Why we still need GiBUU

K. Gallmeister for the GiBUU group
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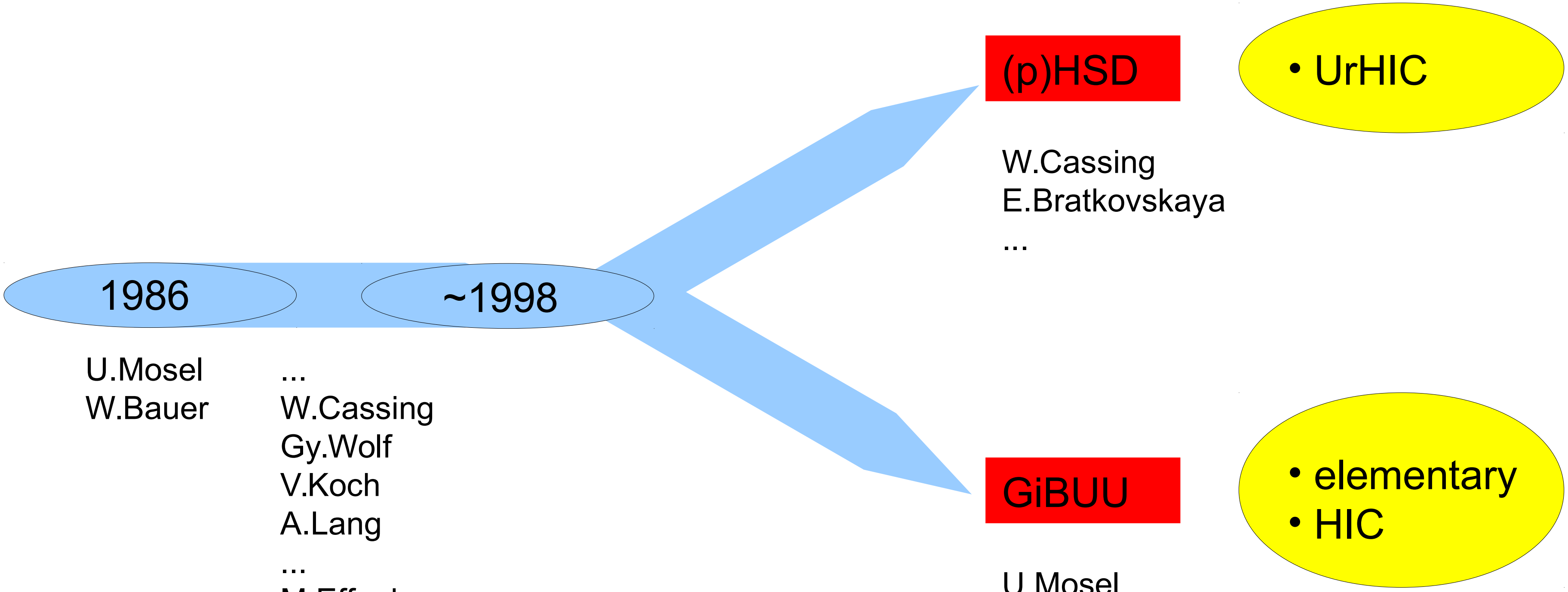
für Bildung
und Forschung

CRC-TR 211 Transport Meeting

Frankfurt, 15.11.2018

BUU@Gießen and GiBUU



1986

U.Mosel
W.Bauer

~1998

...
W.Cassing
Gy.Wolf
V.Koch
A.Lang
...
M.Effenberger
S.Teis
A.Hombach
J.Geiss
...

(p)HSD

- UrHIC

W.Cassing
E.Bratkovskaya
...

GiBUU

- elementary
- HIC

U.Mosel
T.Falter, K.Gallmeister
A.Larionov, T.Gaitanos
J.Lehr
P.Mühlich
O.Buss
T.Leitner,O.Lalakulich
J.Weil
...

U.Mosel retired 2011

Electron and neutrino induced reactions on the nucleus

K. Gallmeister for the GiBUU group
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recent improvements

neutrino nucleus interactions

hadronization in nuclear matter

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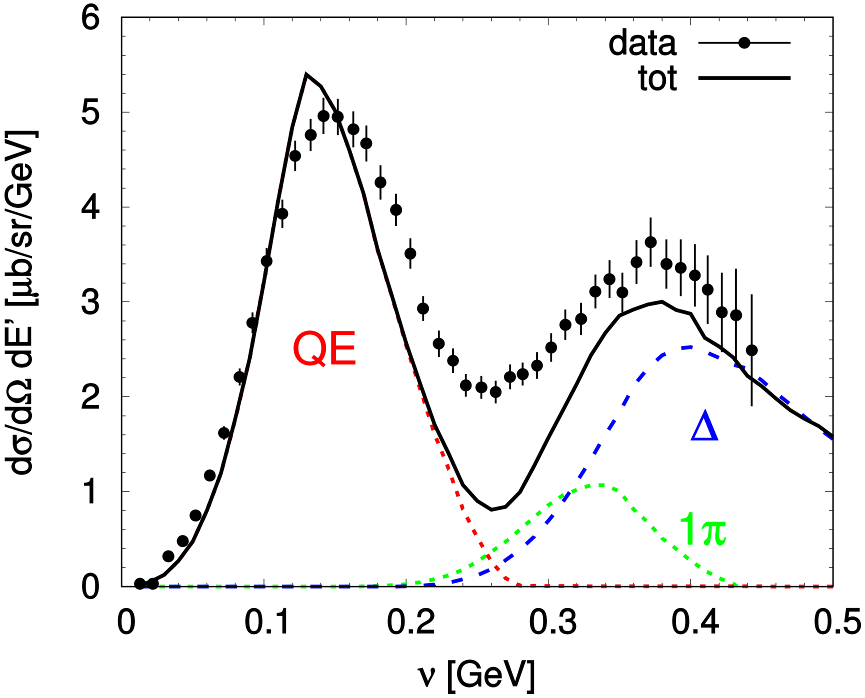
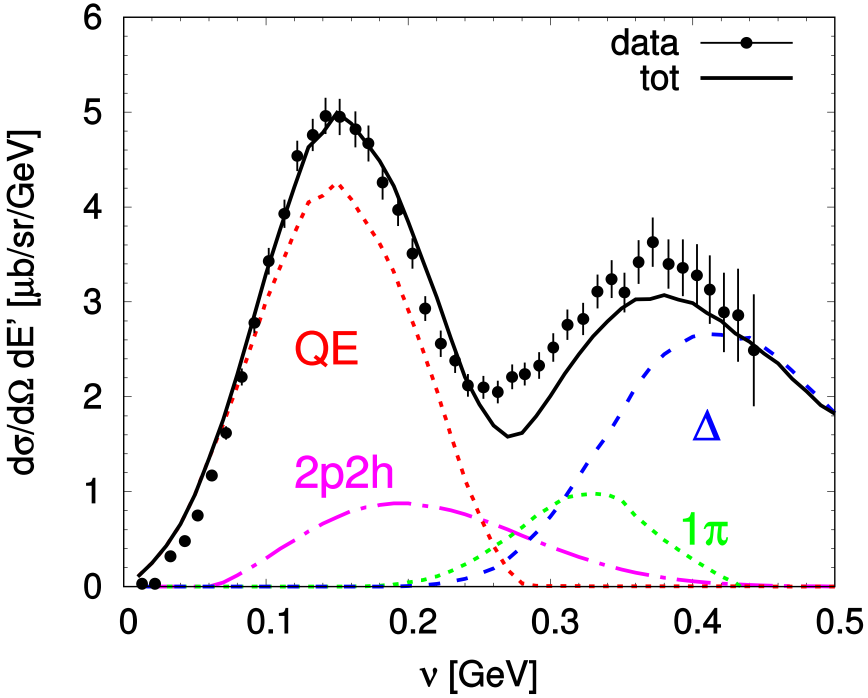
example: eC, E_e=0.56 GeV, θ=60°

- before 2016:



- since 2016:



- Delta: medium modification à la Oset et al. invalid
- QE: new ground state prescription
- 2p2h: very important contribution

nuclear ground state

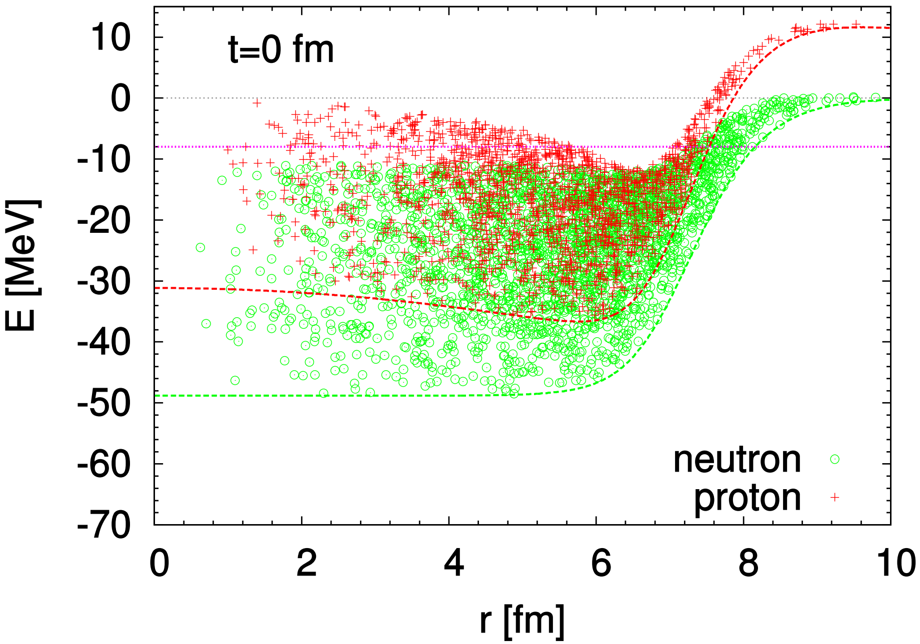
- local Thomas-Fermi:

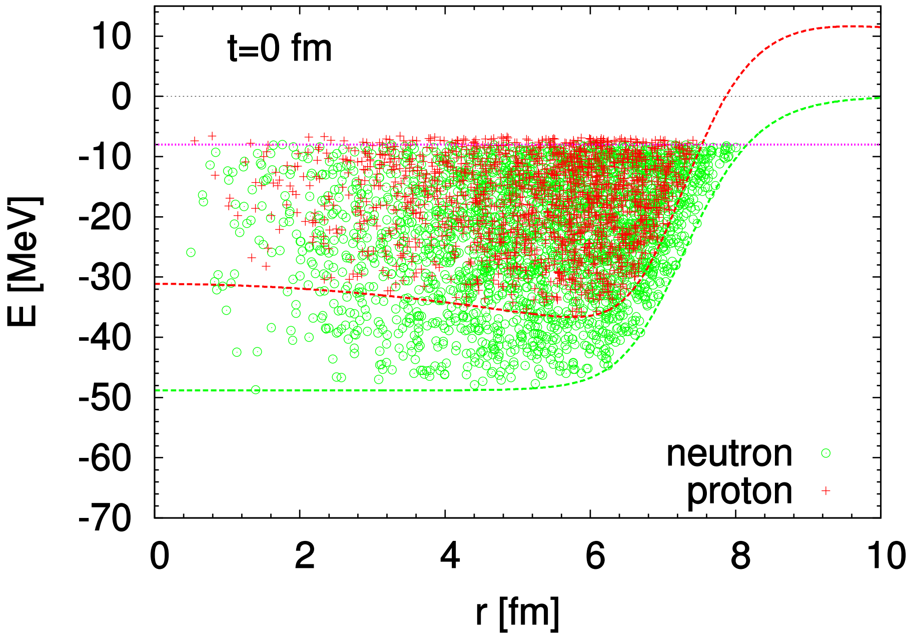
$$|\vec{p}| \ \leq \ p_F(\vec{r}) = \left[3\pi^2 \rho(\vec{r})\right]^{1/3}$$

- constant Fermi-energy

readjust $\rho(r)$

non-mom.dep potential, asymmetry-term, Coulomb





$$E = \sqrt{m_N^2 + p^2} + U(\vec{r}, \vec{p})$$

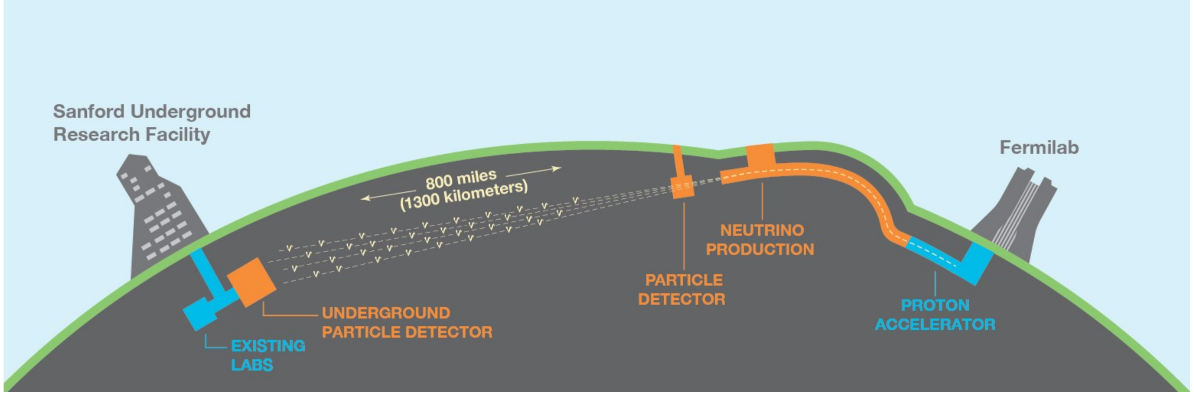
needs iteration for mom.dep potential

(long baseline) neutrino experiments

T2K, HyperK:

