Probing Systematic Differences in Hadronic Interaction Models through the use of a simulated IACT

A review of the results of bachelors thesis

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Goal

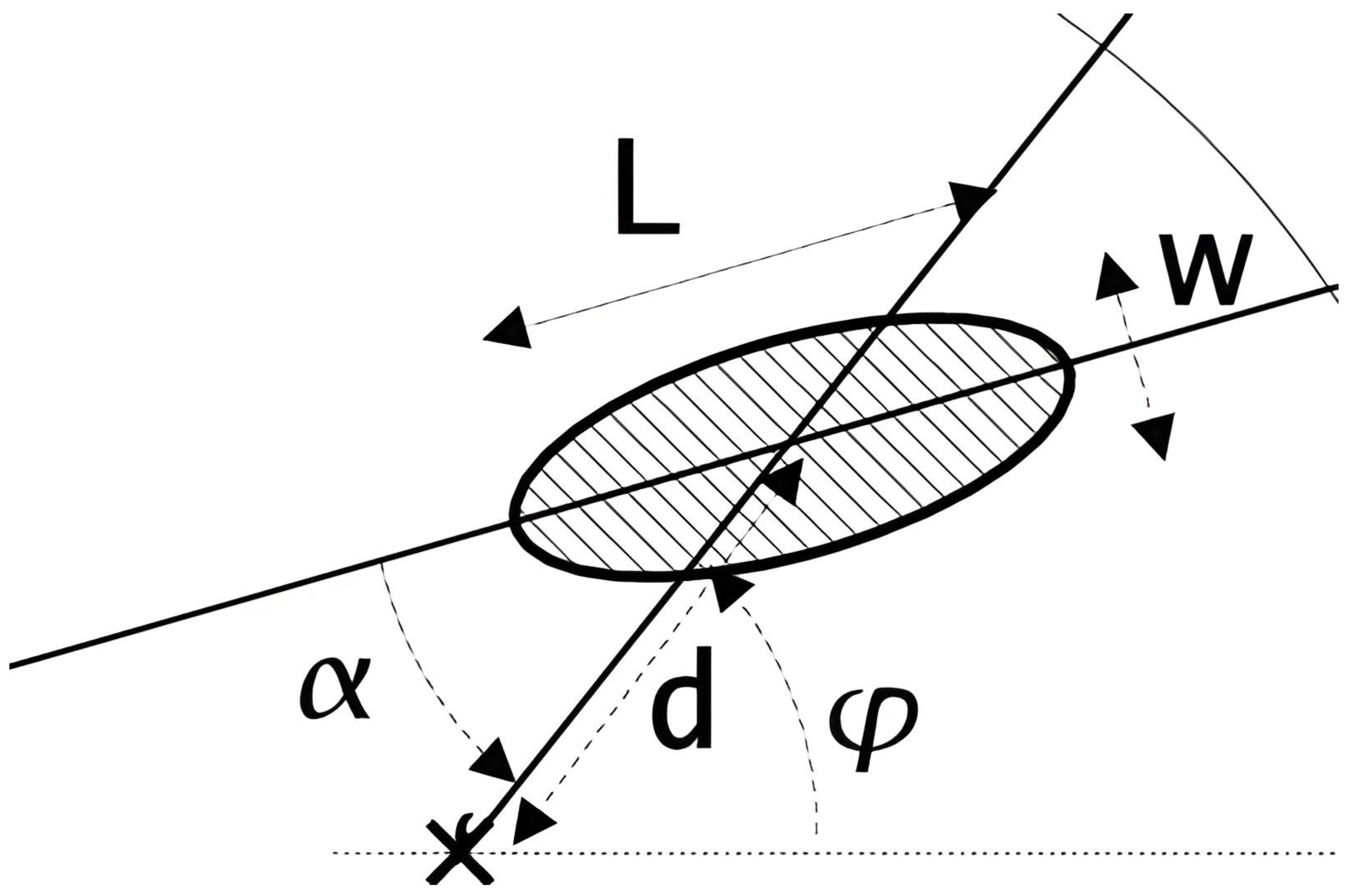
- Goal : examine differences in Hadronic Interaction Models for possible background rejection of IACTs
- Simulating a *Toy Telescope* that reproduces simulated CORSIKA images and characterizes them using Hillas Parameters:

    1. An analysis on „raw" Hillas parameters
    2. Scaling the proton plots and comparing those
    3. Breaking them down into different impact distances to check where the biggest differences arise
    4. Tying things together in a metric called **passing fraction**

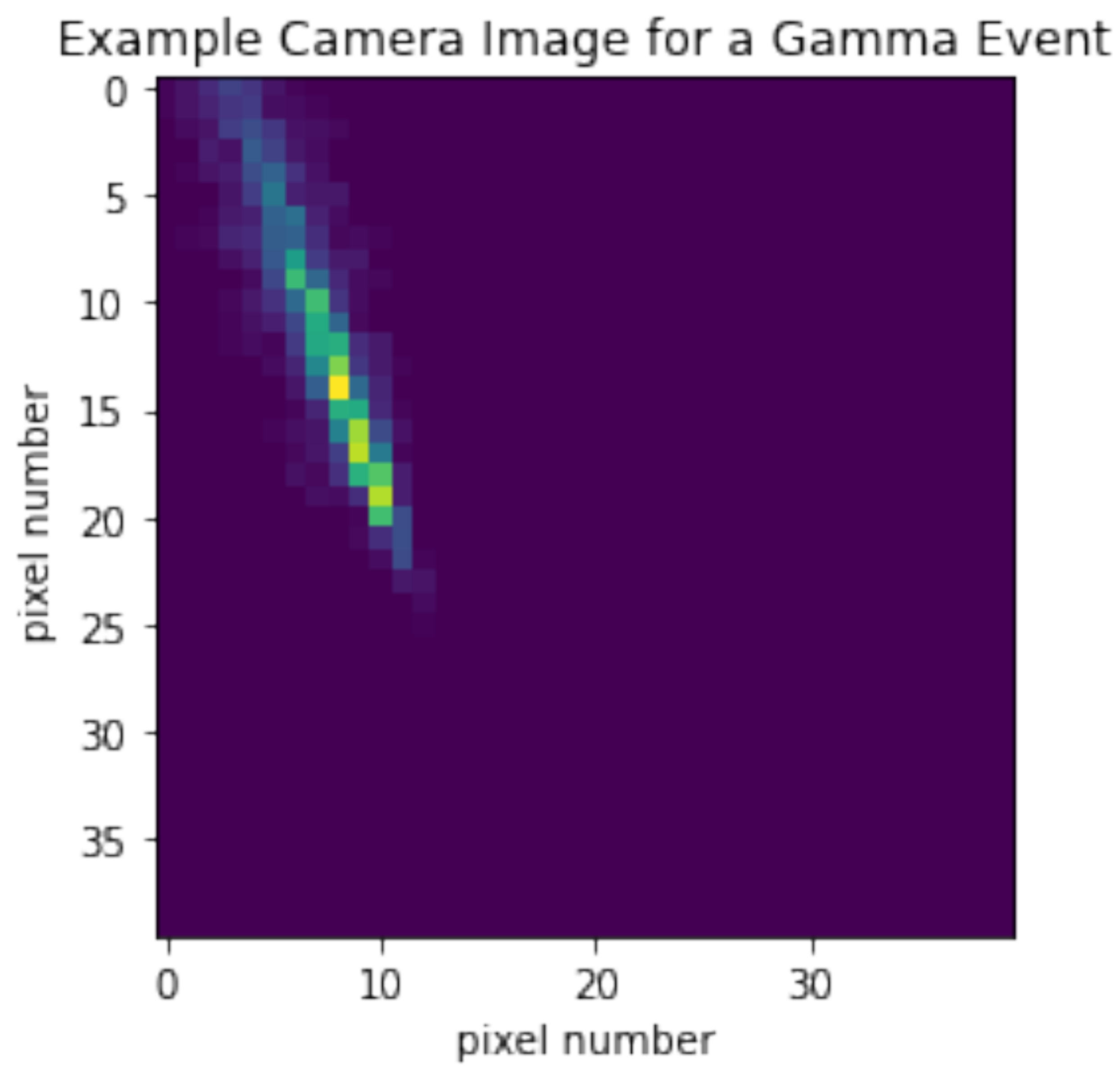
Why care about HP?

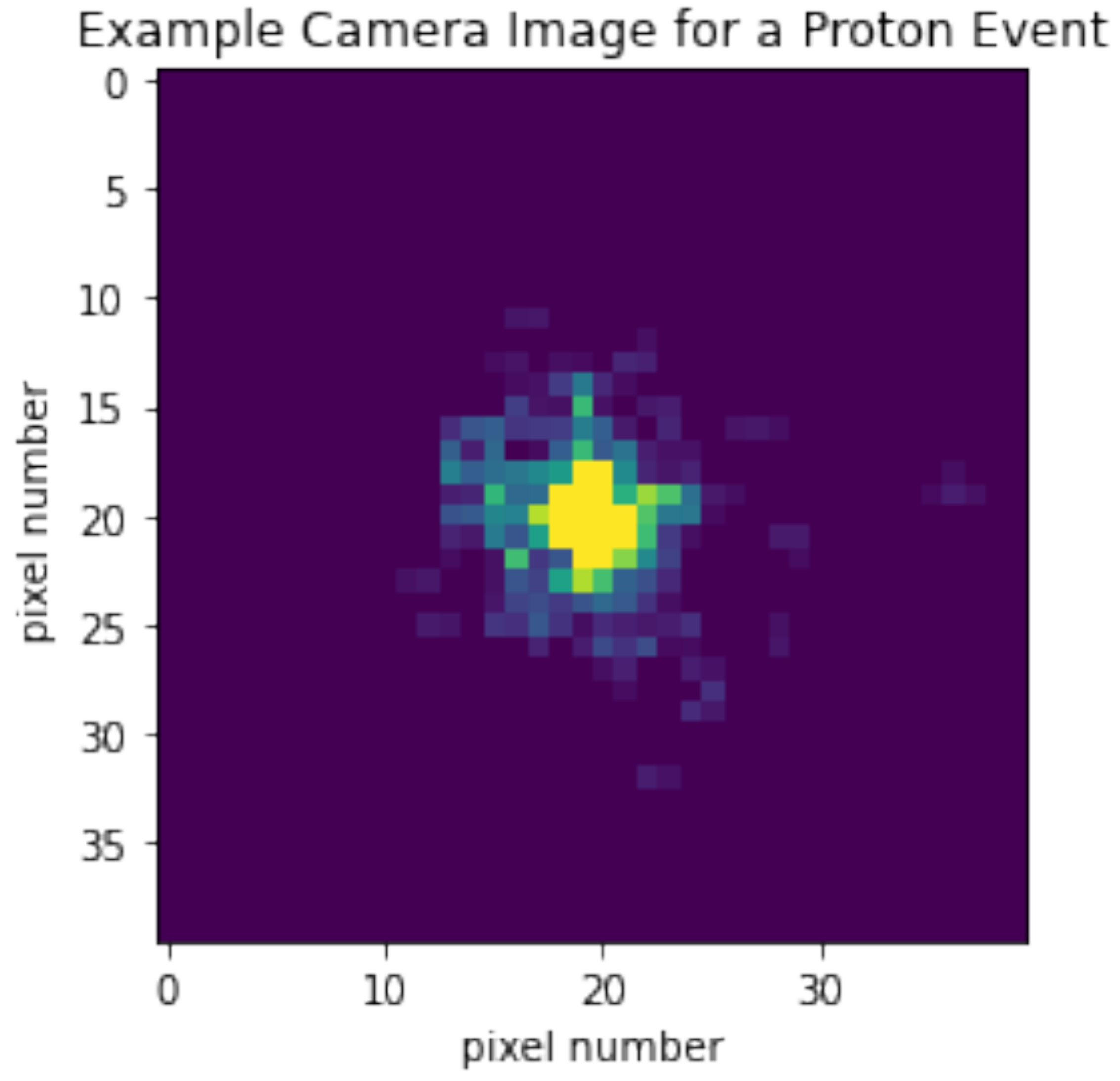
- In his 1985 paper, Hillas showed that Cherenkov images can be modeled using an oval (width&length)

