Search for a pentaquark state decaying to $J/\psi\, p$

Text for the blessed web page – CDF note 7124

The CDF Collaboration

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Abstract

We search for a pentaquark state similar to the R_s^+ [1] in the weak decay channel $J/\psi\, p$ using a J/ψ data sample of $\sim$280 pb^{-1}. For our reference channel we use $B^\pm$ decaying to $J/\psi\ K^\pm$. We start with cuts used in a previous analysis of the reference channel and are able to reproduce a very similar signal in that channel. The lifetimes of the pentaquark states are not known, so for most of our search we drop the cut on the candidate's L_{xy}. This requires that we retune our cuts using a $J/\psi\, p$ Monte Carlo and side band data, maximizing $S/(1.5+\sqrt{B})$. To the retuned cuts we add a a particle ID cut for the proton combining time-of-flight and dE/dx. We search for the pentaquark state in the mass region 5.80–6.305 GeV/c^2. We look again after adding a small L_{xy} cut in case the pentaquark has a measurable lifetime. We calculate an upper limit yield in the signal region of 76.28 without the L_{xy} cut and 20.88 with it.

1 Description

In this analysis we search for the pentaquark state ($udus\bar{b}$), dubbed R_s^+ in Reference [1]. We look for the weak decay of the R_s^+ to $J/\psi\, p$. The complexity of pentaquark states has so far precluded estimates of the relative rates for the W exchange, color suppressed, and tree decay graphs so the reference recommends a comprehensive search. The $J/\psi\, p$ mode has the advantages of simplicity, a very clean J/ψ signal, and a well-understood reference channel $B^+ \to J/\psi\, K^+$. In addition CDF has both a time-of-flight detector and dE/dx measurement which we use to identify protons. The predicted mass of the R_s^+ is 5.920 GeV/c^2. This estimate has a large uncertainty so we start our signal region at 5.800 GeV/c^2 and extend it all the way up to the strong decay threshold at 6.305 GeV/c^2 ($M(B_s^0) + M(p)$). For our data sample we have about 280 pb^{-1} of J/ψ trigger data.

As a reference channel we use $B^+ \to J/\psi\, K^+$ and its charge conjugate which were the subject of a previous CDF analysis. First we replicate the signal produced in that analysis using the same set of cuts. Having done that we must derive a set of cuts for the pentaquark search. Track quality cuts remain unchanged, and the J/ψ signal is so clean that we see no benefit in changing the J/ψ cuts either. That leaves cuts on the p_T of the B (pentaquark), the p_T of the K (p), and the L_{xy} of the B (pentaquark). As the lifetime of the pentaquark is unknown we drop the L_{xy} for the search proper. That is a powerful cut to drop so we must retune the p_T cuts on a Monte Carlo sample in order to regain significance. All our Monte Carlo samples were prepared by applying the full simulation of the CDF detector to the output of the event generator.

We apply each set of cut values to Monte Carlo to calculate the signal S. We also apply them to data sidebands to get a function which from which we derive the background B. We tune to maximize the score function $S/(1.5 + \sqrt{B})$ [2]. This function is good for new signal searches since the scaling of S does not affect the position of the maximum; we do not need to rescale the Monte Carlo signal. Using this procedure we find that we can still get a good B signal, albeit with more background than before. This gives us confidence that a similar tuning procedure gives cuts that retain much of any pentaquark signal present. We present our results using the final tuned cuts with proton identification.

It could well be that a bottom pentaquark has a measurable lifetime or that most of the pentaquarks are not made at the primary vertex. Therefore we also show what happens if we apply a cut on the pentaquark L_{xy}. We make the cut at 100 μm which is routinely used at CDF in B meson analyses.

For particle identification CDF has developed a likelihood ratio LH which combines information from both the time-of-flight detector and from dE/dx measurements in the central drift chamber. We retain pentaquark candidates for which the proton track has LH(proton) $= 0.4$; that value was determined by analyzing a sample of Λ_c.

- $\mathrm{LH(j)} = \frac{\mathrm{L(j)}}{\sum_{\mathrm{i}} \mathrm{L(i)}}$
- $\mathrm{L(i)} = \exp(-\chi^2(\mathrm{i})/2)$
- $\chi^2(\mathrm{i}) = \mathrm{Pull}^2(\mathrm{i};\ \mathrm{dE/dx}) + \mathrm{Pull}^2(\mathrm{i};\ \mathrm{TOF})$
- $\mathrm{Pull(i;mode)} = \frac{\mathrm{measured(mode)} - \mathrm{expected(i;mode)}}{\mathrm{error(i;mode)}}$
- $\mathrm{i} \in \{$ proton, kaon, pion, muon, electron$\}$

Our search results are the distributions of the mass of $J/\psi\, p$ with particle ID applied to the proton and no cut on the L_{xy} of the pentaquark candidate. For each mass bin we also show the upper limit on signal calculates as follows:

- Unbinned likelihood fit of Gaussian signal and exponential background
  - Background ranges from 5.725–6.380 GeV/c^2
  - Mass constrained to 5 MeV/c^2 center $\pm$ 2.5 MeV/c^2
  - Width is constrained to $\sigma(M) \pm 1$ MeV/c^2
- χ^2 probability renormalized to only include positive signal
- 90% confidence level then calculated.

References

[1] I. Stewart, M. Wesling, M. Wise, "Stable Heavy Pentaquark States", hep-ph/0402076, 9 Feb 2004.

[2] G. Punzi, "Sensitivity of searches for new signals and its optimization", physics/0308063, 4 Dec 2003.

2 Results and conclusions

We have searched a 280 pb^{-1} J/ψ sample for a pentquark decaying into $J/\psi\, p$ in the mass region 5.80–6.305 GeV/c^2. We found no signal and have therefore calculated 90% CL upper limits on signal as a function of mass. The largest signal upper limit obtained using proton identification without an L_{xy} cut was 76.28. With an L_{xy} cut of 100 μm added the largest upper limit was 20.88.

3 Blessed figures

The following figures have been blessed for this analysis. More text can be found in CDF note 7124

