Hadronization processes in neutrino interactions

1. Introduction
2. Hadronization model
3. PYTHIA tuning
4. Conclusion

Teppei Katori
Queen Mary University of London

NuFact 2014, Glasgow, Scotland, UK, August 27, 2014

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1. Introduction

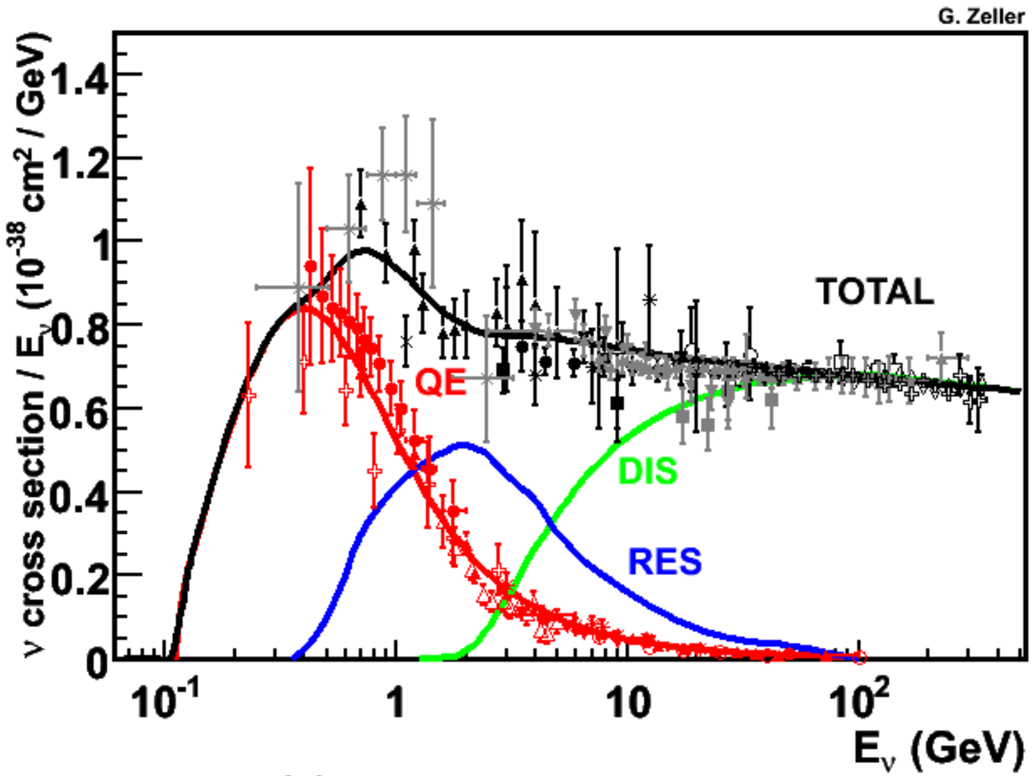
2. Hadronization model

3. PYTHIA tuning

4. Conclusion

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments
- Past to Present: K2K, MiniBooNE, MINOS, T2K
- Present to Future: T2K, NOvA, PINGU, JUNO, HyperK, LBNF



ν_μCC cross section per nucleon

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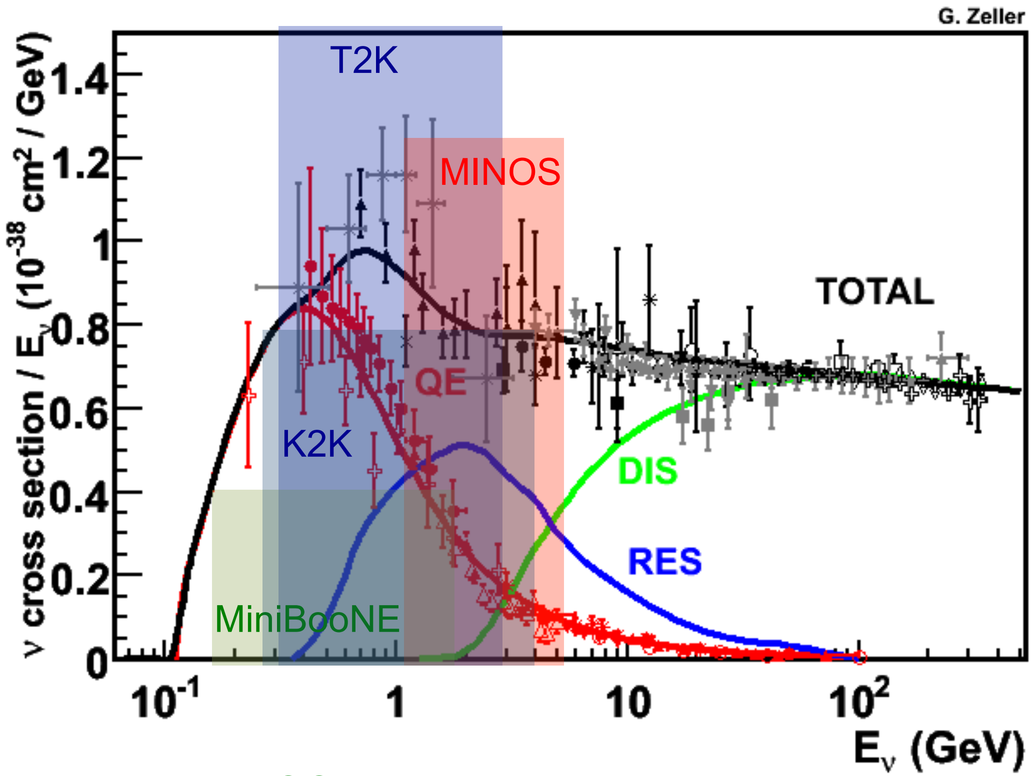

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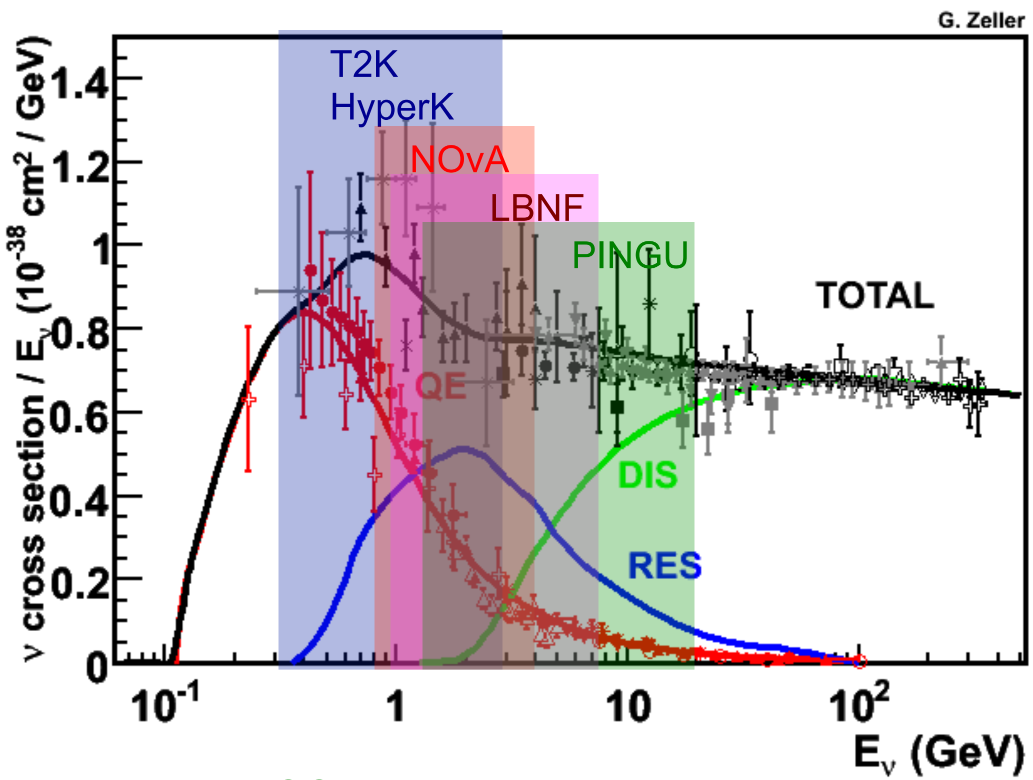

ν_μCC cross section per nucleon

Alvarez-Ruso,Hayato,Nieves,ArXiv:1403.2673

1. Next generation neutrino oscillation experiments

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2-10 GeV seems more important, it's the time to understand pion physics!

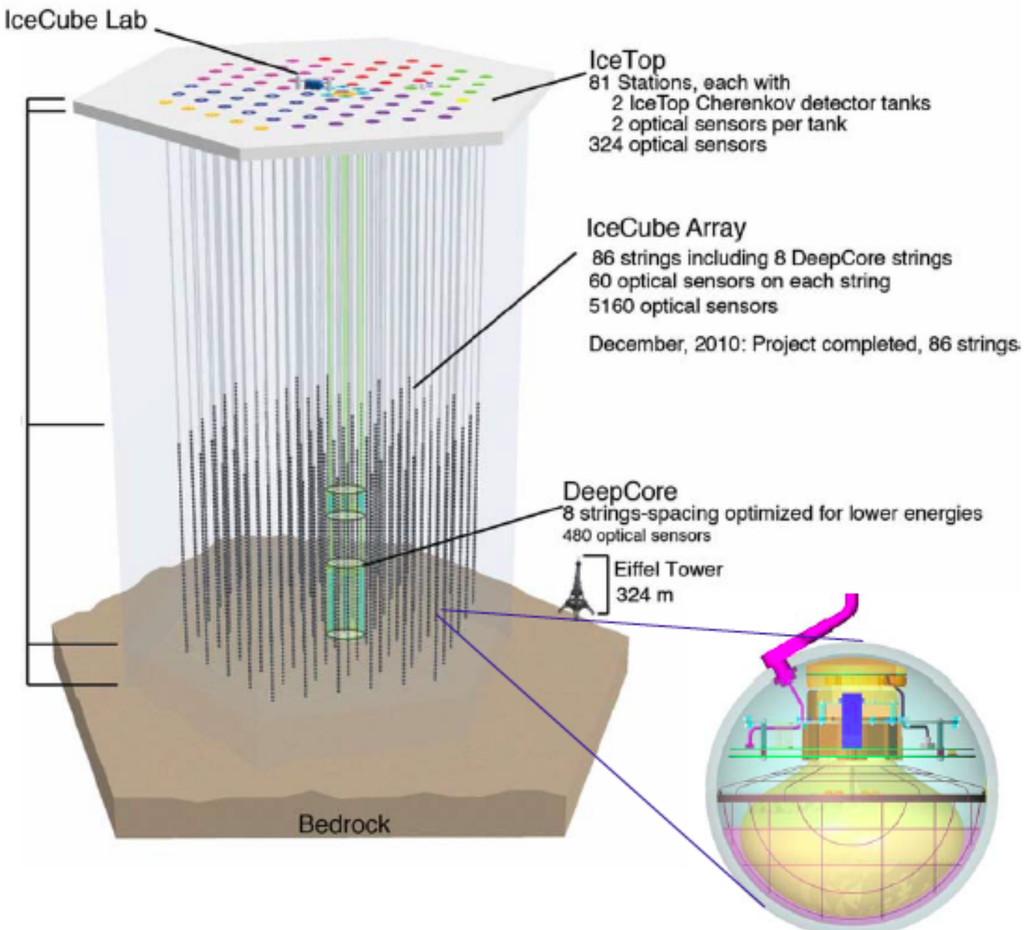
- Resonance production
- Coherent production
- Resonance to DIS transition (shallow inelastic scattering, SIS)
- FSI (pion absorption, charge exchange, re-scattering)
- DIS (GRV98, Bodek-Yang correction)
- Hadronization

