From pixel detectors to a search for new physics

IMRPS Recruitment Workshop

Tiziano Pauletto, 24th July 2024

arxiv.org/abs/astro-ph/0504097

A brief story
My education and research experience

Education

- Obtained my bachelor's degree at the University of Trieste;
- Internship at INFN on the search for gamma counterparts to FRBs with Fermi LAT;
- BSc thesis on evaluation of PDF uncertainties in W boson's mass measurement at the LHC;
- Studying for my master's in Nuclear and Subnuclear Physics at the University of Trieste;
- Internship and MSc thesis on the characterization of a DNN for a search for new physics in $t\bar{t}$ final states in CMS.

Other research experiences

- DESY Summer Student 2023 in Hamburg: simulation of monolithic silicon pixel detectors;
- «Particle Physics to explore the Universe» 3 months INFN scholarship at CERN during this summer: working on track reconstruction in CMS's MTD and HGCAL.

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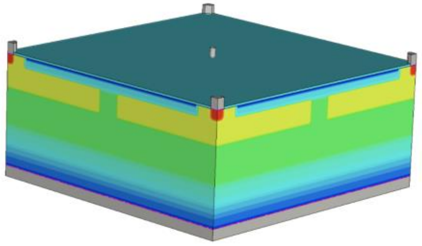
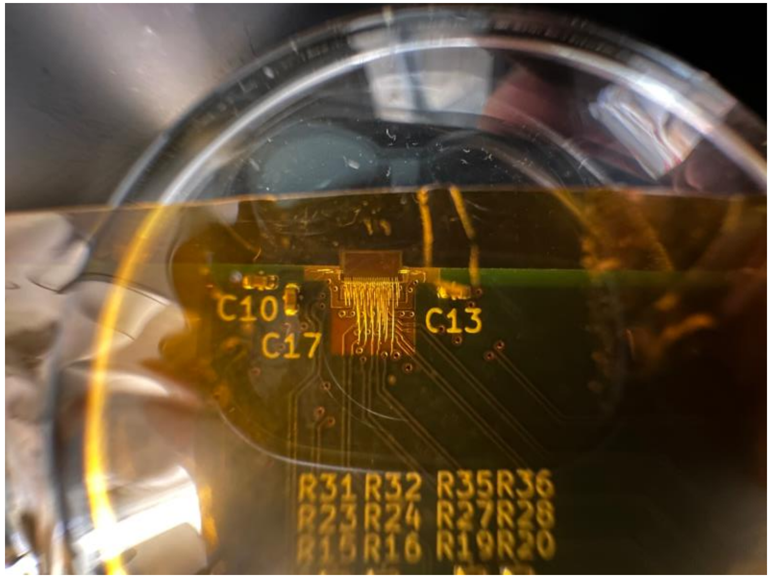
DESY Summer Student

Simulations of monolithic CMOS pixel detectors

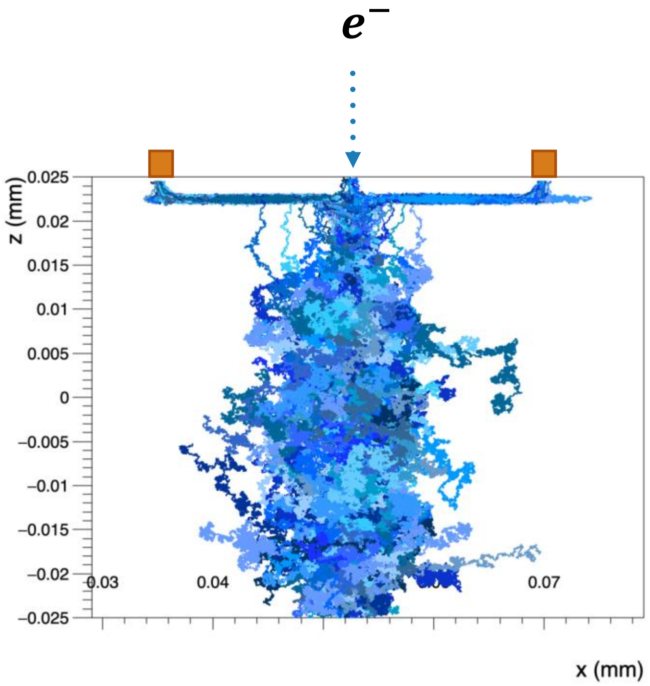
- **Worked in the DESY Tangerine and ATLAS groups;**
- **Simulations of detector prototypes for use in future colliders;**
- **Used AllPix-Squared (based on GEANT4) for simulations and ROOT for data analysis;**
- **Goal: optimizing the detector’s spatial resolution for future prototypes.**



A. Simancas



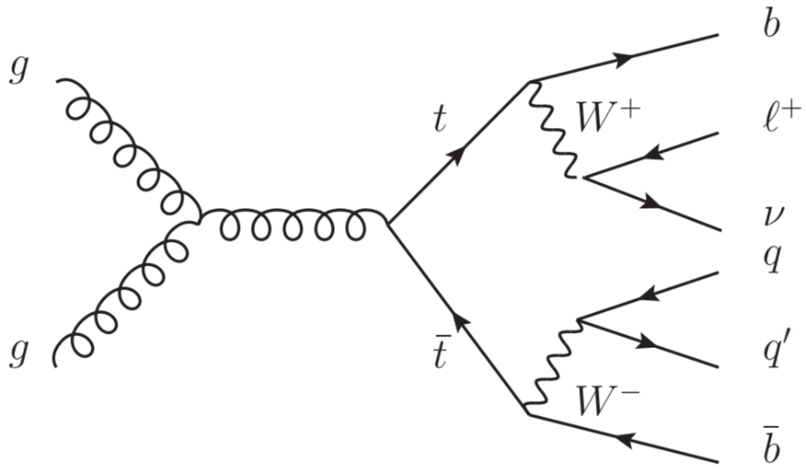
S. Spannagel

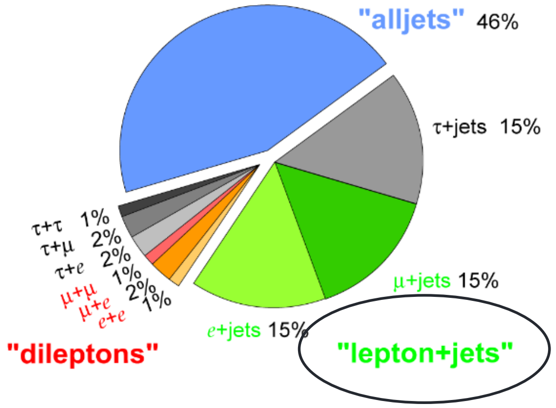


Master's thesis

Search for new physics in the top-antitop final state at CMS

- I'm working in a search for new physics of the CMS experiment;
- Analysis regarding Run II data collected at $\sqrt{s} = 13\ TeV$;
- Top quark pair final state studied in semileptonic decays;
- Two considered topologies: *resolved and boosted;*
- Resolved: isolated lepton and Ak4 jets;
- Boosted: no requirement of isolated lepton, larger (Ak8) jets;
- Considered signals: Kaluza-Klein gluon, Z' as a dark sector-Standard Model mediator, Z' as a topcolor boson, additional Higgs bosons and ALPs.





D0 Collaboration, "Top Pair Branching Fractions"

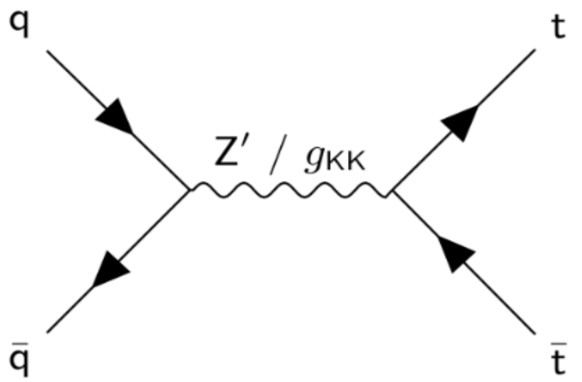
Beyond Standard Model physics
Particles that may decay to top quark pairs

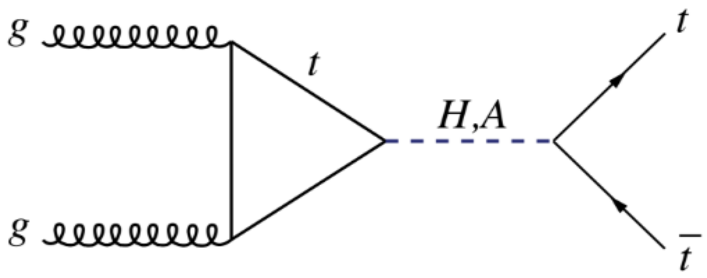
Spin 1

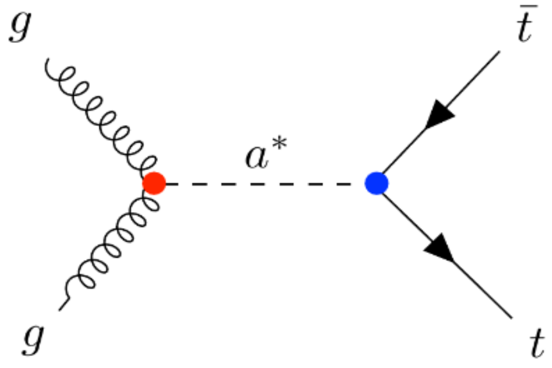
- **Kaluza Klein gluon g_{KK} postulated by the Randall-Sundrum model of extra dimensions, at various masses from 500 to $6000\ GeV$;**
- **Z' as a dark sector mediator, masses: $500 - 6000\ GeV$;**
- **Z' as leptophobic topcolor boson, with preferential coupling to top quarks. $\Gamma/m = 1{,}10{,}30\%$. Masses $400 - 9000\ GeV$;**

Spin 0

- **Scalar or pseudoscalar Higgs boson predicted by the 2 Higgs Doublet Model with widths $\Gamma/m = 2.5, 10, 25\%$. Masses ranging from 365 to $1000\ GeV$;**
- **Light Axion Like Particles ($m < 100\ GeV$).**





