Effect of charm production modelling on prompt neutrino flux estimates

Atri Bhattacharya
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4th Forward Physics Facility Meeting, 2022

Collaborative work

- Collaborators
  - Rikard Enberg Uppsala U.
  - Yu Seon Jeong Chung-Ang U.
  - Felix Kling SLAC & DESY
  - Mary Hall Reno U. Iowa
  - Ina Sarcevic Arizona U.
  - Anna Stasto Penn. State U.
  - AB U. Liège

- Published work

Perturbative charm production and the prompt atmospheric neutrino flux in light of RHIC and LHC

Atri Bhattacharya (Arizona U.), Rikard Enberg (Uppsala U.), Mary Hall Reno (U. Iowa, Iowa City), Ina Sarcevic (Arizona U. and Arizona U., Astron. Dept. - Steward Observ.), Anna Stasto (Penn State U. and Cracow, INP) (Feb 3, 2015)

Published in: *JHEP* 06 (2015) 110 • e-Print: 1502.01076 [hep-ph]

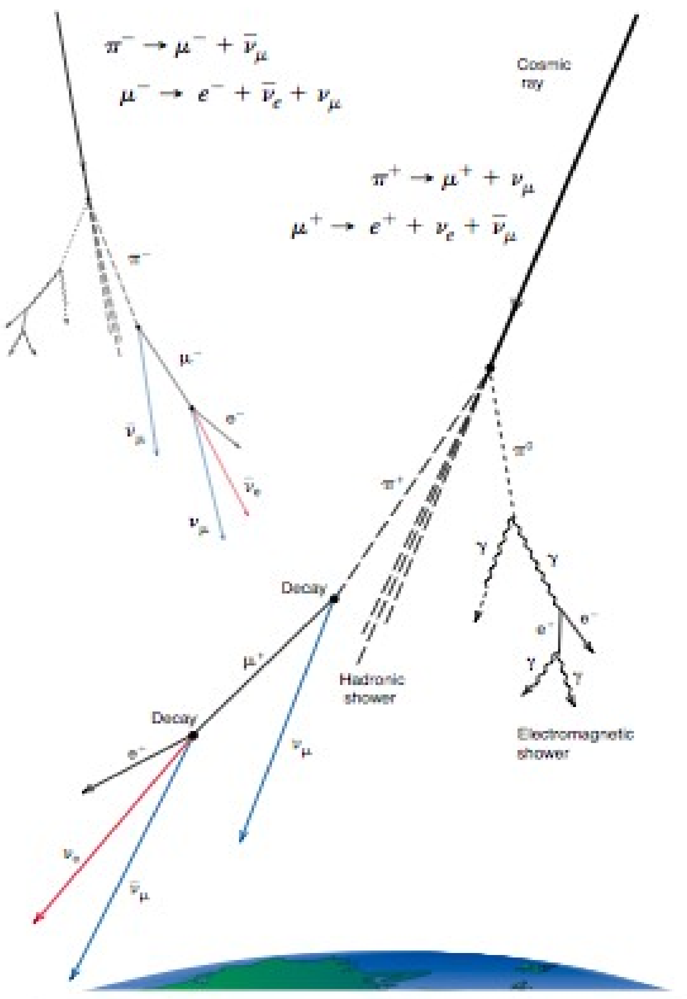
Prompt atmospheric neutrino fluxes: perturbative QCD models and nuclear effects

Atri Bhattacharya (Arizona U. and Liege U.), Rikard Enberg (Uppsala U.), Yu Seon Jeong (KISTI, Daejeon and IPAP, Seoul and Yonsei U.), C.S. Kim (IPAP, Seoul and Yonsei U.), Mary Hall Reno (U. Iowa, Iowa City) et al. (Jul 1, 2016)

Published in: *JHEP* 11 (2016) 167 • e-Print: 1607.00193 [hep-ph]

... and more soon

Neutrino production in the atmosphere



- Cosmic rays at UHE incident on atmospheric nuclei
  - Pions $\pi^{\pm}$, π^{0} [$\tau \sim 10^{-8}$ s]
  - Kaons $K^{\pm}$, K^{0} [$\tau \sim 10^{-8}$ s]

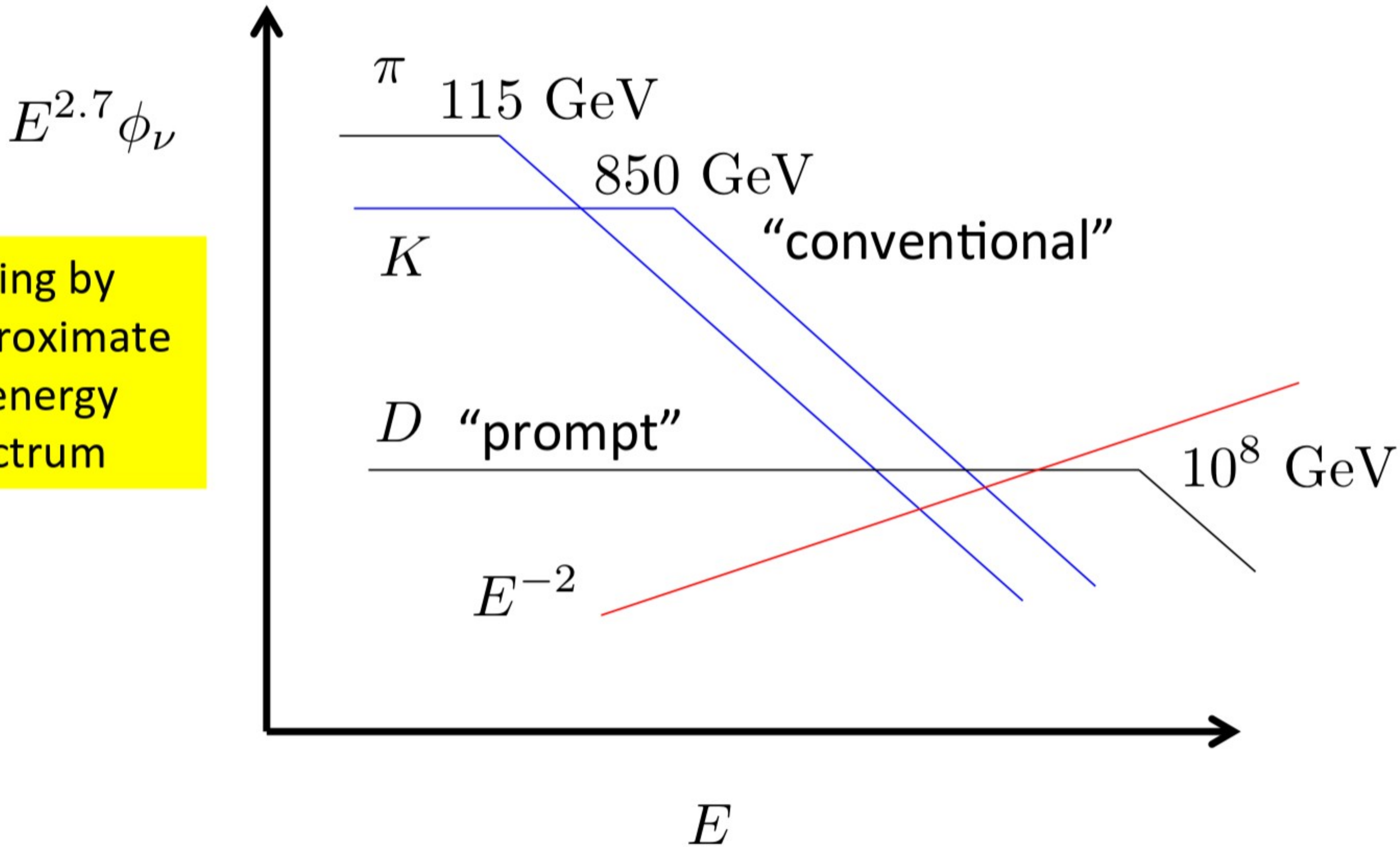
  Conventional

  - Charmed mesons $D^{\pm}$, D^{0} [$\tau \sim 10^{-12}$ s]

  Prompt

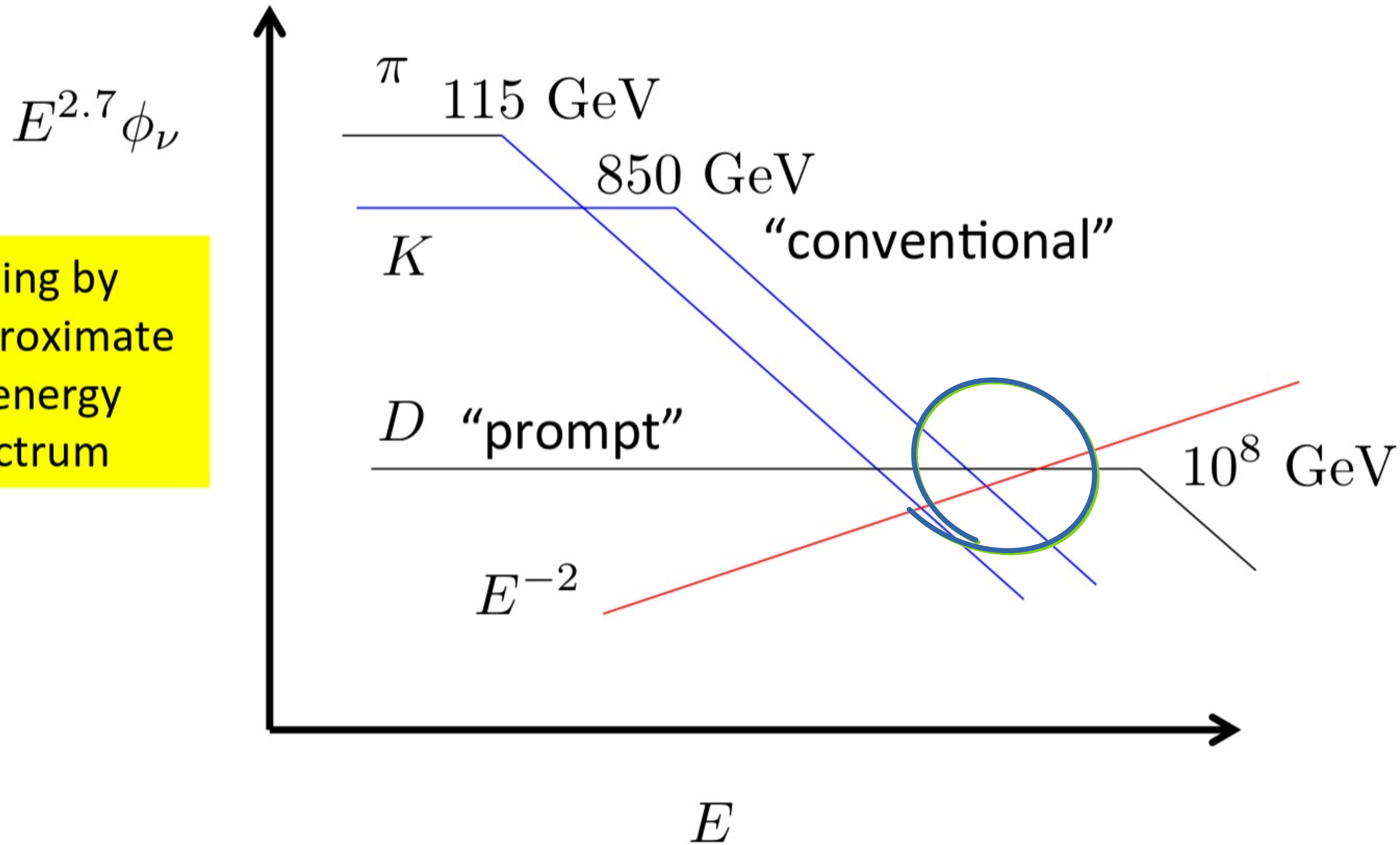
$$D^{+} \rightarrow \bar{K}^{0} e^{+} \nu_{e}$$
$$\rightarrow \bar{K}^{0} \mu^{+} \nu_{\mu}$$

