Karlsruhe Institute of Technology

Progress on Deep Learning Applications for Extensive Air Shower Simulations

Marcel Köpke, Dr. Markus Roth

ErUM-Data IDT Collaboration Meeting Karlsruhe (2019)

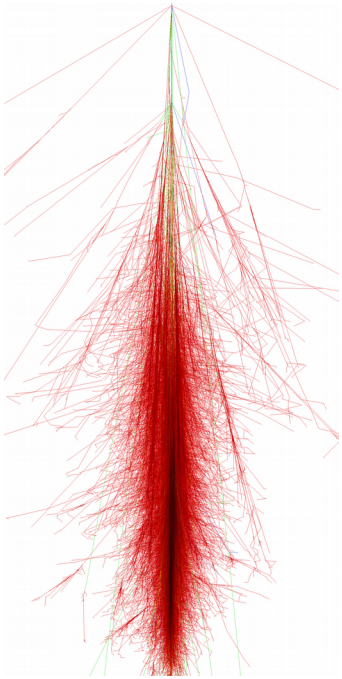
INSTITUTE FOR NUCLEAR PHYSICS (IKP), FACULTY OF PHYSICS
KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT)

Synergies

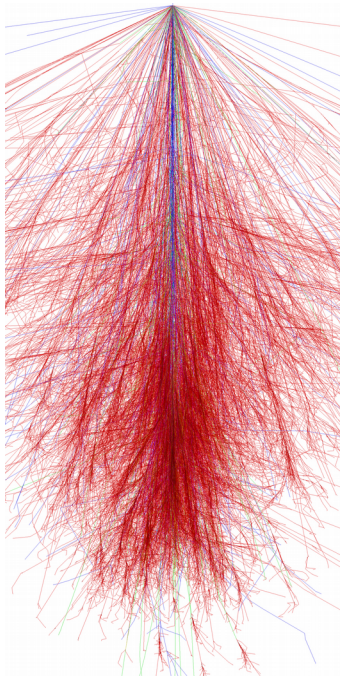
- Prof. Bernlochner is my 2nd supervisor
- Regular meetings with the group of Prof. Bernlochner
  - Markus Roth
  - Pablo Goldenzweig
  - Jubna Irakkathil Jabbar
  - +2 PhDs
- Weekly collaboration with Jubna
- 3 day meeting with Jonas Glombitza in Aachen

CORSIKA 7 [1]

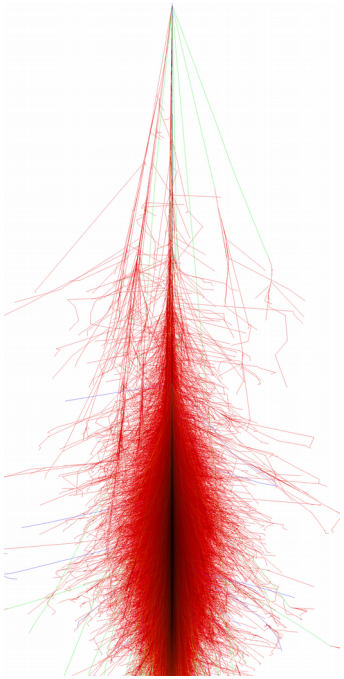
- Extensive air shower Monte Carlo simulation framework
- Different types of interaction models (EPOS-LHC, QGSJET, SIBYLL, ...)



