DPF 2017

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

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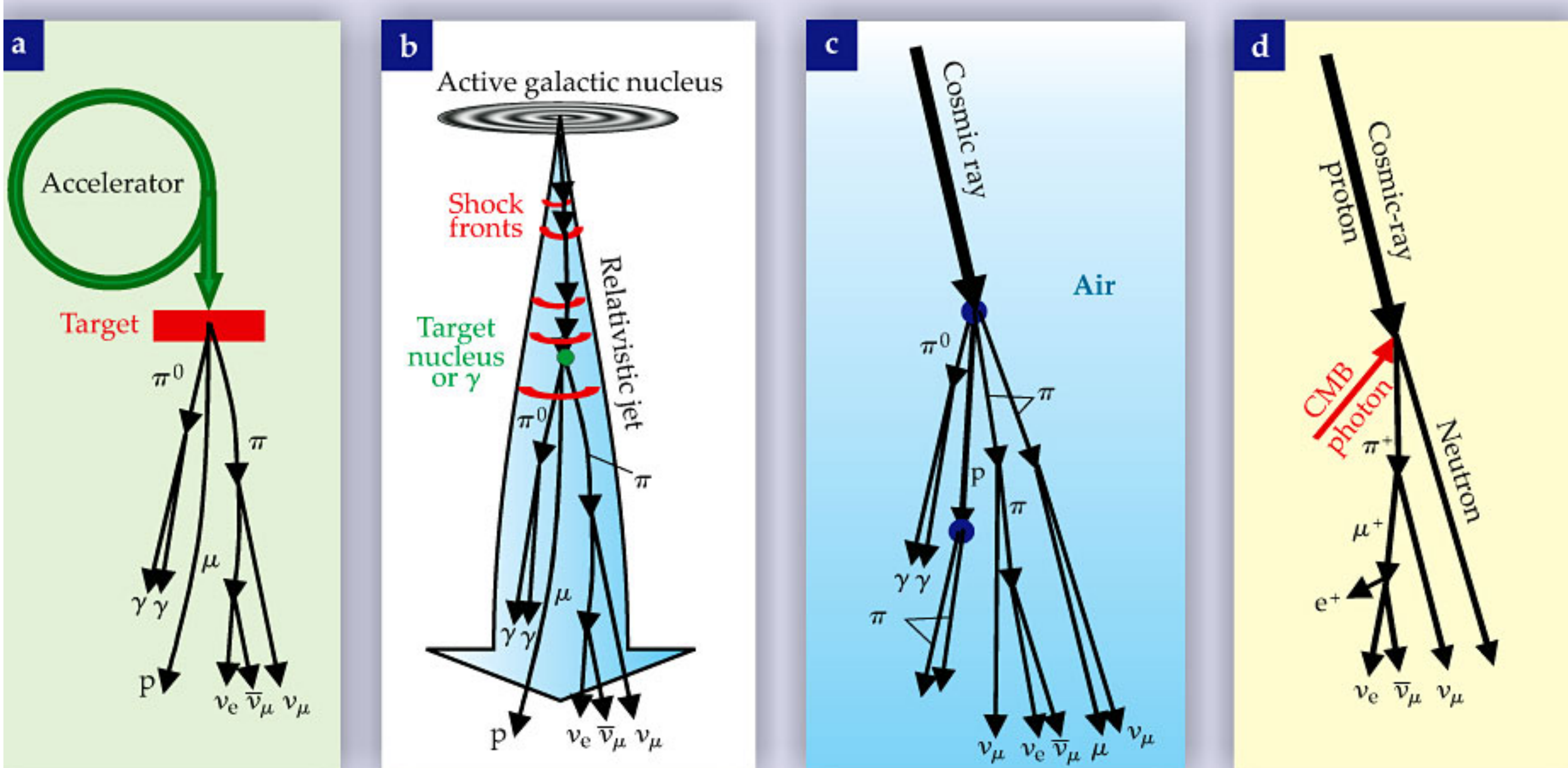
A. Bhattacharya, R. Enberg, Y.S. Jeon, C.S. Kim, M.H. Reno, I. Sarcevic and A. Stasto, JHEP 1611 (2016) 167

