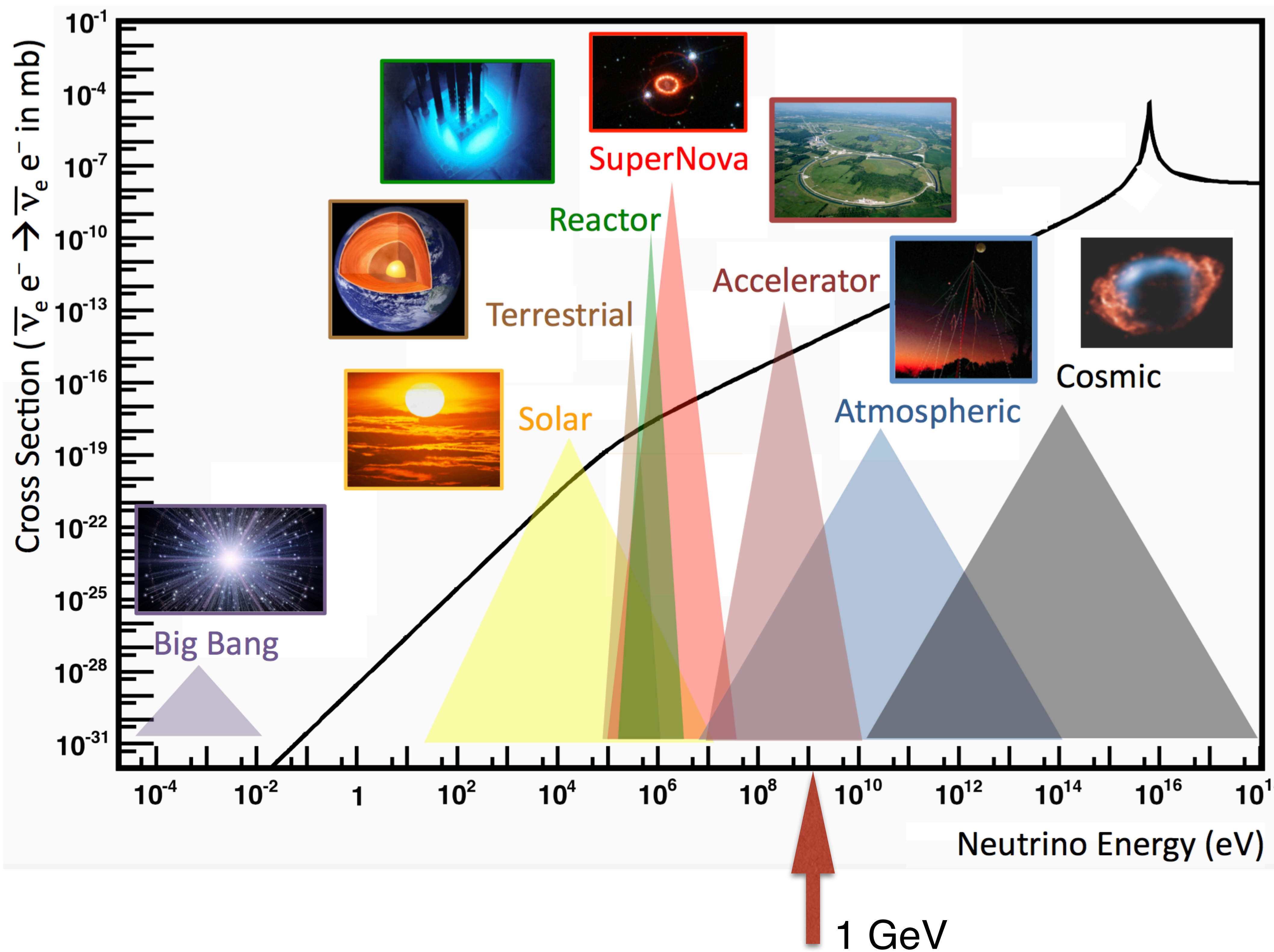
Neutrino Production and interaction II (Neutrinos from heavy flavor)

Yu Seon Jeong

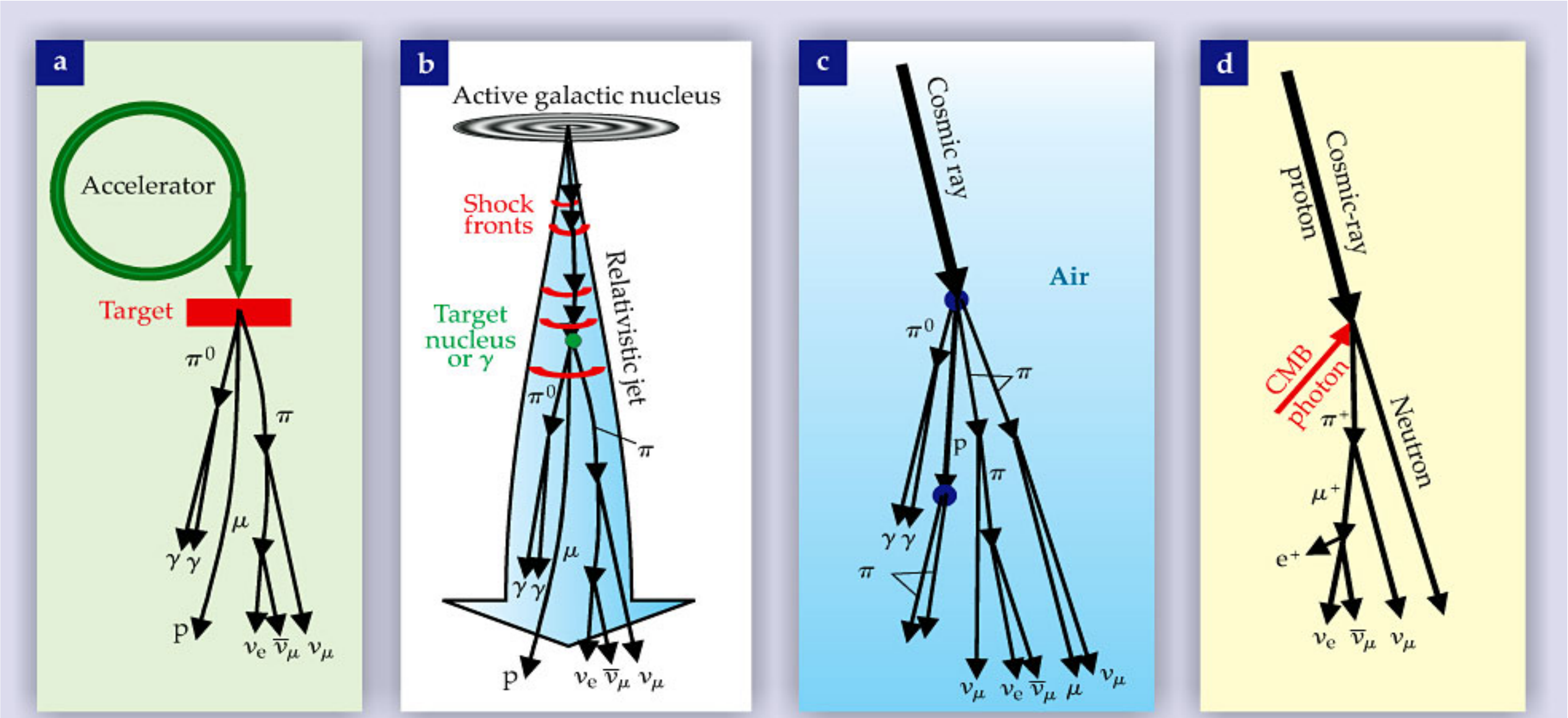
(Chung-Ang University)

CANU2, Jan. 20, 2021

Cross section

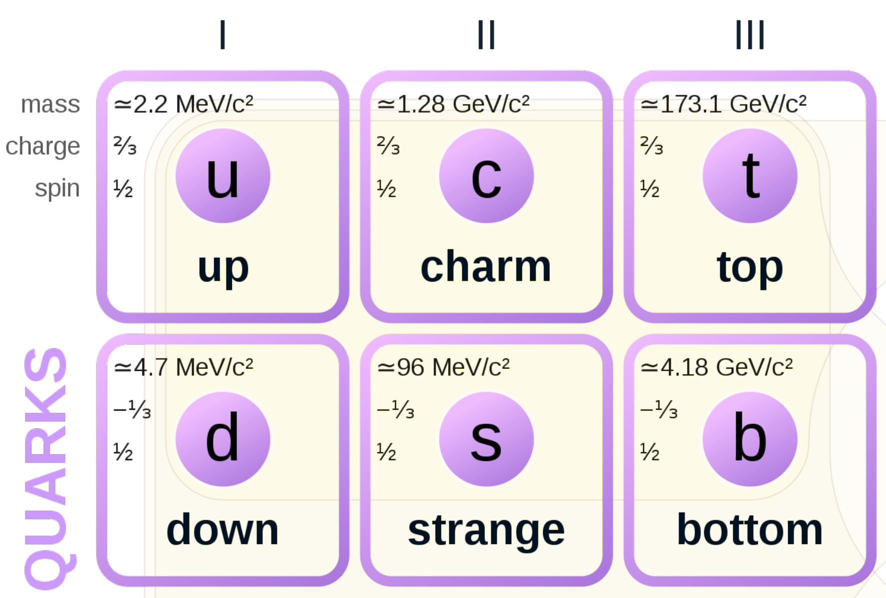


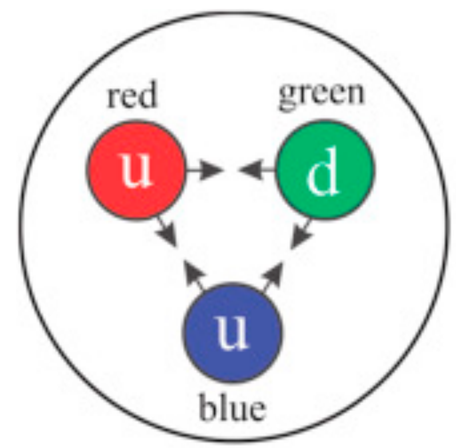
High energy neutrino production mechanism



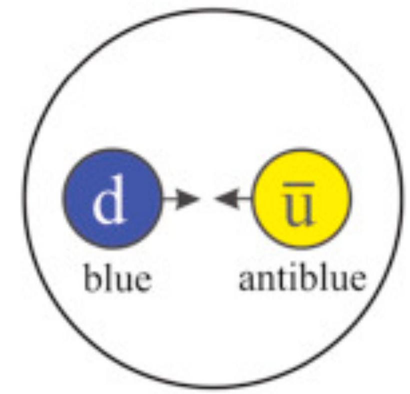
F. Halzen and S. Klein, Physics Today, May 2008

Hadrons





Baryon
(proton, p^+)



Meson
(negative pion, π^-)

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

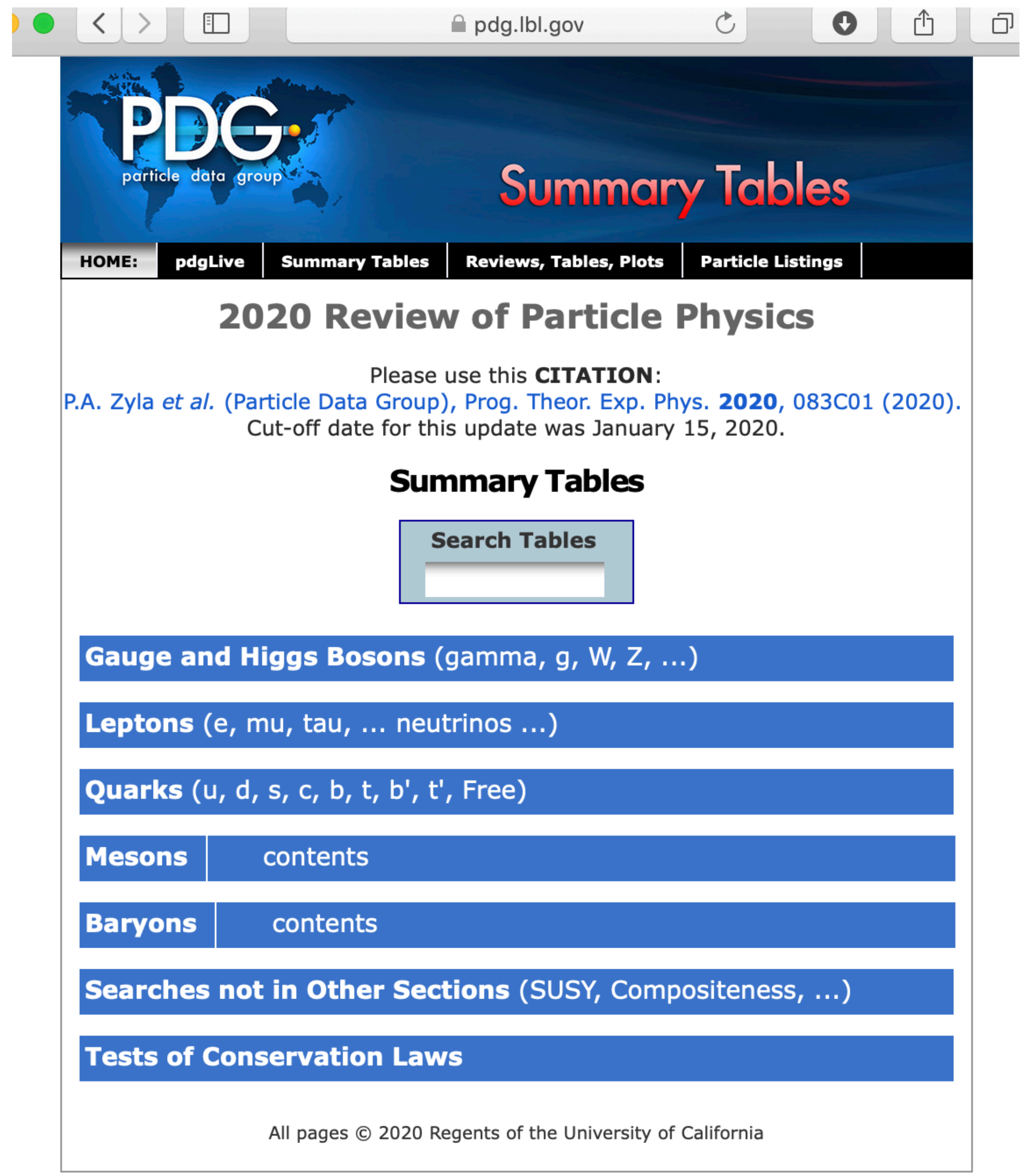
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Mesons $q\bar{q}$

