Search for Beyond the Standard Model physics with Emerging Jets and the ATLAS detector during Run-3

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Summary

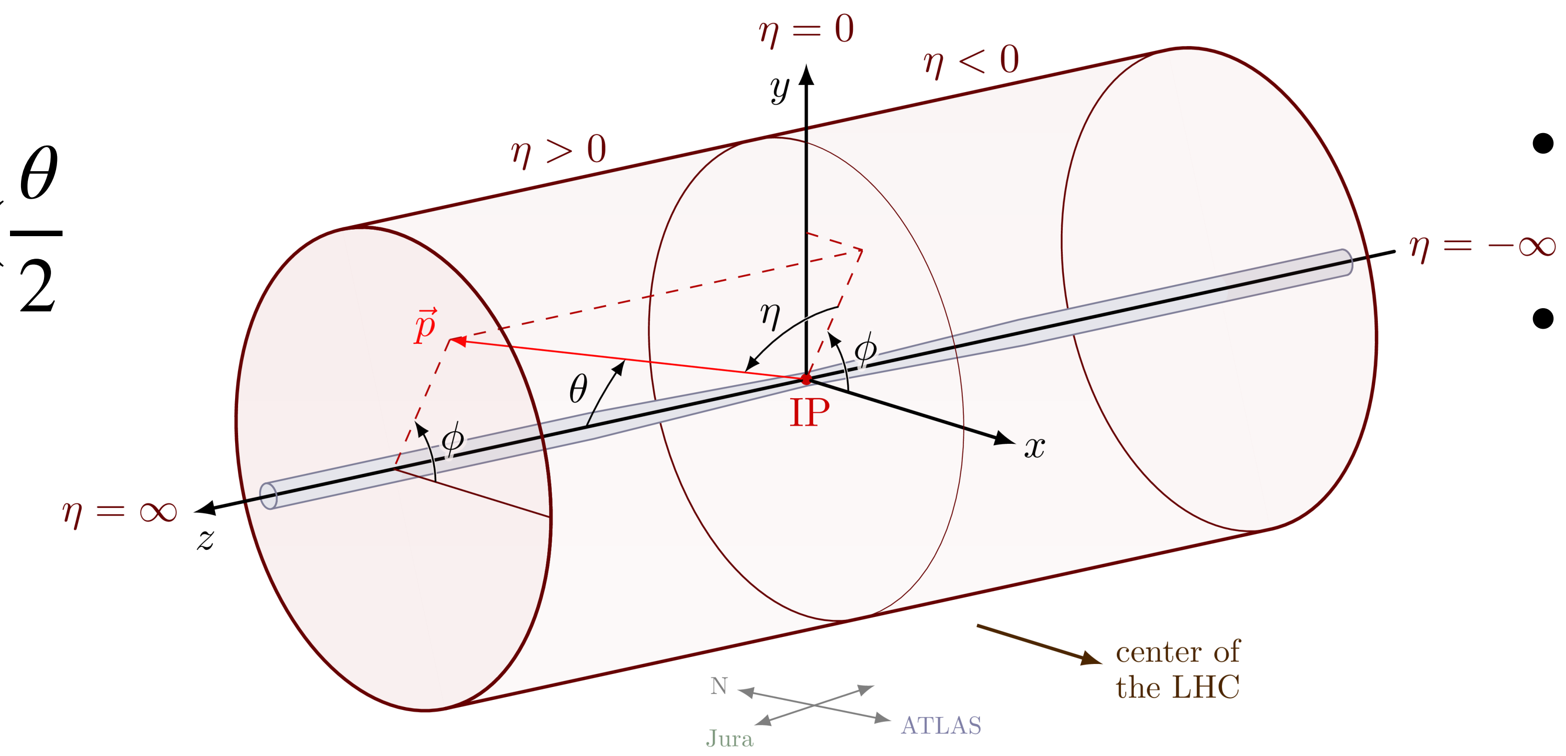
1. Introduction to the Standard Model and motivation for Beyond the Standard Model physics (done by Luca yesterday)
2. The ATLAS detector and physics objects
3. A little bit of phenomenology of dark QCD and Emerging Jets
4. Early Run-3 analysis on Emerging Jets with a two-jets topology

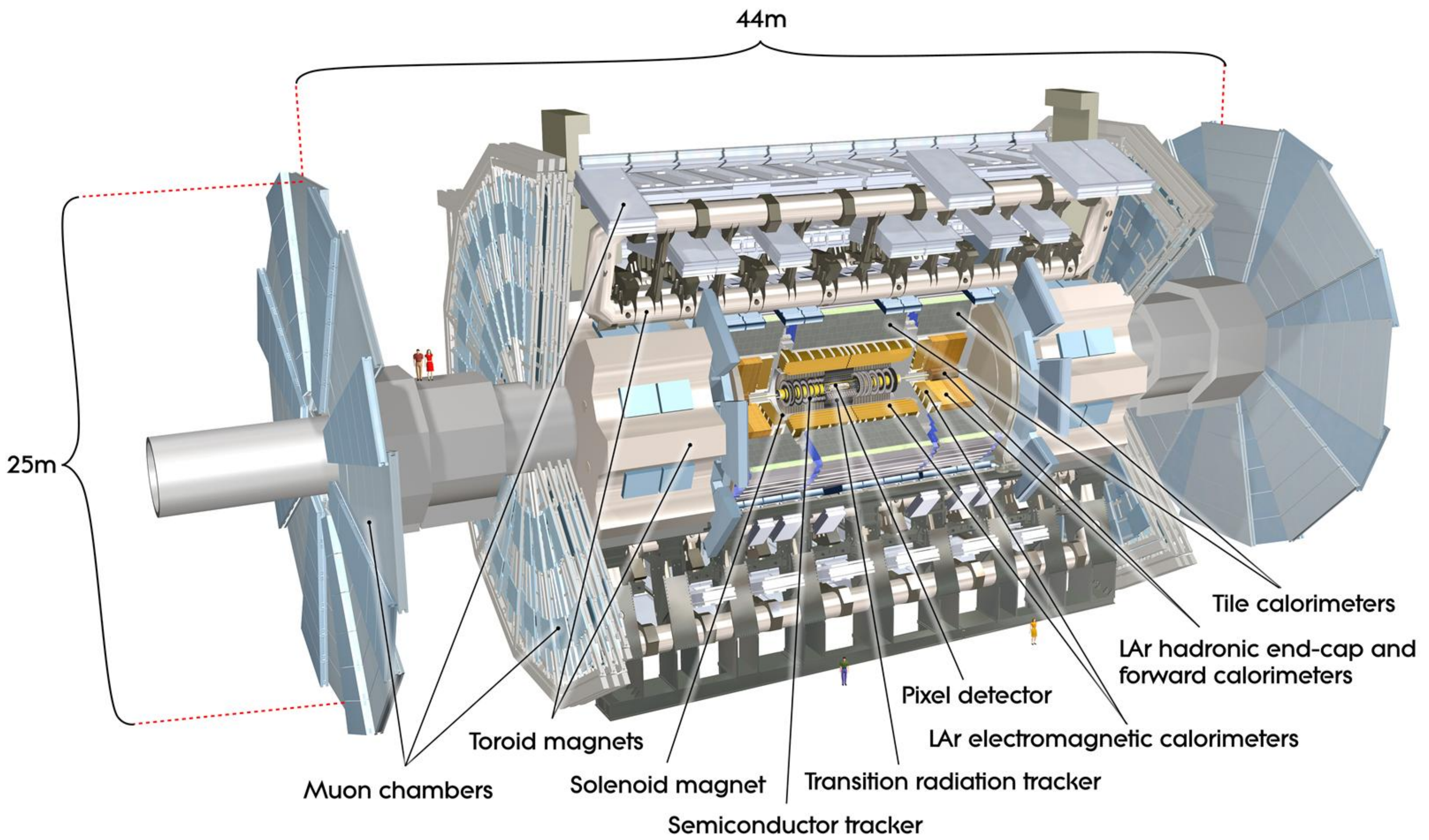
1.
Introduction to the Standard Model and motivation for Beyond the Standard Model physics

2.
The ATLAS detector and physical objects

The ATLAS detector

- ATLAS : one of the 4 main detectors of LHC, general purpose detector like CMS, dedicated to precision measurements of SM physics and to the search of BSM physics
- Multi-layer conception, from inside to outside :
  - **Inner detector** : measure charged particles trajectories → transverse momentum and direction
  - **Calorimeters** : stop charged / neutral particles and measure their energies → energy, mass and ~ direction
  - **Muon spectrometer** : measure muons trajectories → p_T and direction of muons
- Coordinate system of ATLAS :
  - **Pseudo-rapidity** : $\eta = -ln(tan(\frac{\theta}{2}$
  - **Azimuthal angle** : ϕ
  - **Transverse momentum** : p_T



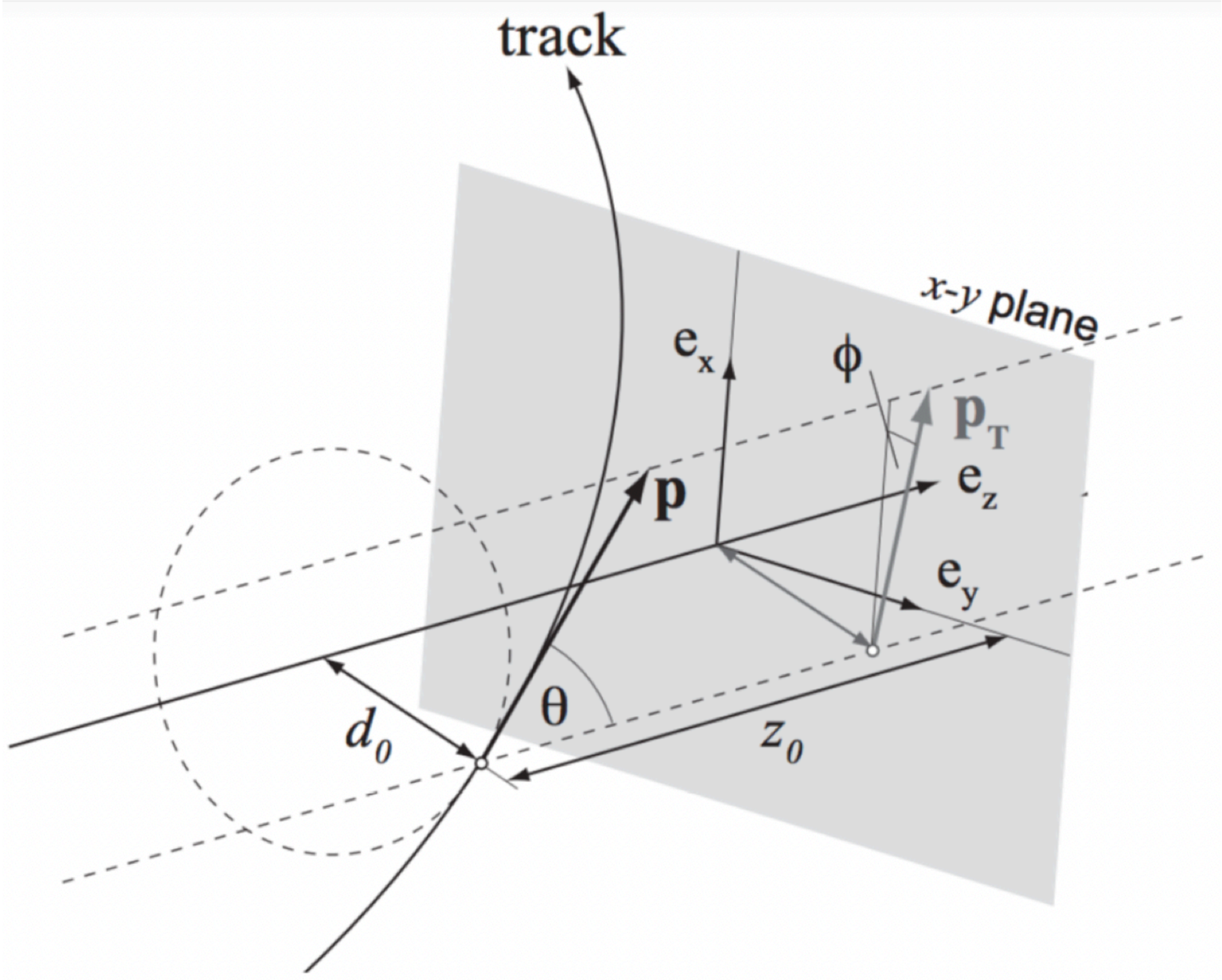


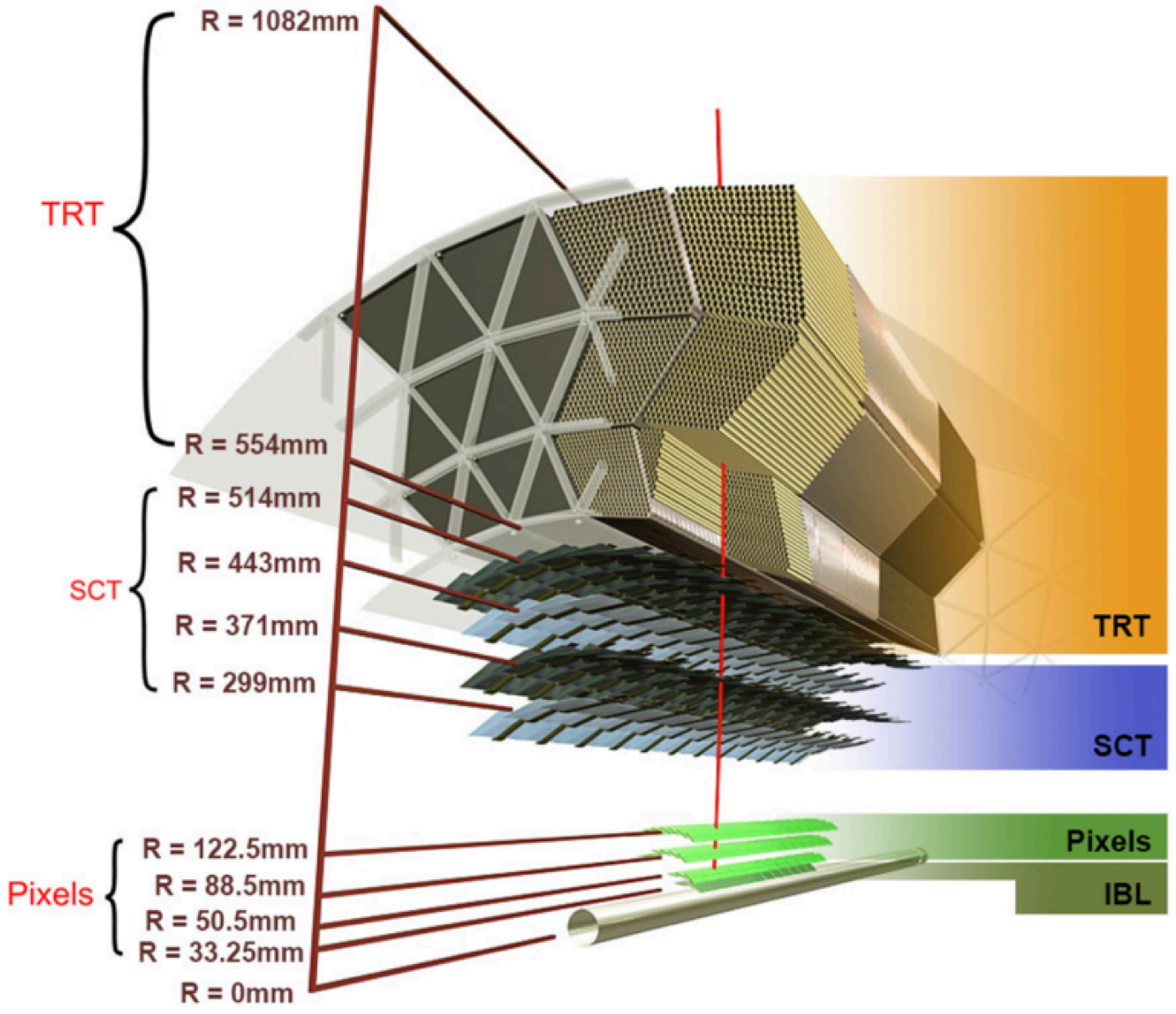
- Instantaneous luminosity of LHC is very high : ‘crossing’ frequency ~ $40 MHz$
- Has two effects :
  - Physically impossible to store so much data → need to select events of interests → trigger systems
  - Multiple interactions in one event → noise called pile-up

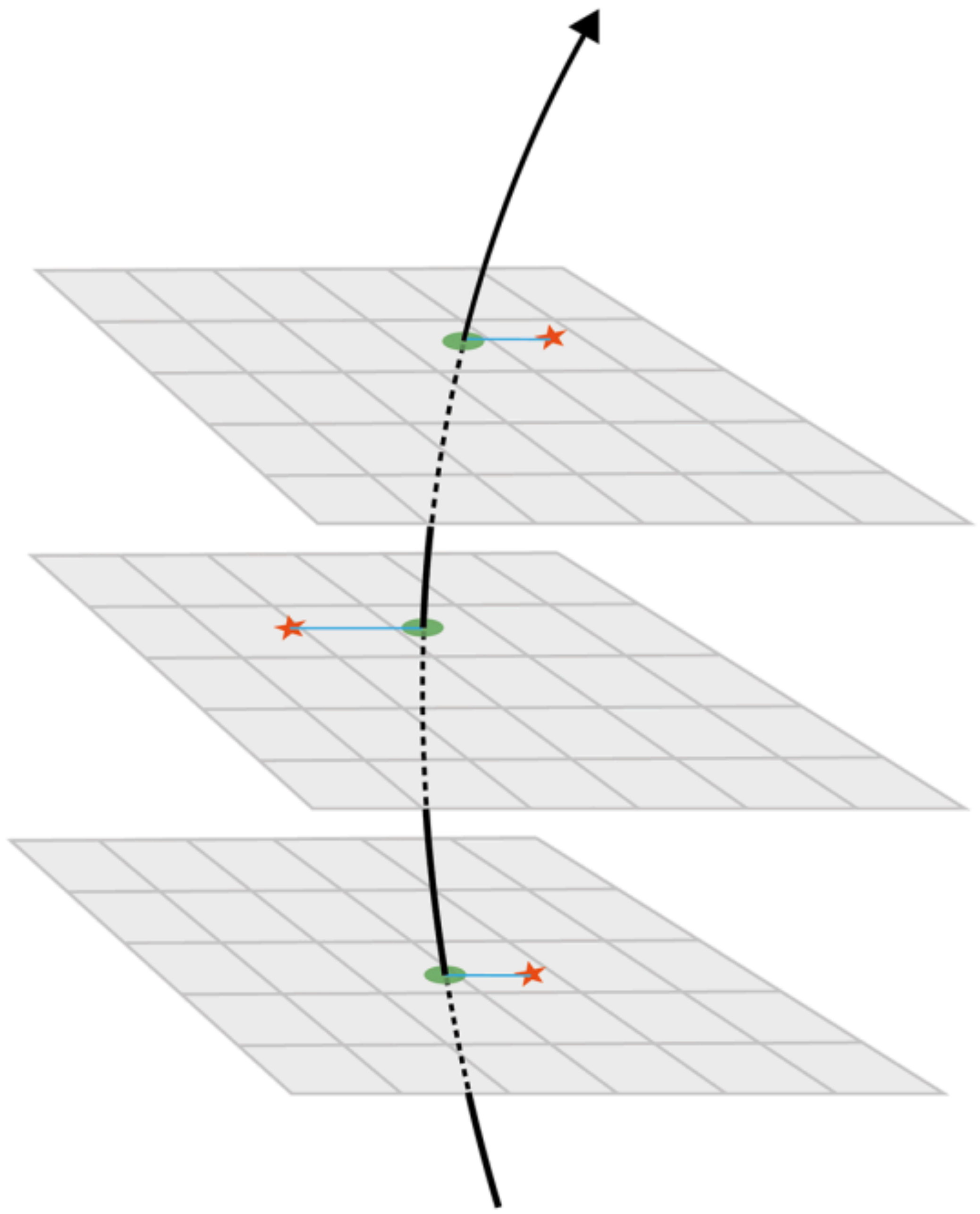
Physics objects of interest in ATLAS

Tracks, particle trajectories

- Inner detector composed of several active layers that detect the crossing of a charged particles (i.e hits)
- A track is the reconstruction of a particle trajectory using all the hits left by this particle
- As the inner detector is immersed in a magnetic field → charged particle trajectory is bent, allowing to measure the p_T of the particle





