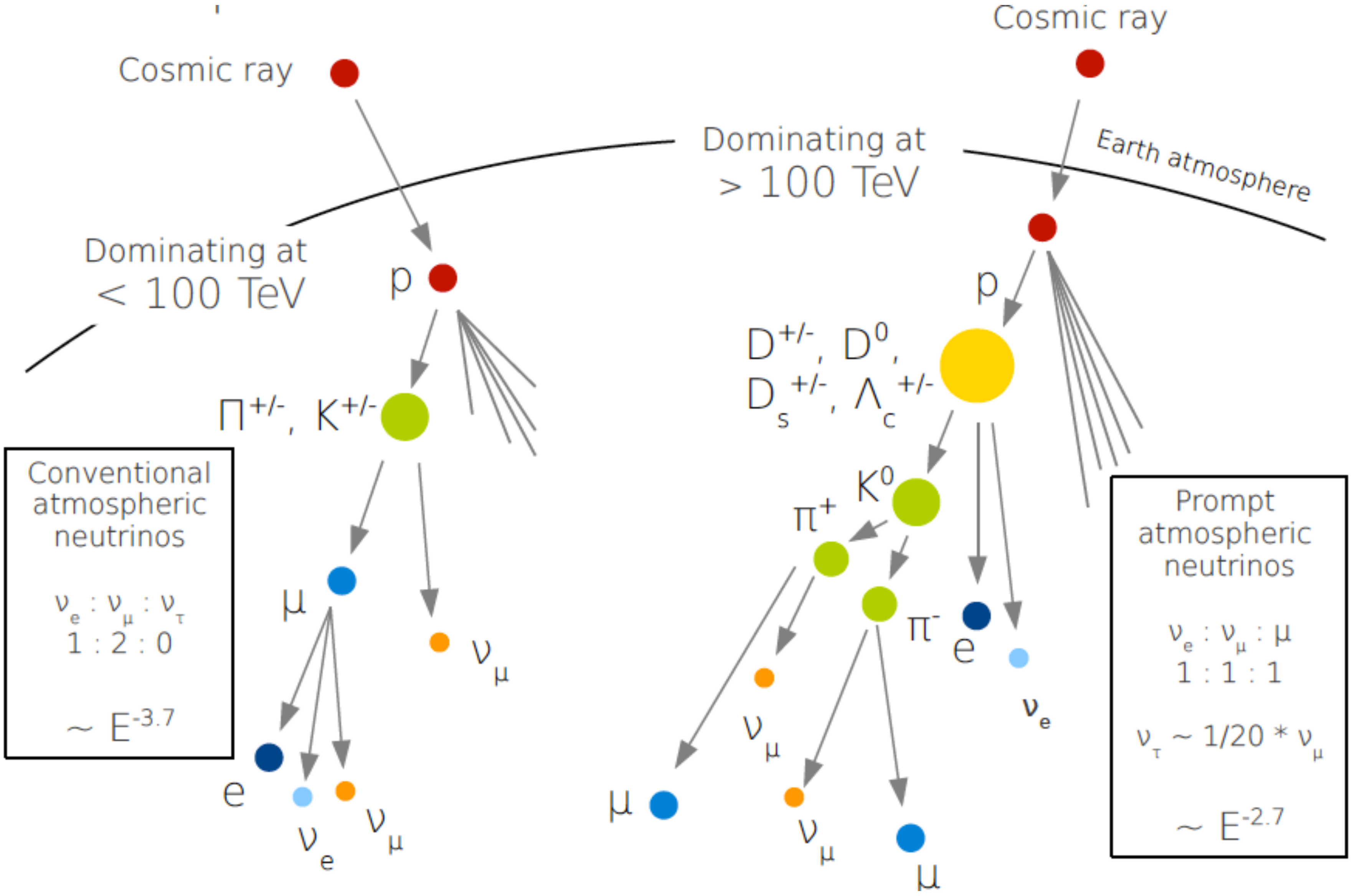
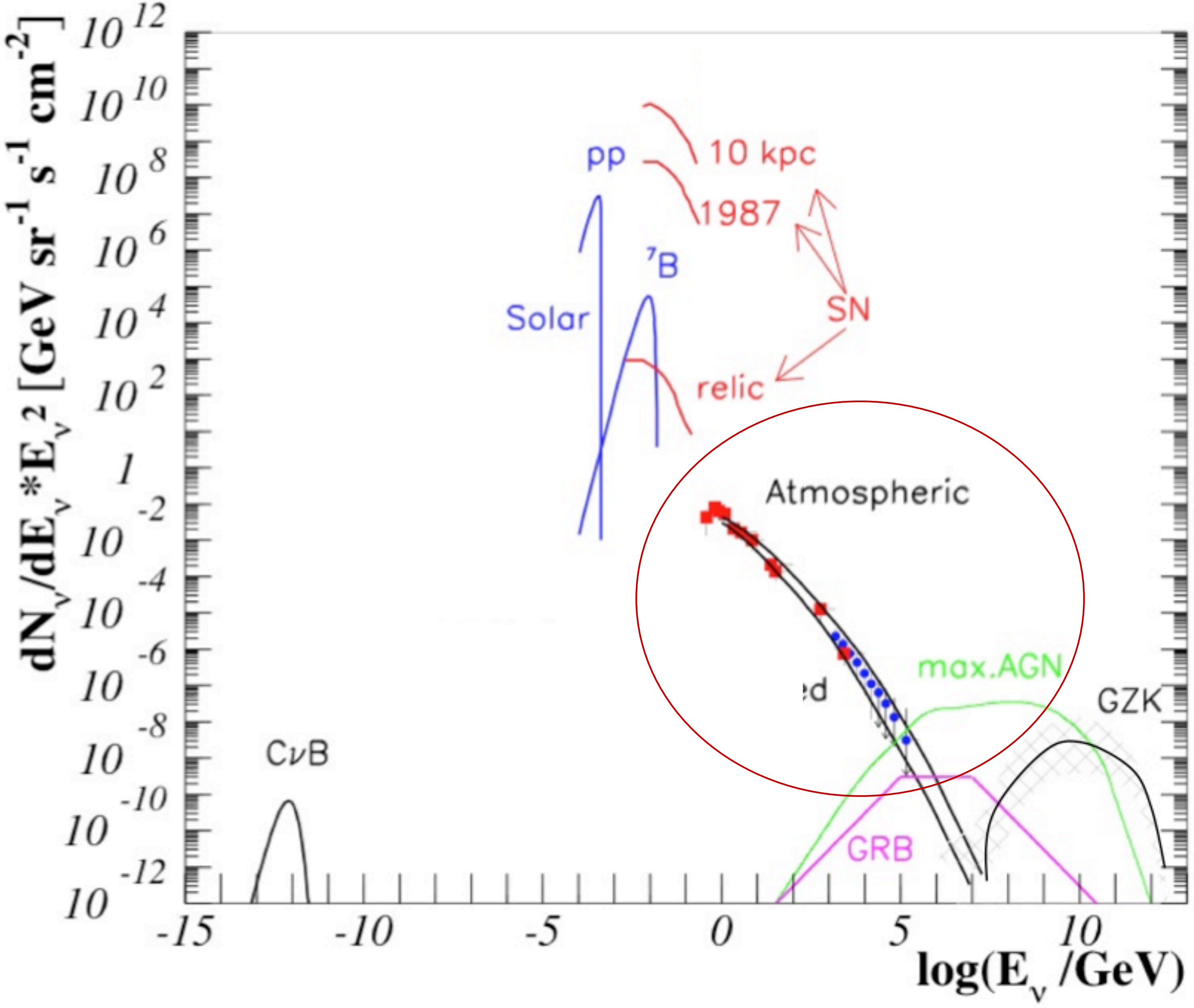


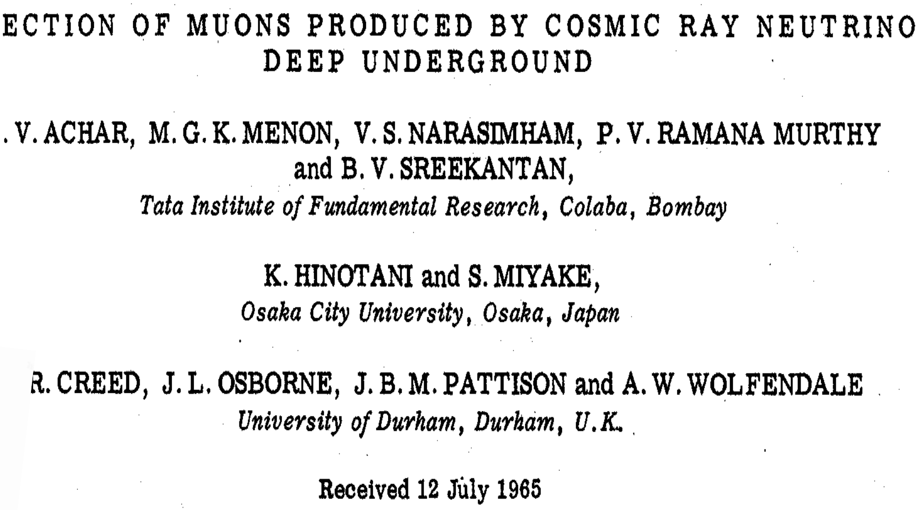
Courtesy: Anne Schukraft

Atmospheric Neutrinos

Detection of naturally generated neutrinos



Discovery of atmospheric neutrinos: 1965



DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

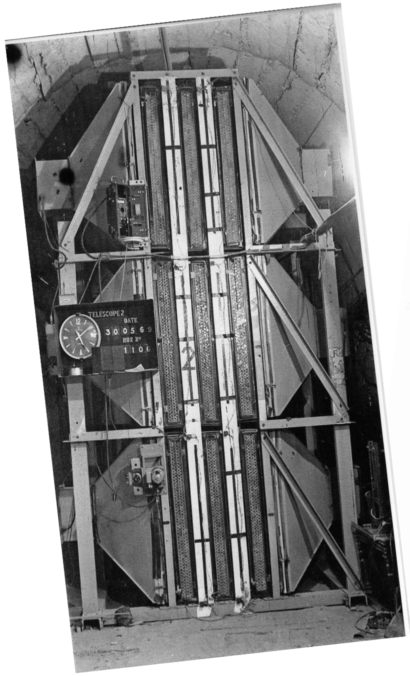
C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY
and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Physics Letters **18** (1965) 196 - published 15th Aug 1965



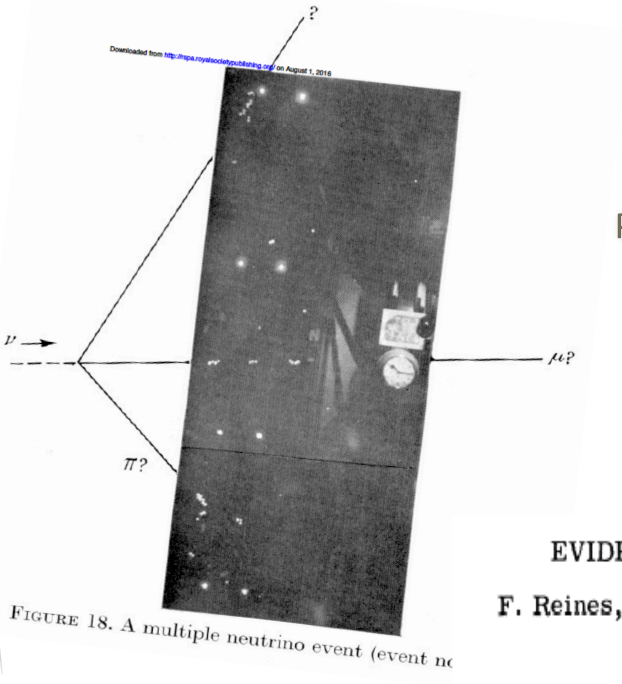
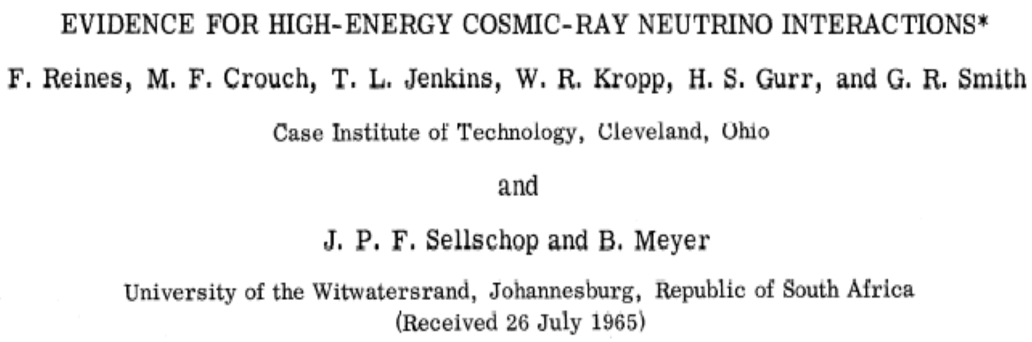


FIGURE 18. A multiple neutrino event (event n



EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio

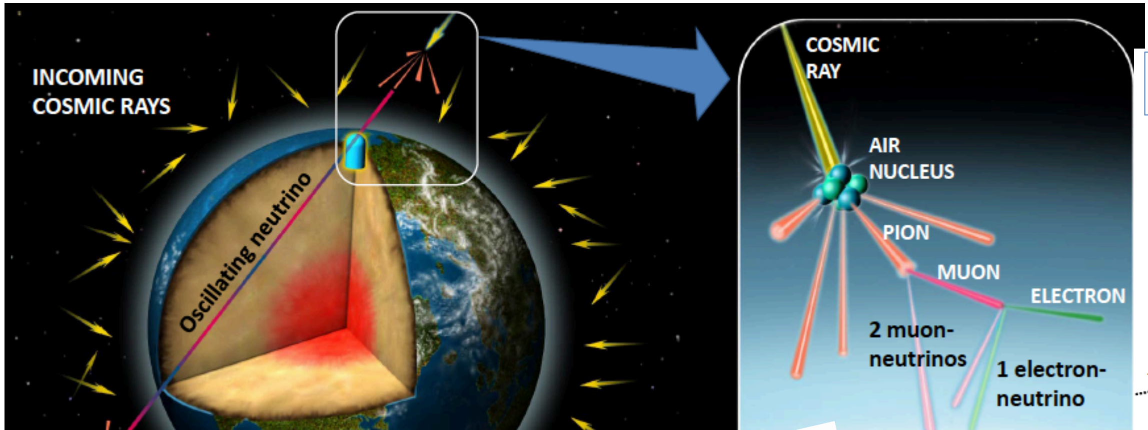
and

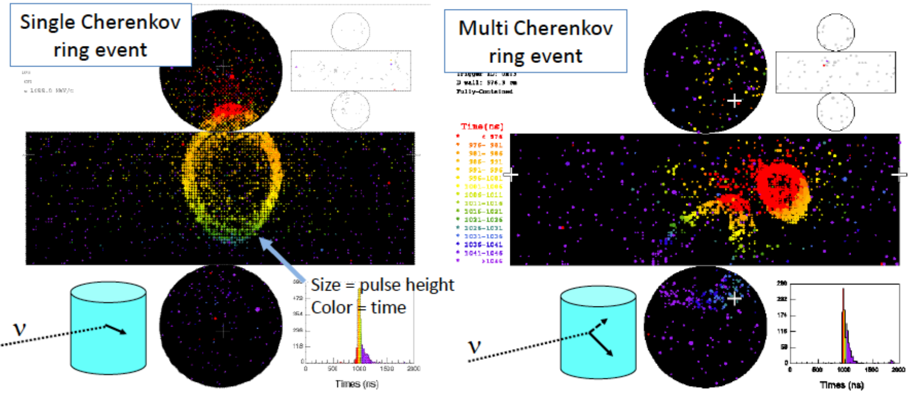
J. P. F. Sellschop and B. Meyer
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

Neutrino detector at the Kolar Gold Fields, India

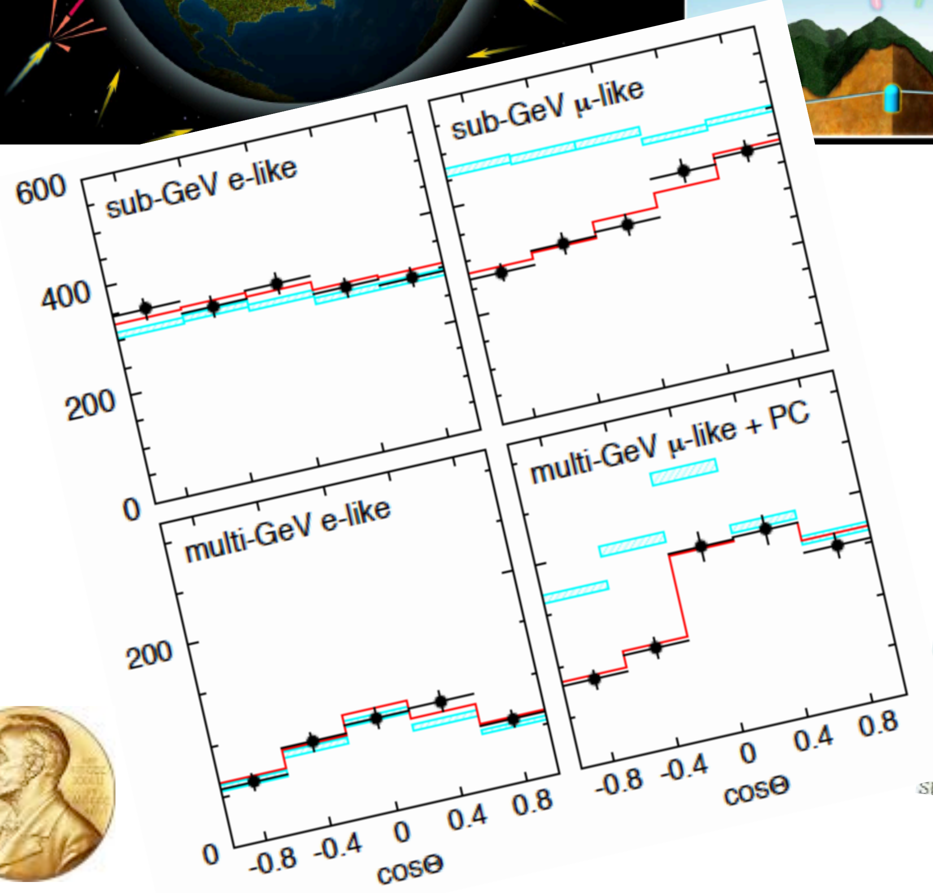
Physical Review Letters **15** (1965) 429 - published 30th Aug 1965

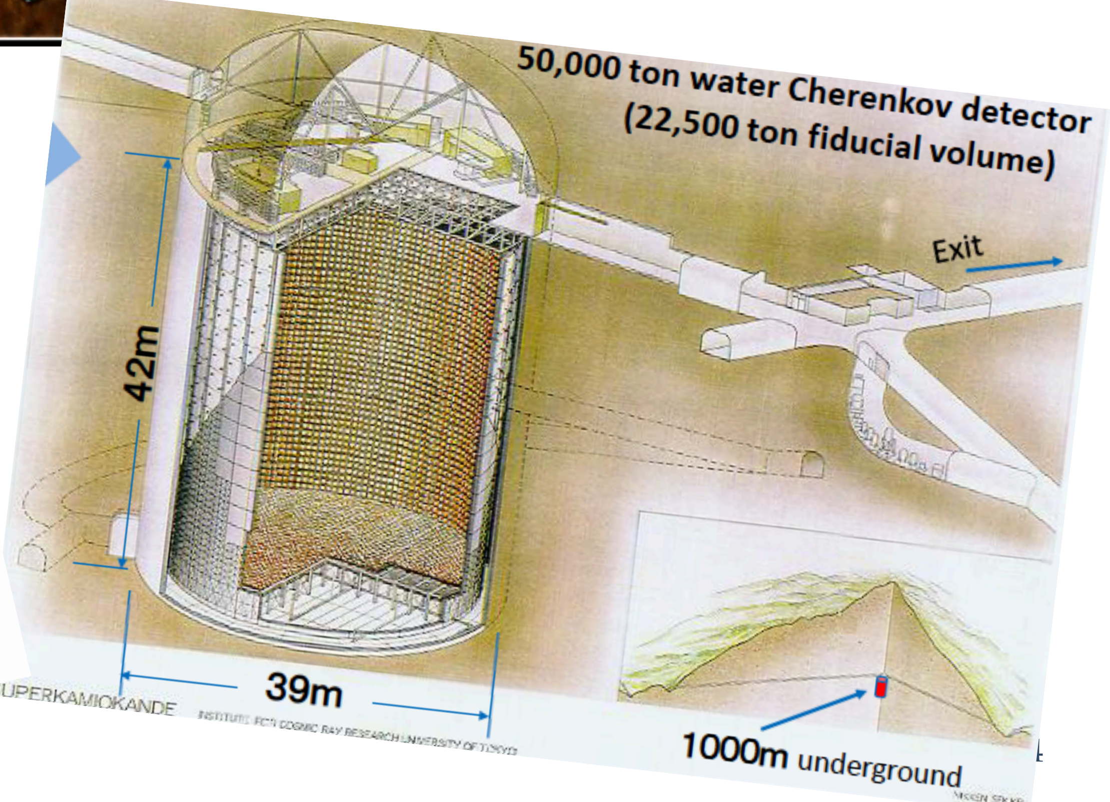
Discovery of atmospheric neutrino oscillations: 1998



