Particle physics challenges in ultra-high energy cosmic rays and atmospheric leptons

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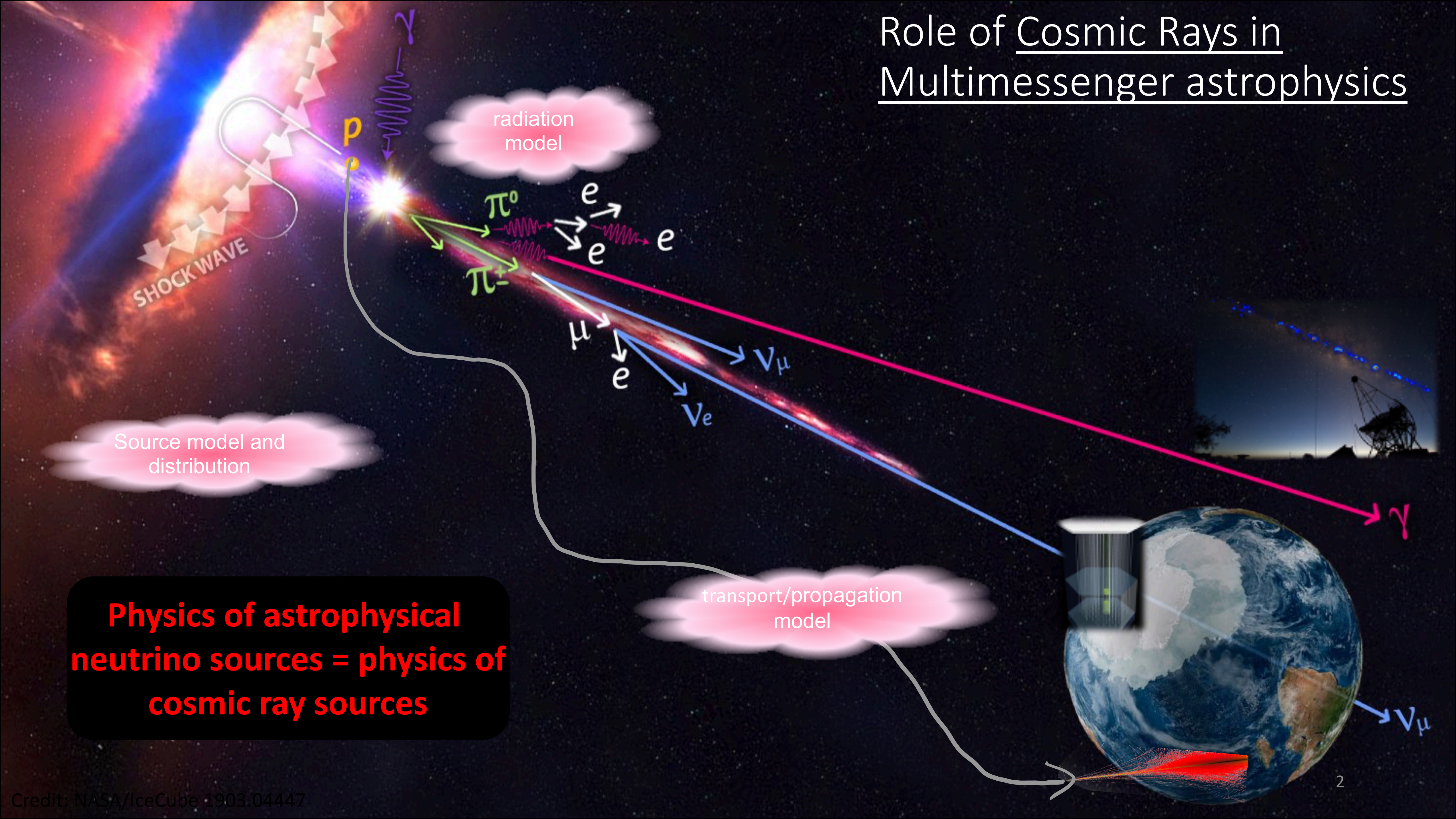
… new Assistant Fellow at Institute of Physics, Academia Sinica

Cosmology Frontier in Particle Physics, 2021/10/13

Institute for Cosmic Ray Research
University of Tokyo

Role of Cosmic Rays in Multimessenger astrophysics

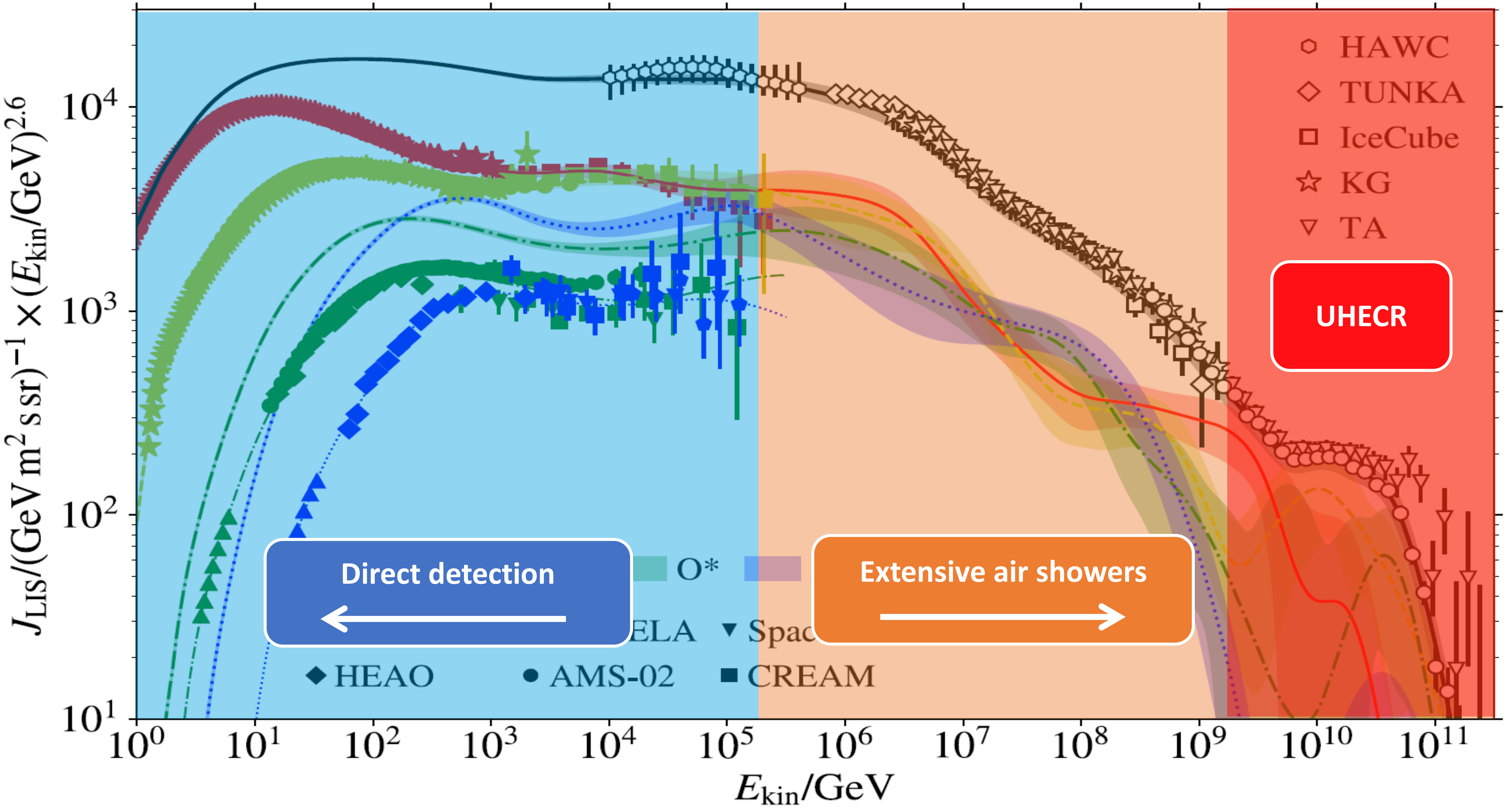


Physics of astrophysical neutrino sources = physics of cosmic ray sources

Credit: NASA/IceCube 1903.04447

Cosmic Rays observations

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533



Cosmic Rays observations

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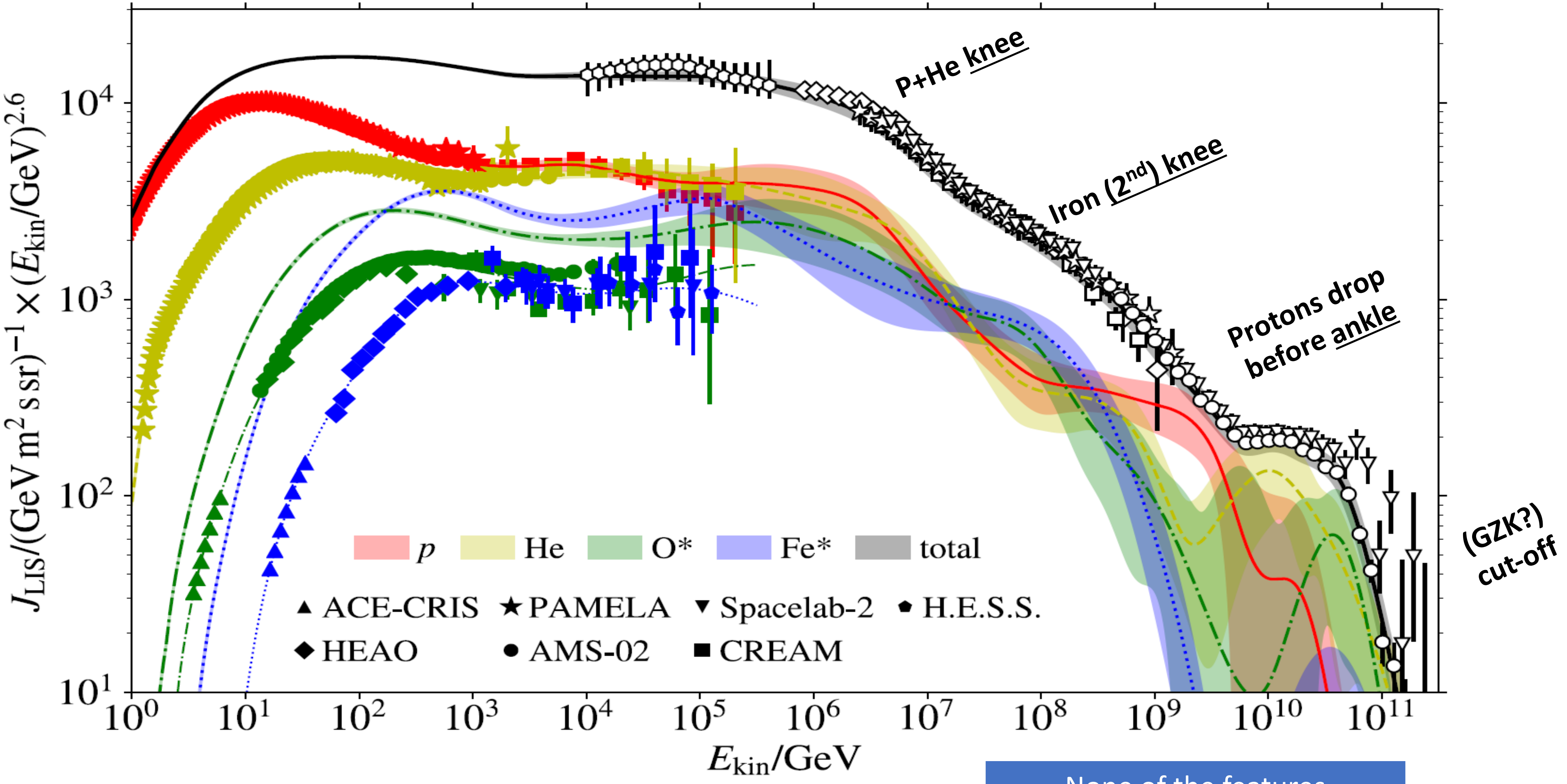
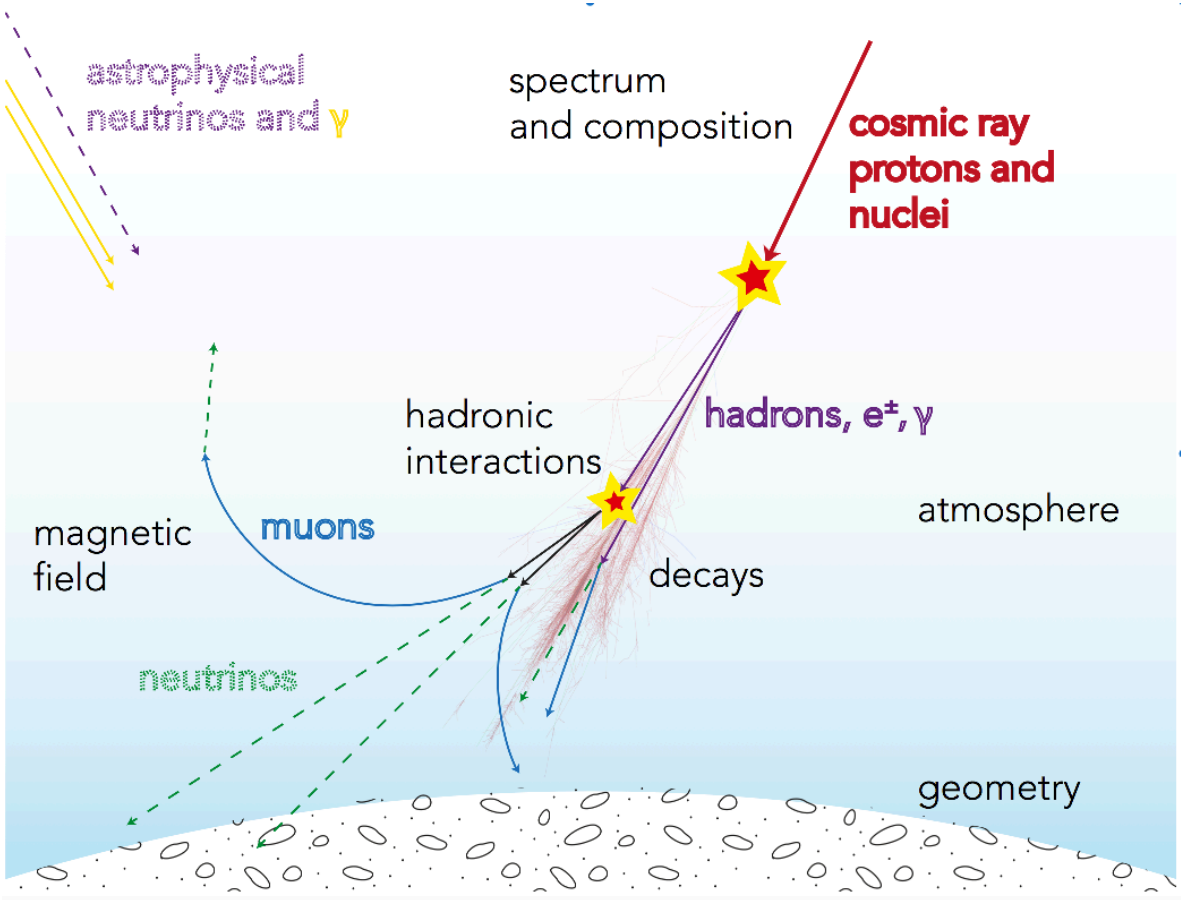


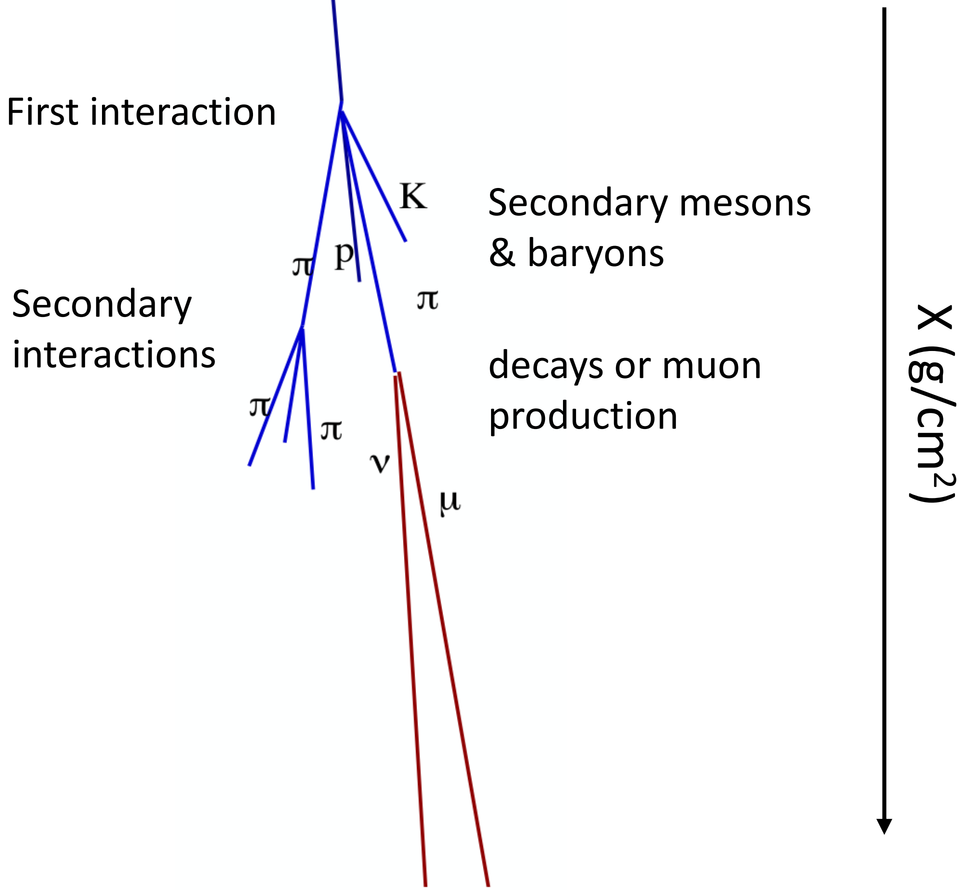
None of the features unambiguously explained!

Interactions of cosmic rays in the atmosphere



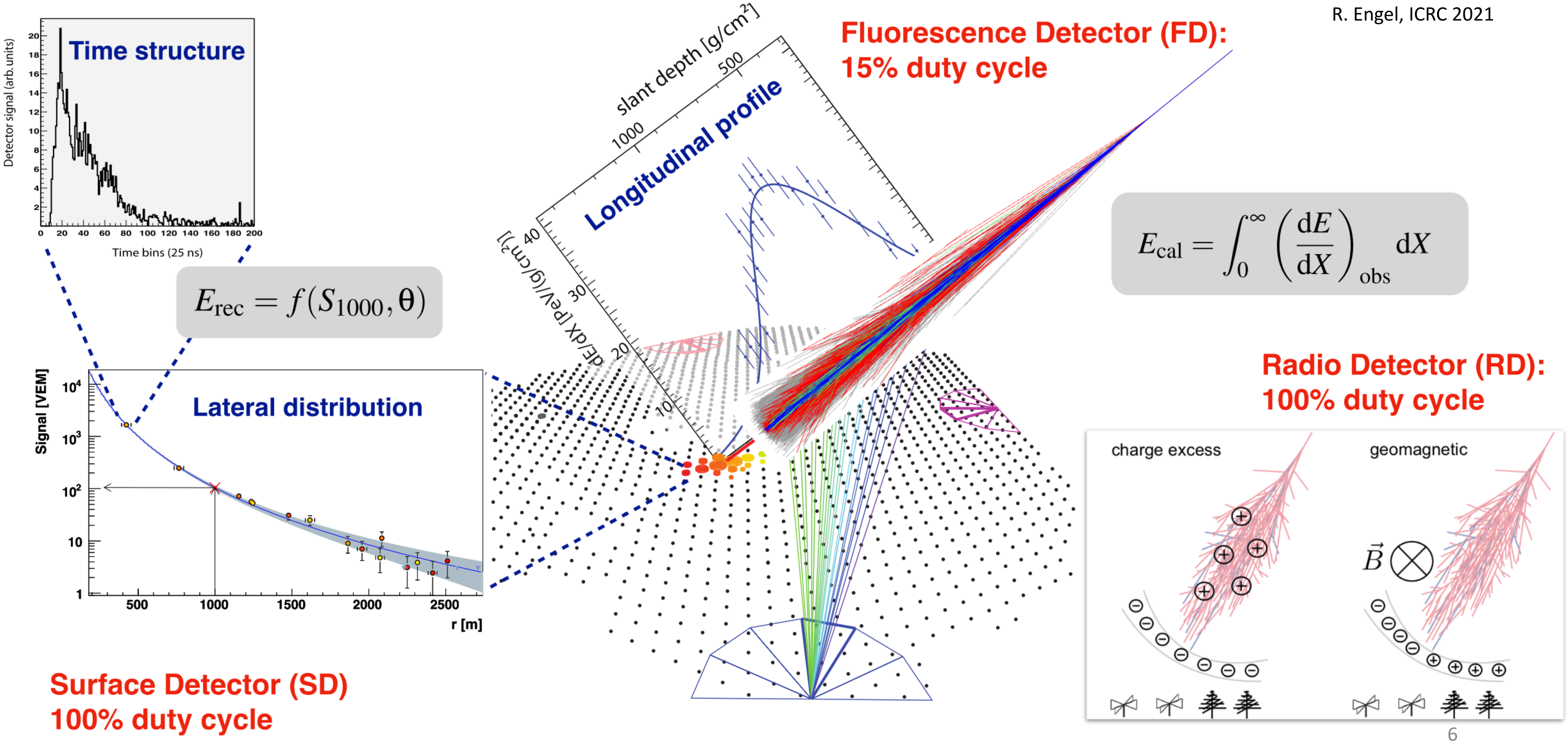
(Column-) depth

$$X(h_0) = \int_0^{h_0} \mathrm{d}k \; \rho_{\mathrm{air}}(\ell)$$



Pierre Auger: hybrid air shower detector

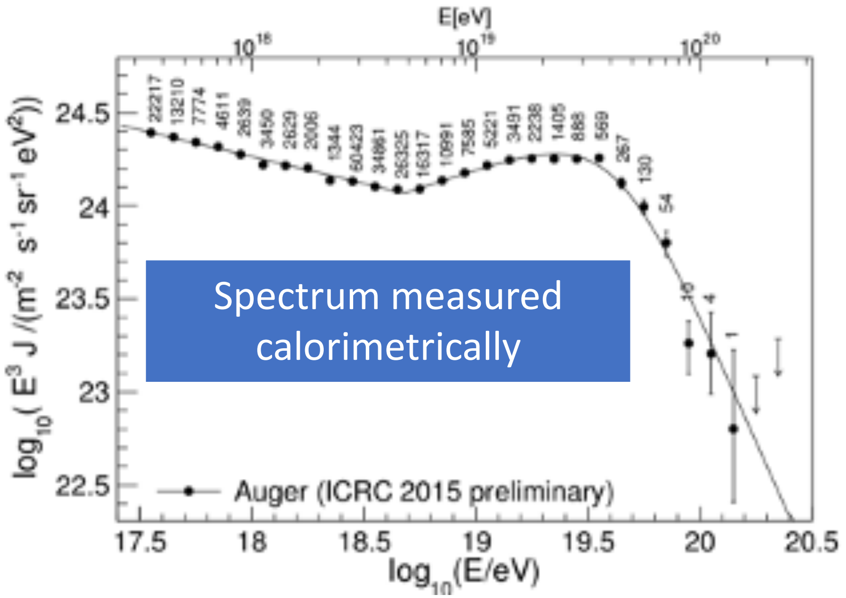
R. Engel, ICRC 2021



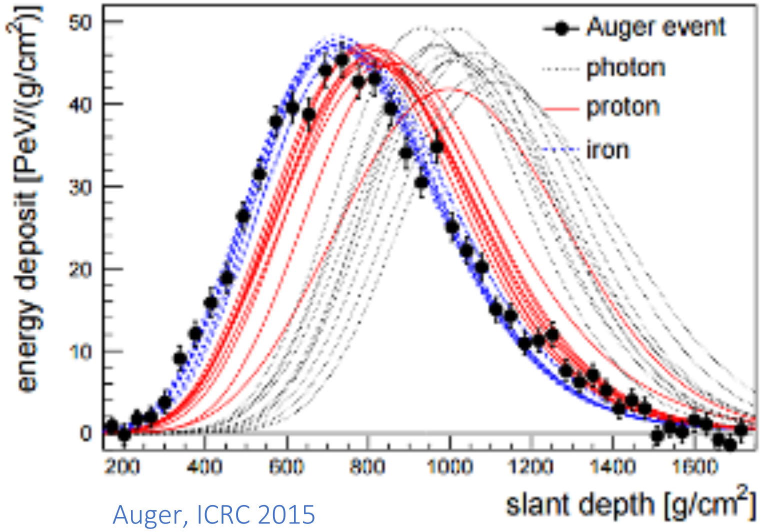
Interpretation of UHECR mass composition

Heinze, AF, et al., ApJ 2019, 1901.03338

Data



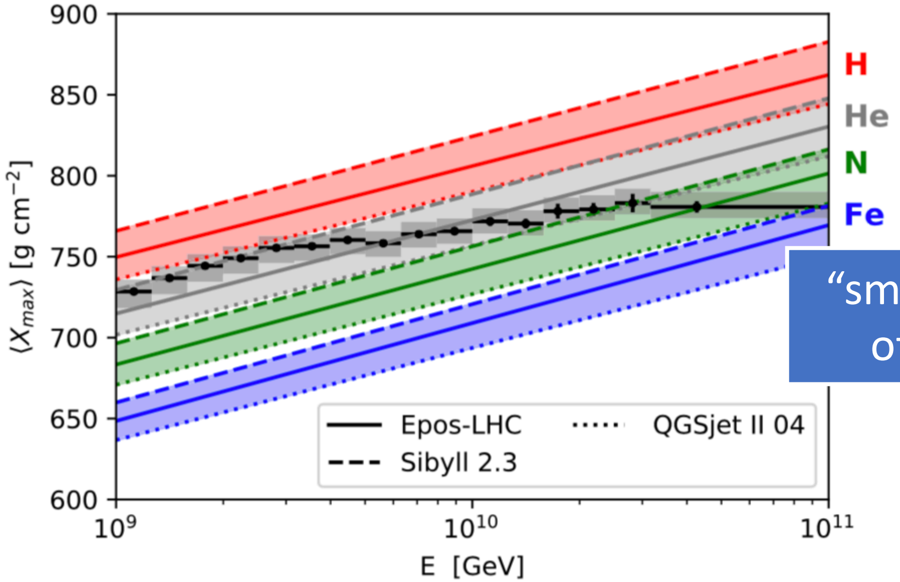
Spectrum measured calorimetrically



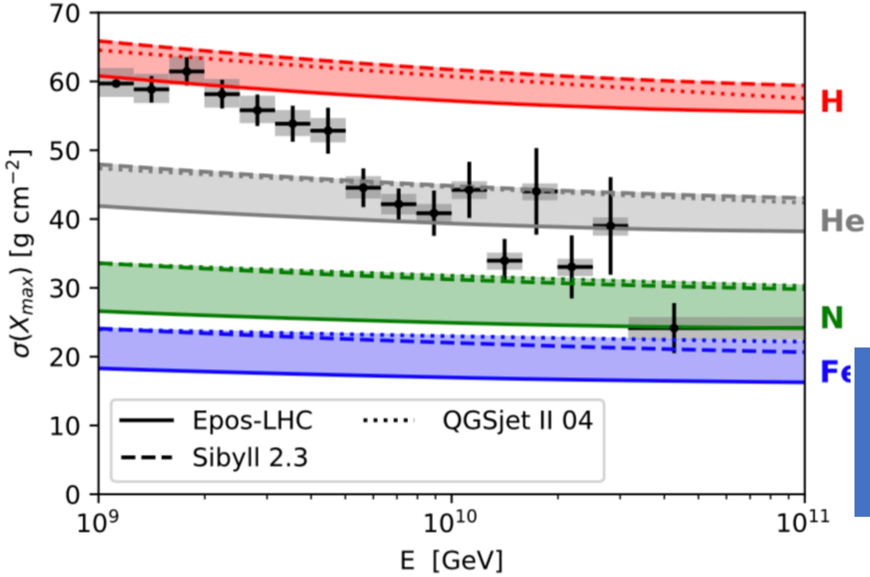
Auger, ICRC 2015

UHECR are nuclei(?)

Model territory

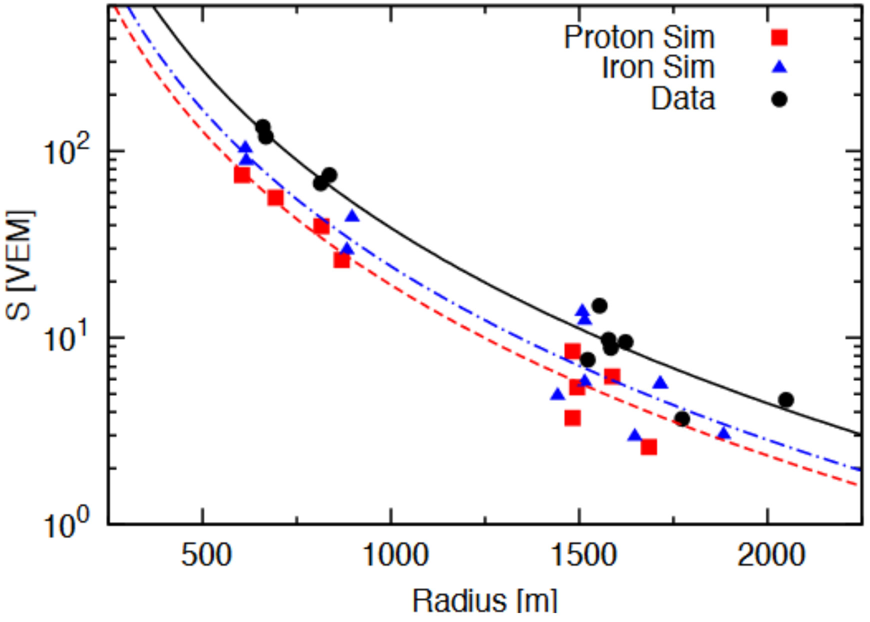


“smooth” increase of mean mass

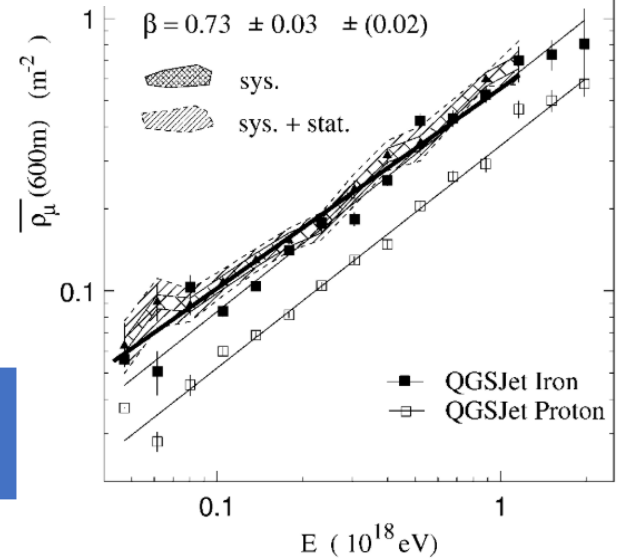


Decreasing fluctuations → mixture masses

Muon Puzzle



HiRes and MIA collabs. Phys.Rev.Lett. 84 (2000) 4276-4279

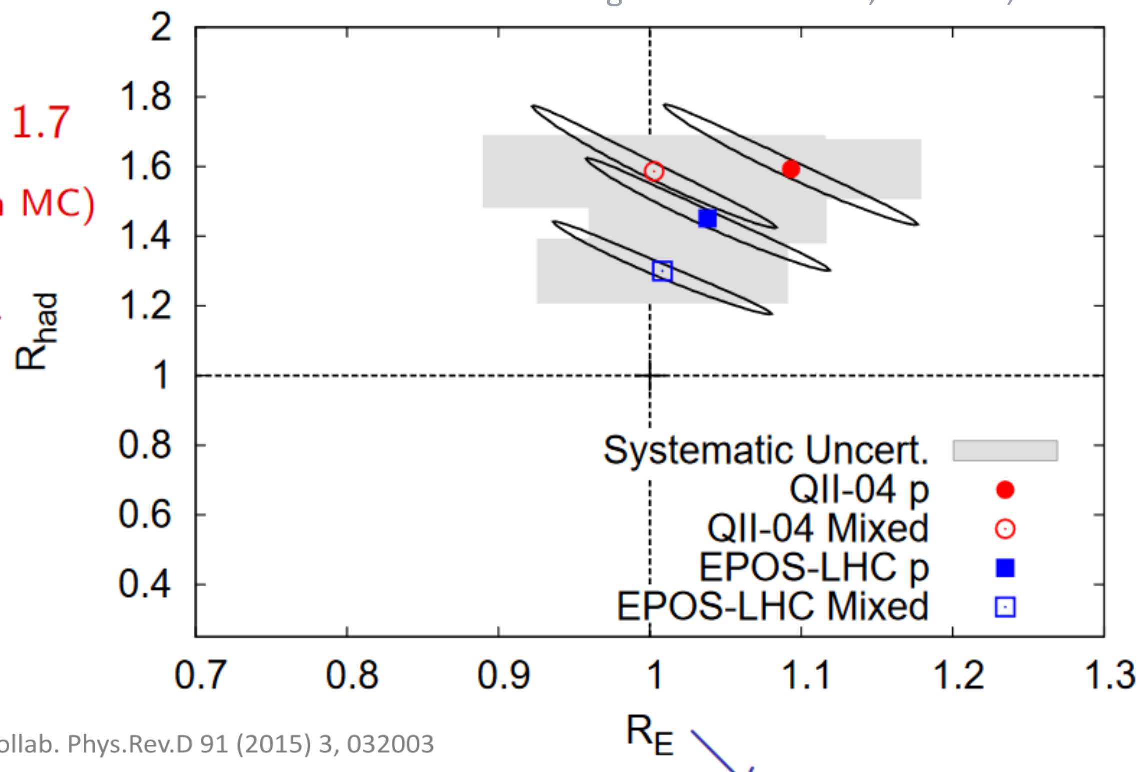


First indication in late 1990's

Pierre Auger Collaboration, PRL 117, 2016

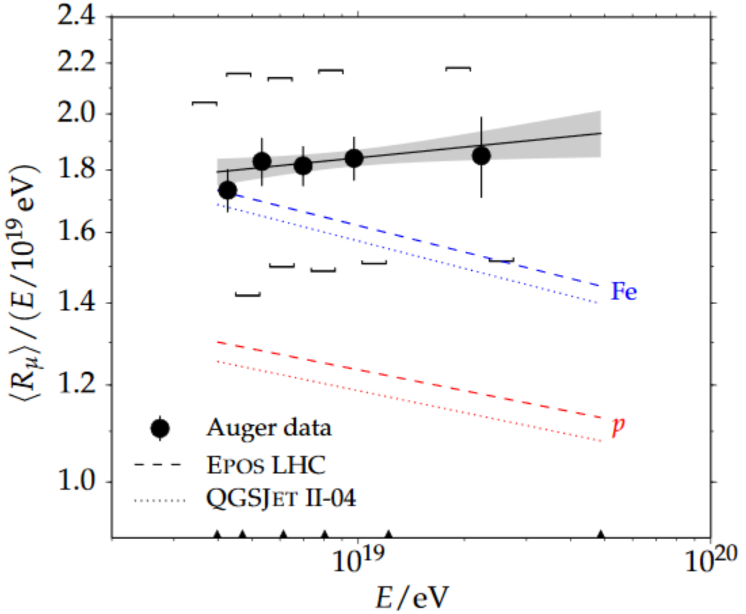
$1.2 < R_{had} < 1.7$

(muon deficit in MC)



energy scale is OK

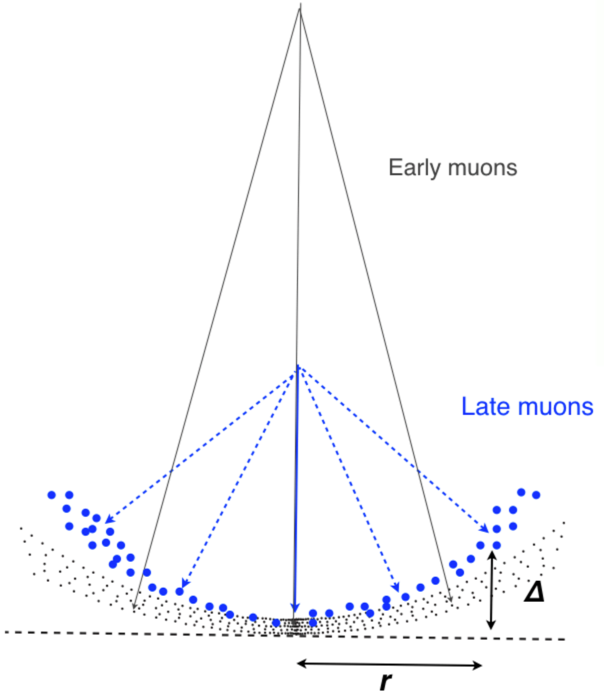
Pierre Auger collab. Phys.Rev.D 91 (2015) 3, 032003

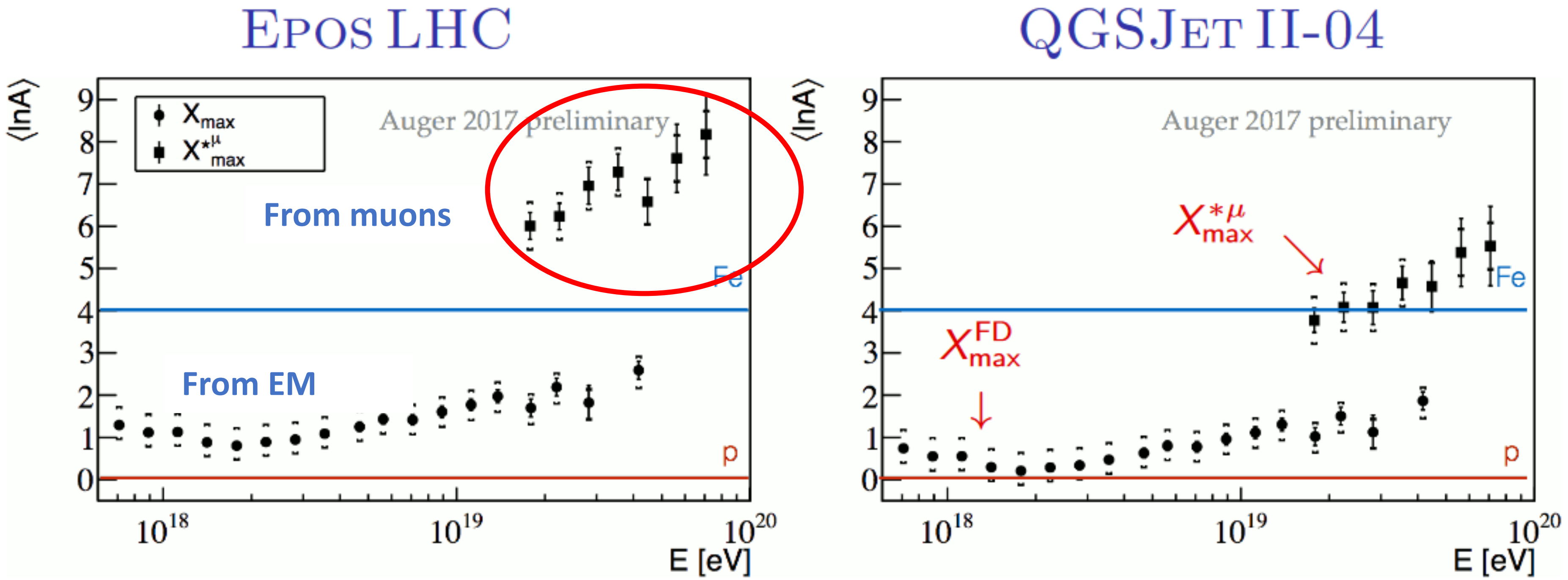


Recent review by: J. Albrecht, L. Cazon, H. Dembinski, AF, KH. Kampert, T. Pierog, W. Rhode, D. Soldin, B. Spaan, R. Ulrich, M. Unger, arXiv:2105.06148