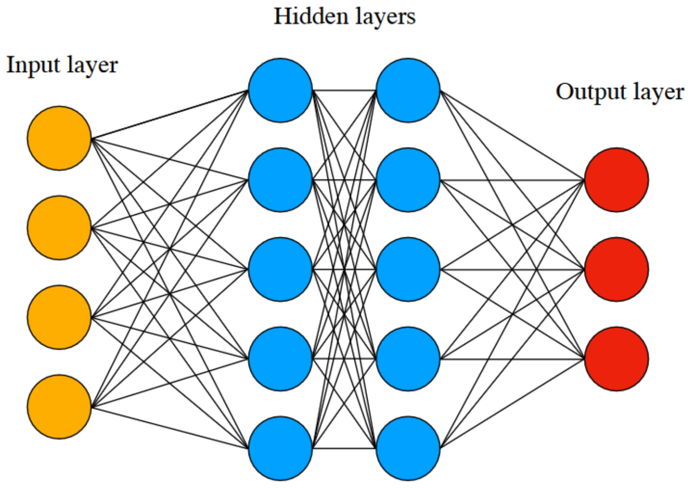


The Deep Neural Network
Architecture and goals of the work

- **The analysis uses a Deep Neural Network for event classification;**
- **Architecture: two hidden layers, 512 neurons each;**
- **Input: 59 variables that describe each event;**

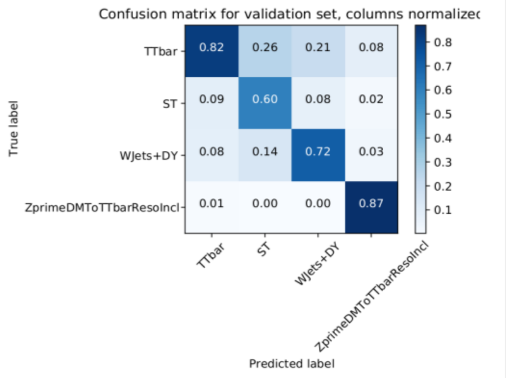
Object	variable
lepton	p_T, η, ϕ, E
neutrino	p_T, ϕ
AK4 jets	N, p_T, η, ϕ, E, m, b-tag score
AK8 jets	N, p_T, η, ϕ, E, m_{SD}, τ_{21}, τ_{32}

5 Ak4 jets
3 Ak8 jets



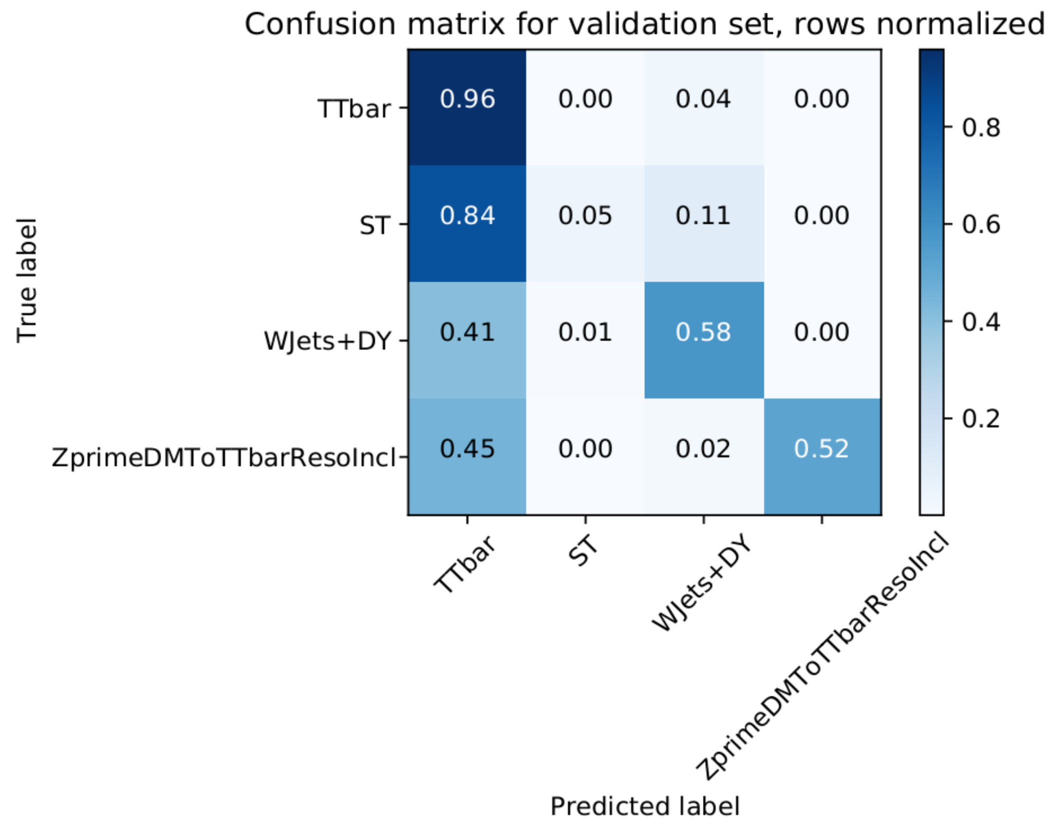
K. de Leo

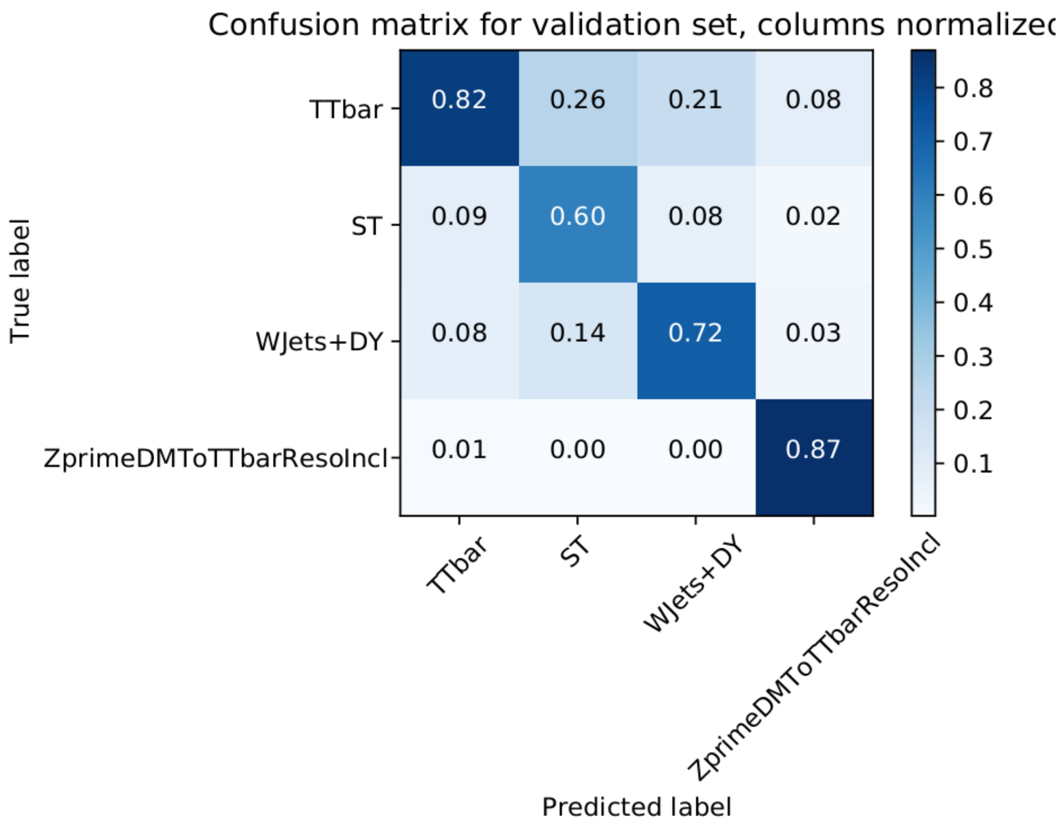
- **As output, score of event belonging to three classes: $t\bar{t}$, single top, and V+jets. Used to define signal and control regions;**
- **First goal: adding a class for signals and optimizing the performance of the DNN in identifying signal from background;**
- **Second goal: parametrizing the DNN in order to enhance sensitivity to new physics at masses not used in training.**



How to assess the DNN’s performance

An example: confusion matrices

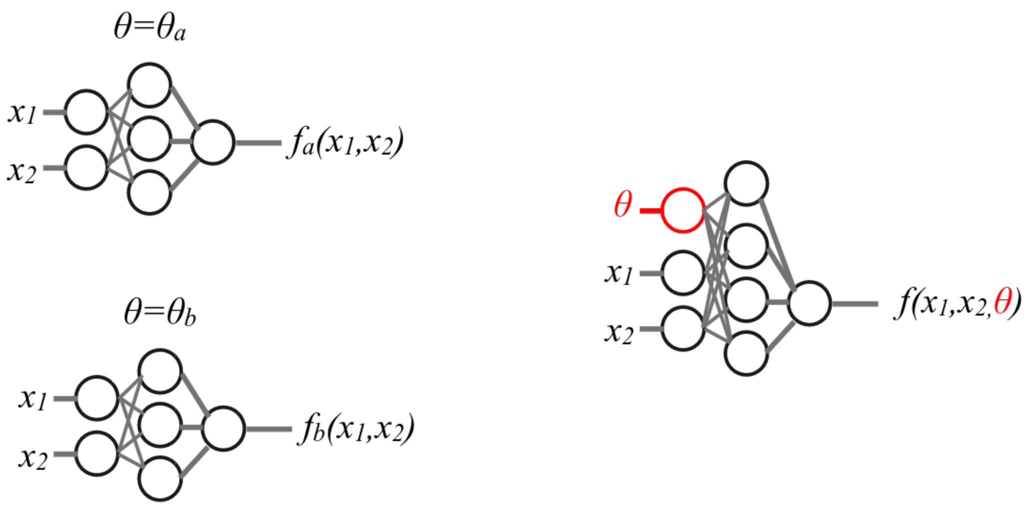




Confusion matrices are useful to study the DNN's performance in the classification task.

