

Search for multi-charged particles

Yury Smirnov

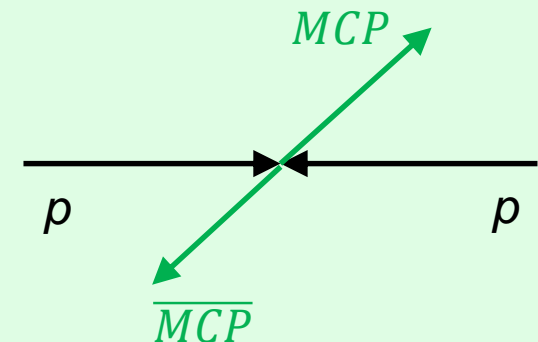
May 13, 2020

Outline

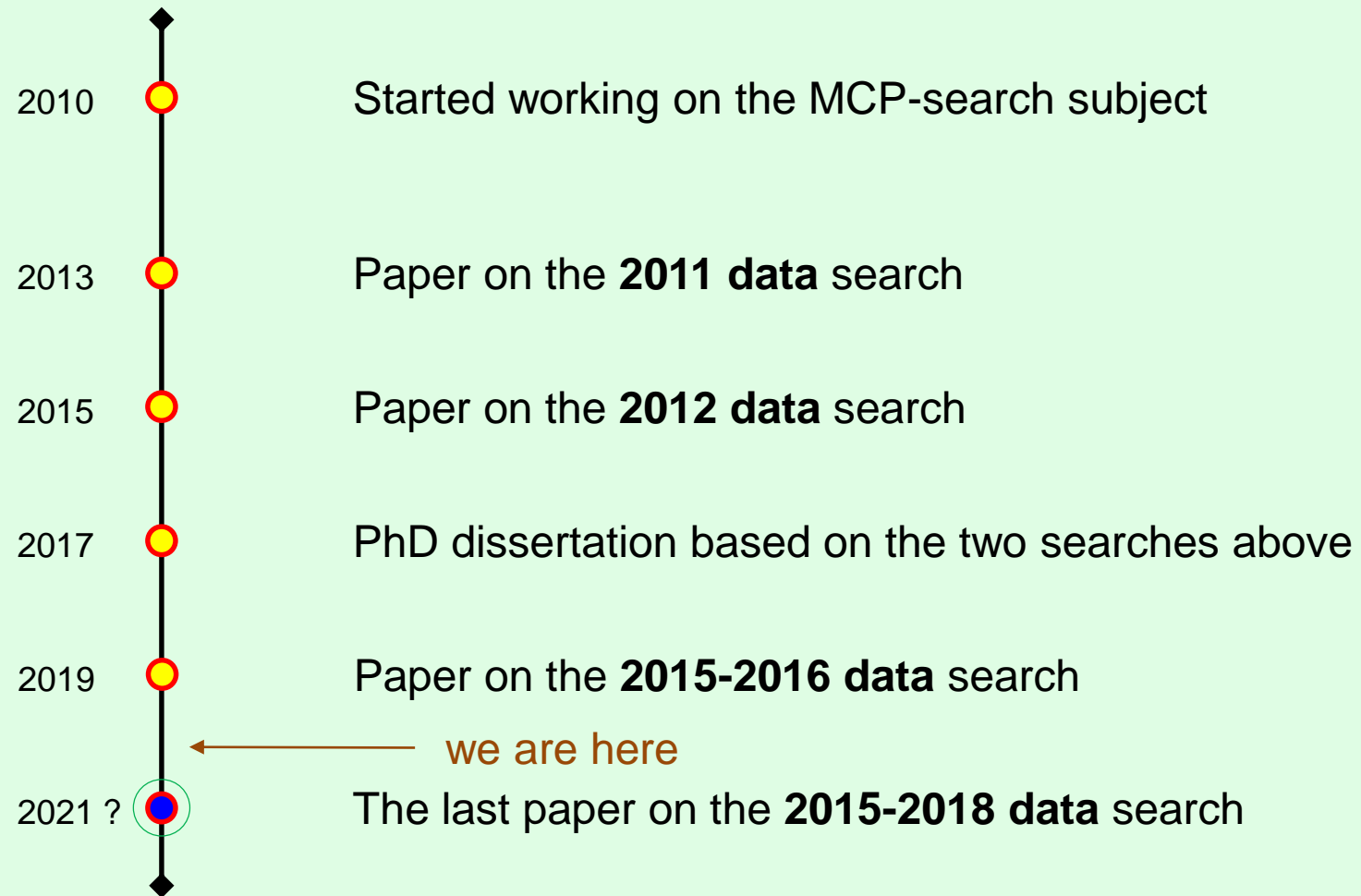
- Multi-charged particles 101
- Project milestones
- Our latest publication
 - General strategy of the search
 - MCP identification
 - Background estimation
 - Search efficiency
 - Analysis uncertainties
 - Results
 - Comparison with CMS results and activities
- Current search in the 2015-2018 data
 - Changes wrt. the 2015-2016 data search
 - Current status
 - $Z \rightarrow \mu\mu$ data/MC comparison of key quantities
 - Existing signal samples and status of requests
 - Nearest plans, ballpark timeline

Multi-charged particles 101

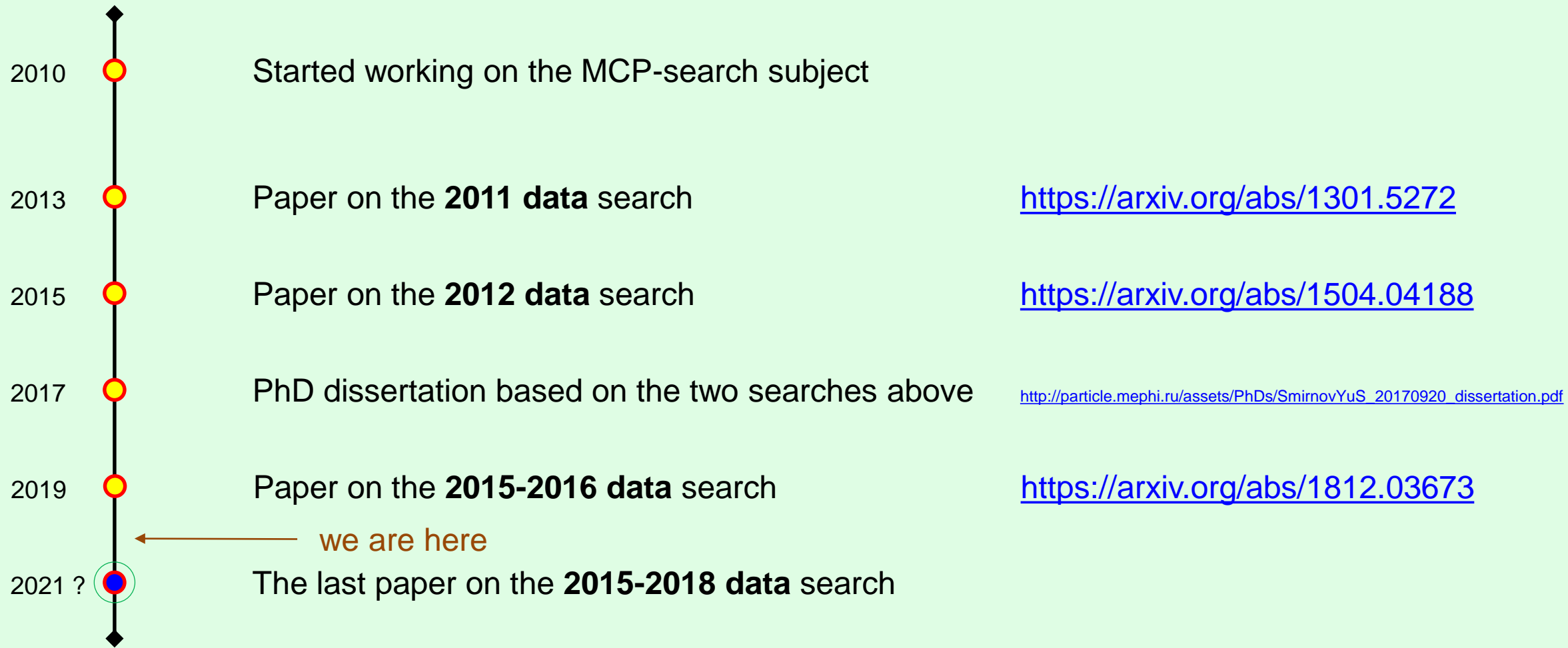
- Multi-charged particles (MCPs): long-lived highly ionizing heavy fermions with high electric charges;
 - no strong interaction;
 - think heavy ($m > 50$ GeV) muons with $z = |q|/e > 1$;
- “Blue-sky” search, but some models in fact predict new particles with charges greater than one:
 - Almost Commutative 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.**



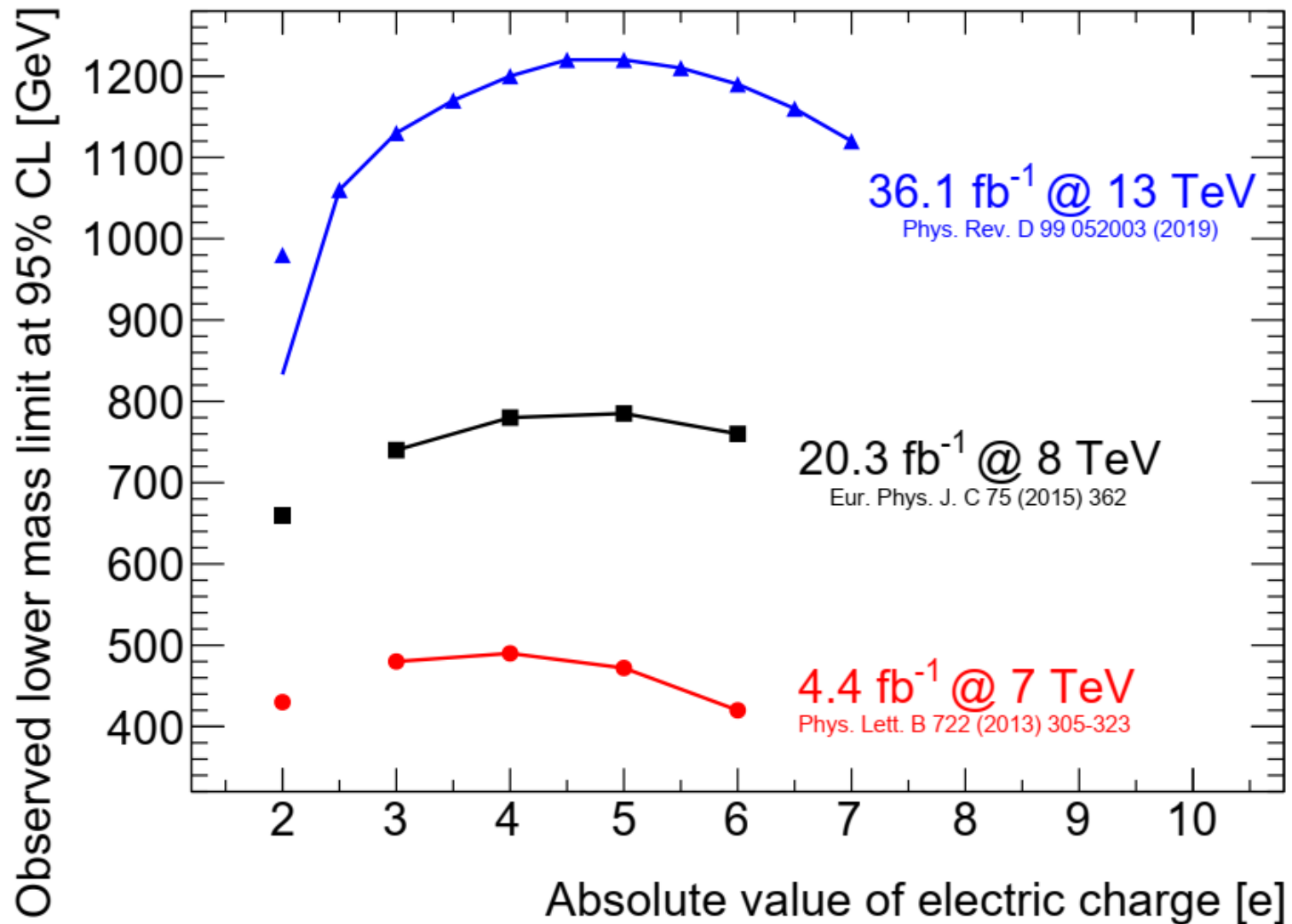
Milestones



Milestones



Milestones



[s/1301.5272](#)

[s/1504.04188](#)

[SmirnovYuS_20170920_dissertation.pdf](#)

[s/1812.03673](#)

Search features

$$dE/dx \sim z^2$$

- Ionization losses are highly sensitive to the electric charge of a particle;
- Long-lived particles \rightarrow 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 \rightarrow low $\beta \rightarrow$ muon-trigger-timing window is too short for these particles;
- Track reconstruction always assumes particles with charge $\pm 1e \rightarrow$ momentum misreconstruction by a factor of z ;
- RPC-trigger timing mismodeling for particles with low $\beta \rightarrow$ 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. Aaboud *et al.*^{*}
(ATLAS Collaboration)



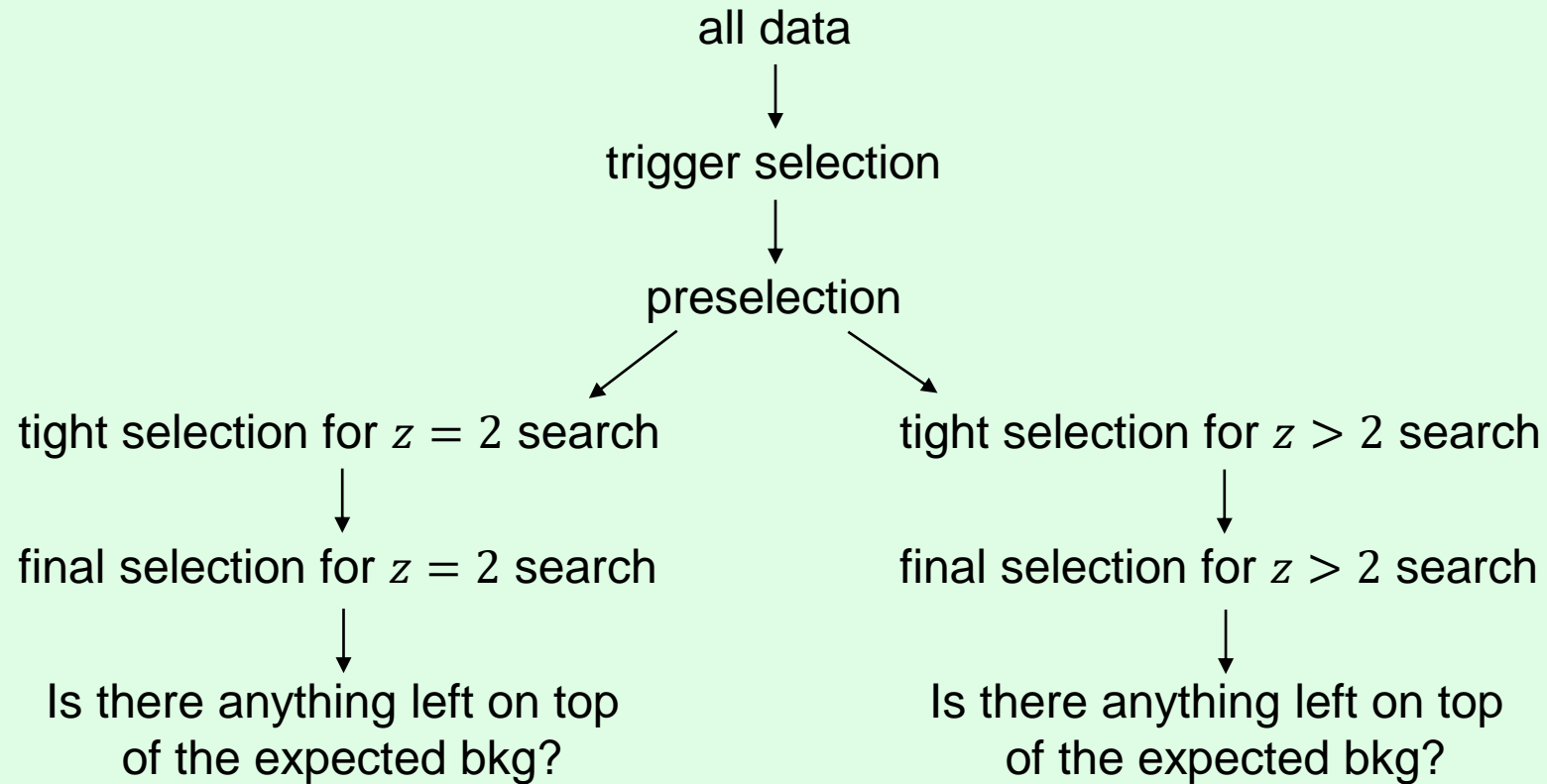
(Received 11 December 2018; published 14 March 2019)

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

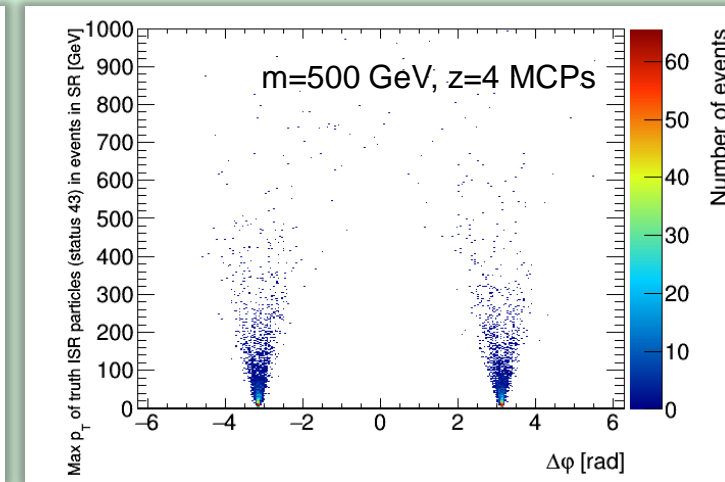
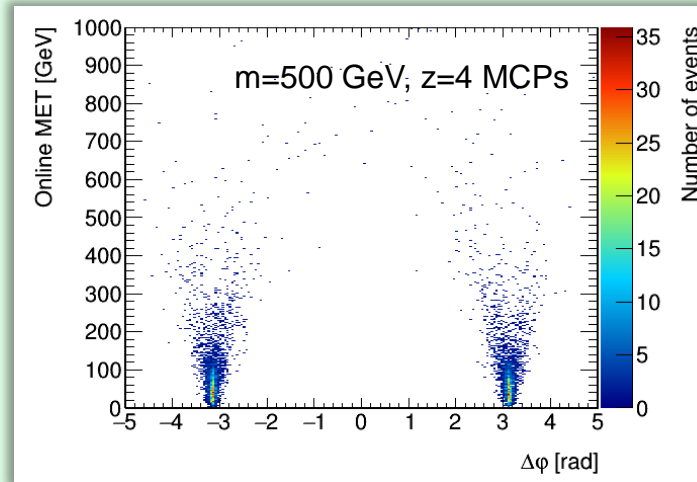
Paper: <https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.052003>
Preprint: <https://arxiv.org/abs/1812.03673>
Supporting note: <https://cds.cern.ch/record/2267181>

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;

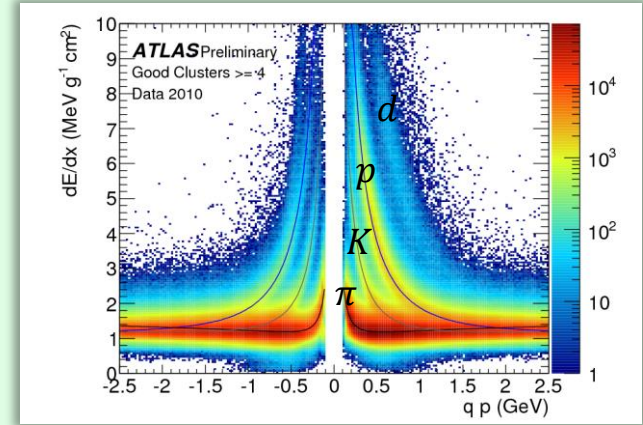


Preselection

- 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

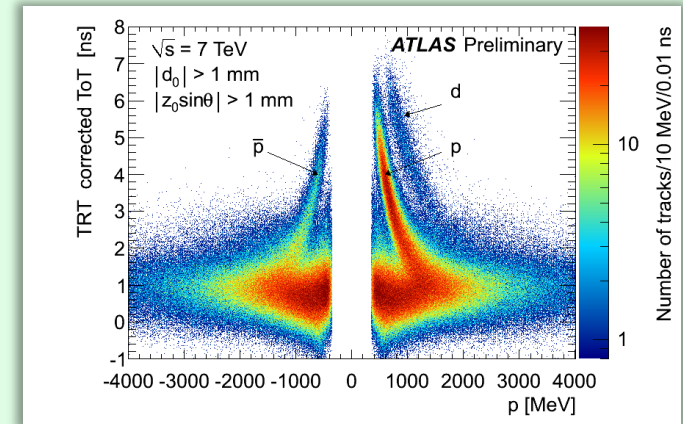
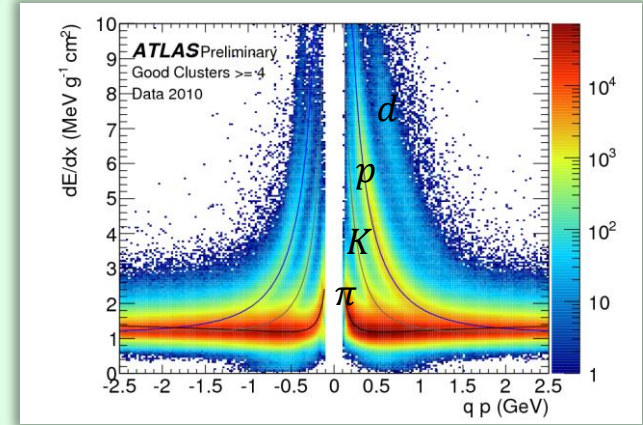
pixel dE/dx : the output-signal width from the discriminator of every pixel is proportional to the collected charge