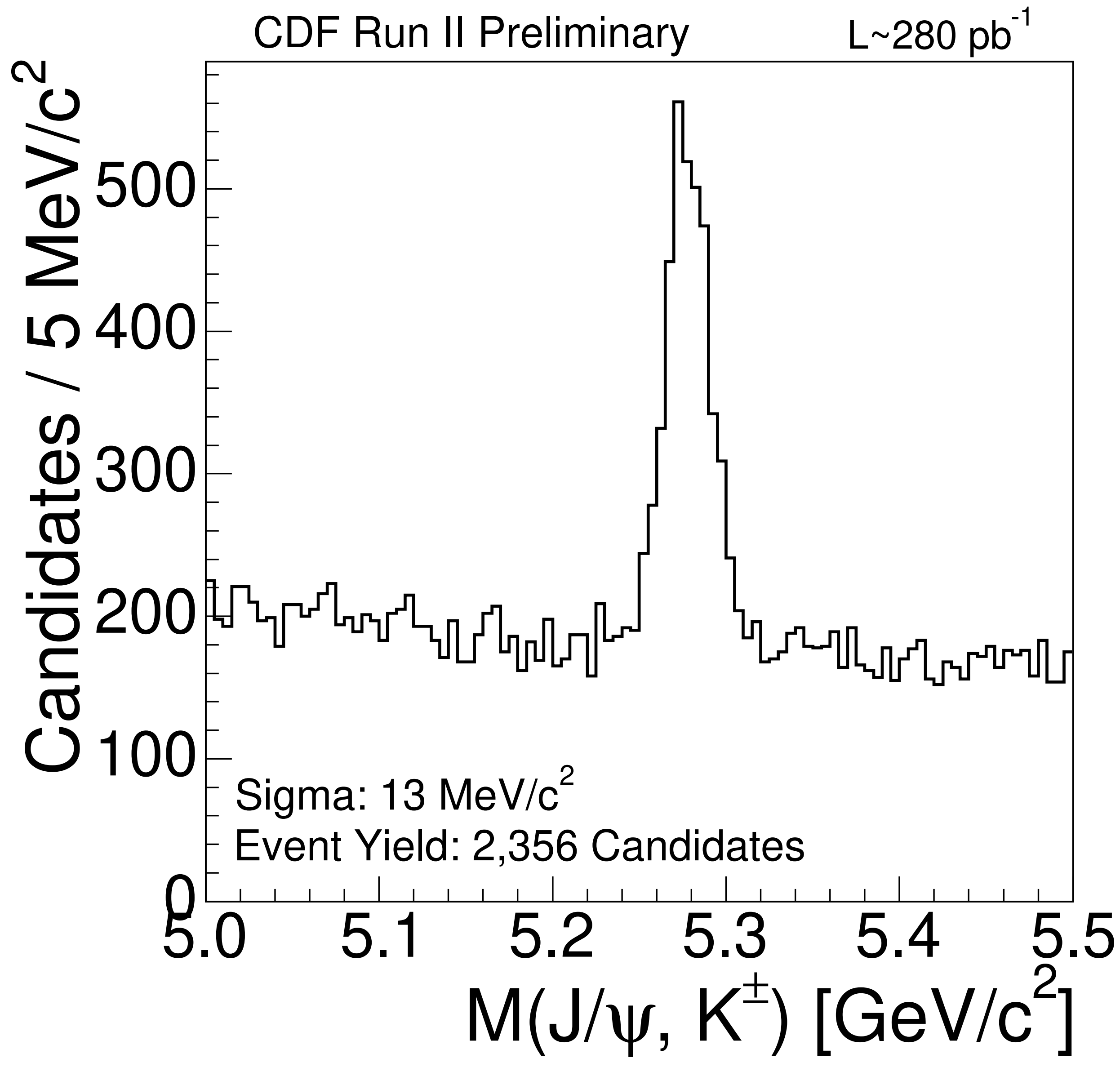

Figure 1: Reconstructed $B^{\pm}$ mass using pentaquarks cuts (no cuts on the particle ID or L_{xy}).

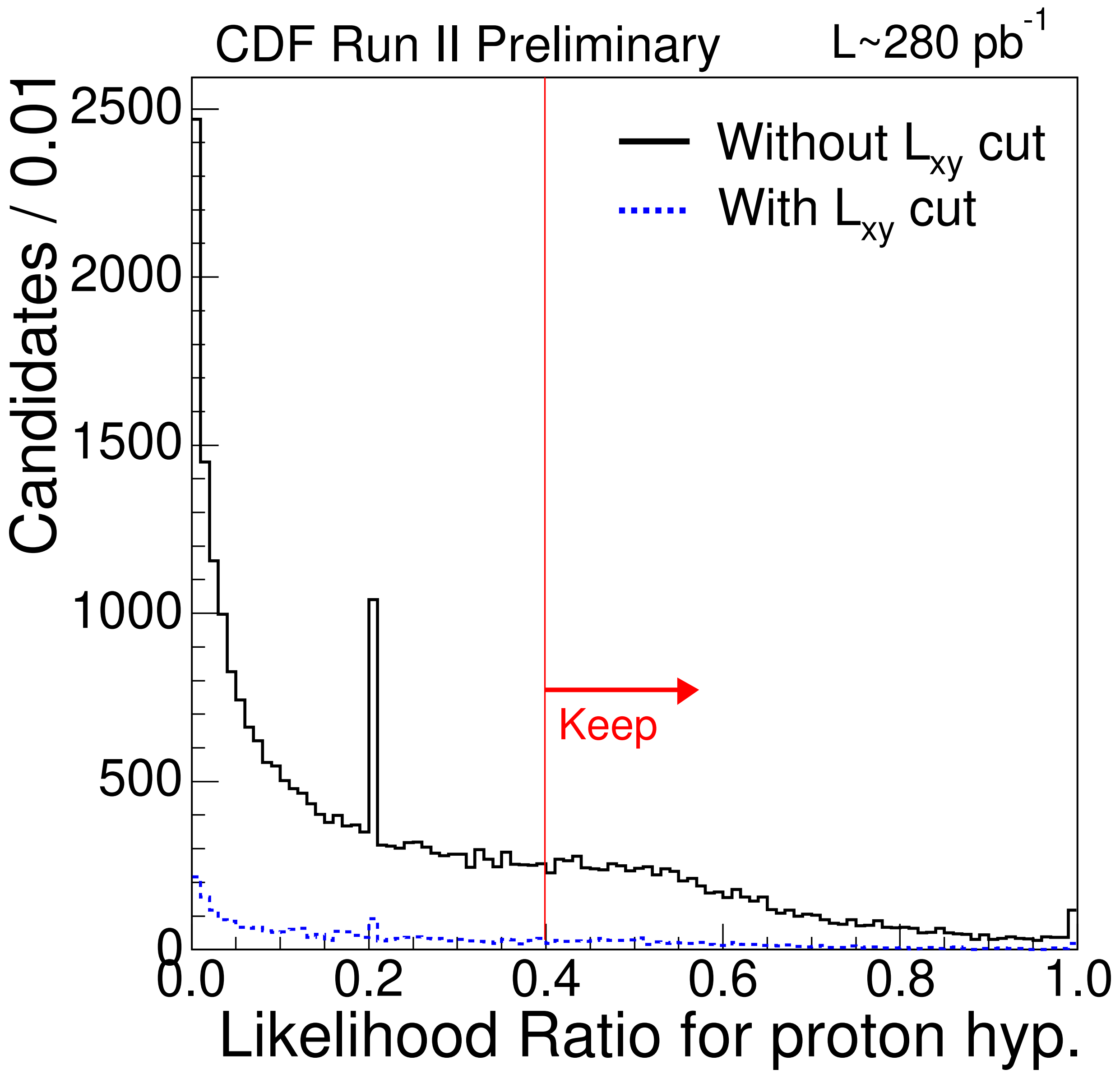

Figure 2: The proton hypothesis likelihood ratios cut after all other cuts have been applied. The bottom plot is with the L_{xy} cut applied and the top plot is without.

