Research Training Group
Physics of the Heaviest
Particles at the LHC

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SR-GAN for SR-gamma: super resolution of photon calorimeter images at collider experiments

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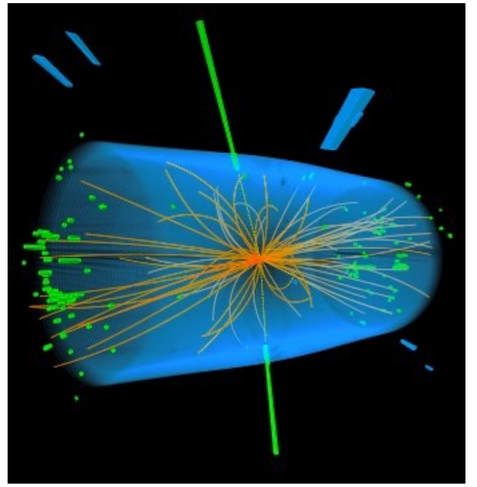
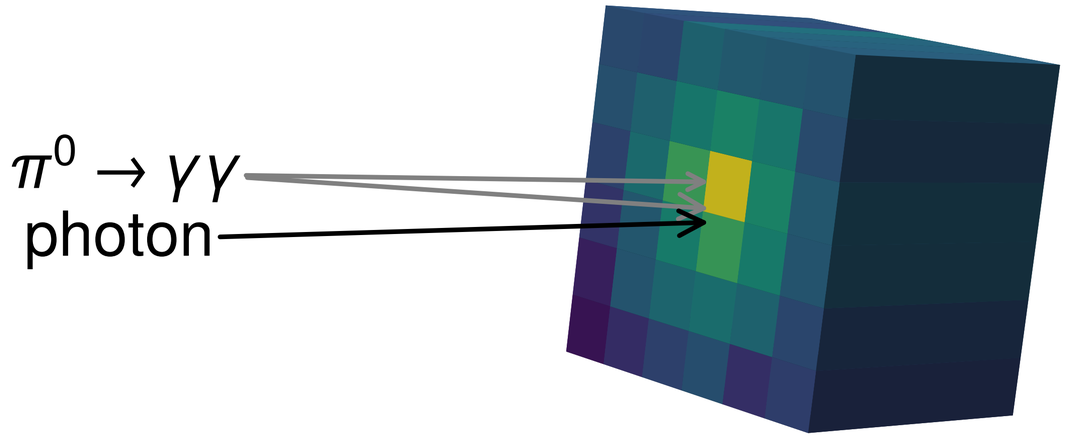
Photons at collider experiments

- Photons are important at the LHC
  - E.g. $H \rightarrow \gamma\gamma$: clean channel to study the Higgs boson
- Signature: cluster of energy depositions in the electromagnetic calorimeter (ECAL)
- Rejecting backgrounds is crucial and challenging
  - Main source: collimated photons from Lorentz-boosted $\pi^0 \rightarrow \gamma\gamma$ decays
- Granularity of ECAL is key feature for photon localisation and background suppression



[cds.cern.ch/record/2736135/]



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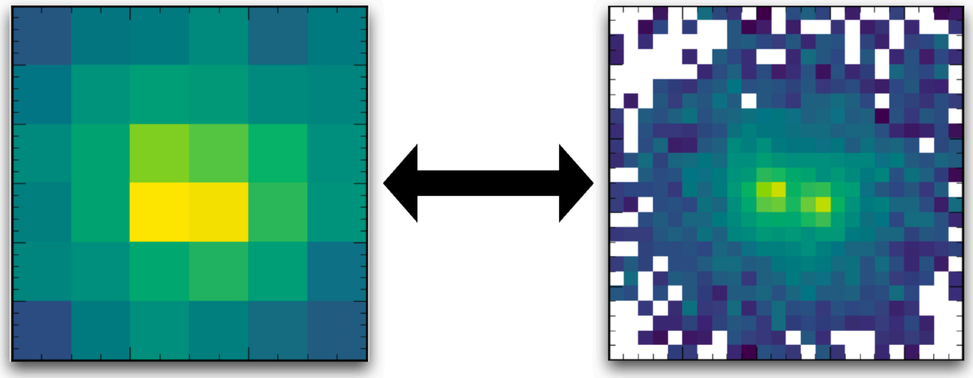
Super resolution

- Super-resolution **(SR)**: estimate of a high resolution **(HR)** image from a single low resolution **(LR)** image
- Intensively studied in the field of image processing
- Has been studied in the context of pion reconstruction, jet substructure, and refinement of fast simulations [2003.08863], [2012.11944], [2308.11700]

Can we improve photon reconstruction by learning from the simulation of a better calorimeter?



