Treatment of atmospheric flux uncertainties

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Global fit workshop

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Why global fit

More precise determination of astrophysical flux

Direct comparisons between samples

Opportunity to probe other physics (e.g. prompt, flavor, BSM)

Try to get atmospheric flux systematics right

Origin of atmospheric flux systematics

Primary CR flux and composition is uncertain

Atmospheric density is uncertain

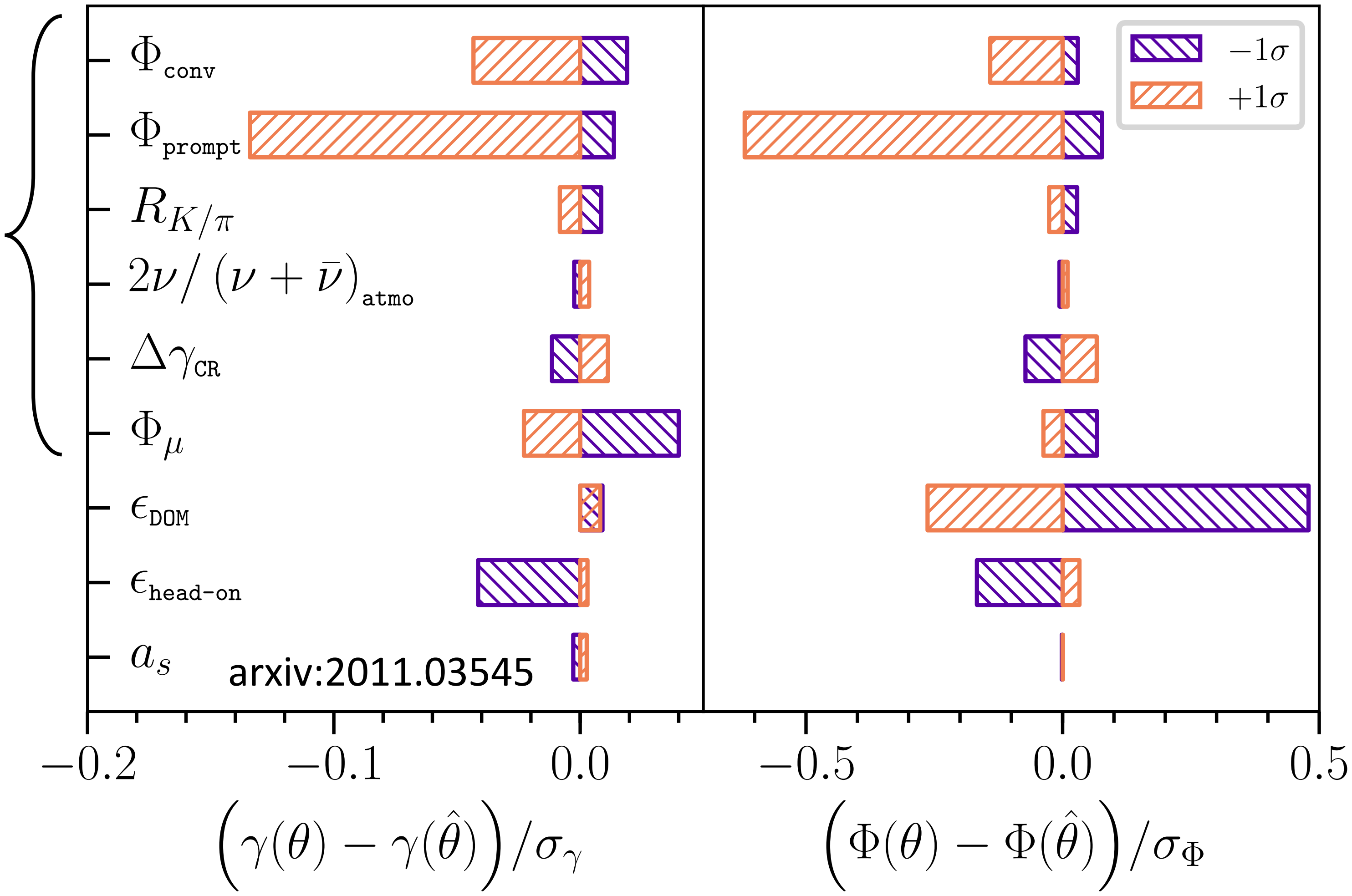
Hadronic interaction models at high energies are uncertain

As such, neutrinos and muons from decay of hadrons in atmosphere is uncertain

Additionally, atmospheric pile up (self-veto) is uncertain due to both flux and detector effects

Impact on astrophysical flux

These are all correlated but we treat them independently



Impact of varying one systematic parameter $\pm1\sigma$ on astrophysical flux

Higher statistics → more systematics limited

Previous plot: highest pull ~-0.6 on astro. norm due to prompt normalization term

Moving towards higher stats means we should be more careful with systematics treatment

Challenges:

- Lack of external data-driven constraints at high energies (progress and discussion: arxiv1909.08365)
- Lack of high statistics muons/bundles in MC
- Uncertainties due to the veto

Treatment in HESE

$$\phi_\nu^{\mathtt{atm}} = \Phi_{\mathtt{conv}} \left(\phi_\nu^\pi + R_{K/\pi} \phi_\nu^K \right) \left(\frac{E_\nu}{E_0^c} \right)^{-\Delta\gamma_{CR}} + \Phi_{\mathtt{prompt}} \phi_\nu^p \left(\frac{E_\nu}{E_0^p} \right)^{-\Delta\gamma_{CR}},$$

