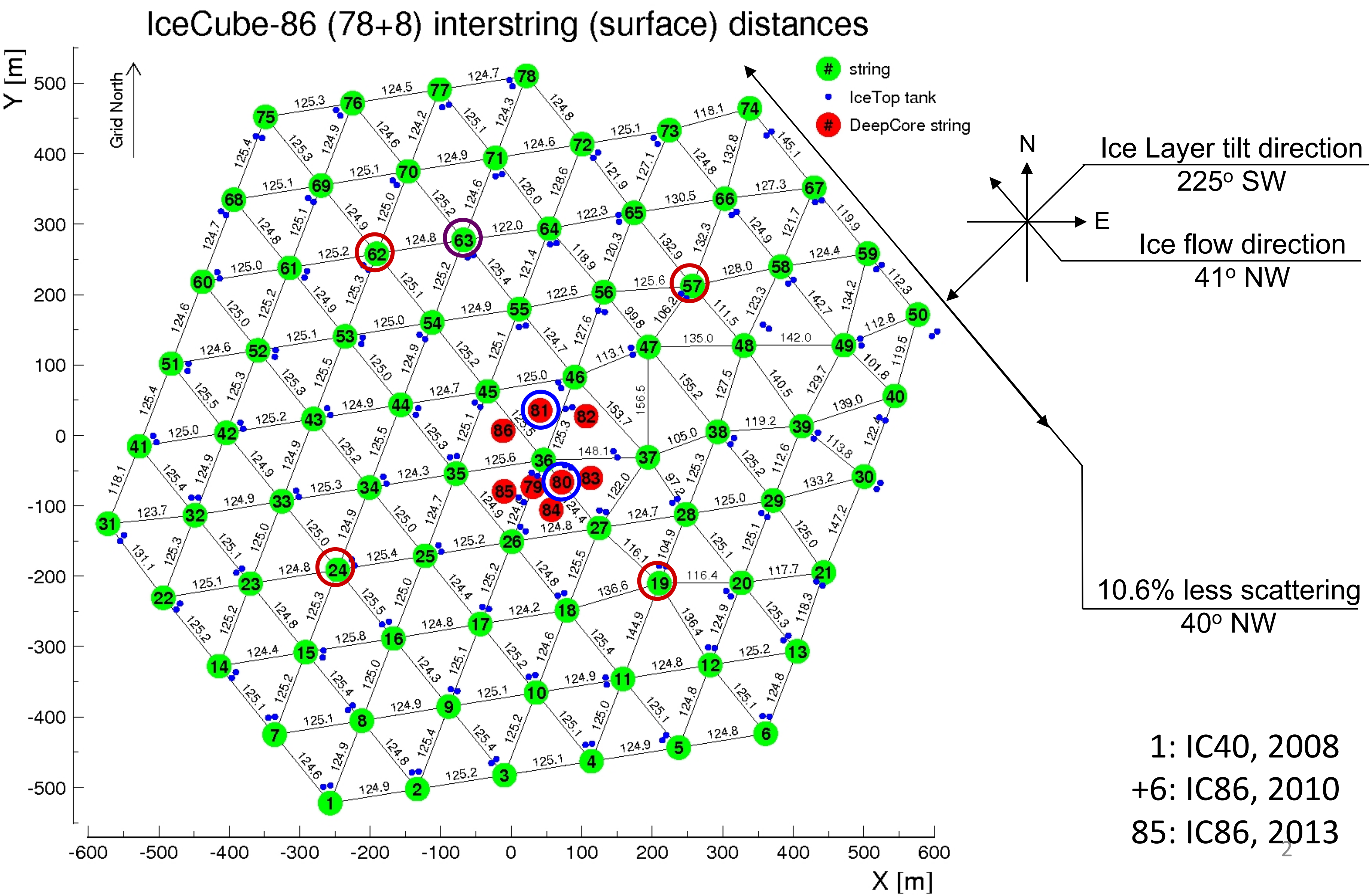
Ice model with flasher unfolding

Dmitry Chirkin, UW-Madison

Flasher data-derived ice models

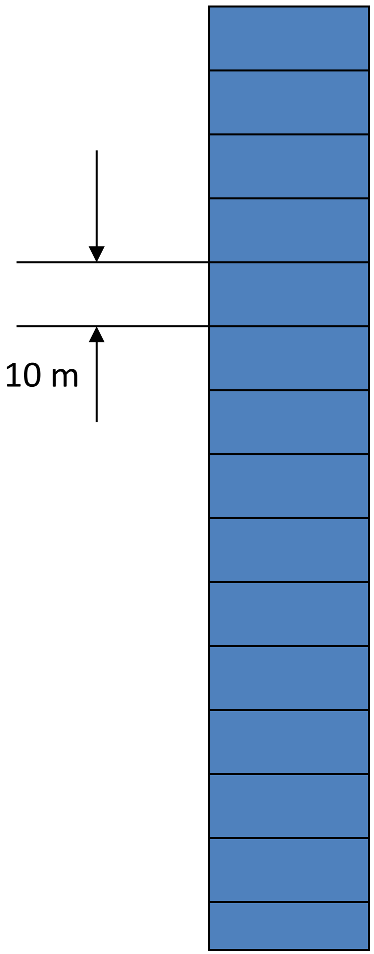


1: IC40, 2008

+6: IC86, 2010

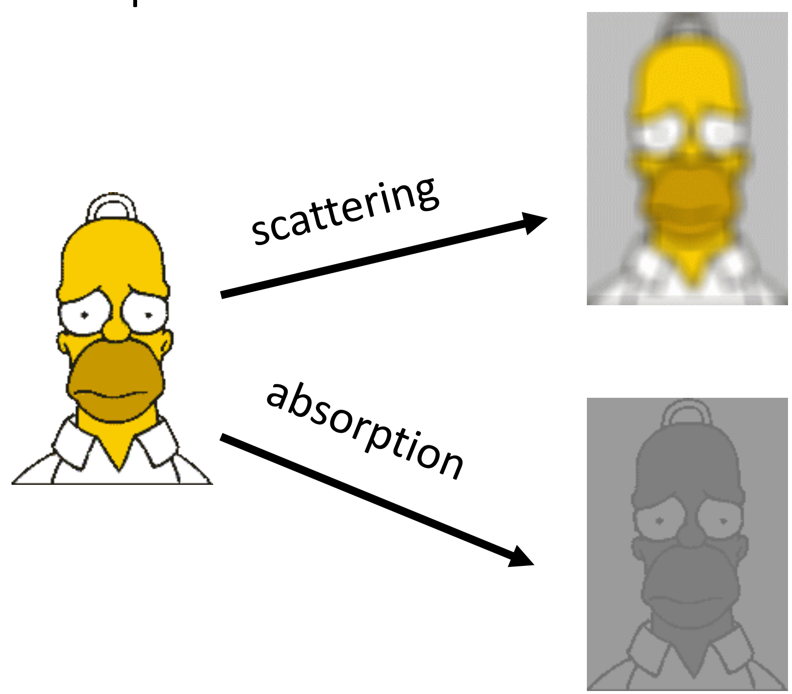
85: IC86, 2013

Ice layer parametrization



In each 10-meter layer define:

- scattering
- absorption

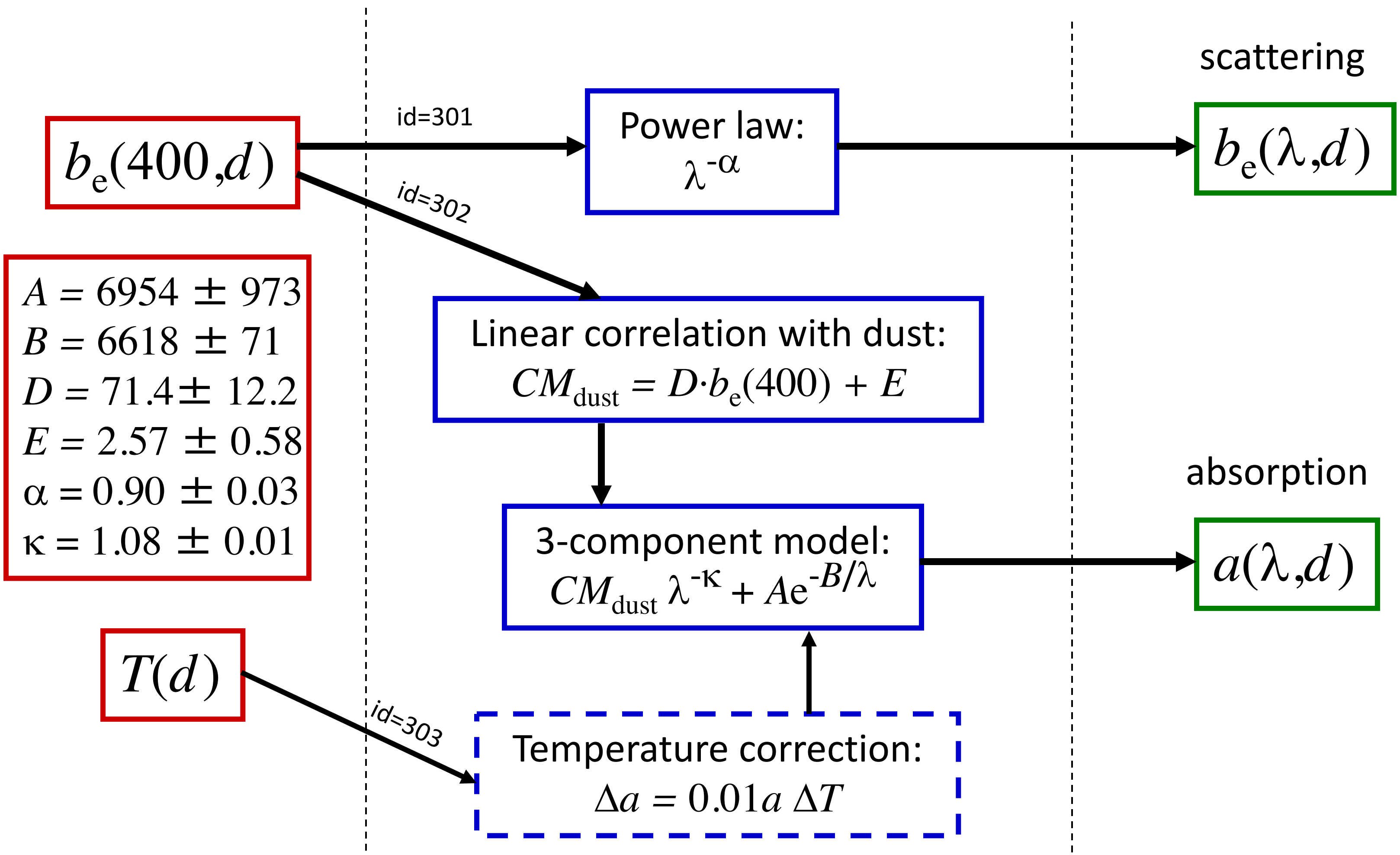


Source is blurred

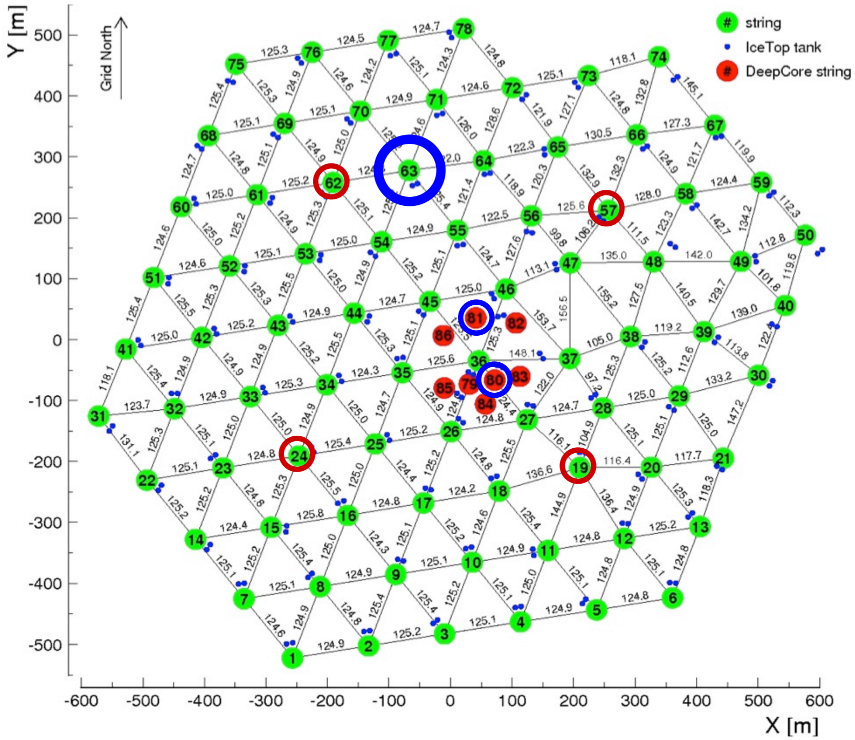
Source is dimmer

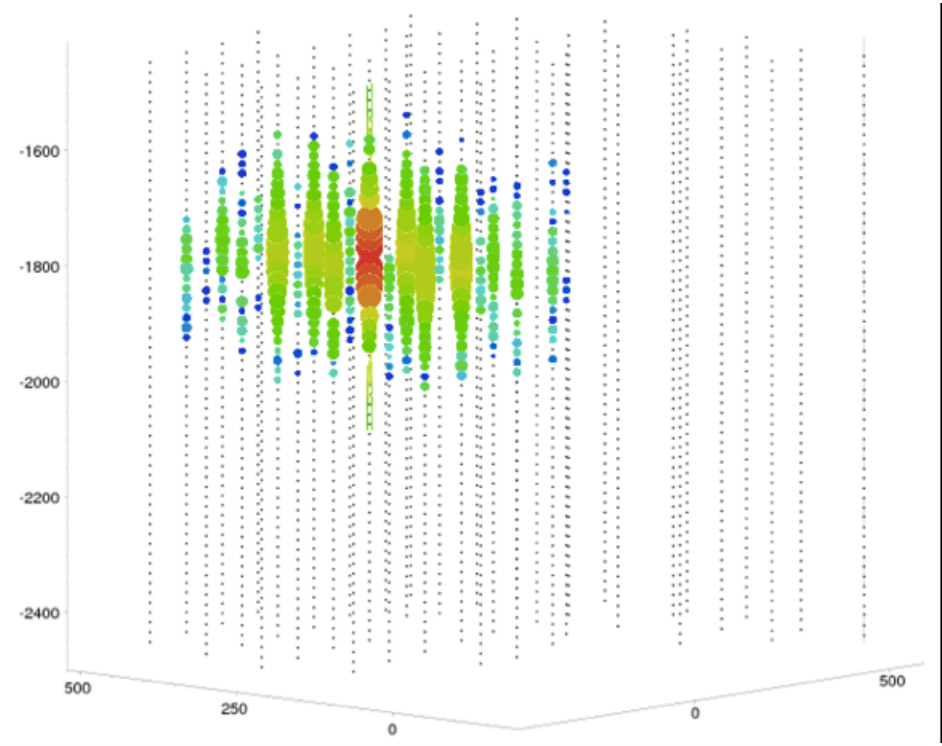
a = inverse absorption length ($1/\lambda_{abs}$)
b = inverse scattering length ($1/\lambda_{sca}$)

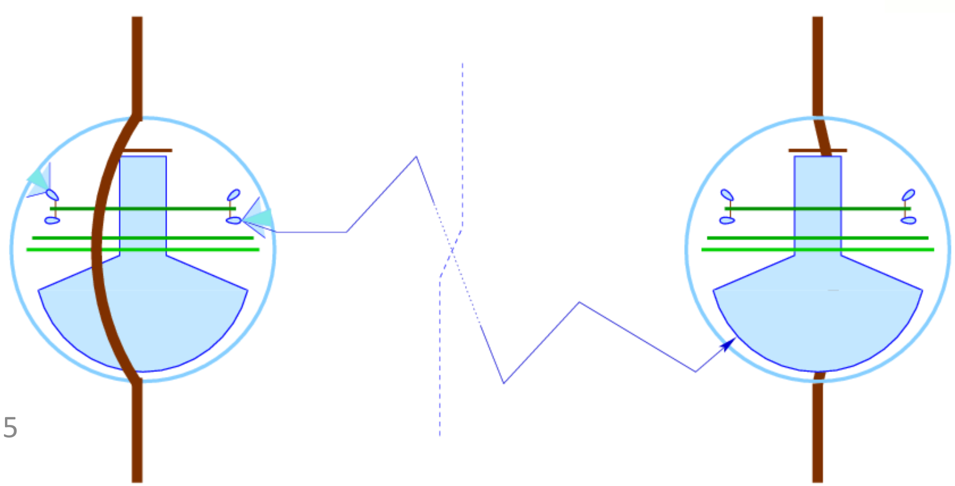
A 6-parameter Plug-n-Play Ice Model

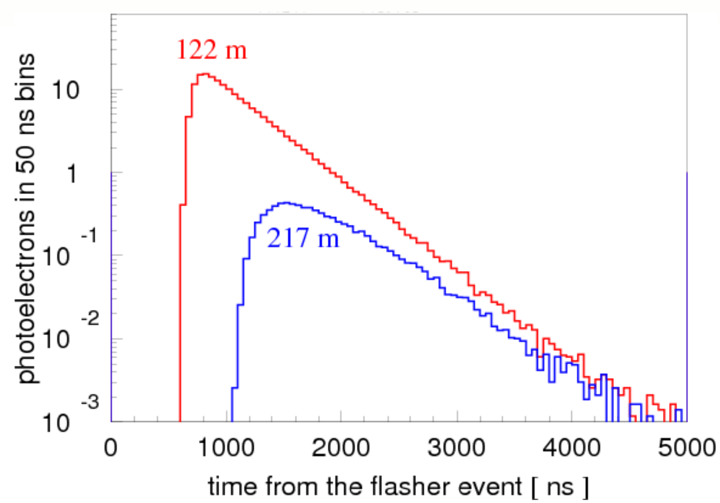


SPICE model fit









Timeline

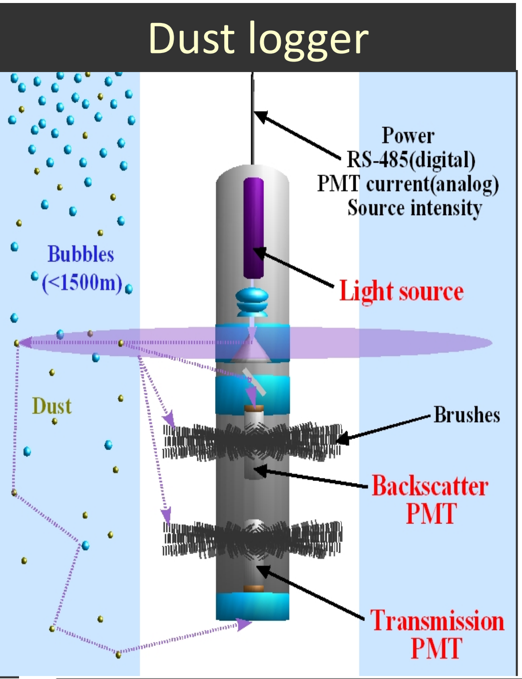
AMANDA ice models:			model error
bulk, f125, mam, mamint, stdkurt, sudkurt, kgm, …			
millennium (published 2006) → AHA (2007)			55%

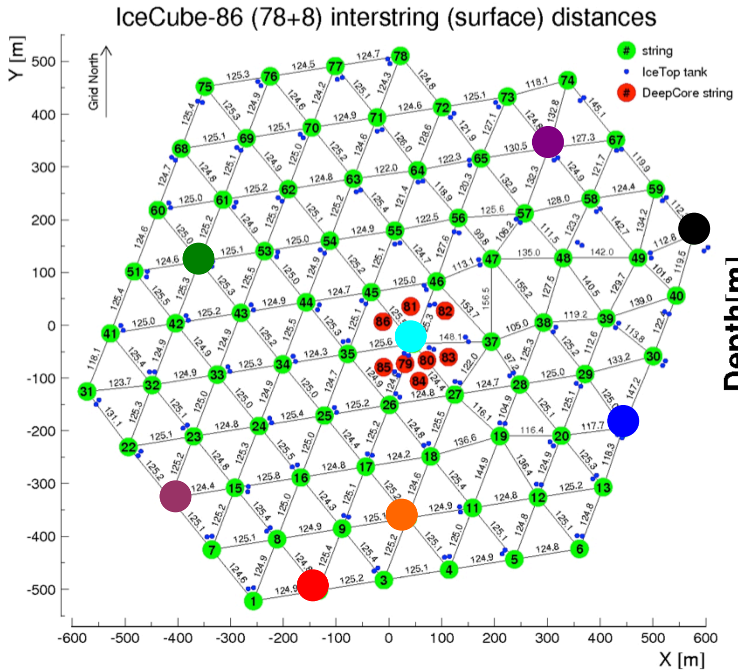
IceCube ice models:			
WHAM	(2011)		42%
SPICE 1	(2009)		29%
SPICE 2, 2+, 2x, 2y	(2010)	added ice layer tilt	
SPICE Mie	(2010)	fit to scattering function	29%
SPICE Lea	(2012)	fit to scattering anisotropy	20%
SPICE (Munich)	(2013)	7-string, LED unfolding	17%
$SPICE^3$ (CUBE)	(2014)	llh fixes, DOM sensitivity fits	11%
SPICE 3.0	(2015)	improved RDE, ang. sens. fits	10%
SPICE 3.1, 3.2	(2016)	85-string, correlated model fit	<10%
SPICE HD, …	direct HI and DOM sens., cable, DOM tilt		<9%

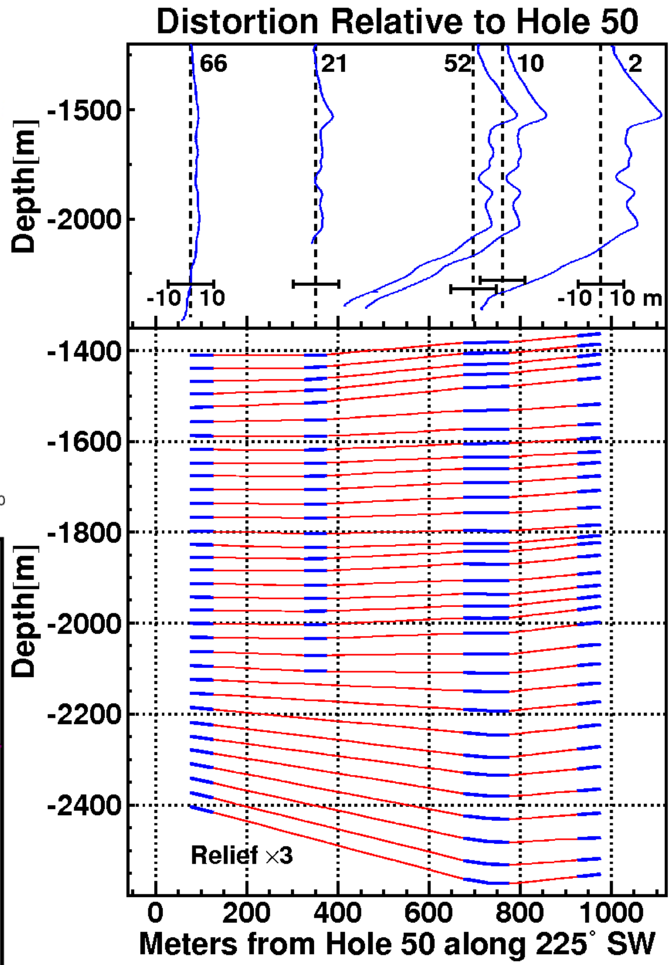
Model error (precision in charge prediction): <10%
Extrapolation uncertainty: 13% (sca) / 15% (abs)
Linearity: < 2% in range 0.1 … 500 p.e.

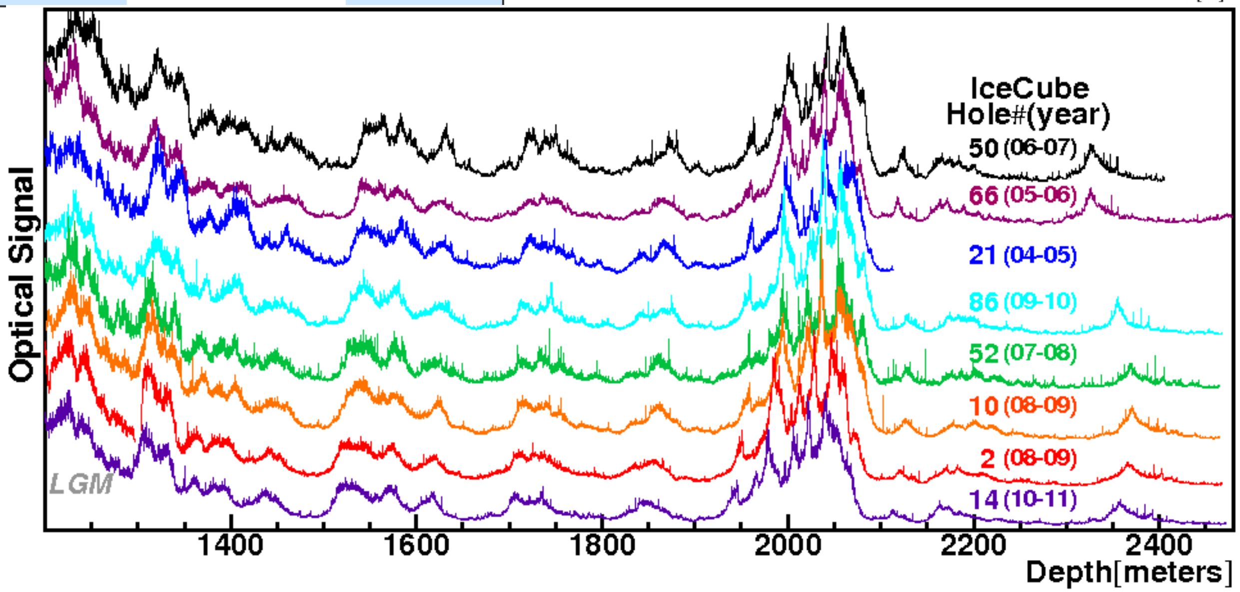
(models available in ice-models module)

Dust logger discovers ice tilt

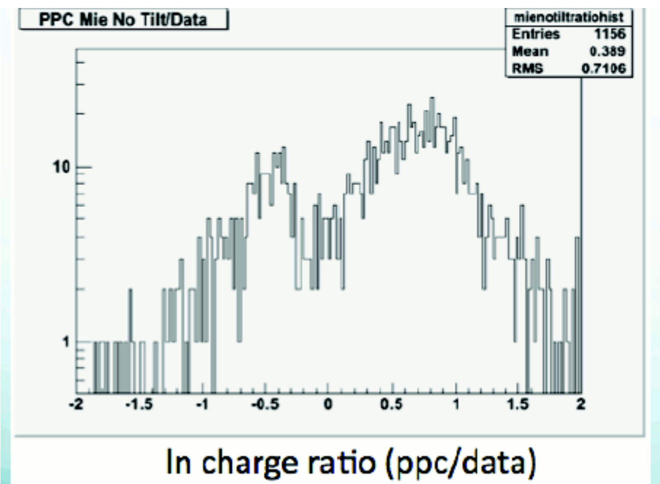




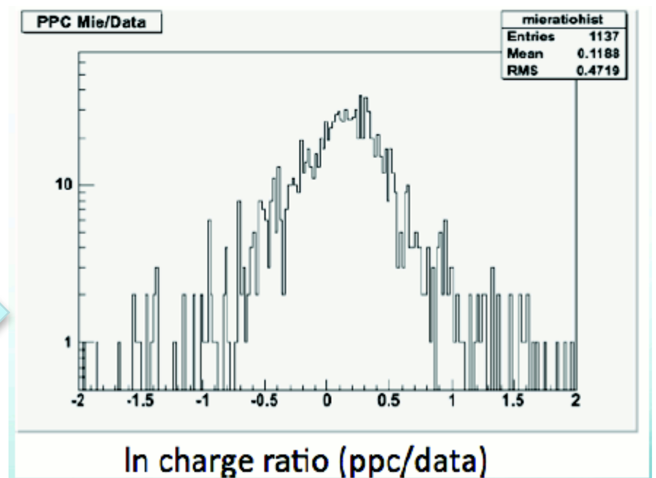




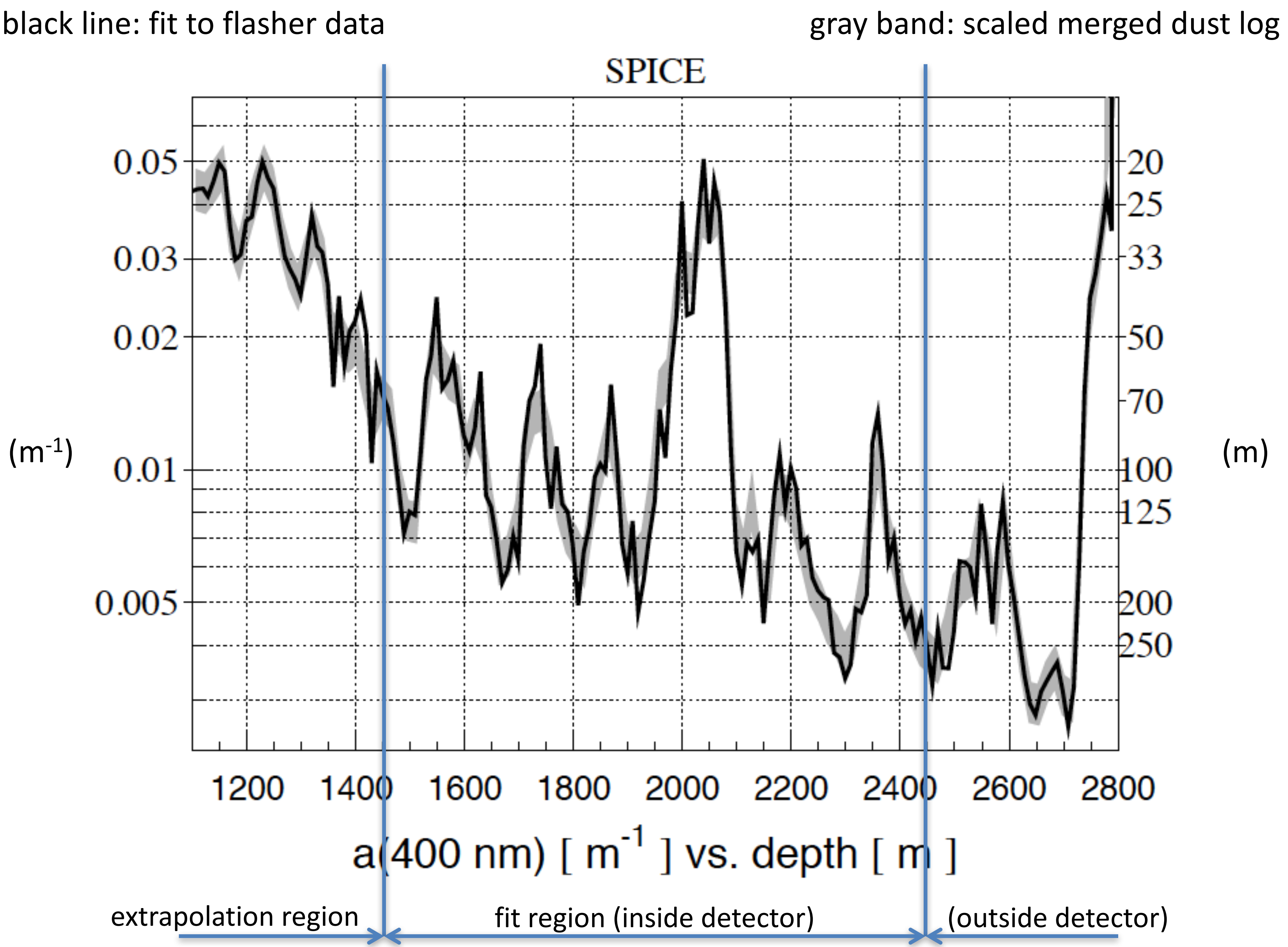
Tilt is important for flasher data!



