Final report - Glueball analysis

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Physics Background

- We look at **central exclusive events** in proton-proton collisions: The protons remain intact and can be measured beyond the interaction point

$$p + p \rightarrow p + p + X$$

- X can be many things which are measured in the CMS tracker whereas protons can be detected in the roman pots
- With this analysis we want to determine if X could be the glueball (=bound state of gluons)
- One glueball candidate is expected to have an invariant mass of 2220 MeV

Experimental Setup

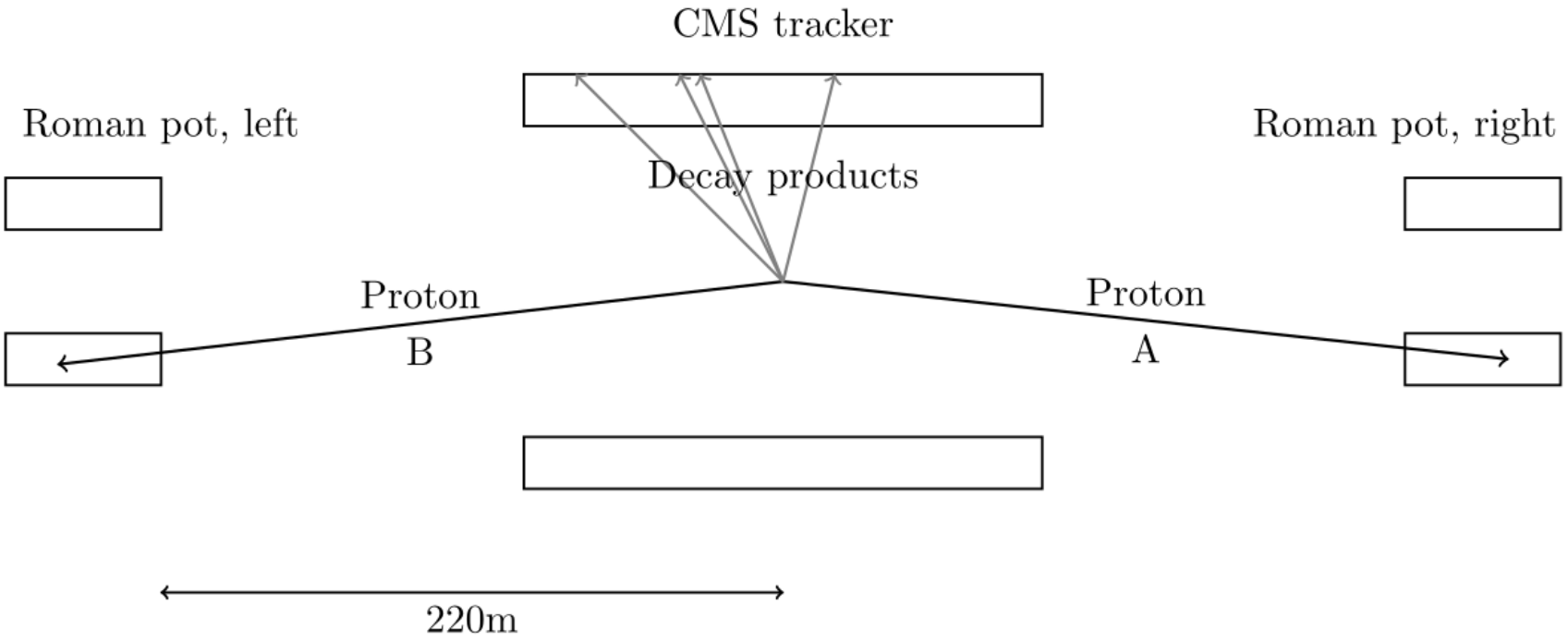


Image taken from previous summer students Younes Elberkennou and Petteri Tuomola

- Diagonal and parallel (shown in picture) configuration

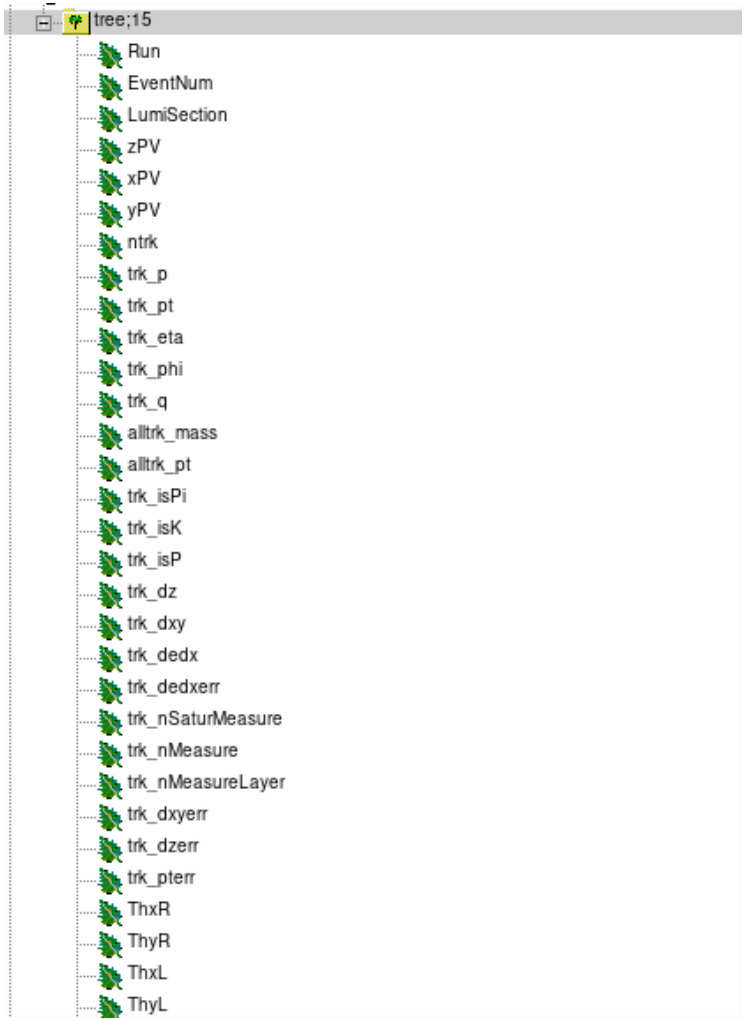
Which data set was used?

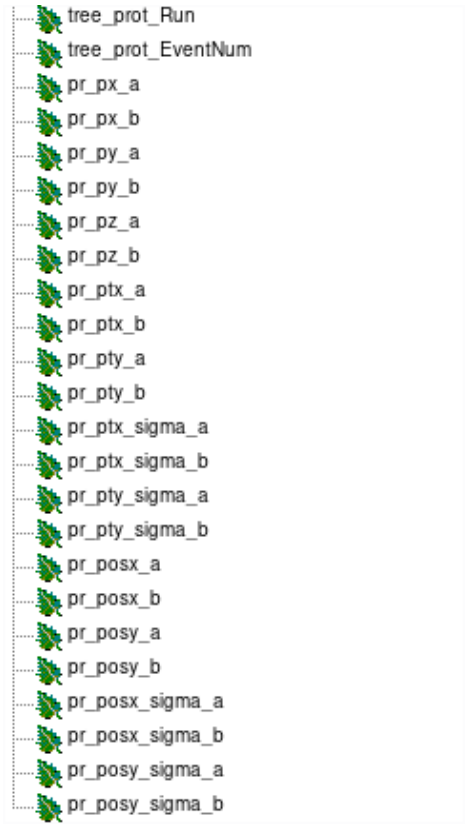
- Original data from: /eos/cms/store/group/phys_diffraction/CMSTotemLowPU2018/YounesNtuples
- Combined all diagonal and parallel data:

$$\text{TOTEM2.root} = \text{TOTEM20.root} + \text{TOTEM21.root} + \text{TOTEM22.root} + \text{TOTEM23.root}$$

$$\text{TOTEM4.root} = \text{TOTEM40.root} + \text{TOTEM41.root} + \text{TOTEM42.root} + \text{TOTEM43.root}$$

Tree structure





Invariant mass analysis

- Cannot use particle identification (unreliable)
- Found no looping tracks
- Focus on 4-track system and demand net charge is zero
- Assume:

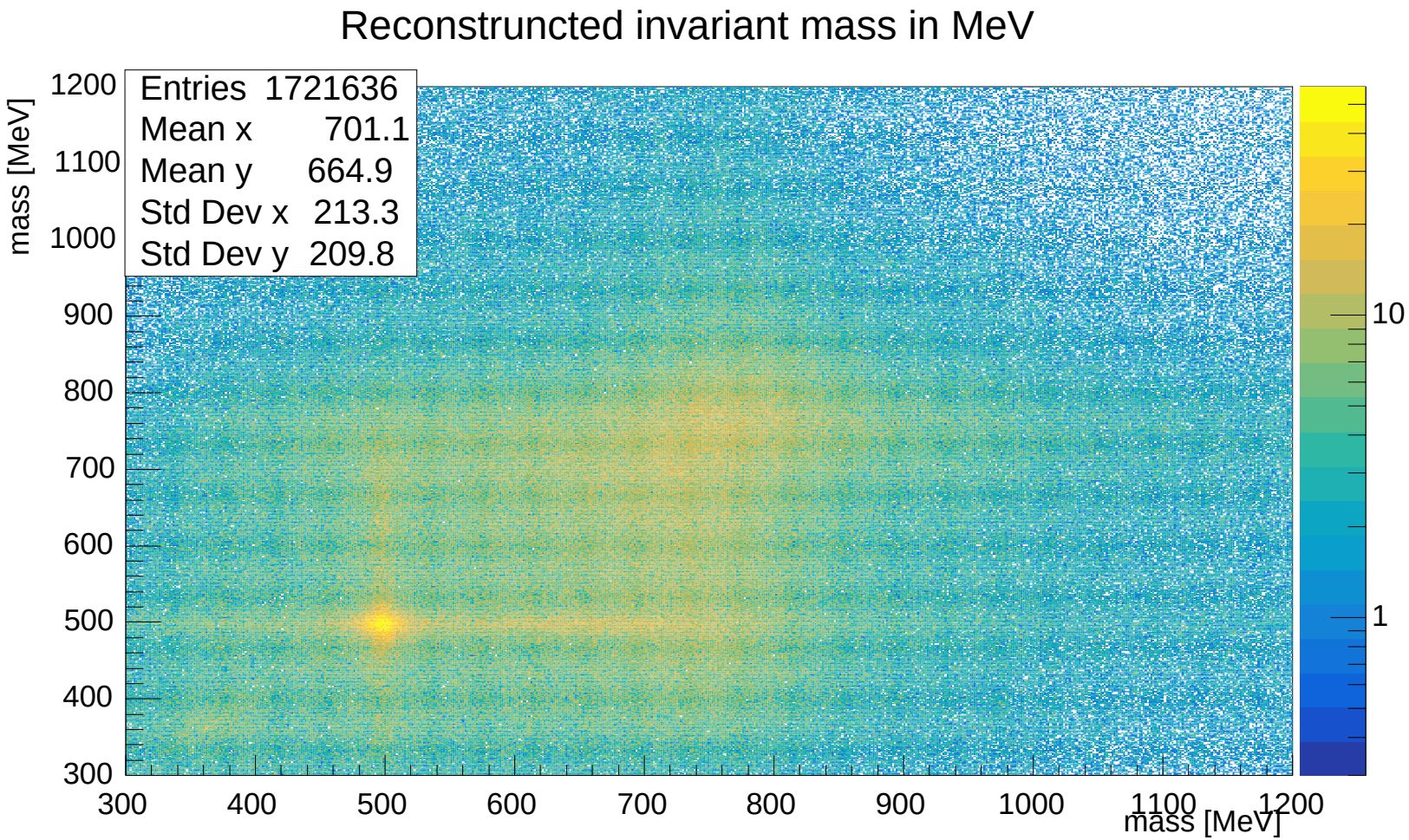
$$X \to \rho\rho \to \pi_1^+\pi_1^-\pi_2^+\pi_2^-$$

- Two ways to form first pion pair:

$$P_1 = \left\{(\pi_1^+, \pi_1^-), (\pi_2^+, \pi_2^-)\right\} \text{ and } P_2 = \left\{(\pi_1^+, \pi_2^-), (\pi_2^+, \pi_1^-)\right\}$$

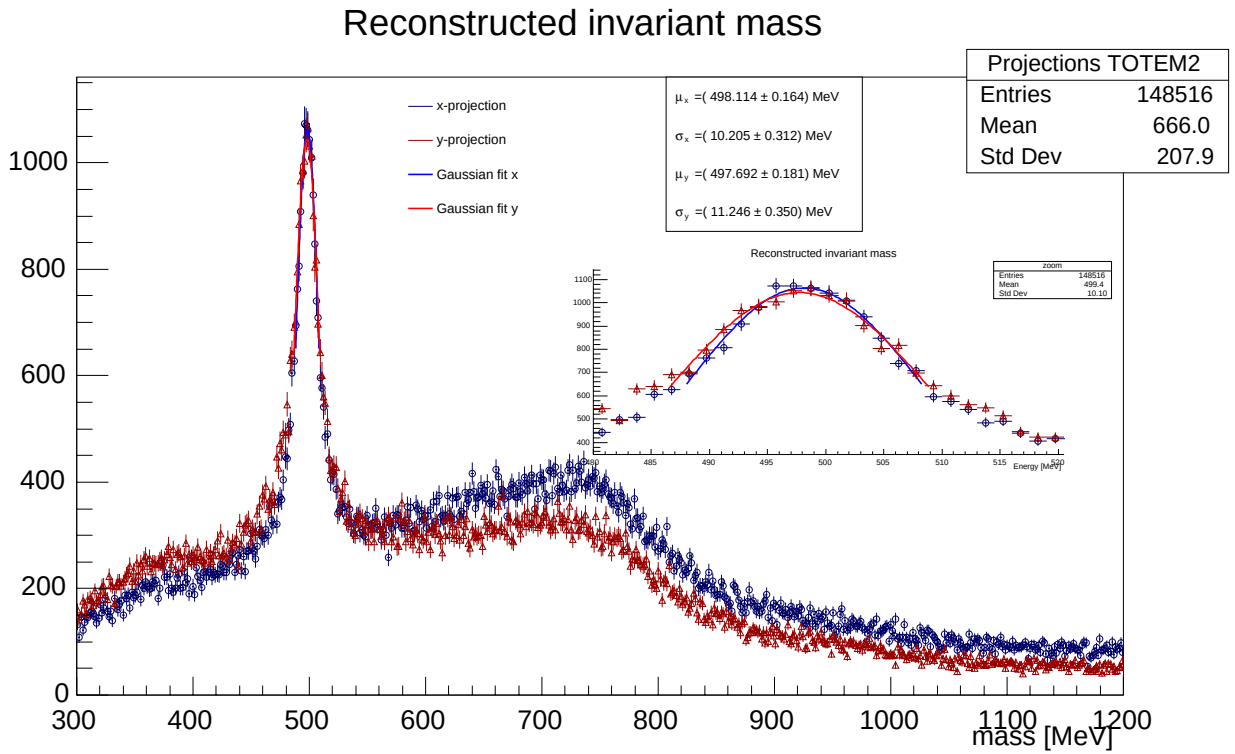
- Add branches *inv_mass_pair1* and *inv_mass_pair2* $\Rightarrow$ Plot invariant mass of both pairs in 2D histogram

2D invariant mass from TOTEM2



Need to remove wrong pairs and Kaon background

Kaon invariant mass analysis TOTEM2



- Used $\pm 3\sigma$ for summation in projection and $\pm 1\sigma$ for fitrange
- PDG value: $m_{K_0} = 497.677(13)\,\text{MeV}$

$$\mu_{\text{avg}} = 497.903(173)\,\text{MeV}$$
$$\sigma_{\text{avg}} = 10.725(331)\,\text{MeV}$$

Conclusion

Background events at $\approx 500\,\text{MeV}$ are indeed Kaons

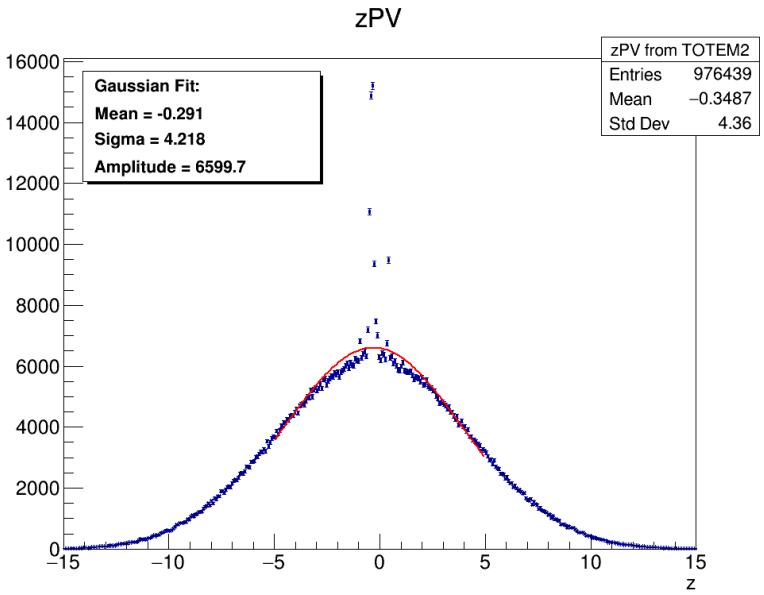
Introduction χ^2-like variable

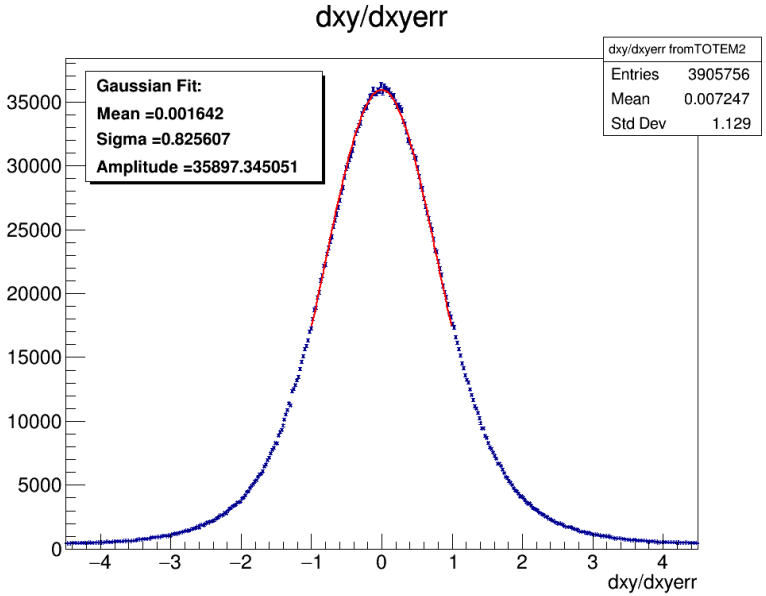
- Define new variable

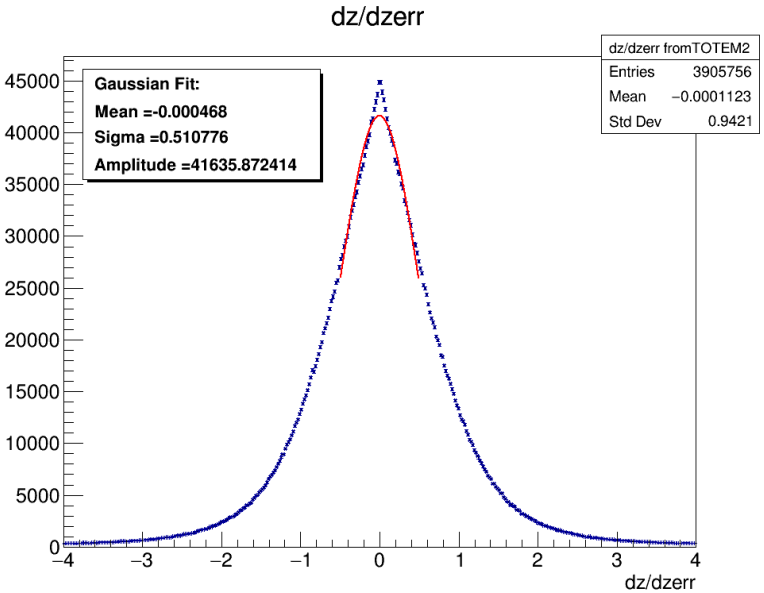
$$\chi^2_x := \sum_{i=1}^{ntrk=4} \frac{(\mu_x - x_i)^2}{\sigma_x^2}, \text{ for } x \in \{\text{zPV}, \text{dxy/dxyerr}, \text{dz/dzerr}\}$$

- $\mu_x, \sigma_{\text{zPV}}$ are constants coming from gaussian fit of x over entire data set
- $\sigma_{\text{dxy/dxyerr}} = \sigma_{\text{dz/dzerr}} = 1$ (dxy/dxyerr and dz/dzerr already dimensionless)
- 4-track system originating from $X \to \overline{K_s} K_s \to \pi^+\pi^-\pi^+\pi^-$ should have higher χ^2_x values
- Compared to previous works we look at average deviation from mean over 4-track system, instead of demanding four good tracks