$\phi_\nu^{\pi/K}$: HKKMS06 flux (PRD.75.043006)
ϕ_ν^p: BERSS (JHEP.06.110)
$2\nu/(\nu+\bar{\nu})_{\mathrm{atmo}}$: modifies overall (anti)neutrino flux

Systematic terms act as coefficients on templates
Priors externally motivated to some approximation

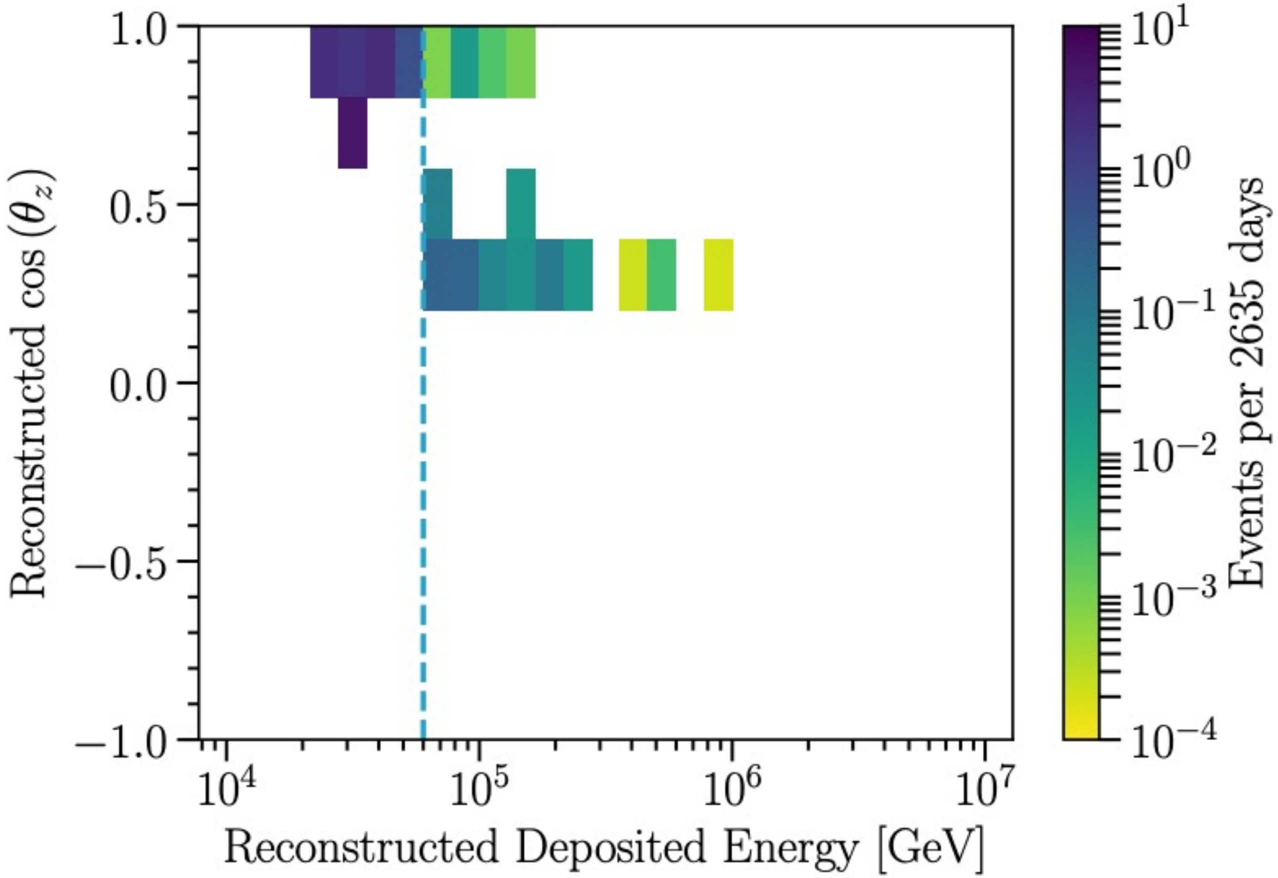
Atmospheric muon background in HESE

Evaluated using MuonGun

Scaled up 2.1x from data-driven factor

- Outer and inner layer veto
- Compare data/MC for events that trigger outer layer but not inner layer

Resulting template →



Self-veto in HESE (7.5 year)