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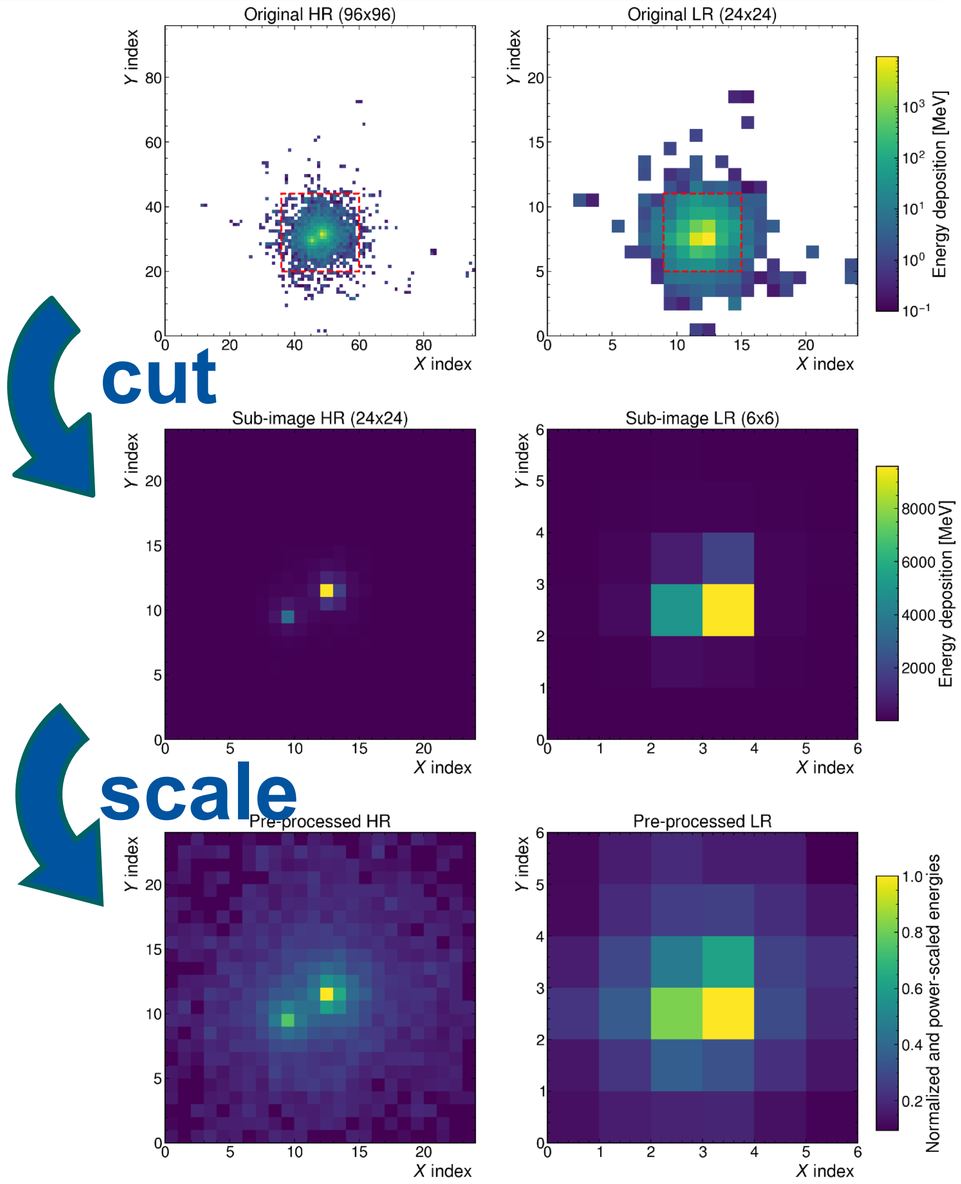
Simulated samples & pre-processing

- Geant4 simulation of photons and $\pi^0 \rightarrow \gamma\gamma$ with 20 GeV and 50 GeV particle gun
- Simplified $PbWO_4$ ECAL inspired by CMS barrel
  - HR ECAL has 4×4 more crystals
- Simulation of LR-HR calorimeter image pairs
- Selection of high-energy part
- Normalisation and power-scaling: $E \rightarrow \left(\frac{E}{E_{\text{tot}}} \right)^{0.3}$



