Nucleon Final State Interactions in NEUT

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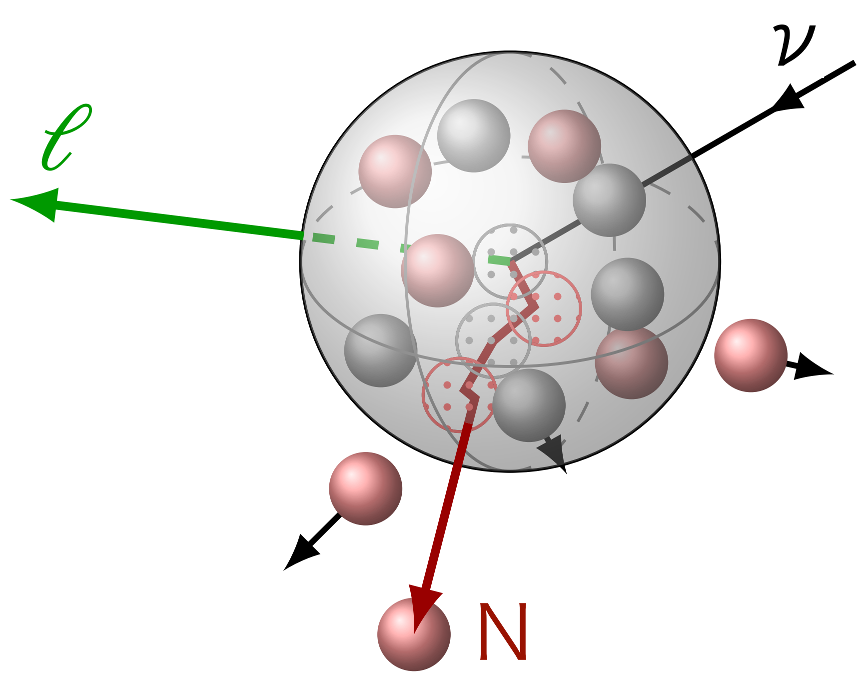
Motivation

- Hadrons produced in neutrino-nucleus interactions may re-interact while propagating through the nuclear medium.

- Final state interactions (FSI) can change the charge and multiplicity of the outgoing hadrons, as well as altering their final state kinematics.

- Pion and nucleon FSI are one of the dominant systematics in T2K.

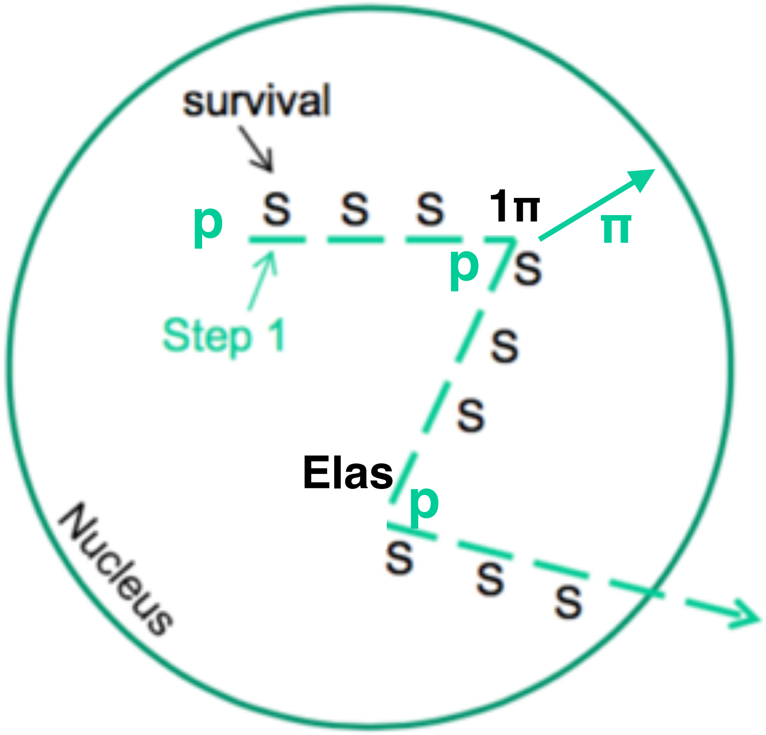


Overview

- Nucleon-nucleus interaction model in NEUT
- Tuning and validating FSI free parameters using external nucleon scattering data
- Comparing FSI model predictions of neutrino event generators

Cascade Model

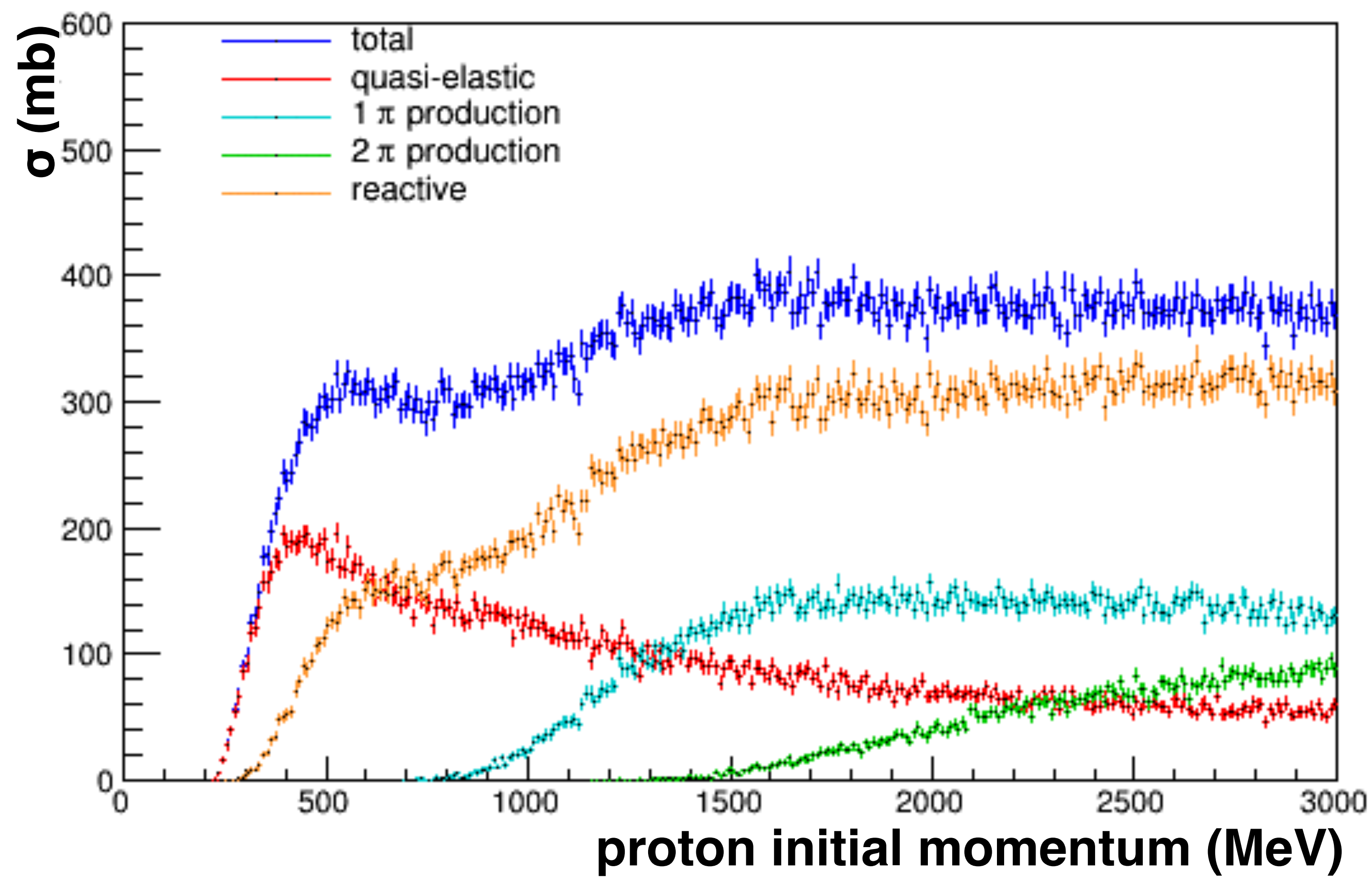
- Hadrons are propagated semi-classically through a nuclear medium in finite steps.
- After the neutrino interaction, final-state particles are “stepped through” the FSI cascade.
- FSI processes: elastic scattering, pion production
- At each step, the interaction probability for each process is calculated.
- Continues until a particle interacts: interaction is simulated, or the particle exits the nucleus.



Interaction channels

- Use NEUT to simulate proton scattering on Carbon target
- Define interaction channels based on outgoing particles for each event

- **Total —** Events in which protons did interact, sub divided into:
  - **Quasi-elastic:** *one* outgoing proton in final state
  - **Single/double pion production**: *one* or *two* pion(s) in final state
  - **Reactive:** 1 π + 2 π + other



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Nucleon FSI Tuning

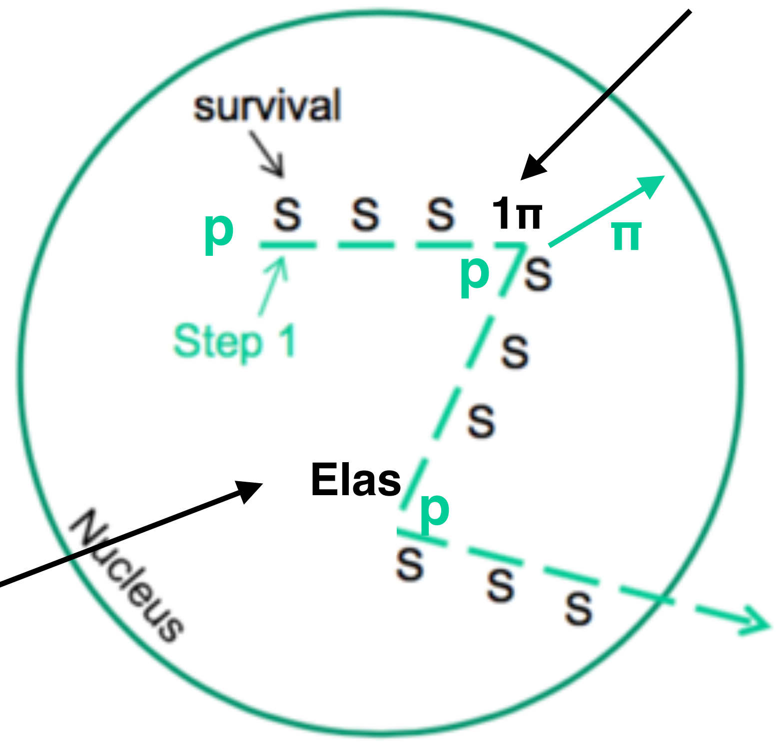
- Nucleon beam scattering data is used for tuning: it isolates the hadronic processes involved in FSI
- This talk, tuning FSI model to proton on Carbon data

Reference	beam	targets	momentum [GeV/c]	interaction type
M.J.Longo 1962 [4]	π+, p	Be, C, Al, Cu	1.4-4.0	total, elastic
M.E.Law 1958 [5]	p	C, O, H, 2H	0.91	total
G. P. Millburn 1954 [6]	n,p,2H	Be, C, Al ,Cu, Pb	0.30-0.87	reactive

Nucleon FSI Tuning

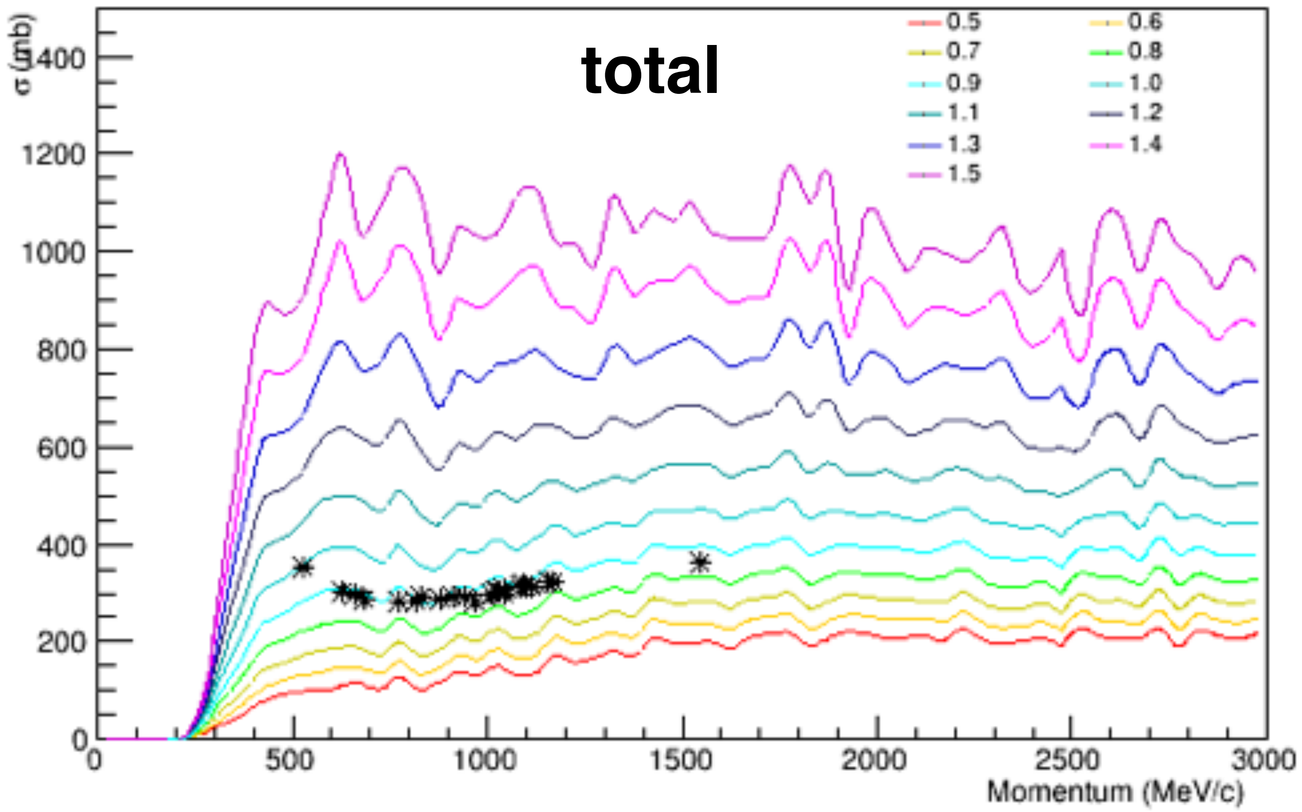
- FSI parameters added for tuning are the multiplicative factors for probability for each interaction: elastic, π production
- Together with one factor for overall probability, 3 tunable parameters

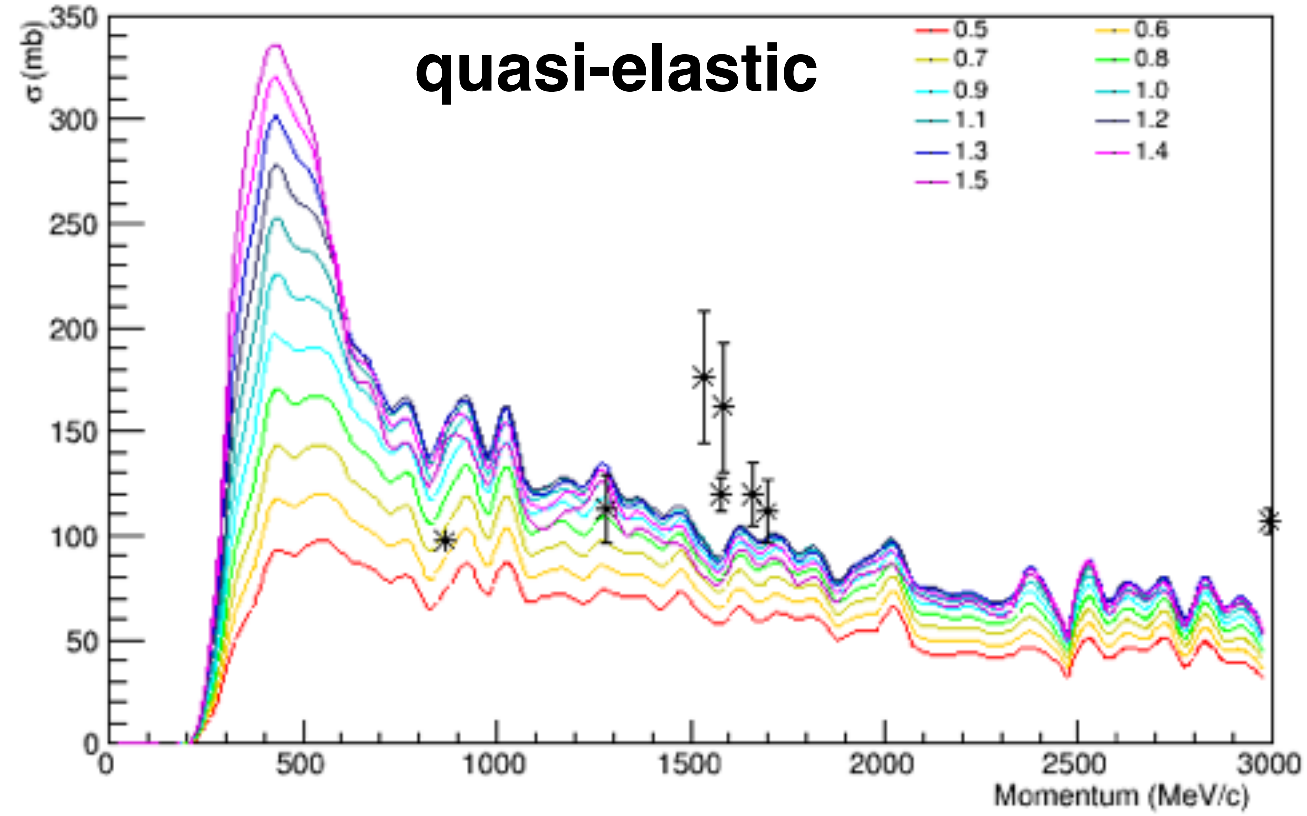
$\text{Prob}_{\pi} \rightarrow \text{Prob}_{\pi} \times \pi$ factor × total factor