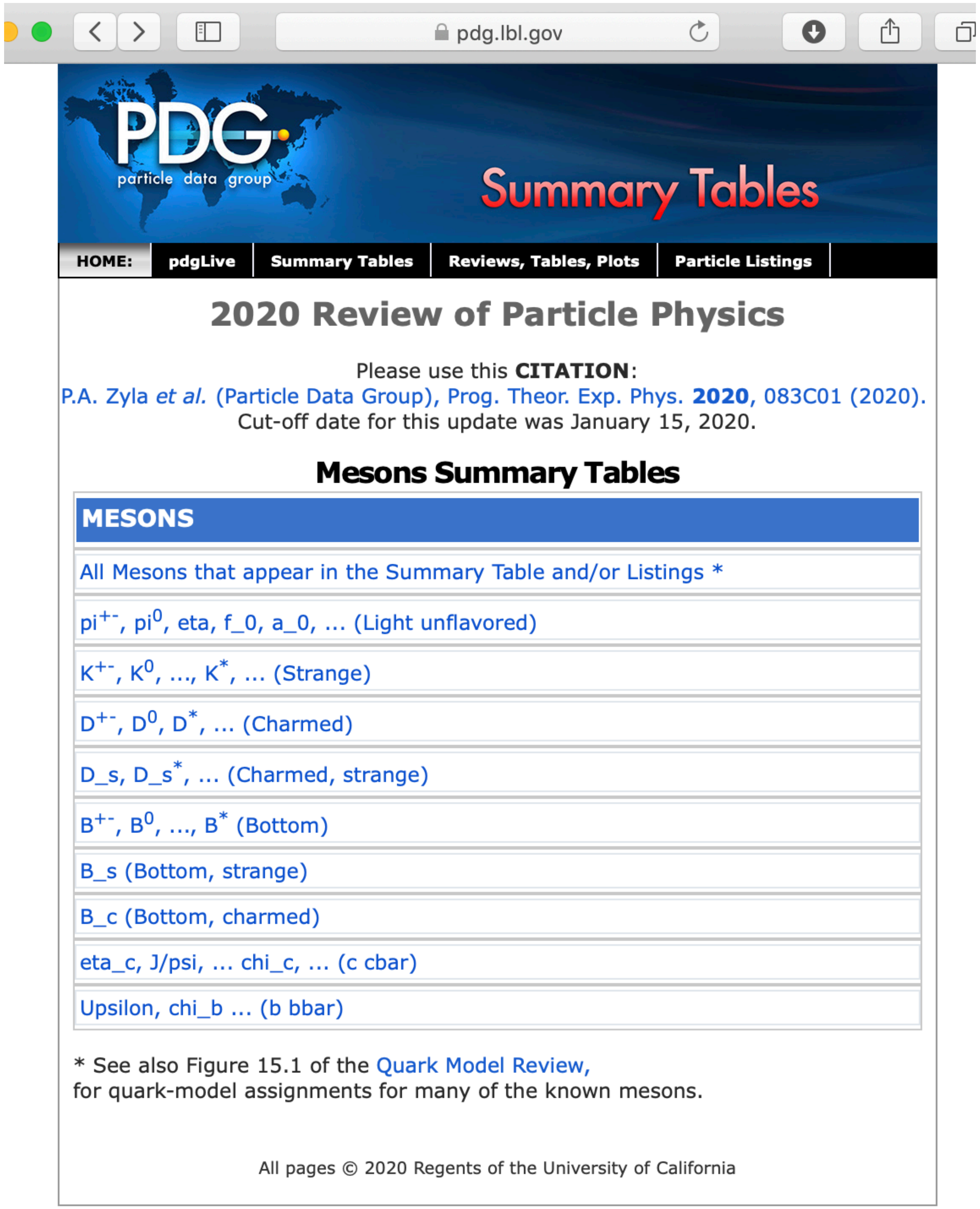
Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Particle Data Group (pdg.lbl.gov)



Particle Data Group (pdg.lbl.gov)



2020 Review of Particle Physics

Please use this **CITATION**:
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).
Cut-off date for this update was January 15, 2020.

Mesons Summary Tables

MESONS
All Mesons that appear in the Summary Table and/or Listings *
pi^{+-}, pi^0, eta, f_0, a_0, ... (Light unflavored)
K^{+-}, K^0, ..., K*, ... (Strange)
D^{+-}, D^0, D*, ... (Charmed)
D_s, D_s*, ... (Charmed, strange)
B^{+-}, B^0, ..., B* (Bottom)
B_s (Bottom, strange)
B_c (Bottom, charmed)
eta_c, J/psi, ... chi_c, ... (c cbar)
Upsilon, chi_b ... (b bbar)

* See also Figure 15.1 of the Quark Model Review,
for quark-model assignments for many of the known mesons.

$$K^{+(-)} = u\bar{s}\,(\bar{u}s)\,, \quad K^0 = d\bar{s}\,,$$

$$D^{+(-)} = c\bar{d}\,(\bar{c}d)\,, \quad D^0 = c\bar{u}$$

$$D_s^{+(-)} = c\bar{s}\,(\bar{c}s)$$

......

Prompt neutrinos

- In pp/pA/AA collisions, various hadrons are produced.

- A number of neutrinos are produced from subsequent decay of the secondary hadrons.

$$\mathrm{e.g.)}\quad \pi,\, K,\, D,\, B\ \ldots \to \nu + X$$

- Neutrinos generated from the decay of charmed/bottom hadrons are called prompt neutrinos.

Discovery of tau neutrino (2000)

- DONUT — Direct Observation of NU Tau.

- 800 GeV proton beam from the Tevatron at Fermilab collides with Tungsten block and produce D mesons.

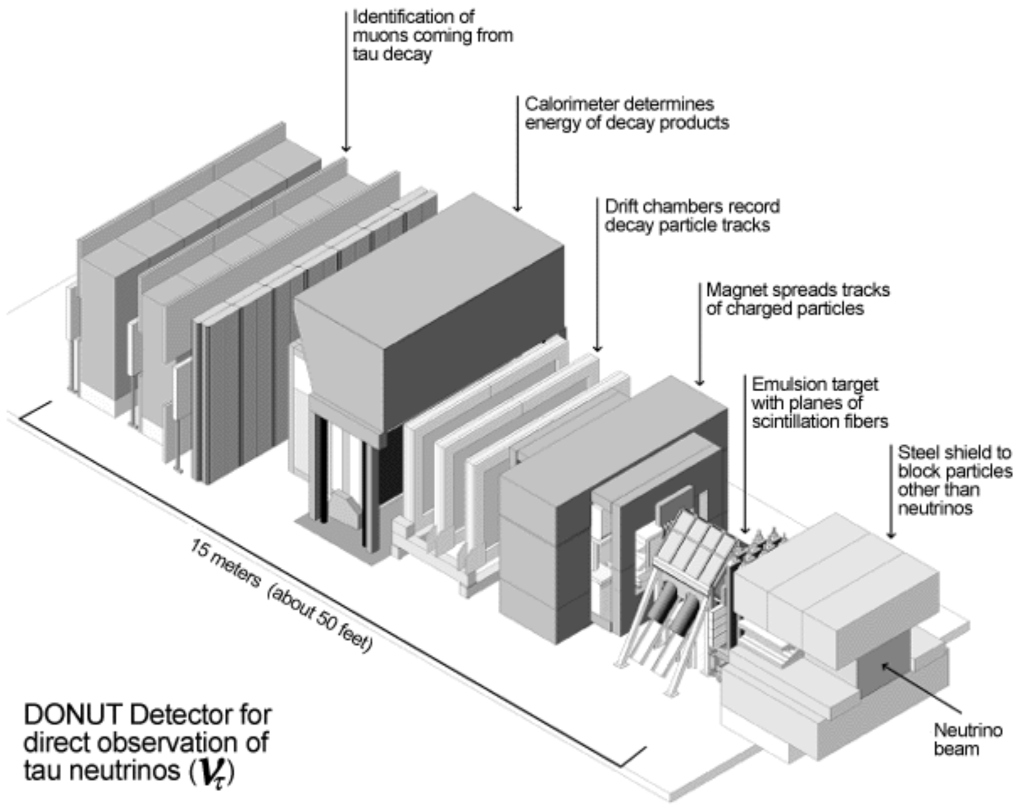
- D_s mesons decay to produce tau neutrinos.

$$D_s^+ \to \nu_\tau + \tau^+$$
$$\to \nu_\tau + (\mu^+ + \nu_\mu + \bar{\nu}_\tau)$$

- Tau neutrinos interact in emulsion targets

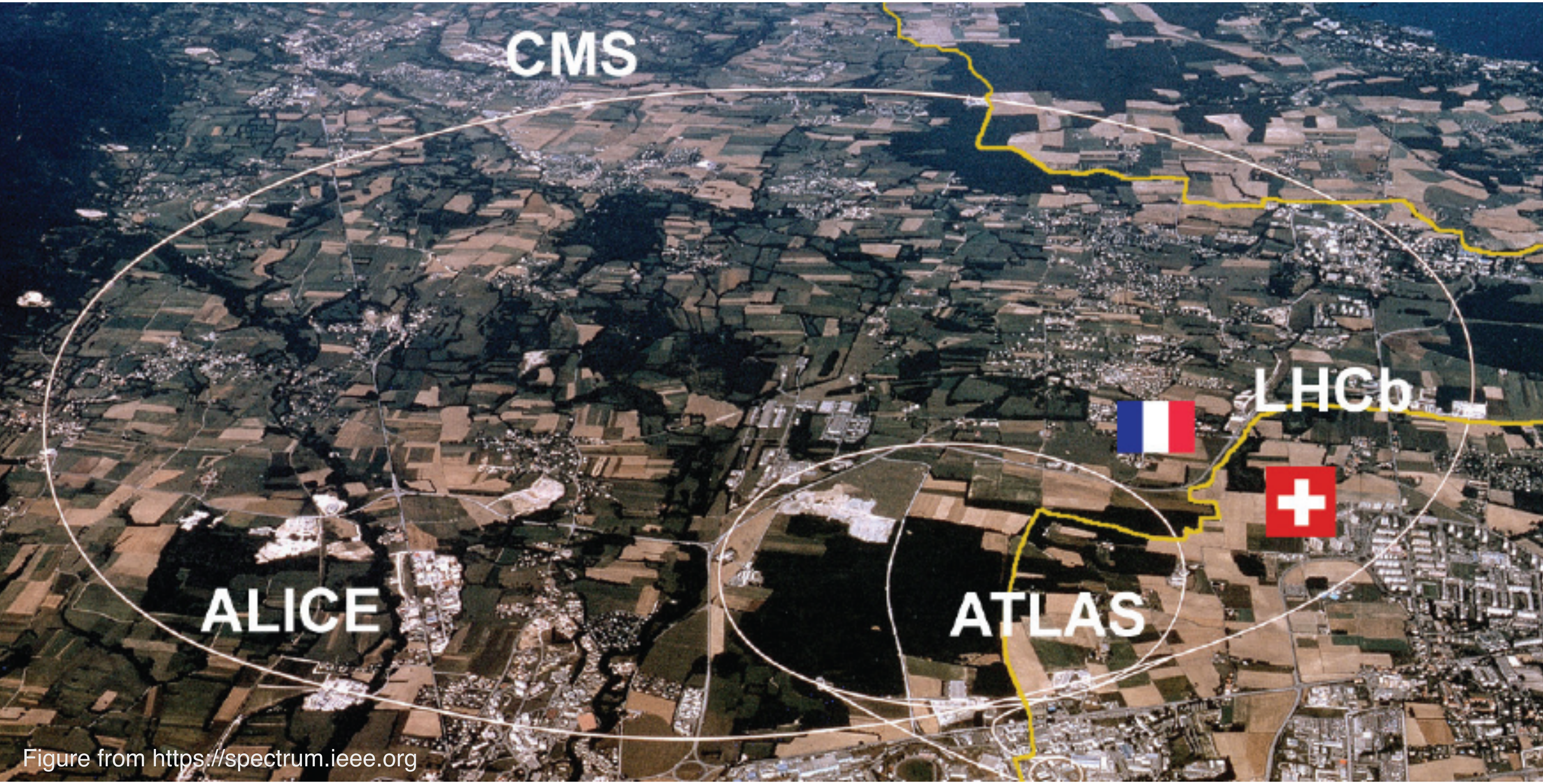
- The evidence of $(\nu_\tau + \bar{\nu}_\tau)$ interactions were found (2000) and 9 $(\nu_\tau + \bar{\nu}_\tau)$ events were observed (2008).

DONUT Detector

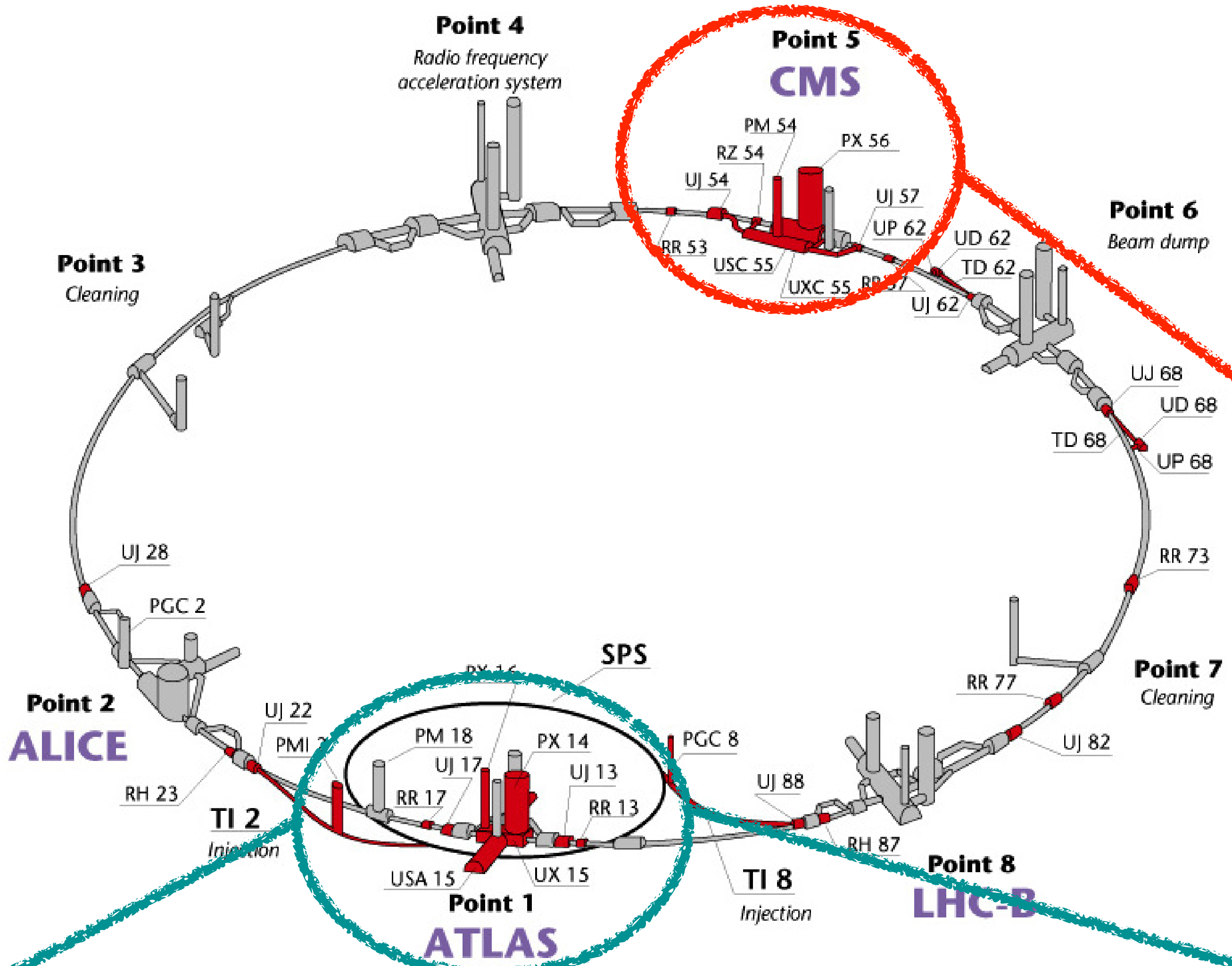


DONUT Detector for direct observation of tau neutrinos (ν_τ)