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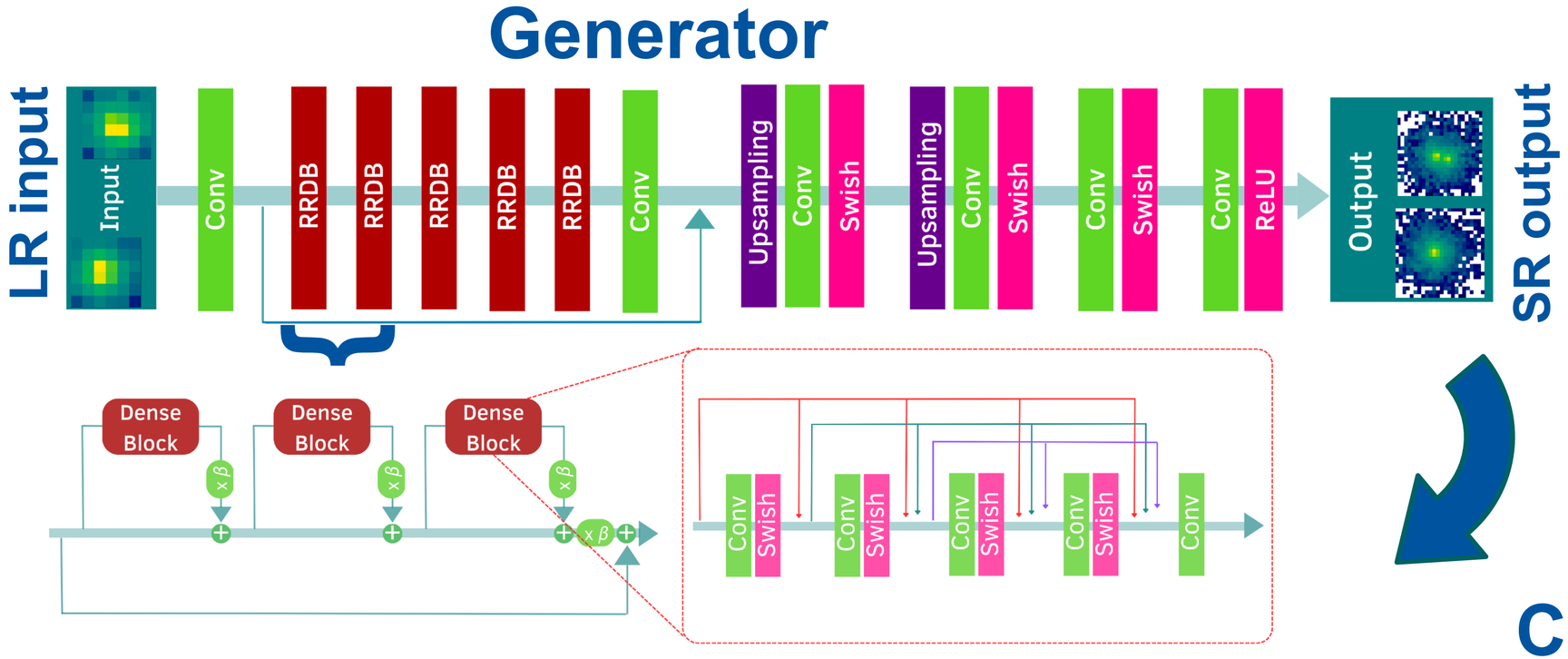
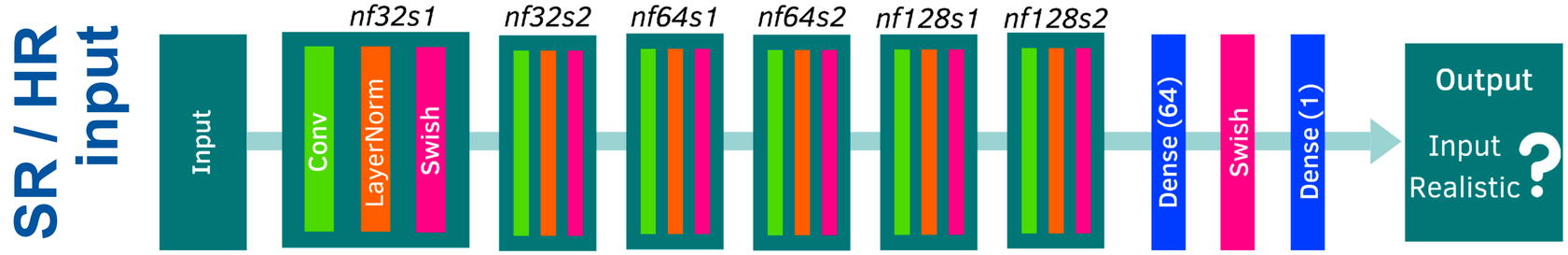
Model architecture

- Model inspired by Enhanced Super-Resolution GAN (ESRGAN) [1809.00219]
- Trained using Wasserstein loss



- Adversarial training of generator and critic leads to increasingly realistic outputs

- Fundamental building block: residual-in-residual dense block (RRDB)