Production depth inconsistent with expectations

R. Prado, ISVHECRI 2018

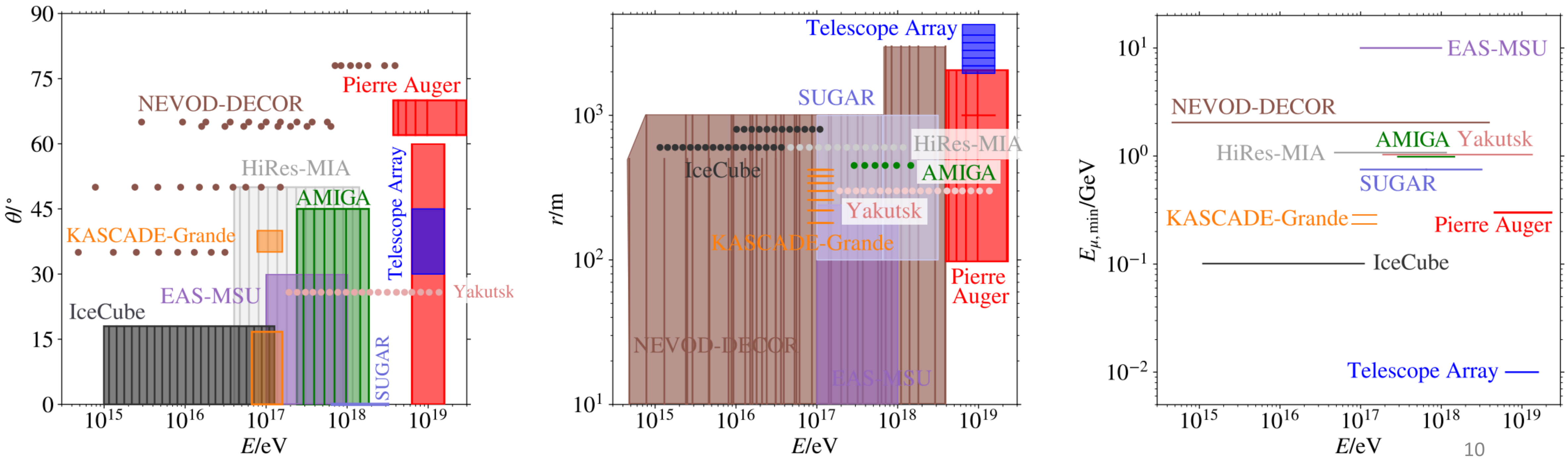




Special working group formed (WHISP)

- 2018: Apparently conflicting evidence from different experiments
- Working group on Hadronic Interactions and Shower Physics (WHISP) formed by members of 8 experimental collaborations for UHECR 2018 conference
- Goal: Combine diverse set of muon measurements

PoS(ICRC2021)349

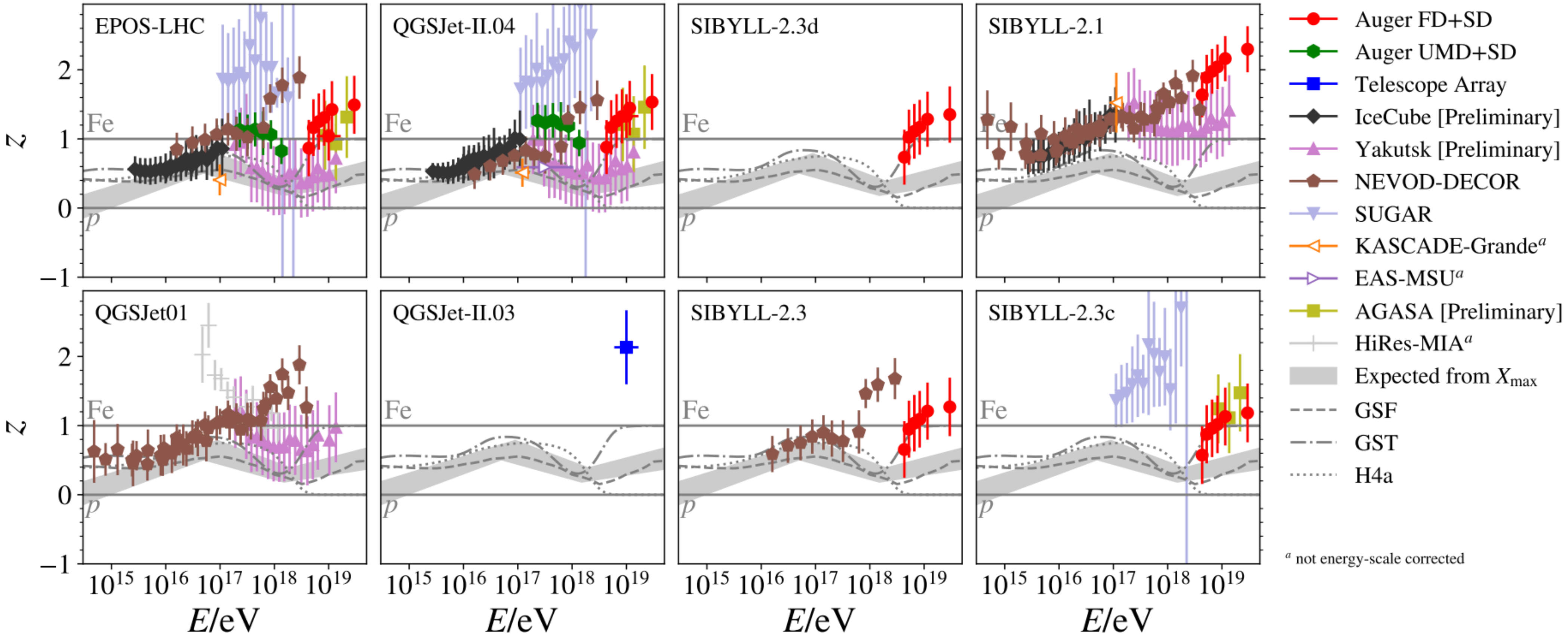


Cross-calibration of data + abstract reference scale

Abstract muon scale
independent of experiment,
dependent on air shower model

$$z = \frac{\overbrace{\ln(N_\mu^{\mathrm{det}})}^{\text{data}} - \overbrace{\ln(N_{\mu_p}^{\mathrm{det}})}^{\text{sim}}}{\underbrace{\ln(N_{\mu_{\mathrm{Fe}}}^{\mathrm{det}})}_{\text{sim}} - \underbrace{\ln(N_{\mu_p}^{\mathrm{det}})}_{\text{sim}}}$$

PoS(ICRC2021)349



Clear evidence muon deficit in simulations

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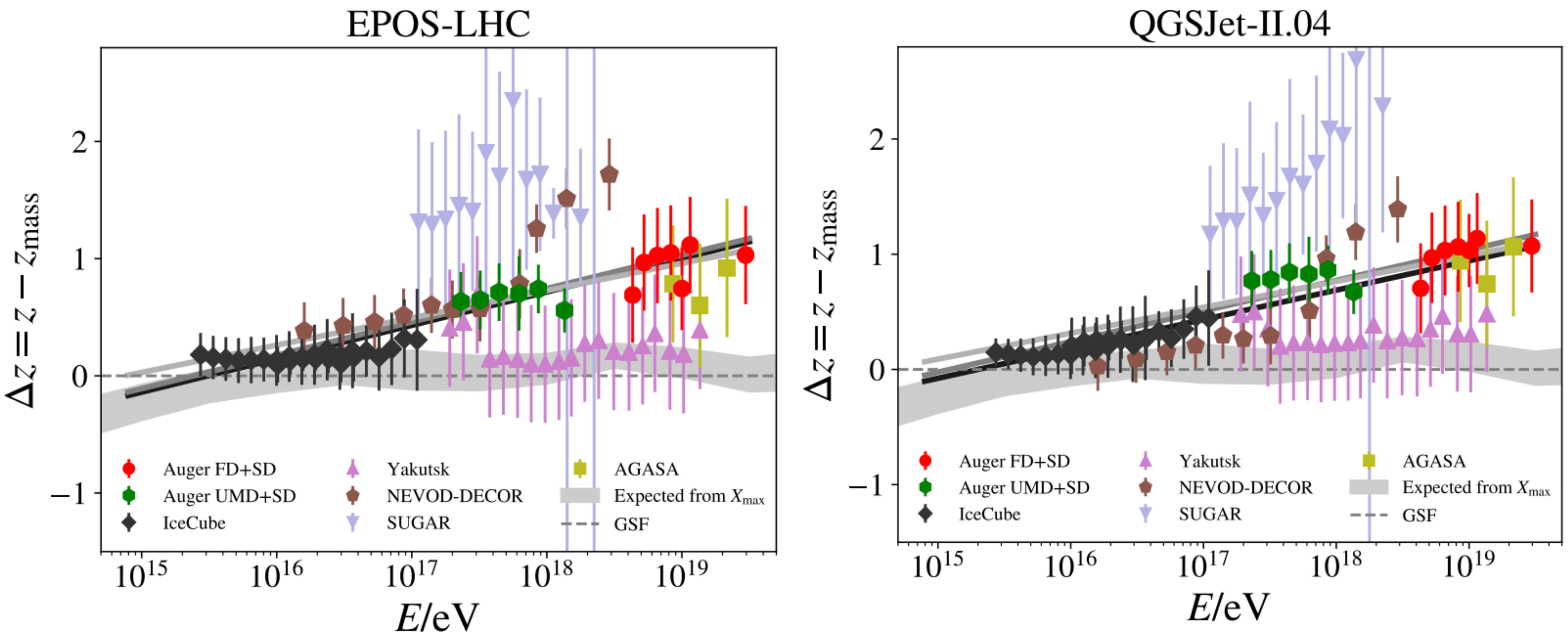


$$z = \frac{\ln(N_{\mu}^{\mathrm{det}}) - \ln(N_{\mu_p}^{\mathrm{det}})}{\ln(N_{\mu_{\mathrm{Fe}}}^{\mathrm{det}}) - \ln(N_{\mu_p}^{\mathrm{det}})}$$

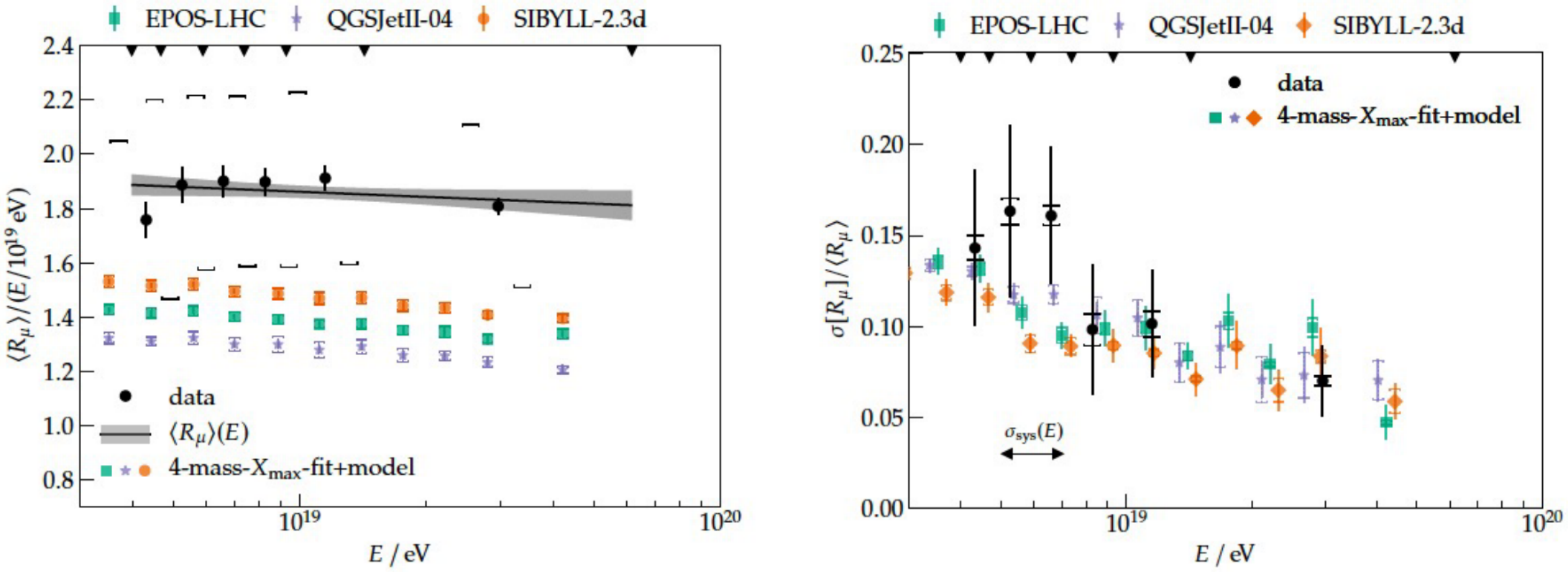
- Slope is 8σ (10σ) away from zero for EPOS-LHC (QGSJet-II.04)
- Onset of deviation around 40 PeV corresponds to $\sqrt{s} \sim 8$ TeV; in reach of LHC

$$z_{\mathrm{mass}} \approx \frac{\langle \ln A \rangle}{\ln 56}$$

From GSF model

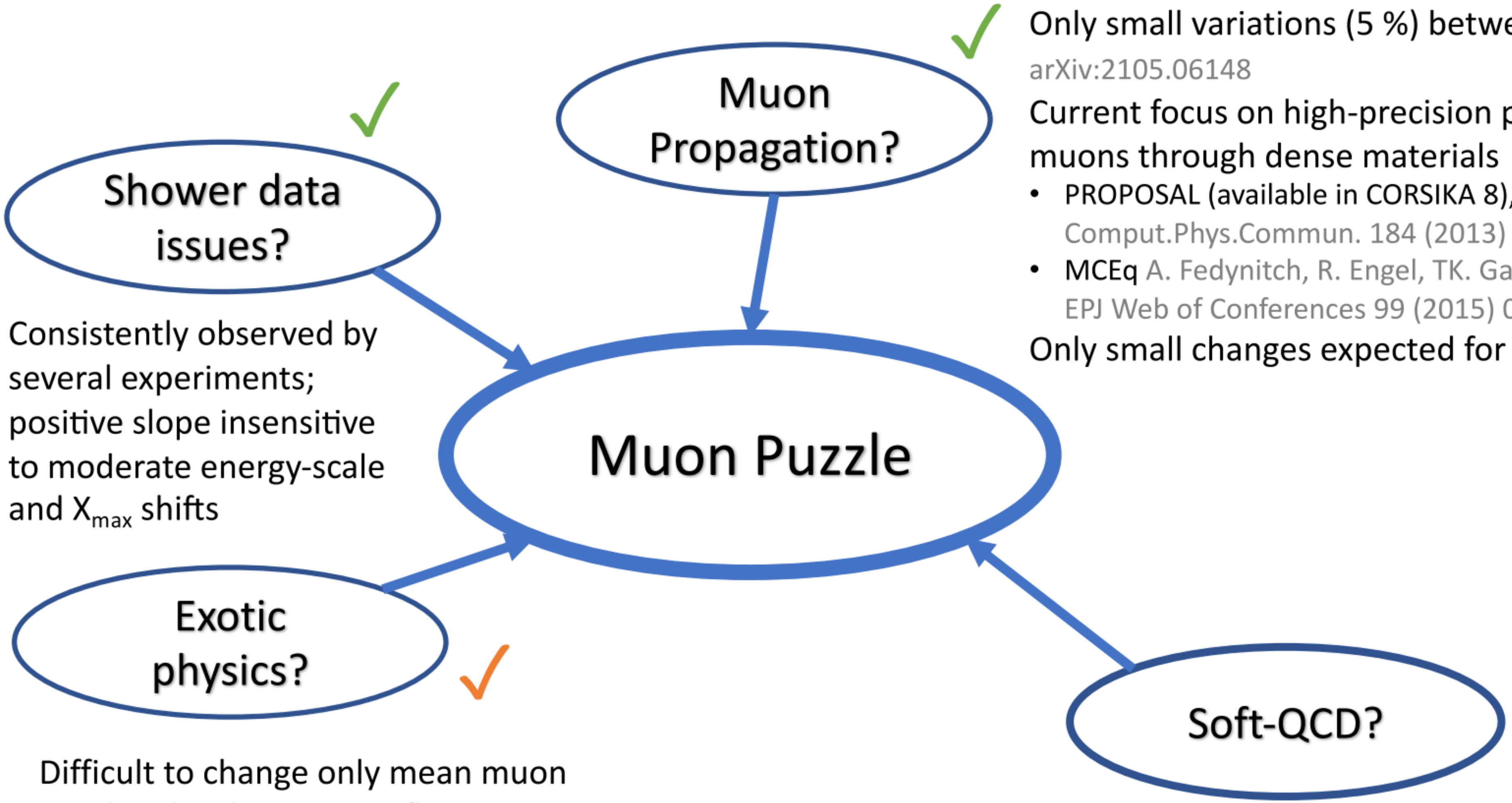
Muon number fluctuations found to be consistent

Pierre Auger collab., Phys.Rev.Lett. 126 (2021) 15, 152002



- First measurement of mean and **variance** of muon number distribution
- Variance of muon number consistent with current model predictions; mean deviates
- Constrains scenarios in which only first (or second) interaction is modified, e.g. in model with violation of Lorentz-invariance PoS(ICRC2021)340

Attempts to explain the Muon Puzzle



Only small variations (5 %) between shower codes
arXiv:2105.06148

Current focus on high-precision propagation of TeV muons through dense materials

- PROPOSAL (available in CORSIKA 8), JH. Koehne et al. Comput.Phys.Commun. 184 (2013) 2070-2090
- MCEq A. Fedynitch, R. Engel, TK. Gaisser, T. Stanev, EPJ Web of Conferences 99 (2015) 08001

Only small changes expected for GeV muons in air

Consistently observed by several experiments; positive slope insensitive to moderate energy-scale and X_{max} shifts

Difficult to change only mean muon number, but keep muon fluctuations of X_{max} and N_μ fluctuations same; early onset of muon discrepancy

H. Dembinski
ICRC2021 plenary

Matthews-Heitler model

J. Matthews, Astroparticle Physics 22 (2005) 387–397

N_{ch}: Particle multiplicity per interactions

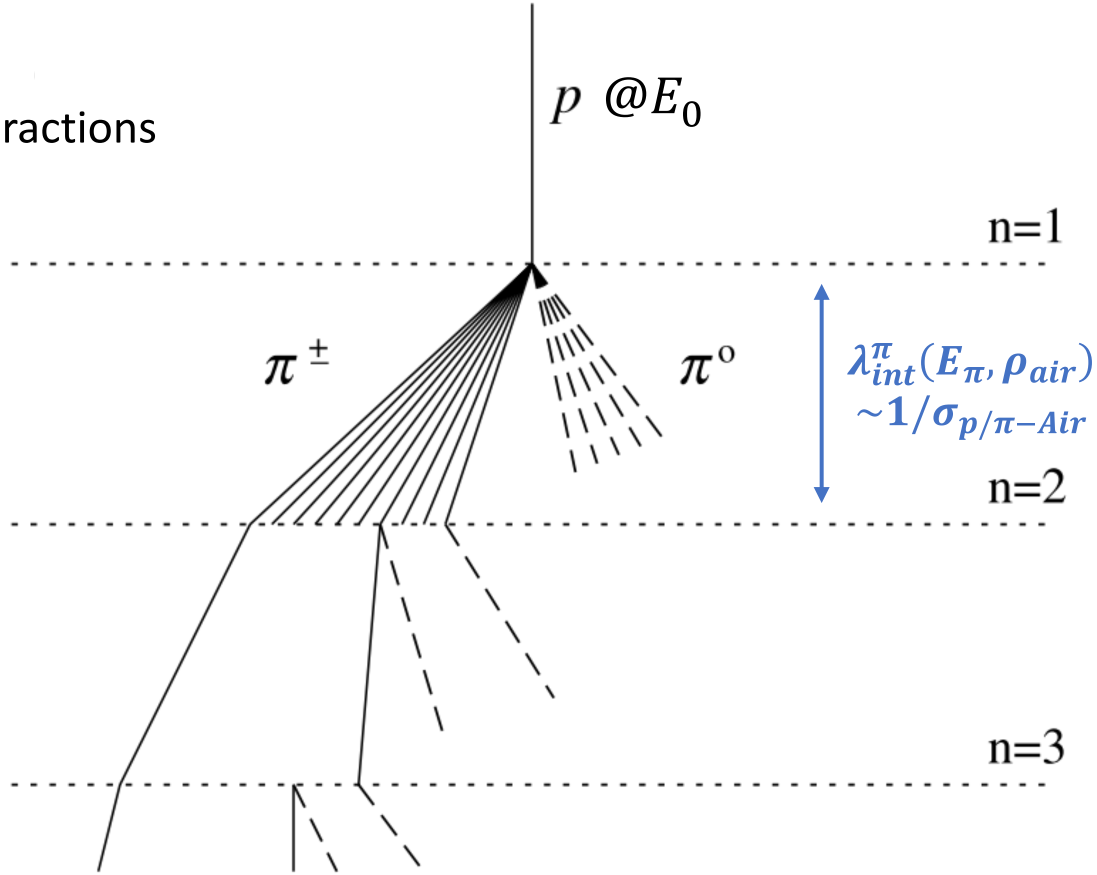
$$N_\pi = N_{ch}$$

$$E_\pi = E_0 / \tfrac{3}{2} N_{ch}$$

⋮

$$N_\pi = (N_{ch})^n$$

$$E_\pi = E_0 / \left(\tfrac{3}{2} N_{ch}\right)^n$$

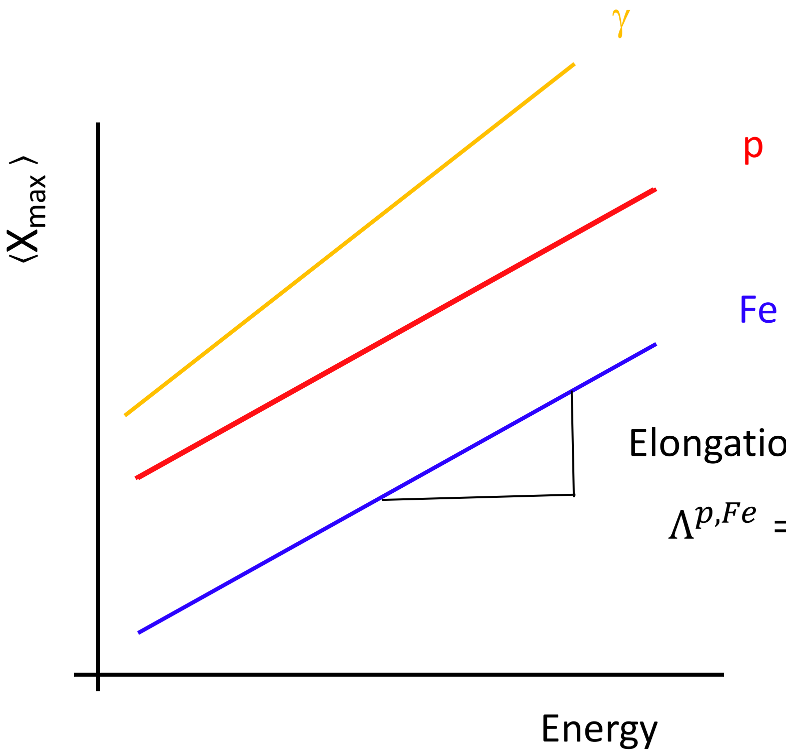


Typical numbers of generations:
n_c = 3,4,5,6 for
E_0= 10^{14}, 10^{15}, 10^{16}, 10^{17} eV

- Critical energy $\xi_c^{\pi^\pm}$ (= pions stop interacting) depends on:
  - Proton, pion cross section
  - Atmosphere
- Critical energy depends on primary energy (10-30 GeV)
- Central conclusions from Heitler model
  - **Cross sections** important
  - **Multiplicity** important

J. Matthews, Astroparticle Physics 22 (2005) 387–397
+ K.-H. Kampert, M. Unger, Astroparticle Physics 35 (2005) 660–678

Understanding X_{max}



Elongation rate:

$$\Lambda^{p,Fe} = \frac{d\langle X_{max}\rangle}{dlog_{10}E}$$

A **third** important parameter is the **(in-)elasticity**, the energy transfer to the **leading** particle
…yields slightly modified formulae.

Assuming **only** energy transfer from had. to EM **in first interaction**:

$$X_{\max}^{\mathrm{p}} = X_\circ + \lambda_{\mathrm{r}} \ln\left[E_\circ/(3N_{\mathrm{ch}}\xi_{\mathrm{c}}^{\mathrm{e}})\right]$$
$$= X_{\max}^{\gamma} + X_\circ - \lambda_{\mathrm{r}} \ln[3N_{\mathrm{ch}}]$$

$$X_\circ = \lambda_I \ln 2$$

EM radiation length in air

The elongation rate is then simply:

Reduction due to **growth of cross section** with energy

$$\Lambda^{\mathrm{p}} = \Lambda^{\gamma} + \frac{\mathrm{d}}{\mathrm{dlog}_{10}E_\circ}\{X_\circ - \lambda_{\mathrm{r}}\ln[3N_{\mathrm{ch}}]\}$$
$$= 58\ \mathrm{g\,cm^{-2}}\ \text{per decade}$$

.. to growth of **multiplicity** …

Seeking the connection to QCD

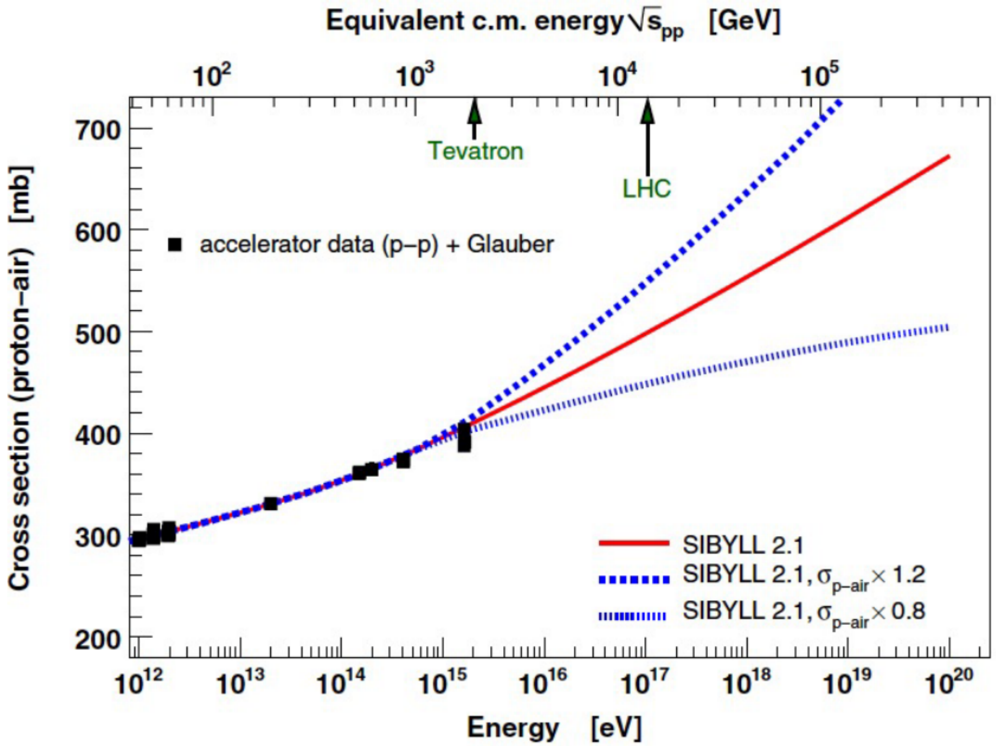
Introduce empirical variation of hadronic interactions

$$f(E) = 1 + (f_{19} - 1) \cdot \begin{cases} 0 & E < 1\,\mathrm{PeV} \\ \frac{\log_{10}\left(\frac{E}{1\,\mathrm{PeV}}\right)}{\log_{10}\left(\frac{10\,\mathrm{EeV}}{1\,\mathrm{PeV}}\right)} & E \geq 1\,\mathrm{PeV} \end{cases}$$

Modified features

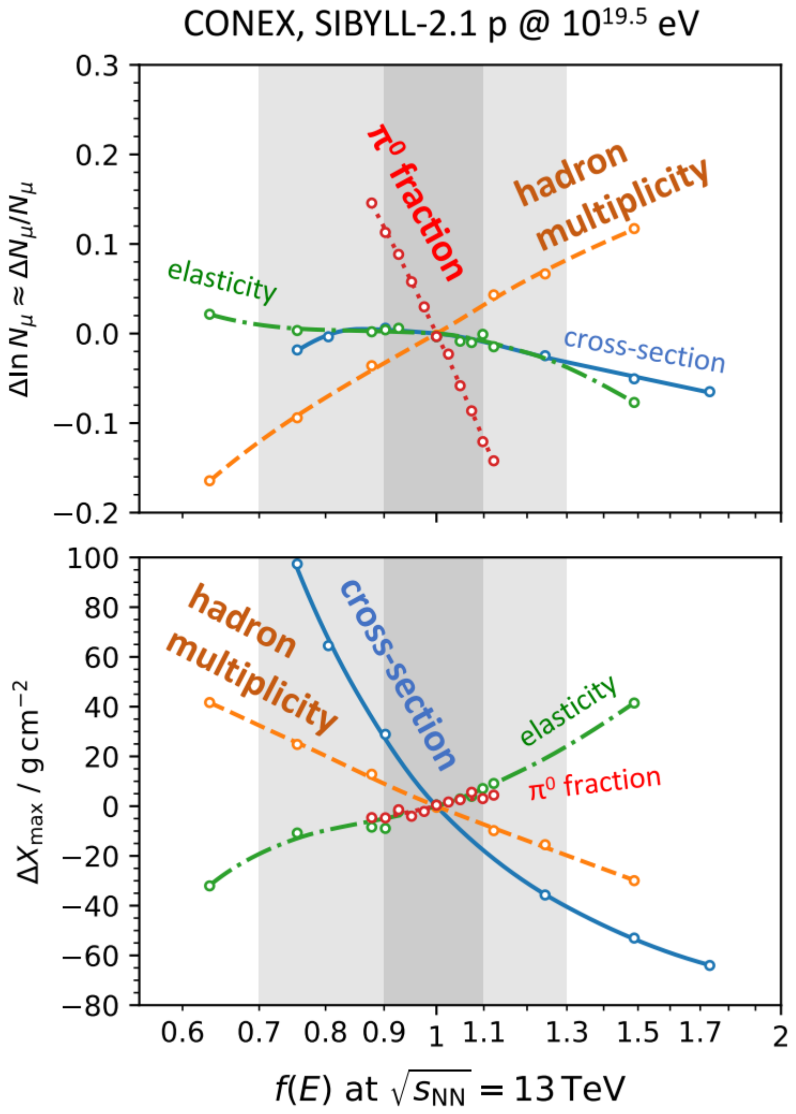
- **cross-sections**
  inelastic cross-section of all interactions
- **hadron multiplicity**
  total number of secondary hadrons
- **elasticity** = $E_{\mathrm{leading}}/E_{\mathrm{all}}$
- π^0 **fraction** = 1-α

R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026



Identify most sensitive hadronic parameters

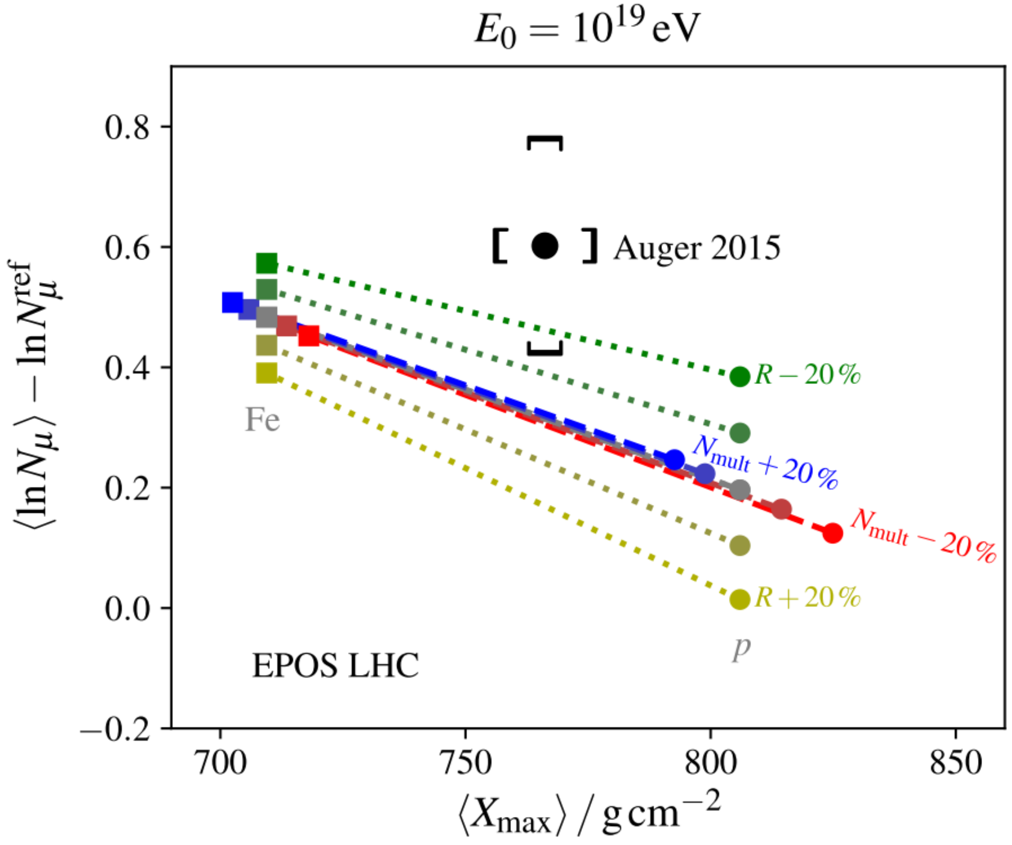
R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026



- Number of muons produced, N_{μ}
  - Very sensitive to π^0 fraction
  - Sensitive to hadron multiplicity
- Depth of shower maximum, X_{max}
  - Very sensitive to cross-section
  - Sensitive to hadron multiplicity
  - Insensitive to π^0 fraction

Changing pi0 fraction seems most promising

S. Baur et al., arXiv:1902.09265



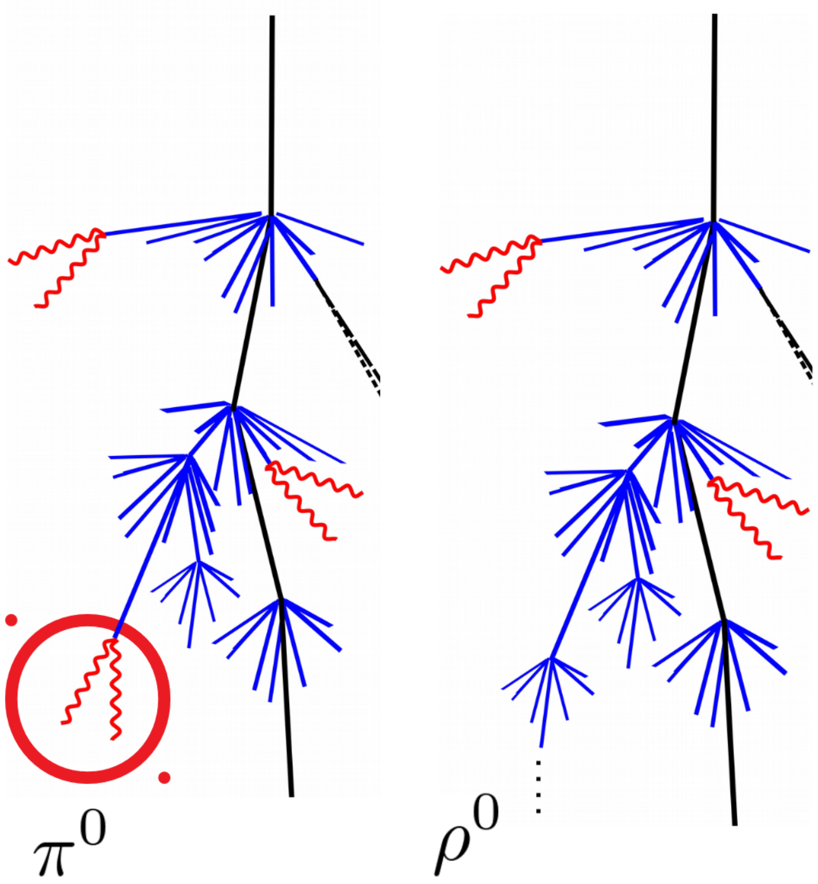
accessible experimental variable

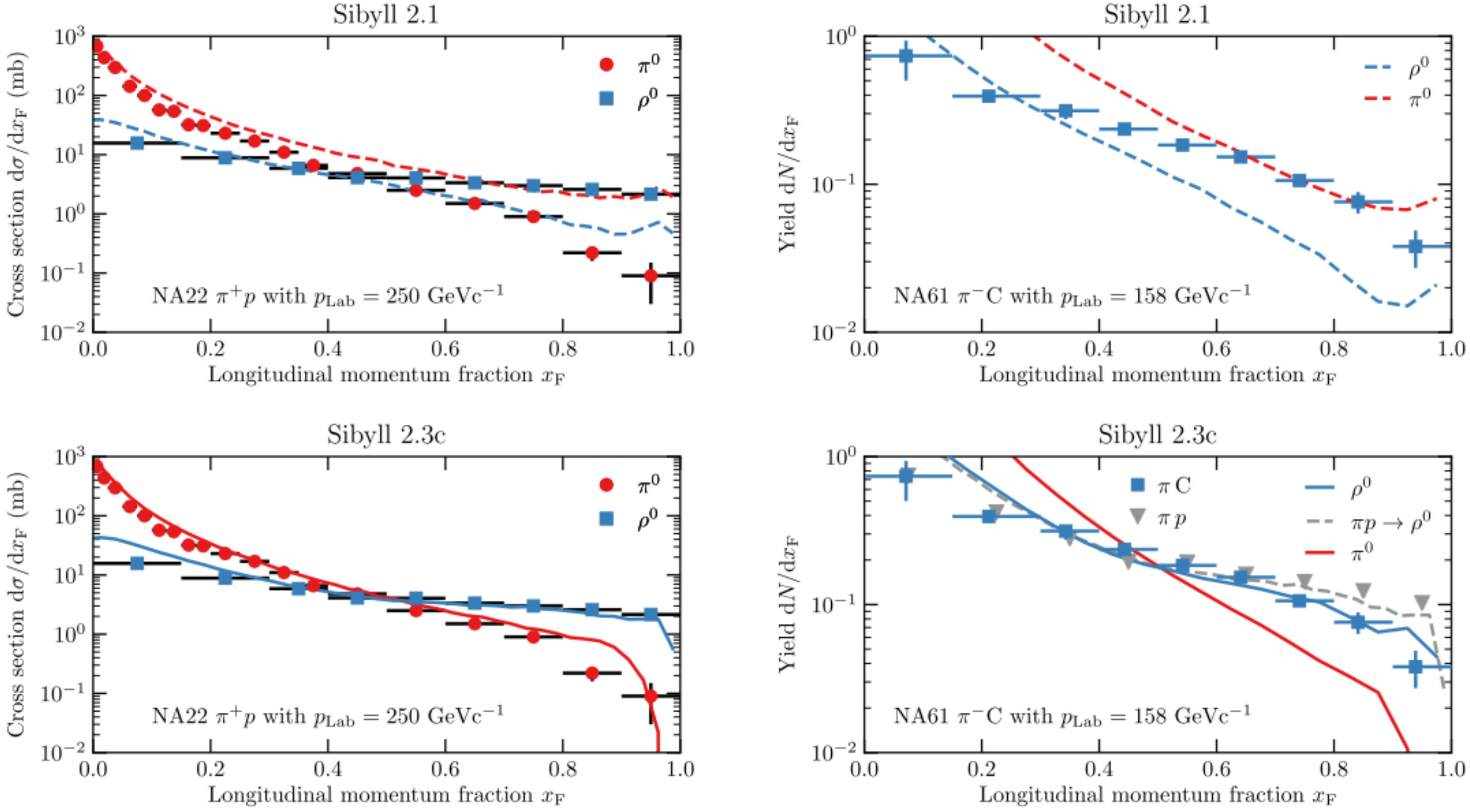
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

