Studying the Production Mechanism of the N^* and Δ in Proton-Proton Collisions using HADES data

MESON 2026

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[3]Forschungszentrum Jülich

Why N* and Δ?

- “They are the simplest system in which the quintessential **non-Abelian character** of QCD is manifest”[1].

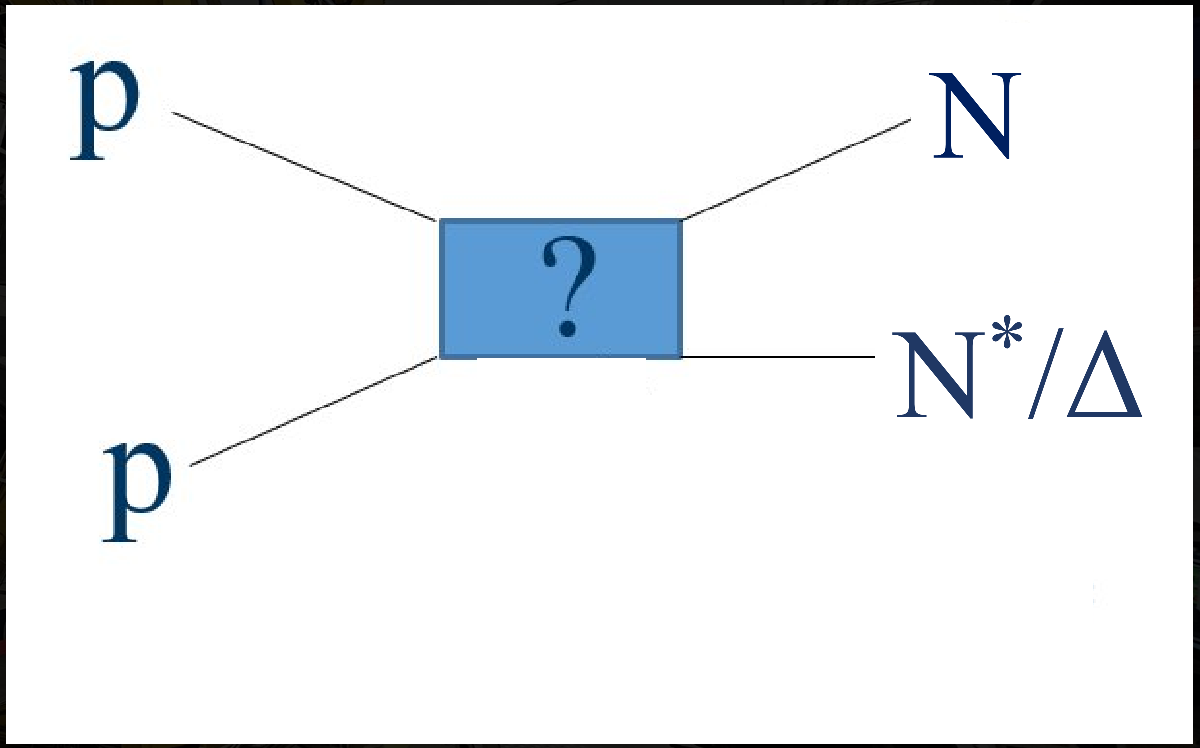
1.N. Isgur, in: V. Burkert, L. Elouadrhiri, J. Kelly, R.M. (eds.) (Eds.), NSTAR2000: Excited Nucleons and Hadronic Structure, Newport News, USA, 2000, pp. 422–445, arXiv:nucl-th/0007008.
2.Volker Burkert, Gernot Eichmann, Eberhard Klempt,Progress in Particle and Nuclear Physics, Volume 146, Part 2,2026, https://doi.org/10.1016/j.ppnp.2025.104214.

Why N* and Δ?

- "They are the simplest system in which the quintessential **non-Abelian character** of QCD is manifest"[1].

- Understanding **the production mechanisms and dynamical behavior** of these resonances is a key objective of this study.

- What is the relationship between **dynamically generated resonances** and **quark-model states**[2]?