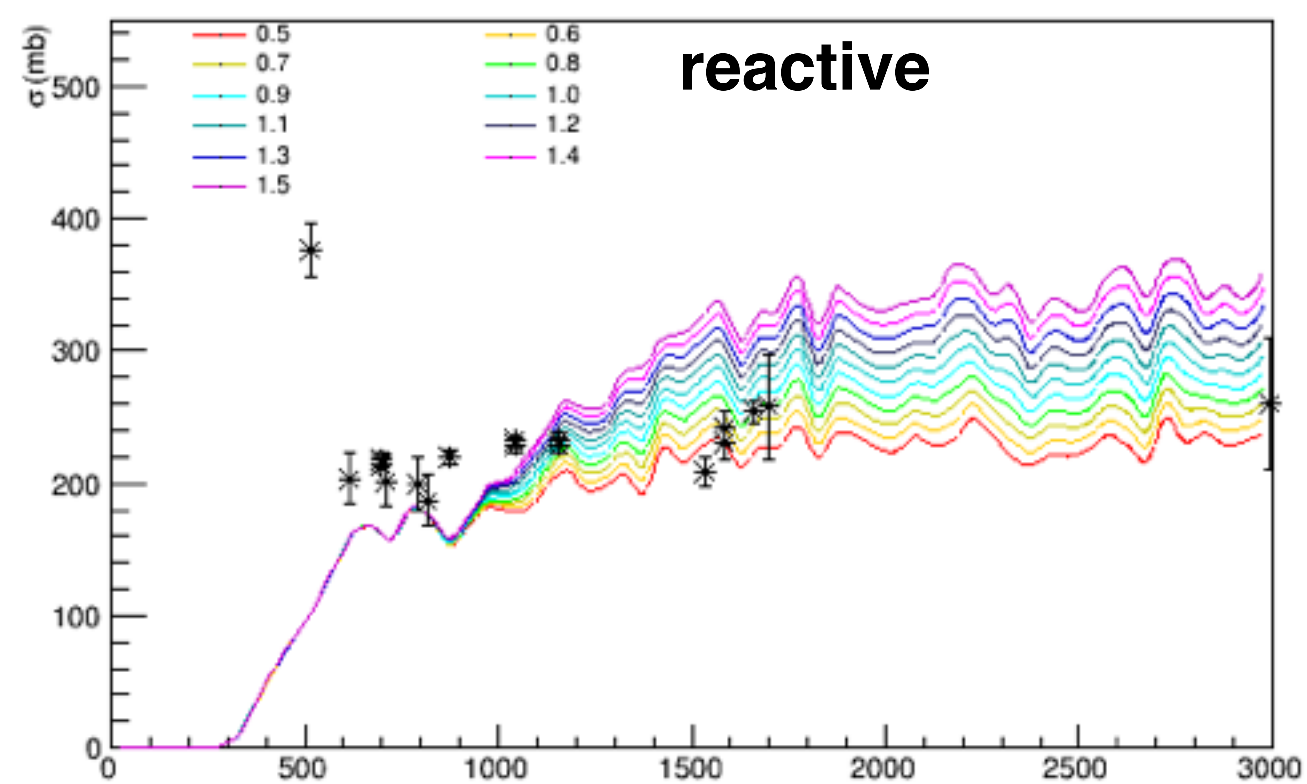


$\text{Prob}_{elas} \rightarrow \text{Prob}_{elas} \times$ elastic factor × total factor

Comparing data to MC







- Vary each factor and compare with data
- No π production data, π production factor contribute to reactive cross-section

Tuning Procedure

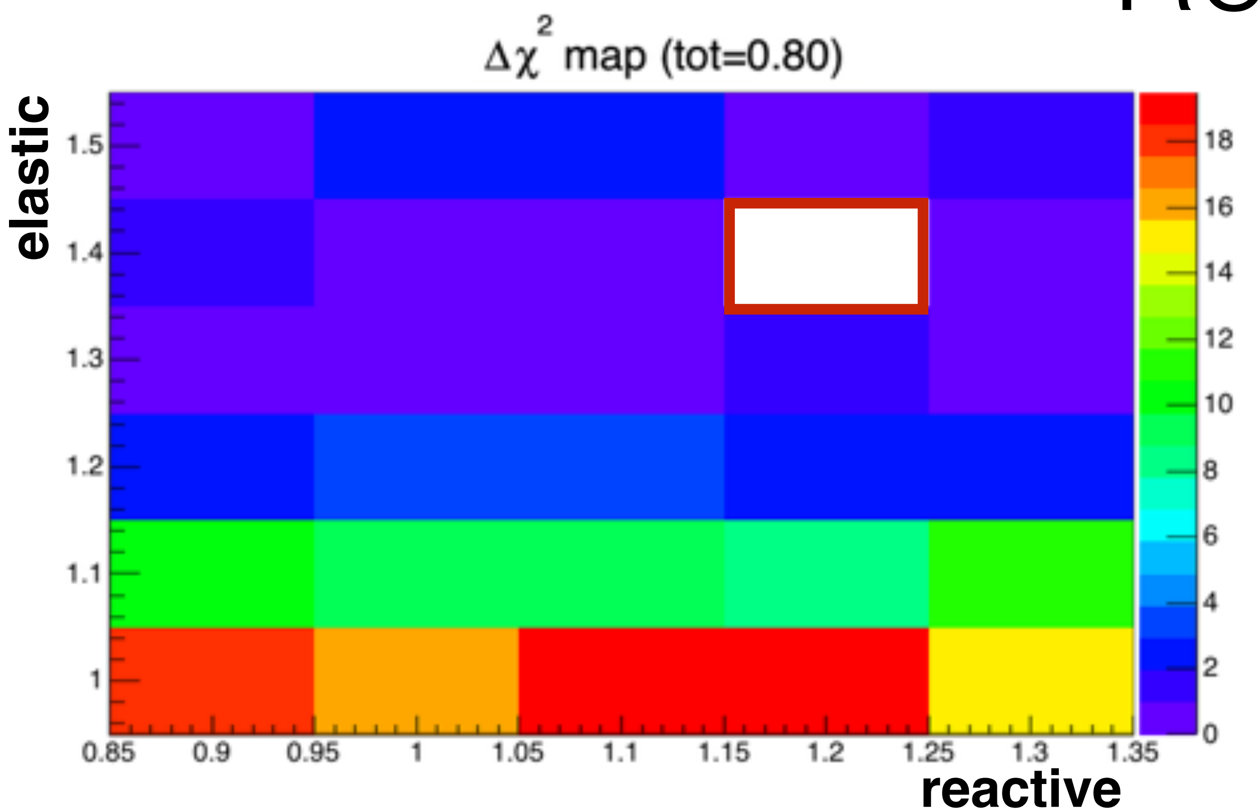
- 3D grid search — Each free parameter (total, elastic, π production) can take values of 0.6, 0.8, 1.0 1.2, 1.4
- For each set of parameters, calculate

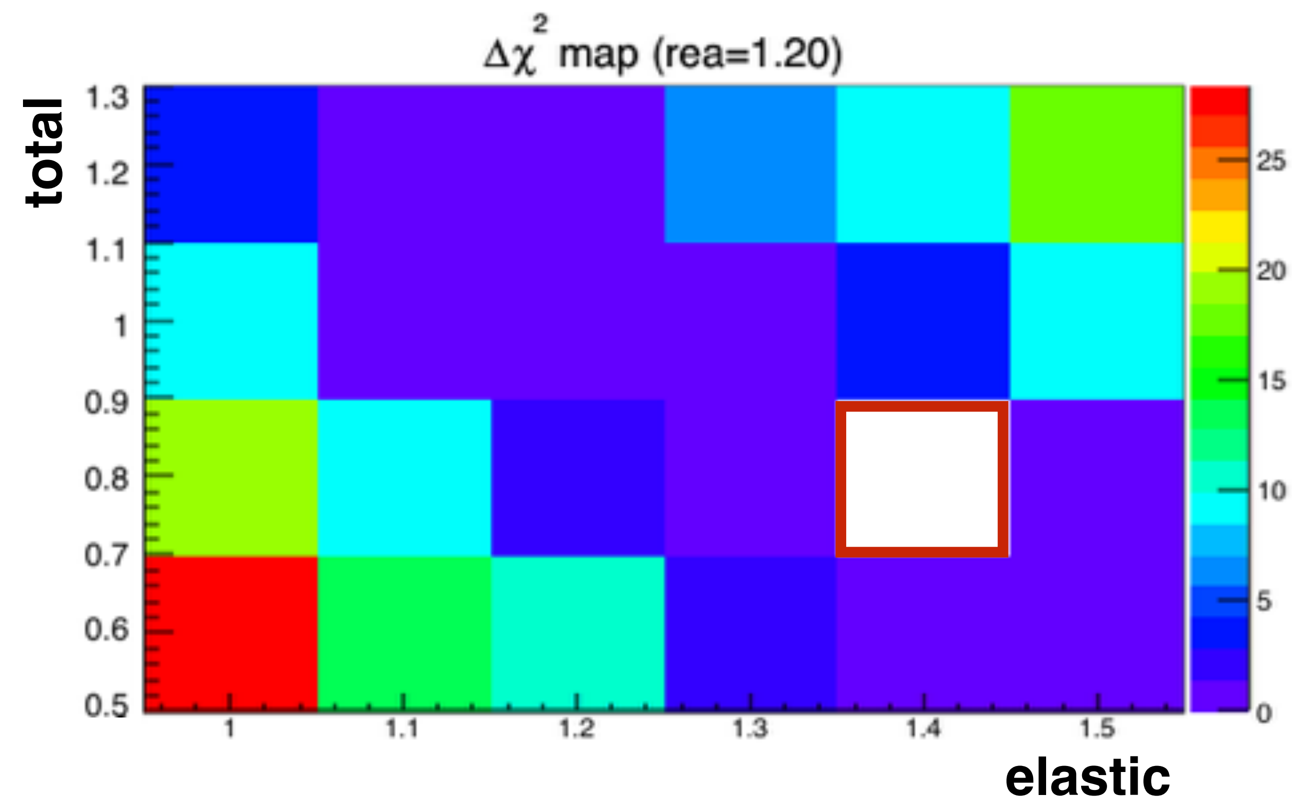
p [MeV/c]	σ [mb]	δ [mb]
628.4	305	9
658.5	296	3
830.9	292	6
965.5	285	14

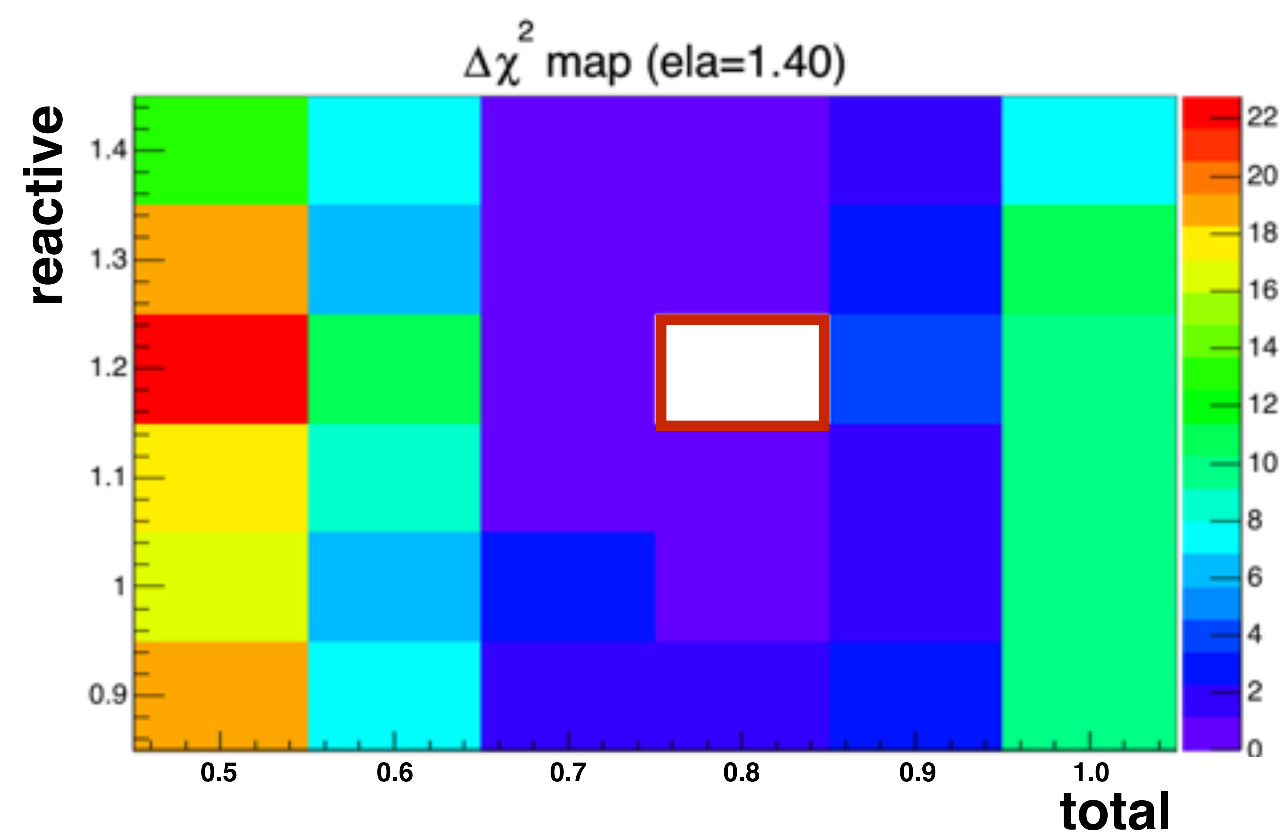
$$\chi^2 = \frac{1}{n}\sum_{i=1}^{i=n}\left(\frac{\sigma_{data}(p_i) - \sigma_{simu}(p_i)}{\delta(\sigma_{data}(p_i))}\right)^2$$

- Assuming all data points are independent — uncorrelated errors
- Find the set of parameters such that χ^2 is at minimum
- Repeat about best fit point with finer grid