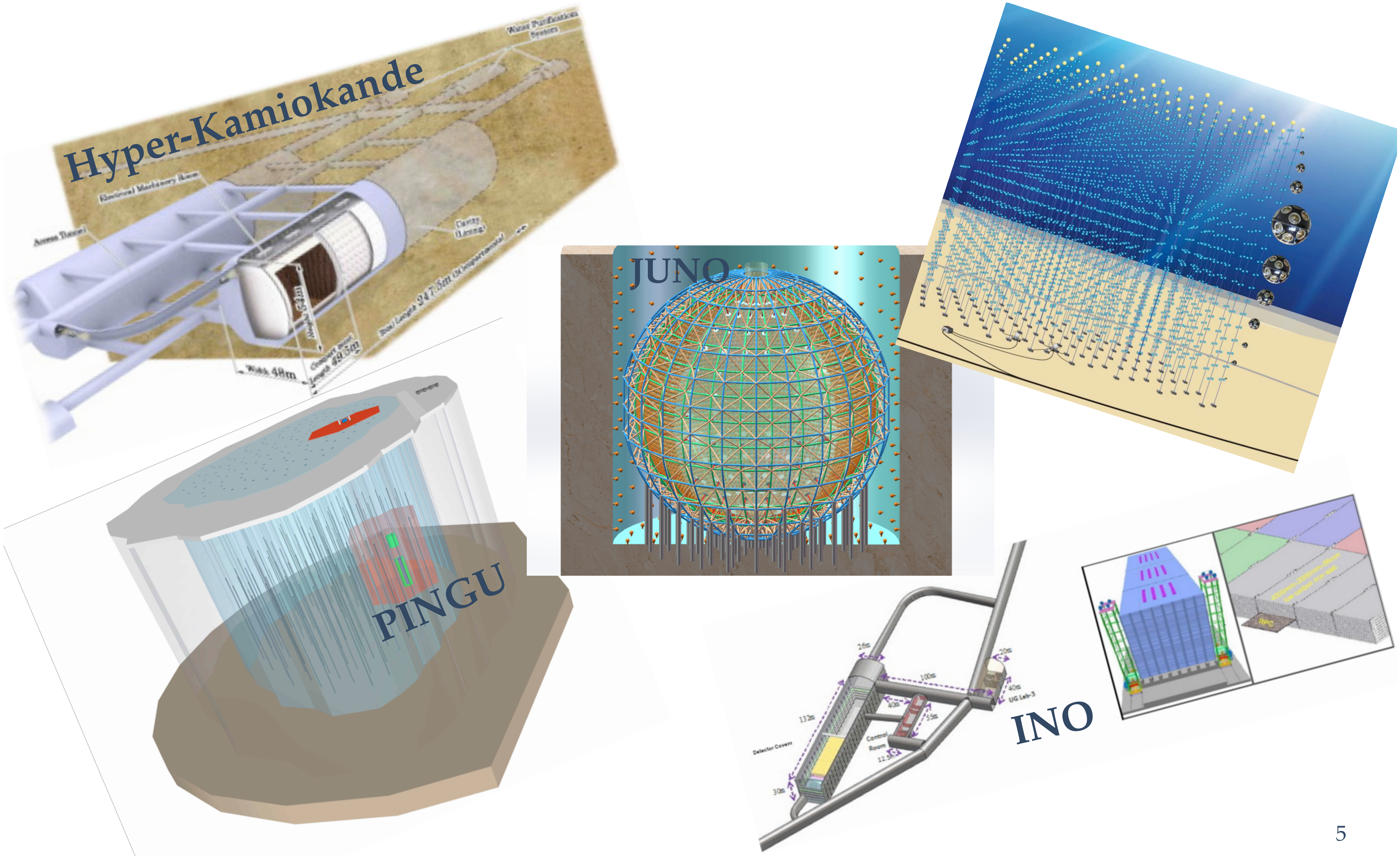


Fukuda *et al*., Phys.Rev.Lett. **81** (1998) 1562





Experiments using the atmospheric neutrino flux



The origin of cosmic rays

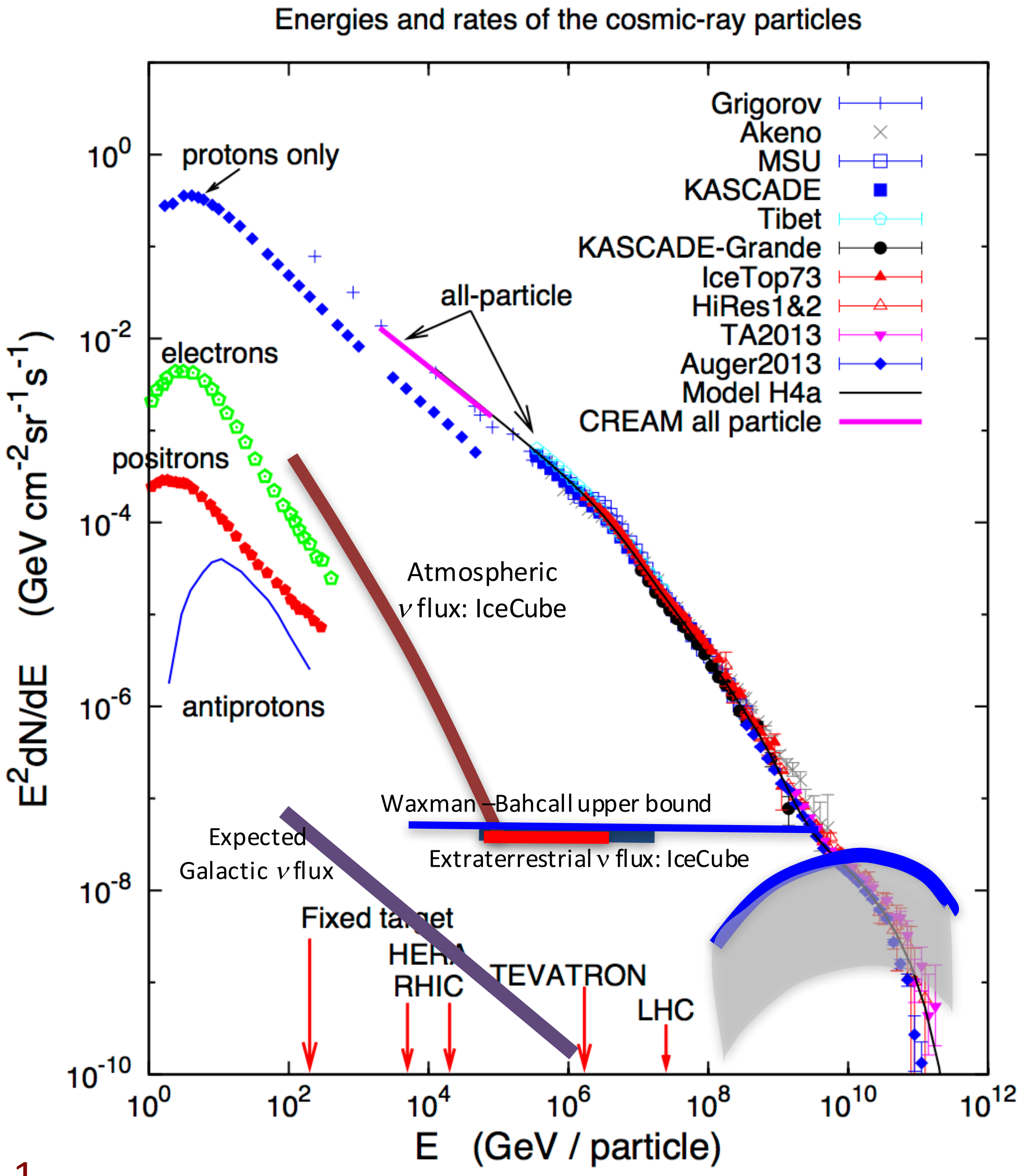
Extraordinary cosmic particle accelerators ***somewhere***, but still **poorly identified** a century after the discovery of cosmic rays!

- Supernova remnants ✓
- Active galactic nuclei ?
- Gamma ray bursts ?
- Radio galaxy jets ?
- Starburst galaxies ?
- …

Cosmic ray interactions with matter and photons, near source or during propagation, produce neutrinos:

$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Oscillations en-route to Earth can equlibrate flavours so: $\nu_e : \nu_\mu : \nu_\tau :: 1 : 1 : 1$



Neutrino production through cosmic ray interactions

conventional

$$p, A + \mathrm{air} \rightarrow \pi^{\pm}, \pi^{0}, \mathrm{K}^{\pm}, \mathrm{K}^{0}_{\mathrm{S,L}}$$

muons and muon neutrinos

$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$$

electron neutrinos

$$K^{\pm}, K^{0}_{L} \rightarrow [\pi^{\pm}, \pi^{0}]e^{\pm}\nu_{e}(\bar{\nu}_{e})$$

prompt

$$p, A + \mathrm{air} \rightarrow \mathrm{D}, \Lambda_{\mathrm{C}} \rightarrow \nu_{\mu}, \nu_{\mathrm{e}}, \mu$$

Subset of dominant decay channels

decay channel	branching ratio (BR)
$\mu^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu}$	100 %
$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$	99.9877 %
$K^{0}_{e3} : K^{0}_{L} \rightarrow \pi^{\pm}e^{\mp}\nu_{e}$	40.55 %
$K^{0}_{\mu 3} : K^{0}_{L} \rightarrow \pi^{\pm}\mu^{\mp}\nu_{\mu}$	27.04 %
$K^{+} \rightarrow \mu^{+}\nu_{\mu}$	63.55 %
$K^{+}_{e3} : K^{+} \rightarrow \pi^{0}e^{+}\nu_{e}$	5.07 %
$K^{+}_{\mu 3} : K^{+} \rightarrow \pi^{0}\mu^{+}\nu_{\mu}$	3.353 %
$D^{+} \rightarrow \overline{K}^{0}\mu^{+}\nu_{\mu}$	9.2 %
$D^{0} \rightarrow K^{-}\mu^{+}\nu_{\mu}$	3.3 %

+ *charge conjugates*

http://pdg.lbl.gov

Prompt vs. conventional flux

- The energy spectrum from semi-leptonic decay products depends on a hadronic '**critical energy**', *below* which the **decay probability** is **> interaction probability**:

$$\epsilon_h = \frac{m_h c^2 h_0}{c\tau_h \cos\theta}$$

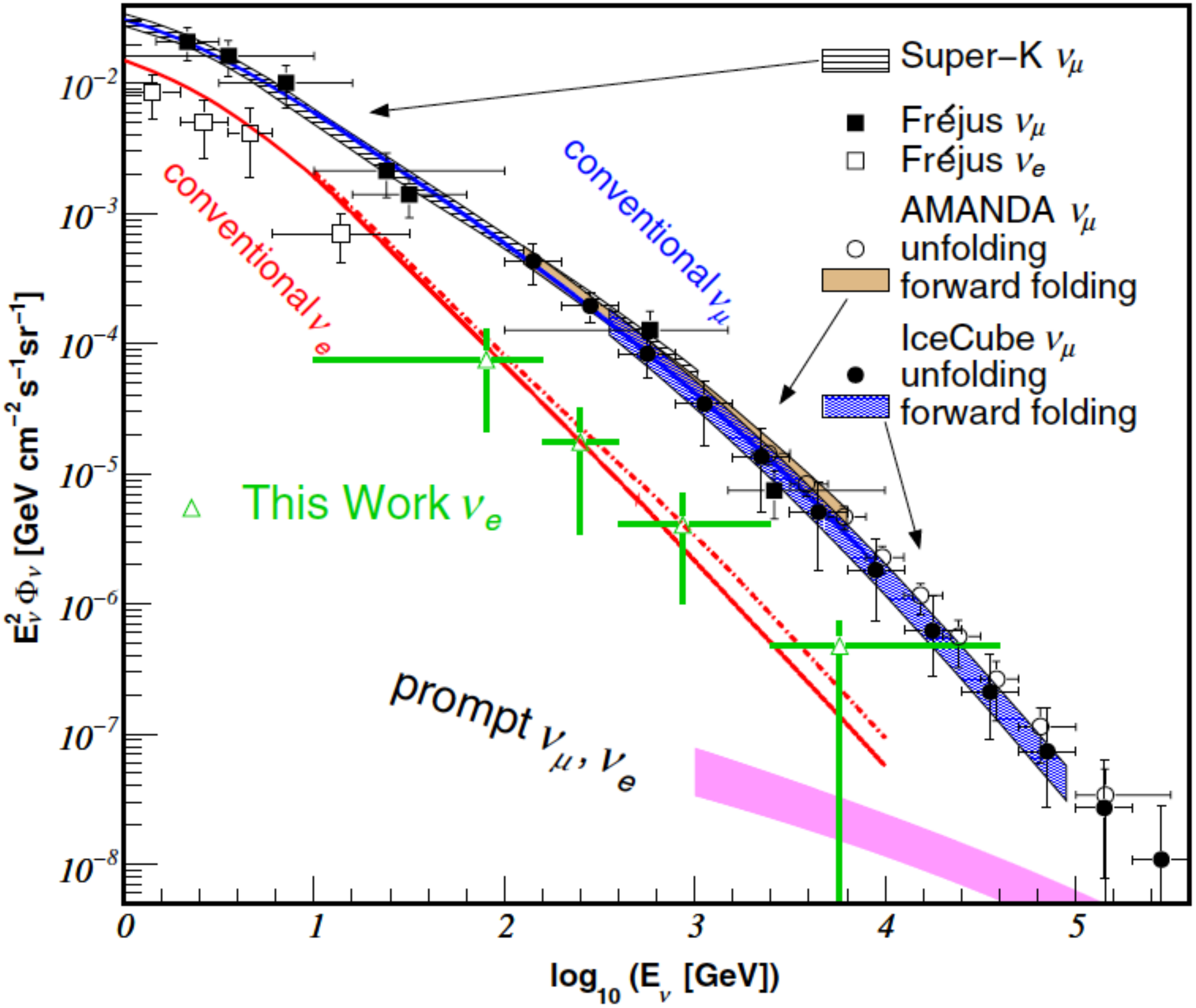
$$\epsilon_{\pi^\pm} = 115\ [GeV]$$
$$\epsilon_{K^\pm} = 850\ [GeV]$$

- For **pions & kaons**, this critical energy is low (decay length is long) hence the leptonic energy spectrum is soft. For **charmed mesons**, the critical energy is high … they **decay *promptly*** to highly energetic leptons:

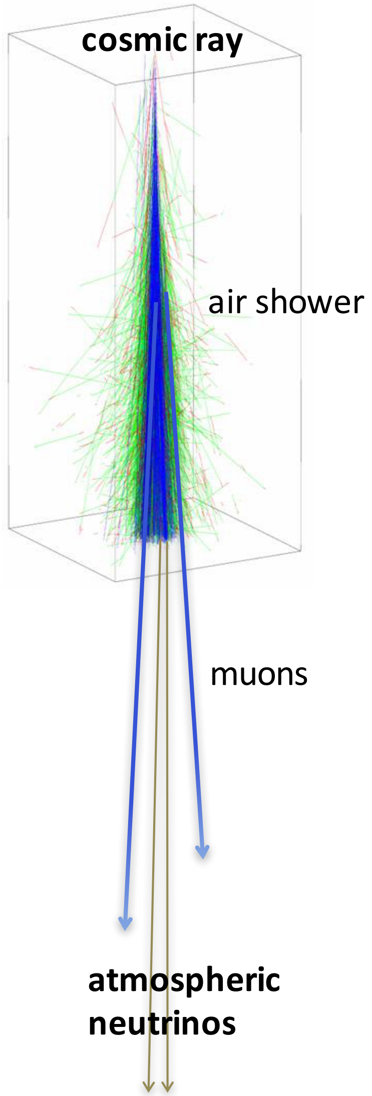
$$\begin{aligned} \epsilon_{D^0} &= 9.71 \times 10^7\ [GeV] \\ \epsilon_{D^\pm} &= 3.84 \times 10^7\ [GeV] \\ \epsilon_{D_s^\pm} &= 8.40 \times 10^7\ [GeV] \\ \epsilon_{\Lambda_c} &= 24.4 \times 10^7\ [GeV] \end{aligned}$$

- The atmospheric neutrino flux from the decay of pions & kaons is the '**conventional flux**,' whereas that from charm decay is called the '**prompt flux**'

Spectrum from π/K decay is measured to high energies

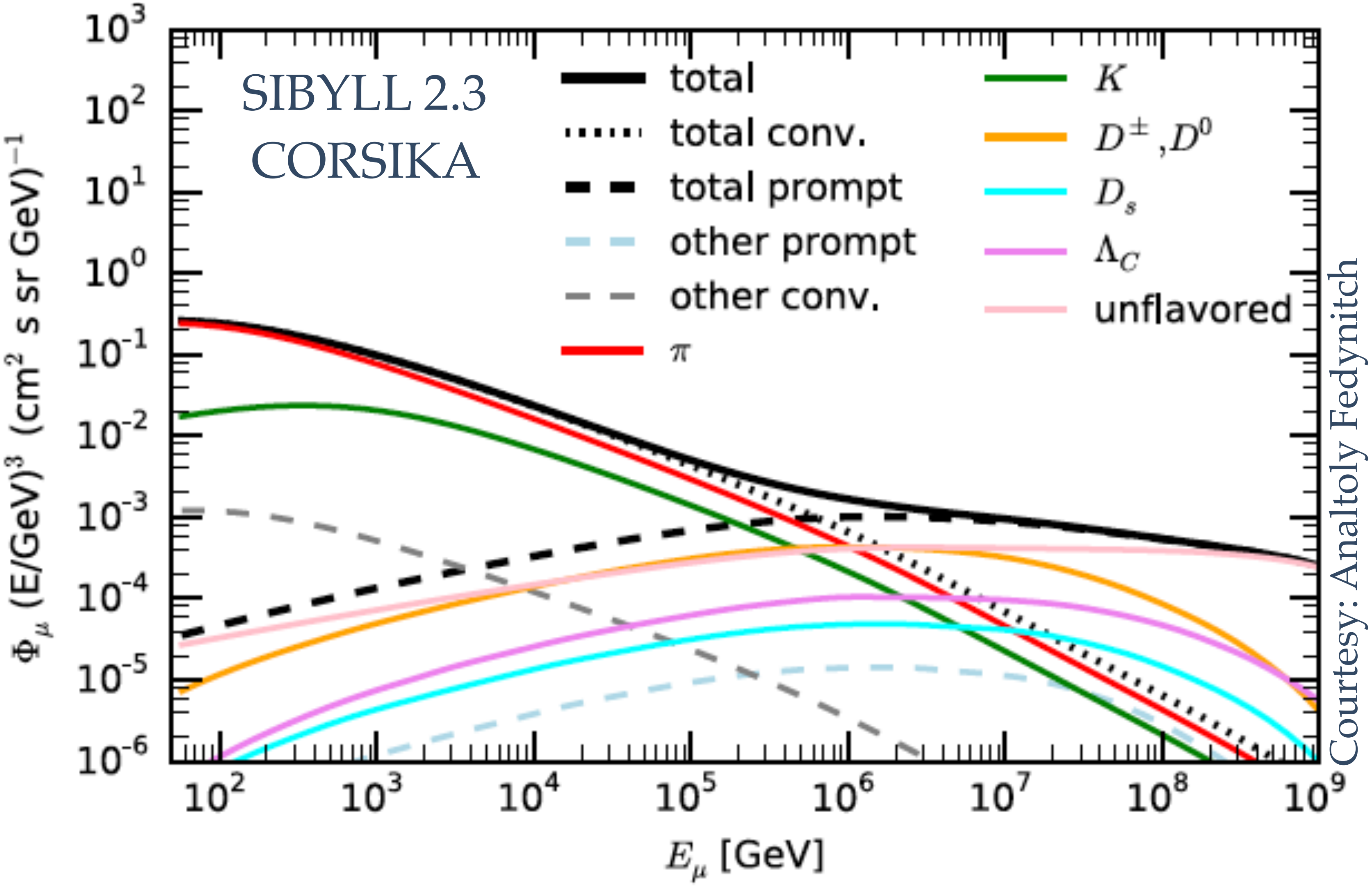


Phys. Rev. Lett. **110** (2013) 151105



Monte Carlo calculation (e.g. http://www.icrr.u-tokyo.ac.jp/~mhonda/)