Gaussian fits for χ^2-like variable definition from TOTEM2

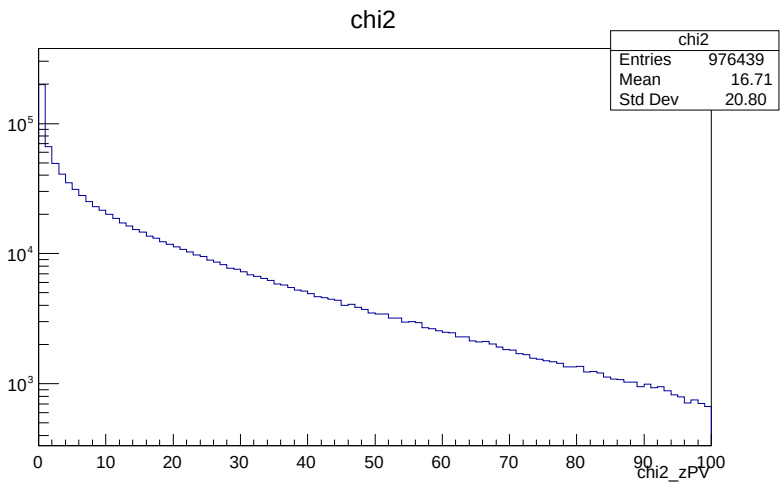




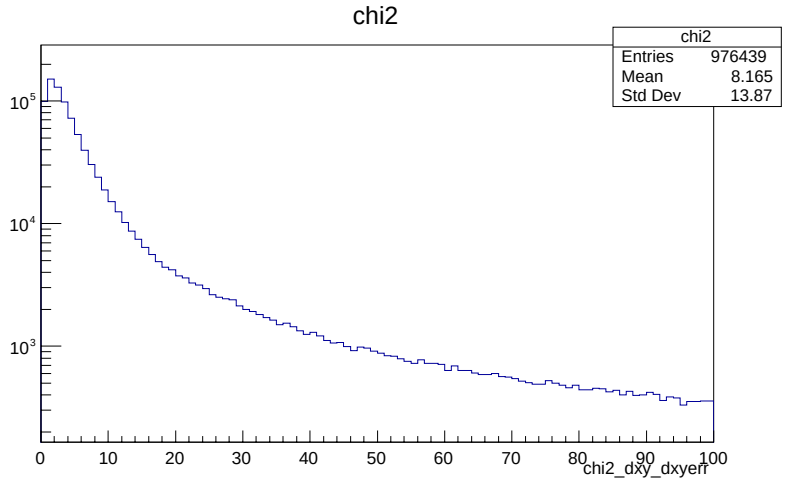


$\Rightarrow$ define χ^2_{zPV}, $\chi^2_{\text{dxy/dxyerr}}$, $\chi^2_{\text{dz/dzerr}}$ branches and add them to tree

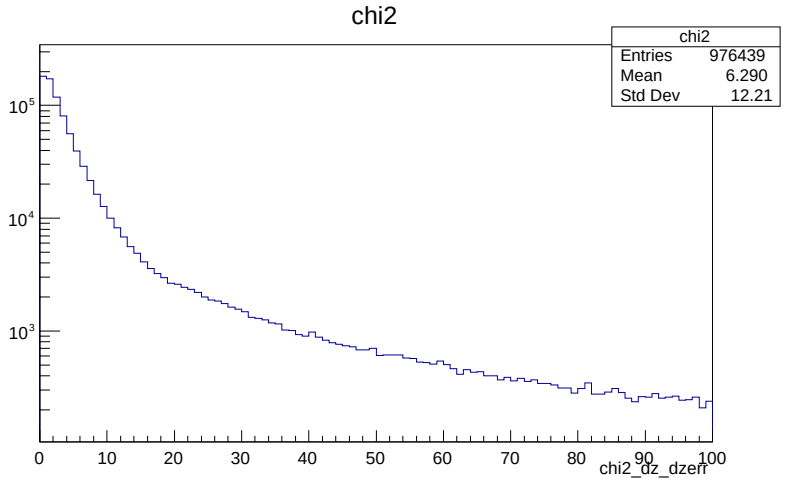
χ^2-like variables from TOTEM2



zPV



dxy/dxyerr



dz/dzerr

Effect of χ^2 cuts

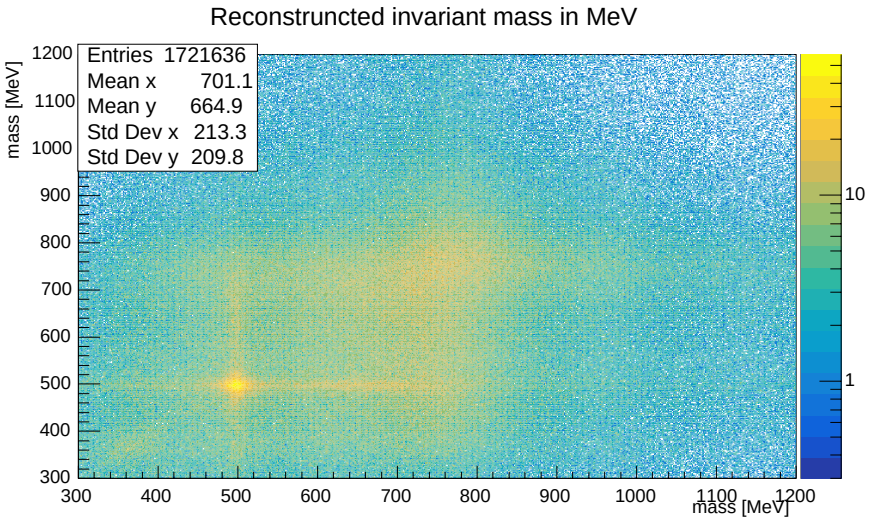


Figure: TOTEM2 before χ^2 cut

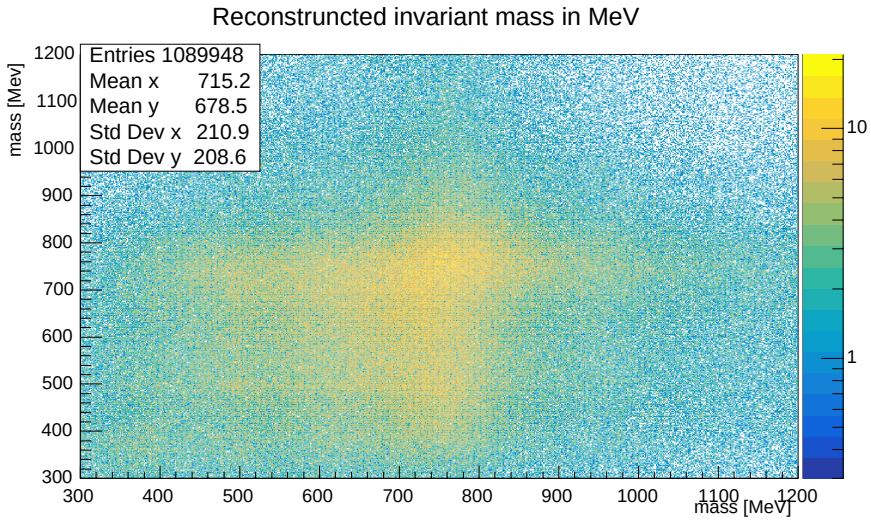


Figure: TOTEM2 after χ^2 cut

- Cuts at $\chi^2_{\text{zPV}} < 30$ and $\chi^2_{\text{dxy/dxyerr}} < 30$ and $\chi^2_{\text{dz/dzerr}} < 30$

Conclusion

Cuts are effectively removing Kaon events as desired

ρ mass fits on χ^2-cutted data

- We project onto x and y axis in the range 600 MeV to 900 MeV
- Formula for fit

$$f(x) = f_{\text{bg}}(x) + f_{\text{sg}}(x) = A(x - B)^C \mathrm{e}^{Dx} + N \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

ρ invariant mass analysis TOTEM2

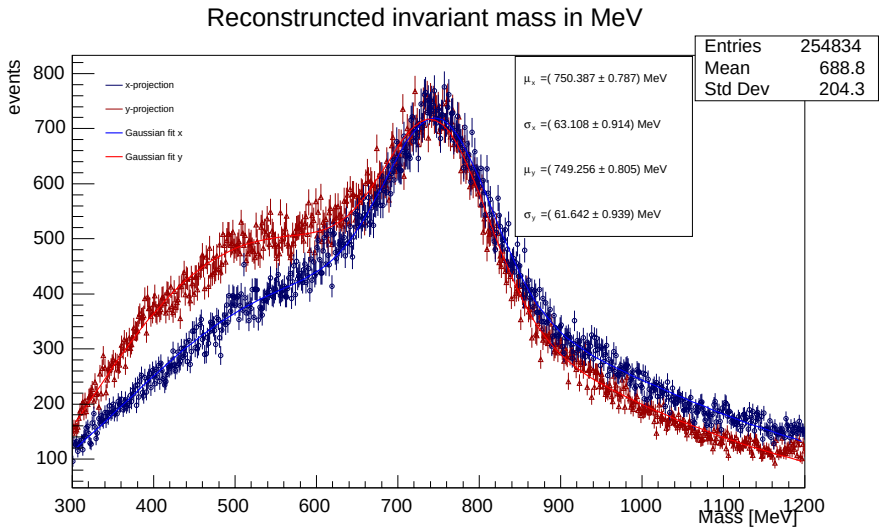


Figure: Cuts $\chi^2 < 10$ for all three

- $\langle \mu_2 \rangle_{\chi^2<10} = 749.823(796)\,\text{MeV}$
- $\langle \sigma_2 \rangle_{\chi^2<10} = 62.375(927)\,\text{MeV}$

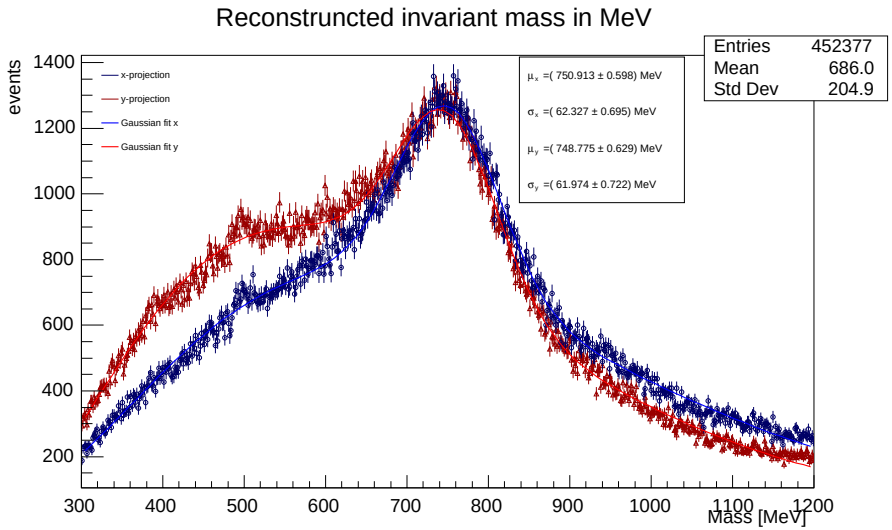


Figure: Cuts $\chi^2 < 30$ for all three

- $\langle \mu_2 \rangle_{\chi^2<30} = 749.844(614)\,\text{MeV}$
- $\langle \sigma_2 \rangle_{\chi^2<30} = 62.151(709)\,\text{MeV}$

Conclusion

No big differences, but smaller fit uncertainty for less restrictive cuts.

Comparison to PDG

Source	K_S^0 **mass [MeV]**	ρ **mass [MeV]**	ρ **width [MeV]**
TOTEM2	497.903(173)	749.844(614)	146.366(1670)
TOTEM4	497.865(164)	748.330(548)	150.008(1505)
PDG	497.611(13)	766.5(11)	150.2(24)

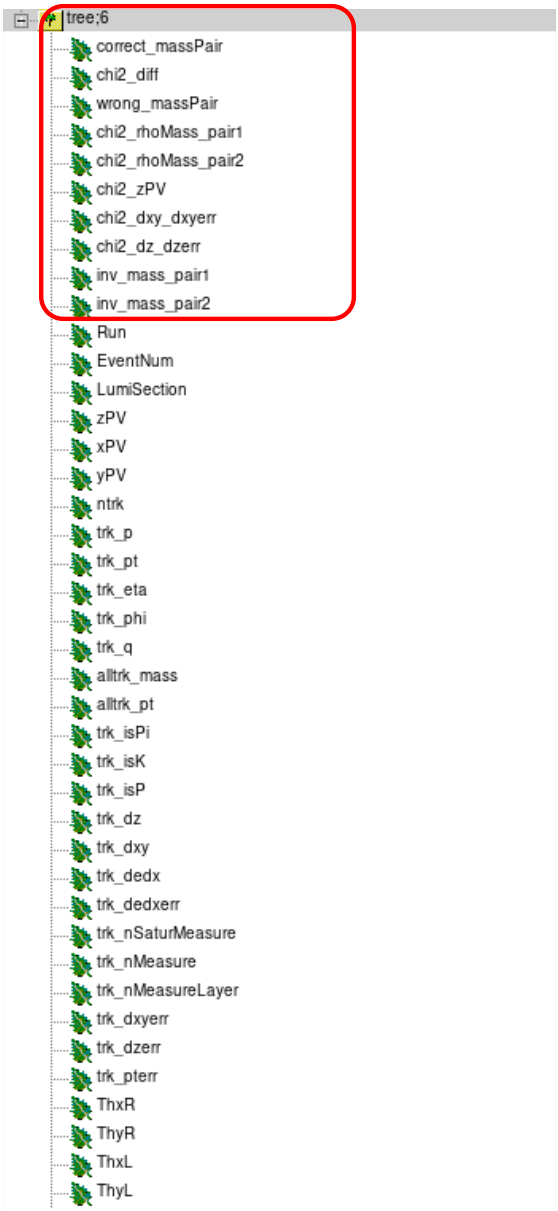
Conclusion

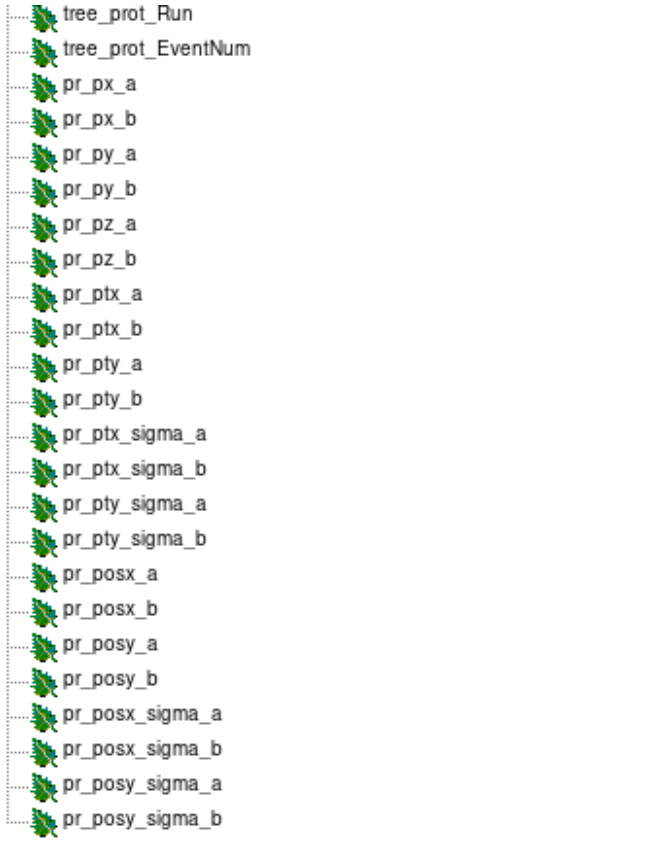
Kaon fits agree very well with PDG. Rho fits underestimate mass but give correct width.

Define χ^2-like variable for invariant mass

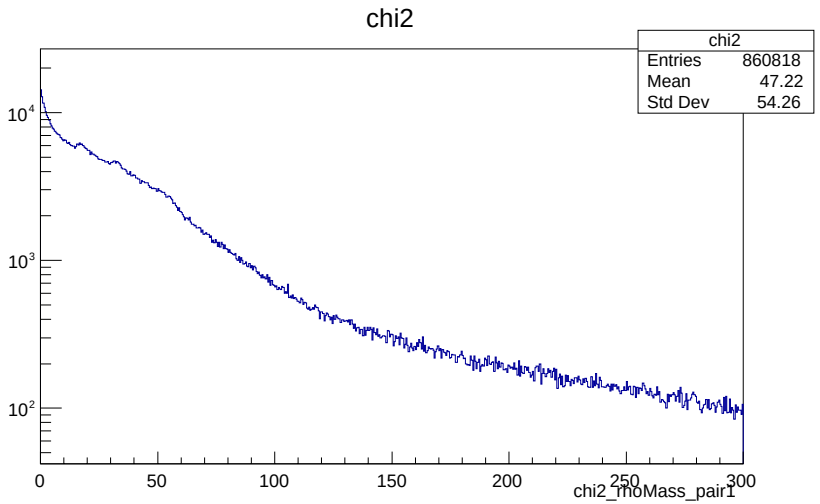
- Define
$$\chi^2_{m_\rho} := \frac{(m_\rho - m_1)^2}{\sigma_\rho^2} + \frac{(m_\rho - m_2)^2}{\sigma_\rho^2}$$
- Take m_ρ and σ_ρ from previous fit
- We get two $\chi^2_{m_\rho}$, one for each pair
- Add two χ^2 branches to tree
- Mass pairing with lower χ^2 is the "correct" one.
- Add branches for correct and wrong mass pairs and for difference of χ^2s of different pairings