Result







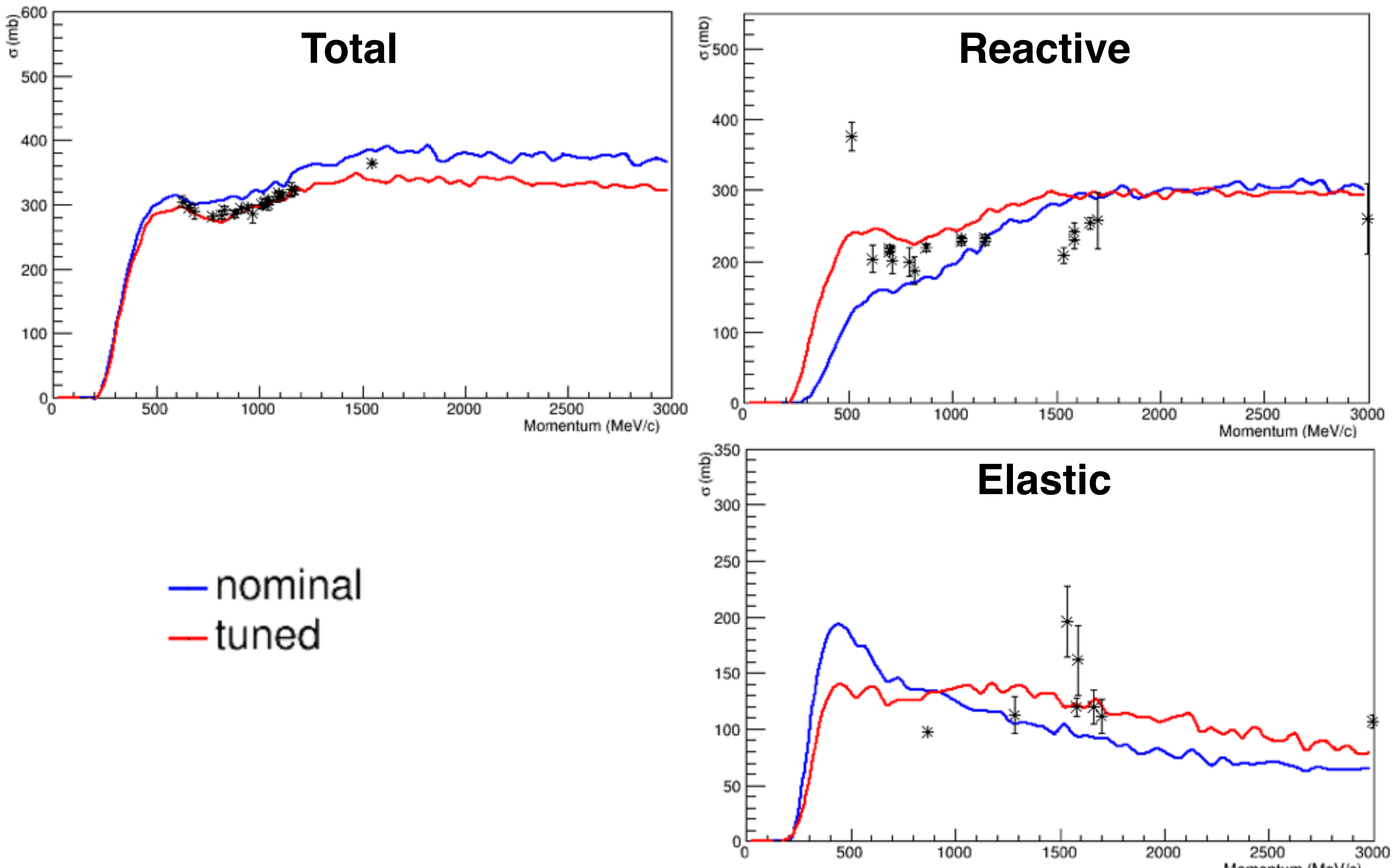
Best fit points for

total: 0.8

reactive:1.2

elastic: 1.4

Result



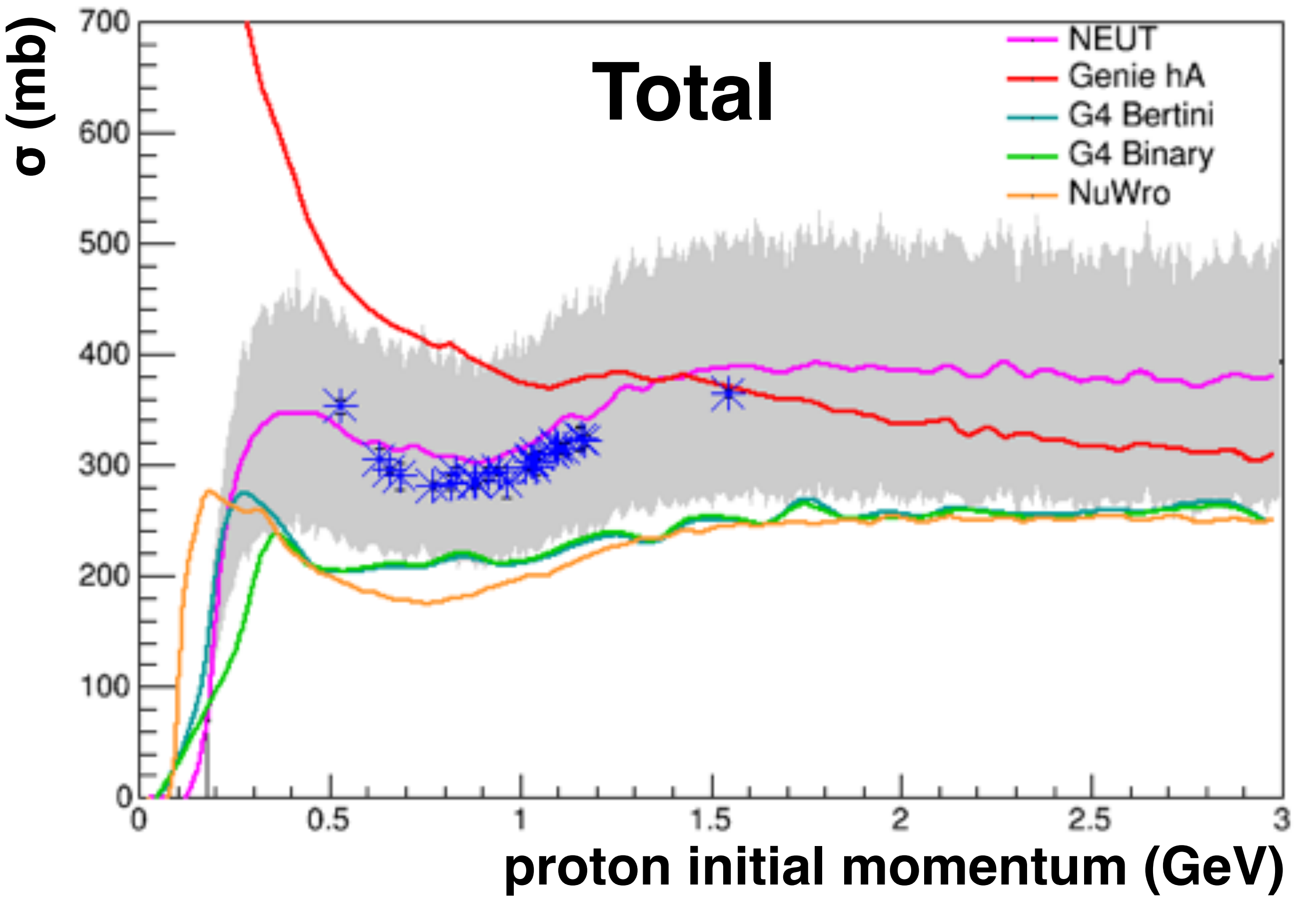
Data points from ref in backup slides

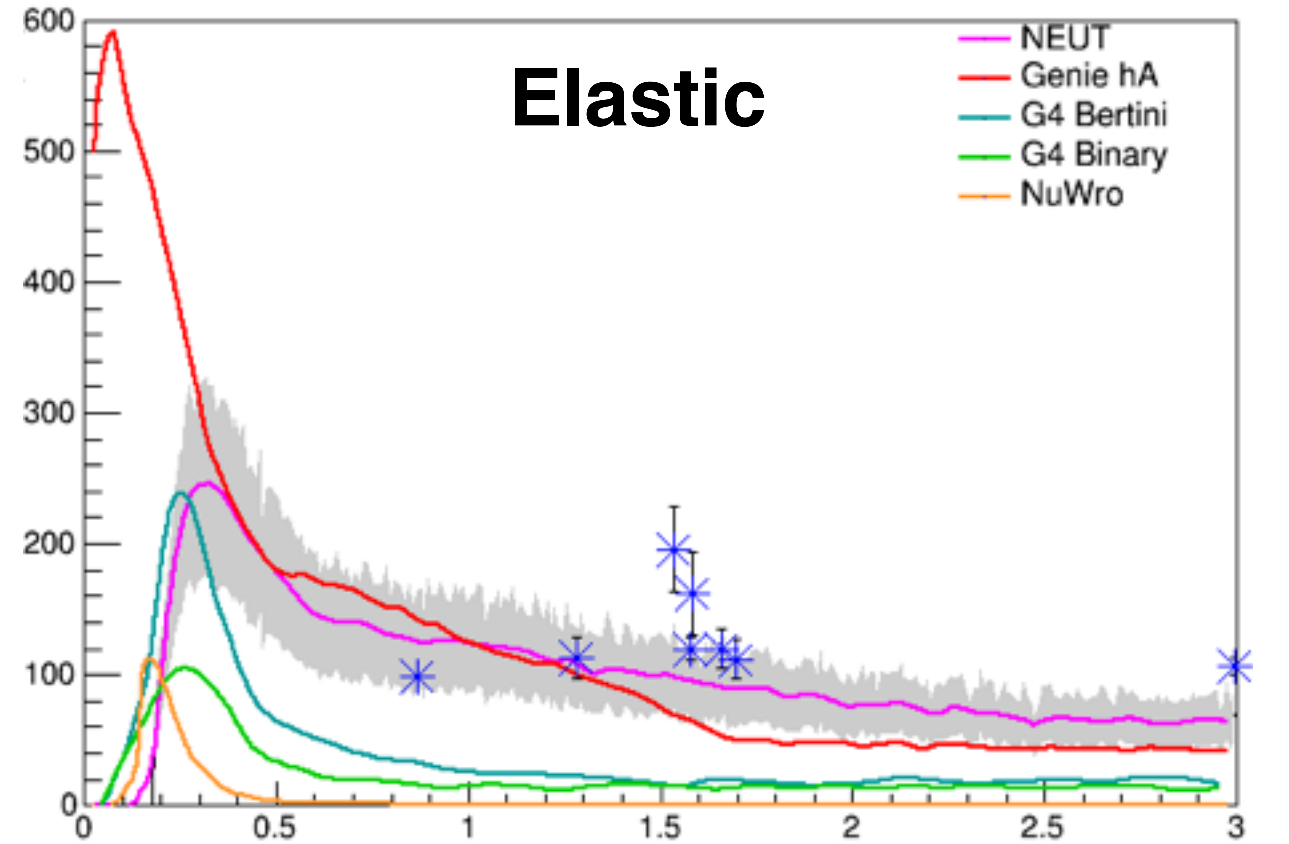
Generator comparison

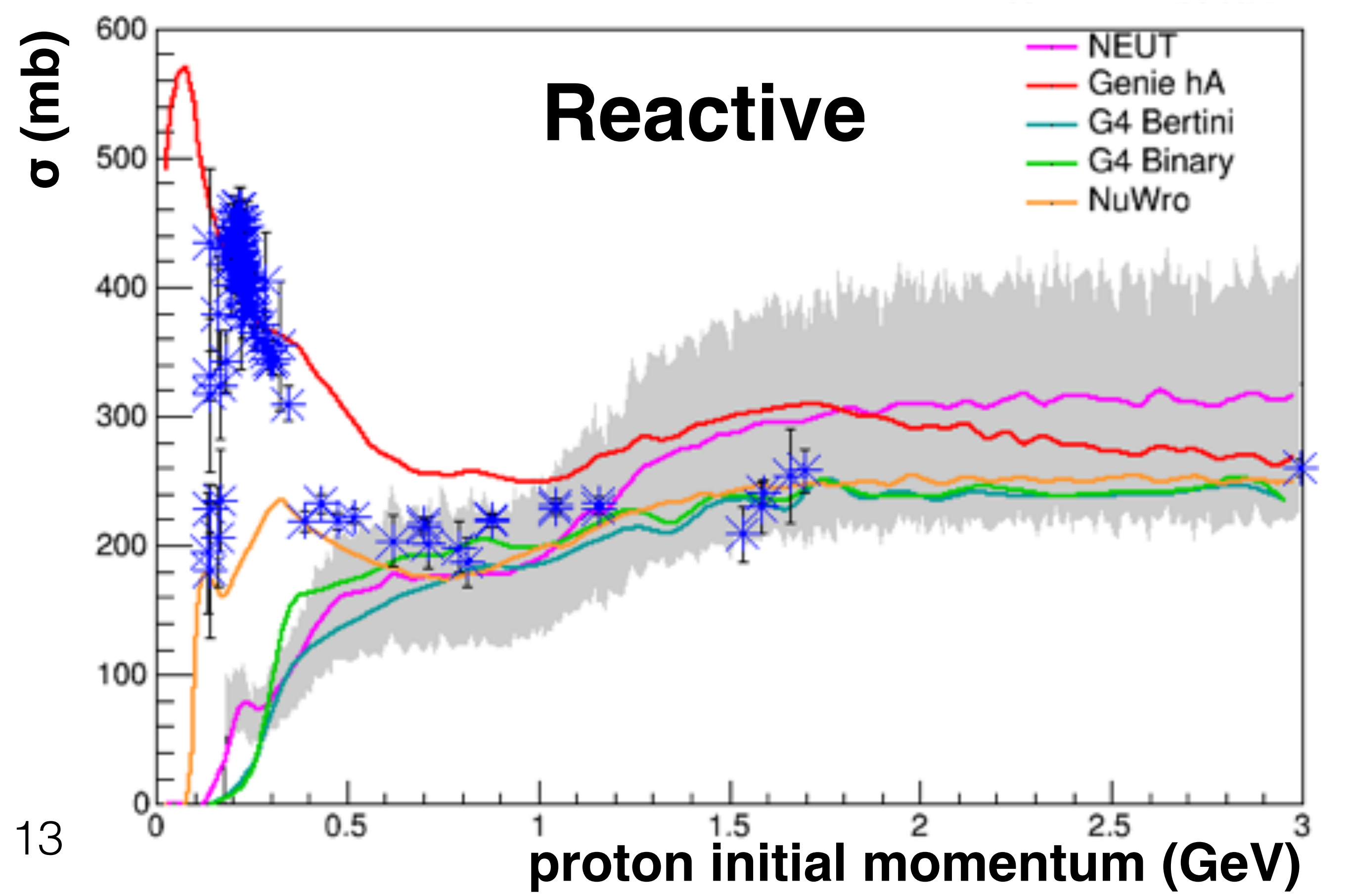
- Study NEUT nucleon FSI model uncertainties by comparing different generators with existing data for different nuclei

- NEUT: Cascade model tuned to pi-C external data
- GENIE: hA model (tuned to external data, effective cascade)
- Geant4: Bertini and Binary cascade model
- NuWro: full cascade model

Generator comparison (p on C)

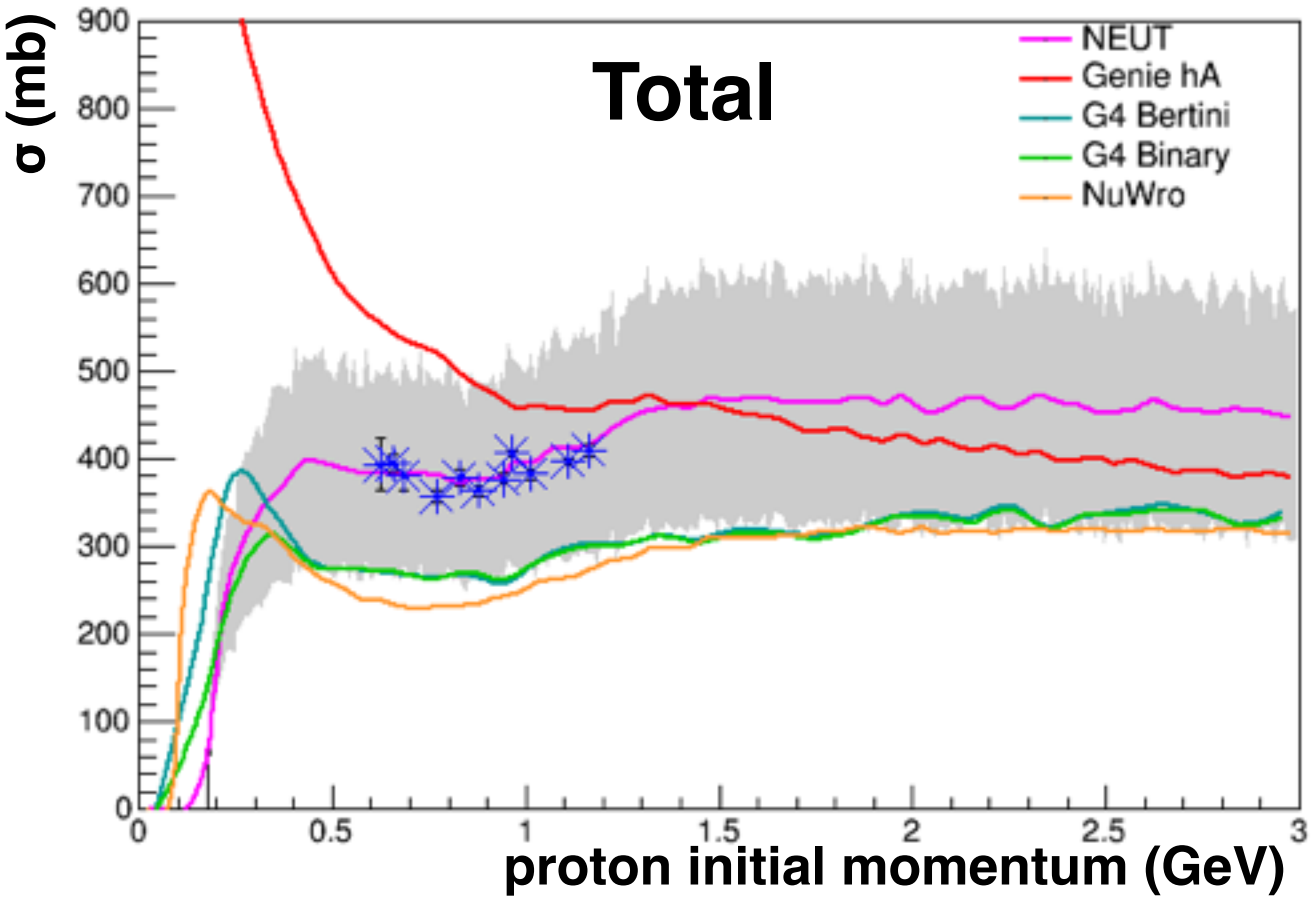


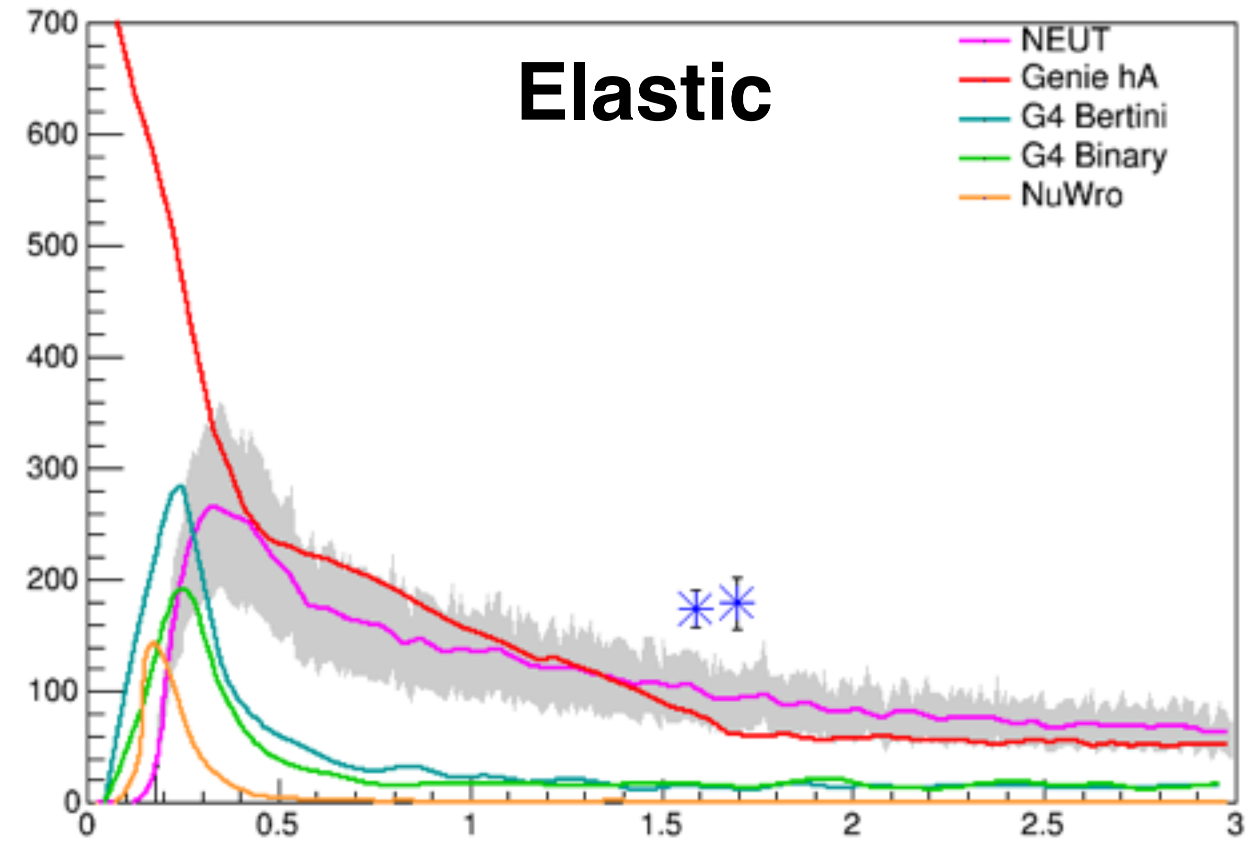


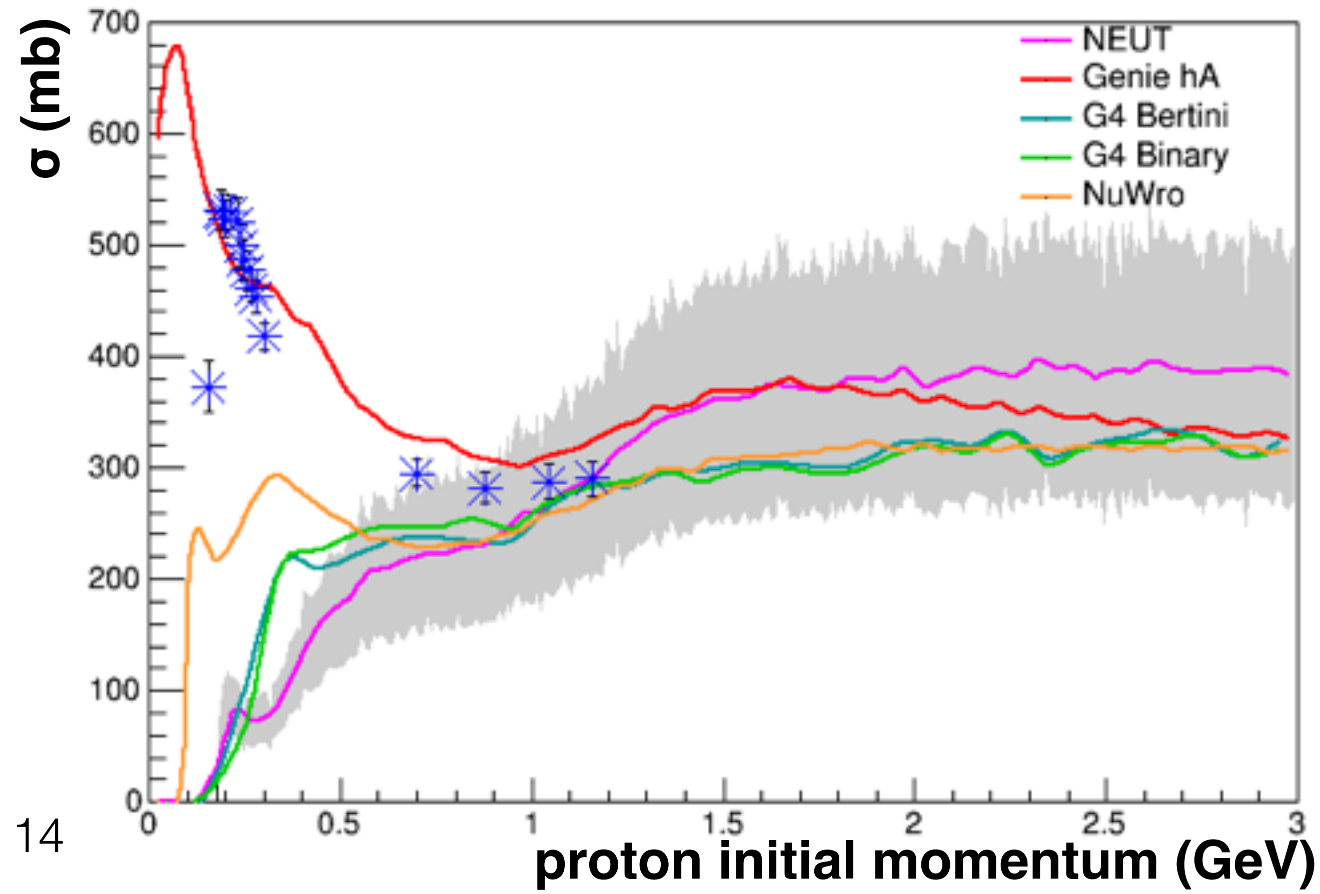


- Error band in NEUT prediction: estimate uncertainty of 30%
- Does not have good agreement with data below 500 MeV

