# Towards a GlobalFit of IceCube's Neutrino Data - Tracks and Cascades

Erik Ganster, Richard Naab, Zelong Zhang

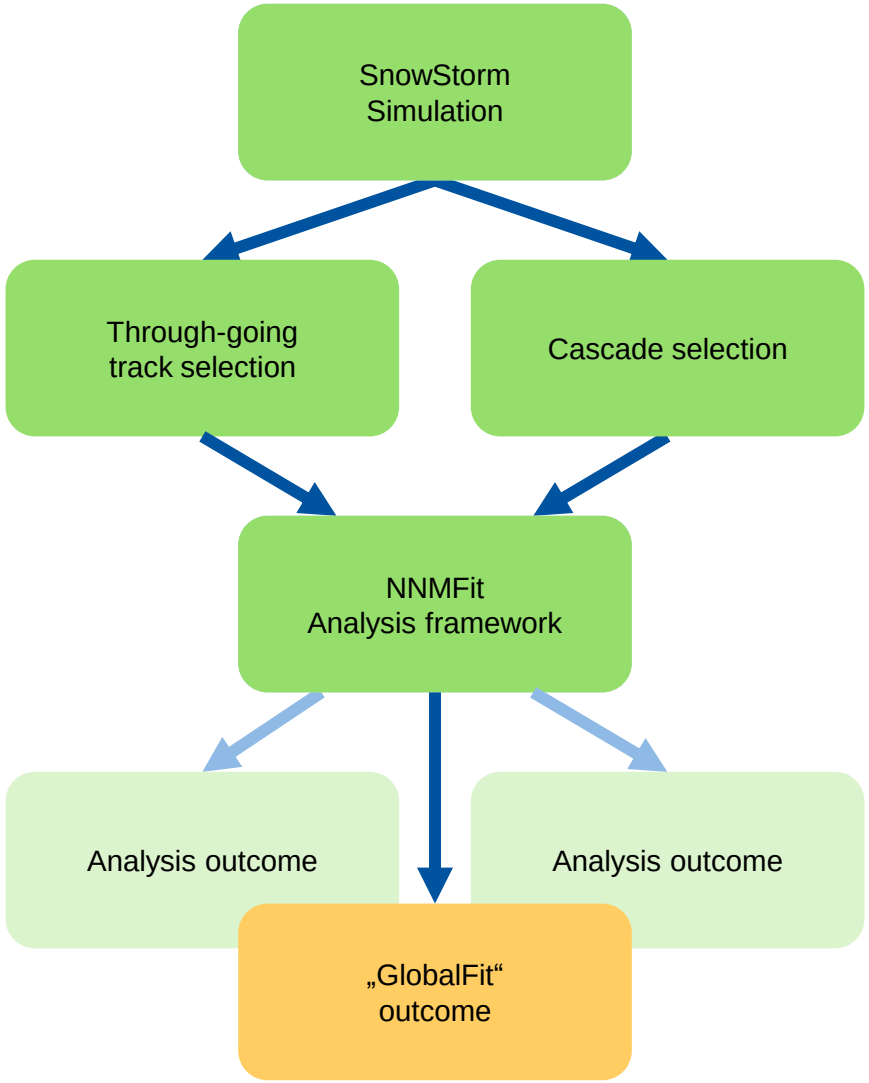
# Towards a GlobalFit

- Richard + Zelong joined the team
- ➢ Goal: combine DiffuseNuMu + Cascades into a first version of a GlobalFit for ICRC

- SnowStorm MC is available and fully processed to both FinalLevel event selections

- Use of the NNMFit analysis framework (github)
  - Originally developed for NuMu, but not limited to it
  - Reduces framework development overhead
  - Simplifies the final combination of the sub-analyses: they are already done in the same framework

- NNMFit was used für DiffuseNuMu already, need to verify it for Cascades
  - The Cascade sample has three “sub-samples”: cascade signal, starting tracks, muons

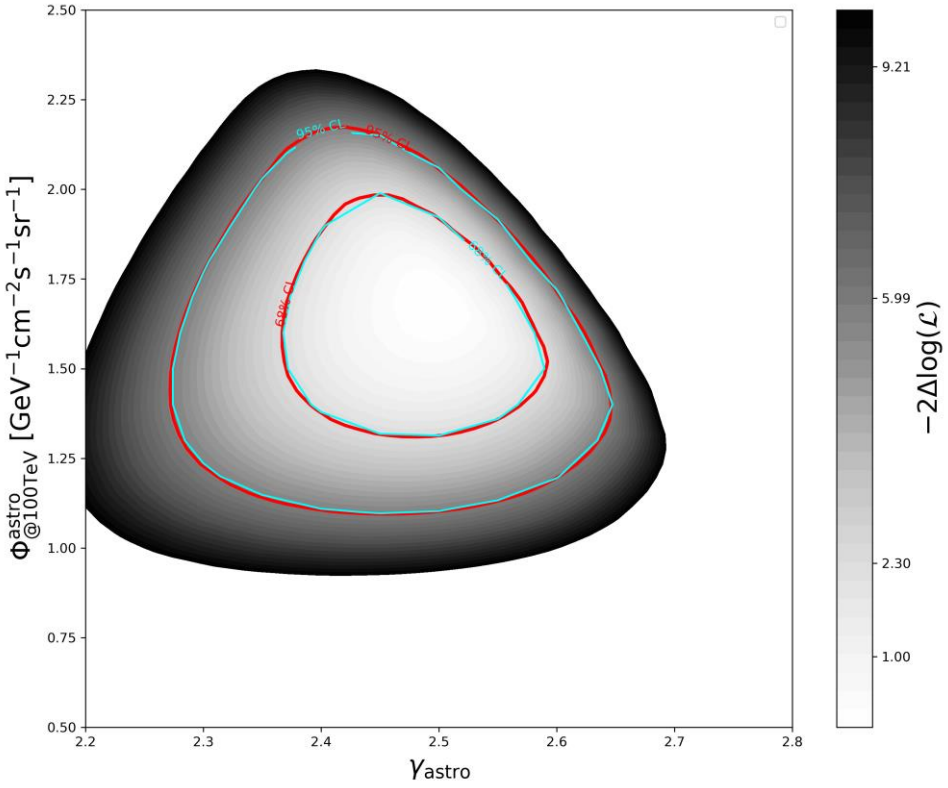


# NNMFit and Cascades

- Colored LLH + red conturs: NNMfit
- Other lines: Zelong's default fit

✓ Verified that NNMfit produces the same fit results/contours for the cascade analysis compared to their default fitting tool
  ✓ Using the same MC + nuisance parameters + conventional neutrino prediction

➢ Performed Asimov fits, 1D and 2D LLH scans of tracks/cascades alone + their combination



# Flux Components/Parameters – Asimov Settings

- Used parameters/components:
  - Astrophysical (SPL):
    - astro_norm, gamma_astro
  - Conventional:
    - conv_norm, delta_gamma, CR_grad
  - Prompt component:
    - prompt_norm, delta_gamma, CR_grad
  - Muons (cascades):
    - muongun_norm
  - Detector systematics:
    - DOMEfficiency, IceAbsorption, IceScattering, HoleIceForward_p0 via SnowSotrm reweighting

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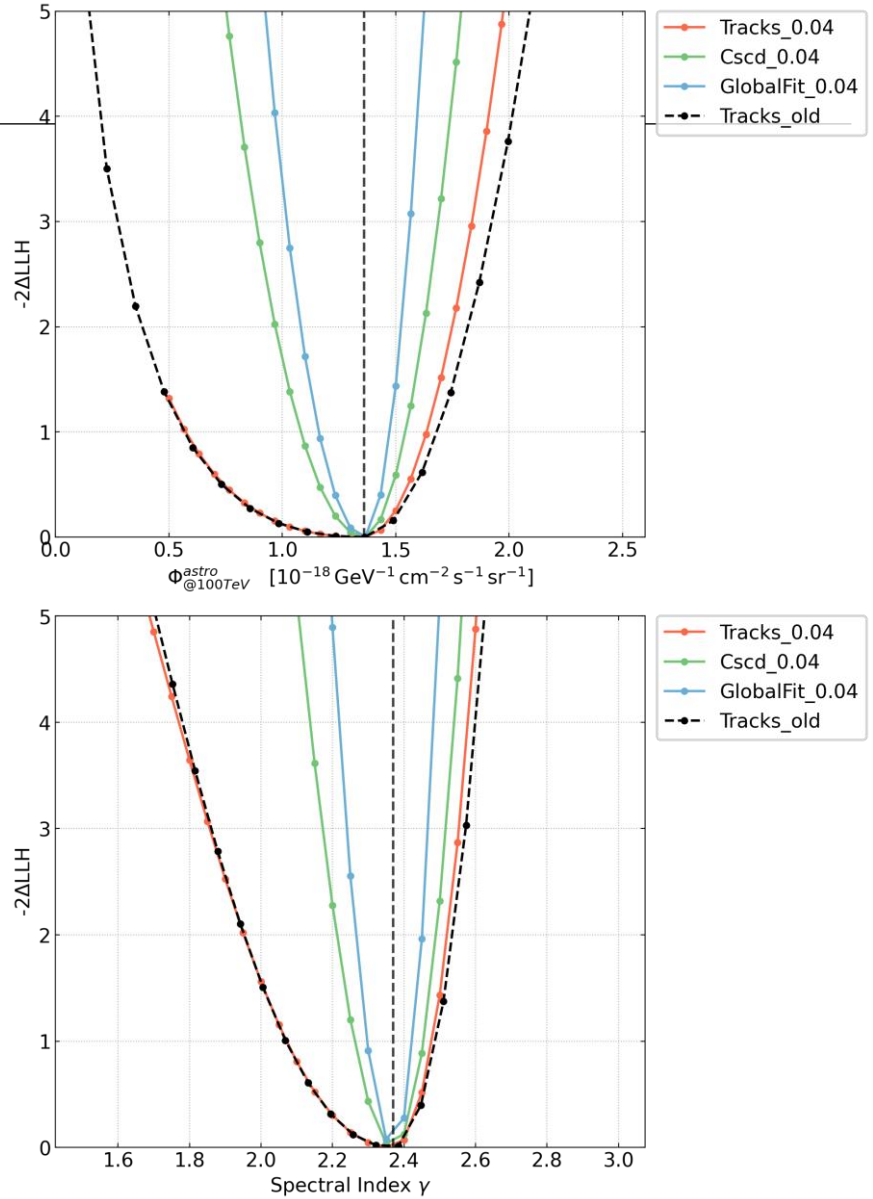
- Barr parameters for modelling atmospheric uncertainties not included yet
  - Small issue with the new splines, not fully understood but ready to fixed
- MuonTemplate for tracks
  - Due to the way Jöran implemented this, it was not directly applicable anymore
- Currently used a livetime of 5.8 yrs
  - Plan to update to 10yrs which is much more realistic for both samples
- Detector systematics not included:
  - HoleIceForward_p1, IceAnisotropy