1. PINGU (Precision IceCube Next Generation Upgrade)

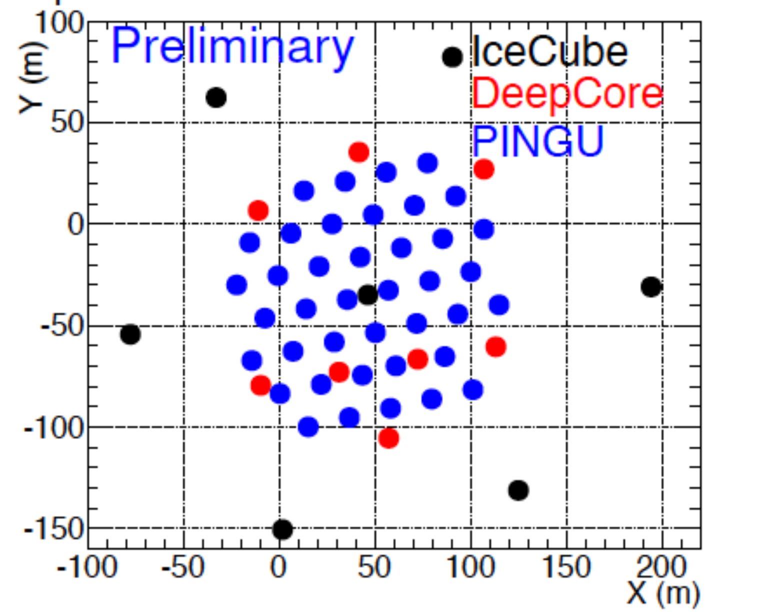
More string in smaller region, but still ~3 Mton

- Muon neutrino disappearance measurement for neutrino mass hierarchy (NMH)
- Important energy region is 2-10 GeV
- P($\nu_\mu \rightarrow \nu_\mu$) of NMH is equivalent with P(anti-$\nu_\mu \rightarrow$anti-ν_μ) of IMH.

$$P^{\mathrm{IH}}_{\alpha\beta} = \bar{P}^{\mathrm{NH}}_{\alpha\beta}, \qquad \bar{P}^{\mathrm{IH}}_{\alpha\beta} = P^{\mathrm{NH}}_{\alpha\beta}$$



Top view of the PINGU new candidate detector



Talk by JP Athayde Marcondes de Andre
(WG1 right now, next room)

Ribordy and Smirnov, PRD87(2013)113007

1. Hadronic information to improve NMH determination

Inelasticity

- It relies on measured hadron energy.
- Differential cross section is function of y.
- y-dependence of ν_μ and anti-ν_μ are different.

$$\frac{d\sigma_\nu^{CC}}{dy} = [-a_0 - a_1(1-y)^2]10^{-38}\ \mathrm{cm}^2 \frac{E_\nu}{1\ \mathrm{GeV}},$$

$$\frac{d\sigma_{\bar{\nu}CC}}{dy} = [-b_0 - b_1(1-y)^2)]10^{-38}\ \mathrm{cm}^2 \frac{E_\nu}{1\ \mathrm{GeV}},$$

$$E_\nu = E_\mu + E_h - m_N, \quad y = \frac{E_\nu - E_\mu}{E_\nu}$$

Small y

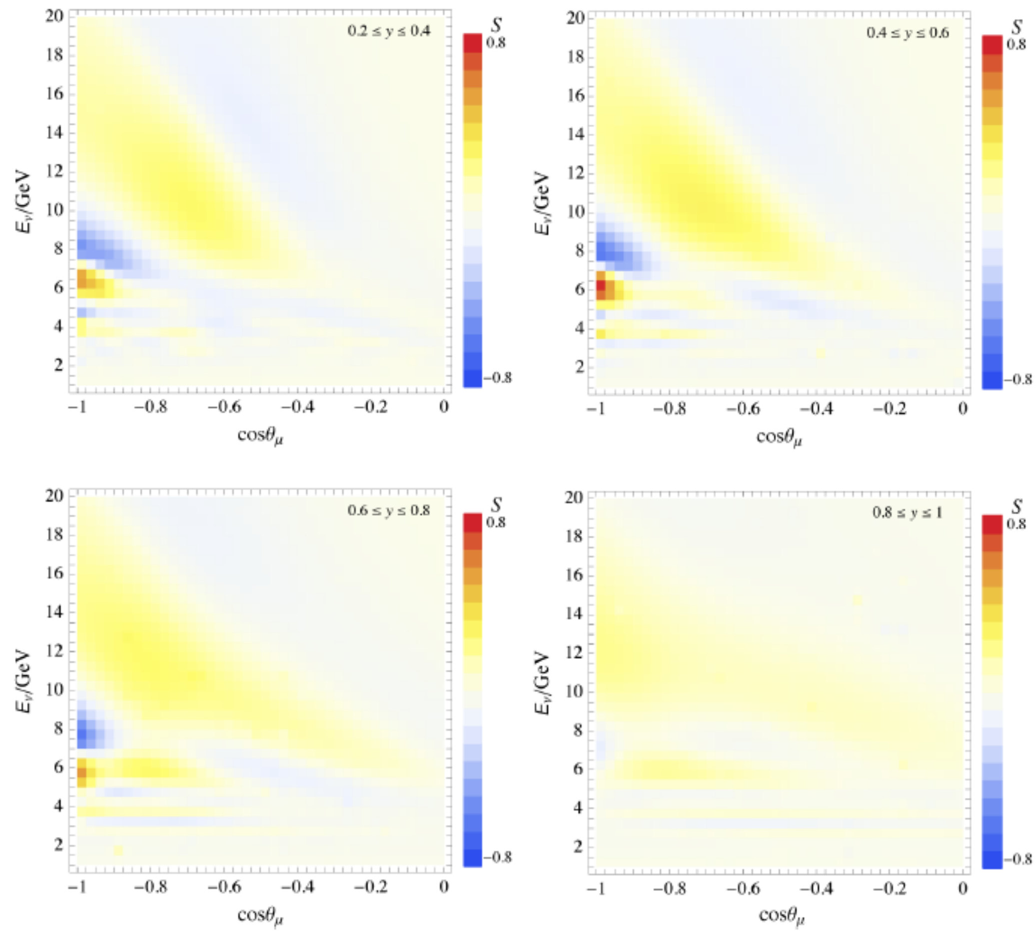
- Better angular resolution

Large y

- Better ν and anti-ν separation

Asymmetry parameter

$$S^{NI} \sim \frac{N^{IH} - N^{NH}}{\sqrt{N^{NH}}}$$



Asymmetry parameter with
function of Eν and cosθ (slice of y)

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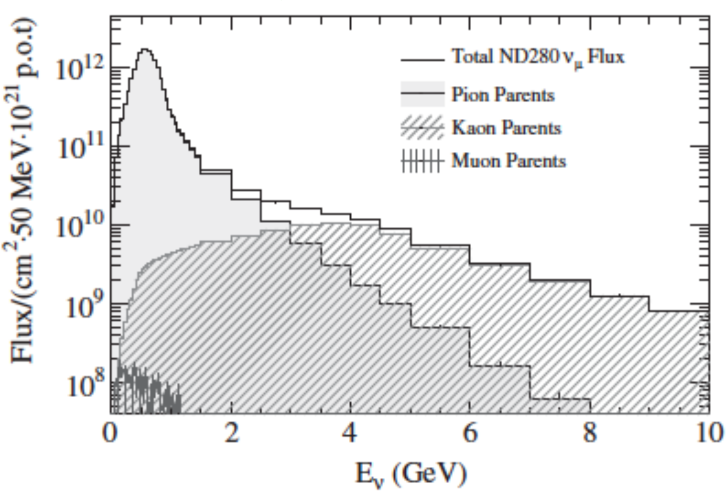
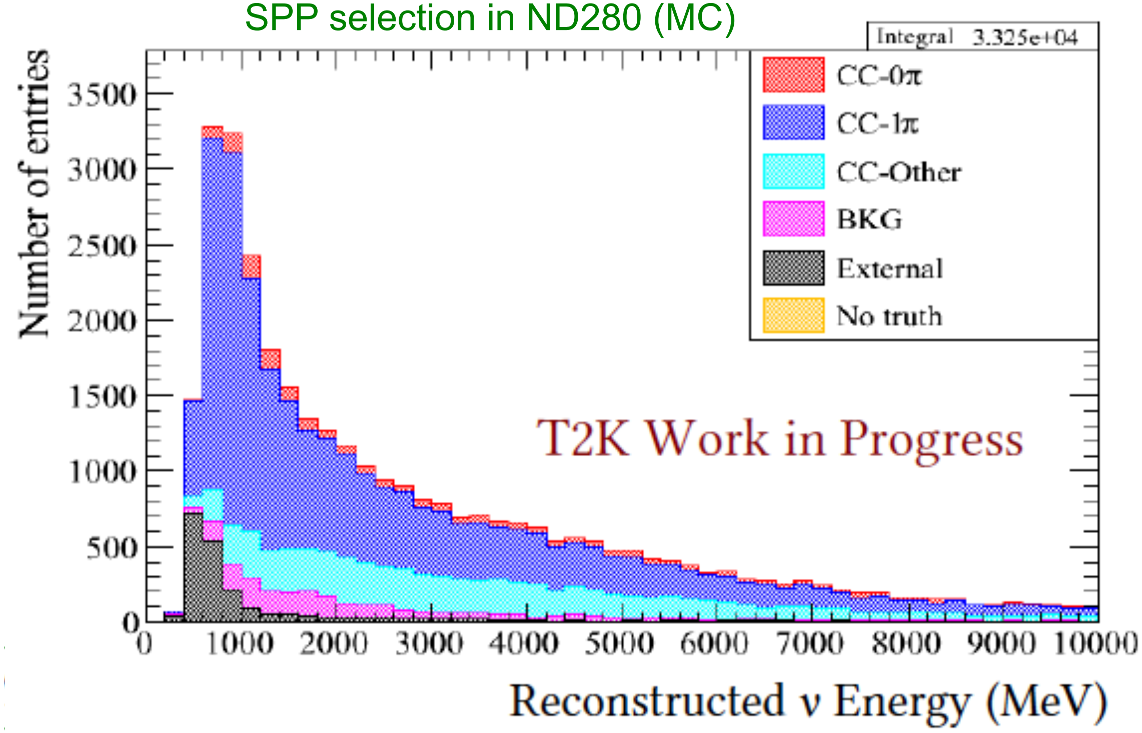
1. T2K

Multi-pion production (CC-Others)
- The largest background to single pion production (SPP) measurement
  → SPP hosts majority of "open question of neutrino cross-sections"
- Poorly understood (large systematic errors)

ν_μ-flux at ND280



SPP selection in ND280 (MC)



Hadronization in neutrino interaction seems to me an important subject for current and future experiments.

