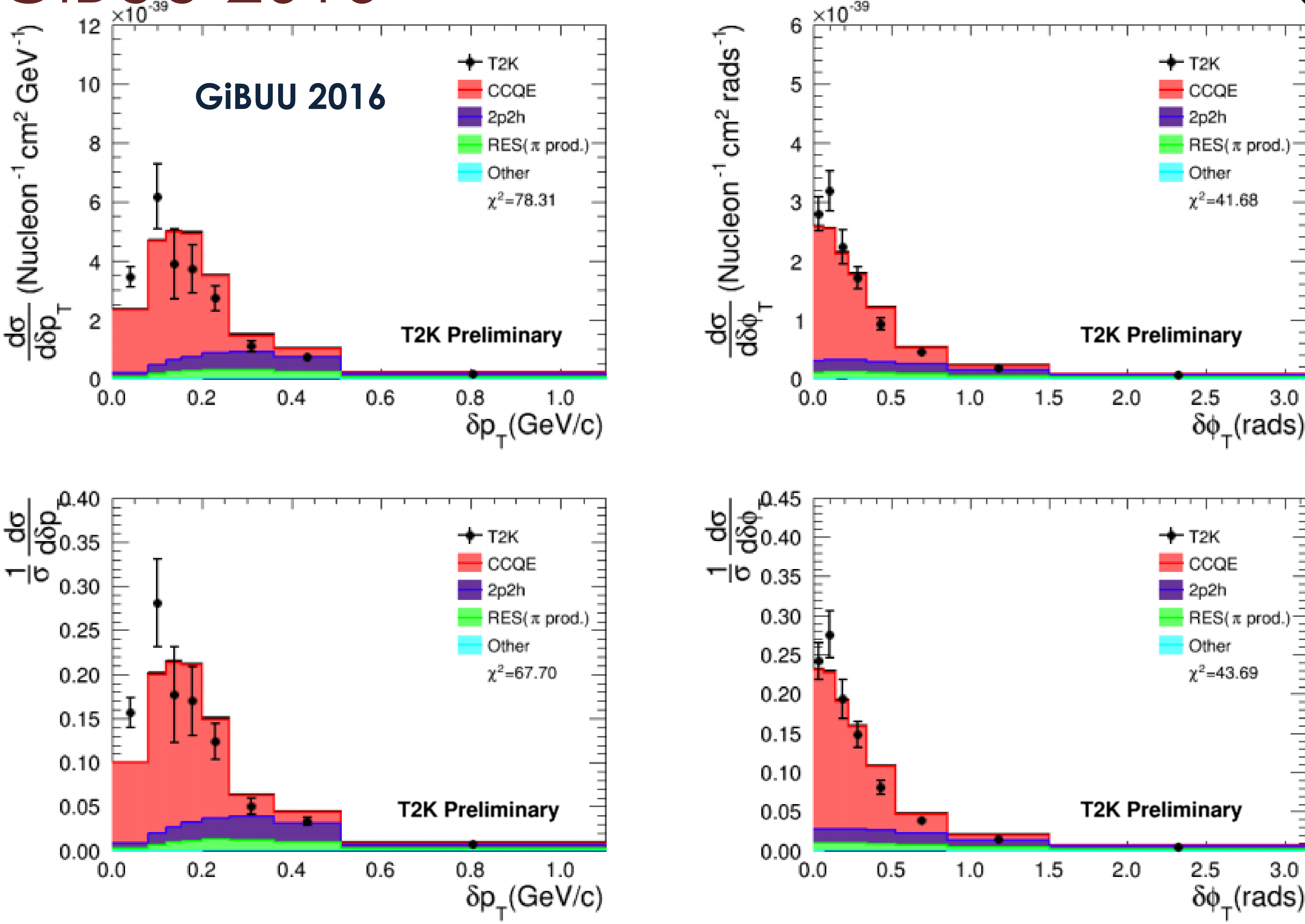
GENIE RFG w/ BR correction (no RPA)



NuWro LFG


NuWro11q
LFG
Nieves 2p2h
T2K
CCQE
2p2h
RES(π prod.)
Other
χ²=79.23
χ²=62.29
χ²=38.48
χ²=28.11
T2K Preliminary
×10⁻³⁹
dσ/dδp_T (Nucleon⁻¹ cm² GeV⁻¹)
dσ/dδφ_T (Nucleon⁻¹ cm² rads⁻¹)
1/σ dσ/dδp_T
1/σ dσ/dδφ_T
δp_T(GeV/c)
δφ_T(rads)

GiBUU 2016



GiBUU 2016
T2K
CCQE
2p2h
RES(π prod.)
Other
χ²=78.31
χ²=41.68
χ²=67.70
χ²=43.69
T2K Preliminary
×10⁻³⁹
dσ/dδp_T (Nucleon⁻¹ cm² GeV⁻¹)
dσ/dδφ_T (Nucleon⁻¹ cm² rads⁻¹)
1/σ dσ/dδp_T
1/σ dσ/dδφ_T
δp_T (GeV/c)
δφ_T (rads)

Summary

Lots of interesting model separation!

- **Shape**: idep. of M_A^{QE} $\rightarrow$ tells us about:
  - Fermi Motion
  - FSI
  - 2p2h

  Characterised by separate STV features

- **Full xsec**: normalisation is sensitive to: nucleon FSI, M_A^{QE} and RPA

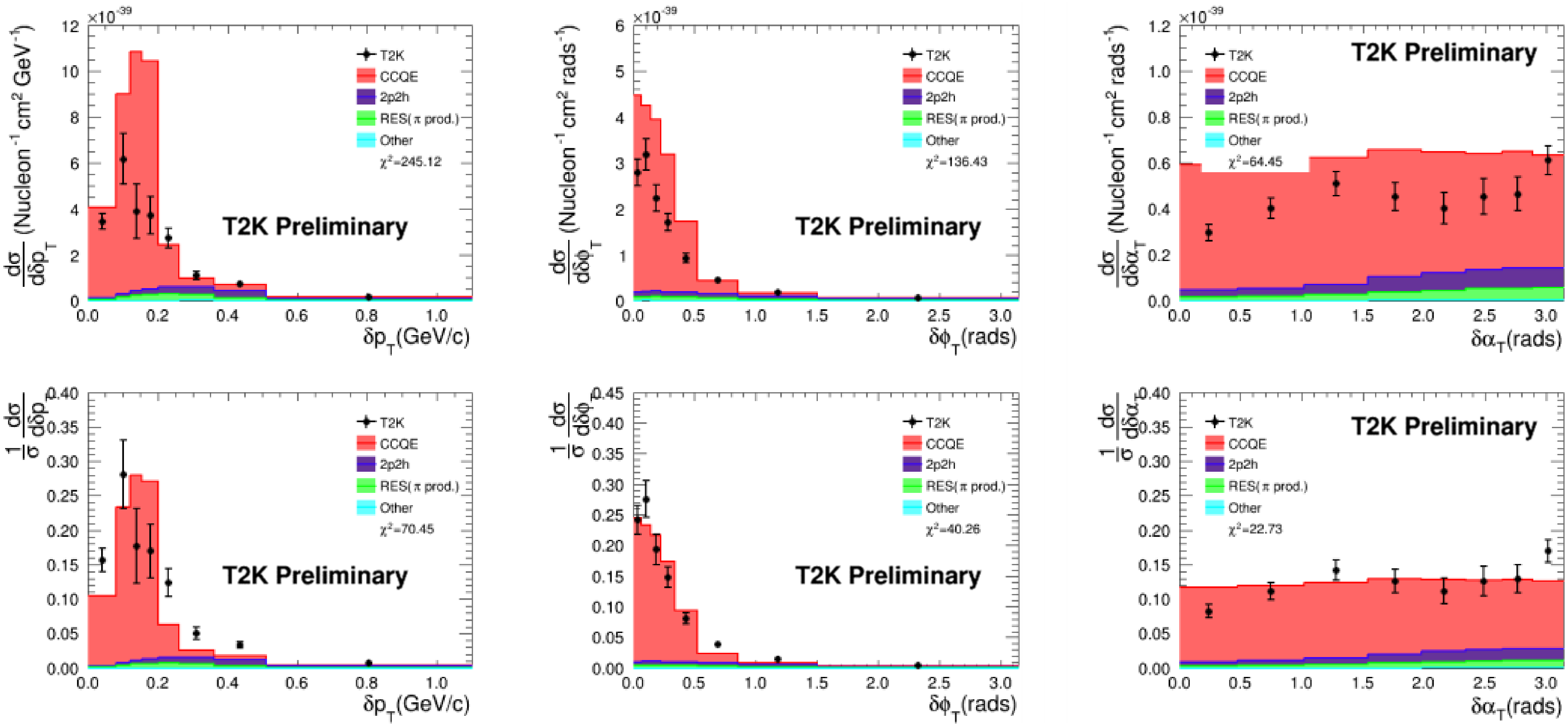
- **Results lift important degeneracies**