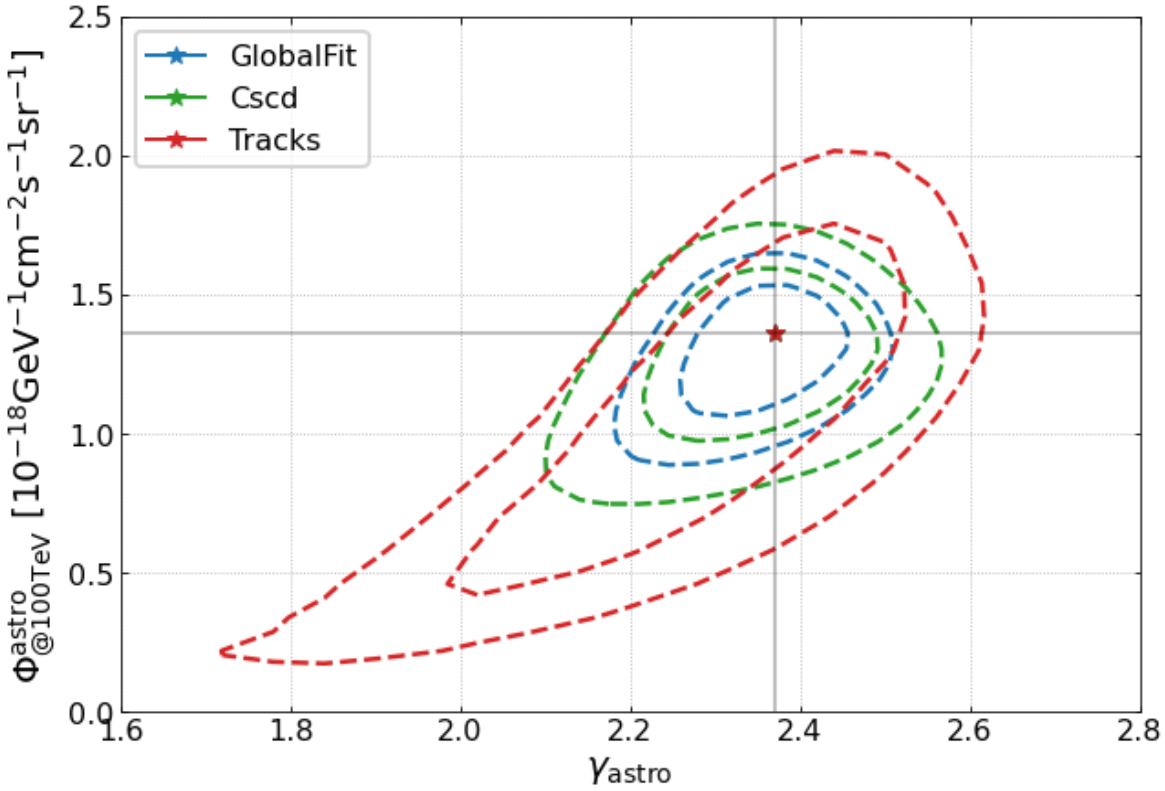
# Signal Parameters (SPL) – 1D

- ✓ Asimov fit is working with both standalone analyses + GlobalFit
  - ✓ Red: Tracks only
  - ✓ Green: Cascades only
  - ✓ Blue: “GlobalFit”
- ✓ Standalone track fit is almost identical in the signal parameters compared to the previous fit iteration
  - – Black: Jöran’s MC + systematic treatment
- ✓ Combination of tracks + cascades leads to a better constrainment of both signal parameters
- • Systematic reweighting using a Gaussian
- ➢ This is 1D only, how does a 2D scan look like?



# Signal Parameters (SPL) – 2D

- ✓ 2D asimov scan of both single power law signal parameters
- ✓ Again: GlobalFit contour (blue) is the smallest one
- The correlation „harder index“ → „lower norm“ is much stronger for tracks than for cascades
- Tracks (only) contour is by far the largest
  - Cascade's energy reconstruction is expected to be closer to the true neutrino energy

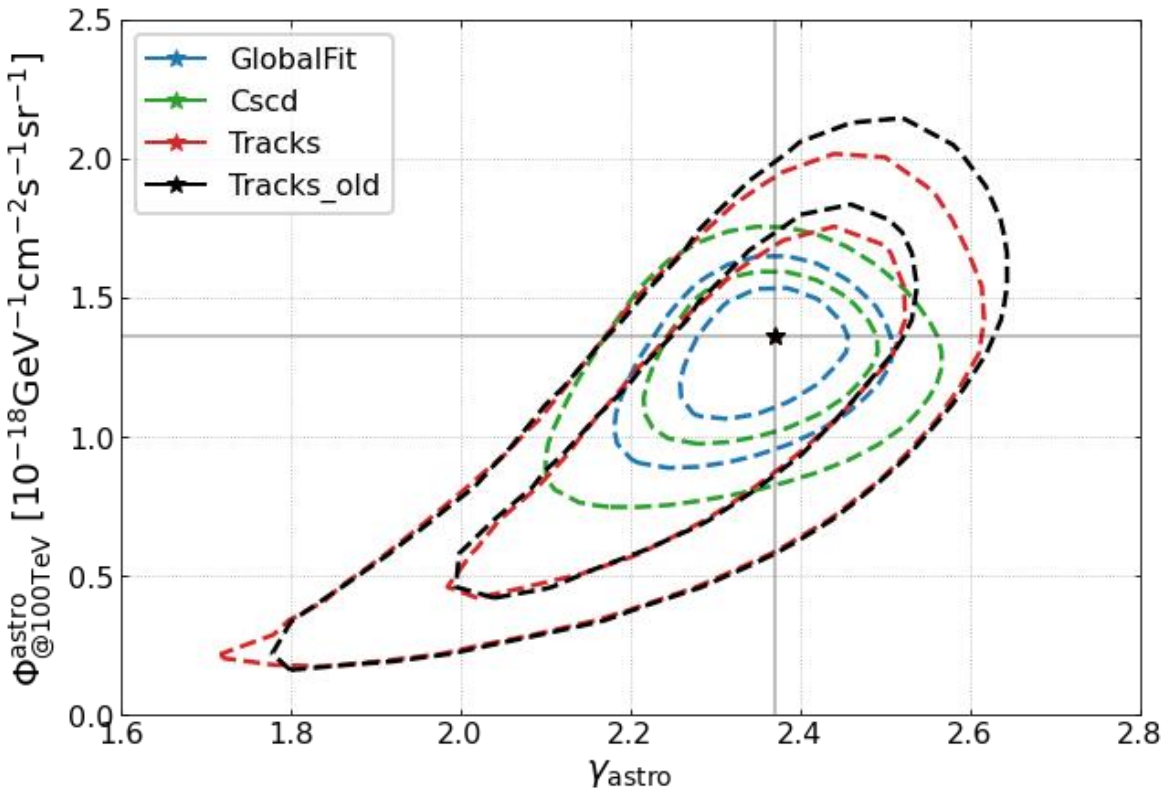


# Signal Parameters (SPL) – 2D

- ✓ As for the 1D scans: perform an identical Asimov scan but using the „old“ (non SnowStorm) MC and systematic treatment (Jöran’s analysis)
  - ✓ Black contour: Almost identical, old contour slightly larger for the ”top right” corner

- „lower left” tail for the tracks is much larger in Asimov than in real data due to a much stronger correlation of both signal parameters in an idealized Asimov sample
  - Is the truth really a SPL?

- ➢ Signal parameters look ok, how does the detector systematics with the new SnowStorm treatment look like?

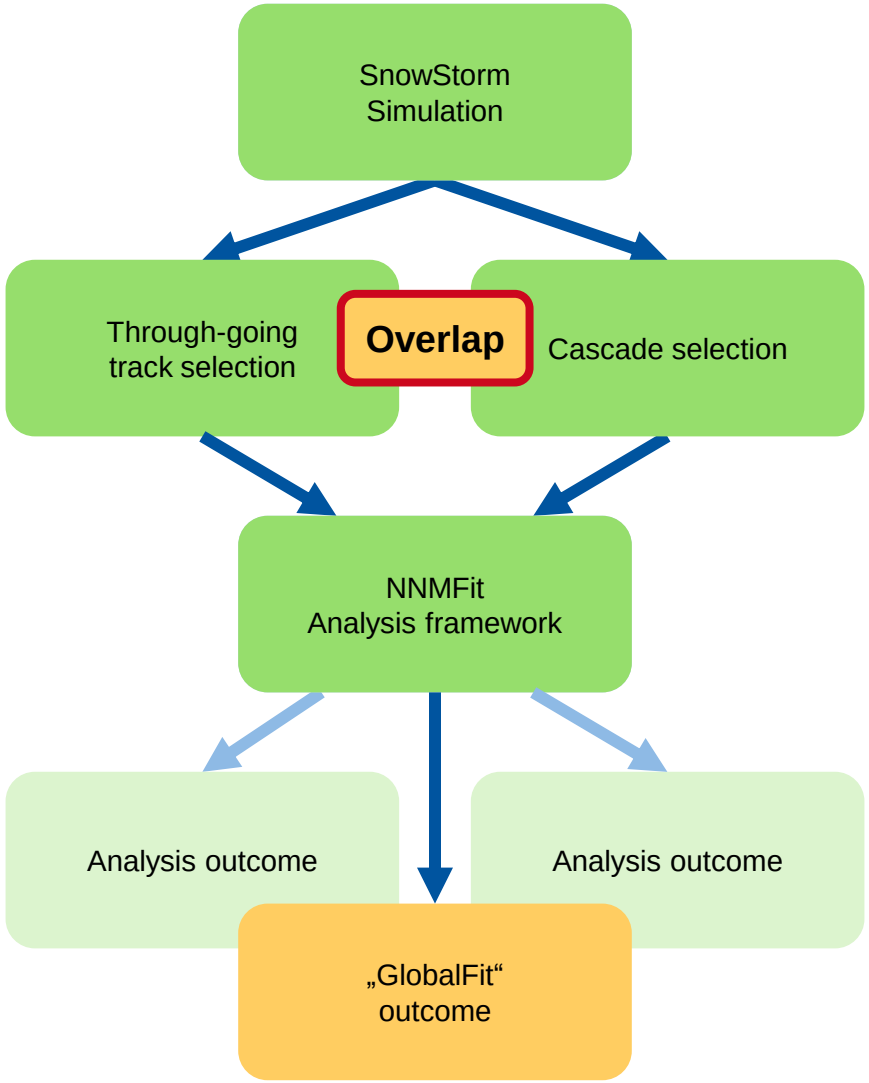


# GlobalFit – Sample Overlap

- We have a certain event overlap for both selections:
  - FinalLevel DiffuseNuMu: ~5.1e6 events
  - FinalLevel Cascade (Signal): ~2.3e5 events
  - ➢ Total event overlap: 899 events

- Test to fully remove those overlap events from either sample and repeat the fit/scan

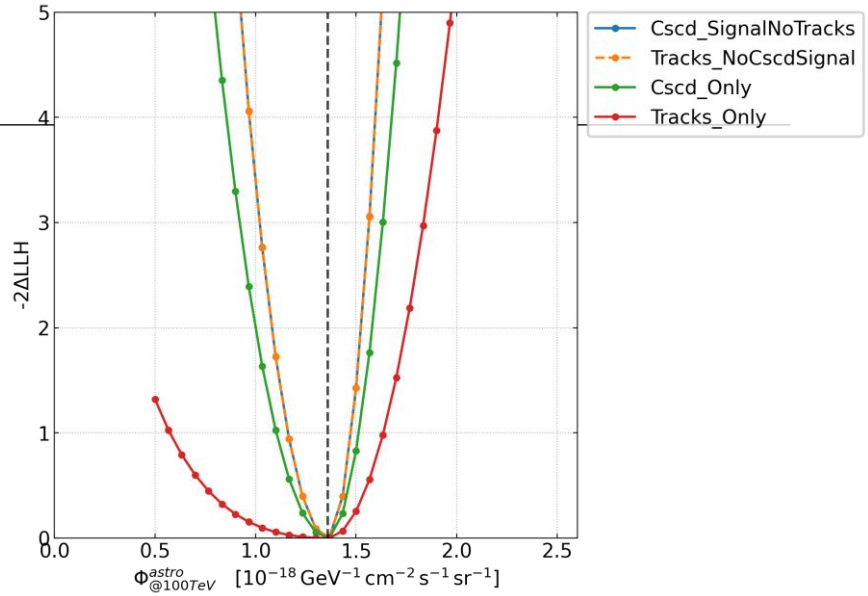
- A few notes:
  - Worse (more) overlap for the Cascade starting track sample
    - We haven't used that sample for the scans shown before, good handle of the conventional norm from the track sample in the combined fit

