A general overview of nu-A DIS

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Workshop on "New directions in Nuclear DIS"
ECT* Trento, Italy, June 8-12, 2015

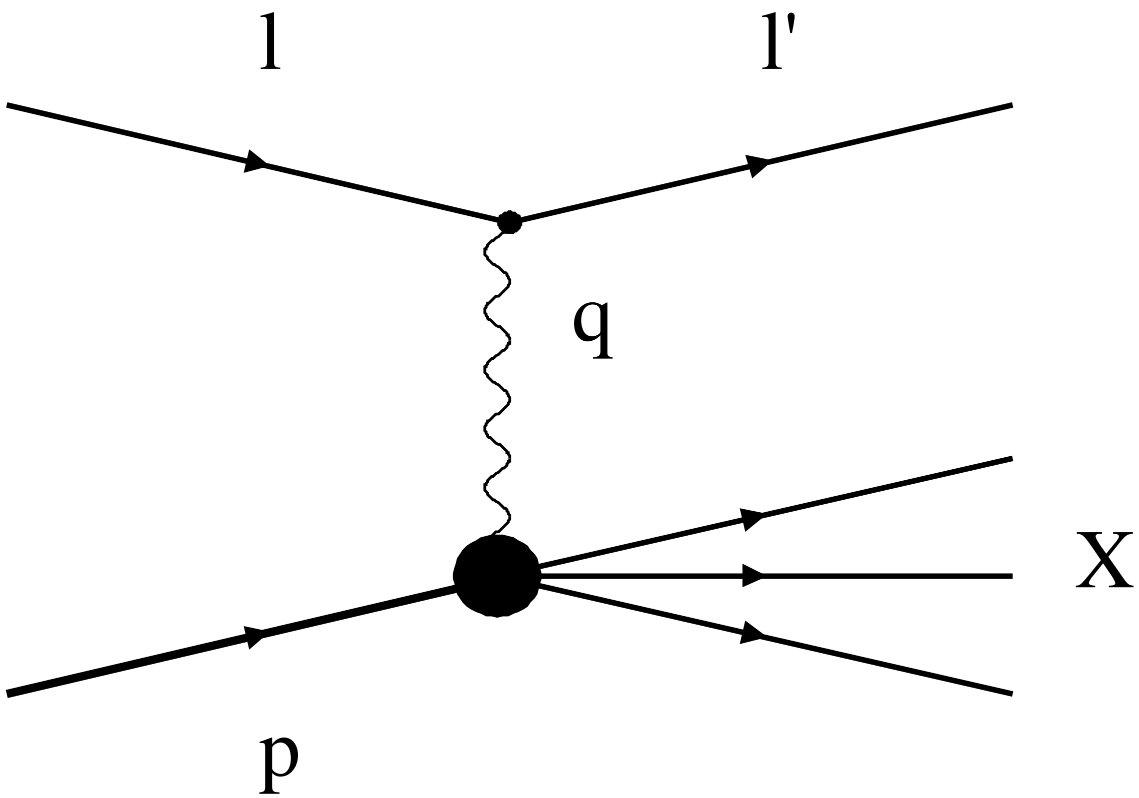
Outline

- Neutrino DIS
- Why neutrino DIS?
- Long baseline experiments and MINERvA
- QCD studies with neutrinos
- SHiP experiment proposal
- nCTEQ nuclear correction factors
- [Global analysis of nPDFs using νA+lA+DY data]
- Conclusions

Neutrino DIS

Kinematics of DIS

(single exchange boson approximation)



Deep: $Q^2 \gg M^2 \simeq 1 \text{ GeV}^2$

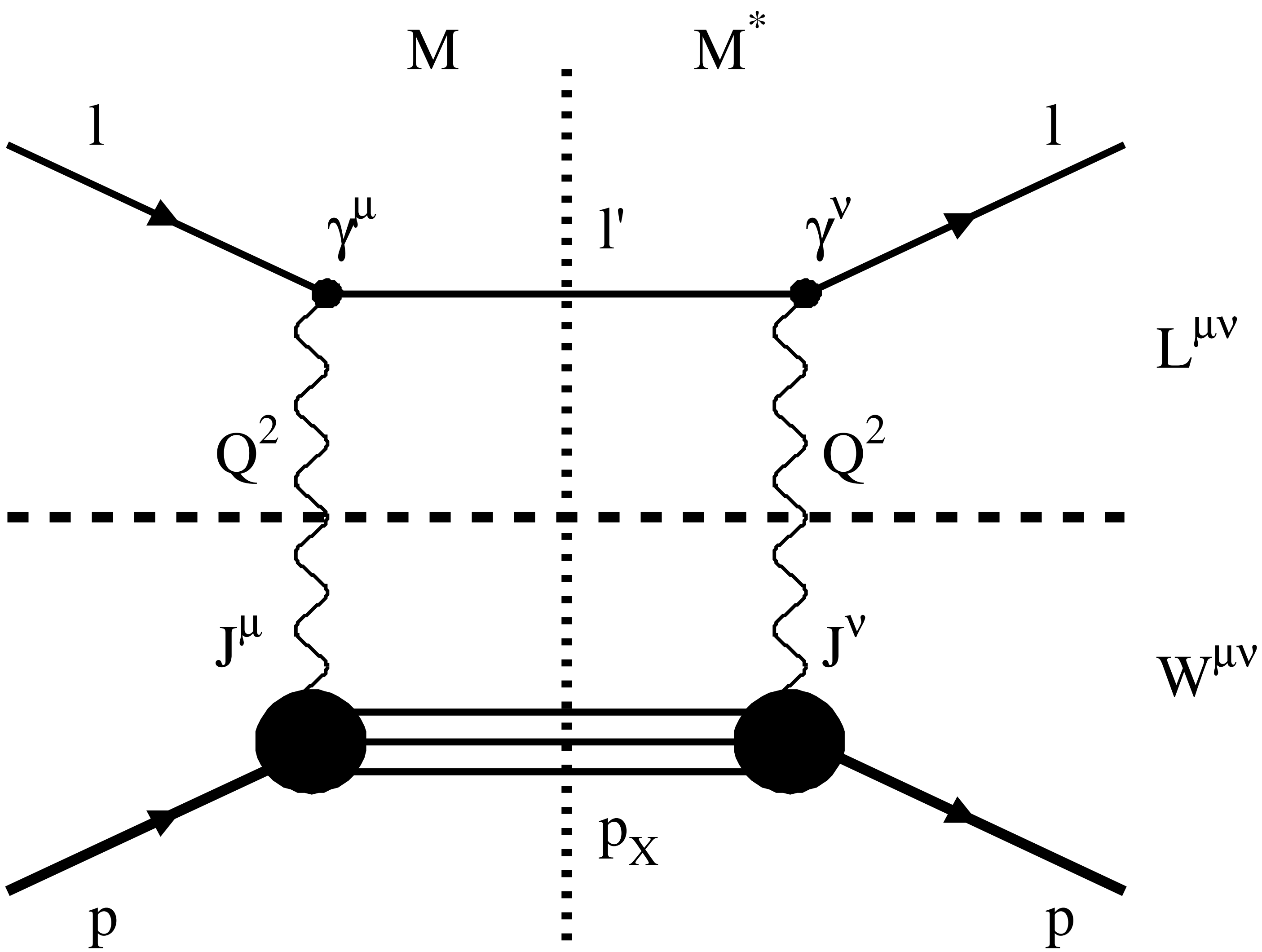
Inelastic: $W^2 >> M^2$

$$W^2 = (p+q)^2 = M^2 + Q/x - Q^2$$

- $Q^2 = -q^2 = -(l - l')^2 > 0$, the square of the momentum transfer,
- $\nu = p \cdot q / M \stackrel{\text{lab}}{=} E_l - E_{l'}$,
- $0 \leq x = Q^2/(2p \cdot q) = Q^2/(2M\nu) \leq 1$, the (dimensionless) Bjorken scaling variable,
- $0 \leq y = p \cdot q / p \cdot l \stackrel{\text{lab}}{=} (E_l - E_{l'})/E_l \leq 1$, the inelasticity parameter,

Cross section

$$d\sigma \propto L_{\mu\nu} W^{\mu\nu}$$



Leptonic tensor
calculable in pert. theory

Hadronic tensor
not calculabe in pert. theory

Hadronic tensor

All possible tensors using momenta p and q:

$$g_{\mu\nu}\,, \quad p_\mu p_\nu\,, \quad q_\mu q_\nu\,, \quad p_\mu q_\nu + p_\nu q_\mu\,,$$

$$\varepsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma\,, \quad p_\mu q_\nu - p_\nu q_\mu\,,$$

Most general form in terms of structure functions:

$$W^{\mu\nu}(p,q) = -g^{\mu\nu} W_1 + \frac{p^\mu p^\nu}{M^2} W_2 - i\varepsilon^{\mu\nu\rho\sigma} \frac{p_\rho q_\sigma}{M^2} W_3 + \frac{q^\mu q^\nu}{M^2} W_4 + \frac{p^\mu q^\nu + p^\nu q^\mu}{M^2} W_5 + \frac{p^\mu q^\nu - p^\nu q^\mu}{M^2} W_6\,.$$

Modern notation:

$$\left\{F_1,\ F_2,\ F_3\right\} = \left\{W_1, \frac{Q^2}{2xM^2} W_2, \frac{Q^2}{xM^2} W_3, \right\}$$

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Most general form in terms of structure functions:

$d\sigma_{|W_4} \propto m_l^2$

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$d\sigma_{|W_5} \propto m_l^2$ $\qquad$ $d\sigma_{|W_6} = 0$

Modern notation:

$$\left\{ F_1,\ F_2,\ F_3 \right\} = \left\{ W_1, \frac{Q^2}{2xM^2} W_2, \frac{Q^2}{xM^2} W_3, \right\}$$

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CC ν_τ-DIS

Albright, Jarlskog'75
Paschos, Yu'98
Kretzer, Reno'02

$$\frac{d^2\sigma^{\nu(\bar\nu)}}{dx\,dy} = \frac{G_F^2 M_N E_\nu}{\pi(1+Q^2/M_W^2)^2}\Big\{(y^2x + \frac{m_\tau^2 y}{2E_\nu M_N})F_1^{W^\pm} + \Big[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{M_N x}{2E_\nu})y\Big]F_2^{W^\pm} \pm \Big[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M_N})\Big]F_3^{W^\pm} + \frac{\mathbf{m_\tau^2(m_\tau^2+Q^2)}}{\mathbf{4E_\nu^2M_N^2x}}\mathbf{F}_4^{W^\pm} - \frac{\mathbf{m_\tau^2}}{\mathbf{E_\nu M_N}}\mathbf{F}_5^{W^\pm}\Big\}$$

Albright-Jarlskog relations:

(derived at LO, extended by Kretzer, Reno)

$$F_4 = 0$$

valid at LO $[\mathcal{O}(\alpha_s^0)]$, $M_N = 0$
(even for $m_c \neq 0$)

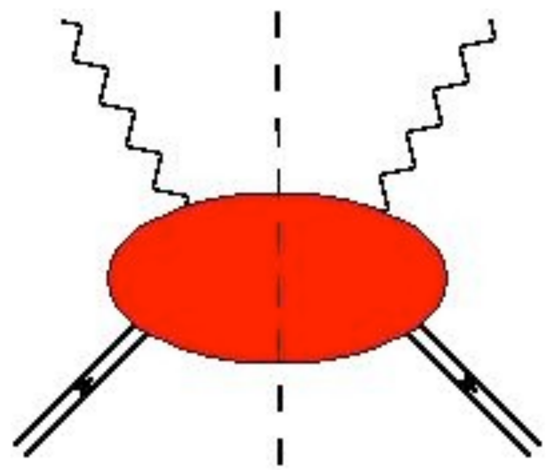
$$F_2 = 2xF_5$$

valid at **all orders** in α_s,
for $M_N = 0$, $m_q = 0$

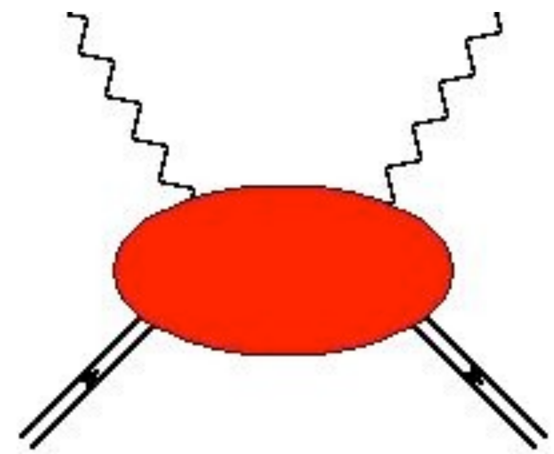
Full NLO expressions ($M_N \neq 0, m_c \neq 0$): Kretzer, Reno'02

Hadronic tensor

Optical theorem: $$W_{\mu\nu} \propto \mathrm{Im}\, T_{\mu\nu}$$



$$\propto \mathrm{Im}$$

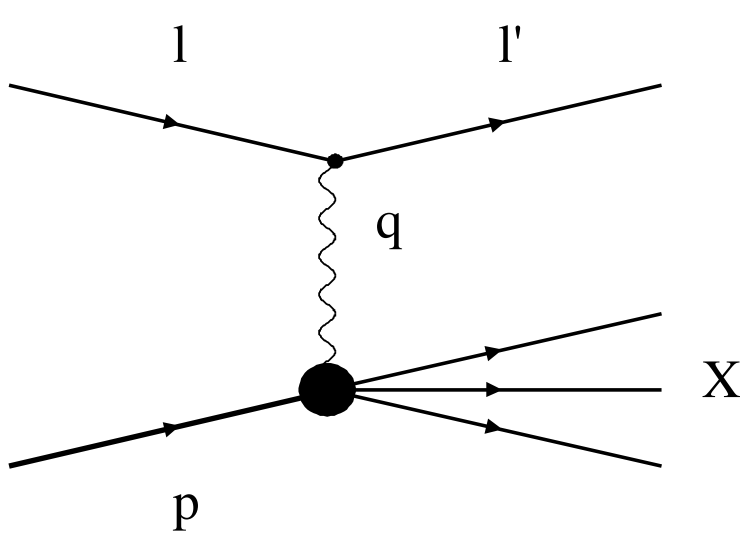


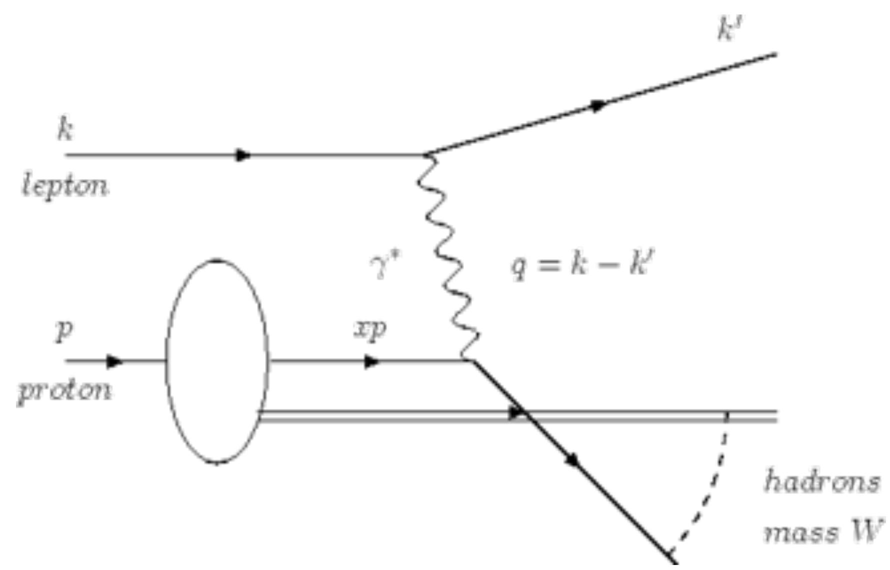
$$T_{\mu\nu} = i \int d^4x \; e^{iqx} \langle N | T[J_\mu^\dagger(x) J_\nu(0)] | N \rangle$$

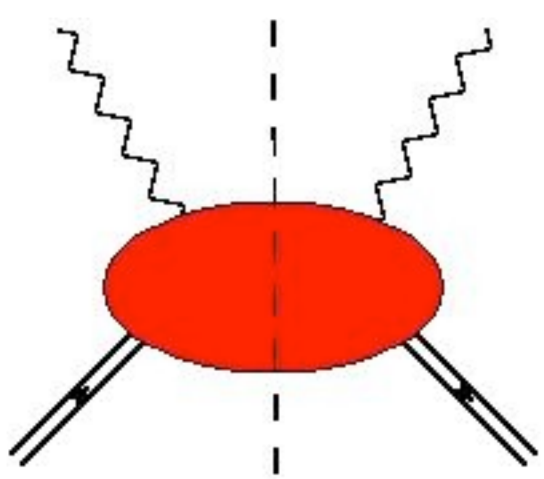
Hadronic tensor

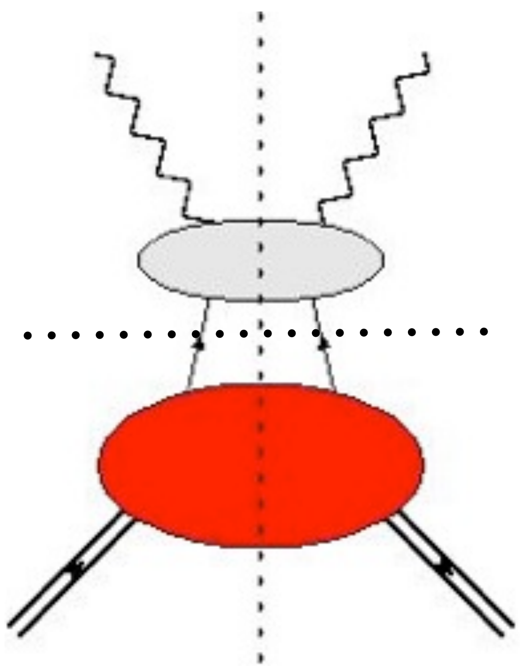
Two approaches (both factorize short and long distances):

1. Parton Model:









$\hat{w}_{\mu\nu}$

$\otimes$

$f_i(\xi)$

Hadronic tensor

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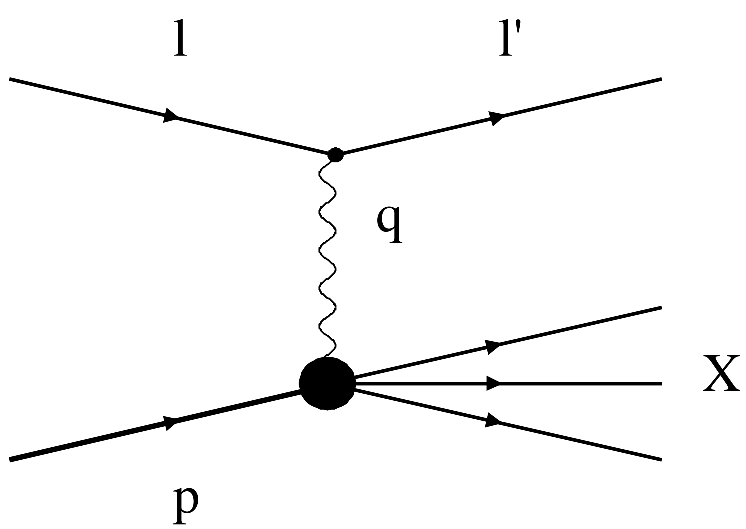
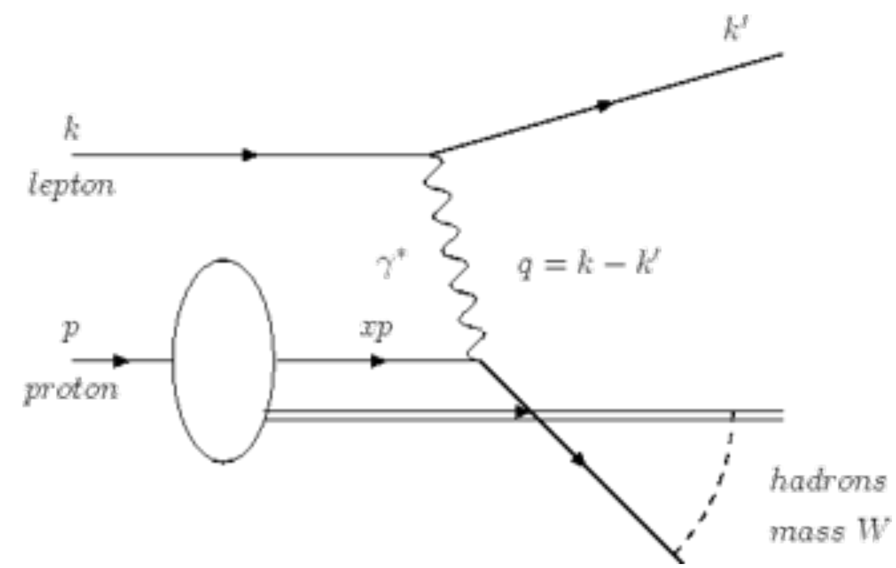
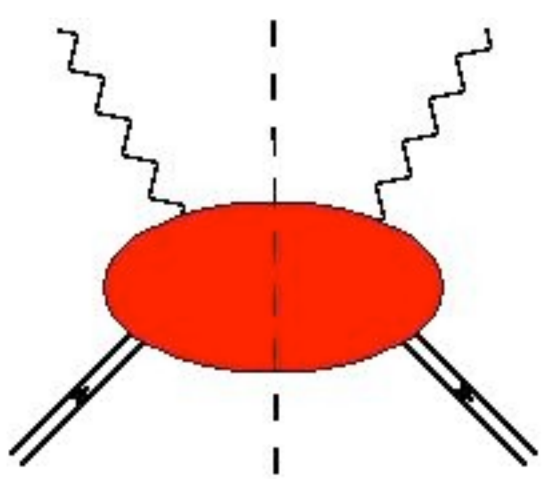
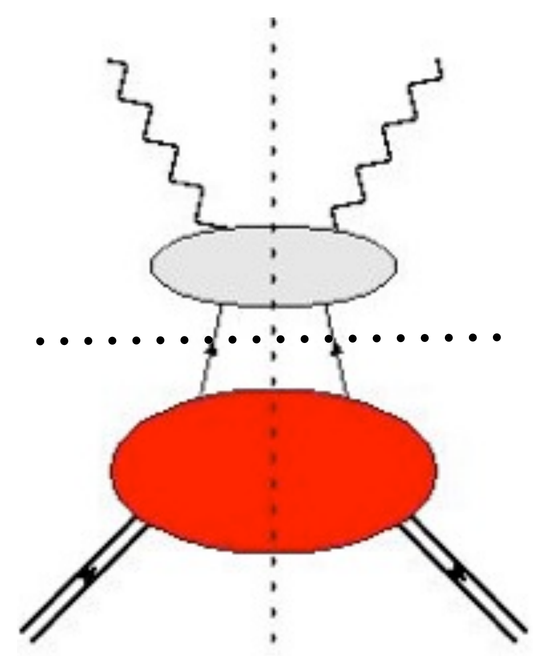








$\hat{w}_{\mu\nu}$

$\otimes$

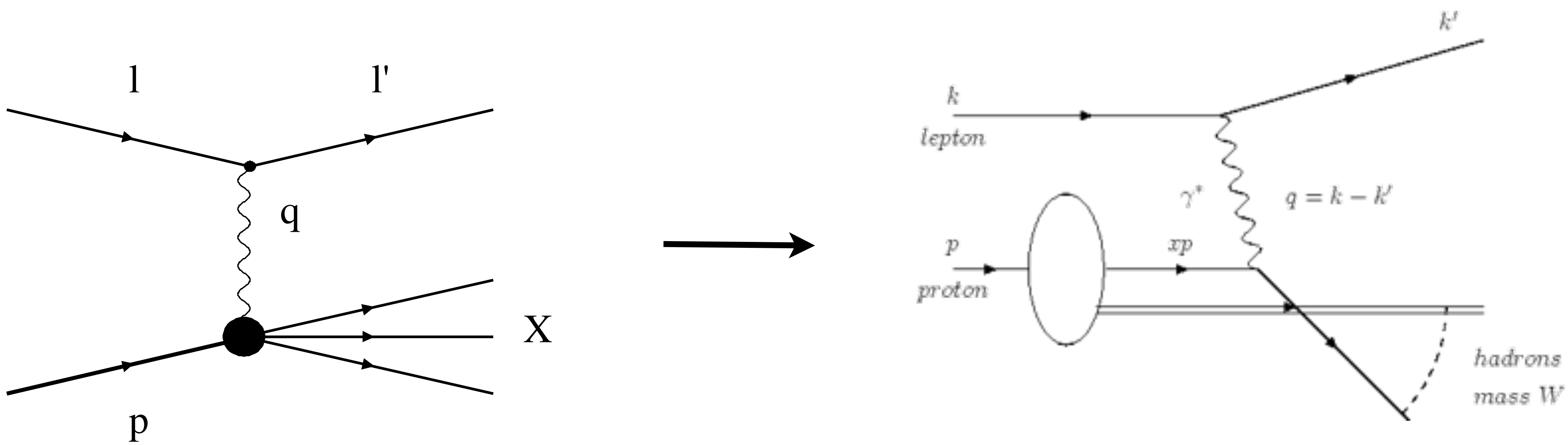
$f_i(\xi)$

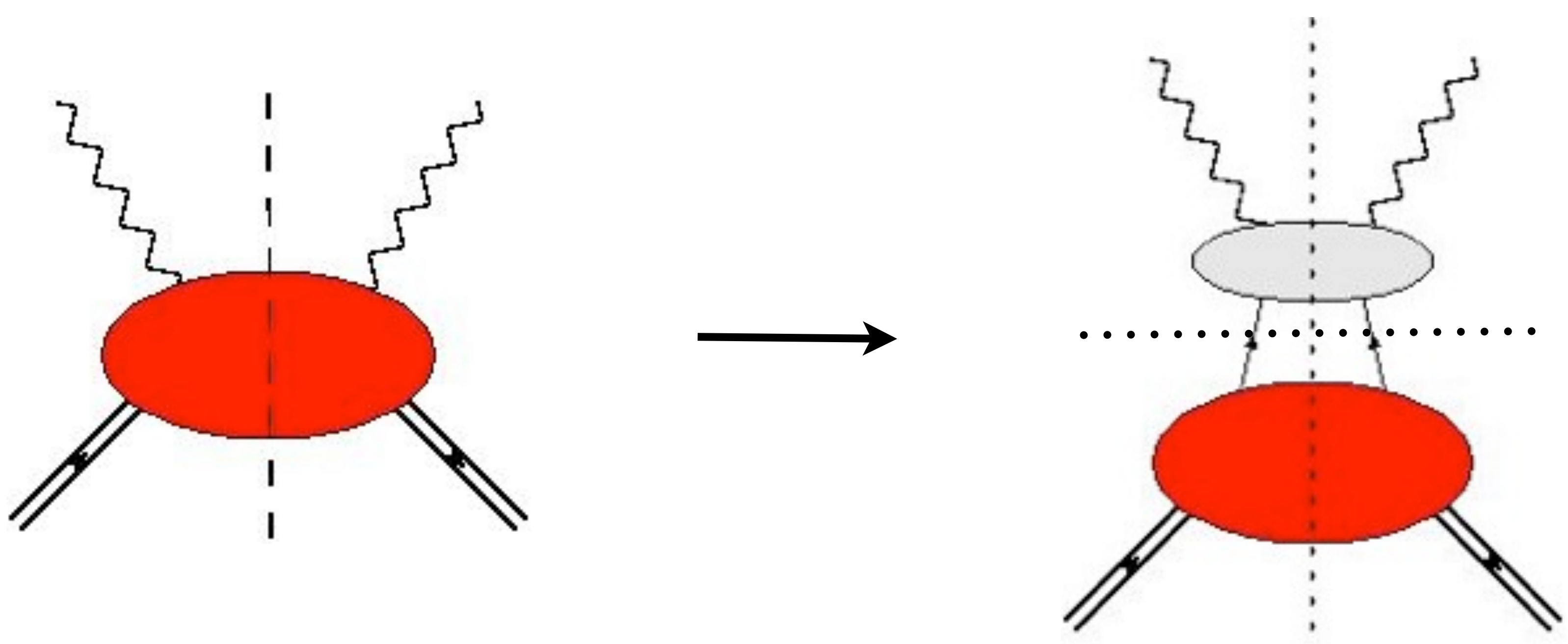
Partonic tensor:
calculable, not IR safe

Hadronic tensor

Two approaches (both factorize short and long distances):

1. Parton Model:





$\hat{w}_{\mu\nu}$

Partonic tensor: calculable, not IR safe

$\otimes$

$f_i(\xi)$

Parton distribution: still not calculable, but **universal**

Higher order coefficient functions

Reference	Boson	SFs	Order	Coefficients	Scheme	Comments
BBDM'78 [18]	NC,CC$^\pm$	F_2, F_L, F_3	α_S^1	C_2	$\overline{\text{MS}}$	$C_{3,+}^{(1)}(x) = C_{3,-}^{(1)}(x)$
AEM'78 [70]	NC,CC$^\pm$	F_2	α_S^1	C_2	$\overline{\text{MS}}$	—
FP'82 [62]	NC,CC$^\pm$	F_2	α_S^1	C_2	$\overline{\text{MS}}$	—
GMMPS'91 [71]	NC,CC$^+$	F_L	α_S^2	$C_{L,q}(x)$, $C_{L,g}(x)$	$\overline{\text{MS}}$	$C_{L,g}$ corrected in [72]
NZ'91 [73]	NC,CC$^\pm$	F_2	α_S^2	$C_{2,q}(x)$	$\overline{\text{MS}}$	first calc.
ZN'91 [72]	NC,CC$^+$	F_2, F_L	α_S^2	$C_{2,g}(x), C_{L,g}(x)$	$\overline{\text{MS}}$	first calc.
ZN'92 [74]	NC,CC$^+$	F_2	α_S^2	C_2	$\overline{\text{MS}}$	—
NV'00 [75]	NC,CC$^+$	F_2, F_L	α_S^2	C_2^{NS}	$\overline{\text{MS}}$	x-space param.
NV'00 [76]	NC,CC$^+$	F_2	α_S^2	C_2^S	$\overline{\text{MS}}$	x-space param.
ZN'92 [77]	NC,CC$^+$	F_3	α_S^2	$C_{3,-}^{(2)}(x)$	$\overline{\text{MS}}$	first calc.
MV'00 [78]	NC,CC$^+$	F_2, F_L, F_3	α_S^2	—	$\overline{\text{MS}}$	all N, confirms [72, 73, 77]
MRV'08 [79]	CC$^-$	F_2, F_L, F_3	α_S^2	$\delta C_{2,L,3}^{(2)}(x)$	$\overline{\text{MS}}$	x-space param., $\delta C_L^{(2)}$ new
MVV'09 [80]	CC$^+$	F_3	α_S^2	$C_{3,-}^{(2)}(x)$	$\overline{\text{MS}}$	x-space param.
VVM'05 [81]	NC,CC$^+$	F_2, F_L	α_S^3	C_2, C_L	$\overline{\text{MS}}$	x-space calc. and param.
MVV'02 [82]	NC,CC$^+$	F_2	α_S^3	C_2^{NS}	$\overline{\text{MS}}$	x-space param.
MVV'05 [83]	NC,CC$^+$	F_L	α_S^3	C_L^{NS}	$\overline{\text{MS}}$	x-space param.
MR'07 [84]	CC$^-$	F_2, F_L, F_3	α_S^3	—	$\overline{\text{MS}}$	N-space, fixed $N \leq 10$
MRV'08 [79]	CC$^-$	F_2, F_L, F_3	α_S^3	$\delta C_{2,L,3}^{(2)}(N)$	$\overline{\text{MS}}$	N-space, first 5 moments
MVV'09 [80]	CC$^+$	F_3	α_S^3	—	$\overline{\text{MS}}$	x-space calc.

Table 2.1: Massless higher order Wilson coefficient functions in the literature. 'NC' corresponds to neutral current DIS with γ and Z exchange while 'CC$^\pm$' stands for charged current DIS with $W^+ \pm W^-$ exchange.

Hadronic tensor

Two approaches (both factorize short and long distances):

2. Operator Product Expansion (OPE):

a) short distance expansion

$$A(x)B(0) \underbrace{\simeq}_{x_\mu \to 0} \sum_i C_i(x) O_i(x/2)$$

b) light cone expansion

$$A(x/2)B(-x/2) \underbrace{\simeq}_{x^2 \to 0} \sum_{j,i} C_i^{(j)}(x) x^{\mu_1} \cdots x^{\mu_j} O^{(j,i)}_{\mu_1 \cdots \mu_j}(0)$$

Light cone dominance of DIS hadronic tensor

Wilson coefficients

local ops. of definite spin j (symmetric traceless tensors of rank j)

$$C_i^{(j)} \underbrace{\propto}_{x^2 \to 0} (\sqrt{x^2})^{d_{j,i} - j - d_A - d_B}$$

twist = dimension - spin

Light cone ops. with lowest twist dominate!

