Search for multi-charged particles

Yury Smirnov

May 15, 2020

Outline

- Multi-charged particles 101
- Project milestones

- Our latest publication
  - General strategy of the search
  - MCP identification
  - Background estimation
  - Search efficiency
  - Analysis uncertainties
  - Results
  - Comparison with CMS results and activities

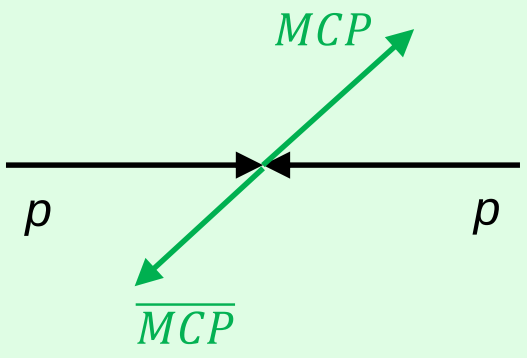
- Current search in the 2015-2018 data
  - Changes wrt. the 2015-2016 data search
  - Current status
    - $Z \to \mu\mu$ data/MC comparison of key quantities
    - Existing signal samples and status of requests
    - Nearest plans, ballpark timeline

Multi-charged particles 101

- Multi-charged particles (MCPs): long-lived highly ionizing heavy fermions with high electric charges;
  - no strong interaction;
  - think heavy ($m > 50$ GeV) muons with $z = {}^{|q|}/_{e} > 1$;

- "Blue-sky" search, but some models in fact predict new particles with charges greater than one:
  - Almost Commutative geometry model (AC leptons) https://arxiv.org/abs/hep-th/0509213
  - Walking technicolor model (techni-leptons) https://arxiv.org/abs/hep-ph/0405209
  - Left-right symmetric model (doubly-charged *H*) https://inspirehep.net/record/89314/

- **Any observation of MCPs would be a striking evidence of physics beyond the SM.**



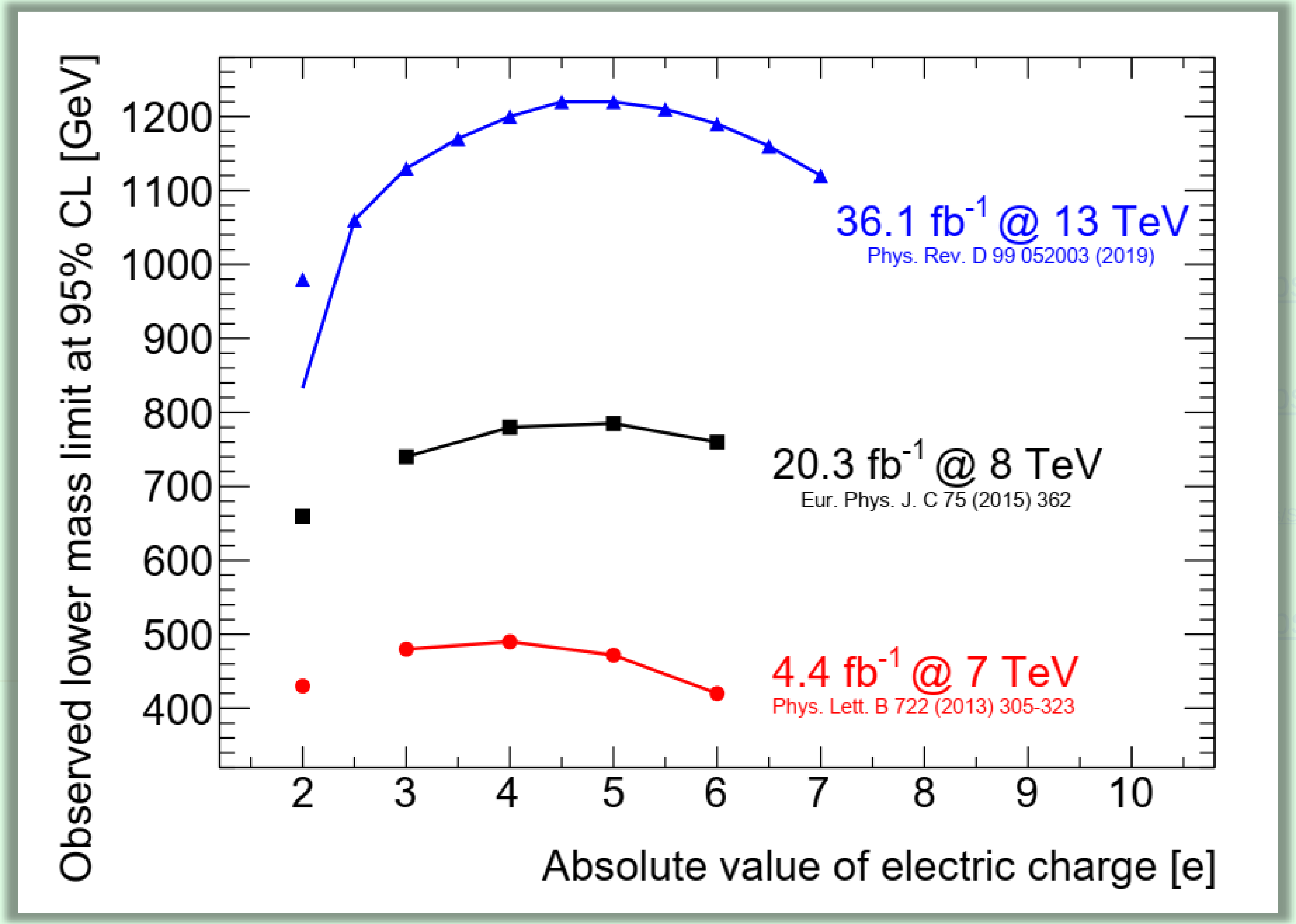
Milestones

- 2010 — Started working on the MCP-search subject
- 2013 — Paper on the **2011 data** search
- 2015 — Paper on the **2012 data** search
- 2017 — PhD dissertation based on the two searches above
- 2019 — Paper on the **2015-2016 data** search
- ← we are here
- 2021 ? — The last paper on the **2015-2018 data** search

Milestones

2010	Started working on the MCP-search subject	
2013	Paper on the **2011 data** search	https://arxiv.org/abs/1301.5272
2015	Paper on the **2012 data** search	https://arxiv.org/abs/1504.04188
2017	PhD dissertation based on the two searches above	http://particle.mephi.ru/assets/PhDs/SmirnovYuS_20170920_dissertation.pdf
2019	Paper on the **2015-2016 data** search	https://arxiv.org/abs/1812.03673
	← we are here	
2021 ?	The last paper on the **2015-2018 data** search	

Milestones



Observed lower mass limit at 95% CL [GeV]
1200
1100
1000
900
800
700
600
500
400
2
3
4
5
6
7
8
9
10
Absolute value of electric charge [e]
36.1 fb^{-1} @ 13 TeV
Phys. Rev. D 99 052003 (2019)
20.3 fb^{-1} @ 8 TeV
Eur. Phys. J. C 75 (2015) 362
4.4 fb^{-1} @ 7 TeV
Phys. Lett. B 722 (2013) 305-323

Search features

- Ionization losses are highly sensitive to the electric charge of a particle;

$$ {}^{dE}/_{dx} \sim z^2 $$

- Long-lived particles → response in muon chambers;

- Direct search (as opposed to a search for a combination of SM particles some exotic particle decayed to): final-state particles are MCPs themselves;

- High mass → low β → muon-trigger-timing window is too short for these particles;

- Track reconstruction always assumes particles with charge $\pm 1e$ → momentum misreconstruction by a factor of z;

- RPC-trigger timing mismodeling for particles with low β → MC overestimates the trigger efficiency.

The latest published paper

PHYSICAL REVIEW D **99**, 052003 (2019)

Search for heavy long-lived multicharged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector

M. Aboud *et al.**
(ATLAS Collaboration)

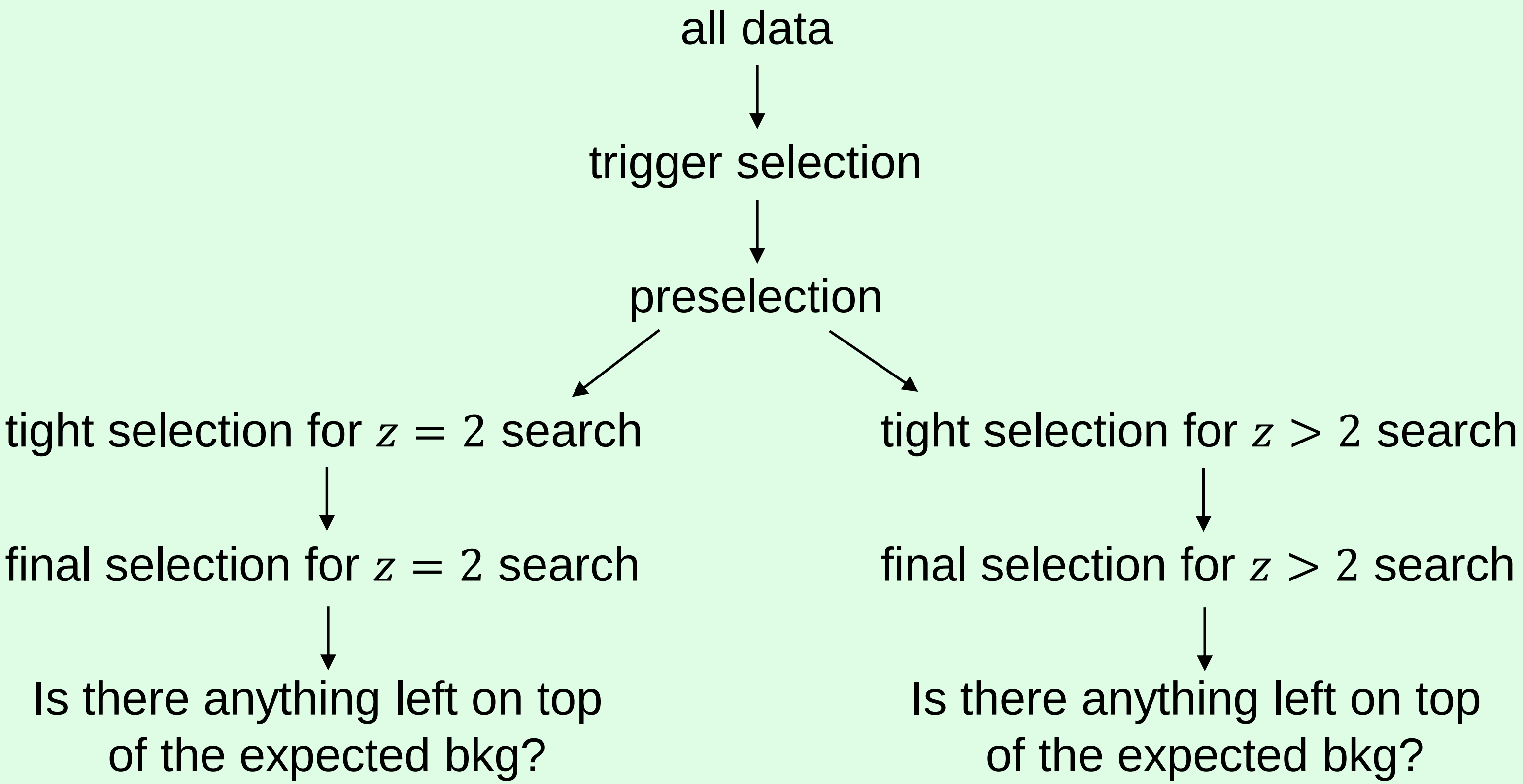
(Received 11 December 2018; published 14 March 2019)

A search for heavy long-lived multicharged particles is performed using the ATLAS detector at the LHC. Data with an integrated luminosity of 36.1 fb^{-1} collected in 2015 and 2016 from proton-proton collisions at $\sqrt{s} = 13$ TeV are examined. Particles producing anomalously high ionization, consistent with long-lived massive particles with electric charges from $|q| = 2e$ to $|q| = 7e$, are searched for. No events are observed, and 95% confidence level cross-section upper limits are interpreted as lower mass limits for a Drell-Yan production model. Multicharged particles with masses between 50 and 980–1220 GeV (depending on their electric charge) are excluded.

DOI: 10.1103/PhysRevD.99.052003

Paper: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.052003
Preprint: https://arxiv.org/abs/1812.03673
Supporting note: https://cds.cern.ch/record/2267181

Search strategy: cut-and-count method

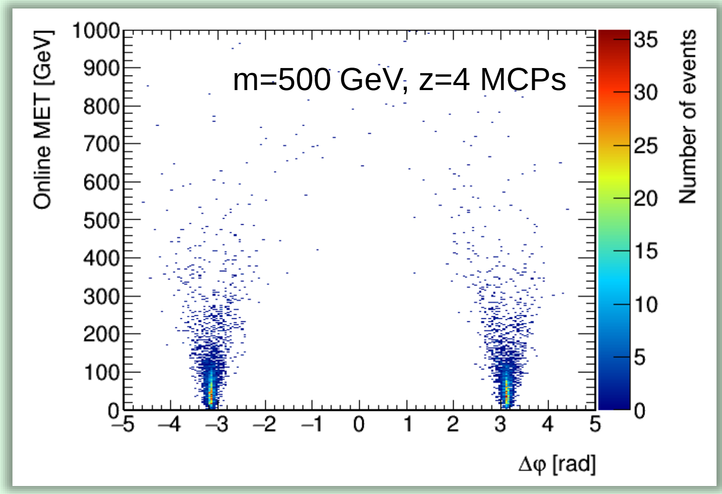


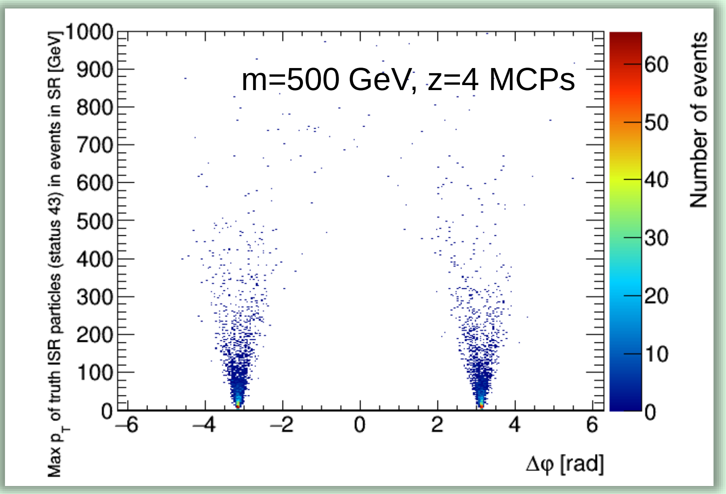
Trigger selection

- Unprescaled triggers with lowest possible thresholds on single muon and MET;

- MET-trigger contribution is $\sim 20\%$ of events triggered by either of two;

- Large E_T^{miss} originates from the ISR jets recoiling off of the MCP pair;



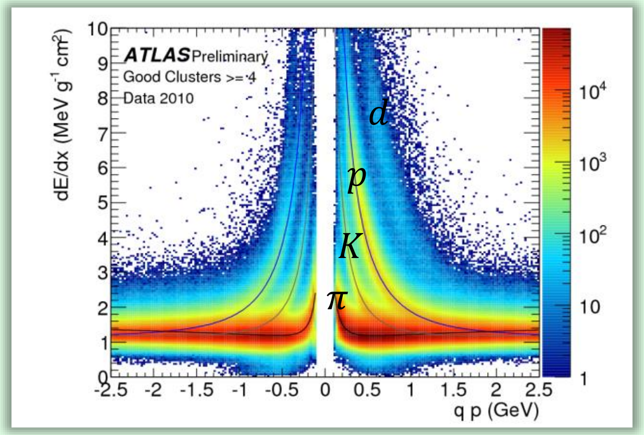


Preselection

- At least one combined muon with medium+ quality, $p_T > 50$ GeV ~~(trigger limitation)~~, $|\eta| < 2.0$ (TRT limitation), and reliable dE/dx estimation in the TRT;

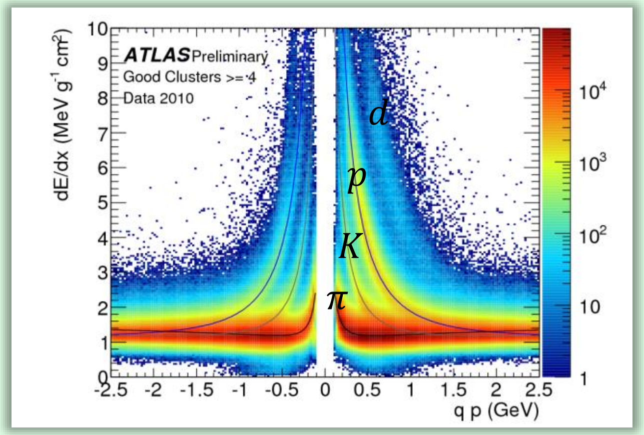
- The corresponding ID-track segments should be isolated (by at least $\Delta R = 0.01$) from other ID tracks/muons to limit the background contribution from 2+ tracks firing the same TRT straws or MDTs.

Process-specific dE/dx quantities



pixel dE/dx: the output-signal width from the discriminator of every pixel is proportional to the collected charge

Process-specific dE/dx quantities



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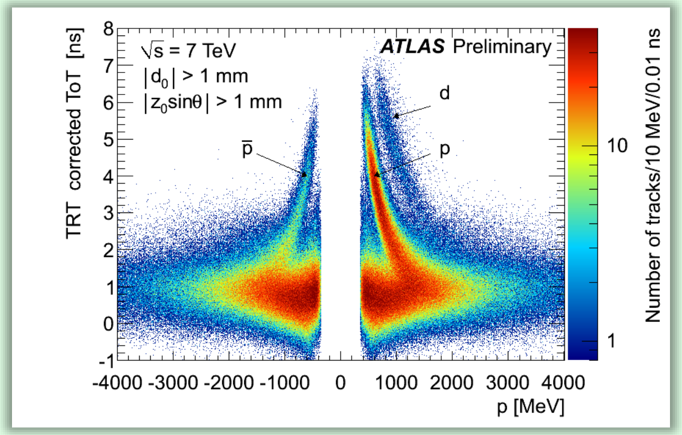

TRT dE/dx: the signal width exceeding lower threshold divided by track-segment length in a straw depends on particle ionization loss

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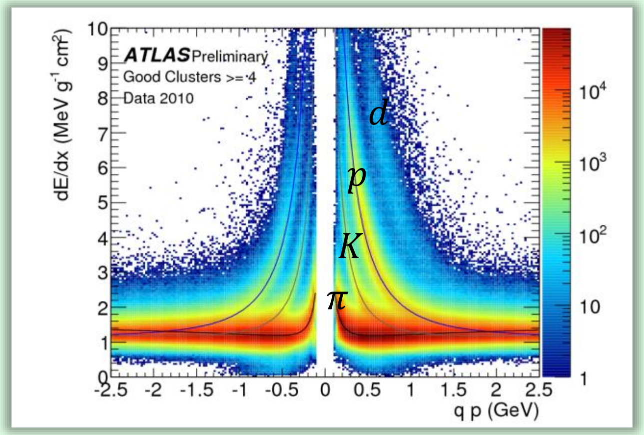

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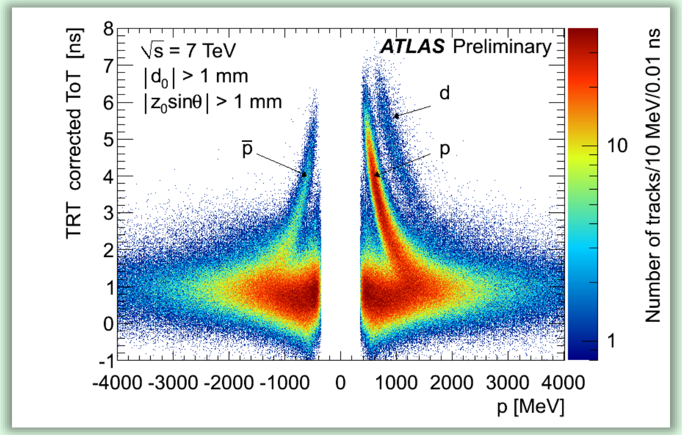
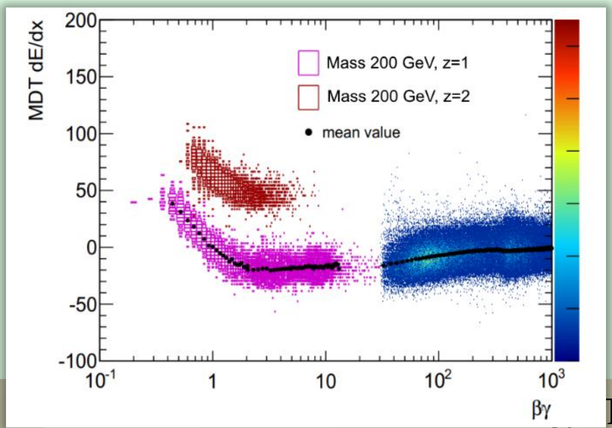
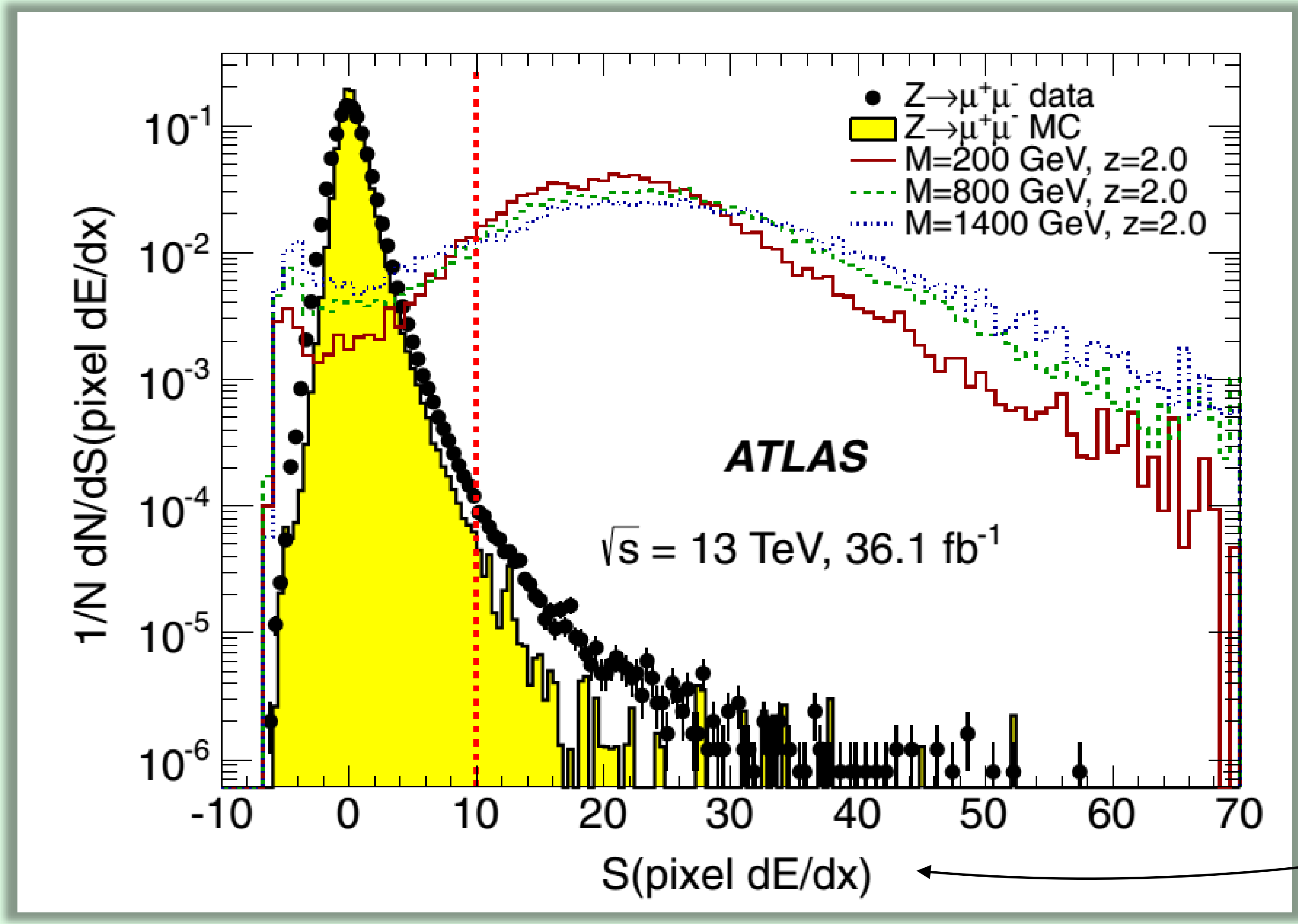


