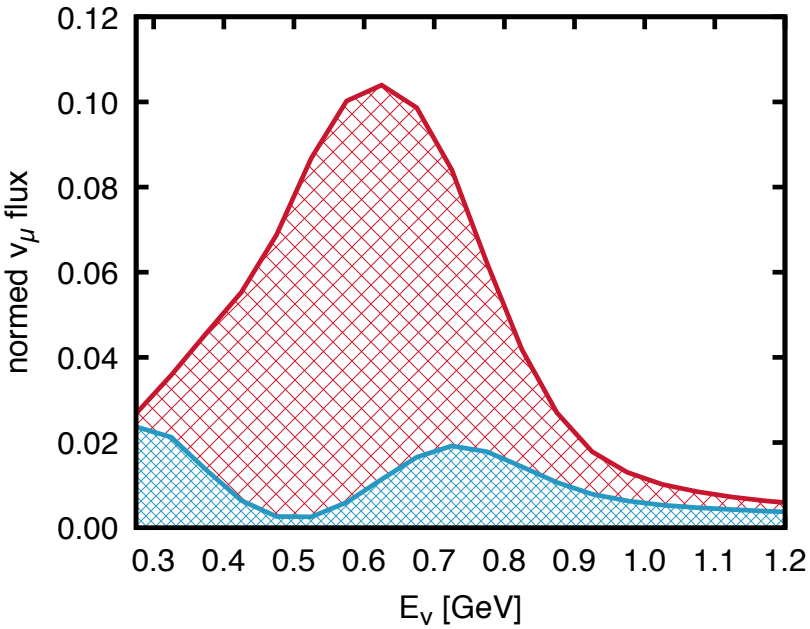
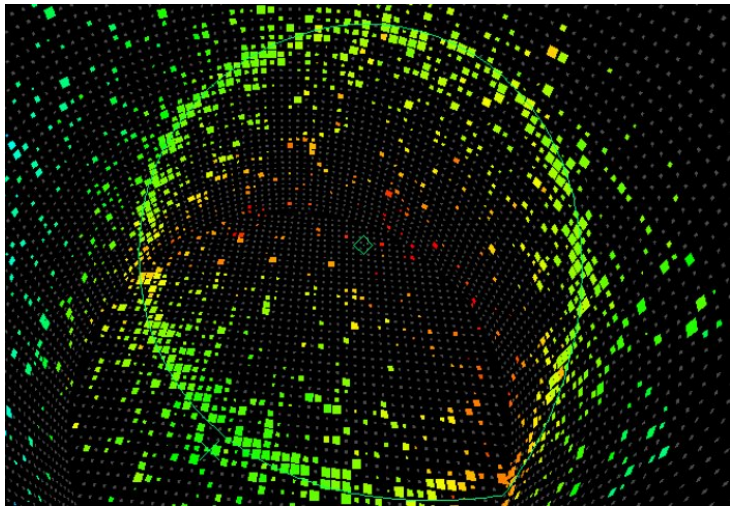
Nuclear Transparency: NuWro vs Data

Kajetan Niewczas

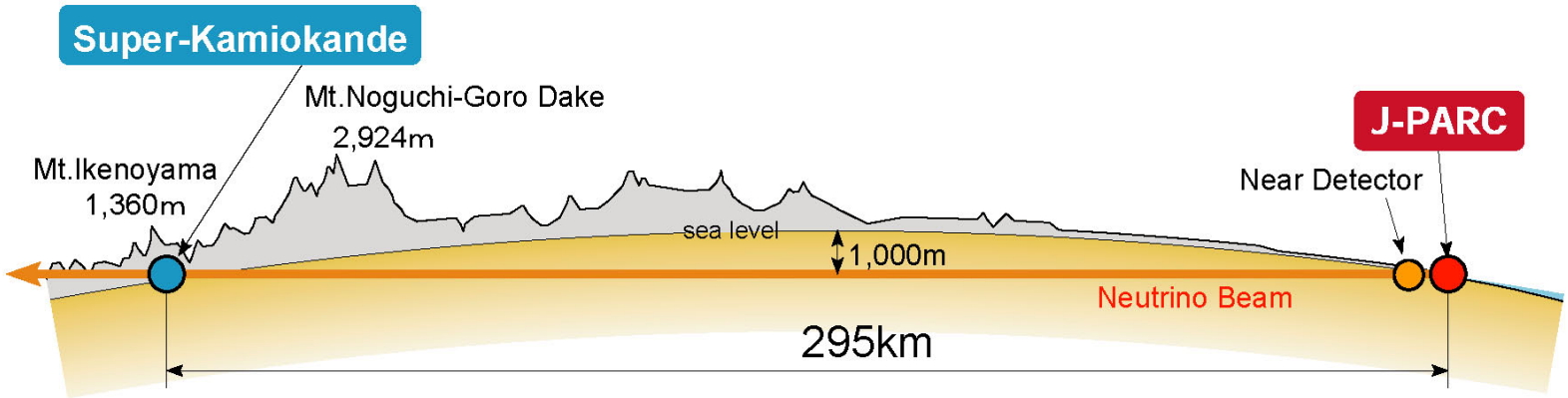
Neutrino oscillation experiments

$$P_{2f}(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

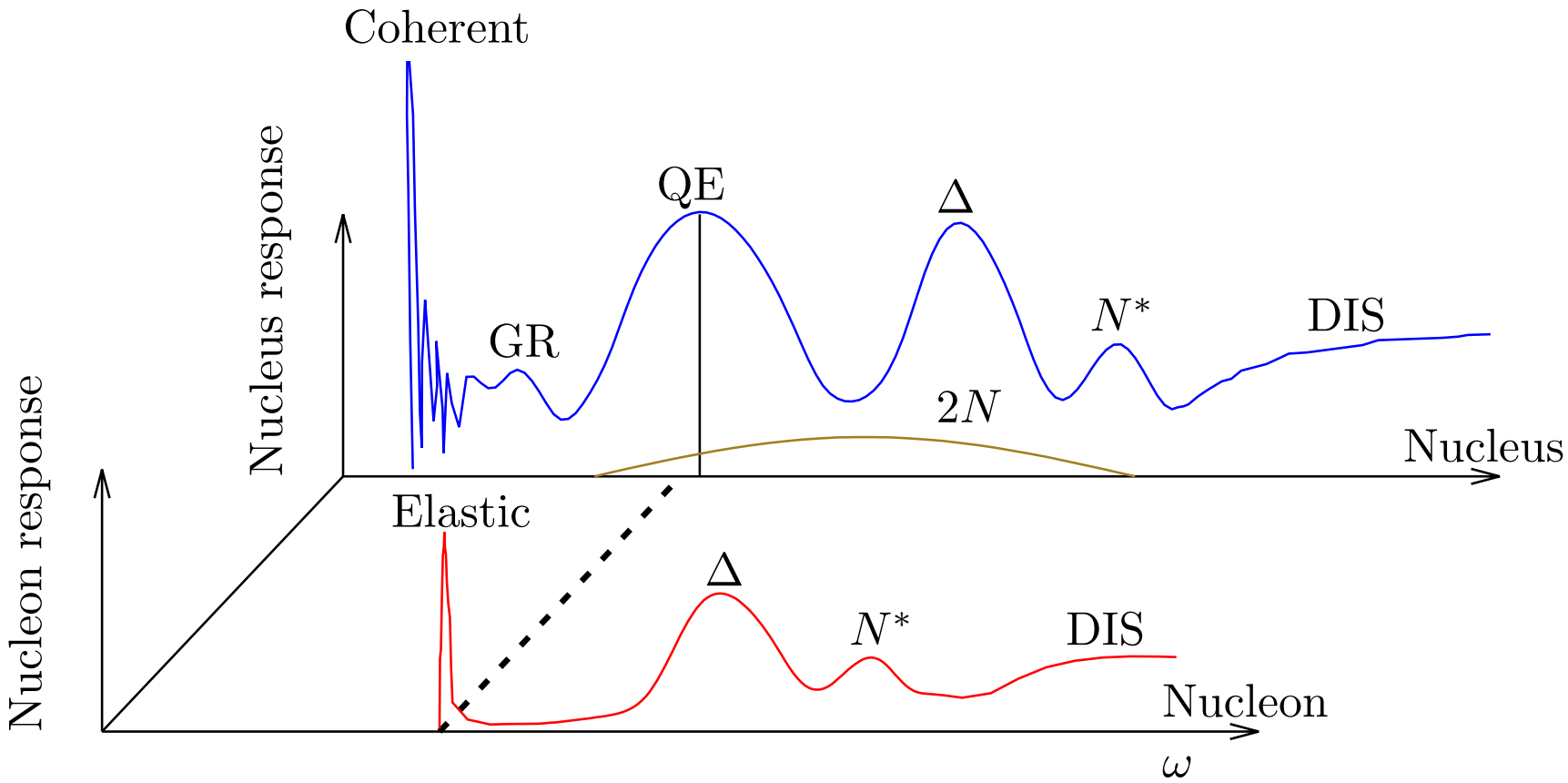




$$E_\nu^{\mathrm{rec}} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2)}{2[M_n - E_B - E_\mu + |\vec{k}_\mu|\cos\theta_\mu]}$$



Nuclear response



T. Van Cuyck

Purpose of generators

Provide **cross sections**:

- for every **significant channel**
- over the **whole phase space**
- taking care of complexity of **detector setups**
- in **efficient** way so it can be used for **experimental analysis**

$\rightarrow$ we solve this complex **integral** using **Monte Carlo** method!

NuWro team since 2006

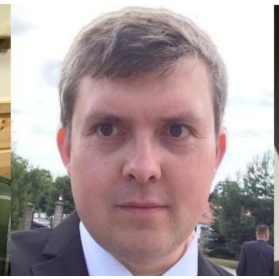
(currently active)


T. Golan


K. Graczyk


C. Juszczak


K. Niewczas


J. Nowak


J.T. Sobczyk


J. Żmuda

Notable supporters

Warsaw


D. Kiełczewska
(passed away in 2016)

General,
many discussions


P. Przewłocki

NuWro at T2K

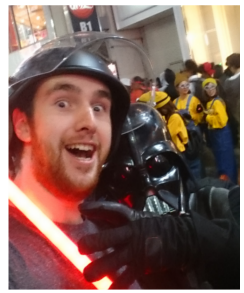
CA, U.S.