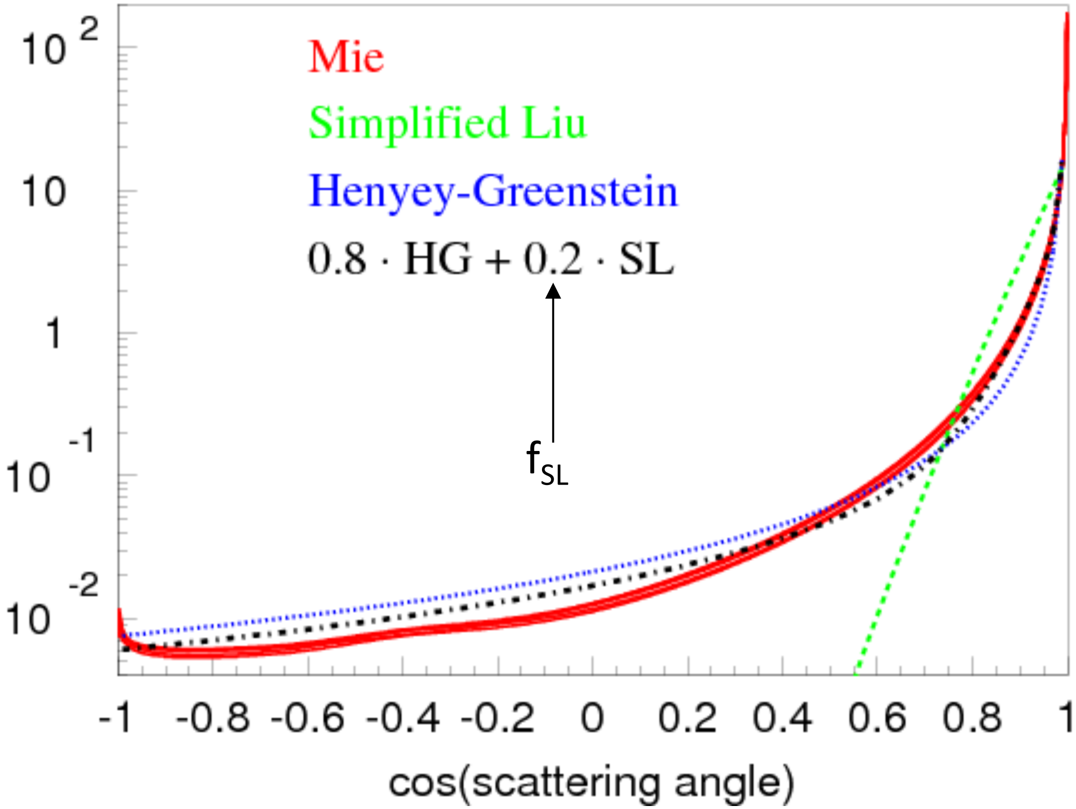
Comparison of LED flasher simulation to data without tilt



Comparison of LED flasher simulation to data with tilt


black line: fit to flasher data
gray band: scaled merged dust log
SPICE
0.05
0.03
0.02
0.01
0.005
(m-1)
20
25
33
50
70
100
125
200
250
(m)
1200
1400
1600
1800
2000
2200
2400
2600
2800
a(400 nm) [m-1] vs. depth [m]
extrapolation region
fit region (inside detector)
(outside detector)

Approximation to Mie scattering



Simplified Liu:

$$p(\cos\theta) \sim (1+\cos\theta)^{\alpha}, \quad \text{with} \quad \alpha = \frac{2g}{1-g}$$

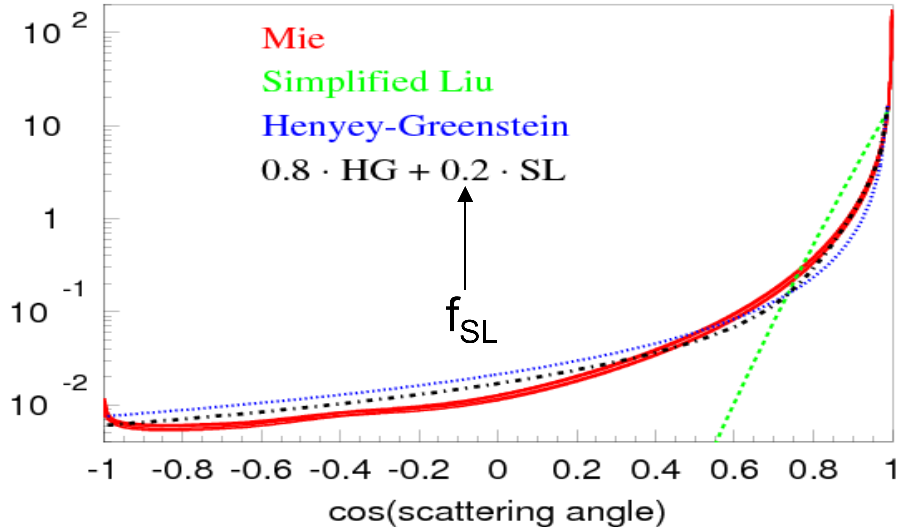
Henyey-Greenstein:

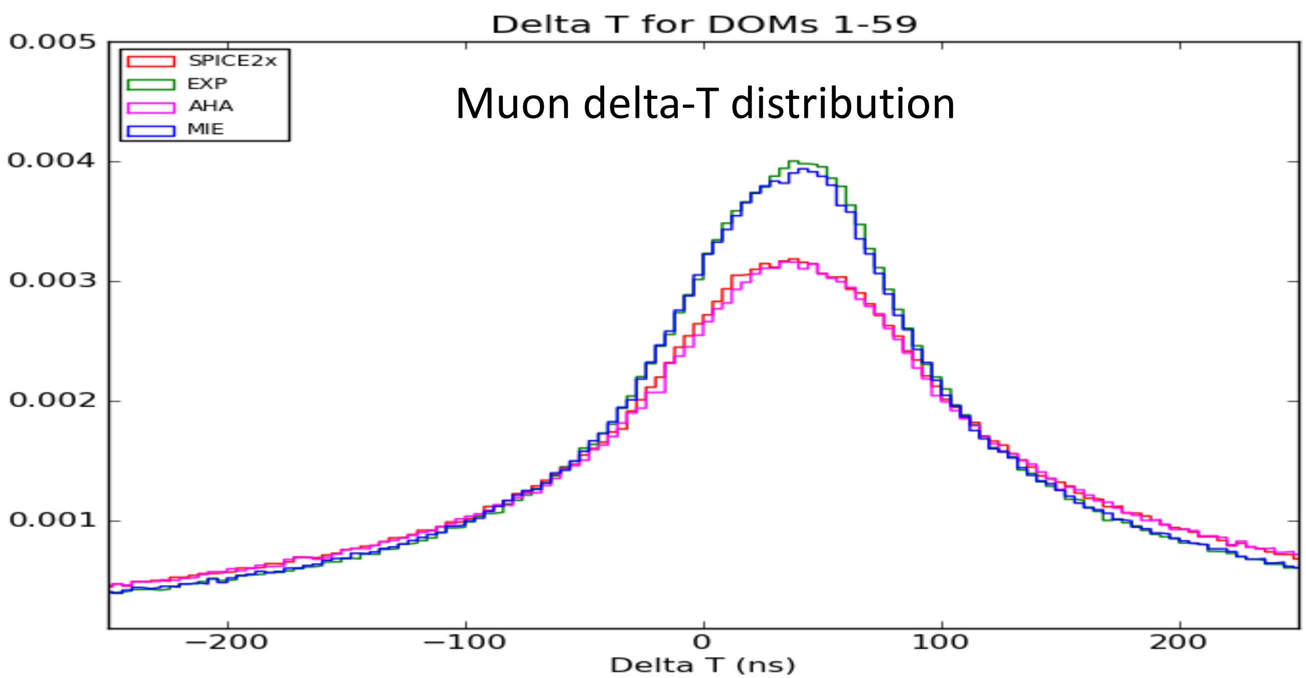
$$p(\cos\theta) = \frac{1}{2}\frac{1-g^2}{[1+g^2-2g\cdot\cos\theta]^{3/2}}$$

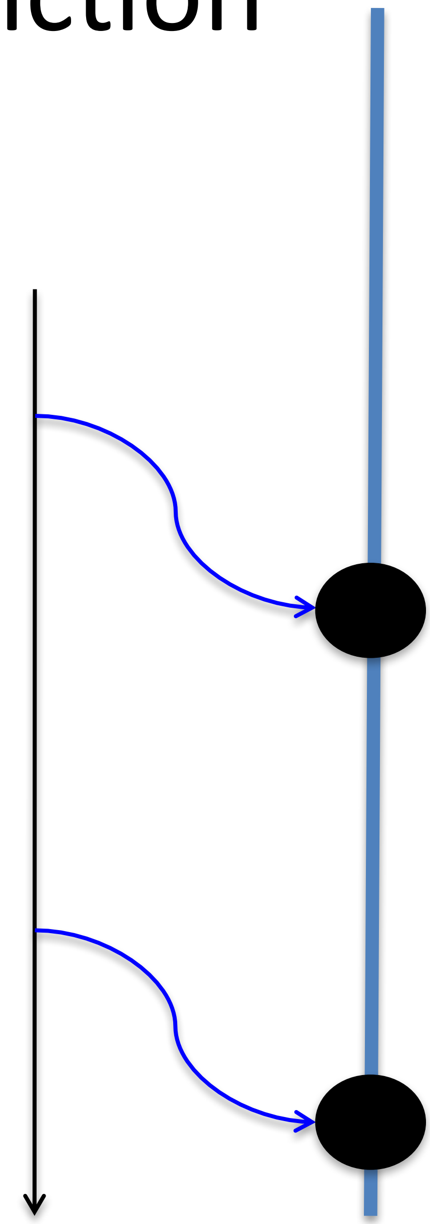
Mie:

Describes scattering on acid, mineral, salt, and soot with concentrations and radii at SP

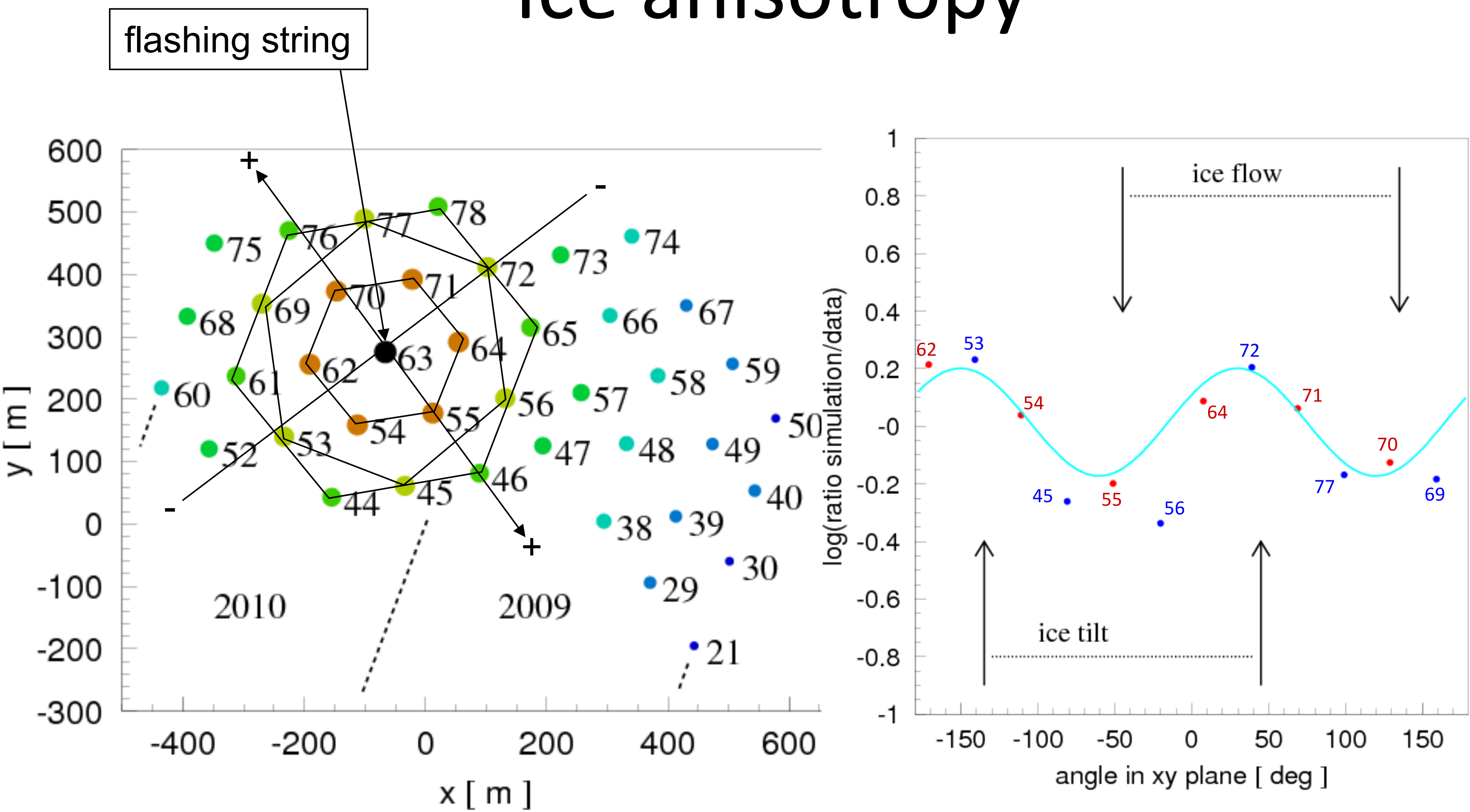
Fitting the scattering function





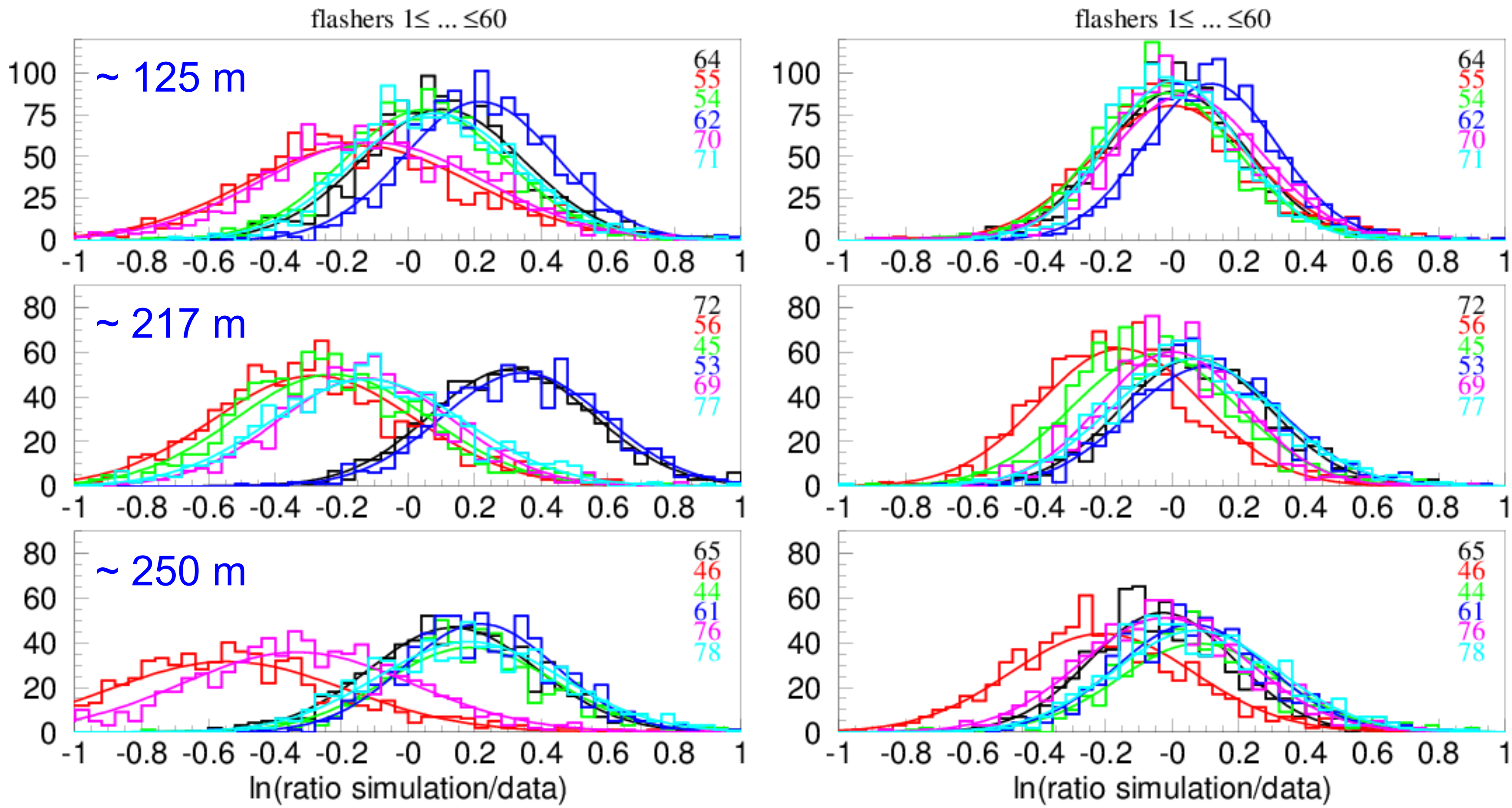


Ice anisotropy



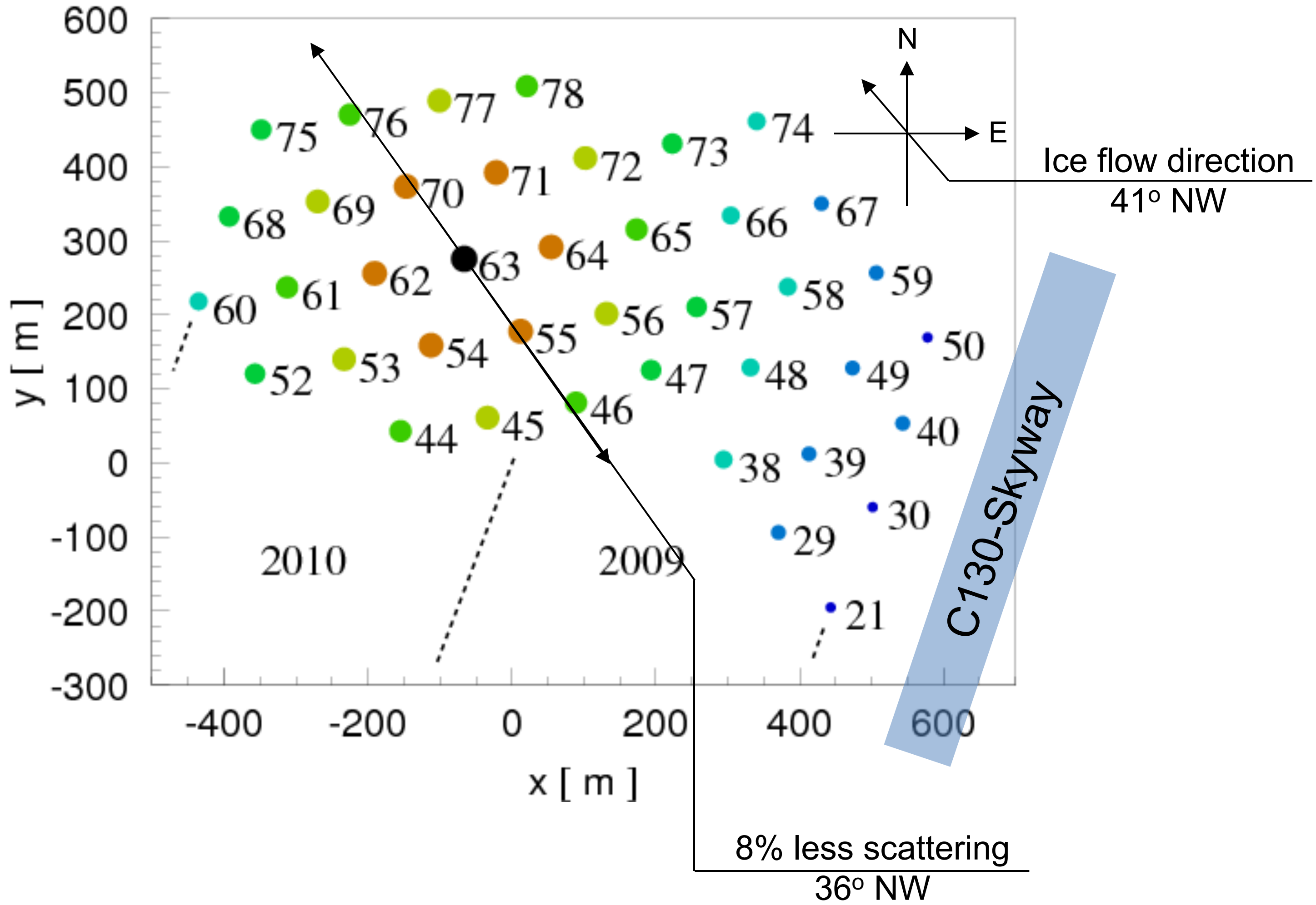
10-20% per 100 m azimuth modulation in charge observed!

Charge variation vs. distance



SPICE Mie [SPICE Paper] → SPICE Lea

Fit to the anisotropy hypothesis



What is Ice anisotropy

Direction of less scattering

Direction of more scattering

Naïve approximation: multiply the scattering coefficient by a function of photon direction, e.g., by

$$1 + \beta (\cos^2\theta - 1/3)$$

However, this is unphysical:

$\sigma(\mathbf{n}_{in},\mathbf{n}_{out}) = \sigma(-\mathbf{n}_{out},-\mathbf{n}_{in})$ (time-reversal symmetry)

$\sigma(\mathbf{n}_{in},\mathbf{n}_{out}) = \sigma(-\mathbf{n}_{in},-\mathbf{n}_{out})$ (symmetry of ice)

$$\rightarrow \sigma(\mathbf{n}_{in},\mathbf{n}_{out}) = \sigma(\mathbf{n}_{out},\mathbf{n}_{in})$$

A possible parameterization

The scattering function we use is f(cos θ), a combination of HG and SL.

How about this extension: $f(\vec{n_i} \cdot \vec{n_o}) \rightarrow f(\vec{k_i} \cdot \vec{k_o}), \quad \vec{k}_{i,o} = \frac{A\vec{n}_{i,o}}{|A\vec{n}_{i,o}|}$

$A = \begin{pmatrix} \alpha & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & \gamma \end{pmatrix}$ the basis of the 2 scattering axes and z (α,β are, e.g., 1.05).

However, function f(cos θ) is well-defined for only cos θ between -1 and 1.

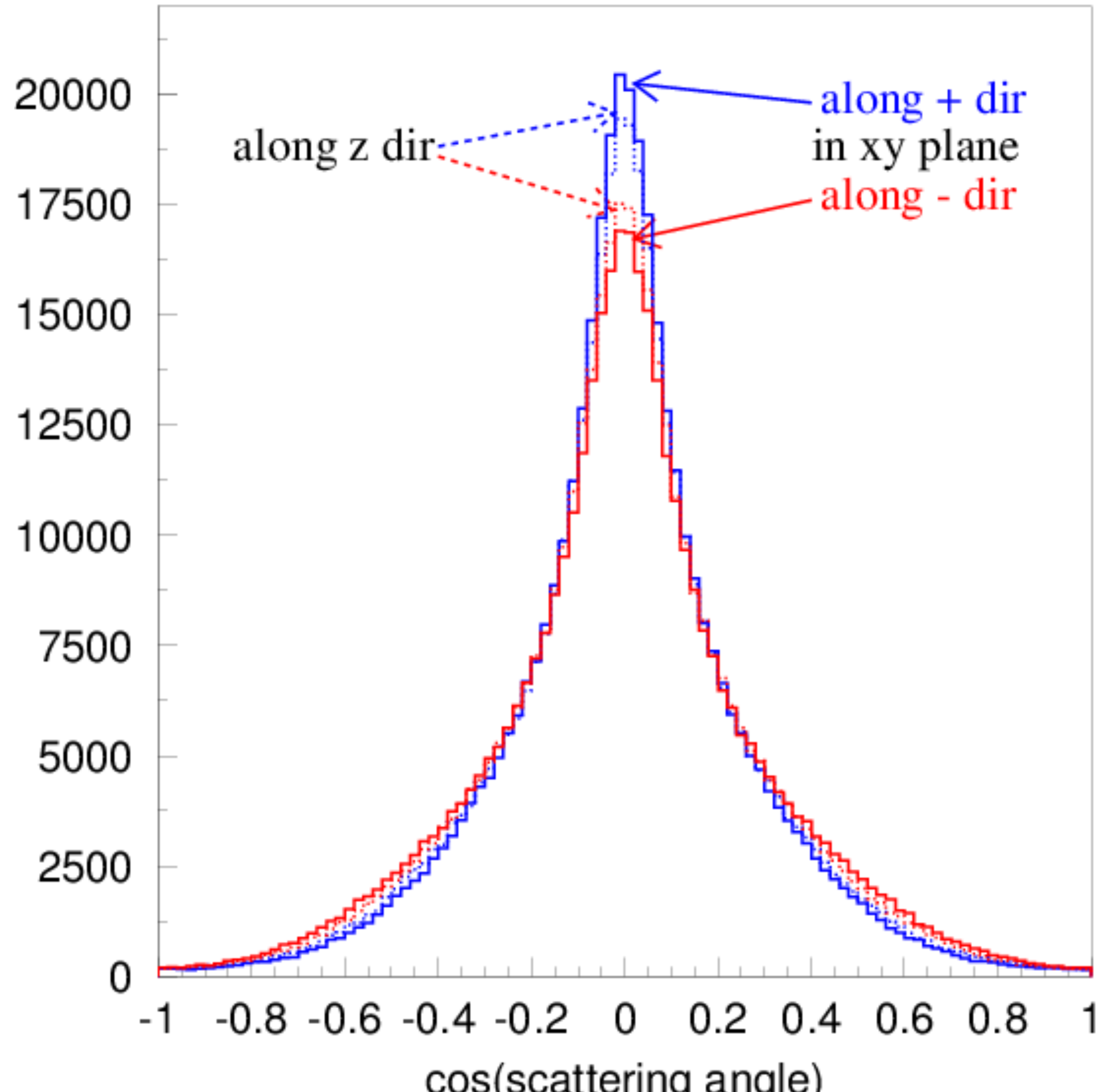
A possible modification is $\mathbf{n}_{in} \rightarrow A\mathbf{n}_{in}/|A\mathbf{n}_{in}| \rightarrow \mathbf{n}_{out} \rightarrow A^{-1}\mathbf{n}_{out}/|A^{-1}\mathbf{n}_{out}|$.

This introduces two extra parameters: α,β (in addition to the direction of scattering preference).