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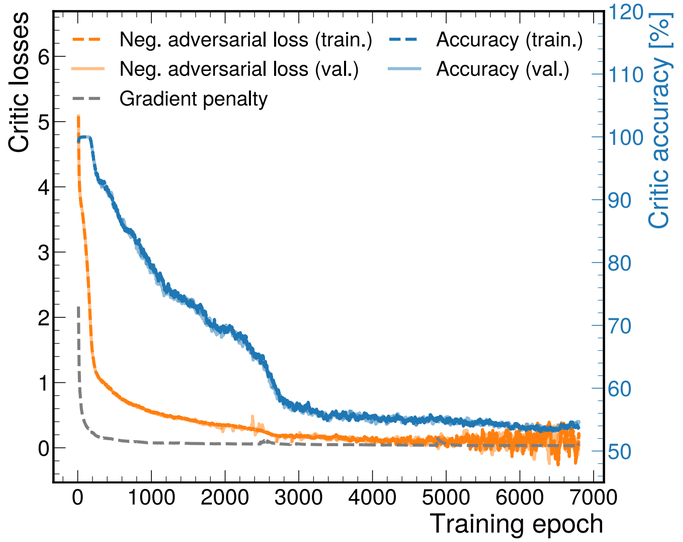
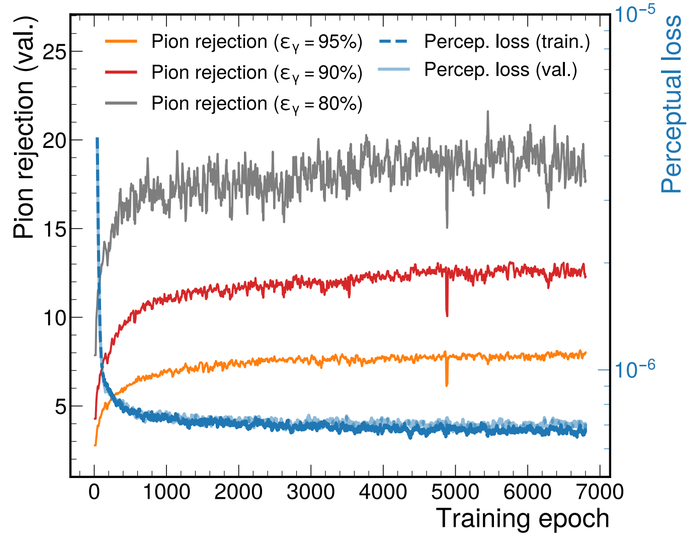
Network training

- Training dataset: 100k photon and 100k pion examples
- Improved training on 2-classes dataset by adding novel, physics-inspired perceptual loss to GAN training
  - Using features Φ extracted from pre-trained CNN:

$$\mathscr{L}_{\text{per}} \propto \left(\Phi(\text{HR}) - \Phi(\text{SR})\right)^2$$ [1603.08155]

  - CNN trained on our HR images to separate photons from pions
- One model for each simulated particle energy as first step
  - Preliminary studies show same architecture also successful on continuous energy spectrum





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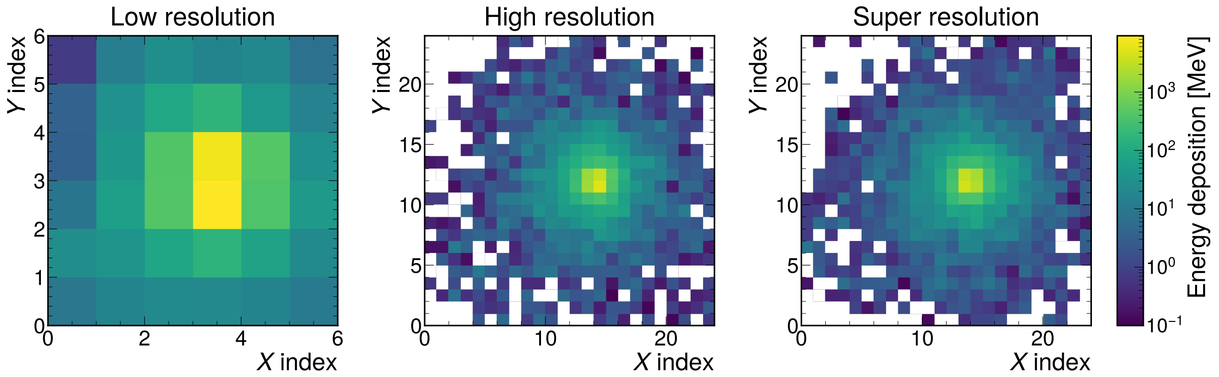
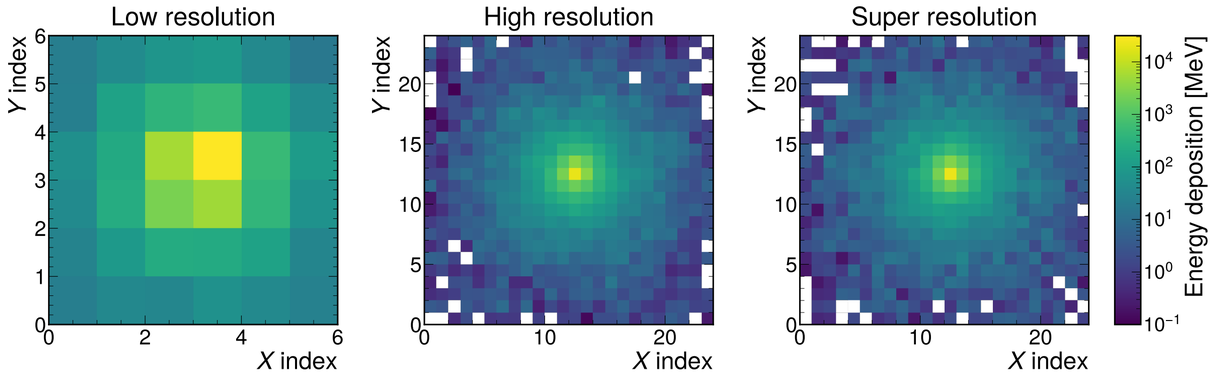
SR image examples

