

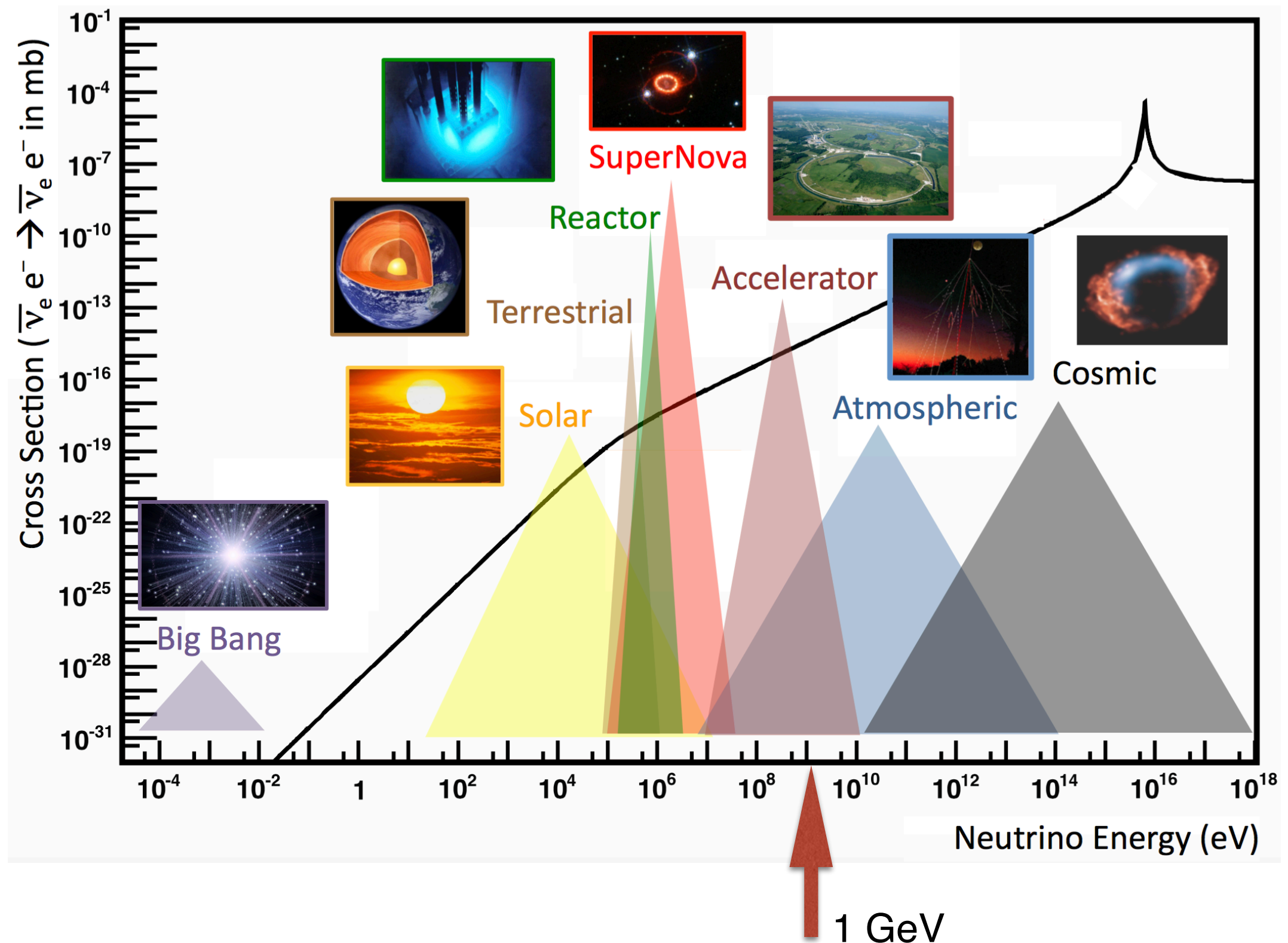
# **Neutrino Production and interaction II**

## **(Neutrinos from heavy flavor)**

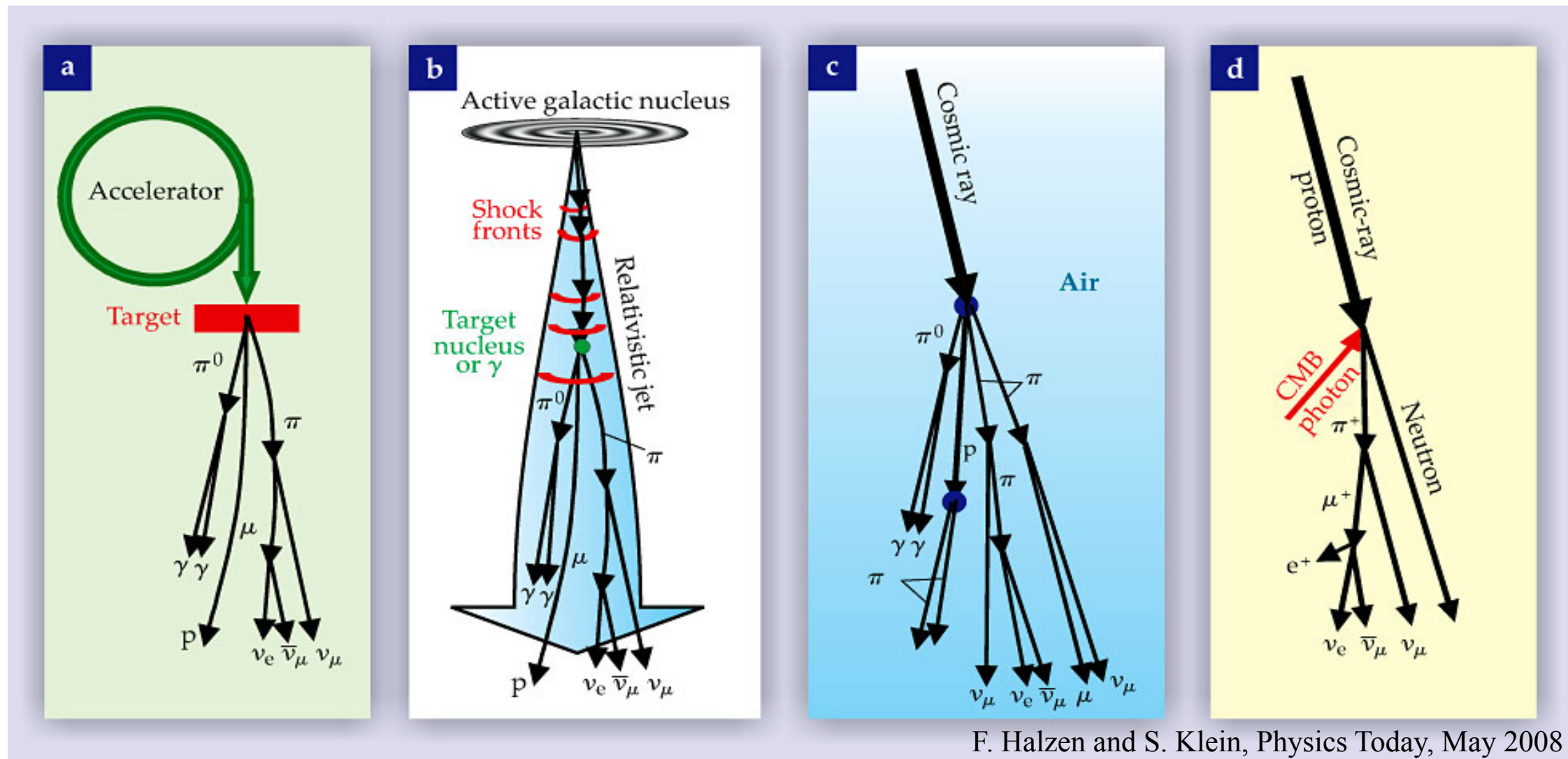
**Yu Seon Jeong**  
(Chung-Ang University)

CANU2, Jan. 20, 2021

# Cross section



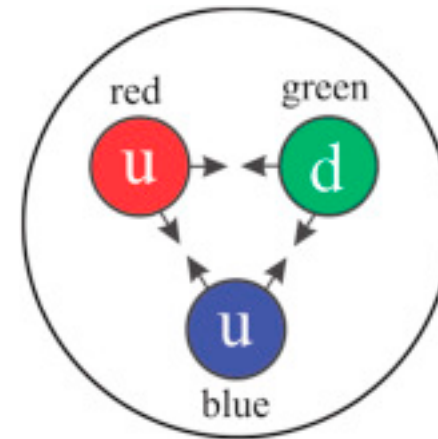
# High energy neutrino production mechanism



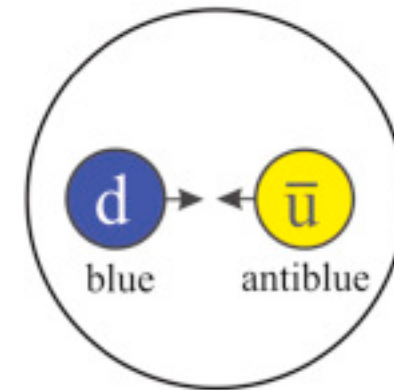
F. Halzen and S. Klein, Physics Today, May 2008

# Hadrons

	I	II	III
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
QUARKS	<b>u</b> up	<b>c</b> charm	<b>t</b> top
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom



Baryon  
(proton,  $p^+$ )



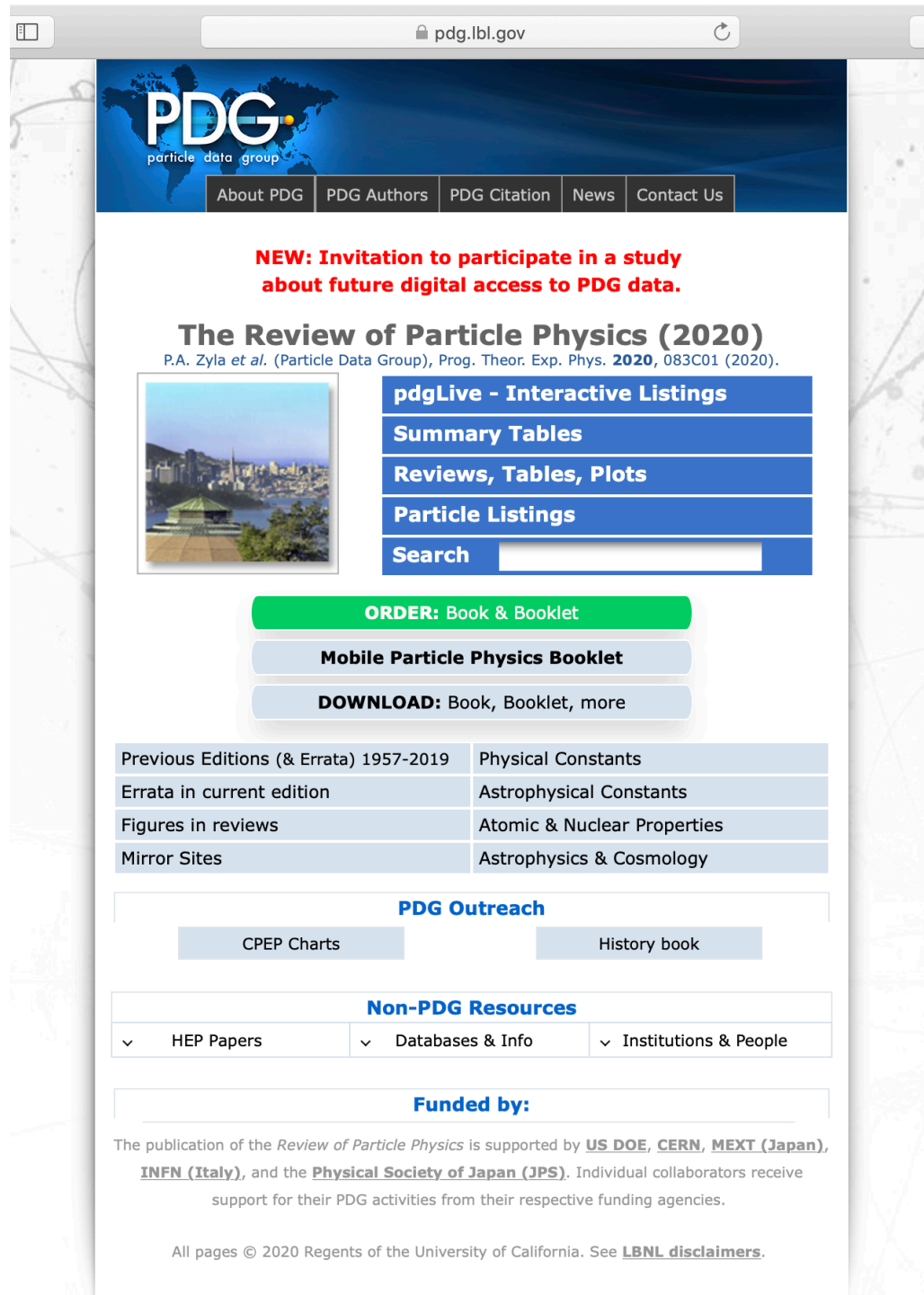
Meson  
(negative pion,  $\pi^-$ )

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 $\text{GeV}/c^2$	Spin
<b>p</b>	proton	<b>uud</b>	1	0.938	1/2
<b><math>\bar{p}</math></b>	anti-proton	<b><math>\bar{u}\bar{u}\bar{d}</math></b>	-1	0.938	1/2
<b>n</b>	neutron	<b>udd</b>	0	0.940	1/2
<b><math>\Lambda</math></b>	lambda	<b>uds</b>	0	1.116	1/2
<b><math>\Omega^-</math></b>	omega	<b>sss</b>	-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 $\text{GeV}/c^2$	Spin
<b><math>\pi^+</math></b>	pion	<b><math>u\bar{d}</math></b>	+1	0.140	0
<b><math>K^-</math></b>	kaon	<b><math>s\bar{u}</math></b>	-1	0.494	0
<b><math>\rho^+</math></b>	rho	<b><math>u\bar{d}</math></b>	+1	0.770	1
<b><math>B^0</math></b>	B-zero	<b><math>d\bar{b}</math></b>	0	5.279	0
<b><math>\eta_c</math></b>	eta-c	<b><math>c\bar{c}</math></b>	0	2.980	0



# Particle Data Group (pdg.lbl.gov)



The screenshot shows the PDG homepage with a navigation bar at the top containing links: About PDG, PDG Authors, PDG Citation, News, and Contact Us. A red banner announces a new invitation to participate in a study about future digital access to PDG data. The main heading is 'The Review of Particle Physics (2020)' by P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020). Below this is a small image of a cityscape. To the right of the image is a vertical menu with links: pdgLive - Interactive Listings, Summary Tables, Reviews, Tables, Plots, Particle Listings, and a Search bar. Below the menu are three buttons: 'ORDER: Book & Booklet' (green), 'Mobile Particle Physics Booklet' (blue), and 'DOWNLOAD: Book, Booklet, more' (blue). A table lists previous editions and errata from 1957 to 2019, categorized by Physical Constants, Astrophysical Constants, Atomic & Nuclear Properties, and Astrophysics & Cosmology. Below the table is a section for PDG Outreach with links to CPEP Charts and History book. A section for Non-PDG Resources includes links to HEP Papers, Databases & Info, and Institutions & People. A section for Funded by lists the US DOE, CERN, MEXT (Japan), INFN (Italy), and the Physical Society of Japan (JPS). The footer states that the publication is supported by these agencies and that individual collaborators receive support from their respective funding agencies. The footer also includes a copyright notice: All pages © 2020 Regents of the University of California. See LBNL disclaimers.