A. Ankowski

Spectral function

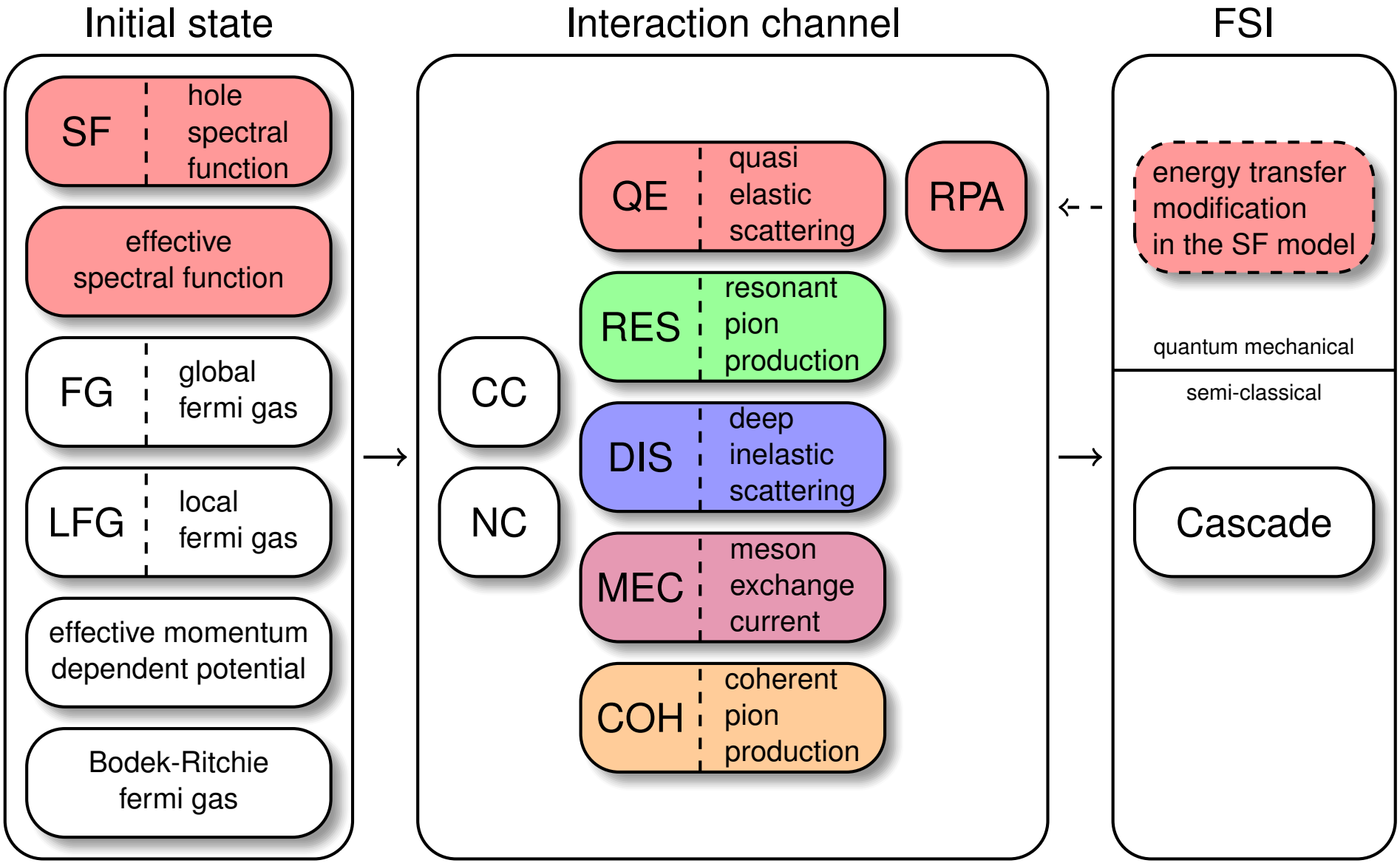
U.K.


L. Pickering


P. Stowell

Reweightning tools

NuWro blueprint



Intranuclear cascade

- **Propagates particles** through the nuclear medium
- **Probability** of passing a distance λ:

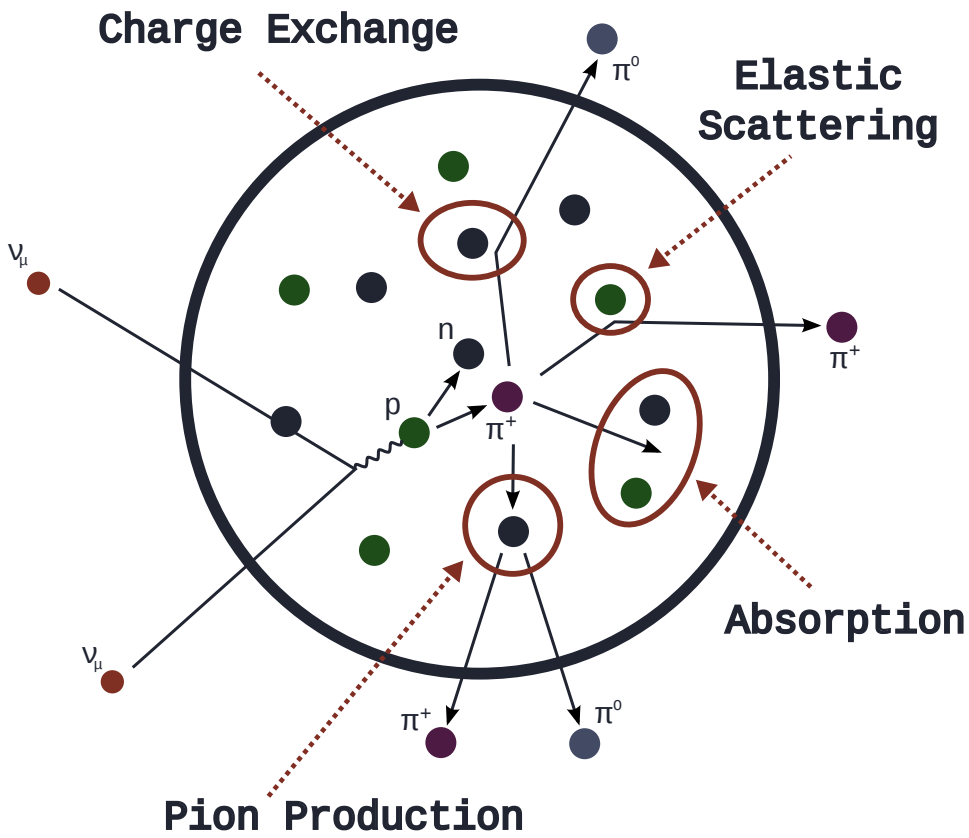
$$P(\lambda) = e^{-\lambda/\tilde{\lambda}}$$

where $\tilde{\lambda} = (\rho\sigma)^{-1}$
ρ - local density
σ - cross section

- Implemented for **nucleons** and **pions**

T. Golan, C. Juszczak, J.T. Sobczyk,
Phys.Rev. C86 (2012) 015505

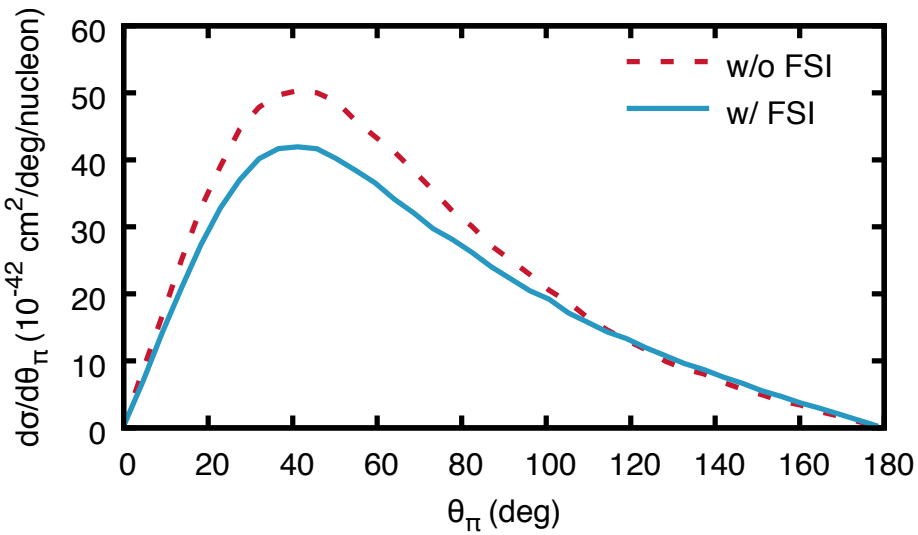
- **Semi-classical** – neglects quantum mechanical effects



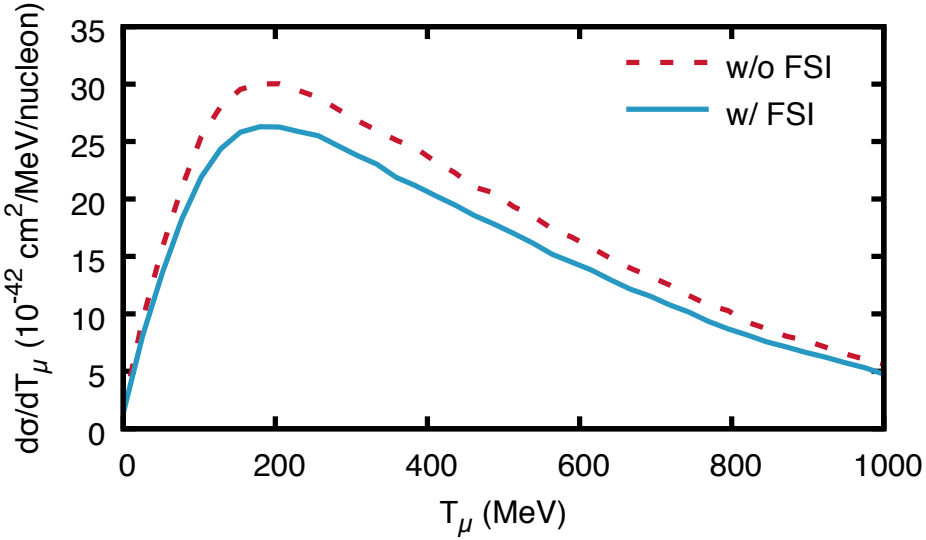
T. Golan

FSI effects

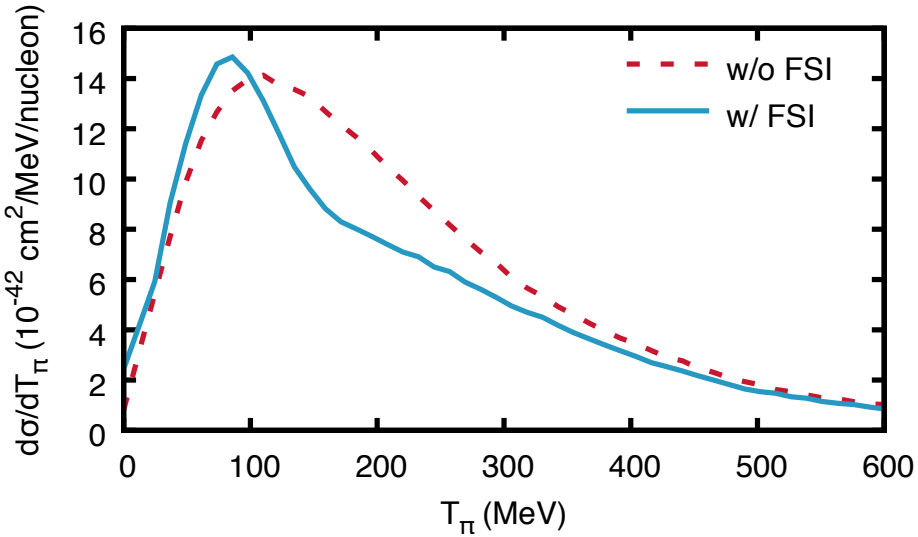
- Reduction



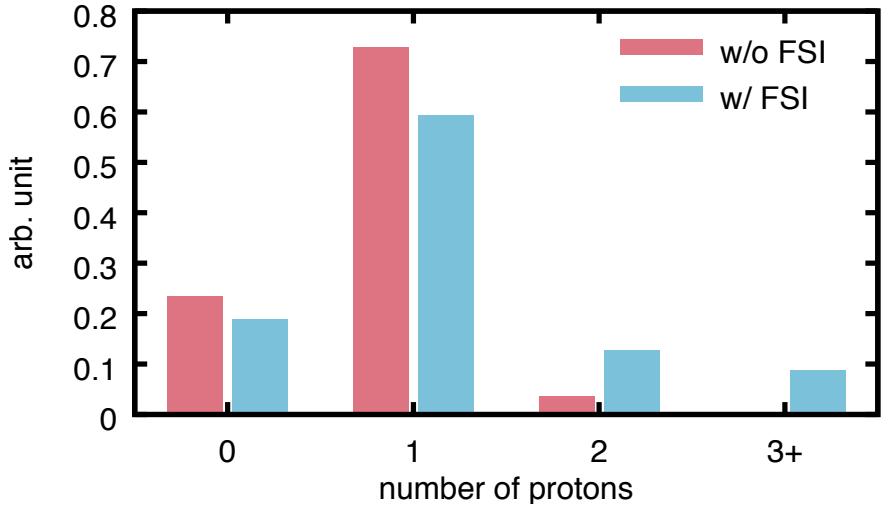
- Indirect effects



- Redistribution



- New channels



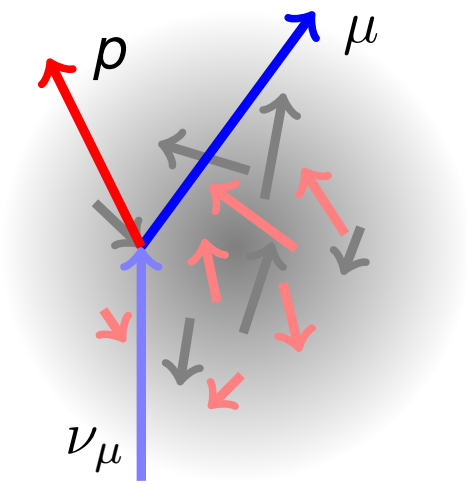
Nuclear transparency

Definition

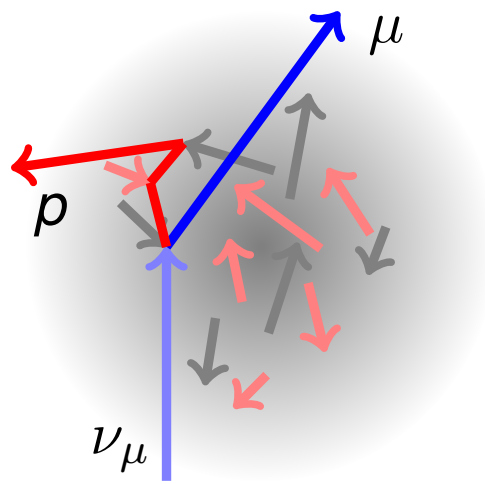
Nuclear transparency is the average **probability** for a knocked-out **proton** to **escape** the nucleus **without significant reinteraction**.

