Prompt Muons from Cosmic Ray Air Showers in IceCube

Summary of my Master's Thesis

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2023-11-10

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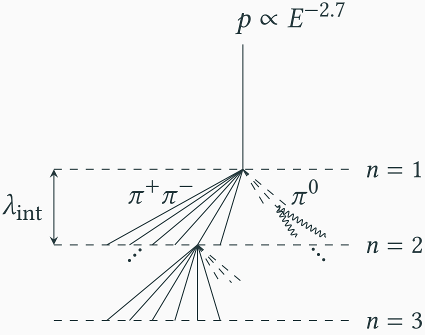
Outline

Physics of Extensive Air Showers

Where the Muons are coming from: Extensive Air Showers (EAS)



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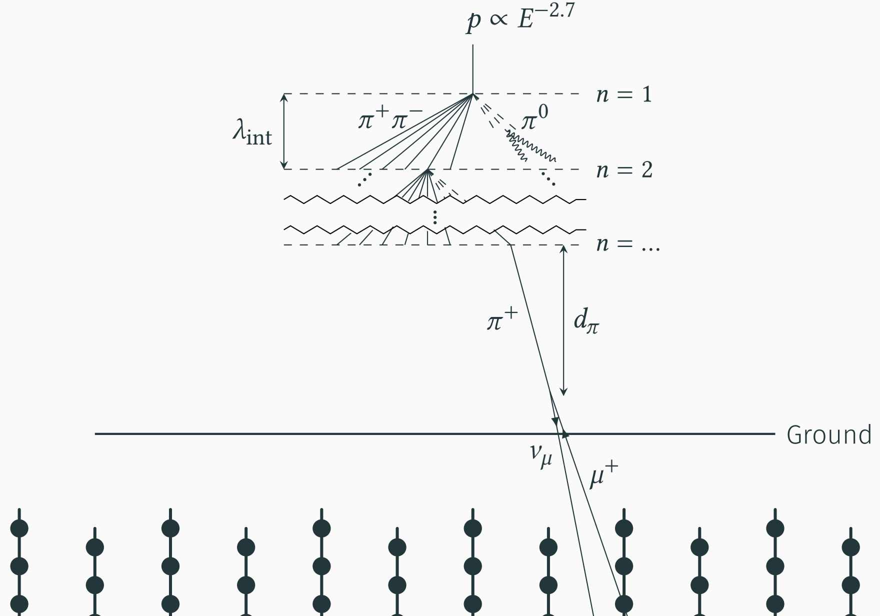

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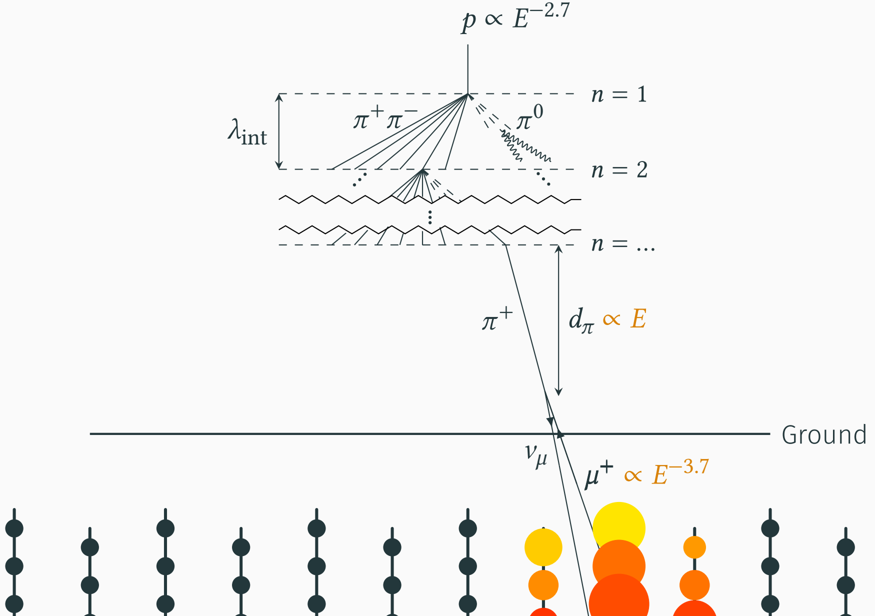

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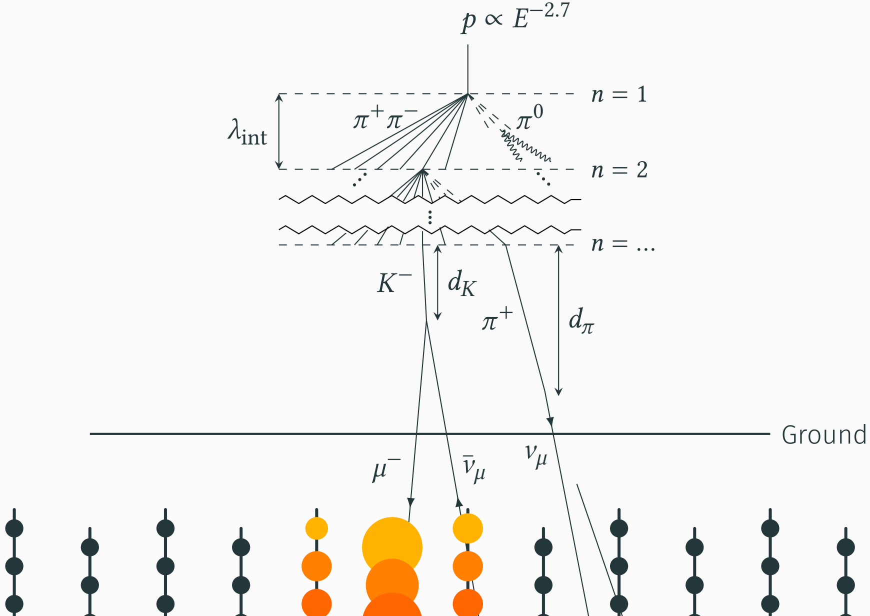

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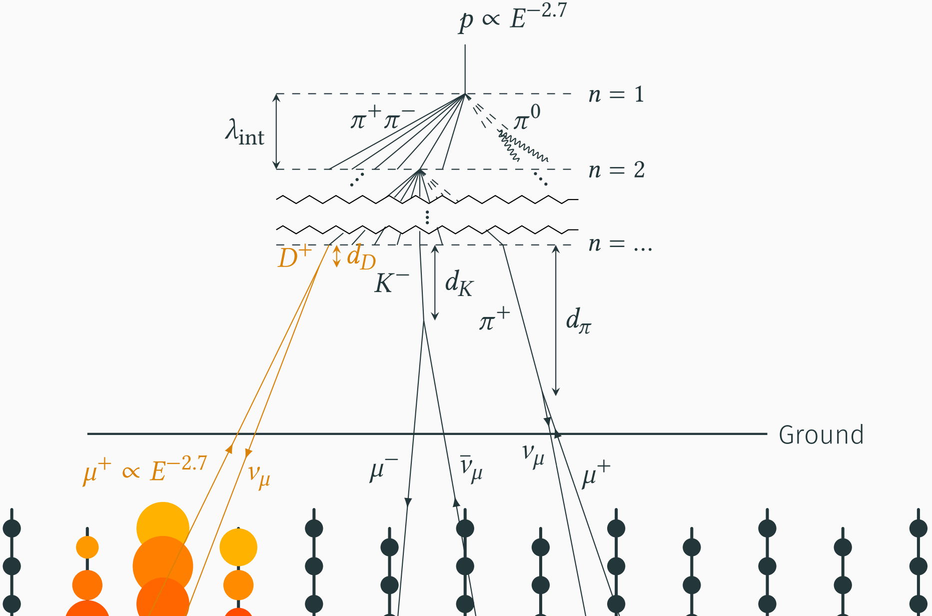
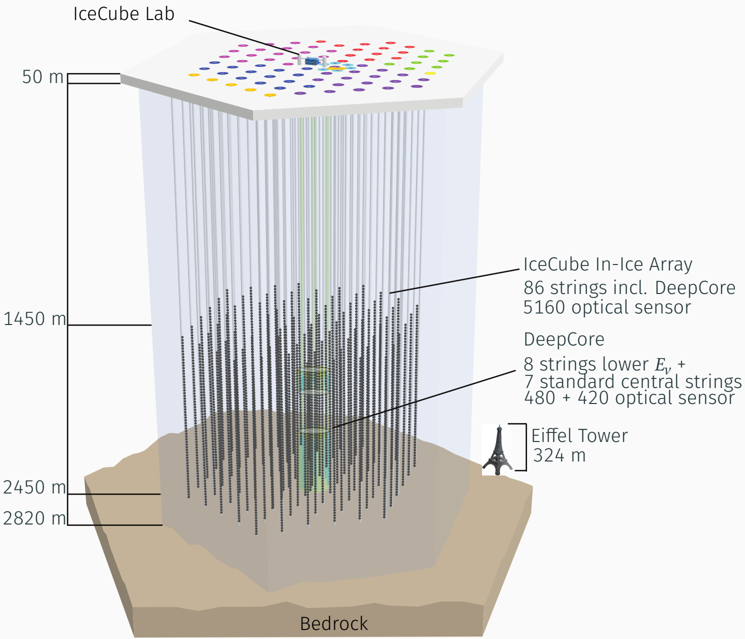


The IceCube Detector...