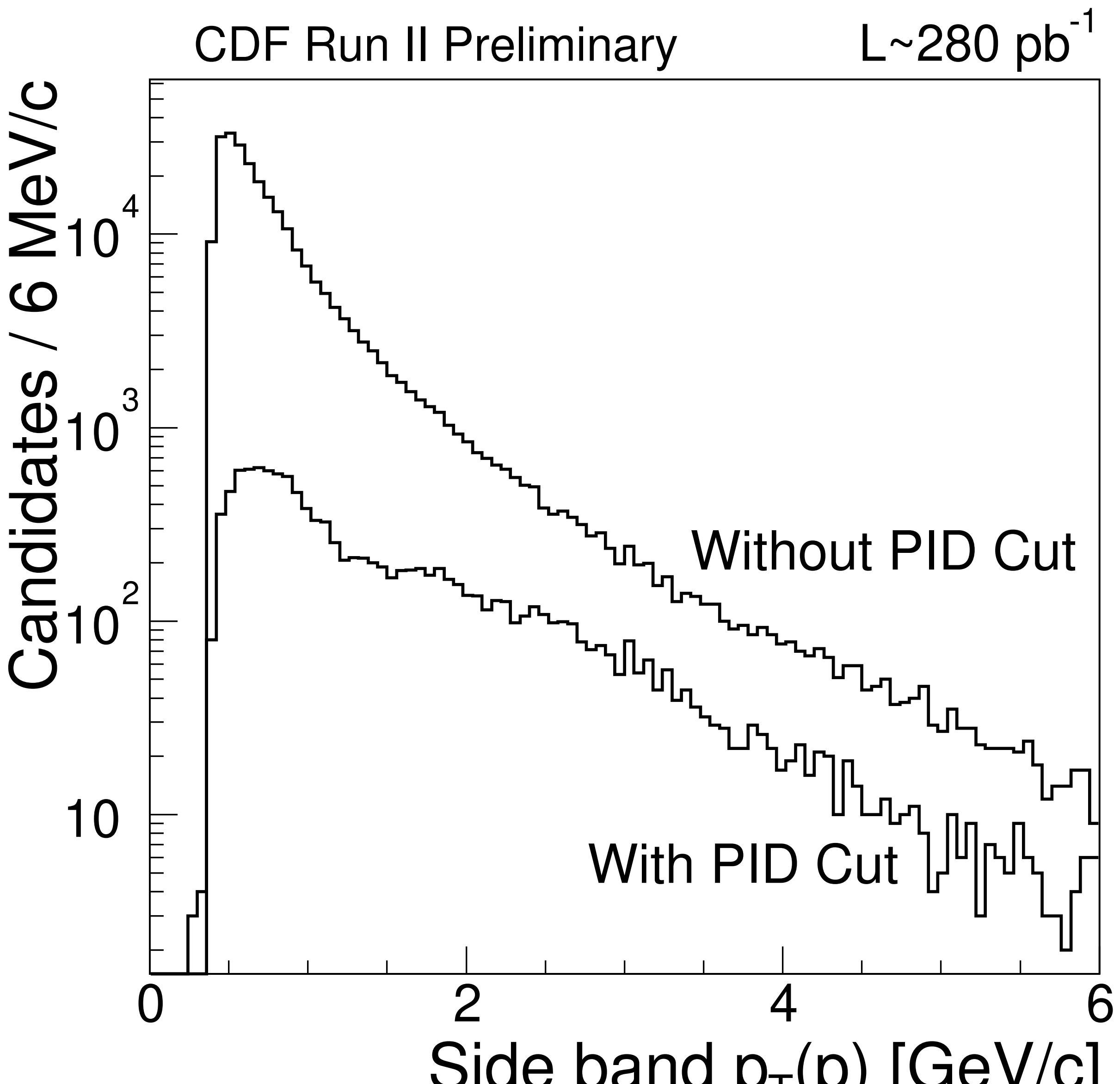

Figure 3: The proton side band p_T spectra before and after the particle ID cut. There is no L_{xy} cut applied.

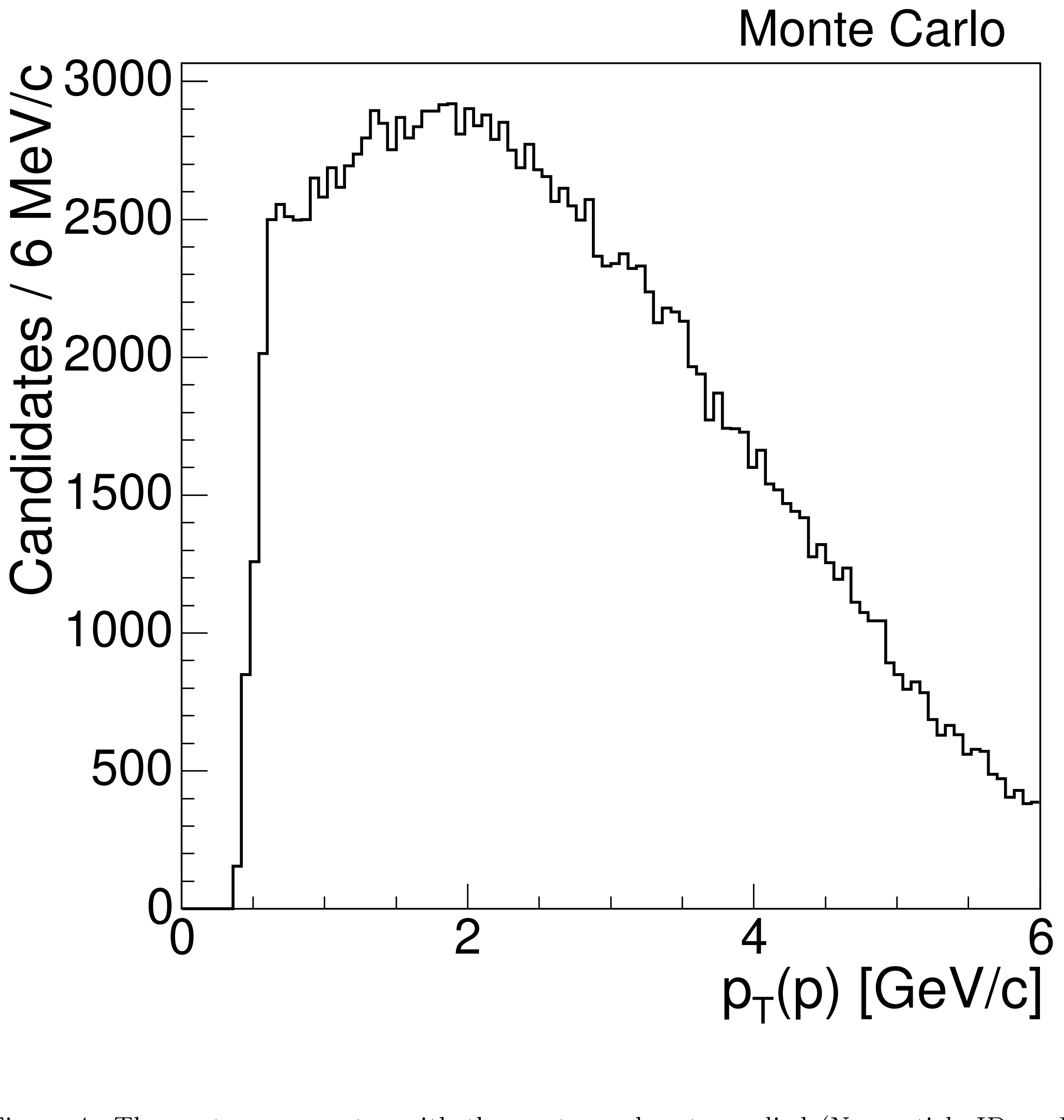

Figure 4: The proton p_T spectra with the pentaquark cuts applied (No particle ID or L_{xy} cuts).

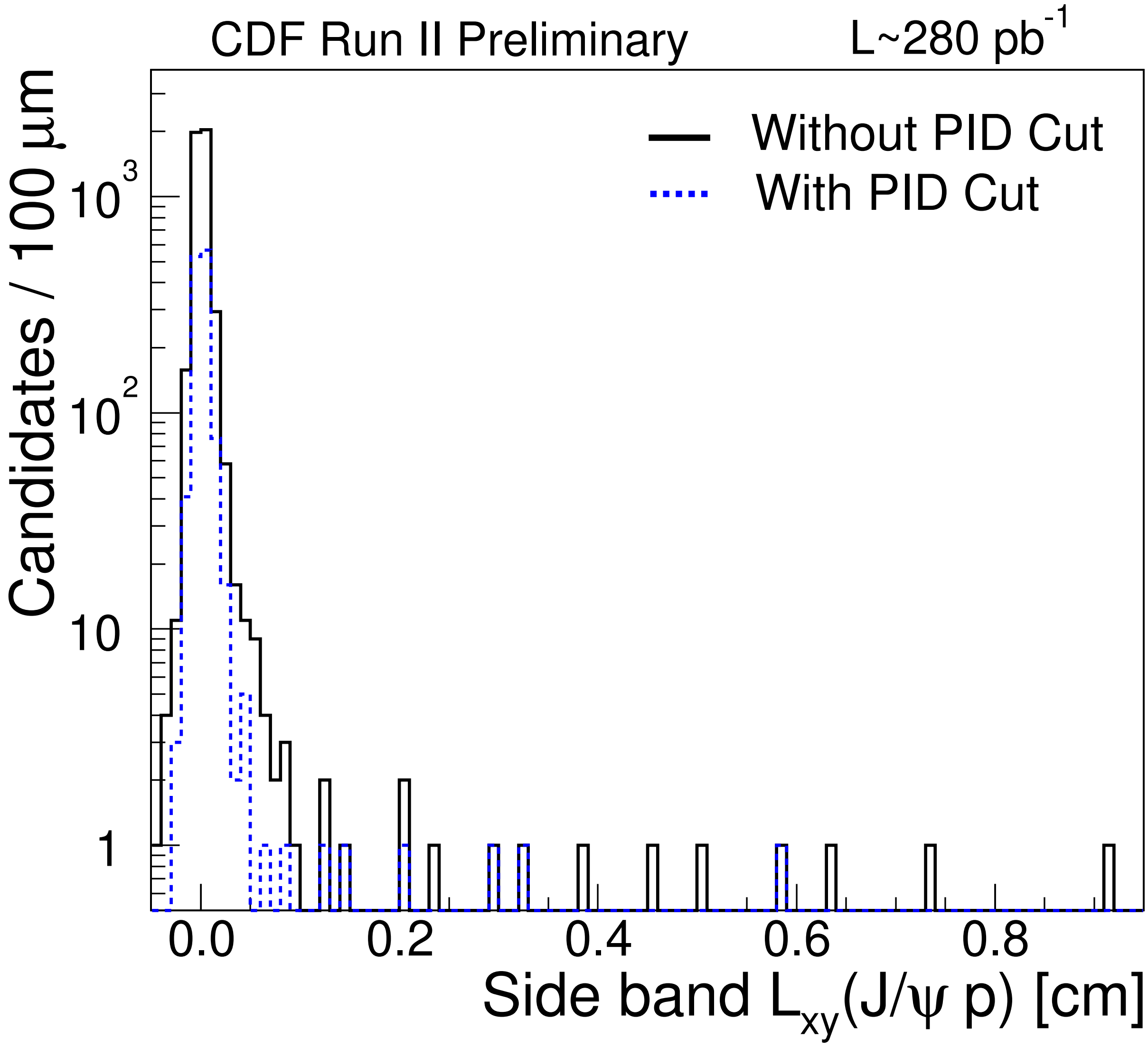

Figure 5: The pentaquark L_{xy} spectra before and after the particle ID cut.