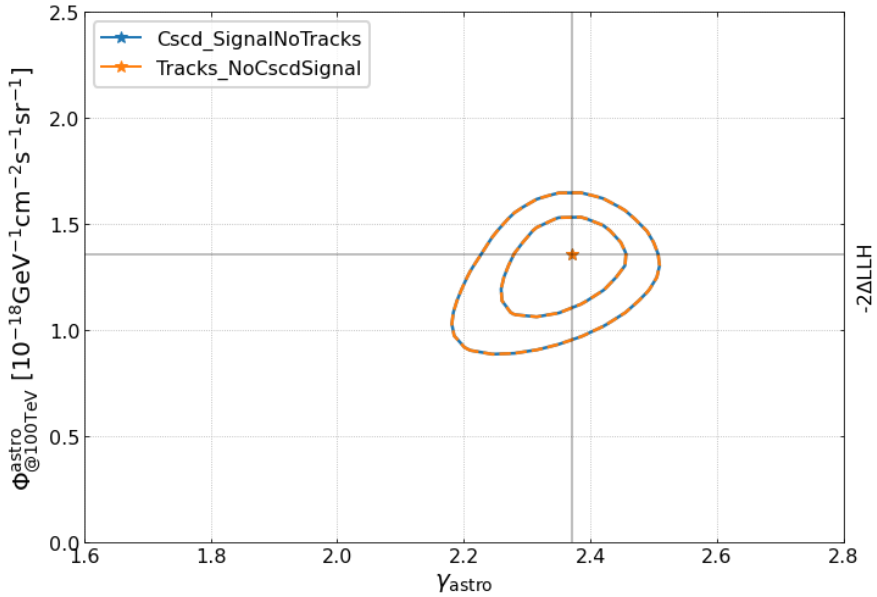


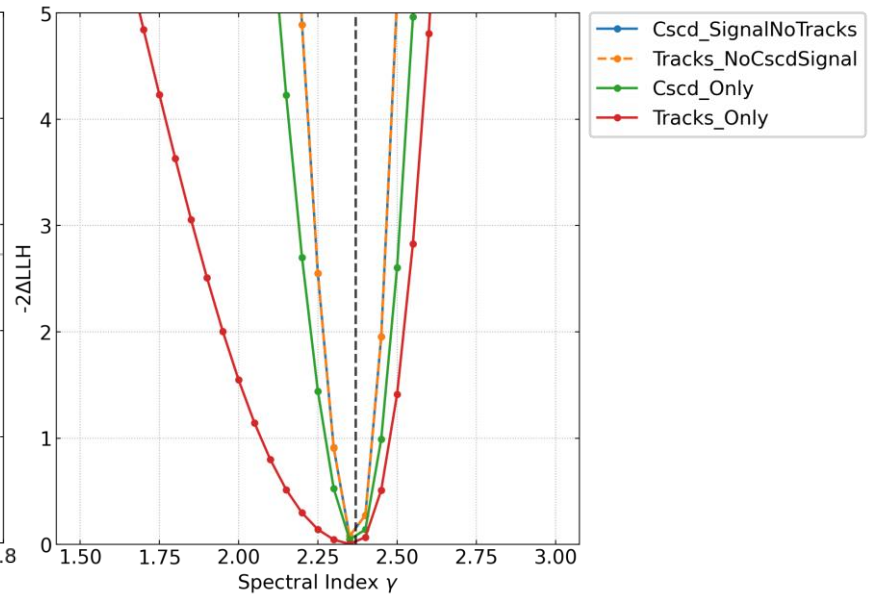
# GlobalFit – Sample Overlap

- Green/Red: Cascades/tracks only
- Blue: Full track sample, overlap removed from cascades signal
- Orange: Full cascade sample, overlap removed from tracks

➢ Conclusion: It doesn‘t matter, both yield exactly the same contours/results



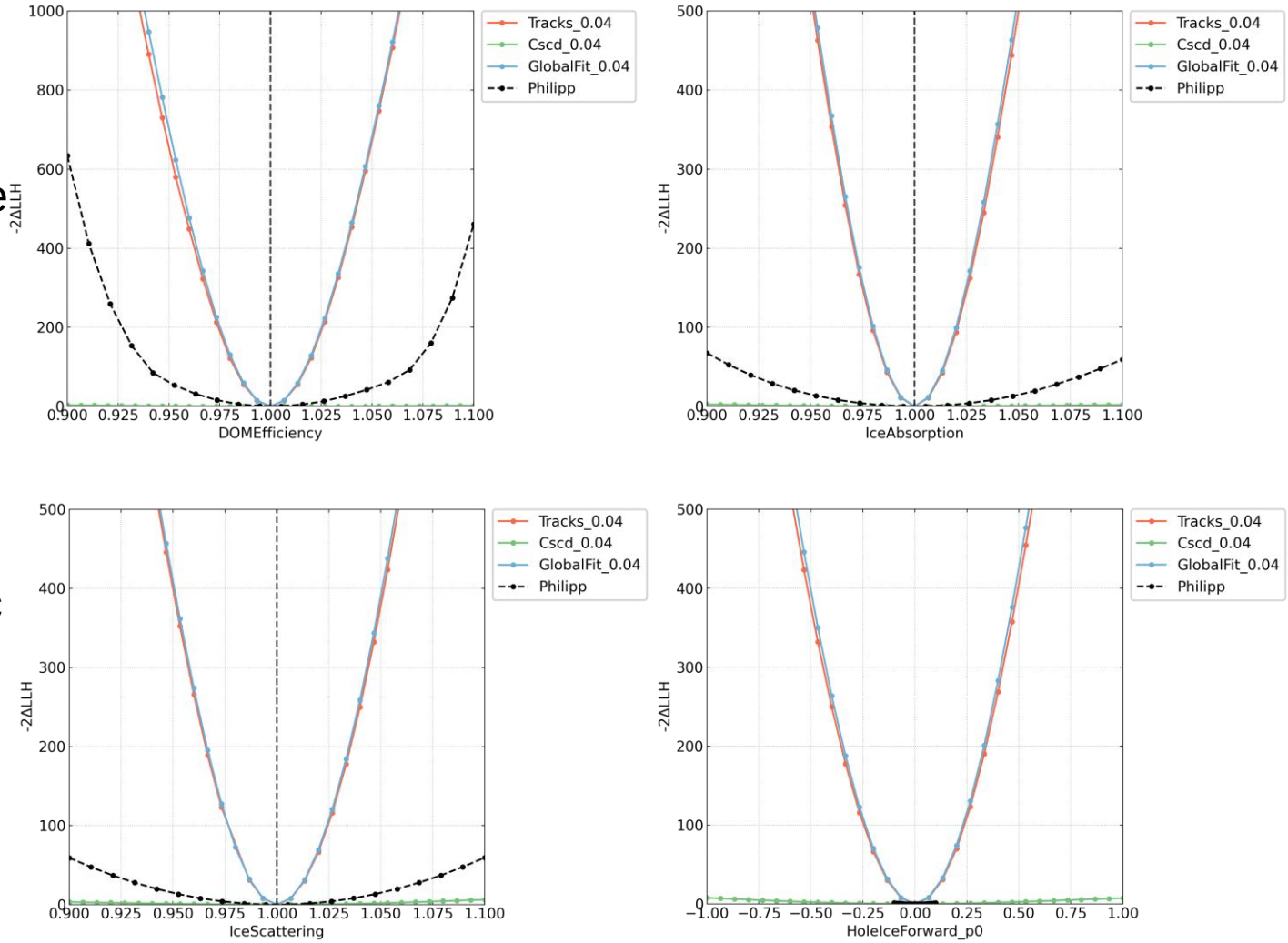



# Detector systematics

- 1D profile LLH scans of all detector systematics
- Qualitative: almost no sensitivity for the cascade standalone analysis compared to the tracks…
- GlobalFit closely to the tracks

➢ Difference for tracks using SnowStorm vs. old/previous systematic treatment
  ➢ Much smaller profile for SnowStorm

➢ Reminder, how does the SnwoStorm systematic treatment work



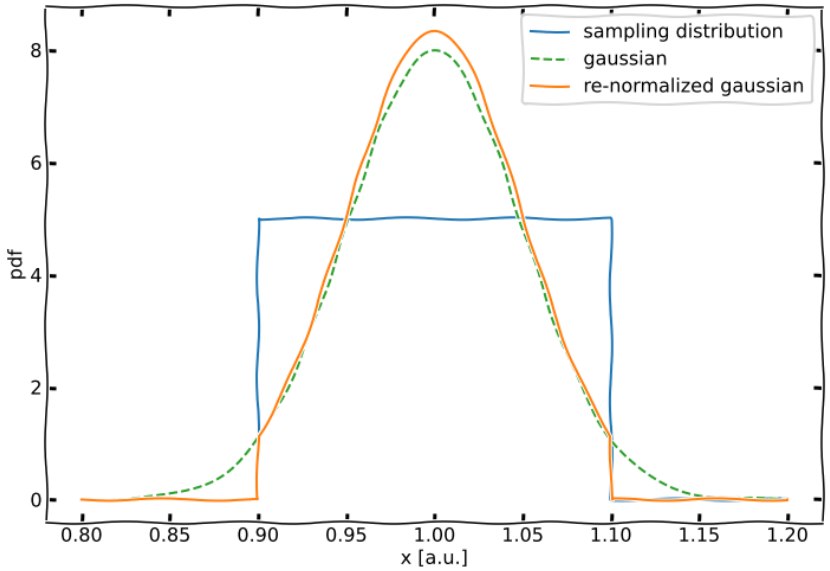
# Systematic Treatment – SnowStorm Reweighting

- Re-weighting of the SnowStorm parameters within the MC set to a Gaussian on analysis level
  - Directly yields a MC prediction for a specific choice of nuisance parameters, i.e. the current hypothesis, in the fit

- Can easily be achieved by adding an additional weight to each MC event:

$$w_i = \frac{p_{sys}\,(sys_i, \xi_i)}{p_{sys}^{sim}(sys_i)} \cdot \ldots$$

$p_{sys}$ : reweighting distribution
$p_{sys}^{sim}$ : sampling distribution
$sys_i$ : event's systematic value
$\xi_i$ : nuisance parameter

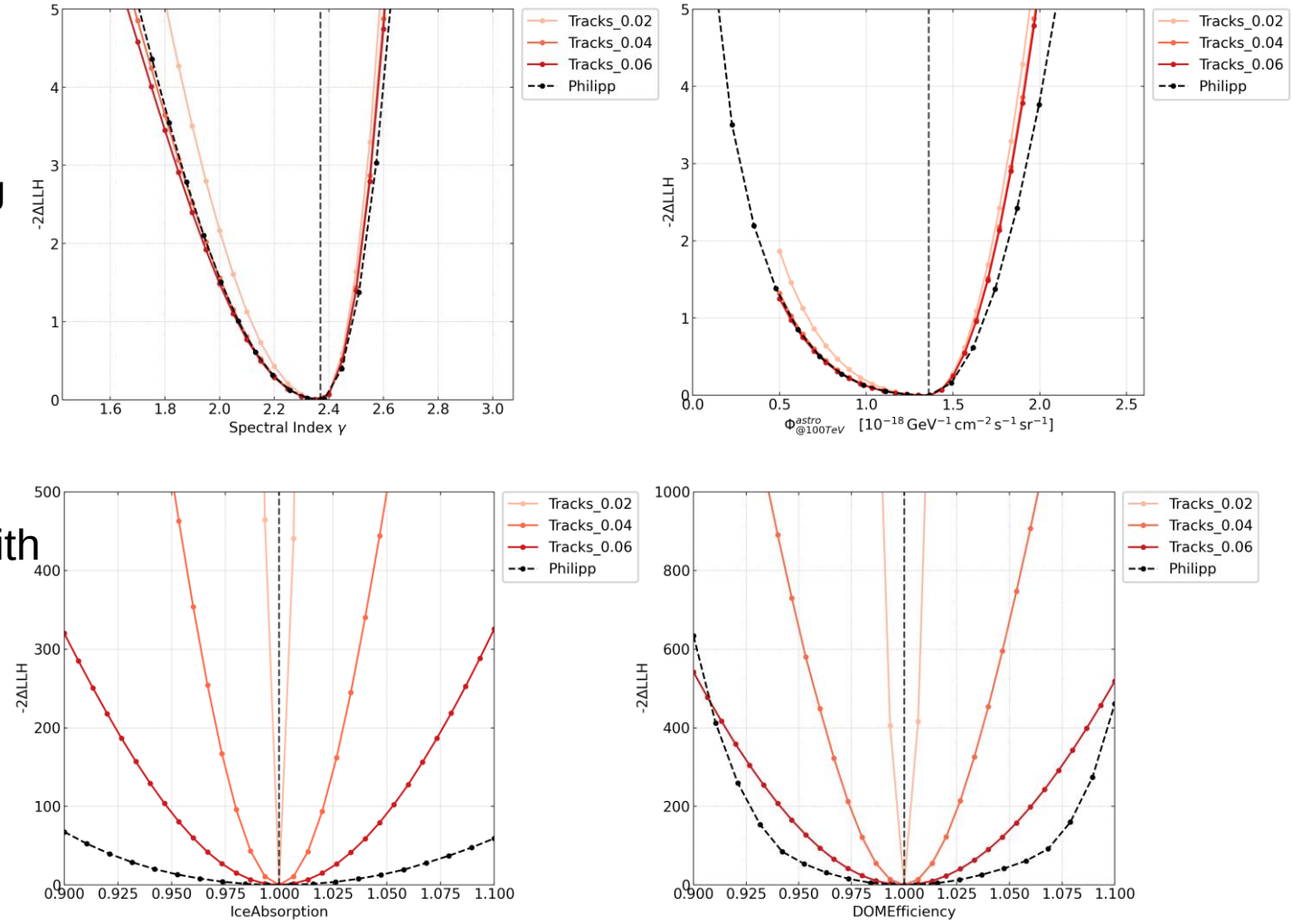



- $\mu$: nuisance parameter value
- $\sigma$: the smaller, the better the predictionbut the lower the statistics… try different widths?