MDT dE/dx: time interval when signal amplitude from the amplifier/shaper/discriminator exceeds a certain threshold within the first 18 ns of that signal is proportional to the electric charge of the particle



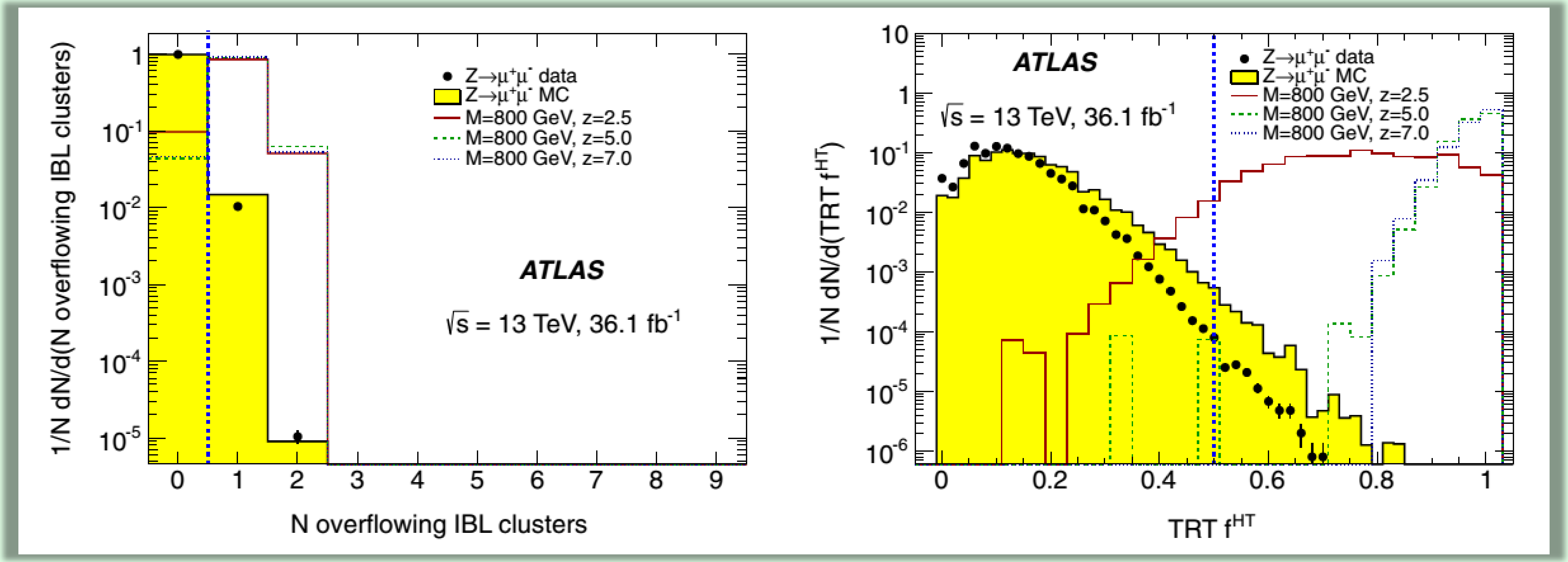
Tight selection for the $z = 2$ MCPs



Ionization-loss significance shows how much the current energy loss differs from the one from muons from Z decays:

$$S = \frac{{dE}/{dx} - \mu^{Z^0\text{−}decay\ muons\ dE/dx}}{\sigma^{Z^0\text{−}decay\ muons\ dE/dx}}$$

Tight selection for the $z > 2$ MCPs

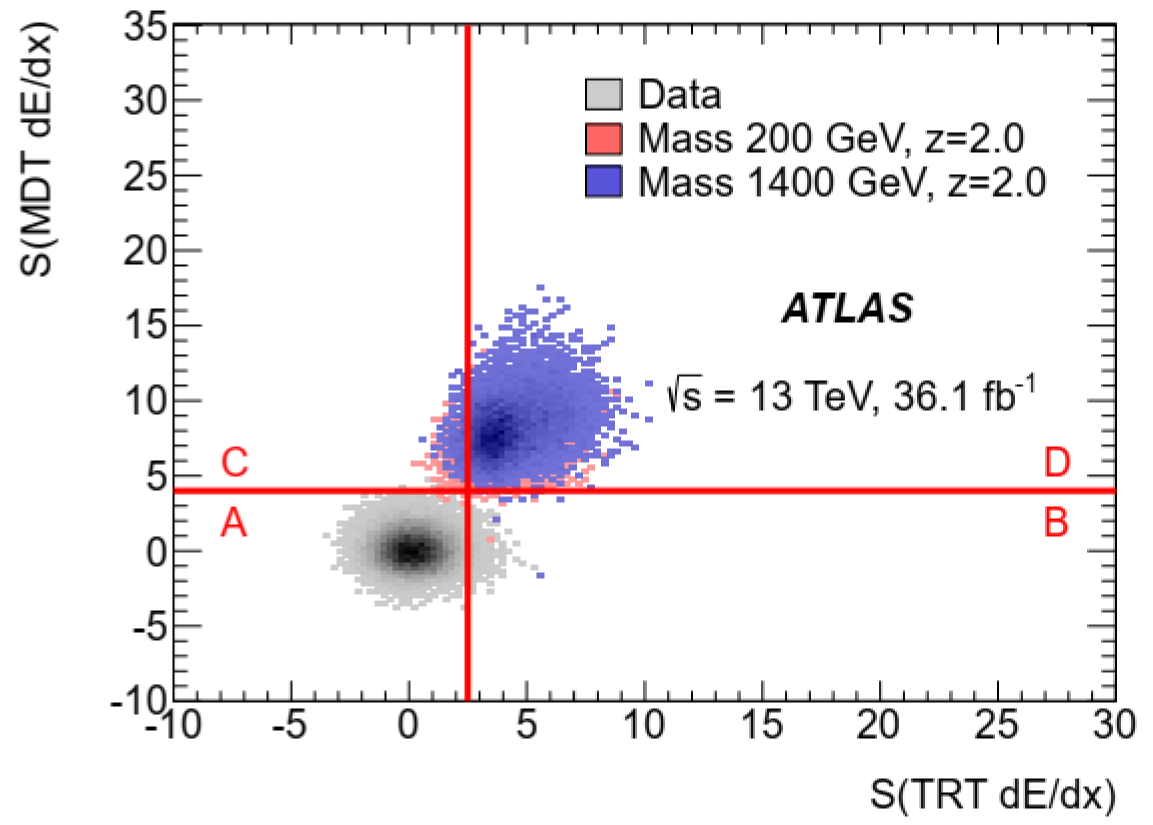


Number of clusters on the track segment in IBL with 1+ hit having registered the charge of at least 1.5 times higher than the average charge of a MIP with its track normal to the detector plane and depositing all its ionization charge into a single pixel

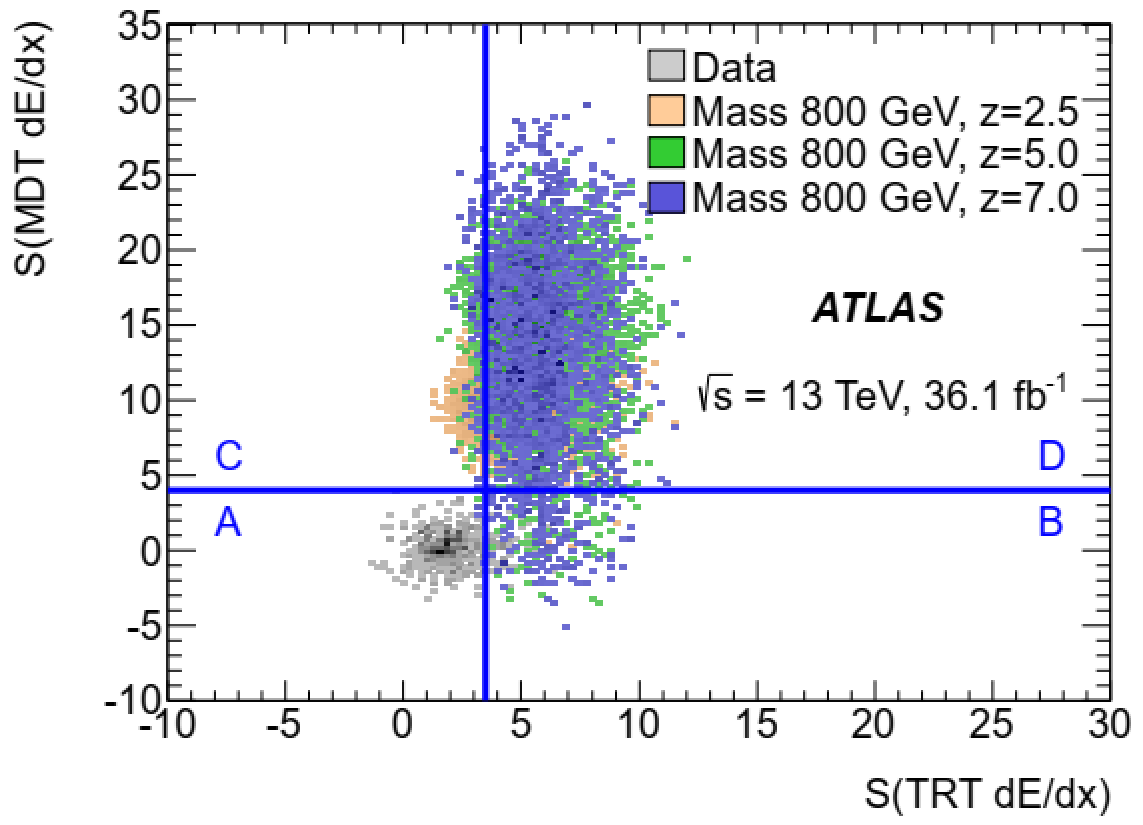
Fraction of hits on a TRT track segment with a signal amplitude over 6 keV

Final selection on ABCD planes

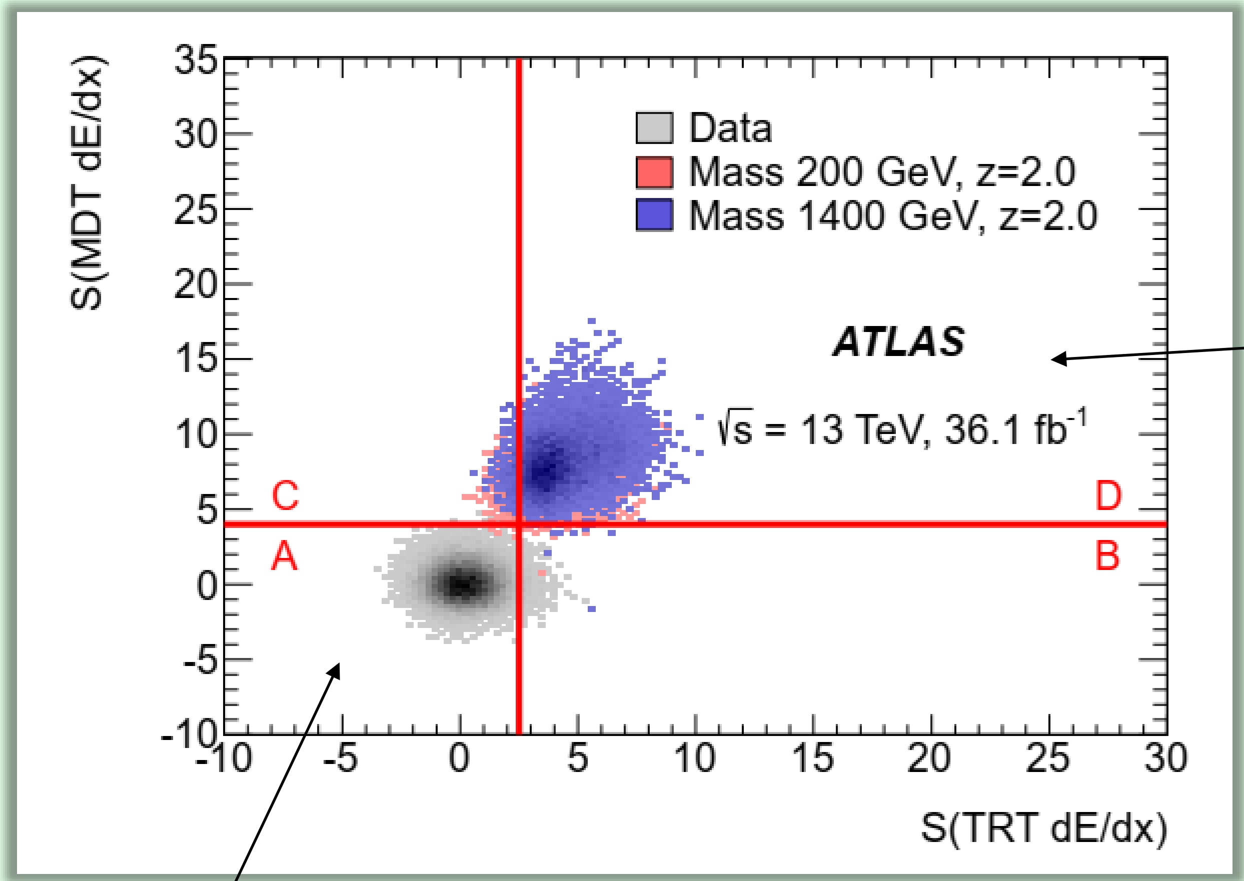
$z = 2$ MCP search



$z > 2$ MCP search



Background estimation for the $z = 2$ MCP search

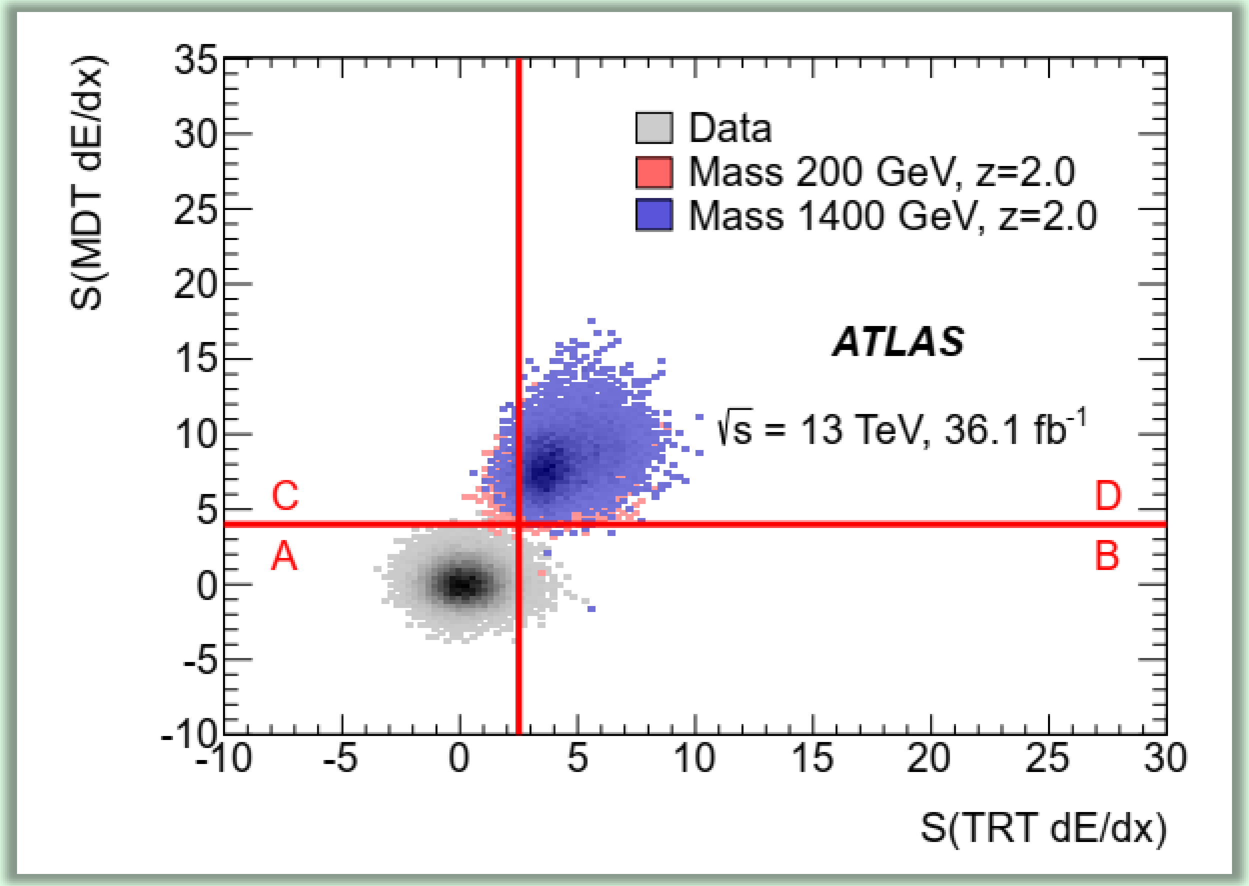


signal-dominated region, blind to data at first

bkg-dominated region

Bkg estimation is purely data-driven

Background estimation for the $z = 2$ MCP search



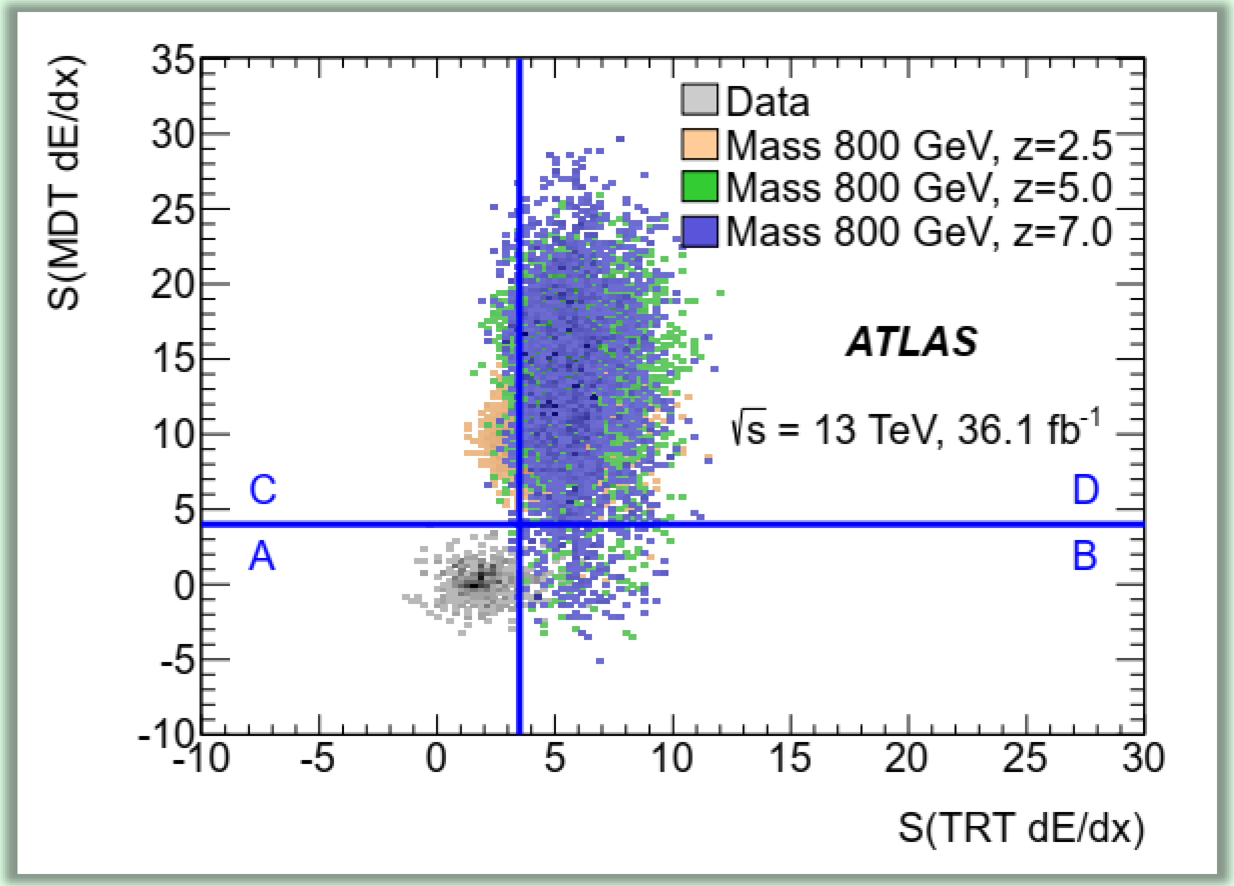
Regular ABCD method:

$$N_D^{expected\ events} = \frac{N_B^{observed\ events} \cdot N_C^{observed\ events}}{N_A^{observed\ events}} =$$

$$= 0.15 \pm 0.05\ (stat.) \pm 0.10\ (syst.)$$

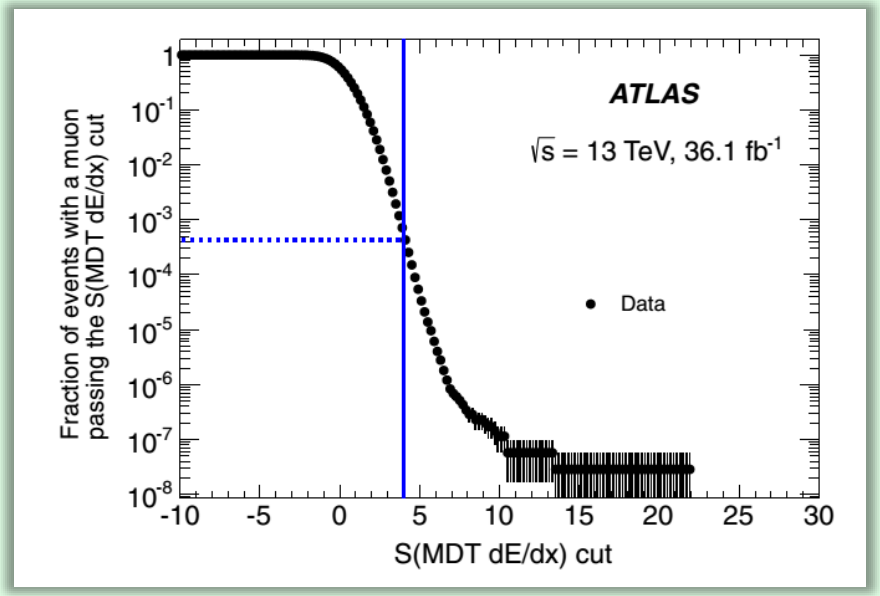
Background estimation for the $z > 2$ MCP search

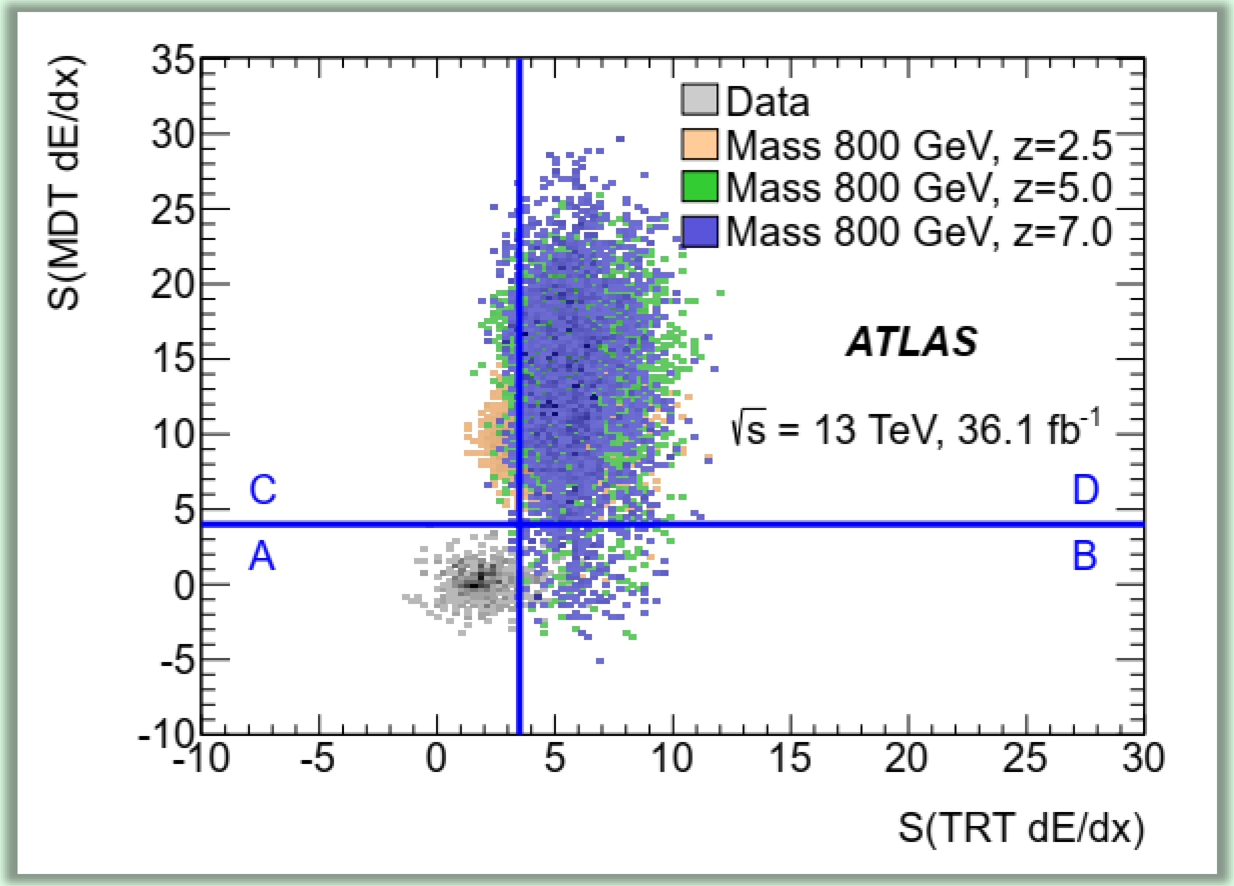
- The same formula is not used as $N_C^{observed\ events} = 0$;
- In principle, an upper limit on the $N_C^{observed\ events}$ can be taken instead of 0, i.e. we can assume $N_C^{observed\ events} = 2.996$, but the estimate of $N_D^{expected\ events}$ will be too rough: both the central value and the statistical uncertainty will be overestimated.