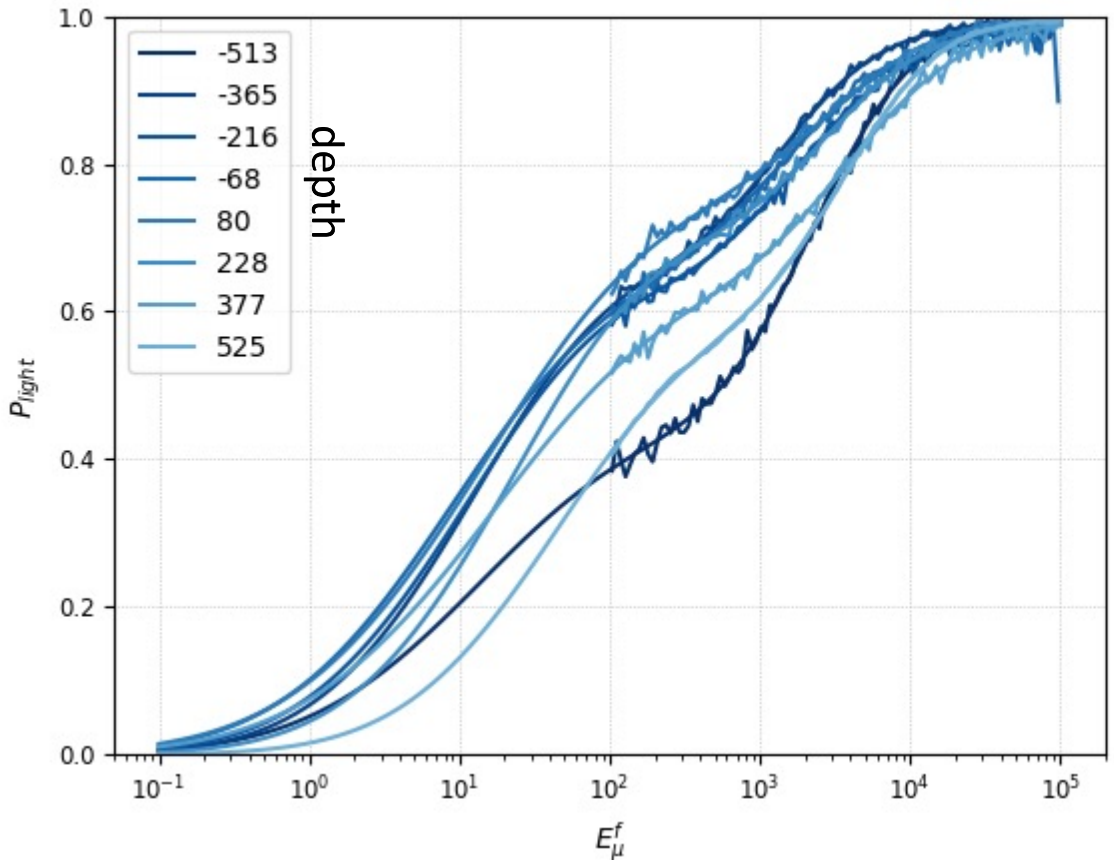
Assuming: H3a primary CR flux + SIBYLL2.3c interaction

- Effect of variations on astro. flux was small

Detector response parametrized using MuonGun simulations →

- Extrapolated below 100 GeV

Probability of triggering veto



Treatment in Multi-year Cascades

Similar parameters as HESE

Hadronic interaction uncertainties on atmos. nu flux were studied using MCEq

- Found to be small and thus neglected

MuonGun for single muon MC

- Studied using control sample

TABLE II. Best fit values and uncertainties for all parameters included in the single power-law fit. PRL.125.121104

Parameter	Prior constraint	Result $\pm 1\sigma$ ($<$ 90% upper limit)
γ	...	$\mathbf{2.53 \pm 0.07}$
ϕ_{astro}	...	$\mathbf{1.66^{+0.25}_{-0.27}}$
ϕ_{conv}	...	$(1.07^{+0.13}_{-0.12}) \times \Phi_{\mathrm{HKKMS06}}$
ϕ_{prompt}	...	$< 5.0 \times \Phi_{\mathrm{BERSS}}$
ϕ_{muon}	...	1.45 ± 0.04
$\Delta\gamma_{\mathrm{CR}}$	0.00 ± 0.05	0.02 ± 0.03
$\epsilon^{\mathrm{BI}}_{\mathrm{scat}}$	1.00 ± 0.07	1.02 ± 0.03
$\epsilon^{\mathrm{BI}}_{\mathrm{abs}}$	1.00 ± 0.07	$1.03^{+0.05}_{-0.04}$
$\epsilon^{\mathrm{HI}}_{\mathrm{scat}}$	...	1.72 ± 0.19
$\epsilon^{\mathrm{DOM}}_{\mathrm{eff}}$	0.99 ± 0.10	$1.03^{+0.08}_{-0.07}$