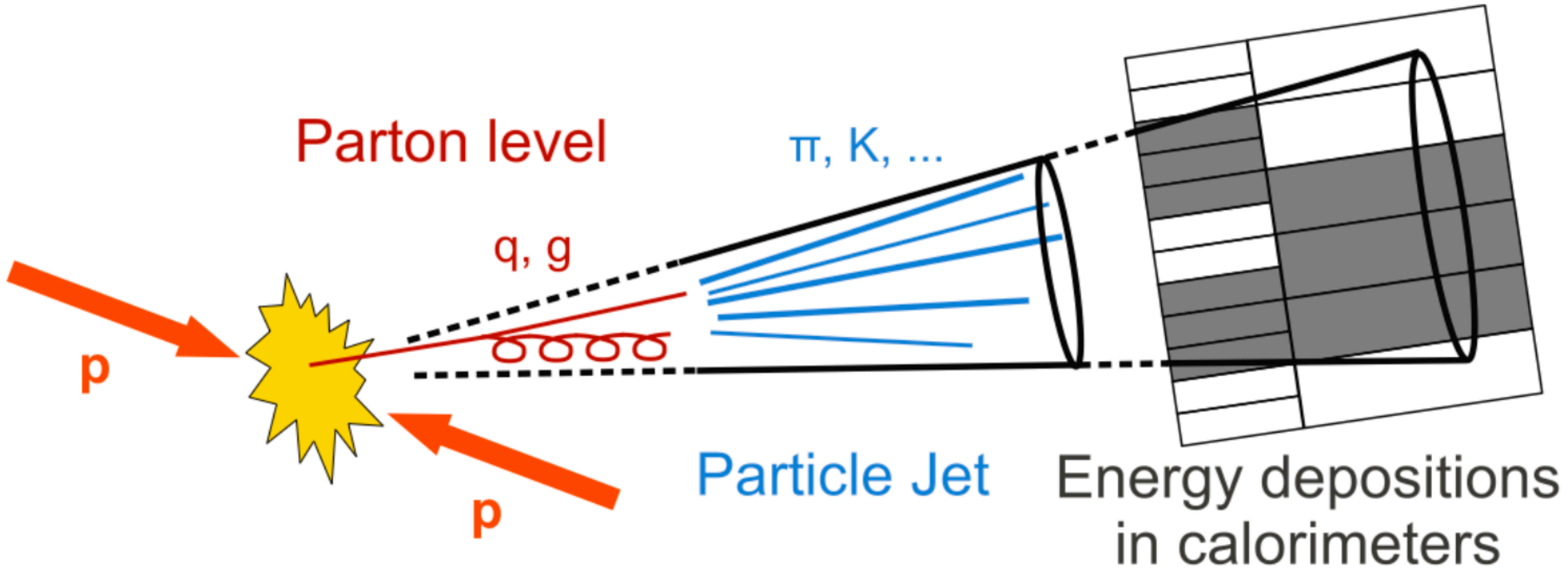


- Reconstructed track parameters :
  - p_T
  - η, ϕ
  - d_0, z_0 (distances of the point of closest approach to the Primary Vertex*)

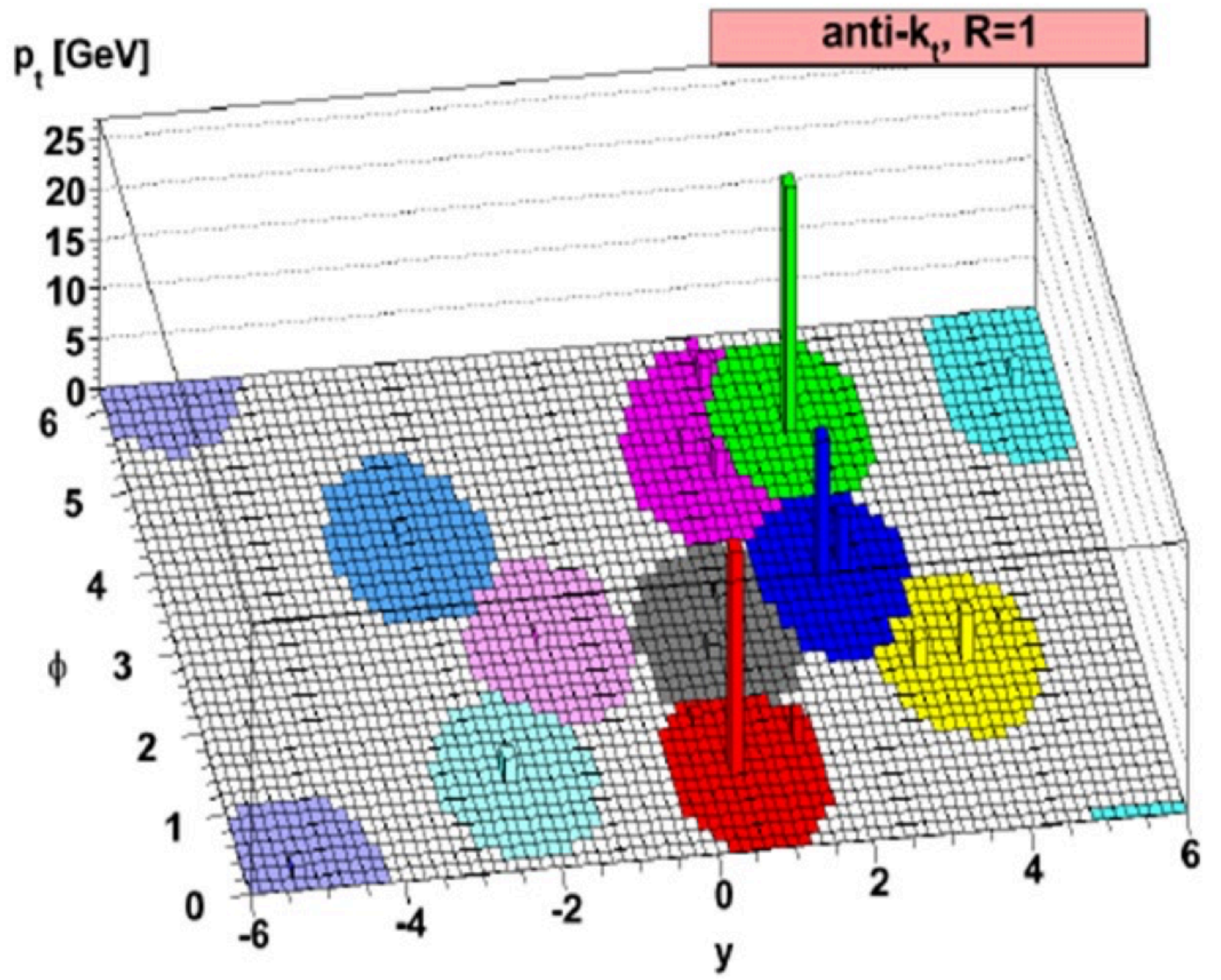
*Primary Vertex (PV) : hard scatter vertex, p-p interaction point

Physics objects of interest in ATLAS

Jets, QCD signature



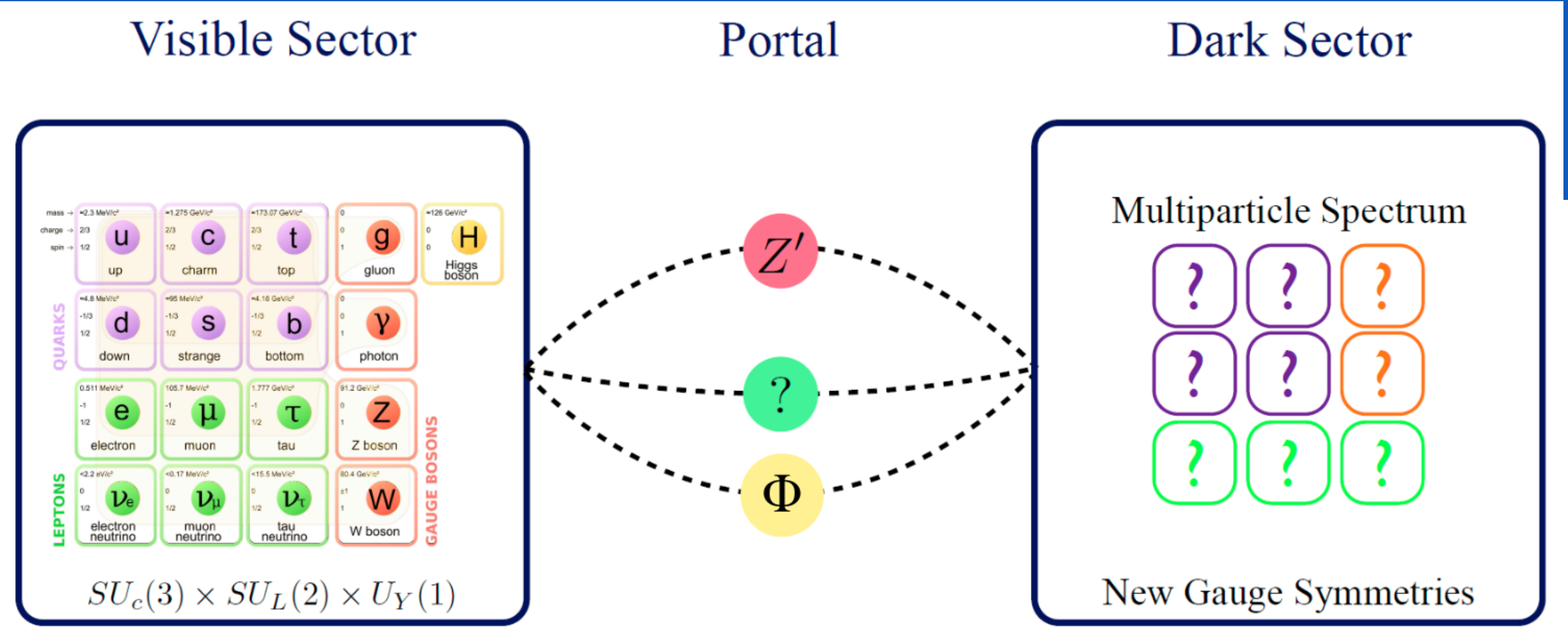
- Quarks and gluons cannot propagate freely due to color confinement
- At LHC emitted quark or gluon will radiate new quarks/gluons creating a parton shower
- The partons produced then regroup into hadrons = hadronisation
- All the hadrons produced form a conic object called **jet**



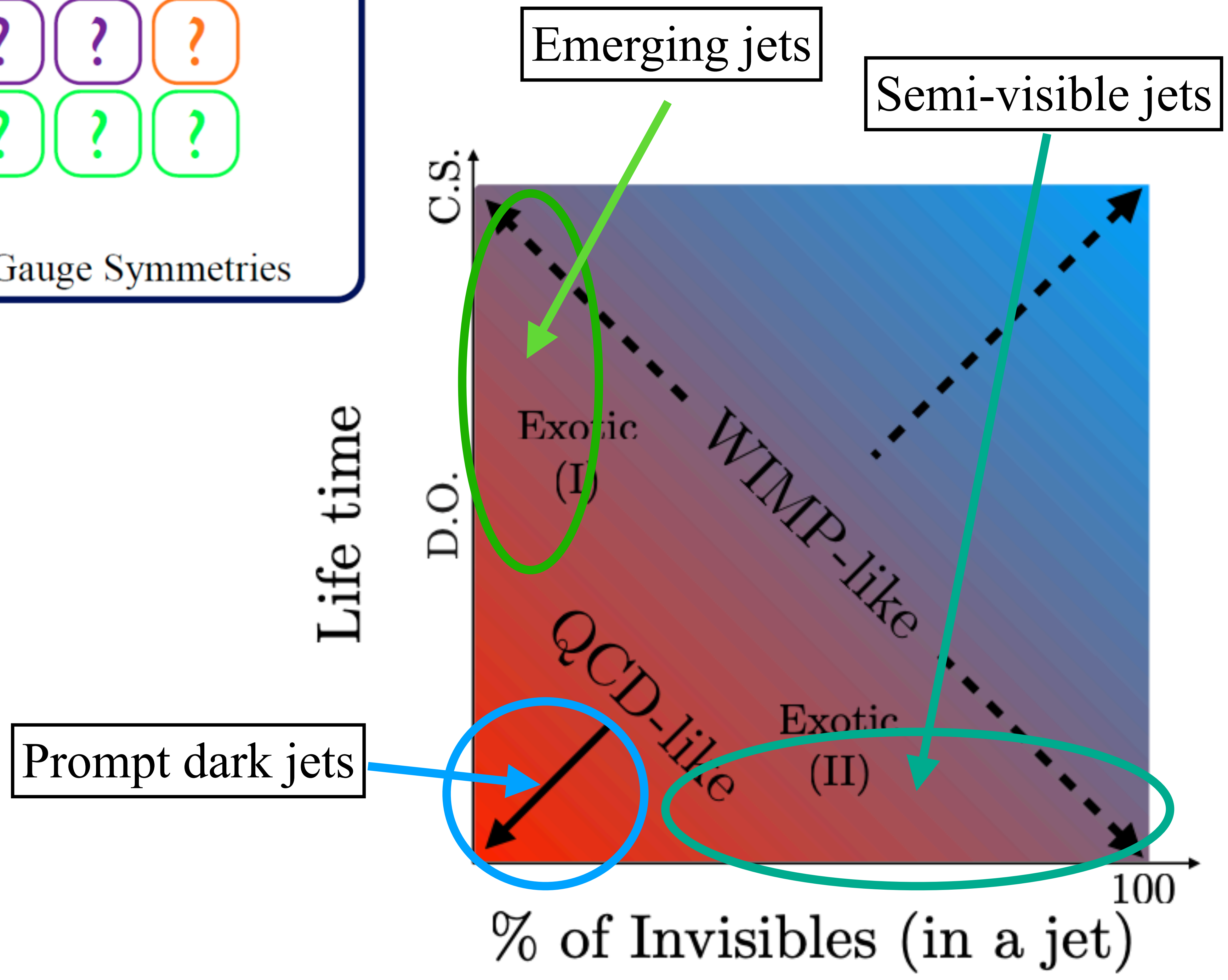
- In ATLAS these jets are reconstructed using energy deposits in the calorimeters and tracks in the inner detector

3.
Phenomenology of dark QCD and Emerging Jets

Dark QCD



- Dark QCD = extension of SM with a new hidden/dark sector with :
  - particles content & interactions ~ standard model QCD
  - dark particles can :
    - be stable and invisible → dark matter candidates
    - decay to SM particles → signal in detectors
  - can be produced in collider through a portal and will have similar signatures to SM QCD (jets)
- Search possible with ATLAS and the LHC (but large background)



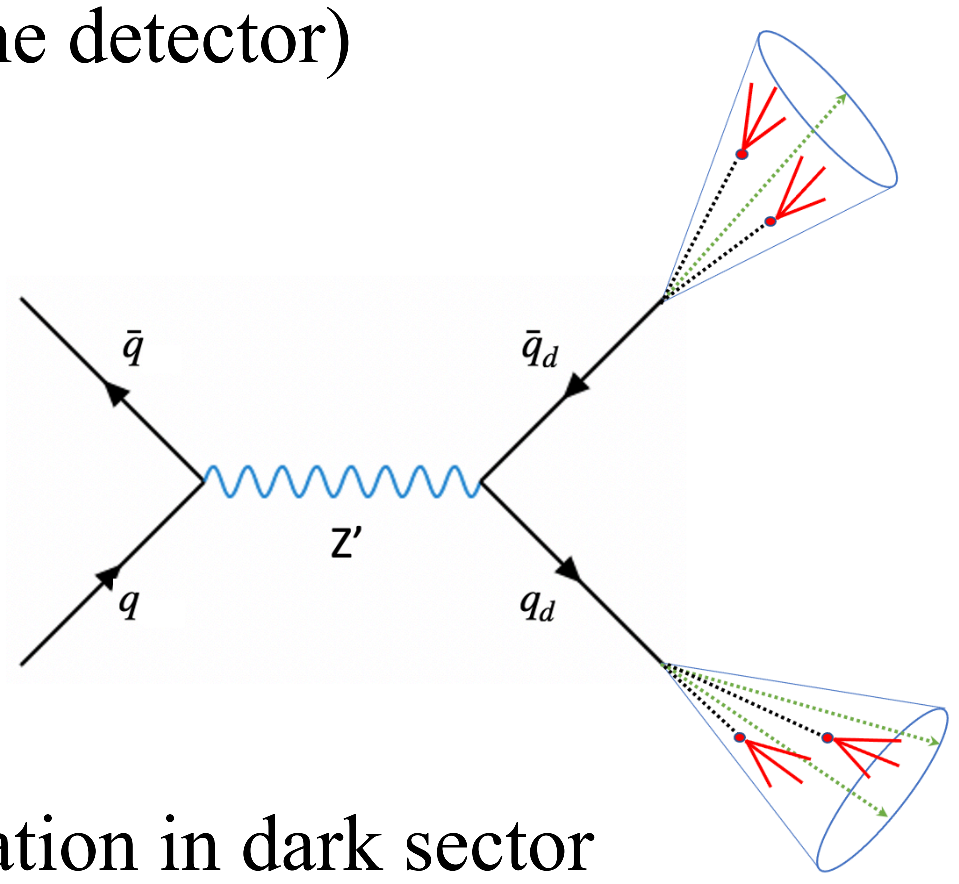
Expected signatures from a dark sector depending on the % of invisible particles and lifetime of the dark particles [1]

[1] M. Park and M. Zhang, "Tagging a jet from a dark sector with Jet-substructures at colliders," Phys. Rev. D, vol. 100, no. 11, p. 115009, 2019.

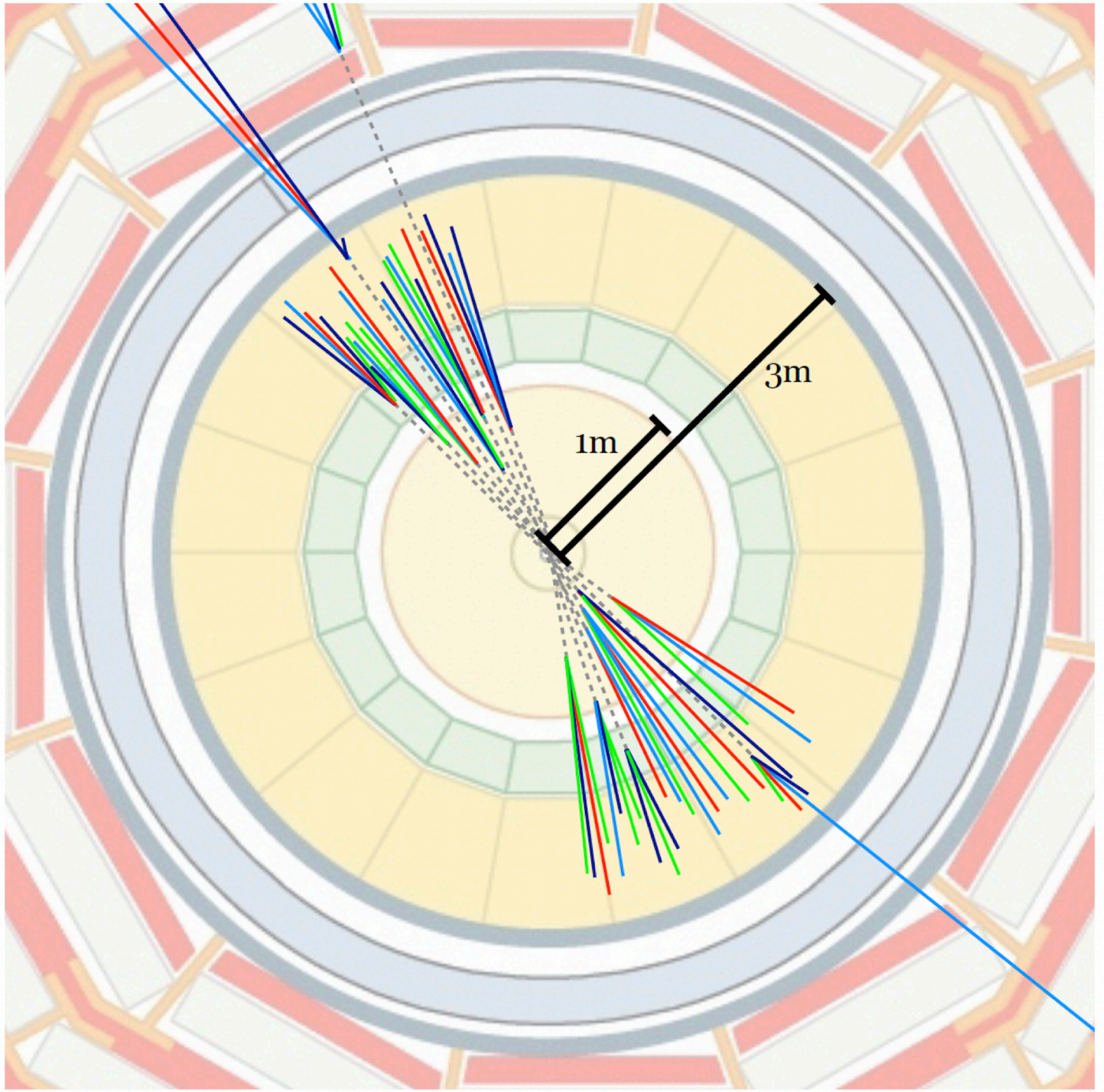
Dark QCD + LLP = Emerging Jets

Signature

- Emerging jets models obtained by having dark particles decay back to SM with a **sizeable lifetime** (providing visible displacement in the detector)
- Model :
  - Production of new vector boson Z'
  - Z' decays to two dark quarks
  - Dark quarks undergo parton shower and hadronisation in dark sector
  - All dark hadrons produced decay back to SM quarks at different points in the detector