# Detector systematics – Focus on Tracks

- Tried different widths of the Gaussian used for reweighting (label)
  - Corresponds to 10/20/30% of the uniform sampling distribution
- Similar to what we showed at the Collaboration meeting: almost no change for the signal parameters (good), but large changes for the systematics (bad?)

❖ Attention: the asimov sets here were created with the different Gaussian widths as well.
  - ❖ Fix the Asimov set? Use the full SnowStorm set (no reweighting/injecting), same/single Gaussian width for injection?
  - ➢ Some more plots in the Backup



# Some thoughts on the SnowStorm MC statistic…

# Effective number of MC events / effective weights

## Definitions

For one bin with m events:

$$\mu = \sum_{i=1}^{m} \omega_i \qquad \sigma^2 = \sum_{i=1}^{m} \omega_i^2$$

Obtain effective number of MC events $m_{eff}$ & effective weight $w_{eff}$:

$$m_{eff} = \frac{\mu^2}{\sigma^2} \qquad \omega_{eff} = \frac{\sigma^2}{\mu}$$

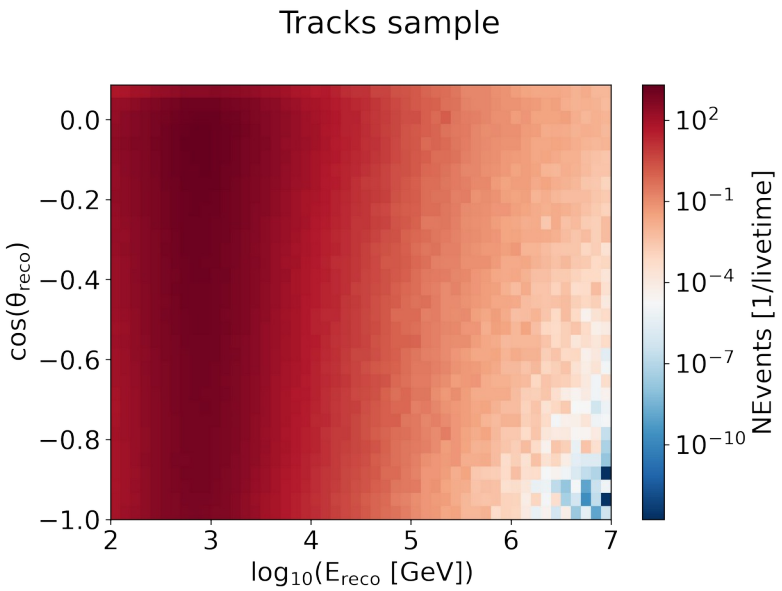
Interpretation? We obtain a per-bin prediction with MC → subject to fluctuations (following a compound Poisson distritbution (CPD), as were dealing with weighted MC). Approximate CPD with scaled Poisson distribution with parameters $m_{eff}$ and $w_{eff}$

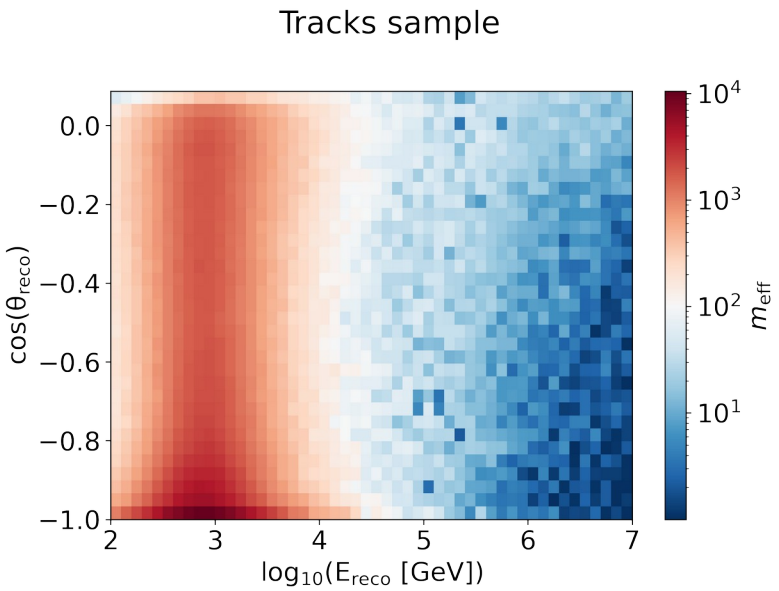
The per-bin estimation $\lambda = m_{eff} * w_{eff}$ fluctuates with $Var[\lambda] = \sigma^2 = w^2_{eff} * m_{eff}$

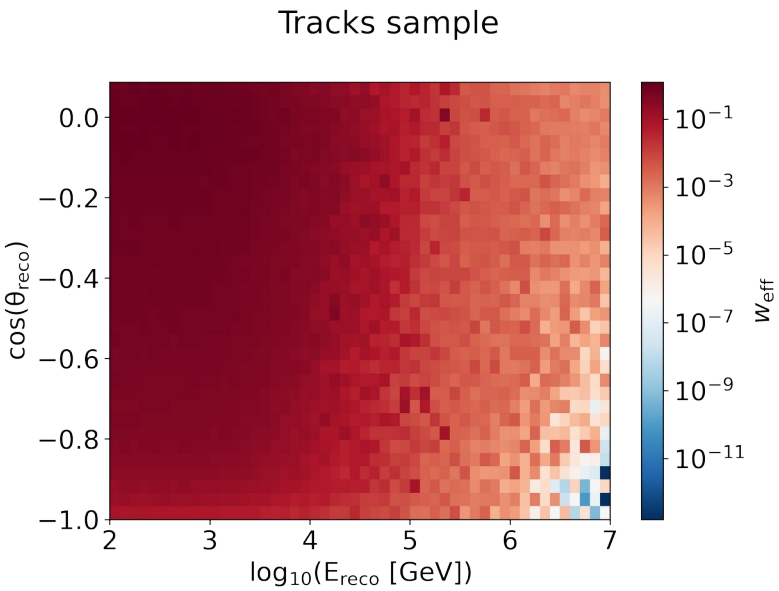
# Effective number of MC events / effective weights

## Calculated for asimov sets

Predictions obtained for SnowStorm MC, re-weighted with a Gaussian (σ=0.03), using $Dom_{eff}$ and $Ice_{abs}$



# Test different likelihood

## Taking limited MC statistics into account

from 1901.04645:

$$\mathcal{L}_{\mathrm{Eff}}(\vec{\theta}|k) = \left(\frac{\mu}{\sigma^2}\right)^{\frac{\mu^2}{\sigma^2}+1} \Gamma\left(k+\frac{\mu^2}{\sigma^2}+1\right) \left[k!\left(1+\frac{\mu}{\sigma^2}\right)^{k+\frac{\mu^2}{\sigma^2}+1} \Gamma\left(\frac{\mu^2}{\sigma^2}+1\right)\right]^{-1}$$

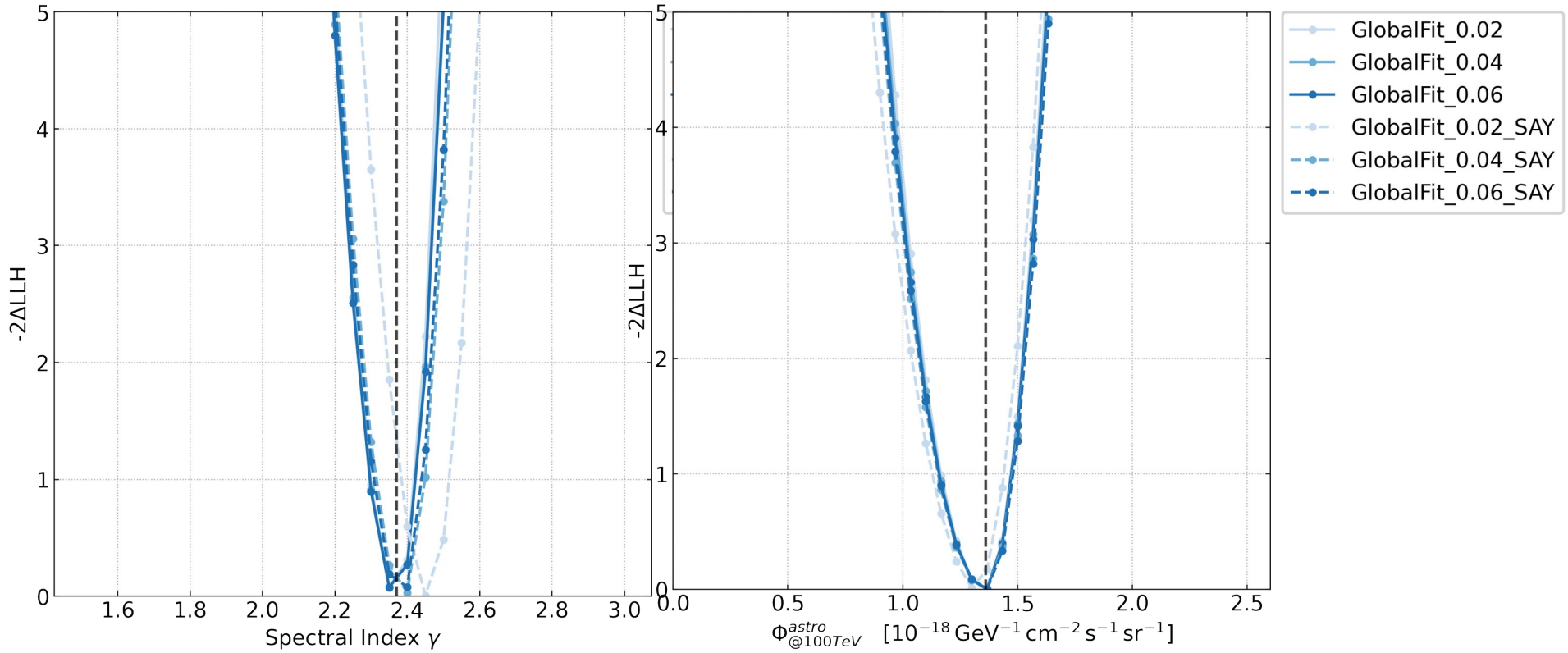
Implemented (&tested) in NNMFit, exchange this likelihood with Poisson-Likelihood and redo scans

# Test different likelihood

## Taking limited MC statistics into account

Almost no effect on 1D scans of signal parameters, except for Gauss width of 0.02