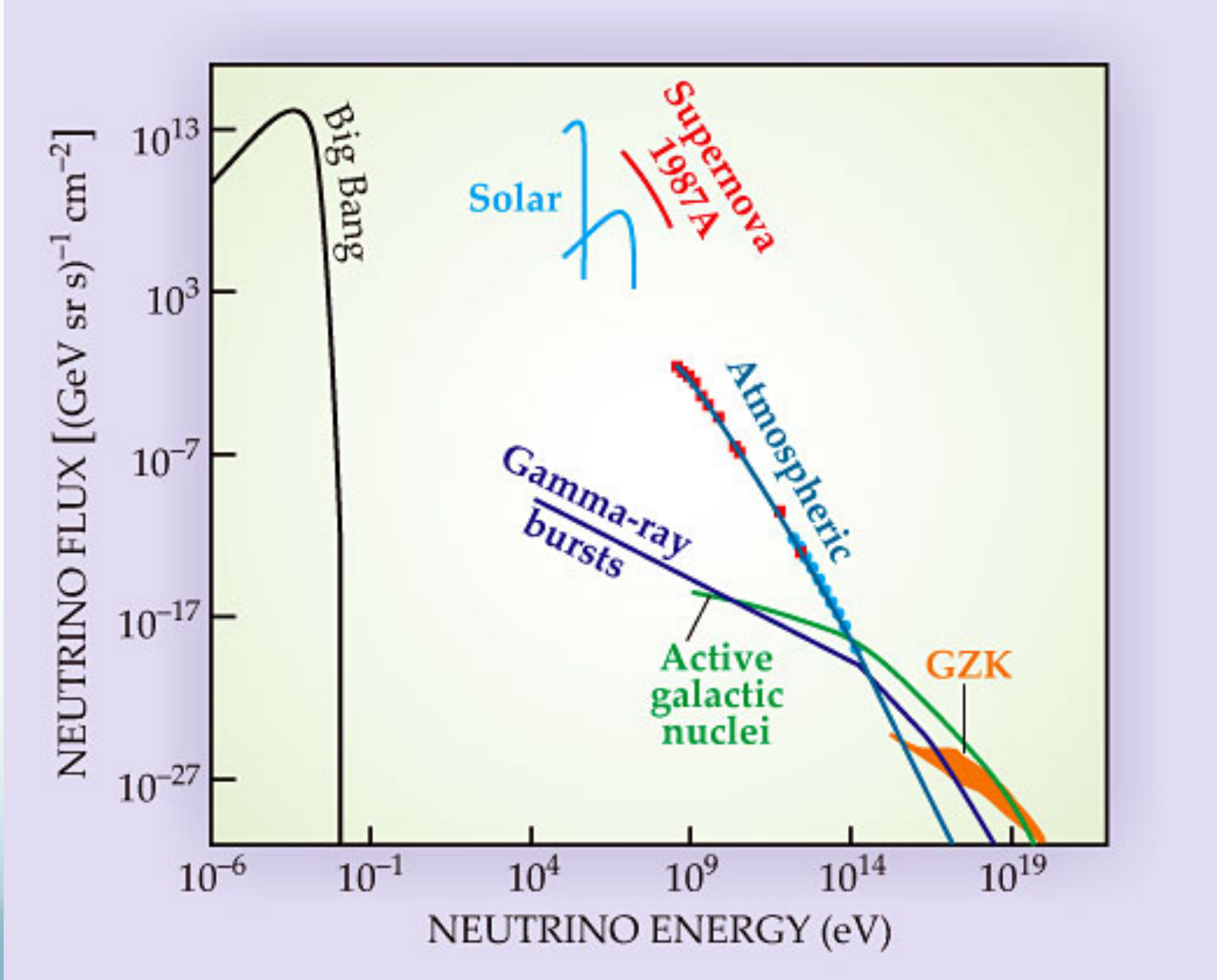
Neutrinos from Cosmic Accelerators

Atmospheric neutrinos

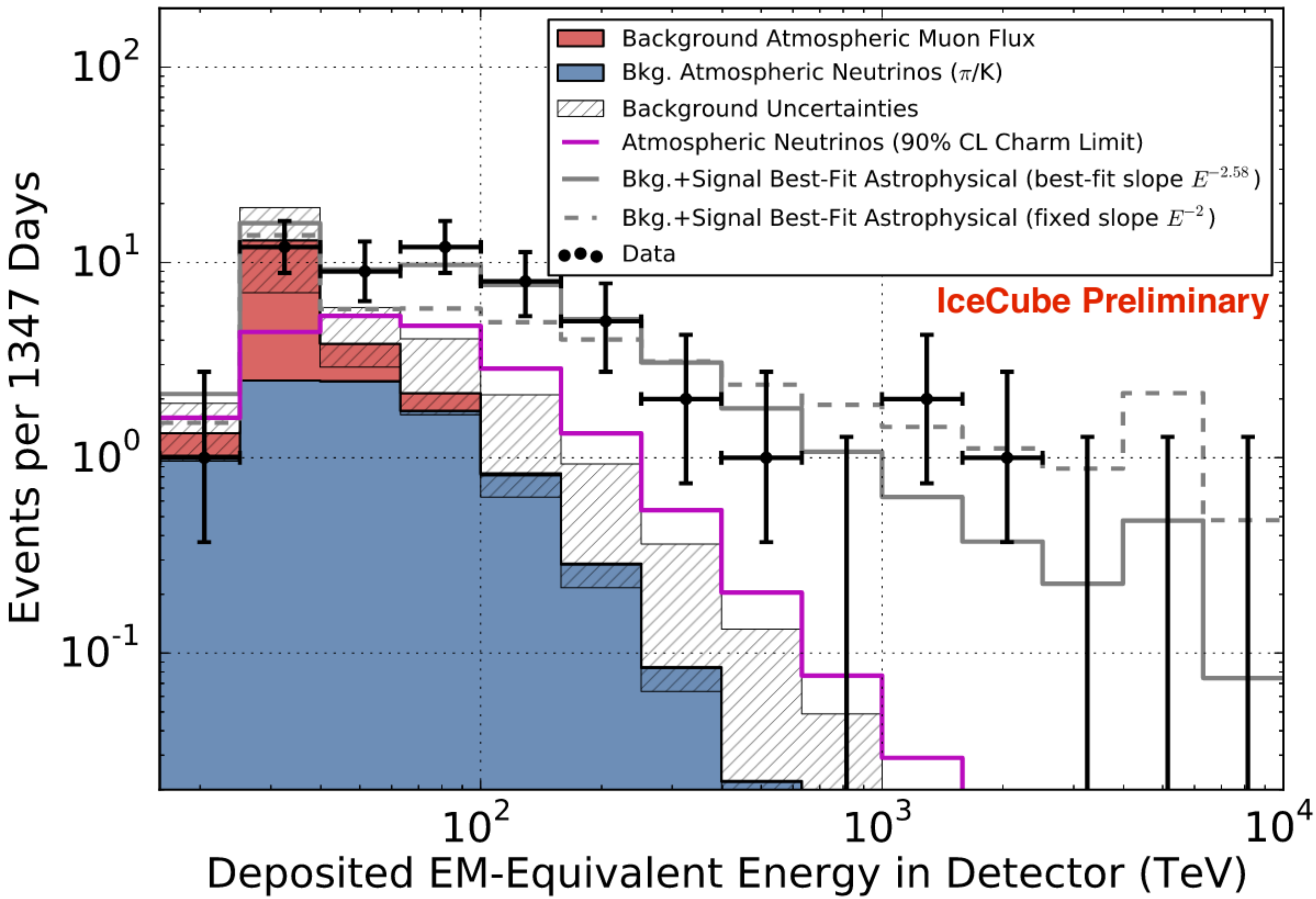


Physics Today 2009

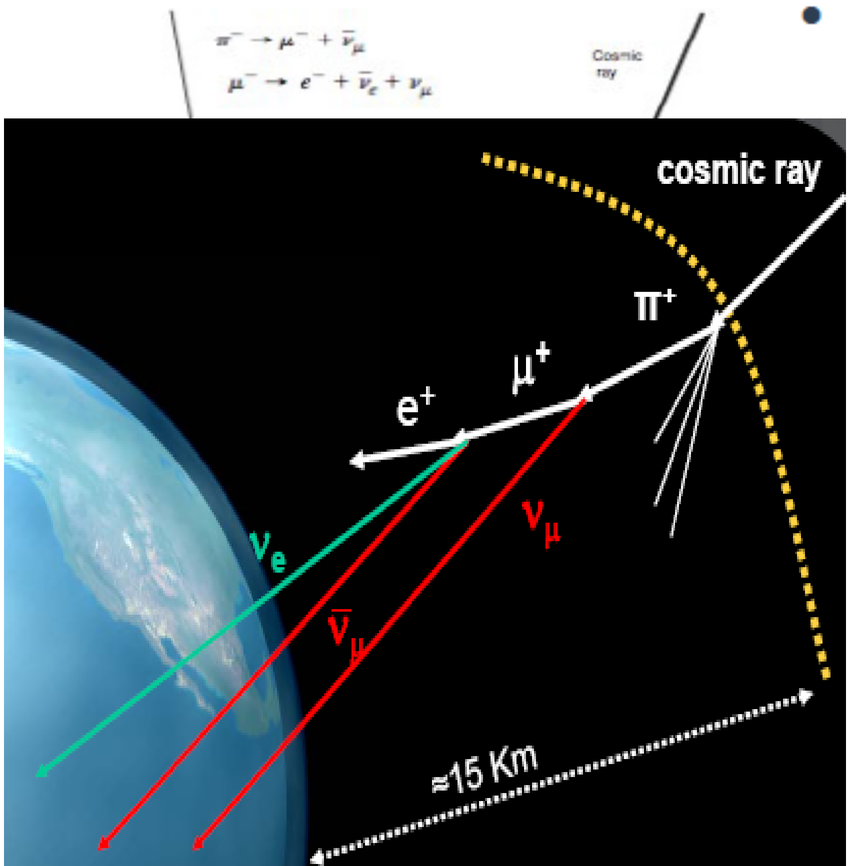
Neutrino fluxes



First Observation of HE Cosmic Neutrinos



Atmospheric Neutrino Flux



- **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

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

- Evaluation of atmospheric neutrino flux depends on cosmic ray (CR) flux and composition
- Interactions of cosmic rays with air nuclei producing mesons (pions, kaons, D-mesons, etc) that decay into neutrinos.