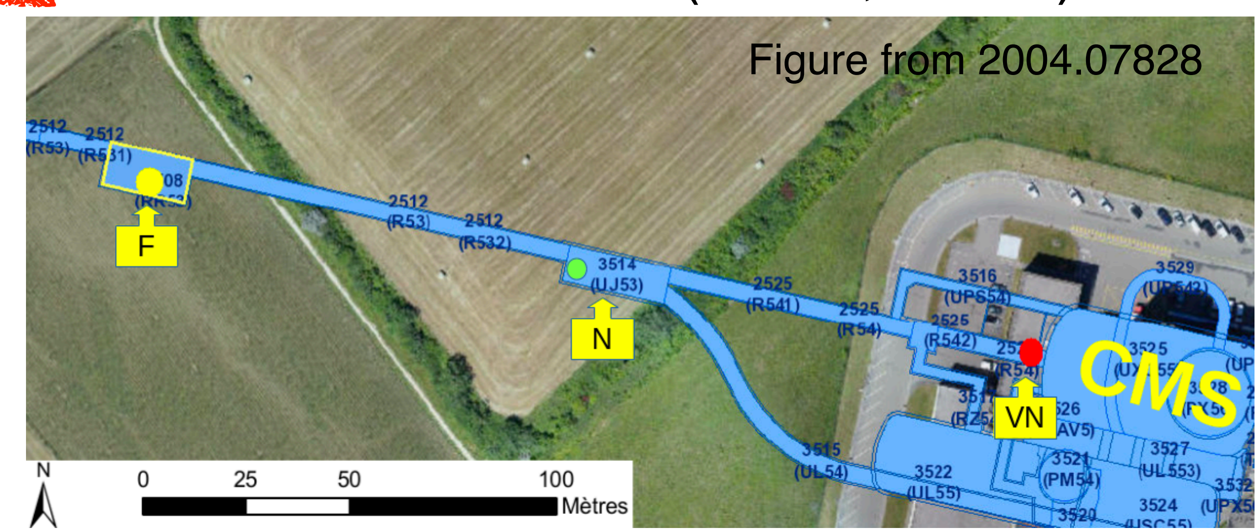
Large Hadron Collider (LHC)

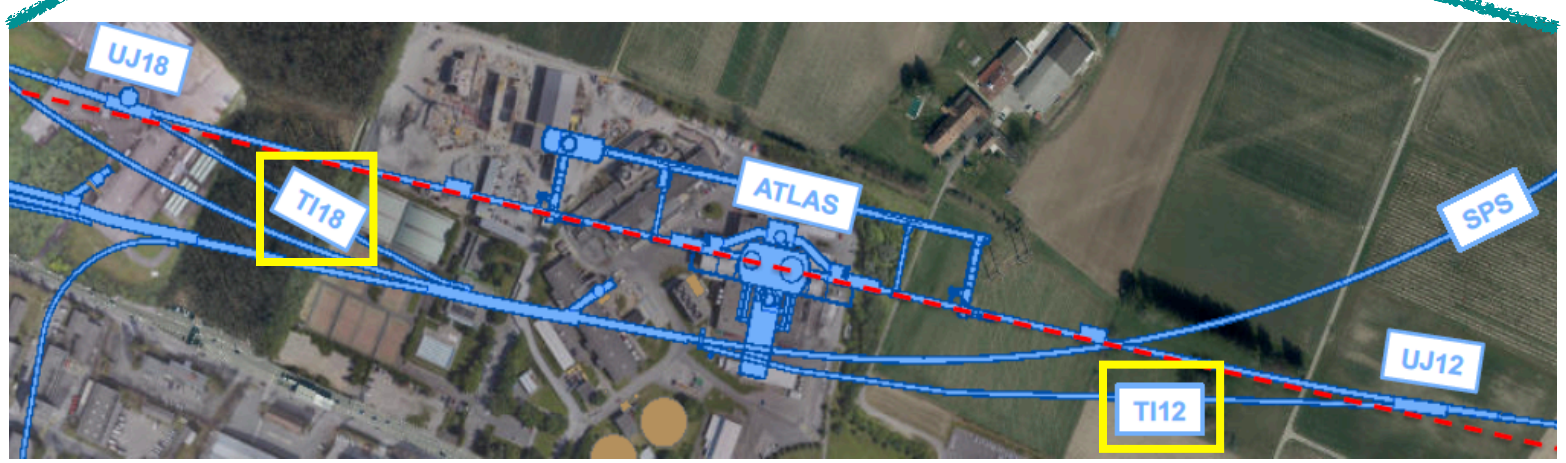


Possible sites for detection at the LHC



- Near CMS interaction point (IP)
  - VN: 25 m from IP (Q1)
  - N: 90, 120 m from IP (UJ53, UJ57)
  - F: 240 m from IP (PR53, PR57)





- Near ATLAS IP
  - VF: 480 m from IP (TI18, TI12)

Ref:1903.06564 (CMS note), 2004.07828
1901.04468 (FASER)

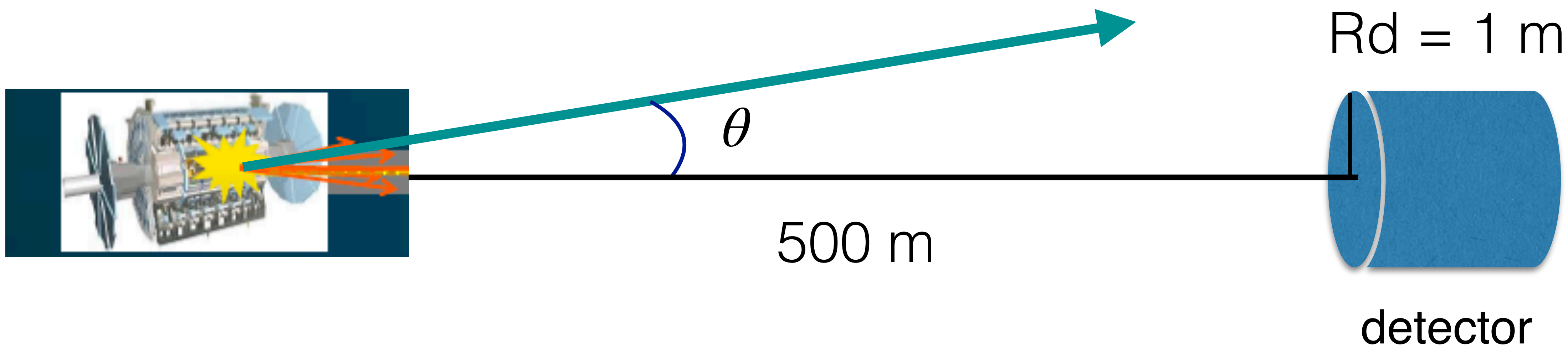
Rapidity/ pseudo rapidity

$$y = \frac{1}{2} \ln \frac{E + p_z c}{E - p_z c}$$: rapidity

$$\eta = -\ln\left[\tan\frac{\theta}{2}\right]$$: pseudo rapidity

$$\eta = 0 \quad \text{for} \quad \theta = 90^\circ$$

$$\eta = \infty \quad \text{for} \quad \theta = 0^\circ$$



e.g.) Baseline = 500m, Radius of detector = 1m

$$\theta \approx \tan\theta = 1/500 \quad \rightarrow \quad \eta \approx 6.9$$

FASER / FASERν

- ForwArd Search ExpeRiment (FASER)
- Detector Location: 480 m from ATLAS interaction point (TI12)
- During Run 3 (2022-2024) with $\mathscr{L}$ = 150 fb^{-1}
  - FASER: R_d = 10 cm, L_d = 1.5 m, $\eta \gtrsim 9.2$ (approved)
  - FASERν: A_d = 25x25 cm^2, L_d = 1.35 m, 1.2 ton of tungsten, $\eta \gtrsim 8.3$ (approved)
- During HL-LHC (2027-2036/*40*) with $\mathscr{L}$ = 3000 fb^{-1}
  - FASER 2: R_d = 1.0 m, L_d = 5.0 m, $\eta \gtrsim 6.9$
  - FASERν2: ~ 10 tons of detector

Ref: 1901.04468, 2001.03073

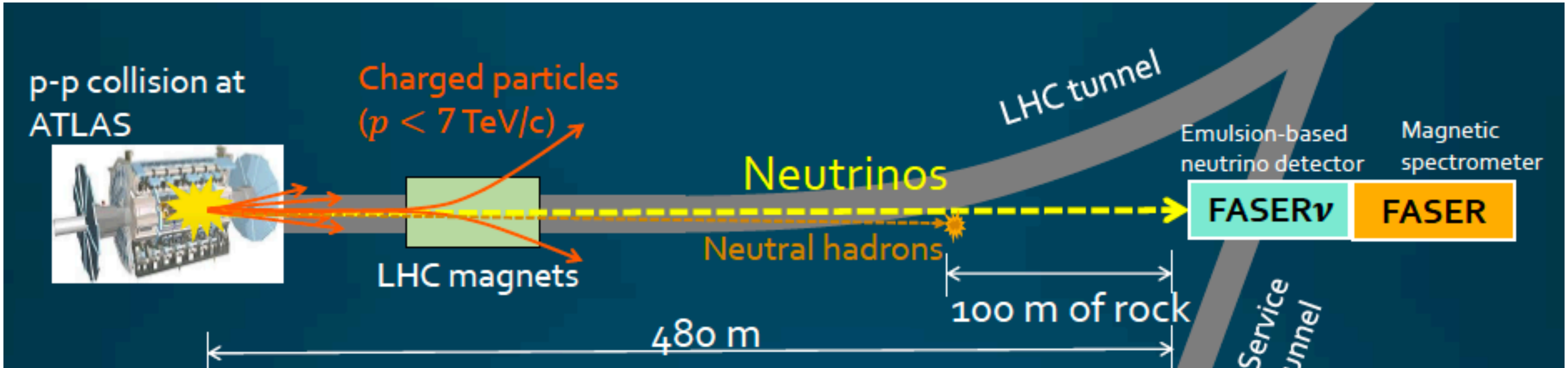


Figure taken from Akitaka Ariga's slides at FPF Kickoff meeting

XSEN, SND@LHC (proposed)

- Detector Location: 480 m from ATLAS IP (TI18)

- XSEN (Cross Section of Energetic Neutrinos)
  - Investigated potential of experiments in $4 < \eta < 5$ and $6.5 < \eta < 9.5$.
  - Proposed an experiment for $7.5 < \eta < 9.5$ to take date during Run 3.
  - Letter of Intent - arXiv:1910.11340

- SND@LHC (SHiP Collaboration)
  - A prototype of Scattering and Neutrino Detector of the SHiP experiment
  - Pseudo rapidity: $7.2 < \eta < 8.6$ (SND)
  - Letter of Intent - arXiv:2002.08722

Neutrino sources at the LHC

- π, K ($c\tau \sim O(1)$ m):
  - Many of them do not decay before they reach to the detector at distance of 480 m when $E \gtrsim \sim 9$ (65) GeV for π (K).
  - Still exist neutrinos from the π, K decays. More than tau neutrinos.
- W/Z : neutrinos from weak boson decays are distributed in $|\eta| \lesssim 6$.
- Heavy flavor hadrons: contribute to the neutrino flux for $\eta \gtrsim 6.5$
  - D/B mesons ($c\tau \sim O(100)$ μm)
  - Λ_c ($c\tau \sim O(10)$ μm)
- ν_τ are only from $D_s^\pm$, $B^\pm$, $B^0(\bar{B}^0)$.

  the main source of ν_τ

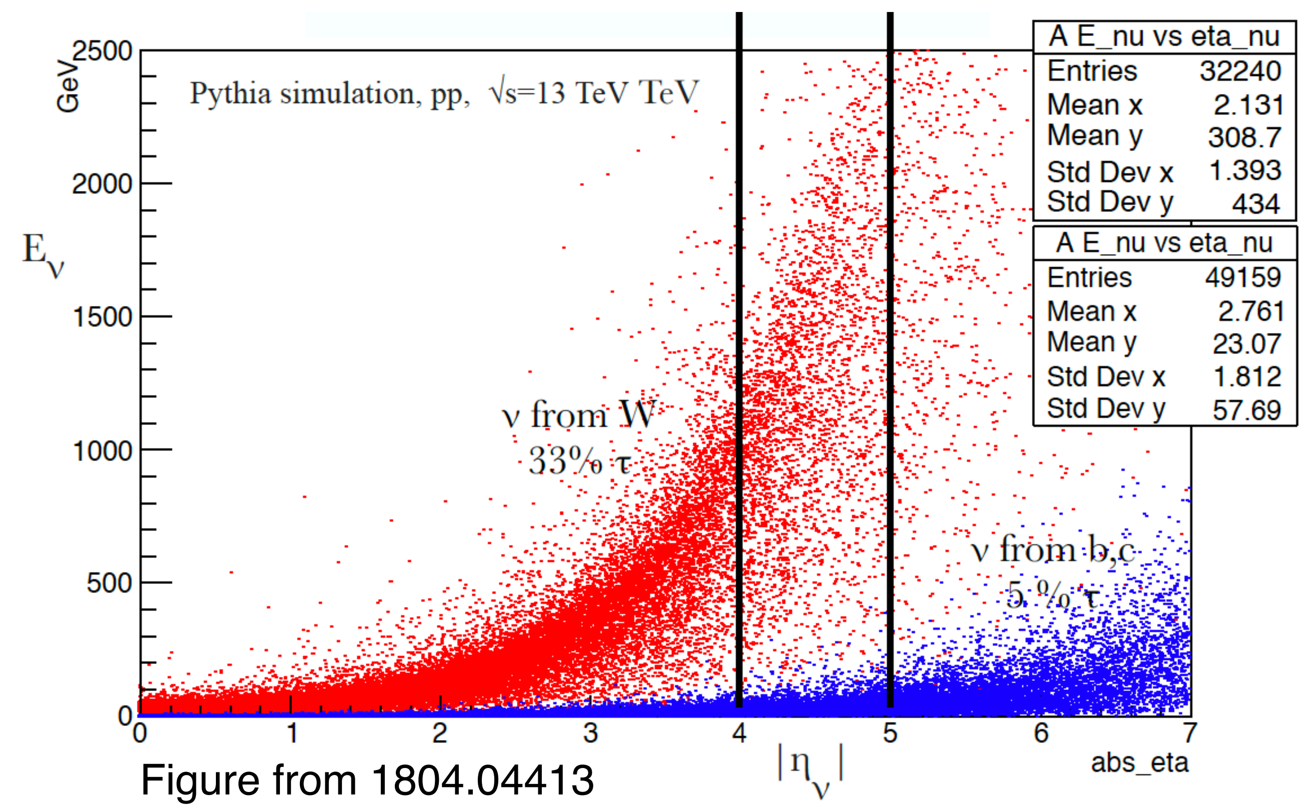


Figure from 1804.04413

Physics motivation

- Forward neutrinos at the LHC will provide a good opportunity for measurement of neutrino cross section in the TeV energy region.
- Sizeable number of tau neutrino will make it possible to test lepton universality in neutrino interaction.
- Abundant tau neutrinos will help investigate oscillation in/beyond the SM.
- To better understand heavy quark production in the more forward region than measured by the LHCb ➙ useful to explore high energy neutrinos at IceCube and Km3net.

