Perturbative Charm Production and the Prompt Atmospheric Neutrino Flux in light of RHIC and LHC

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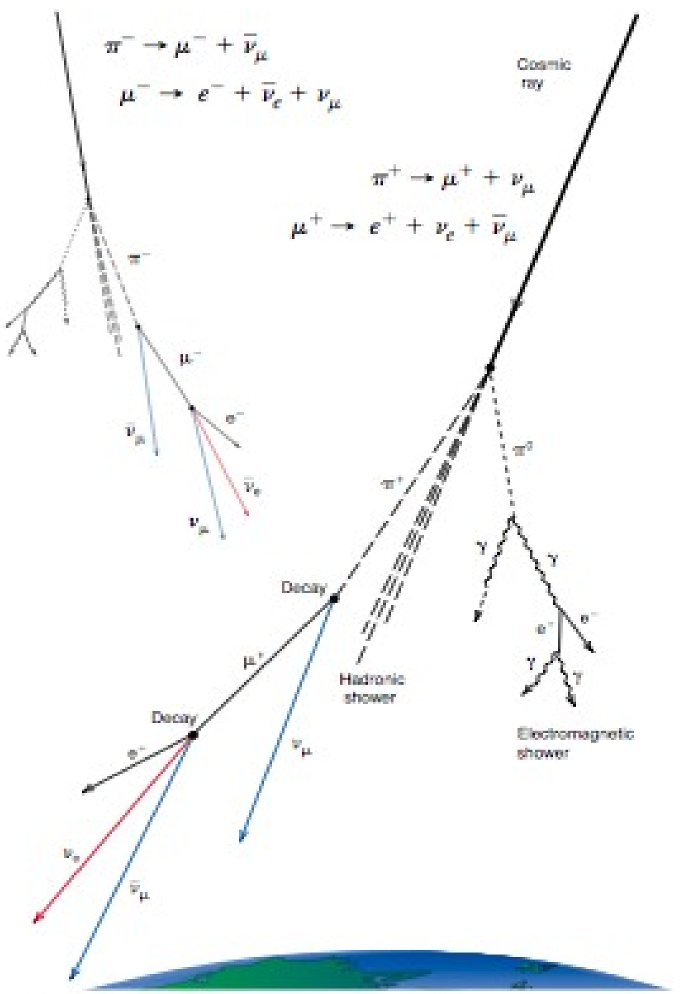
ICHEP 2020

AB, Enberg, Reno, Sarcevic, Stasto
JHEP 1506 (2015) 110

Neutrino production in the atmosphere



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

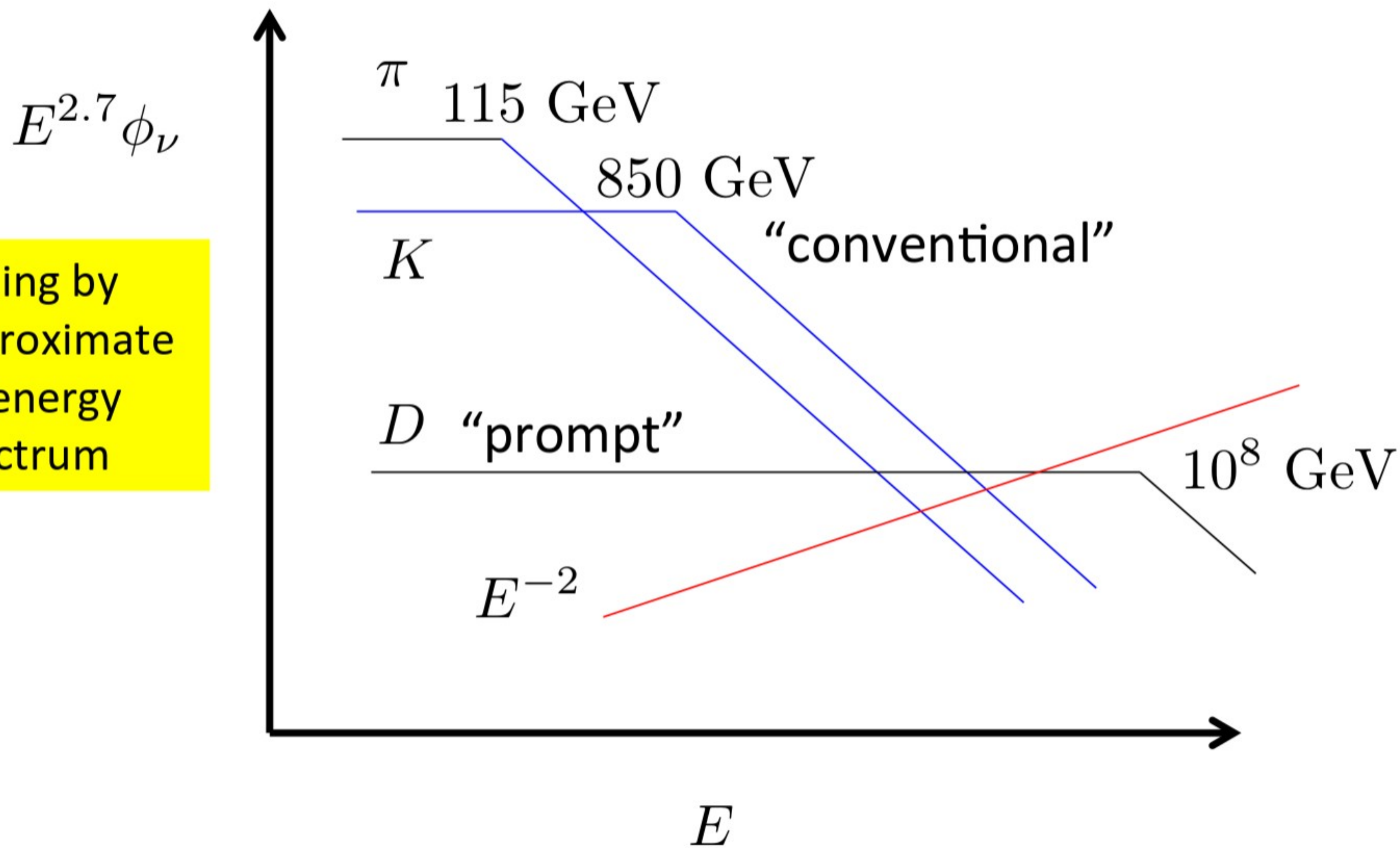
  Conventional

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

  Prompt

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

Neutrino fluxes at high energies



Scaling by approximate CR energy spectrum

From CR to prompt neutrinos: Challenges

Incident cosmic ray flux and its proton content

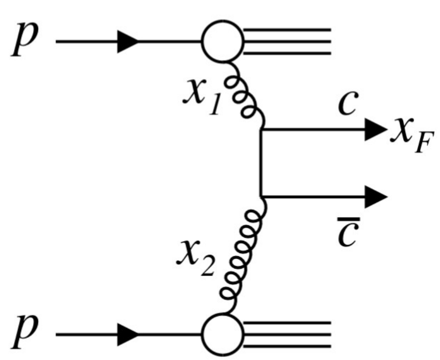
Uncertainties in CR spectral shape and composition at $E \gtrsim 10^6$ GeV

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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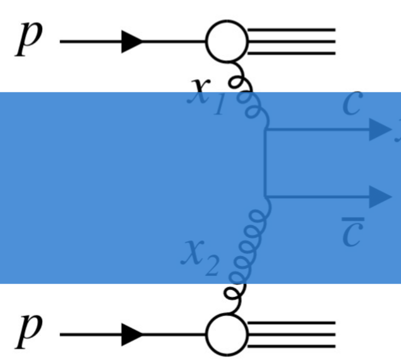

