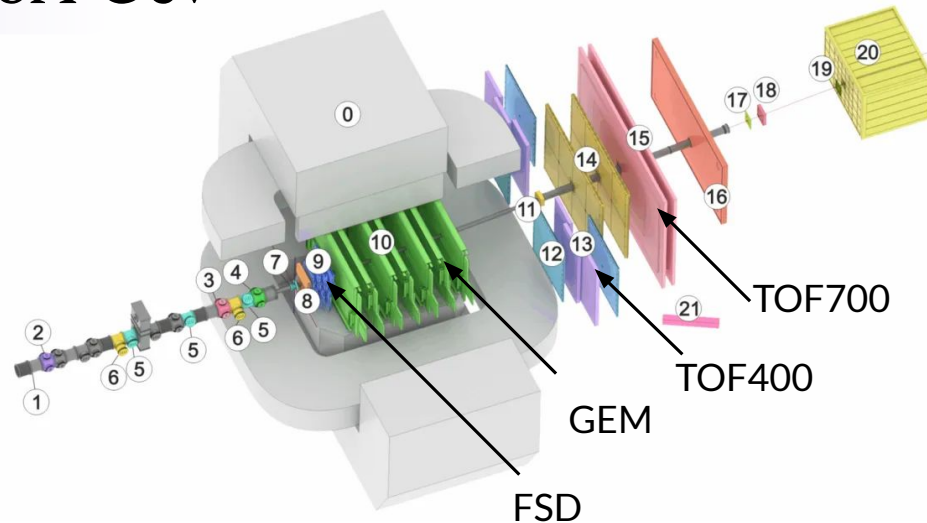
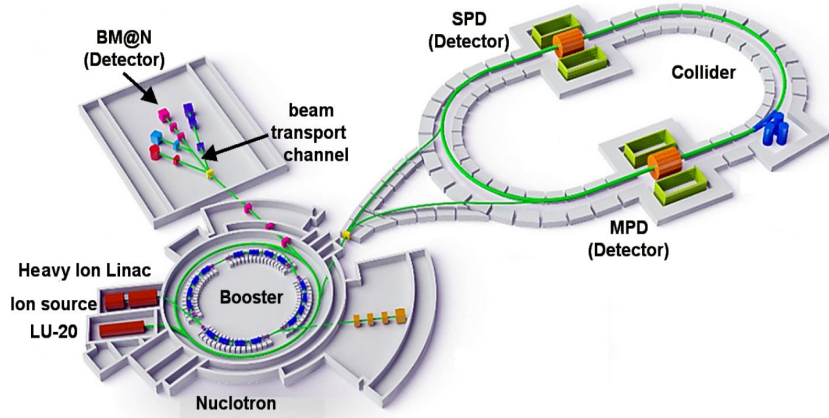


Particle identification with Time-of-flight and Energy Loss methods with BM@N Xe+Cs(I) at 3.8A GeV collision data

Irina Zhavoronkova
VBLHEP, Joint Institute for Nuclear Research, Dubna

The 2026 International Conference on
Instrumentation for Colliding Beam Physics

The BM@N Setup: Xe+CsI 3.8A Gev

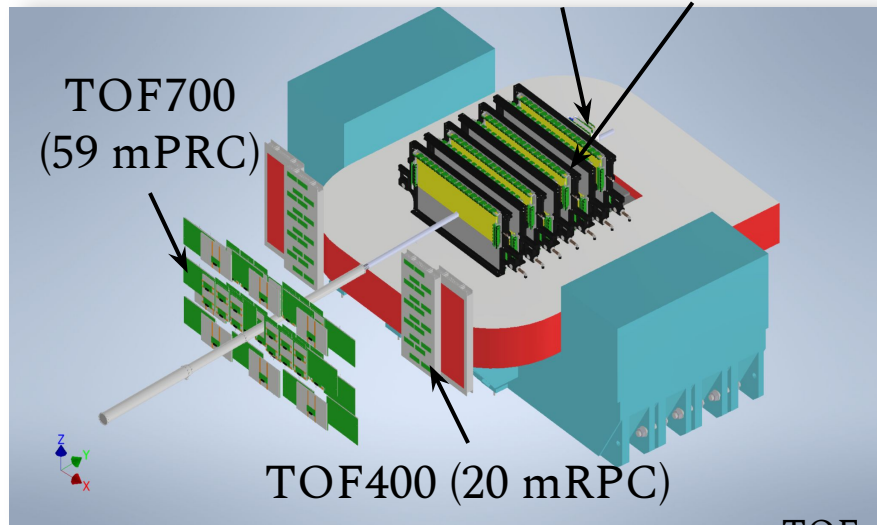


The first physics Run was carried out at the BM@N experiment in December, 2022 - February, 2023:
Xe+CsI, 3.0 AGeV (53M events), 3.8 AGeV (580M events).

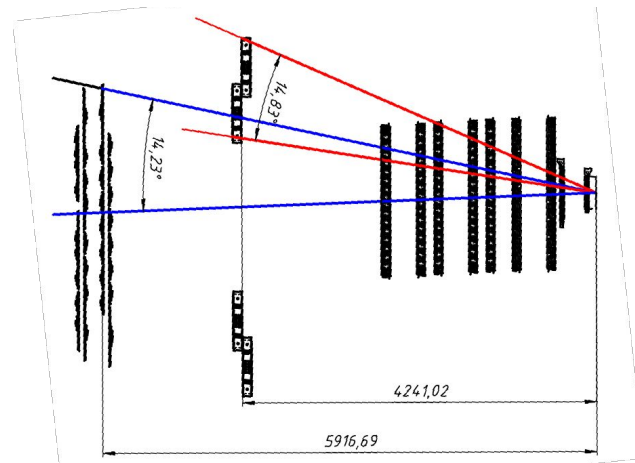
Major systems:

- ❑ Inner tracking system FSD+GEM (Forward Silicon Detector + Gaseous Electron Multipliers, [9,10 on the scheme]);
- ❑ Outer tracking system CSC (Cathod Strip Chambers, big, small [12, 14]);
- ❑ PID system TOF400 + TOF700, [13, 15];
- ❑ FHCAL (Forward Hadron Calorimeter, [20]) - centrality and reaction plane determination.

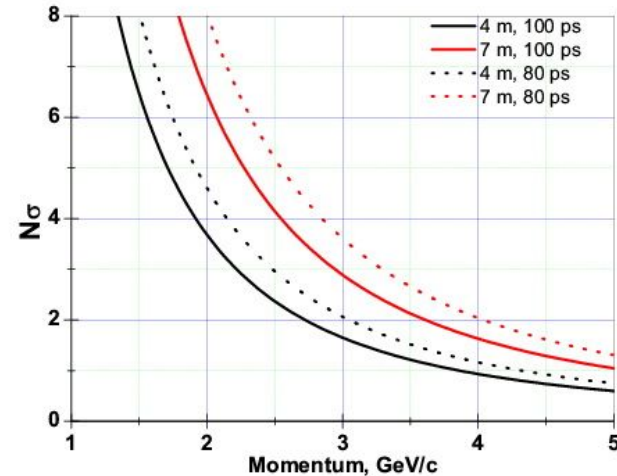
Closer look



BM@N tracking and TOF systems



TOF400 and TOF700 geometrical acceptance



TOF separation power as a function of momentum for different flight path lengths and time resolutions

Method: Time of Flight

By measuring a particle's time of flight as the time, one get the velocity and then the squared mass as follows:

$$\beta = \frac{L}{ct} \quad m^2 = \frac{p^2}{q^2} \left(\frac{1 - \beta^2}{\beta^2} \right)$$

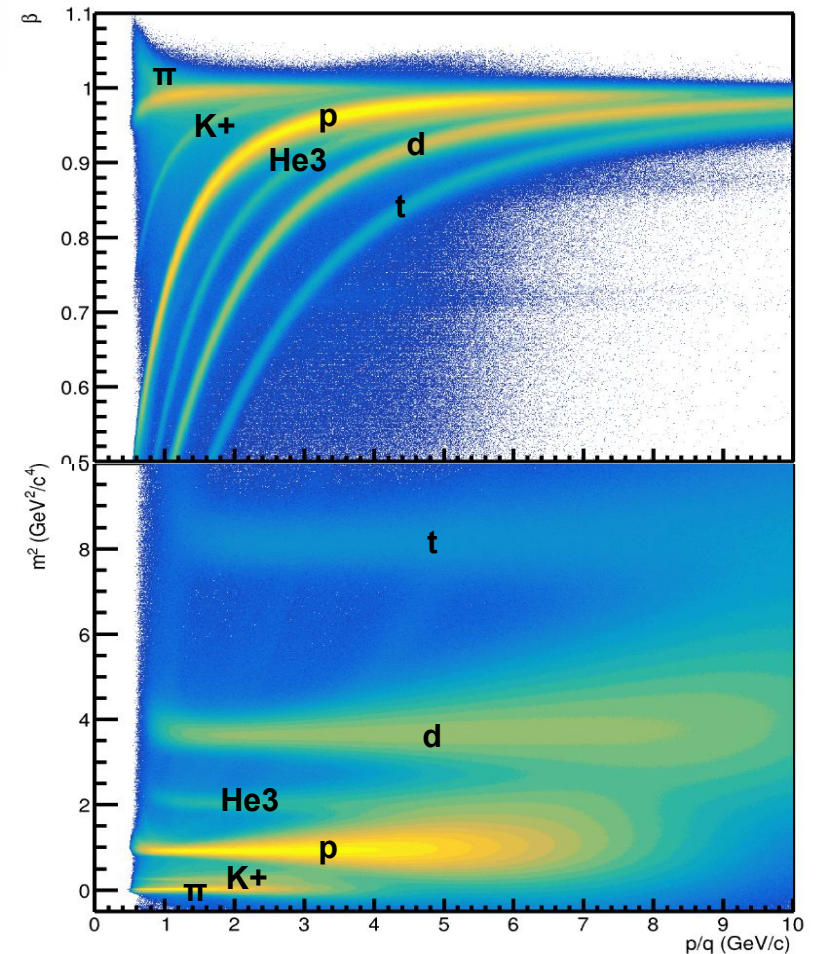
The difference in time of flight for two particle species of masses m_1 and m_2 carrying the same momentum p will be:

$$\Delta t = \frac{L}{c} \left(\sqrt{1 + \frac{m_1^2}{p^2}} - \sqrt{1 + \frac{m_2^2}{p^2}} \right)$$