- Changing hadron multiplicity is not a solution to the muon puzzle
- R has large effect on muon number and needs to be well known

More charged hadrons through leading rho0 production

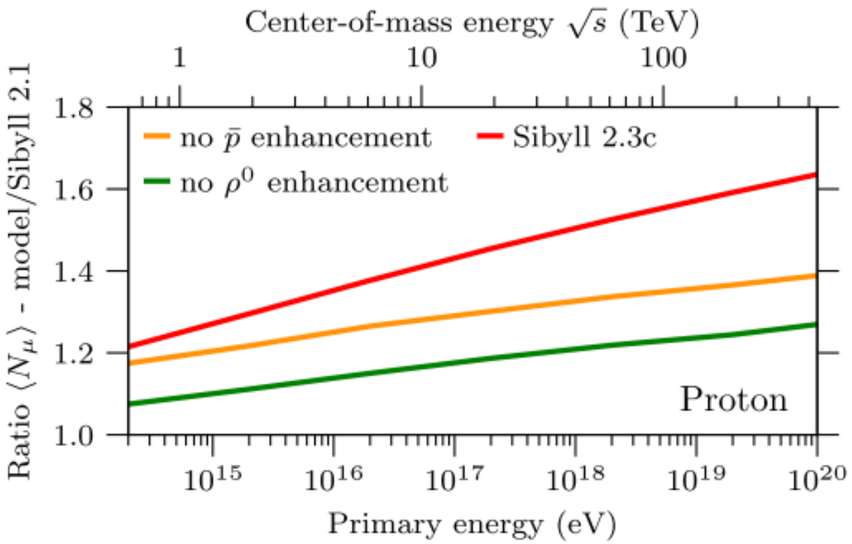
F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300, PRD 102

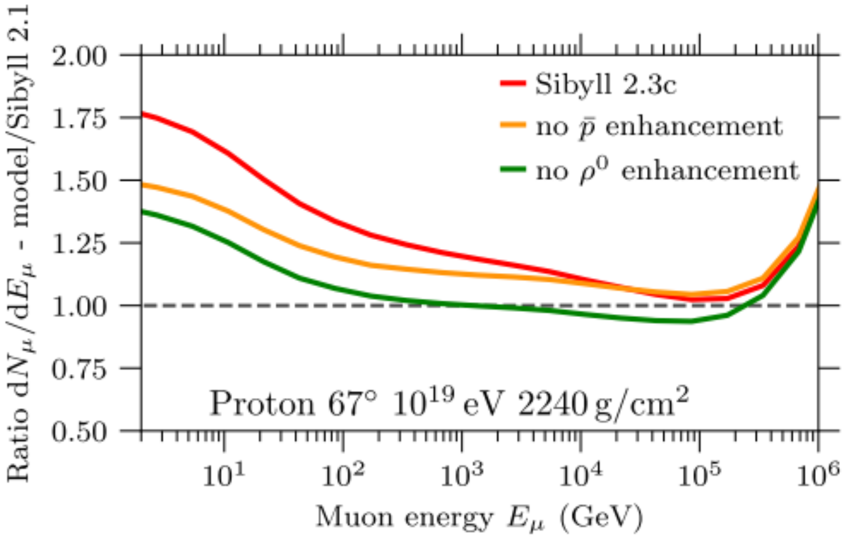




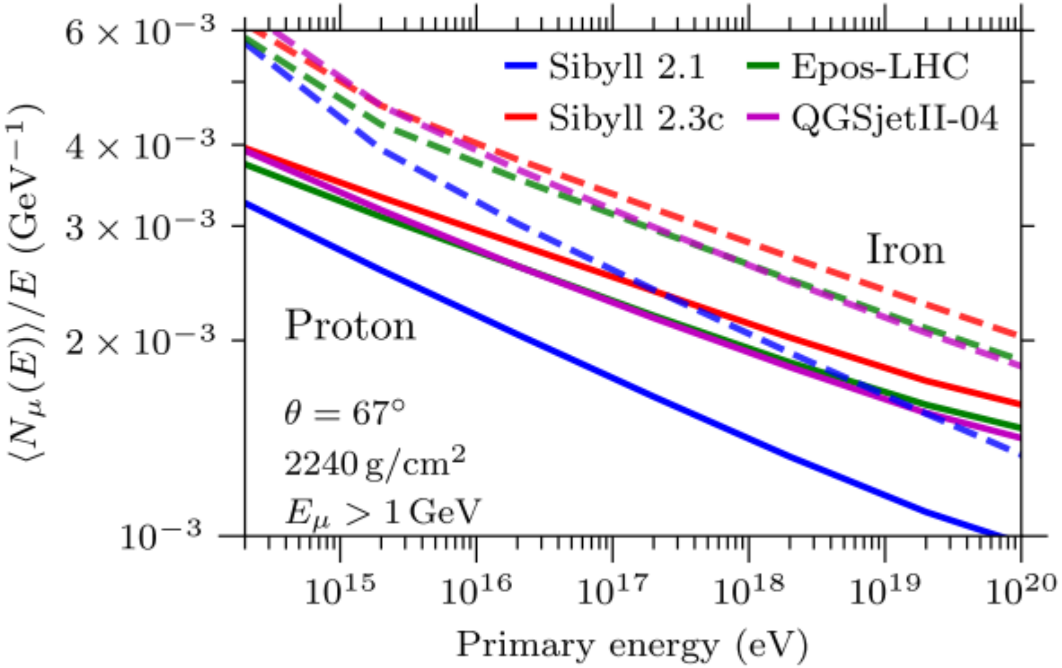
No fixed-target measurement of π^0 production off nulei

Impact of corrections on expected muon number





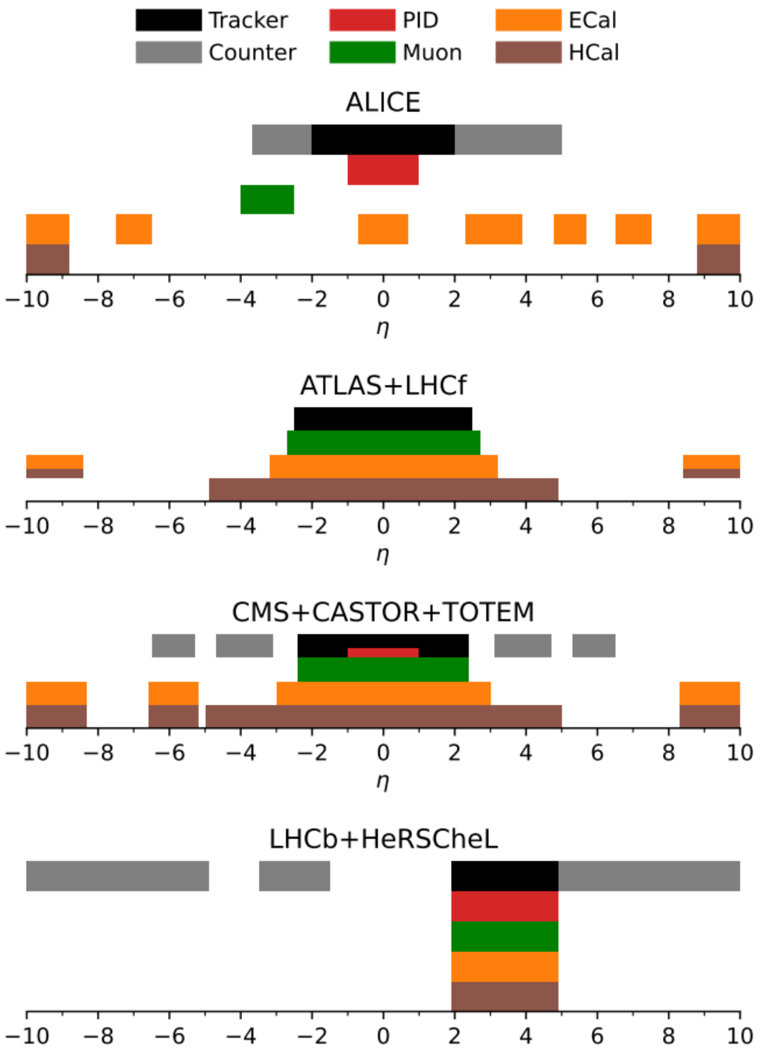
F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300 , **PRD 102**



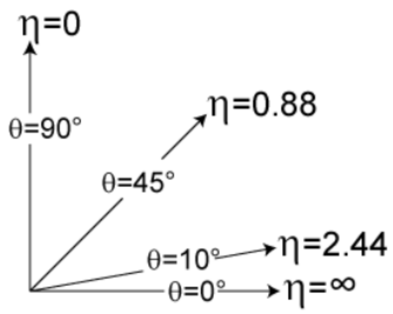
!75%! more muons in newer models at certain energies

Possibilities to learn from LHC data?

arXiv:2105.06148



pseudorapidity η



η related to emission angle

Image credit: JabberWok - Wikipedia CC BY-SA 3.0

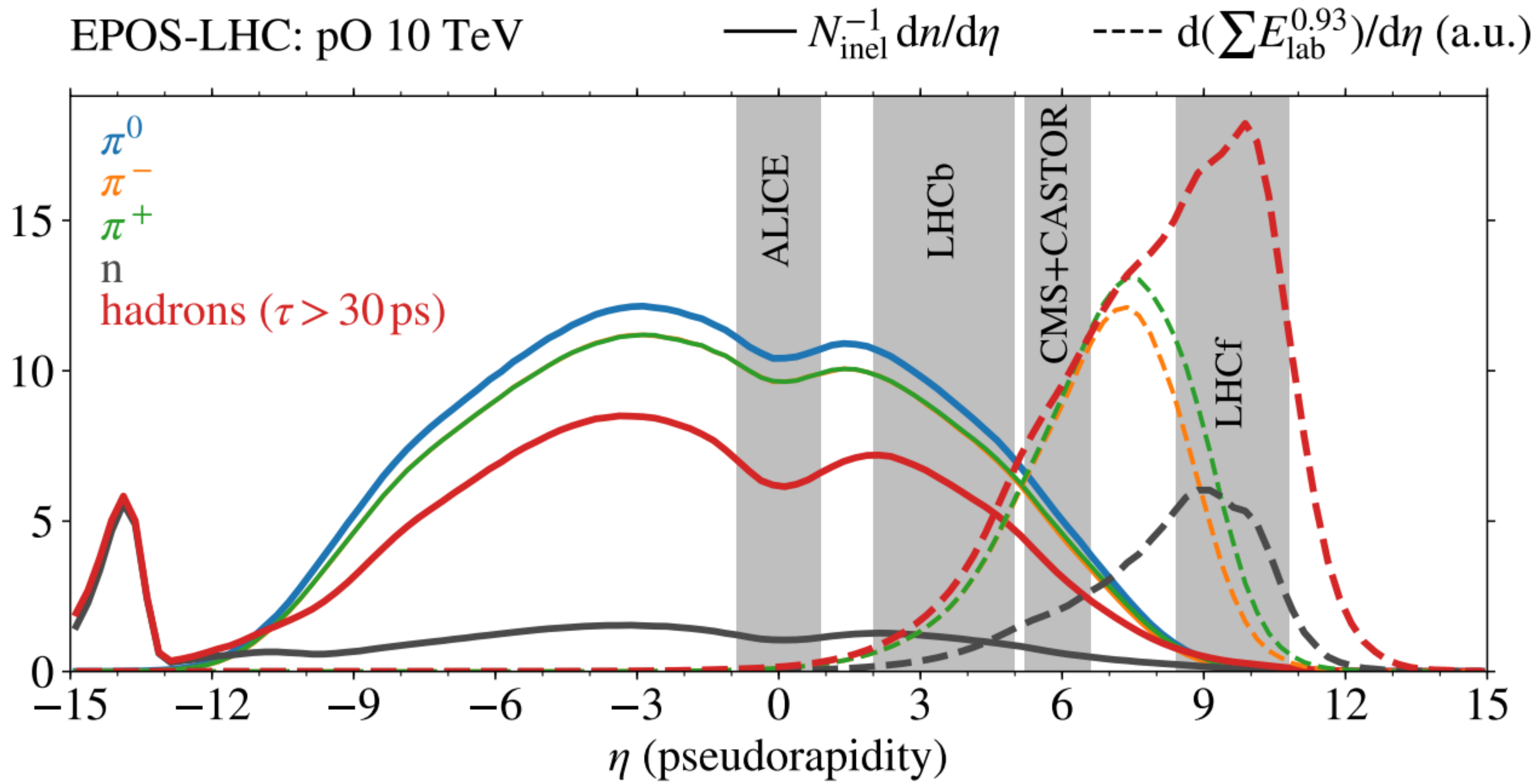
- Most LHC experiments focus on $|\eta| < 2$ region
  - Detectors well instrumented here
- Forward capabilities $|\eta| > 2$
  - ALICE, TOTEM: counters
  - CMS-CASTOR: Calorimeters for eγ and hadrons
  - LHCb: full tracking and PID at $2 < \eta < 5$
  - LHCf: neutral particles $\eta > 8$

Relevant phase space – a challenge for instrumentation

„Muon production weight“

how many muon would be produced in shower by secondaries in this collision

arXiv:2105.06148



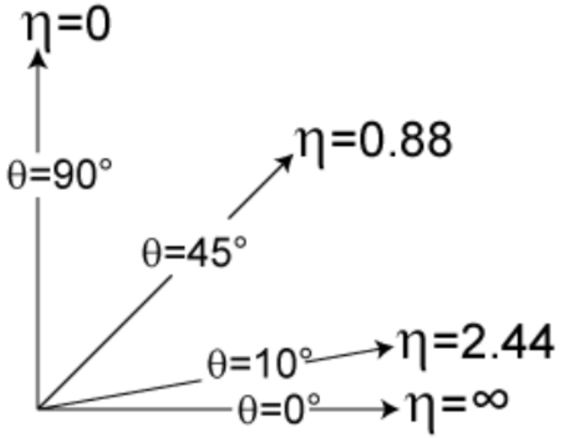
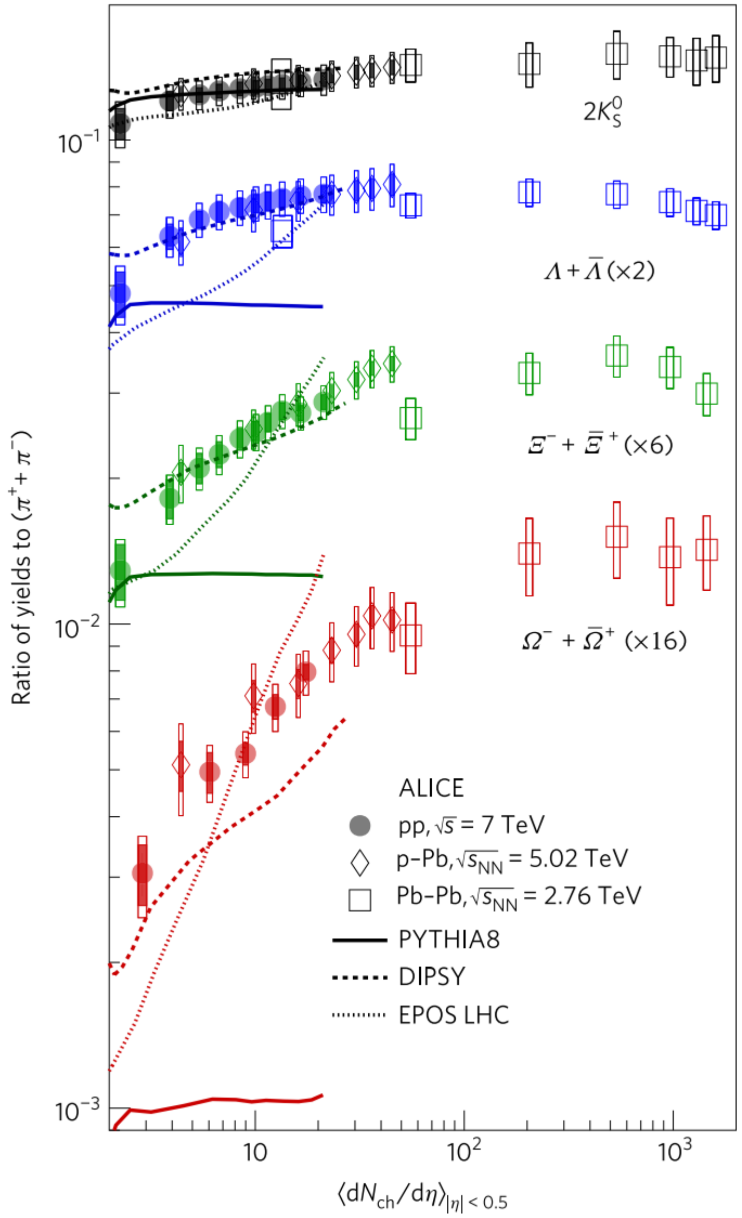


Image credit:
JabberWok - Wikipedia CC BY-SA 3.0

Other ways to modify R?



- Difficult to change R within standard QCD
- Fragmentation of strings and excited nuclear remnant believed to be universal
- Iso-spin symmetry: π+: π-: π0 ~ 1: 1: 1
- ALICE discovered universal enhancement of strangeness production in *pp*, *p*Pb, PbPb
  ALICE, Nature Phys. 13 (2017) 535
- More strangeness → less π^0 → more muons in air showers
  $R \approx 0.41 - 0.45$ (low density) $R \approx 0.34$ (high density)
- Enhancement seems to depend **only** on density of charged particles produced in the event → predictive power!
- Open question: Does it extend forward to η ≫ 1?

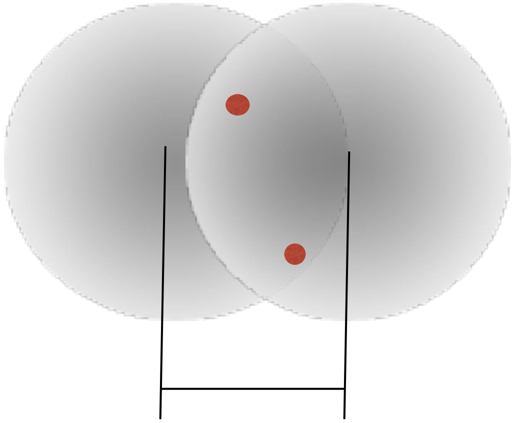
Hadronic models for air-shower simulation

	DPMJet-III.19-1	EPOS-LHC	QGSJetII-04	Sibyll2.3d	Pythia 8
Domain	EAS, HEP	EAS, HIC	EAS	EAS	HEP
Theoretical basis	GRFT + minijet	GRFT + energy sharing	GRFT + resummation	GRFT + minijet	parton model
Nuclear collisions	Glauber	extended GRFT	extended GRFT	extended superposition	Glauber via Argantyr
Pomeron	soft+hard	semi-hard	semi-hard	soft+hard	soft+hard
Energy evolution of parton densities	via $Q_0(s)$ cut	parameterised	Higher-order Pomeron graphs	via $Q_0(s)$ cut	via $Q_0(s)$ cut
Energy evolution of elasticity	constant	falling	falling	constant	—
Parton distributions	CT14	custom	custom	GRV	various
Non-diffractive remnant	—	multi-quark exchange (low to high mass)	one-quark exchange (low mass)	one-quark exchange (low mass)	low mass
Diffraction (low mass)	2-channel eikonal	diffractive Pomeron	3-channel eikonal	2-channel eikonal	Pomeron emission
Diffraction (high mass)	cut enhanced graphs	Pomeron exchange	cut enhanced graphs	Pomeron exchange	Pomeron exchange
String fragmentation (fitted data)	Lund (e^+e^-)	area law (e^+e^-)	custom (pp)	Lund (pp)	Lund (e^+e^-)
Forward-central correlation	weak	strong	strong	weak	strong
Charm production	pQCD (incomplete)	—	—	parameterised + intrinsic	pQCD
Collective effects	string fusion	core-corona (parameterised)	—	—	colour reconnection, rope hadronization, string shoving

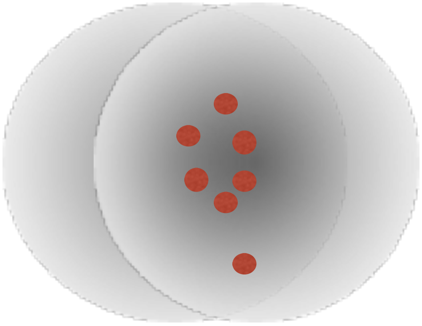
GRFT: Glauber-Regge-Field-Theory

Multiplicity scales with MPI and depends on transverse parton density

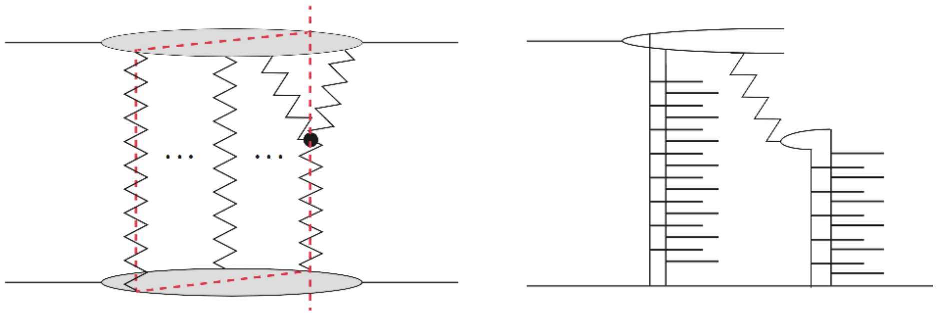
Low energy



High energy



Example for cut topologies



Simple MPI model:

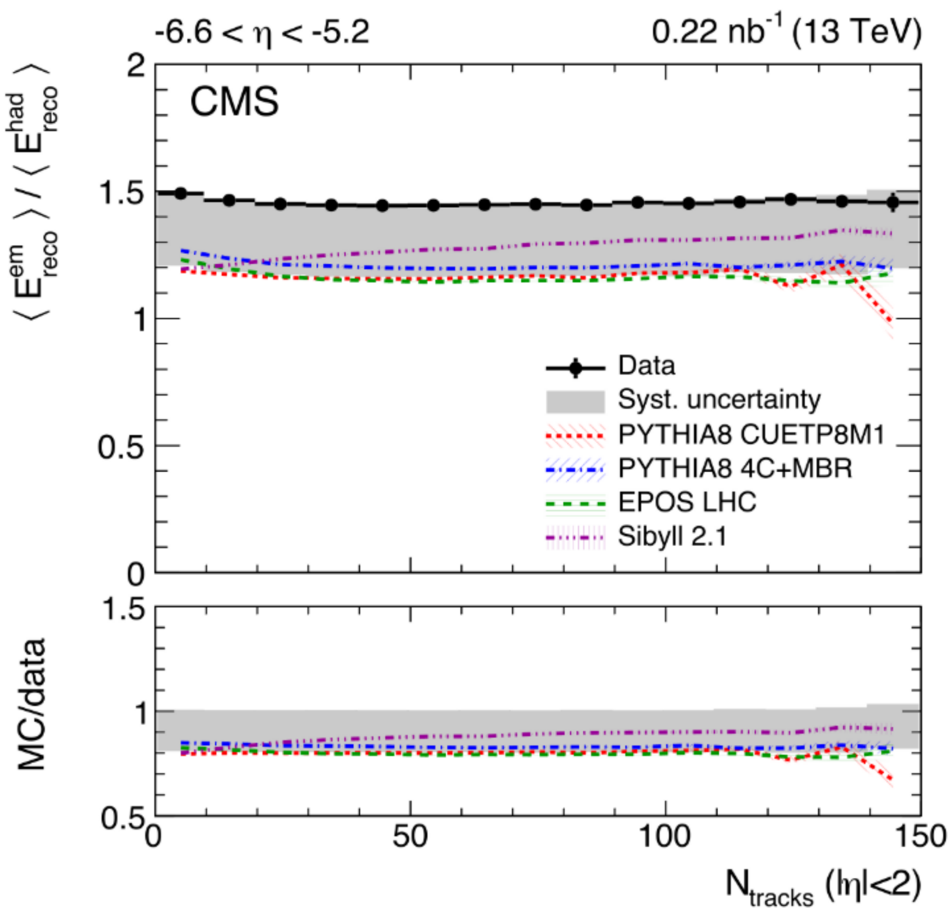
$$\sigma(n_S, n_H, \dots) = \int d^2\vec{B} \frac{(-2\chi_S)^{n_S}}{n_S!} \frac{(-2\chi_H)^{n_H}}{n_H!} \dots e^{-2\chi}$$

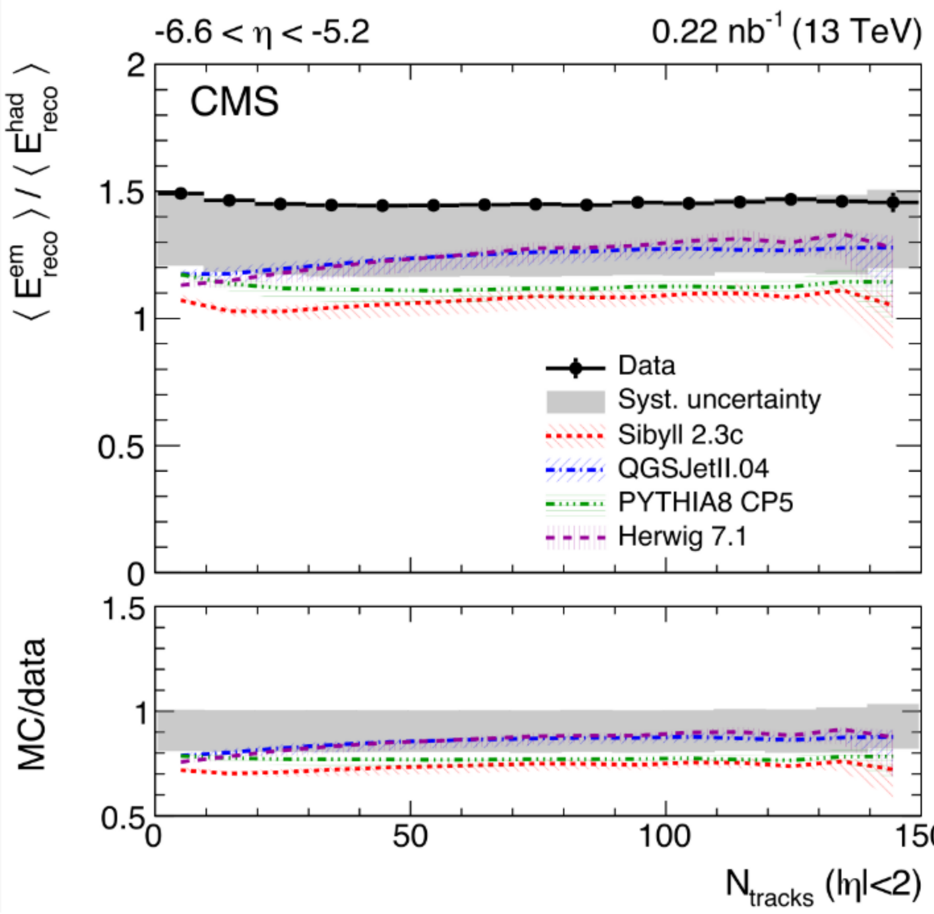
- Unitarity and multiple-cut structure from Eikonal expansion
- uncorrelated multiple interactions
- Collinear factorization not applicable due to missing transverse dependence
- Problems: Saturation? Hydro? Core-corona? Energy evolution? FSI?→ …cooking…cooking…

Direct measurements of R in pp suggest that R already too low → less muons

CMS, Eur.Phys.J. C79 (2019) no.11, 893;

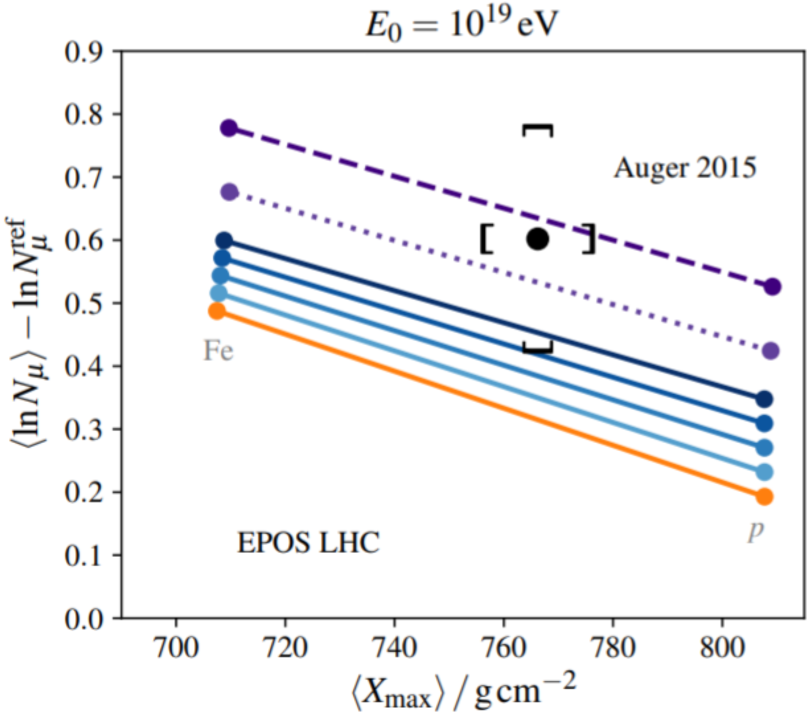
p-p @ 13 TeV

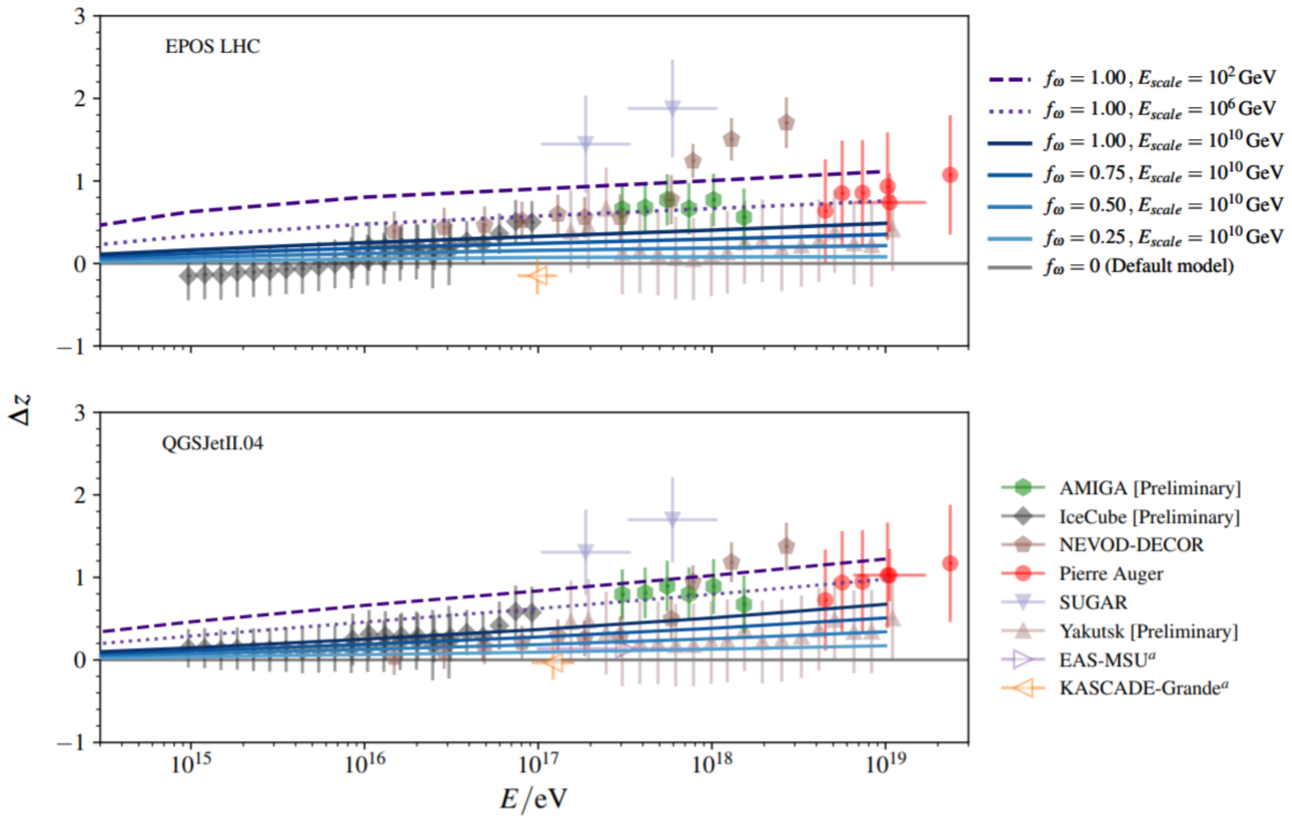




Another possibility is the (mis-)understanding of strangeness at high energy

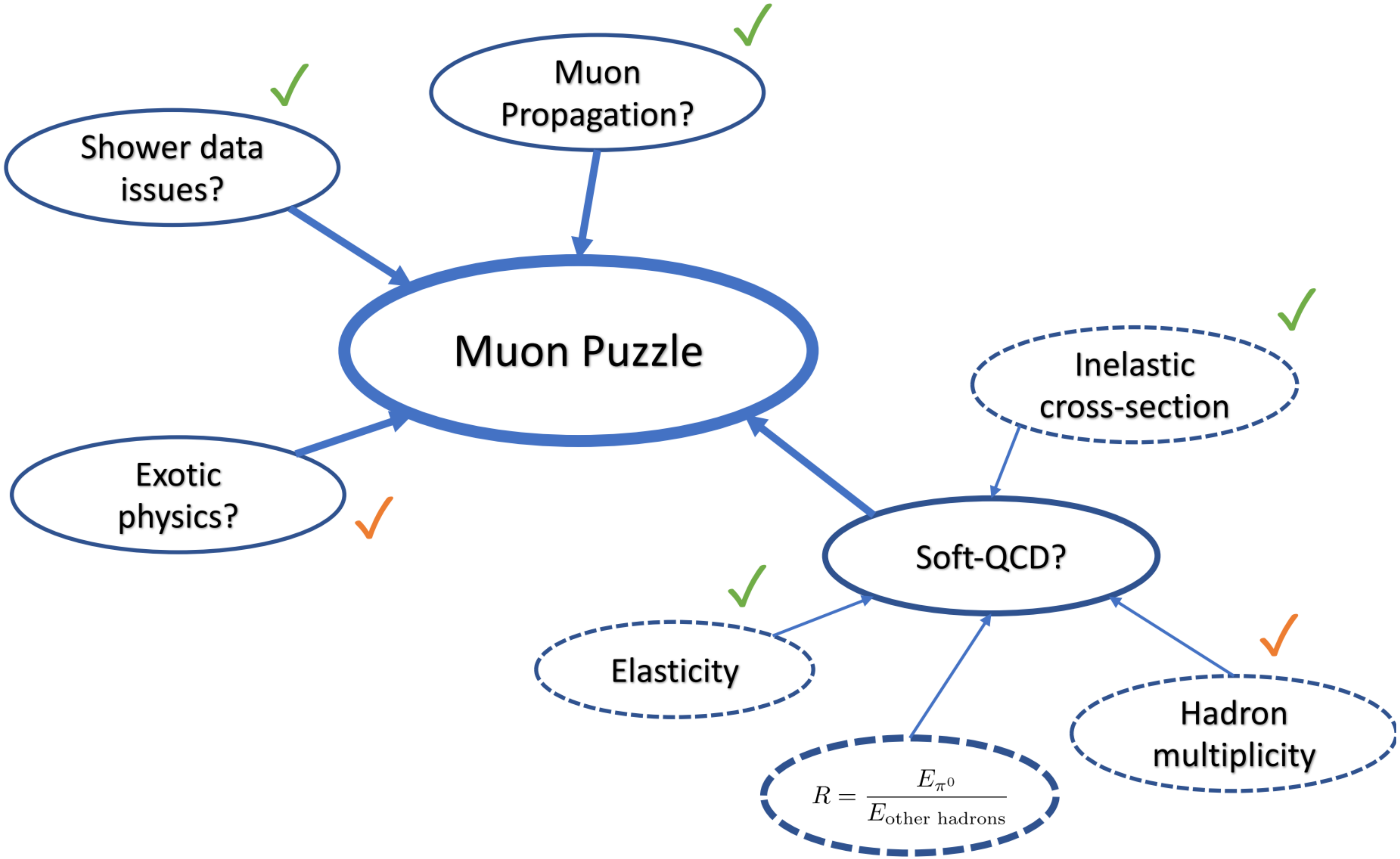
S. Baur et al., arXiv:1902.09265





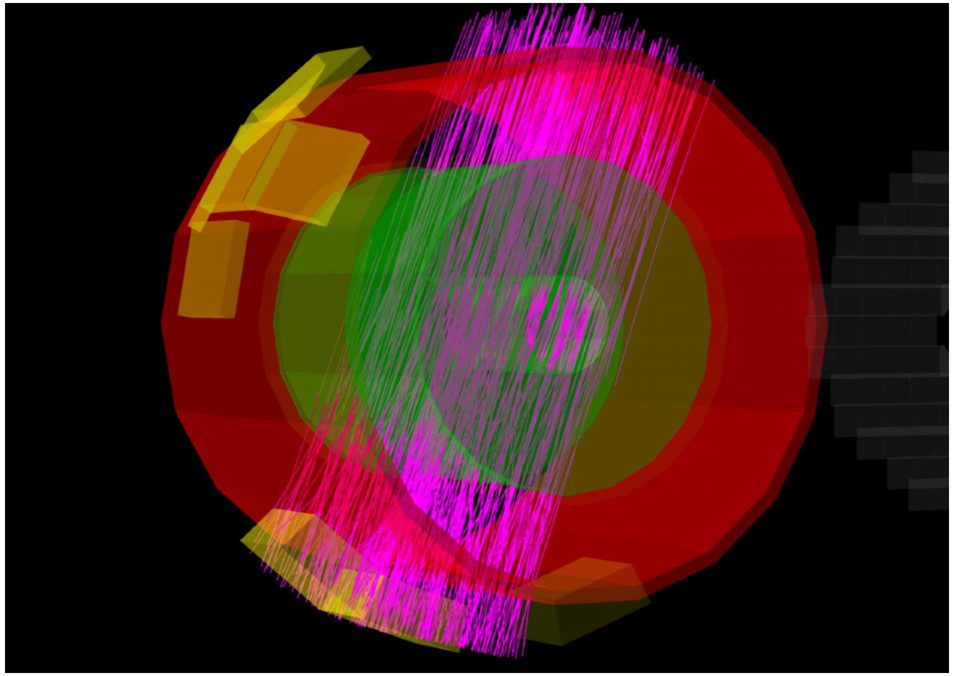
- Toy model with statistical hadronization (core) in addition to string/remnant fragmentation (corona)
  - Statistical hadronization needed to describe strangeness enhancement seen by ALICE
  - Can close muon number gap number in air showers and matches faster increase with energy
- Constrained by CMS-CASTOR measurements of *R*
- Can be tested further with data on forward strangeness production from LHCb and LHCf