e.g. measured for Carbon: $\mathrm{T} \simeq 0.60$ [D. Abbott *et al.*, PRL 80 (1998), 5072]

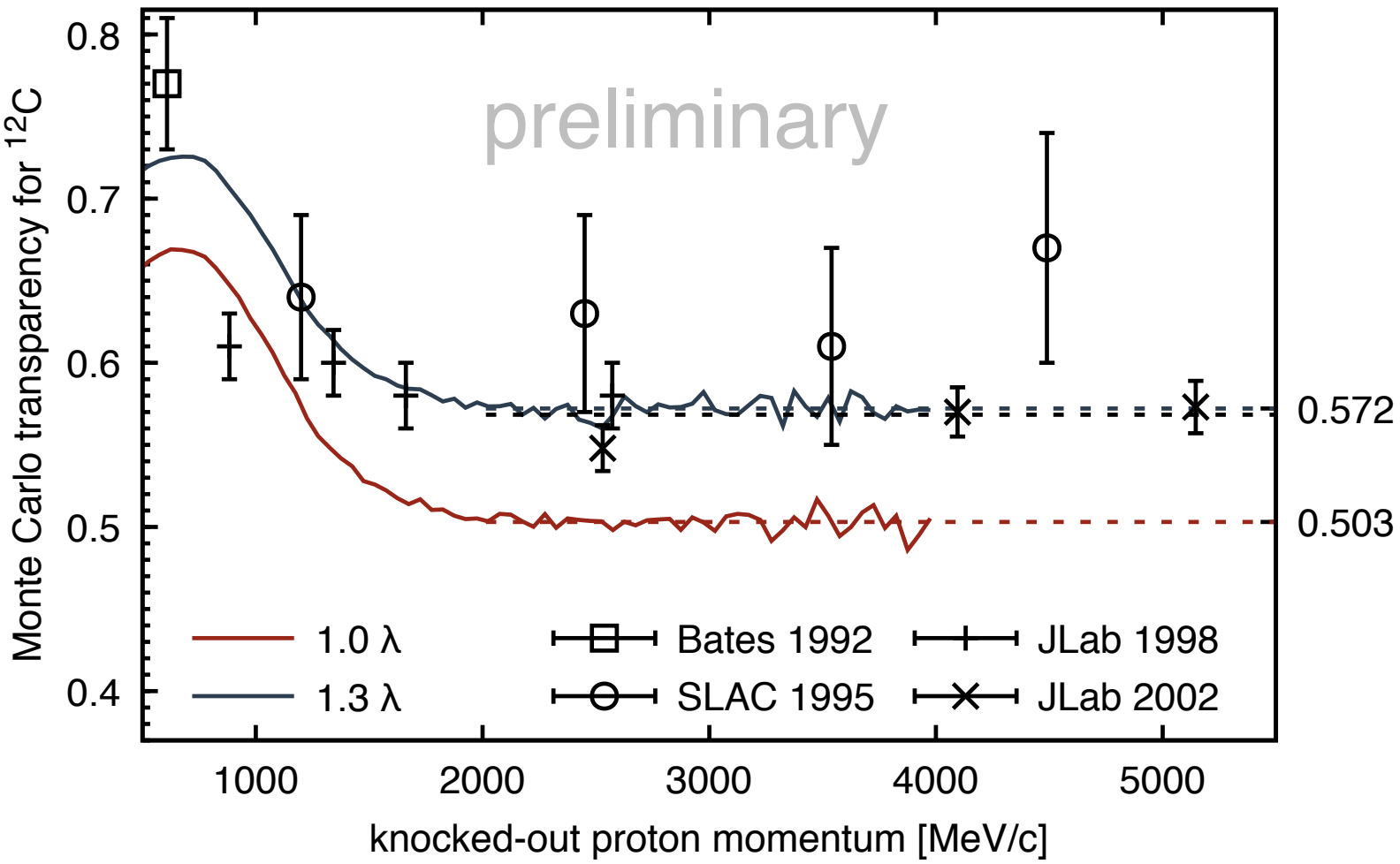
$\sim$ 60% without FSI



$\sim$ 40% with FSI



NuWro comparison with data

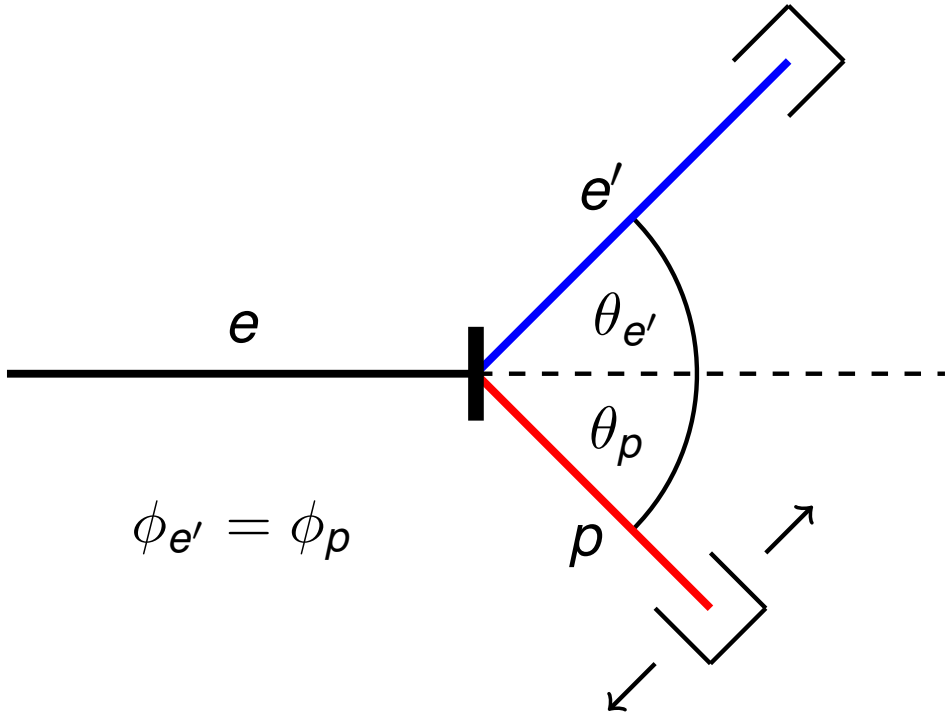


The simplest Monte Carlo transparency **definition** $\rightarrow$ **no rescattering**.

Experiment: D. Abbott *et al.*, PRL 80 (1998), 5072
$(e, e'p)$ D. Dutta *et al.*, PRC 68 (2003), 064603

Exclusive QE proton knockout
at **fixed kinematics**:

- beam: E_e
- electron: $E_{e'}$, $\theta_{e'}$, $\phi_{e'}$
- proton: E_p, θ_p, ϕ_p



Transparency:

$$\langle T \rangle_{\theta_p} = \frac{\sigma_{\mathrm{exp}}}{\sigma_{\mathrm{PWIA}}}$$

σ_{PWIA} - expected value without FSI
(model dependent)

How **precisely** are the **kinematics fixed**?

- electrons:

  $\frac{\Delta p}{p} \pm 10\%$

  $\Delta\theta \pm 2.4°$

  $\Delta\phi \pm 4.7°$

- protons:

  $\frac{\Delta p}{p} \pm 20\%$

  $\Delta\theta \pm 3.4°$

  $\Delta\phi \pm 2.3°$

Cuts on "missing" variables:

- energy: $E_m = \omega - T_{p'} - T_{A-1}$
- momentum: $\vec{p}_m = \vec{p}_{p'} - \vec{q}$

$$E_m < 80\ \mathrm{MeV},\ \ |\vec{p}_m| < 300\ \mathrm{MeV/c}$$

This ultimately ensures **lack of FSI** $\rightarrow$ the **definition** of **soft interactions**!

Beam energy (GeV)	Central electron energy (GeV)	Central electron angle (deg)	Central proton energy (MeV)	Central proton angle (deg)	Q^2 (GeV^2/c^2)
2.445	2.075	20.5	350	36.4,39.4 43.4,47.4 51.4,**55.4** 59.4,63.4 67.4,71.4 75.4	0.64
0.845	0.475	78.5	350	27.8 **31.8** 35.8,39.8, 43.8,47.8	0.64
3.245	2.255	28.6	970	32.6.36.6, **40.6**, 44.6,48.6, 52.6	1.80
1.645	0.675	80.0	970	**22.8**, 26.8,30.8 34.8	1.83
2.445	1.725	32.0	700	31.5,35.5 39.5,**43.5** 47.5,51.4 55.4	1.28
3.245	1.40	50.0	1800	**25.5** 28.0,30.5	3.25

Main problems in experimental comparison

- We use ν_e NC on protons
  (**kinematics** is the **same**, $\sigma_{\mathrm{EM}} \propto Q^{-4}$)
- In experiments the **kinematics** is **fixed**
  (with some precision)
- Experiements provide transparency as a function of Q^2
  (FSI is mainly a **function** of **proton momentum**)
- Definition of **soft interactions** by "**missing**" **variables**
  (energy: $E_m = \omega - T_{p'} - T_{A-1}$, momentum: $\vec{p}_m = \vec{p}_{p'} - \vec{q}$)