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**The Review of Particle Physics (2020)**  
P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).



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**Summary Tables**

**Reviews, Tables, Plots**

**Particle Listings**

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Previous Editions (& Errata) 1957-2019	Physical Constants
Errata in current edition	Astrophysical Constants
Figures in reviews	Atomic & Nuclear Properties
Mirror Sites	Astrophysics & Cosmology

**PDG Outreach**

**CPEP Charts** **History book**

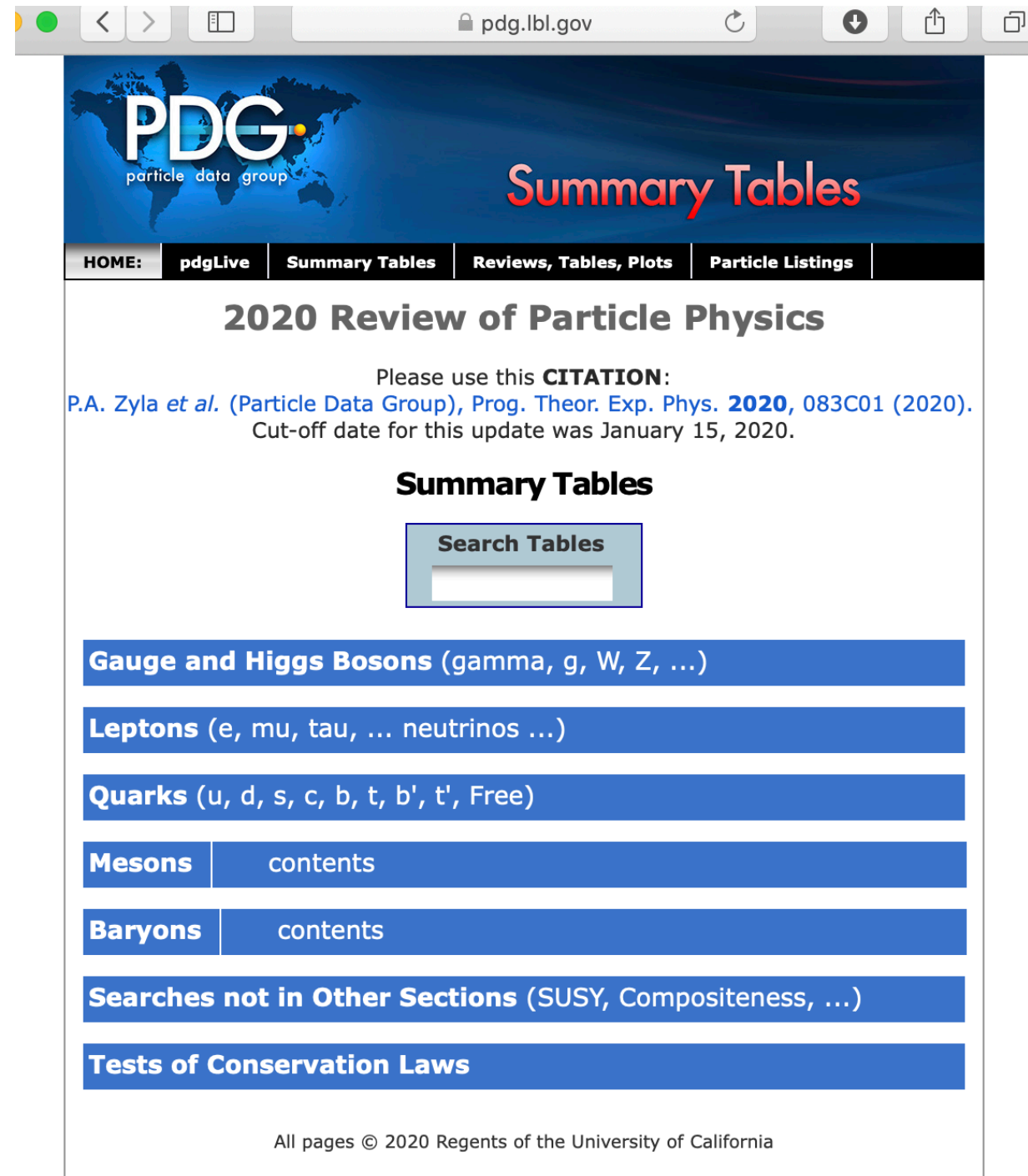
**Non-PDG Resources**

HEP Papers Databases & Info Institutions & People

**Funded by:**

The publication of the Review of Particle Physics is supported by **US DOE**, **CERN**, **MEXT (Japan)**, **INFN (Italy)**, and the **Physical Society of Japan (JPS)**. Individual collaborators receive support for their PDG activities from their respective funding agencies.

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The screenshot shows the PDG Summary Tables page. The navigation bar at the top contains links: HOME, pdgLive, Summary Tables, Reviews, Tables, Plots, and Particle Listings. The main heading is '2020 Review of Particle Physics'. Below this is a citation: 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. The section is titled 'Summary Tables' and features a search bar labeled 'Search Tables'. Below the search bar is a list of particle categories, each with a link to its content: Gauge and Higgs Bosons (gamma, g, W, Z, ...), Leptons (e, mu, tau, ... neutrinos ...), Quarks (u, d, s, c, b, t, b', t', Free), Mesons (contents), Baryons (contents), Searches not in Other Sections (SUSY, Compositeness, ...), and Tests of Conservation Laws. The footer states: All pages © 2020 Regents of the University of California.

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**Summary Tables**

**HOME: pdgLive Summary Tables Reviews, Tables, Plots Particle Listings**

**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.

**Summary Tables**

**Search Tables**

**Gauge and Higgs Bosons** (gamma, g, W, Z, ...)

**Leptons** (e, mu, tau, ... neutrinos ...)

**Quarks** (u, d, s, c, b, t, b', t', Free)

**Mesons** contents

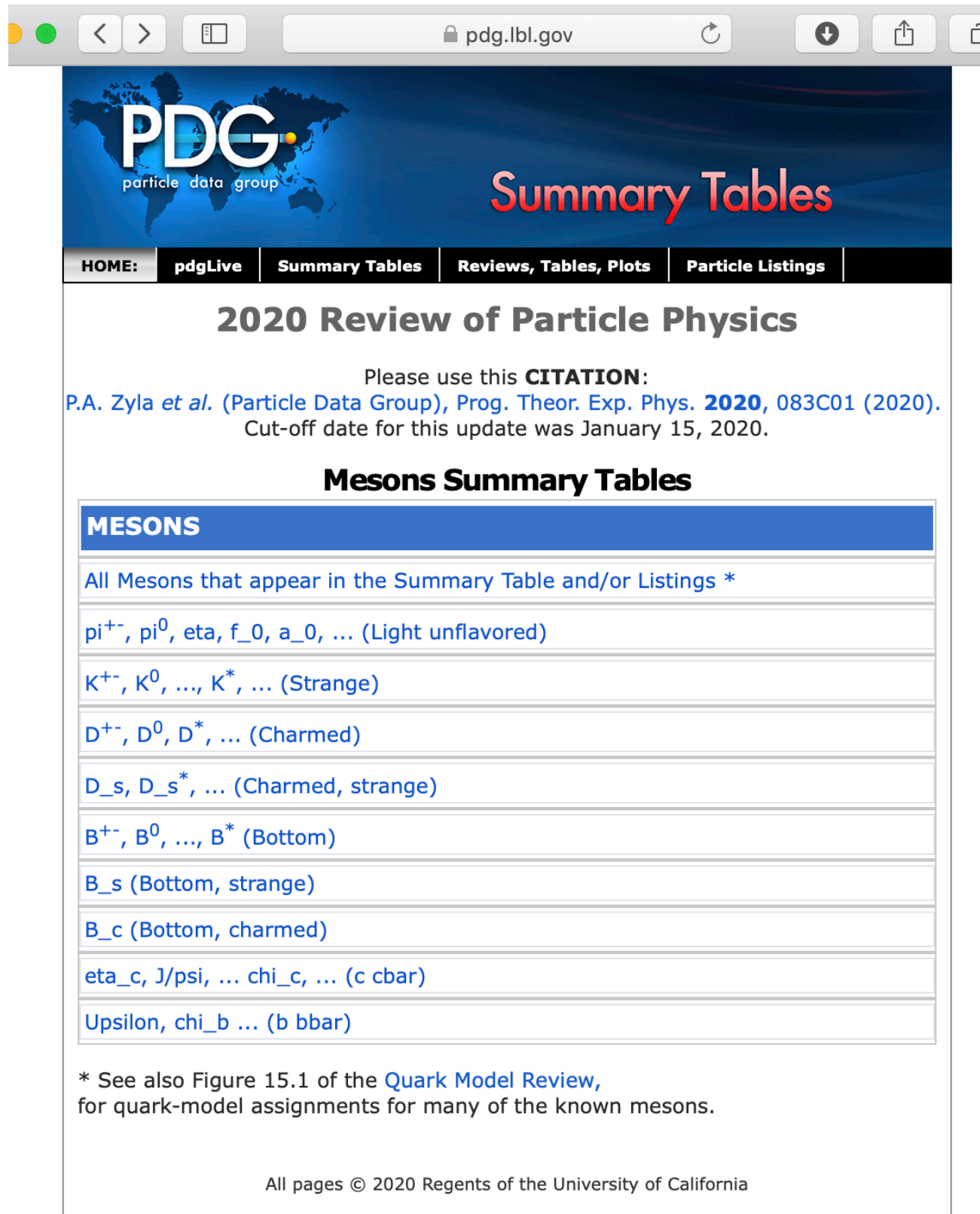
**Baryons** contents

**Searches not in Other Sections** (SUSY, Compositeness, ...)

**Tests of Conservation Laws**

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# Particle Data Group (pdg.lbl.gov)



The screenshot shows the PDG website interface. At the top, there's a navigation bar with links: HOME, pdgLive, Summary Tables (selected), Reviews, Tables, Plots, and Particle Listings. Below this is the title "2020 Review of Particle Physics". A citation notice states: "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." The main section is titled "Mesons Summary Tables". It contains a table with the following rows:

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

\* See also Figure 15.1 of the [Quark Model Review](#), for quark-model assignments for many of the known mesons.

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

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

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

.....

# Prompt neutrinos

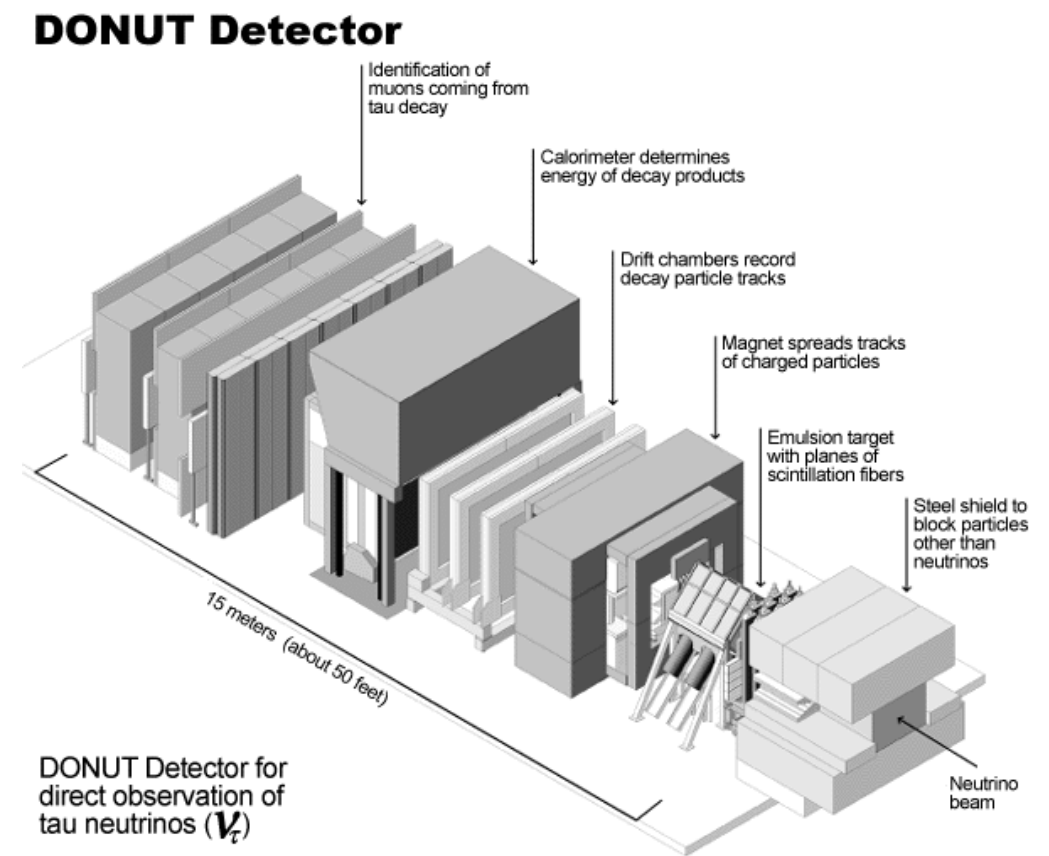
- In pp/pA/AA collisions, various hadrons are produced.
- A number of neutrinos are produced from subsequent decay of the secondary hadrons.

$$\text{e.g.) } \pi, K, D, B \dots \rightarrow \nu + X$$

- 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.
$$D_s^+ \rightarrow \nu_\tau + \tau^+$$
$$\rightarrow \nu_\tau + (\mu^+ + \nu_\mu + \bar{\nu}_\tau)$$
- 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).