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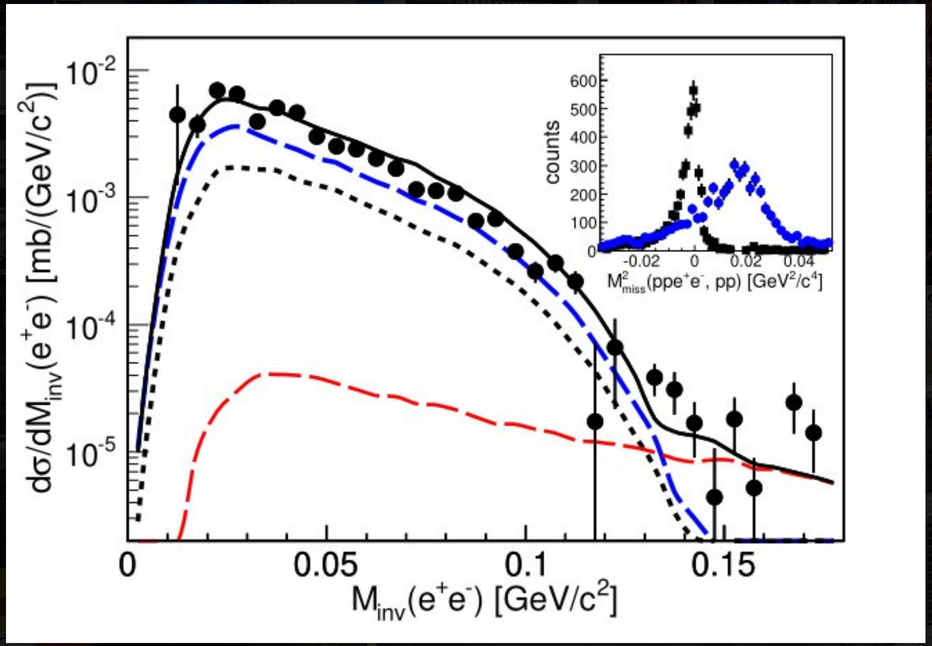
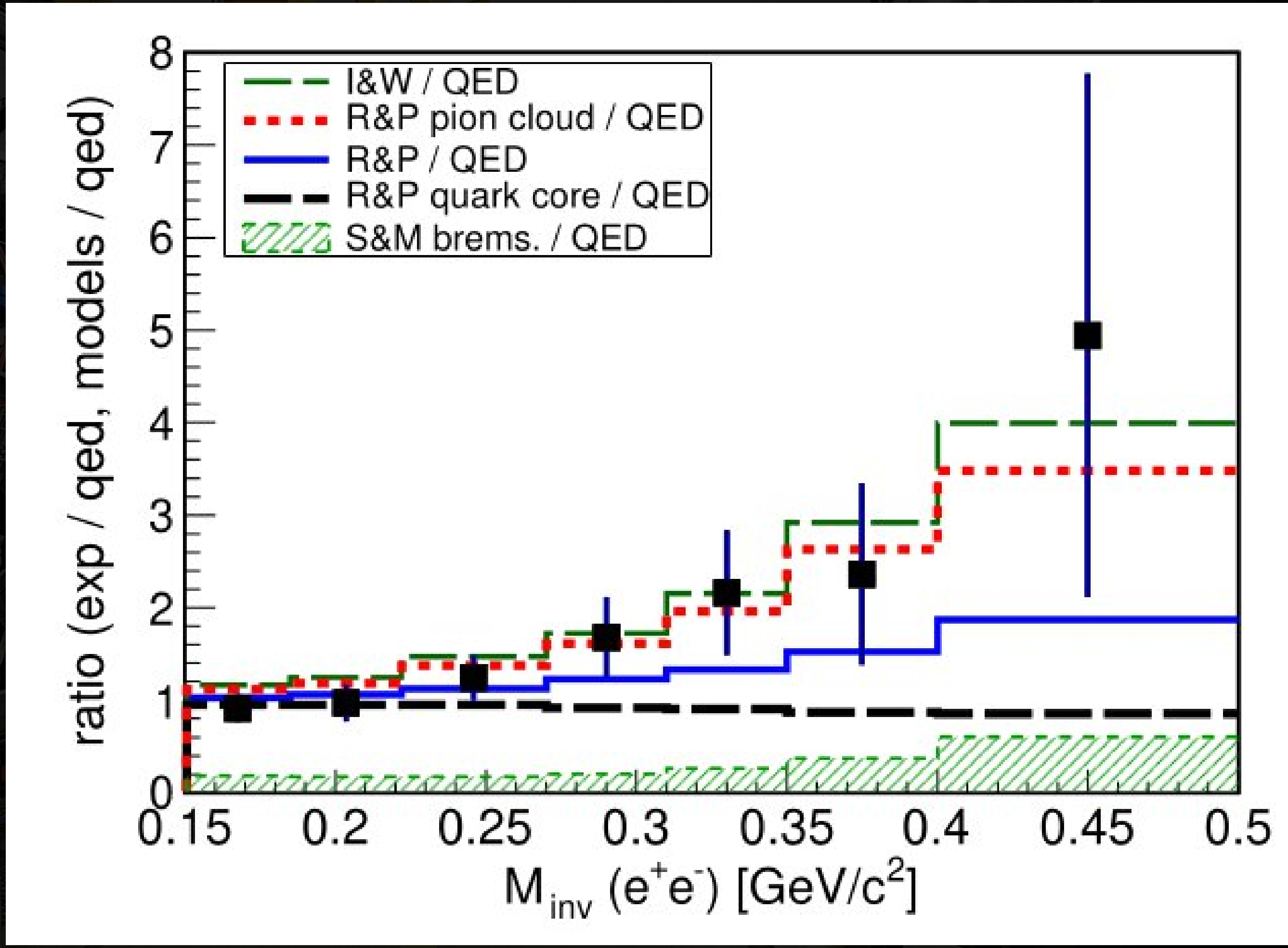
Towards Studying the Electromagnetic Properties of Light Baryons