Atmospheric muon spectrum



Courtesy: Analtoly Fedynitch

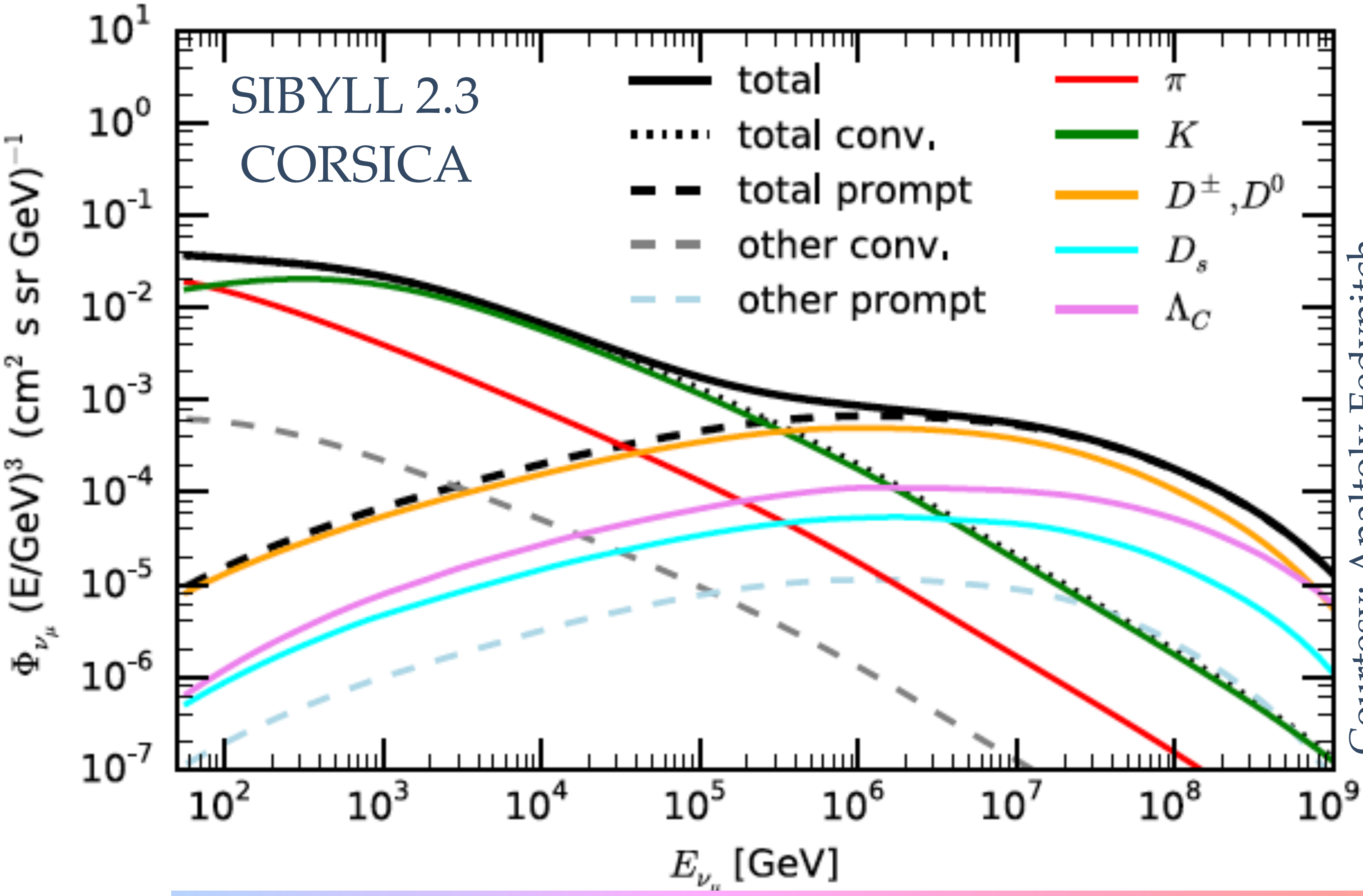
mostly **pion** decay

charm
decays

charm
interacts

unflavored
decays

Atmospheric muon neutrino spectrum



Courtesy: Analtoly Fedynitch

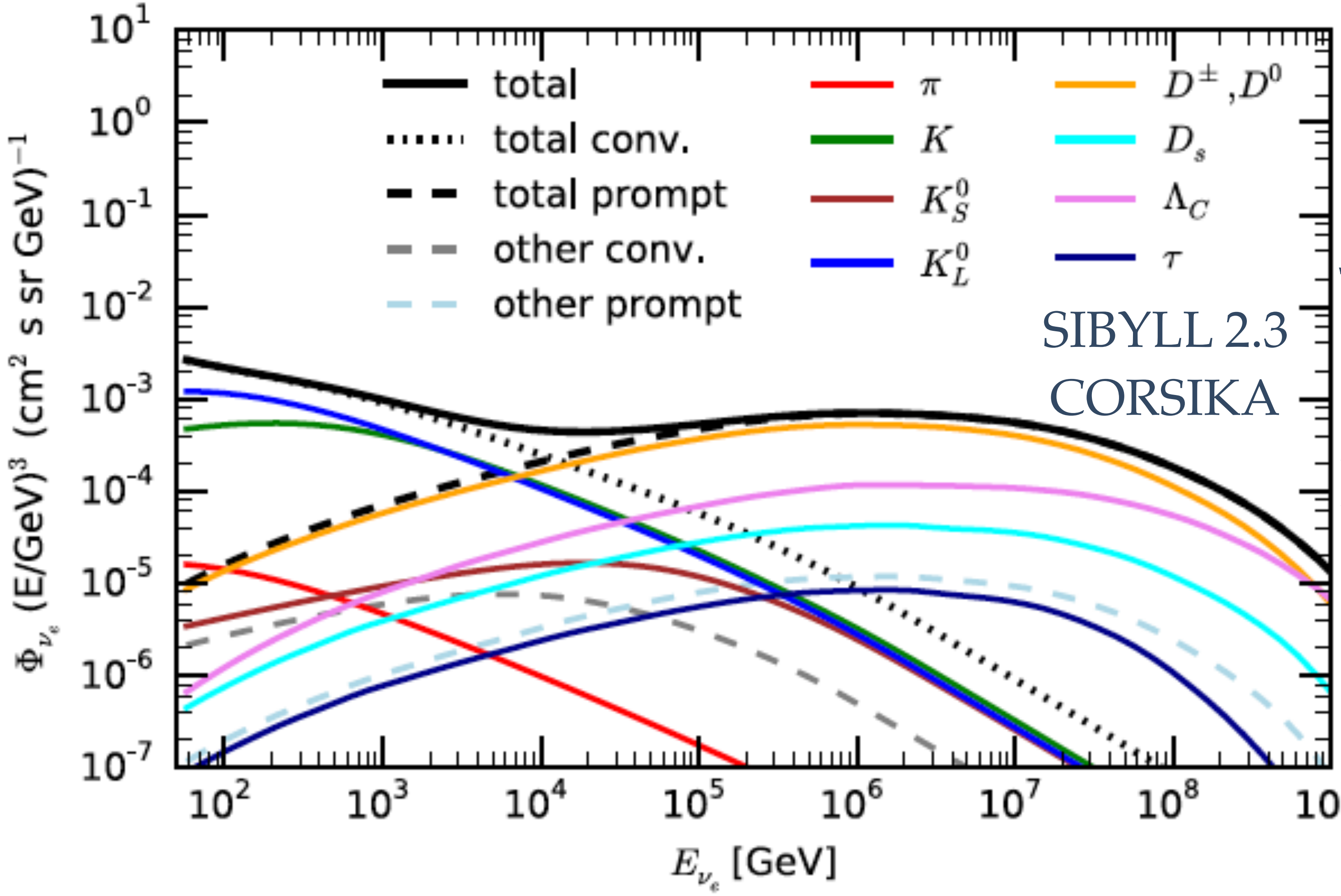
mostly **kaon** decay

charm
decays

charm
interacts

no
unflavored
decays

Atmospheric electron neutrino spectrum



Courtesy: Analtoly Fedynitch

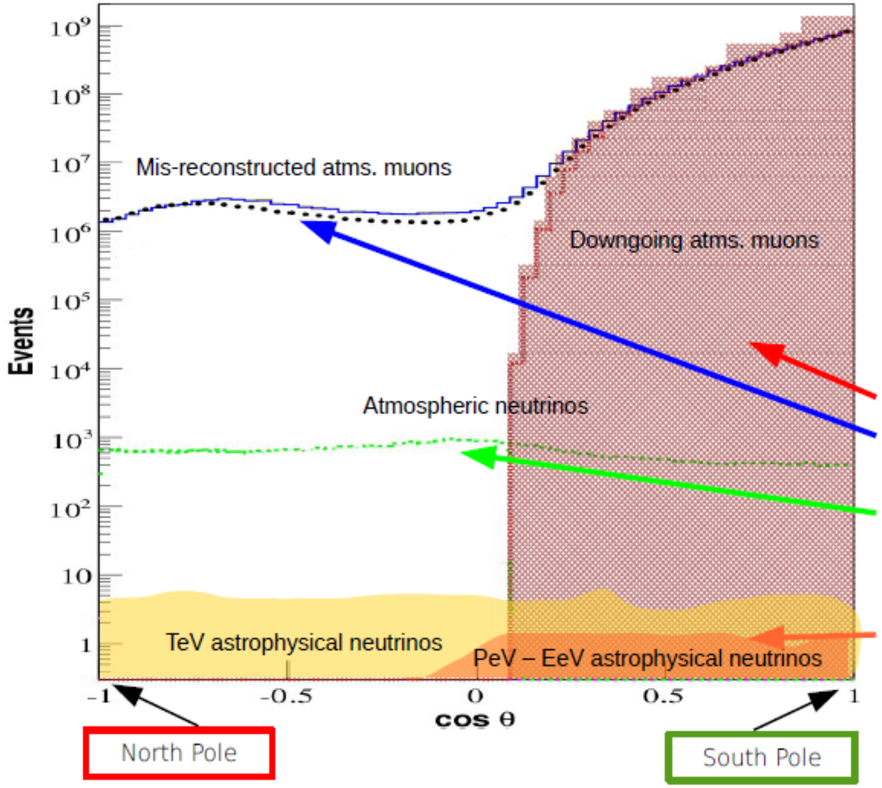
mostly **pion** decay

charm decays

charm interacts

unflavored decays

Beating the atmospheric background



There is an enormous background of cosmic ray muons going *down*

(only *misreconstructed* muons apparently going up since muons are all absorbed in the Earth)

Atmospheric neutrinos come from the *same* showers (1 in 10^6 events)

By using a veto for downgoing events, we remove the atmospheric neutrinos … because we remove the muons coming from the *same* Cosmic Ray Air Shower

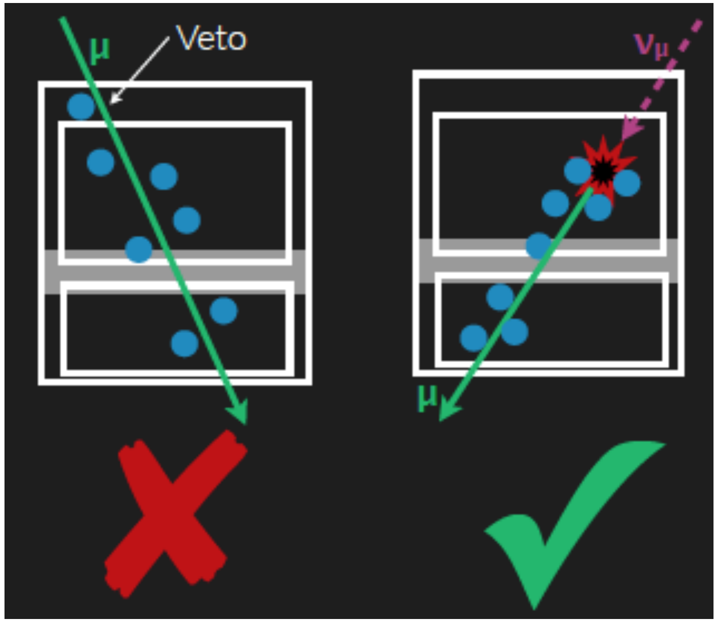
What’s left is: PeV-EeV astrophysical neutrinos coming from above

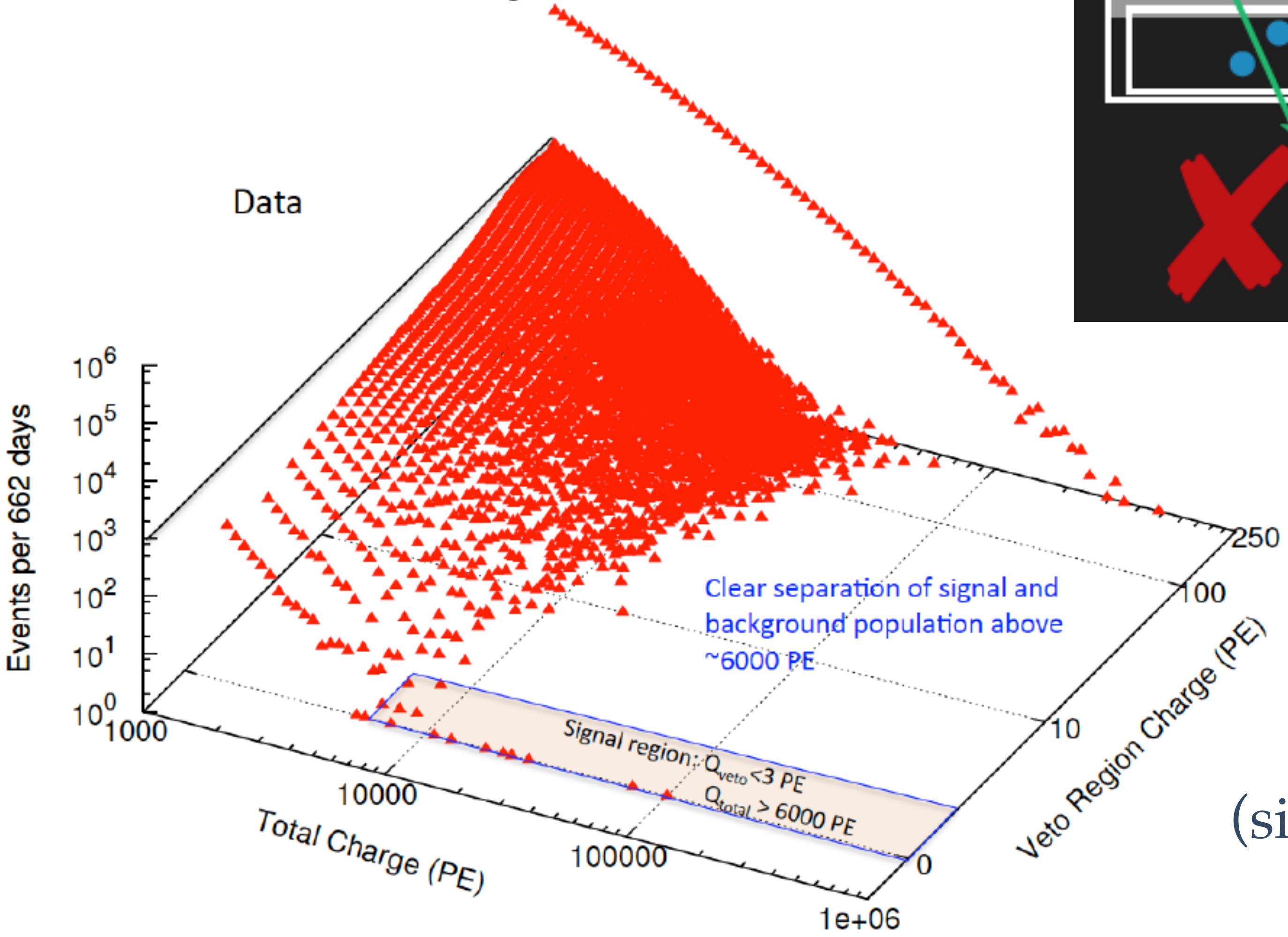
NB: Doesn’t work for upgoing, since the Earth absorbed the muons …
so Southern Sky (downgoing events) becomes the best channel.