Thank you for listening

BACKUPS

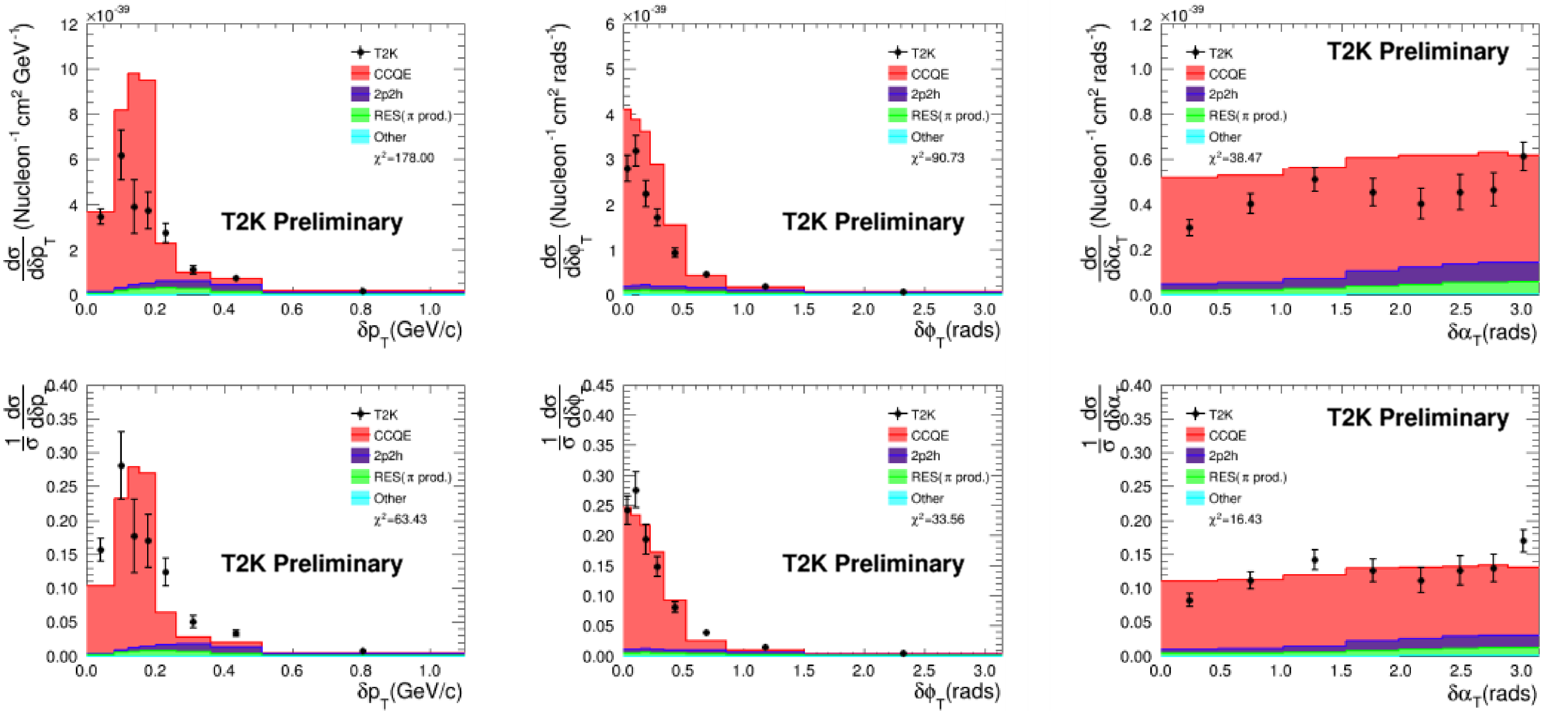
Impact of RPA (relativistic)

NEUT 5.3.2.2 RFG + RPA (relativistic), $M_A = 1.03\ GeV$, 2p2h is Nieves et. al

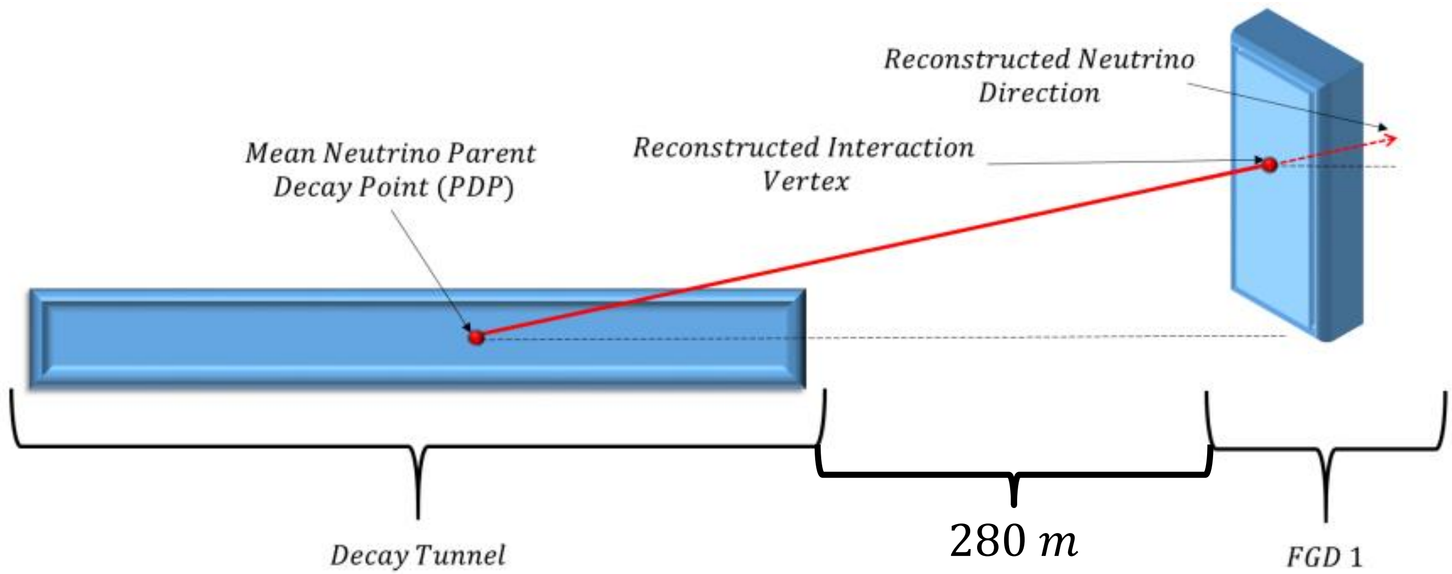


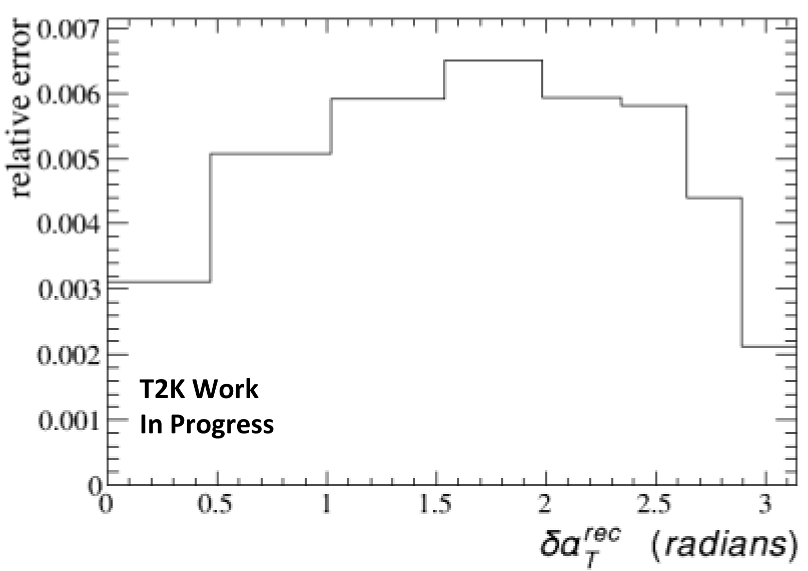
Impact of RPA (relativistic)