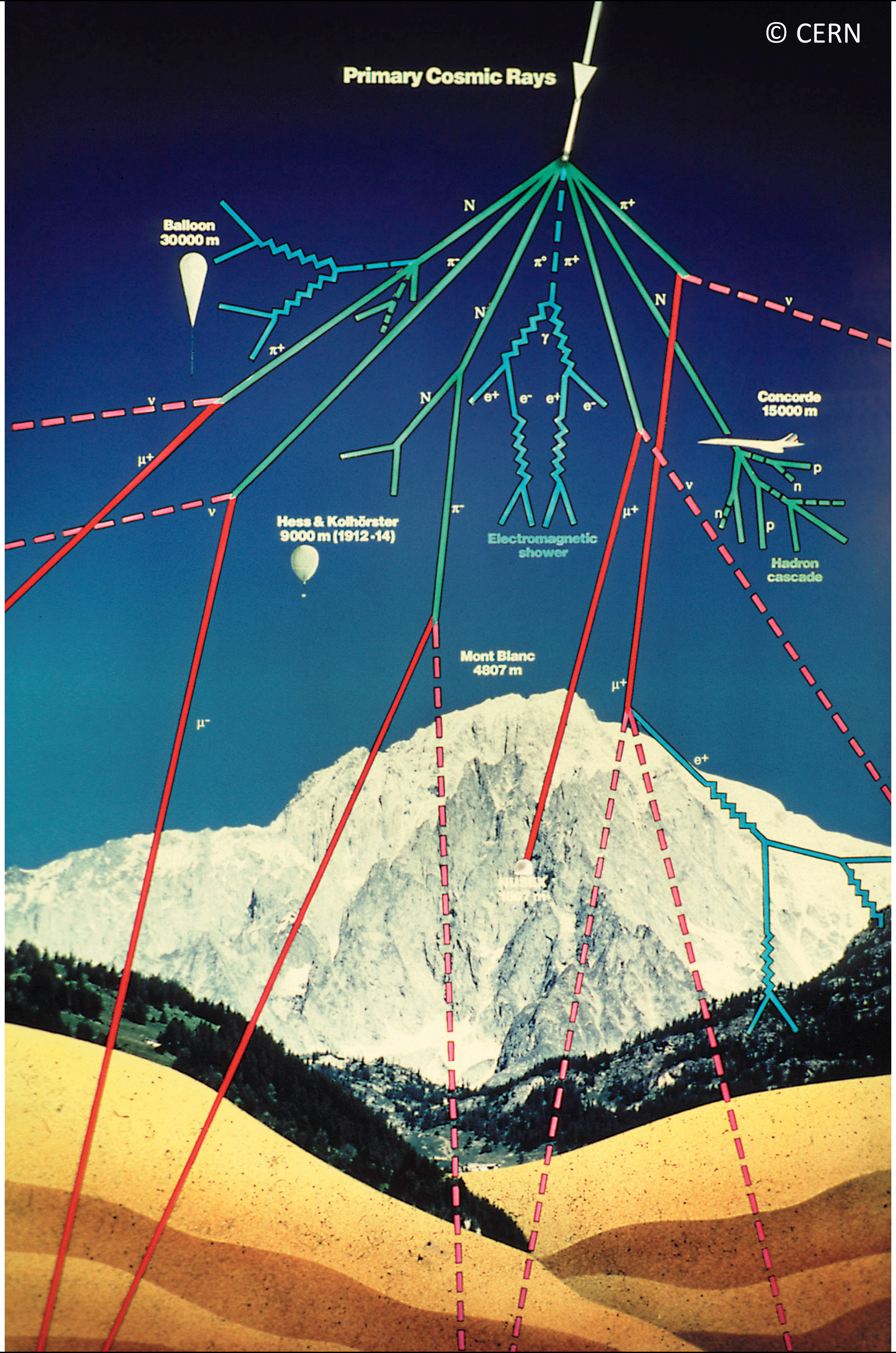
The Muon Puzzle



Inclusive atmospheric muons

ALICE Collaboration



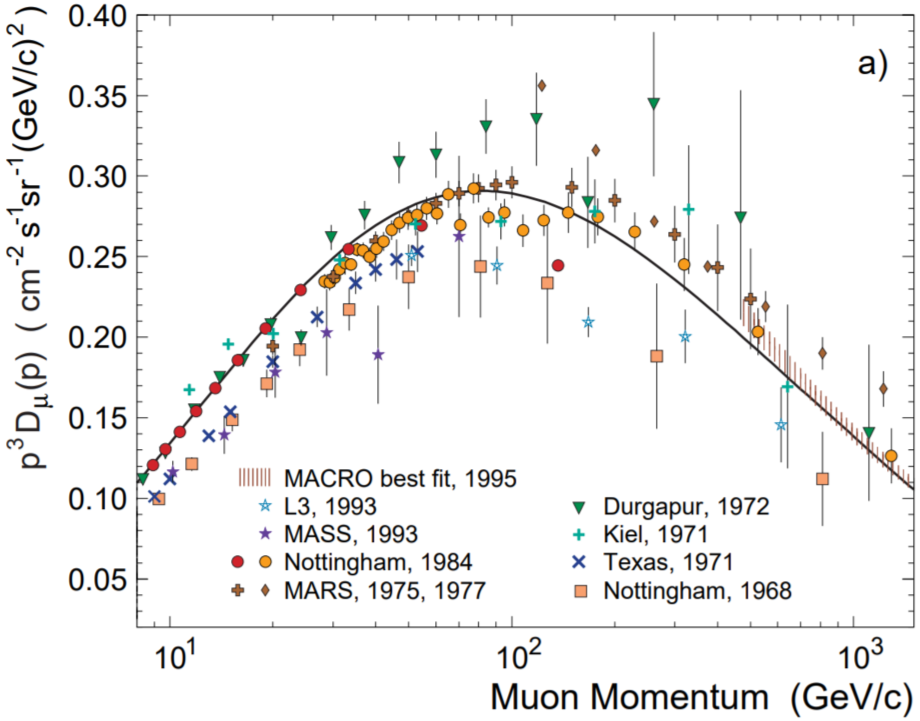


- **Muon bundle:** muons within a single air showers

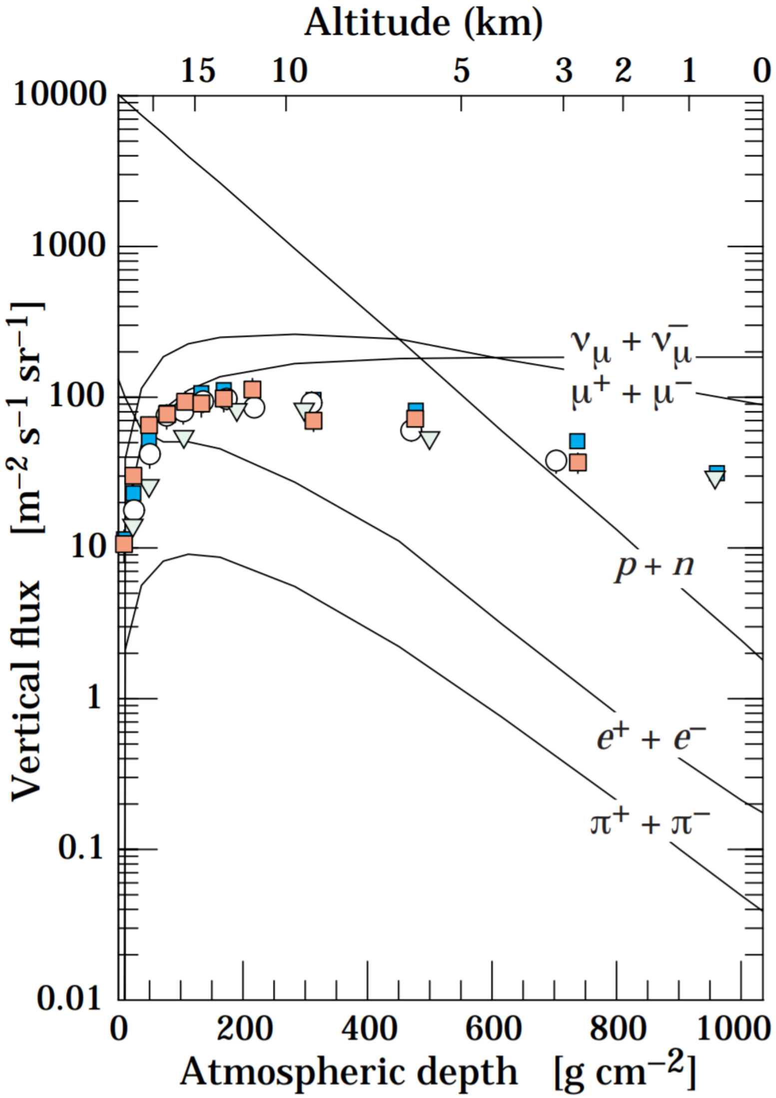
- **Inclusive muons:** Each atmospheric muon counted individually (integral over many showers)

Muon fluxes in the atmosphere

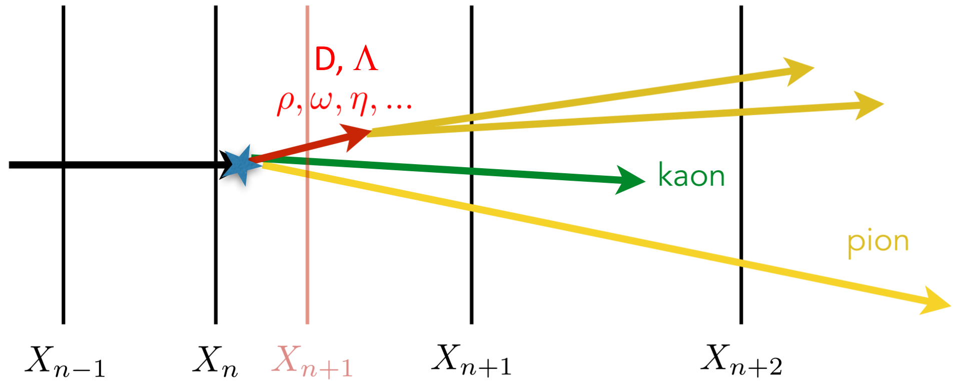
Bugaev et al., PRD58, 1998



Particle Data Group



Hadronic components



conventional

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

muons and muon neutrinos

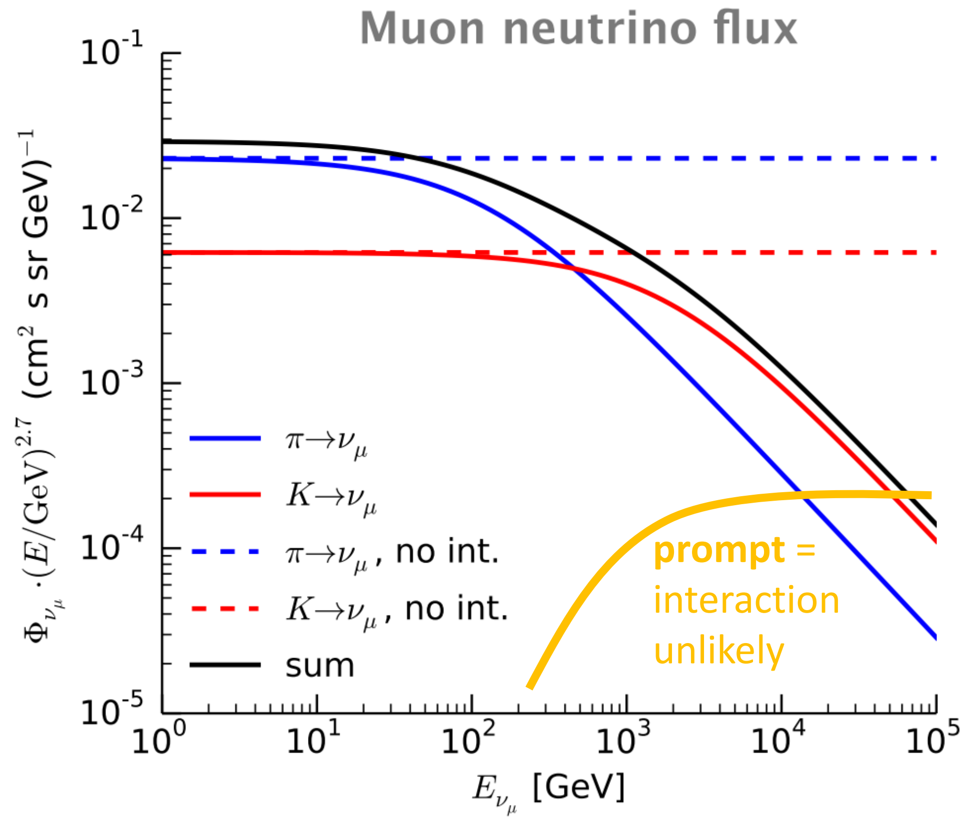
$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$$

electron neutrinos

$$K^{\pm}, K^0_L \rightarrow [\pi^{\pm}, \pi^0]e^{\pm}\nu_e(\bar{\nu}_e)$$

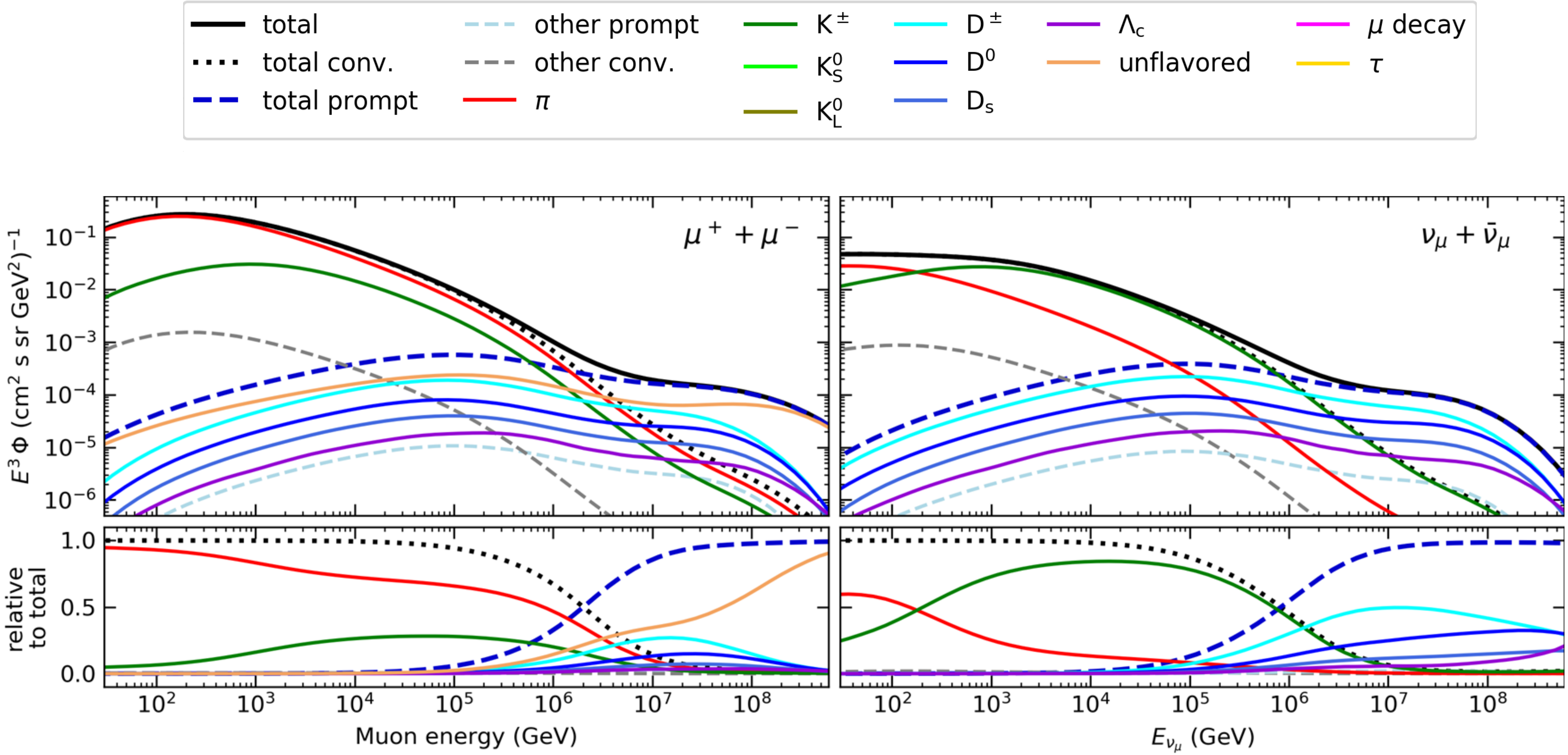
prompt

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



High-energy mesons live long enough to interact → **Spectral steepening**

Spectral and angular distribution related to



AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

Building a bridge to particle physics at accelerators

For atmospheric leptons

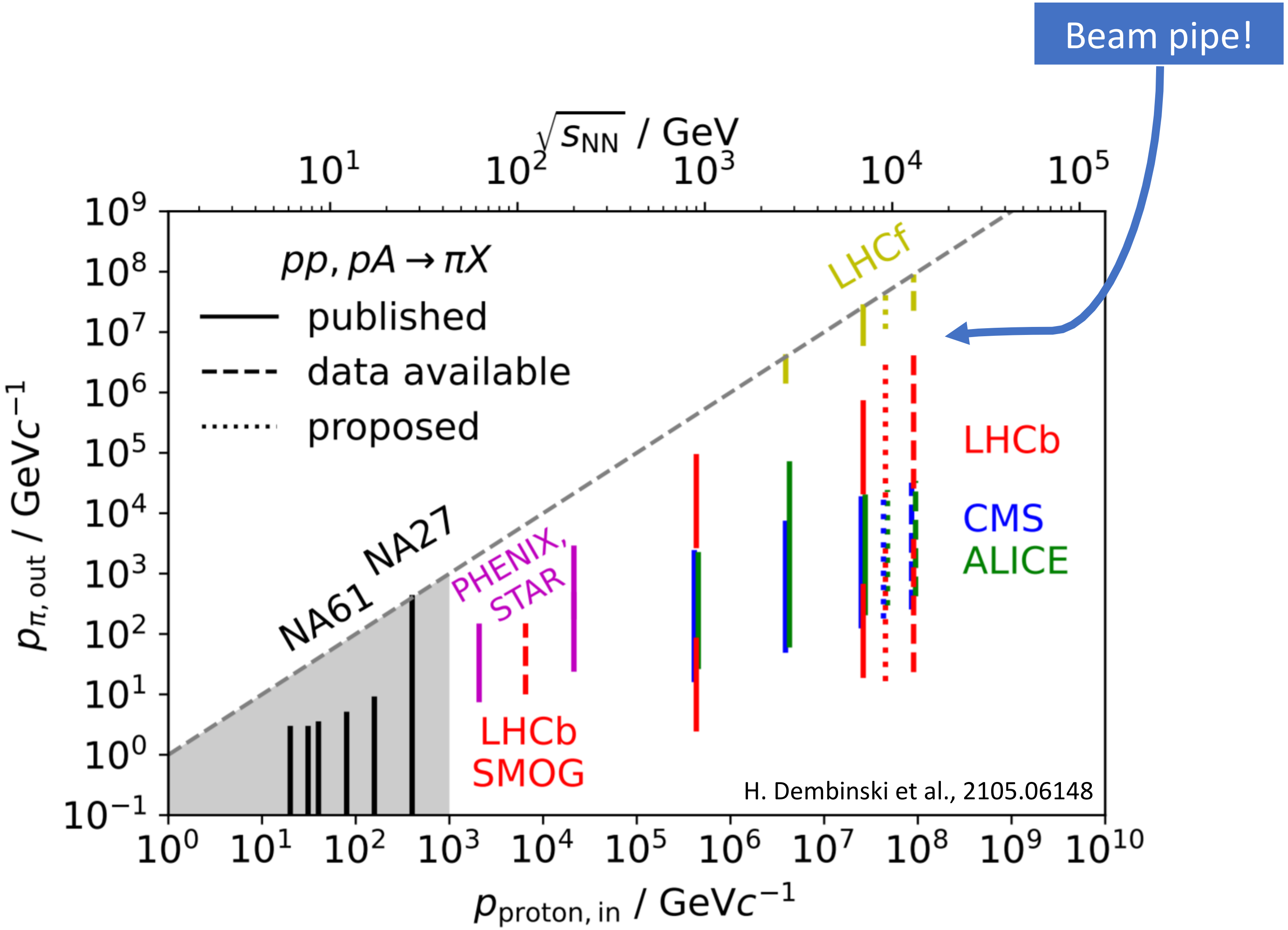
$p_z \sim \text{TeV} - \text{PeV}$

$p_T \sim \text{few GeV}$

$\theta \sim \mu\text{rad}$

$$x_{\text{lab}} = \frac{E_{\text{secondary}}}{E_{\text{primary}}} \approx \frac{p_{z,\text{secondary}}}{E_{\text{primary}}}$$

$$x_{\text{lab}} > 0.1, \quad \eta \to \infty$$



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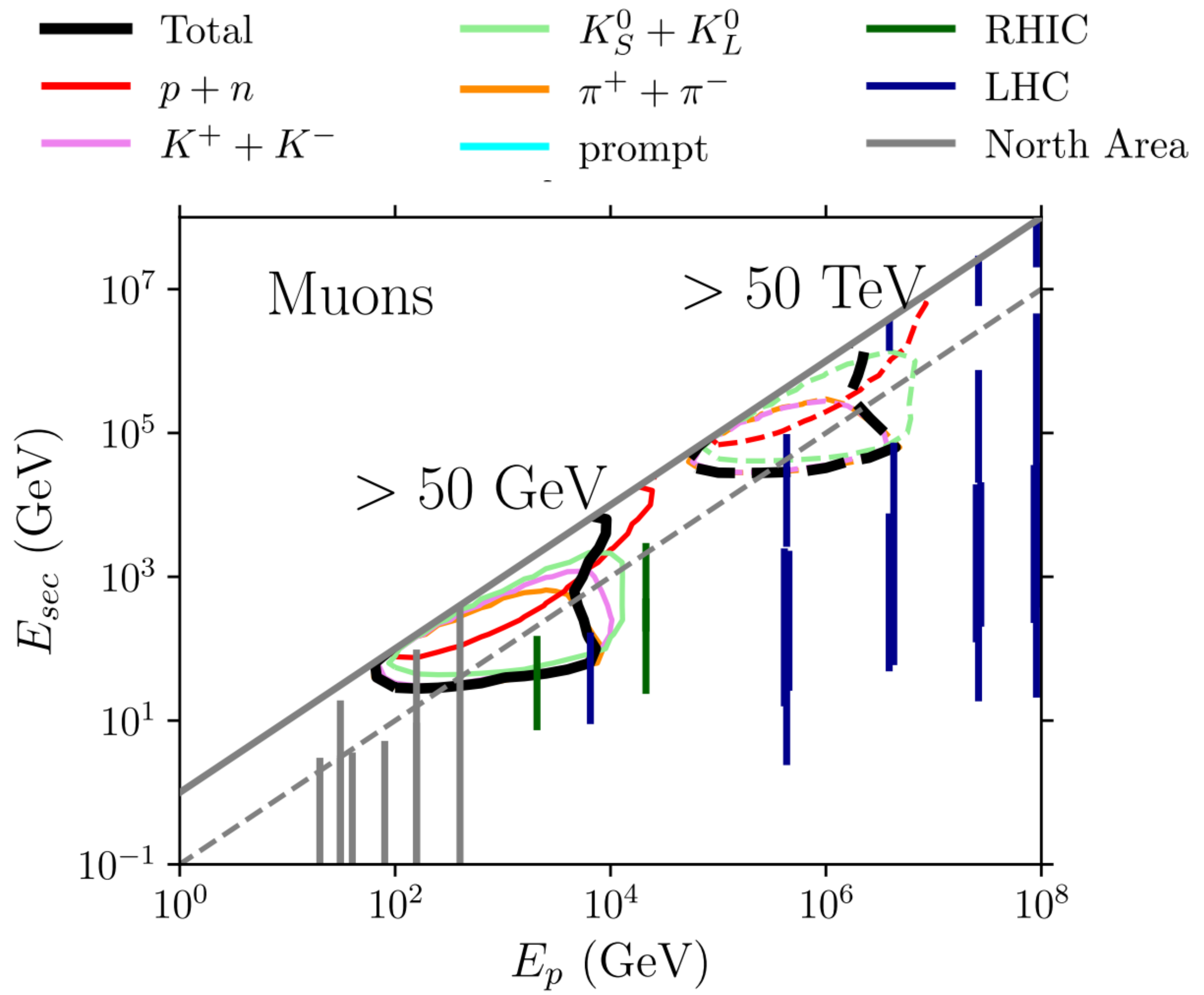
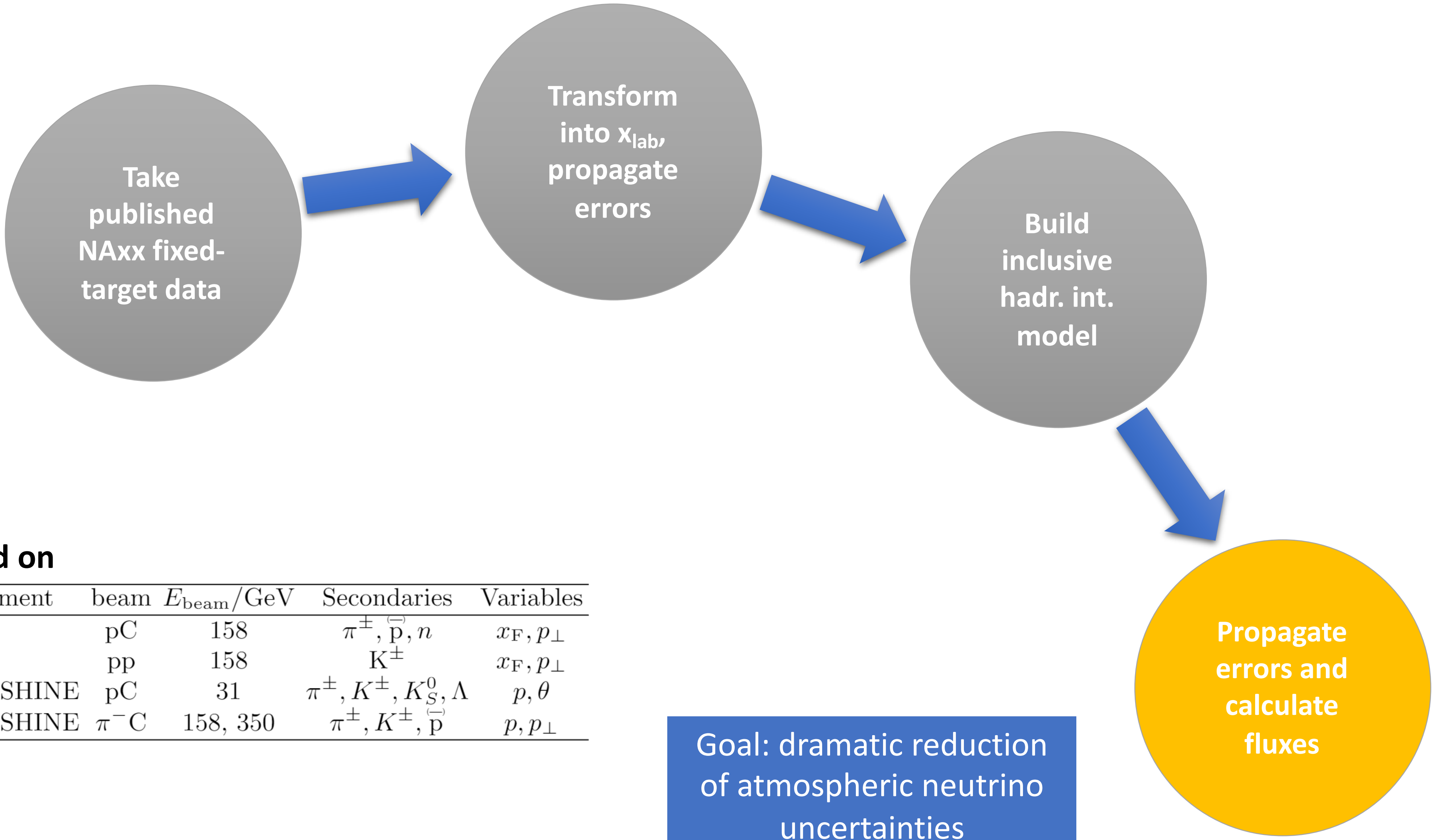


AF & M. Huber, ICRC 2021 & in prep.

DDM: Data-Driven hadronic interaction Model



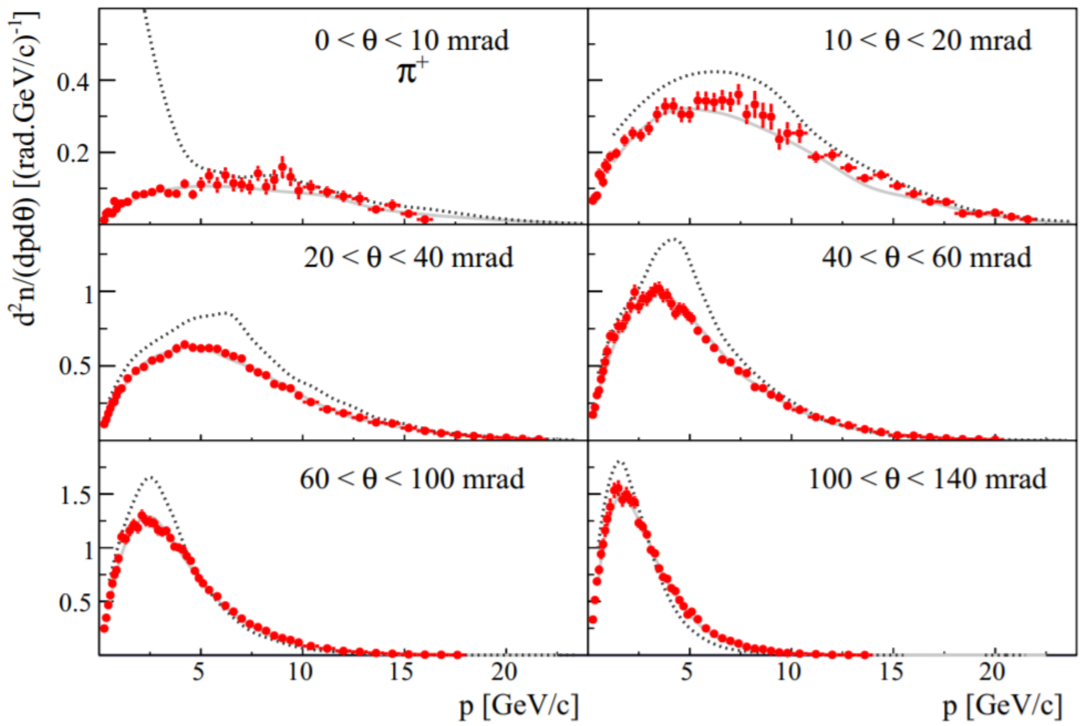
Based on

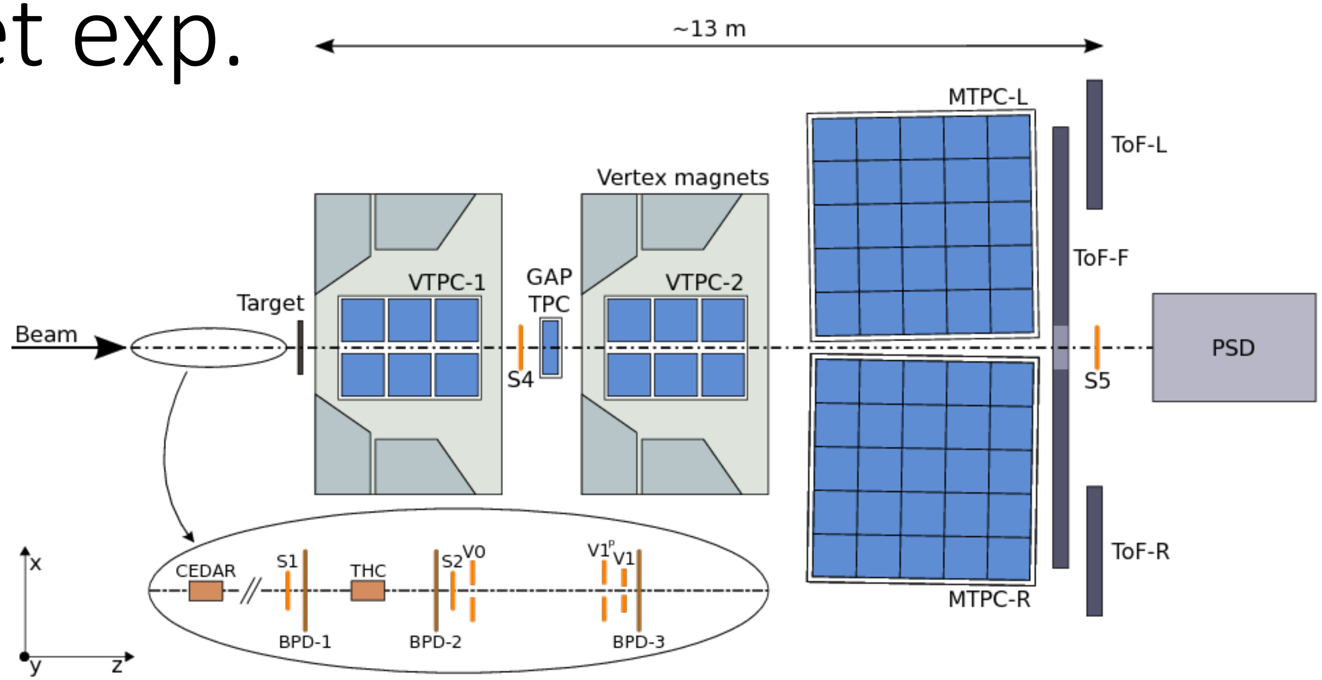
Experiment	beam	$E_{\mathrm{beam}}/\mathrm{GeV}$	Secondaries	Variables
NA49	pC	158	$\pi^\pm, \overset{(-)}{\mathrm{p}}, n$	$x_\mathrm{F}, p_\perp$
NA49	pp	158	$\mathrm{K}^\pm$	$x_\mathrm{F}, p_\perp$
NA61/SHINE	pC	31	$\pi^\pm, K^\pm, K^0_S, \Lambda$	p, θ
NA61/SHINE	π^-C	158, 350	$\pi^\pm, K^\pm, \overset{(-)}{\mathrm{p}}$	$p, p_\perp$

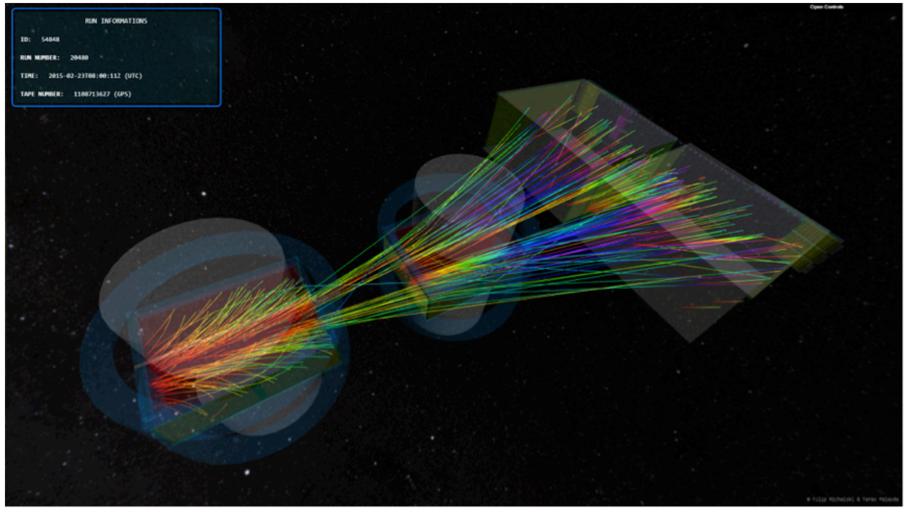
Goal: dramatic reduction of atmospheric neutrino uncertainties

NA61/SHINE fixed-target exp.