‘High energy starting events’ (HESE) analysis

Use outer-most layer of IceCube as a **veto**

Removes atmospheric background
(muon + neutrino) **from above**
Earth filters muon background **from below**



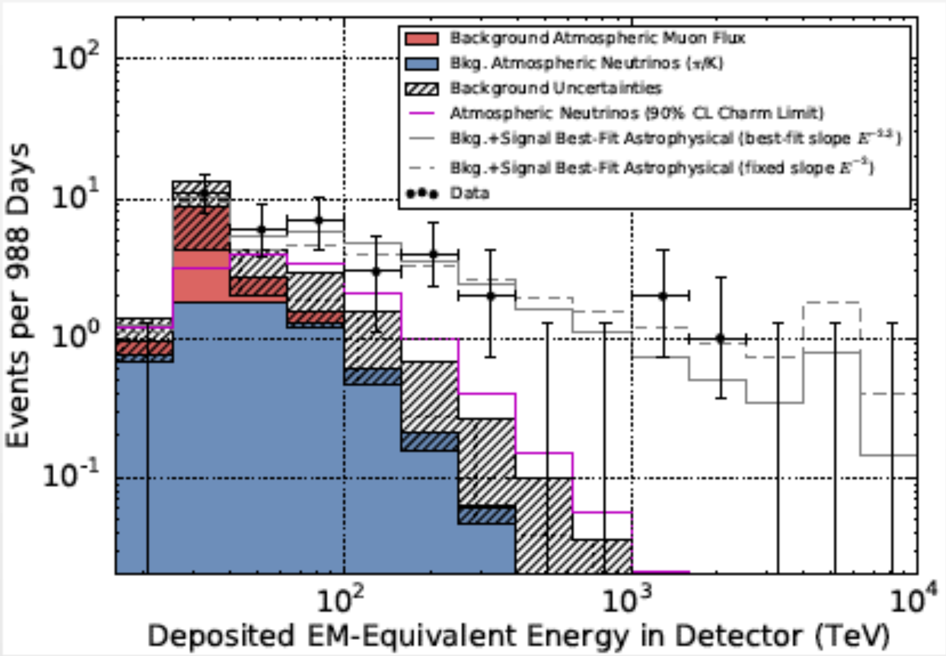


Clear separation of signal and background population above ~6000 PE

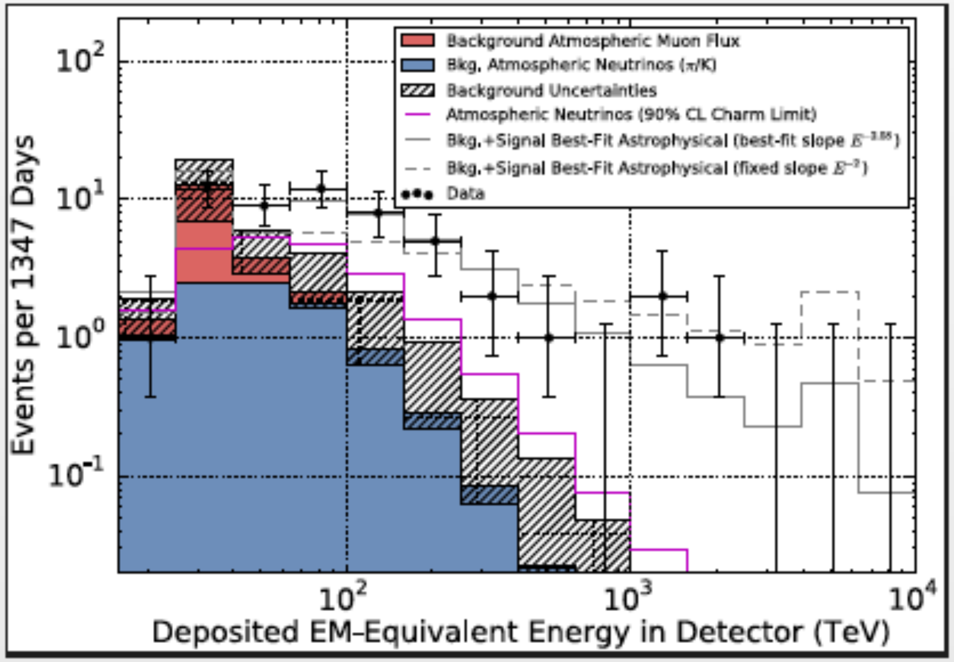
Can now see signal of interest … albeit at the cost of throwing out most of the data! (similar to collider expts)

Discovery of high energy cosmic neutrinos

- **2013**: 662-day analysis, with **28** candidates in the energy range [50 TeV - 2 PeV]. (4.1 σ excess over the expected atmospheric background).
- **2014**: 988-day analysis, with a total of **37** events with energy [30 TeV - 2 PeV] (5.7 σ excess), no events in the energy range [400 TeV - 1 PeV], spectral $\Gamma = -2.3 \pm 0.3$.
- **2015**: 1347-day analysis, with a total of **53 + 1** events, previous energy gap partially filled, (7 σ excess), spectral $\Gamma = -2.58 \pm 0.25$.



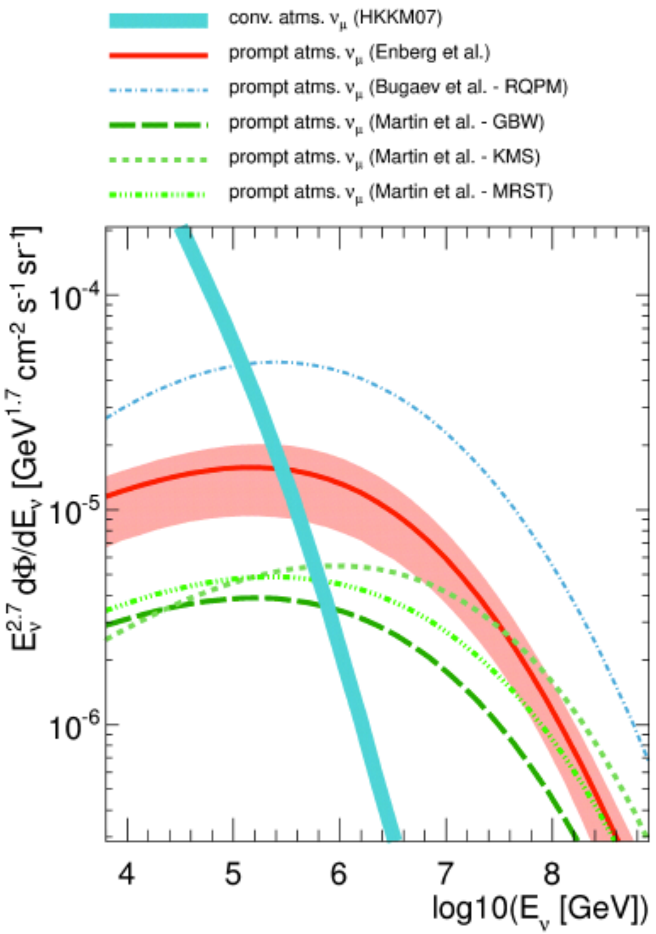
2014



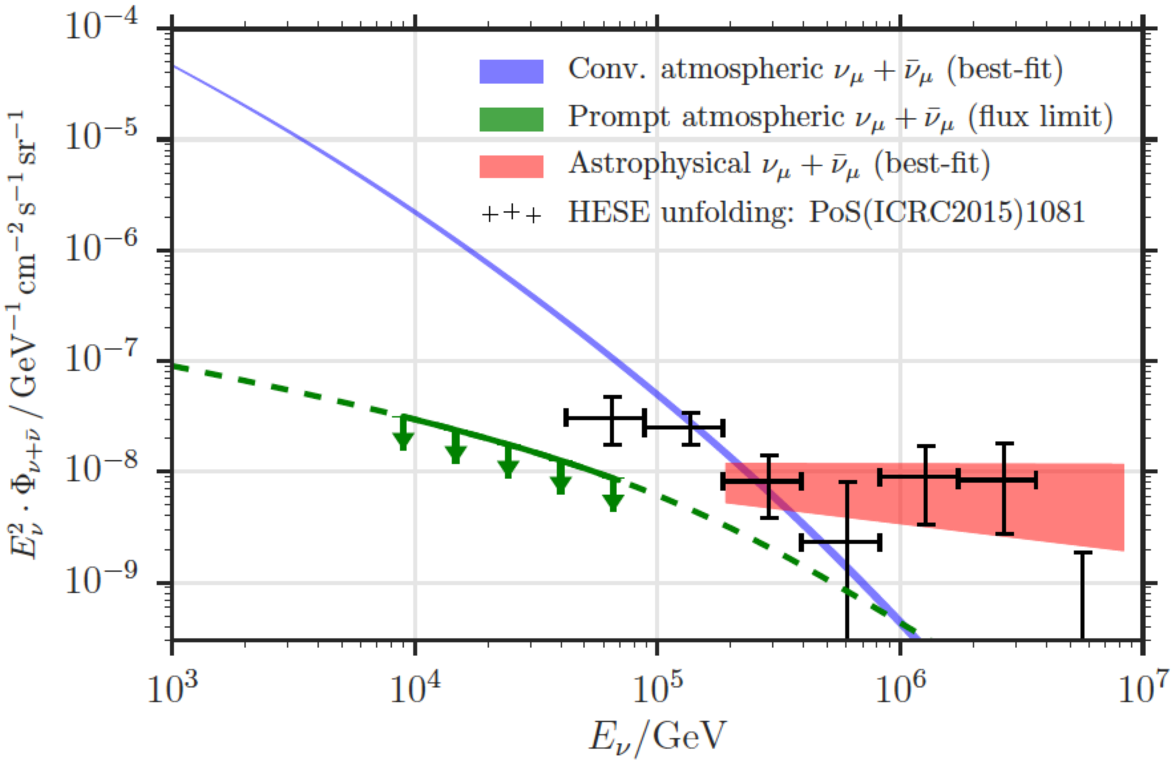
2015

But where are the prompt neutrinos?

- The flux of prompt neutrinos is *harder* than that of conventional neutrinos, and was predicted to **dominate** the total atmospheric flux at energies above ~10^{5-6} GeV



No prompt flux seen so far … however astrophysical signal with ~similar spectrum has been discovered!

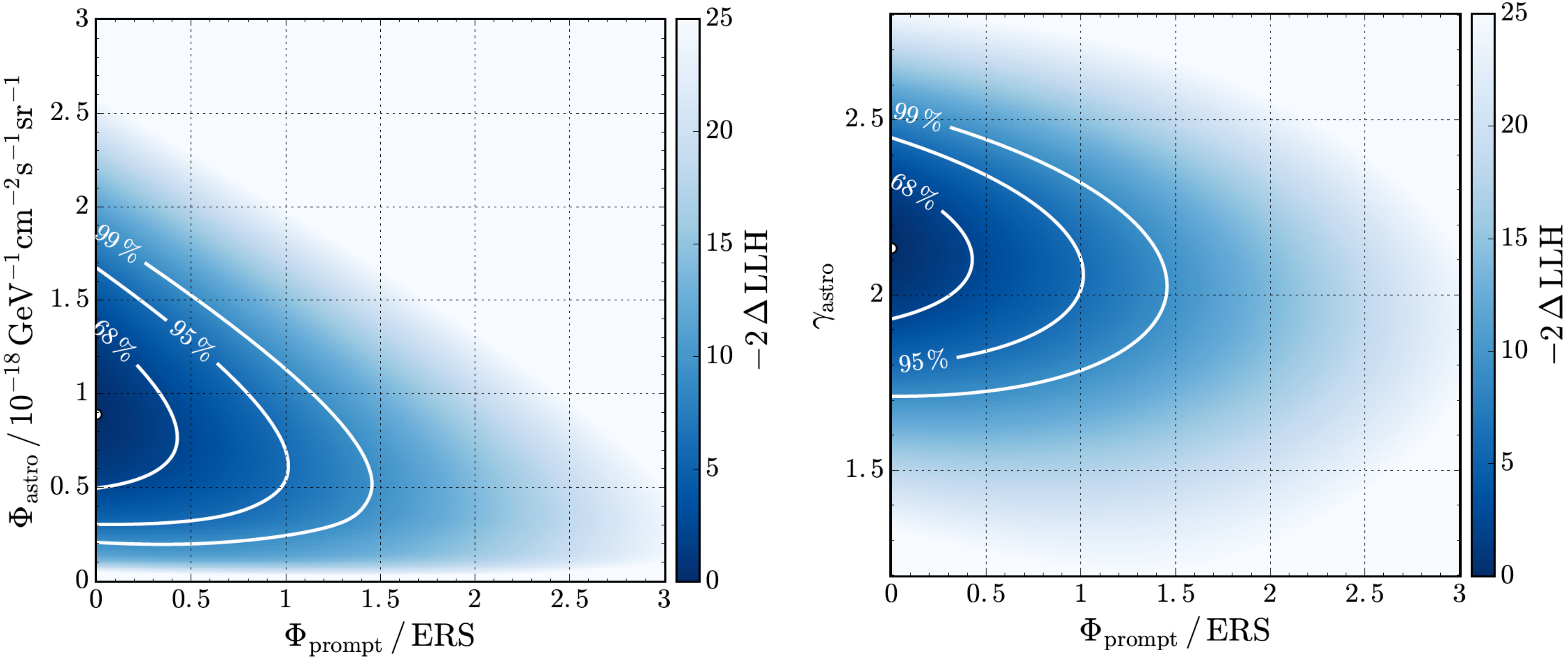


arXiv:1607.08006

- The conventional background is well understood as it has been calibrated against many observations … uncertainties in charm production make the prompt flux less so but **it is the most important background for the expected astrophysical flux**!

Tension with ERS 'benchmark'

arXiv:astro-ph/1410.1749
arXiv:hep-ph/0806.0418



- Recent data put an **upper limit** on the prompt flux above 1 TeV, which is *less* than ~1.06 x the benchmark ERS 2008 calculation (arXiv:1607.08006)

Even stronger limit of 0.54×ERS @ 90% C.L. from combined IC59 + IC79 + IC86 data

(Sebastian Schonen, IPA 2015)

Need a better calculation of cosmic ray charm hadroproduction and decay

Theoretical calculations

- **Volkova**, Sov. J. Nucl. Phys. 12 (1980) 784
- **Bugaev, Naumov, Sinegovksy, Zaslavskaya**, Il Nuovo Cim. C **12** (1989) 41
- **Lipari**, Astropart. Phys. **1** (1993) 195
- **Thunman, Ingelman, Gondolo** (TIG), Astropart. Phys. **5** (1993) 309
- **Pasquali, Reno, Sarcevic** (PRS), Phys. Rev. D**59** (1999) 034020
- **Gelmini, Gondolo, Varieschi** (GGV1), Phys. Rev. D**61** (2000) 036005
- **Gelmini, Gondolo, Varieschi** (GGV2), Phys. Rev. D**61** (2000) 056011
- **Martin, Ryskin, Stasto** (MRS), Acta Phys. Polonica B**34** (2003) 3273
- **Enberg, Reno, Sarcevic** (ERS), Phys. Rev. D**78** (2008) 043005
- **Bhattacharya, Enberg, Reno, Sarcevic, Stasto** (BERSS), JHEP **06** (2015) 110
- **Garzelli, Moch, Sigl** (GMS), JHEP **10** (2015) 115
- **Gauld, Rojo, Rottoli, Sarkar, Talbert** (GRRST), JHEP **02** (2016) 130

Calculating the prompt flux of atmospheric neutrinos requires a synthesis of QCD, cosmic ray physics, and neutrino physics

Tracing a particle through the atmosphere

- The flux of particle j can be generically written as:

$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_j^{dec}} + \sum S(k \to j)$$

Interaction
decay
production

- This depends on the '**slant depth**' X measuring the atmosphere traversed:

$$X(l,\theta) = \int_l^\infty \rho(H(l',\theta)dl' \qquad H(l,\theta) \simeq l\cos\theta + \frac{l^2}{2R_0}\sin^2\theta$$

- Adopt a simple **isothermal model** of the atmosphere:

$$\rho(H) = \rho_0 e^{-\frac{H}{H_0}}$$

$$\rho_0 = 2.03 \times 10^{-3} \quad [\frac{g}{cm^3}]$$

$$H_0 = 6.4 \quad [km]$$

- Such that sample values of X are:

$$X = 0\,[\frac{g}{cm^2}] \;\; (space) \qquad X = 1300\,[\frac{g}{cm^2}] \;\; (\theta = 0)$$

$$X = \infty\,[\frac{g}{cm^2}] \;\; (ground) \qquad X = 36000\,[\frac{g}{cm^2}] \;\; (\theta = \frac{\pi}{2})$$

Cascade Formalism: Sources & Z-moments

$$S(k \to j) = \int_E^\infty \frac{\phi_k(E_k^{'})}{\lambda_k(E_k^{'})} \frac{dn(k \to j; E^{'}, E)}{dE} dE^{'}$$

- Assuming factorisation in energy vs. depth in atmosphere , the S-moments simplify:

$$S(k \to j) = \frac{\phi_k}{\lambda_k} Z_{kj}$$

  - For particle **production**:

$$Z_{kh} = \int_E^\infty dE' \frac{\phi_k(E', X, \theta)}{\phi_k(E, X, \theta)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(kA \to hY; E', E)}{dE}$$

$$\frac{dn(pA \to hY; E', E)}{dE} = \frac{1}{\sigma_{pA}(E')} \frac{d\sigma(pA \to hY; E', E)}{dE}$$

  - For particle **decay**:

$$Z_{h\to l} = \int_E^\infty dE' \frac{\phi_h(E', X)}{\phi_h(E, X)} \frac{d_h(E)}{d_h(E')} \frac{dn(h \to lY; E', E)}{dE}$$

$$\frac{dn(h \to lY; E', E)}{dE} = \frac{1}{\Gamma} \frac{d\Gamma}{dE}$$

Atmospheric Nucleon Flux

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} + S(NA \to NY) = -\frac{\phi_N}{\lambda_N} + Z_{NN}\frac{\phi_N}{\lambda_N}$$

Assume a **factorisation** of fluxes → $\phi_k(E, X) = \phi_k(E)\phi_k(X)$

Define the **interaction** length → $\lambda_N(E) = \dfrac{A}{N_0\sigma_{pA}(E)}$

Define the **attenuation** length → $\Lambda_N = \frac{\lambda_N}{(1-Z_{NN})}$

$$\frac{d\phi_N}{dX} = \frac{\phi_N}{\lambda_N}(Z_{NN} - 1) \to \frac{d\phi_N}{dX} + \frac{\phi_N}{\lambda_N}(1 - Z_{NN}) = 0$$

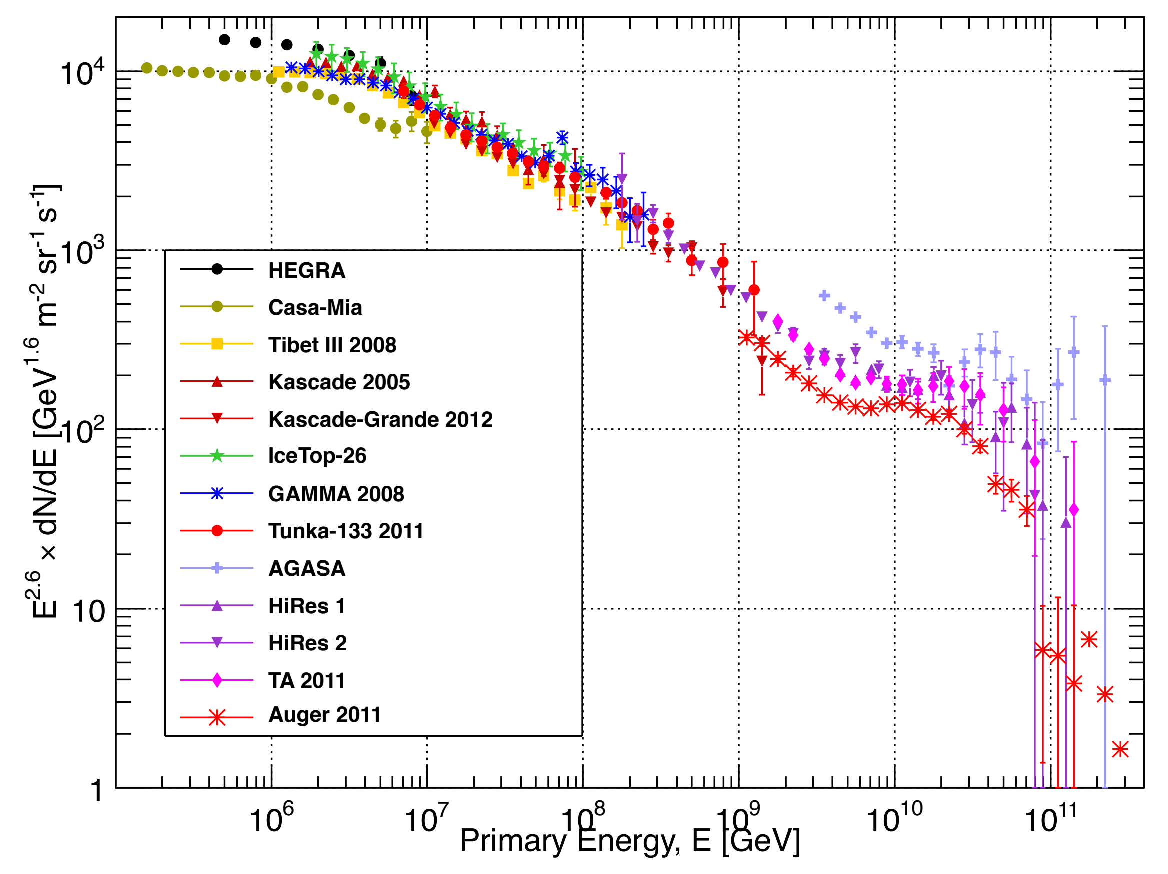
↓ ↓ ↓

$$\boxed{\phi_N = \phi_N^0(E)\ e^{-\frac{X}{\Lambda_N}}}$$

What is the primary nucleon flux?