Background estimation for the $z > 2$ MCP search

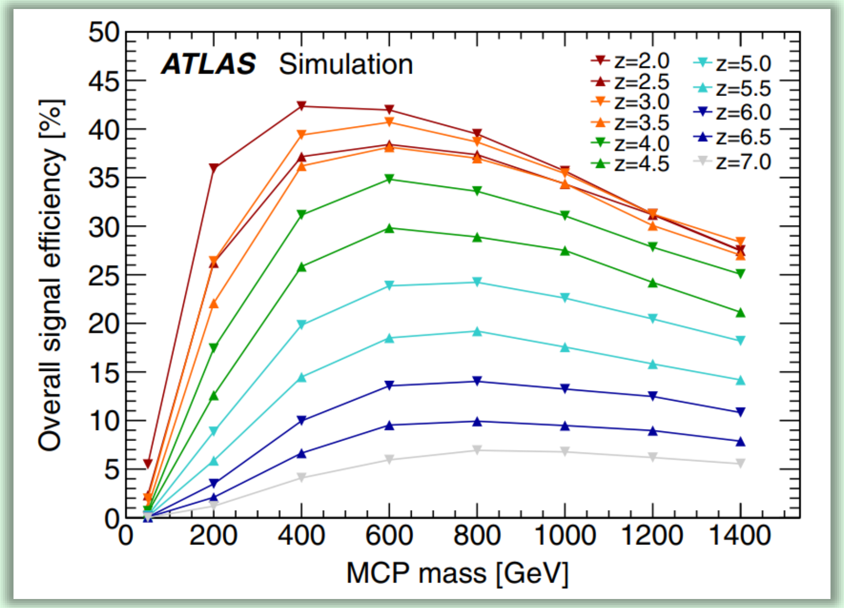
- Another technique: $N_D^{expected\ events} = f \cdot N_B^{observed\ events}$, where f is a probability to observe an event with an S(MDT dE/dx) > 4 particle using the S(MDT dE/dx) distribution after the "anti-tight" selection.
- The "anti-tight" selection:
  - provides a lot of statistics,
  - is orthogonal to the regular selection, so no risk of unintended unblinding.

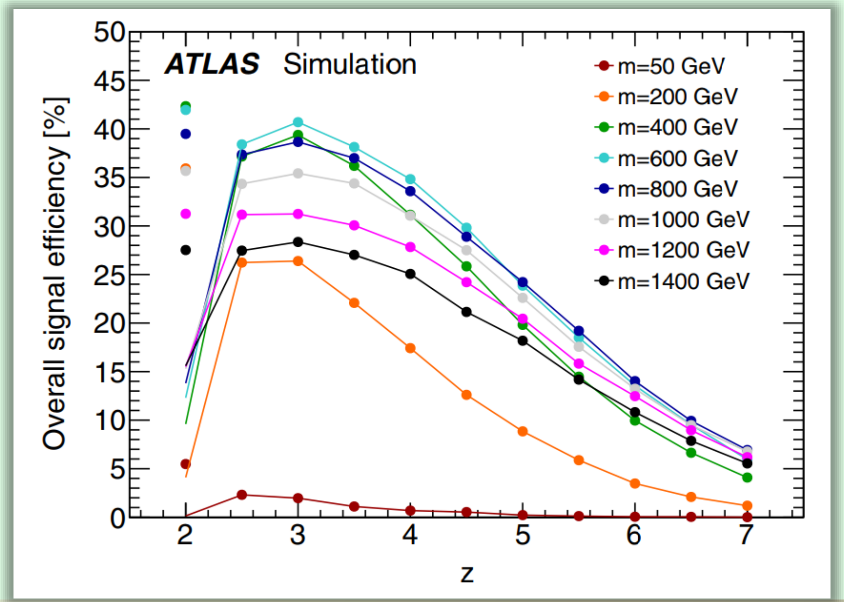




$$N_D^{expected\ events} = (2.9 \pm 0.4\ (stat.) \pm 2.2\ (syst.)) \cdot 10^{-2}$$

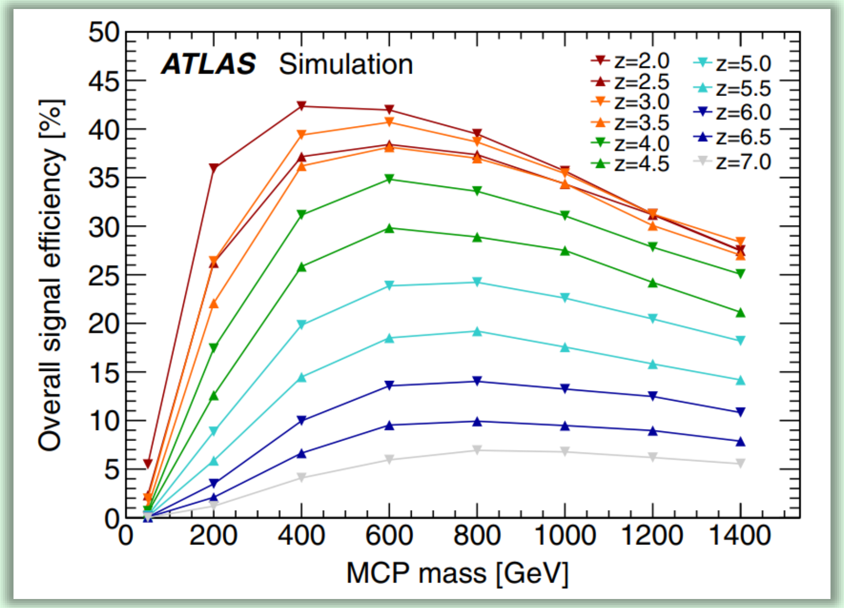
Search efficiency

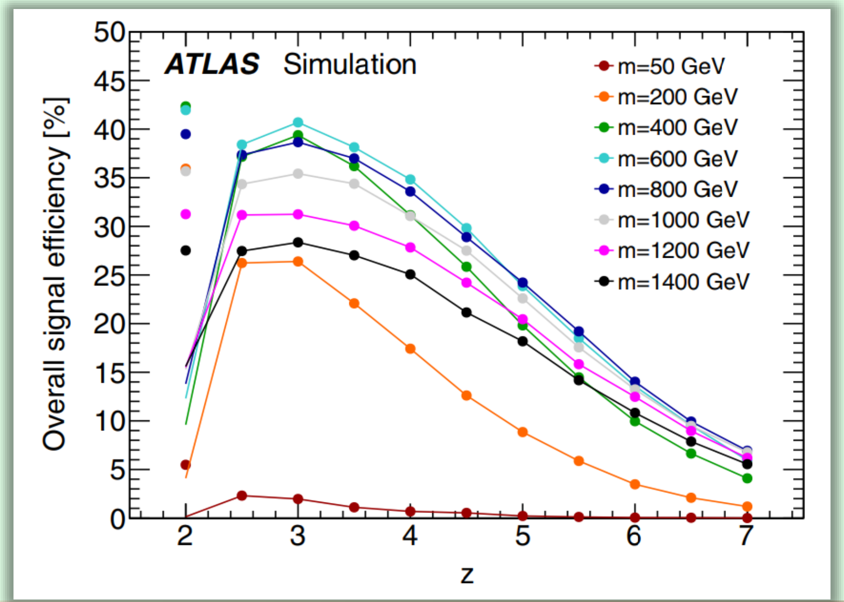




- Overall efficiency is a fraction of MC events with at least one MCP in the D region among all generated events;

Search efficiency





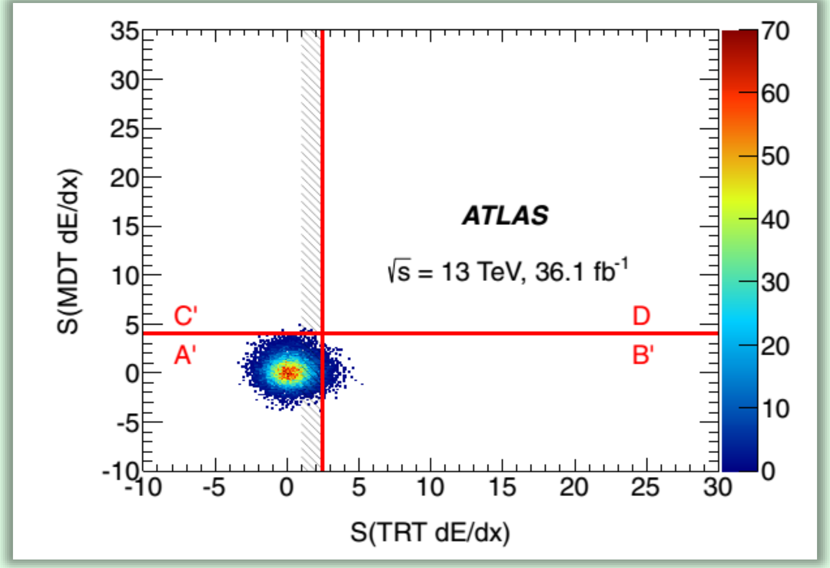
- Overall efficiency is a fraction of MC events with at least one MCP in the D region among all generated events;

- Reasons for relatively low efficiency:
  - **low masses**: η and especially $^{p_T}/_{z}$ requirements;
  - **high masses**: a requirement to reach the MS with high enough velocity to make it into the trigger timing window;
  - **high charges**:
    - large ionization losses slow particles down – they may not make it into the timing window anymore and/or may lose all their kinetic energy before the MS;
    - stricter effective $^{p_T}/_{z}$ requirement;
    - large δ-electron yield distorts timing parameters of MDT hits from MCPs leading to a smaller number of reconstructed combined muons and to a lower ionization registered in the MDTs (signal from δ-electrons is registered instead of the one of MCPs).

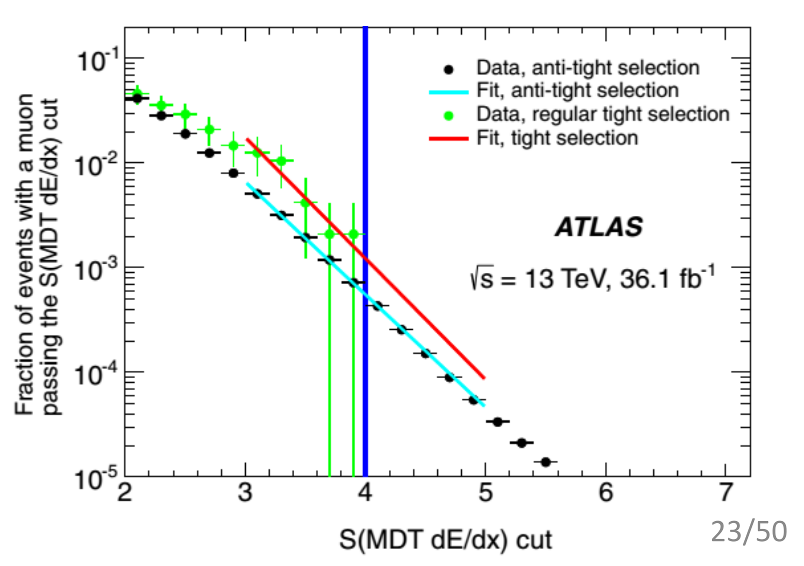
Background-estimation uncertainties

67% for $z = 2$ and **75**% for $z > 2$:

- The so-called "dead zones" were introduced between A+C and B+D (shown) and between A+B and C+D (not shown) → bkg estimation is recalculated without accounting for the entries in the dead zones;
- Systematic uncertainty is the relative difference between the nominal bkg estimation ($D = B \cdot C/A$) and the new one ($D = B' \cdot C'/A'$);



- The degree of disagreement of the spectra we use for the f-value calculation between tight and anti-tight selections around S(MDT dE/dx)=4 was also derived;
- Systematic uncertainty is the relative difference between two $10^{p_0 x + p_1}$ fits within 3 < S(MDT dE/dx) < 5.



Search-efficiency uncertainties

- Data/MC disagreement: **11**% in average;
  - This is derived by varying the requirements on p_T, N overflowing IBL clusters, pixel dE/dx, TRT dE/dx, TRT f^{HT}, and MDT dE/dx by a factor equal to the degree of data/MC disagreement of the respective quantity;
- Trigger-efficiency uncertainty: **4**% in average;
- Limited statistics of signal MC: **4**% in average;
- Track-reconstruction uncertainty: **1**% in average;
- Pile-up-reweighting uncertainty: **3**% in average;
- PDF-parametrization uncertainty: **11**% in average.

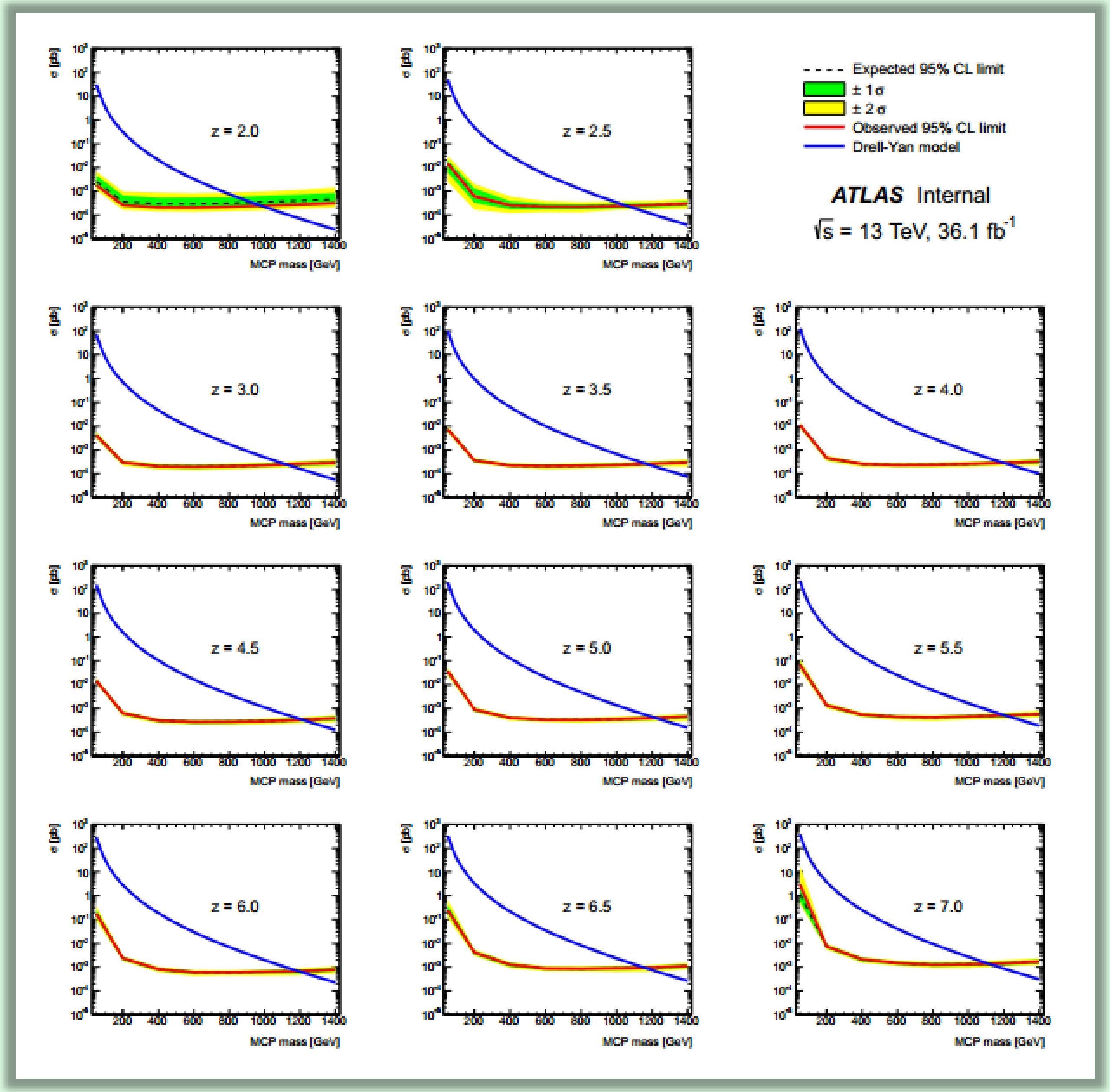
TRT f^{HT} data/MC disagreement

	z										
Mass [GeV]	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
50	16	78	19	15	15	16	23	31	37	45	115
200	14	61	15	12	12	12	12	13	13	17	14
400	12	39	14	11	10	10	11	12	13	14	15
600	13	29	14	11	11	12	11	12	13	13	13
800	13	25	15	15	14	12	13	14	13	14	16
1000	17	24	15	14	14	16	15	15	16	16	16
1200	16	23	17	16	15	16	17	16	18	17	19
1400	19	25	21	20	20	21	19	19	19	20	21

Lots of kinetic energy is lost in the calorimeter

Heavy and highly-charged MCPs slow down significantly

Results: X-section limits

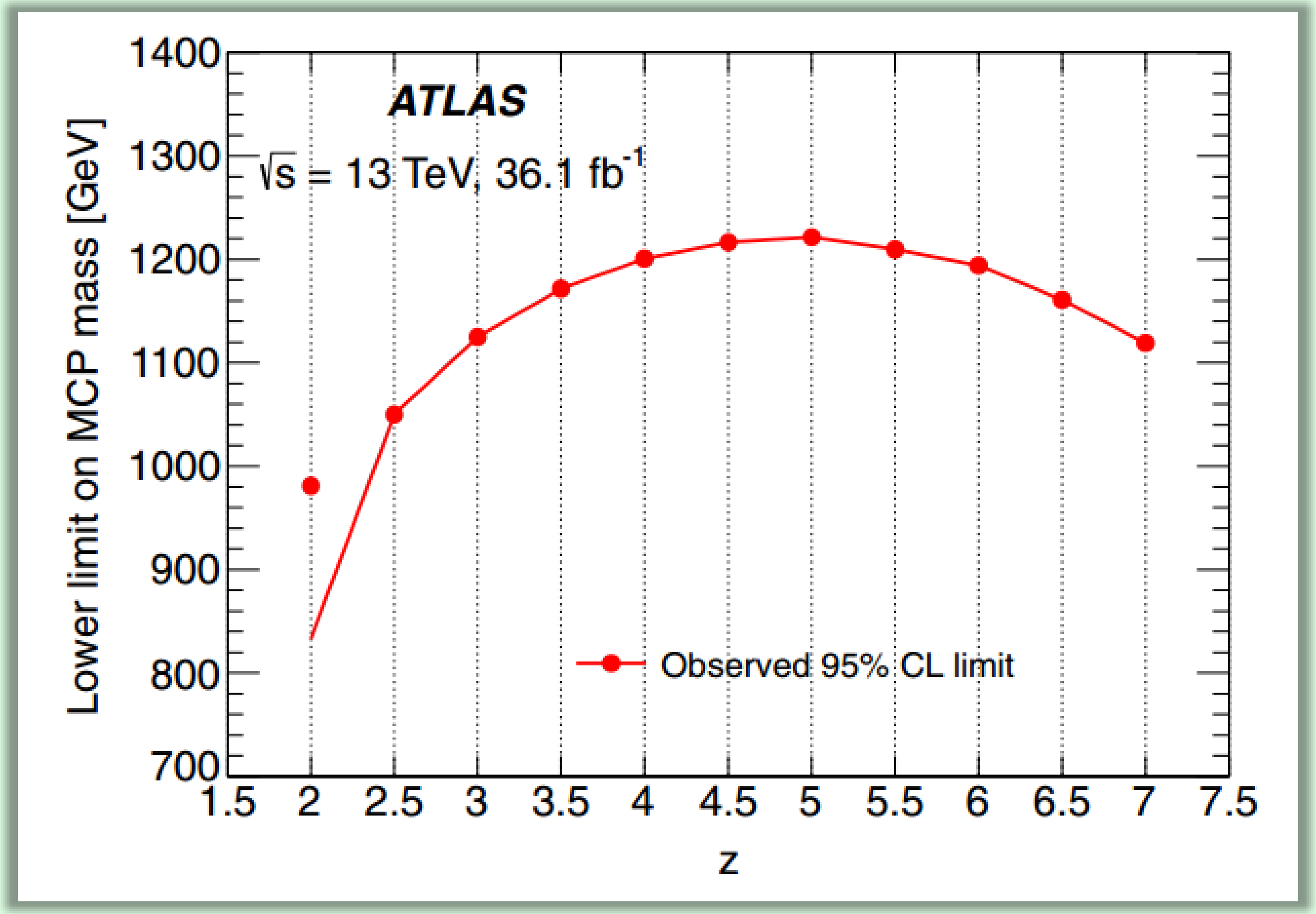


Not a single event was found in the SRs → upper limits on the X-section.

$$\sigma_{limit} = \frac{N}{\varepsilon \cdot \mathcal{L}}$$

(number of observed events minus number of events expected from the bkg) at 95% CL

Results: mass limits



As of today, these are the most stringent mass limits for **every** charge;

Limits for the half-integer-charge and $z = 7$ MCPs were obtained for the first time in ATLAS;

Published one year ago: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.052003

CMS results and activities

- Search for $z = 2, 3, 4, 5, 6, 7, 8$ particles on 5.0 fb^{-1}+18.8 fb^{-1} of 2011+2012 data, lower mass limits are $685 - 796$ GeV;

  https://link.springer.com/article/10.1007%2FJHEP07%282013%29122

- Search for $z = 2$ particles on 2.5 fb^{-1} of 2015 data, lower mass limit is 680 GeV;

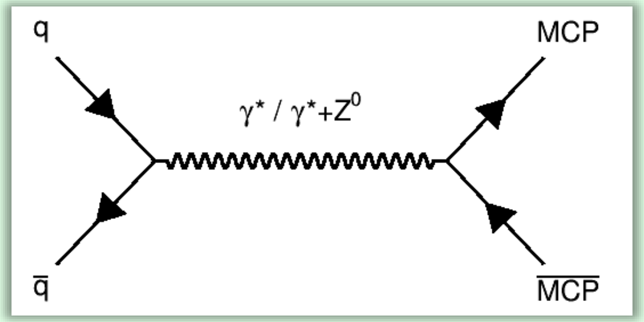
  https://journals.aps.org/prd/abstract/10.1103/PhysRevD.94.112004