... is located at the South-Pole.

... has $1\,\mathbf{km}^3$ total volume.

... finished construction in 2010.

... was designed as a neutrino detector.

... but is also a wonderful muon detector.

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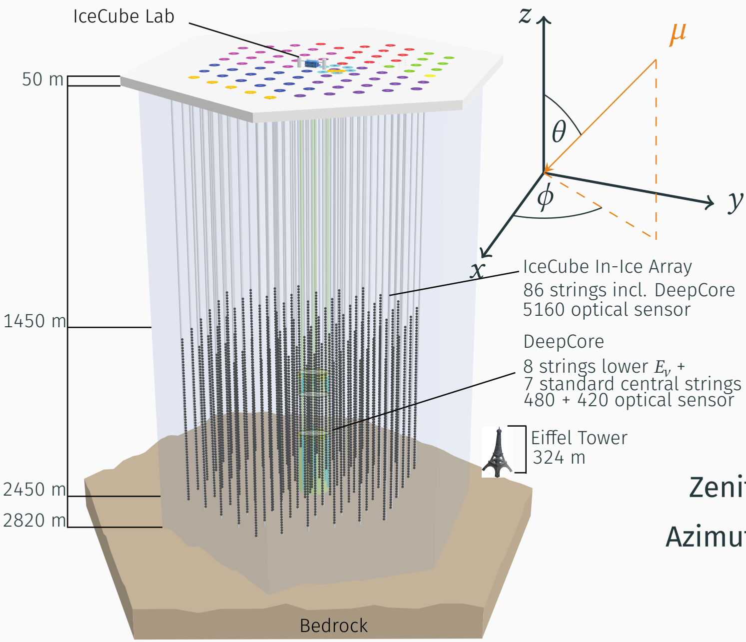

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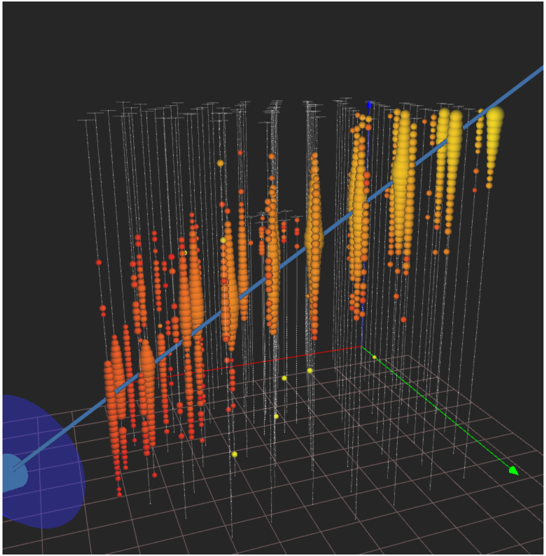
Vocabulary:

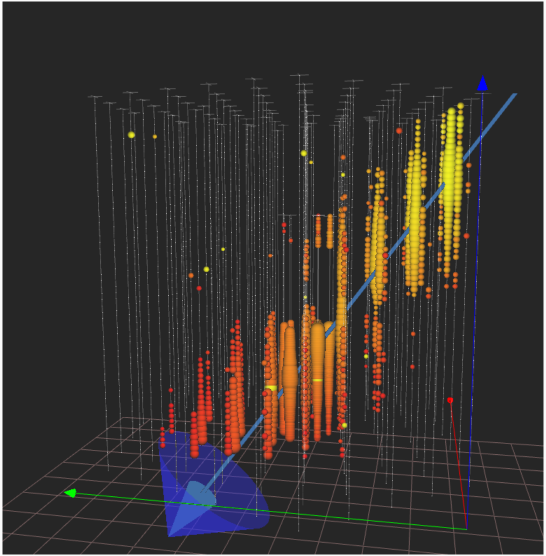
Zenith θ

Azimuth ϕ

Prompt Events in IceCube



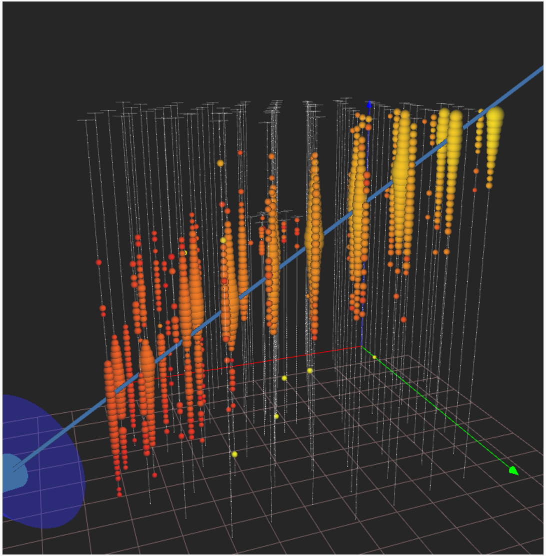
(a) $E_{\mu,\max} = 1.2$ PeV, $E_{\text{bundle}} = 1.6$ PeV, $n_{\text{bundle}} = 1812$.



(b) $E_{\mu,\max} = 1.1$ PeV, $E_{\text{bundle}} = 1.8$ PeV, $n_{\text{bundle}} = 1880$.

Prompt Events in IceCube

Prompt Muon



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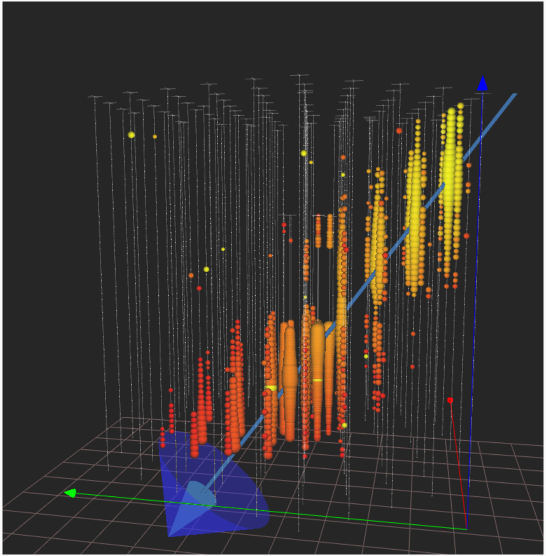
Conventional Muon



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The Cascade Equations

$$\frac{\mathrm{d}\Phi_i(E,X)}{\mathrm{d}X} = -\left(\frac{1}{\lambda_i} + \frac{1}{d_i}\right)\Phi_i(E,X) + \sum_j \left(\frac{Z_{ji}}{\lambda_j} + \frac{Z_{ji}^d}{d_j}\right)\Phi_j(E,X)$$

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H	ϵ_H/GeV
$\mu^\pm$	1
$\pi^\pm$	115
$K^\pm$	850
Λ	9.04×10^4
$D^\pm$	3.7×10^7
D^0	9.9×10^7
Λ_c	2.4×10^8
$\omega(782)$	2.2×10^{17}

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$$\Phi_\mu^{\mathrm{tot}} = \sum_H \frac{\Phi_{H\to\mu}^{\mathrm{low}E}\cdot\Phi_{H\to\mu}^{\mathrm{high}E}}{\Phi_{H\to\mu}^{\mathrm{low}E}+\Phi_{H\to\mu}^{\mathrm{high}E}} = \Phi_\mathrm{p}(E)\sum_H \frac{\mathscr{A}_{HL}}{1+\mathscr{B}_{HL}\frac{E}{\epsilon_H f(\theta)}}$$

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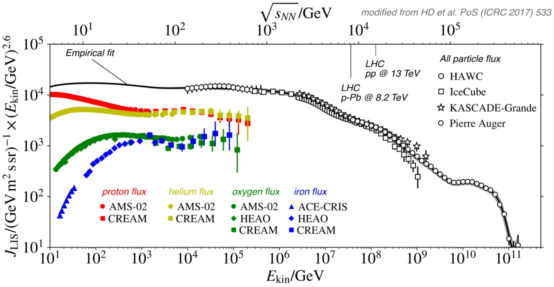
Air Shower Simulation and CORSIKA's EHistory

Primary Models and Reweighting



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- Large uncertainties in the high energy region