OPE

Operator product expansion

$$\int d^4x\; e^{iq\cdot x}\langle N|T(J^\mu(x)J^\nu(0))|N\rangle$$

$$= \sum_k \left(-g^{\mu\nu}q^{\mu_1}q^{\mu_2} + g^{\mu\mu_1}q^\nu q^{\mu_2} + q^\mu q^{\mu_1}g^{\nu\mu_2} + g^{\mu\mu_1}g^{\nu\mu_2}Q^2\right)$$

$$\times q^{\mu_3}\cdots q^{\mu_{2k}}\frac{2^{2k}}{Q^{4k}}\underbrace{A_{2k}\Pi_{\mu_1\cdots\mu_{2k}}}_{\langle N|\mathcal{O}_{\mu_1\cdots\mu_{2k}}|N\rangle}$$

local operators

Georgi, Politzer (1976)

$$\Pi_{\mu_1\cdots\mu_{2k}} = p_{\mu_1}\cdots p_{\mu_{2k}} - (g_{\mu_i\mu_j}\ \text{terms})$$

$$= \sum_{j=0}^{k}(-1)^j\frac{(2k-j)!}{2^j(2k)^j}g\cdots g\; p\cdots p$$

traceless, symmetric
rank-$2k$ tensor

TMC: Master formula

$$
\begin{aligned}
F_1^{\mathrm{TMC}}(x,Q^2) &= \frac{x}{\eta r}F_1^{(0)}(\eta,Q^2) + \frac{M^2x^2}{Q^2r^2}h_2(\eta,Q^2) + \frac{2M^4x^3}{Q^4r^3}g_2(\eta,Q^2) \ , \\
F_2^{\mathrm{TMC}}(x,Q^2) &= \frac{x^2}{\eta^2r^3}F_2^{(0)}(\eta,Q^2) + \frac{6M^2x^3}{Q^2r^4}h_2(\eta,Q^2) + \frac{12M^4x^4}{Q^4r^5}g_2(\eta,Q^2) \ , \\
F_3^{\mathrm{TMC}}(x,Q^2) &= \frac{x}{\eta r^2}F_3^{(0)}(\eta,Q^2) + \frac{2M^2x^2}{Q^2r^3}h_3(\eta,Q^2) + 0 \ ,
\end{aligned}
$$

- Modular, easy to use!
- Resums leading twist TMC to all orders in $(M^2/Q^2)^n$
- Input: standard structure functions in the parton model with M=0
  - any order in α_s
  - can include quark masses

IS et al. '08, A review of TMC

NuTEV data

TMC important at large x and small Q^2

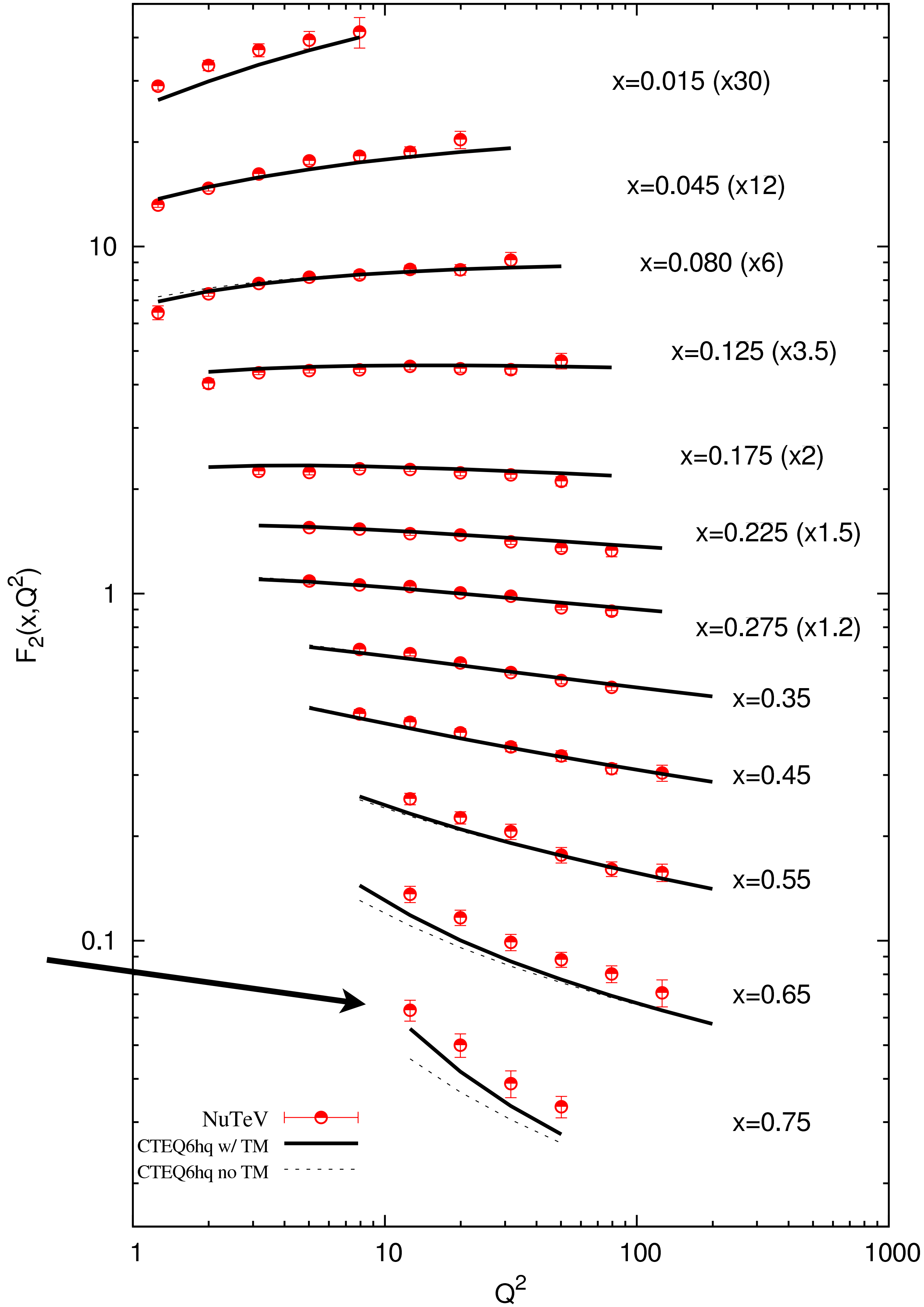


Figure 9. Comparison of the F_2 structure function, with and without target mass corrections, and NuTeV data [64]. The base PDF set is CTEQ6HQ [7].

Why neutrino DIS?

ν DIS: From Atmospheric to UHE neutrinos

Atmospheric neutrinos

LBL experiments, MINERvA

CCFR, NuTEV, CHORUS, CDHSW, NOMAD, SHIP, ...

ICECUBE

UHE neutrinos AUGER

1 — 10 — 100 — // — 10^6 — 10^{10} — E_ν [GeV]

Neutrino oscillations; precise knowledge of νA interactions needed

Astrophysical neutrinos observed!

Flavor separation of PDFs, nPDFs;
Proton PDFs: nuclear corrections;
dimuon production: main source of information on strange sea;
Non-singlet evolution of F_3: α_s;
Paschos-Wolfenstein relation, ...

Neutrino interactions in the atmosphere;
CC DIS dominant;
small-x ($x\sim10^{-7}...10^{-5}$);
No UHE neutrinos observed so far

Nuclear modifications

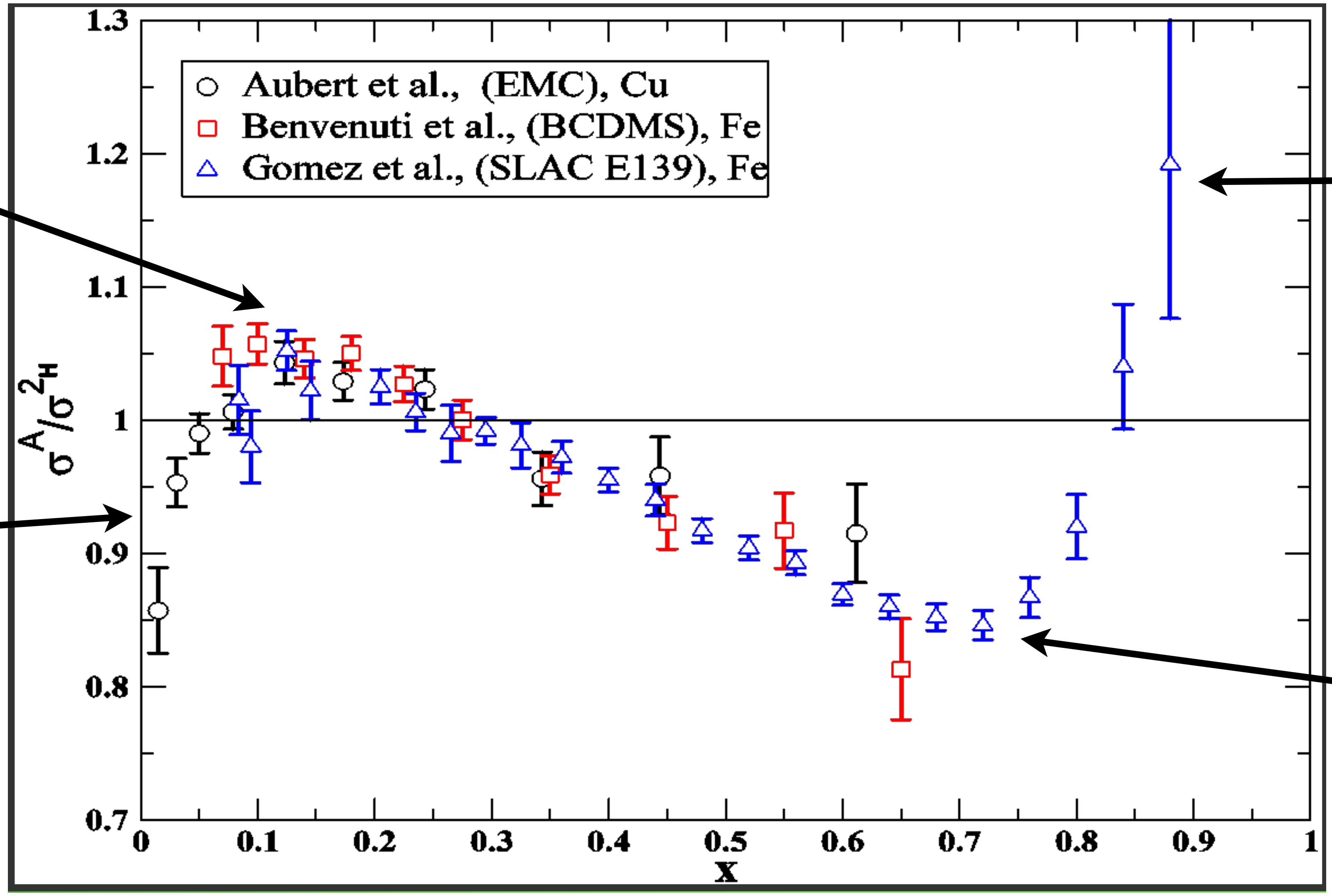
- **Neutrino experiments use heavy nuclear targets**:
  Pb, Fe, Ar, H_2O, C
- As discovered more than 30 years ago by the European Muon Collaboration, nucleon structure functions are modified by the nuclear medium (EMC effect)
- Studies of nucleon structure:
  need to correct for nuclear effects
- **Nuclear effects interesting in its own right!**
  - Many models exist.
  - However, charged lepton nuclear effects still not fully explained, in particular the EMC effect ($0.3 < x < 0.7$)

The EMC effect

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

Anti-shadowing enhancement

Shadowing suppression at small x



Rise due to Fermi motion

EMC effect

Are the nuclear effects the same with neutrinos?

Longbaseline experiments and MINERvA

J. Mousseau, talks at DIS 2015 and Fermilab Joint Experimental-Theoretical Physics seminar, May 8, 2015

Neutrino properties: What we know in 2012

- very weakly interacting, electrically neutral, spin 1/2, tiny mass
- long lived (or stable), tiny or vanishing magnetic moment
- 3 light 'SM families' ($\nu_e , \nu_\mu , \nu_\tau$)
- neutrinos oscillate $\Longleftrightarrow$ $m_\nu \neq 0$

Neutrino Properties

See the note on "Neutrino properties listings" in the Particle Listings.

Mass $m < 2$ eV (tritium decay)
Mean life/mass, $\tau/m > 300$ s/eV, CL = 90% (reactor)
Mean life/mass, $\tau/m > 7 \times 10^9$ s/eV (solar)
Mean life/mass, $\tau/m > 15.4$ s/eV, CL = 90% (accelerator)
Magnetic moment $\mu < 0.32 \times 10^{-10}$ μ_B, CL = 90% (solar)

Number of Neutrino Types

Number $N = 2.984 \pm 0.008$ (Standard Model fits to LEP data)
Number $N = 2.92 \pm 0.05$ (S = 1.2) (Direct measurement of invisible Z width)

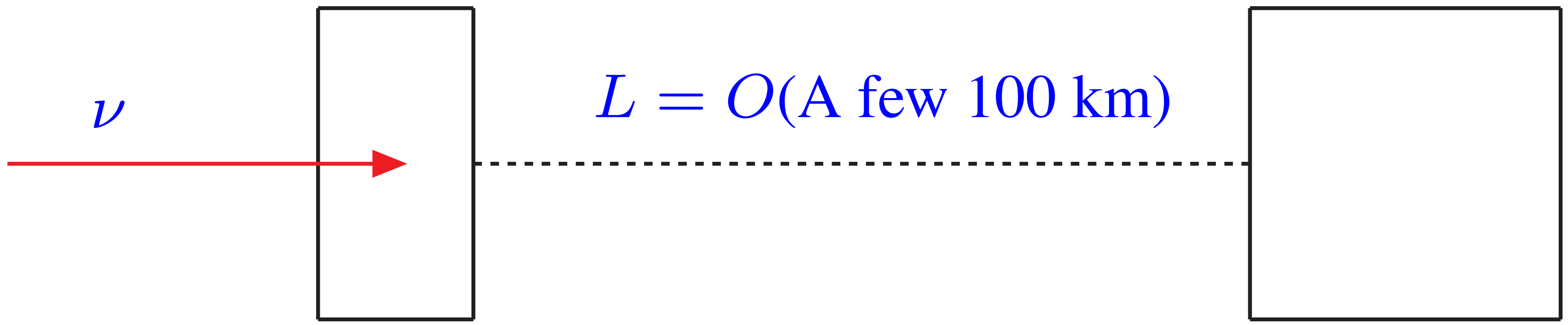
Neutrino Mixing

$\sin^2(2\theta_{12}) = 0.857 \pm 0.024$
$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV^2
$\sin^2(2\theta_{23}) > 0.95$ [i]
$\Delta m^2_{32} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2 [j]
$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$

Neutrino properties:
What we want to know

- **nature of neutrinos**:
  - Majorana or Dirac fermions?
  - are there sterile neutrinos?
- **neutrino masses**:
  - what are the absolute neutrino masses?
  - normal ($m_2 \ll m_3$) or inverted ($m_2 \gg m_3$) mass hierarchy?
    [we know $m_2 > m_1$ from MSW effect]
- **mixing matrix** (PMNS-matrix):
  - more precise measurement of mixing angles
  - is the PMNS matrix unitary?
  - is there leptonic CP violation?

Long Baseline experiments



Near detector:

- neutrino flux
- neutrino beam energy spectrum
- cross sections before oscillation

Far detector:

- observation of charged and neutral current reactions

Detection requires good understanding of neutrino interactions

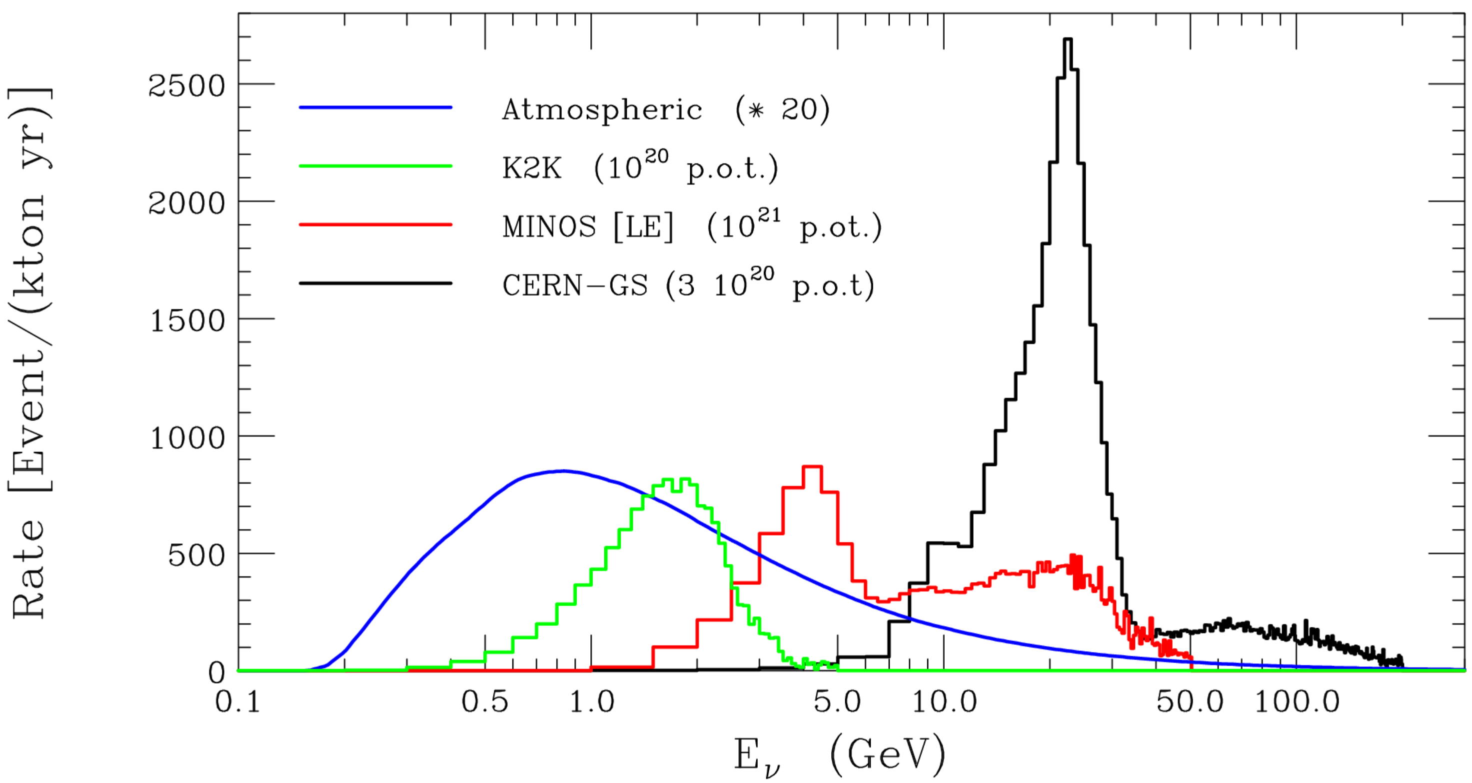
Nuclear effects distort measured kinematics of the neutrinos

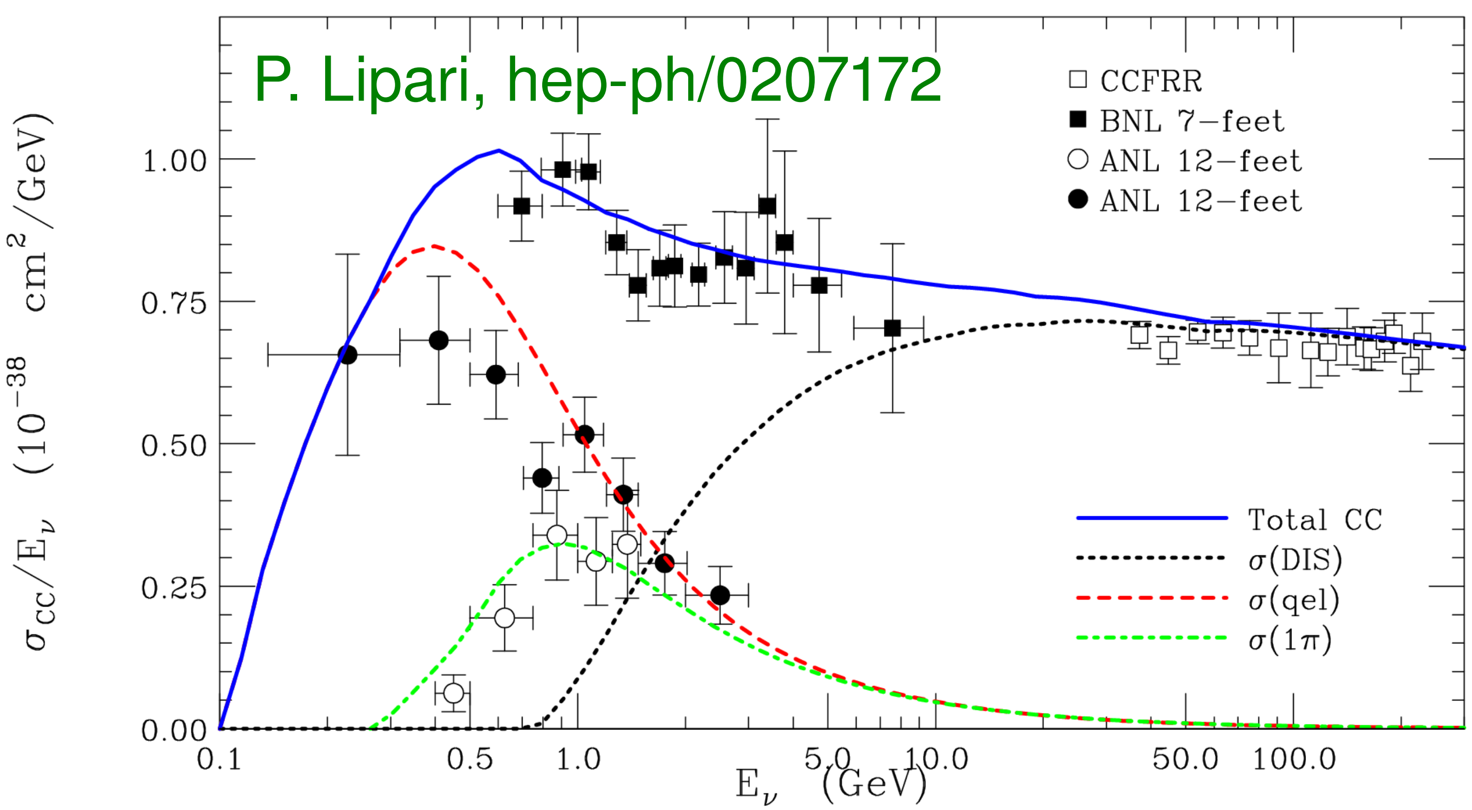
Two (similar) detectors will not fully solve the problem:
Nuclear effects modify near and far spectra differently

Effects not well understood in neutrino physics.
General strategy has been to adapt nuclear effects from lA DIS in νA DIS.

Dedicated experiments like **MINERvA**!

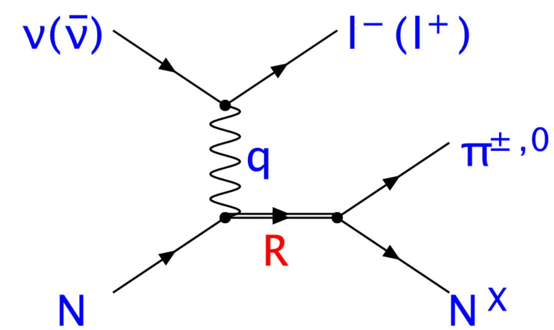
Neutrino cross sections at atmospheric ν energies



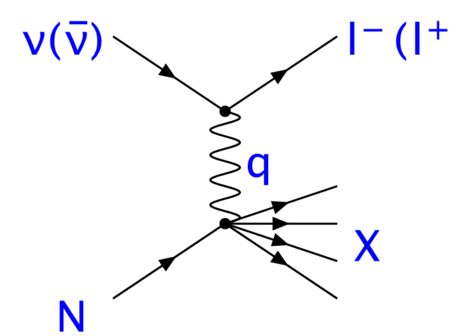


Paschos,JYY,PRD65(2002)033002

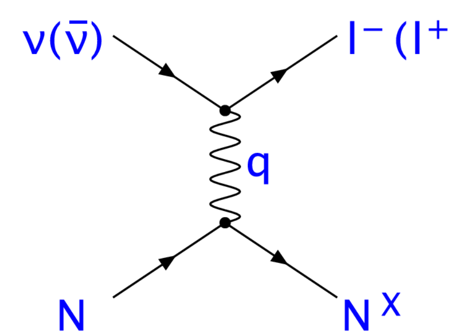
- Resonance production (RES)



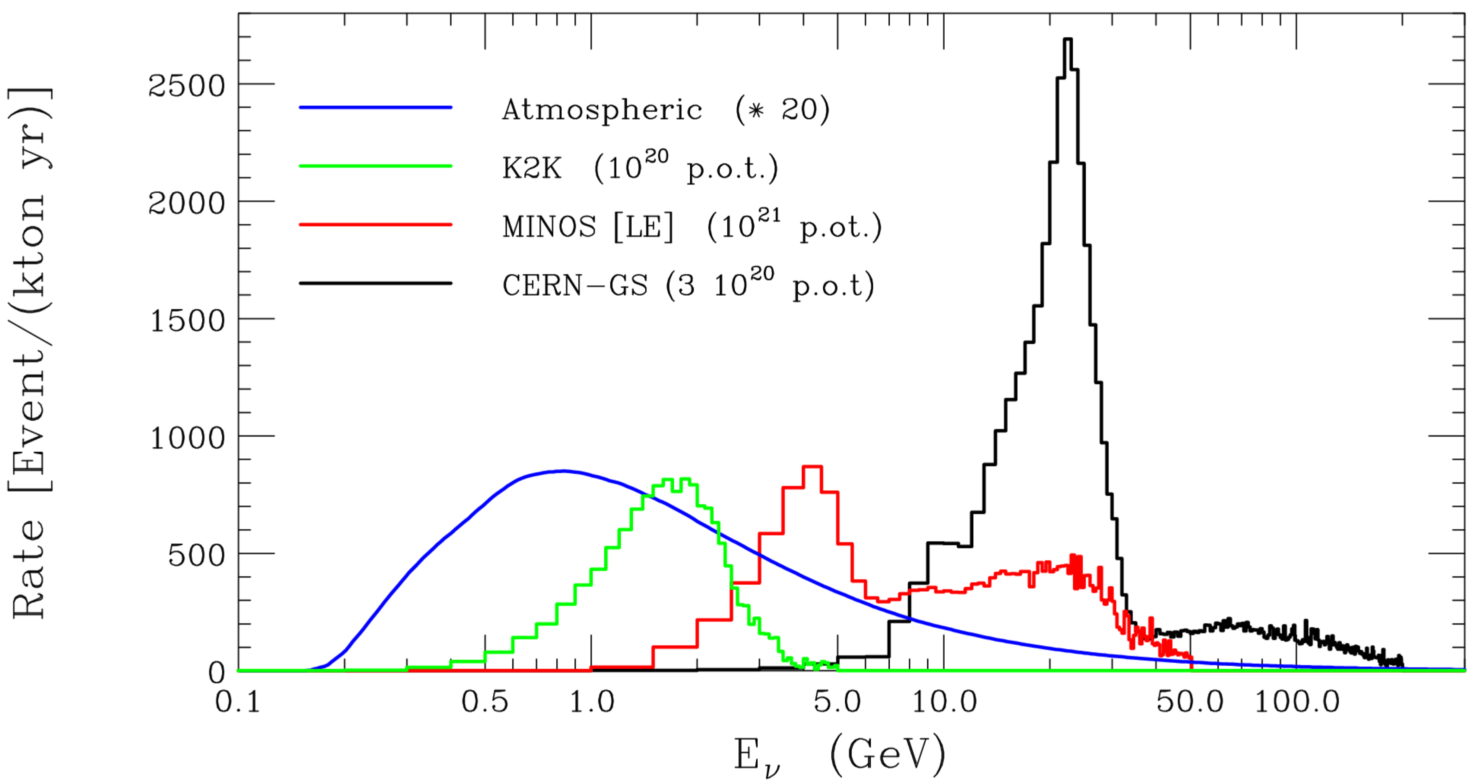
- Deep inelastic scattering (DIS)



- Quasi-elastic scattering (QE)



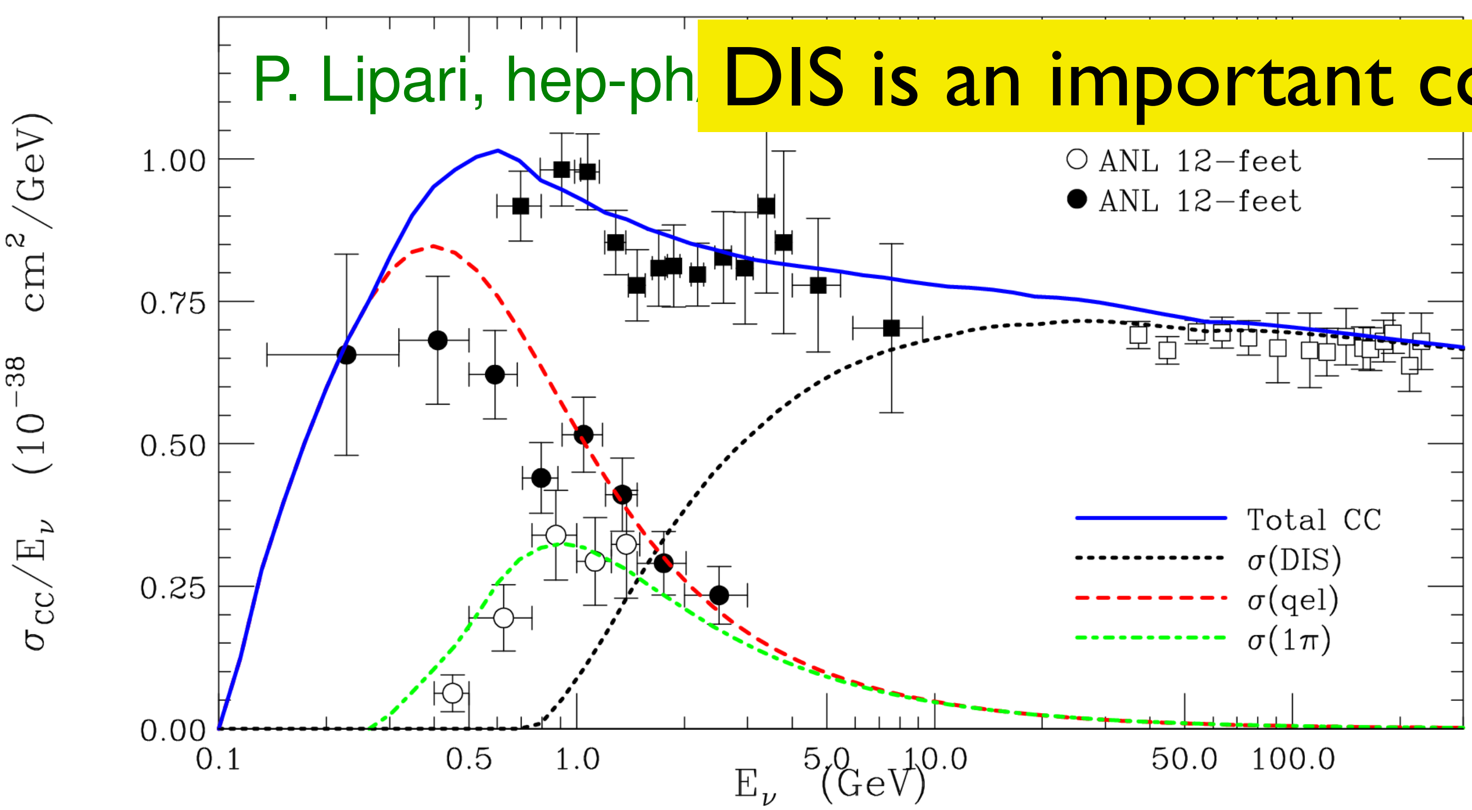
Neutrino cross sections at atmospheric ν energies