- Search for $z = 2$ particles on 12.9 fb^{-1} of 2016 data, lower mass limit is 890 GeV **(preliminary results, not published)**

  https://inspirehep.net/record/1479657/

Our current search in the 2015-2018 data

- 139 fb^{-1};
- Will be our last search for MCPs;
- Three changes wrt. the 2015-2016 data search:
  - virtual boson exchange: $Z + \gamma$ instead of just γ;



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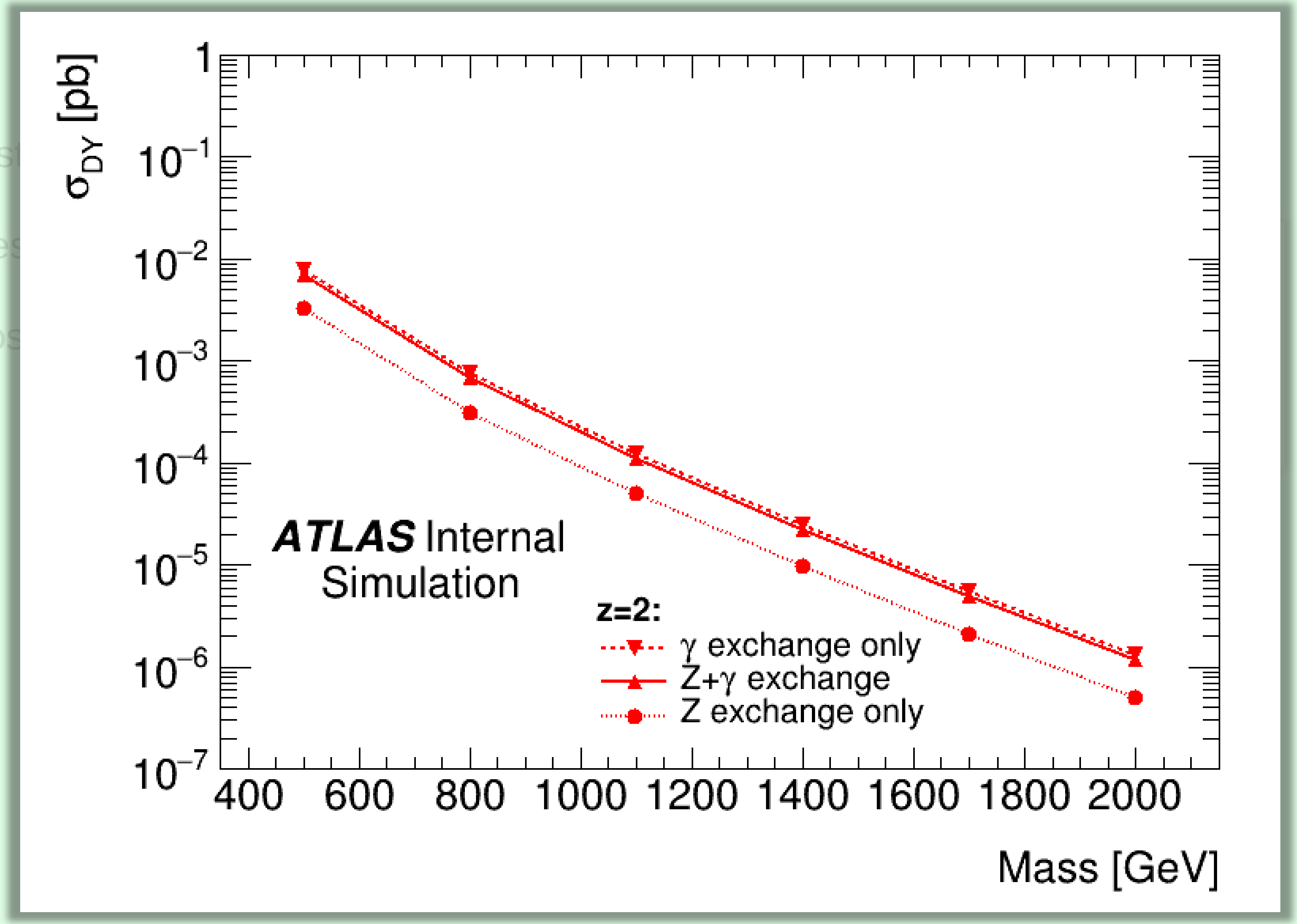

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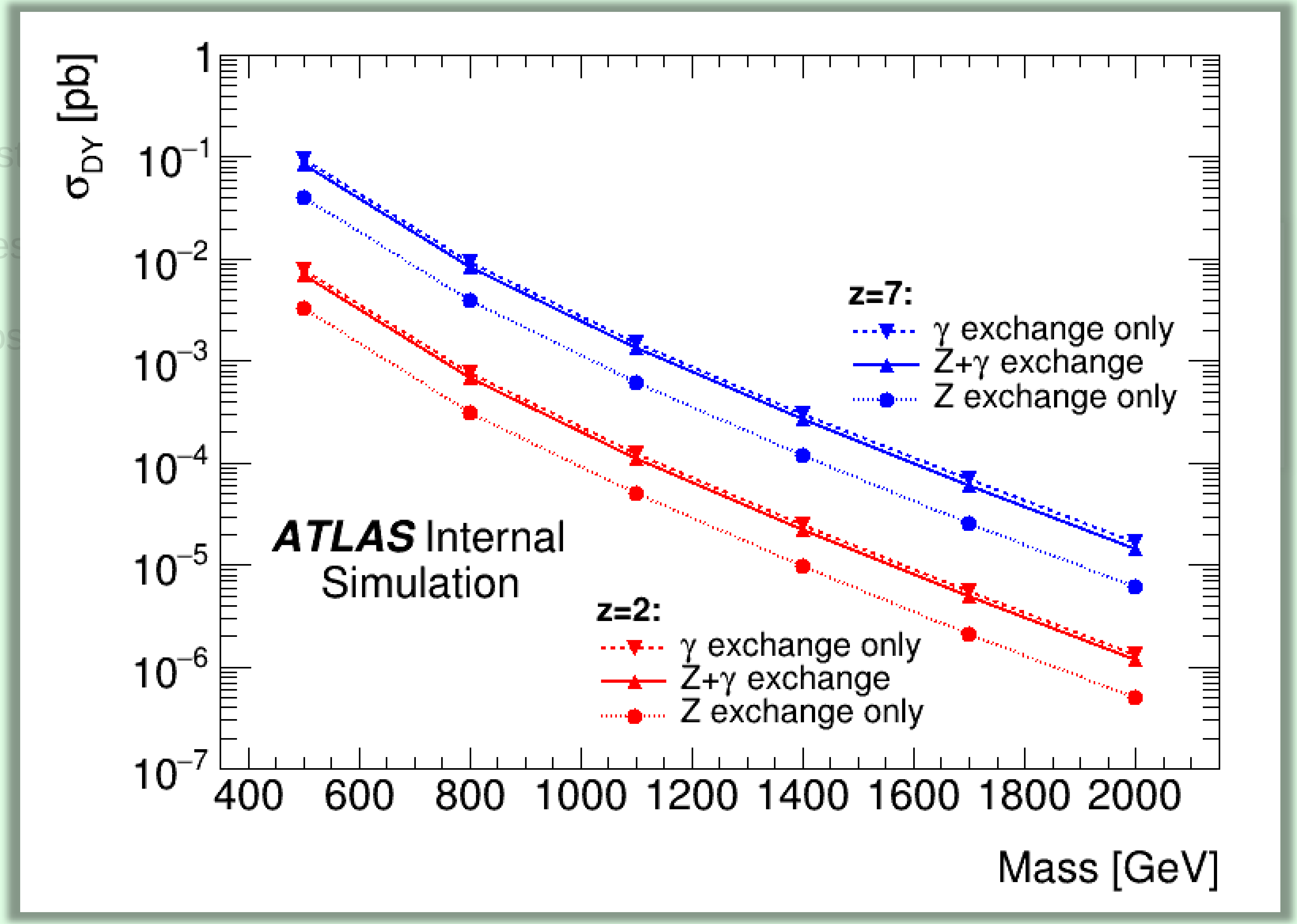

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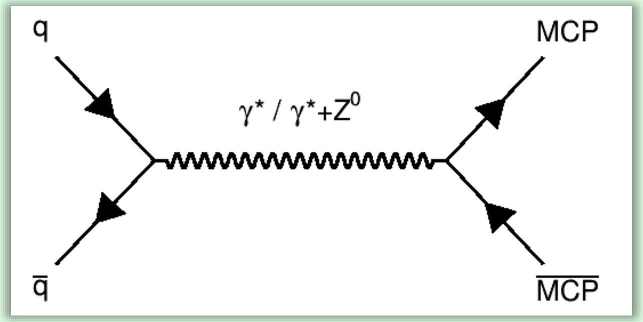

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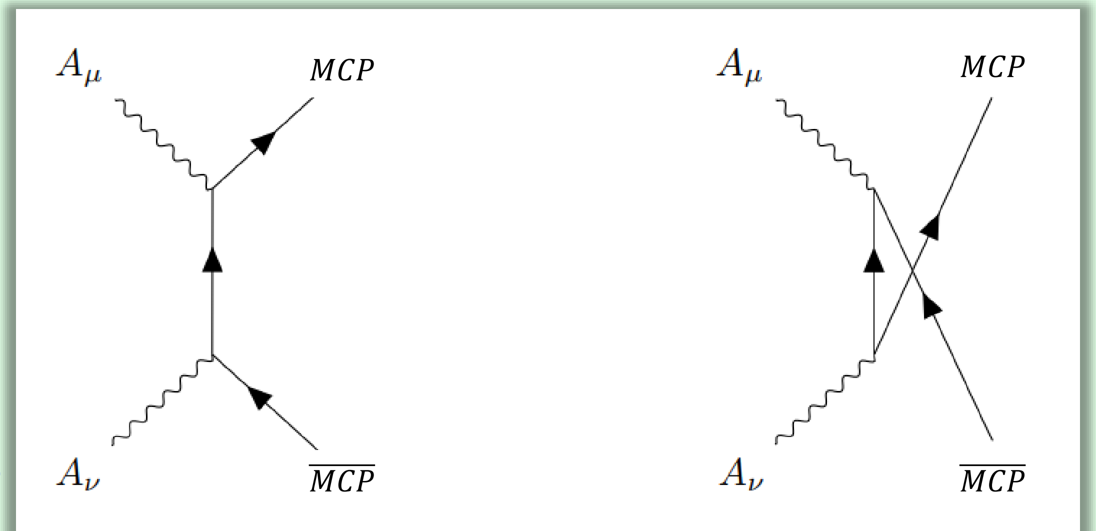
from https://cds.cern.ch/record/2686947



(a) t-channel (b) u-channel

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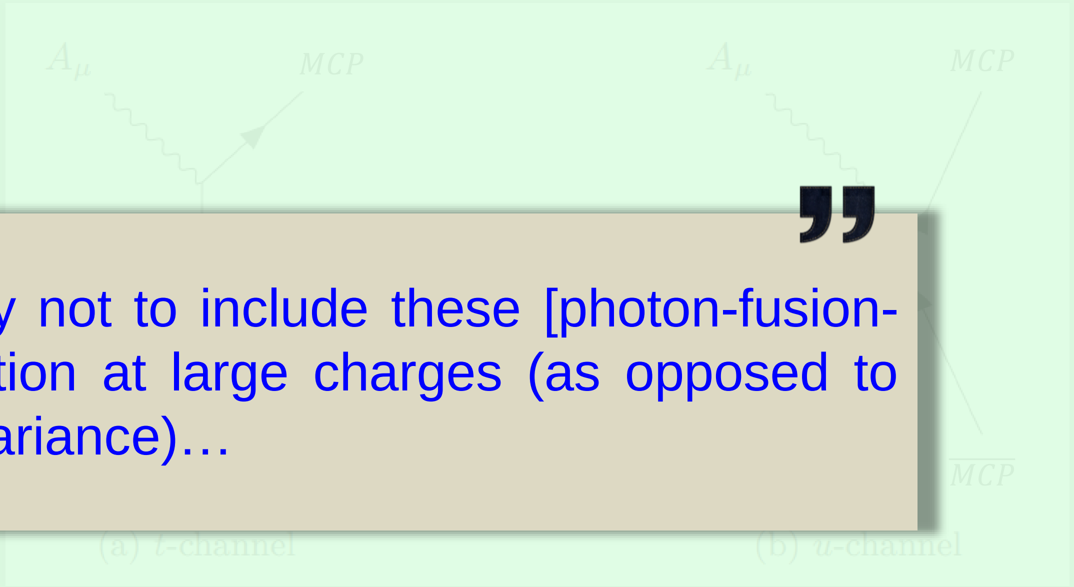

An email we received from Weizmann-Institute theorists concerning our 2015-2016 data search:

> …We do not think that there is any consistent way not to include these [photon-fusion-production] processes which dominate the production at large charges (as opposed to only considering DY production, it breaks gauge invariance)…

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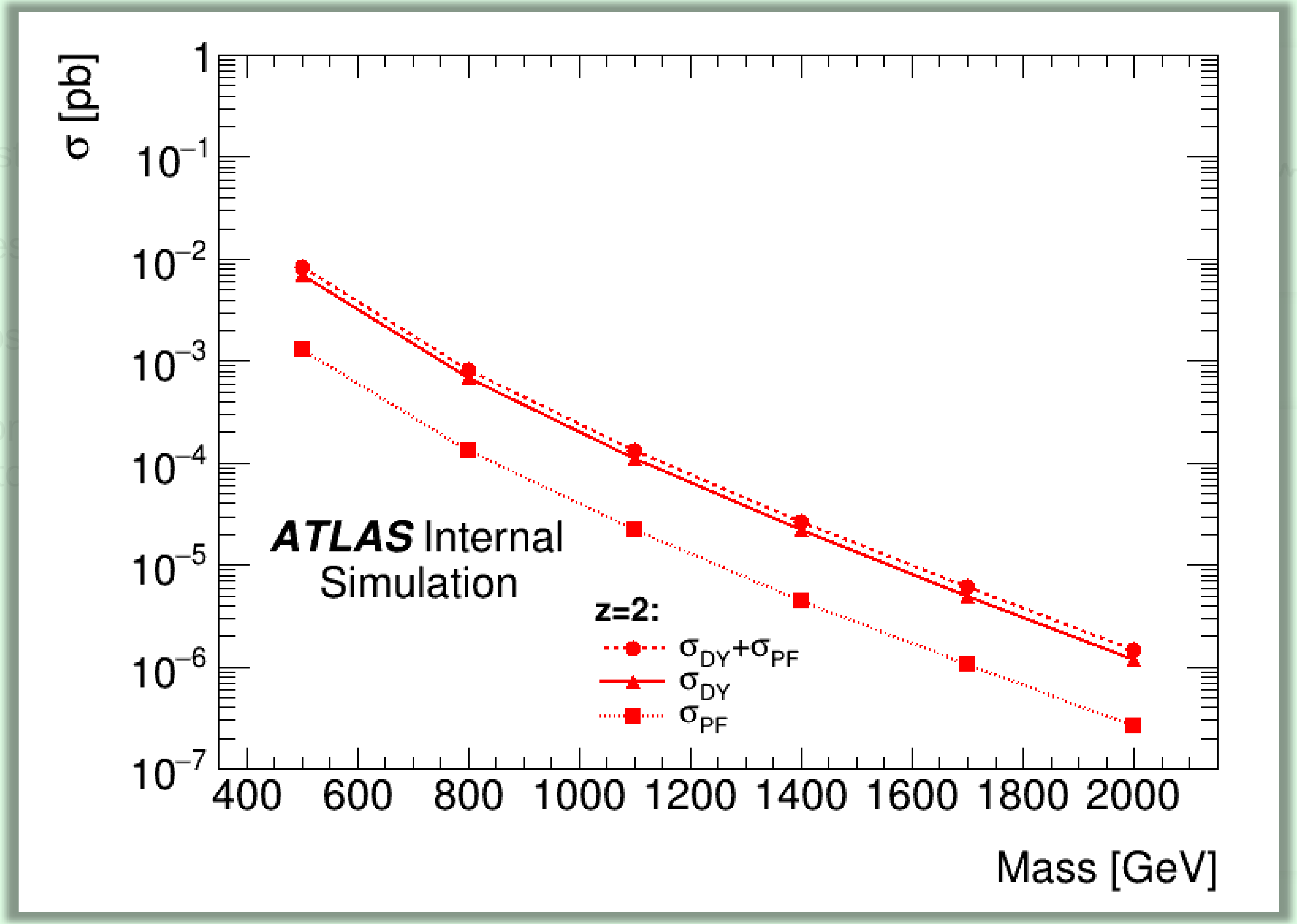

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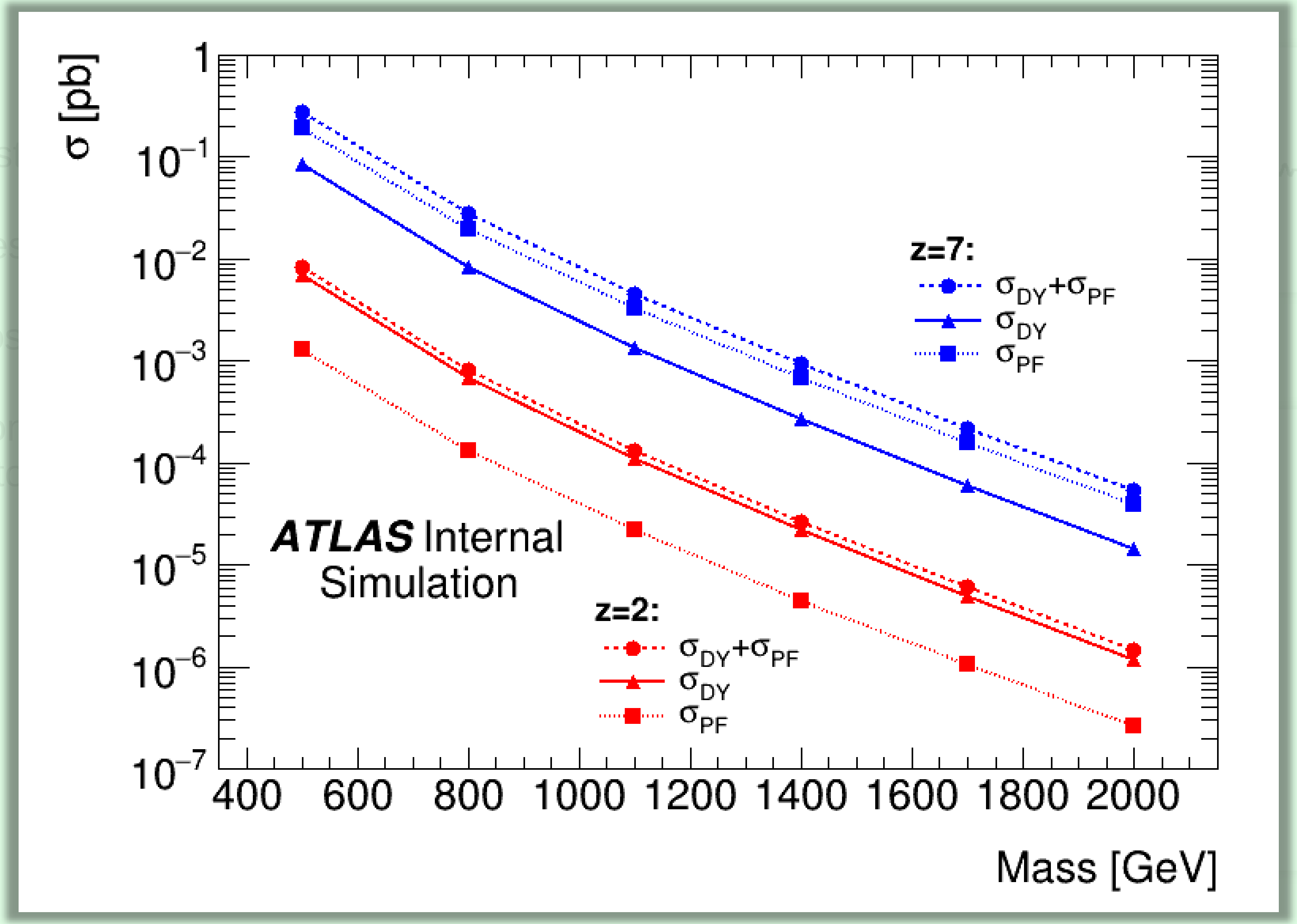

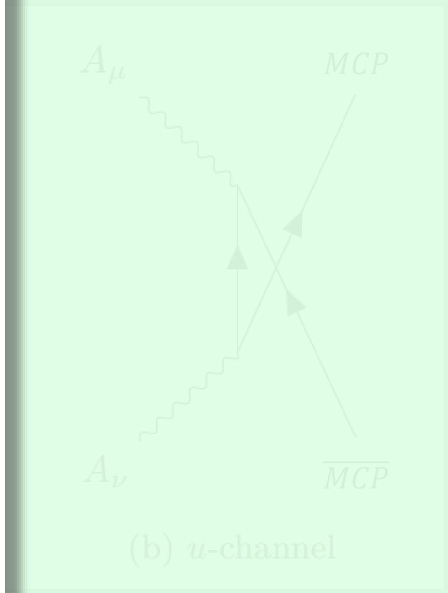

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  - production process: adding photon-fusion process to the Drell-Yan one;
  - triggers: adding new late-muon trigger.

