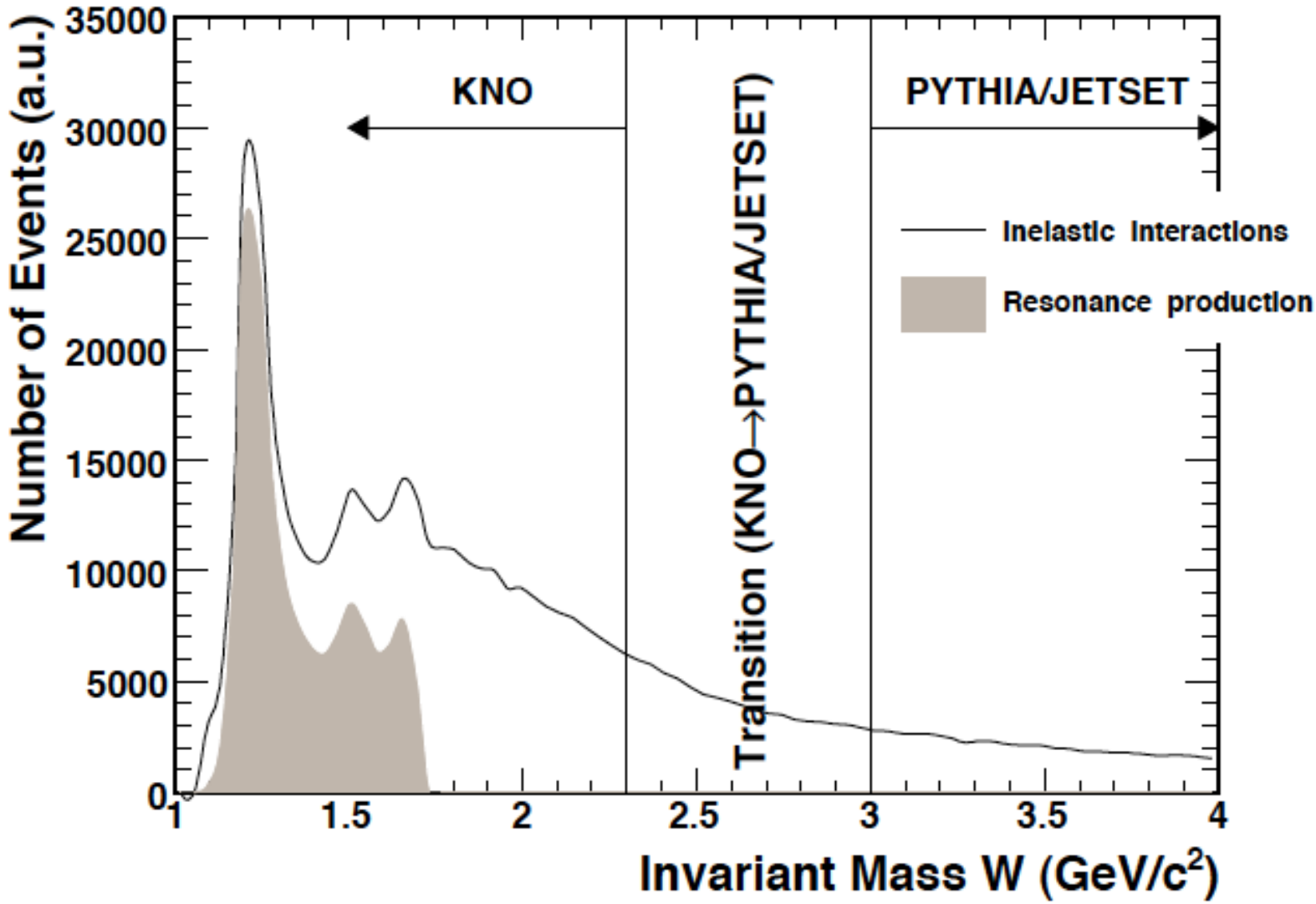
PICTURES OF HADRONIZATION

For Inelastic Processes:

- Resonance region, all hadronic distributions calculable in principle from the resonance model. Often treated as phase space decays - isotropic in hadronic c.m.

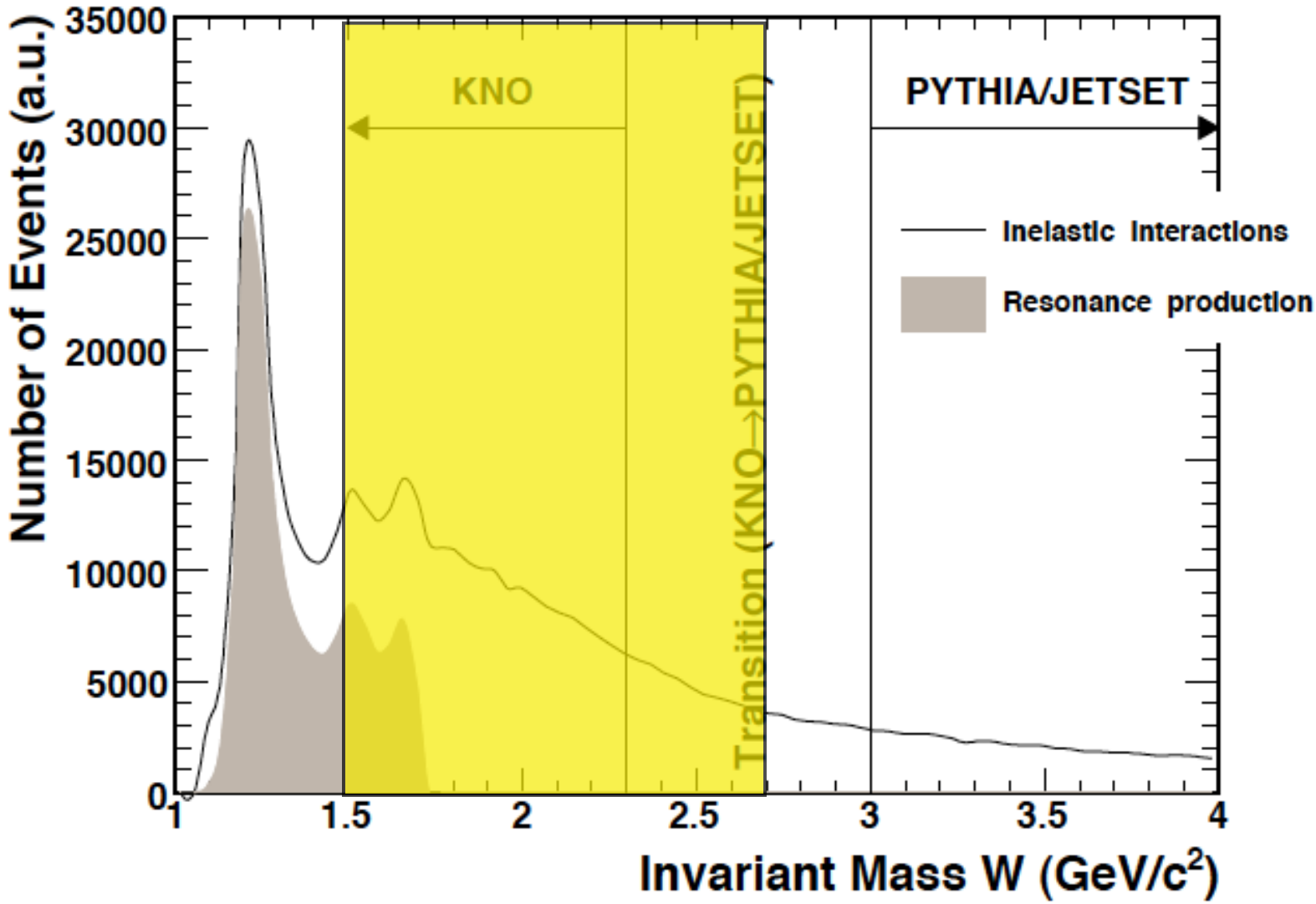
- At high energy: ‘current’ and ‘target’ jets.
  Pt is low.
  Need to look at the interaction in the hadronic center of mass to understand the dynamics.

T. Yang et al, Eur.Phys.J. C63 (2009) 1-10.
T. Yang, Ph. D Thesis, Stanford U (2009)



The model for the cross section will affect many things.
DIS vs. 'non-resonant background' in the resonance region.

T. Yang et al, Eur.Phys.J. C63 (2009) 1-10.
T. Yang, Ph. D Thesis, Stanford U (2009)



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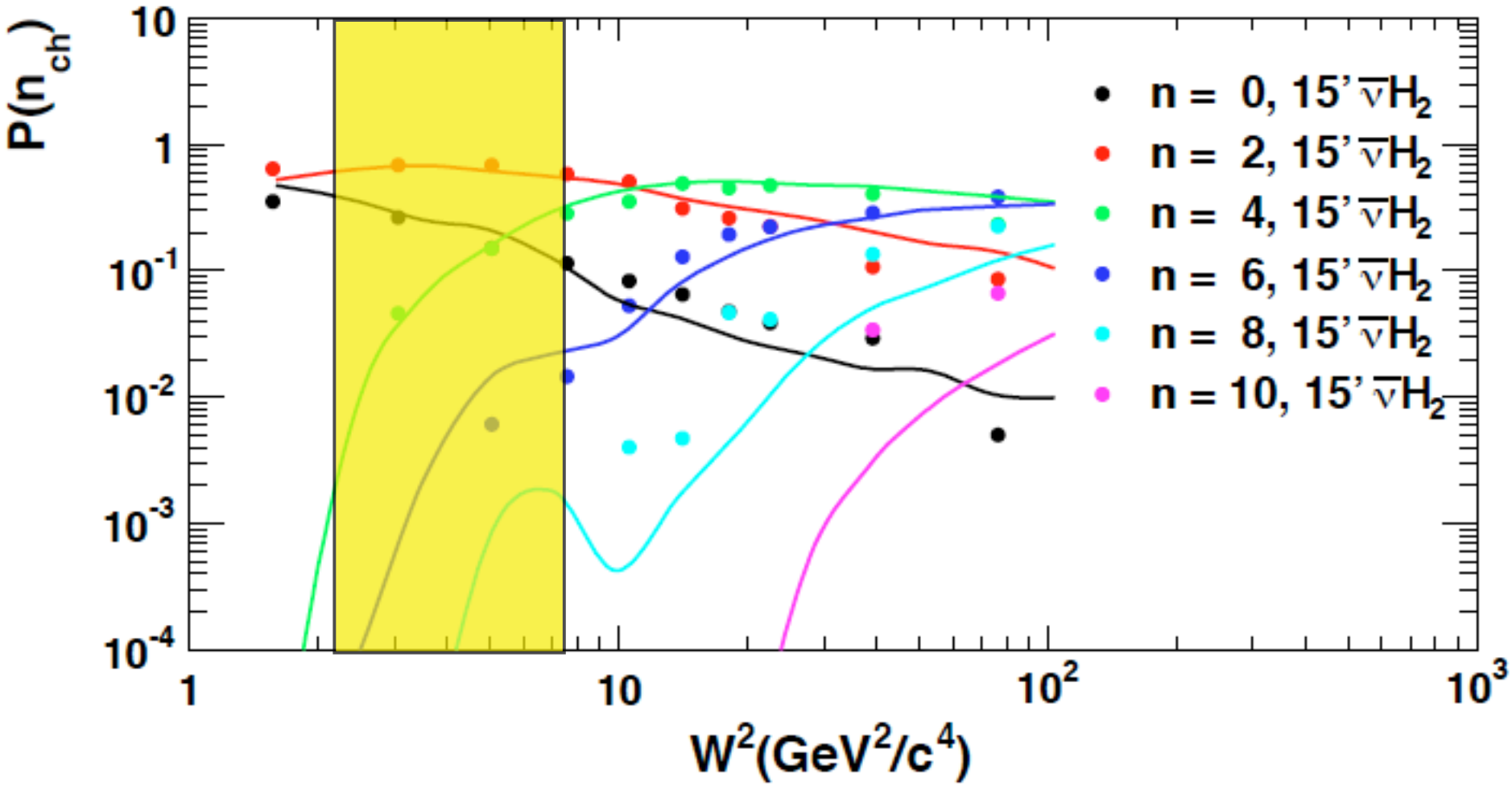


Resonance model, parameters like m_A.

$d\sigma/dW$ for the non-resonant inclusive model

The assignment of $d\sigma/dW$ into particular multiplicities (Levy function).

The parameters that remove part of the low multiplicity non-resonant inclusive cross section.

The branching ratio for multiplicity m to channel X.

Start by reconstructing overall kinematics (E, W, Q^2)

Particle counting:

- Average charged particle multiplicities.
- pizero and neutral strange particle multiplicities.
- charged particle multiplicities.
- (some) neutral - charged multiplicity correlations

Characteristics of the hadronic system (c.m.):

- Multiplicities in forward and backward hemispheres
- Fragmentation functions
- x_F distributions
- Transverse momentum distributions
- x_F-transverse momentum correlations

$$z \equiv \frac{E_{hadron}}{\nu} \qquad D(z) = \frac{1}{N_{\text{events}}} \frac{dN}{dz}$$

$$x_F \equiv \frac{p_L^*}{p_{L,\max}^*}$$

N. Schmitz, "Production of Hadrons in Charged Current Neutrino and Anti-Neutrino Reactions", Proceedings of Lepton-Photon 1981.