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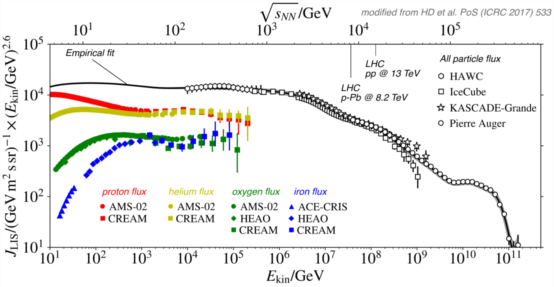

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MCEq/Theory:

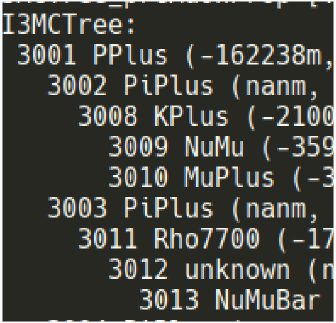
- "Transform" primary model to lepton fluxes
- Via cascade equations
- New calculation for every primary model

MC (CORSIKA):

- Simulate events drawing from simple $E^{-\gamma}$ (e.g. $\gamma = -1$)
- Weight events to realistic Φ_p
- Fast reweighting after simulation

CORSIKA Compilation Option: Extended History (EHIST)

$$\overbrace{p + \text{air}}^{\text{Input}} \to \ldots \to \overbrace{\mu^- + \bar{\nu}_\mu}^{\text{Output}}$$



```
I3MCTree:
 3001 PPlus (-162238m,
   3002 PiPlus (nanm,
     3008 KPlus (-2100
       3009 NuMu (-359
       3010 MuPlus (-3
   3003 PiPlus (nanm,
     3011 Rho7700 (-17
       3012 unknown (n
         3013 NuMuBar
```

- Additions to the CORSIKA DAT output files
- Includes information about “mother” and “grandmother”
- Modification of the CORSIKA reader is needed

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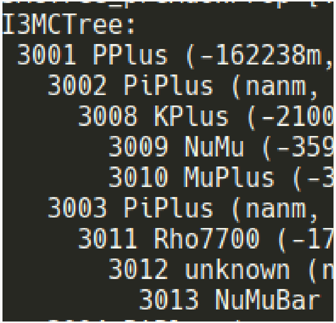
$$\overbrace{p + \mathrm{air}}^{\text{Input}} \rightarrow \ldots \rightarrow \overbrace{\pi^{+} + \mathrm{air} \rightarrow D^{-}}^{\text{EHIST}} \rightarrow \overbrace{\mu^{-} + \bar{\nu}_{\mu}}^{\text{Output}}$$



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Pitfalls:

- A “mother” is not necessarily the particle, which decays into the muon
- Inconsistent documentation (C7 User Guide / EHIST technical report)
- Somewhat buggy and documentation is out-of-date

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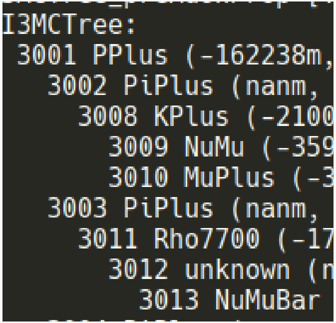

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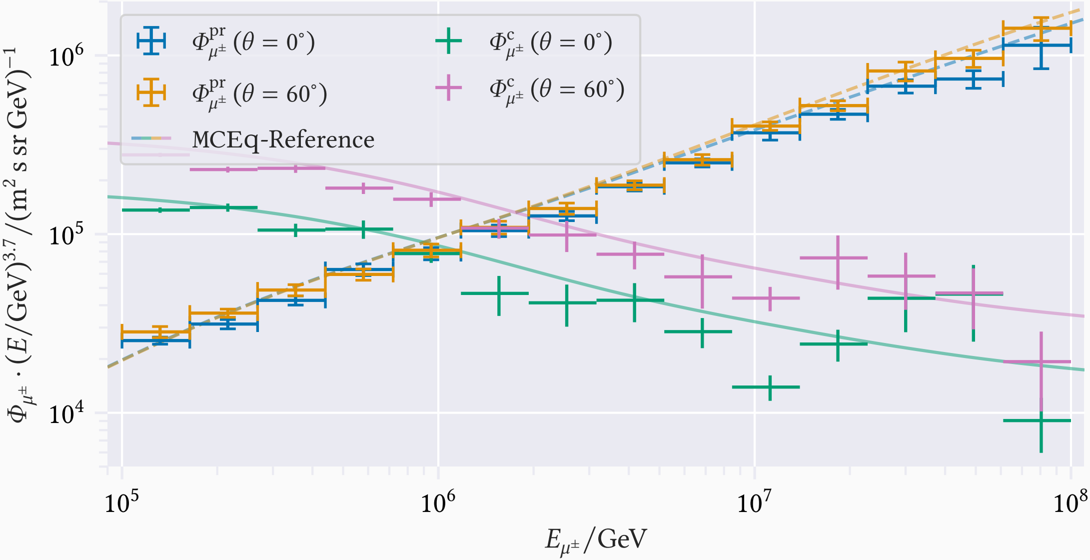
→ Correct readout implemented in IceTray

→ **PANAMA** (PANdas And Mulitcore utils for corsikA7) for python / CORSIKA7 standalone

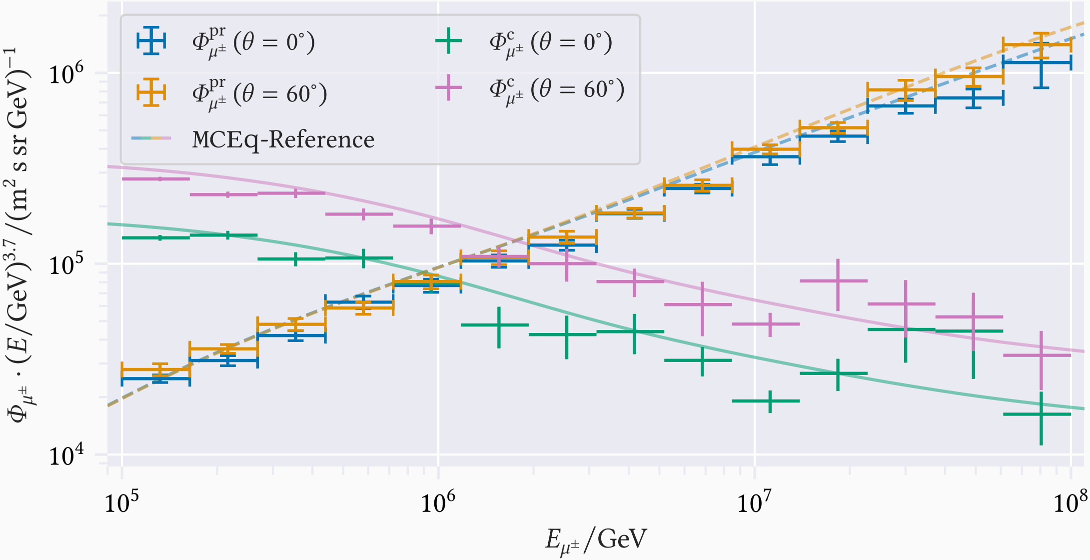
Definitions of Prompt

Definition: π/K (Dennis)

If parent is $\pi^{\pm}/K^{\pm}/K_L/K_S$, particle is conventional → Rest is prompt