Parametrization of the neural network
Working principle

- The MC signals used in training are generated for particular signal masses;
- Computing resources constrain the range of masses that can be generated;
- Parametrized neural networks are introduced with the goal of enhancing the DNN's performance on signals not seen during training and making the model mass-agnostic.



arXiv:1601.07913

Parametrization of the neural network

An example: the Z' sample

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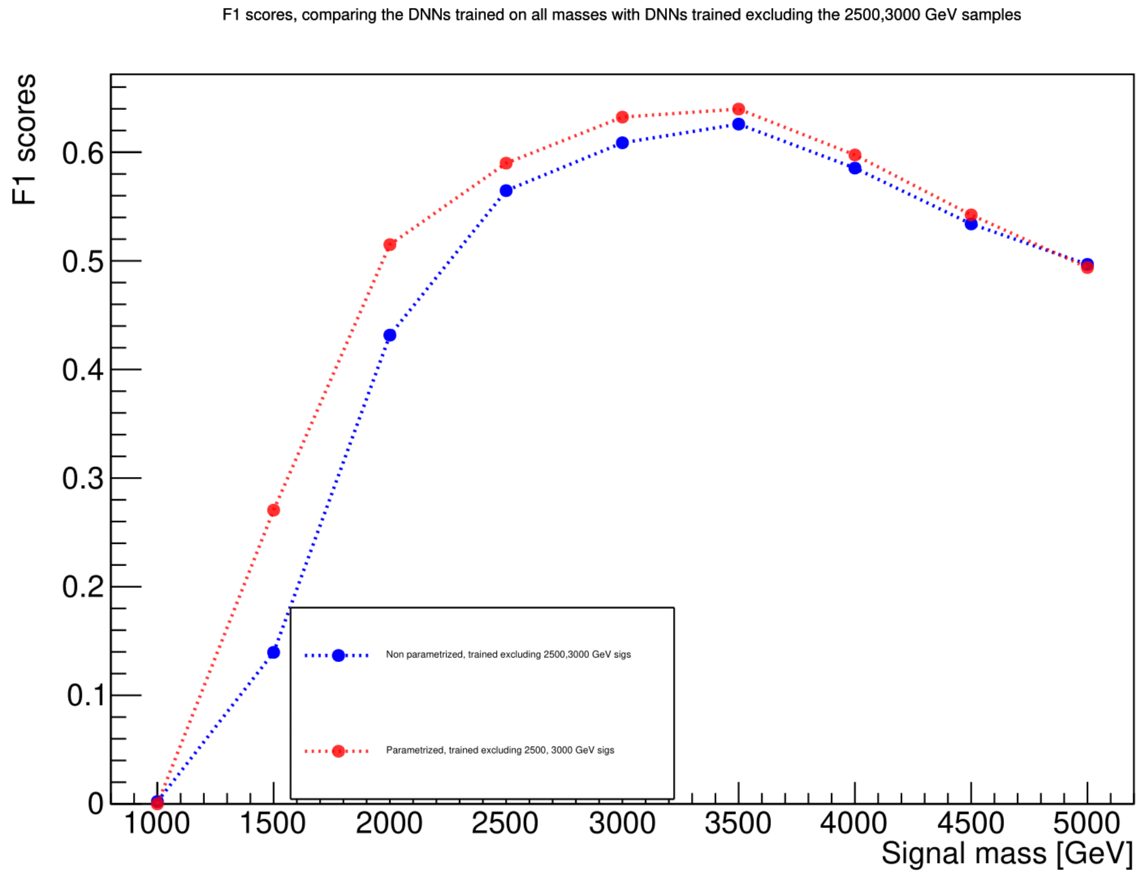


F1 scores for the Z' dark matter samples

F1 score defined as:

$$F1 = 2\frac{precision \cdot recall}{precision + recall}$$

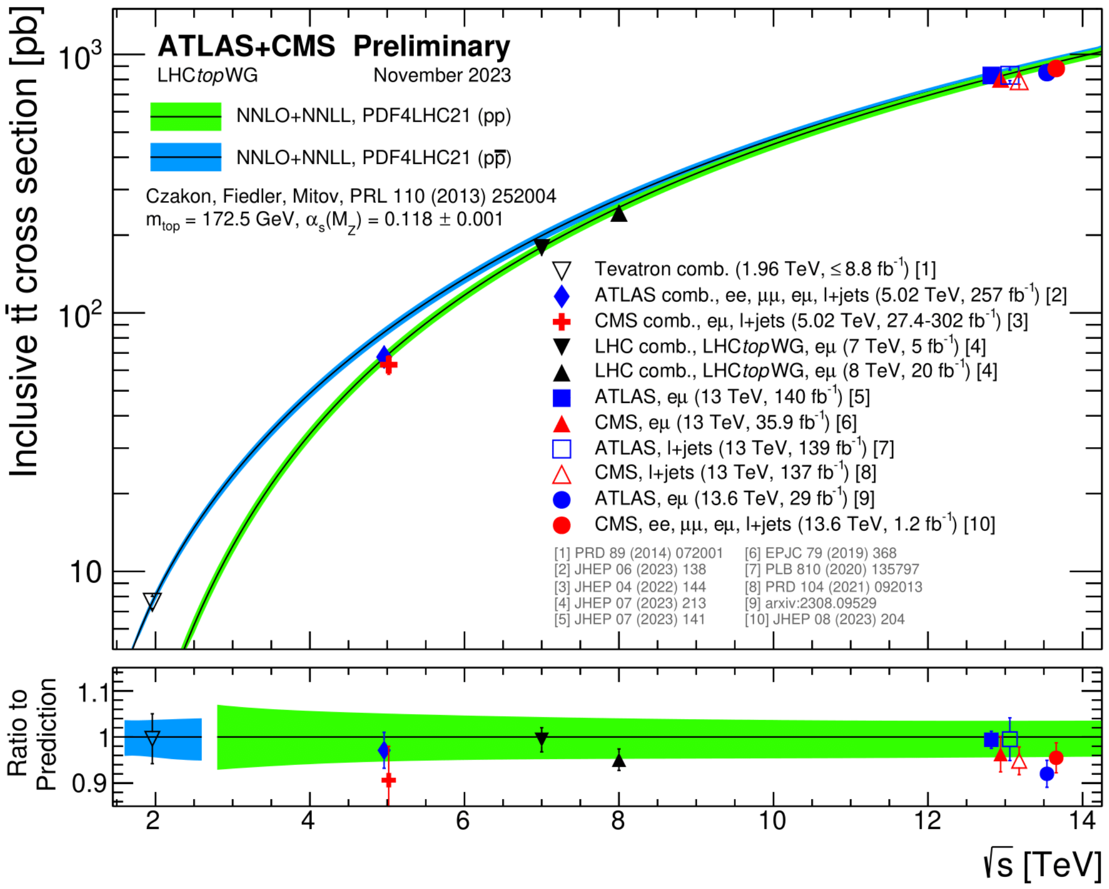

Thank you for your attention
NASA, ESA, and J. Lotz and the HFF Team (STScI)

Backup

NASA, ESA, and J. Lotz and the HFF Team (STScI)

Master’s thesis

Top quark production cross section



https://twiki.cern.ch/twiki/pub/LHCPhysics/TopPairCrossectionSqrtsHistory/tt_curve_toplhcwg_nov23.png

Master’s thesis

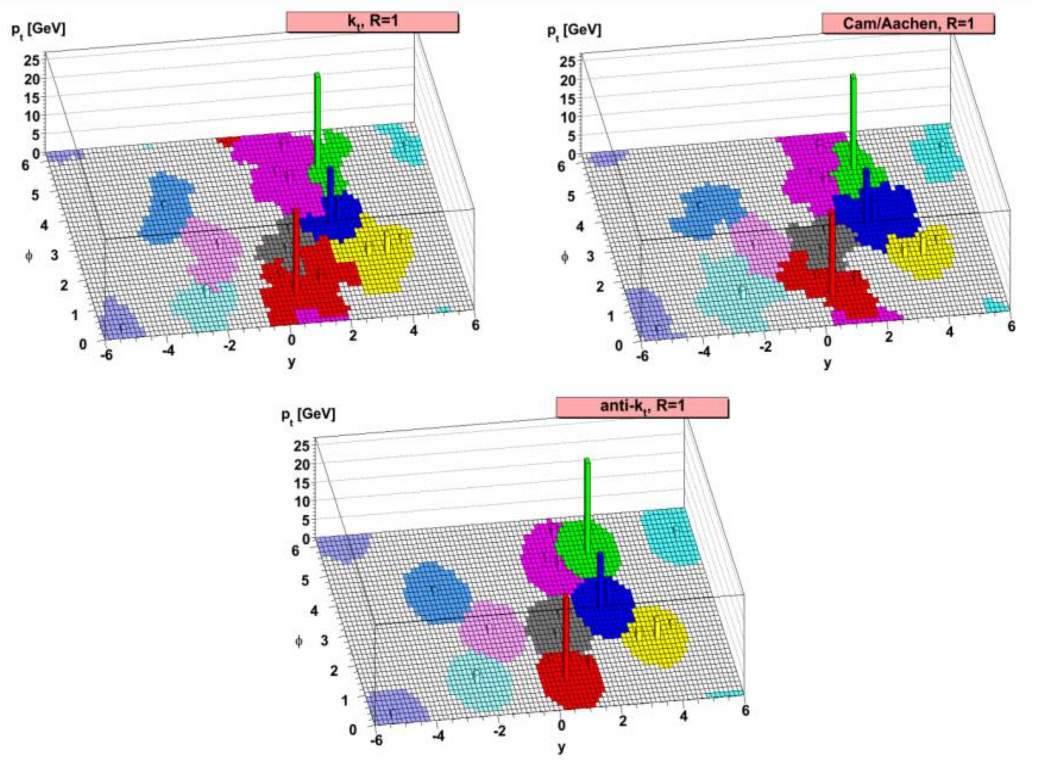
The kt algorithm

- If the smallest among the distances is d_{ij} with, i, j not being the beam axis, then combine the two entities in a single one;
- If the smallest distance is of the king d_{iB}, then call i a jet and remove it from the list of objects;
- Repeat the same procedure for all the objects.