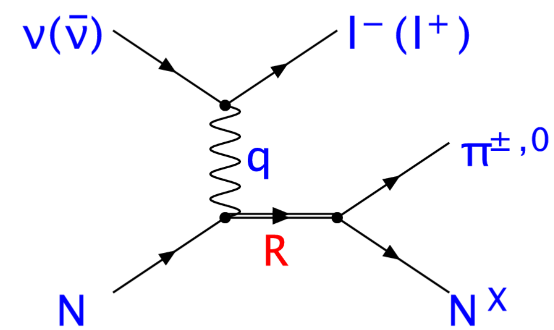
Paschos,JYY,PRD65(2002)033002

P. Lipari, hep-ph

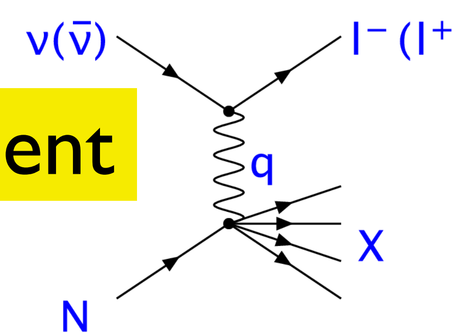
DIS is an important component



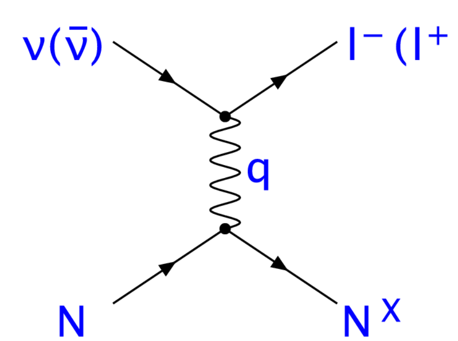
- Resonance production (RES)



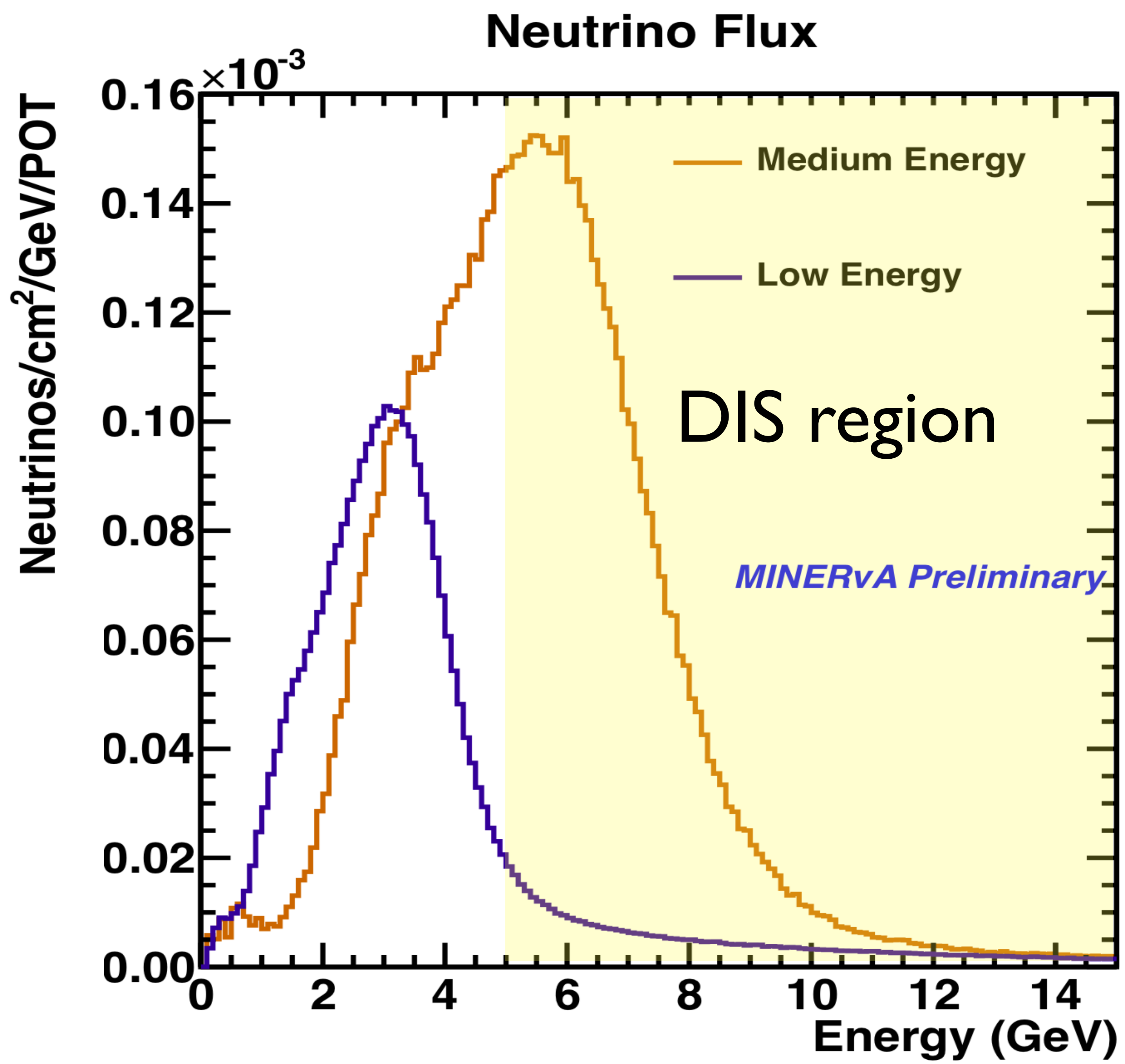
- Deep inelastic scattering (DIS)



- Quasi-elastic scattering (QE)



MINERvA neutrino flux

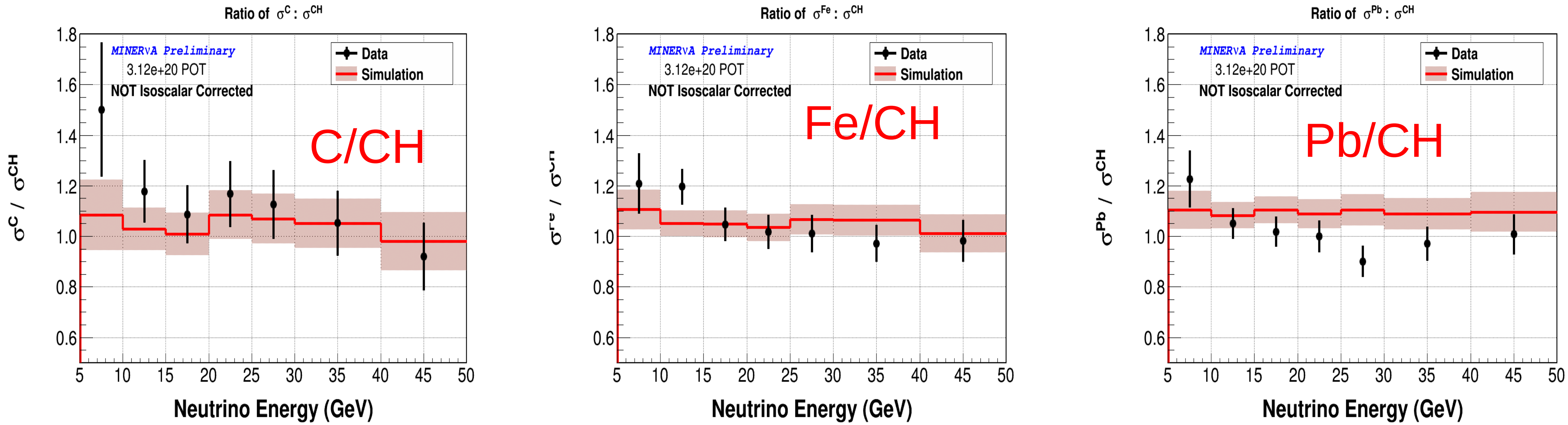


Results so far with LE flux;
Large contributions from QE and RES

Data taking at the moment with ME flux;
much better sensitivity at low and high-x

CC DIS ratios: σ(Eν)

Cuts on (published) inclusive sample: $Q^2 > 1\ \mathrm{GeV}^2,\ W > 2\ \mathrm{GeV}$

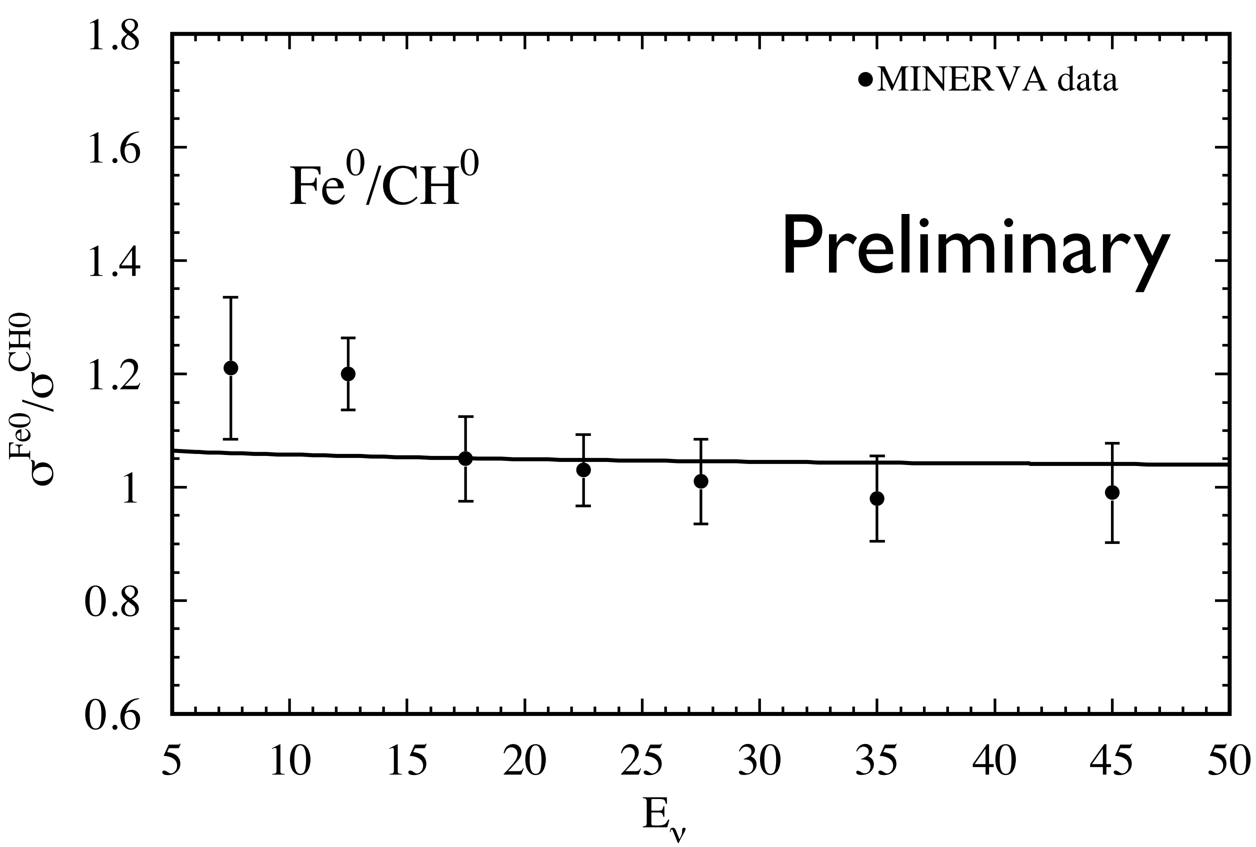


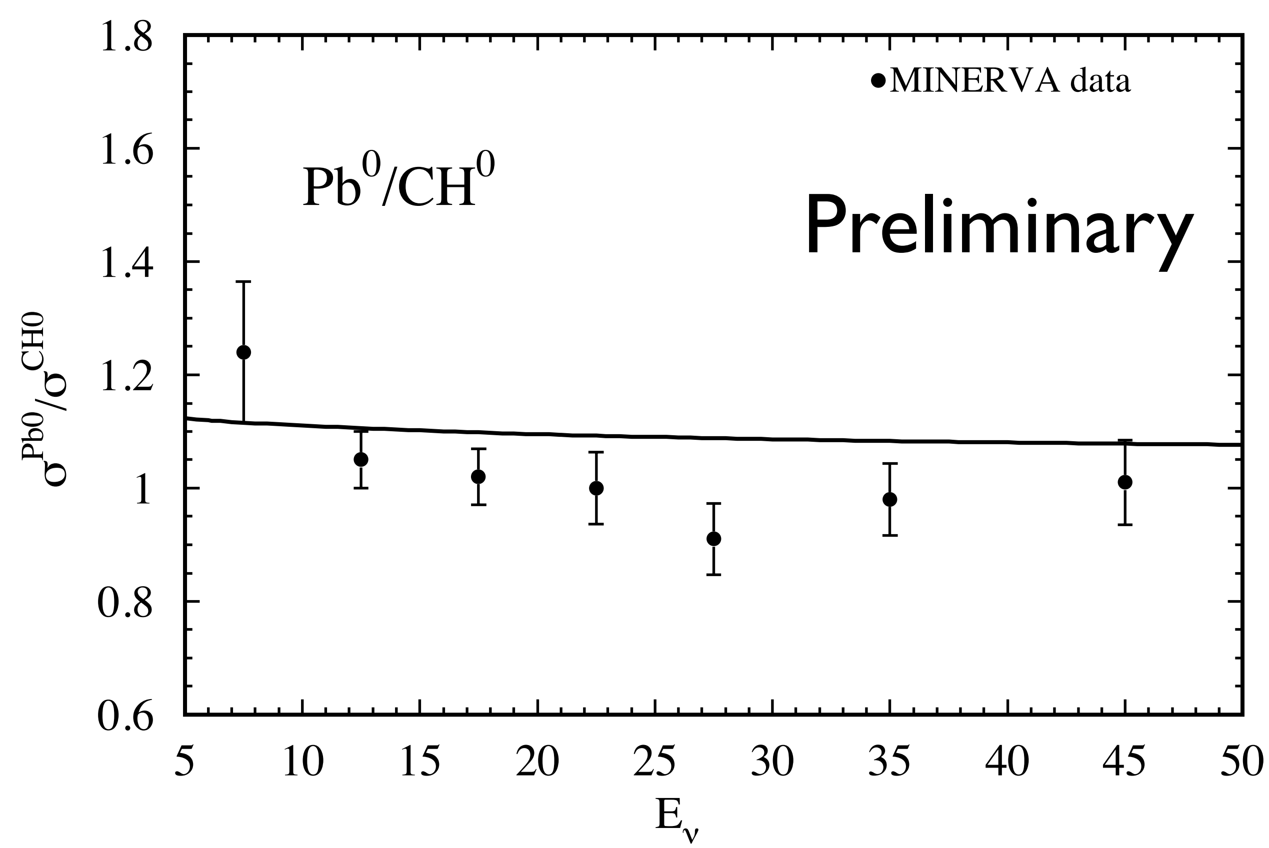
- Not isoscalar corrected!
- Data show no significant deviation from simulation with GENIE which does not include any nuclear effects.
- The parton model results using nPDFs are consistent with unity.
- Small nuclear effects in the integrated cross section.

CC DIS ratios: σ(Eν)

Ratio using **free** proton and neutron PDFs ($Z f^p + N f^n$)

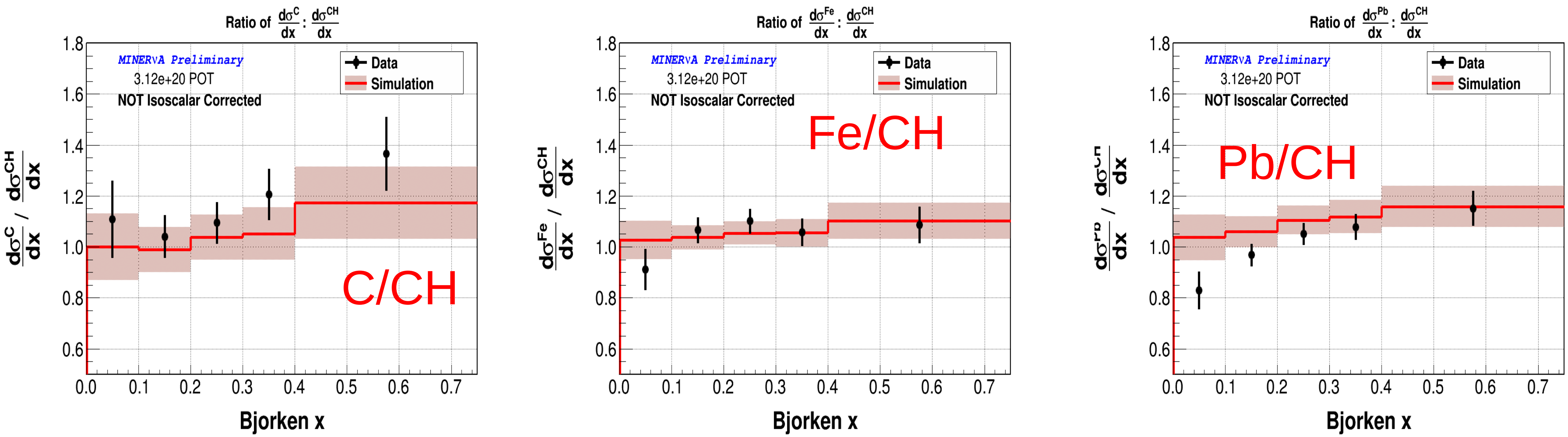
No nuclear effects; deviation from unity due to non-isoscalarity





CC DIS ratios: dσ/dx (flux averaged)

Cuts on (published) inclusive sample: $Q^2 > 1\ \mathrm{GeV}^2$, $W > 2\ \mathrm{GeV}$

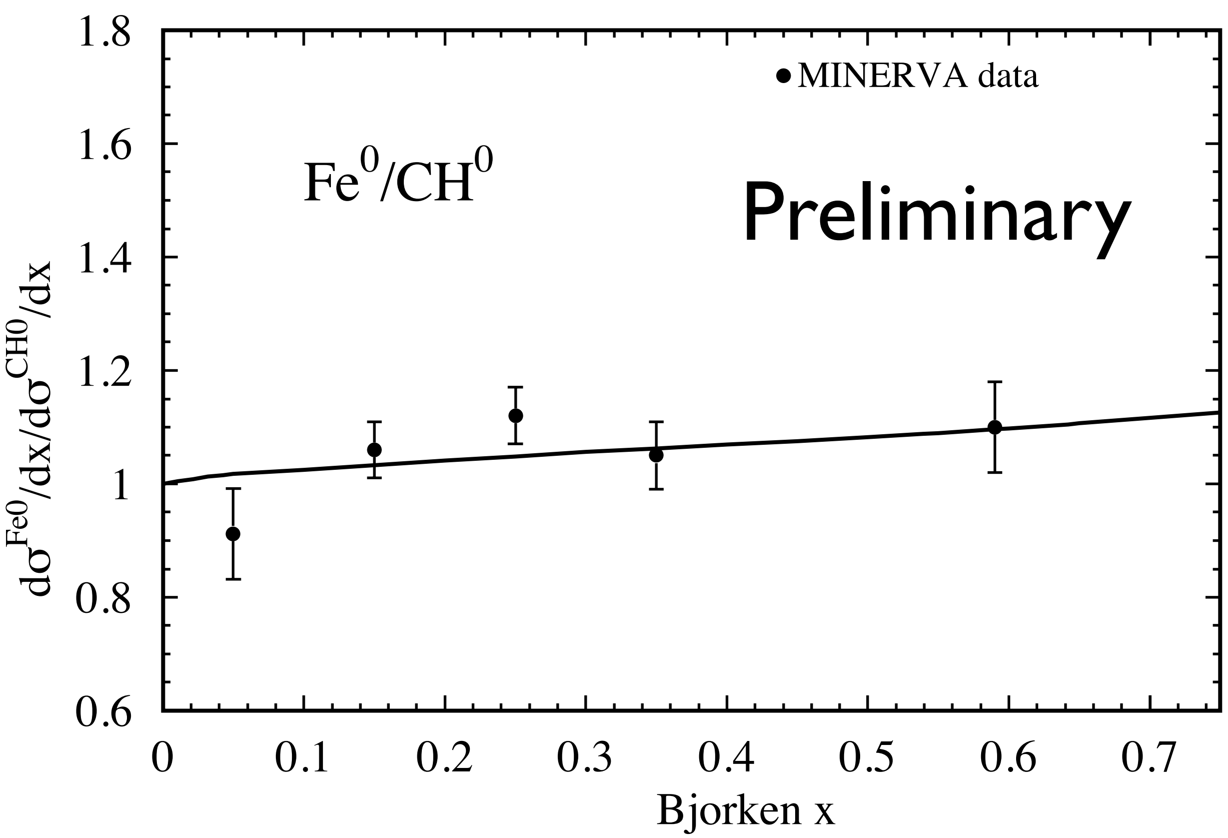


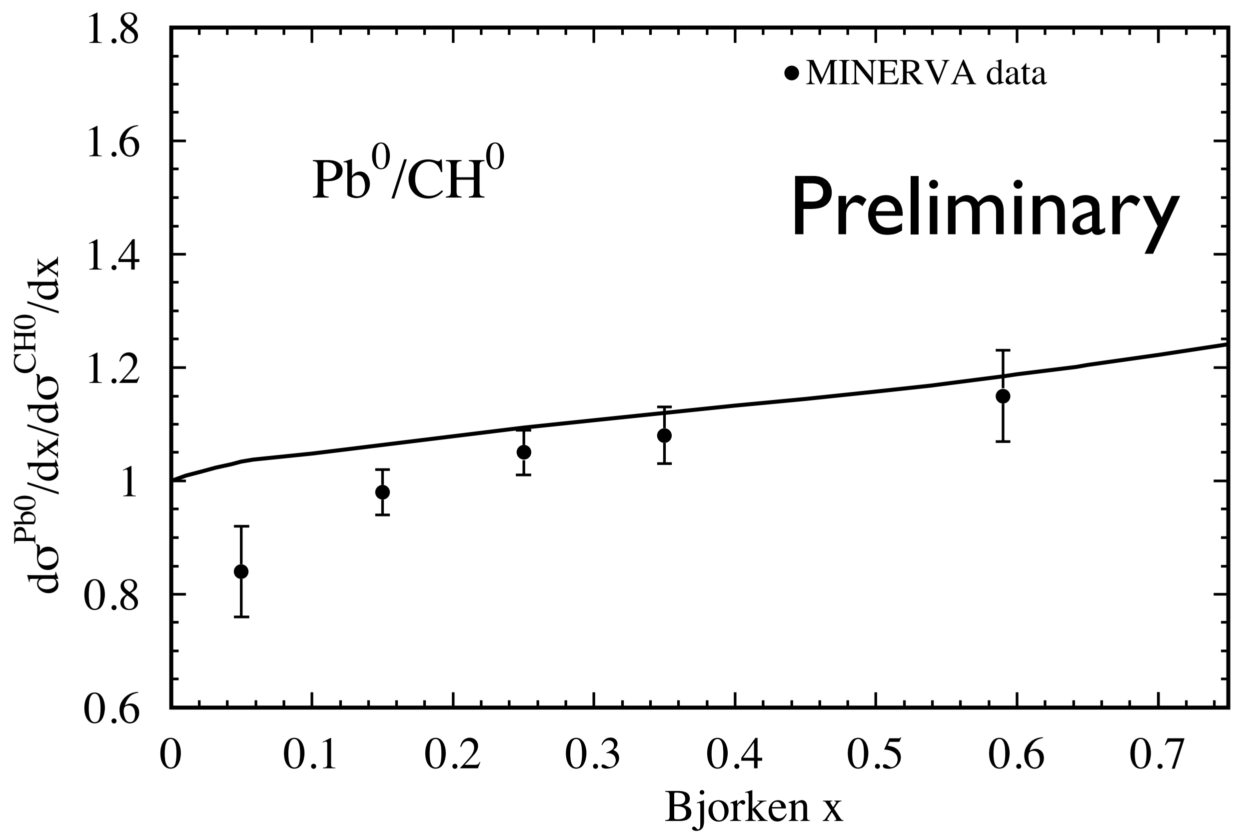
- Not isoscalar corrected! Need to disentangle non-isoscalar effects from nuclear effects!
- Currently, simulation assumes same x-dependent nuclear effects for C, Fe and Pb based on charged lepton DIS.
- Lowest x bin is $<x>\sim 0.07$ and $<Q^2> \sim 2.0\ \mathrm{GeV}^2$. Data suggest additional nuclear shadowing (Pb,Fe). A-dependent higher-twist effects might also play a role.
- In the EMC region ($0.3<x<0.75$) good agreement between data and simulation.
- Data errors mostly statistics dominated. Future improvements at small and high-x due to ME flux.

CC DIS ratios: $d\sigma/dx$ (flux averaged)

Ratio using **free** proton and neutron PDFs ($Z\ f^p + N\ f^n$)

No nuclear effects; deviation from unity due to non-isoscalarity





Conclusions

First **preliminary** results from MINERvA on neutrino DIS using LE flux

Exciting results to come in the future!

EMC effect, shadowing, ... in neutrino interactions

QCD studies with neutrinos

Flavor separation of PDFs

NC charged lepton DIS: 2 structure functions (γ-exchange)

$$F_2^{\gamma}(x) \sim \frac{1}{9}[4(u + \bar{u} + c + \bar{c}) + d + \bar{d} + s + \bar{s}](x)$$

$$F_2^{\gamma}(x) = 2xF_1^{\gamma}(x)$$

CC Neutrino DIS: 6 additional structure functions $F_{1,2,3}^{W+}$, $F_{1,2,3}^{W-}$

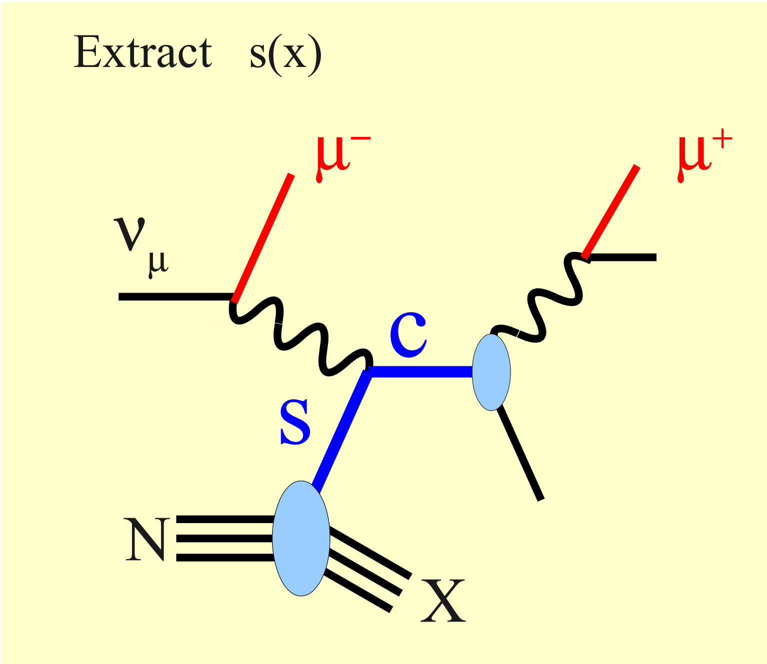
$$F_2^{W^+} \sim [d + s + \bar{u} + \bar{c}] \qquad F_3^{W^+} \sim 2[d + s - \bar{u} - \bar{c}]$$

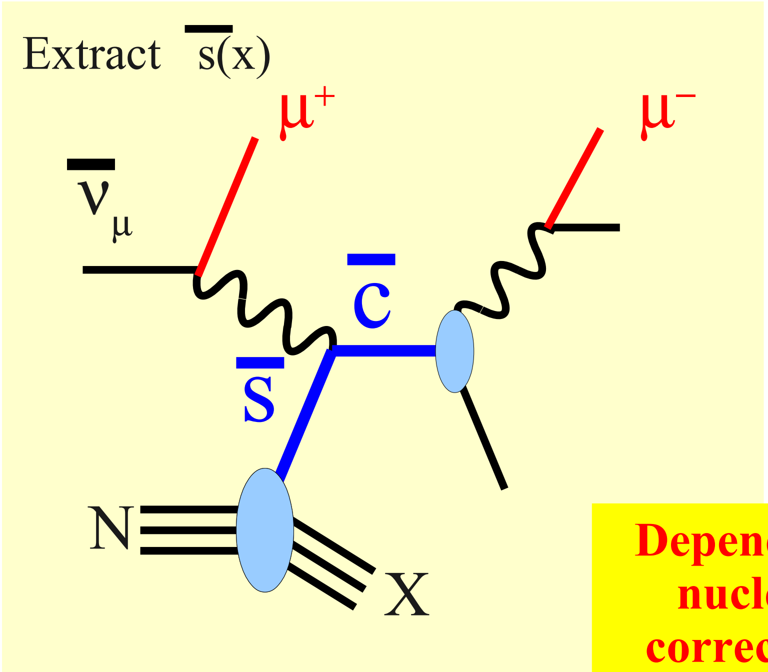
$$F_2^{W^-} \sim [\bar{d} + \bar{s} + u + c] \qquad F_3^{W^-} \sim 2[u + c - \bar{d} - \bar{s}]$$

Useful/needed to disentangle different quark parton flavors in a global analysis of proton or nuclear PDFs

Dimuon production and the strange PDF

Opposite sign dimuon production in neutrino DIS: $\nu N \rightarrow \mu^+ \mu^- X$



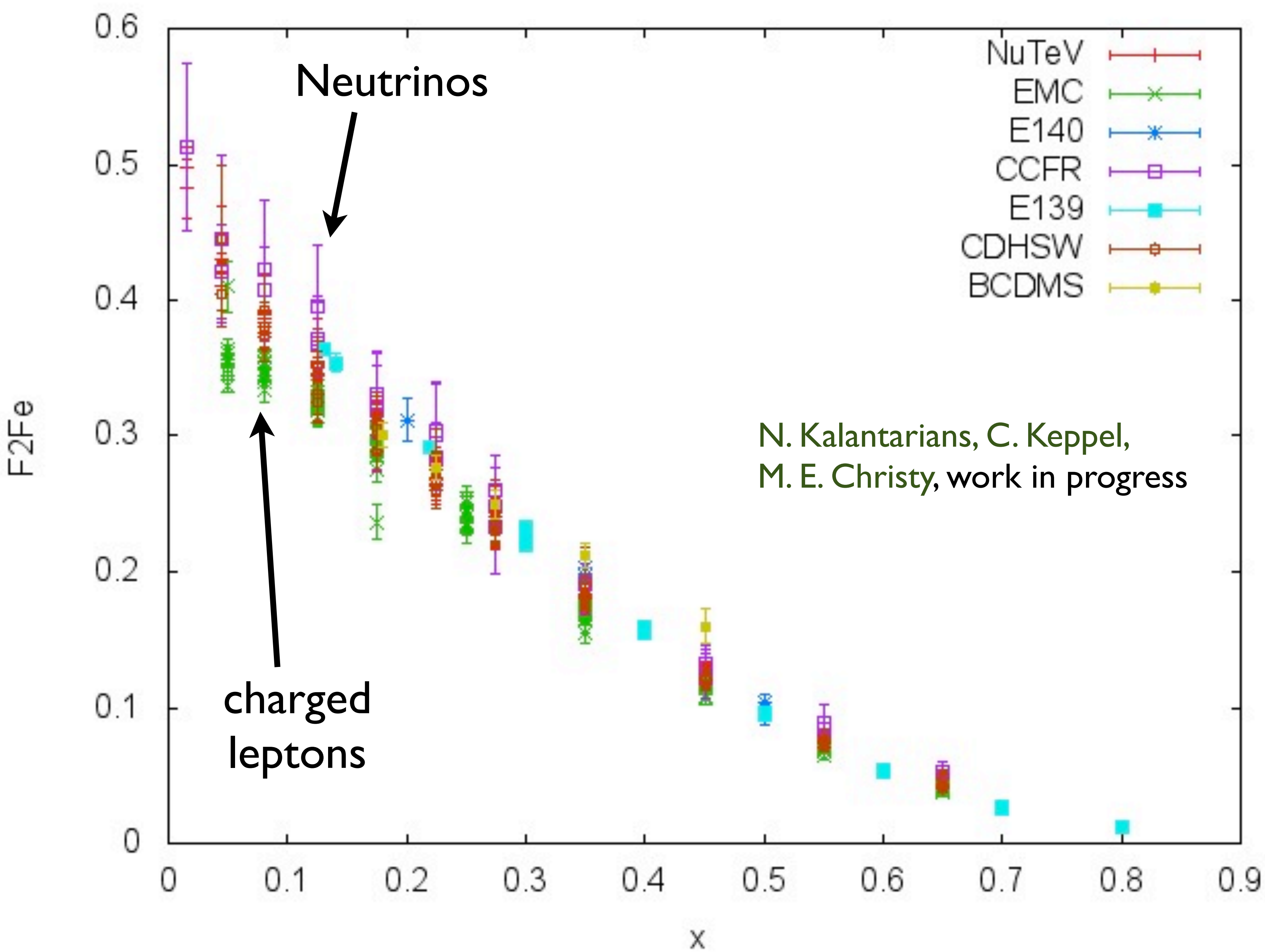


Depends on nuclear corrections

- High-statistics data from CCFR and NuTeV: **Main source** of information!
- x~[0.01,0.4]
- νFe DIS: need nuclear corrections! Problem: Final State Interactions (FSI)
- CHORUS (νPb): compatible with NuTeV, could be included
- NOMAD (νFe): data not yet published, in principle very interesting