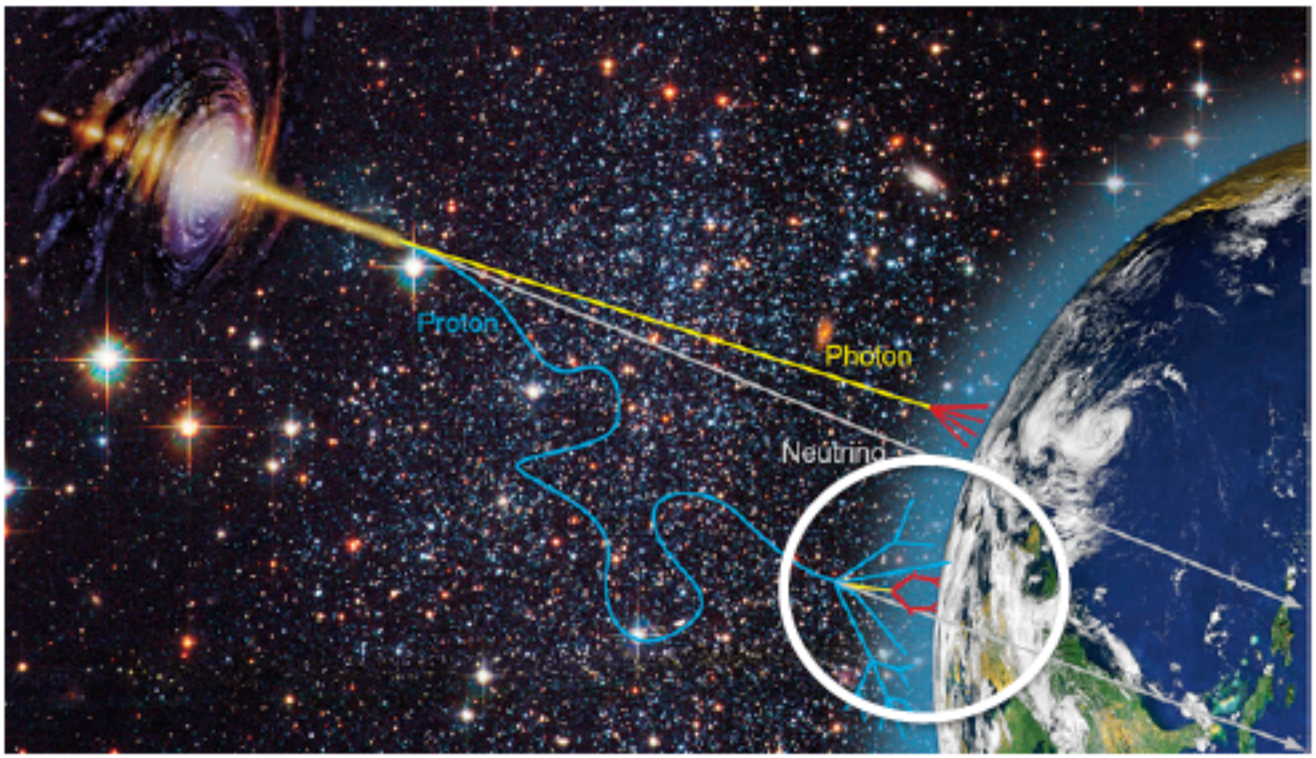
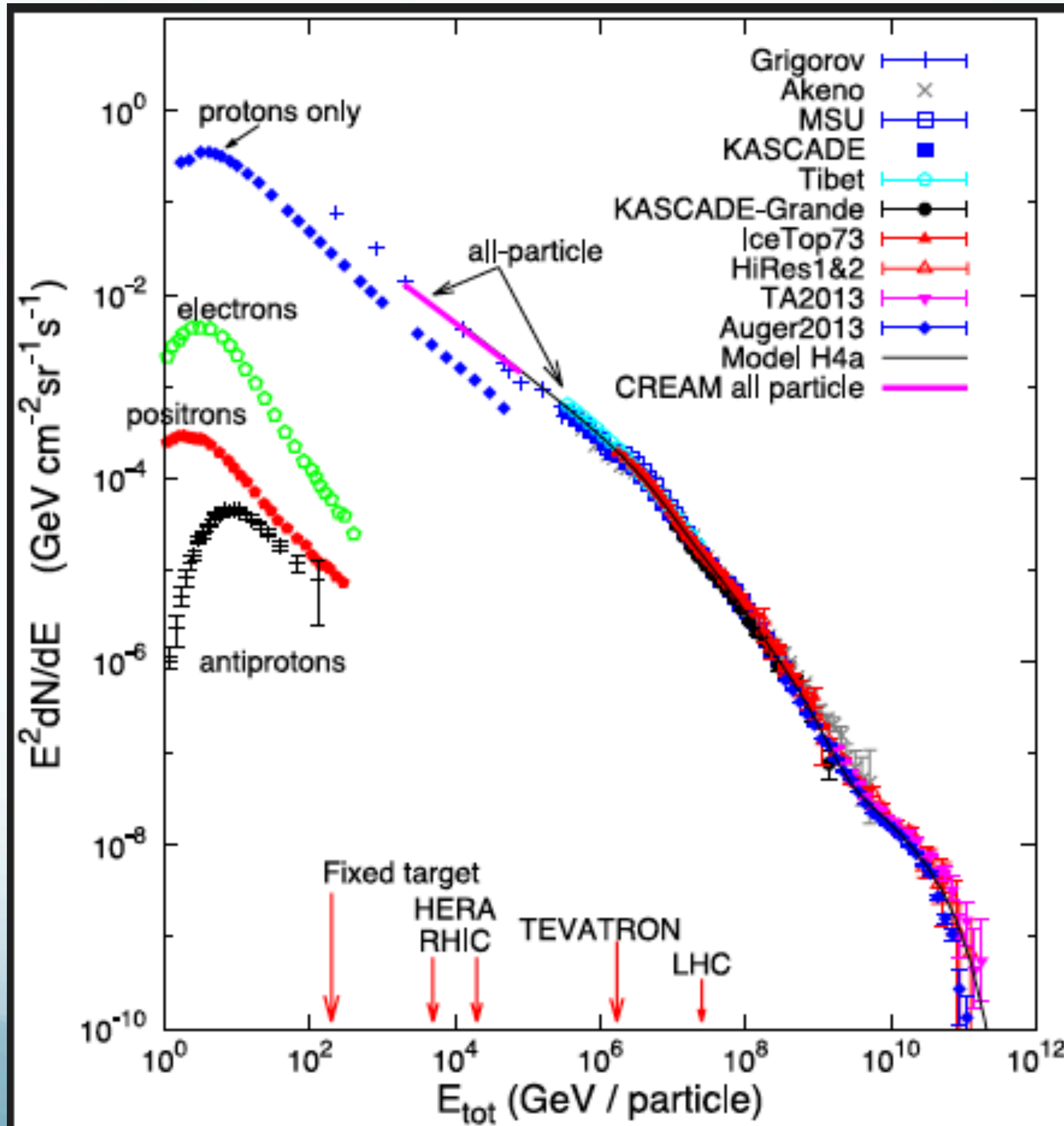