Process-specific dE/dx quantities

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

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

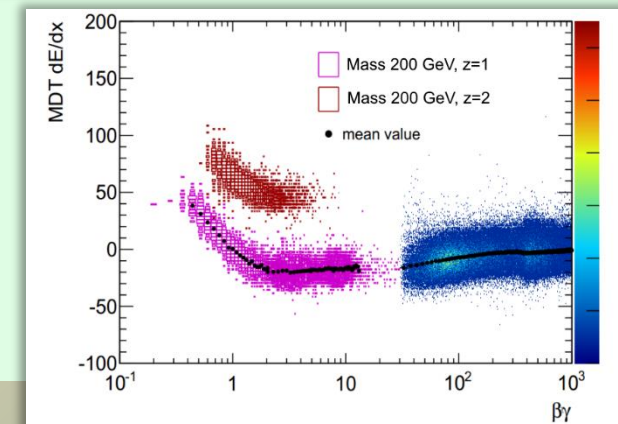
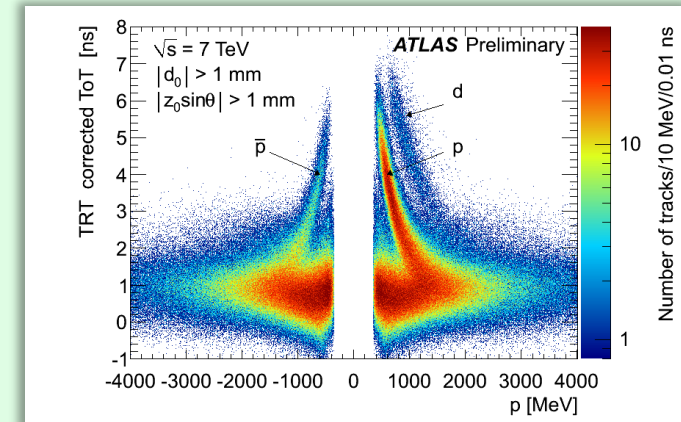
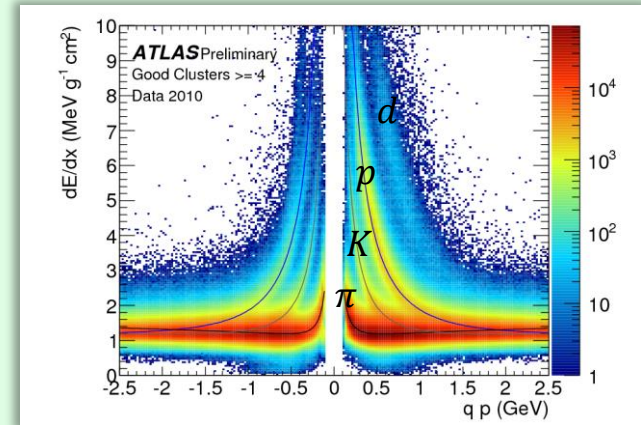


Process-specific dE/dx quantities

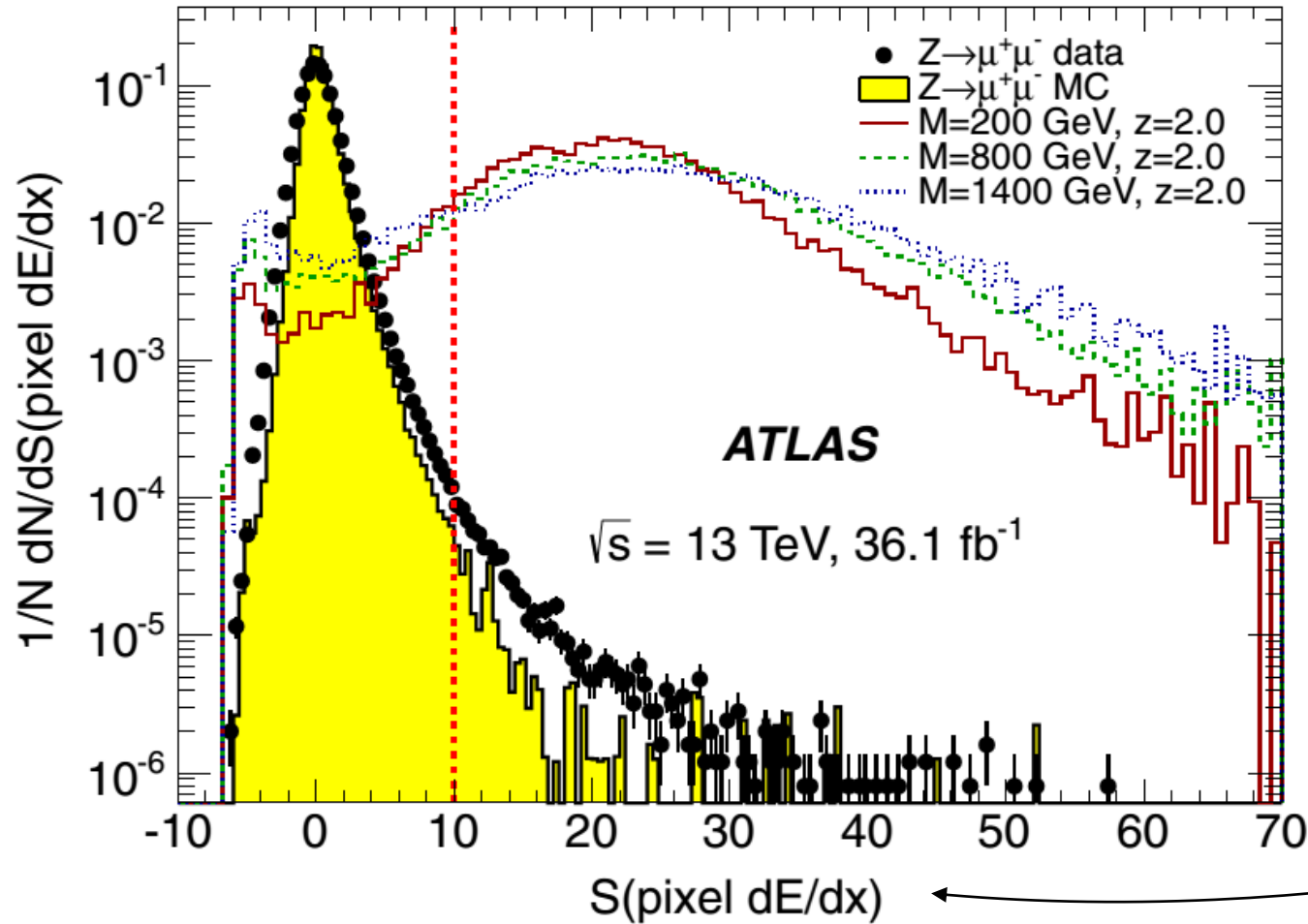
pixel dE/dx : the output-signal width from the discriminator of every pixel is proportional to the collected charge

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

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



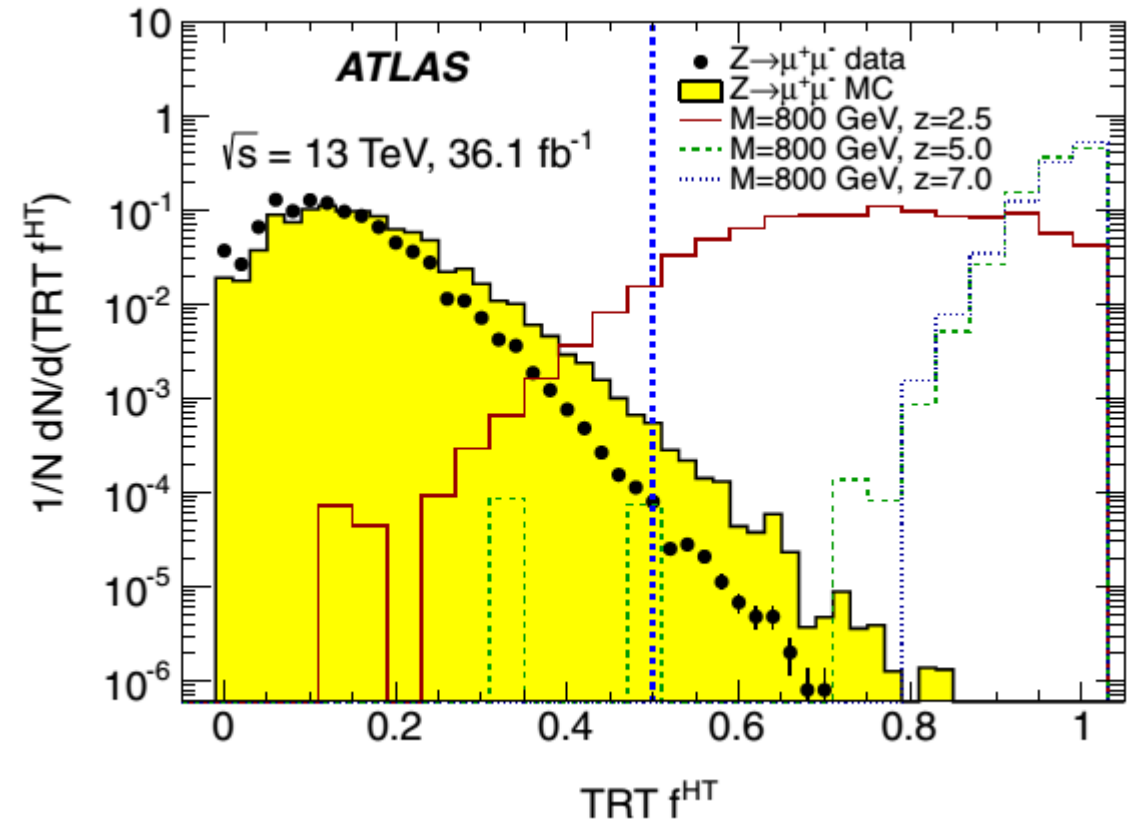
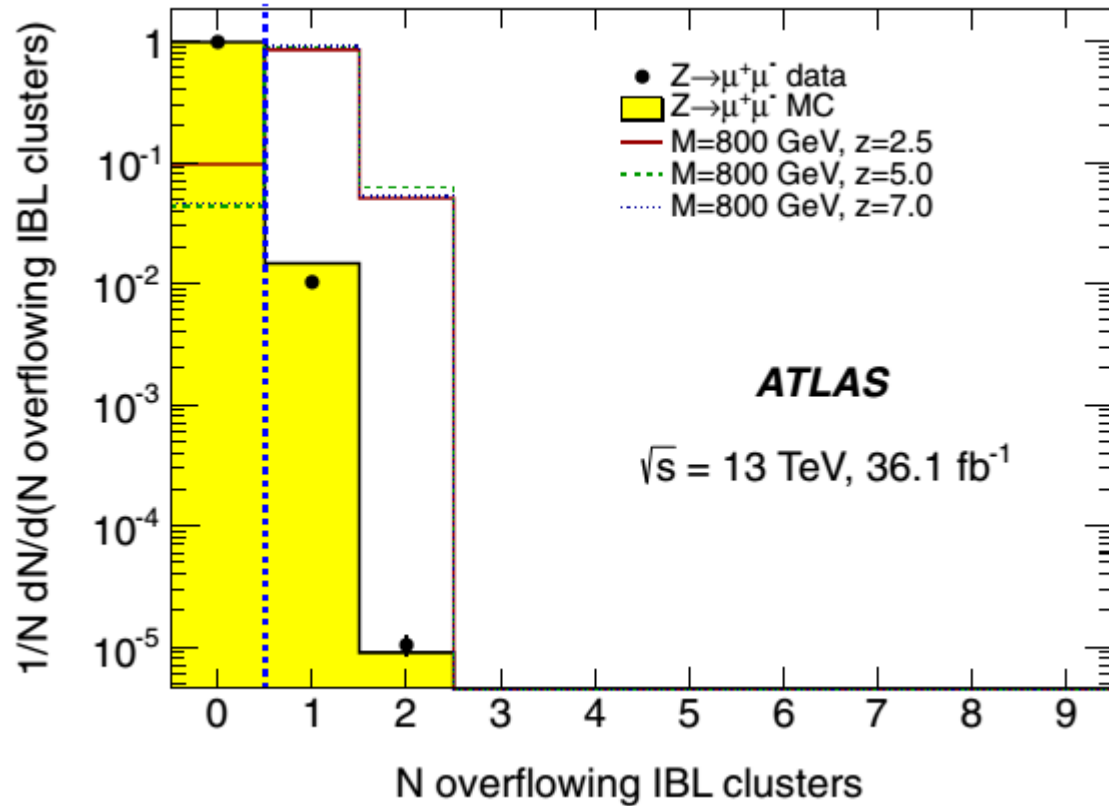
Tight selection for the $z = 2$ MCPs



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

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

Tight selection for the $z > 2$ MCPs

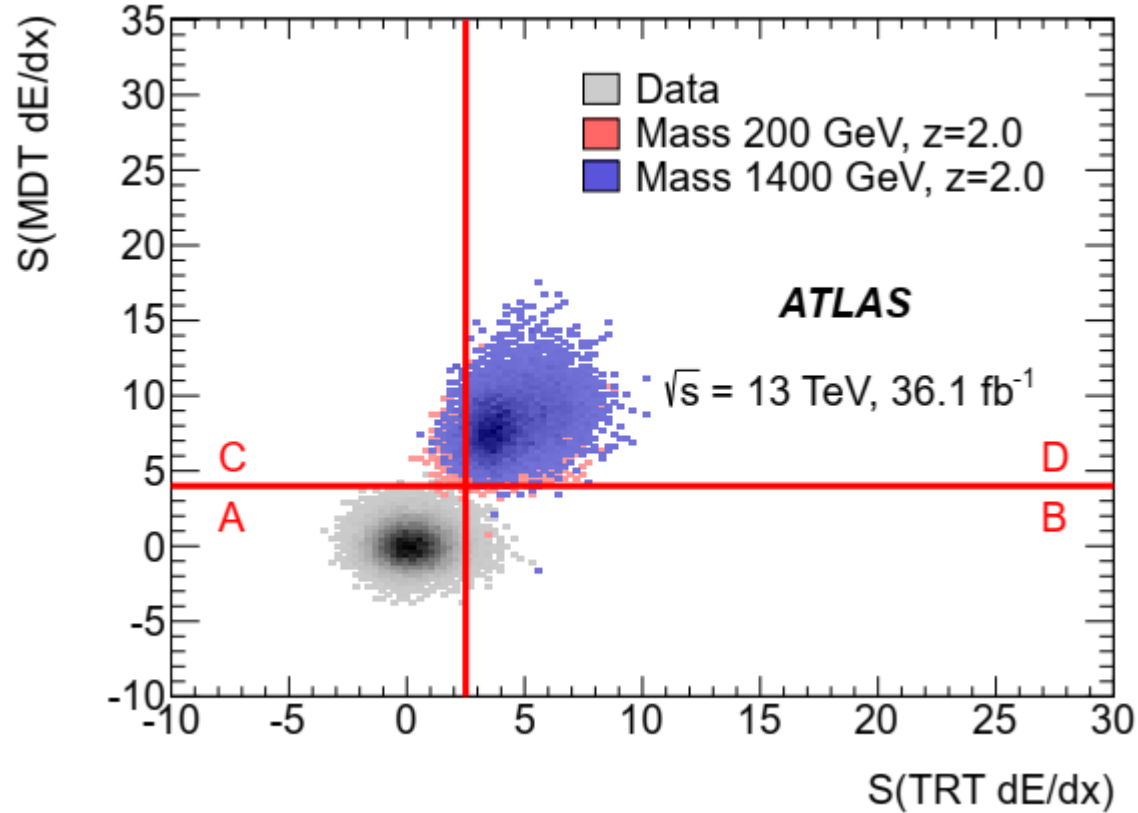


Number of clusters on the track segment in IBL with 1+ hit having registered the charge of at least 1.5 times higher than the average charge of a MIP with its track normal to the detector plane and depositing all its ionization charge into a single pixel

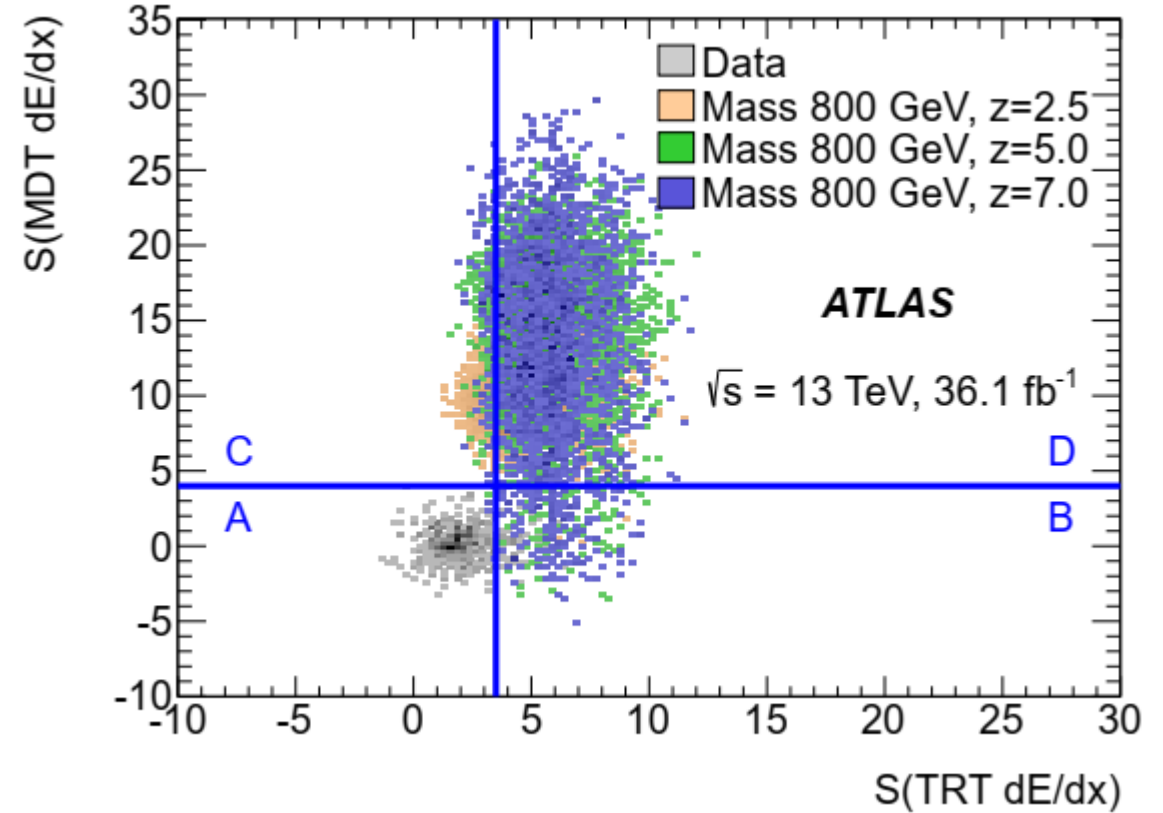
Fraction of hits on a TRT track segment with a signal amplitude over 6 keV