- Signature :
  - 2 **large-R jets** with **un-prompt tracks** and **secondary vertices**
- First effort to study this signature

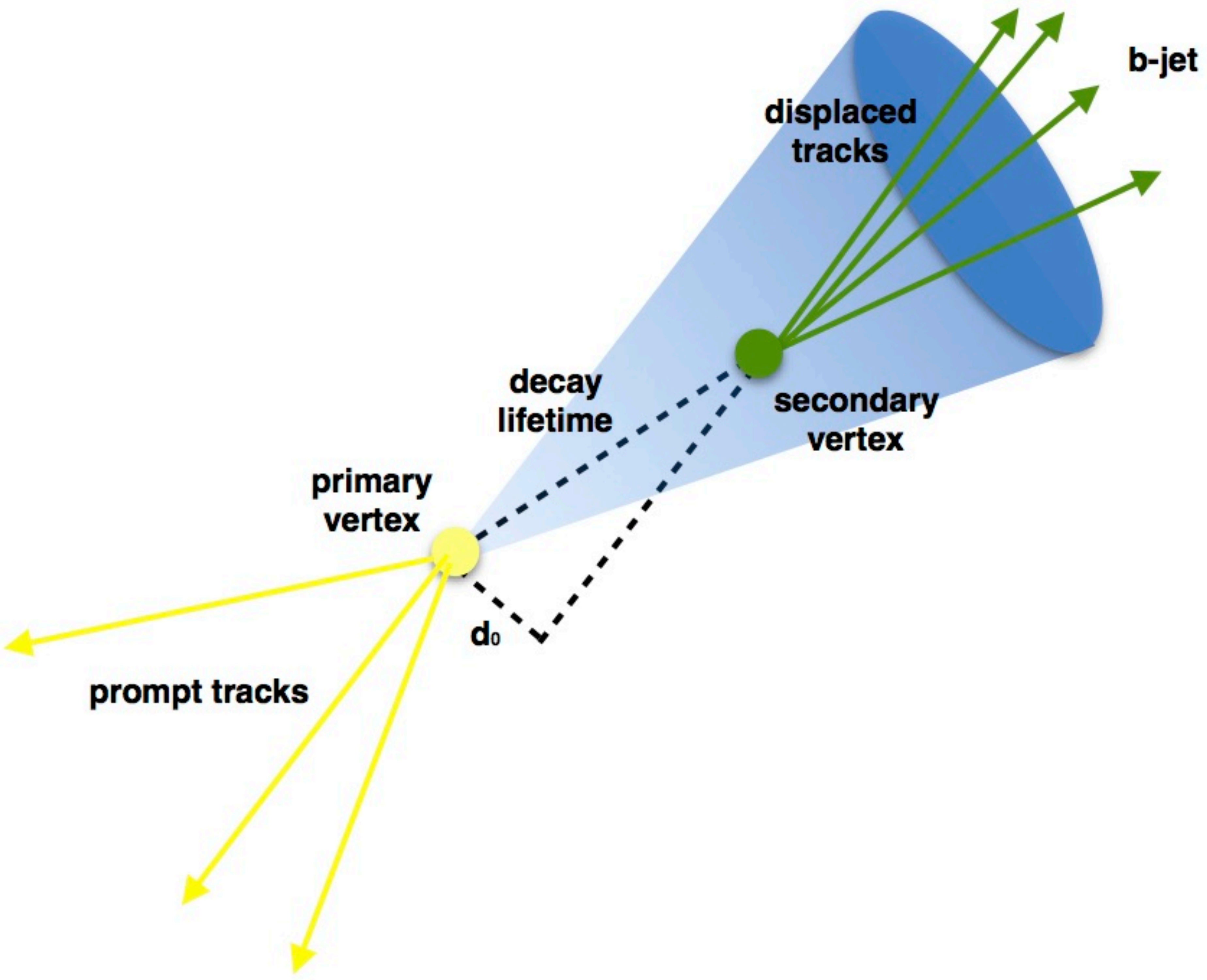


Signal specificities

- Large-R jet : large radius jet (larger than standard QCD jets) due to the double hadronisation (one in the dark sector, one in the SM sector) → broader particle dispersion

- Secondary vertex : decay position of a long lived particle = point of production of new particles, reconstructed from out-coming tracks

- Un-prompt track : tracks that are not produced at the interaction point but later at secondary vertices, characterised by large d_0, z_0



4.
Early Run-3 analysis on Emerging Jets with a two-jets topology

Emerging Jets models

MC simulation

- Models generated with Pythia Hidden Valley :
  - allows the addition of a simplified dark sector
  - with only two lightest dark hadrons (π_d and ρ_d)
  - tuneable free parameters
- **Free parameters** : $m_{Z'}$, N_f (number of flavours), N_c (number of colours), m_{π_d}, m_{ρ_d}, $c\tau_{\pi_d}$, decay modes, Λ_d
- Simulation of ATLAS detector with Geant4
- For now, only have access to one (small) lifetime

	Mogette ~~Model~~ A	Mogette ~~Model~~ E
m_{π_d}	5 GeV	0.8 GeV
$c\tau_{\pi_d}$	1 mm	1 mm
$m_{Z'}$	600-800-1000 GeV	600-800-1000 GeV
Decay to SM	Dark pions to quarks	
Decay in dark sector	Dark rhos to dark pions	

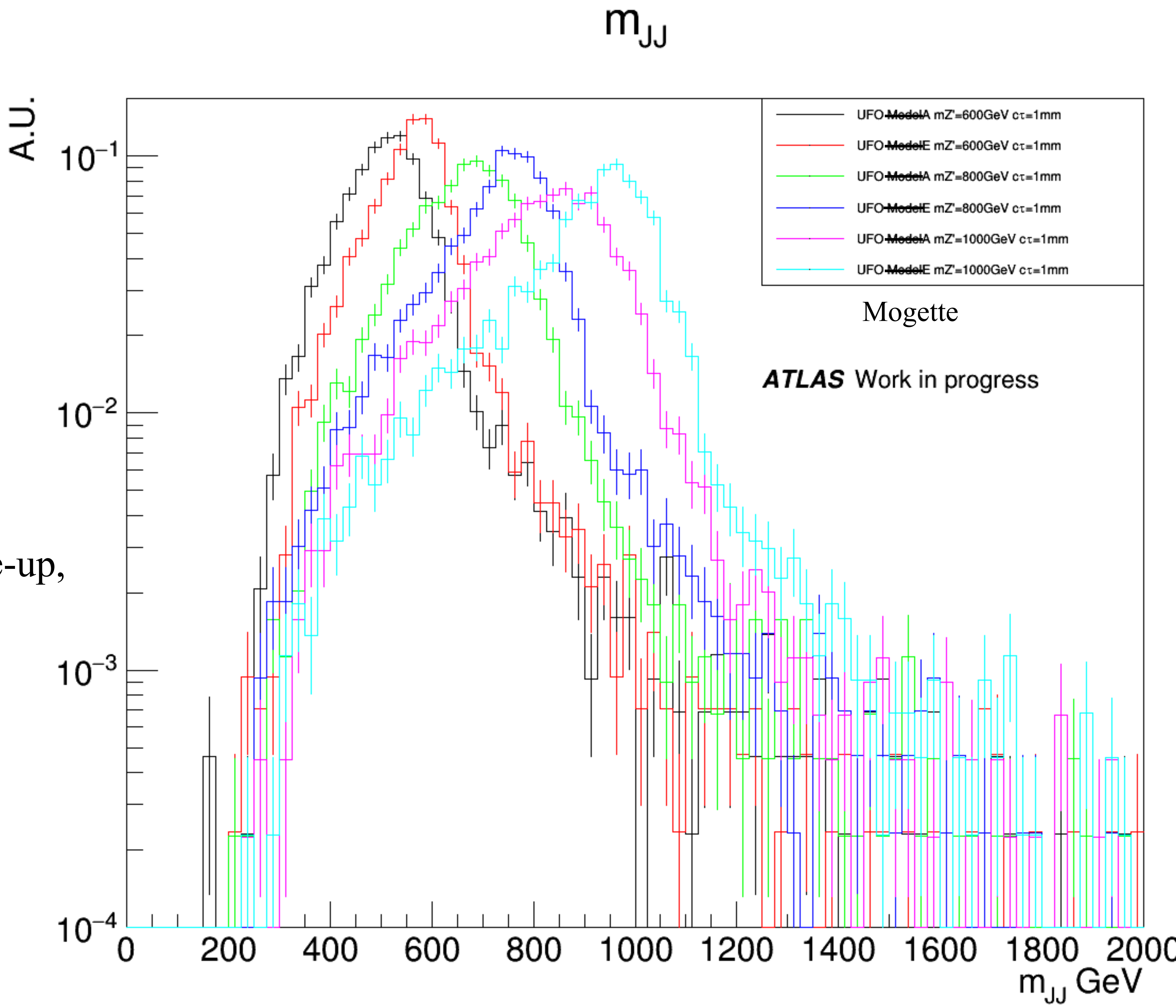
Signal characteristics

Invariant mass

- Dijet invariant mass : $m_{JJ} = |P_{j1} + P_{j2}|$
- Momentum conservation → should be equal to the mass of the Z'
- But :
  - jet reconstruction not perfect : some particles may be outside jet cone

    +

  - jet grooming : removing of low pT components of the jets to mitigate pile-up, affects dark QCD signal which produces a lot of soft particles



Trigger studies

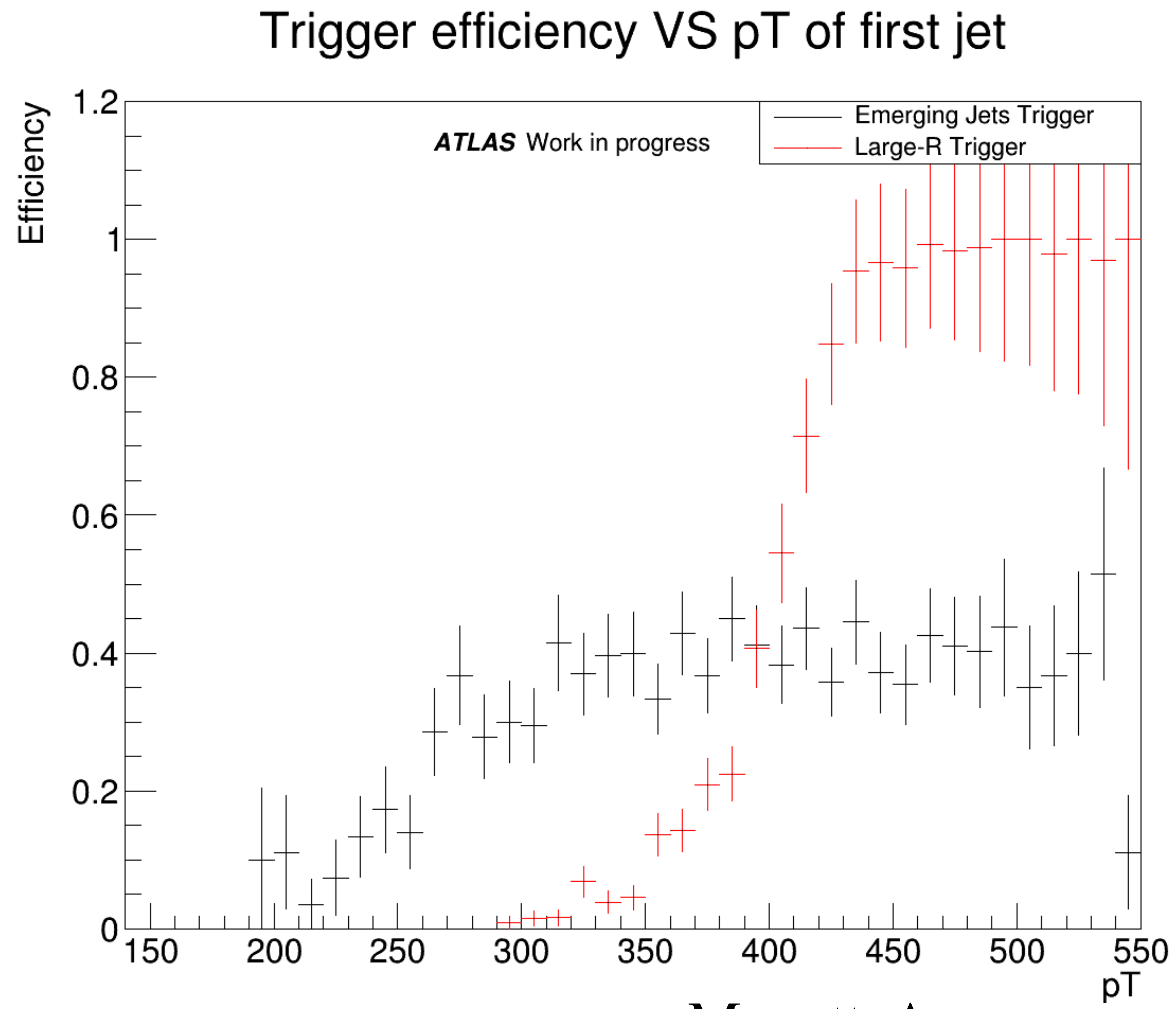
New emerging jets trigger for Run-3

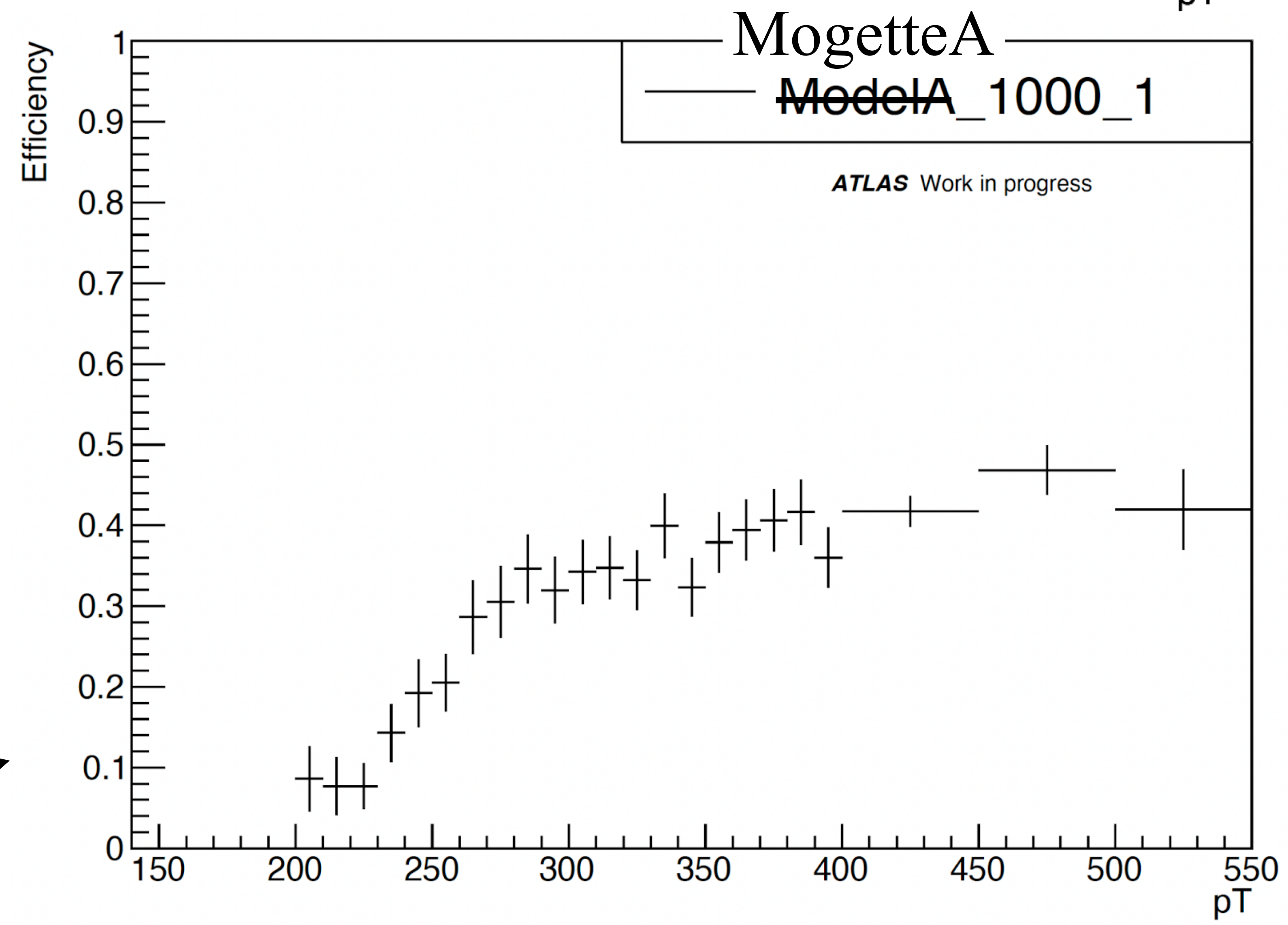
- New trigger for emerging jets is implemented in the Run-3 trigger menu
- HLT_j200_0eta180_emergingPTF0p08dR1p2_a10sd_cssk_pf_jes_ftf_preselj200_L1J100
- 1-jet trigger :
  - Based on large-R jets
  - Preselection : $p_T > 200 GeV$ and $|\eta| < 1.8$
  - Uses PTF variables as main selection (different PTF as the one in next slides)
- PTF = prompt track p_T fraction

$$PTF^{jet} = \frac{\sum_{trk \in jet} p_T^{trk}(d0 < 2.5\sigma_{d0,bkg}(p_T))}{p_T^{jet}}$$

- Selection of prompt tracks based on the d0 significance

→ Good efficiency on EJ samples / allows to lower the energy threshold

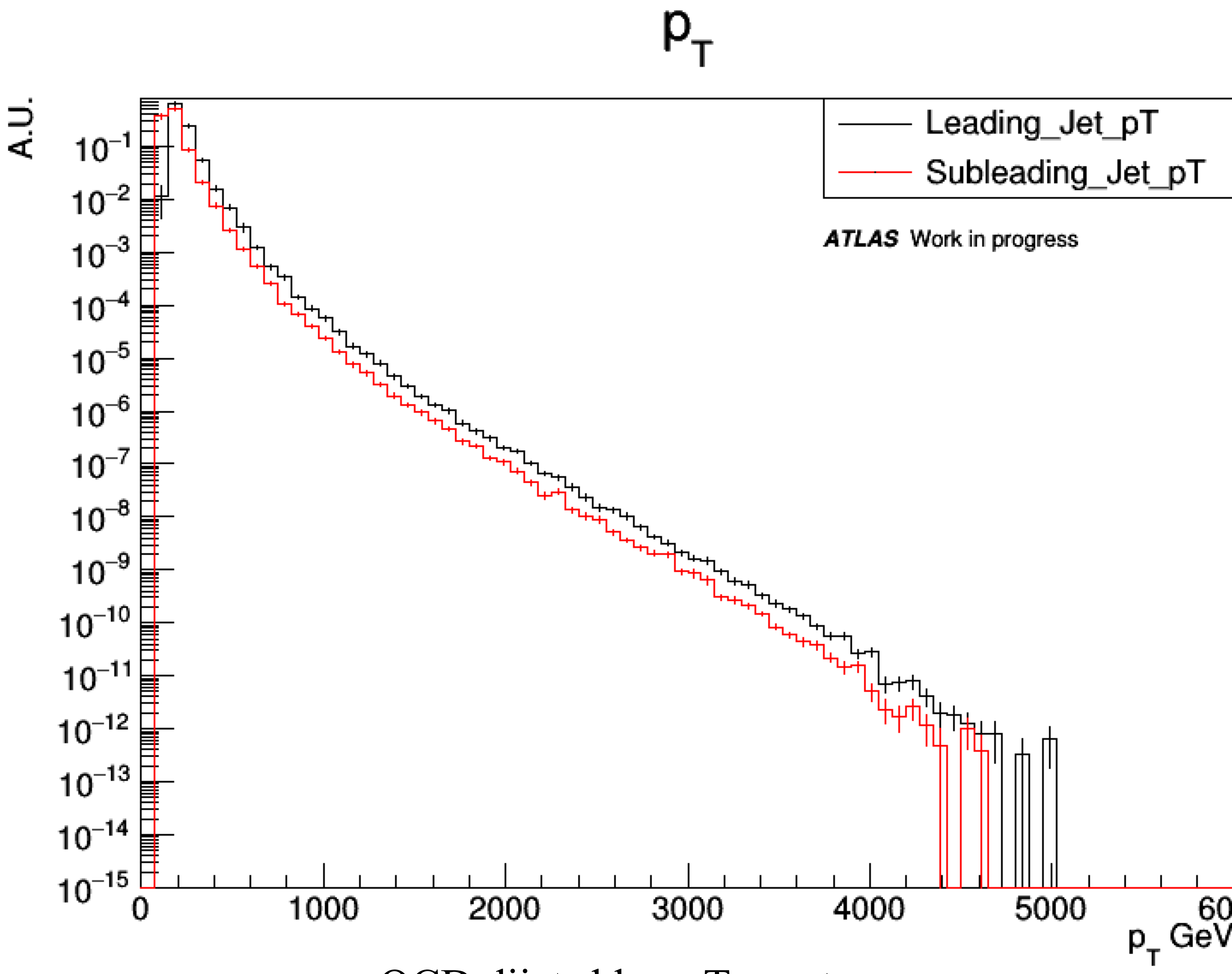




Signal discrimination

QCD dijets background

- Main objective of the analysis : **discriminate signal from SM background events**
- Main background of this analysis : QCD dijets events
  - events with two standard QCD jets
  - mostly with prompt tracks and no secondary vertices
  - but bottom initiated jets can lead to long lived B-mesons producing secondary vertices and un-prompt tracks
- Need to construct variables that are discriminating between EJs and QCD jets