NuWro simulation

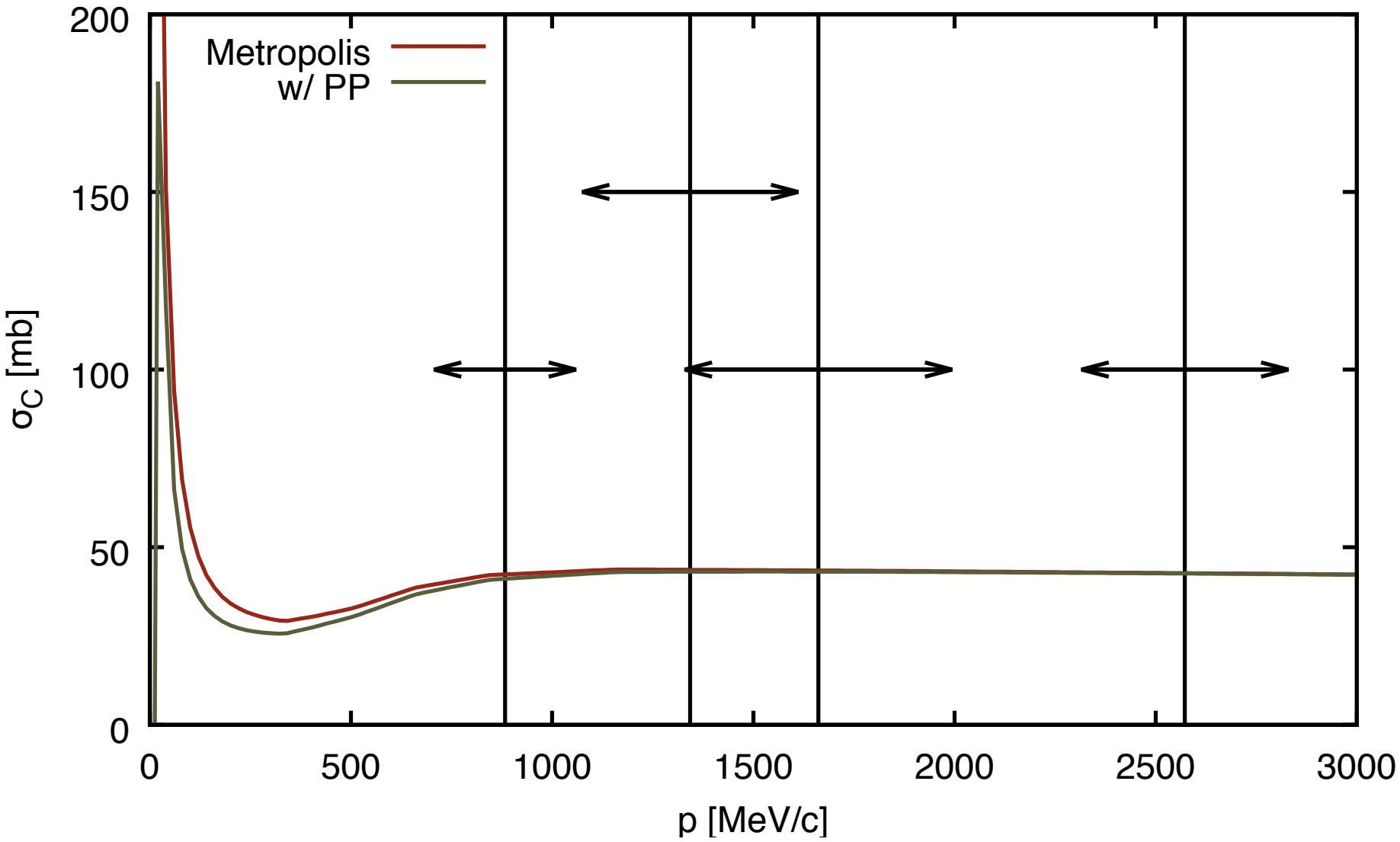
- Variables in the exclusive QE process: $E_{e'}, \theta_{e'}, \phi_{e'}, E_p, \theta_p, \phi_{p'}$
- Differential cross section: $\frac{\mathrm{d}^5\sigma}{\mathrm{d}E_{e'}\,\mathrm{d}\cos\theta_{e'}\,\mathrm{d}E_p\mathrm{d}\Omega_p}$

  $\rightarrow$ cross section is **independent** on one of the ϕ angles!
- To resemble the experiment, where the spectrometers are in the same plane, we chose to fix ϕ_{ep}.
- We fix the kinematics by:

  $p_{e'} \pm 10\%$, $\theta_{e'} \pm 2.4^\circ$, $p_p \pm 20\%$, $\theta_p \pm 3.4^\circ$, $\theta_{ep} \pm 4.7^\circ \pm 2.3^\circ$

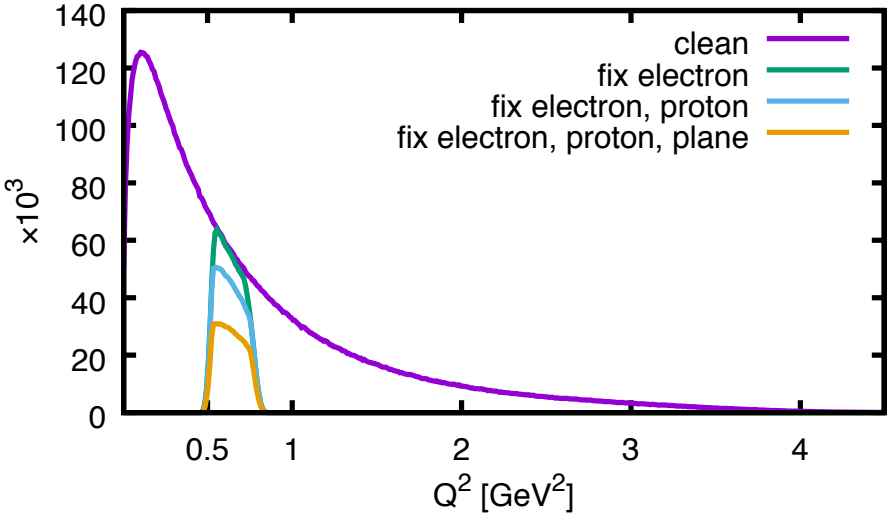
  around the central, given, values.