Treatment of self-veto in MyC

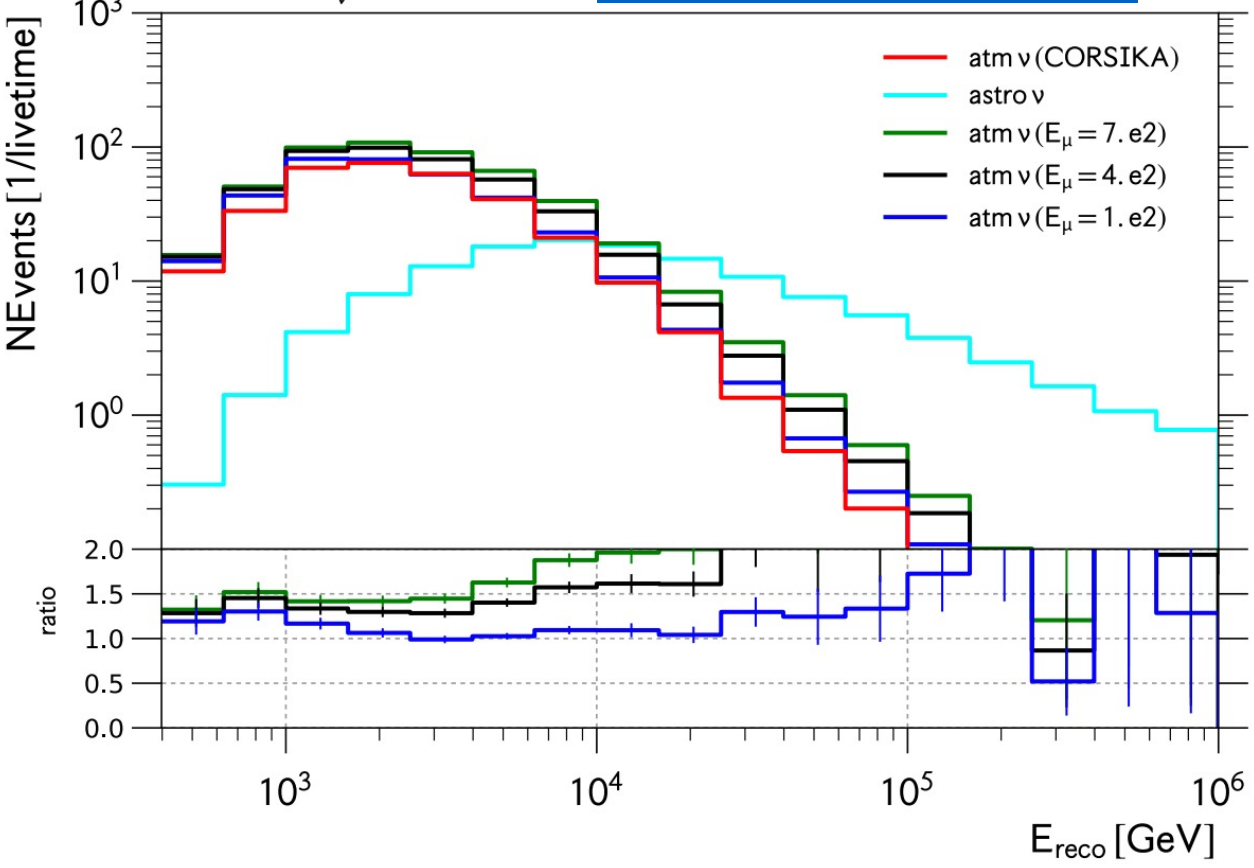
Self-veto approximated assuming 100 GeV muon threshold

- Step function at 100 GeV (all higher-E muons will veto the event)
- Tested with different thresholds (100, 400, 700) GeV

Less impact at lower energies where atmospheric nu flux dominates

- Conclusion was impact negligible
- However, probably important to distinguish prompt

Hans N. diffuse call 1/24/18



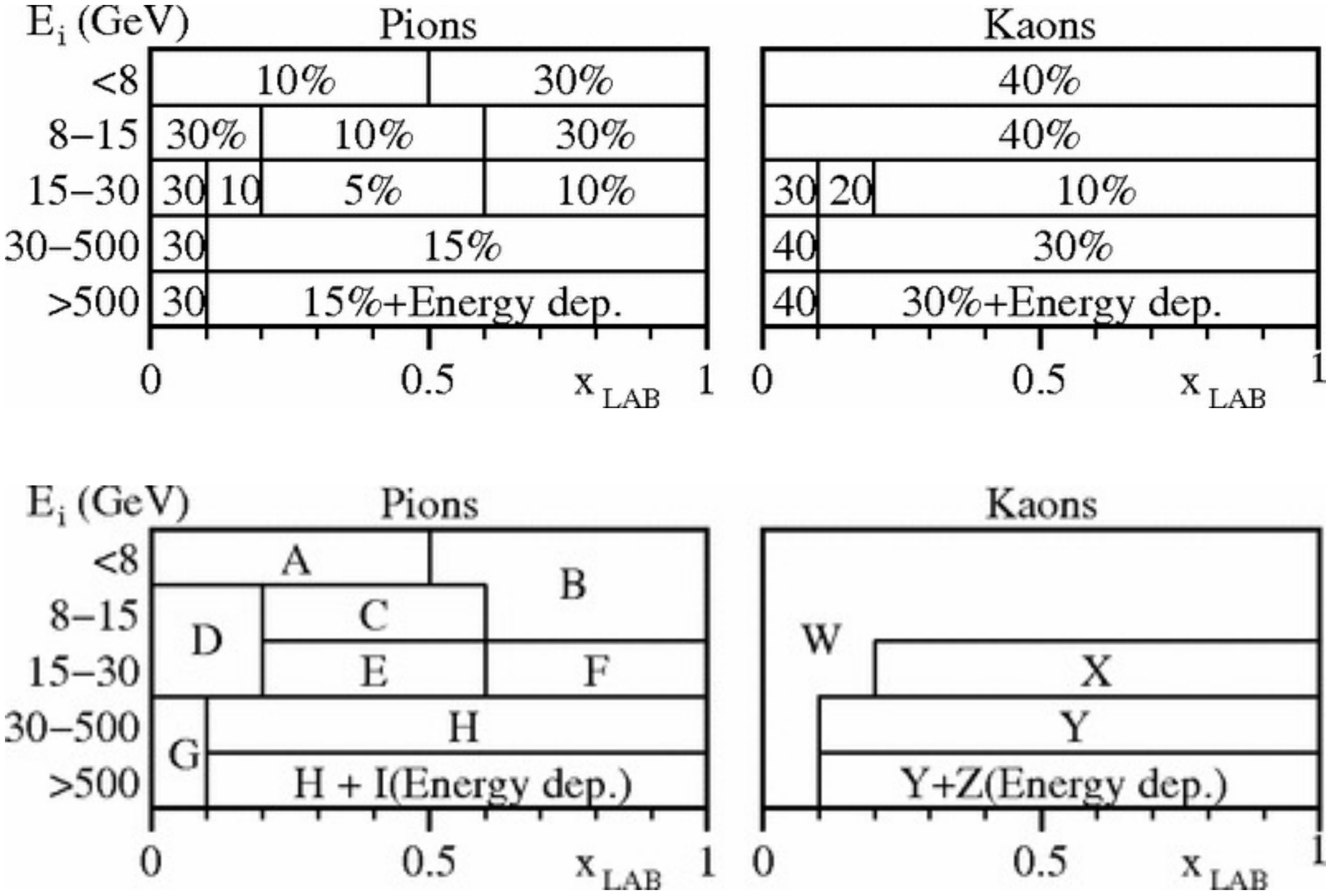
Treatment in Diffuse-Numu (9.5 year)