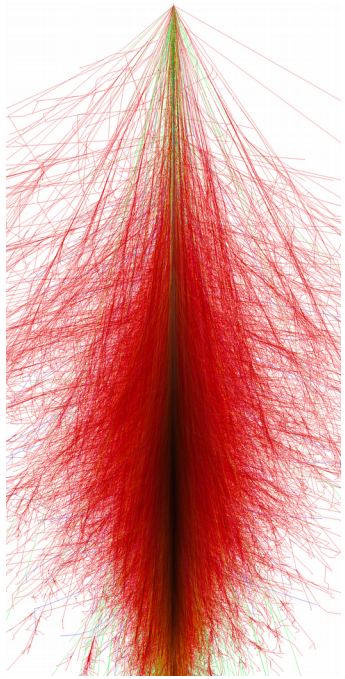
1 TeV Proton



1 TeV Iron

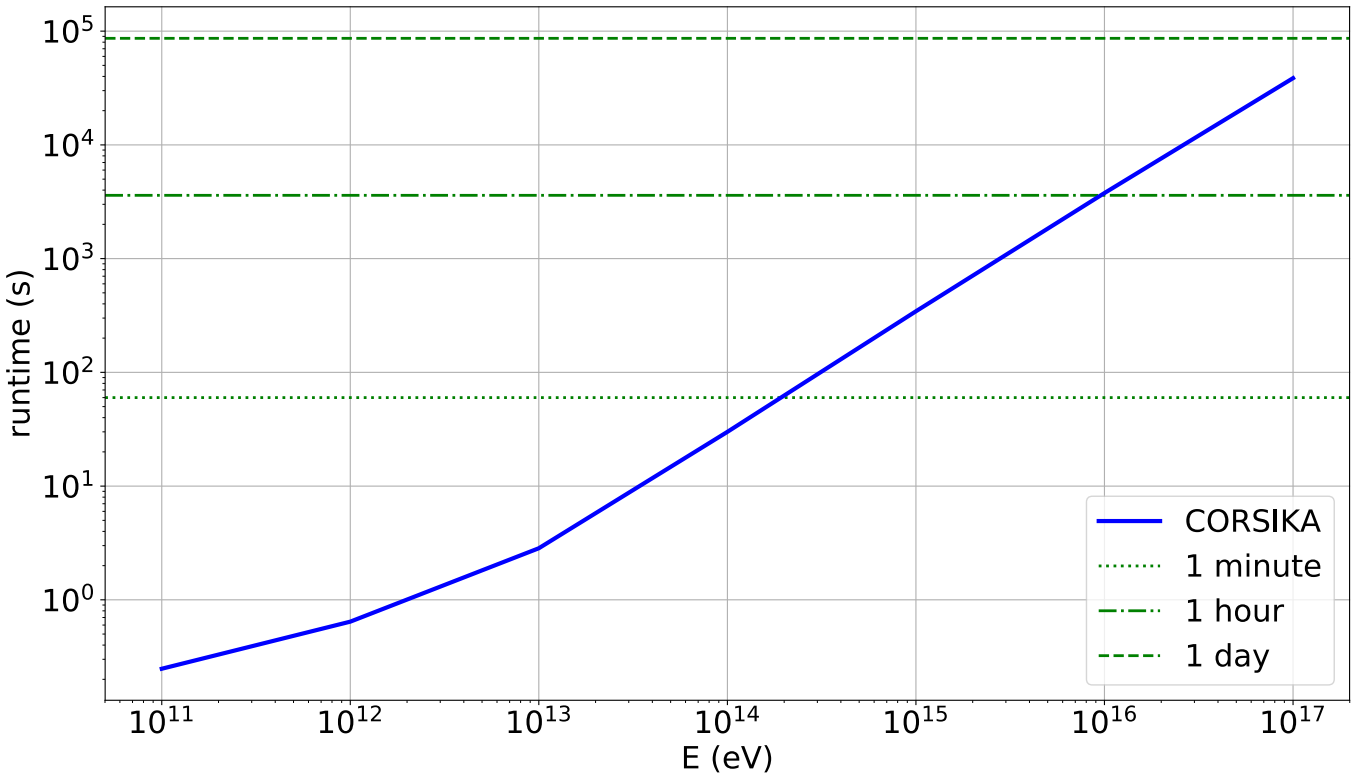


10 TeV Proton



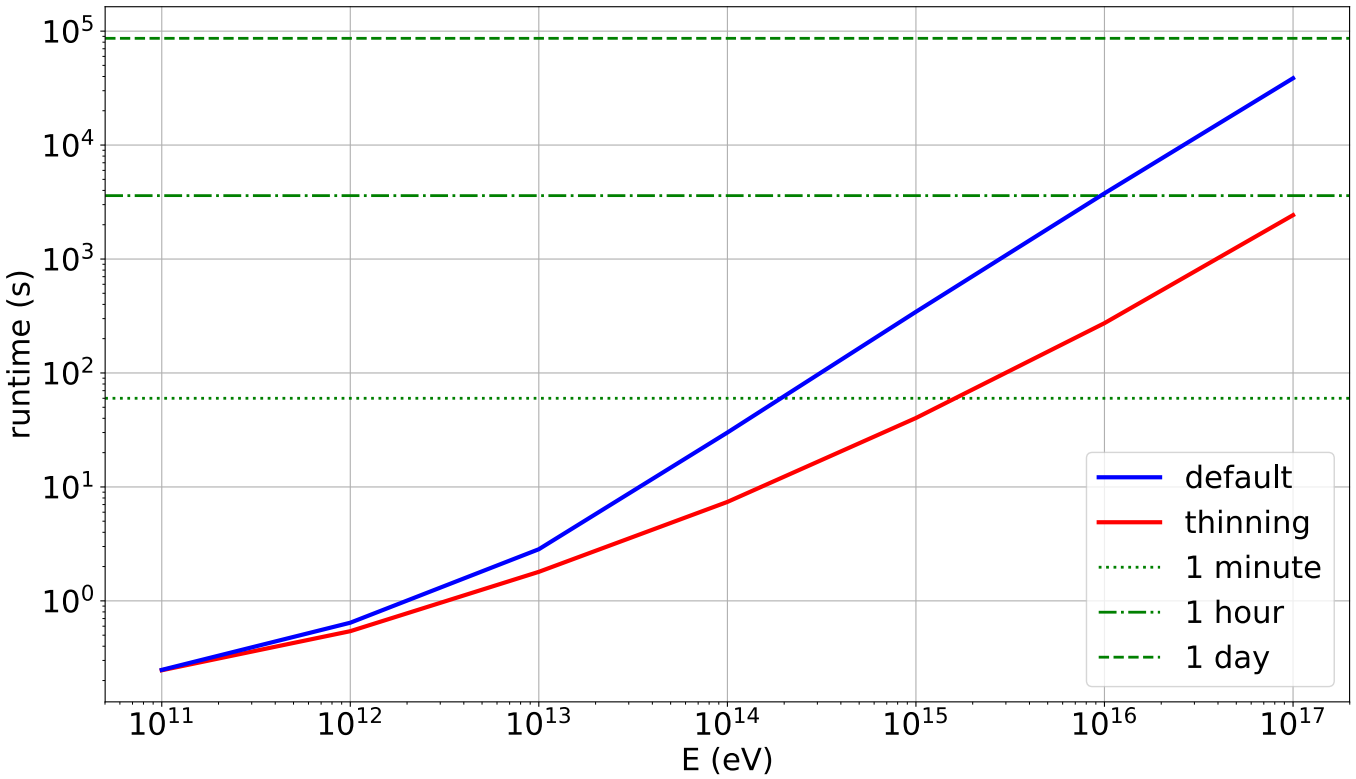
10 TeV Iron

Motivation



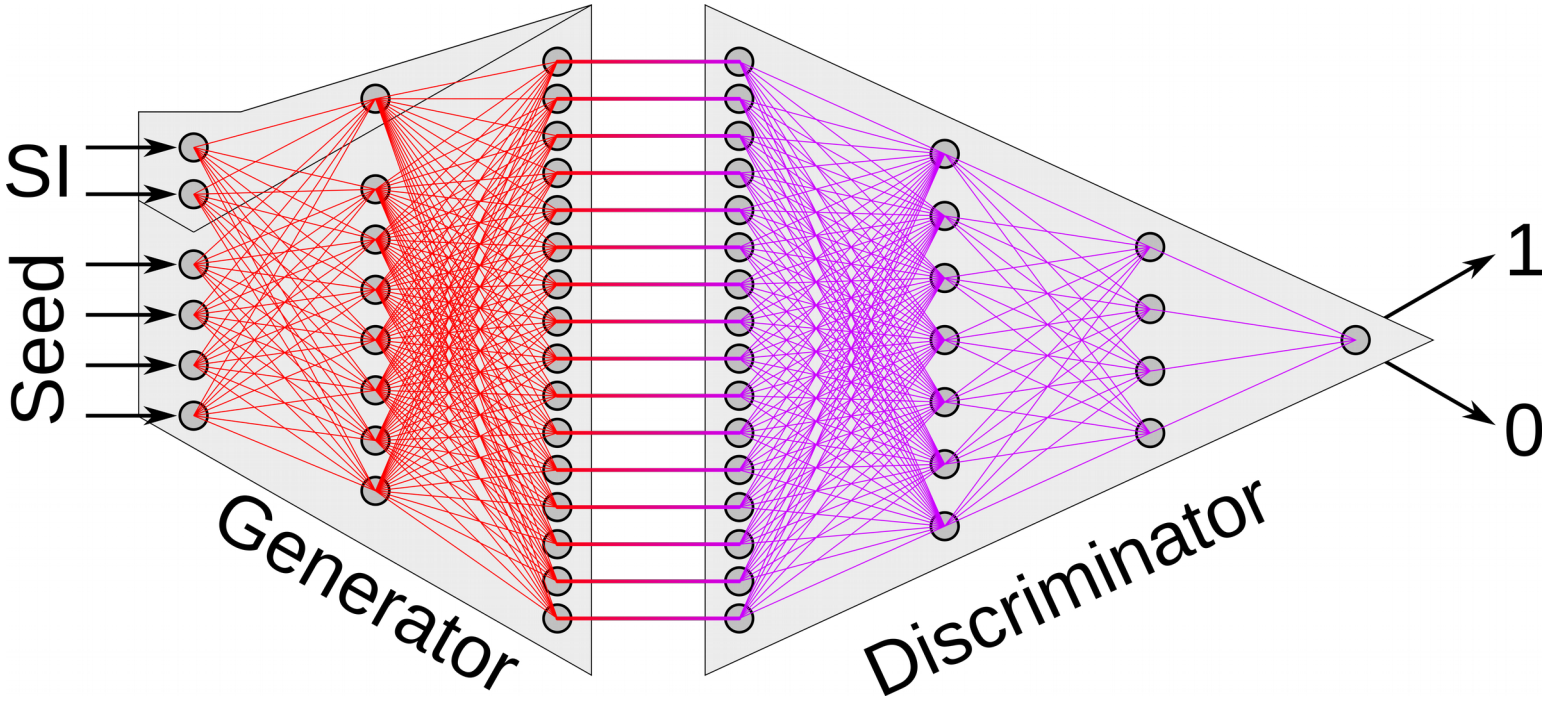
- The time complexity of CORSIKA 7 simulations rises approximately linearly with the primary particle energy

Thinning



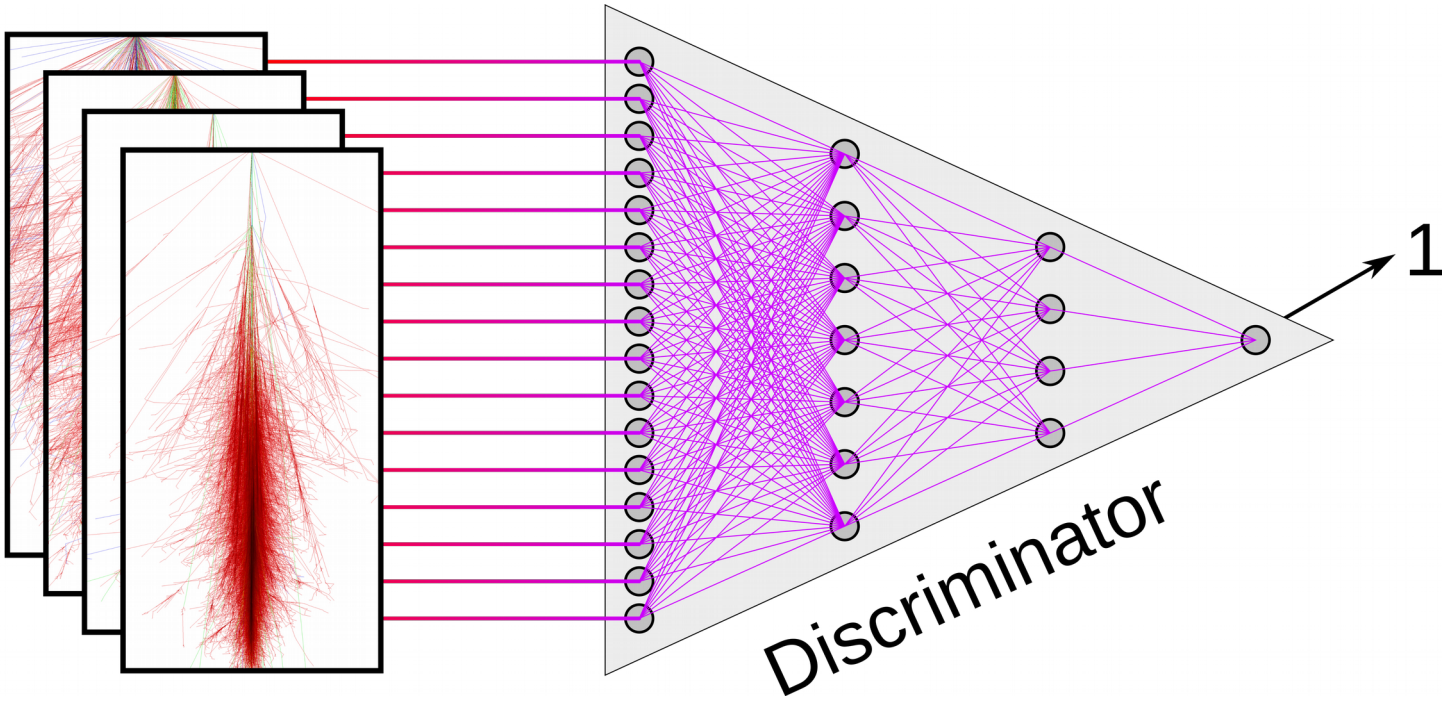
- Reduces (effective) particle content by particle-aggregation
- Preserves shower properties to leading order
- Reduces shower-to-shower fluctuations

Generative Adversarial Neural Network (GAN)



- Train discriminator on real (1) and generated (0) data
- Train generator to outsmart the discriminator

Training: Discriminator (Part 1)



- Train discriminator on real (1) and generated (0) data
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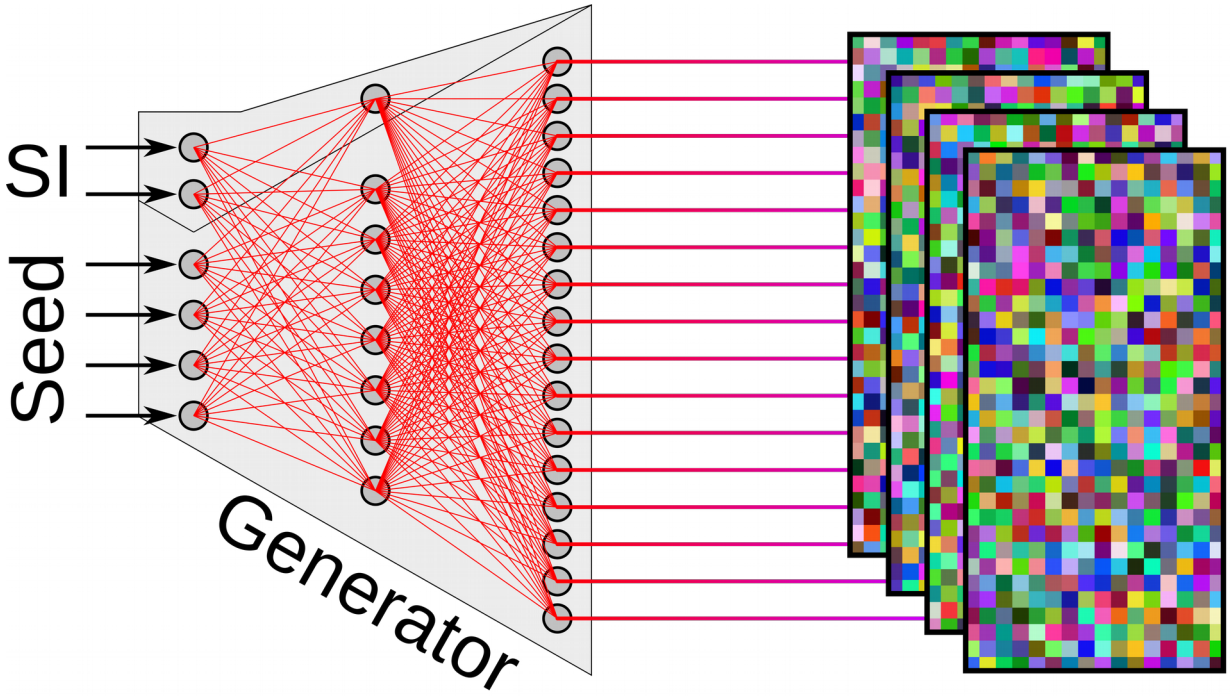
Training: Sampling