New Tree structure

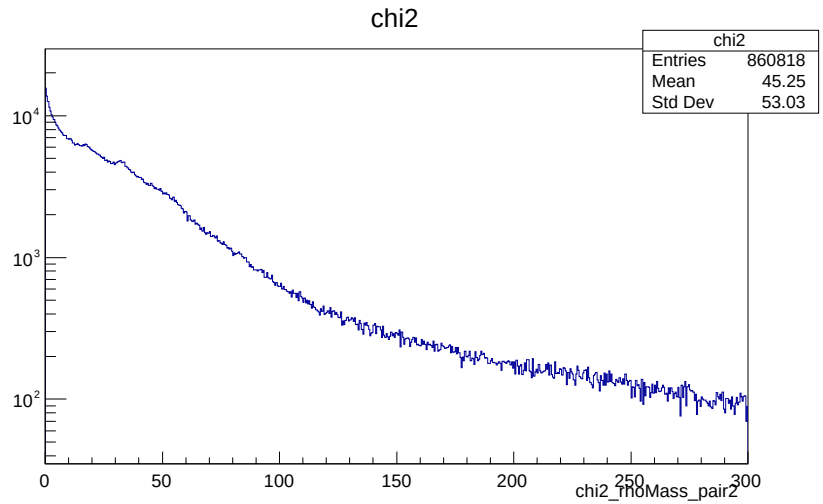




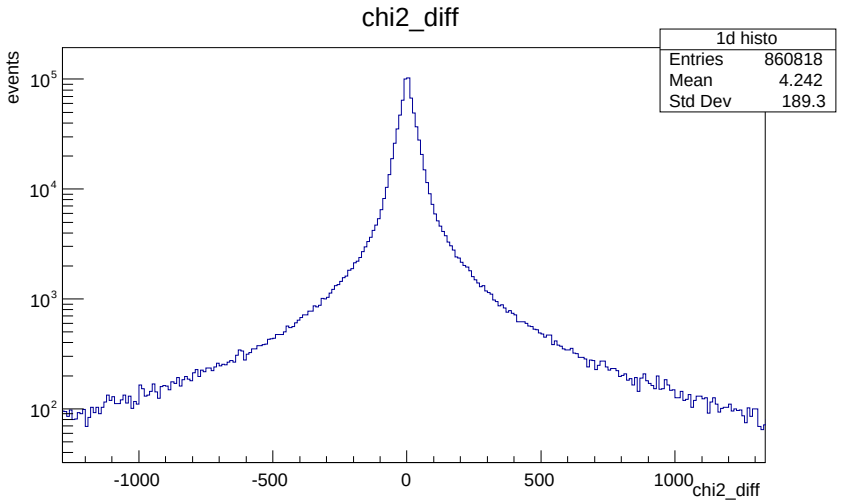
$\chi^2_{m_\rho}$ from TOTEM2



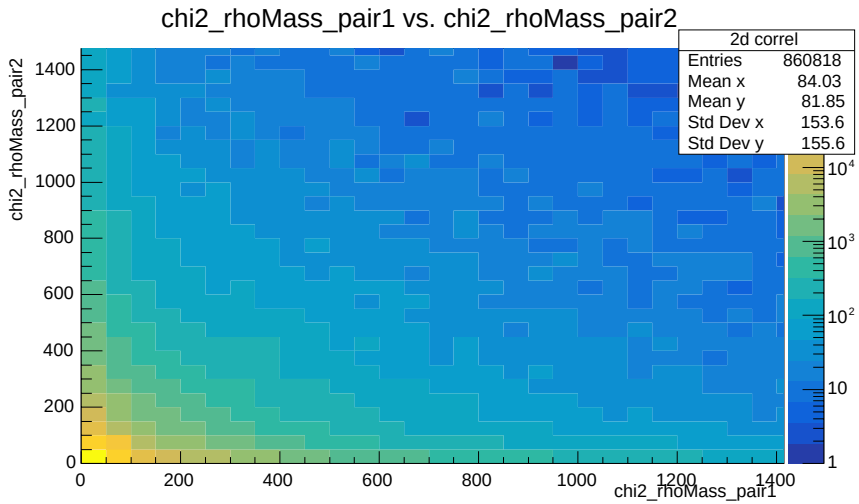
mass pair 1



mass pair 2

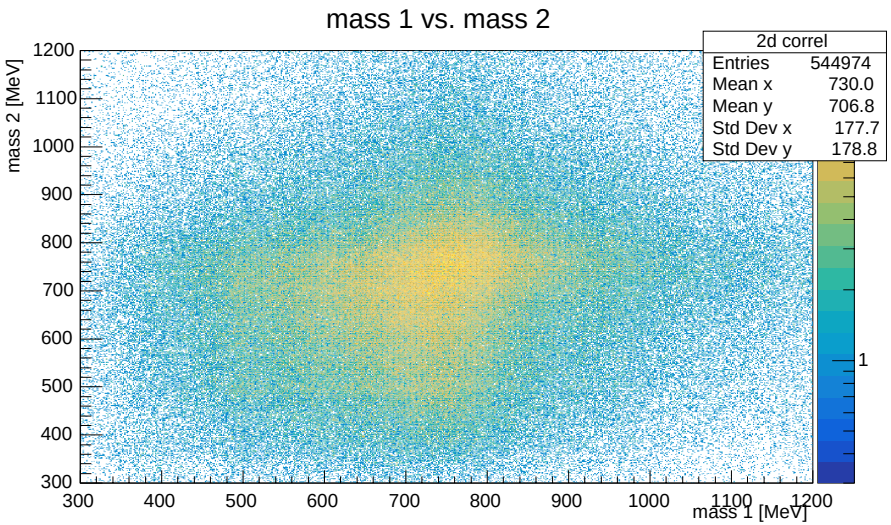


$\chi^2_{m1} - \chi^2_{m2}$

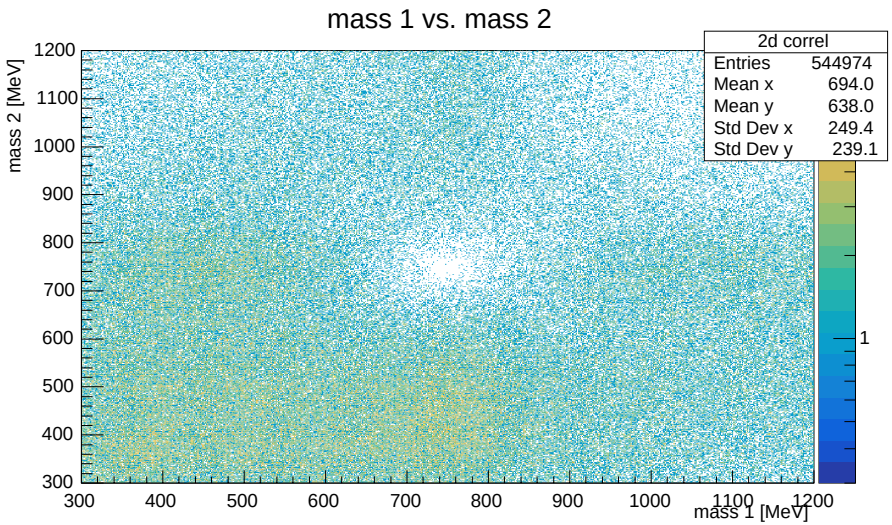


χ^2_m correlation

Identifying correct pairs $\chi^2_{\text{zPV,dxy,dz}} < 30$ cut TOTEM2



correct pairs

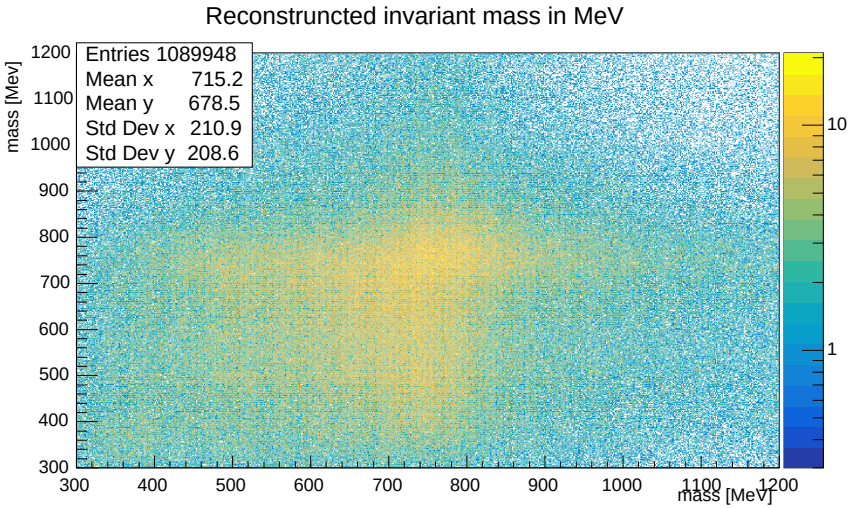


wrong pairs

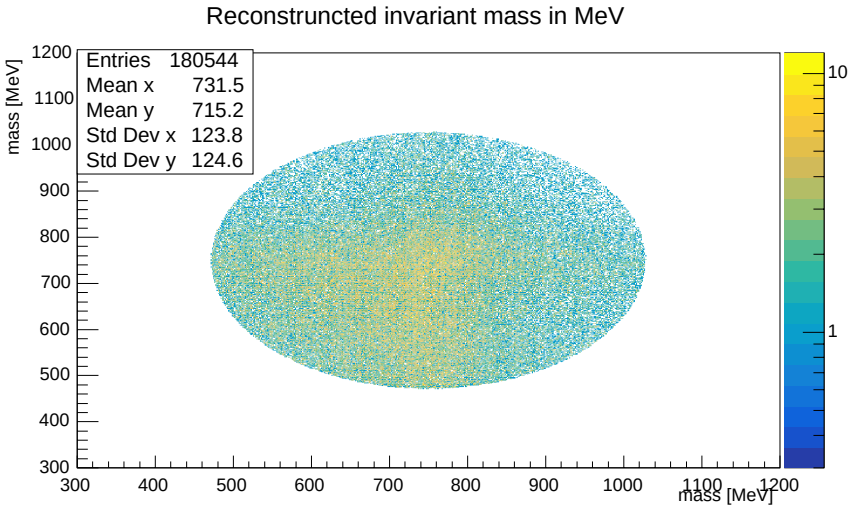
Conclusion

Identification of mass pairs seems to work, but the difference of χ^2 is centrally distributed and the two χ^2 are uncorrelated

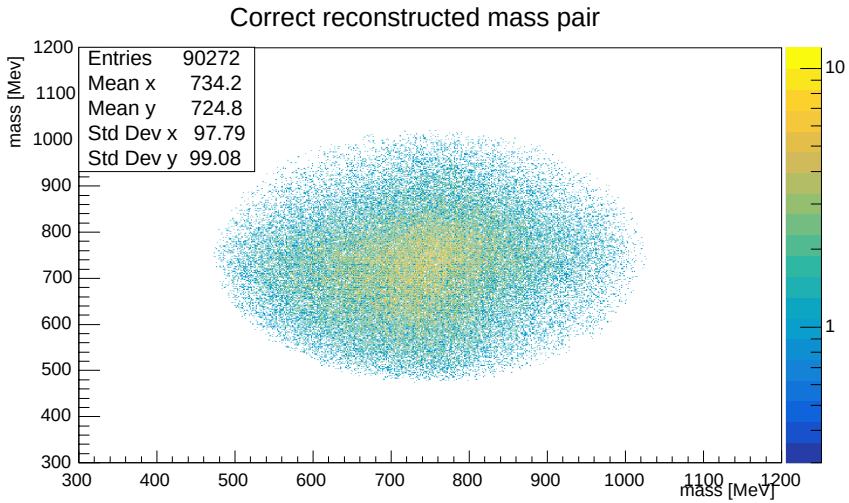
Effect of $\chi^2_{m_\rho}$ cuts on TOTEM2



$\chi^2_{\text{zPV,dxy,dz}} < 30$



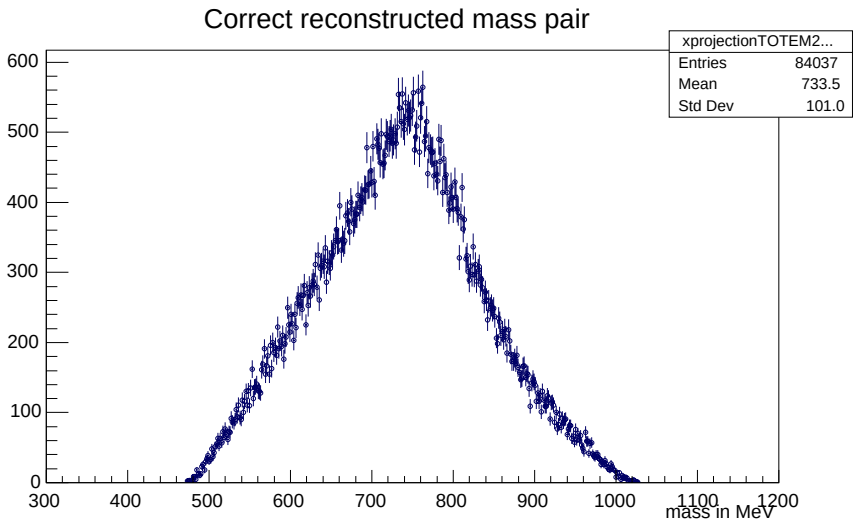
$\chi^2_{\text{zPV,dxy,dz}} < 30$ and $\chi^2_{m_\rho} < 20$