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2},$$

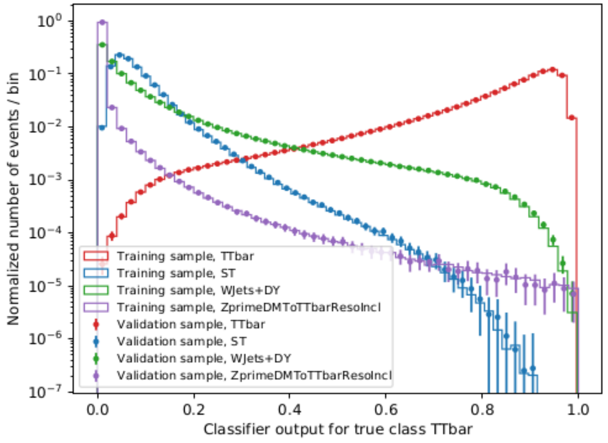
$$d_{iB} = k_{ti}^{2p},$$

- With $p = 1$ one obtains the k_t algorithm;
- $p = 0$ leands to the Cambridge-Aachen algorithm;
- Finally, $p = 1$ leads to the anti-k_t algorithm.

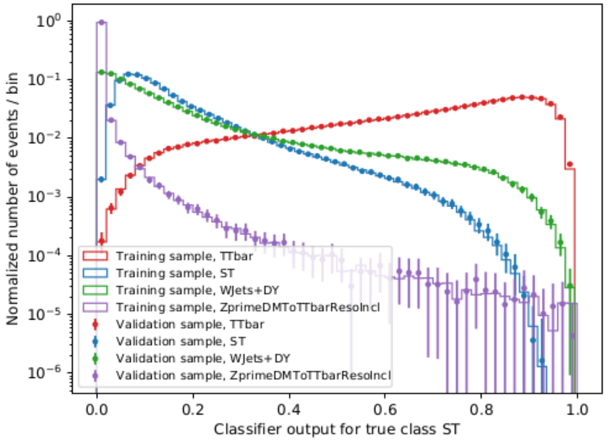


Master’s thesis

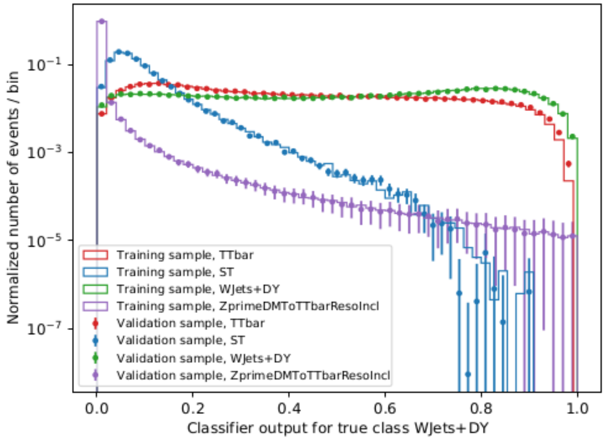
Output scores of the DNN trained on the Z' signal



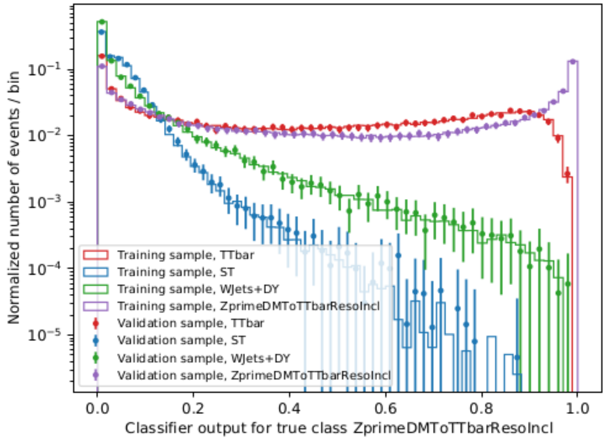
(a) Output score for the $t\bar{t}$ class.



(b) Output scores for the single top class.



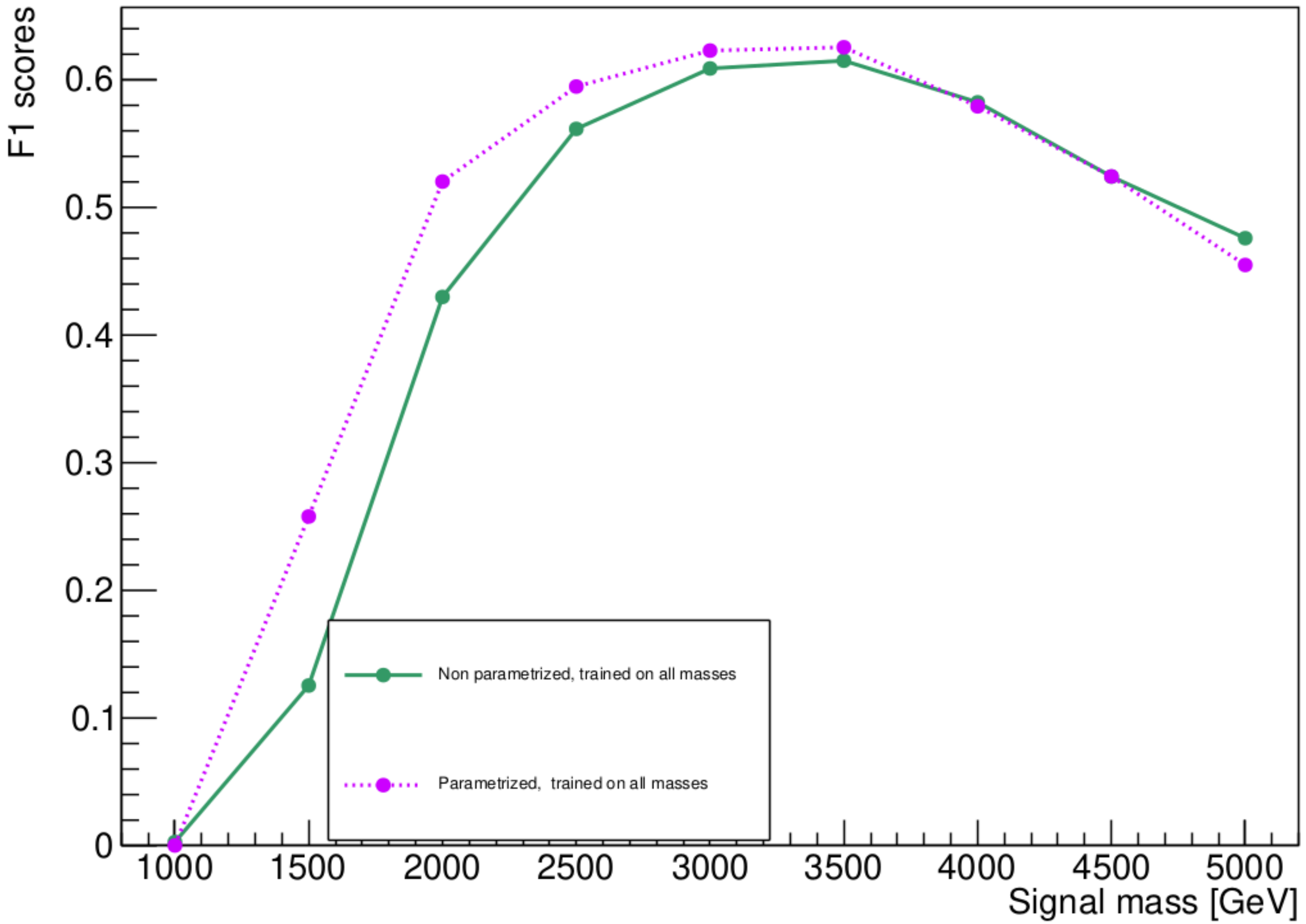
(c) Output scores for the class V+jets.



(d) Output scores for the signal class.

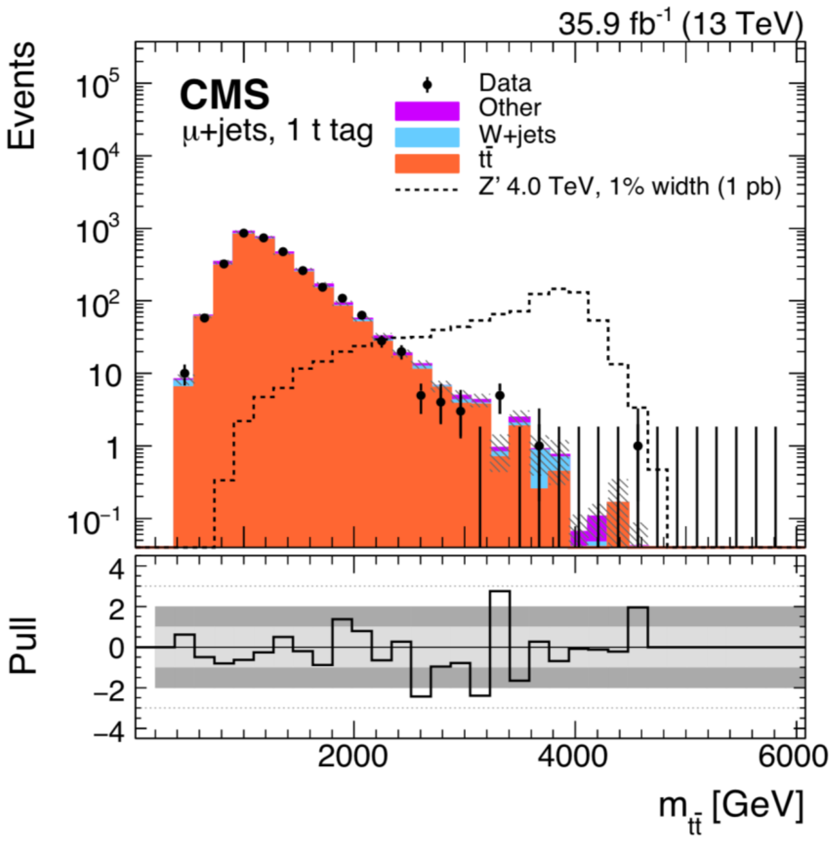
Master’s thesis
Parametrized vs non-parametrized network