- Train discriminator on real (1) and generated (0) data
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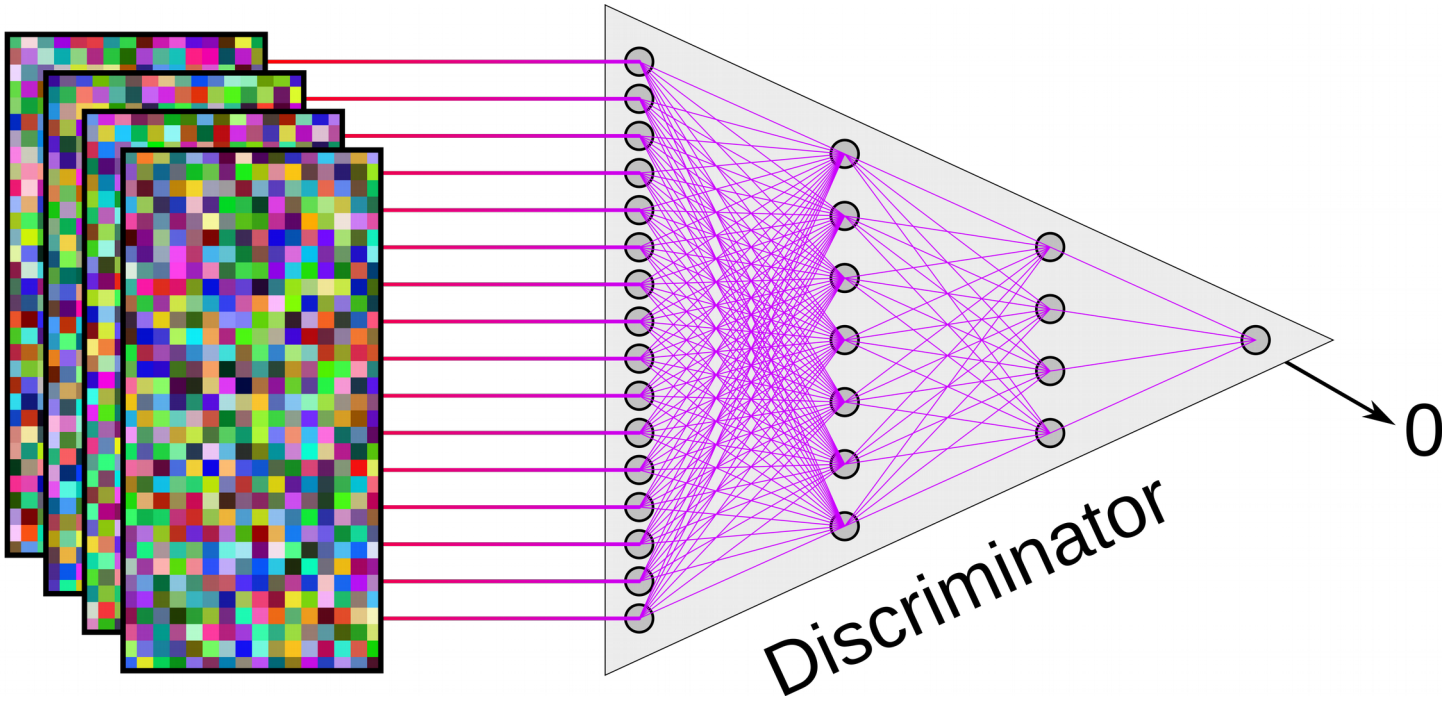
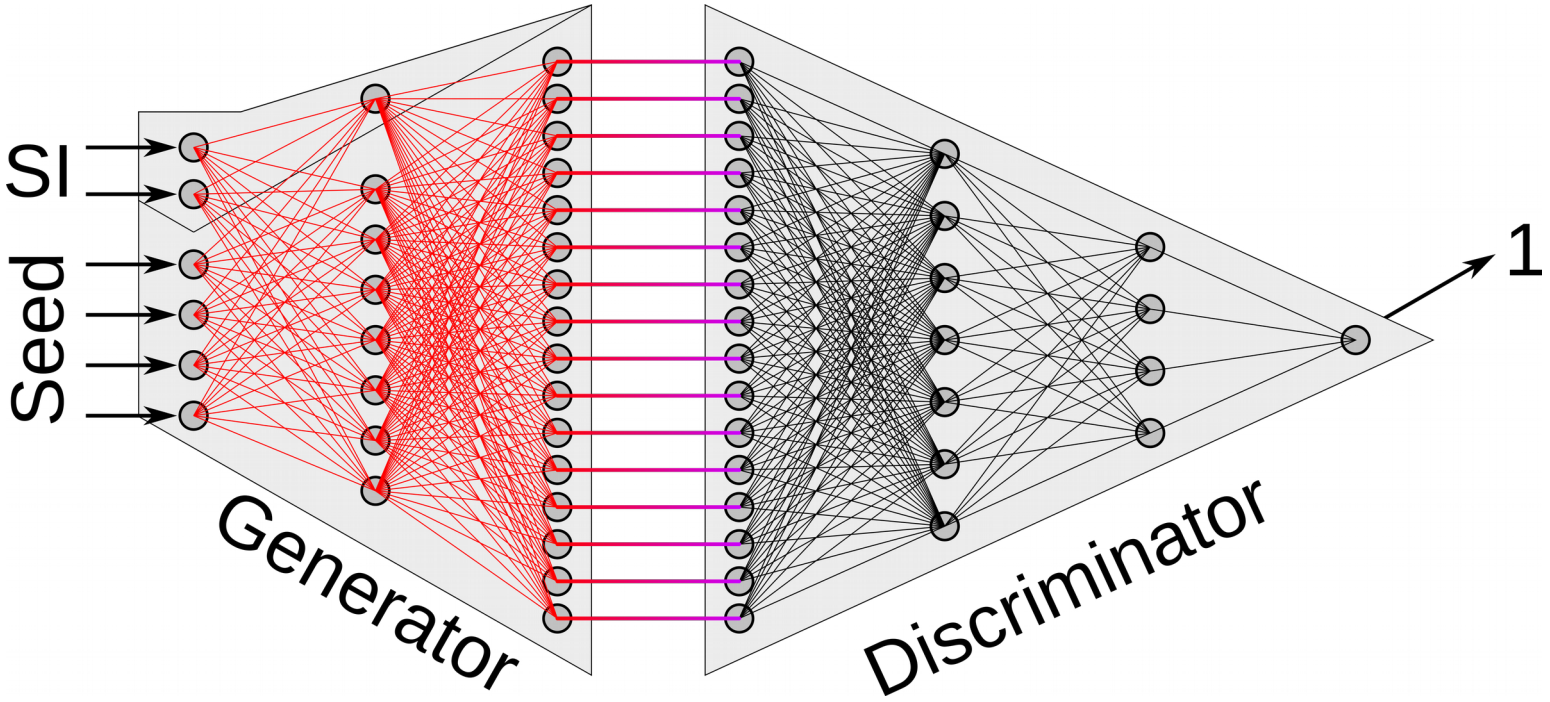
Training: Discriminator (Part 2)



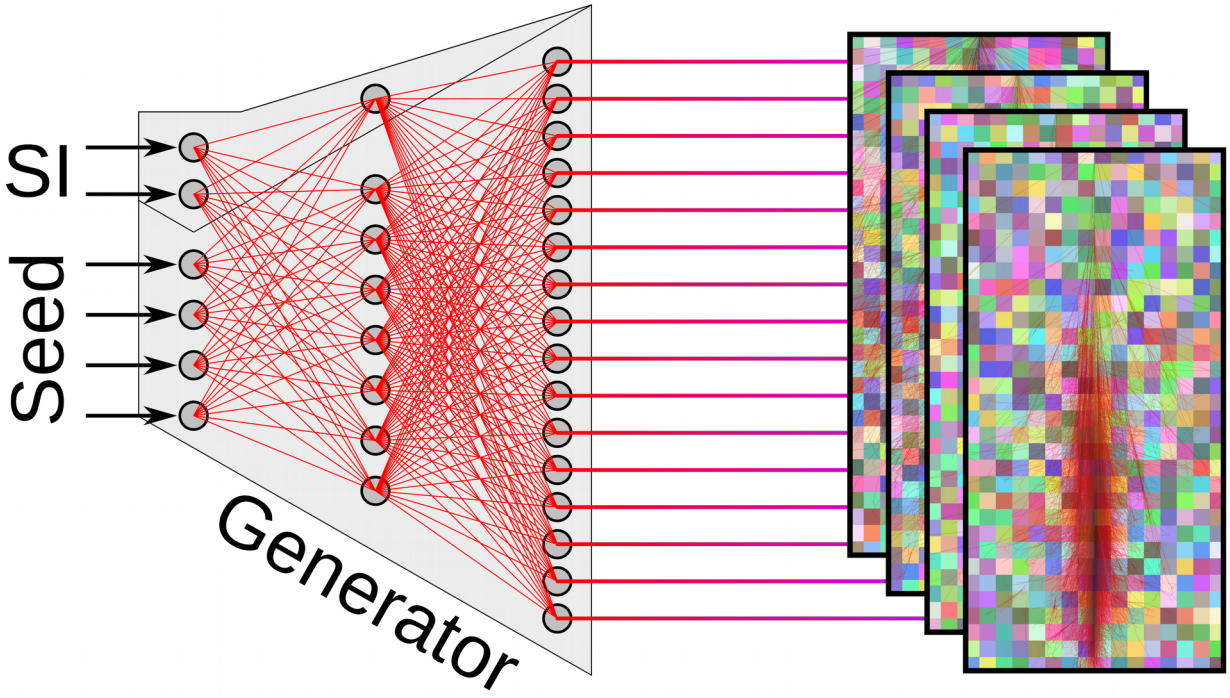
- Train discriminator on real (1) and generated (0) data
- Train generator to outsmart the discriminator

Training: Generator



- Train discriminator on real (1) and generated (0) data
- Train generator to outsmart the discriminator

Training: Result



- Train discriminator on real (1) and generated (0) data
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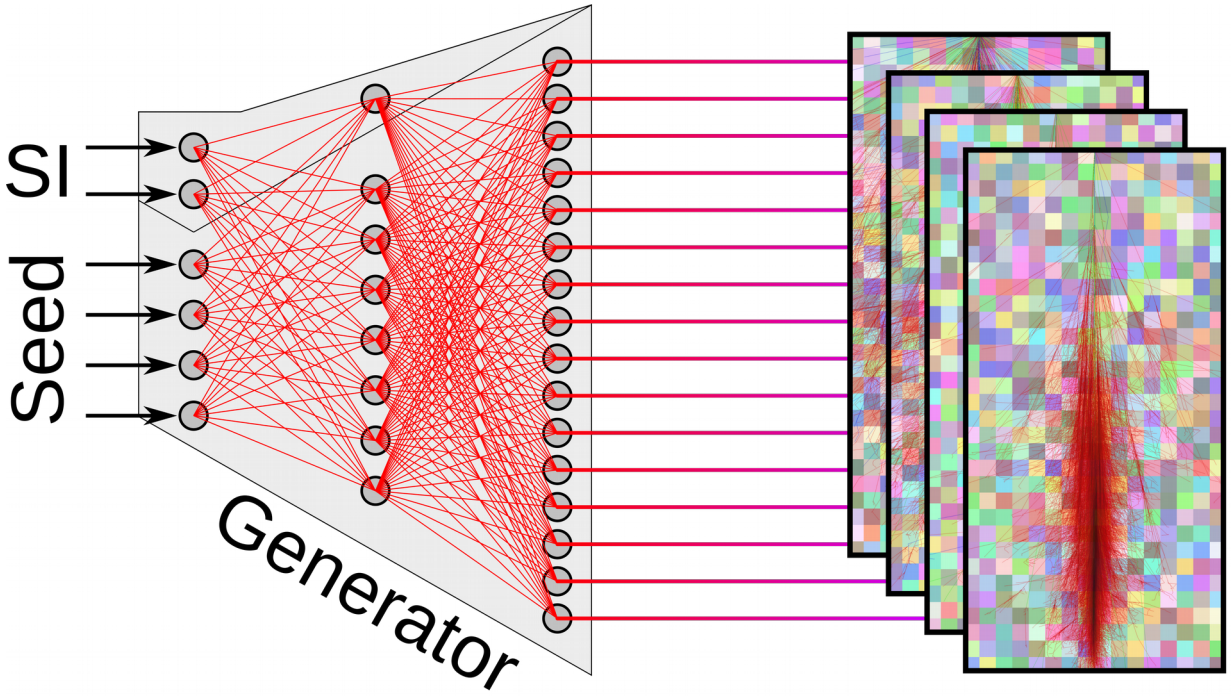
Training: Result



- Train discriminator on real (1) and generated (0) data
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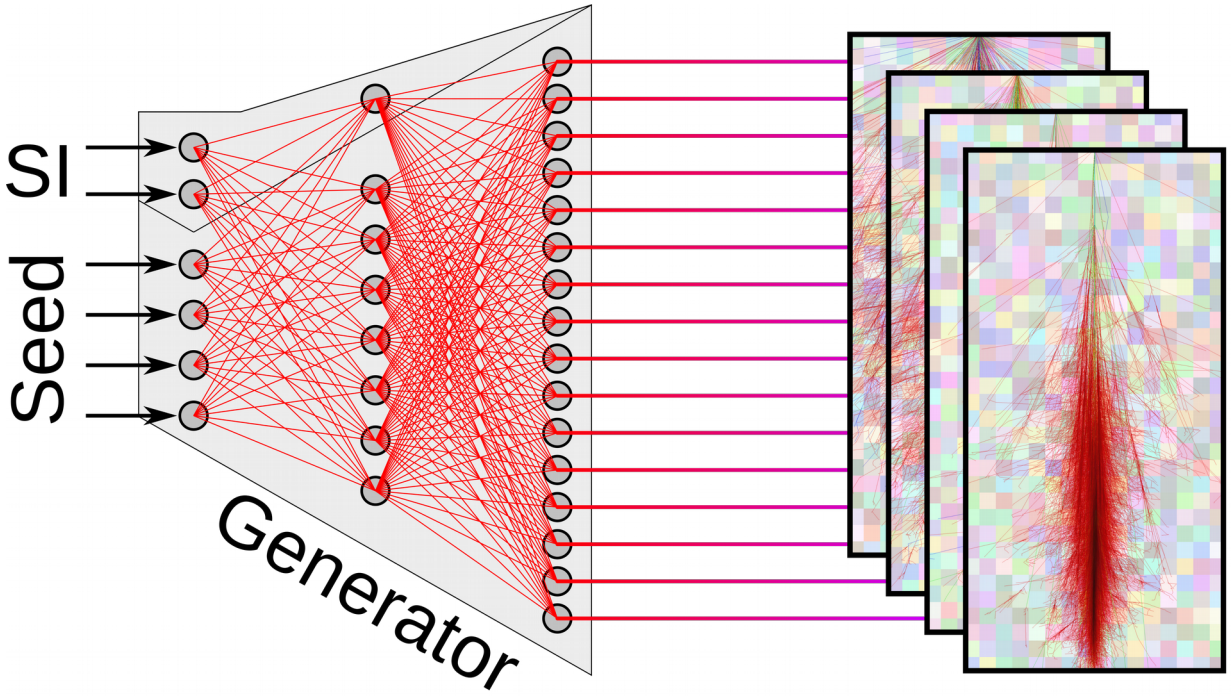
Training: Result