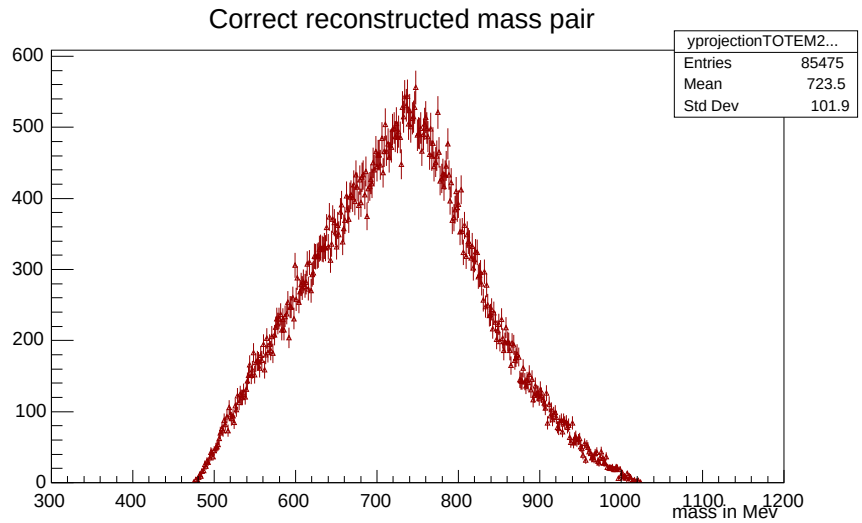
same cuts only correct pairs

Cuts $\chi^2_{\text{zPV,dxy,dz}} < 40$ and $\chi^2_{m_\rho} < 30$ on TOTEM2

- We make projections and use the sum range 600 to 900 MeV

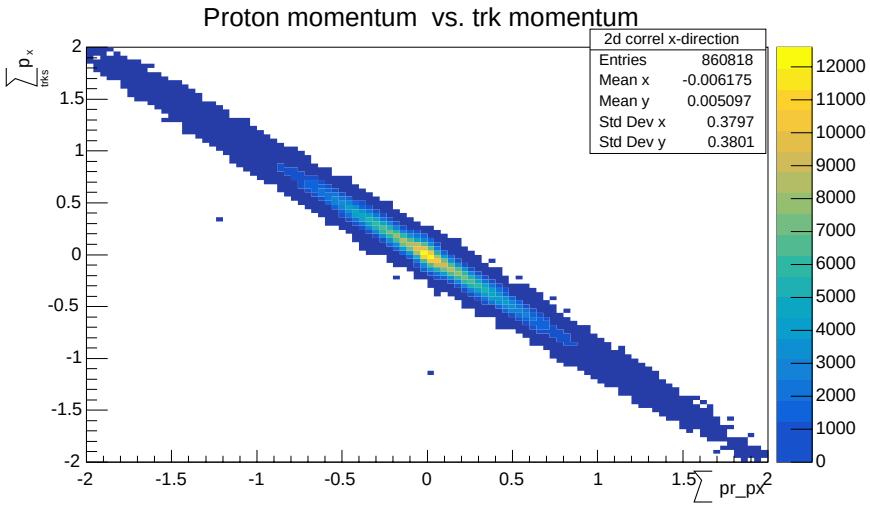


x-projection

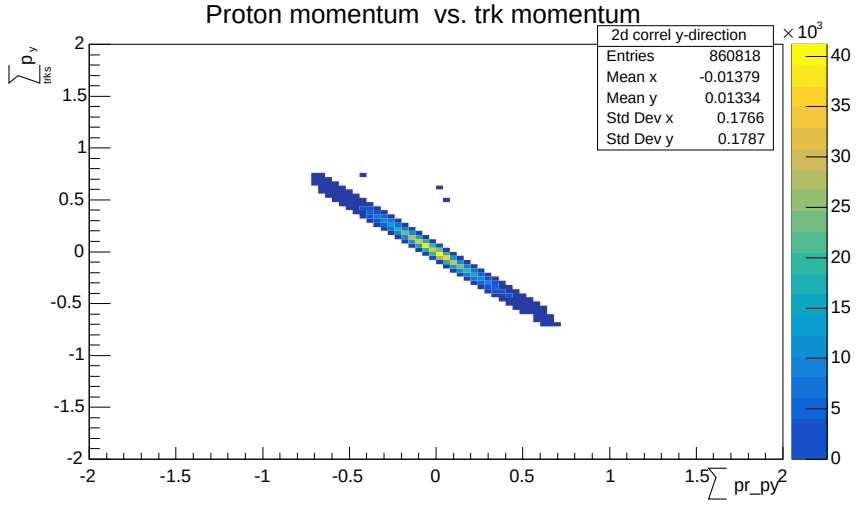


y-projection

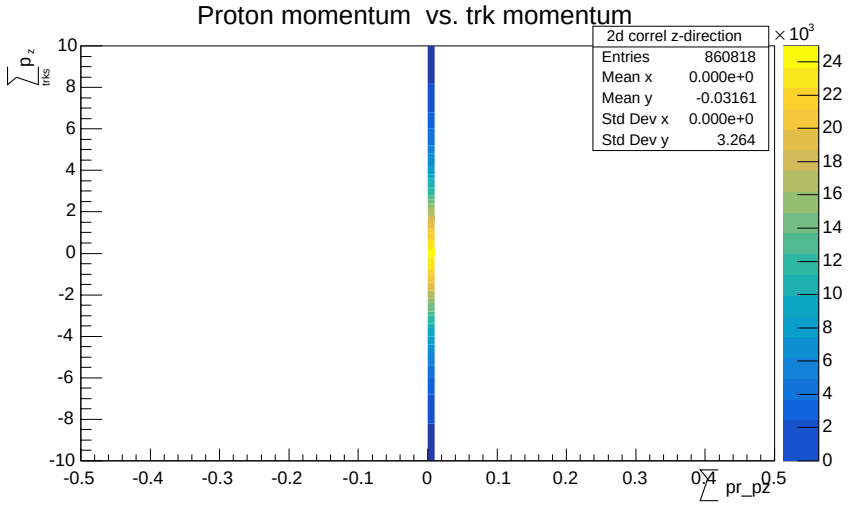
Momentum correlation uncut TOTEM2



p_x

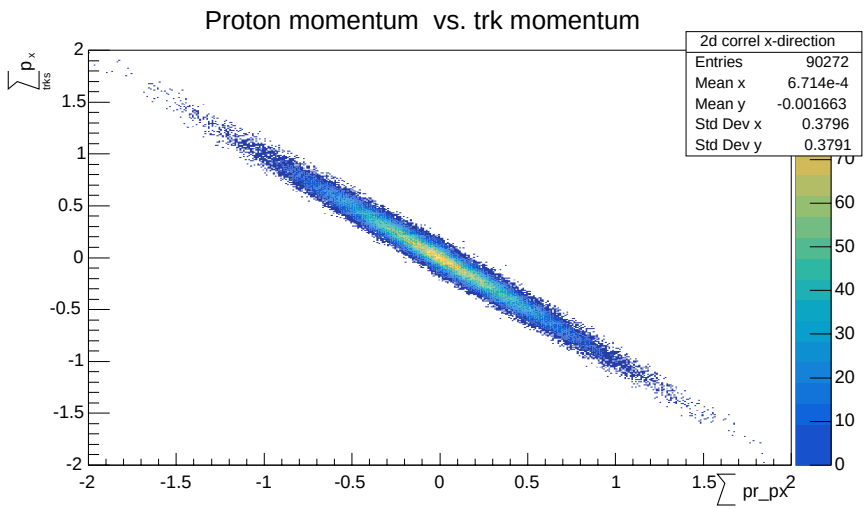


p_y

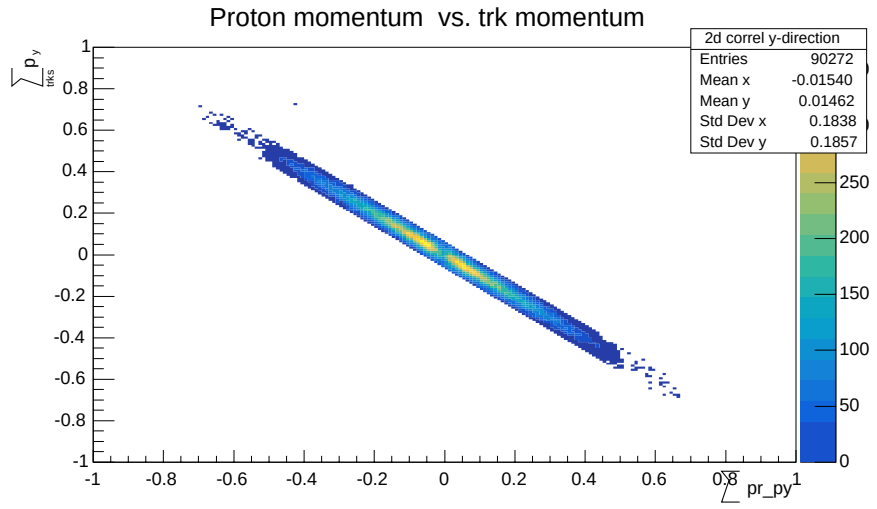


p_z

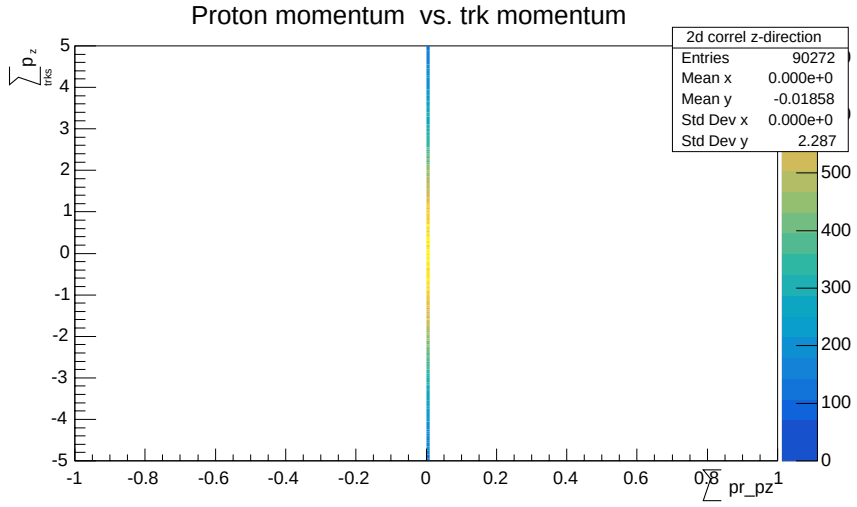
Momentum correlation χ^2-cutted TOTEM2



p_x

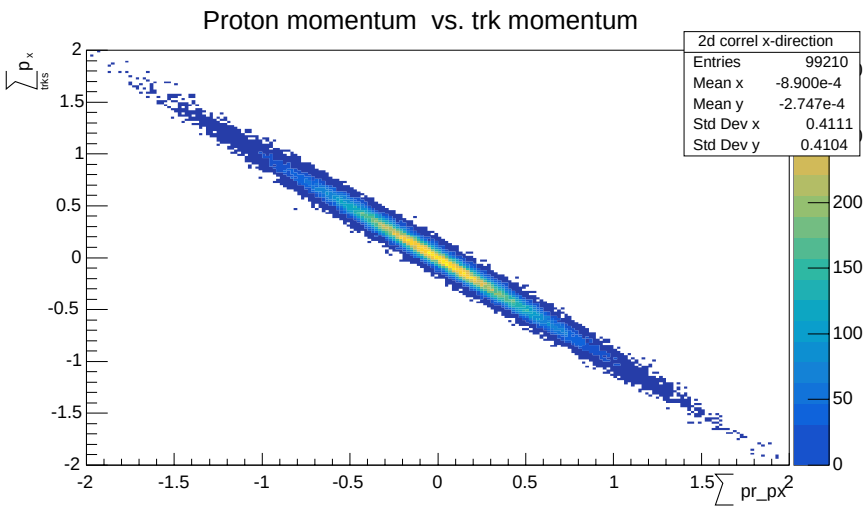


p_y

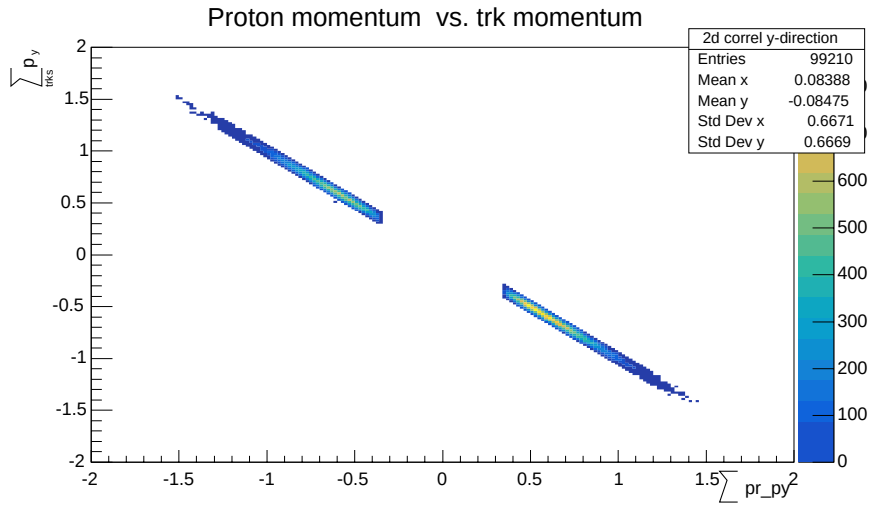


p_z

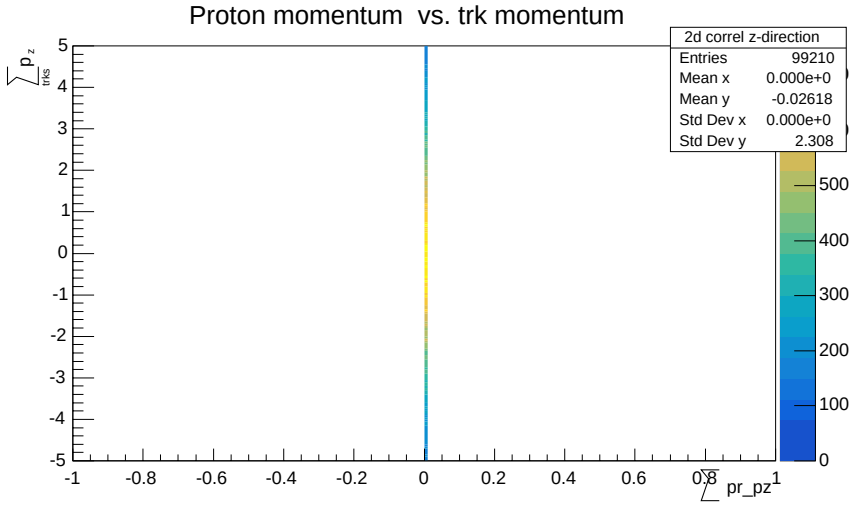
Momentum correlation χ^2-cutted TOTEM4



p_x



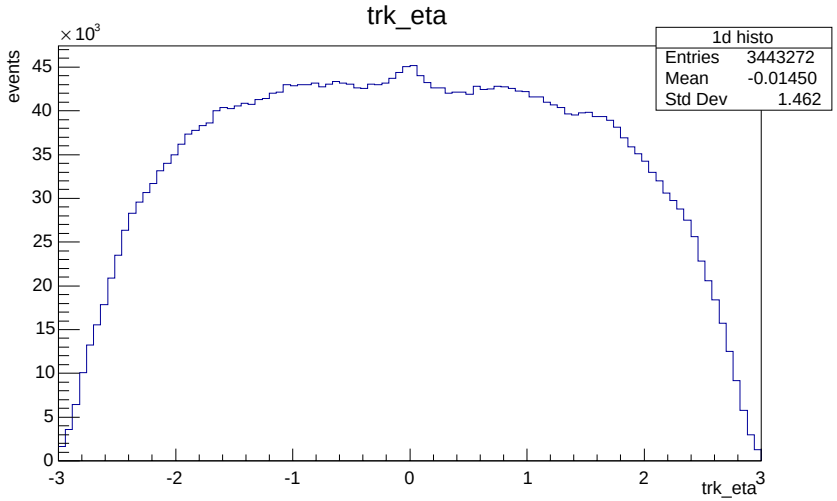
p_y

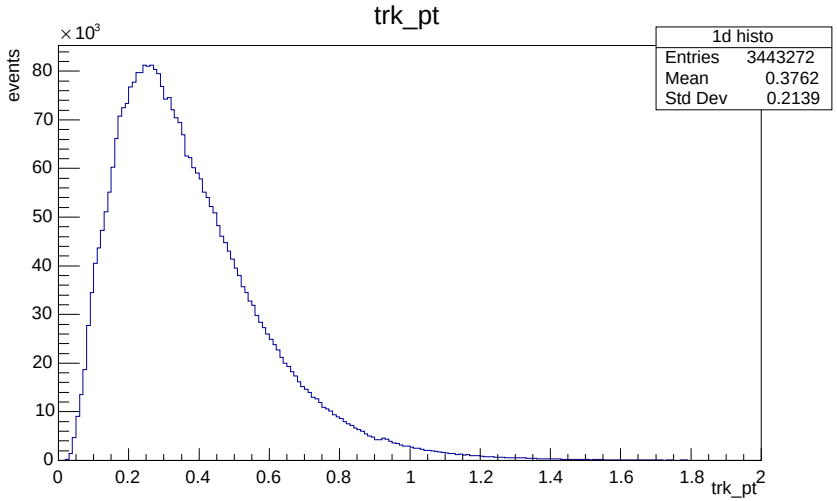


p_z

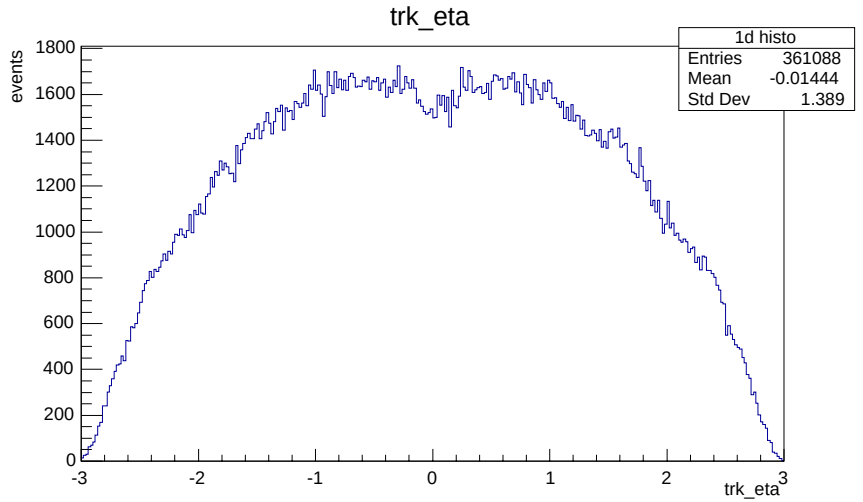
Pseudorapidity and transverse momentum of cutted data

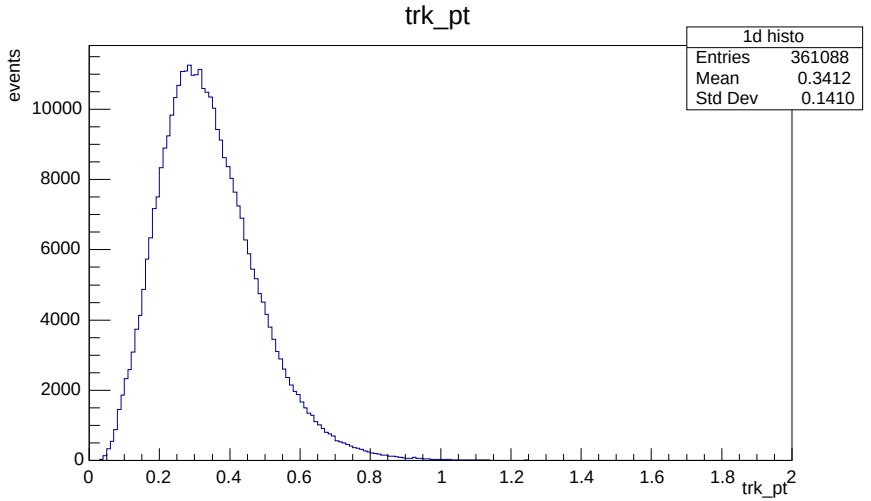
Uncut TOTEM2





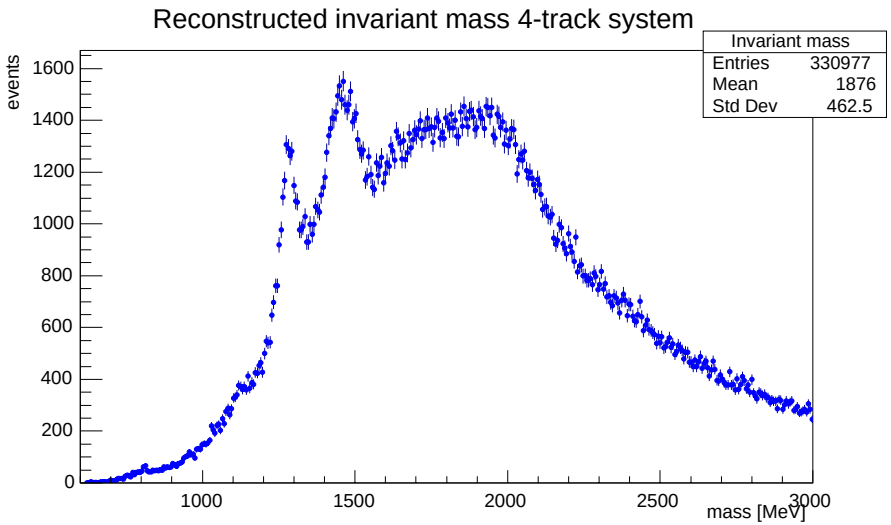
χ^2-cut TOTEM2



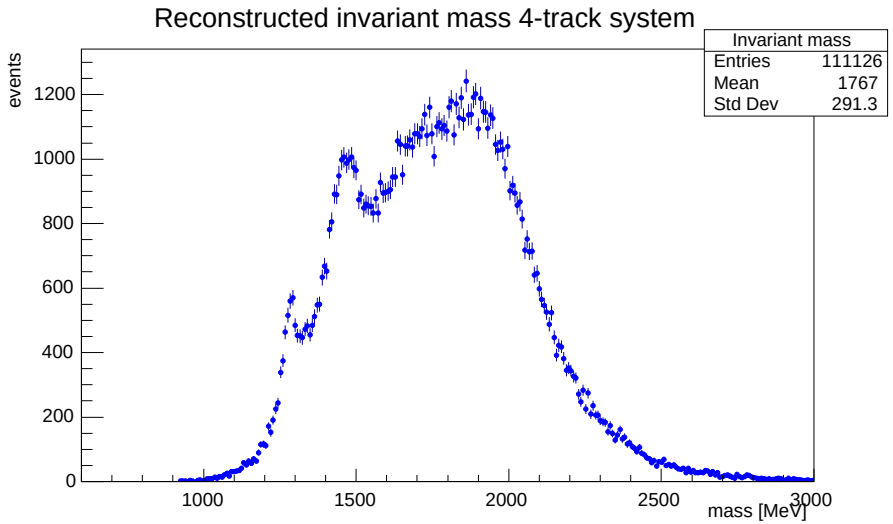


4-track invariant mass reconstruction TOTEM2

For all ntrk=4 and net charge zero



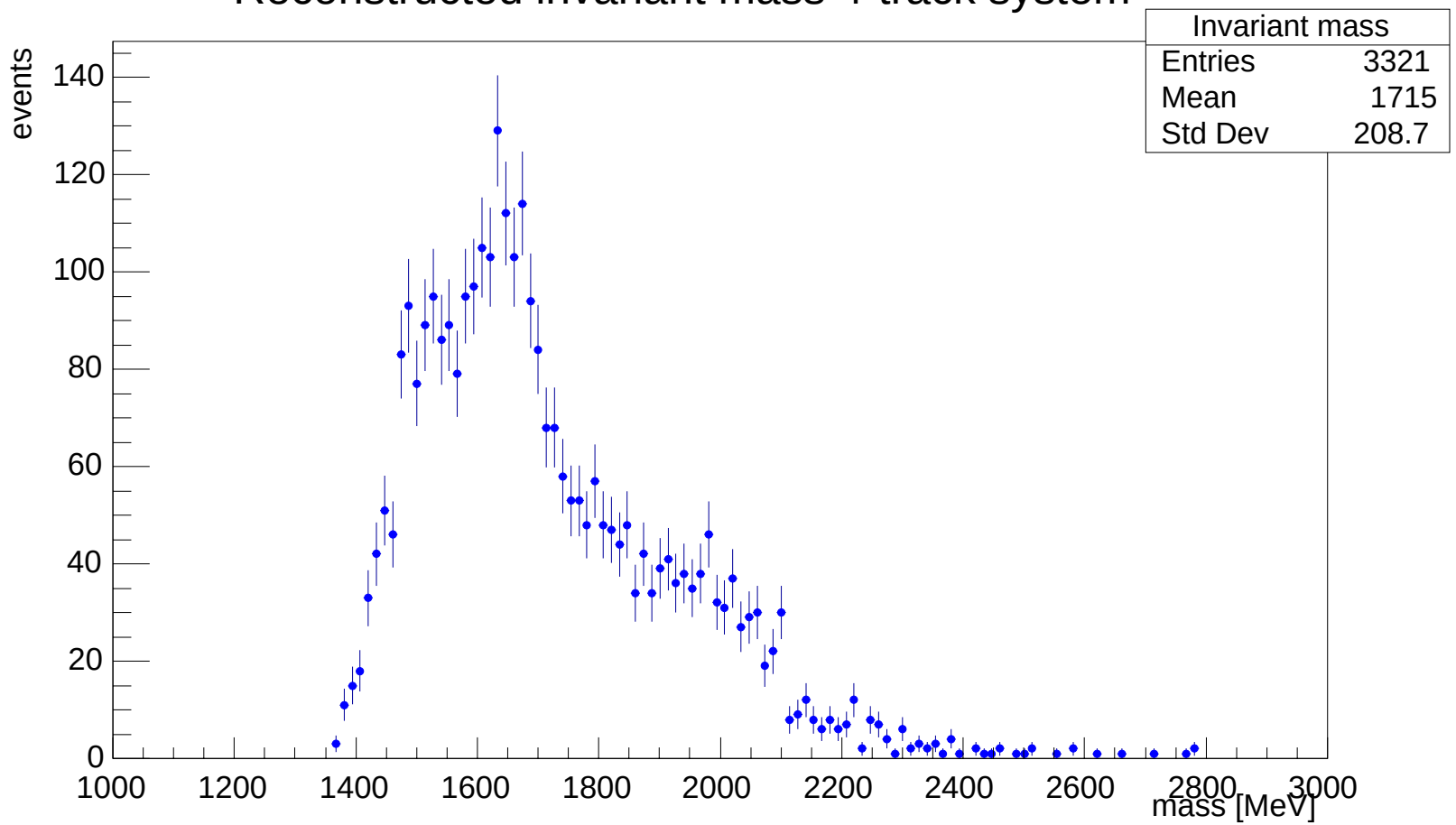
only $\chi^2_{\text{zPV,dxy,dz}} < 10$



$p_t < 800\,\text{MeV}$, $|\eta| < 3.0$,
$\chi^2_{\text{zPV,dxy,dz}} < 50$ and $\chi^2_{m_\rho} < 50$

4-track invariant mass reconstruction TOTEM2

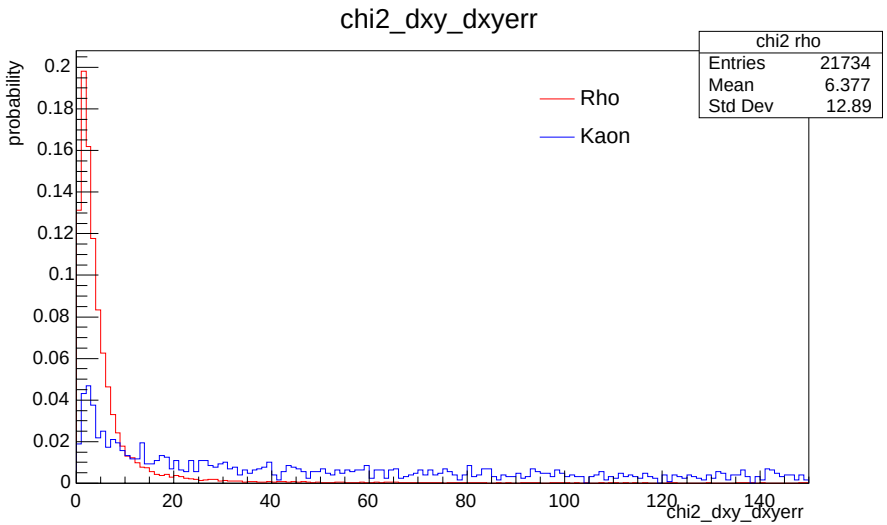
For all ntrk=4 and net charge zero



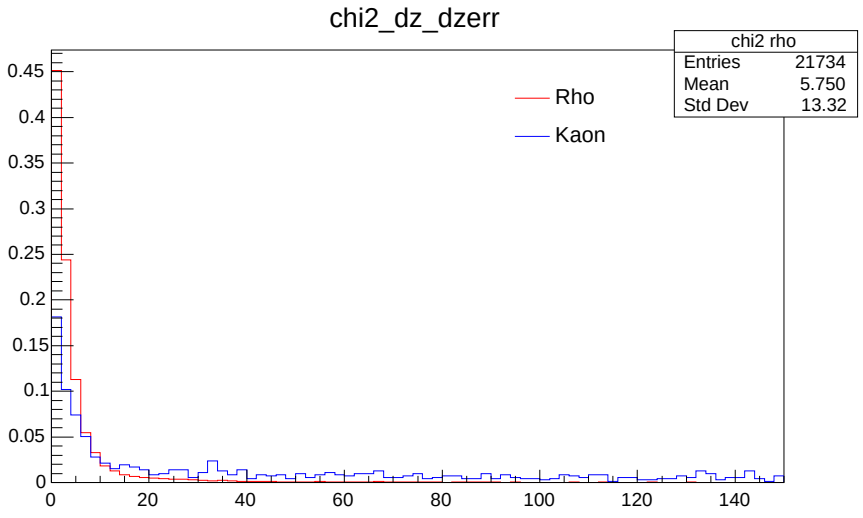
$\sum p_t < 800\,\text{MeV}$, $|\eta| < 3.0$, $|\text{dxy}| < 0.0435$, $|\text{zPV}| < 5$, $\chi^2_{\text{zPV,dxy,dz}} < 16$ and $\chi^2_{m_\rho} < 4$

"Pure" Kaon and Rho χ^2 variables of TOTEM4

- We try to extract samples of "pure" Kaons and "pure" Rhos so we can find typical values of χ^2_ρ for both
- χ^2 values from uncut 2D invariant mass histogram in interval $\mu \pm 0.5\sigma$ in x and y
- Normalised to histogram area, for comparability $\Rightarrow$ probability density function for χ^2 distributions

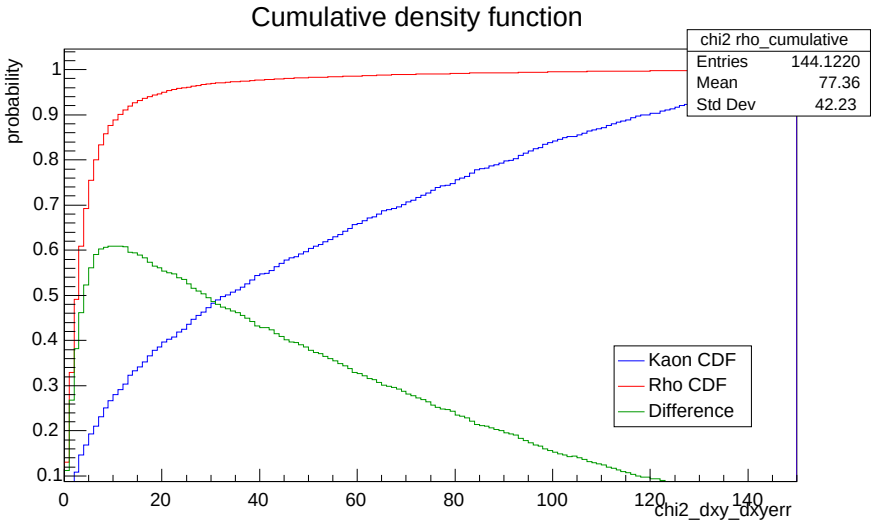


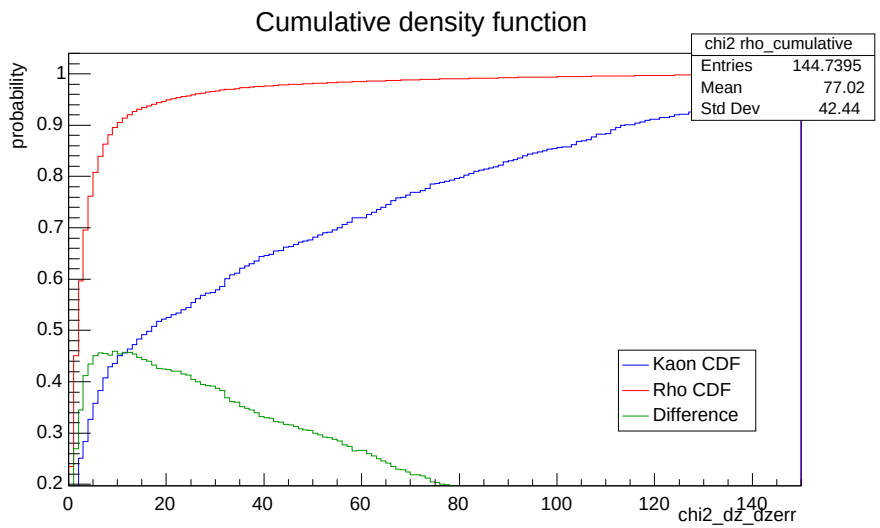
χ^2_{dxy}



χ^2_{dz}

Where to place optimal cut?