Talk by Raquel Castillo (WG2, Tuesday)

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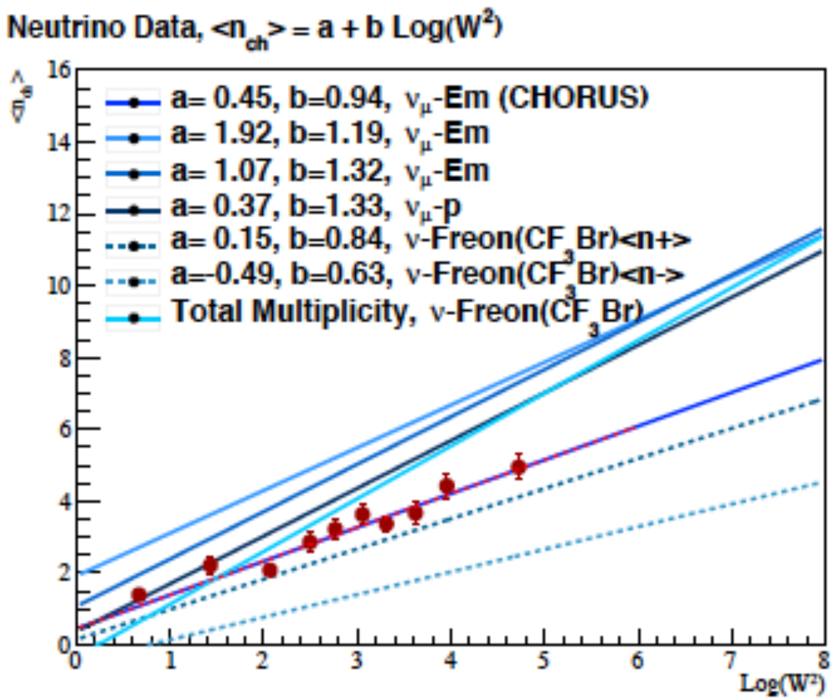
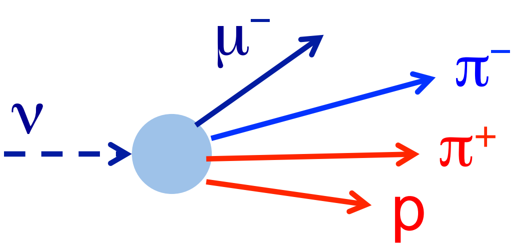
2. Hadronization model

Averaged charged hadron multiplicity $<n_{ch}>$

- Parameters extracted from data are used to model hadronization process
- The bubble chamber data are not consistent consistent



$$< n_{ch} >= a + bLog(W^2)$$

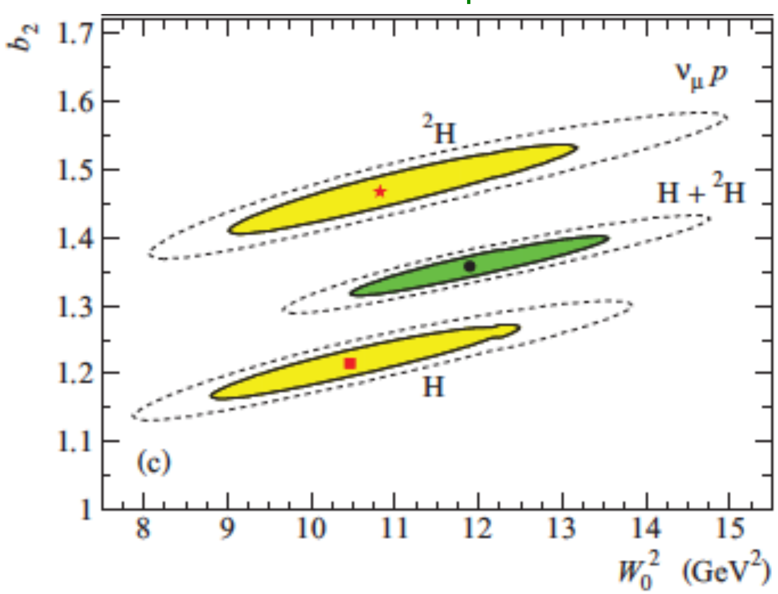


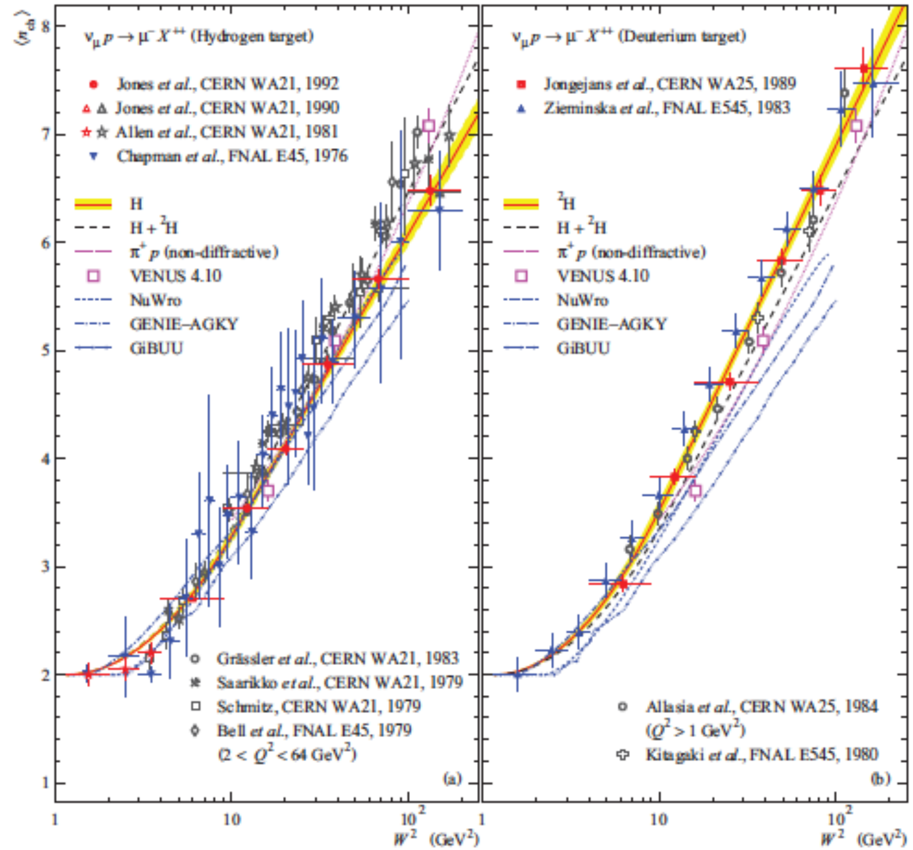
2. Hadronization model

Kuzmin-Naumov fit

- They systematically analysed all bubble chamber data
  - Difference of hydrogen and deuterium data
  - Presence of kinematic cuts
  - Better parameterization

Kuzmin-Naumov parameter





Average charged hadron multiplicity with function of W^2

2. Hadronization model

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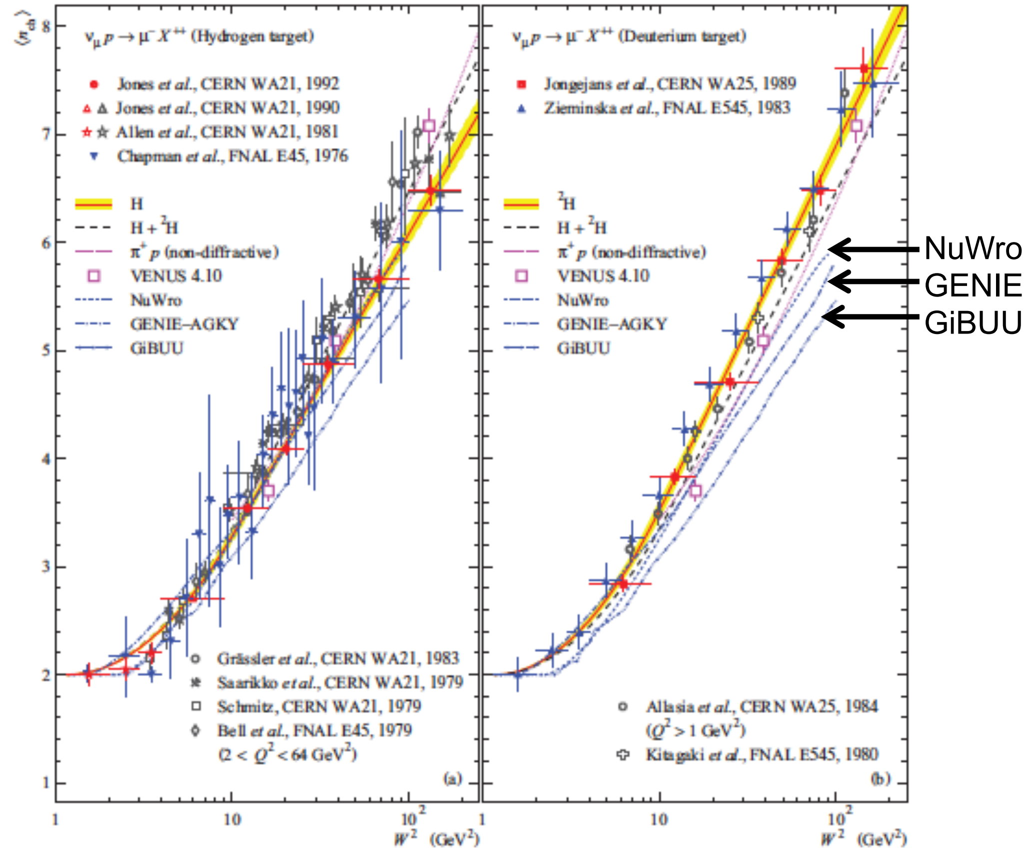
All PYTHIA-based models underestimate averaged charged hadron multiplicity data (GiBUU, GENIE, NuWro)



Average charged hadron multiplicity with function of W^2

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Kuzmin and Naumov, PRC88(2013)065501
Connolly, PhD thesis (2014)

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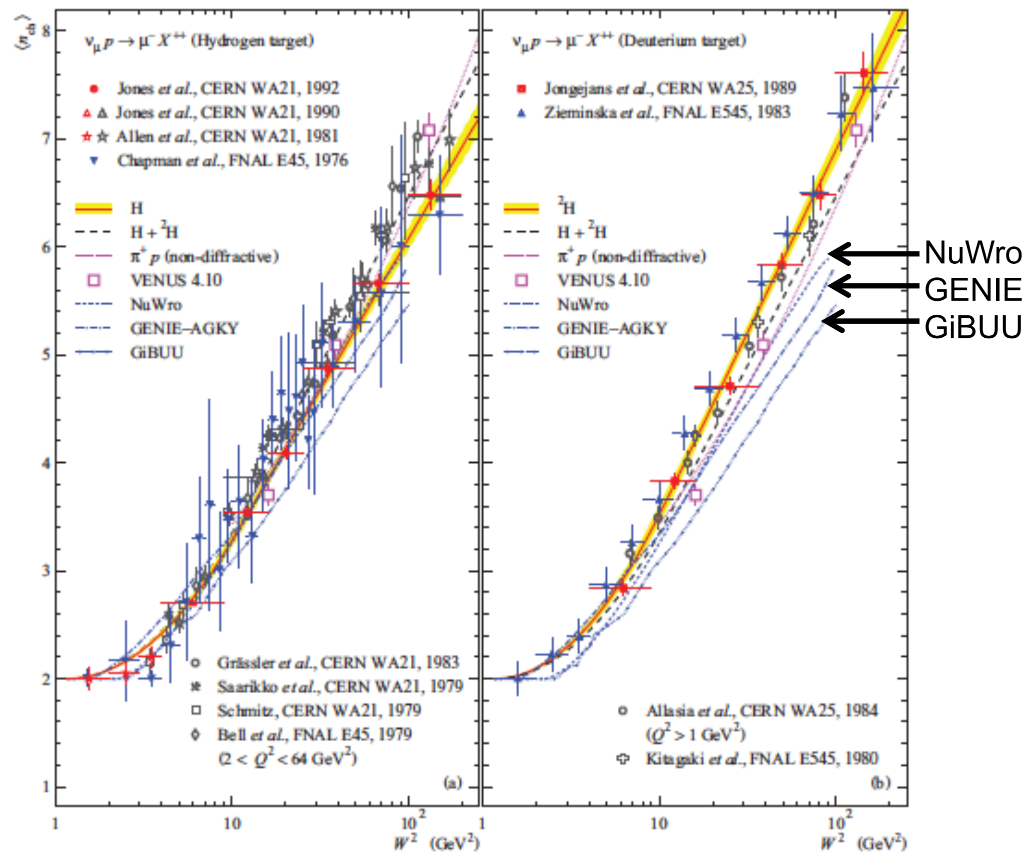
NEUT (T2K)