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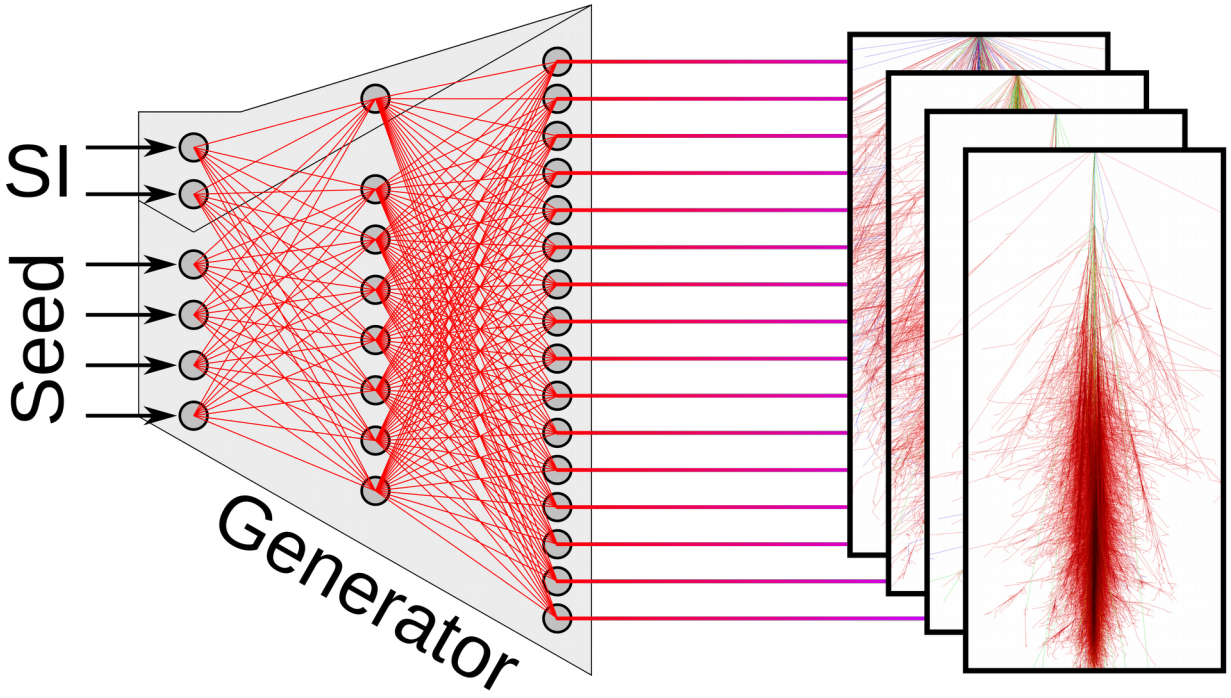
Training: Result



- Train discriminator on real (1) and generated (0) data
- Train generator to outsmart the discriminator

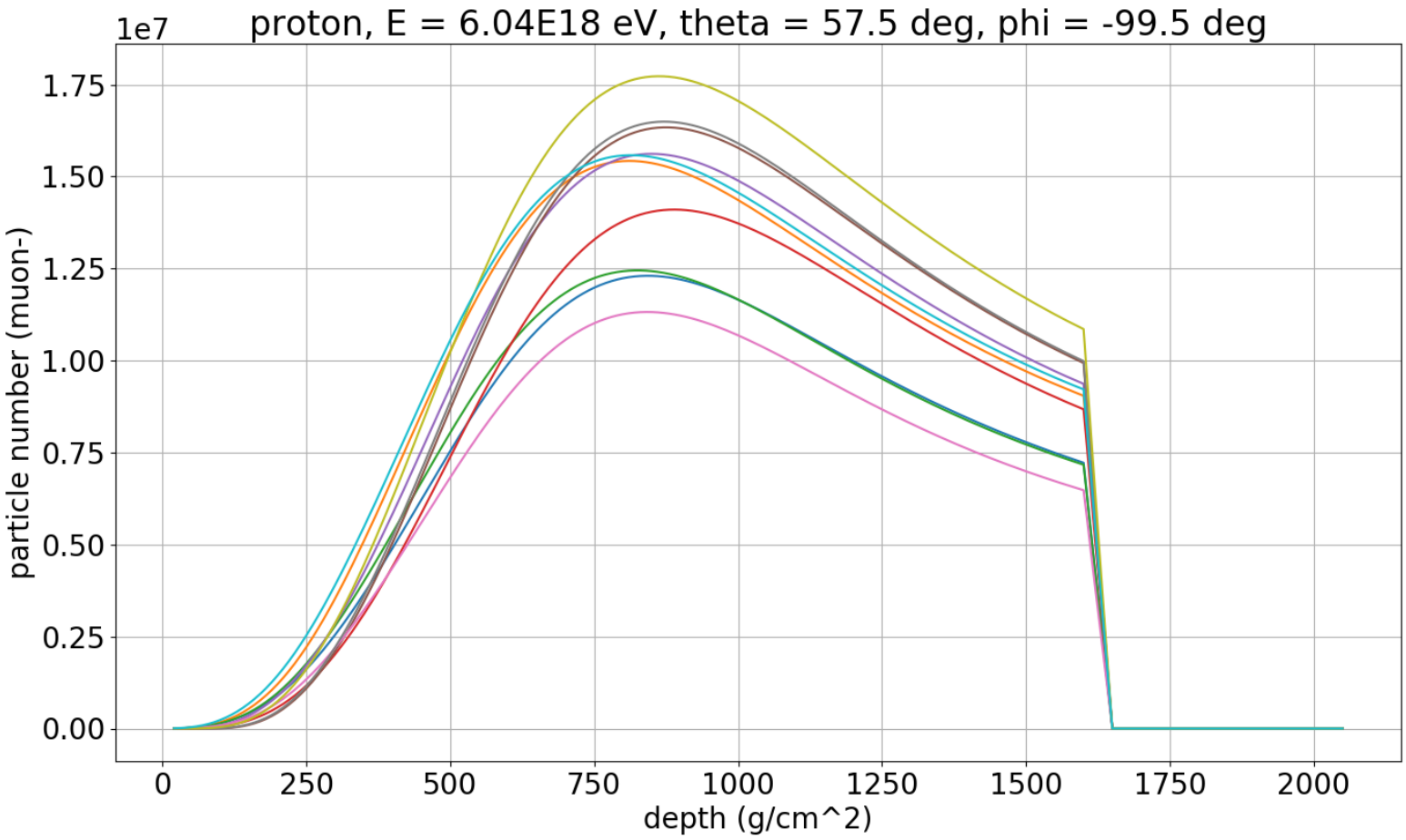
First Test (CONEX)

- CONEX: Hybrid Extenisve Air Shower Simulation
  - first: Monte Carlo until energy threshold (3D)
  - then: cascade equation solver (1D)
  - provides longitudinal profile only
  - runtime: seconds – minutes

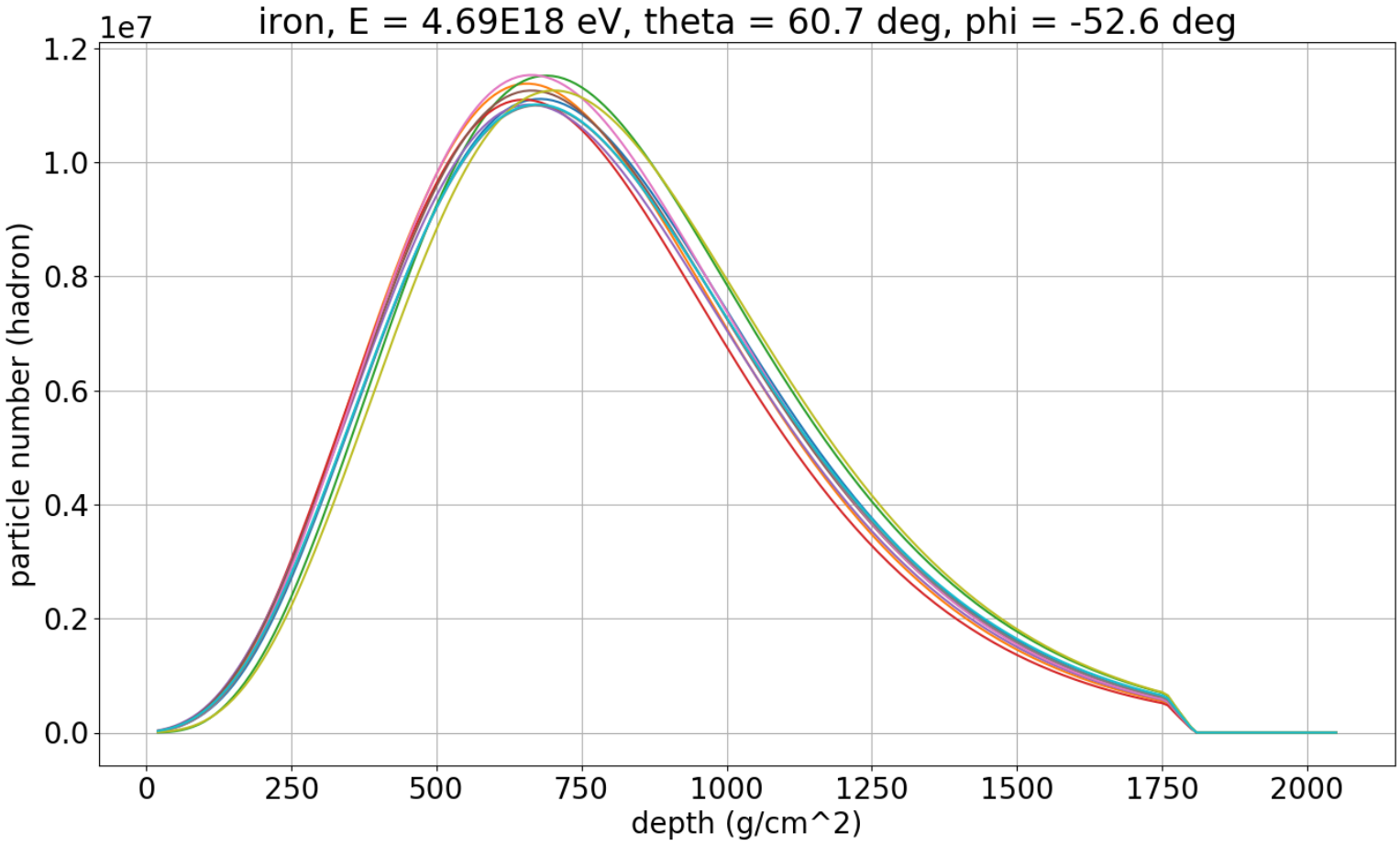
- Configuration:
  - E = 1E17 ... 1E19 eV
  - Zenith = 0 ... 65 deg
  - Azimuth = -180 ... 180 deg