Fires if there is a $p_T > 50$ GeV jet in the current BXing and a $p_T > 10$ GeV muon in the next BXing

available starting period C of 2017

Our current search in the 2015-2018 data

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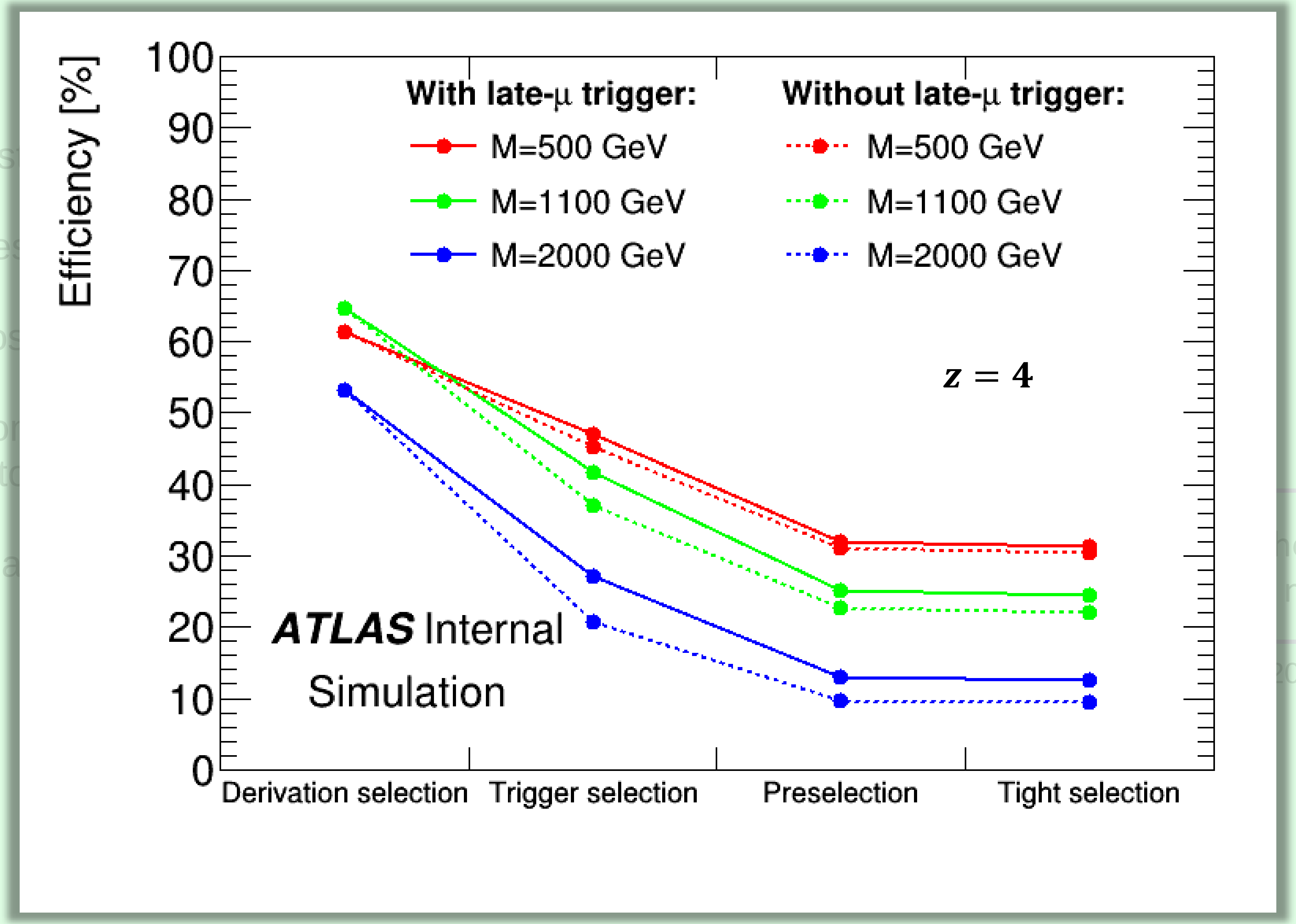
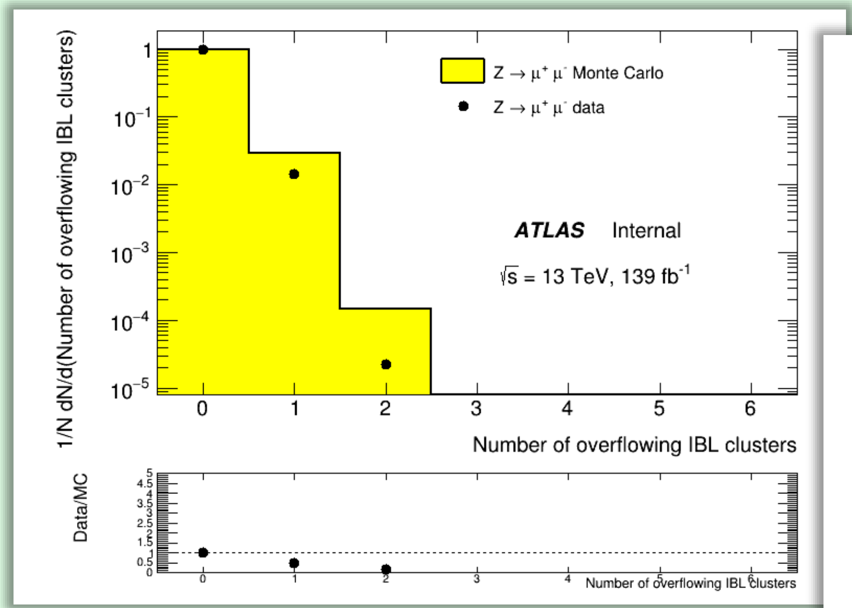
    process t
  - triggers: a

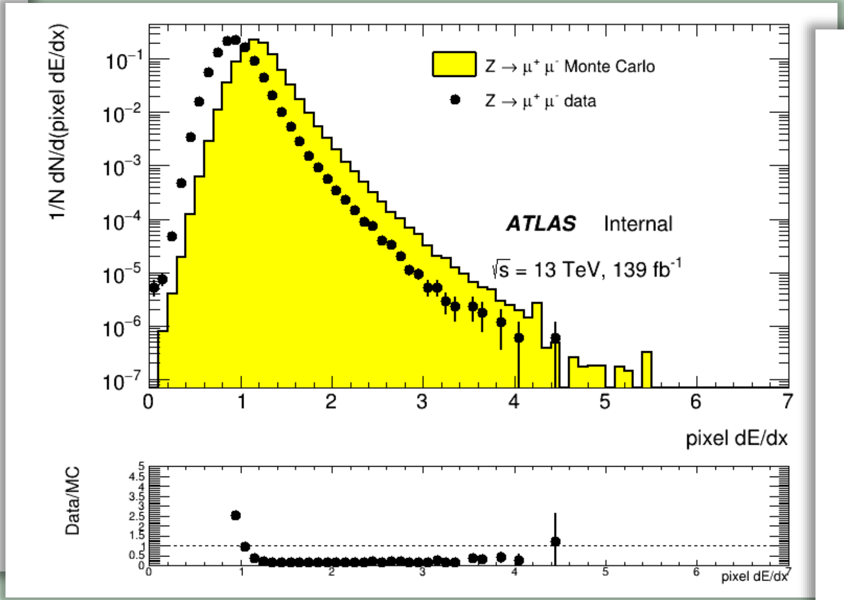


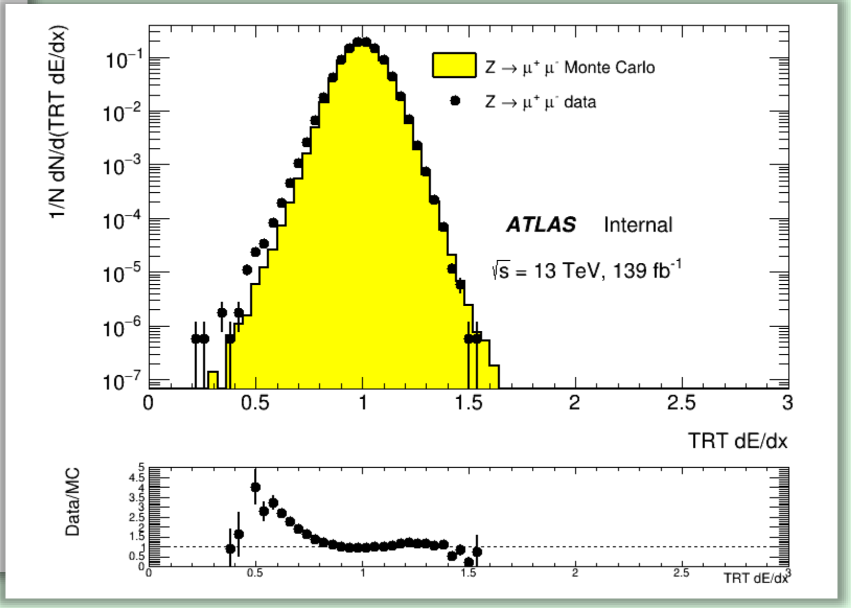
he current BXing
next BXing

2017

Current status: $Z \to \mu\mu$ data/MC comparison

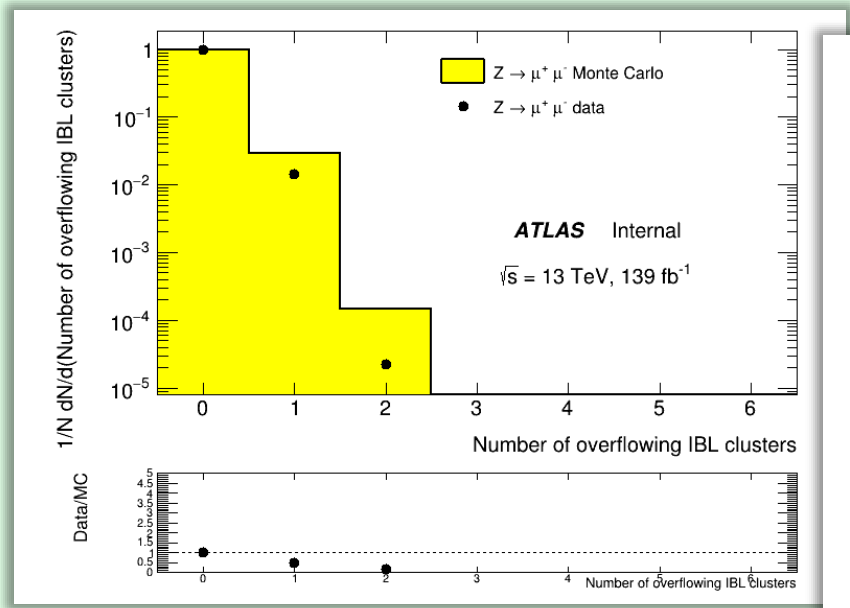


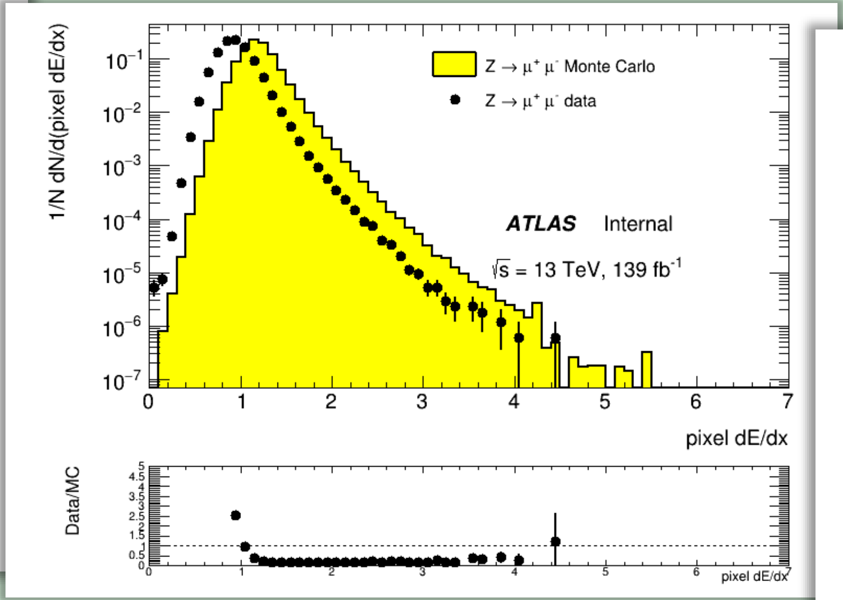


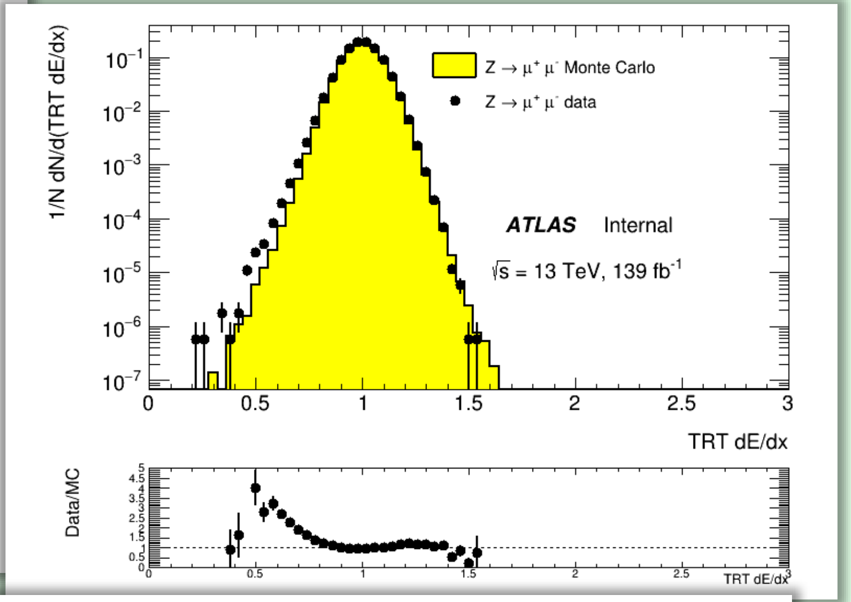


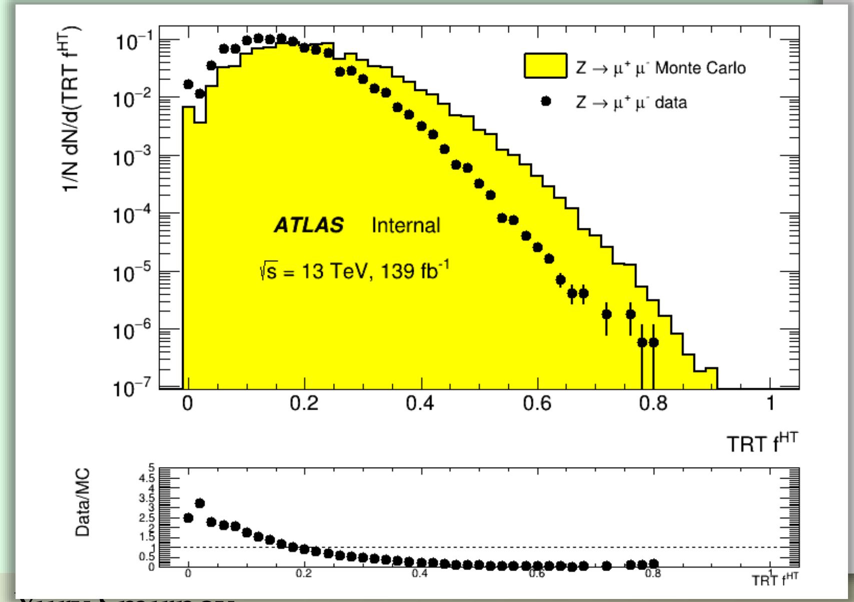
This pair of spectra will agree more after the tool factoring in the radiation-damage effect and η-dependence of the variable is available (the values will be corrected at the analysis level)

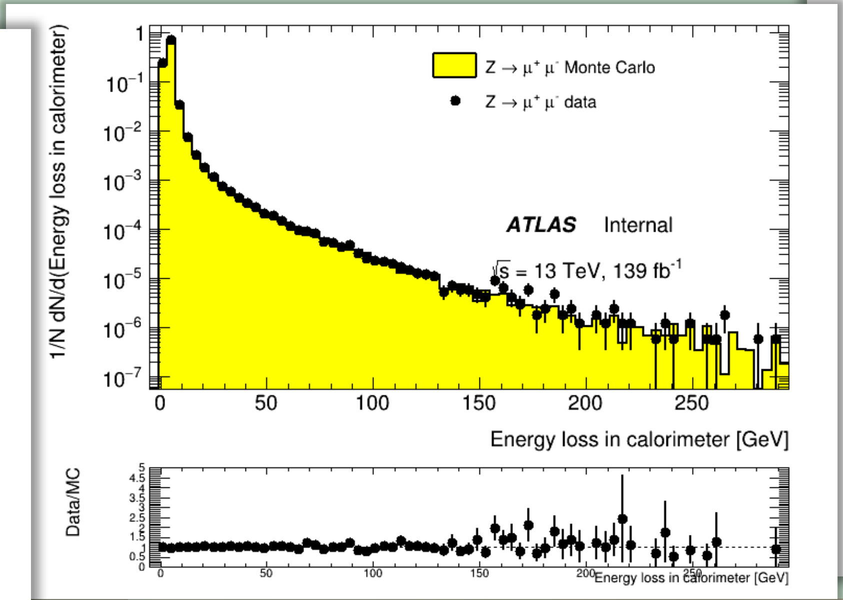
Current status: $Z \to \mu\mu$ data/MC comparison

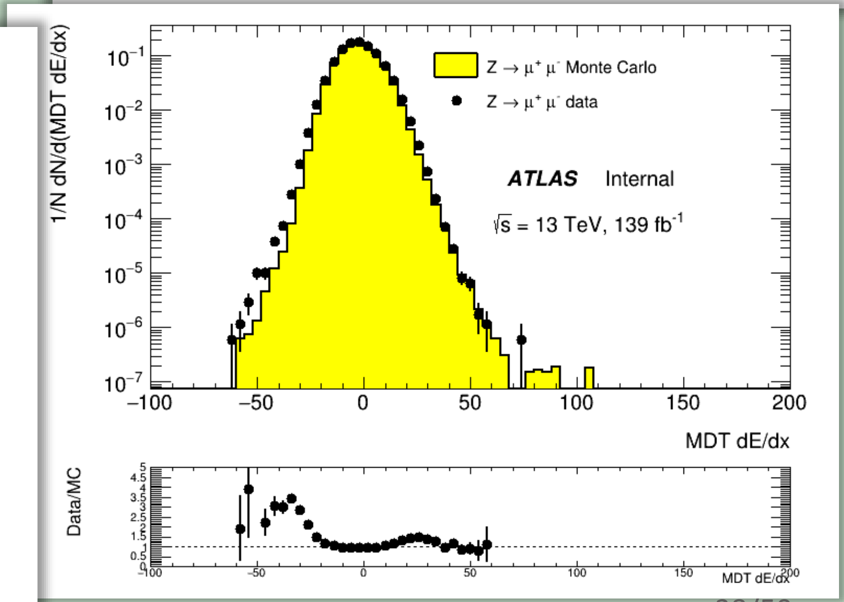












Current status: $Z \to \mu\mu$ data/MC comparison

Breaking this one down to many histograms:

2015

- $0 < \mu \leq 10$ barrel endcap
- $10 < \mu \leq 20$ barrel endcap
- $20 < \mu \leq 30$ barrel endcap

2016

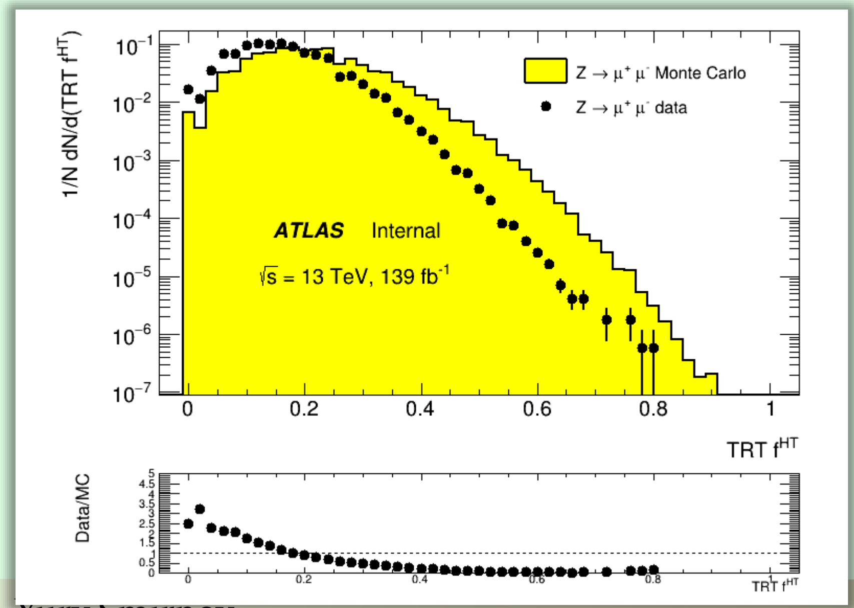
- $0 < \mu \leq 10$ barrel endcap
- $10 < \mu \leq 20$ barrel endcap
- $20 < \mu \leq 30$ barrel endcap
- $30 < \mu \leq 40$ barrel endcap
- $40 < \mu \leq 50$ barrel endcap

2017

- $0 < \mu \leq 10$ barrel endcap
- $10 < \mu \leq 20$ barrel endcap
- $20 < \mu \leq 30$ barrel endcap
- $30 < \mu \leq 40$ barrel endcap
- $40 < \mu \leq 50$ barrel endcap
- $50 < \mu \leq 60$ barrel endcap
- $60 < \mu \leq 70$ barrel endcap
- $70 < \mu \leq 80$ barrel endcap
- $80 < \mu \leq 90$ barrel endcap

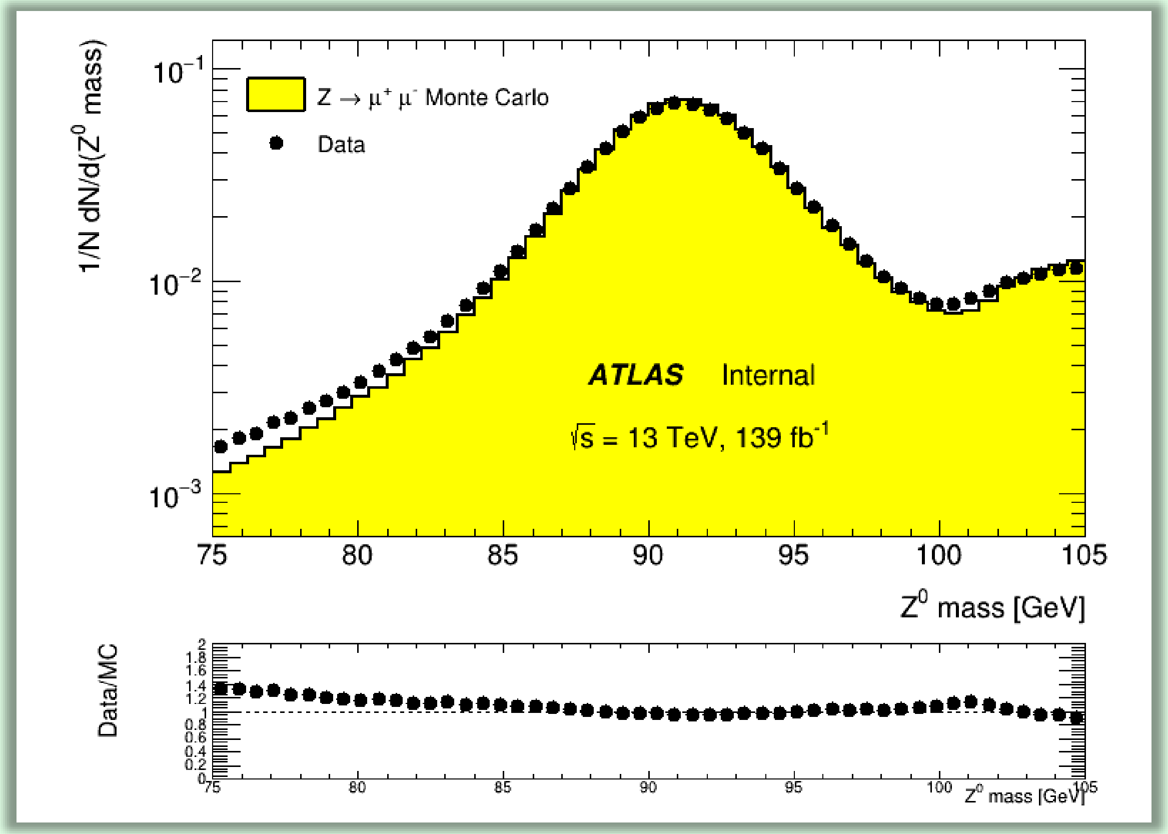
2018

- $0 < \mu \leq 10$ barrel endcap
- $10 < \mu \leq 20$ barrel endcap
- $20 < \mu \leq 30$ barrel endcap
- $30 < \mu \leq 40$ barrel endcap
- $40 < \mu \leq 50$ barrel endcap
- $50 < \mu \leq 60$ barrel endcap
- $60 < \mu \leq 70$ barrel endcap
- $70 < \mu \leq 80$ barrel endcap
- $80 < \mu \leq 90$ barrel endcap



Current status: $Z \to \mu\mu$ data/MC comparison

Are these really muons from Z decays?



- Based on PDG ID of the selected particles, 100% of them are indeed muons;
- Based on PDG ID of their parental particles, 99.9992% of these are indeed Z bosons;
- The selection is the same between data and MC (we do not throw away the remaining $8 \cdot 10^{-4}\%$ events in MC).

Current status: signal samples

- MC16 signal samples official request
  - Round I
  - Round II
  - Round III

Already had three requests for signal samples:

1. In November 2018, see ATLMCPROD-6719;

Went sideways: we ended up with AODs with no reconstructed MCPs;

What happened: a new filter was placed in MC16: if a particle was not flagged beforehand as interacting with detector material, it is not passed to simulation. And MCPs were never flagged as such. Fixed in 21.0.95 by MRs 21422 and 21660.

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2. In March 2019, see later comments in the same ATLMCPROD-6719;
   Went sideways: MDT-dE/dx calculation turned out to be broken in r21: there is no difference between its values for muons and MCPs;
   What happened: a line of digitization code in Athena defining MDT-dE/dx dependence of z and γ used to work in r20, but stopped working in r21 → neither charge nor mass of MCPs is taken in account. Fixed in 21.0.100 by MR 24737. Also, we noticed a critical disagreement of TRT dE/dx between data and MC → couldn't decide if we needed to fix it in on reconstruction or analysis level → requests paused.