- It underestimates bubble chamber data



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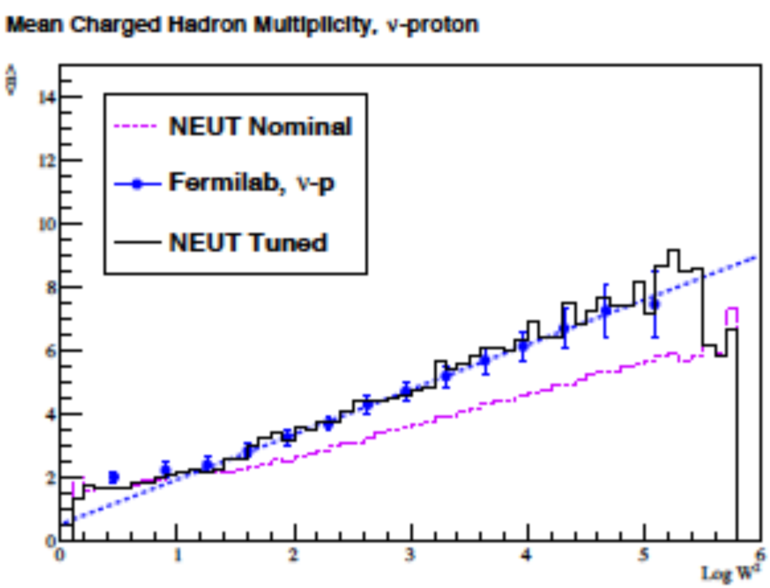

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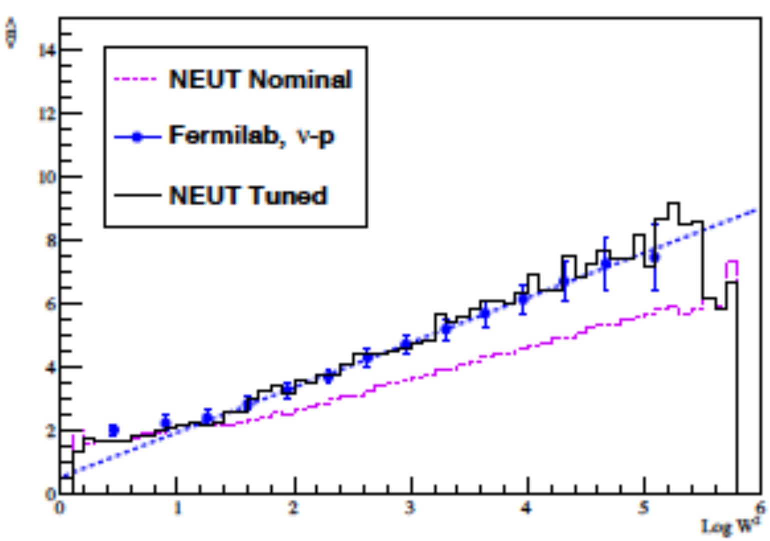
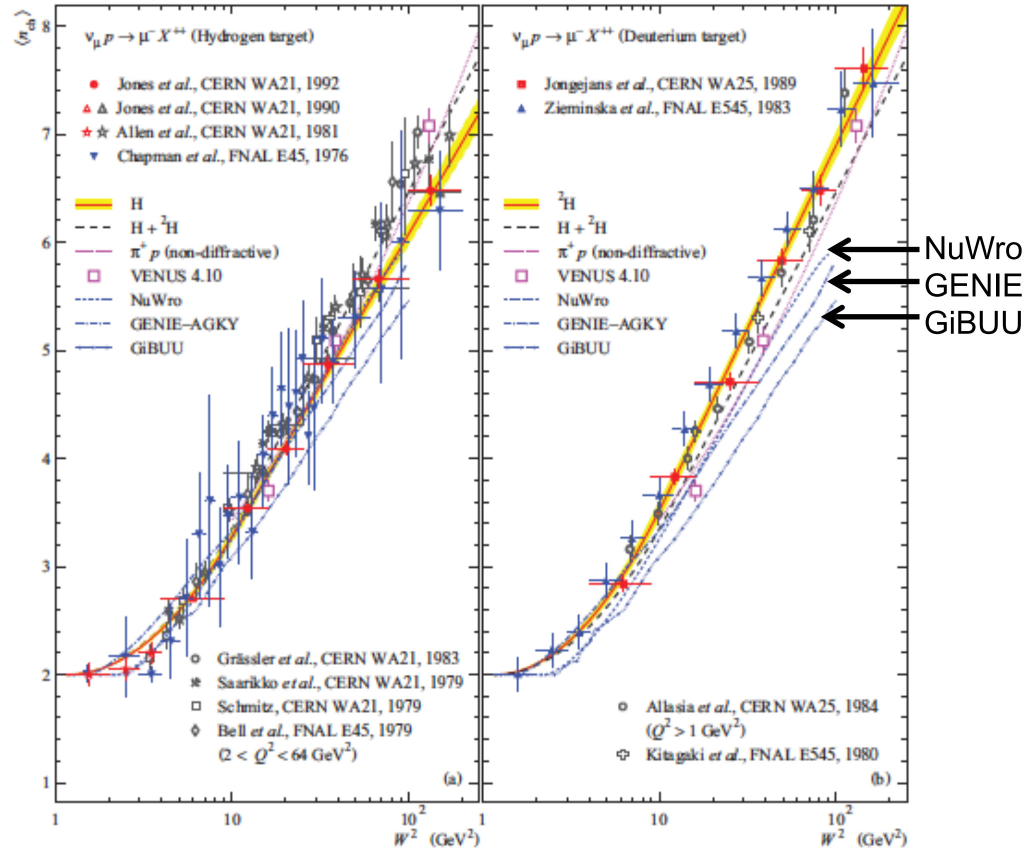




PYTHIA fragmentation based models tend to underestimate data. In fact, GENIE and NuWro tuned parameters to increase multiplicity.

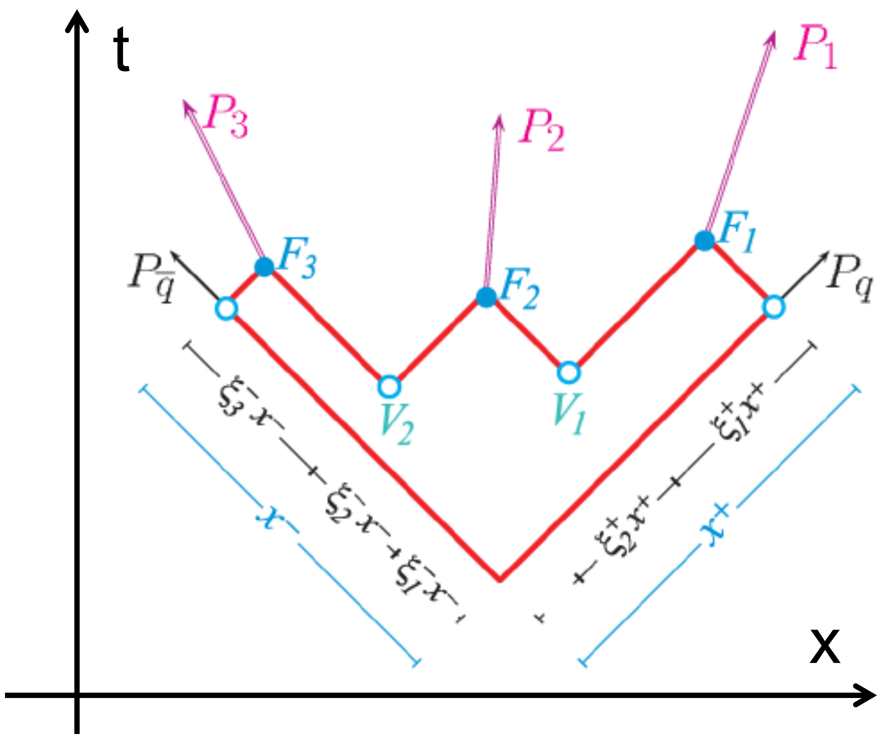
Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
Gallmeister and Falter, PLB630(2005)40

2. Hadronization

PYTHIA6

- Lund string model based fragmentation
- Used by many experiments (all collider experiments)
- Recently, everyone moves to PYTHIA8

Sketch of fragmentation from q-$\bar{q}$ string breaking



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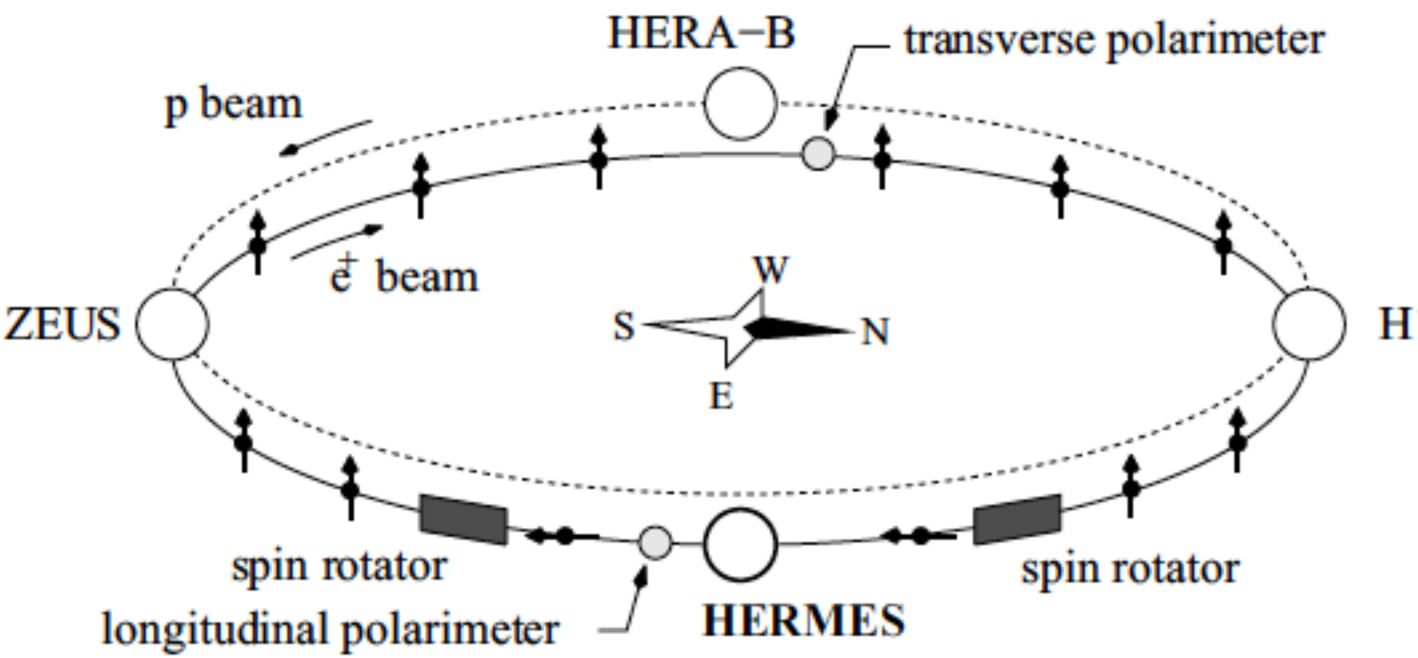
3. HERMES