Proton on carbon, 31 GeV, NA61, EPJC 76, 2016

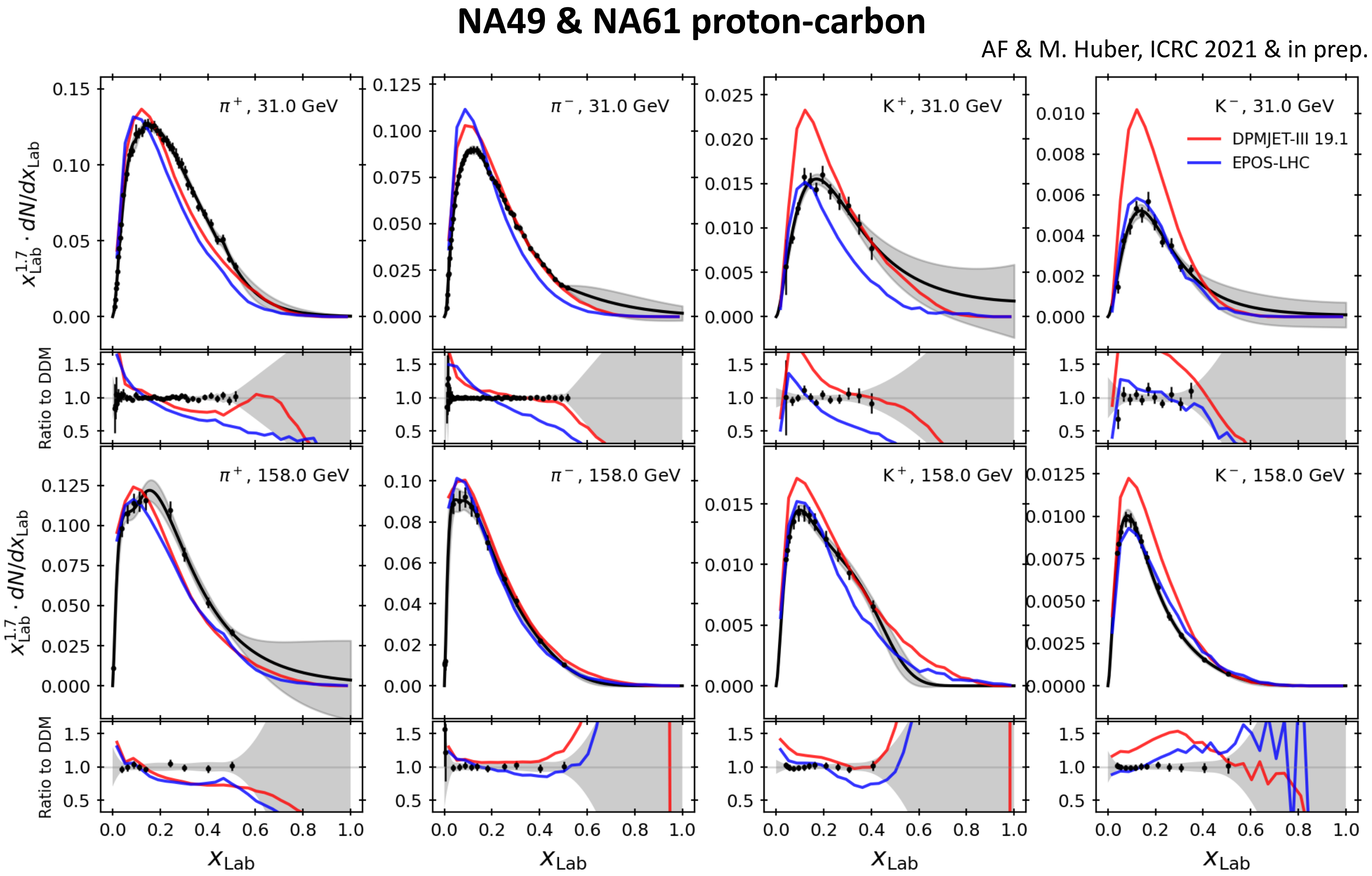






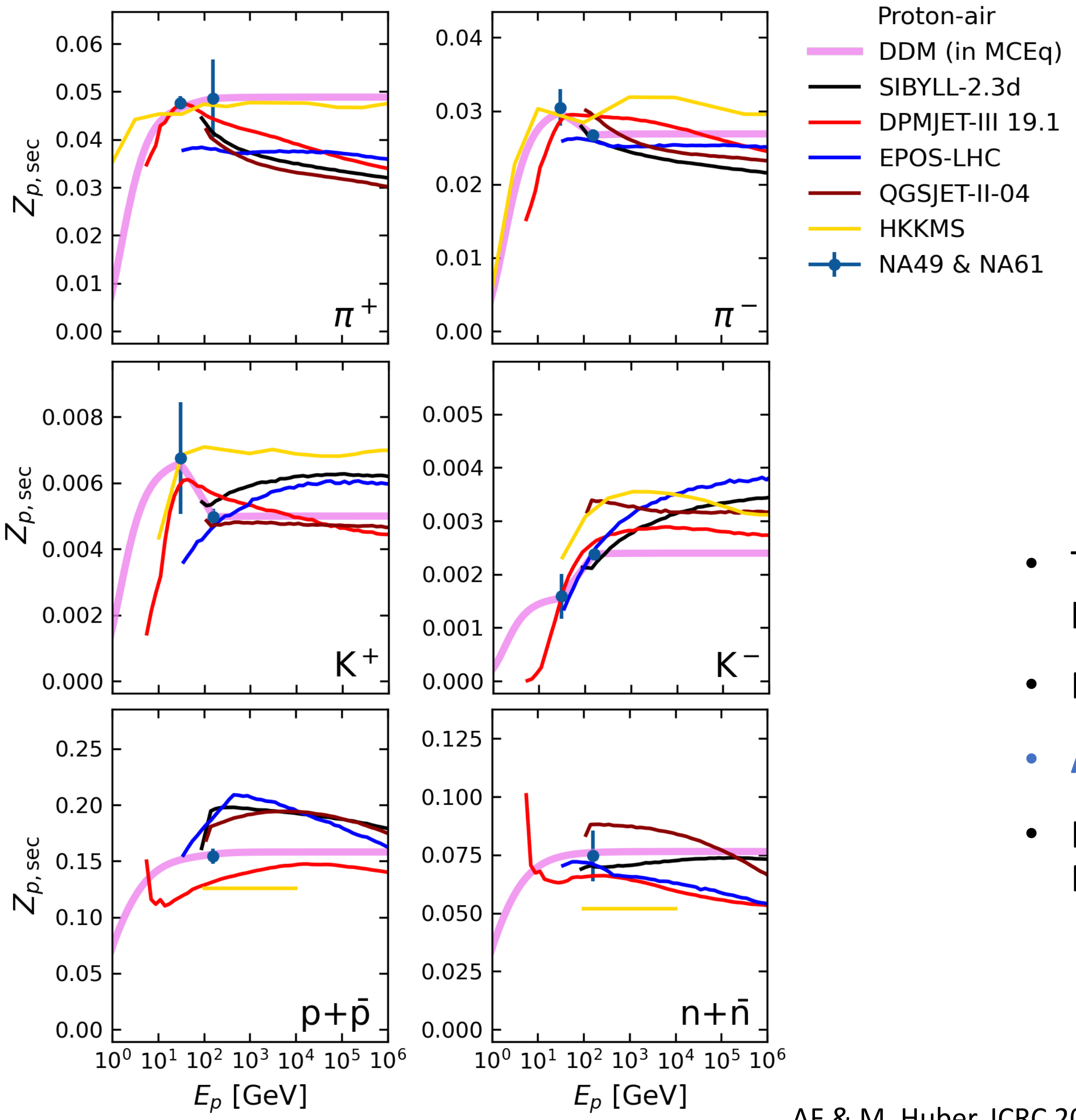
Courtesy of CERN (home.cern)

Fits to proton-carbon data



- **Conservative uncertainties consistently scale up** in absence of forward data
- Models weak for π^+ (both energies) and K^- at 158 GeV
- K+- data at 158 GeV corrected from pp→pC
- Carbon to air correction < 1%

Benchmark against post-LHC interaction models



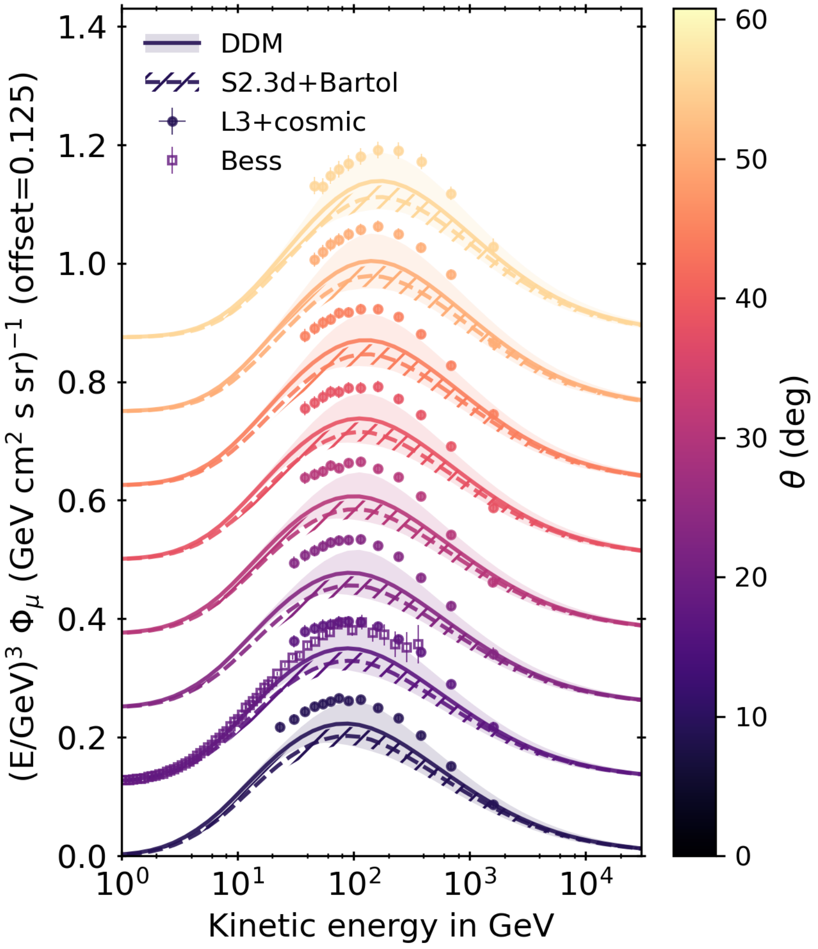
Spectrum-weighted moments:

$$Z_{N\pi} = \int_0^1 x_L^{\gamma-1} F_{N\pi}(x_L)\, \mathrm{d}x_L = \int_0^1 x_L^{\gamma} \frac{\mathrm{d}n_\pi}{\mathrm{d}x_L}\, \mathrm{d}x_L$$

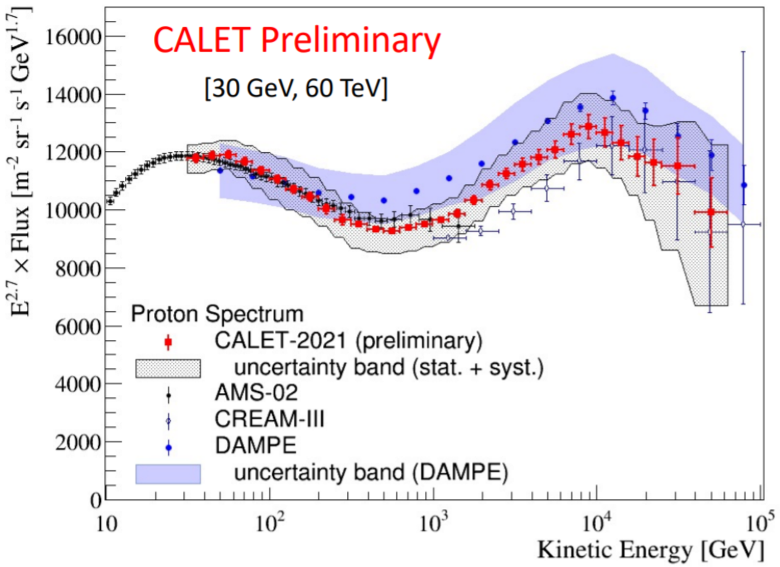
- The spectrum weighted moments (Z-factors) are integrated particle production yields
- Represent particle production in relevant phase space
- **Assumption in DDM: Feynman scaling** beyond 158 GeV
- Higher-energy data from NA59 and intermediate energies from NA61 can be included in future

AF & M. Huber, ICRC 2021 & in prep.

Results of the high-precision calculation



Marocchesi, ICRC 2021, Highlight talk



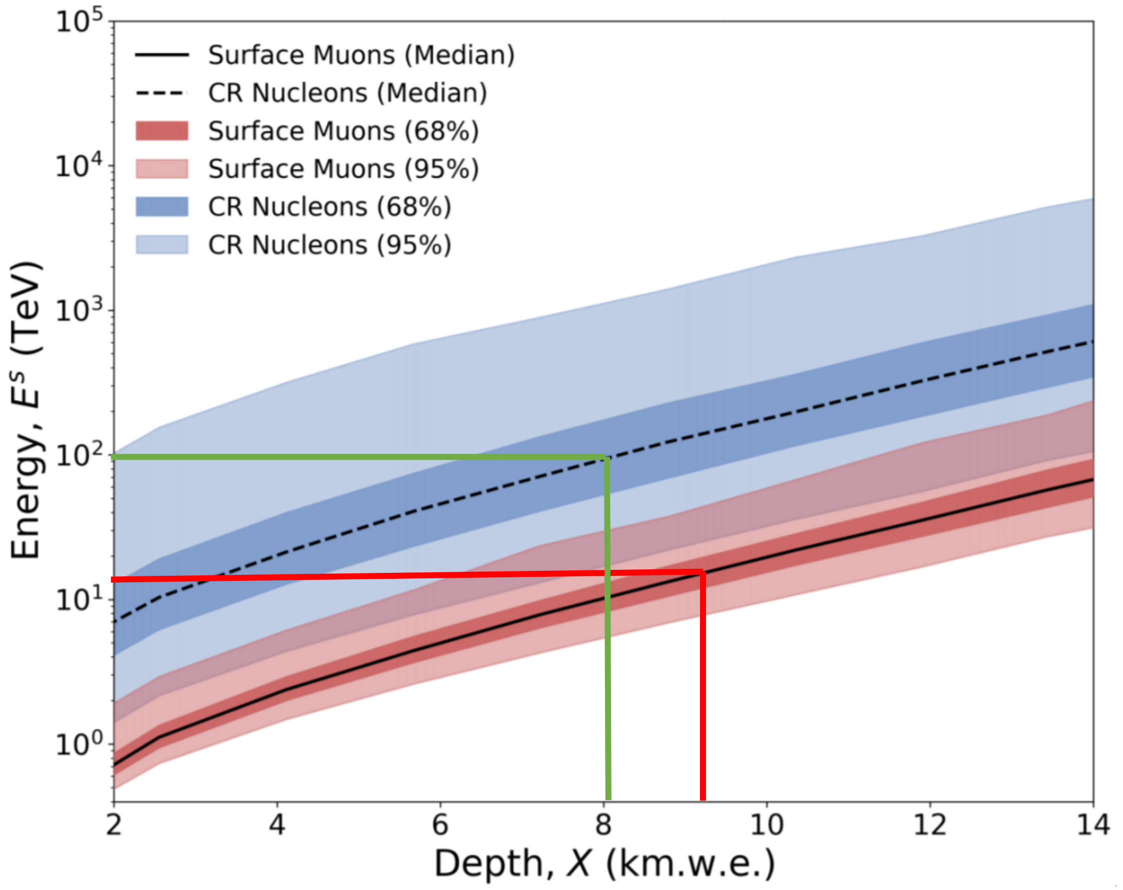
- Deviation in vertical fluxes
- Barely compatible within uncertainties
- Fitting to data imposes pulls of 2-5 sigma on the NA49/61 data
- May strongly indicate that the **direct cosmic ray measurements are not as well known as believed**
- Or processes missing that are larger than believed:
  - Photo-hadronic
  - Quasi-elastic VM production
  - ?

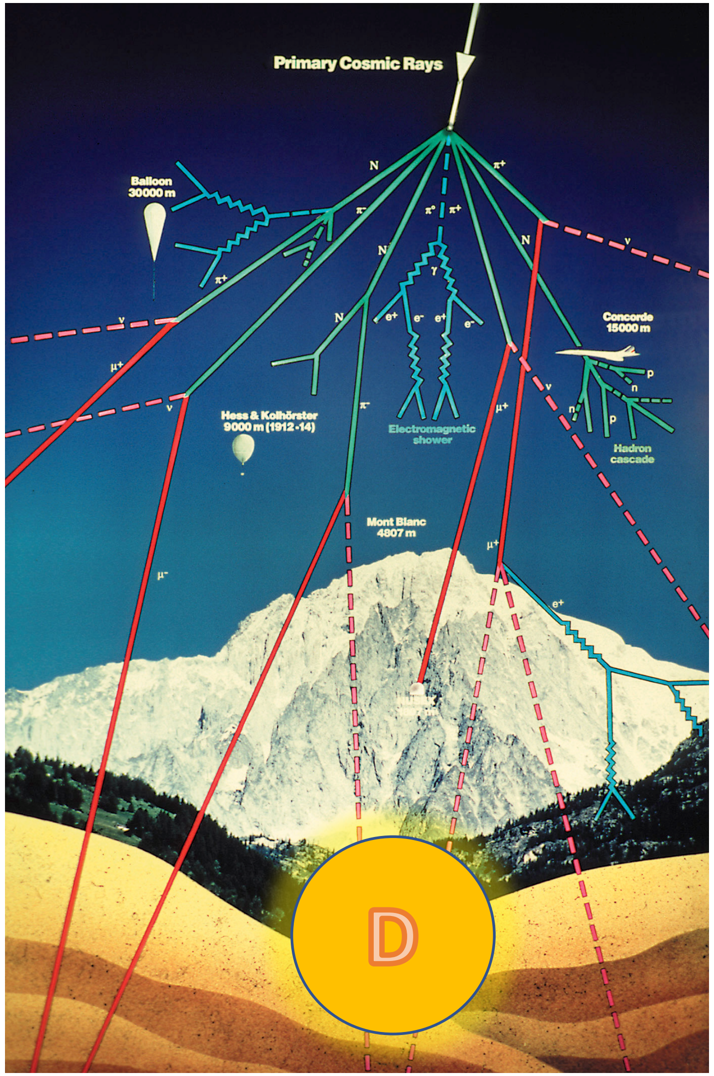
Summary

- **The Muon Puzzle is real** with significance > 8 sigma
- Origin is still unclear and is likely related to intermediate (LHC) energies
- Possible explanations: strangeness at high energy or “density”, non-perturbative effects, non-universality of string fragmentation, and new physics
- At IOP, I aim to launch a project to improve/rewrite the DPMJET-III hadronic interaction model to test new ideas. International collaborators, tools and know-how are available
- Inclusive atmospheric leptons show also a discrepancy with data but very likely of different origin
- None the less, atmospheric neutrino flux uncertainties have been significantly reduced
- Systematic differences between space-borne cosmic ray detectors may explain these differences

Very high-energy muons

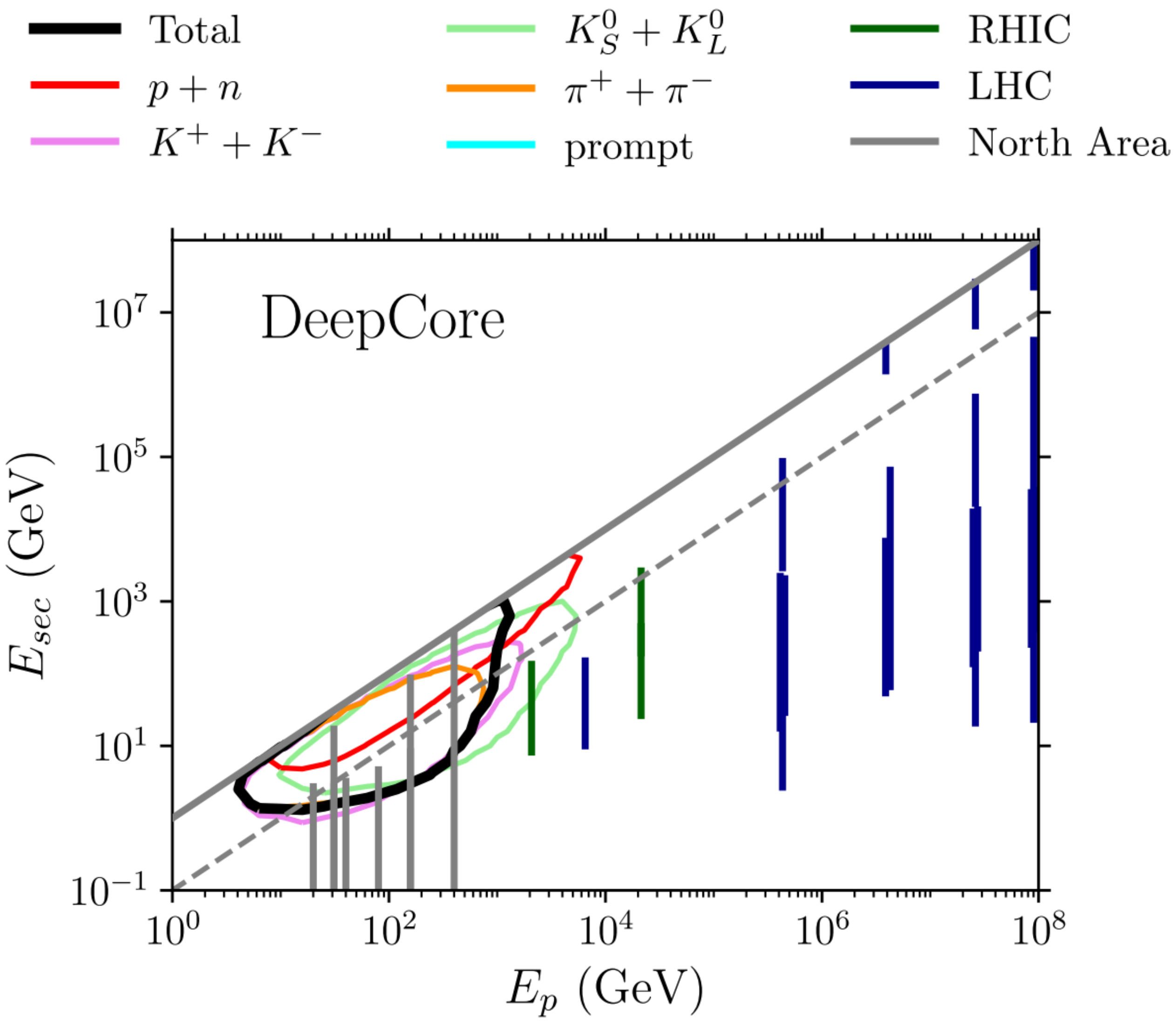
W. Woodley, AF, M.-C. Piro, ICRC 2021

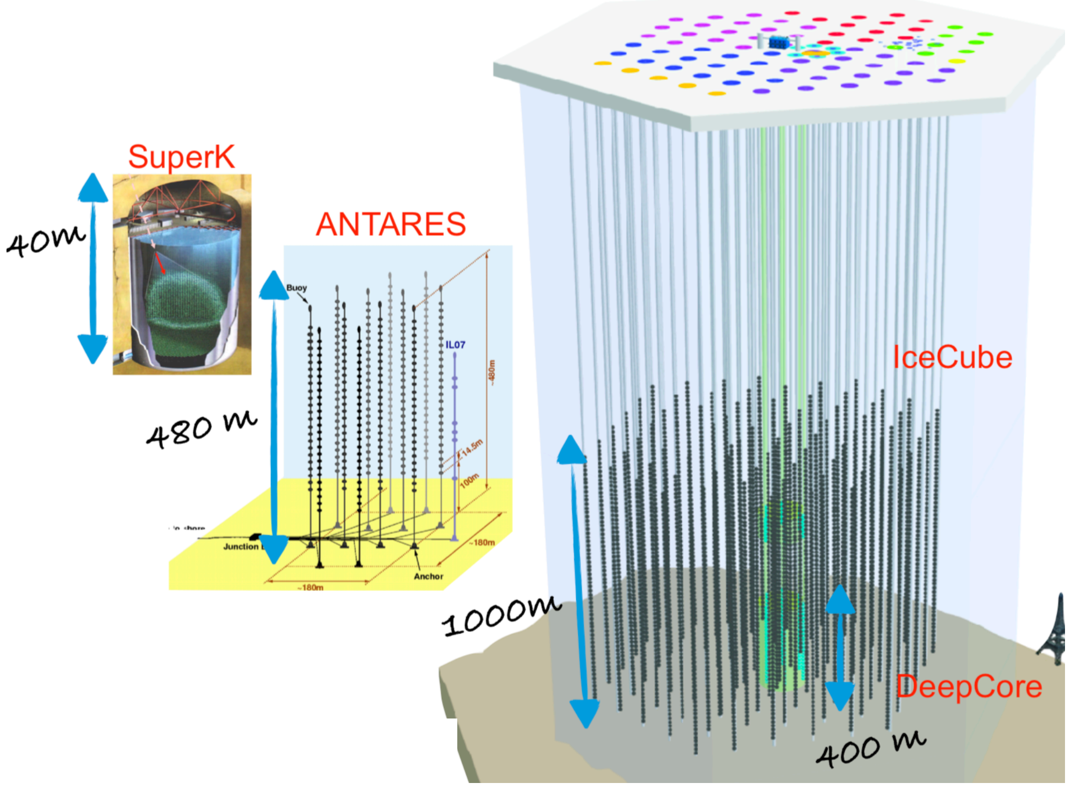




Probe interactions at multi-TeV energies (lab)

GeV-neutrinos, an energy range covered by accelerator data

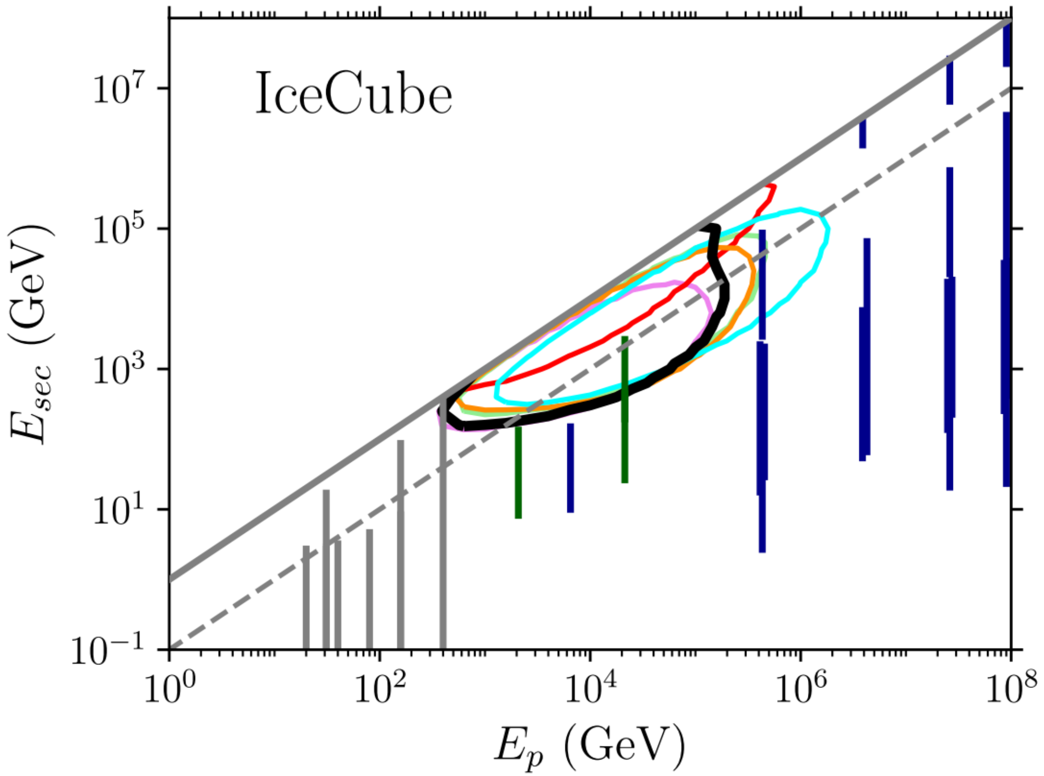




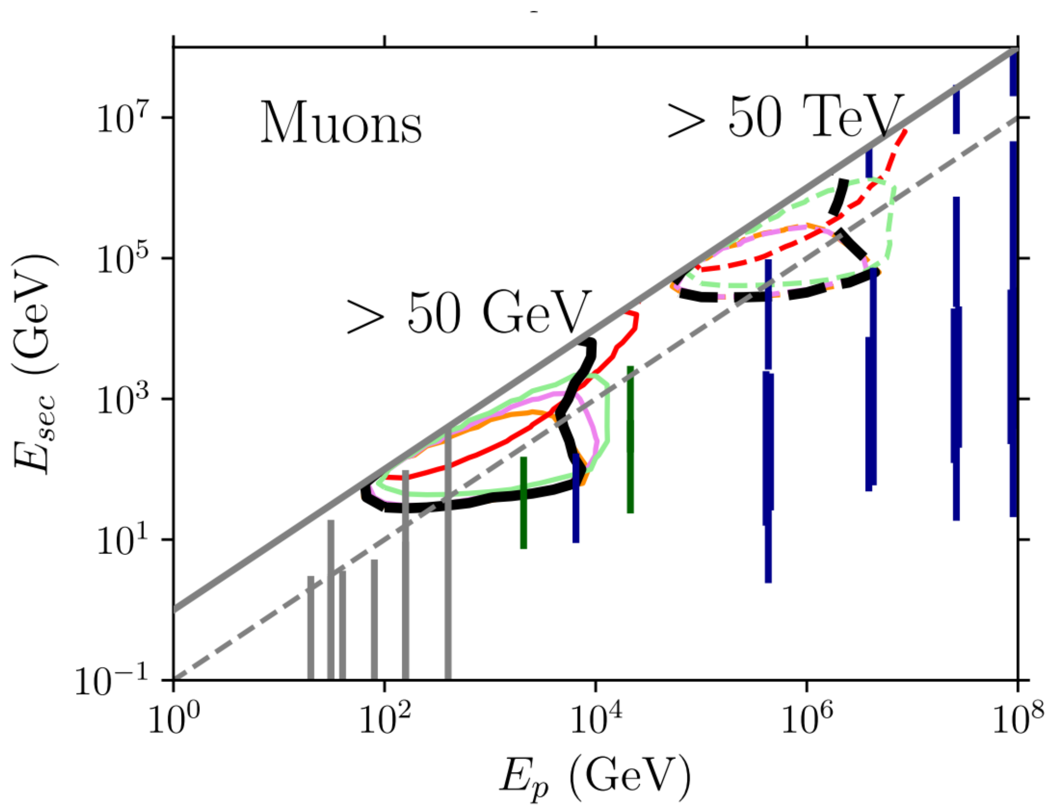
AF & M. Huber, ICRC 2021 & in prep.

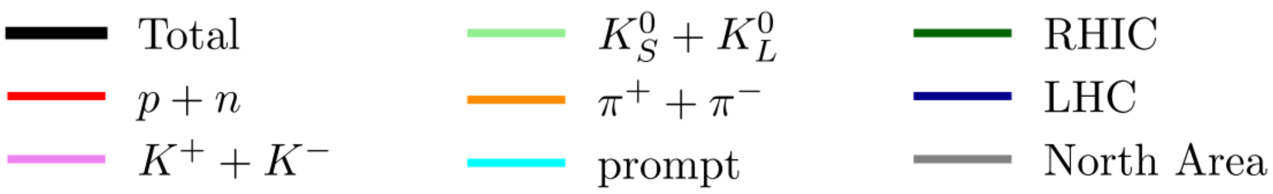
Chances to probe the "blind spot" of colliders

High-energy atmospheric neutrinos



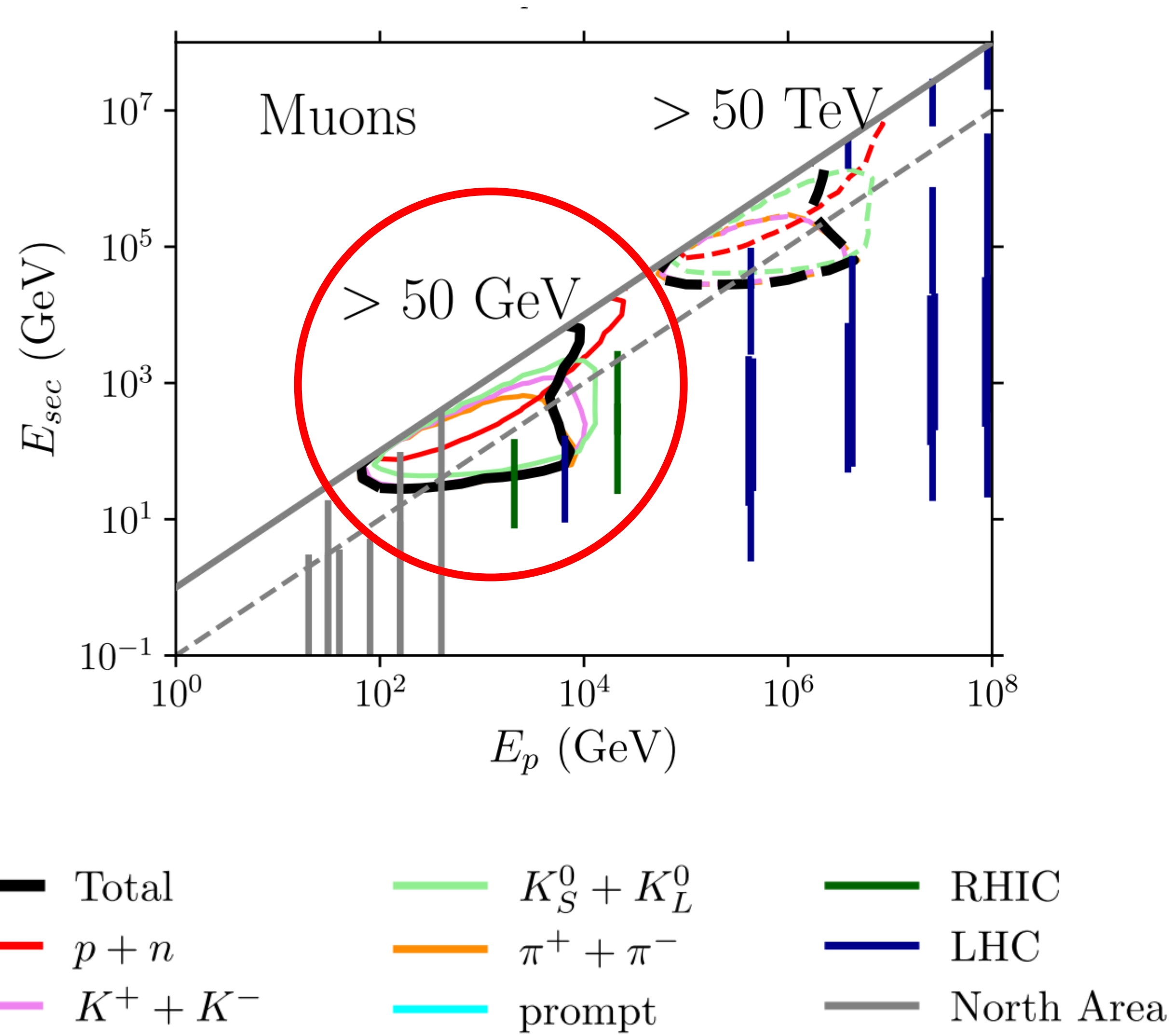
High-energy atmospheric underground muons



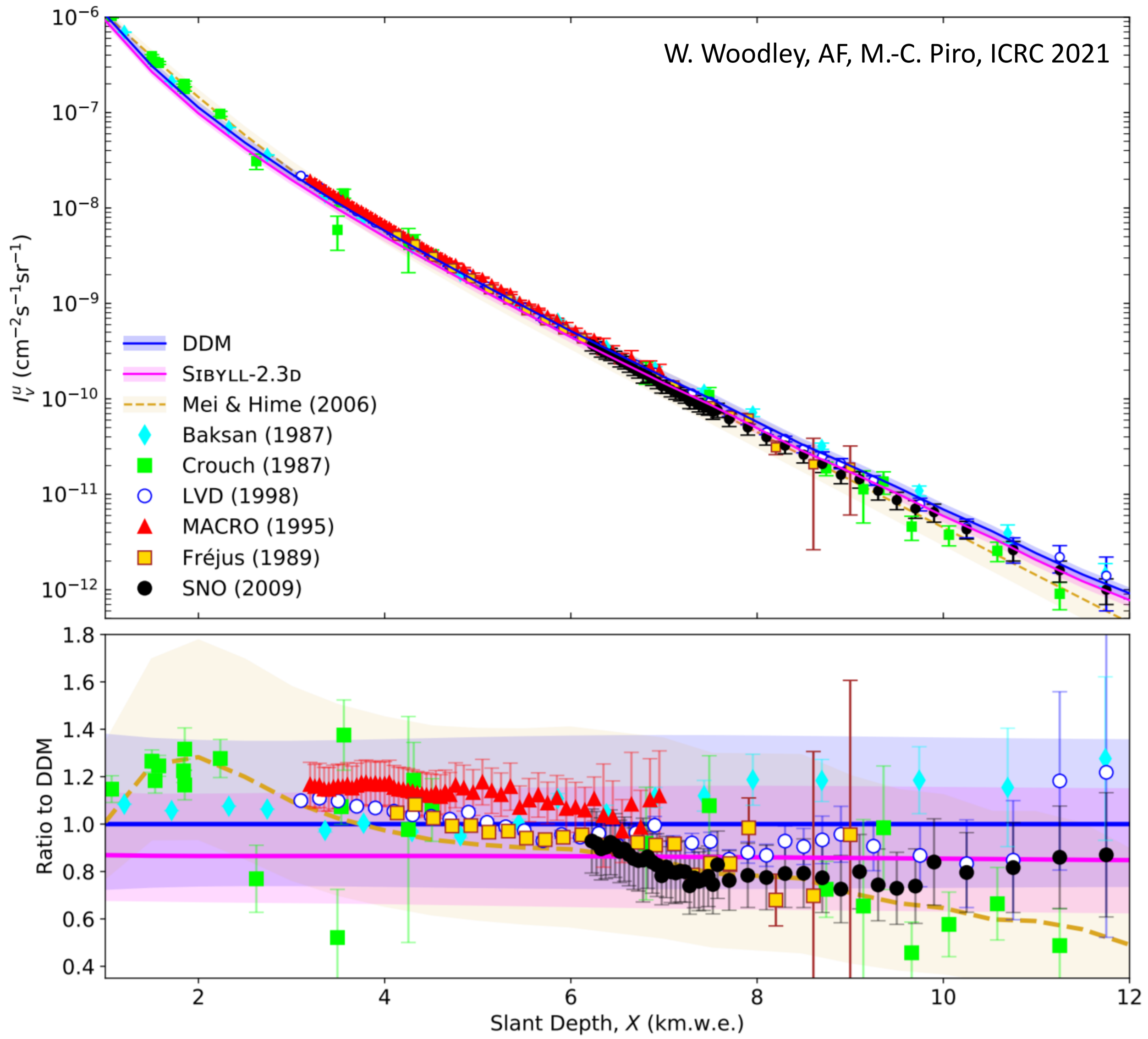


AF & M. Huber, ICRC 2021 & in prep.