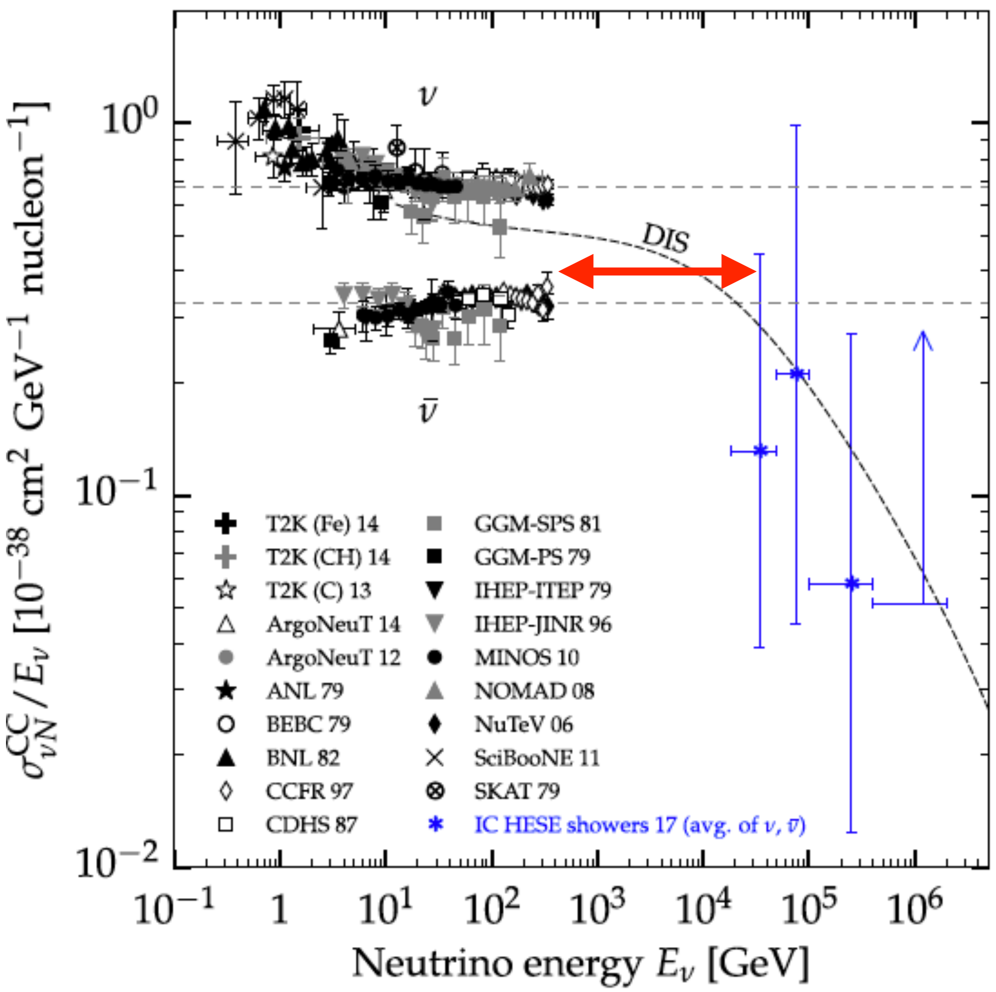
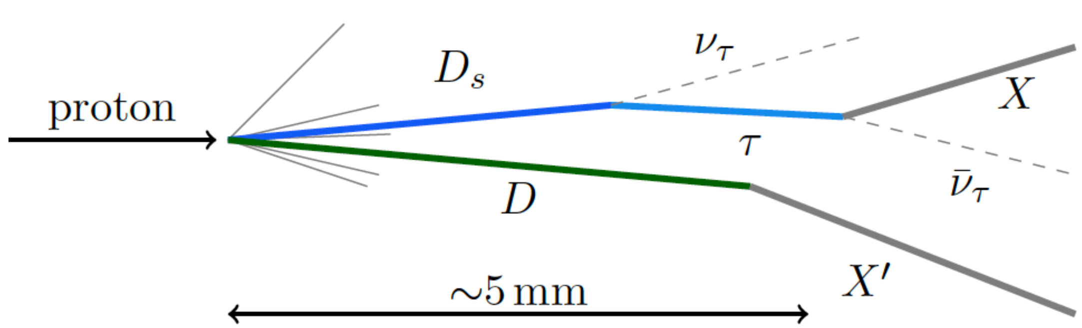


Figure from Bustamante and Connolly, PRL 122, 041101 (2019)

Prompt tau neutrinos at CERN — Ds tau

- NA65/DsTau experiment (SPS)
  - 400 GeV proton beam on tungsten target
  - Study tau neutrino production, $D_s \to \tau \to X$
  - Provide ν_τ flux prediction for neutrino beam for future experiments.
  - Approved in 2019 and will run in 2021 - 2022



Ref: JHEP 01 (2020) 033 (DsTau)

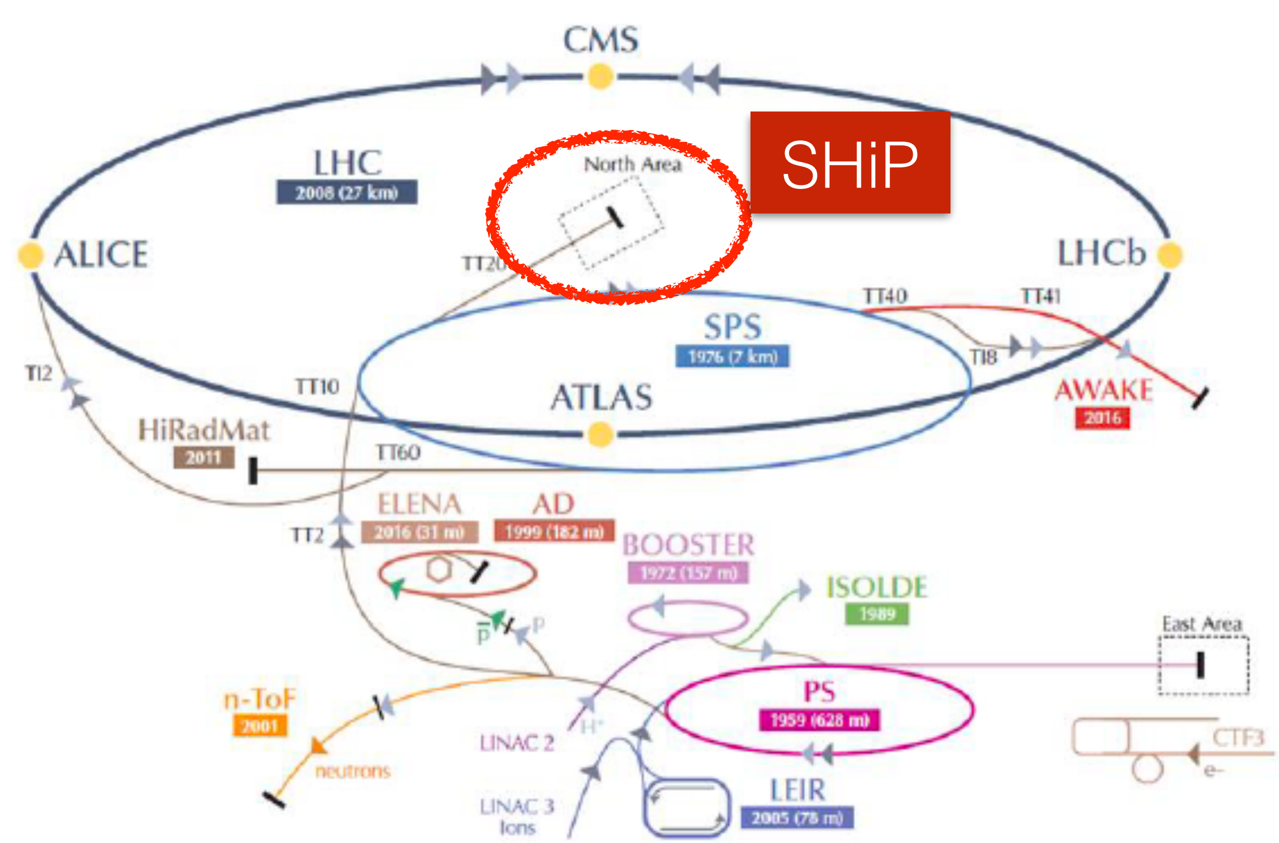
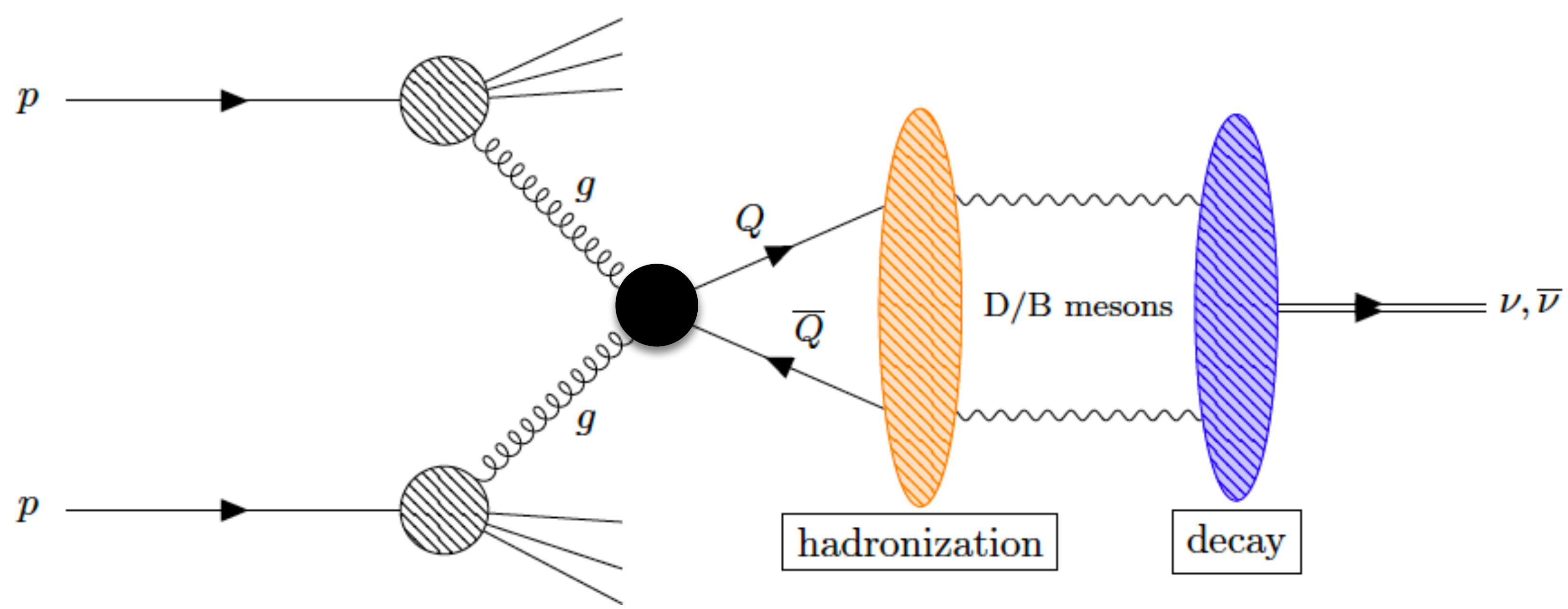


Figure by Marco Andreini

Ingredients for evaluation

- Heavy quark production cross section in pp collision
- Fragmentation of heavy quark to hadrons
- Decay rate and distribution
- Neutrino interaction cross section in a detector

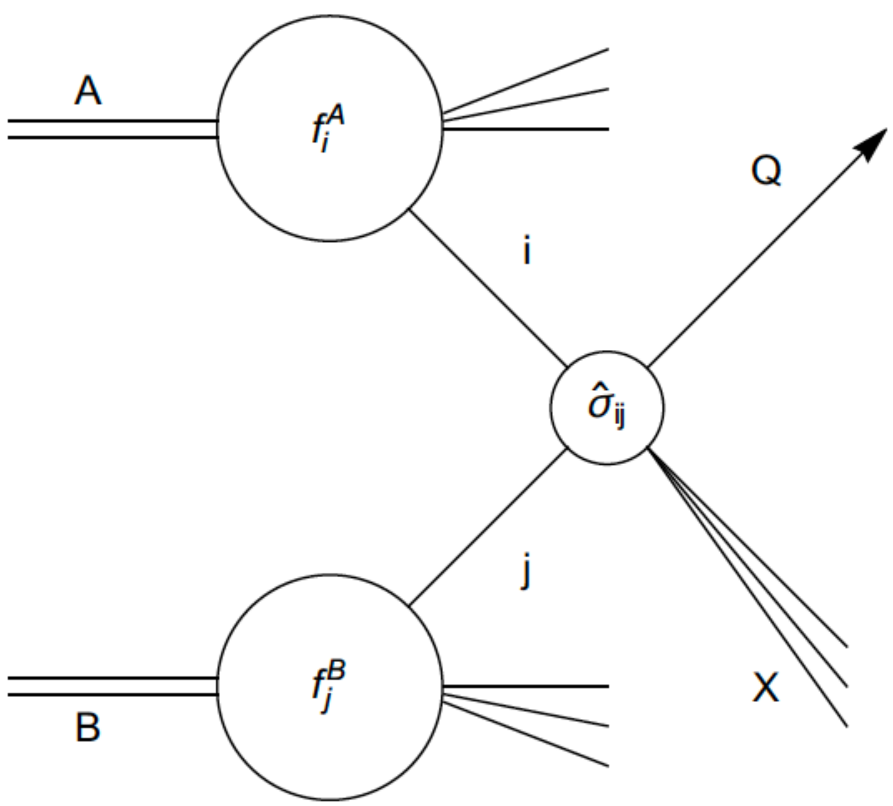


Heavy quark production

- Perturbative QCD with collinear approximation
  - The HQ production cross section (NLO)