F1 scores, comparing the DNNs trained on all masses with DNNs trained excluding the 2500,3000 GeV samples



Master's thesis

How to probe the new physics models



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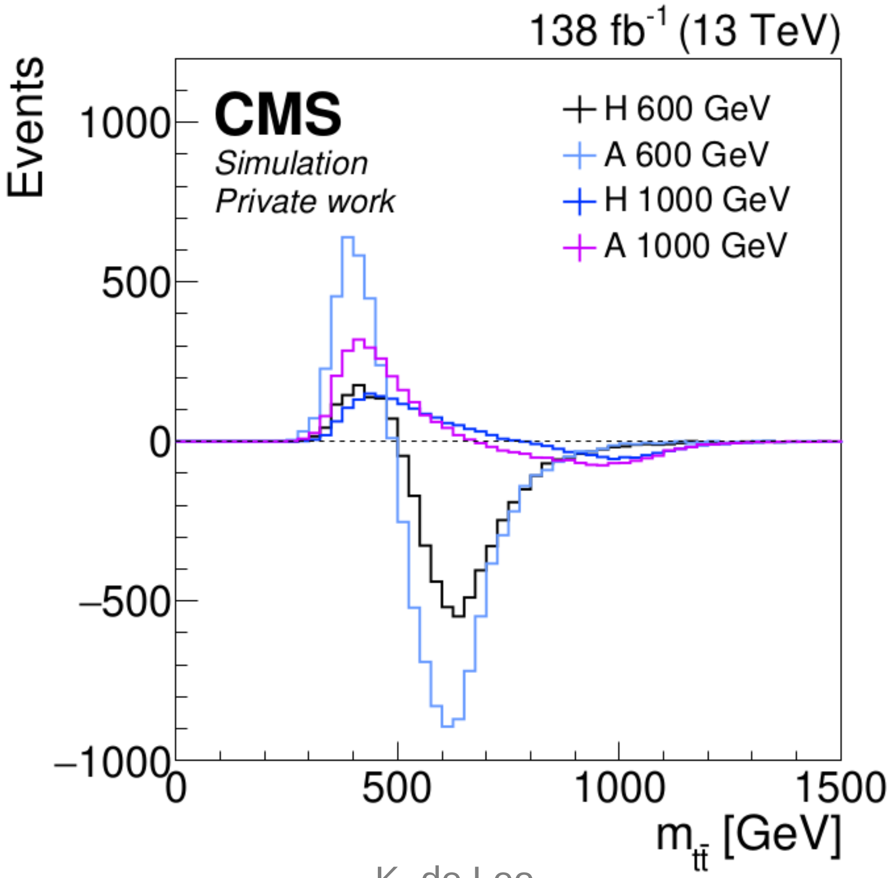

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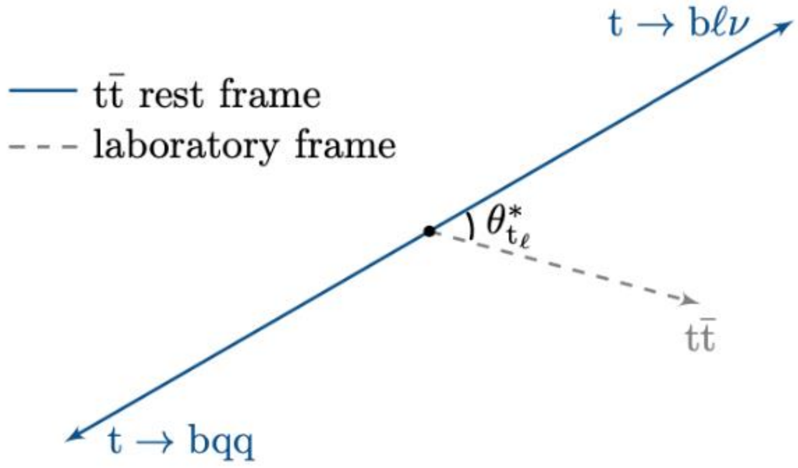
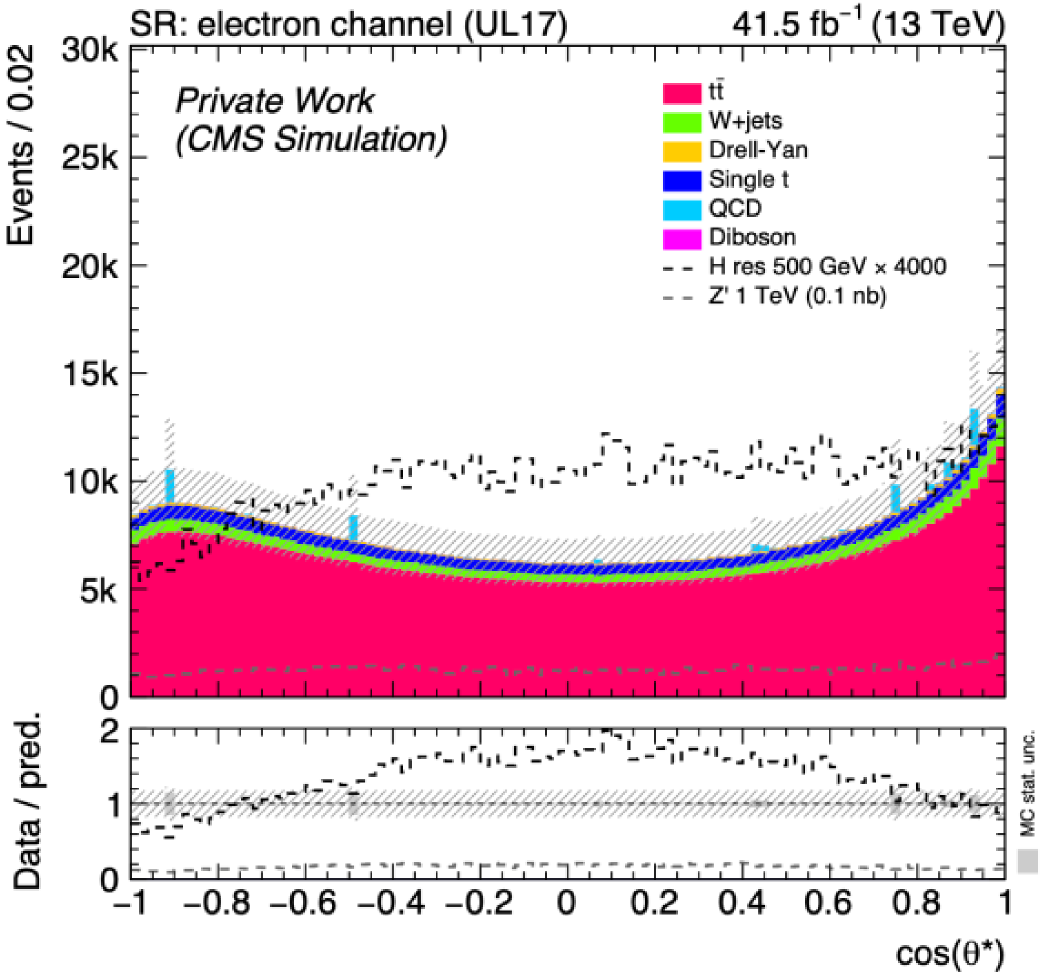
Master’s thesis
How to probe the new physics models

An observable sensitive to the spin of the mediator particle and can be used to probe new physics models is $\cos(\theta^*)$.
Def. θ^*: angle between the $t\bar{t}$ system in the laboratory reference frame and the leptonically decaying top quark.