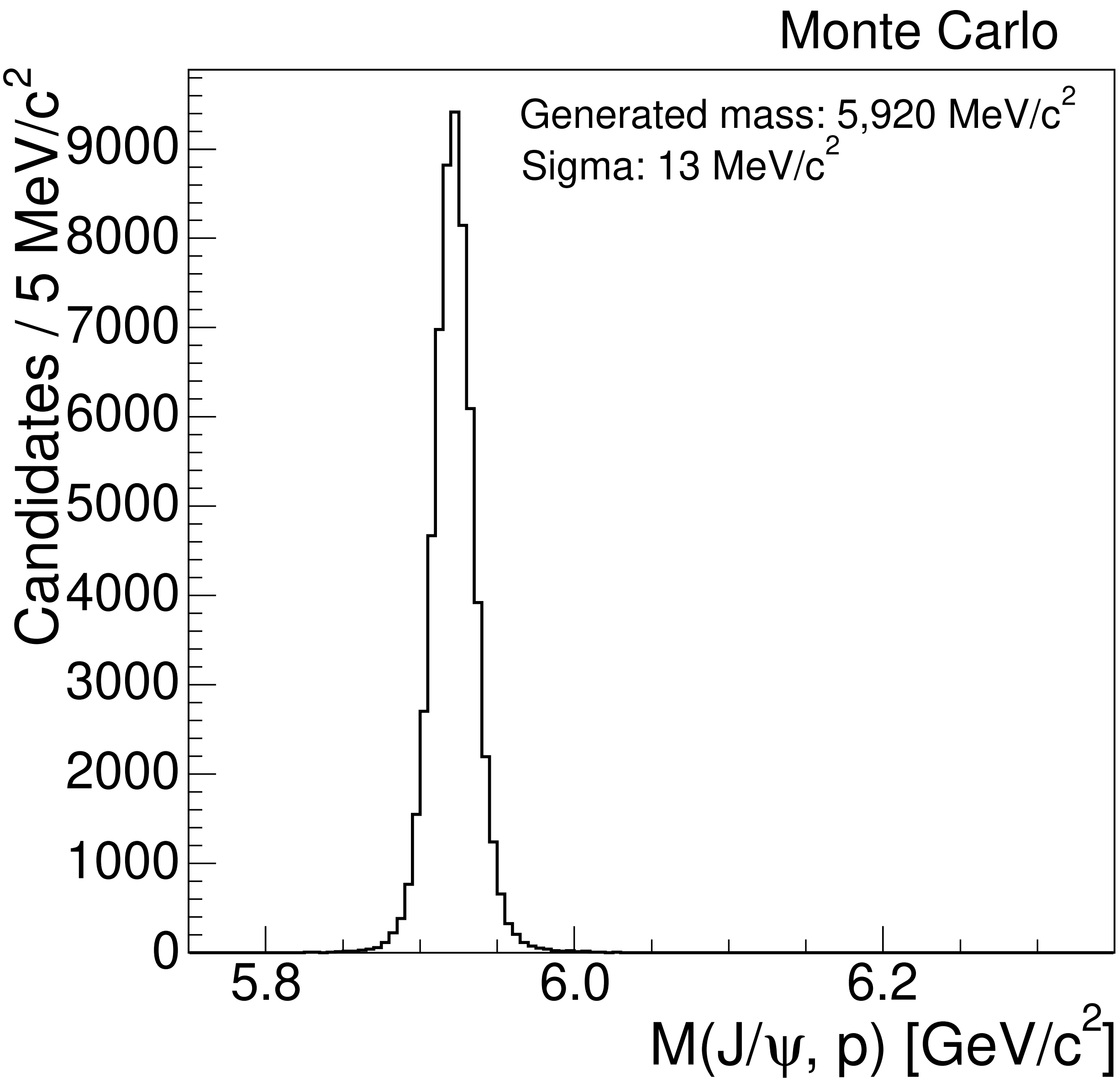

Figure 6: The reconstructed Monte Carlo pentaquark mass plot with pentaquark cuts applied (no particle ID or L_{xy} cuts).

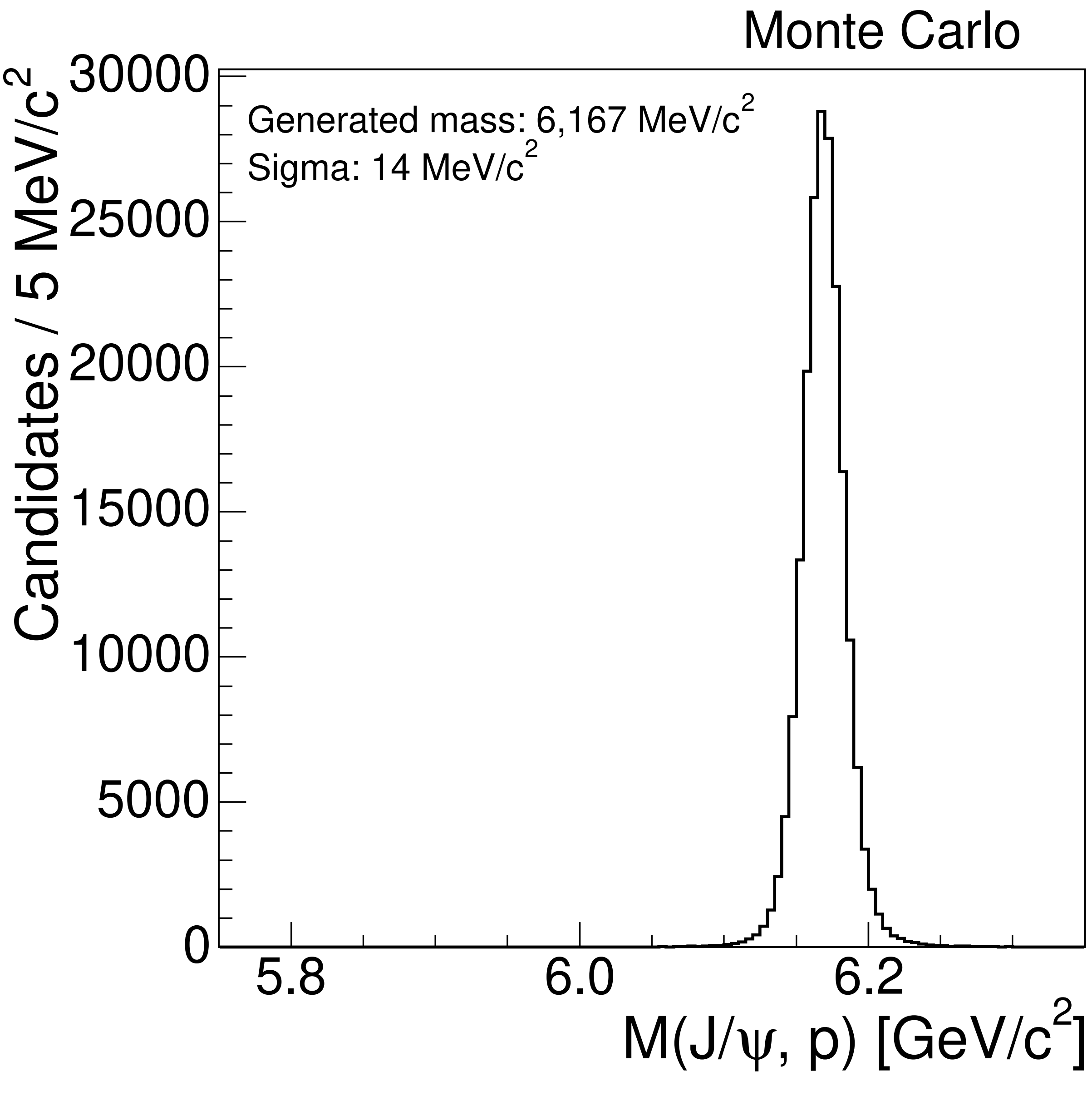

Figure 7: The reconstructed Monte Carlo pentaquark mass plot with pentaquark cuts applied (no particle ID or L_{xy} cuts).