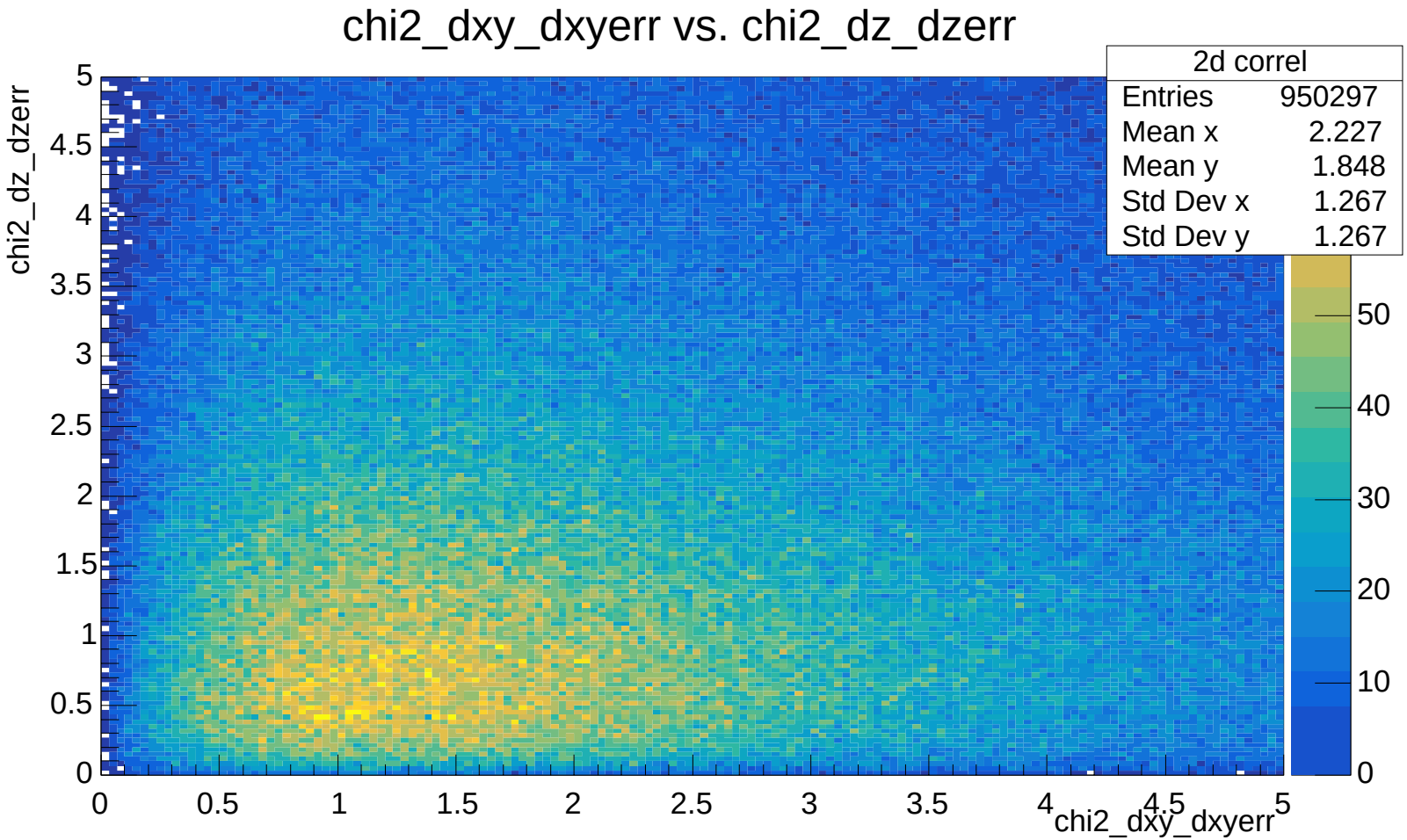




χ^2_{dxy} χ^2_{dz}

- I tried hypothesis tests, but Rho and Kaon distributions overlap too much to get sensible results
- Put the "optimal" cutoff at maximum of difference of CDFs $\Rightarrow \chi^2 \sim 10$

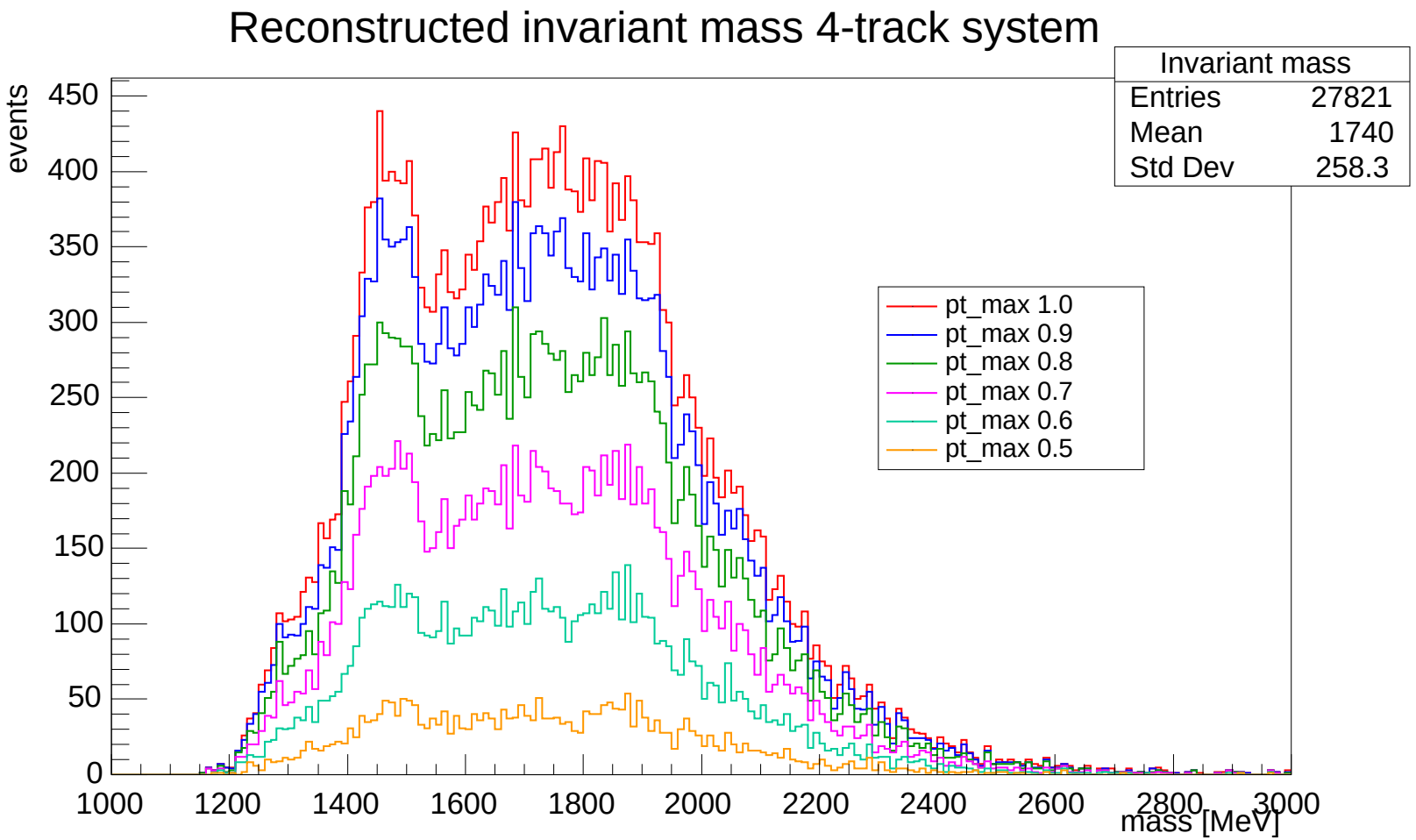
Correlation betwen dxy and dz?



Four-track invariant mass

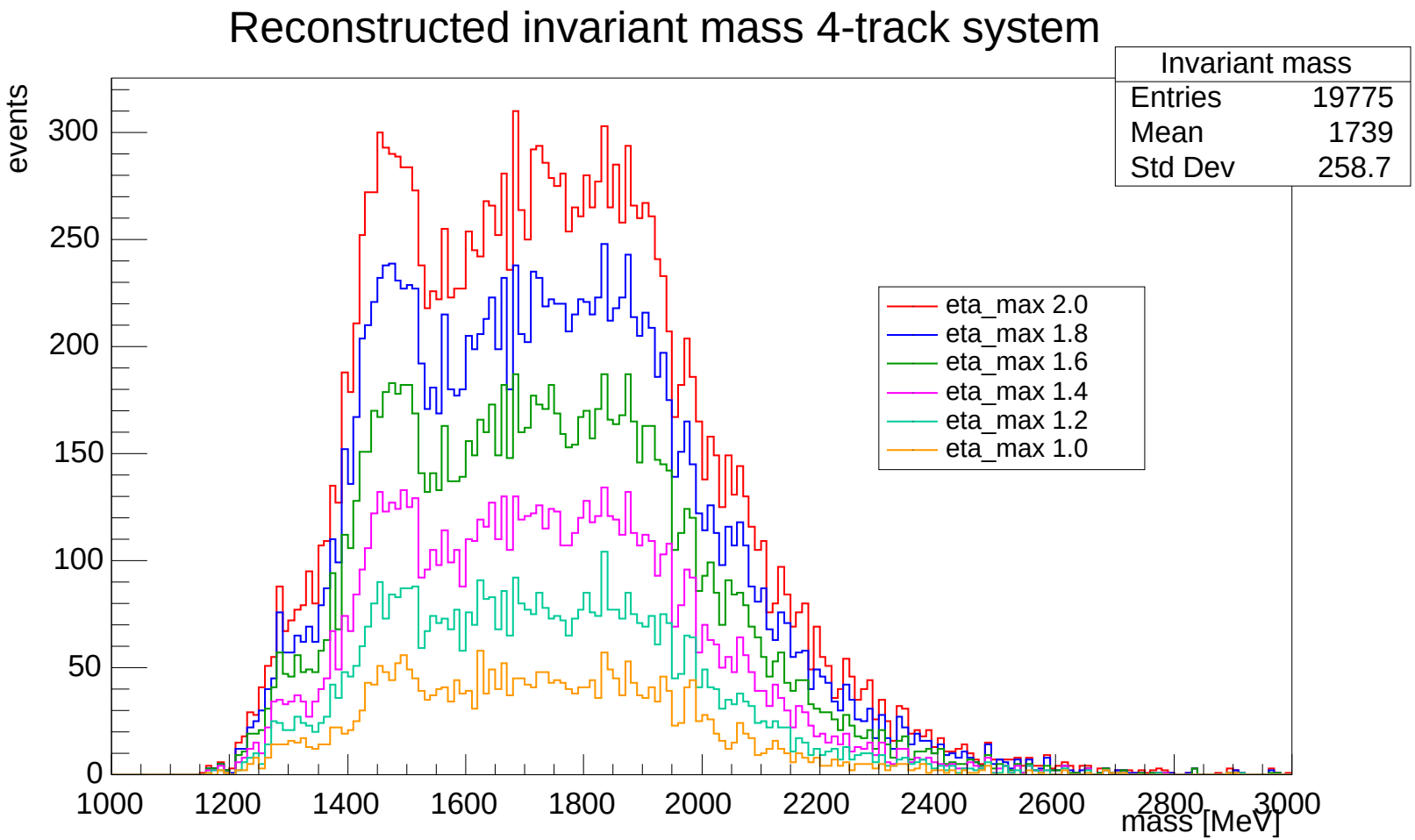
- We plot invariant mass histograms of the four-track system and try so see how different cuts influence these
- If we can reproduce the results from 2015 data taking we should see a peak around 2220 MeV
- We start by looking parallel configuration (TOTEM4) since we do not need an elastic veto here

Effect of p_T cuts on TOTEM4



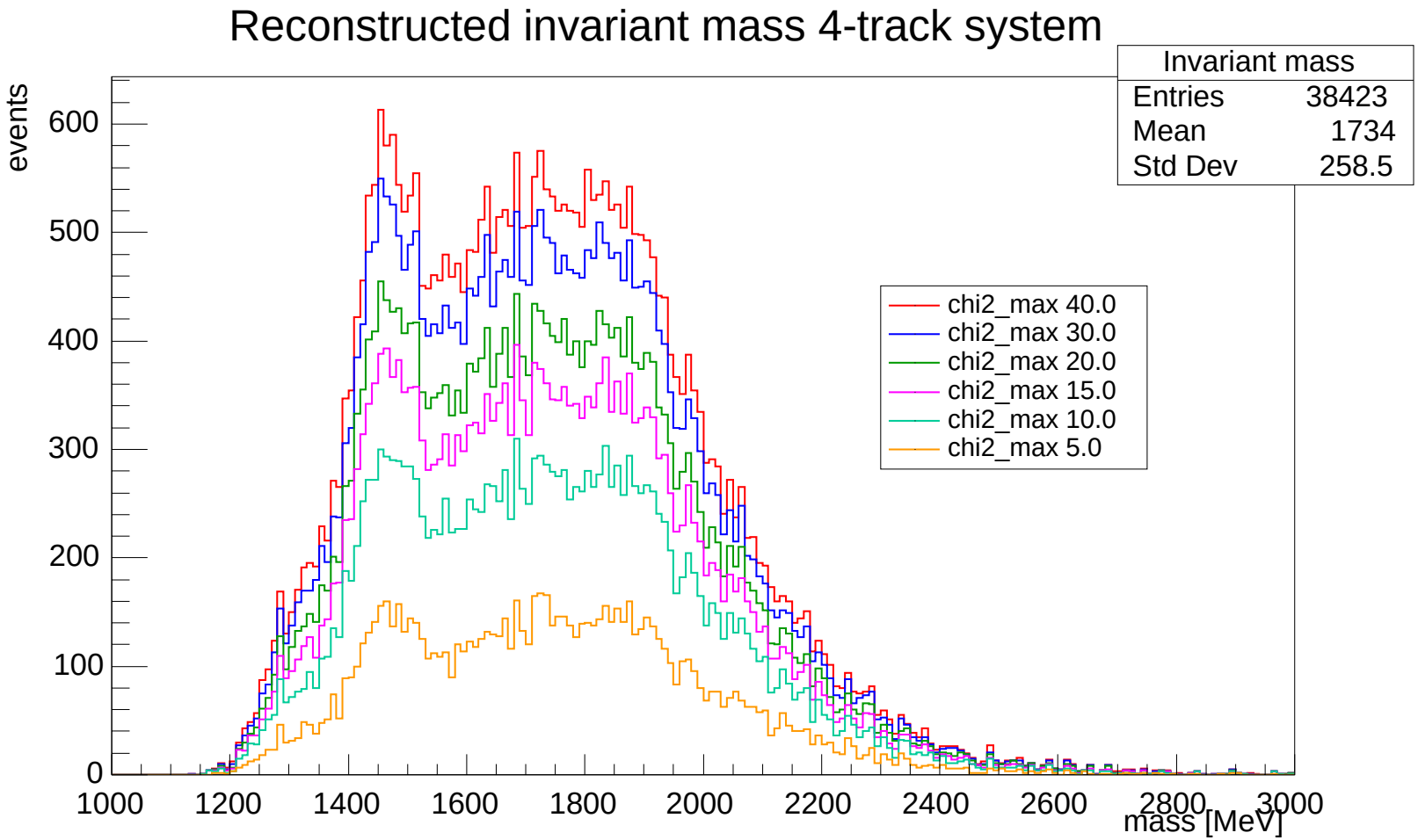
$$|\eta| < 2,\ \chi^2_{\text{zPV,dxy,dz}} < 10,\ \chi^2_\rho < 20$$

Effect of η cuts on TOTEM4



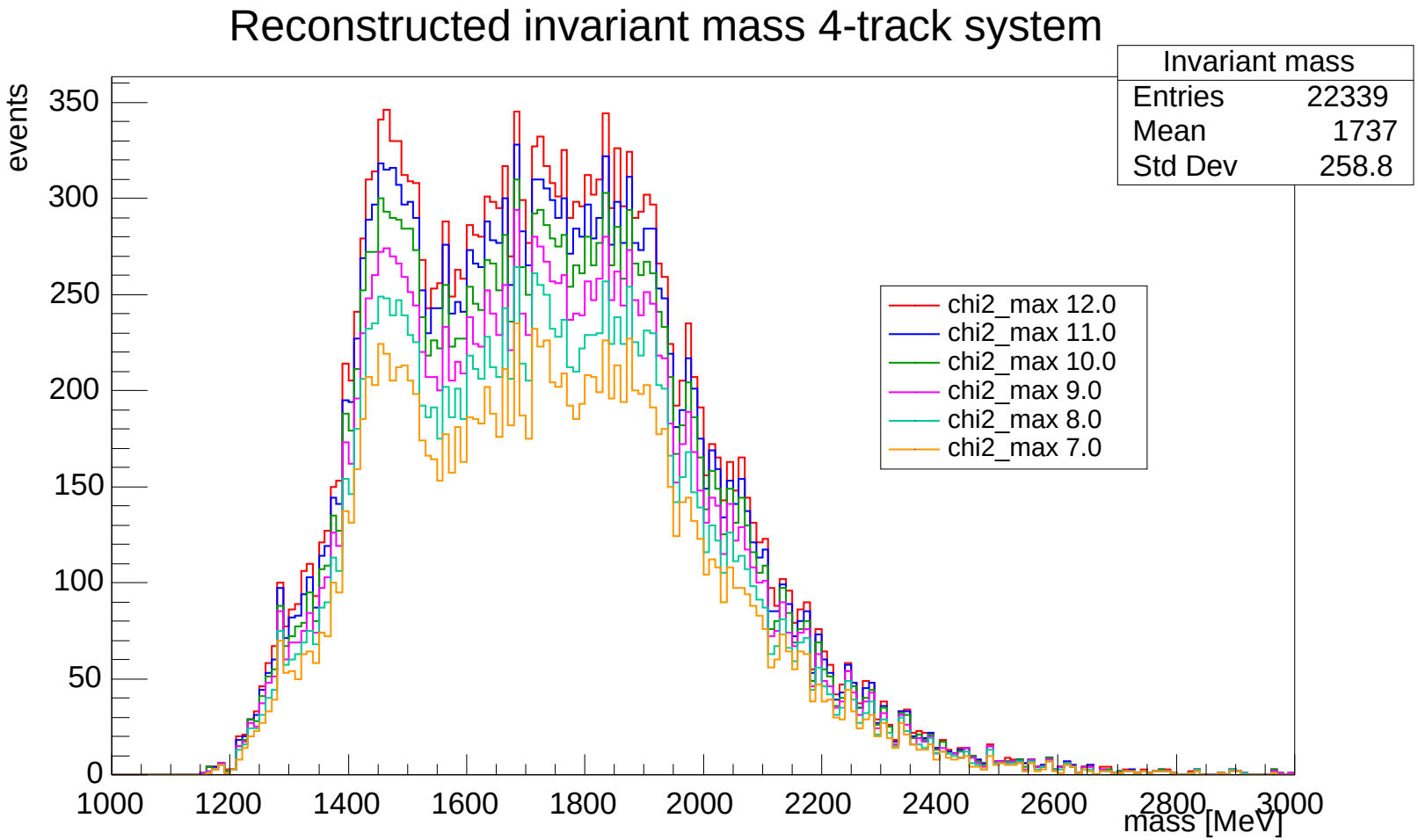
$$p_T < 0.8\,\text{GeV},\ \chi^2_{\text{zPV,dxy,dz}} < 10,\ \chi^2_\rho < 20$$

Effect of coarse $\chi^2_{\text{zPV,dxy,dz}}$ cuts on TOTEM40



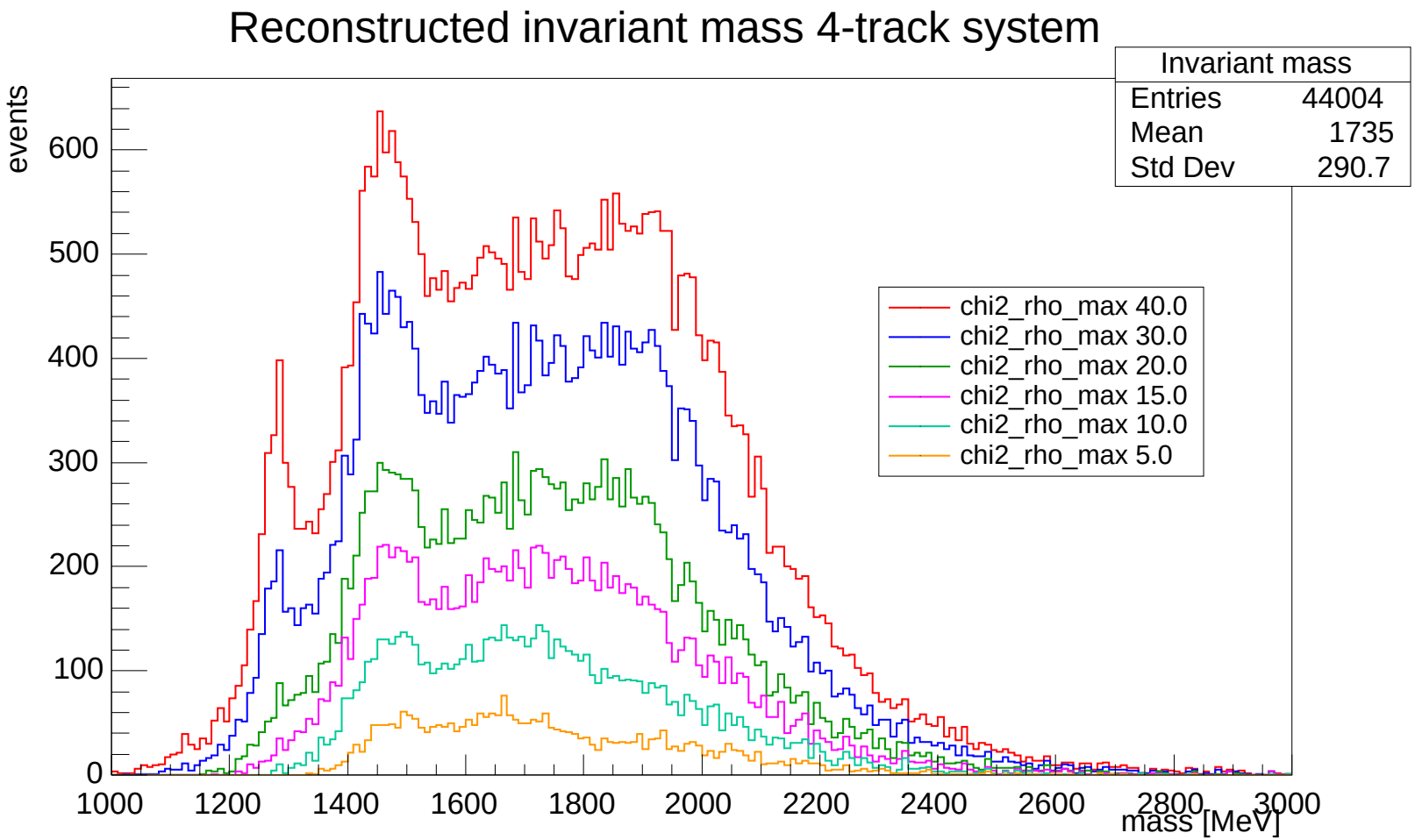
$p_T < 0.8\,\text{GeV},\ |\eta| < 2,\ \chi^2_\rho < 20$