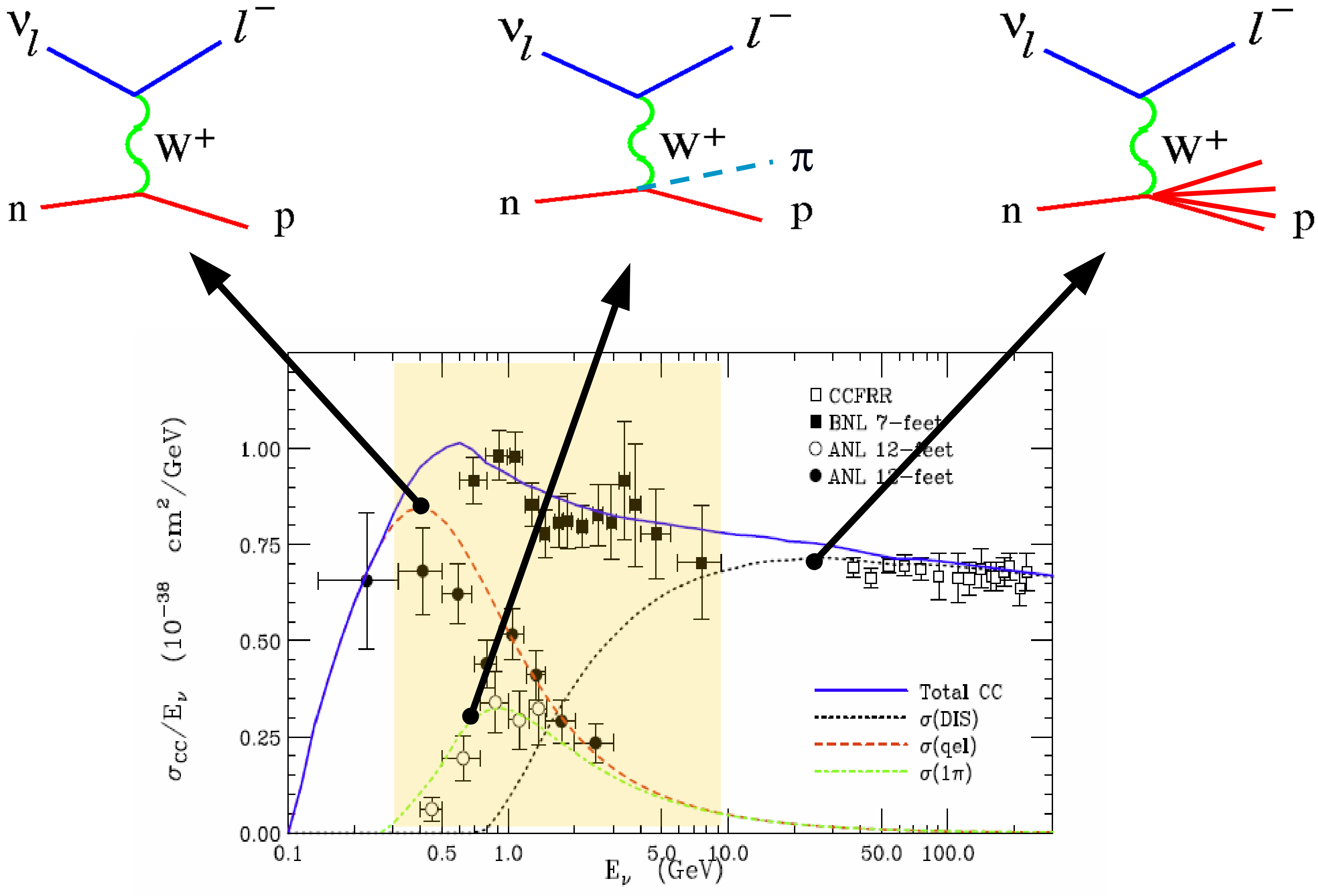
NOvA:

DUNE (2027):



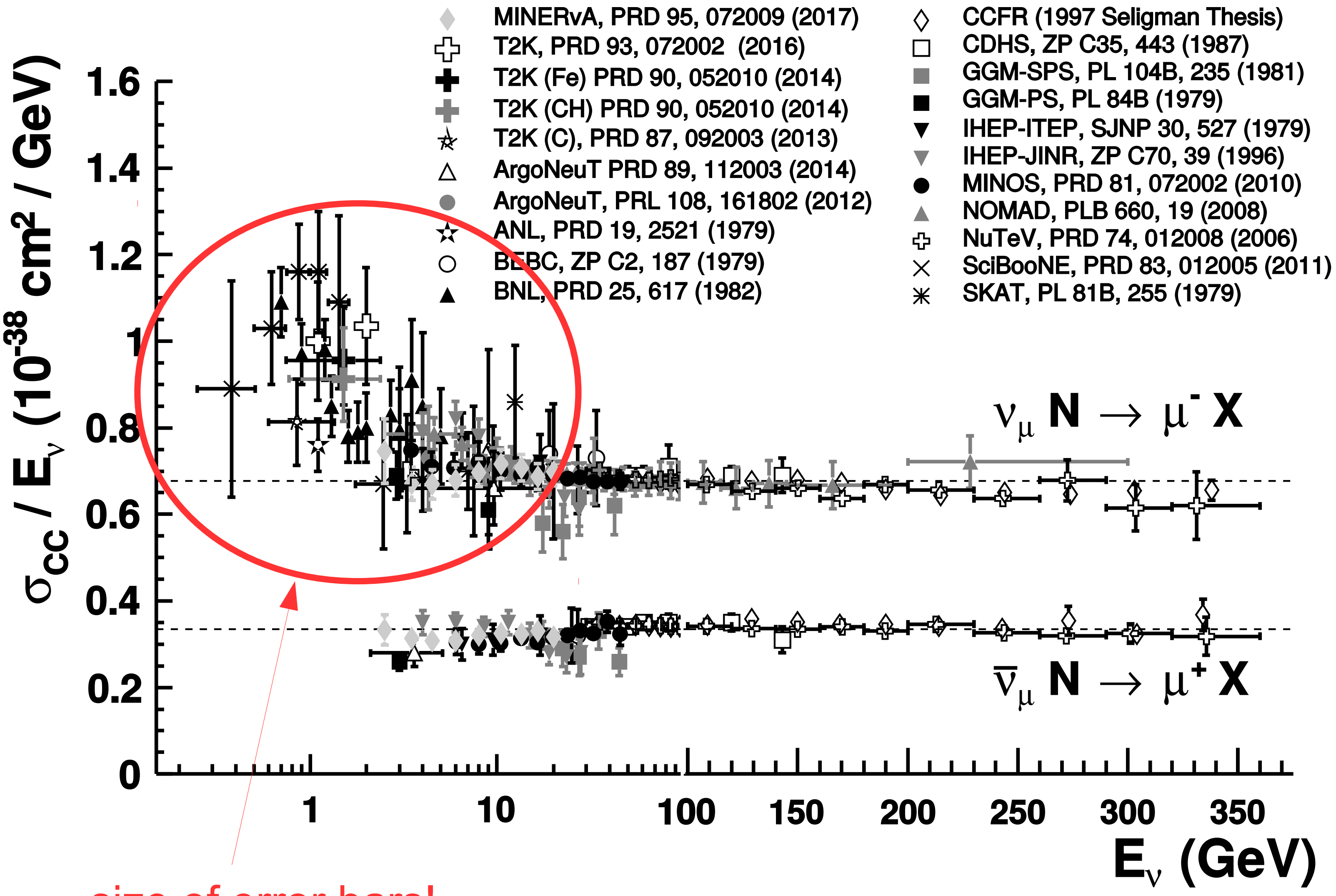
neutrino-nucleon cross section

CCQE 1-pion DIS (= “>1 pion“)



$$10^{-38}\,\mathrm{cm}^2 = 10^{-11}\,\mathrm{mb}$$

neutrino-nucleon cross section

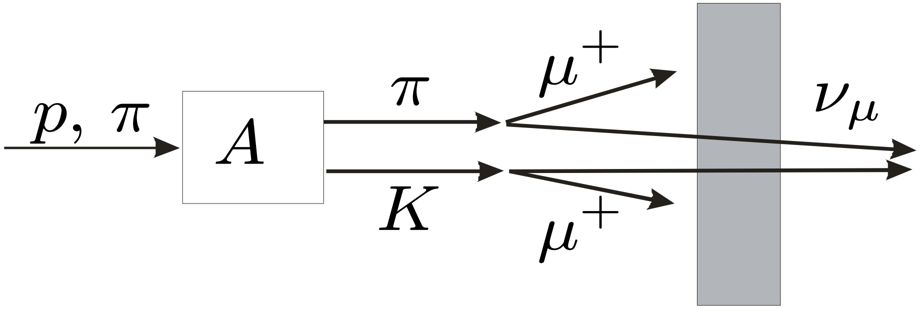


size of error bars!

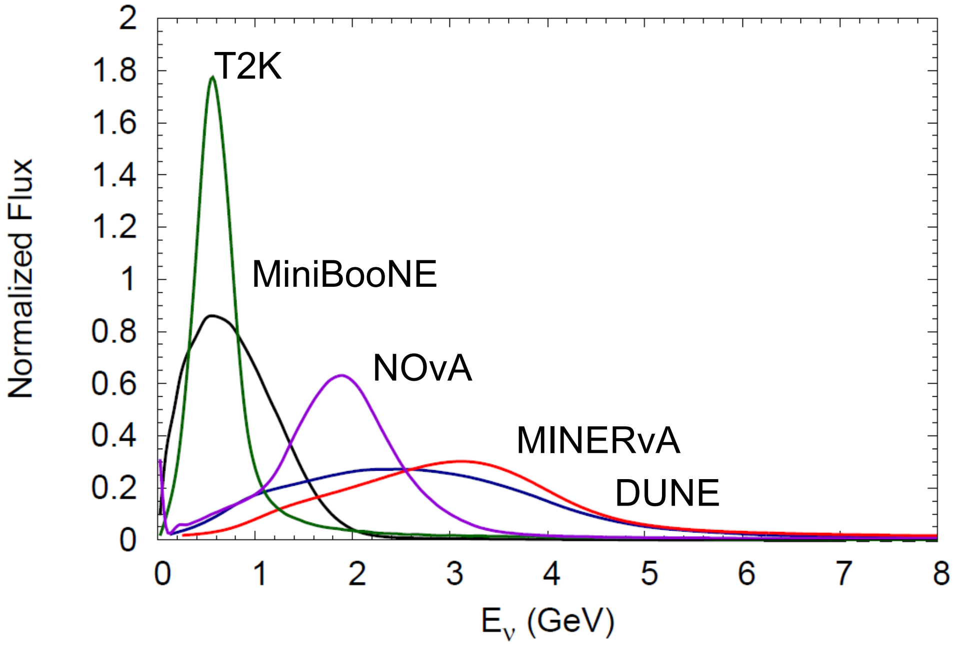
from: PDG, 2018

accelerator based neutrino experiments

- problem 1: **the beam**



broad energy spectrum:



cf. LHC: $\Delta E/E = 0.1\%$

energy of incident neutrino has to be **reconstructed** from:

- scattered lepton (QE-like)
- final state particles

accelerator based neutrino experiments

- problem 1: **the beam**
- problem 2: **the target**

experiments use nuclear targets:

- H_2**O** (T2K)
- **C**H (NOvA)
- ^{40}**Ar** (DUNE)
- …

- increase the rate
- true QE: $\nu n \to \mu^- p$
- security (cf. 'Die Hindenburg')
- costs (eg. standard baby oil)
- target material needed for detector

description of nucleus ?