- He showed that hadronic showers have longer and more fluctuating images (leading particle effect), and are wider (due to emission angle of pions)



Geometrical definition of Hillas Parameters.
L and W refer to lenght and width respectively
Image reproduced from (de Naurois, 2006)





Example IACT camera image of gamma (top) and proton (bottom) event.

Raw Hillas Parameters

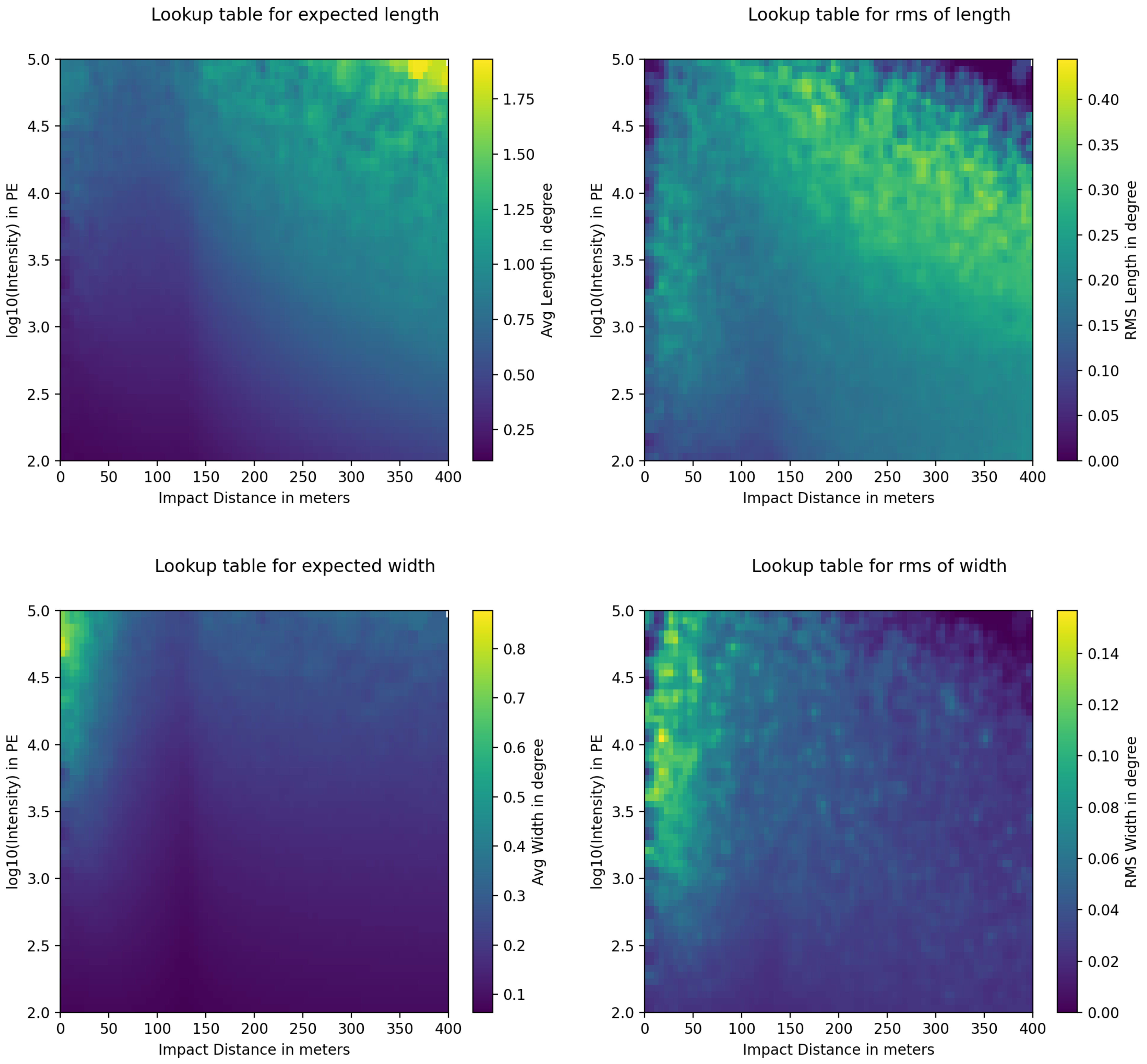
- Telescopes placed every 40m, using cleaned images that pass selection cuts
- Shows average shower shape (length&width) in comparison to EPOS
- Overall quite small differences $\mathcal{O}(5\%)$ between models, differences biggest at the edges of the plots due to thresholding effects

Scaling Hillas Parameters

- Gamma ray data to produce lookup tables used for interpolation

$$SCW = \frac{width - < width >}{\sigma_{width}}$$

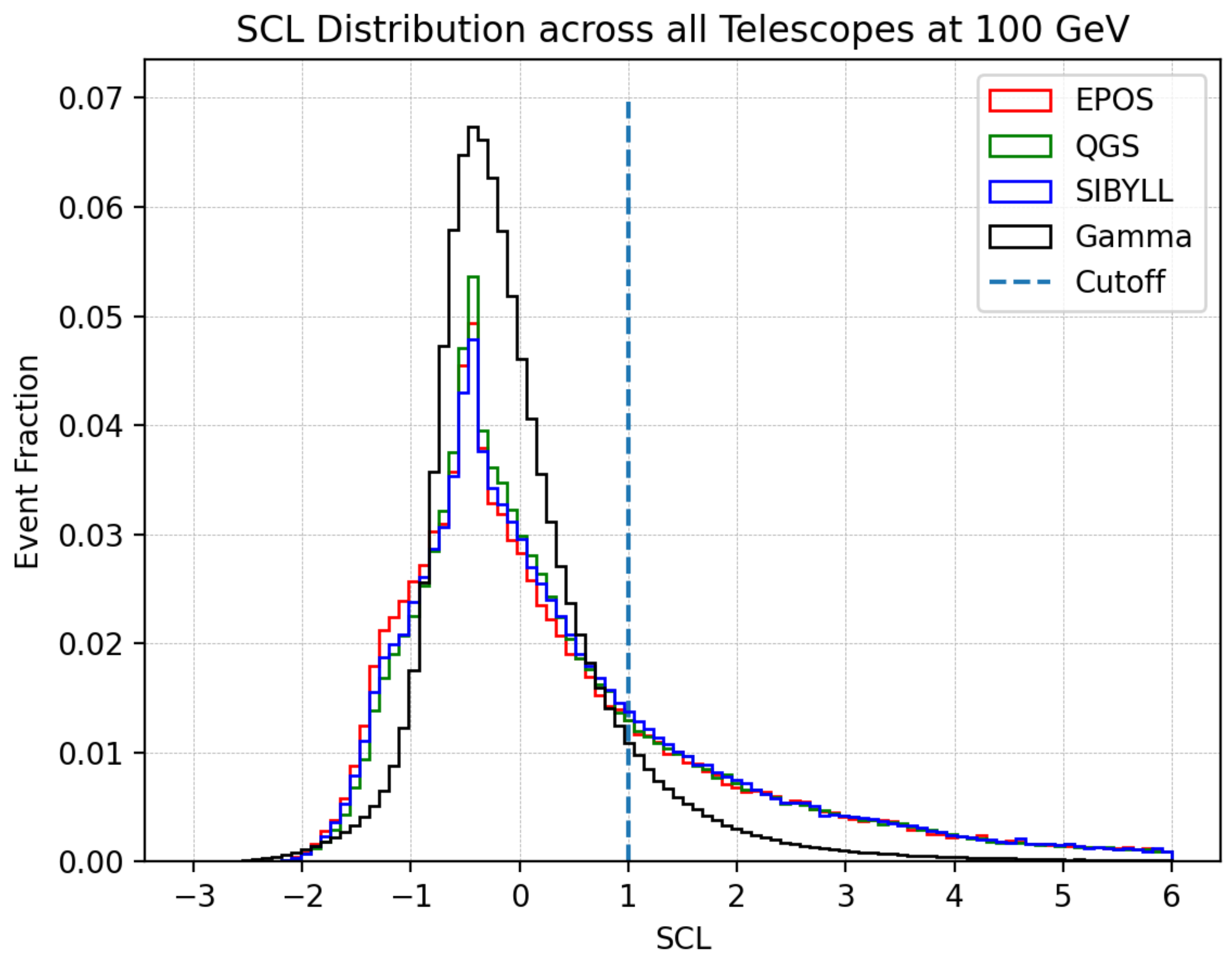
- For better comparison between different energies and distances, we introduce SC(W/L) values
- Example Cut for background rejection: $SCW < 0.7$ and $SCL < 1.0$ to enhance photon signal

