Exclusive channels and Final State Interactions

K. Gallmeister for the GiBUU group
Goethe-Universität, Frankfurt

Kinetic Theory and BUU equation

GiBUU implementation & some results

Hands On: Final state with neutrino init

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NuSTEC School 2017

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Outline

- Part 1:
  - BUU equation
  - degrees of freedom
  - potentials
  - collision term
  - baryon-meson, baryon-baryon-collisions
- Part 2:
  - ...
- Part 3:
  - ...

GiBUU

- GiBUU
  = The Giessen Boltzmann-Uehling-Uhlenbeck Project
- flexible tool for simulation of nuclear reactions
  - $e + A$
  - $\gamma + A$
  - $\nu + A$
  - $\mathrm{hadron} + A\ (p + A, \pi + A)$

  and
  - $A + A$
- energies: 10 MeV … 10-100 GeV
- degrees of freedom: Hadrons (Baryons, Mesons)
- propagation and collisions of particles in mean fields
- Boltzmann-Uehling-Uhlenbeck equation

GiBUU

- GiBUU
  = The Giessen Boltzmann-Uehling-Uhlenbeck Project
- Gießen: Town in Hesse, Germany
  84000 inhabitants
  70 km north of Frankfurt

  Institute for Theoretical Physics, Justus-Liebig University

- ‚official' pronounciation: ghee – bee – you – you

  alternatives: gee – bee – you – you (ala „Bee Gees")
  giii – buuh (ala „Hui Buh")

Some kinetic theory

- distribution function $f(x,p) \quad x = (t, \vec{x}\,),\ p = (E, \vec{p}\,)$
  describes (density) distribution of (single) particles
- number of particles in a given phase-space volume:

$$\Delta N = f(x,p)\, \Delta^3 x \Delta^3 p$$

- for each particle species: $f_N,\ f_\pi,\ f_\Delta,\ ,\ldots$

- continuity equation for free, non-interacting particles

$$p^\mu \partial_\mu\, f(x,p) = 0$$

straight line propagation of particles, no collisions

- adding external forces (mean field potentials): Vlasov eq.

$$\left[\partial_t + (\nabla_p E)\nabla_r - (\nabla_r E)\nabla_p\right] f(x,p) = 0$$

propagation through mean field, no collisions

Adding collisions

- forget about mean fields, but add collisions…
- continuity eq. + collision term → Boltzmann eq.

$$p^\mu \partial_\mu f(x,p) = C(x,p)$$

- collision integral has gain and loss term

$$C(x,p) = C_{\text{gain}}(x,p) + C_{\text{loss}}(x,p)$$

- mean fields and collision term:

Boltzmann-Uehling-Uhlenbeck eq. (BUU or VUU)

$$\left[\partial_t + (\nabla_p H_i)\nabla_r - (\nabla_r H_i)\nabla_p\right] f_i(\vec{r},t,\vec{p}) = C\left[f_i, f_j, \ldots\right]$$

The BUU equation

$$\left[\partial_t + (\nabla_p H_i)\nabla_r - (\nabla_r H_i)\nabla_p\right] f_i(\vec{r}, t, \vec{p}) = C\left[f_i, f_j, \ldots\right]$$

- describes space-time evolution of single particle densities
- index i represents particle species
  → one equation for each species

$$i = N, \Delta, \pi, \rho, \ldots$$

- Hamiltonian H_i
  - hadronic mean fields (Skyrme/Welke or RMF)
  - Coulomb
  - „off-shell-potential"
- collision term C
  - decay and scattering processes: 1-, 2- and 3-body
  - (low energy: resonance model, high energy: string model)
  - contains Pauli-blocking
- equations coupled via mean fields and via collision term

Degrees of Freedom

- GiBUU is purely hadronic (no partonic phase)
- leptons: usually not ‚transported', but
  - e+N, nu+N, gamma+N initial events
  - leptonic/photonic decays
- 61 baryons, 22 mesons
  (strangeness and charm included, no bottom)
- properties from Manley analysis (PDG for strange/charm)

- in principle one needs:
  - cross sections for collisions between all of them (all energies)
  - mean-field potentials for all species

often not known, thus use hypothesis/models/guesses

Particle species

- important particles:

particle	mass	width	GiBUU ID	PDG IDs
N	0.983	0	1	p=2212, n=2112
Δ	1.232	0.118	2	2224, 2214, 2114, 1114
N^*			3-18	
Δ^*			19-31	
Λ	1.116	0	32	3122
Σ	1.189	0	33	3222,3212,3112
Λ^*, Σ^*			34-52	
π	0.138	0	101	$\pi^+ = 211$, $\pi^0 = 111$, $\pi^- = -211$
η	0.547		102	
ρ	0.775	0.149	103	213,113,-213
σ			104	
ω	0.782	0.004	105	
η'	0.957		106	
K	0.496	0	110	$K^+ = 321$, $K^0 = 311$
$\bar{K}$	0.496	0	111	$K^- = -321$, $\bar{K}^0 = -311$

https://gibuu.hepforge.org/trac/wiki/ParticleIDs

Mean-field potentials

- two types of mean-field potentials:
  - non-relativistic Skyrme-type potentials
  - relativistic mean fields (RMF)

- potential may enter single-particle energy as

$$H = \sqrt{(m+V)^2 + (\vec{p} + \vec{U}\,)^2} + U_0$$

- RMF is Lorentz vector U^μ
- Skyrme enters as U_0, bound to specific frame (LRF)

- Scalar Potential V: mass shift

RMF potentials

- proper relativistic mean-field description
- based on (nonlinear) Walecka-type Lagrangian

$$
\begin{aligned}
\mathcal{L} =& \overline{\psi}[\gamma_\mu(i\partial^\mu - g_\omega\omega^\mu - g_\rho\tau\rho^\mu - \frac{e}{2}(1+\tau^3)A^\mu) - m_N - g_\sigma\sigma]\psi \\
&+ \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^2 \\
&- \frac{1}{4}R_{\mu\nu}R^{\mu\nu} + \frac{1}{2}m_\rho^2\rho^2 - \frac{1}{16\pi}F_{\mu\nu}F^{\mu\nu}
\end{aligned}
$$

- theoretically cleaner, computationally more demanding
- limited range of applicability in energy

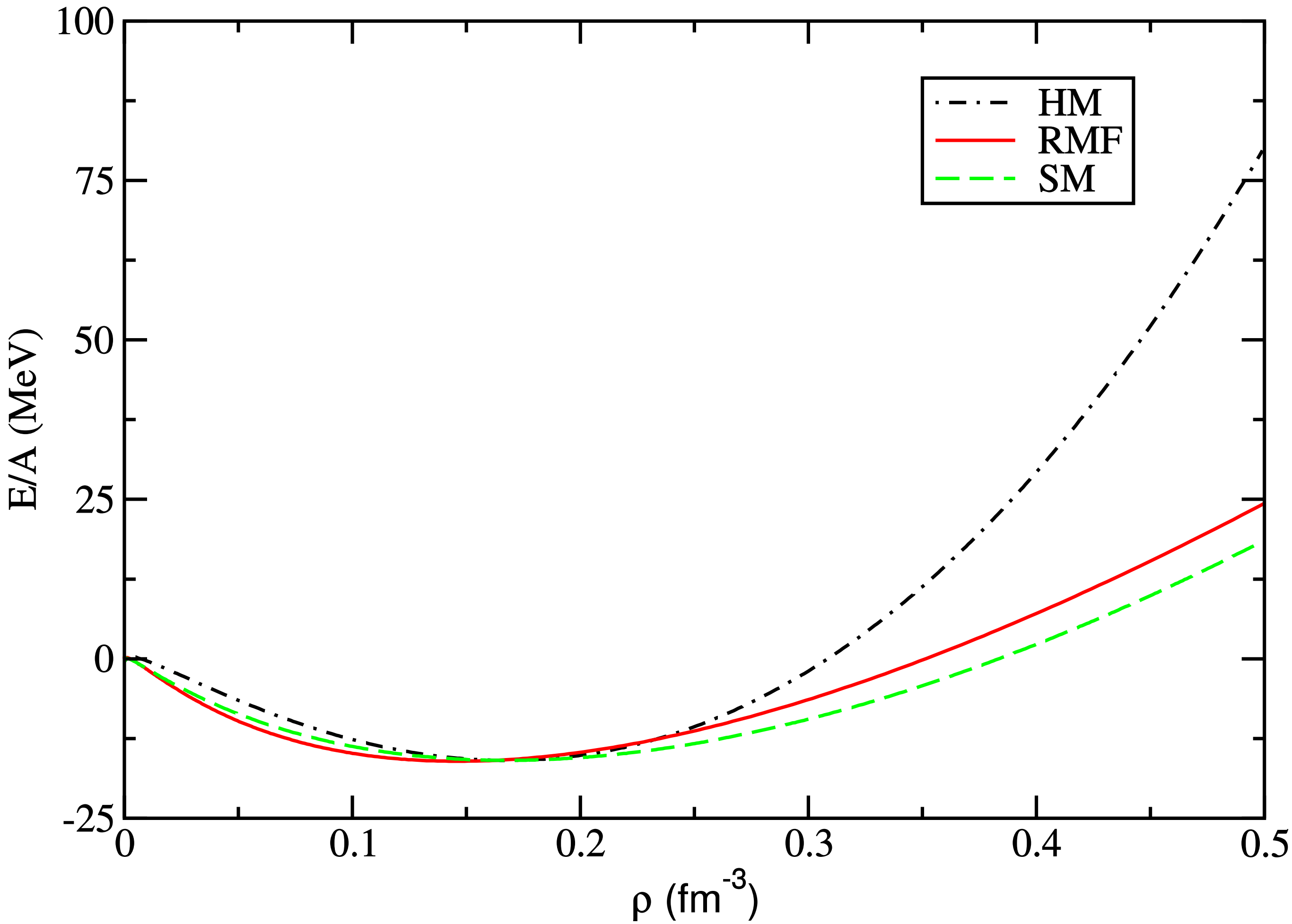
Skyrme/Welke-like potential

$$U_0(x,\vec{p}) = A\frac{\rho}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^{\gamma} + \frac{2C}{\rho_0}\sum_{i=p,n}\int \frac{g\mathrm{d}^3p'}{(2\pi)^3}\frac{f_i(x,\vec{p}')}{1+(\vec{p}-\vec{p}')^2/\Lambda^2} + d_{\mathrm{symm}}\frac{\rho_p(x)-\rho_n(x)}{\rho_0}\tau_i$$

$$\rho_0 = 0.168\,\mathrm{fm}^{-3}$$

- defined in local rest frame (LRF, baryon current vanishes)
- six parameters
- fixed to
  - nuclear binding energy of 16 MeV at $\rho=\rho_0$ (iso-spin symm. matter)
  - nuclear-matter incompressibility K=200-380 MeV

Equation of State



HM: hard momentum-dependent Skyrme

SM: soft momentum-dependent Skyrme

Collision term

- contains one-, two-, and three-body collisions

$$C = C_{1\to X} + C_{2\to X} + C_{3\to X}$$

(1) resonance decays

(2) two-body collisions

  - elastic and inelastic
  - any number of particles in final state
  - baryon-meson, baryon-baryon, meson-meson

(3) three-body collisions (only relevant at high densities)

- low energies: cross sections based on resonances

$$\text{e.g. } \pi N \to N^*,\ NN \to NN^*$$

- high energies: string fragmentation

Collision term

- 2-to-2 term $(12 \leftrightarrow 1'2')$

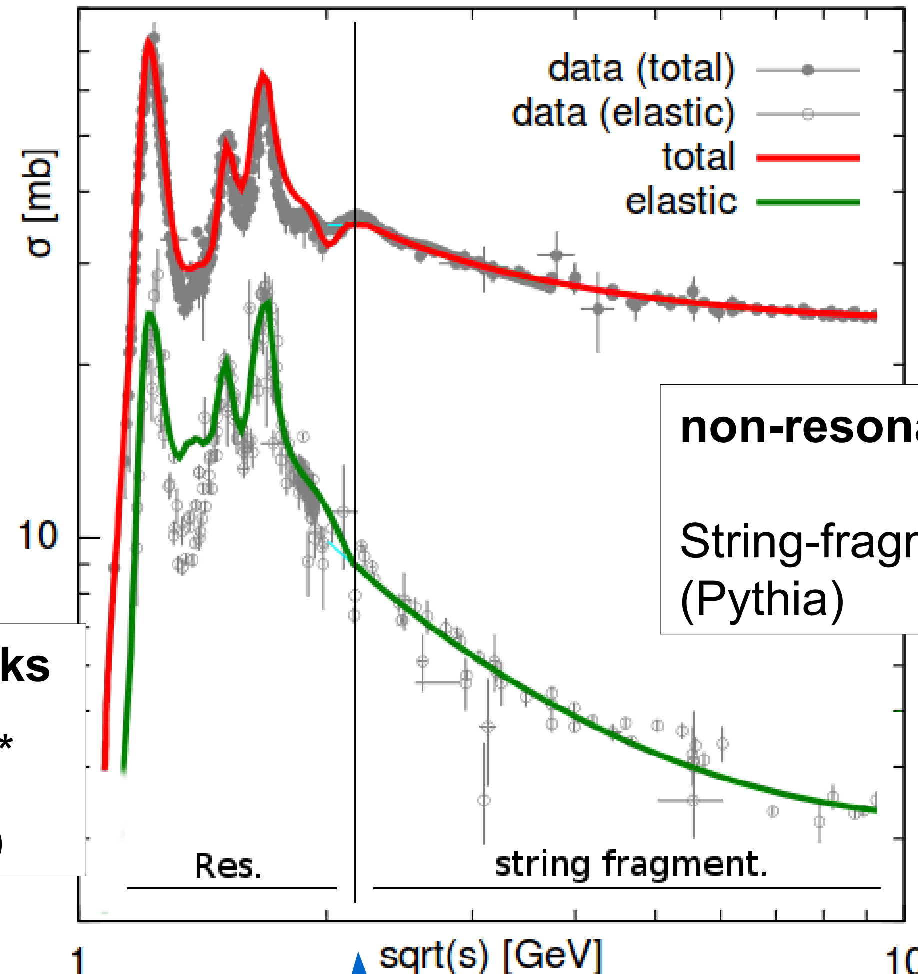
$$C^{(2,2)}(x,p_1)$$
$$= C^{(2,2)}_{\rm gain}(x,p_1) - C^{(2,2)}_{\rm loss}(x,p_1)$$
$$= \frac{\mathcal{S}_{1'2'}}{2p_1^0 g_{1'} g_{2'}} \int \frac{\mathrm{d}^4 p_2}{(2\pi)^4 2p_2^0} \int \frac{\mathrm{d}^4 p_{1'}}{(2\pi)^4 2p_{1'}^0} \int \frac{\mathrm{d}^4 p_{2'}}{(2\pi)^4 2p_{2'}^0}$$
$$\times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_{1'} - p_{2'}) \overline{|\mathcal{M}_{12\to1'2'}|^2}$$
$$\times [F_{1'}(x,p_{1'}) F_{2'}(x,p_{2'}) \overline{F}_1(x,p_1) \overline{F}_2(x,p_2)$$
$$- F_1(x,p_1) F_2(x,p_2) \overline{F}_{1'}(x,p_{1'}) \overline{F}_{2'}(x,p_{2'})]$$

- $F(x,p) = 2\pi g\, f(x,p)\, \mathcal{A}(x,p)$

  $\overline{F}(x,p) = 2\pi g\, [1 - f(x,p)]\, \mathcal{A}(x,p)$ Pauli-blocking

Baryon-Meson collisions

- example: πN cross section



non-resonant

String-fragmentation (Pythia)

clear resonance peaks

excitation of N* and Δ*

(Breit-Wigner shapes)

$$\mathcal{A}(p) = \frac{1}{\pi} \frac{\sqrt{p^2}\Gamma}{(p^2 - M_0^2)^2 + p^2\Gamma^2}$$

$$\sqrt{s} = 2.2 \pm 0.2\,\mathrm{GeV}$$

Resonance Model

- resonance parameters, decays modes, widths:
  D.Manley, E.Saleski, PRD45 (1992) 4002
  PWA of $\pi N \to \pi N$ and $\pi N \to \pi\pi N$, consistency!!!

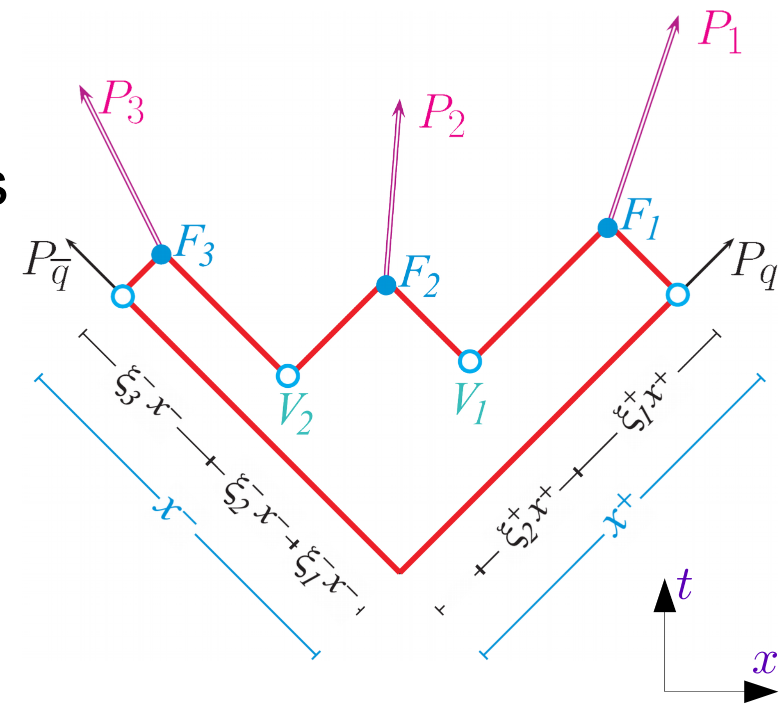
		M_0	Γ_0	$\lvert\mathcal{M}^2\rvert/16\pi$ [mb GeV^2]		branching ratio in %						
	rating	[MeV]	[MeV]	NR	ΔR	πN	ηN	$\pi\Delta$	ρN	σN	$\pi N^*(1440)$	$\sigma\Delta$
$P_{11}(1440)$	****	1462	391	70	—	69	—	22_P	—	9	—	—
$S_{11}(1535)$	***	1534	151	8	60	51	43	—	$2_S + 1_D$	1	2	—
$S_{11}(1650)$	****	1659	173	4	12	89	3	2_D	3_D	2	1	—
$D_{13}(1520)$	****	1524	124	4	12	59	—	$5_S + 15_D$	21_S	—	—	—
$D_{15}(1675)$	****	1676	159	17	—	47	—	53_D	—	—	—	—
$P_{13}(1720)$	*	1717	383	4	12	13	—	—	87_P	—	—	—
$F_{15}(1680)$	****	1684	139	4	12	70	—	$10_P + 1_F$	$5_P + 2_F$	12	—	—
$P_{33}(1232)$	****	1232	118	OBE	210	100	—	—	—	—	—	—
$S_{31}(1620)$	**	1672	154	7	21	9	—	62_D	$25_S + 4_D$	—	—	—
$D_{33}(1700)$	*	1762	599	7	21	14	—	$74_S + 4_D$	8_S	—	—	—
$P_{31}(1910)$	****	1882	239	14	—	23	—	—	—	—	67	10_P
$P_{33}(1600)$	***	1706	430	14	—	12	—	68_P	—	—	20	—
$F_{35}(1905)$	***	1881	327	7	21	12	—	1_P	87_P	—	—	—
$F_{37}(1950)$	****	1945	300	14	—	38	—	18_F	—	—	—	44_F

$$\Gamma_{R\to ab}(m) = \Gamma^0_{R\to ab}\frac{\rho_{ab}(m)}{\rho_{ab}(M^0)}$$

$$\rho_{ab}(m) = \int p_a^2 p_b^2 \mathcal{A}_a(p_a^2)\mathcal{A}_b(p_b^2)\frac{p_{ab}}{m}B^2_{L_{ab}}(p_{ab}R)\mathcal{F}^2_{ab}(m)$$