World data on 18/5 F_2^{NC} and F_2^{CC} on iron

$$\Delta F_2 = \frac{5}{18} F_2^{CC} - F_2^{NC} \simeq \frac{x}{6}[s(x) + \bar{s}(x)]$$



Data available at Durham database;

Data brought to the same Q^2=8 GeV^2

Info on nuclear corrections in ν-Fe DIS vs l-Fe DIS:
Advantage: no deuterium

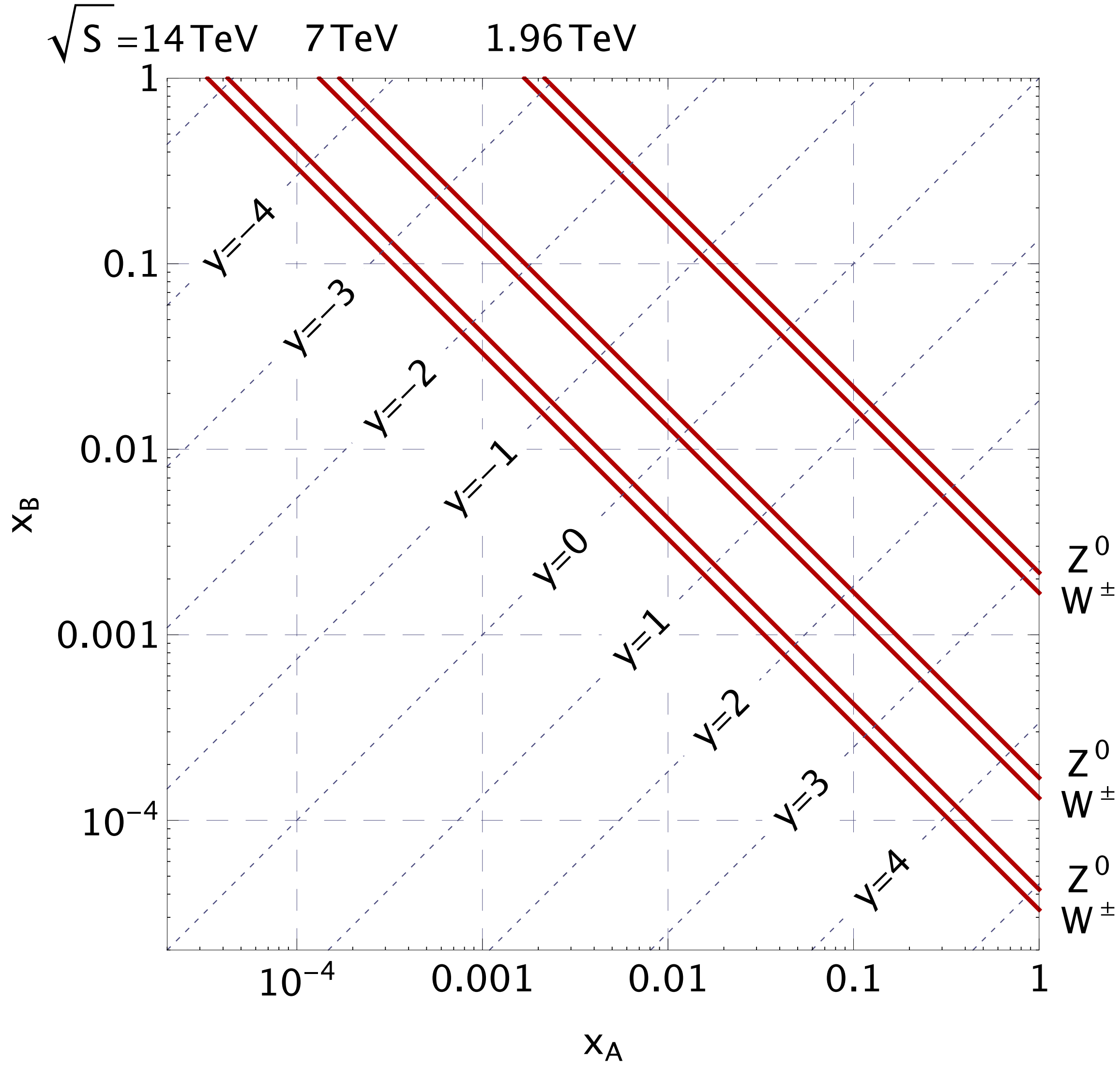
Info on strange PDF in iron:

Advantage: inclusive, no FSI

Disadvantage: difference of two large numbers

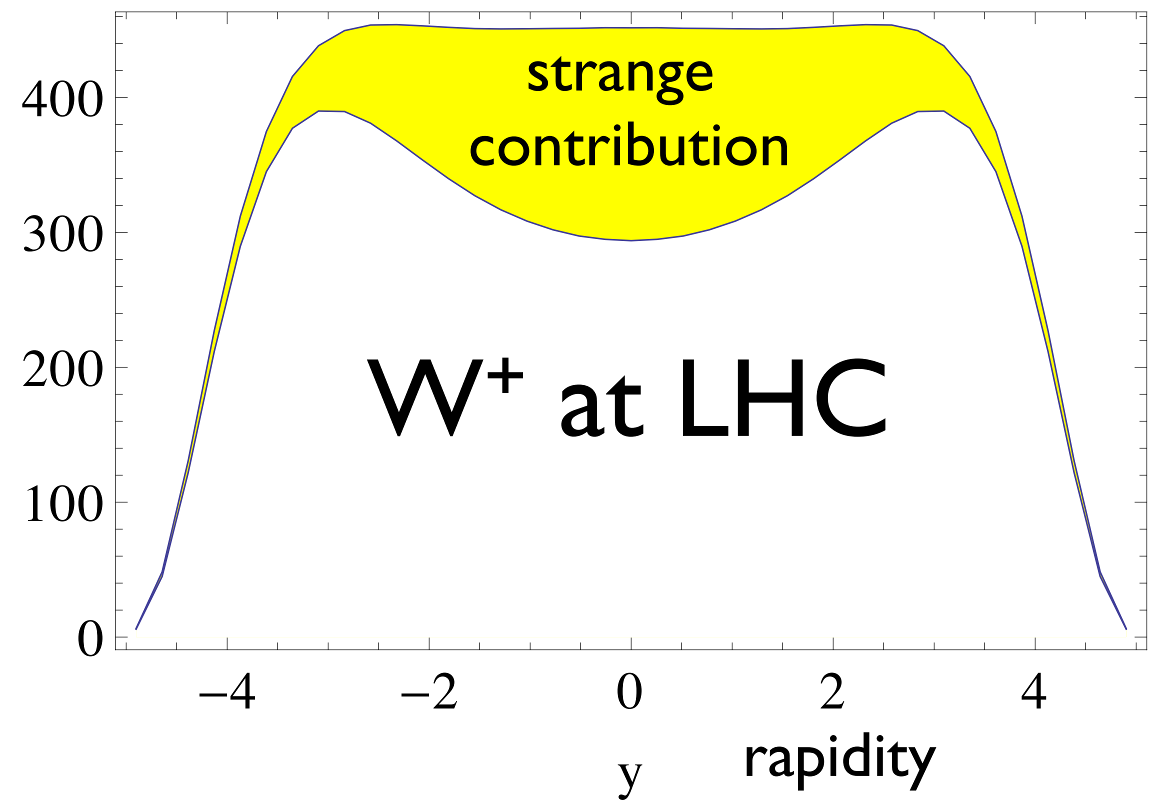
Drell-Yan production of W/Z at the LHC

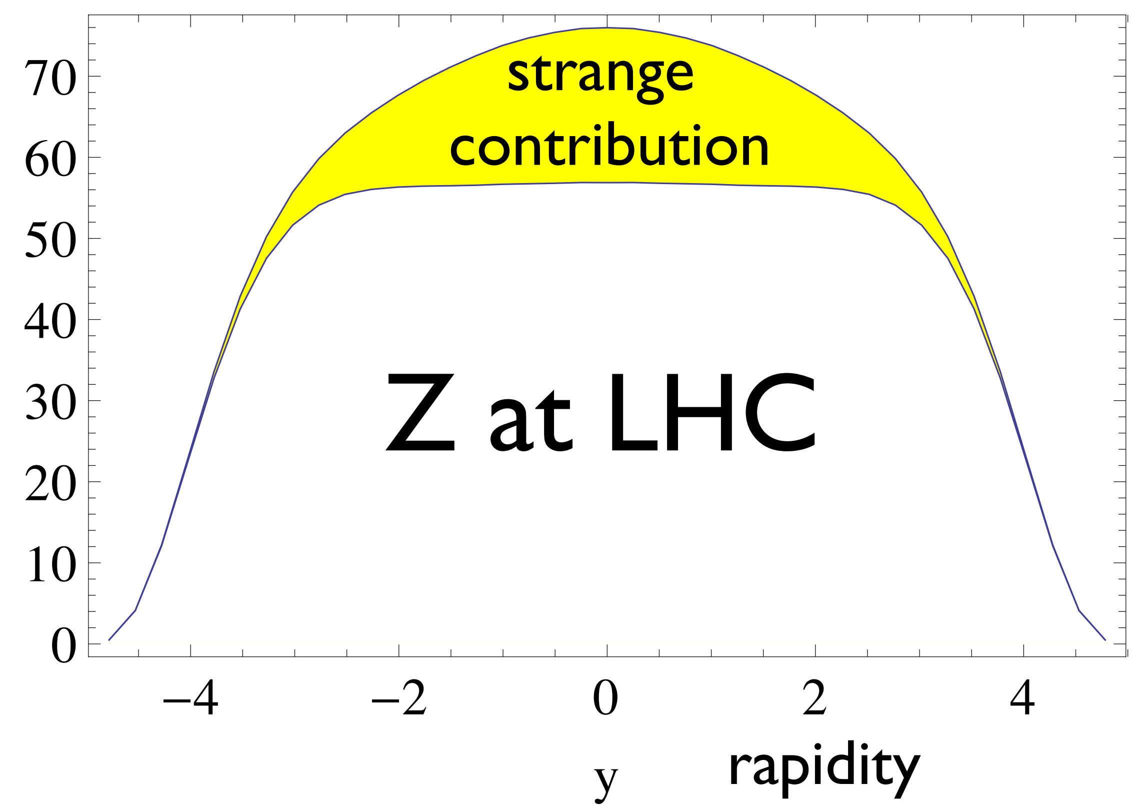
Kinematic plane



Uncertainty of strange-PDF will feed into benchmark process

$d^2\sigma/dM/dy\,[\mathrm{pb/GeV}]$

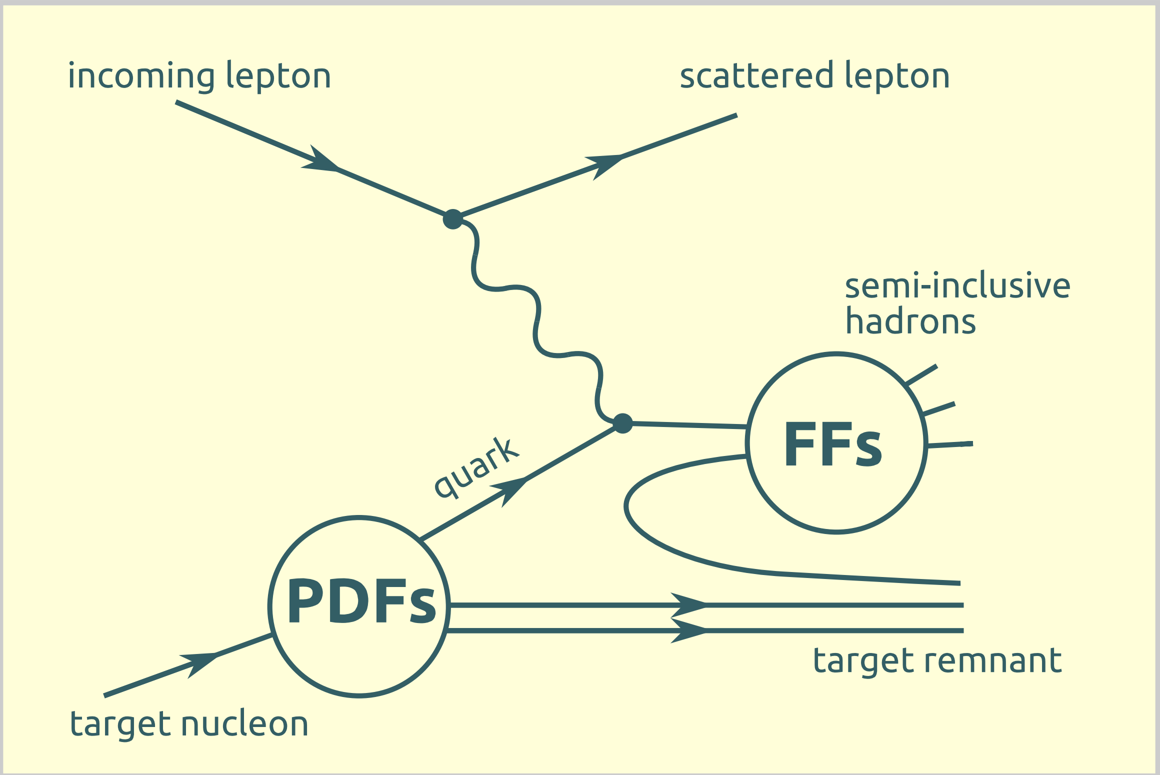




VRAP code: Anastasiou, Dixon, Melnikov, Petriello, PRD69(2004)094008

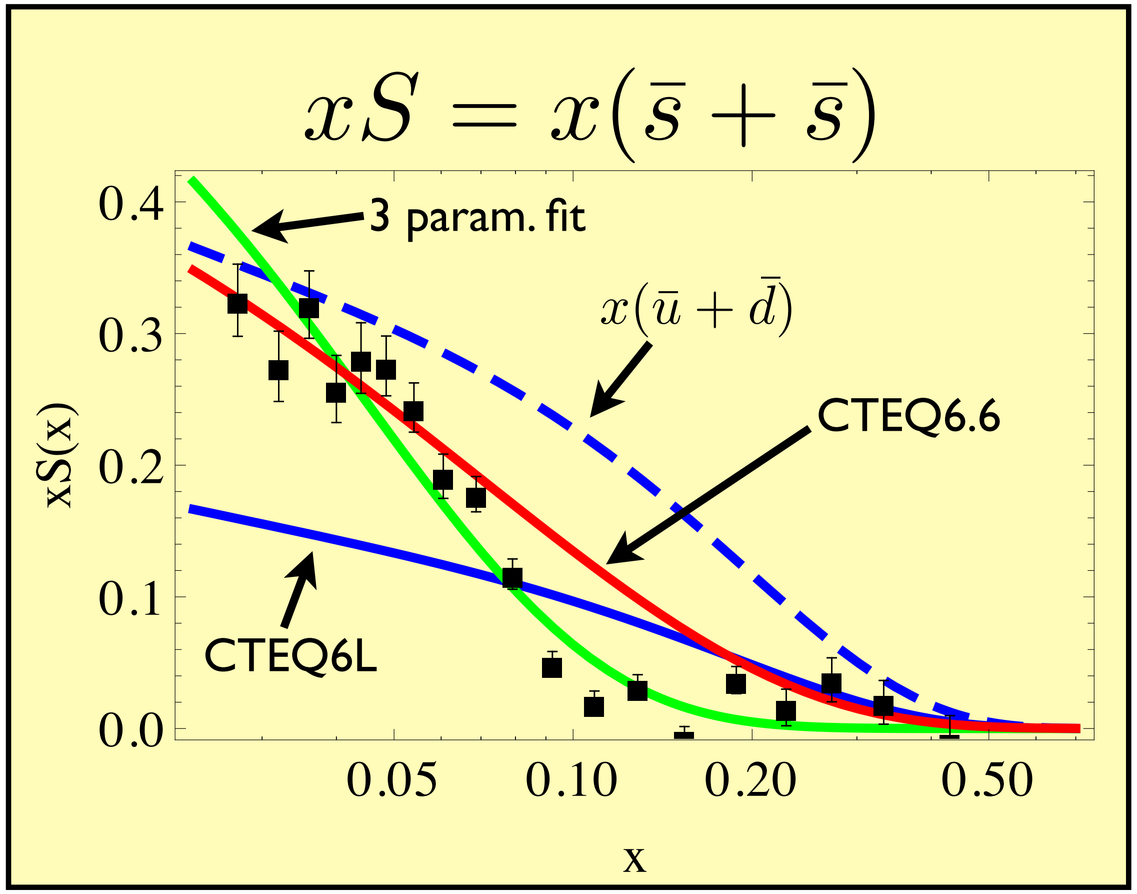
Strange PDF: experimental constraints

Semi-Inclusive DIS (SIDIS): e+N→K+X



$$\frac{d\sigma}{dx dQ^2 dz} \propto \sum_q e_q^2 f_q(x, Q^2) D_q^K(z, Q^2)$$
$$\sim \frac{1}{9} s(x, Q^2) D_s^K(z, Q^2)$$

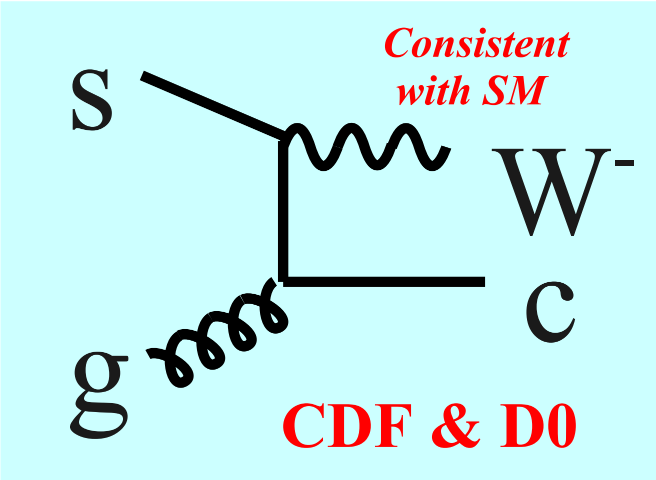
- SIDIS data from HERMES
- $e^+ + D \rightarrow K + X$
- depends on fragmentation functions (FF)
- not (yet) included in global analyses
- compatible with CTEQ6.6 (red curve)



Strange PDF: experimental constraints

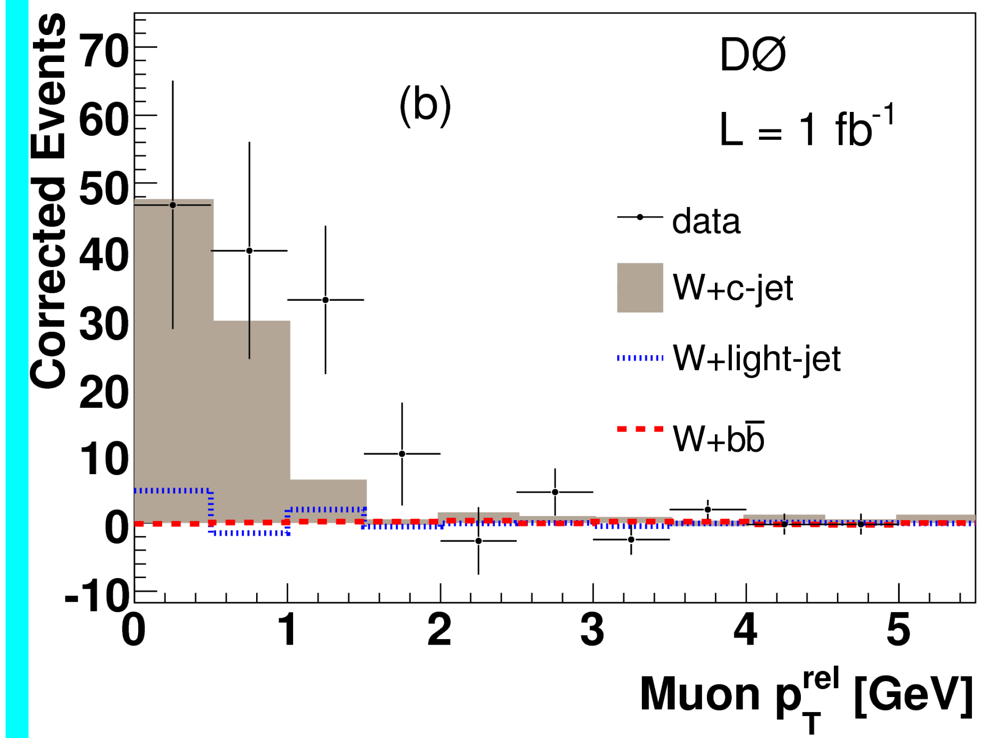
Production of a vector boson+heavy quark: s+g →W+c

s g→Wc at the Tevatron



CDF: PRL 100:091803,2008.
D0: PLB666:23,2008.

- Tevatron: analysis with ~1 fb^{-1} consistent with SM
- no nuclear corrections
- different kinematic region than neutrino DIS
- hadron-hadron initial state more challenging
- not yet competitive but updated analyses in progress



Also a challenge at LHC

xF_3 and Isospin Violation

- xF_3 uniquely determined by neutrino-DIS

$$\boxed{\begin{aligned} \frac{1}{2}F_3^{\nu A}(x) &= d_A + s_A - \bar{u}_A - \bar{c}_A + ..., \\ \frac{1}{2}F_3^{\bar{\nu} A}(x) &= u_A + c_A - \bar{d}_A - \bar{s}_A + ... \end{aligned}}$$

- The sum is sensitive to the valence quarks

→ Nonsinglet QCD evolution, $\boxed{\text{determination of } \alpha_s(Q)}$

- The difference can be used to constrain isospin violation

$$\boxed{\begin{aligned} \Delta x F_3 &= xF_3^{\nu A} - xF_3^{\bar{\nu} A} = 2xs_A^+ - 2xc_A^+ + x\,\delta I^A + \mathcal{O}(\alpha_S) \\ \delta I^A &= \left(d_{p/A} - u_{n/A}\right) + \left(d_{n/A} - u_{p/A}\right) + \left(\bar{d}_{p/A} - \bar{u}_{n/A}\right)\left(\bar{d}_{n/A} - \bar{u}_{p/A}\right) \end{aligned}}$$

Hadronic Precision Observables

$$\boxed{\begin{aligned} R^{\nu} &= \frac{\sigma^{\nu}_{\mathrm{NC}}}{\sigma^{\nu}_{\mathrm{CC}}} \simeq g_L^2 + r g_R^2 \\ R^{\bar{\nu}} &= \frac{\sigma^{\bar{\nu}}_{\mathrm{NC}}}{\sigma^{\bar{\nu}}_{\mathrm{CC}}} \simeq g_L^2 + r g_R^2 \\ r &= \frac{\sigma^{\bar{\nu}}_{\mathrm{CC}}}{\sigma^{\nu}_{\mathrm{CC}}} \end{aligned}}$$

g_L and g_R are effective L and R νq couplings

$$\begin{aligned} g_L^2 &= \rho^2\left(\frac{1}{2} - s_w^2 + \frac{5}{9}s_w^4\right) \\ g_R^2 &= \rho^2\left(\frac{5}{9}s_w^4\right) \end{aligned}$$

Paschos-Wolfenstein (PW):

$$\boxed{\begin{aligned} R^{-} &= \frac{\sigma^{\nu}_{\mathrm{NC}} - \sigma^{\bar{\nu}}_{\mathrm{NC}}}{\sigma^{\nu}_{\mathrm{CC}} - \sigma^{\bar{\nu}}_{\mathrm{CC}}} \\ &\simeq g_L^2 - g_R^2 = \rho^2\left(\frac{1}{2} - s_w^2\right) \end{aligned}}$$

QCD for PW-style analysis

$$R^- = \frac{\sigma^\nu_{\rm NC} - \sigma^{\bar\nu}_{\rm NC}}{\sigma^\nu_{\rm CC} - \sigma^{\bar\nu}_{\rm CC}} \simeq \frac{1}{2} - s_w^2 + \delta R_A^- + \delta R_{QCD}^- + \delta R_{EW}^-$$

non-isoscalarity of the target

QCD effects

higher order ew effects

$$\delta R_{QCD}^- = \delta R_s^- + \delta R_I^- + \delta R_{NLO}^-$$

due to strangeness asymmetry:

$$s^- \equiv s - \bar{s} \neq 0$$

due to isospin violation:

$$u^p(x) \neq d^n(x)$$

higher order QCD effects

see, e.g., hep-ph/0405221

SHiP experiment proposal

SHiP Proposal

PHYSICAL

CERN-SPSC-2015-017/SPSC-P_350-ADD-1

arXiv:1504.04855 (hep-ph)

TECHNICAL

CERN-SPSC-2015-016/SPSC-P_350

arXiv:1504.04956 (hep-ph)

PREPARED FOR SUBMISSION TO JHEP

A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case

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85 theorists
200 pages

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

CERN-SPSC-2015-016
SPSC-P-350
8 April 2015

Technical Proposal

A Facility to Search for Hidden Particles (SHiP) at the CERN SPS

The SHiP Collaboration[1]

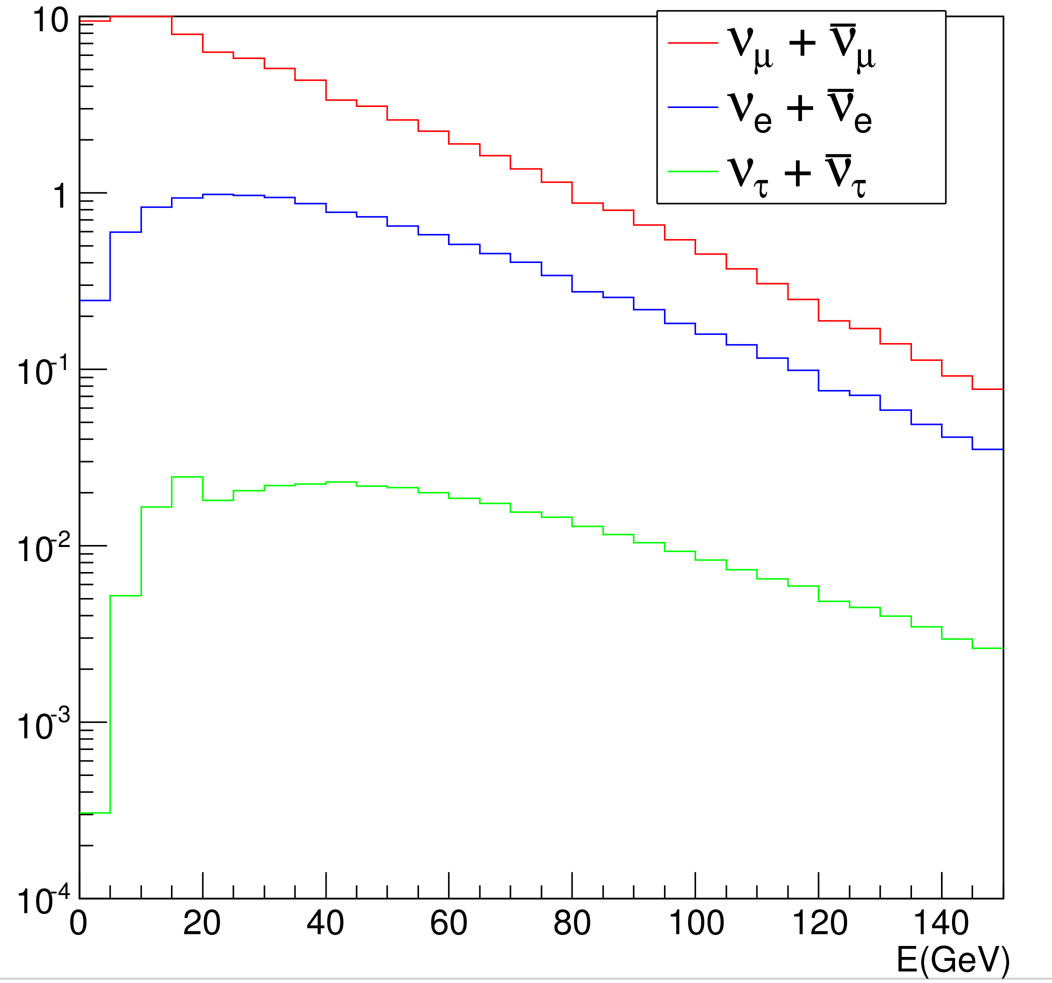
234 authors
44 institutions
13 countries

Abstract

A new general purpose fixed target facility is proposed at the CERN SPS accelerator which is aimed at exploring the domain of hidden particles and make measurements with tau neutrinos. Hidden

Talk by A. Di Crescenzo at DIS 2015

Neutrino Physics@SHiP



Energy spectrum of different neutrino flavors interacting in the target

CC DIS neutrino interactions in 5 years run (2×10^{20} pot)

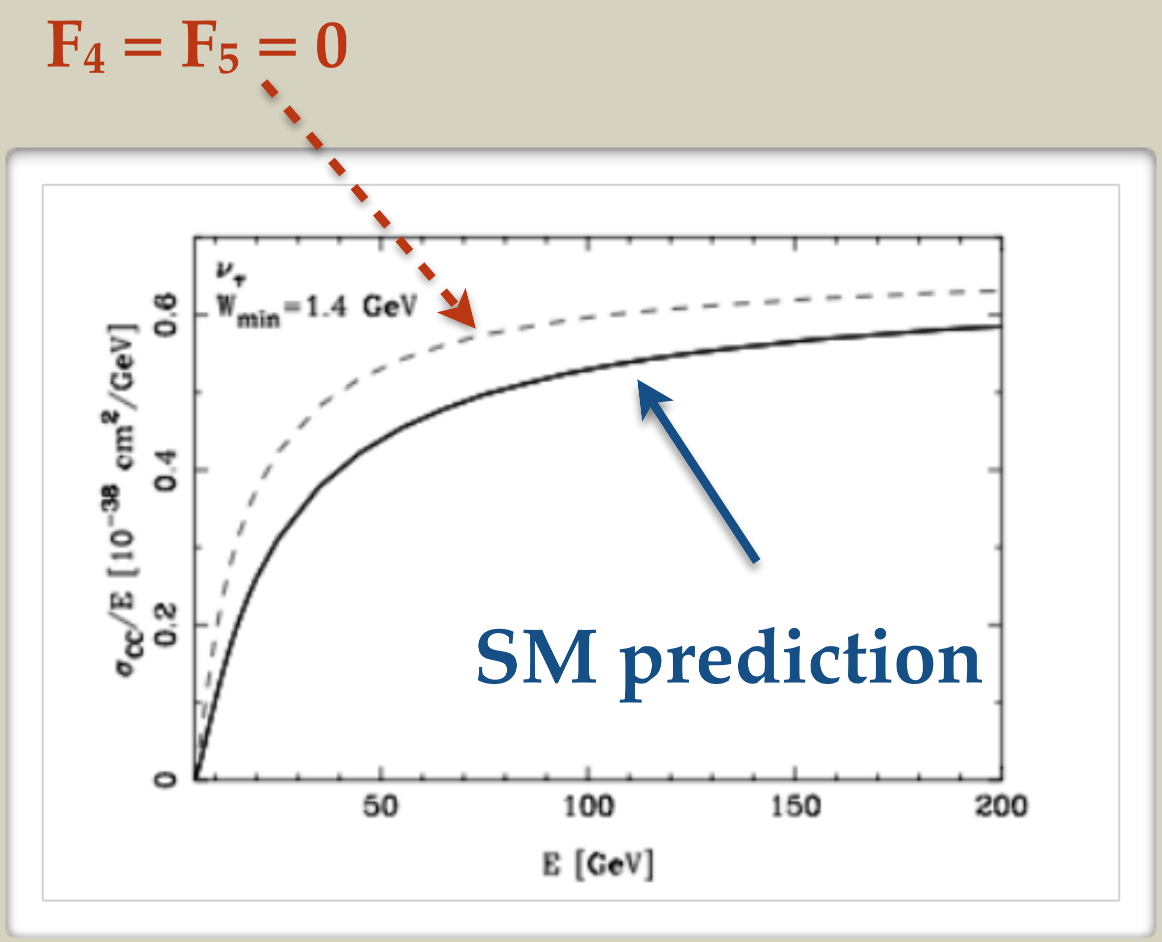
	<E> (GeV)	CC DIS interactions
N_{ν_μ}	29	1.7×10^6
N_{ν_e}	46	2.5×10^5
N_{ν_τ}	59	6.7×10^3
$N_{\overline{\nu}_\mu}$	28	6.7×10^5
$N_{\overline{\nu}_e}$	46	9.0×10^4
$N_{\overline{\nu}_\tau}$	58	3.4×10^3

SHiP

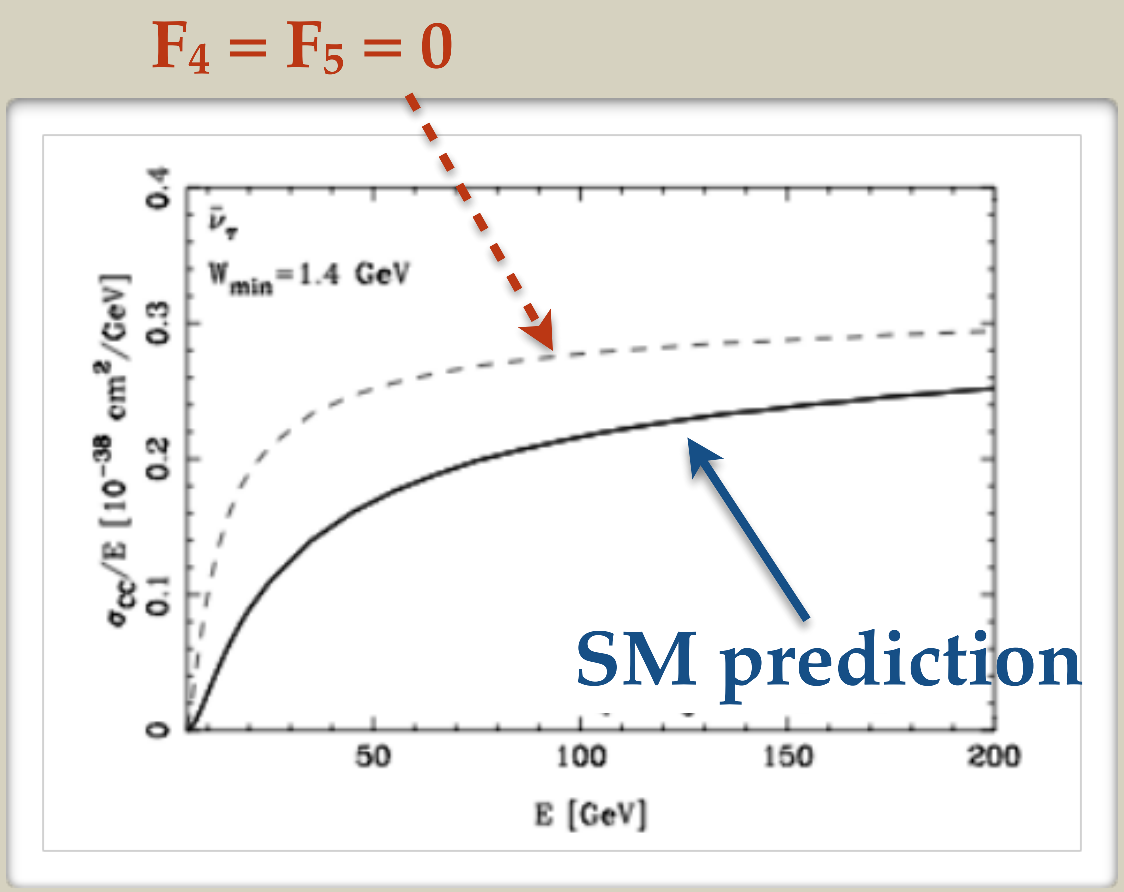
- Proposal: fixed target experiment at the CERN SPS
- SPS: 4×10^{13} protons per spill@400 GeV → 2×10^{20} pot in 5 years (same as CNGS)

- Search for new physics beyond SM: explore the intensity frontier
- Rich Standard Model physics program:
  - first observation of anti-ν_τ
  - ν_τ and anti-ν_τ cross section measurements: sensitive to F_4 and F_5
  - structure functions studies: W^+: F_1, F_2, F_3 ; W^-: F_1, F_2, F_3
  - charm physics with neutrinos and anti-neutrinos: strange PDF
  - electroweak measurements: Paschos-Wolfenstein relation, ...