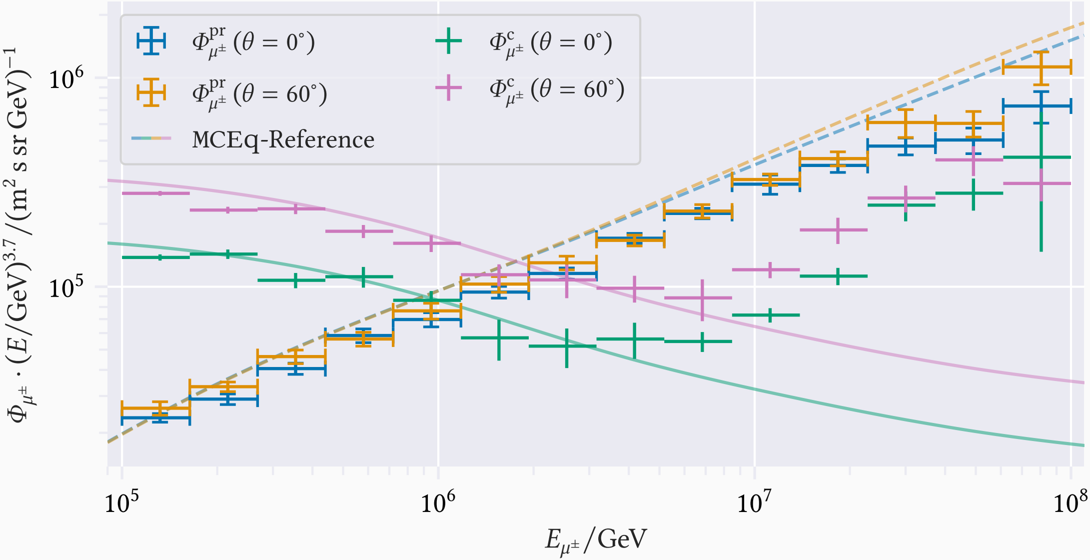


If parent has $\tau_M < 10 \cdot \tau_{D^\pm}$, particle is prompt



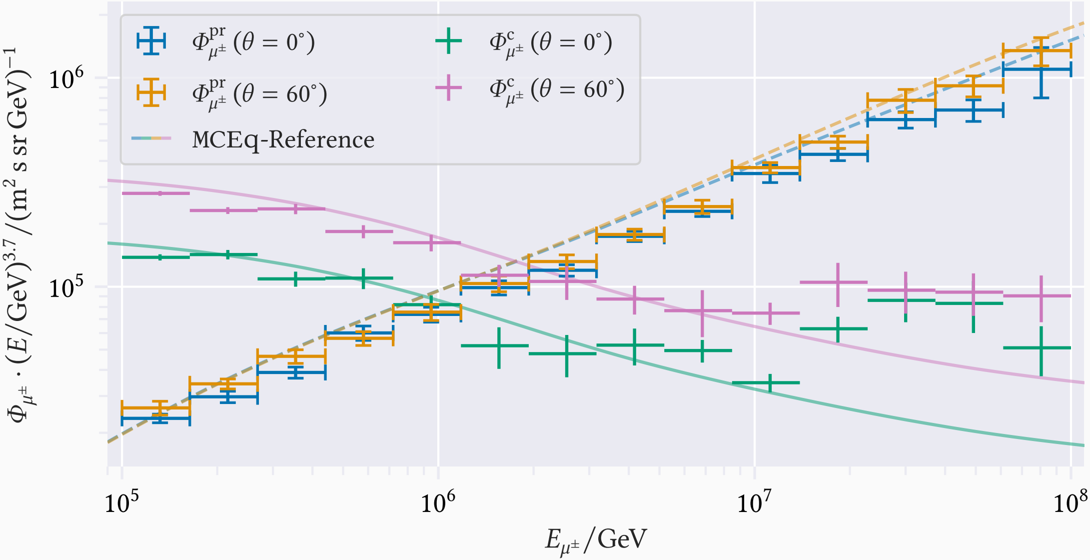
Definition: Energy

If parent has $E_{\mathrm{Parent}} < \epsilon_{\mathrm{Parent}}$, particle is prompt



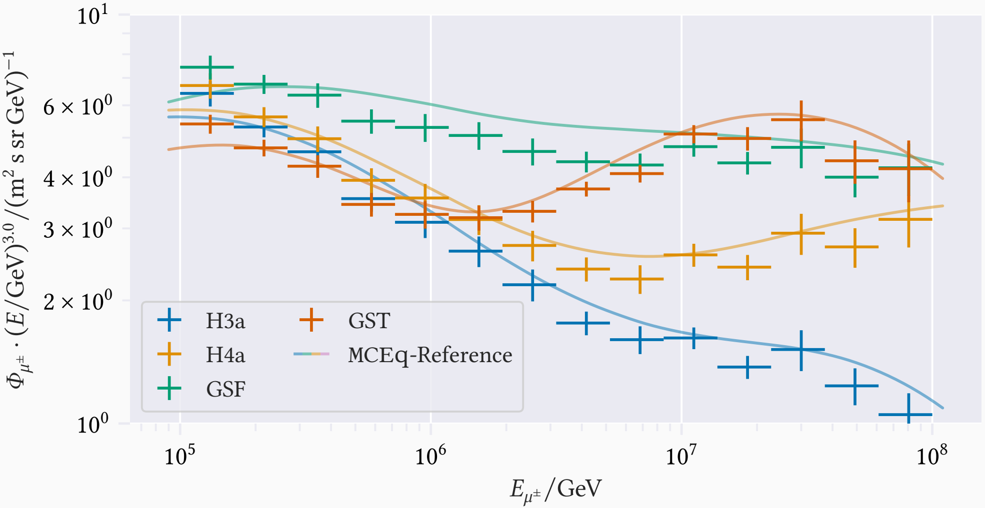
Definition: Grandmother

If parent or grandparent is $\pi^{\pm}/K^{\pm}/K_L/K_S$, particle is conventional



Properties of Prompt

Prompt with Different Primary Models

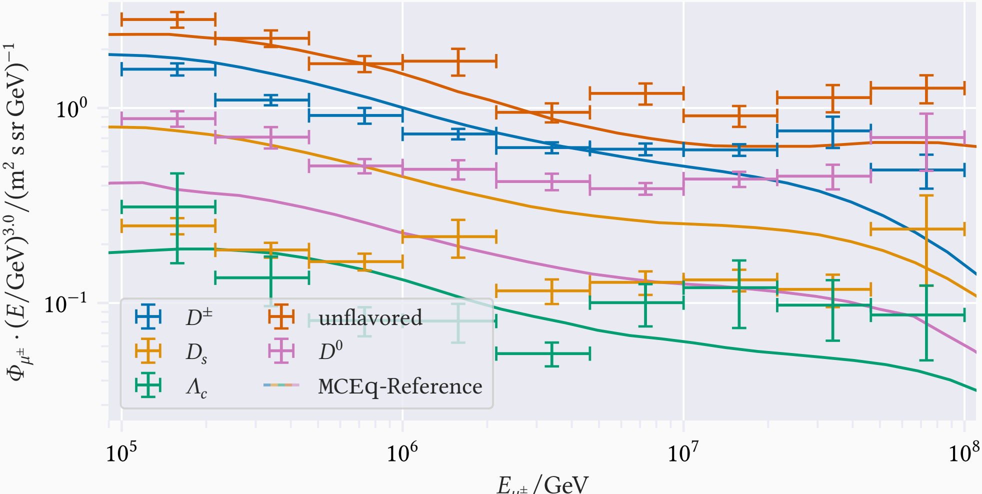


→ Dembinski et. al.'s Global Spline Fit produces most prompt

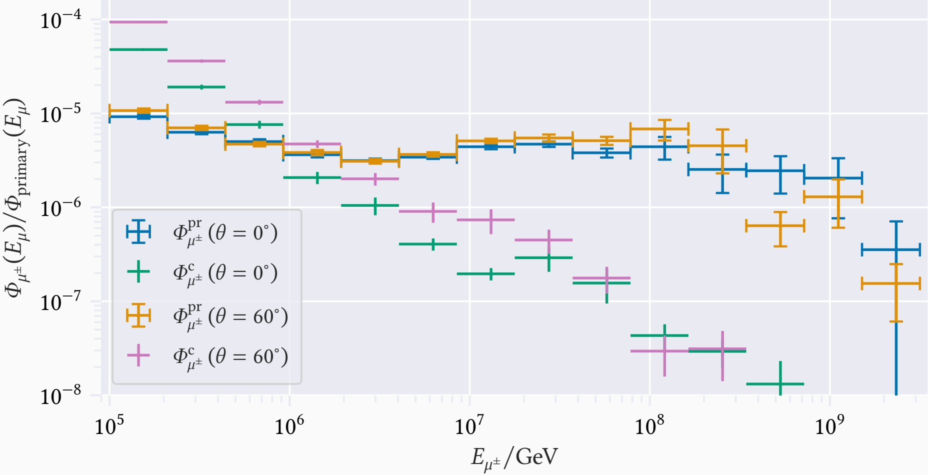
- GSF now also implemented in `simweights`

Prompt: Not only Charm

- For muons: $\Phi_{\text{charm}} \approx \Phi_{\text{unflavored}}$
- LHCb @ $\sqrt{s} = 13\,\text{TeV} \equiv E_{\text{FT}} = 90\,\text{PeV}$: $\sigma_{D_0} = (2072 \pm 124)\,\mu\text{b} > \sigma_{D_s} = (353 \pm 77)\,\mu\text{b}$



Fraction of primary flux

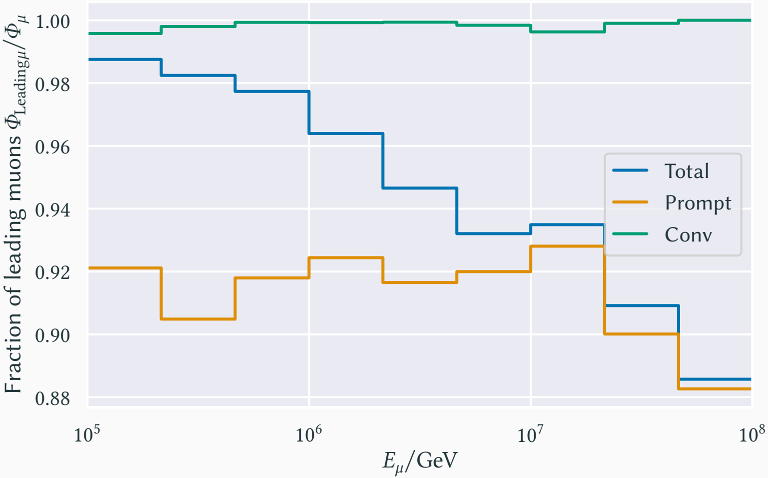


$$\Phi^{\text{low}E}_{H\to\mu}(E) = Z^d_{H\mu}\frac{Z_{pH}}{1-Z_{pp}} \cdot \Phi_p(E)$$