# Large Hadron Collider (LHC)

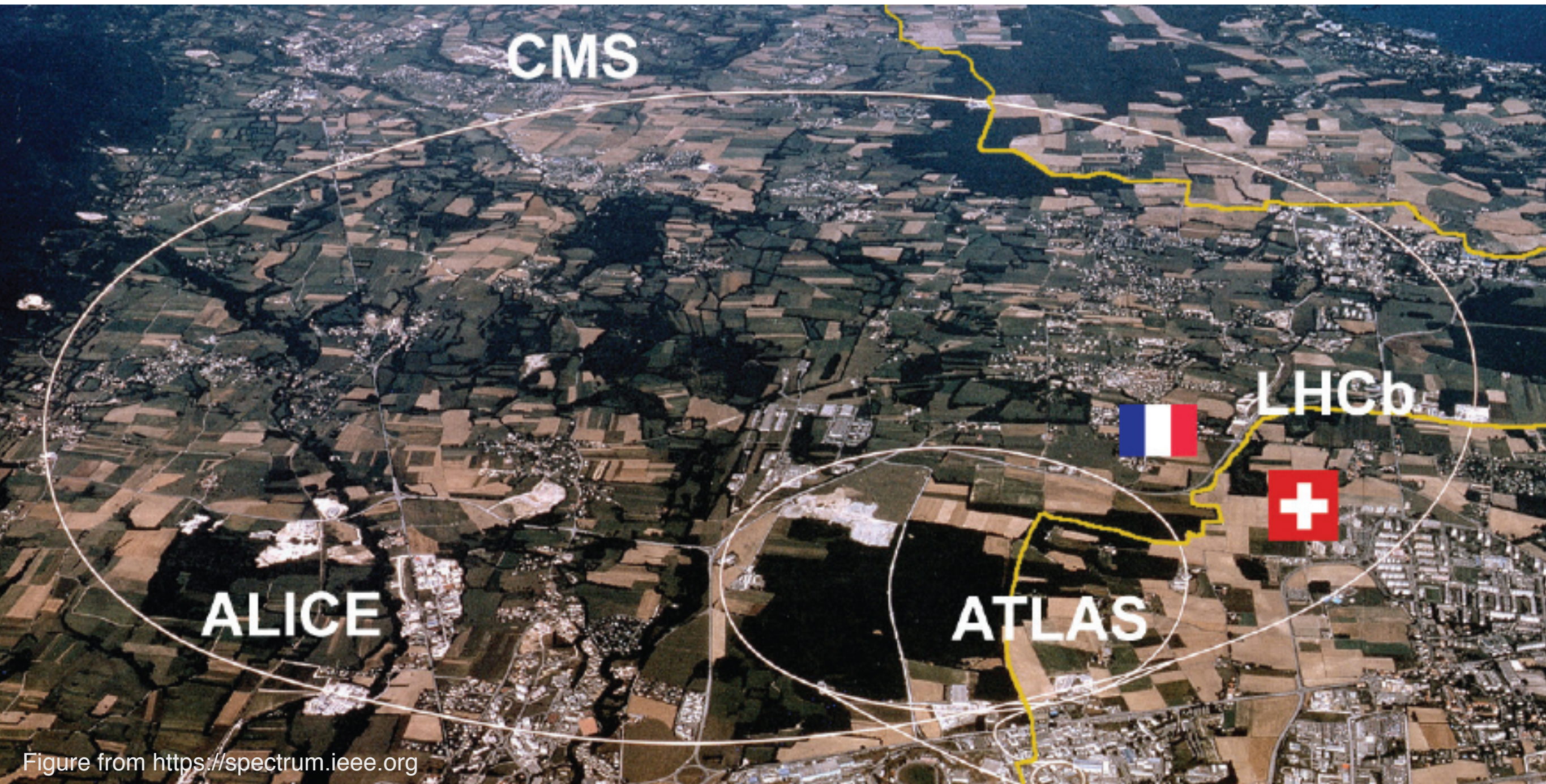
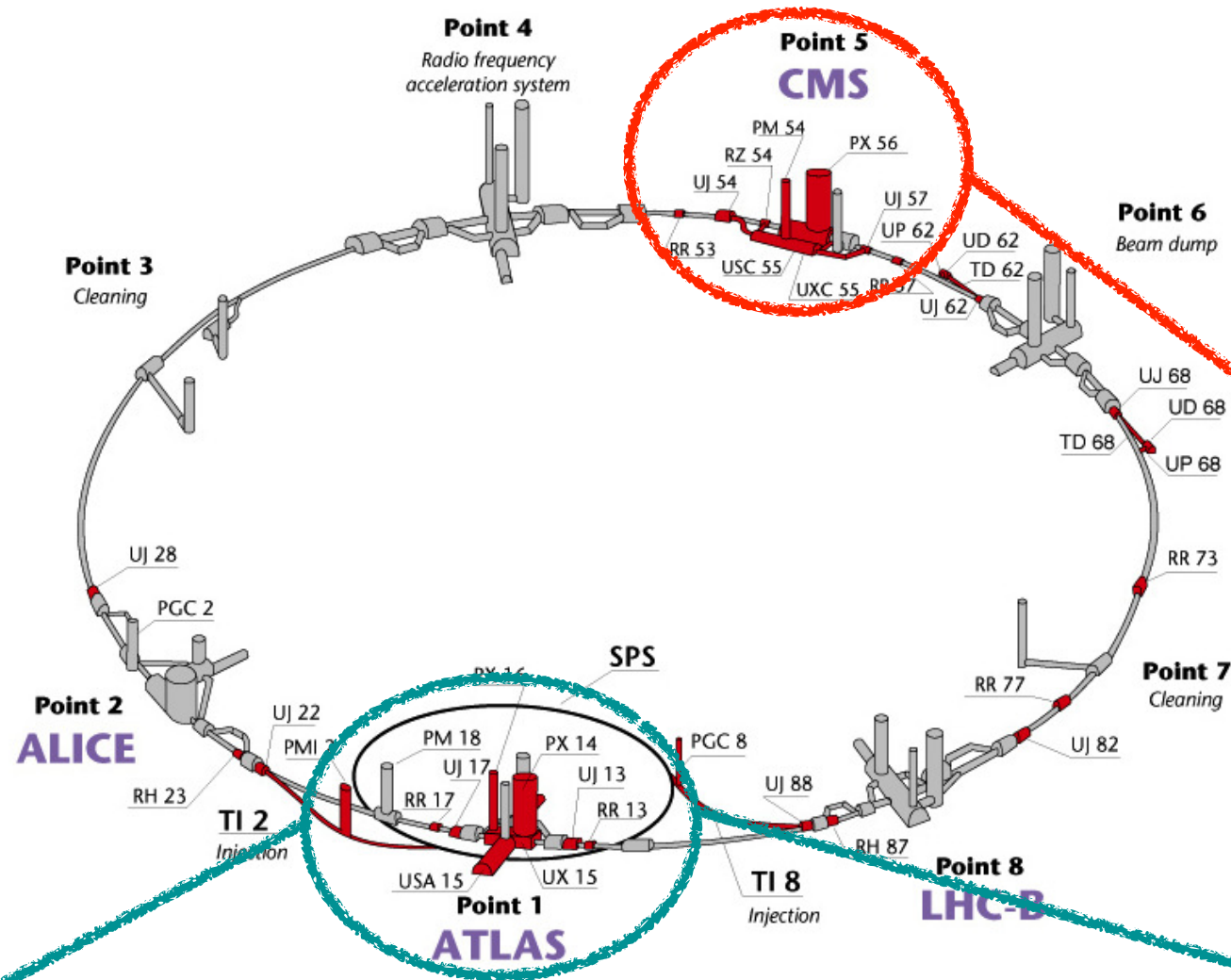


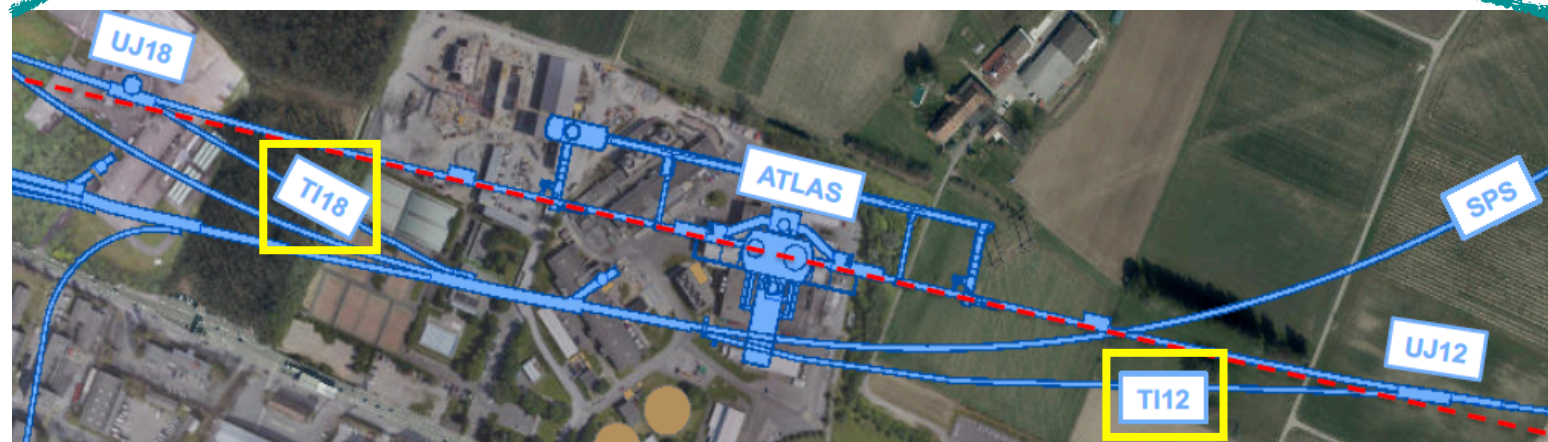
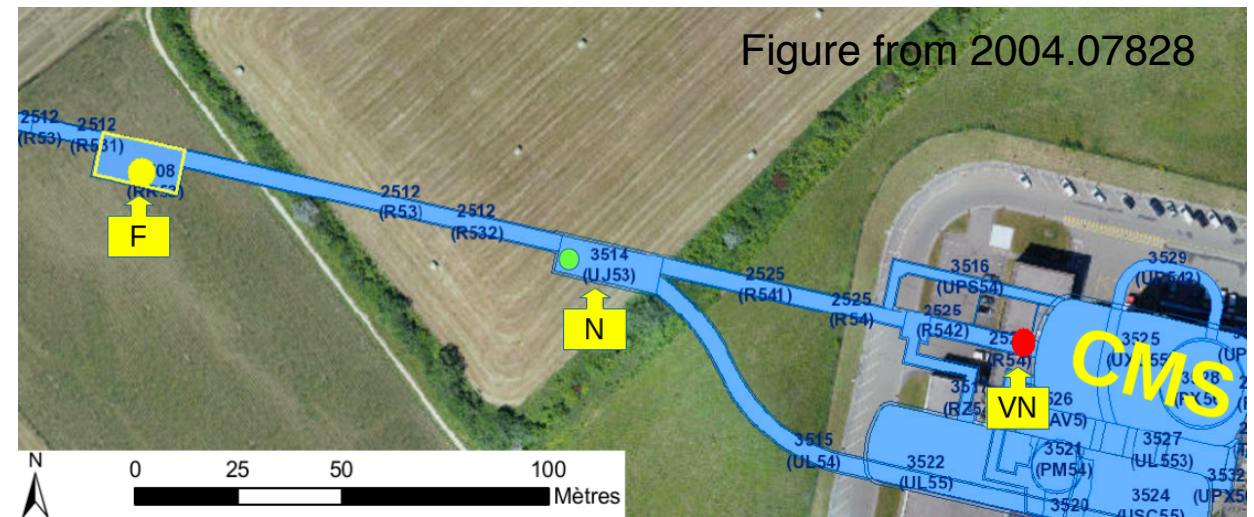
Figure from <https://spectrum.ieee.org>