Generator comparison (p on O)







- Error band in NEUT prediction: estimate uncertainty of 30%
- Does not have good agreement with data below 500 MeV

Conclusion

- Important to understand nucleon-nucleus interaction because it can affect final state particles
- I parameterised the NEUT FSI model and tuned to nucleon scattering data.
- Generator comparison allow model discrimination over certain momentum ranges
- This work will lead to a better understanding of FSI uncertainties at T2K

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T2K

Backup

Data used for fitting

1. **ATOMIC DATA AND NUCLEAR DATA** TABLES 63, 93–116 (1996) ARTICLE NO. 0010
2. **PROTON TOTAL CROSS SECTIONS ON H,He,Be IN THE ENERGY RANGE 181.1 TO 560 MeV** (Nuclear Physics A316 (1979) 317-344)
    - P.SCHWALLER and M .PEPIN
3. **Cross Sections for Fast Particles and Atomic Nuclei**
    - V. S. BARASHENKOKV.,K. GUDIMA,V. D. TONEE
4. **Nucleon and Nuclear Cross Sections for Positive pions and protons above 1.4 BeV/c**
    - M.J.Longo, B.J.Moyes Phys. Rev. 125,701 (1962)
5. **Total Cross sections for 910 MeV Protons(1958)**
6. **Nuclear Radii from Inelastic Cross-Section Measurements** (1954)

Experimental Setup

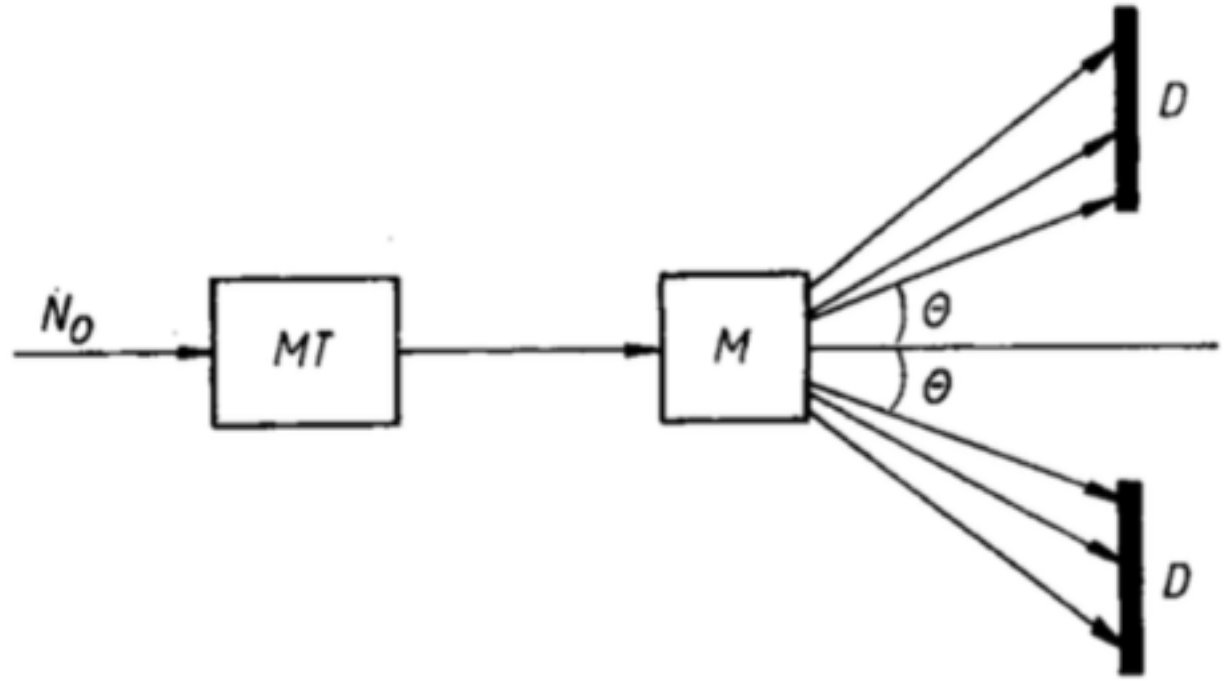
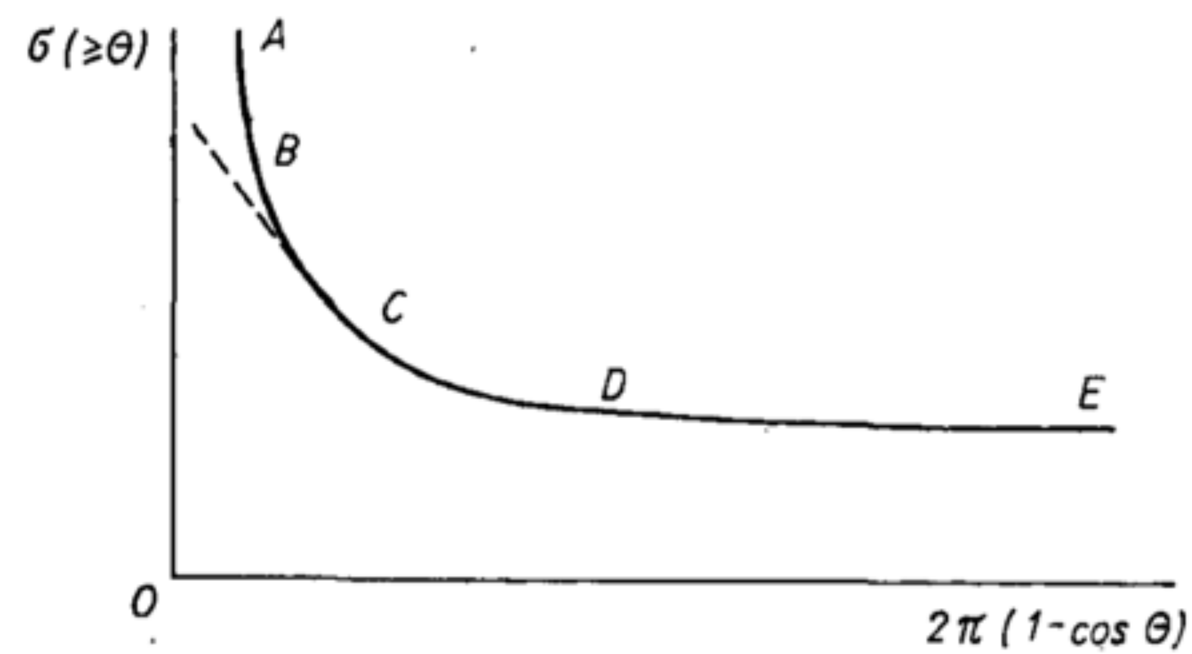


Diagram taken from Ref.3

- General scheme of experiments to the measurement of nuclear xsec by attenuation method

$$\sigma(\geqq \Theta) = \frac{1}{n} \ln \frac{N(\geqq \Theta)}{N_0}$$



Future work

- Quantify systematic uncertainty and apply to SK nue selection
- Overlay uncertainty band for GENIE
    - Can exclude models in certain momentum range
    - Add FLUKA and GIBUU for comparison

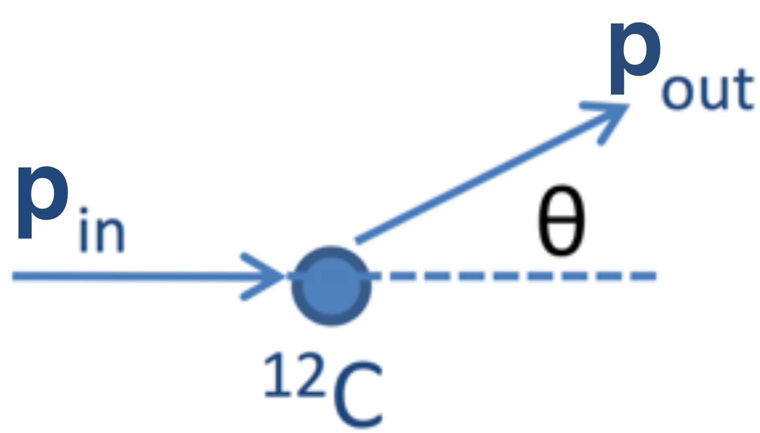
Generator comparison

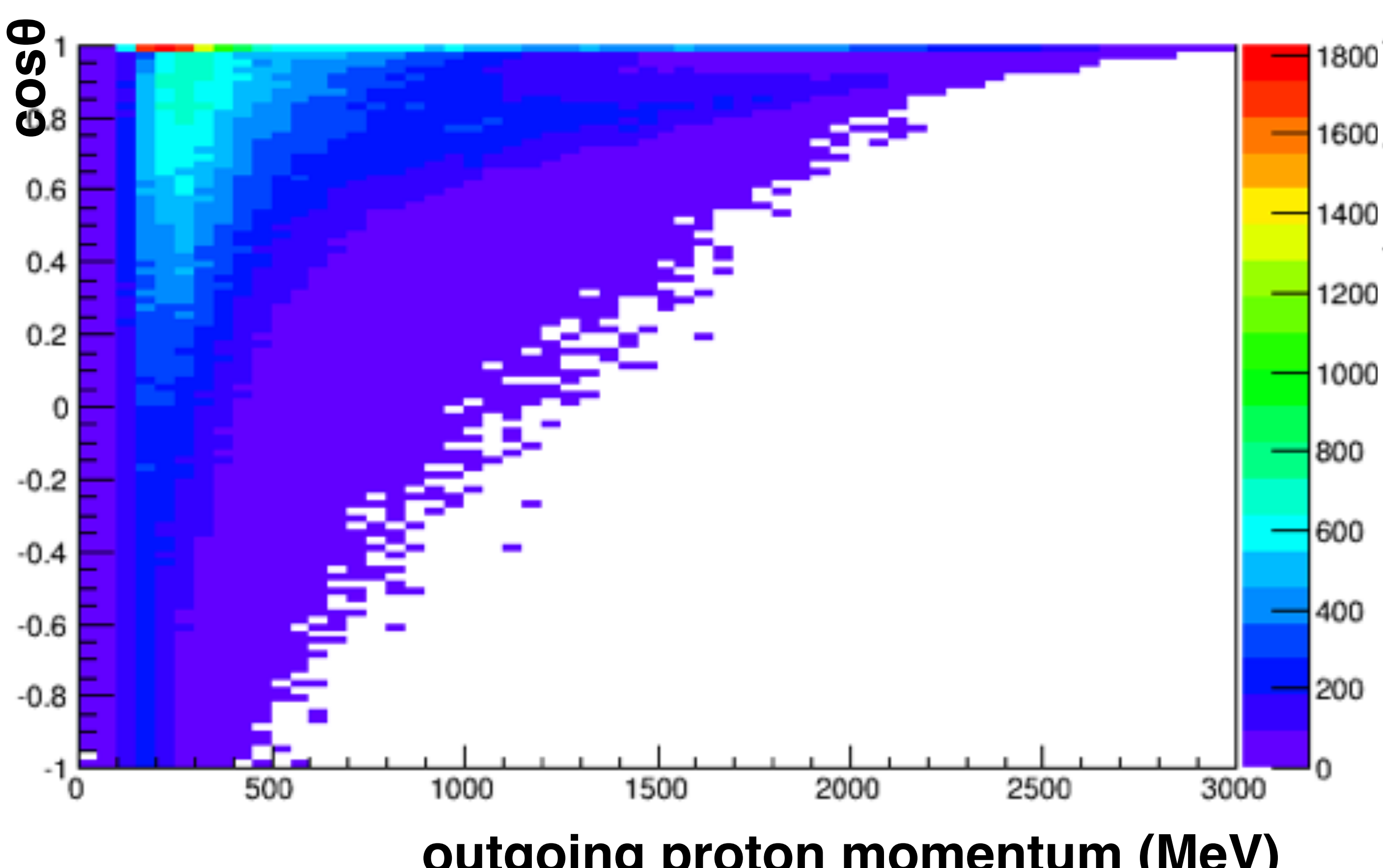
- Study NEUT nucleon FSI model uncertainties by comparing different generators with existing data for different nuclei

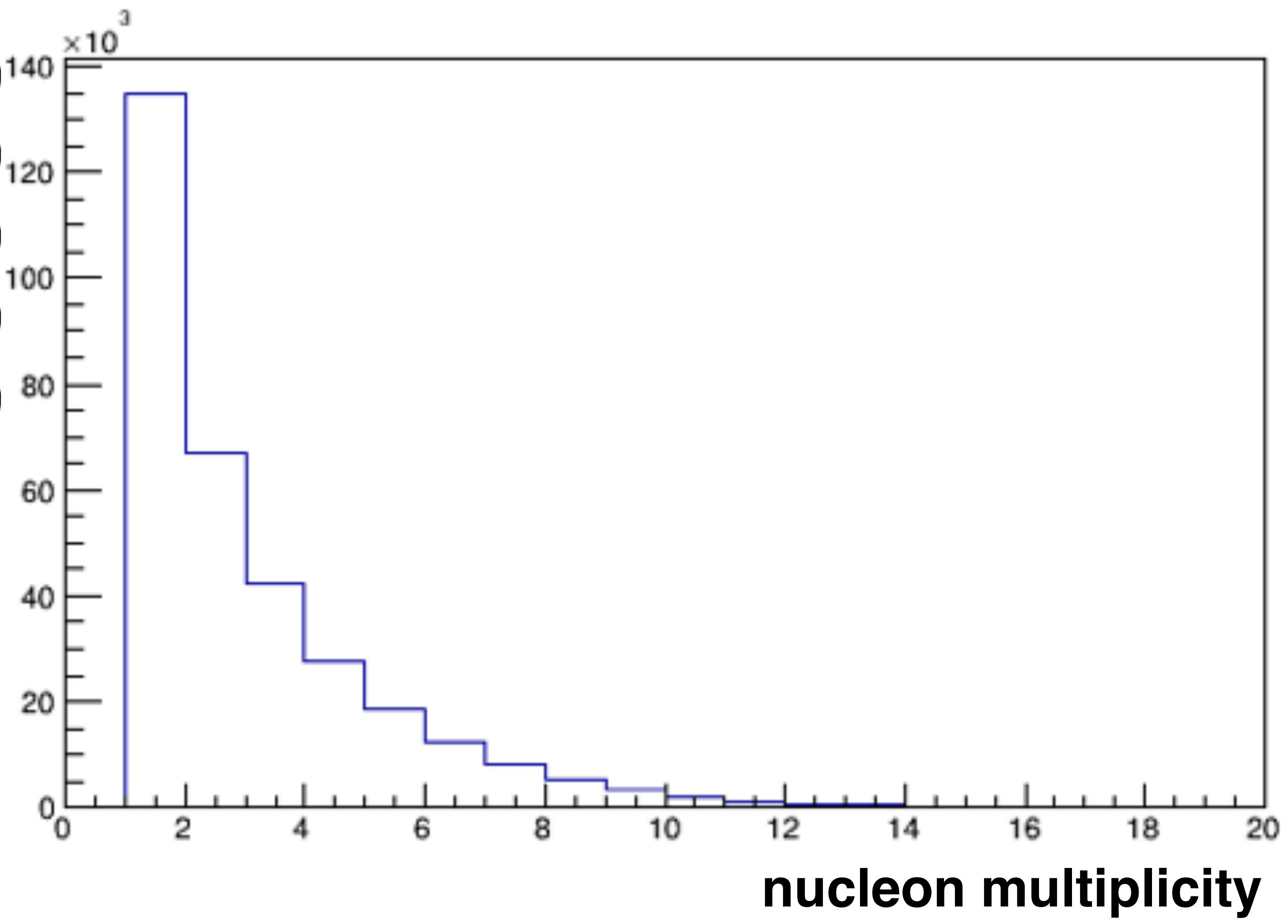
- NEUT: Cascade model tuned to pi-C external data
- GENIE 2.9.0: hA model (tuned to external data, effective cascade)
- Geant4 4.10: Bertini and Binary cascade model
- NuWro: kaskada (full cascade model)

Other kinematics

- Can also compare outgoing proton phase space and nucleon multiplicity (interacted proton only)