(binding effects, Fermi motion, Pauli blocking, …)

final state interactions ?

accelerator based neutrino experiments

- problem 1: **the beam**
- problem 2: **the target**
- problem 3: **the final state**

all particles observed?

no detector is a 4π detector

final state interactions:

detected: e.g. scattered lepton, no pion

questions:

- was it QE?
- was it Δ or 1-pion event, but pion was absorbed?
- was it something else?

accelerator based neutrino experiments

- problem 1: **the beam**
- problem 2: **the target**
- problem 3: **the final state**

⋮

- problem X: **the community relies on “generators”**
  - GENIE (10-15 experimentalists, no theory)
  - NEUT
  - NuWro

no predictive power !!!
- only νA, no eA
- fitted to data to describe
- data ‘massaged’ by generator

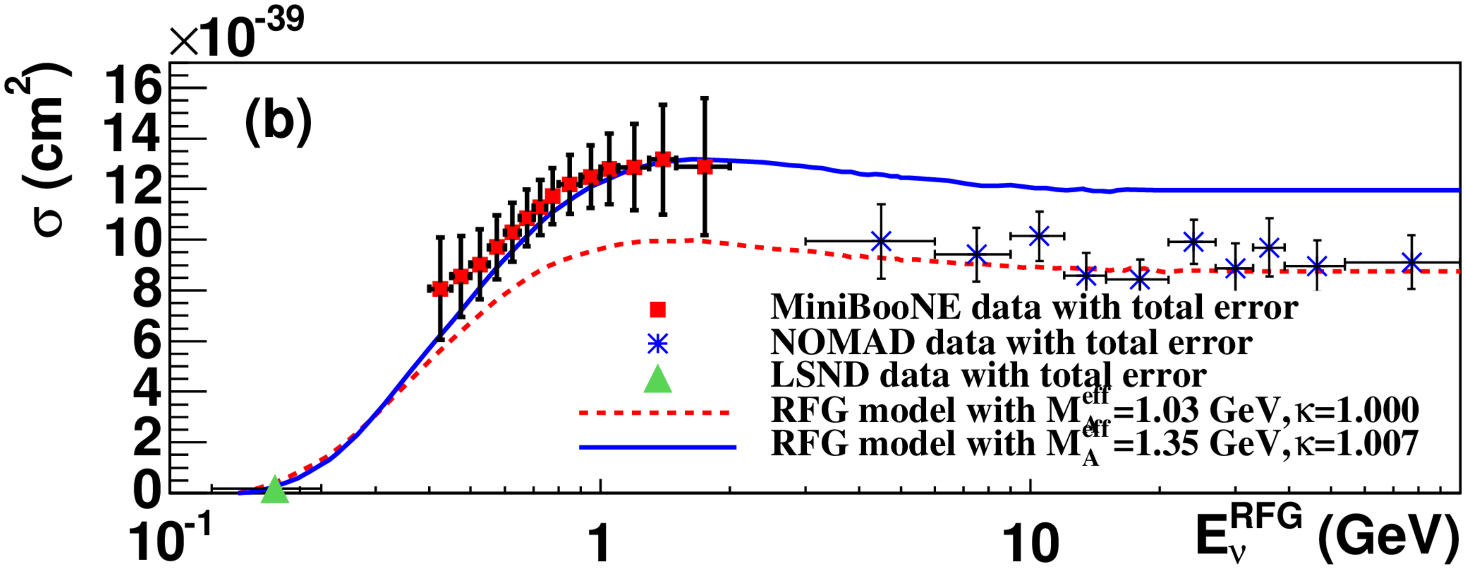
outdated nuclear physics:

- Fermi-gas, no binding
- crude FSI
- ...

improves slowly

“GiBUU is nature,
but too slow”

“The MiniBooNE QE Puzzle”



T. Katori, NuInt09

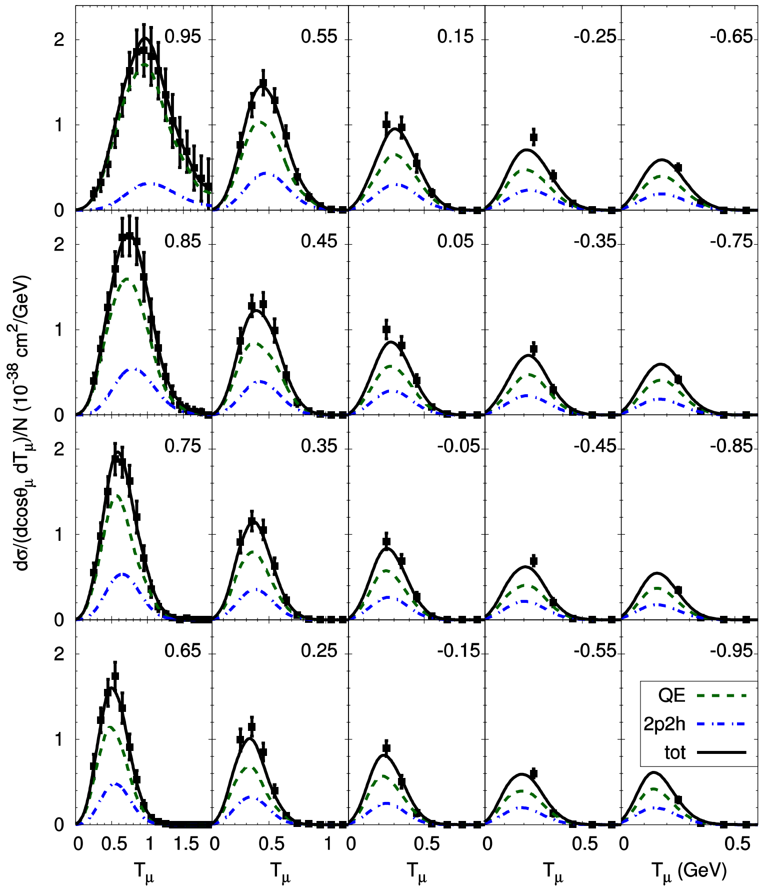
- possible explanations:
  - larger axial mass $M_A \simeq 1.3\,\mathrm{GeV}$ *[exp, generator: NUANCE]*
  - change of axial FF *[Hill]*
  - change of vector FF *[Bodek]*
  - **2p2h** *[Ericsson, Martini, GiBUU]*
- problem:

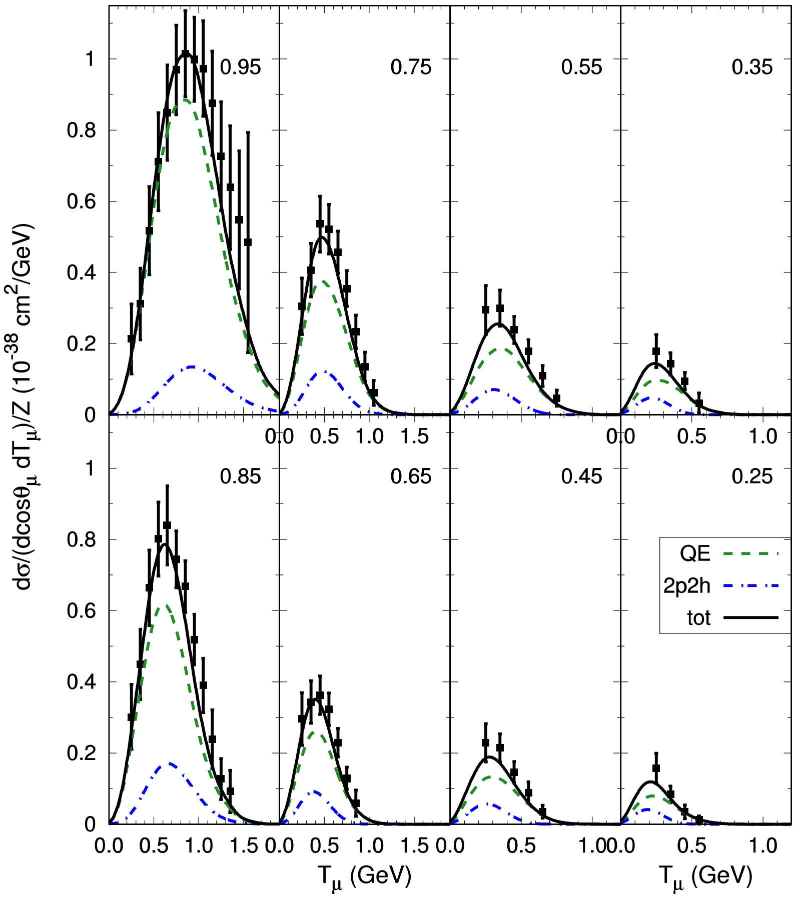
data was ‘massaged’ by generator!

inclusive cross section (MiniBooNE)

- neutrino

- anti-neutrino





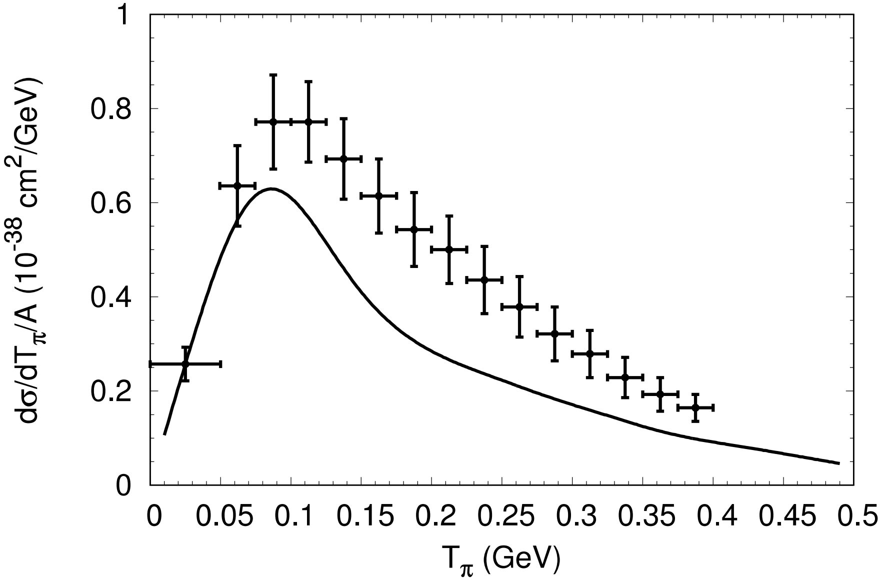
theory describes data perfectly

curves show actual GiBUU calculations

1-pion data “The MiniBooNE 1pi Puzzle”

- **MiniBooNE** (2011)

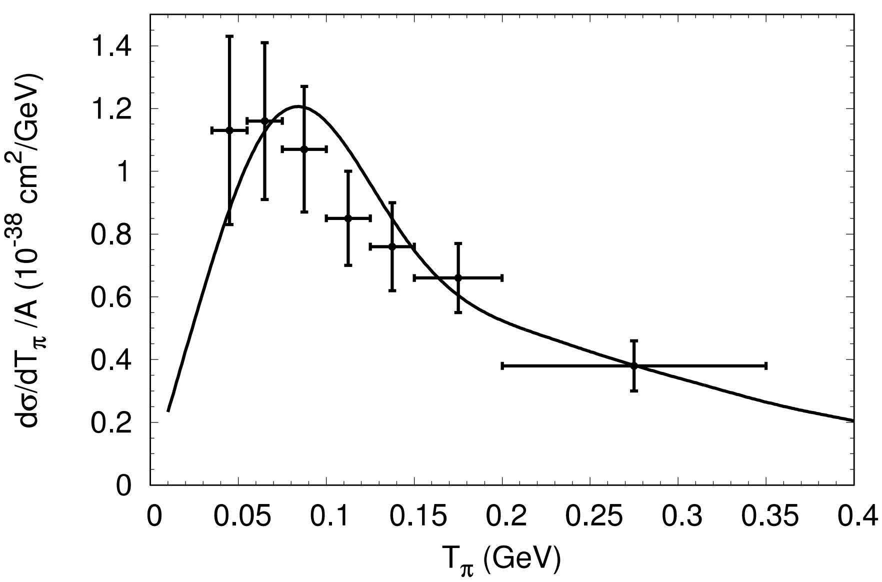
$$\mathrm{CH_2} \qquad \langle E_\nu \rangle \sim 0.6\,\mathrm{GeV}$$



(all theories are too low)

- **MINERvA** (2015)

$$\mathrm{CH} \qquad \langle E_\nu \rangle \sim 4.0\,\mathrm{GeV}$$



data are incompatibel

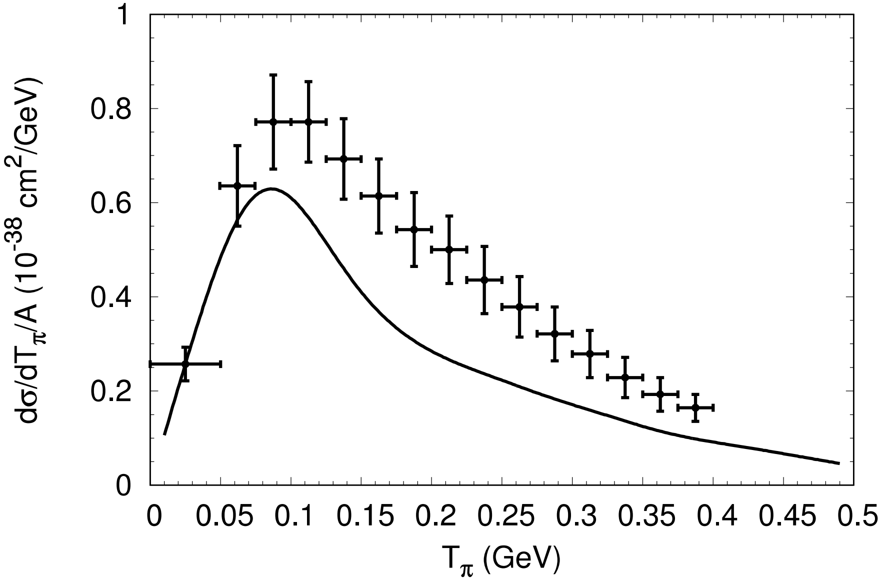
curves show actual GiBUU calculations

1-pion data

“The MiniBooNE 1pi Puzzle”