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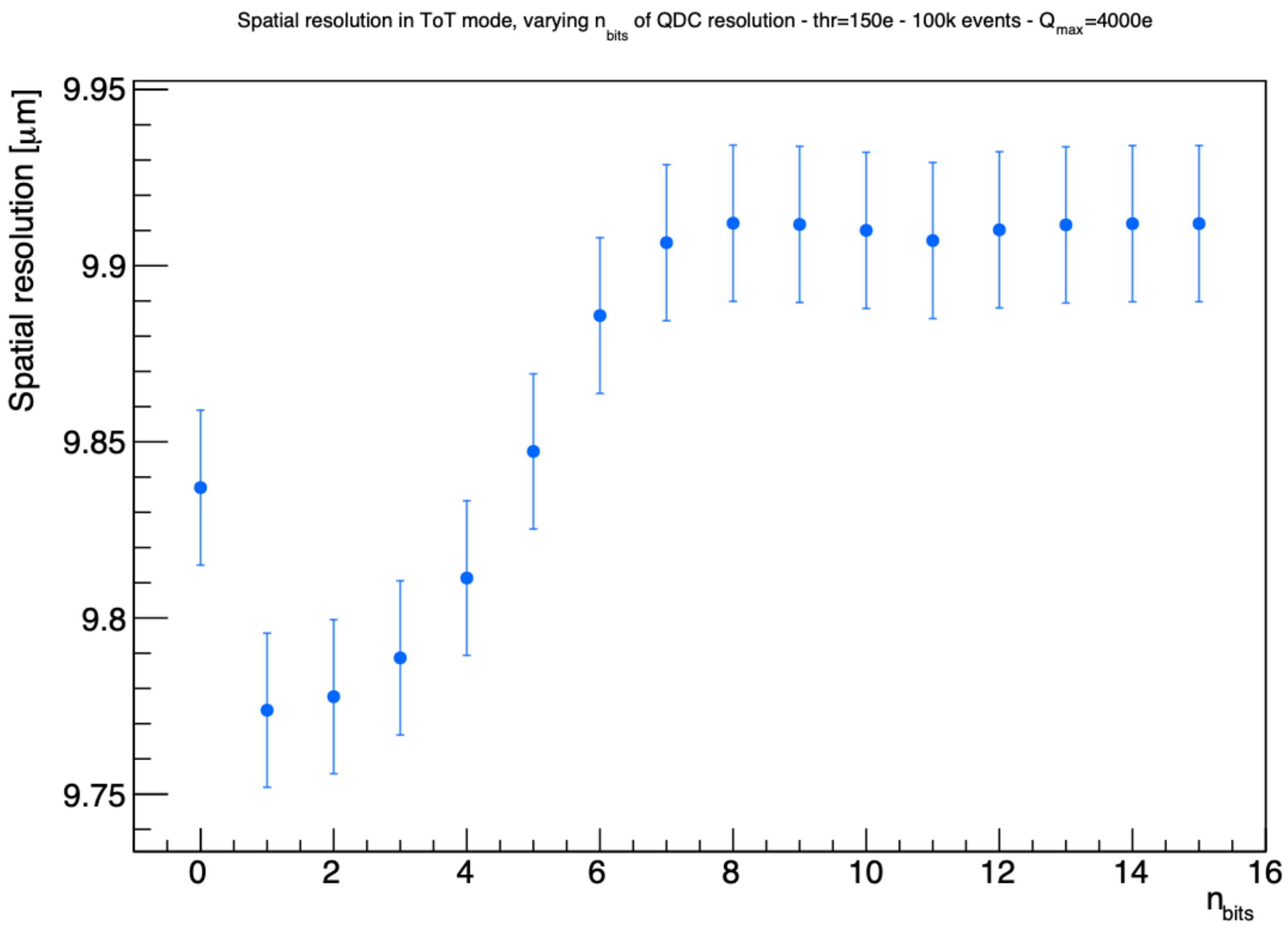
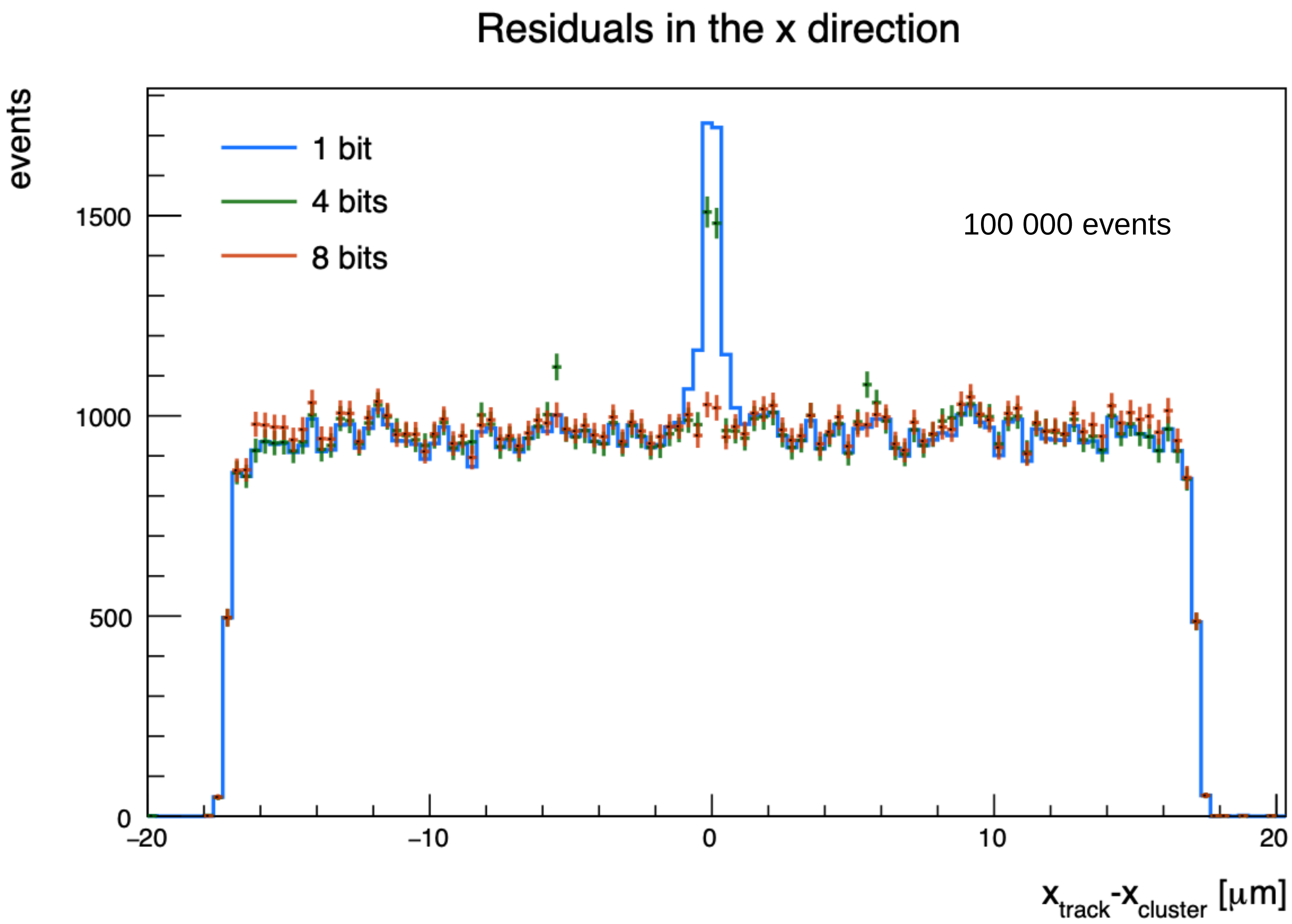
Spatial resolution as function of the QDC resolution



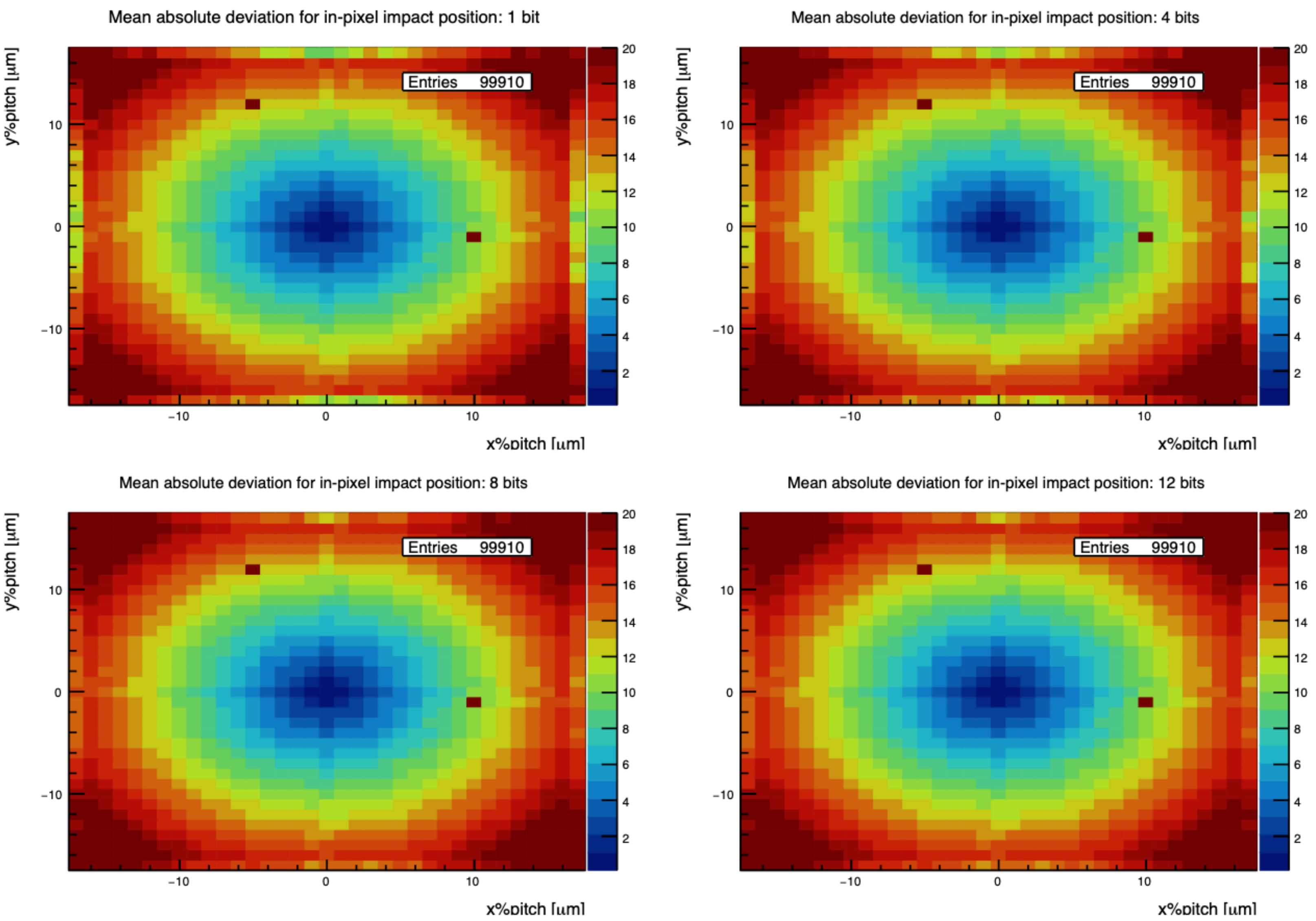
Unexpected behaviour: spatial resolution gets worse with better QDC resolution