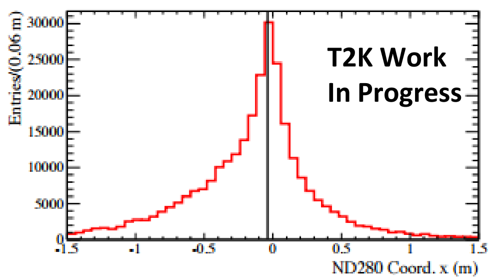
NEUT 5.3.2.2 RFG, no RPA, $M_A = 1.03\ GeV$, 2p2h is Nieves et. al

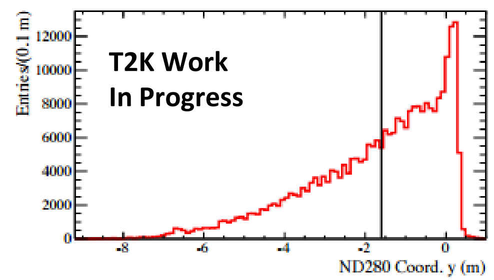


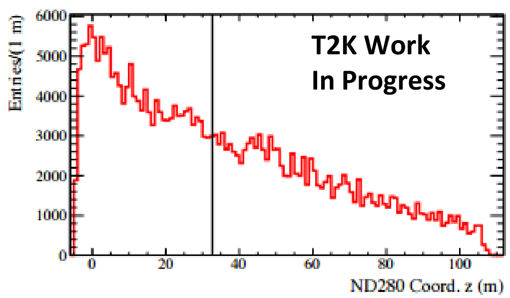
Reconstructing the Neutrino Direction





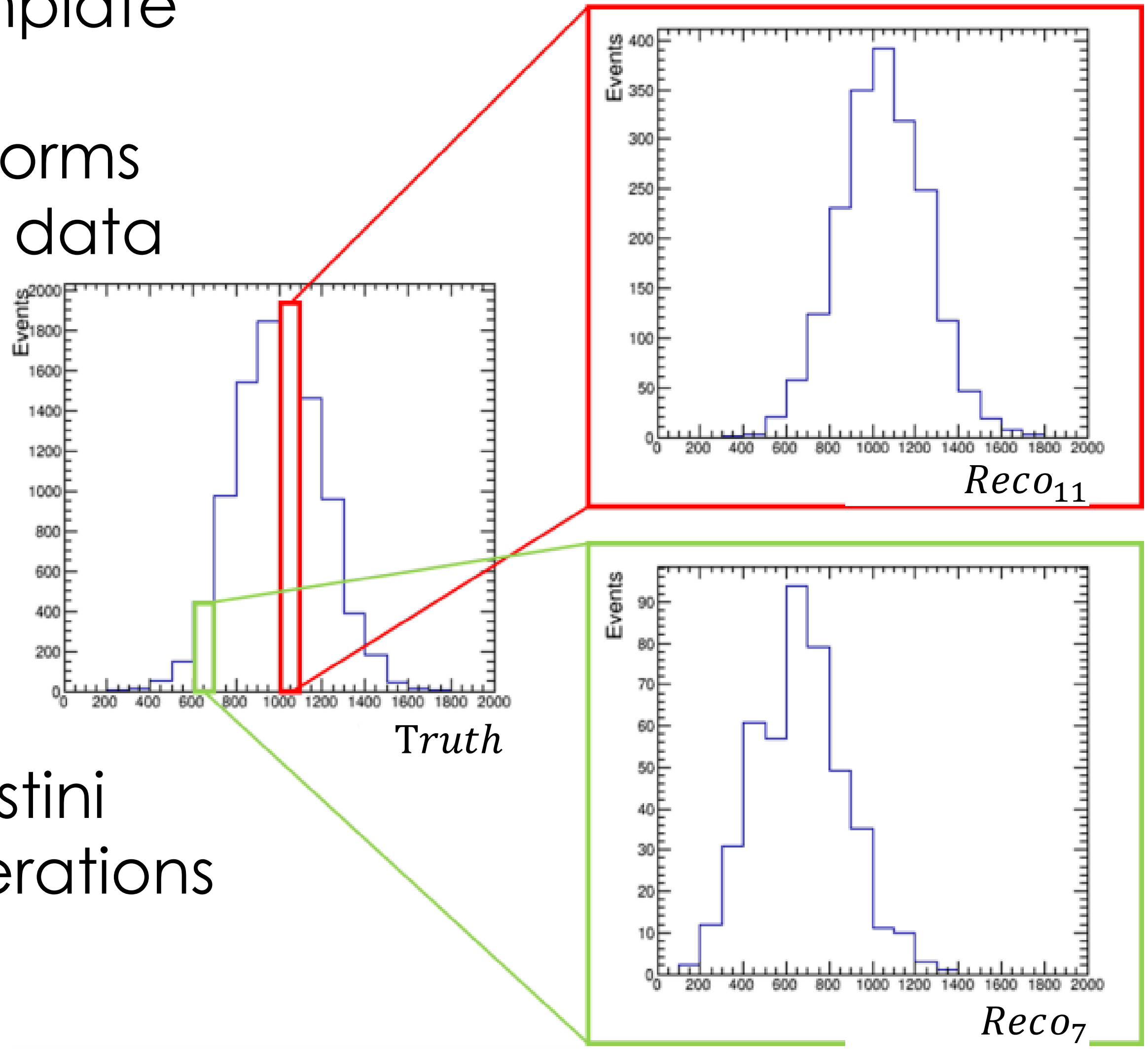






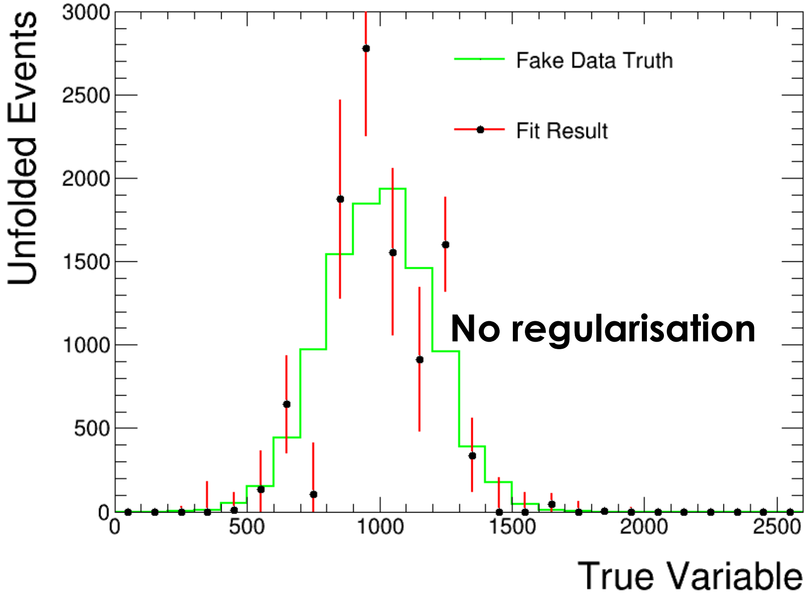
Binned likelihood fitting

- True bin → Reco. template
- Vary MC template norms (c_i) and compare to data
- Maximise Poisson likelihood + syst. penalty term
  (using max. gradient decent)
- Equivalent to D'Agostini (1995) with infinite iterations



The ill-posed problem in fit results

- If there is significant smearing between bins → **ill-posed problem** (a typical feature of all unfolding methods)
- Seen as a "zig-zagging" result with **strong anti-correlations** between bins
- Can apply **regularisation** to penalise such results.
- Many ways to regularise, best method depends on the analysis.