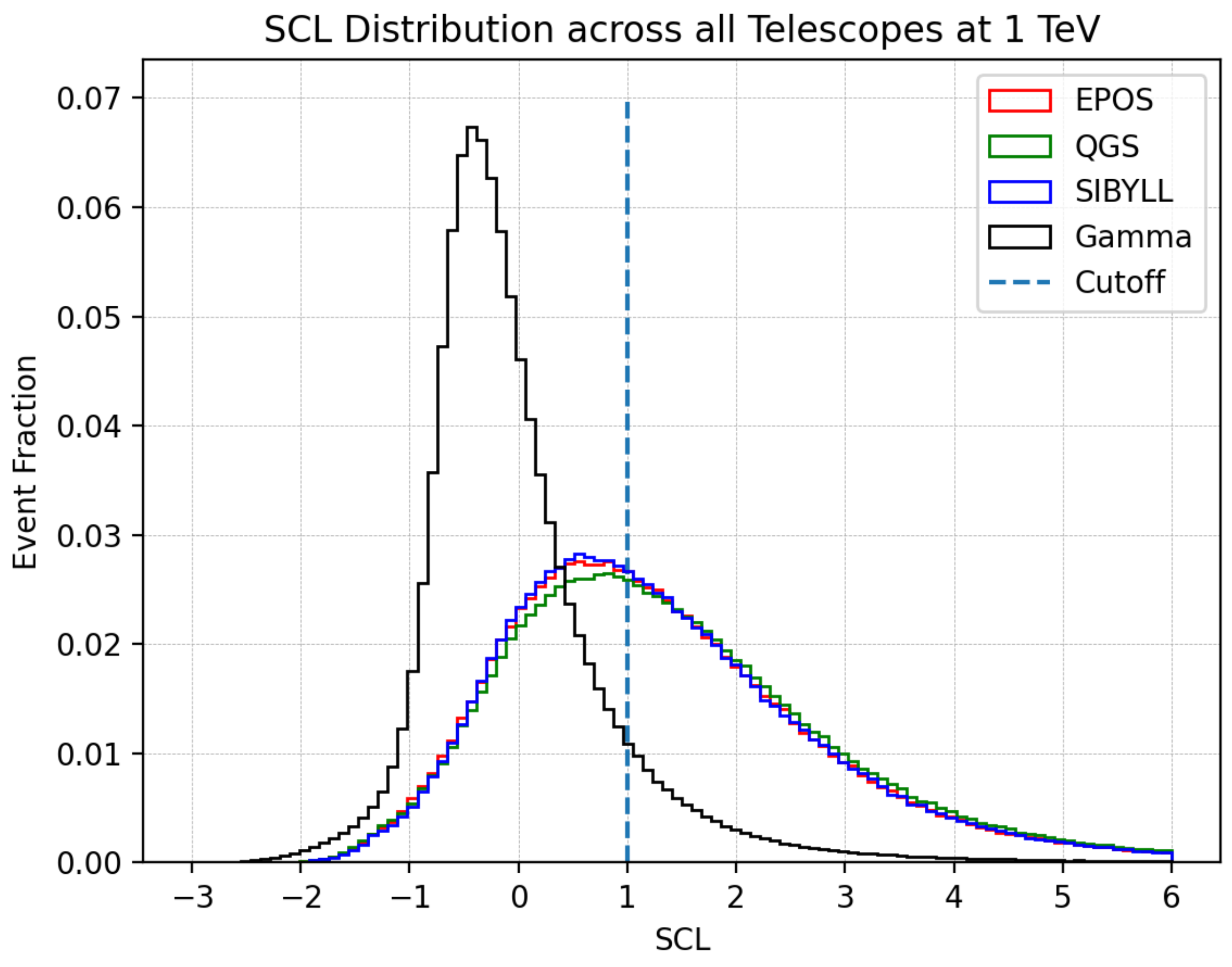


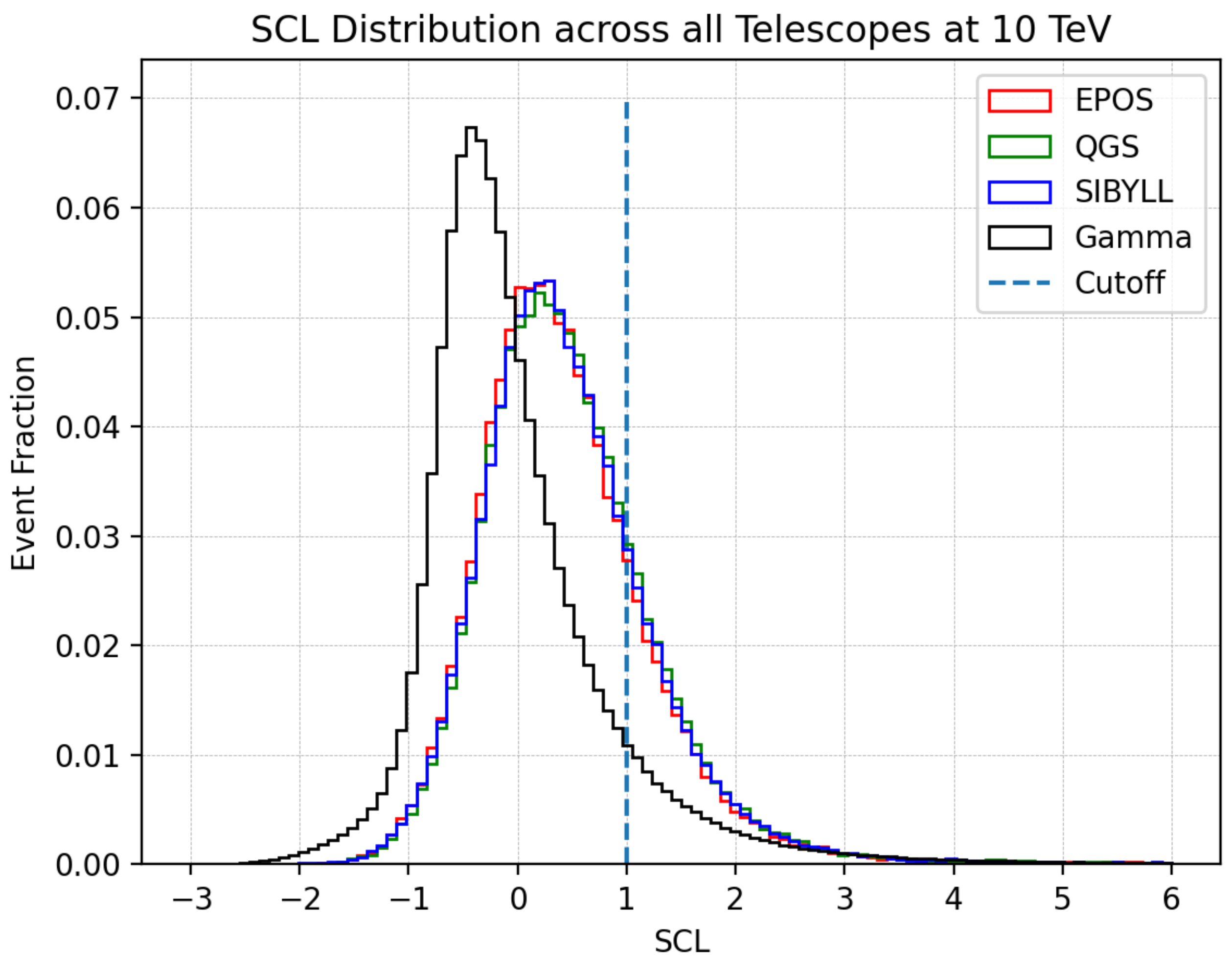
Scaled Length Parameter

- Gamma-like region smallest for 1 TeV as distribution peaks lowest
- Biggest differences:
  - SIBYLL at 100 GeV
  - QGS at 1 TeV and 10 TeV

Energy	EPOS	QGS	SIBYLL
100 GeV	$(72.4 \pm 0.2)\%$	$(72.6 \pm 0.2)\%$	$(71.9 \pm 0.2)\%$
1 TeV	$(46.8 \pm 0.1)\%$	$(44.5 \pm 0.1)\%$	$(46.9 \pm 0.1)\%$
10 TeV	$(79.8 \pm 0.3)\%$	$(77.9 \pm 0.3)\%$	$(78.6 \pm 0.3)\%$