Neutrino fluxes at high energies



Scaling by approximate CR energy spectrum

Neutrino fluxes at high energies

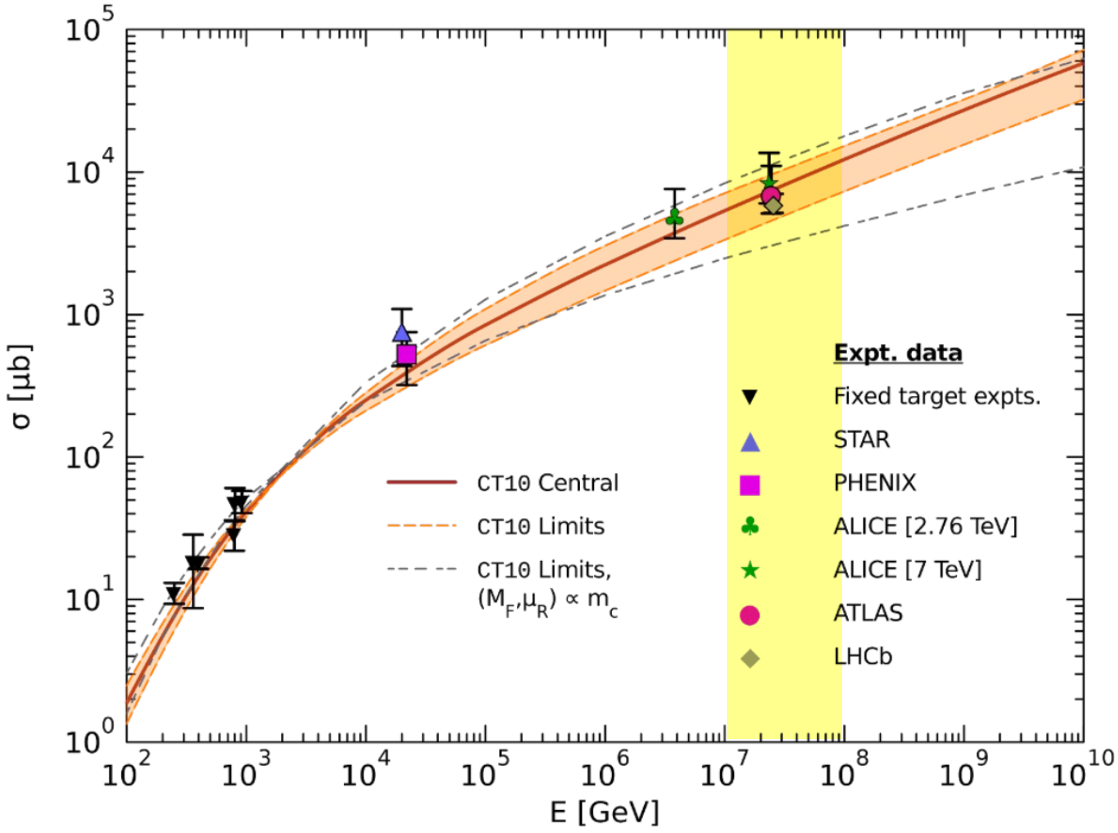


Scaling by approximate CR energy spectrum

Connecting with collider observables

- pp interactions at 10^7–10^8 GeV *lab* energies

$\Rightarrow \sqrt{s}$ = 4–14 TeV at LHC



Connecting with collider observables

- pp interactions at 10^7–10^8 GeV *lab* energies

  $\Rightarrow\sqrt{s}$ = 4–14 TeV at LHC

- Prompt ν flux
  - Forward charm from pp
  - PeV-scale ν from y ≥ 4.5
  - i.e., LHCb rapidities & higher

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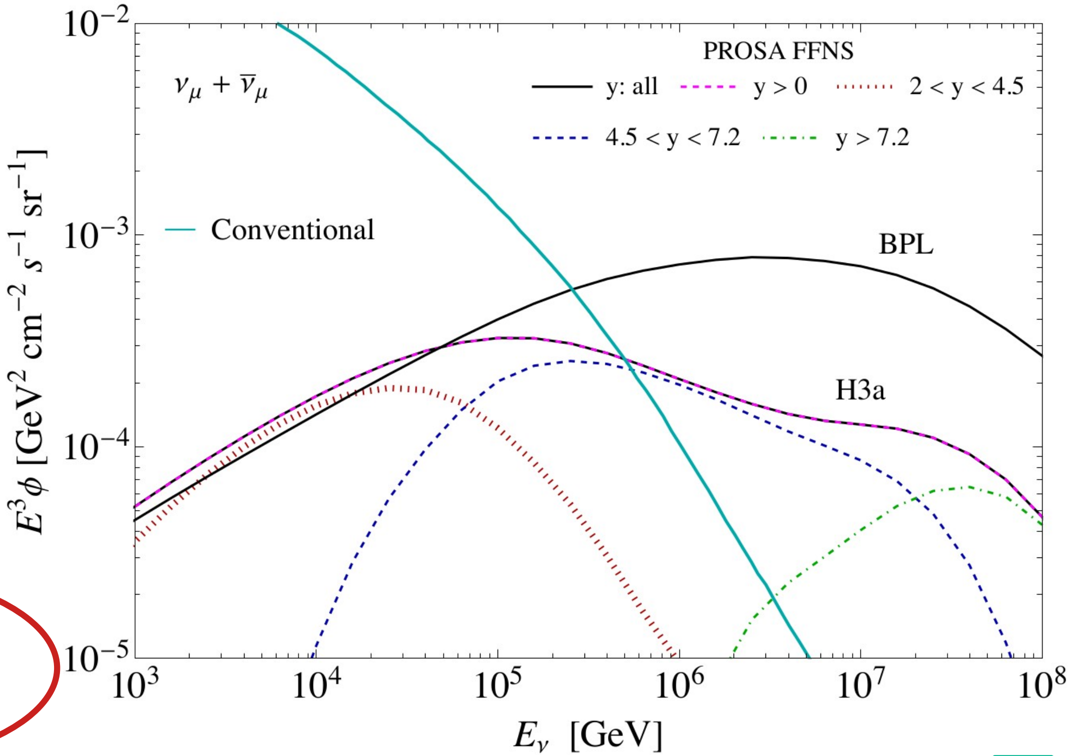


From CR to prompt neutrinos: Challenges

Incident cosmic ray flux and its proton content

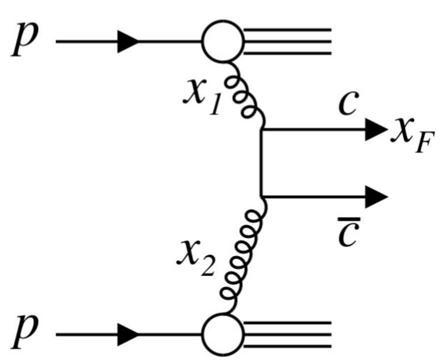
Uncertainties in CR spectral shape, composition at $E \gtrsim 10^6$ GeV

From CR to prompt neutrinos: Challenges

Incident cosmic ray flux and its proton content

QCD of charm pair production

$pp \to c\bar{c}X$



$$\sigma(pp \to c\bar{c}X) \simeq \int dx_1\, dx_2\, G(x_1,\mu)G(x_2,\mu)\hat{\sigma}_{GG\to c\bar{c}}(x_1 x_2 s)$$

$x_1,\ x_2:$

$$x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M_{c\bar{c}}}{s}} \pm x_F\right)$$

$$x_F = x_1 - x_2$$

$$x_F \simeq x_E = E/E'$$

$$x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1 \qquad E \sim 10^7 \text{ GeV} \to x_2 \sim 10^{-6}$$

From CR to prompt neutrinos: Challenges

Incident cosmic ray flux and its proton content

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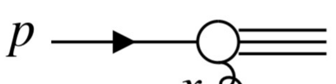


$$\sigma(pp \to c\bar{c}X) \simeq \int dx_1\, dx_2\, G(x_1, \mu) G(x_2, \mu) \hat{\sigma}_{GG \to c\bar{c}}(x_1 x_2 s)$$

Dominated by gluon fusion

$x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1 \qquad E \sim 10^7 \text{ GeV} \to x_2 \sim 10^{-6}$

From CR to prompt neutrinos: Challenges

Incident cosmic ray flux and its proton content

QCD of charm pair production

$$pp \to c\bar{c}X$$

- Perturbative order?
- Probes extremely low-x
- Quark mass (m_c) uncertainty

- Uncertainties in scales:
  - Renormalisation (μ_R)
  - Factorisation (M_F)

From CR to prompt neutrinos: Challenges

QCD of charm pair production

Charm to charmed mesons

$c\bar{c} \rightsquigarrow D^{\pm,0}$

- Subject to theoretical modelling:
  - Fragmentation fn: Kneihl-Kramers, etc.
  - Lund string model in, e.g., `PYTHIA`
  - Other novel models, e.g., Braaten et al

From CR to prompt neutrinos: Challenges

Charm to charmed mesons

Meson decays to prompt ν

$D^{\pm,0} \rightsquigarrow \nu$

Previous prompt neutrino flux estimates*

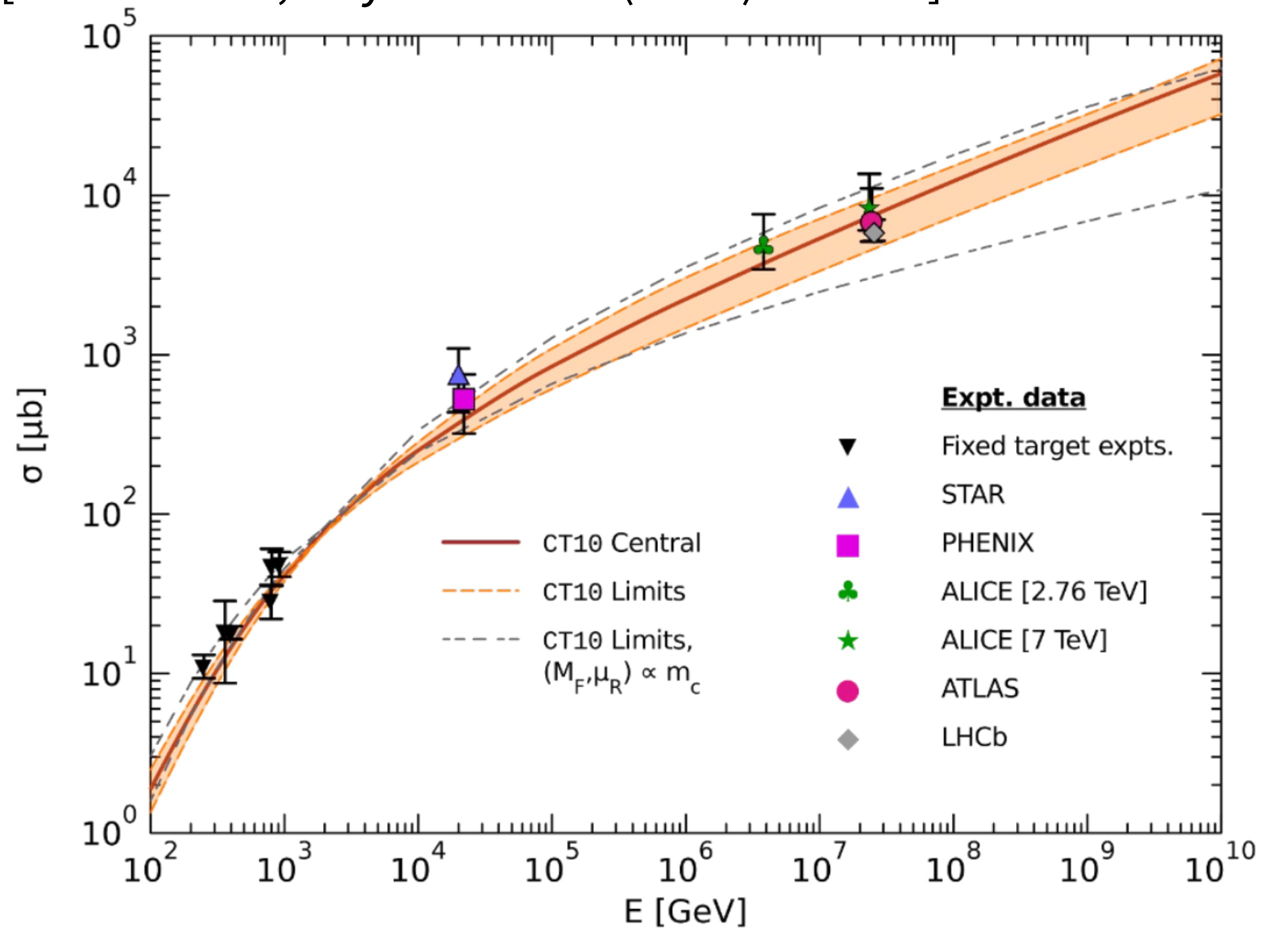
- **Existing reference prompt flux estimate used by IceCube:**
  - Dipole model estimate by Enberg, Reno, Sarcevic (ERS) [Phys.Rev. D78 (2008) 043005]
    - Accounts for saturation of gluon at very low *x*
    - LO CTEQ6 PDF's used for the high-x distributions
  - Perturbative QCD by Pasquali, Reno, Sarcevic (PRS) [Phys.Rev. D59 (1999) 034020]
    - CTEQ3 LO computation, multiplied by scale factors to approximate NLO results
    - Higher than ERS because of sharply rising gluon distributions at low-*x*