$$\sigma(pp \to c\bar{c}X) = \sum_{i,j=q,\bar{q},g} \int dx_1 dx_2 f_i(x_1, \mu_F^2)\, f_j(x_2, \mu_F^2)\, \hat{\sigma}_{ij\to c\bar{c}}(\mu_F^2, \mu_R^2, \ldots)$$

$$\mu_{F/R} \propto m_T = \sqrt{m_Q^2 + p_T^2}$$



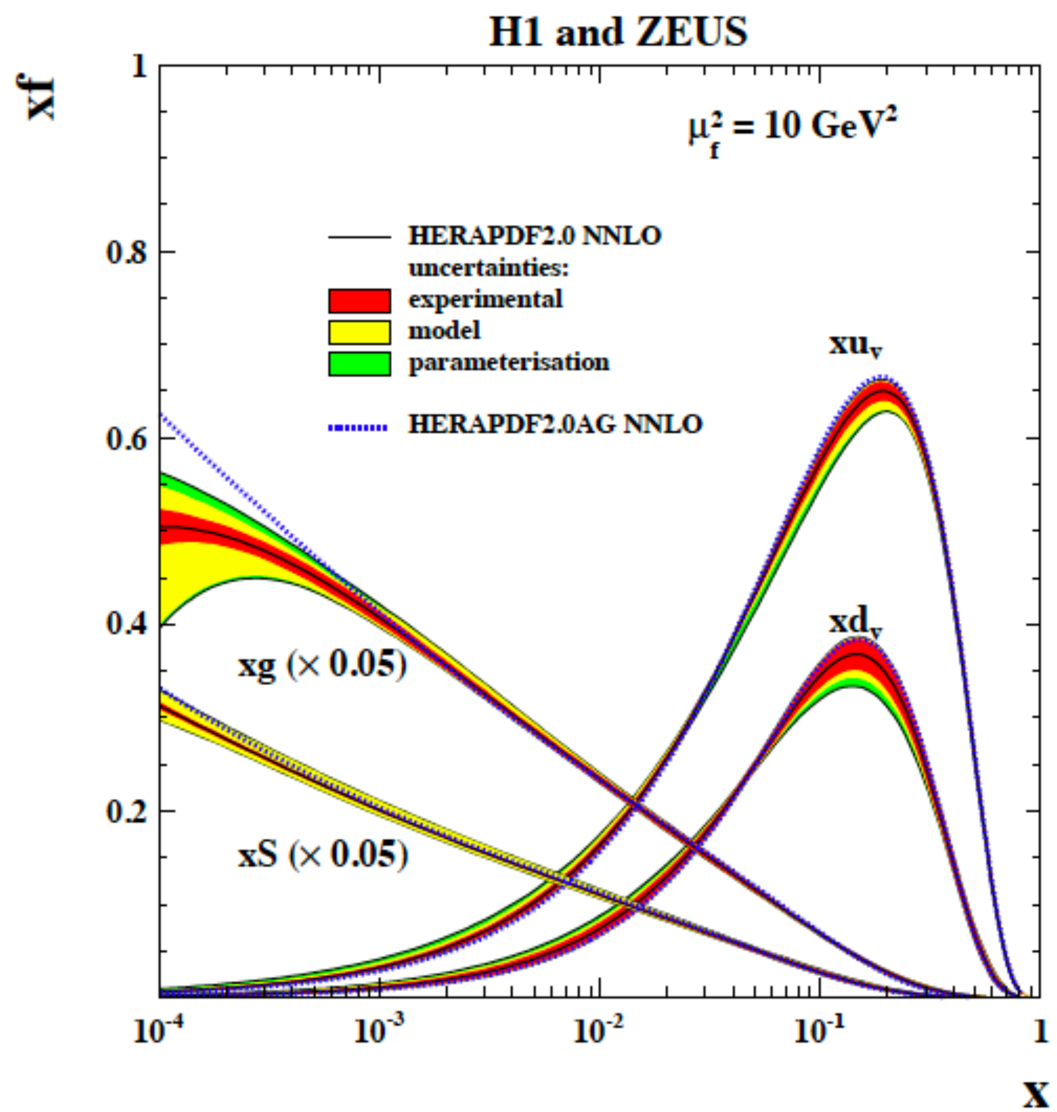
  - Contributed processes

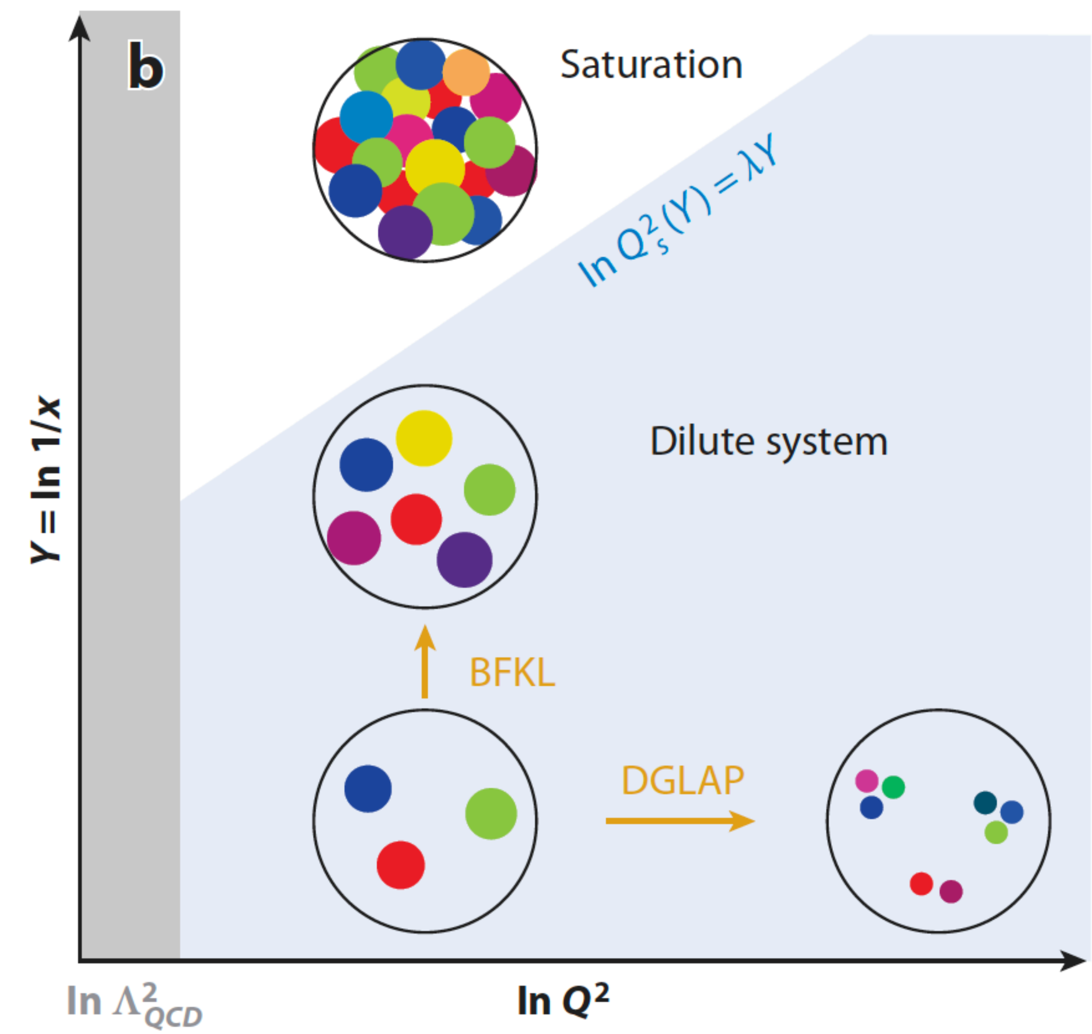
$$q + \bar{q} \to Q + \bar{Q}$$
$$g + g \to Q + \bar{Q} \qquad \alpha_s^2,\ \alpha_s^3$$

$$q + \bar{q} \to Q + \bar{Q} + g$$
$$g + g \to Q + \bar{Q} + g \qquad \alpha_s^3$$

$$g + q \to Q + \bar{Q} + q$$
$$g + \bar{q} \to Q + \bar{Q} + \bar{q} \qquad \alpha_s^3$$

Gluon distributions and saturation





- Alternative way to evaluate the HQ production
  - Dipole mode, k_T factorization

Fragmentation

- Heavy quark to heavy hadron

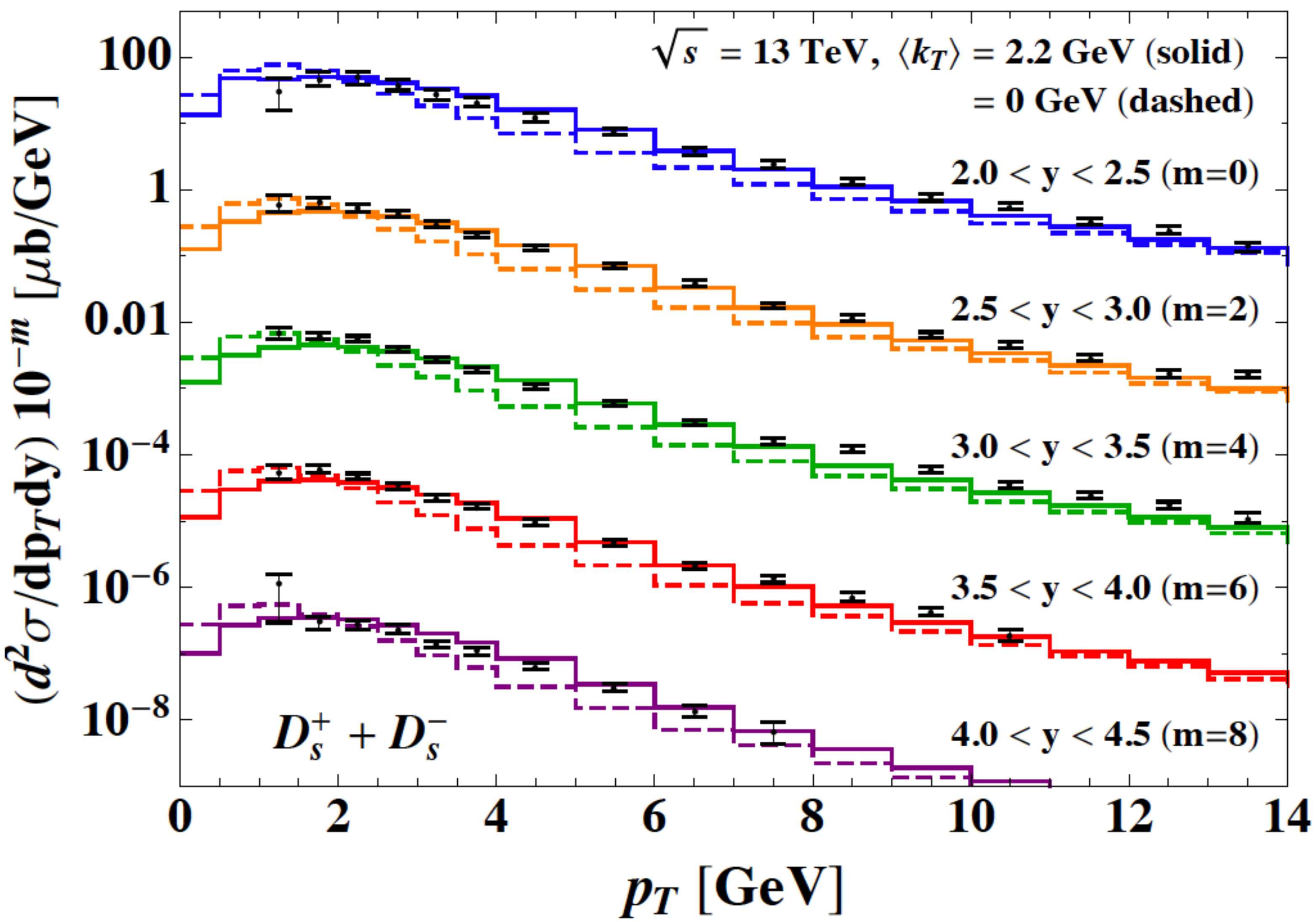
$$\left(E\frac{d^3\sigma}{dp_Q^3}\right)_H = \left(E\frac{d^3\sigma}{dp_Q^3}\right)_Q \otimes D_Q^H(z)$$

$$\text{where} \quad D_Q^H(z) = \frac{Nz(1-z)^2}{((1-z)^2+\epsilon z)^2} \quad \text{and} \quad z = p_H/p_Q$$

: Fragmentation function

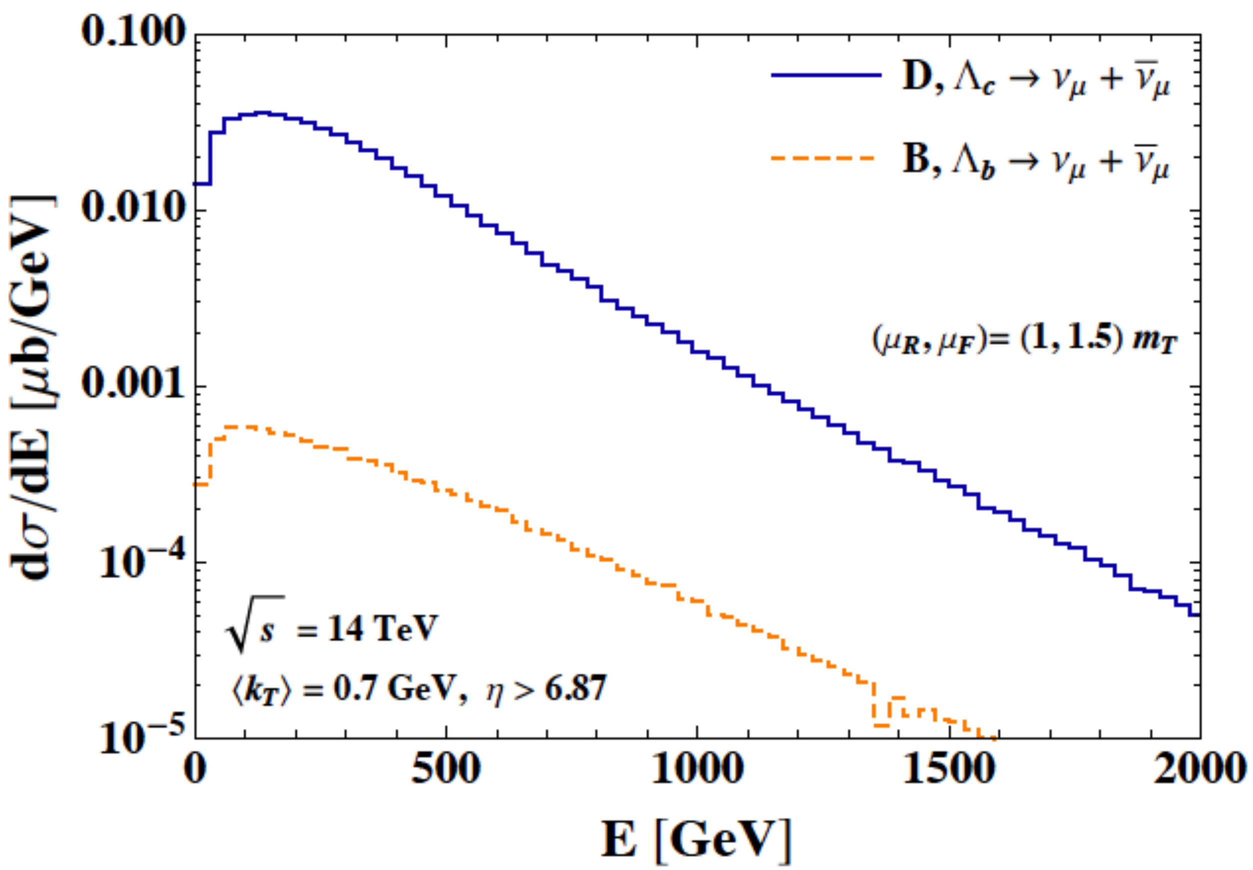
Hadrons	D^-	D^0	D_s^-	Λ_c^+	B/B^0
ϵ	0.039	0.028	0.008	0.011	0.0033