Fixed target e-scattering experiment at HERA
- E=27.6 GeV
- Gas jet target (H, D, etc)
- Data taking 1995 - 2007



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Fixed target e-scattering experiment at HERA
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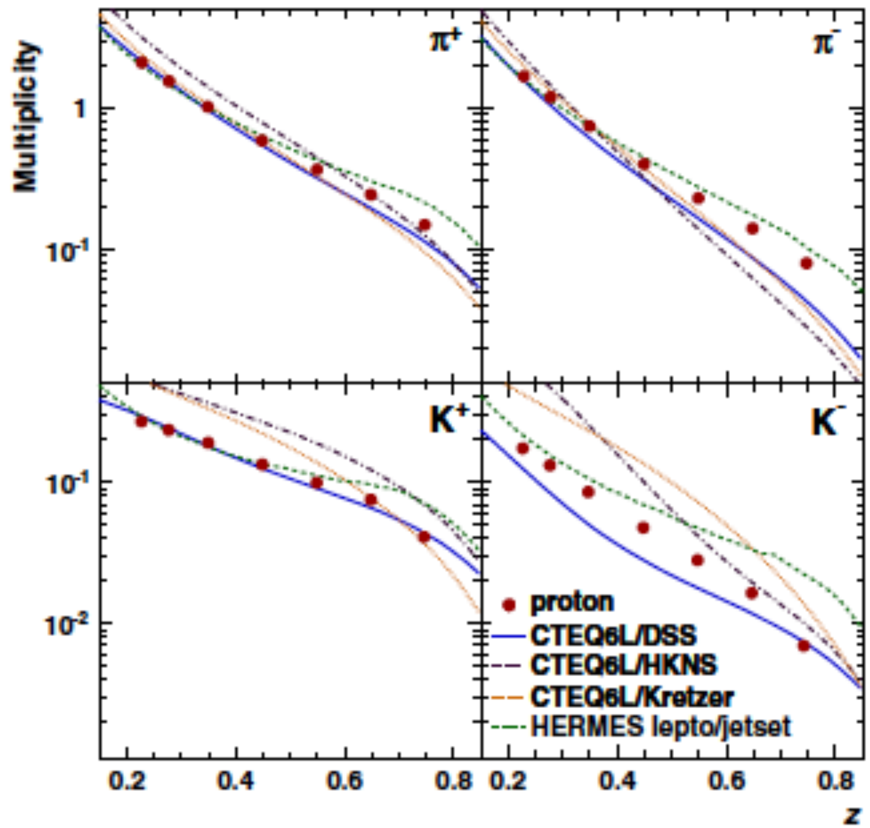
HERMES has a long history to tune PYTHIA with their own data, because default parameter set of PYTHIA is not optimized for low energy experiment, such as HERMES.

PHYSICAL REVIEW D 87, 074029 (2013)



Rubin, PhD thesis (UIUC)

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Fixed target e-scattering experiment at HERA

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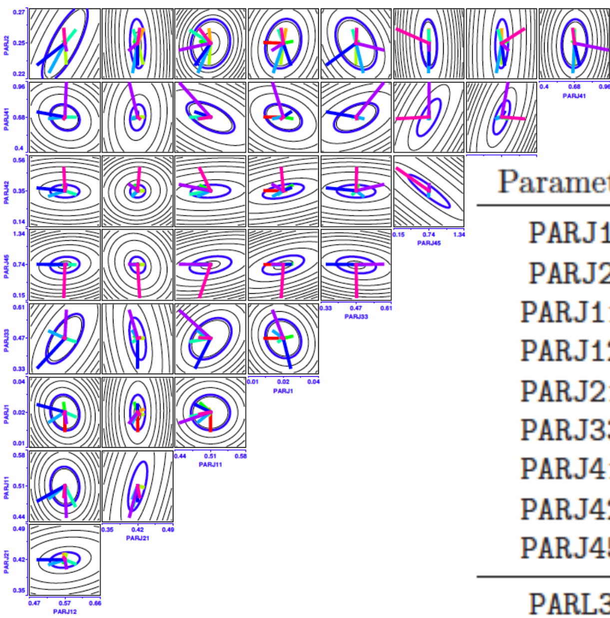
HERMES has a long history to tune PYTHIA with their own data, because default parameter set of PYTHIA is not optimized for low energy experiment, such as HERMES.

We picked one of the latest parameter set (called "Lund-scan"), and implemented in GENIE.



Parameter	$\Delta q(x)$ paper	2004c	"Lund-scan"	Parameter Description
PARJ1	0.02	0.029	0.02	Diquark suppression
PARJ2	0.20	0.283	0.25	Strange quark suppression
PARJ11	0.5*	0.5*	0.51	Vector meson suppression (light mesons)
PARJ12	0.6*	0.6*	0.57	Vector meson suppression (strange mesons)
PARJ21	0.37	0.38	0.42	Width of Gaussian $p_{h\perp}$ distribution [GeV]
PARJ33	0.8	0.8	0.47	String breaking mass cutoff
PARJ41	1.74	1.94	0.68	Lund-String "a" parameter
PARJ42	0.23	0.544	0.35	Lund-String "b" parameter
PARJ45	0.5*	1.05	0.74	"a" adjustment for diquark
PARL3	0.44	0.44	(0.44)	Gaussian width of intrinsic k_T [GeV]
PARJ23	0.03	0.01	(0.01)	Fraction of $p_{h\perp}$ distribution to have additional non-Gaussian tails
PARJ24	2.50	2.0	(2.0)	Strength of non-Gaussian $p_{h\perp}$ tails

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3. HERMES tuned PYTHIA6

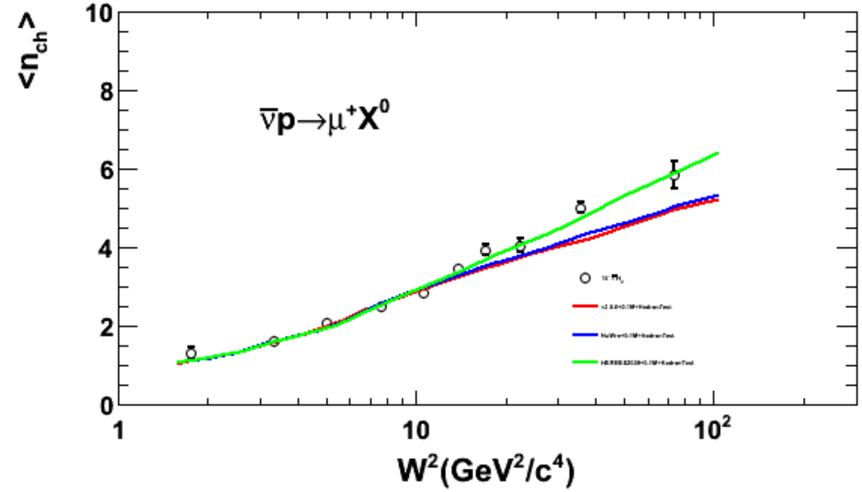
GENIE v2.8.0
- Latest version
- HERMES PYTHIA parameters are implemented

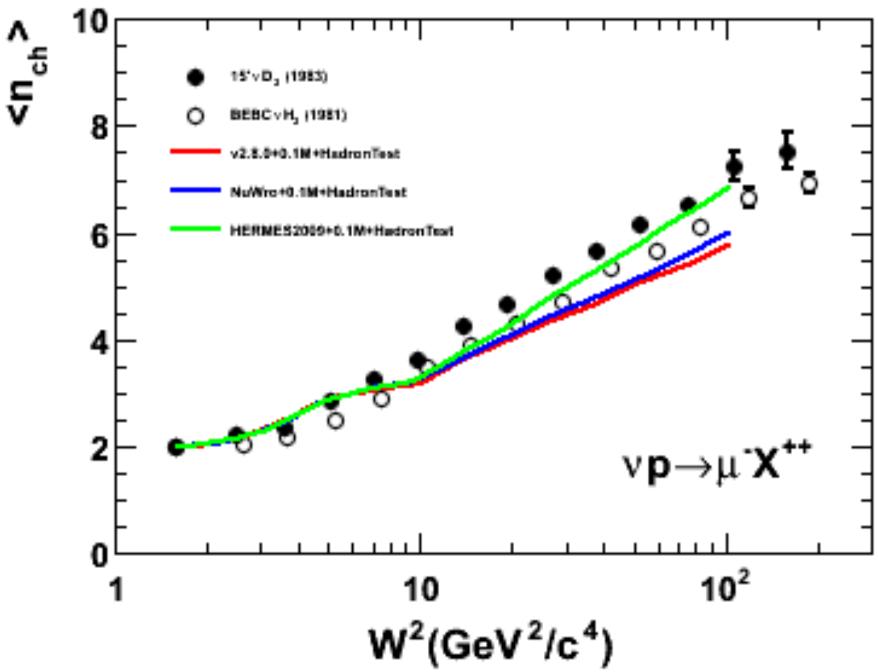
GENIE hadronization validation tool
- GENIE has an ability to compare the model with data (validation tools).
- GENIE hadronization validation tool is used to compare with bubble chamber hadron production data

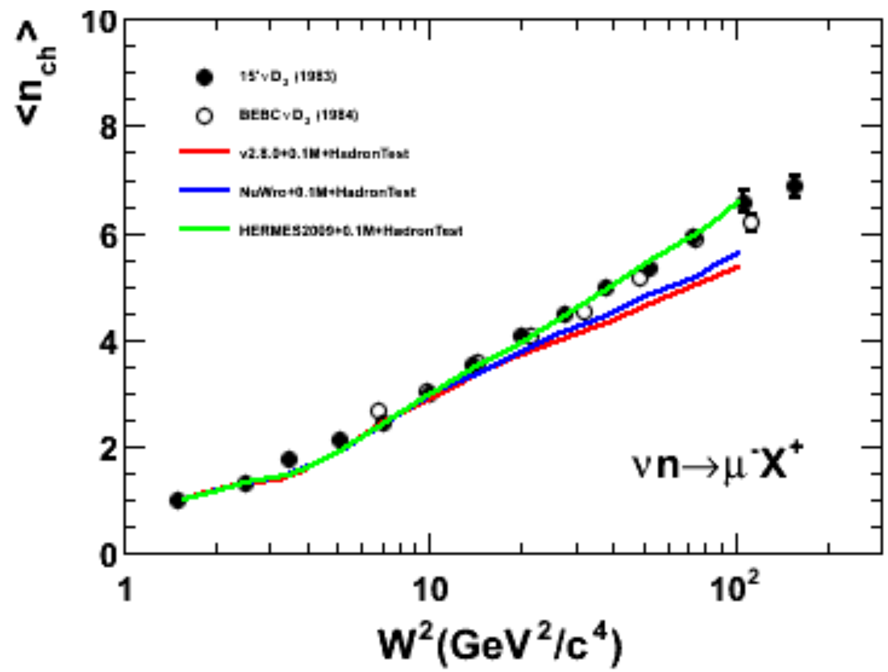
3. HERMES tuned PYTHIA6

Averaged charged hadron multiplicity <n_{ch}>

- Lund-scan increases <n_{ch}> (→ better agreement with bubble chamber data) both neutrino and antineutrino.