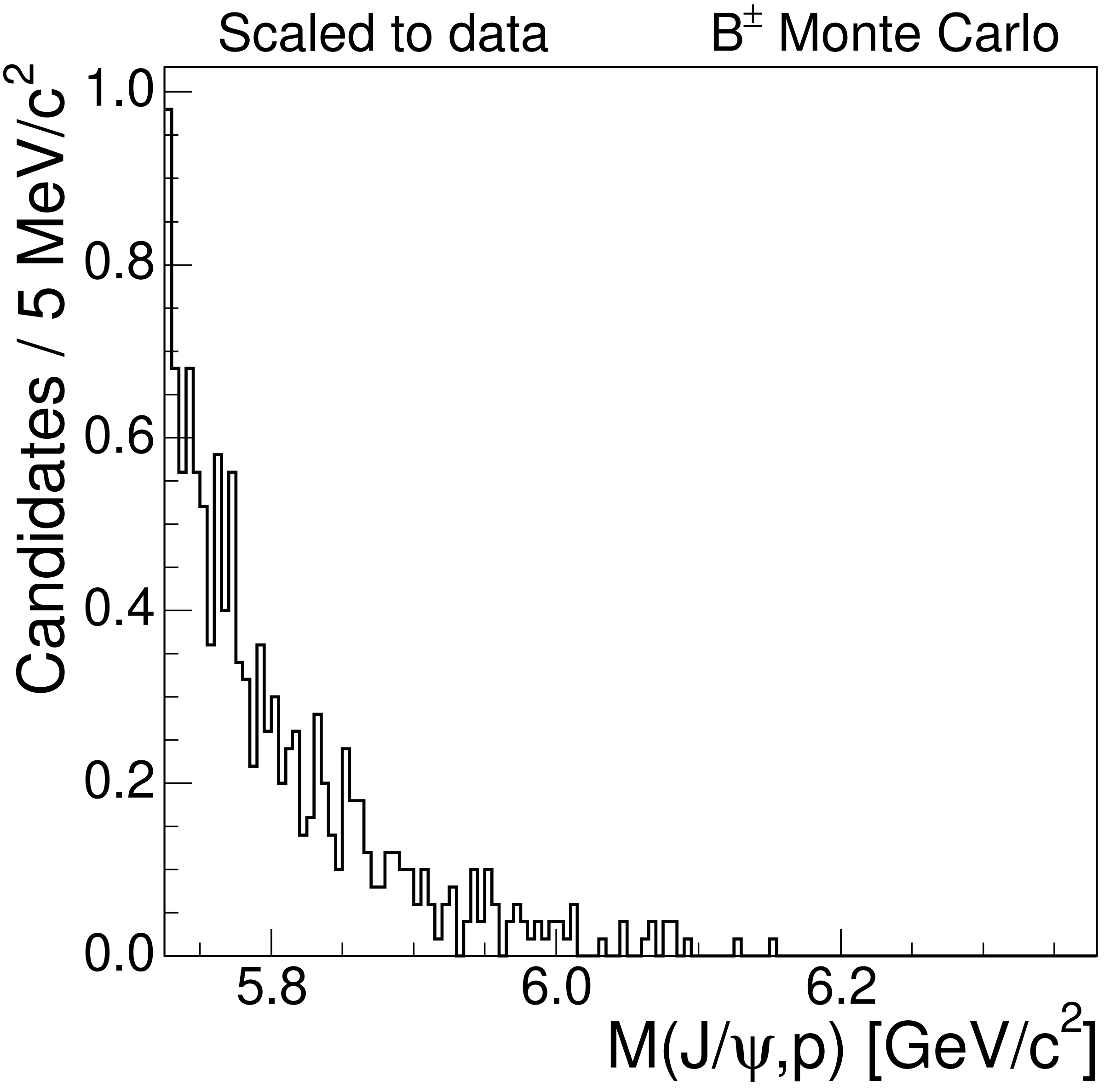

Figure 8: The reconstructed B Monte Carlo with signal scaled to data with pentaquark cuts (no particle ID or L_{xy} cuts) applied.

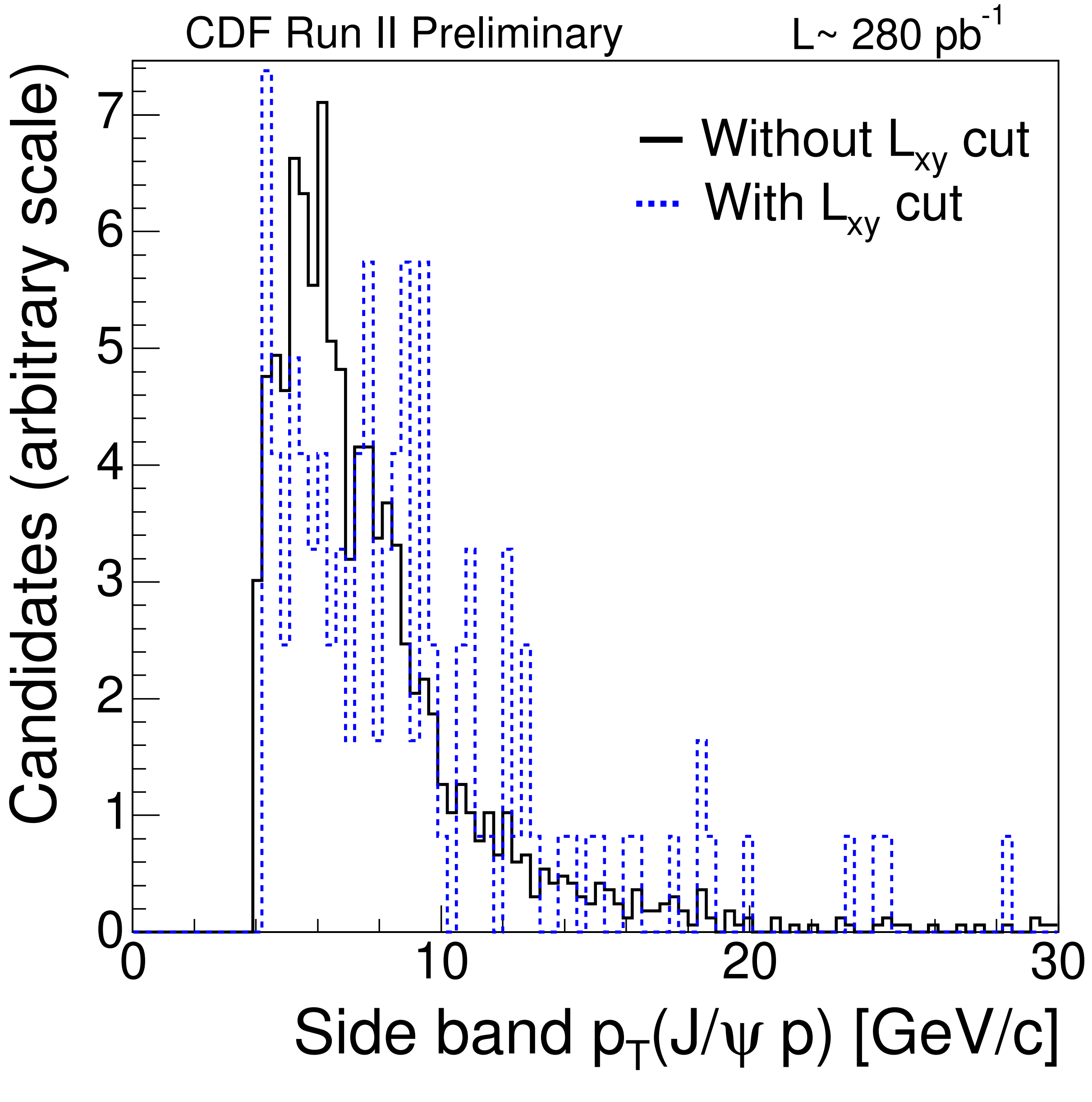

Figure 9: Pentaquark side band p_T spectra from data with (lower) and without (upper) the L_{xy} cut.