Sensitivity to F_4 and F_5



ν_τ CC DIS cross-section



$\bar{\nu}_\tau$ CC DIS cross-section

nCTEQ nuclear correction factors

νA DIS vs lA DIS

- Not much information on nuclear ratios in νA DIS
- Often use information from lA DIS to correct for nuclear effects
- Sometimes the same nuclear correction factor is applied independent of the neutrino observable, Q^2, or the nuclear A
- **Big question**:

  Are nuclear effects in νA DIS the same as in lA DIS?

  (Problem: term "nuclear effect" used for different things)

Nuclear corrections: Parton model perspective

- Be O an observable calculable in the parton model
- Define **nuclear correction** factor in the following way:

$$\boxed{R[O] = O[Z\, f^{p/A} + N\, f^{n/A}]/O[Z\, f^{p} + N\, f^{n}]}$$

- **Advantages**:
  - very flexible: any $Q^2 > 1\ \mathrm{GeV}^2$, different nuclear A
  - different observables: $F_{1,2,3}^{W+}$, $F_{1,2,3}^{W-}$, $F_{1,2}^{\gamma}$, DY, $d\sigma/dxdy$
  - calculation of uncertainties possible
- Of course, no explanation of nuclear effects

Nuclear corrections: Parton model perspective

Even with same nuclear modification of the different parton flavors:

$$R[F_2^{\nu A}](x) \neq R[F_2^{lA}](x) \qquad R[F_3^{\nu A}](x) \neq R[F_2^{\nu A}](x)$$

simply because different observables depend differently on the partons.

Often similar but **not** the same: $\underbrace{F_2^A/F_2^D}_{\text{measured}} \neq \underbrace{R[F_2^A]}_{\text{needed correction factor}}$

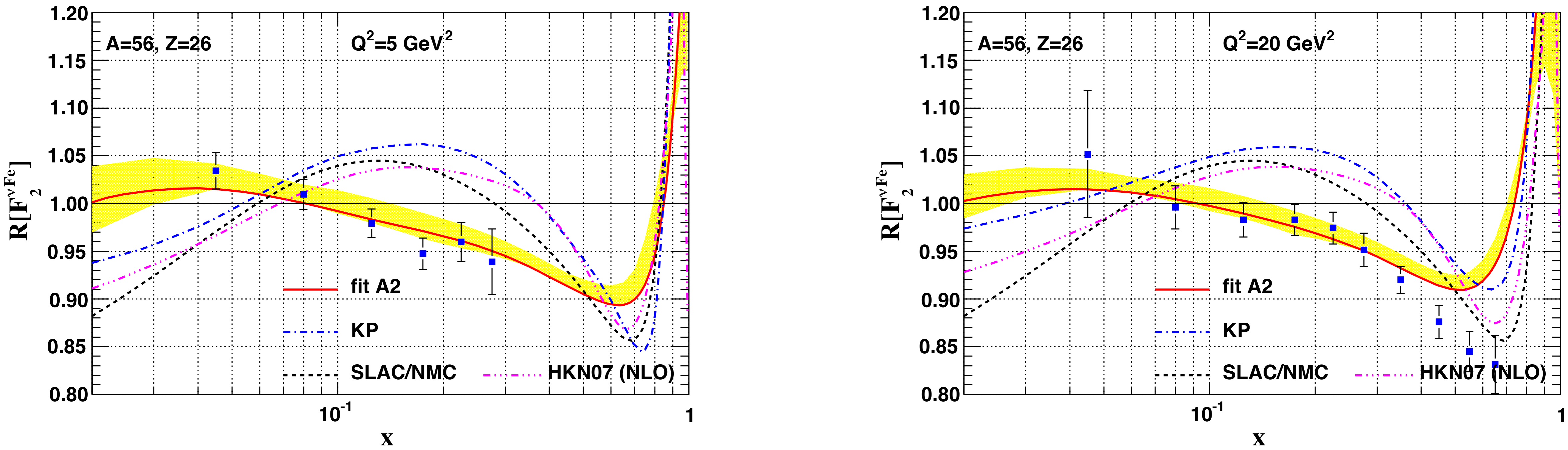
Non-isoscalarity effects; Deuteron has its own nuclear corrections.

In summary:

Nuclear correction factors will be (more or less) different even if the same nuclear mechanisms are at work/even if there are universal NPDFs

Big question: can νA+lA data be described by a universal set of NPDFs?

NUCLEAR CORRECTION FACTOR $R[F_2^{\nu Fe}]$



- Are nuclear corrections in charged-lepton and neutrino DIS different?
- Obviously the PDFs from fi ts to ℓA + DY data do not describe the neutrino DIS data.
- However, a better flavor decomposition could be possible resulting from a global analysis of ℓA, DY and νA data.

Note: $x_{\min} = 0.02$ in these figures.

Global analysis of νA+lA+DY data

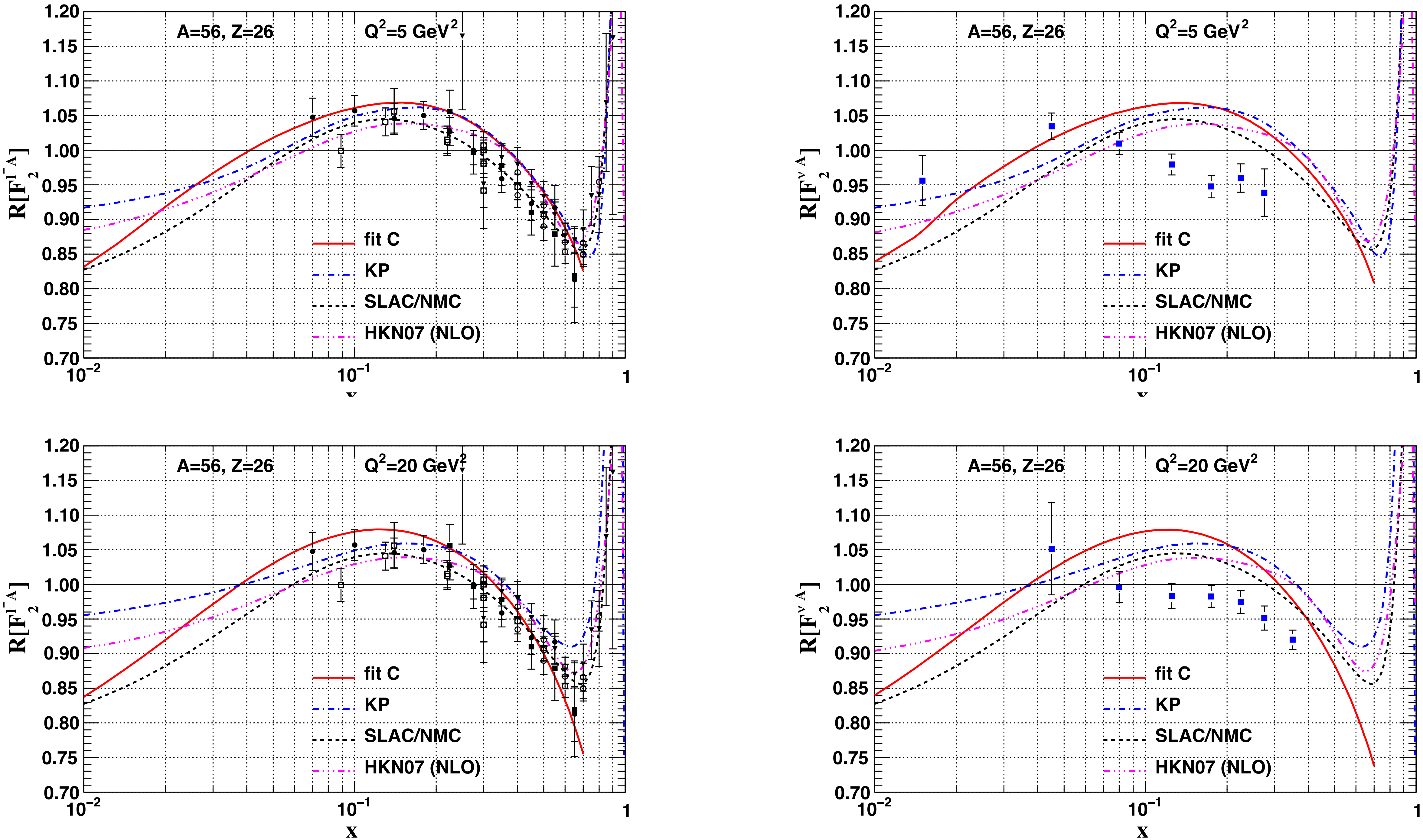
COMBINING ℓA DIS, DY AND νA DIS DATA

- ℓA and DY data sets as before
- 8 Neutrino data sets
  - NuTeV cross section data: νFe, $\bar{\nu} Fe$
  - CHORUS cross section data: νPb, $\bar{\nu} Pb$
  - NuTeV dimuon data: νFe, $\bar{\nu} Fe$
  - CCFR dimuon data: νFe, $\bar{\nu} Fe$
- Problem: Neutrino data sets have much higher statistics. Systematically study fi ts with different weights.

Weight	Fit name	ℓ data	χ^2 (/pt)	ν data	χ^2 (/pt)	total χ^2 (/pt)
$w = 0$	decut3	708	639 (0.90)	-	-	639 (0.90)
$w = 1/7$	glofac1a	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
$w = 1/4$	glofac1c	708	654 (0.92)	3134	4501 (1.43)	5155 (1.34)
$w = 1/2$	glofac1b	708	680 (0.96)	3134	4405 (1.40)	5085 (1.32)
$w = 1$	global2b	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
$w = \infty$	nuanua1	-	-	3134	4192 (1.33)	4192 (1.33)

$R[F_2^{\ell Fe}]$ (LEFT) VS $R[F_2^{\nu Fe}]$ (RIGHT)

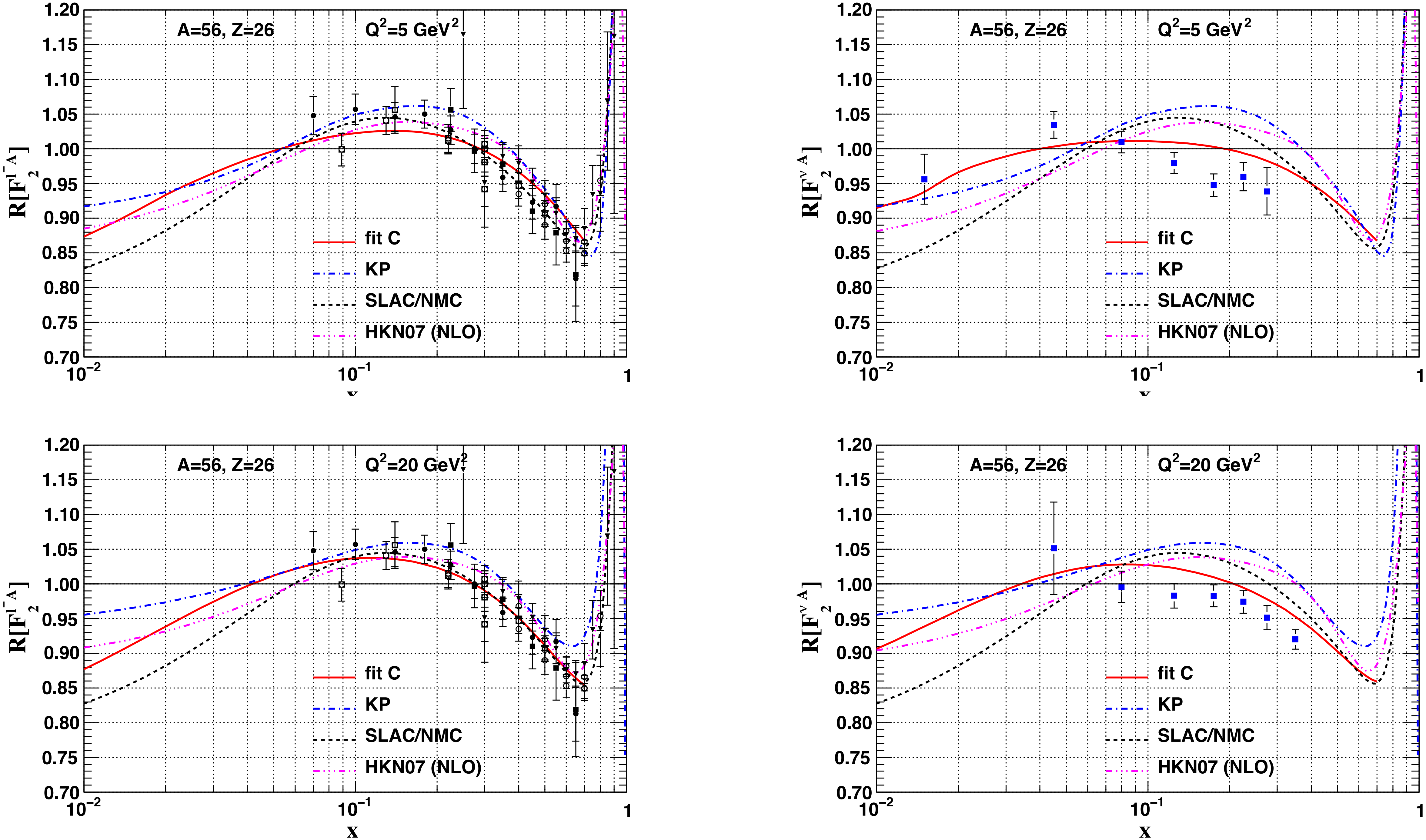
decut3 ($w = 0$)



Monday, June 8, 15

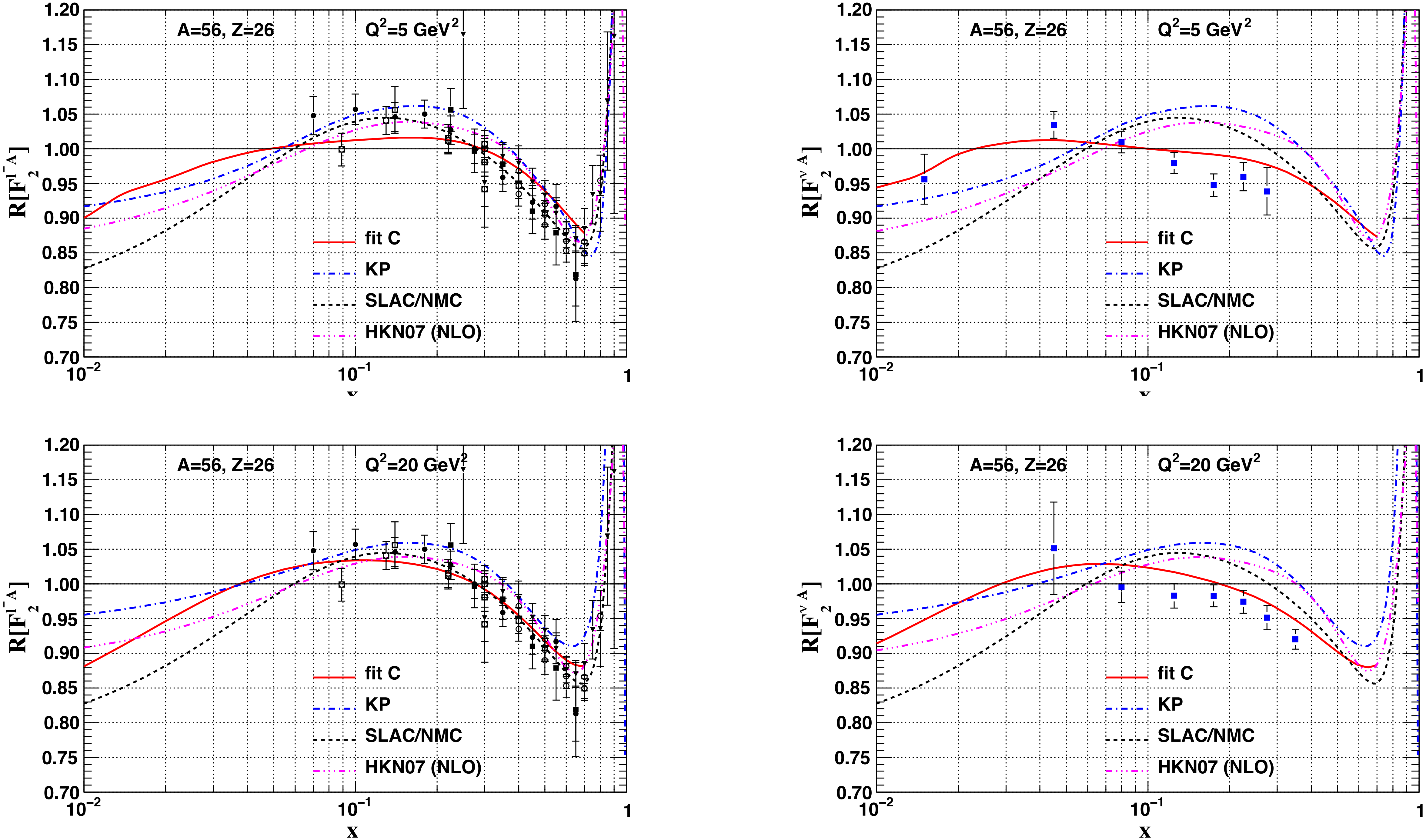
$R[F_2^{\ell Fe}]$ (LEFT) VS $R[F_2^{\nu Fe}]$ (RIGHT)

glofac1a ($w = 1/7$)



$R[F_2^{\ell Fe}]$ (LEFT) VS $R[F_2^{\nu Fe}]$ (RIGHT)

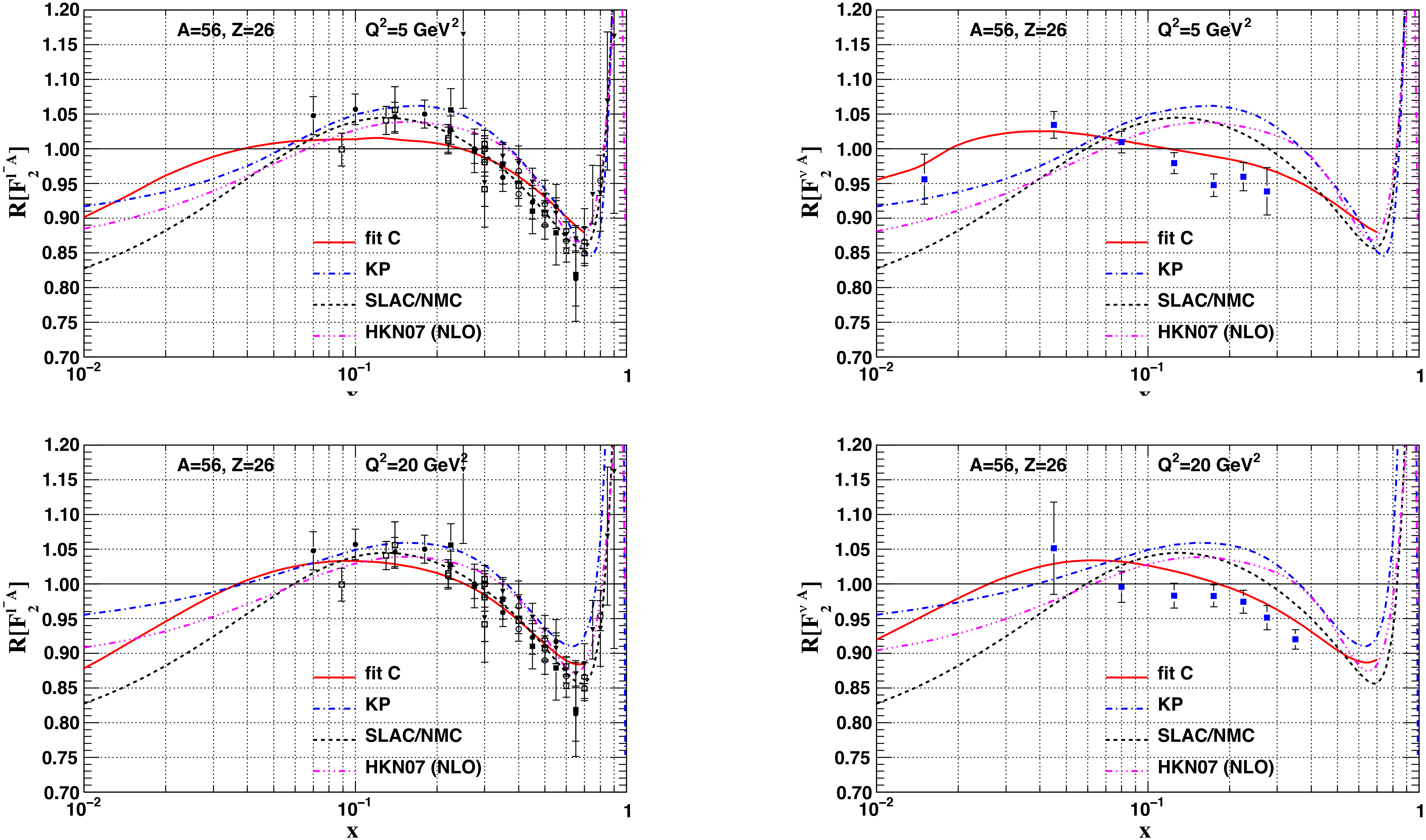
glofac1c ($w = 1/4$)



Monday, June 8, 15

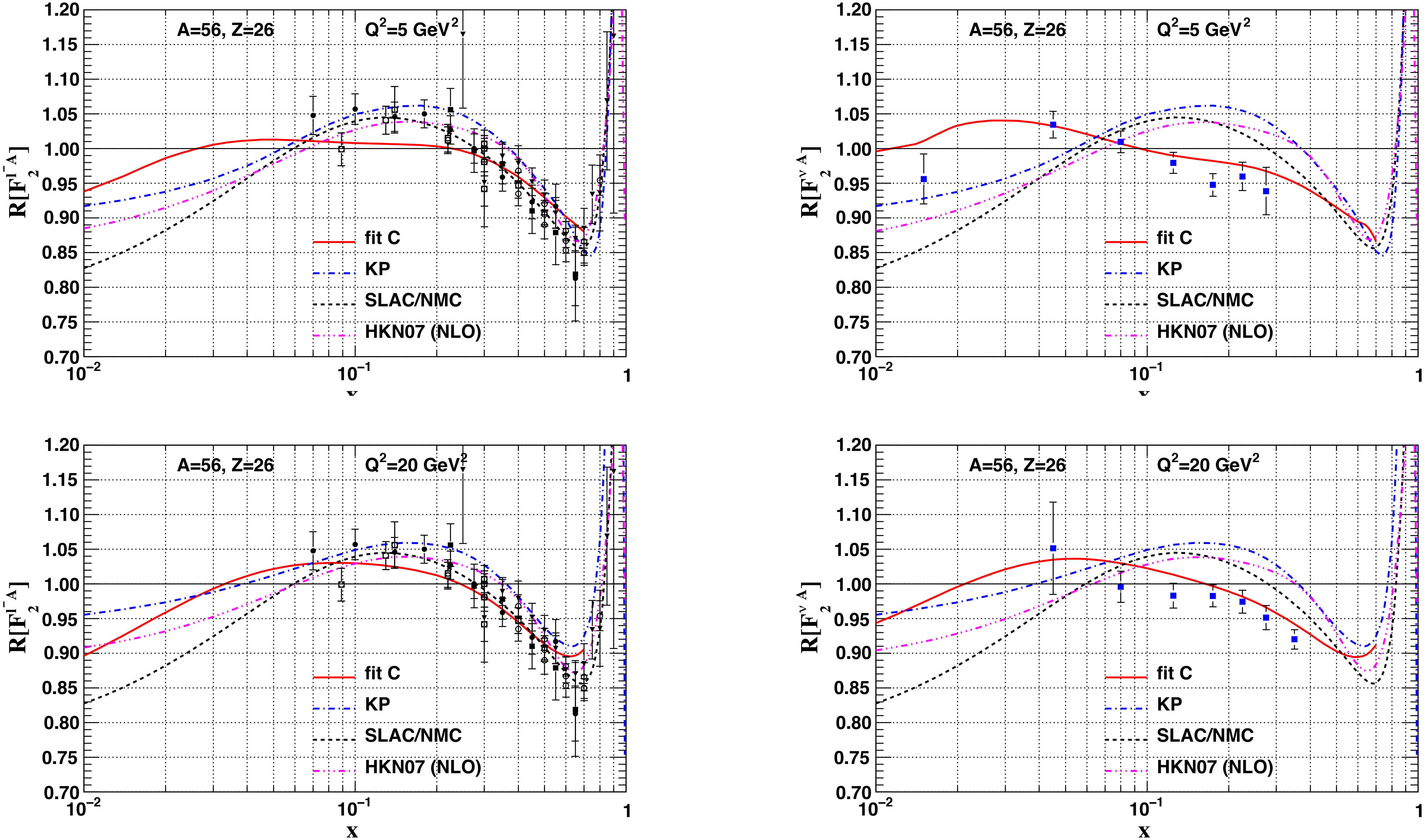
$R[F_2^{\ell Fe}]$ (LEFT) VS $R[F_2^{\nu Fe}]$ (RIGHT)

glofac1b ($w = 1/2$)



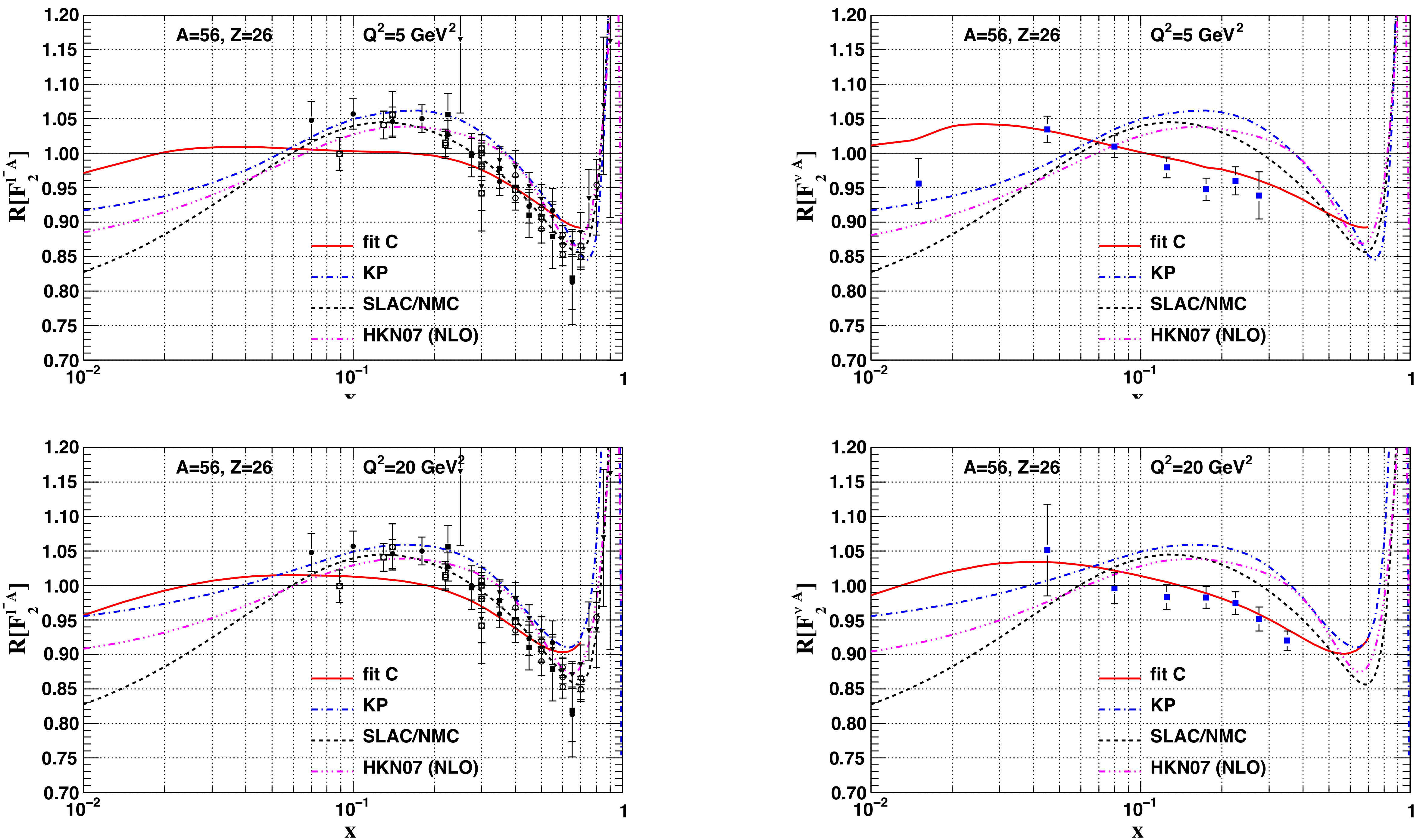
$R[F_2^{\ell Fe}]$ (LEFT) VS $R[F_2^{\nu Fe}]$ (RIGHT)

global2b ($w = 1$)



$R[F_2^{\ell Fe}]$ (LEFT) VS $R[F_2^{\nu Fe}]$ (RIGHT)

nuanua1 ($w = \infty$)



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Is there a reasonable compromise fit?