Attention: the asimov sets here were created with the different Gaussian widths as well

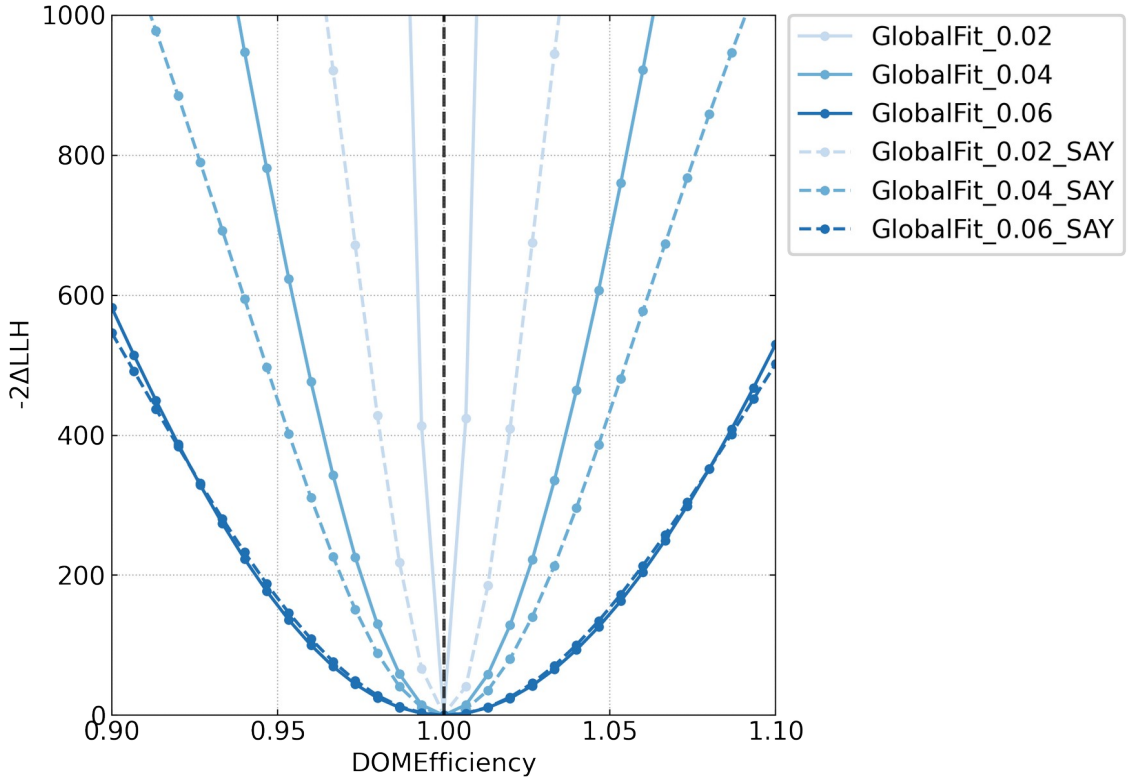


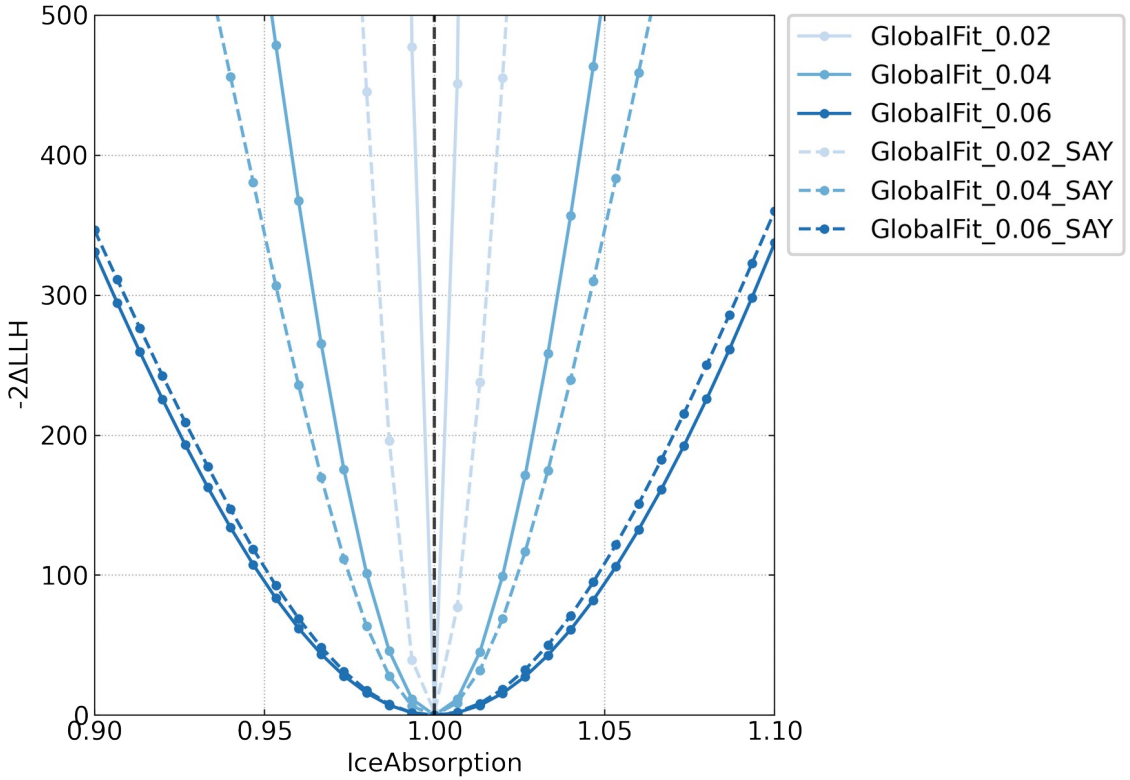
# Test different likelihood

## Taking limited MC statistics into account

SnowStorm systematics affected more:

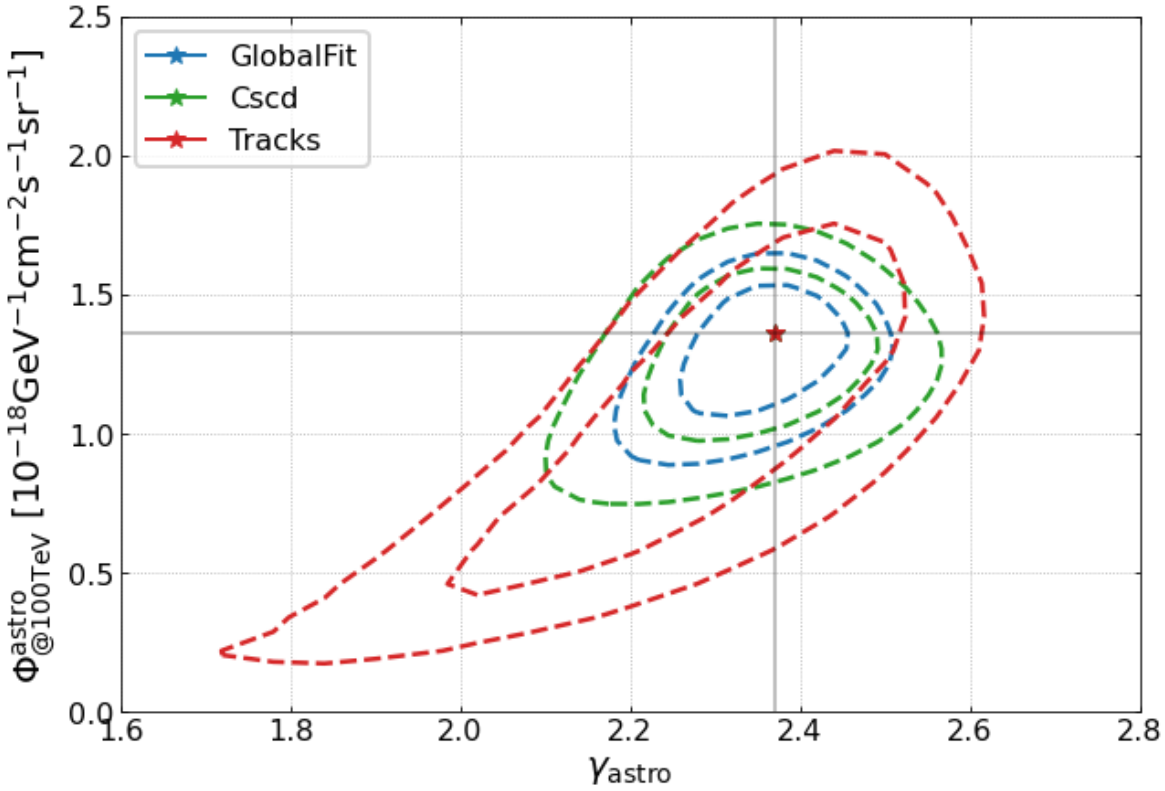
Attention: the asimov sets here were created with the different Gaussian widths as well



# Summary and Outlook

- ✓ Combined fit of tracks and cascades
- ✓ Consistent treatment of detector systematics using SnowStorm
- ✓ Preliminary Asimov fits/scans are looking promising
- ✓ Comparison of Poisson and SAY LLH