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- MC16 signal samples official request
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3. In March 2020, see ATLMCPROD-8394;

Status: finished last Sunday (five days ago)

The most recent signal-sample request: general info

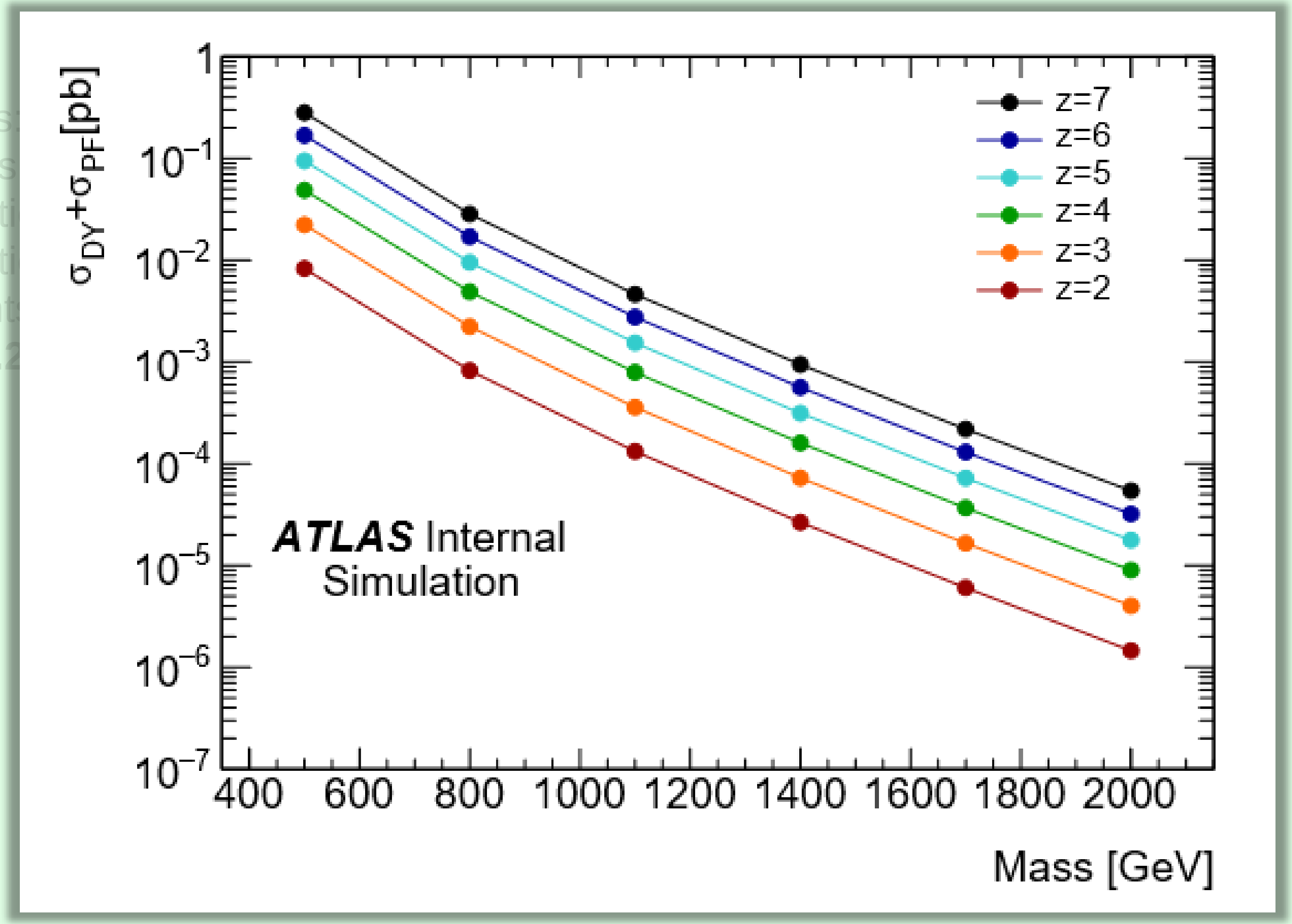
72 samples:

- 6 masses: 500, 800, 1100, 1400, 1700, and 2000 GeV;
- 6 charges: ±2e, ±3e, ±4e, ±5e, ±6e, and ±7e;
- 2 production models: DY and PF;
- 3 production campaigns: MC16a, MC16d, and MC16e;
- 10k events per mass per charge per model per campaign;
- almost **2.2M fullsim events** overall**.**

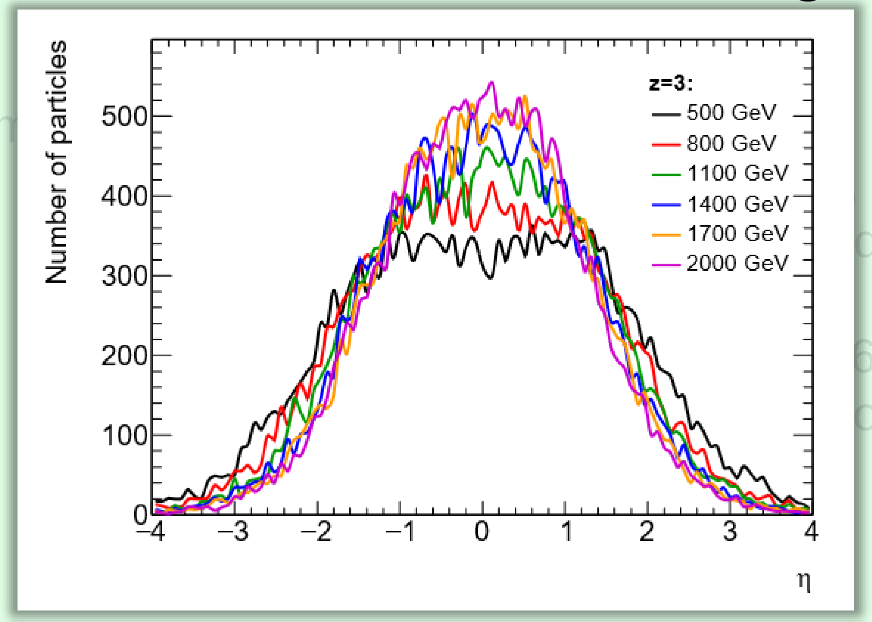
The most recent signal-sample request: X-sections vs. mass

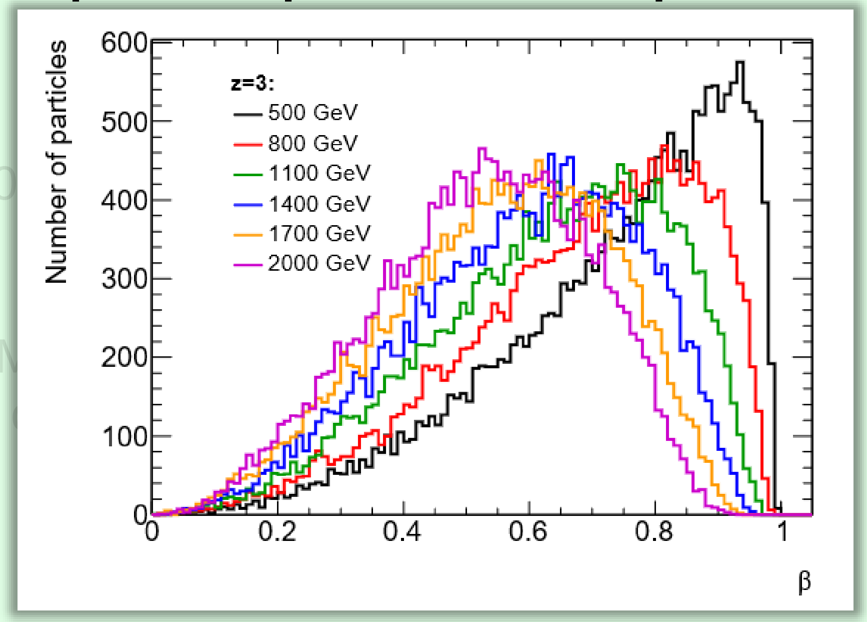
72 samples:

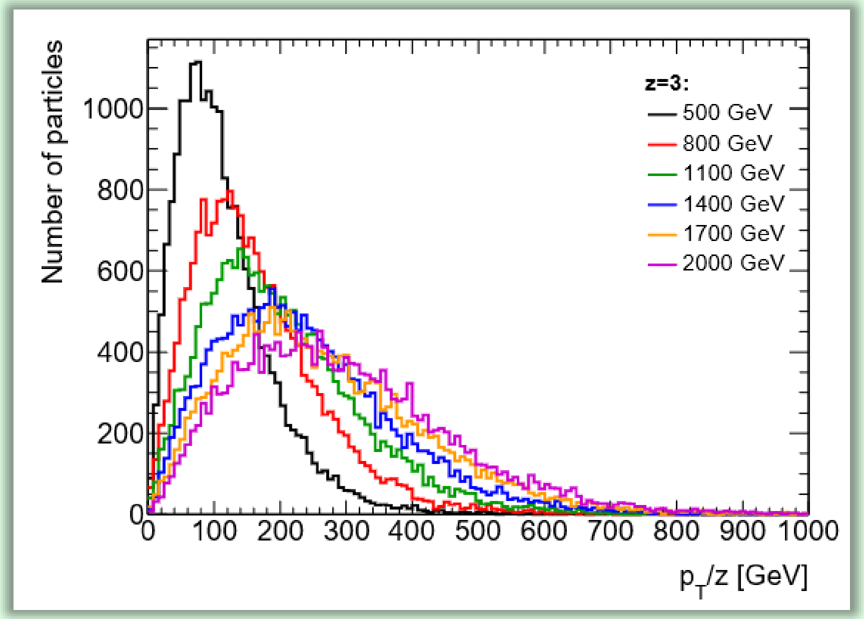
- 6 masses:
- 6 charges
- 2 producti
- 3 producti
- 10k event
- almost **2.2**

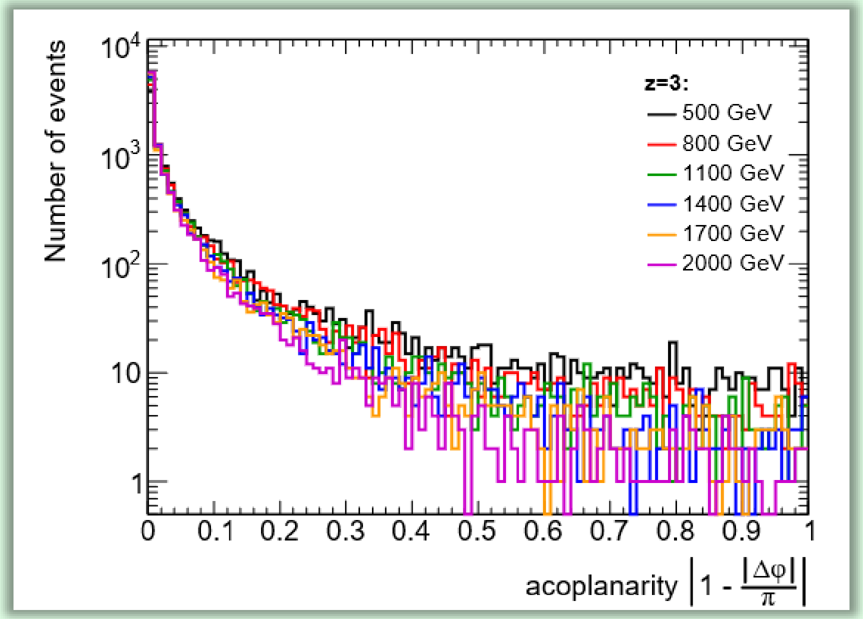


The most recent signal-sample request: truth plots



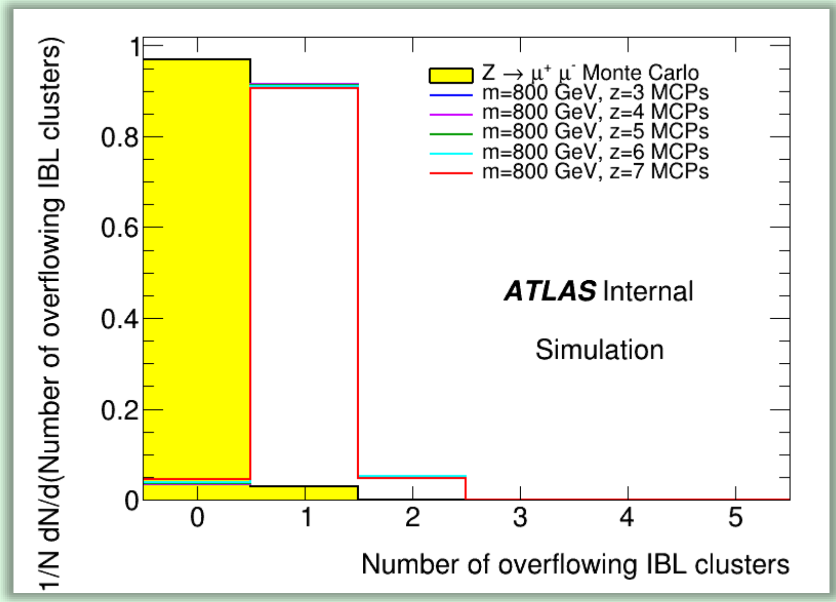


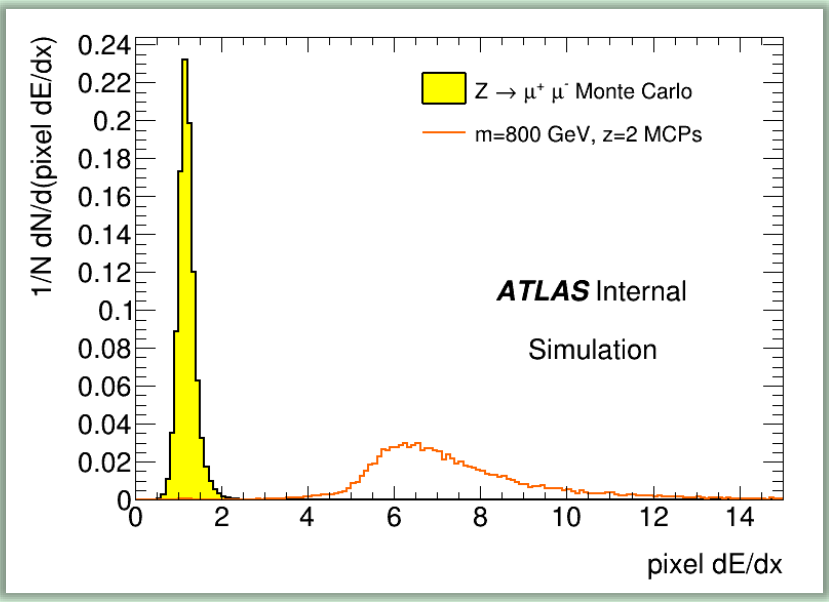


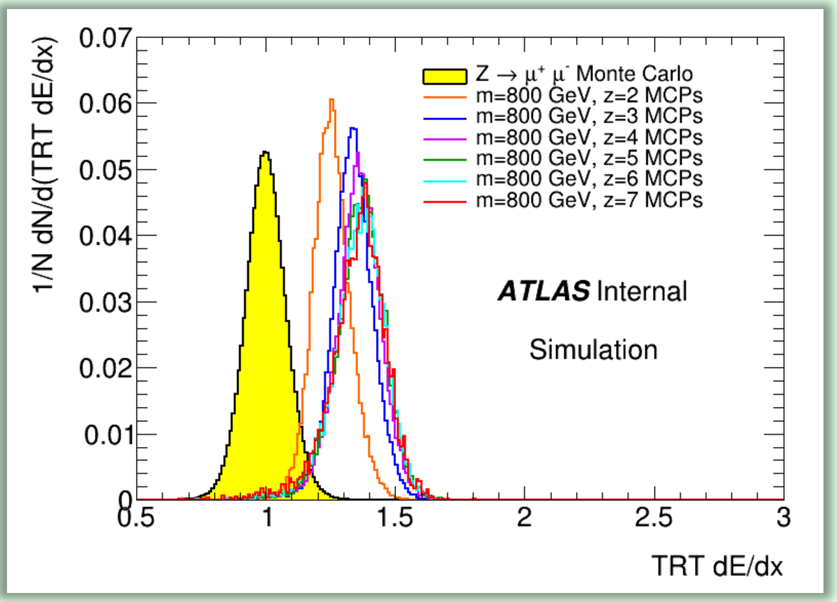


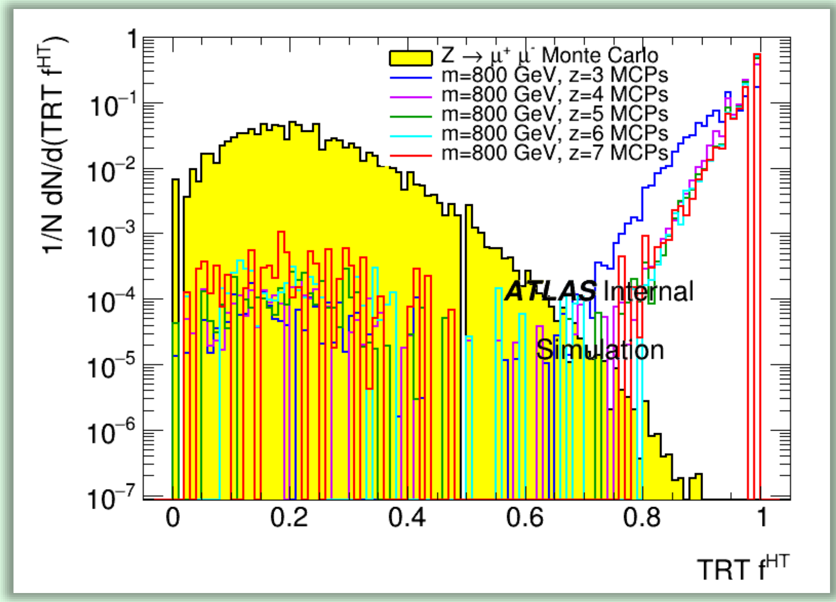
More plots on the truth level:
https://twiki.cern.ch/twiki/bin/view/AtlasProtected/MC16MultiChargedParticlesValidationPlots?rev=6

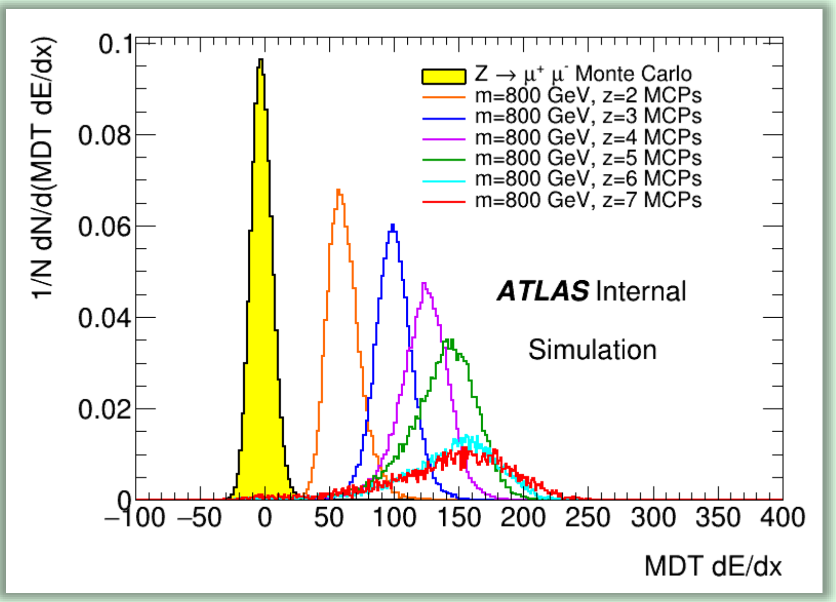
The most recent signal-sample request: key signal/bkg discriminators





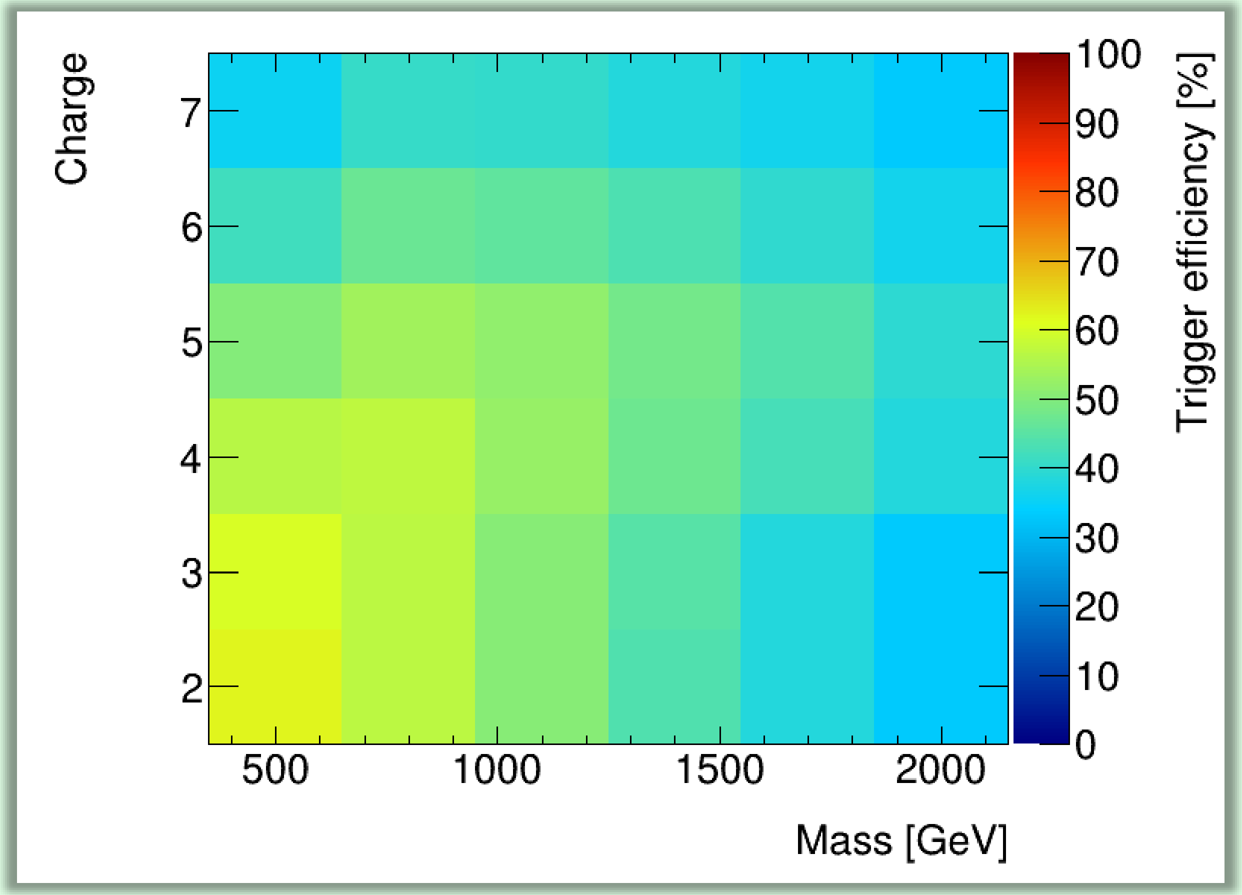




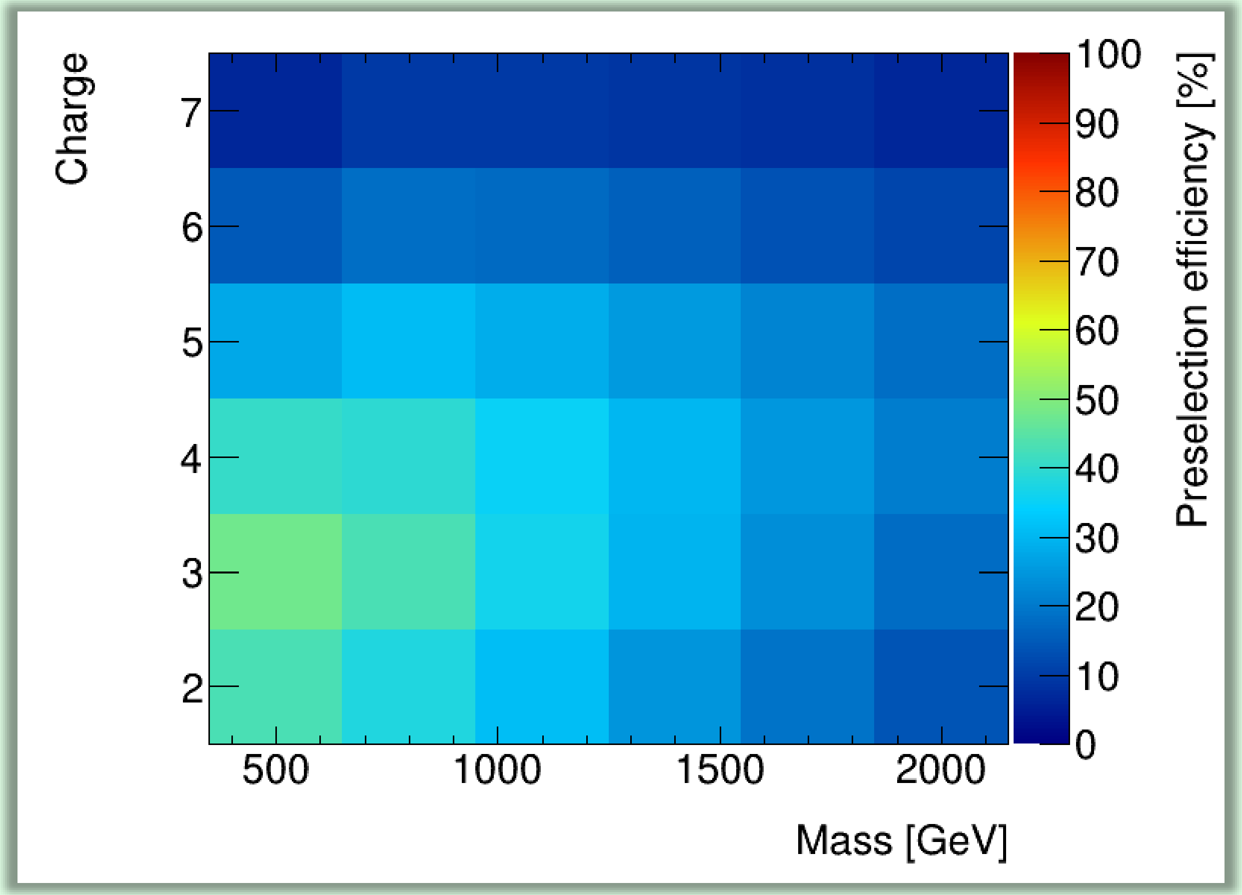


The most recent signal-sample request: efficiency maps

Trigger efficiency



Preselection efficiency



Documentation

Twiki: https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/ExoticMultiChargeFullRun2