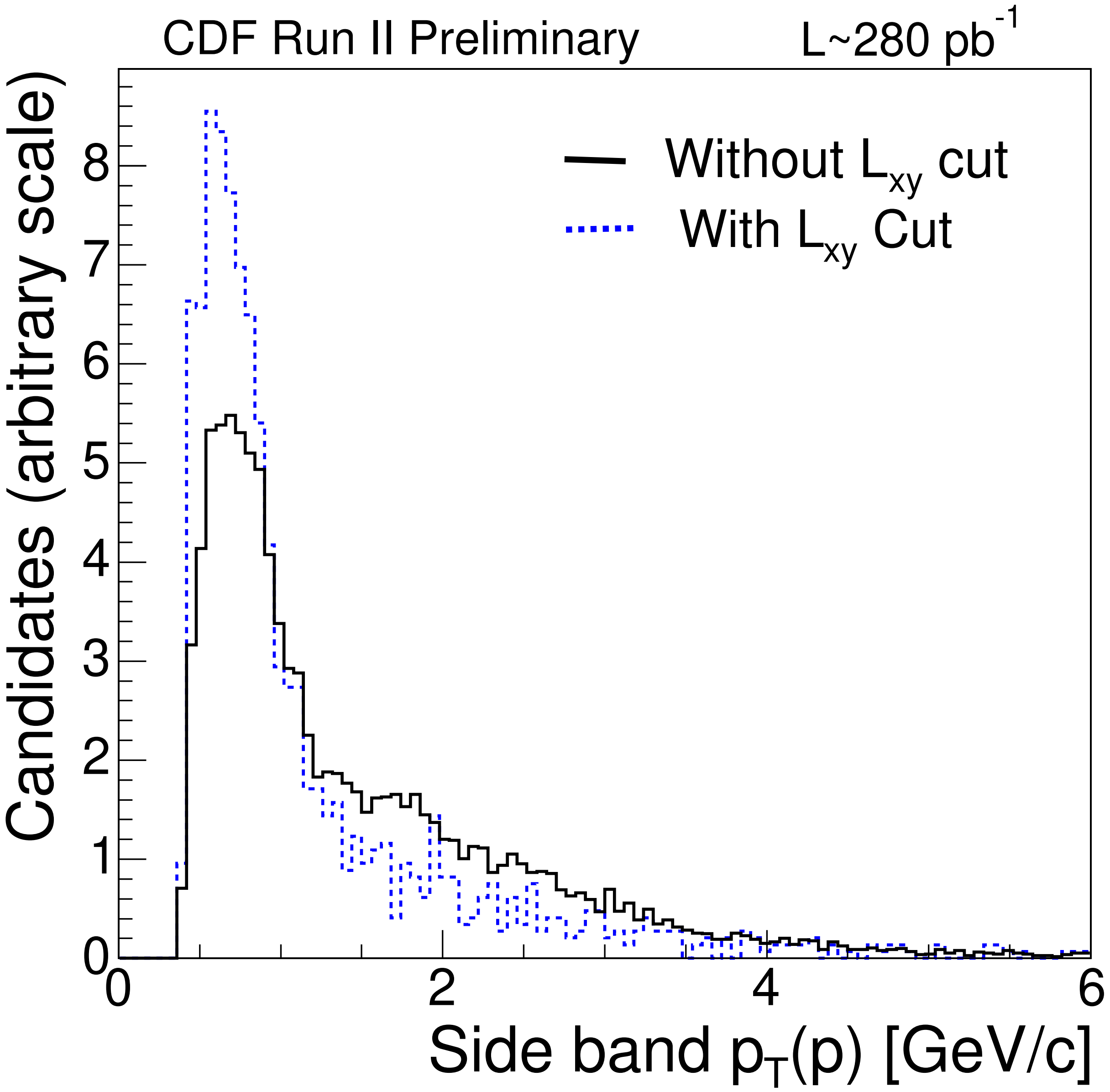

Figure 10: p side band p_T spectra from data with (lower) and without (upper) the L_{xy} cut.

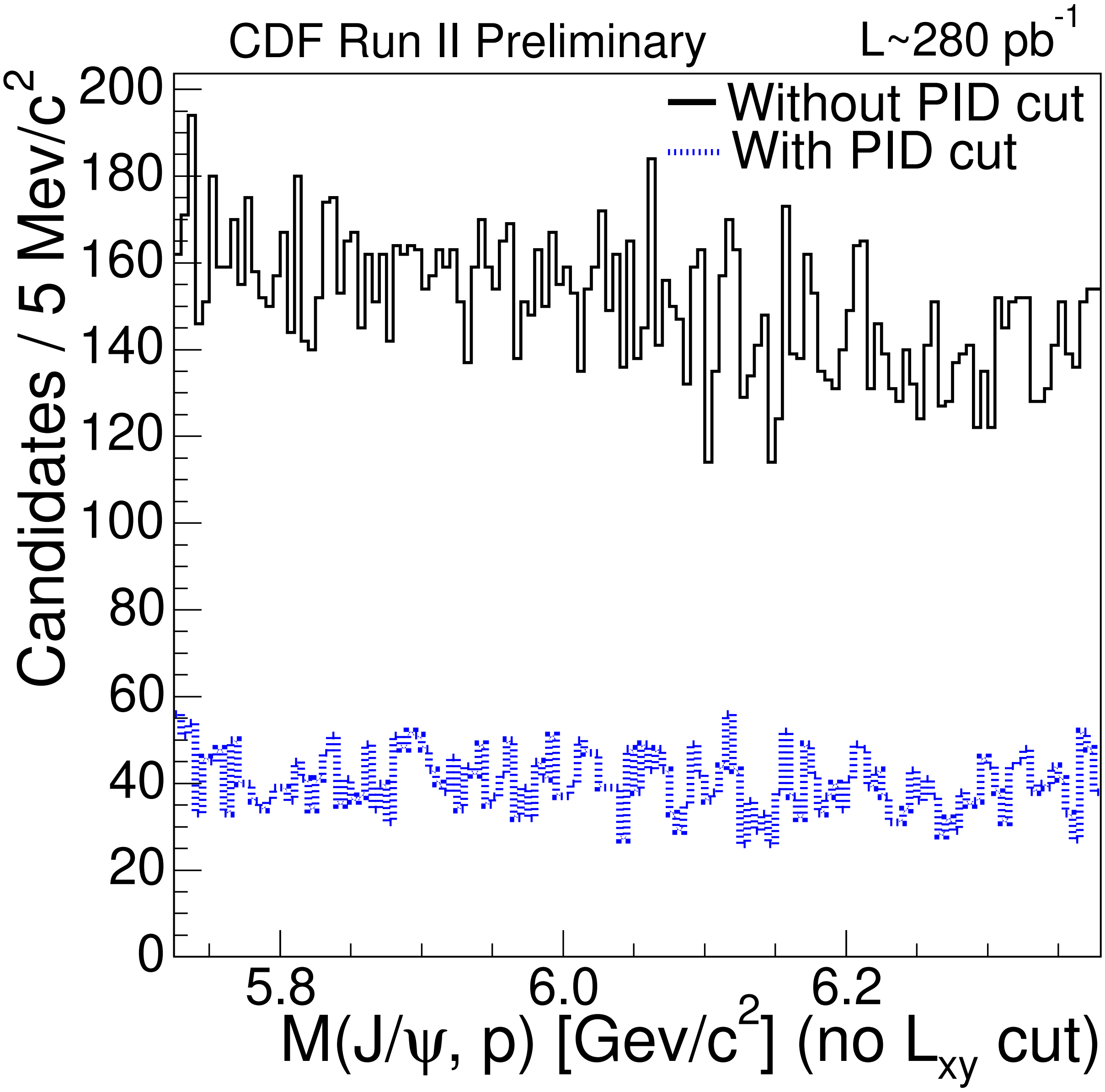

Figure 11: The pentaquark state mass plot with no L_{xy} cut before (upper) and after (lower) particle ID Cut.