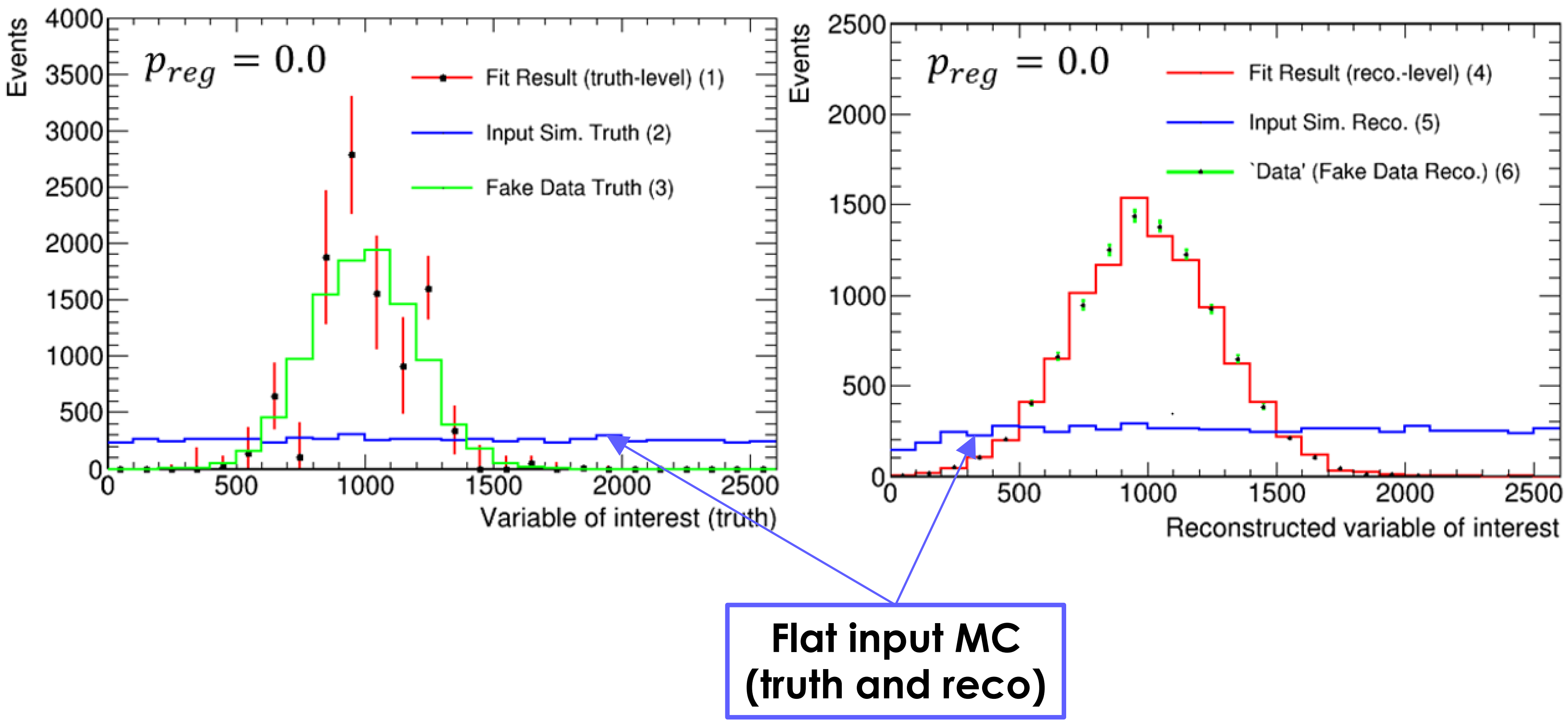


- One option:

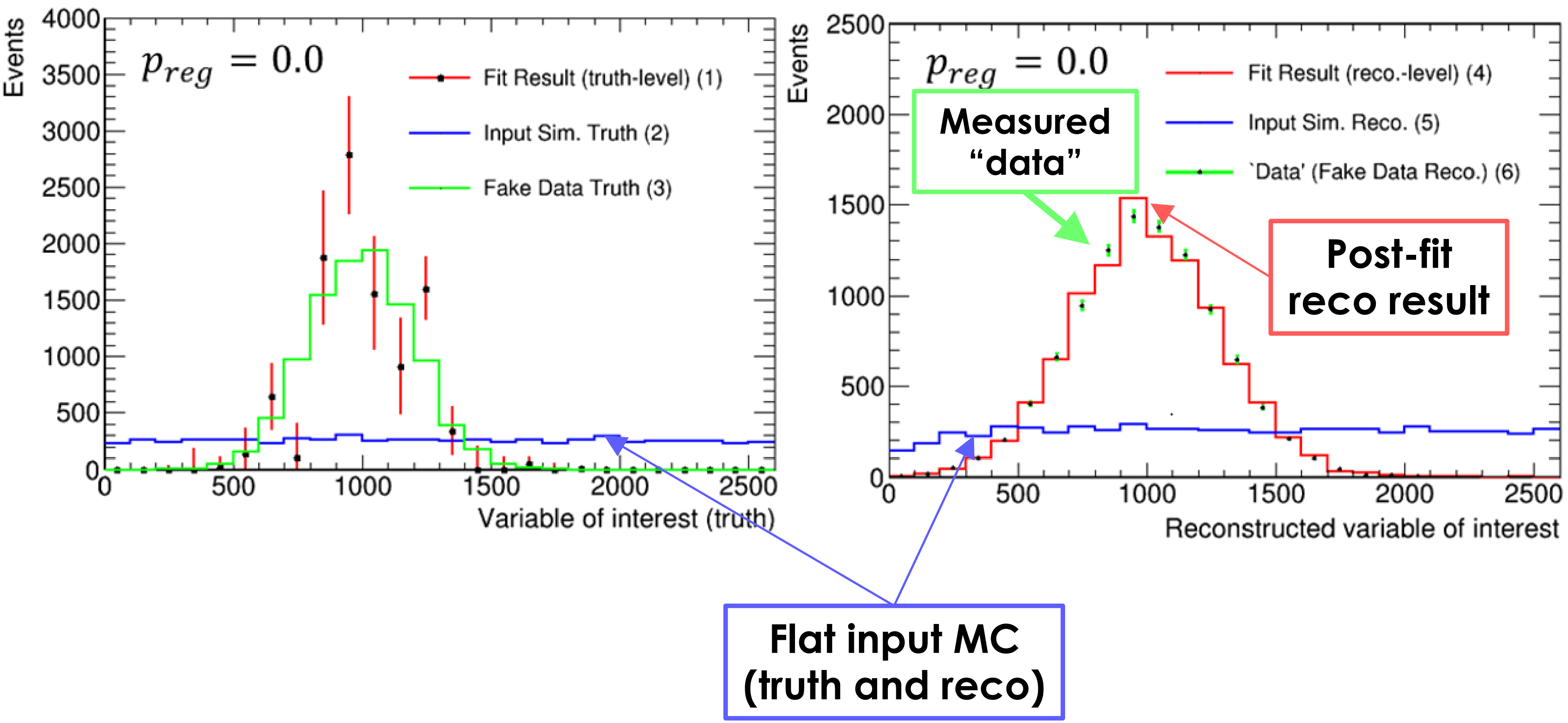
$$\chi^2_{reg} = p_{reg} \sum_{i}^{truebins-1} (c_i - c_{i+1})^2 = p_{reg}(\vec{c} - \vec{c}_{prior})(V^{reg}_{cov})^{-1}(\vec{c} - \vec{c}_{prior})$$

- But note that the **unregularised result is the most correct representation of the truth** (and T2K will provide this!)