Weight	Fit name	ℓ data	χ^2 (/pt)	ν data	χ^2 (/pt)	total χ^2 (/pt)
$w = 0$	decut3	708	639 (0.90)	-	-	639 (0.90)
$w = 1/7$	glofac1a	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
$w = 1/4$	glofac1c	708	654 (0.92)	3134	4501 (1.43)	5155 (1.34)
$w = 1/2$	glofac1b	708	680 (0.96)	3134	4405 (1.40)	5085 (1.32)
$w = 1$	global2b	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
$w = \infty$	nuanua1	-	-	3134	4192 (1.33)	4192 (1.33)

- $w = 0$: No. Problem: $R[F_2^{\nu Fe}]$
- $w = 1/7$: No. Problem: $R[F_2^{\nu Fe}]$
- $w = 1/4, 1/2$: No.
    - $Q^2 = 5$: Undershoots $R[F_2^{\ell Fe}]$ for $x < 0.2$. Overshoots $R[F_2^{\nu Fe}]$ for $x \in [0.1, 0.3]$
    - $Q^2 = 20$: $R[F_2^{\ell Fe}]$ still ok. Overshoots $R[F_2^{\nu Fe}]$.
- $w = 1$: No. Possibly there is a compromise if more strict Q^2 cut?
    - $Q^2 = 5$: Undershoots $R[F_2^{\ell Fe}]$ for $x < 0.2$. $R[F_2^{\nu Fe}]$ ok.
    - $Q^2 = 20$: $R[F_2^{\ell Fe}]$ still ok. $R[F_2^{\nu Fe}]$ ok.
- $w = \infty$: No. Problem: $R[F_2^{\ell Fe}]$

DISCUSSION/INTERMEDIATE CONCLUSION

Discussion based on the comparison of the nuclear correction factors $R[F_2^{\ell A}]$ and $R[F_2^{\nu A}]$

- There is defi nitely a tension between the NuTeV and the charged lepton data
  - There is a clear dependence on the weight.
  - Theory curves for $R[F_2^{\ell A}]$ and $R[F_2^{\nu A}]$ are both shifted down with increasing weight of the neutrino data.
- Preliminary conclusion: At the level of the (high) precision there doesn't seem to be a good compromise fi t of the combined ℓA, DY and νA data.
- However one has to be careful:
  - These are precision effects
  - For each weight, the curves have uncertainty bands not considered
  - The figures show the comparison to only few (representative) data

Consider next quantitative criterion based on χ^2

Tolerance criterion

Probability distribution for the χ^2 function

$$P_N(\chi^2) = \frac{(\chi^2)^{N/2-1} e^{-\chi^2/2}}{2^{N/2}\Gamma(N/2)}$$

Determine ξ_{50}^2 and ξ_{90}^2 (i.e. $p = 50$, $p = 90$):

$$\int_0^{\xi_p^2} d\chi^2 P_N(\chi^2) = p/100$$

Condition for compatibility of two fits:
The 2nd fit (χ_n^2) should be within the 90% C.L. region of the first fit ($\chi_{n,0}^2$)

$$\boxed{\chi_n^2/\chi_{n,0}^2 < \xi_{90}^2/\xi_{50}^2 \quad \Leftrightarrow \quad C_{90} \equiv \frac{\Delta\chi^2}{\frac{\chi_{n,0}^2}{\xi_{50}^2}(\xi_{90}^2 - \xi_{50}^2)} < 1}$$

see CTEQ'01, PRD65(2001)014012; MSTW'09, EPJC(2009)63,189-285

TOLERANCE CRITERION $C_{90} < 1$:

TOTAL χ^2 FOR A) ℓA+DY DATA AND B) NEUTRINO DATA

90% tolerance condition for the **charged lepton** χ^2 and the **neutrino** χ^2

- decut3: 638.9 ± 45.6 (best fit to only charged lepton and DY data)
- nuanua1: 4192 ± 138 (best fit to only neutrino data)

Is there a compromise fit compatible to both, decut3 **and** nuanua1?

Weight	Fit name	ℓ data	χ^2	ν data	χ^2	total χ^2 (/pt)
$w = 0$	decut3	708	639	-	nnnn **NO**	639 (0.90)
$w = 1/7$	glofac1a	708	645 **YES**	3134	4710 **NO**	5355 (1.39)
$w = 1/4$	glofac1c	708	654 **YES**	3134	4501 **NO**	5155 (1.34)
$w = 1/2$	**glofac1b**	708	680 **YES**	3134	4405 **NO*** **	5085 (1.32)
$w = 1$	global2b	708	736 **NO**	3134	4277 **YES**	5014 (1.30)
$w = \infty$	nuanua1	-	nnn **NO**	3134	4192	4192 (1.33)

Observations:

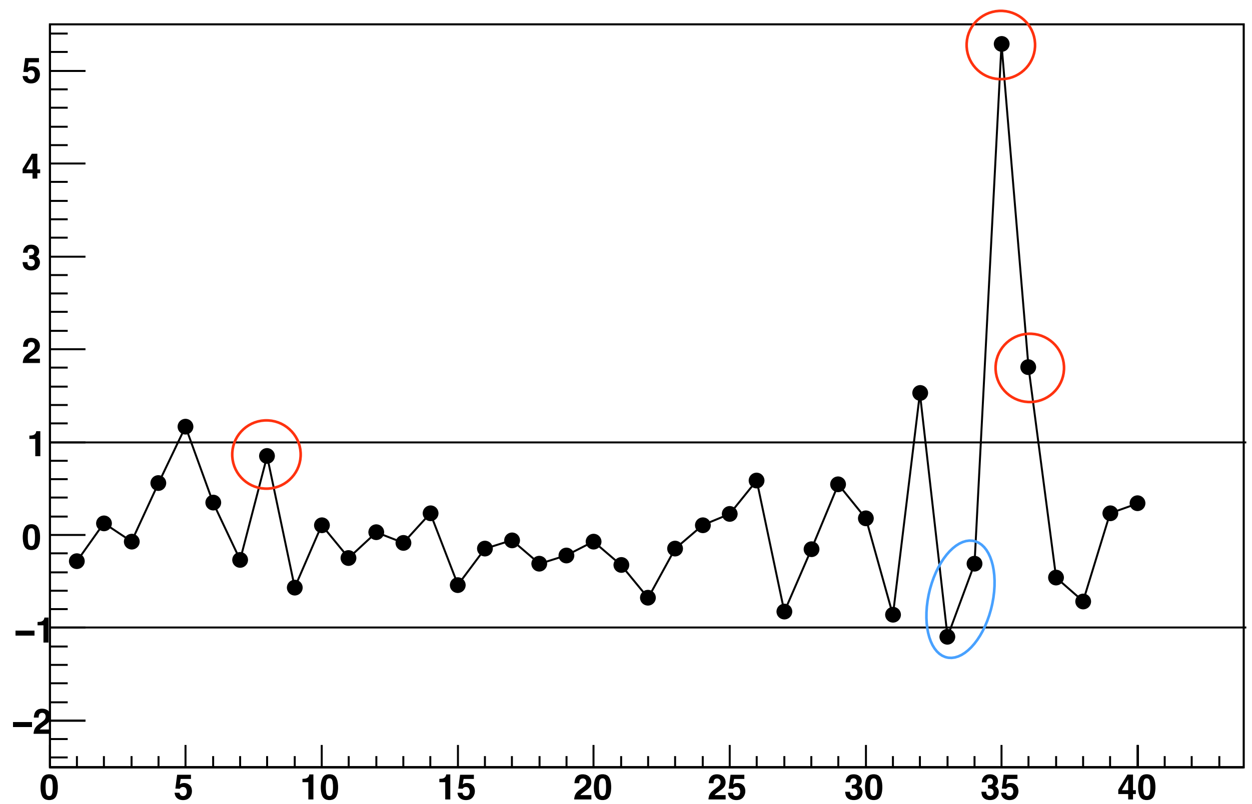
- There is no good compromise fit based on the 90% C.L. criterion.
- Our best candidate is **glofac1b** which is *marginally* compatible: $4405 - 4192 \simeq 1.5 \times 138$
- Observations in agreement with the previous conclusions based on $R[F_2^{\ell Fe}]$ and $R[F_2^{\nu Fe}]$.

Let's have a look at the tolerance criterion applied to the individual data sets!

TOLERANCE CRITERION $C_{90} < 1$:

INDIVIDUAL DATA SETS: $n = 1, \ldots, 32$ VS DECUT3; $n = 33, \ldots, 40$ VS NUANUA1

glofac1a ($w = 1/7$)

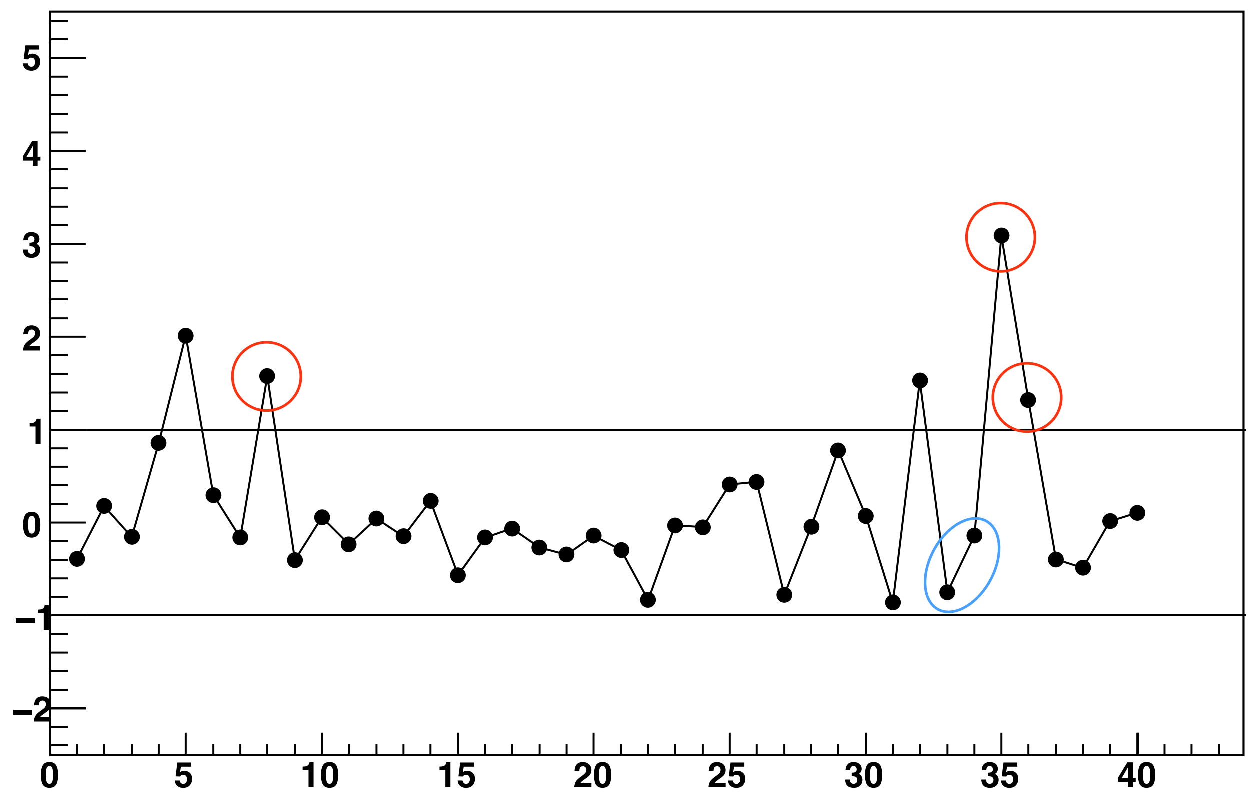


- **Y-axis**: C_{90}; **X-axis**: Number of the data set ($n = 1, \ldots, 40$)
- Important data sets:
  - $n = 8$ (red circle): Fe/D charged lepton data
  - blue ellipse: CHORUS νPb, $\bar{\nu} Pb$ cross section data
  - $n = 35, 36$ (red ellipse): NuTeV νFe, $\bar{\nu} Fe$ cross section data

TOLERANCE CRITERION $C_{90} < 1$:

INDIVIDUAL DATA SETS: $n = 1, \ldots, 32$ VS DECUT3; $n = 33, \ldots, 40$ VS NUANUA1

glofac1c ($w = 1/4$)

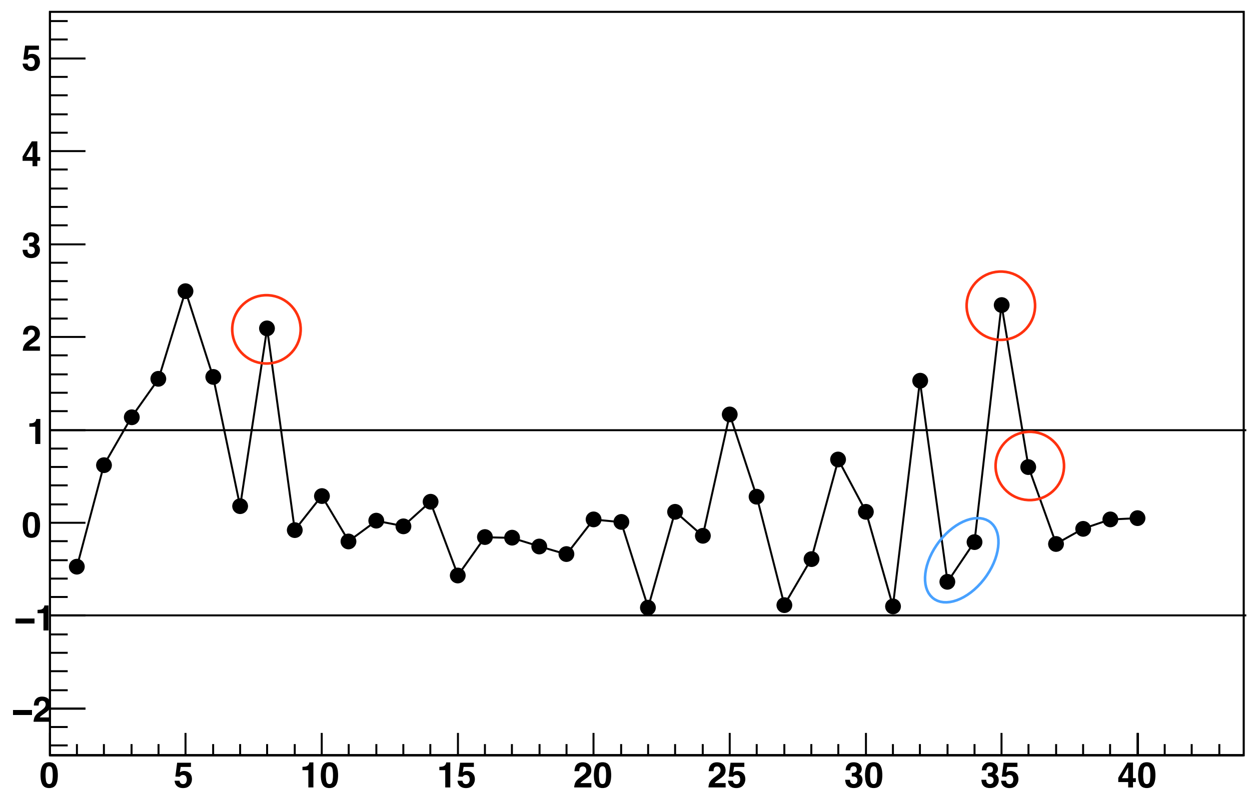


- **Y-axis**: C_{90}; **X-axis**: Number of the data set ($n = 1, \ldots, 40$)
- Important data sets:
  - $n = 8$ (red circle): Fe/D charged lepton data
  - blue ellipse: CHORUS νPb, $\bar{\nu} Pb$ cross section data
  - $n = 35, 36$ (red ellipse): NuTeV νFe, $\bar{\nu} Fe$ cross section data

TOLERANCE CRITERION $C_{90} < 1$:

INDIVIDUAL DATA SETS: $n = 1, \ldots, 32$ VS DECUT3; $n = 33, \ldots, 40$ VS NUANUA1

glofac1b ($w = 1/2$)

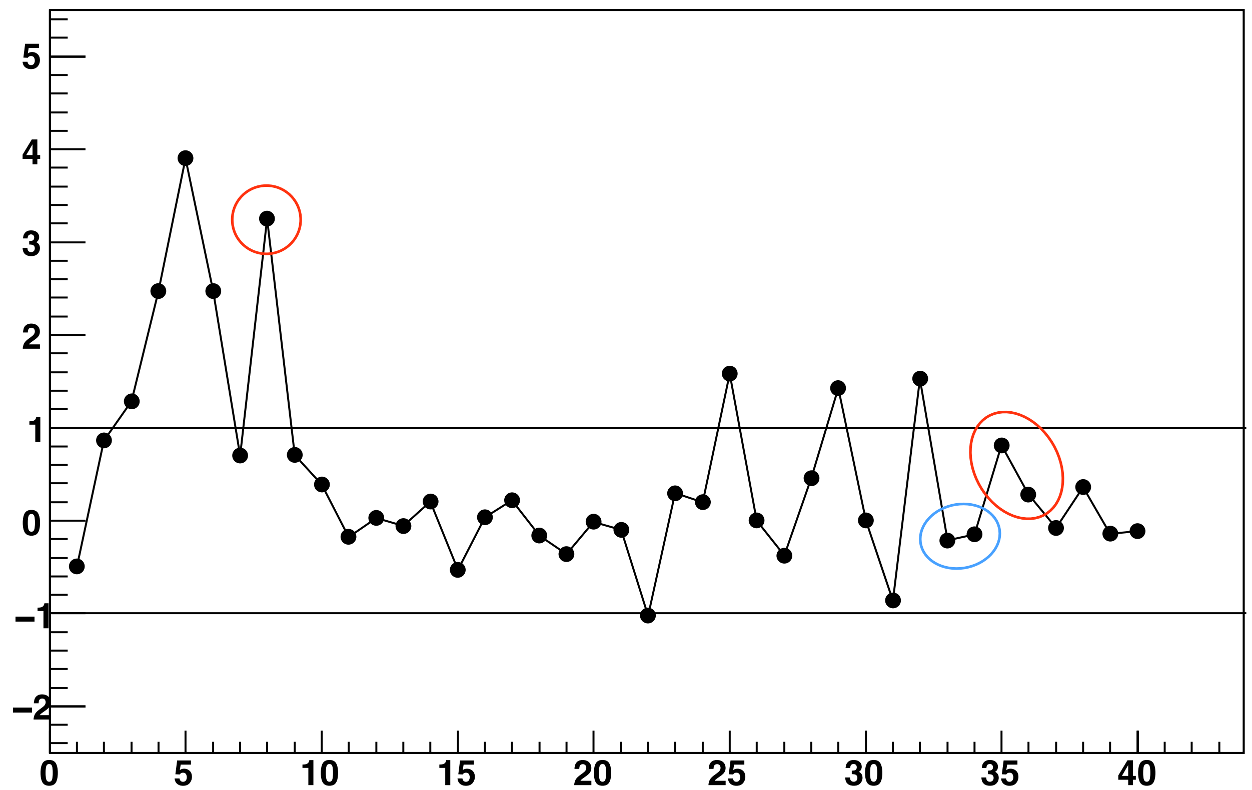


- **Y-axis**: C_{90}; **X-axis**: Number of the data set ($n = 1, \ldots, 40$)
- Important data sets:
  - $n = 8$ (red circle): Fe/D charged lepton data
  - blue ellipse: CHORUS νPb, $\bar{\nu} Pb$ cross section data
  - $n = 35, 36$ (red ellipse): NuTeV νFe, $\bar{\nu} Fe$ cross section data

Tolerance criterion $C_{90} < 1$:

individual data sets: $n = 1, \ldots, 32$ vs decut3; $n = 33, \ldots, 40$ vs nuanua1

global2b ($w = 1$)



- **Y-axis**: C_{90}; **X-axis**: Number of the data set ($n = 1, \ldots, 40$)
- Important data sets:
  - $n = 8$ (red circle): Fe/D charged lepton data
  - blue ellipse: CHORUS νPb, $\bar{\nu} Pb$ cross section data
  - $n = 35, 36$ (red ellipse): NuTeV νFe, $\bar{\nu} Fe$ cross section data

Observations:

- $w = 1/7$: $C_{90} > 5$ for NuTeV νFe; $C_{90} \simeq 1.8$ for NuTeV $\bar{\nu} Fe$
- CHORUS data (blue ellipse) always compatible; little dependence on weight w
- increasing weight: NuTeV cross section data improve; charged lepton Fe/D data get worse
- our best candidate ($w = 1/2$)
    - Fe/D ($n = 8$): $C_{90} \simeq 2$
    - NuTeV νFe ($n = 35$): $C_{90} \simeq 2.2$
    - NuTeV $\bar{\nu} Fe$ ($n = 36$): $C_{90} < 1$
    - some other data sets $n = 3, 4, 5, 6, 32$ with $C_{90} > 1$
- $w = 1$: Fe/D ($n = 8$): $C_{90} > 3$
- Confi rms and quantifi es observations based on R plots

CONCLUSIONS III

Based on nuclear corrections factors R and the tolerance criterion $C_{90} < 1$:

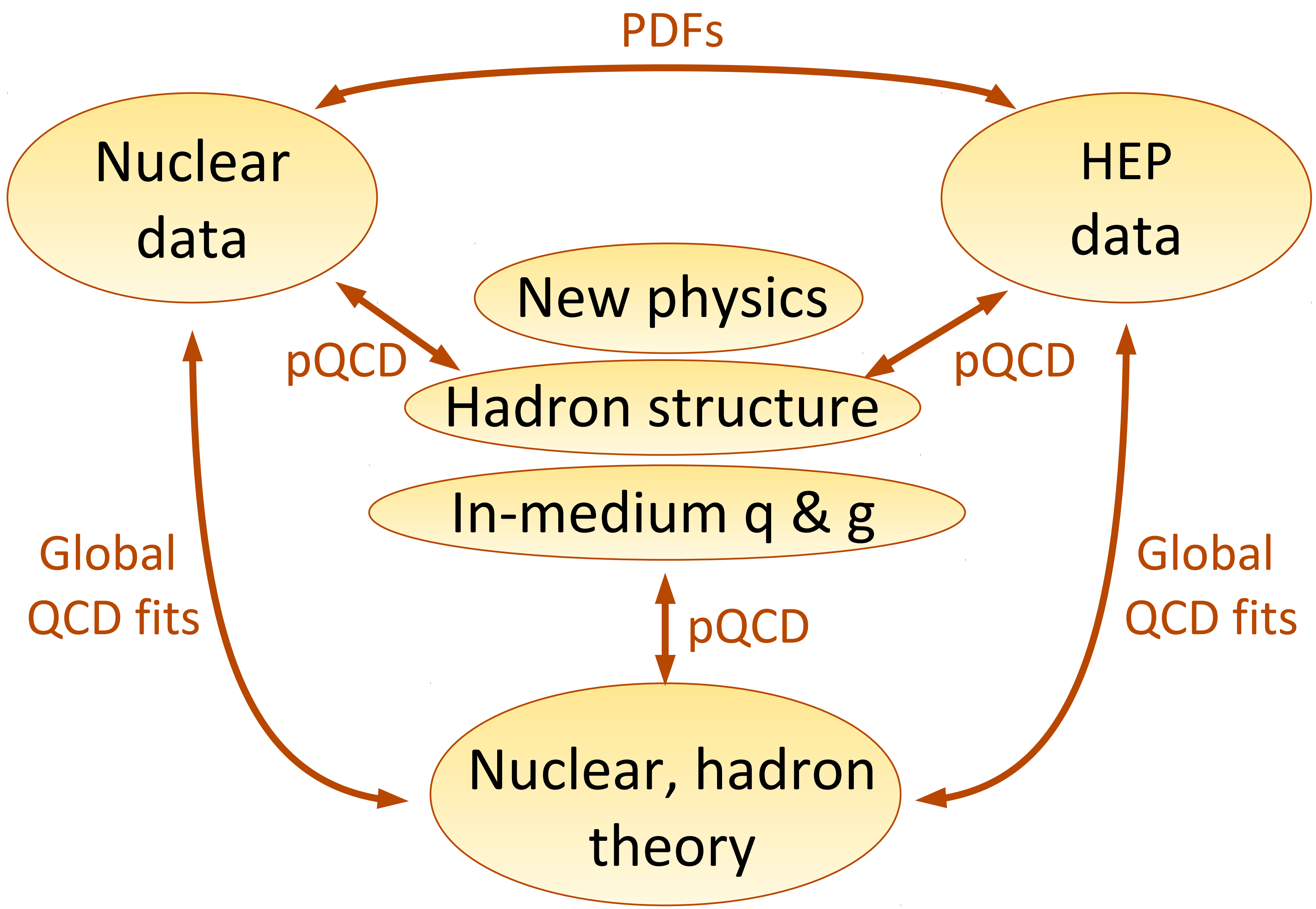
- There is no good compromise fi t to the ℓA DIS + DY + νA DIS data.
- Most problematic: tension between NuTeV νFe cross section data and Fe/D data in charged lepton DIS.
- The NuTeV $\bar{\nu} Fe$ data are less problematic. They have larger errors.
- The CHORUS νPb and $\bar{\nu} Pb$ data are compatible with both, the charged lepton+DY and the NuTeV data, as is well known. They also have larger errors.

- Relaxing the tolerance criterion to $C_{90} \lesssim 2$ the fi t with weight $w = 1/2$ would be *marginally* acceptable.
- This can also (qualitatively) be verifi ed with the R-plots.
- A larger Q^2-cut, say $Q^2 > 5\ \mathrm{GeV}^2$, could also help to reduce the tension. (In particular, this would remove some of the rather precise NuTeV cross section data at small x.)

Last words

Last words

- A global approach across subfields



Exciting contributions from νA DIS to this picture

Backup

Strange PDF

- Before dimuon data (~2001) essentially no experimental constraints on strange sea
- Theoretical assumptions necessary!
  - Early parametrisations (Duke-Owens): SU(3)-symmetric sea
  - Even SU(2)-symmetry is broken! (Gottfried sum rule, E866 experiment)
  - Later parametrisations (e.g. CTEQ6.1): SU(3) symmetry is broken; strange sea ~ 1/2 light sea
- CTEQ6.6 and later: dimuon data! strange PDF fitted with 2 free parameters

$$x\bar{u} = x\bar{d} = x\bar{s} = A_S(1-x)^{\eta_S} S/6$$

$$\bar{d}(x) > \bar{u}(x)$$

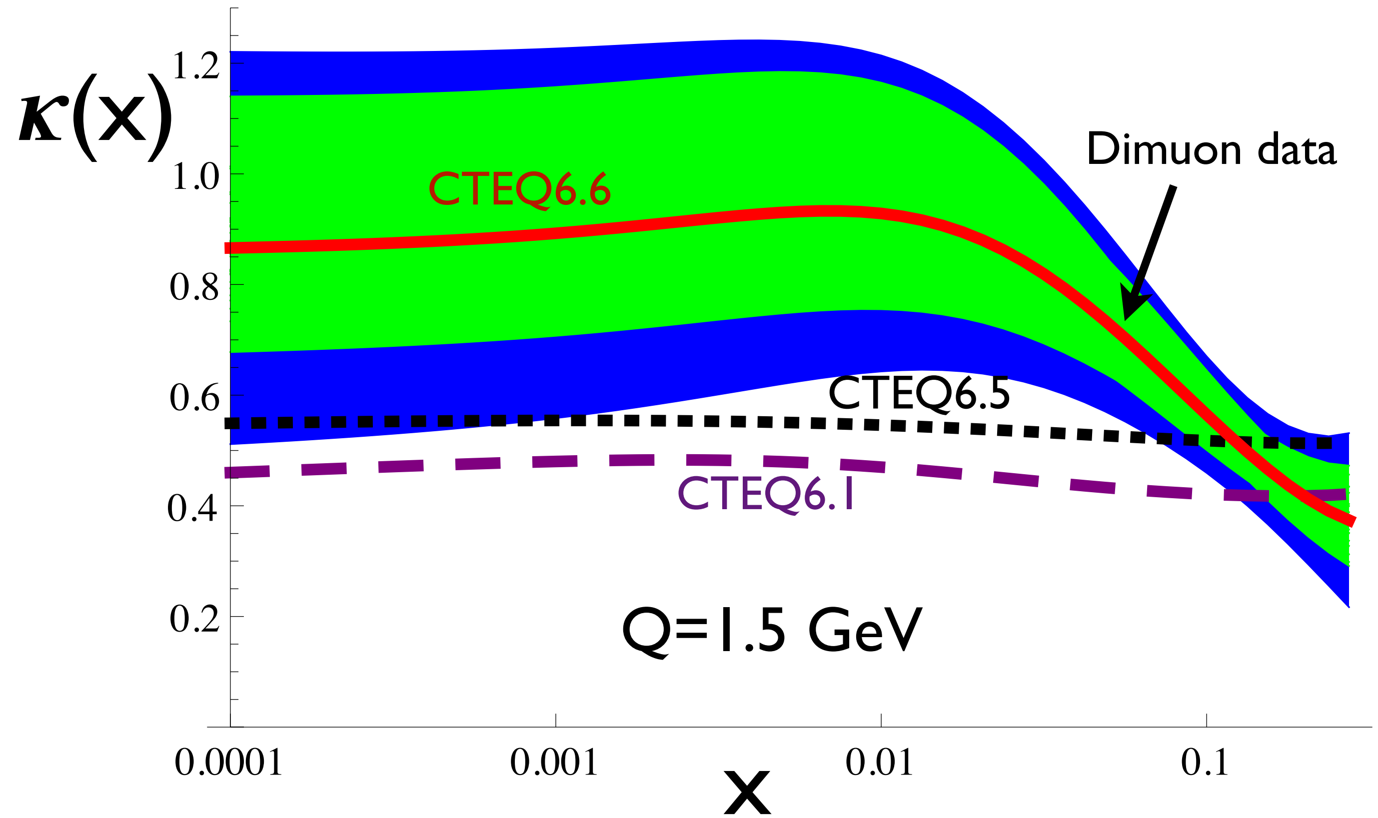
$$s = \bar{s}$$
$$(s+\bar{s})(x, Q_0) = \kappa(\bar{u}+\bar{d})(x, Q_0)$$
$$\kappa \simeq 0.5$$