Nucleon-nucleon cross section

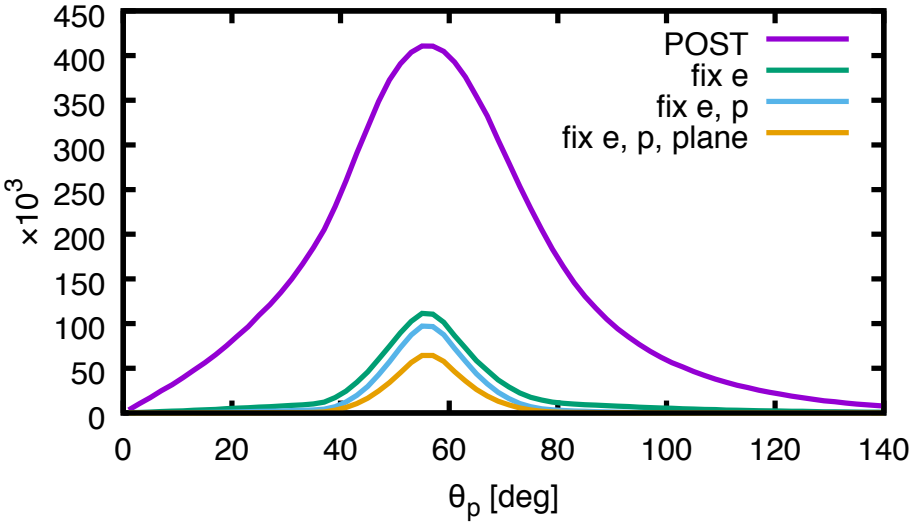


Carbon, $Q^2 = 0.64\ \mathrm{GeV}^2$

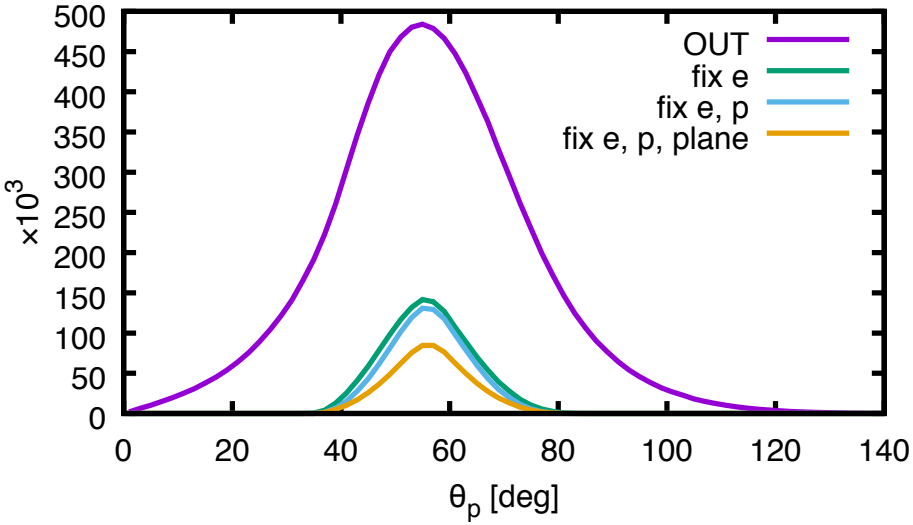
- Lepton kinematics



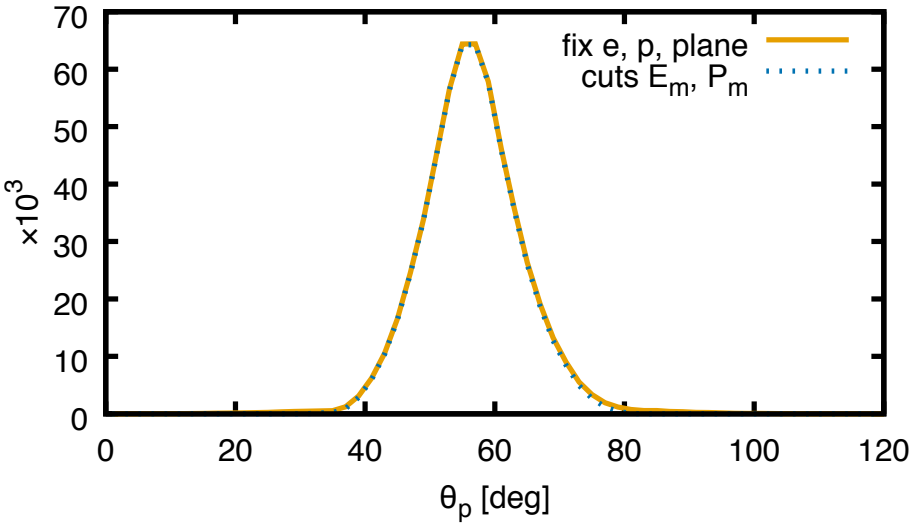
- Proton angle with FSI



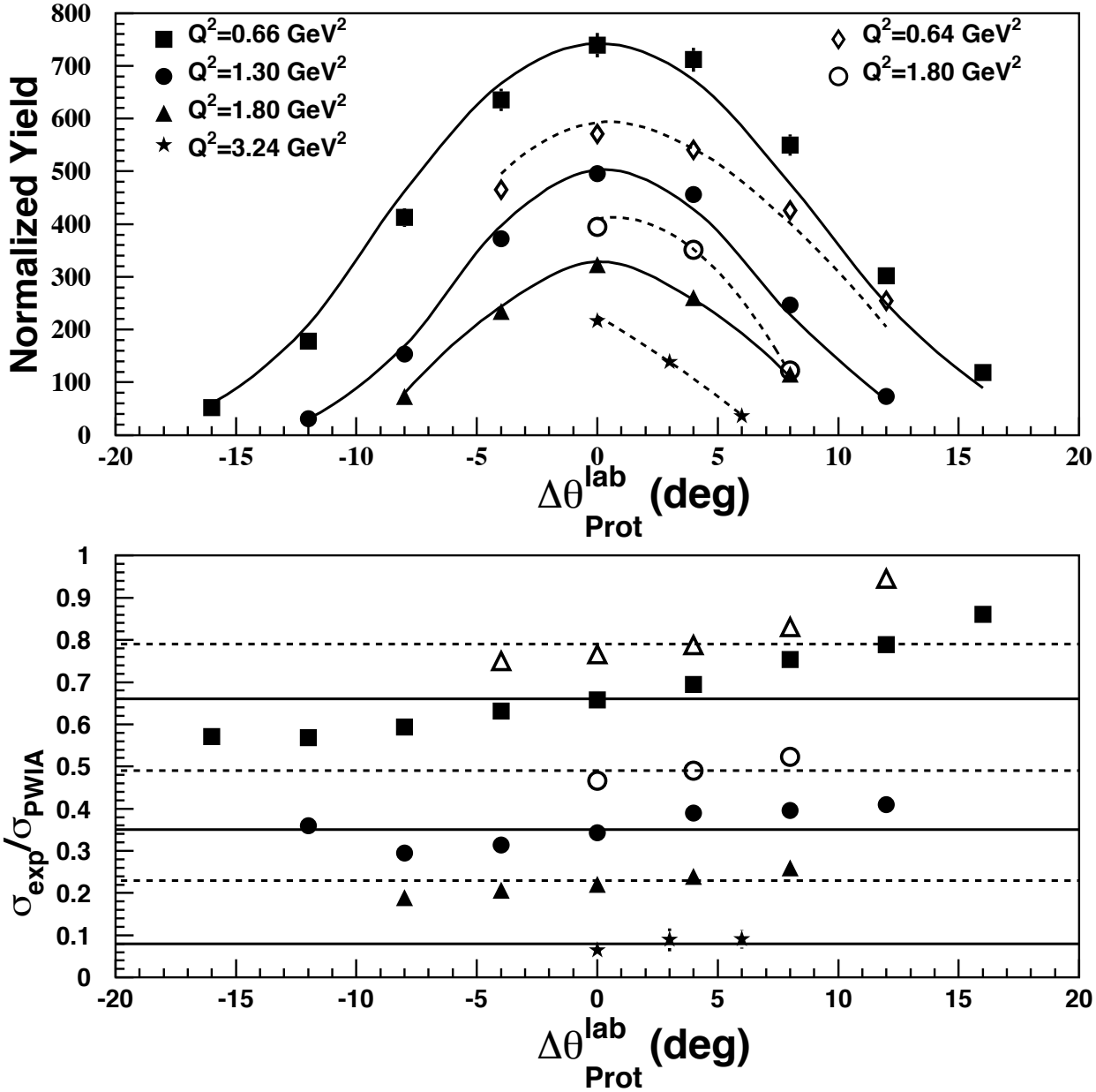
- Proton angle without FSI



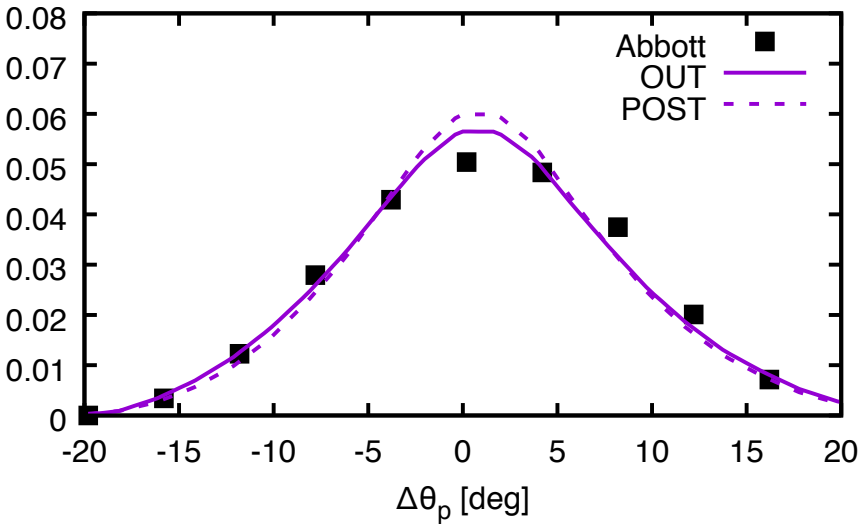
- Cuts on "missing" variables

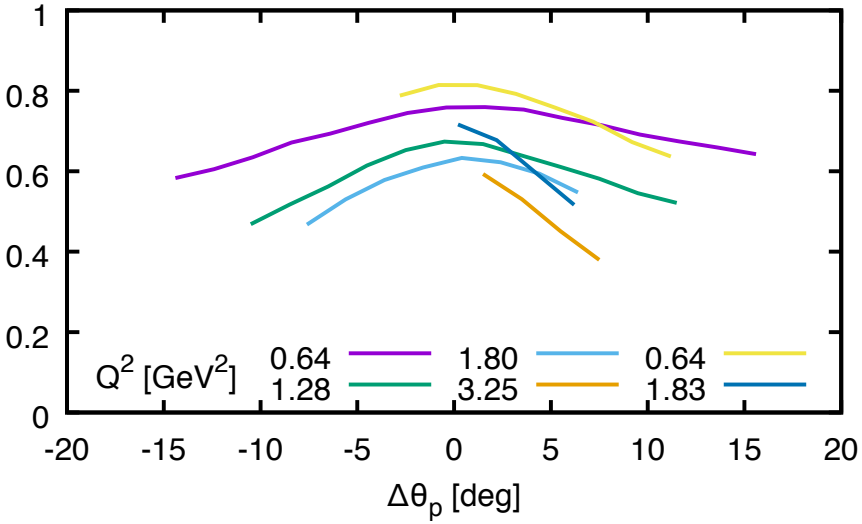