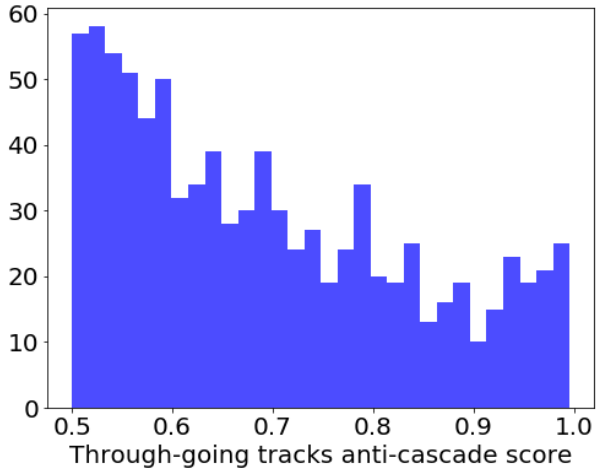


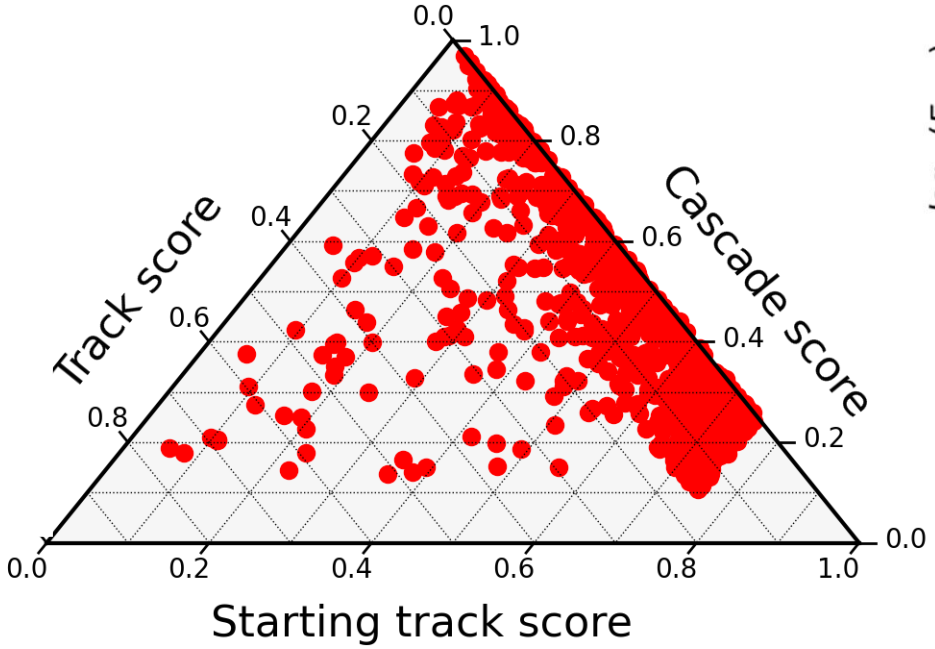
# Backup

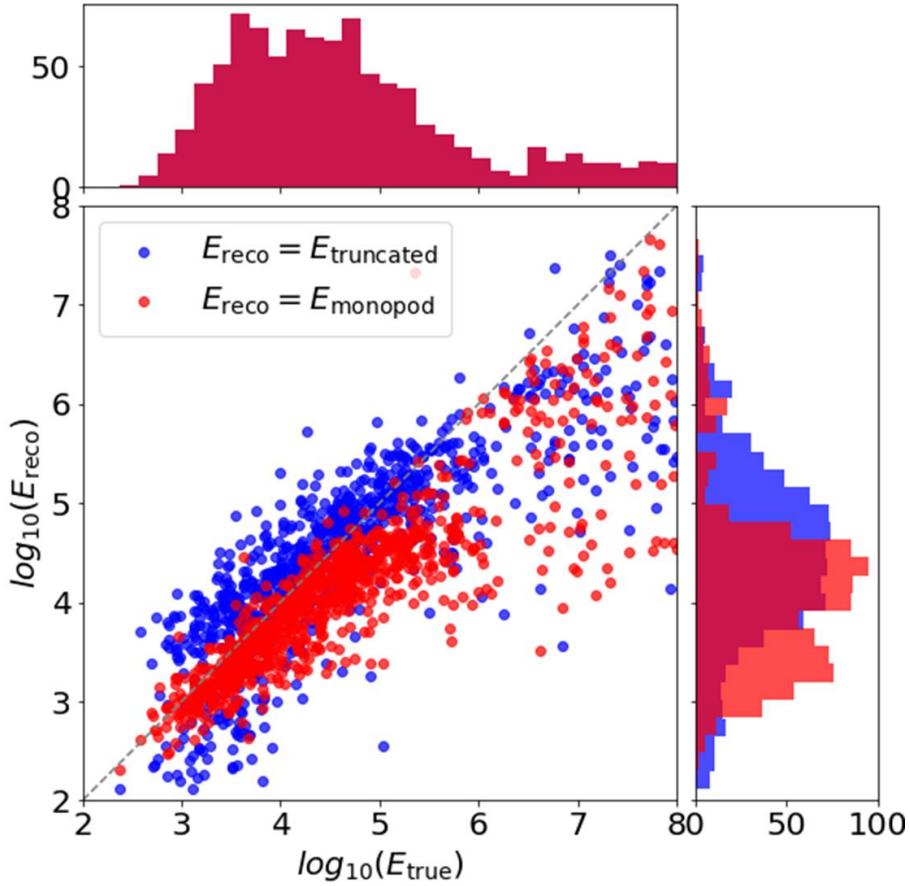
# DiffuseNuMu and Cascades – Sample Overlap

- Focus on NuMu simulations
  → Work in progress for NuE + NuTau

- FinalLevel DiffuseNuMu: ~5.1e6 events
  FinalLevel Cascade (Signal): ~2.3e5 events
➢ Total event overlap: 899 events



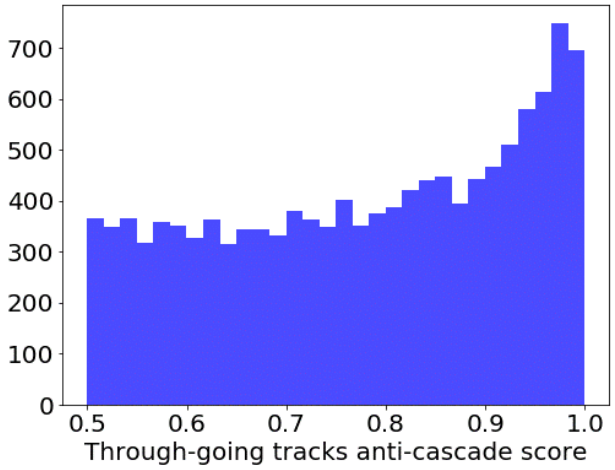



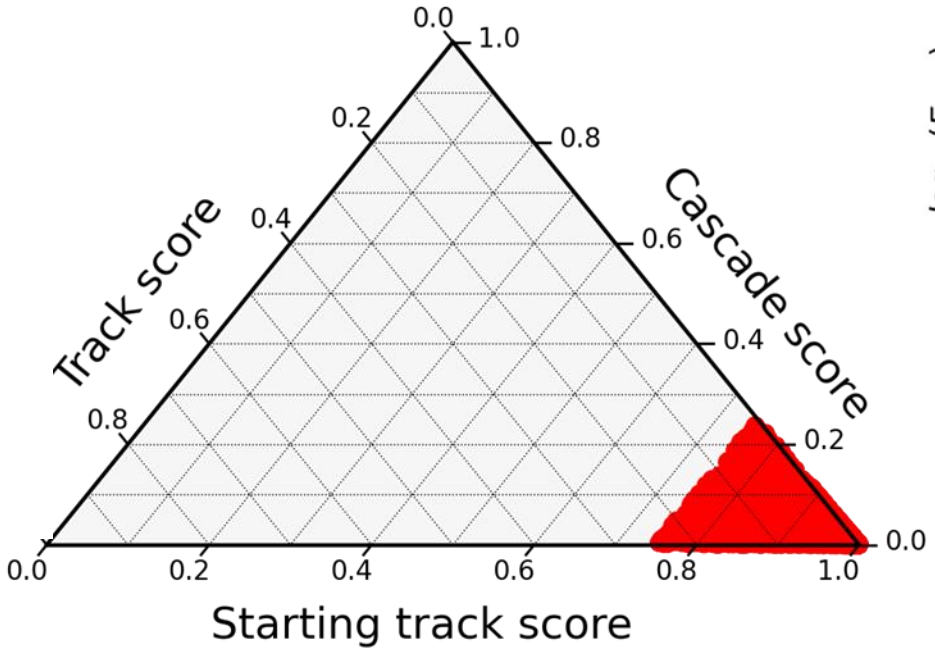



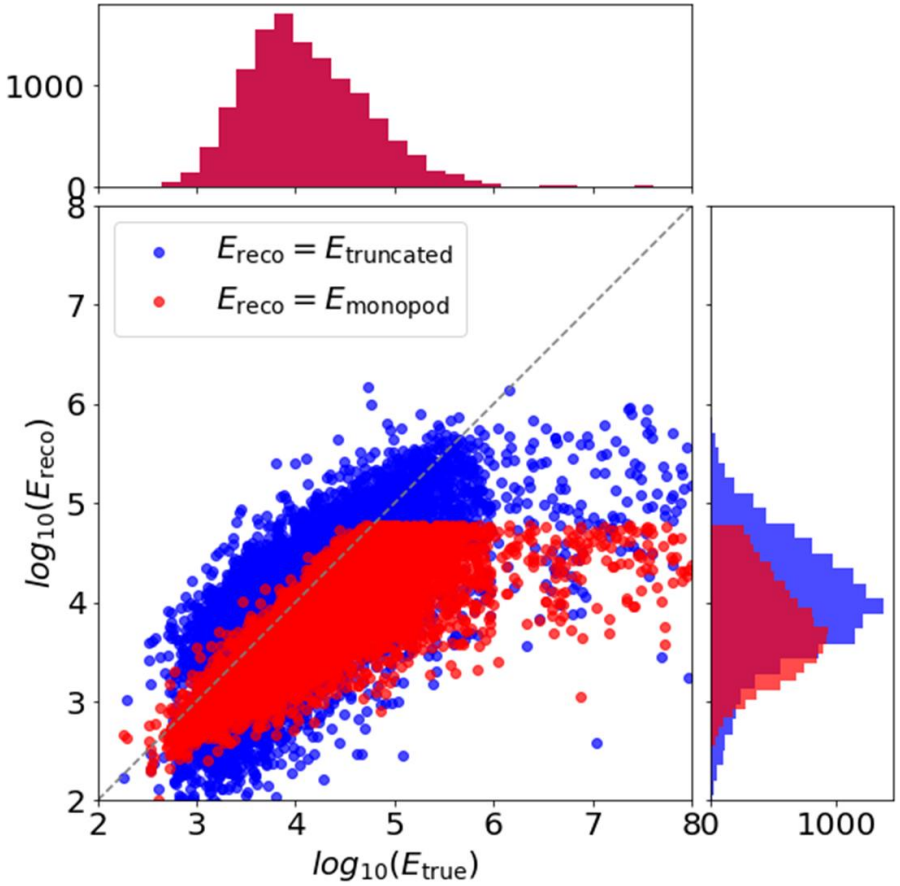
# DiffuseNuMu and Cascades – Sample Overlap

- Focus on NuMu simulations
  → Work in progress for NuE + NuTau

- FinalLevel DiffuseNuMu: ~5.1e6 events
  Cascade Control Sample: ~1.2e5 events
➢ Total event overlap: ~1.3e4 events