Strange PDF: Uncertainty

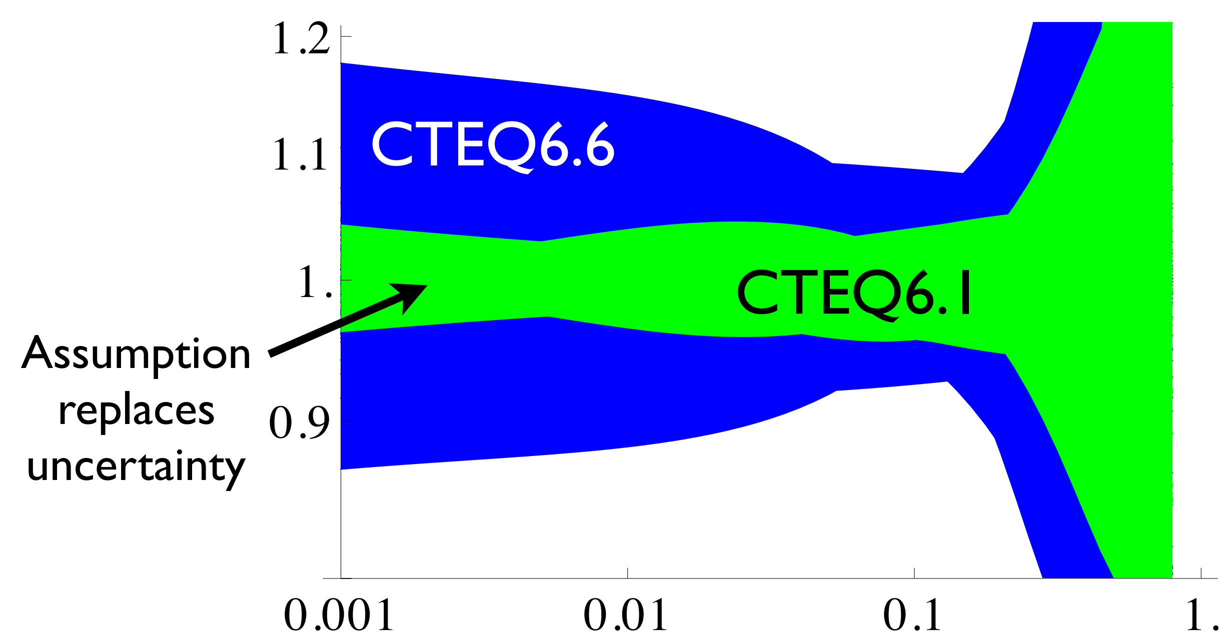
- Knowledge of strange PDF is limited (see figures)
- If exact SU(3) symmetry: ubar = dbar = sbar and κ=1
- $m_s \gg m_u, m_d$: expect ubar = dbar > sbar and κ<1
- CTEQ6.1, CTEQ6.5: κ=0.5 by design
- CTEQ6.6: κ=0.5 at x=0.1 central PDF a factor 2 larger for small x
- Green error band: (upper figure) enveloppe of 44 CTEQ6.6 error PDFs
- Blue error band: (upper figure)

$$\Delta X = \frac{1}{2}\sqrt{\sum_{i=1}^{N_p}[X(S_i^+) - X(S_i^-)]^2}$$

$$\kappa(x,Q) = \frac{s(x,Q)}{[\bar{u}(x,Q)+\bar{d}(x,Q)]/2}$$

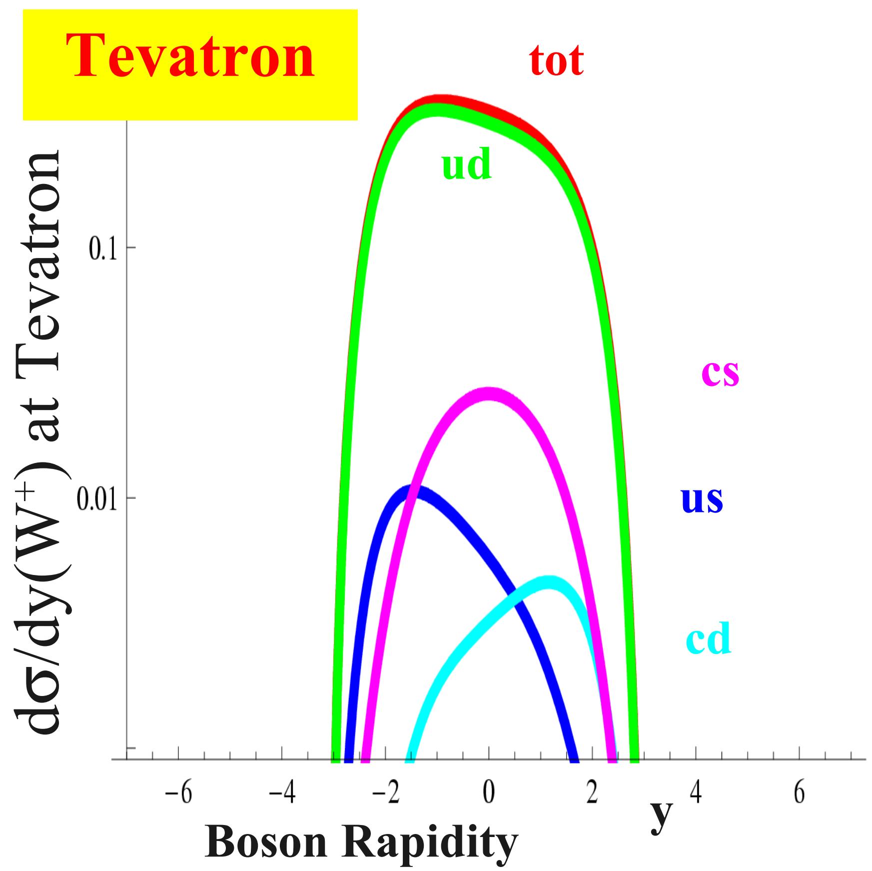


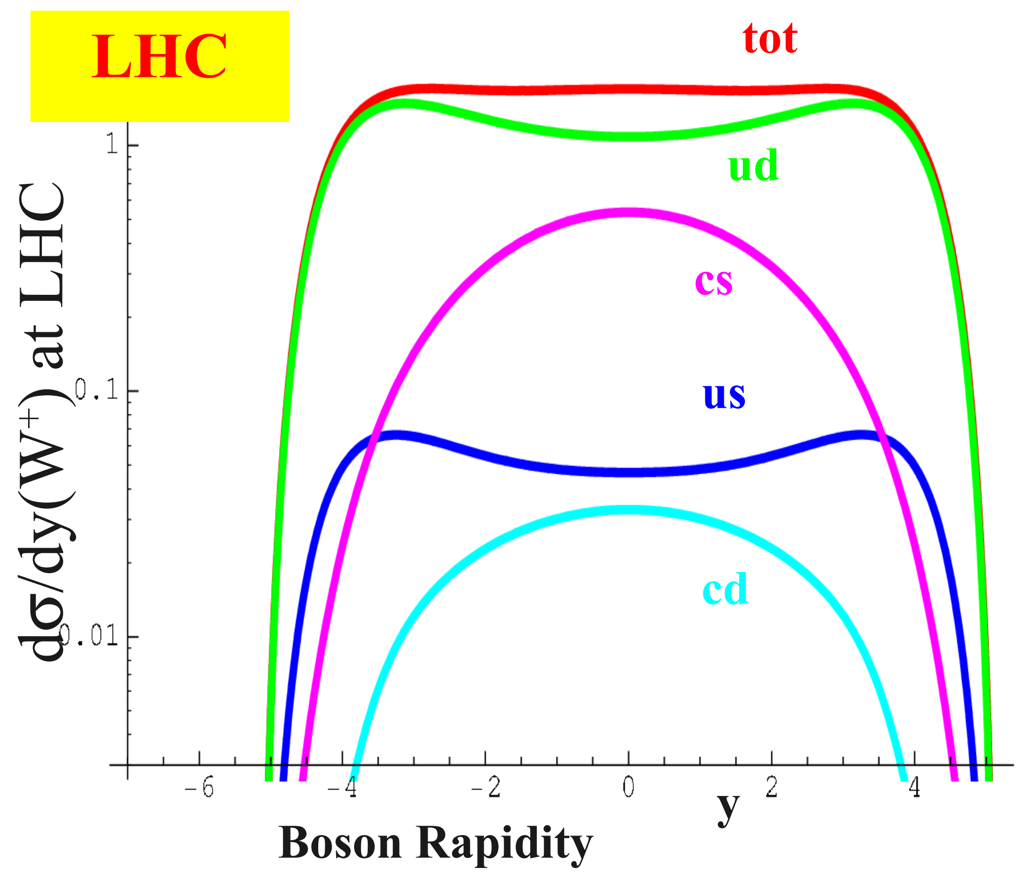
Relative uncertainty of strange sea at Q=2 GeV



Drell-Yan production of W/Z at the LHC

- Benchmark processes, essential to know impact of PDF uncertainties
- Conversely, W/Z production to constrain PDFs



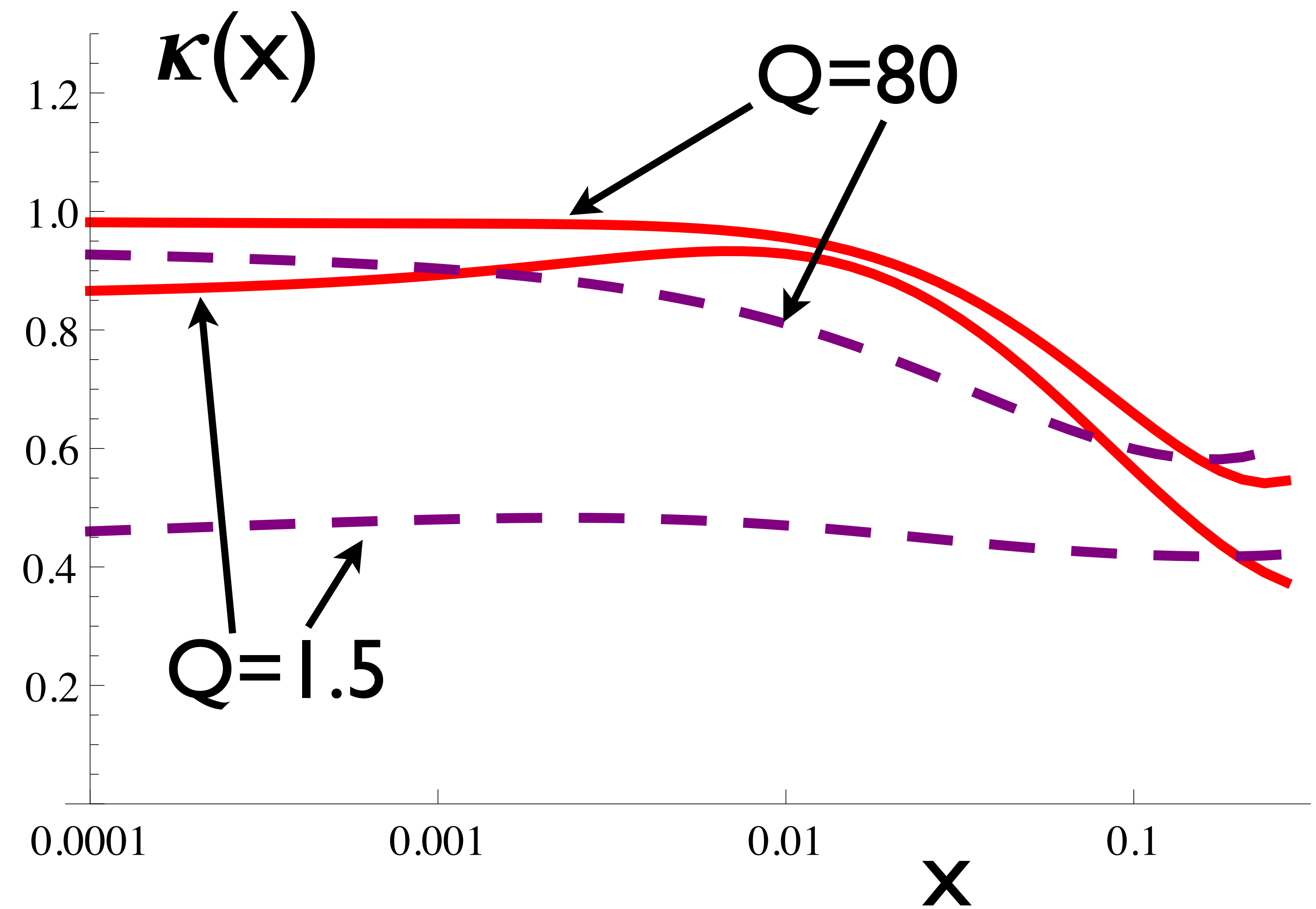


- Larger energy $\Rightarrow$ probes PDFs to small momentum fractions x
- Larger rapidity (y) $\Rightarrow$ access to **very** small x
- Larger contribution from the **sc-channel**

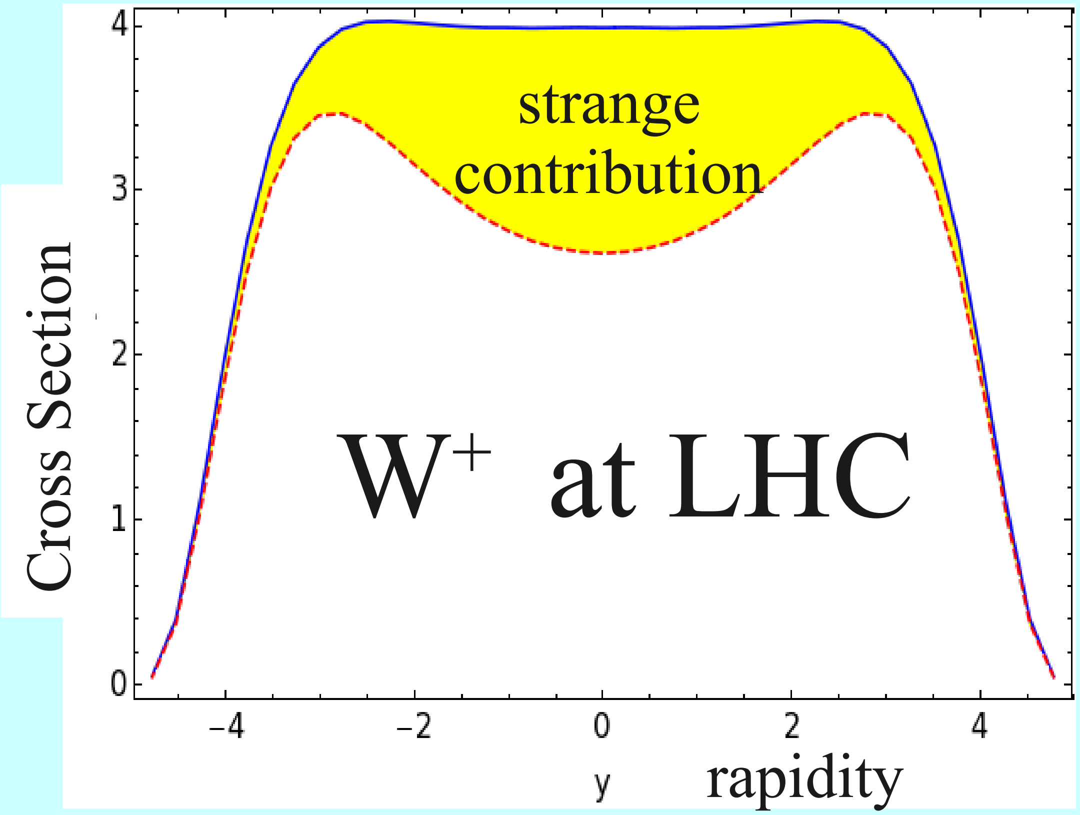
Evolution of Kappa

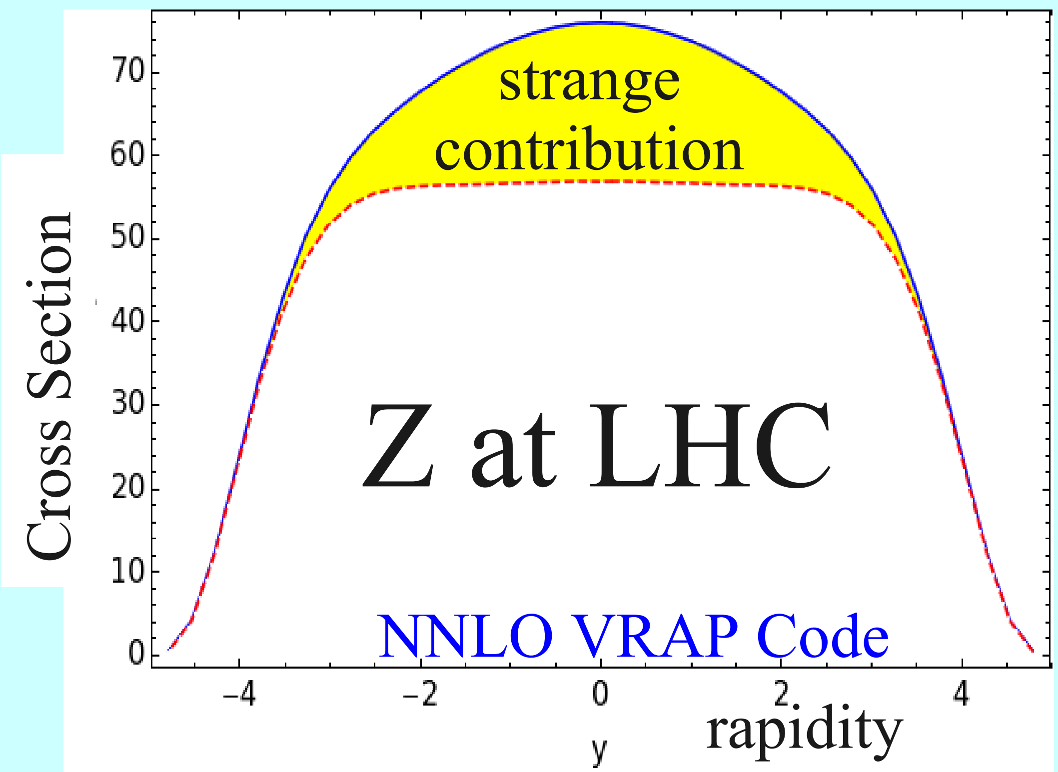
Can W/Z data constrain the strange PDF?

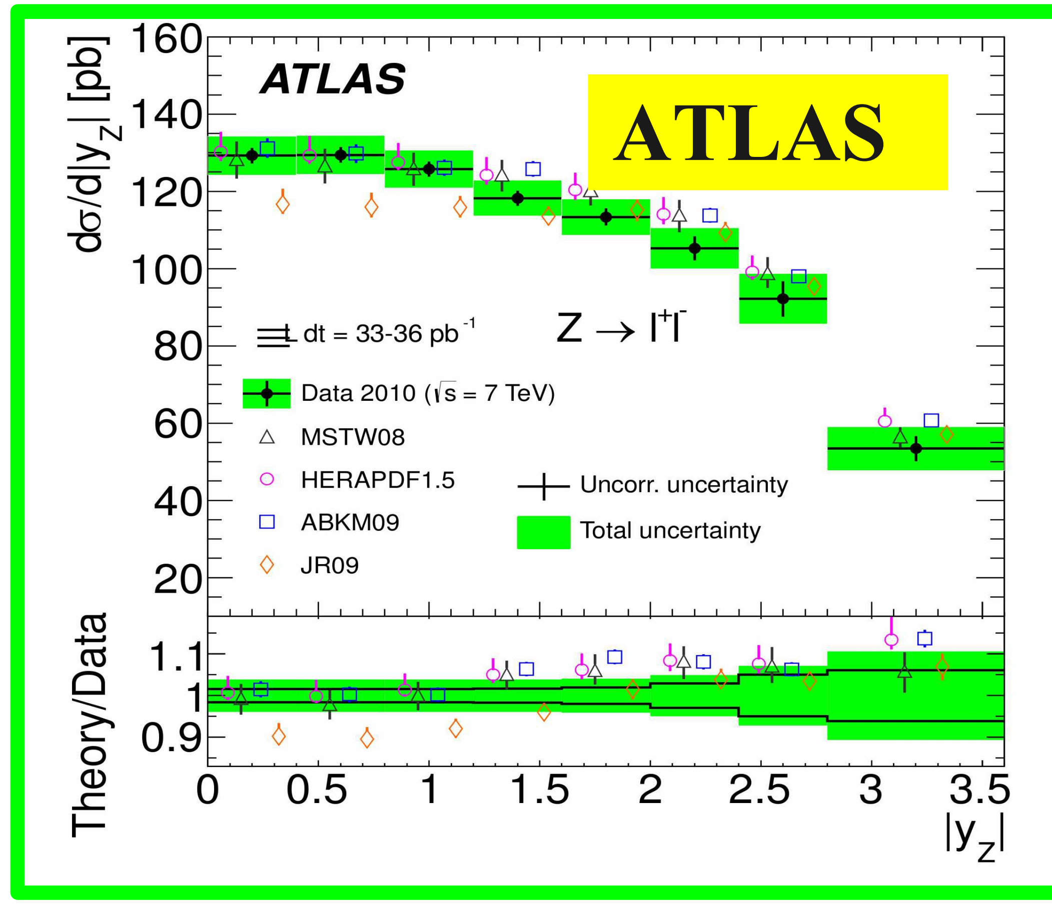
- Higher scales: production of s(x) via gluon splitting moves $\kappa(x)$ to the SU(3) symmetric limit!
- LHC7 sensitive to x~0.01
- LHC14 sensitive to x~0.005
- Need very precise measurement at Q=80 GeV to constrain strange PDF at Q=1.5 GeV!

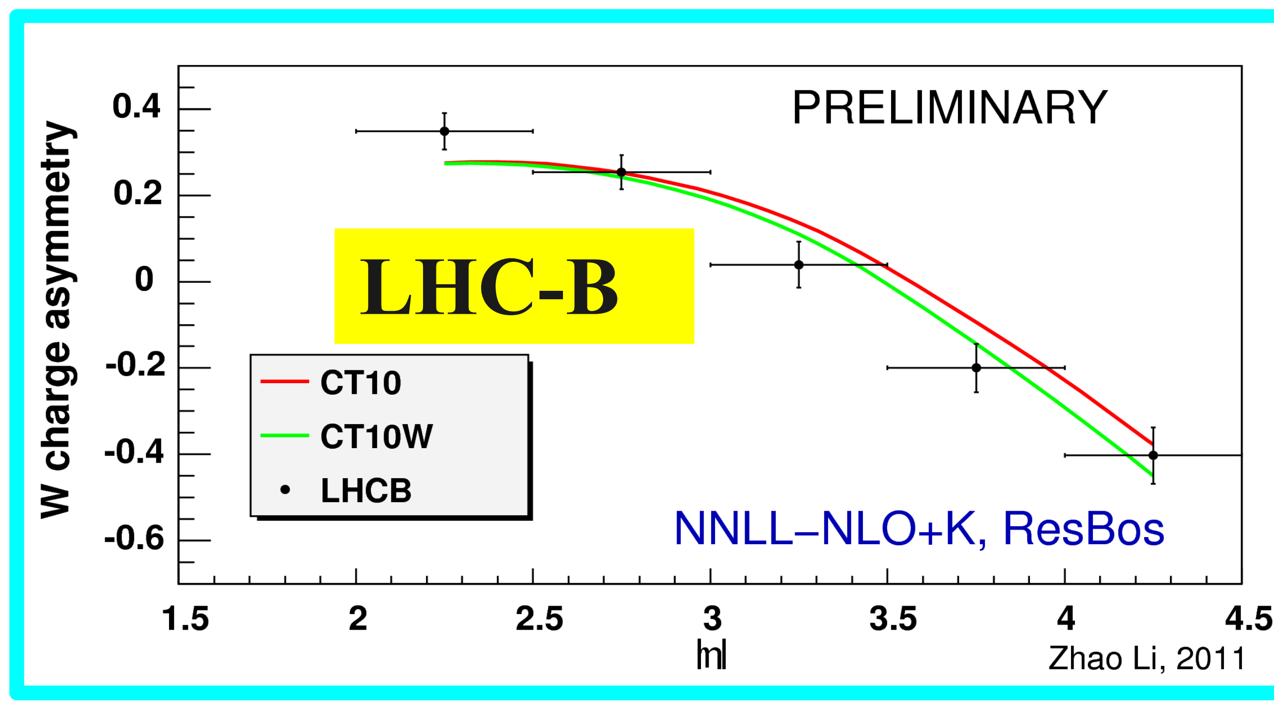


PDF Uncertainties ⇒ S(x) PDF ⇔ W/Z at LHC









NNLO VRAP Code
Anastasiou, Dixon, Melnikov, Petriello,
Phys.Rev.D69:094008,2004.

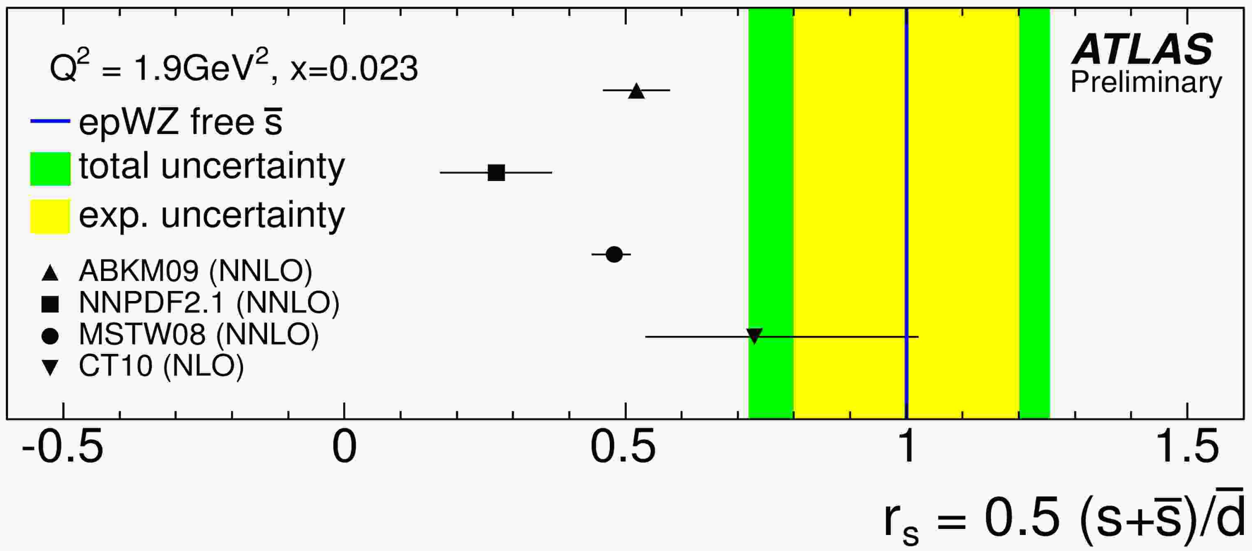
Kusina, Stavreva, Berge, Olness, Schienbein, Kovarik, Jezo, Yu, Park
Phys.Rev. D85 (2012) 094028

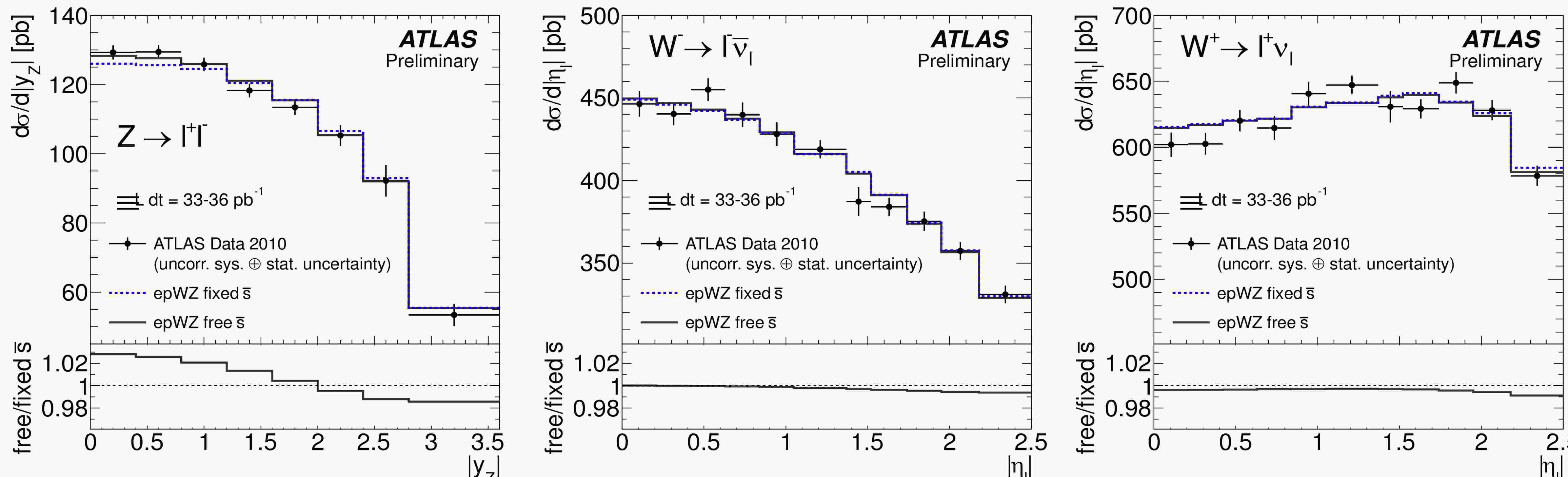
y distribution shape can constrain s(x) PDF

W, Z data sensitivity to strange sea

- ATLAS performed NNLO QCD fit to Z, W^+, W^- + HERA ep DIS cross sections: significant tension for Z observed when suppressing strange by 50% at low scale $1.9\,\mathrm{GeV}^2$
- Fit with free strange sea gives no supression

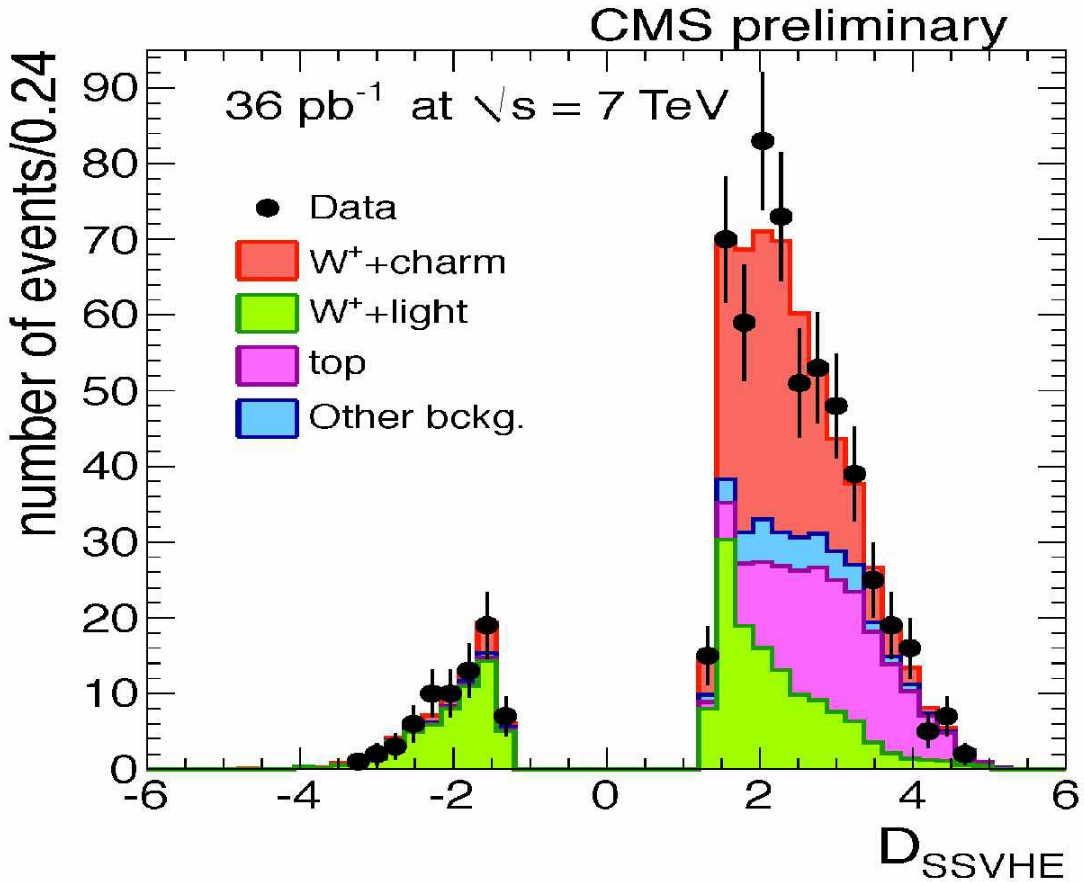
$$\boxed{r_s = 1.00 \pm 0.20_{\mathrm{exp}}\ {}^{+0.16}_{-0.20}\ \mathrm{sys}}$$