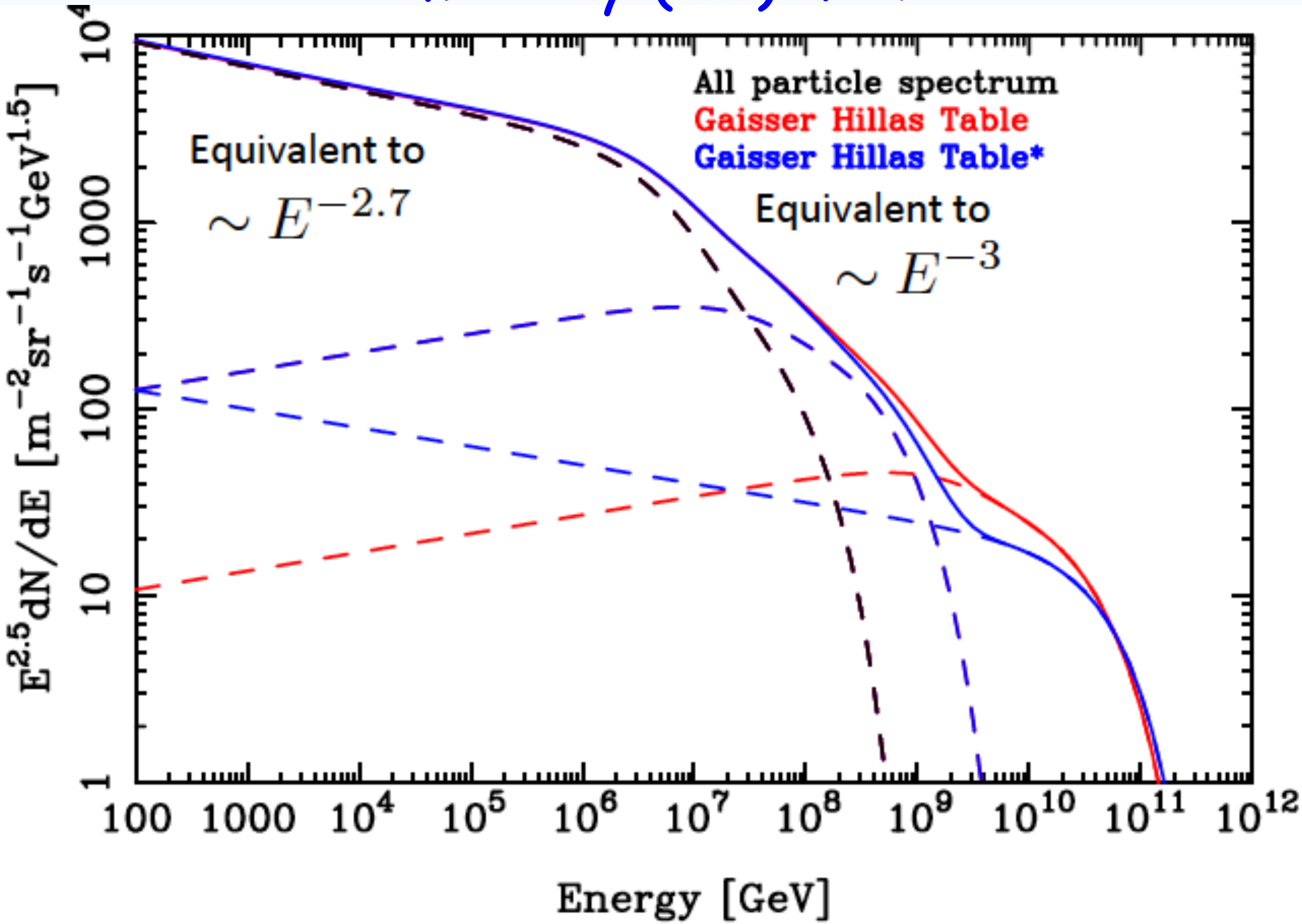
Figure from https://astro.desy.de/

Cosmic Rays



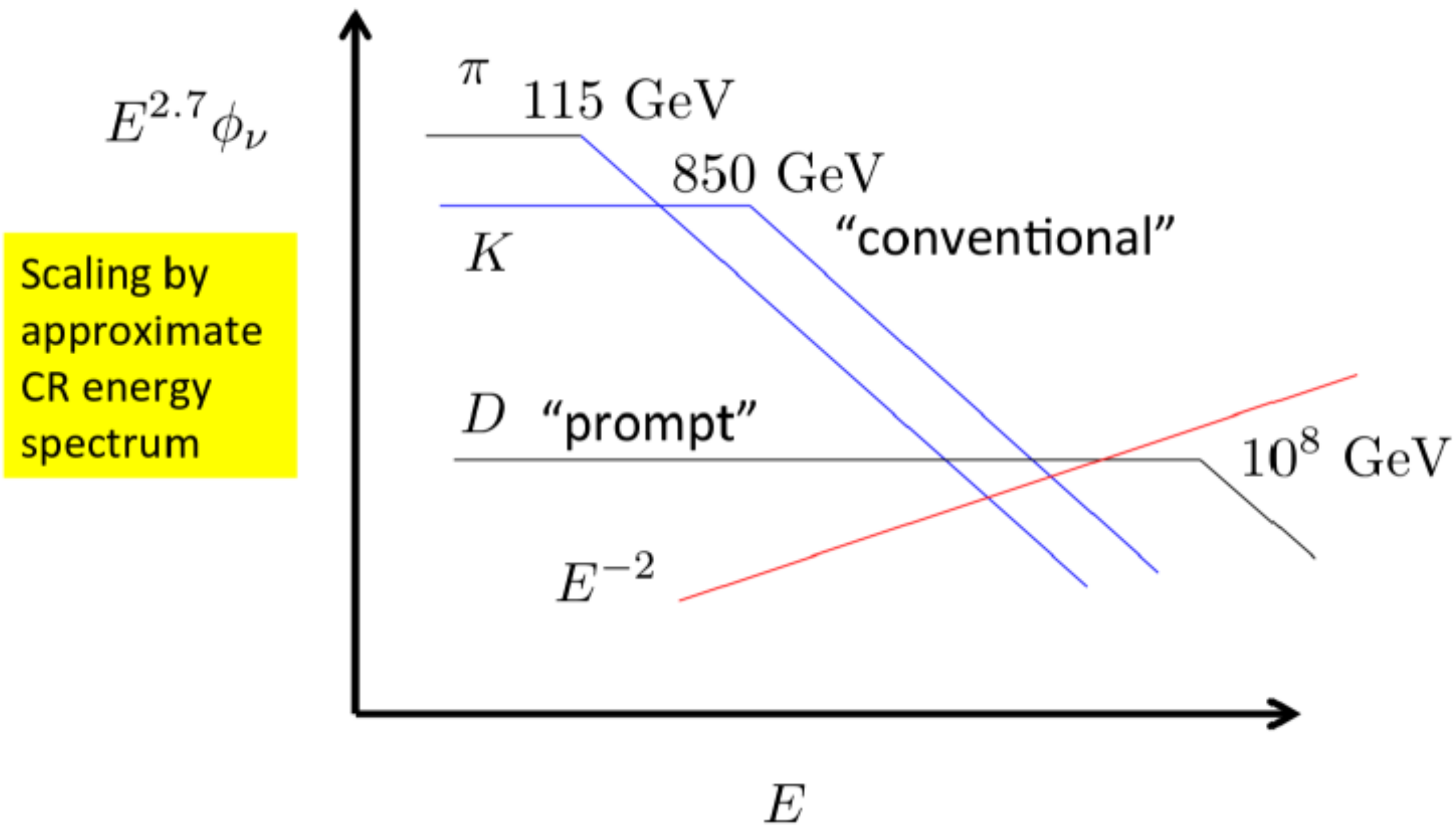
Grigorov
Akeno
MSU
KASCADE
Tibet
KASCADE-Grande
IceTop73
HiRes1&2
TA2013
Auger2013
Model H4a
CREAM all particle
protons only
all-particle
electrons
positrons
antiprotons
Fixed target
HERA
RHIC
TEVATRON
LHC
$E^2 dN/dE$ $(GeV\ cm^{-2} sr^{-1} s^{-1})$
E_{tot} (GeV / particle)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}

Cosmic Ray (CR) Flux



From Table 1, Gaisser, Astropart. Phys. 35 (2012) 801

Dominant components of the atmospheric neutrino flux (schematic view)