The GENIE Hadronization Model (AGKY)

By hadronization model we mean the piece of code that gives a list of final state particles and 4-momenta given an interaction (CC/NC, nu/nubar, n/p) and the event kinematics.

```
TClonesArray * KNOHadronization::Hadronize(const Interaction * interaction)
```

Takes a 4-vector for a hadronic system with some charge produced from a particular neutrino interaction and produces the vector of particles with their 4-momenta.

The GENIE model (AGKY) take it in two steps:

* Decide what particles to create

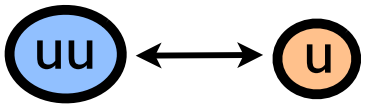
```
PDGCodeList * KNOHadronization::SelectParticles(const Interaction * interaction)
```

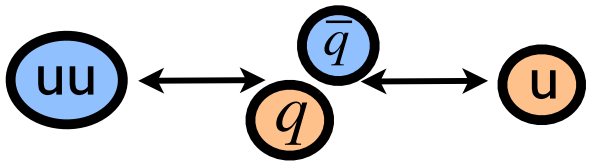
* Choose the 4-momenta of each

```
TClonesArray * KNOHadronization::DecayMethod2(double W, const PDGCodeList &
pdgv, bool reweight_decays)
```

e.g nu+p CC

in hadronic c.m.





continues until invariant mass is too low, then cluster fragmentation/collapse.

Q: sea quark scattering?

also GENIE except for

Parameter	Value (Wroclaw)	Value (NUX)	Description
PARJ(2)	-	0.21	(D=0.30) is P(s)/P(u), the suppression of s quark pair production in the field compared with u or d pair production.
PARJ(21)	-	0.44	(D=0.36 GeV) corresponds to the width σin the Gaussian px and py transverse momentum distributions for primary hadrons. See also PARJ(22) -PARJ(24).
PARJ(23)	-	0.01	PARJ(23-24) : (D=0.01, 2.) a fraction PARJ(23) of the Gaussian transverse momentum distribution is taken to be a factor PARJ(24) larger than input in PARJ(21). This gives a simple parametrization of non-Gaussian tails to the Gaussian shape assumed above.
PARJ(32)	0.1 GeV	-	(D=1. GeV) is, with quark masses added, used to define the minimum allowable energy of a colour-singlet jet system.
PARJ(33)	0.5 GeV	0.2 GeV	(D=0.8 GeV, 1.5 GeV) are, together with quark masses, used to define the remaining energy below which the fragmentation of a jet system is stopped and two final hadrons formed. PARJ(33) is normally used, except for MSTJ(11)=2, when PARJ(34) is used.
PARJ(34)	1.0 GeV	-	
PARJ(36)	0.3 GeV	-	(D=2.) represents the dependence on the mass of the final quark pair for defining the stopping point of the fragmentation. Is strongly correlated to the choice of PARJ(33)

also MSTJ(17)=3 in NuWRO

J. Nowak (NuWRO), Phys.Scripta T127 (2006) 70-72

```
~~~
```

1) average multiplicity selected from measured multiplicity relations

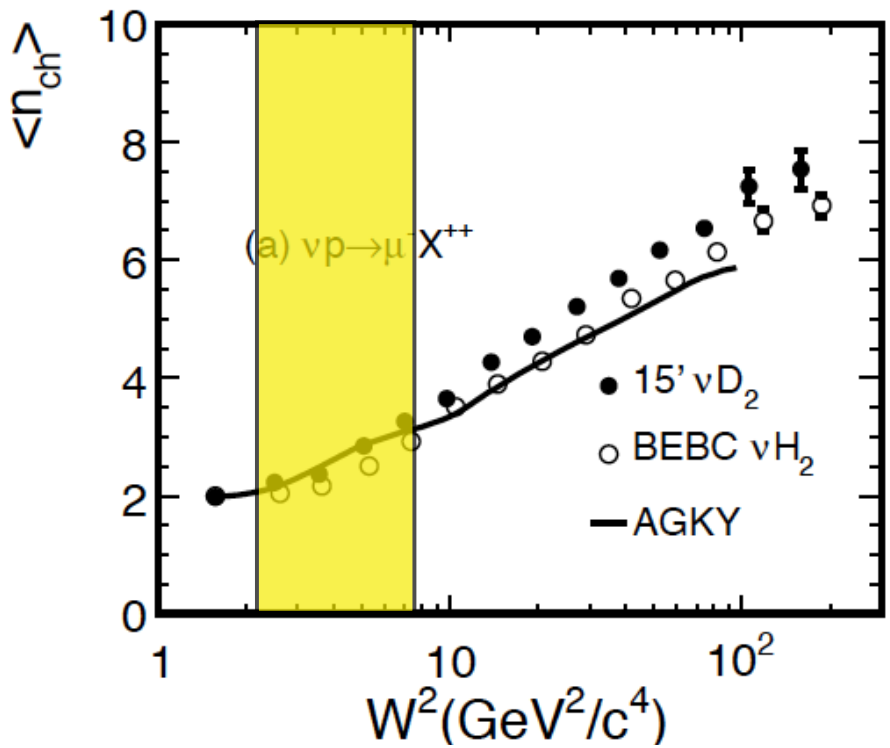
$$\langle n_{ch} \rangle = a + b \ \log W^2$$

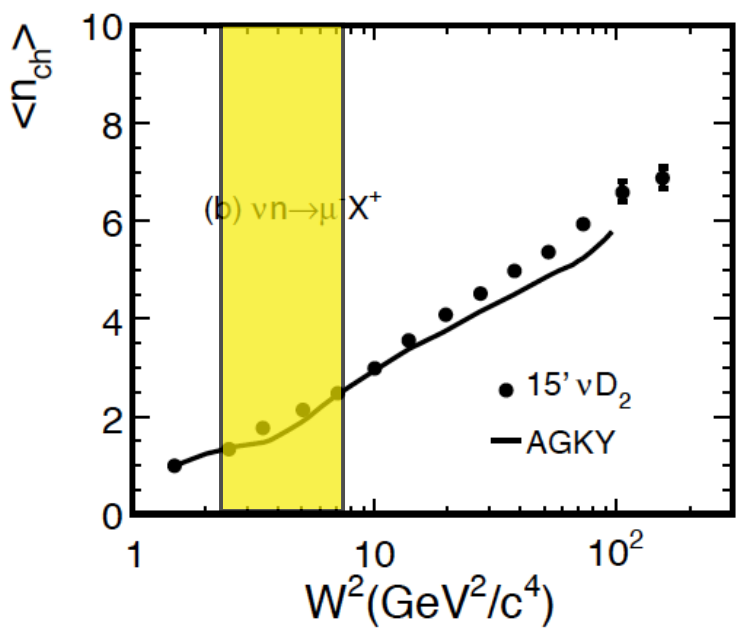
$$\langle n_{tot} \rangle = 1.5 \langle n_{ch} \rangle$$

	νp	νn	$\bar{\nu} p$	$\bar{\nu} n$
a_{ch}	0.40 [7]	-0.20 [7]	0.02 [13]	0.80 [13]
b_{ch}	1.42 [7]	1.42 [7]	1.28 [13]	0.95 [13]
c_{ch}	7.93 [7]	5.22 [7]	5.22	7.93
$a_{hyperon}$	0.022	0.022	0.022	0.022
$b_{hyperon}$	0.042	0.042	0.042	0.042

[7] D. Zieminska, et al. Phys. Rev., **D27**, 47 (1983)

[13] S. Barlag, et al. Zeit. Phys., **C11**, 283 (1982)





```
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```
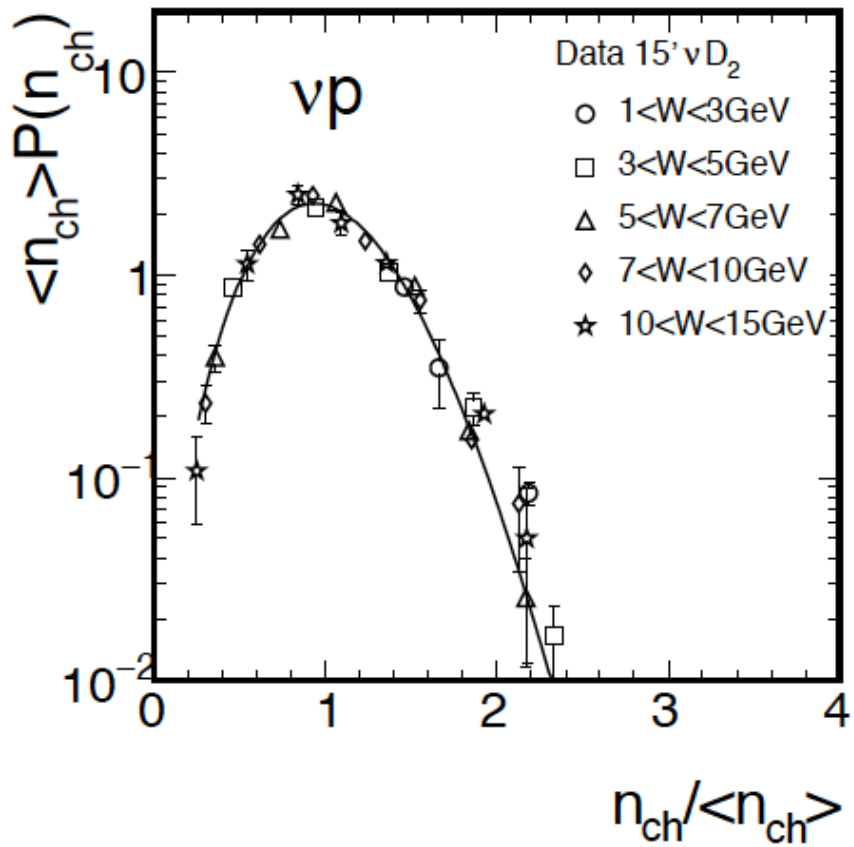

2) multiplicity for event selected based on KNO scaling

(<n>P(n,W) vs. n/<n> is independent of W)