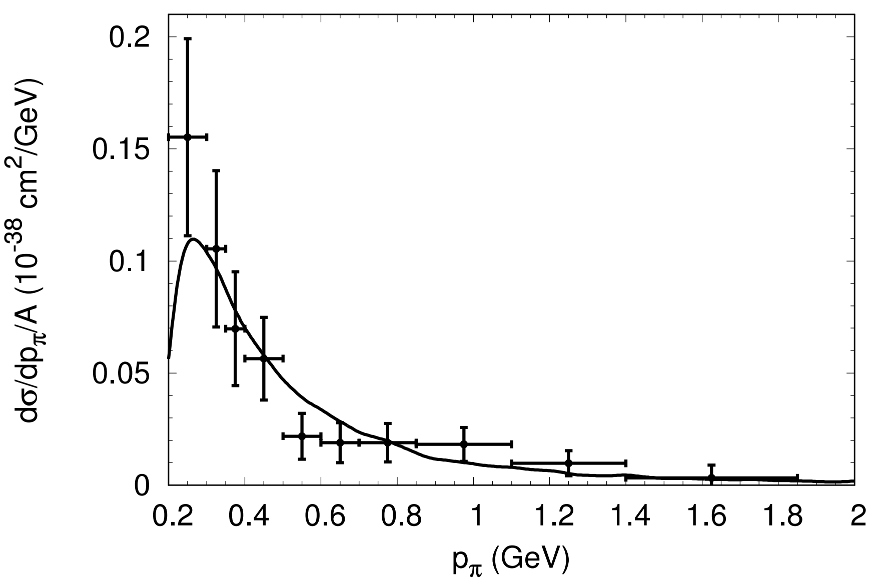
- **MiniBooNE** (2011)

$\mathrm{CH_2} \qquad \langle E_\nu \rangle \sim 0.6\,\mathrm{GeV}$



- **T2K** (2017)

$\mathrm{H_2O} \qquad \langle E_\nu \rangle \sim 0.6\,\mathrm{GeV}$



(all theories are too low)

theory describes simultanously MINERvA and T2K, but not MiniBooNE

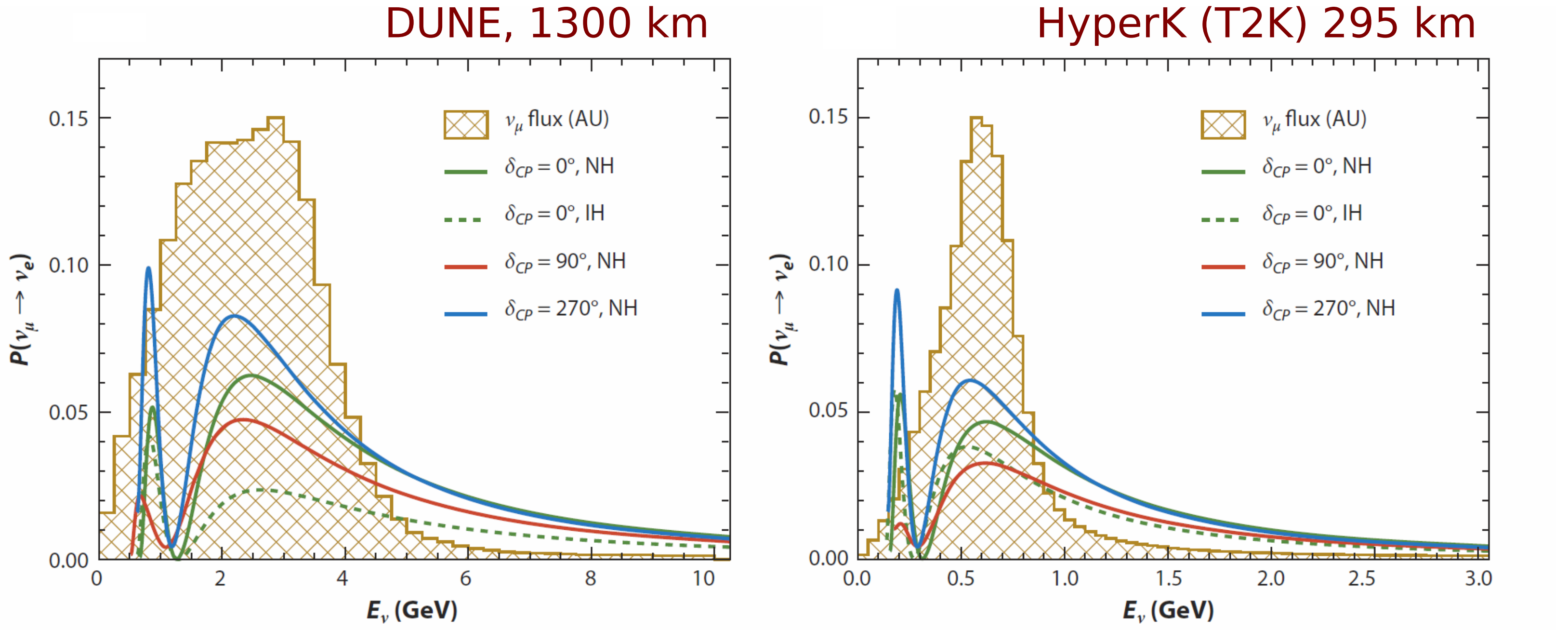
curves show actual GiBUU calculations

Oscillation experiments

- 2 flavor

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2 \left(\frac{\Delta m^2 \, L}{4E_\nu} \right)$$

- 3 flavor



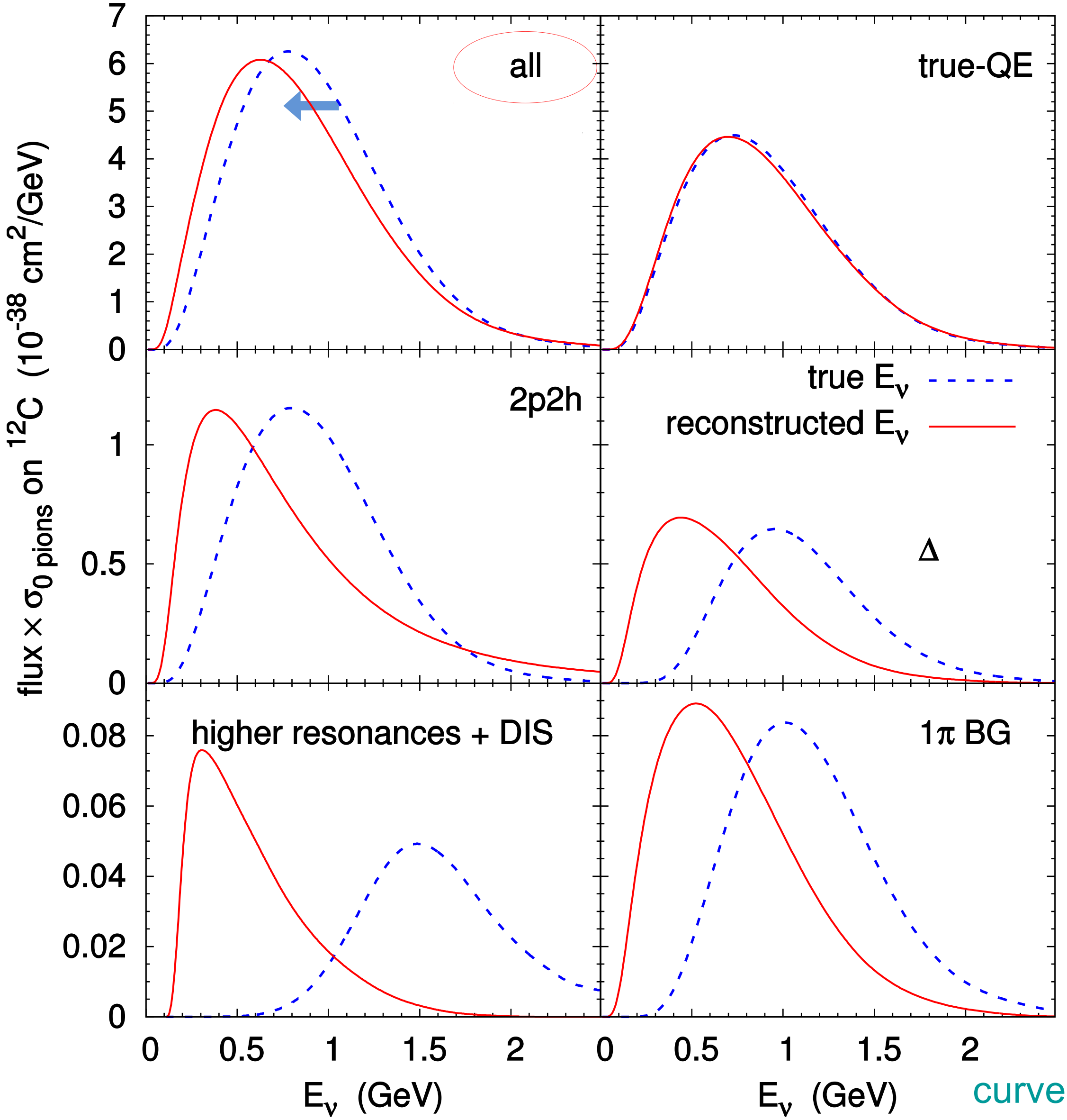
from: Diwan et al., Ann. Rev. Nucl. Part. Sci 66 (2016)

Pontecorvo-**M**aki-**N**akagawa-**S**akata matrix

- necessary accuracy: energy: 100 MeV (DUNE), 50 MeV (T2K)
  rates: 10%

energy reconstruction @ MiniBooNE

$\sim 200\,\mathrm{MeV}$



Cerenkov detector:
only 1 ring
(muon, no pion)
= “QE-like”

reconstructed energy:

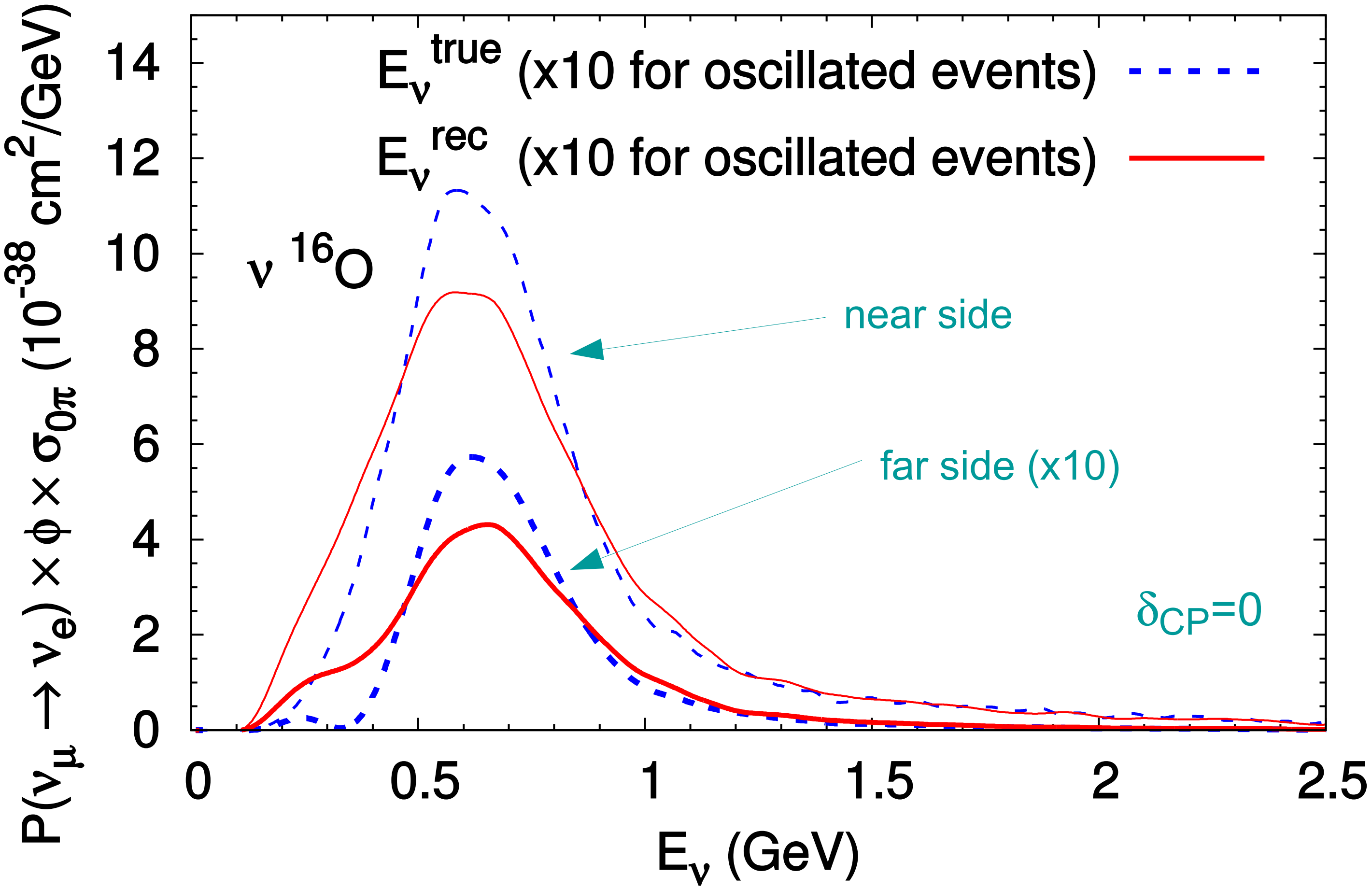
- nucleon at rest
- fixed removal energy

curves show actual GiBUU calculations

energy reconstruction @ T2K

same technique as MiniBooNE

appearance probability



near side

far side (x10)