*** Not a full list**

Why now?

- **Recent collider data (√s ~ 7 TeV) constrains QCD parameters**

[Nelson et al, Phys.Rev. C87 (2013) 014908]



$$m_c = 1.27 \text{ GeV}$$

Central

$$M_F = 2.1 m_T$$

$$\mu_R = 1.6 m_T$$

Shaded band

$$M_F = 1.25 - 4.65 m_T$$

$$\mu_R = 1.48 - 1.71 m_T$$

Dashed band

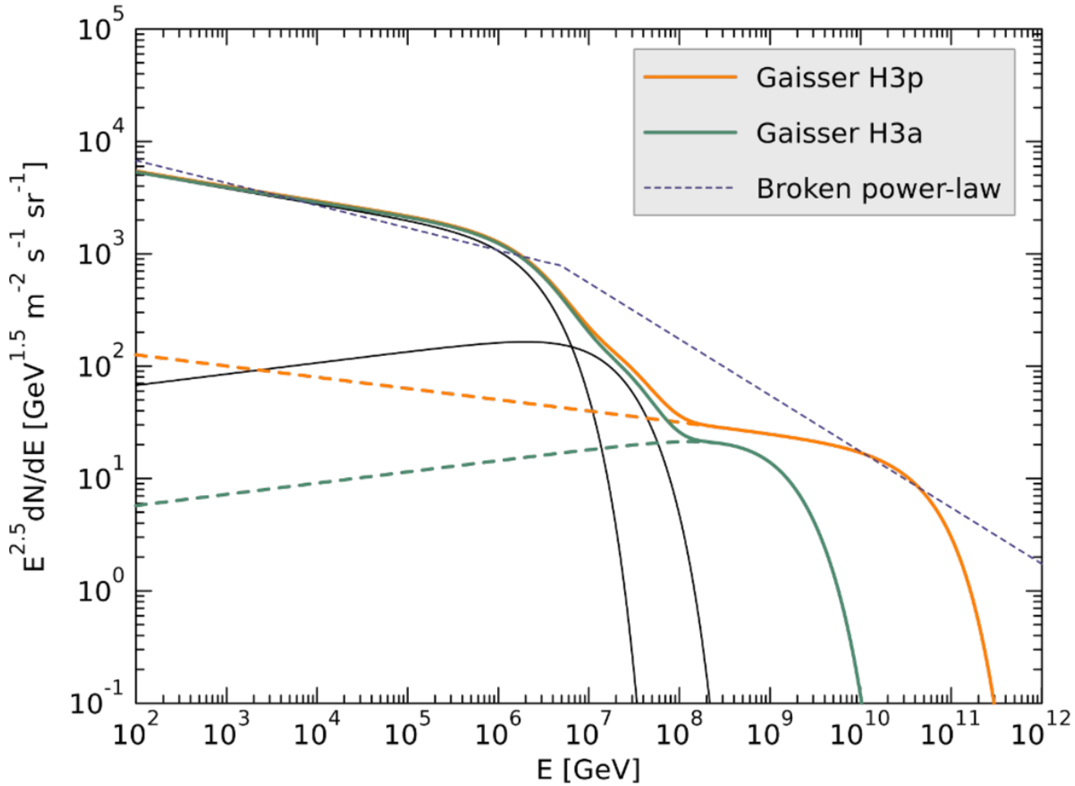
$$M_T, \mu_R \propto m_c$$

Why now?

- Recent collider data ($\sqrt{s} \sim 7$ TeV) constrains QCD parameters
- **Improved theoretical modelling of cosmic ray fluxes at UHE using up-to-date CR experiments**
  - Gaisser
    - *Earth Planets Space 62 (2010) 195-199*
    - *Astropart.Phys. 35 (2012) 801-806*
  - Stanev et al *Nucl.Instrum.Meth. A742 (2014) 42-46*

Why now?

- Recent collider data ($\sqrt{s}$ ~ 7 TeV) constrains QCD parameters
- **Improved theoretical modelling of cosmic ray fluxes at UHE using up-to-date CR experiments**



Why now?

- Recent collider data ($\sqrt{s} \sim 7$ TeV) constrains QCD parameters
- Improved theoretical modelling of cosmic ray fluxes at UHE using up-to-date CR experiments
- IceCube looking at neutrinos beyond 10 TeV

Improving prompt neutrino estimates

Or, what's new in our work

- **Replace charm-production cross-section computations based on LO QCD by a full NLO scheme**
  - PRS : LO ⊕scaling functions
  - ERS : LO ⊕Dipole moments

Improving prompt neutrino estimates

Or, what's new in our work

- Replace charm-production cross-section computations based on LO QCD by a full NLO scheme
- **Use parameters consistent with recent charm production data**

$$m_c = 1.27 \text{ GeV}$$

$$M_F = 2.10^{+2.55}_{-0.85} \times m_T$$

$$\mu_R = 1.60^{+0.11}_{-0.12} \times m_T$$

Expt.	$\sqrt{s}$ [TeV]	σ [mb]
PHENIX	0.20	$\mathbf{0.551}^{+0.203}_{-0.231}$ (sys)
STAR	0.20	$\mathbf{0.797} \pm 0.210$ (stat)$^{+0.208}_{-0.295}$ (sys)
ALICE	2.76	$\mathbf{4.8} \pm 0.8$ (stat)$^{+1.0}_{-1.3}$ (sys) ± 0.06 (BR) ±0.1(frag) ± 0.1 (lum)$^{+2.6}_{-0.4}$ (extrap)
ALICE	7.00	$\mathbf{8.5} \pm 0.5$ (stat)$^{+1.0}_{-2.4}$ (sys) ± 0.1 (BR) ±0.2(frag) ± 0.3 (lum)$^{+5.0}_{-0.4}$ (extrap)
ATLAS	7.00	$\mathbf{7.13} \pm 0.28$ (stat)$^{+0.90}_{-0.66}$ (sys) ±0.78 (lum)$^{+3.82}_{-1.90}$ (extrap)
LHCb	7.00	$\mathbf{6.100} \pm 0.930$

Improving prompt neutrino estimates

Or, what's new in our work

- Replace charm-production cross-section computations based on LO QCD by a full NLO scheme
- Use parameters consistent with recent charm production data
- **Updated CT10 NLO PDFs instead of CTEQ3/6**
  - PRS: CTEQ3, 1998 ($10^{-4} \leqslant x \leqslant 1$)
  - ERS: CTEQ6 LO ($10^{-5} \leqslant x \leqslant 1$)
  - **BERSS: CT10nlo, 2010 ($10^{-7} \leqslant x \leqslant 1$)**

Improving prompt neutrino estimates

Or, what's new in our work

- Replace charm-production cross-section computations based on LO QCD by a full NLO scheme
- Use parameters consistent with recent charm production data
- Updated CT10 NLO PDFs instead of CTEQ3/6
- Updated incident cosmic-ray spectrum
  - ERS/PRS: Broken power law
  - **BERSS:**
    - **Gaisser (2012)**
    - **Gaisser, Stanev, and Tilav (2013, 2014)**

Technical details: $c\bar{c} \rightsquigarrow D^{\pm,0} \rightsquigarrow \nu$

- Fragmentation factors
  - $\frac{d\sigma}{dx}(pp \to hX) \sim F_h \times \frac{d\sigma}{dx}(pp \to c\bar{c}X)$

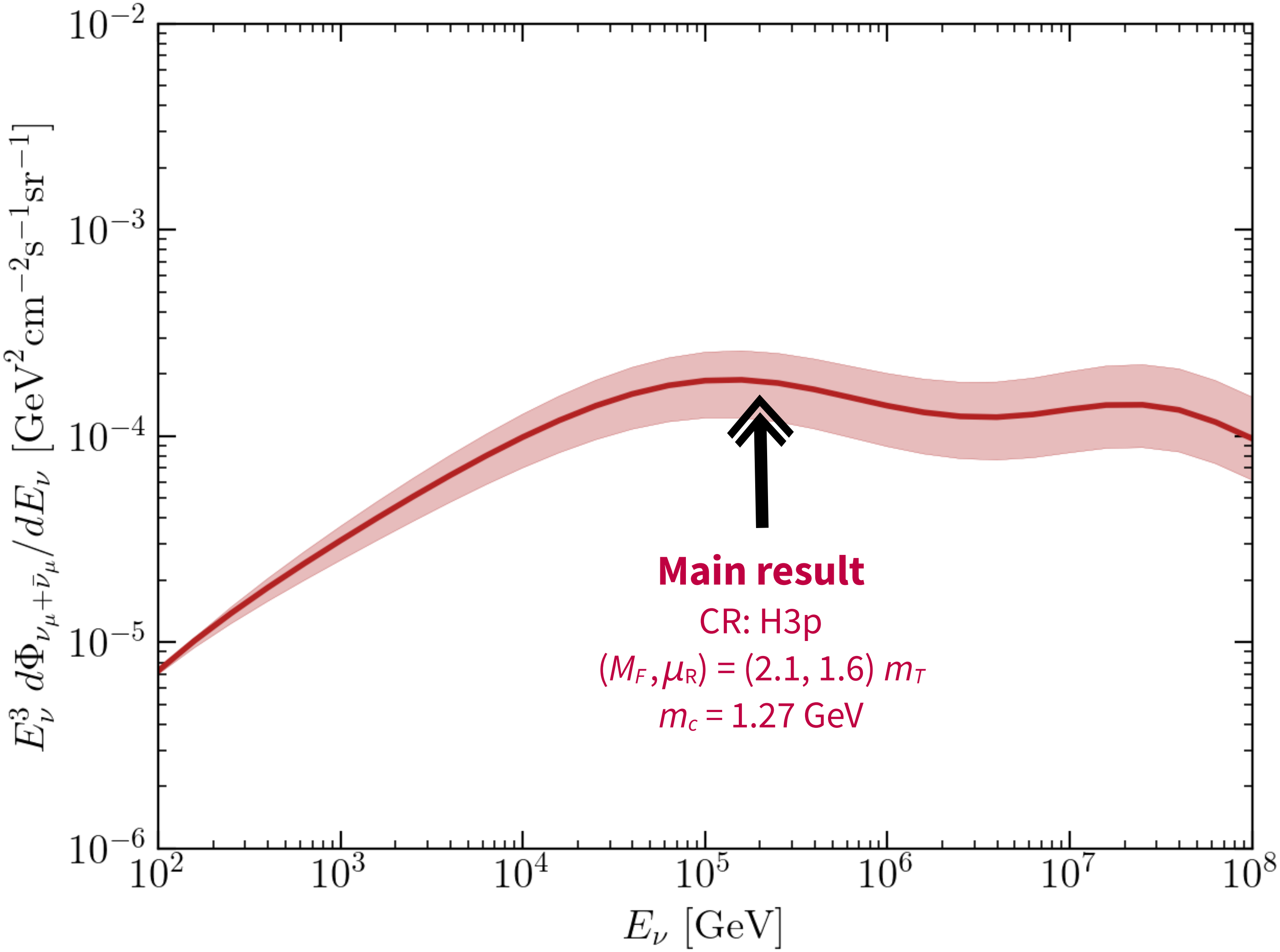
Fit to Kneihl-Kramers
Phys.Rev. D74 (2006) 037502