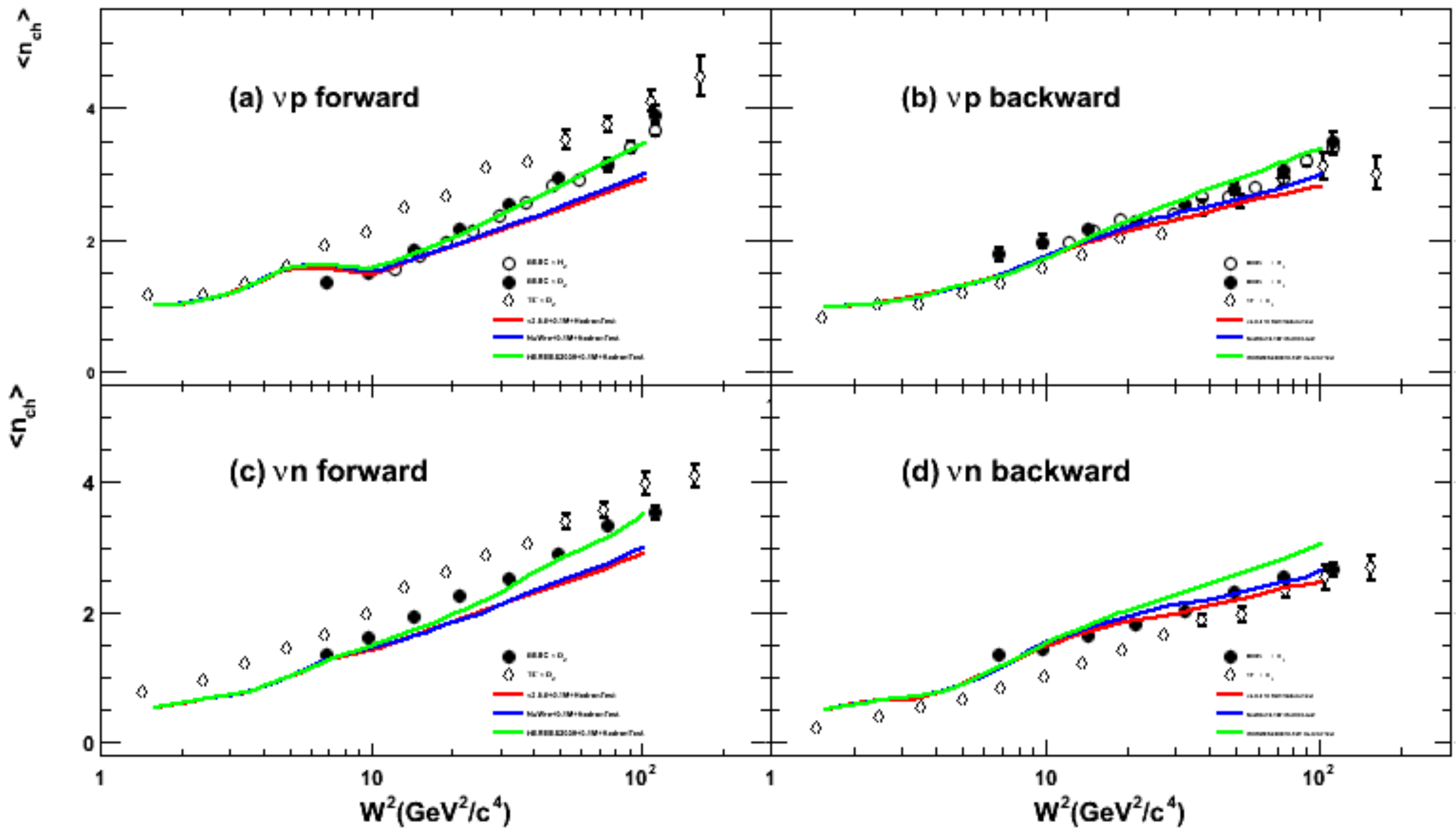


Red: GENIE v2.8.0
Green: Lund-scan

3. HERMES tuned PYTHIA6

Averaged charged hadron multiplicity $<n_{ch}>$
- Lund-scan increases $<n_{ch}>$ (→ better agreement with bubble chamber data) both neutrino and antineutrino.

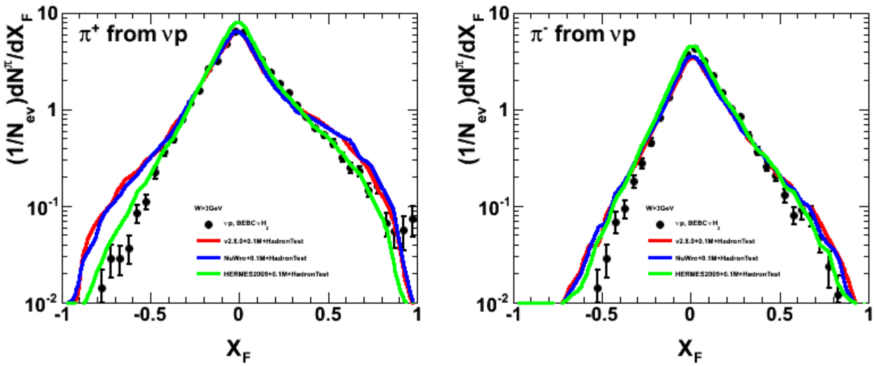
neutrino forward and backward charged hadron multiplicity



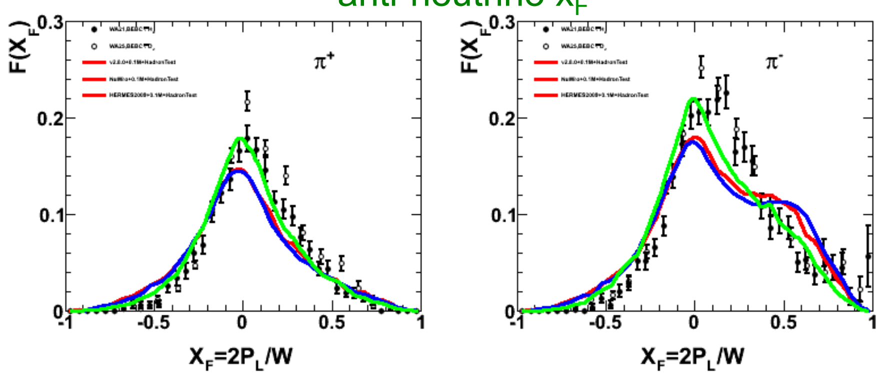
3. HERMES tuned PYTHIA6

Charged hadron x_F distribution
- HERMES parameters also improve x_F distribution