Incident Cosmic Ray Fluxes: $\phi_N^0(E)$

- Cosmic ray spectrum constrained ~up to 10^5 GeV by balloon and space expts, e.g. **AMS** and **CREAM**

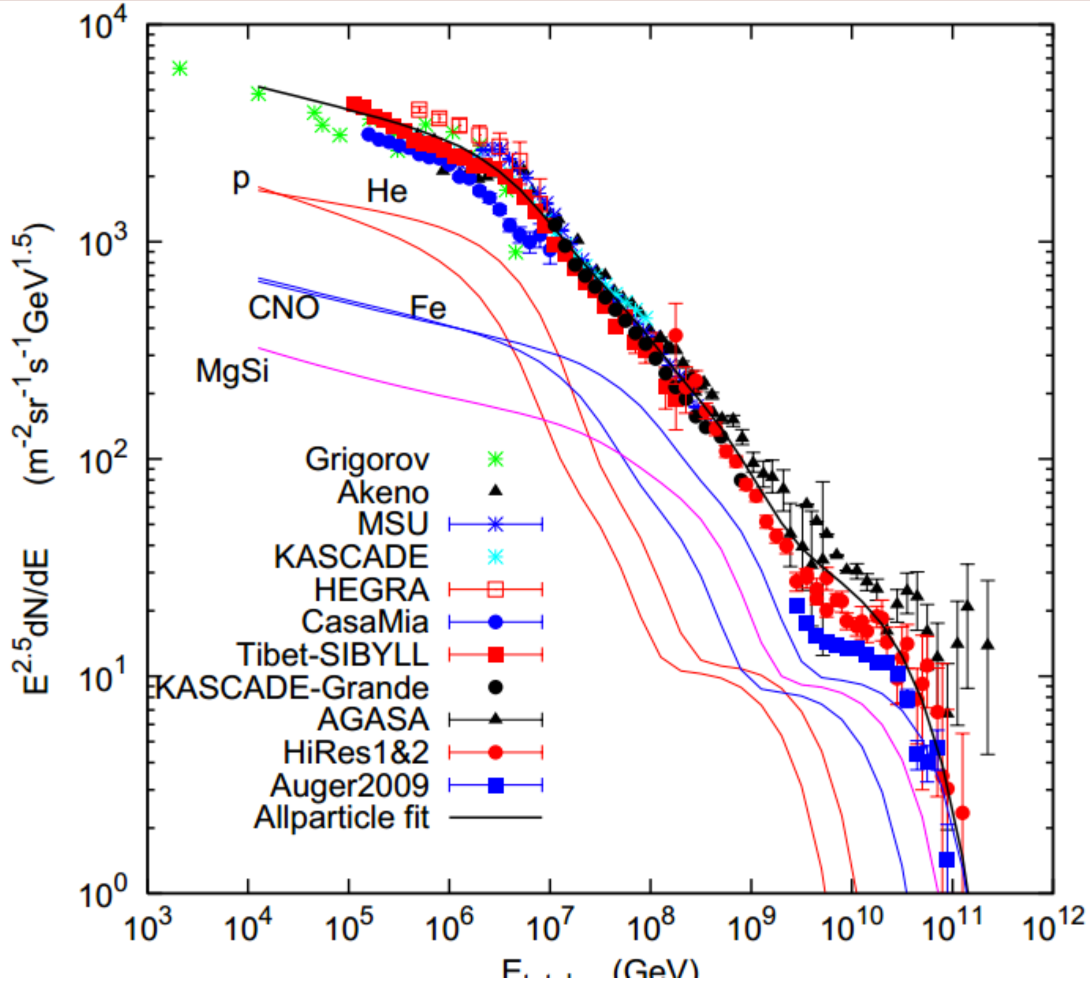


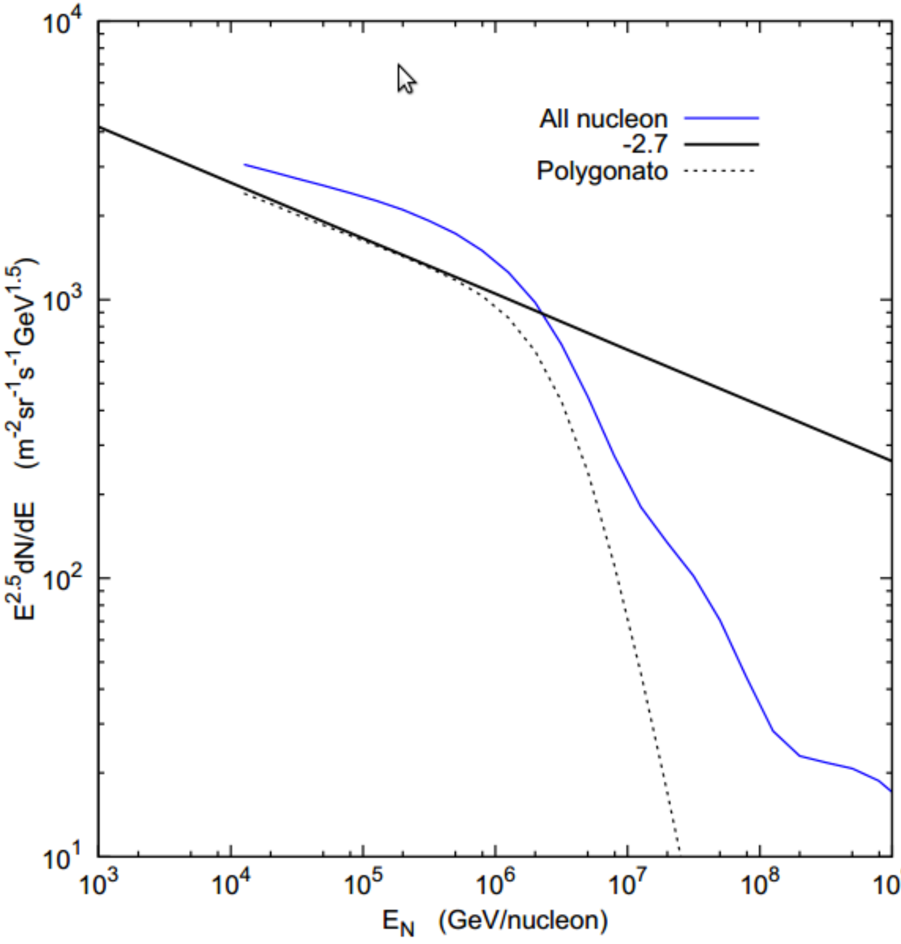
- Higher energies rely on air shower arrays, e.g. **Kascade, Auger & TA …** *many* uncertainties regarding CR composition

Does a 'Broken-Power-Law' (BPL) fit the data?

$$\phi_N^0(E) = \begin{cases} 1.7\ E^{-2.7} & for\ E < 5 \times 10^6\ \ GeV \\ 174\ E^{-3} & for\ E > 5 \times 10^6\ \ GeV \end{cases}$$

But cosmic rays are not just protons!

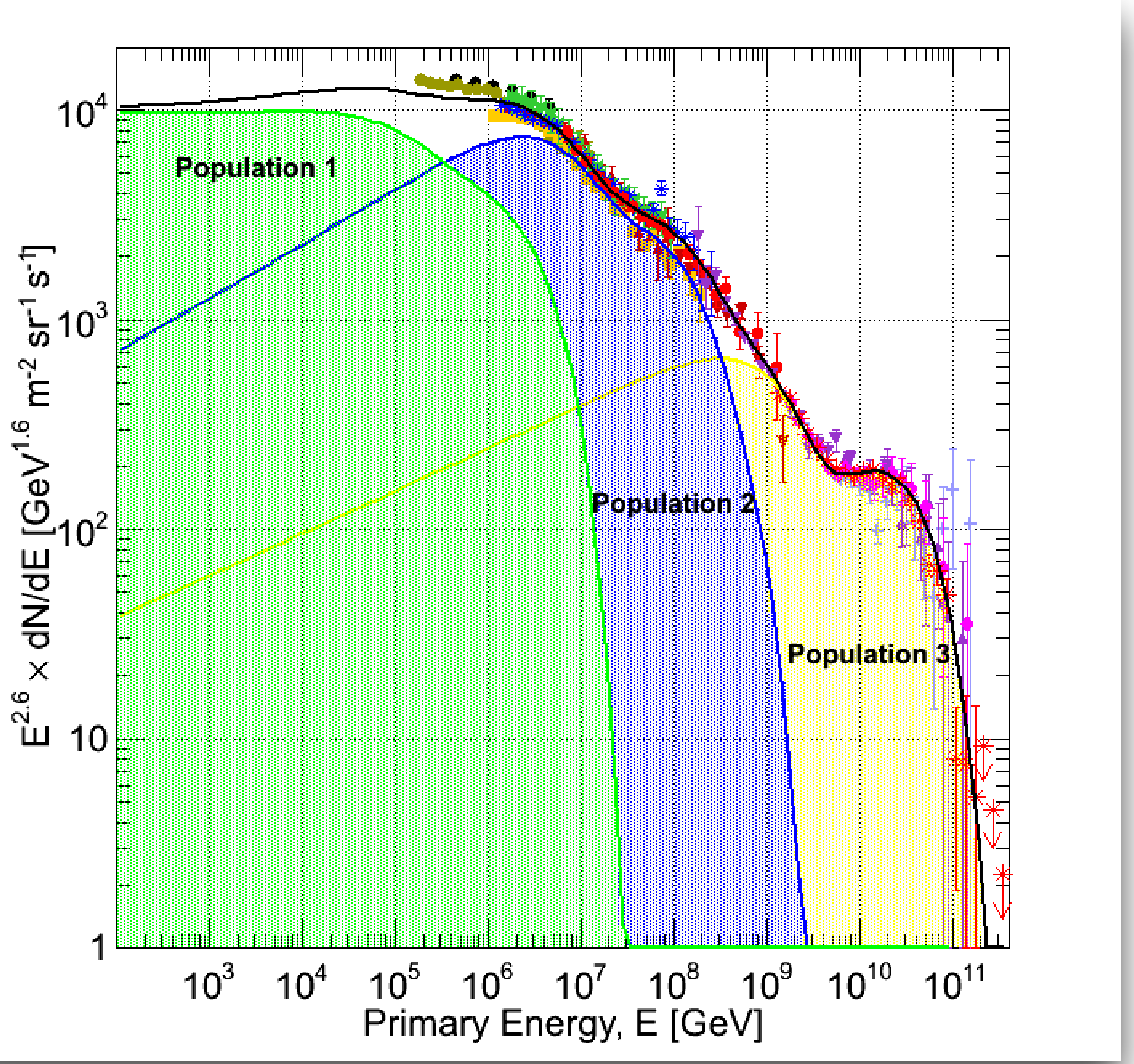




The composition is not very well known at high energies hence empirical parameterisations must be used (guided by some ‘theoretical’ expectations and the energy spectrum shape)

Gaisser *et al.* fits: $\phi_N^0(E)$

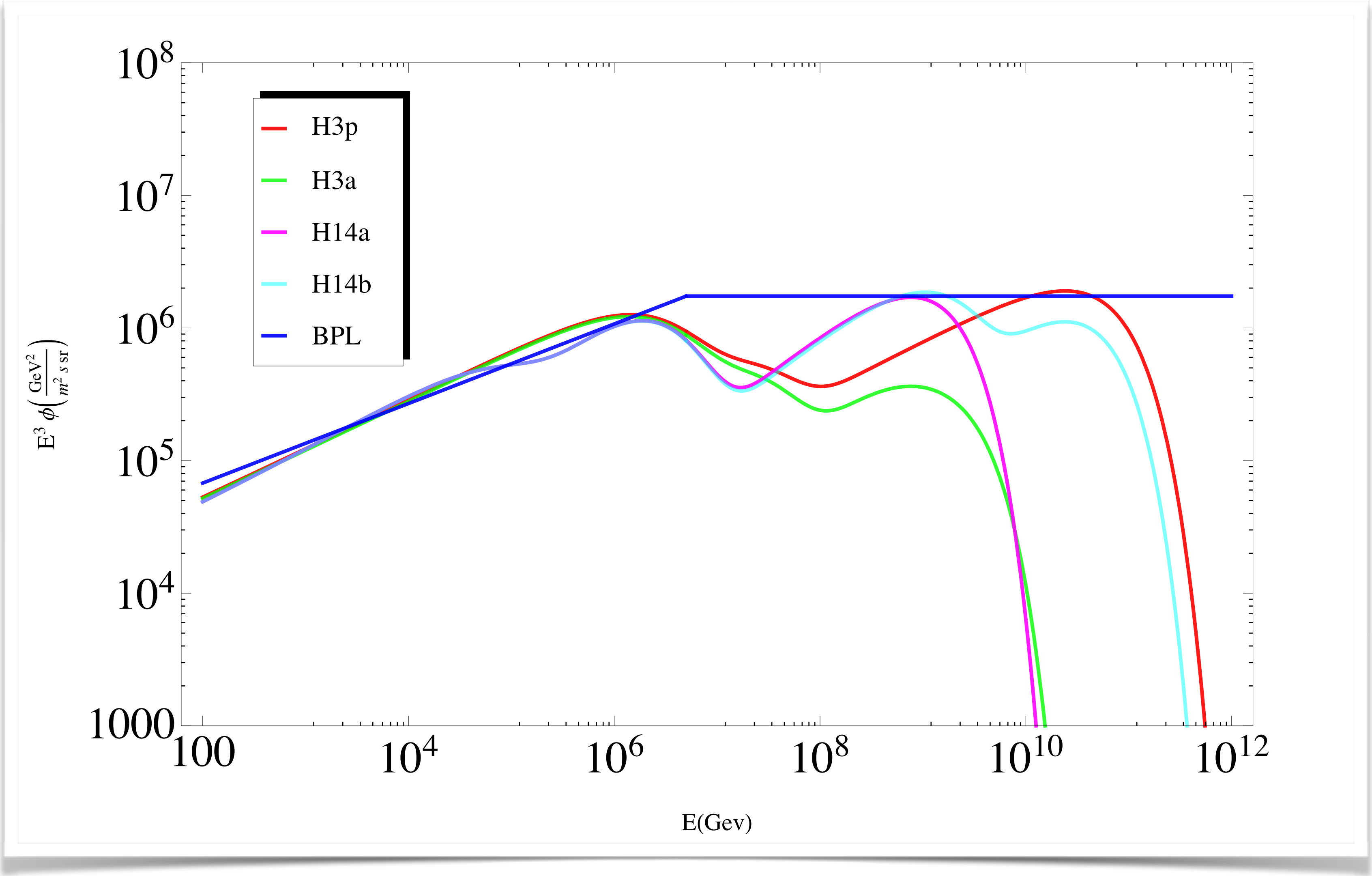
arXiv:astro-ph/1111.6675
arXiv:astro-ph/1303.3565



$$\phi_i(E) \;=\; \Sigma_{j=1}^{3}\, a_{i,j}\, E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$

	p	He	CNO	Mg-Si	Fe
Pop. 1:	7860	3550	2200	1430	2120
$R_c = 4$ PV	1.66 1	1.58	1.63	1.67	1.63
Pop. 2:	20	20	13.4	13.4	13.4
$R_c = 30$ PV	1.4	1.4	1.4	1.4	1.4
Pop. 3:	1.7	1.7	1.14	1.14	1.14
$R_c = 2$ EV	1.4	1.4	1.4	1.4	1.4
Pop. 3(*):	200	0.0	0.0	0.0	0.0
$R_c = 60$ EV	1.6				

BPL vs. Gaisser parameterisations



- The effect of the new parameterisations is **significant above ~10^6 GeV …**

Atmospheric hadron flux

$$\frac{d\phi_h}{dX} = -\frac{\phi_h}{\rho d_h(E)} - \frac{\phi_h}{\lambda_h} + Z_{hh}\frac{\phi_h}{\lambda_h} + Z_{ph}\frac{\phi_p}{\lambda_p}$$

- In the low energy limit, the probability for hadron interaction is minimal, so we can
- **neglect the interaction and regeneration terms**:

$$\phi_h|_{low} = \frac{Z_{ph}}{\Lambda_p(1 - Z_{pp})}\rho d_h \phi_p(E) e^{-\frac{X}{\Lambda_p}}$$

- At high energies the decay length becomes large, hence we **neglect the decay term**:

$$\phi_h|_{high} = \frac{Z_{ph}\phi_p(E)}{(1 - Z_{pp})} \frac{(e^{-\frac{X}{\Lambda_h}} - e^{-\frac{X}{\Lambda_p}})}{(1 - \frac{\Lambda_p}{\Lambda_h})}$$

- These solutions then **feed into asymptotic solutions for the final leptonic flux** (note that the low-energy solution scales with an additional power of E):

$$\begin{array}{ll} high & \phi_h \propto \phi_p \\ low & \phi_h \propto E\phi_p \end{array}$$

Lepton flux @ detector

1. $$\frac{d\phi_p}{dX} = -\frac{\phi_p}{\lambda_p} + Z_{pp}\frac{\phi_p}{\lambda_p}$$

2. $$\frac{d\phi_h}{dX} = -\frac{\phi_h}{\rho d_h(E)} - \frac{\phi_h}{\lambda_h} + Z_{hh}\frac{\phi_h}{\lambda_h} + Z_{ph}\frac{\phi_p}{\lambda_p}$$

3. $$\frac{d\phi_l}{dX} = \sum_h Z_{h\to l}\frac{\phi_h}{\rho d_h}$$

Full series of **cascade equations**, from incoming cosmic ray nucleons to final state leptons

$$\phi_l|_{low} = \phi_p(E)\; Z^{low}_{h\to l}\frac{Z_{ph}}{(1-Z_{pp})}$$

$$\phi_l|_{high} = \frac{Z_{h\to l}\epsilon_h}{E}\frac{Z_{ph}\phi_p(E)}{(1-Z_{pp})(1-\frac{\Lambda_p}{\Lambda_h})}\ln\frac{\Lambda_h}{\Lambda_p}$$

Geometric Interpolation:

$$\phi_l = \sum_h \frac{\phi_l^{low}\phi_l^{high}}{\phi_l^{low}+\phi_l^{high}}$$

- Our final flux includes all (interpolated) contributions from **charmed hadrons**

The QCD input: Z_{ph}

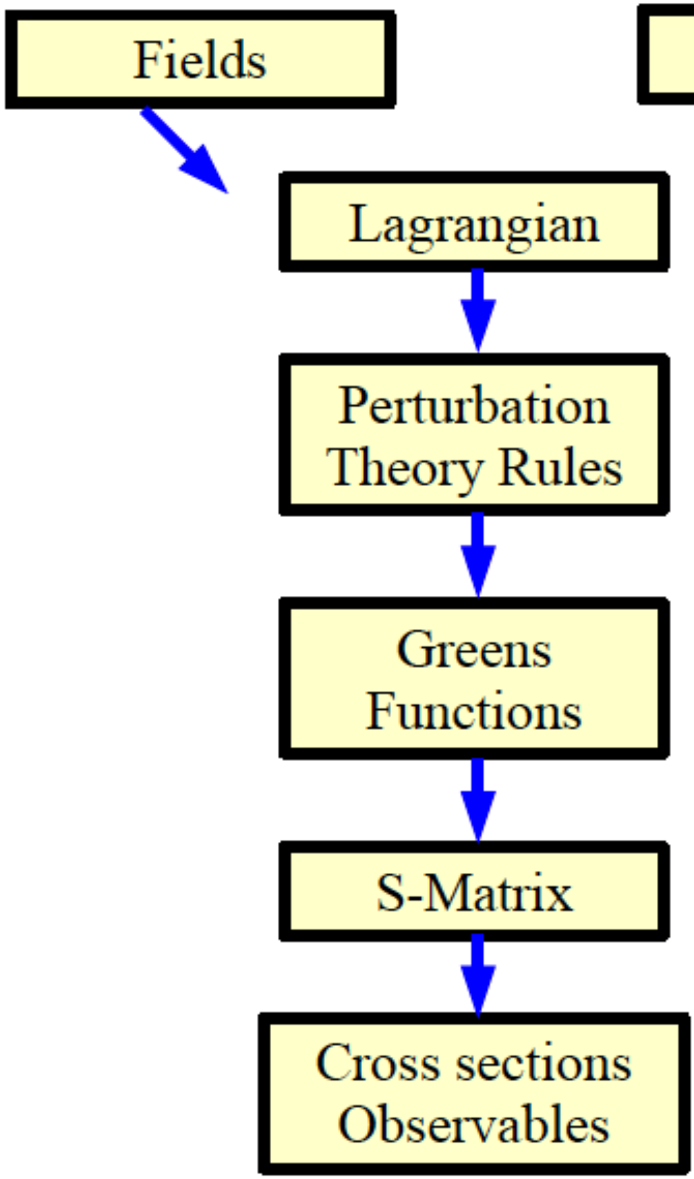
$$Z_{ph} = \int_E^\infty dE' \frac{\phi_p(E')}{\phi_p(E)} \frac{A}{\sigma_{pA}(E)} \frac{d\sigma(pp \to c\bar{c}Y; E', E)}{dE}$$