(Lund) String-fragmentation (Pythia)

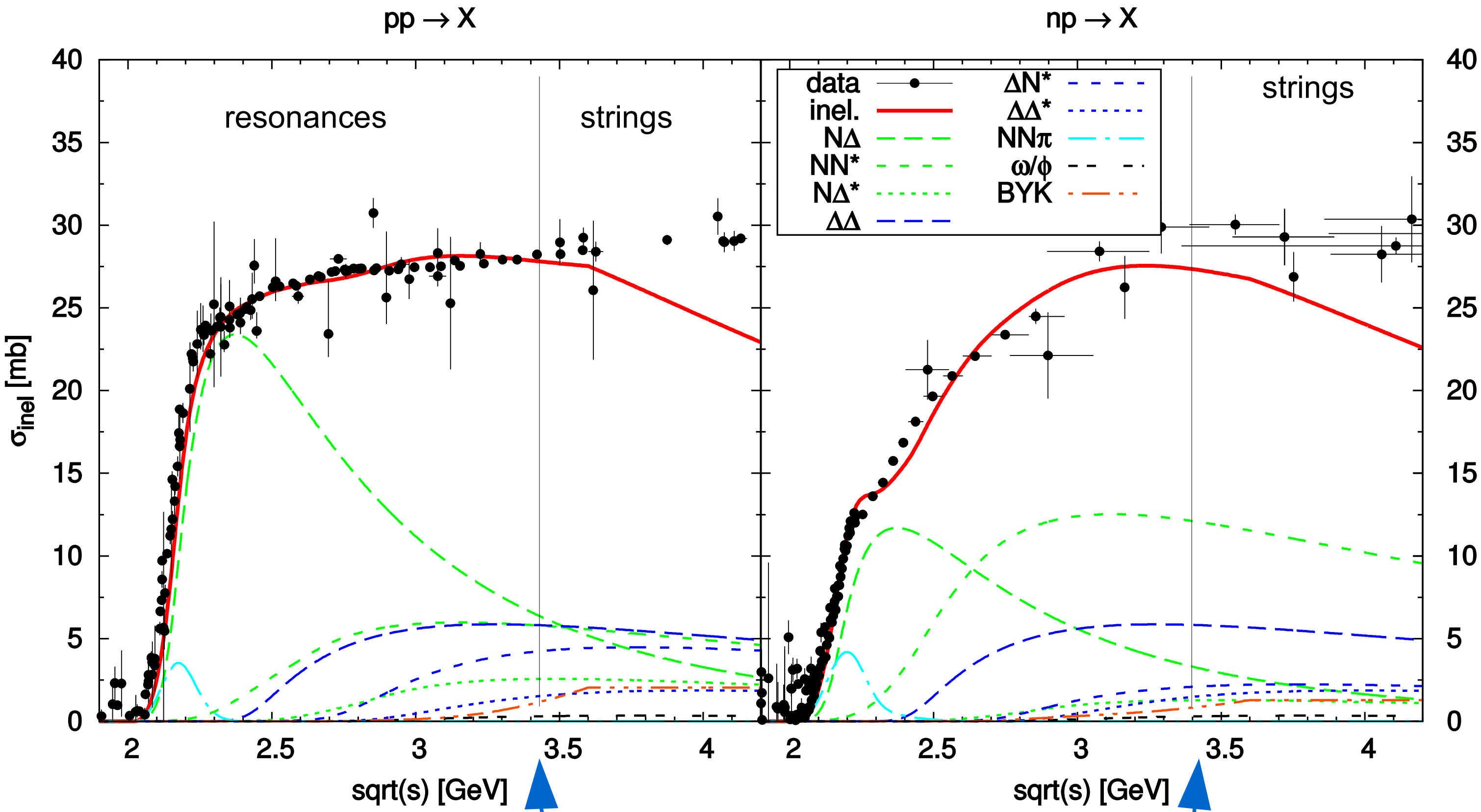
- *idea:*
  hard qq scattering (pQCD)
  creates a color flux tube ('string')
  which then fragments into hadrons
  (via $q\bar{q}$ pair production)



- high energy: 10 GeV...
- "Lund string model"
  implementation: Pythia (Jetset)
- only low-lying resonances
- phenomenological fragmentation function
  (when and how does a string break?)
- parameters fitted to data (different 'tunes' available)

Baryon-Baryon Collisions

- low energy: resonance model, high energy: string model
- no nice peaks due to two-body kinematics
- *NN→NR,ΔR* (*R*=Δ,*N**,Δ*)



$$\sqrt{s} = 3.4 \pm 0.1\,\mathrm{GeV}$$

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Outline

- Part 1:
  - ...
- Part 2: Implementation & Some results
  - Testparticles
  - Parallel vs. Full ensemble
  - Local collision criterion (beyond 2-particle collisions)
  - Initial state
    - Local Thomas Fermi vs. Readjusting
    - Frozen particles
  - some results
    - photoproduction: meson+N cross sections
    - hadron attenuation @ EMC, Hermes, JLAB
    - HARP
    - neutrino induced
- Part 3: Hands On
  - ...

Testparticle ansatz

$$\left[\partial_t + (\nabla_p H_i)\nabla_r - (\nabla_r H_i)\nabla_p\right] f_i(\vec{r},t,\vec{p}) = C\left[f_i, f_j, \ldots\right]$$

- *idea:*
  approximate full phase-space density distribution by a sum of delta-functions

$$f\left(\vec{r},t,\vec{p}\right) \sim \sum_{i=1}^{N_{\mathrm{test}}} \delta\left(\vec{r} - \vec{r}_i(t)\right)\delta\left(\vec{p} - \vec{p}_i(t)\right)$$

- each delta-function represents one (test-)particle with a sharp position and momentum
- large number of test particles needed

Ensemble techniques

- **"full ensembles" technique**
- every testparticle may interact with every other one
- rescaling of cross section

$$\sigma_{ij} \to \frac{1}{N_{\text{test}}} \sigma_{ij}$$

- Pros:
  - locality of collisions
- Cons:
  - calculational time: collisions scale with $(N_{\text{test}})^2$
  - energy not conserved per ensemble, on average only
  - conserved quantum numbers are respected on average only ('canonical')

$$\underbrace{K}_{\text{ensemble } i} + \underbrace{\overline{K}}_{\text{ensemble } j} \to \pi\pi$$

Ensemble techniques

- **“parallel ensembles” technique**
- *idea:*

  testparticle index is also ensemble index

- $N_{\rm test}$ independent runs, densities etc. may be averaged

- Pros:
  - calculational time: collisions scale with $N_{\rm test}$
  - conserved quantum numbers are strictly respected (‘microcanonical’)
- Cons:
  - non-locality of collisions $\sigma_{ij} \simeq 30\,\mathrm{mb} \;\rightarrow\; r = 1\,\mathrm{fm}$

Time evolution

- time axis is discretized
- collisions only happen at discrete time steps,
- between collisions: propagation (through mean fields)
- typical time-step size: $\Delta t = 0.1\text{-}0.2\,\mathrm{fm}/c$
- start at $t{=}0$ and run N timesteps until $t_{\max}$
- typically:

$$N\,\Delta t = t_{\max} \approx 20\text{-}50\,\mathrm{fm}/c$$

$$\Longrightarrow \; N \approx 100\text{-}1000$$

- density/potentials: if not analytically, recalc at every step

Cross section: Geometric interpretation

- particle i and particle j collide, if during timestep Δt

$$r_{ij}(t) = |\vec{r}_i(t) - \vec{r}_j(t)| \stackrel{!}{\leq} \frac{\sqrt{\sigma_{ij}}}{\pi}$$

- problem 1: only for 2-body collisions
- problem 2: not invariant under Lorentz-Trafos
  - different frames may lead to different ordering of collisions
  - specific frame (‘calculational frame’) needed

Cross section: Stochastic interpretation

- collision rate per unit phase space

massless, no $(2\pi)^3$

$$\frac{\Delta N^{2\to 2}_{\rm coll}}{\Delta t \Delta^3 x \Delta^3 p_1} = \frac{\Delta^3 p_2}{2E_1\, 2E_2} f_1 f_2 \int \frac{\mathrm{d}^3 p_1'}{2E_1'} \frac{\mathrm{d}^3 p_2'}{2E_2'} |\mathcal{M}| \delta^{(4)}(p_1 + p_2 - p_1' - p_2')$$

$$\sigma_{22} = \frac{1}{2s} \int \frac{\mathrm{d}^3 p_1'}{2E_1'} \frac{\mathrm{d}^3 p_2'}{2E_2'} |\mathcal{M}| \delta^{(4)}(p_1 + p_2 - p_1' - p_2')$$

$$f_i = \frac{\Delta N_i}{\Delta^3 x \Delta^3 p}$$

- collision probability in unit box $\Delta^3 x$ and unit time Δt

$$P_{22} = \frac{\Delta N^{2\to 2}_{\rm coll}}{\Delta N_1 \Delta N_2} = v_{\rm rel}\, \sigma_{22} \frac{\Delta t}{\Delta^3 x}$$

$$\left(v_{\rm rel} = \frac{s}{2E_1 E_2} \right)$$

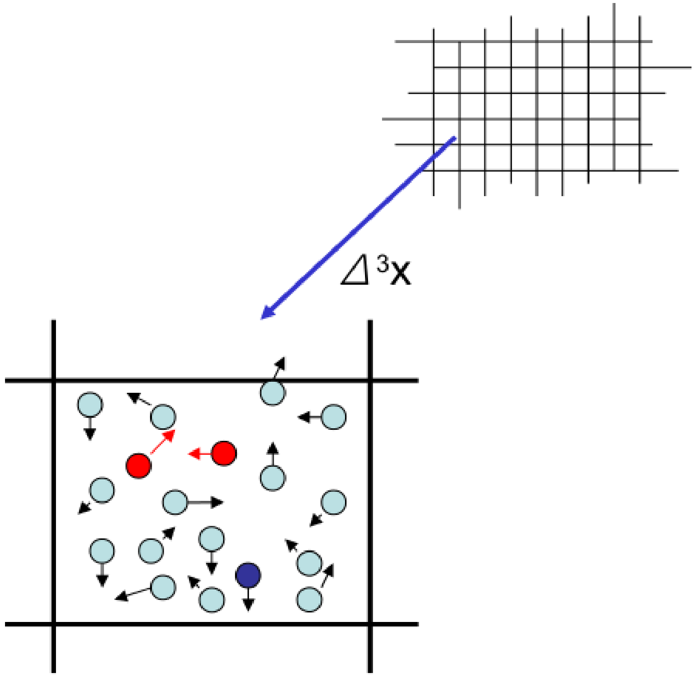
- generalisable to n-body collisions

Cross section: Stochastic interpretation

- discretize time and space

$$P_{2\to X} = v_{\mathrm{rel}}\sigma_{2\to X}\frac{\Delta t}{\Delta V}$$

$$P_{3\to X} = \frac{I_{3\to X}}{8E_1E_2E_3}\frac{\Delta t}{(\Delta V)^2}$$



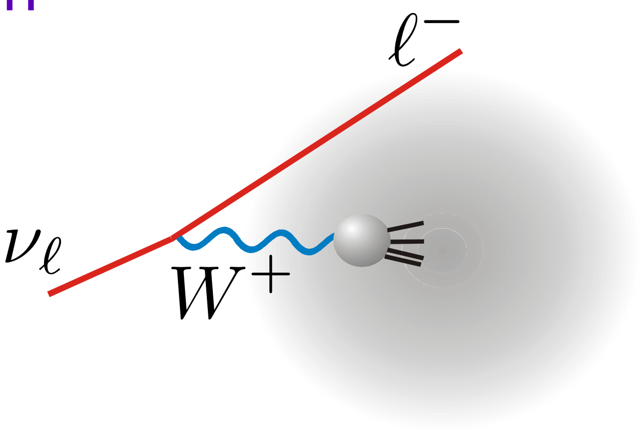
- together with 'full ensemble'
- n particles in cell, randomly select $n/2$ pairs

$$P_2 \to \frac{n(n-1)/2}{n/2}P_2$$

- calculational time: collisions scale approx. with N_{test}
- labeled as "local ensemble method"

Nuclear Reactions

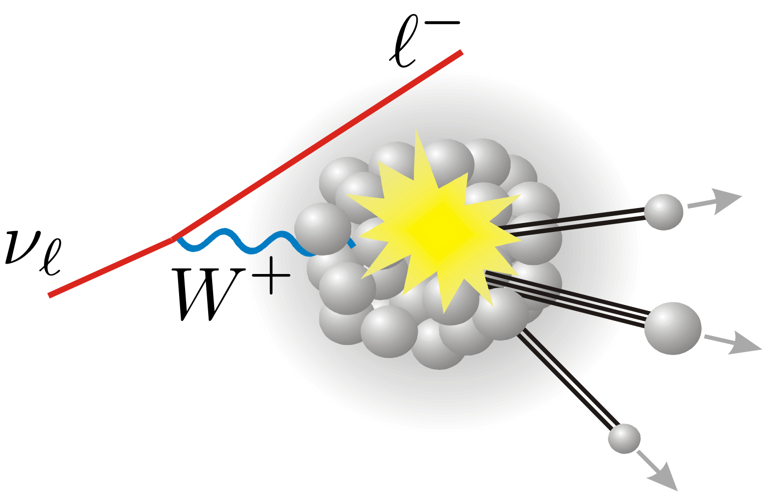
- elementary interaction on nucleon



additional:

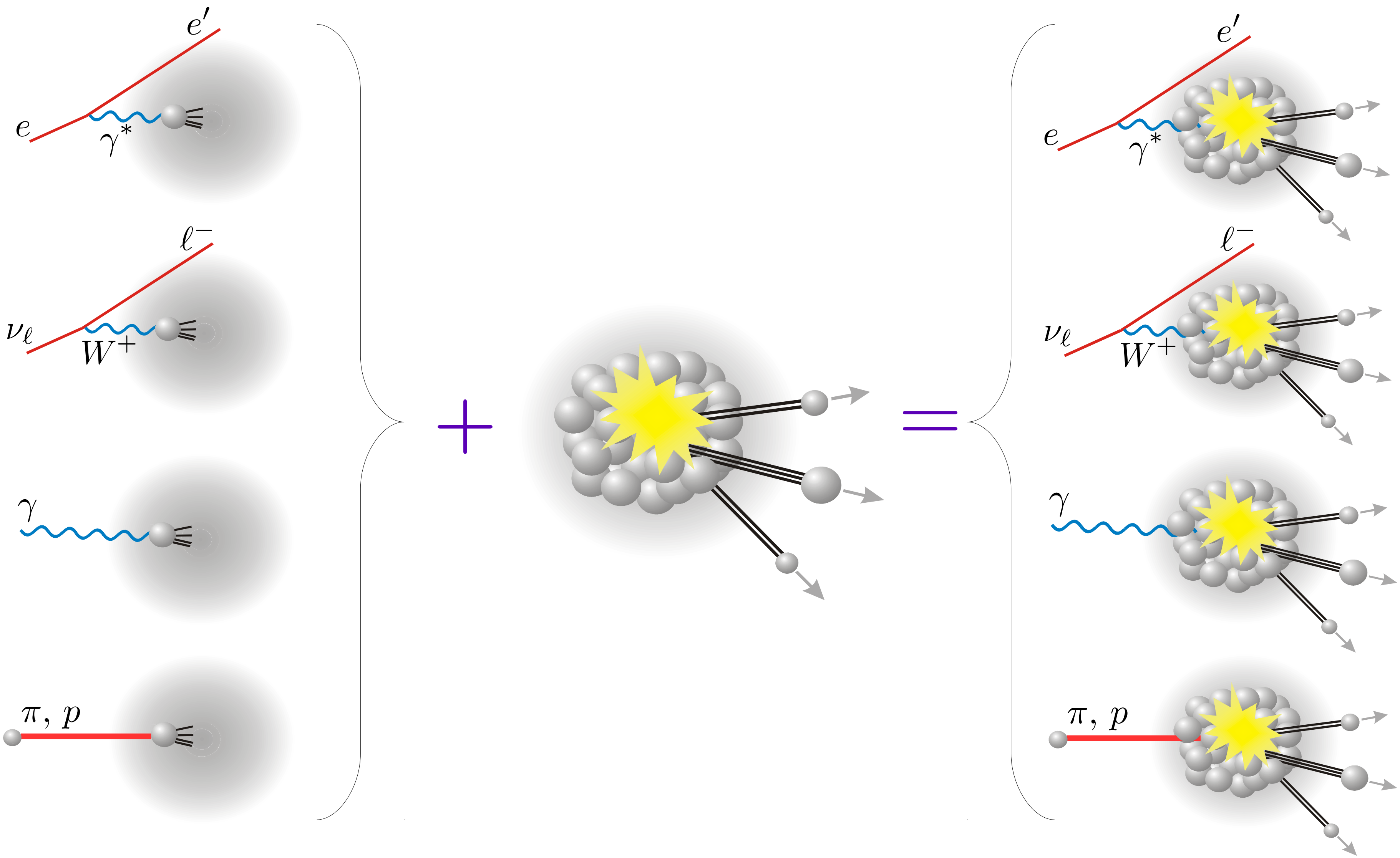
- binding energies
- Fermi motion
- Pauli blocking
- (coherence length effects)

- propagation of final state



- elastic/inelastic scatterings
- mean fields

GiBUU = plug-in system



init + FSI = full event

Nuclear ground state

- density distribution: Woods-Saxon (or harm. Oscillator)
- particle momenta: 'Local Thomas-Fermi approximation'

$$f_{(\mathrm{n,p})}(\vec{r},\vec{p}) = \Theta\left[p_{F(\mathrm{n,p})}(\vec{r}) - |\vec{p}|\right]$$

- Fermi-momentum:

$$p_{F(\mathrm{n,p})}(\vec{r}) = \left(3\pi^2\rho_{(\mathrm{n,p})}(\vec{r})\right)^{1/3}$$