Garzelli et al. “Lepton fluxes from atmospheric charm revisited” :

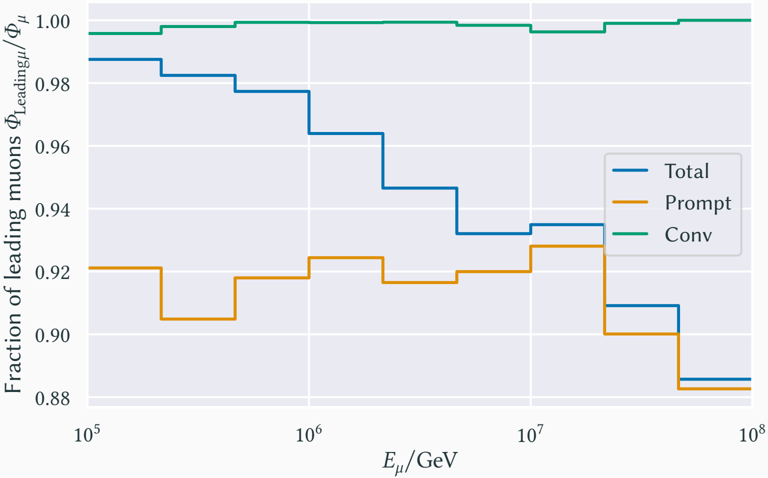
$$Z^d_{H\mu}\frac{Z_{pH}}{1-Z_{pp}} \approx 5 \times 10^{-6} - 1 \times 10^{-5}$$

Percent Leading Muons



- Leading = Most energetic muon
- Conventional muons are more leading than prompt ones

Percent Leading Muons



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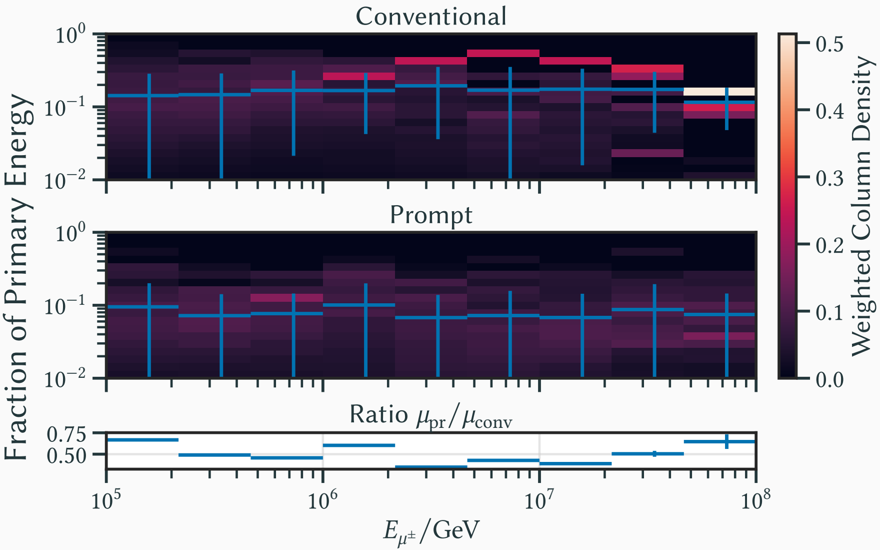
Almost the whole muon flux is coming from a single leading muon in the shower

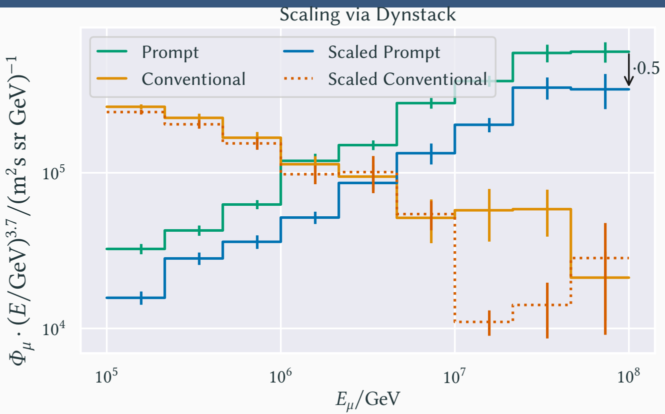
Fraction of Primary Energy



An Analysis Concept for the IceCube Detector

Dynstack Idea

- Modify the `CORSIKA` simulation via `DYNSTACK`
- Replace prompt meson with a probability p with $\pi^{\pm}/K^{\pm}$
- Generate different datasets with different p



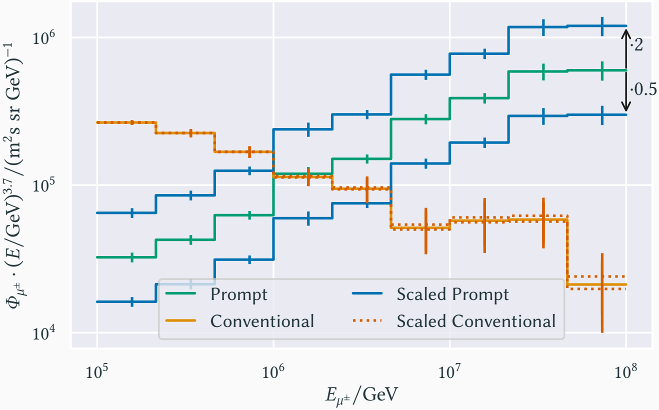
Pros

- Physically changes the shower-development
- Get handle on prompt

Cons

- Slow and expensive
- Replacement is non-trivial to do physically correct: Phase space, π/K-ratios...

Prompt Tagging



- Read creation history of muon from `CORSIKA`
- Assign a per-shower weight to scale the prompt component
- Fit weight to data

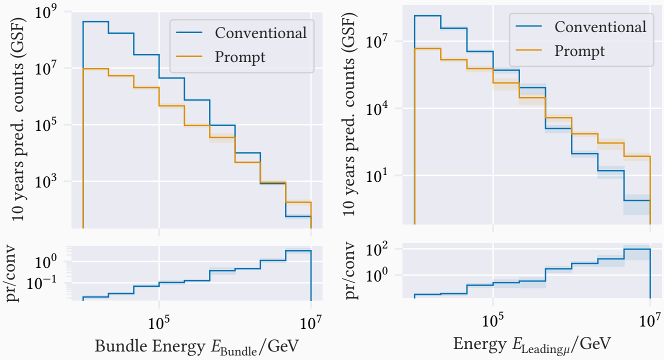
Pros

- Fast& Simple
- Nice-to-have anyway: Characterize prompt muons in the simulation

Cons

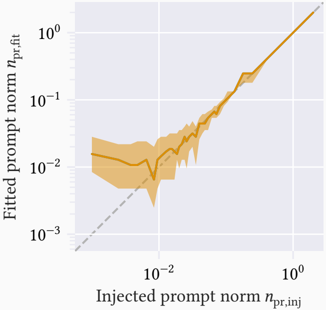
- No change in the shower development
- EHistory

What IceCube will see...

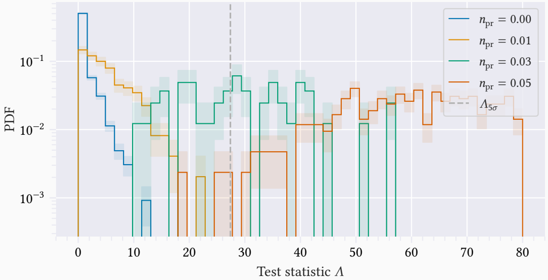


- IceCube does not measure muon-by-muon but the whole shower
- At relevant energies: No single-muon events
- Prompt/Conv transition also in bundle energy

Analysis Results of Toy Monte Carlo



- Inject variable prompt normalization
  $C_i^{\mathrm{MC}} = n_{\mathrm{pr}} C_i^{\mathrm{MC,pr}} + n_{\mathrm{conv}} C_i^{\mathrm{MC,conv}}$
- Draw Pseudo-Dataset
- Fit prompt and conv normalization with a Likelihood-fit
- Perform a Likelihood-Ratio test $\Lambda = -2\ln\frac{\mathcal{L}(n_{\mathrm{pr}}=\hat{n}_{\mathrm{pr}})}{\mathcal{L}(n_{\mathrm{pr}=0})}$



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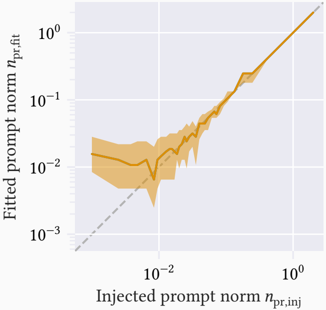