Effect of fine $\chi^2_{\text{zPV,dxy,dz}}$ cuts on TOTEM40



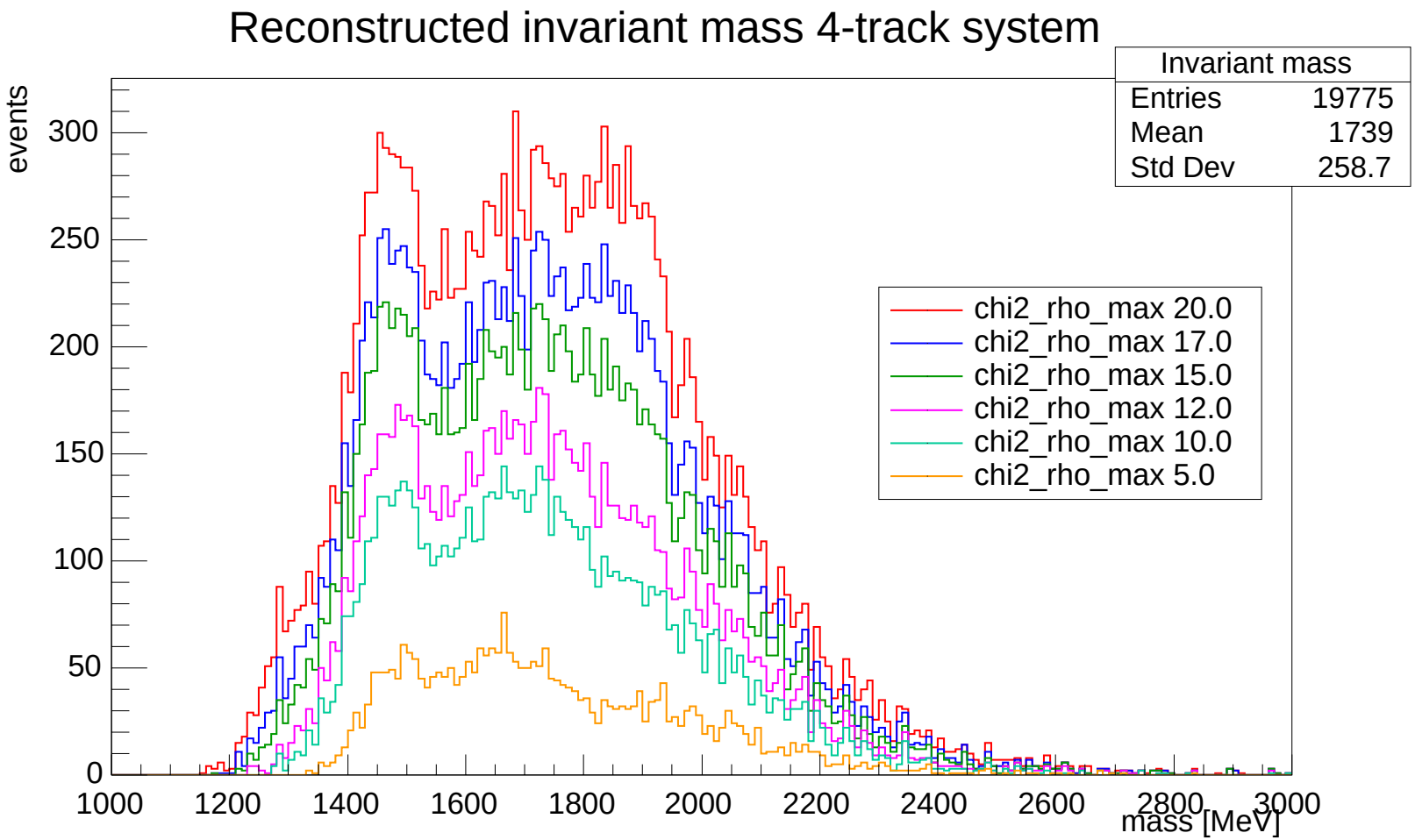
$p_T < 0.8\,\text{GeV},\ |\eta| < 2,\ \chi^2_\rho < 20$

Effect of coarse χ^2_ρ cuts on TOTEM4



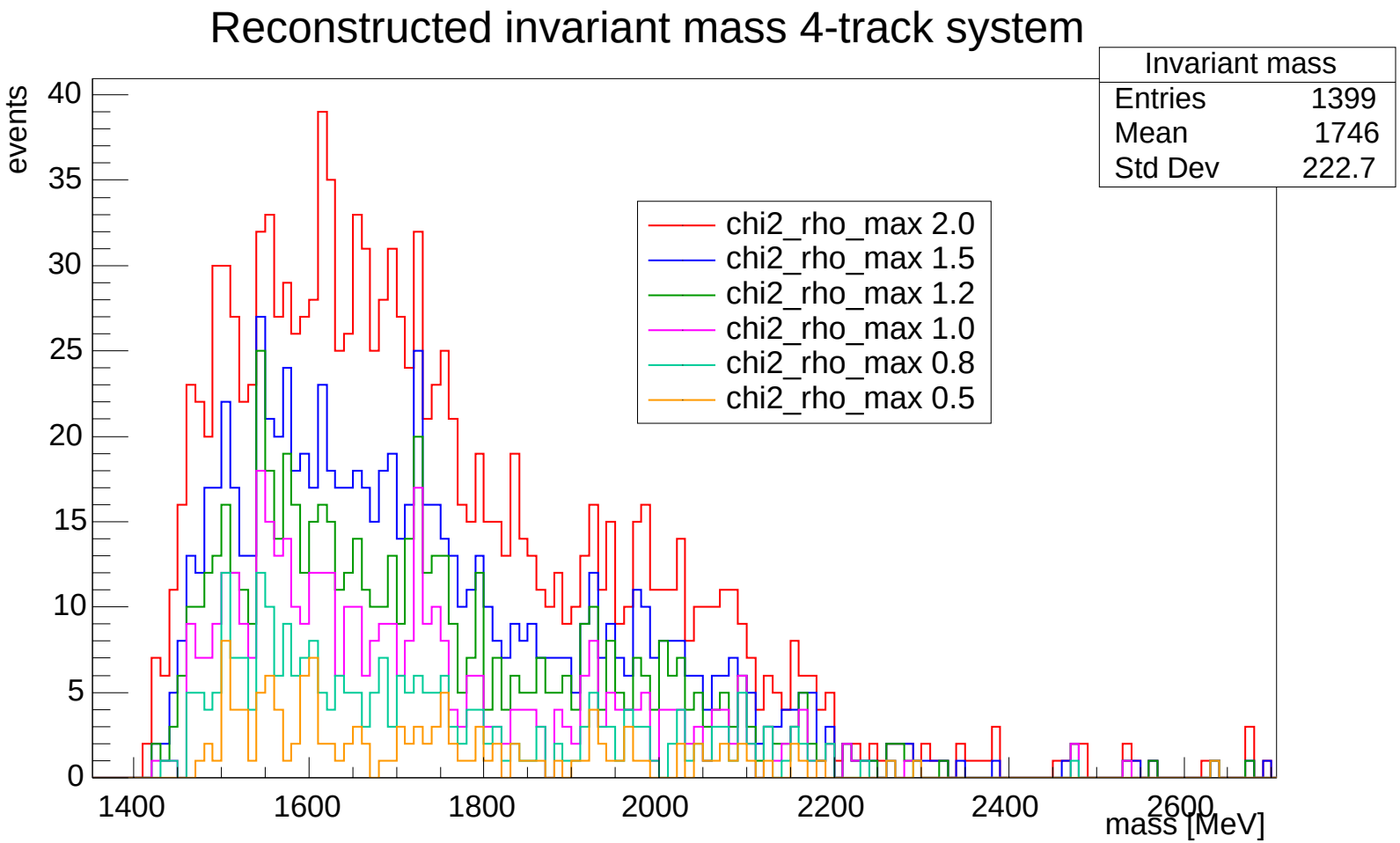
$$p_T < 0.8\,\text{GeV},\ |\eta| < 2,\ \chi^2_{\text{zPV,dxy,dz}} < 10,$$

Effect of fine χ^2_ρ cuts on TOTEM4



$$p_T < 0.8\,\text{GeV},\ |\eta| < 2,\ \chi^2_{\text{zPV,dxy,dz}} < 10,$$

Effect of hyperfine χ^2_ρ cuts on TOTEM4

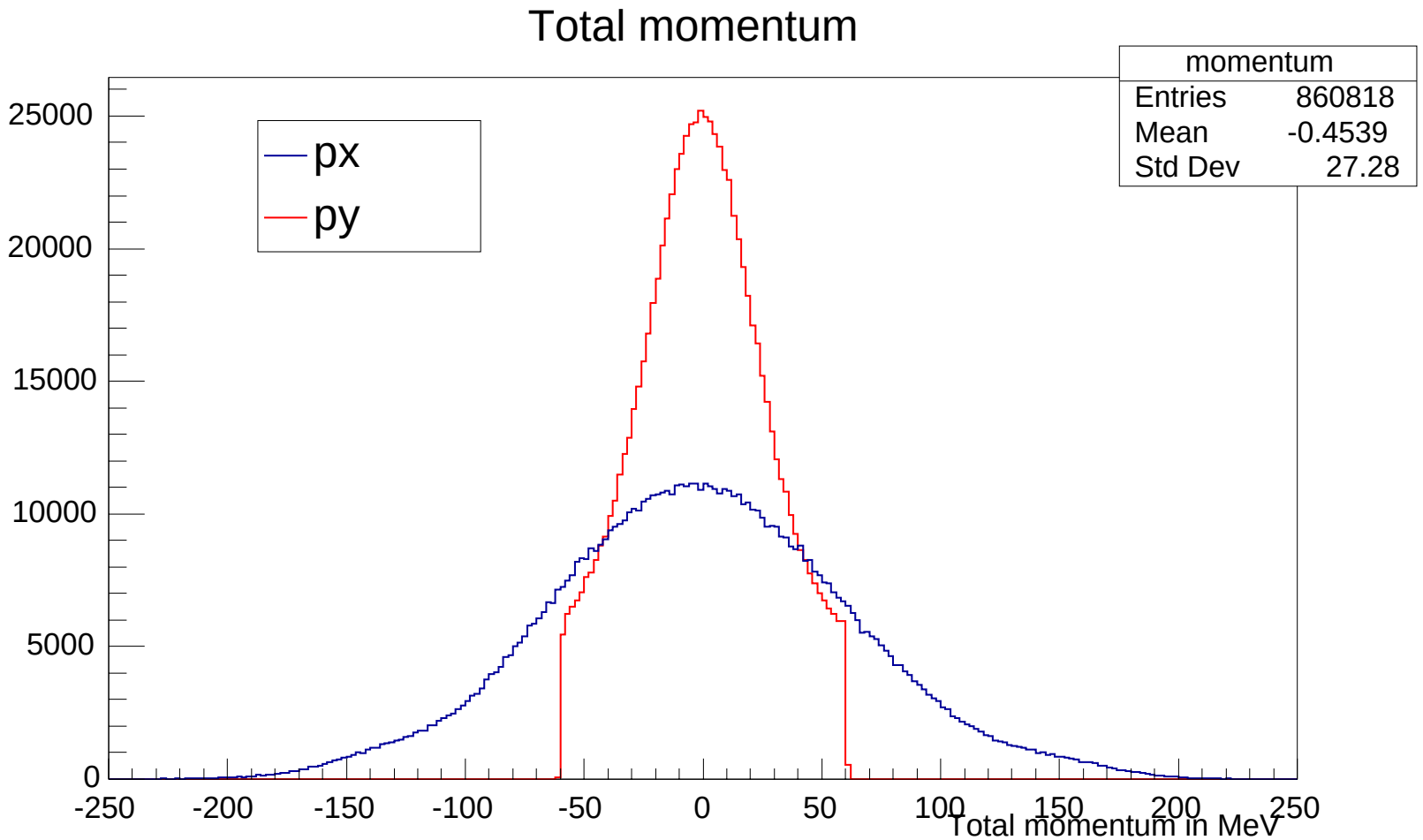


$$p_T < 1.2\,\text{GeV},\ |\eta| < 2,\ \chi^2_{\text{zPV,dxy,dz}} < 15,$$

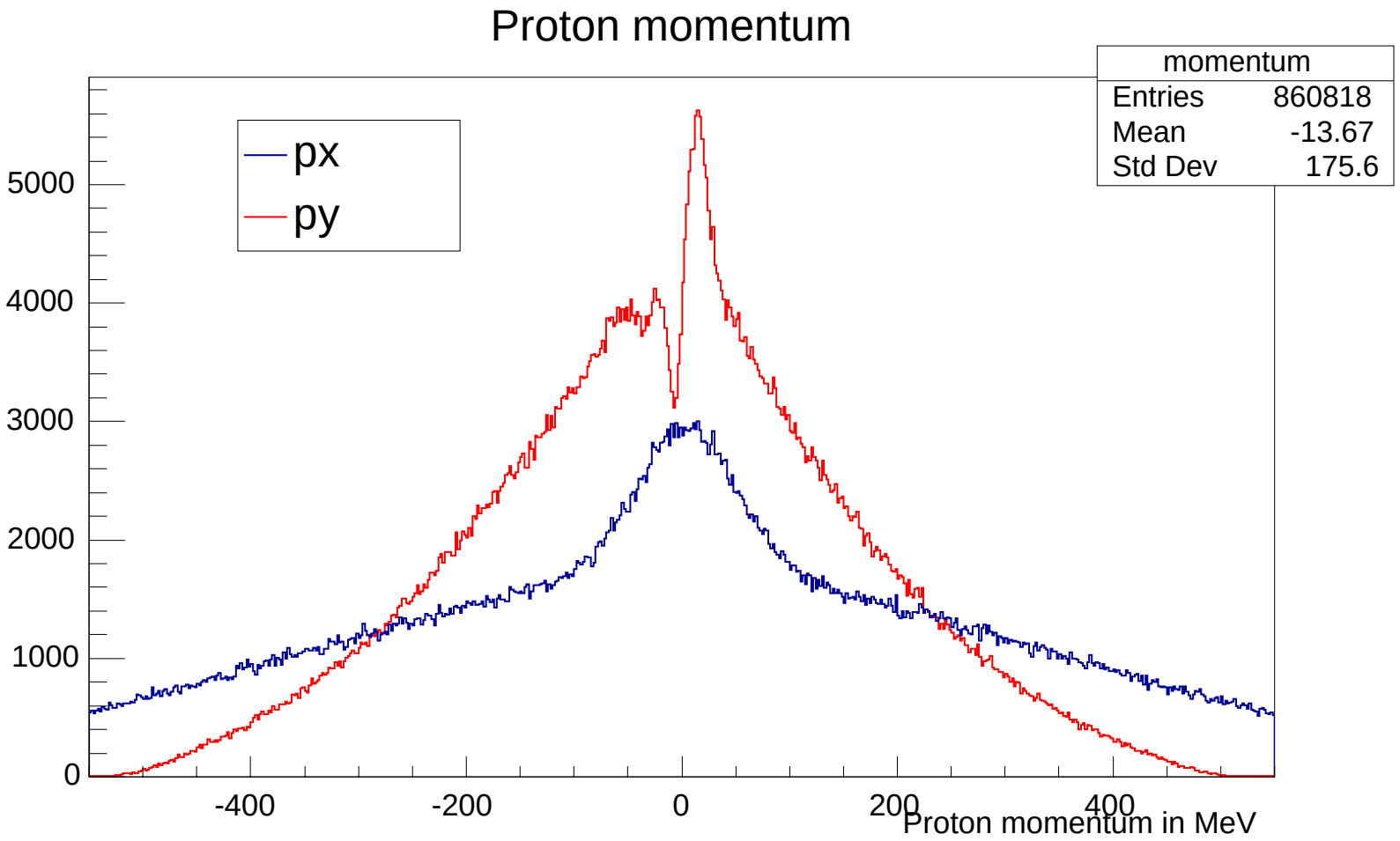
Some observations

- In general we do not see a clear peak at 2.2 GeV for any of the cuts
- In general more restrictive cuts simply reduce amount of data without changing the shape of the histograms to much
- In most histograms there is a peak around 1.4 GeV (roughly two times the ρ mass). This peak get less prominent for more restrictive cuts
- More restrictive cuts on χ^2_ρ shift the location of the first non-empty bin to the right
- If the cuts singled out the desired 4-track events, we would expect that for some cut more restriction means more bin entries around 2.2 GeV. This is not observed for any of the cuts. (Note that the order (from high to low) is always red, blue, green, purple, cyan, orange)

Sum of proton momenta TOTEM4



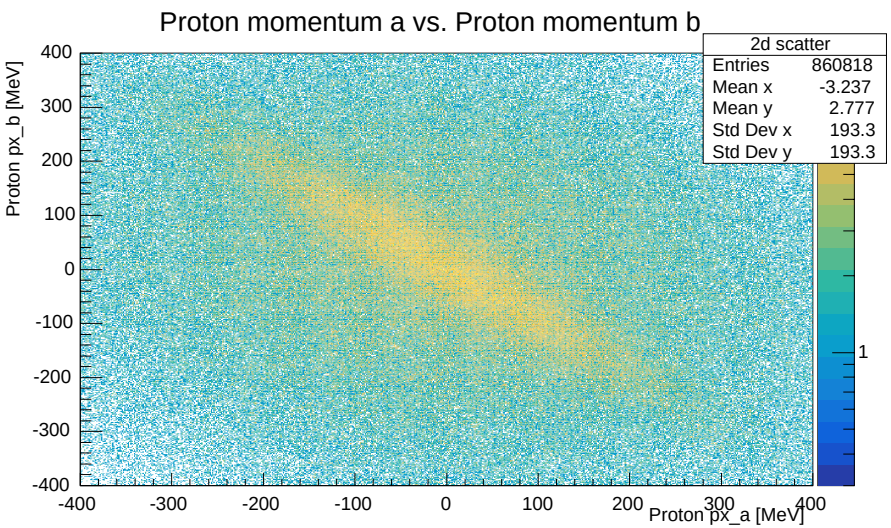
Sum of proton momenta TOTEM2



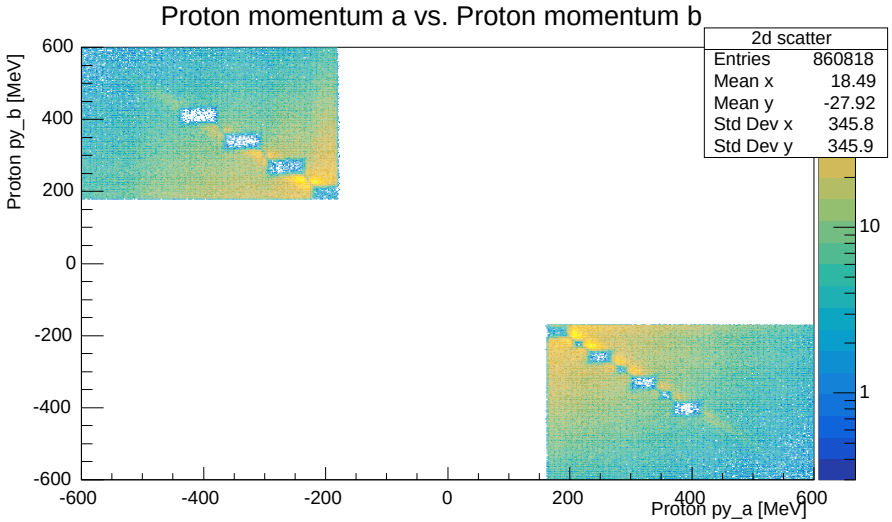
Difference between TOTEM2 and TOTEM4 proton momenta distributions

- We can see that the proton momentum distribution for TOTEM4 looks a lot cleaner (more gaussian)
- This is because in diagonal configuration there are a lot of elastic background events that need to be filtered out
- There is some elastic veto in the triggers during data acquisition, but they are not perfect
  $\Rightarrow$ We need to impose a new elastic veto on the data