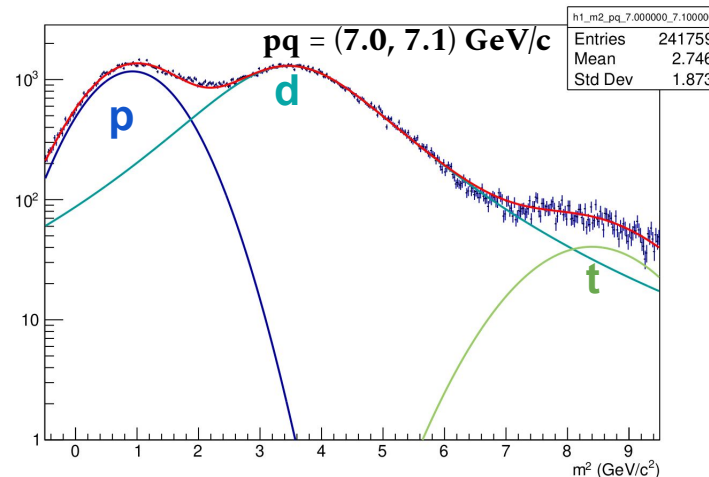
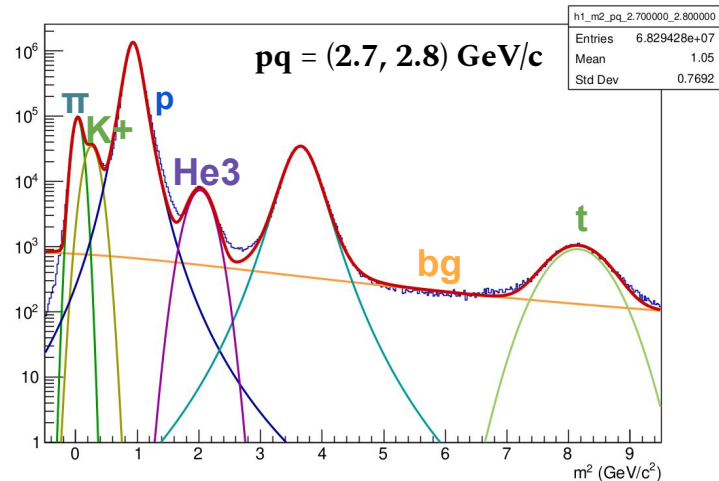
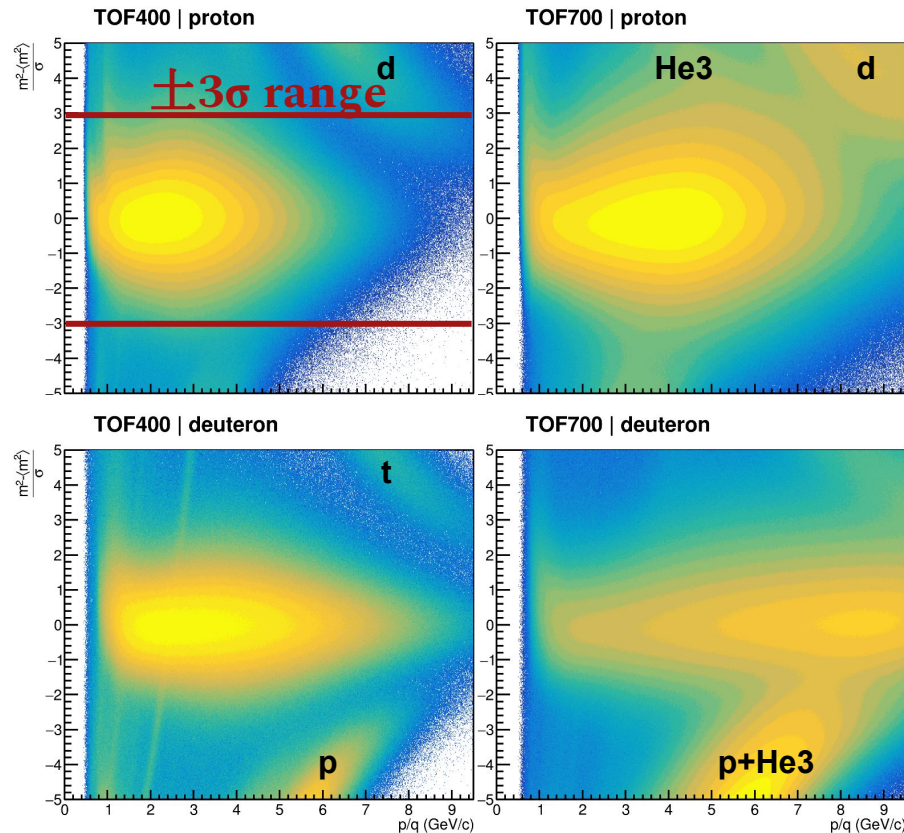
$$\sigma_{ToF} = \sqrt{\sigma_{start}^2 + \sigma_{stop}^2 + \sigma_{FEE_start}^2 + \sigma_{FEE_stop}^2 + \sigma_{TDC_start}^2 + \sigma_{TDC_stop}^2 + \sigma_{syn}^2}$$

$$\sigma_{m^2}^2 = 4m^4 \left(\frac{\sigma_p}{p} \right)^2 + 4E^4 \left(\frac{\sigma_t}{t} \right)^2 + 4E^4 \left(\frac{\sigma_L}{L} \right)^2$$

Time resolution of TOF400 is approx. 80 ps, of TOF700 – approx. 120 ps



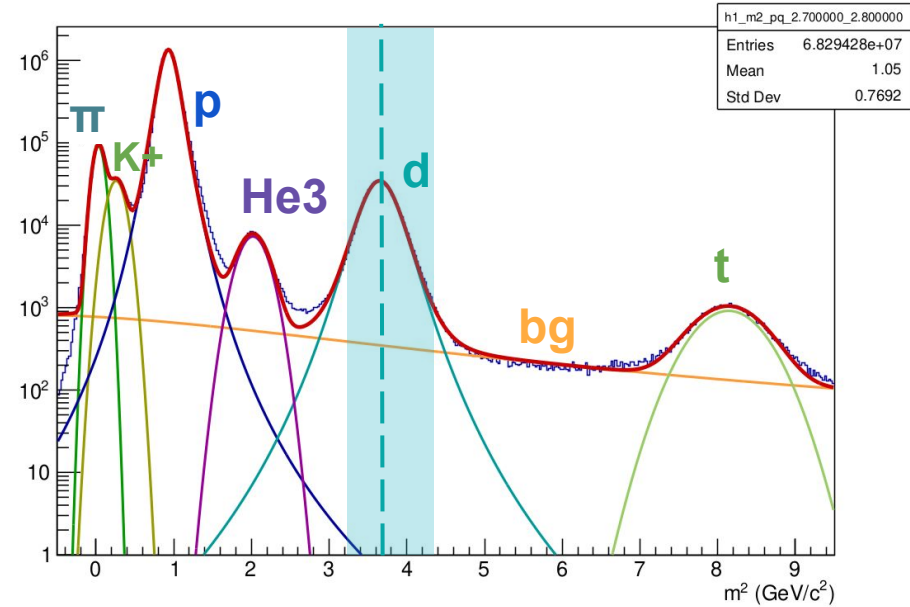
PID with TOF and n-sigma method



Purity: definition

We define purity as the ratio of integral of the particle of interest to the sum of all the functions integrals in the $(\langle m^2 \rangle - n\sigma; \langle m^2 \rangle + n\sigma)$ GeV^2/c^4 interval

$$\text{purity}^d = \frac{\int_{\langle m^2 \rangle - n\sigma}^{\langle m^2 \rangle + n\sigma} f^d(x) dx}{\sum^{\text{pdg}} \left(\int_{\langle m^2 \rangle - n\sigma}^{\langle m^2 \rangle + n\sigma} f^{\text{pdg}}(x) dx \right)}$$