- **Production mechanisms** and **reaction dynamics** of N* and Δ states in $pp \rightarrow NN\pi$ provide access to their **electromagnetic structure** through **dilepton decays**.



contribution of Δ and N(1440)[3]



effective transition form factor for $\Delta \rightarrow pe^+e^-$ [3]

3.Adamczewski-Musch, J. *et al.* Δ(1232) Dalitz decay in proton-proton collisions at T=1.25 GeV measured with HADES at GSI. *Phys. Rev. C* 95, 065205 (2017).

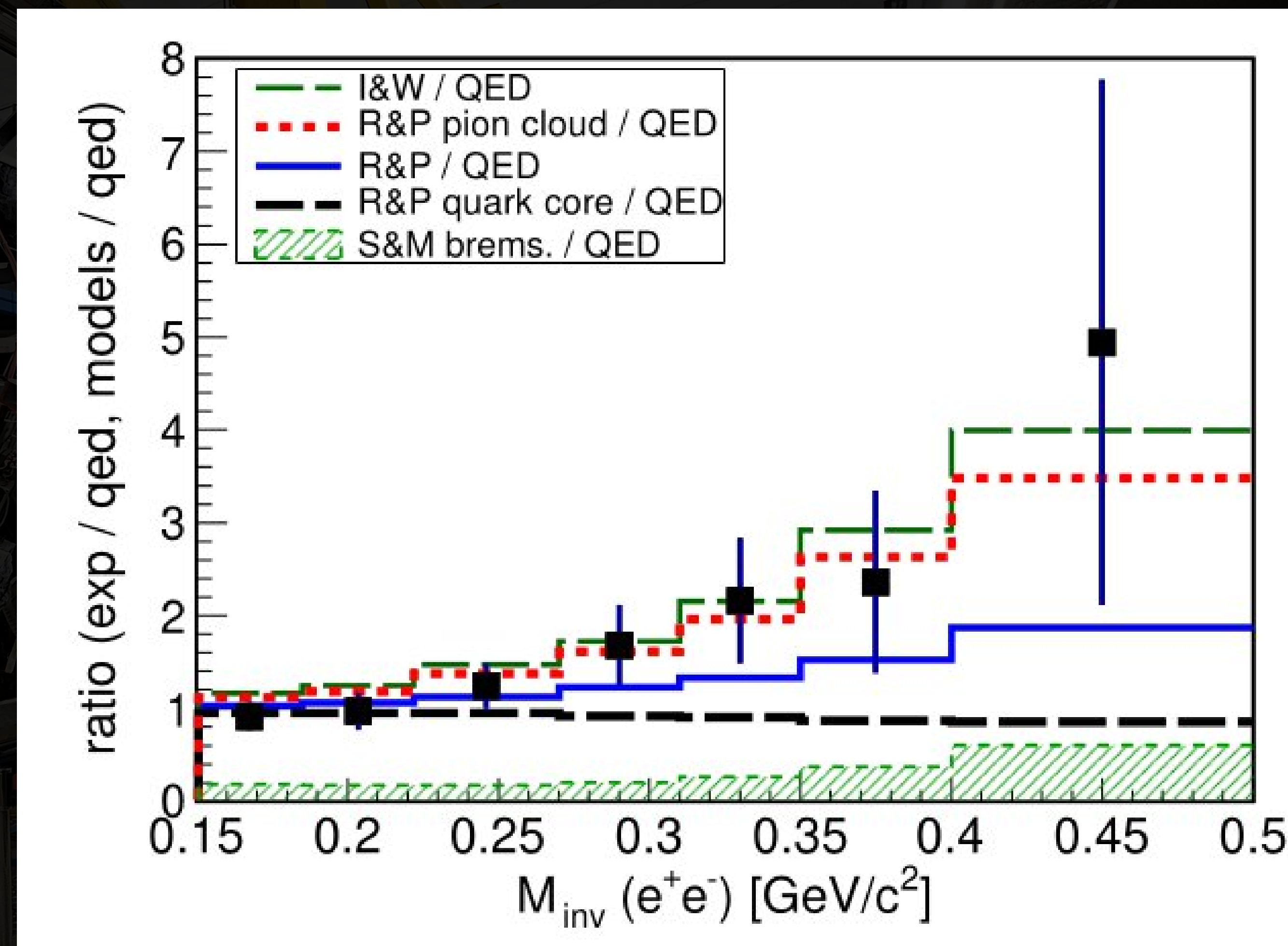
*Plenary talk (Friday) Béatrice Ramstein