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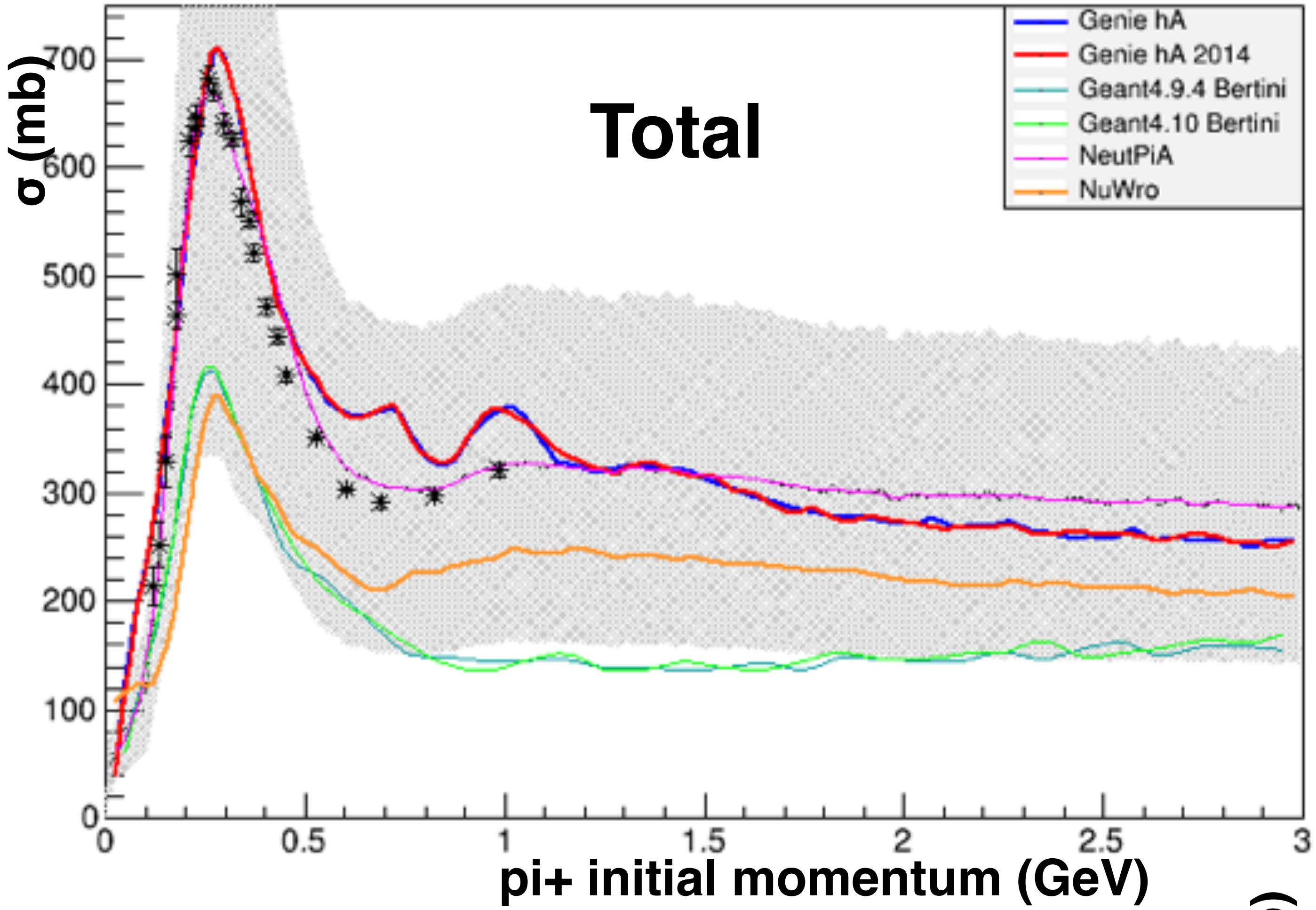
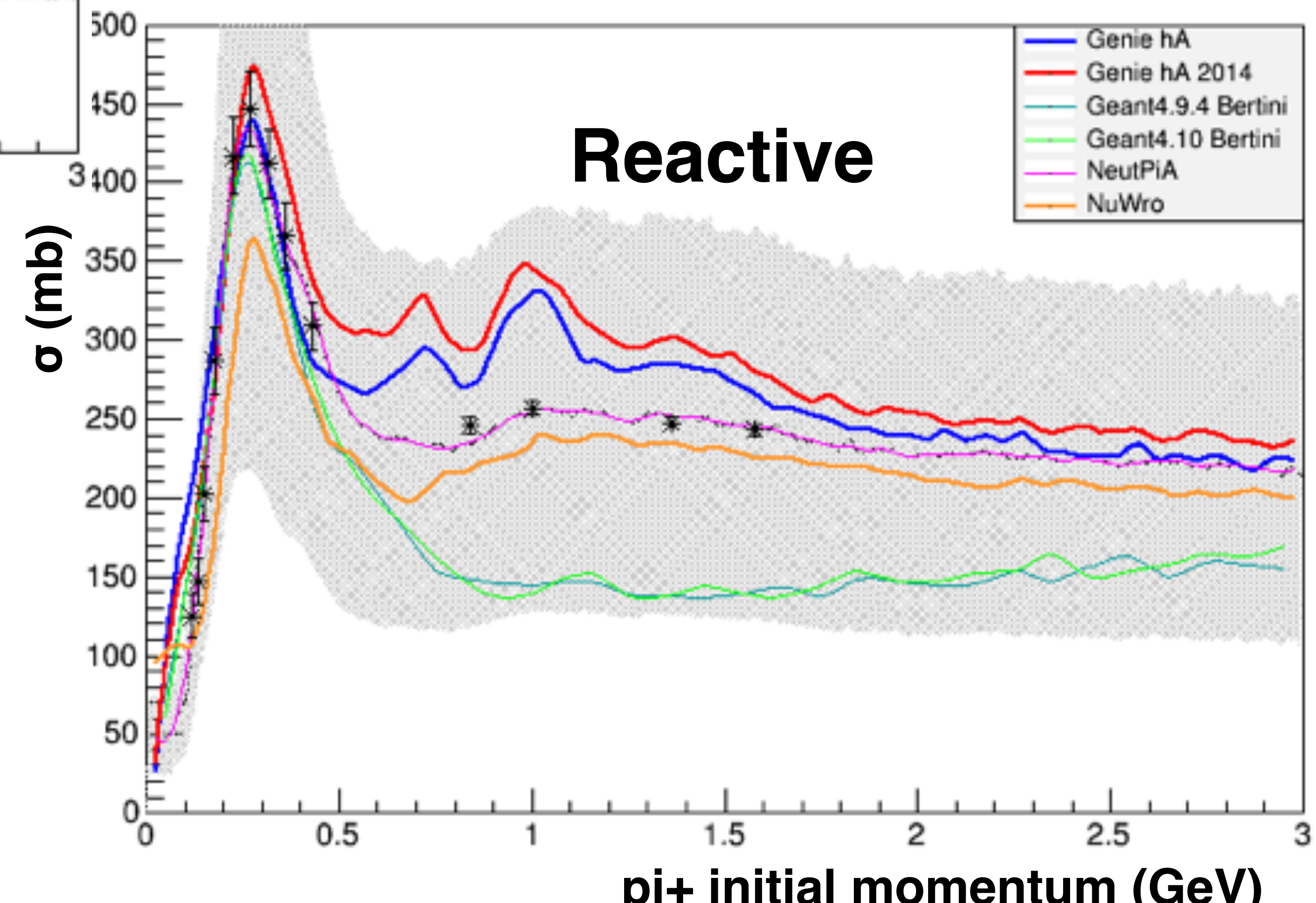
Generator comparison (pi+ on C)

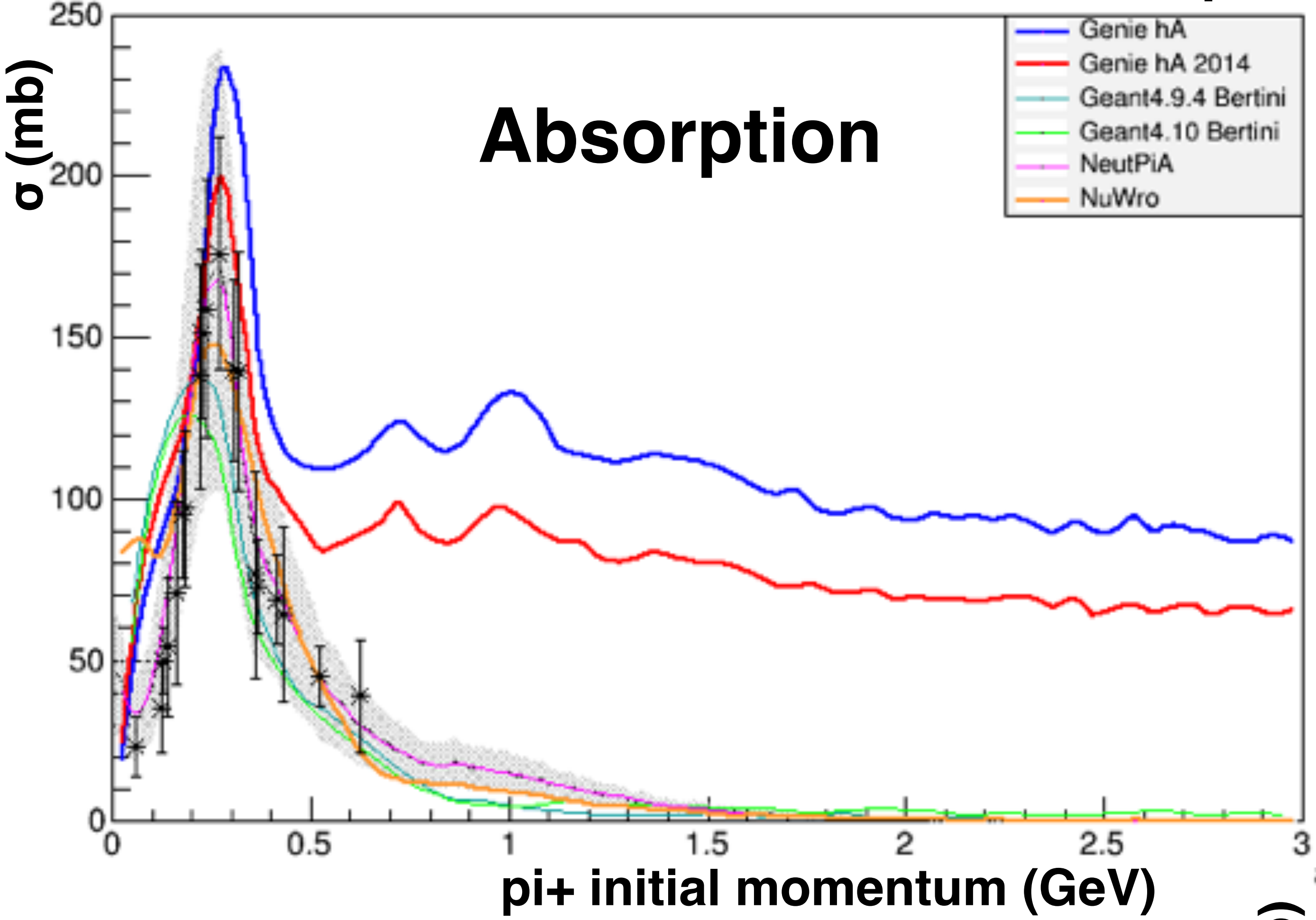


- Uncertainty of weights set in src/reweight/NSystUncertainty.cc
- Put 50% uncertainty on total, reactive

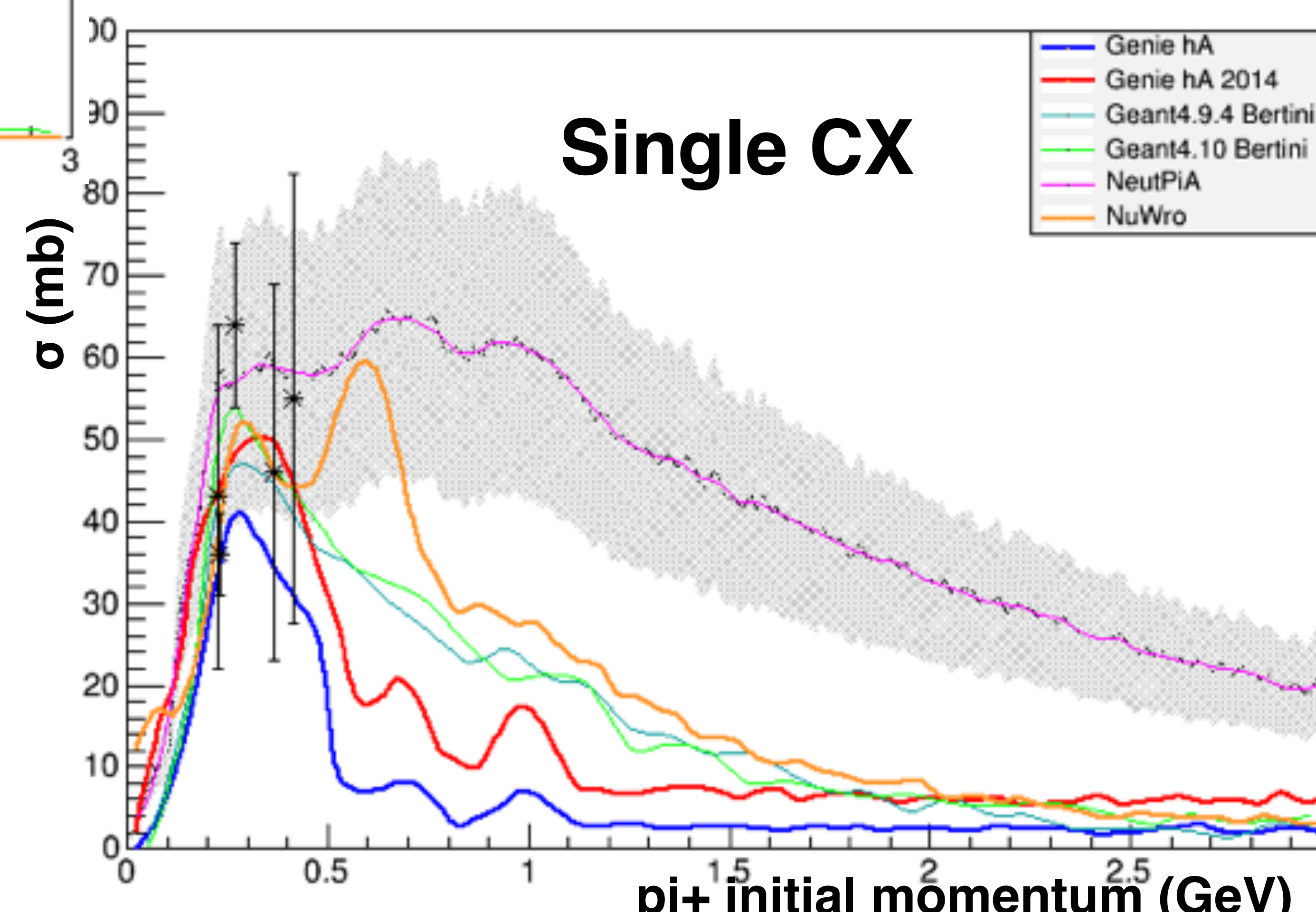
Dials	Default	Uncertainty
CExHigh	1.8	0.3
CExLow	1.0	0.5
InelHigh	1.8	0.3
InelLow	1.0	0.4
Abs	1.1	0.4
PiProd	1.0	0.5



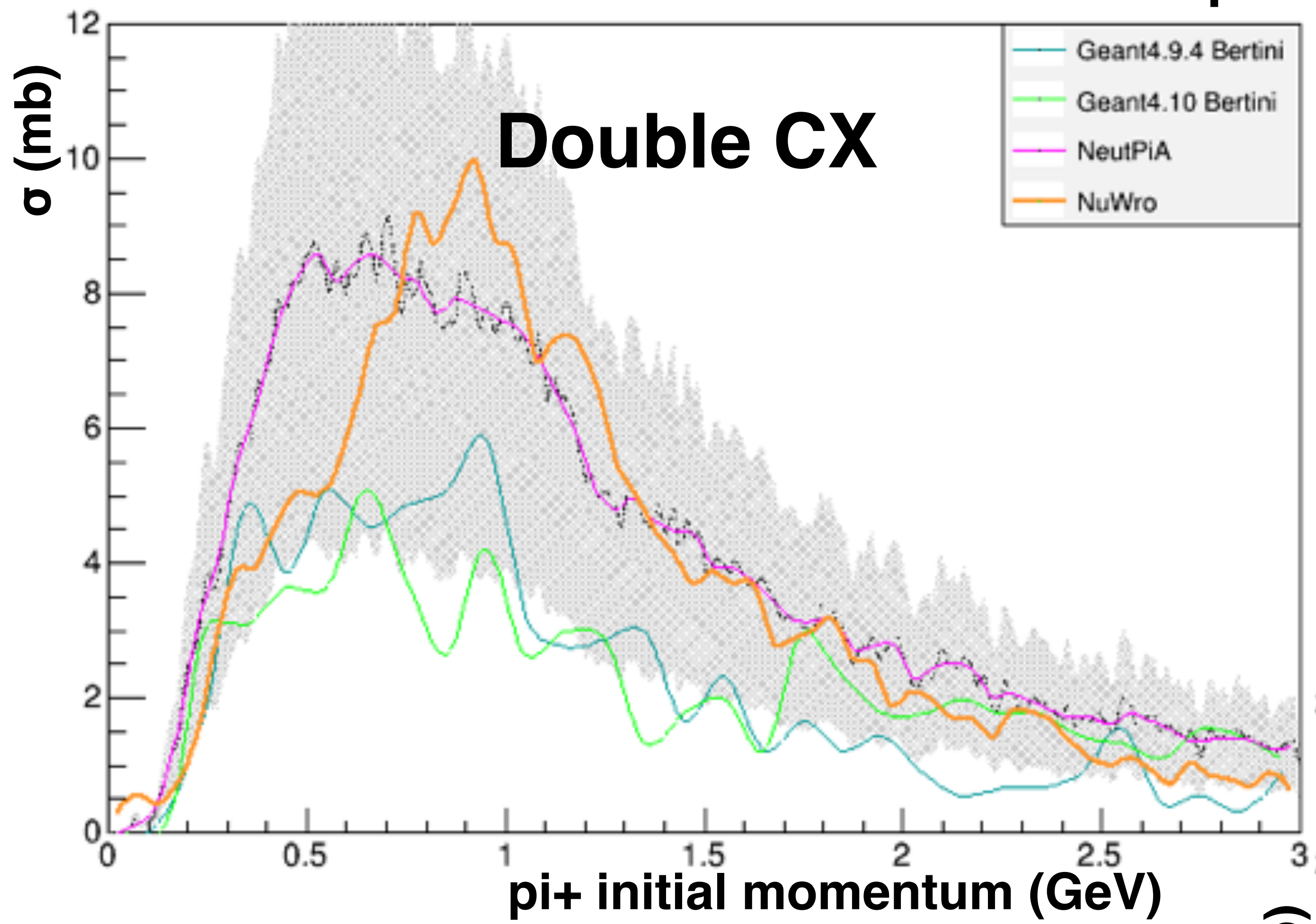
Generator comparison (pi+ on C)