$$\langle n \rangle P(n) = f(n / \langle n \rangle)$$

$$Levy(z;c) = \frac{2e^{-c}c^{cz+1}}{\Gamma(cz+1)}$$



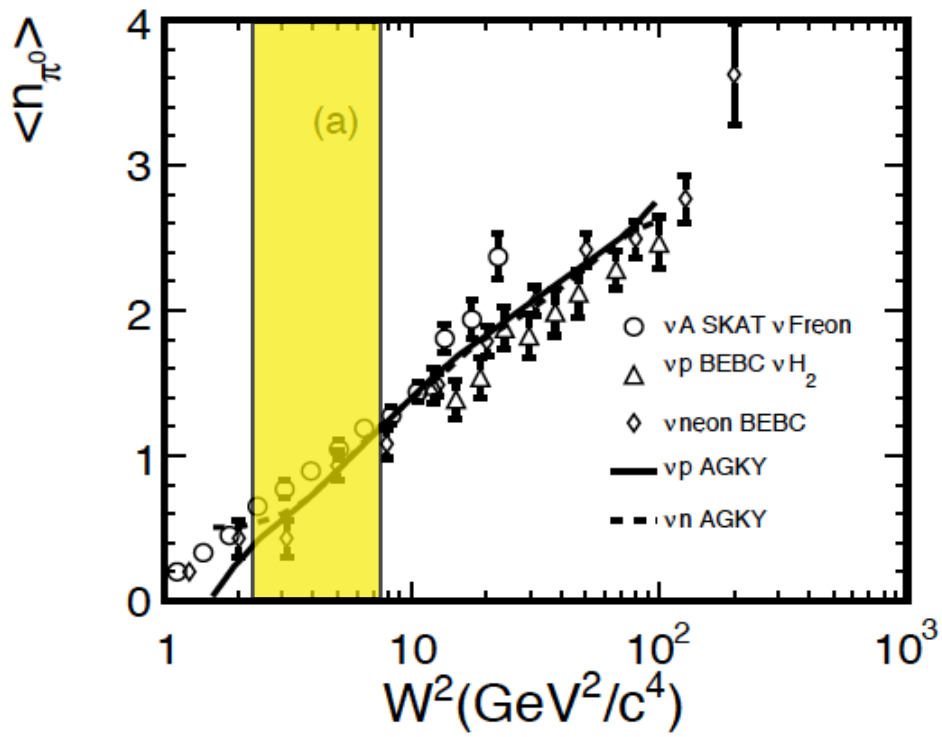

```
double KNOHadronization::KNO(int probe_pdg, int nuc_pdg, double z) const
~~~
```

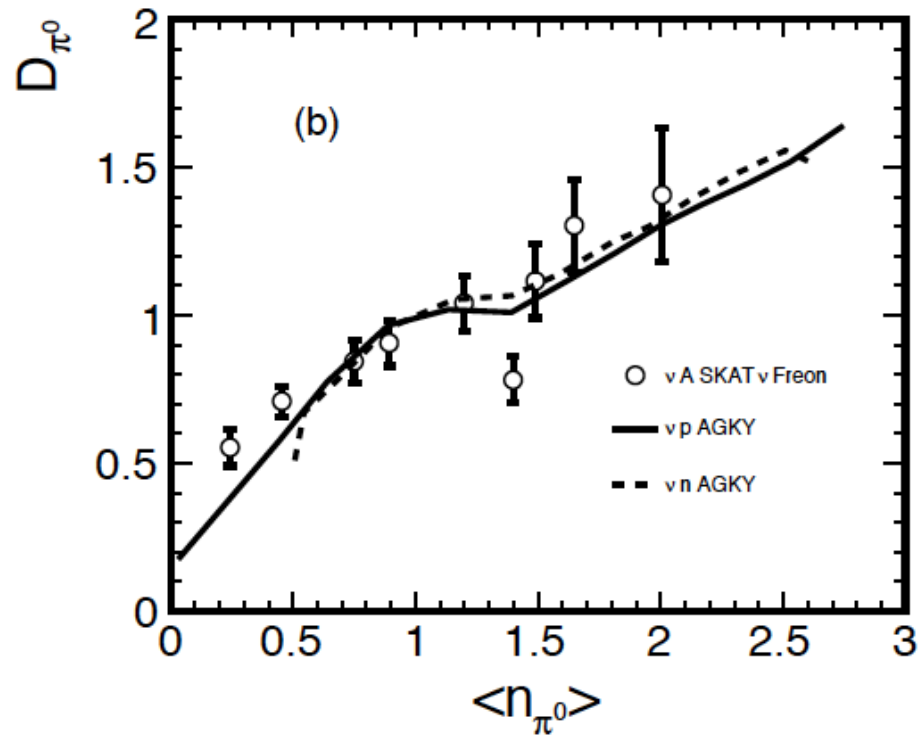
3) Select baryon in the event (probability for selecting a proton depends only on the initial state). Net charge of the system is reduced to zero by creating charged pions. Remaining particle types assigned according to simple pair production probabilities.

particles

	2	>2
νp	100	67
νn	33	50
$\bar{\nu} p$	67	50
$\bar{\nu} n$	0	33

Probability (%) of choosing a proton for the baryon



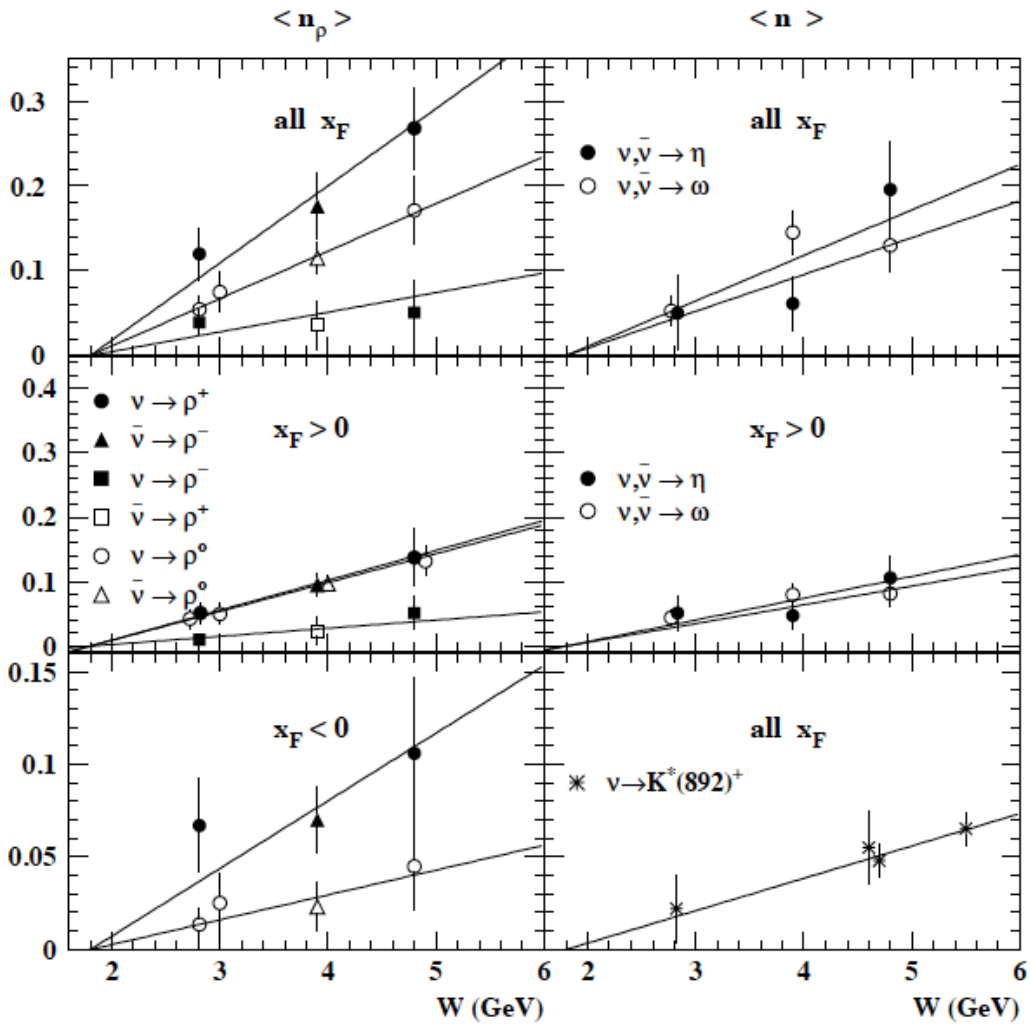


```
PDGCodeList * KNOHadronization::GenerateHadronCodes   (int mult, int maxQ, double W);

int KNOHadronization::GenerateBaryonPdgCode(int multiplicity, int maxQ, double W) const
```

```
~~~
```

Lots of data from SKAT (hep-ex arXiv:0811.2343)

$\langle E_\nu \rangle = 9.8$ GeV, $\langle W \rangle = 2.8$ GeV,



shold)

Table 3: The slope parameter b (in GeV^{-1}).

reaction	all x_F	$x_F > 0$	$x_F < 0$
$\nu(\bar{\nu} \to)\eta$	0.044±0.011	0.034±0.005	—
$\nu(\bar{\nu} \to)\rho^0$	0.056±0.007	0.045±0.004	0.013±0.005
$\nu \to \rho^+$ or $\bar{\nu} \to \rho^-$	0.091±0.011	0.046±0.006	0.037±0.006
$\nu \to \rho^-$ or $\bar{\nu} \to \rho^+$	0.023±0.008	—	—
$\nu(\bar{\nu}) \to \omega$	0.054±0.007	0.029±0.007	—
$\nu \to K^*(892)^+$	0.017±0.002	—	—

$$\langle n \rangle = b(W - 1.8 \text{ GeV})$$

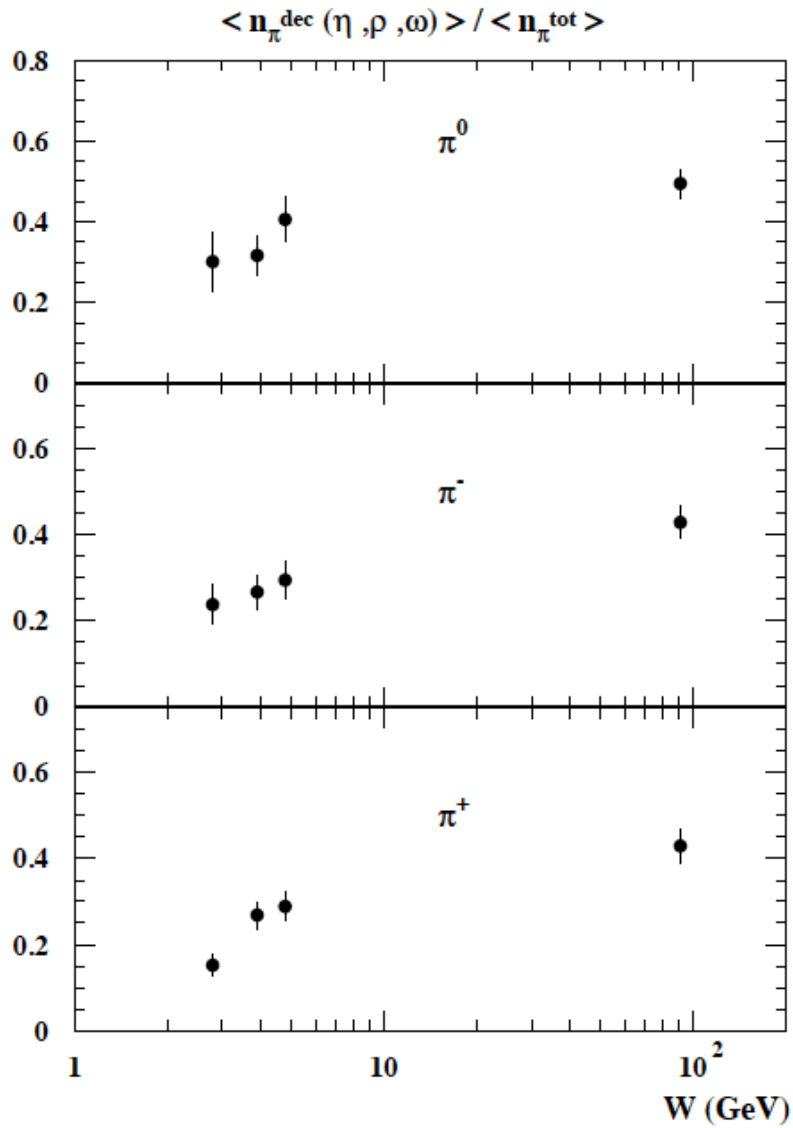


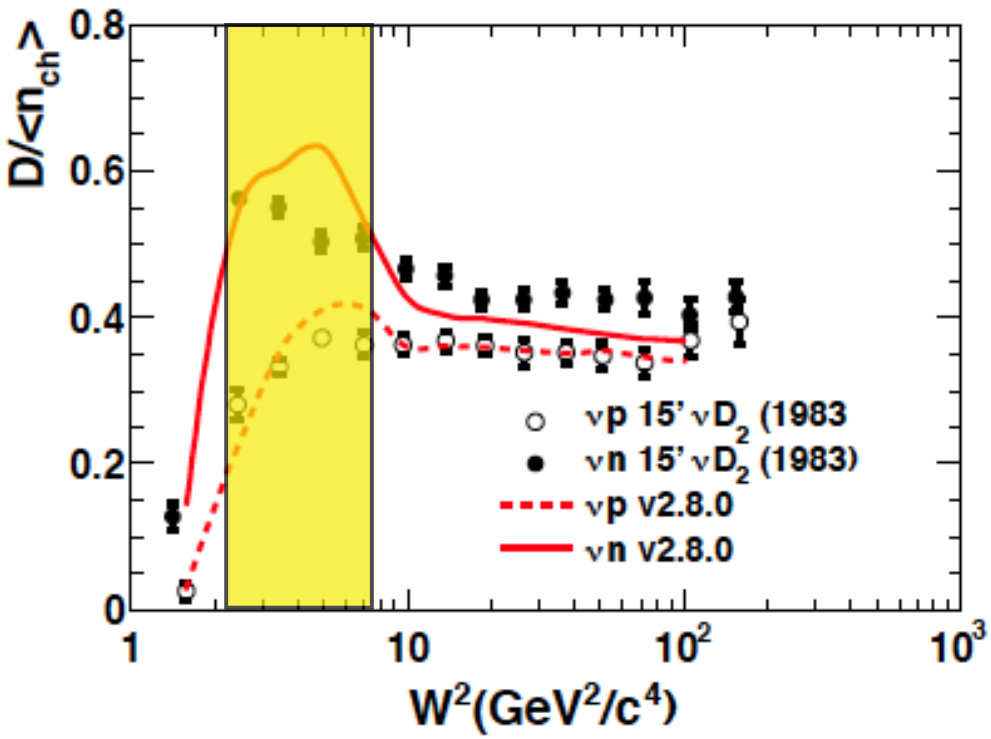
Figure 7: The fraction of pions originating from the η, ρ, ω decays. The data at $W = 3.9$ GeV for $\pi^+(\pi^-)$ in $\overline{\nu}Ne$ interactions [2] are replaced by those for $\pi^-(\pi^+)$.