- The **differential cross-section** can be calculated in a variety of formalisms, e.g. the ERS 'colour dipole model' which is *empirical* (but is the basis of the benchmark calculation)
- However, **perturbative QCD (**with **DGLAP evolution)** *can* describe charm production for the *entire* kinematical region of interest, hence can calculate with **Next-to-Leading-Order QCD+Parton Shower Monte-Carlo event generators**
- Boosting from CM to the rest frame of the (atmospheric) fixed target, one finds:

$$\boxed{\sqrt{s} = 7\ [TeV] \ \longleftrightarrow \ E_b = 2.6 \times 10^7\ [GeV]}$$

- Thus there is **complementarity with LHC physics**. We can predict the prompt neutrino flux at energies **up to 10^7 GeV** … at these energies, the charm production cross section is dominated by **gluon fusion**, hence we are sensitive to the behaviour of the **gluon PDF** (parton distribution function) **at small-*x***

The (perturbative) QCD approach



Fields

Symmetry

Lagrangian

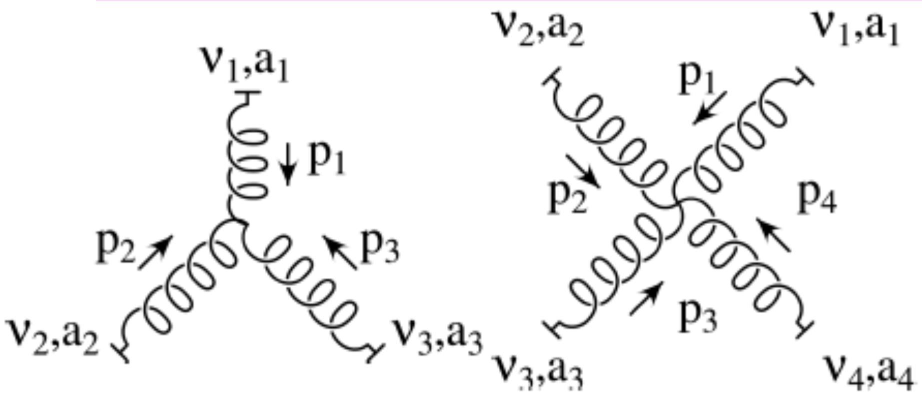
Perturbation Theory Rules

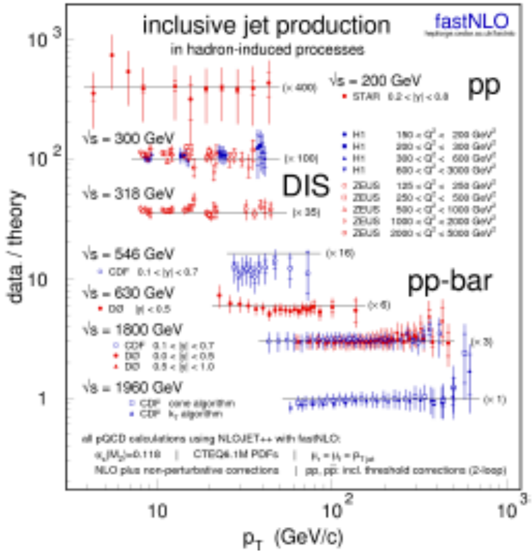
Greens Functions

S-Matrix

Cross sections Observables

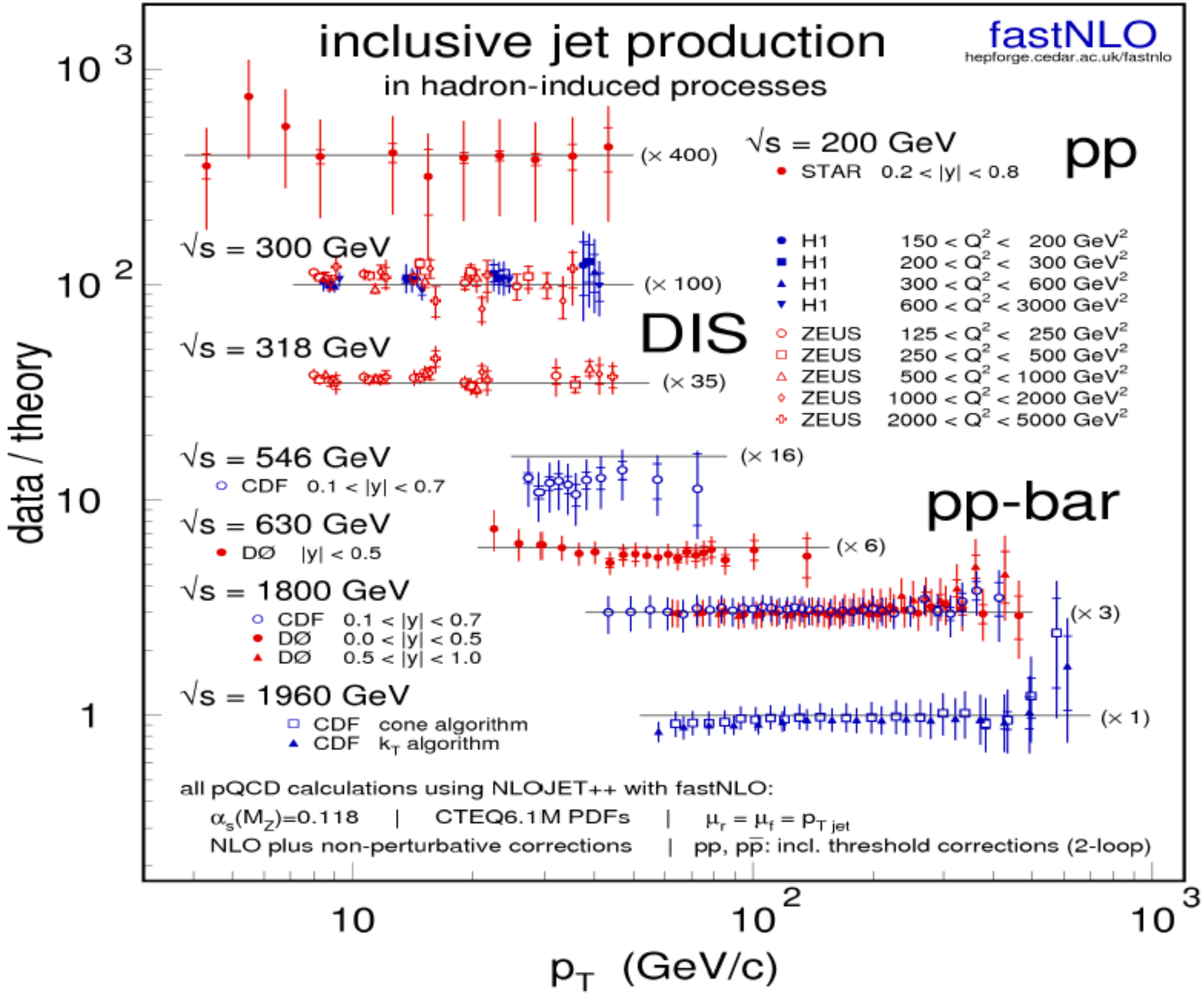
$$\begin{aligned}\mathcal{L}_{\rm QCD} &= \bar{\psi}_i\left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij}\right)\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a \\ &= \bar{\psi}_i(i\gamma^\mu\partial_\mu - m)\psi_i - gG^a_\mu\bar{\psi}_i\gamma^\mu T^a_{ij}\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a\,,\end{aligned}$$





Courtesy: Fred Olness

… does a great job!



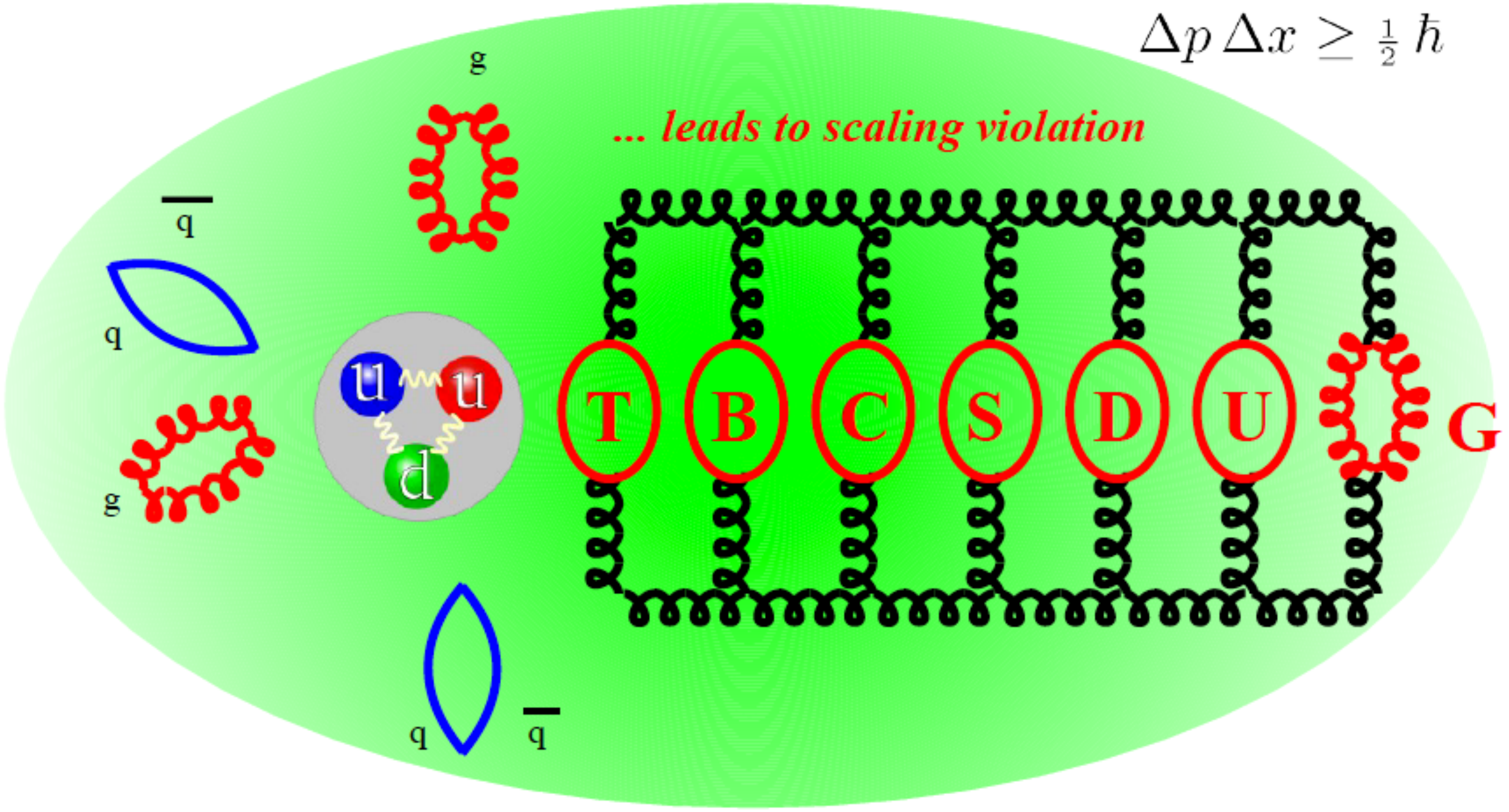
Courtesy: Fred Olness

… of understanding high energy collisions

Proton is a complex object

$$\Delta E\,\Delta t \geq \tfrac{1}{2}\,\hbar$$

$$\Delta p\,\Delta x \geq \tfrac{1}{2}\,\hbar$$



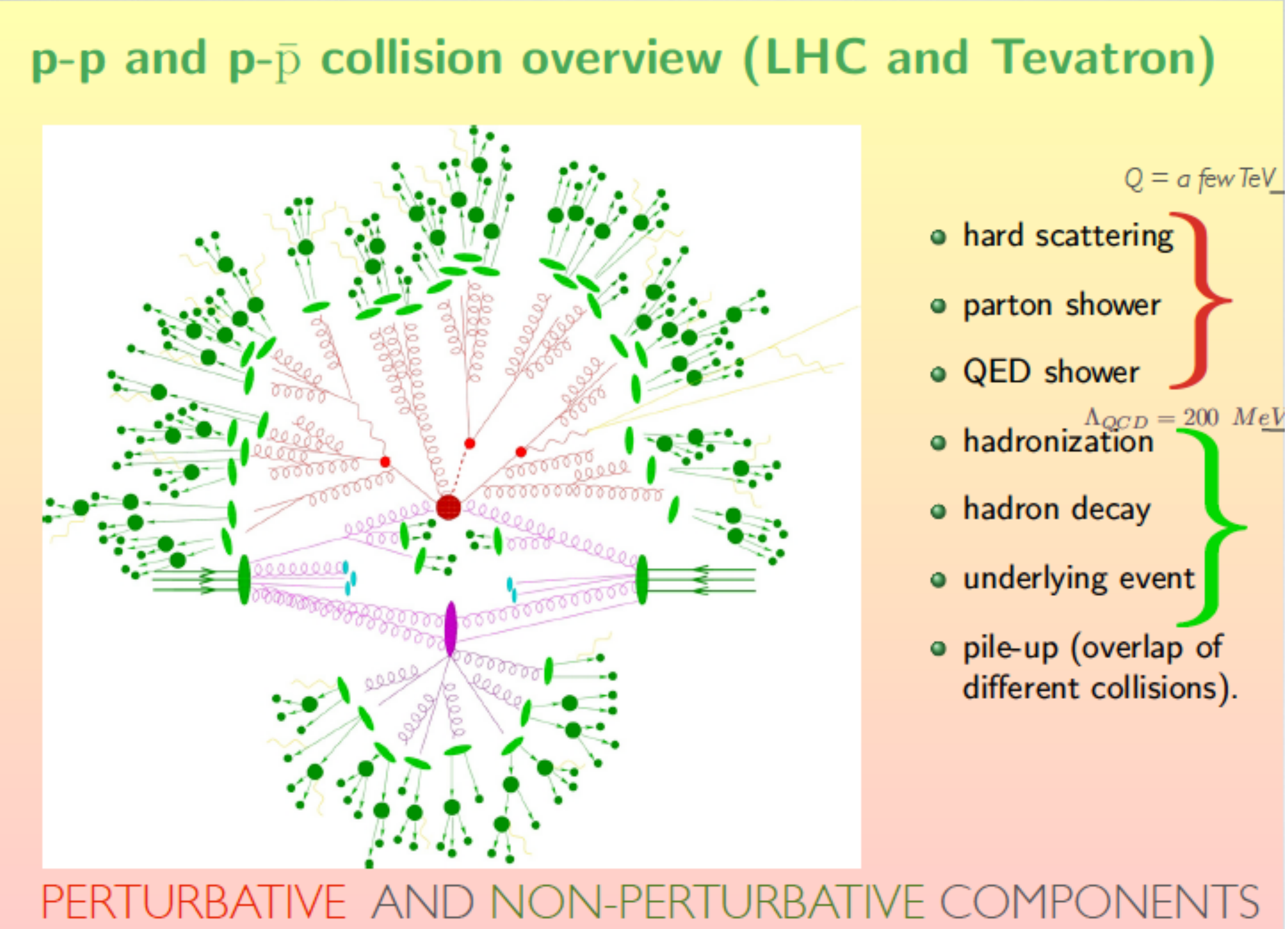
… leads to scaling violation

$$\Lambda_{QCD} \sim 200\,\mathrm{MeV}$$

m_t	m_b	m_c	m_s	m_d	m_u	m_g
175	4.5	1.3	0.3	0.00?	0.00?	0

Courtesy: Fred Olness

The QCD input: Z_{ph}



p-p and p-$\bar{\text{p}}$ collision overview (LHC and Tevatron)

$Q =$ a few TeV

- hard scattering
- parton shower
- QED shower

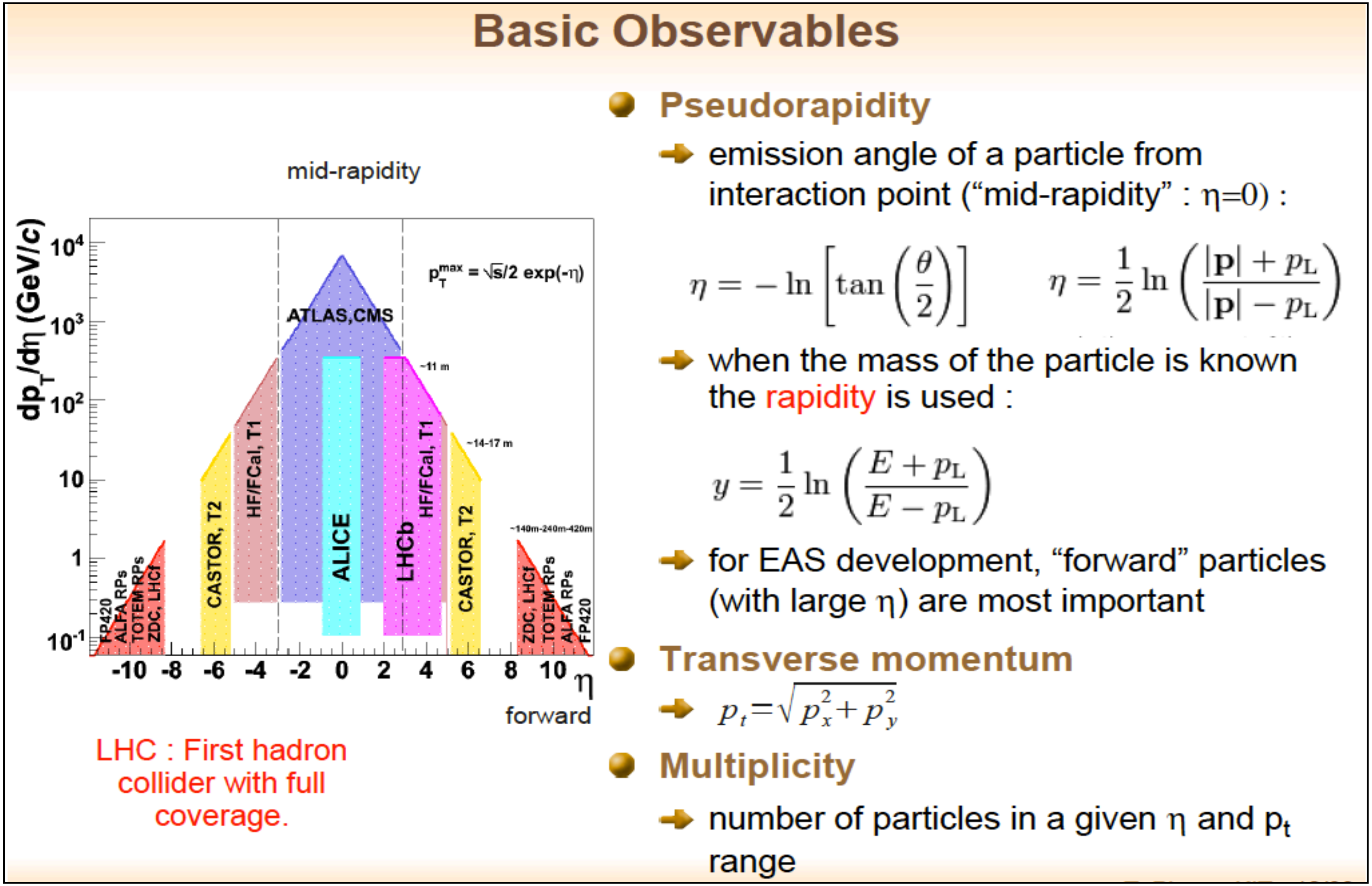
$\Lambda_{QCD} = 200\ MeV$

- hadronization
- hadron decay
- underlying event
- pile-up (overlap of different collisions).