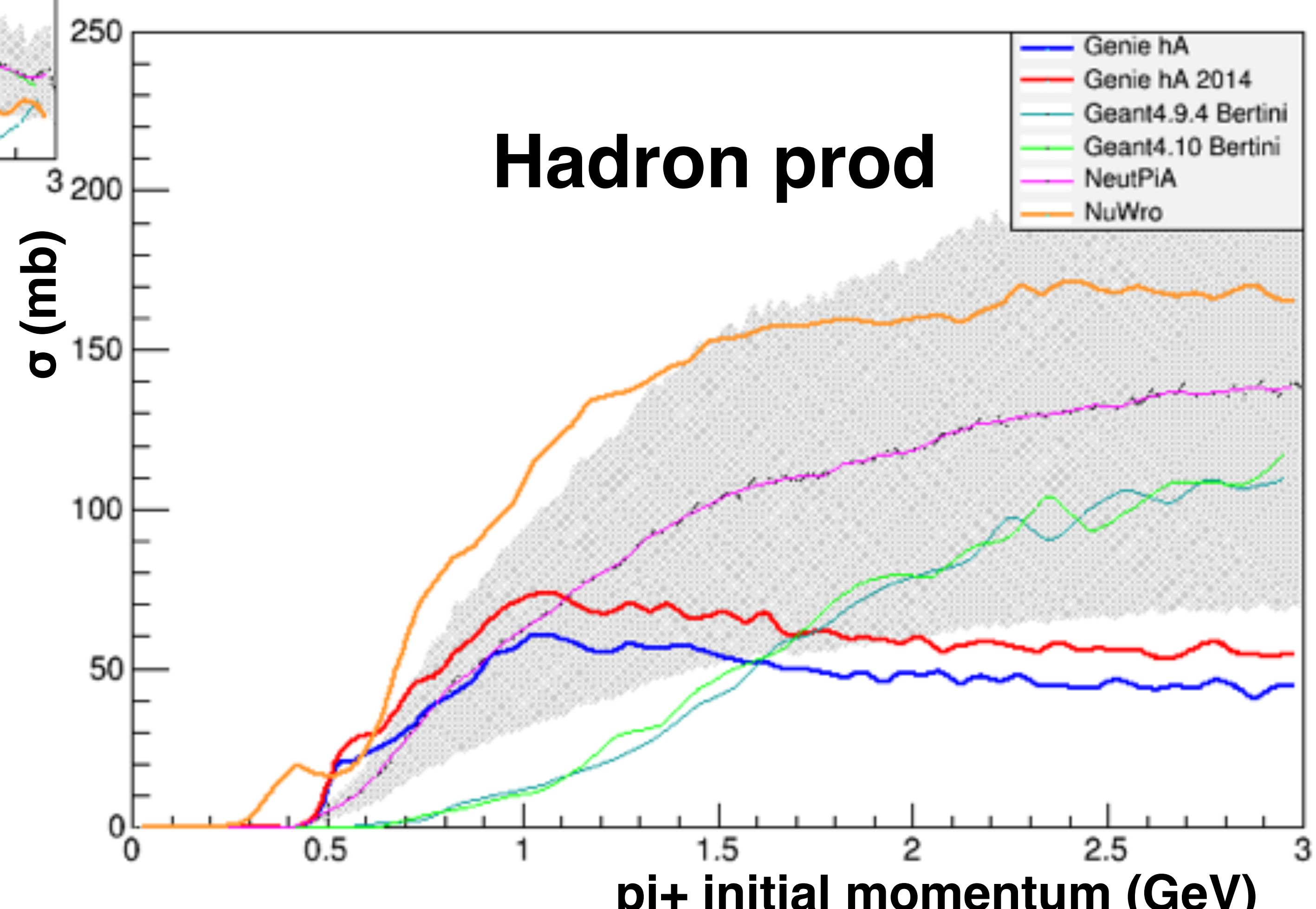
- 40% uncertainty on absorption, 30% on single cx



Generator comparison (pi+ on C)

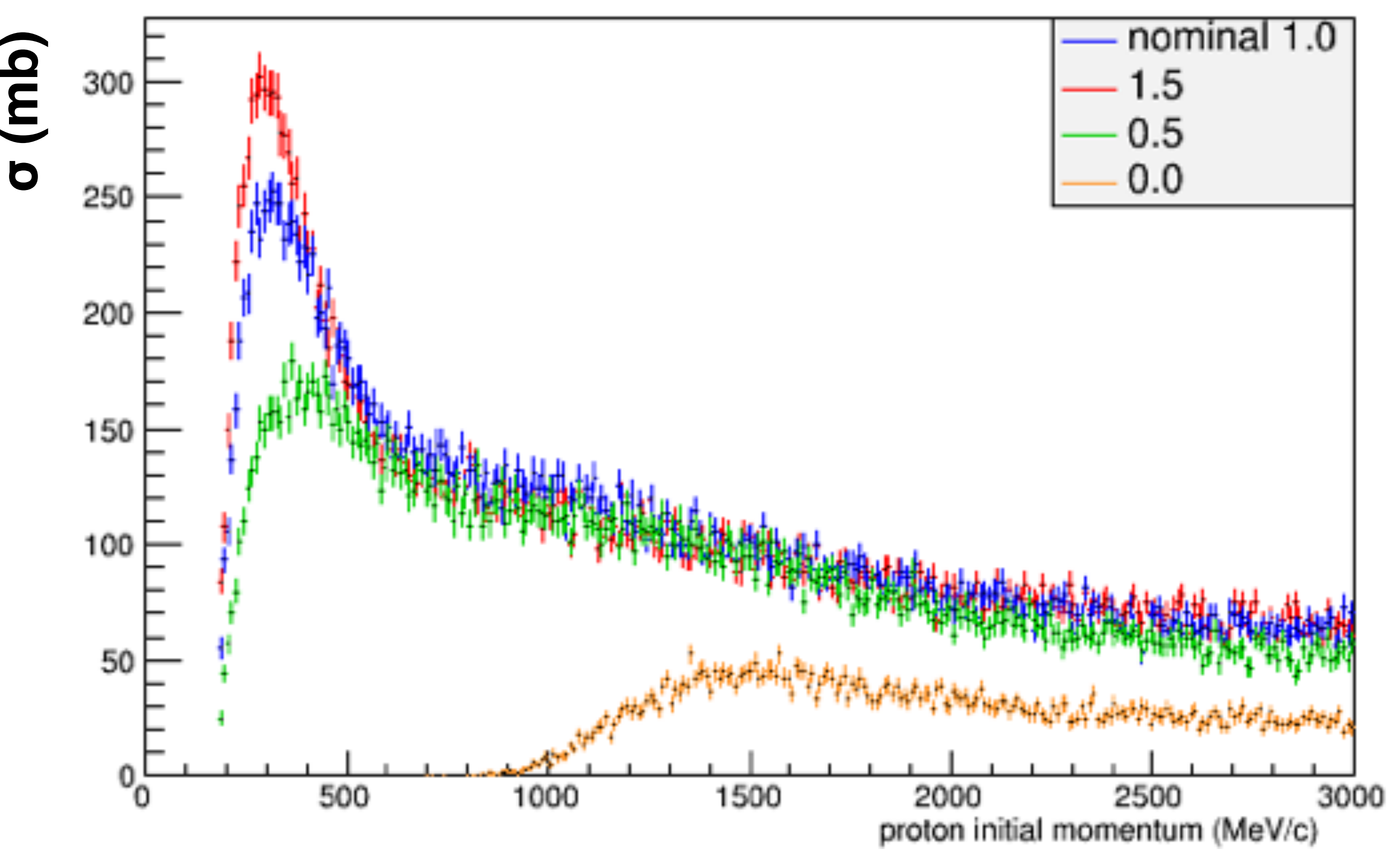


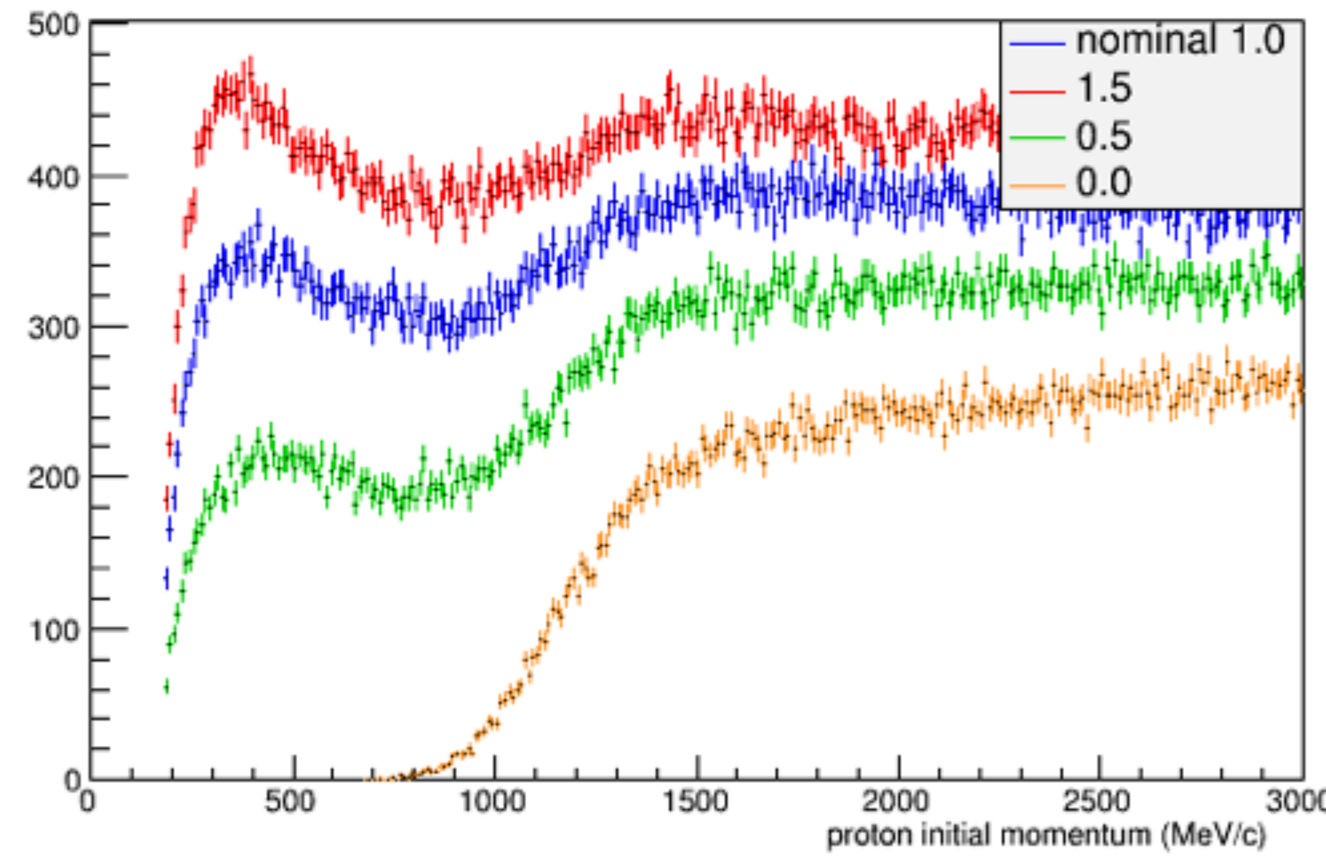
- 50% uncertainty on these



Test: elastic scattering factor

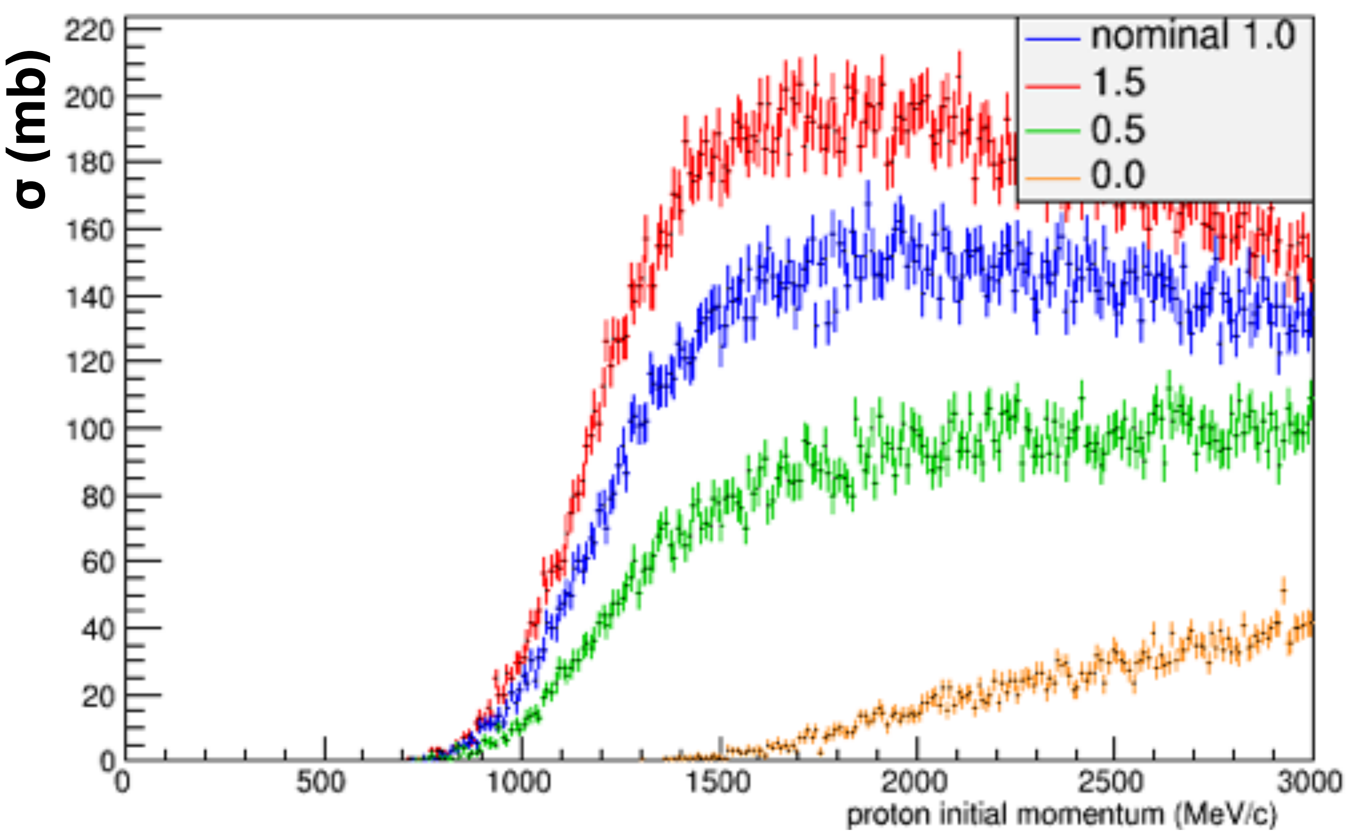
- Back to the new parameters, tweak elastic scattering factor
- Left: “elastic” xsec for different elastic scattering factor
- Right: total xsec for different elastic scattering factor

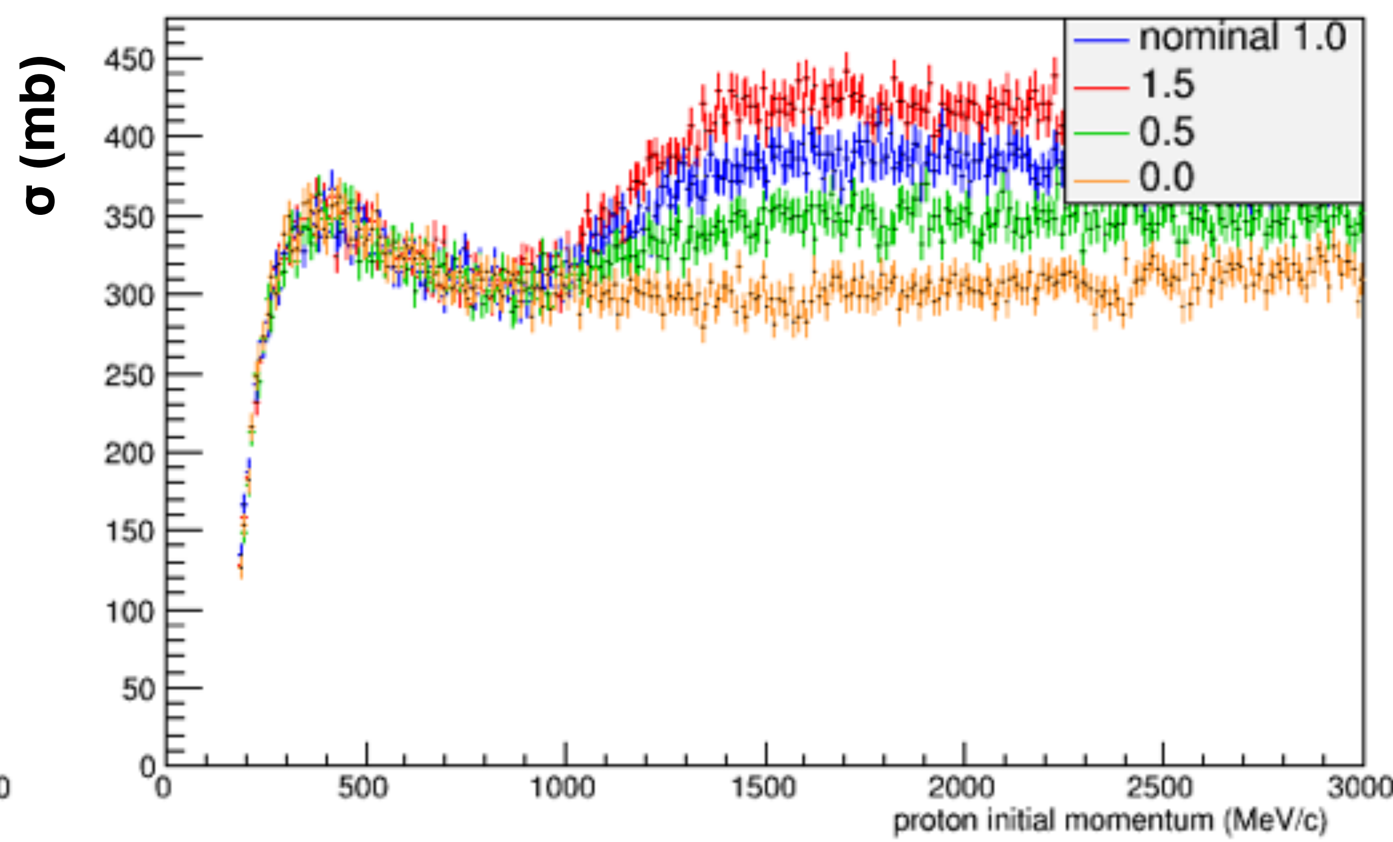




Test: single pi prod factor

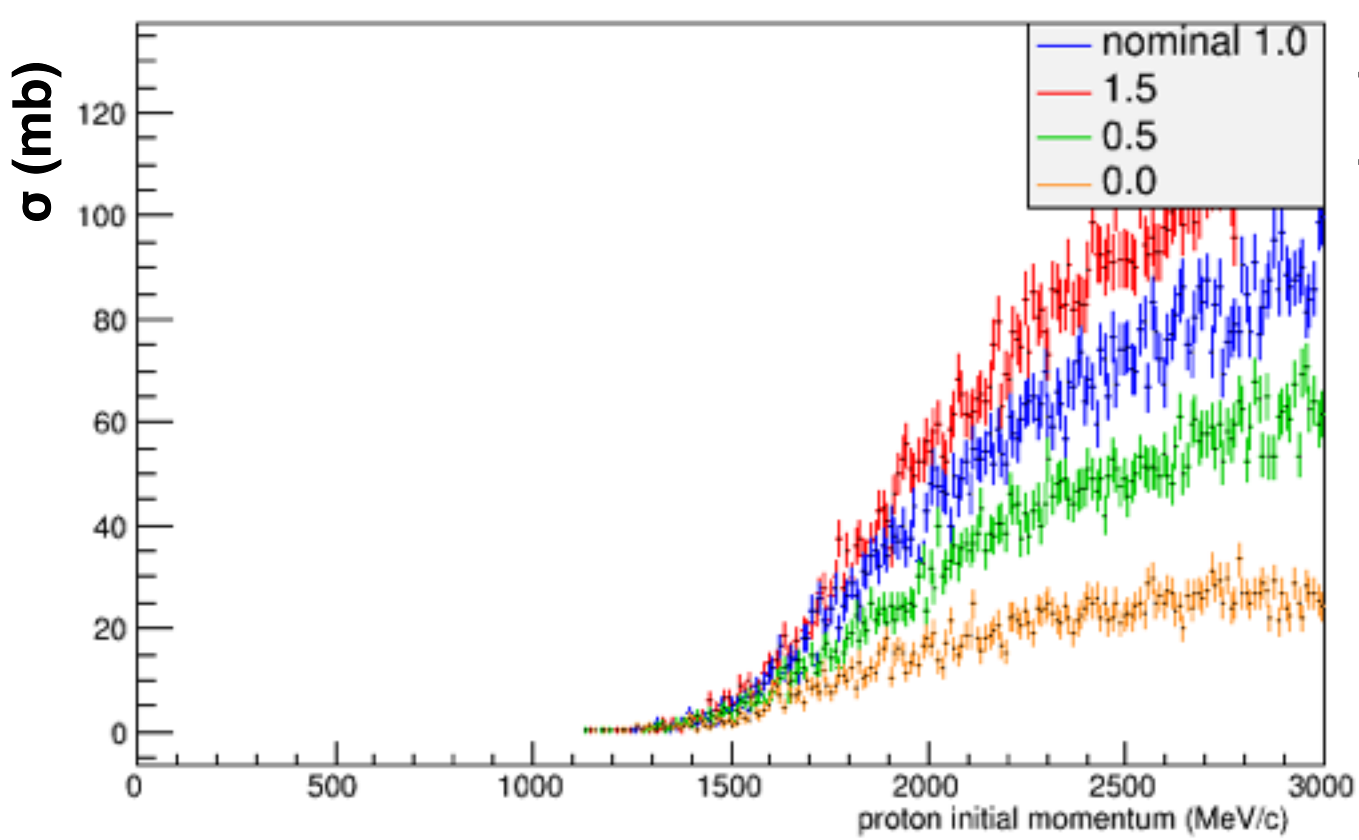
- Tweak single pi production factor
- Left: pi production xsec for different pi production factor
- Right: total xsec for different pi production factor