Includes normalizations $\phi_\nu^{conv}, \phi_\nu^{p}$, and $\Delta\gamma_{CR}$

In *addition*:

$\lambda_{CRModel}$ linearly interpolates between H4a and GST-4gen flux models based on MCEq

Hadronic interaction uncertainties varied based on (Barr et al. PRD.74.094009) in regions H, W, Y and Z

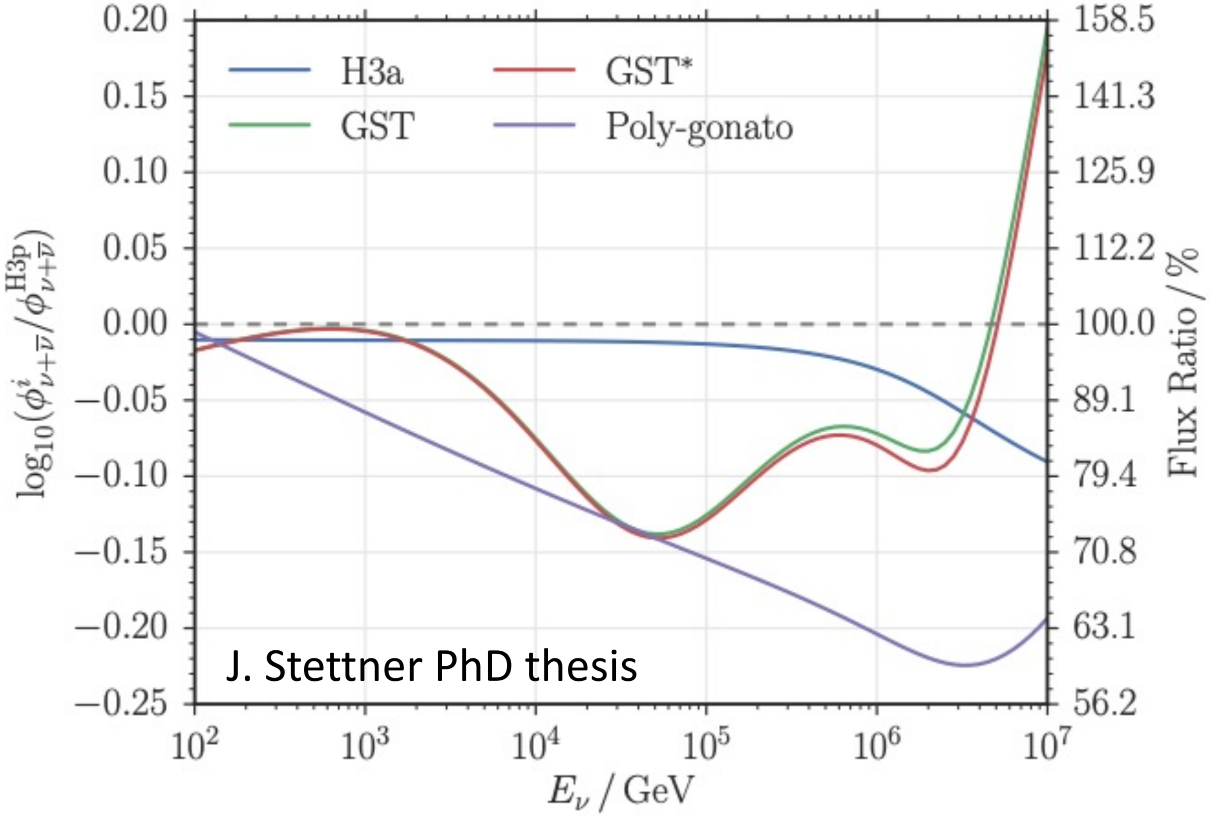


Overlapping systematics

Basing variations on MCEq is an improvement

But now systematics overlap