Glance entry: https://glance.cern.ch/atlas/analysis/analyses/details.php?id=2107

Supporting note: https://cds.cern.ch/record/2711648

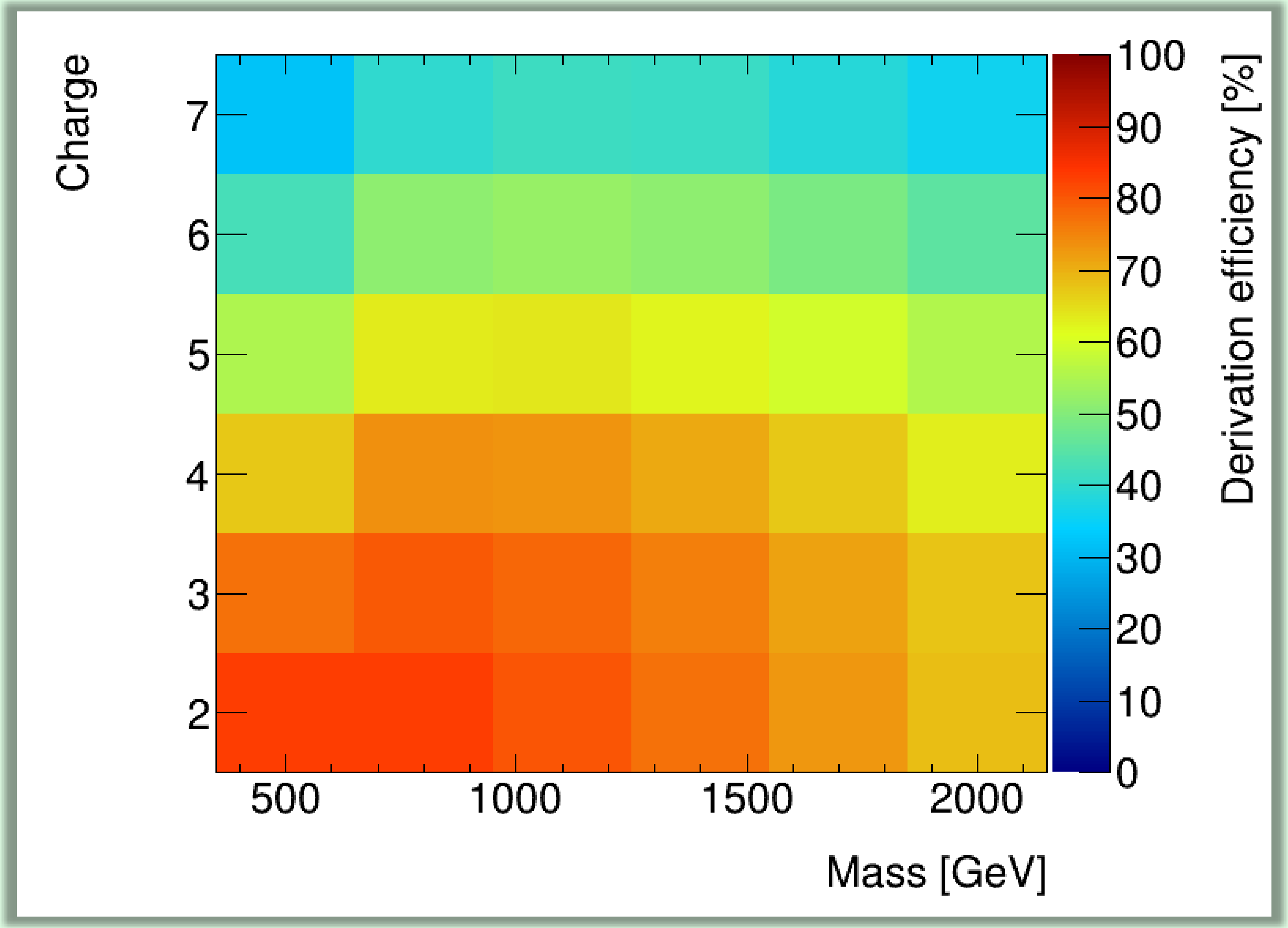
almost empty;
nevertheless, most of
the plots are obsolete
already

Ballpark timeline

Entire selection, efficiency calculation, bkg estimation	by July
Uncertainties	by September
Mass limits, paper draft	by October/November
RECAST	???
First circulation	2021

THANKS!

The most recent signal-sample request: efficiency maps

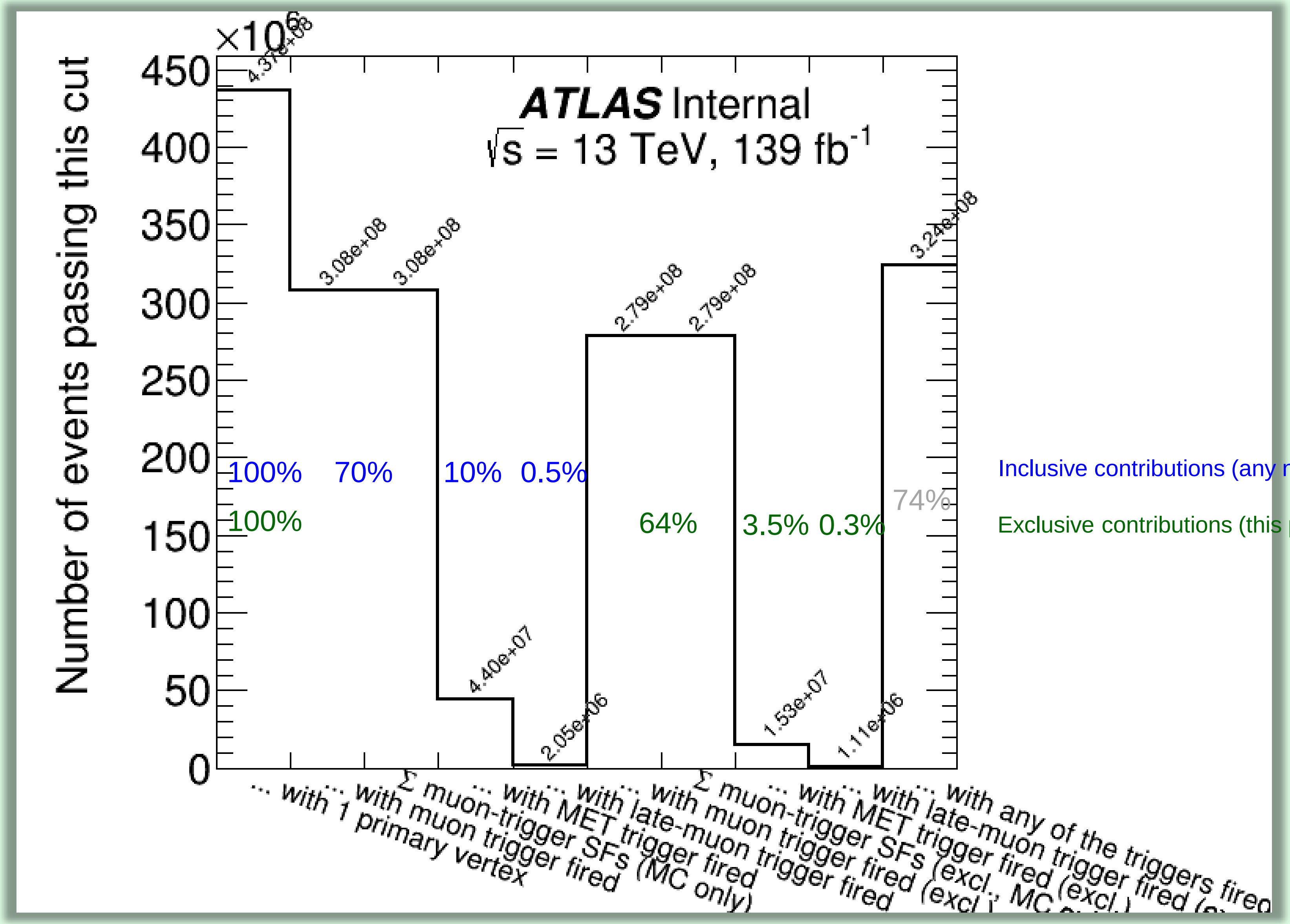


Trigger selection in the current analysis

Trigger	HLT chain	Period
Single-muon trigger	**HLT_mu50**	2015 2016 2017 2018
OR		
MET trigger	**HLT_xe70_mht**	2015
	HLT_xe90_mht_L1XE50	2016, up to run 302900
	HLT_xe110_mht_L1XE50	2016, run 302900 onwards
	HLT_xe110_pufit_L1XE55	2017
	HLT_xe110_pufit_xe70_L1XE50	2018
OR		
NEW! late-muon trigger	–	2015 - 2016
	HLT_mu10_mgonly_L1LATE-MU10_J50	2017 (run 329000 onwards) - 2018

Fires on a $p_T > 50$ GeV jet in the current BXing and a $p_T > 10$ GeV muon in the next BXing

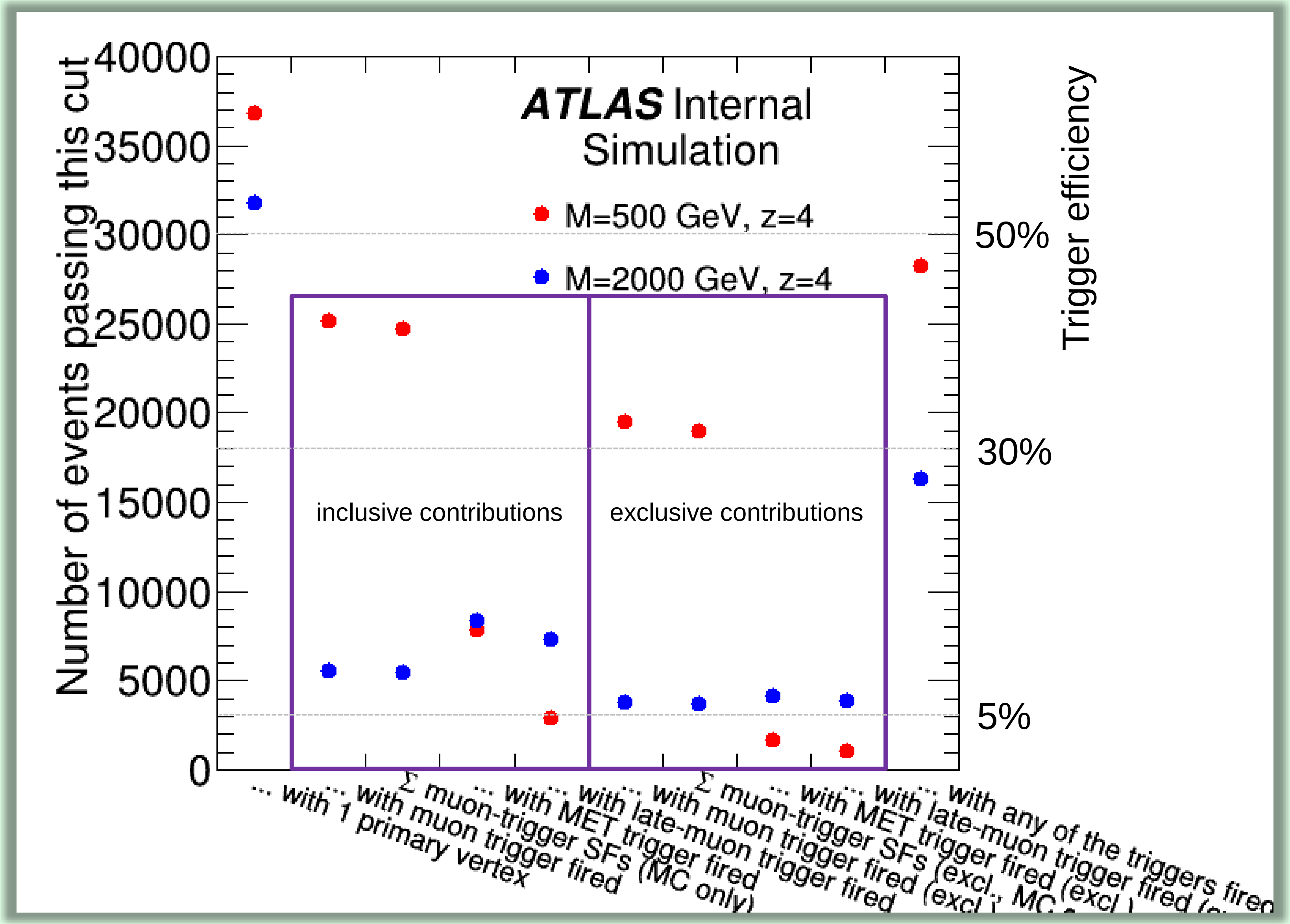
Contribution of different triggers in data



Inclusive contributions (any number of these three triggers may fire in an event)

Exclusive contributions (this particular trigger fired, but the other two did not)

Contribution of different triggers in signal MC



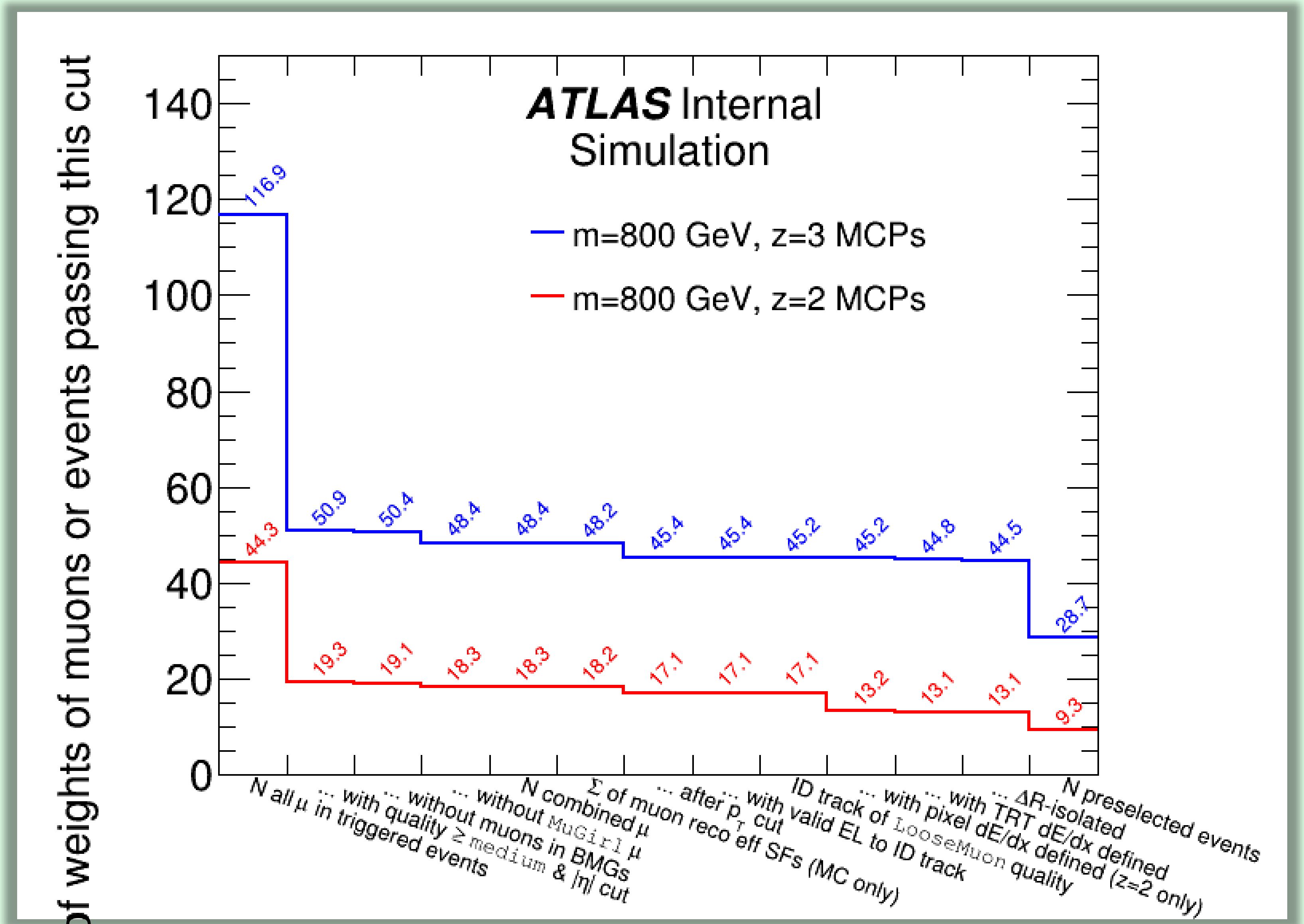
M=500 GeV:
MET trigger exclusive contribution: **~10%** of the single-muon-trigger contribution;
Late-muon-trigger exclusive contribution: **~5%** of the single-muon-trigger contribution.

M=2000 GeV:
MET trigger exclusive contribution: **~100%** of the single-muon-trigger contribution;
Late-muon-trigger exclusive contribution: **~100%** of the single-muon-trigger contribution.

Preselection criteria

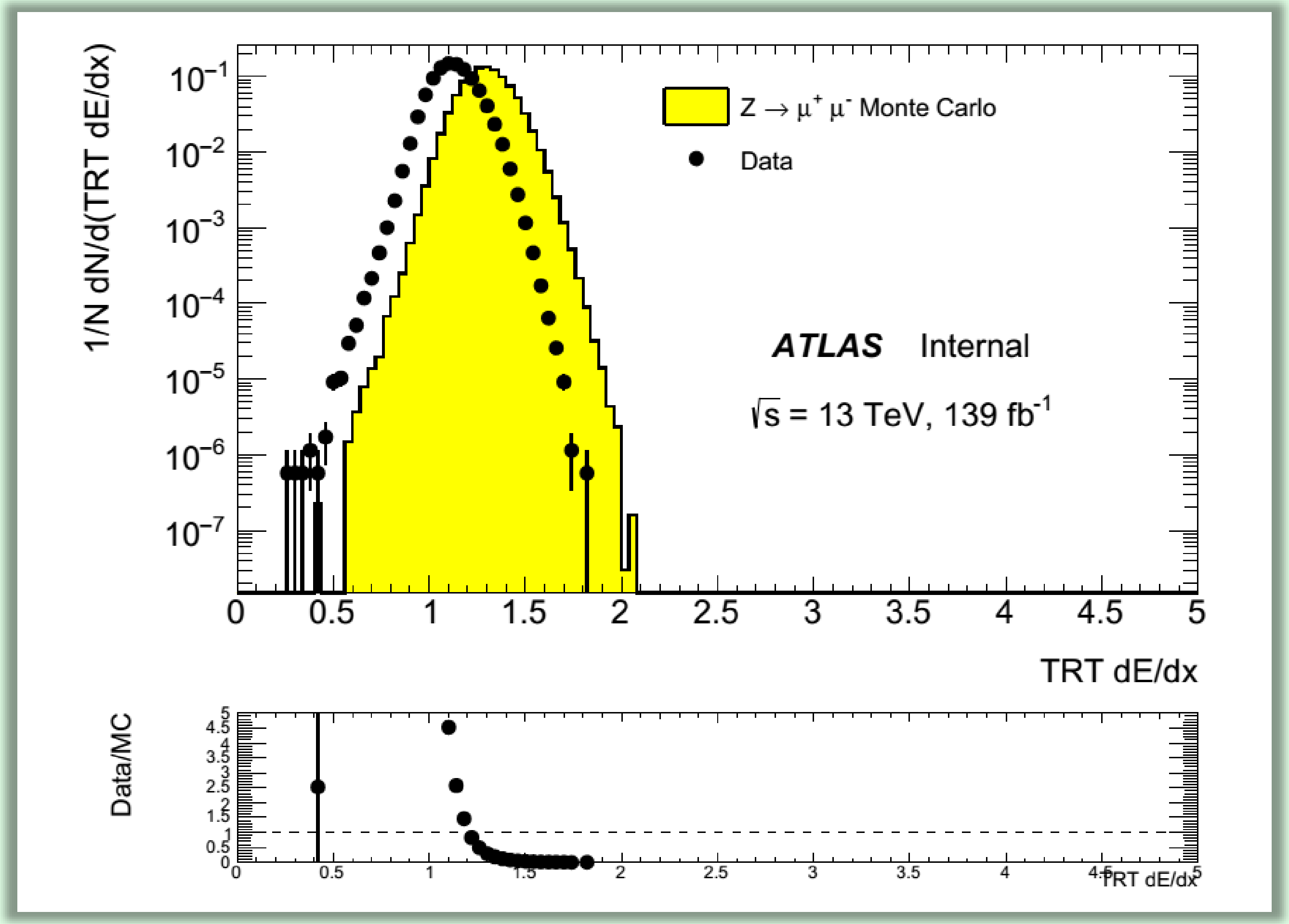
Muons		ID tracks	
Variable	Value	Variable	Value
Type	combined	Quality	“LooseMuon”
η, ϕ	$\|\eta\| < 2.0$ and not in BMG chambers	# TRT hits used for TRT dE/dx calculation	≥ 6
Transverse momentum	$p_T > 50$ GeV	Isolation	no other ID tracks within $\Delta R < 0.01$
Quality	“medium”	# pixel hits used for pixel dE/dx calculation	≥ 2
Author	any but `MuGirl`	# pixel hits shared between at least two tracks	none