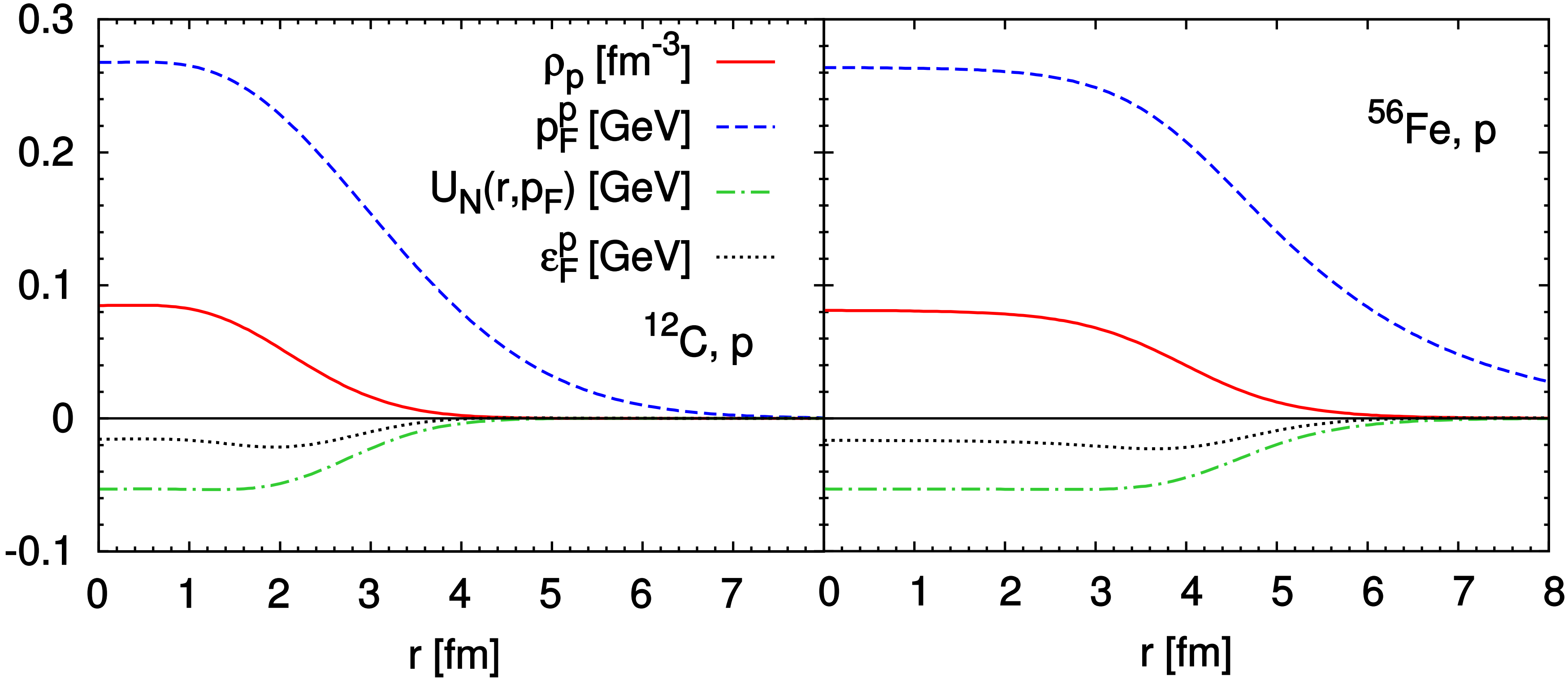
- Fermi-energy:

$$E_{F(\mathrm{n,p})} = \sqrt{p^2_{F(\mathrm{n,p})} + m_N^2} + U_{(\mathrm{n,p})}(\vec{r}, p_F)$$

potential: see above

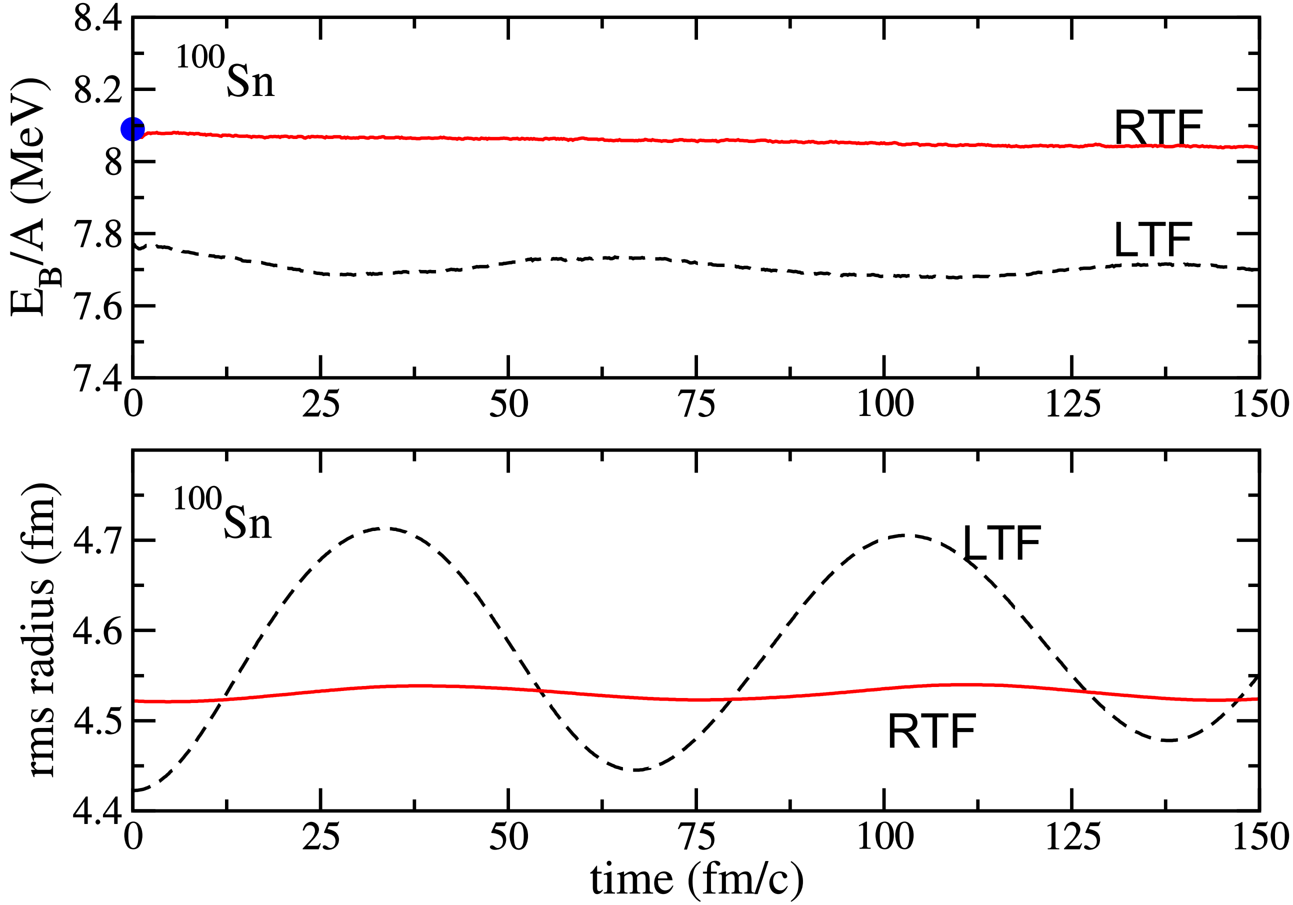
Nuclear ground state

- protons



Nuclear ground state

- time evolution



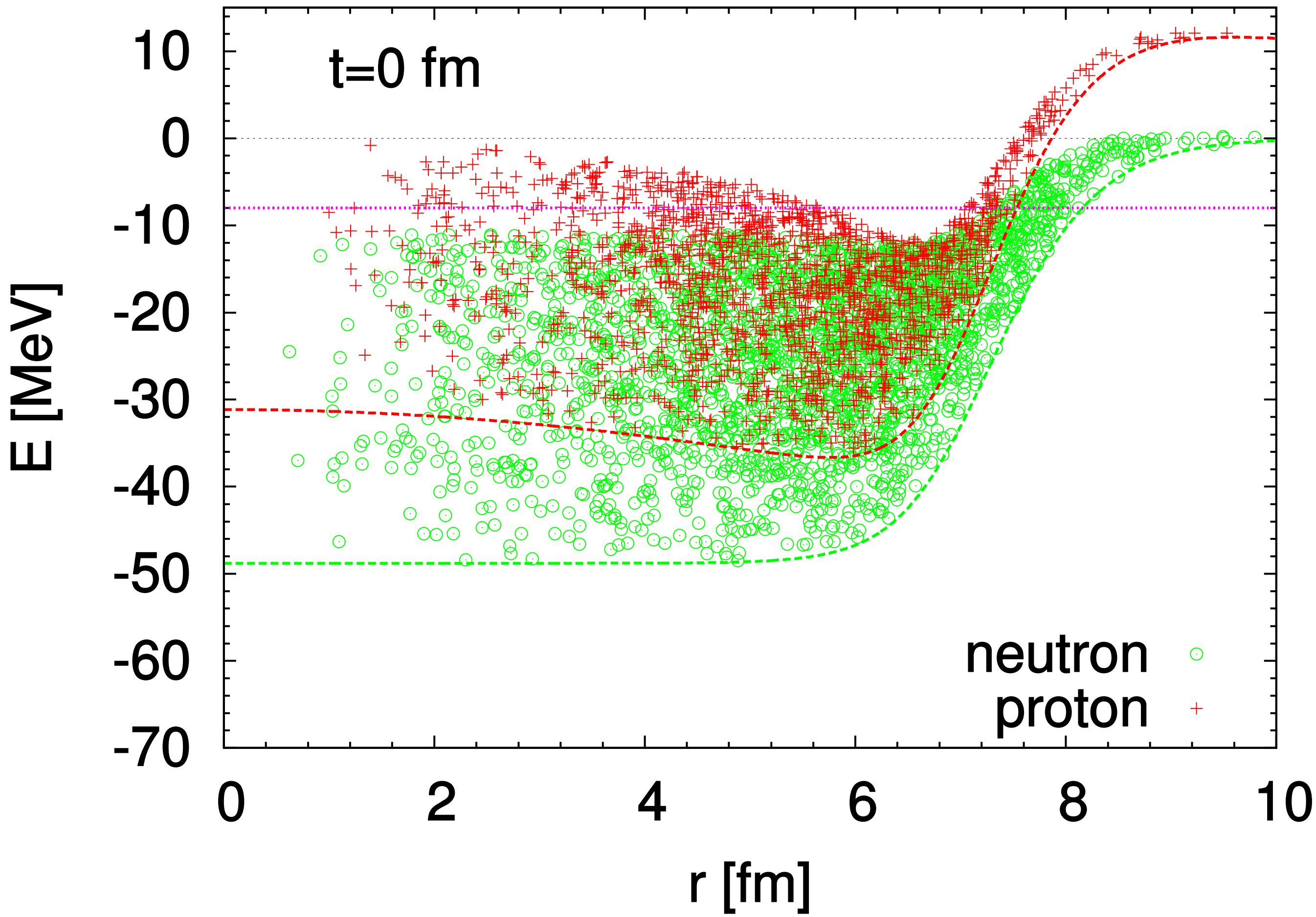
LTF: ‘Local Thomas-Fermi’: oscillating nuclei

RTF: ‘Relativistic Thomas-Fermi’, improvement

Nuclear ground state

- LTF: time evolution en detail

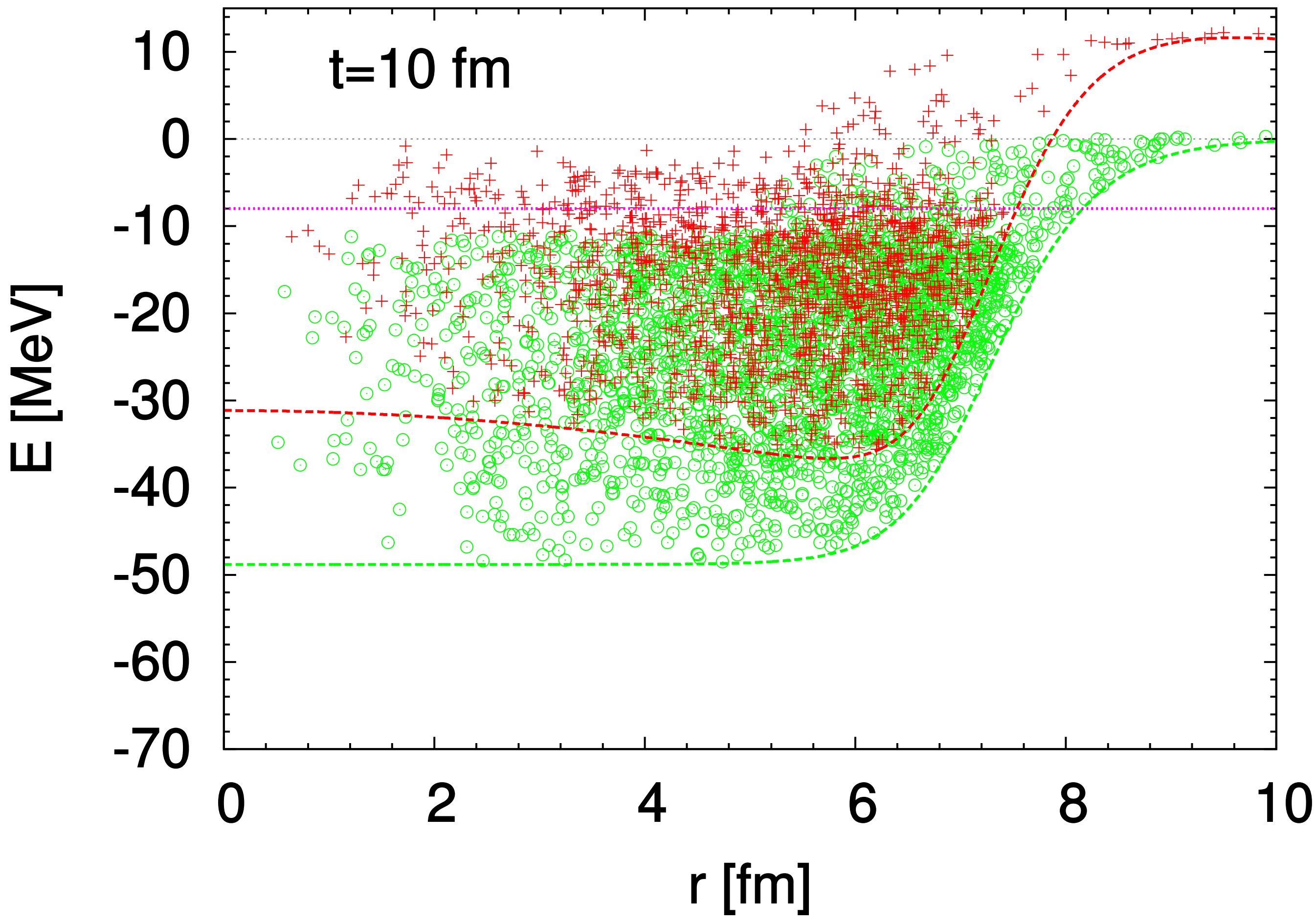
non-mom.dep potential, asymmetry-term, Coulomb



Nuclear ground state

- LTF: time evolution en detail

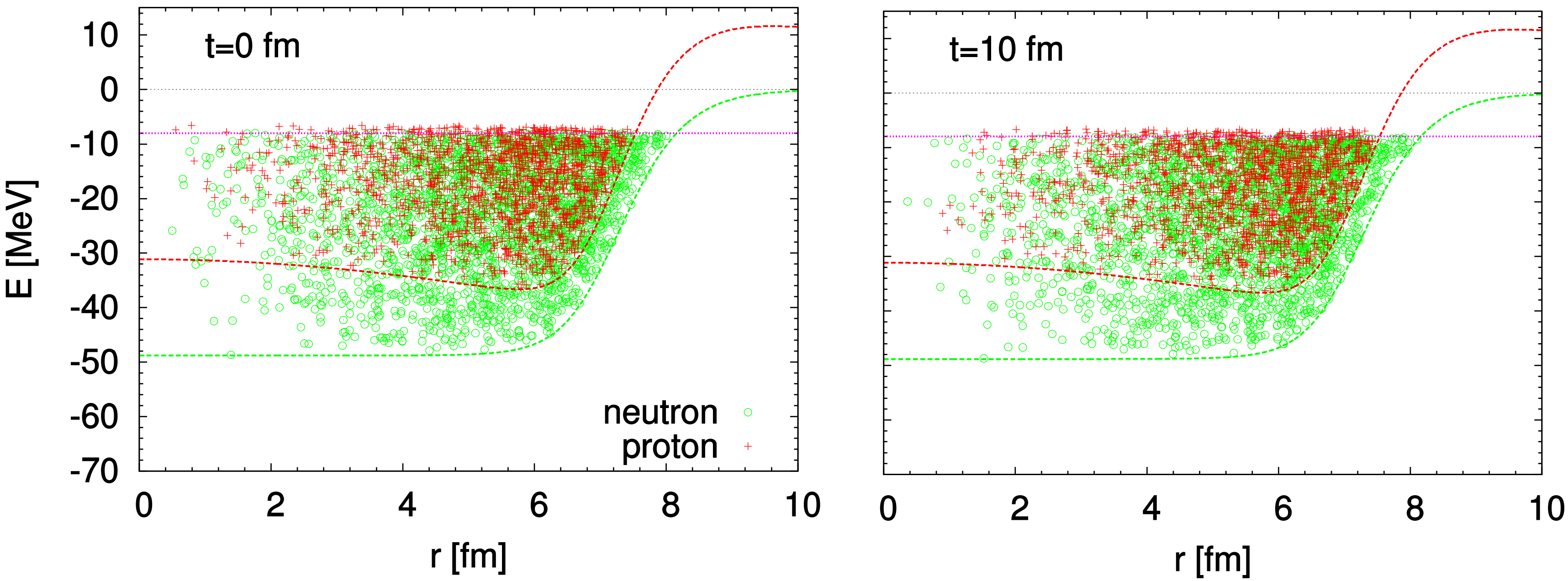
non-mom.dep potential, asymmetry-term, Coulomb



Nuclear ground state

- improvement: ensure constant Fermi-Energy

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



- needs iteration for mom.dep potential
- important for QE-peak (Gallmeister, Mosel, Weil, PRC94 (2016) 035502)

Init

- in principle:
  1) initialize nucleons
  2) perform **one** initial elementary event on **one** nucleon
  3) propagate nucleons and final state particles
- correct, but ‘waste of time’

- *idea:*
  final state particles do not really disturb the nucleus

- 2 particle classes:
  - ‘real particles’
  - ‘perturbative particles’

Particle classes

- ‘real particles’
  - nucleons
  - may interact among each other
  - interaction products are again ‘real particles’
- ‘perturbative particles’
  - final state particles of initial event
  - may only interact with ‘real particles’
  - interaction products are again ‘perturbative particles’
- ‘real particles’ behave as if other particles are not there
- total energy, total baryon number, etc. not conserved!

Init with perturbative particles

- init
  1) initialize nucleons
  2) perform **one** initial elementary event on **every** nucleon
  3) propagate nucleons and final state particles

  - final states particles are ‘perturbative particles’
  - different final states do not interfere

- every final state particle gets a ‘perturbative weight’:
  - value: cross section of initial event
  - is inherited in every FSI
  - *for final spectra the ‘perturbative weights’ have to be added, not only the particle numbers*

Init with perturbative particles

- *idea:*

  simple workaround against oscillating ground states:
  freeze nucleon testparticles

- since nucleons are real particles, their interactions among each other should not influence final state particles

- advantage: computational time
- disadvantage: ???

electron and neutrino induced

- Implemented processes on nucleon

QE		
resonance production	Δ, 30 higher resonances	
1-pion background	via MAID	
2-pion background	via MAID	only electron
VMD	Pythia	only electron, W>2GeV
DIS	Pythia	
2p2h		

electron and neutrino induced

- 2p2h (since 2016)
  - electrons

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

  - neutrinos

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

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

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

Some results

- photoproduction
- attenuation ratios at Hermes/EMC
- HARP
- neutrino induced

Photoproduction

- $\gamma A \to \pi X$
  - reduction of yield by FSI: factor 3
- $\gamma A \to \pi\pi X$
  - expectation: shift of σ strength to lower masses (chiral rest.)
  - experiment is explained by pion FSI alone

P.Mühlich, L.Alvarez-Ruso, O.Buss, U.Mosel, PLB 595(2004) 216

- $\gamma A \to \eta X$
  - $S_{11}(1535)$ T.Mertens et al., EPJA 38 (2008) 195
  - $\sigma_{\eta N} = 30 \ldots 10\,\mathrm{mb}$
- $\gamma A \to \phi X$
  - $\sigma_{\phi N} = 27\,\mathrm{mb}$

P.Mühlich, U.Mosel, NPA 765(2006) 188

- $\gamma A \to \omega X$
  - $\sigma_{\omega N} \simeq 50\,\mathrm{mb}$ M.Kotulla et al., PRL 100(2008) 192302

large!

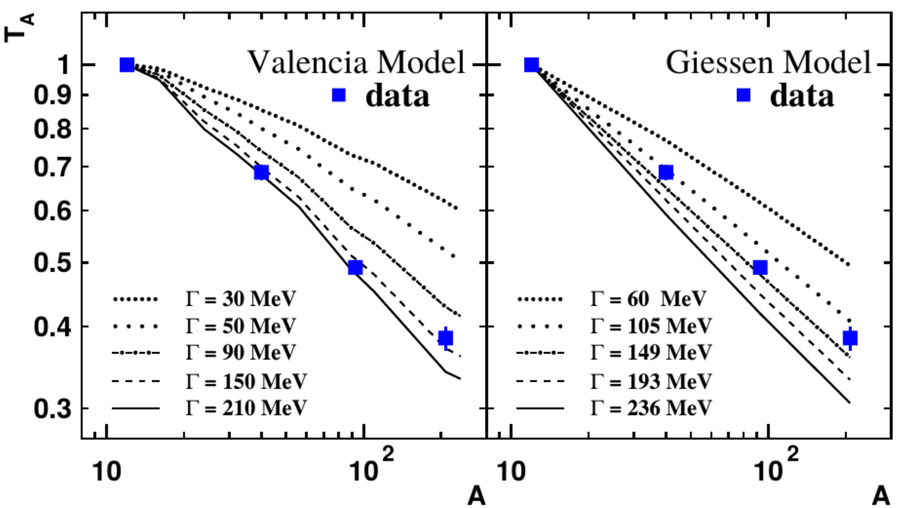
You have to know your FSI !