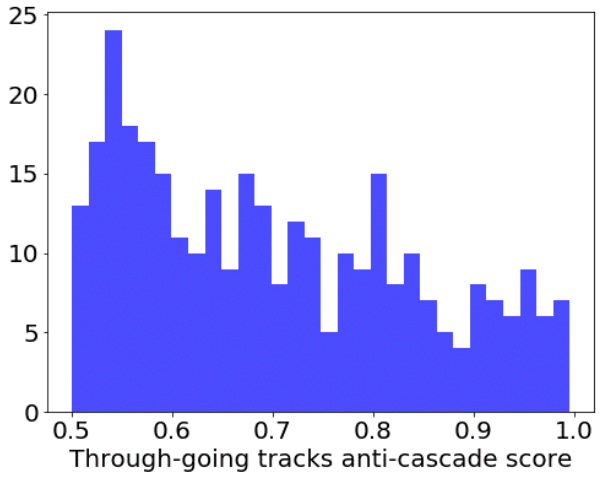



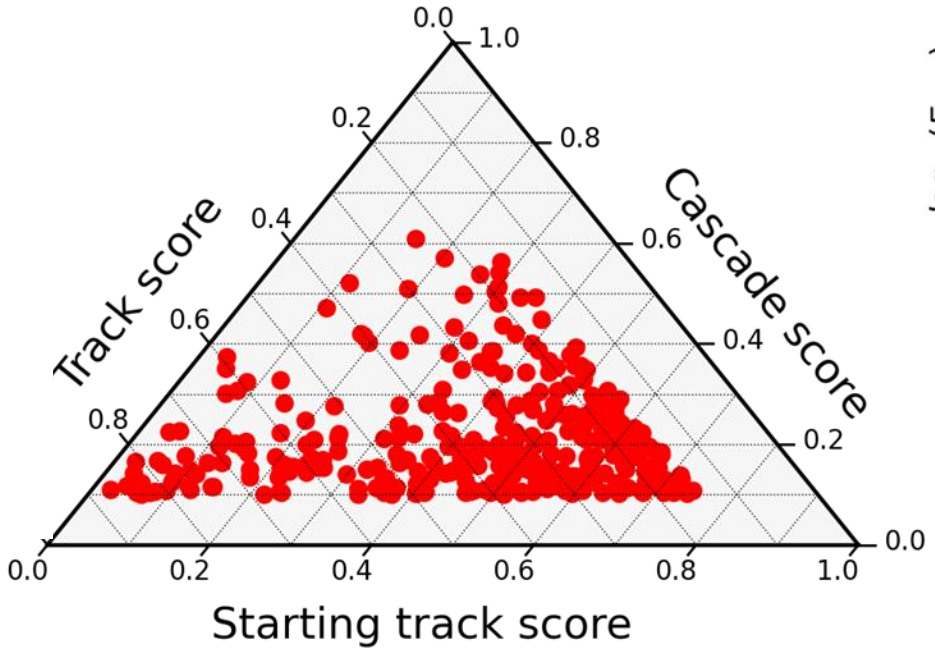



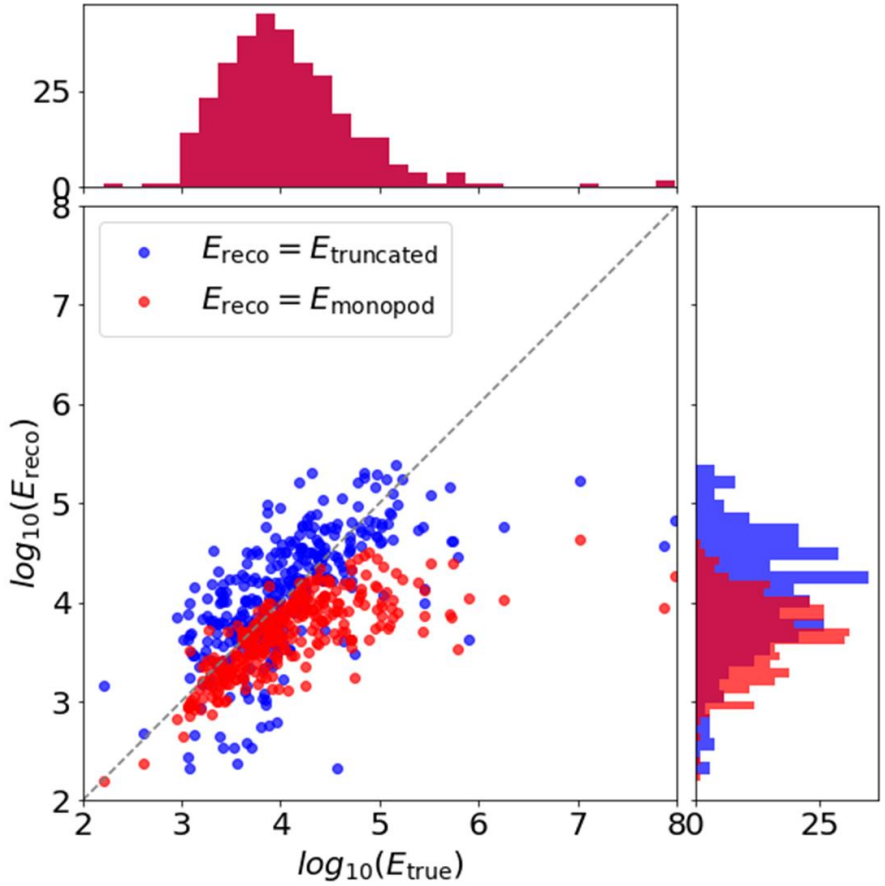
# DiffuseNuMu and Cascades – Sample Overlap

- Focus on NuMu simulations
  → Work in progress for NuE + NuTau

- FinalLevel DiffuseNuMu: ~5.1e6 events
  Muon control sample: ~4.0e4 events
➢ Total event overlap: 323 events

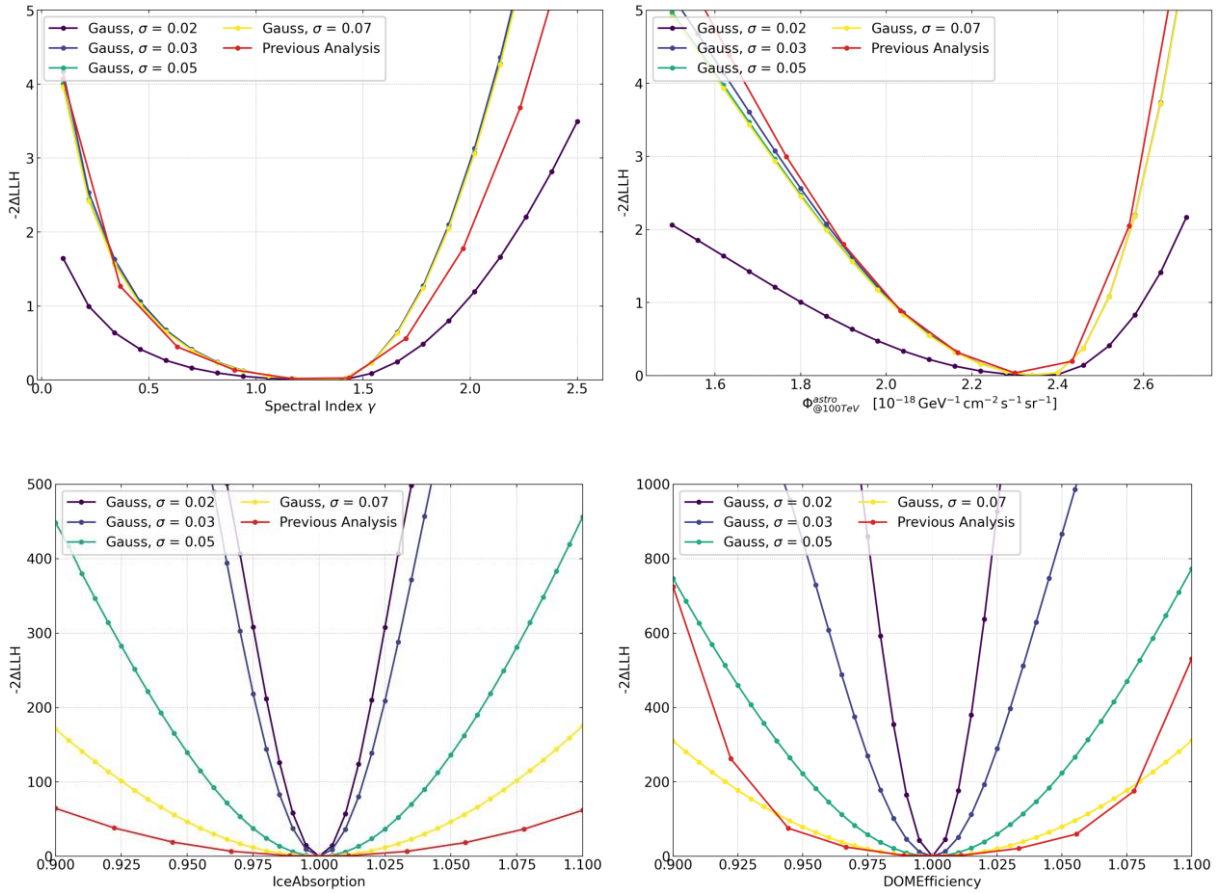


# SnowStorm in DiffuseNuMu – Spring Collaboration Meeting 2021

- Does the width of the gaussian used for reweighting changes the LLH space?
- ➢ Yes, it does change…
- ➢ Small changes for the signal parameter, but much bigger changes for the systematic parameter



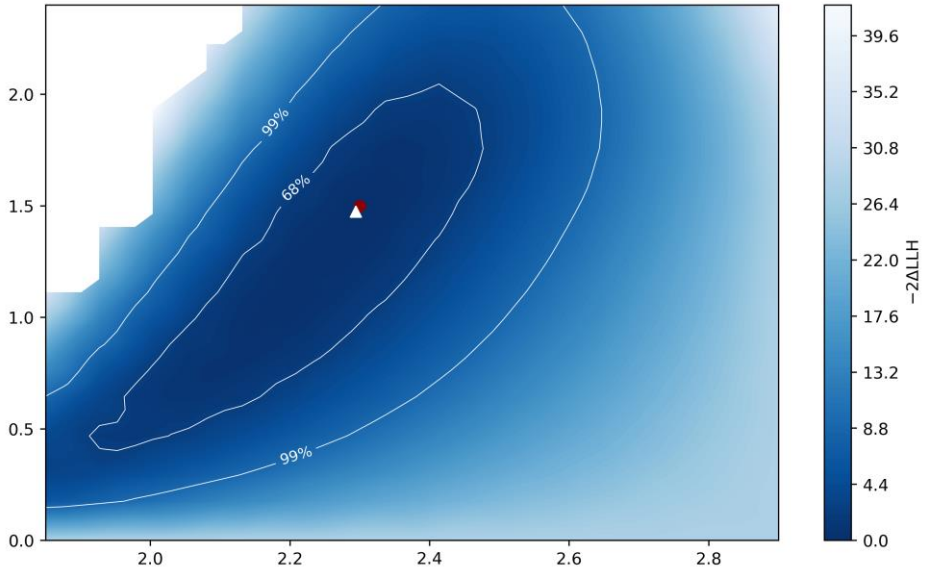
# Signal Parameters (SPL) – 2D

- Did Jörans asimov scans look similiar?

➢ (Very) old asimov scan from Jöran

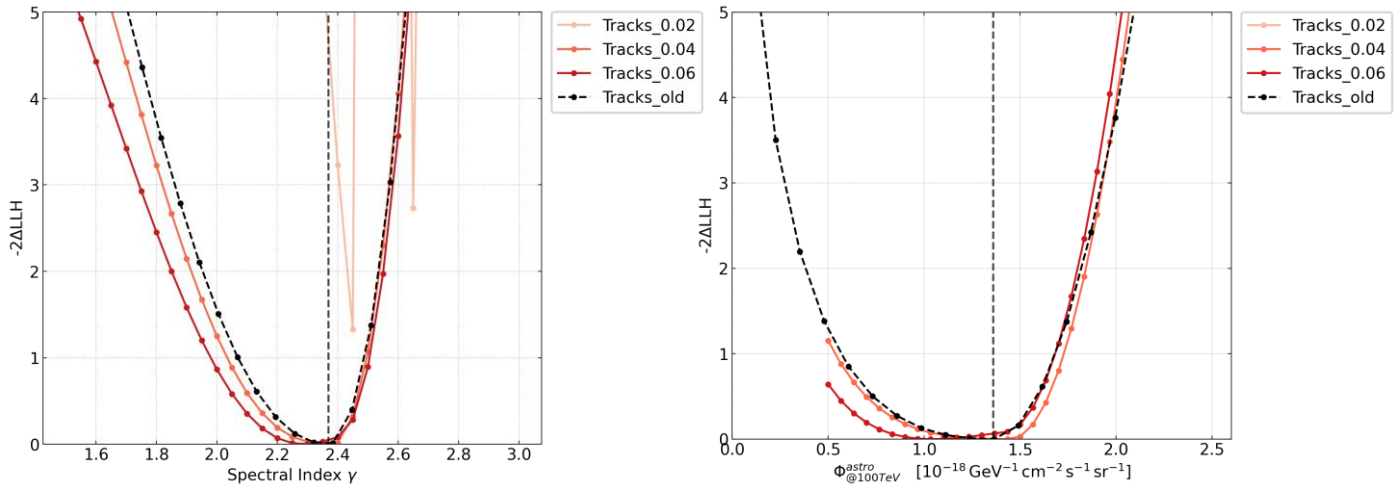
- Exact settings/parameters forgotten (lost?)
  - Similiar signal parameters injected 2.3/1.5

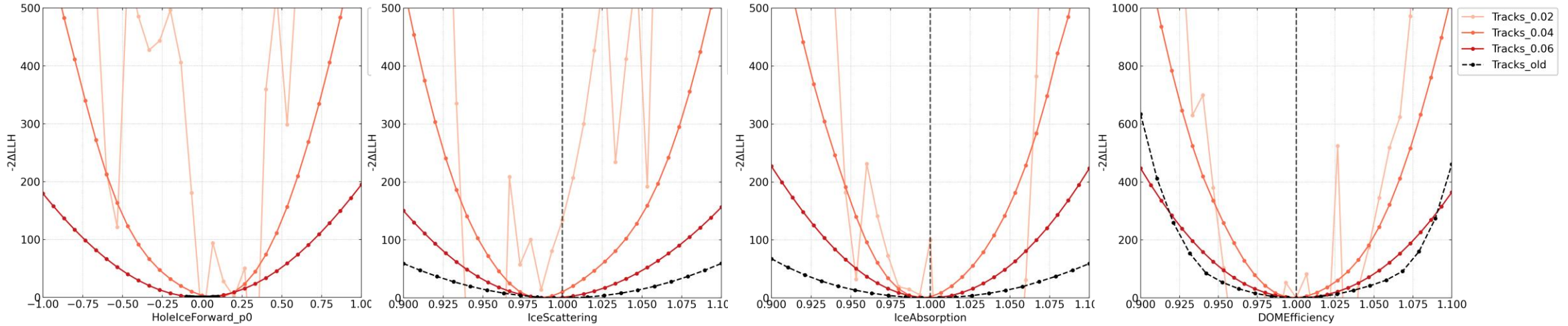
- Similar to what we see with SnowStorm/re-doing Jörans scans