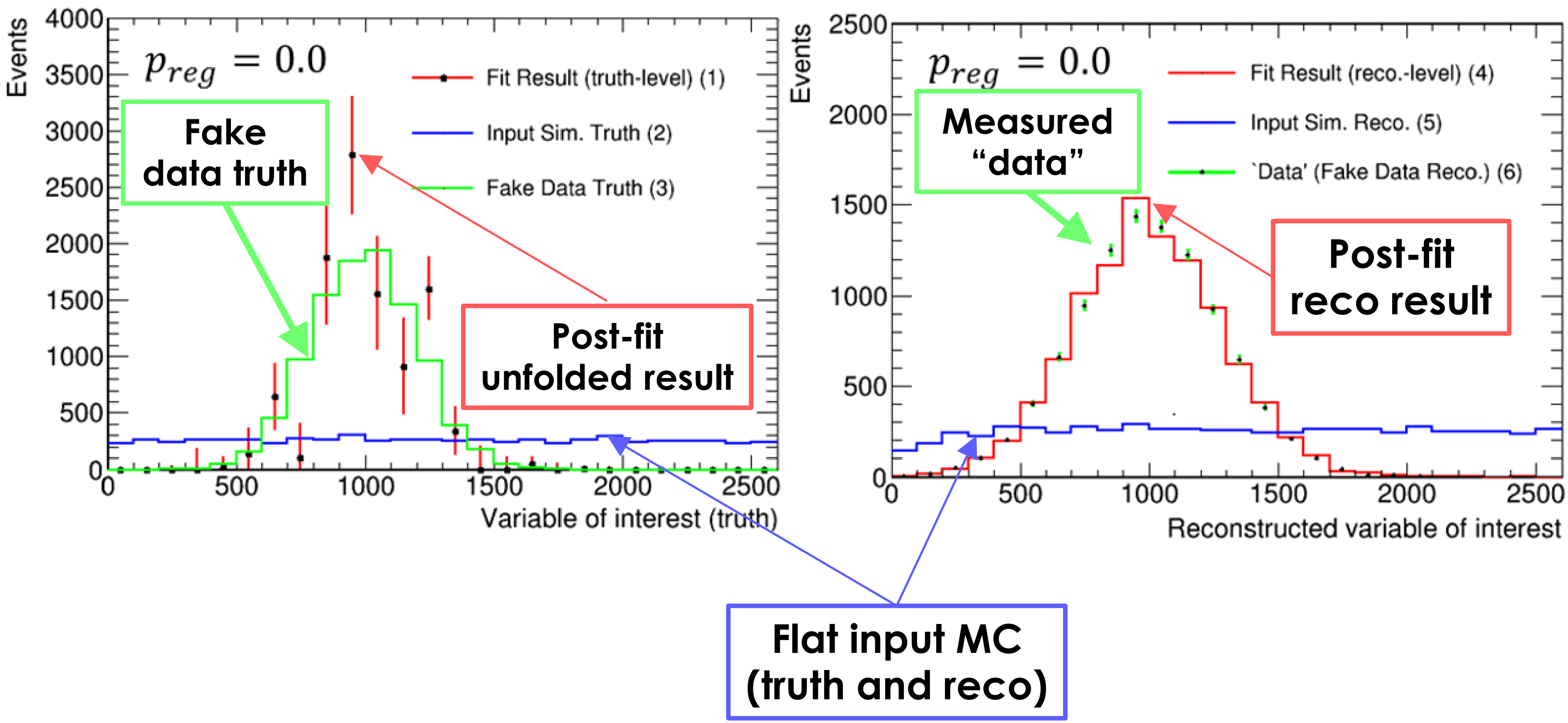
The role of regularisation



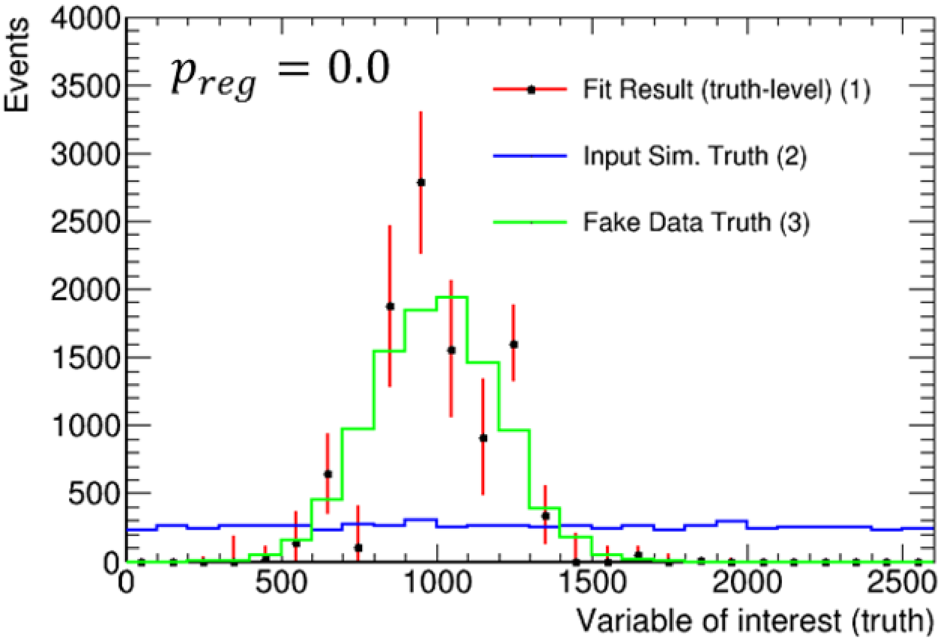
The role of regularisation

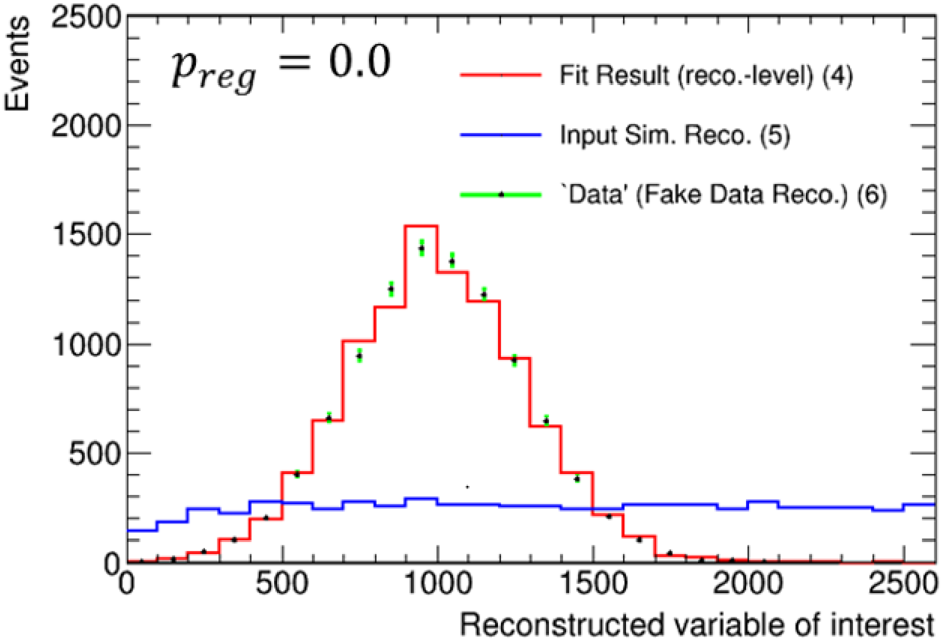


The role of regularisation



The role of regularisation





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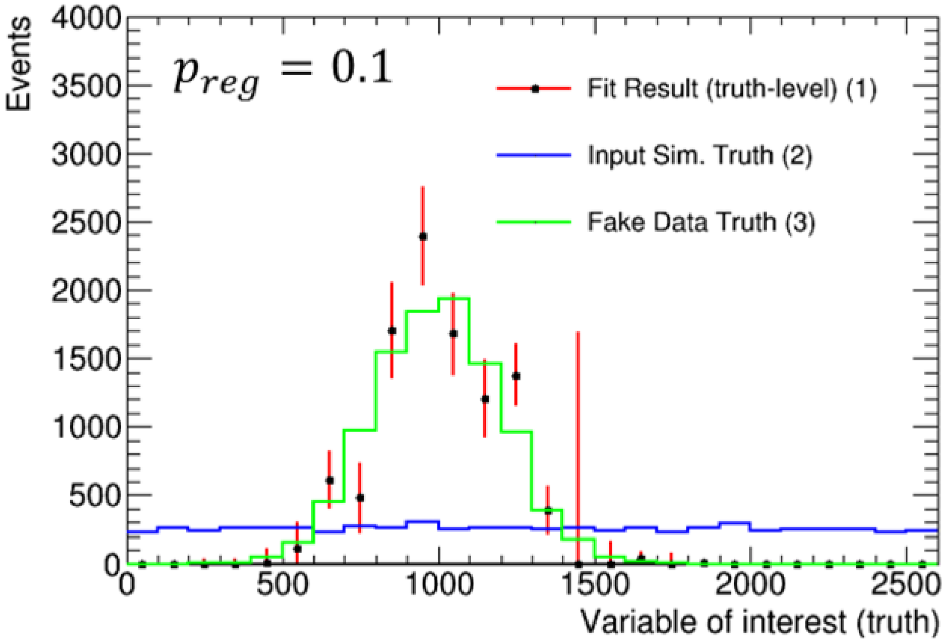