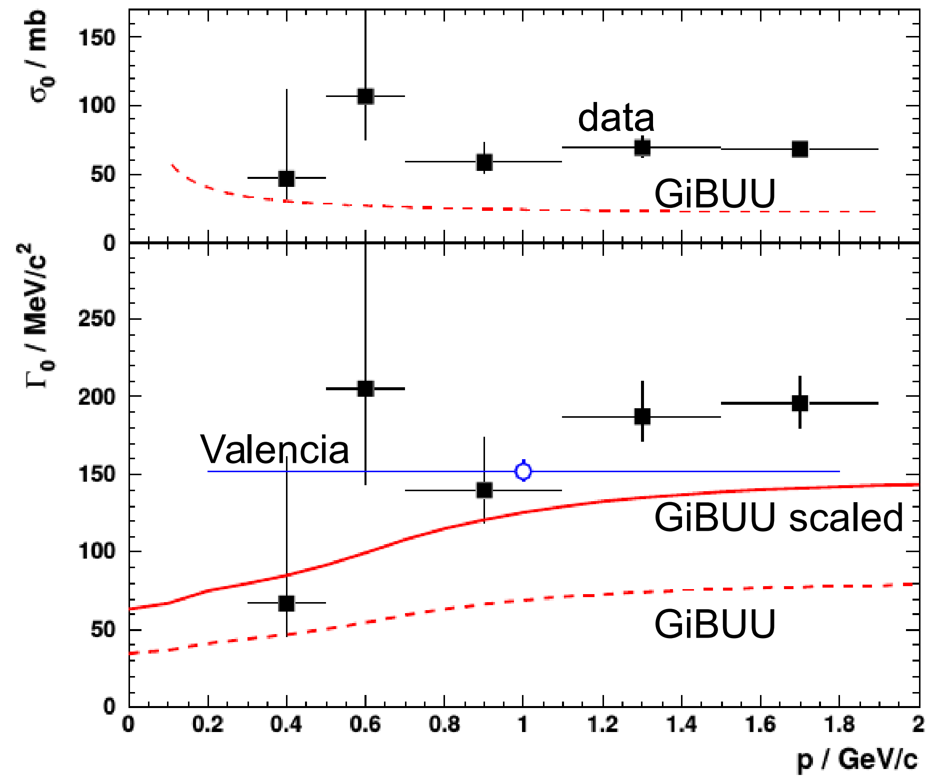
Photoproduction

- ω-Meson
  CBELSA/TAPS $E_\gamma = 0.64\text{-}2.53\,\mathrm{GeV}$

M.Kotulla et al., PRL 100(2008) 192302

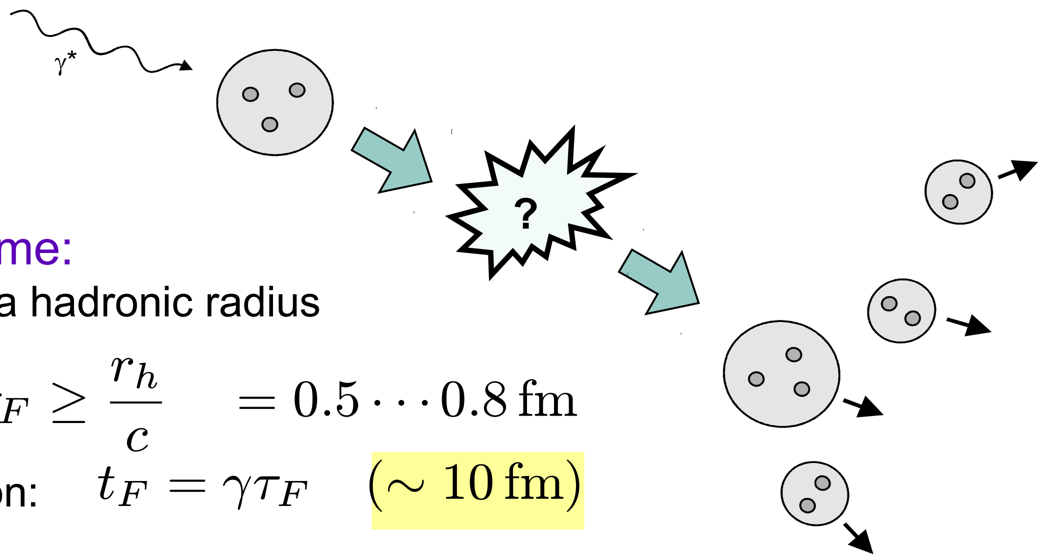
$$T_A = \frac{12 \cdot \sigma_{\gamma A \to V X}}{A \cdot \sigma_{\gamma C_{12} \to V X}}$$





Hadronization: Motivation

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



formation time:
estimation via hadronic radius

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

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

reaction products hadronize long before they reach the detector

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

interactions with nuclear medium during formation

→ space-time picture of hadronization

$$\sigma^* / \sigma_H \sim t^{0|1|2\cdots}$$

Observables, Experiments

- $$R^h(z_h,\dots) = \frac{\left.\frac{N_h(z_h,\dots)}{N_e(\dots)}\right|_A}{\left.\frac{N_h(z_h,\dots)}{N_e(\dots)}\right|_D}$$

- $$\Delta p_T^2 = \langle p_T^2\rangle_A - \langle p_T^2\rangle_D$$

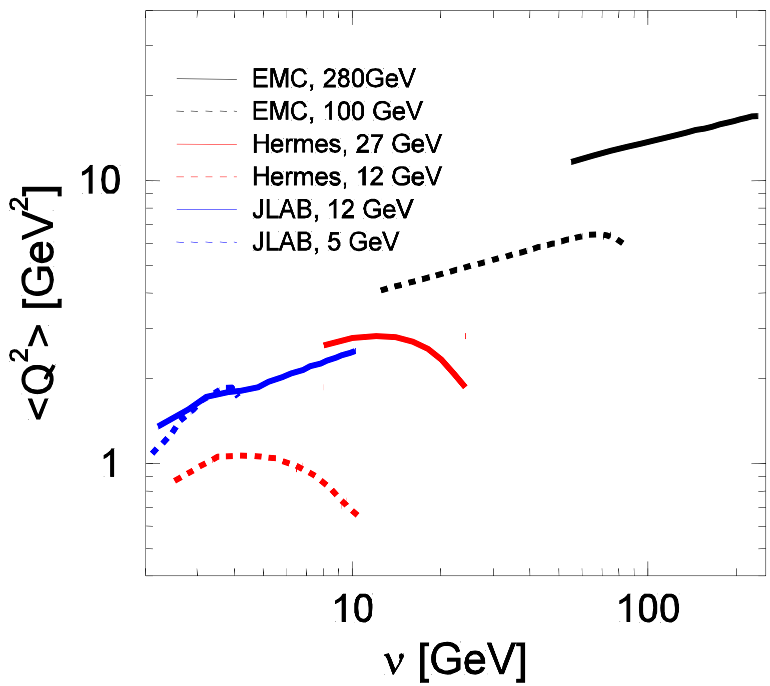
- hadronic: $z_h = \frac{E_h}{\nu}\ ,\quad p_T\ ,\cdots$

- photonic: $\nu\ ,\ Q^2\ ,\ W\ ,\ x_B\ ,\dots$

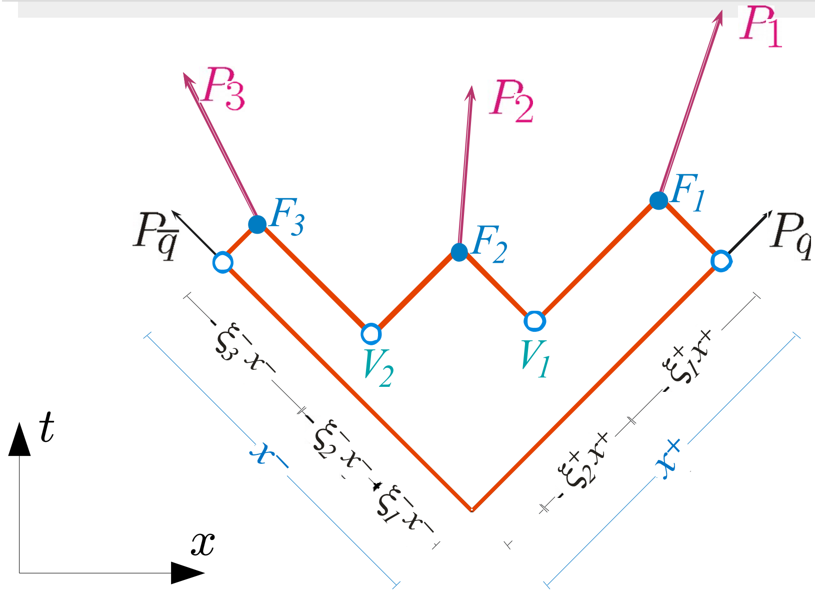
Experiments

	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)



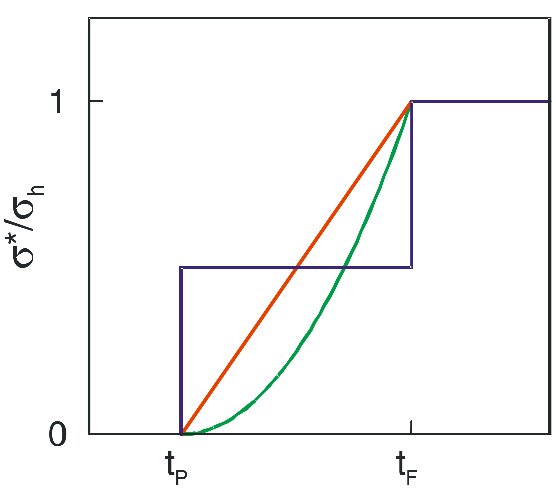
- 3 times/points per particle:
  - „Production 1" *String-Breaking*
  - „Production 2" *String-Breaking*
  - „Formation" *Line Meeting*

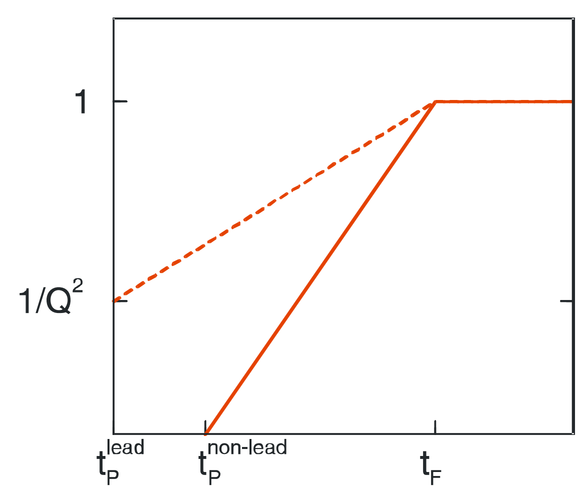
- Leading vs. Non-leading

  Connection to interaction vertex

CT

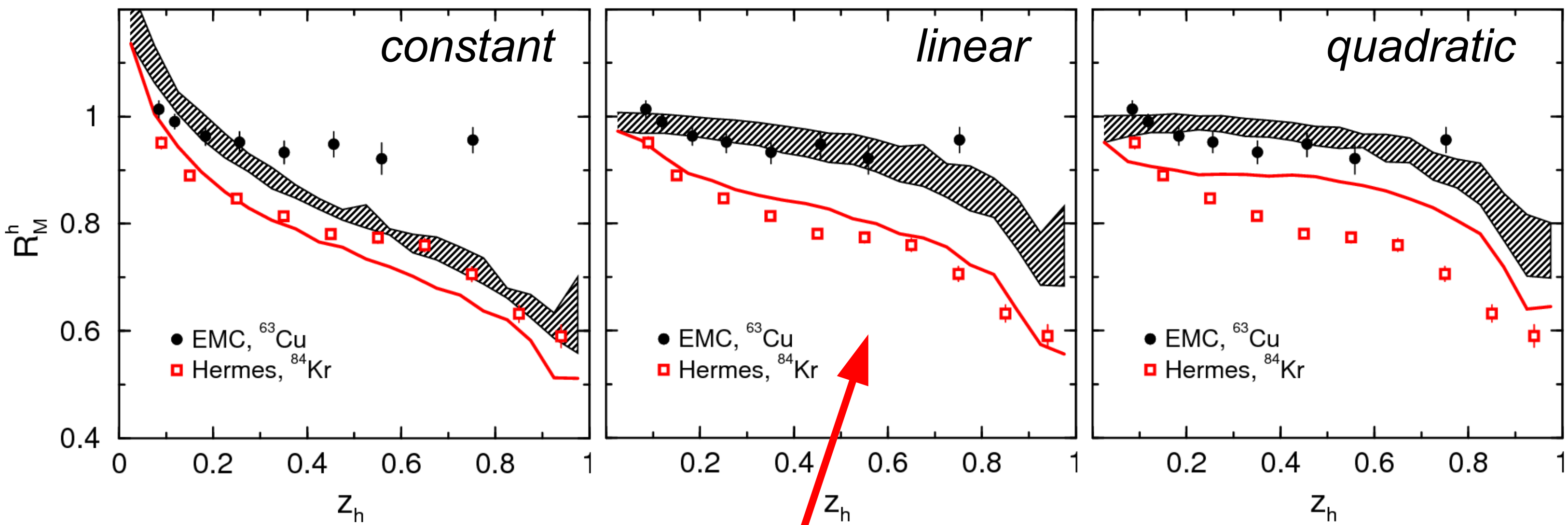
- cross section evolution scenarios:





EMC & Hermes

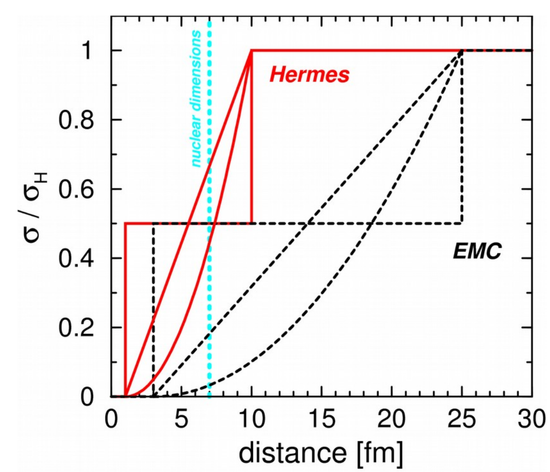
describe simultanously: • EMC@100...280 GeV • Hermes@27 GeV



pre-hadronic cross section:

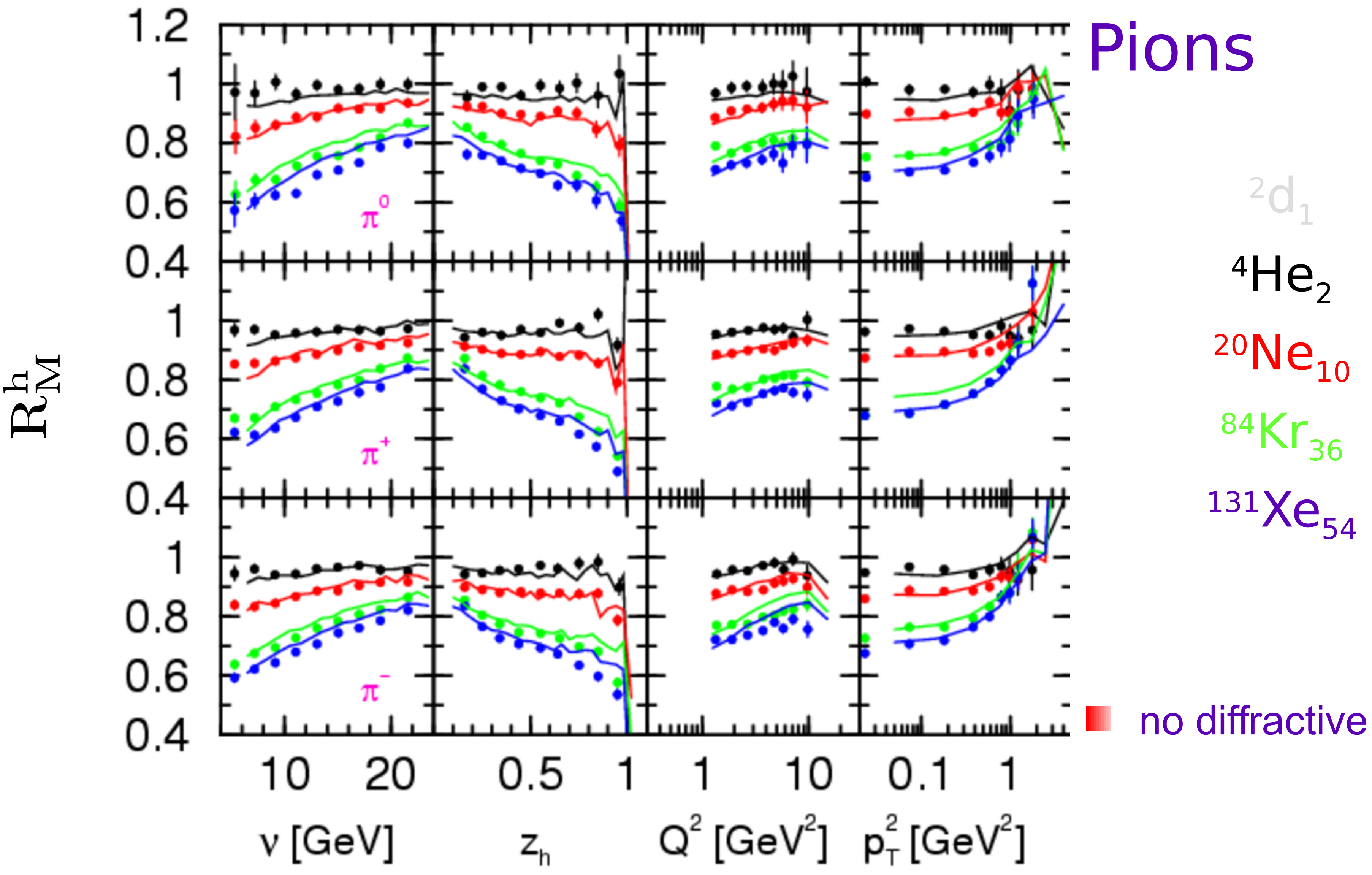
linear increase with time

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

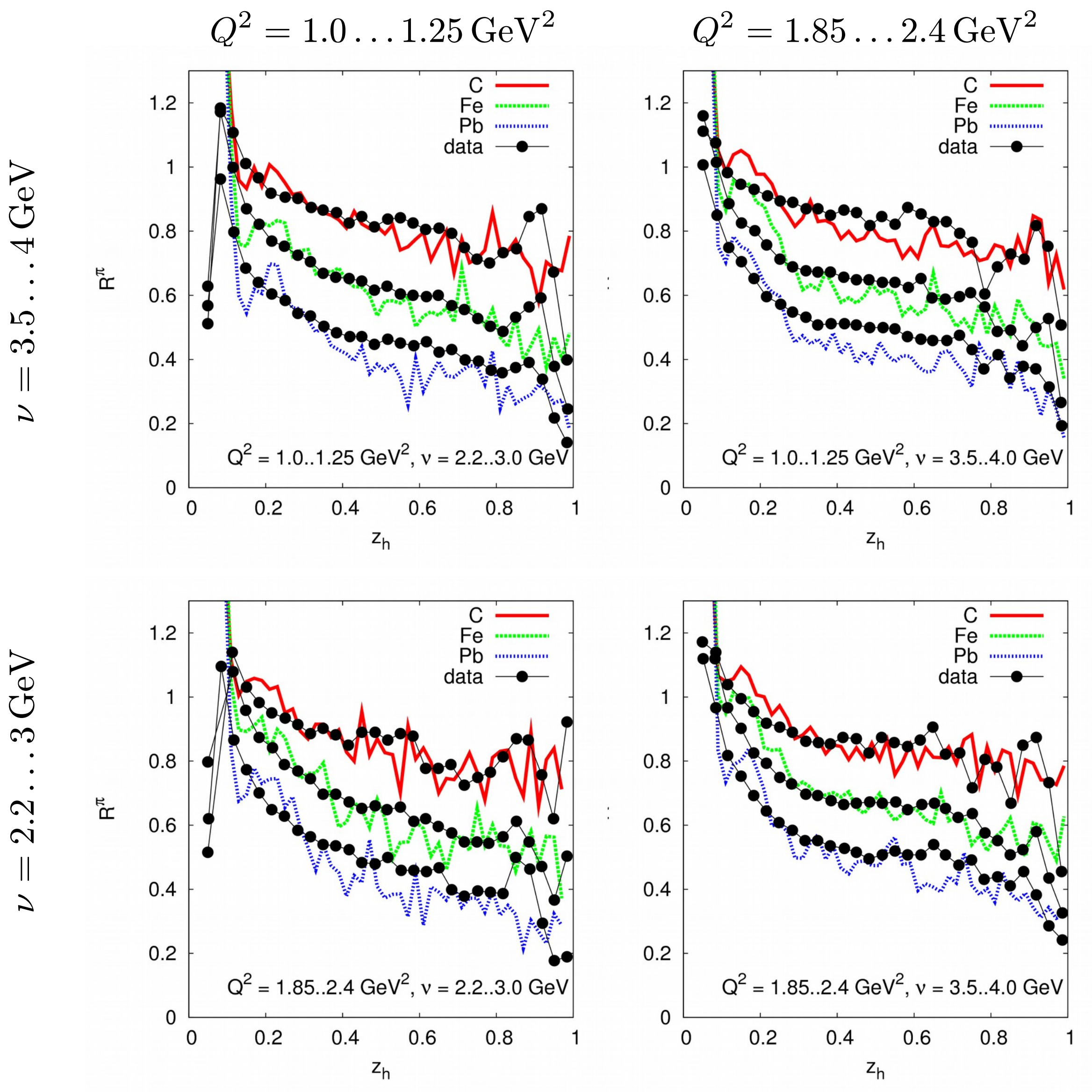


cf. also Dokshitzer et al.; Farrar et al.