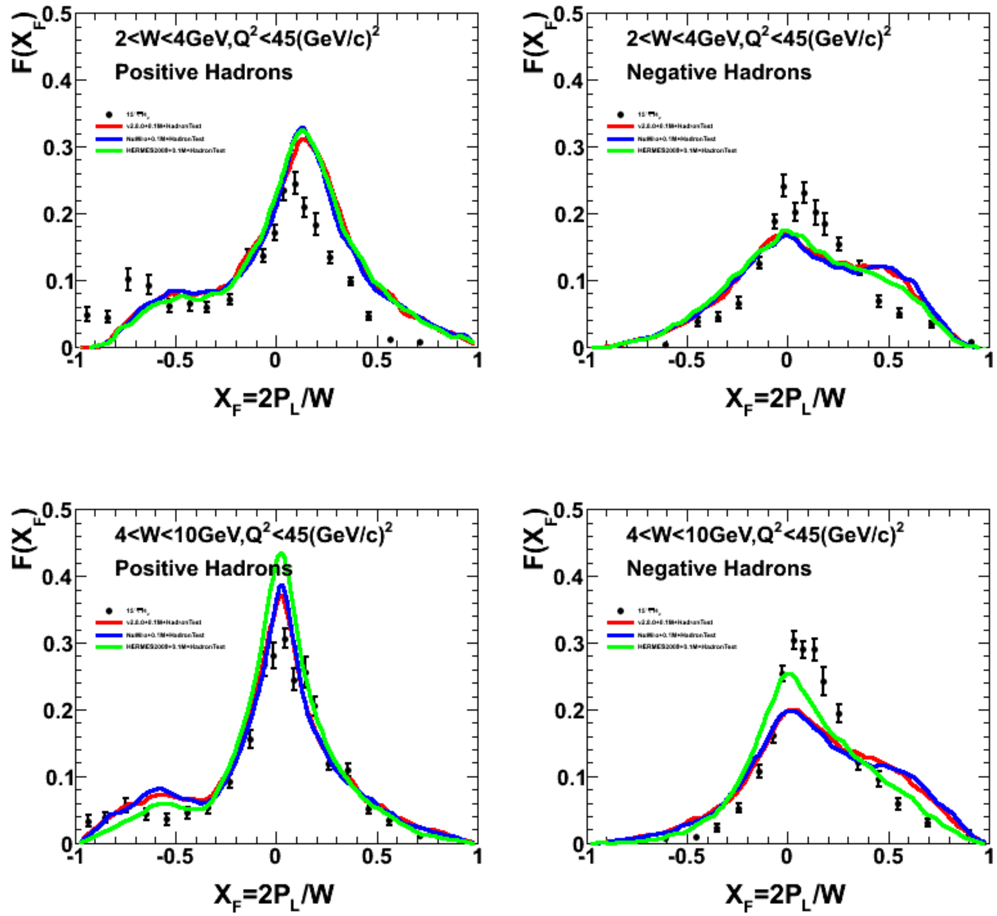
neutrino x_F



anti-neutrino x_F



anti-neutrino x_F with Q^2 bin



Red: GENIE v2.8.0
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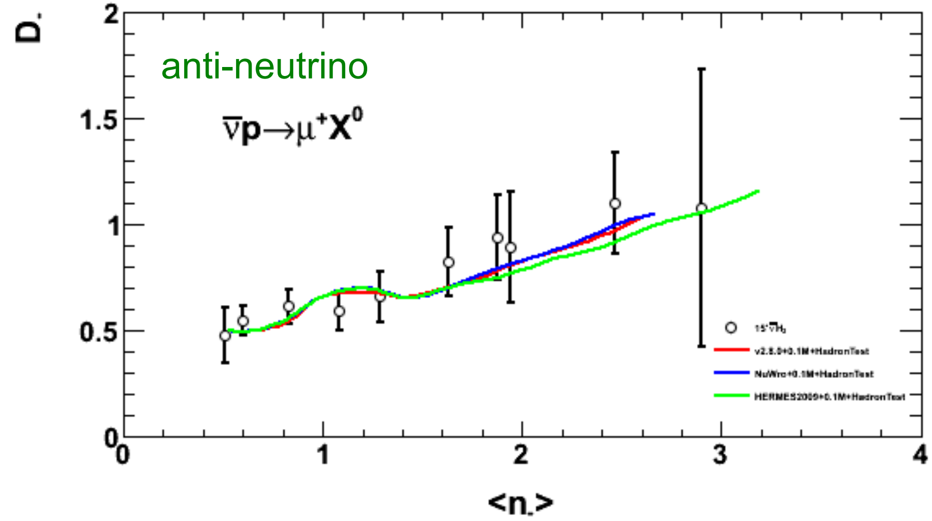
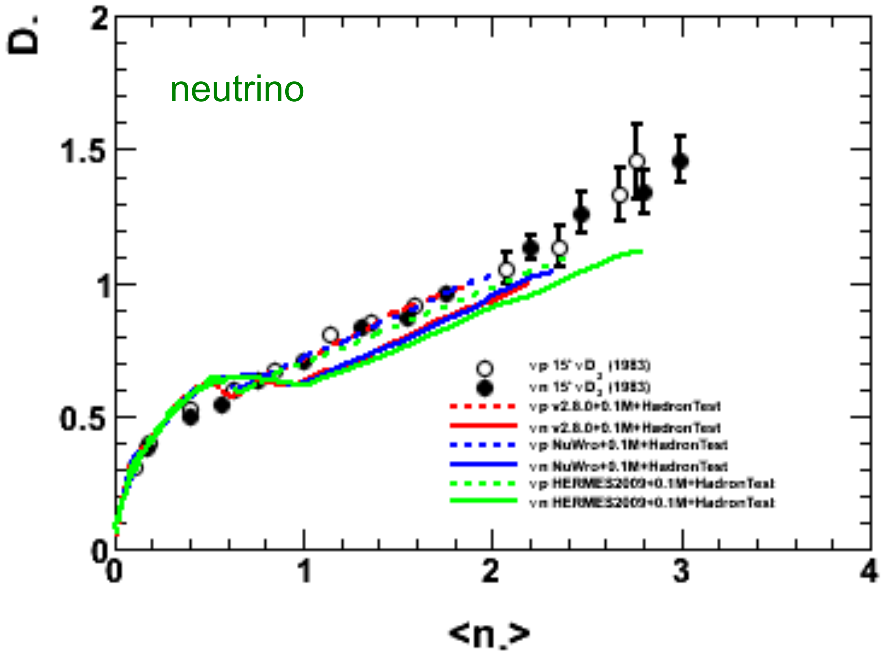
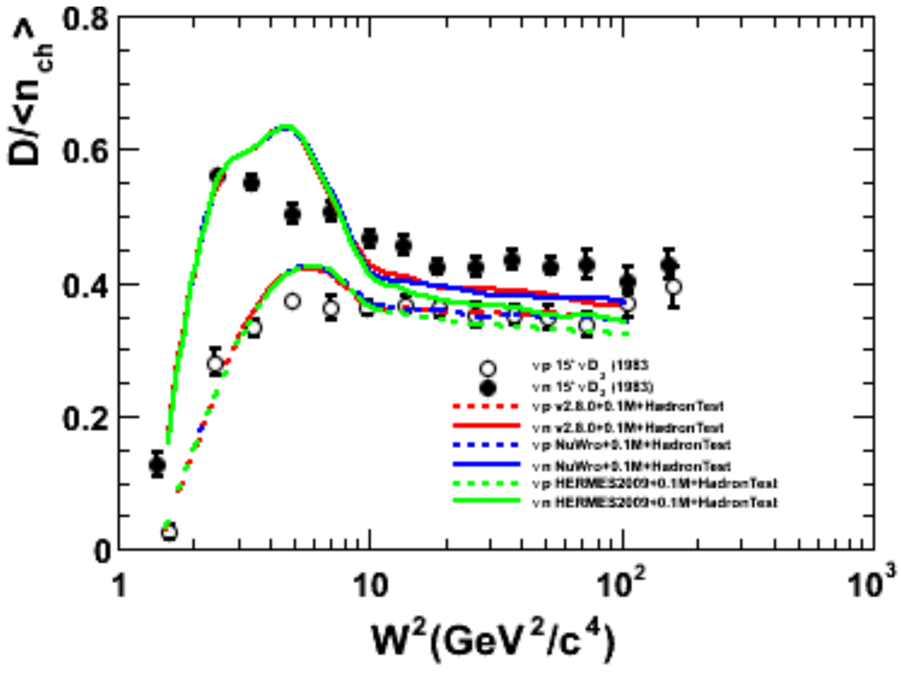
3. HERMES tuned PYTHIA6

Dispersion of charged hadron multiplicity
- Dispersion is unchanged







3. HERMES tuned PYTHIA6

Summary of hadronization tuning

In general, HERMES parameter set improves all charged hadron distributions.

We all find some difficulties (mainly neutral hadron distribution). Further work is on-going.

3. Atmospheric neutrino rate prediction

The variation of charged hadron multiplicity can be used to estimate hadronization error in PINGU

GENIE v2.8.0

1. GENIE v2.8.0 (default)
2. GENIE v2.8.0 with HERMES best fit PYTHIA6 parameters

Flux weighted cross section for PINGU

- South Pole Honda flux with neutrino energy = 2-20 GeV

Kinematics:

- Only particles above Cherenkov threshold are considered
- Muon energy, E_μ: $E_\nu^{generator} - \omega$
- Hadron energy, E_{had}: total energy of charged hadrons
- Neutrino energy, E_ν: $E_\nu = E_\mu + E_{had} - m_N$
- Inelasticity, y: $y = (E_\nu - E_\mu)/E_\nu$

This study is based on "generator-level" (perfect detector, no particle propagation, no detector simulation)

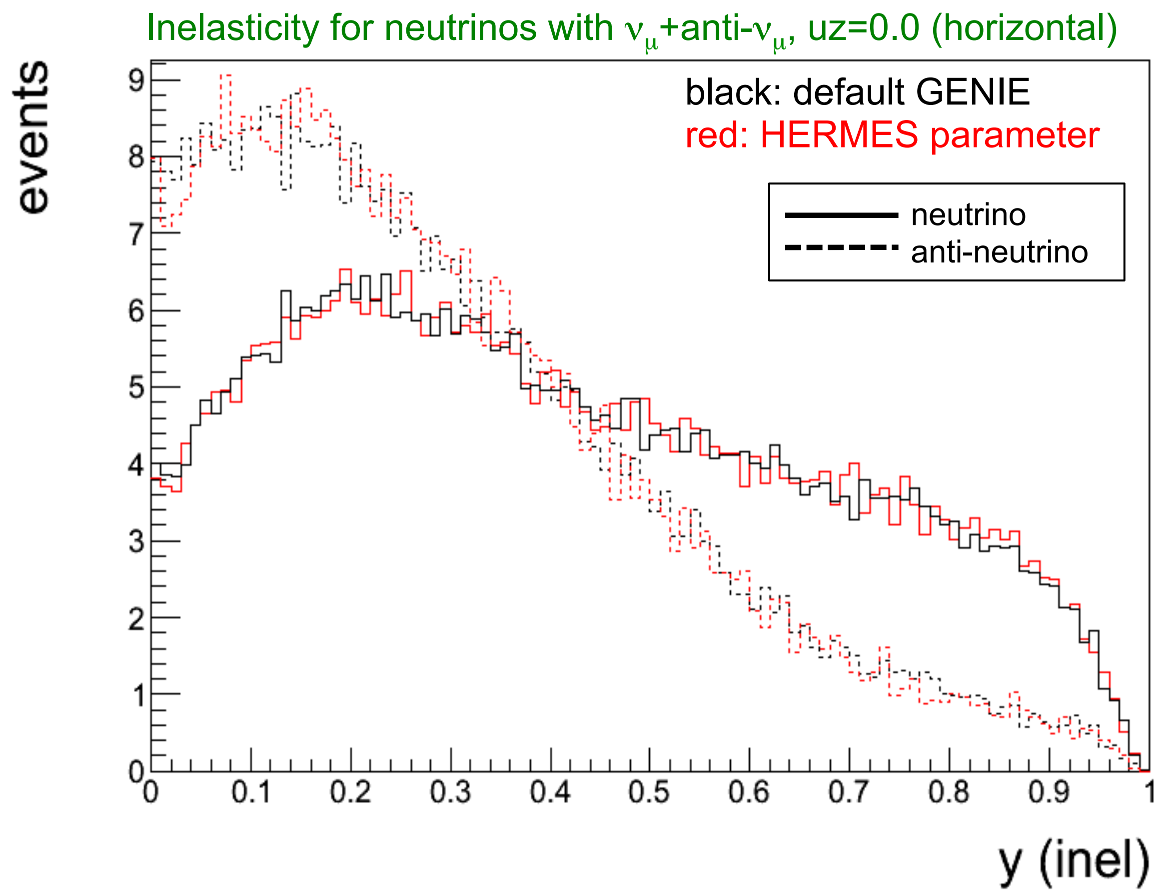
3. Atmospheric neutrino rate prediction

Inelasticity

- Inelasticity distribution for ν_μ and anti-ν_μ, with default and HERMES parameter PYTHIA

Hadronization model difference is a negligible effect

At PINGU energy (2-20 GeV), most of events are $W^2 < 5$ GeV^2, and choice of PYTHIA parameters only affect small number of events.



4. Conclusion

PYTHIA-based Hadronization model can be improved by tuning parameters. This work is on-going with help from HERMES collaborators.

Improved hadronization model should provide better inelasticity measurement for PINGU, and better errors for SPP measurements, such as T2K.

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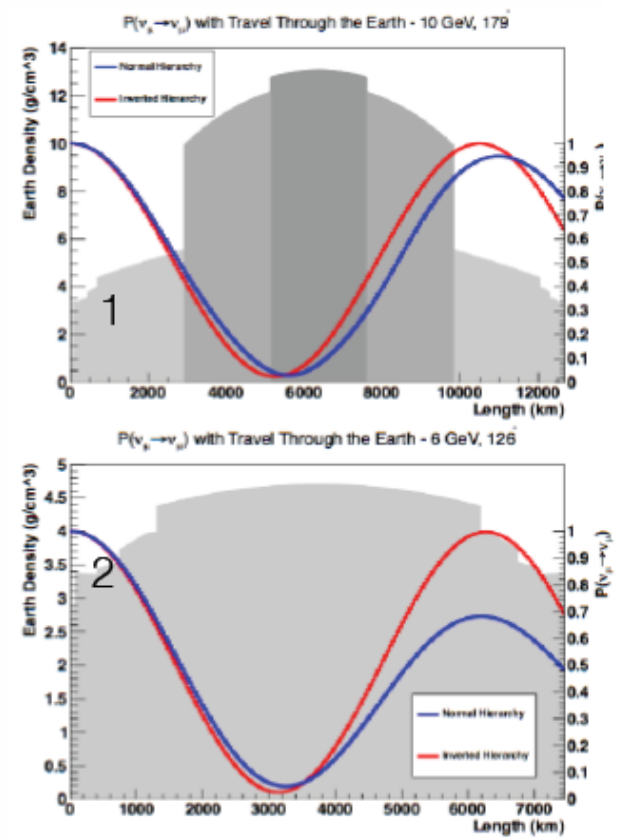
Back up

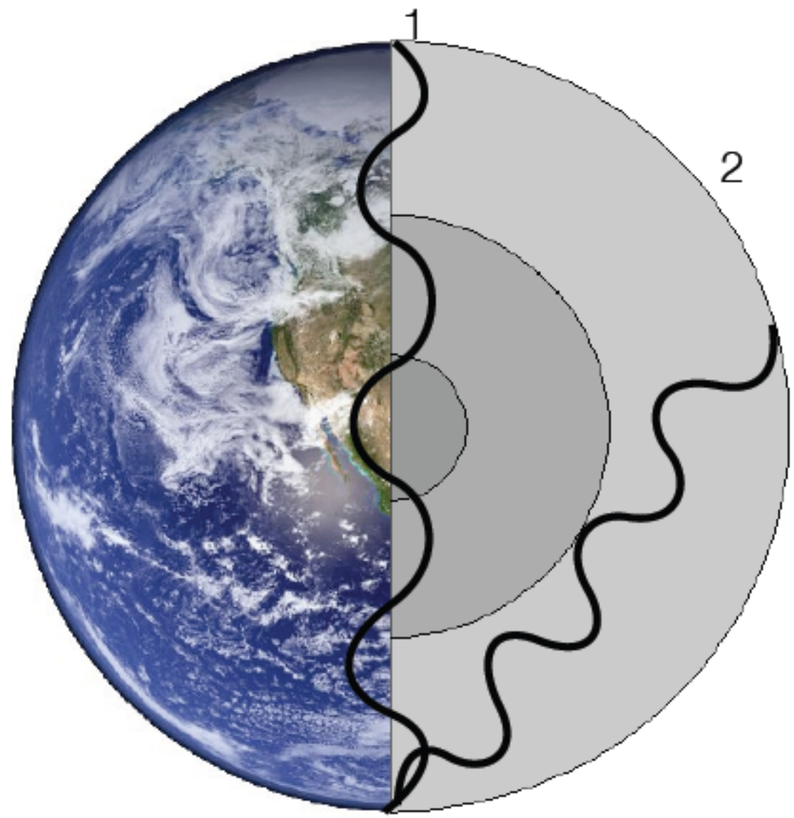
Grant, Neutrino2014

1. PINGU (Precision IceCube Next Generation Upgrade)

More string in smaller region, but still ~3 Mton

- Muon neutrino disappearance measurement for neutrino mass hierarchy (NMH)
- Important energy region is 2-10 GeV