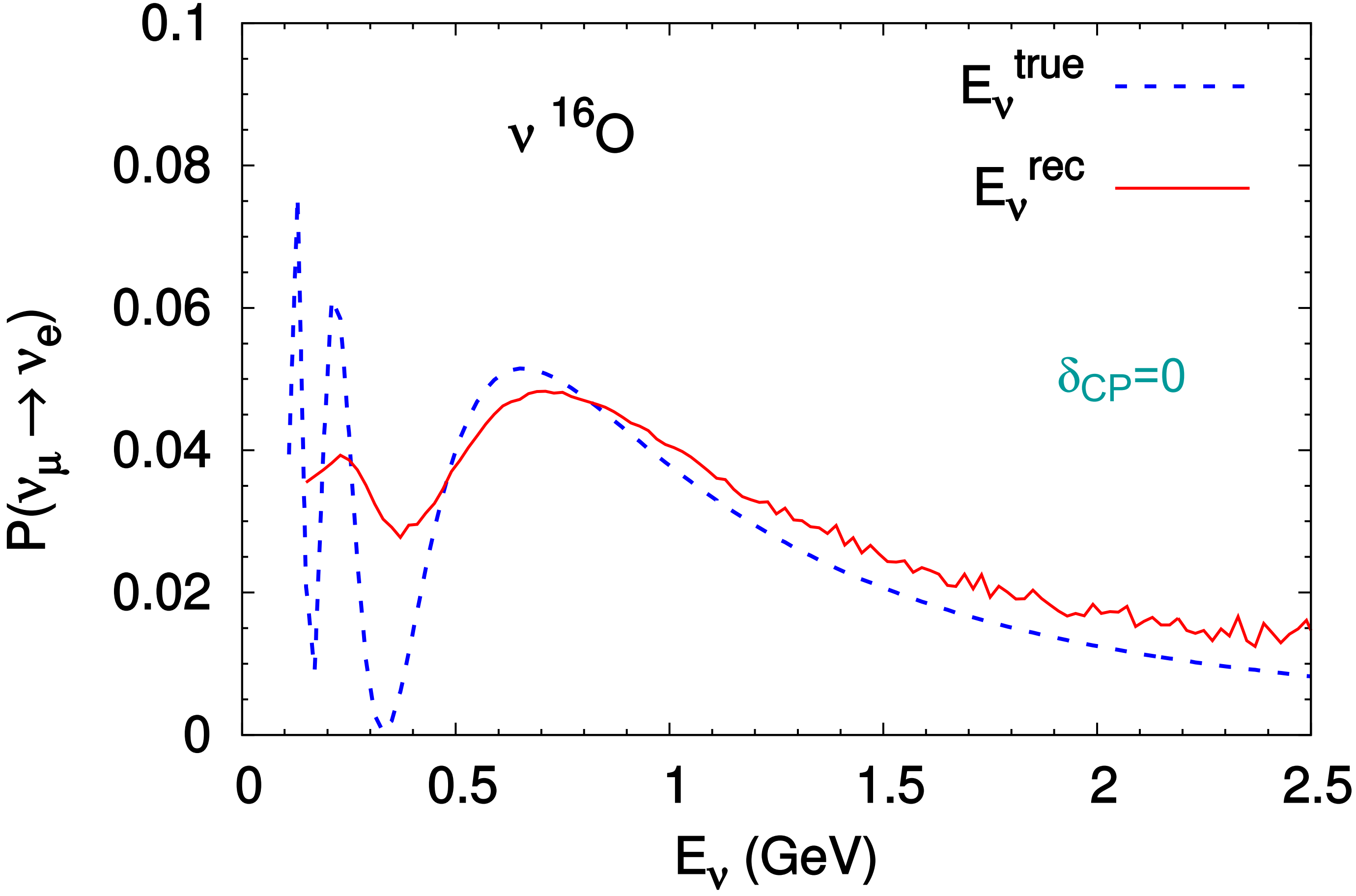
$\delta_{CP}=0$

curves show actual GiBUU calculations

oscillation signal @ T2K

same technique as MiniBooNE

appearance probability



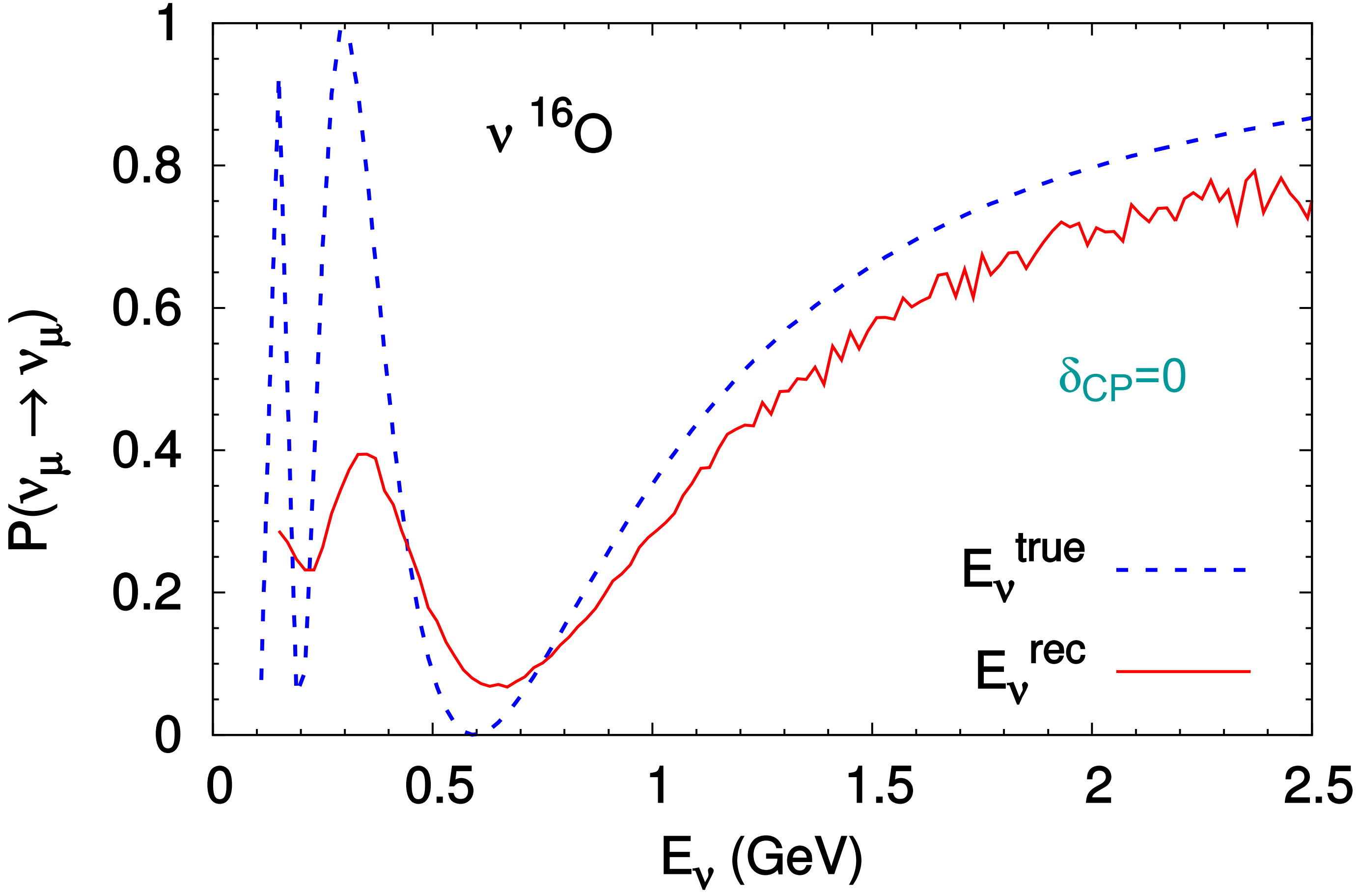
- uncertainty in E_ν = uncertainty in Δm^2: cancels nearly
- **but**: uncertainty in height nearly as big as effect of δ_{CP}

curves show actual GiBUU calculations

oscillation signal @ T2K

same technique as MiniBooNE

survival probability

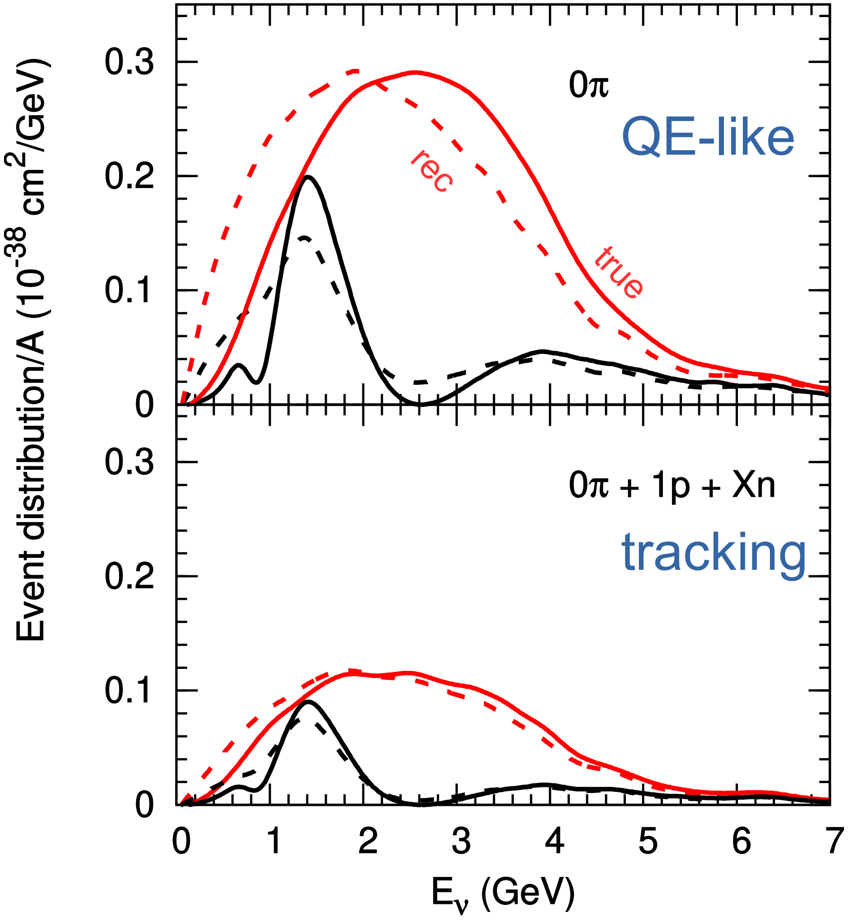


- uncertainty in E_ν = uncertainty in Δm^2: shift by 50 MeV

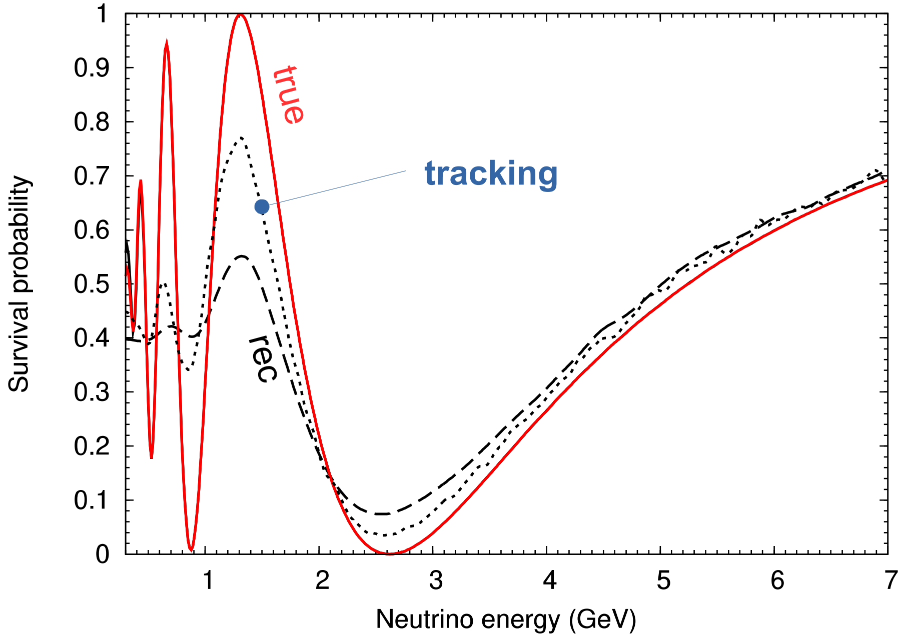
curves show actual GiBUU calculations

oscillation signal @ DUNE

appearance probability



survival probability



- tracking detector is essential

Essential References

- **O.Buss et al., *Phys. Rept. 512 (2012) 1***

  THE GiBUU paper: contains both theory and practical implementation of transport theory