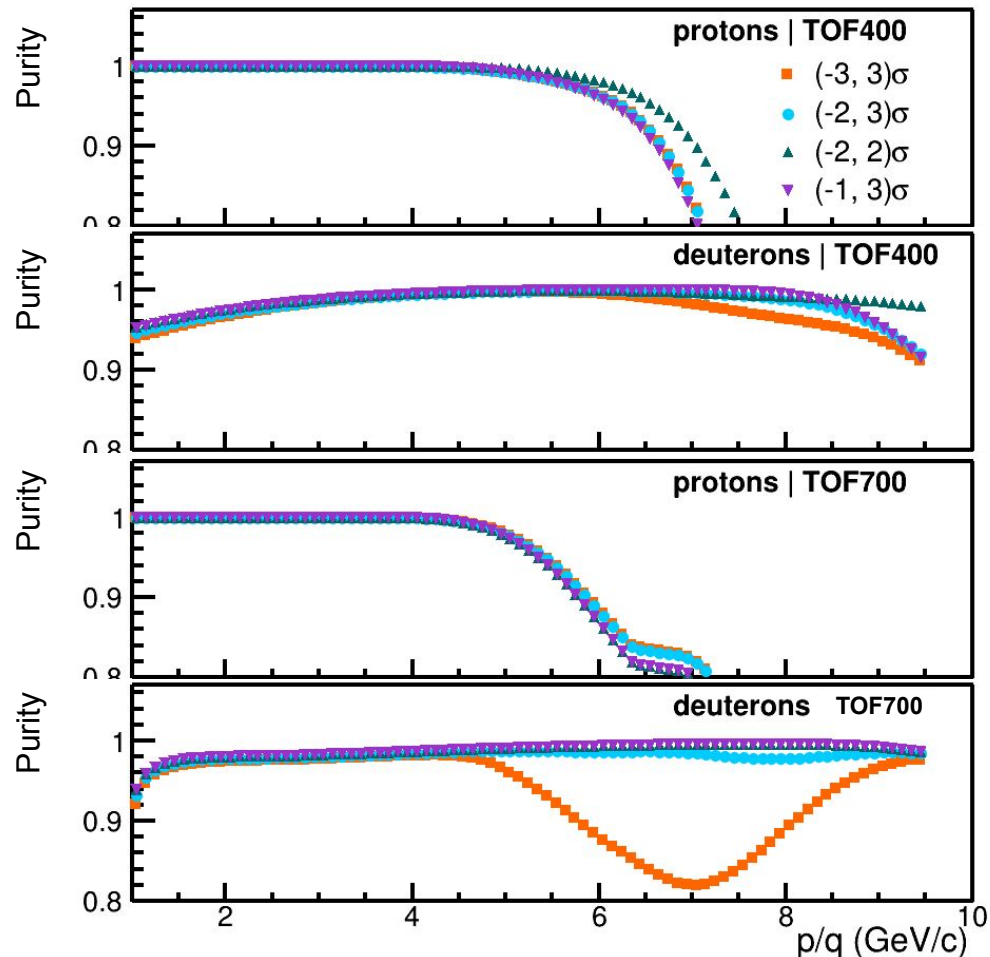


Purity: result

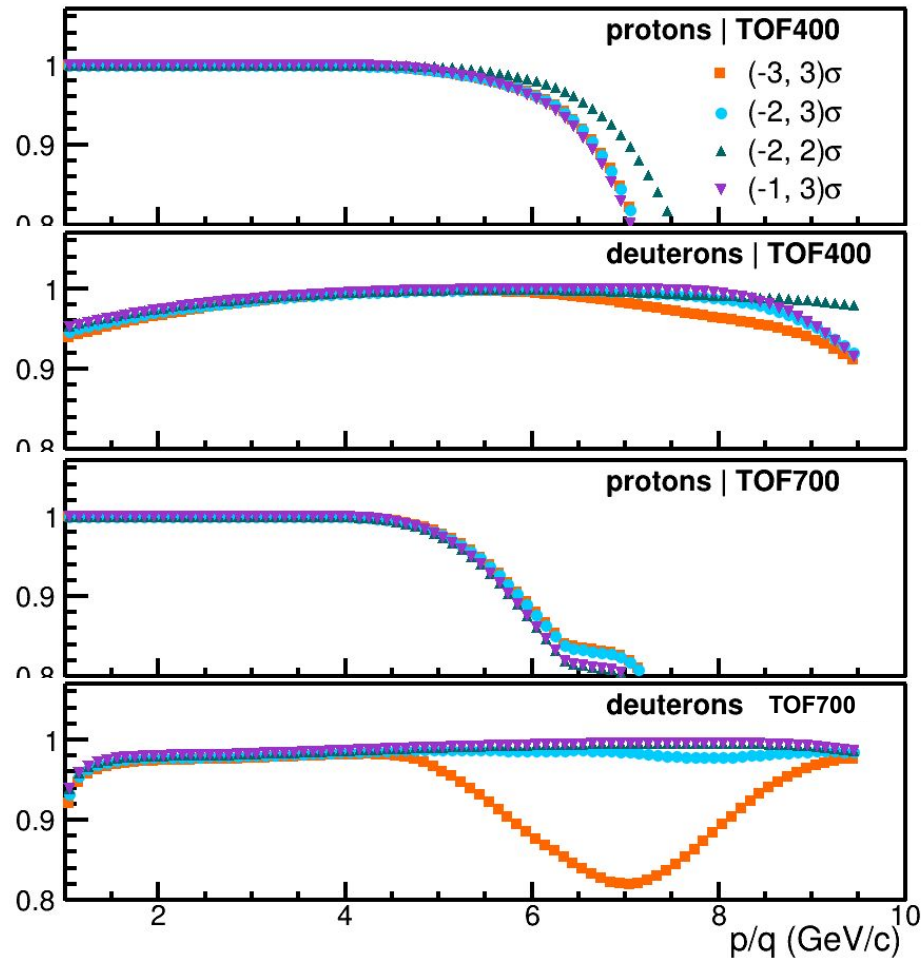
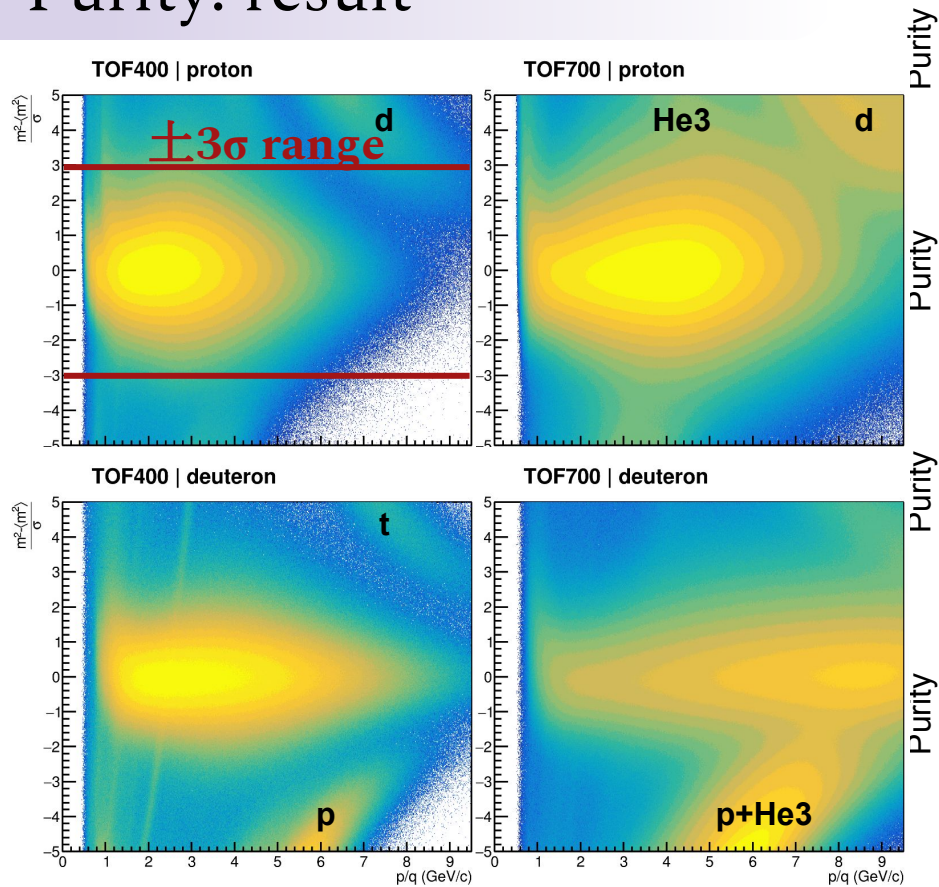
For purity estimation n-sigma range was varied as follows:

	TOF400	TOF700
protons	$(-3,3)$	$(-3,3)$
	$(-2,3)$	$(-2,3)$
	$(-2,2)$	$(-2,2)$
deuteron	$(-3,3)$	$(-3,3)$
	$(-2,3)$	$(-2,3)$
	$(-1,3)$	$(-1,3)$

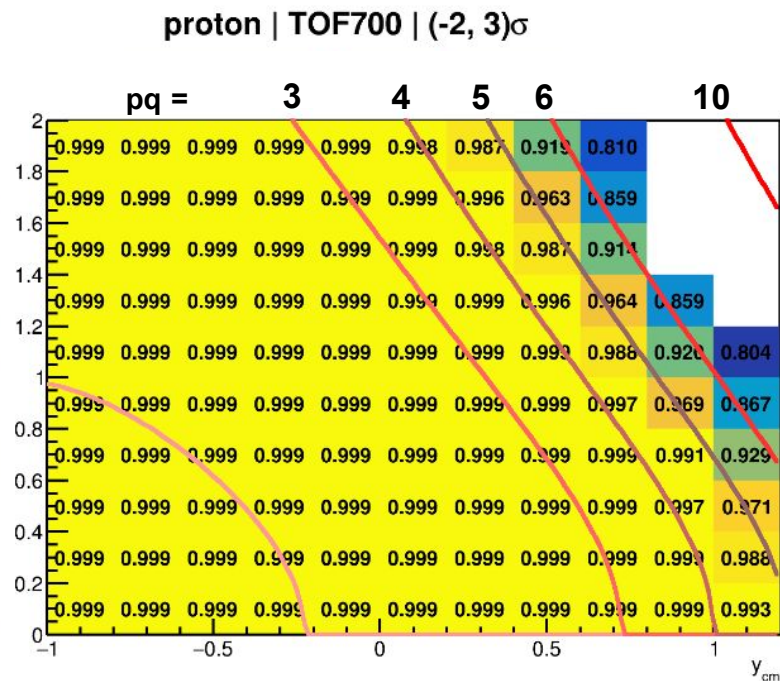
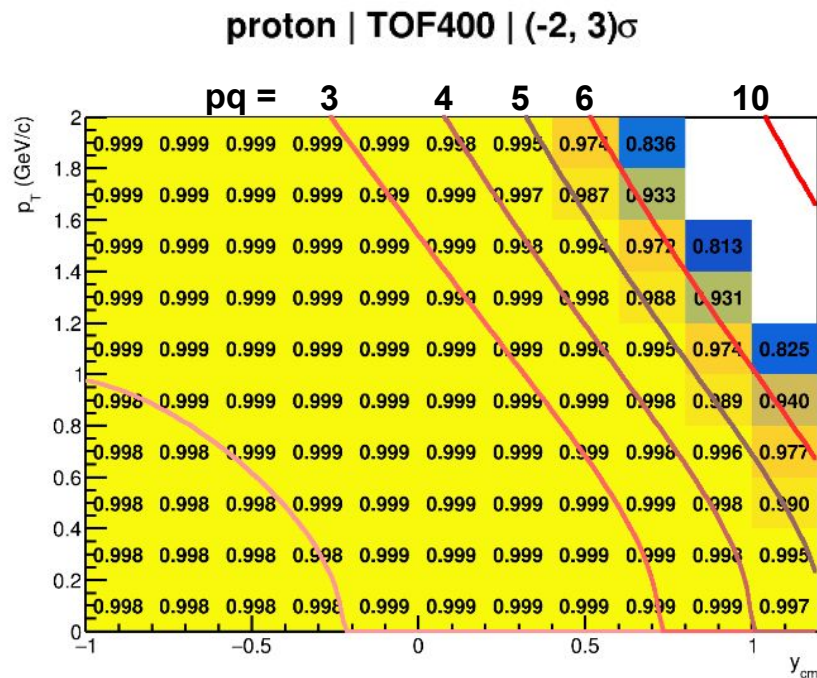
Expected contamination for protons is from deuterons at $p/q > 6$ GeV/c; for deuterons is from protons (especially in TOF700) and, to a lesser extent, from tritons.