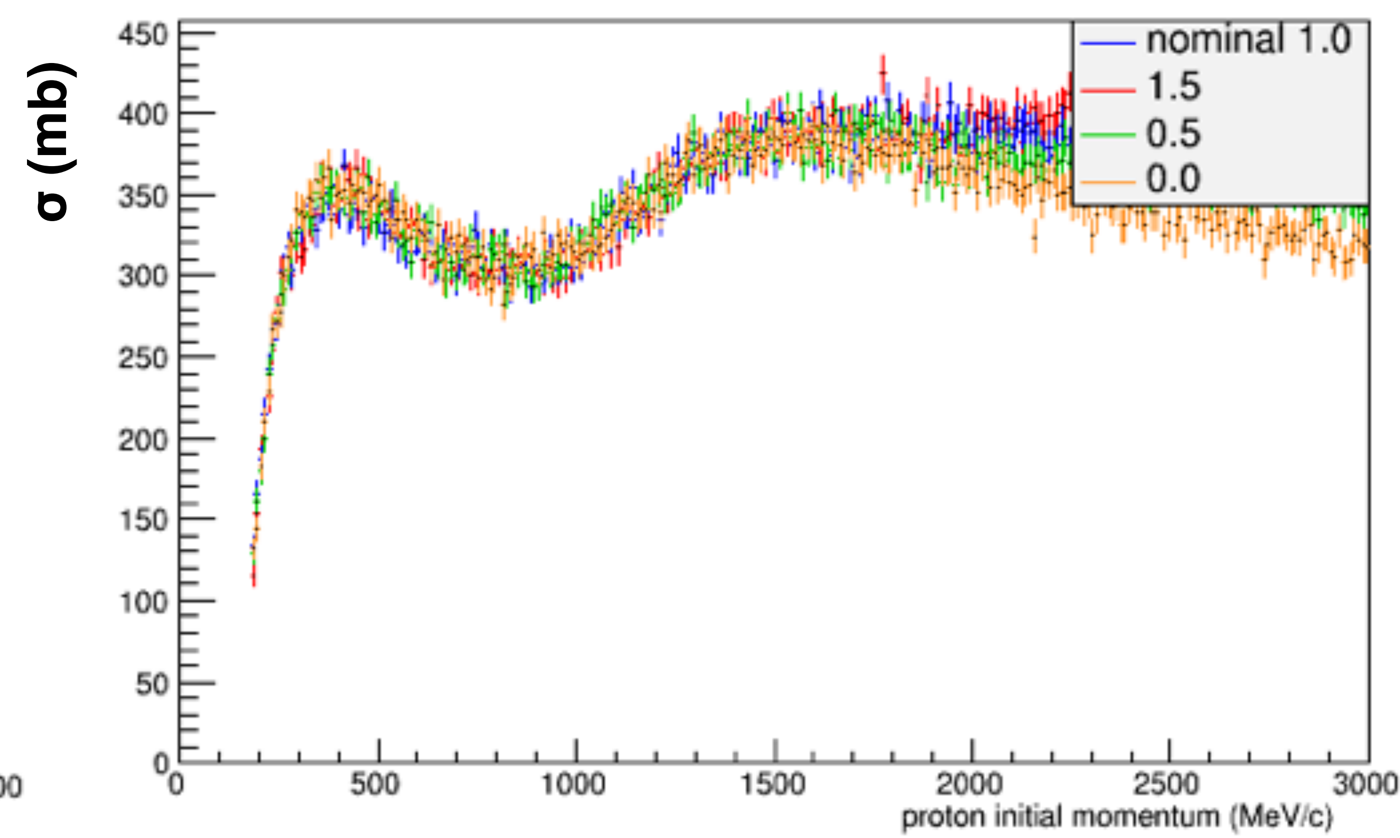




Test: double pi prod factor

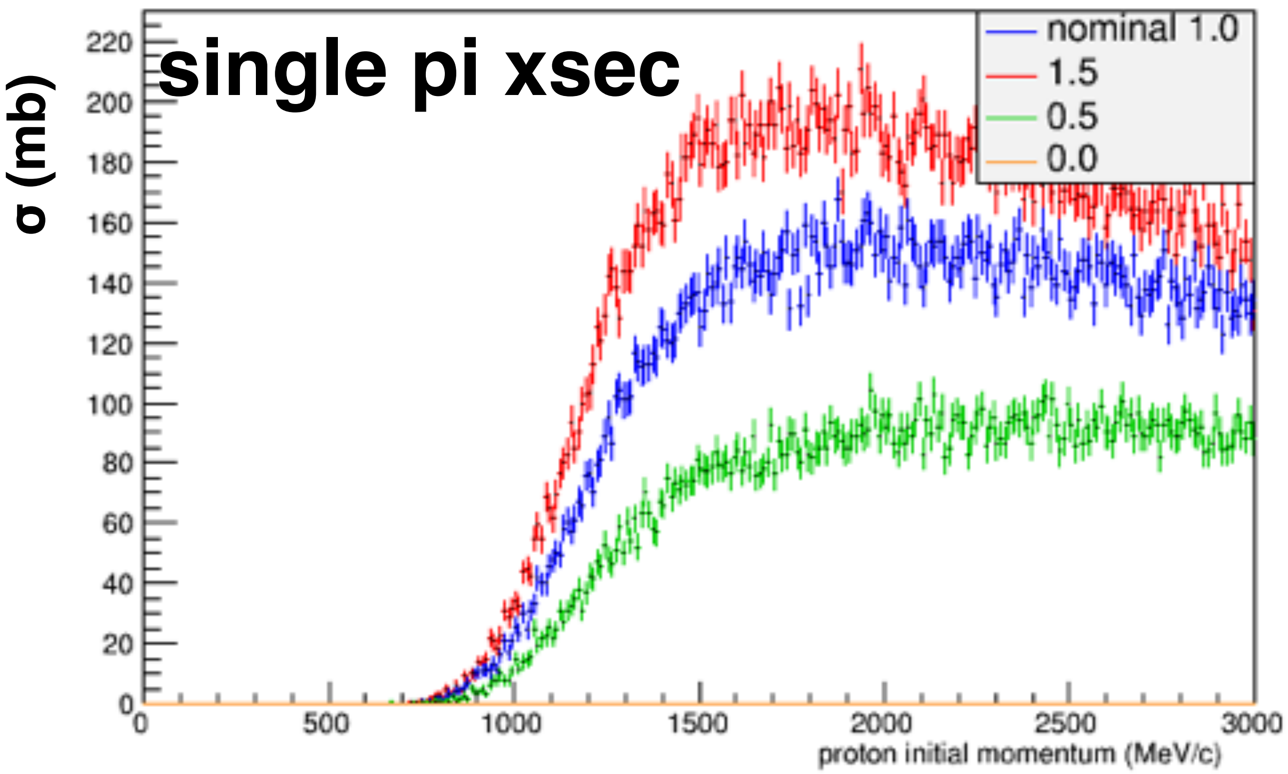
- Tweak single/double pi production factor
- Left: pi production xsec for different pi production factor
- Right: total xsec for different pi production factor

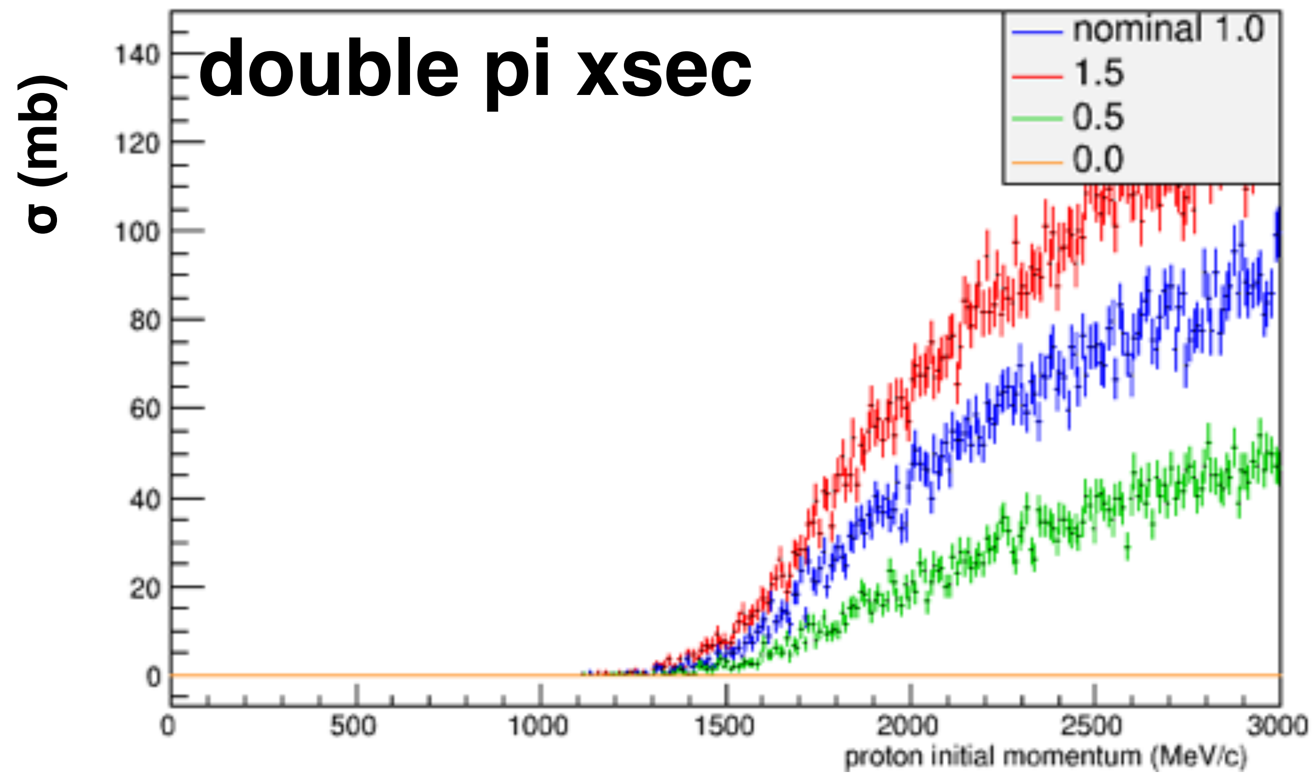


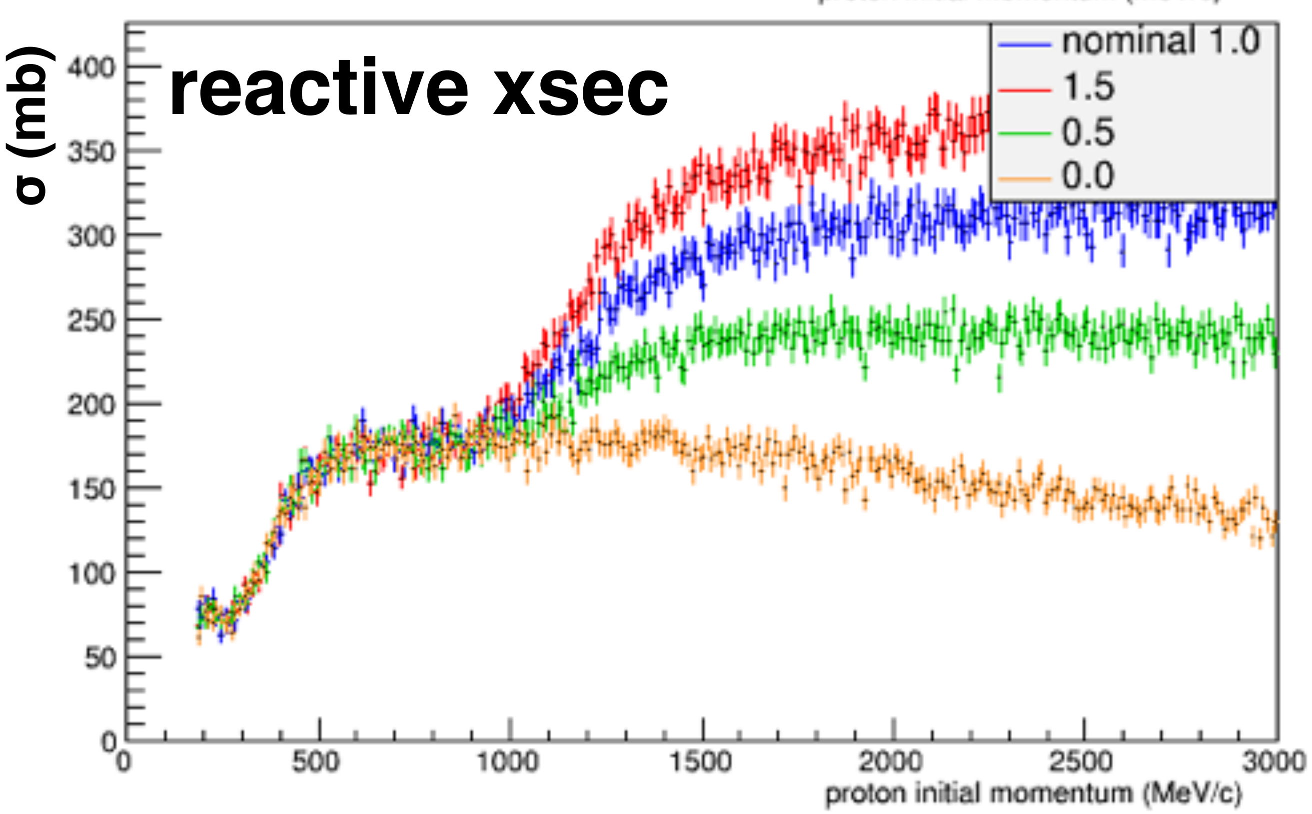


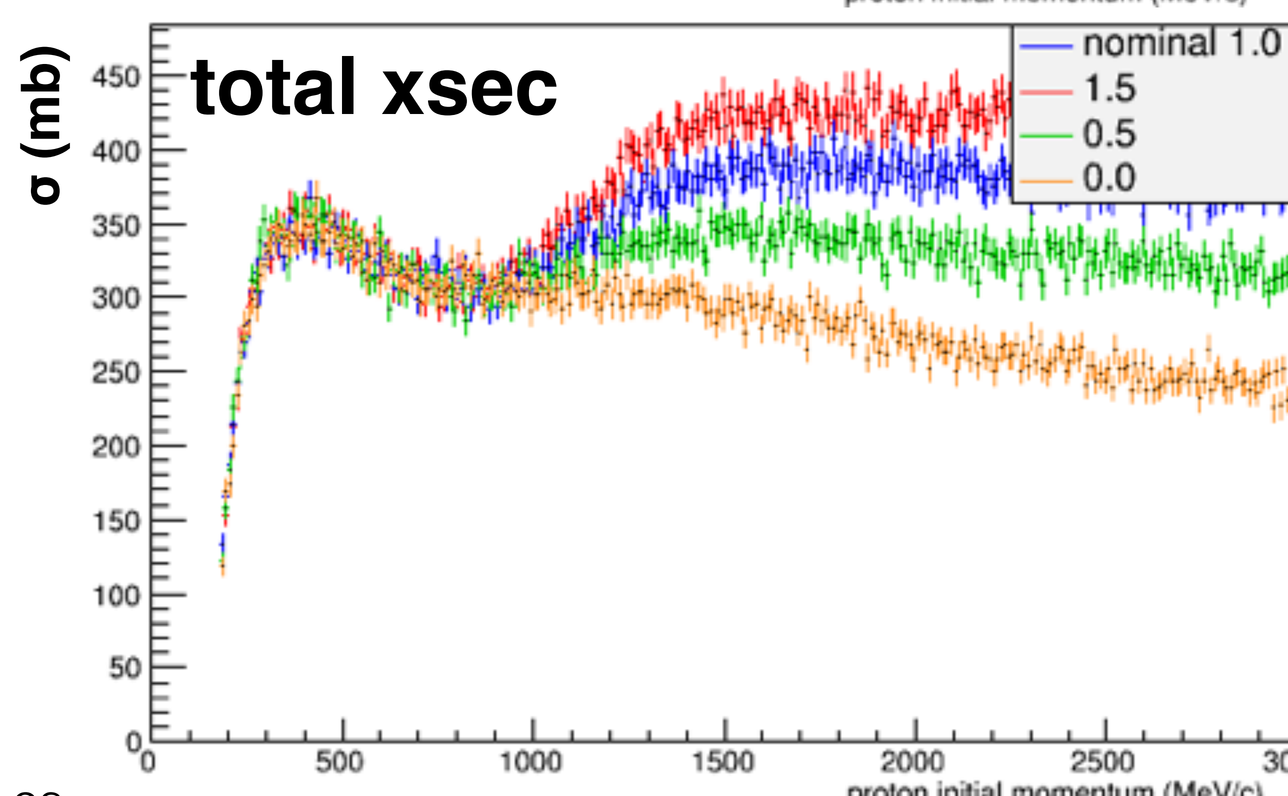
Test: Combine pi prod factor

- Tweak single+double pi production factor (to reflect reactive xsec)