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$x_F = x_1 - x_2$

Dominated by gluon fusion

$x_F \simeq x_E = E/E'$

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

From CR to prompt neutrinos: Challenges

Incident cosmic ray flux and its proton content

QCD of charm pair production

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

- 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*

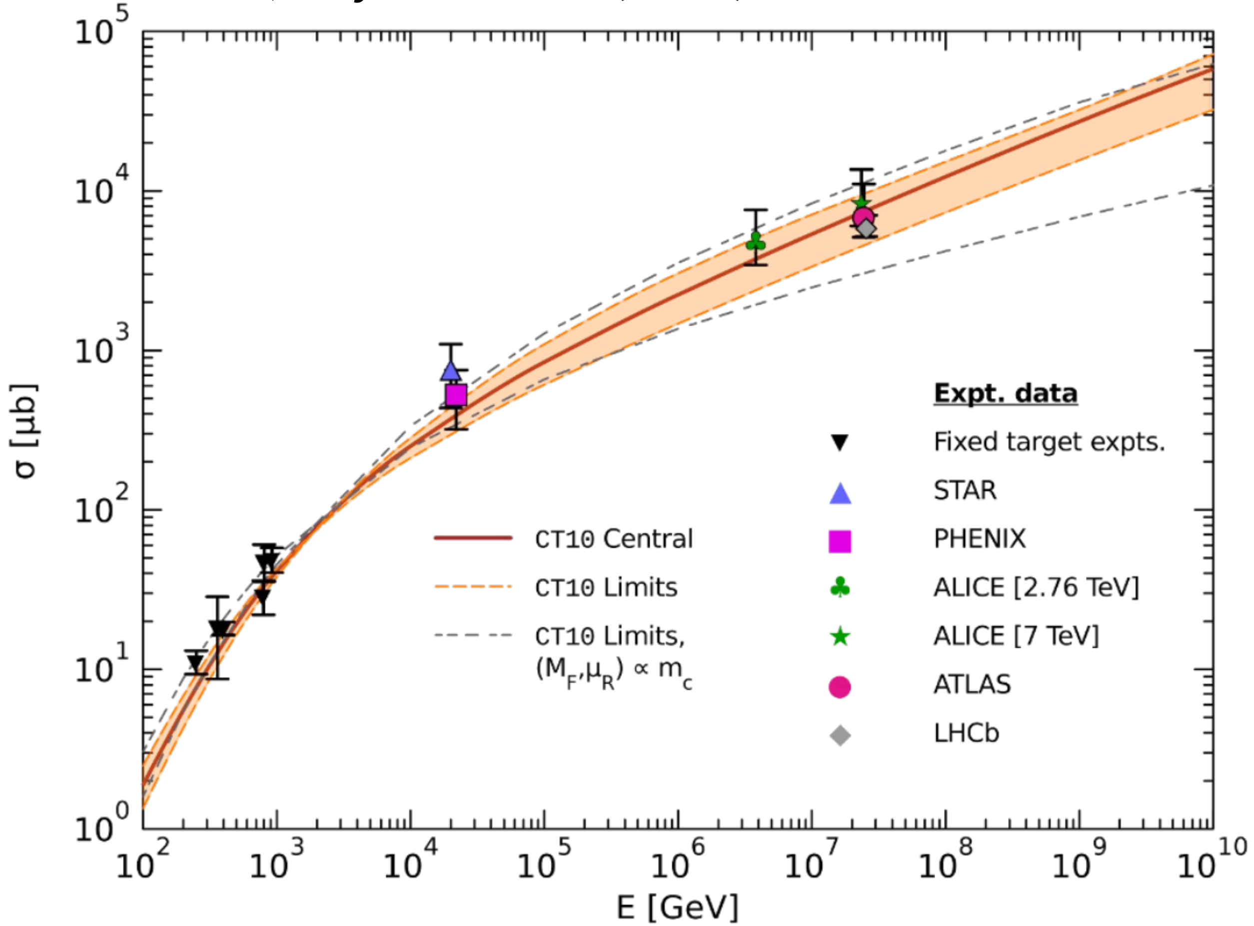
- **Existing reference prompt flux estimate used by IceCube:**
  - Dipole model estimate by Enberg, Reno, Sarcevic (ERS) [Phys.Rev. D78 (2008) 043005]
    - Accounts for saturation of gluon at very low *x*
    - LO CTEQ6 PDF's used for the high-x distributions
  - Perturbative QCD by Pasquali, Reno, 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*

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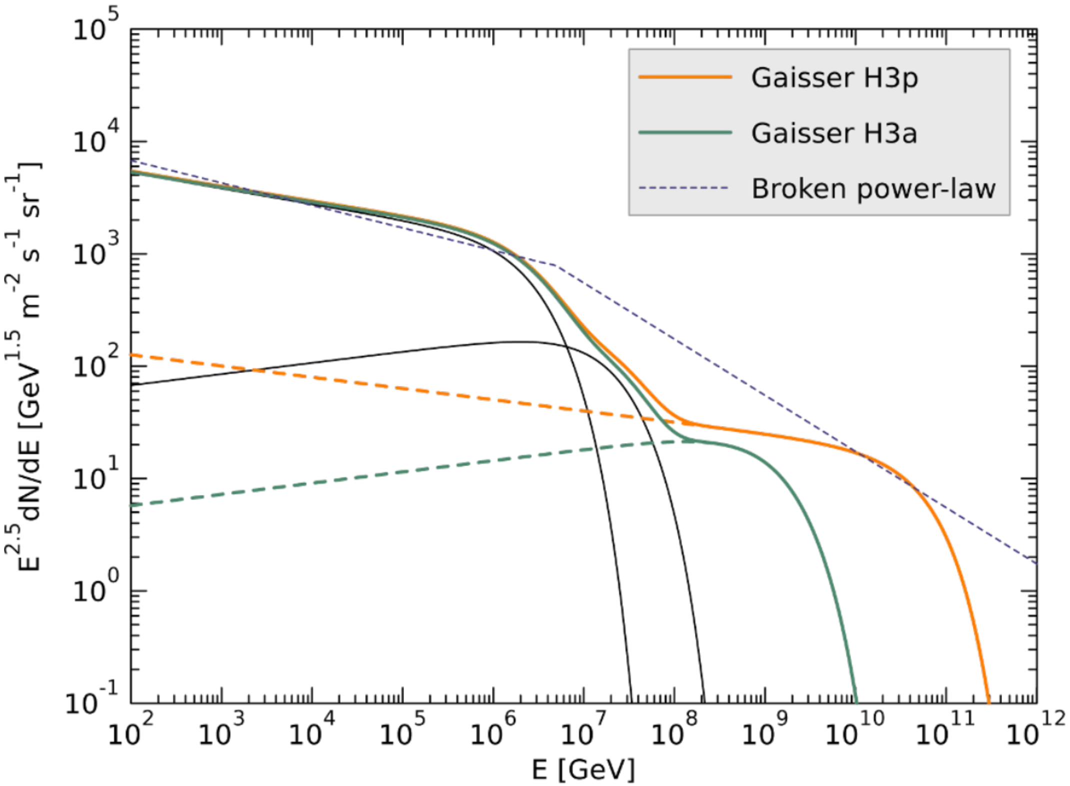


Why now?