- U.Mosel, O.Lalakulich, K.G., *PRC 86 (2012) 054606, PRL 112 (2014) 151802*

  energy reconstruction for MiniBooNE, T2K and DUNE

- **K.G., U.Mosel, J.Weil, *PRC 94 (2016) 035502***

  contains the latest changes in GiBUU2016

- U.Mosel, K.G., *PRC 94 (2016) 034610*

  A-dependence of 2p2h

- U.Mosel, *Ann. Rev. Nucl. Part. Sci. 66 (2016) 171*

  review, contains some discussion of generators

- U.Mosel, K.G., *PRC 96 (2017) 015503* + *arXiv:1708.04528*

  pion production comparison of MiniBooNE, T2K and MINERvA

- U.Mosel, K.G., *PRC 97 (2018) 045501*

  zero pion T2K

- S.Dolan, U.Mosel, K.G., L.Pickering, S.Bolognesi, *PRC 98 (2018) 045502*

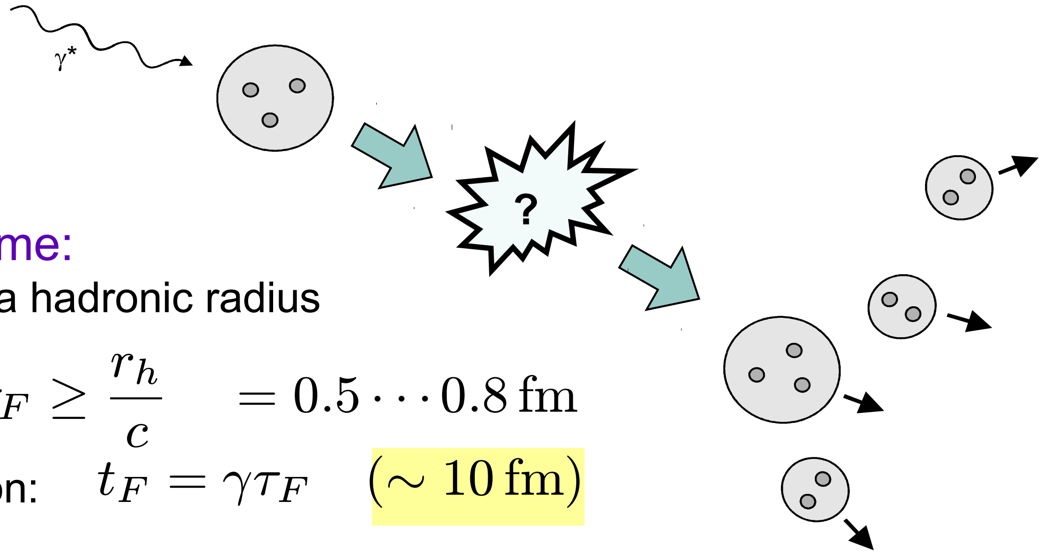
  2p2h: T=1 or 2

see also:

- **PDG: 42. Monte Carlo Neutrino Generators**
- **PDG: 50. Neutrino Cross Section Measurments**

Hadronization in eA

- elementary reactions (*eN*, γ*N*) on nucleon:



reaction products hadronize long before they reach the detector

formation time:
estimation via hadronic radius

$$\tau_F \geq \frac{r_h}{c} \qquad = 0.5 \cdots 0.8\,\mathrm{fm}$$

time dilatation: $t_F = \gamma \tau_F \quad (\sim 10\,\mathrm{fm})$

- nuclear reactions (*eA*, γ*A* @ GeV energies) :

interactions with nuclear medium during formation

→ space-time picture of hadronization

$$\sigma^* / \sigma_H \ \sim \ t^{0,1,2,\ldots}$$

development of wave function

Observables, Experiments

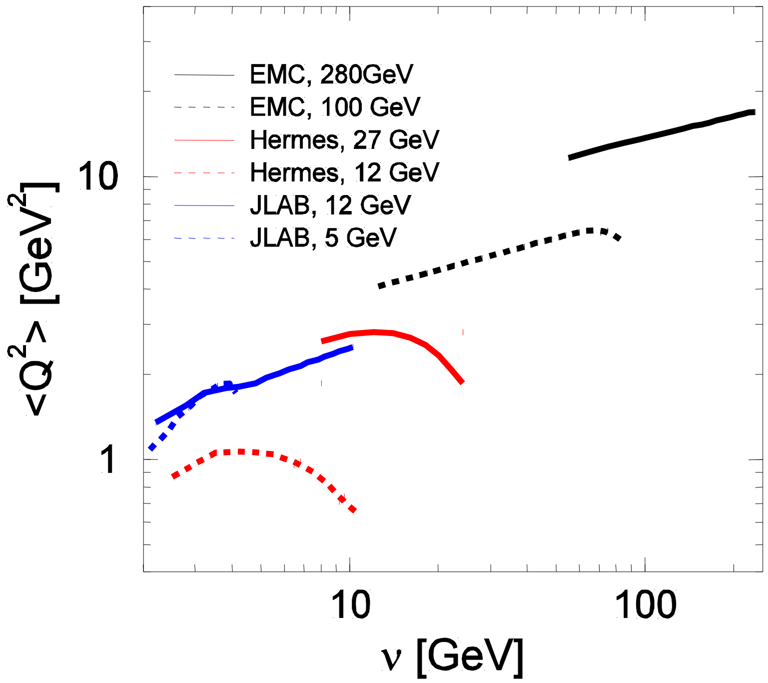
- $$R^h(z_h, \dots) = \frac{\left.\frac{N_h(z_h, \dots)}{N_e(\dots)}\right|_A}{\left.\frac{N_h(z_h, \dots)}{N_e(\dots)}\right|_D}$$
- $$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

- hadronic: $z_h = \frac{E_h}{\nu} \, , \quad p_T \, , \cdots$
- photonic: $\nu \, , \; Q^2 \, , \; W \, , \; x_\text{B} \, , \dots$

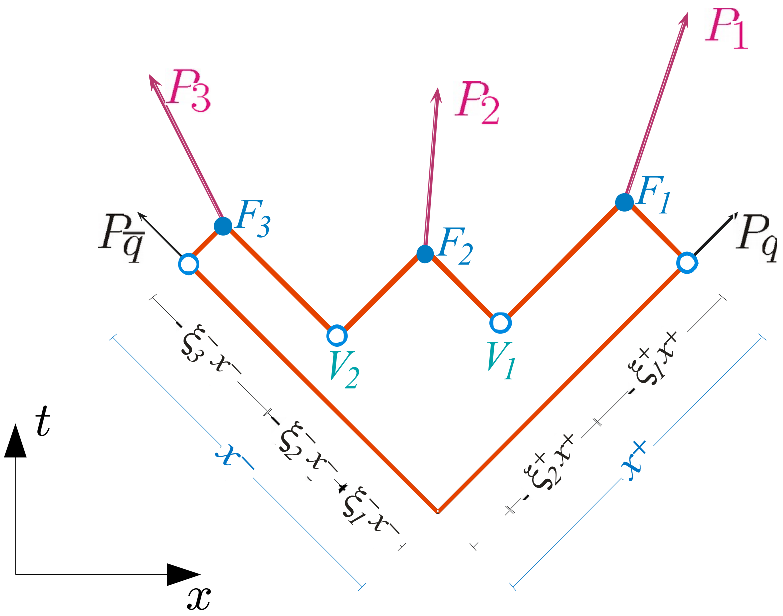
- Experiments

	E_lepton =
EMC	**100…280 GeV**
Hermes	**27 GeV** 12 GeV
CLAS	12 GeV (upgrade) **5 GeV**
EIC	e.g. 3+30 GeV

…multiple combinations of targets



Model: Hadronization in String Model (PYTHIA/JETSET)



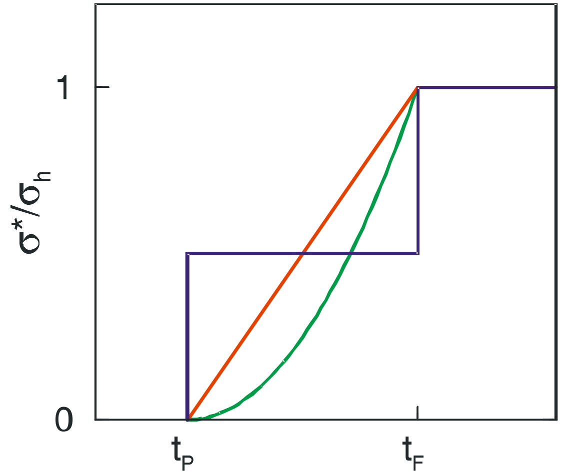
- 3 times/points per particle:
  - „Production 1“ *String-Breaking*
  - „Production 2“ *String-Breaking*
  - „Formation“ *Line-Meeting*

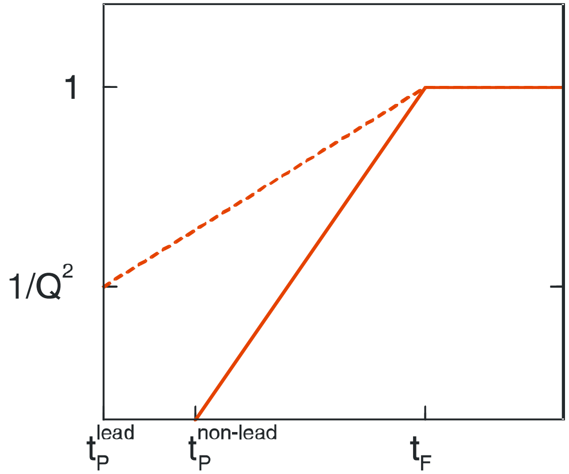
- Leading vs. Non-leading

  Connection to interaction vertex

CT

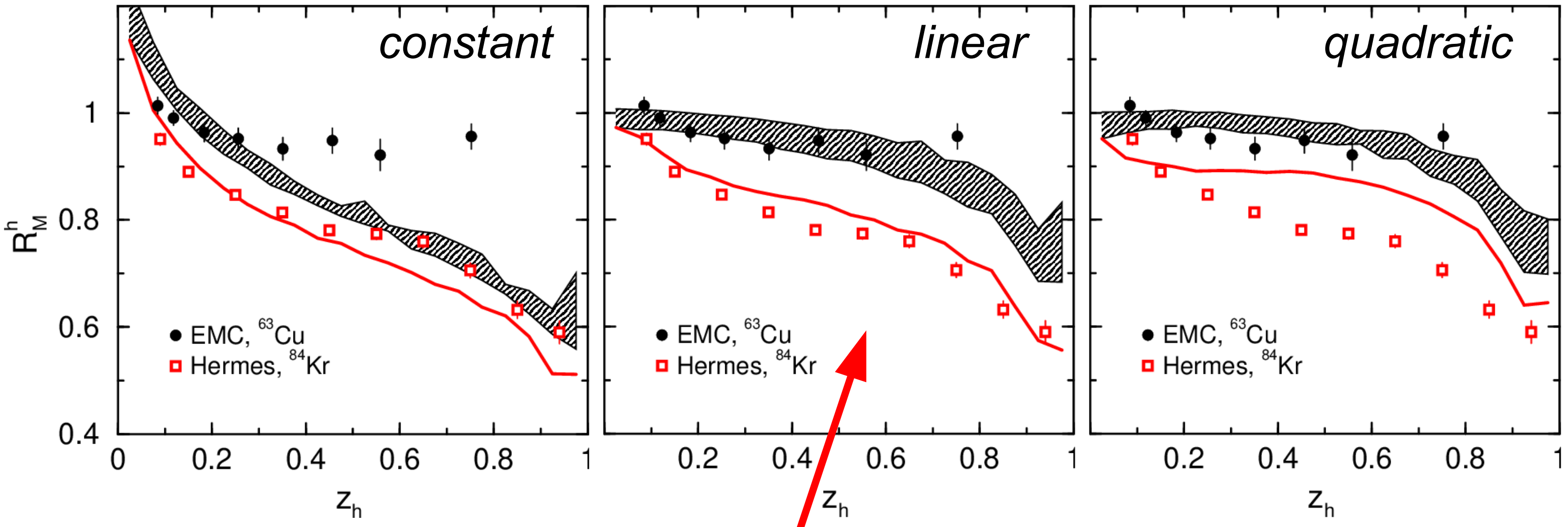
- Cross section evolution scenarios:





EMC & Hermes

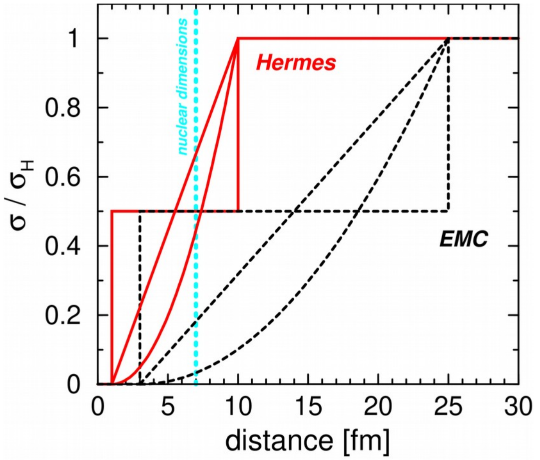
describe simultanously:
- EMC@100...280 GeV
- Hermes@27 GeV



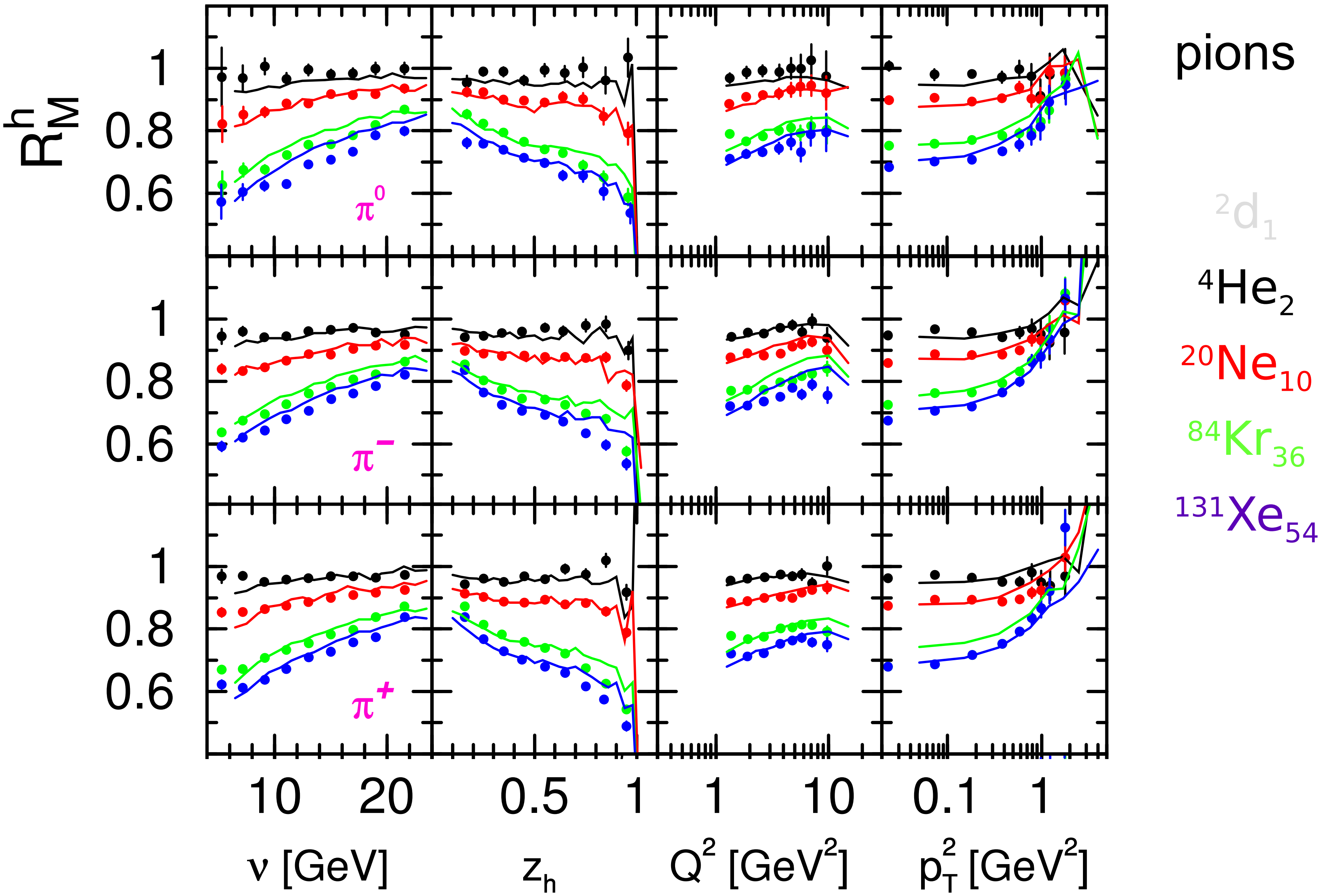
pre-hadronic cross section:

linear increase with time

$$\frac{\sigma^*}{\sigma_H} = \frac{r_{\mathrm{lead}}}{Q^2} + \left(1-\frac{r_{\mathrm{lead}}}{Q^2}\right)\left(\frac{t-t_{\mathrm{P}}}{t_{\mathrm{F}}-t_{\mathrm{P}}}\right)$$



Hermes@27: A.Airapetian et al., NPB780(2007)1

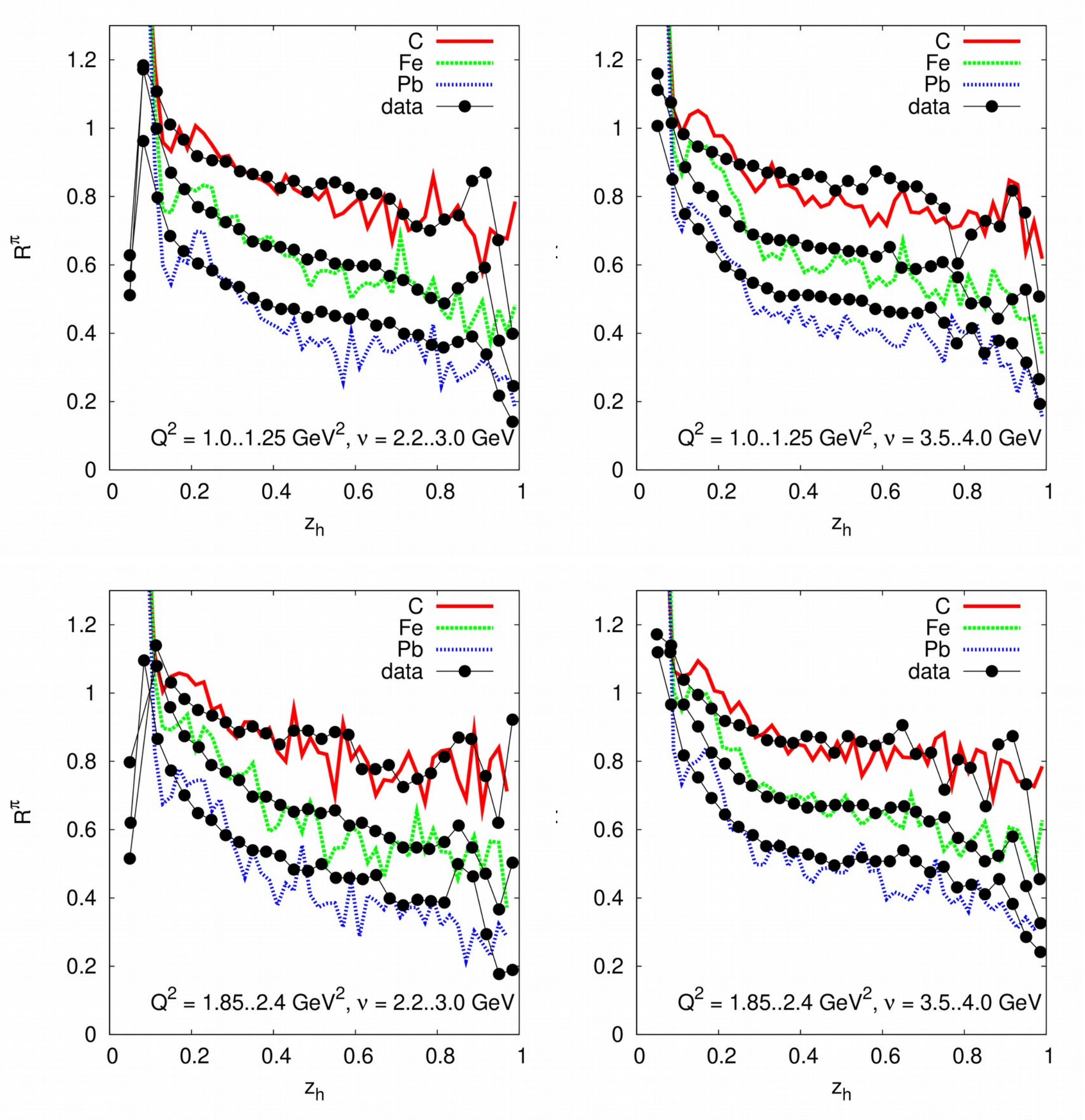


CLAS@5, π^+ : selected (ν,Q^2) bins

$Q^2 = 1.0 \ldots 1.25\,\mathrm{GeV}^2$ $\quad$ $Q^2 = 1.85 \ldots 2.4\,\mathrm{GeV}^2$

$\nu = 3.5 \ldots 4\,\mathrm{GeV}$

$\nu = 2.2 \ldots 3\,\mathrm{GeV}$



Data:

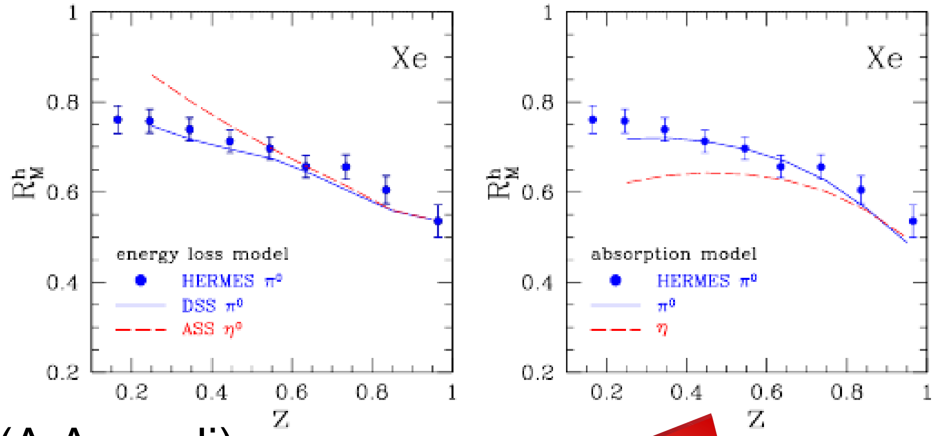
- CLAS preliminary
- no error bars shown

Calculations:

- not tuned !!!
- no Fermi Motion
  (W<2 GeV possible)
- no potentials

As good as at
higher energies !