Photon examples

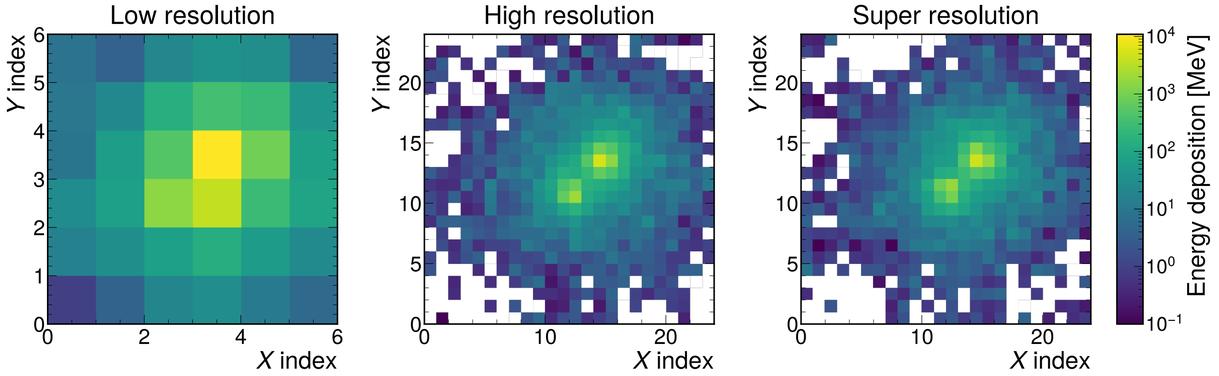
20 GeV

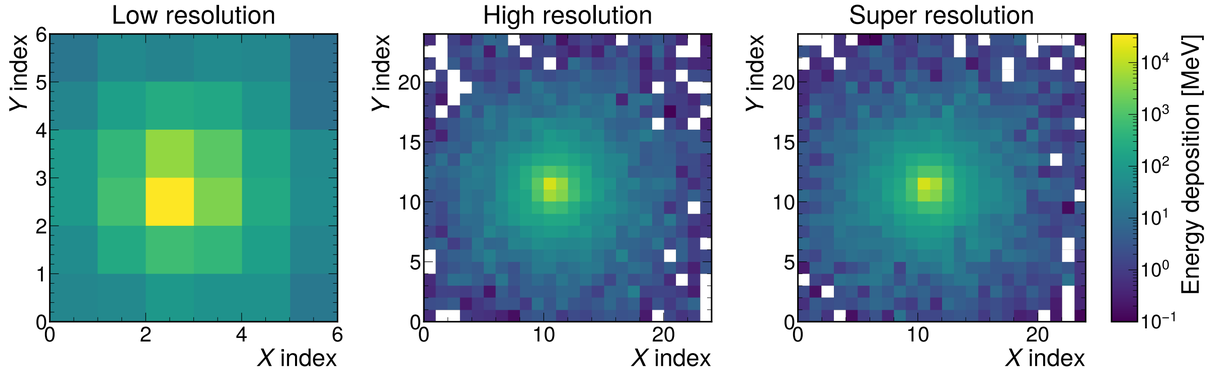


50 GeV



Pion examples





- Convincing quality of SR images
- Networks generate details which are not obvious from LR images by eye