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



CLAS@5, π^+ : selected (ν,Q^2) bins



Data:

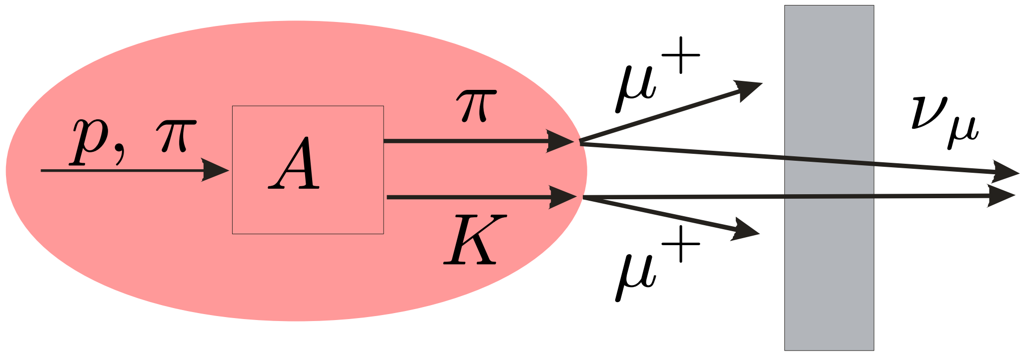
- CLAS preliminary
- no error bars shown

Calculations:

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

As good as at higher energies !

HARP, NA61/Shine



understand hadronic FSI

aim: adjust flux for …

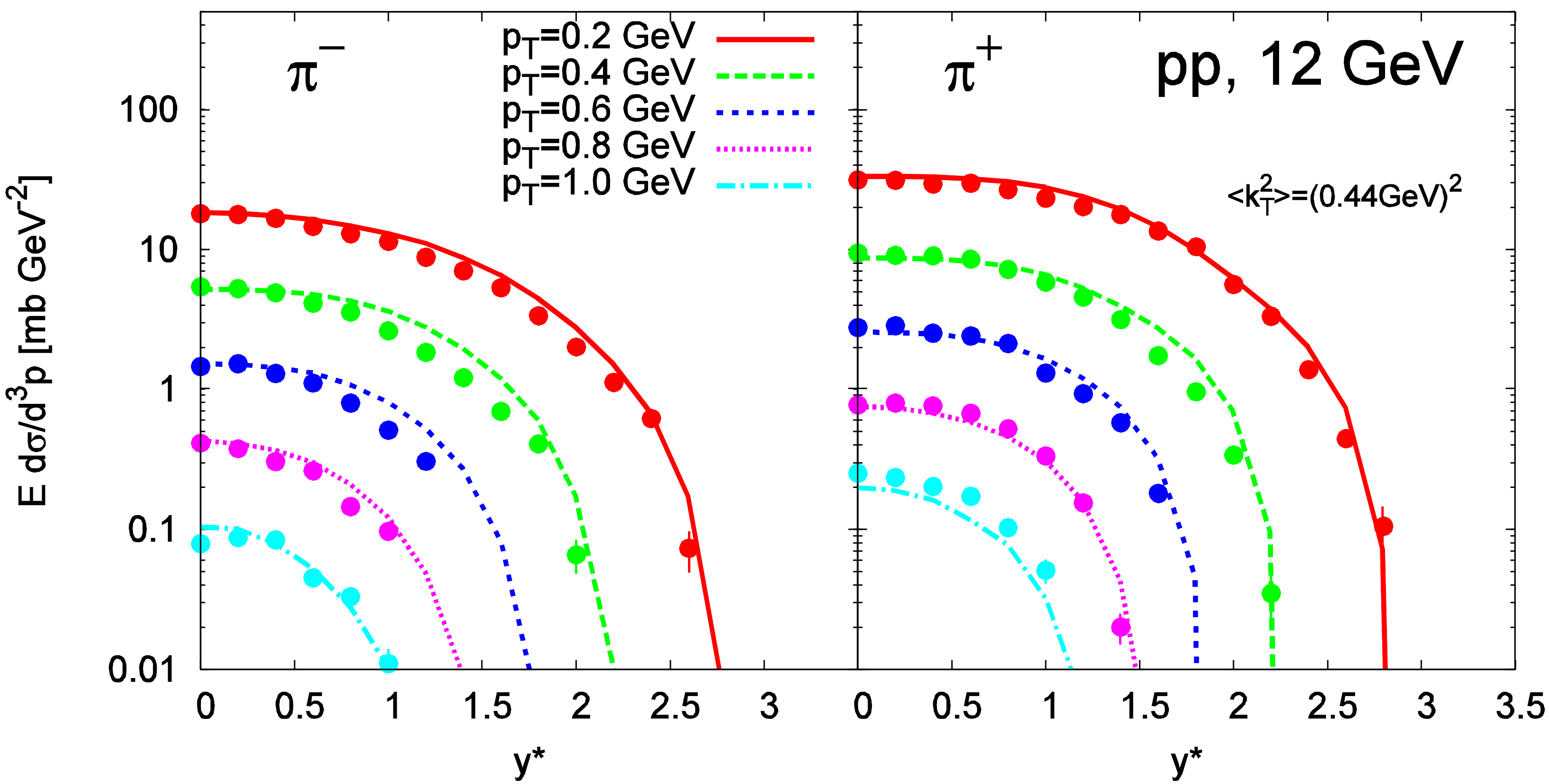
- MiniBooNE
- SciBooNE
- K2K

- proton, pion beam
- beam energies: 3 – 30 GeV/c

- critical test for hadronic fsi

elementary: $pp \rightarrow \pi^{\pm} X$

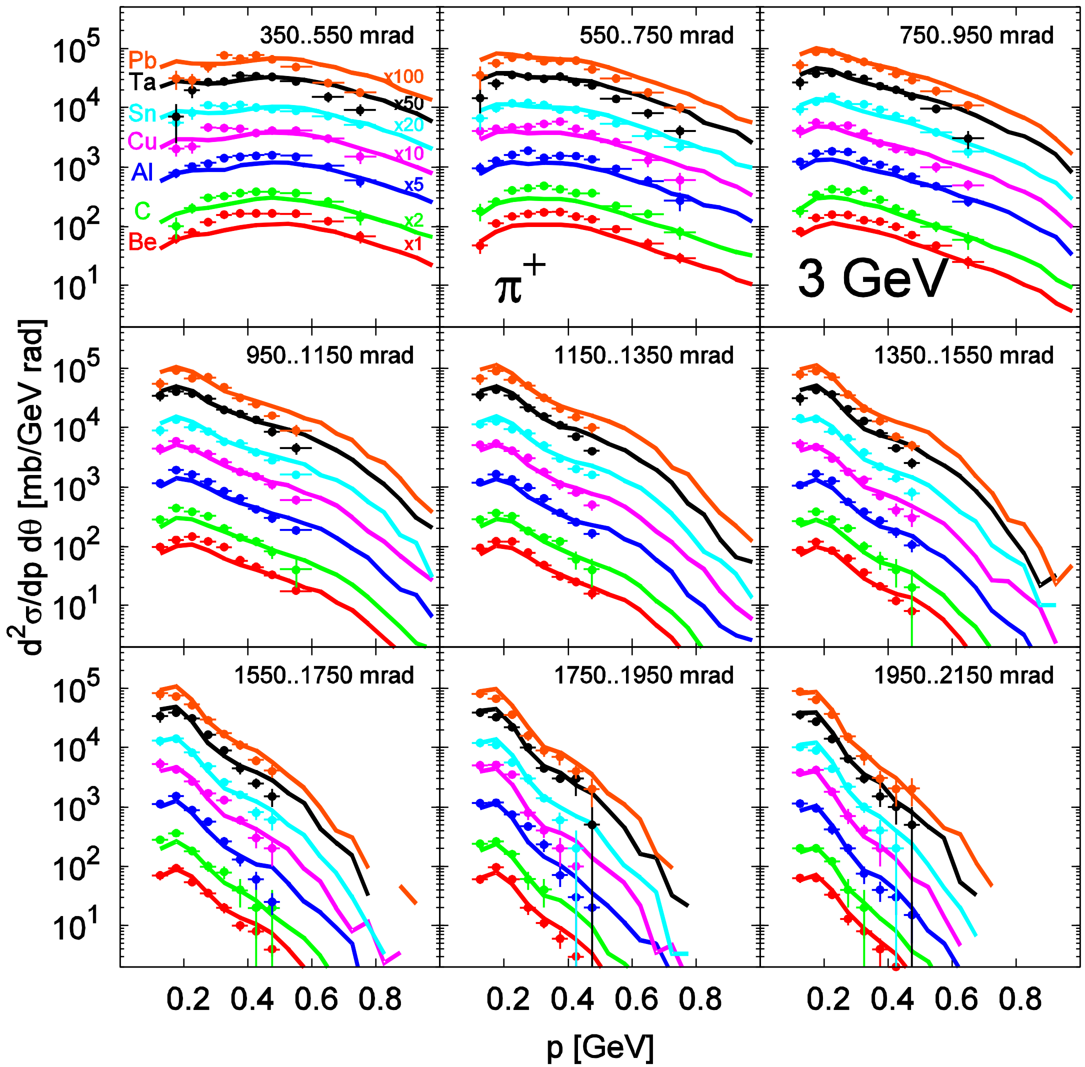
data: V. Blobel et al., Nucl. Phys. B69 (1974) 454



- Pythia v6.4 decribes elementary data very well

$pA \to \pi^+ X$ (backward, 3 GeV/c)

data: M.G. Catanesi et al. (HARP), Phys. Rev. C 77 (2008) 055207

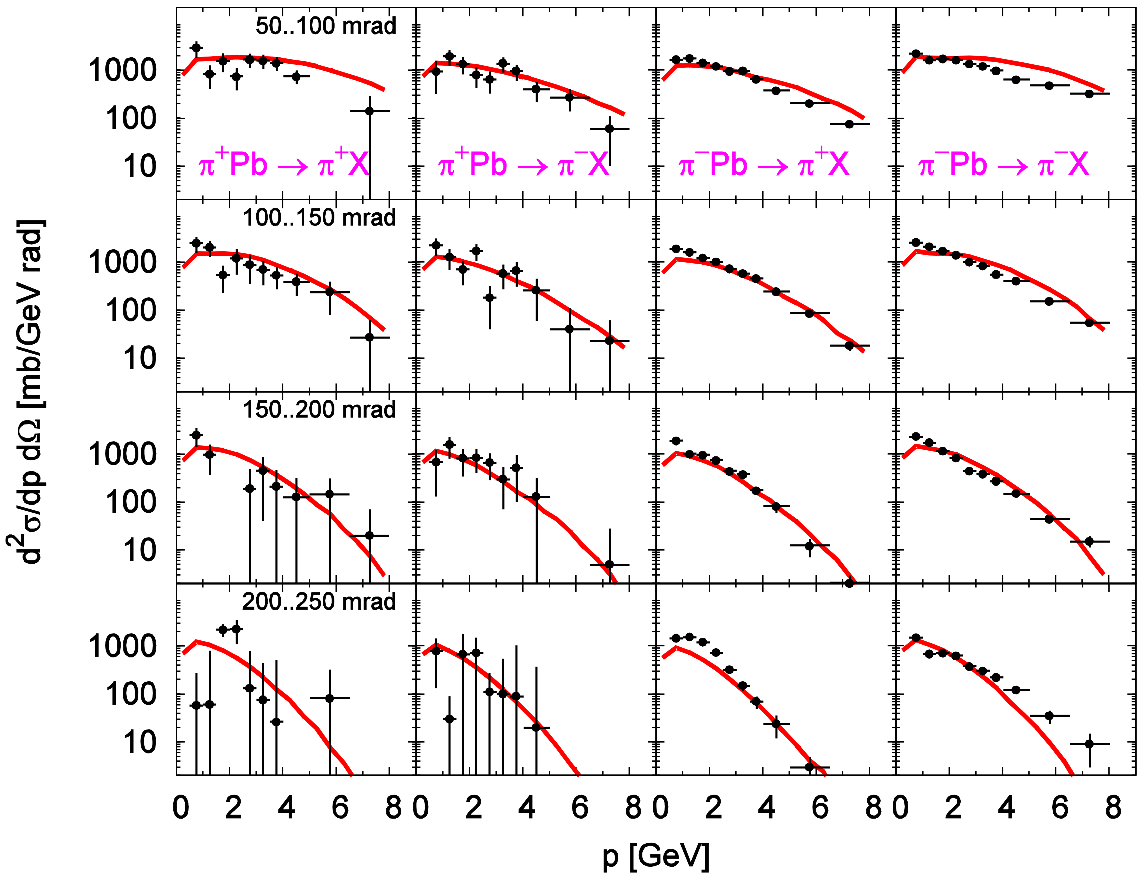


Note:

Official HARP vs. HARP-CDP

$\pi^\pm$ *Pb* $\rightarrow$ $\pi^\pm$ *X* (forward, 12 GeV/c)

data: M.G. Catanesi et al. (HARP), arXiv:0902.2105 [hep-ex]

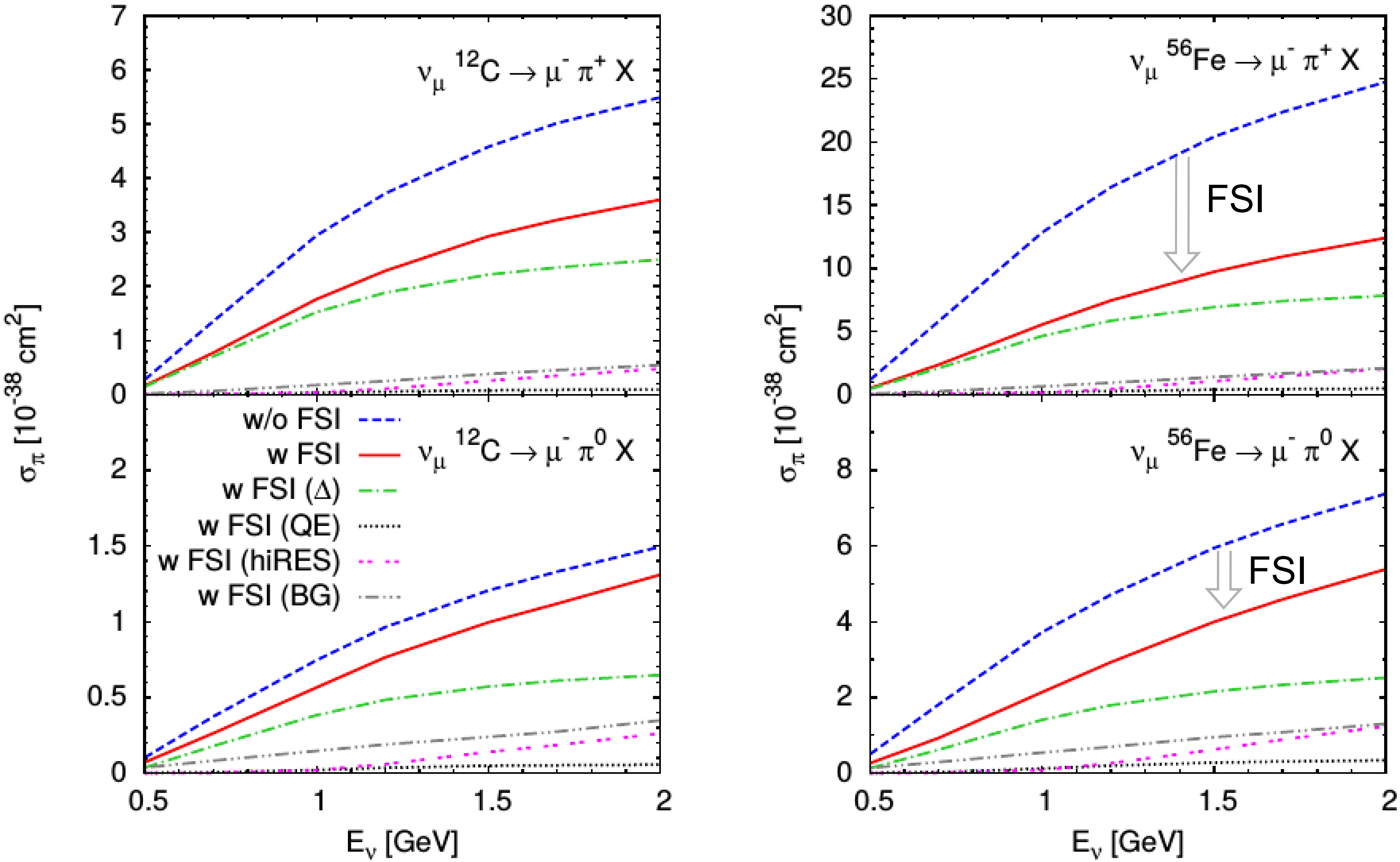


- forward production described very well
- pion beam slightly better described than proton beam