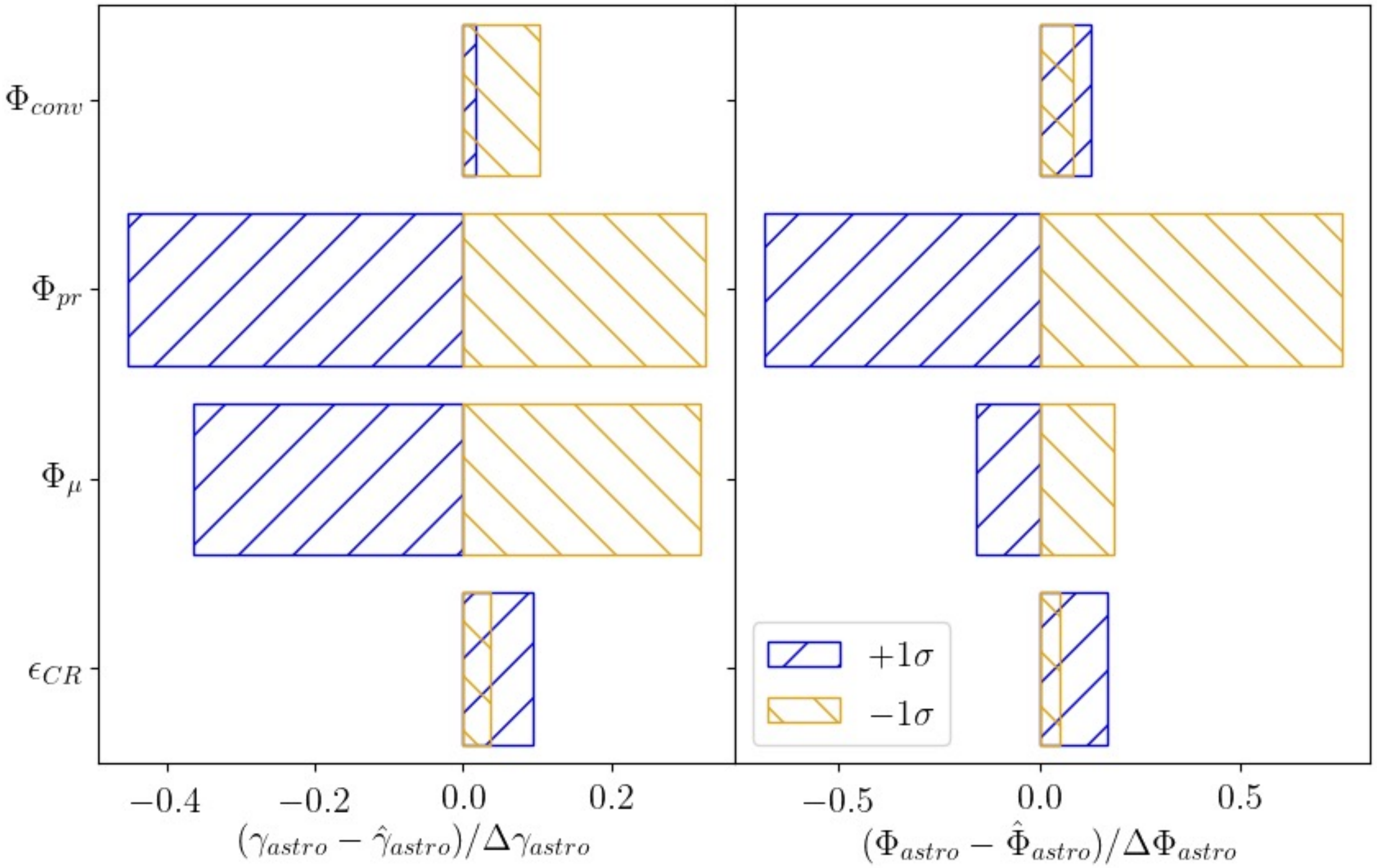
- E.g. $\lambda_{CRModel}$ and hadronic interaction variations both affect ϕ_{ν}^{conv}
- Probably more conservative but can do better



ESTES treatment (WIP)

ESTES-diffuse also plans to use MCEq for CR and hadronic uncertainties

Manuel studied implications of overlapping/correlated systematics



Plots by Manuel
Thanks!

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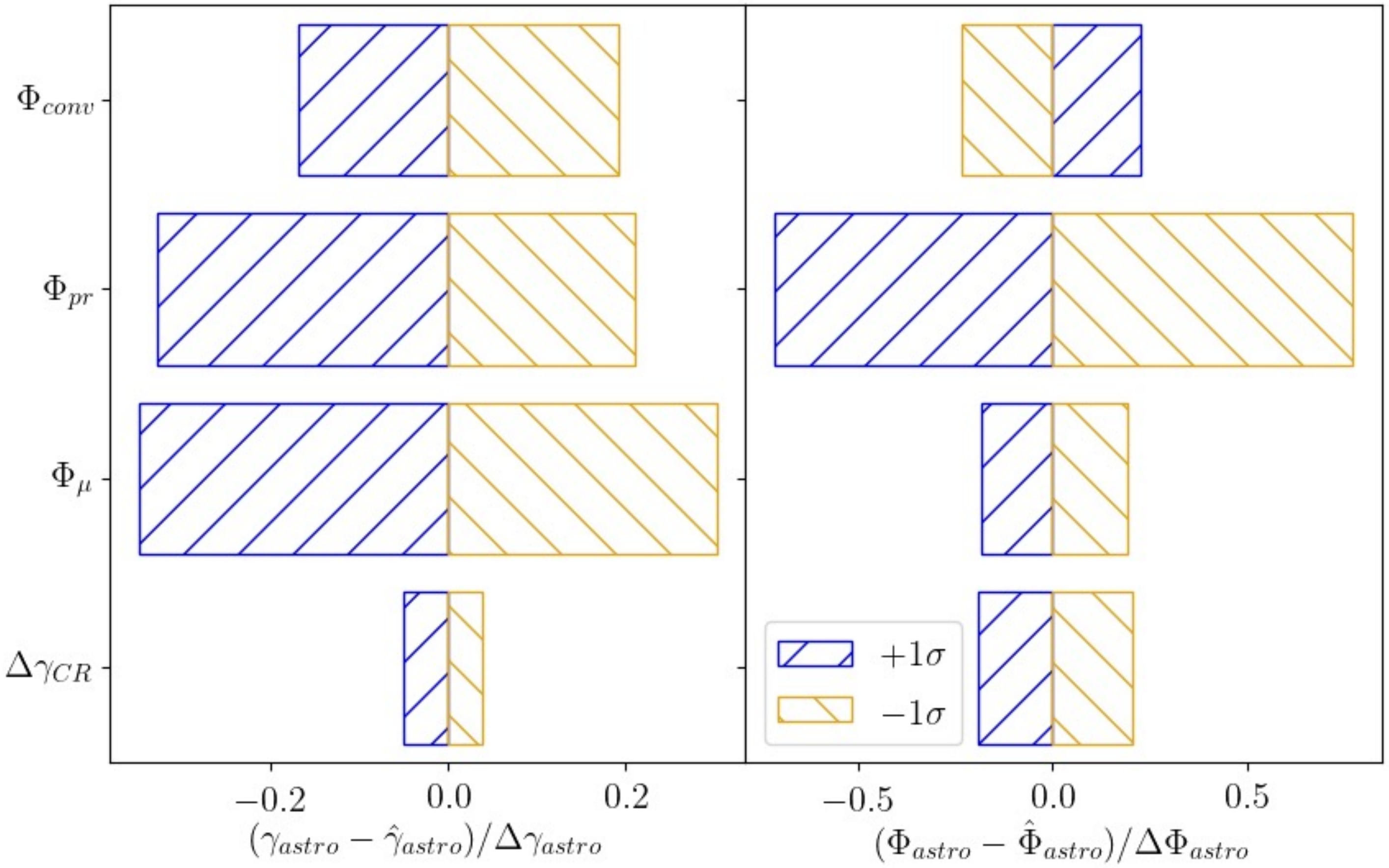