Residual distribution for different QDC resolutions



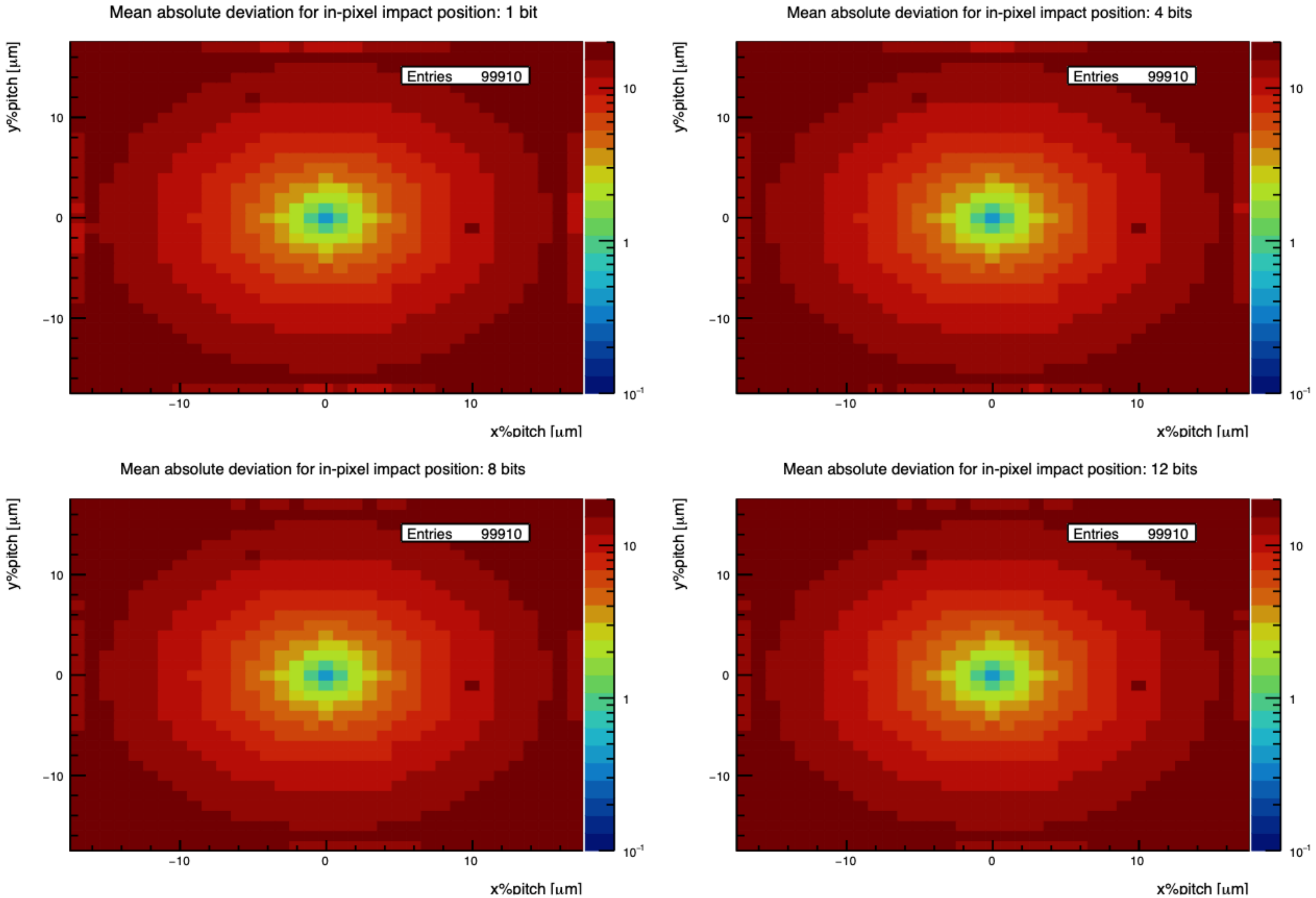
There are some precise (~$1\mu m$) track position reconstructions for 1-4 bit resolutions that do not show up at better QDC resolutions

Residual map for different QDC resolutions



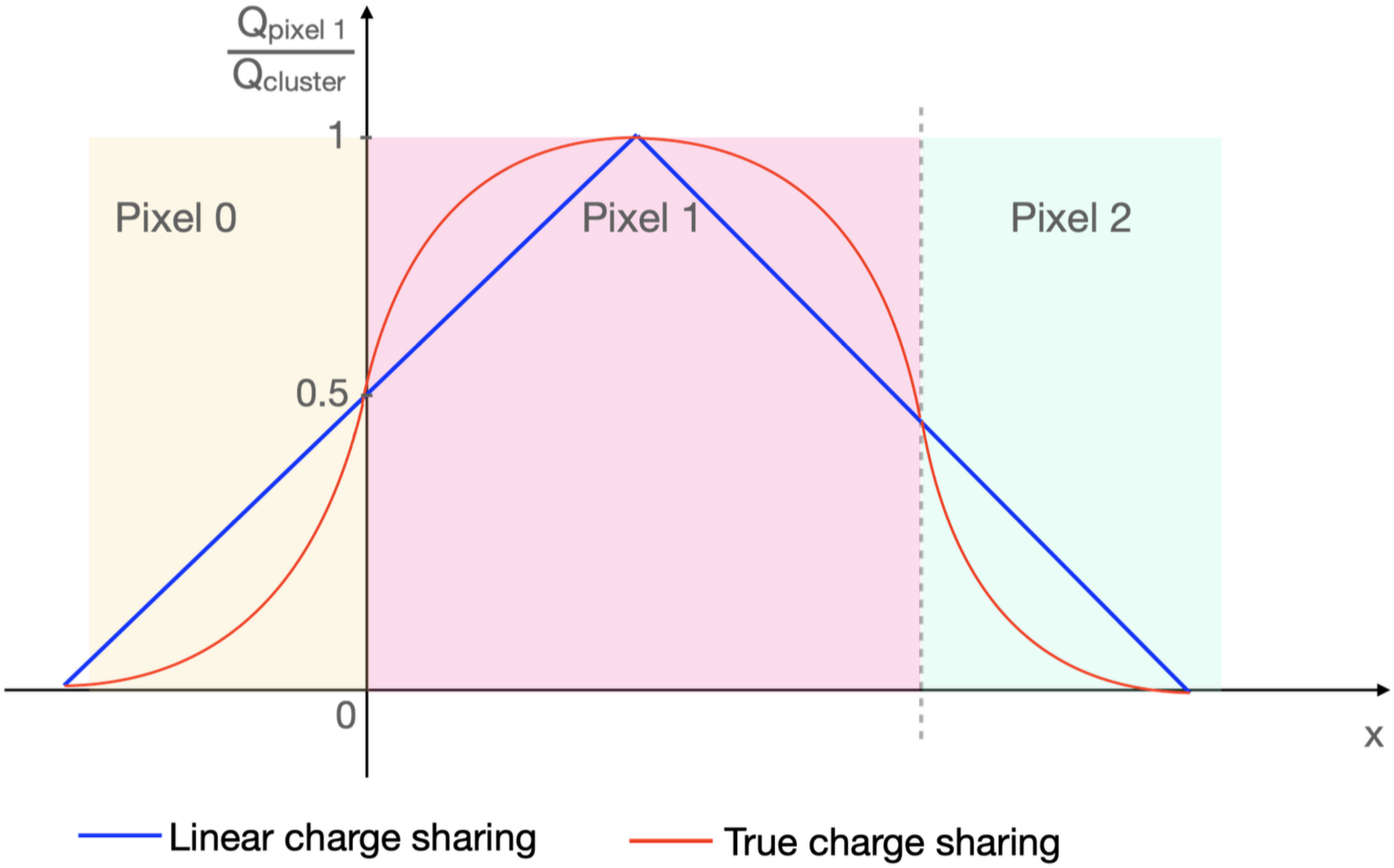
Better track position reconstruction at the sides of the pixel for low QDC resolution

Residual map for different QDC resolutions - log scale

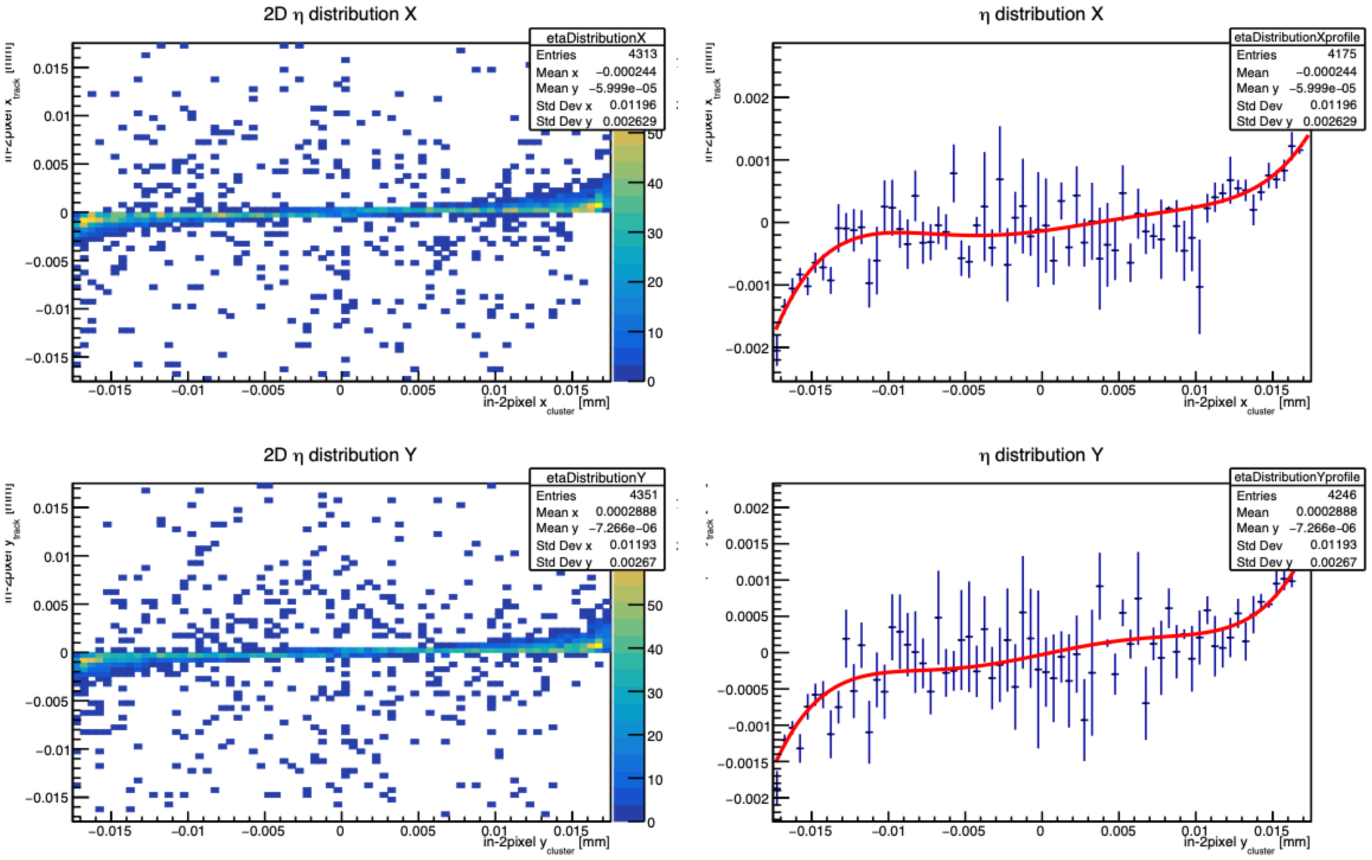


Better track position reconstruction at the sides of the pixel for low QDC resolution