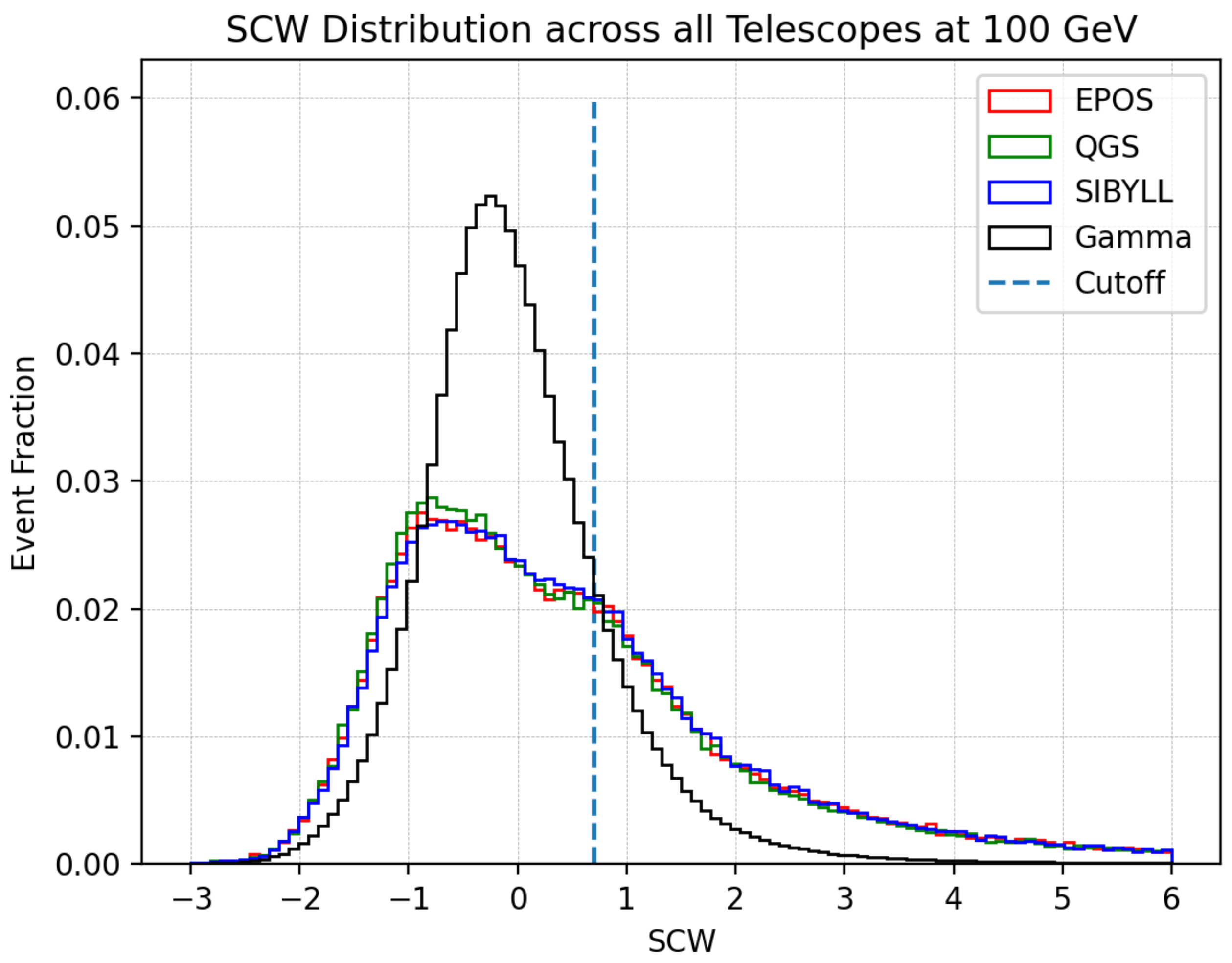


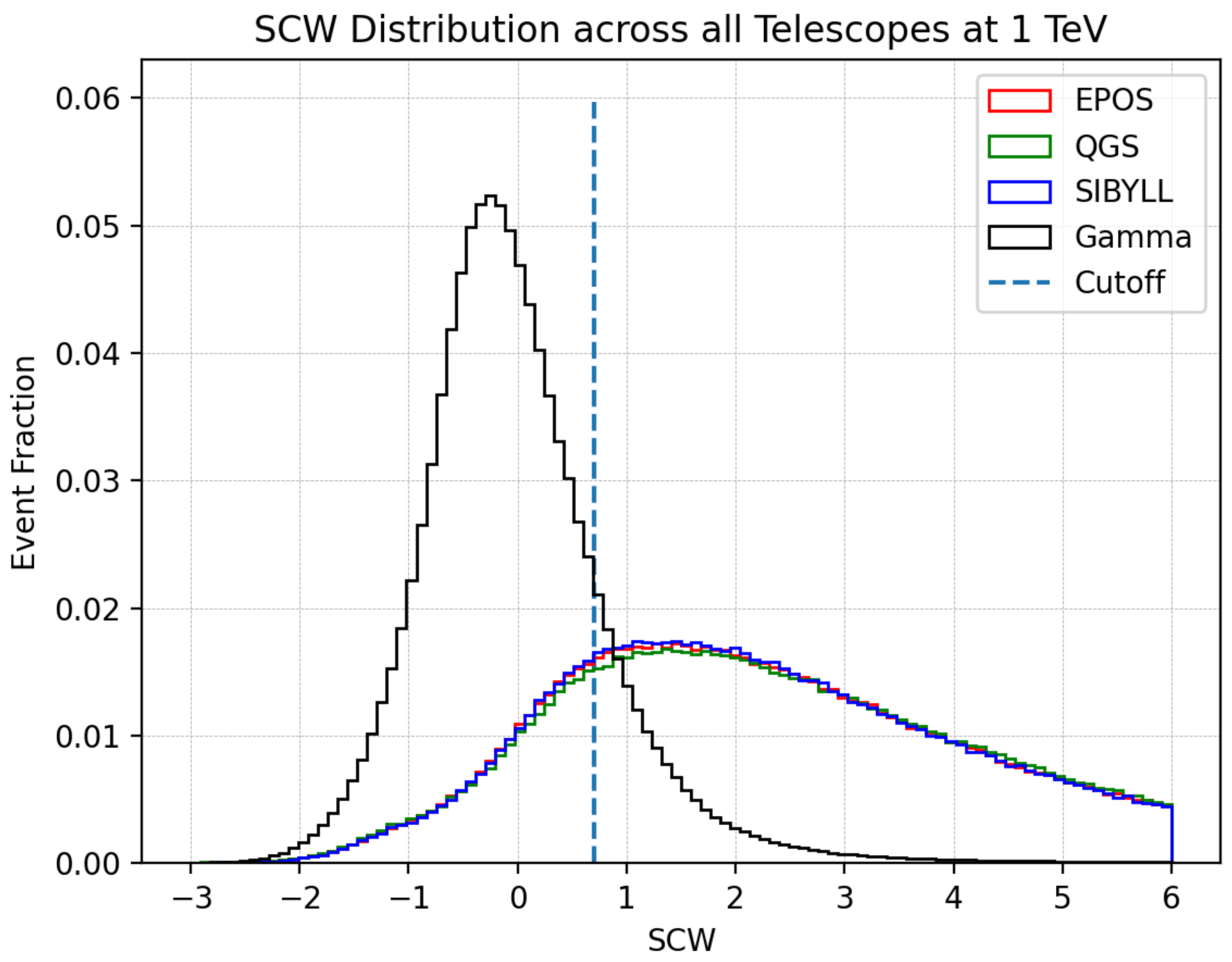


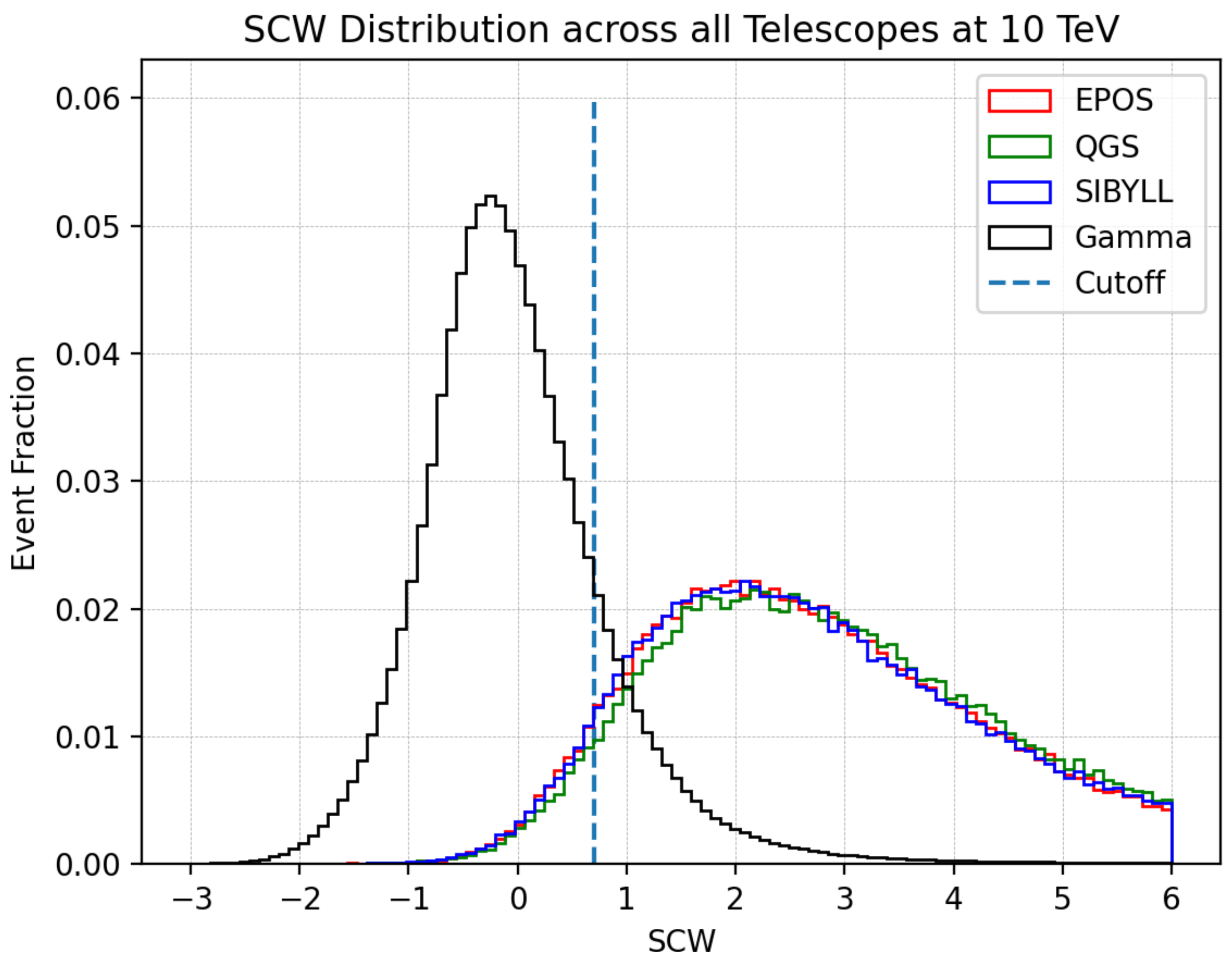
Scaled Width Parameter

- Strong dependency of „gamma-likeness“ on energy in width parameter
  - Most effective parameter at distinguishing between gammas and proton primaries at TeV energies
- Differences between the models biggest at 100 GeV, as at other energies differences are beyond cut-off
  - QGS slightly above others in terms of acceptance at 100 GeV

Energy	EPOS	QGS	SIBYLL
100 GeV	$(61.6 \pm 0.2)\%$	$(62.9 \pm 0.2)\%$	$(61.3 \pm 0.2)\%$
1 TeV	$(19.7 \pm 0.1)\%$	$(19.0 \pm 0.1)\%$	$(19.5 \pm 0.1)\%$
10 TeV	$(6.7 \pm 0.1)\%$	$(5.6 \pm 0.1)\%$	$(6.6 \pm 0.1)\%$