QCD dijets bkg, pT spectrum

Signal discrimination

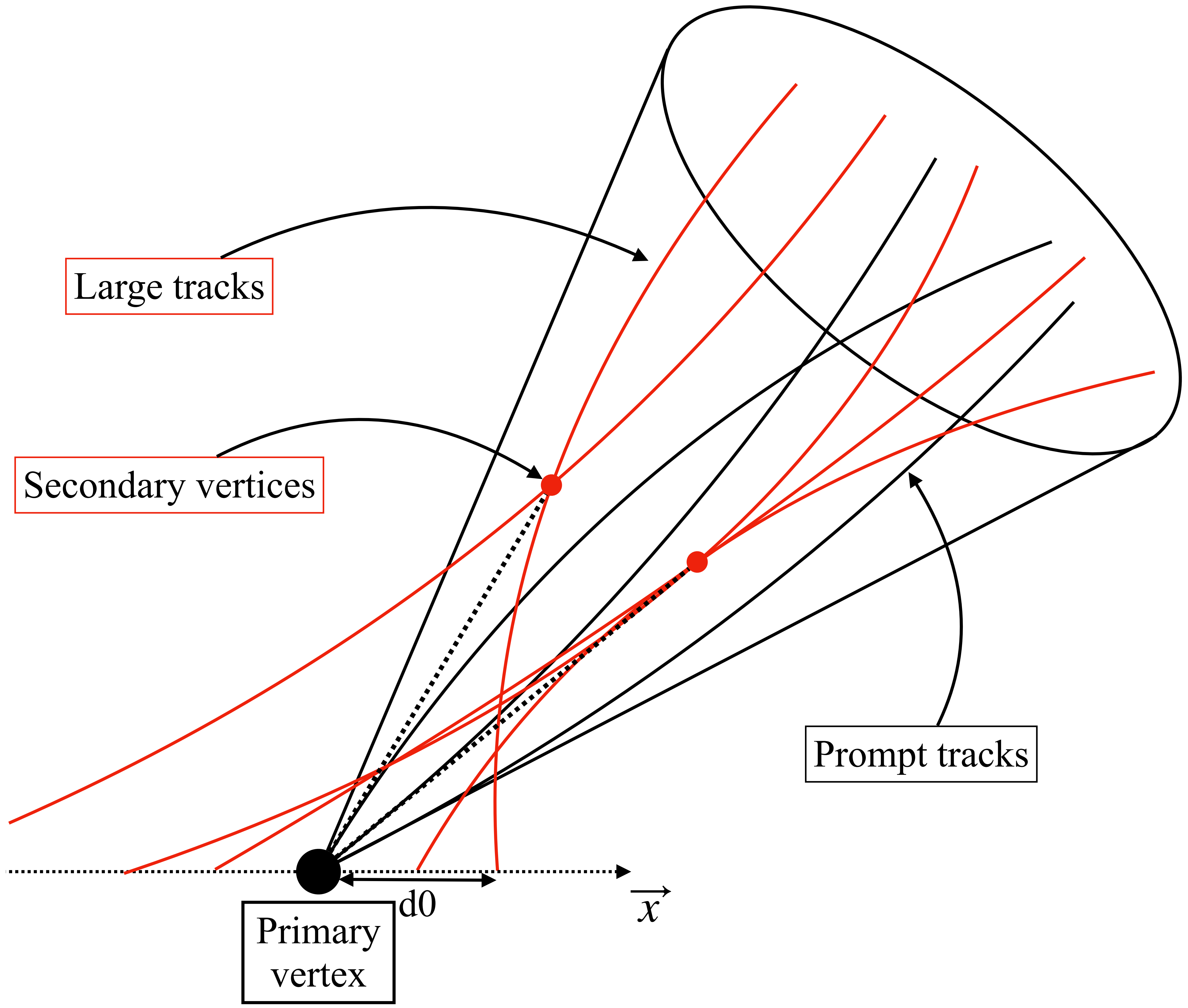
Tagging emerging jets

- **Tagging variables :**
  - fraction of prompt/large tracks in a jet $(\frac{N_{prompt/large}}{N_{tot}})$
  - pT fraction of prompt/large tracks in a jet $(\frac{\Sigma_{prompt/large}\ p_{T_{trk}}}{p_{T_{jet}}})$
  - median of $|d0|$ of all tracks in a jet

- **Selection on tracks :**
  - p_T and $\Delta z = |z0_{trk} - z_{PV}|$ cut (for pile-up mitigation)
  - Prompt/large tracks distinction :
    - z0-based definition (need a good identification of the hard scatter PV)
    - d0-based definition
    - can use track association to the selected PV as definition for prompt tracks
    - or combinations

Signal discrimination

Select prompt tracks



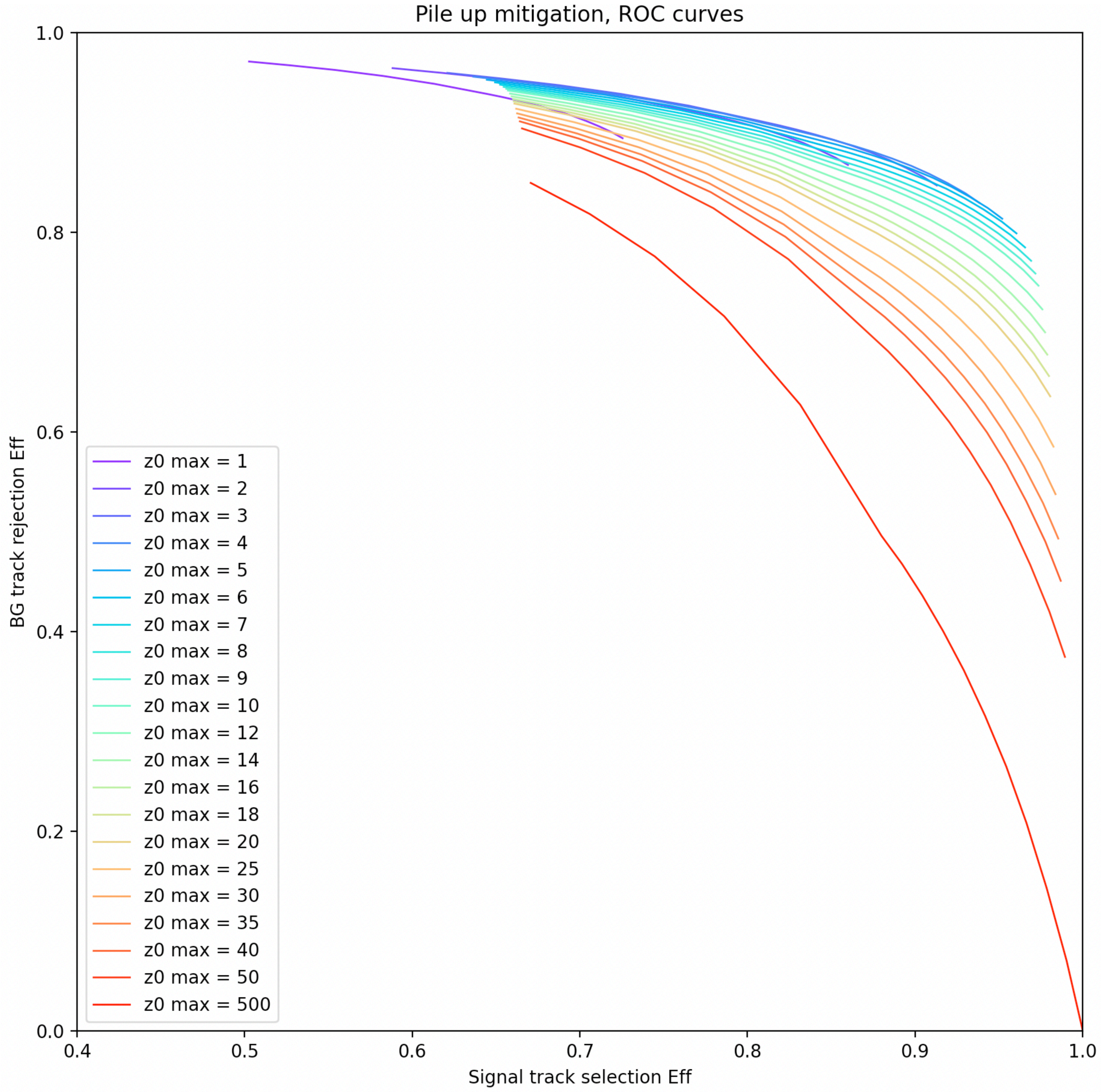
- Easiest way to select prompt tracks = select tracks associated to the main Primary Vertex (PV)
- Reciprocally, large tracks = tracks not associated to the main PV
- Definition can lead to the selection of large tracks coming from other interactions (other PVs)

  → pile-up mitigation, remove tracks coming from different PV

Signal discrimination

Pile-up tracks mitigation

- Some tracks in a jet are not coming from the decays of dark mesons
- Comes from others interaction in the event (pile-up)
- Need a way to select signal tracks as much as possible and removes others
- Apply cut :
  - $p_{T_{trk}} > p_{T_{min}}$
  - $\Delta z = |z0_{trk} - z_{PV}| < z_{max}$
- Compute signal track selection efficiency / noise track rejection efficiency
- Best cut :
  - $p_{T_{min}} = 0.7 GeV$
  - $z_{max} = 4mm$
  - **Sel eff : 89.6% / Rej eff : 86.8%**

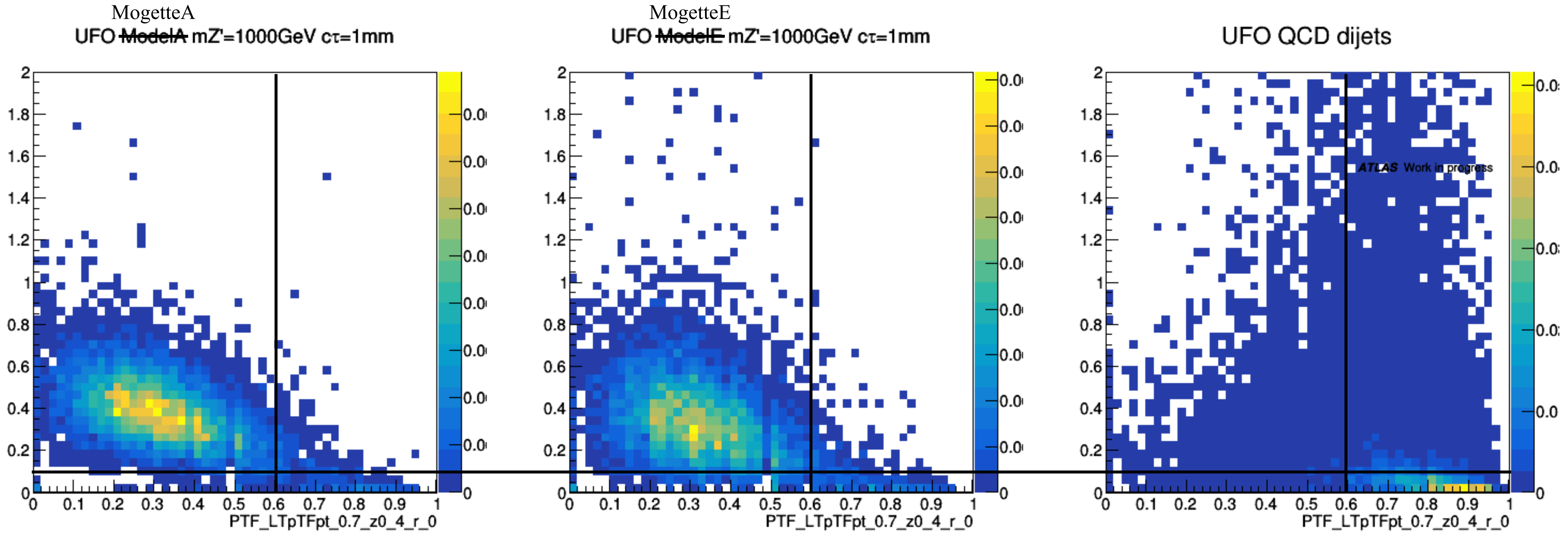


Mogette A, $m_{Z'} = 1TeV, \quad c\tau = 1mm$

Signal discrimination

Preliminary results

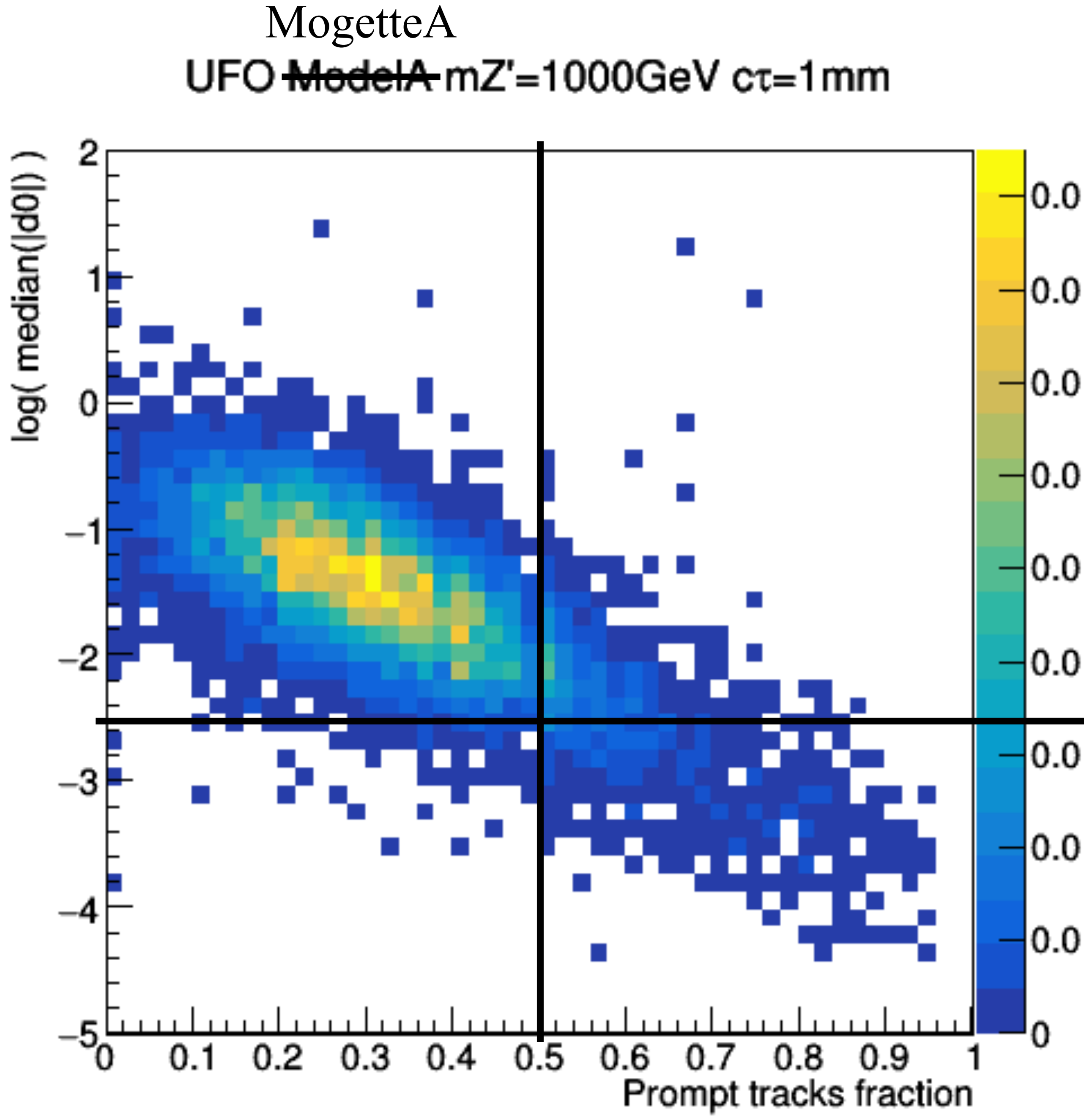
- Prompt track fraction VS Large track pT fraction
- Prompt tracks = tracks ∈ PV
- Tracks selection : $p_{T_{min}} = 0.7GeV \,/\, z_{max} = 4mm$
- Very good discriminating power