Purity: result

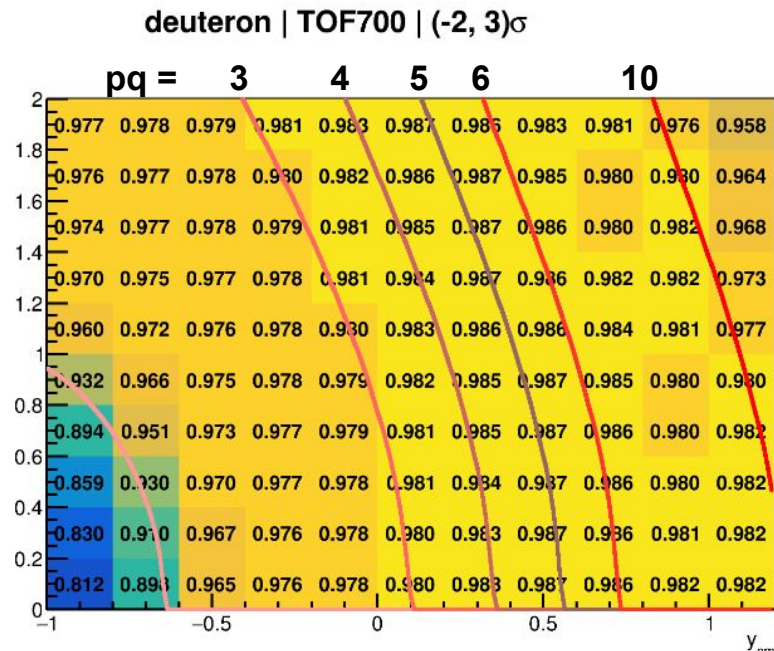
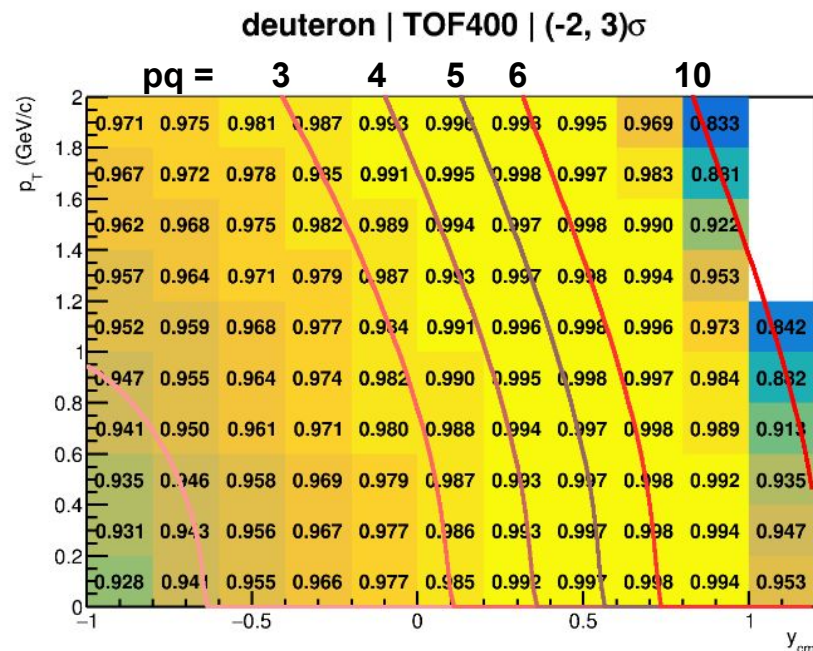


Purity in p_T -rapidity space



Purity of protons identified with TOF systems in $(-2, 3)\sigma$ range in p_T - y_{cm} space.

Purity in p_T -rapidity space



Purity of deuterons identified with TOF systems in $(-2,3)\sigma$ range in p_T - y_{cm} space.

Method: Specific Energy Losses

Tracking measures only p/q ratio: $\frac{p}{q} \propto BR$

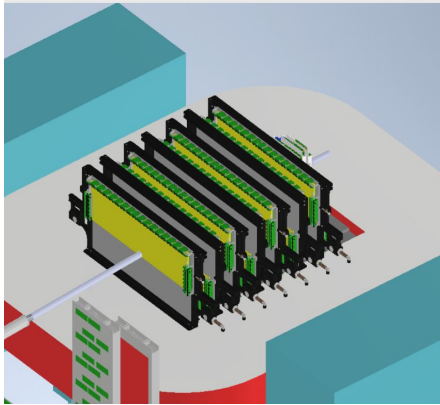
Particles with the same p/q ratio are inseparable with the TOF systems alone, for example, deuterons and helium-4 m^2 fall into one “band” when reconstructed with TOFs. dE/dx is proportional to q^2

$$\left(-\frac{dE}{dx}\right)_{cp} = \frac{2\pi \cdot e^4 z^2 Z n}{m v^2} \left(\ln \frac{2 m v^2 T_{max}}{I^2 (1 - \beta^2)} - 2\beta^2 - \delta - U \right)$$

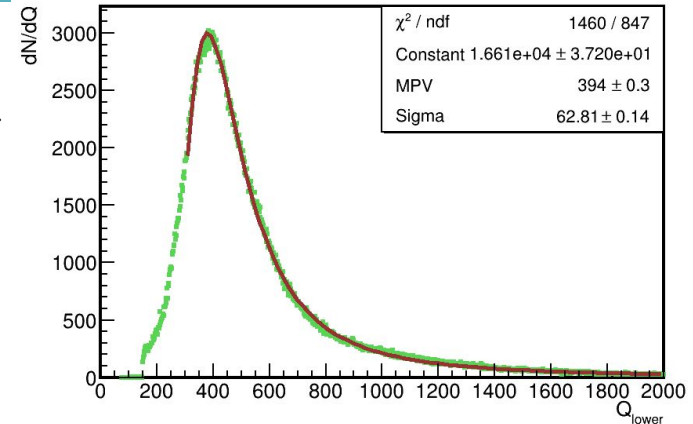
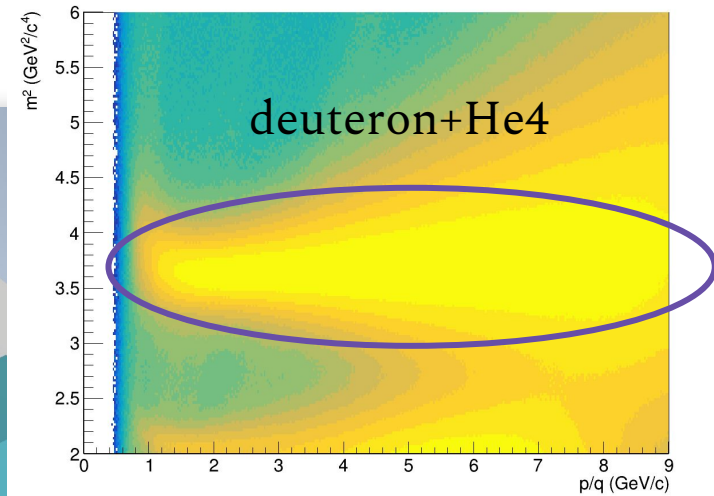
Signals in tracking system are **proportional** to dE/dx – hence, separation b/w particles with the same p/q is feasible.

The core idea: let’s sum up all the cluster charges Q_i collected in N STS stations after a particle had passed, calculate **truncated** mean and call it $\langle dQ/dN \rangle$ (a.u.) $\propto dE/dx$ – and we have it, we’re good to go.

But! Variations of detector performance (due to temperature, voltage) result in variations in signal Q distributions (dependence on runId and station number) – calibration is needed to equalize distributions.

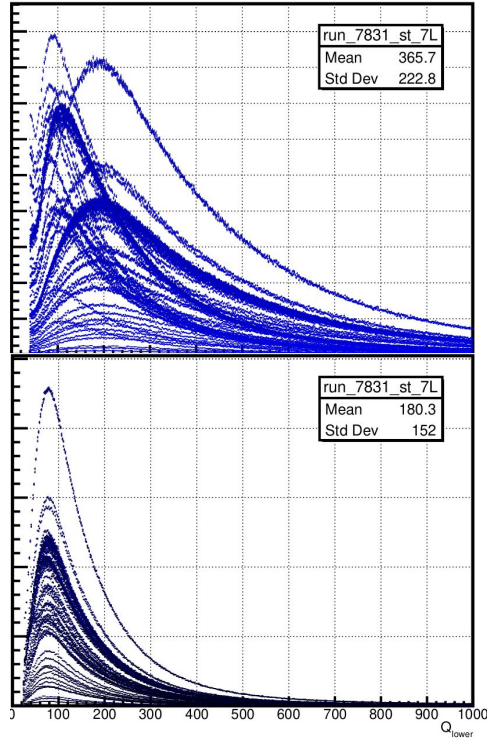


A tracks in tracking system is reconstructed from “hits” in STS stations, hits in turn are reconstructed as center of mass of **charge** clusters, formed after the particle’s trespassing. The **averaged charge sum** from all the clusters the track is reconstructed from is $\langle dQ/dN \rangle$