- 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**

$$\mathrm{m}_c = 1.27 \text{ GeV}$$

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

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

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

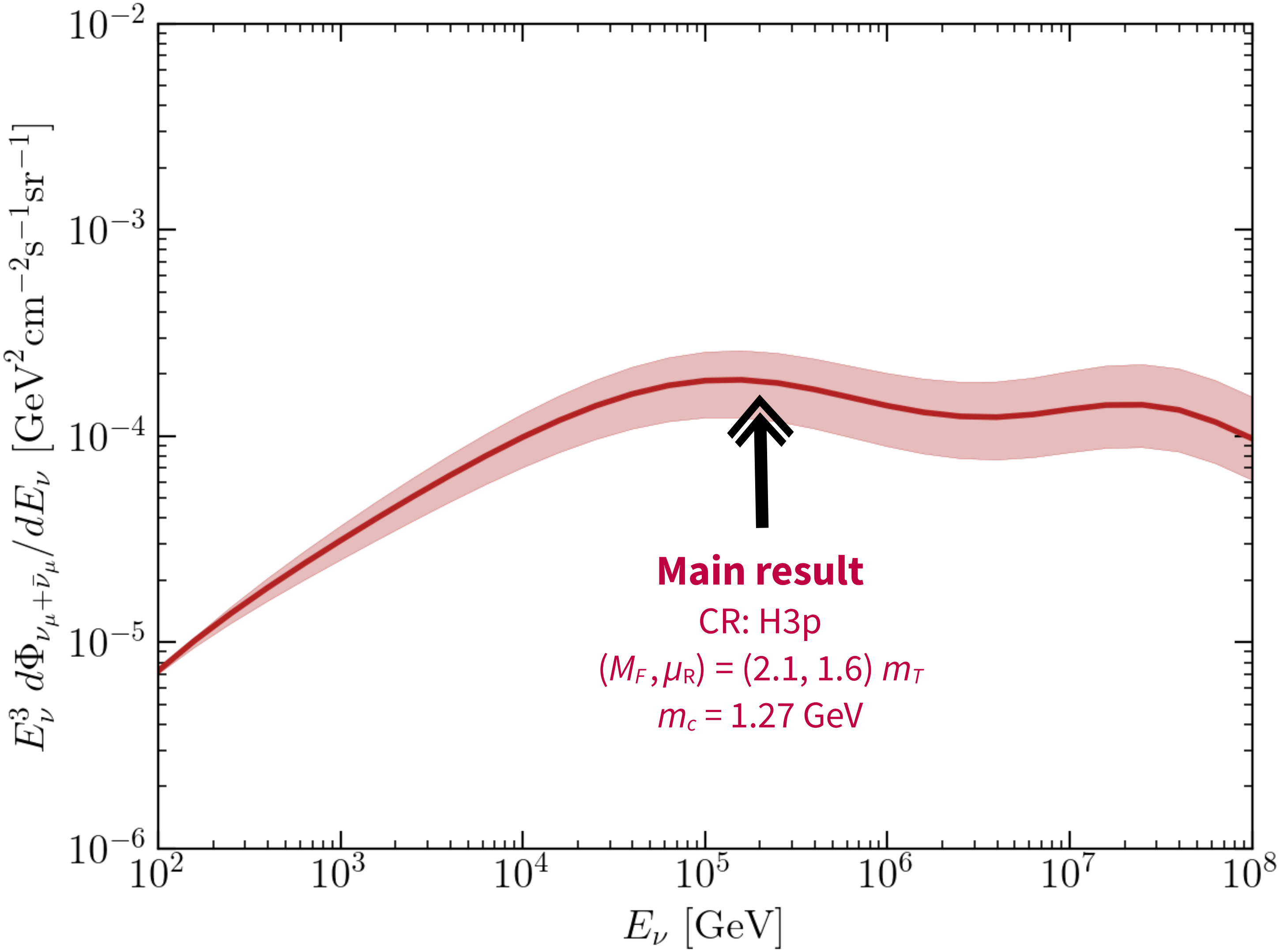
Kneihl-Kramers
Phys.Rev. D74 (2006) 037502