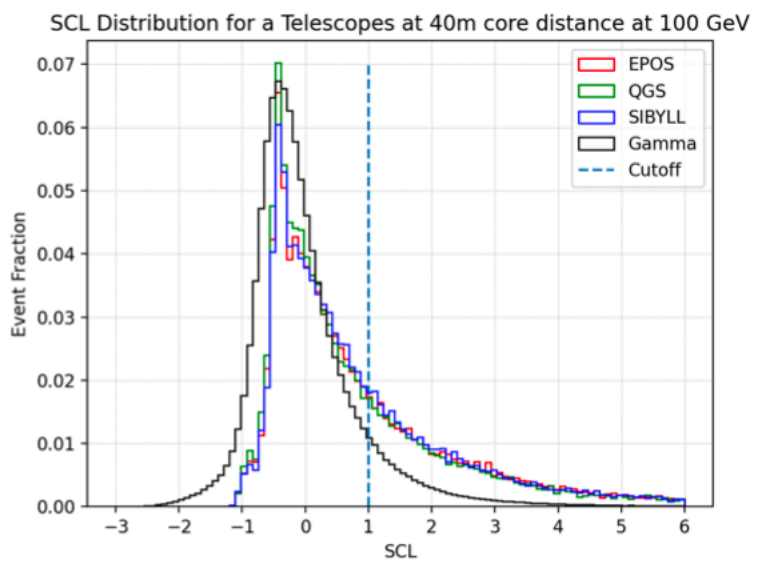
Single Telescopes

Splitting Scaled Lengths Plots

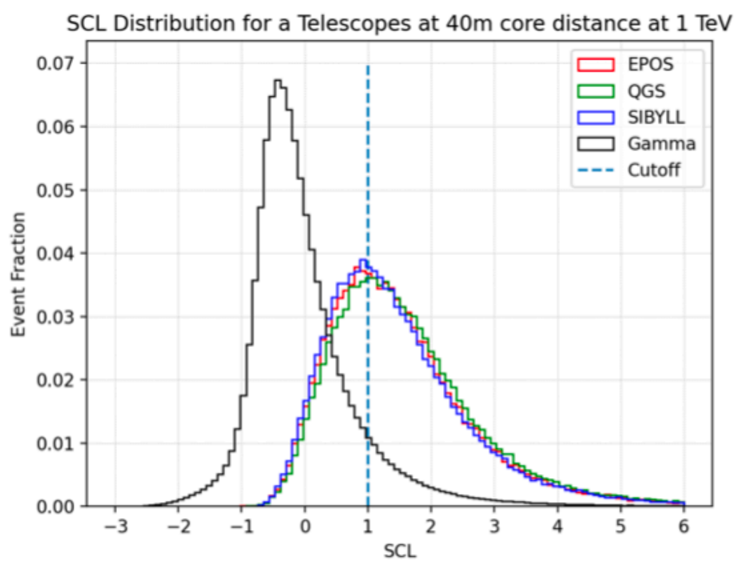
- Further analysis for single core distances

- Most notable plots:
  - Biggest disagreement of models in (a)
  - (b) shows difference of QGS at 1 TeV well
  - (i) seems to match expectations perfectly

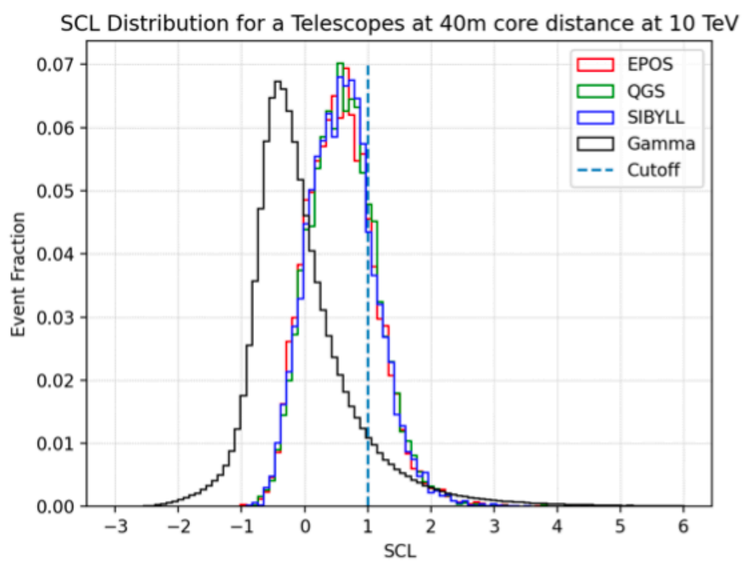
- Low core distance of most interest



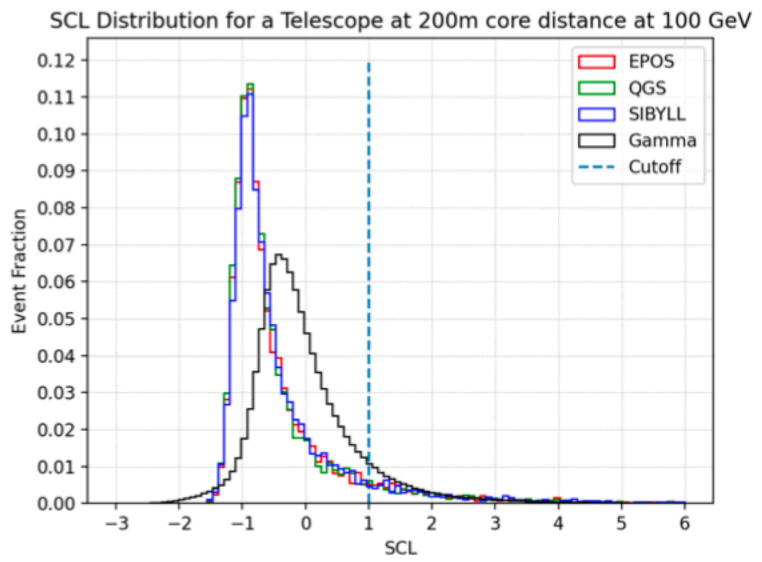
(a) Scaled lengths at 100 GeV at 40m core distance



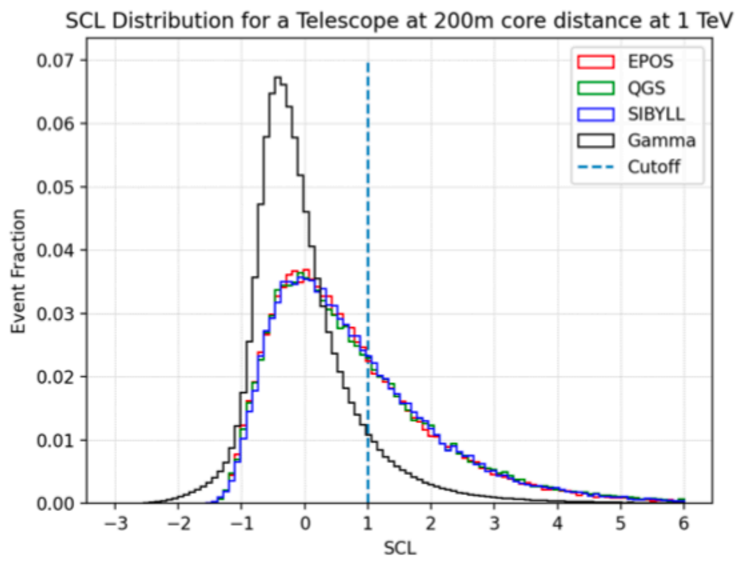
(b) Scaled lengths at 1 TeV at 40m core distance



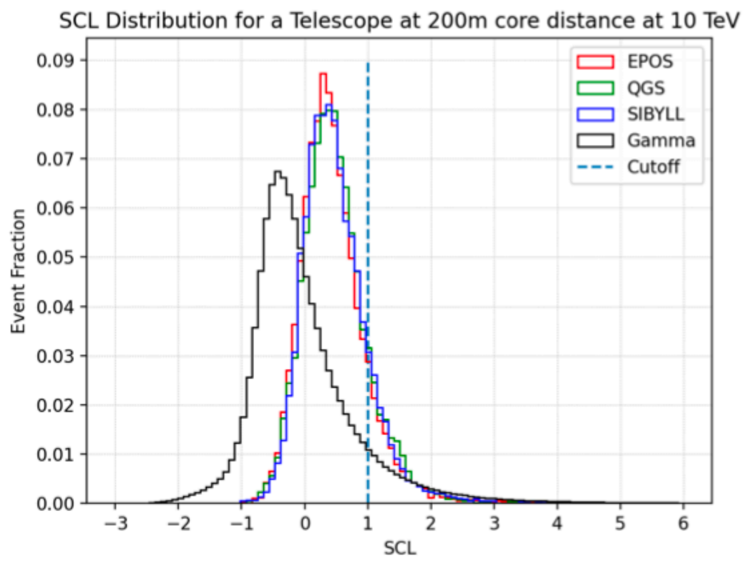
(c) Scaled lengths at 10 TeV at 40m core distance



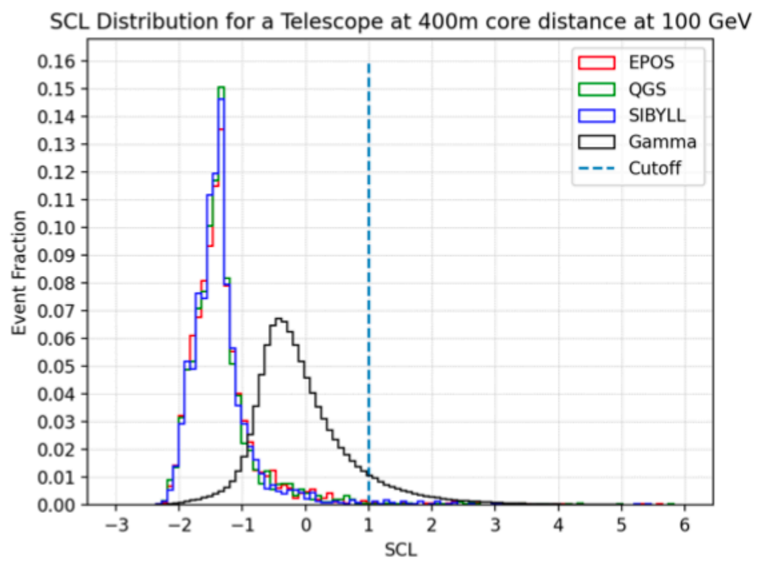
(d) Scaled lengths at 100 GeV at 200m core distance



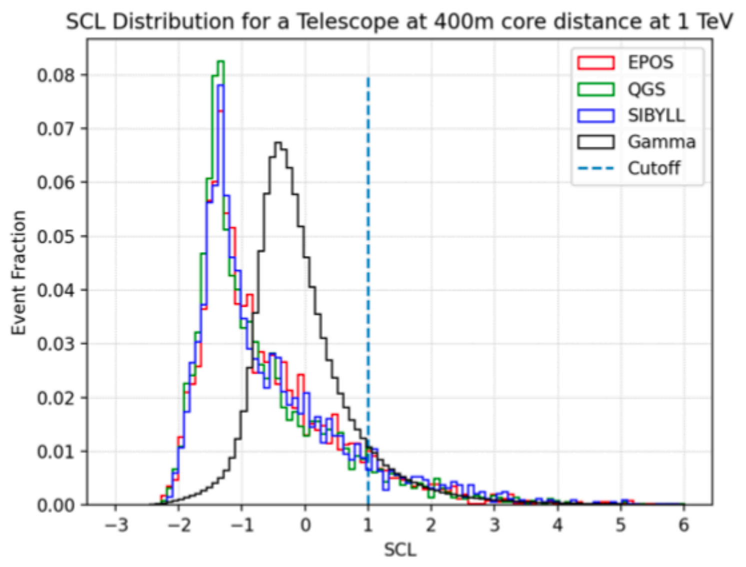
(e) Scaled lengths at 1 TeV at 200m core distance