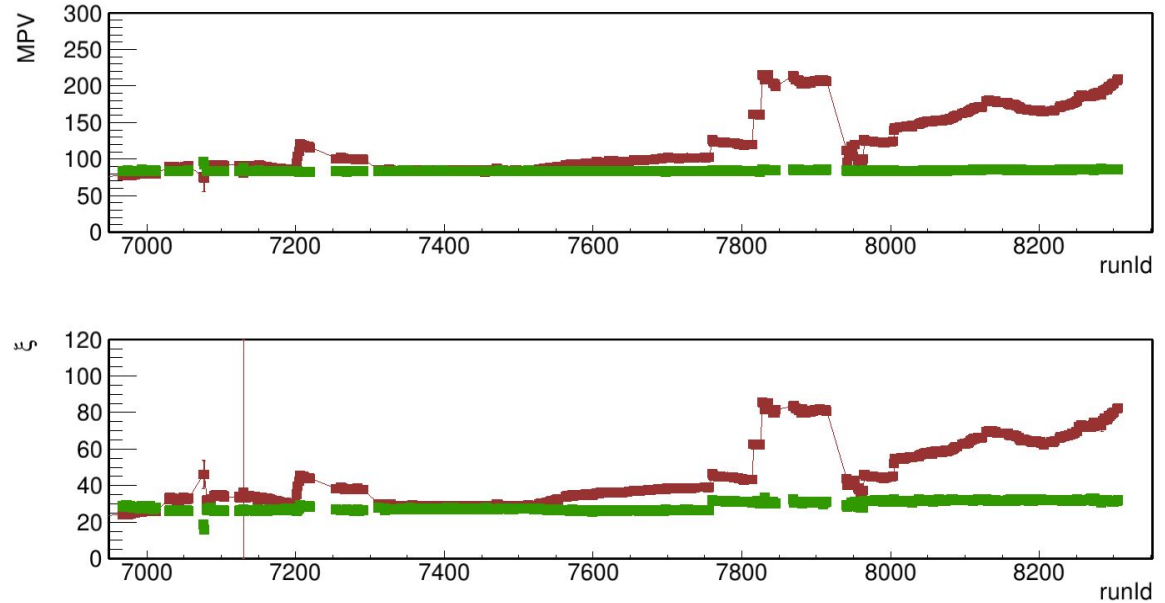


dN/dQ follows Landau distr. with heavy tail

Calibration for run number dependency

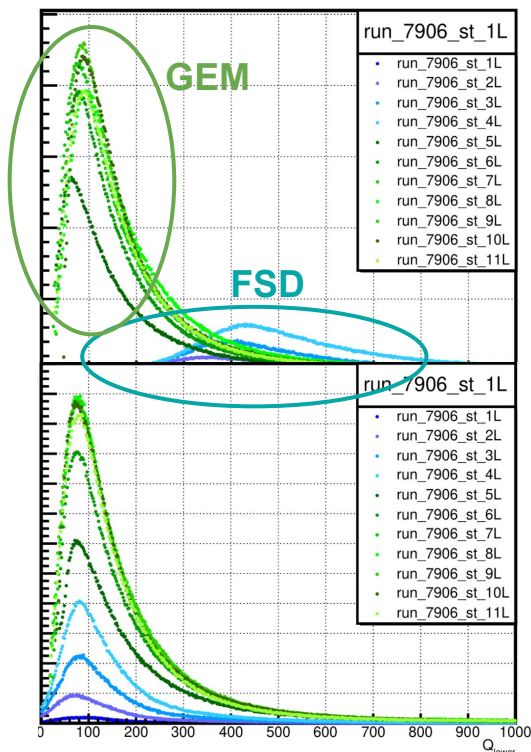


dN/dQ, uncalibrated (top) and calibrated (down) on run number dependency in a single station.

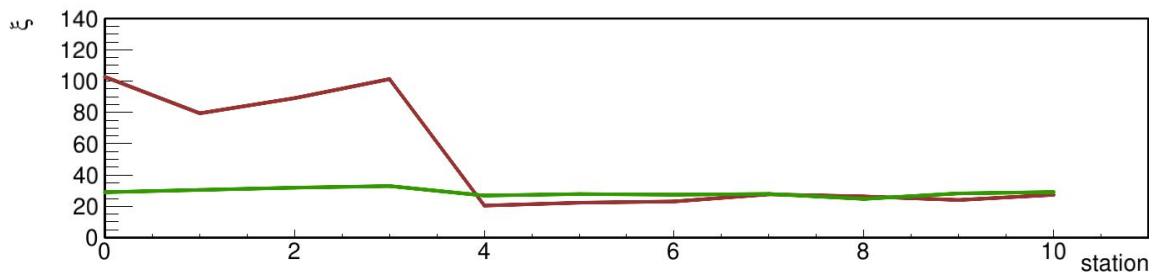
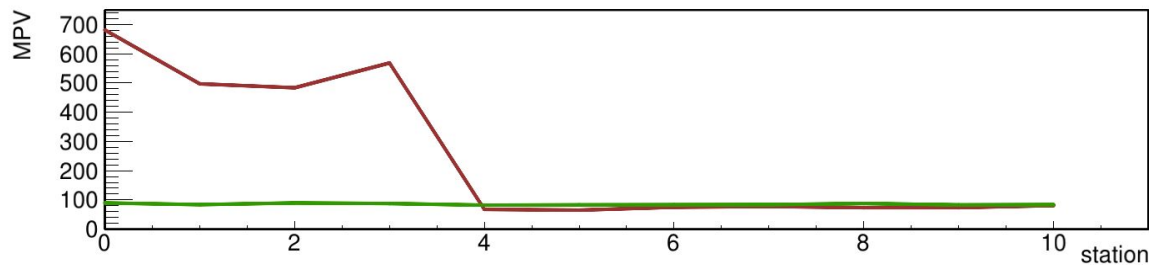


MPV and ksi (“width”) values of dN/dQ Landau fits for different runs of the tracking system before (red) and after (green) calibration
Cluster charge Q is from from protons, identified with the TOF system, in 2–4 GeV/c momentum range

Calibration for station number dependency

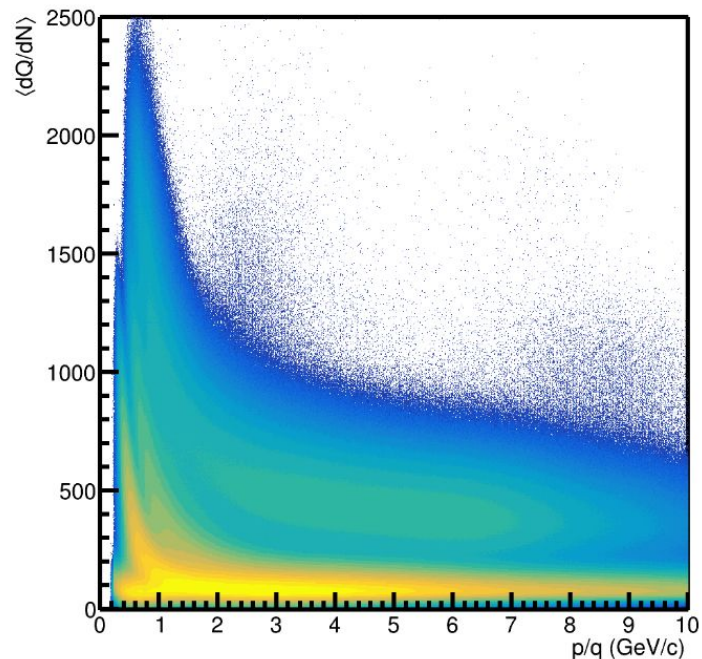


dN/dQ , uncalibrated (top) and calibrated (down)
on station number dependence in a single run.
Calibration on run number dep. is applied.

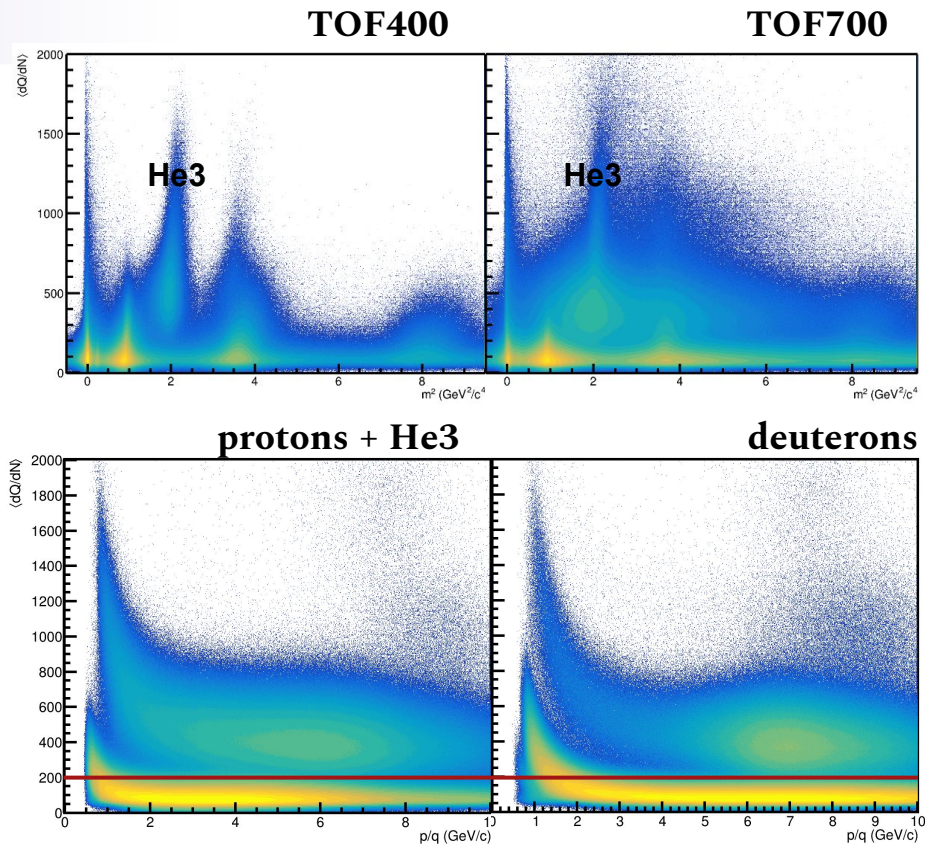


MPV and κ ("width") values of dN/dQ Landau fits for different stations
of the tracking system before (red) and after (green) calibration
Cluster charge Q is from from protons, identified with the TOF system, in
2–4 GeV/c momentum range

$\langle dQ/dN \rangle$ on real data

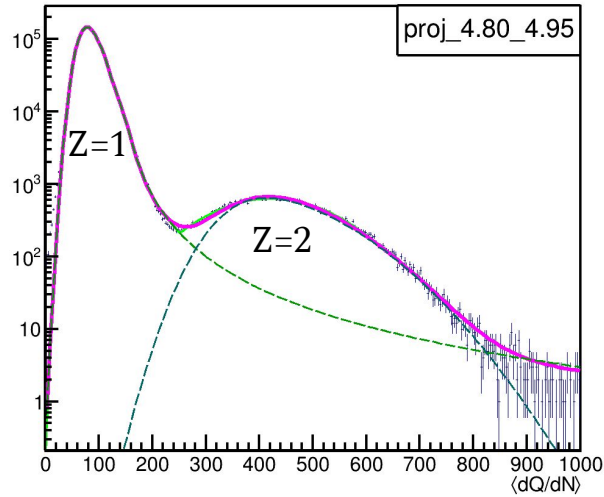


$\langle dQ/dN \rangle$ for all the tracks, before PID

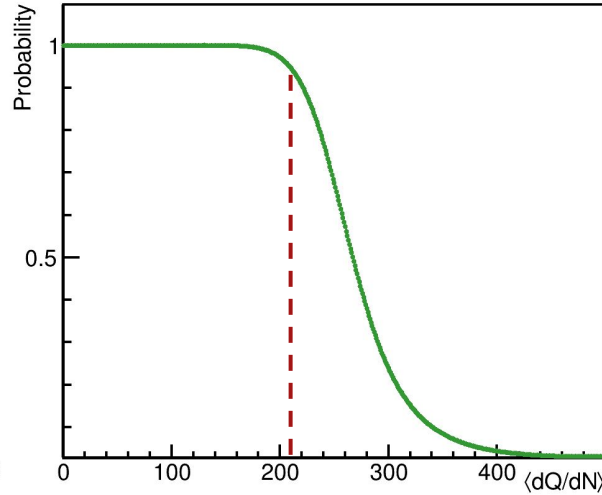


Proton OR Helium 3; deuterons
identified with TOFs, in $(-3,3)\sigma$ window.