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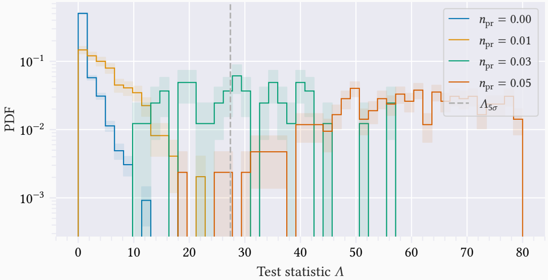
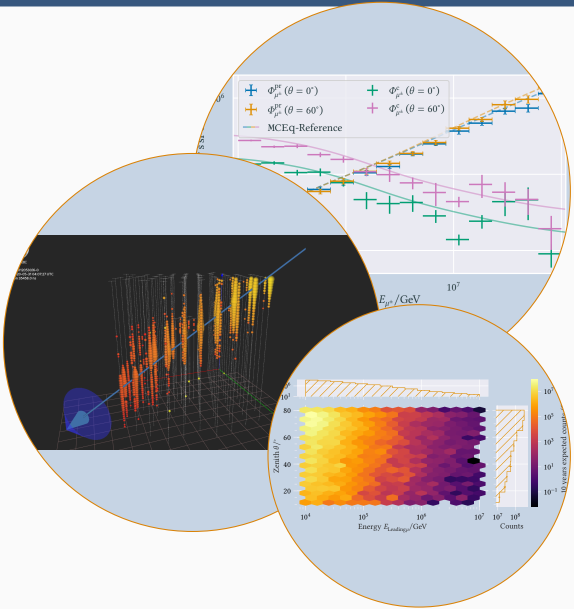
Very Early-Stage 5σ Discovery
Potential: $(3.24 \pm 0.13)\,\%$



Conclusion

- We can now identify the prompt component in `CORSIKA7` simulations
- With prompt tagging we can evaluate how prompt events behave in the detector
- Basis for measuring the prompt normalization



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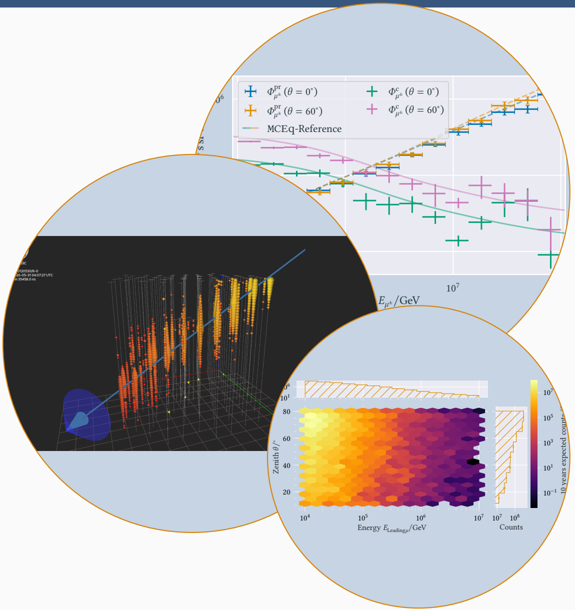
- Unfolding: model-independent results



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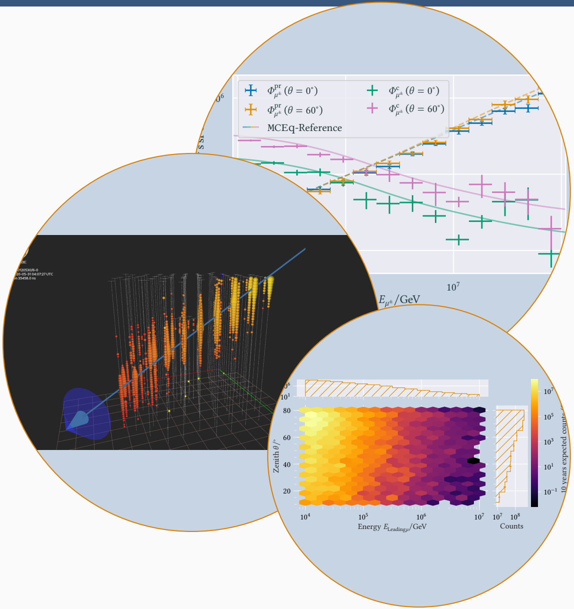

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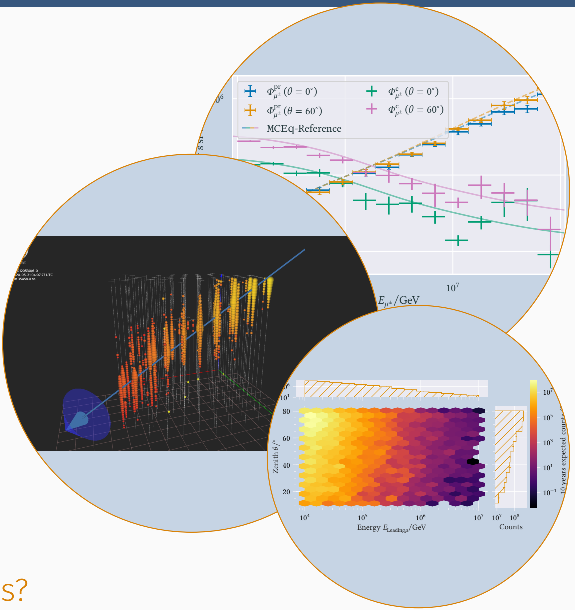
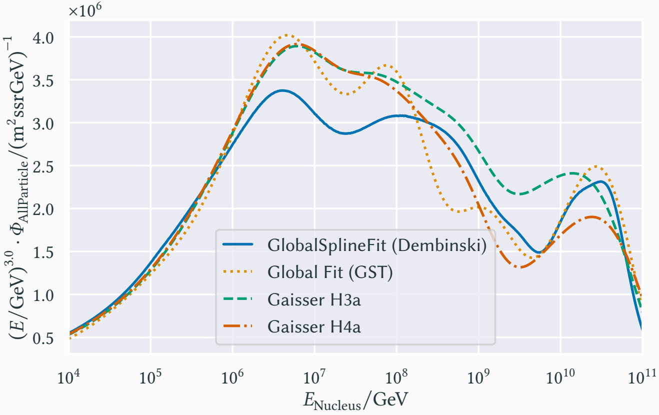
- Unfolding: model-independent results
- Combination with prompt ν-flux measurement: Results on unflavored and charm production



Thanks for your attention — any questions?

Backup

Used Primary Models



GST and Gaisser H3a/H4a:

$$\Phi_p(E) = \sum_j a_{p,j} E^{-\gamma_{p,j}} \exp\left(-\frac{E}{Z_p R_{c,j}}\right)$$

$p = 1 \dots 5$ (p, He, C, Si, Fe)

$j = 1 \dots 3$ (Three populations)

Global Spline Fit (GSF):

$$\Phi_p(E) = \sum_j a_{p,j} \left(\frac{E}{Z_p}\right)^{-3} B_j\left(\ln \frac{E}{Z_p}\right)$$

$j = 1 \cdots \approx 100$, $p = 1 \dots 4$ (p, He, O, Fe)

(+All other Z as $\Phi_Z = c \cdot \Phi_p$)

How to: Find the True Parent Particle with EHIST

1. Read out the hadron generation counter (HGC) of the particle and it’s “mother”
2. Calculate the difference in the hadron generation counter
3. If difference is 0 or 1 *and* mother is no resonance: ✓
4. Else if difference is 30 *and* mother has charm: ✓
5. Else if difference is 51 *and* mother is pion: ✓
6. Else: given mother particle is not the true parent particle ✗

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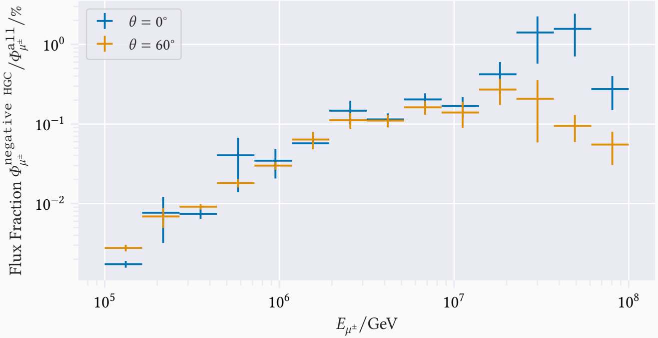
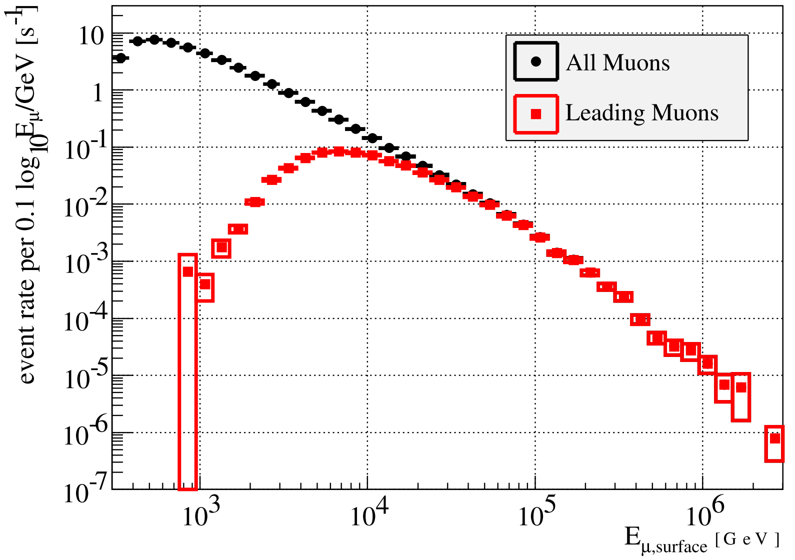
Discovered "bugs":