Carbon, experimental results

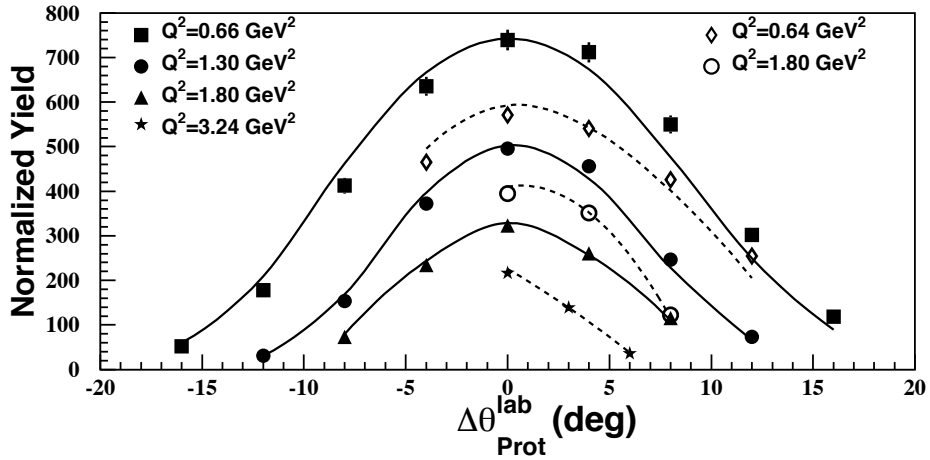


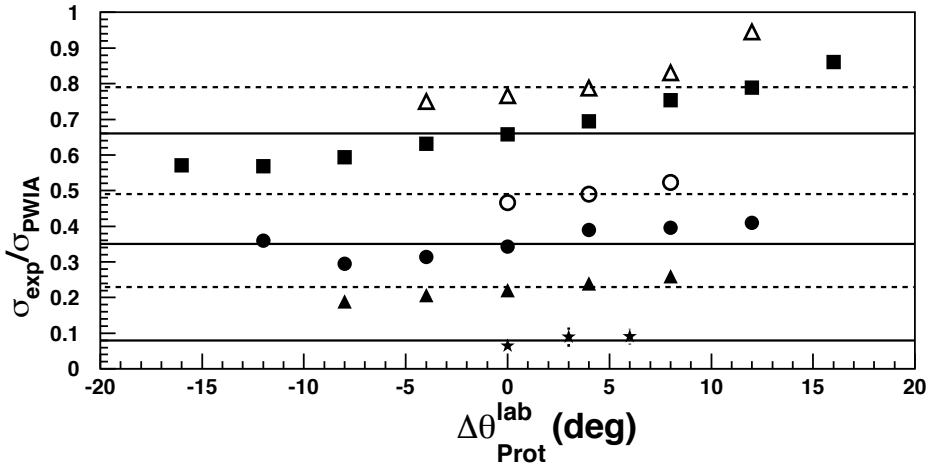
Carbon, NuWro vs data





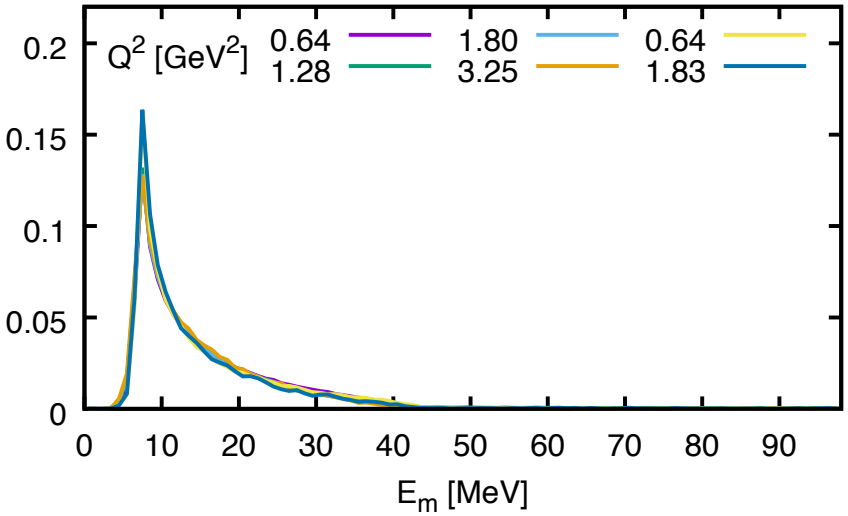
← we compare with squares



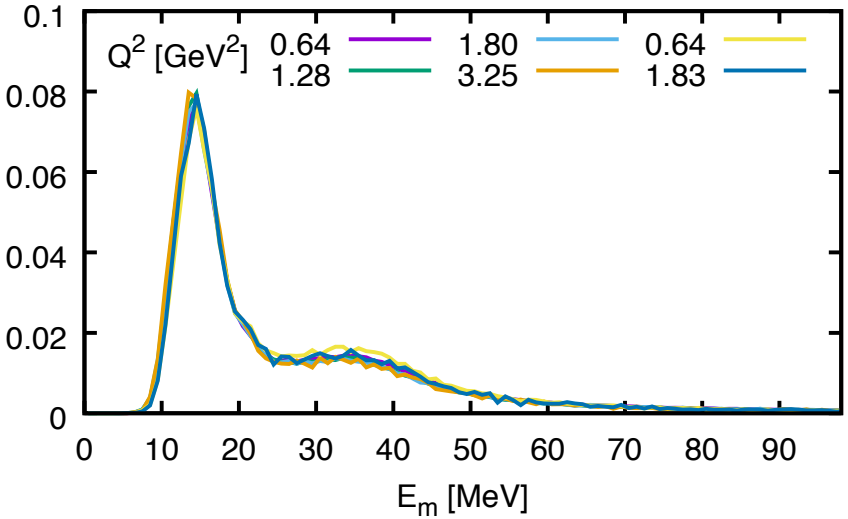


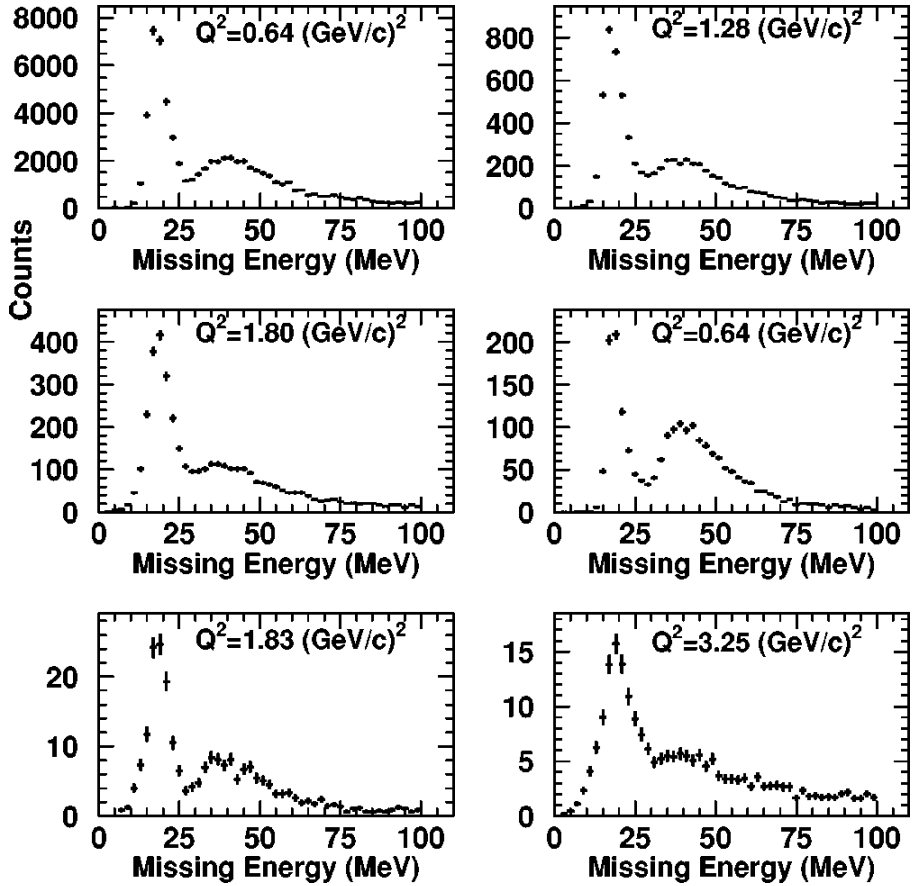
Carbon, NuWro vs data

- Local Fermi Gas

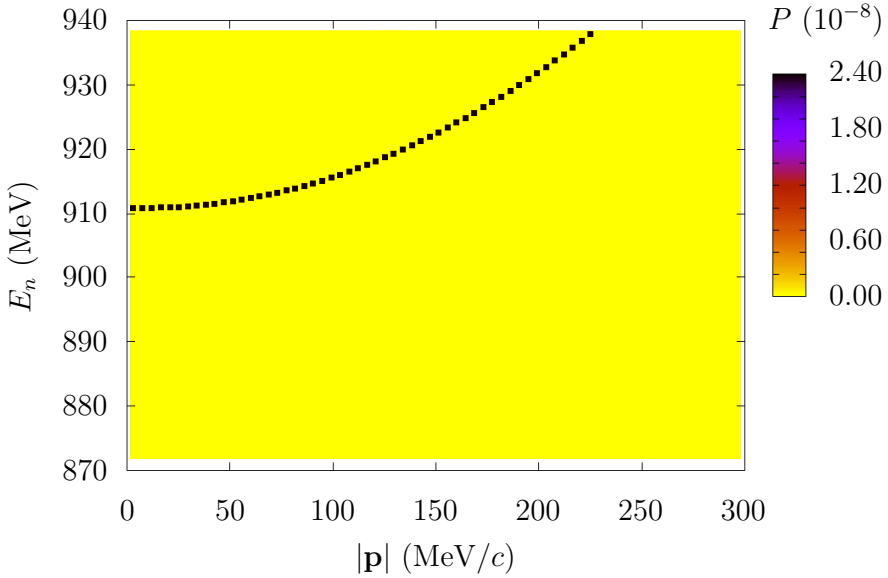


- Spectral Function

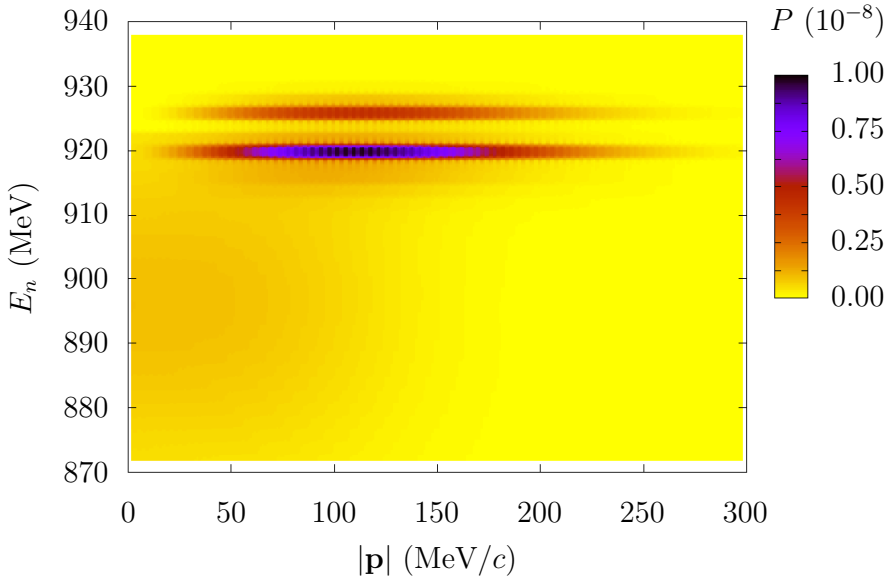