neutrino induced

- CC: π^+ and π^0 production

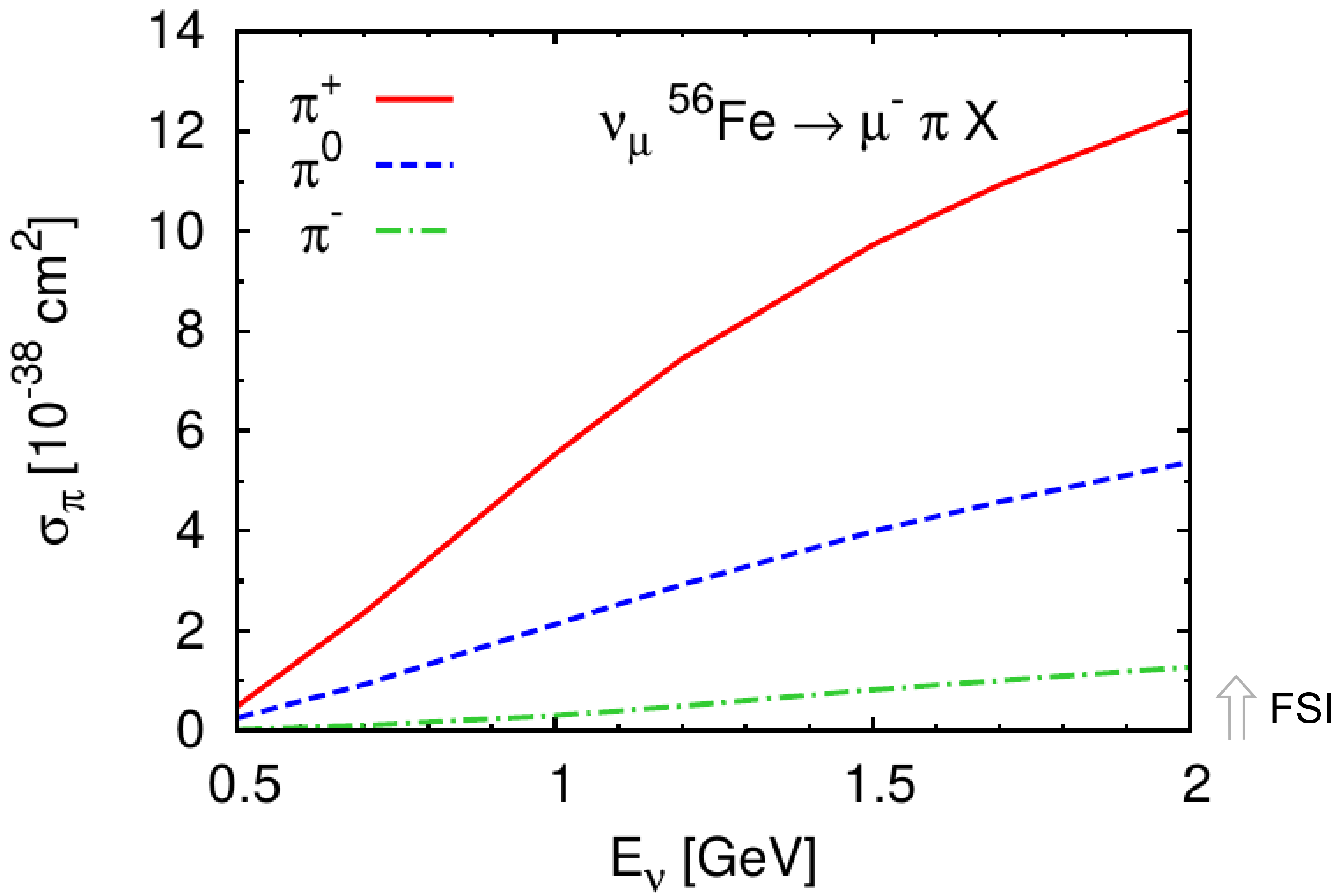
T.Leitner, PhD thesis, 2009



neutrino induced

- CC: π^- production: only via FSI

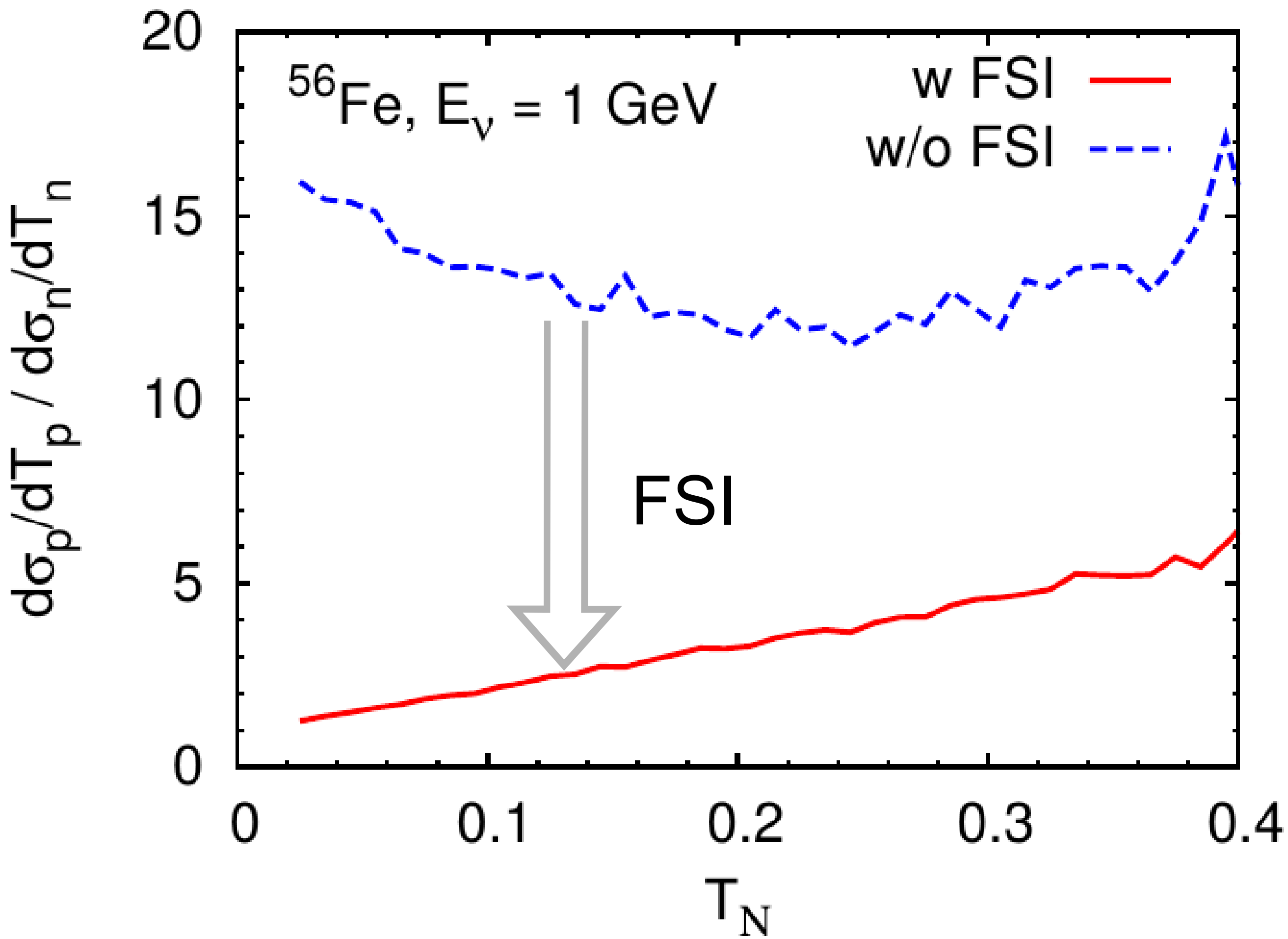
T.Leitner, PhD thesis, 2009



neutrino induced

- CC: single nucleon knockout

T.Leitner, PhD thesis, 2009



neutrons produced via side-feeding by charge exchange scattering

ratios not FSI save

Essential References

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

  contains both theory and practical implementation of transport theory

- KG, U.Mosel, J.Weil, Phys.Rev. C94 (2016) 035502

  contains the latest changes in GiBUU2016

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

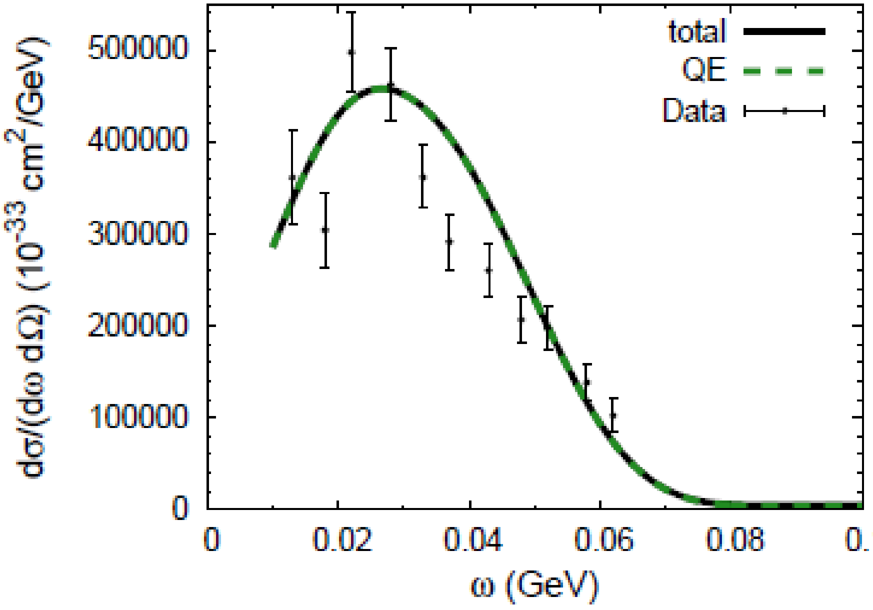
  review, contains some discussion of generators

- U.Mosel, KG, Phys.Rev. C96 (2017) 015503
  + arXiv:1708.04528

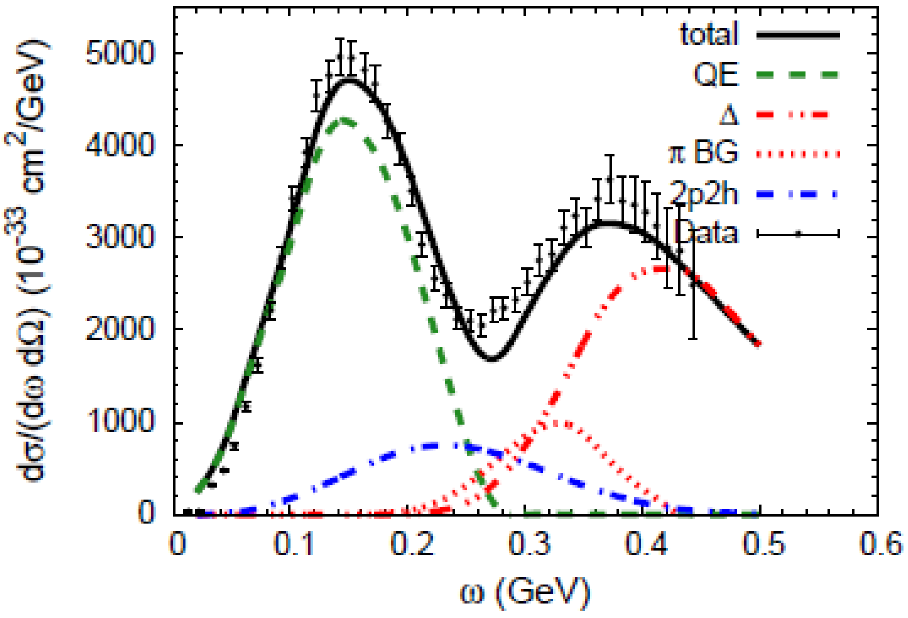
  pion production comparison of MiniBooNE, T2K and MINERvA

Test with electron Data: QE+Res

- a necessary test



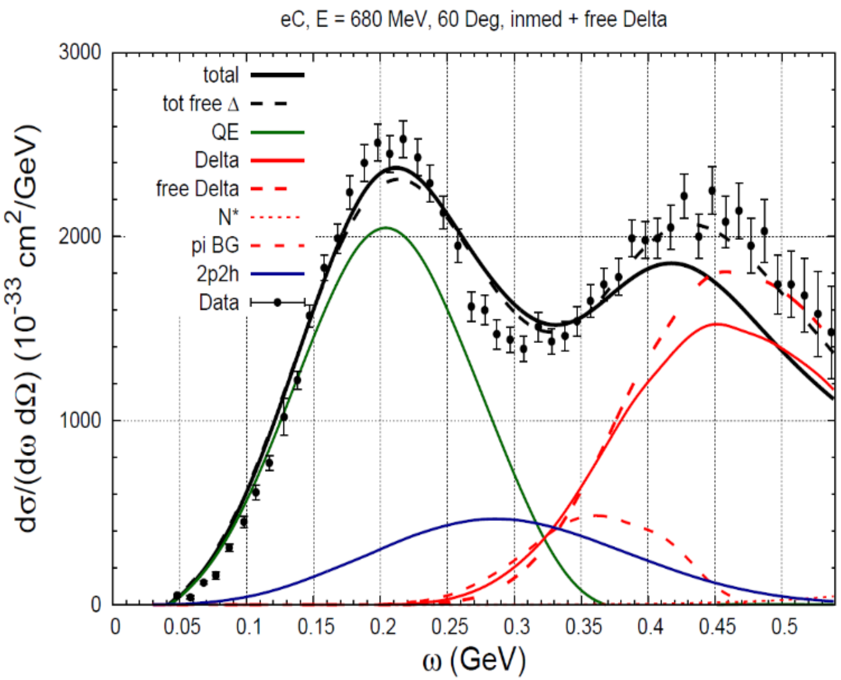
0.24 GeV, 36 deg, $Q^2 = 0.02$ GeV^2

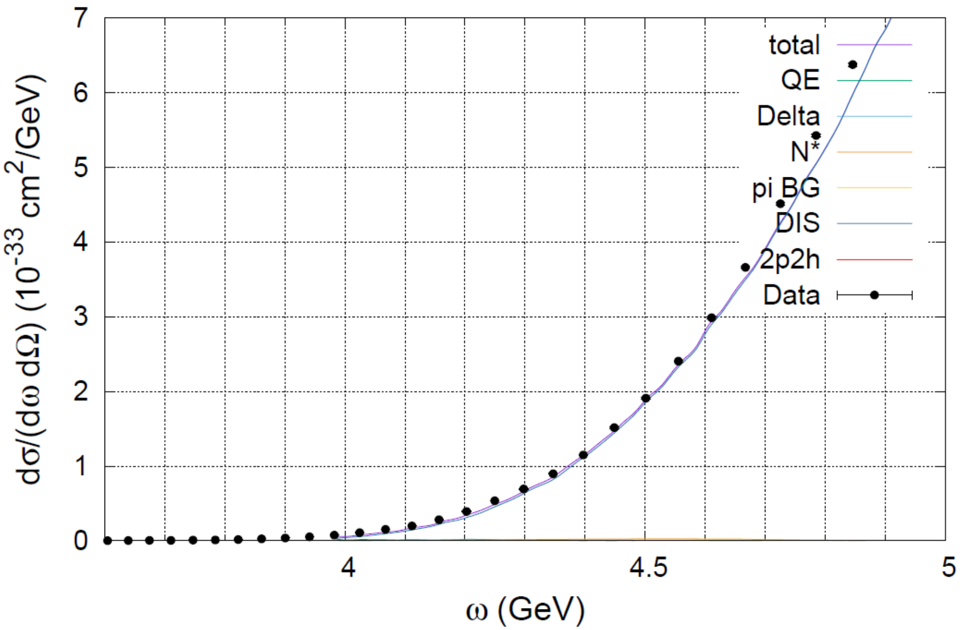


0.56 GeV, 60 deg, $Q^2 = 0.24$ GeV^2

Test with electron Data: QE+Res

- a necessary test



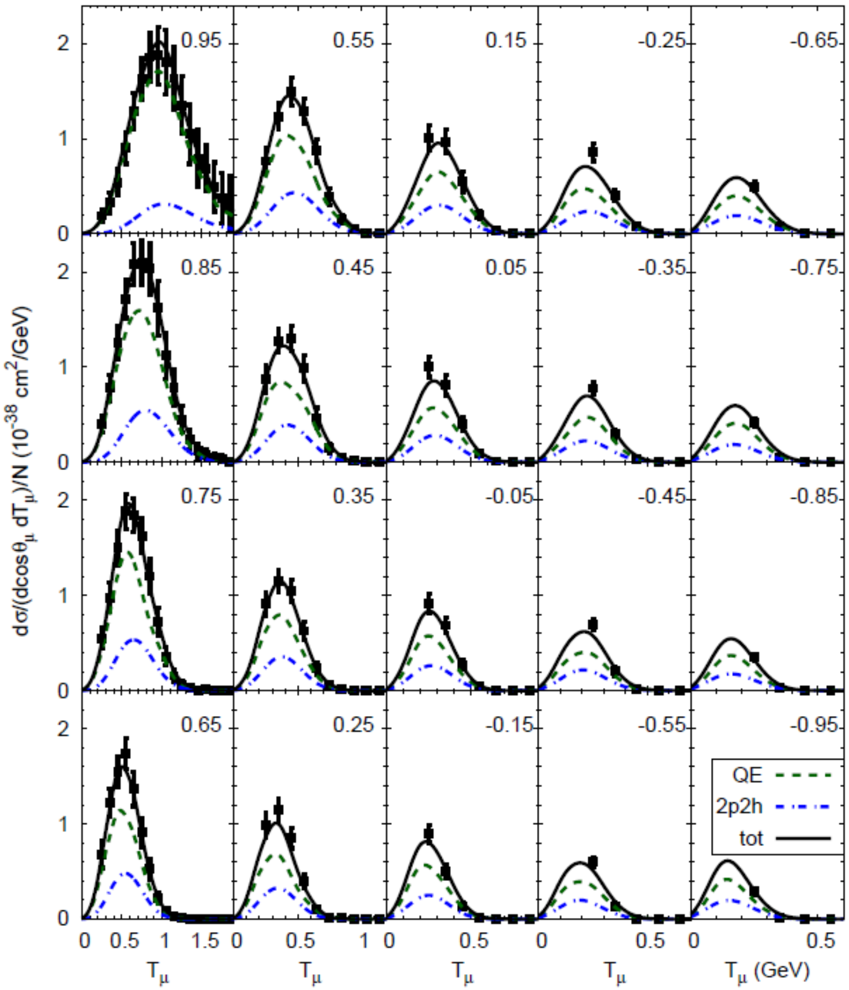


$Q^2 = 0.32\ GeV^2$

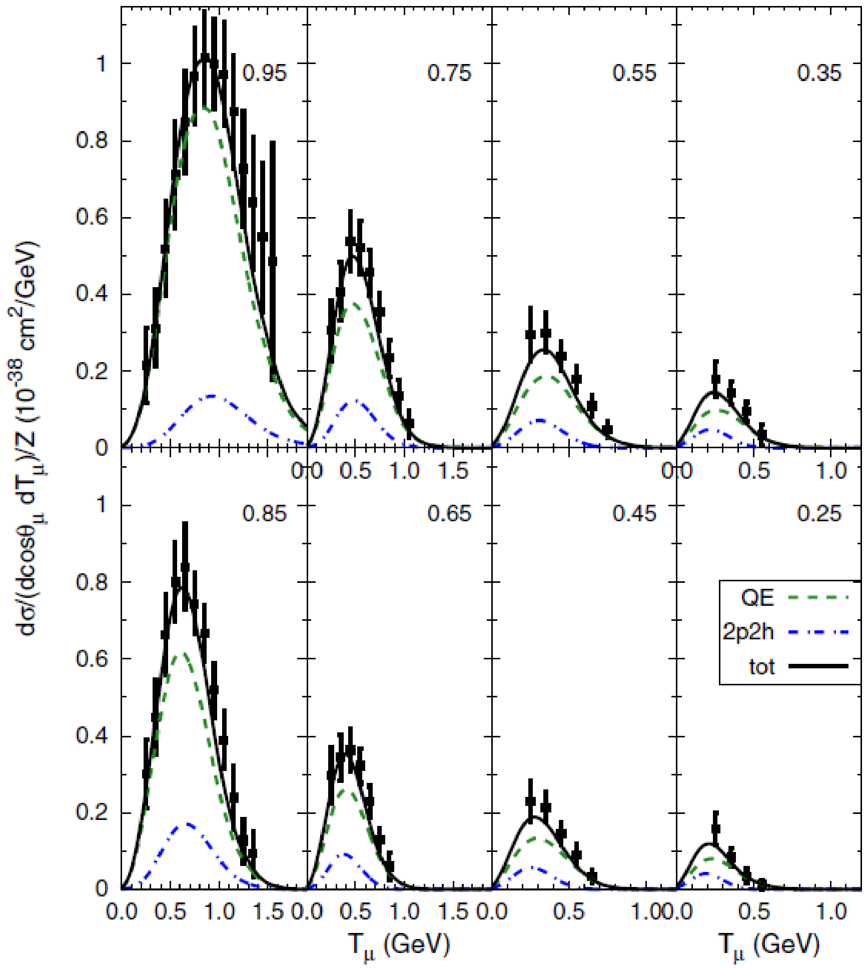
$E = 5.766$ GeV, 50 deg, $Q^2 = 7.3\ GeV^2$