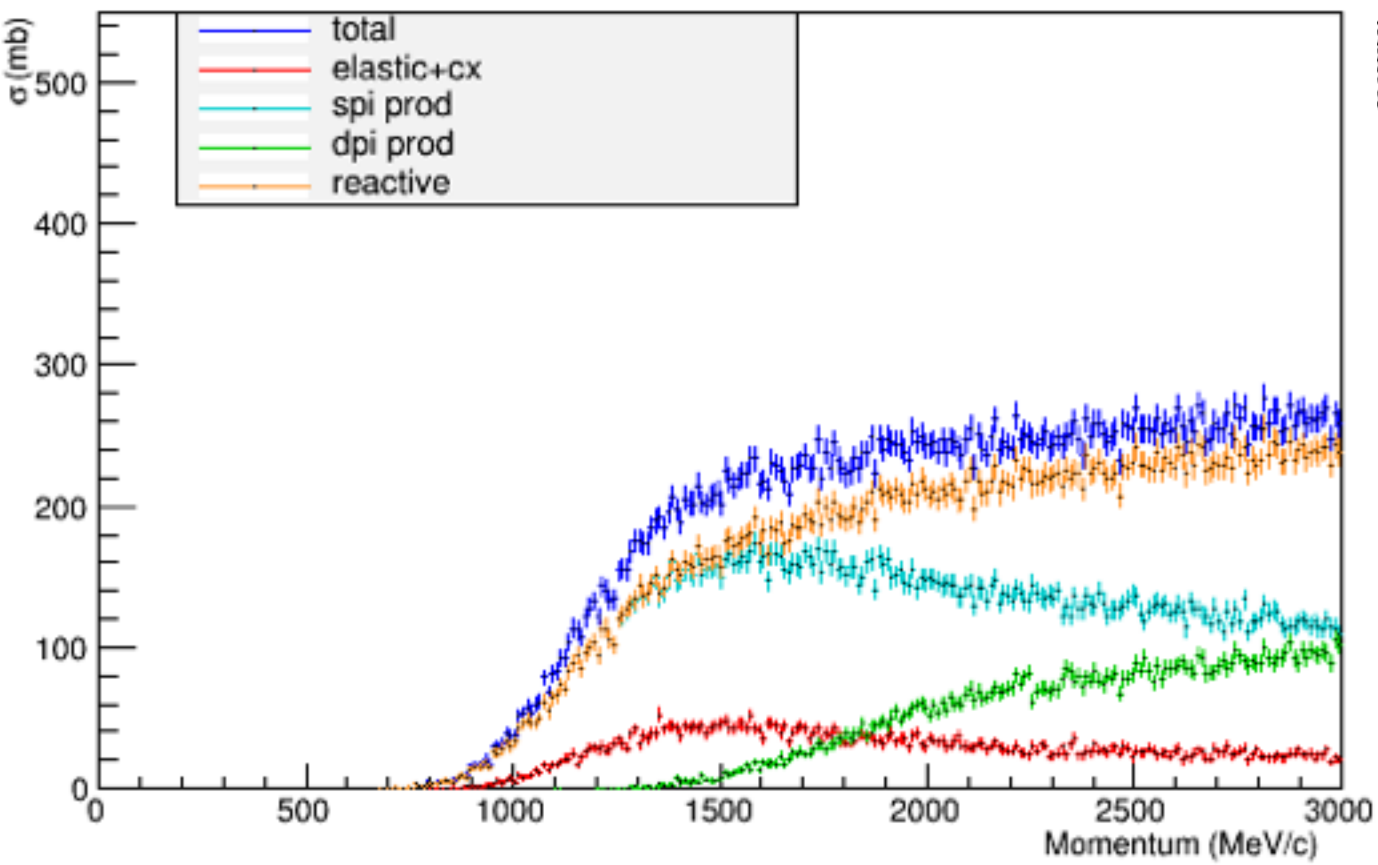


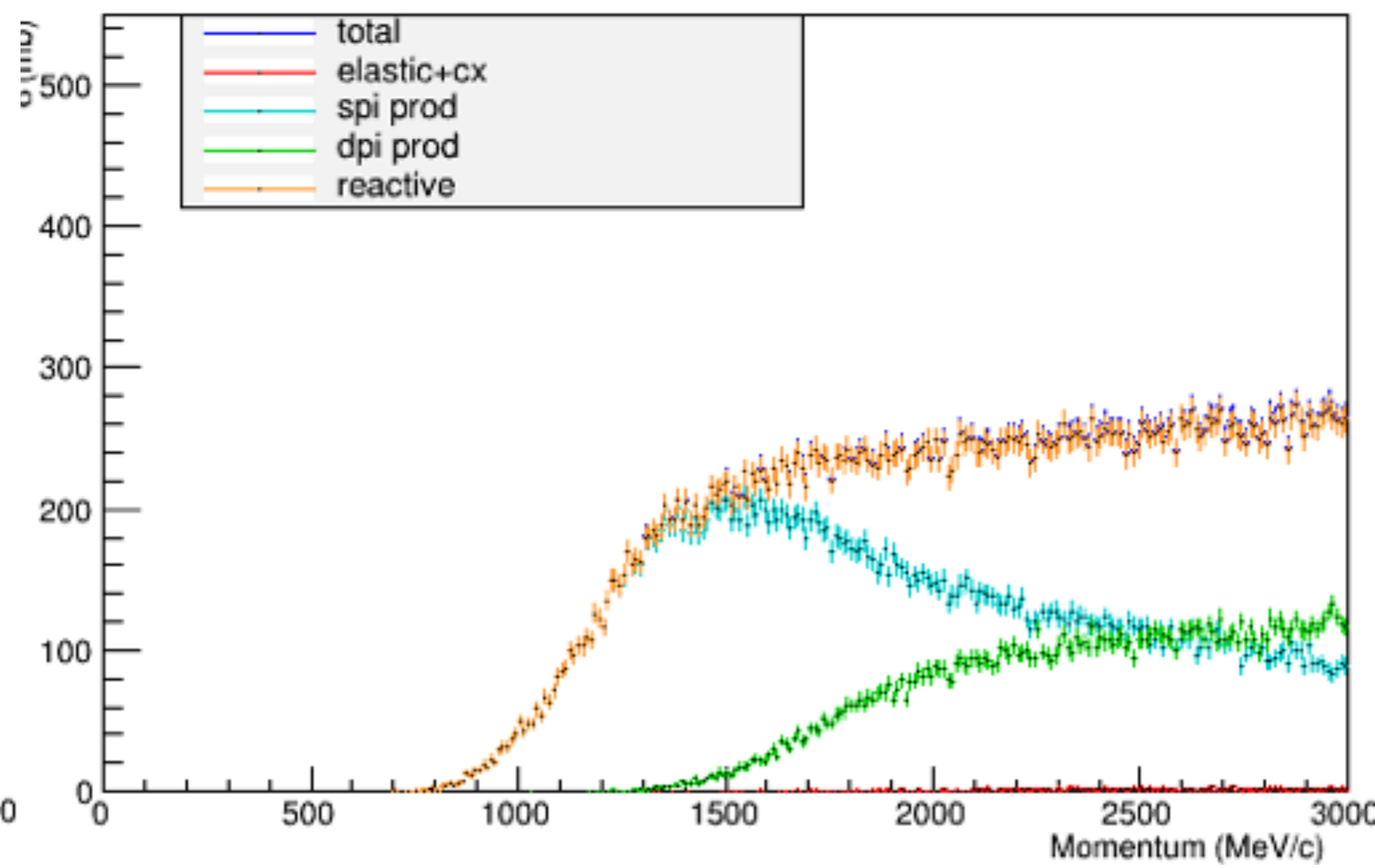
To Summarize

- The added parameters are working
- xsec doesn't go to 0 when each factor is set to 0
- This is because I define the interaction base on outgoing particle!
- Pions are rescattered in the nucleus, i.e. affected by pion FSI
- As a result, charged pi production external data will not make a good comparison (even though charges of pions and the nucleon are selected to be equally distributed)
- Also, elastic data is not useful because there is only quasi-elastic interaction
- It is not possible to implement as GENIE does because of the assumptions and/or modelings are different.

Turning off pion FSI

- Set elastic scattering factor = 0
- Compare with/without pion FSI
- No FSI, there are always pions in FS





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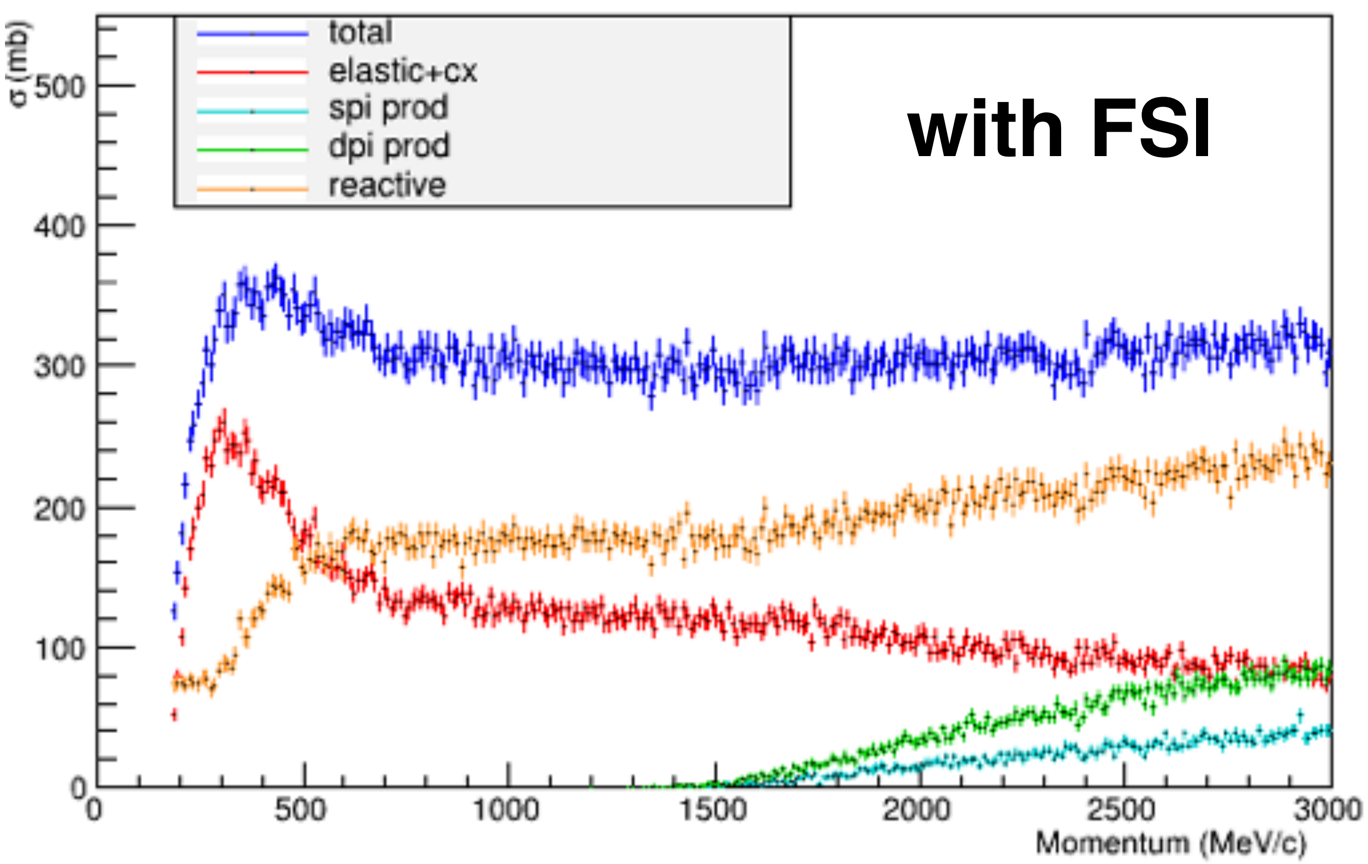
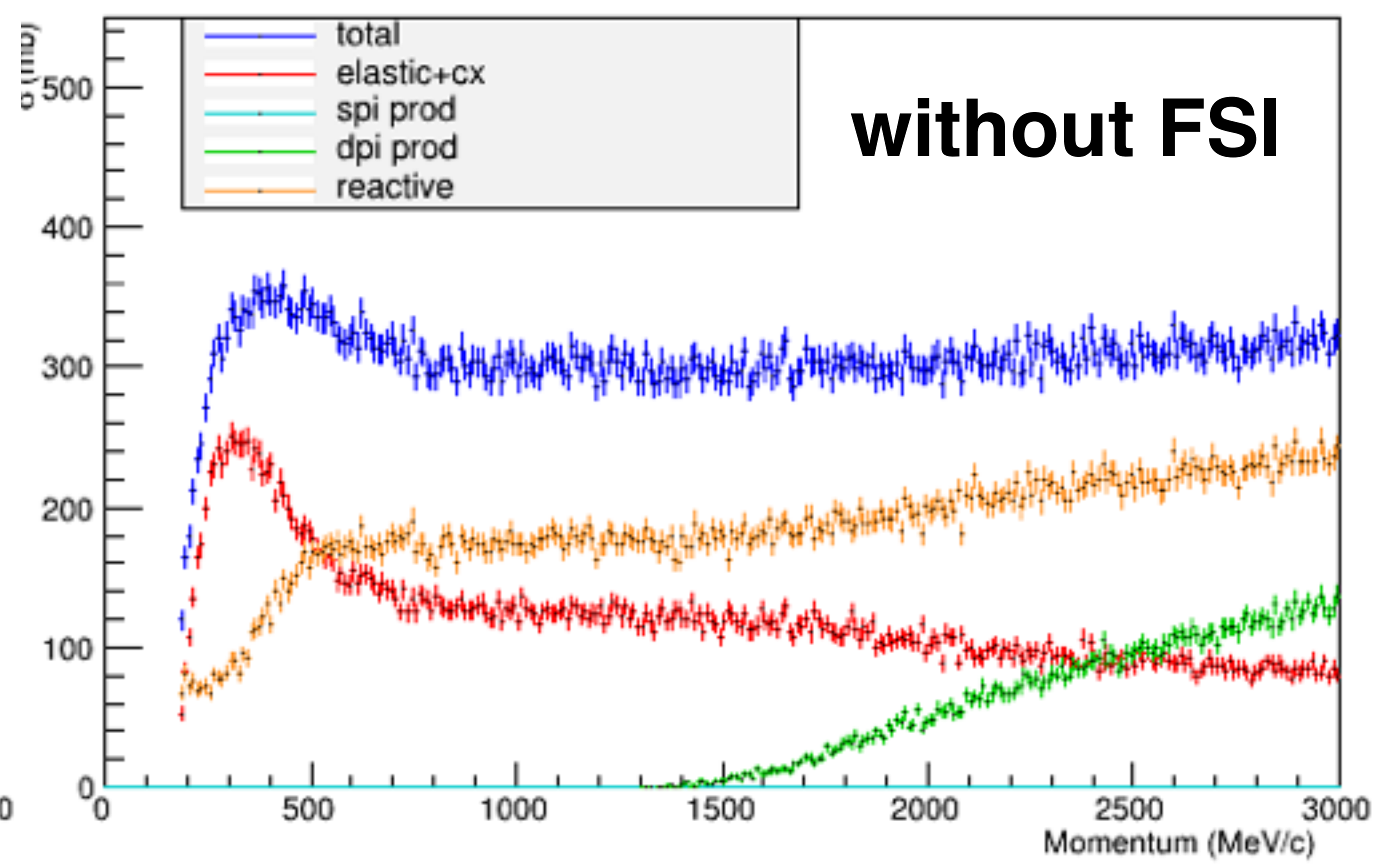
Turning off pion FSI

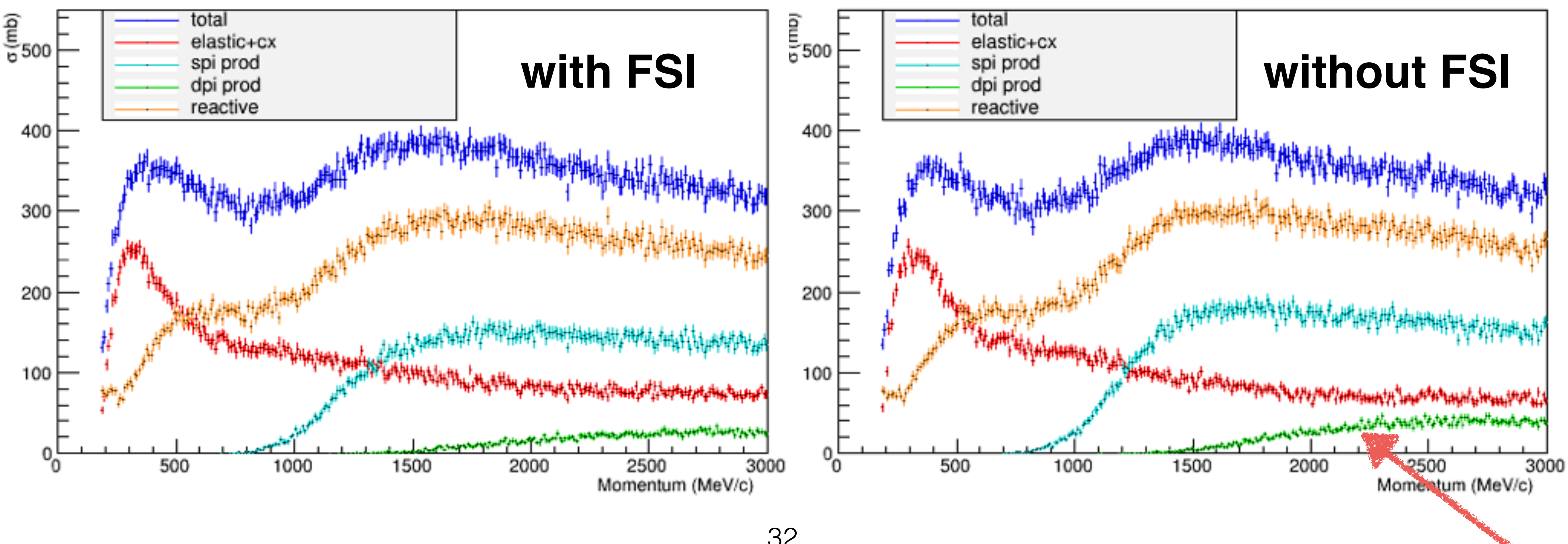
- Set single pion production factor = 0
- Compare with/without pion FSI
- No FSI, should only find 0/2 pions in FS





Turning off pion FSI

- Set double pion production factor = 0
- Compare with/without pion FSI
- No FSI, there is still a distribution of double pi prod?



Turning off pion FSI

- Set single/double pion production factor = 0
- Can only undergo elastic interaction
- Reactive: more than 2 nucleons in FS