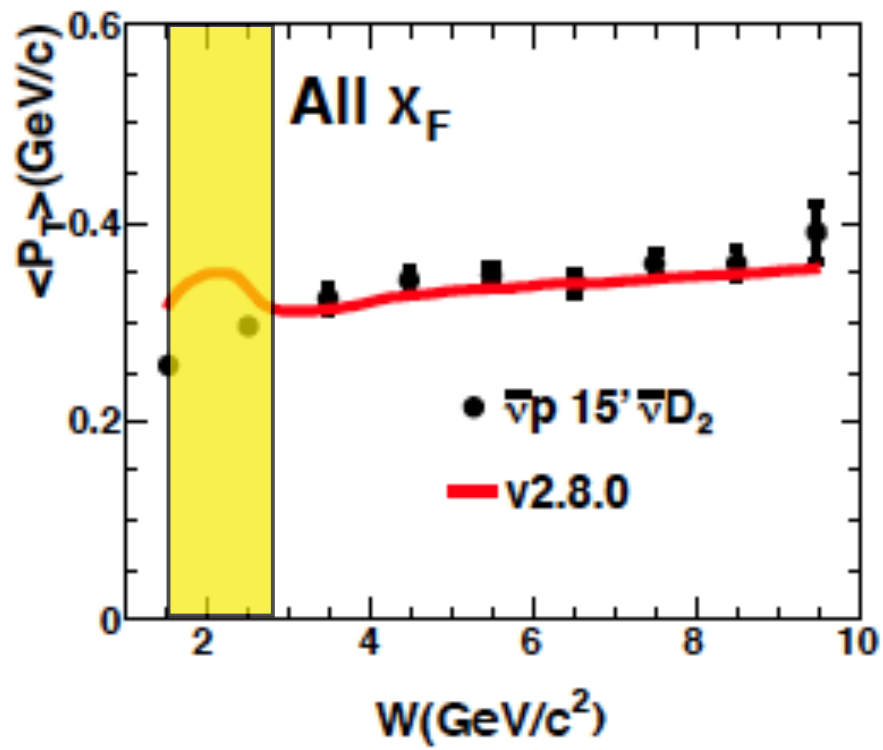
+ Data on the fraction of pions coming from the decay of light resonances.

		π^0	π^-	π^+
total		0.904±0.066	0.652±0.010	1.55±0.06
η	0.050±0.044	6.65±5.85	2.10±1.85	0.88±0.78
ρ^0	0.054±0.017	–	8.28±2.58	3.50±1.09
ρ^+	0.120±0.031	13.27±3.56	–	7.74±2.02
ρ^-	0.039±0.015	4.41±1.73	5.98±2.30	–
ω	0.053±0.017	5.75±1.84	7.38±2.37	3.10±1.00
$\eta'(958)$	0.025±0.020	1.13±0.90	2.78±2.22	1.17±0.93
$K^*(892)^0$	0.023±0.013	0.85±0.49	2.18±1.26	–
$\overline{K}^*(892)^0$	0.015±0.010	0.57±0.38	–	0.66±0.45
$K^*(892)^+$	0.022±0.012	0.81±0.47	–	0.95±0.52
$K^*(892)^-$	0.006±0.005	0.20±0.17	0.56±0.47	–
$f_0(980)$	0.014±0.010	1.03±0.73	1.42±1.00	0.60±0.42
ϕ	0.009±0.006	0.05±0.03	0.06±0.05	0.03±0.02
sum		**34.7±7.6%**	**31.2±5.7%**	**18.4±3.0%**

Lots of work in MINOS (T. Yang in particular on evaluating the model)
minos-docs: 2587, 2918, 3105, 3213, 3469, 3473, 3496, 3563, 3631, 3770, 3806, 4842, 5014, 5317.

Several known issues:
1) JETSET tuning
2) Charged and neutral pion selection in KNO
3) An excess of 1-π production in ν-n scattering.
4) 4-momenta selection for KNO





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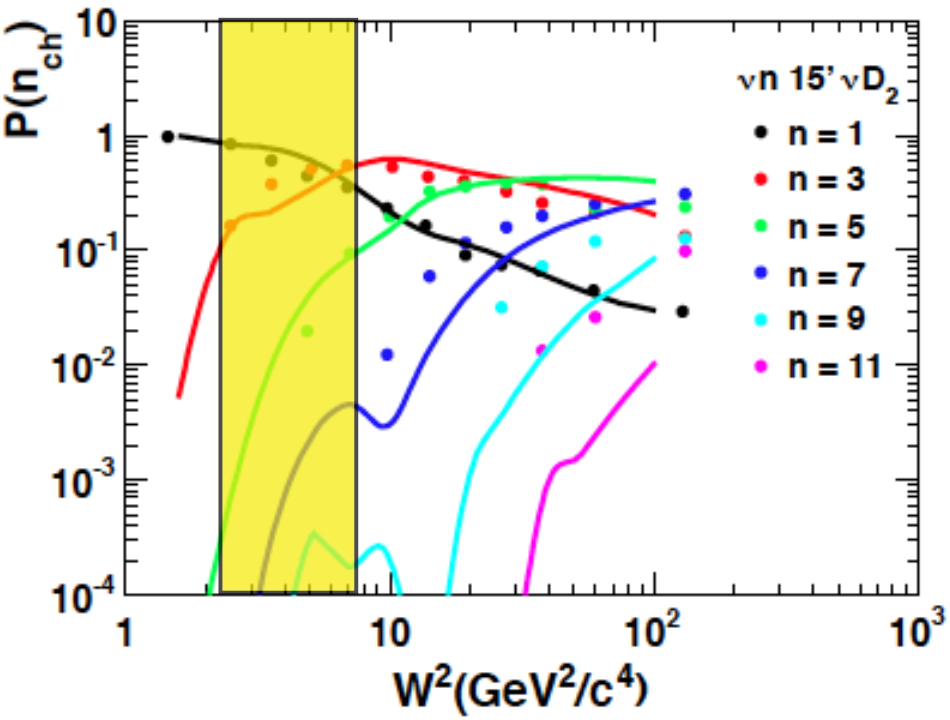
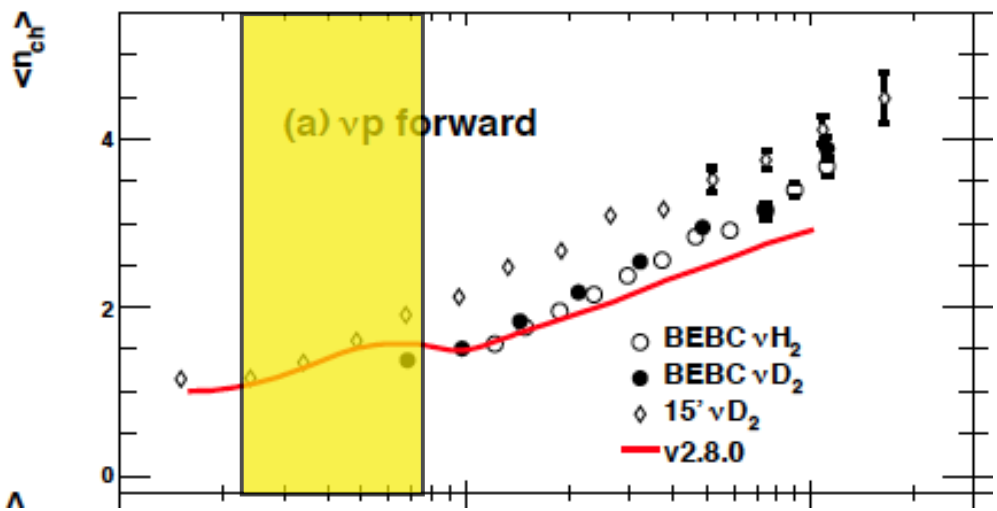
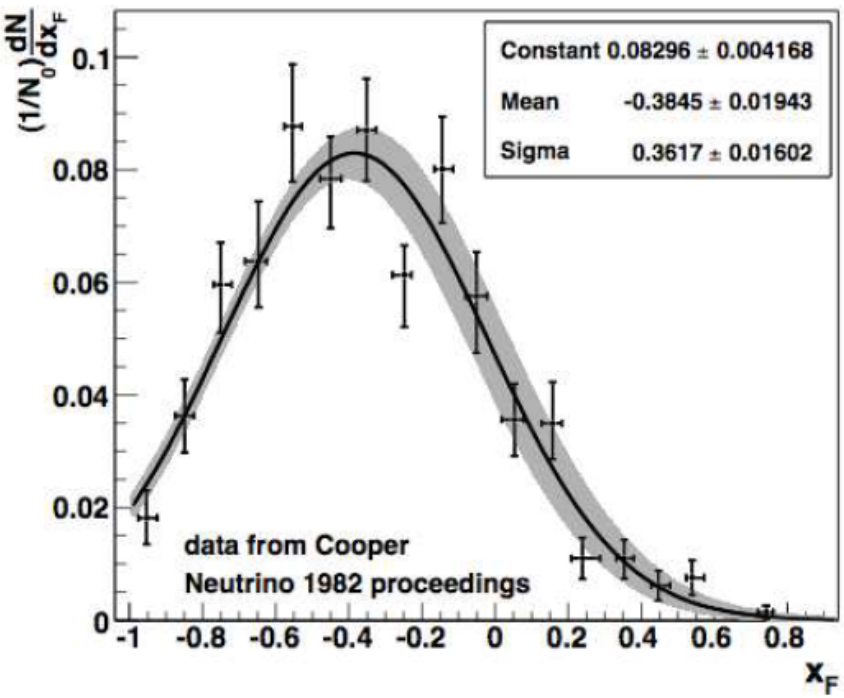
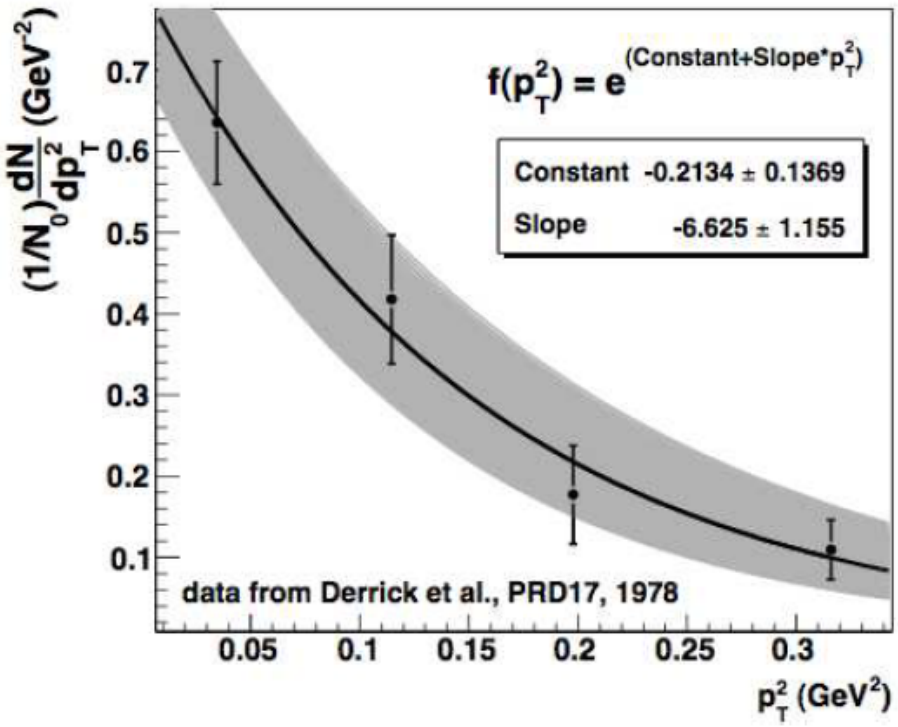




4) Select baryon 4-momentum from empirical distribution $P(x_F, pt)$.