The disagreement can be studied within the “comfort zone”



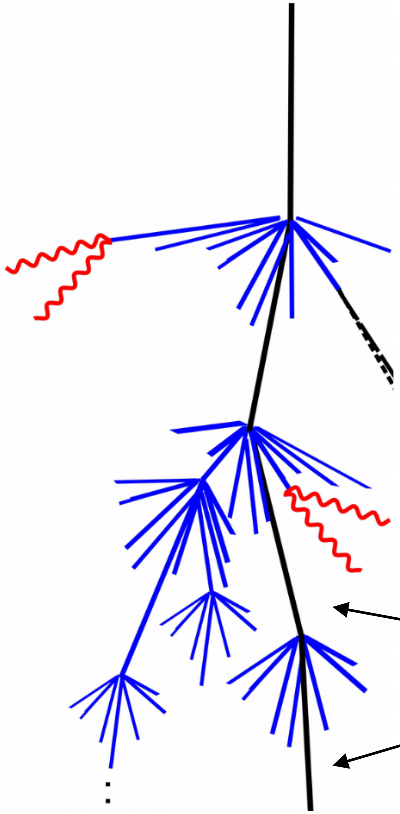
Accurate calculation of deep-underground muons



- Calculation uses MCEq and PROPOSAL ← a TUDO product!
- Calculation is fast → possible to be used in a fit
- Constrains neutrino fluxes at energies relevant for:
    1. Neutrino cross section measurement
    2. Sterile neutrino searches
    3. Astrophysical flux characterization

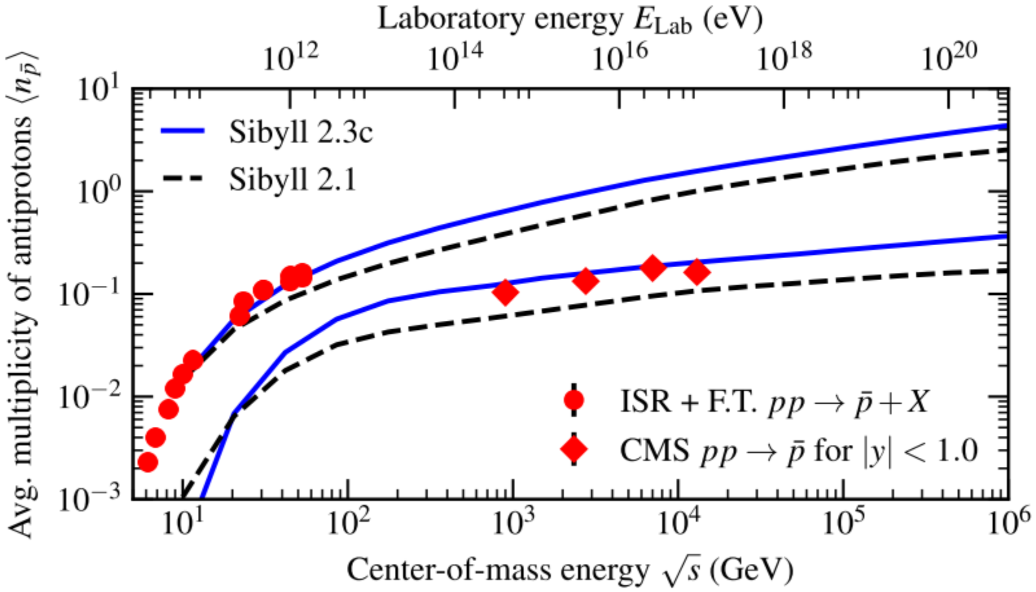
More low-energy muons through anti-baryons production

F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300



Baryon number conservation results in cascade regeneration:

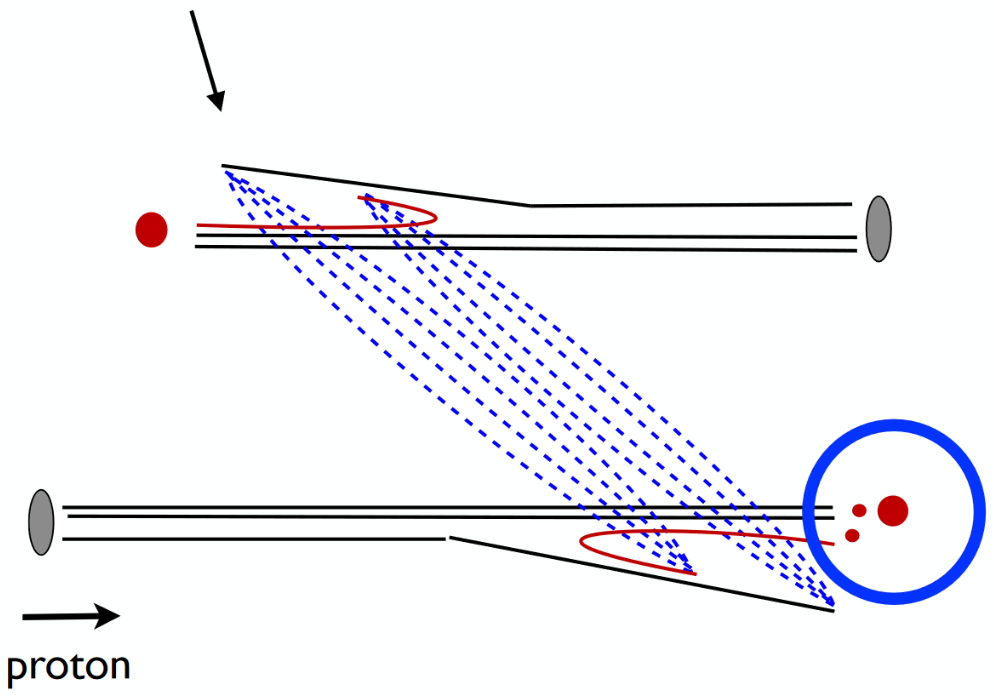
- Each interaction yields at least one baryon
- These baryons re-interact, producing more pions
- Production was off in older models



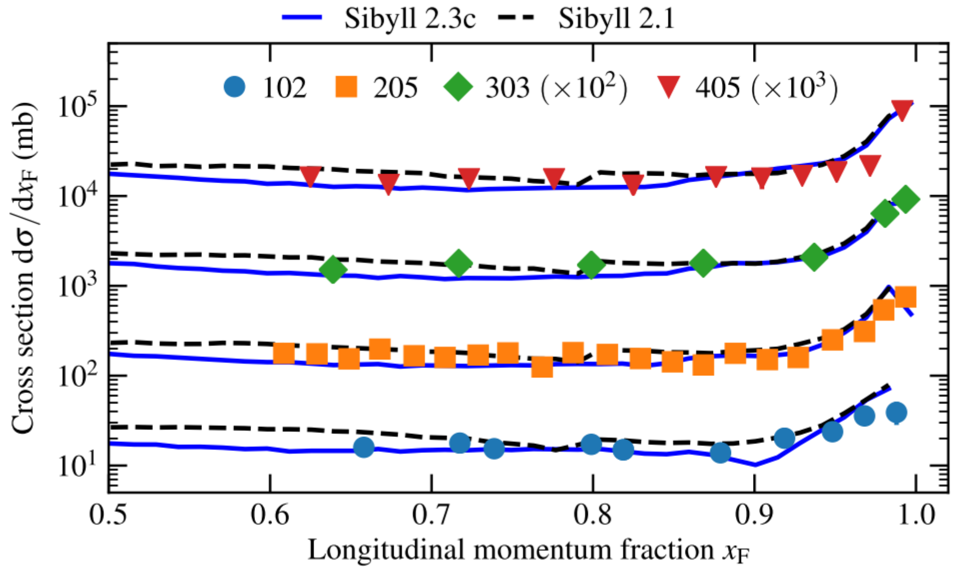
F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev, PRD102, 2020

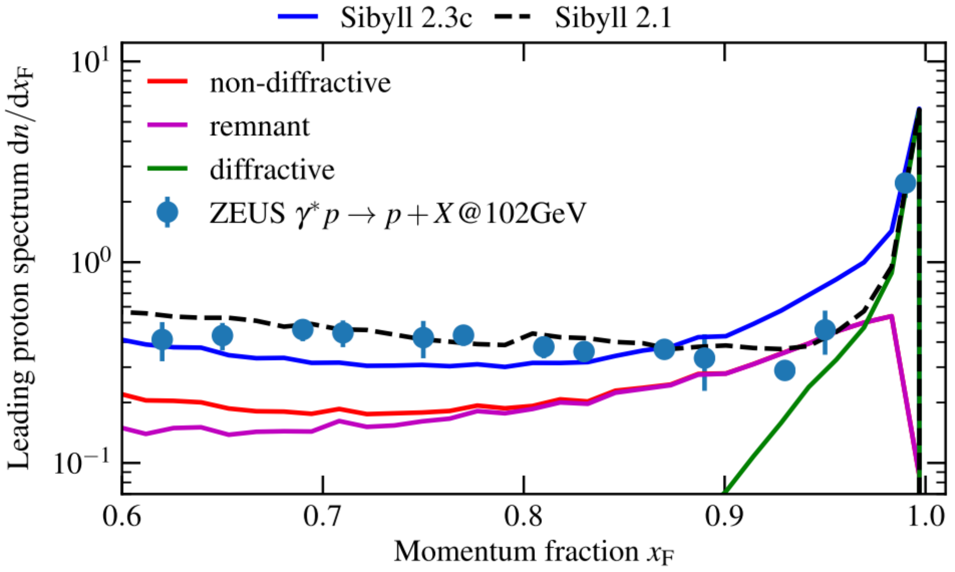
Leading particles

Model-dependent distributions of momentum given to partons

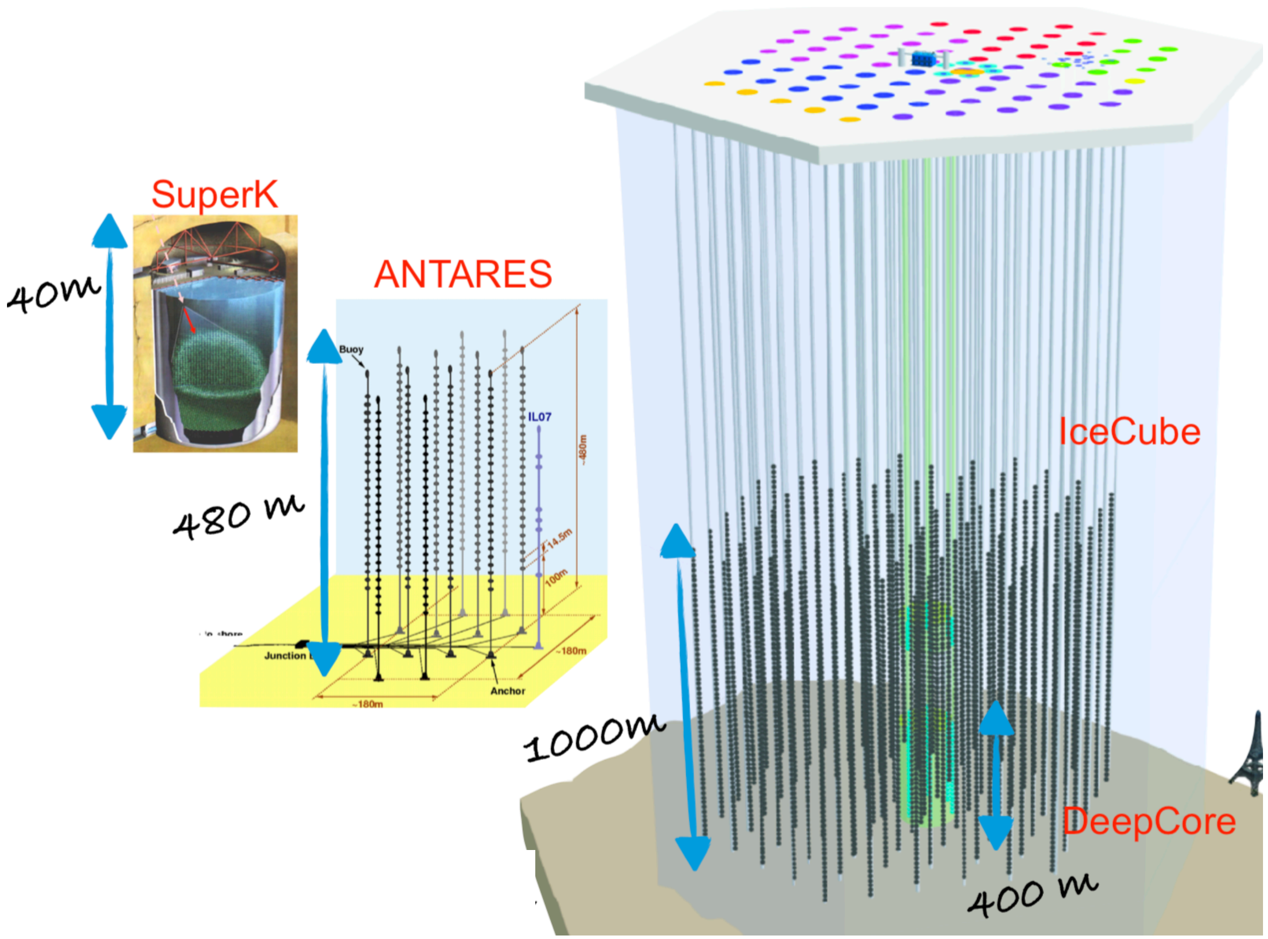


Fluctuations: Generation of sea quark anti-quark pair and leading/excited hadron

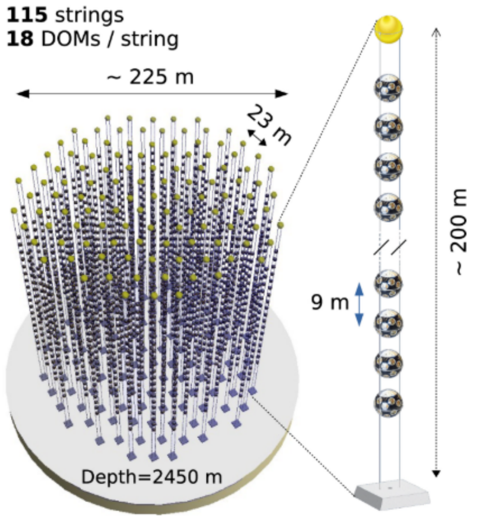


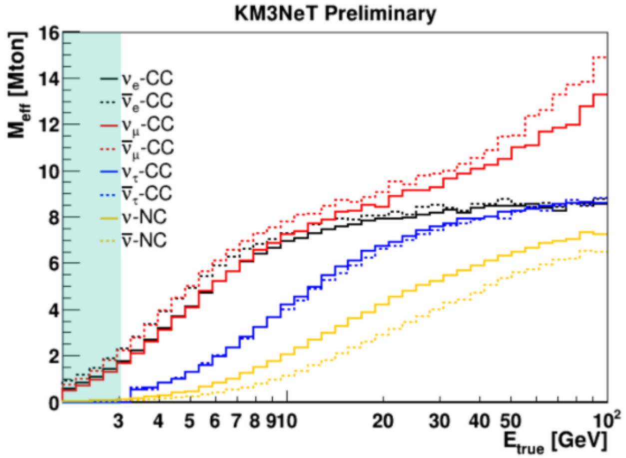


Difference to the late-90's: modern atmospheric neutrino detectors

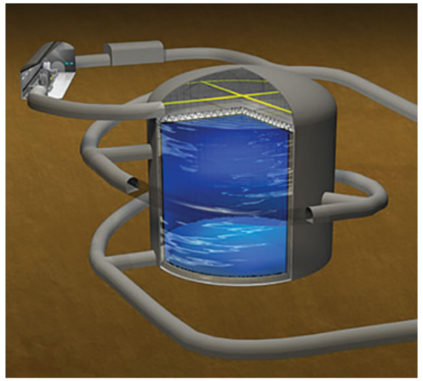


KM3NeT/ORCA

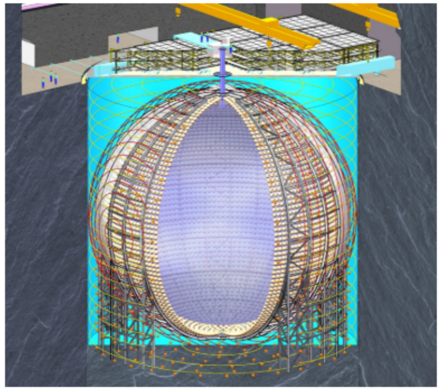




Hyper-Kamiokande



JUNO



Muon fluxes in the atmosphere

Equations for fluxes of particles of type *h* in the atmosphere:

Depth along CR trajectory *l:*

$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell \; \rho_{\mathrm{air}}(\ell)$$

$$\frac{\mathrm{d}\Phi_h(E, X)}{\mathrm{d}X} =$$

- absorption by **interactions**

- absorption by **decays**

} Depend on density or *X*

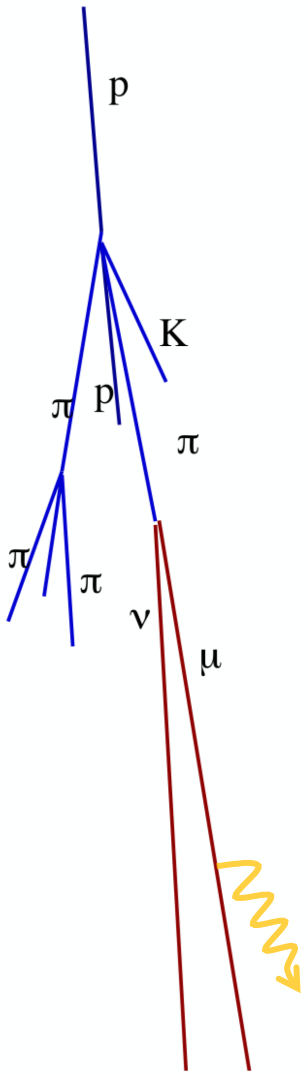
- ionization and radiation **losses**

+ particle production in **hadronic interactions** ← !

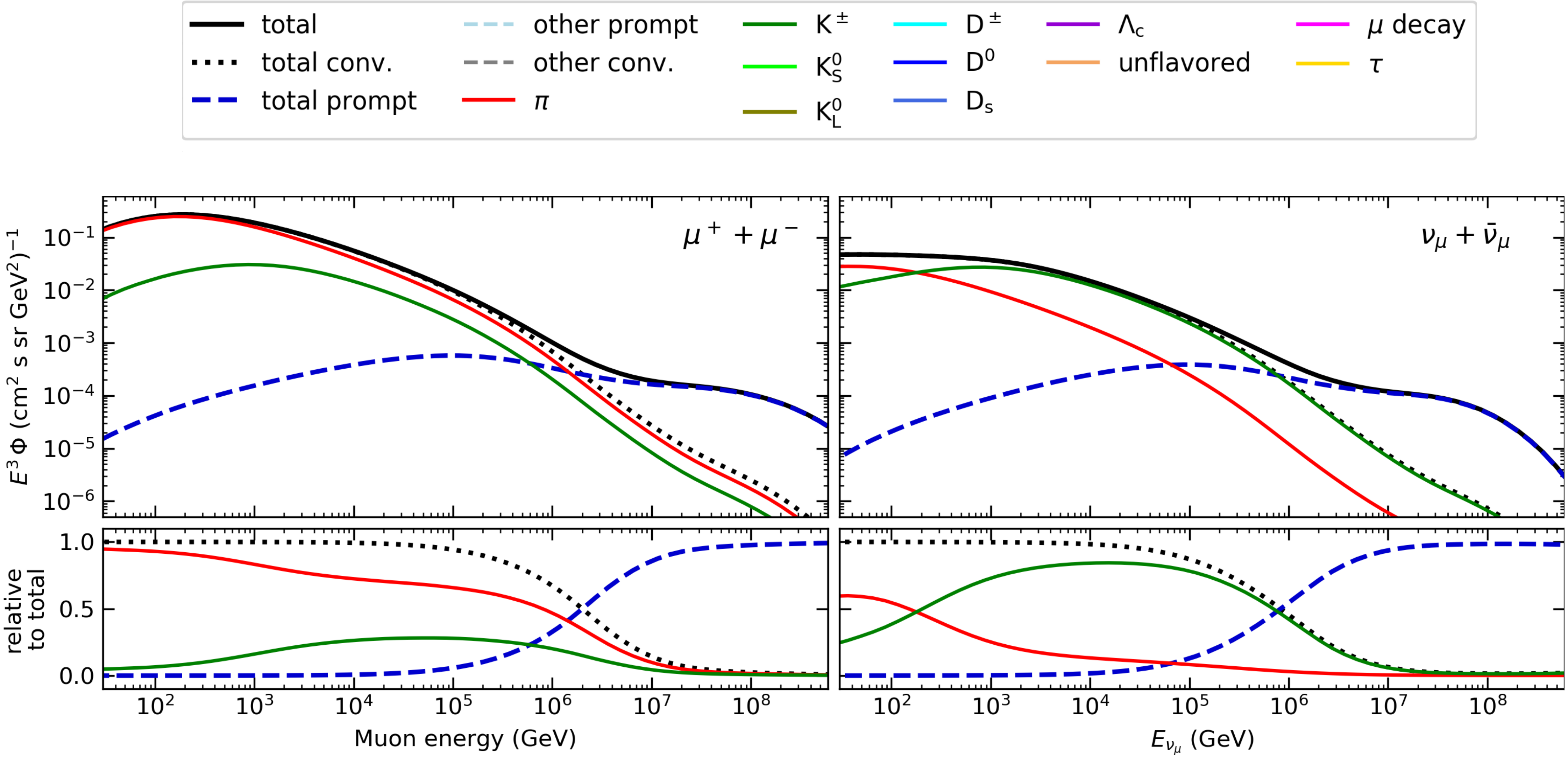
+ particle production through decays

Coupling between particle types {

Initial condition is the flux of cosmic ray nucleons at *X=0*.

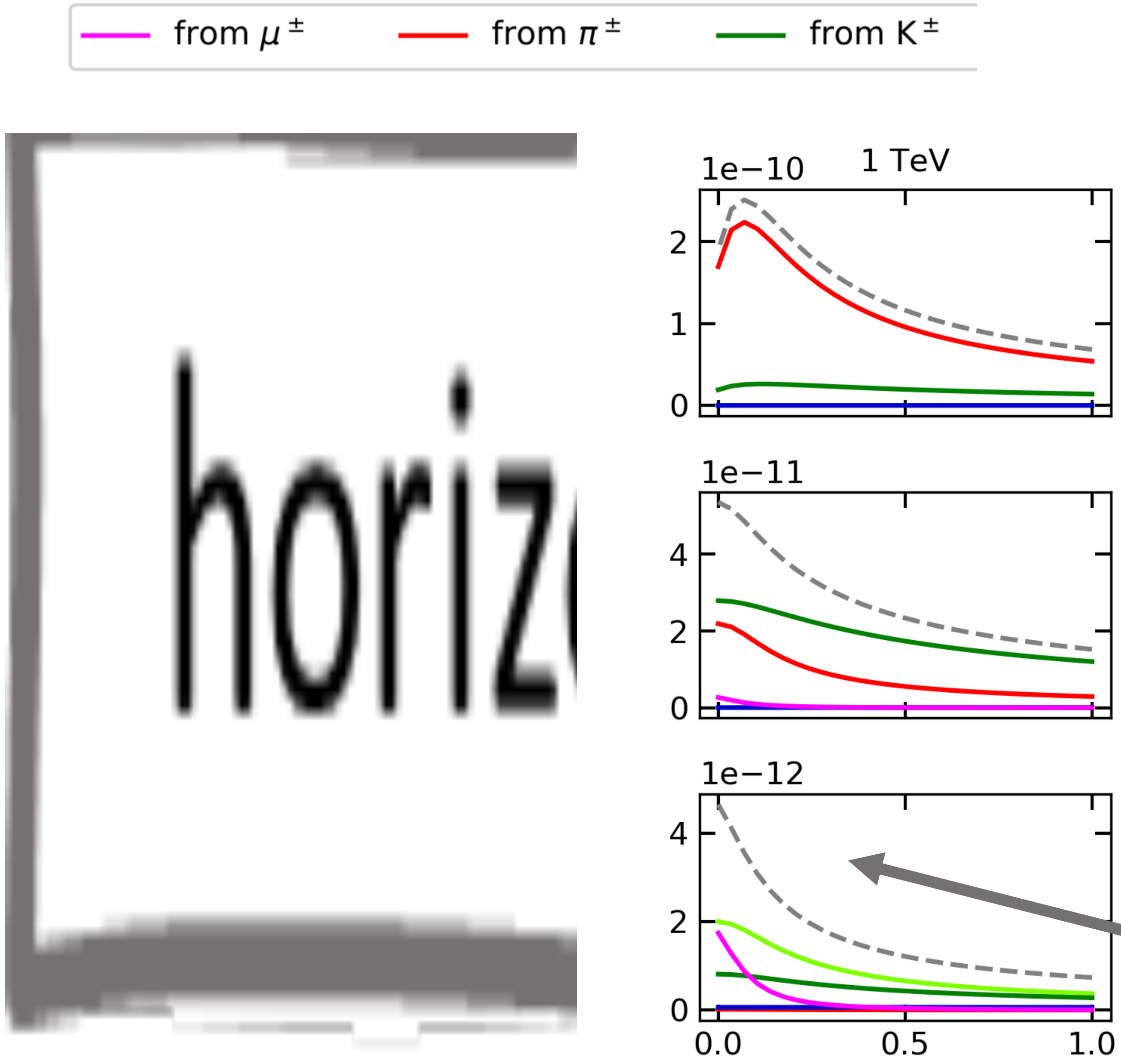


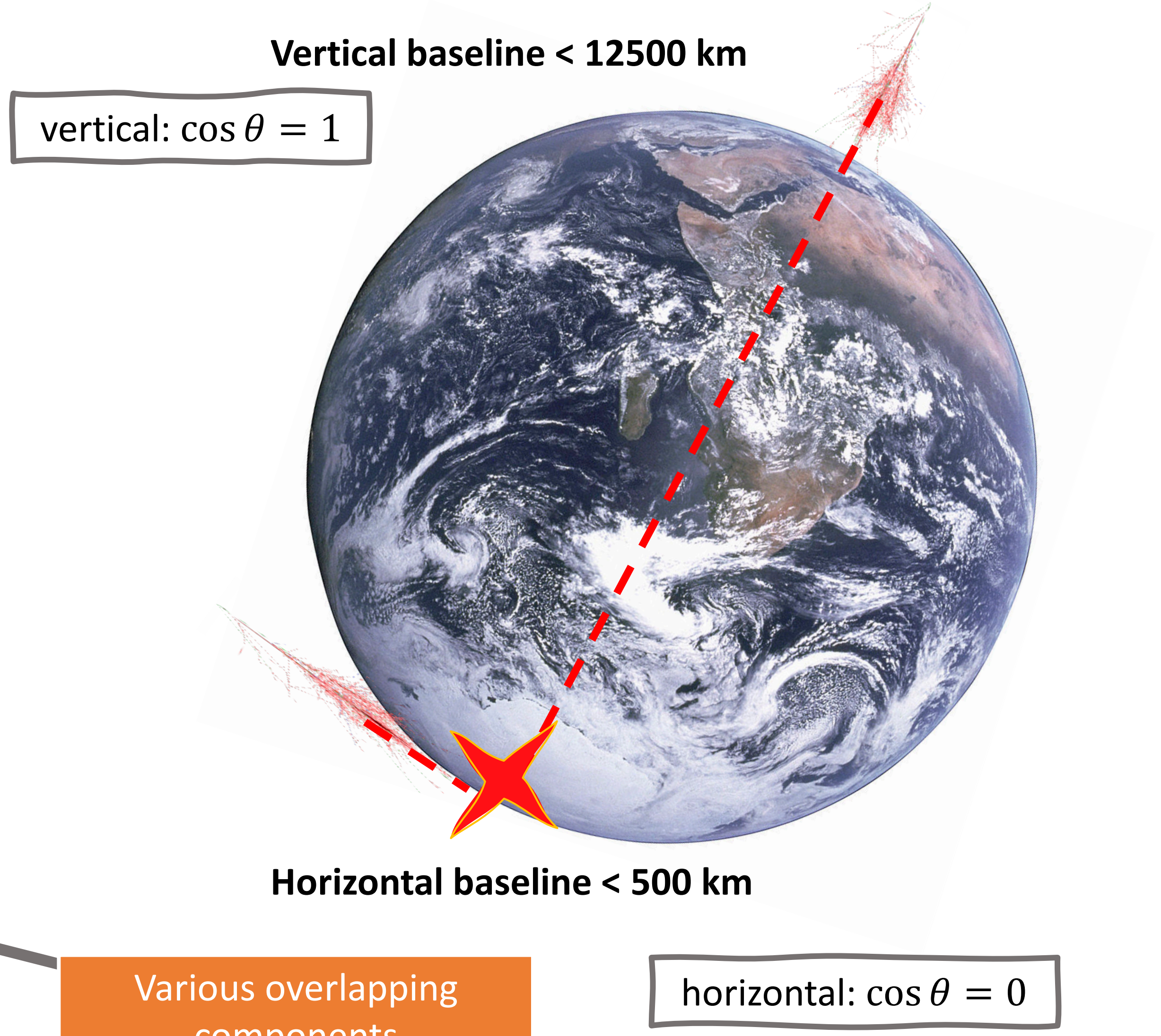
The reality is a bit more complicated



AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

The zenith angle is an additional handle on hadronic components



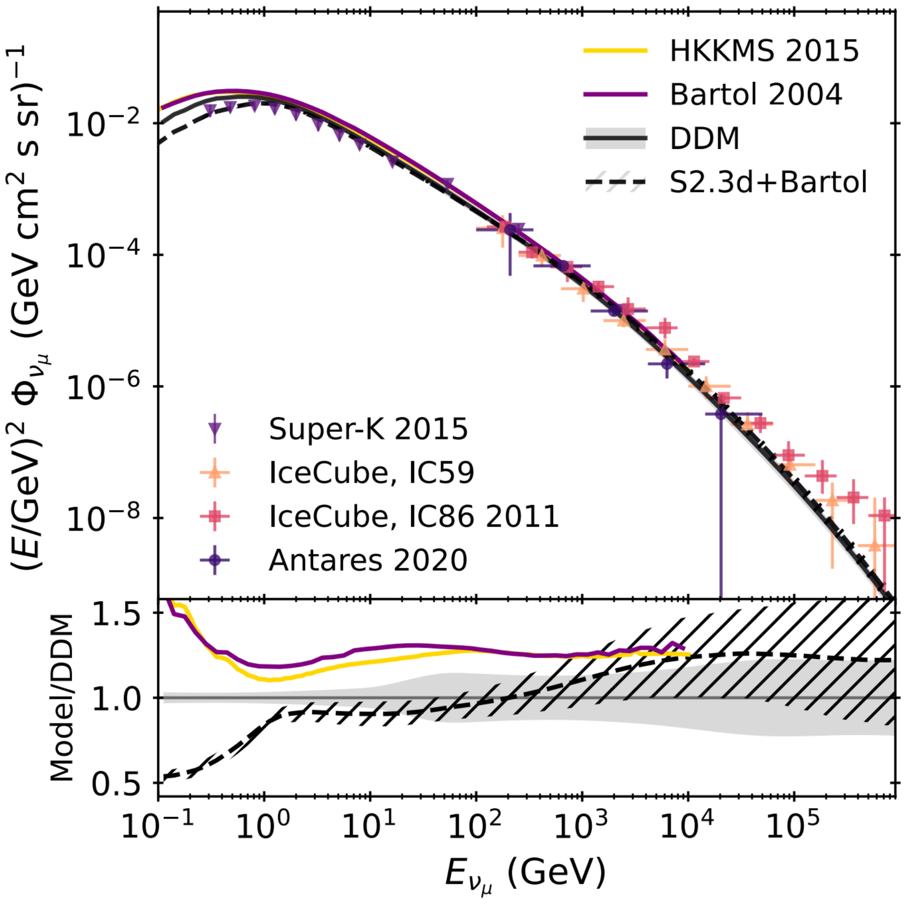


Various overlapping components

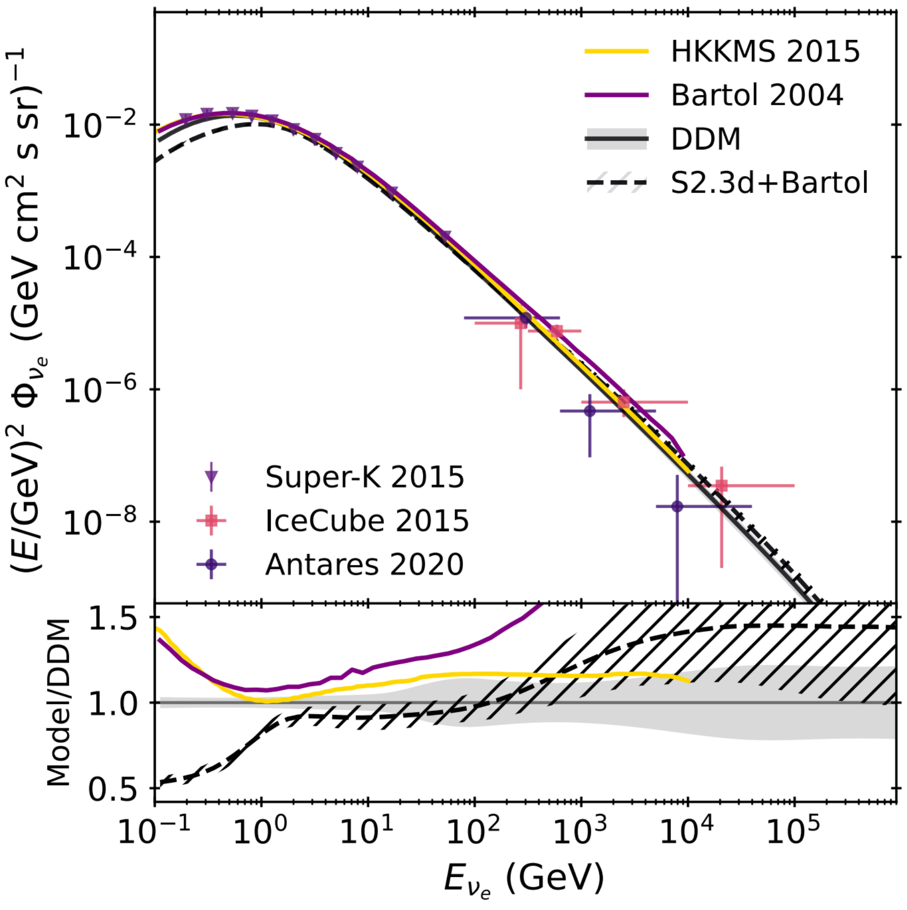
AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

DDM: conventional neutrino fluxes

Muon neutrinos+antineutrinos

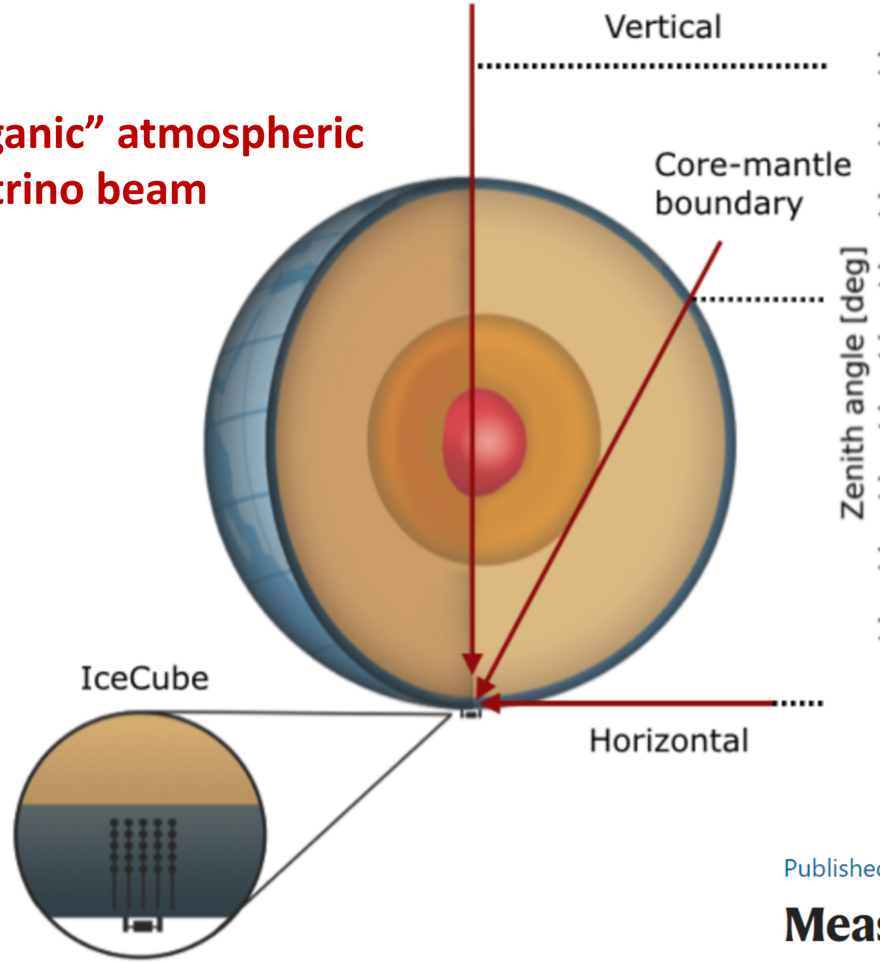


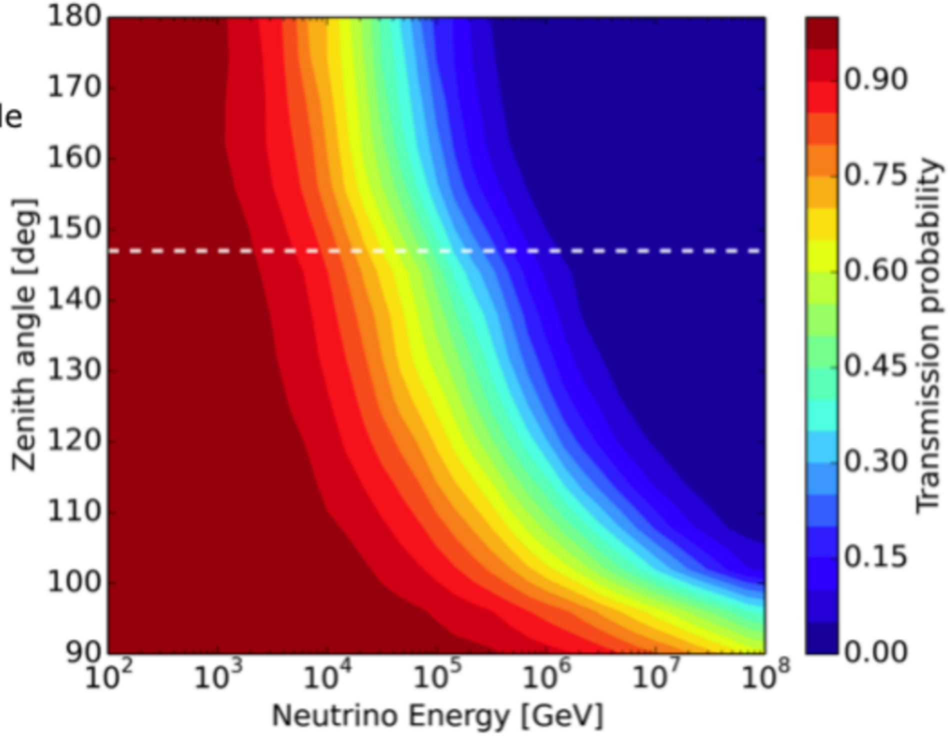
Electron neutrinos+antineutrinos



Example: why uncertainties matter?