- Transport equations and Z-moments (Z_{ph}, Z_{hl})
  - $Z_{ph}(E_h) = \int_{x_{E_{\min}}}^{1} \frac{dx_E}{x_E} \frac{\phi_p^0(E_h/x_E)}{\phi_p^0(E_h)} \frac{1}{\sigma_{pA}(E_h)} \times A \frac{d\sigma}{dx_E}(pN \to hX)\ .$

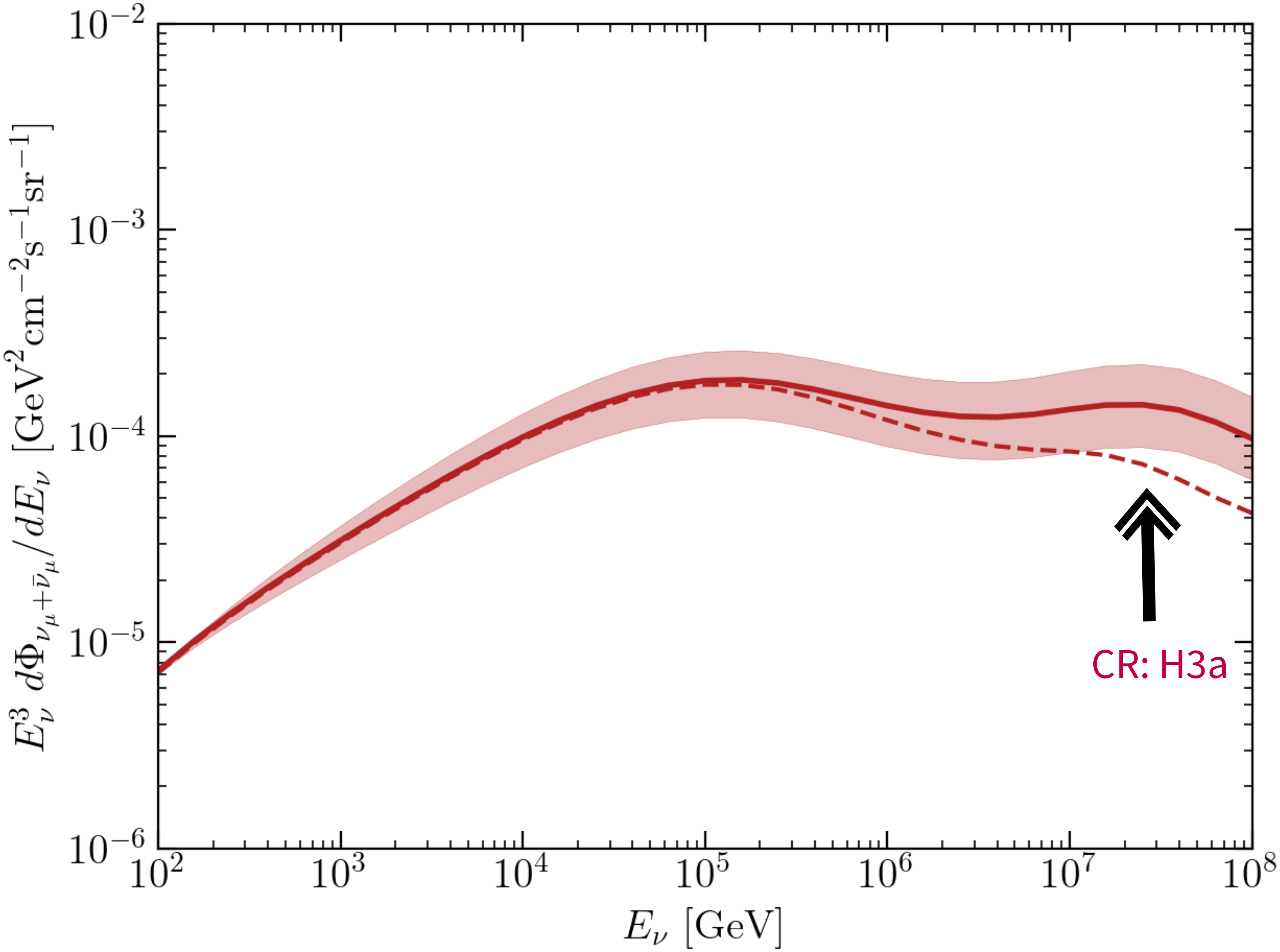
CR flux

- 1*d* atmosphere column modelling

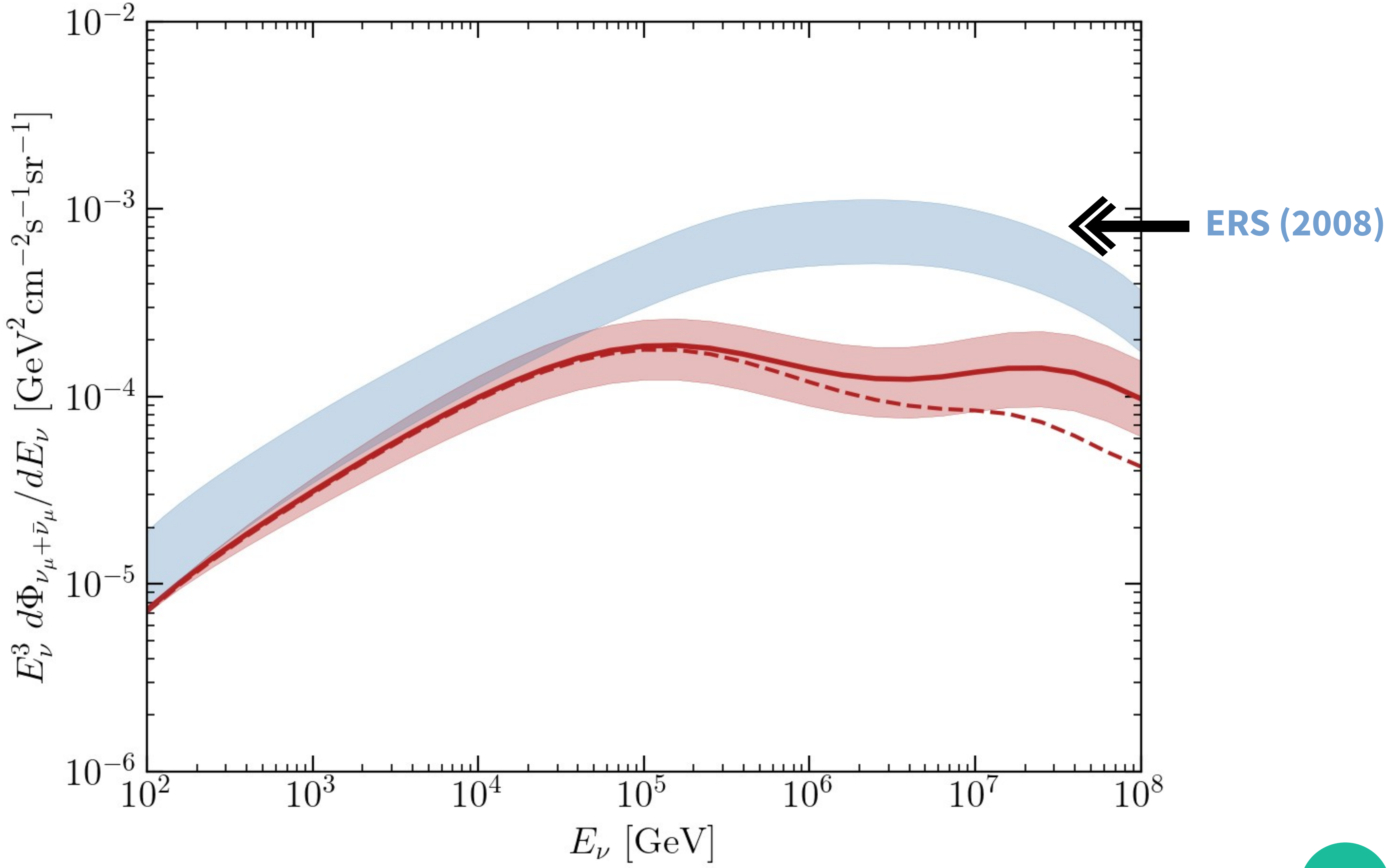
Prompt Neutrino fluxes: Results



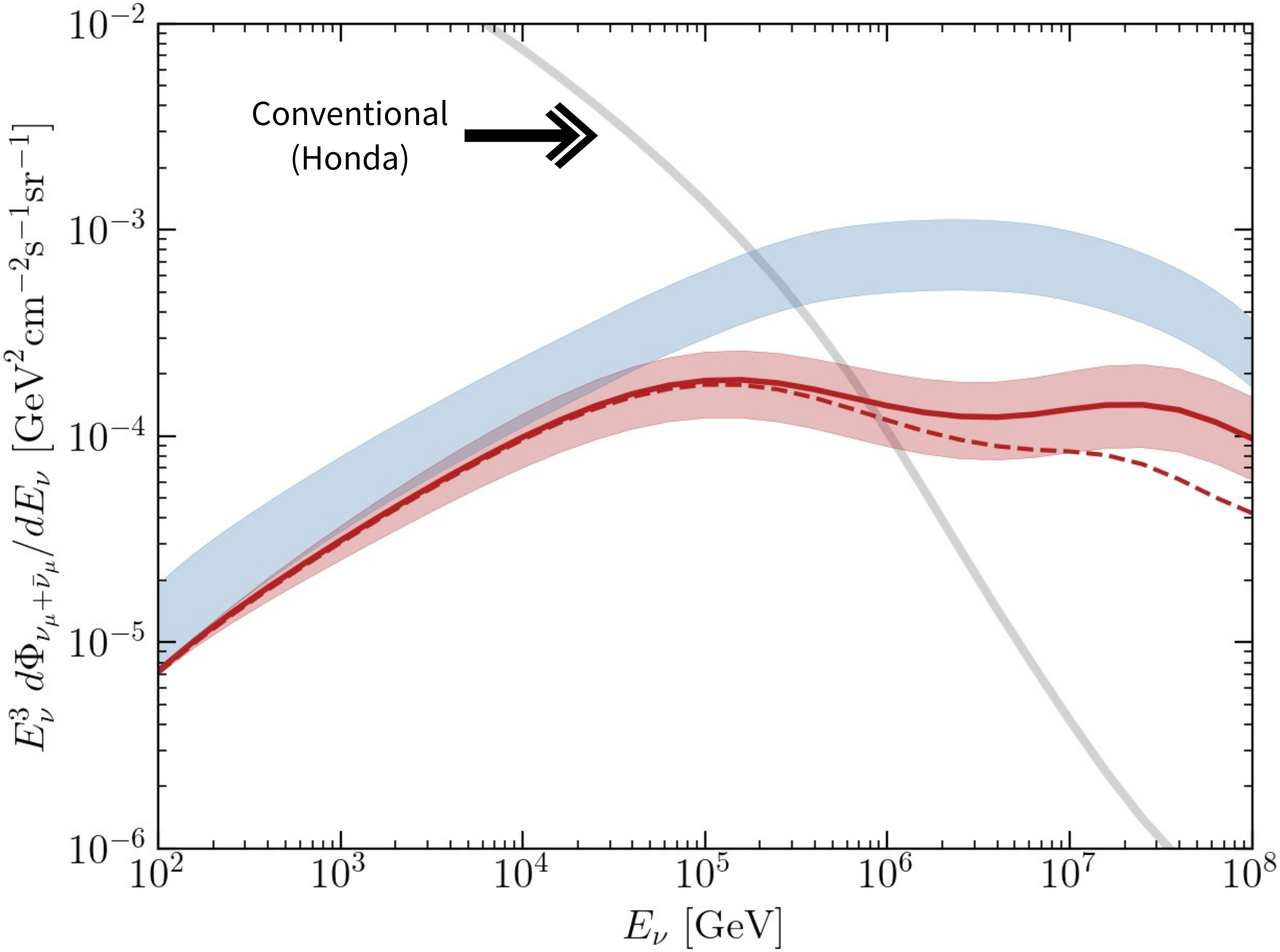
Prompt Neutrino fluxes: Results



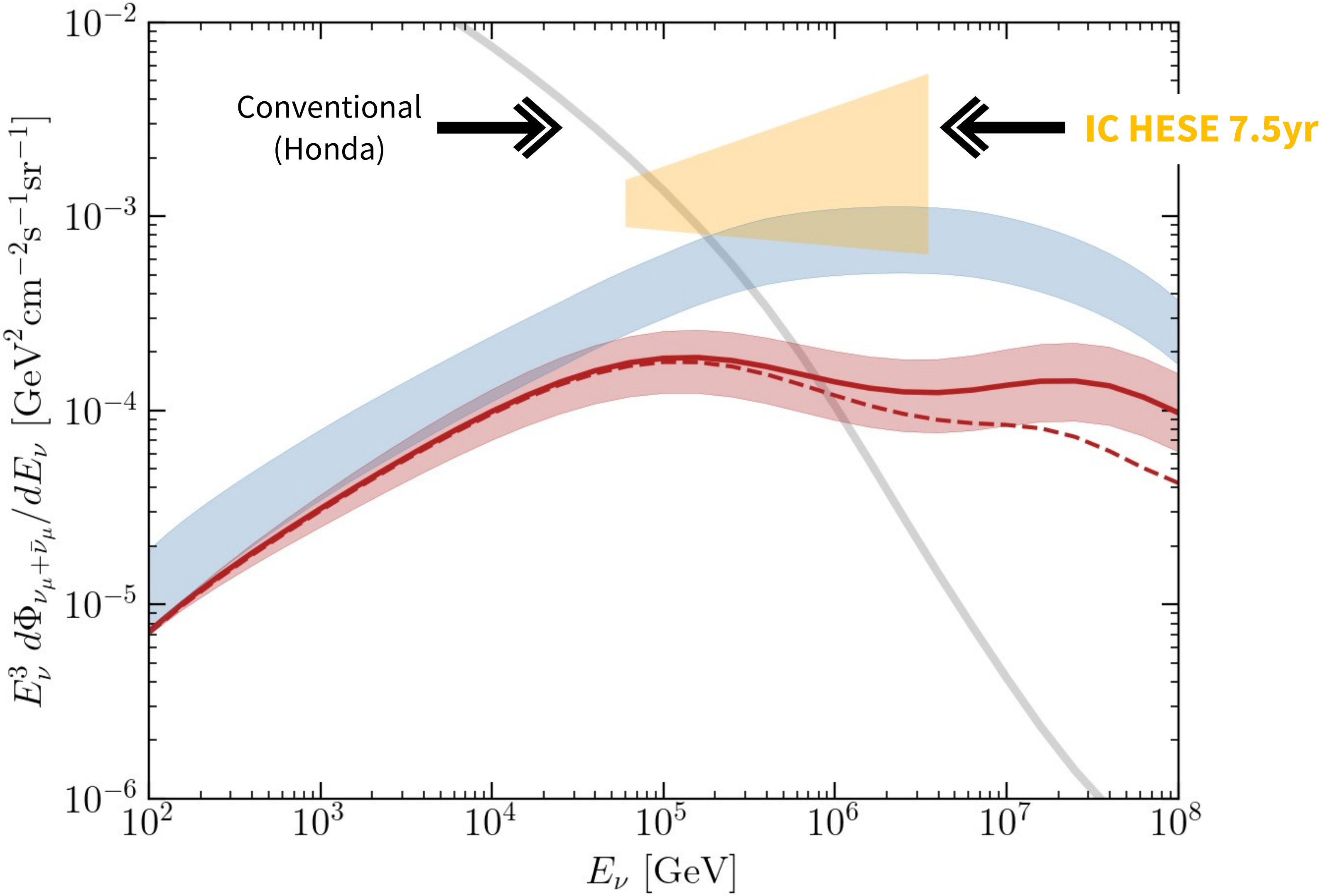
Prompt Neutrino fluxes: Results



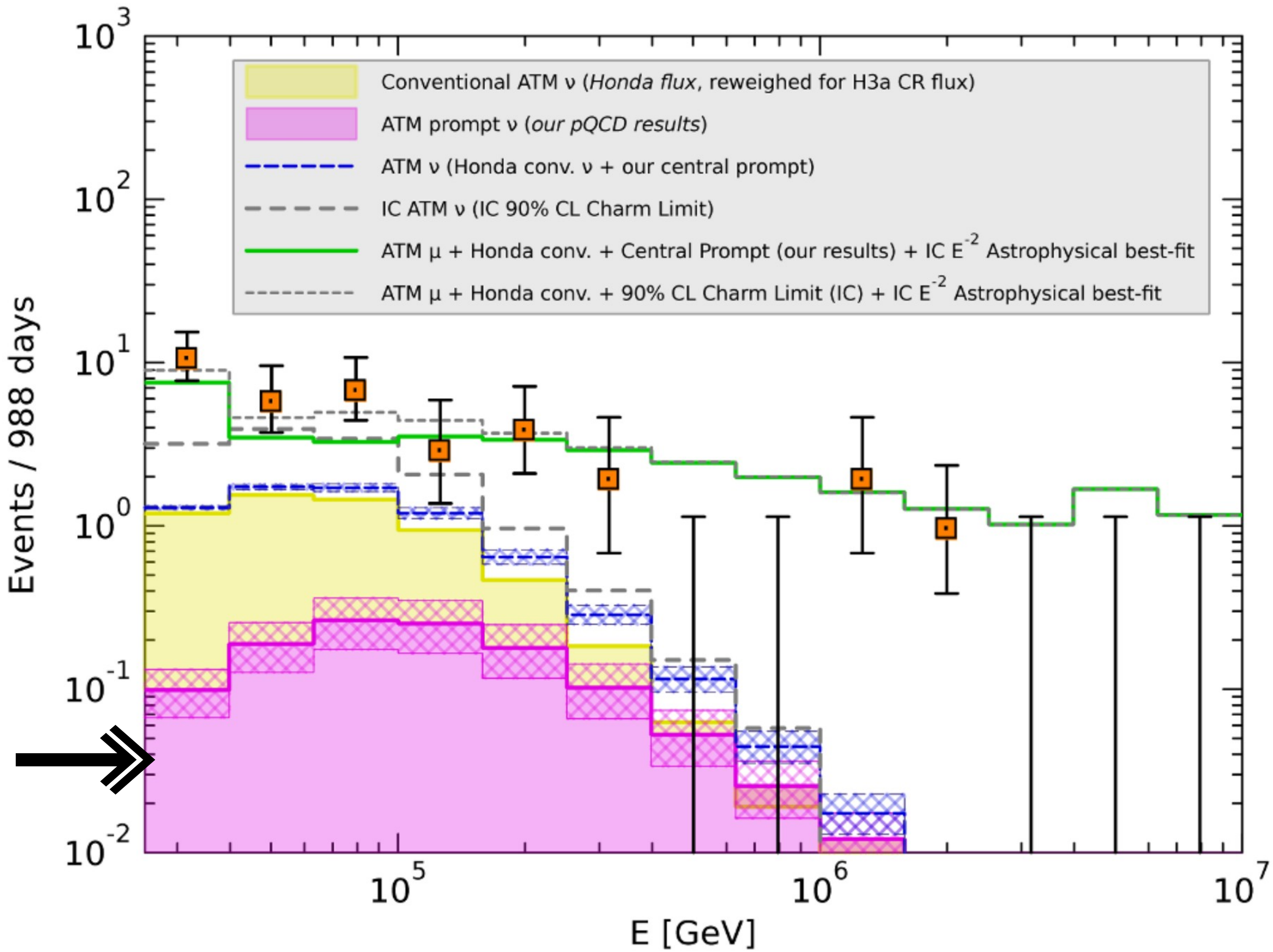
Prompt Neutrino fluxes: Results



Prompt Neutrino fluxes: Results



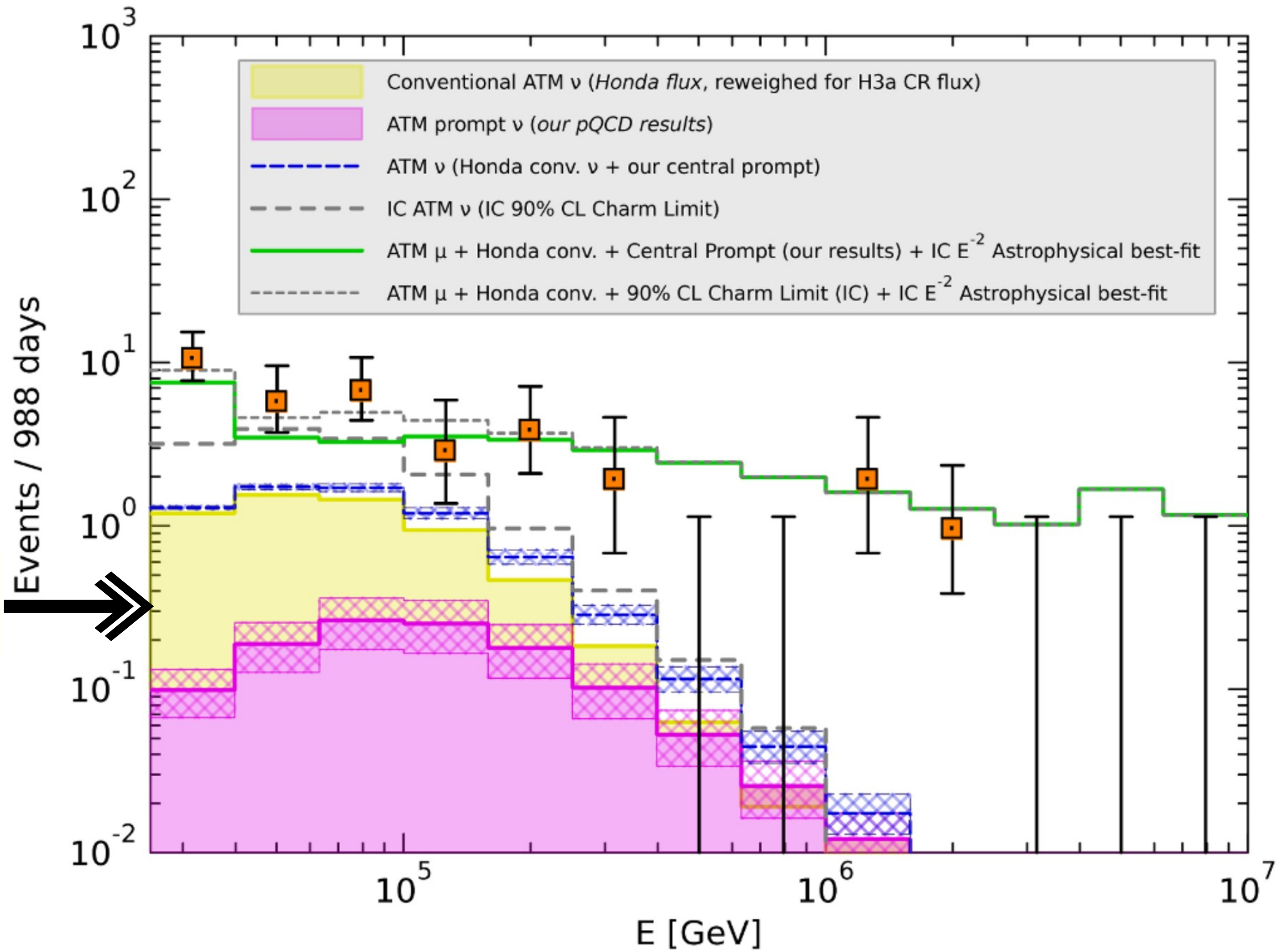