5) Perform a phase space decay on the remaining particles in the hadronic system, and then "p_t squeezing" – rejection factor based on p_t for each particle. Clegg and Donnachie, "Description of Jet Structure by pt-limited Phase Space", Z. Phys. C 13: 71 (1982). $W_i = \exp(-A * p_t^i)$





```
TClonesArray * KNOHadronization::DecayMethod2(double W, const PDGCodeList &
pdgv, bool reweight_decays)
```

```
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```
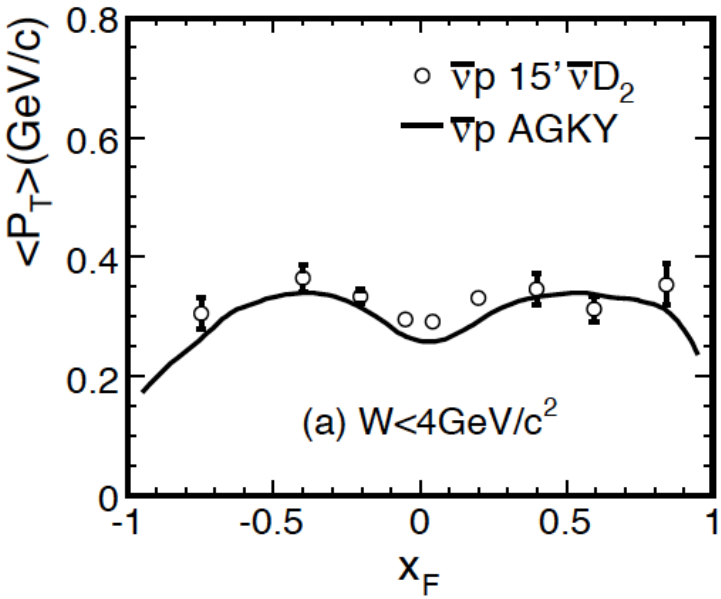
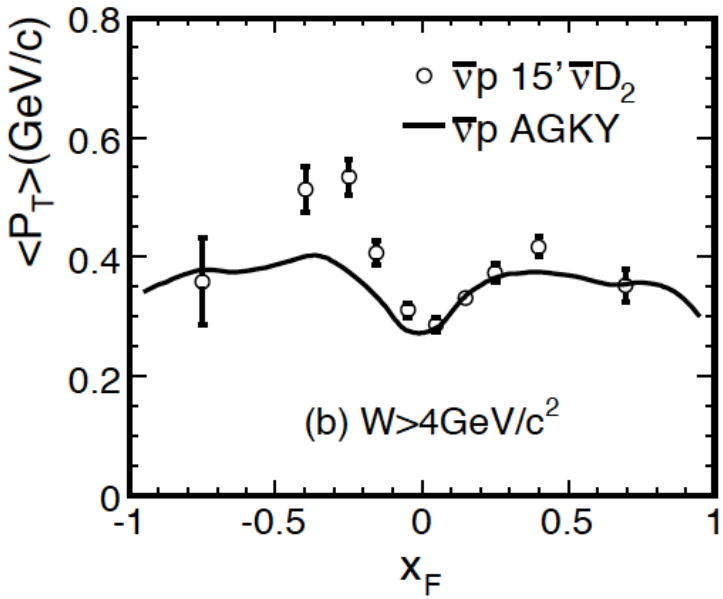
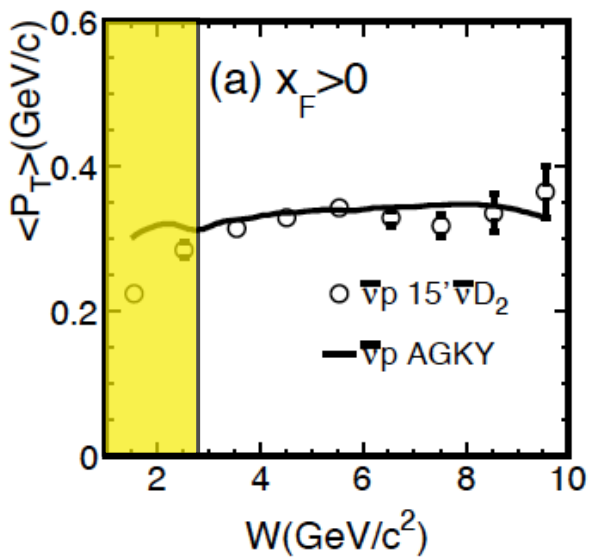
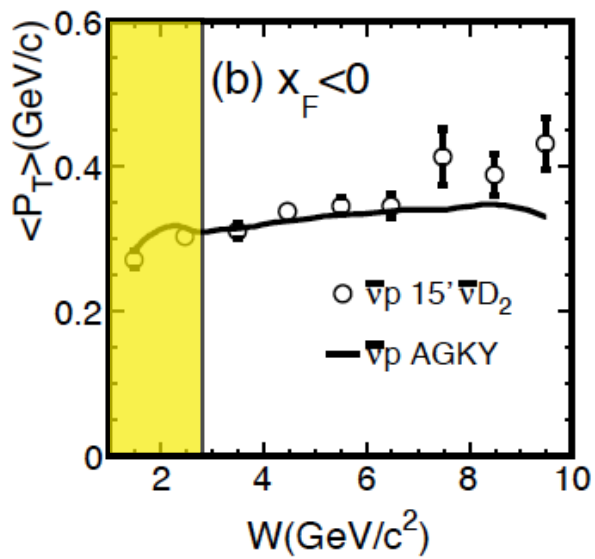

T. Yang et al, Eur.Phys.J. C63 (2009) 1-10.
T. Yang, Ph. D Thesis, Stanford U (2009)

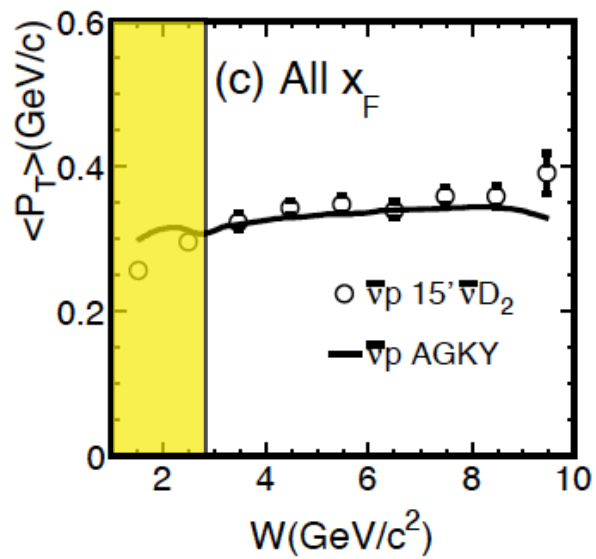




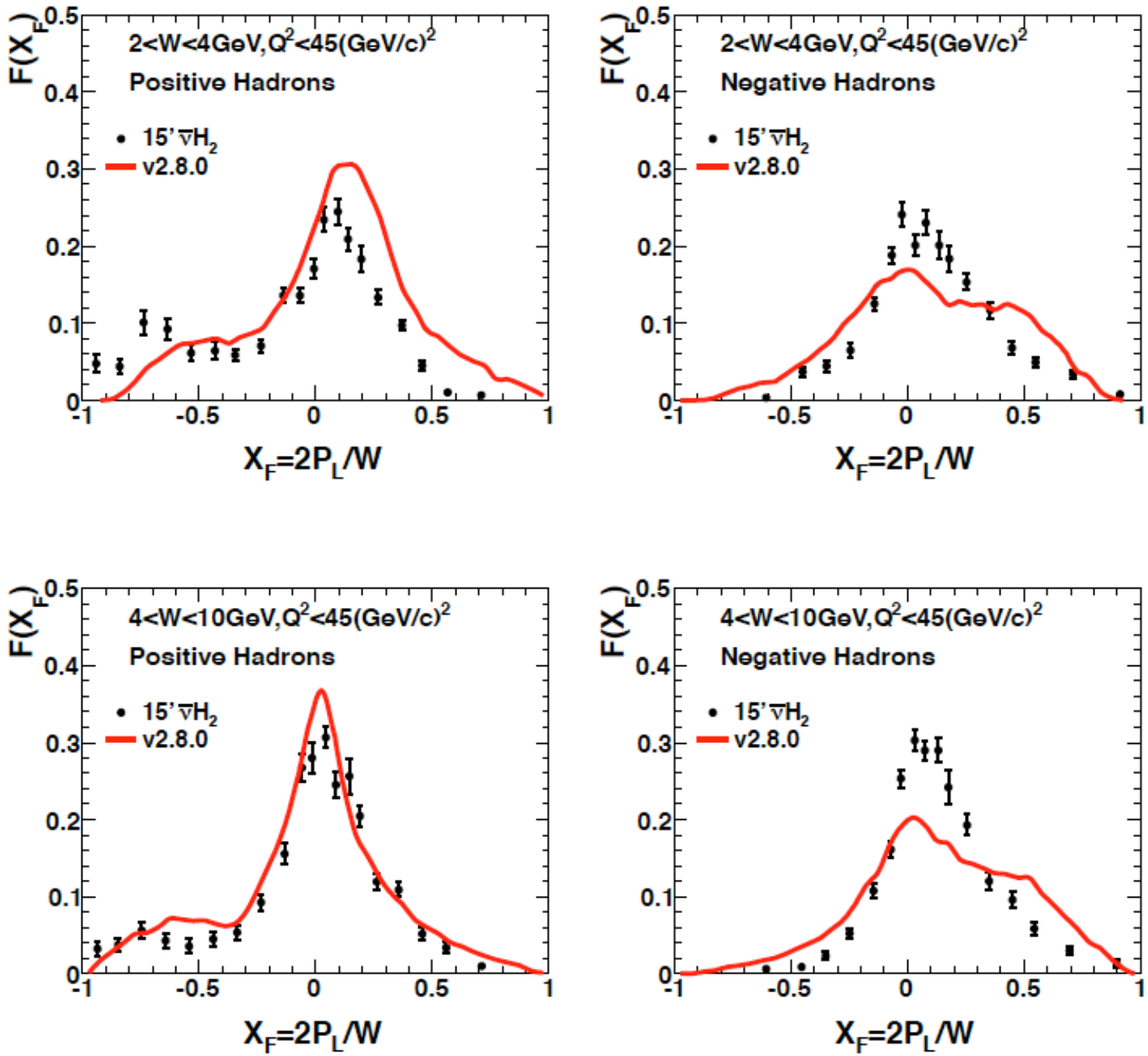
$$x_F \equiv \frac{p_L^*}{p_{L,\max}^*}$$







Data: M. Derrick et al., Phys. Rev. D 24, 1071 (1981) [Erratum-ibid. D 30, 1129 (1984)].


2<W<4GeV,Q²<45(GeV/c)²
Positive Hadrons
15' $\bar{\nu}H_2$
v2.8.0
F(X_F)
X_F=2P_L/W
2<W<4GeV,Q²<45(GeV/c)²
Negative Hadrons
15' $\bar{\nu}H_2$
v2.8.0
F(X_F)
X_F=2P_L/W
4<W<10GeV,Q²<45(GeV/c)²
Positive Hadrons
15' $\bar{\nu}H_2$
v2.8.0
F(X_F)
X_F=2P_L/W
4<W<10GeV,Q²<45(GeV/c)²
Negative Hadrons
15' $\bar{\nu}H_2$
v2.8.0
F(X_F)
X_F=2P_L/W

$$z \equiv \frac{E_{hadron}}{\nu}$$

Fraction of the energy transfer carried by a particular hadron in the lab frame.

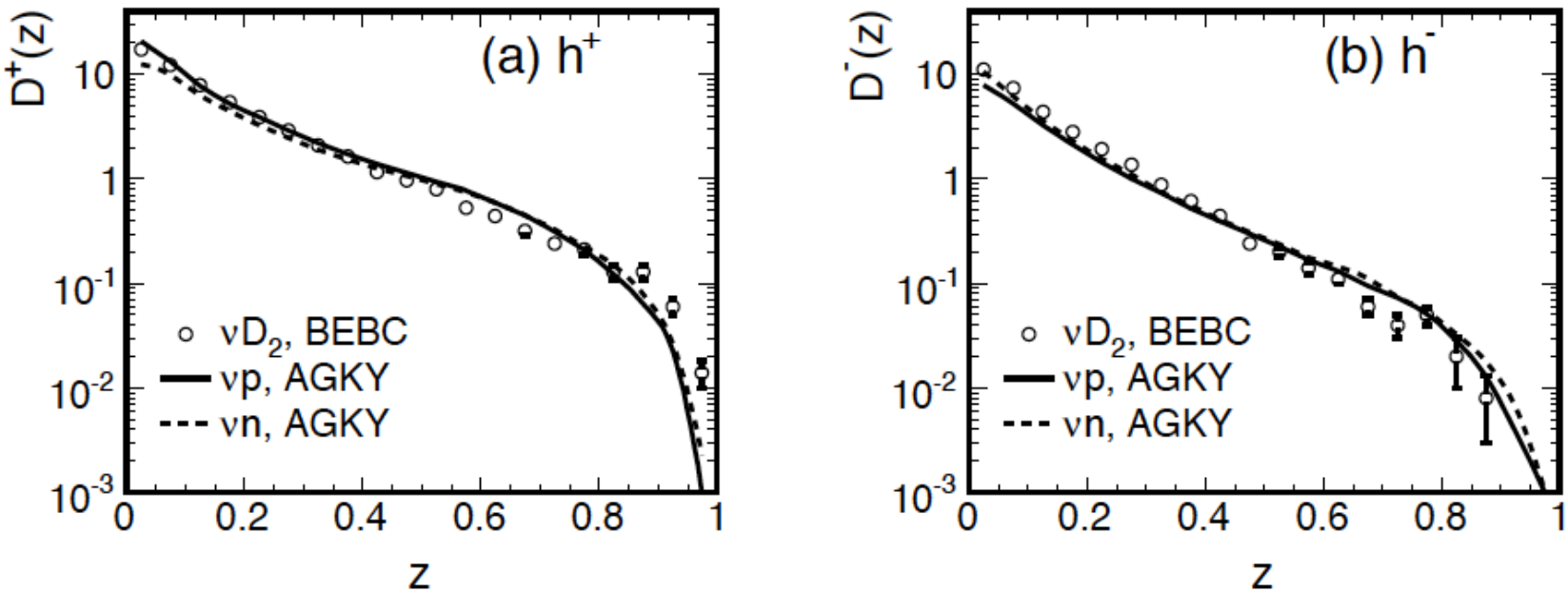


Figure 10: Fragmentation functions for positive (a) and negative (b) hadrons. Applied cuts: $W^2 > 5(GeV/c^2)^2$, $Q^2 > 1(GeV/c)^2$. Data points are taken from [23].

T. Yang et al, Eur.Phys.J. C63 (2009) 1-10.
T. Yang, Ph. D Thesis, Stanford U (2009)

“Inclusive Charged Hadron Spectra in nu-A and nubar-A Interactions at E_ν<30 GeV” - SKAT, ZPC 21, 197-204 (1984):

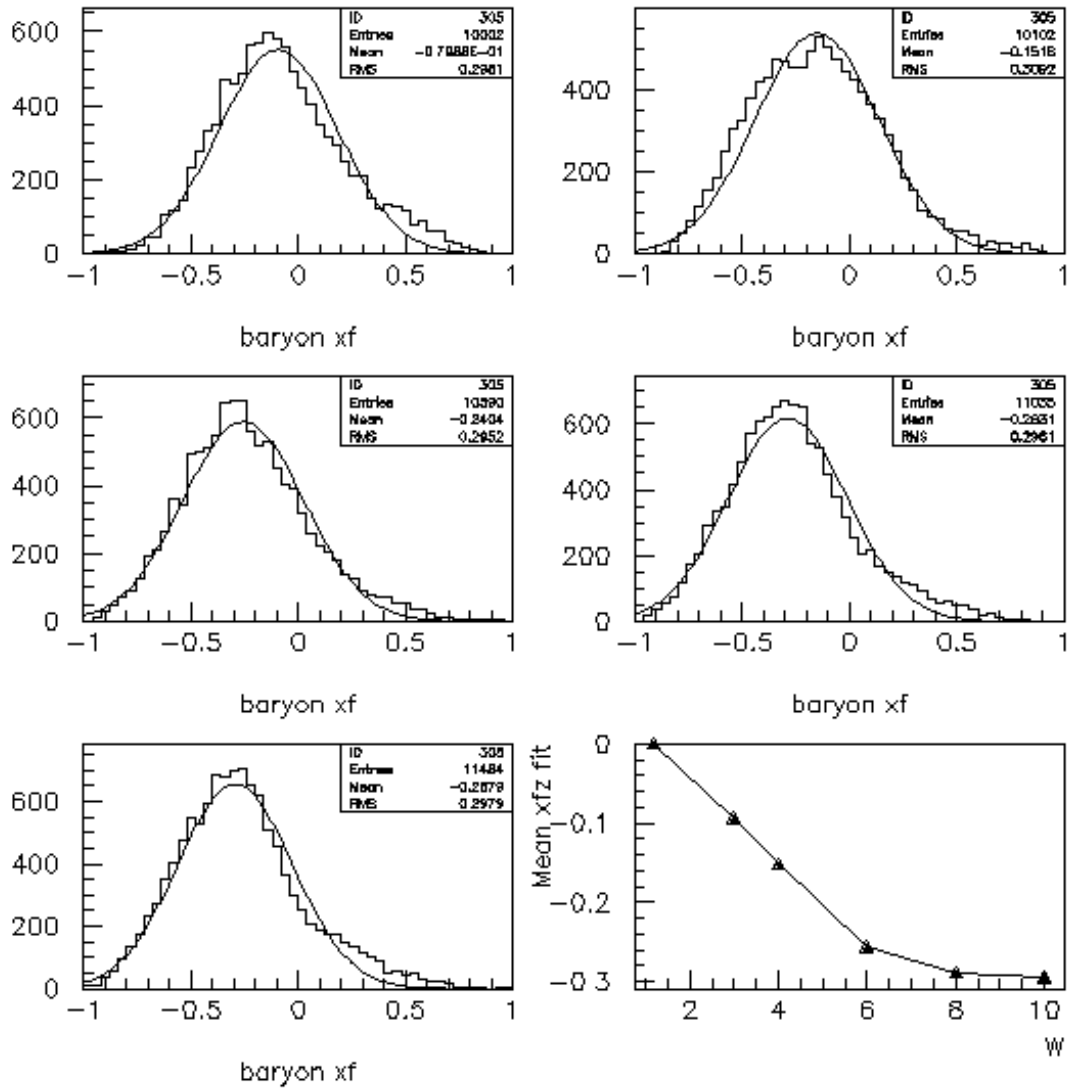
“The phase space model used reproduces the main features of our data *rather well* up to $W^2 = 25GeV^2$.” (emphasis mine)

“The recoil nucleon is generated with a flat distribution in Feynman x_F in the range $-0.95<x_F<0.00$ exponentially decreasing in the forward hemisphere.” [ref. to Cooper, .

Also a question about the use of the particular baryon x_F PDF.

It is based on data at higher invariant mass (W> 4 GeV).

Introduce a W dependence to the baryon x_F distribution?



"Mean charged multiplicities in charged-current neutrino scattering on hydrogen and deuterium"

Kuzmin and Naumov, arXiv:1311.4047

Extremely careful examination of data:

- Identifying duplicate data sets
- Only data without kinematic cuts used in fits
- A variety of other careful tests and consistency checks

Suggested fitting functions:

$$\langle n_{\rm ch} \rangle = \begin{cases} a_1 + b_1 \ln X + c_1 \ln^2 X & \text{for } X \le X_0, \\ a_2 + b_2 \ln X + c_2 \ln^2 X & \text{for } X > X_0. \end{cases}$$

$a_1 = 2$
$b_1 = 0$
$c_2 = 0$

gives good fits

Comparisons to generators and pi-p data.

Disagreement between hydrogen and deuterium fits.

Get from data

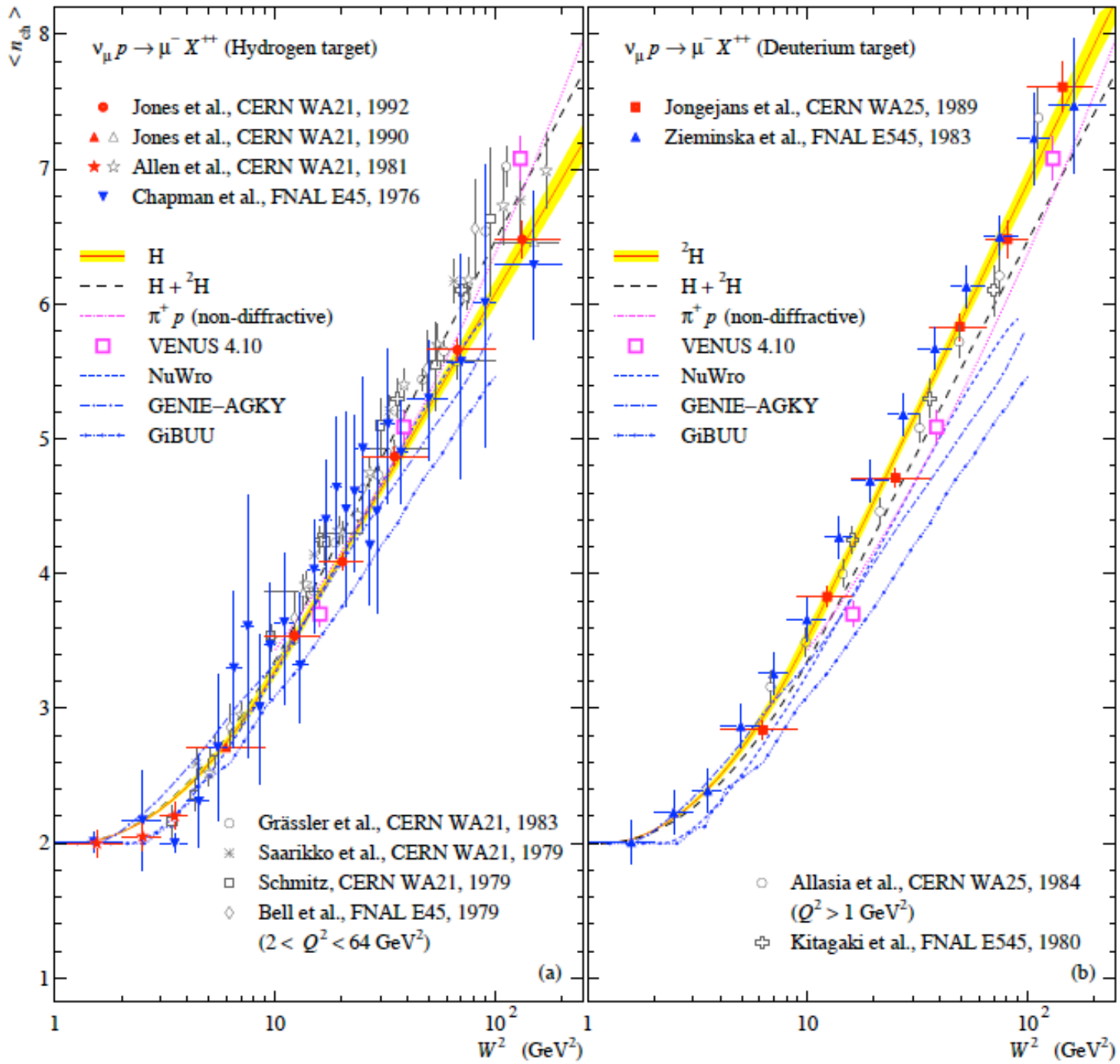
$$\frac{\langle n_{\rm ch}^{\nu p} \rangle_{\rm free}}{\langle n_{\rm ch}^{\nu p} \rangle_{\rm bound}} = \frac{\langle n_{\rm ch}^{\nu n} \rangle_{\rm free}}{\langle n_{\rm ch}^{\nu n} \rangle_{\rm bound}}$$

Apply to get "free" neutron values

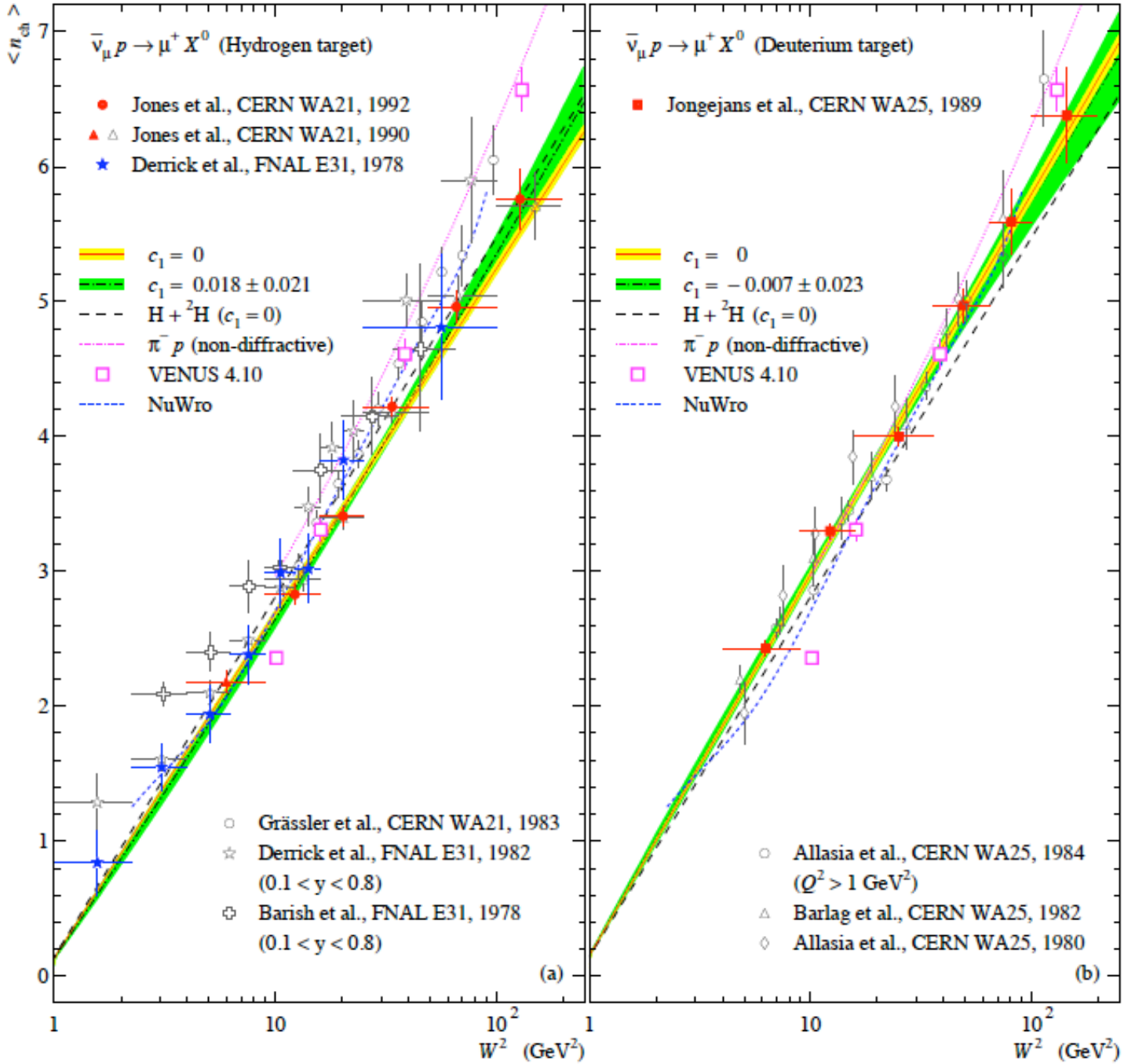
Author(s), experiment, publ. date	Ref.	Target	W range	Kinematic cuts	Intercept a	Slope b
			$\nu_\mu p \to \mu^- X^{++}$			
Coffin *et al.*, FNAL E45, 1975	[21]	H	$4-200$		1.0 ± 0.3	1.1 ± 0.1
Chapman *et al.*, FNAL E45, 1976	[22]	H	$4-200$		1.09 ± 0.38	1.09 ± 0.03
Bell *et al.*, FNAL E45, 1979	[23]	H	$4-100$	$Q^2 = 2-64$ GeV^2	–	1.35 ± 0.15
Kitagaki *et al.*, FNAL E545, 1980	[26]	^{2}H	$1-100$		0.80 ± 0.10	1.25 ± 0.04
Zieminska *et al.*, FNAL E545, 1983	[27]	^{2}H	$4-225$		0.50 ± 0.08	1.42 ± 0.03
Saarikko *et al.*, CERN WA21, 1979	[28]	H	$3-200$		0.68 ± 0.04	1.29 ± 0.02
Schmitz, CERN WA21, 1979	[29]	H	$4-140$		0.38 ± 0.07	1.38 ± 0.03
Allen *et al.*, CERN WA21, 1981	[30]	H	$4-200$		0.37 ± 0.02	1.33 ± 0.02
Grässler *et al.*, CERN WA21, 1983	[32]	H	$11-121$		-0.05 ± 0.11	1.43 ± 0.04
Jones *et al.*, CERN WA21, 1990	[33]	H	$16-196$		0.911 ± 0.224	1.131 ± 0.086
Jones *et al.*, CERN WA21, 1992	[34]	H	$9-200$		0.40 ± 0.13	1.25 ± 0.04
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	$2-60$		1.07 ± 0.27	1.31 ± 0.11
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	$8-144$	$Q^2 > 1$ GeV^2	0.13 ± 0.18	1.44 ± 0.06
			$\bar{\nu}_\mu p \to \mu^+ X^0$			
Derrick *et al.*, FNAL E31, 1976	[14]	H	$4-100$	$y > 0.1$	0.04 ± 0.37	1.27 ± 0.17
Singer, FNAL E31, 1977	[15]	H	$4-100$	$y > 0.1$	0.78 ± 0.15	1.03 ± 0.08
Derrick *et al.*, FNAL E31, 1978	[16]	H	$1-50$		0.06 ± 0.06	1.22 ± 0.03
Derrick *et al.*, FNAL E31, 1982	[20]	H	$4-100$	$0.1 < y < 0.8$	-0.44 ± 0.13	1.48 ± 0.06
Grässler *et al.*, CERN WA21, 1983	[32]	H	$11-121$		-0.56 ± 0.25	1.42 ± 0.08
Jones *et al.*, CERN WA21, 1990	[33]	H	$16-144$		0.222 ± 0.362	1.117 ± 0.141
Jones *et al.*, CERN WA21, 1992	[34]	H	$9-200$		-0.44 ± 0.20	1.30 ± 0.06
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	$7-50$		0.55 ± 0.29	1.15 ± 0.10
Barlag *et al.*, CERN WA25, 1981	[36]	^{2}H	$6-140$		0.18 ± 0.20	1.23 ± 0.07
Barlag *et al.*, CERN WA25, 1982	[37]	^{2}H	$6-140$		0.02 ± 0.20	1.28 ± 0.08
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	$8-144$	$Q^2 > 1$ GeV^2	-0.29 ± 0.16	1.37 ± 0.06