- Generated ~187k datapoints

Shower-to-Shower Fluctuations



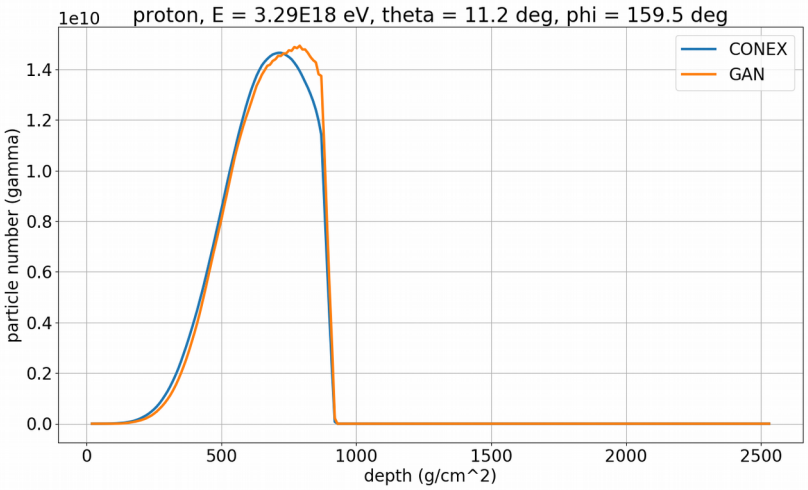
Shower-to-Shower Fluctuations

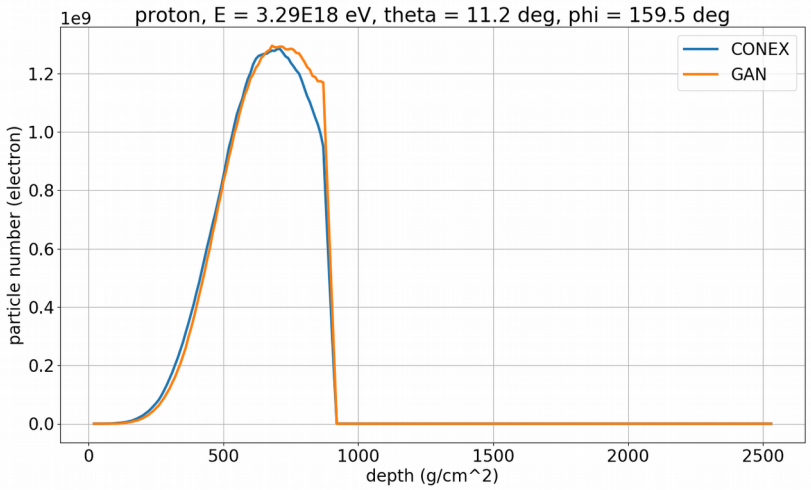


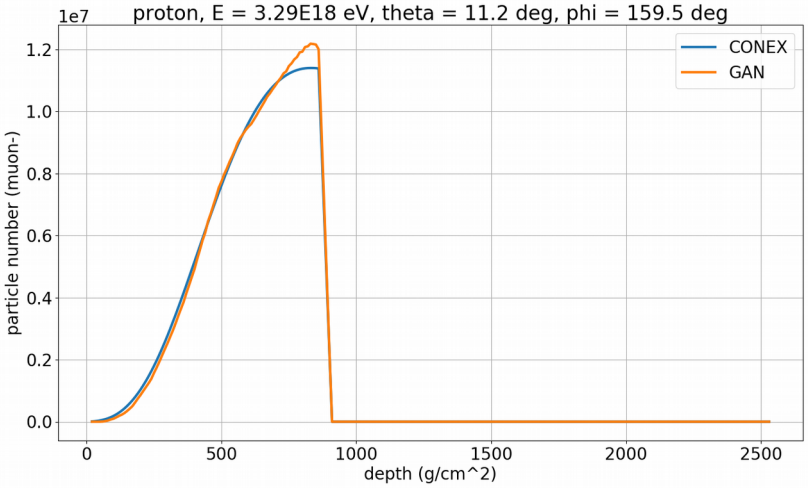
(conditional) WGAN

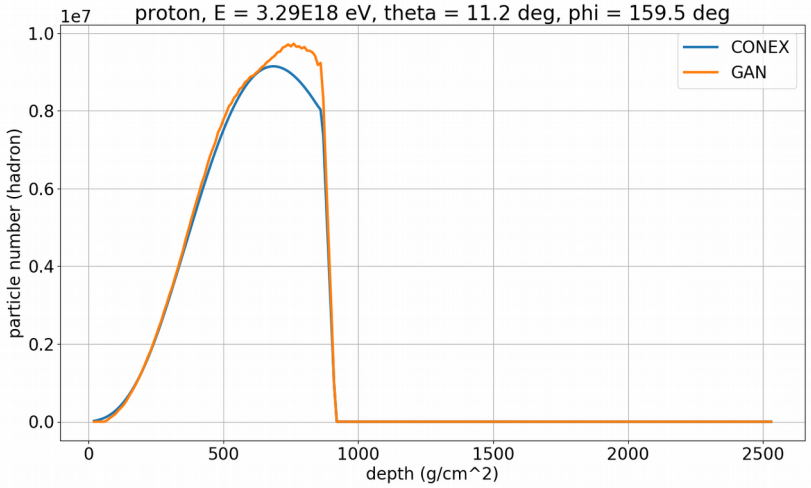
- Generator:
  - 2x Dense
  - 3x TransposeConvolution + Convolution
  - Activation: ReLU
- Discriminator:
  - 1x Dense
  - 4x Convolution
  - 1x Dense
  - Activation: LeakyReLU
- Trainable parameters: 2.317.737

CONEX vs. GAN

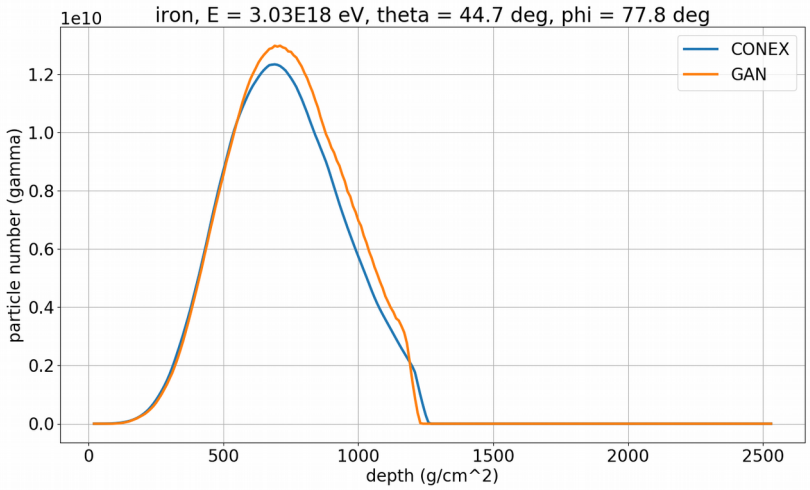

1e10
proton, E = 3.29E18 eV, theta = 11.2 deg, phi = 159.5 deg
CONEX
GAN
particle number (gamma)
depth (g/cm^2)

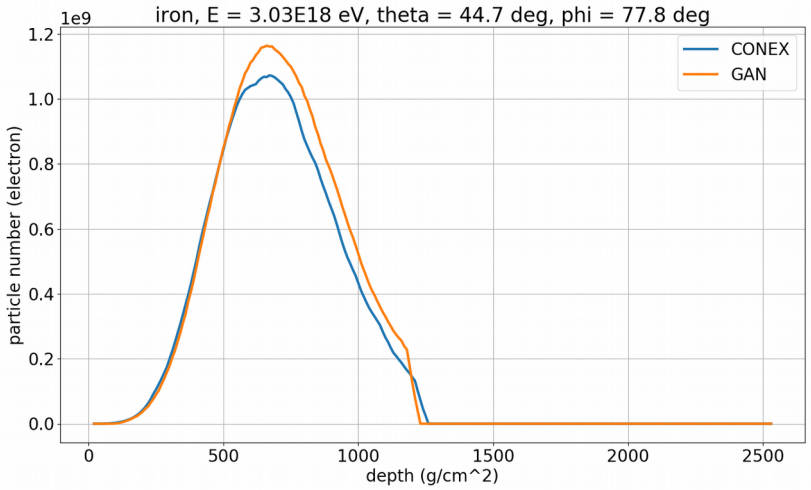

1e9
proton, E = 3.29E18 eV, theta = 11.2 deg, phi = 159.5 deg
CONEX
GAN
particle number (electron)
depth (g/cm^2)

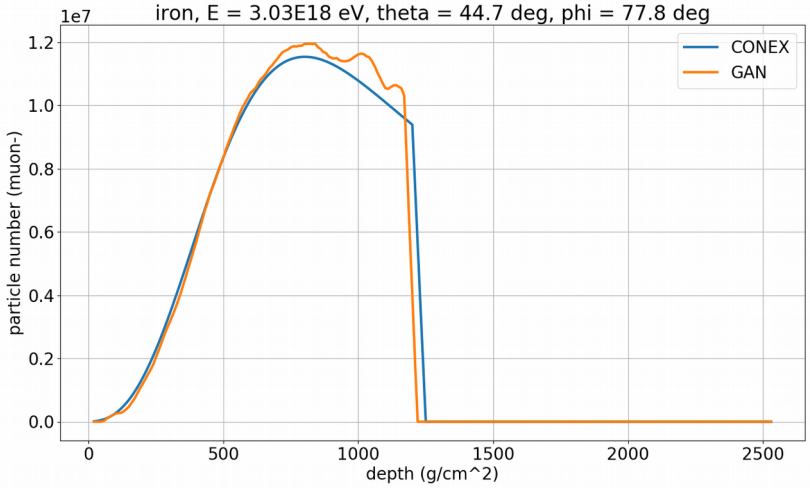

1e7
proton, E = 3.29E18 eV, theta = 11.2 deg, phi = 159.5 deg
CONEX
GAN
particle number (muon-)
depth (g/cm^2)

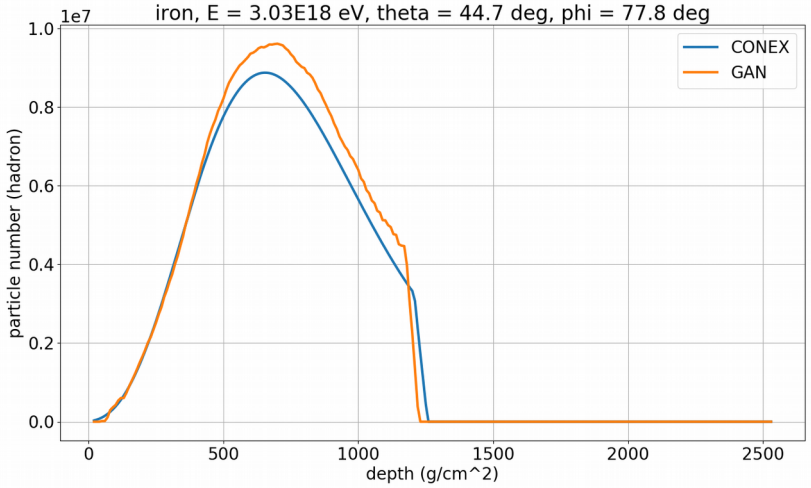

1e7
proton, E = 3.29E18 eV, theta = 11.2 deg, phi = 159.5 deg
CONEX
GAN
particle number (hadron)
depth (g/cm^2)

CONEX vs. GAN

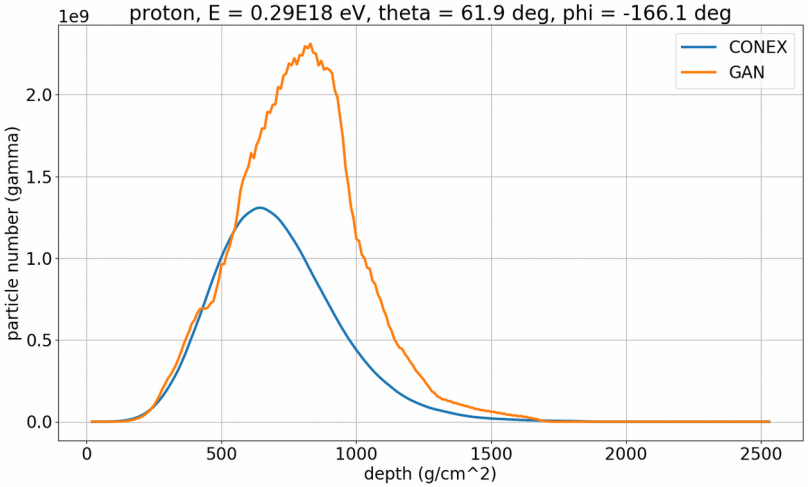

iron, E = 3.03E18 eV, theta = 44.7 deg, phi = 77.8 deg
1e10
particle number (gamma)
depth (g/cm^2)
CONEX
GAN