Proton momentum correlation in TOTEM2 before veto



x-direction

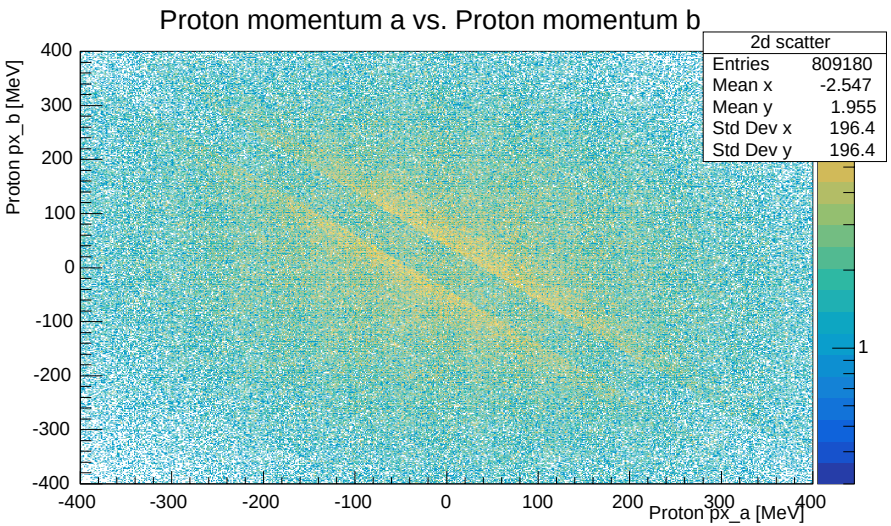


y-direction

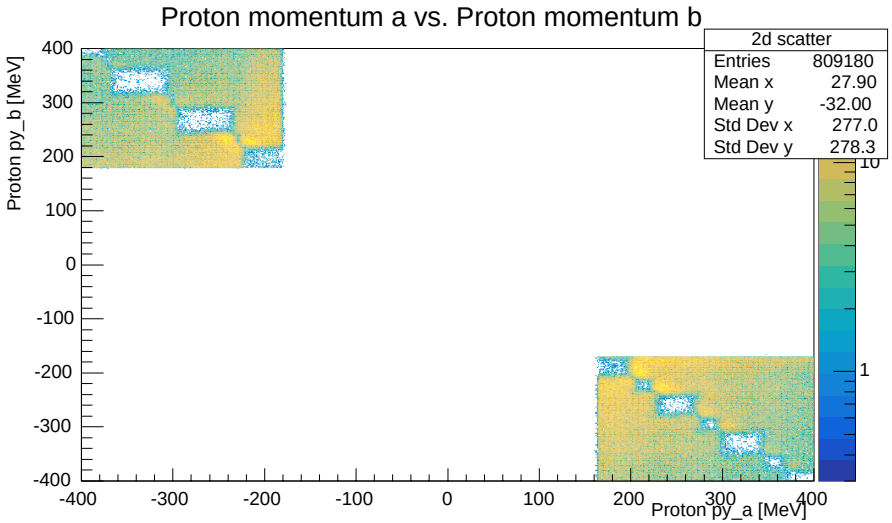
- Small boxes in *y*-direction are due to veto at trigger level

Proton momentum correlation

- Only looking at x and y-direction
- Demand ($|pr\_p_x^a + pr\_p_x^b| >$ cutoff && $|pr\_p_y^a + pr\_p_y^b| >$ cutoff) otherwise reject



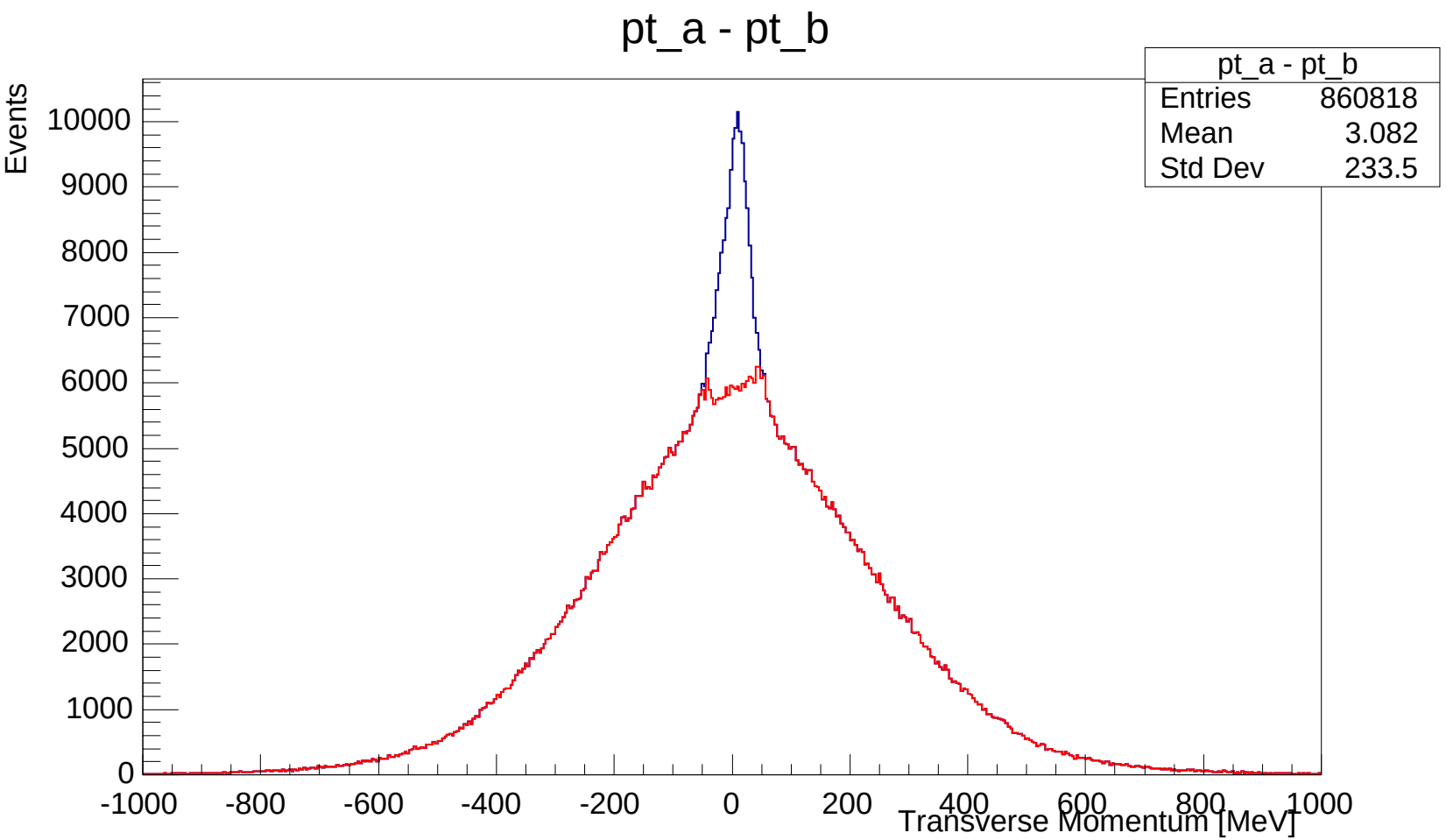
x-direction



y-direction

- Through experimenting we find cutoff$=$ 40 MeV works best

Verifying the veto I - p_T difference

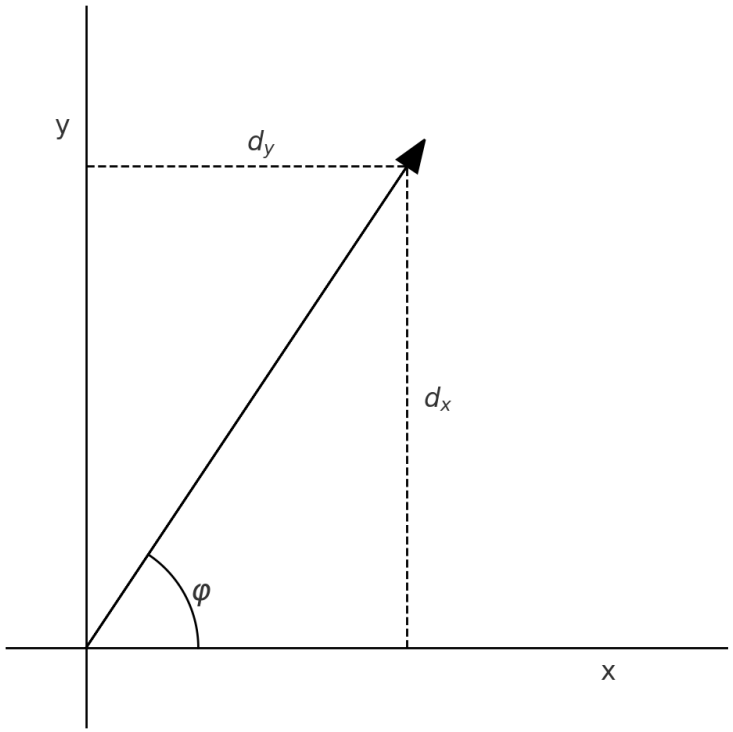


$\Rightarrow$ Elastic veto filters out with low p_T difference

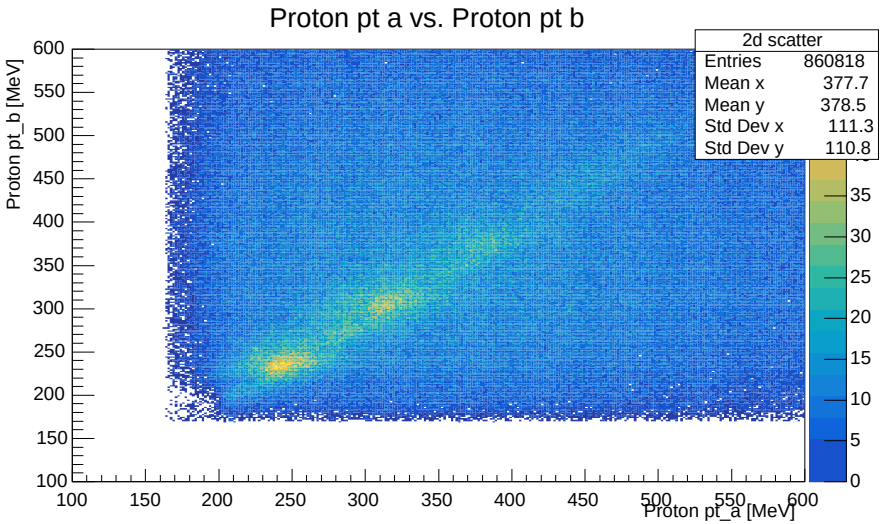
Verifying the veto II - Azimuthal angle difference

- In TTree we have variables: *ThxR*, *ThxL*, *ThyL*, *ThyR*
- In small angle approximation: $d_x \approx \theta_x$ and $d_y \approx \theta_y$
- Azimuthal angle Φ in xy-plane given by:

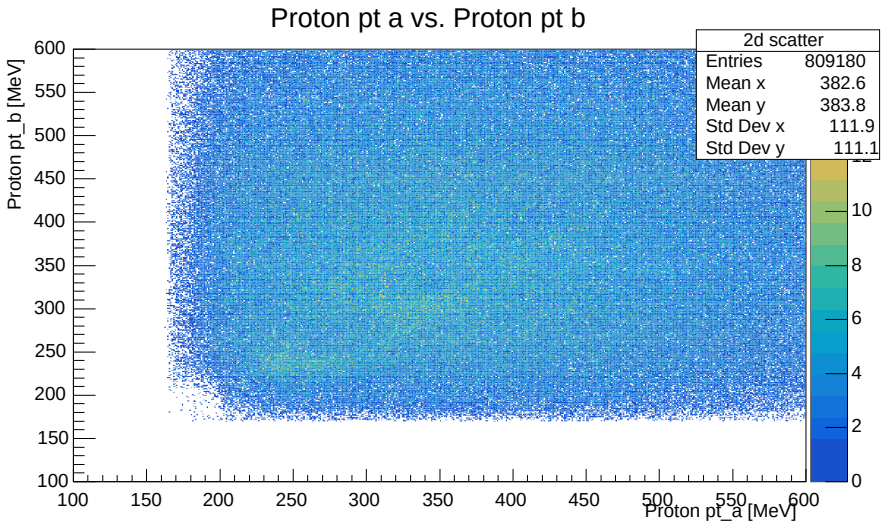
$$\Phi_{L/R} = \arctan\left(\frac{\Theta_{x_{L/R}}}{\Theta_{y_{L/R}}}\right)$$



Transverse momentum correlation



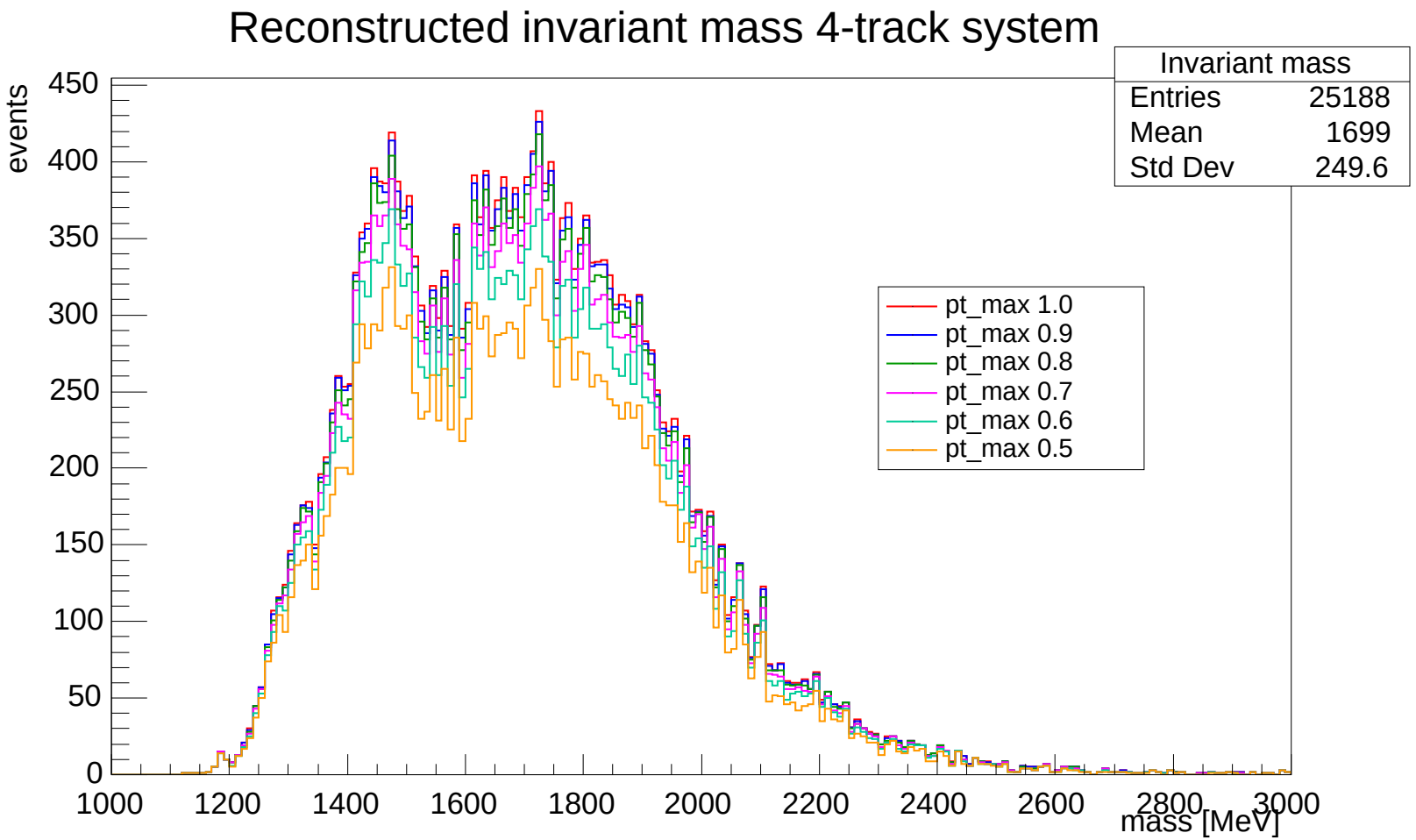
No veto



Veto 40 MeV

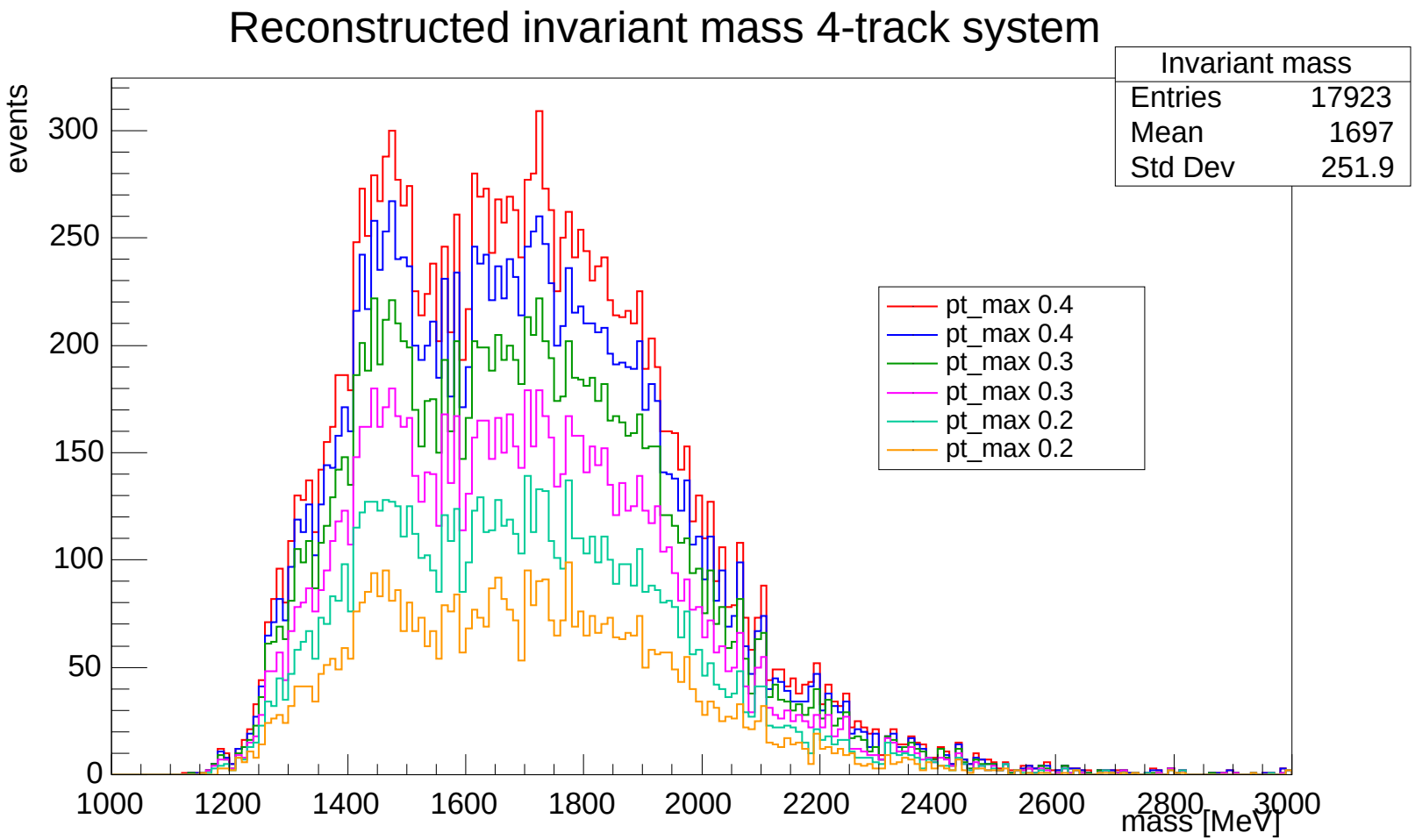
- REMARK: The following plots have been made with a veto of 20 MeV instead of the better 40 MeV due to an earlier bug in the veto. Thus the veto for the plots was not restrictive enough

Effect of p_T cuts on vetoed TOTEM2



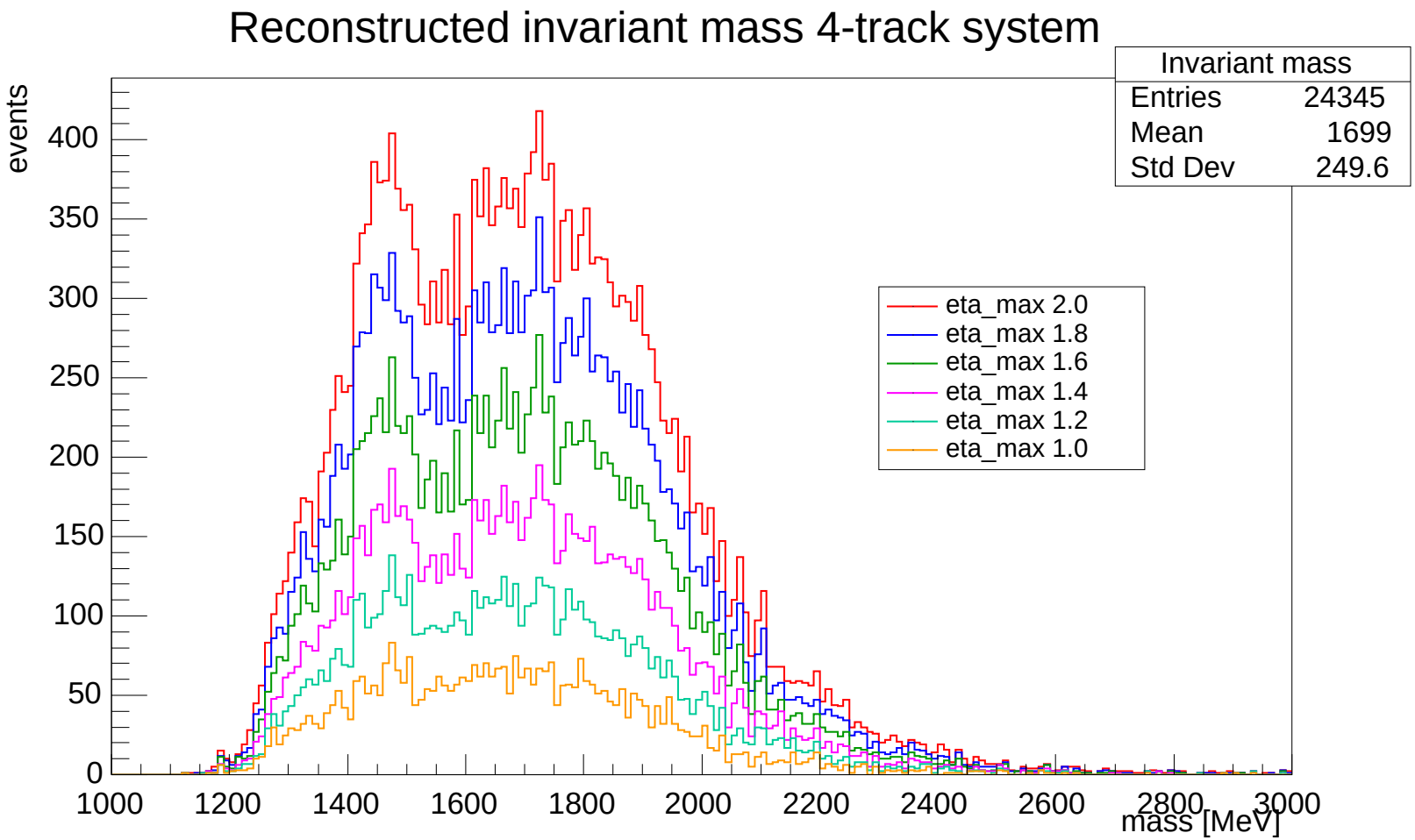
$$|\eta| < 2,\ \chi^2_{\text{zPV,dxy,dz}} < 10,\ \chi^2_\rho < 20$$