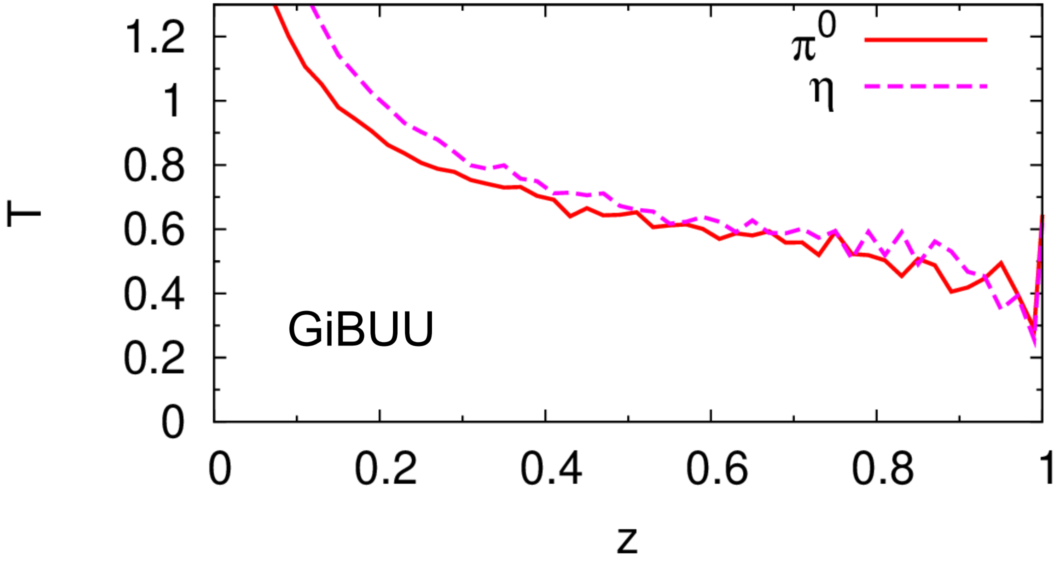
EIC@3+30: π° vs. η

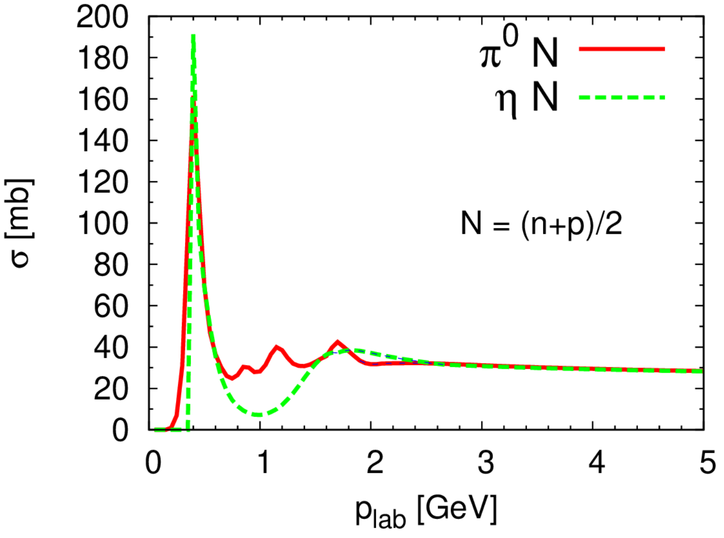


(A.Accardi)

Figure 4. Multiplicity ratio for HERMES neutral pions from a Xenon target together with calculations in an energy loss model[29] calculation from 2007 and in an absorption model[30] for neutral pions and the eta meson. These calculations suggest that the comparison of η and π^0 will distinguish between these two reaction mechanisms.

EIC science case report, D.Boer et al., 2010





Conclusions

- GiBUU is not dead yet!
  - UMO and K.G. are the leftovers
  - external users really work with the code
  - email support costs a lot of time
  - hepforge modifications in 2018 were a big pain in the …
- GiBUU is still needed!
  - neutrino community uses special tuned `generators`
  - “GiBUU is nature” (but too slow)

  - JLAB@5 & 12 GeV: no other code available
  - EIC@low energy modes: important for hadronization studies
  - ultraperipherical UrHICs: simply replace photon flux
- GiBUU well prepared for future projects like DUNE and EIC

People

- ~~Oliver Buss~~
- Theo Gaitanos, Thessaloniki
- Kai Gallmeister, Frankfurt
- Hendrik van Hees, Frankfurt
- ~~Olga Lalakulich~~
- Alexei Larionov, *free lancer*
- ~~Tina Leitner~~
- Ulrich Mosel, Gießen
- ~~Janus Weil~~

- ~5-10 **active** external users

electron and neutrino induced

- 2p2h (since 2016)

  - electrons

$$\frac{\mathrm{d}^2\sigma^{2p2h}}{\mathrm{d}\Omega \mathrm{d}E'} = \frac{8\alpha^2}{Q^4} E'^2 \cos^2\frac{\theta}{2} \left(\frac{Q^2}{2\mathbf{q}^2} + \tan^2\frac{\theta}{2}\right) W_1^e(Q^2,\omega)$$

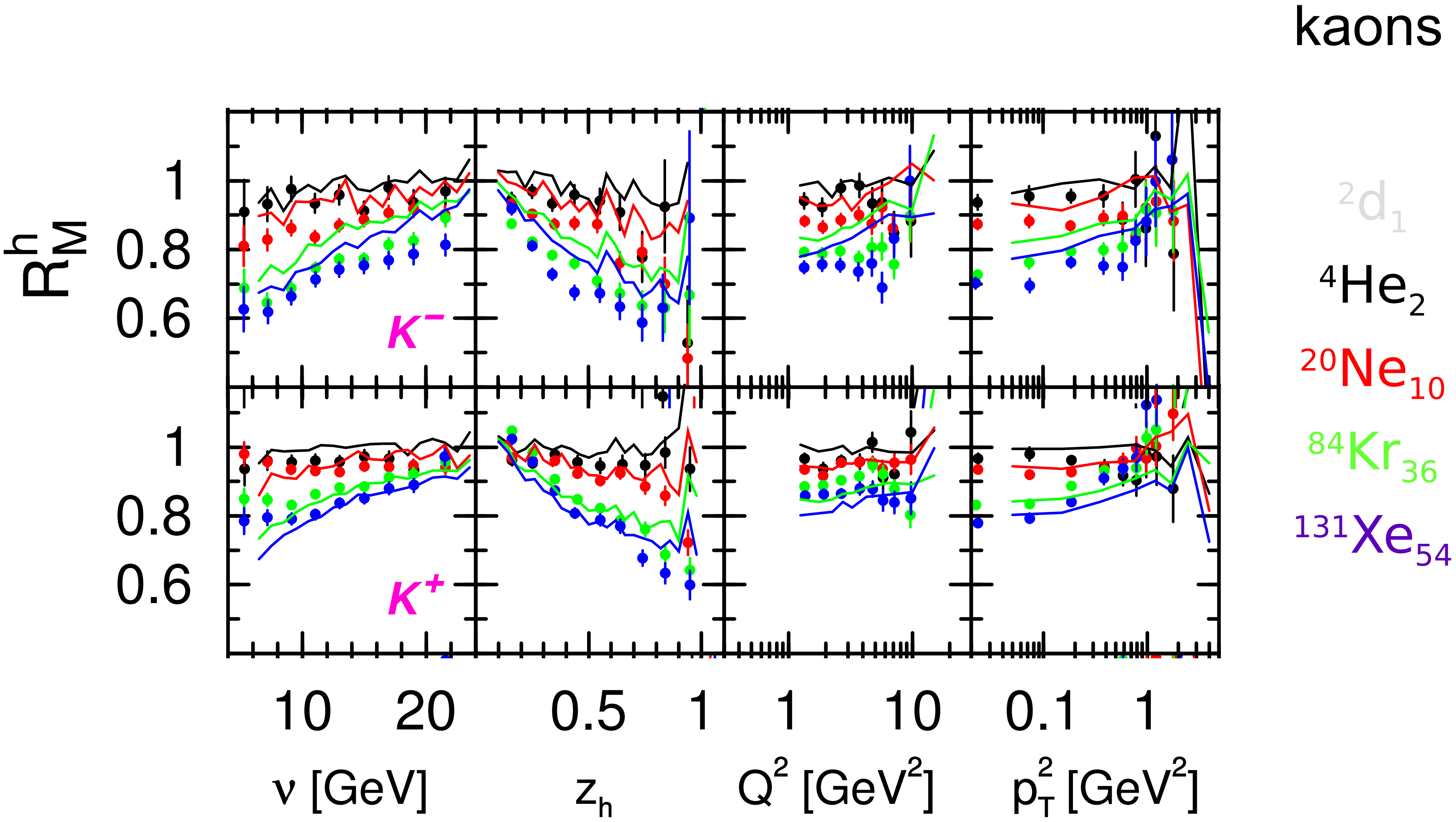
  - neutrinos

$$\frac{\mathrm{d}^2\sigma^{2p2h}}{\mathrm{d}\Omega \mathrm{d}E'} = \frac{G^2}{2\pi^2} E'^2 \cos^2\frac{\theta}{2} \left[2W_1^\nu \left(\frac{Q^2}{2\mathbf{q}^2} + \tan^2\frac{\theta}{2}\right) \mp W_3^\nu \frac{E+E'}{M} \tan^2\frac{\theta}{2}\right]$$

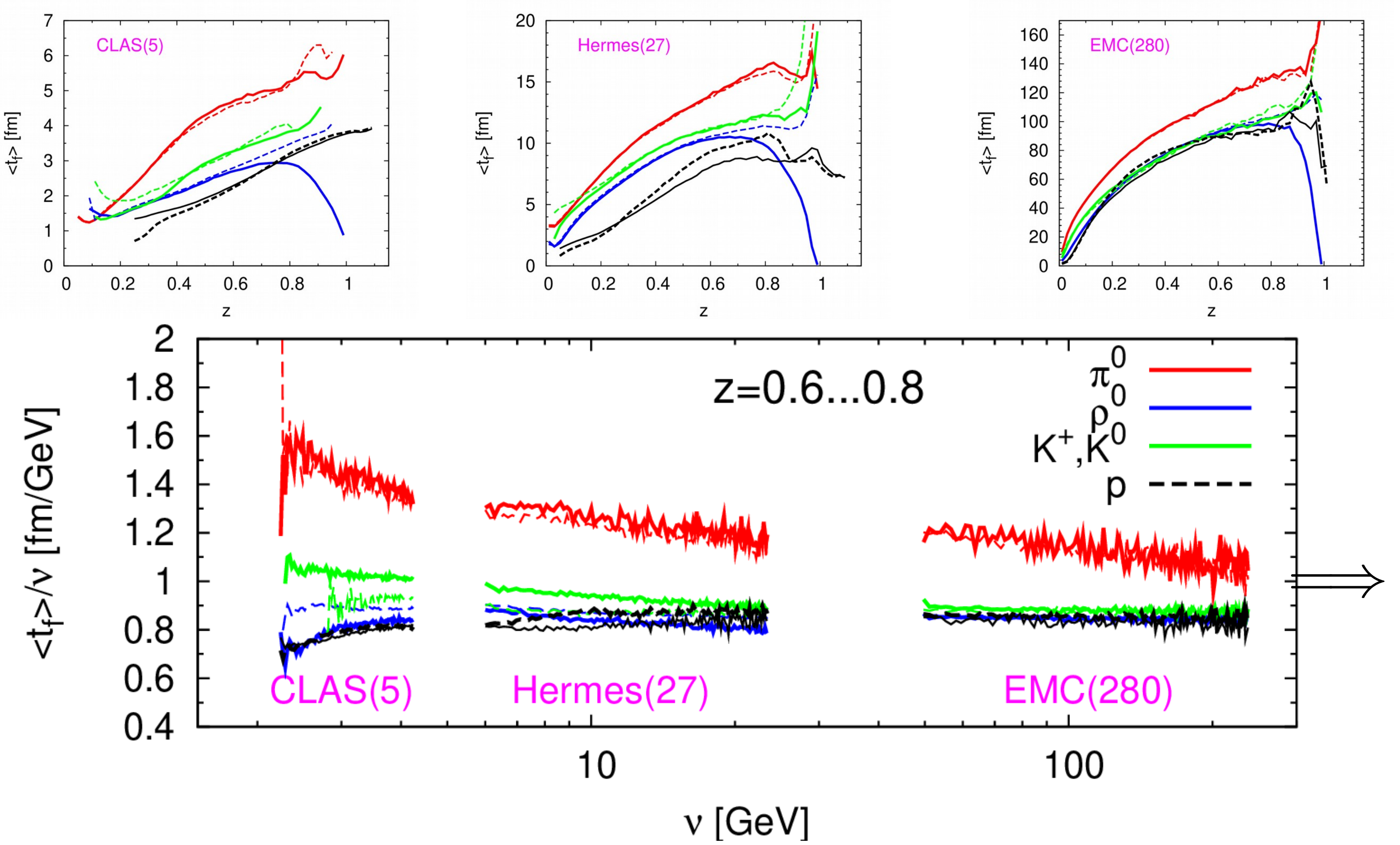
$$W_1^\nu = \left(G_M^2 \frac{\omega^2}{\mathbf{q}^2} + G_A^2\right) \frac{1}{2G_A G_M} W_3^\nu$$

  - $W_1^{\mathrm{MEC}}(Q^2,\omega)$ from Bosted/Christy

Hermes@27: A.Airapetian et al., NPB780(2007)1



Times



$$\Longrightarrow 1$$

$$t_F = \gamma \tau_F = \frac{E_h}{m_h} \tau_F$$

$$\frac{t_F}{\nu} \sim \frac{t_F}{E_h} \sim 1$$

$$\tau_F \sim m_h$$