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

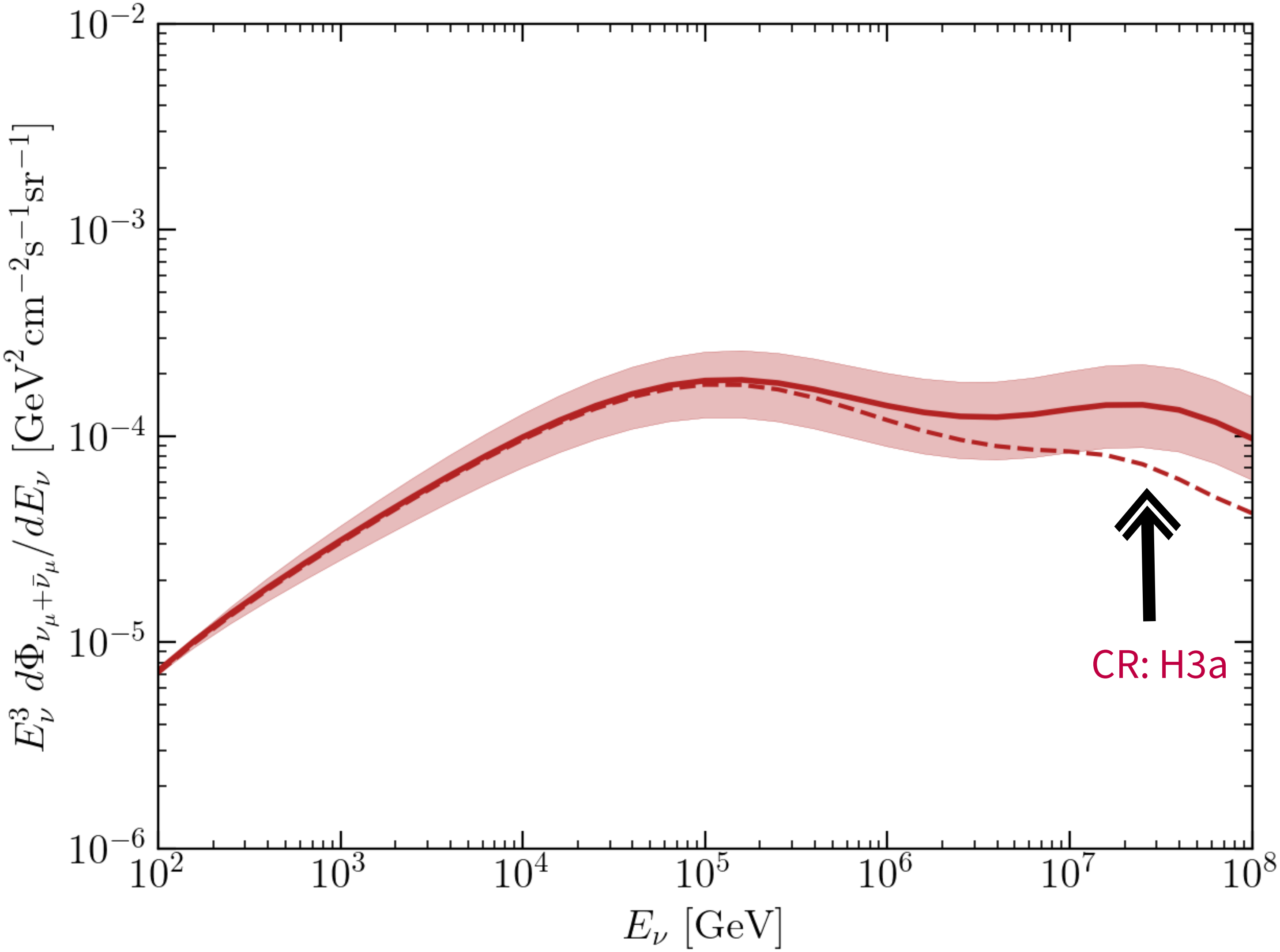
CR flux

- 1*d* atmosphere column modelling

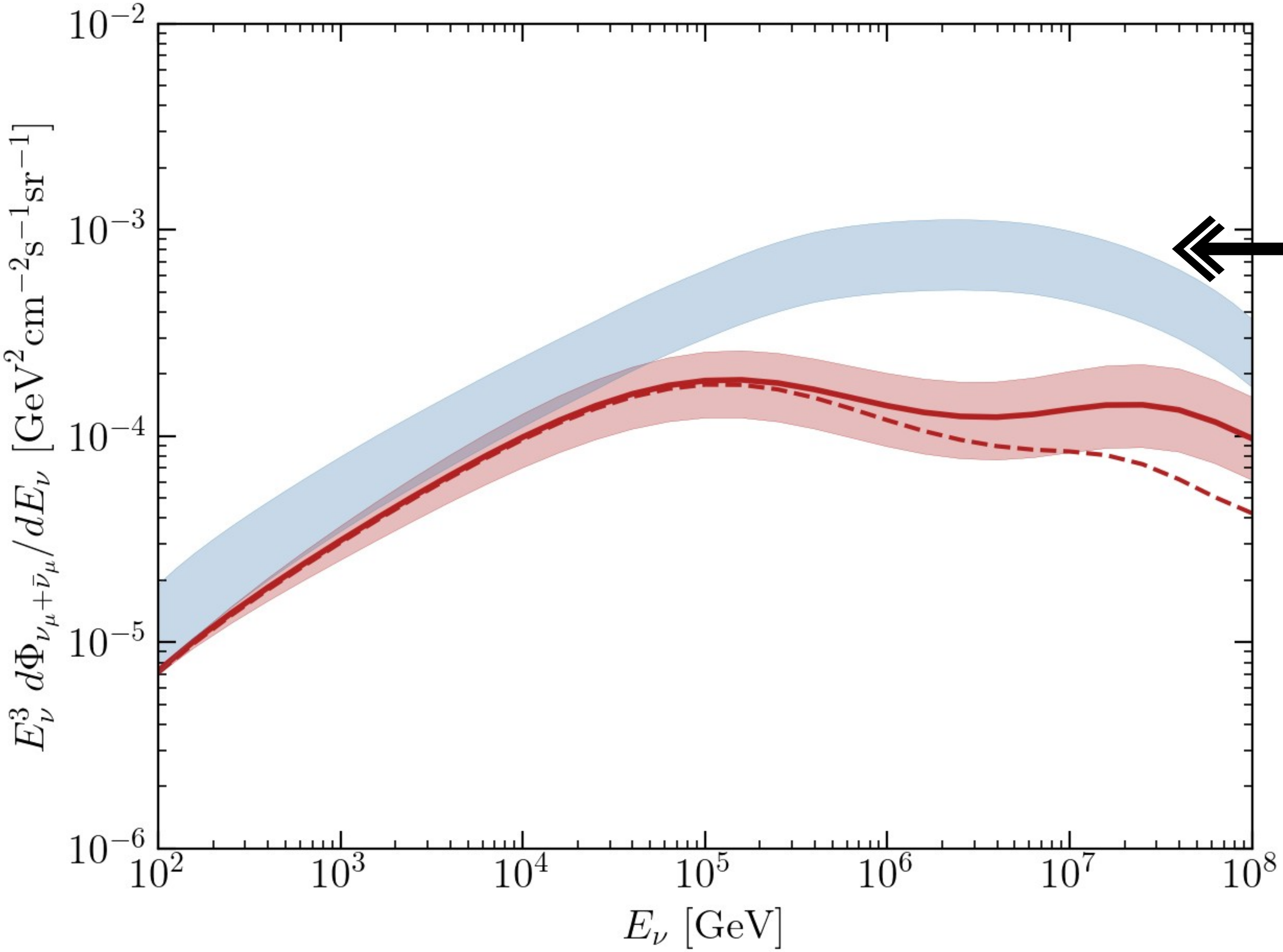
Prompt Neutrino fluxes: Results



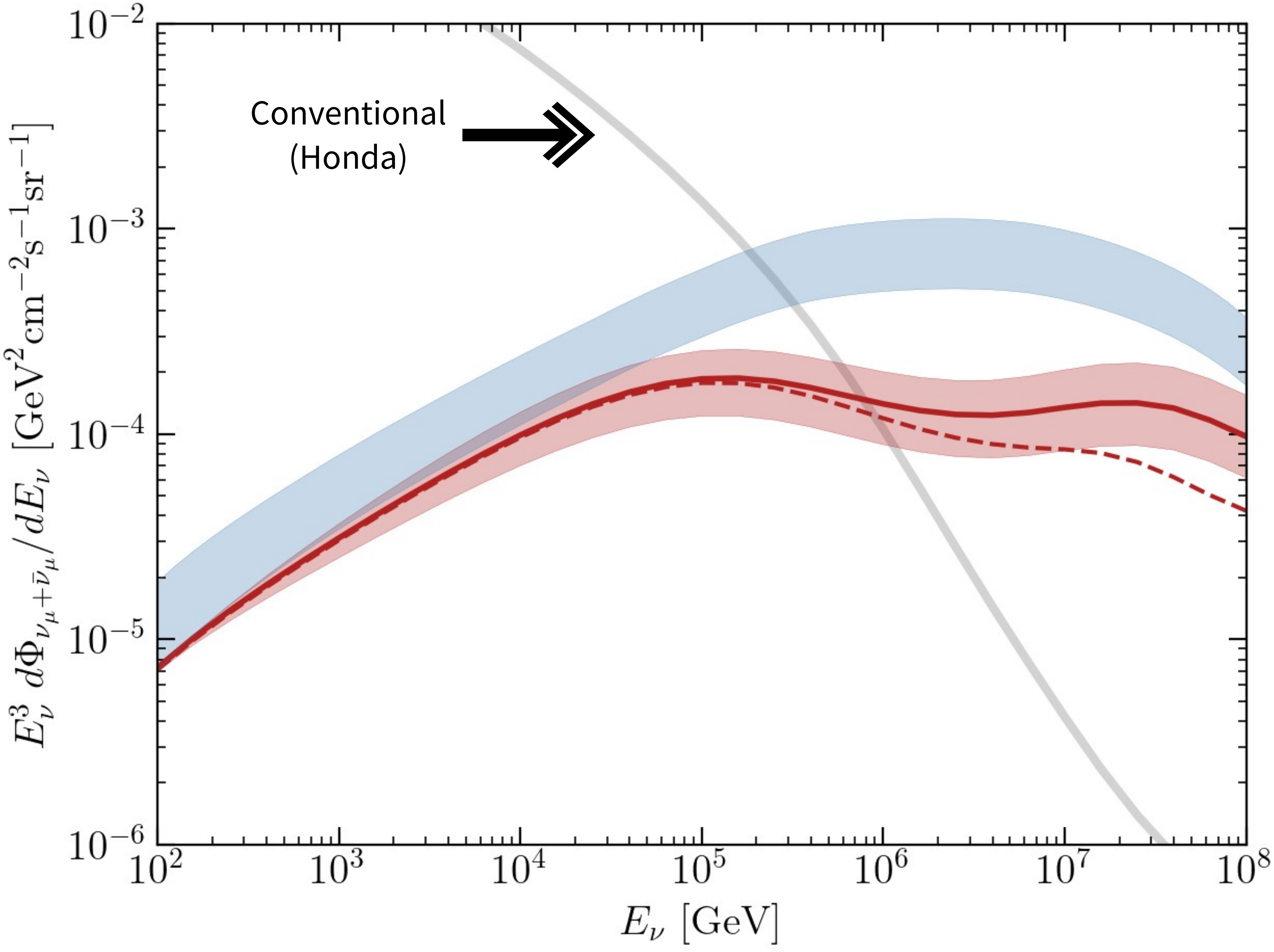