The geometric scattering coefficient is constant with azimuth. However, the effective scattering coefficient receives azimuthal dependence as:

$$1 - \langle \cos\theta \rangle = (1-g) \cdot \frac{1}{2} \cdot (B_{in}B_{in} - n^i B_{in} n^j B_{jn}) \cdot |A\vec{n}|^2 \qquad B = A^{-1}$$

Scattering example (5% anisotropy)



Anisotropy coefficient

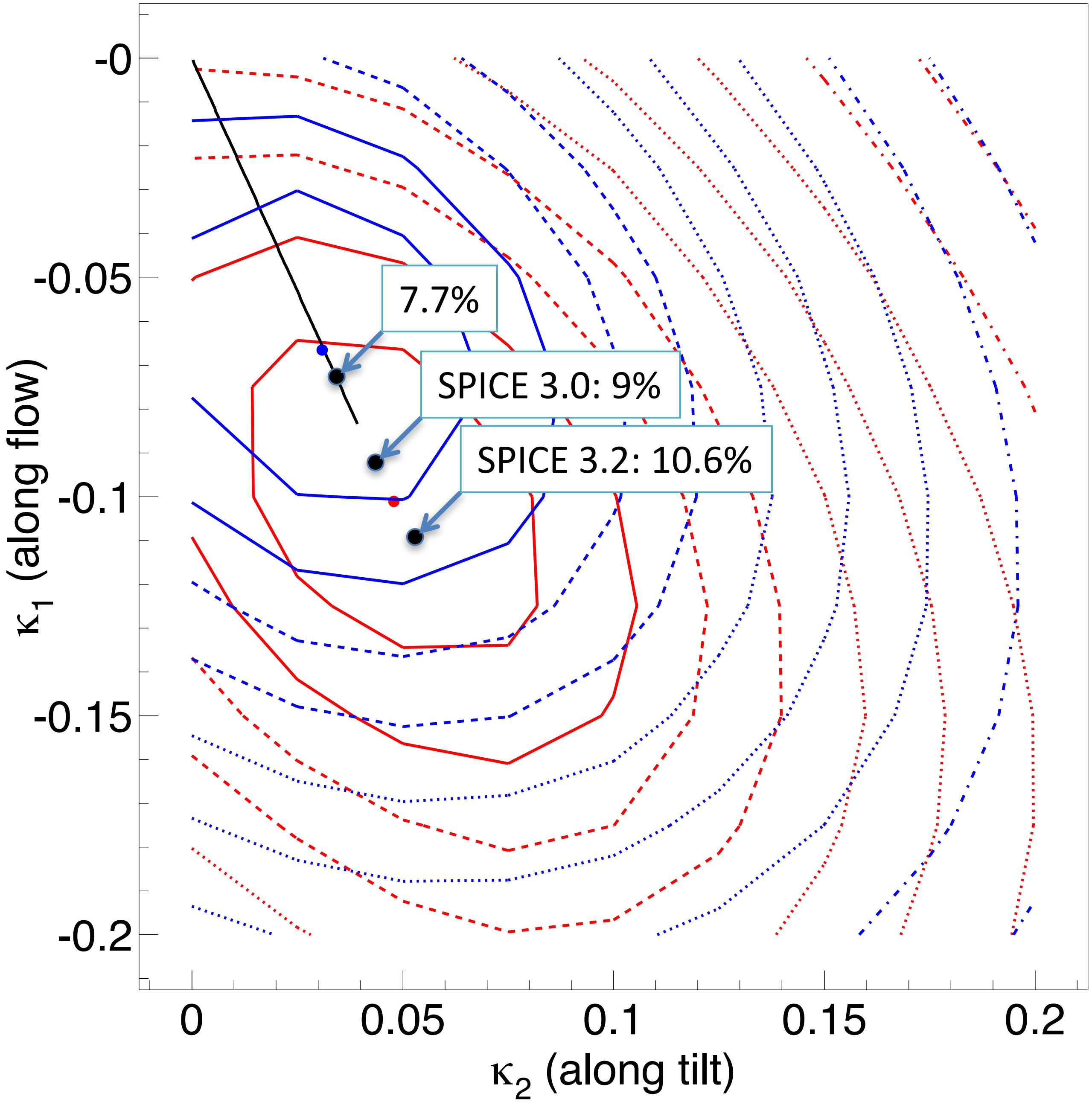
Two values are currently derived from the same data:

10.6% (SPICE 3.2) – fit uses full flasher light profile unfolding and RDE table

7.7% (SPICE HD) – fit uses cylindrically-symmetrical (or otherwise fixed) emitted light pattern and nominal DOM efficiencies

The unfolded flasher light pattern has an overall shape that is correlated with the direction of (main axis of) ice anisotropy – this is not good

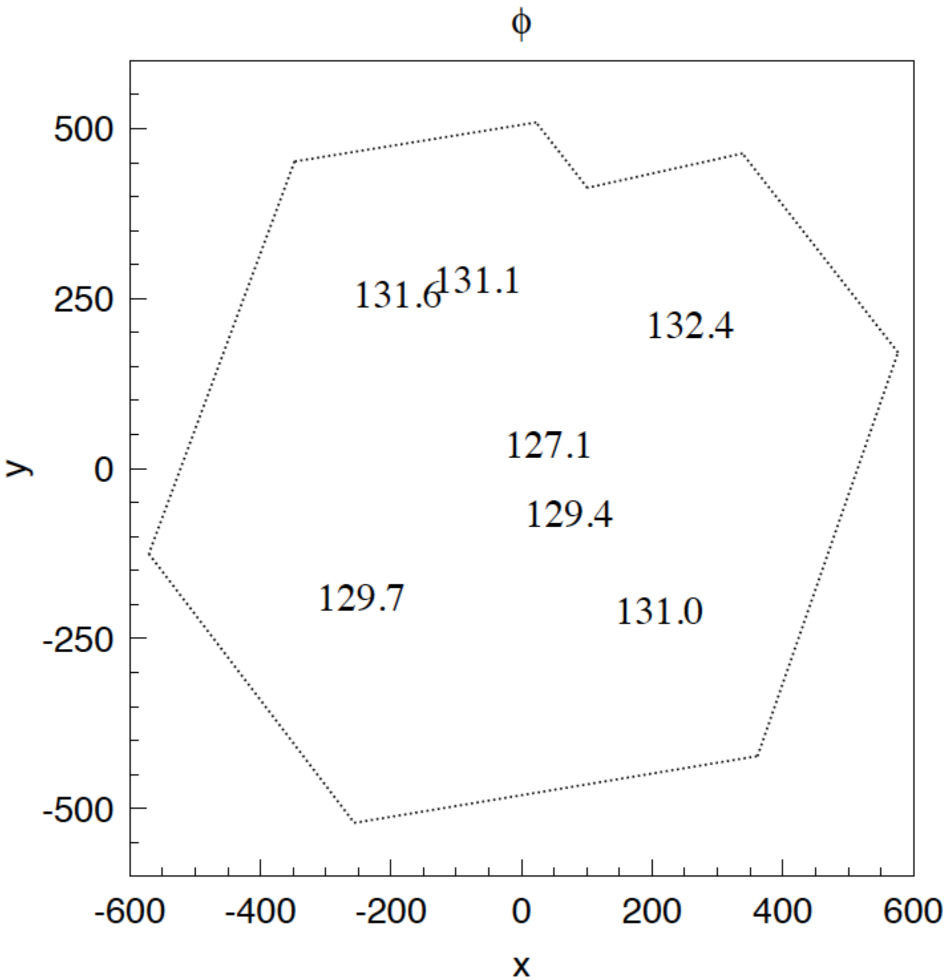
Also, Martin R. found evidence for depth-dependence of anisotropy by fitting the anisotropy coefficient at different depths

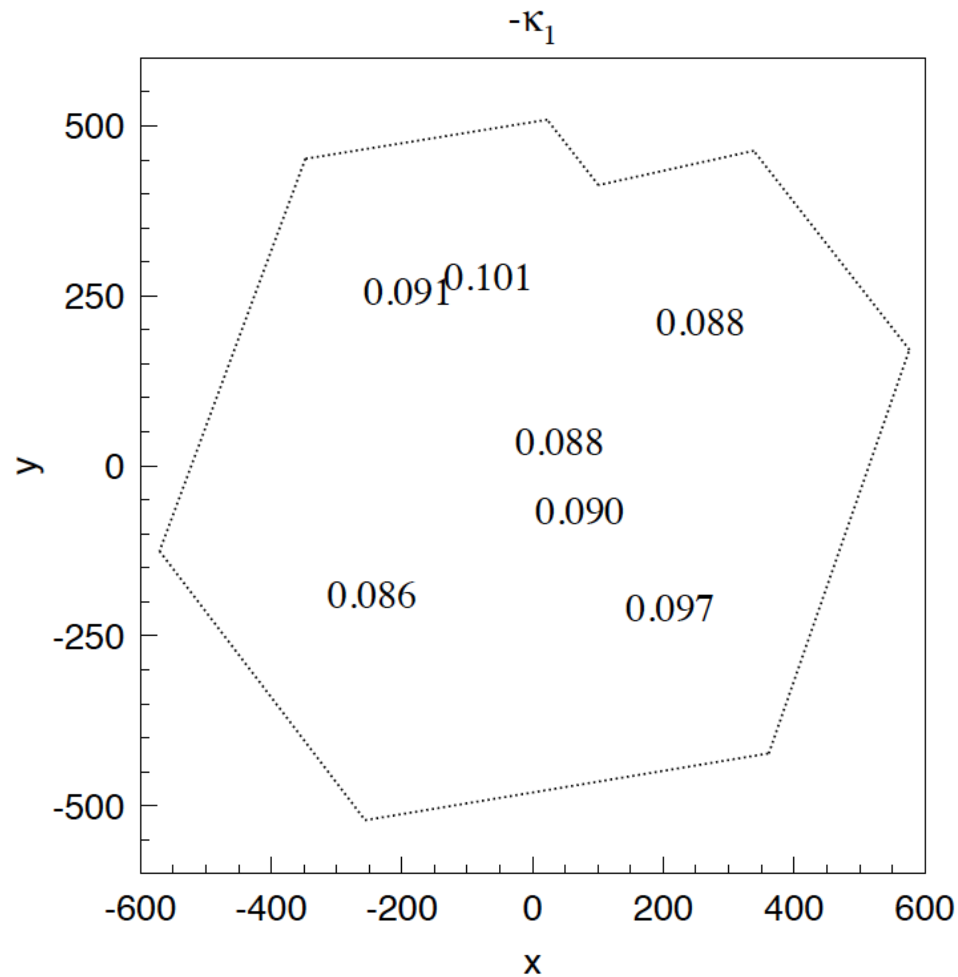


From SPICE Lea ICRC report:

Red: charge-only
Blue: time-binned

ϕ/κ_1 inhomogeneity





SPICE 3.x

SPICE 3.0 used flashers on 7 strings, updated tilt maps and extrapolation data, fitted individual DOM sensitivities and flasher DOM LED pattern unfolding

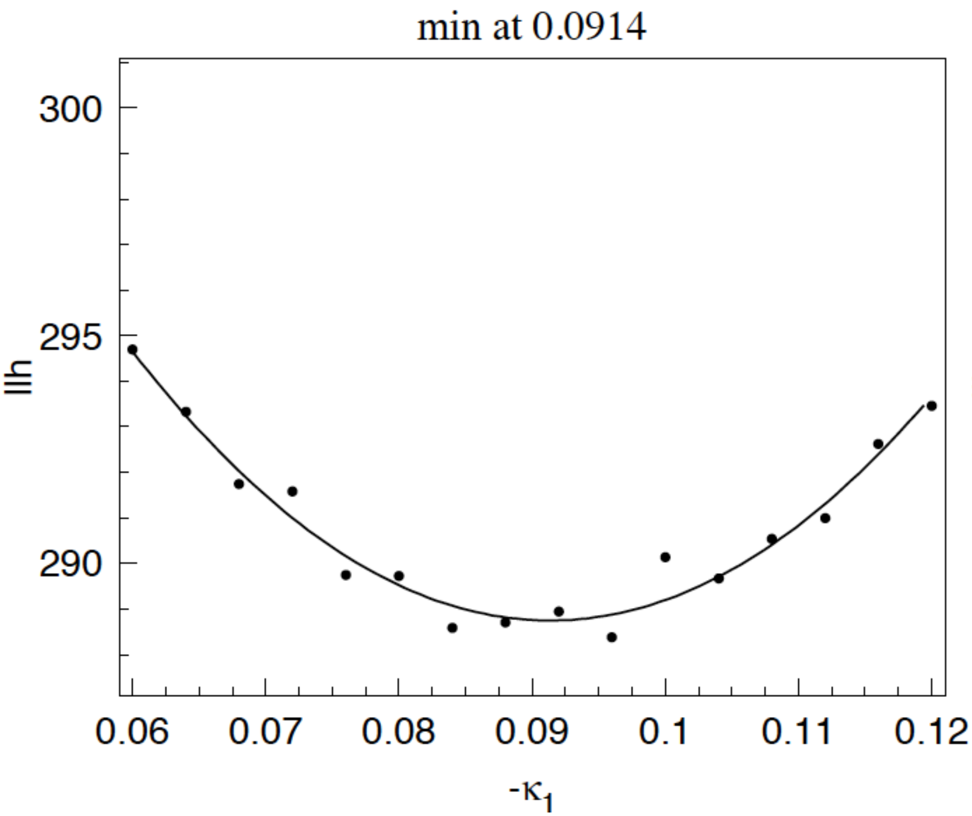
SPICE 3.1 updated the model using flashers on 85 strings, full likelihood fit to the DOM sensitivities with regularizations around nominal values (1 and 1.35)
Also: unfolded angular sensitivity to the same set of flasher data

SPICE 3.2 employed a special (correlation model) refining method for adding small corrections to the table of scattering and absorption coefficients

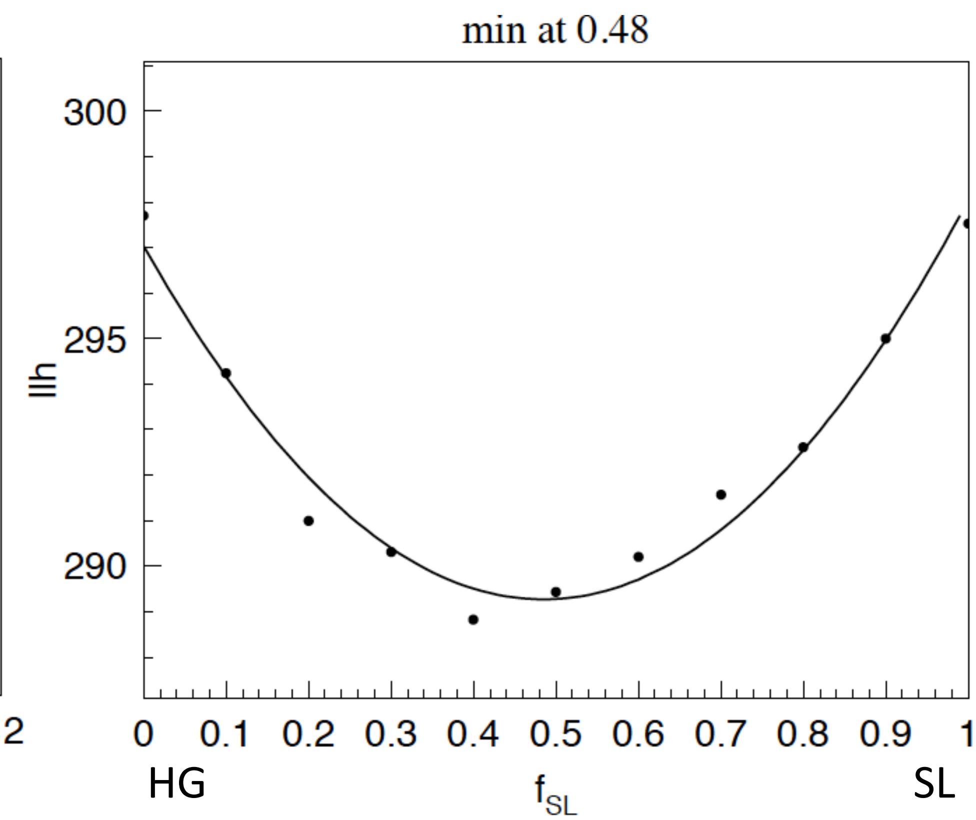
(available in ice-models module)

Selected ice model parameters

SPICE 3.0



SPICE Lea: 0.08

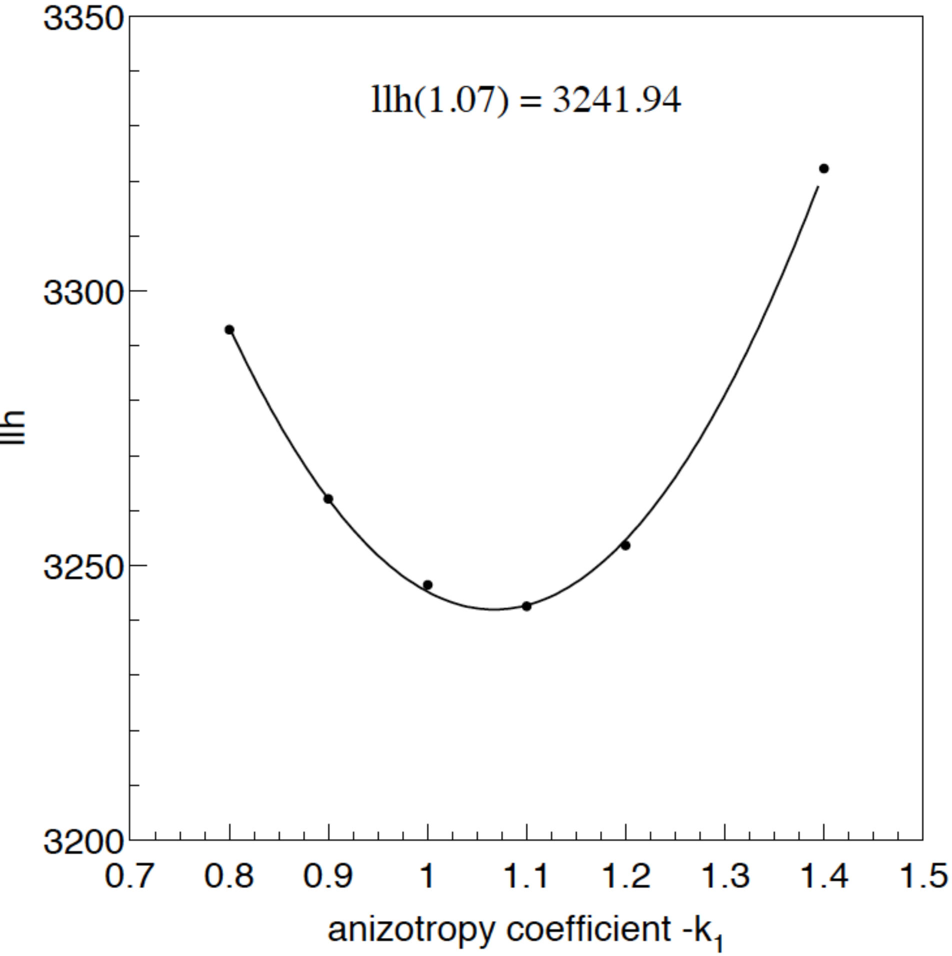


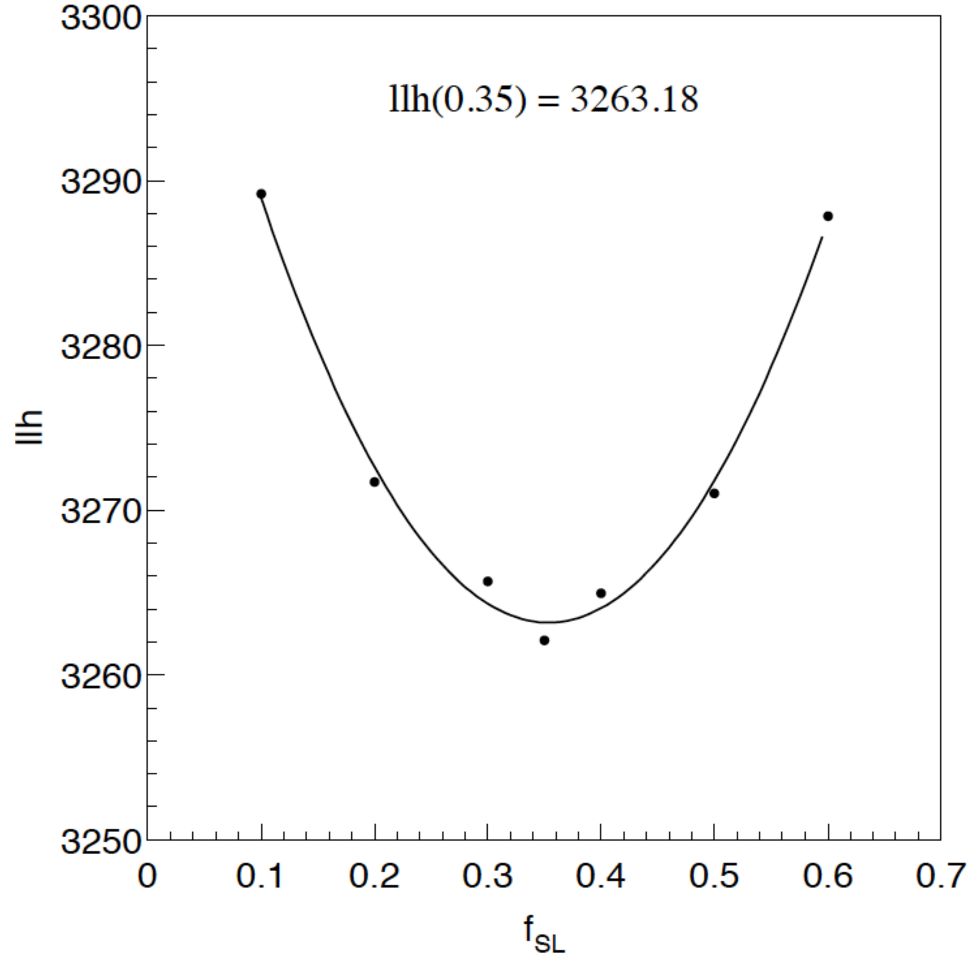
SPICE Mie: 0.45

SPICE Lea: 0.41

Selected ice model parameters

SPICE 3.1

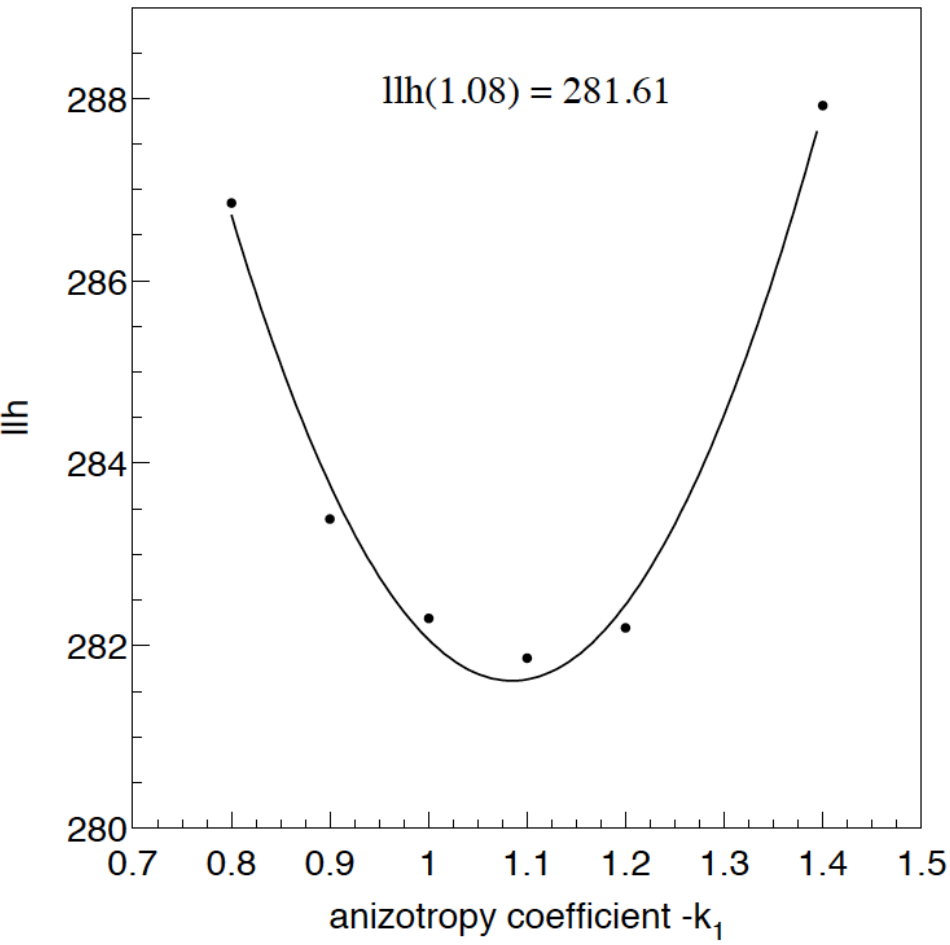


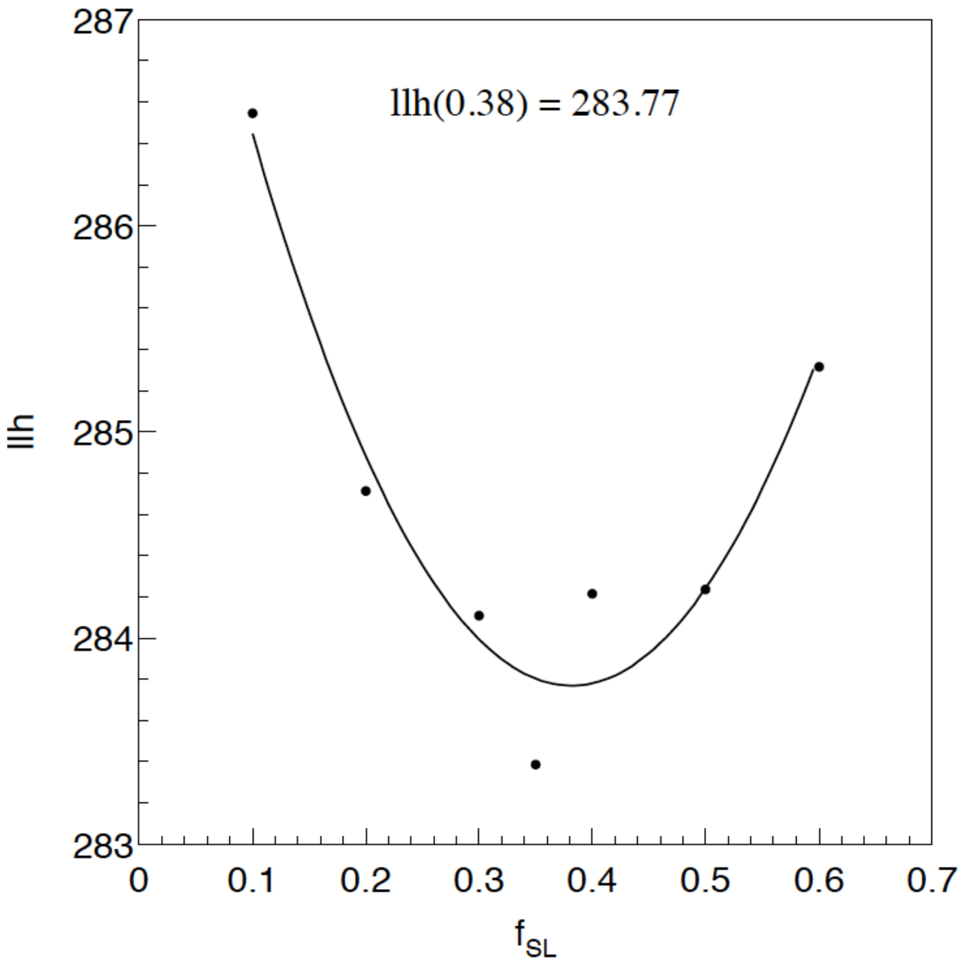


85 strings of flasher data

Selected ice model parameters

SPICE 3.1





Applied to only 7 strings of flasher data

Ice model comparison

Ice models	SPICE Mie	SPICE Lea	SPICE 3	SPICE 3.1	SPICE 3.2
Strings fit	1	1	7	85	85
Anizotropy	0	8%	9%	10.8%	10.6%
f_{SL} (scat.)	0.45	0.41	0.5	0.35	0.35
Model error	29%	20%	10.7%	9.8%	9.8%
g.o.f (x10)				1.2115	1.1799

Other improvements in SPICE 3:

updated tilt maps and extrapolation (relies on dust logger/EDML data)

DOM sensitivity fits and flasher DOM LED pattern unfolding

Main difference to Mie and Lea: 4% less absorption on average

(all of the above models are available in ice-models module)

Dmitry Chirkin, UW-Madison

SPICE HD

Ice model developed by Martin R

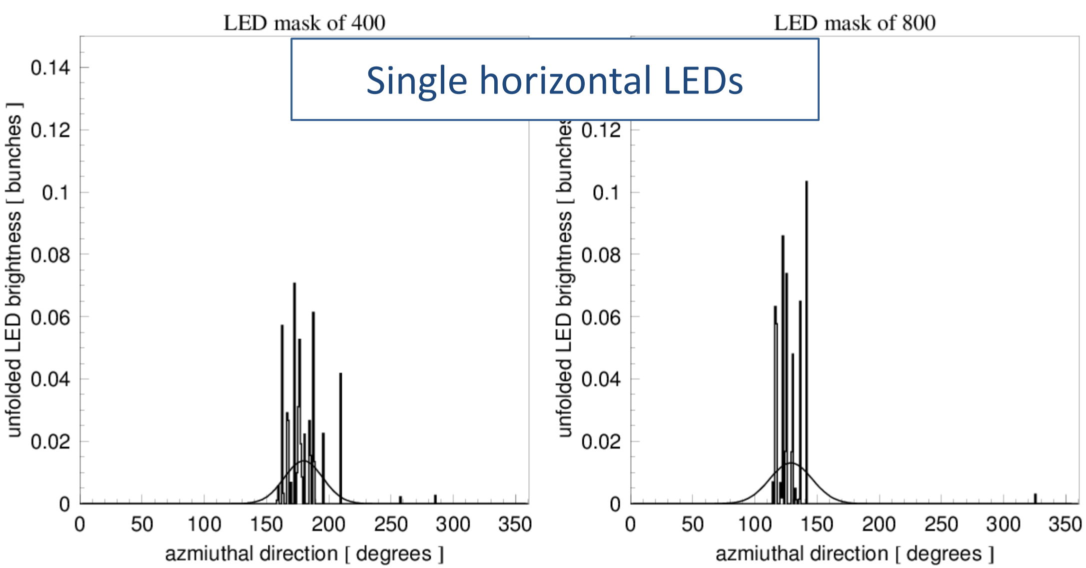
shares the ice tables with SPICE 3.2
(except with smaller anisotropy coefficient, 7.7%)
(new: with depth-dependent anisotropy)
(new: with different anisotropy model)

Unfolding of flasher LEDs

- Simulate LED light (2d gaussian with 9.7 degree rms) every 5 degrees in azimuthal direction from 0 to 355 degrees, also up and down components

- Create a [azimuth x charge_in_DOM] matrix, and unfold to charge_in_DOM in data

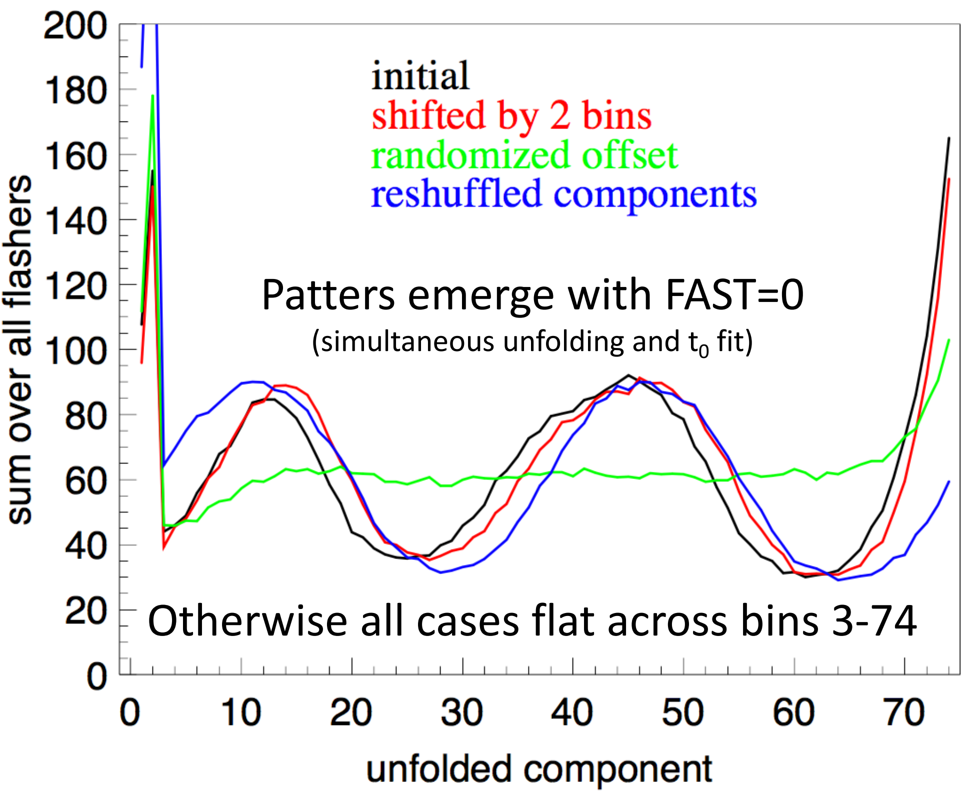
- The unfolded pattern is re-simulated and llh is calculated



This adds 30340 (410*74) nuisance parameters

Additional parameters optionally introduced at a later step: individual DOM efficiencies (~ 3400 values)

Correlated unfolded pattern

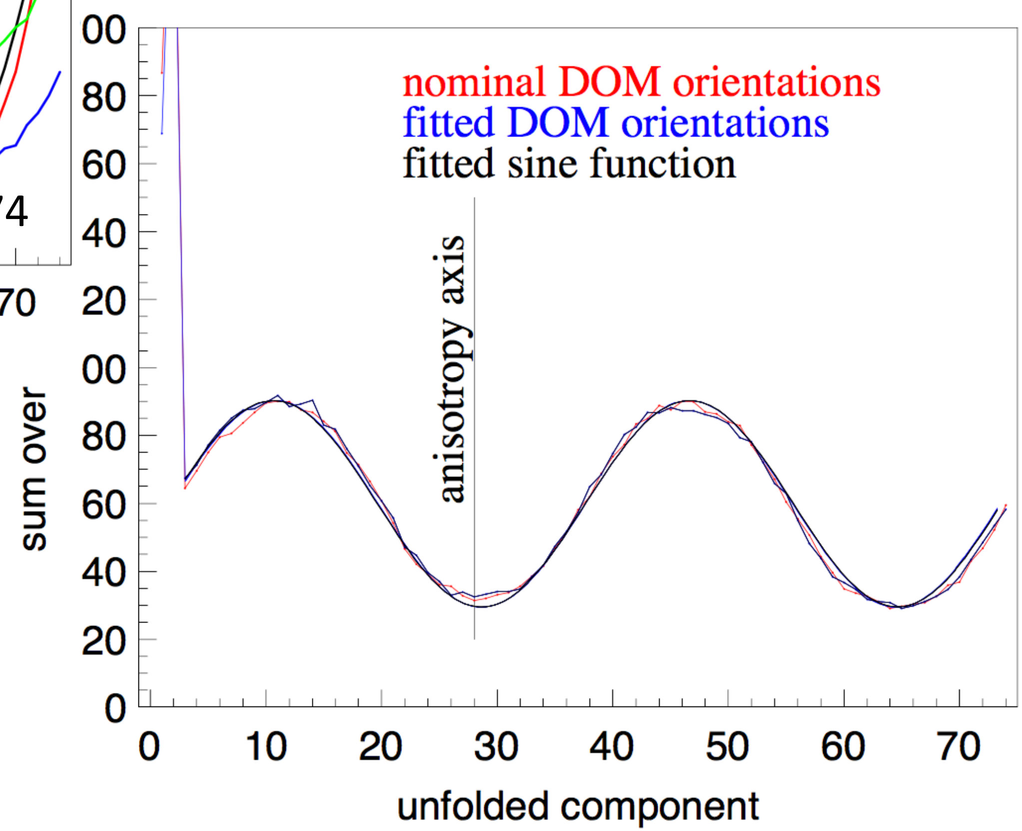


Starting (initial) LLH=3189.17
Reshuffled (fixed) LLH=3097.57

Model error: 11.2%→10.9%

SREP=10

Fixed pattern is now sine-like



components 1,2 are up/down
components 3-74 correspond to
0-355 degrees spaced by 5 degrees