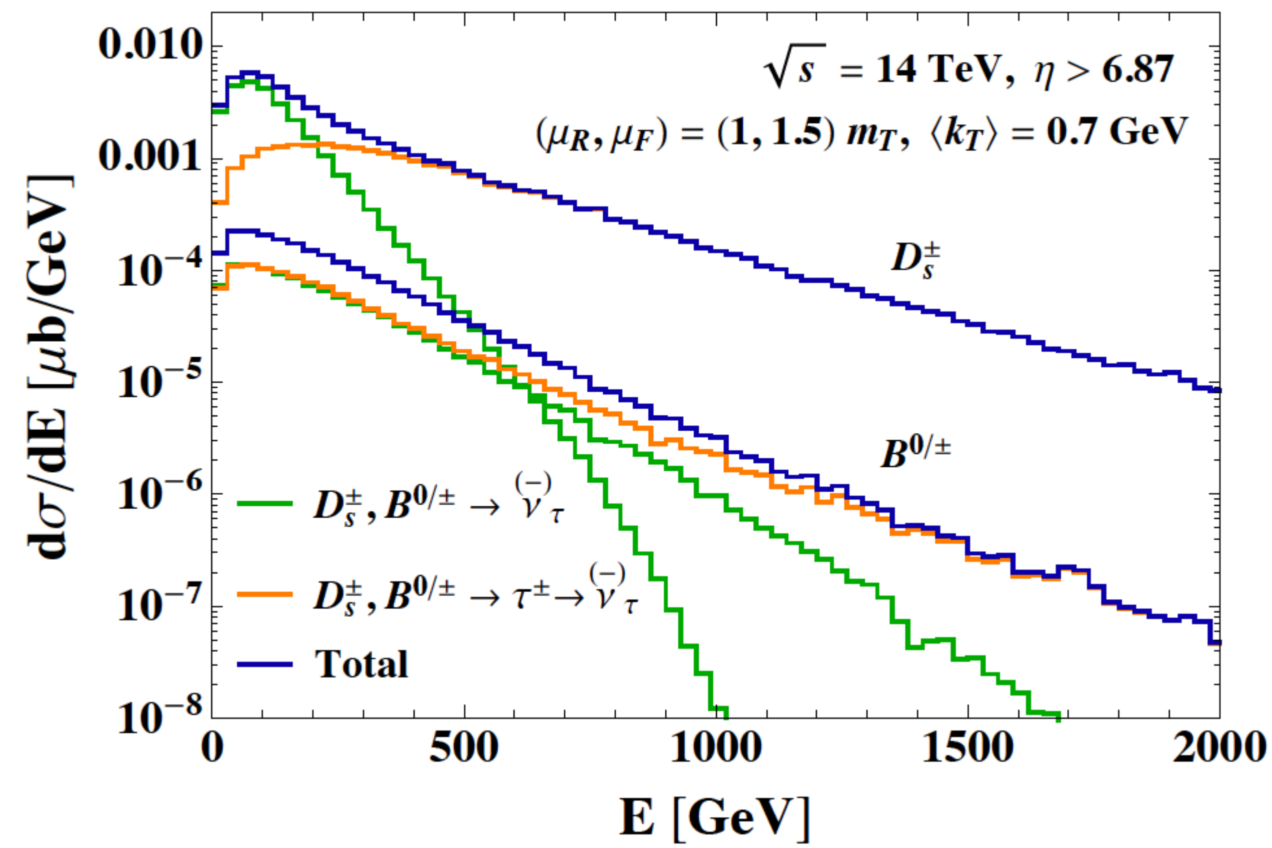
Comparison with the LHCb data



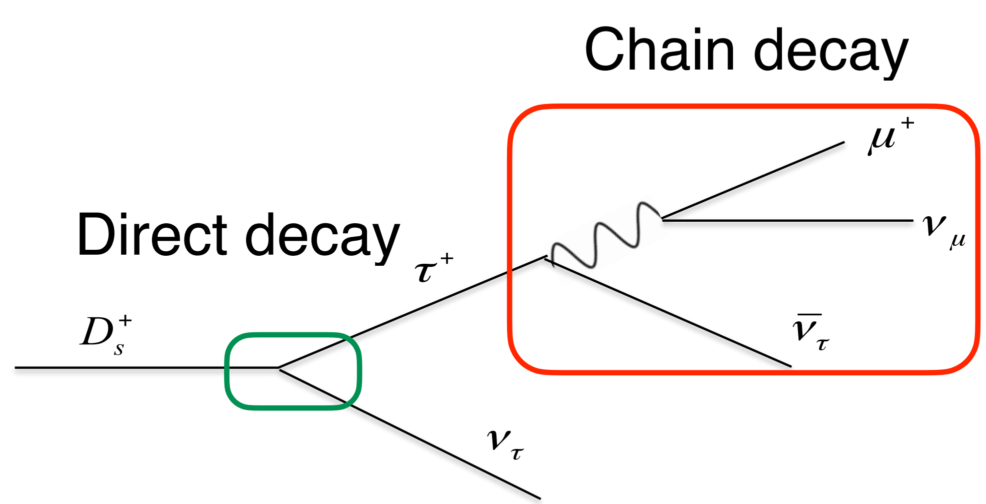
- The LHCb experiment probes the forward region.
- Relevant parameters can be found by comparing evaluation with the LHCb data for the total and differential cross sections.

Differential cross sections for $\nu + \bar{\nu}$

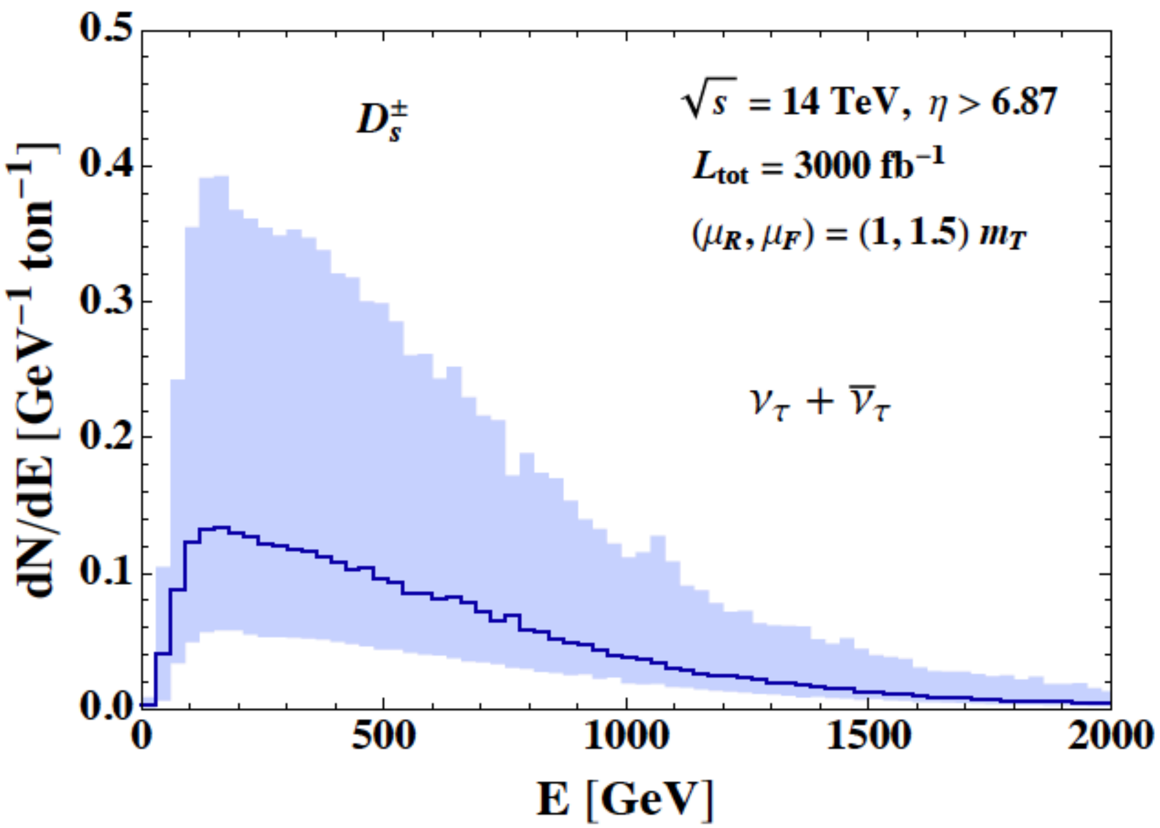




- $\frac{d\sigma}{dE} \times \mathscr{L}$: total flux of neutrinos incoming to the detector area.



Energy spectrum of event rate & event numbers



- The band reflects the uncertainty range due to QCD scale variation.
- Number of $\nu_\tau + \bar{\nu}_\tau$ — over thousands of events
- Uncertainty range due to the scale variation: a factor of ~ 6

	ν_τ	$\bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$				
$(\mu_R,\ \mu_F)$	$(1,\ 1.5)\ m_T$			$(1,\ 1.5)\ m_T$			$(0.5,\ 1.5)\ m_T$	$(1,\ 0.75)\ m_T$
$\langle k_T \rangle$	0.7 GeV			0 GeV	1.4 GeV	2.2 GeV	0.7 GeV	
D_s	2451	1191	3642	3799	3261	2735	11008	1716
$B^{\pm,0}$	96	46	142	144	137	127	214	115
Total	2547	1237	3784	3943	3398	2862	11222	1831

Atmospheric neutrinos

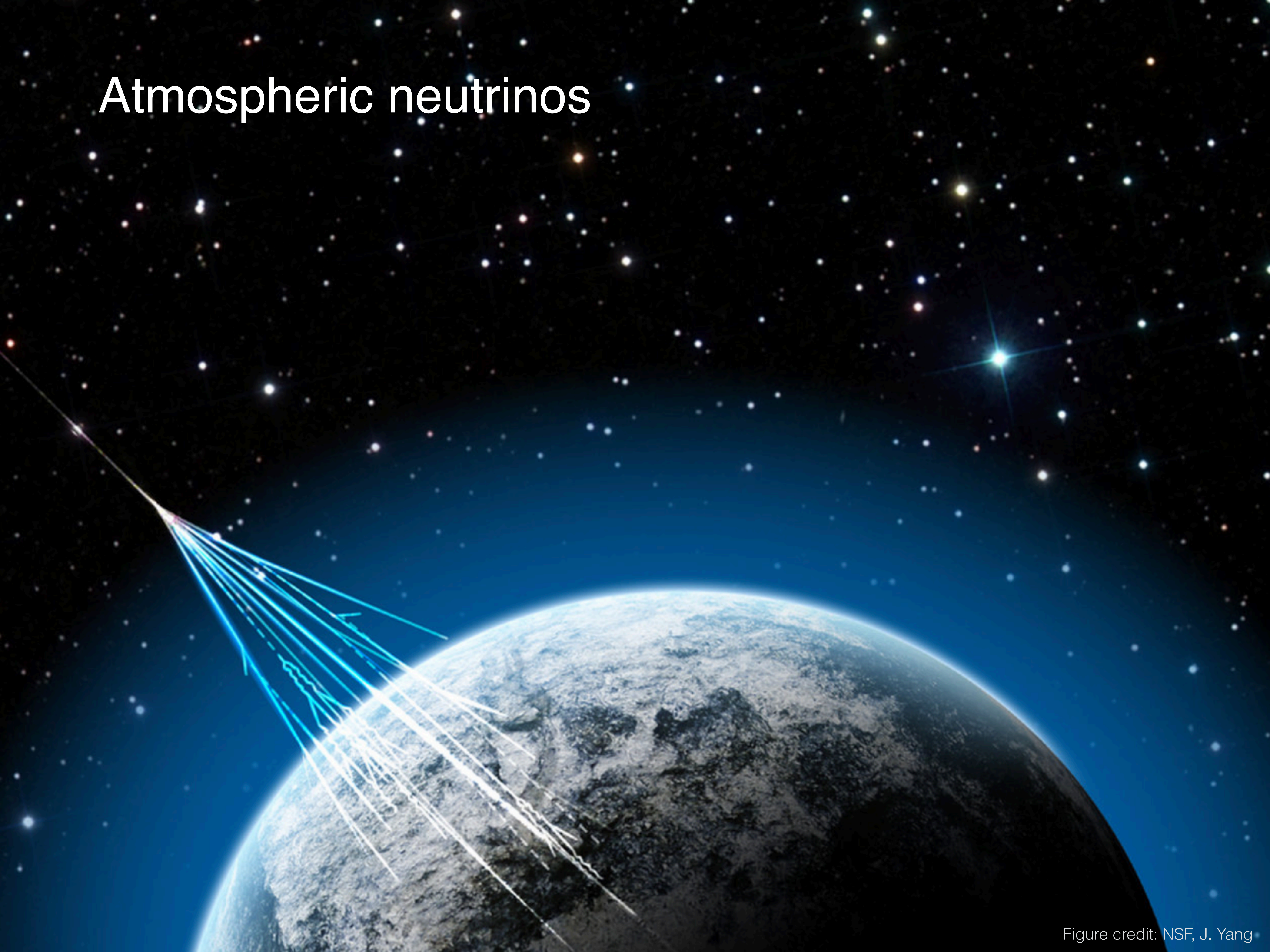
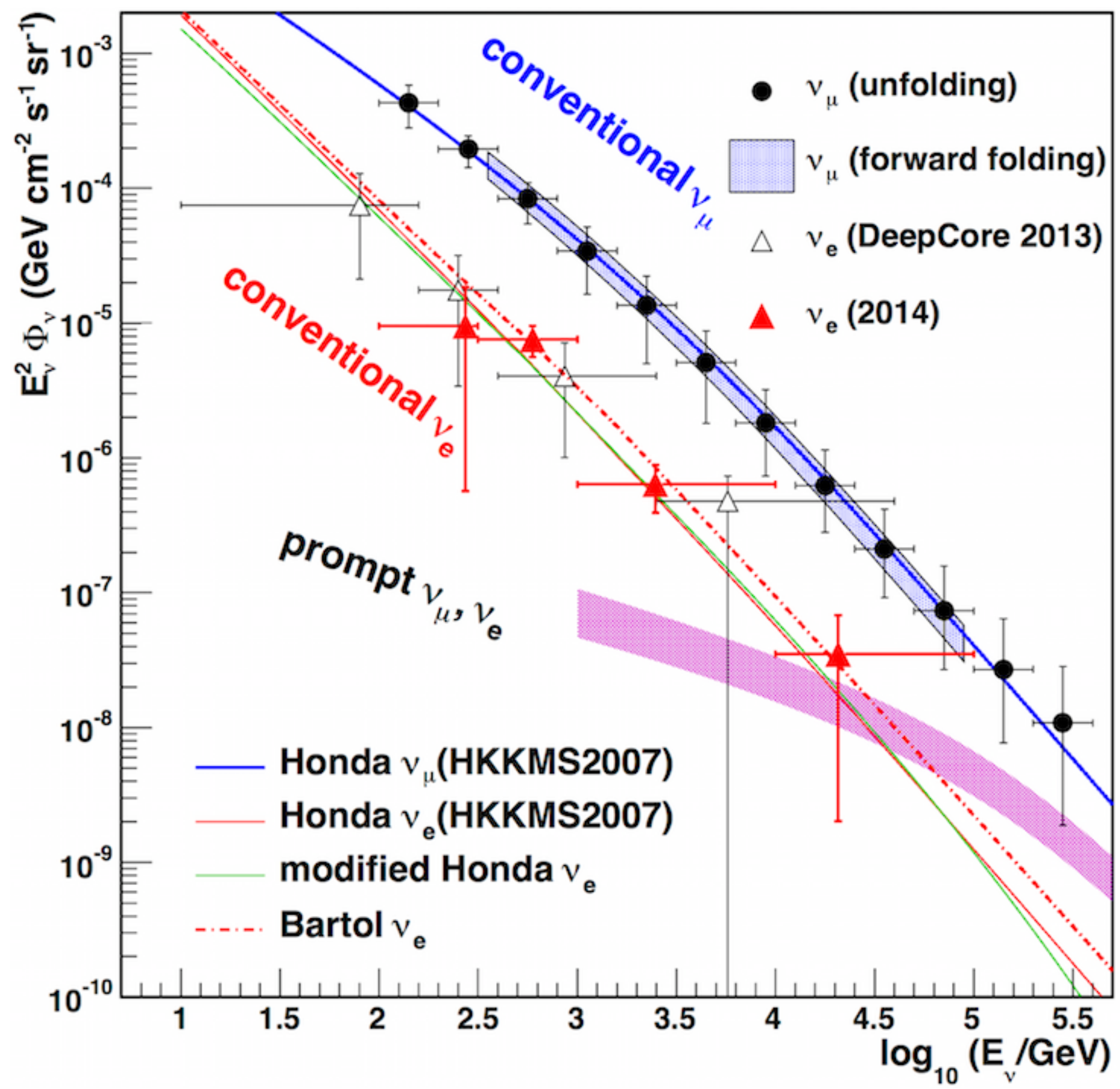