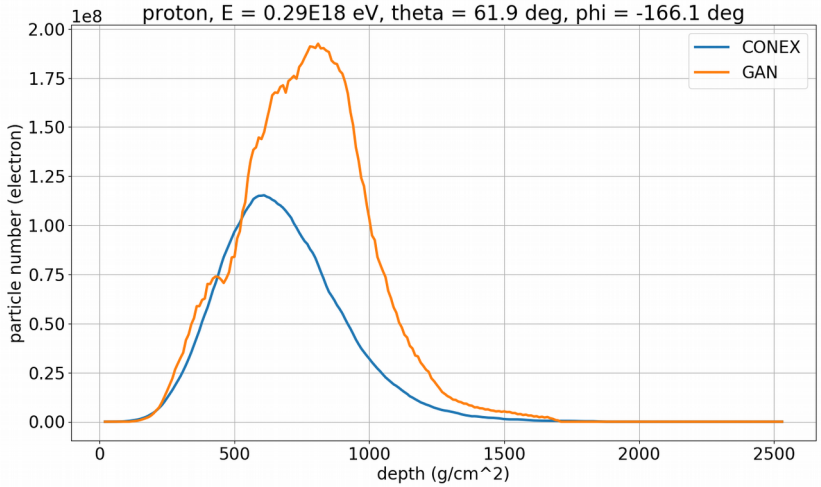

iron, E = 3.03E18 eV, theta = 44.7 deg, phi = 77.8 deg
1e9
particle number (electron)
depth (g/cm^2)
CONEX
GAN

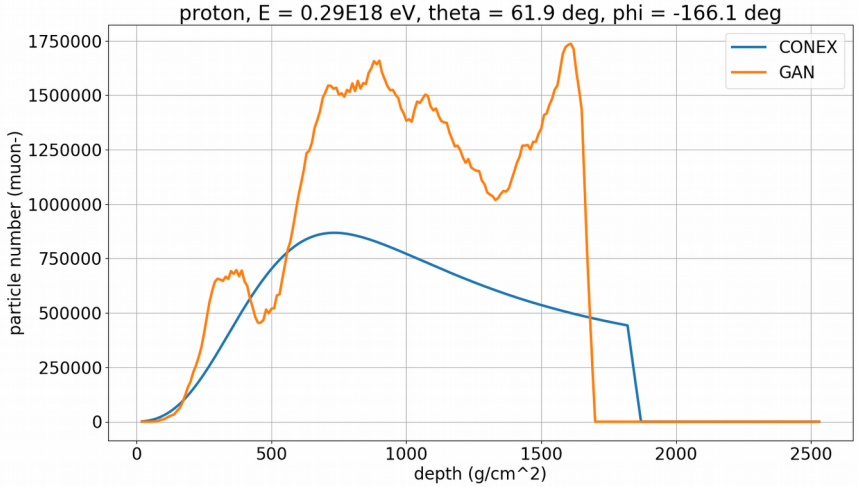

iron, E = 3.03E18 eV, theta = 44.7 deg, phi = 77.8 deg
1e7
particle number (muon-)
depth (g/cm^2)
CONEX
GAN

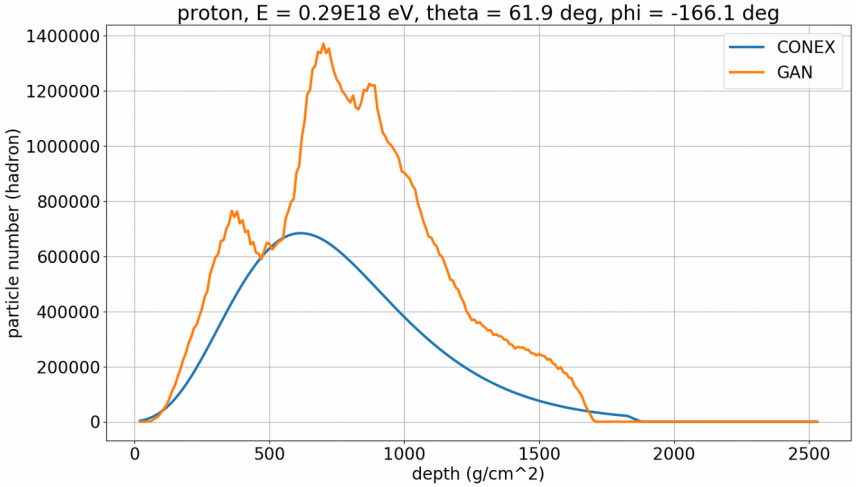

iron, E = 3.03E18 eV, theta = 44.7 deg, phi = 77.8 deg
1e7
particle number (hadron)
depth (g/cm^2)
CONEX
GAN

CONEX vs. GAN


proton, E = 0.29E18 eV, theta = 61.9 deg, phi = -166.1 deg
1e9
CONEX
GAN
particle number (gamma)
depth (g/cm^2)


proton, E = 0.29E18 eV, theta = 61.9 deg, phi = -166.1 deg
1e8
CONEX
GAN
particle number (electron)
depth (g/cm^2)

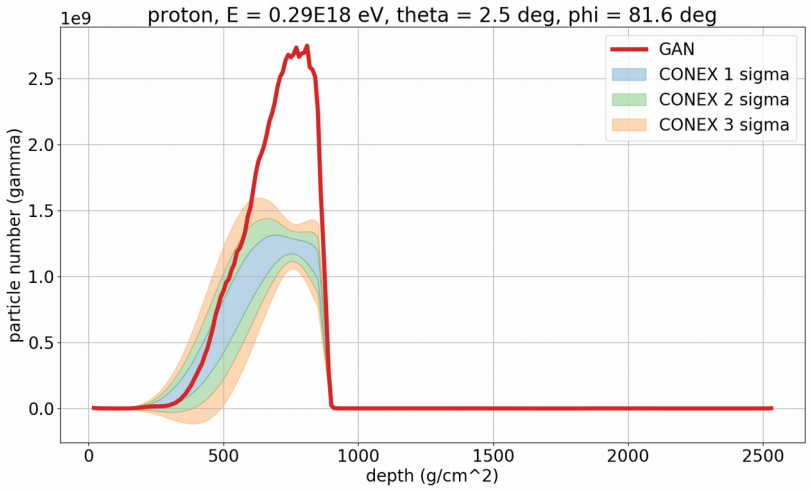

proton, E = 0.29E18 eV, theta = 61.9 deg, phi = -166.1 deg
CONEX
GAN
particle number (muon-)
depth (g/cm^2)

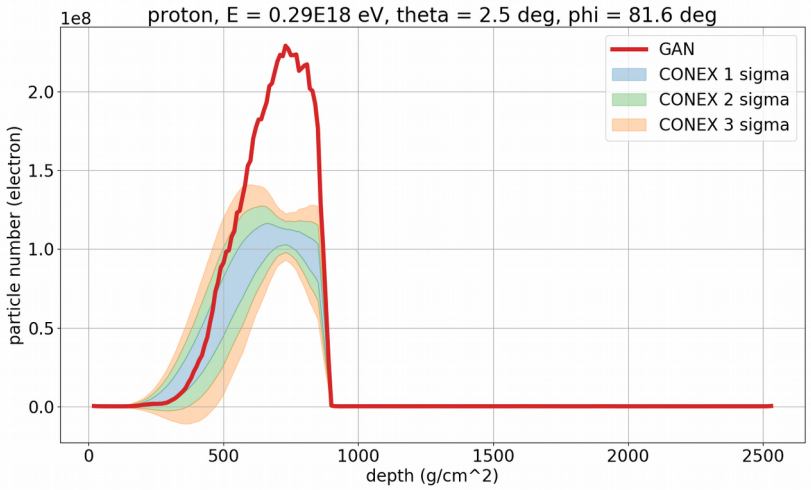

proton, E = 0.29E18 eV, theta = 61.9 deg, phi = -166.1 deg
CONEX
GAN
particle number (hadron)
depth (g/cm^2)

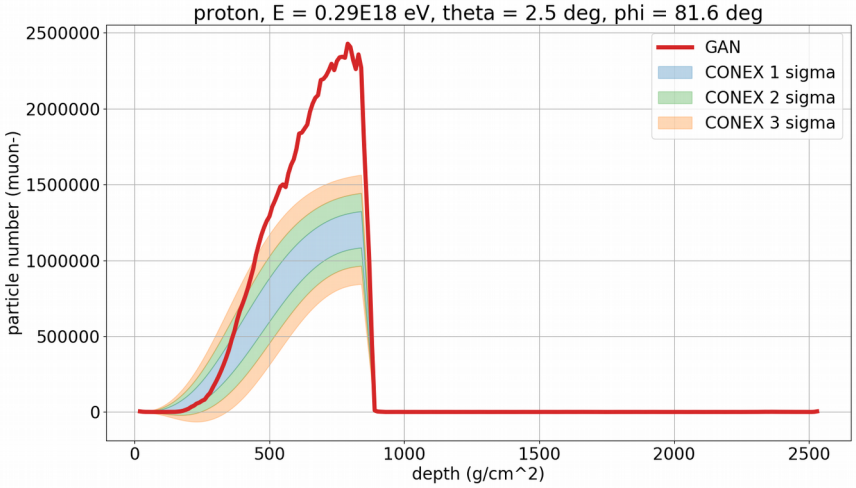
(conditional) WGAN: 2nd attempt

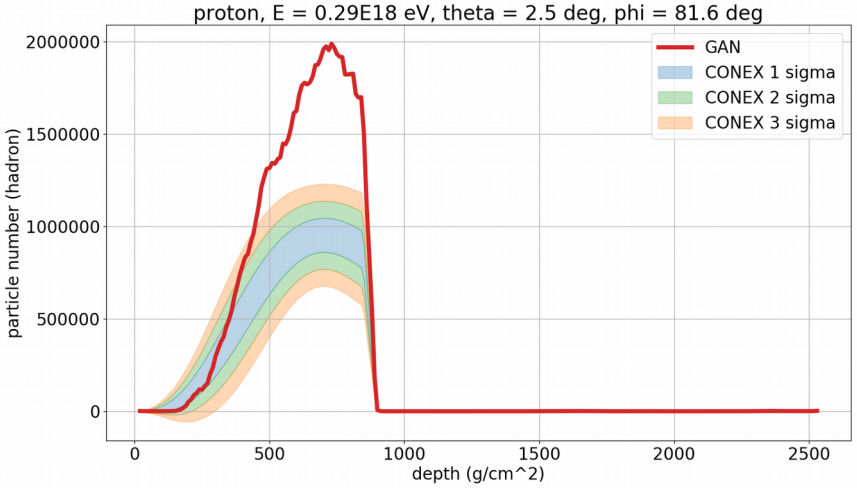
- Generator:
  - 5x Dense (+3)
  - 5x TransposeConvolution + Convolution (+2)
  - Activation: tanh
- Discriminator:
  - 3x Dense (+2)
  - 7x Convolution (+3)
  - 2x Dense (+1)
  - Activation: tanh
- Trainable parameters: 79.072.457