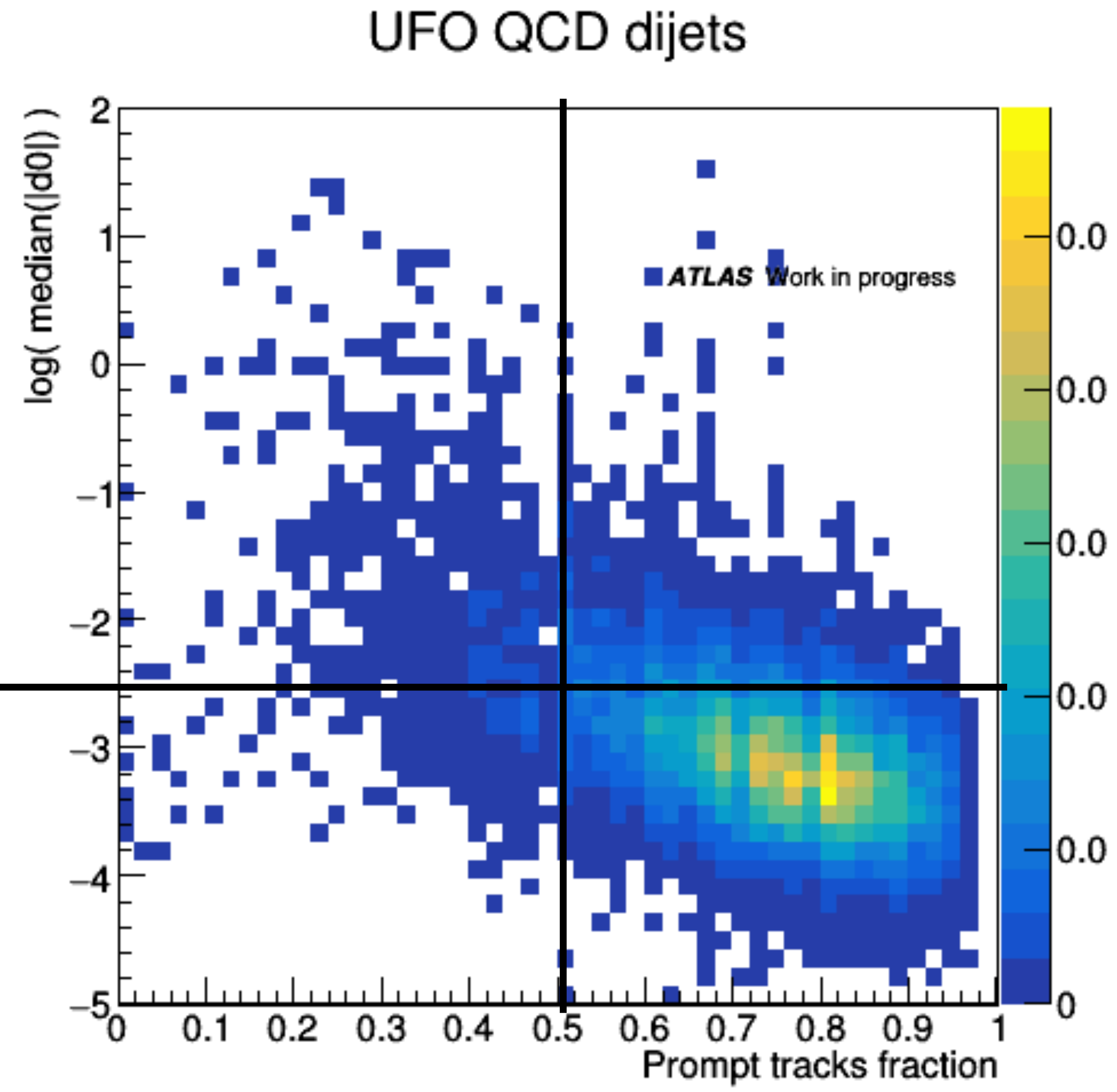


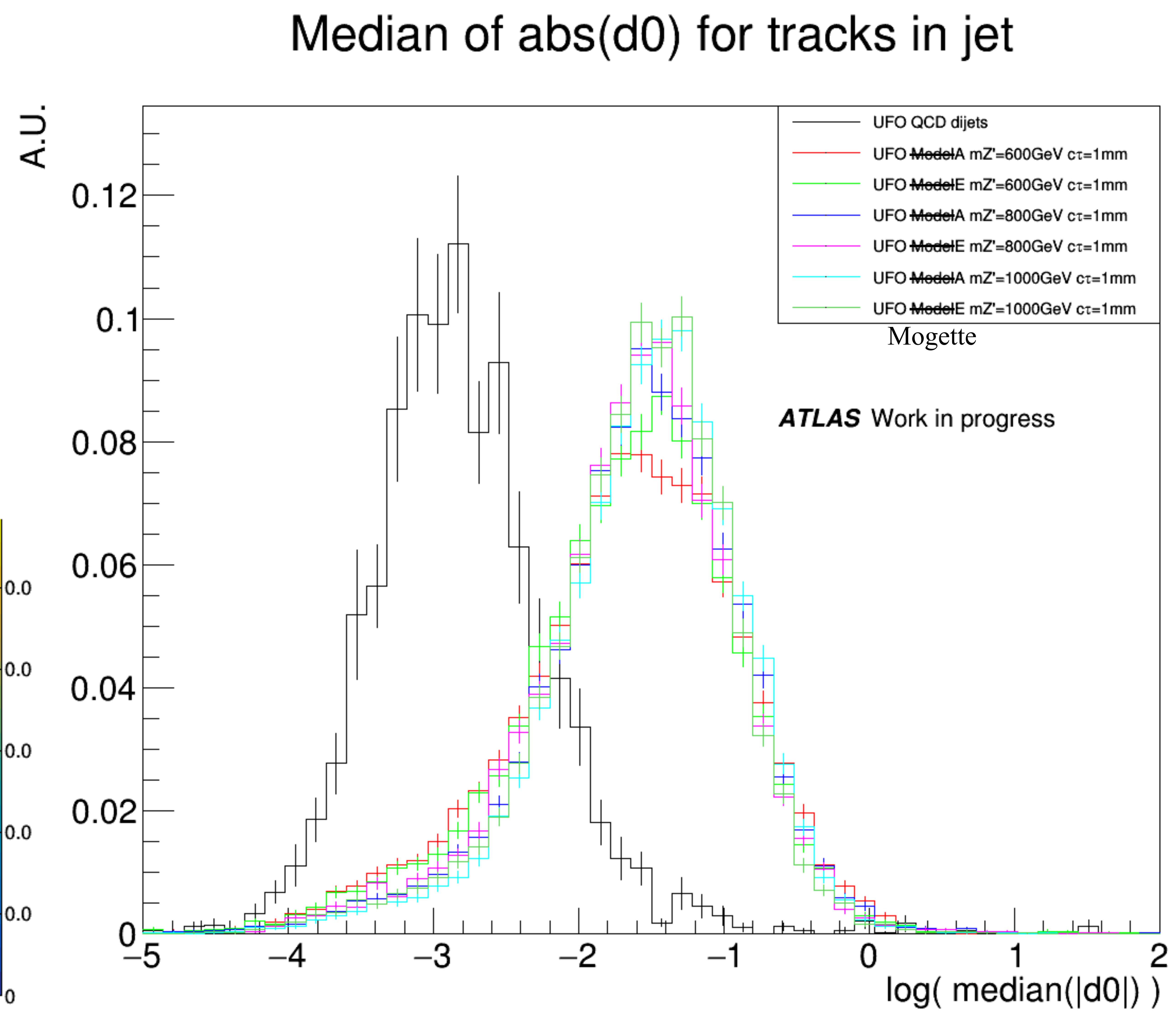
Signal discrimination

Preliminary results

- Median of tracks' $|d0|$
- Tracks selection : $p_{T_{min}} = 0.7GeV / z_{max} = 4mm$
- Really interesting as it does not need to differentiate between prompt and large tracks







Signal discrimination

First try of selection efficiency

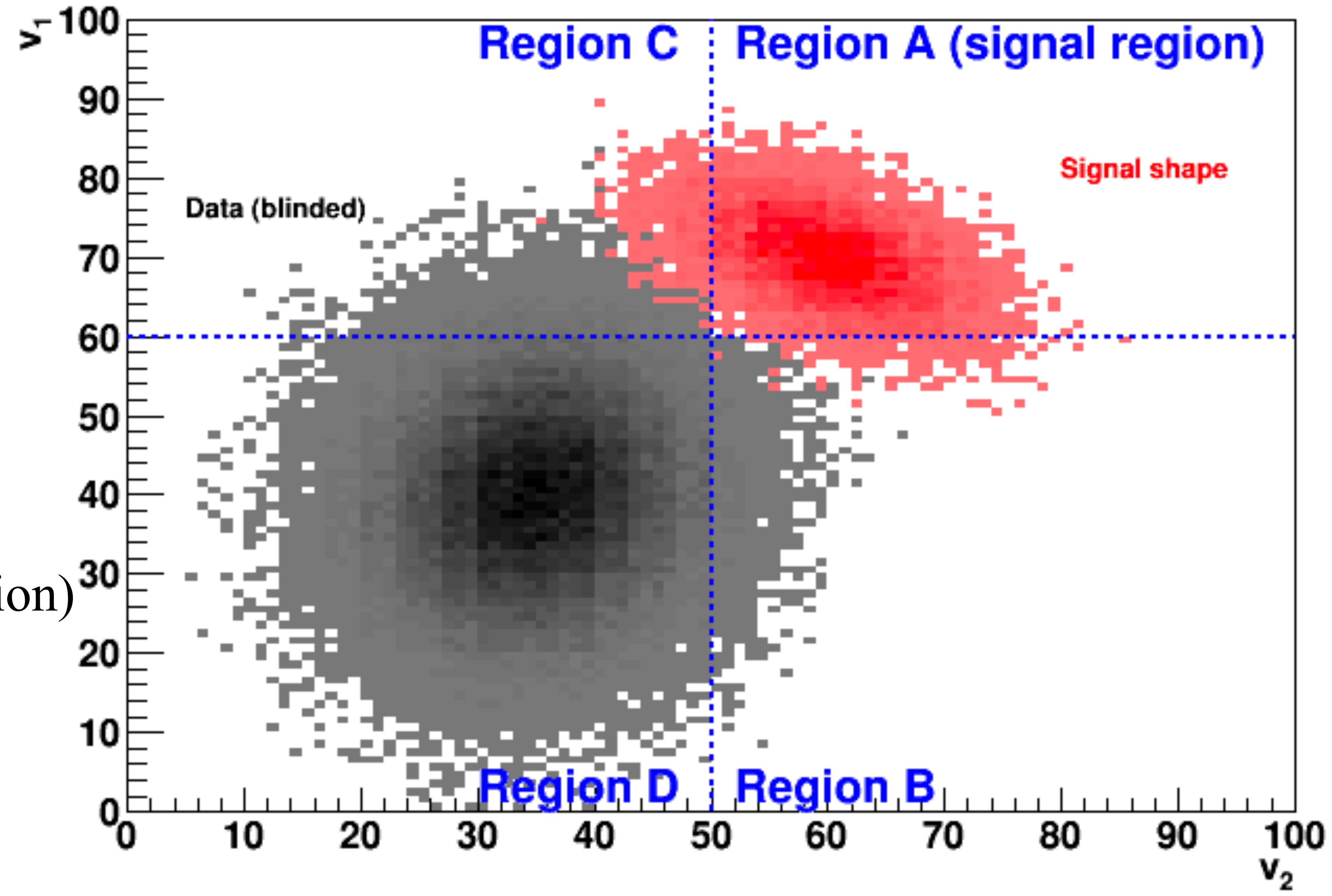
- Apply a list of selection to signal / background
- Pre-selections to mimic the EJ trigger : at least one jet with pT > 300GeV and trigger-PTF < 0.08 (pre-sel efficiency : 39.72%)
- Tracks selection : $p_{T_{trk}} > p_{T_{min}}$; $\Delta z = |z0_{trk} - z_{PV}| < z_{max}$
- Jet selection : p_T, PTF (prompt track frac), LTpTF (large track pT frac), medD0 (median of |d0|)
- Apply these selection for different cut values

- Best efficiencies :
  - Tracks : pT > 0.5 GeV, $\Delta z < 12$ mm
  - 2 first jets : pT > 300 GeV, PTF < 0.7 , LTpTF > 0.05 , med d0 > 0.01 mm
  - Signal selection efficiency : 32.84 %
  - Bkg rejection efficiency : 99.92%

Analysis strategy

Cut and count analysis

- EJs signature is highly specific and different from SM jets → **simple cut and count analysis**
- Define a signal region where most of the signal is selected and the bkg are mostly rejected
- Estimate the remnant number of background event using an **ABCD method**
- Principle :
  - construct 4 regions based on two variables* :
    - A (signal region, enriched in signal events)
    - B, C, D (control regions, enriched in background events and poor signal contamination)
  - use the assumption that $\frac{N_C^{bkg}}{N_D^{bkg}} = \frac{N_A^{bkg}}{N_B^{bkg}}$ (background evenly distributed)
  - Then $N_A^{bkg,estimated} = \frac{N_C^{bkg}}{N_D^{bkg}} N_B^{bkg}$
- Finally look for an excess of events in the signal region : does $\mathbf{N_A^{obs}} > \mathbf{N_A^{bkg,estimated}}$?

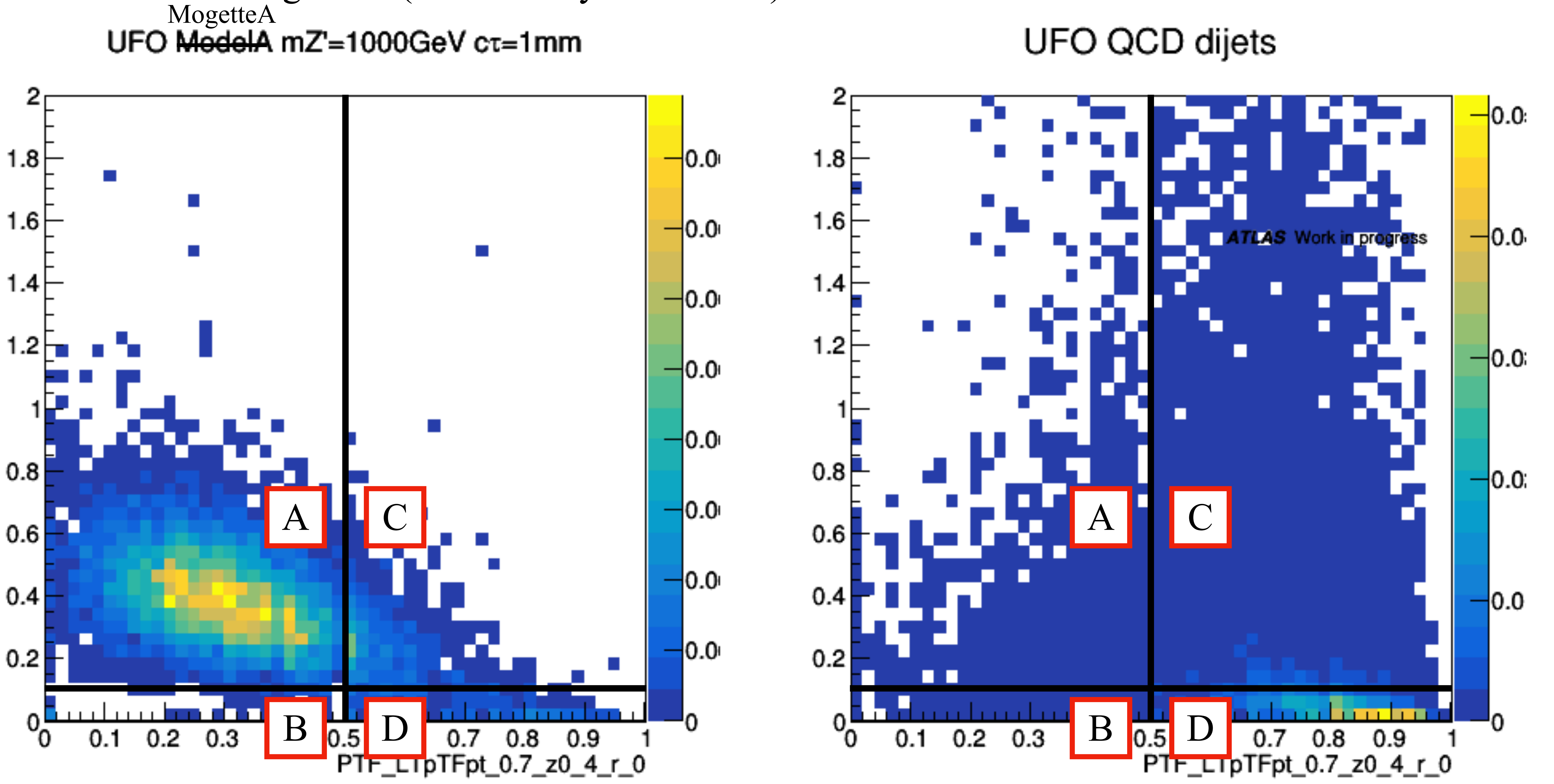


*have to un or lowly correlated

Background estimation

First test

- To work this method needs two variables that are uncorrelated for background (to be evenly distributed)
- Use PTF / LTpTF plane for background estimation :
  - $N_A^{bkg} = 1112$
  - $N_B^{bkg} = 2448$
  - $N_C^{bkg} = 9261$
  - $N_D^{bkg} = 52472$



- $N_A^{bkg,estimated} = \frac{N_C^{bkg}}{N_D^{bkg}} N_B^{bkg} = 432$

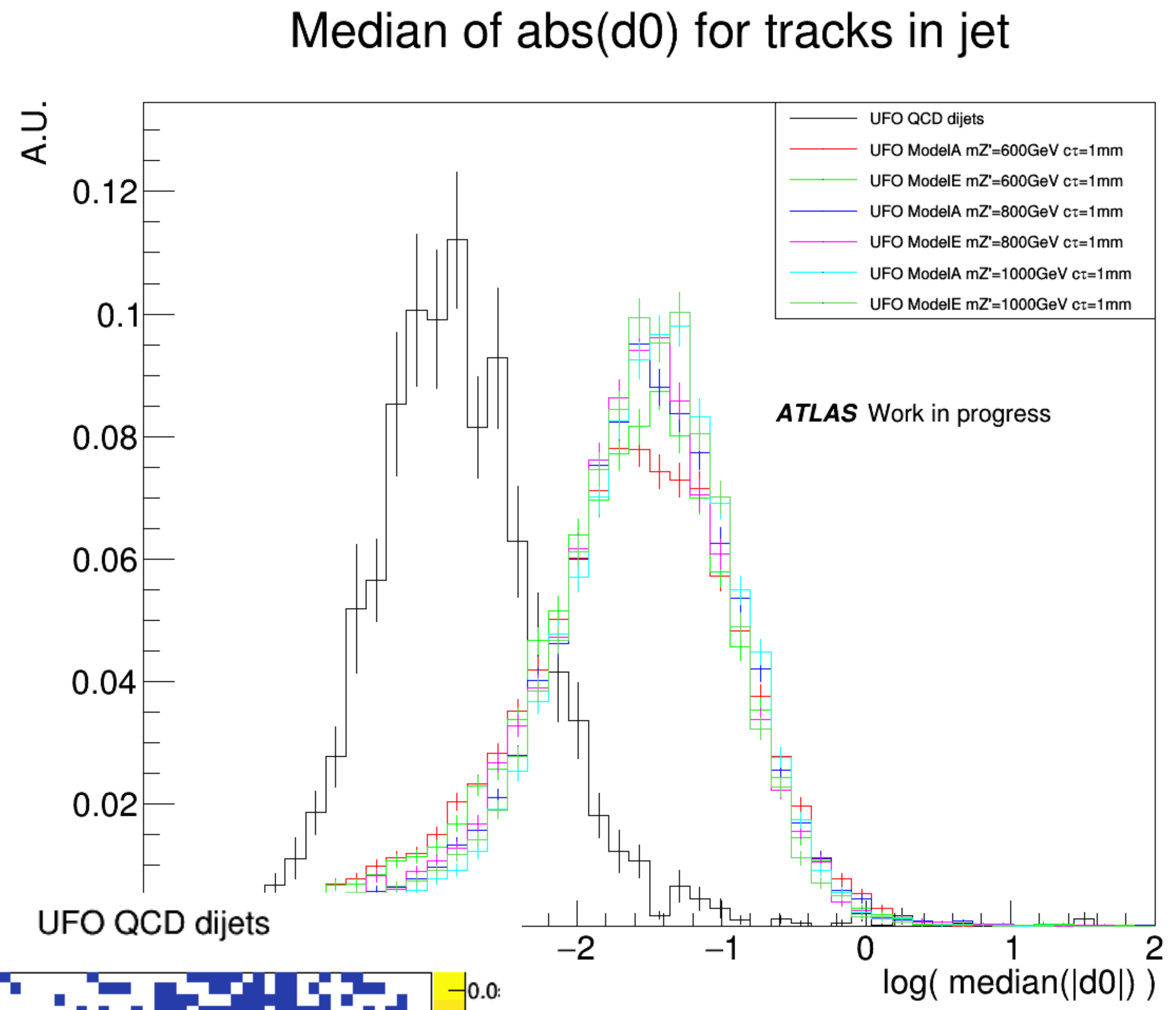
- Does not give a good estimation even by adding statistics and systematics uncertainties

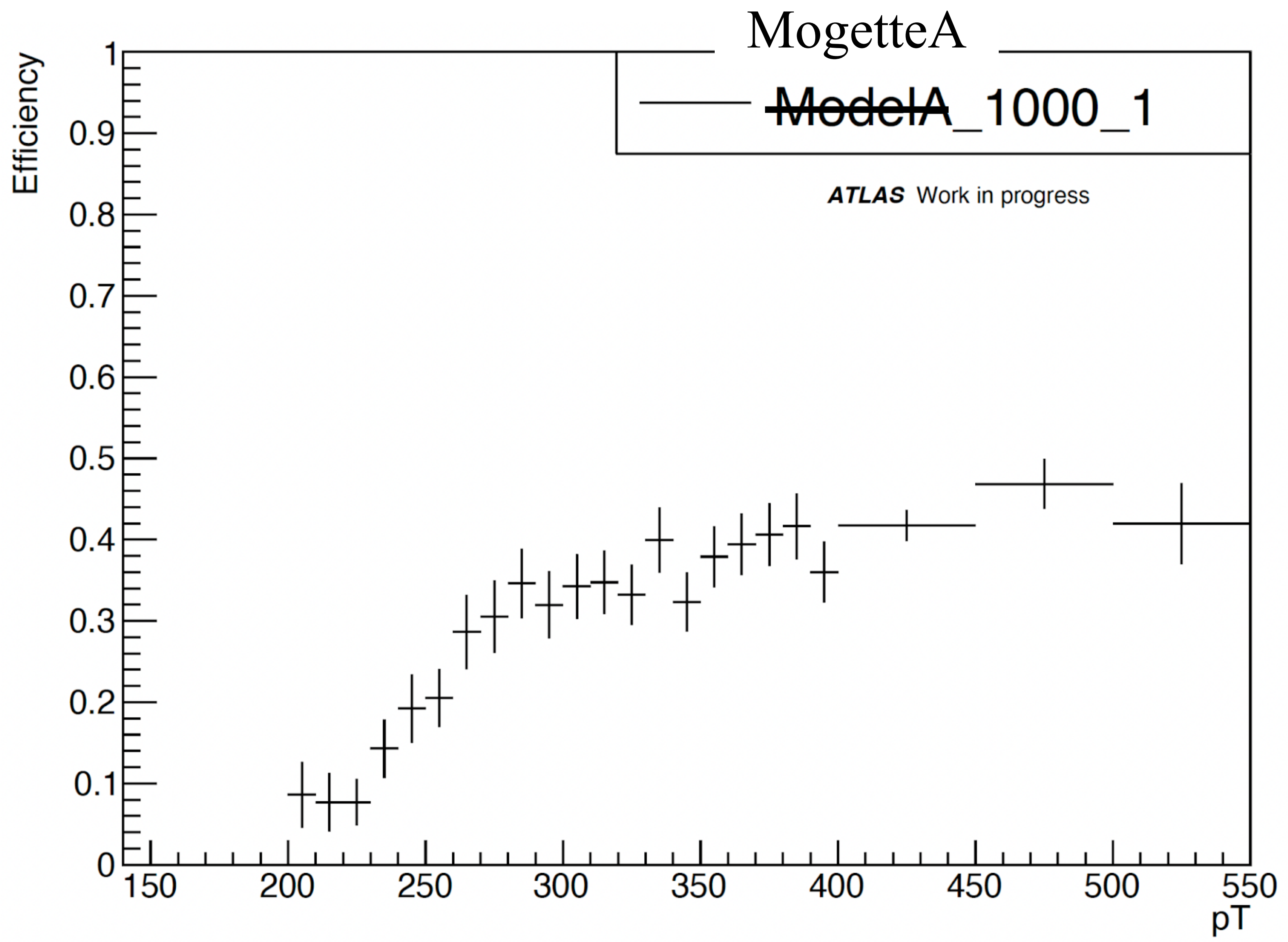
  → variables are not uncorrelated, have to search for a better set of variables (plan to look in jets' substructure variables)