# Detector systematics – Focus on Tracks

- Different widths of the Gaussian used for reweighting (label)
  - Corresponds to 10/20/30% of the uniform sampling distribution
- Input set: Full SnowStorm set without any reweighting for the detector systematic



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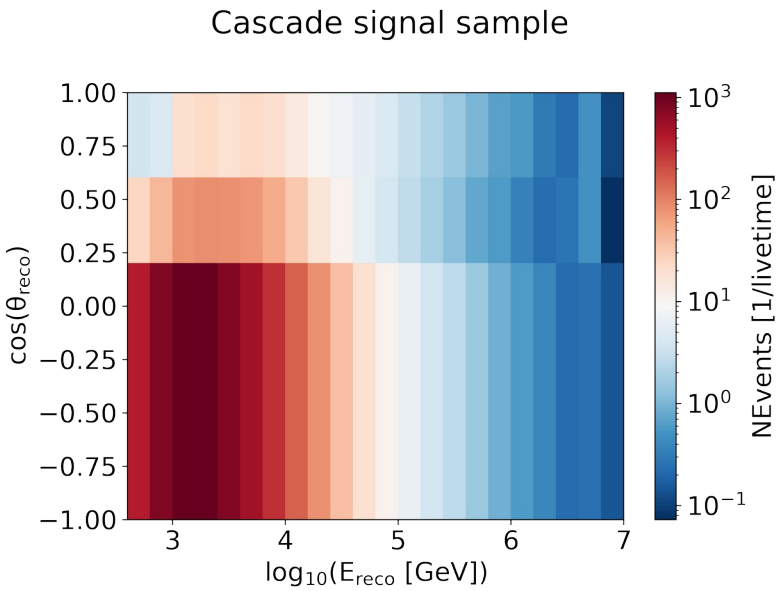
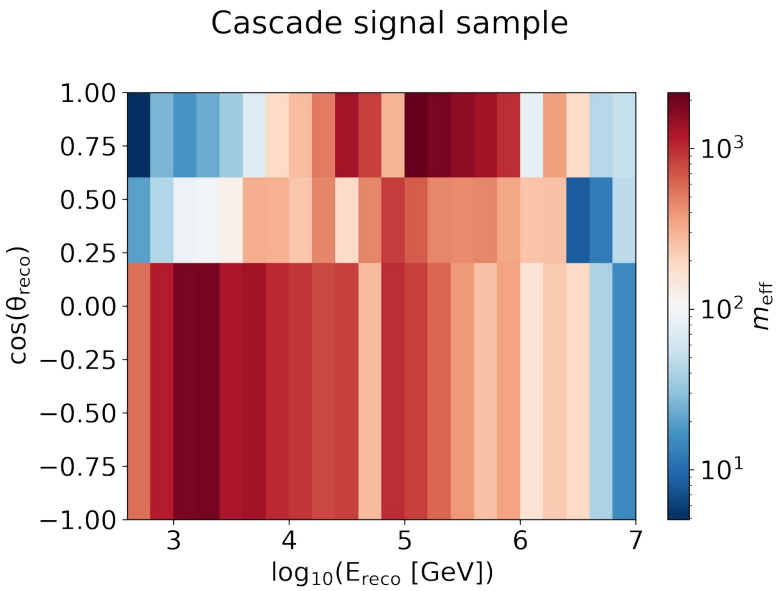
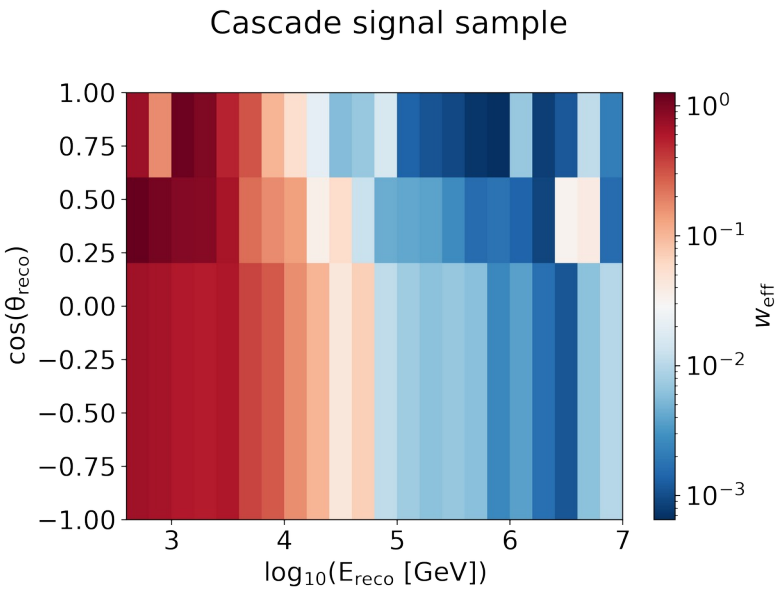


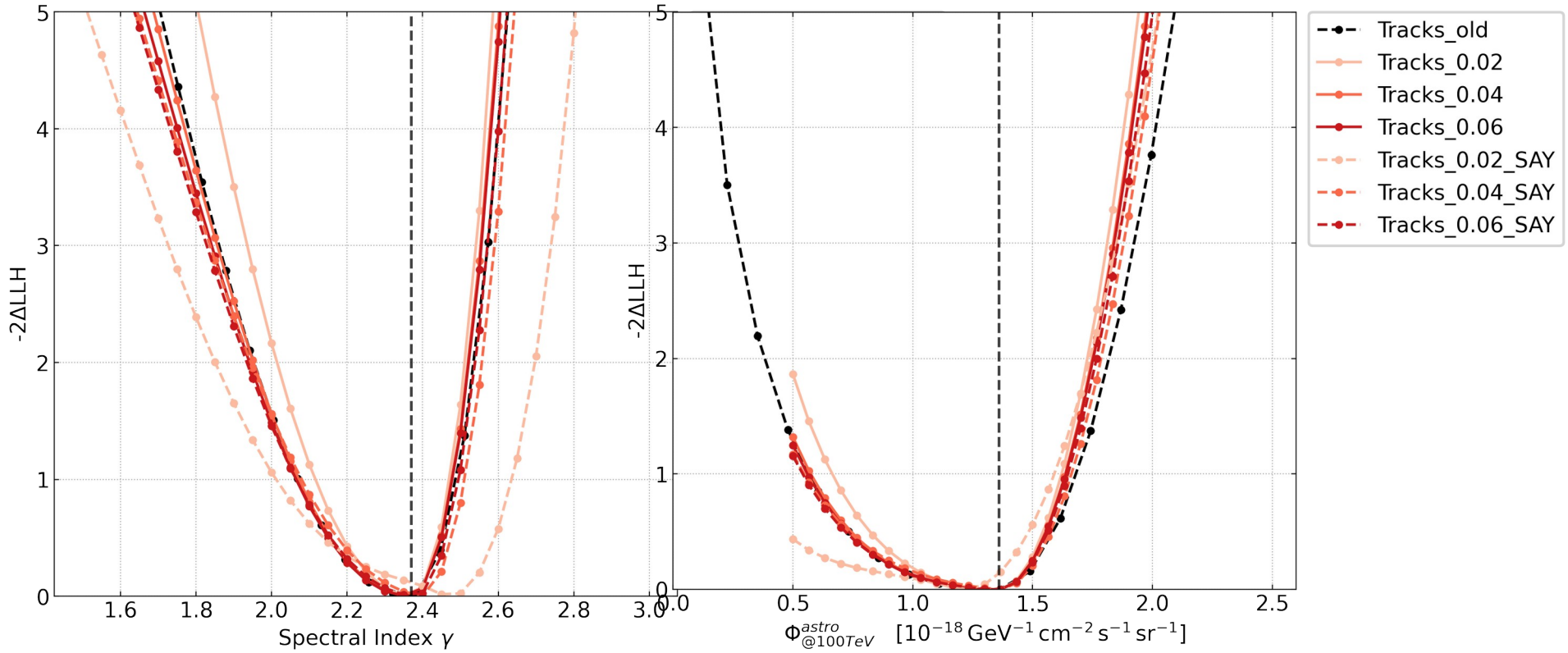



# Test different likelihood

## Taking limited MC statistics into account

Almost no effect on 1D scans of signal parameters, except for Gauss width of 0.02

Attention: the asimov sets here were created with the different Gaussian widths as well



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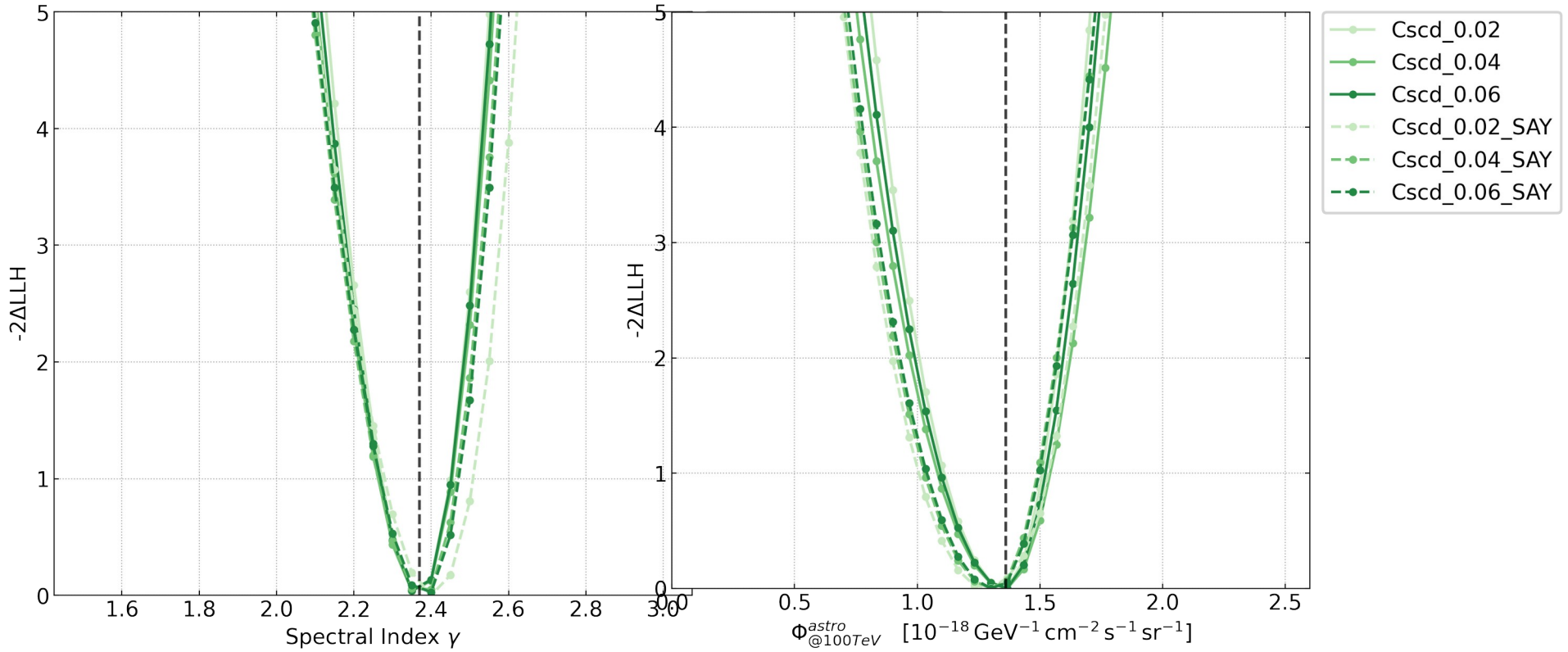

# Test different likelihood

## Taking limited MC statistics into account

SnowStorm systematics affected more:

Attention: the asimov sets here were created with the different Gaussian widths as well