Towards Studying the Electromagnetic Properties of Light Baryons

- **Production mechanisms** and **reaction dynamics** of N* and Δ states in $pp \rightarrow NN\pi$ provide access to their **electromagnetic structure** through **dilepton decays**.

- Extract differential cross-sections and also the coupling strengths N^* and Δ resonances.

- How do these measurements improve the baseline for transport models and heavy-ion collisions?



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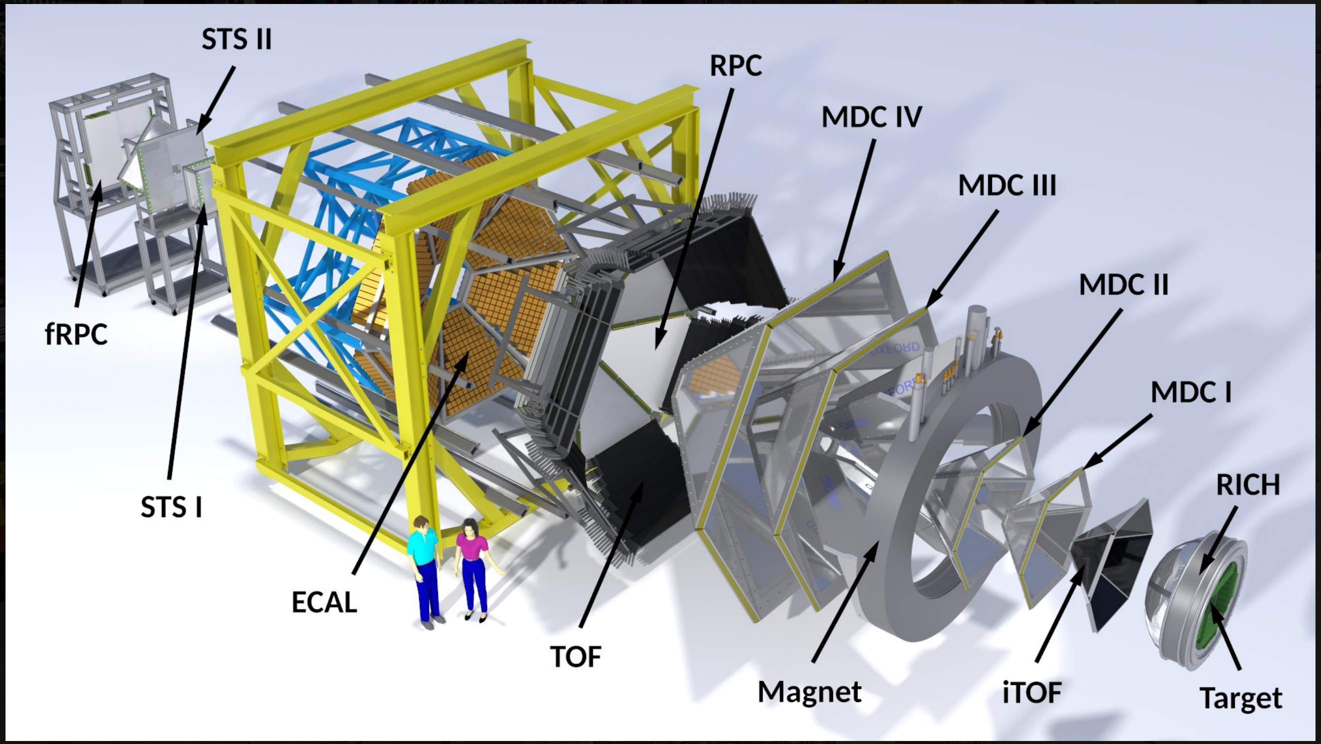
Donges
work in progress
CAEN SY4527
TRAGLAST 3.000 KG
Durchgang verboten!
Zutritt nur für HADES Mitarbeiter
this line!