			$\nu_\mu n \to \mu^- X^+$			
Kitagaki *et al.*, FNAL E545, 1980	[26]	^{2}H	$1-100$		0.21 ± 0.10	1.21 ± 0.04
Zieminska *et al.*, FNAL E545, 1983	[27]	^{2}H	$4-225$		-0.20 ± 0.07	1.42 ± 0.03
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	$2-60$		0.28 ± 0.16	1.29 ± 0.07
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	$8-144$	$Q^2 > 1$ GeV^2	1.75 ± 0.12	1.31 ± 0.04
			$\bar{\nu}_\mu n \to \mu^+ X^-$			
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	$7-50$		0.10 ± 0.28	1.16 ± 0.10
Barlag *et al.*, CERN WA25, 1981	[36]	^{2}H	$4-140$		0.79 ± 0.09	0.93 ± 0.04
Barlag *et al.*, CERN WA25, 1982	[37]	^{2}H	$2-140$		0.80 ± 0.09	0.95 ± 0.04
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	$8-144$	$Q^2 > 1$ GeV^2	0.22 ± 0.21	1.08 ± 0.06

Kuzmin and Naumov, arXiv:1311.4047

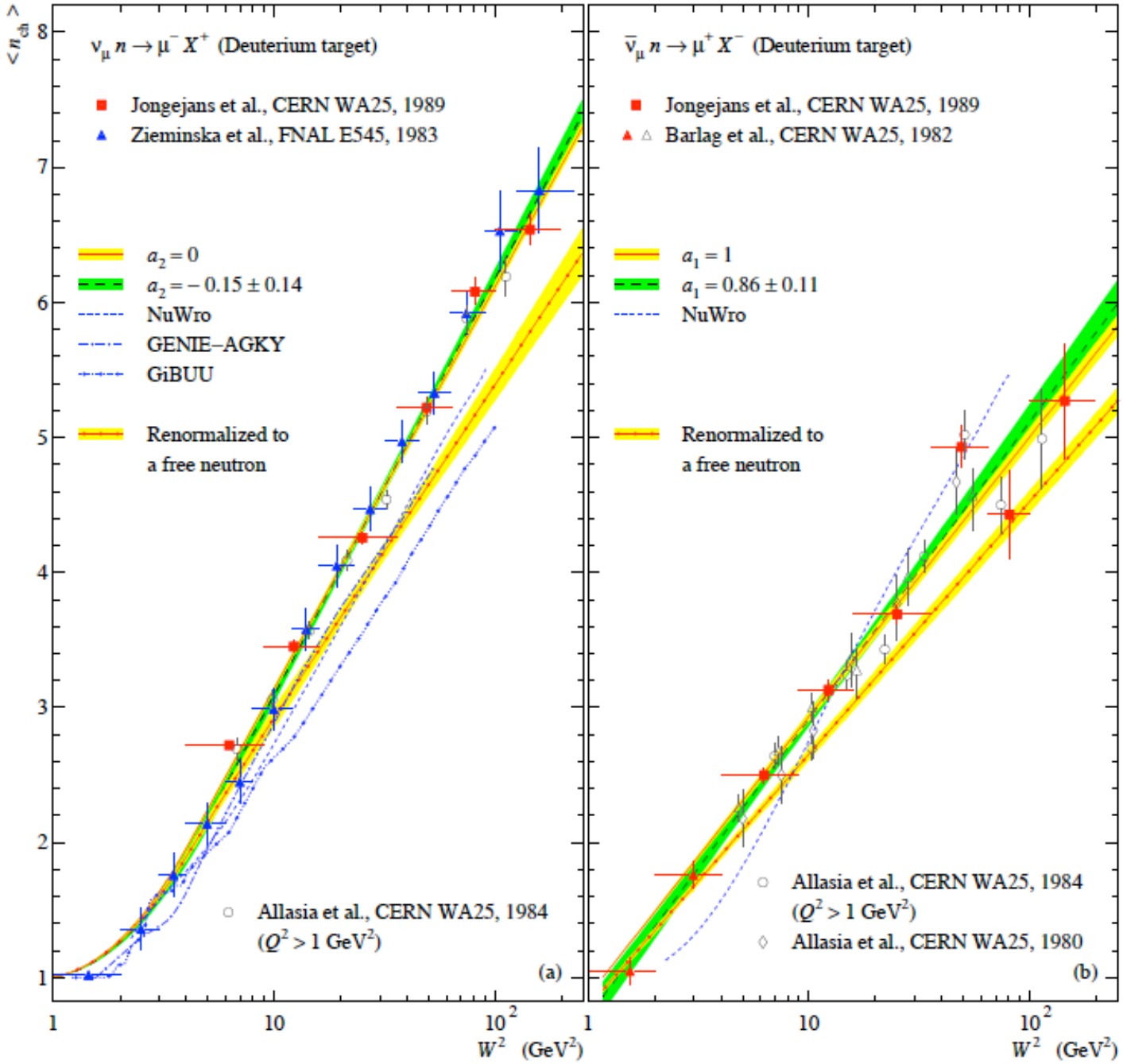
Kuzmin and Naumov, arXiv:1311.4047

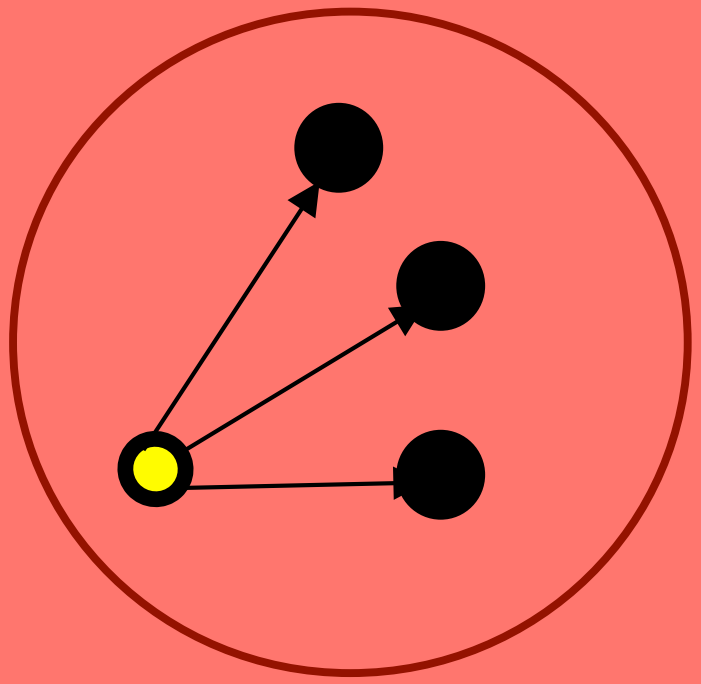


Kuzmin and Naumov, arXiv:1311.4047



Kuzmin and Naumov, arXiv:1311.4047





HADRONIZATION IN NUCLEI

HADRONIZATION IN NUCLEI

A rich theoretical topic that has been studied in some detail in lepton scattering (JLab/Hermes).

QCD Phenomena of Color Transparency (CT). At high momentum transfer, a struck particle is produced with a small size which suppresses its reinteraction cross section.

Detailed QCD models discuss different timescales over which partonic constituents form 'normal' hadrons in the medium.

In many generators, a single "formation time" is often assumed.

Based on Uncertainty Principle Arguments

QEL: GENIE transports nucleons with the full interaction probability starting from the interaction vertex.

NuWRO uses coherence lengths, no interactions during a time:

$$t_{CL} = \frac{E}{|p \cdot q|}$$

***p* is outgoing nucleon 4-vector**
***q* is 4-momentum transfer**

Sobczyk, nucl-th:1202.4197

RES: GENIE decays resonances at the interaction vertex and transports decay products with the full interaction probability. In GiBUU the delta itself is transported. In NuWRO, before decay transport the delta a distance:

$$t_{\Delta} = \frac{E_{\Delta}}{M\Gamma}$$

Sobczyk, nucl-th:1202.4197

Range of Models

Golan et al., Phys.Rev. C86 (2012) 015505

Large differences in treatment of:

- nucleons
- QE/RES events

- Smaller difference in treatment of: pions in DIS events

MC	QE	RES[a]	DIS
NEUT	–	SKAT	SKAT
FLUKA	Coh length	Rantf	Rantf
GENIE	–	–	Rantf-like
NUANCE	1 fm	1 fm	1 fm

[a] Note that every MC has its own slightly different definition of what does RES and DIS terms mean.

TABLE III. FT models in MC event generators

Transparency - Nucleons

D. Rohe et al (E97-006)