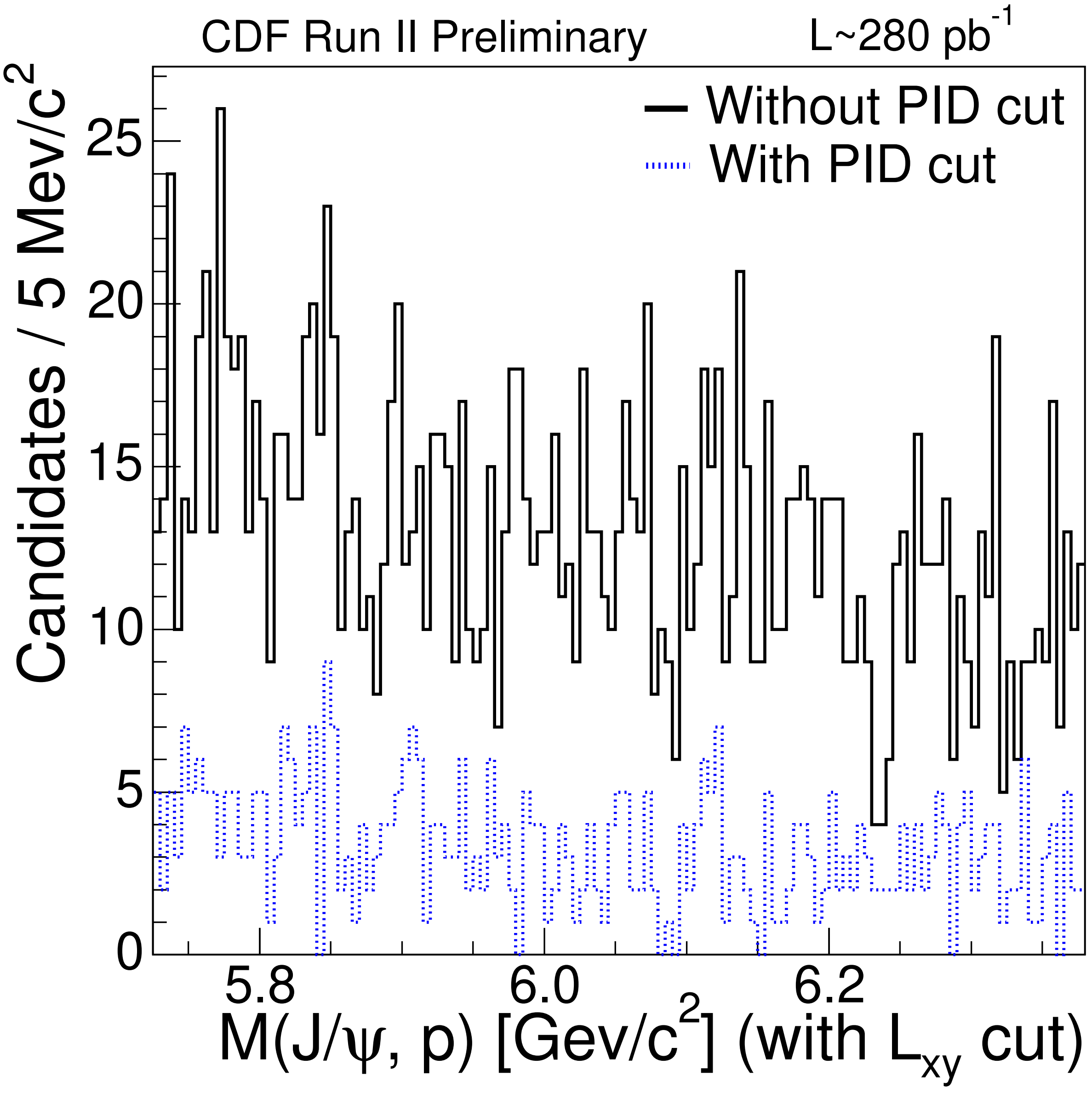

Figure 12: The pentaquark state mass plot with L_{xy} cut before (upper) and after (lower) particle ID Cut.

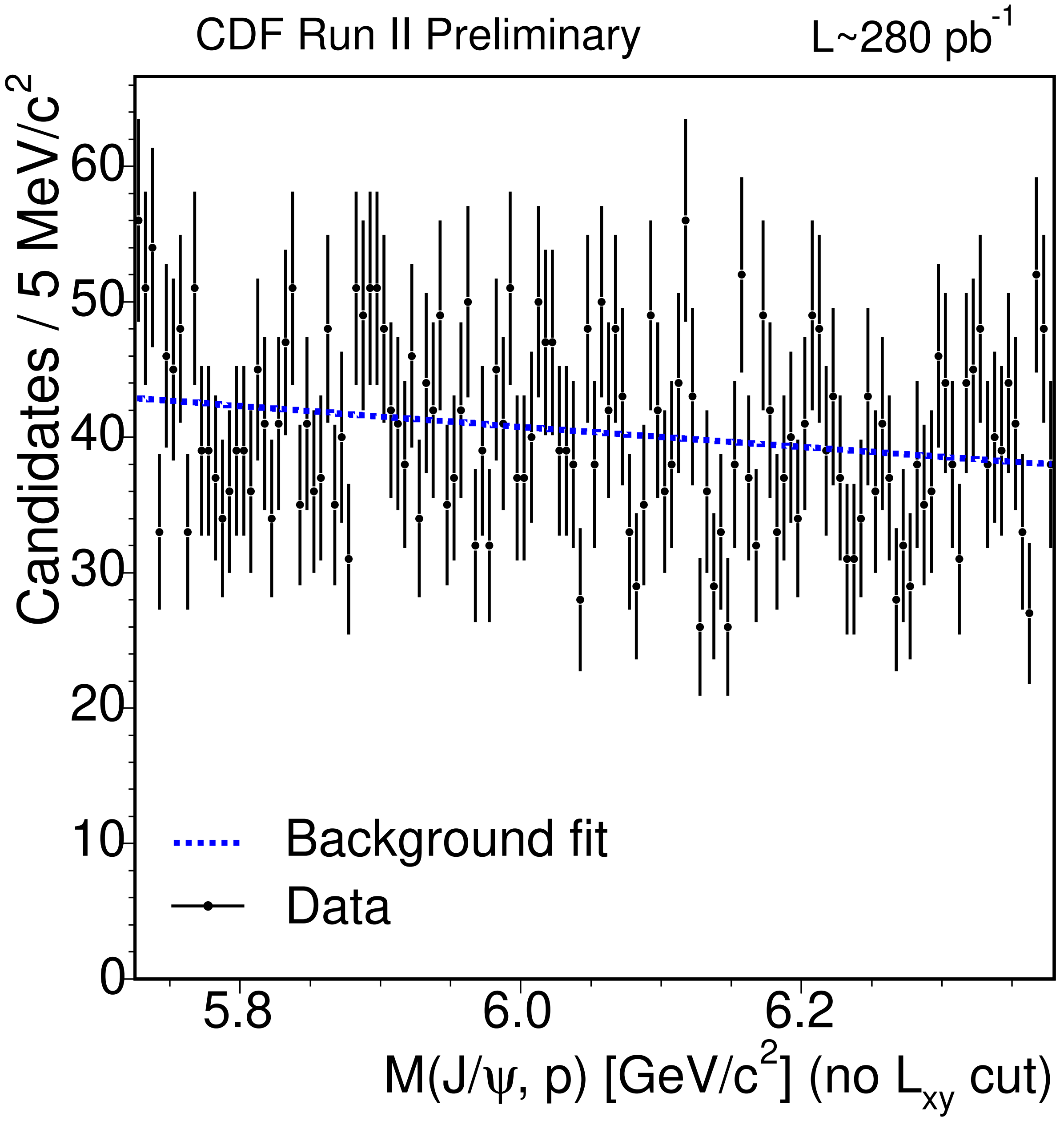

Figure 13: The mass plot with particle ID and no L_{xy} cut, fit to an exponential background.