Preselection cutflow

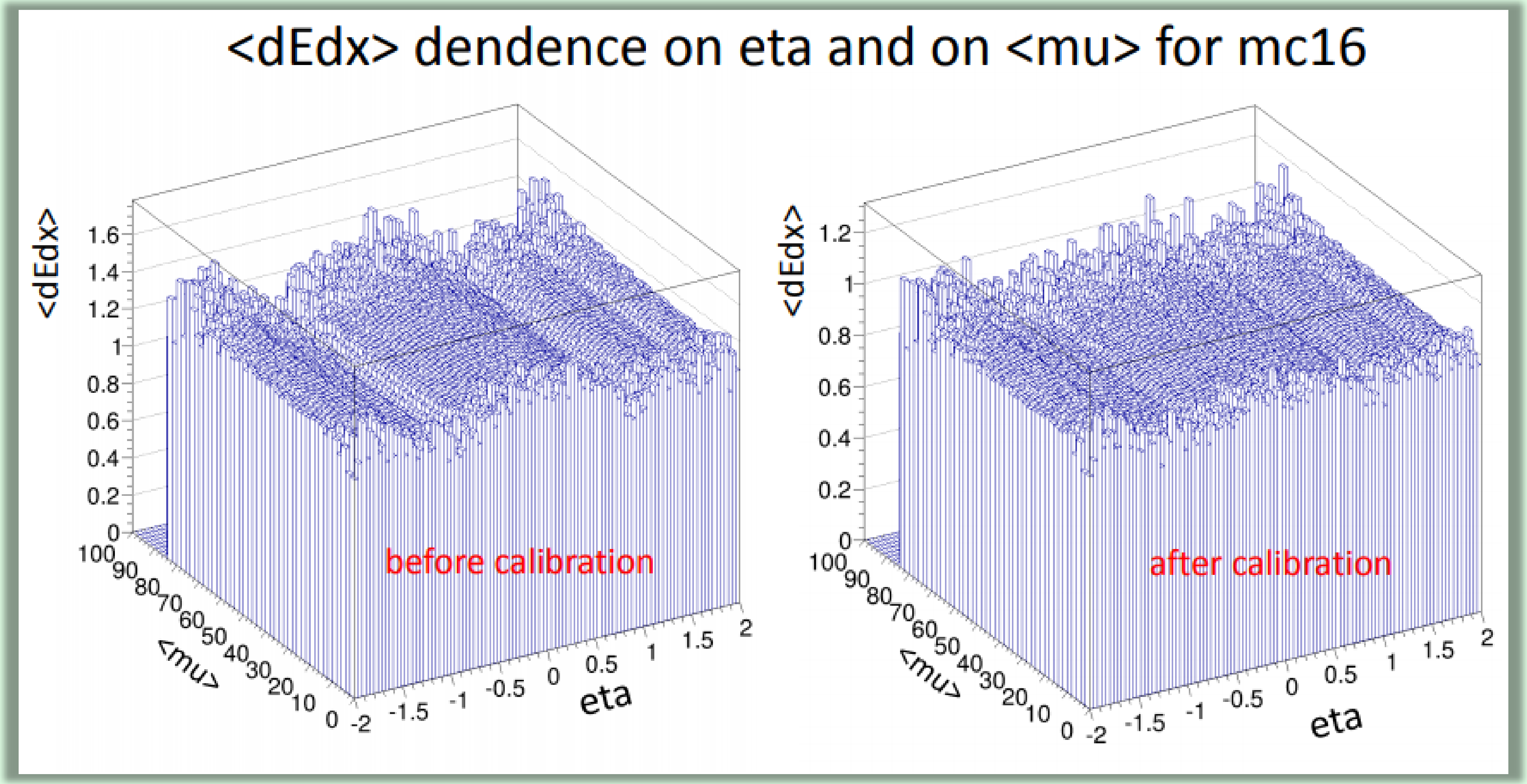


57/50

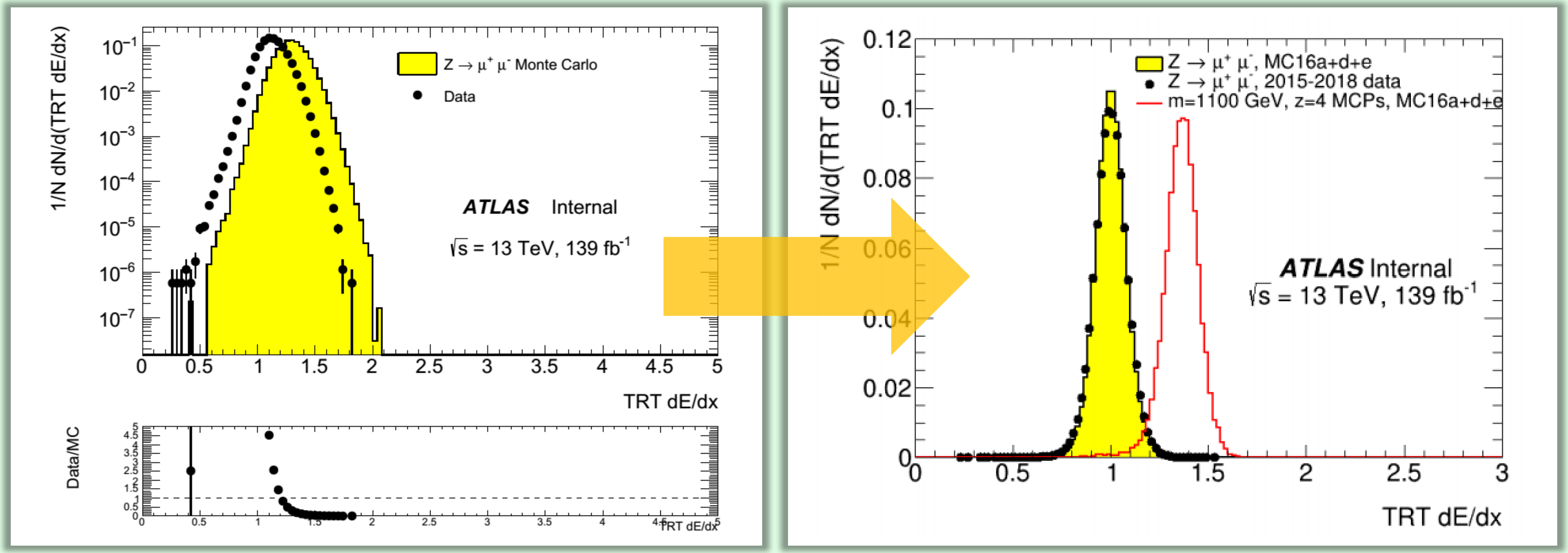
TRT dE/dx issue in r21



TRT dE/dx issue in r21



TRT dE/dx issue in r21

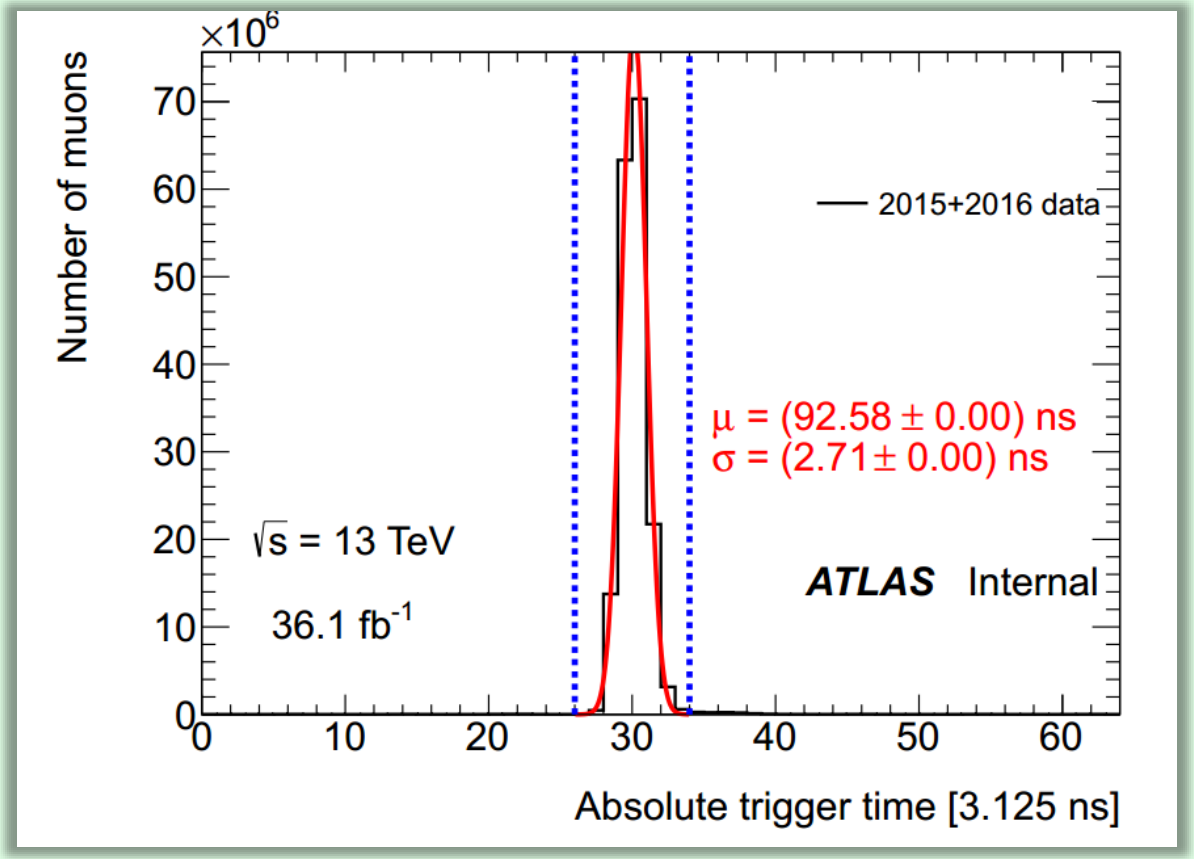


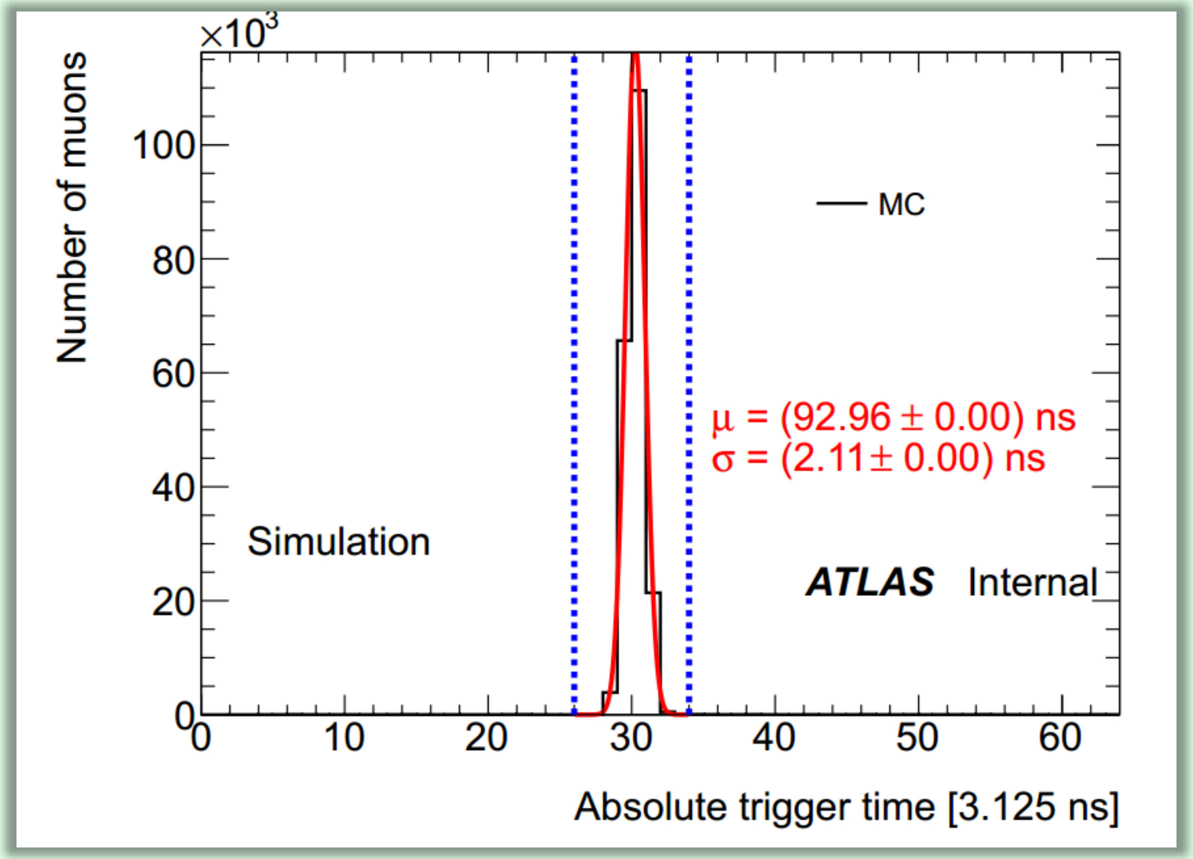
More info:

https://indico.cern.ch/event/836962/contributions/3509024/attachments/1886097/3109287/MCPs_TRT_v01.pdf
https://indico.cern.ch/event/885038/contributions/3744021/attachments/1991125/3321322/bulekov_TRT_dEdx_Calibrations_TRT_Days_20_02_20.pdf

Trigger-efficiency scaling

The trigger-timing distributions of the RPC triggers in the readout window differ in data and Monte-Carlo. This can be quantified by peak positions within the readout window $\Delta = t_{end\ of\ readout\ window} - \mu$ and the width of the distribution σ:

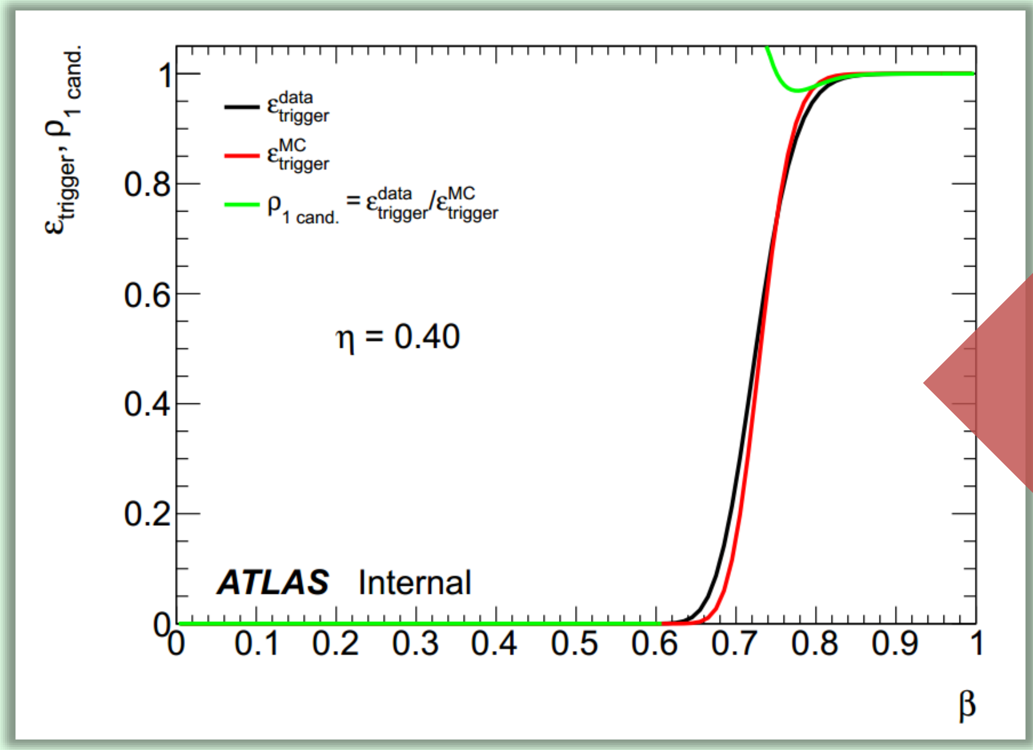


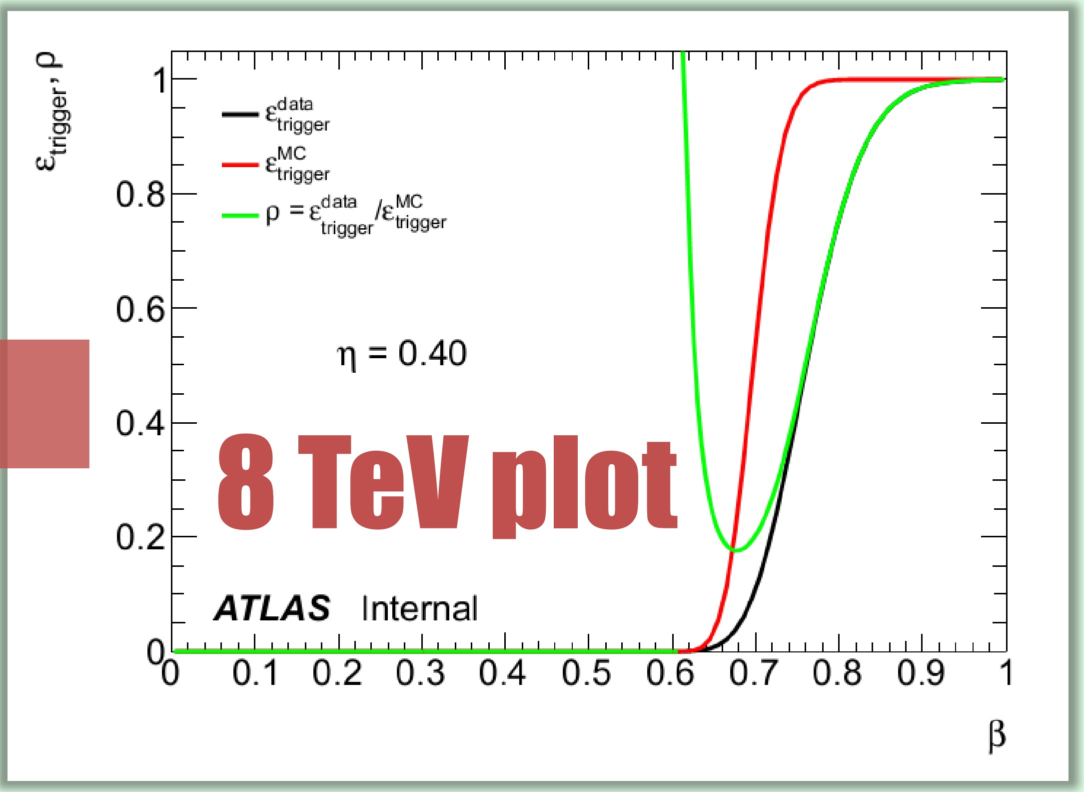


Trigger-efficiency scaling

The effect is taken care of by applying scaling ρ to all MCPs triggered by RPCs ($|\eta| < 1.05$), and finally translating this “muon-level scaling” to the “event-level scaling”

Scaling is β- and η-dependent quotient of calculated trigger efficiencies in data and MC.





Trigger-efficiency scaling

Everything you did not want to know about trigger-efficiency scaling on one slide

Calculated trigger efficiencies depend on Δ, σ, β & η:

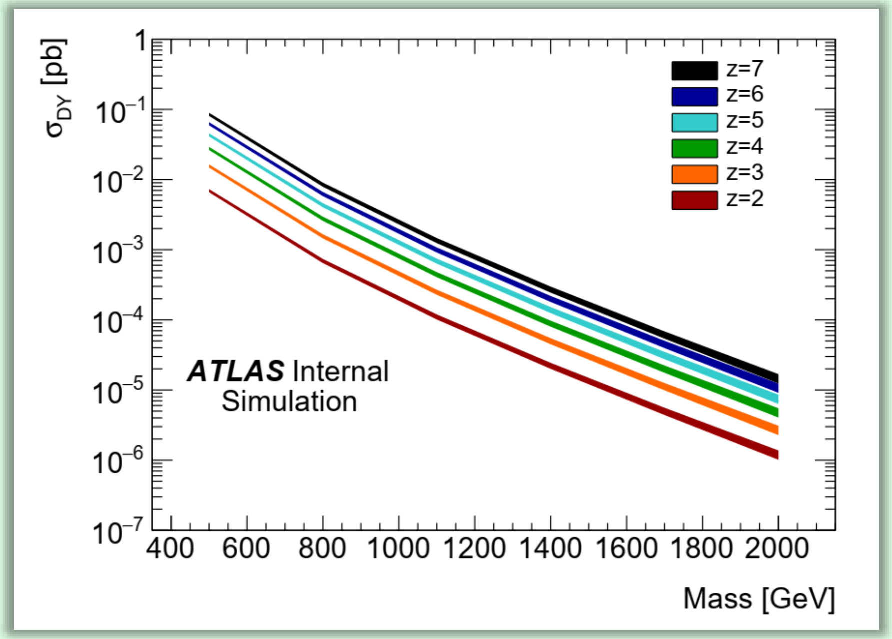
$$\varepsilon_{trigger}^{data/MC} = \frac{1}{2}\left(1 - erf\left(\frac{t - t_0 - \Delta_{data/MC}}{\sqrt{2}\sigma_{data/MC}}\right)\right)$$, where

$t = \frac{L}{\beta c}$ - time the signal particles take to reach the outermost RPC plane

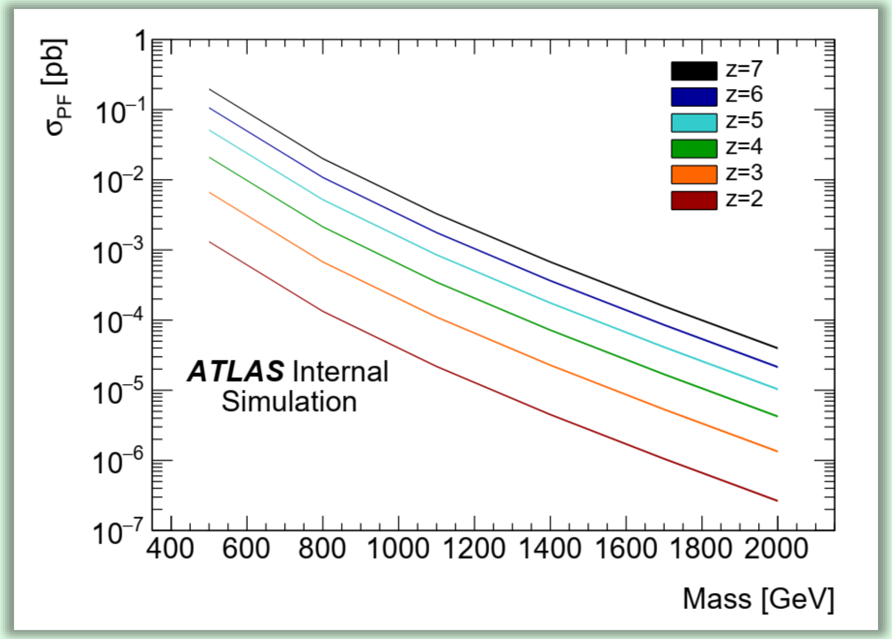
$t_0 = \frac{L}{c}$ - time muons take to reach the outermost RPC plane

$\beta = \frac{\beta_{ID} + \beta_{MS}}{2}$ - effective β

$L = \frac{r}{\sin\theta}$ - distance between the IP and outermost RPC plane, $r = 10$ m $\rightarrow \eta$ dependence



+



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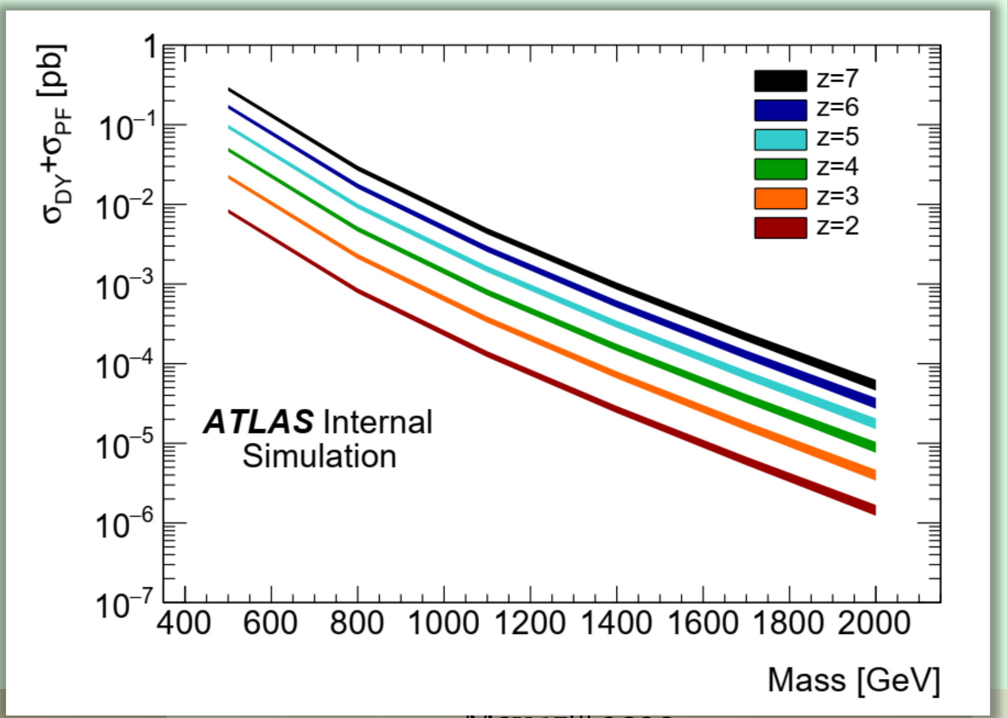

Mind different line widths!

More on the MET origin