Prompt neutrino event rates at IceCube



Benchmark prompt

Prompt neutrino event rates at IceCube

Conventional (Honda)



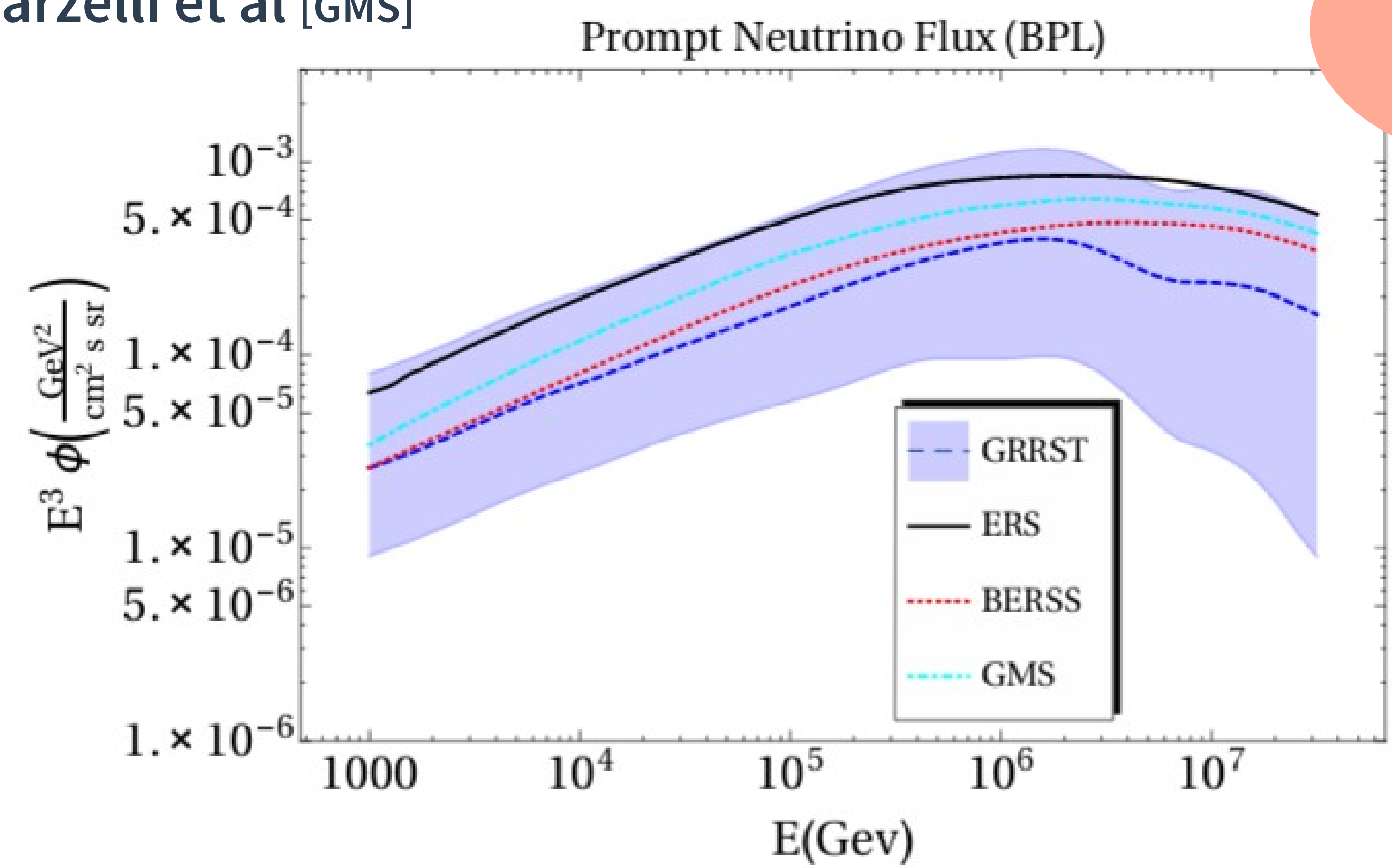
Related recent works

- **Garzelli et al**
  [JHEP 1510 (2015) 115]
  - Different PDF’s [ABM11]
  - Larger error bars compared to BERSS
  - Central flux slightly higher consistently across energies
- **Gauld et al**
  [JHEP 1602 (2016) 130]
  - Perturbative QCD; NNPDF
  - Uncertainty band constrained by incorporating LHCb charm hadroproduction at $\sqrt{s} = 13$ TeV
  - Central flux nearly identical to that in BERSS up to a PeV

Related recent works

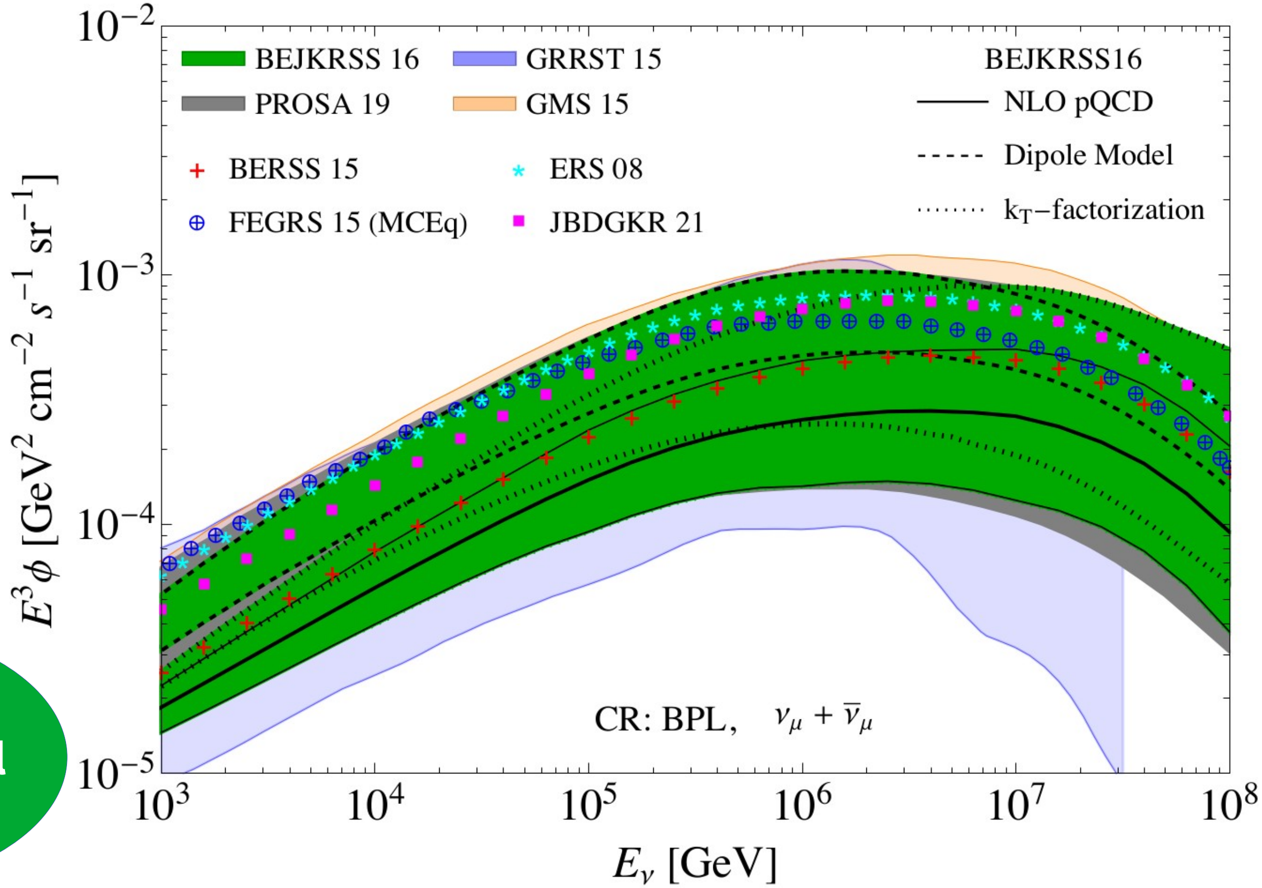
- Bhattacharya et al [BERSS]
- Garzelli et al [GMS]
- Gauld et al [GRRST]

Plot from Gauld et al



Related recent works

- Bhattacharya et al 2015 [BERSS]
- Bhattacharya et al 2016 [BEJKRSS]
- Jeong et al [PROSA]
- Garzelli et al [GMS]
- Gauld et al [GRRST]



Y. S. Jeong, et al

On-going work

- **Improved fragmentation modelling at high y**
  - Test existing functions against LHCb data **[2 ≤ y ≤ 4.5]**
  - Simulate fragmentation from MC gens `PYTHIA`, `SHERPA`
- **Predict ν from charm at FASERν**
  - Same essential set-up
  - Predictions from multiple QCD models
  - When data available
    - ⇒ Test for accuracy
    - ⇒ Refine QCD model, fragmentation functions, etc.