Final selection on ABCD planes

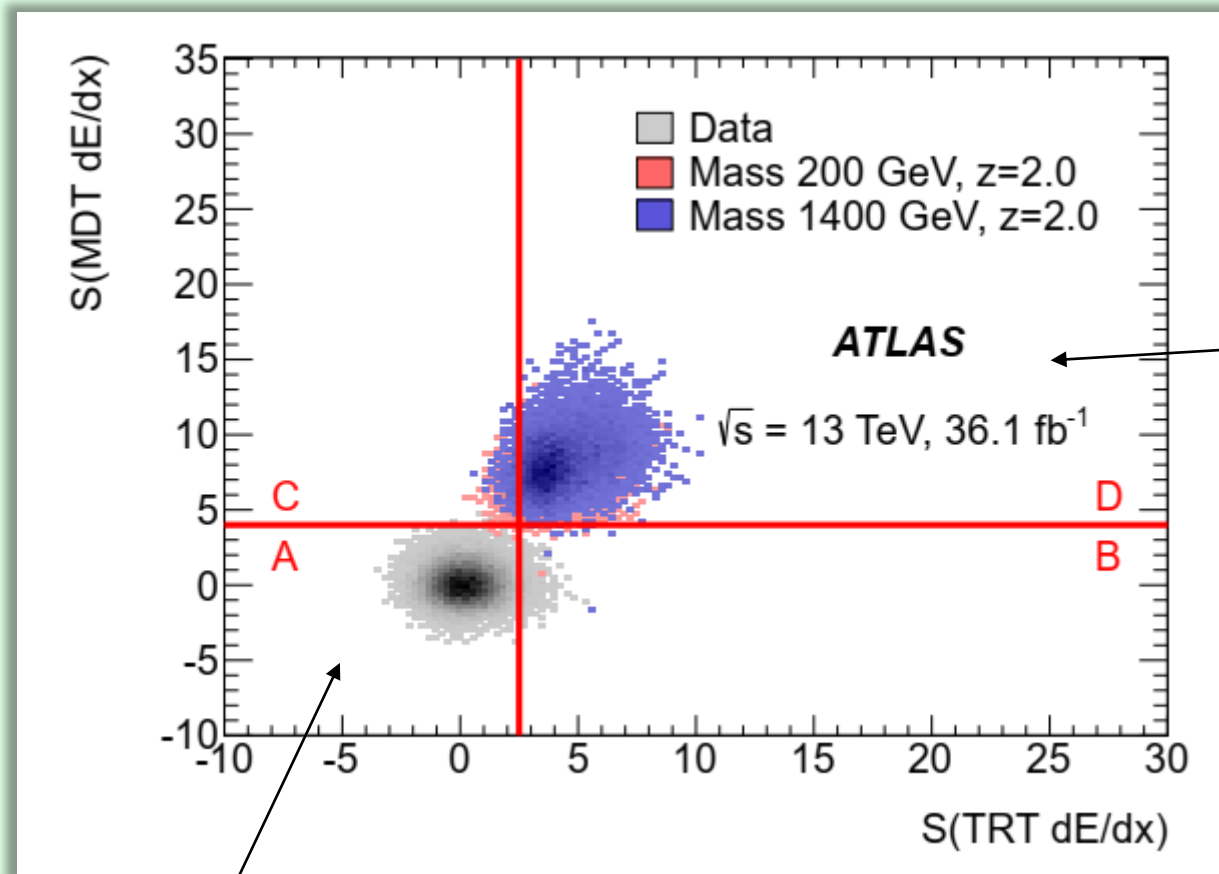
$z = 2$ MCP search



$z > 2$ MCP search



Background estimation for the $z = 2$ MCP search

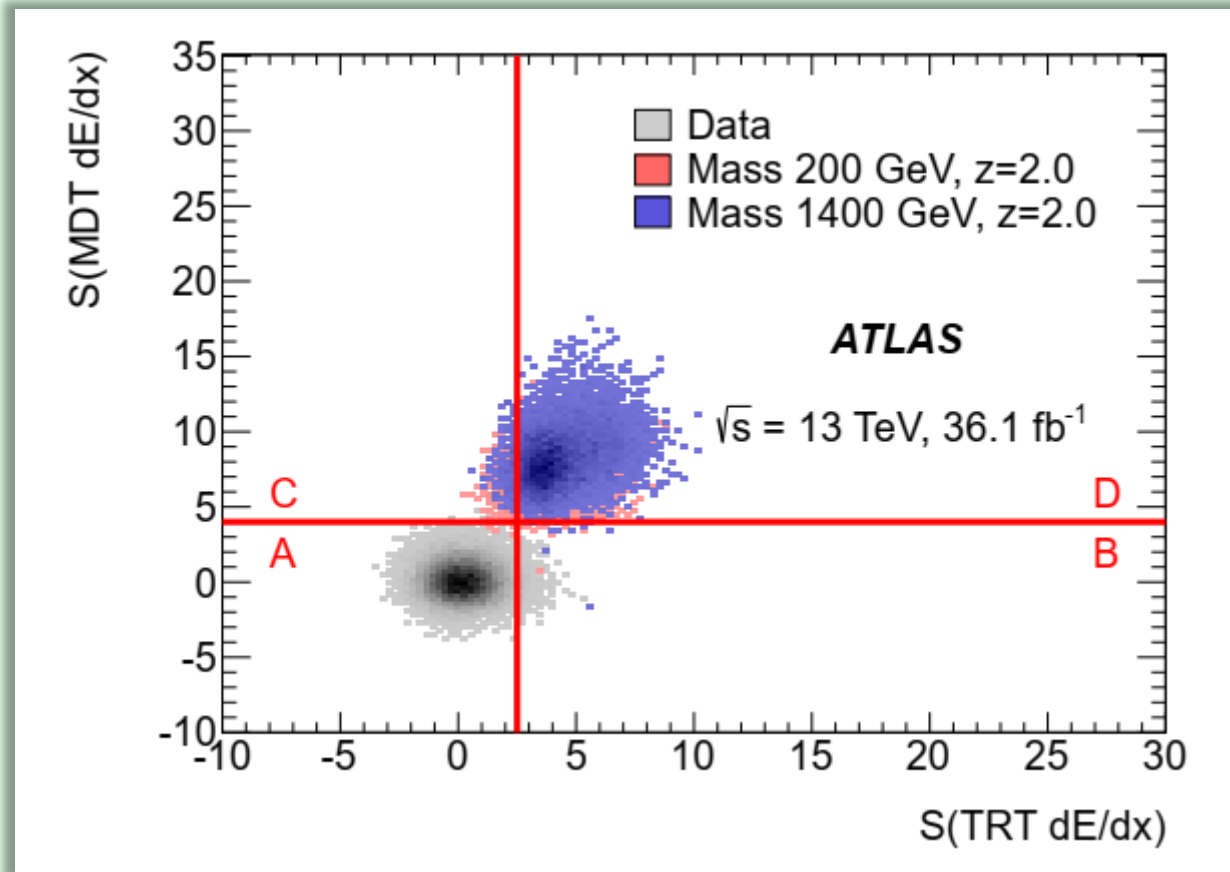


signal-dominated region,
blind to data at first

Bkg estimation is purely data-driven

bkg-dominated region

Background estimation for the $z = 2$ MCP search



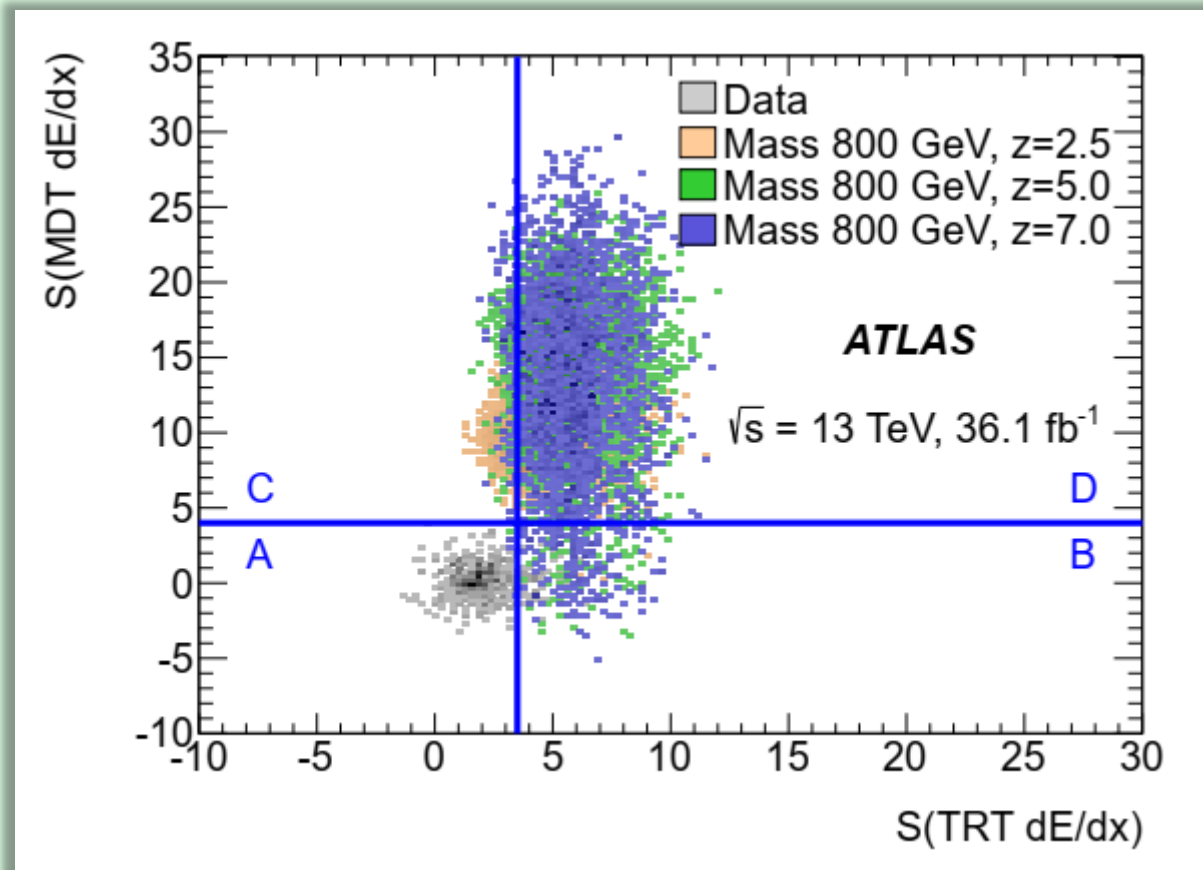
Regular ABCD method:

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

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

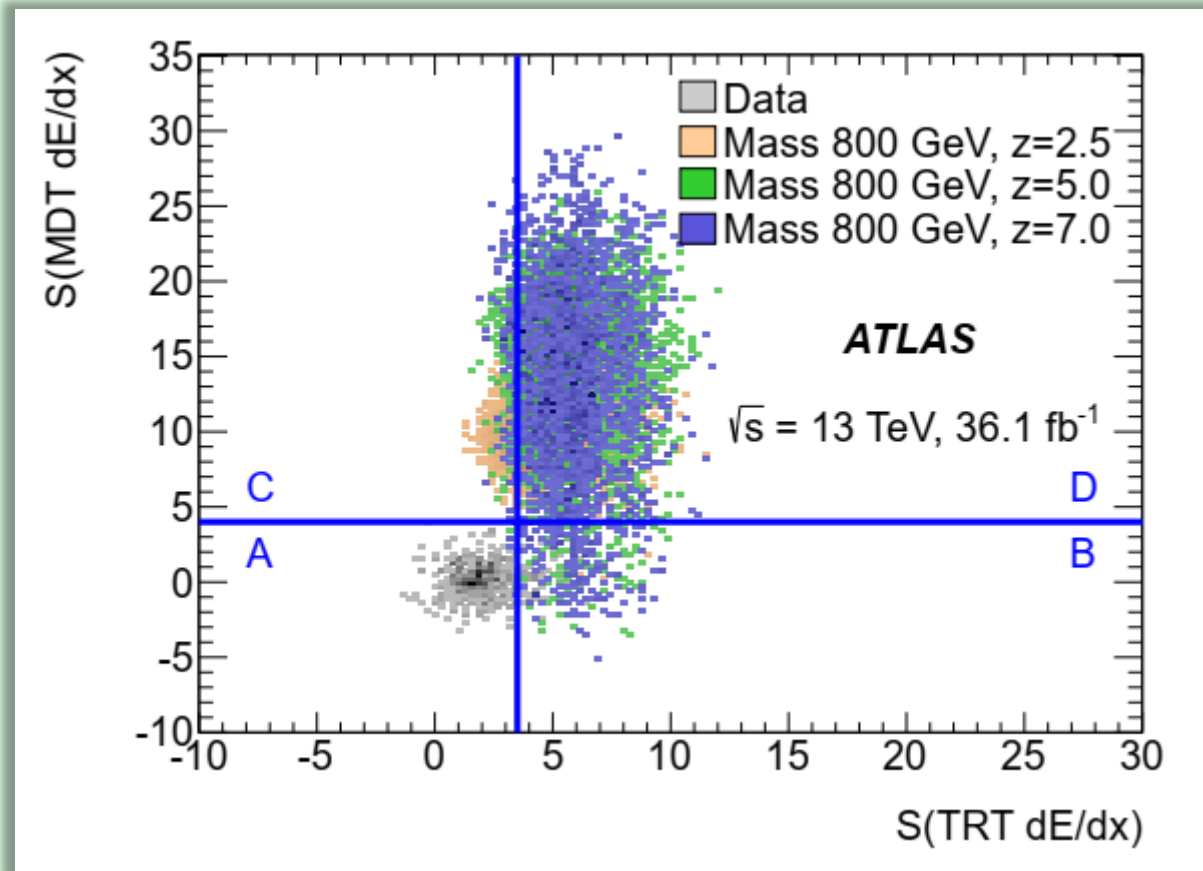
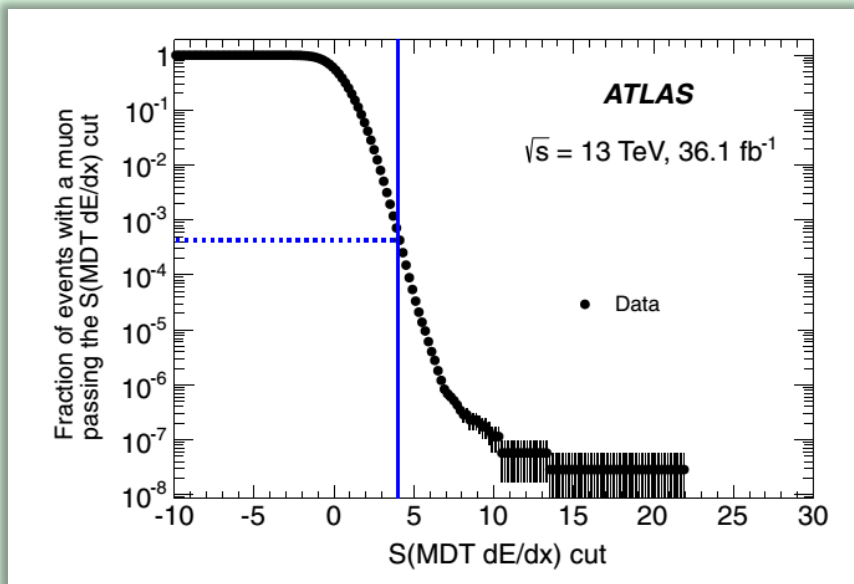
Background estimation for the $z > 2$ MCP search

- 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

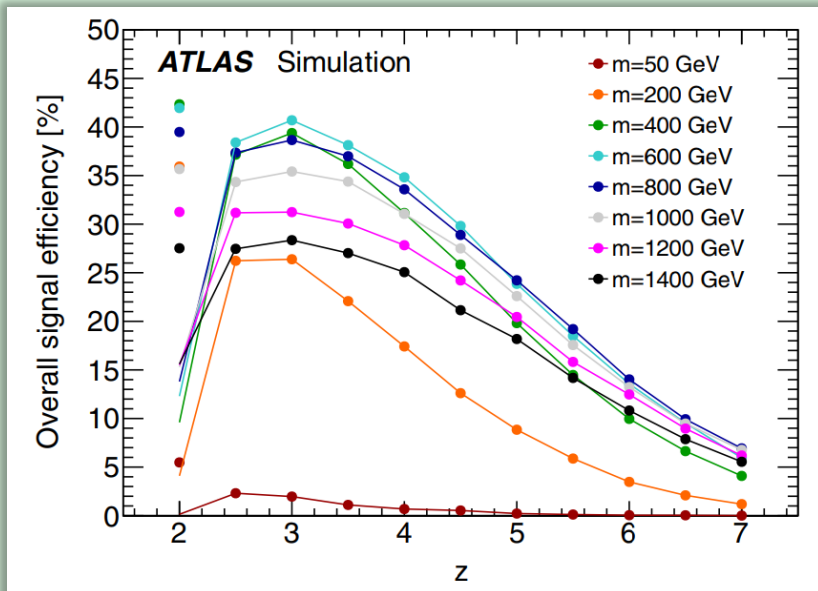
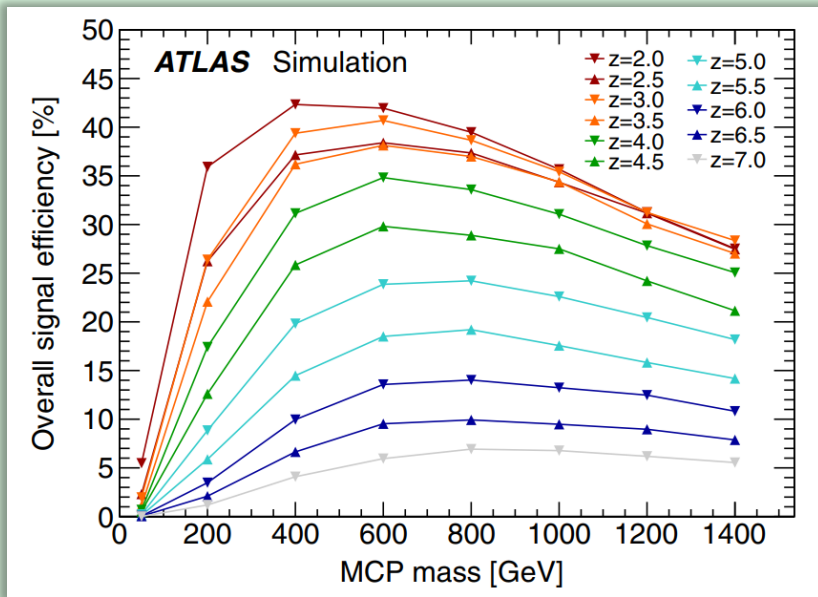
- Another technique: $N_D^{expected\ events} = f \cdot N_B^{observed\ events}$, where f is a probability to observe an event with an $S(MDT\ dE/dx) > 4$ particle using the $S(MDT\ dE/dx)$ distribution after the “anti-tight” selection.
- The “anti-tight” selection:
 - provides a lot of statistics,
 -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



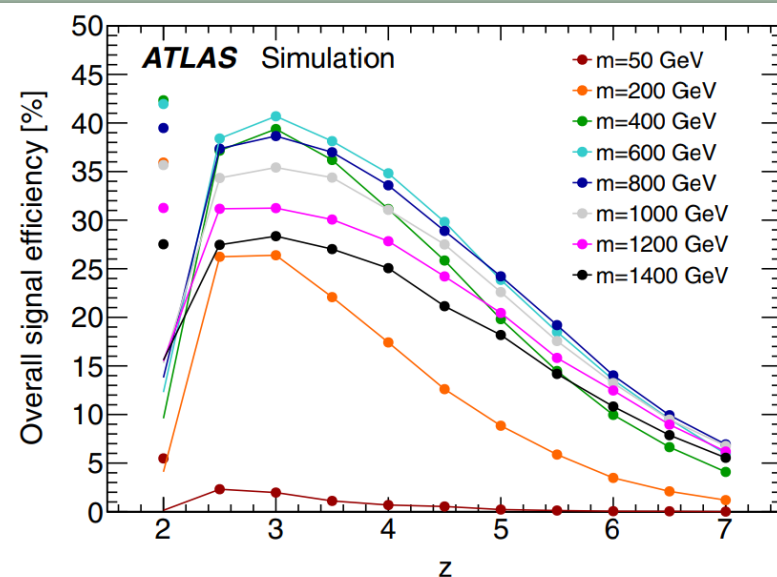
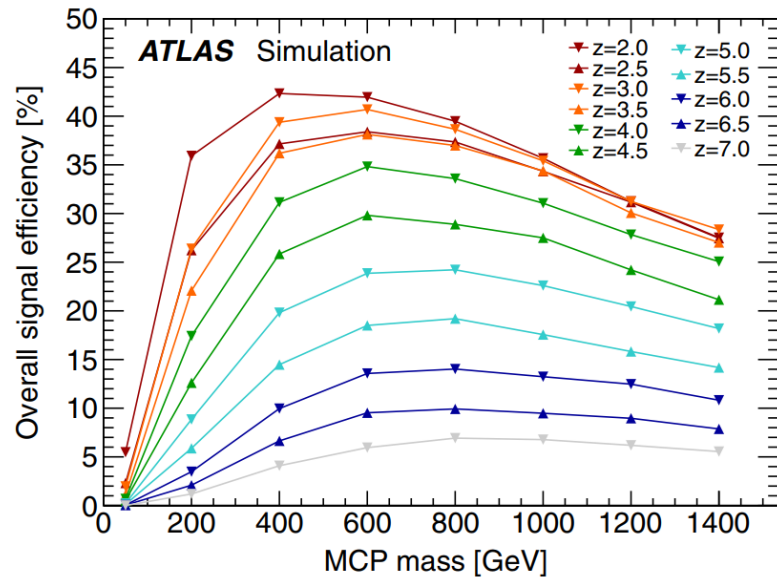
$$N_D^{expected\ events} = (2.9 \pm 0.4\ (stat.) \pm 2.2\ (syst.)) \cdot 10^{-2}$$

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

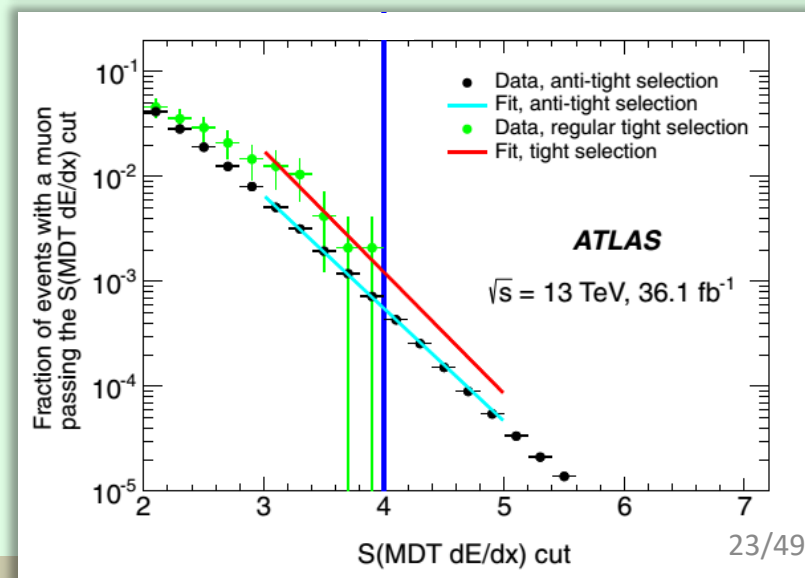
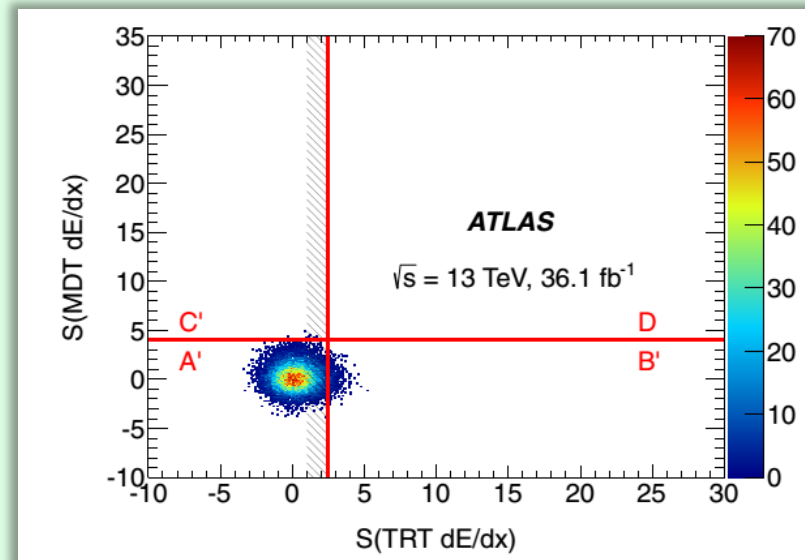


- Overall efficiency is a fraction of MC events with at least one MCP in the D region among all generated events;
- Reasons for relatively low efficiency:
 - **low masses:** η and especially p_T/z requirements;
 - **high masses:** a requirement to reach the MS with high enough velocity to make it into 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.

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 $S(\text{MDT } dE/dx)=4$ was also derived;
- Systematic uncertainty is the relative difference between two $10^{p_0 x + p_1}$ fits within $3 < S(\text{MDT } dE/dx) < 5$.



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.