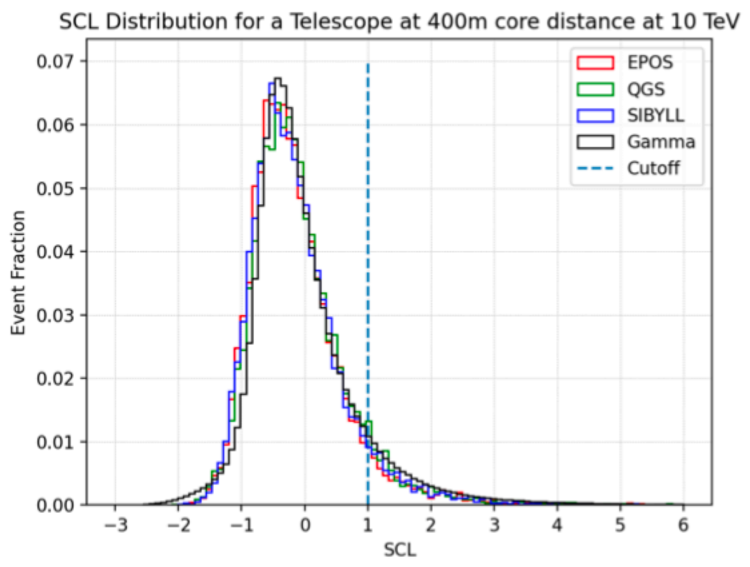
(f) Scaled lengths at 10 TeV at 200m core distance



(g) Scaled lengths at 100 GeV at 400m core distance



(h) Scaled lengths at 1 TeV at 400m core distance

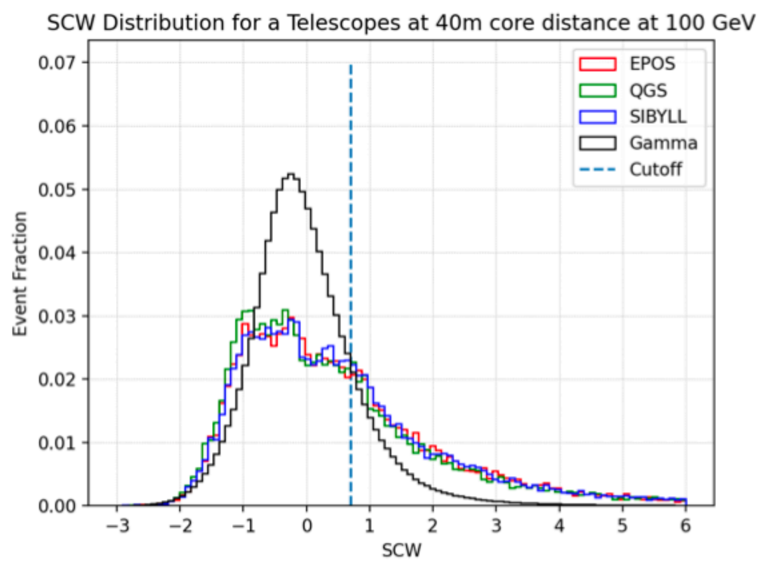


(i) Scaled lengths at 10 TeV at 400m core distance

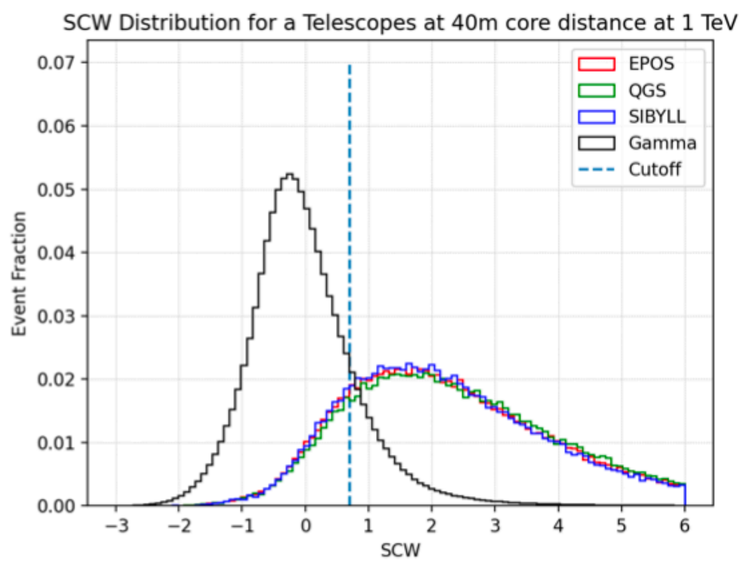
Single Telescopes

Splitting Scaled Width Plots

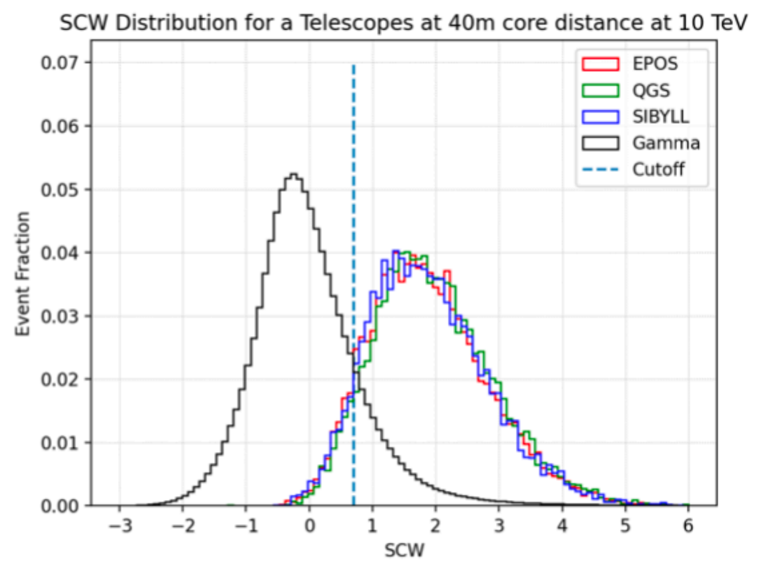
- Again, splitting up the prior SCW plots
- Most notable differences:
  - (b) shows difference of QGS again, but mostly beyond cut-off
  - High core distances sparsely populated (due to being far outside light pool) thus showing a lot of disagreement
- Gamma-like region mostly in agreement



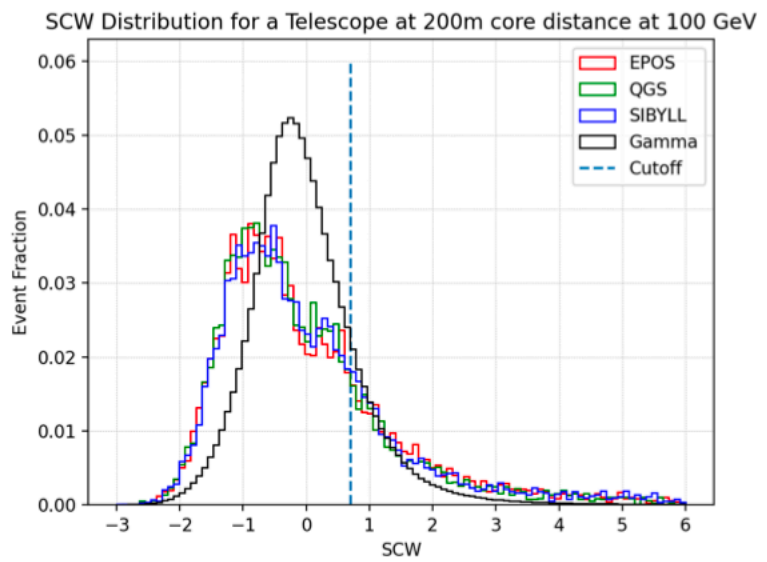
(a) Scaled widths at 100 GeV at 40m core distance



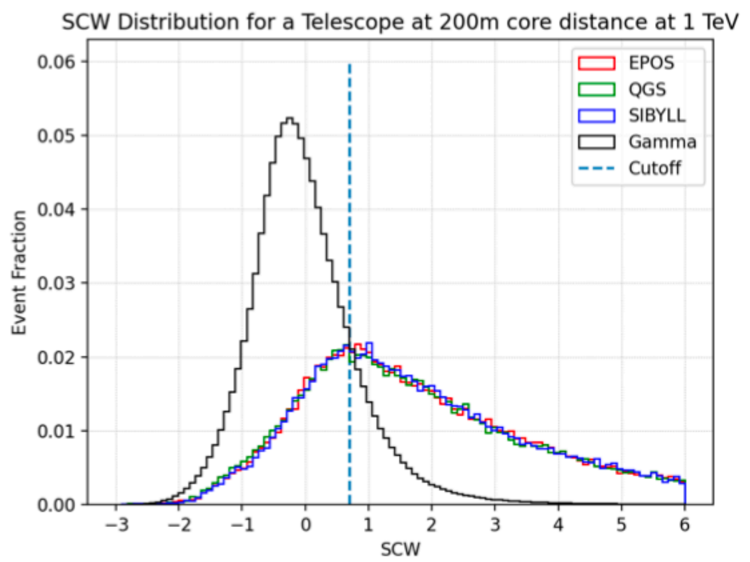
(b) Scaled widths at 1 TeV at 40m core distance



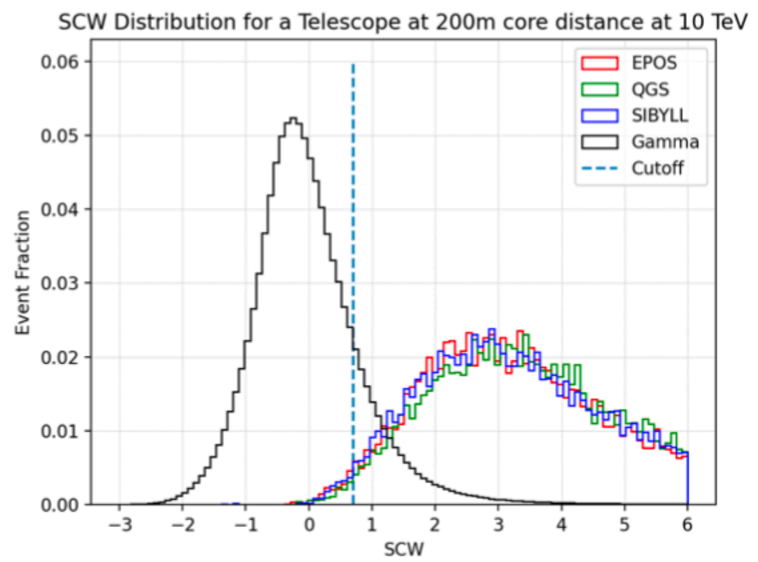
(c) Scaled widths at 10 TeV at 40m core distance