On-going work

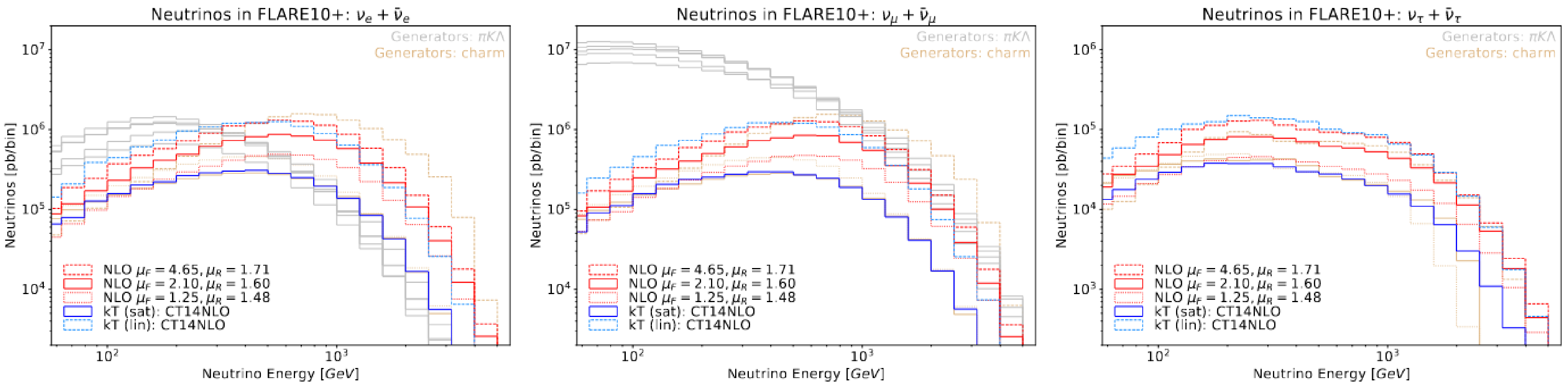


FIG. 4. Predictions for the neutrino fluxes going through the 50 cm × 50 cm cross sectional area of the FLArE detector with nominal mass of 10 tons. The panels show number of electron (left) muon (center) and tau (right) neutrinos per energy bin passing through the experiments cross section. We show the predictions of different MC event generators as light brown curve. The predictions using the NLO and the kT factorization approaches are shown in red and blue, respectively. In addition, we show the neutrino fluxes from light meson decays obtained as gray lines.

Take away

- **Substantially (~ 3×) reduced estimates for atmospheric prompt neutrino flux at high energies**
  - Full NLO pQCD computation
  - Using recent PDFs, incident Cosmic Ray estimates
  - Using QCD parameters consistent with recent collider limits
  - Effect of shadowing in atm. nuclei (−40% at ~ 10^6 GeV)
  - Different QCD schemes (dipole model, *kT* factorisation)

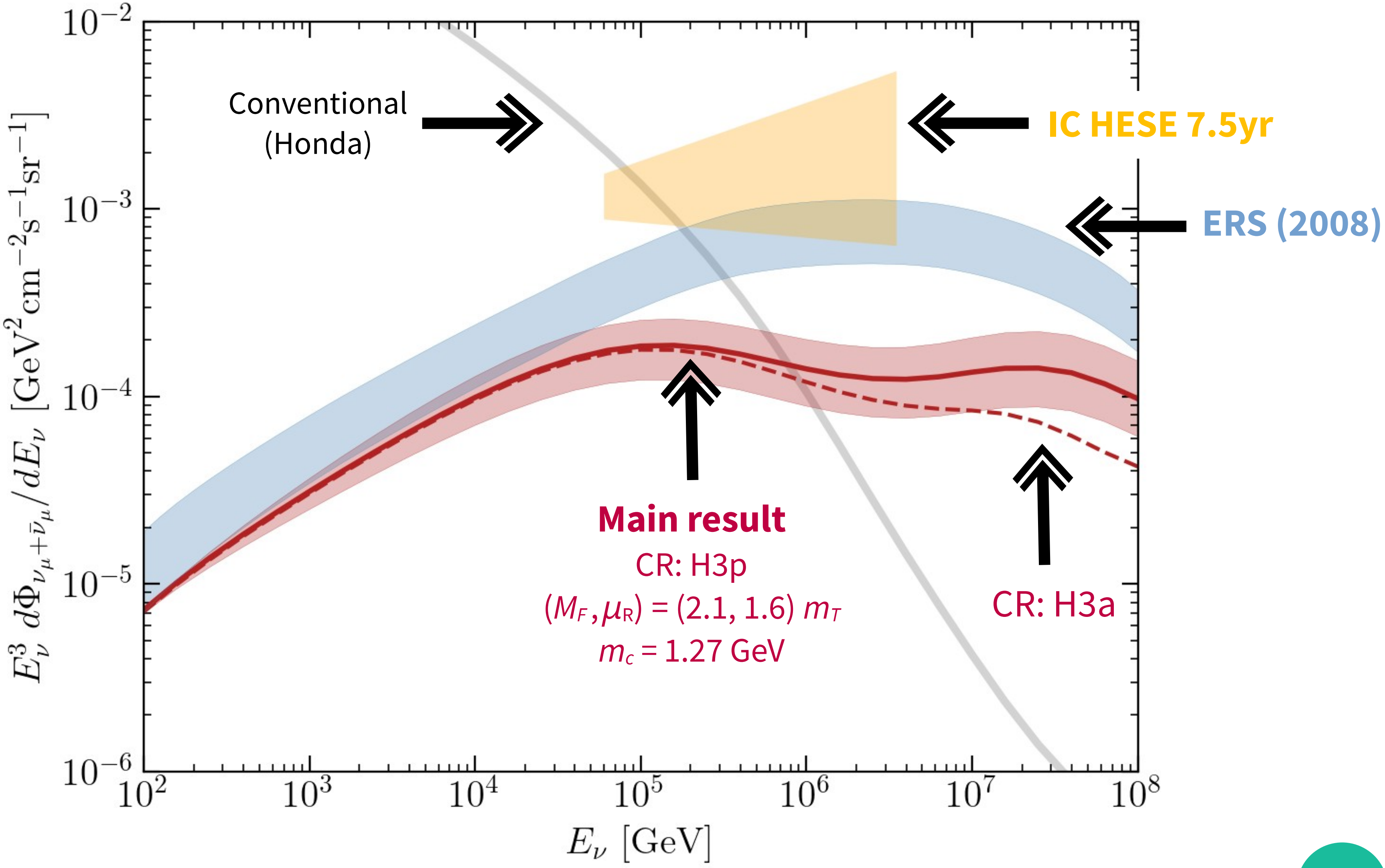
AB *et al*
JHEP 11 (2016) 167

- **Ongoing work**
  - Improved fragmentation modelling
  - Predictions for — and, in the future, checks against — FASERν

References

- **AB, Enberg, Reno, Sarcevic, Stasto** ***JHEP 1506 (2015) 110***
- **AB, Enberg, Jeong, Kim, Reno, Sarcevic, Stasto** ***JHEP 11 (2016) 167***
- **Updated cosmic ray incidence**
  - Gaisser
    - *Earth Planets Space 62 (2010) 195-199*
    - *Astropart.Phys. 35 (2012) 801-806*
  - Stanev et al *Nucl.Instrum.Meth. A742 (2014) 42-46*
- **Older results**
  - Enberg et al *Phys.Rev. D78 (2008) 043005*
  - Pasquali et al *Phys.Rev. D59 (1999) 034020*

Results



Conventional
(Honda)
IC HESE 7.5yr
ERS (2008)
Main result
CR: H3p
$(M_F, \mu_R) = (2.1, 1.6)\ m_T$
$m_c = 1.27$ GeV
CR: H3a
$E_\nu^3\ d\Phi_{\nu_\mu+\bar{\nu}_\mu}/dE_\nu\ [\mathrm{GeV^2 cm^{-2} s^{-1} sr^{-1}}]$
E_ν [GeV]

BACKUPS

Full list of Experiments

Expt.	$\sqrt{s}$ [TeV]	σ [mb]
PHENIX [31]	0.20	$\mathbf{0.551}^{+0.203}_{-0.231}$ (sys)
STAR [32]	0.20	$\mathbf{0.797} \pm 0.210$ (stat)$^{+0.208}_{-0.295}$ (sys)
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LHCb [30]	7.00	$\mathbf{6.100} \pm 0.930$

Dipole cross-section: Raw expressions

$$\sigma^{gp\to q\bar{q}X}(x, M_R, Q^2) = \int dz\, d^2\vec{r}\, |\Psi_g^q(z, \vec{r}, M_R, Q^2)|^2 \sigma_d(x, \vec{r})$$

$$|\Psi_g^q(z, \vec{r}, M_R, Q^2 = 0)|^2 = \frac{\alpha_s(M_R)}{(2\pi)^2} \left[\left(z^2 + (1-z)^2\right) m_q^2 K_1^2(m_q r) + m_q^2 K_0^2(m_q r) \right] ,$$

$$\sigma_d(x, \vec{r}) = \frac{9}{8} \left[\sigma_{d,em}(x, z\vec{r}) + \sigma_{d,em}(x, (1-z)\vec{r}) \right] - \frac{1}{8} \sigma_{d,em}(x, \vec{r}) \; .$$

Models: Soyez, AAMQS, Block, etc.

$$\frac{d\sigma(pp \to q\bar{q}X)}{dx_F} \simeq \frac{x_1}{\sqrt{x_F^2 + \frac{4M_{q\bar{q}}^2}{s}}} g(x_1, M_F) \sigma^{gp\to q\bar{q}X}(x_2, M_R, Q^2 = 0) \; ,$$

LO gluon PDF

k_T factorisation: Raw expressions

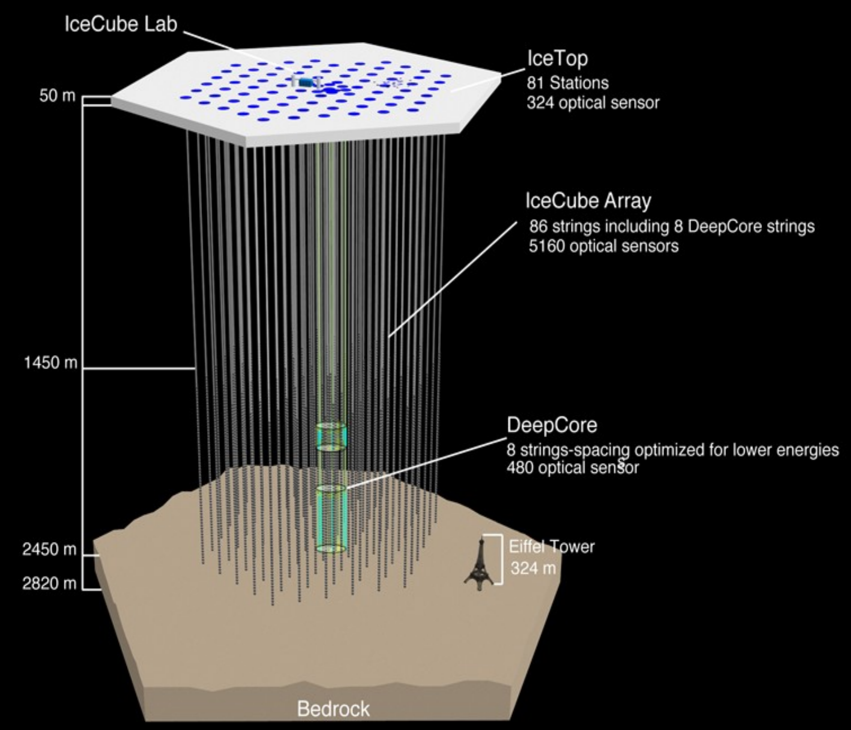
$$\frac{d\sigma}{dx_F}(s, m_Q^2) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\, dz\, \delta(zx_1 - x_F)\, x_1 g(x_1, M_F) \int \frac{dk_T^2}{k_T^2}\hat{\sigma}^{\rm off}(z, \hat{s}, k_T)\, f(x_2, k_T^2)\ .$$

Projectile
Integrated g density

$gg^* \to Q\bar{Q},$

Target
Unintegrated g density

A quick IceCube outline



- Operational since 2010
  - Full exposure since Dec. 2011
- Capable of flavour discrimination
  - Limited to detection of three distinct event signatures
- Excellent energy reconstruction
  - < 10% for contained cascades
  - ~ 30% for tracks with contained vertices
- Good direction reconstruction
  - Up to 1° for tracks
  - ~30° for cascades
- Designed to run (minimal op. cost) for 10+ yrs
- **37 UHE events in 998 days of run-time**
  - **3 events at PeV+ energies**