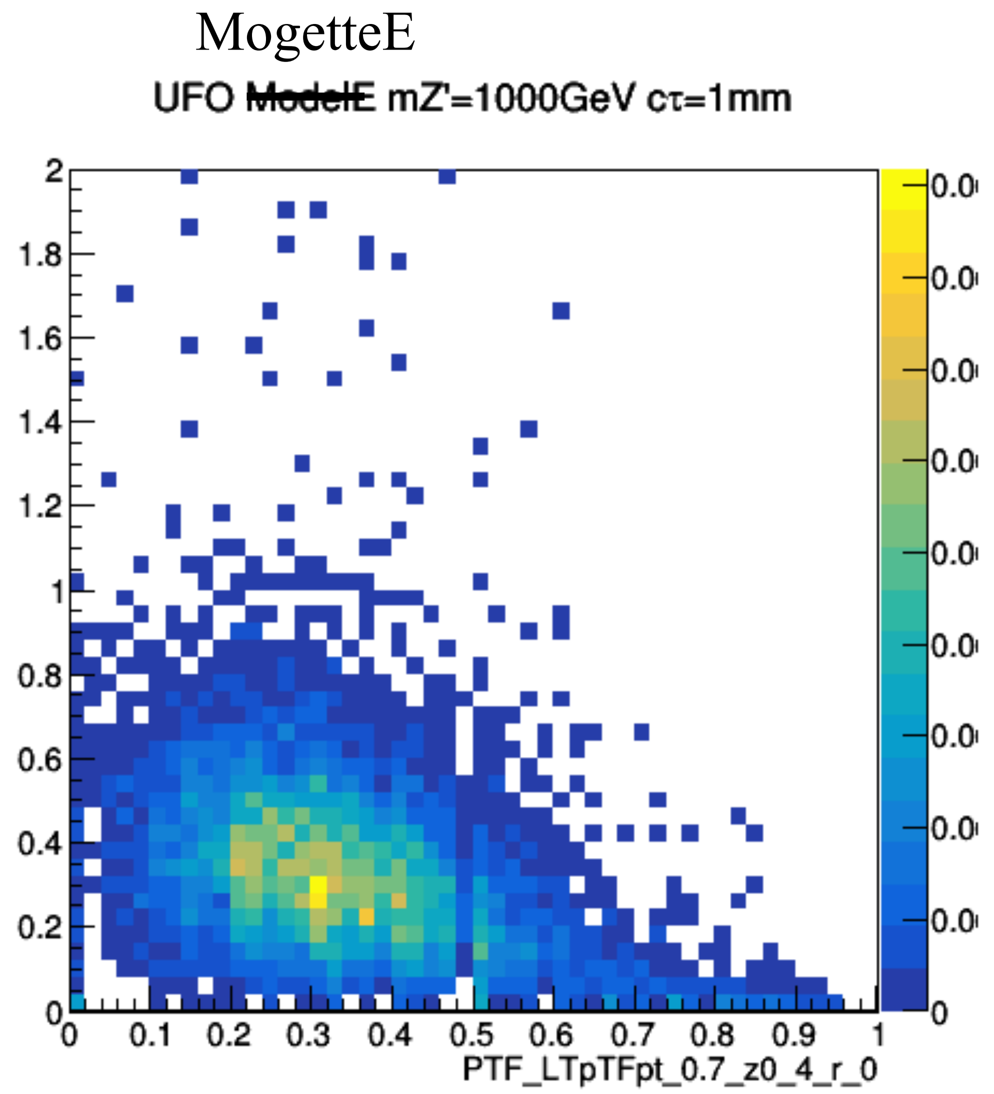
Conclusion

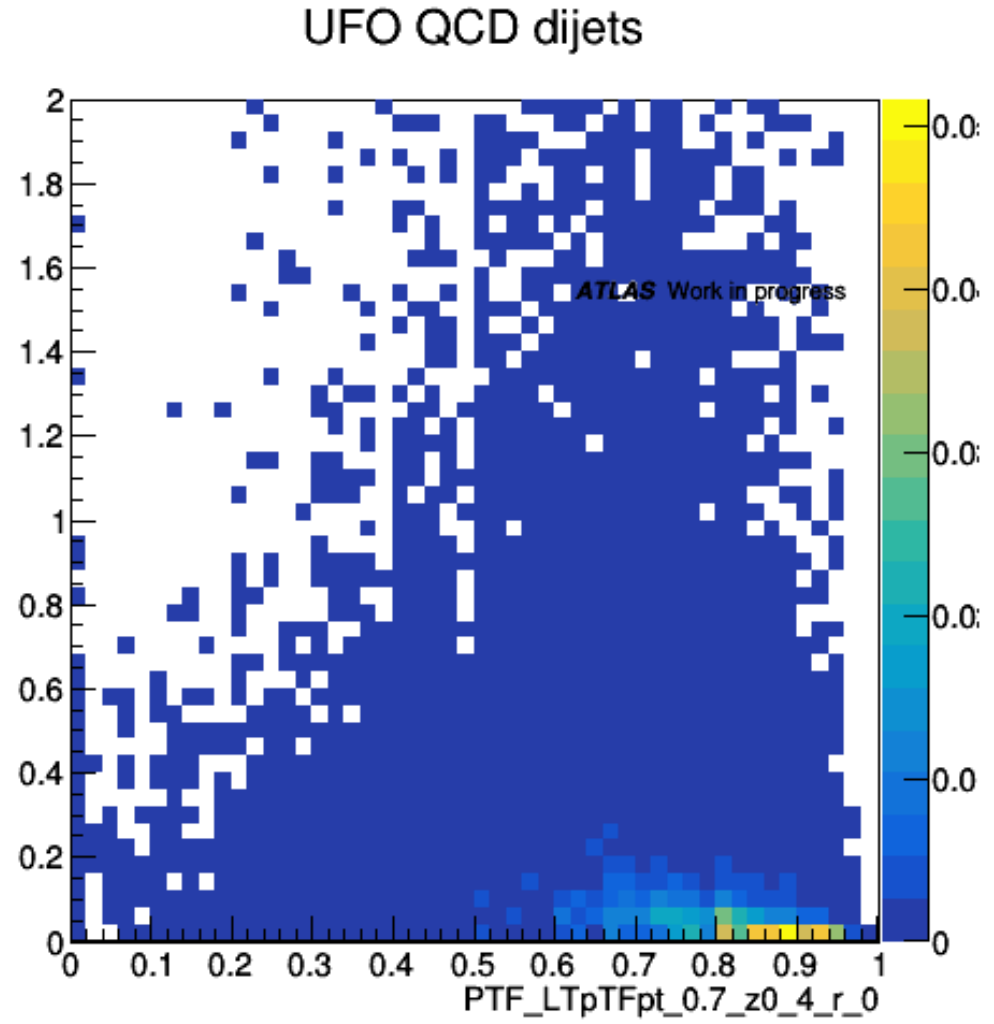
Conclusion

- Presented here the status of an Early Run-3 analysis aiming at Emerging Jets with ATLAS
- It is the first effort on this signature
- Preliminary studies have shown promising results for signal discrimination
- A complete re-investigation will be needed for samples with longer lifetimes
- Analysis strategy in place and needs validation







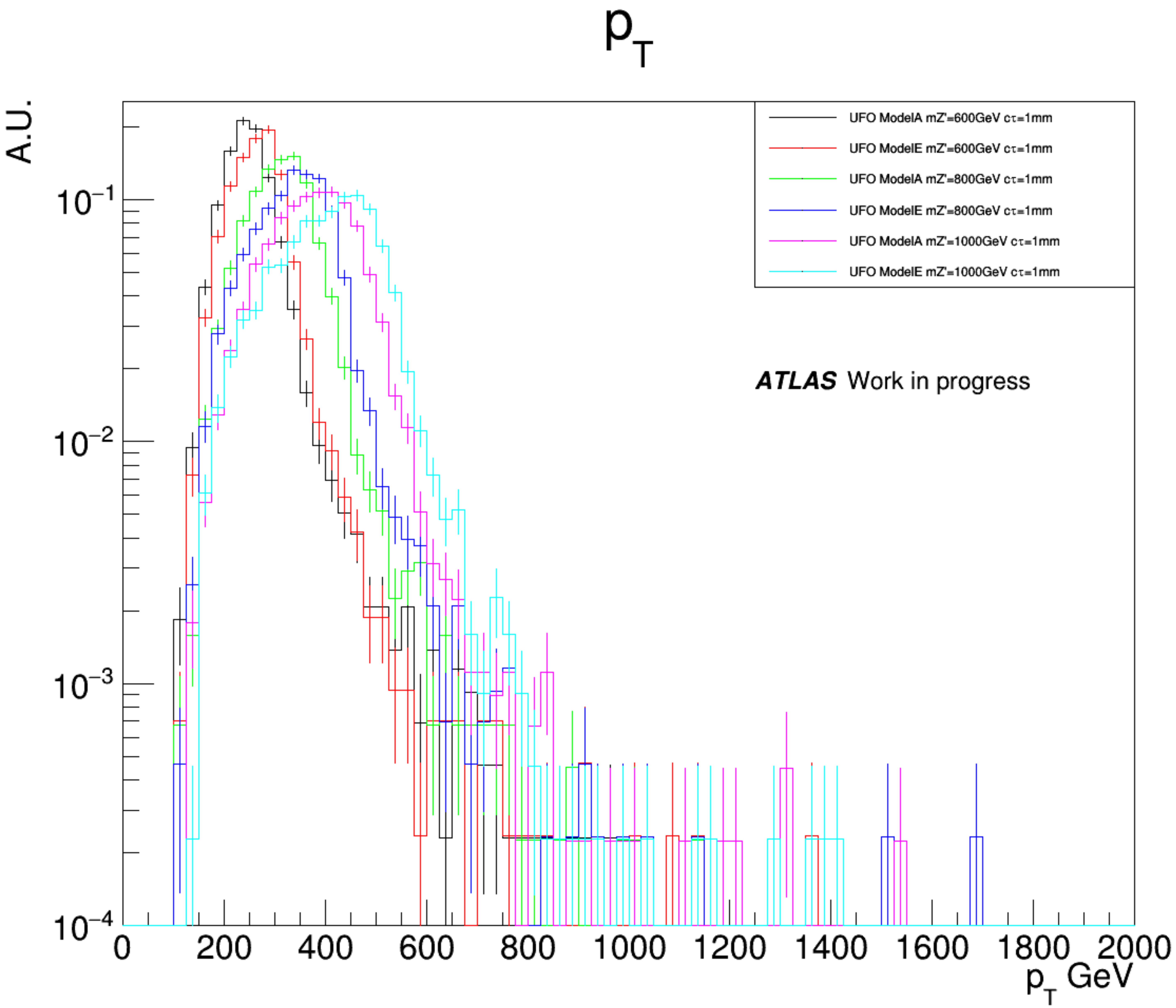


Thank You

Back-up

Signal characteristics

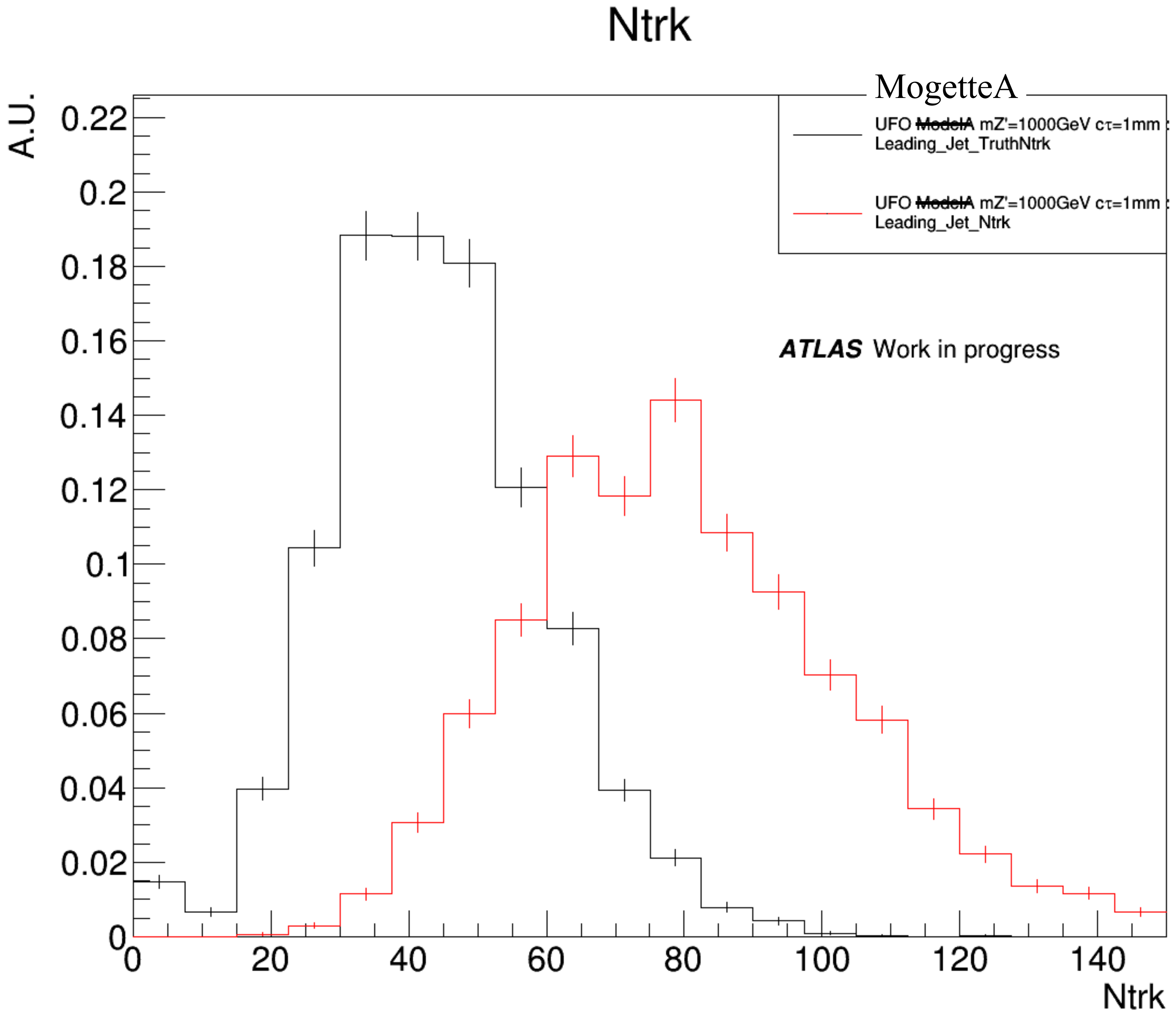
pT spectrum

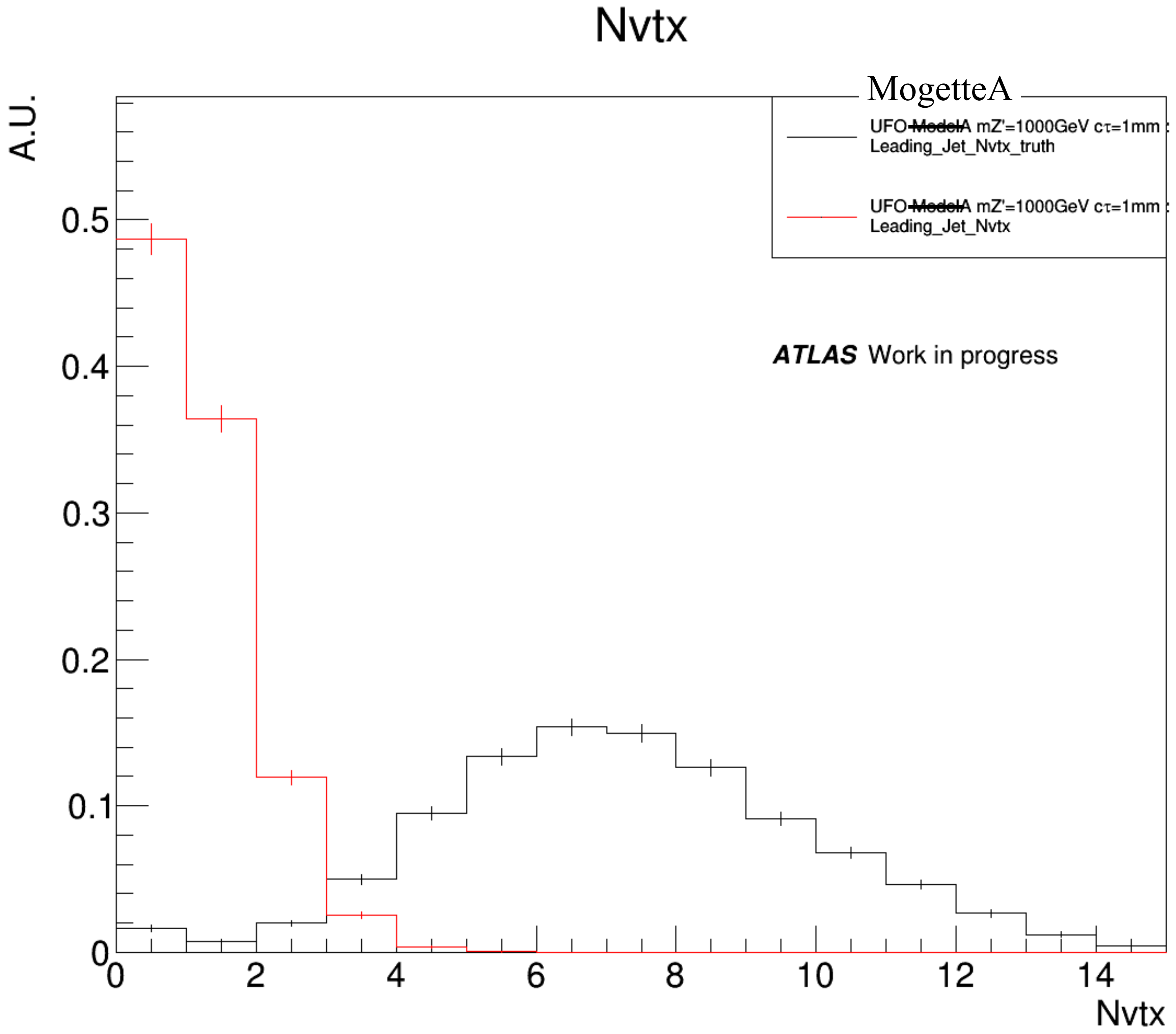


Signal characteristics

Inner detector objects

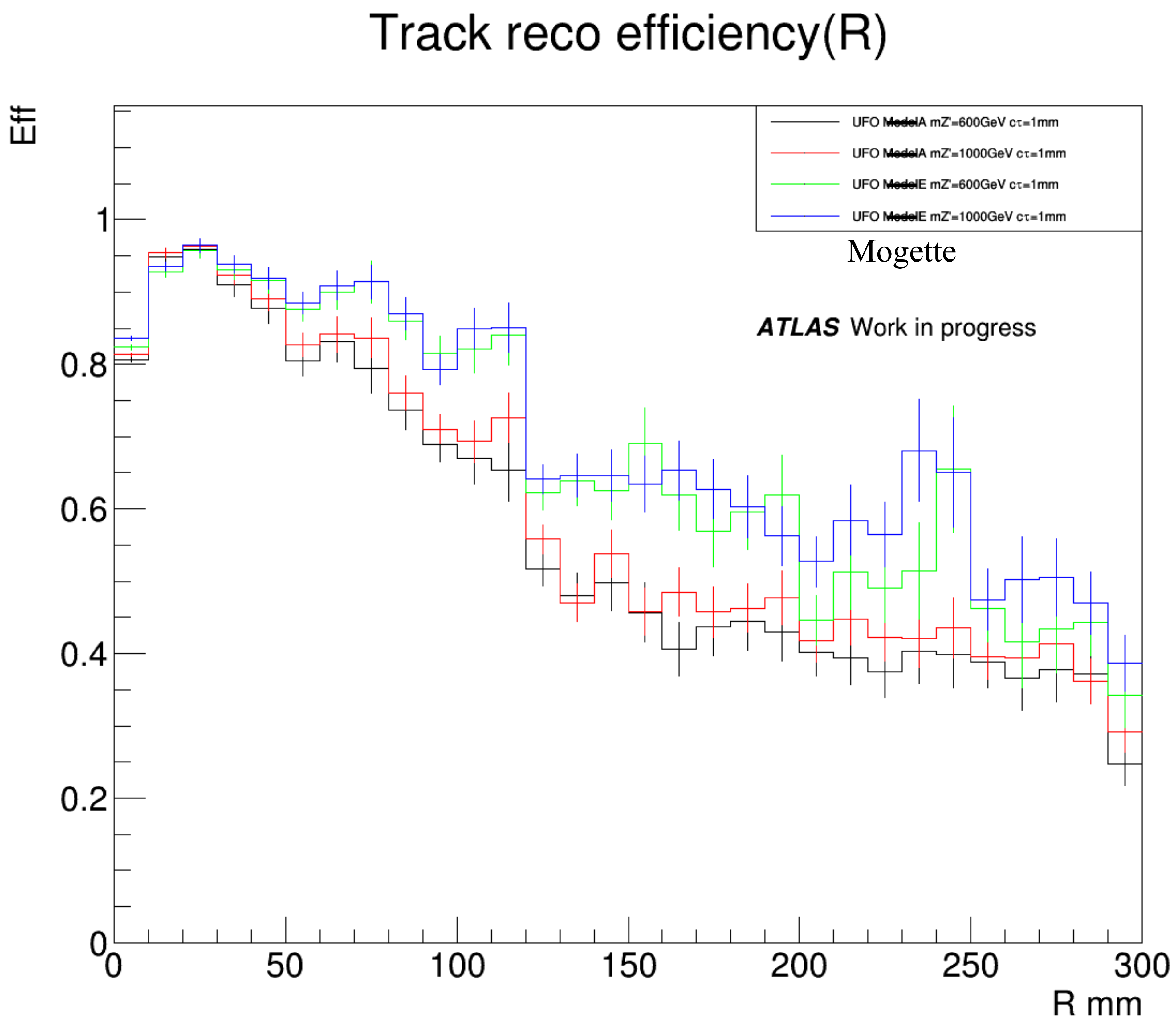
- Number of tracks and secondary vertices in one jet
- Large differences between truth and reconstructed numbers
- For different reasons :
  - Reconstruction efficiencies
  - Pile-up