# 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)

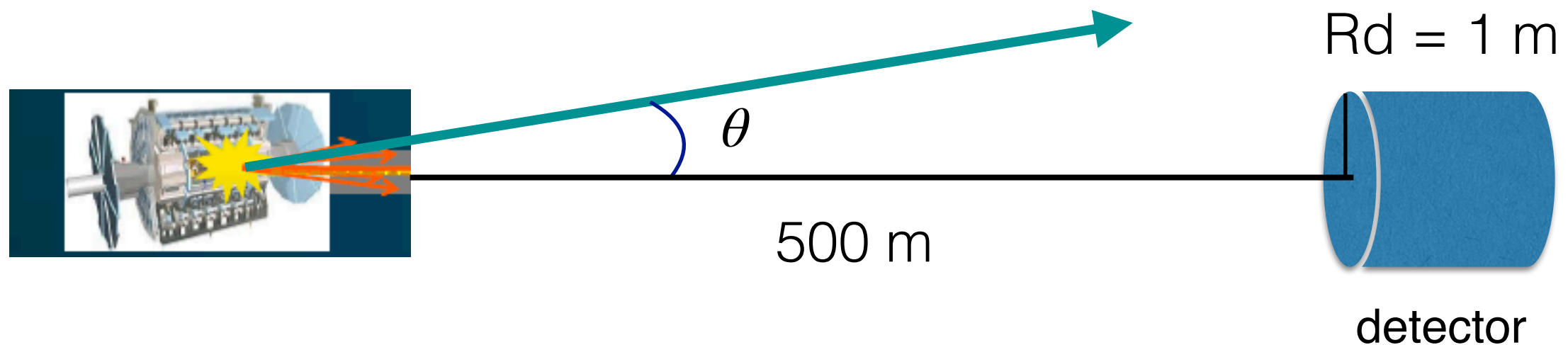
# Rapidity/ pseudo rapidity

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

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

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

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



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

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

# FASER / FASER $\nu$

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

Ref: 1901.04468, 2001.03073

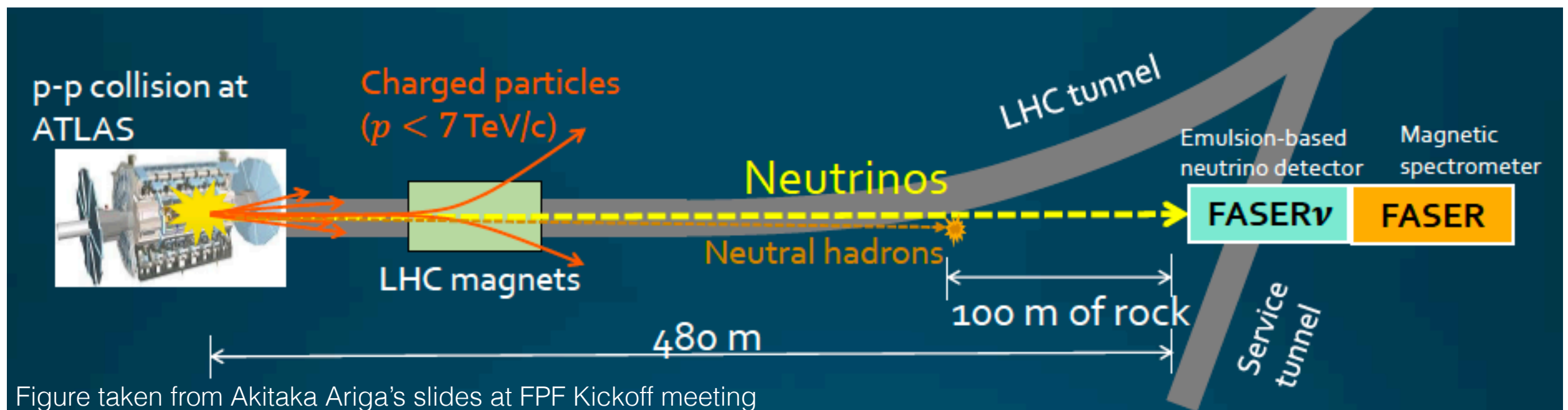


Figure taken from Akitaka Ariga's slides at FPF Kickoff meeting

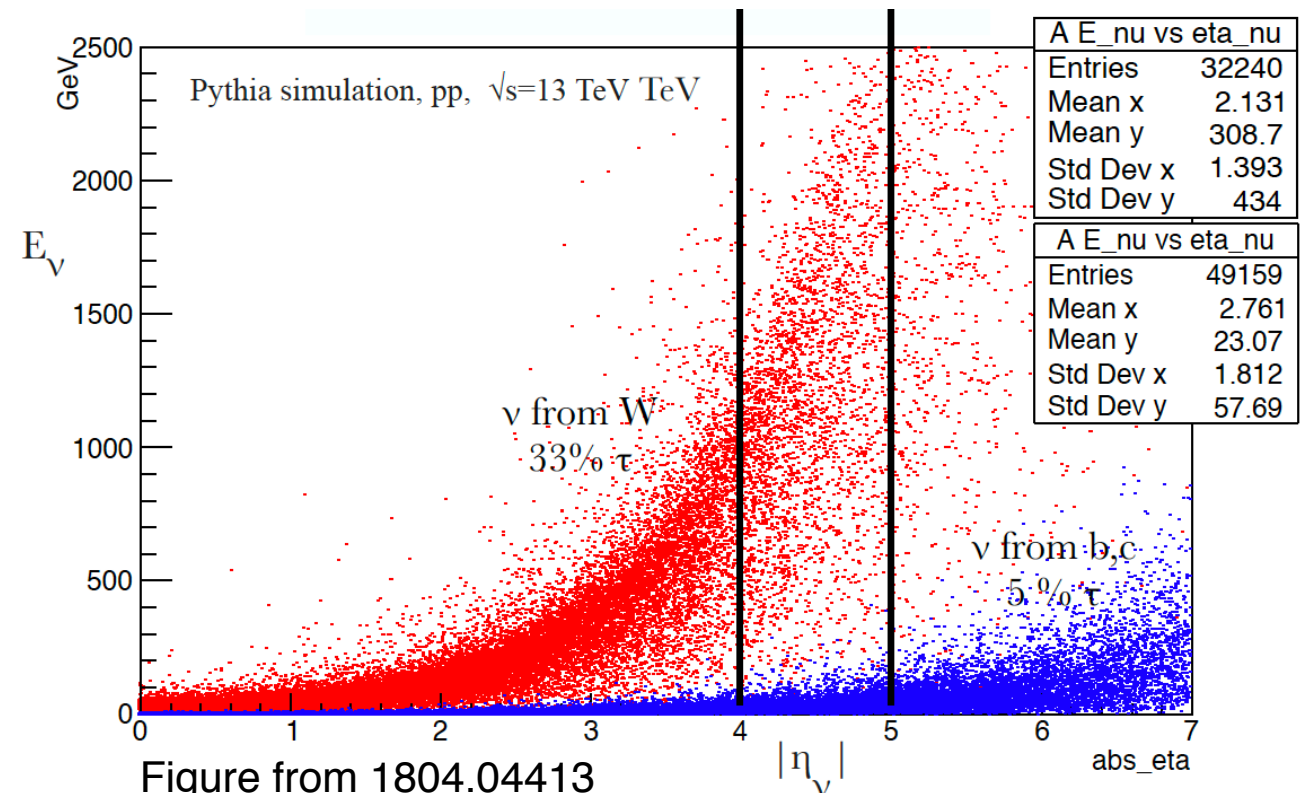
# XSEN, SND@LHC (proposed)

- 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 data 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

- $\pi, K$  ( $c\tau \sim O(1)$  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  $\pi$  ( $K$ ).
  - Still exist neutrinos from the  $\pi, K$  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 ( $c\tau \sim O(100)$   $\mu\text{m}$ )
  - $\Lambda_c$  ( $c\tau \sim O(10)$   $\mu\text{m}$ )
- $\nu_\tau$  are only from  $D_s^\pm, B^\pm, B^0(\bar{B}^0)$ .  
 the main source of  $\nu_\tau$





# 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.

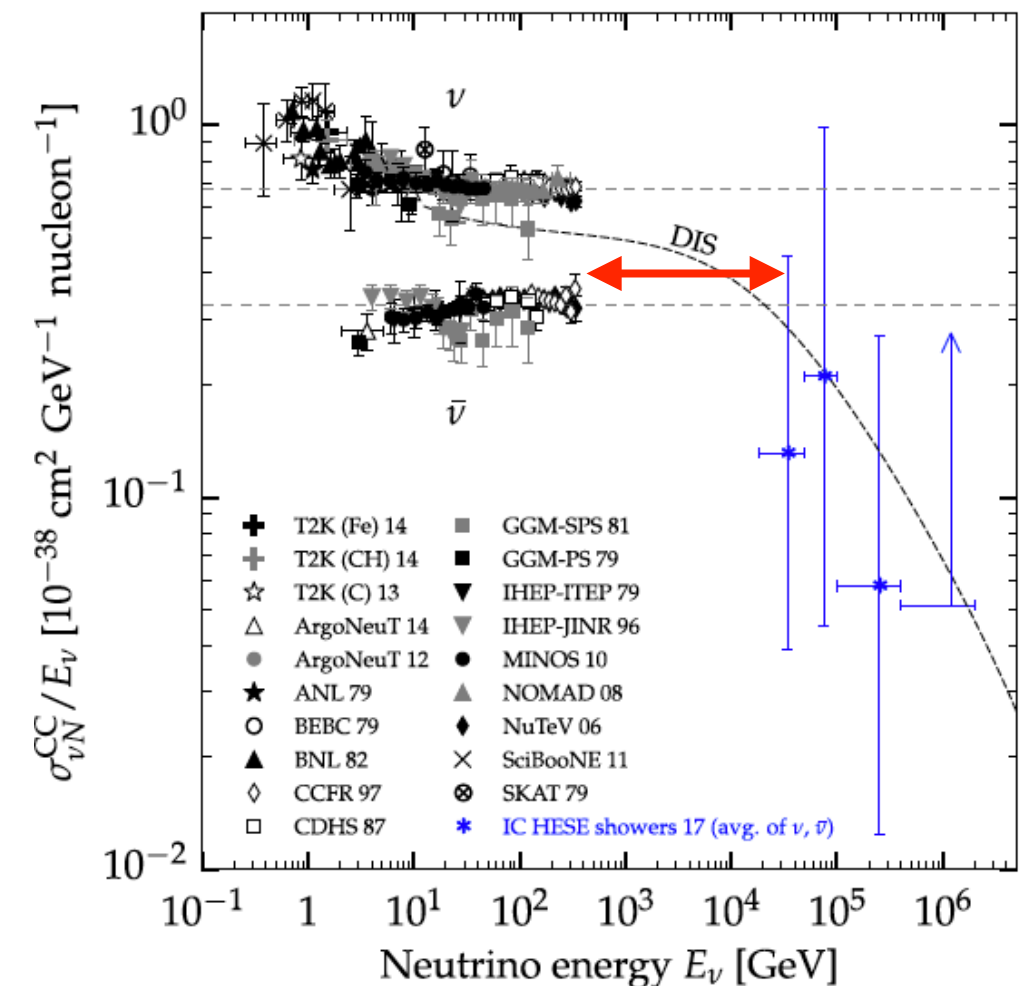
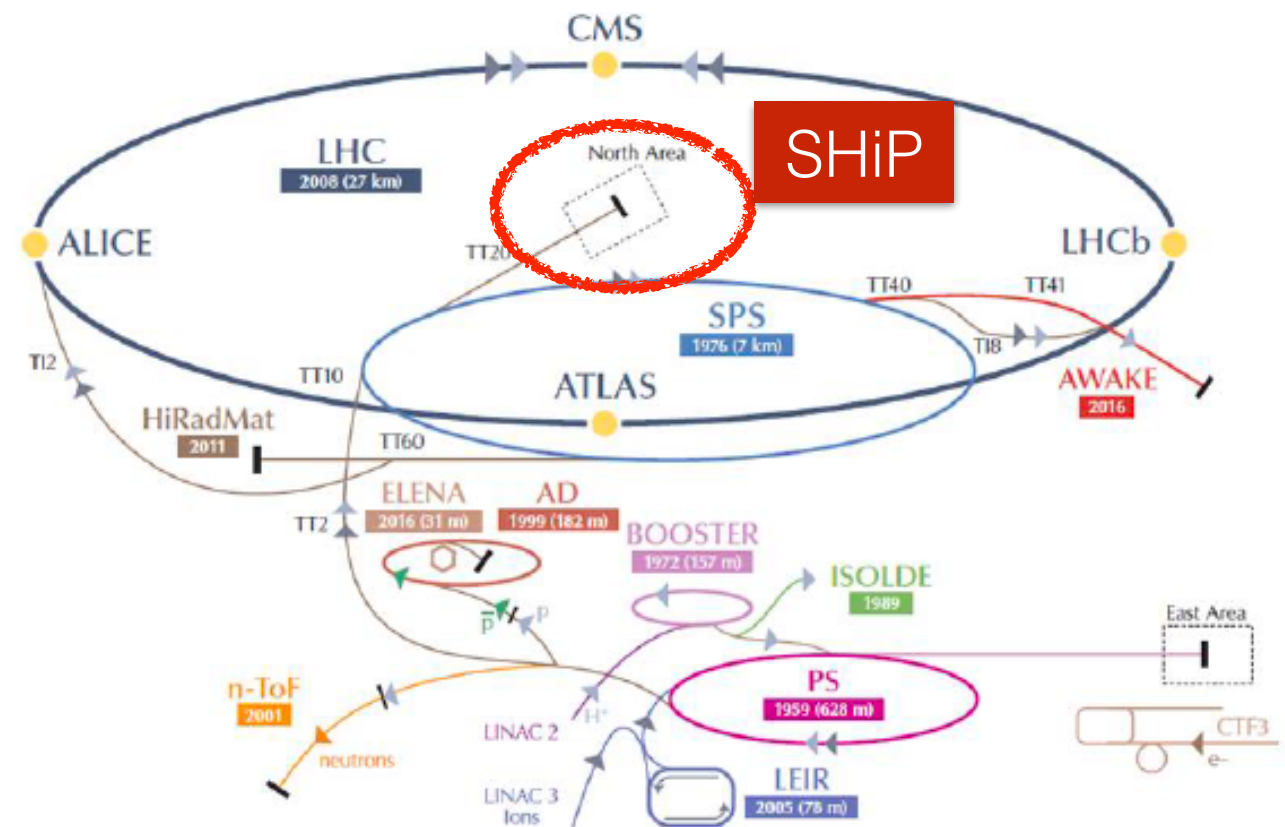
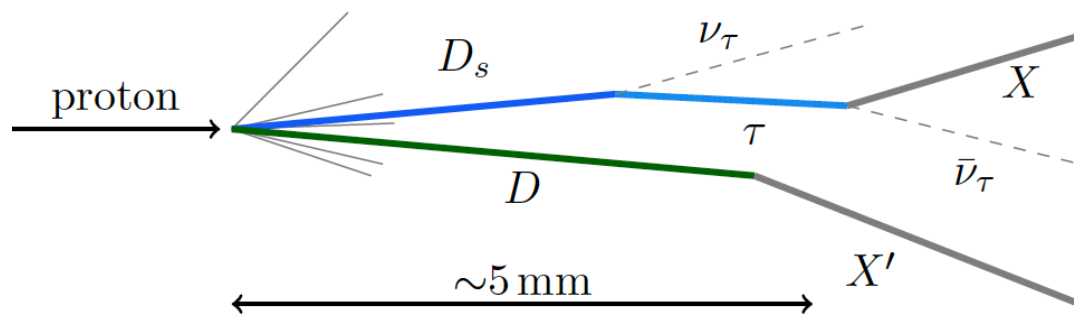


Figure from Bustamante and Connolly, PRL 122, 041101 (2019)

# Prompt tau neutrinos at CERN — Ds tau

## ■ NA65/DsTau experiment (SPS)

- 400 GeV proton beam on tungsten target
- Study tau neutrino production,  $D_s \rightarrow \tau \rightarrow X$
- Provide  $\nu_\tau$  flux prediction for neutrino beam for future experiments.
- Approved in 2019 and will run in 2021 - 2022

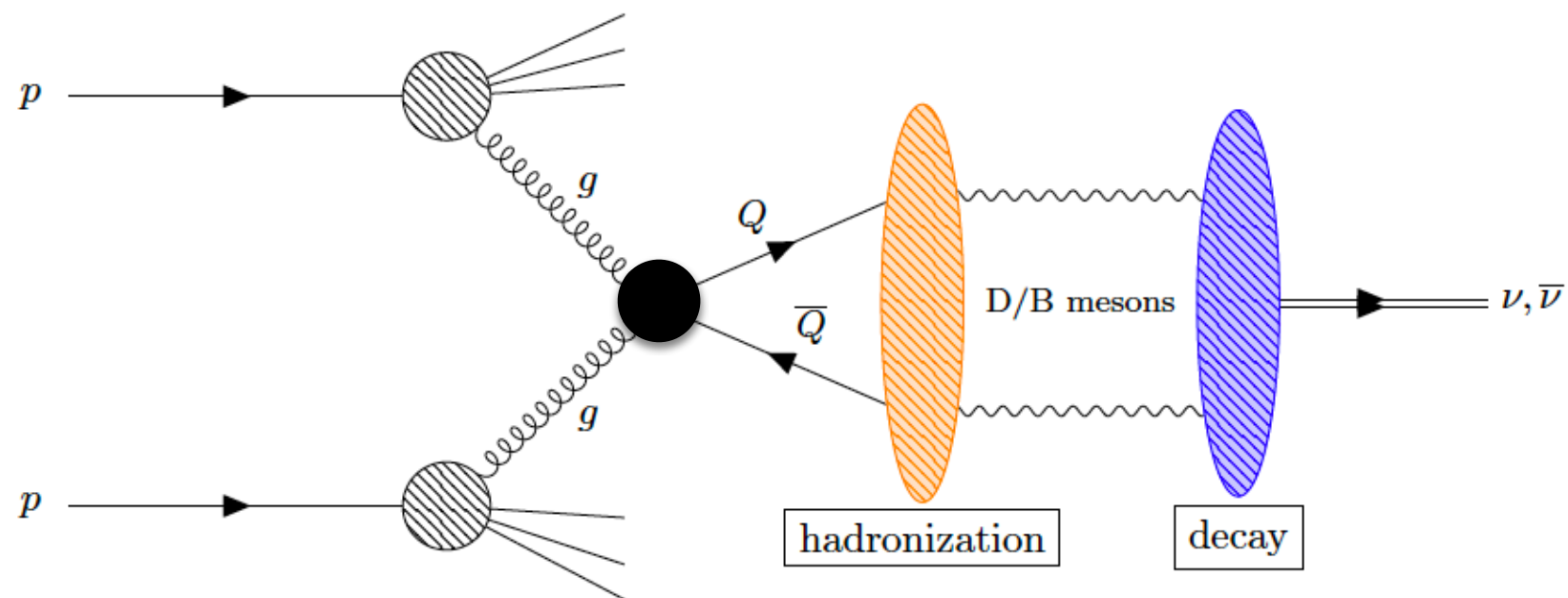


Ref: JHEP 01 (2020) 033 (DsTau)