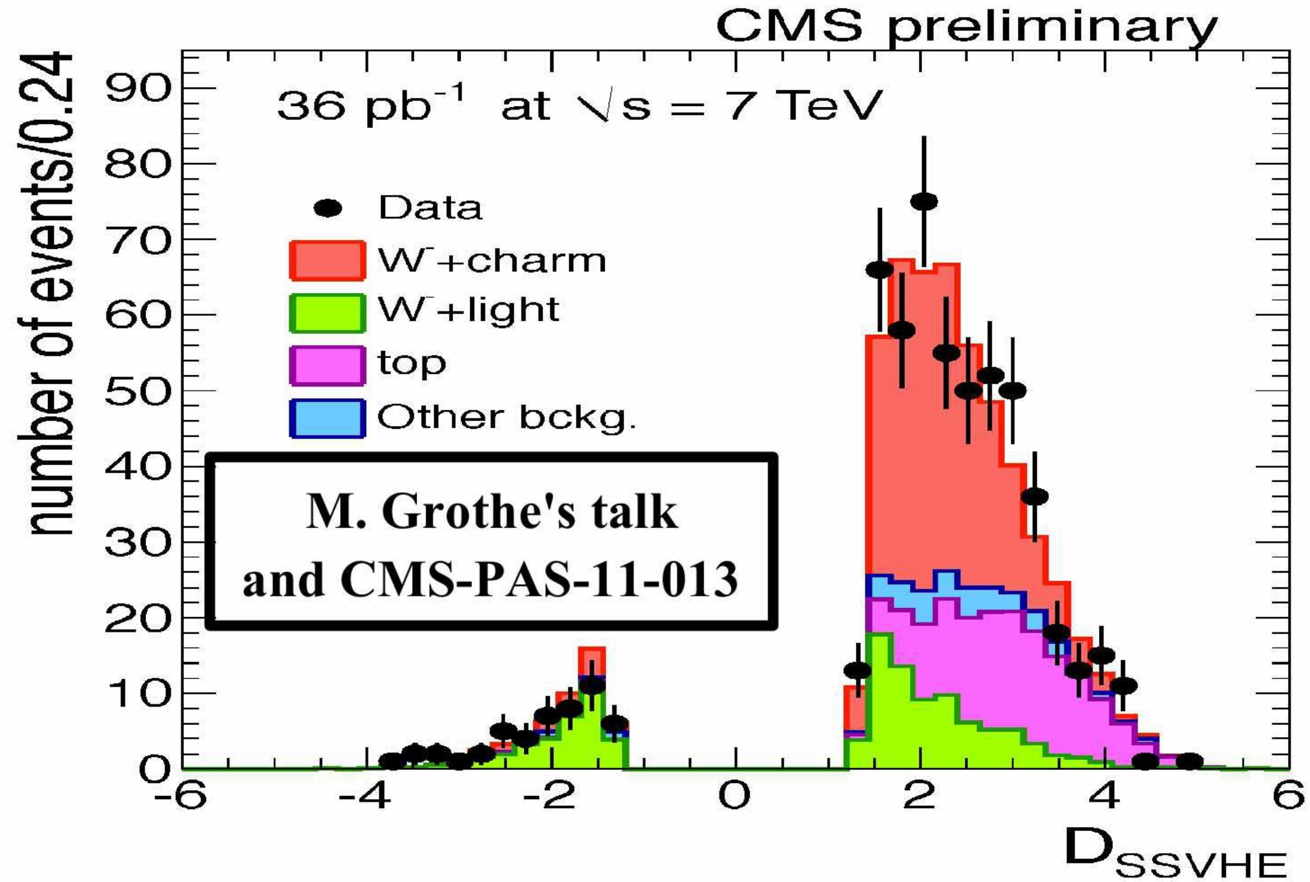




ATLAS-STDM-2011-43 → PRL

First LHC results on W+charm (CMS)





- Sensitive to strange quark PDFs (process dominated by s+g → W + charm):
  - PDF uncertainties from the second quark generation are a potential source of uncertainty for the W mass measurement at the LHC
  - Data-driven control of light-quark and top backgrounds
  - Enormous margin for improvement (only 2010 statistics used), new method (secondary vertex tagging), complementary to the one employed until now at Tevatron (semileptonic charm decay tagging):

$$\underline{For \quad p_T^{jet} > 20 \quad GeV, |\eta^{jet}| < 2.1}:$$

$$\frac{\sigma(W^+ + charm)}{\sigma(W^- + charm)} = 0.92 \pm 0.19(stat.) \pm 0.04(syst.); \quad \frac{\sigma(W + charm)}{\sigma(W + jets)} = 0.142 \pm 0.015(stat.) \pm 0.024(syst.)$$

Requirements

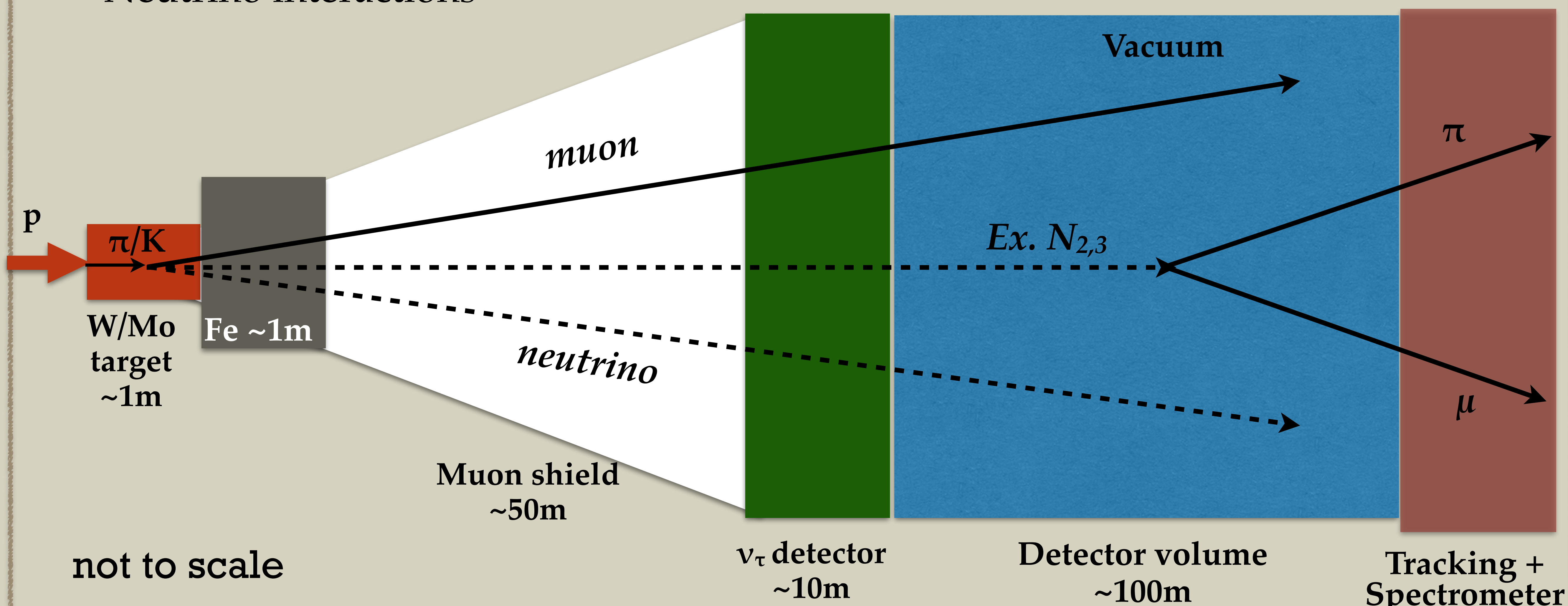
- Proposal: fixed target experiment at the CERN SPS
- SPS: $4x10^{13}$ protons per spill @ 400 GeV ➙ $2x10^{20}$ pot in 5 years (same as CNGS)

1) BACKGROUND REDUCTION

- Combinatorial background
- Neutrino flux
- Muon flux
- Neutrino interactions

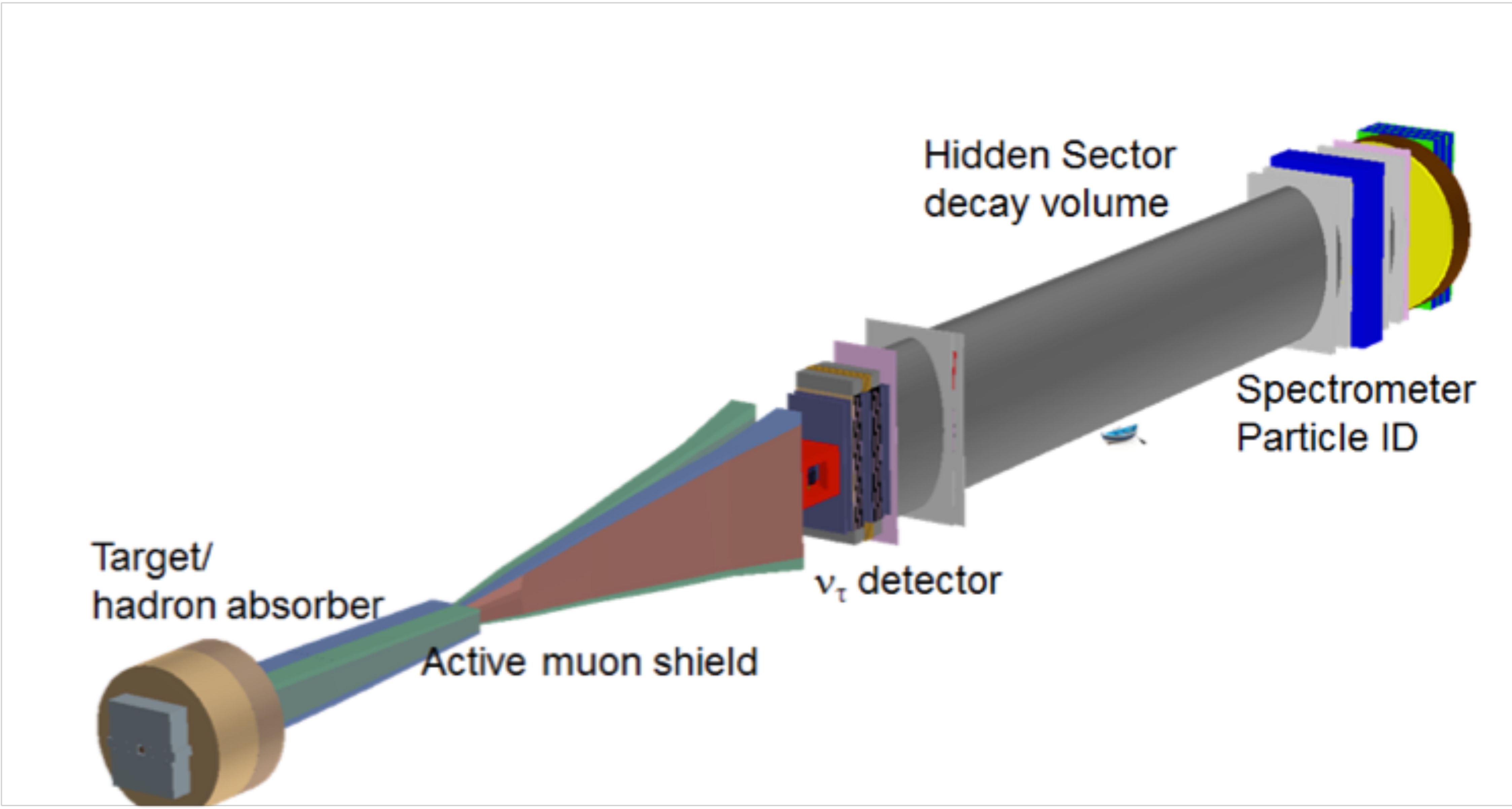
1) SIGNAL ENHANCEMENT

- Geometrical acceptance
- Reconstruction of decays
- High sensitivity

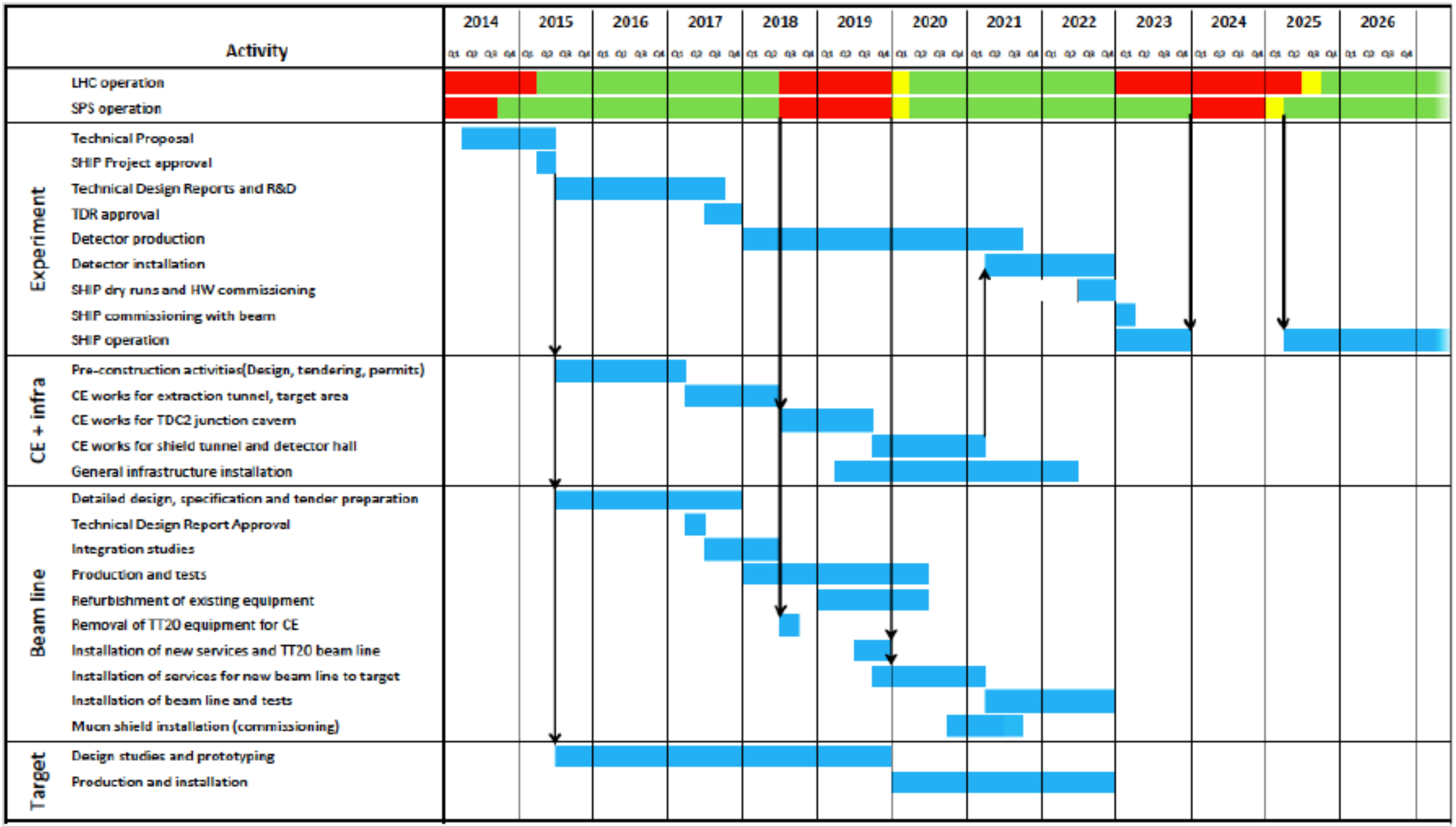


not to scale

DETECTOR LAYOUT



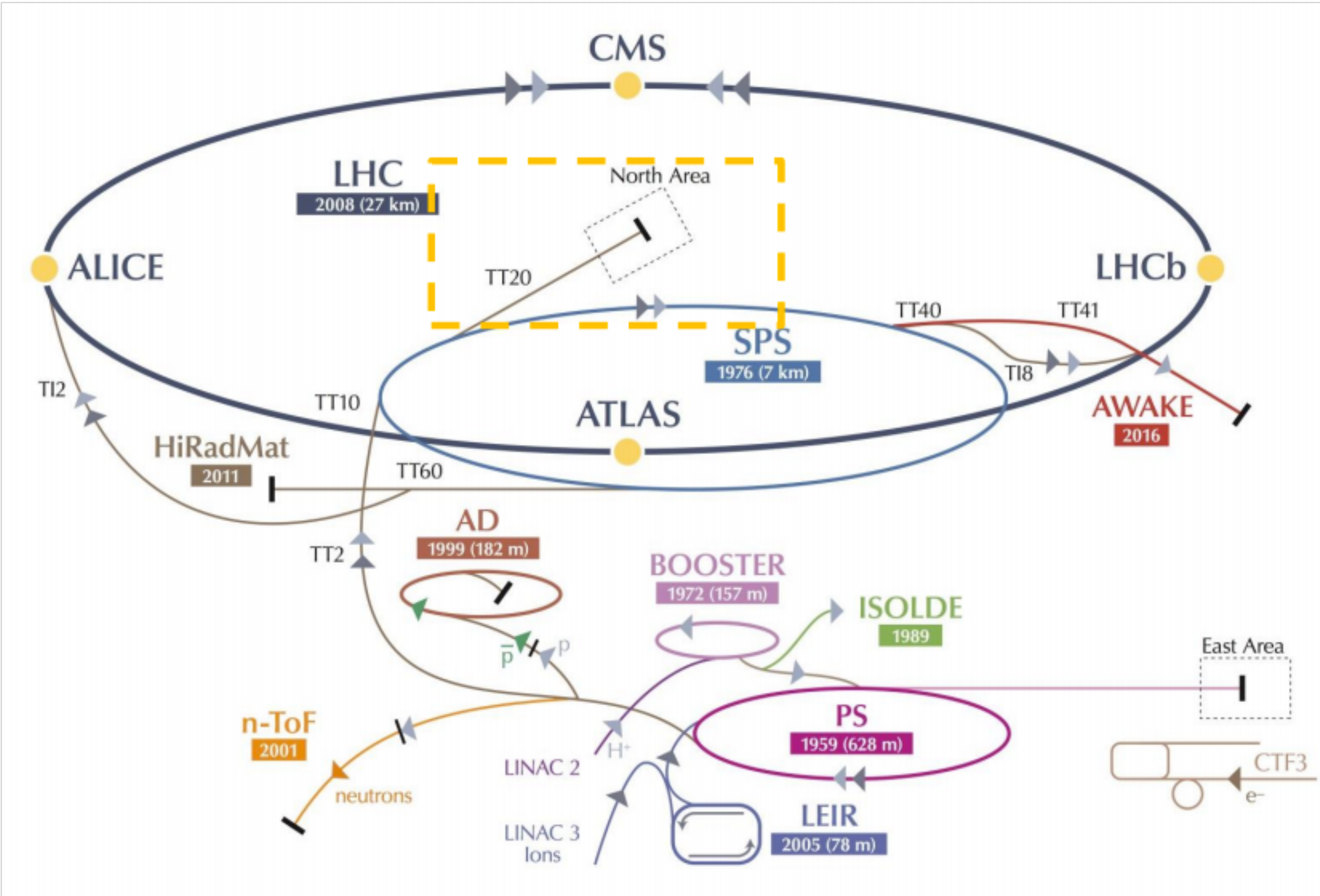
TIMESCALE



- **Form SHiP Collaboration** — **December 2014 ✔**
- **Technical Proposal** — **April 2015 ✔**
- Technical Design Report — 2018
- Construction and Installation — 2018-2022
- Commissioning — 2022
- Data taking and analysis — 2023-2027

SHiP Location

- Proposed location by CERN beams and support departments



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Cost Estimation

Table 6.2: Overall cost of the SHiP facility and the detectors.

Item		Cost (MCHF)
Facility		**135.8**
Civil engineering	57.4	
Infrastructure and services	22.0	
Extraction and beamline	21.0	
Target and target complex	24.0	
Muon shield	11.4	
Detector		**58.7**
Tau neutrino detector	11.1	
Hidden Sector detector	46.8	
Computing and online system	0.2	
Grand total		**194.5**

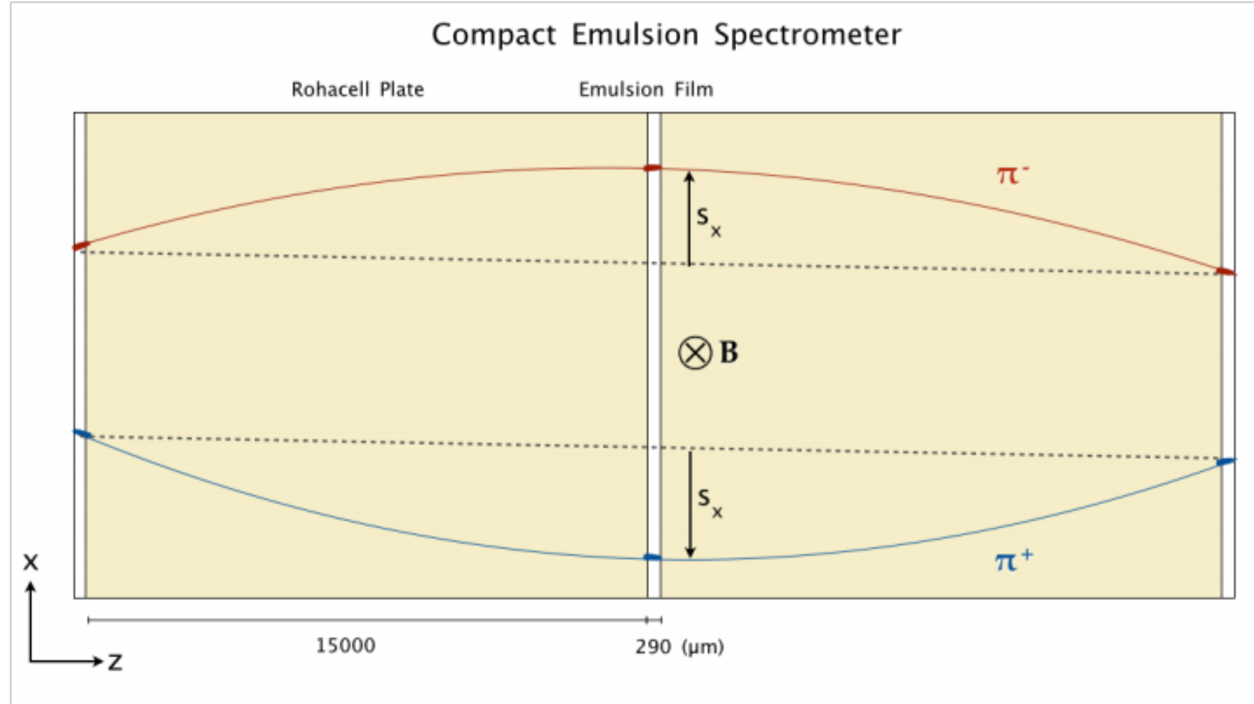
NEUTRINO FLAVOR IDENTIFICATION

REQUIREMENTS

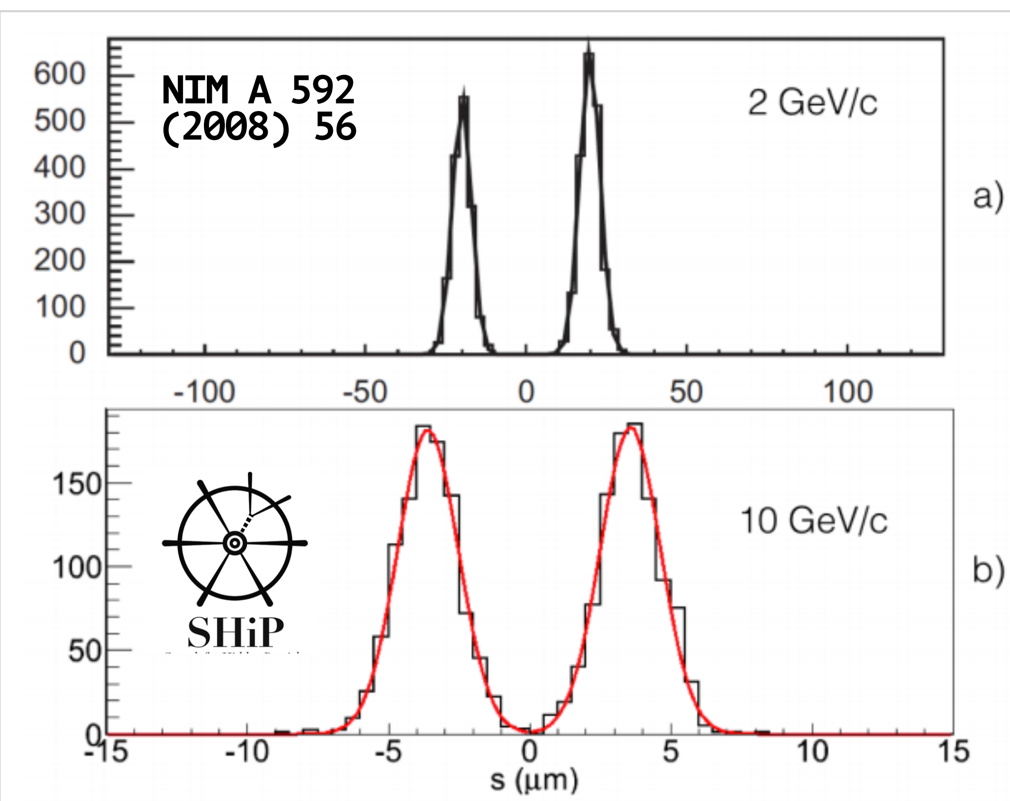
- Electric charge measurement of τ lepton decay products
- Key role for $\nu_\tau/\bar{\nu}_\tau$ separation in the $\tau \to h$ decay channel
- Momentum measurement

LAYOUT

- 3 OPERA-like emulsion films
- 2 Rohacell spacers (low density material)
- 1 Tesla magnetic field



Charge measured from the curvature of the track with the **sagitta** method



PERFORMANCES

- Sign of the **electric charge** can be determined with better than 3 standard deviation level up to 12 GeV
- The **momentum** of the track can be estimated from the sagitta
- $Dp/p < 20\%$ up to 12 GeV/c

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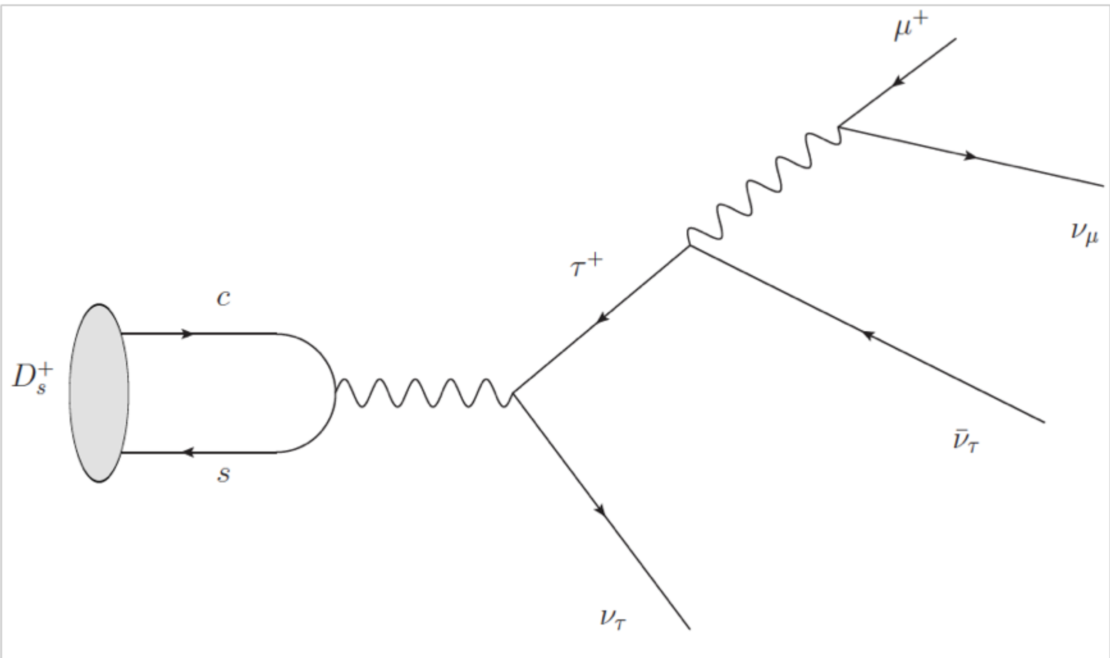
NEUTRINO PHYSICS

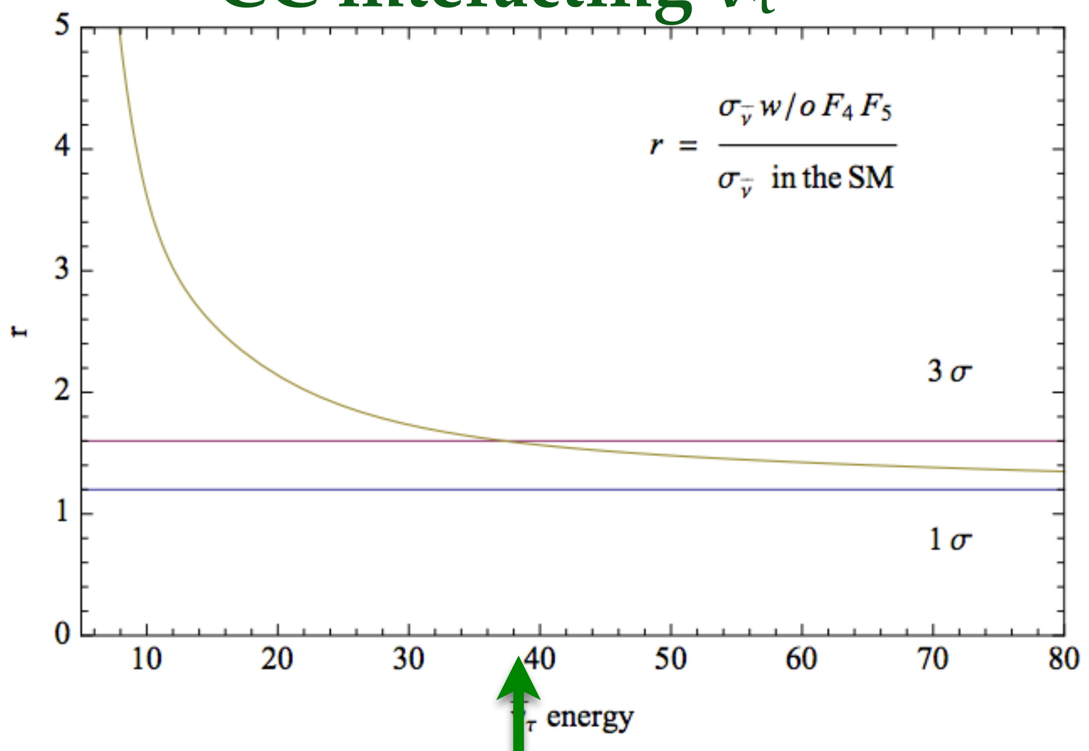


τ DECAY CHANNEL	BR (%)
$\tau \to \mu$	17.7
$\tau \to e$	17.8
$\tau \to h$	49.5
$\tau \to 3h$	15.0

$$N_{\nu_\tau+\bar{\nu}_\tau} = N_p \frac{2\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau) 2 = 2.85 \times 10^{-5} N_p$$

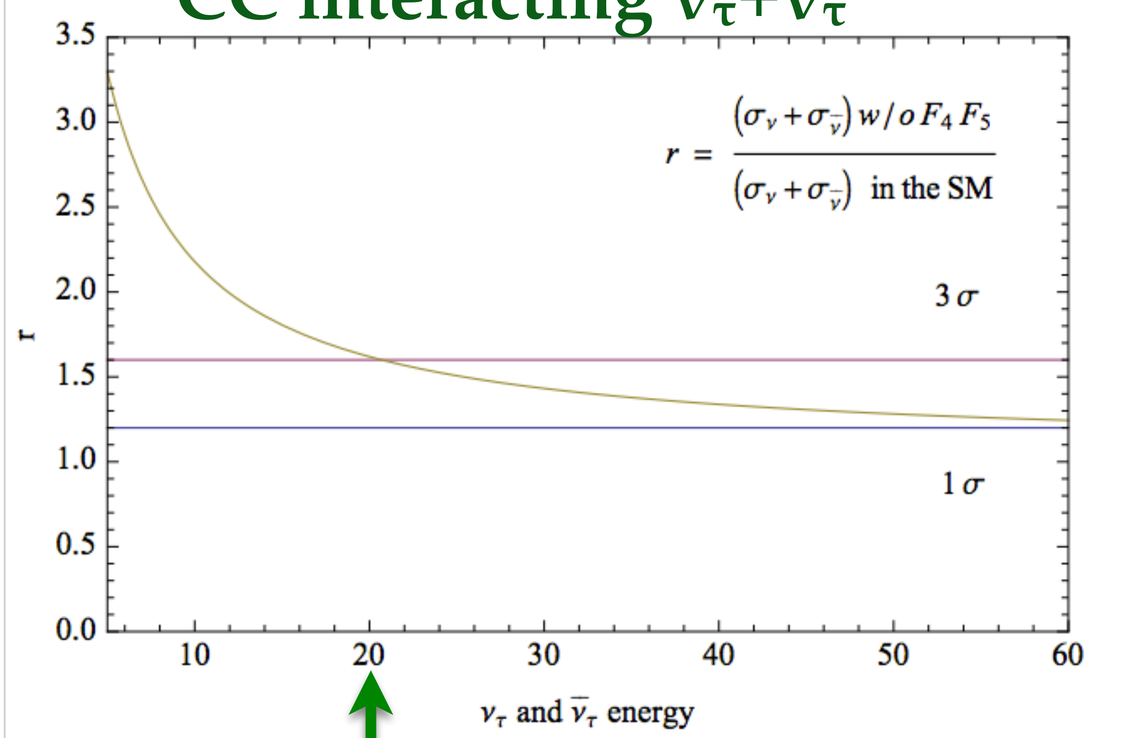
SENSITIVITY TO F_4 AND F_5

CC interacting $\bar{\nu}_\tau$



r = ratio between the cross sections in the two hypotheses

CC interacting $\nu_\tau + \bar{\nu}_\tau$



$E(\bar{\nu}_\tau) < 38$ GeV

(~300 events expected)

$E(\nu_\tau + \bar{\nu}_\tau) < 20$ GeV

(~420 events expected)

r>1.6

→ evidence for non-zero values of F_4 and F_5

Monday, June 8, 15