Effect of fine p_T cuts on vetoed TOTEM2



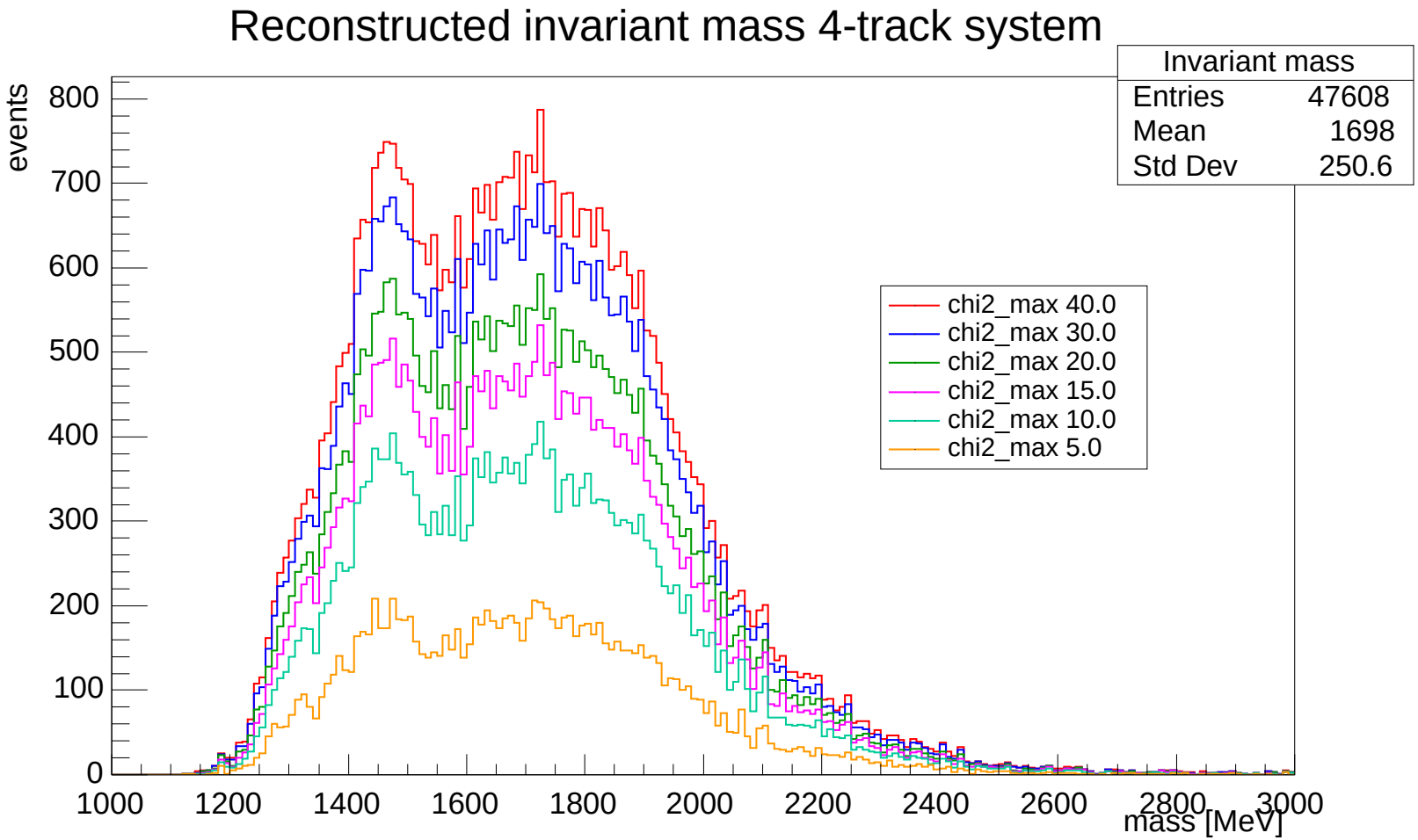
$$|\eta| < 2,\ \chi^2_{\text{zPV,dxy,dz}} < 10,\ \chi^2_{\rho} < 20$$

Effect of η cuts on vetoed TOTEM2



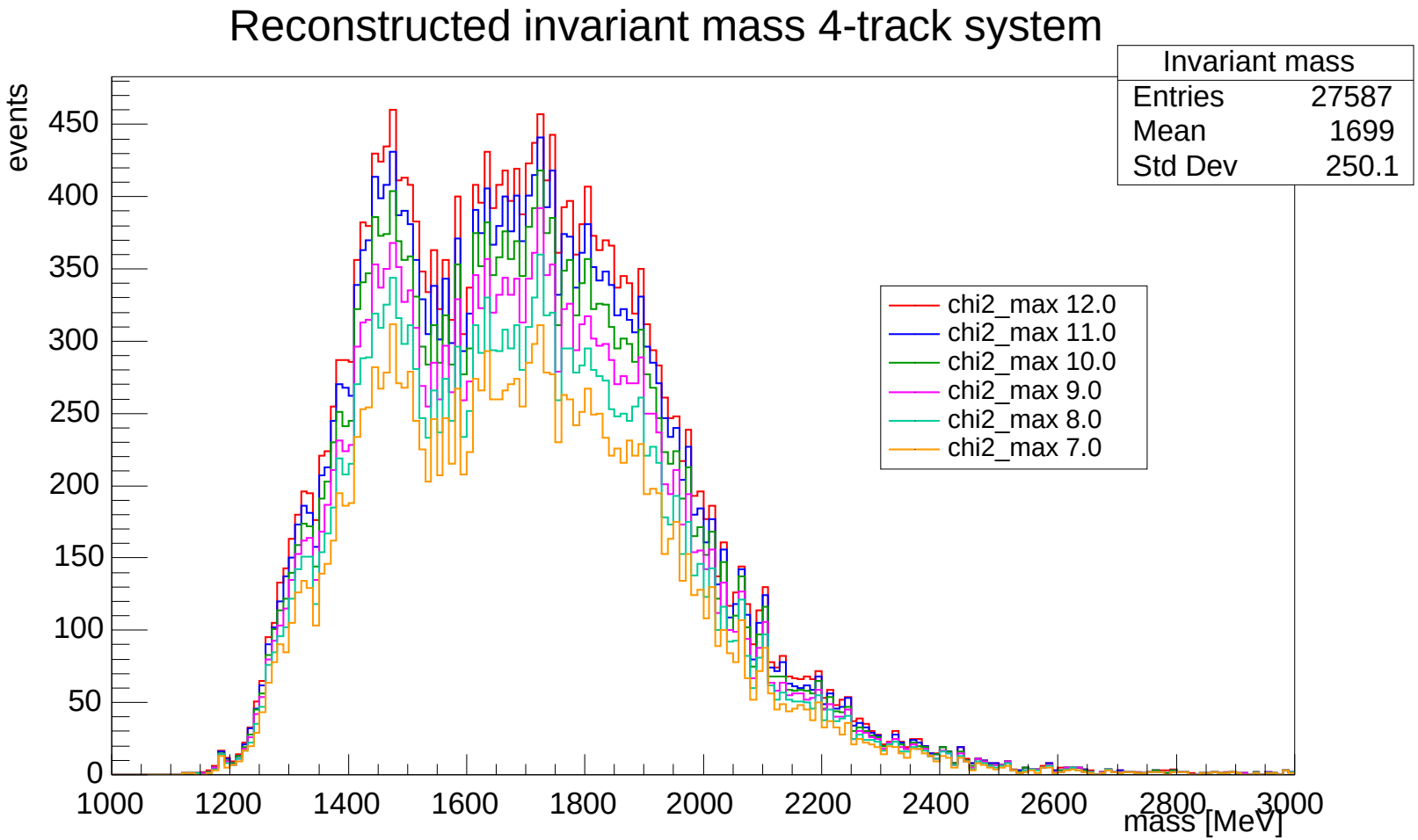
$$p_T < 0.8\,\text{GeV},\ \chi^2_{\text{zPV,dxy,dz}} < 10,\ \chi^2_\rho < 20$$

Effect of coarse $\chi^2_{\text{zPV,dxy,dz}}$ cuts on vetoed TOTEM20



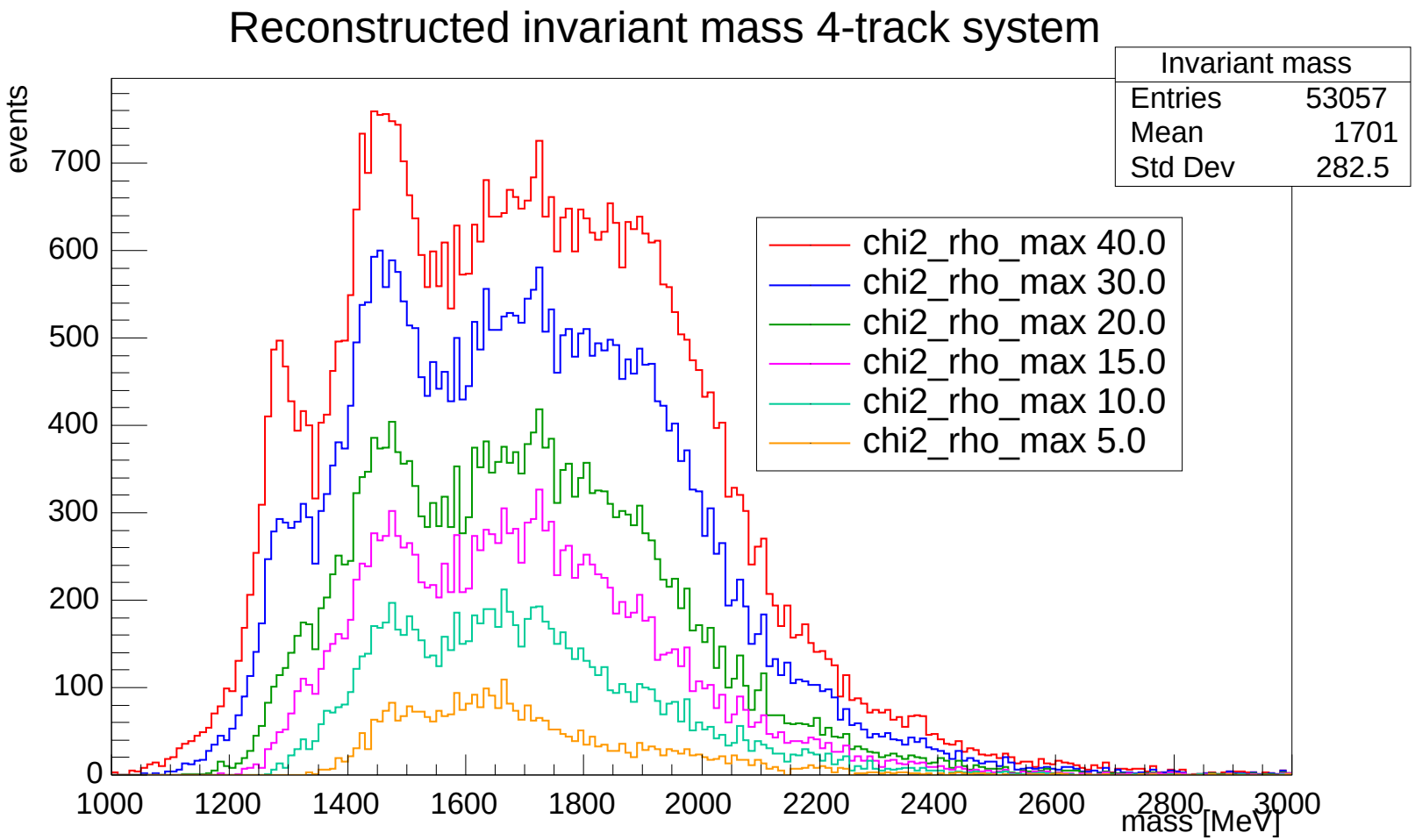
$p_T < 0.8\,\text{GeV},\ |\eta| < 2,\ \chi^2_\rho < 20$

Effect of fine $\chi^2_{\text{zPV,dxy,dz}}$ cuts on vetoed TOTEM20



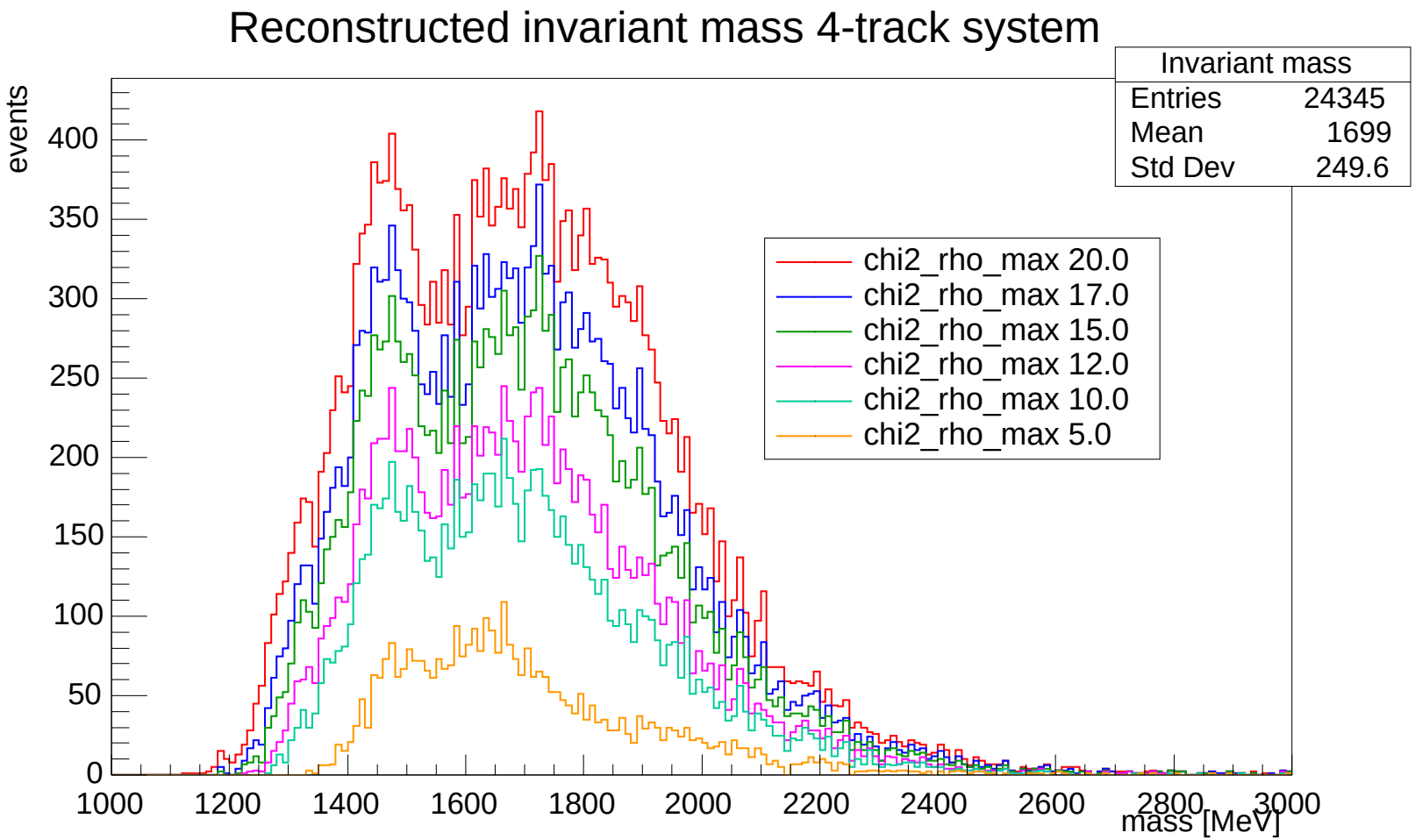
$p_T < 0.8\,\text{GeV},\ |\eta| < 2,\ \chi^2_\rho < 20$

Effect of coarse χ^2_ρ cuts on vetoed TOTEM2



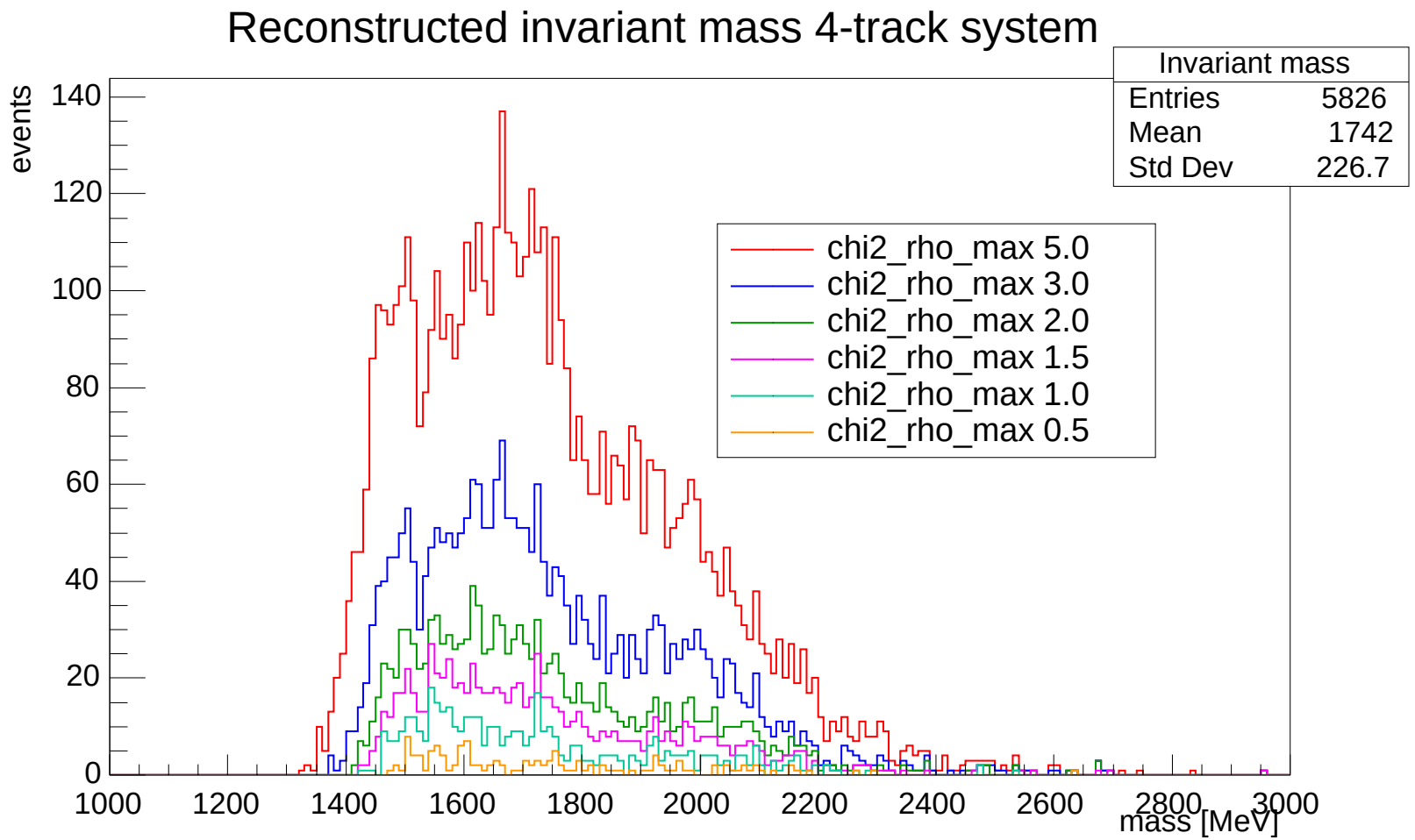
$$p_T < 0.8\,\text{GeV},\ |\eta| < 2,\ \chi^2_{\text{zPV,dxy,dz}} < 10,$$

Effect of fine χ^2_ρ cuts on vetoed TOTEM2



$$p_T < 0.8\,\text{GeV},\ |\eta| < 2,\ \chi^2_{\text{zPV,dxy,dz}} < 10,$$

Effect of superfine χ^2_ρ cuts on TOTEM4



$$p_T < 1.2\,\text{GeV},\ |\eta| < 2,\ \chi^2_{\text{zPV,dxy,dz}} < 15,$$

Some observations

- We observe that compared to the parallel configuration we have a larger number of events for the same cuts.
- Otherwise, we make the same observations as for the parallel configuration. (see Slide 39)

Conclusion

- After successfully implementing different χ^2-like variables and cutting on kinematic variables and the χ^2-like variables there seems to be no conclusive evidence for a peak in the 4-track invariant mass spectrum around the hypothesised 2.2 GeV. This is true for both the diagonal and parallel configuration.

If you have any questions regarding the contents of this presentation or my analysis in general, please contact me via email: jan.loder@helsinki.fi