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



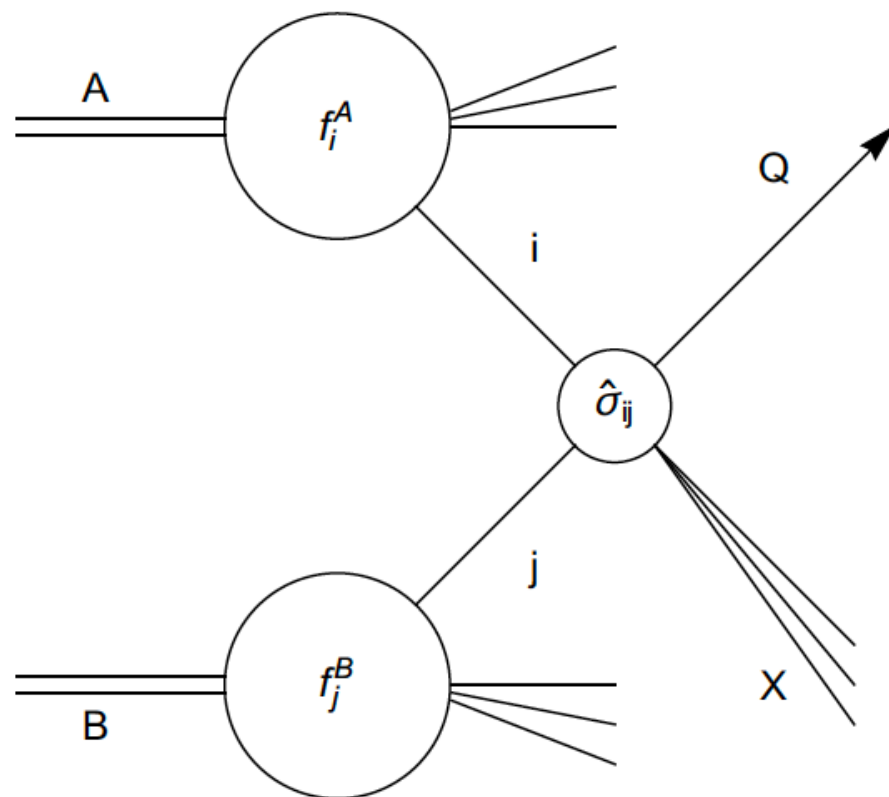
# Heavy quark production

## ■ Perturbative QCD with collinear approximation

- The HQ production cross section (NLO)

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

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



- Contributed processes

$$q + \bar{q} \rightarrow Q + \bar{Q}$$

$$g + g \rightarrow Q + \bar{Q}$$

$$\alpha_s^2, \alpha_s^3$$

$$q + \bar{q} \rightarrow Q + \bar{Q} + g$$

$$g + g \rightarrow Q + \bar{Q} + g$$

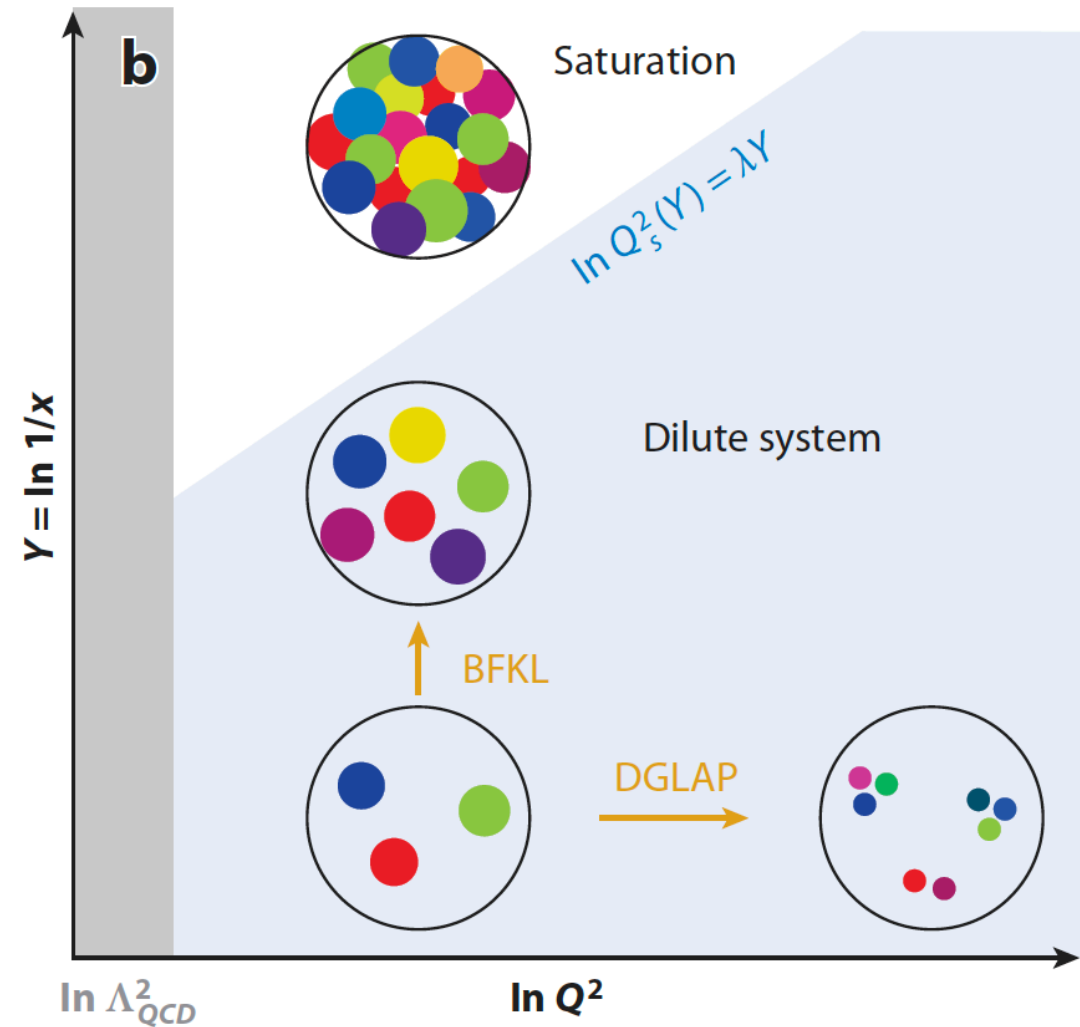
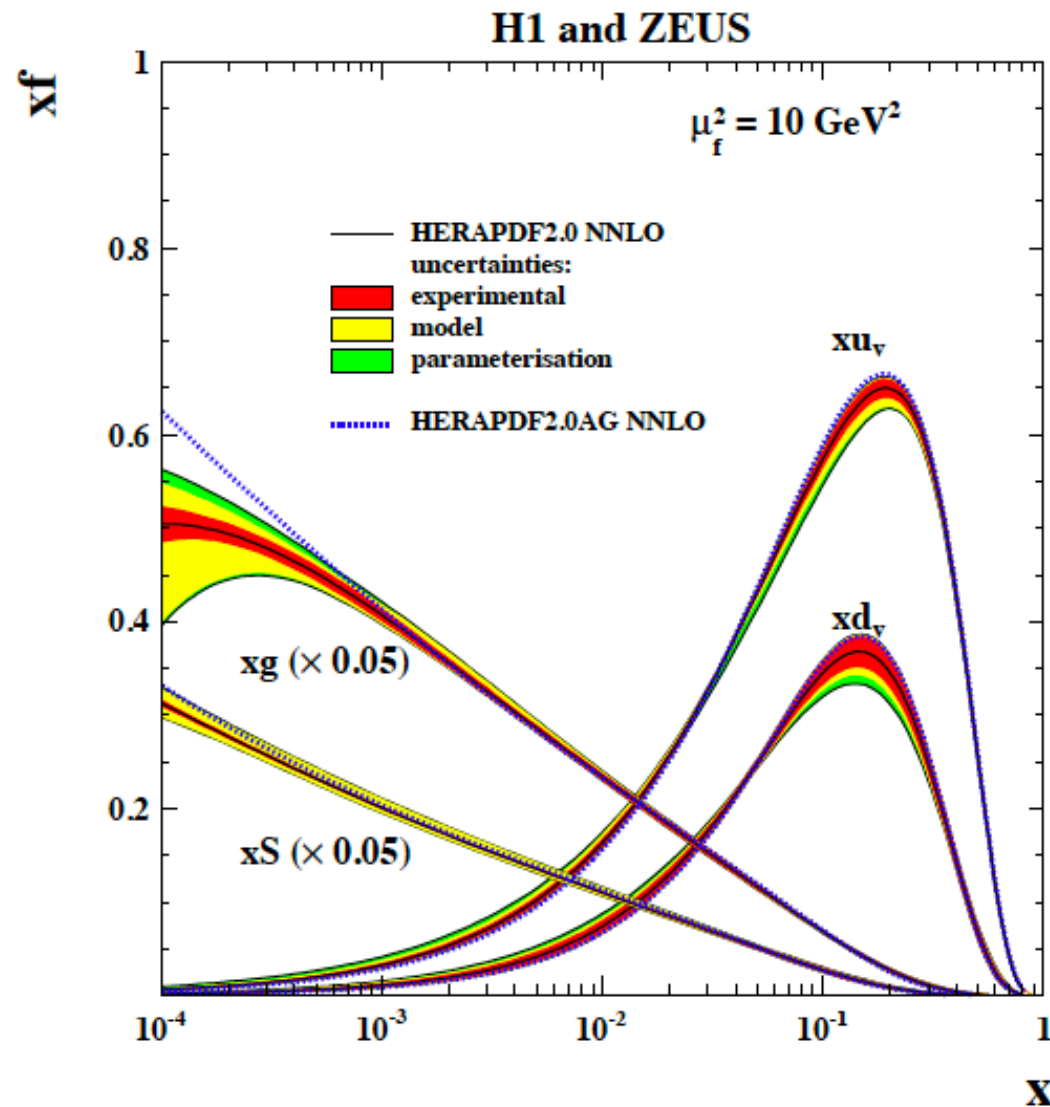
$$\alpha_s^3$$

$$g + q \rightarrow Q + \bar{Q} + q$$

$$g + \bar{q} \rightarrow Q + \bar{Q} + \bar{q}$$

$$\alpha_s^3$$

# Gluon distributions and saturation



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



# Fragmentation

- Heavy quark to heavy hadron

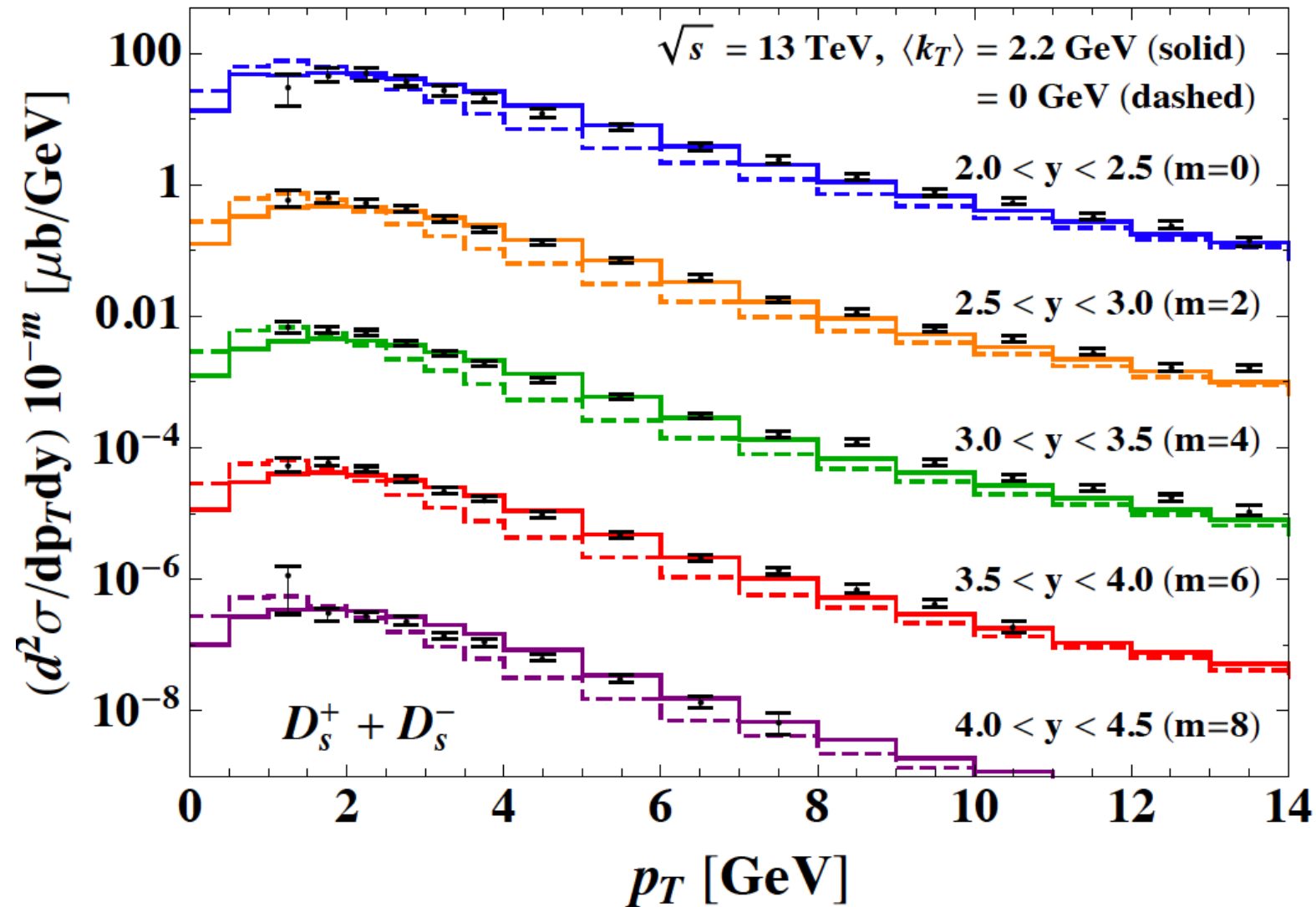
$$\left( E \frac{d^3\sigma}{dp_Q^3} \right)_H = \left( E \frac{d^3\sigma}{dp_Q^3} \right)_Q \otimes D_Q^H(z)$$