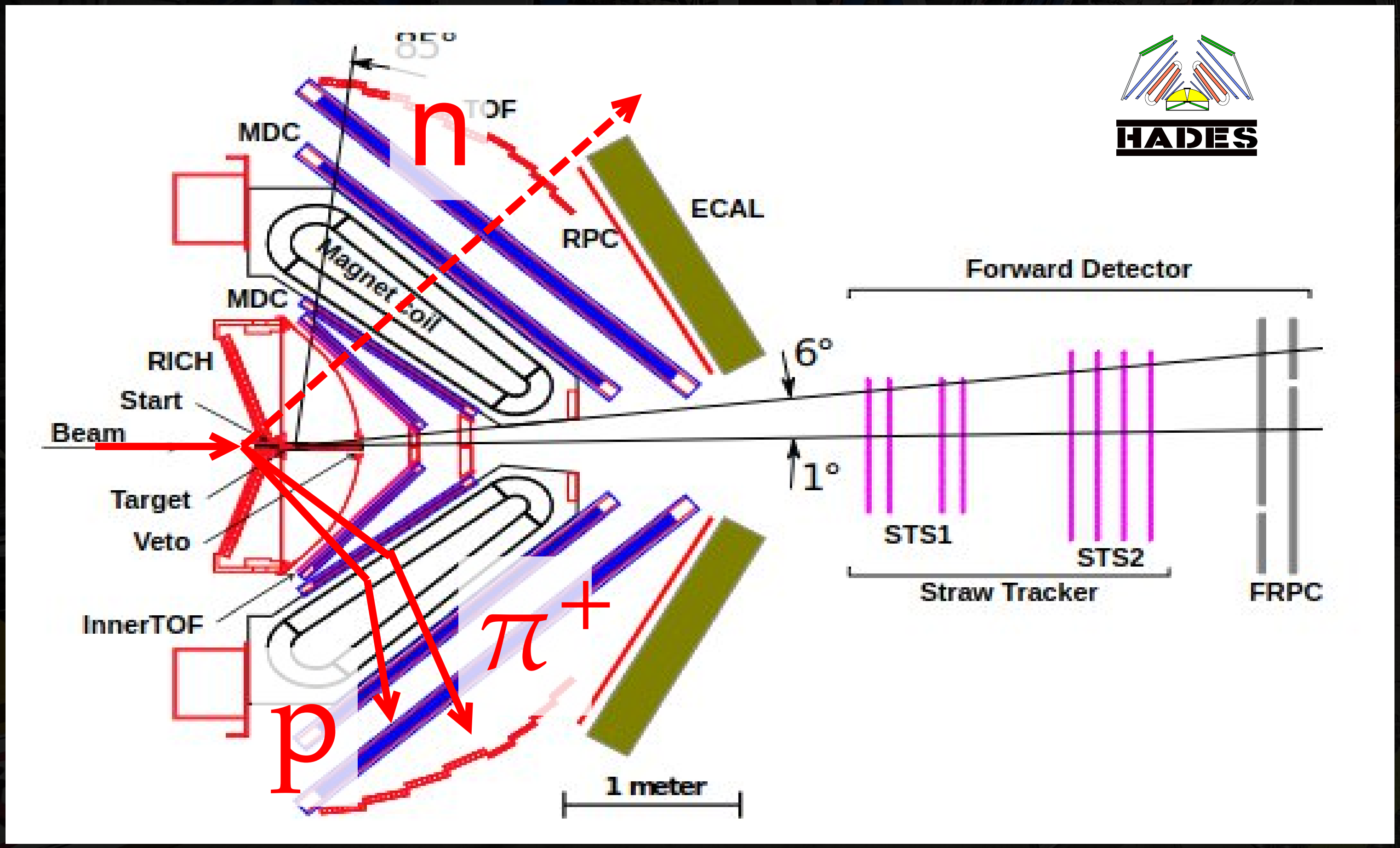
HADES - High Acceptance DiElectron Spectrometer