"Organic" atmospheric neutrino beam





Published: 22 November 2017

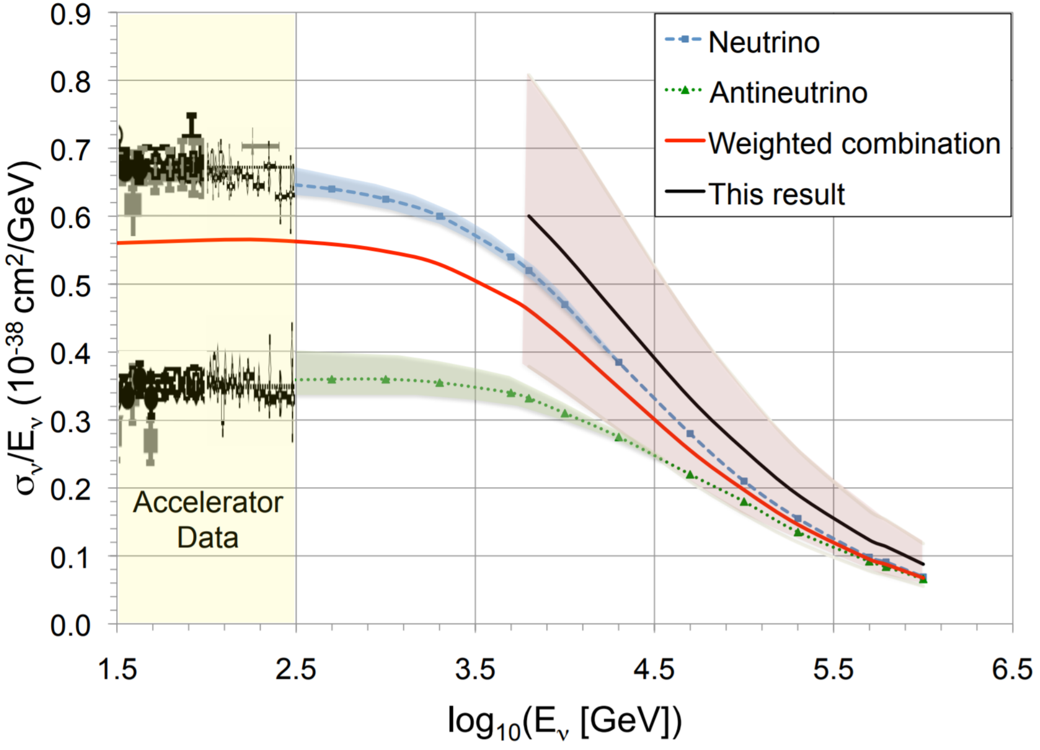
Measurement of the multi-TeV neutrino interaction cross-section with IceCube using Earth absorption

The IceCube Collaboration

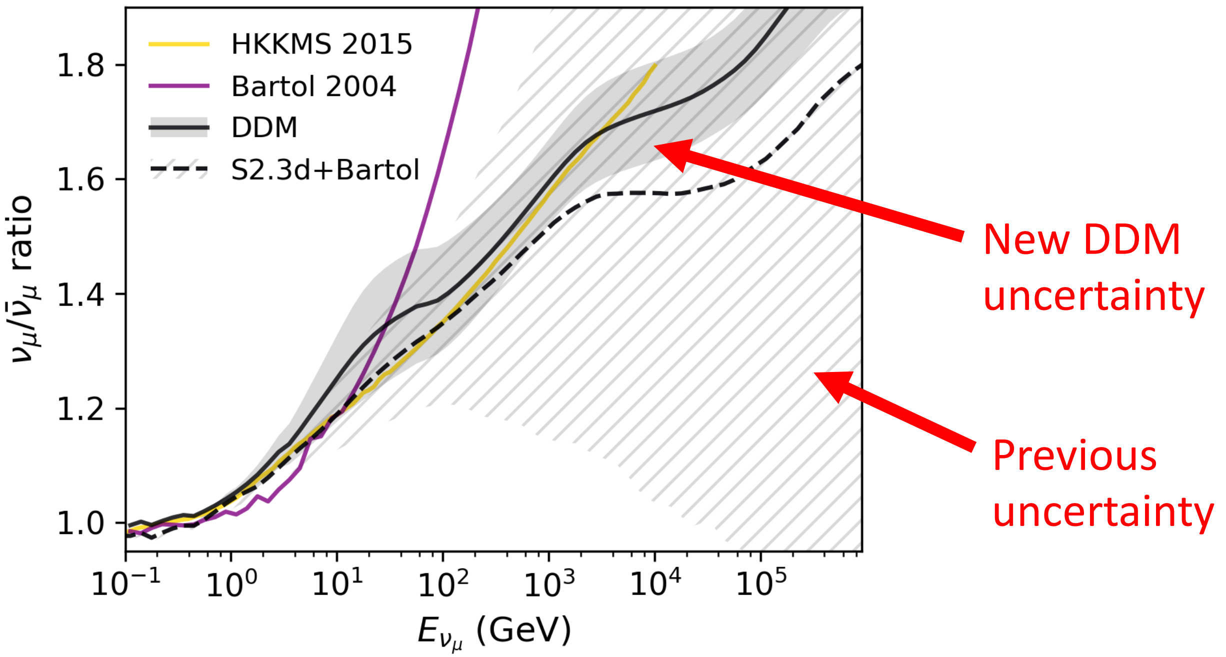
Nature **551**, 596–600 (2017) | Cite this article

The uncertainties of the cross section measurement

IceCube, Nature, 551, 2017

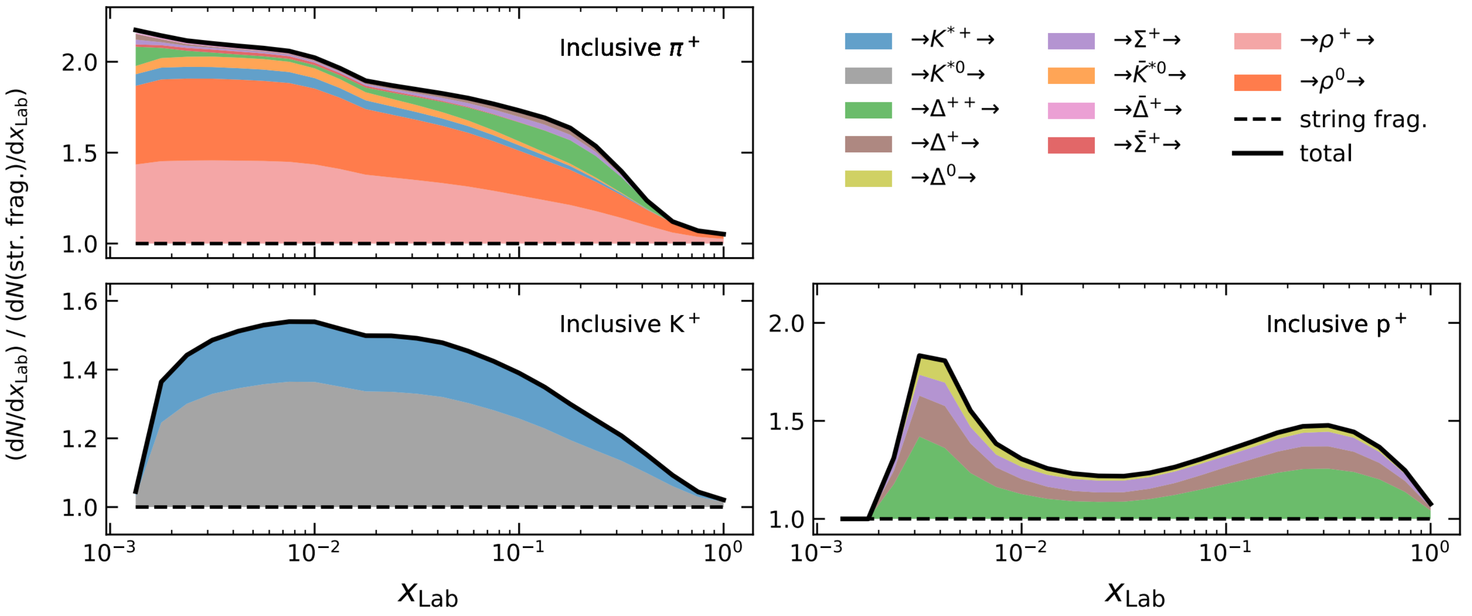


- IceCube can't separately measure neutrino and anti-neutrino
- Observed cross section is an average, weighted by the atmospheric ratio
- The result is 30% higher than the standard model prediction, but compatible within uncertainties



Why is it so difficult to just make better models

Feed-down from higher-mass states

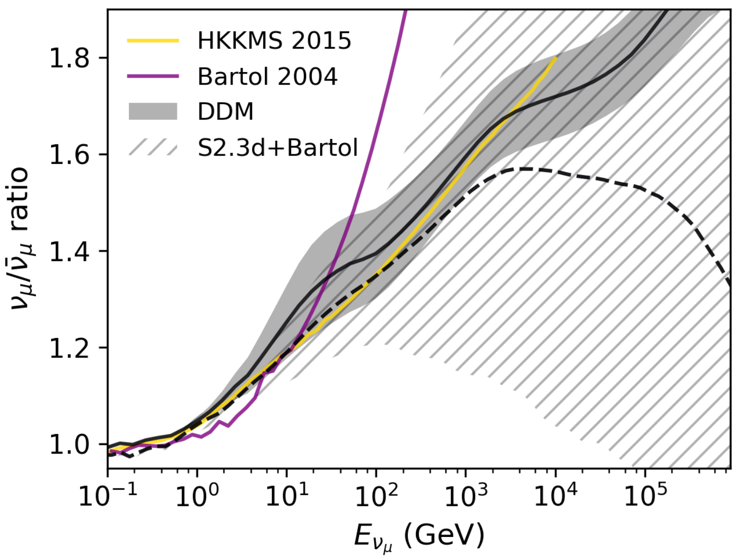


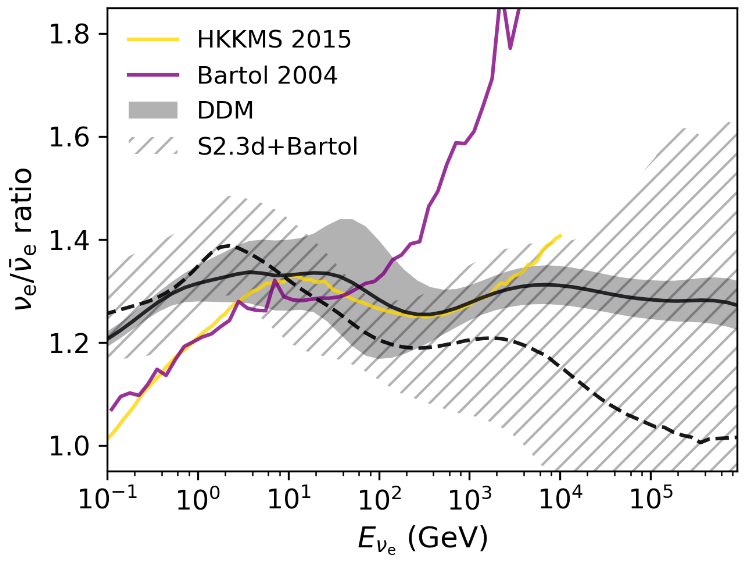
AF et al. PRD 100 (2019)

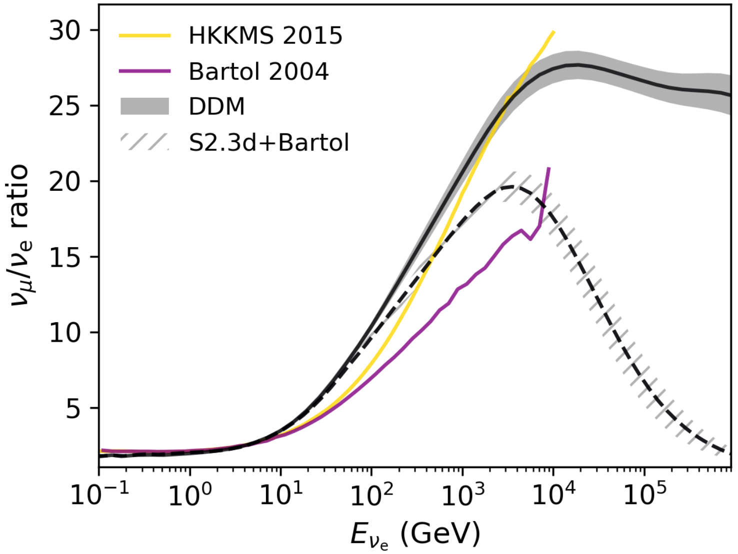
- We tried (see Fedynitch et al. PRD 100 (2019) and Riehn et al. PRD102 (2020))
- A major problem is the definition of what “pions” or “kaons” are, since a large fraction originates from feed-down of higher mass states
- For cascades in the atmosphere, the definition coincides with that of NA49/61 that only correct for longer lived strange particles like Λ
- Older data from accelerators may not be useful, since it is not corrected for feed-down (see e.g. epic papers by S. Wenig and H.G. Fischer from NA49)
- For most interaction models the inclusive (pion) yields are a superposition of ρ, Δ etc., which are explicitly produced in the model’s fragmentation routines
- There are no “easy to tune” free parameters

DDM+ GSF vs data: neutrino ratios

Neutrino-antineutrino ratios





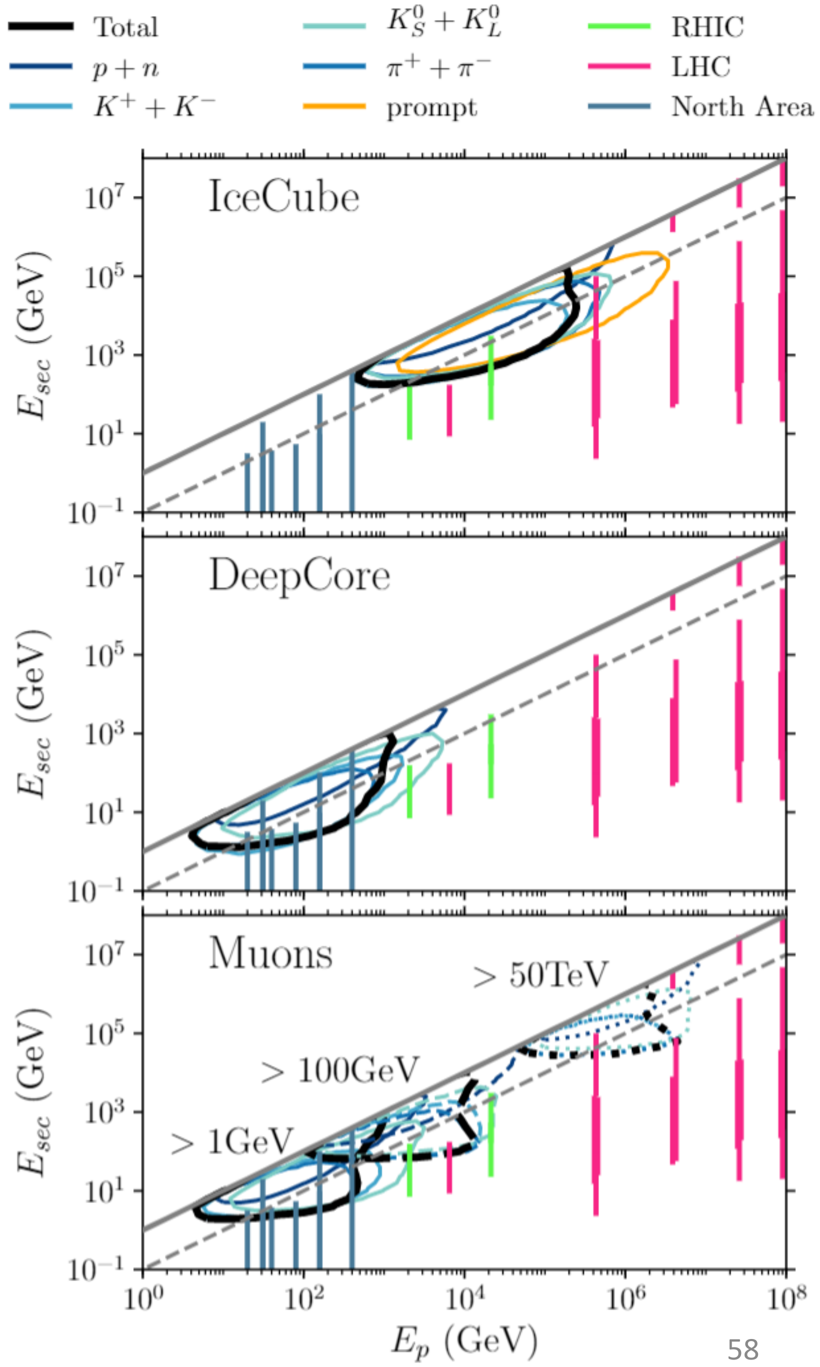


Flavor ratio

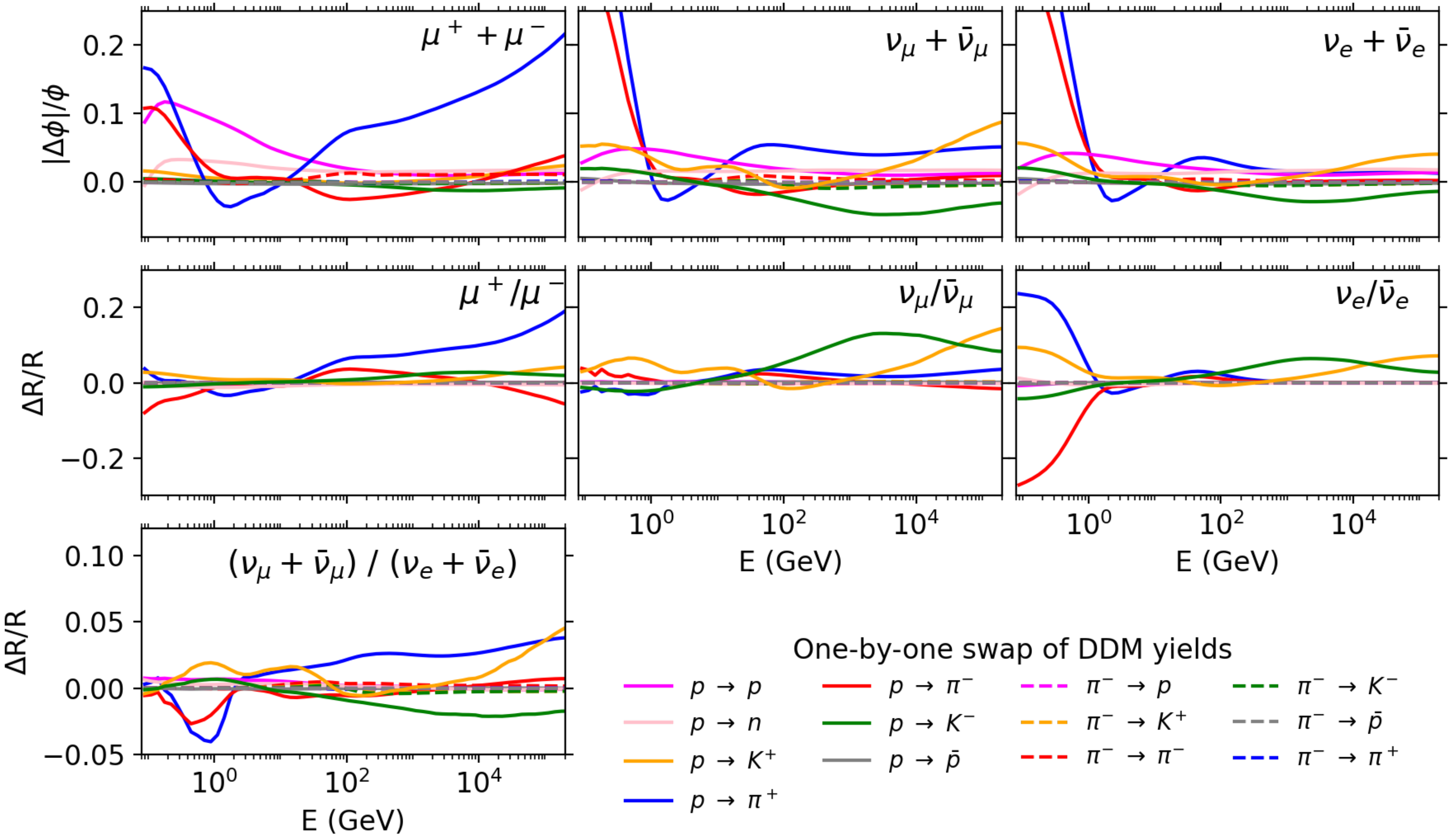
- Neutrino antineutrino ratio compatible over a wide energy range with HKKMS within error
- At low energy notable improvement compared to Bartol errors due to NA61 31 GeV dataset
- Error on ratios at 100 MeV — GeV may be slightly underestimated due to extrapolation in DDM below 31 GeV
- Flavor ratio above 20 GeV significantly different due to less kaons in DDM wrt HKKMS or Bartol 2004

Atm. leptons <-> accelerators

- Contours show phase-space probed by atmospheric muon and neutrino experiments
- The lines show **taken** data (not necessarily analyzed) assuming pion secondaries
- Interactions within contours responsible for 90% of the event rate
- Atmν in IceCube probes hadronic interactions at $E < E_{LHC.}$
- DeepCore probes same phase-space as Super-/Hyper-K
- Muons: vertical, surface, flux integrated above threshold



Impact of individual DDM channels



- Exchanging only one channel of a DPMJET prediction
- Largest impact from π^+ and K^- as expected from sub-panels on Sl. 10
- Only small differences for most ither channels: DPMJET (also, SIBYLL and QGSJET) similar to DDM
- Large impact on low energy muons → hence also neutrinos from muon decay
- Baryon distributions can shift production depth that matters for unstable particles such as muons

Neutrinos from charm

Charm production in SIBYLL 2.3d

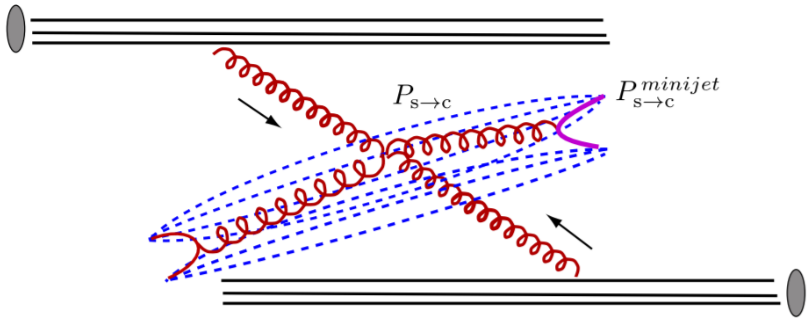
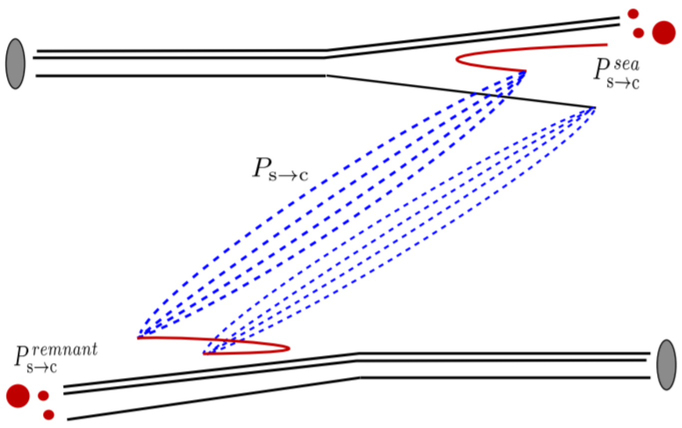
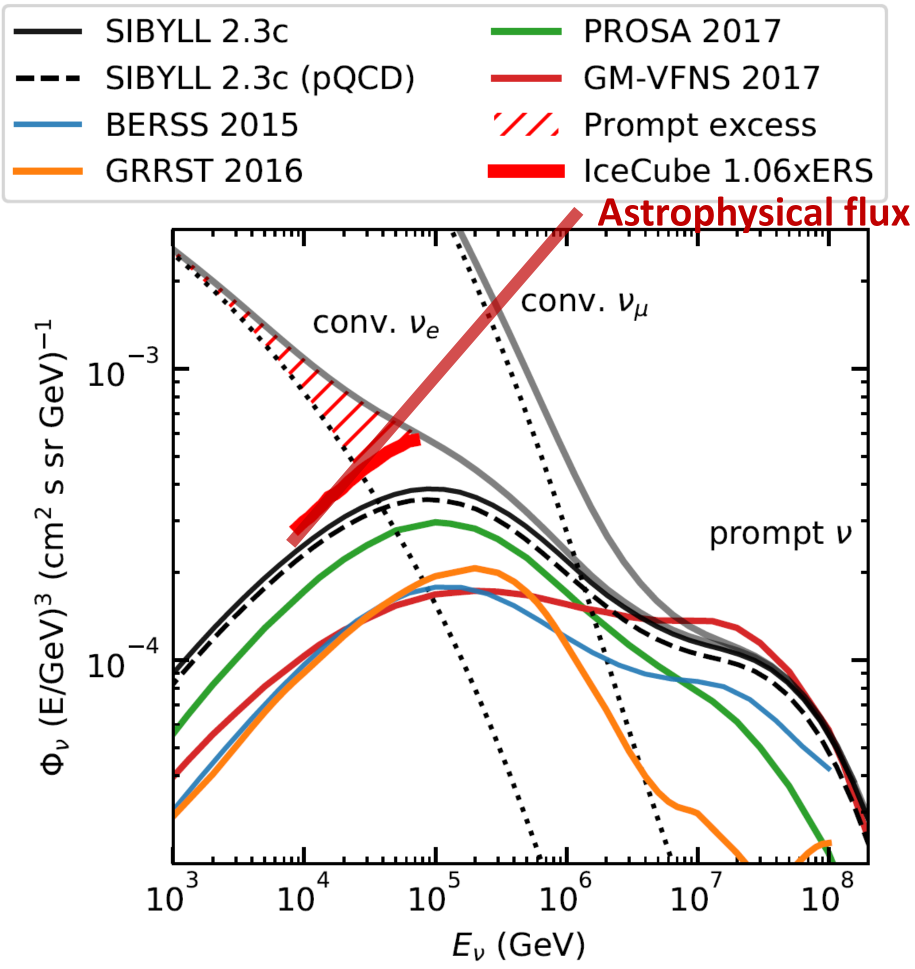


FIG. 5.7. String configuration for minijets in SIBYLL.

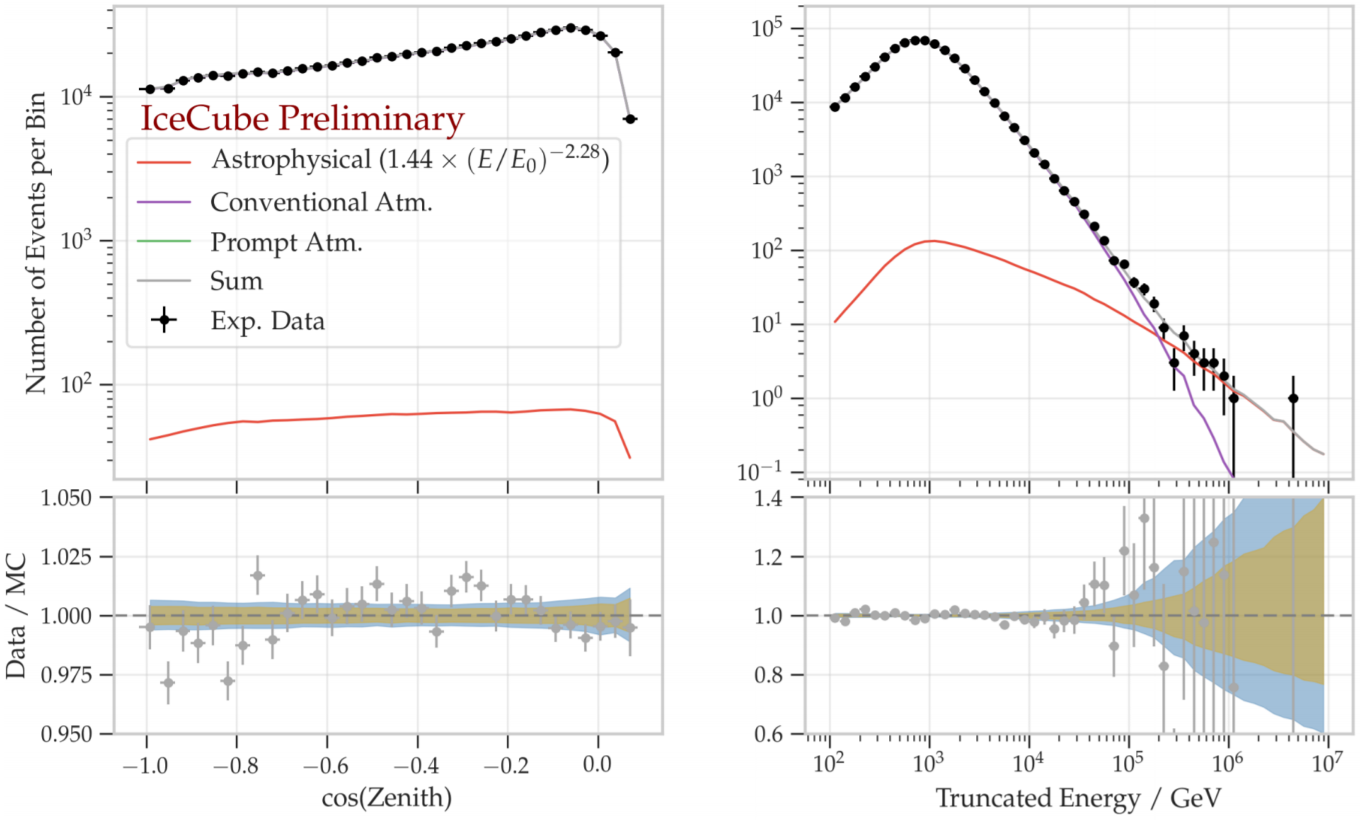




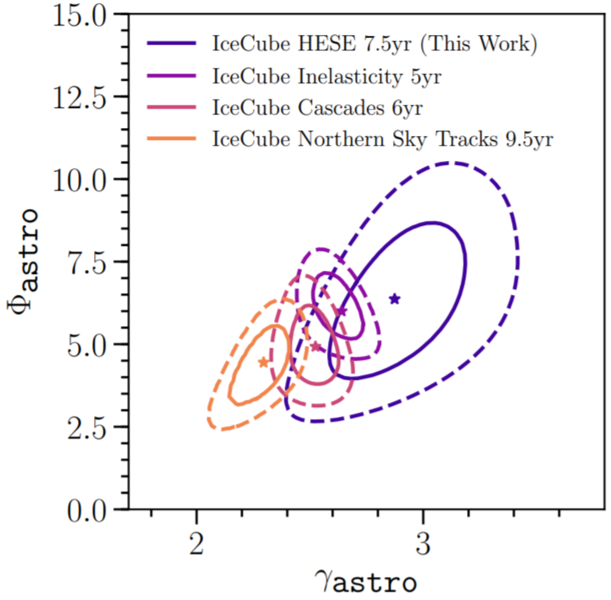
AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

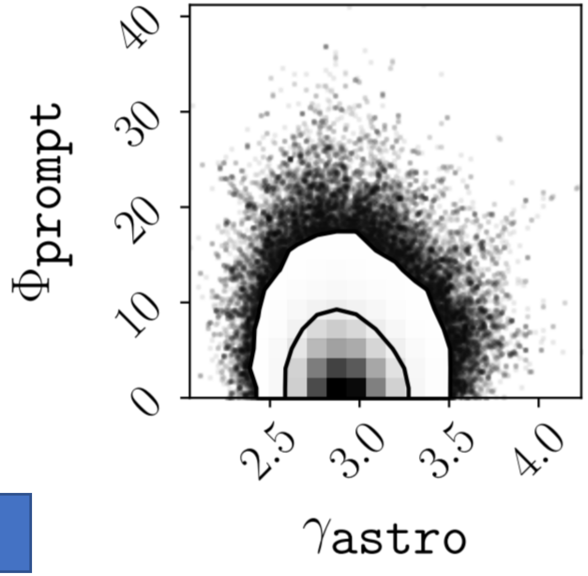
Challenge: where is the charm?

J. Stettner, IceCube Collaboration, ICRC 2019



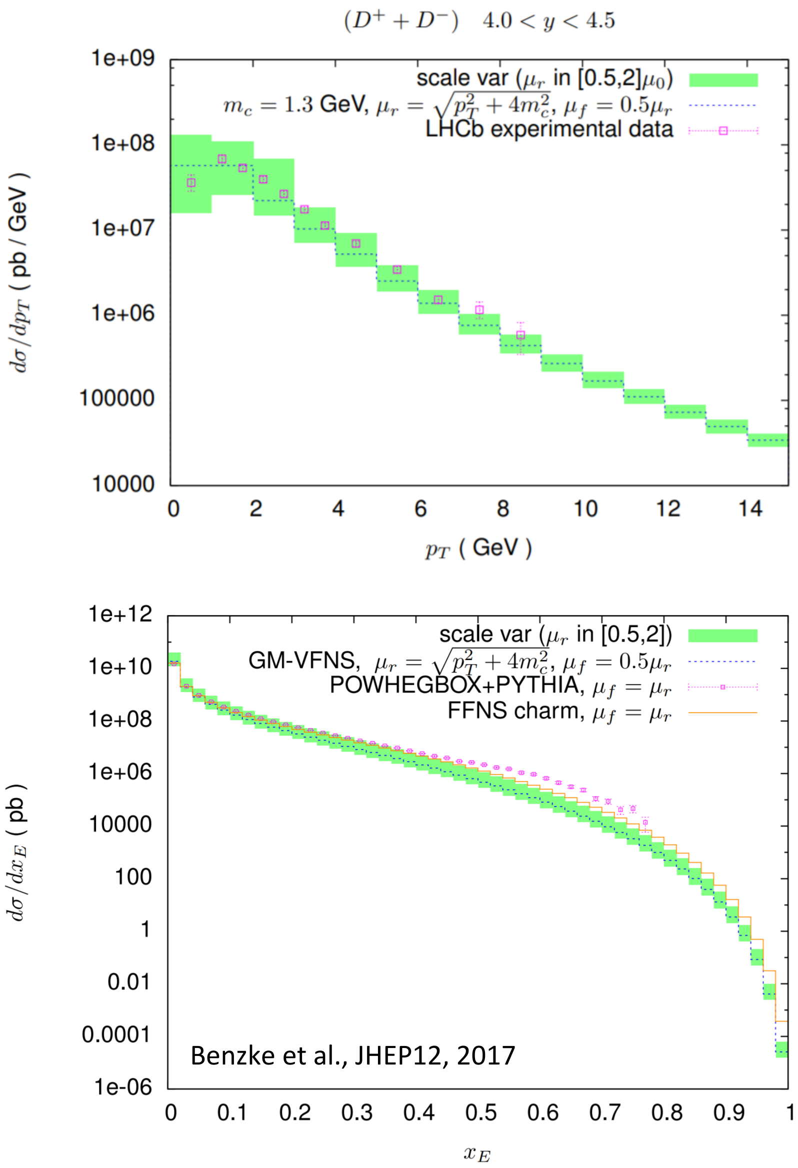
HESE 7.5 yr, IceCube, PRD 104, 2020



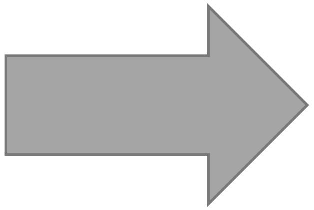


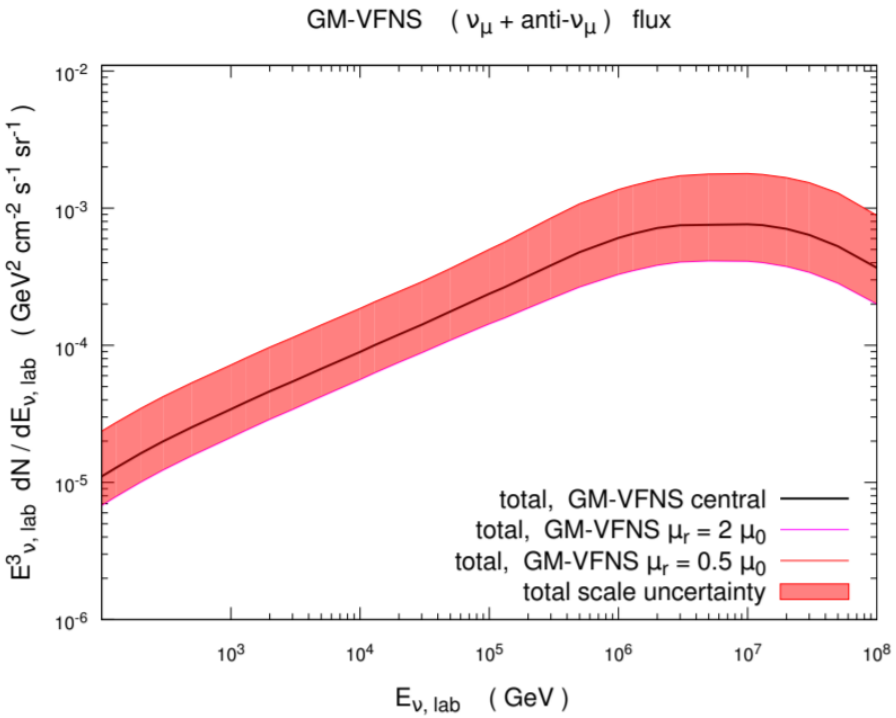
IceCube is not really sensitive to charm given the poor theoretical constraints.