Prompt Neutrino fluxes: Results



Prompt Neutrino fluxes: Results



Prompt Neutrino fluxes: Results



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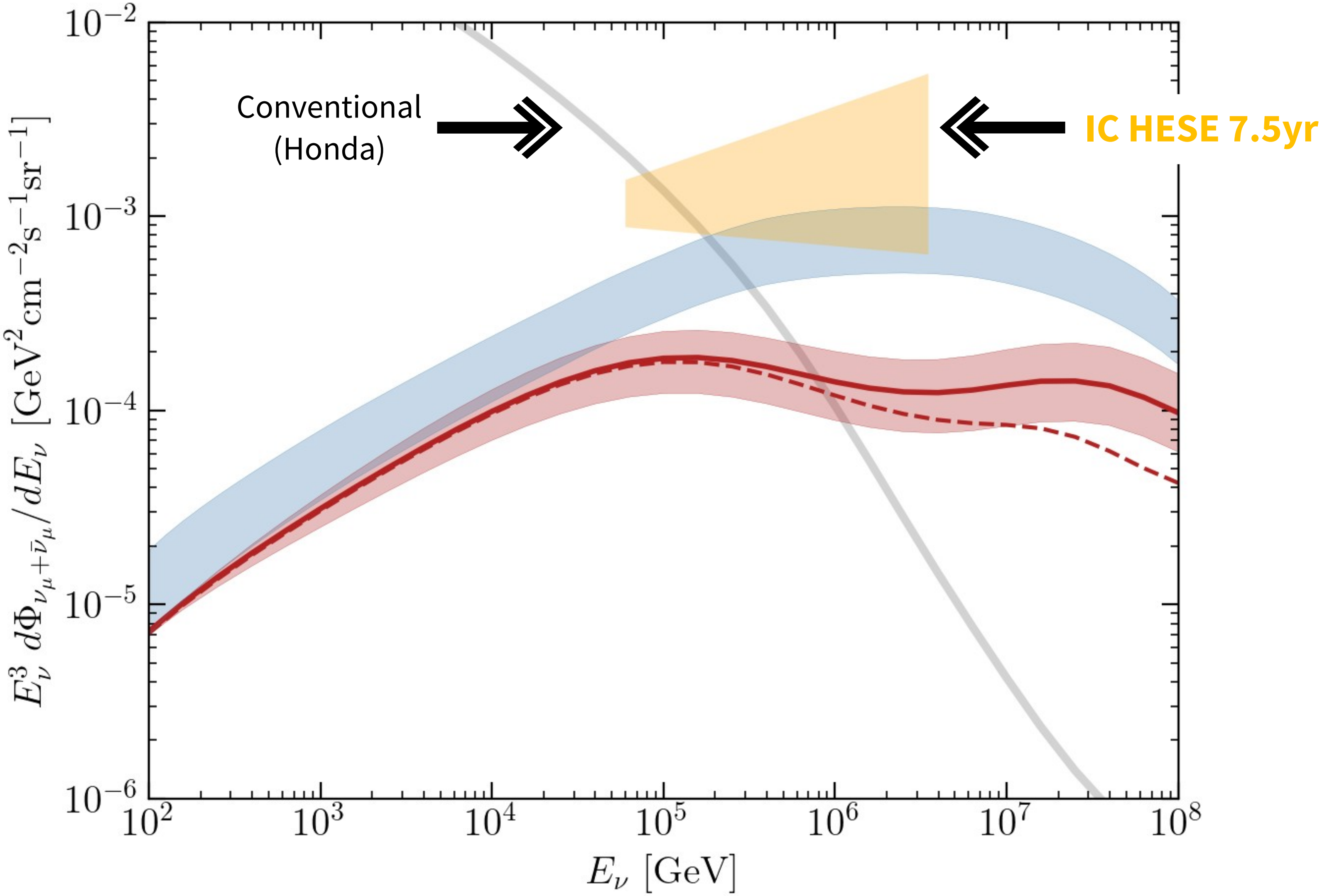
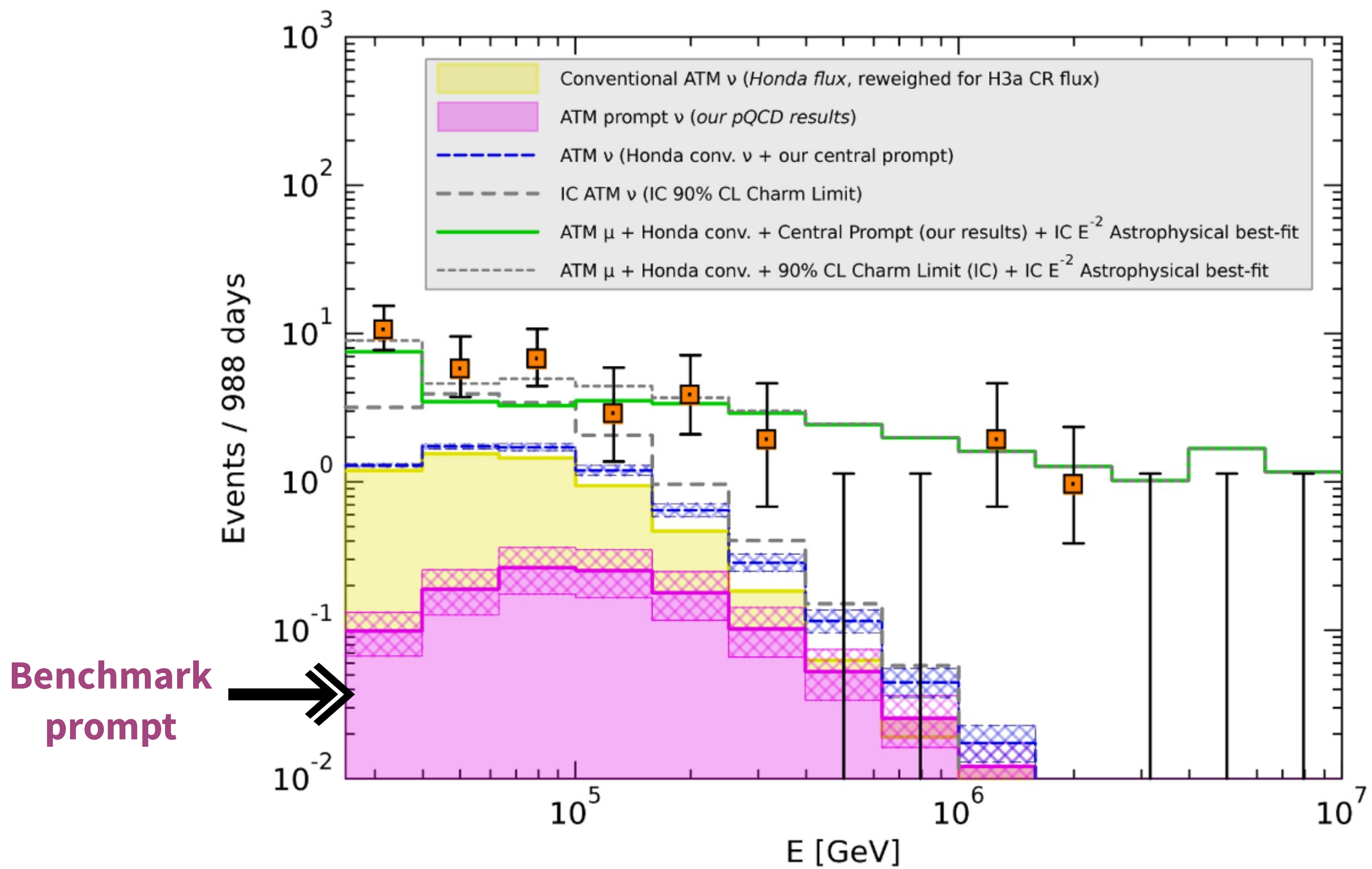
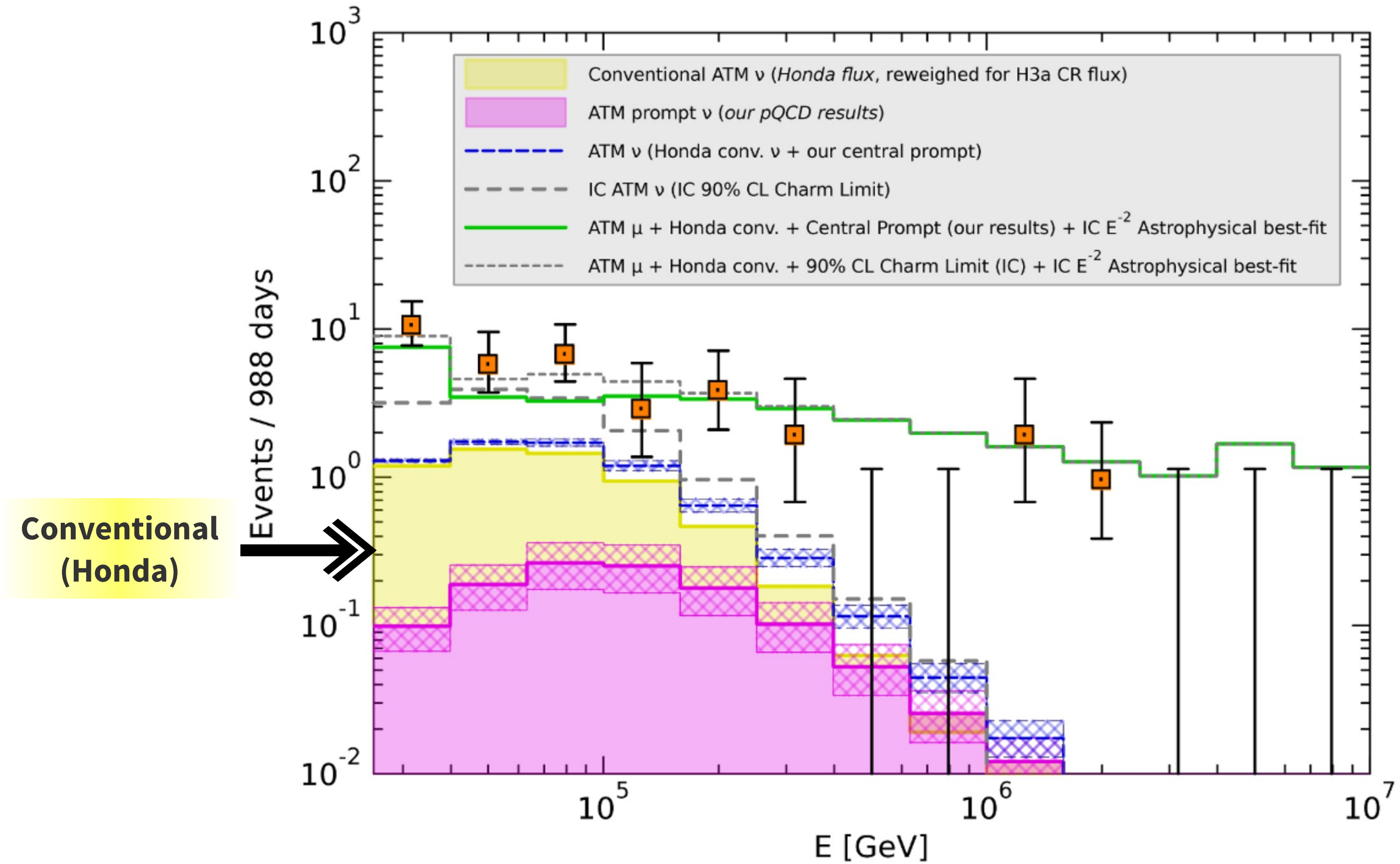