PERTURBATIVE AND NON-PERTURBATIVE COMPONENTS

Courtesy: Maria Garzelli

… can now confront with LHC data!



Basic Observables

LHC : First hadron collider with full coverage.

- **Pseudorapidity**
  - emission angle of a particle from interaction point ("mid-rapidity" : η=0) :

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \qquad \eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}|+p_L}{|\mathbf{p}|-p_L}\right)$$

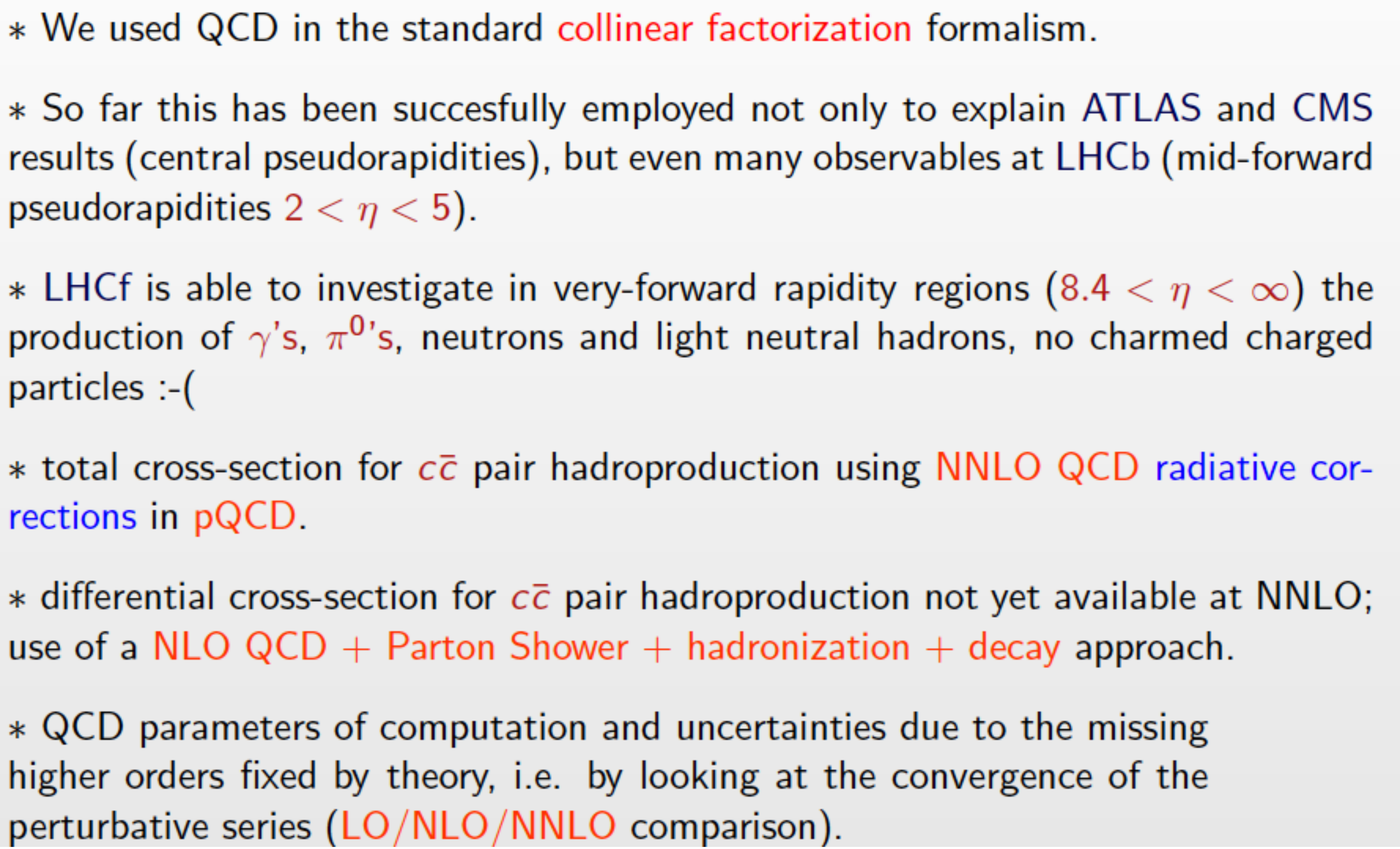
  - when the mass of the particle is known the rapidity is used :

$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

  - for EAS development, "forward" particles (with large η) are most important
- **Transverse momentum**
  - $p_t = \sqrt{p_x^2 + p_y^2}$
- **Multiplicity**
  - number of particles in a given η and p_t range

Cosmic ray interactions probe the very 'forward' region

The QCD input: Z_{ph}



$*$ We used QCD in the standard collinear factorization formalism.

$*$ So far this has been succesfully employed not only to explain ATLAS and CMS results (central pseudorapidities), but even many observables at LHCb (mid-forward pseudorapidities $2 < \eta < 5$).

$*$ LHCf is able to investigate in very-forward rapidity regions $(8.4 < \eta < \infty)$ the production of γ's, π^0's, neutrons and light neutral hadrons, no charmed charged particles :-(

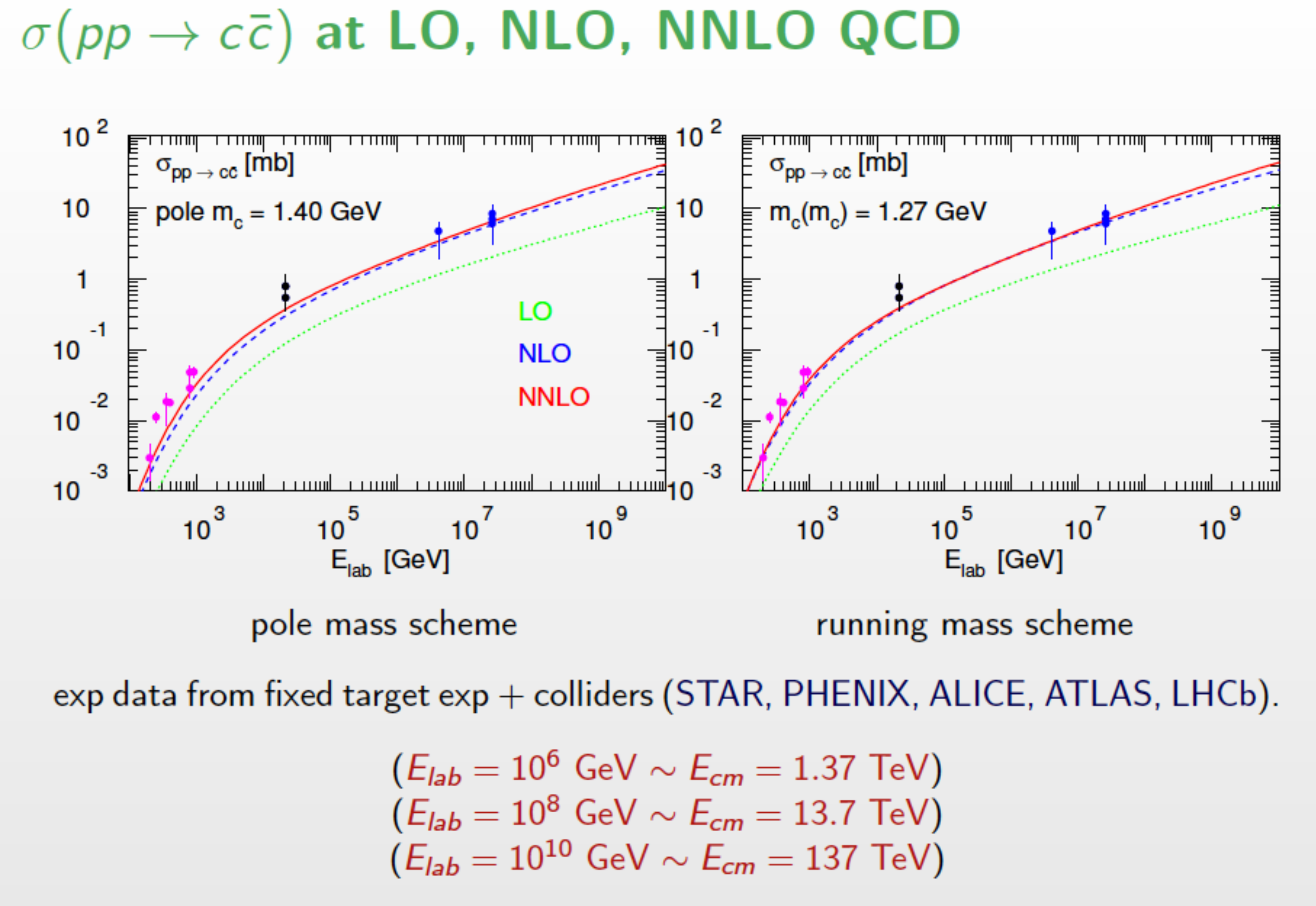
$*$ total cross-section for $c\bar{c}$ pair hadroproduction using NNLO QCD radiative corrections in pQCD.

$*$ differential cross-section for $c\bar{c}$ pair hadroproduction not yet available at NNLO; use of a NLO QCD + Parton Shower + hadronization + decay approach.

$*$ QCD parameters of computation and uncertainties due to the missing higher orders fixed by theory, i.e. by looking at the convergence of the perturbative series (LO/NLO/NNLO comparison).

Courtesy: Maria Garzelli

Predicting total #-secn in perturbative QCD



$\sigma(pp \to c\bar{c})$ at LO, NLO, NNLO QCD

pole mass scheme

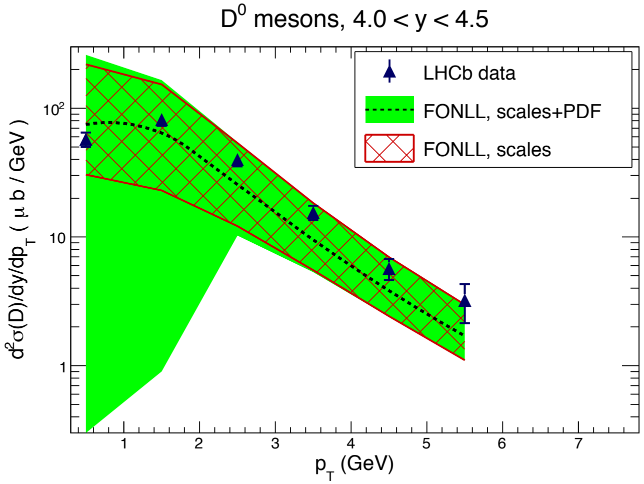
running mass scheme

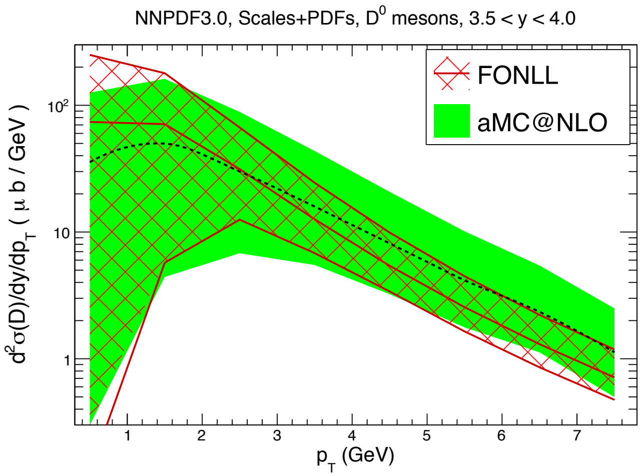
exp data from fixed target exp + colliders (STAR, PHENIX, ALICE, ATLAS, LHCb).

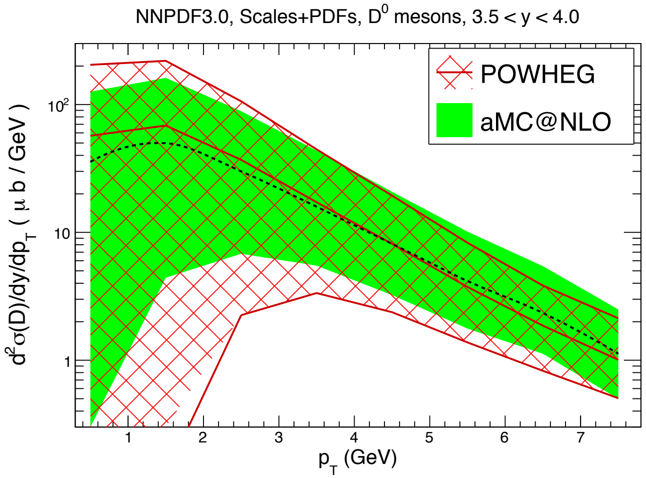
$$(E_{lab} = 10^6 \text{ GeV} \sim E_{cm} = 1.37 \text{ TeV})$$
$$(E_{lab} = 10^8 \text{ GeV} \sim E_{cm} = 13.7 \text{ TeV})$$
$$(E_{lab} = 10^{10} \text{ GeV} \sim E_{cm} = 137 \text{ TeV})$$

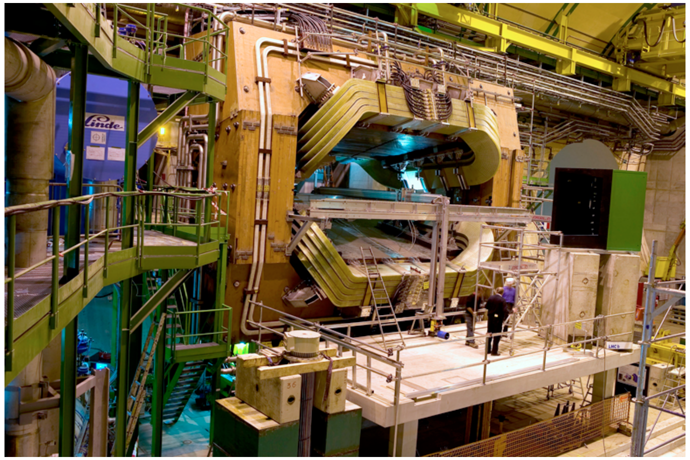
Courtesy: Maria Garzelli

Forward Charm Production & LHCb





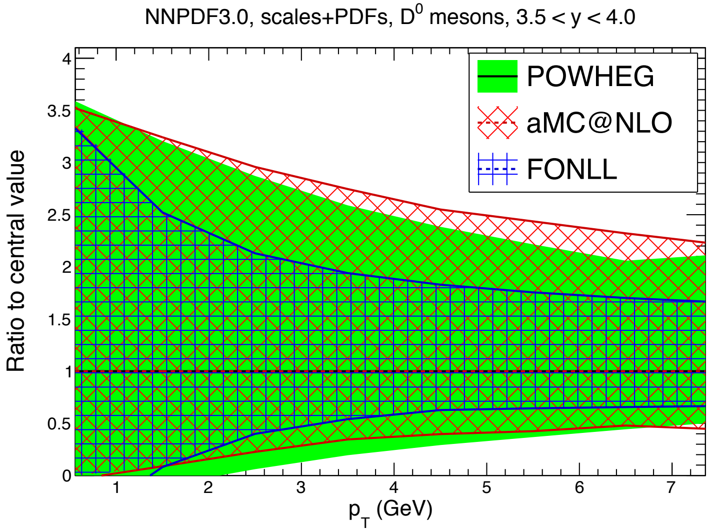




$$\boxed{\sqrt{s} = 7\ [TeV]}$$

arXiv:1506.08025

arXiv:1302.2864 (LHCb)



- We first **validate our NLO predictions** for forward charm production against recent LHCb data … finding **good agreement** between the 3 calculation schemes

arXiv: 1506.08025

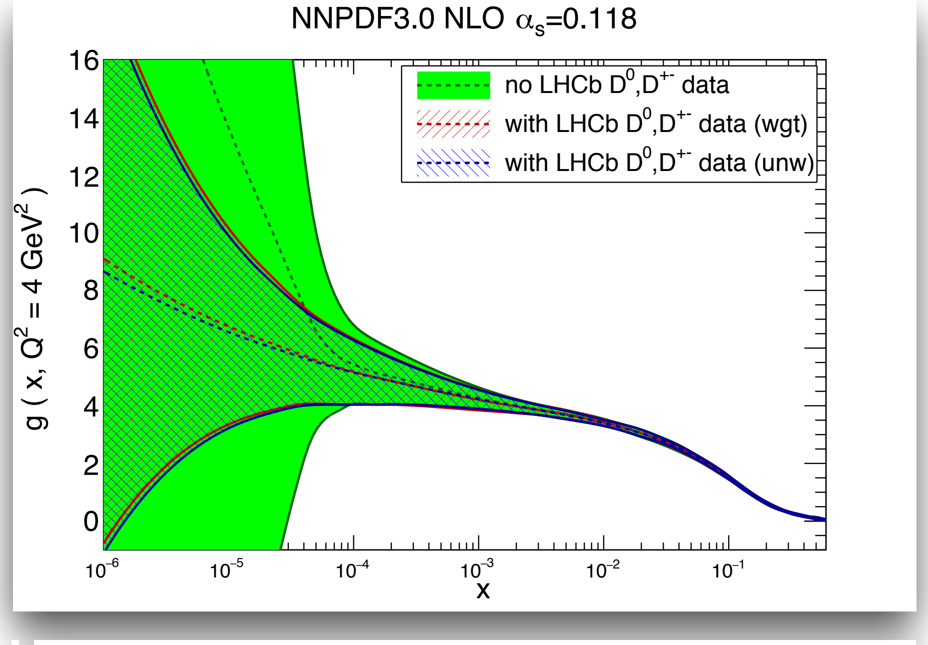
Small-x Gluon NNPDF: LHCb constraints

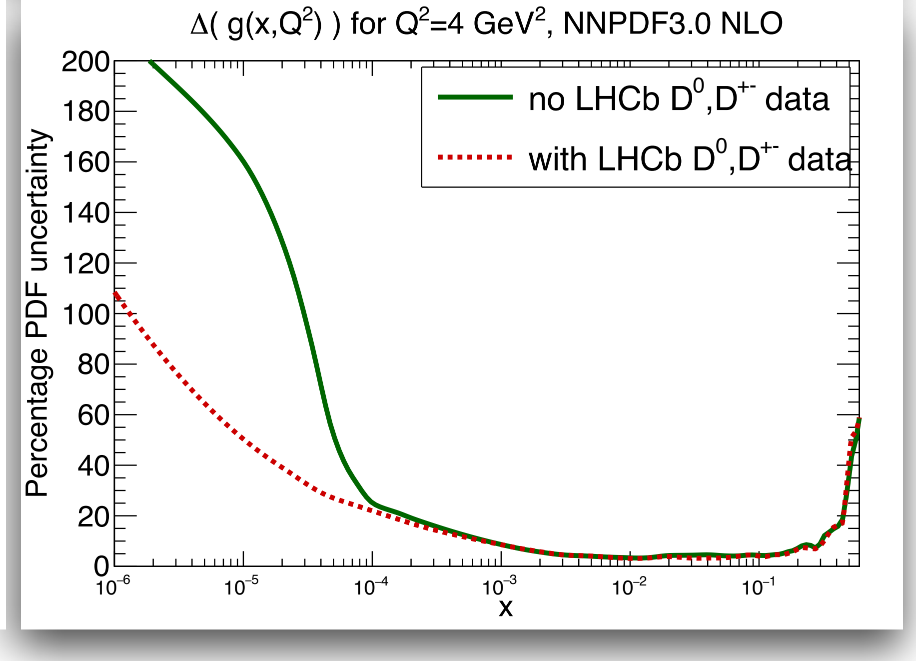
- We utilise charm production data from LHCb to **reduce the uncertainties in the small-x gluon PDF**

- By implementing a **Bayesian reweighting technique**, the impact of the new data is estimated … 75 data points added to NNPDF3.0 analysis