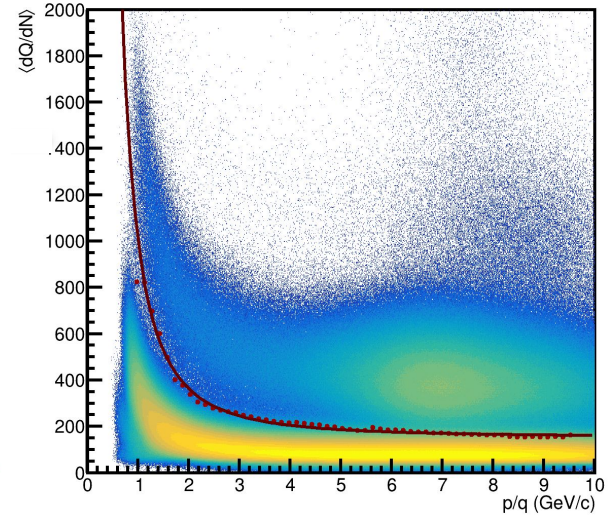
<dQ/dN> on real data



<dQ/dN> fitted
throughout all p/q range
in slices



0.95 probability for a
particle to be deuteron -
gives dQ/dN cut value



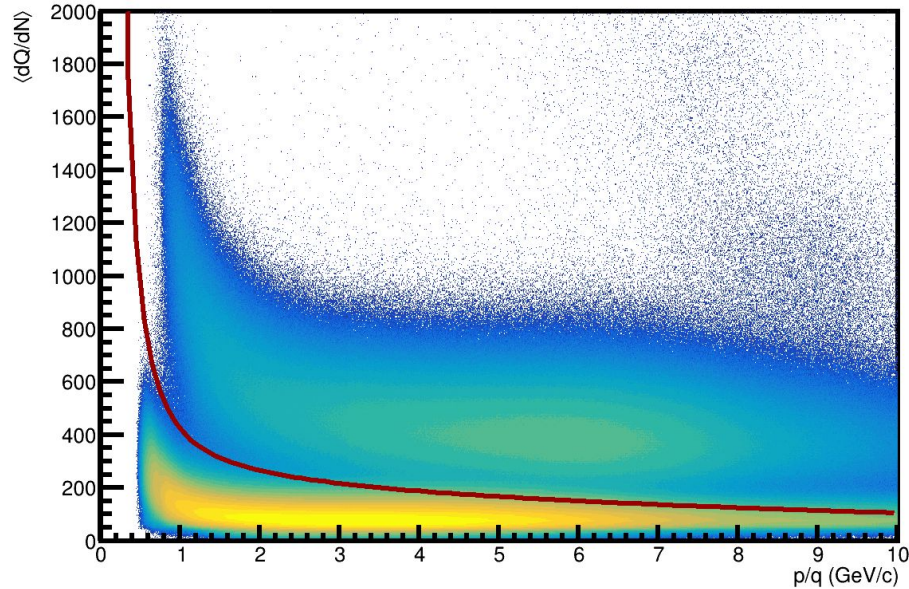
The graph is fitted with
Bethe-Bloch function in form

$$-\frac{dE}{dx} = \frac{A}{\beta^2} (-5.296 + \ln(\beta\gamma) + \ln(T_{max}) - 2\beta^2 - \delta)$$

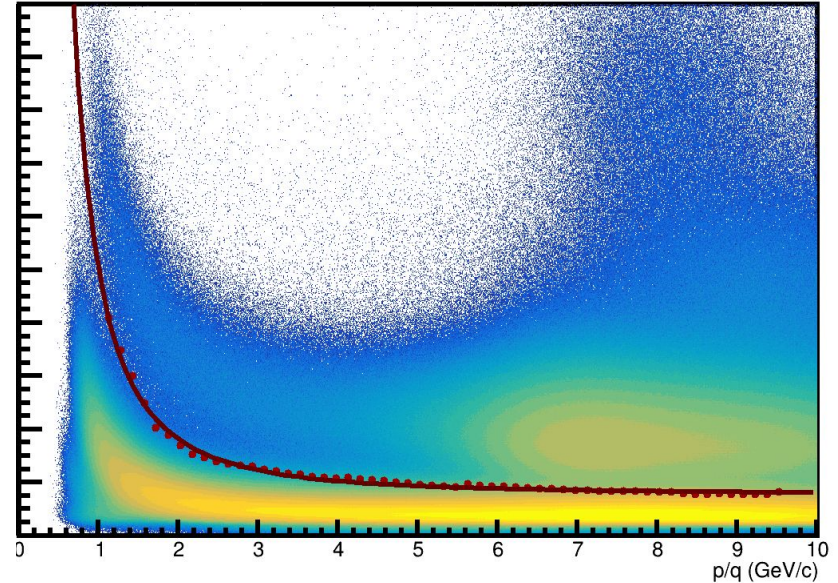
$$T_{max} = \frac{2m_e(m\gamma + m_e)^2}{m^2}$$

Bethe-Bloch functions for charge separation

protons + He3

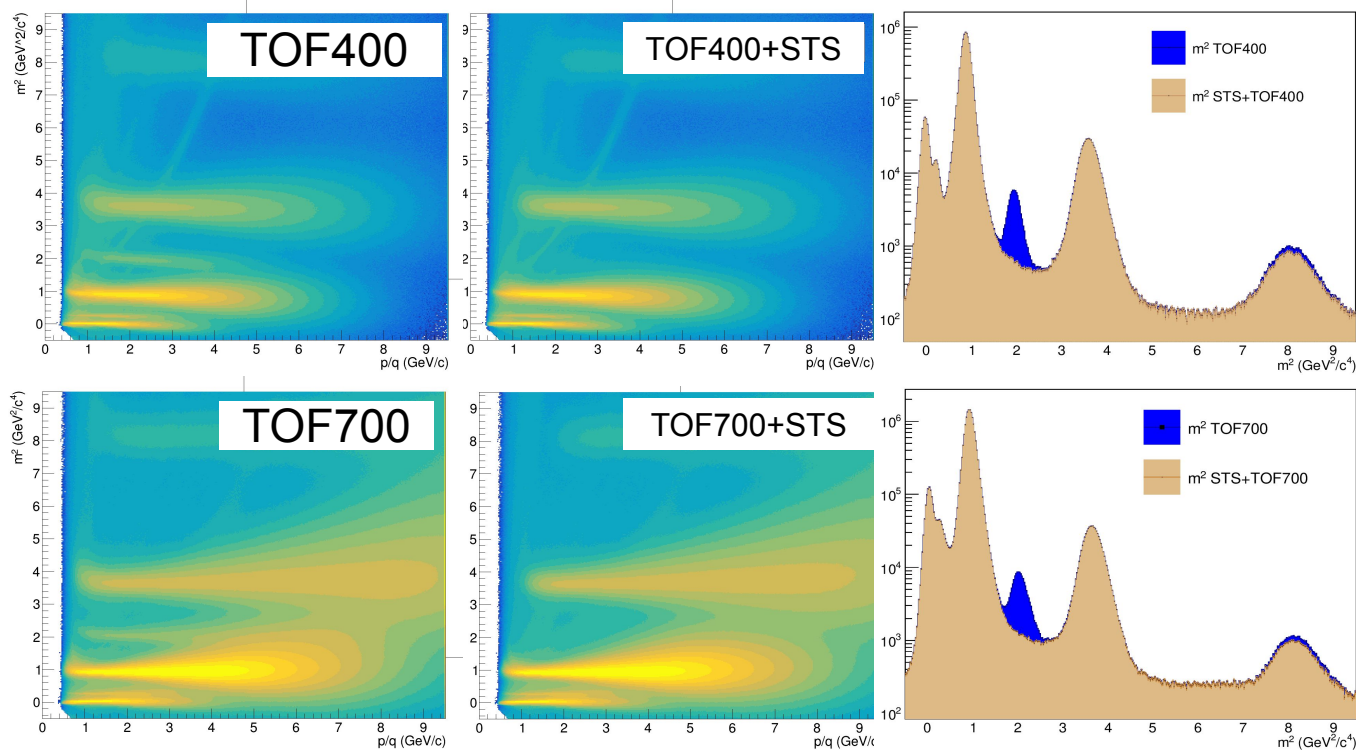


deuterons



The functions are further used as a graphical cut on charge when selecting protons or deuterons.
For other particles the hard cut value of 200 a.u. of $\langle dQ/dN \rangle$ is used.

Applying $\langle dQ/dN \rangle$ to real data

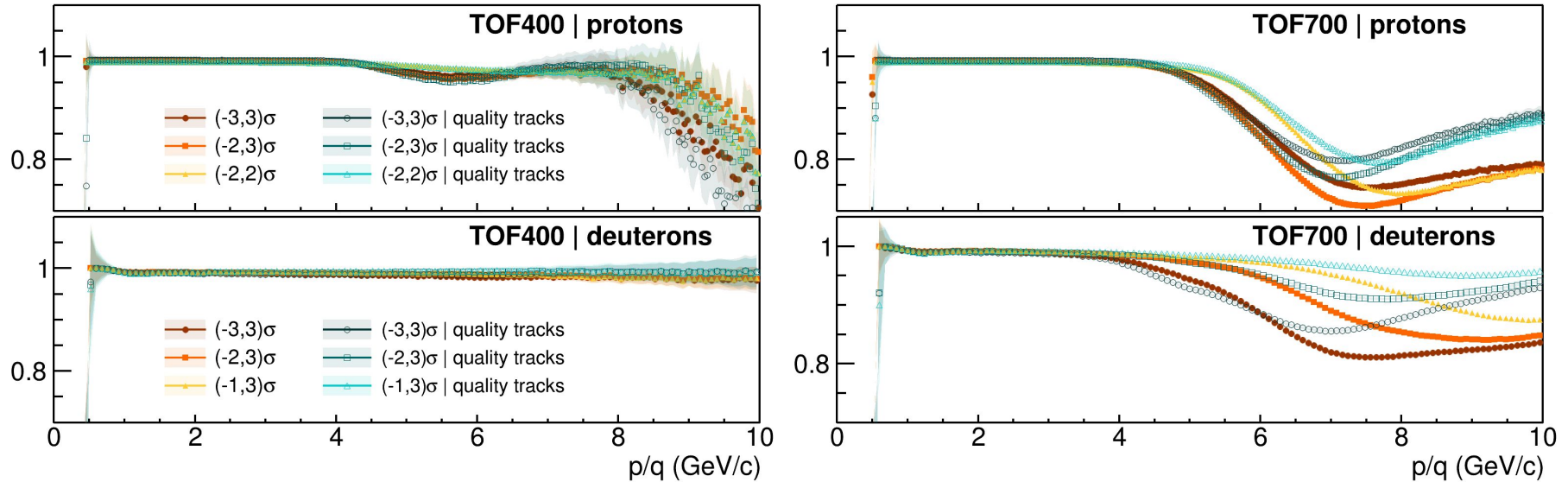


m^2 vs p/q in TOF400 and TOF700 before and after applying $\langle dQ/dN \rangle$ selection criteria.
Clearly seen how He3 is removed.