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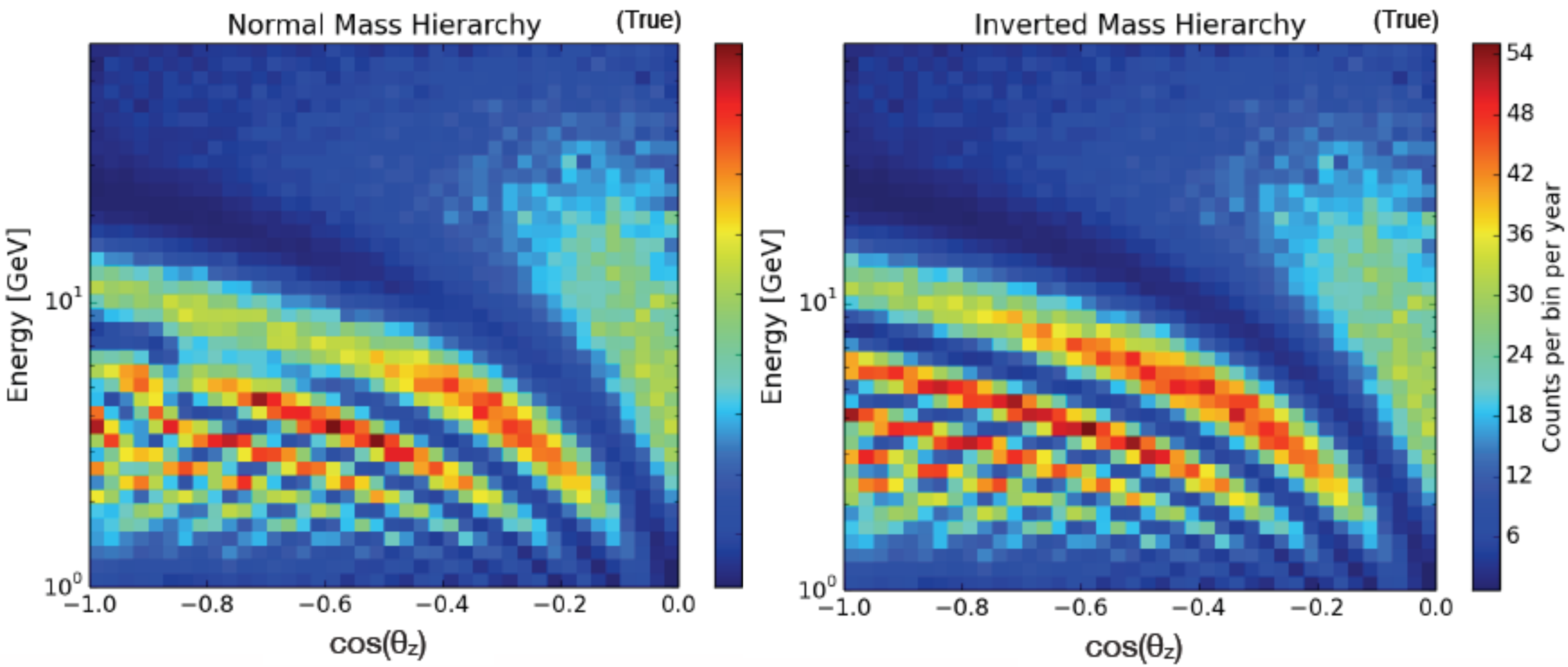
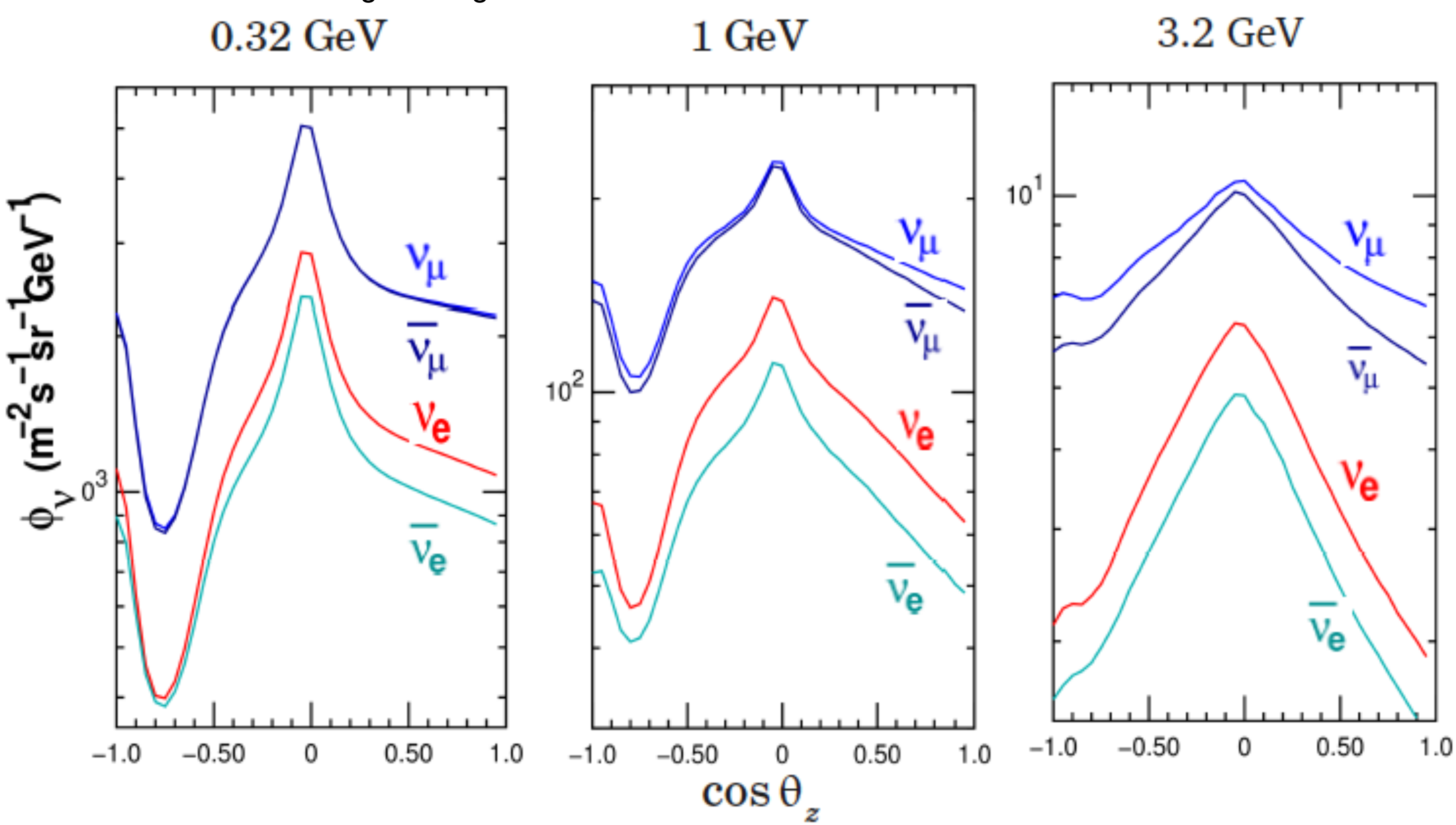


1. Flux

Honda flux prediction at the South Pole

- ν_μ and anti-ν_μ show clear difference in angular dependence (vertical muon has shorter propagation length)
- The difference becomes larger at high E

Zenith angle dependence of atmospheric neutrino flux at the South Pole



Akhmedov, Dighe, Lipari, and Smirnov, Nucl.Phys.B542(1999)3
Akhmedov, Razzaque, and Smirnov, JHEP02(2013)082

1. PINGU

effective 2-ν matter oscillation

interference of propagation states

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta_{23} - s_{23}^4 P_A + \frac{1}{2}\sin^2 2\theta_{23}\sqrt{1-P_A}\cos\phi_X$$

Effective 2 neutrino oscillation

- P($\nu_\mu \to \nu_\mu$) of NMH is equivalent with P(anti-$\nu_\mu \to$anti-ν_μ) of IMH.

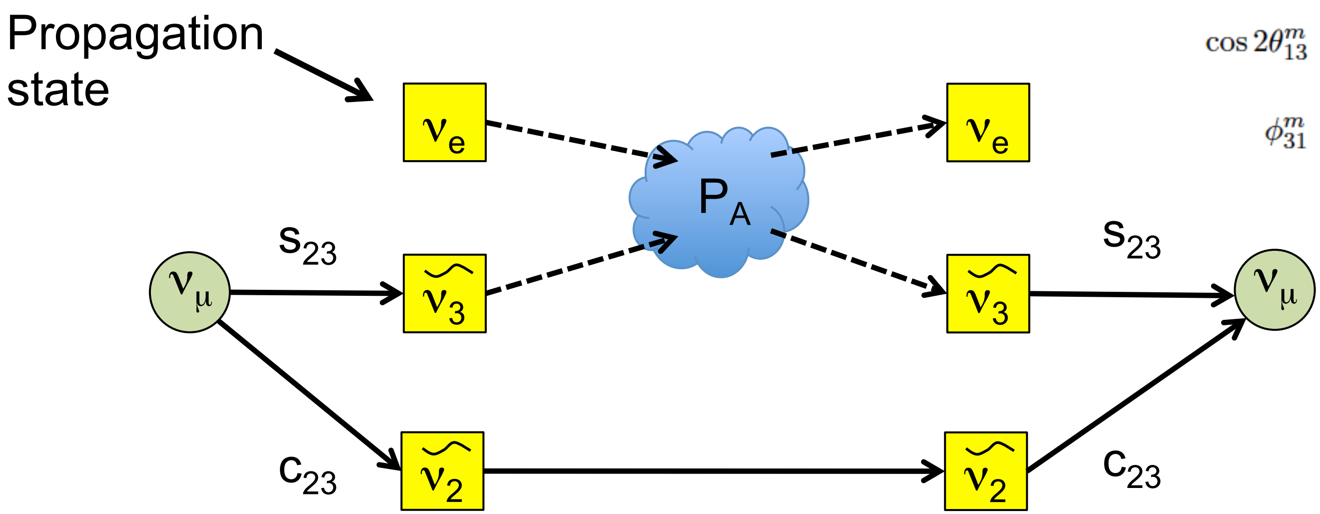
$$P_{\alpha\beta}^{IH} = \bar{P}_{\alpha\beta}^{NH}, \qquad \bar{P}_{\alpha\beta}^{IH} = P_{\alpha\beta}^{NH}$$

$$P_A = \sin^2 2\theta_{13}^m \sin^2 \frac{\phi_{31}^m}{2}$$

$$\cos 2\theta_{13}^m = \frac{\cos 2\theta_{13}\Delta - V}{\sqrt{(\cos 2\theta_{13}\Delta - V)^2 + \Delta^2 \sin^2 2\theta_{13}}},$$

$$\phi_{31}^m = x\sqrt{(\cos 2\theta_{13}\Delta - V)^2 + \Delta^2\sin^2 2\theta_{13}}$$

$$\Delta \equiv \frac{\Delta m_{31}^2}{2E_\nu}$$



Cherenkov detector has no charge separation ability.
→ Is there any information we can use to separate ν_μ and anti-ν_μ?
(or negative muon and positive muon, equivalently)

2. Hadronization

Low W hadronization process (AGKY model)
- KNO scaling based model
- 2.3<W(GeV)<3.0 is used as a window of transition to PYTHIA6.