Figure credit: NSF, J. Yang

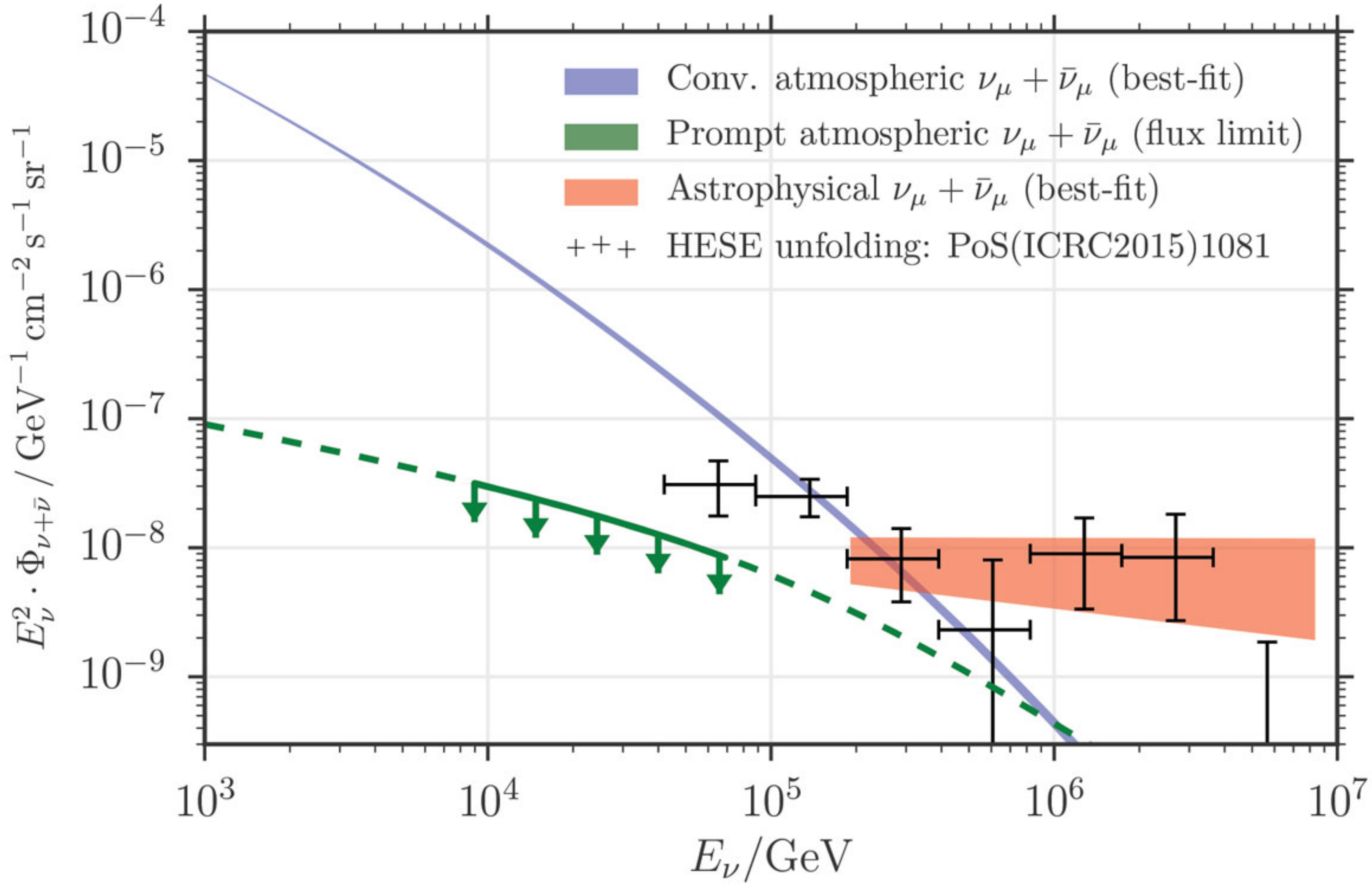
Conventional vs. Prompt

- Conventional neutrinos
  - from the pion(π)/ kaon (K) decays
  - lose energy due to interaction before decaying
  - dominates at relatively low energies and rapidly decreases with energy.



- Prompt neutrinos
  - from the charm/bottom hadrons.
  - promptly decay before interacting and losing energy ($\tau \sim 10^{-12}\, s$).
  - less depends on the energy
  - dominates at high energies (~1 PeV)
  - has large uncertainty

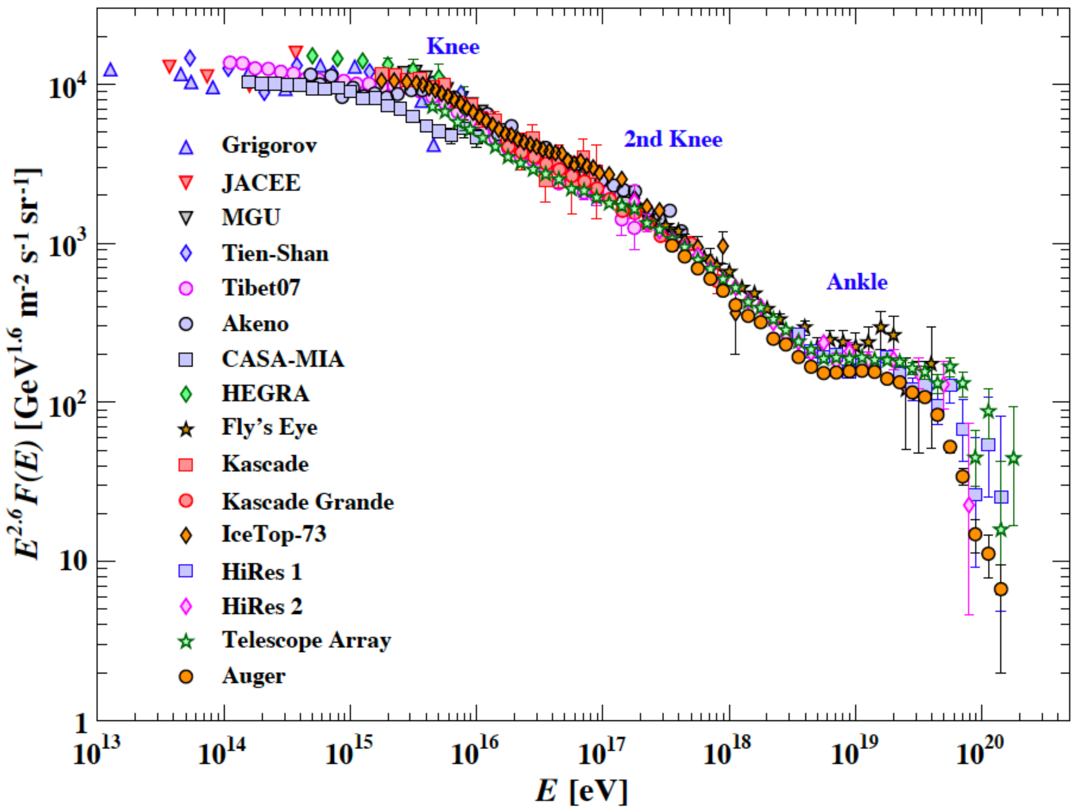
Atmospheric neutrinos

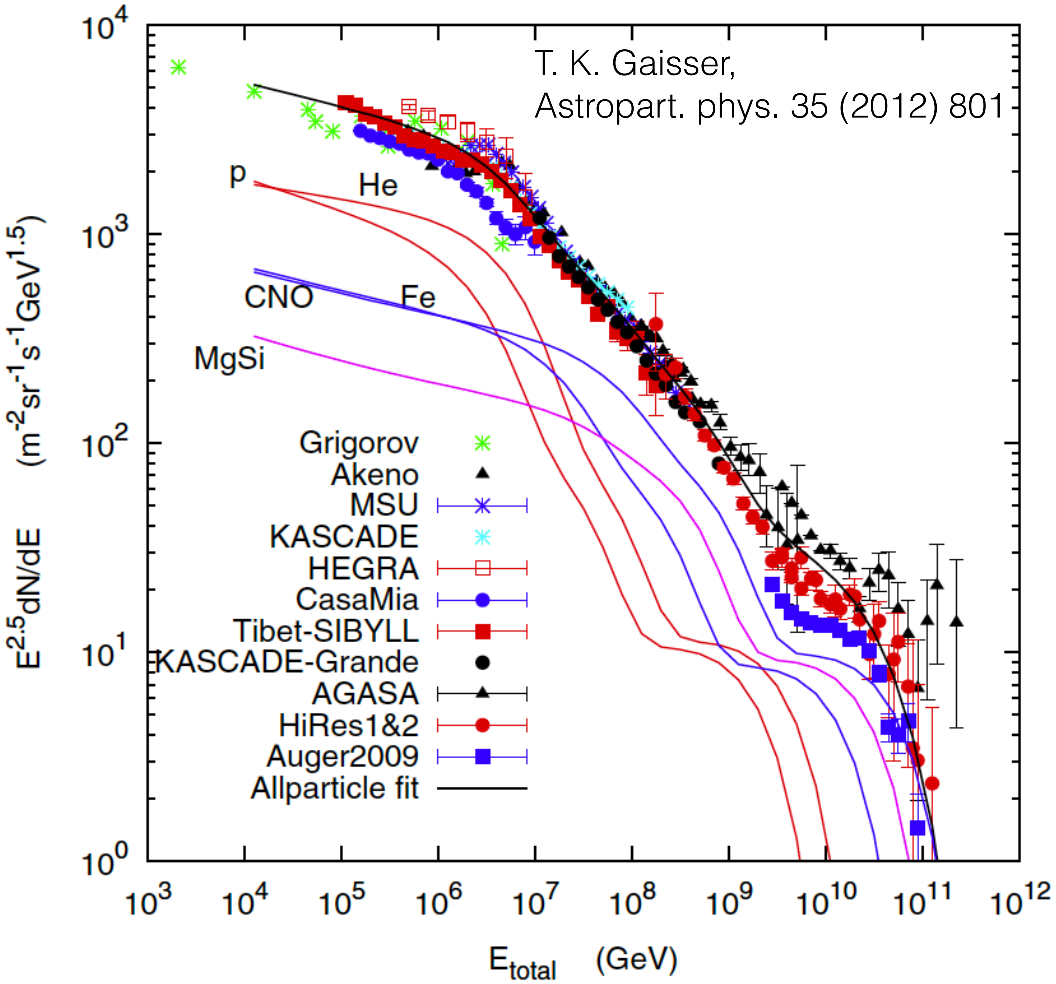


Components for evaluation

- Incident cosmic ray flux
- Heavy quark production cross section in pA collision
- Fragmentation of heavy quark to hadrons
- Decay rate and distribution
- Propagation in the atmosphere, atmosphere density, …