Atmospheric Neutrino Flux

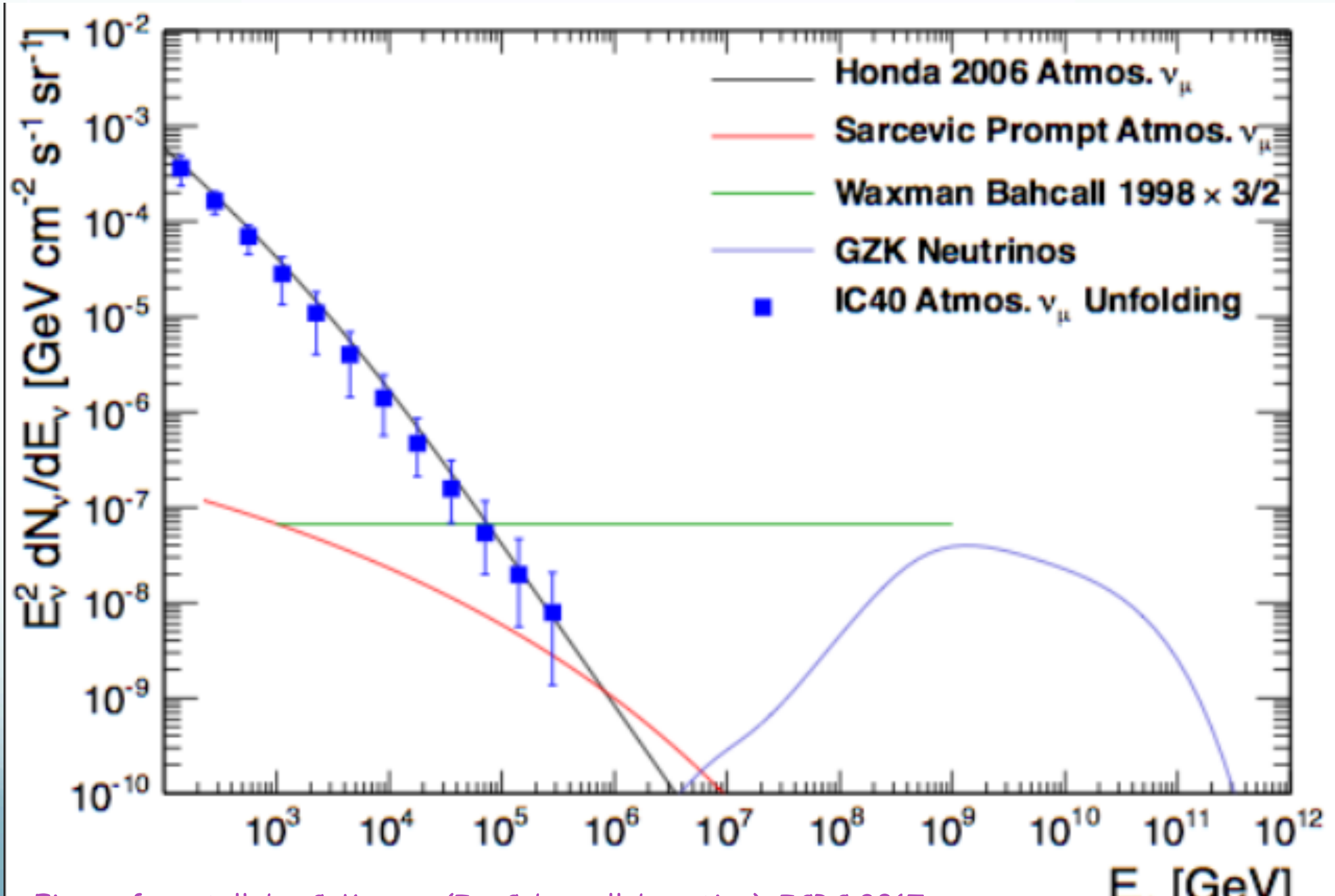
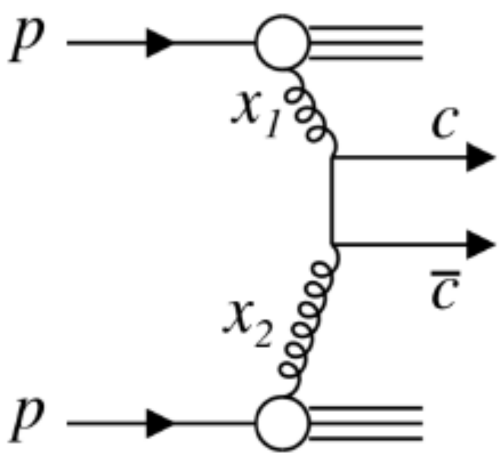


Figure from talk by C. Kopper (IceCube collaboration), ICRC 2017

Theoretical issues with charm production

- **Probes extremely low-x**

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



$x_1,\ x_2:$

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

$$x_F = x_1 - x_2$$

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

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

Theoretical QCD Approaches

- NLO perturbative QCD
- k_T factorization including low-x resummation
- Dipole model including saturation
- Include nuclear effects in p-Air collisions
- Charm fragmentation functions (Kniehl and Kramer; Braaten et al.)