Prompt neutrino event rates at IceCube



Prompt neutrino event rates at IceCube



Related recent works

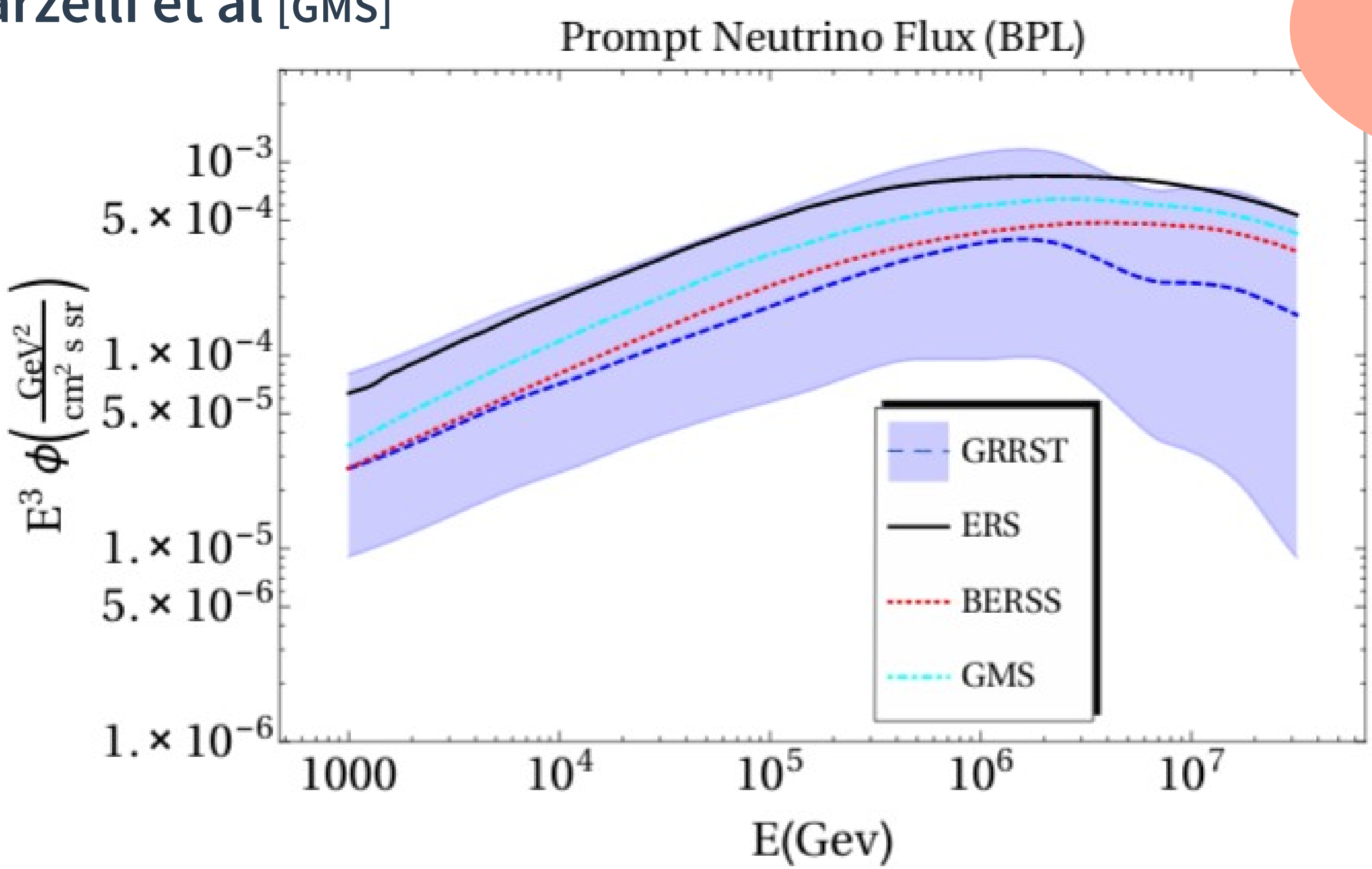
- **Garzelli et al**
  [JHEP 1510 (2015) 115]
  - Different PDF's [ABM11]
  - Larger error bars compared to BERSS
  - Central flux slightly higher consistently across energies

- **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



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)
- **Updated IC prompt bkg**
  - Present IC limits consistent with revised estimates + Self-veto
  - Work to infer robust upper limits on prompt underway