Theoretical issues with charm production

- **Uncertainties**
  - QCD of charm production
    - Scales: Renormalisation (μ_R), factorisation (M_F)
    - Heavy quark mass (m_c)
    - Perturbative? Dipole model?
  - Uncertainties in fragmentation $(c\bar{c} \to D)$
    - Modelled by fragmentation fn: Kramers-Kneihl, etc.
    - Fragmentation in event generators, e.g. `PYTHIA`

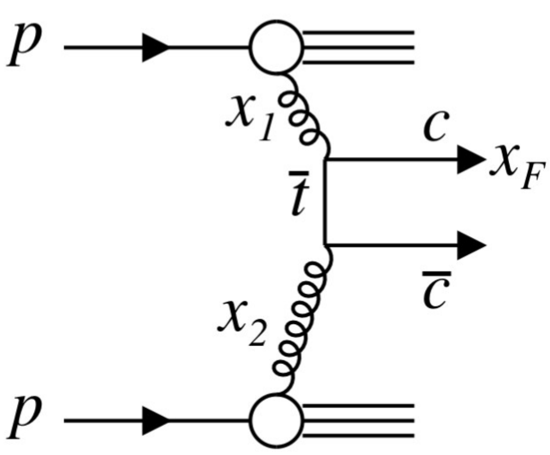
From CR to prompt neutrinos: Challenges

- **Incident cosmic ray flux and its proton content**
  - Uncertainties in CR shape and composition at $E \gtrsim 10^6$ GeV
- **QCD of charm pair production**
- **Charm to charmed mesons** $c\bar{c} \rightsquigarrow D^{\pm,0}$
  - Modelled by fragmentation fn: Kramers-Kneihl, etc.
  - Fragmentation in event generators, e.g. `PYTHIA`

Challenges of computing prompt neutrinos

- **QCD of charm pair production**
  - Probes extremely low-x

$$\sigma(pp \to c\bar{c}X) \simeq \int dx_1\, dx_2\, G(x_1,\mu)G(x_2,\mu)\hat{\sigma}_{GG\to c\bar{c}}(x_1 x_2 s)$$



$$x_1,\ x_2:$$

$$x_{1,2} = \frac{1}{2}\left(\sqrt{x_F^2 + \frac{4M_{c\bar{c}}}{s}} \pm x_F\right)$$

$$x_F = x_1 - x_2$$

$$x_F \simeq x_E = E/E'$$

$$x_1 \simeq x_F \sim 0.1, \quad x_2 \ll 1 \qquad E \sim 10^7\ \mathrm{GeV} \to x_2 \sim 10^{-6}$$

Challenges of computing prompt neutrinos

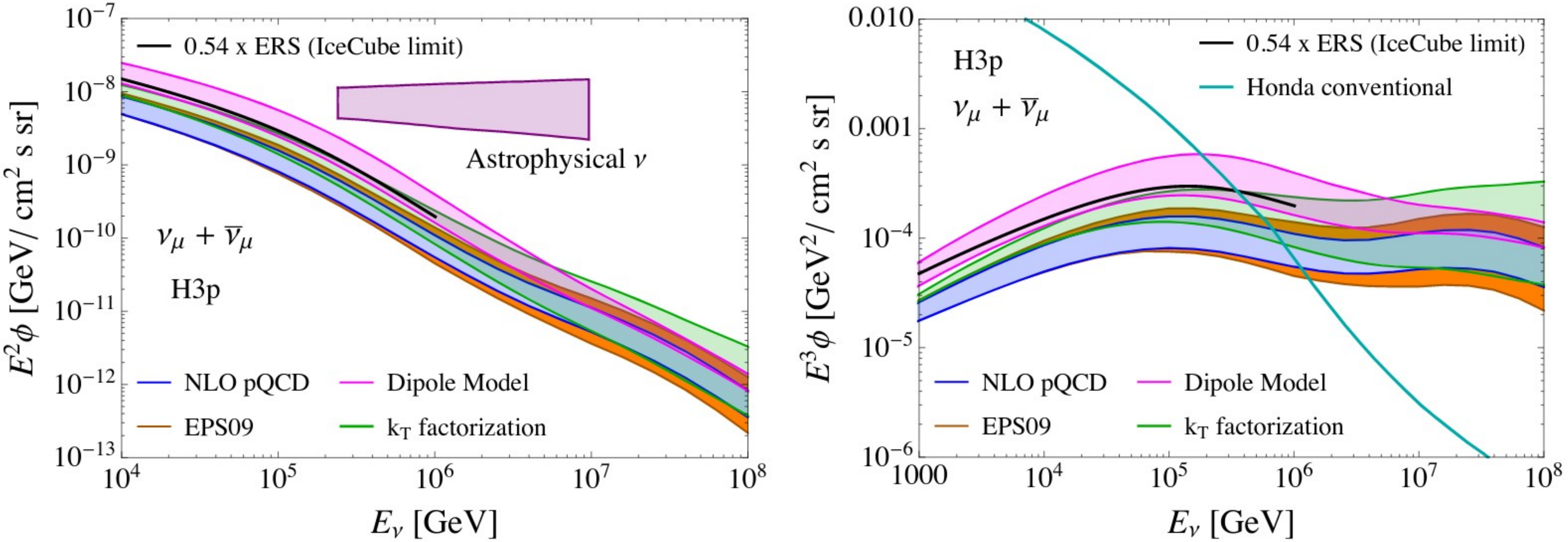
- **QCD of charm production**
  - Probes extremely low-x
  - Uncertainties in scales:
    - Renormalisation (μ_R)
    - Factorisation (M_F)
  - Heavy quark mass (m_c) uncertainty
  - Perturbative? Dipole model?

Prompt Neutrino fluxes: Update II

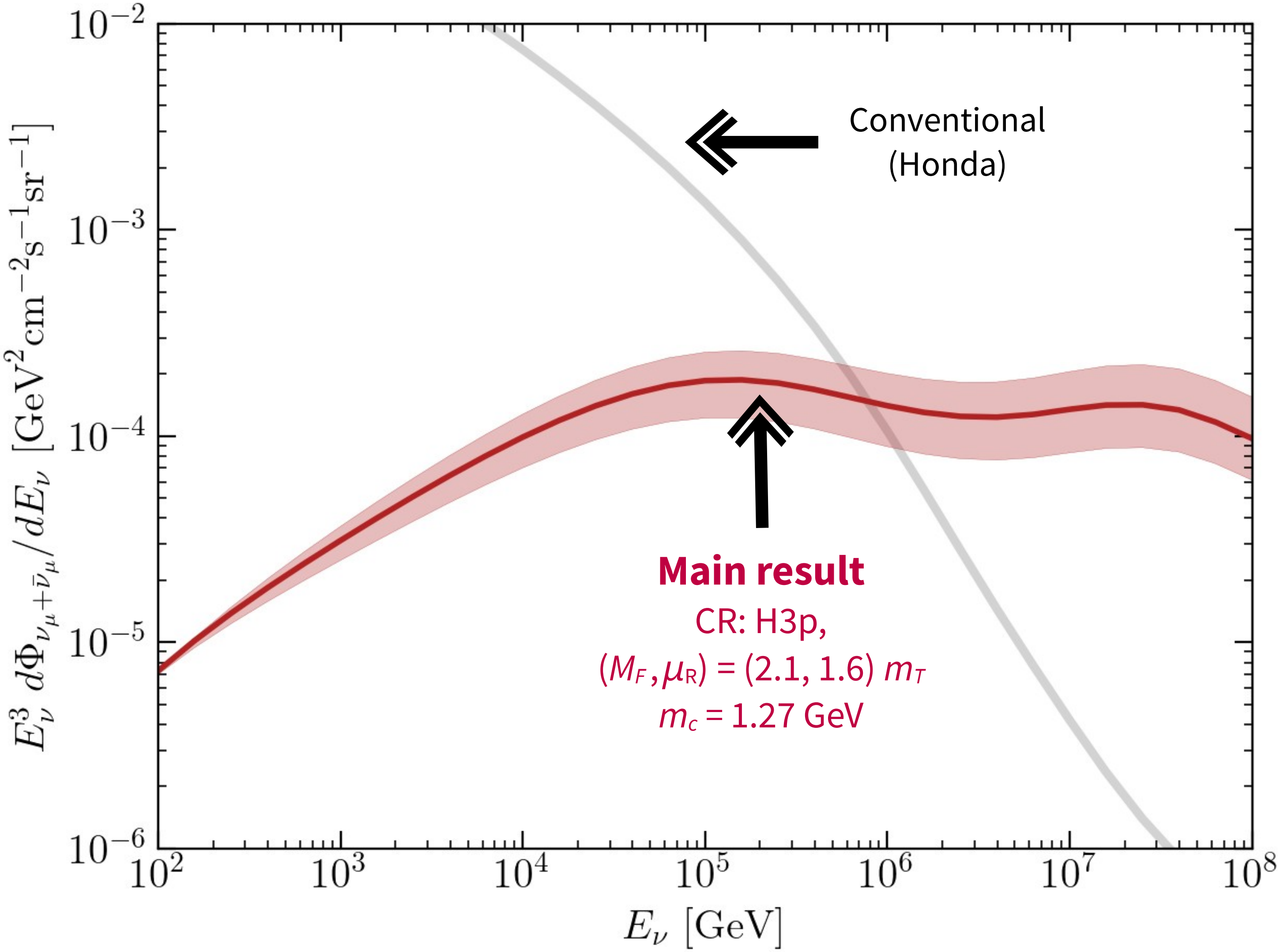
arxiv:1607.00193

- **Perturbative calculation**
  - Use nuclear PDF's instead of proton PDF's (upto –40%)
    EPS [Eskola et al], nCTEQ15
  - Check consistency with updated LHCb results at 13 TeV [✓]
- **Updated Dipole computation**
  - Choose dipole parameters/schemes consistent with recent collider results
  - Updated CT14LO PDF's
- **k_T Factorisation scheme**
  - Integrated gluon density for the projectile, unintegrated gluon density with k_T dependence for target

Prompt Neutrino fluxes: Update II



Prompt Neutrino fluxes: Results



From $pp \to \nu$ via Z-moments

- Z_{ph} : From *pp* to hadrons

$$Z_{ph}(E_h) = \int_{x_{E_{\min}}}^{1} \frac{dx_E}{x_E} \frac{\phi_p^0(E_h/x_E)}{\phi_p^0(E_h)} \frac{1}{\sigma_{pA}(E_h)} \times A \frac{d\sigma}{dx_E}(pN \to hX) \ .$$

- Z_{hl} : Hadrons decaying to leptons

$$\phi_\ell^{\mathrm{low}}(h) = Z_{h\ell}^{\mathrm{low}} \frac{Z_{ph}}{1 - Z_{pp}} \phi_p^0 , \qquad \phi_\ell^{\mathrm{high}}(h) = Z_{h\ell}^{\mathrm{high}} \frac{Z_{ph}}{1 - Z_{pp}} \frac{\ln(\Lambda_h/\Lambda_p)}{1 - \Lambda_p/\Lambda_h} \phi_p^0$$

$$\phi_\ell = \sum_h \frac{\phi_\ell^{\mathrm{low}}(h)\phi_\ell^{\mathrm{high}}(h)}{\phi_\ell^{\mathrm{low}}(h) + \phi_\ell^{\mathrm{high}}(h)}$$

Thunman, Ingelman, Gondolo
Astropart.Phys.5:309-332,1996