Deuteron peak is not quantitatively affected, as seen from the integral in p/q plots.

$\langle dQ/dN \rangle$ cut effect estimation

Ratio of particles identified with TOF+STS system, to the particles identified with the TOF system only, as a function of p/q . Additionally shown as cyan markers are the ratios for the case of strict requirements on track quality (e.g. nHits in STS, χ^2/N_{df} , DCA).



Great m^2 separation in TOF400 results in dE/dx having almost no effect.

In TOF700 dE/dx rejects up to 20-25% of selected hadrons.

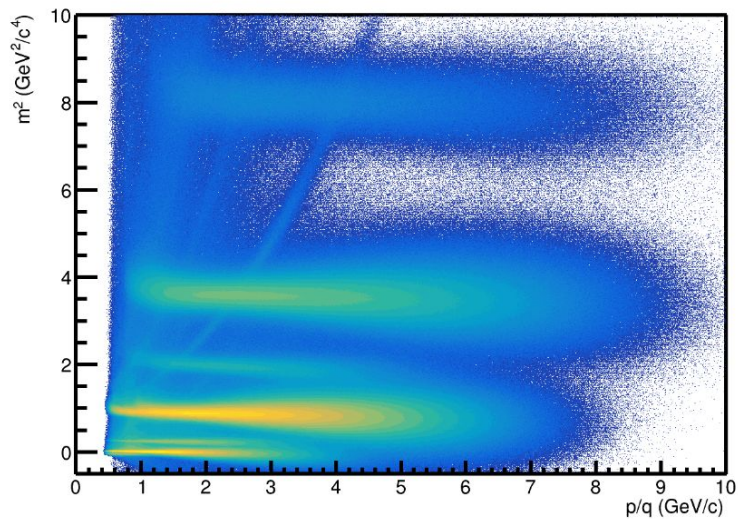
Selecting tracks carefully cleans the data sample reducing the part being rejected to 5–20%.

Summary

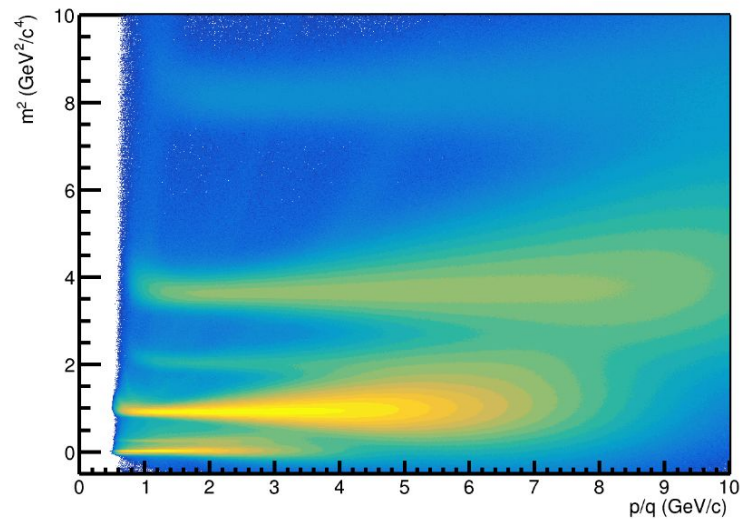
- Two PID method, TOF and dE/dx , are demonstrated on data from at the BM@N experiment.
- Identification of protons and deuteron with TOF systems allows to achieve 95% purity by narrowing $n\sigma$ range.
- Complementing to TOF method, dE/dx method allows isolation of double charged particle. Most of these are He3, removing which should improve separation of deuterons and protons.
- The ratio of particle rejected as “double-charged” depends strongly on track selection criteria and can vary from 5 to 25%. Besides, Bethe-Block cutting function is a subject for variation and investigation itself.