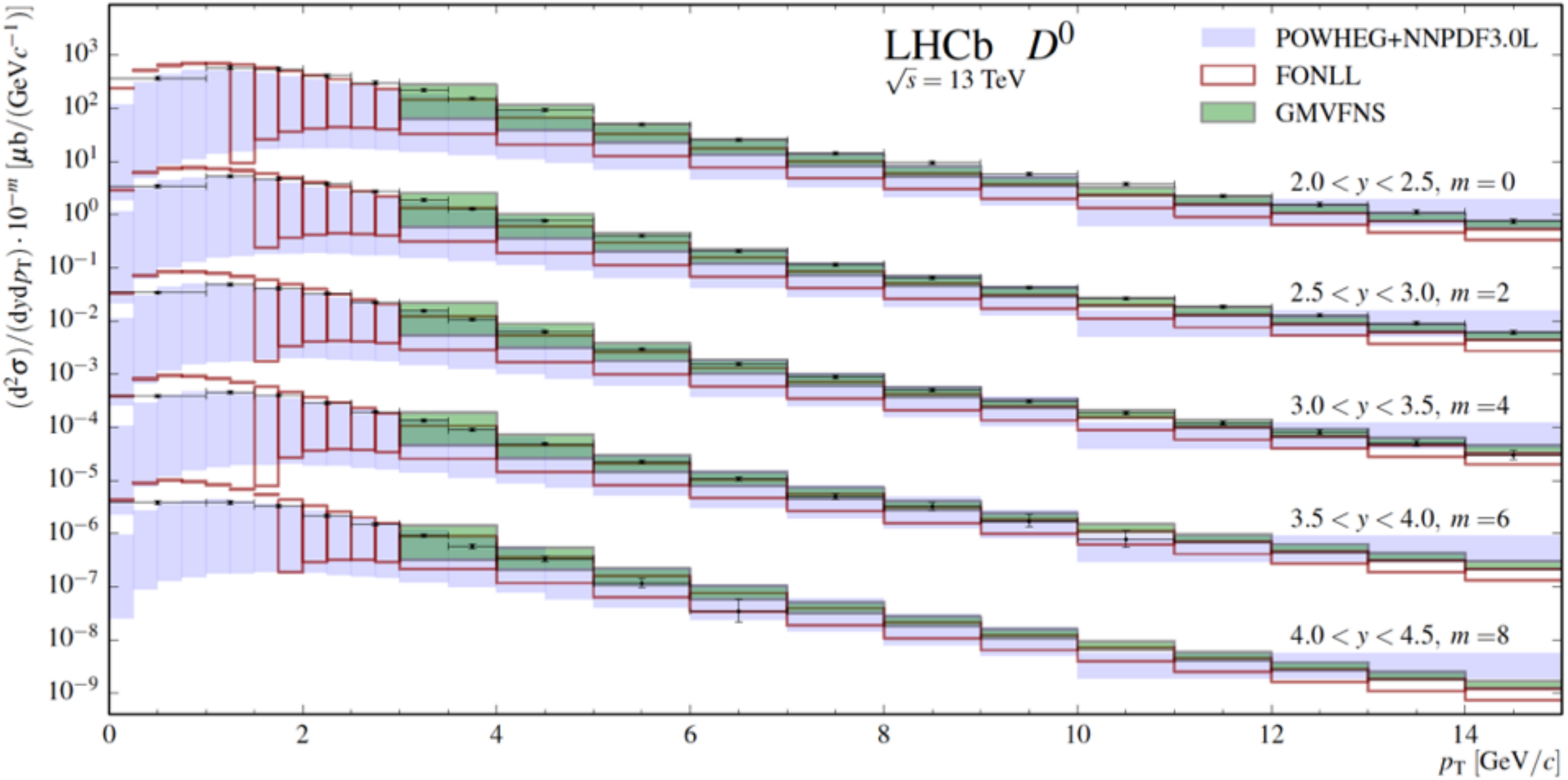
- The impact is negligible for $x > 10^{-4}$, but substantial in the smaller-x region where data was previously unavailable. At **$x \sim 10^{-5}$**, we achieve a **3x reduction in uncertainty**

- We utilise these improved PDFs to make **predictions for 13 TeV** physics





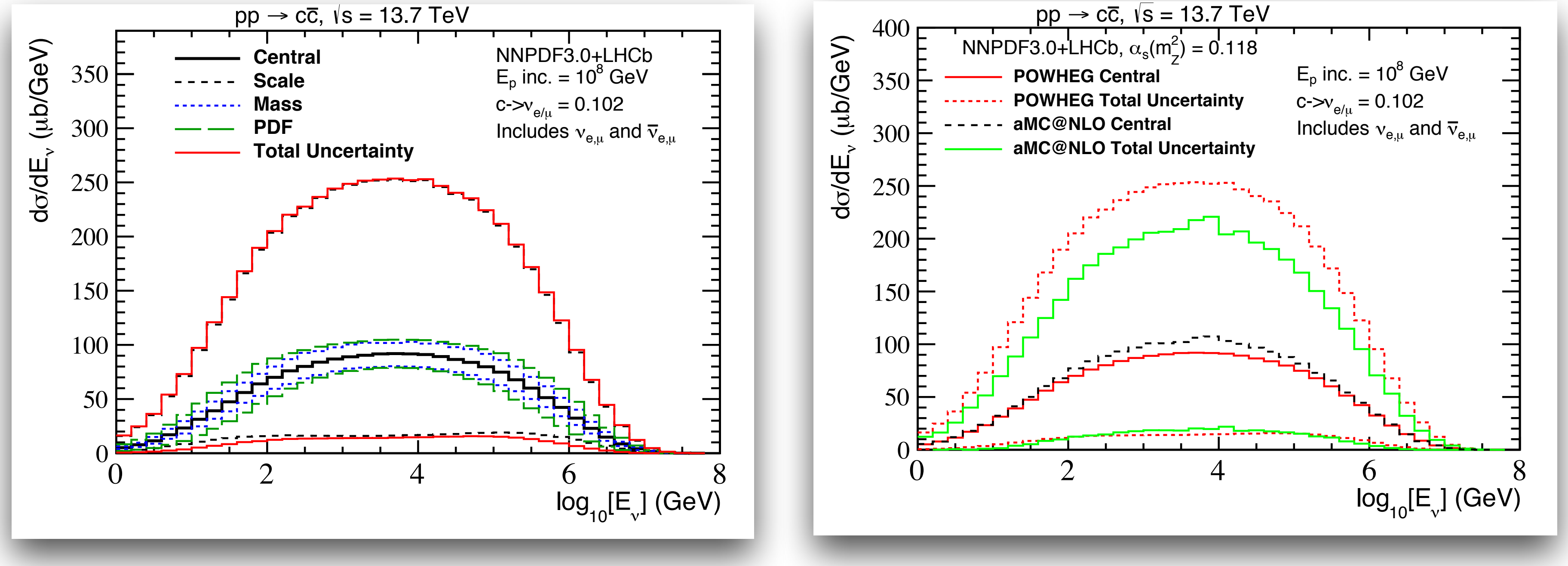
Validation with LHC Run II data @13 TeV



Our new result: Z_{ph}

$$Z_{ph} = \int_E^\infty dE' \frac{\phi_p(E')}{\phi_p(E)} \frac{A}{\sigma_{pA}(E)} \frac{d\sigma(pp \to c\bar{c}Y; E', E)}{dE}$$

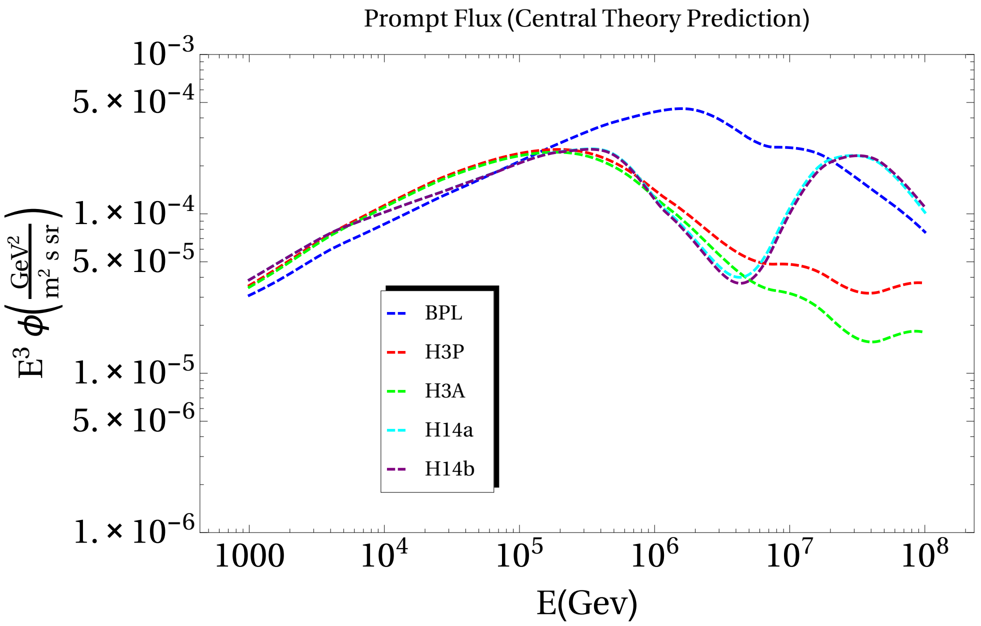
- The differential cross-section is generated at various E′ between 10^3 and 10^{10} GeV with **POWHEG+PYTHIA8**, and incorporates our updated **NNPDF3.0+LHCb** … Cross-checks made with aMC@NLO



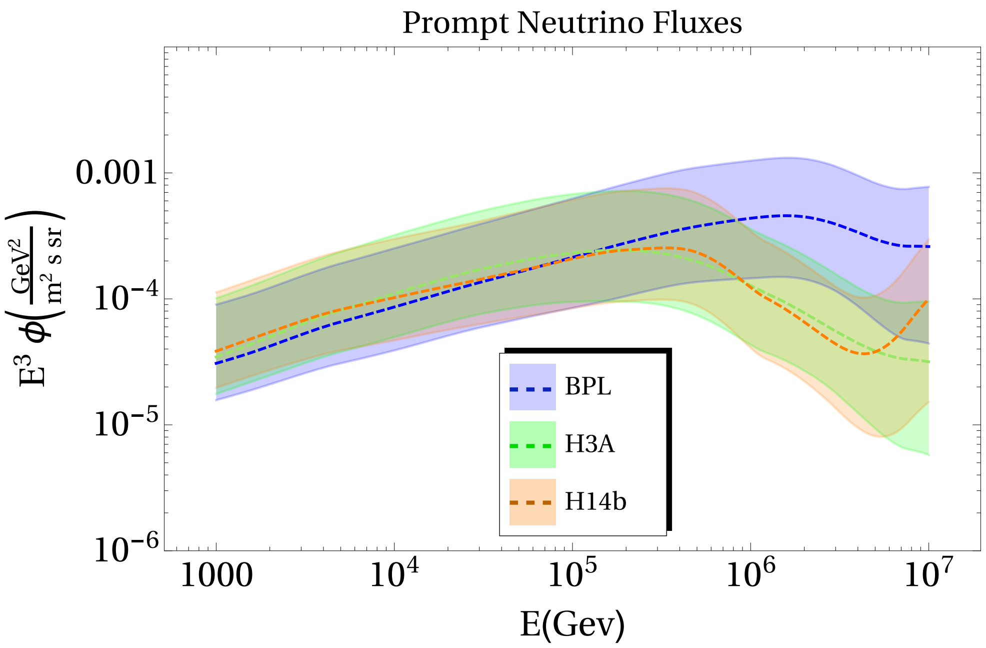
Gauld, Rojo, Sarkar, Rotolli, Talbert, arXiv:1506.08025

Benchmark NNPDF3.0+LHCb data

- Predictions for **prompt atmospheric neutrino flux** adopting the broken power-law (BPL) as well as H3A and H3P cosmic-ray spectra



Prompt Flux (Central Theory Prediction)

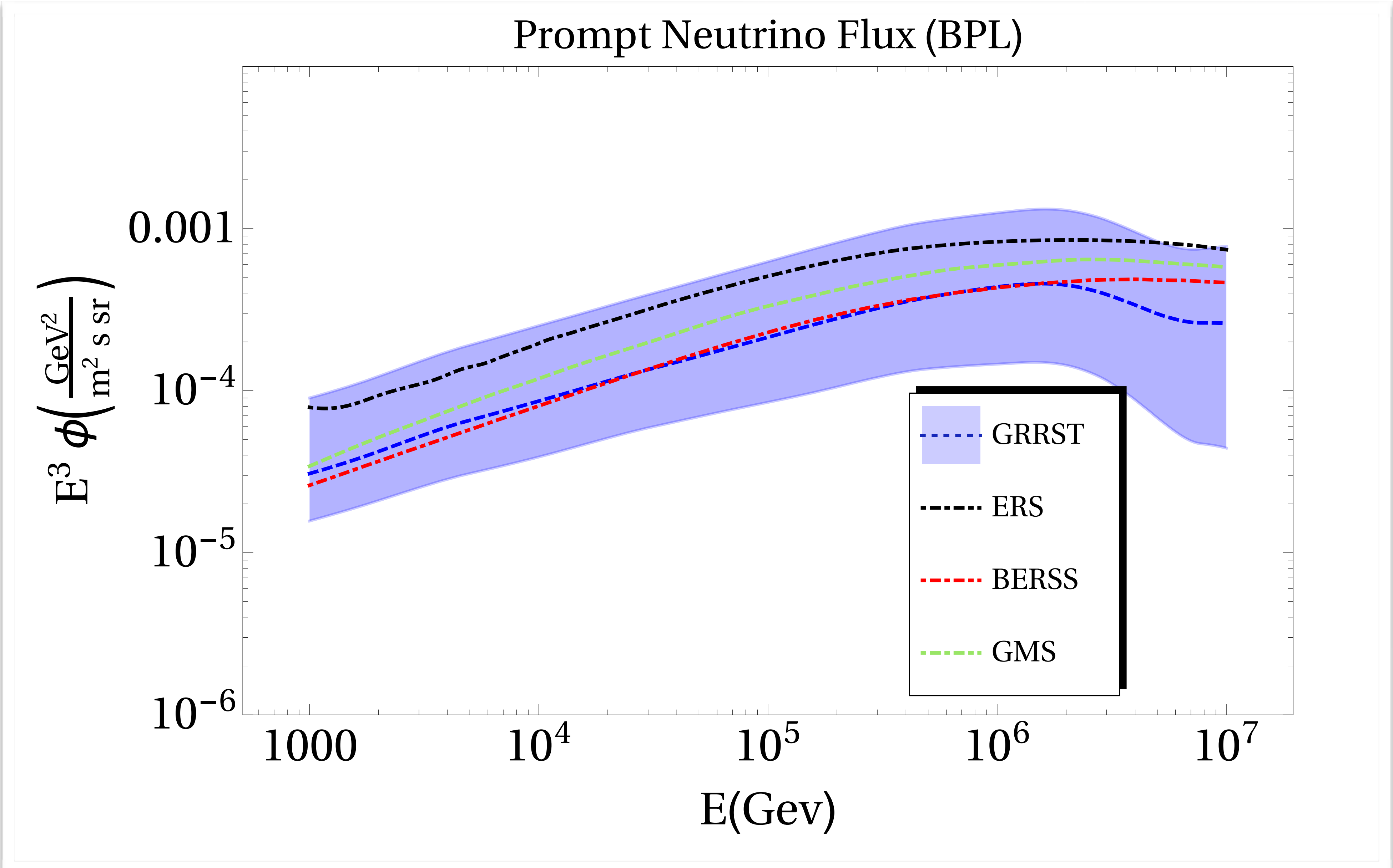


Prompt Neutrino Fluxes

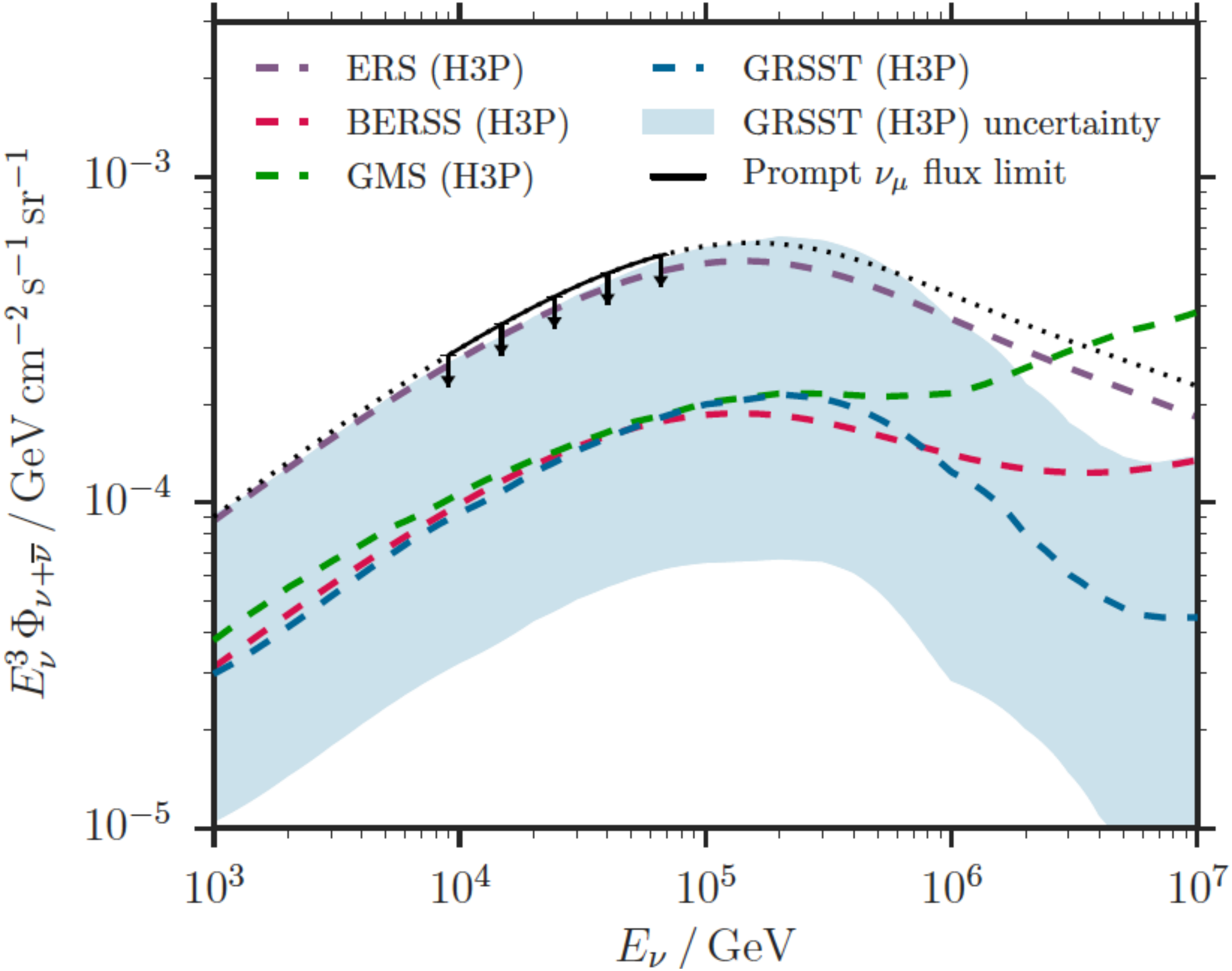
****Scale, PDF, and charm mass uncertainty****

- Different cosmic ray spectrum parameterisations
- => **significant differences in the expected flux above ~100 TeV**

Consistency with previous calculations



Consistent with recent IceCube data



arXiv:1607.08006

Conclusions

- The most important background for the detection of cosmic neutrinos is the (uncertain) flux of **prompt atmospheric neutrinos**

- This can be calculated in **perturbative QCD**, incorporating:

  1. State-of-the-art calculation of **charmed hadron production** in the **forward region**, validated against recent LHCb measurements

  2. A **small-x gluon PDF** which is also constrained by LHCb data

- Current estimates are consistent with previous studies but provide a **more reliable estimate of uncertainties** and alleviate the tension between the previous empirical (ERS) calculation and IceCube data

The prompt flux should be seen *soon* (and provide a probe of low-x QCD)