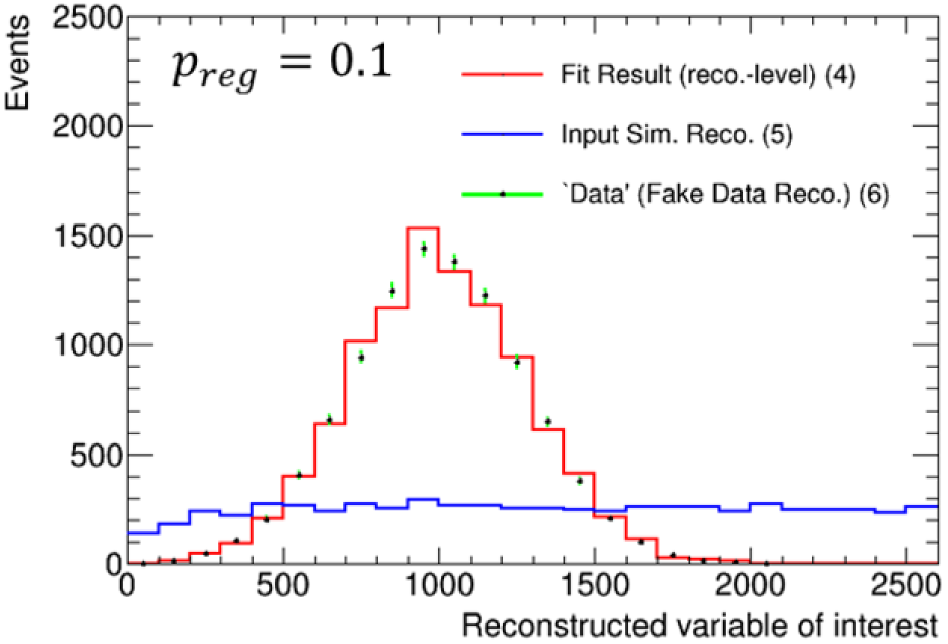

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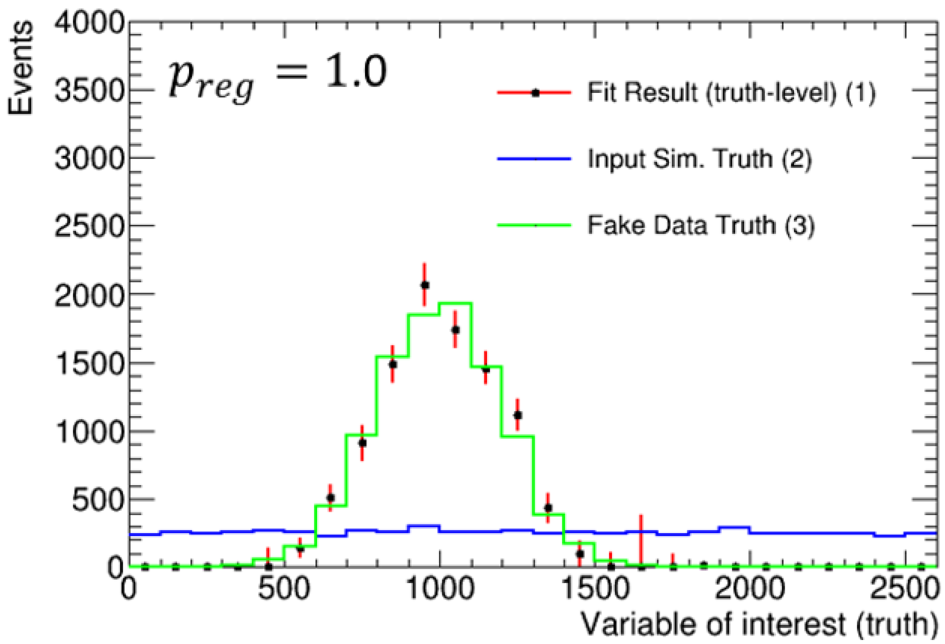

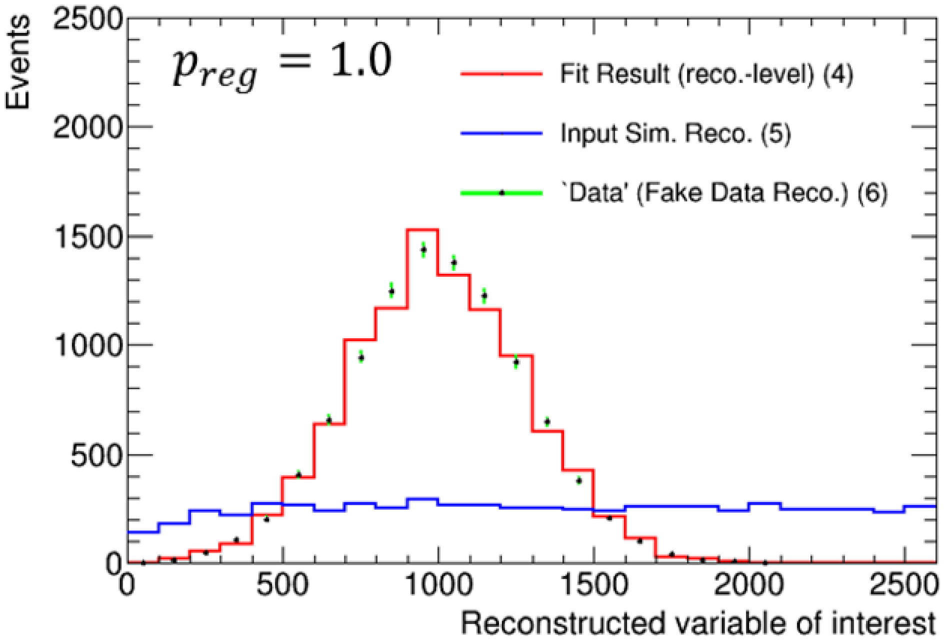

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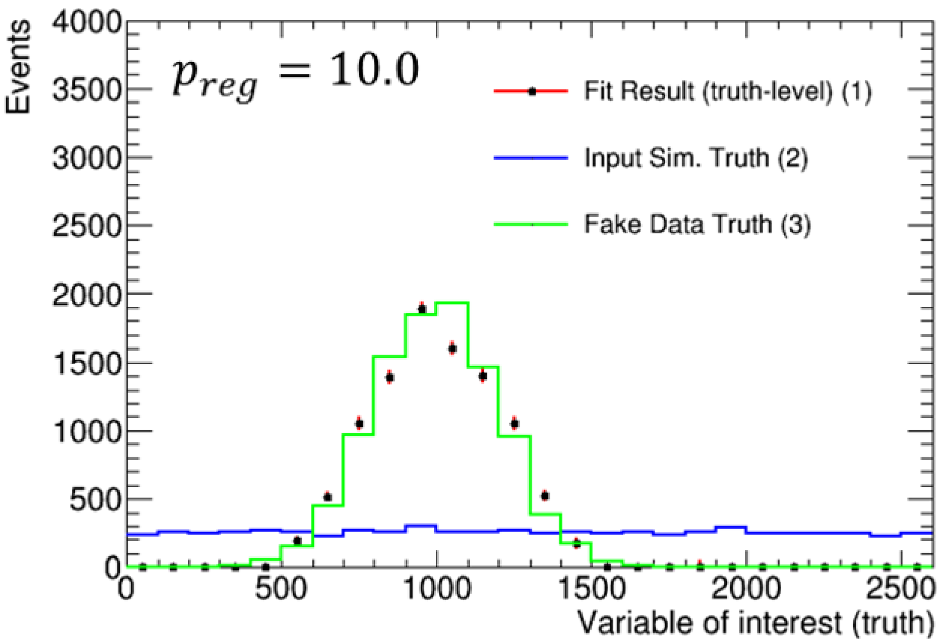