Unfolding favors higher components

One ice table for everything

Nominal DOM efficiencies, h2-50cm hole ice model, 1x simulation (10 events)

Ice model comparison: GOF

Nominal DOM efficiencies, h2-50cm hole ice model, 1x simulation (10 events)

With flasher LED pattern unfolding, spice 3.2: 3656.51 (over 4746 flashers)

No unfolding:

anizotropy	✔	✖	✖
tilt	✔	✔	✖
SPICE Mie	4664.05	5735.30	6649.60
SPICE Lea	4415.63	5746.48	6504.19
SPICE 3.2	4330.60	5303.99	6277.33

By removing anizotropy and, if necessary tilt, from SPICE 3.2, the resulting ice model is improved over SPICE Mie and SPICE Lea

Ice model comparison: model error

Nominal DOM efficiencies, h2-50cm hole ice model, 1x simulation (10 events)

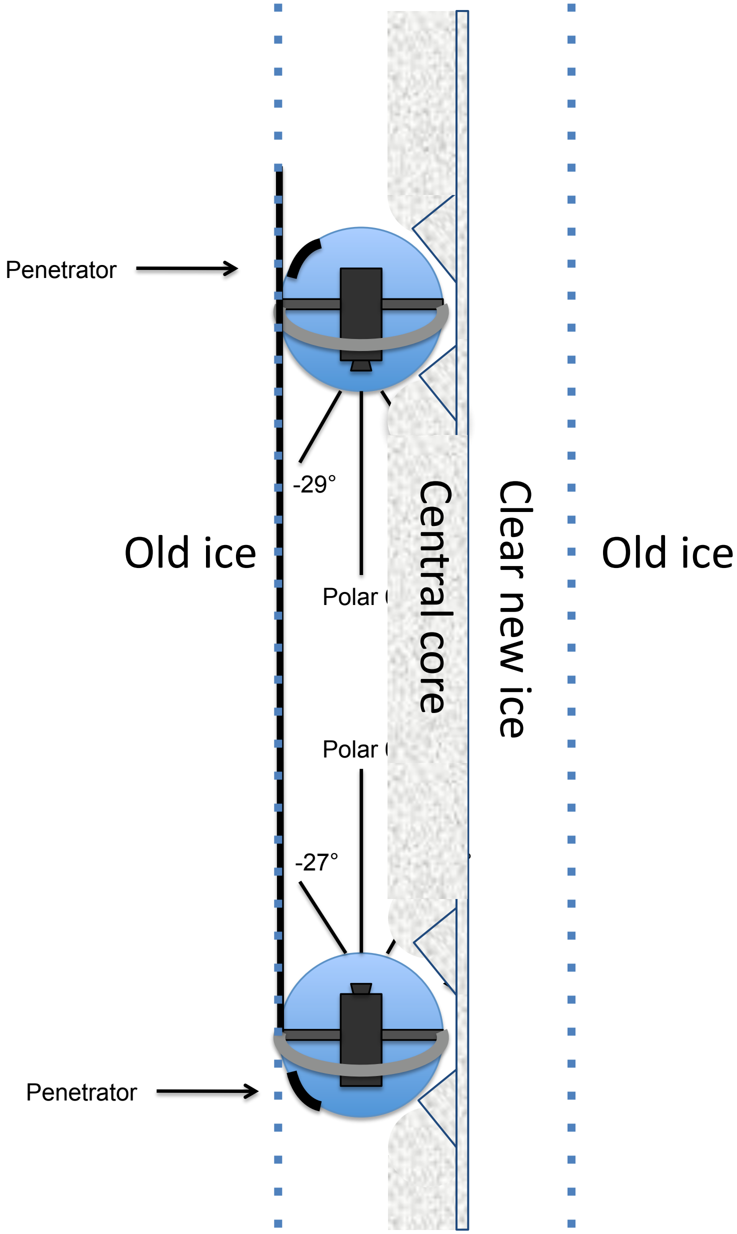
With flasher LED pattern unfolding, spice 3.2: 14.7%

No unfolding:

anizotropy	✔	✖	✖
tilt	✔	✔	✖
SPICE Mie	17.4%	26.6%	29.6%
SPICE Lea	18.6%	27.5%	30.0%
SPICE 3.2	16.5%	25.4%	28.6%

By removing anizotropy and, if necessary tilt, from SPICE 3.2, the resulting ice model is improved over SPICE Mie and SPICE Lea

Hole ice



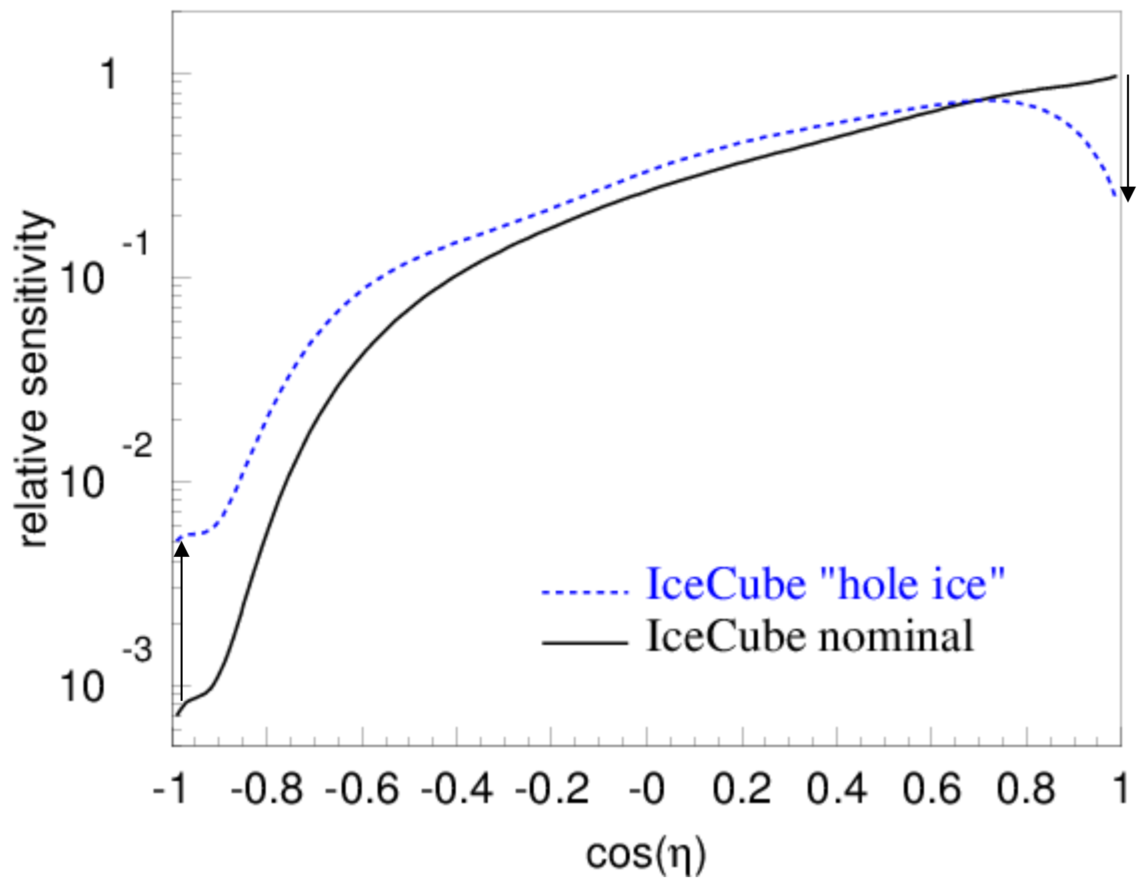
Penetrator
-29°
Old ice
Polar (
Central core
Clear new ice
Old ice
Polar (
-27°
Penetrator

4

U -19 902 29 255 1 50 1.4
01:07:22 04/03/11 234 2094 9

L -5 2702 9 1 50 1.4
02:44:40 18/02/11 -2 829 29

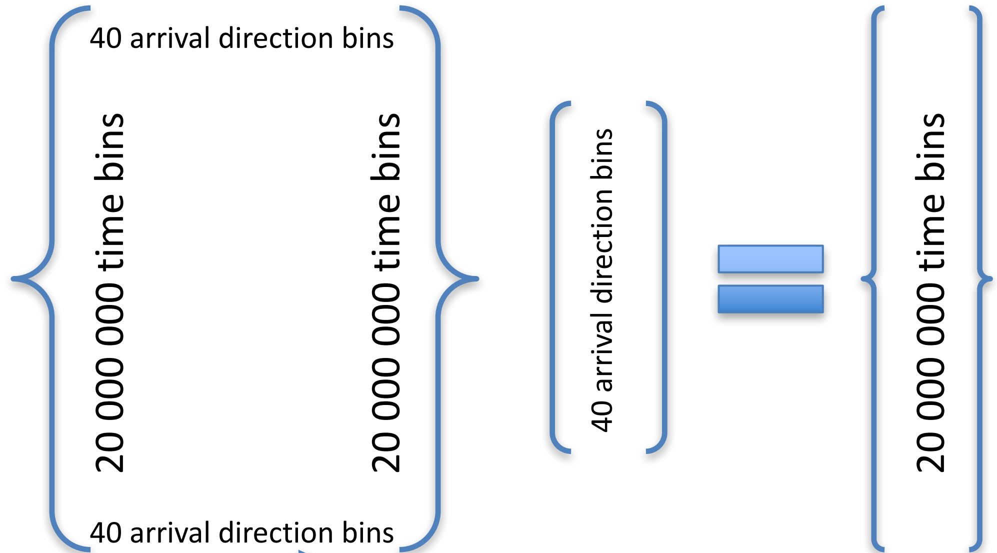
Traditional "hole ice" angular sensitivity

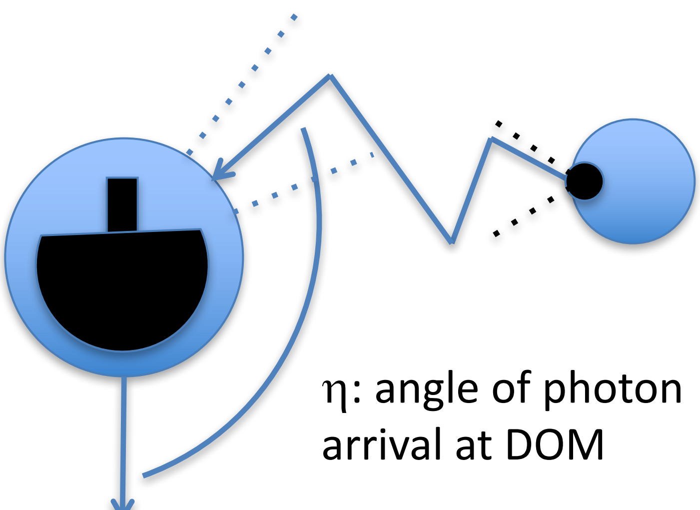


Unfolding the angular sensitivity

Same likelihood construction as in SPICE[3] fit to flasher data

Nuisance parameters:
5046 receiver DOM efficiencies
(72+2)*4746 flasher parameters



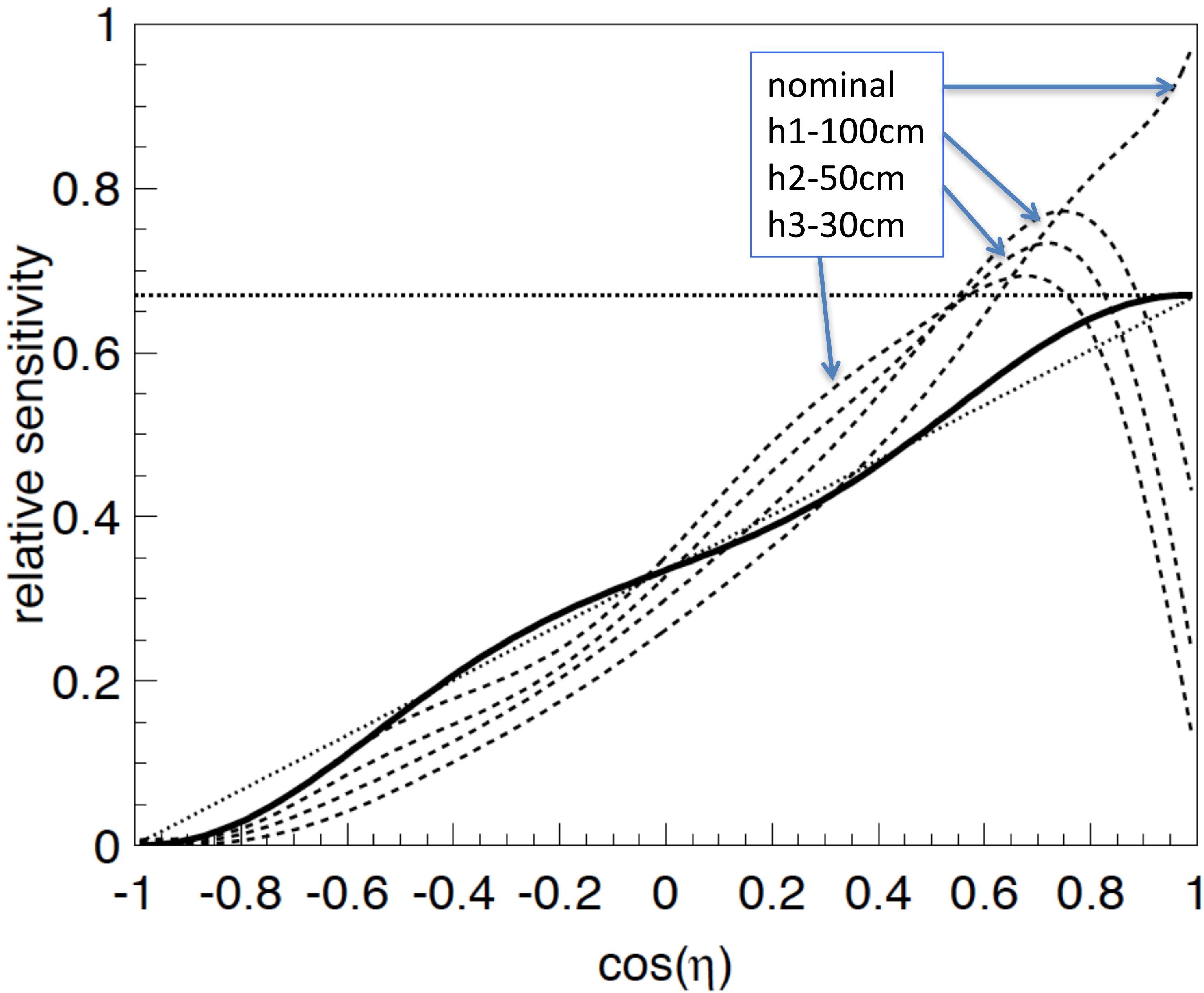


Unfolding matrix (from simulation):

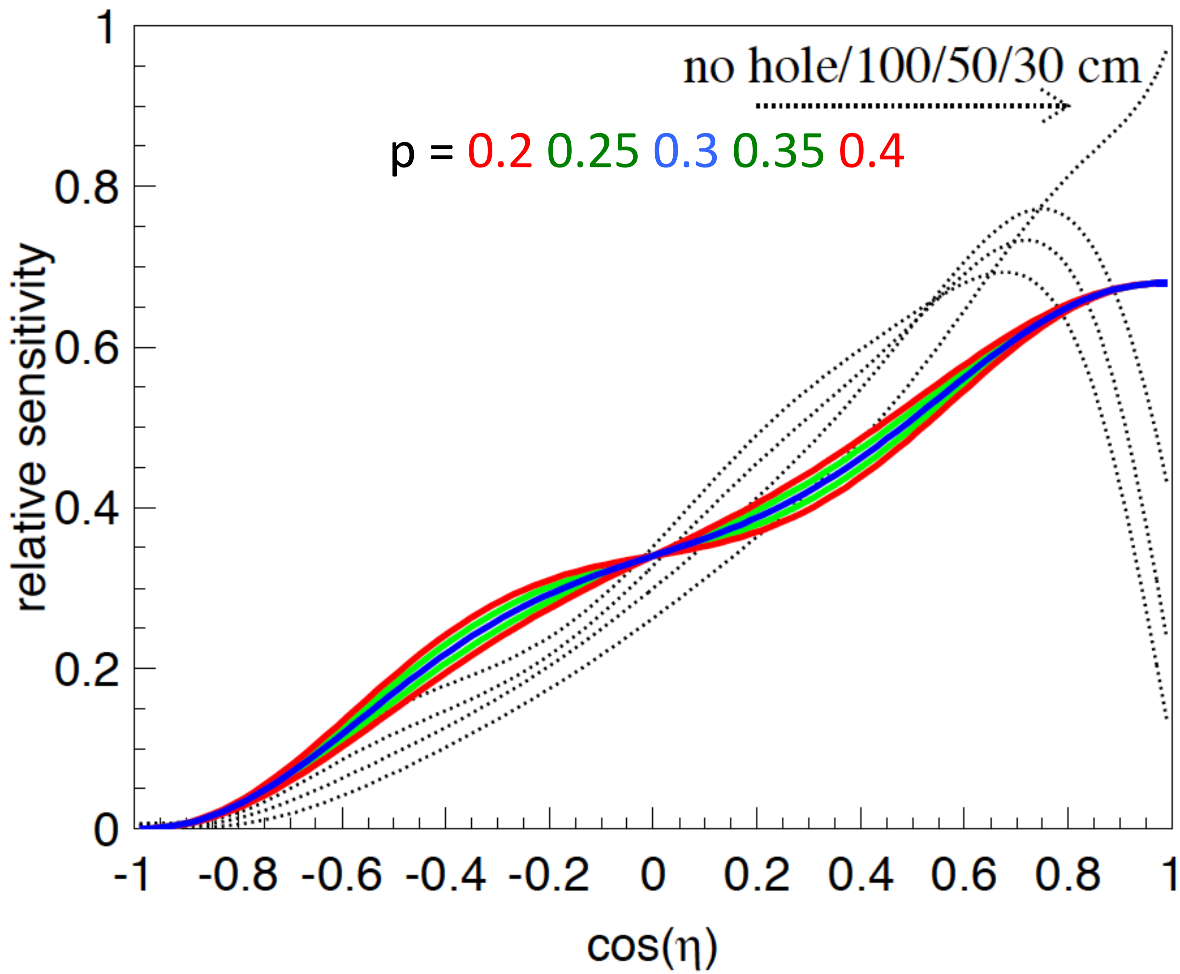
40 cos(η) unfolding bins

20 000 000 charge values of emitter-receiver time bin pairs (4746 flashers)

Best fit to all-string flasher set



Fitted shape parameter: p=0.3+-0.1



An unfolded solution as fitted to the all-purpose flasher data

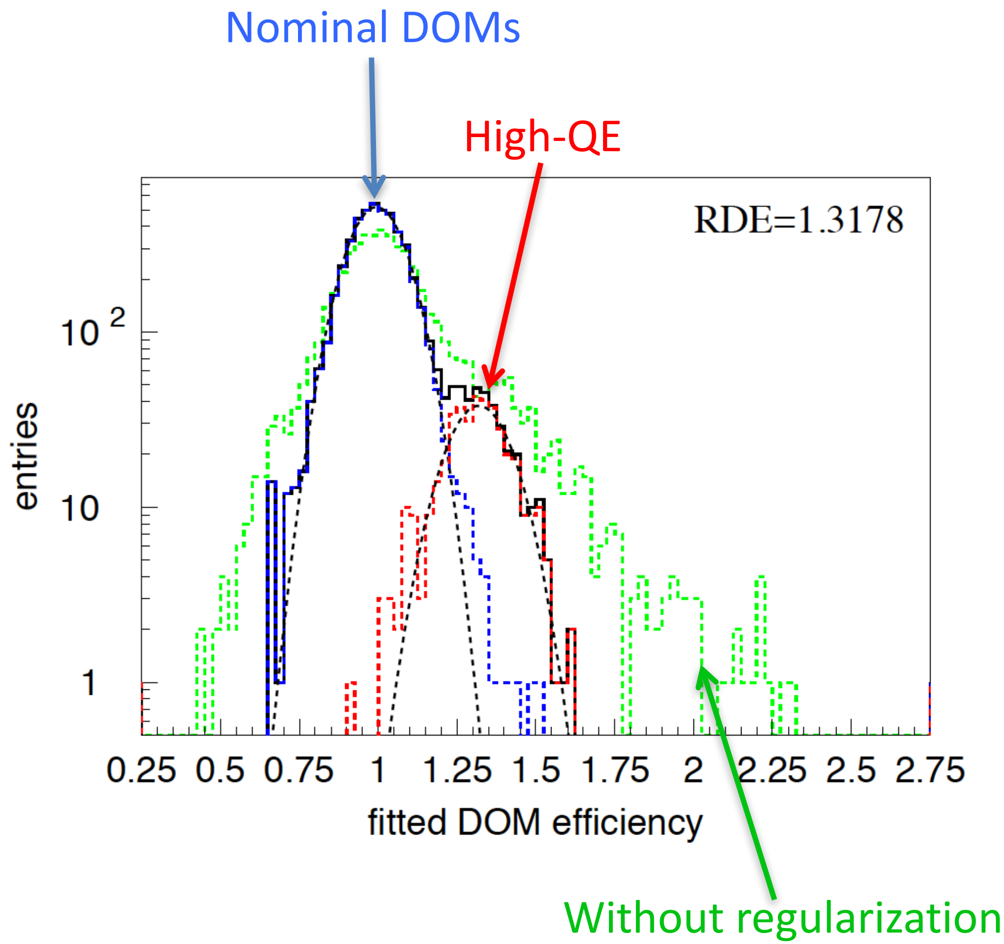
Hole ice

Low-energy group developed an extension that uses an additional shape parameter (p_2) to describe the peak

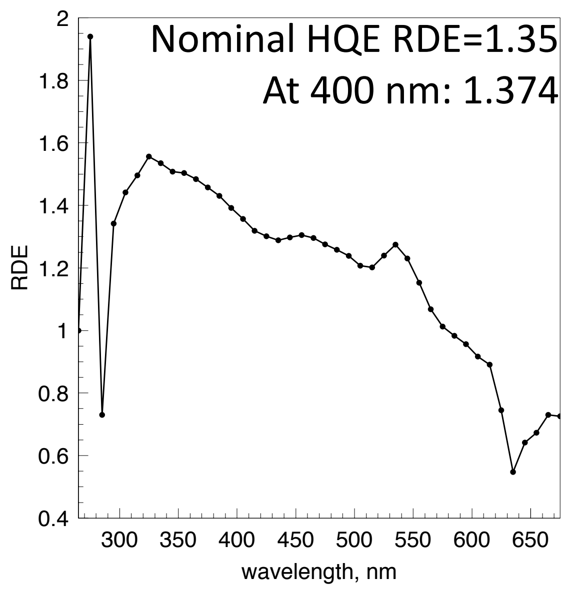
Martin R. has DARD-derived and lab measurement models, with an ice model extension, SPICE HD

Relative DOM efficiencies (RDE)

DOM efficiencies



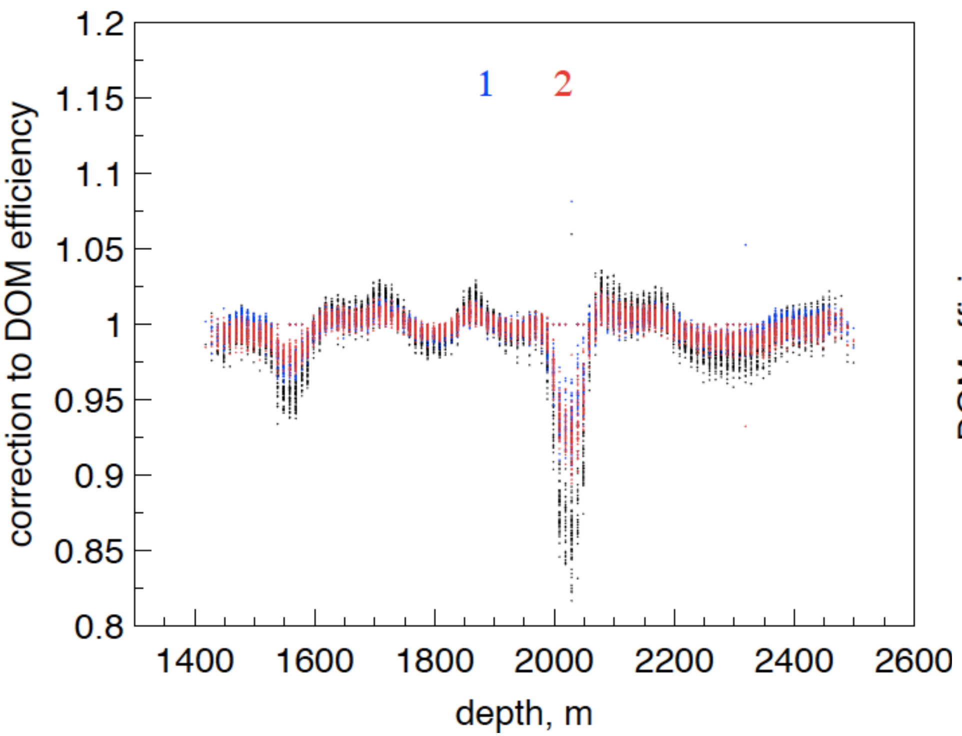
Use fitted RDE table and two wavelength acceptance curves (nominal and high-QE) simultaneously

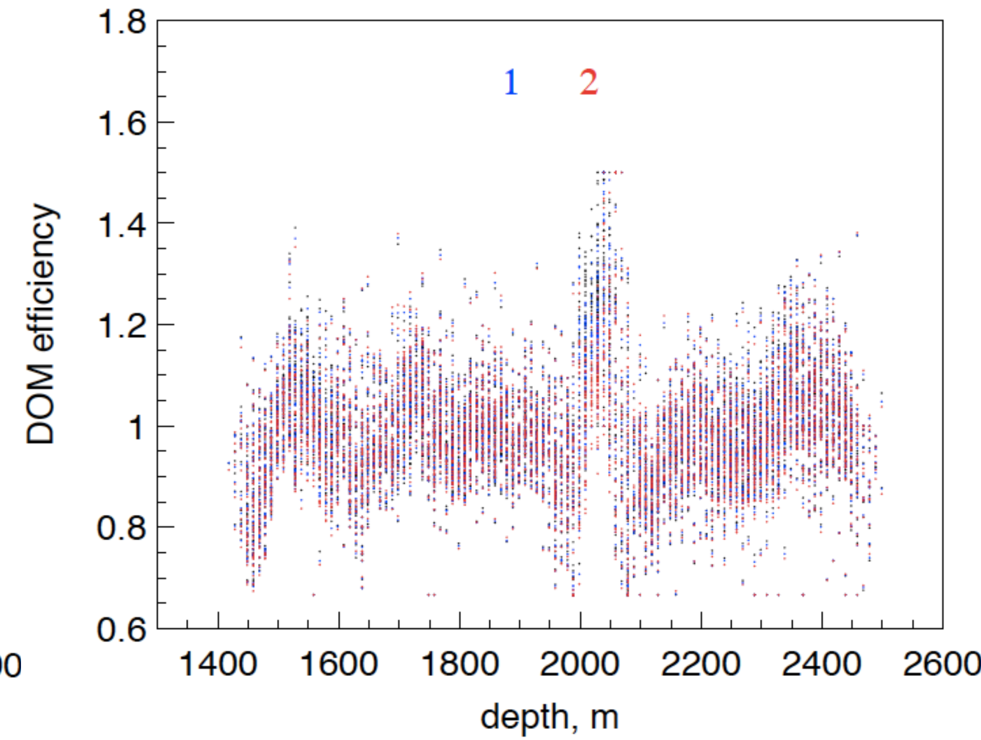


(available in ice-models module, directory resources/models/spice-latest-full)