MiniBooNE 0pion = QE + 2p2h

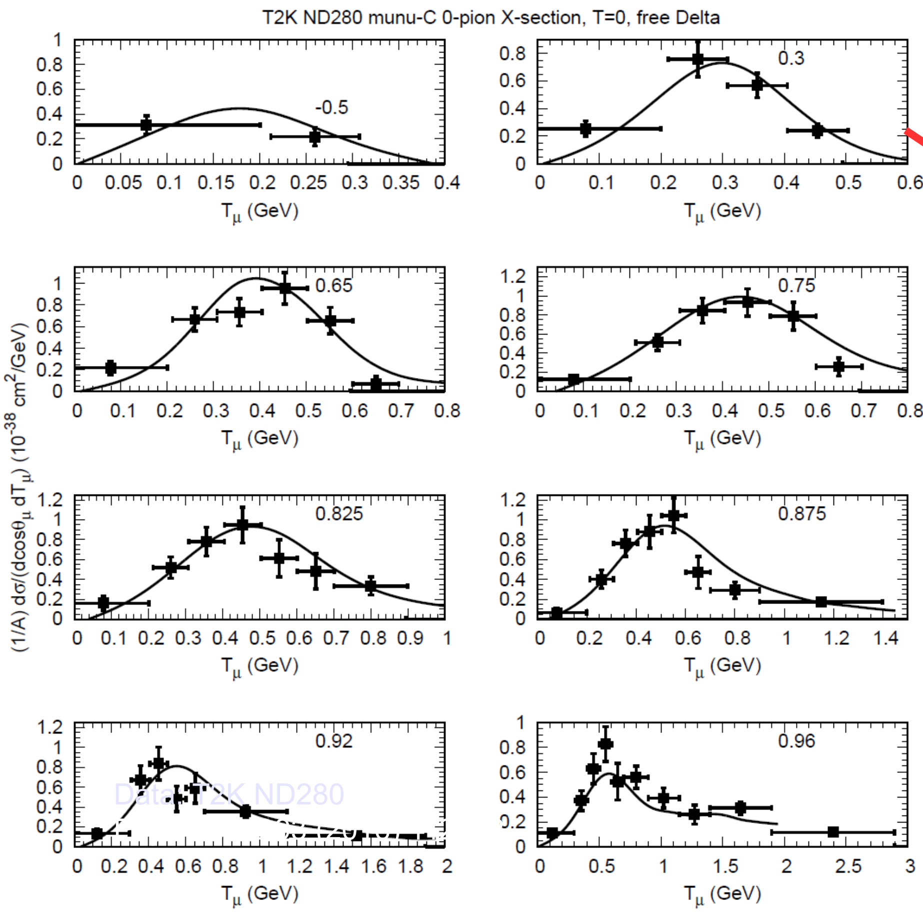
neutrinos

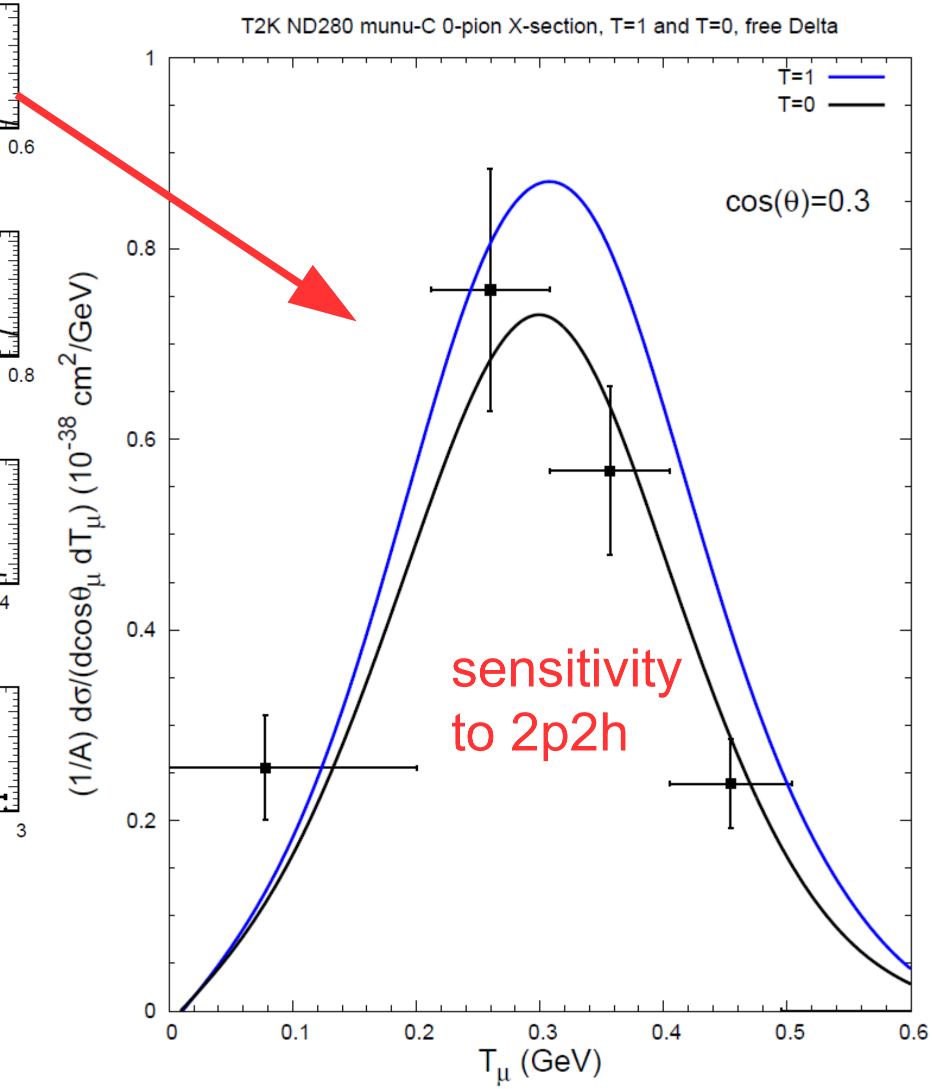


antineutrinos



T2K 0pion = QE + 2p2h + stuck pions



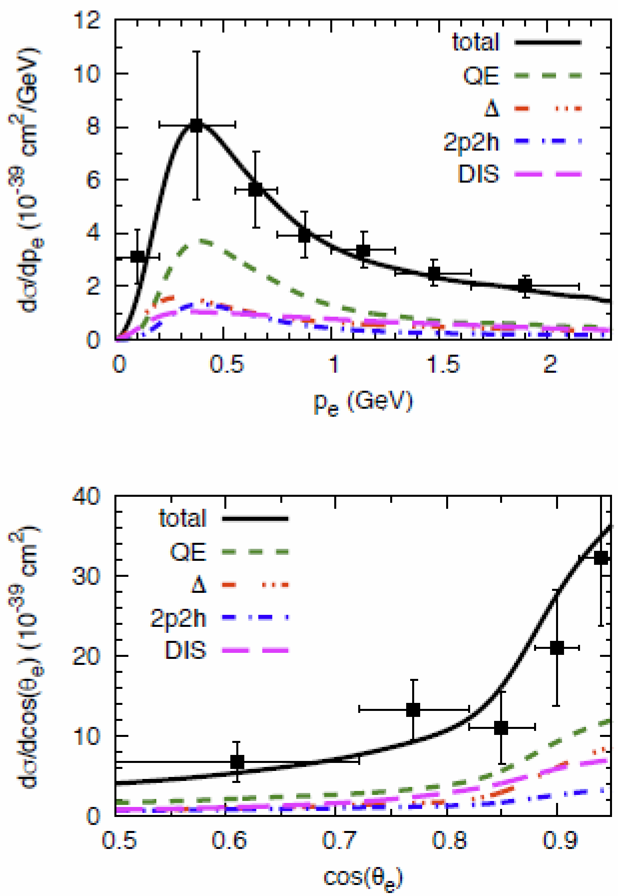


Data: T2K ND280
Phys.Rev. D93 (2016) 112012

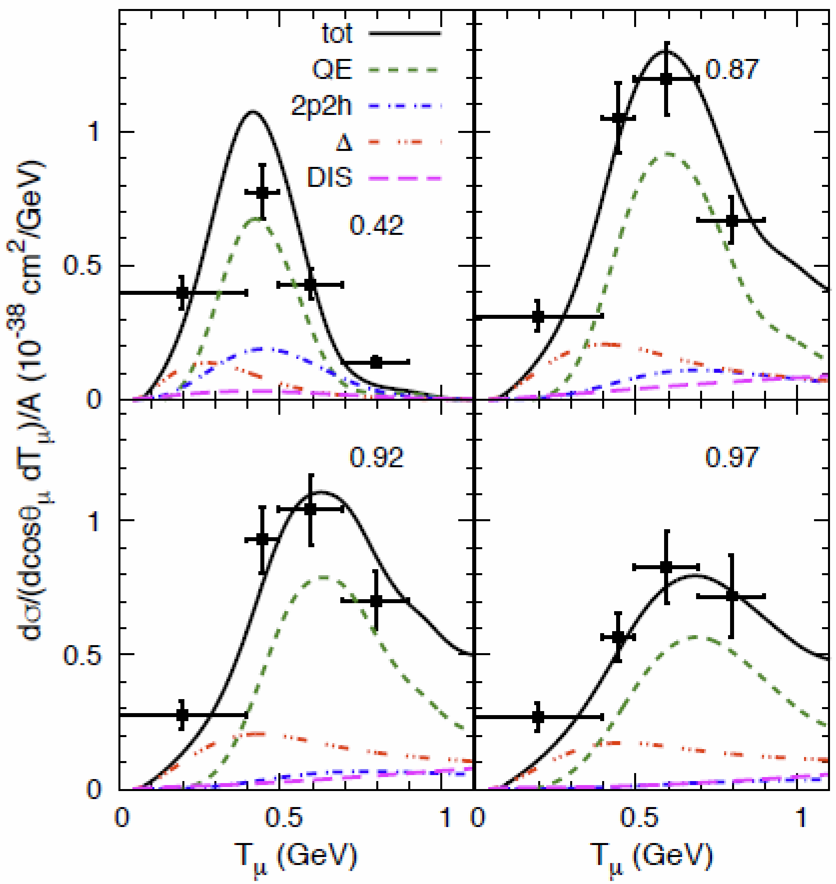
T2K incl. Data

- agreement for different neutrino flavors

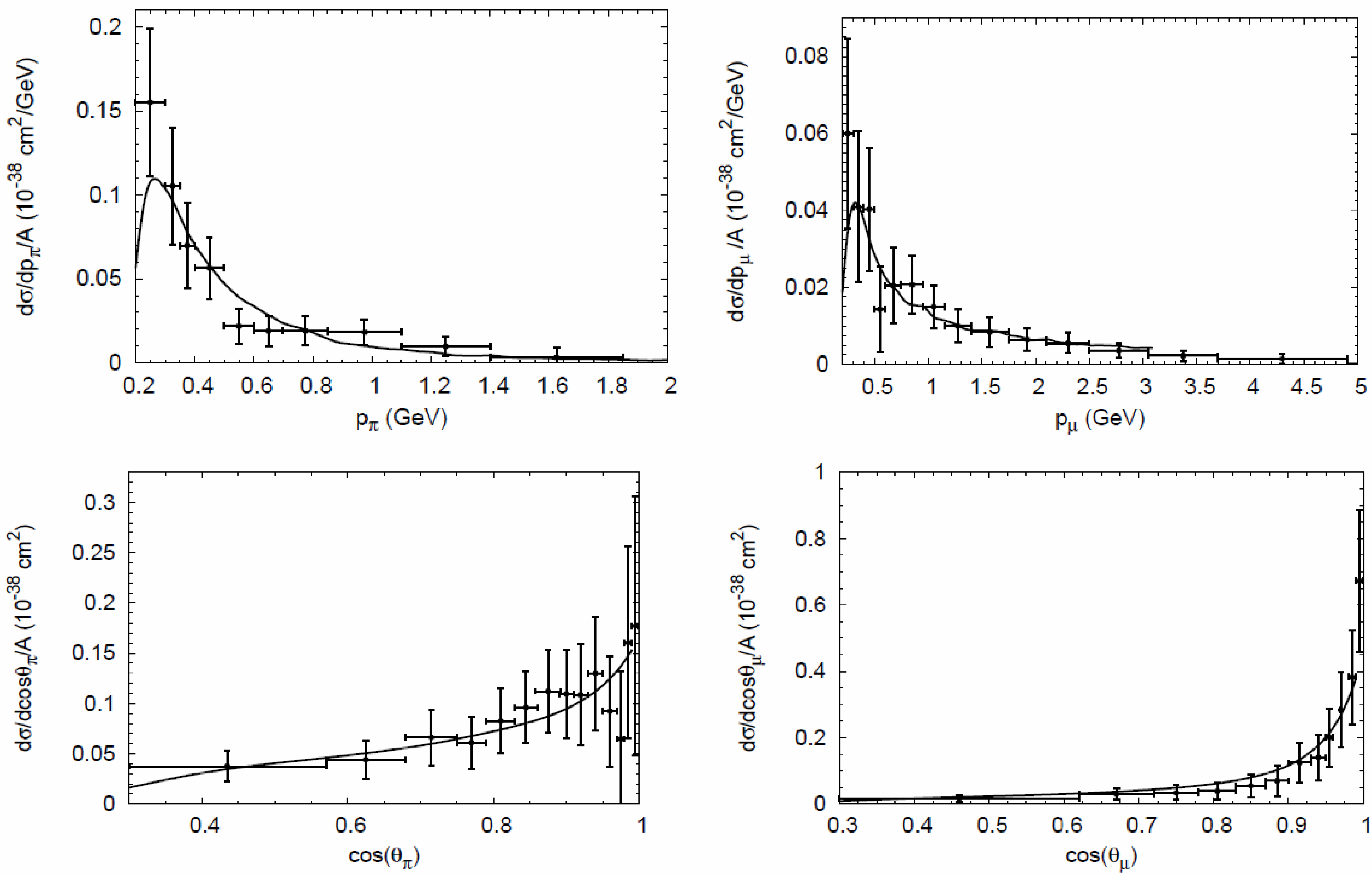
ν_e



ν_μ



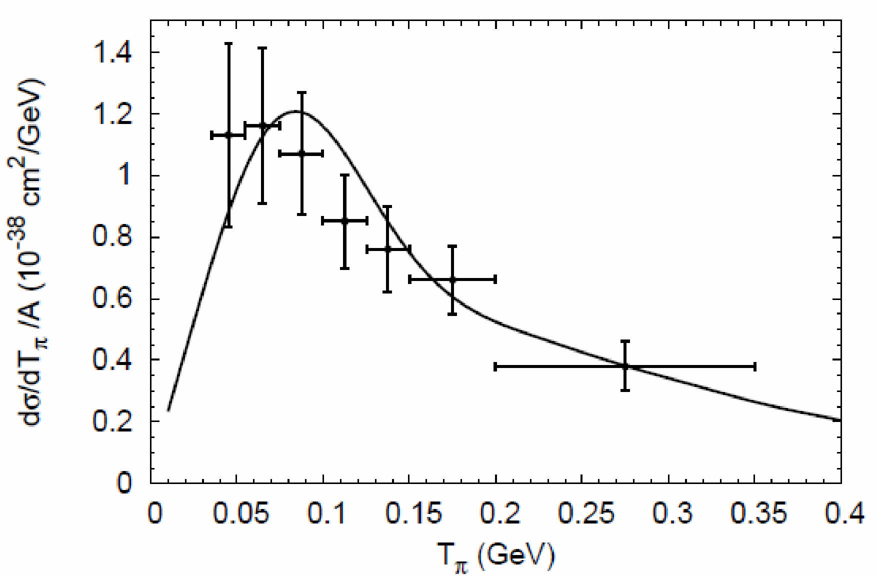
T2K ND280 pions on water



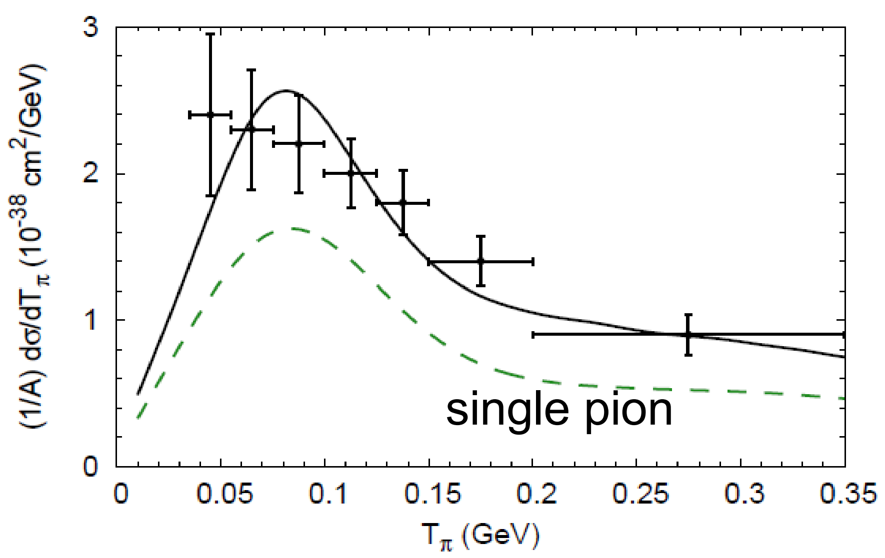
Data: T2K ND280
Phys.Rev. D95 (2017) 012010