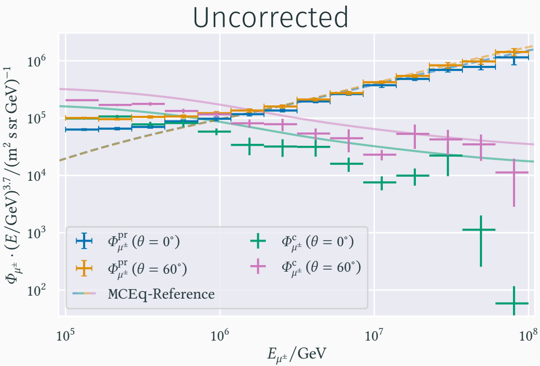
- Negative HGC differences
- Otherwise implausible HGC
- Muons as parents to muons

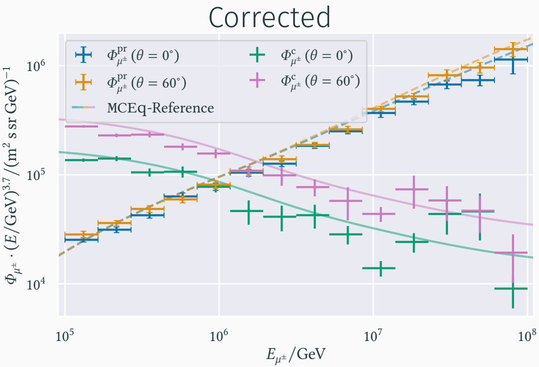


Leading Muon in Previous IceCube Analysis

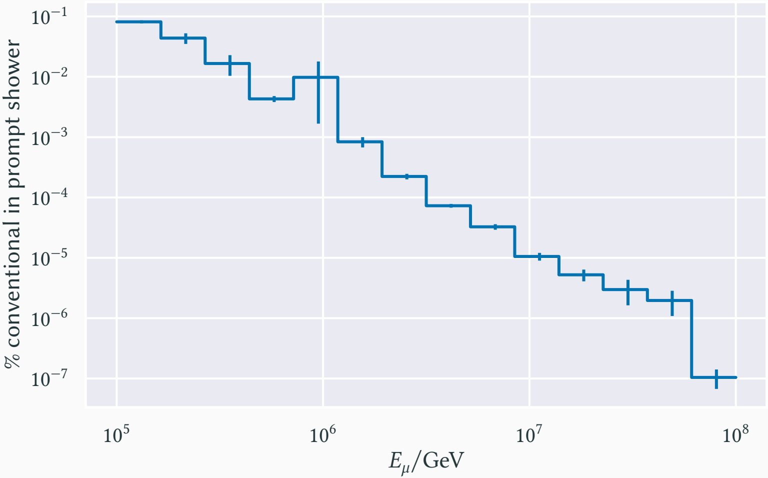


MCEq and Corsika Comparison



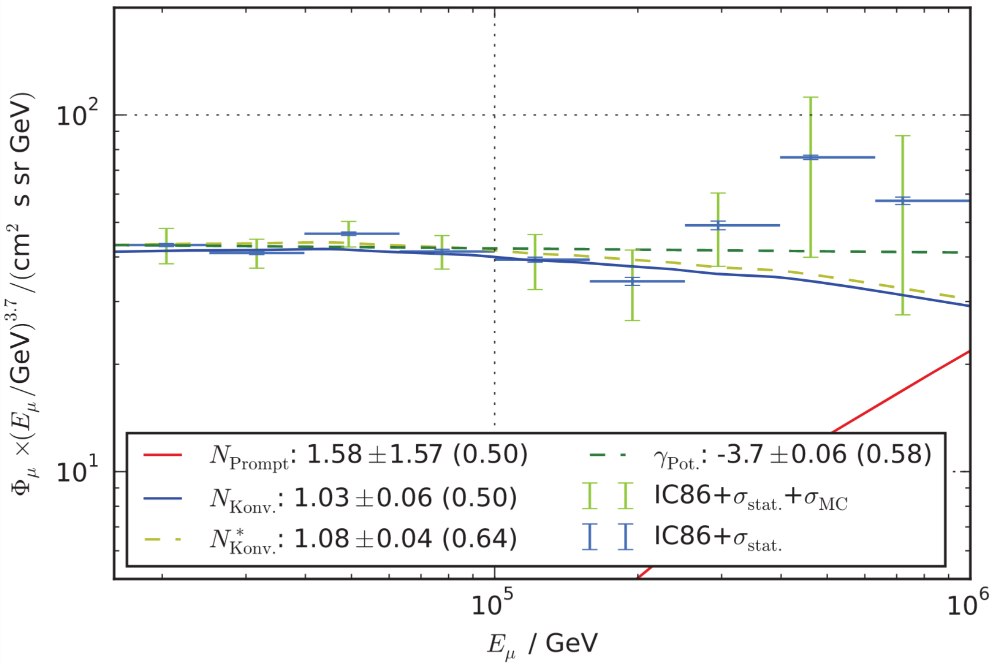


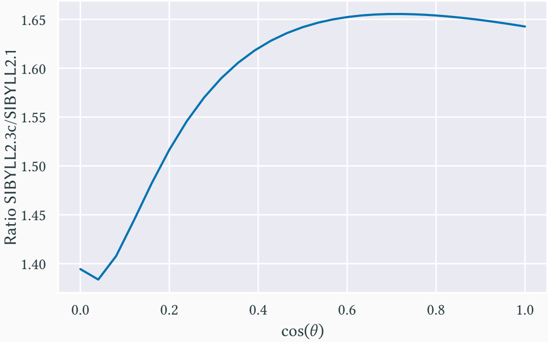
Weighting Prompt per Event?



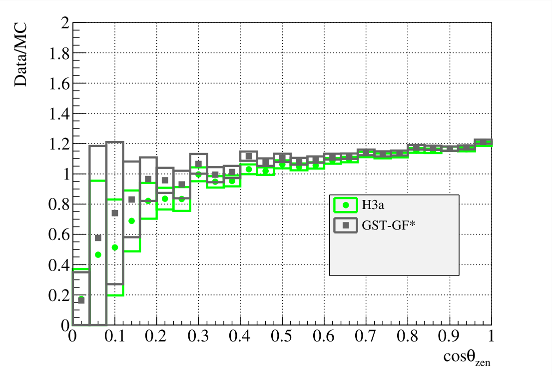
- Weighting a whole shower (event) as prompt
- Conventional particles in prompt-tagged shower will be weighted too
- Number of conventional particles in a shower with *any* prompt in the interesting energy region is $< 0.1\%$