Derived DOM efficiencies

Shown are nominal DOMs only

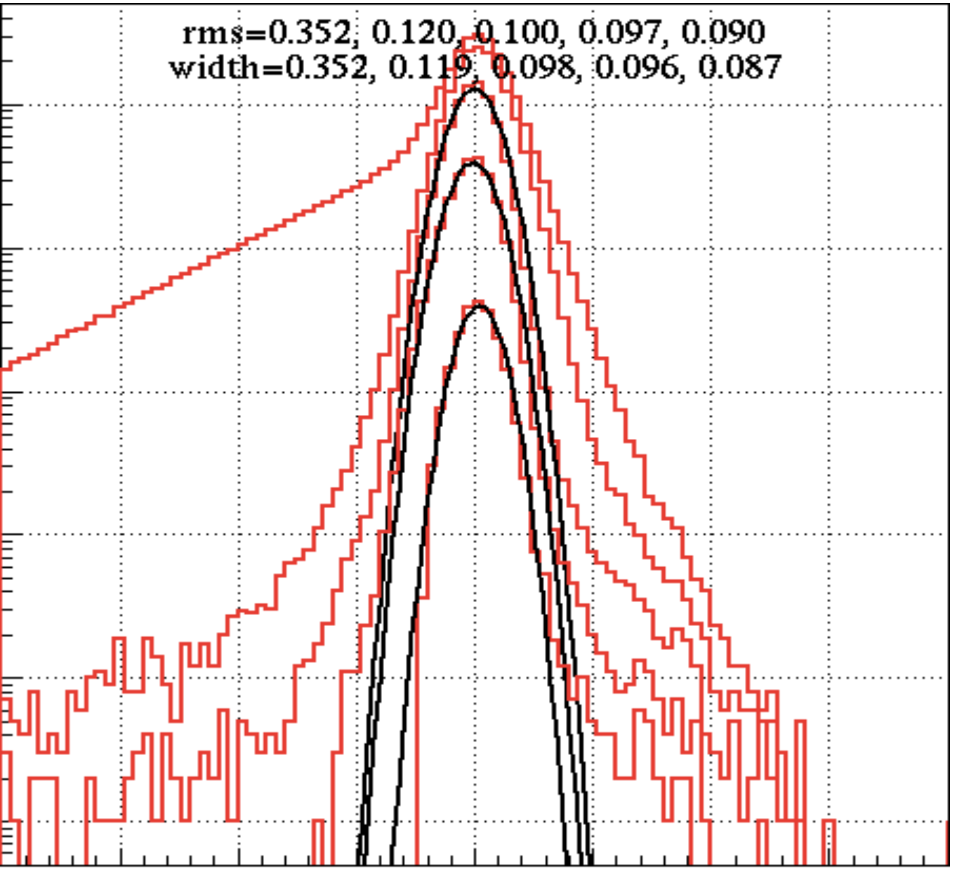




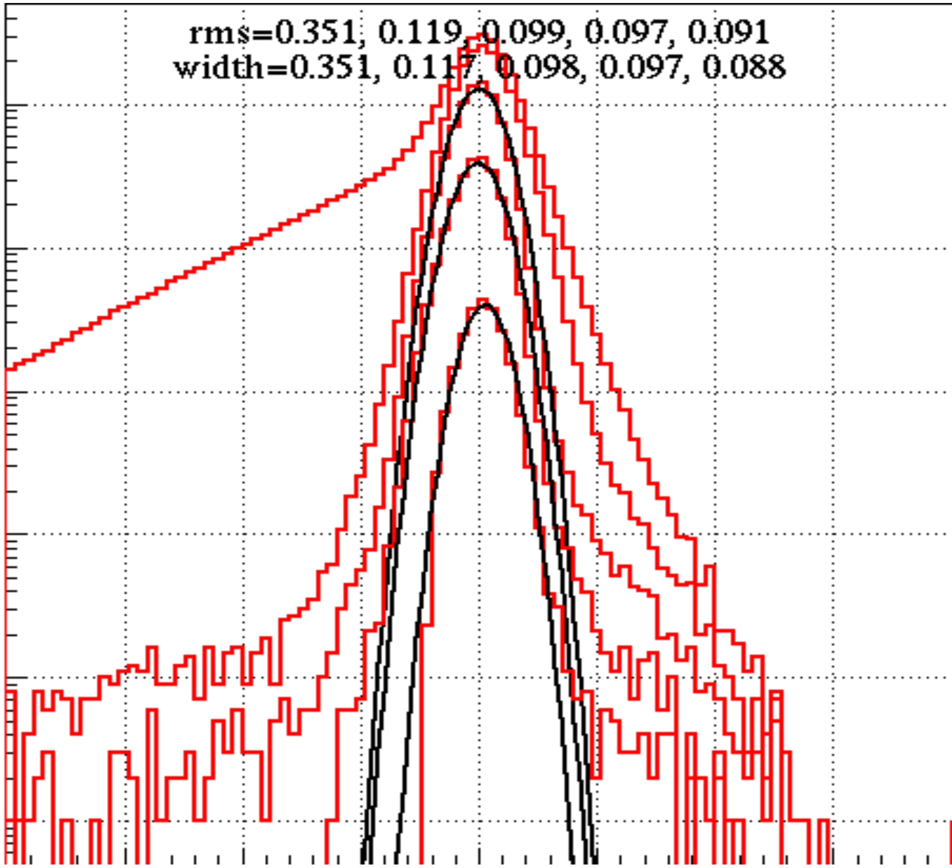
Cumulative change shown in black (in plot on the left)
(available as part of ice-models module in resources/models/spice-latest-full/eff-f2k)

Other

Model error



SPICE 3.1



SPICE 3.2

100 sim. events (10x statistics)

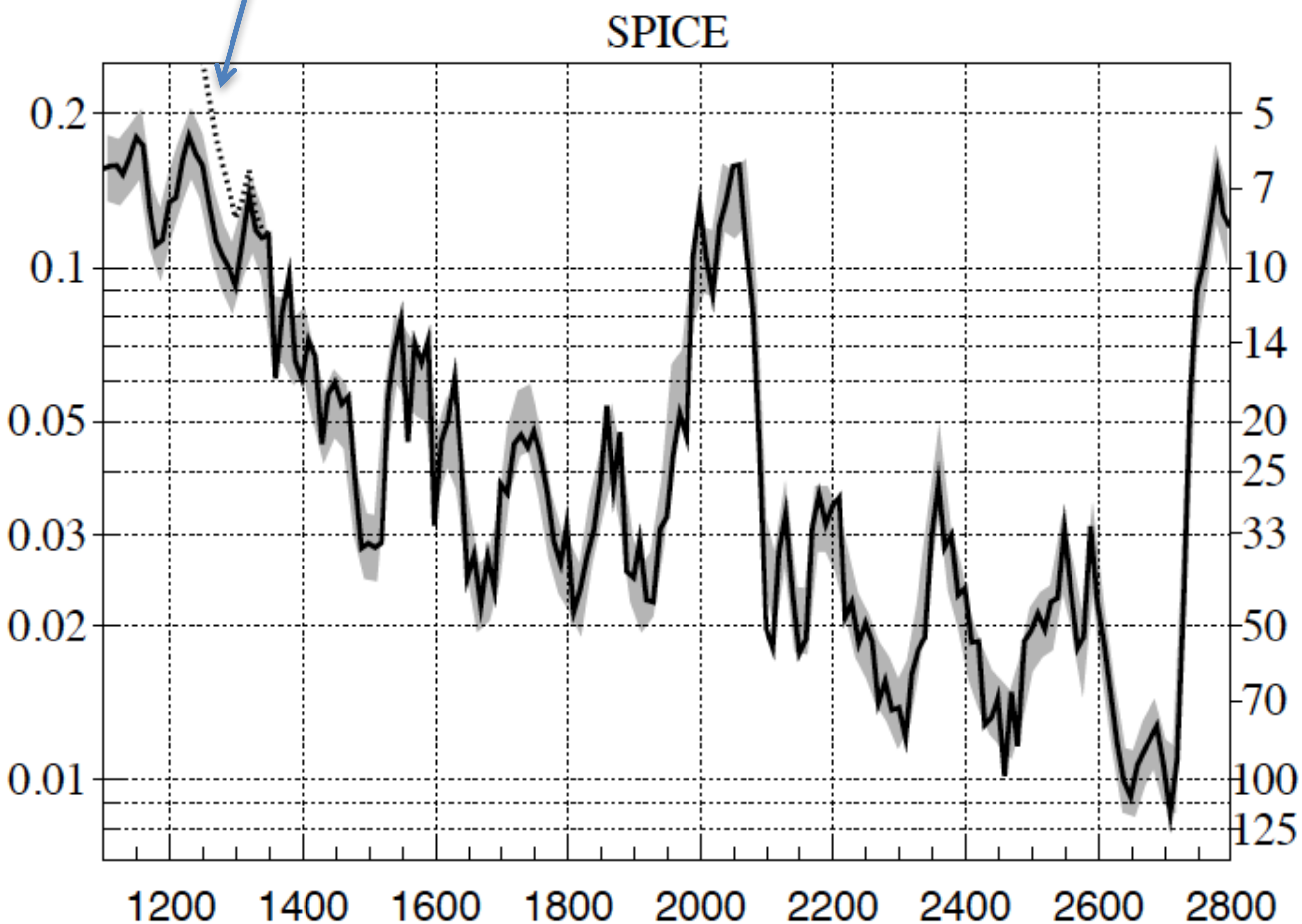
benchmark value unchanged at 9.8%

Very slight improvement for smaller charge: 11.9 → 11.7

Air bubbles at shallow depths

Parameterized in file icemodel.bbl

Air bubble contribution (from WHAM!):
11.7*(1-d/1350)*(1-d/1400)



b_e(400 nm) [m^{-1}] vs. depth [m]

Backup: anisotropy coefficient

κ_1=10.6%

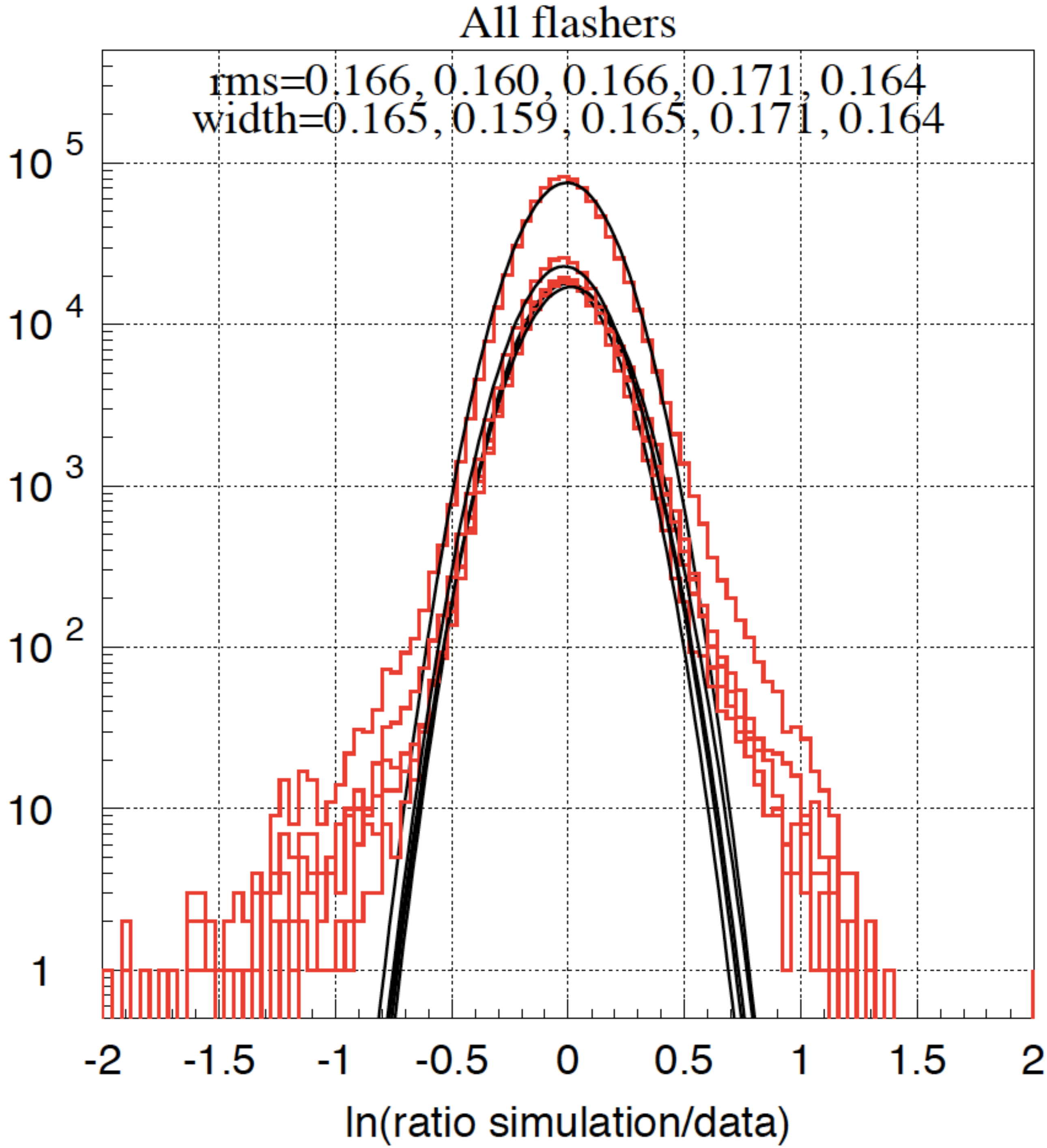
0: all directions

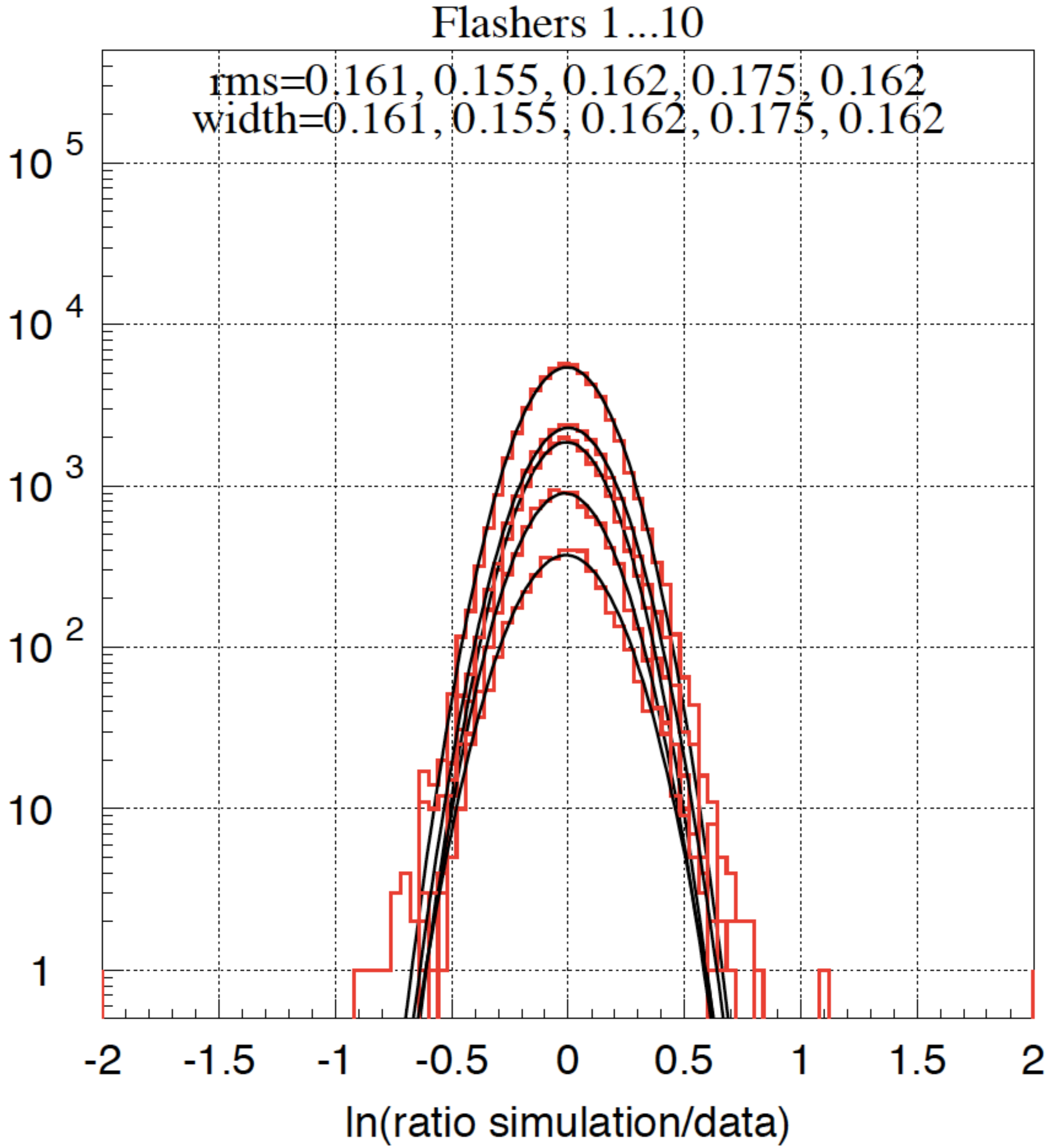
1,3: flasher-receiver directions within 45 degrees of major anisotropy axis

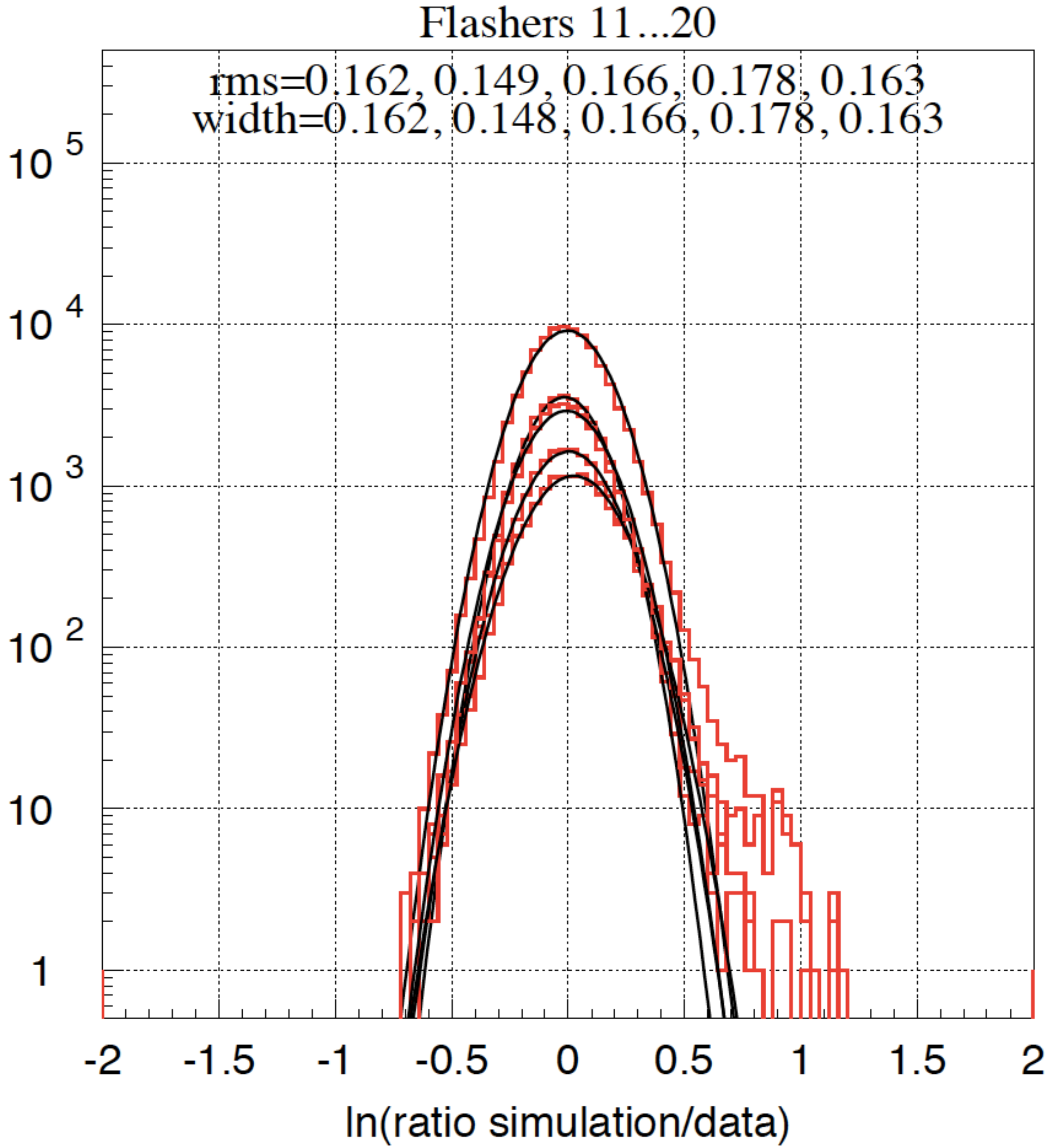
2,4: flasher-receiver directions within 45 degrees of minor anisotropy axis

No unfolding, nominal DOM efficiencies, h2-50cm hole ice

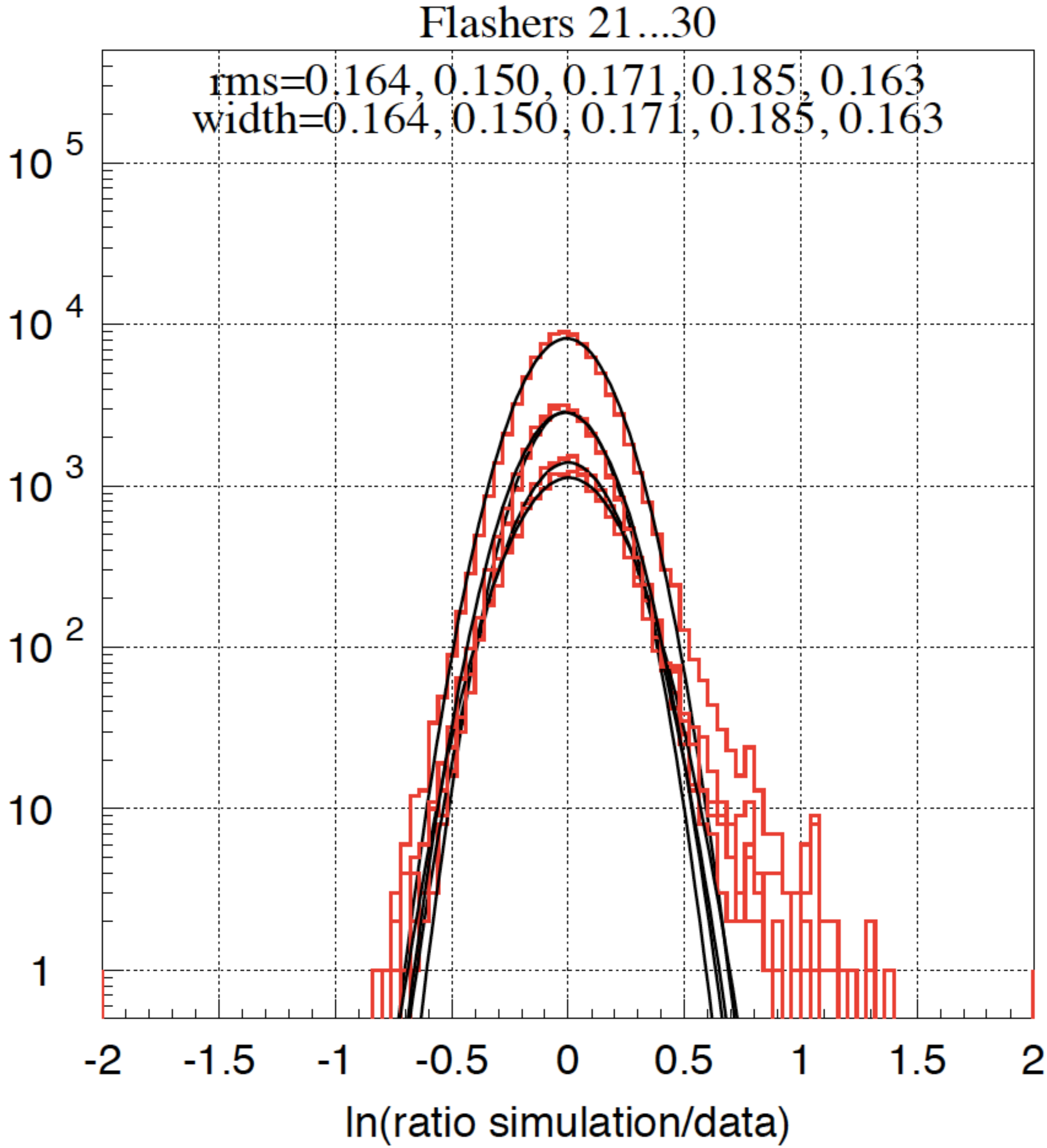
GOF=4330.6

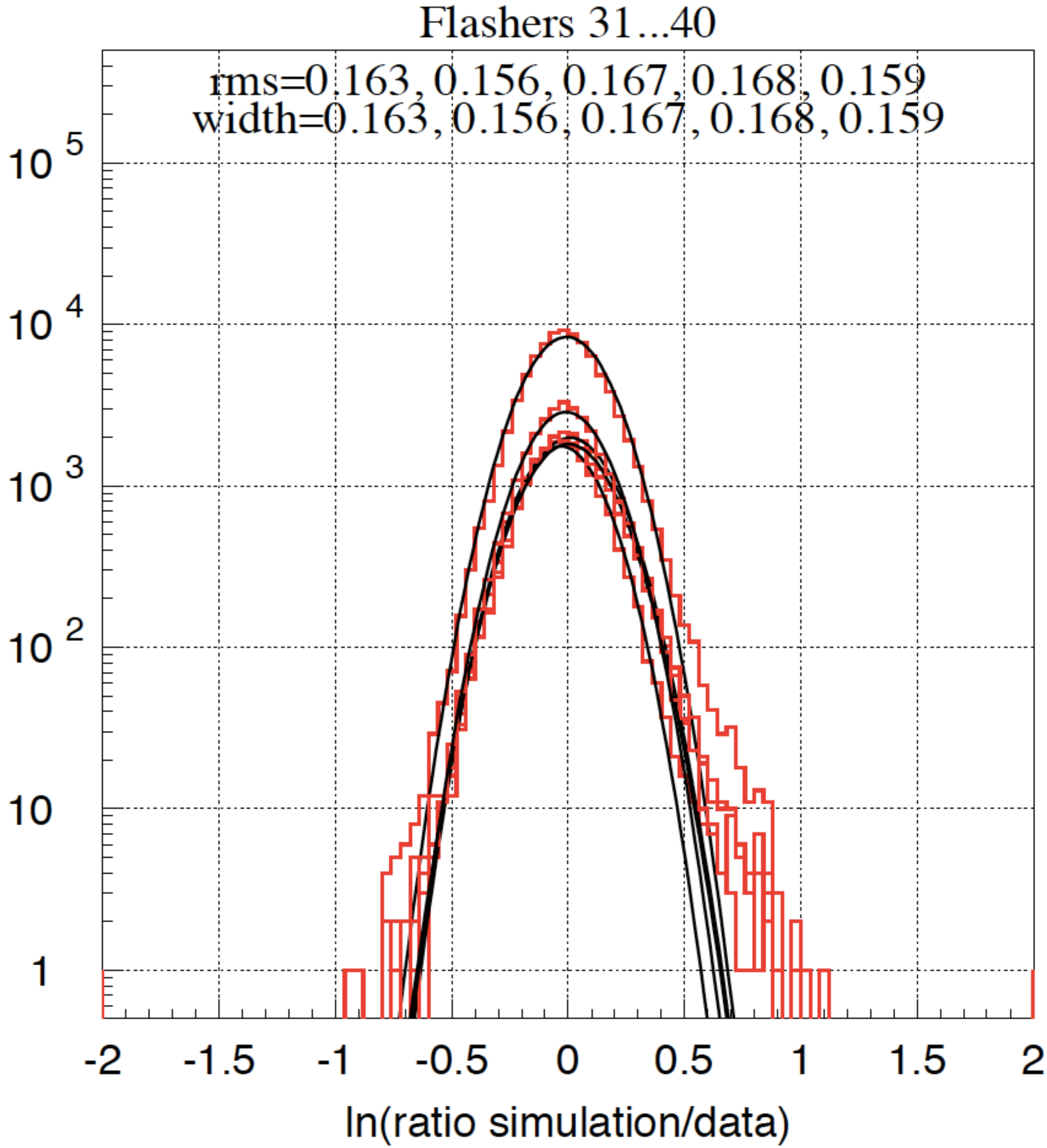

All flashers
rms=0.166, 0.160, 0.166, 0.171, 0.164
width=0.165, 0.159, 0.165, 0.171, 0.164
10^5
10^4
10^3
10^2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)

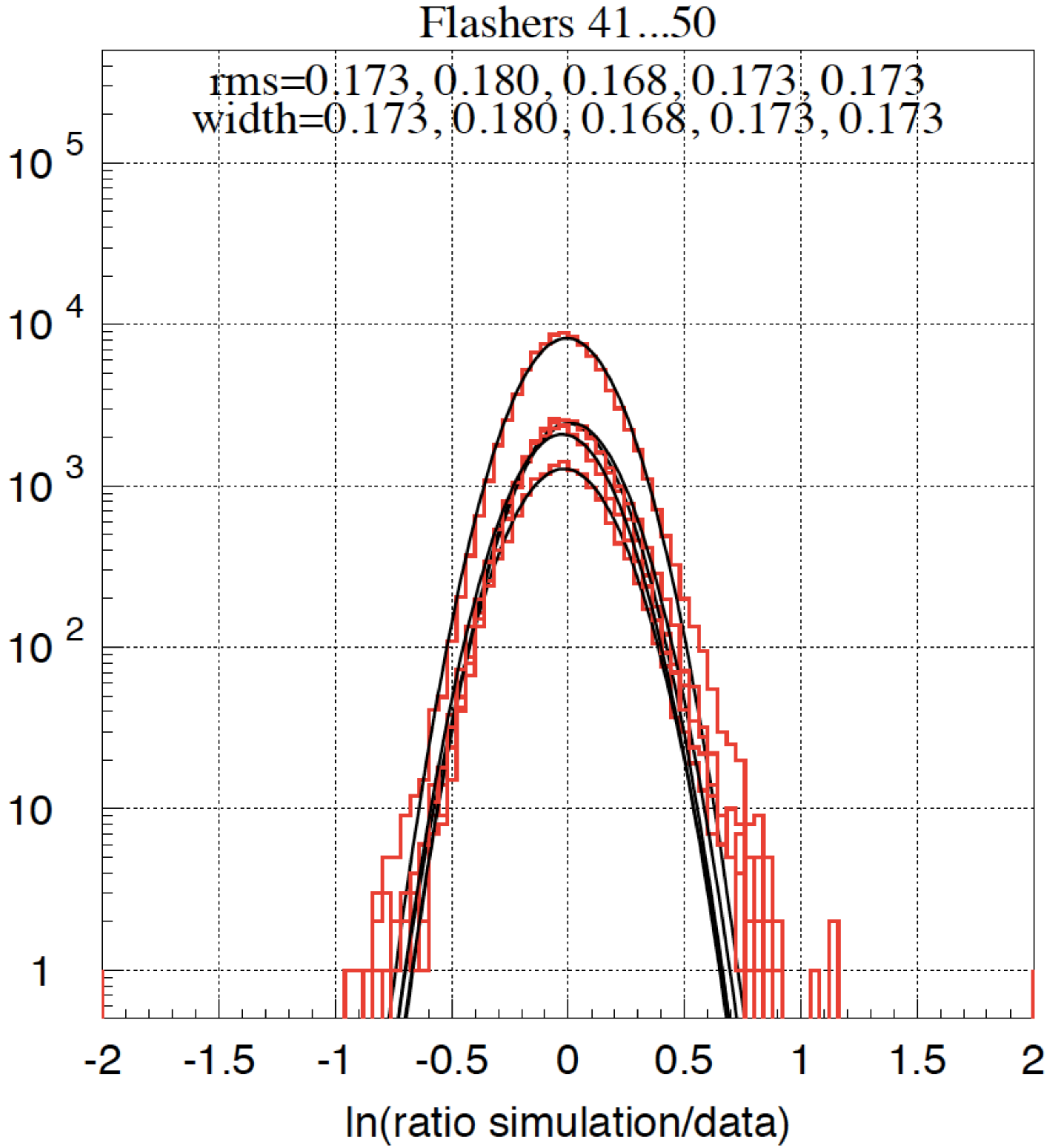

Flashers 1...10
rms=0.161, 0.155, 0.162, 0.175, 0.162
width=0.161, 0.155, 0.162, 0.175, 0.162
10 5
10 4
10 3
10 2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)