CONEX vs. GAN

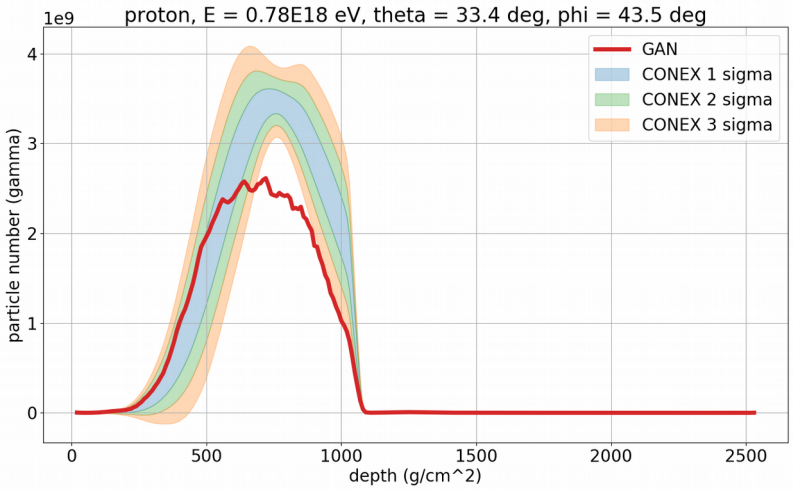

proton, E = 0.29E18 eV, theta = 2.5 deg, phi = 81.6 deg
1e9
particle number (gamma)
depth (g/cm^2)
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma

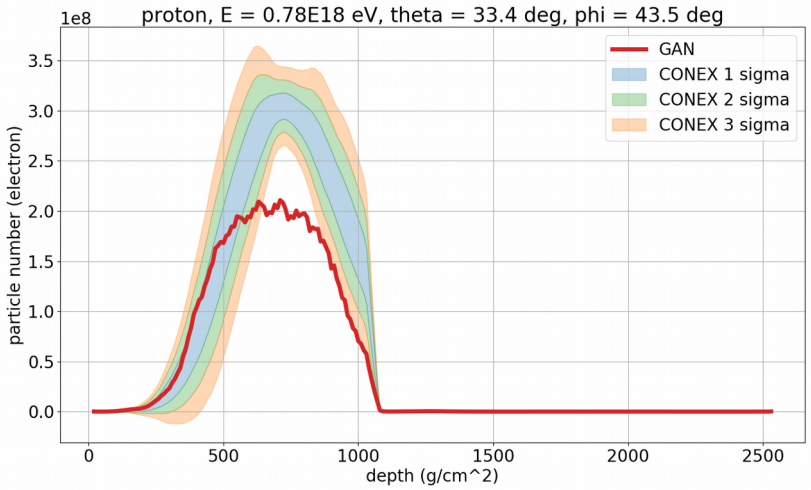

proton, E = 0.29E18 eV, theta = 2.5 deg, phi = 81.6 deg
1e8
particle number (electron)
depth (g/cm^2)
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma

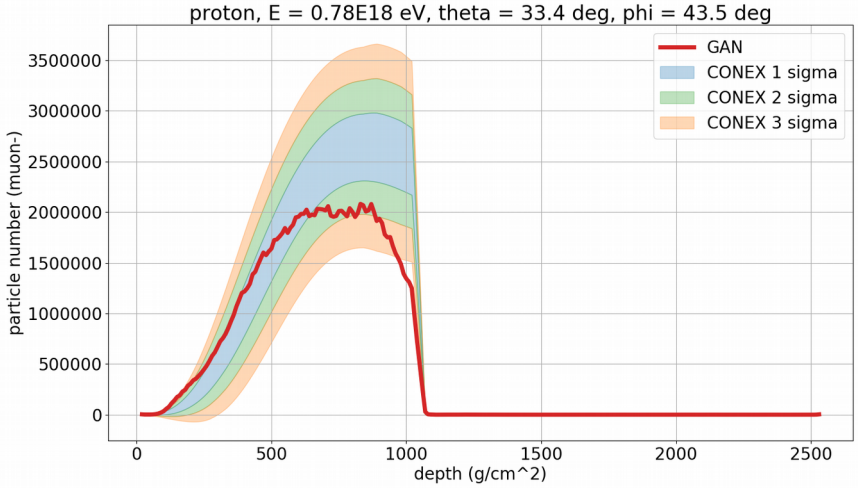

proton, E = 0.29E18 eV, theta = 2.5 deg, phi = 81.6 deg
particle number (muon-)
depth (g/cm^2)
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma

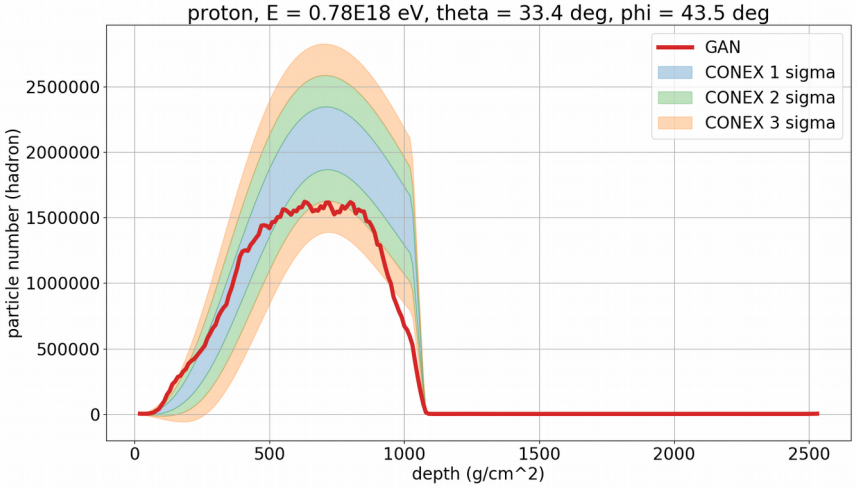

proton, E = 0.29E18 eV, theta = 2.5 deg, phi = 81.6 deg
particle number (hadron)
depth (g/cm^2)
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma

CONEX vs. GAN

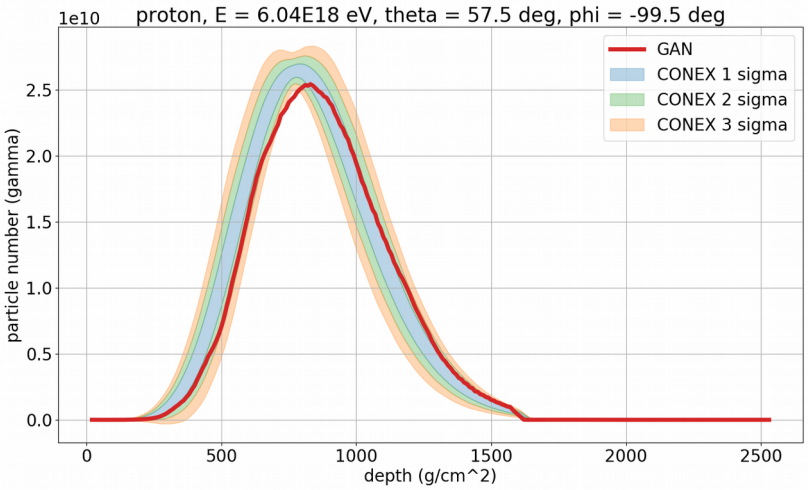

proton, E = 0.78E18 eV, theta = 33.4 deg, phi = 43.5 deg
1e9
particle number (gamma)
depth (g/cm^2)
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma

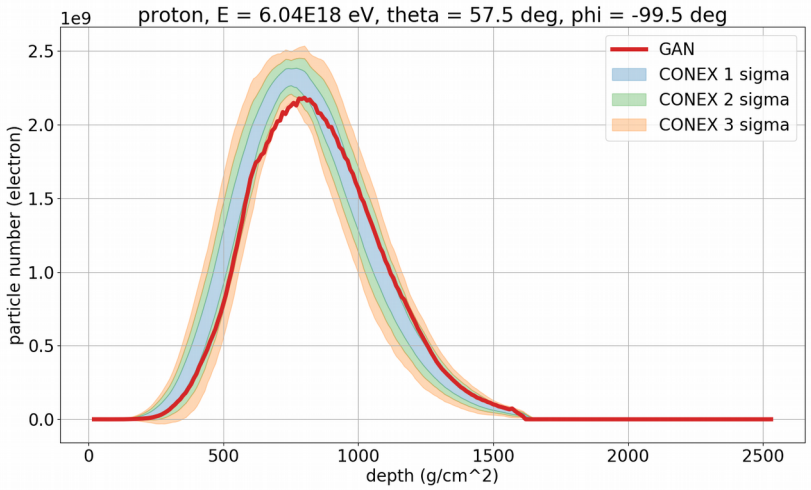

proton, E = 0.78E18 eV, theta = 33.4 deg, phi = 43.5 deg
1e8
particle number (electron)
depth (g/cm^2)
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma

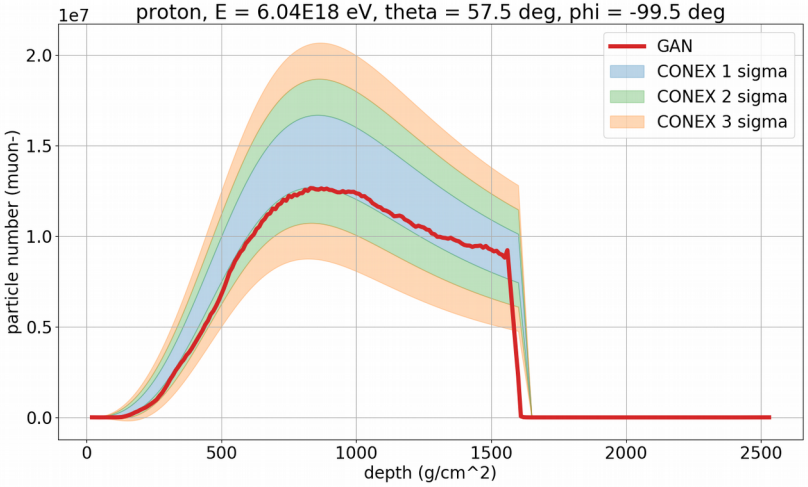

proton, E = 0.78E18 eV, theta = 33.4 deg, phi = 43.5 deg
particle number (muon-)
depth (g/cm^2)
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma

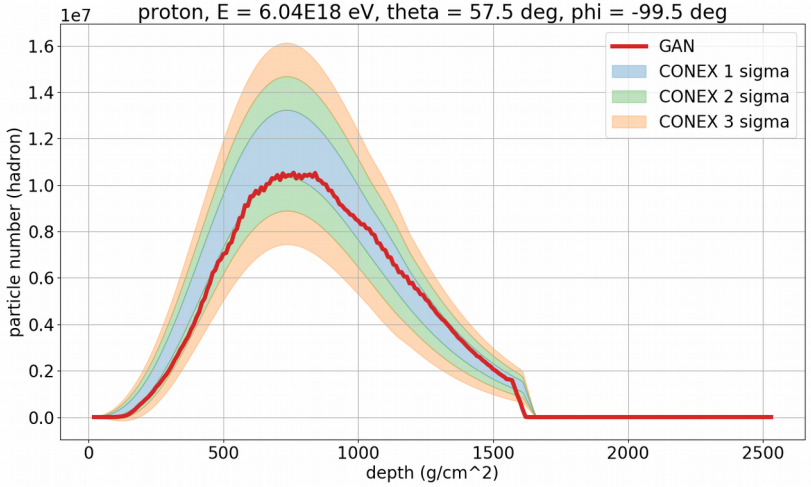

proton, E = 0.78E18 eV, theta = 33.4 deg, phi = 43.5 deg
particle number (hadron)
depth (g/cm^2)
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma