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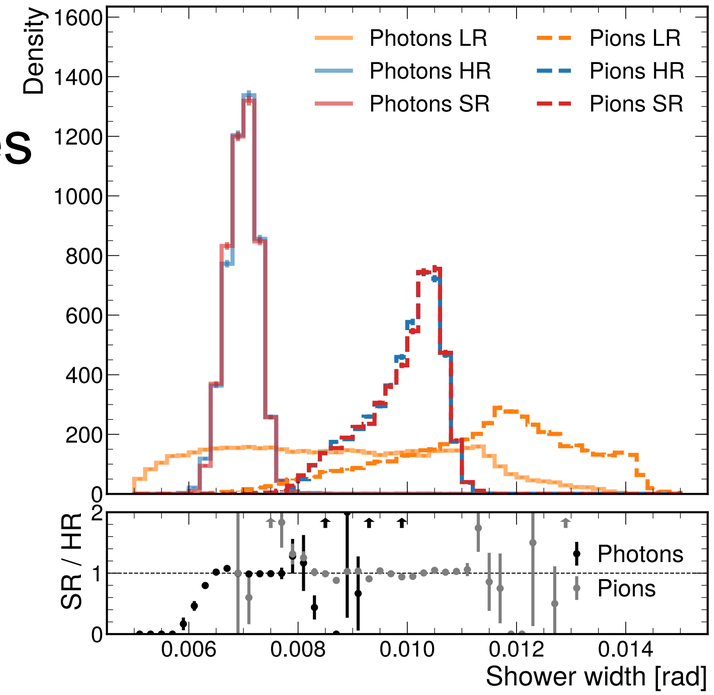
Shower properties

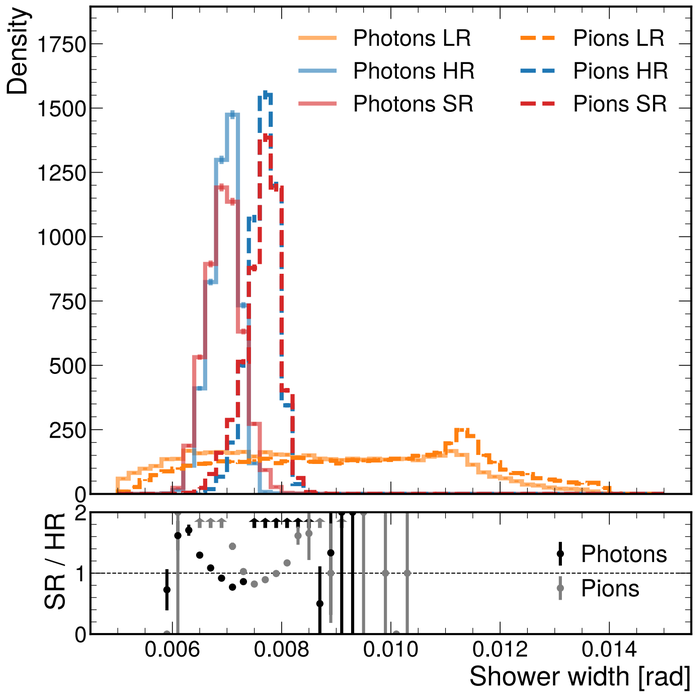
- Width as example of a shower-shape variable considered at LHC experiments
  - Discriminative features for background rejection, quality criteria for categorisations
- SR provides good approximation of HR distributions
  - Better for 20 GeV case due to stronger γ vs. $\pi^0 \rightarrow \gamma\gamma$ differences
- Separation between the classes strongly increased over LR