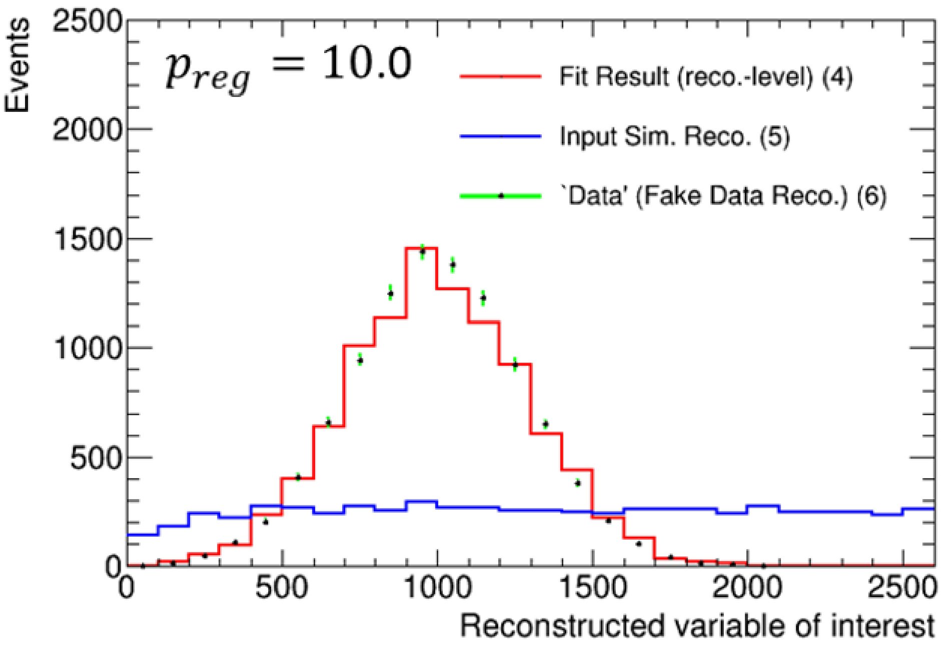

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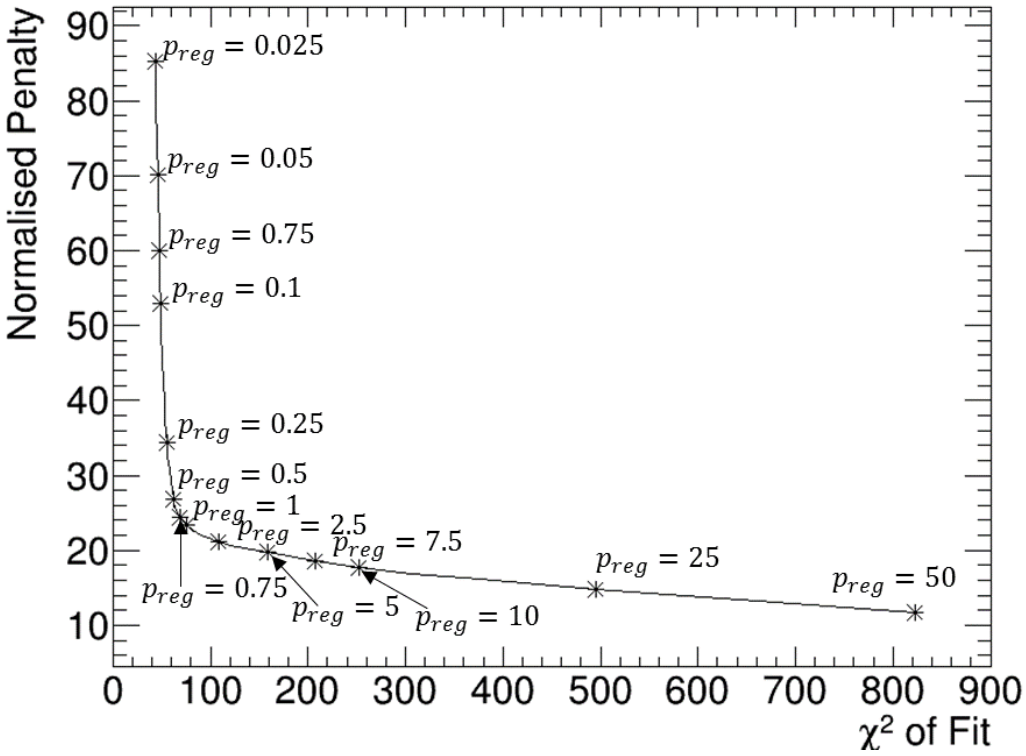
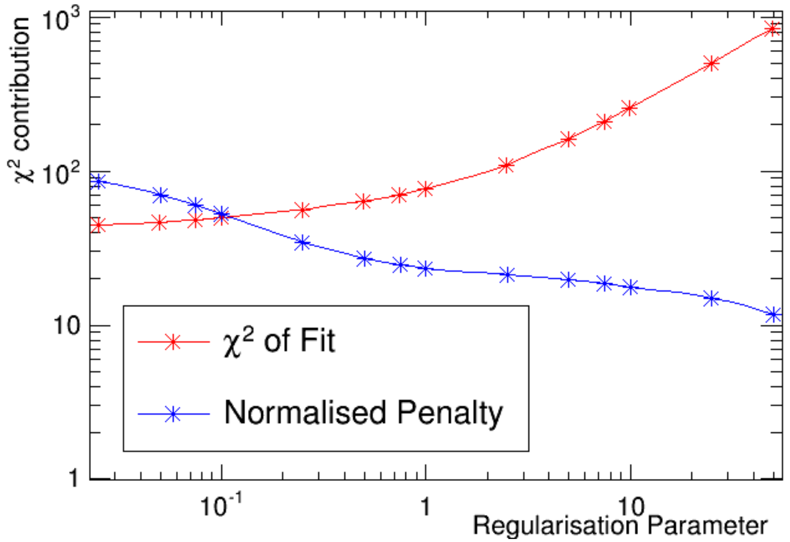




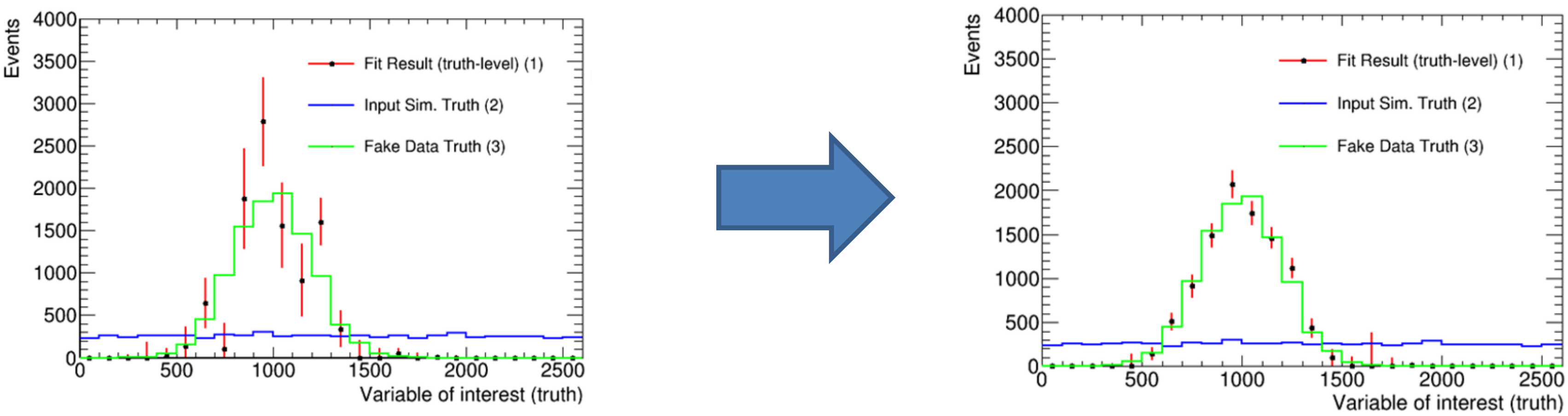
$$Normalised\ Penalty = \chi^2_{reg}/p_{reg}$$