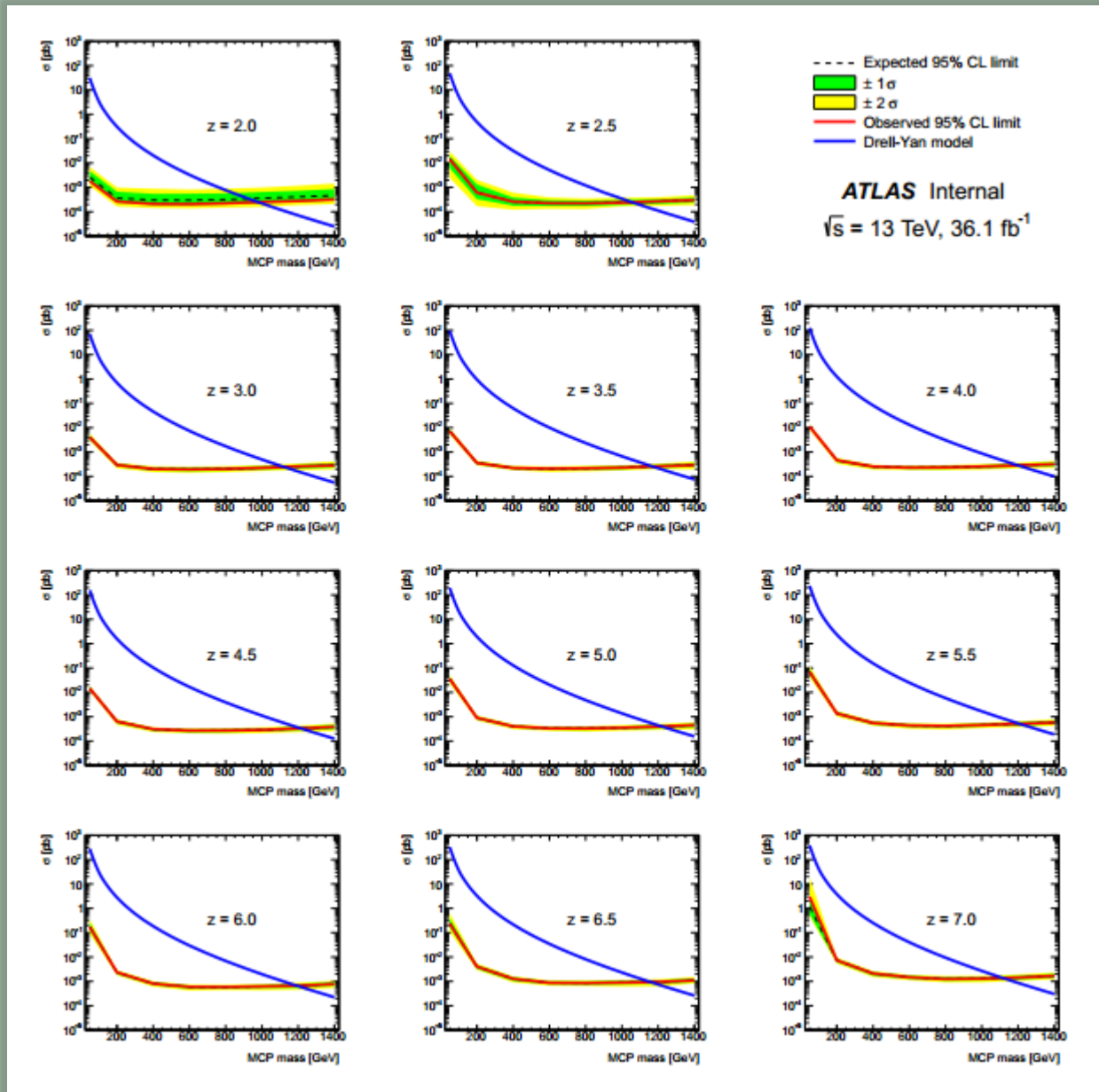
TRT f^{HT} data/MC
disagreement

	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

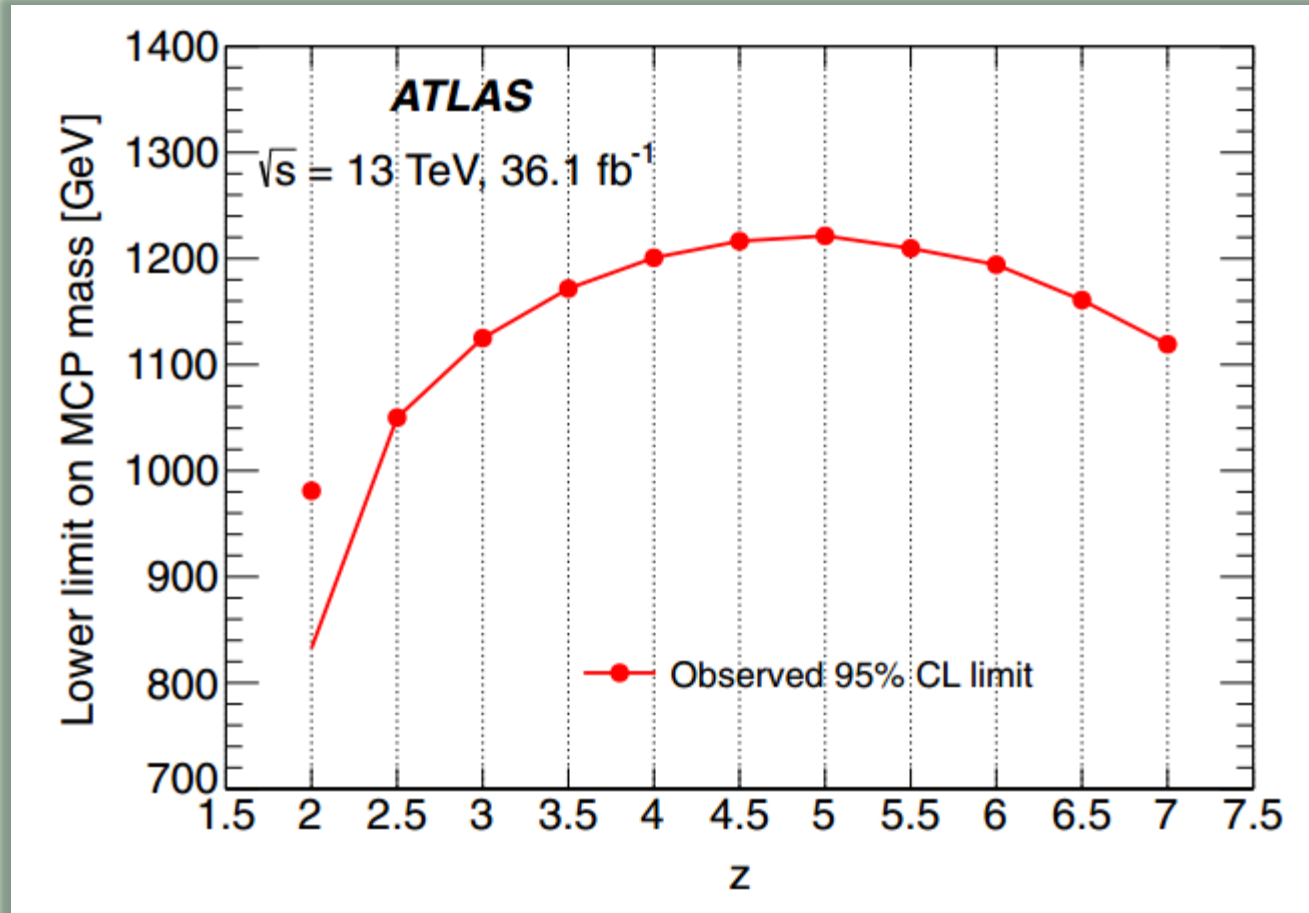


Not a single event was found in the SRs → upper limits on the X-section.

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

(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 $5.0 \text{ fb}^{-1} + 18.8 \text{ fb}^{-1}$ of 2011+2012 data, lower mass limits are 685 – 796 GeV;
- Search for $z = 2$ particles on 2.5 fb^{-1} of 2015 data, lower mass limit is 680 GeV;
- Search for $z = 2$ particles on 12.9 fb^{-1} of 2016 data, lower mass limit is 890 GeV **(preliminary results, not published)**

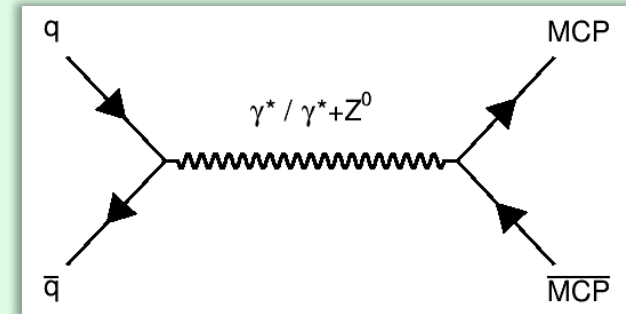
<https://link.springer.com/article/10.1007%2FJHEP07%282013%29122>

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

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

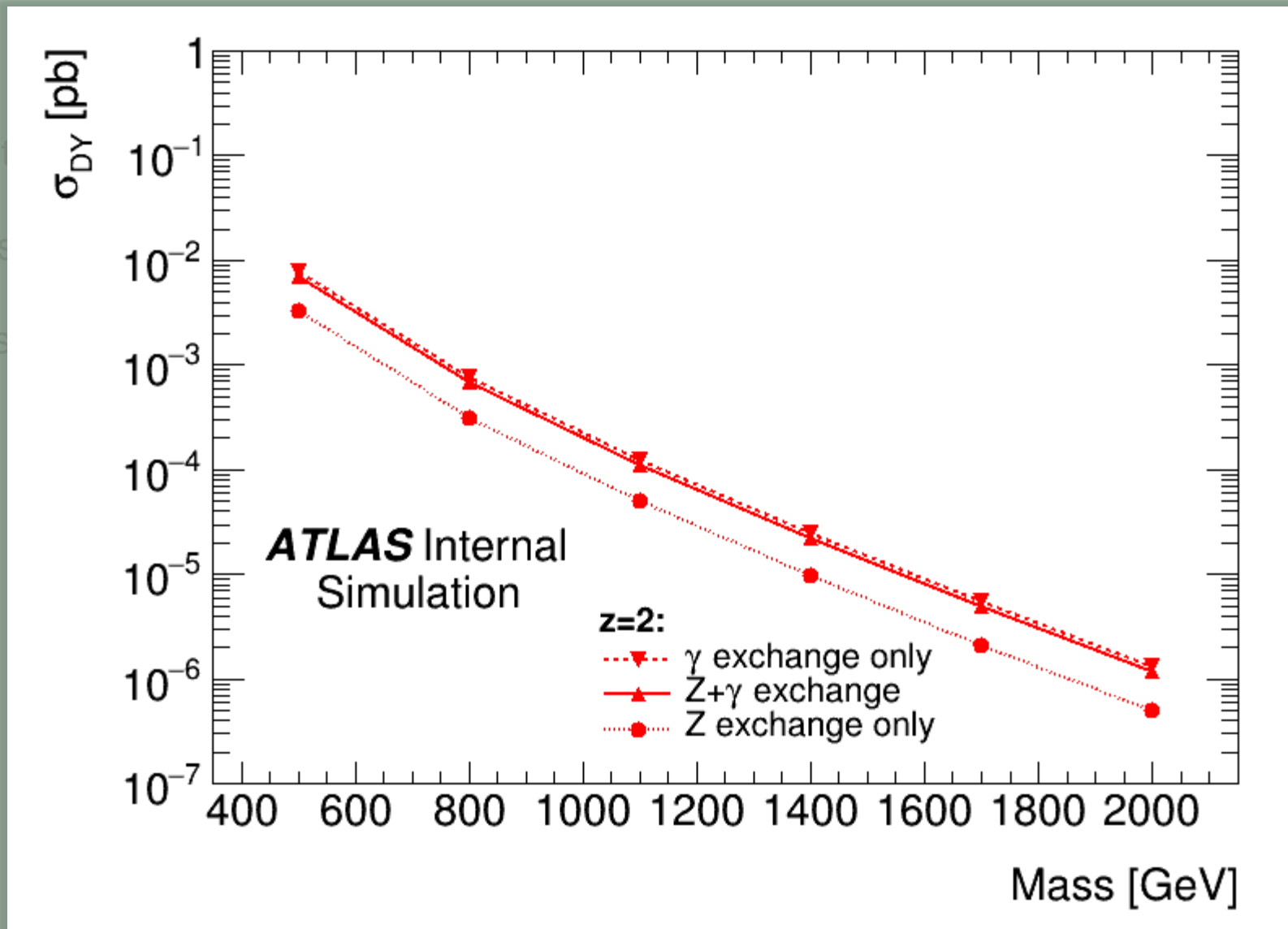
Our current search in the 2015-2018 data

- 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 ;



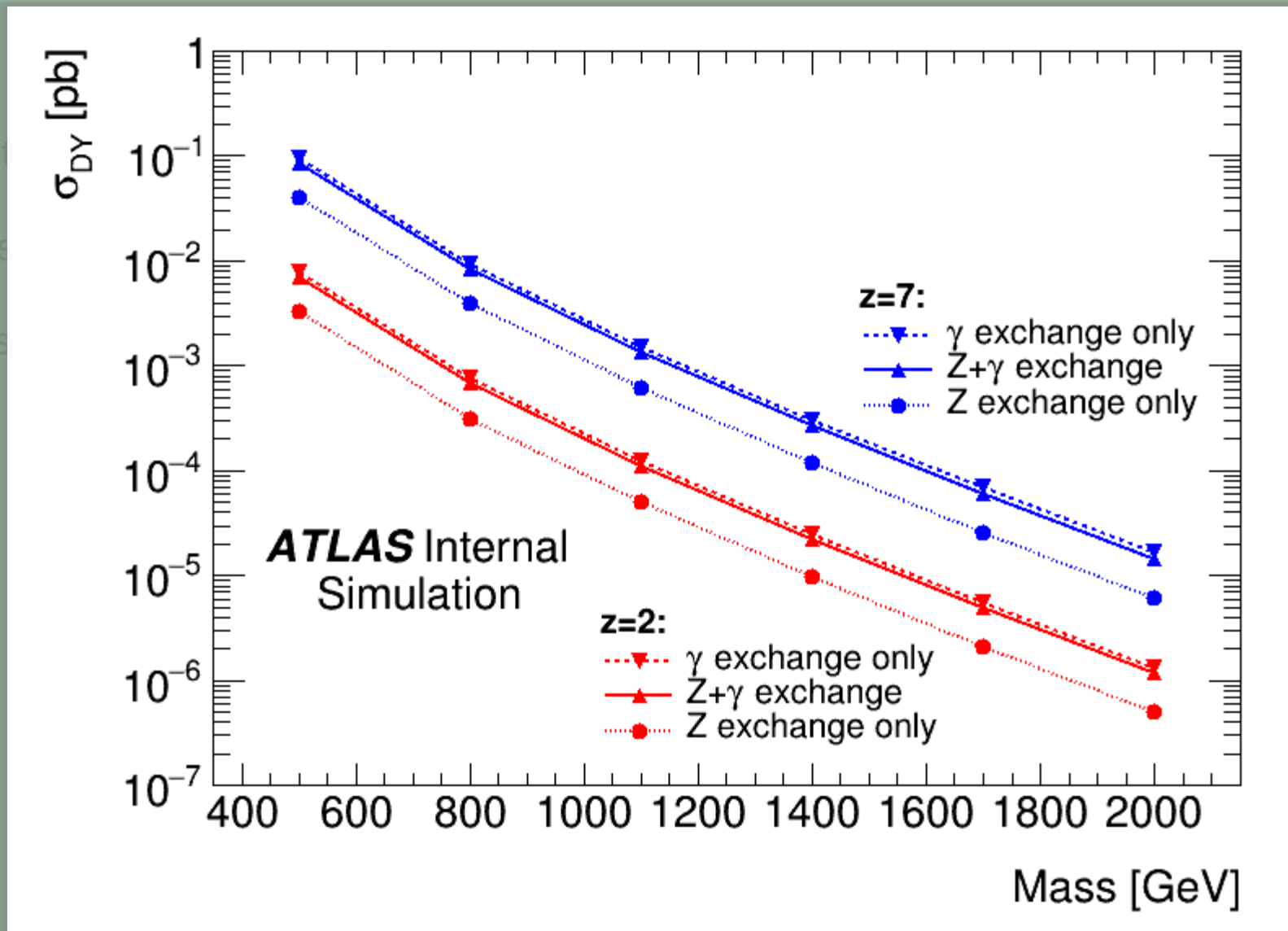
Our current search in the 2015-2018 data

- 139 fb⁻¹;
- Will be our last
- Three changes
 - virtual bos



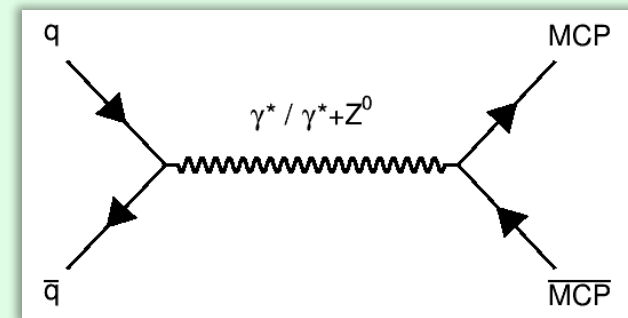
Our current search in the 2015-2018 data

- 139 fb⁻¹;
- Will be our last
- Three changes
 - virtual bos



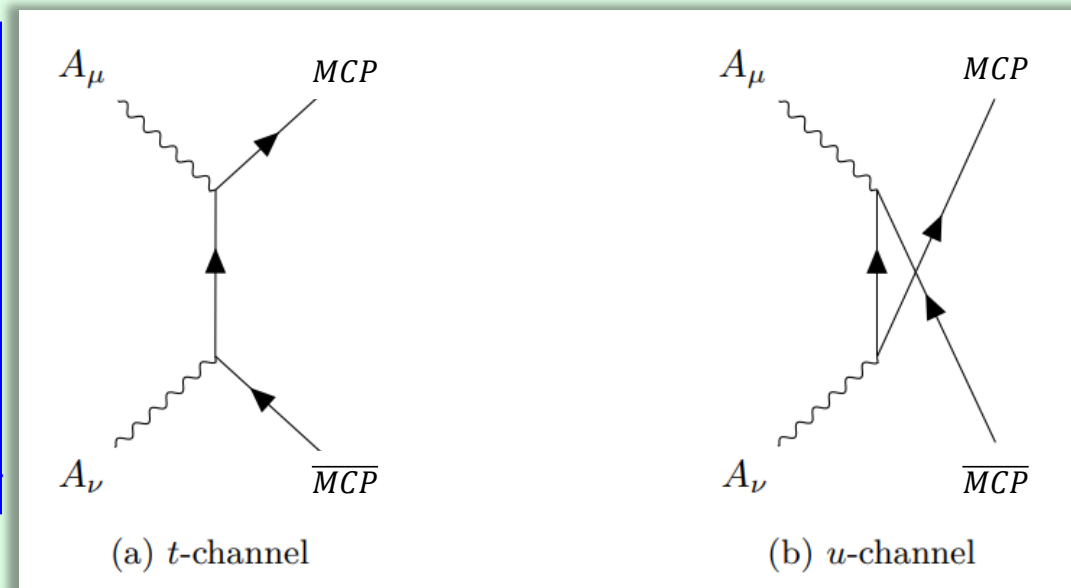
Our current search in the 2015-2018 data

- 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 ;
 - production process: adding photon-fusion process to the Drell-Yan one;



+

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



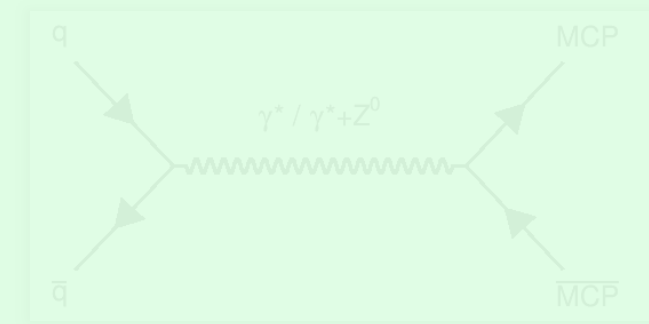
Our current search in the 2015-2018 data

- 139 fb⁻¹;
- Will be our last search for MCPs;
- Three changes wrt. the 2015-2016 data search:

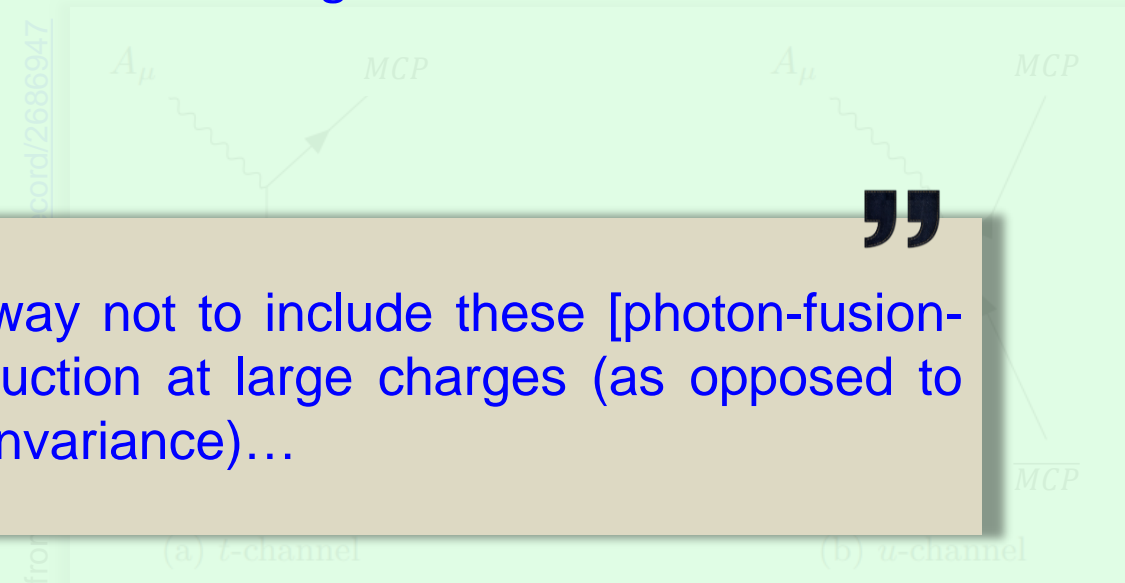
- virtual boson exchange: $Z + \gamma$ instead of just γ ;

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

- production process: adding photon-fusion process to the Drell-Yan one;



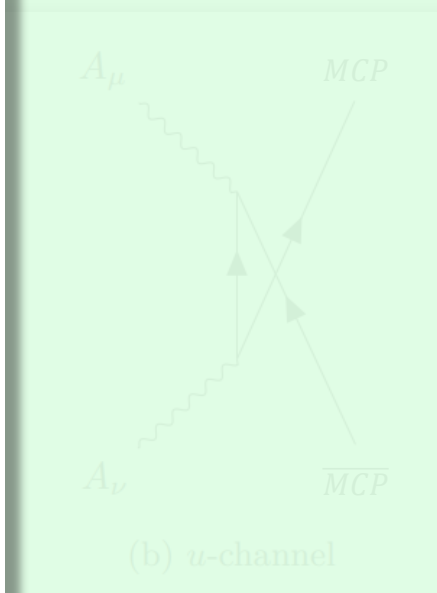
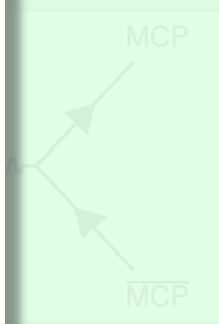
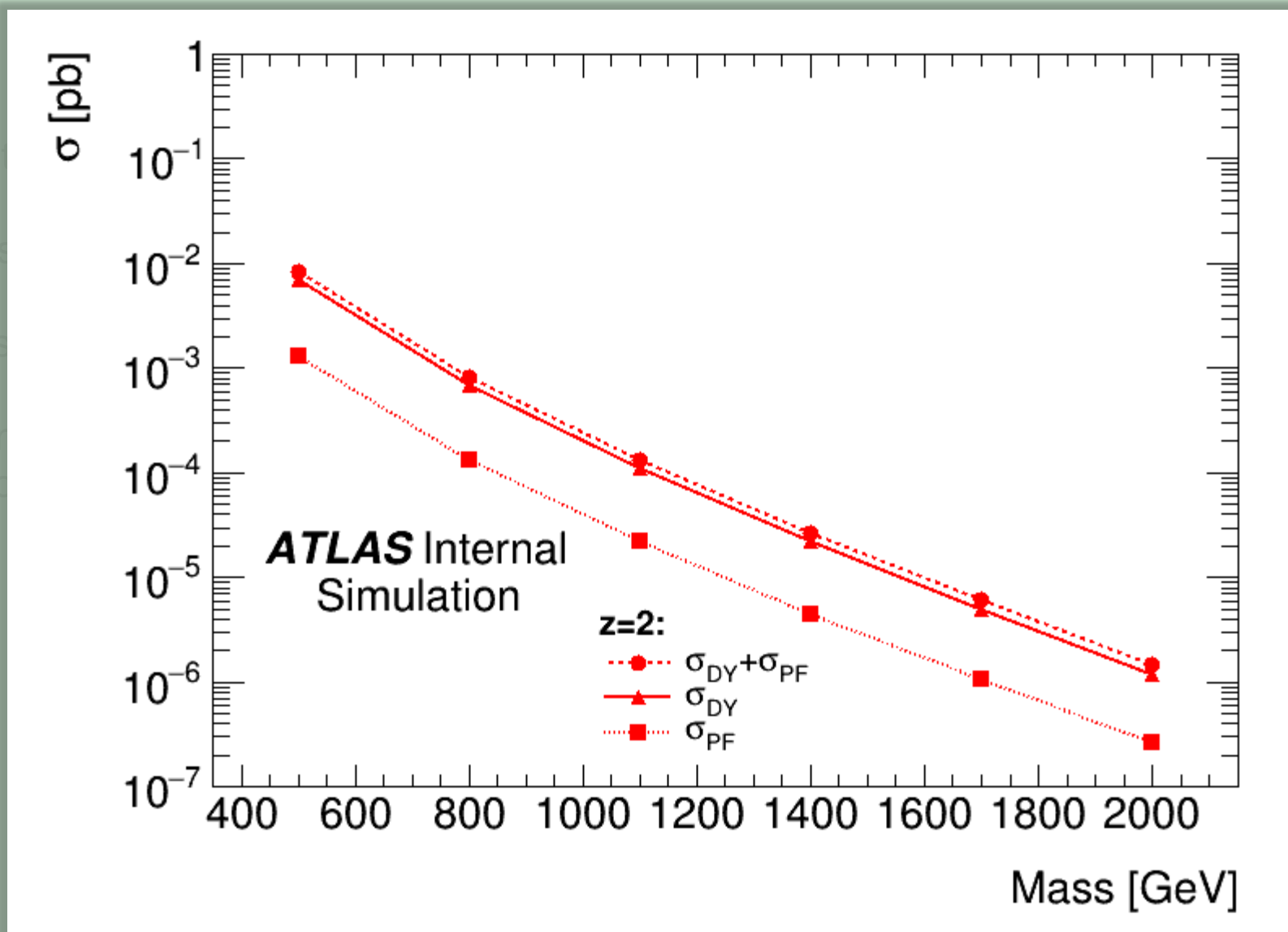
+



...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)...