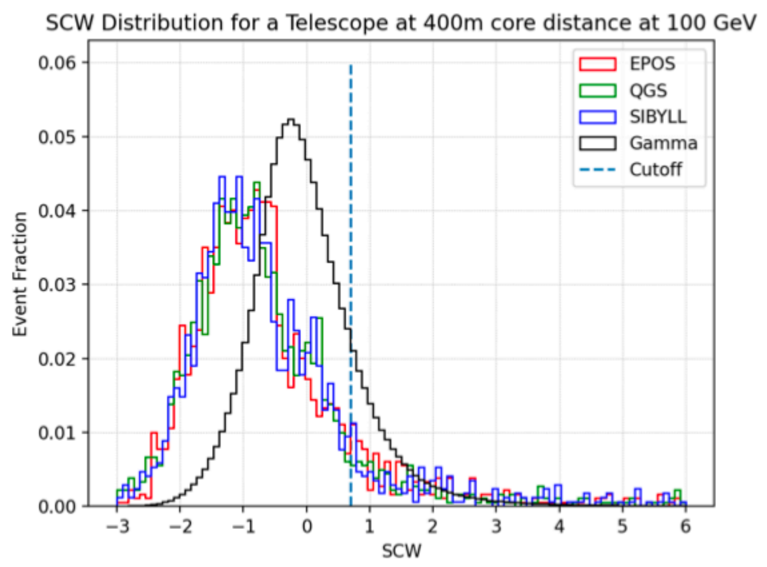
(d) Scaled widths at 100 GeV at 200m core distance



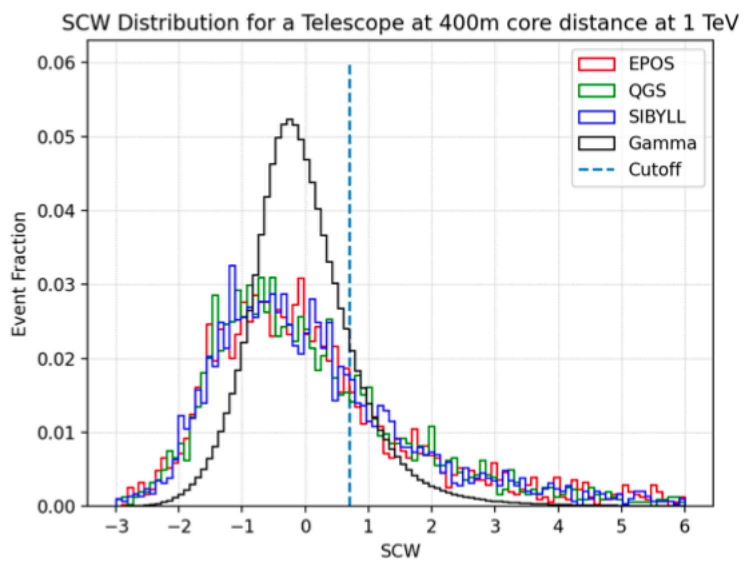
(e) Scaled widths at 1 TeV at 200m core distance



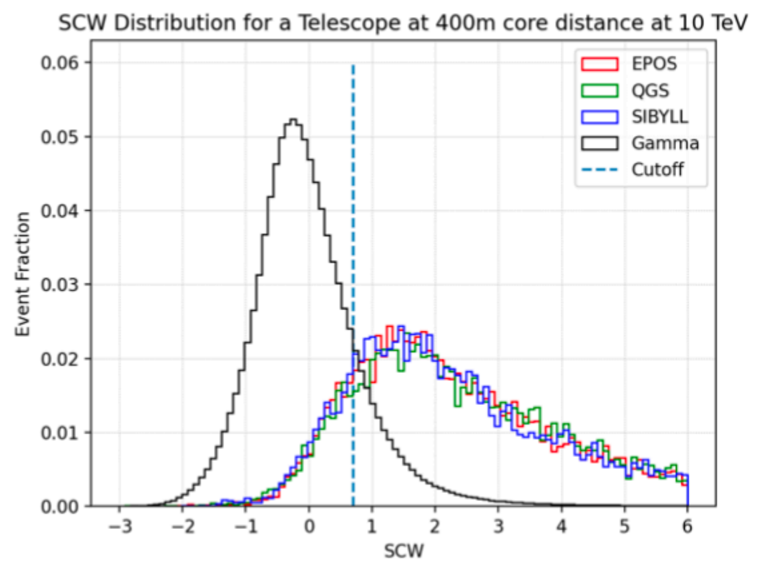
(f) Scaled widths at 10 TeV at 200m core distance



(g) Scaled widths at 100 GeV at 400m core distance



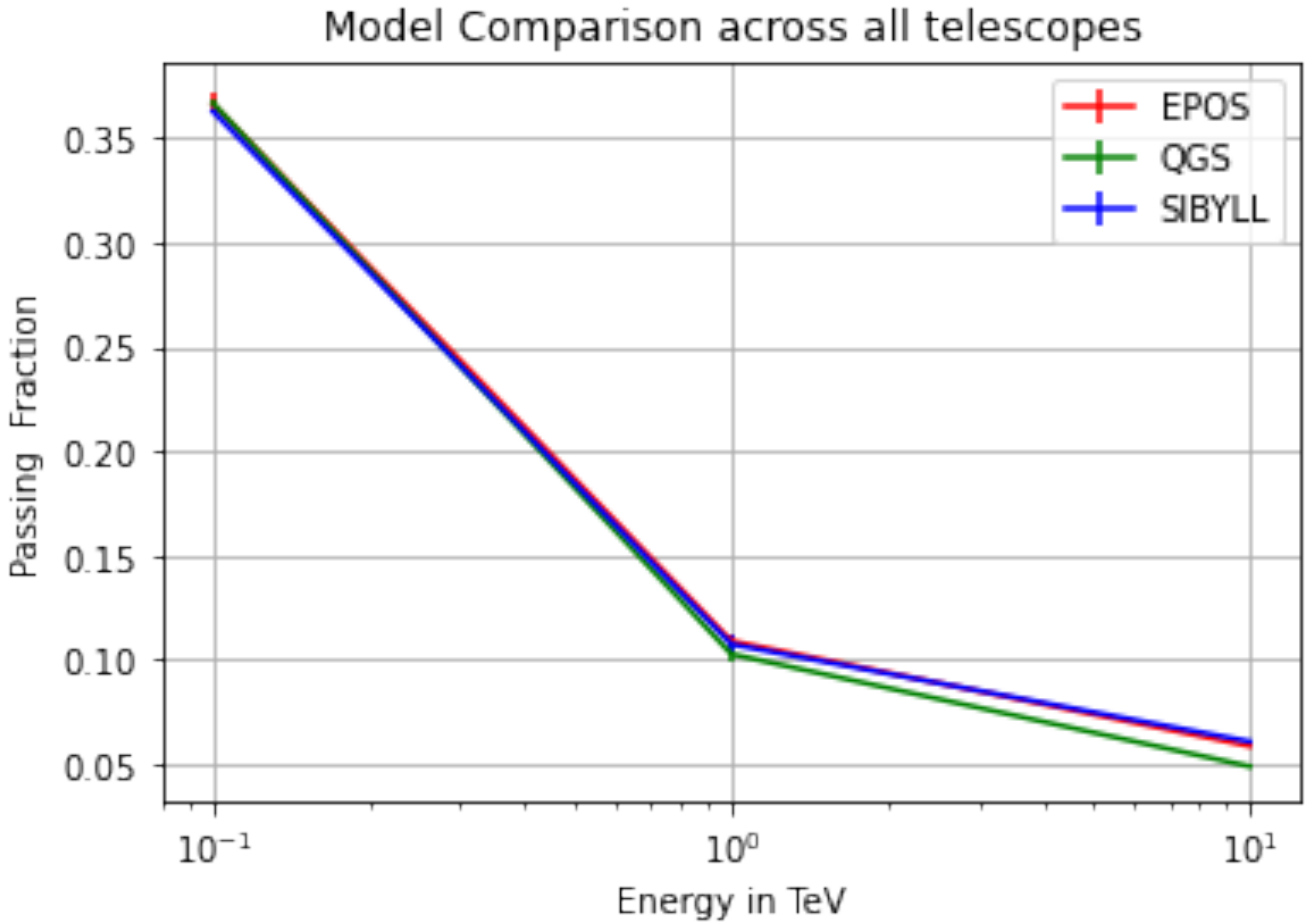
(h) Scaled widths at 1 TeV at 400m core distance



(i) Scaled widths at 10 TeV at 400m core distance

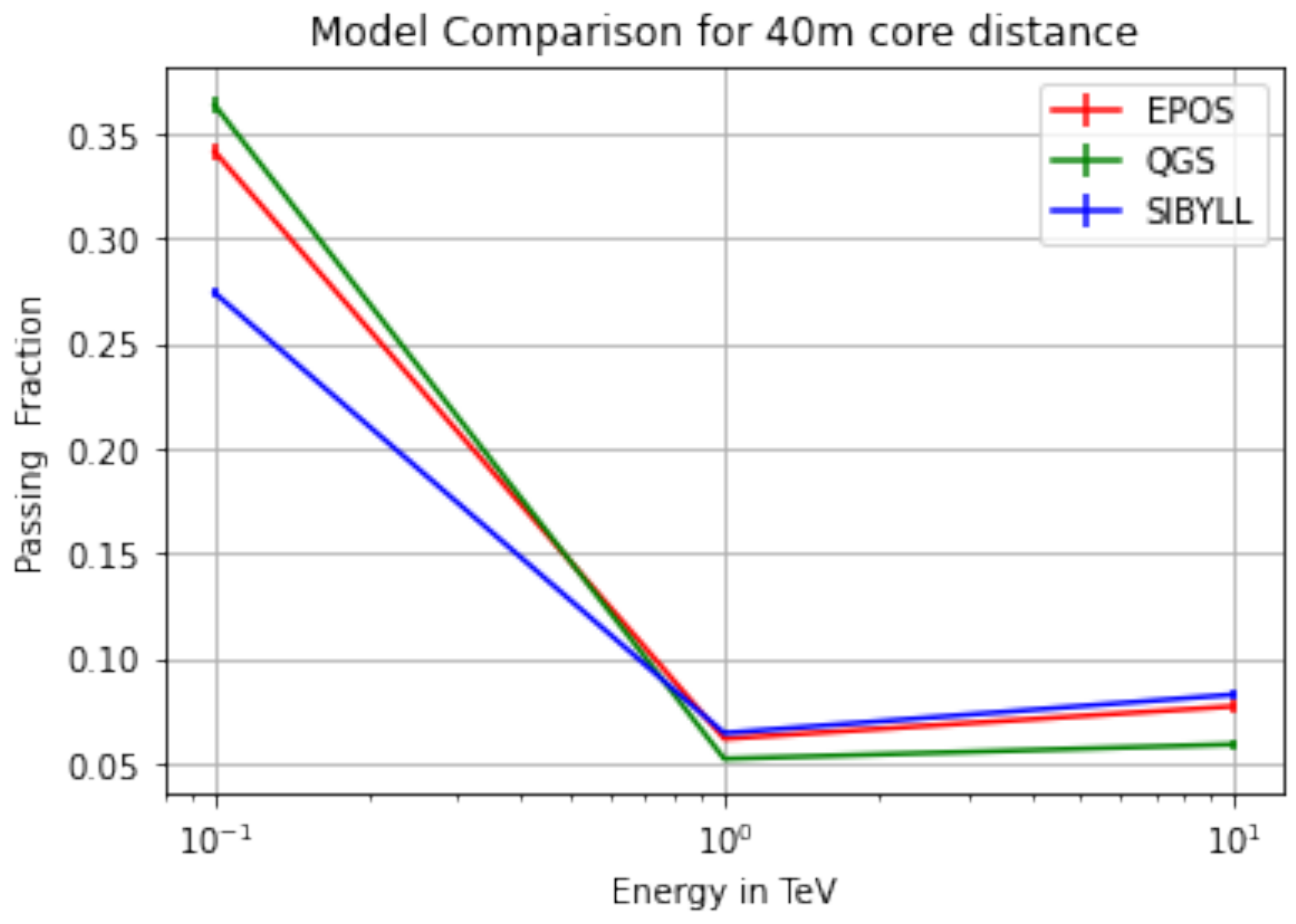
So, what does that all amount to ?