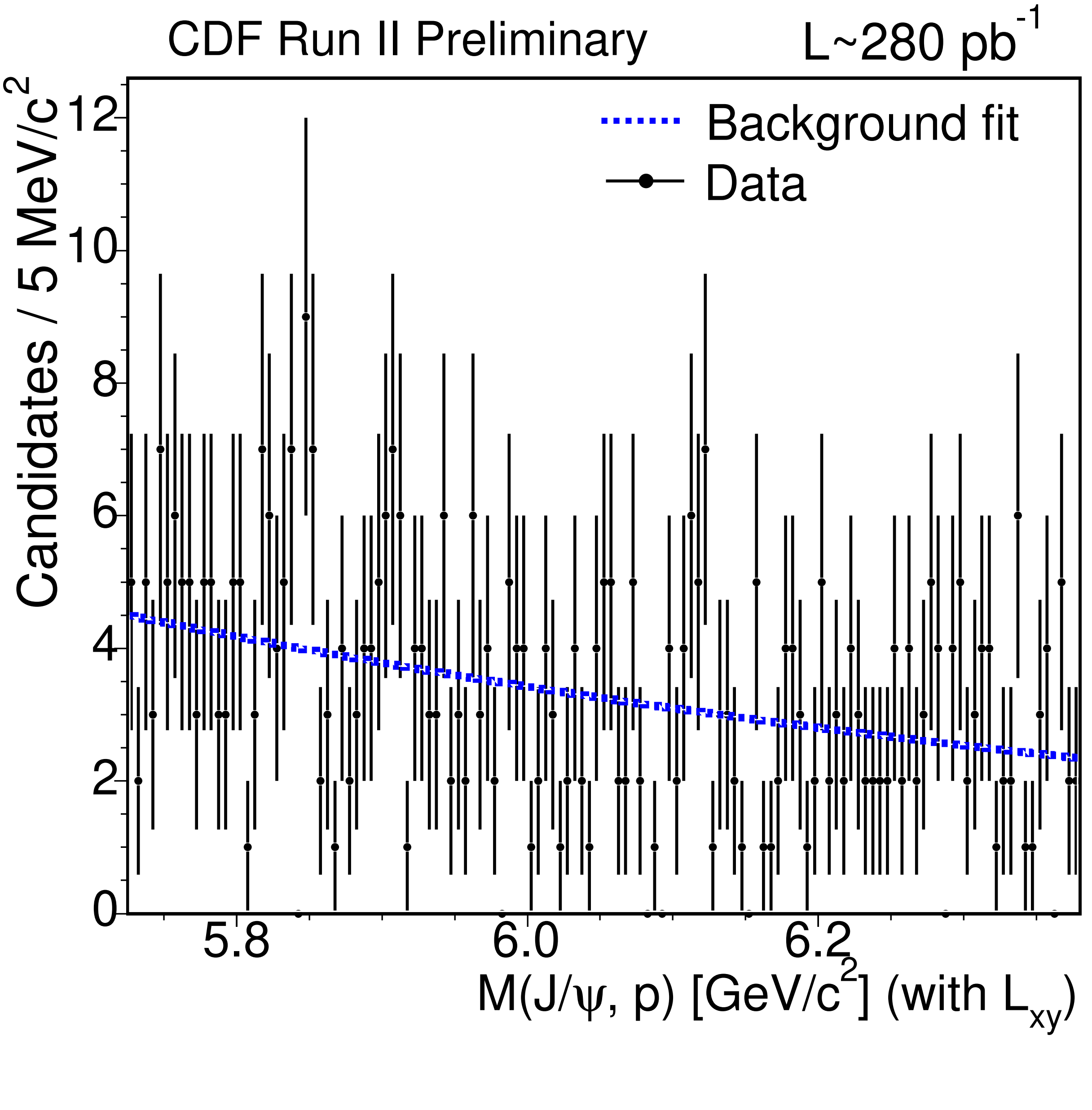

Figure 14: The mass plot with particle ID and L_{xy} cut, fit to an exponential background.

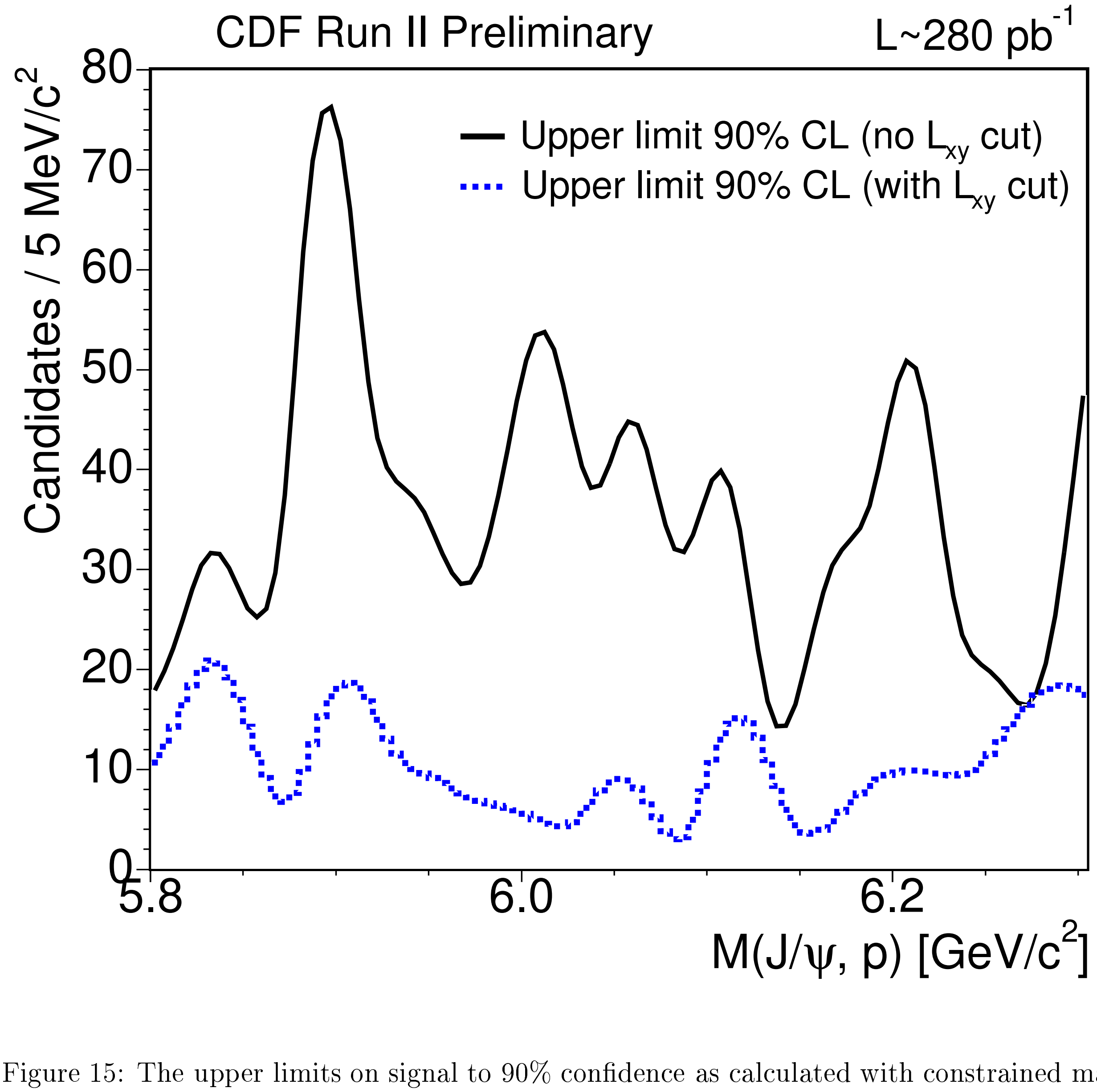

Figure 15: The upper limits on signal to 90% confidence as calculated with constrained mass and width and exponential background. Limits are shown both with and without the 100 μm cut on L_{xy}.