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

: Fragmentation function

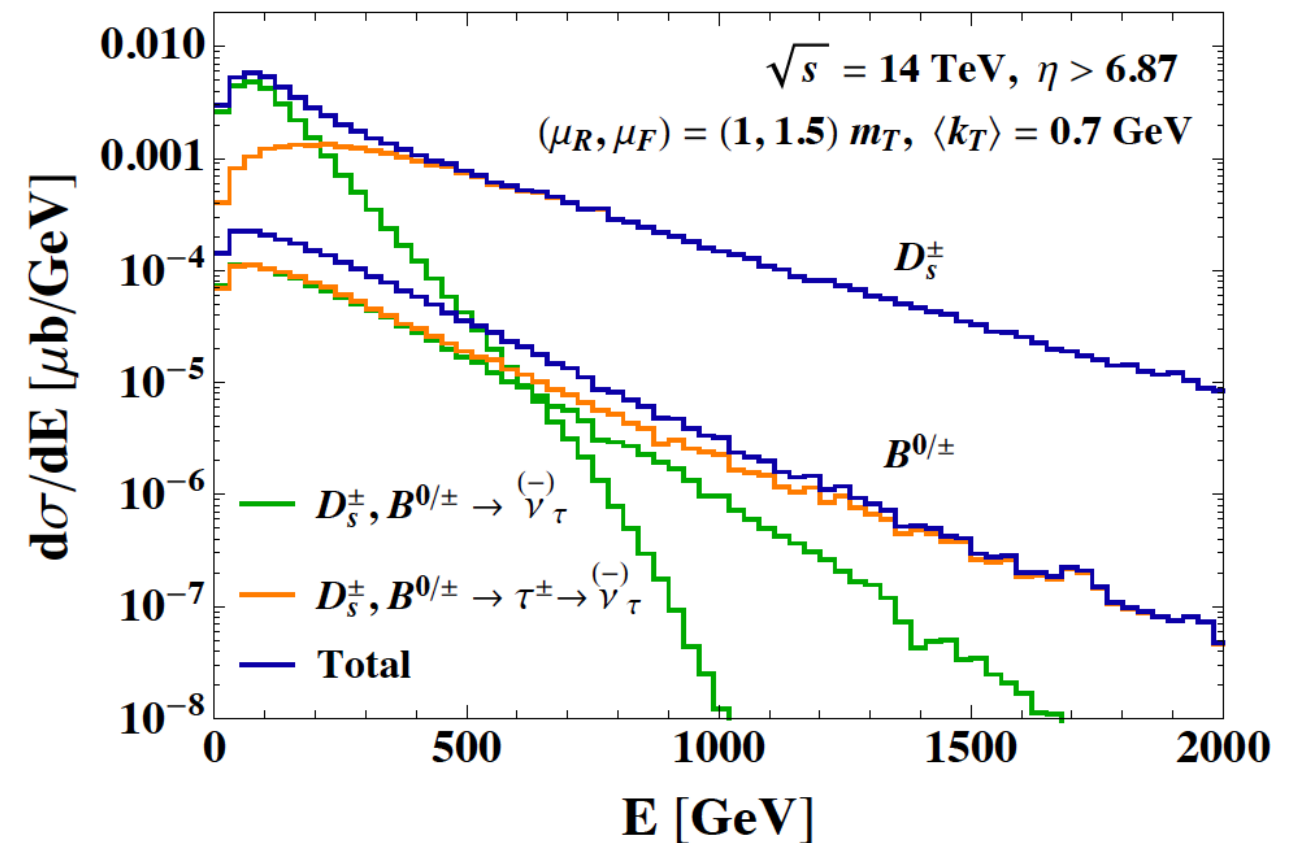
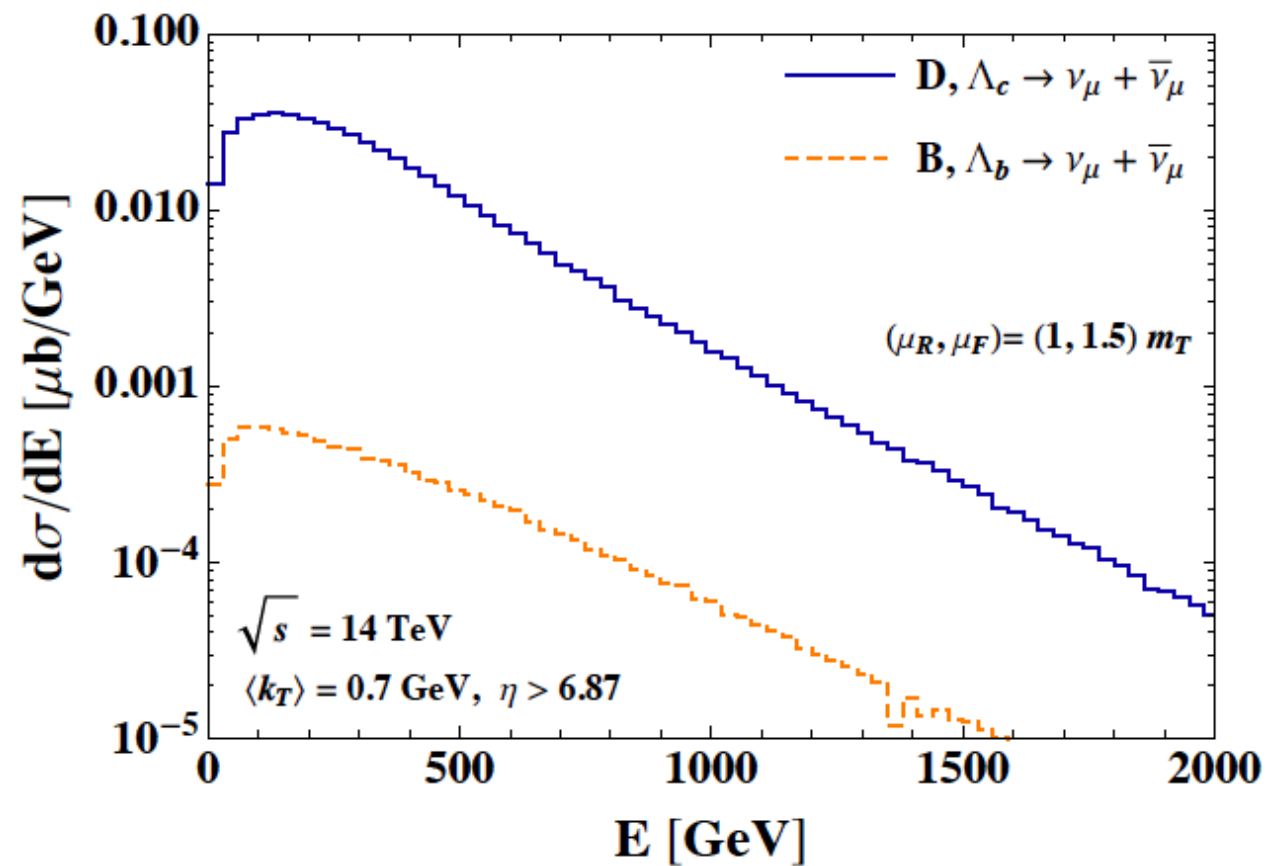
Hadrons	$D^-$	$D^0$	$D_s^-$	$\Lambda_c^+$	$B/B^0$
$\epsilon$	0.039	0.028	0.008	0.011	0.0033

# Comparison with the LHCb data

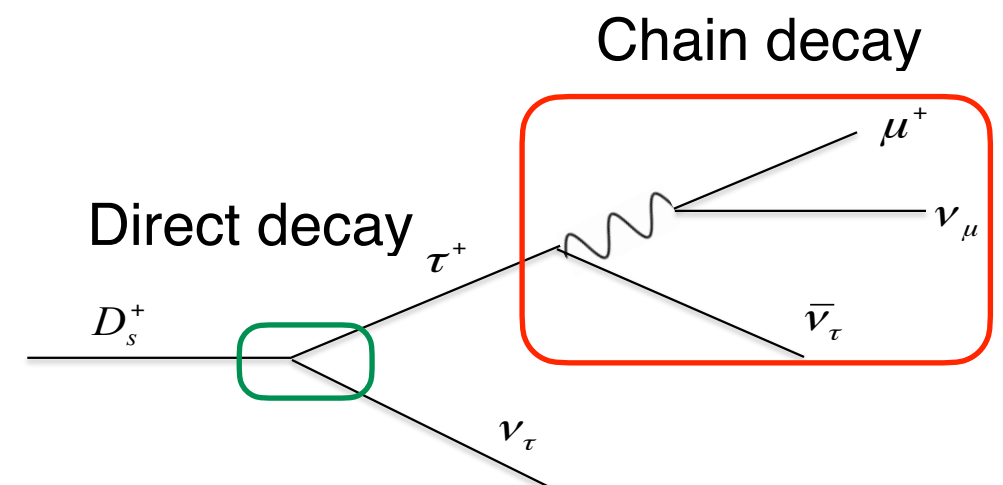


- The LHCb experiment probes the forward region.
- Relevant parameters can be found by comparing evaluation with the LHCb data for the total and differential cross sections.

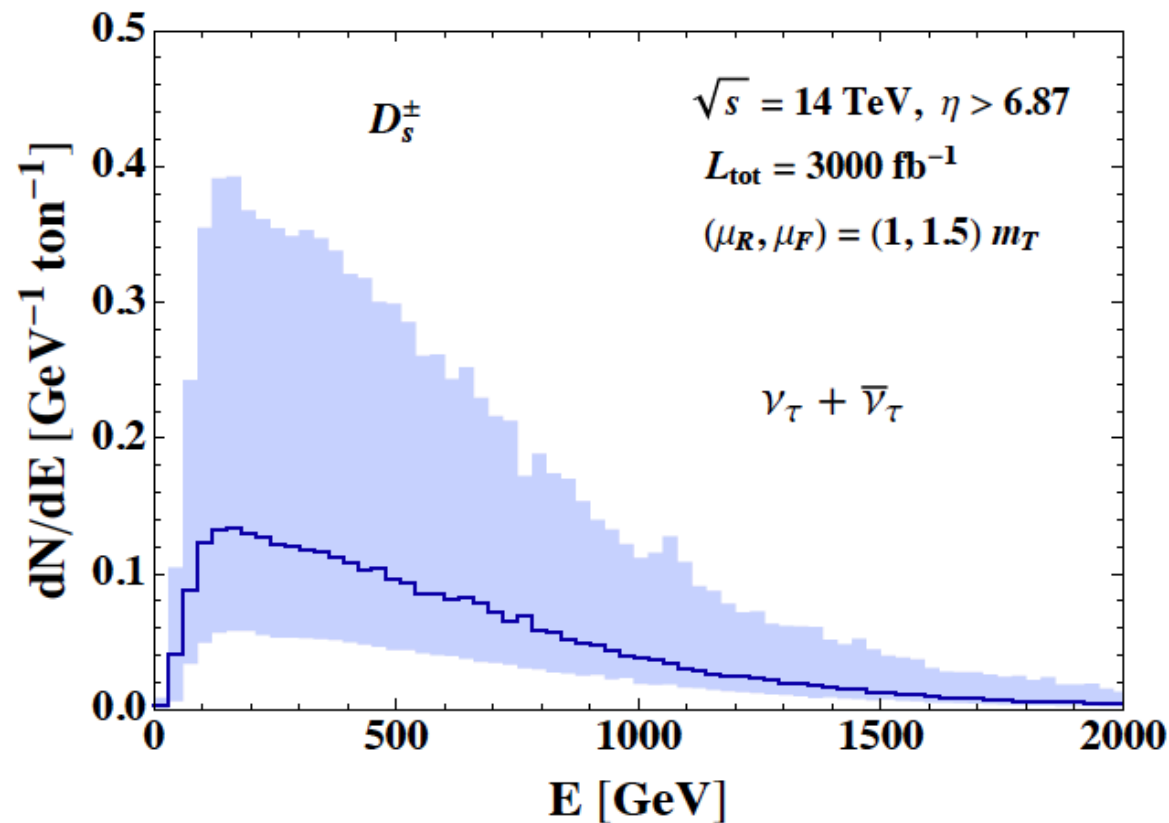
# Differential cross sections for $\nu + \bar{\nu}$



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



# Energy spectrum of event rate & event numbers

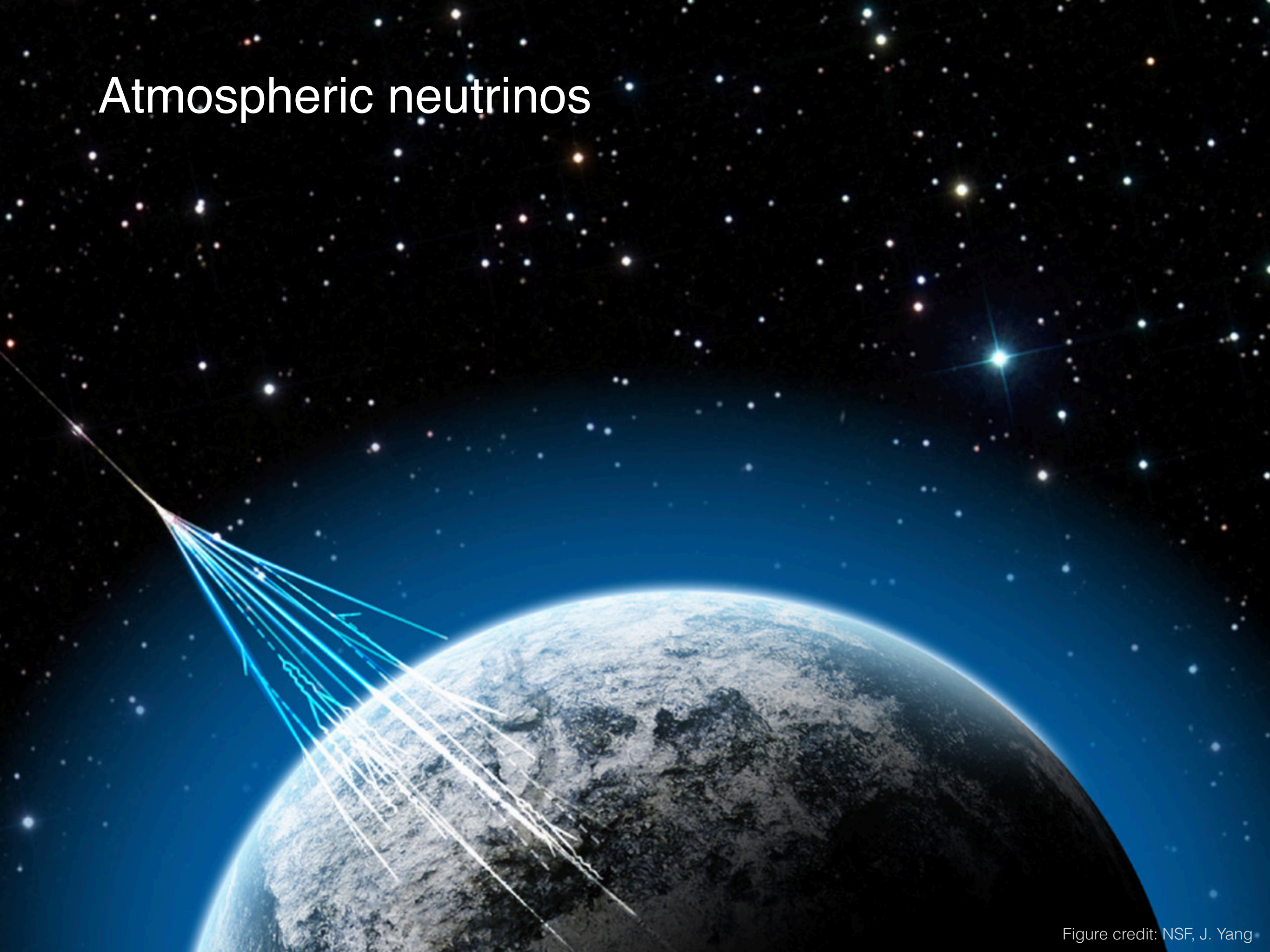


- The band reflects the uncertainty range due to QCD scale variation.
- Number of  $\nu_\tau + \bar{\nu}_\tau$  — over thousands of events
- Uncertainty range due to the scale variation: a factor of  $\sim 6$