η-correction

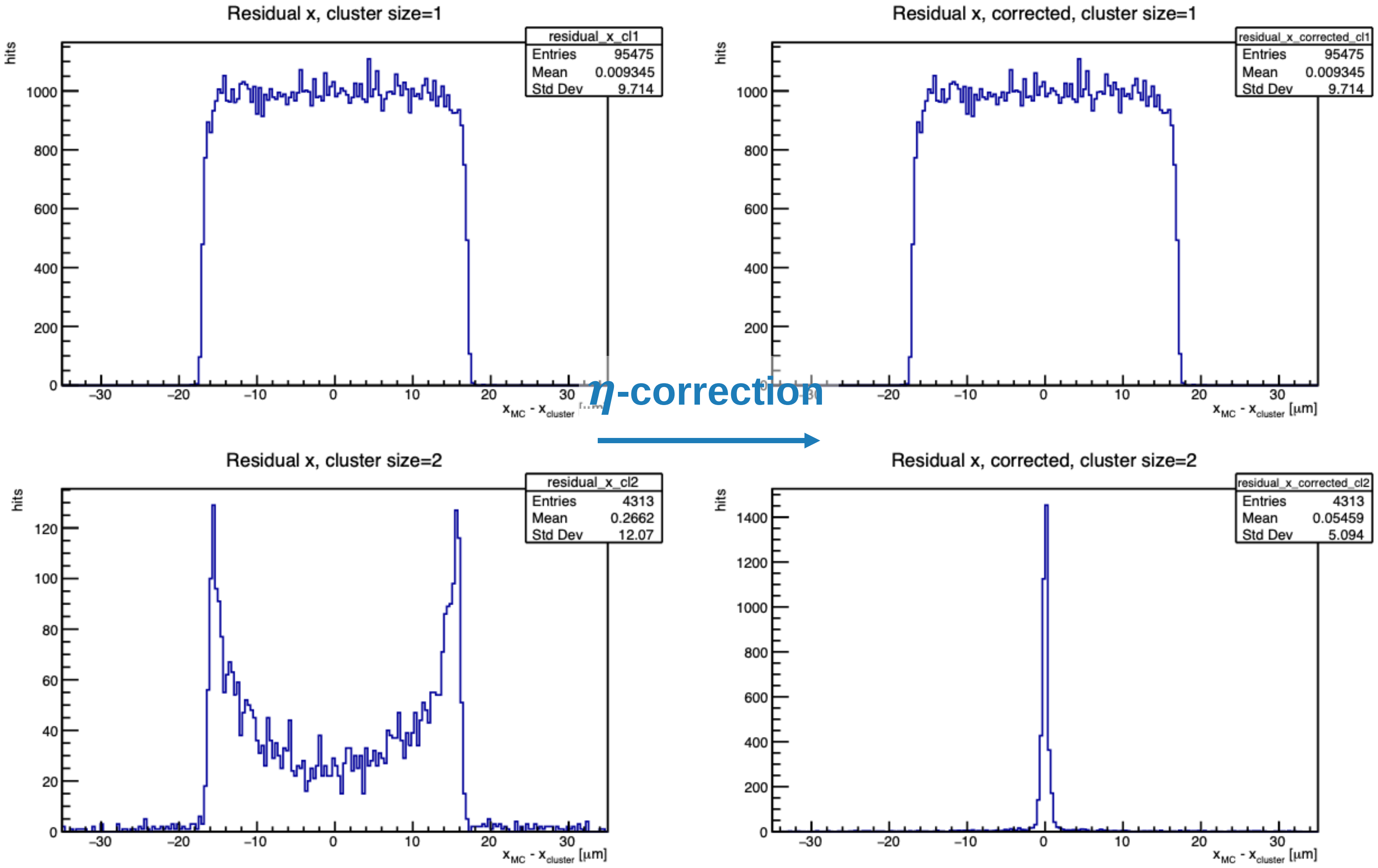


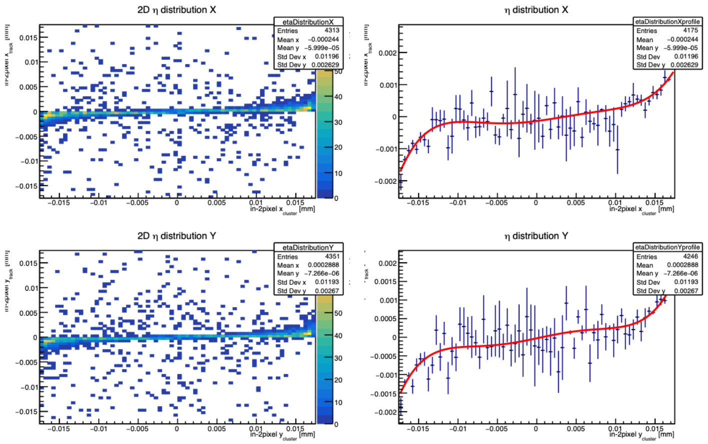
η-correction



- Plotting true track position vs reconstructed track position
- Fitting with a 5th order polynomial
- Afterwards all reconstructed track positions are recalculated using the fitted function

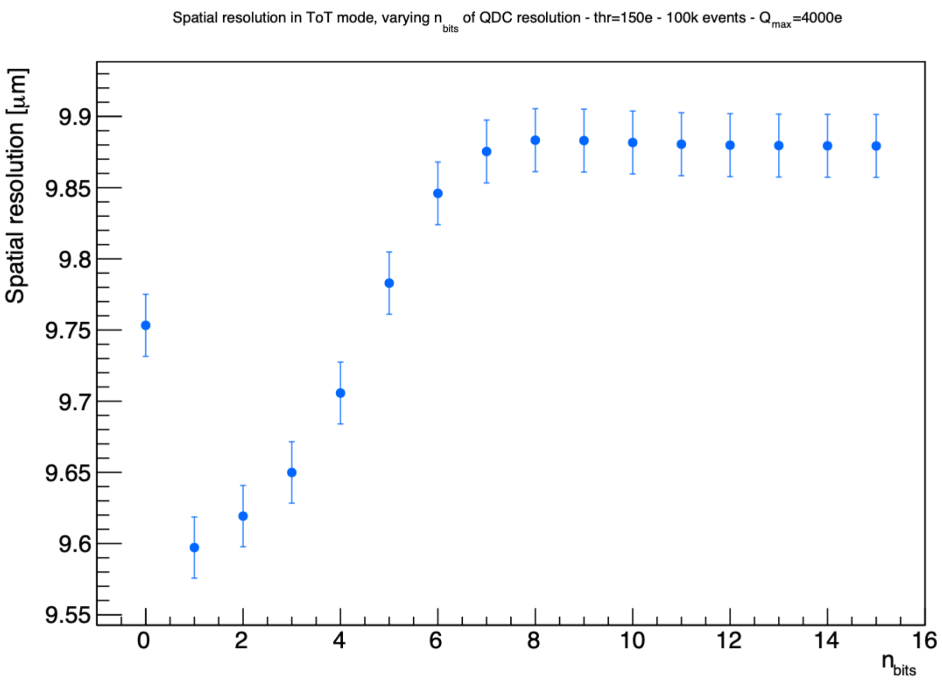
η-correction



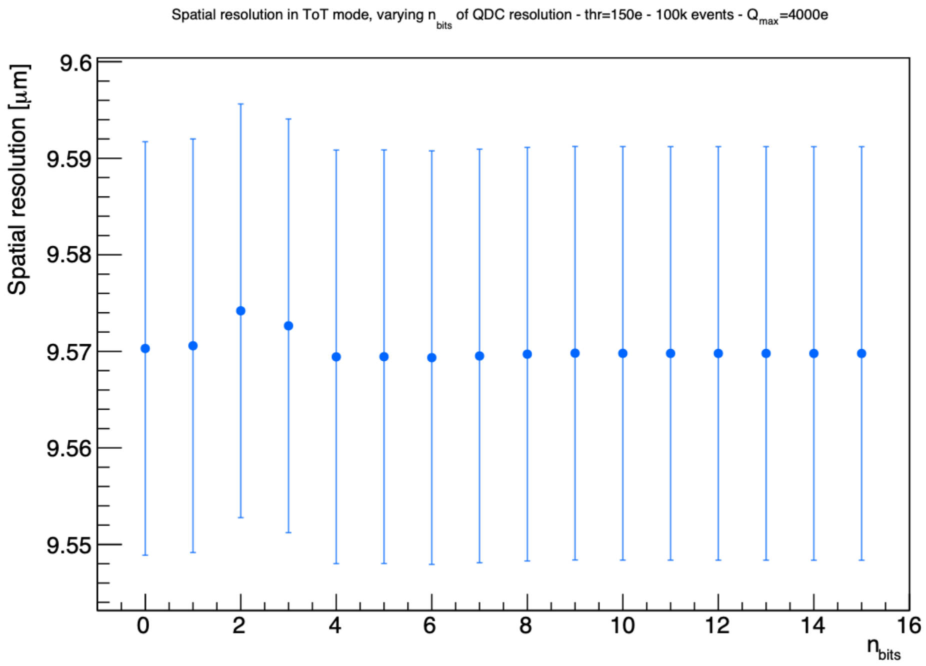


- Cluster size 1 events left unchanged
- Cluster size 2 events have a much narrower residual distribution after correction

η-correction



η-correction



Gain of $\sim 0.2\mu m$ in spatial resolution, but no dramatic change of it for different QDC resolutions.
Now that is the expected behaviour of the detector: the n-gap design has a small fraction of events with cluster size > 1. Only those events gain in spatial resolution from the charge sharing across pixels. So the resolution's value is mostly due to the cluster size 1 events.