$$\text{Width}: \frac{\sum_i \Delta R_i E_i}{\sum_i E_i}$$

20 GeV

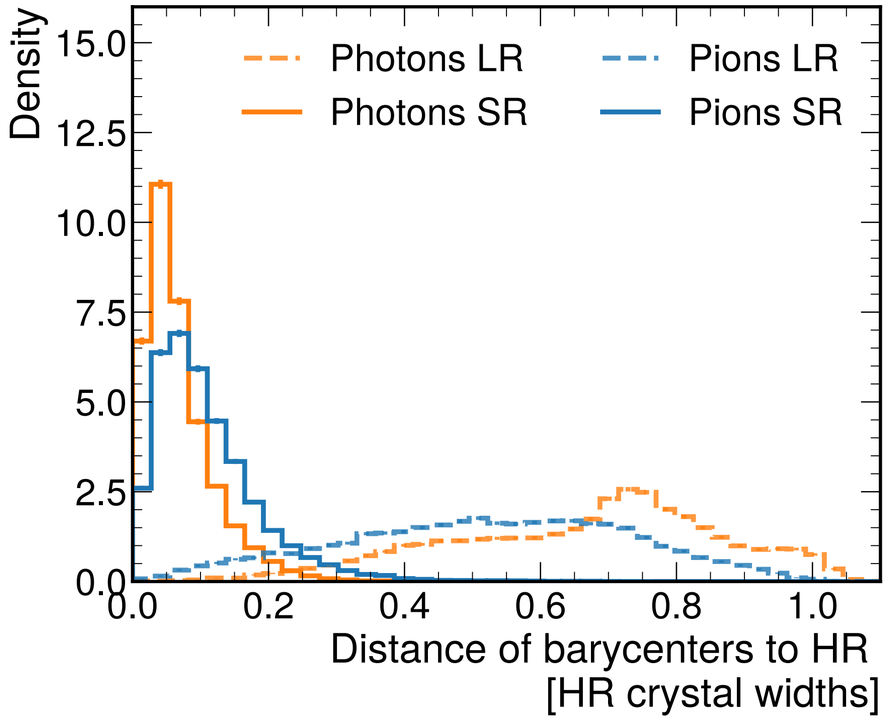


50 GeV



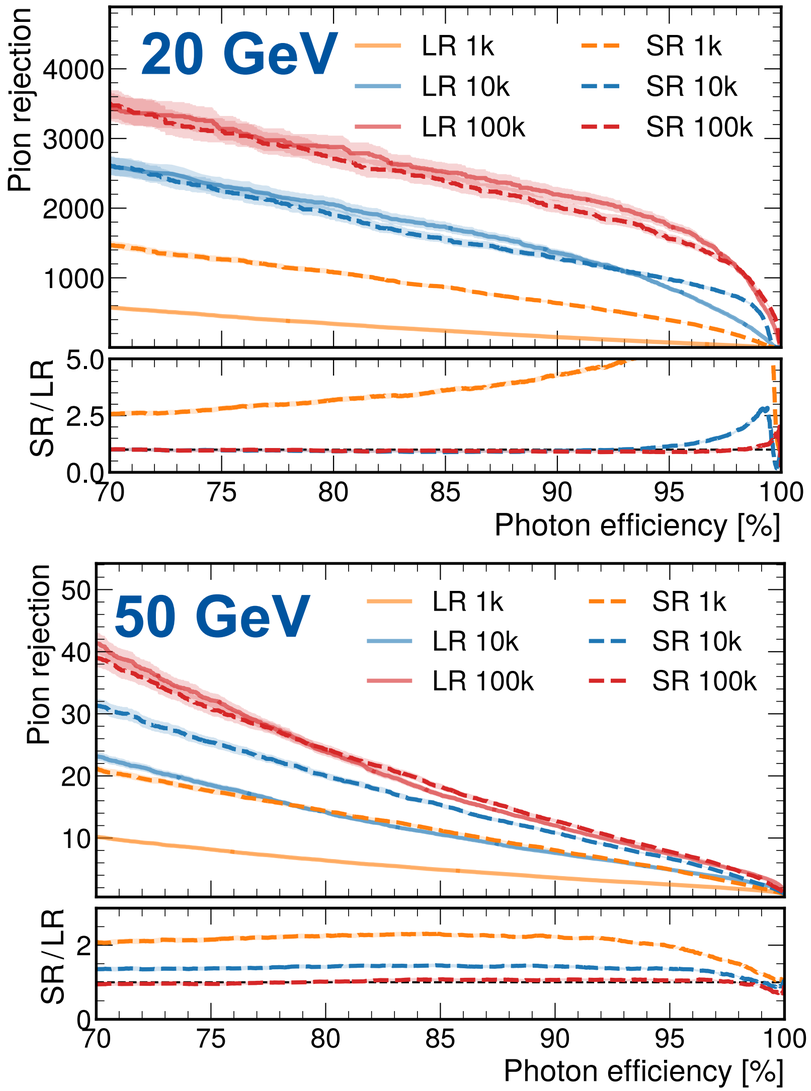
Photon localisation

- Photons localisation in experiments mostly calorimeter-based
  - No tracker signature in case of no $\gamma \rightarrow e^+e^-$ conversion
- Shower barycentre typically used for localisation
- Barycentres obtained from SR images are significantly closer to truth than from LR
  - ➡ Improved angular resolution
  - ➡ Possible improvement in mass resolution for diphoton events as $H \rightarrow \gamma\gamma$



Impact on identification algorithms

- Training of CNNs to separate photons from pions, either using LR or SR inputs
- Simple structure, same width and depth for LR and SR
- Similar performance when using large training datasets
- Strong improvements when training on small samples
  - Photon ID: typically limited background statistics