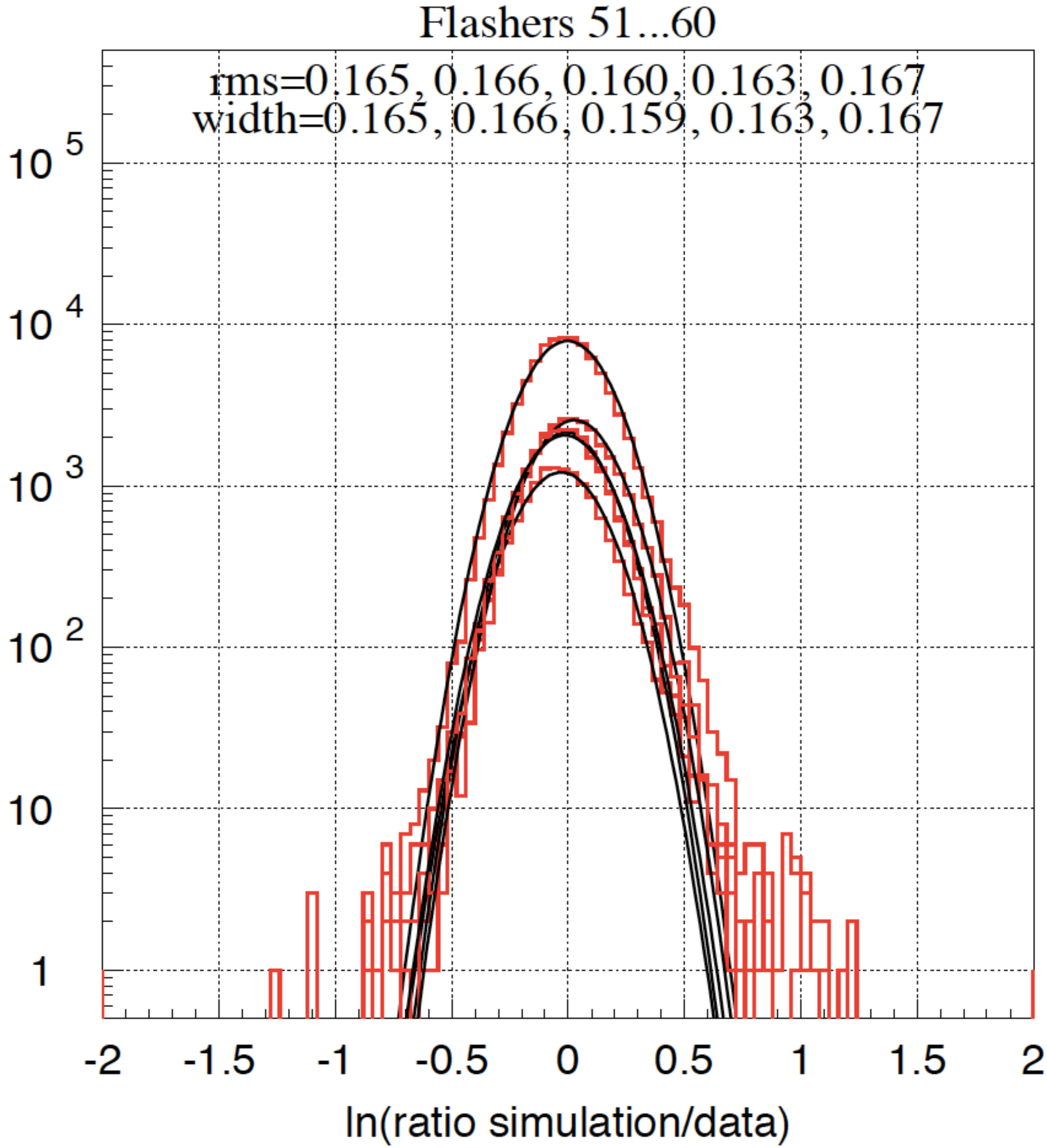


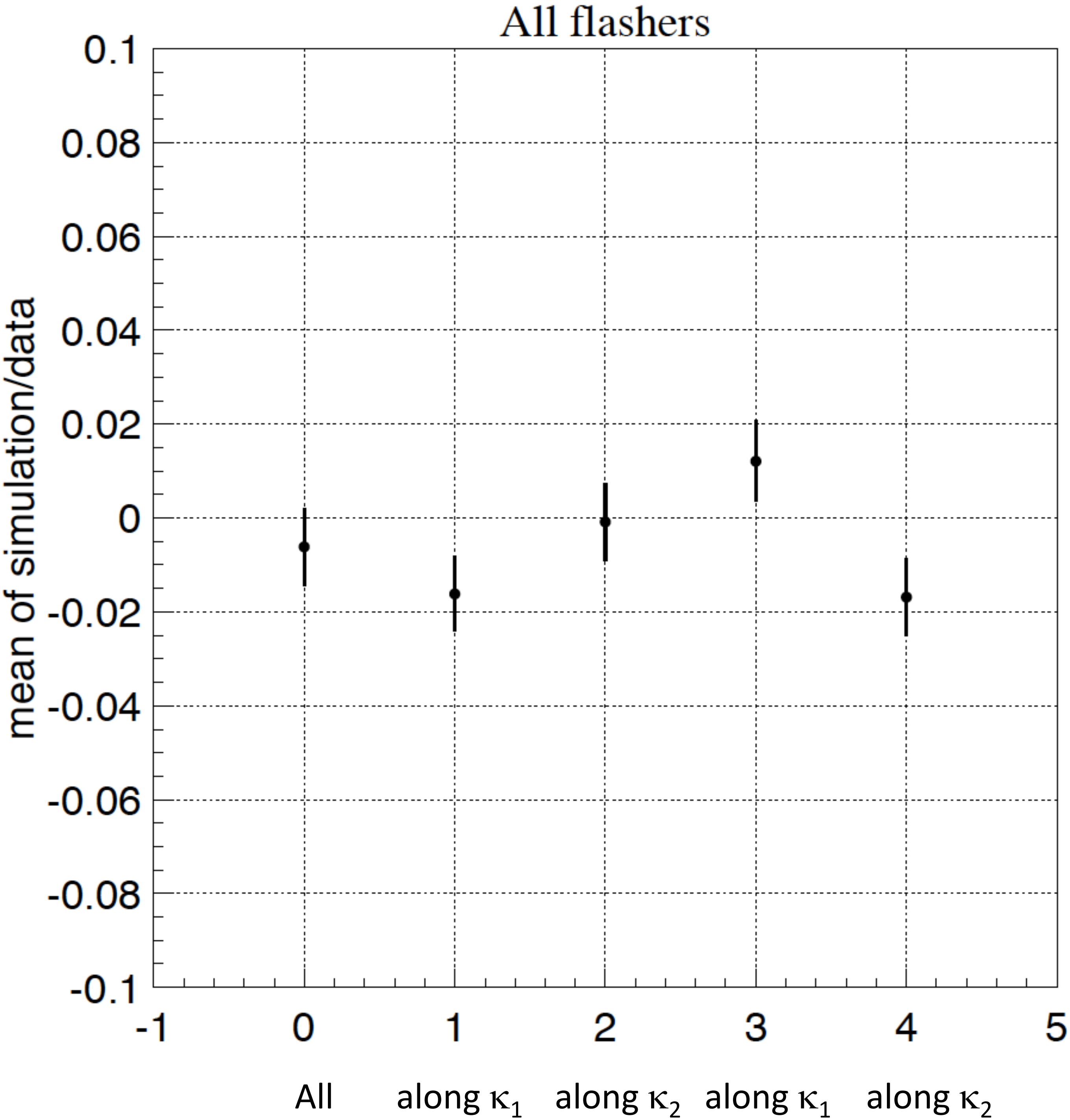
Flashers 11...20
rms=0.162, 0.149, 0.166, 0.178, 0.163
width=0.162, 0.148, 0.166, 0.178, 0.163
10 5
10 4
10 3
10 2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)


Flashers 21...30
rms=0.164, 0.150, 0.171, 0.185, 0.163
width=0.164, 0.150, 0.171, 0.185, 0.163
10 5
10 4
10 3
10 2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)

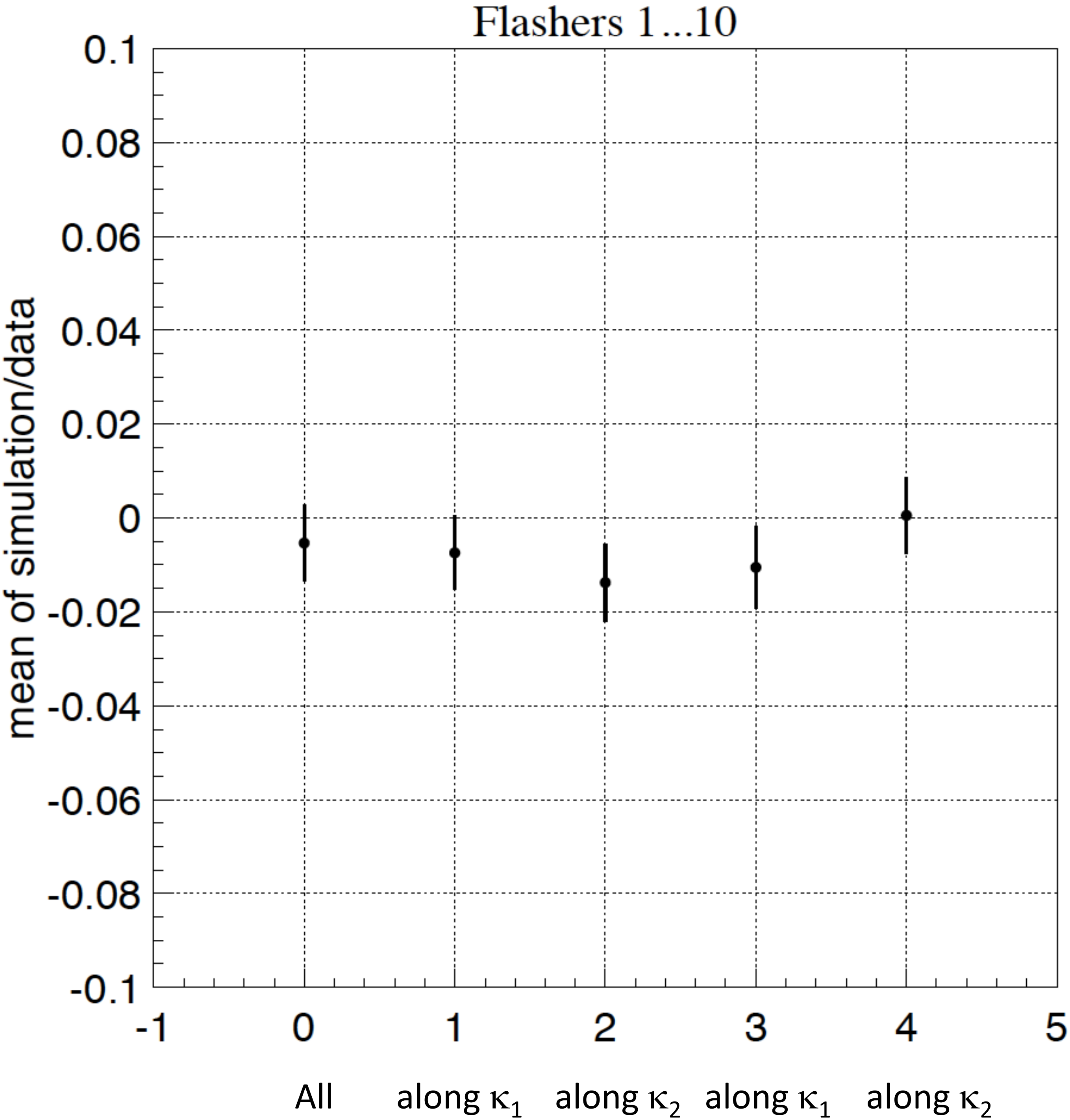

Flashers 31...40
rms=0.163, 0.156, 0.167, 0.168, 0.159
width=0.163, 0.156, 0.167, 0.168, 0.159
10^5
10^4
10^3
10^2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)

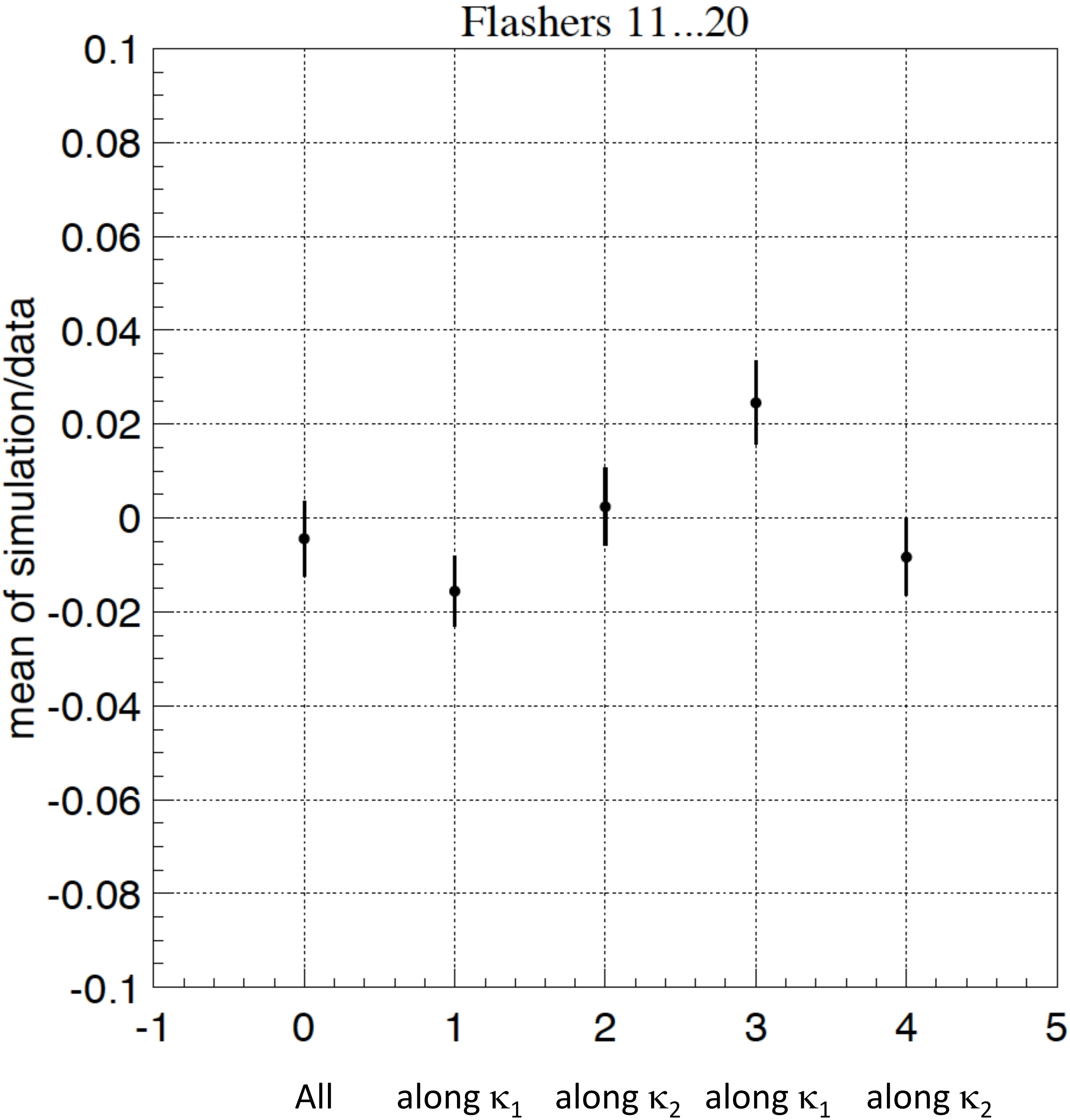

Flashers 41...50
rms=0.173, 0.180, 0.168, 0.173, 0.173
width=0.173, 0.180, 0.168, 0.173, 0.173
10 5
10 4
10 3
10 2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)


Flashers 51...60
rms=0.165, 0.166, 0.160, 0.163, 0.167
width=0.165, 0.166, 0.159, 0.163, 0.167
10 5
10 4
10 3
10 2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)

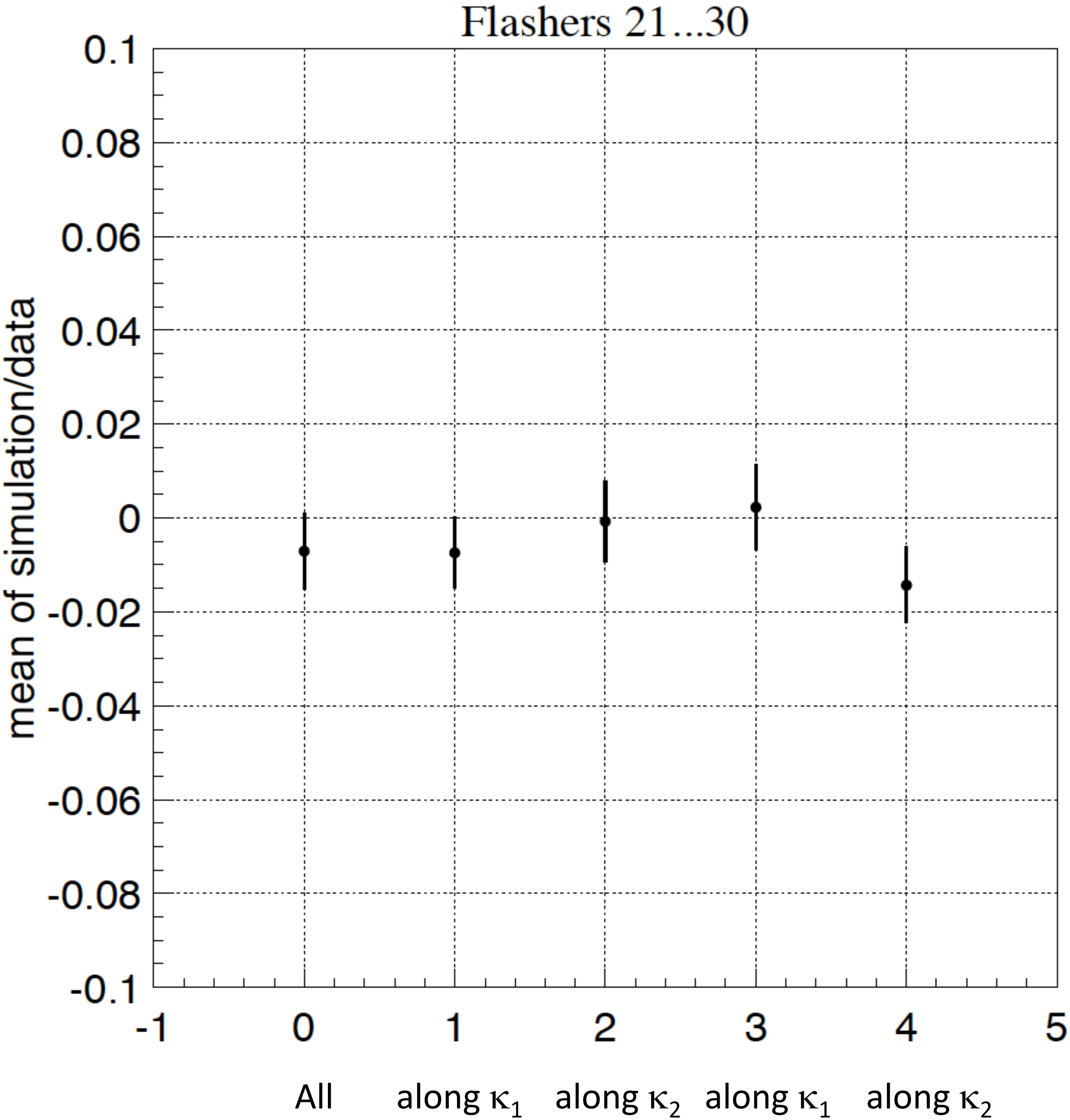


All flashers
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ1
along κ2
along κ1
along κ2

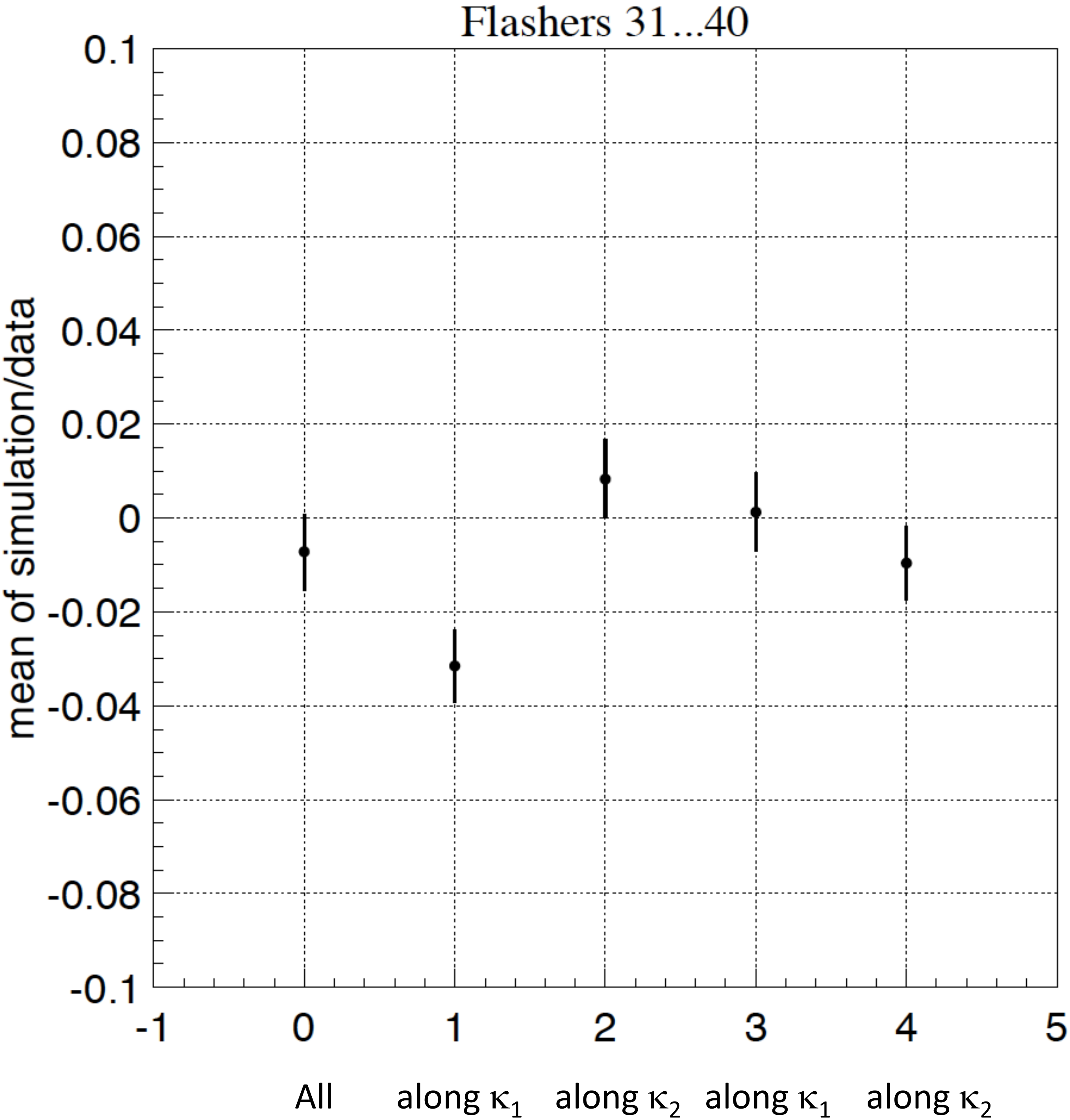

Flashers 1...10
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ1
along κ2
along κ1
along κ2



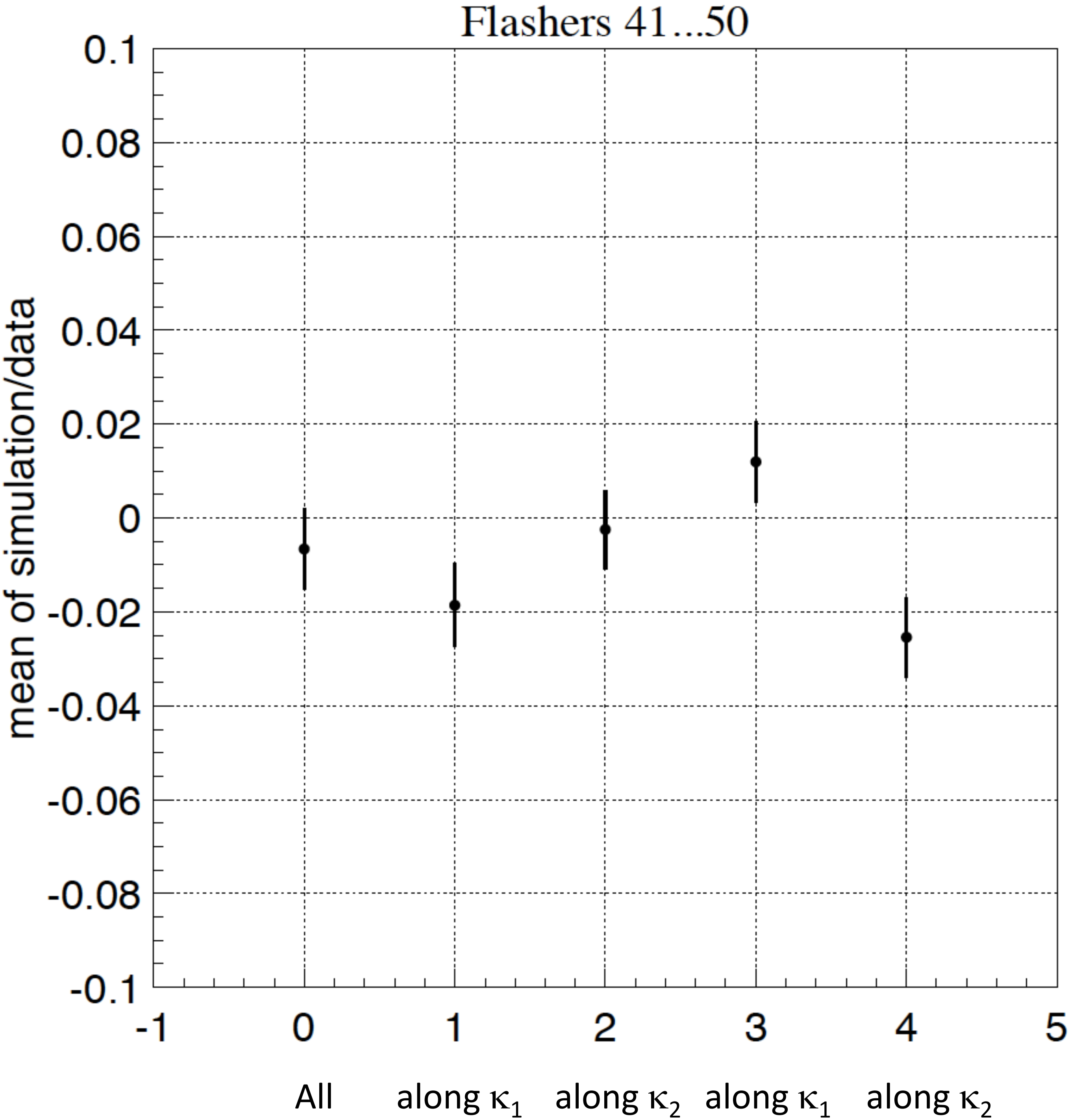
Flashers 11...20
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ1
along κ2
along κ1
along κ2



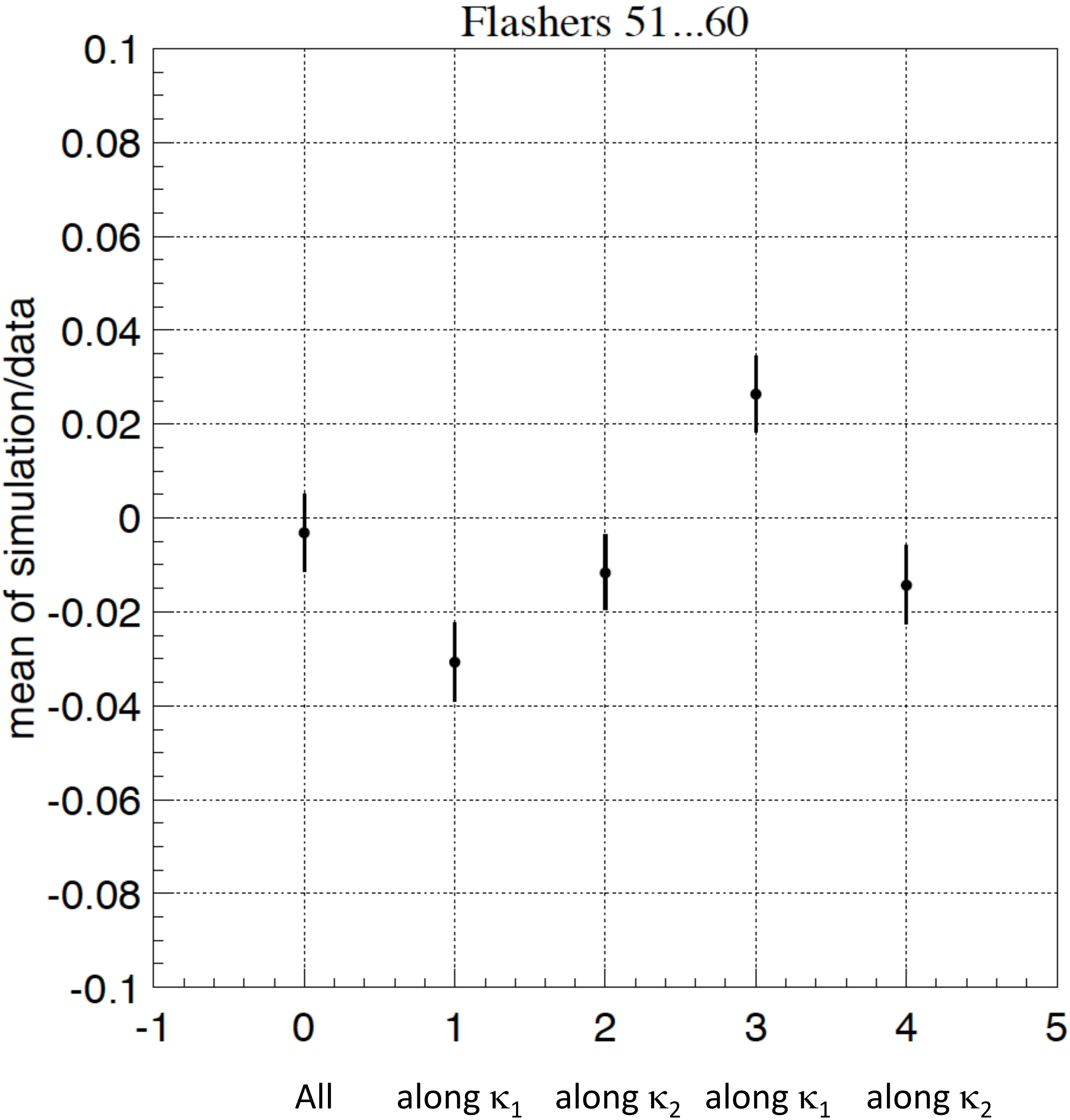
Flashers 21...30
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
mean of simulation/data
-1
0
1
2
3
4
5
All
along κ1
along κ2
along κ1
along κ2



Flashers 31...40
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ_1
along κ_2
along κ_1
along κ_2



Flashers 41...50
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ1
along κ2
along κ1
along κ2


Flashers 51...60
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ_1
along κ_2
along κ_1
along κ_2