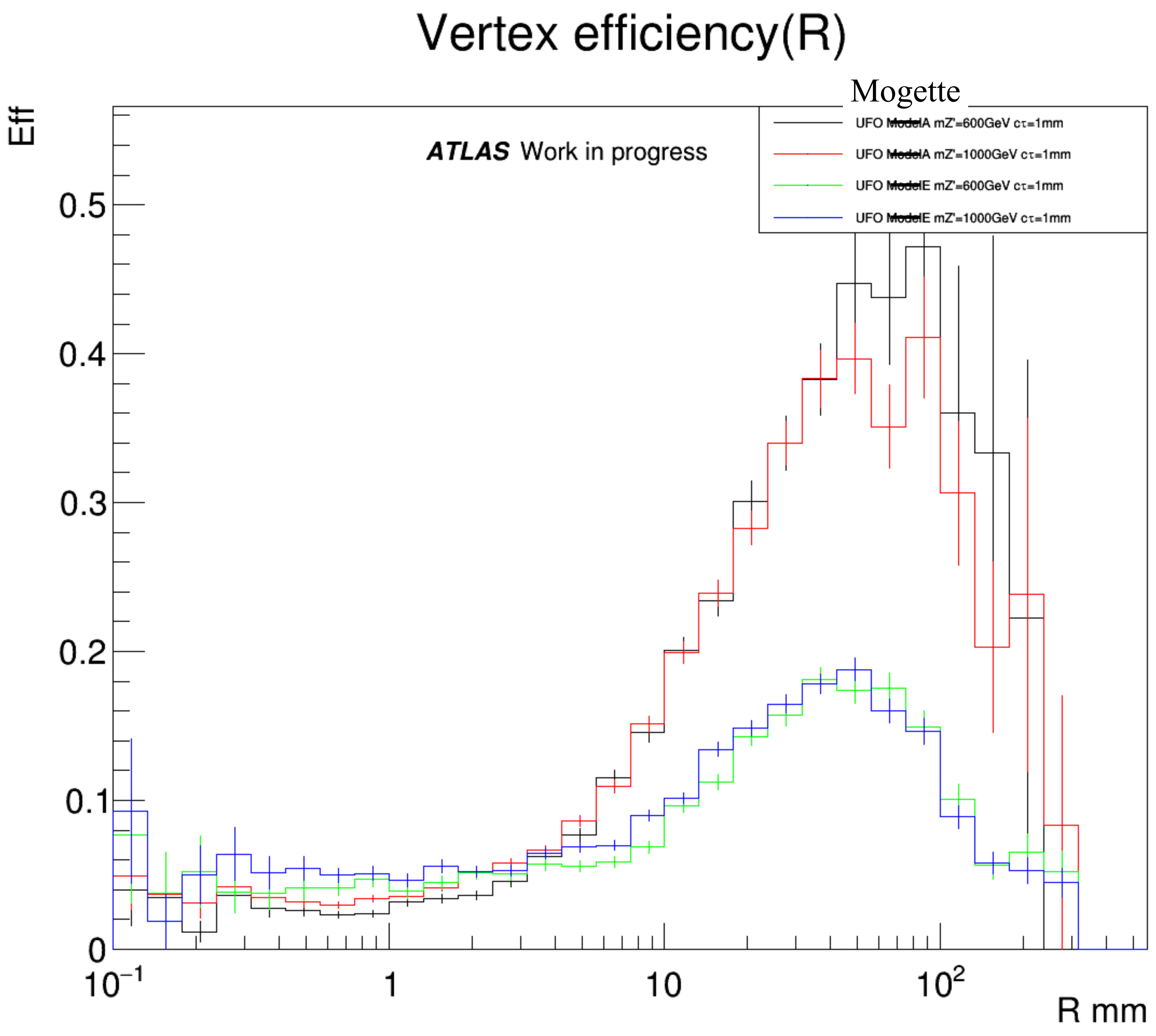




Tracks and vertices reconstruction efficiencies

- Computed reconstruction efficiencies in function of the production radii
- Quite low vertex reconstruction efficiency but still enough to have several reconstructed vertices per jets

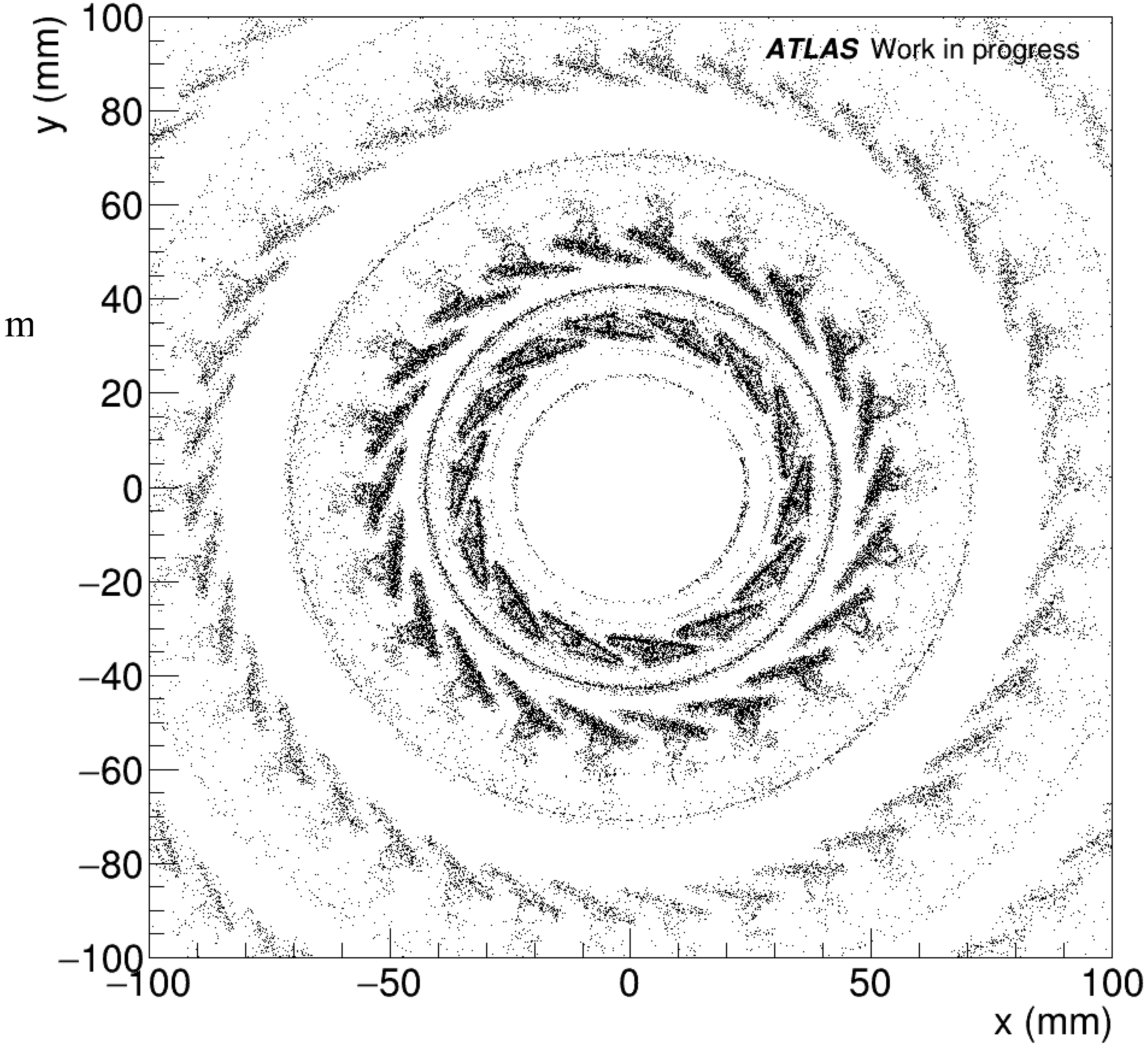




Vertex selection

- Fake vertices from interaction of particles with the inner detector
- Need to put a material veto on vertices
- Other quality cut can be applied to select vertices :
  - $m > O(GeV) \rightarrow$ avoid b-hadron displaced vertices at low mass but for some m
  - $n_{trk} > 2$
  - …

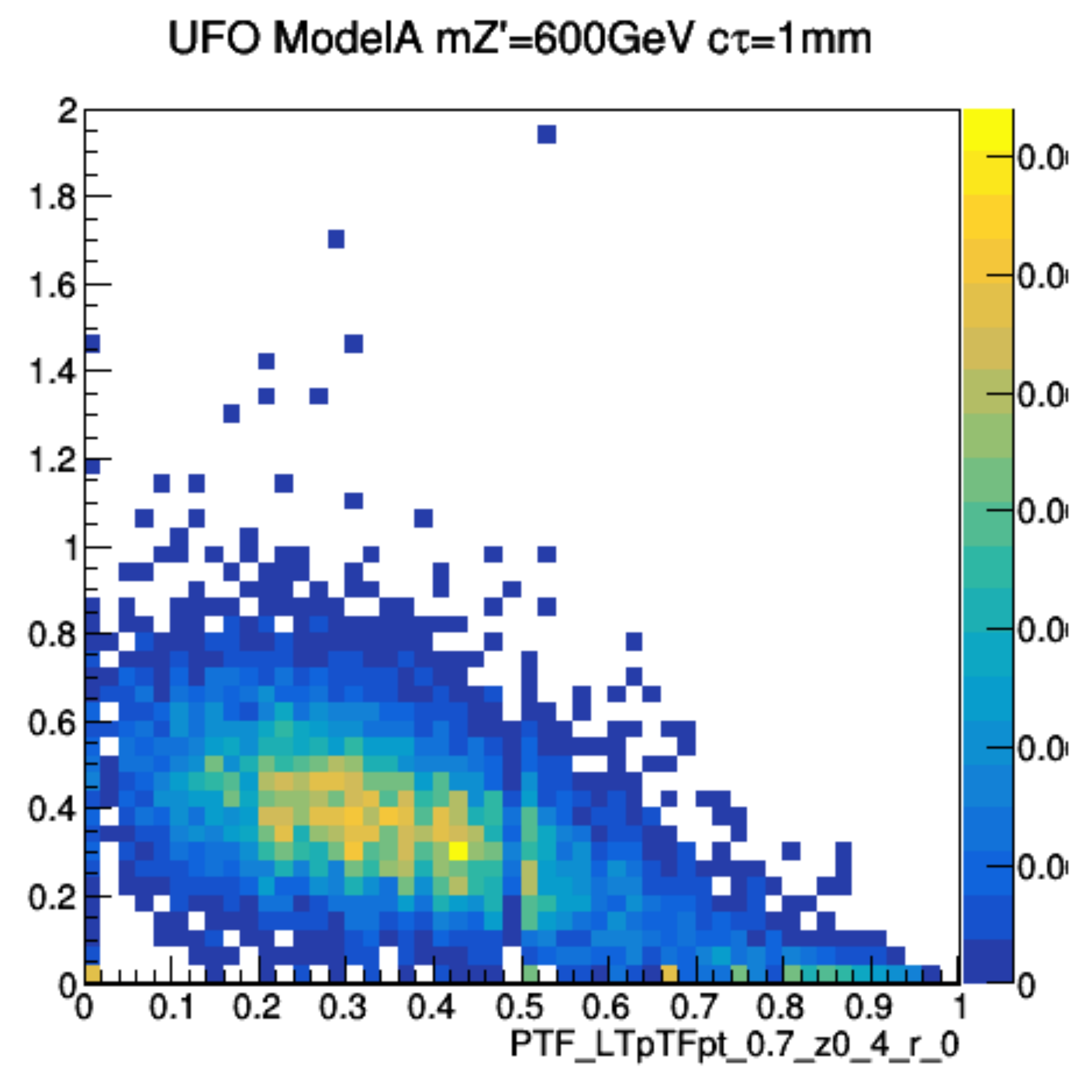
(x,y) coordinates of fake vertices



Signal discrimination

First try of selection efficiency

- Apply a list of selection to signal / background
- Pre selections to mimic the EJ trigger : at least one jet with pT > 300GeV and trigger-PTF < 0.08 (sel efficiency : 39.72%)
- Tracks selection : $p_{T_{trk}} > p_{T_{min}}$; $\Delta z = |z0_{trk} - z_{PV}| < z_{max}$
- Jet selection : p_T, PTF (prompt track frac), LTpTF (large track pT frac), medD0 (median of |d0|)
- Apply these selection for different cut values
- Best significance :
  - Max significance : 1227240.4551976915
  - Nsig = 1278.0 , Nbkg = 1.0844321423064684e-06
  - Tracks : pT > 0.6 GeV, $\Delta z < 4$ mm
  - 2 first jets : pT > 300 GeV, PTF < 0.5 , LTpTF > 0.15 , med d0 > 0.01 mm
  - Selection eff : 25.56 %
  - Rejection eff : 99.99999999999287 %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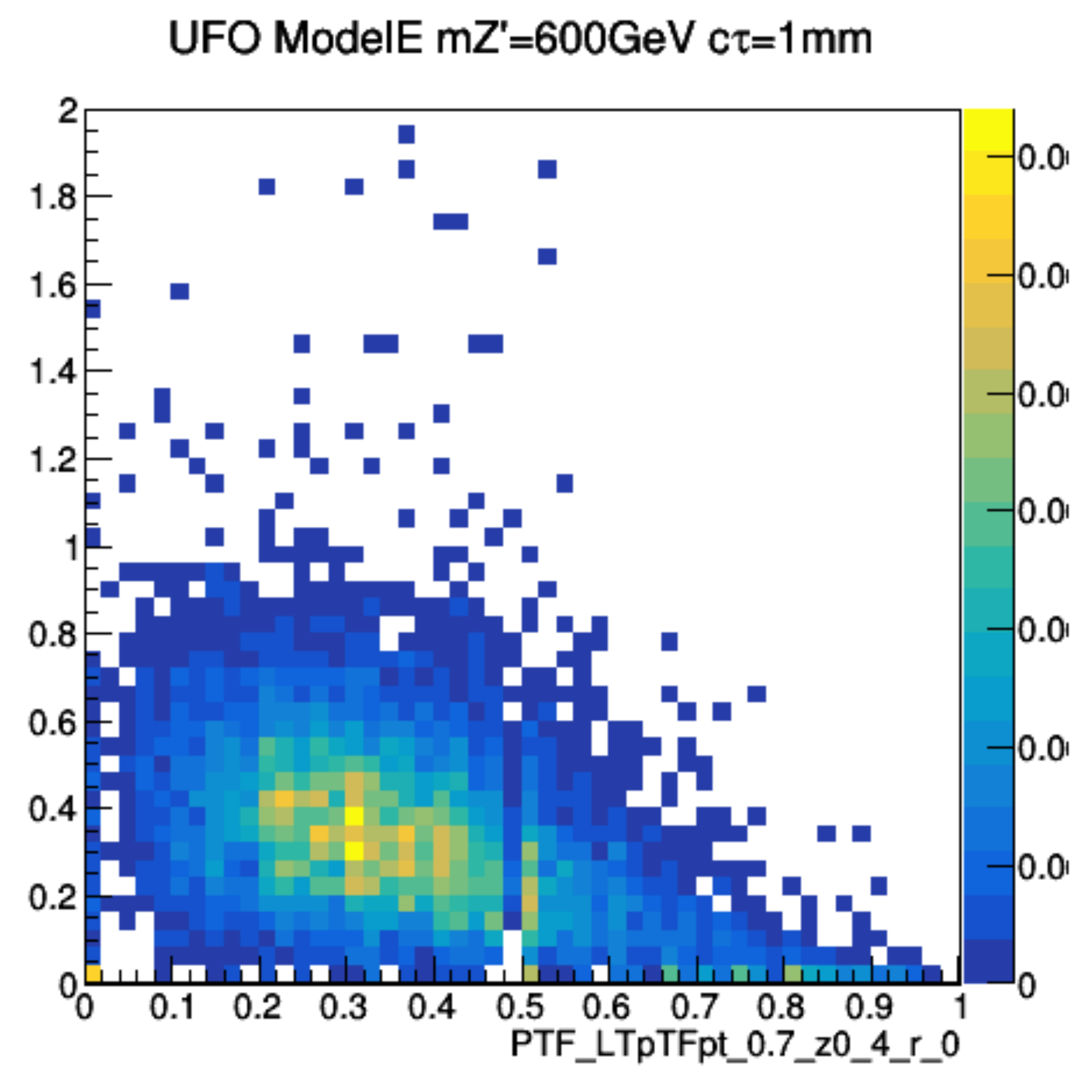
PTF_LTpTFpt_0.7_z0_4_r_0