	$\nu_\tau$	$\bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$	$\nu_\tau + \bar{\nu}_\tau$				
$(\mu_R, \mu_F)$	$(1, 1.5) m_T$			$(1, 1.5) m_T$			$(0.5, 1.5) m_T$	$(1, 0.75) m_T$
$\langle k_T \rangle$	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





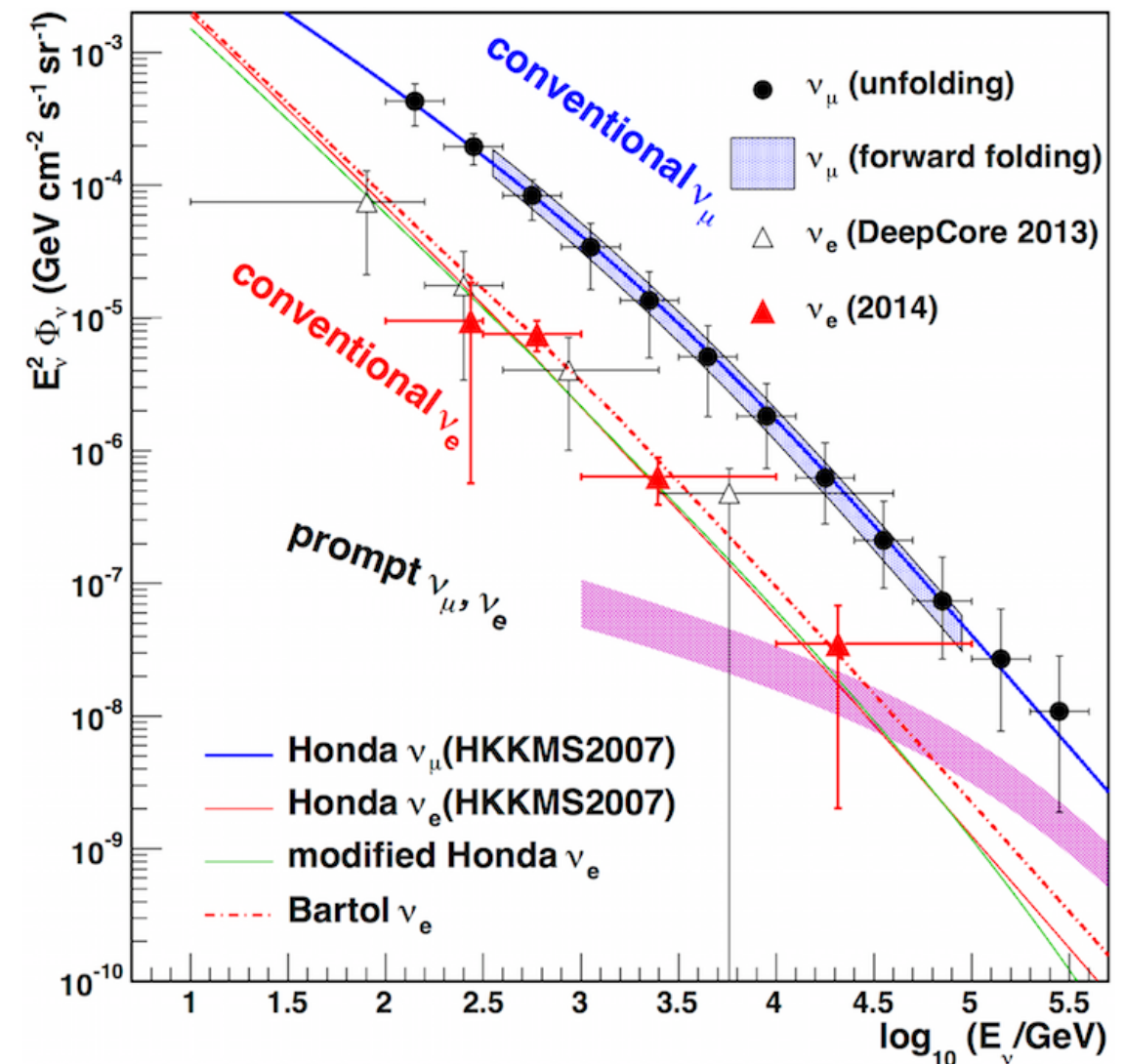
# Conventional vs. Prompt

## ■ Conventional neutrinos

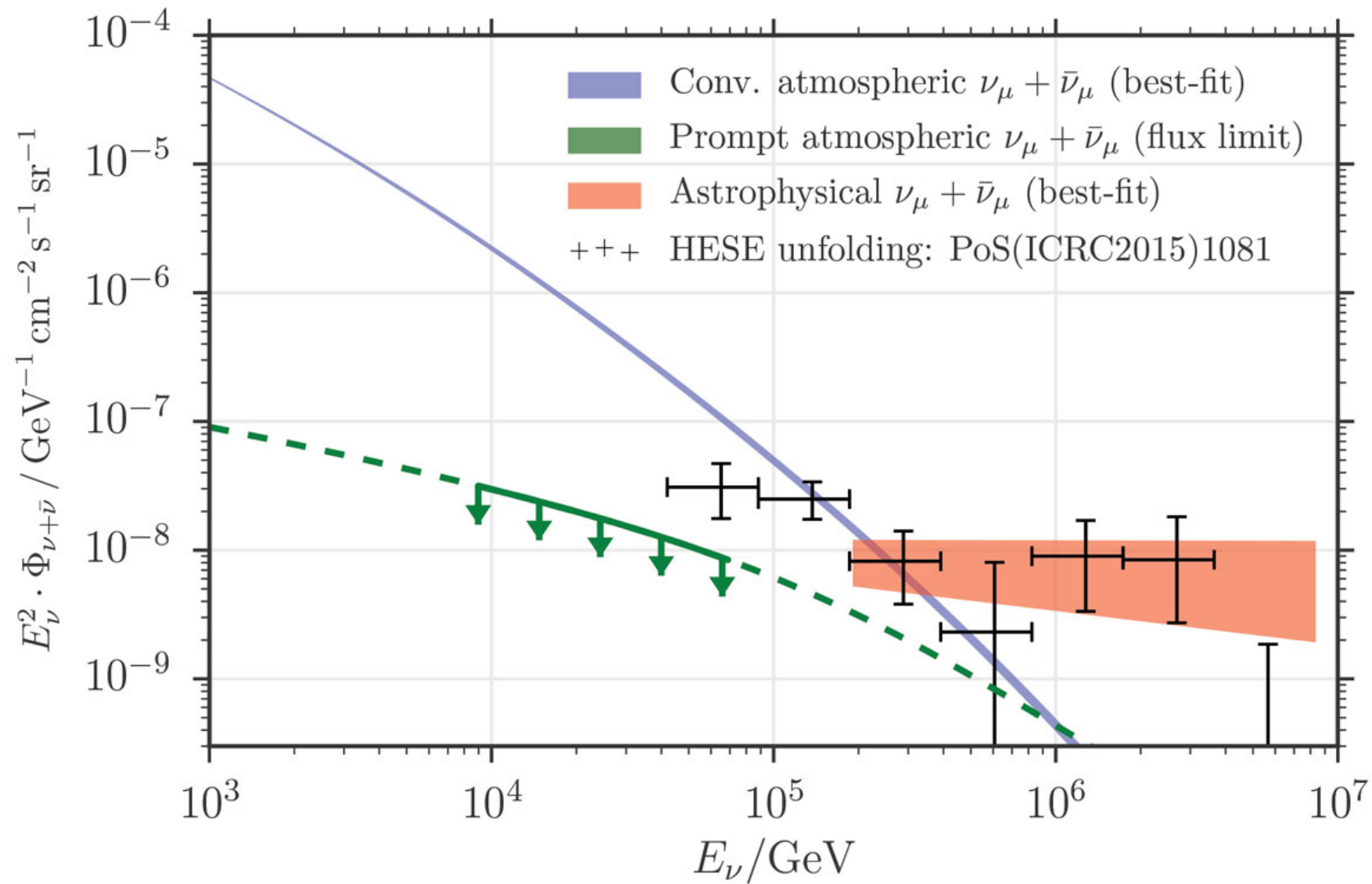
- from the pion( $\pi$ )/ kaon (K) decays
- lose energy due to interaction before decaying
- dominates at relatively low energies and rapidly decreases with energy.

## ■ 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 ( $\sim 1$  PeV)
- has large uncertainty



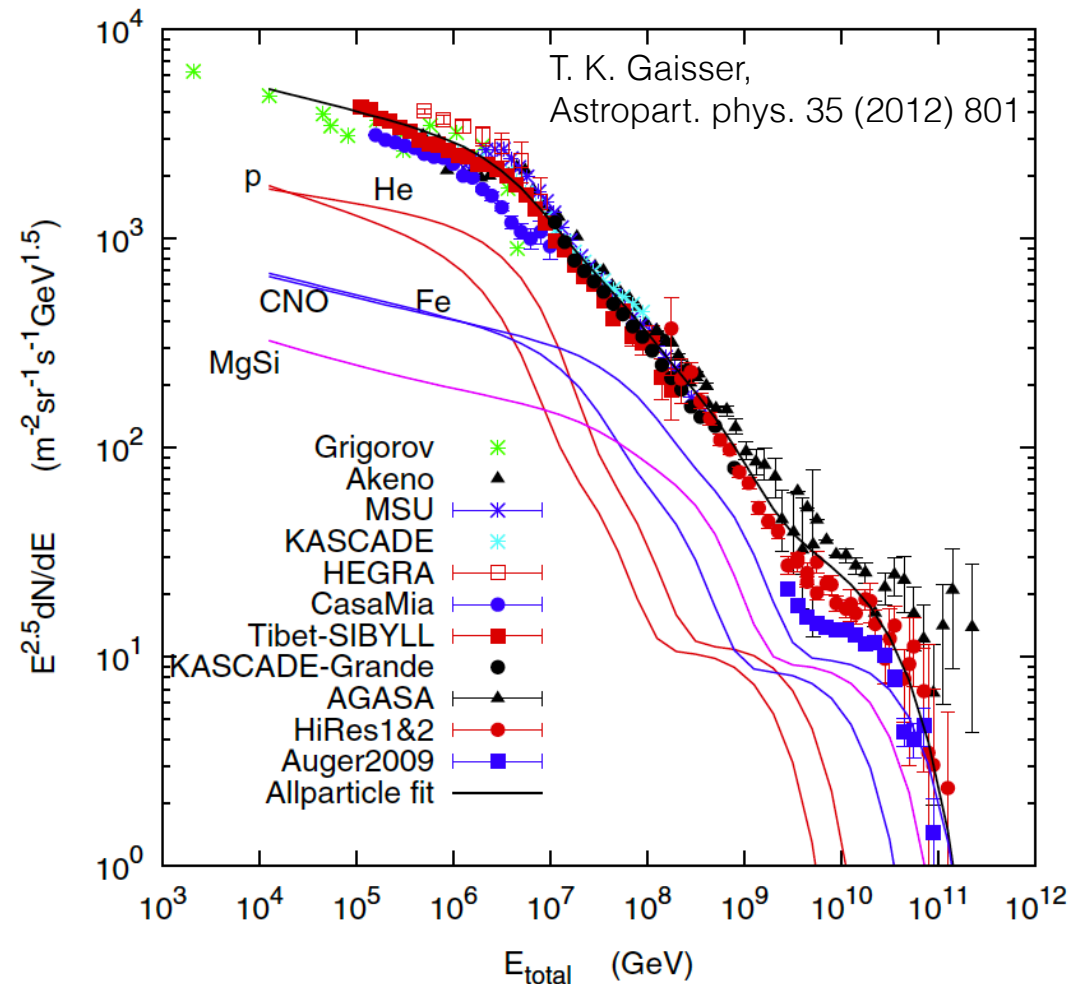
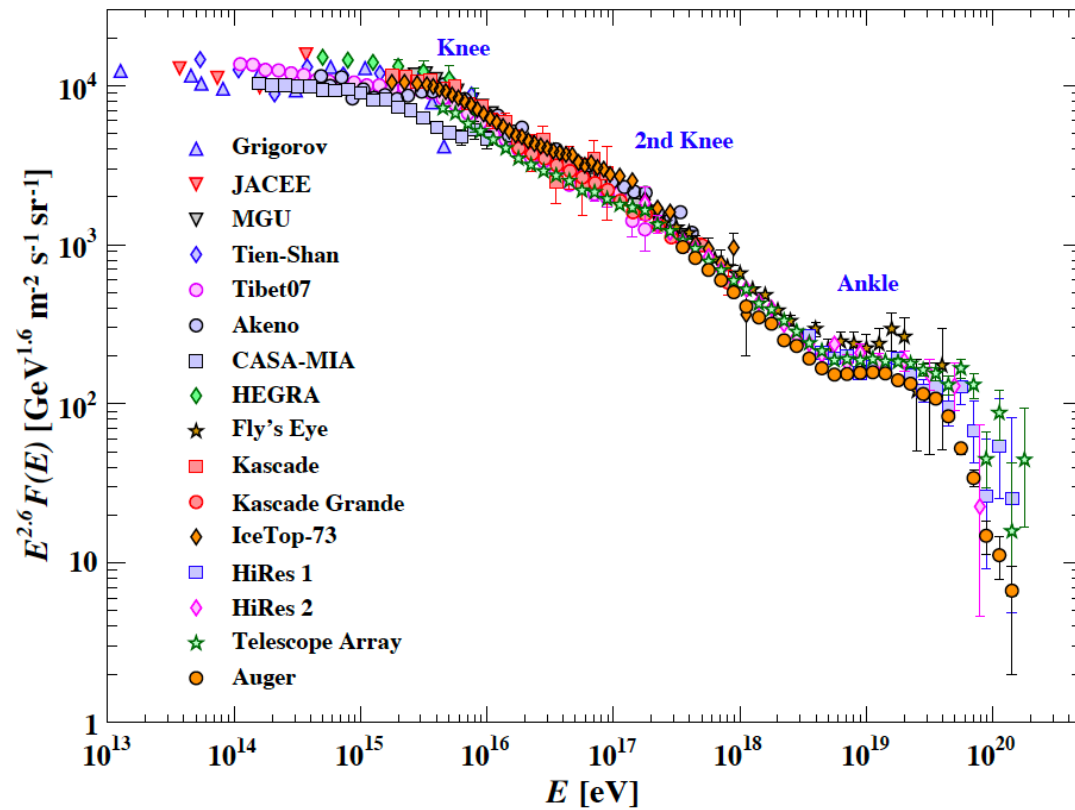
# Atmospheric neutrinos