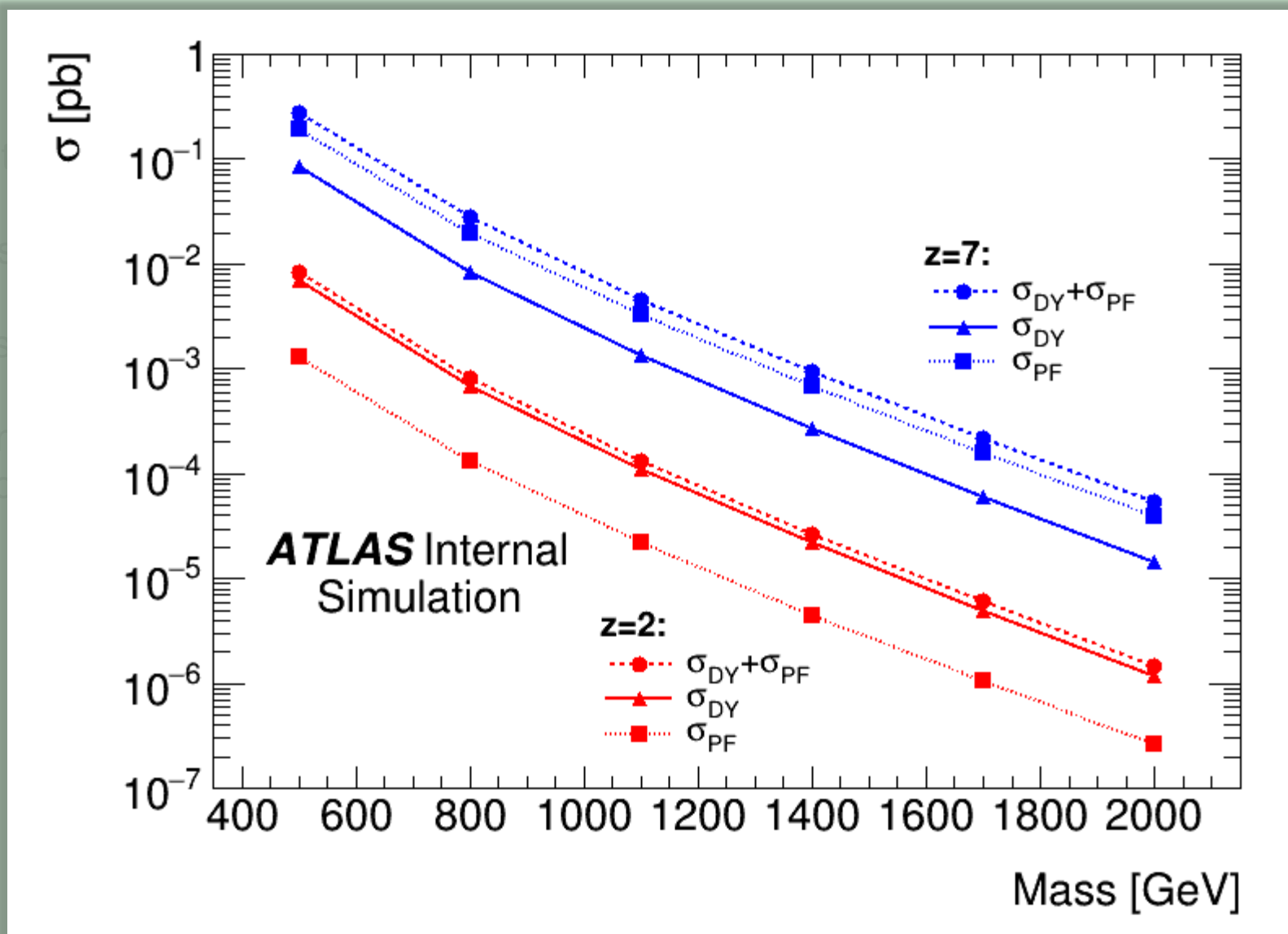
Our current search in the 2015-2018 data

- 139 fb⁻¹;
- Will be our last
- Three changes
 - virtual bos
 - production process to



Our current search in the 2015-2018 data

- 139 fb⁻¹;
- Will be our last
- Three changes
 - virtual bos
 - production
 - process to



Our current search in the 2015-2018 data

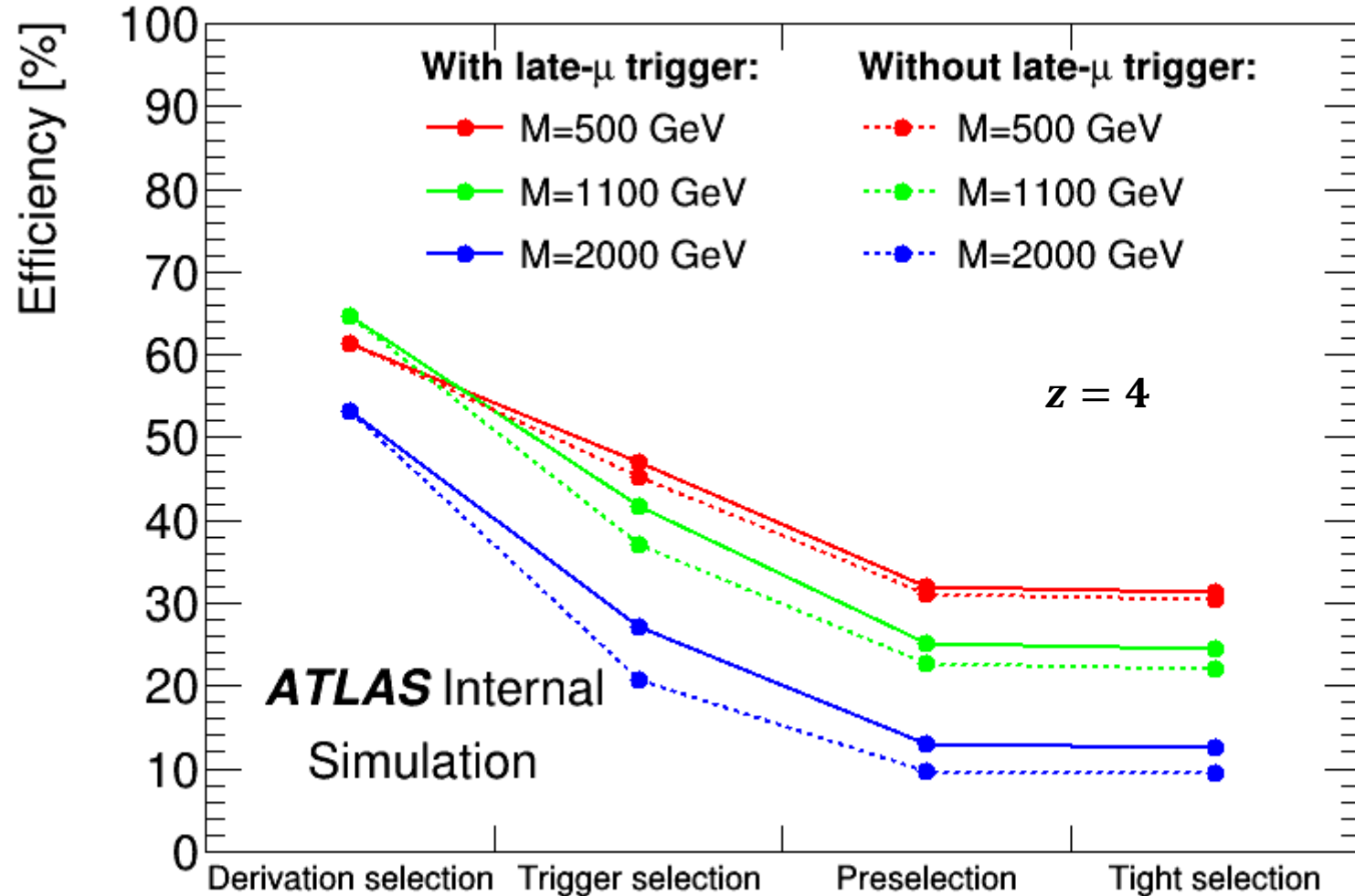
- 139 fb⁻¹;
- Will be our last search for MCPs;
- Three changes wrt. the 2015-2016 data search:
 - virtual boson exchange: $Z + \gamma$ instead of just γ ;
 - production process: adding photon-fusion process to the Drell-Yan one;
 - triggers: adding new late-muon trigger.

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

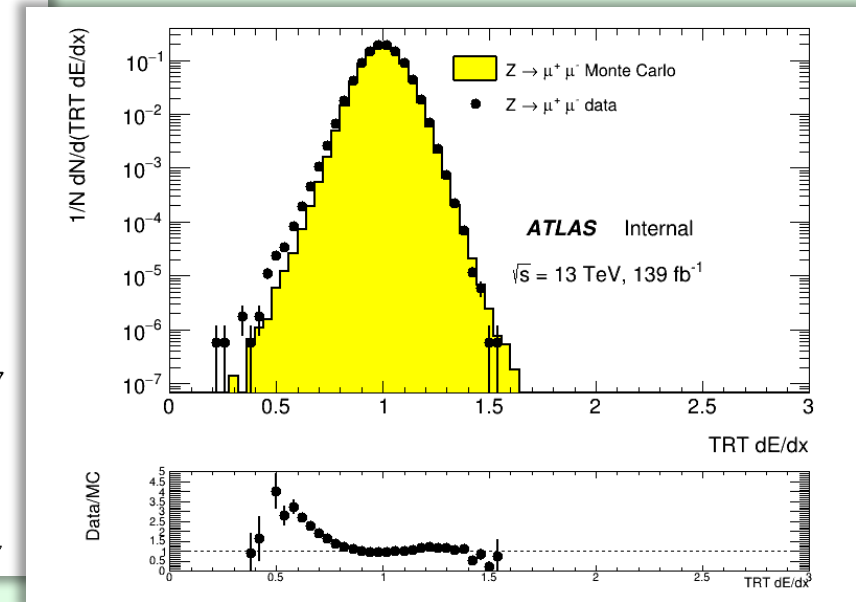
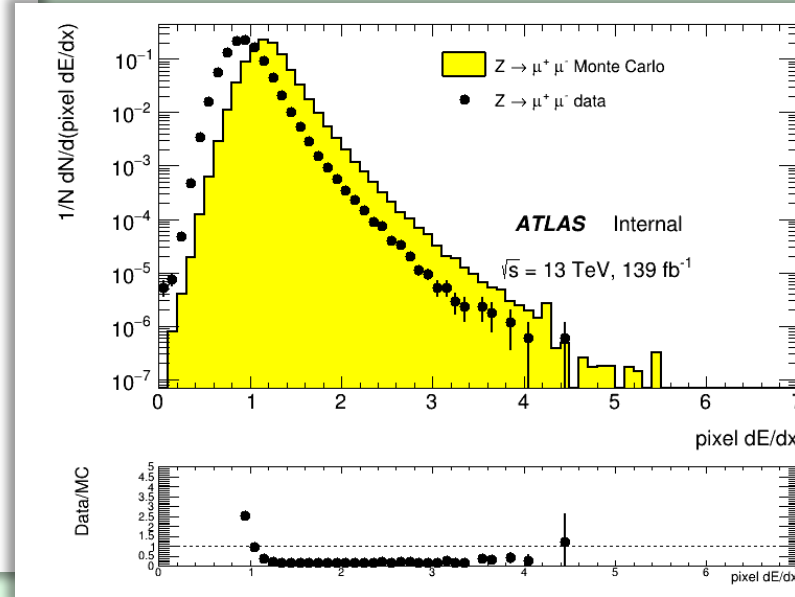
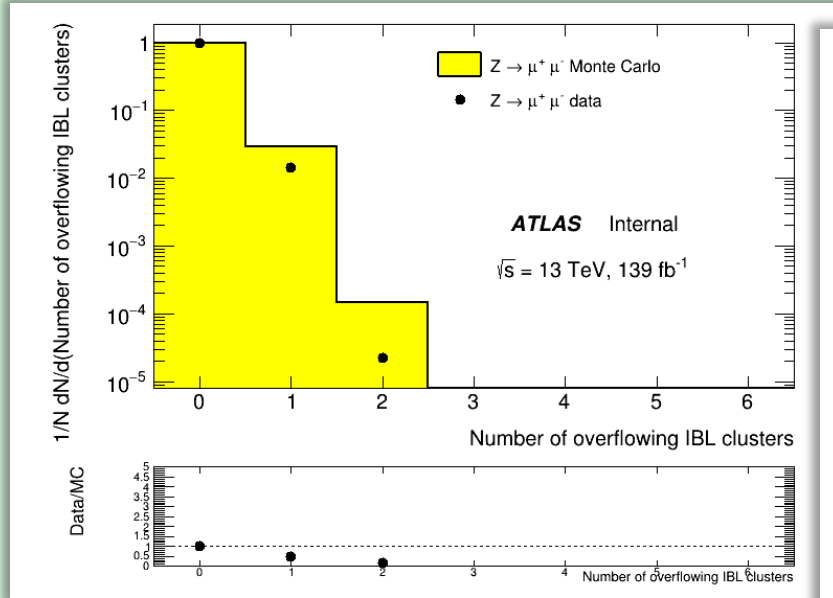
- 139 fb⁻¹;
- Will be our last
- Three changes
 - virtual bos
 - production process to
 - triggers: a



the current BXing
next BXing

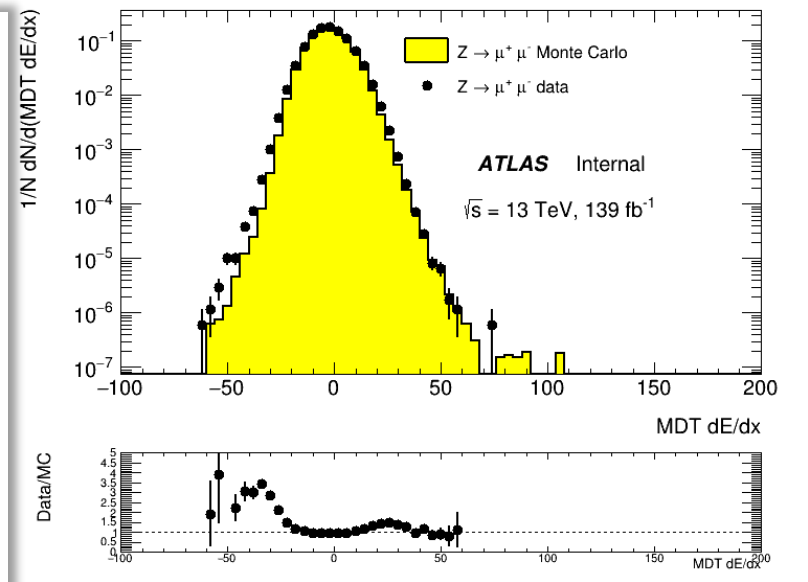
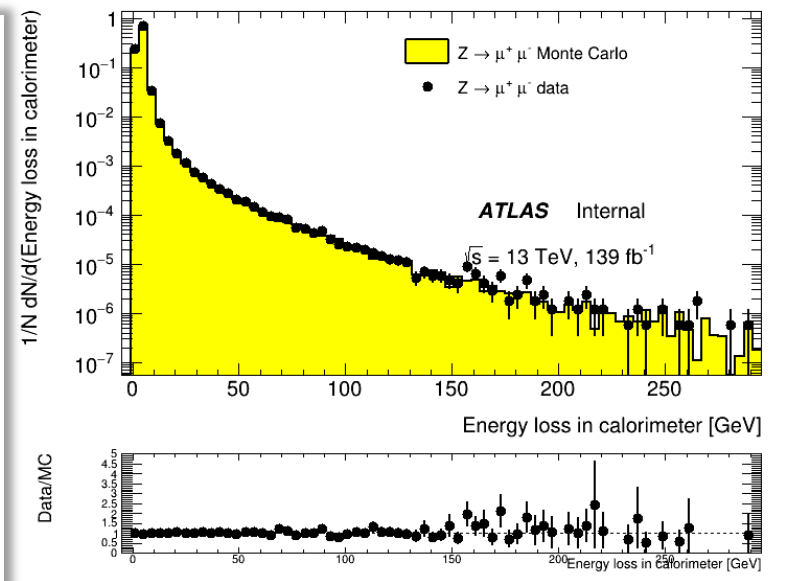
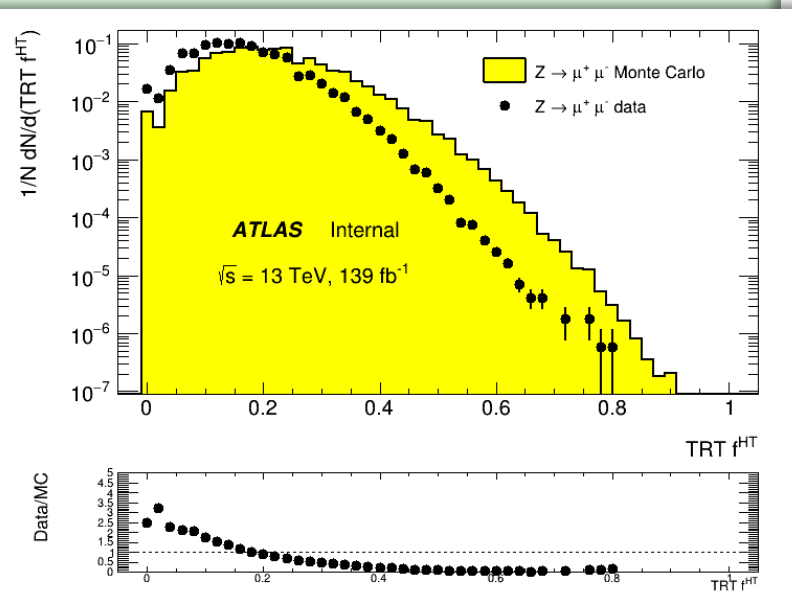
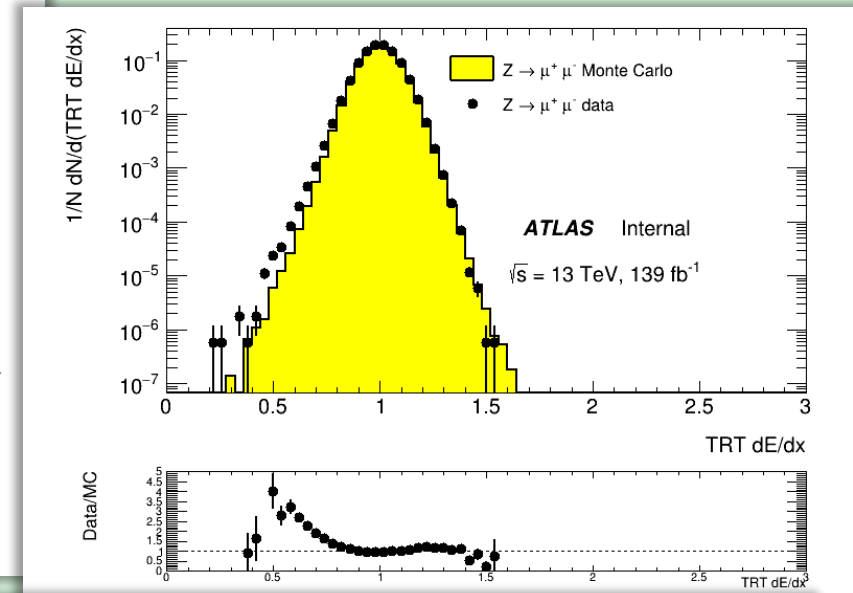
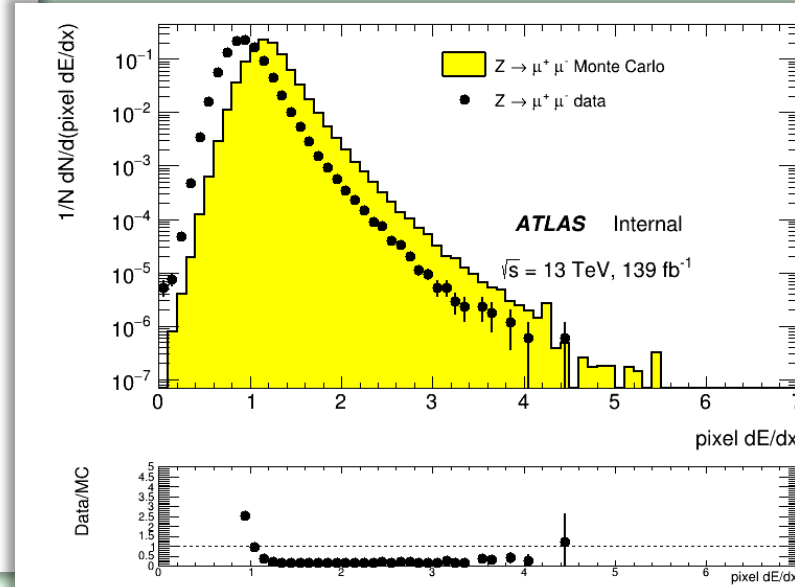
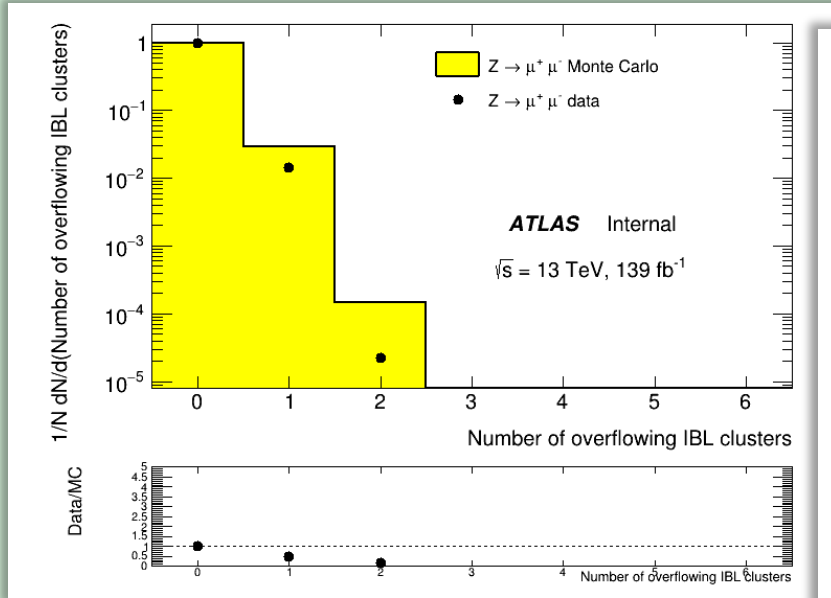
2017