κ_1=7.7%

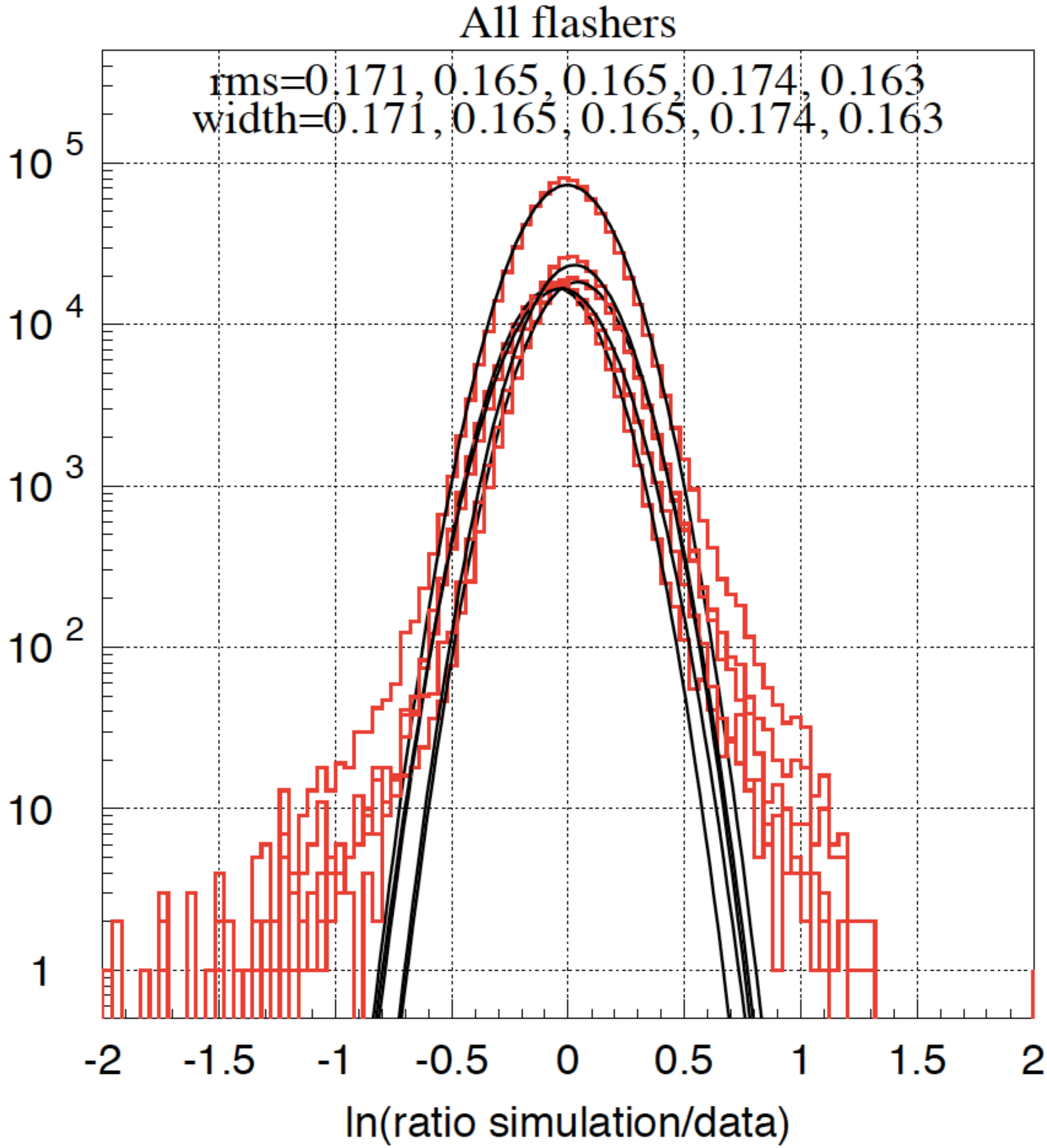
0: all directions

1,3: flasher-receiver directions within 45 degrees of major anisotropy axis

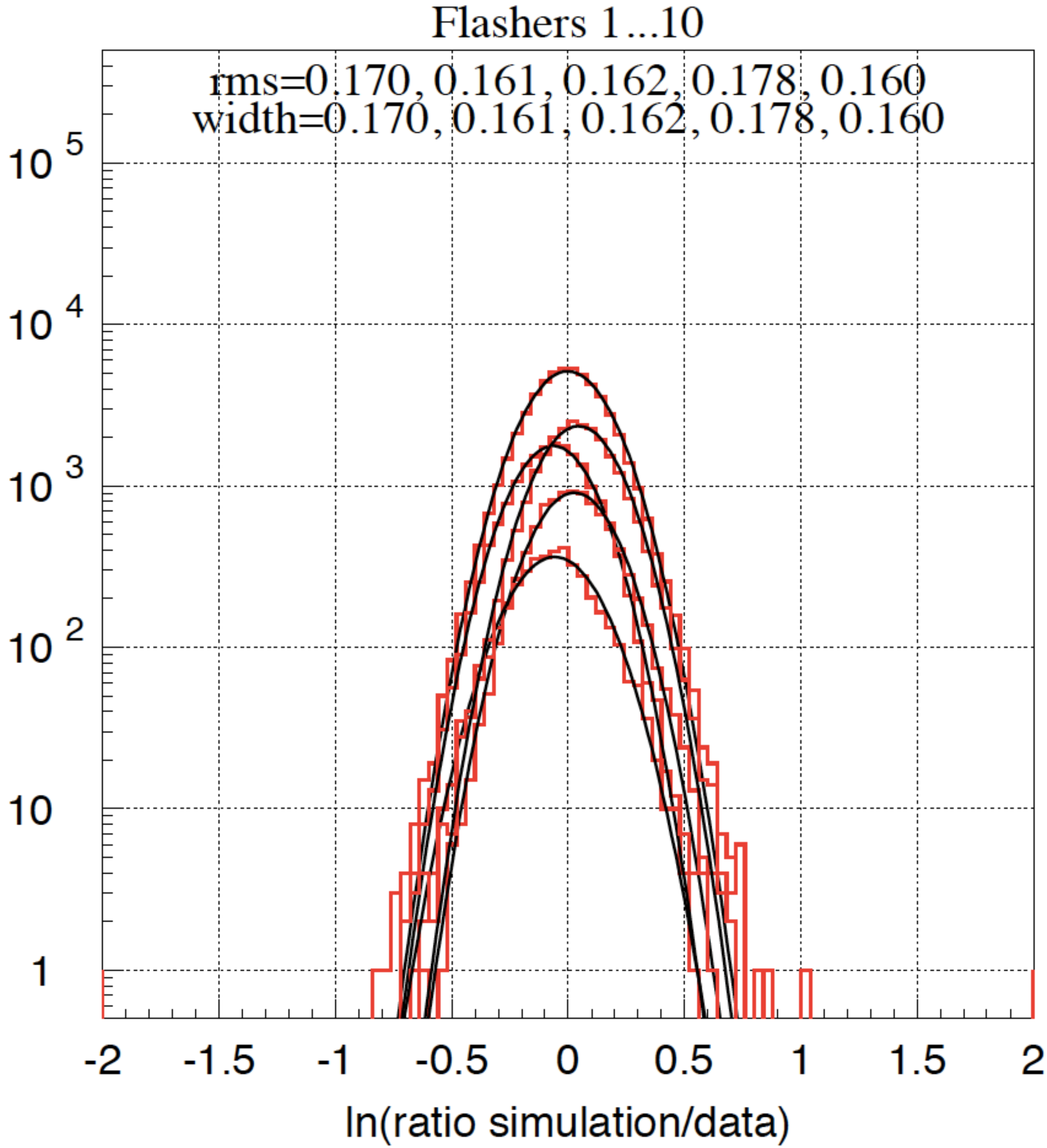
2,4: flasher-receiver directions within 45 degrees of minor anisotropy axis

No unfolding, nominal DOM efficiencies, h2-50cm hole ice

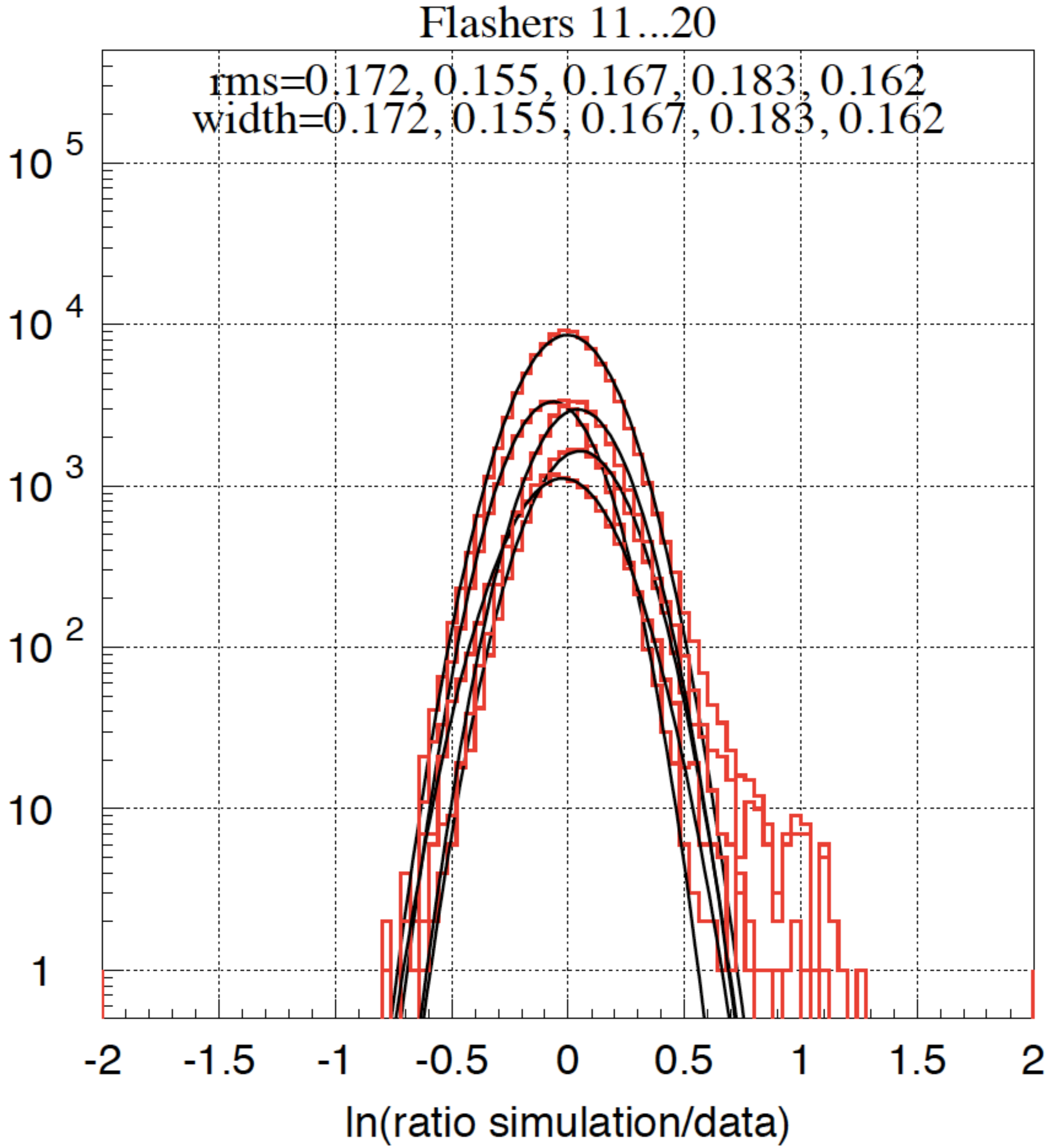
GOF=4163.65



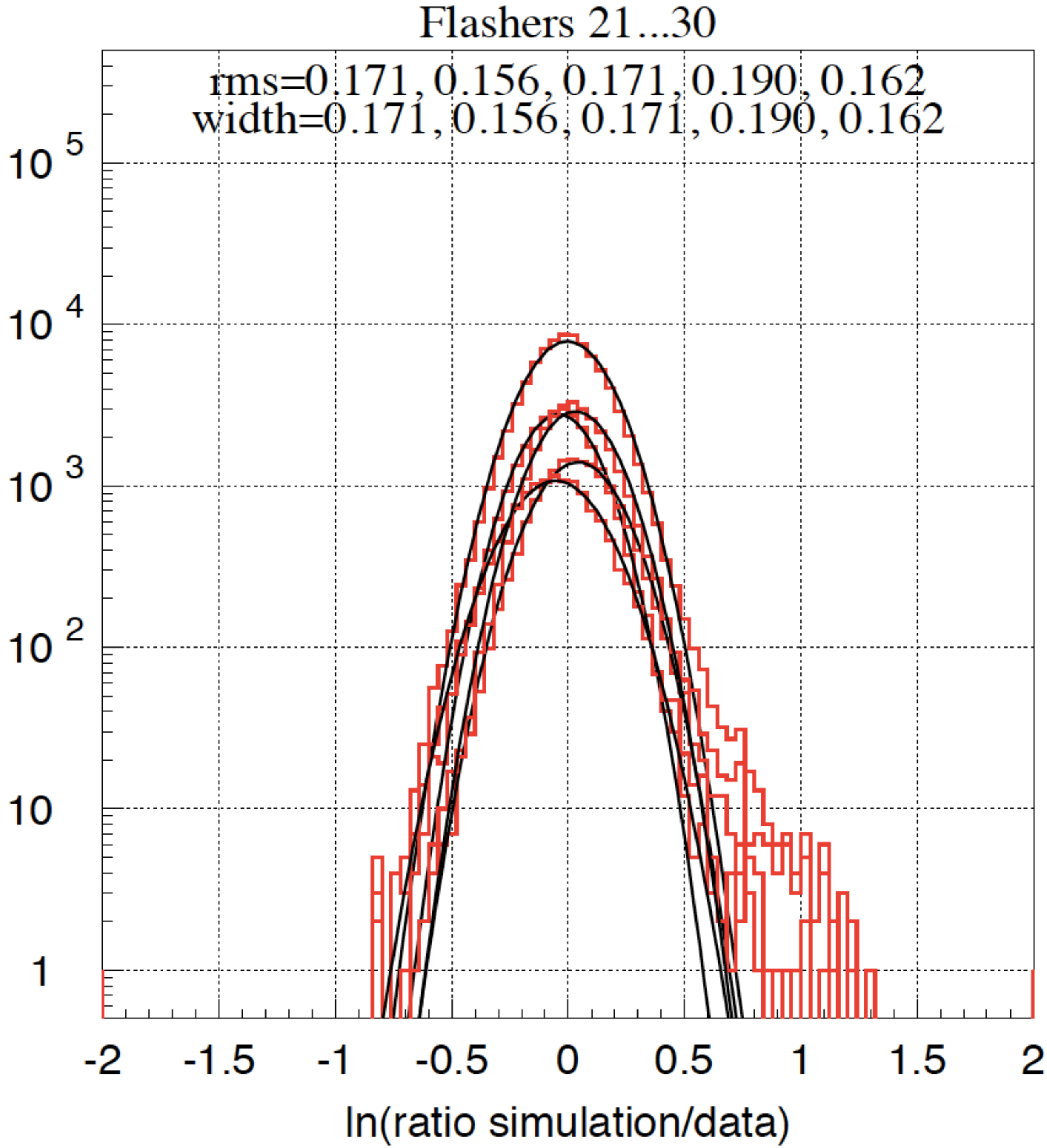
All flashers
rms=0.171, 0.165, 0.165, 0.174, 0.163
width=0.171, 0.165, 0.165, 0.174, 0.163
10 5
10 4
10 3
10 2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)



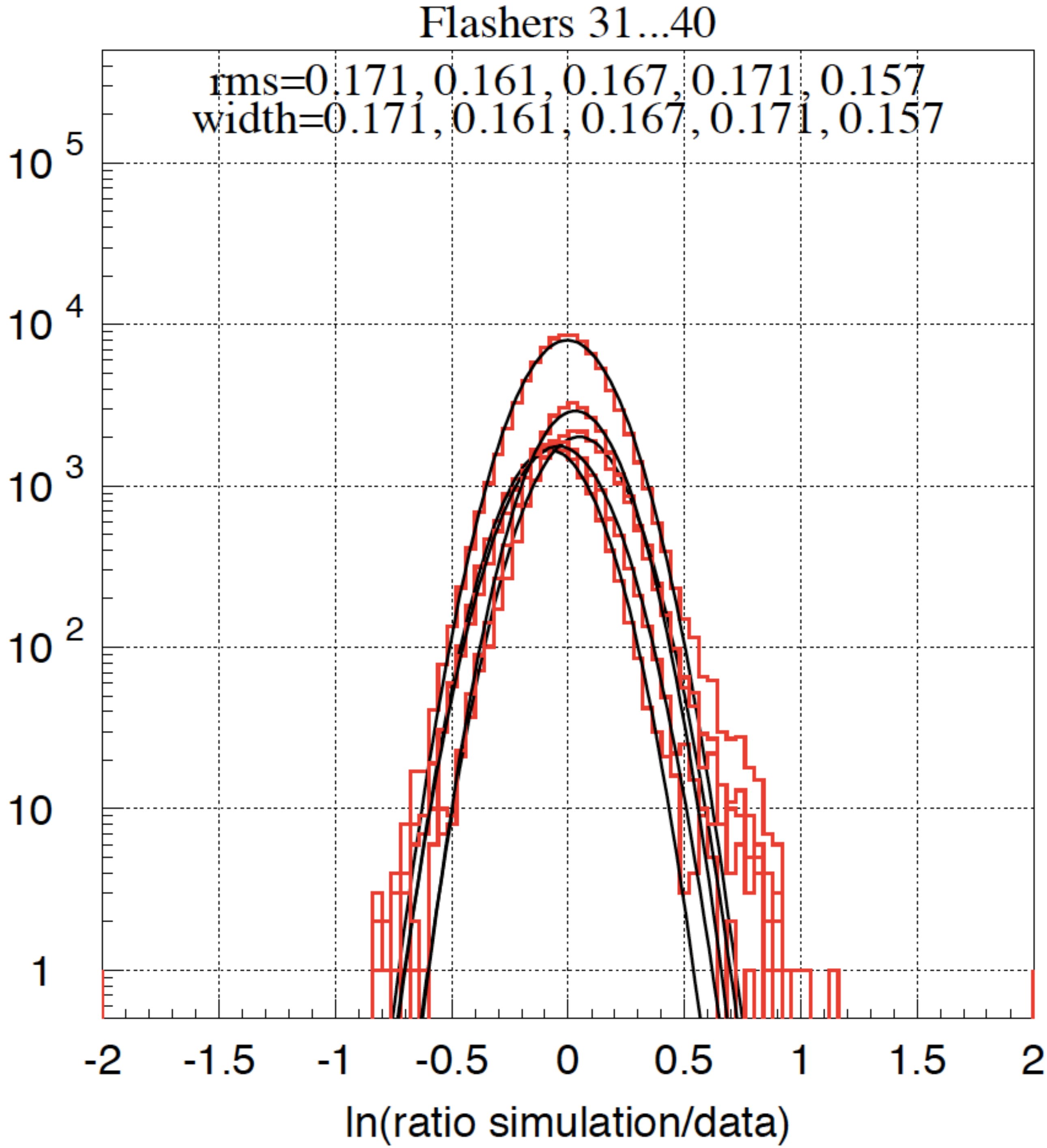
Flashers 1...10
rms=0.170, 0.161, 0.162, 0.178, 0.160
width=0.170, 0.161, 0.162, 0.178, 0.160
10^5
10^4
10^3
10^2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)



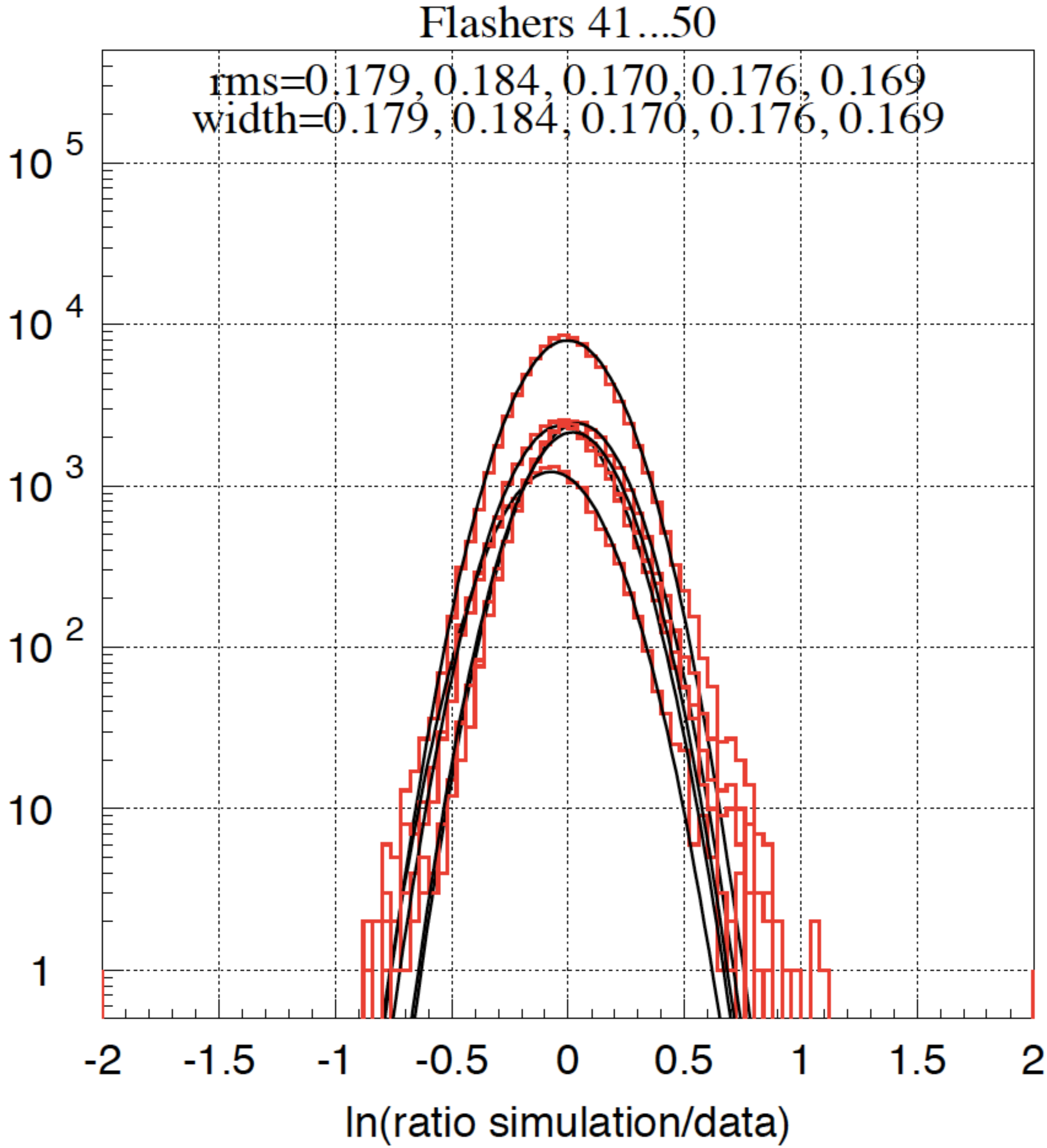
Flashers 11...20
rms=0.172, 0.155, 0.167, 0.183, 0.162
width=0.172, 0.155, 0.167, 0.183, 0.162
10^5
10^4
10^3
10^2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)



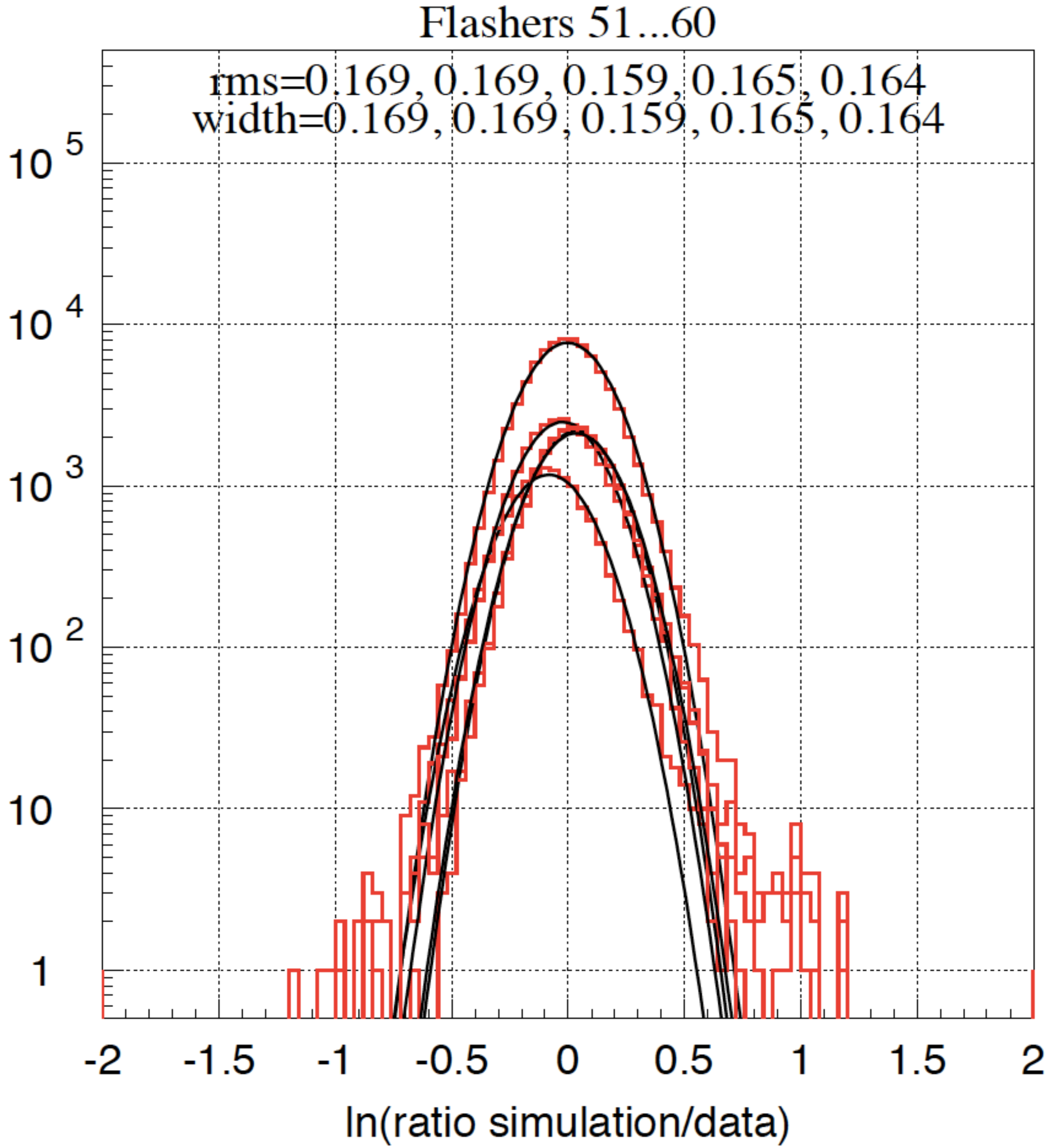
Flashers 21...30
rms=0.171, 0.156, 0.171, 0.190, 0.162
width=0.171, 0.156, 0.171, 0.190, 0.162
10^5
10^4
10^3
10^2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)



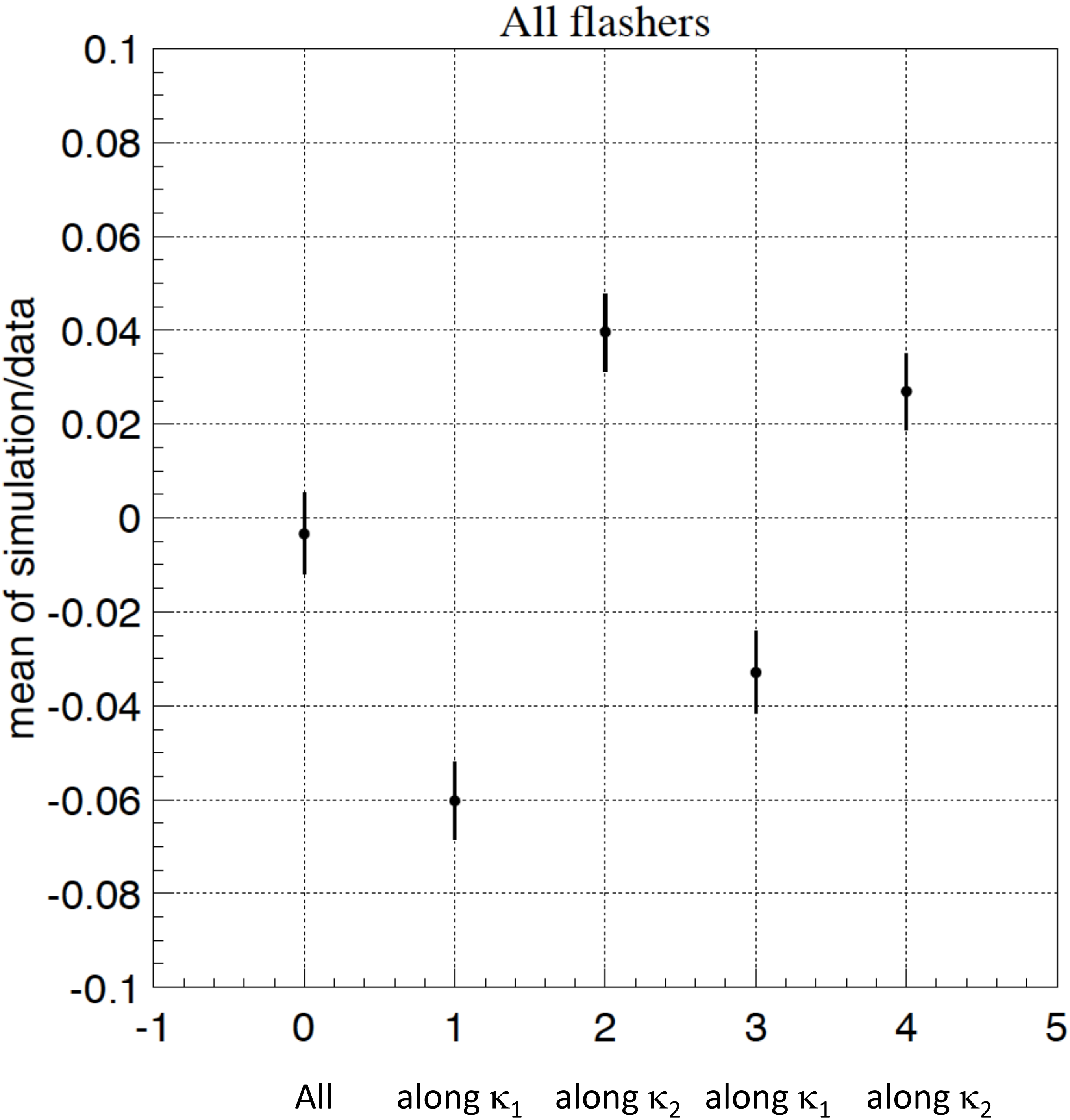
Flashers 31...40
rms=0.171, 0.161, 0.167, 0.171, 0.157
width=0.171, 0.161, 0.167, 0.171, 0.157
10 5
10 4
10 3
10 2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)