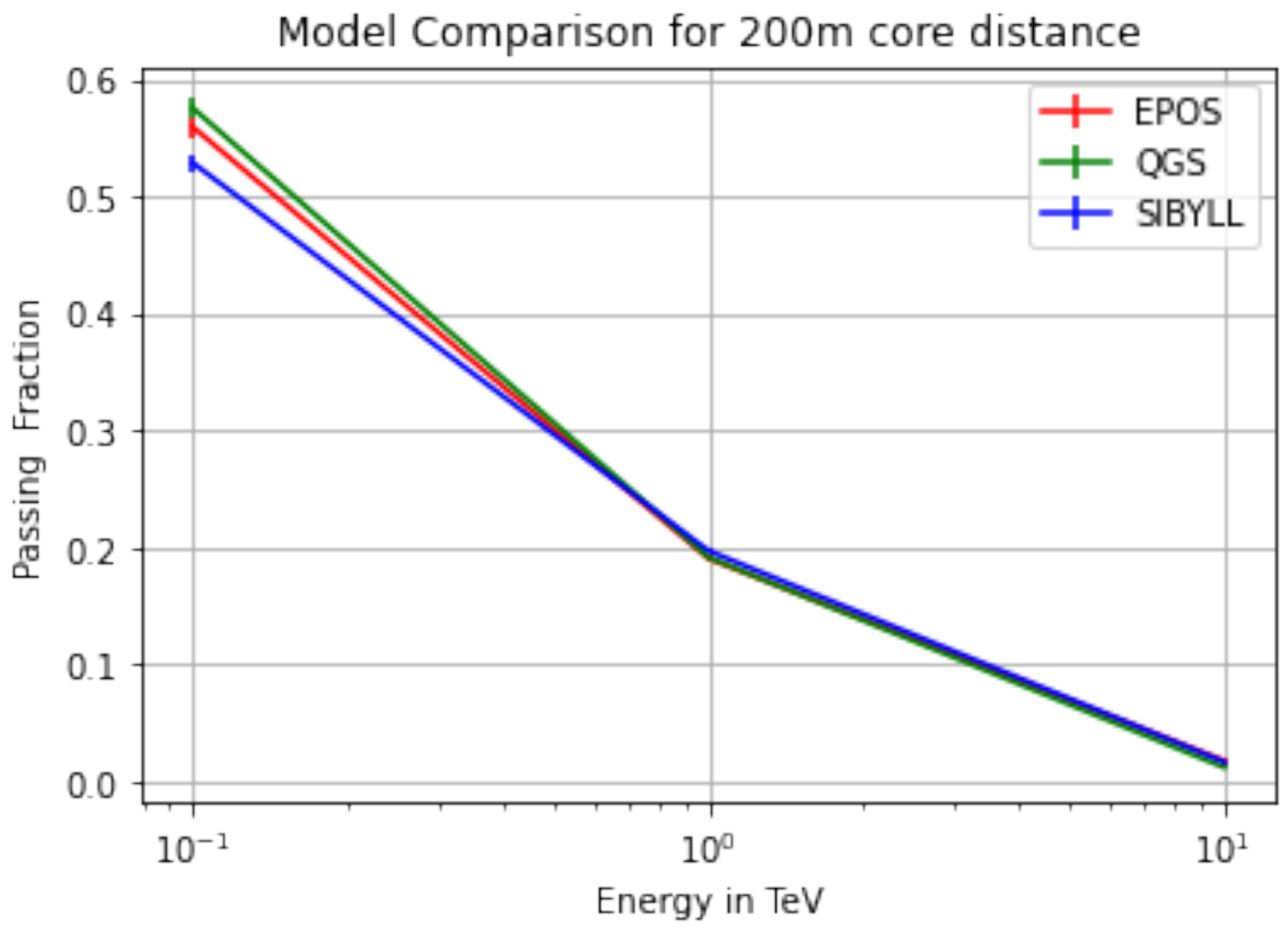
- We've seen that the Width parameter drives the difference in higher energies
- Higher core distances skew the distributions
- Overall percentage agreement between the models seems to go up with energy, but the passing fraction shows biggest differences at 10 TeV
  - QGS differs from EPOS: $(16.61 \pm 1.55)\ \%$
  - QGS differs from SIBYLL: $(19.60 \pm 1.48)\ \%$

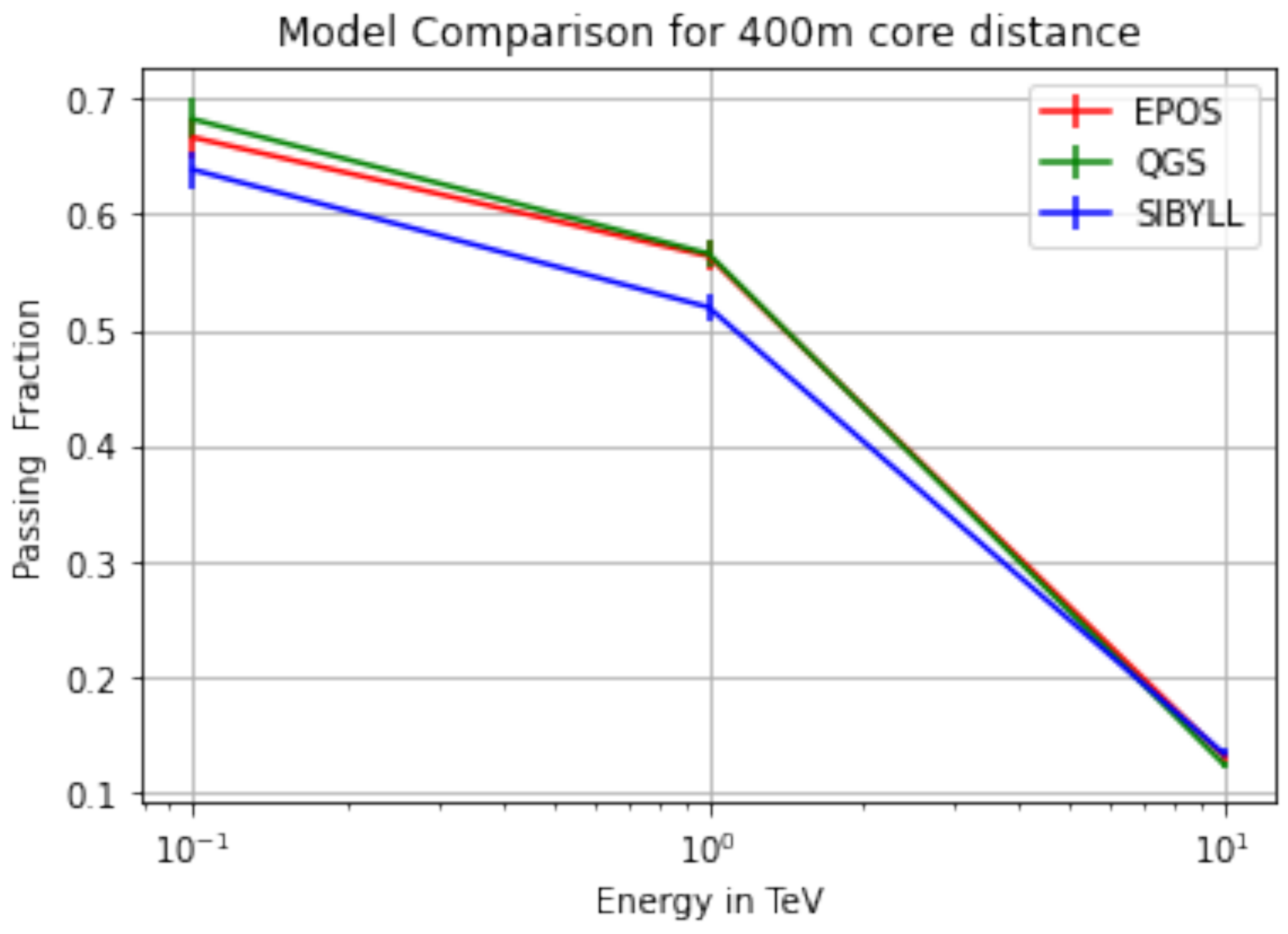


Single Telescope Passing Fractions

- For low energy, passing fraction increases strongly with higher core distance
- Differences between models highest at 40m, i.e. inside Cherenkov light pool
  - There, showers are the brightest, thus differences between models can be resolved in detail
  - QGS differs (23.34 ± 4.2) % from EPOS at 10 TeV, driving factor in plot on previous page
  - SIBYLL differs (19.7 ± 1.2) % from EPOS at 100 GeV, stemming from (a) on p.8







Conclusion

- Trend seen by Michiko Ohishi (2021) that QGS produces shorter and narrower images reproduced, mostly seen in high energy events inside Cherenkov light pool

- Low core distances account for most of the differences seen between models, as seen by Parsons and Shoorlemmer (2019)

- Differences are sizable and thus, follow up studies like Marcels' need to be done