# 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, ...

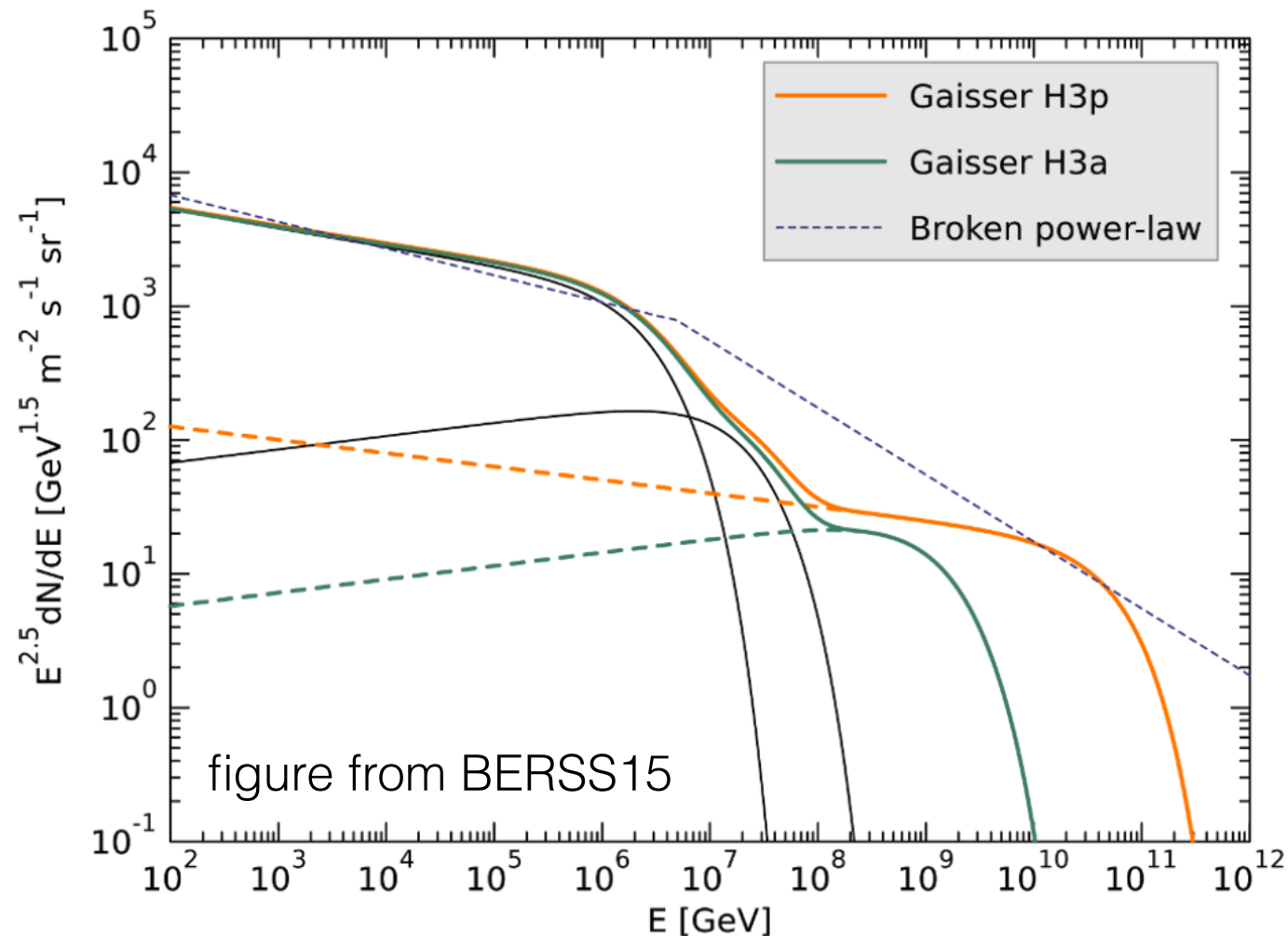
# Cosmic ray spectrum (all particle)



## ■ Parameterizations by Gaisser

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

# Cosmic ray nucleon spectrum



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

- **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 extragalactic population.

# Cascade equations

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

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

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

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

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

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

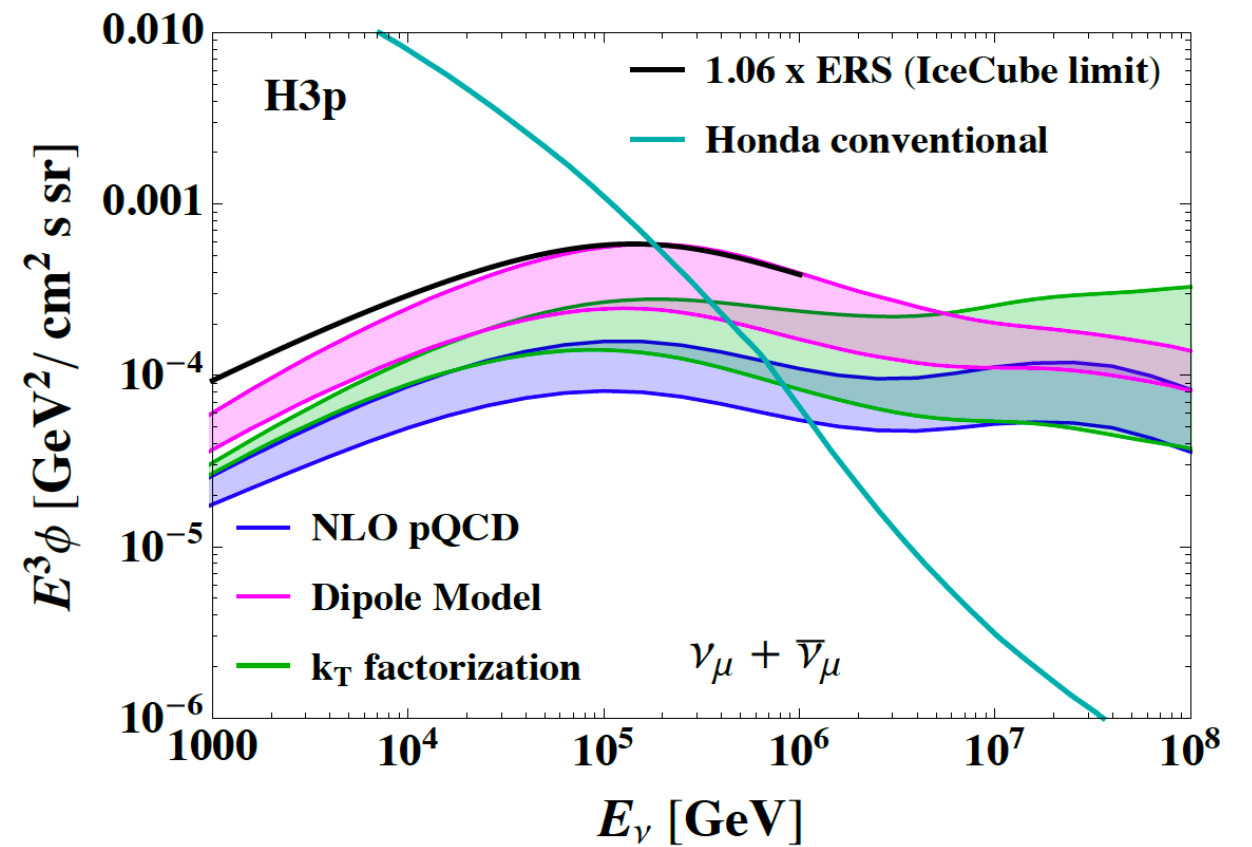
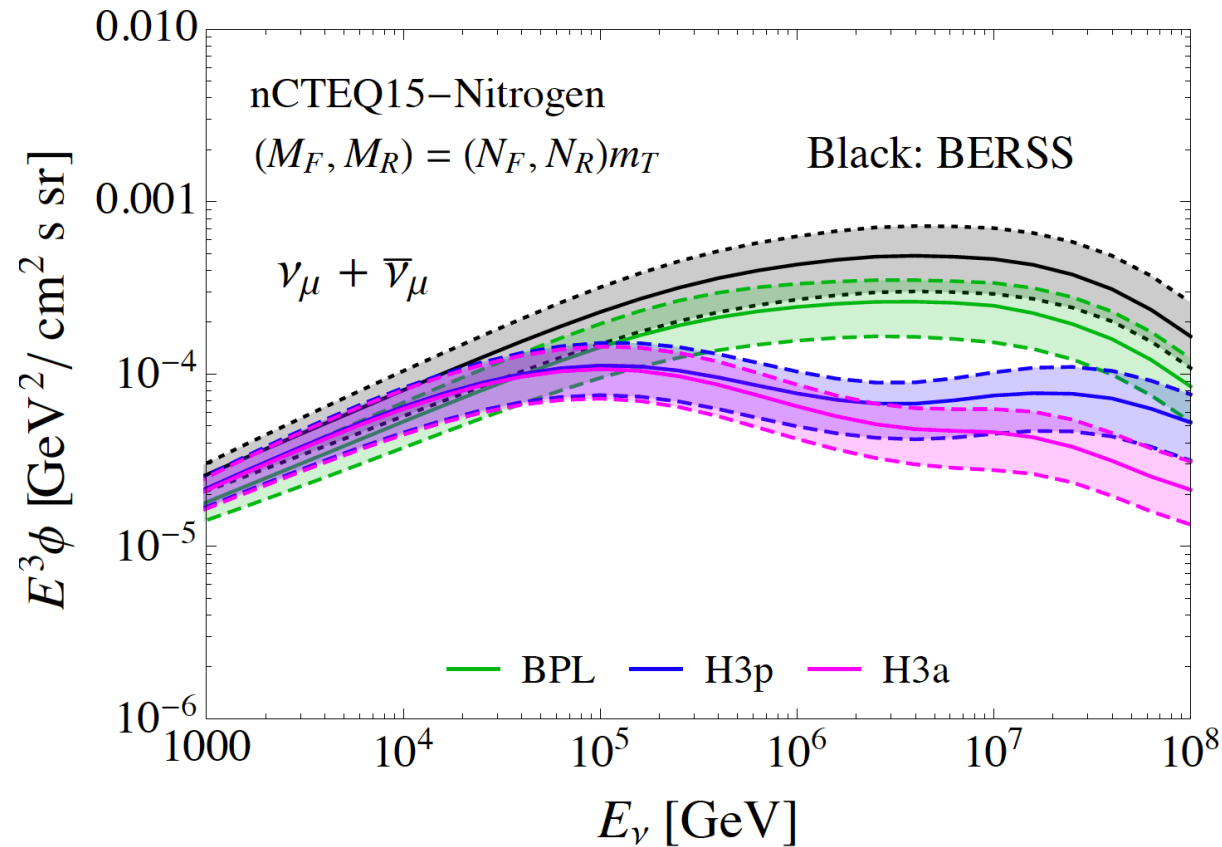
- production/decay distribution

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

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

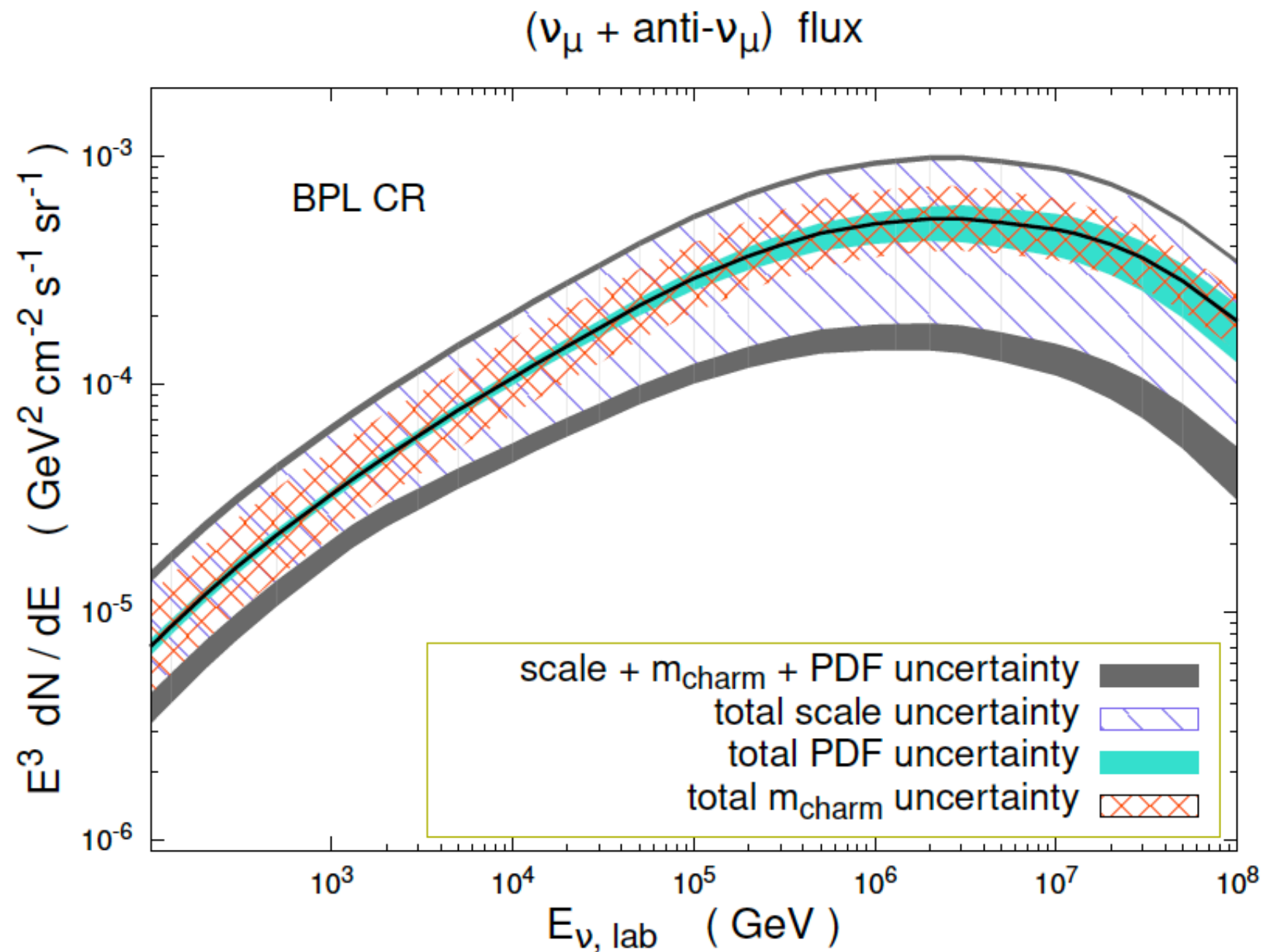


# Prompt atmospheric neutrino fluxes



- 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  $\sim 5 - 8$  at  $E = 10^{5-8}$  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*