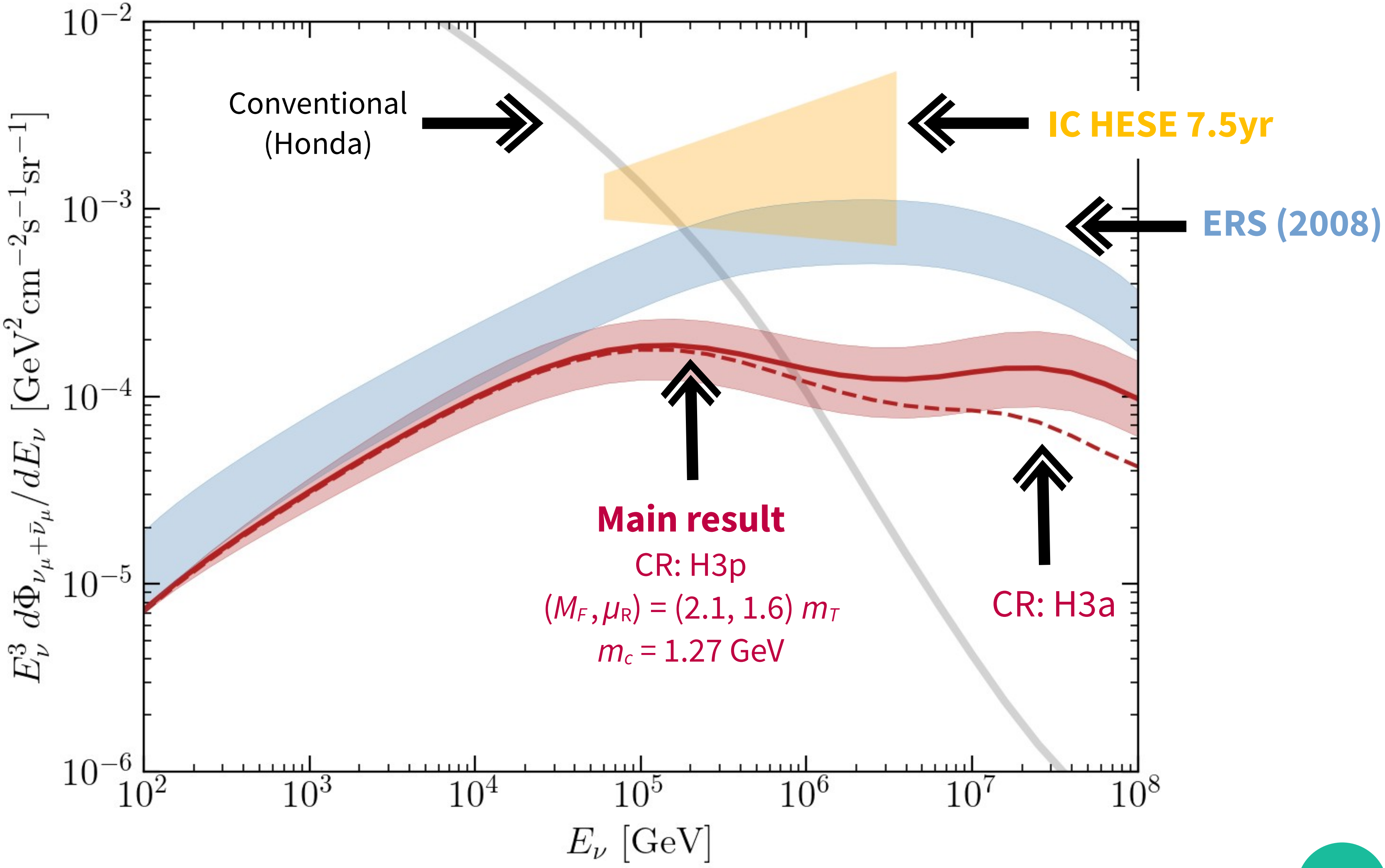
AB *et al*
JHEP 11 (2016) 167

Argüelles et al
JCAP 07 (2018) 047

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
$E_\nu^3 \, d\Phi_{\nu_\mu+\bar{\nu}_\mu}/dE_\nu$ [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)
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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

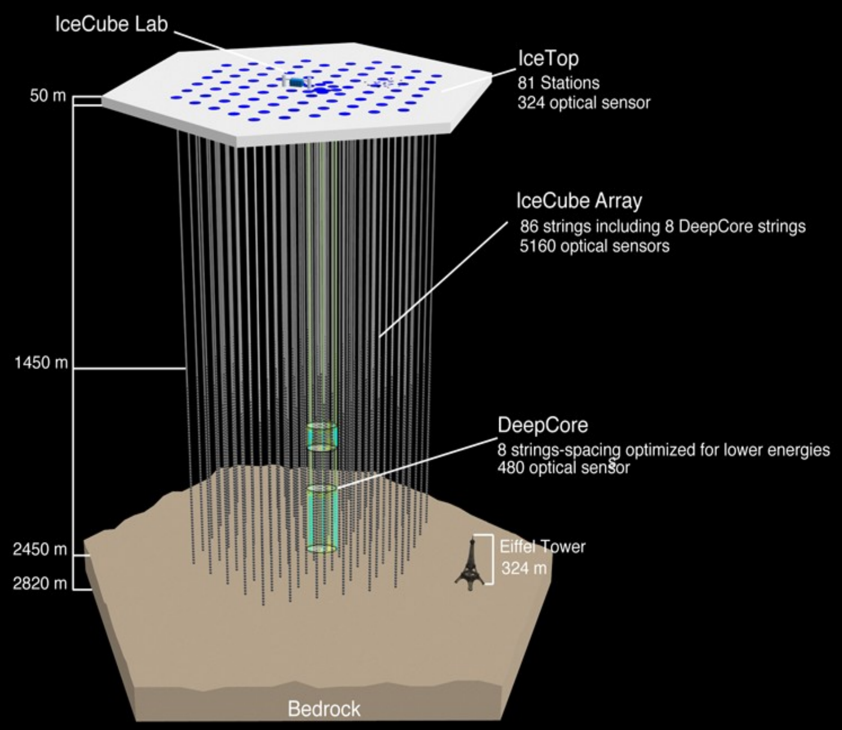
$$\frac{d\sigma}{dx_F}(s, m_Q^2) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\, dz\, \delta(zx_1 - x_F)\, x_1 g(x_1, M_F) \int \frac{dk_T^2}{k_T^2} \hat{\sigma}^{\text{off}}(z, \hat{s}, k_T)\, f(x_2, k_T^2)\ .$$

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`

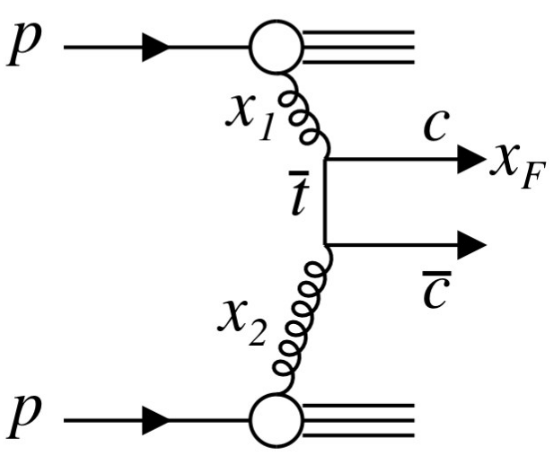
From CR to prompt neutrinos: Challenges

- **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

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



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Challenges of computing prompt neutrinos