MINERvA pions

- CC charged pions



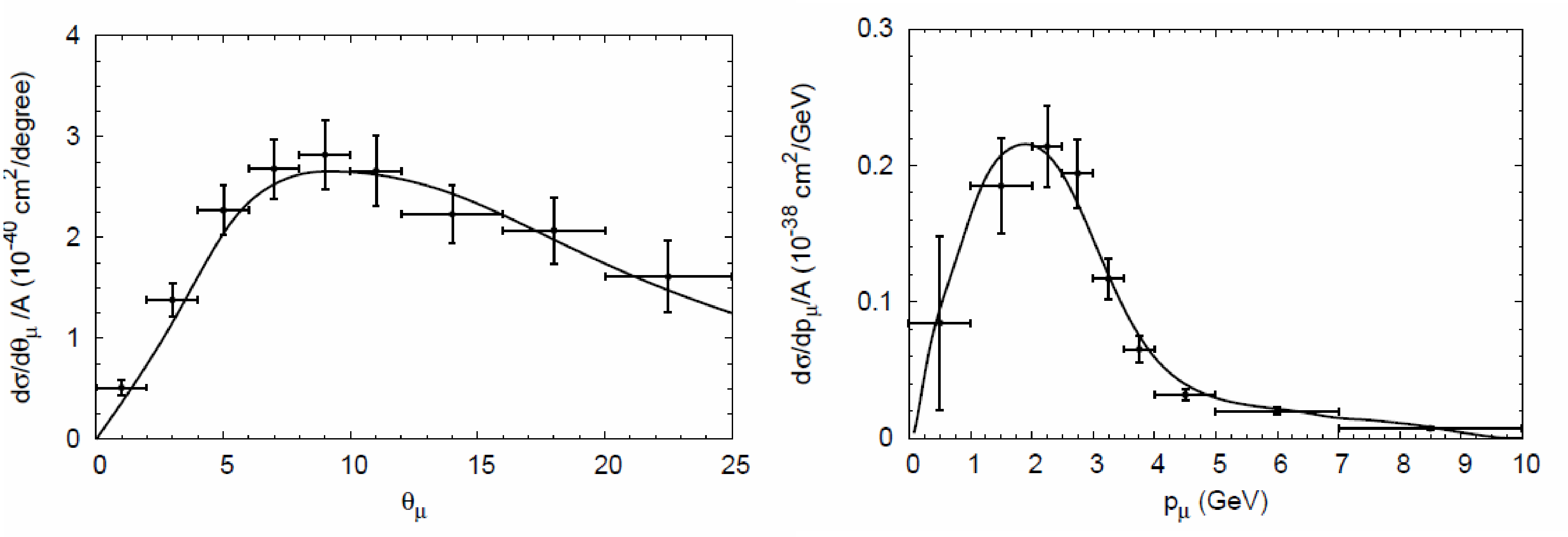
W < 1.4 GeV



W < 1.8 GeV, multiple pions

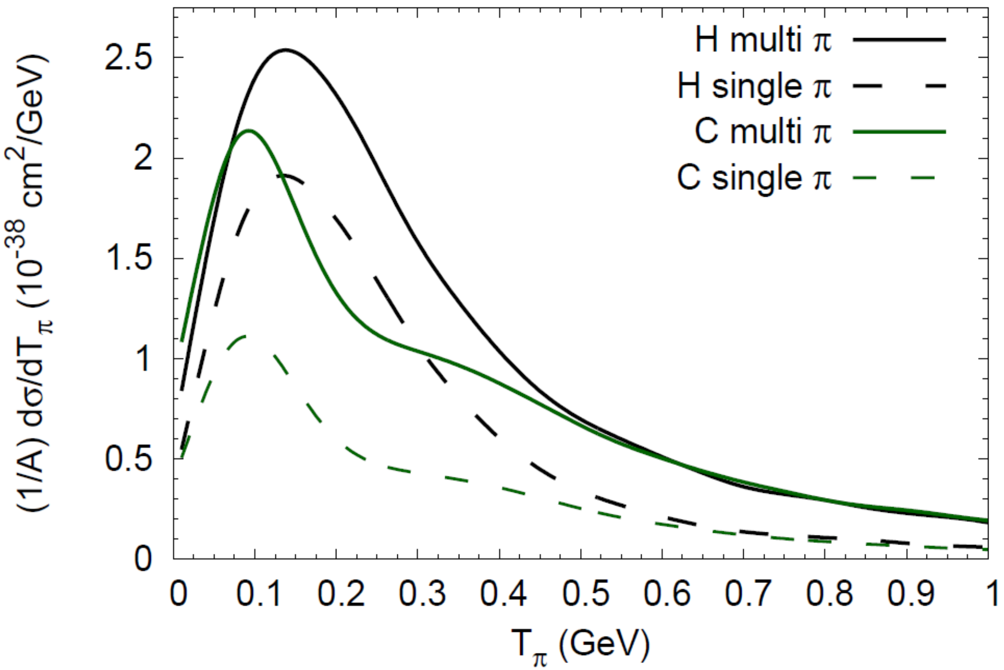
MINERvA pions

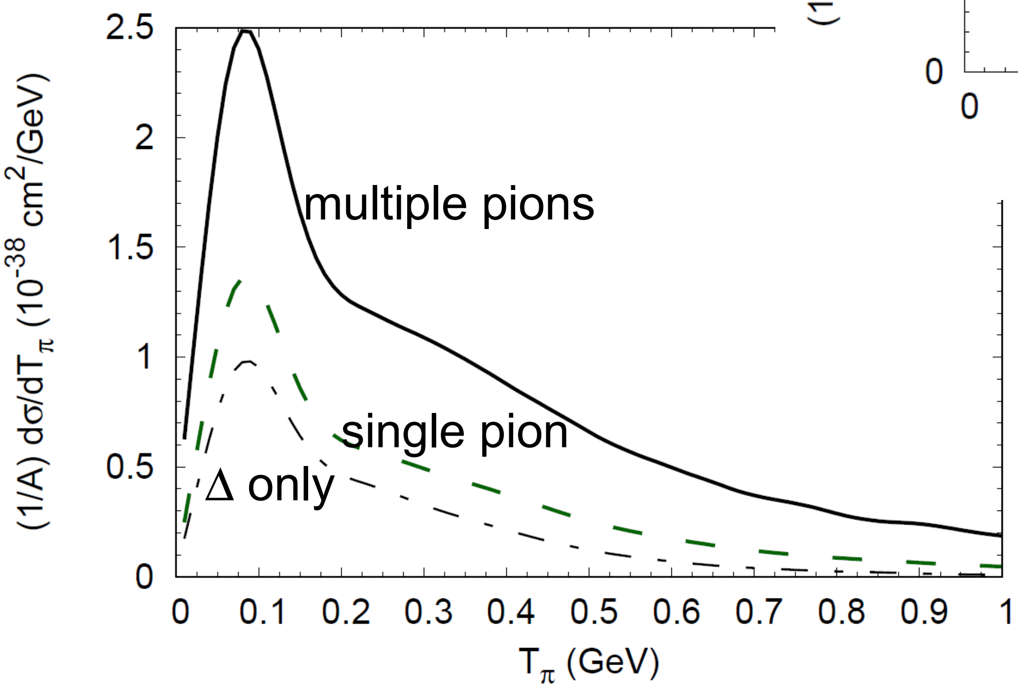
- CC charged pions



W < 1.8 GeV

Pions at NOvA





neutrino induced

- Conclusion:

  One and the same consistent model describes all the CC charged pion data from T2K and MINERvA without any special tune.

  MiniBooNE data do not agree with model

  (Does T2K data on H_20 confirms this?)

- Calculational time (on ^{12}C, flux averaged):
  - inclusive: ~ 1hour
  - exclusive: ~ 1 day

Exclusive channels and Final State Interactions

K. Gallmeister for the GiBUU group
Goethe-Universität, Frankfurt

Kinetic Theory and BUU equation

GiBUU implementation & some results

Hands On: Final state with neutrino init

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Bundesministerium für Bildung und Forschung

NuSTEC School 2017

Fermilab, USA, 7-15 Nov 2017

Outline

- Part 1:
  - ...
- Part 2: Implementation & Some results
  - ...
- Part 3: Hands On
  - GiBUU code & history
  - details for neutrino event generation

BUU@Gießen and GiBUU

- long history
  - 1986: first code — *(W.Bauer)*
  - ~1996: rewrite of code — *(S.Teis, M.Effenberger)*
  - ~2005: rewrite of code — *(O.Buss)*
  - lifetime: ~10 yrs
- actual version: „GiBUU“
  - modular, Fortran 2003, single threaded
  - semi-automatic documentation (robodoc)
  - version control (svn + trac)
- bottlenecks:
  - PYTHIA (very slow at low energies)
  - huge code (185 000 lines + docu + 'externals')
  - „long history“ (old structures)
  - …
  - transparency ratios = ratios of MC calculations: ~50 weeks per curve

People

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

- ~150 registered users

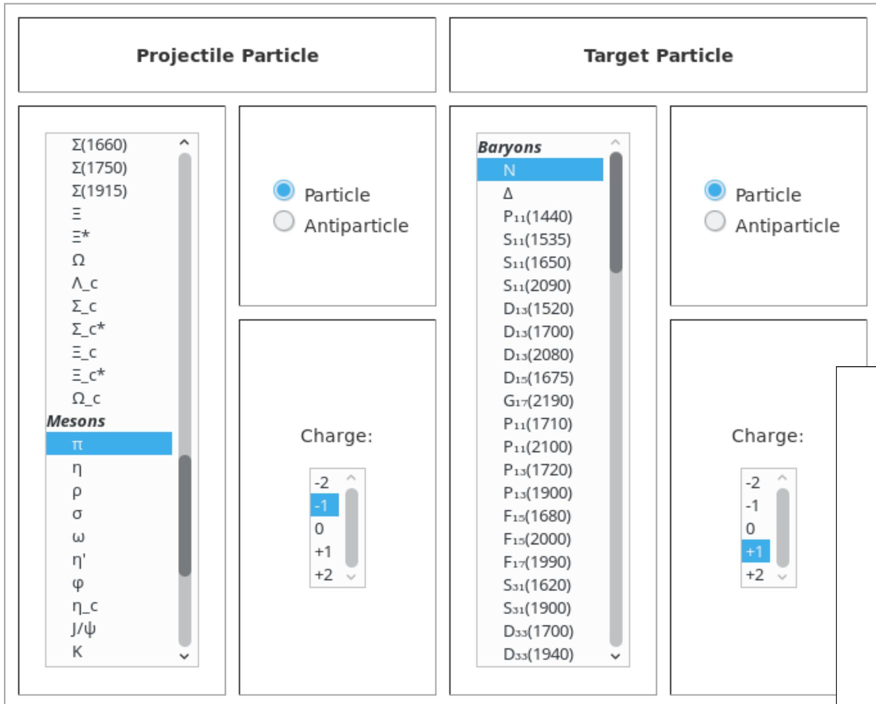
The GiBUU website

https://gibuu.hepforge.org

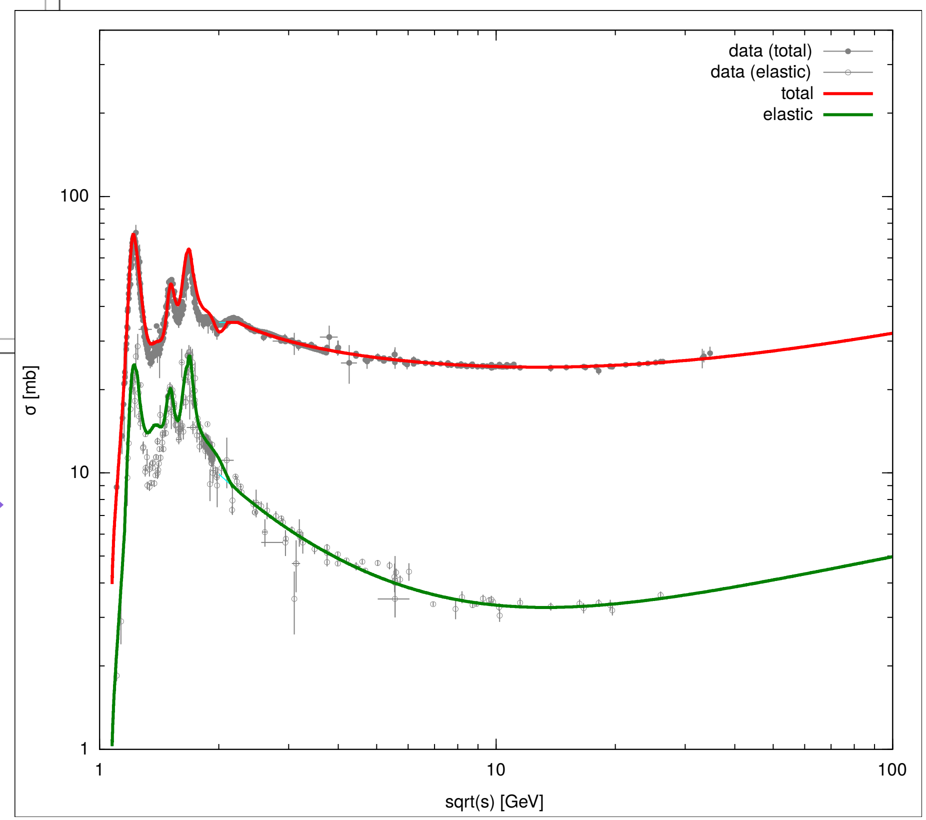
- central place for all information on GiBUU
- based on a wiki system (‘trac’)
- contains lots of information about the model and code
- documentation of input parameters, output files etc.
- source code viewer for svn repository
- timeline of news & changes

- cross section plotter

Cross section plotter



https://gibuu.hepforge.org/XSection/



Technical Prerequisites

- GiBUU runs on Linux, Mac, Windows
- Linux is preferred platform
- needed software tools:
  - subversion (for code checkout)
  - GNU make
  - a Fortran compiler (e.g. gfortran 5.4)
  - perl
  - libbz2

  - see website for supported compilers
  - private observation: ifort generates fastest code

Getting the code

- ...via check-out from svn repository

- create a new directory

```
mkdir GiBUU; cd GiBUU
```

- check-out the code

```
svn co
http://gibuu.hepforge.org/svn/releases/release2017
```

- check out the input files

```
svn co
http://gibuu.hepforge.org/svn/releases/buuinput2017
./buuinput
```

git access (GitHub) possible, but not really maintained

Compiling the code

- go to directory and make!

```
cd release2017; make
```

- takes about 3 minutes on my laptop (one core)

- parallel make

```
make -j 4
```

- choosing a compiler

```
make FORT=gfortran-4.8
```

- no optimization

```
make MODE=opt0
```

- re-compile everything

```
make renew
```

SUCCESS: GiBUU.x generated.

Updating the code via svn

- from time to time there will be changes in the code (bugfixes, new features, …)
- latest release: GiBUU 2017 (Oct. 29, 2017)
- you should keep your local copy of the code up to date
- do in the code directory:

```
svn update
```

- check output for modified files and conflicts
- after updating, you need to recompile

```
make
```

Running the code

- after successful compilation, there is the executable `./objects/GiBUU.x` (linked also `./testRun/GiBUU.x`)
- run the executable with input and output files

```
./GiBUU.x < input.job > log.txt
```

- either
  - run ‘in-tree’, i.e. in the directory testRun
    `cd testRun; ./GiBUU.x`
  - copy it somewhere else
  - use it from somewhere else with full path

  } recommended, since several output files are generated

- the file ‘log.txt’ will contain a log of GiBUU control & debug messages, physics output will be written to other files

Input parameters

- input via the Fortran way: 'jobcard'
  (plain text file with data in some specific format)
- sample jobcards in `./testRun/jobCards`
- format: data in a 'jobcard' is grouped in 'namelists'

```
&namelist1
  switch1 = value1     ! some comment
  switch2 = value2     ! another comment
/

&namelist2
  switch3 = value3
  switch4 = value4
/
```

- capitalization (upper/lower case) does not matter

Input parameters

- there are a lot of input parameters!
- documented at website

  https://gibuu.hepforge.org/Documentation2017/code/robo_namelist.html

  (new overview documentation under development)

- most of them not relevant for beginners
- most of them have reasonable default values

- some relevant namelists for neutrino events:
  - 'input' (basics)
  - 'neutrino_induced'
  - 'target'
  - 'EventOutput' (producing particle output)
  - ...

The Namelist ‘input’

- the basic settings that need to be supplied

```
&input
        eventtype           =              5 ! neutrino interactions
        numEnsembles        =           1000
        numTimeSteps        =            100
        delta_T             =            0.2 ! time step size [fm]
        freezeRealParticles   = T
        localEnsemble       = T

        path_To_Input       = '/some/path/to/buuinput'
/
```

- ‘path_to_input’ must point to local path of buuinput directory

The Namelist ‘neutrino_induced’

- infos about the elementary neutrino event

```
&neutrino_induced
      process_ID        =  2 ! 2:CC, 3:NC, -2:antiCC, -3:antiNC
      flavor_ID         =  2 ! 1:electron, 2:muon, 3:tau

      nuXsectionMode    = 16 ! 16: EXP_dSigmaMC
      nuExp             =  9 !  9: T2K-2.5kA-ND280

!   subprocesses to take into account:
      includeQE         = T
      includeDELTA      = T
      includeRES        = T
      include1pi        = T
      includeDIS        = T
      include2p2hQE     = T
      include2p2hDelta= F
      include2pi        = F
/
```

The Namelist ‘neutrino_induced’

- nuXsectionMode: (required input)

$0 =$ integratedSigma: E_ν

$1 =$ dSigmadCosThetadElepton: E_ν, $\cos\theta$, $E_{\rm lepton}$

$2 =$ dSigmadQsdElepton: E_ν, Q^2, $E_{\rm lepton}$

$3 =$ dSigmadQs: E_ν, Q^2

$4 =$ dSigmadCosTheta: E_ν, $\cos\theta$

$5 =$ dSigmadElepton: E_ν, $E_{\rm lepton}$

$6 =$ **dSigmaMC**: E_ν

$7 =$ dSigmadW: E_ν, W

$+10$ for taking experimental flux into account

The Namelist ‘neutrino_induced’

- nuExp:

1 MiniBooNE neutrino flux (in neutrino mode] positive polarity)

2 ANL

3 K2K

4 BNL

5 MiniBooNE anti-neutrino flux (in antineutrino mode] negative polarity)

6 MINOS muon-neutrino in neutrino mode

7 MINOS muon-antineutrino in neutrino mode

8 NOVA neutrino (medium energy NuMI, 14 mrad off-axis), FD

9 T2K neutrino off-axix 2.5 degrees (at ND280 detector)

10 *uniform distribution* from $E_{\text{flux,min}}$ to $E_{\text{flux,max}}$

11 MINOS muon-neutrino in antineutrino mode

12 MINOS muon-antineutrino in antineutrino mode

The Namelist 'neutrino_induced'

- nuExp: (cnt'd)

  13 MINERvA muon neutrino, old flux

  14 MINERvA muon antineutrino, old flux

  15 LBNF/DUNE neutrino in neutrino mode

  16 LBNF/DUNE antineutrino in antineutrino mode

  17 LBNO neutrino in neutrino mode

  18 NOMAD

  19 BNB nue BNB= Booster Neutrino Beam

  20 BNB nuebar

  21 BNB numu

  22 BNB numubar

  23 NOvA ND

  24 T2K on axis

  25 MINERvA, 2016 flux

The Namelist ‘target’ etc.

- infos about the nucleus as target

```
&target
      Target_A = 12
      Target_Z =  6
!      ReAdjustForConstBinding = T
/
```

- analytic density treatment

```
&initDensity
      densitySwitch = 2          ! 2=analytic
/

&initPauli
      pauliSwitch = 2            ! 2=analytic
/
```

Analysis strategies

- direct ‘on-line’ analysis inside GiBUU
  - direct analysis of desired quantity during the simulation
  - directly produce histograms etc.
  - no intermediate particle output
  - advantage: access to all internal information
  - disadvantage: needs recompile for changes
  - *mainly only for developers*
- ‘off-line’ analysis
  - output all particles/events
  - LesHouches format, convertible to ROOT for analysis
  - analysis may be changed after simulation run
  - disadvantage: may produce large amount of data
- GiBUU tends to be ‘silent’ by default

on-line analysis

- inclusive output

```
&neutrino_induced
       ...
       printAbsorptionXS = T
       ...
/
```

- final state analysis

```
&neutrinoAnalysis
       XSection_analysis     = T ! for multiplicities
       detailed_diff_output = T ! differential cross sections
       ...
/
```

+ 4 other namelists

- ~80 parameters

off-line analysis

- neutrino events:
  due to historical reasons also proprietary event format

```
&neutrino_induced
        ...
        outputEvents = T
        ...
/
```

writes file ‘FinalEvents.dat”

The Namelist 'EventOutput'

- generate particle output

```
&EventOutput
      WritePerturbativeParticles = T
      WriteRealParticles = F
!      EventFormat = 1 ! 1=LesHouches
/
```

- output only for perturbative particles
- file(s) generated 'EventOutput.Pert.*.lhe'

- possible formats:

1 = LesHouches	http://arxiv.org/abs/hep-ph/0609017
2 = OSCAR 2013	http://phy.duke.edu/~jeb65/oscar2013
3 = Shanghai 2014	http://www.physics.sjtu.edu.cn/hic2014/node/12

Output format 'Les Houches'

- XML-like event format
- named after a town in France
- basic structure:

arXiv:hep-ph/0609017v1

```
<LesHouchesEvents version="1.0">
<header>
  ...
</header>
<init>
  ...
</init>
<event>
  ...
</event>
... (any number of <event> blocks can follow) ...
```

Output format ‘Les Houches’ (2)

```
<event>
     1      0   5.06E-07   0.00E+00   0.00E+00   0.00E+00
    2212 0 0 0 0 0   0.024   0.028   0.308   1.010   0.958E-01 0. 9.
# 5 1 5.06E-07 0.61 0. 0. 0.61 0.54 0.09 -8.03E-04 0.52 0.97 0.11 -3
</event>
```

- line 1: N=number of lines, 0, weight, boring zeros
- following: N lines, representing one particle each
  columns: 1 = ID (PDG code), 7-9 = $p_{x,y,z}$, 10 = E, 11 = mass
- last line: comment
  ‘magic number’ 5 = special info for neutrino events
  eventtype, weight, momLepIn(0:3), momLepOut(0:3), momNuc(0:3)

- eventtype: 1 = QE, 2-31 = resonance, 32 = 1pi, ...

Conclusions

Exclusive channels and Final State Interactions

K. Gallmeister for the GiBUU group
Goethe-Universität, Frankfurt

Kinetic Theory and BUU equation

GiBUU implementation & some results

Hands On: Final state with neutrino init

Take-home-message

GiBUU = plug-in system