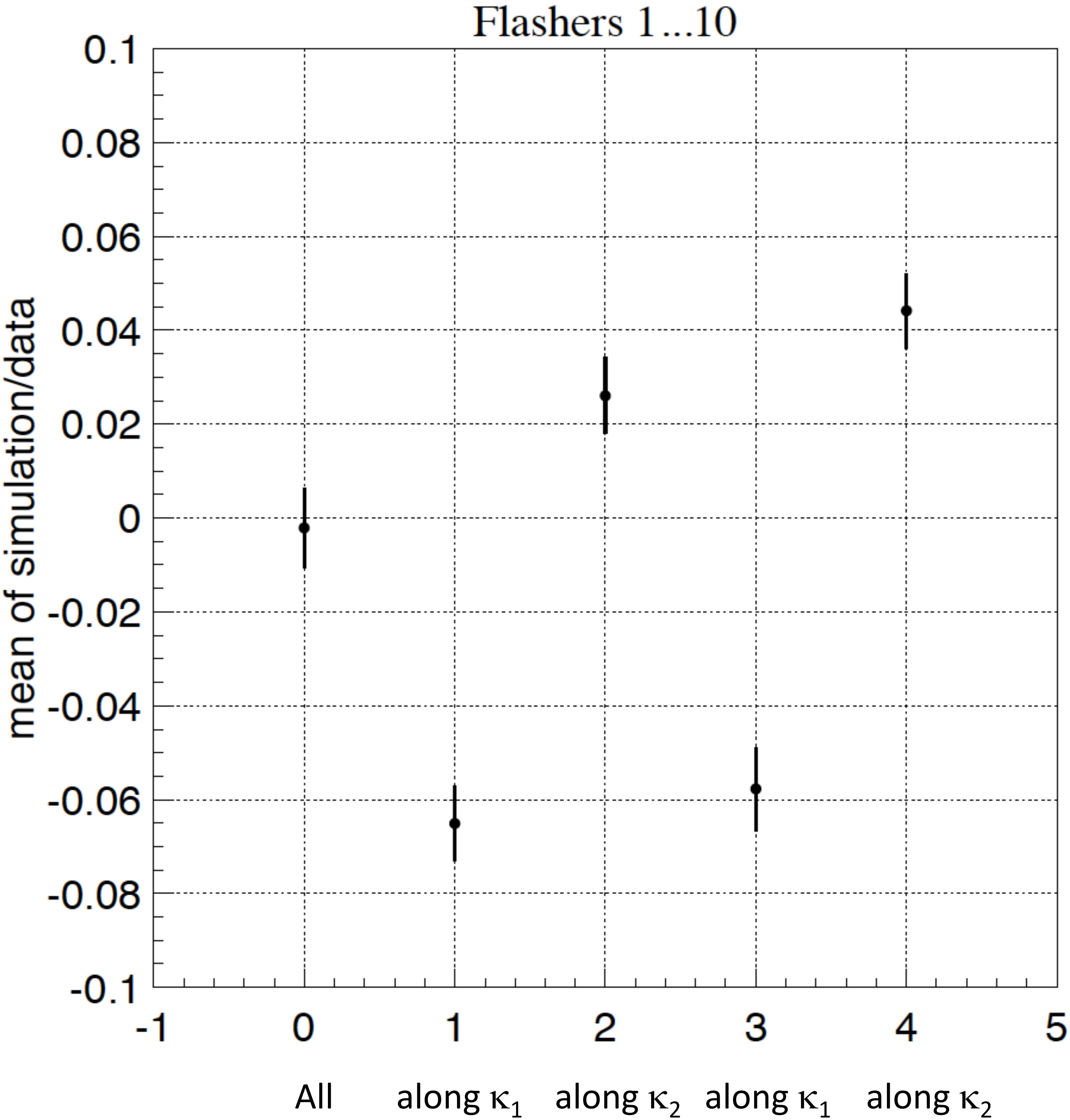


Flashers 41...50
rms=0.179, 0.184, 0.170, 0.176, 0.169
width=0.179, 0.184, 0.170, 0.176, 0.169
10 5
10 4
10 3
10 2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)

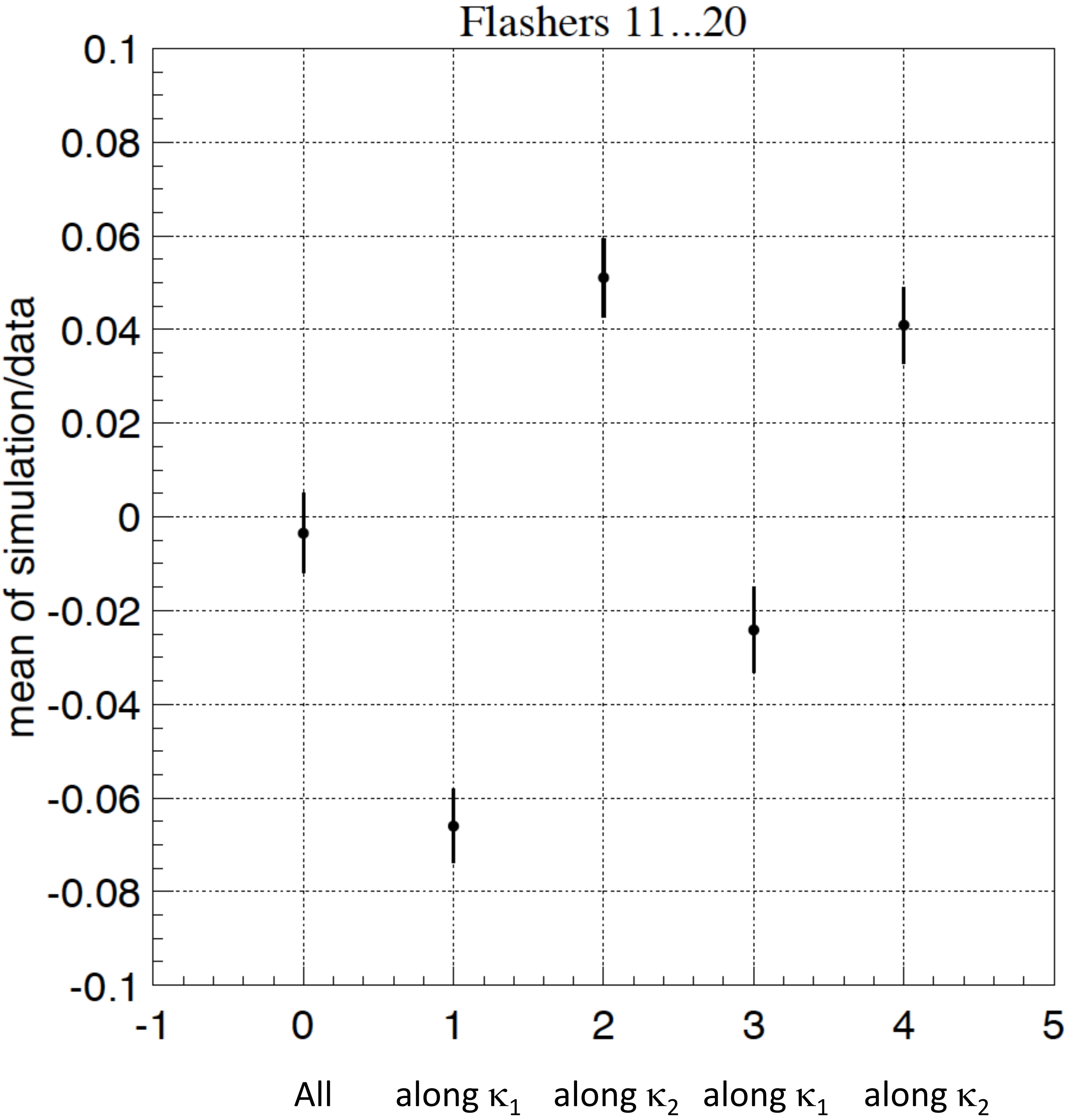


Flashers 51...60
rms=0.169, 0.169, 0.159, 0.165, 0.164
width=0.169, 0.169, 0.159, 0.165, 0.164
10 5
10 4
10 3
10 2
10
1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
ln(ratio simulation/data)

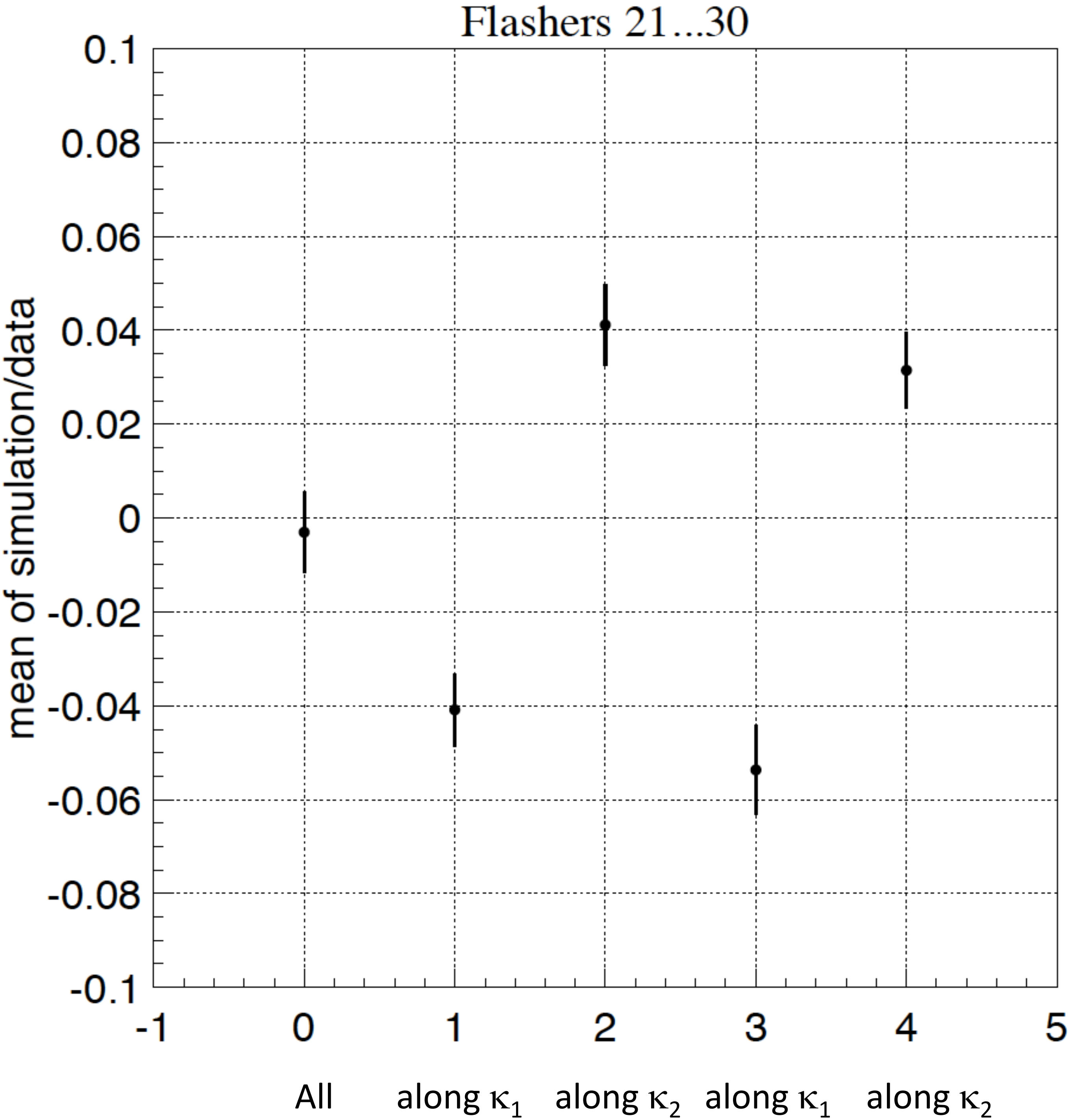

All flashers
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ1
along κ2
along κ1
along κ2



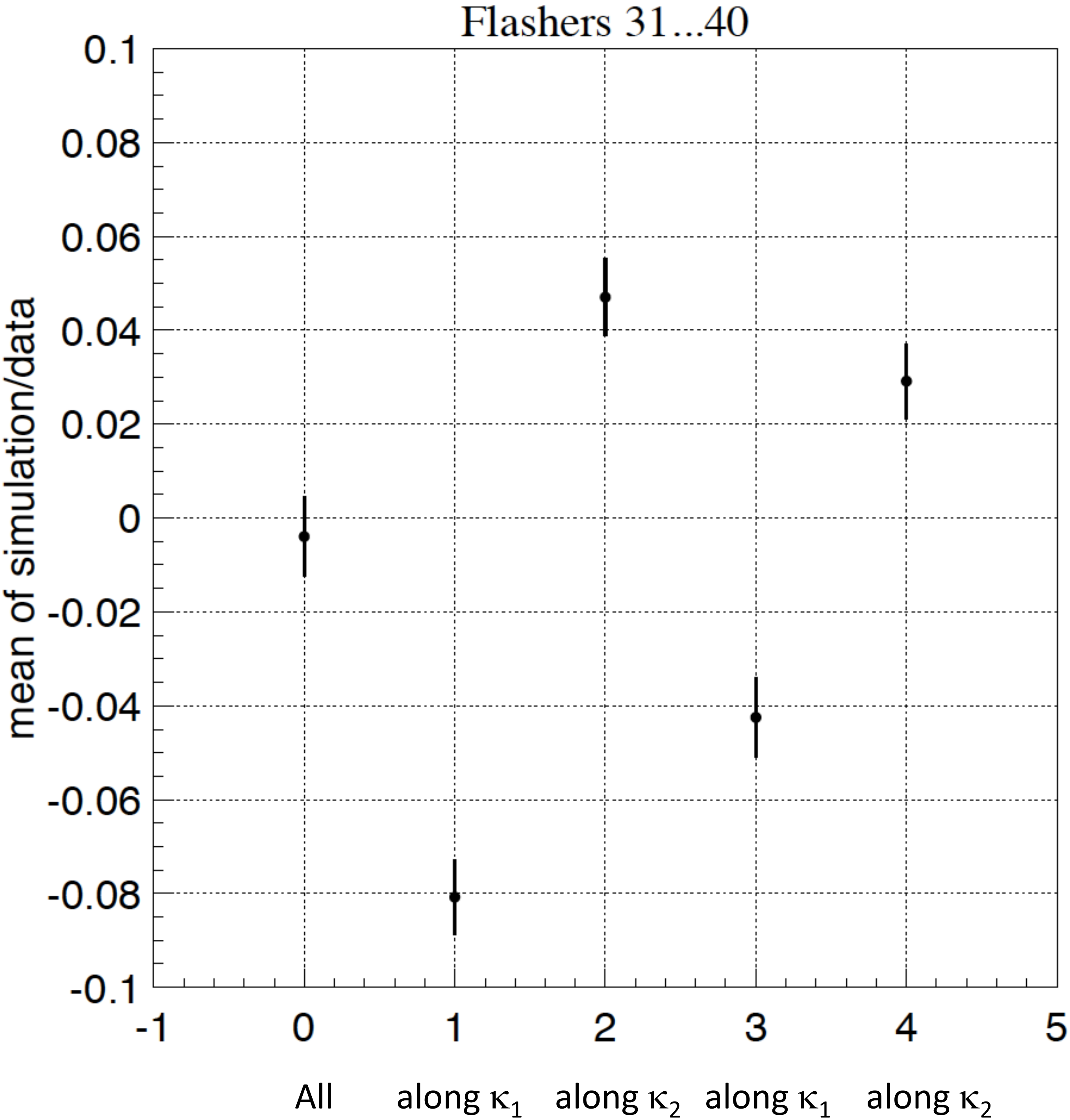
Flashers 1...10
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ_1
along κ_2
along κ_1
along κ_2



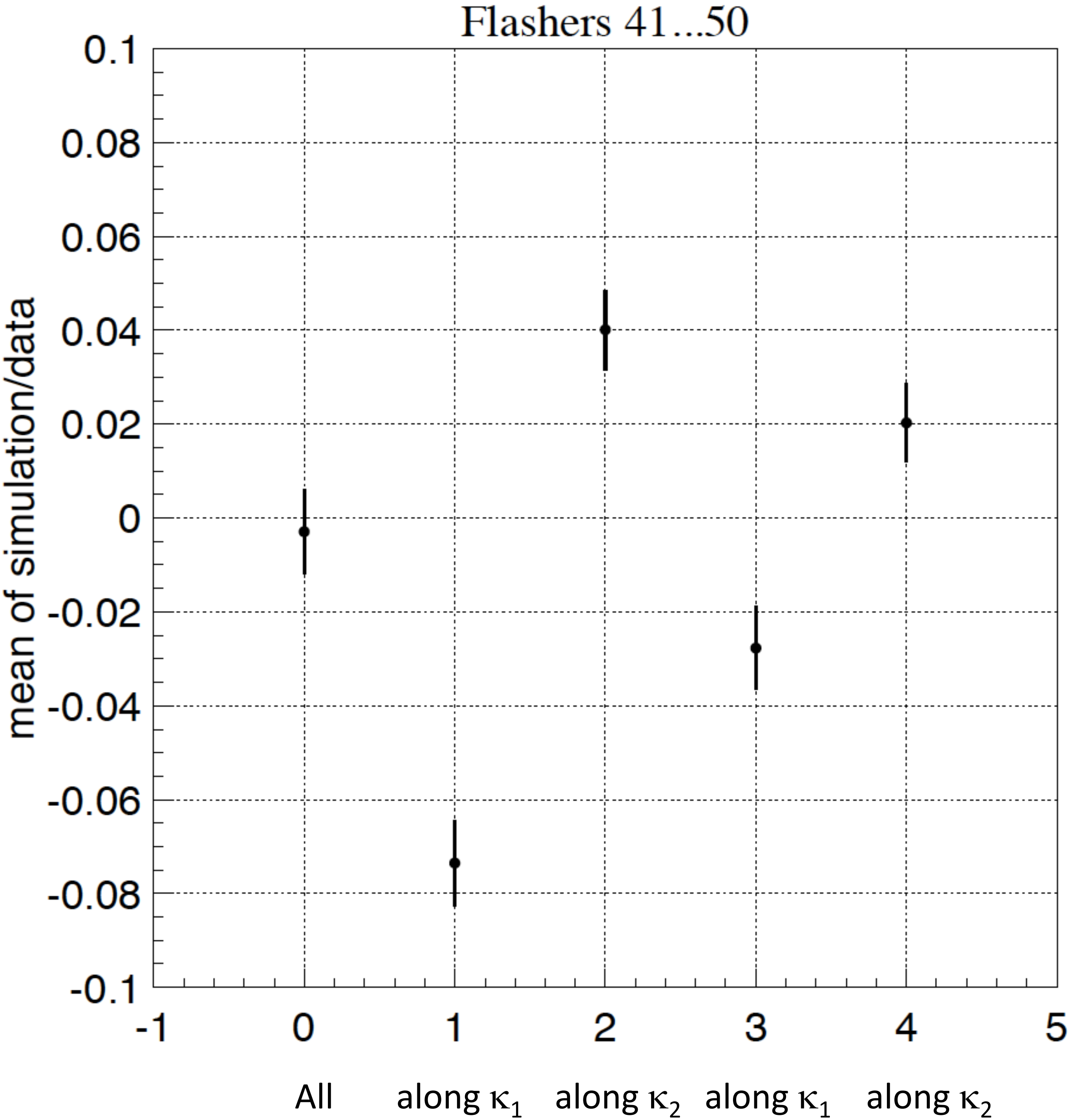
Flashers 11...20
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ1
along κ2
along κ1
along κ2



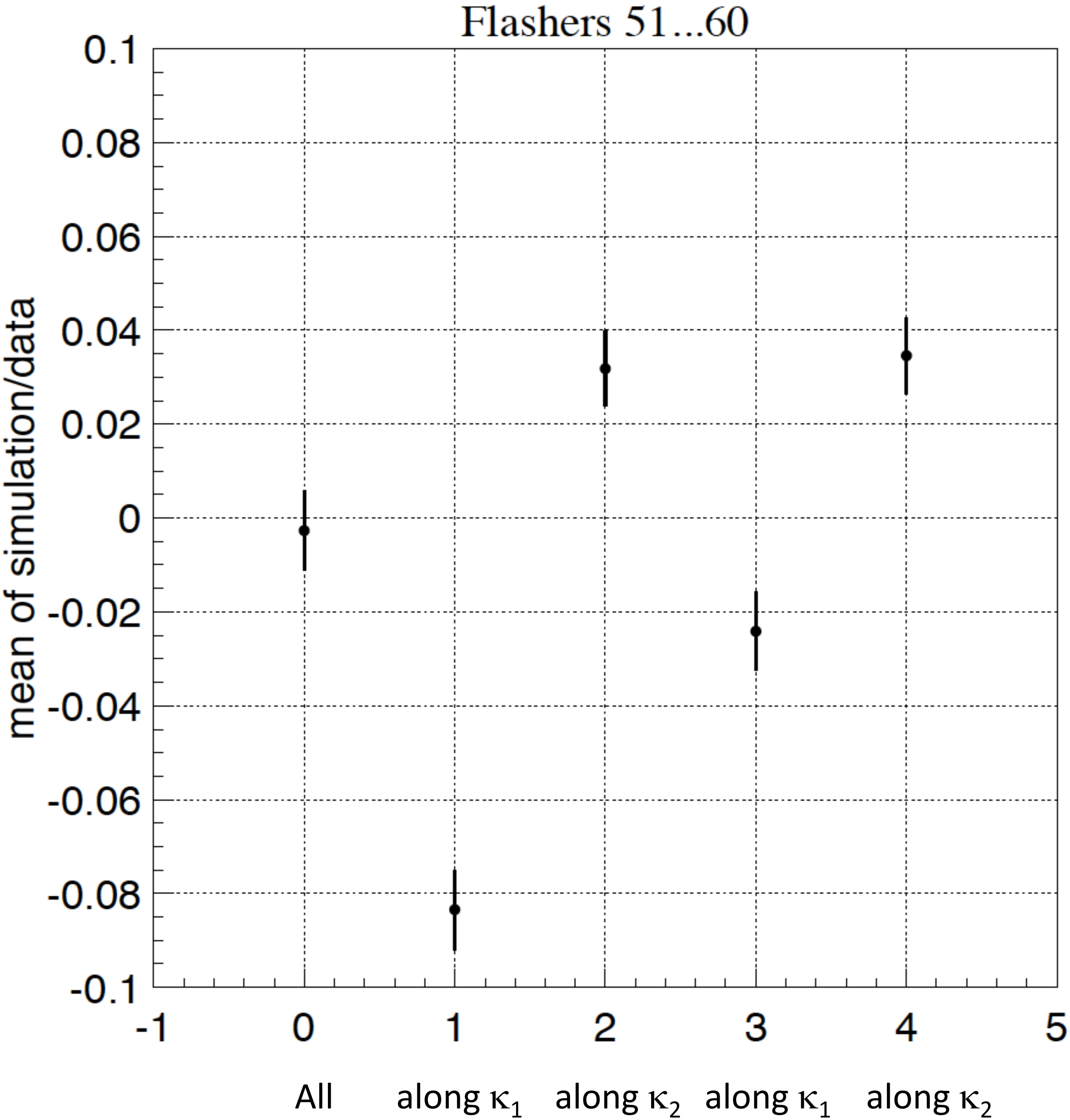
Flashers 21...30
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ1
along κ2
along κ1
along κ2



Flashers 31...40
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
mean of simulation/data
-1
0
1
2
3
4
5
All
along κ1
along κ2
along κ1
along κ2



Flashers 41…50
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ1
along κ2
along κ1
along κ2



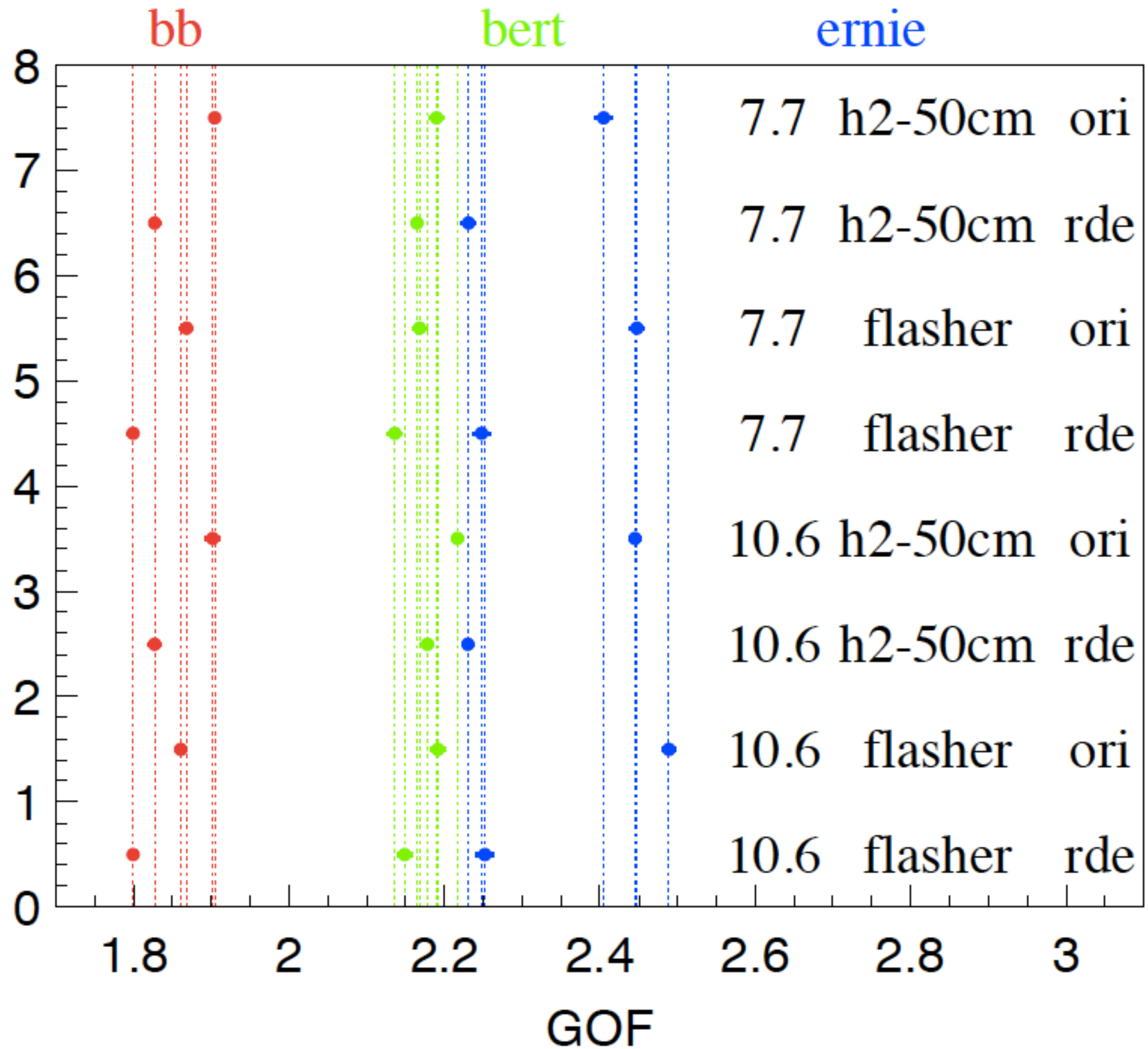
Flashers 51...60
mean of simulation/data
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-1
0
1
2
3
4
5
All
along κ1
along κ2
along κ1
along κ2

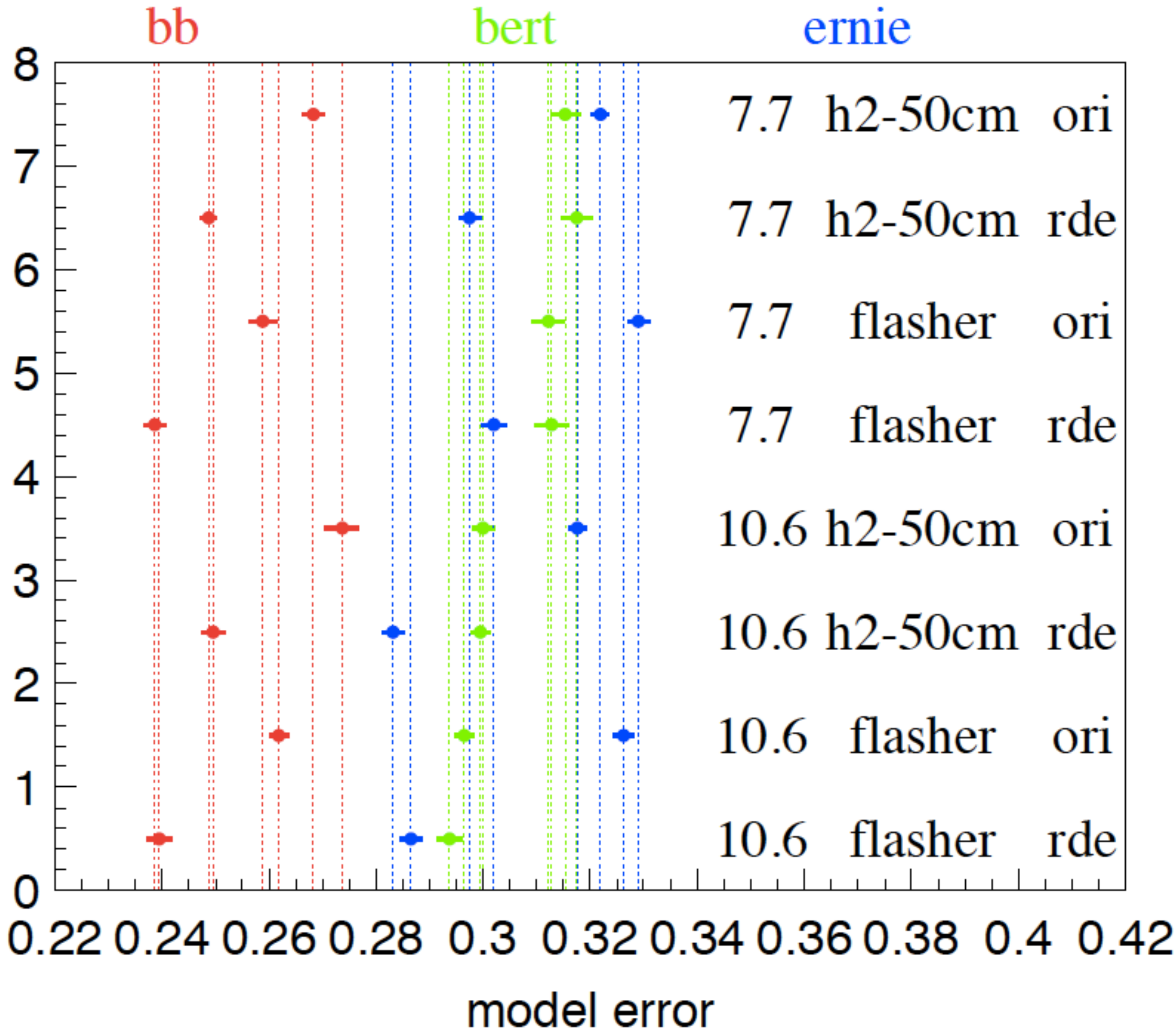
Ice variations with HESE cascades

Testing variations of the ice model (based on SPICE 3.2):

- anisotropy coefficient of 7.7% or 10.6%
- hole ice model: h2-50cm or flasher-derived (with p=0.30)
- DOM efficiency table: nominal (ori) or flasher-derived (rde)

25 events simulated in each case with 100x statistics (s_{rep}=100)


bb
bert
ernie
7.7 h2-50cm ori
7.7 h2-50cm rde
7.7 flasher ori
7.7 flasher rde
10.6 h2-50cm ori
10.6 h2-50cm rde
10.6 flasher ori
10.6 flasher rde
0
1
2
3
4
5
6
7
8
1.8
2
2.2
2.4
2.6
2.8
3
GOF



w/total WF charges above 5 p.e.

Flasher-derived DOM efficiencies improve both the GOF and model error for these cascade events in all cases!

10.6% anisotropy is slightly better than the 7.7% in the model error for Bert (for all combinations of the DOM efficiency and hole ice settings). It is also better for Ernie with the flasher-derived DOM efficiencies. Where 10.6% is worse the difference is smaller.