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



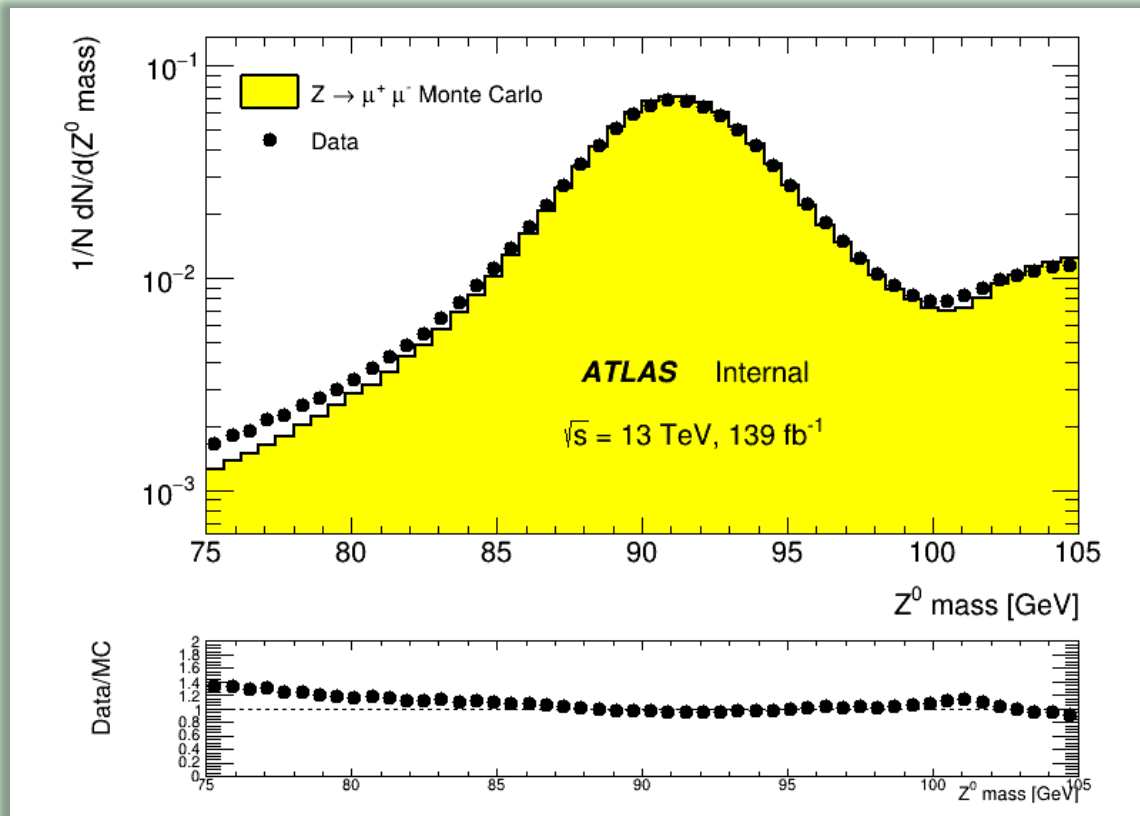
This pair of spectra will agree more after the tool factoring in the radiation-damage effect and η -dependence of the variable is available (the values will be corrected at the analysis level)

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



Current status: $Z \rightarrow \mu\mu$ 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

Already had three requests for signal samples:


↓ [MC16 signal samples official request](#)

↓ [Round I](#)



↓ [Round II](#)

↓ [Round III](#)



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](#).

Current status: signal samples

Already had three requests for signal samples:


↓ [MC16 signal samples official request](#)

↓ [Round I](#)



↓ [Round II](#)

↓ [Round III](#)




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](#).

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.

Current status: signal samples

Already had three requests for signal samples:


↓ [MC16 signal samples official request](#)

↓ [Round I](#)



↓ [Round II](#)

↓ [Round III](#)




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](#).

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.

3. In March 2020, see  [ATLMCPROD-8394](#);

Status: finished last Sunday (three days ago)

The most recent signal-sample request: general info

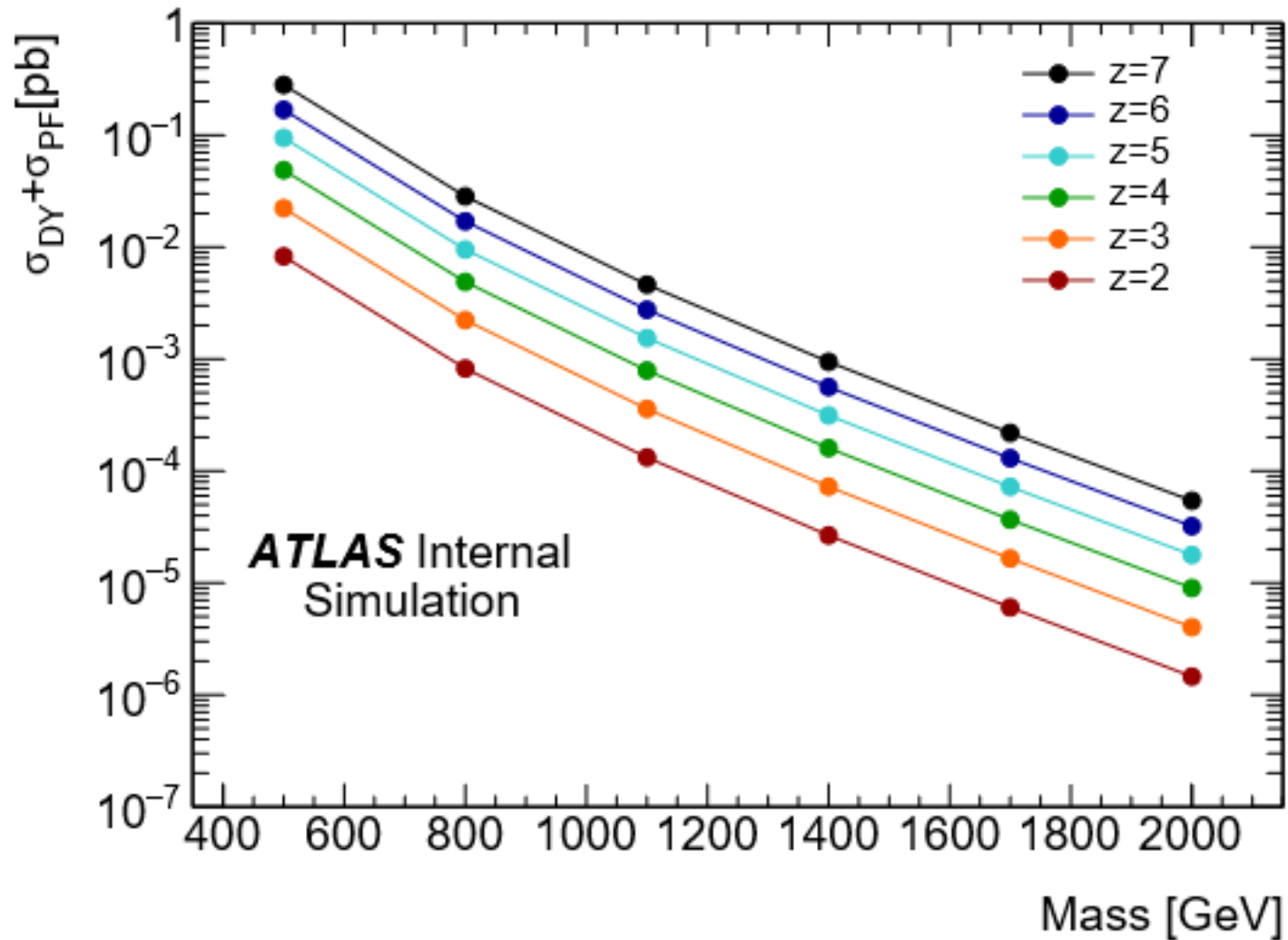
72 samples:

- 6 masses: 500, 800, 1100, 1400, 1700, and 2000 GeV;
- 6 charges: $\pm 2e$, $\pm 3e$, $\pm 4e$, $\pm 5e$, $\pm 6e$, and $\pm 7e$;
- 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.

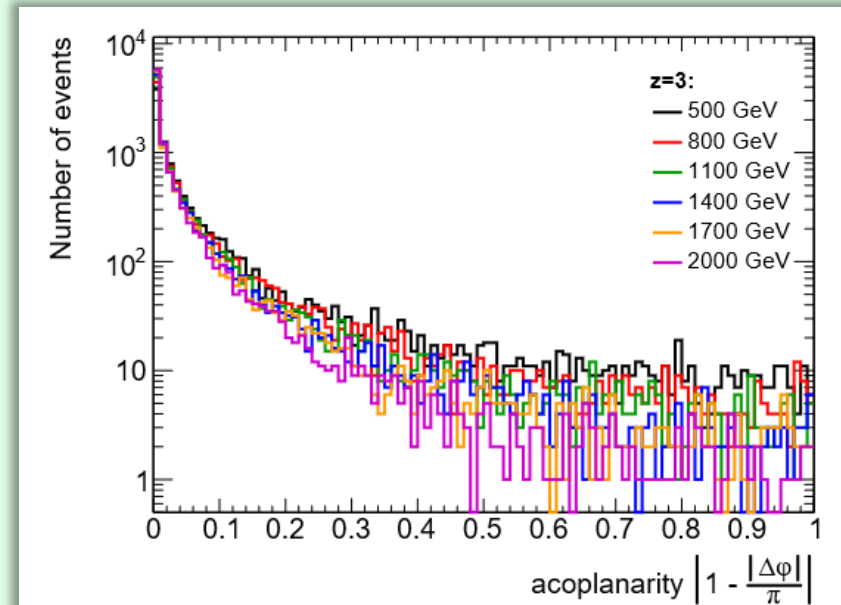
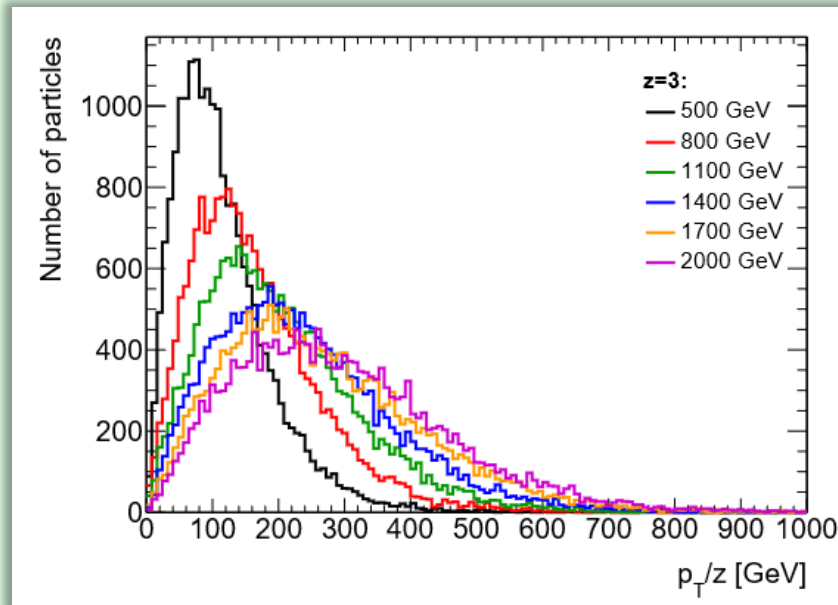
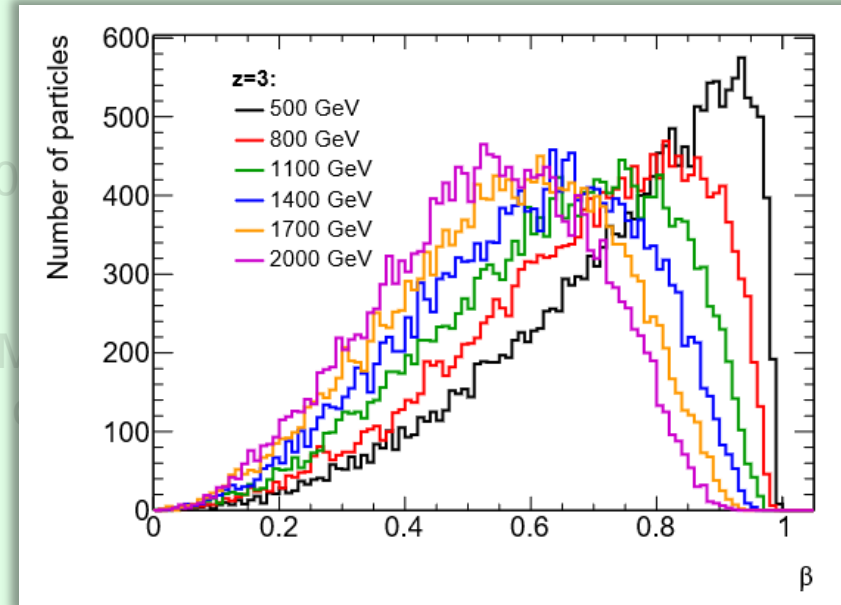
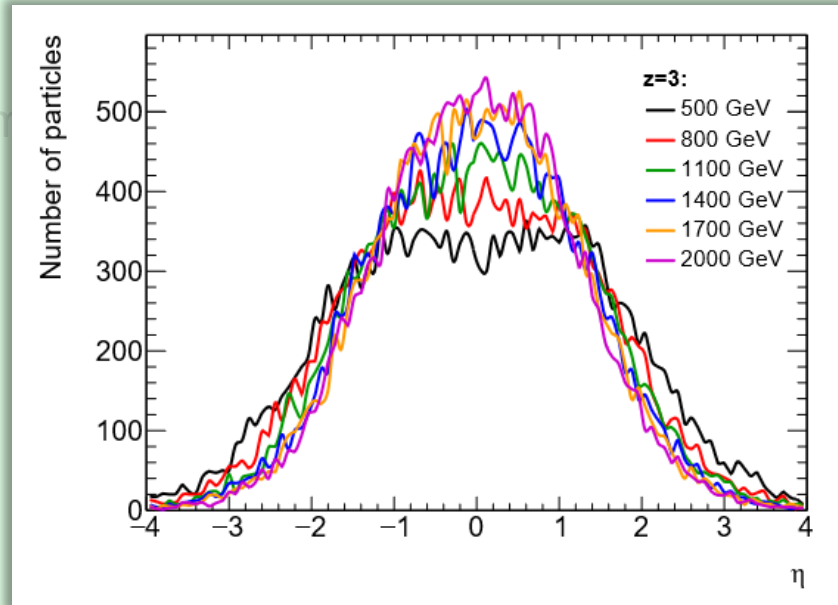
The most recent signal-sample request: X-sections vs. mass

72 samples:

- 6 masses
- 6 charges
- 2 products
- 3 products
- 10k events
- almost 2.2



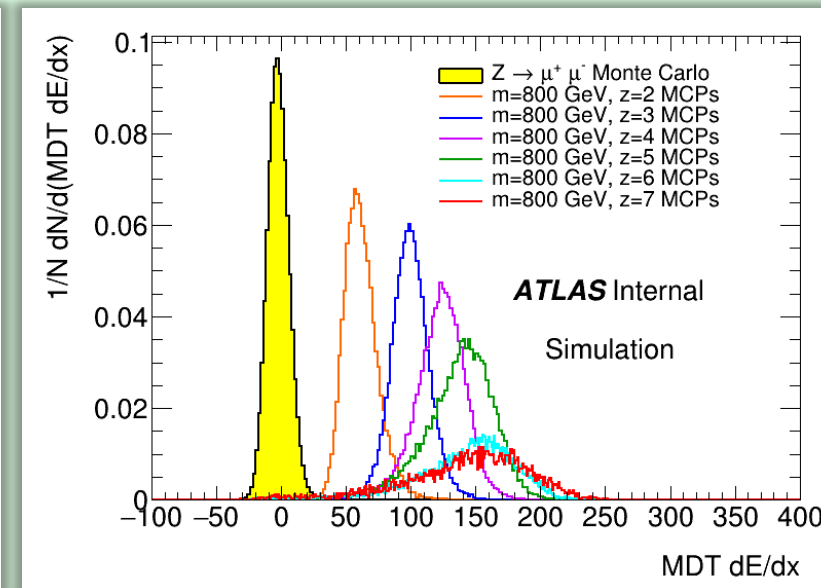
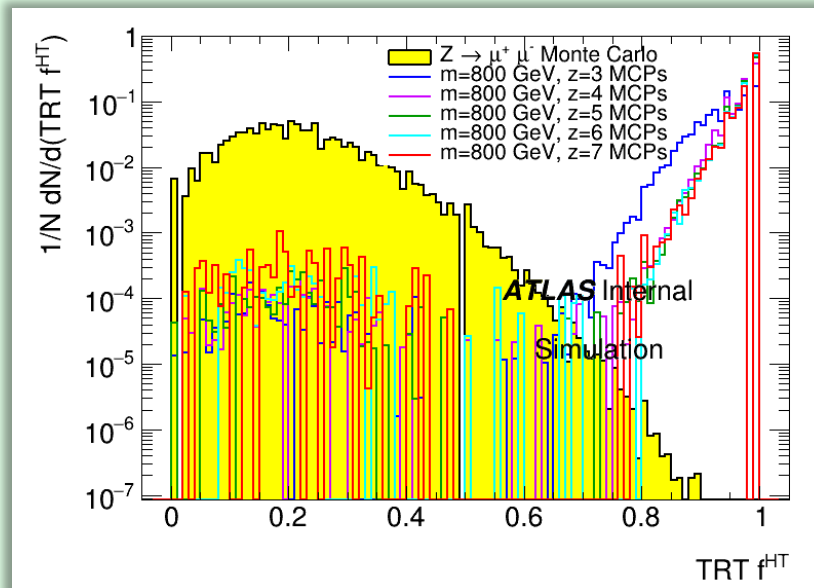
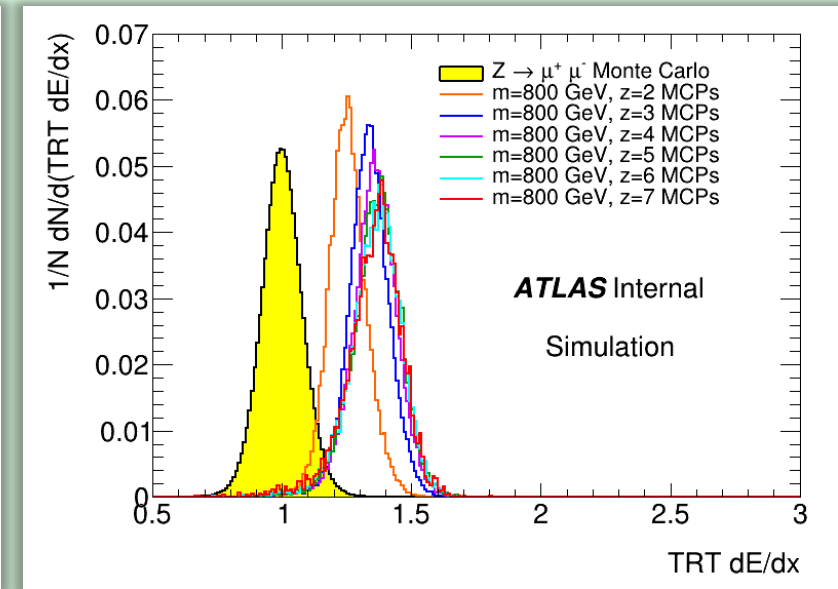
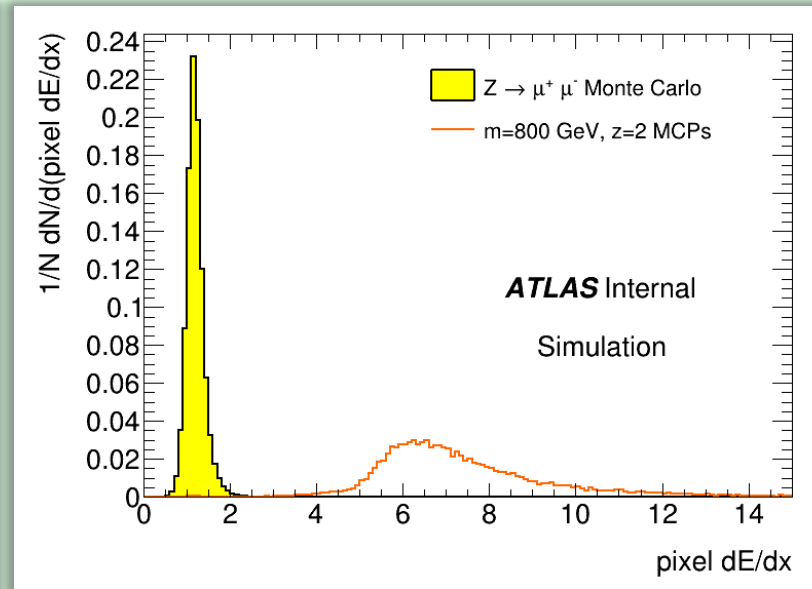
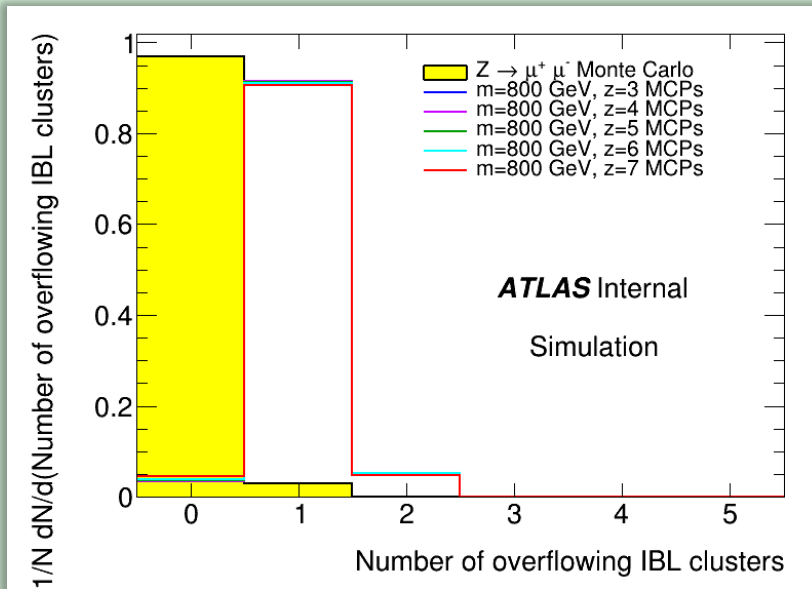
The most recent signal-sample request: truth plots