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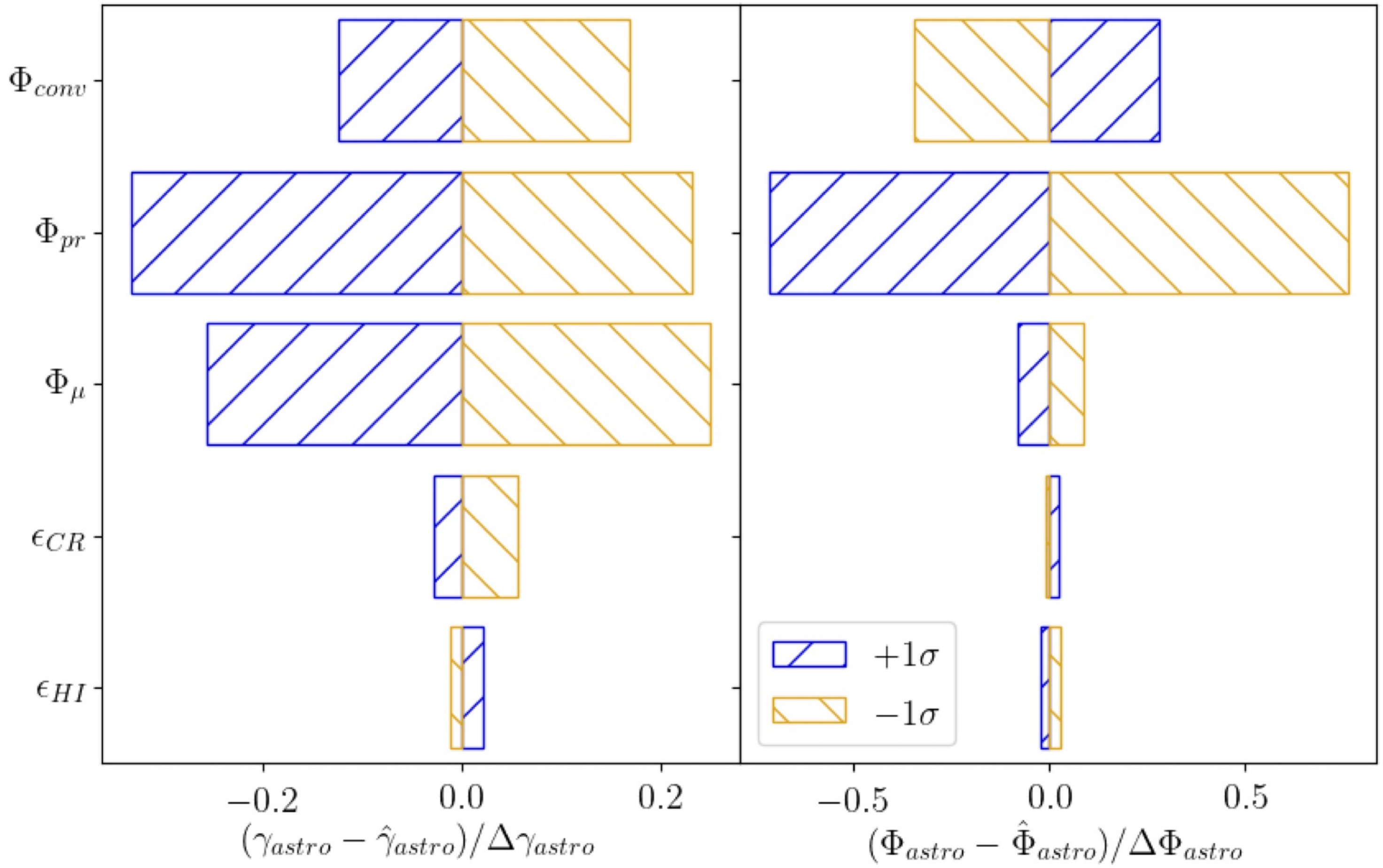
Thanks!