CONEX vs. GAN

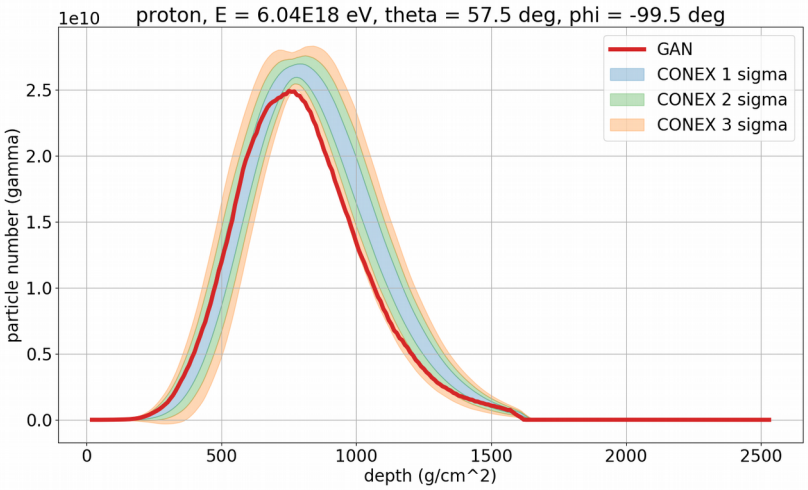

1e10
proton, E = 6.04E18 eV, theta = 57.5 deg, phi = -99.5 deg
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma
particle number (gamma)
depth (g/cm^2)

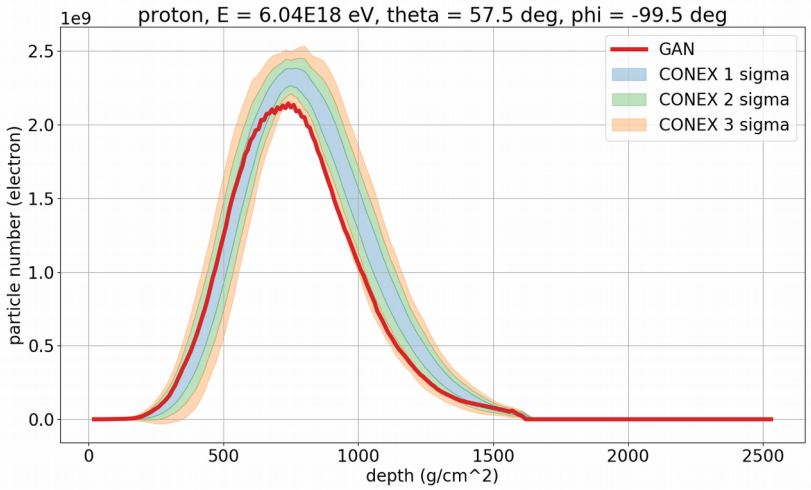

1e9
proton, E = 6.04E18 eV, theta = 57.5 deg, phi = -99.5 deg
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma
particle number (electron)
depth (g/cm^2)

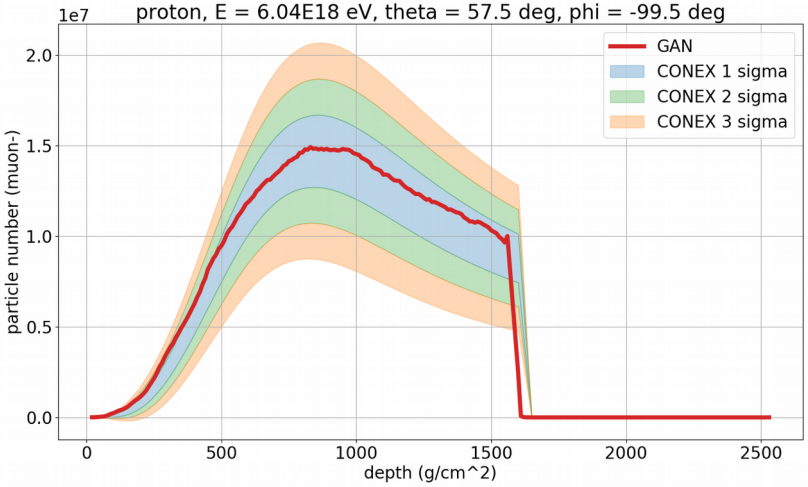

1e7
proton, E = 6.04E18 eV, theta = 57.5 deg, phi = -99.5 deg
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma
particle number (muon-)
depth (g/cm^2)

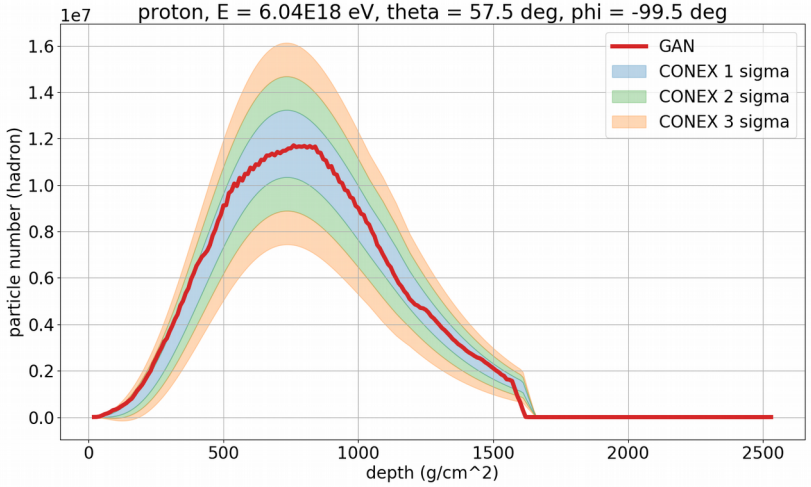

1e7
proton, E = 6.04E18 eV, theta = 57.5 deg, phi = -99.5 deg
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma
particle number (hadron)
depth (g/cm^2)

CONEX vs. GAN


1e10
proton, E = 6.04E18 eV, theta = 57.5 deg, phi = -99.5 deg
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma
particle number (gamma)
depth (g/cm^2)


1e9
proton, E = 6.04E18 eV, theta = 57.5 deg, phi = -99.5 deg
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma
particle number (electron)
depth (g/cm^2)


1e7
proton, E = 6.04E18 eV, theta = 57.5 deg, phi = -99.5 deg
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma
particle number (muon-)
depth (g/cm^2)


1e7
proton, E = 6.04E18 eV, theta = 57.5 deg, phi = -99.5 deg
GAN
CONEX 1 sigma
CONEX 2 sigma
CONEX 3 sigma
particle number (hadron)
depth (g/cm^2)

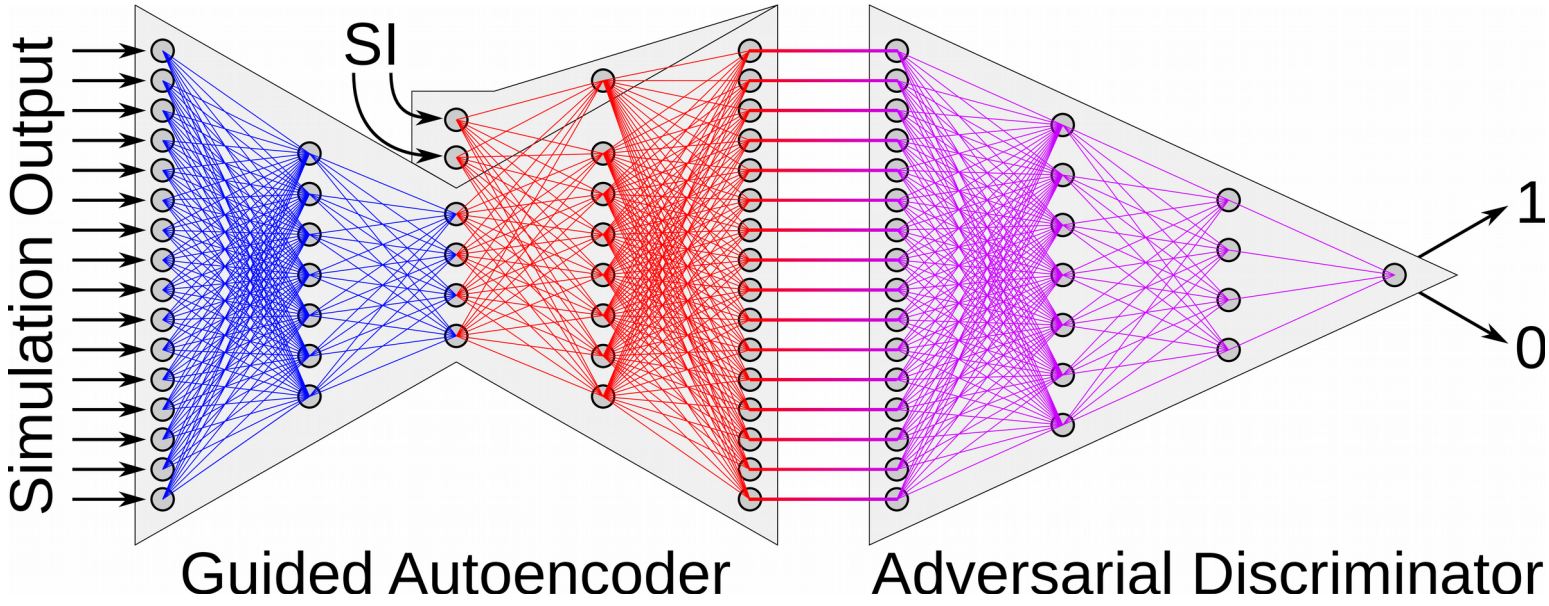
What‘s next?

- Fix it (oversampling, architecture, constrainers, ...)
- (Meta)parameter tests
- Test adversarial vulnerability
- Template matching/reconstruction
- Refining with data

Backup

Fast Implicit Simulation Heuristic (FISH)

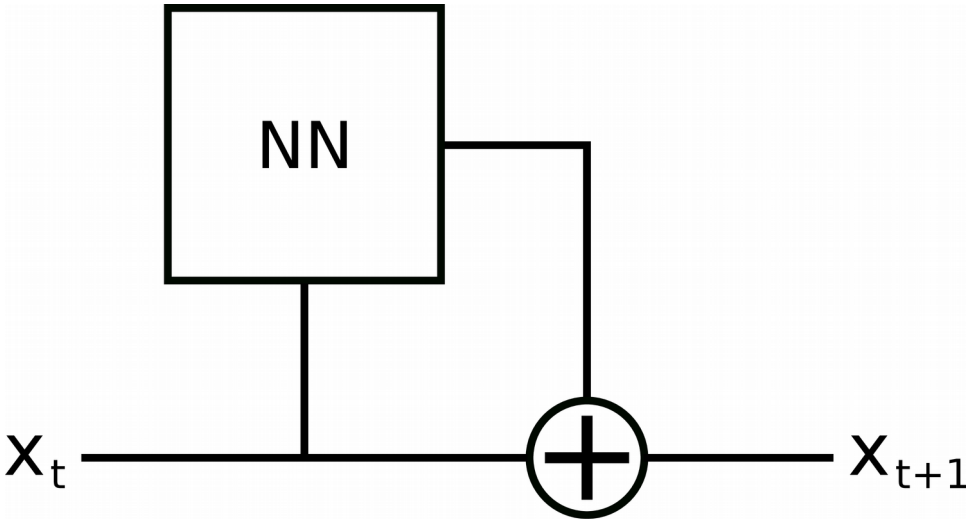
- Autoencoder with Adversarial Metric



- Simulation Input (SI) can be extended with meta-parameters
- Discriminator can be refined with real measurements

Adjustable Accuracy [2]

- ResNet



- Translate to ordinary differential equation (ODE)

$$x_{t+1} = x_t + f(x_t, \theta_t) \quad \Rightarrow \quad \frac{dx(t)}{dt} = f(x(t), t, \theta)$$

- Solve with standard ODE solver

- Adapt solver accuracy on the fly (training: high, inference: low)

References

- Title picture:
  Karlsruhe Castle - Meph666 [CC BY-SA 3.0]
  https://commons.wikimedia.org/wiki/File:Karlsruhe-Schloss-meph666-2005-Apr-22.jpg

- Backup picture:
  Photo by Anthony from Pexels

- [1] CORSIKA 7: https://www.ikp.kit.edu/corsika/

- [2] „Neural Ordinary Differential Equations“ - Ricky T. Q. Chen, Yulia Rubanova, Jesse Bettencourt, David Duvenaud – arXiv: 1806.07366