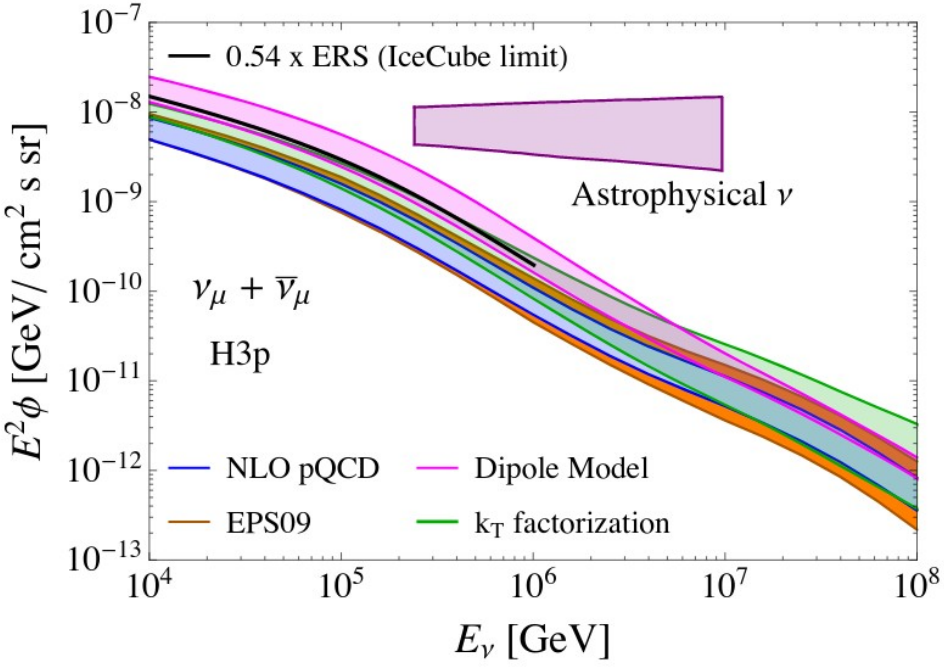
- **QCD of charm production**
  - Probes extremely low-x
  - Uncertainties in scales:
    - Renormalisation (μ_R)
    - Factorisation (M_F)
  - Heavy quark mass (m_c) uncertainty
  - Perturbative? Dipole model?

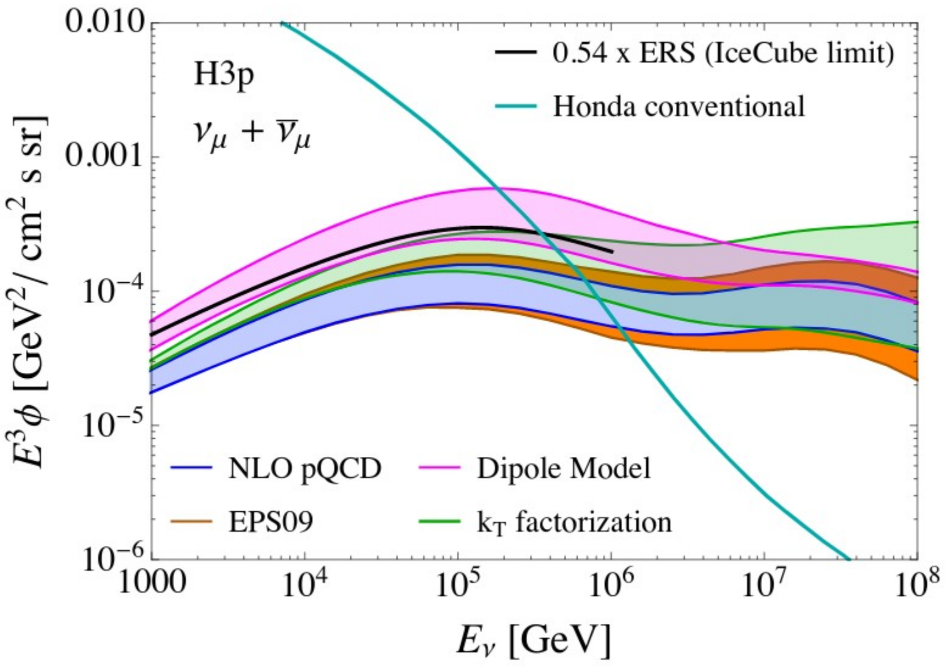
Prompt Neutrino fluxes: Update II

arxiv:1607.00193

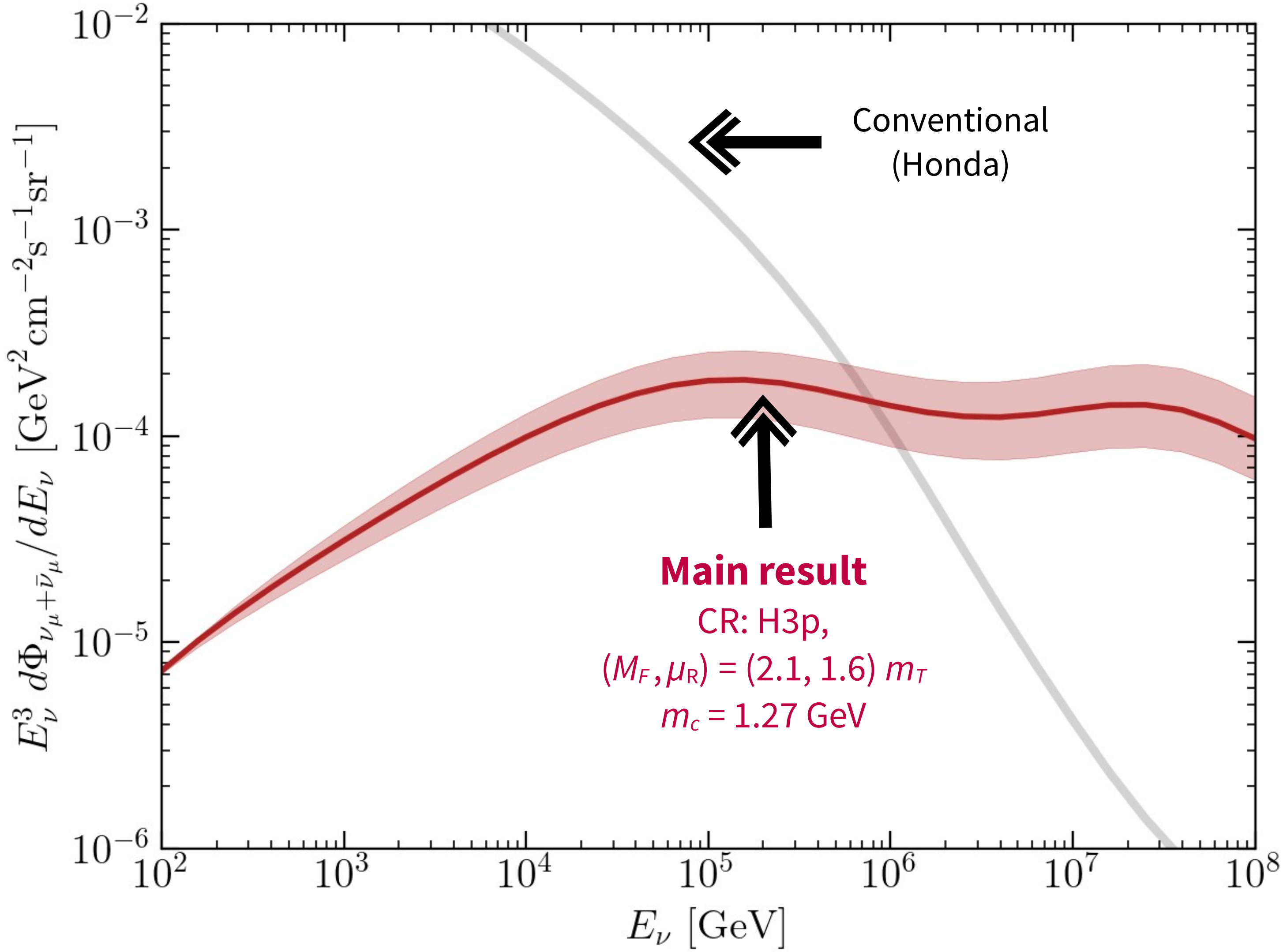
- **Perturbative calculation**
  - Use nuclear PDF's instead of proton PDF's (upto –40%)
    EPS [Eskola et al], nCTEQ15
  - Check consistency with updated LHCb results at 13 TeV [✓]
- **Updated Dipole computation**
  - Choose dipole parameters/schemes consistent with recent collider results
  - Updated 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 $pp \rightarrow \nu$ via Z-moments

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

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

- Z_{hl} : Hadrons decaying to leptons

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

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

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