New approach

Keep ϕ_{conv} and ϕ_p as normalization terms

Use MCEq-derived uncertainties to vary shape only



Plots by Manuel
Thanks!

Discussion items

1. Unify treatment of atmospheric flux systematics

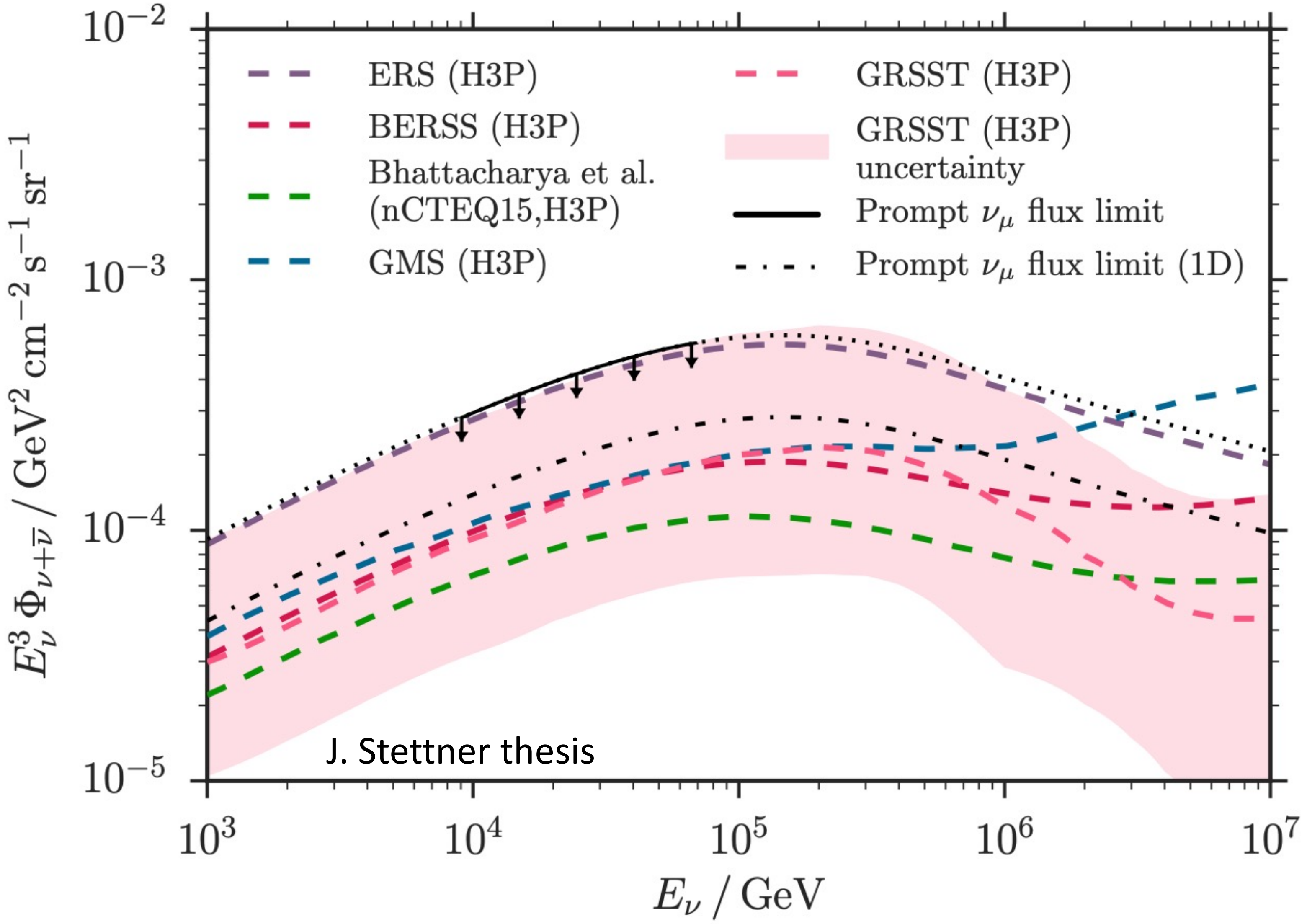
2. Remove the older parametrizations and switch to MCEq-derived errors for e.g. normalization terms
   - Alternative could be to separate normalization and shape uncertainties

3. Include a self-veto systematic (detector and atmospheric)
   - Parametrized detector approach needs to be carefully thought through
   - Atmospheric part should feed through consistently

4. Try to improve background MC statistics

Backups

Prompt flux



ERS (H3P)
BERSS (H3P)
Bhattacharya et al. (nCTEQ15,H3P)
GMS (H3P)
GRSST (H3P)
GRSST (H3P) uncertainty
Prompt ν_μ flux limit
Prompt ν_μ flux limit (1D)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$E_\nu^3\,\Phi_{\nu+\bar{\nu}}$ / GeV^2 cm^{-2} s^{-1} sr^{-1}
10^3
10^4
10^5
10^6
10^7
E_ν / GeV
J. Stettner thesis