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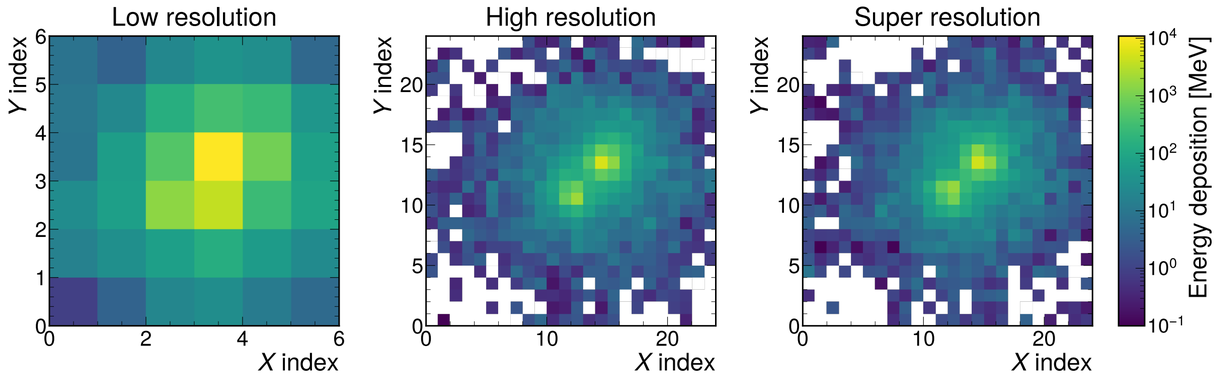
Conclusions

- Super resolution applied to photon calorimetry
- Adapted ESRGAN architecture, enhanced with physics-inspired perceptual loss
- Improved reconstruction of photons!
  - Localisation of barycentres
  - Shower-shape reconstruction



- Classifier training on SR images improves over LR for small training samples
- Application of particle-gun-based SR on full collider events to be studied
- Reference: Eur. Phys. J. C 83 (2023) 1001

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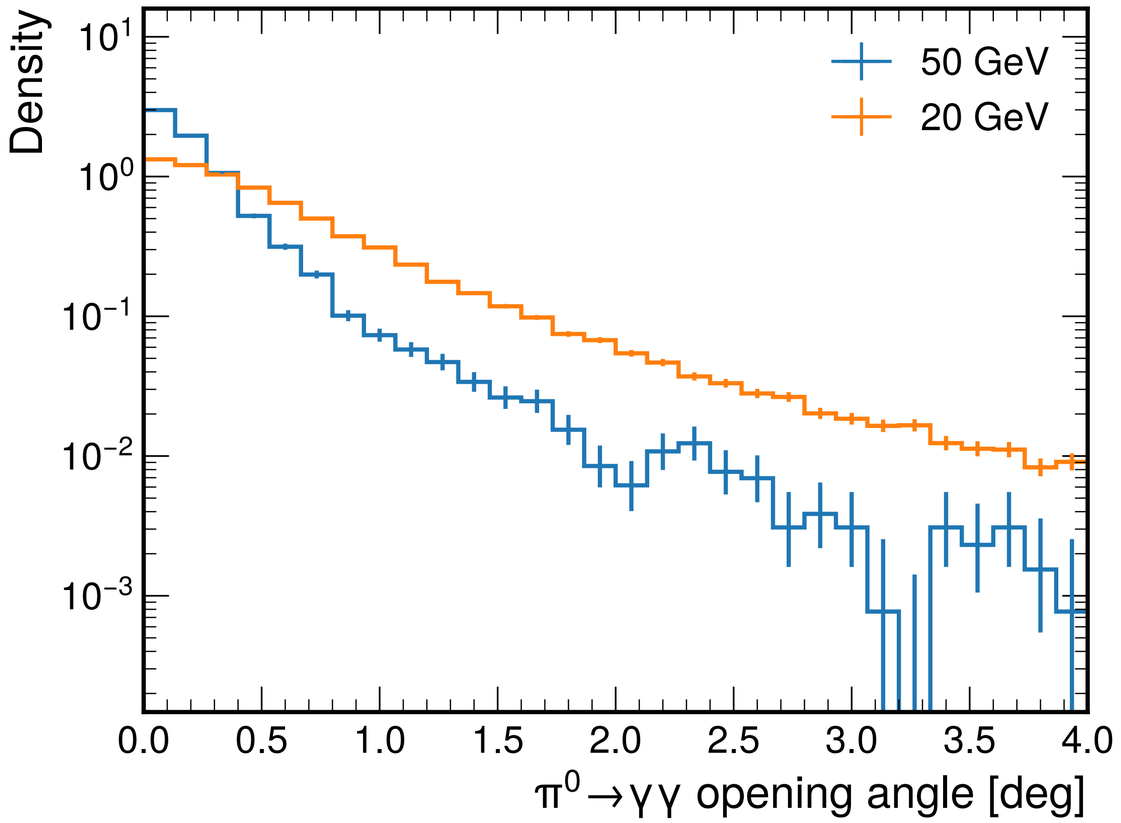
Backup

Pion energies



Network training

- Known issue: GANs hard to train
- Training leads to smooth average images, no checkerboard artefacts
- Epoch with best agreement in width distributions selected