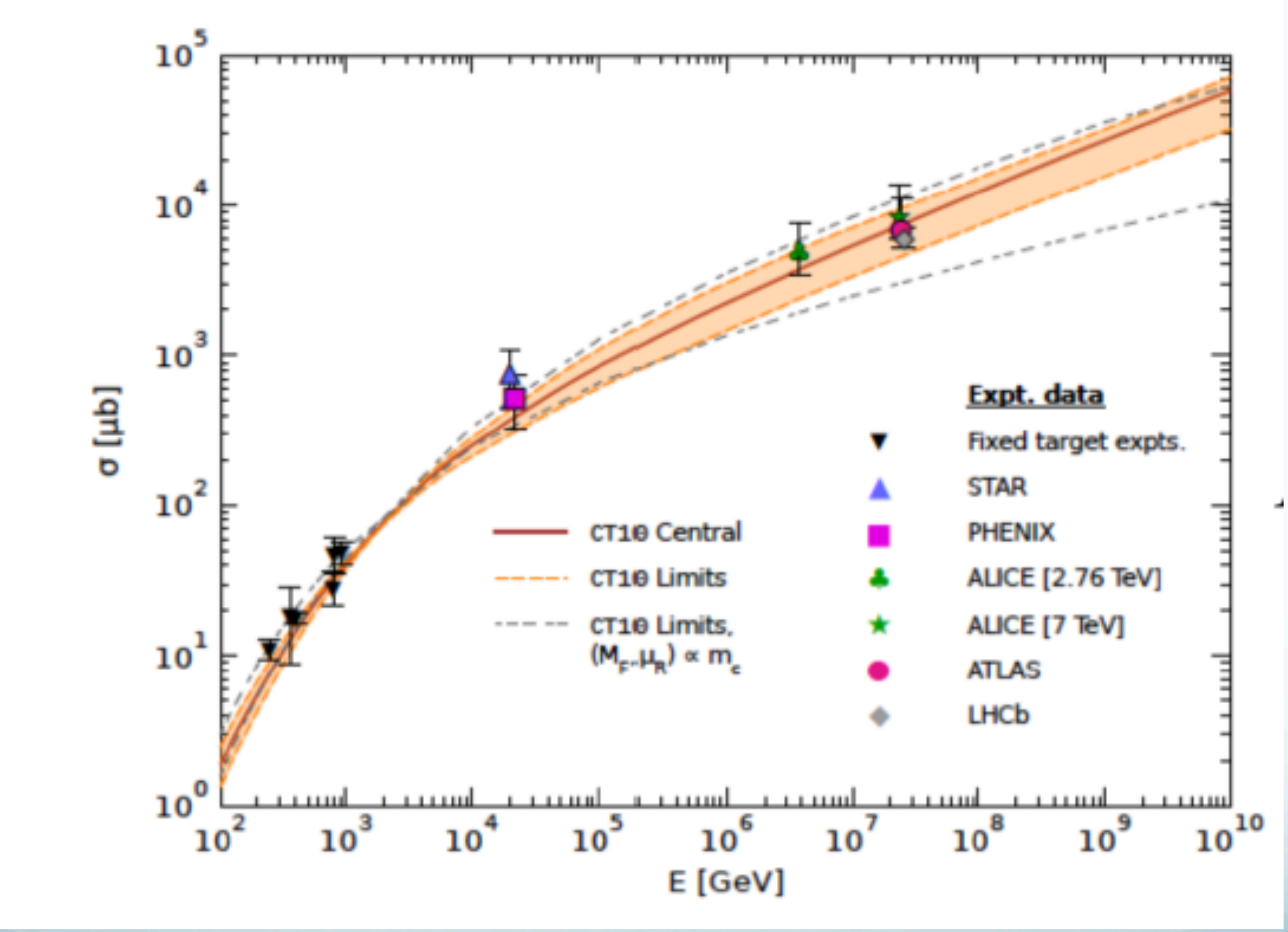
Theoretical uncertainties

- **Uncertainties**
  - QCD of charm production
    - Scales: Renormalisation, factorisation
    - Heavy quark mass (m_c ~ 1.2–1.5 GeV)
    - Perturbative? Dipole model?
  - Uncertainties in fragmentation $(c\bar{c} \to D)$
    - Modeled by fragmentation fn: Kramers-Kneihl, etc.
    - Fragmentation in event generators, e.g. `PYTHIA`

Reducing theoretical uncertainties

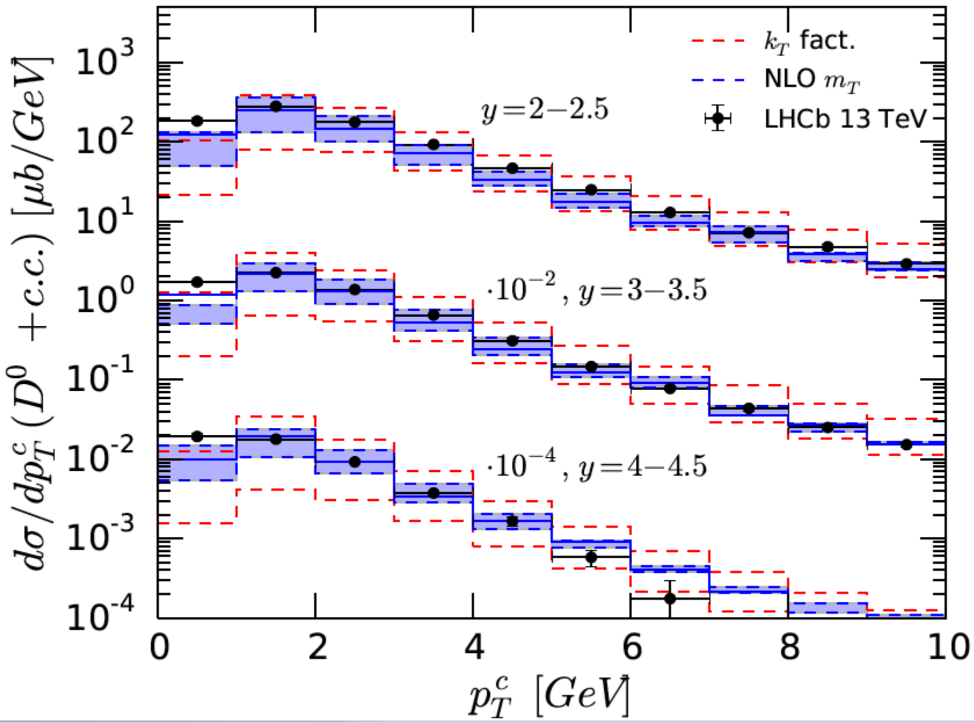
- Use total charm cross section measured up to LHC energies (ALICE, LHCb)
- Use differential charm distributons (transverse momentum and rapidity distributions measured by LHCb at 7TeV and 13TeV
- Evaluate charm production in several perturbative QCD approached: NLO pQCD, dipole model and k_T factorization approach.