m2-pq acceptance

TOF400

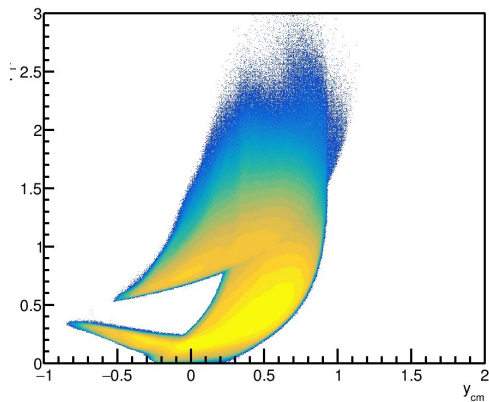


TOF700

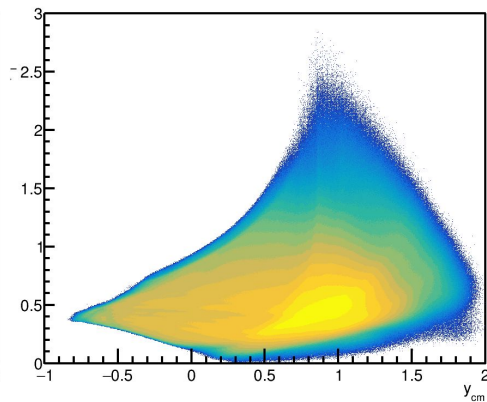


p_T - y_{cm} acceptance

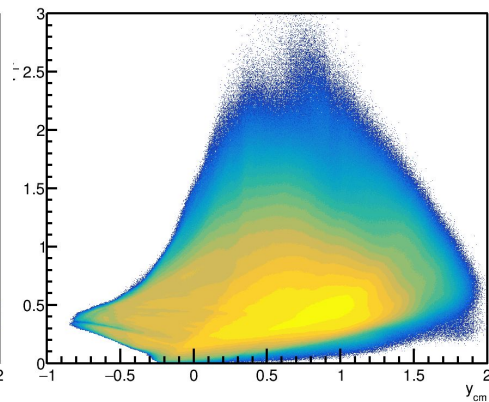
TOF400 | protons



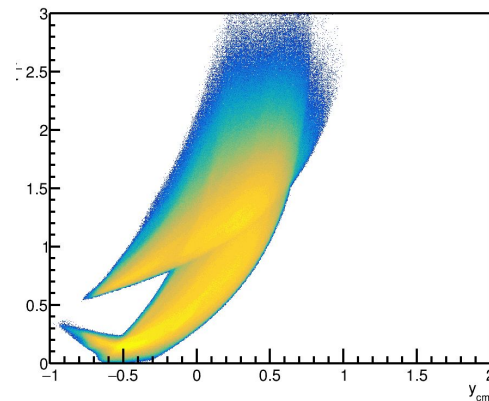
TOF700 | protons



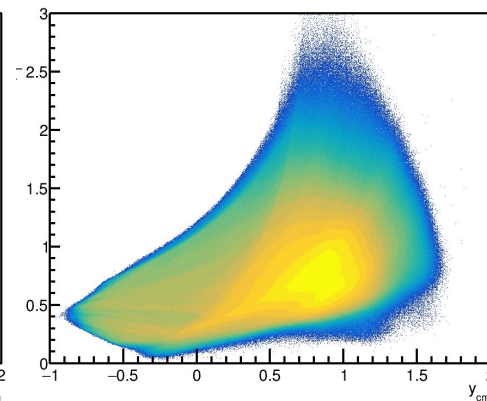
combined | protons



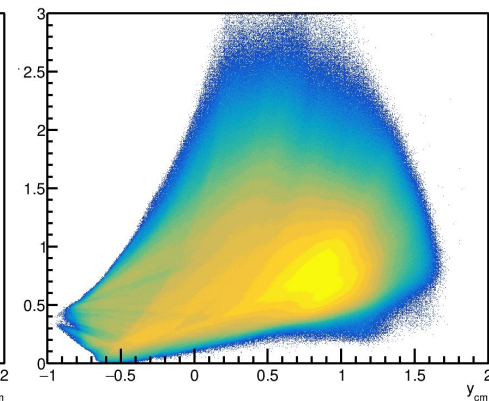
TOF400 | deuterons



TOF700 | deuterons

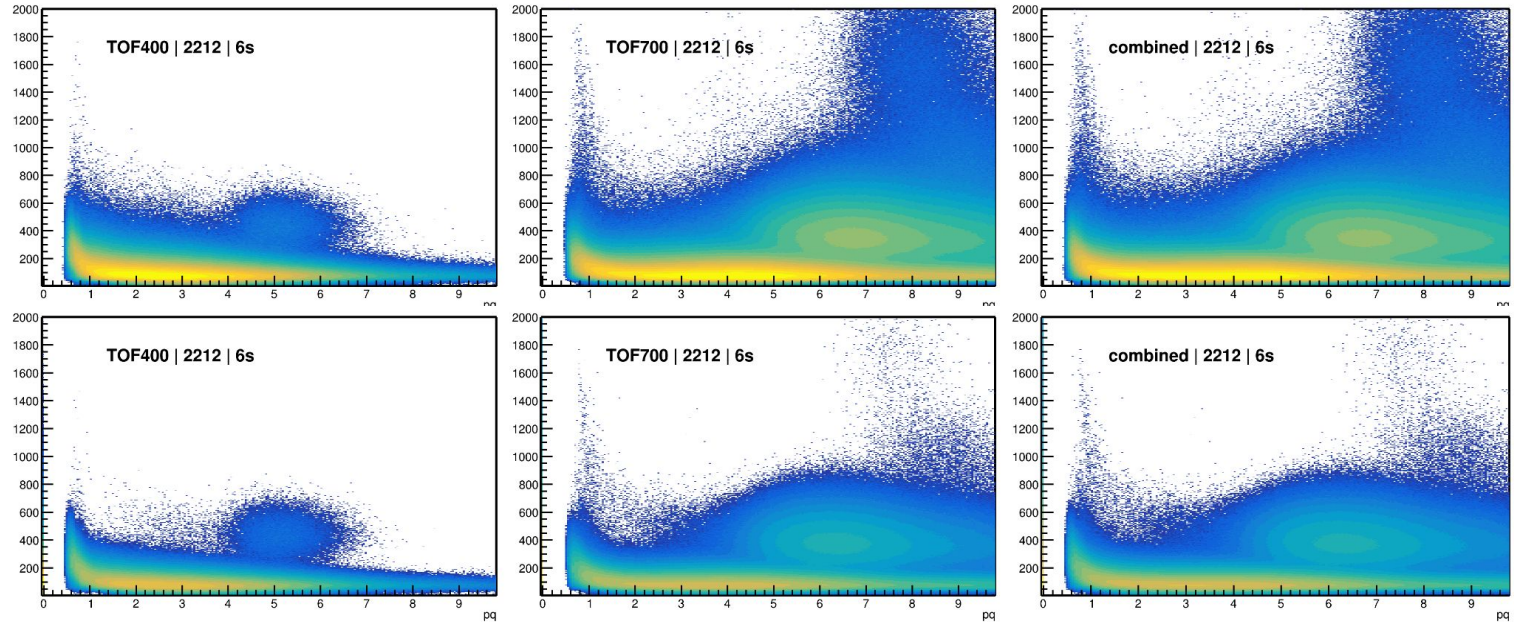


combined | deuterons



$\langle dQ/dN \rangle$ for protons in TOF400 and TOF700

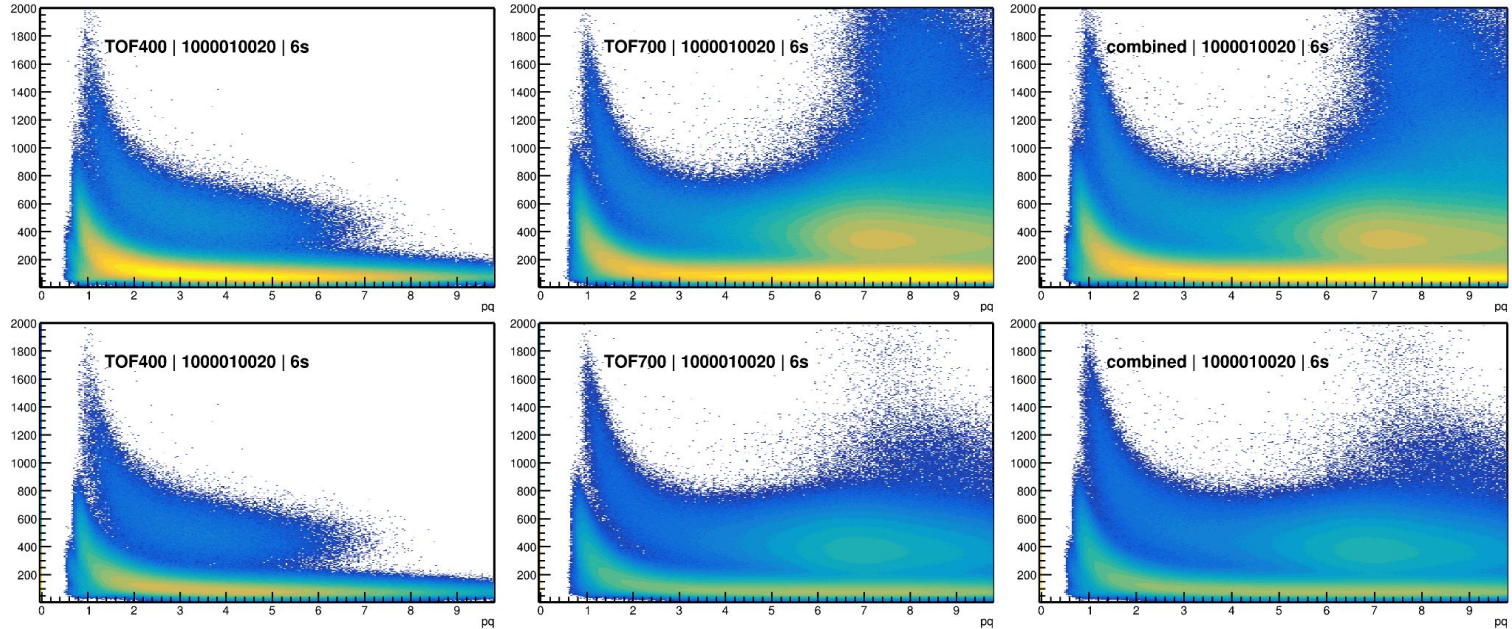
For all the tracks



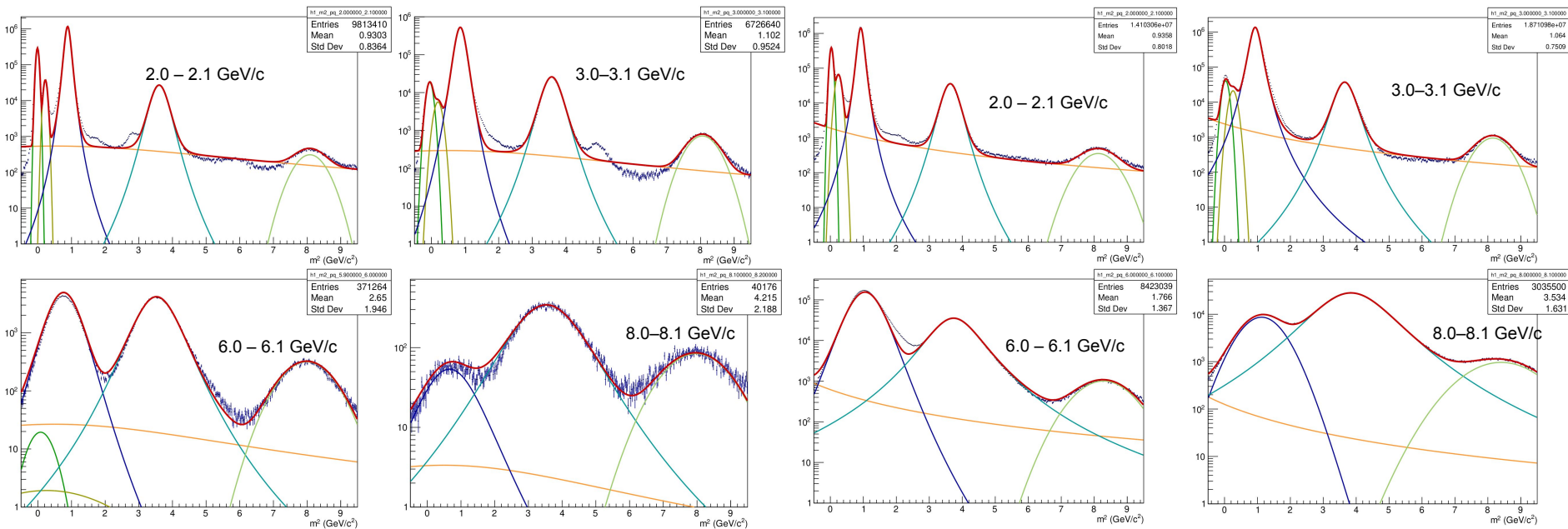
For tracks passed the quality track selection criteria

$\langle dQ/dN \rangle$ for deuterons in TOF400 and TOF700

For all the tracks

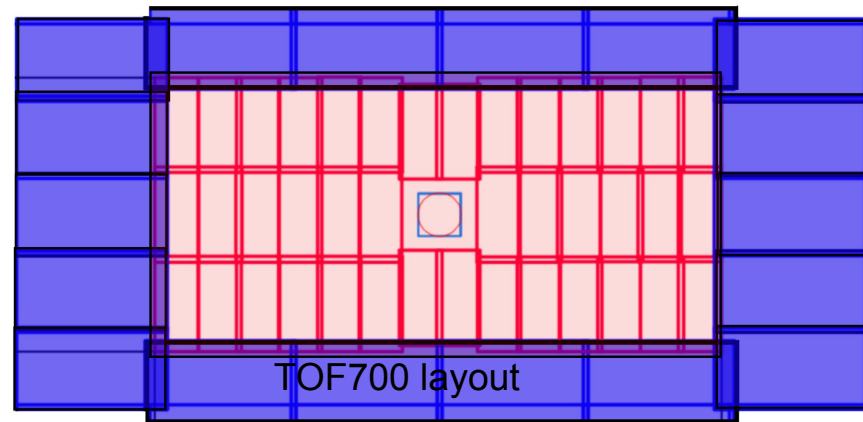
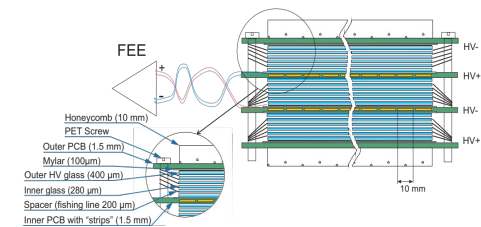
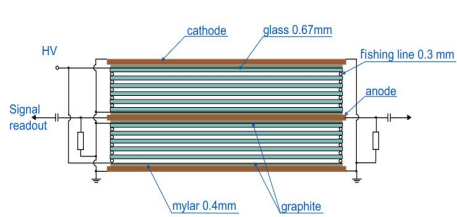


For tracks passed the quality track selection criteria

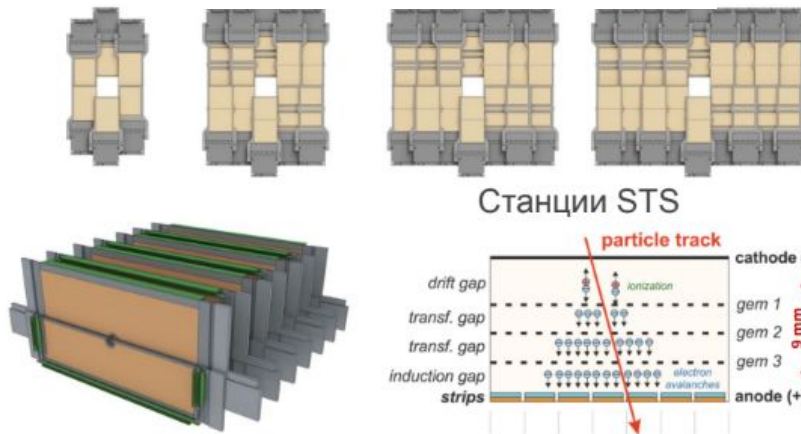


Fitting of the m_2 distributions in pq slices (TOF400)

Fitting of the m_2 distributions in pq slices (TOF700)



FSD stations



GEM stations