Initial state models



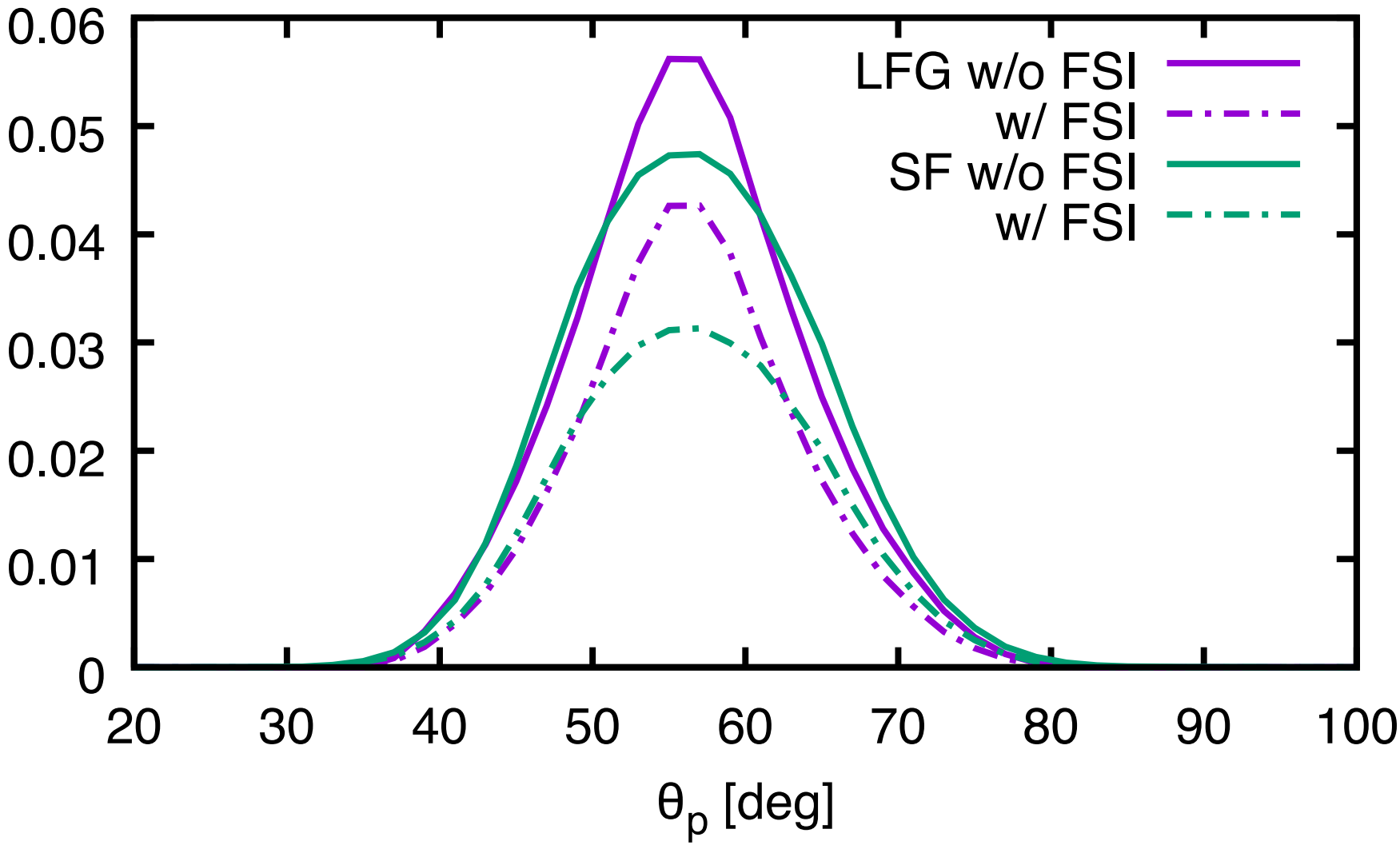
Local Fermi Gas



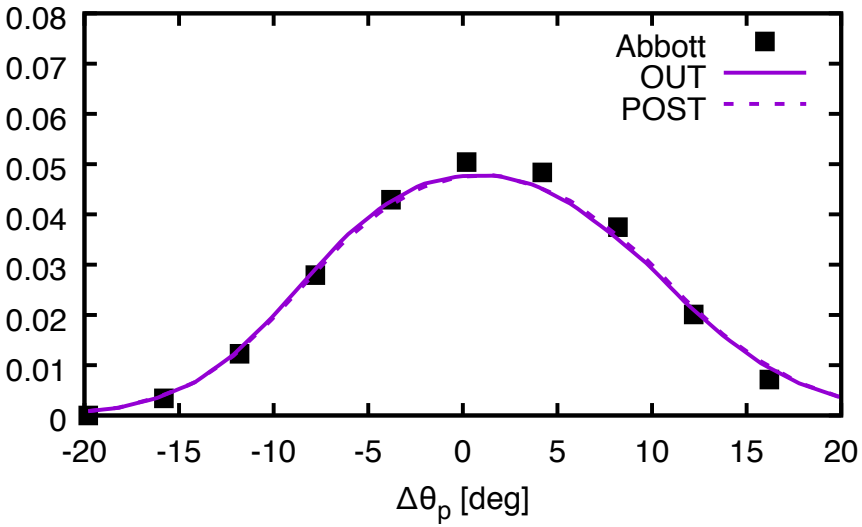
Spectral Function

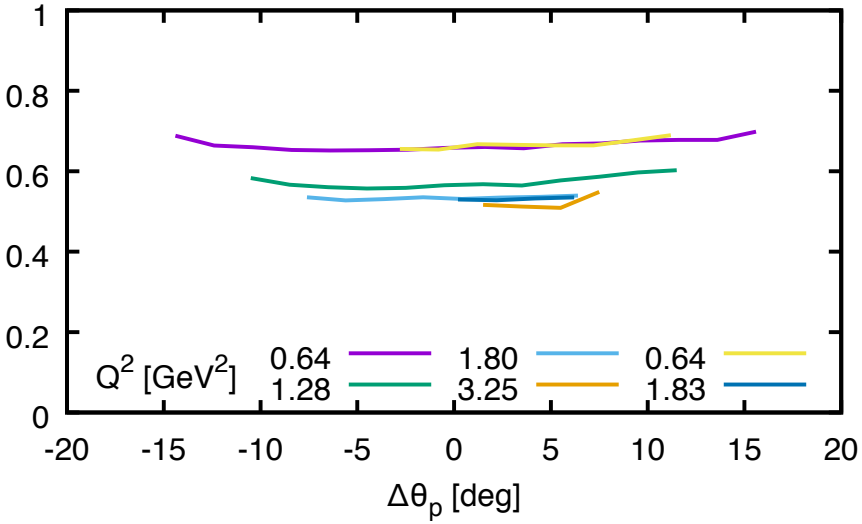
A. Ankowski

Carbon, LFG vs SF

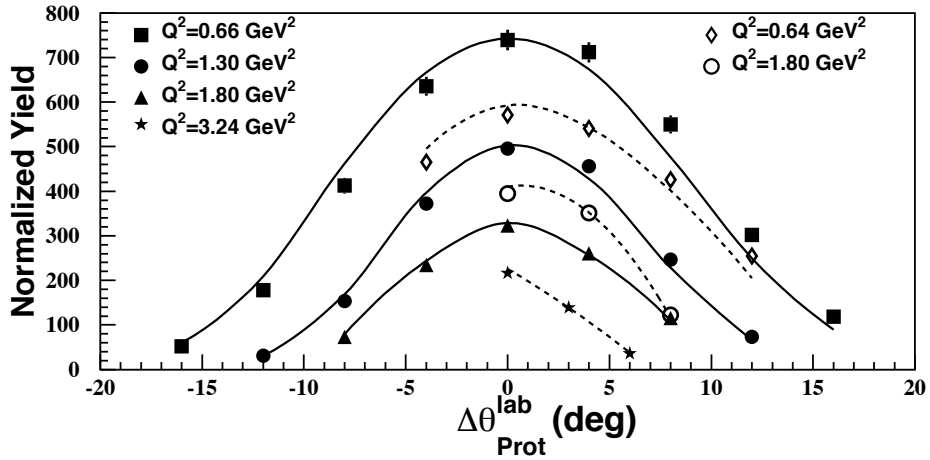


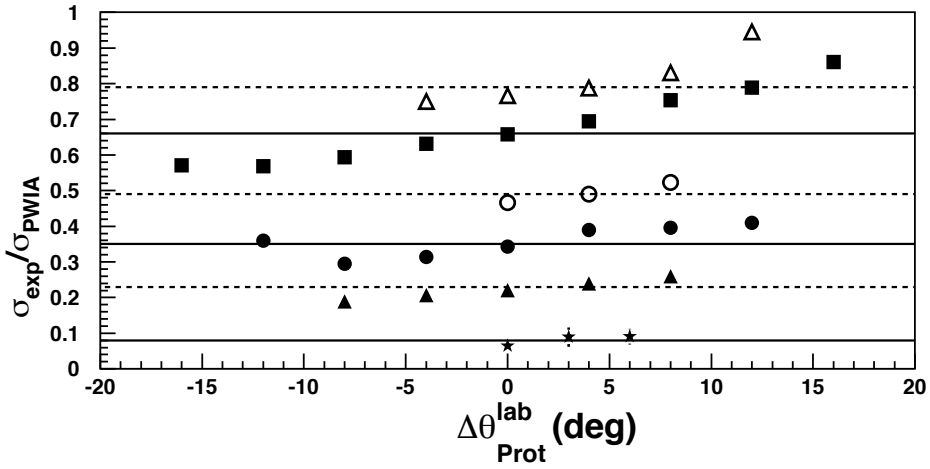
Carbon, NuWro vs data



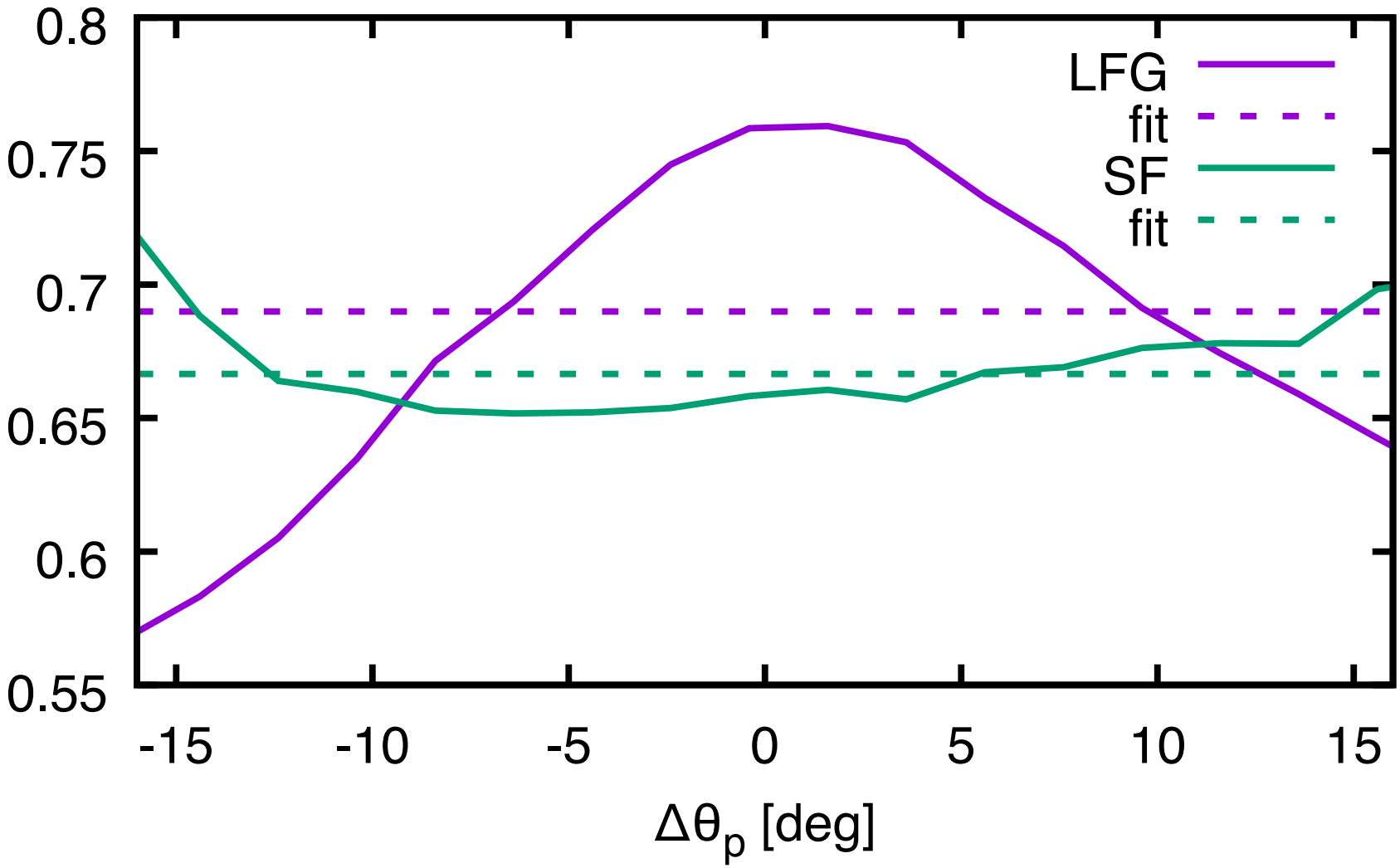


← we compare with squares

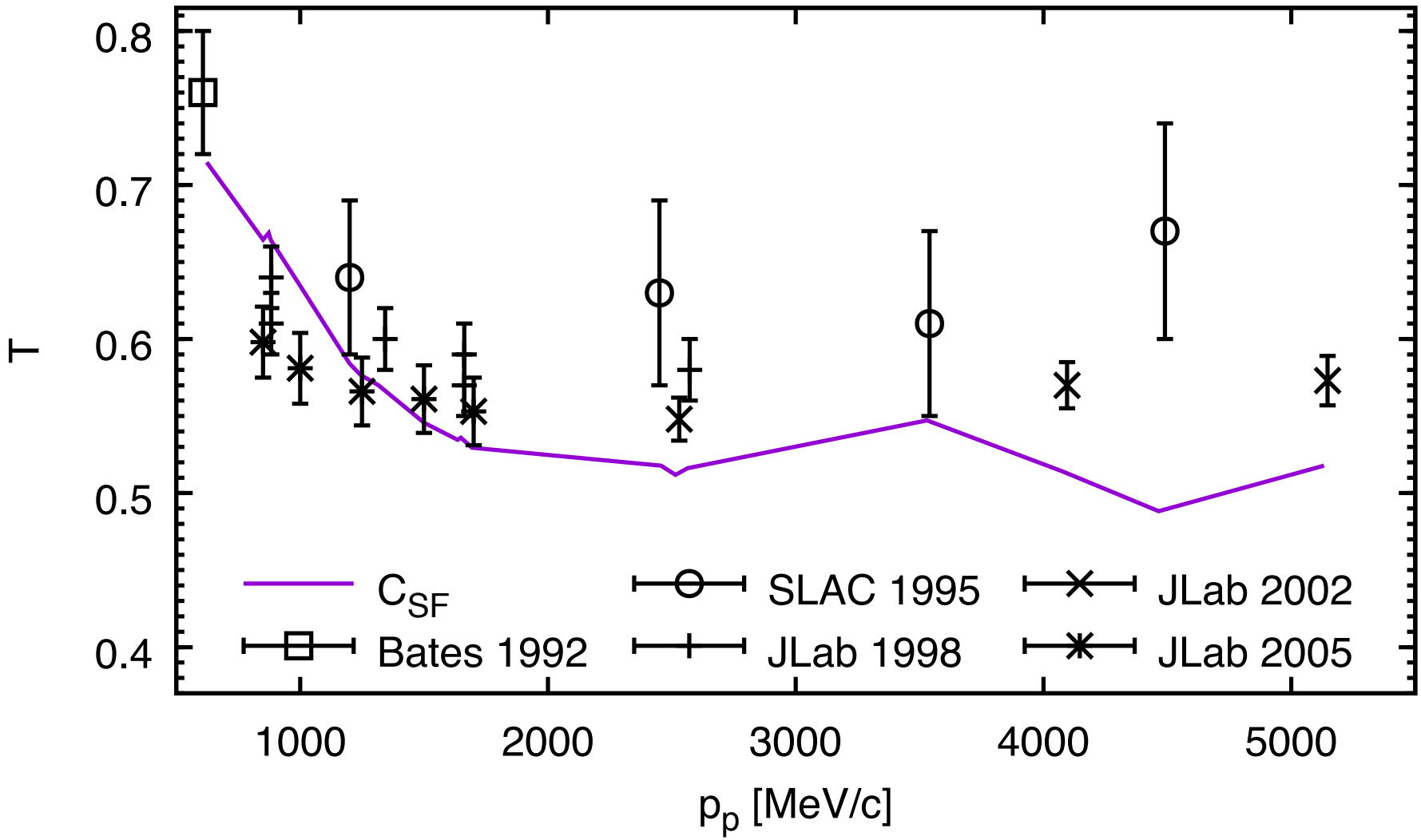