More plots on the truth level:

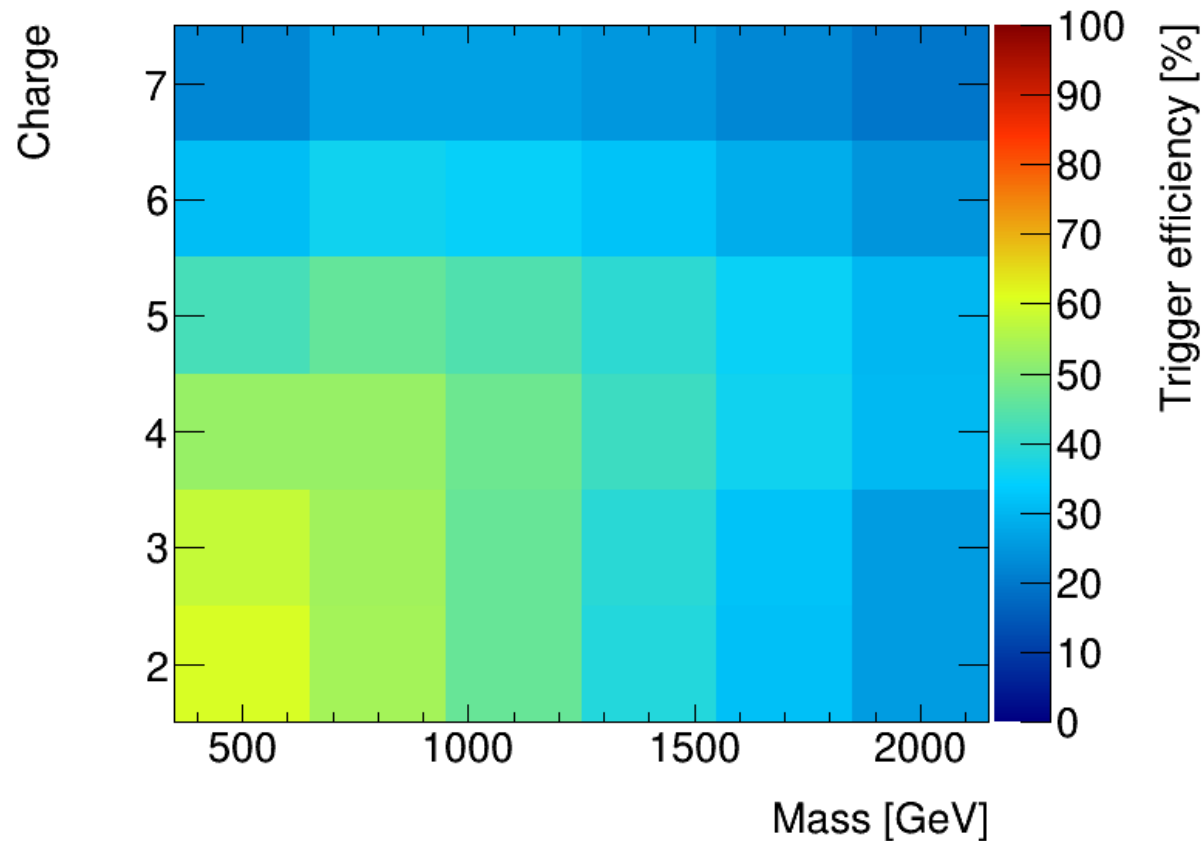
<https://twiki.cern.ch/twiki/bin/view/AtlasProtected/MC16MultiChargedParticlesValidationPlots?rev=6>

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

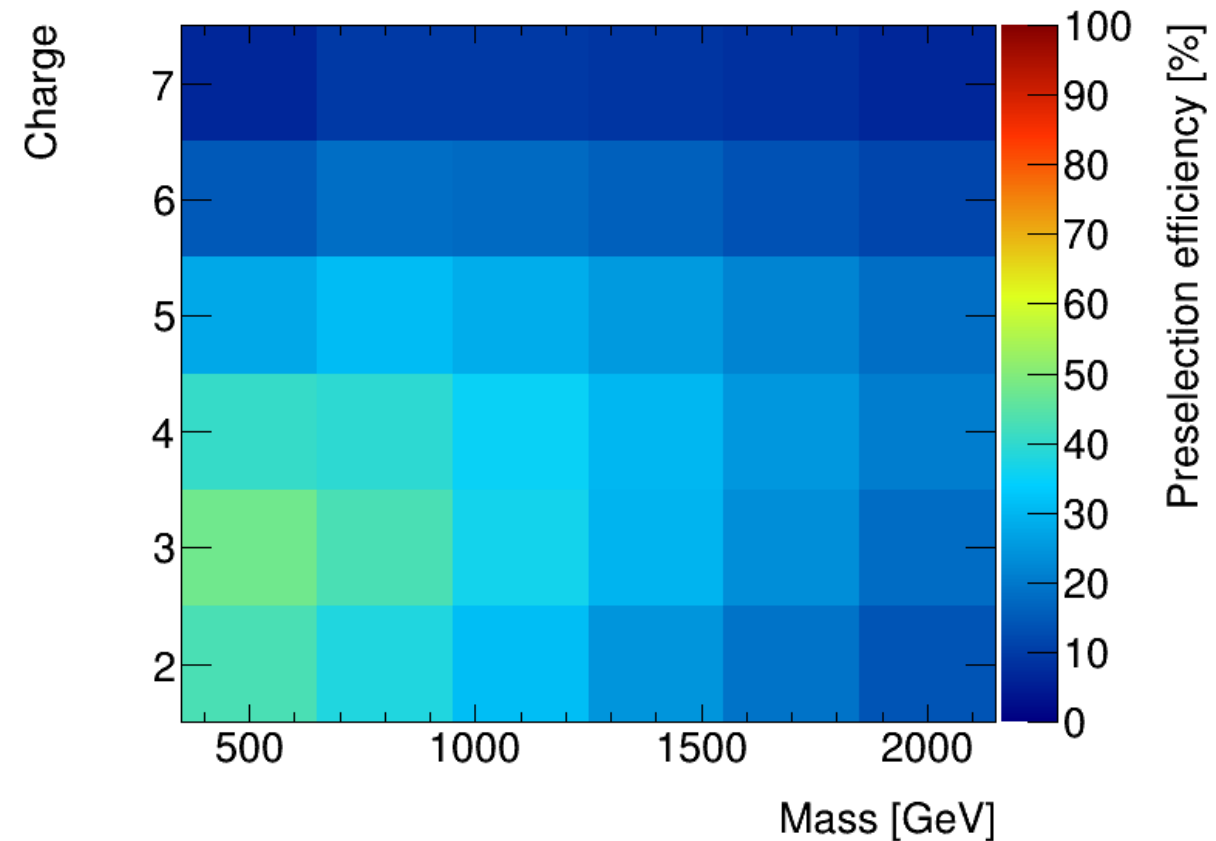


The most recent signal-sample request: efficiency maps

Trigger efficiency *



Preselection efficiency



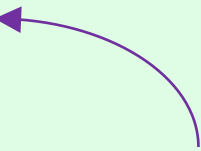
* Trigger efficiency implicitly factors in a part of the preselection criteria present in the DAOD skimming

Documentation

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

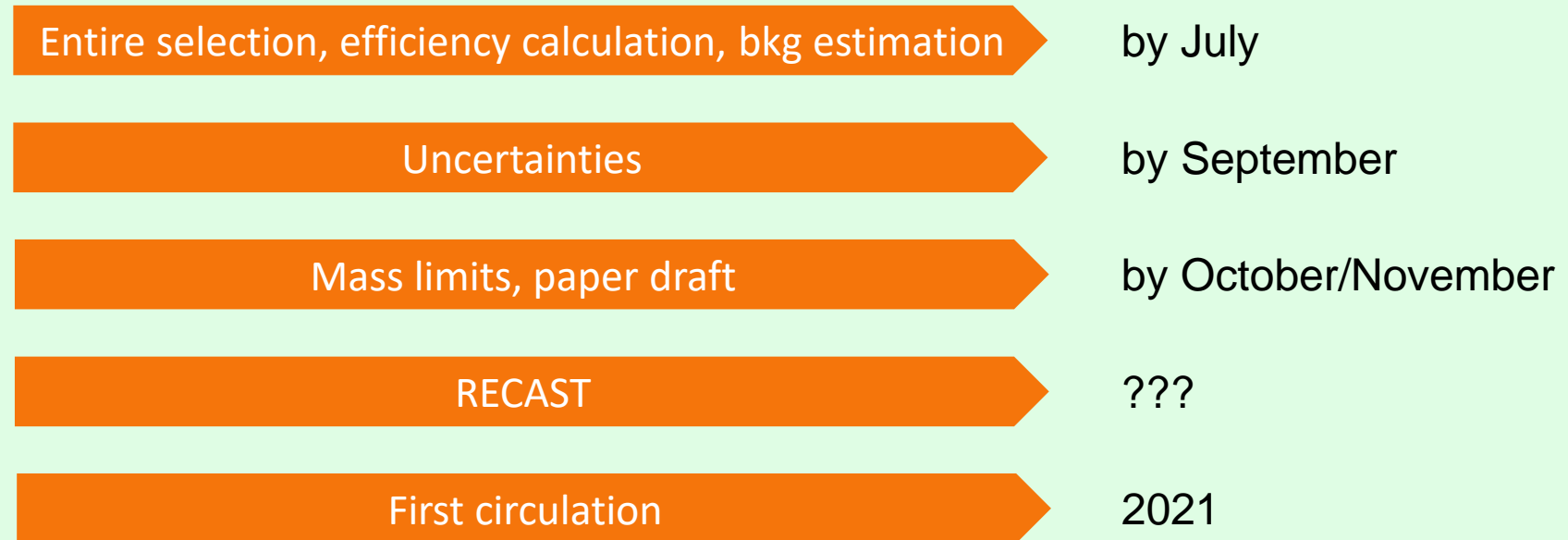
Glance entry: <https://glance.cern.ch/atlas/analysis/analyses/details.php?id=2107>

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



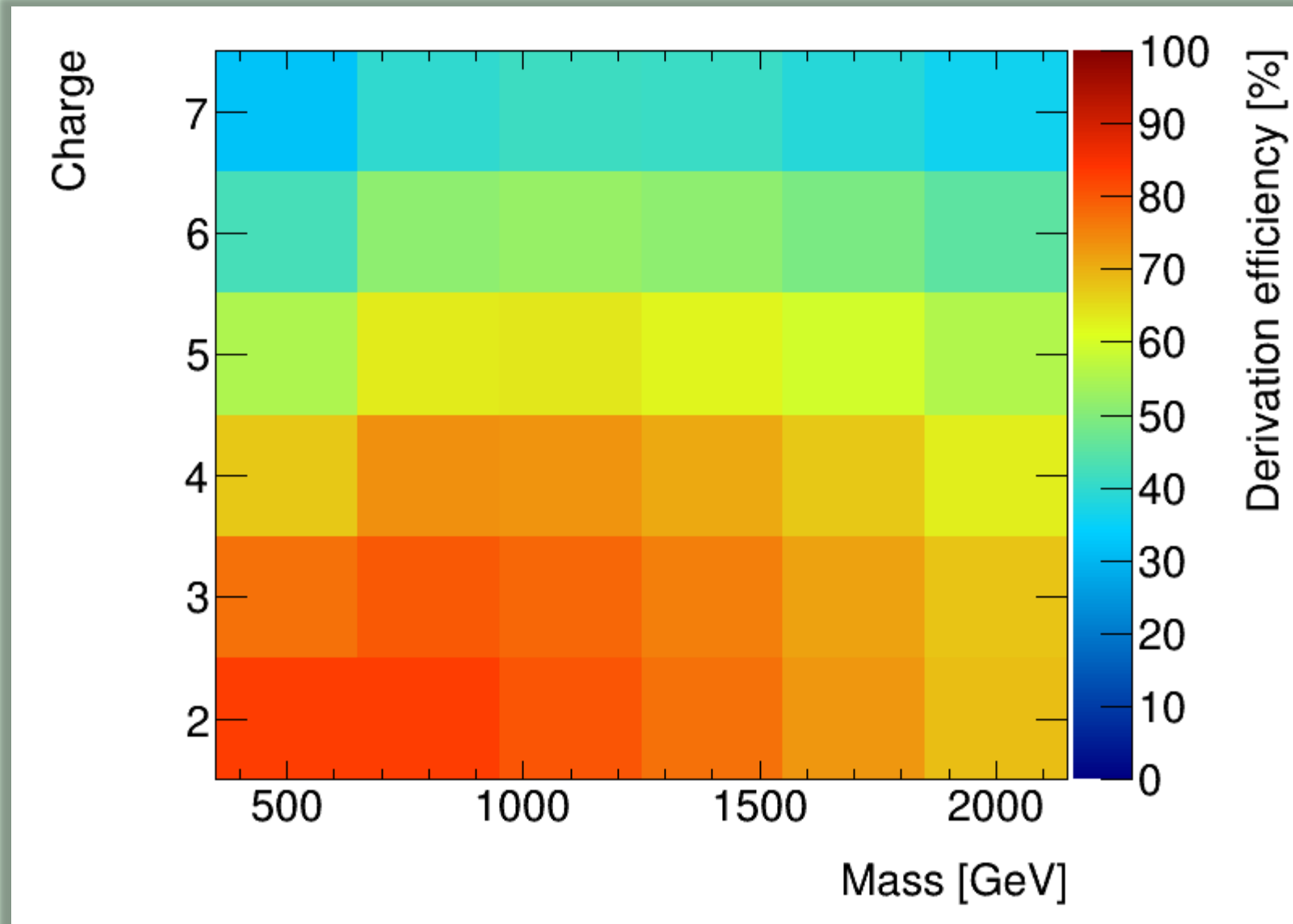
almost empty;
nevertheless, most of
the plots are obsolete
already

Ballpark timeline



THANKS!

The most recent signal-sample request: efficiency maps



Trigger selection in the current analysis

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



late-muon trigger

–

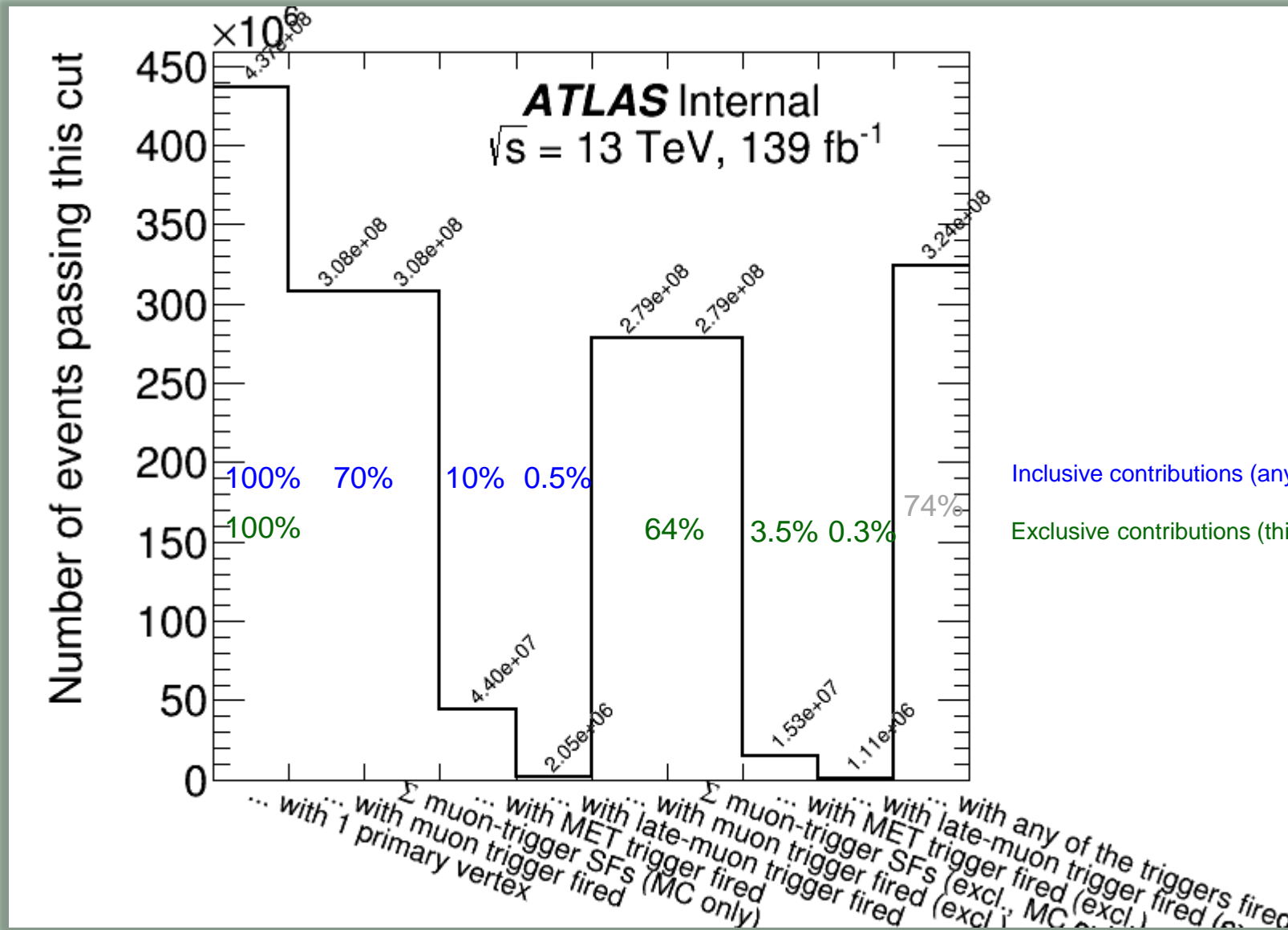
2015 - 2016

HLT_mu10_mgonly_L1LATE-MU10_J50

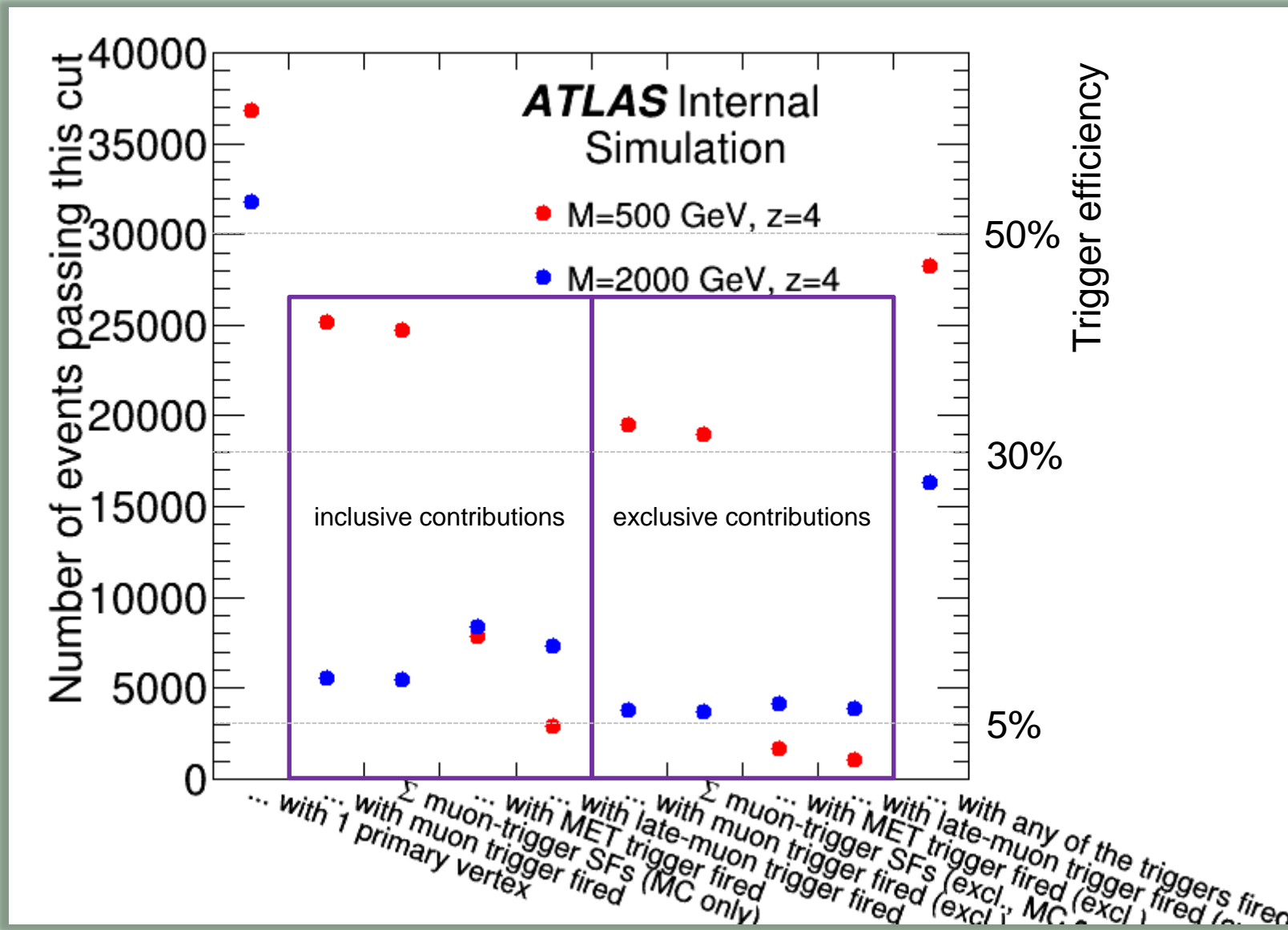
2017 (run 329000 onwards) - 2018

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



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

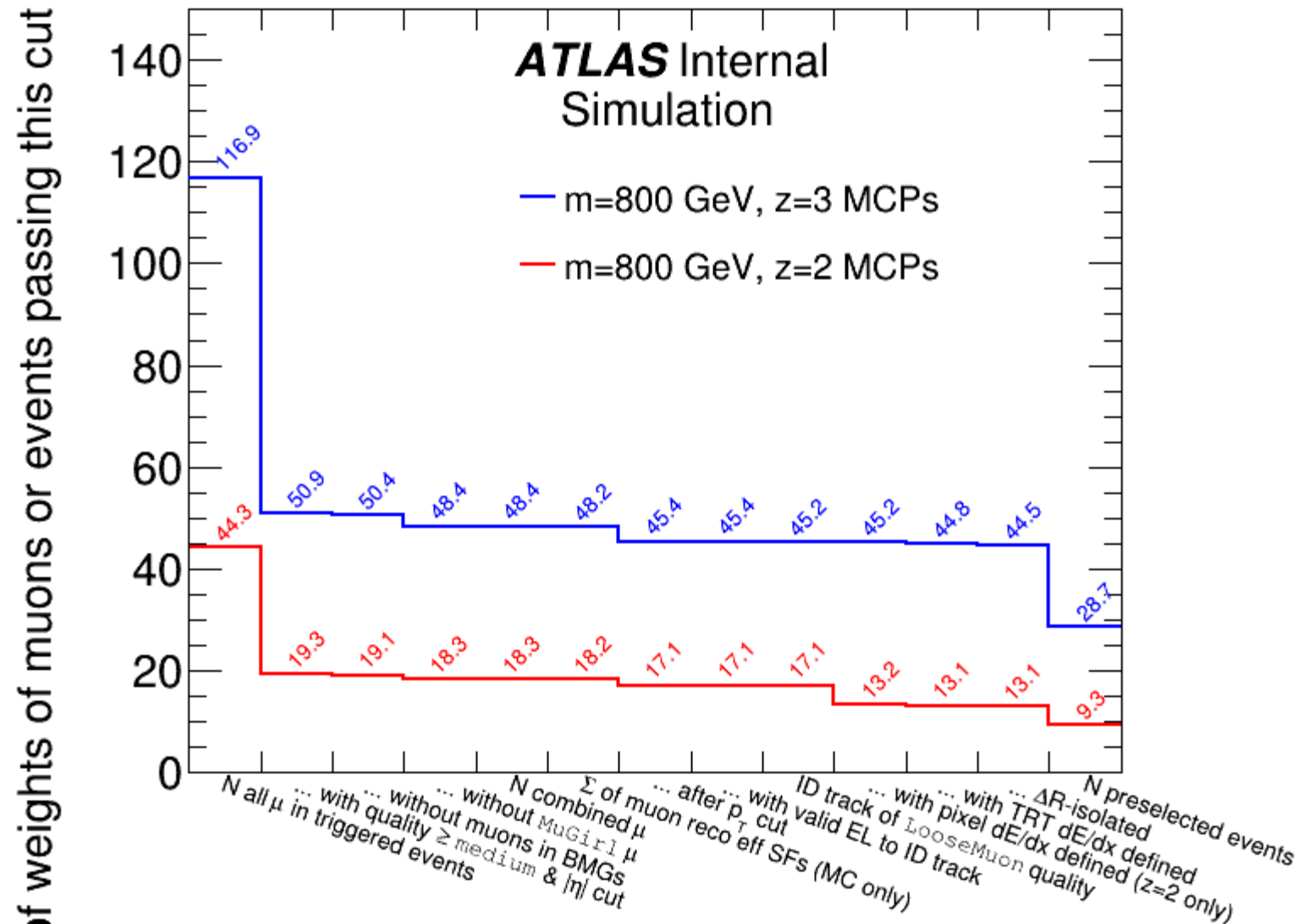
contribution: **~100%** of the single-muon-trigger contribution;
Late-muon-trigger exclusive

contribution: **~100%** of the single-muon-trigger contribution.