- Best p_{reg} is the kink of the curve (in this case ~1)
- Balances regulation (in this case smoothness) with bias
- **L-curve can be formed on real data** – data driven regularisation

http://epubs.siam.org/doi/abs/10.1137/1034115
http://epubs.siam.org/doi/abs/10.1137/0914086 http://arxiv.org/pdf/1205.6201v4.pdf - use in TUnfold

Resolving the ill-posed problem

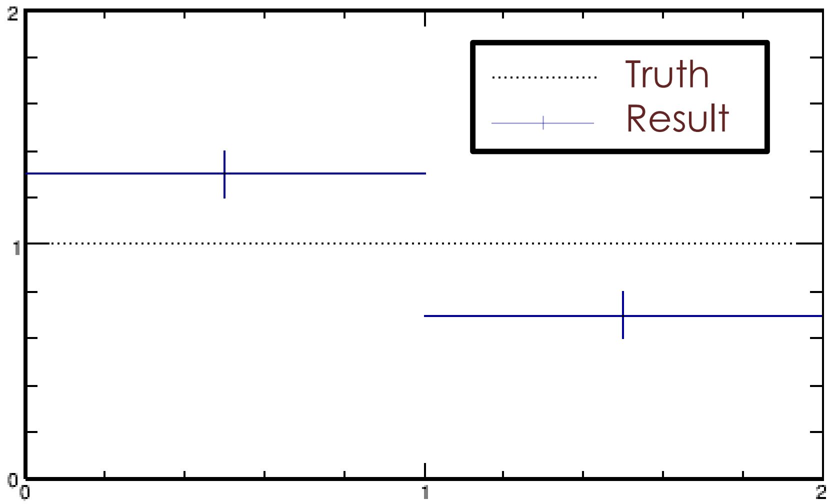
- Unfolding methods mostly differ in the way they resolve these degeneracies (i.e. their **regularisation** implementation)
- Ideally, regularisation should be selecting the “smoothest” of many (almost) degenerate solutions

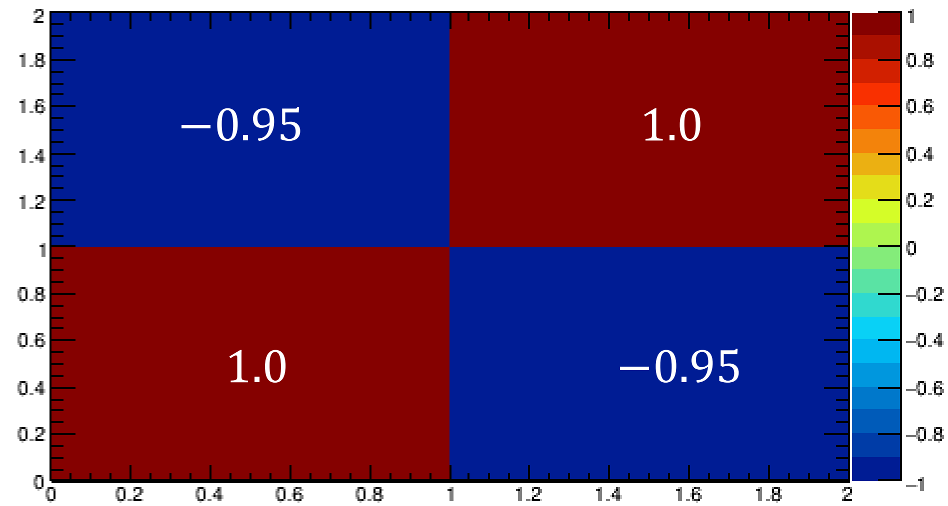


- **Regularisation always adds some bias**
- The unregularised result is the most “correct” representation of the true unfolded result

But the unregularised result looks awful!?

- Consider a two bin result:





$$pull_i = \frac{N_{fit} - N_{true}}{Error}$$

$$pull_0 = 3$$
$$pull_1 = 3$$

Fairly awful pull

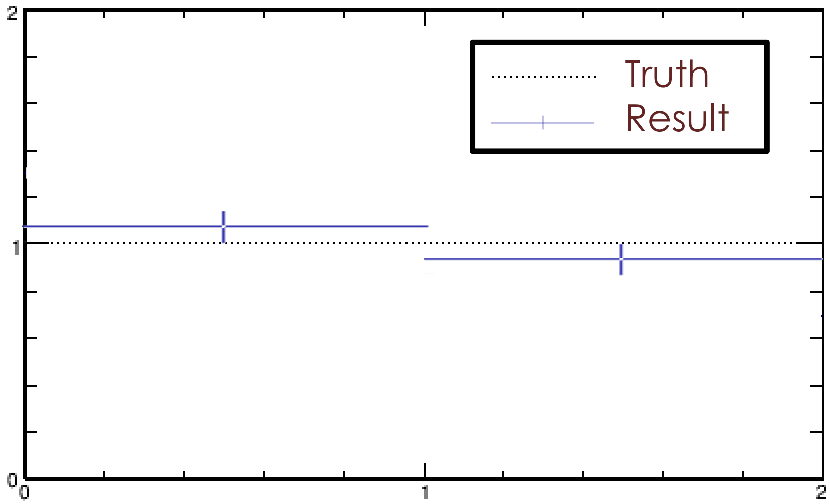
$$\chi^2 = (\overline{N_{fit}} - \overline{N_{true}})(V_{cov})^{-1}(\overline{N_{fit}} - \overline{N_{true}})$$

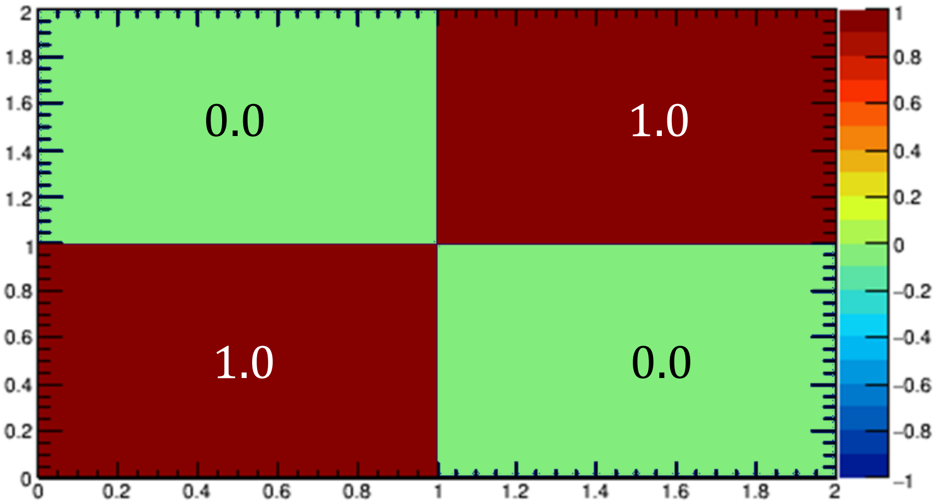
$\chi^2 = 1.69$ **Good χ^2**

- Need to see the correlation matrix to tell whether the result is good or not.

But the unregularised result looks awful!?

- Consider a two bin result:





$$pull_i = \frac{N_{fit} - N_{true}}{Error}$$

$$pull_0 = 1$$

$$pull_1 = 1$$

Better pull

$$\chi^2 = (\overline{N_{fit}} - \overline{N_{true}})(V_{cov})^{-1}(\overline{N_{fit}} - \overline{N_{true}})$$

$$\chi^2 = 2.0$$

Worse χ^2

- Pulls/bin-to-bin bias doesn't tell the whole story