Earlier Analyses: Tomasz Unfolding



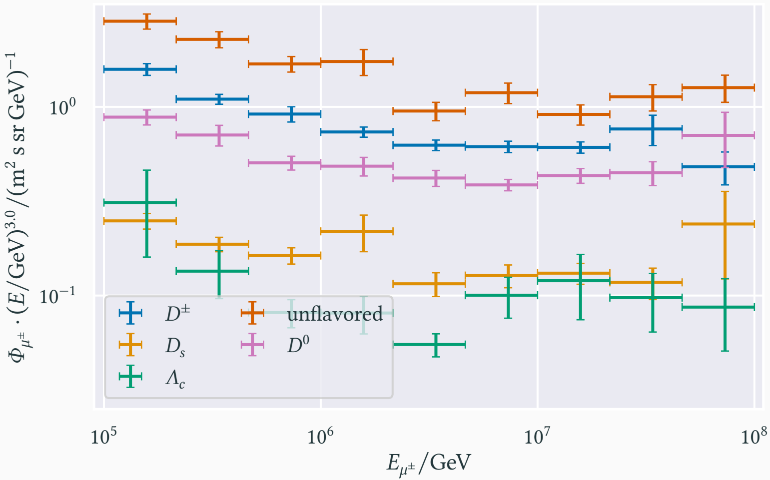


MCEq: `SIBYLL-2.3c/SIBYLL-2.1` ratio

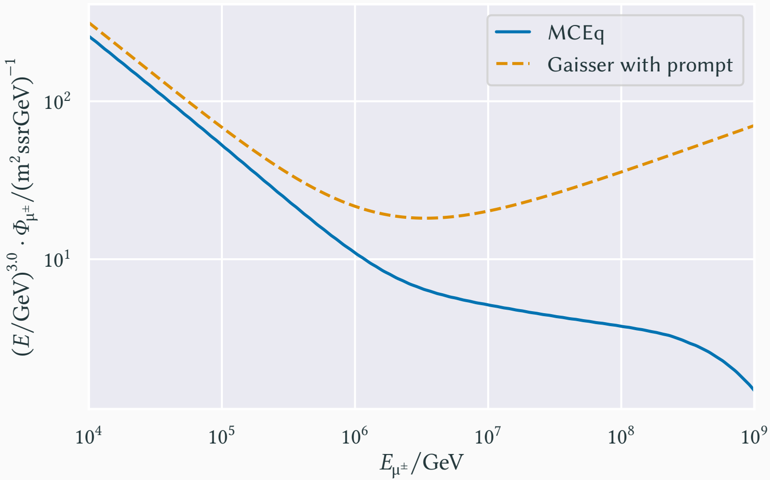


Zenith-dependent Data/MC mismatch

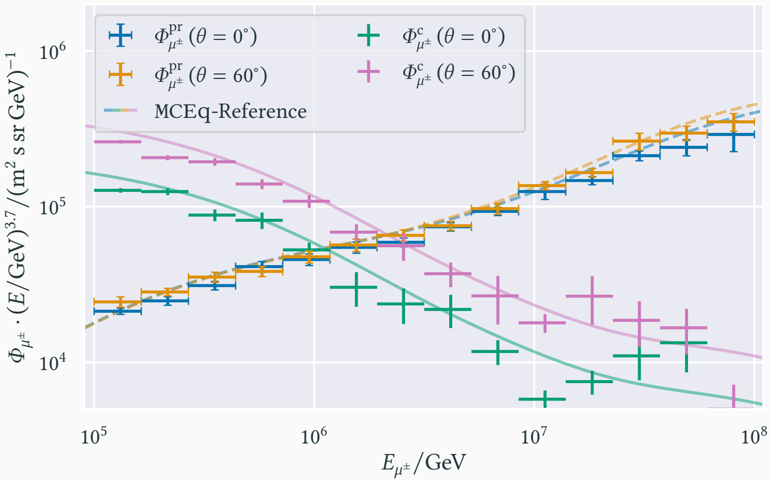
Per Parent Particle



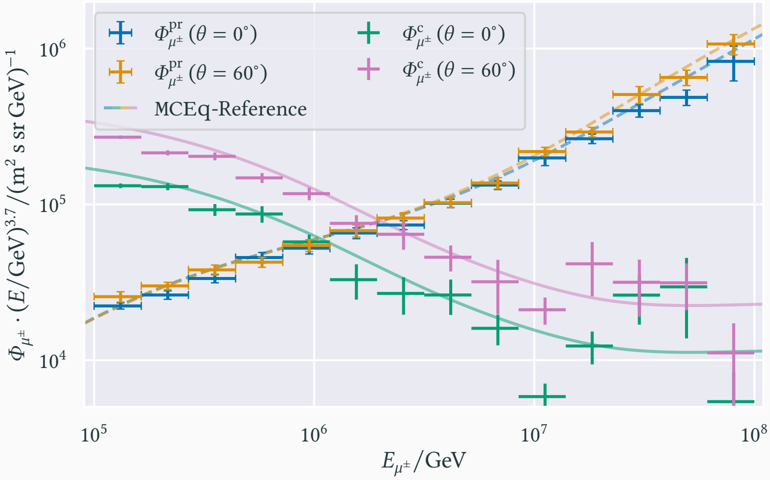
Gaisser Prompt Model



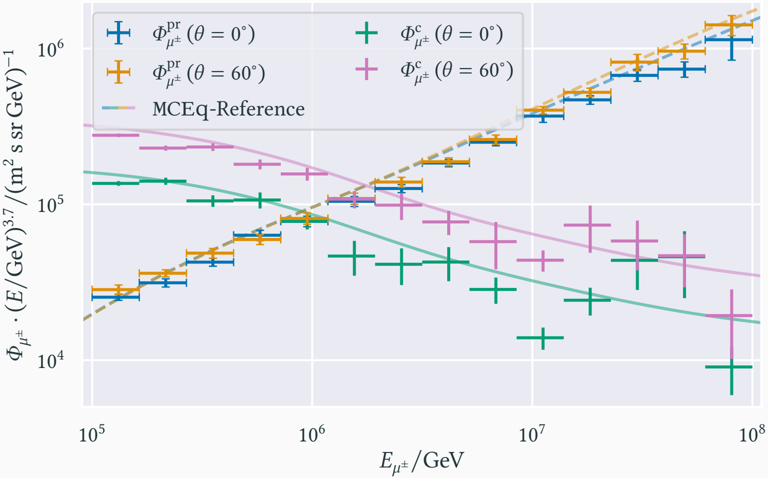
Weighting: H3a



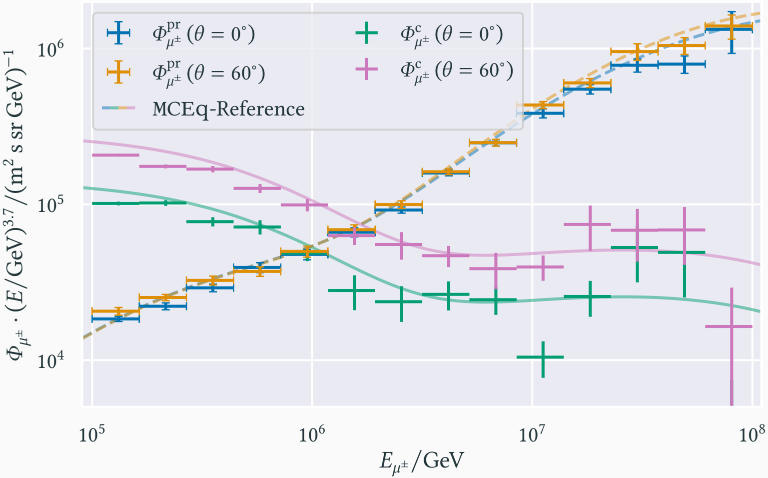
Weighting: H4a



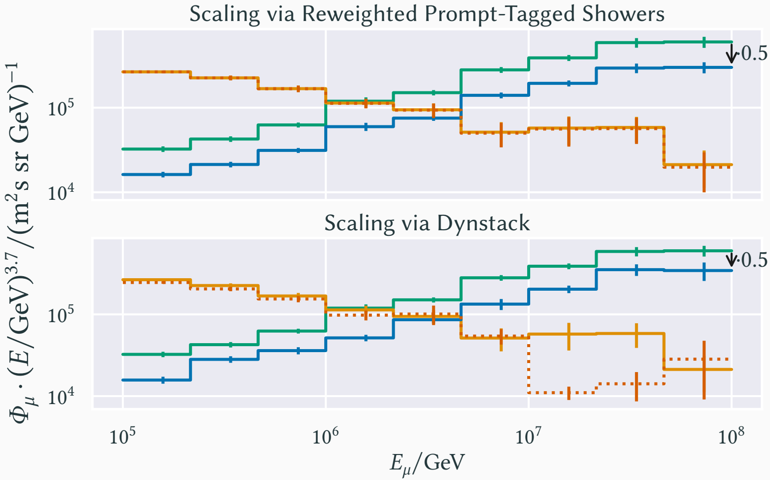
Weighting: GSF



Weighting: GST



Dynstack and Tagging



Dataset

Number	Primary	E_{min} / GeV	E_{max} / GeV	Spec. Index	Zenith-Angle
10×10^6	H1	1×10^5	1×10^9	-1	$0°$,$60°$
10×10^6	He4	1×10^5	1×10^9	-1	$0°$,$60°$
10×10^6	C12	1×10^5	1×10^9	-1	$0°$,$60°$
1×10^6	Si28	1×10^5	1×10^9	-1	$0°$,$60°$
1×10^6	Fe54	1×10^5	1×10^9	-1	$0°$,$60°$
100×10^3	H1	1×10^9	5×10^{10}	-1	$0°$,$60°$
100×10^3	He4	1×10^9	5×10^{10}	-1	$0°$,$60°$
100×10^3	C12	1×10^9	5×10^{10}	-1	$0°$,$60°$
10×10^3	Si28	1×10^9	5×10^{10}	-1	$0°$,$60°$
10×10^3	Fe54	1×10^9	5×10^{10}	-1	$0°$,$60°$