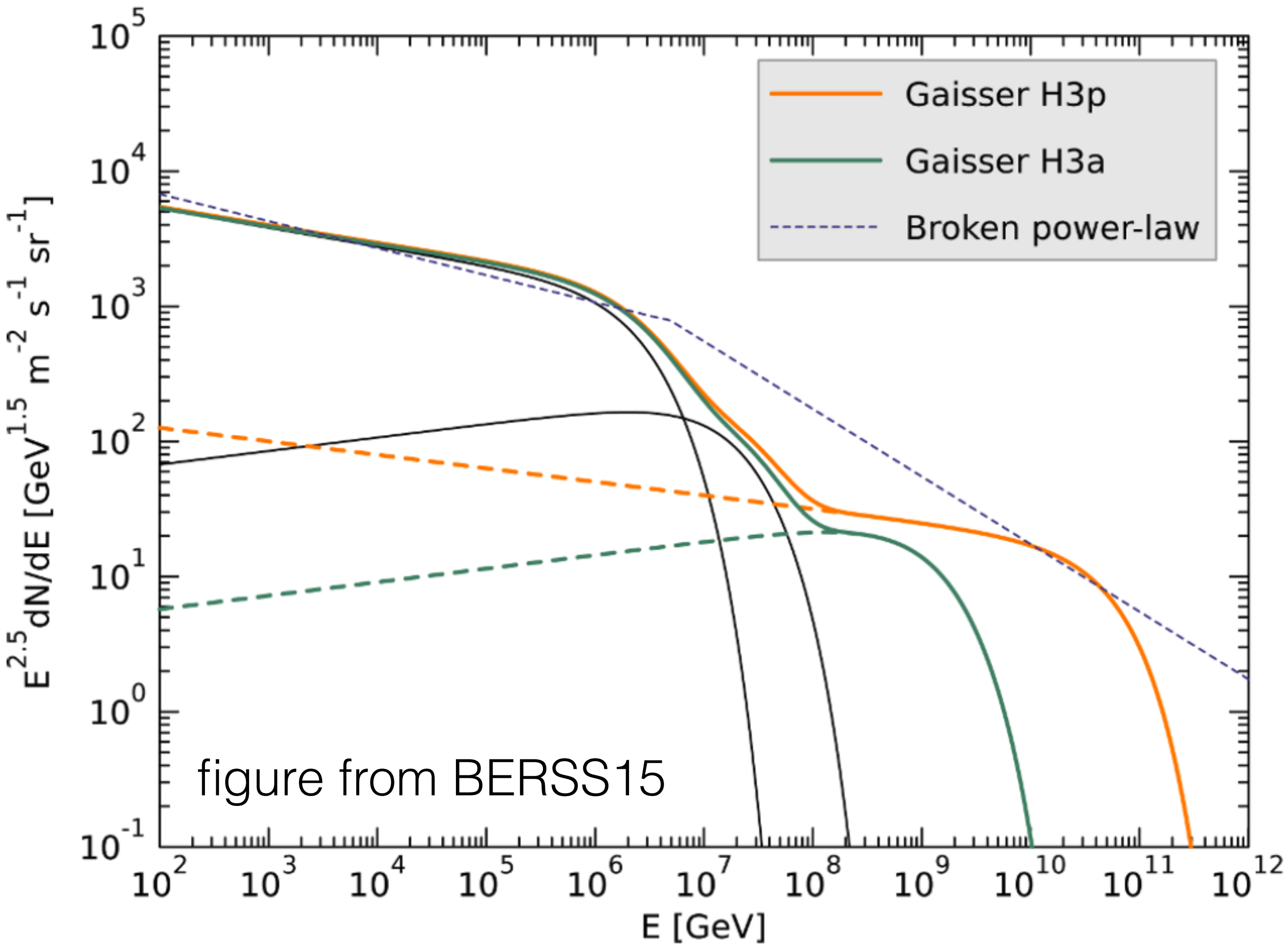
Cosmic ray spectrum (all particle)





- Parameterizations by Gaisser
  - source populations : SN remnants, other galactic and extra galactic sources
  - multi nuclear species:

Cosmic ray nucleon spectrum



- **BPL** - all CR particles are protons.

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

- Gaisser's parameterizations
  - H3p - all protons in extragalactic population.
  - H3a - mixed composition in extra galactic population.

T. K. Gaisser,
Astropart. phys. 35 (2012) 801

Cascade equations

- Cascade equations describe the propagation of high energy particles in the atmosphere.

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

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

$$X(\ell,\theta) = \int_\ell^\infty d\ell' \rho(h(\ell',\theta))$$

$$\rho = \rho_0 \exp(-h/h_0)$$

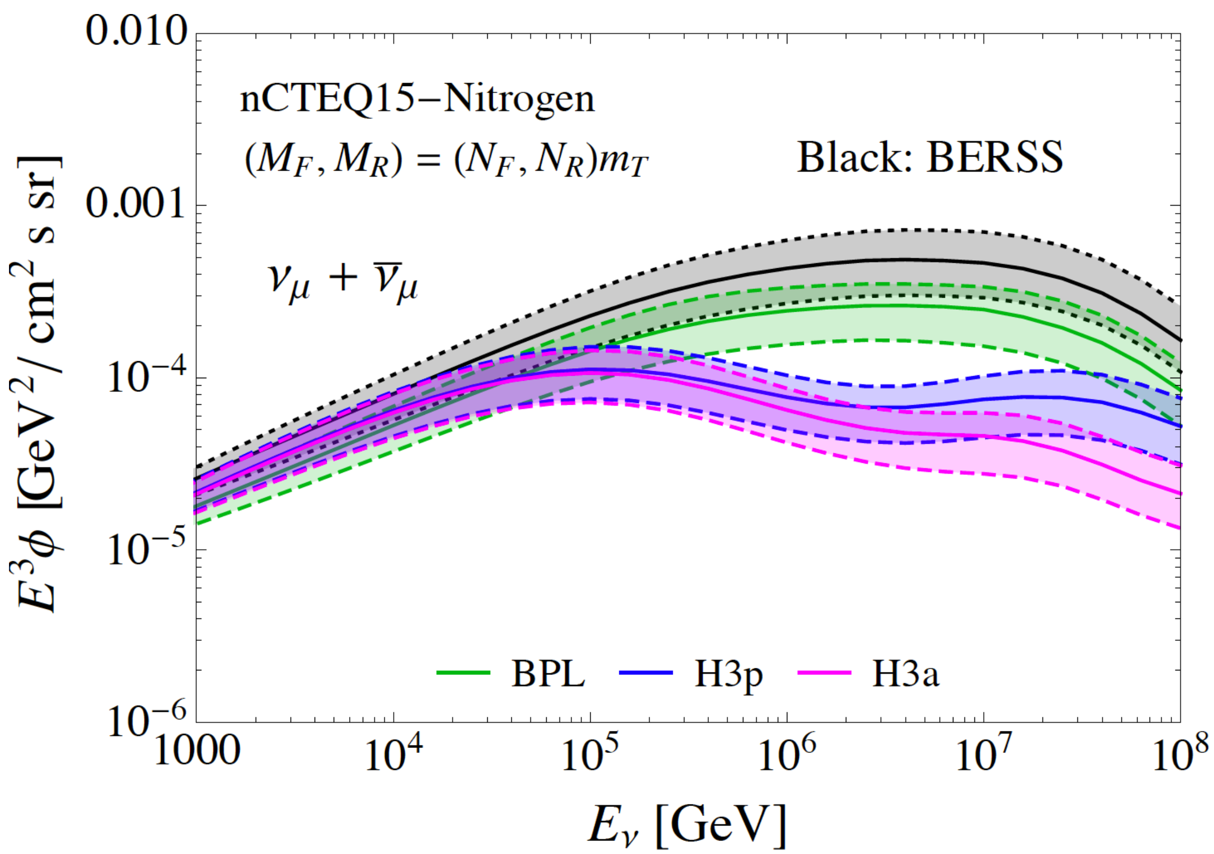
$$h_0 = 6.4\,\mathrm{km} \quad \rho_0 h_0 = 1300\,\mathrm{g/cm^2}$$

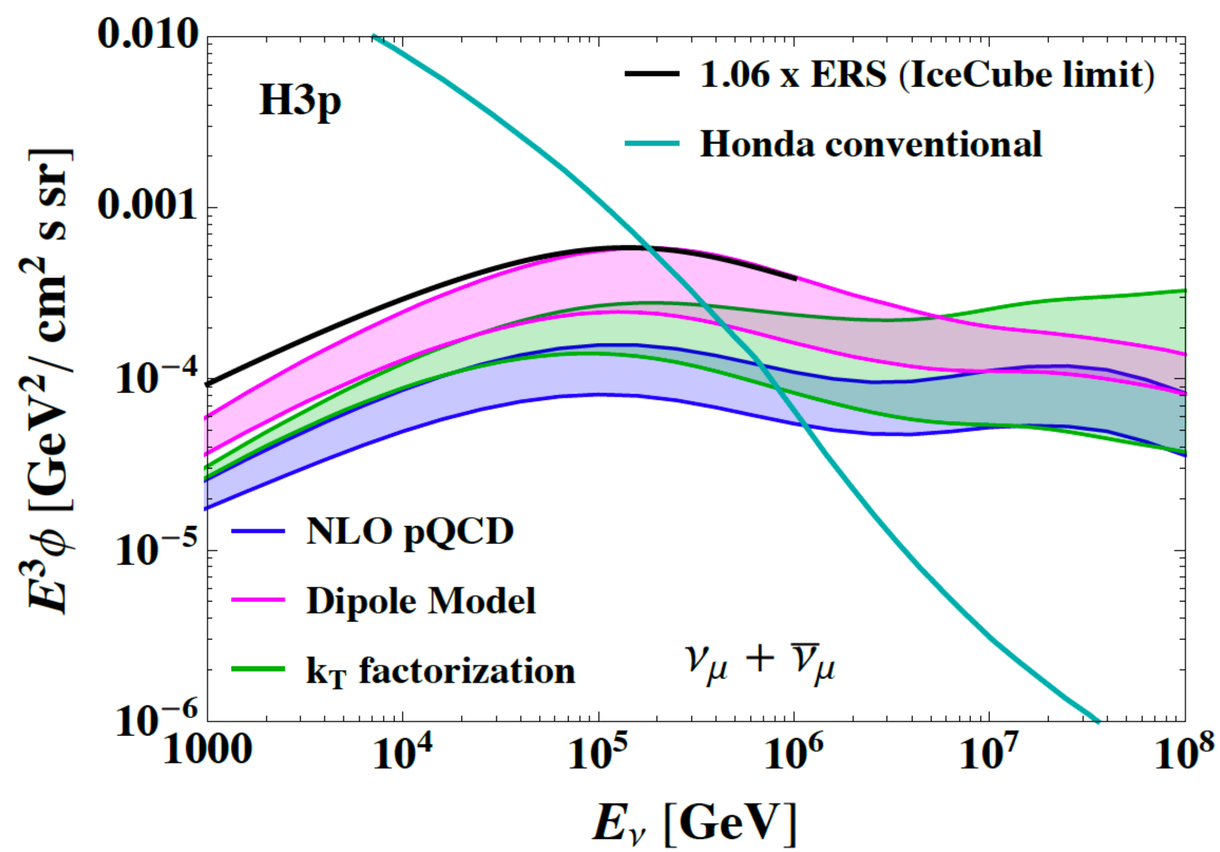
- production/decay distribution

$$\frac{dn(k \to j; E', E)}{dE} = \frac{1}{\sigma_{kA}(E')} \frac{d\sigma(kA \to jY; E', E)}{dE} \qquad \text{(production)}$$

$$= \frac{1}{\Gamma_k(E')} \frac{d\Gamma(k \to jY; E', E)}{dE} \qquad \text{(decay)}$$

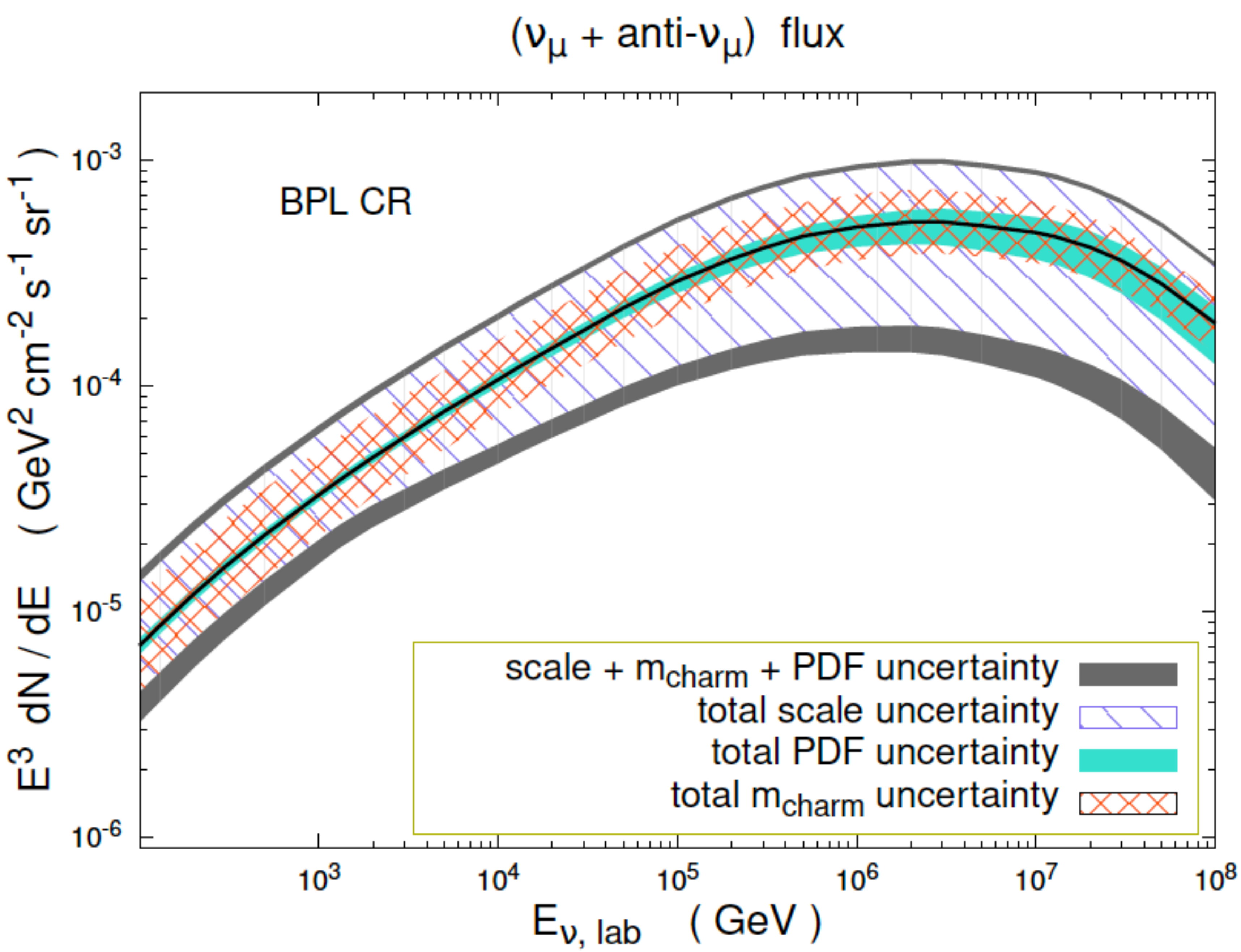
Prompt atmospheric neutrino fluxes





- Recent cosmic ray spectrum reduces the flux significantly with respect to the BPL for $E \gtrsim 10^5$ GeV.
  - H3p: 30 – 70 % (↓); H3a: 40 – 80 % (↓)
- Different frameworks for heavy quark production yield difference by a factor of ~ 5 – 8 at E = $10^{5\text{-}8}$ GeV.
- All predictions are below the IceCube limit.

Uncertainties in prompt atm. neutrinos



PROSA Collaboration, Zenaiev et al, JHEP 118 (2020)

Thank you for your attention