$$T_A(Q^2) = \frac{\int_V d\mathbf{p}_m \, dE_m \, N^{exp}(E_m, \mathbf{p}_m)}{\int_V d\mathbf{p}_m \, dE_m \, N^{sim}(E_m, \mathbf{p}_m)}$$

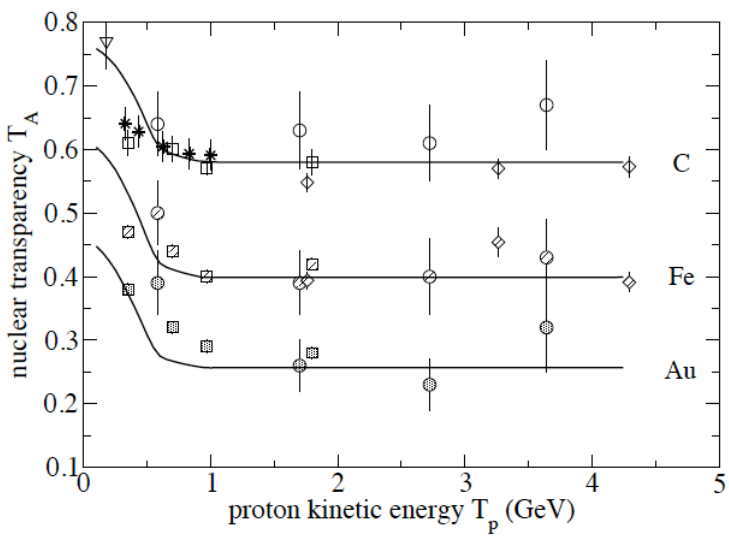


FIG. 4: Nuclear transparency T_A for C, Fe and Au as a function of the proton kinetic energy T_p compared to the correlated Glauber calculations (solid lines). The data indicated by circles are from the NE18–experiment at SLAC [22], squares and diamonds are Jlab data of [23] and [1] and from Bates [3] (triangle down). The result indicated by stars is obtained with the correlated spectral function of [8].

Hadron Attenuation

$$R_M^h(z_h, \nu, p_T^2, Q^2) = \frac{\left.\frac{N_h(z_h,\nu,p_T^2,Q^2)}{N_e(\nu,Q^2)}\right|_A}{\left.\frac{N_h(z_h,\nu,p_T^2,Q^2)}{N_e(\nu,Q^2)}\right|_D}$$

EMC, HERMES, JLab

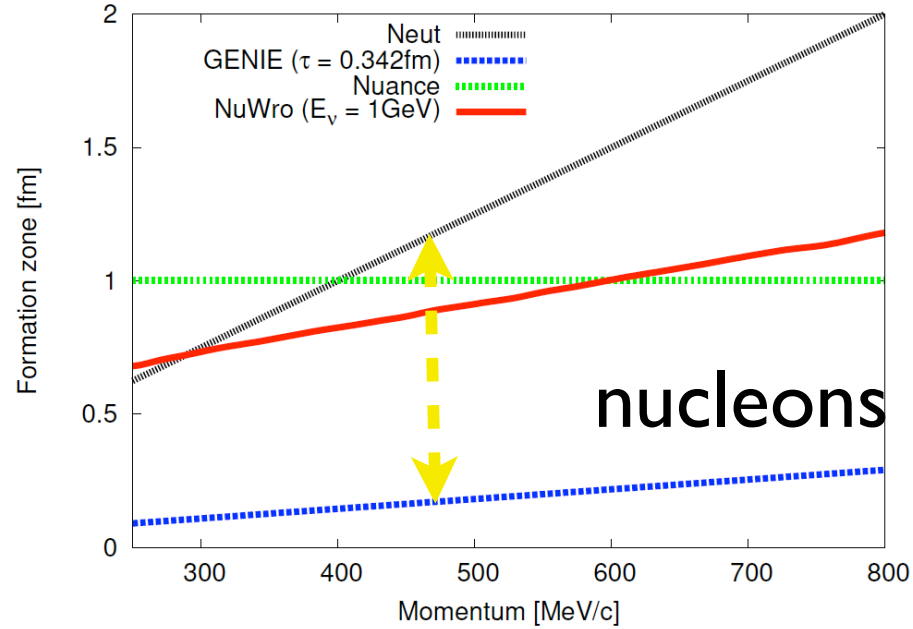
"DIS" Events
(really non-resonant inelastic)

Starting point in the neutrino world for this was the treatment proposed by the SKAT experiment.

$$l = \frac{|\vec{p}|}{\mu^2}$$

SKAT: Baranov et al., PHE 84-04 (1984)

$$\mu = 0.08^{+0.05}_{-0.04}\,\mathrm{GeV}^2$$



Sobczyk, nucl-th:1202.4197

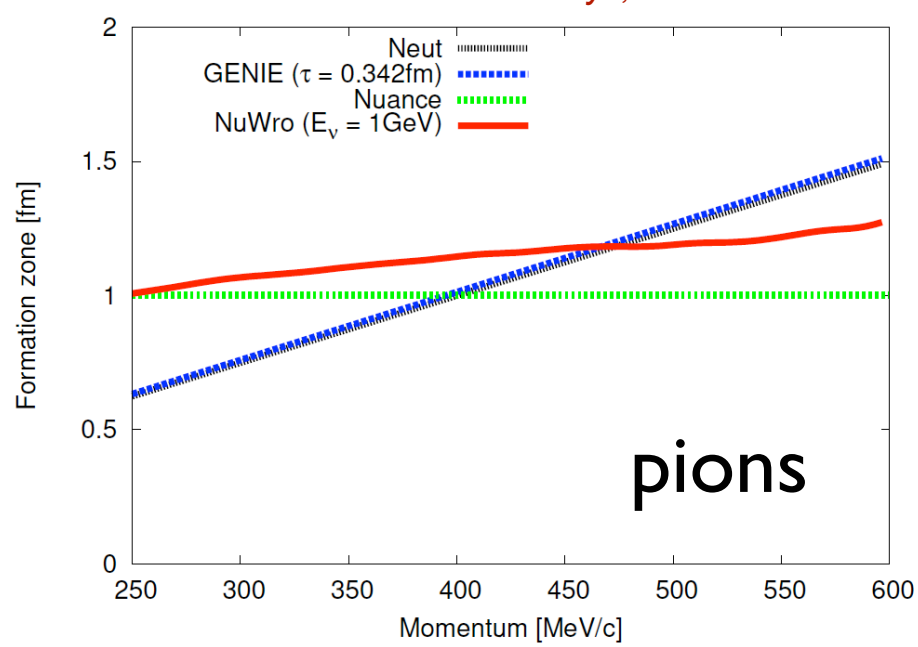
DPMJET/NOMAD treatment is based on the equation of Ranft et al.

$$l = \frac{|\vec{p}|(c\tau_0)m}{(m^2 + Kp_t^2)}$$

SKAT-equivalent with:

$c\tau_0 = 0.342 \pm 0.171$ fm

K=0

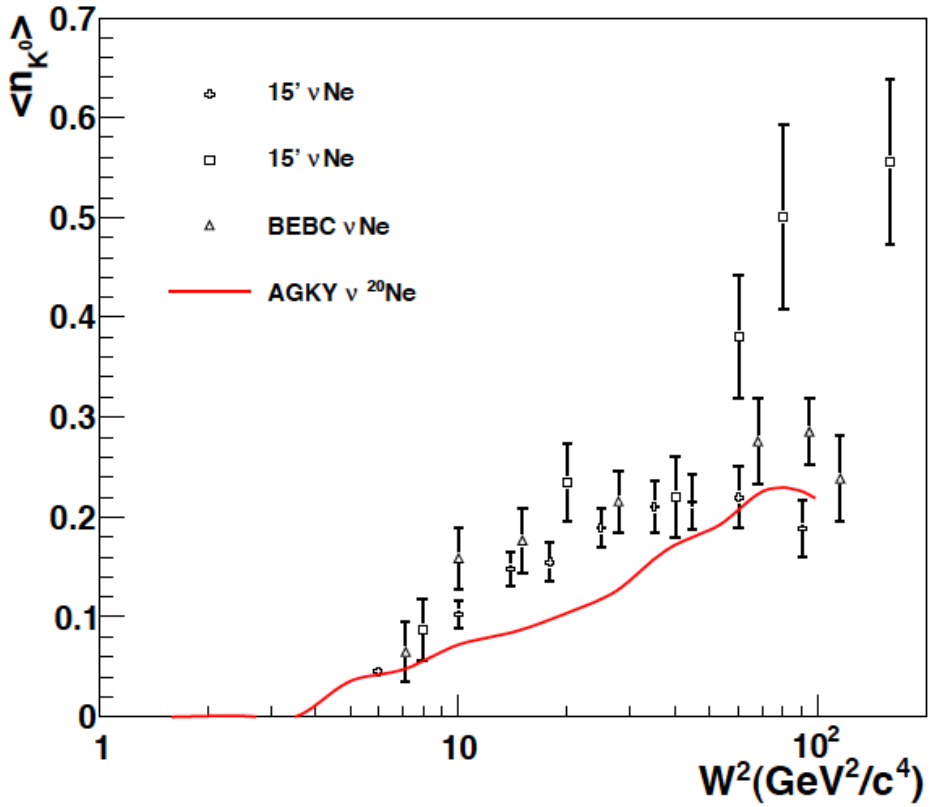


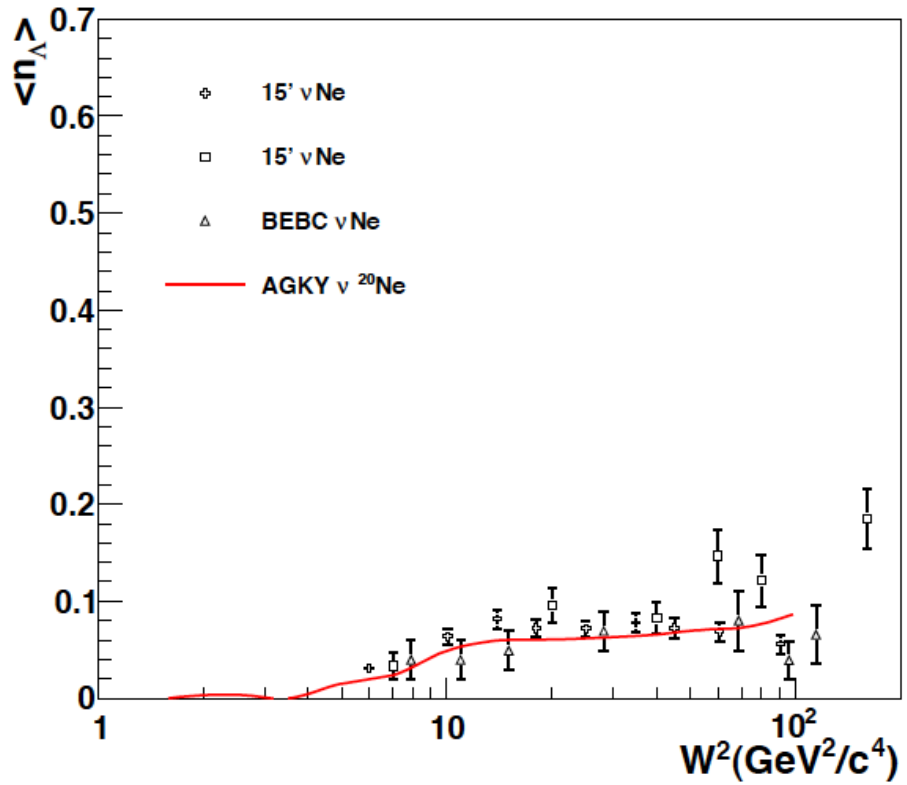
So SKAT expression holds for pions, but not nucleons. To agree with SKAT GENIE needs different formation times for pions and nucleons.

Do not trust F/B data for experiments which do not account for the ambiguity in pi/K/p mass assignment.

Grassler, NPB 223 (1982) 269:
"It should be noted that the results presented here for the positive multiplicities in vp scattering differ from our results published previously (Allen et al.). In contrast to ref. [1] $<n_F^+>$ is now lower than $<n_B^+>$ over the whole energy range … The discrepancy is mainly due to particle misidentification which has been corrected for in this, but not in the earlier, analysis.

For nubar-p scattering we find $<n_F^->$ > $<n_B^->$ and $<n_F^+>$ <= $<n_B^+>$. The latter relation may be contrasted with the observation of a previous nubar H2 experiment (Derrick et al, PRD 25 (1982) 624), which did not correct for the π:K:p mass assignment ambiguities and which found $<n_F^+>$ > $<n_B^+>$"


$\langle n_{K^0} \rangle$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
10^2
$W^2(GeV^2/c^4)$
15' νNe
15' νNe
BEBC νNe
AGKY ν ^{20}Ne


$\langle n_{\Lambda} \rangle$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
10^2
$W^2(GeV^2/c^4)$
15' νNe
15' νNe
BEBC νNe
AGKY ν ^{20}Ne