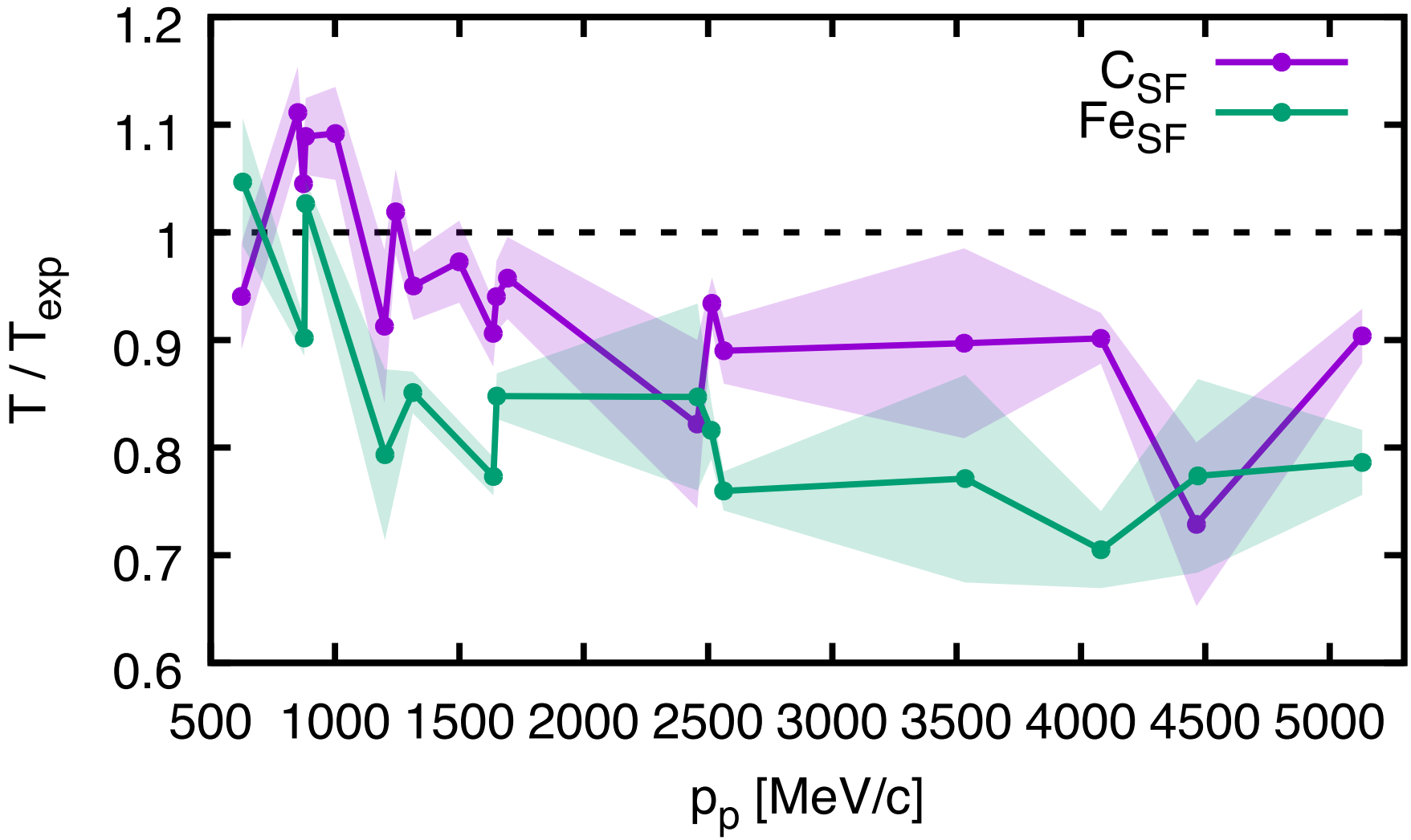
Carbon, LFG vs SF



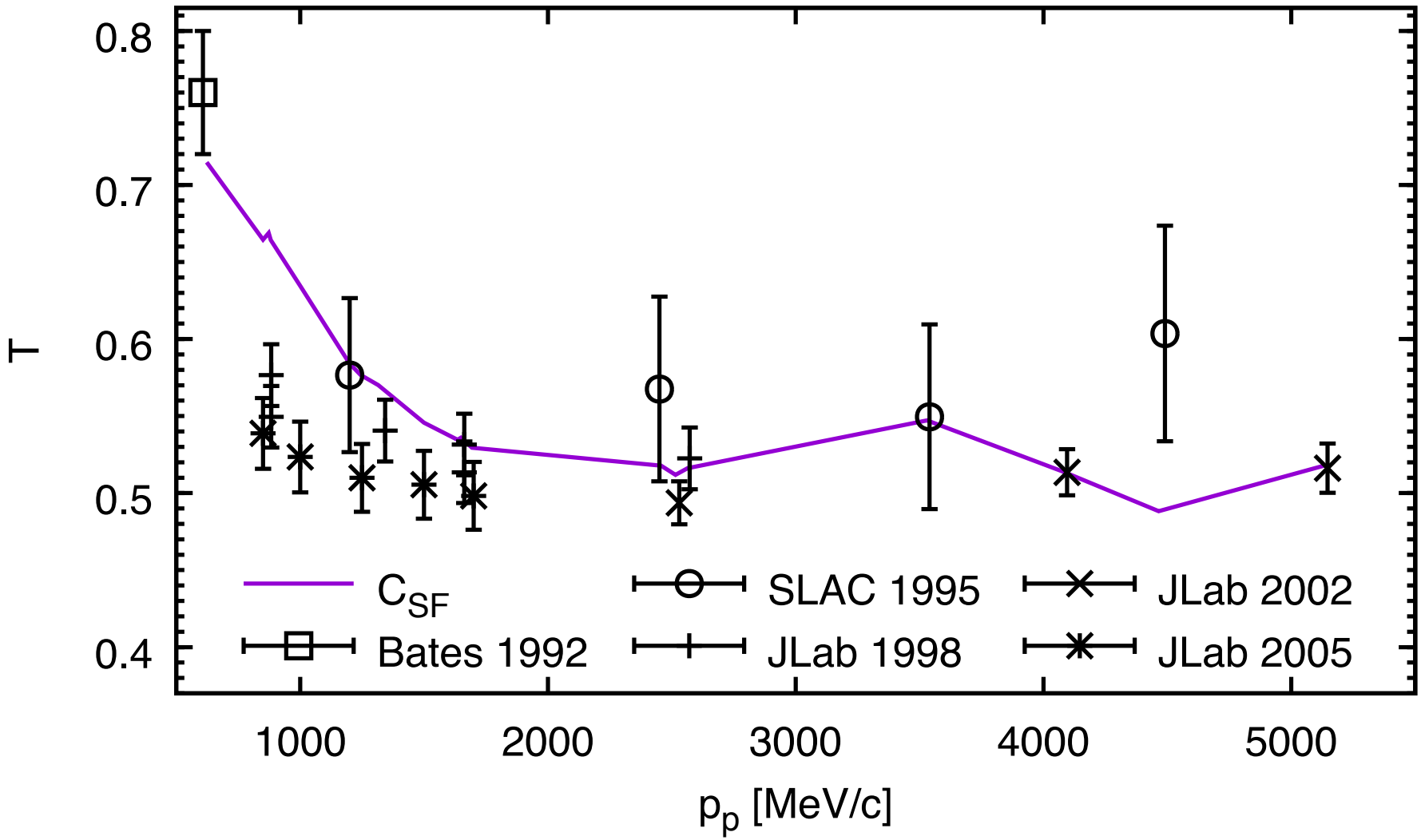
Transparency for Carbon



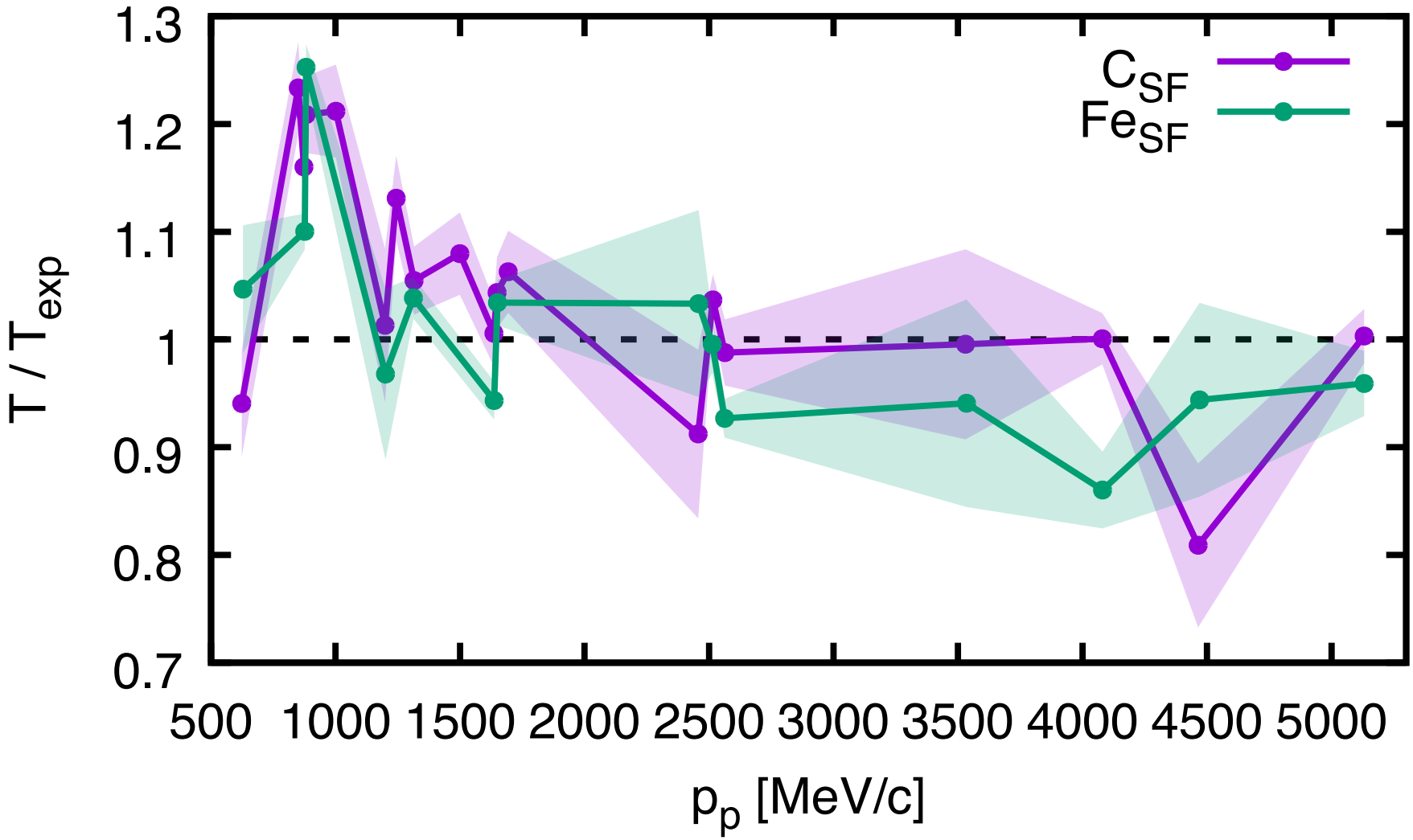
Ratio to data for Carbon and Iron



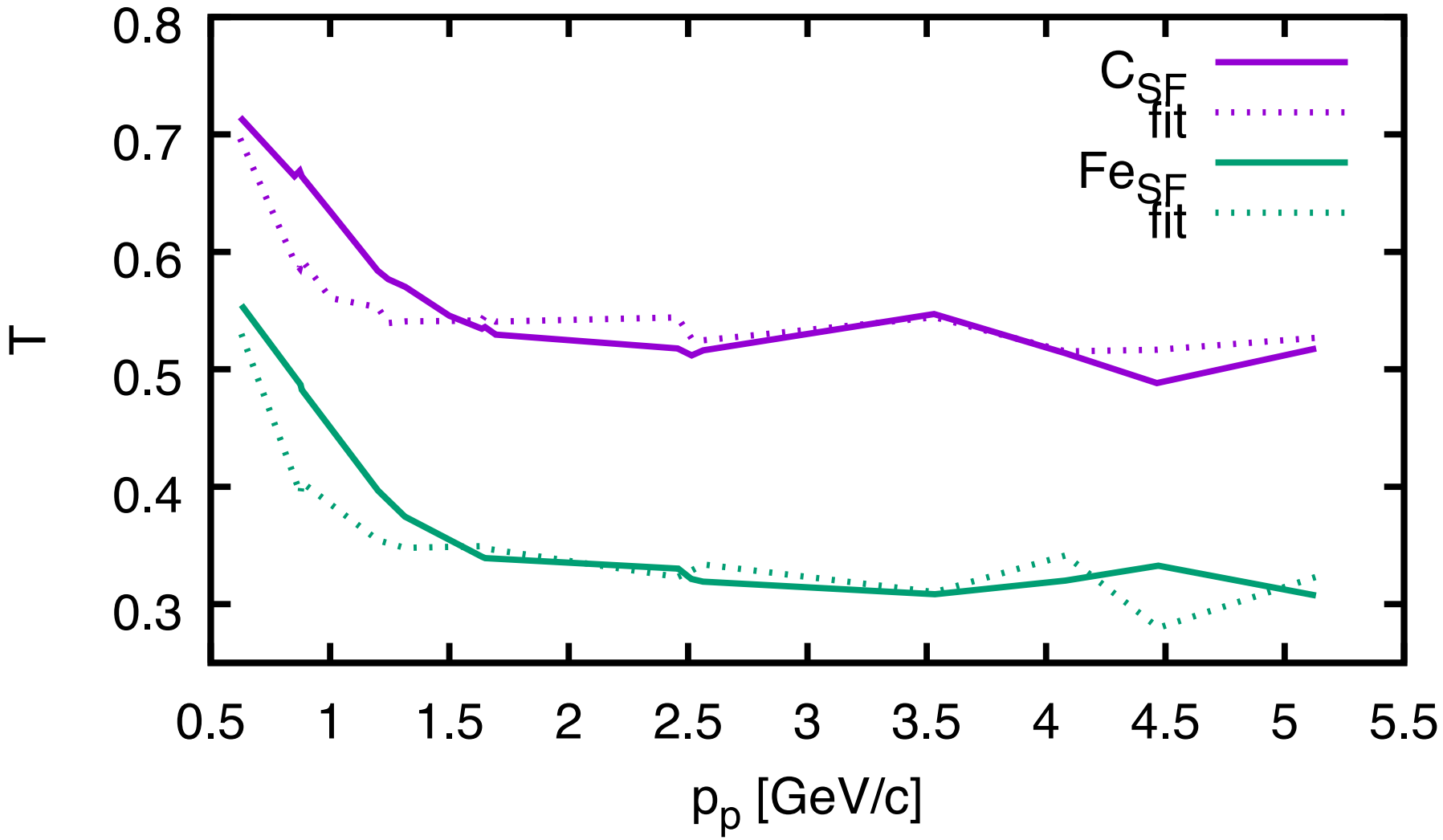
Transparency, data without spectroscopic factors



Ratio to data without spectroscopic factors



Transparency fit to data without spectroscopic factors



Fitted ratio to data without spectroscopic factors