Prompt neutrinos: theoretically challenging



Benzke et al., JHEP12, 2017





Intrinsic charm is back in the game

Stan Brodsky

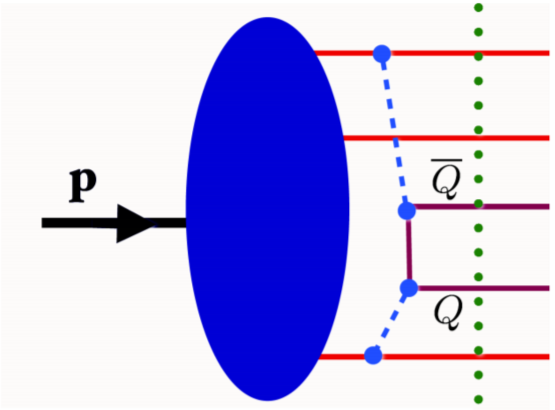
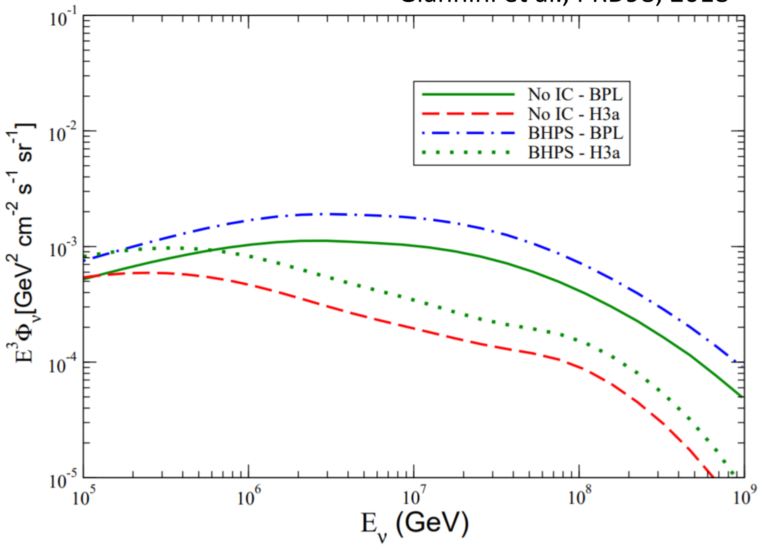


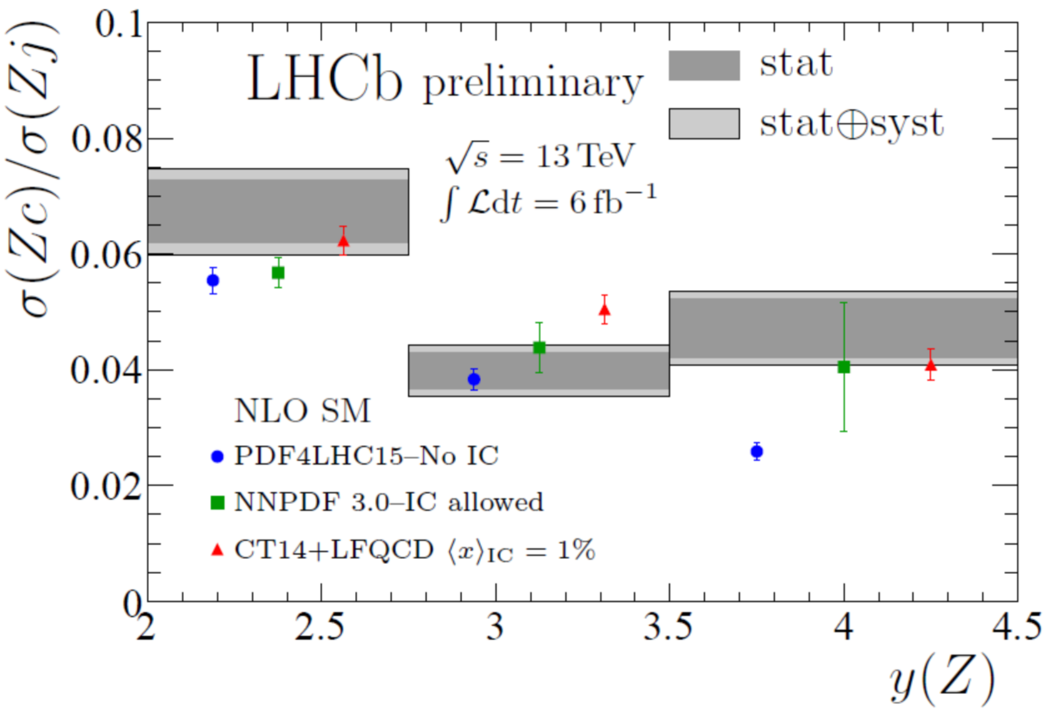
Figure 1: Five-quark Fock state $|uudQ\overline{Q}\rangle$ of the proton and the origin of the intrinsic sea.

Giannini et al., PRD98, 2018



(b)

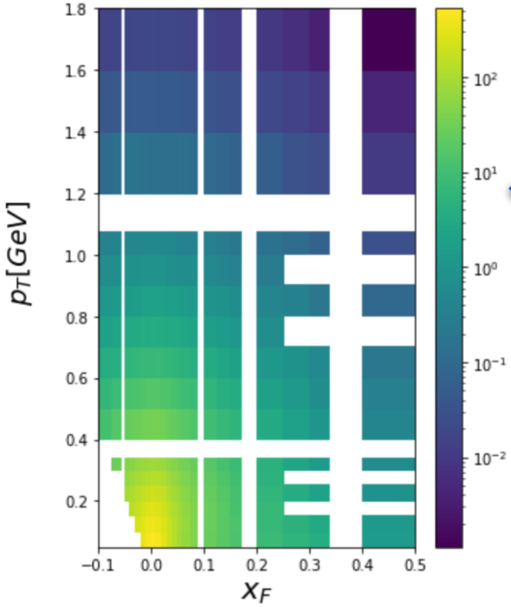
LHCb, EPS-HEP 2021



IC can have some impact for IceCube.

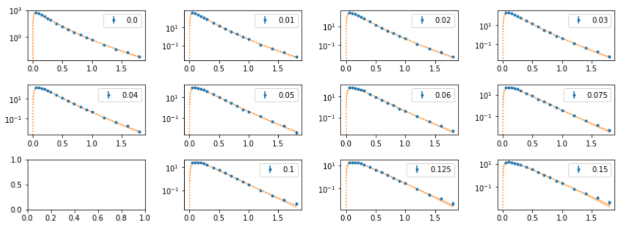
Building the DDM

NA49 proton-carbon @ 158 GeV

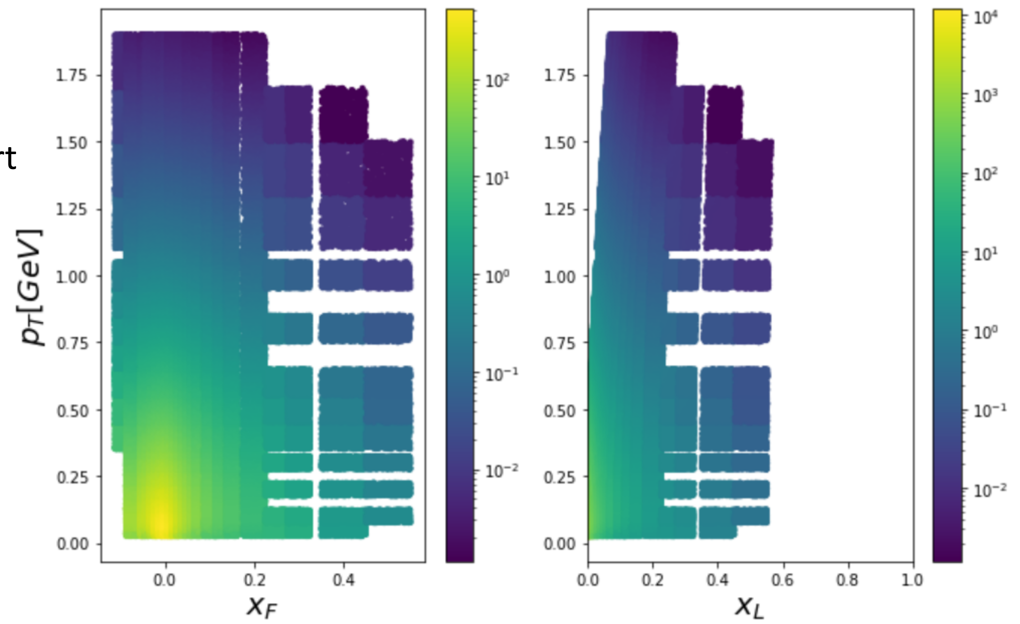


Sample from
x_F = pz/sqrt(s) and convert
into $x_L = E_{secondary}/E_{proj}$

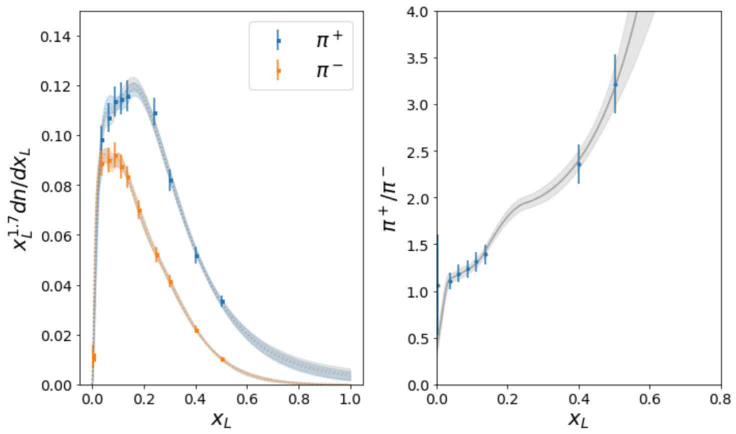
$$x_{Lab} = \frac{E_c}{E_a} = \frac{\gamma\sqrt{m_c^2 + \frac{1}{4}x_F^2 E_{c.m.}^2 + p_{c,T}^{*2}} + \frac{1}{2}\gamma\beta x_F^2 E_{c.m.}}{E_a}$$



Fit pT in each x_F bin using $\frac{\mathrm{d}n}{\mathrm{d}p_\perp} = a_0 p_\perp^{a_1}\ e^{a_2 p_\perp^{a_3}}$



Fit dn/dx_L with splines, get covariance matrix



Included data

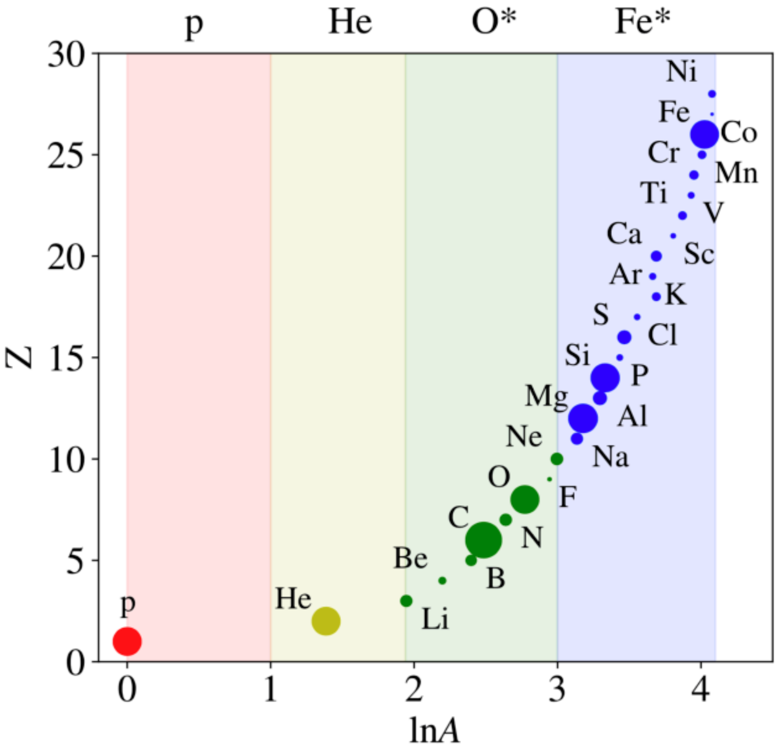
Experiment	beam	$E_{\rm beam}$/GeV	Secondaries	Variables
NA49	pC	158	$\pi^\pm, \overset{(-)}{\rm p}, n$	$x_{\rm F}, p_\perp$
NA49	pp	158	$K^\pm$	$x_{\rm F}, p_\perp$
NA61/SHINE	pC	31	$\pi^\pm, K^\pm, K_S^0, \Lambda$	p, θ
NA61/SHINE	π^-C	158, 350	$\pi^\pm, K^\pm, \overset{(-)}{\rm p}$	$p, p_\perp$

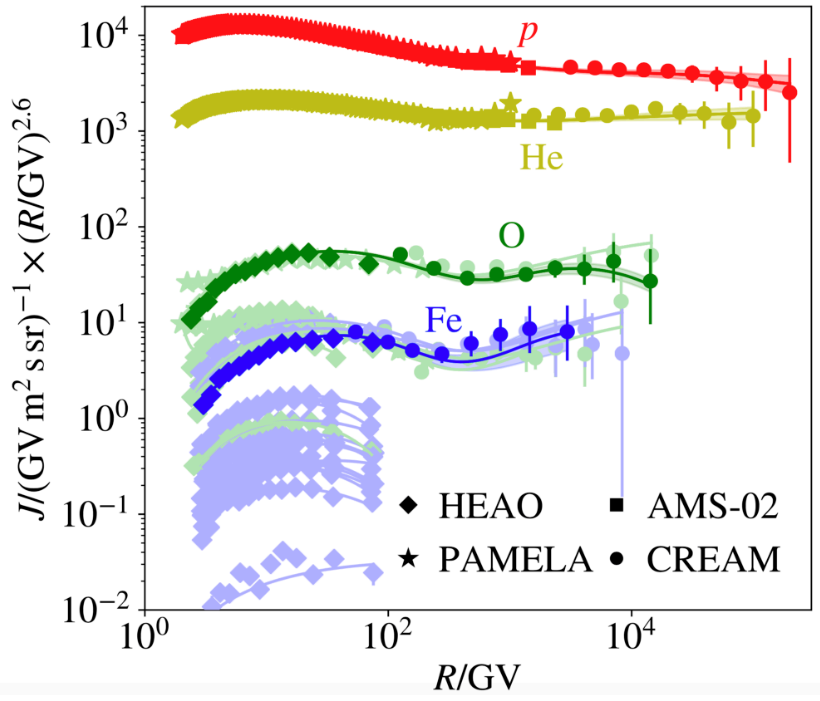
(In the next iteration we would like to include new results from NA61 and old results from NA59 that require Be->C extrapolation.

Global Spline Fit – fit to direct & indirect observations

H. Dembinski, AF, T. Gaisser
PoS(ICRC2017)533

- Fit **four** independent mass groups, which cover equal ranges in lnA:
  proton (p), helium (He), oxygen group (O*), and iron group (Fe*)
- Assumption: this holds **at all energies**
- One leading element *L* per group described by smooth spline curve
- Other elements *j* in a group kept in constant ratio: $J_j(R)/ J_L(R) = const.$



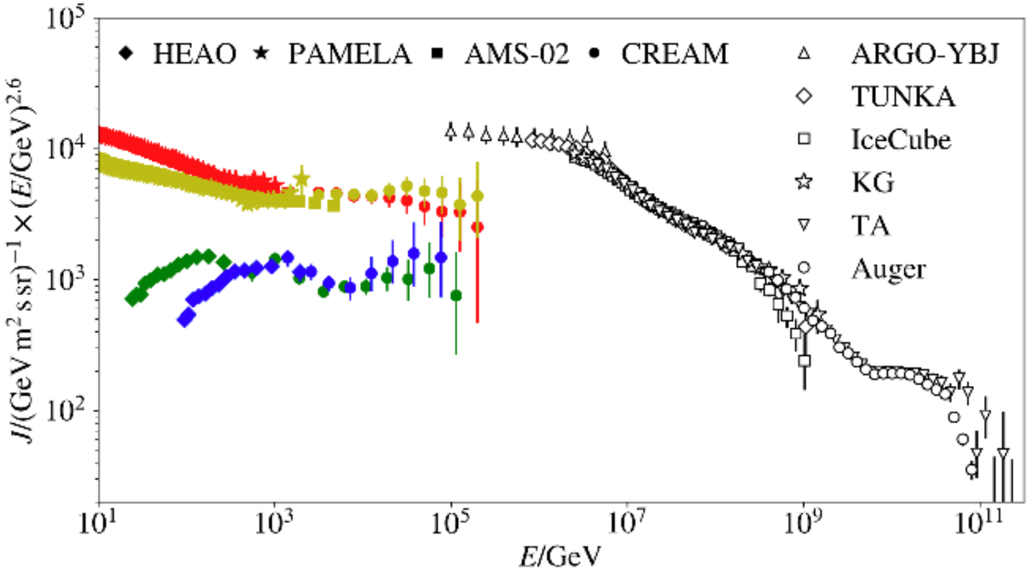


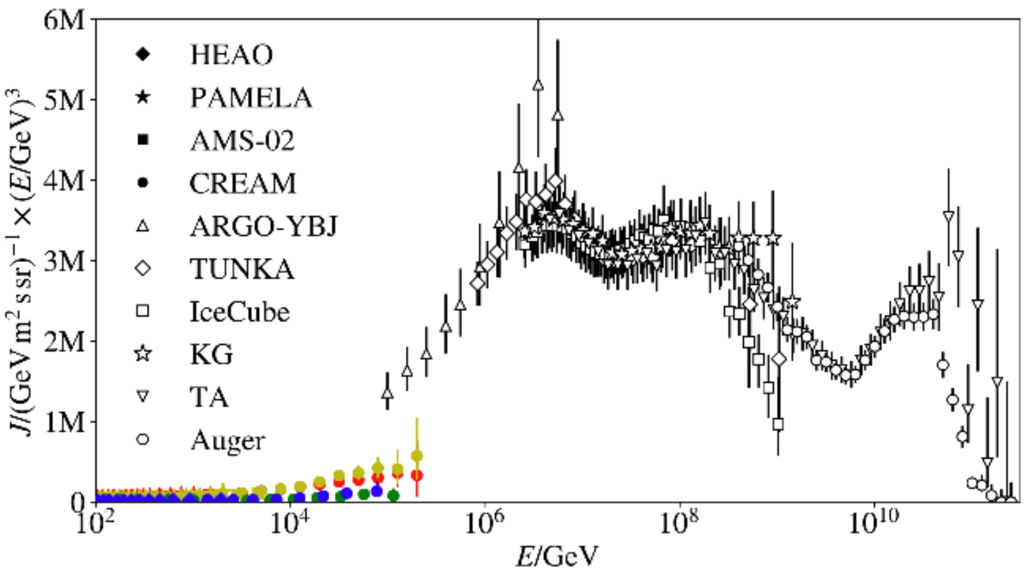
Mass sensitivity of air-shower experiments is ~ lnA

Handling energy-scale uncertainty

H. Dembinski, AF, T. Gaisser
PoS(ICRC2017)533

Adjusted data





- The determination of **energy scale in air-shower experiments is uncertain**
- This is caused by inconsistencies of **hadronic interaction models**
- Fit adjusts energy scales **within systematic uncertainties** of the experiment

$$\tilde{J}(\tilde{E}) = J(E)\frac{\mathrm{d}E}{\mathrm{d}\tilde{E}} = J\left(\frac{\tilde{E}}{1+z_E}\right)\frac{1}{1+z_E}$$

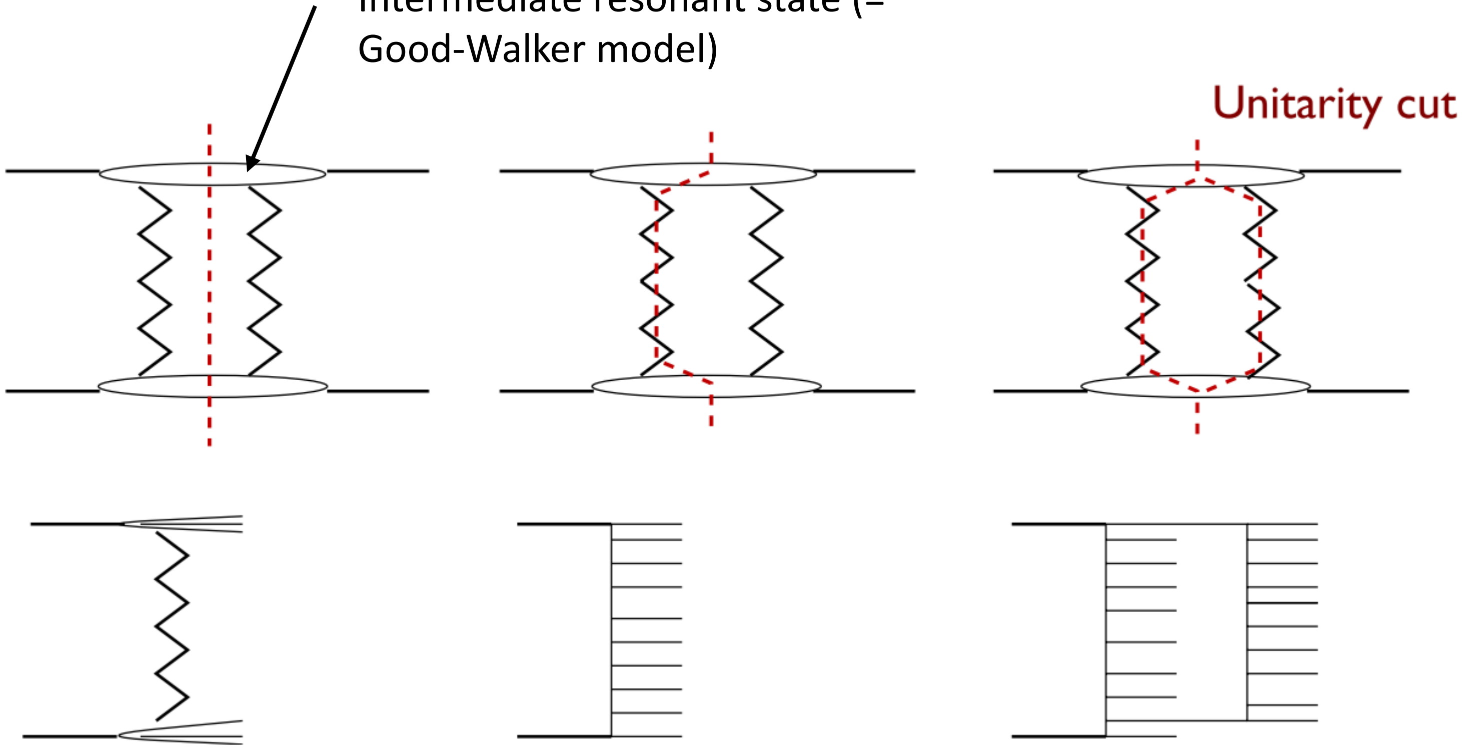
Flux distortion caused by energy-scale offset z_F

$$S = \sum_i z_i^2 + \sum_j \left(\frac{z_{Ej}}{(\sigma[E]/E)_j}\right)^2$$

Flux residuals   Energy-scale offset residuals

AGK cutting rules = unitarity cuts

Intermediate resonant state (= Good-Walker model)



elastic scattering

inelastic scattering

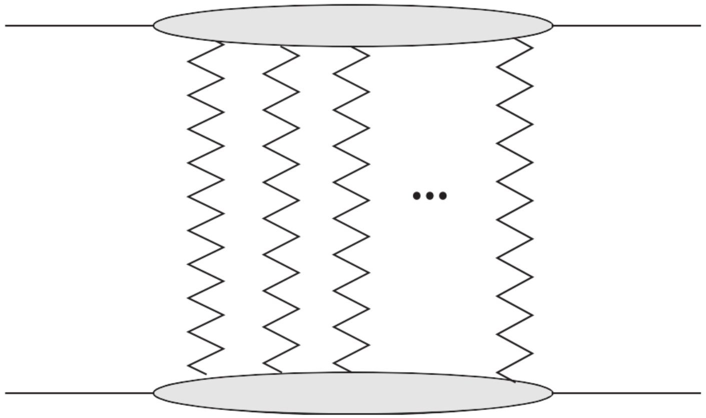
Weights: (-1) (+4) (-2)

(Abramovskii, Gribov, Kancheli 1974)

Mathematical model that tells how to sum the different combinations of cut graphs to conserve unitarity without double counting

Construction of scattering amplitudes

N-Pomeron exchange graph



t-channel (momentum space) N-pomerton scattering amplitude,
t = $(q)^2 \sim (k_T)^2$

$$A^{(n)} = -i(i)^n \frac{1}{n!} \left(\frac{1}{2s}\right)^{n-1} \prod_{i=1}^{n} \left(\int \mathrm{d}^2 k_{\perp,i} A^{(1)}(s, k_{\perp,i}^2) \right) \frac{\delta^{(2)}(q_\perp - \sum_{i=1}^{n} k_{\perp,i})}{(2\pi)^{2(n-1)}}$$

One-pomeron elastic amplitude

$$A_{AB}^{I\!P_s} = i s_0 g_{AI\!P}(t) g_{BI\!P}(t) \left(\frac{s}{s_0}\right)^{\alpha_{I\!P_s(t)}}$$

Couplings to particle A, B

$$g_{iI\!P}(t) = g_{iI\!P}^0(t) \exp\left(\frac{1}{2} b_{iI\!P}^0 t\right)$$

Connected to transverse/impact-parameter b-space via inv. Fourier-tr.

$$A(s,t) = 4s \int_0^\infty \mathrm{d}^2 \vec{B}\ a(s, \vec{B}) \mathrm{e}^{i\vec{q}\vec{B}}$$

Multi-Pomeron amplitude in impact parameter space (Eikonal approximation). Much simpler representation!!

$$a(s, \vec{B}) = \sum_{n=1}^{\infty} a^{(n)}(s, \vec{B}) = \frac{i}{2}\left(1 - \exp\left[-\chi(s, \vec{B})\right]\right)$$

$$\chi(s, \vec{B}) = -2i a^{(1)}(s, \vec{B}) \qquad \text{and} \qquad 2 \int \mathrm{d}^2 \vec{B}\ \chi(s, \vec{B}) = \sigma^{\mathrm{Born}}(s)$$

Computation of cross sections (for all models similar)

Optical theorem for total cross section
(needs only elastic amplitude)

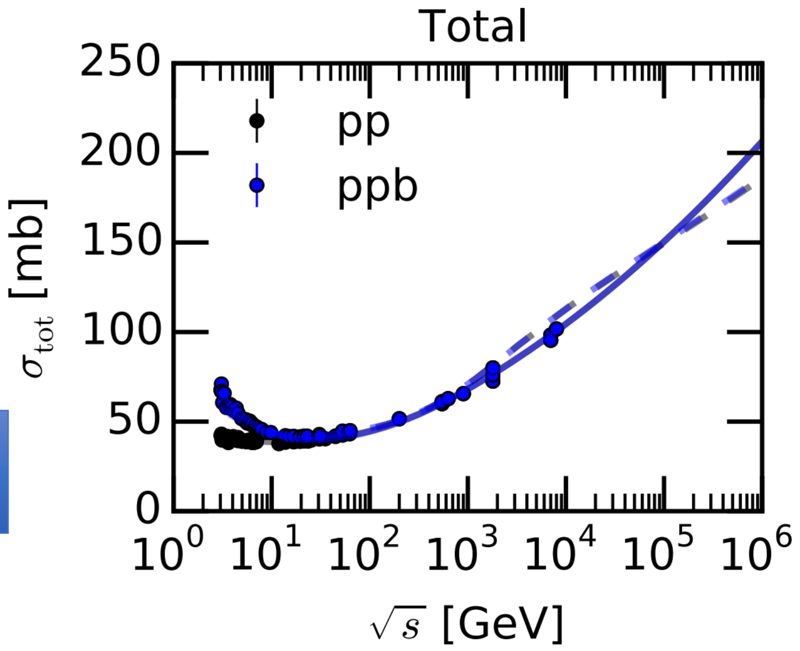
$$\sigma_{\mathrm{tot}} \approx \frac{1}{s} \Im m(A(s,t=0))$$

In practice done in impact parameter space

$$\sigma_{\mathrm{tot}} = 2\int \mathrm{d}^2\vec{B}\; \Im m(a(s,\vec{B})) = 2\int \mathrm{d}^2\vec{B}\; (1 + e^{-\chi_{\mathrm{R}}} \sin\chi_{\mathrm{I}})$$

$$\sigma_{\mathrm{el}} = 2\int \mathrm{d}^2\vec{B}\; |a(s,\vec{B})|^2 = \int \mathrm{d}^2\vec{B}(1 + 2e^{-\chi_{\mathrm{R}}} \sin\chi_{\mathrm{I}} + e^{-\chi_{\mathrm{R}}})$$

$$\sigma_{\mathrm{inel}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}} = \int \mathrm{d}^2\vec{B}(1 - e^{-2\chi_{\mathrm{R}}})$$

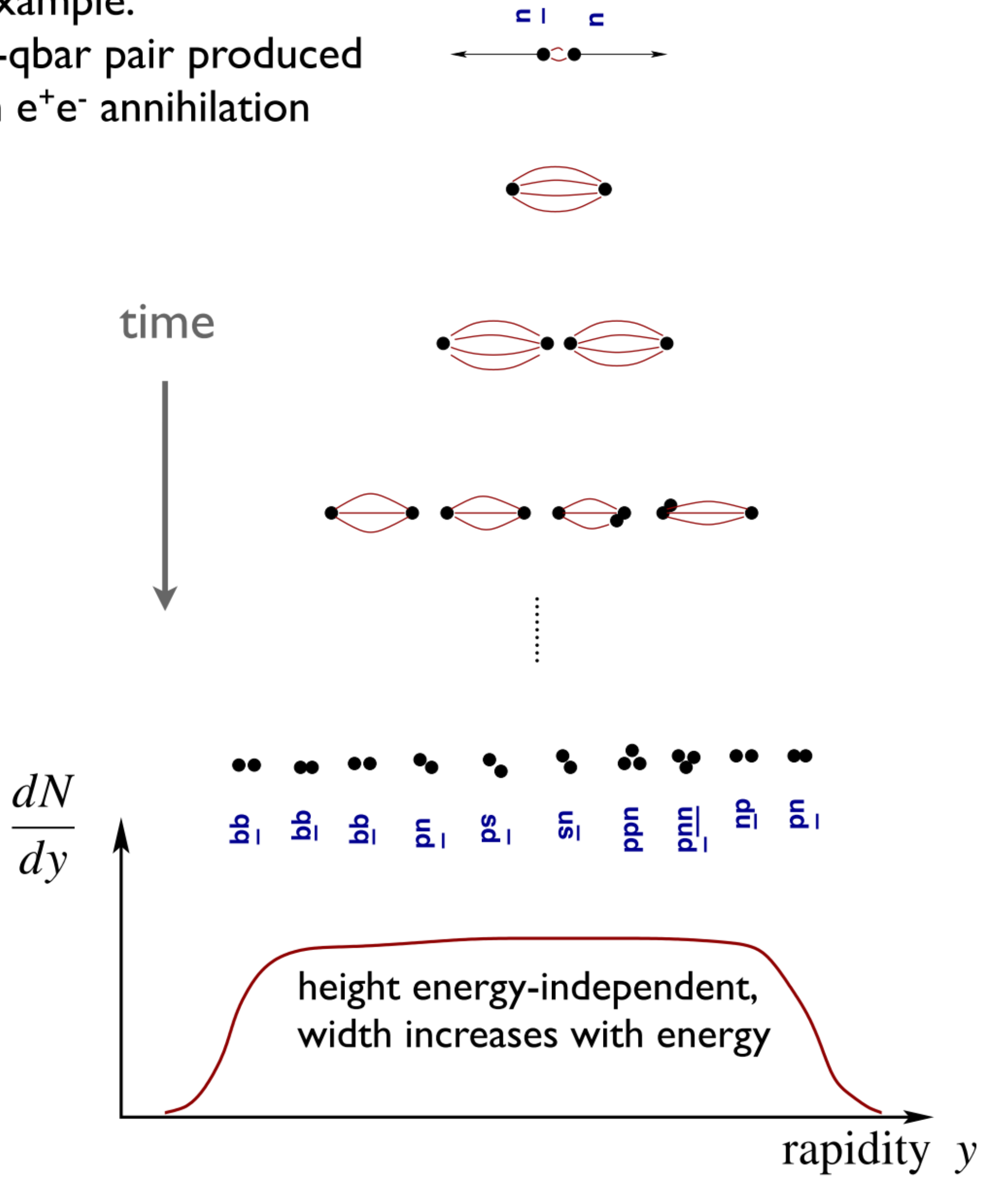


Pomeron component: growth with s
(cms-energy squared) $s^{\Delta_P} \sim s^{0.08}$

Reggeon component: drop with s
(at low energy) $s^{\Delta_R} \sim s^{-0.5}$

String fragmentation (Lund-model)

Example:
q-qbar pair produced
in e^+e^- annihilation



Rapidity

$$y = \frac{1}{2}\ln\frac{E+p_{\parallel}}{E-P_{\parallel}}$$

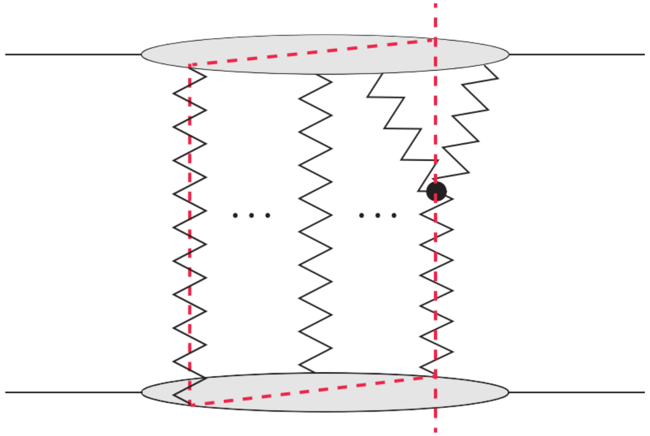
Rapidity of massless particles

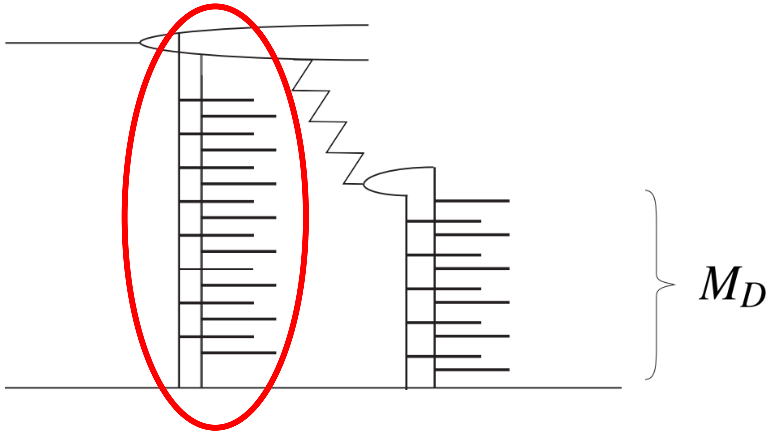
$$y = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\tan\frac{\theta}{2}$$

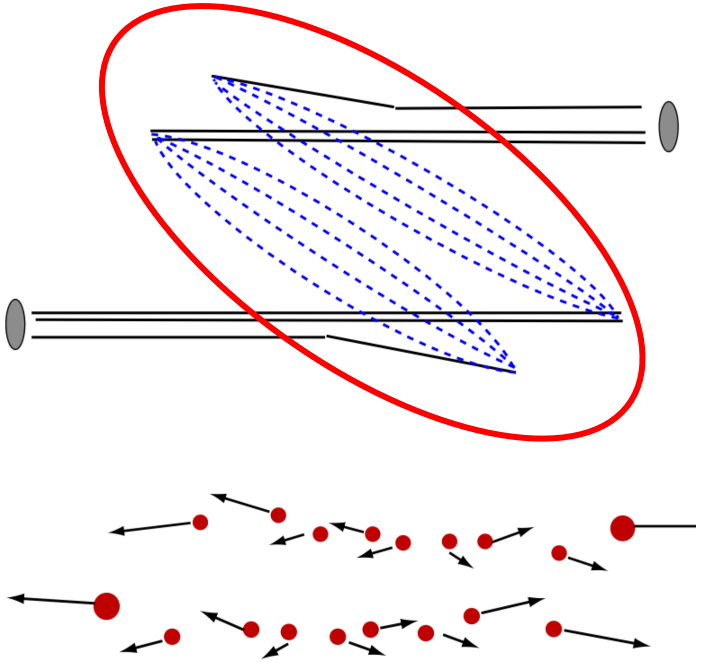
Pseudorapidity

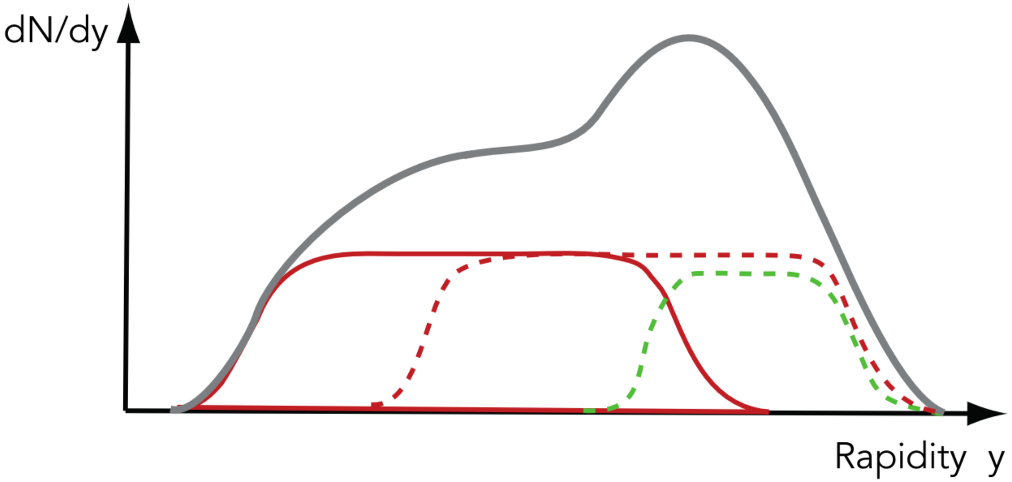
$$\eta = -\ln\tan\frac{\theta}{2}$$

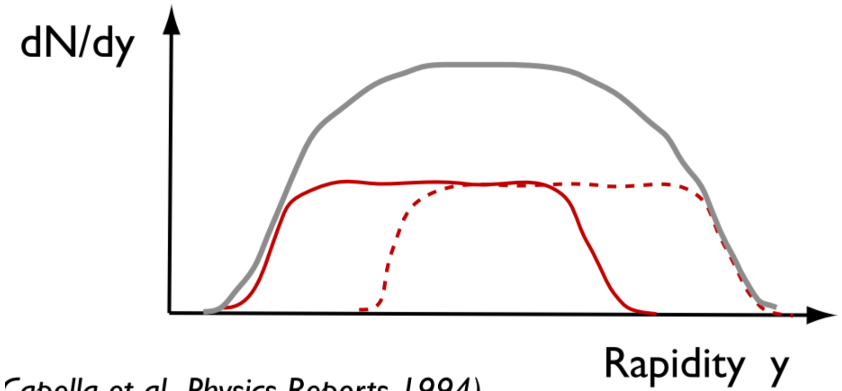
Realization of cut graphs with string fragmentation











Capella et al., Physics Reports 1994)