UFO ModelE mZ'=600GeV cτ=1mm
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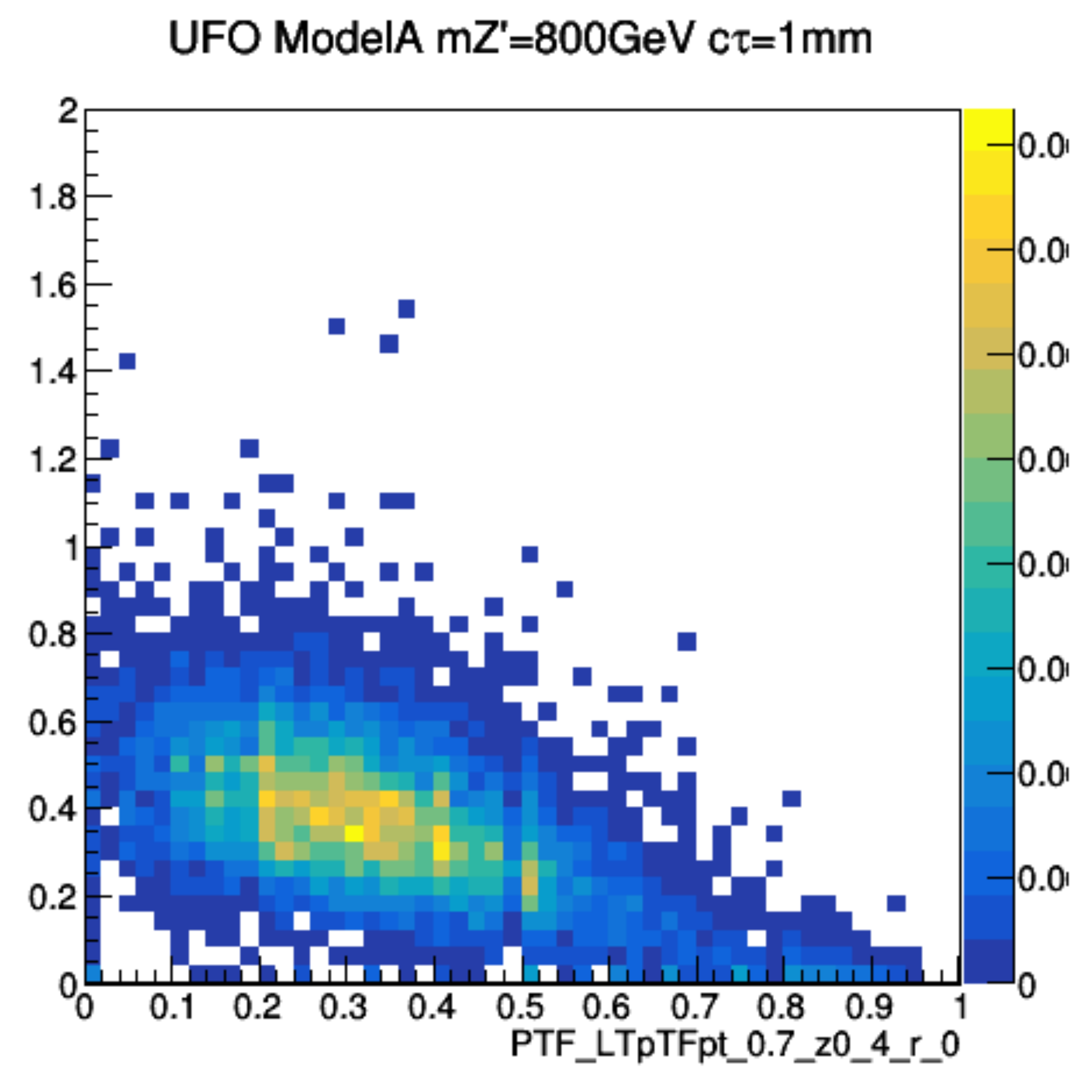
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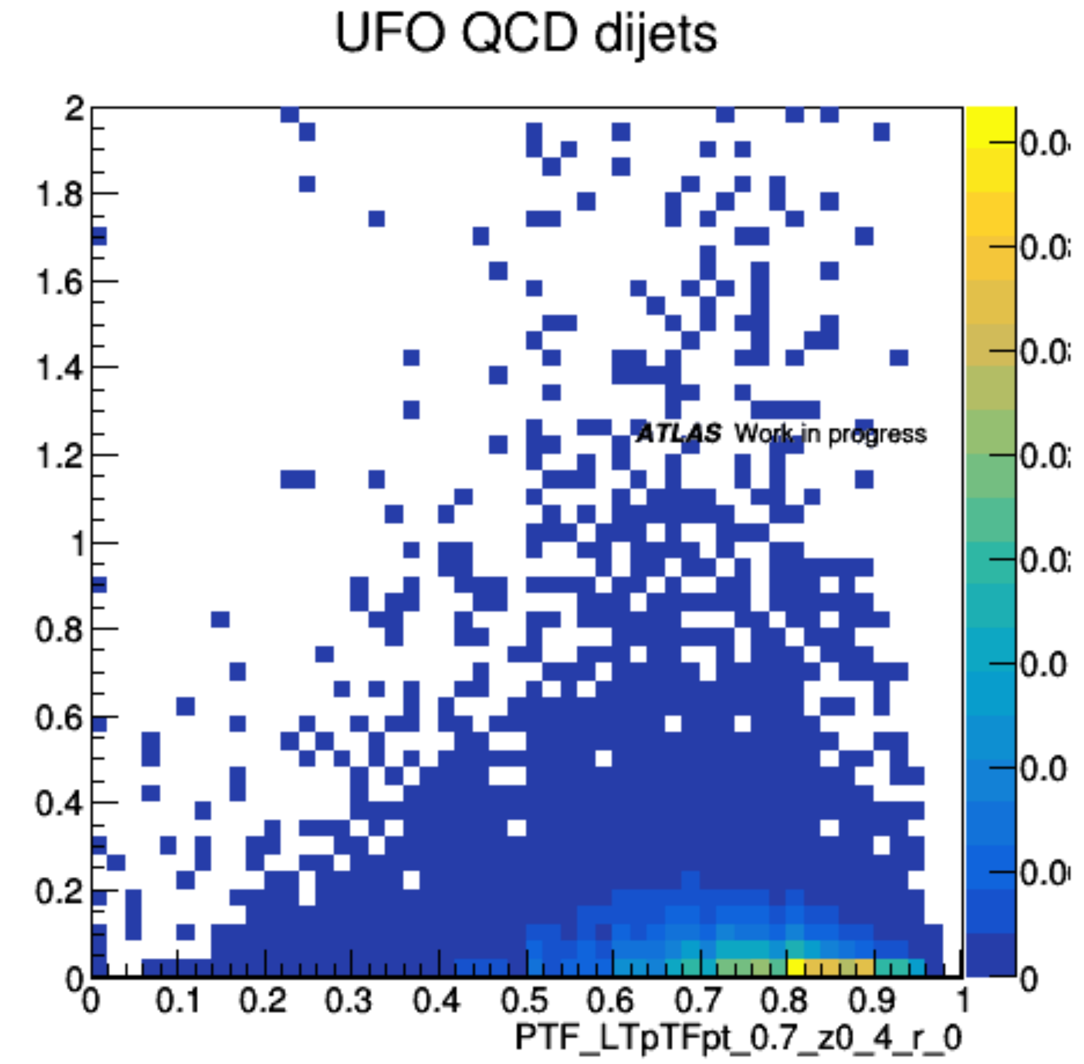
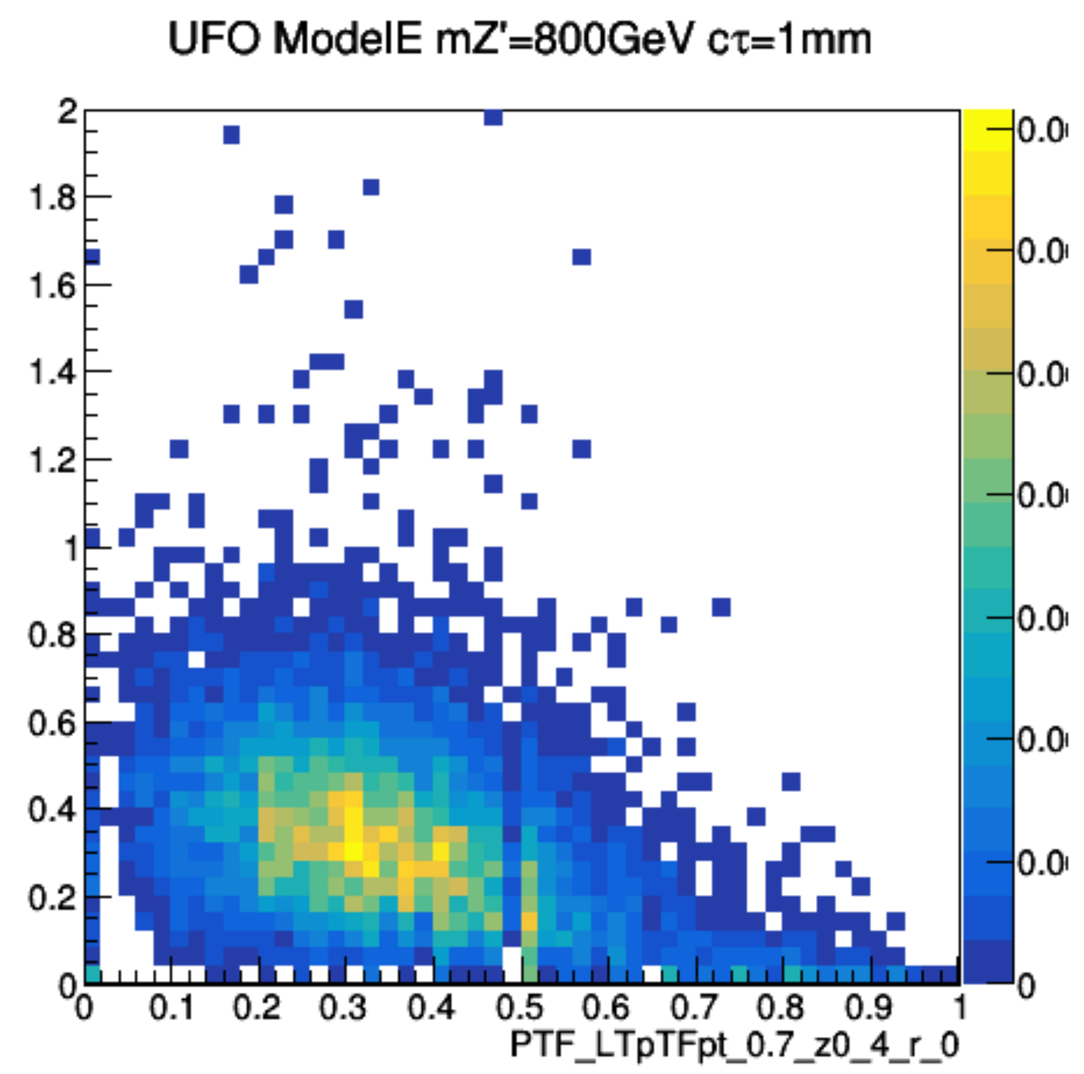
PTF_LTpTFpt_0.7_z0_4_r_0


UFO QCD dijets
ATLAS Work in progress
PTF_LTpTFpt_0.7_z0_4_r_0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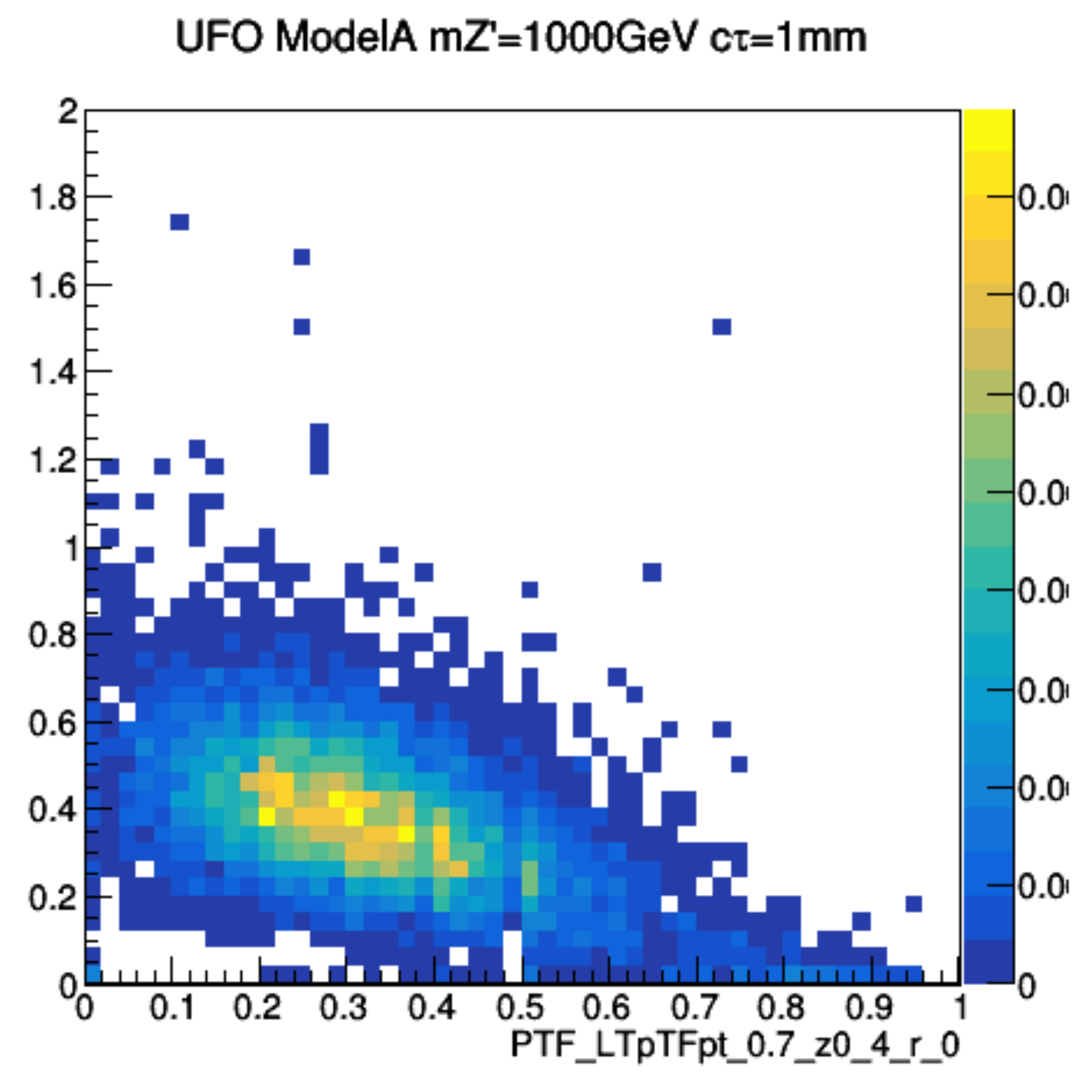
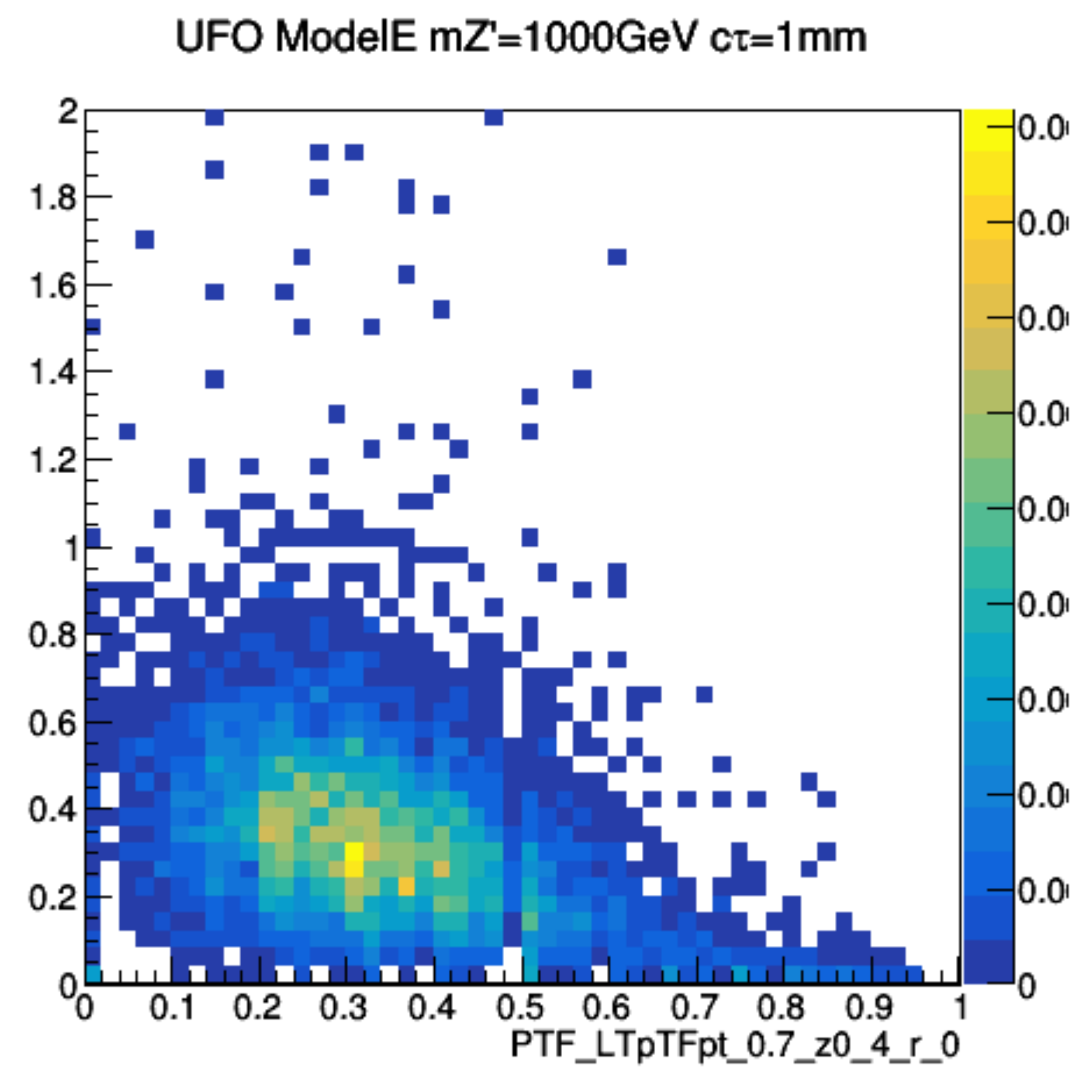

UFO ModelA mZ'=1000GeV cτ=1mm
PTF_LTpTFpt_0.7_z0_4_r_0


UFO ModelE mZ'=1000GeV cτ=1mm
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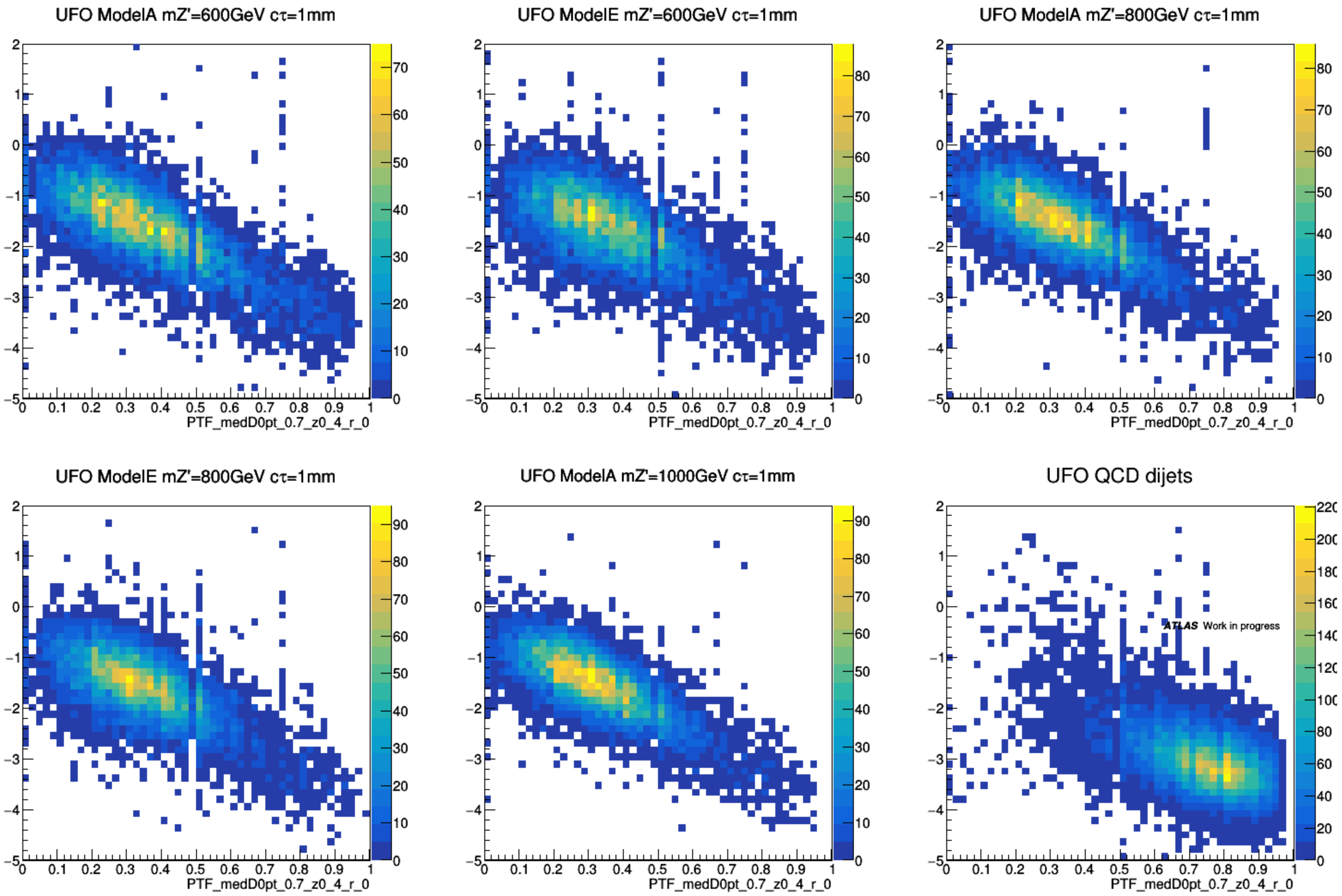
UFO ModelA mZ'=600GeV cτ=1mm
UFO ModelE mZ'=600GeV cτ=1mm
UFO ModelA mZ'=800GeV cτ=1mm
UFO ModelE mZ'=800GeV cτ=1mm
UFO ModelA mZ'=1000GeV cτ=1mm
UFO QCD dijets
ATLAS Work in progress
PTF_medD0pt_0.7_z0_4_r_0