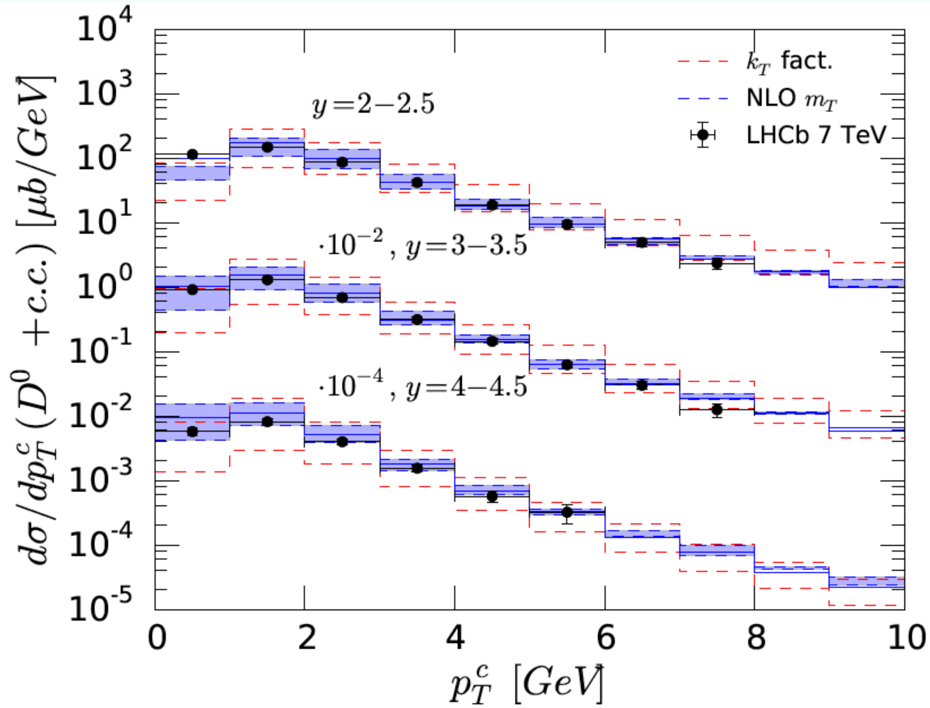
Total charm cross section



Transverse momentum distribution at the LHC compared to LHCb data

A. Bhattacharya, R. Enberg, Y.S. Jeon, M.H. Reno, I. Sarcevic and A. Stasto,
JHEP 1611 (2016) 167





Prompt Neutrino FLux

A. Bhattacharya, R. Enberg, Y.S. Jeong, M.H. Reno, I. Sarcevic and A. Stasto,
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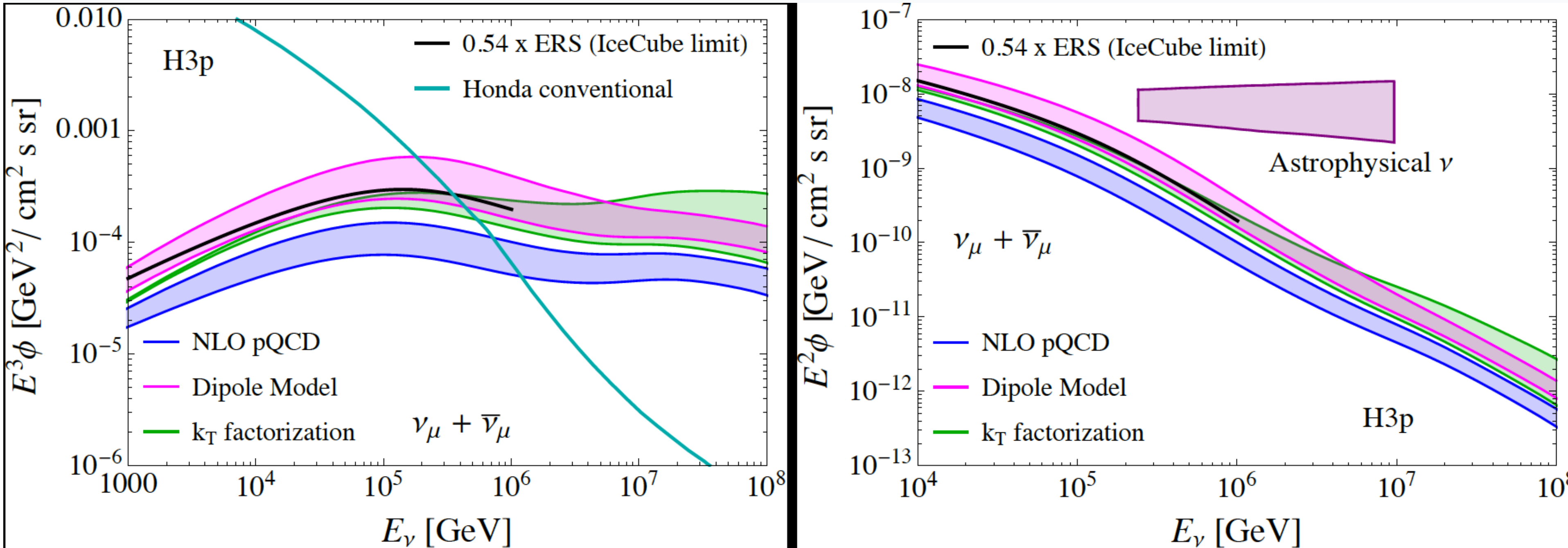

Summary

- Prompt neutrino flux probes pQCD at low x and low Q
- RHIC and LHC charm p_T and rapidity distribution, and the energy dependence of the total cross section reduce theoretical uncertainty in predicting prompt neutrino
- We evaluated prompt neutrino flux using NLO pQCD, dipole model and the k_T factorization approach, including nuclear effects.
- Measurements of prompt neutrinos with IceCube can provide valuable information about pQCD at small x.

Back-up Slides

Dipole Cross Sections

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

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

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

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 Factorization approach

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

Projectile
Integrated g density

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

Target
Unintegrated g density