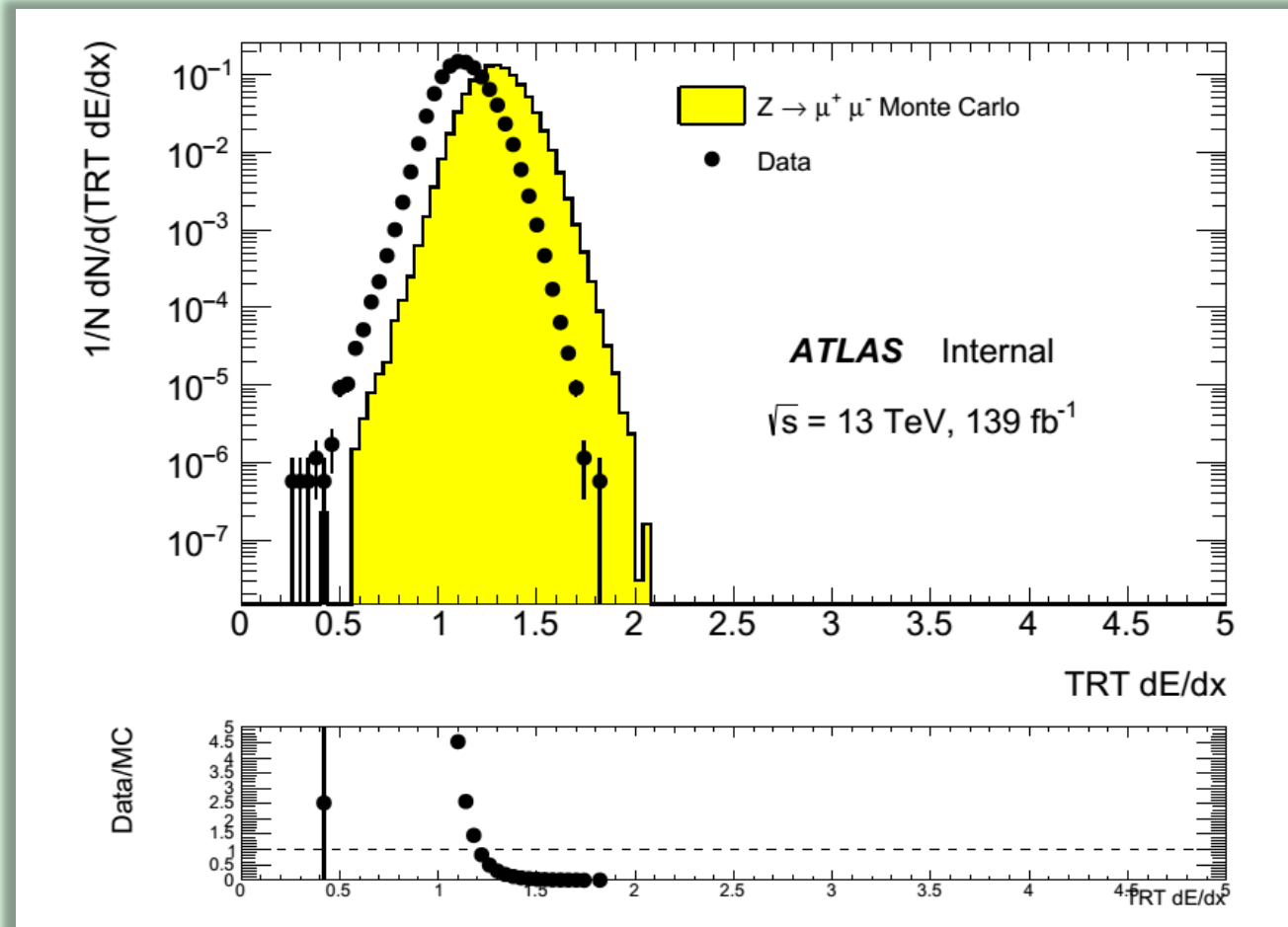
Preselection criteria

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	$p_T > 50 \text{ GeV}$	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

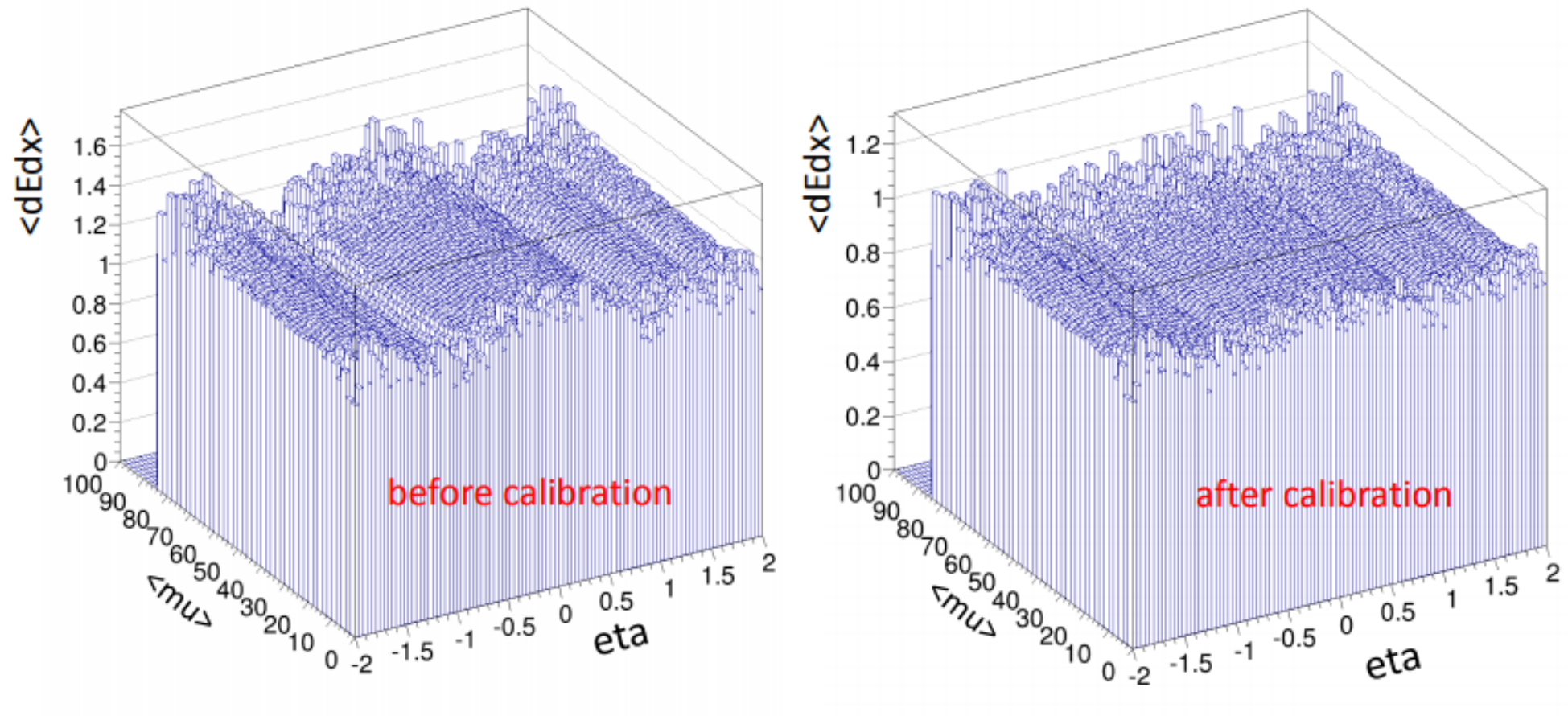


TRT dE/dx issue in r21

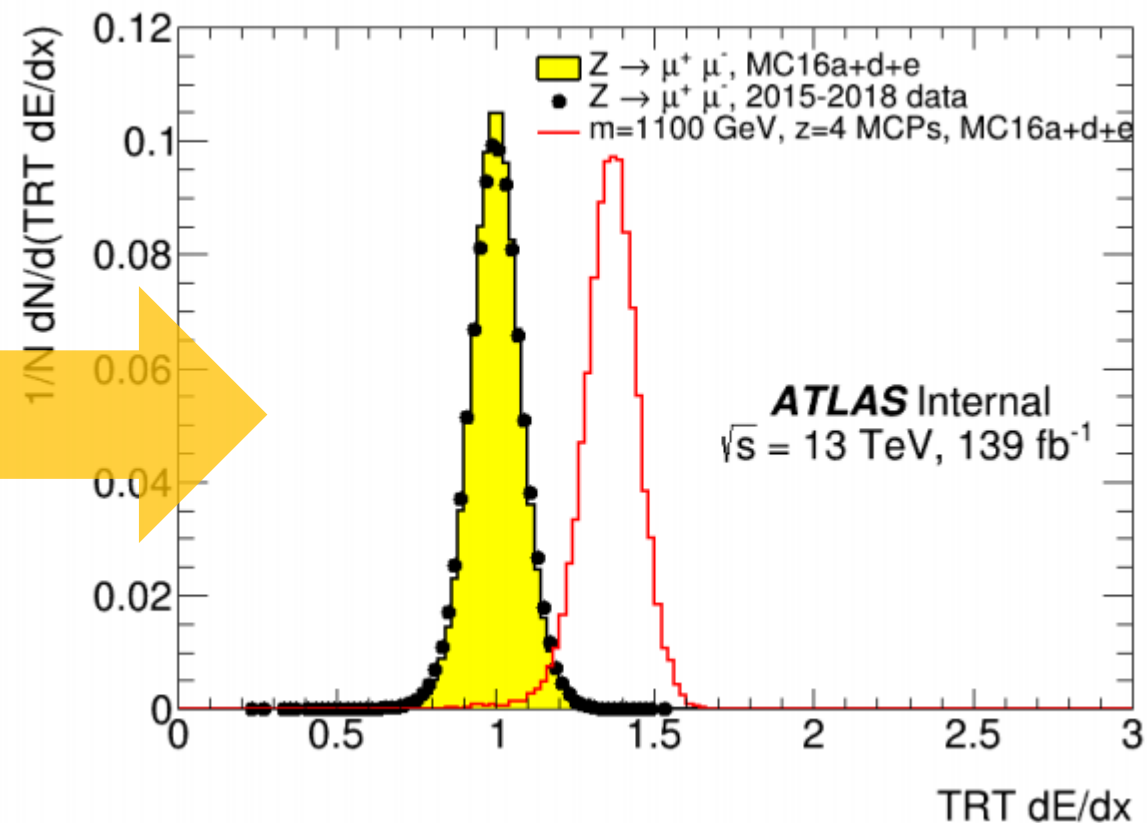
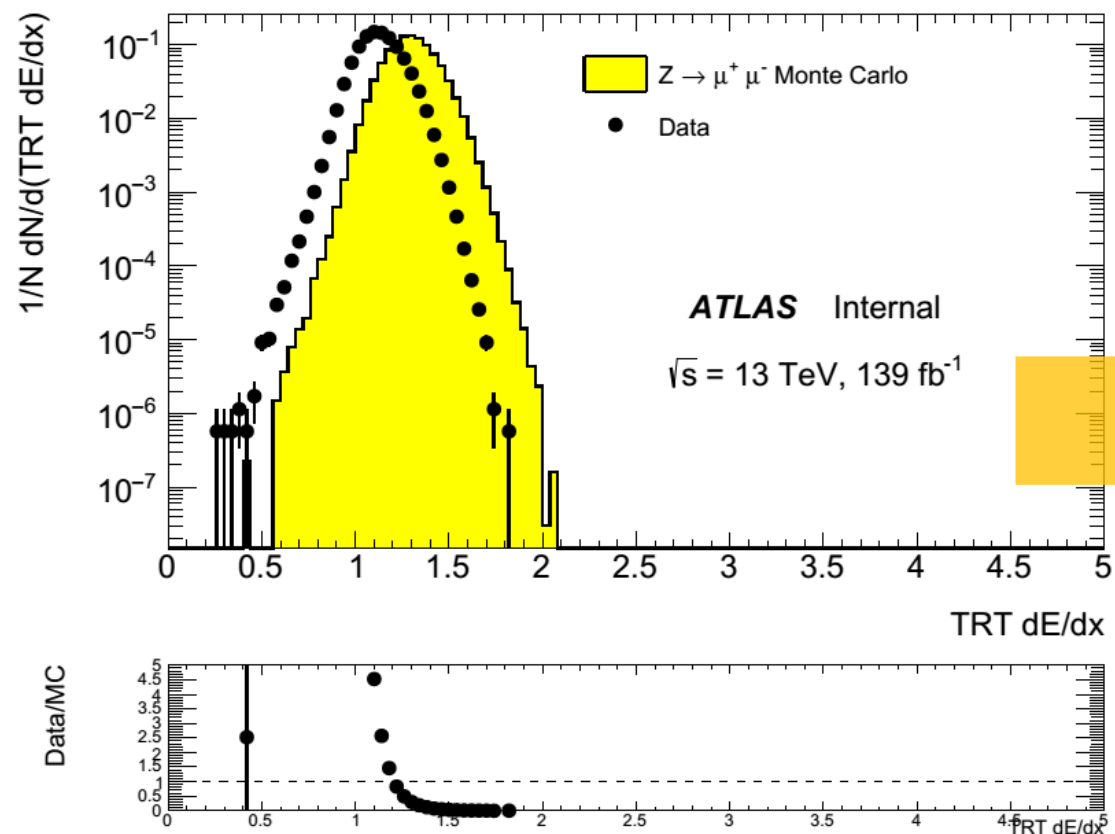


TRT dE/dx issue in r21

$\langle dE/dx \rangle$ dependence on eta and on $\langle \mu \rangle$ for mc16



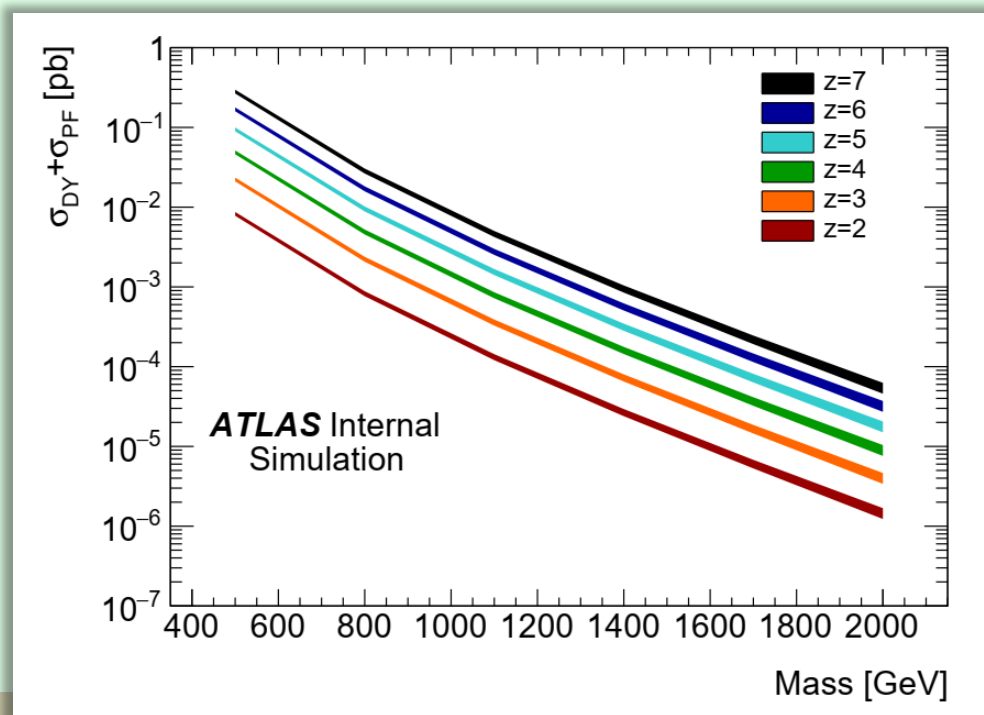
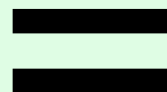
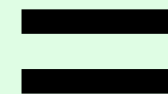
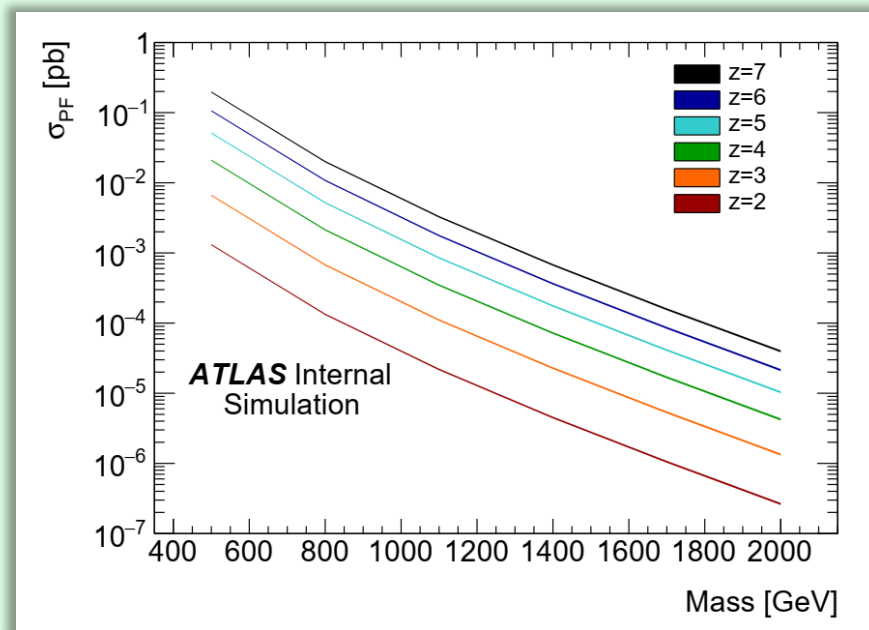
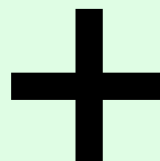
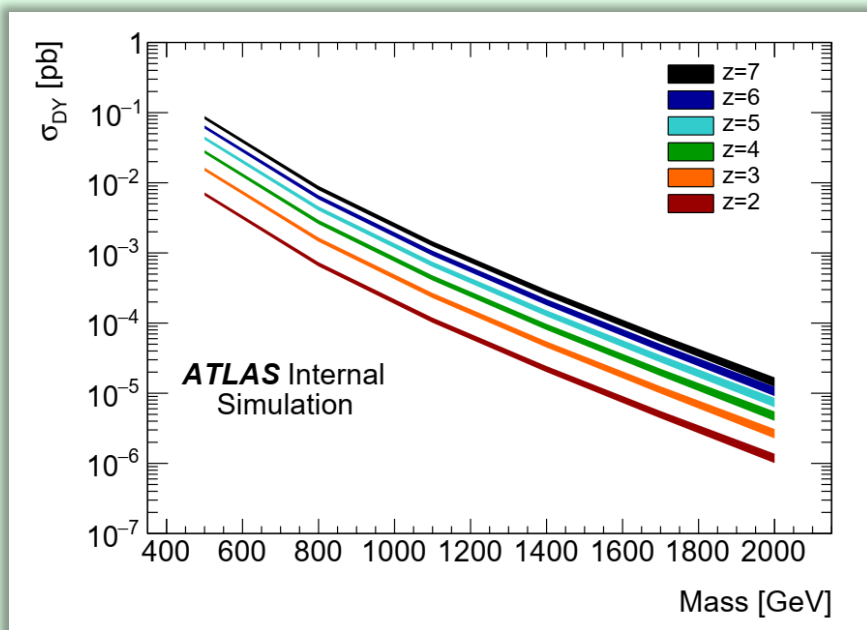
TRT dE/dx issue in r21



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



Mind different line widths!

More on the MET origin