- Versatile magnetic spectrometer located at GSI Darmstadt.
- Can measure wide range of particles, has excellent e^+/e^- reconstruction.



Particle Identification

- Reconstruct momenta of proton and π^+ with two track particle identification (PID) procedure.
- Reconstruct neutron momenta with missing mass analysis



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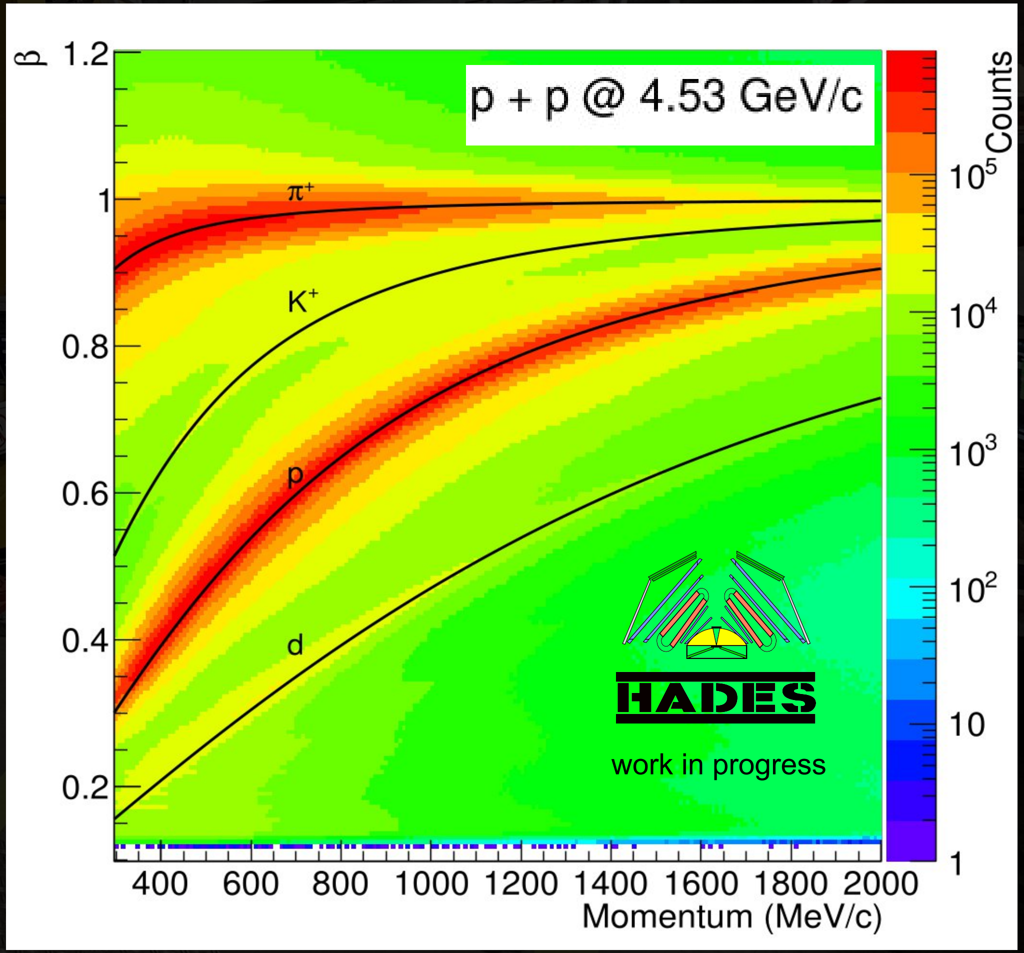

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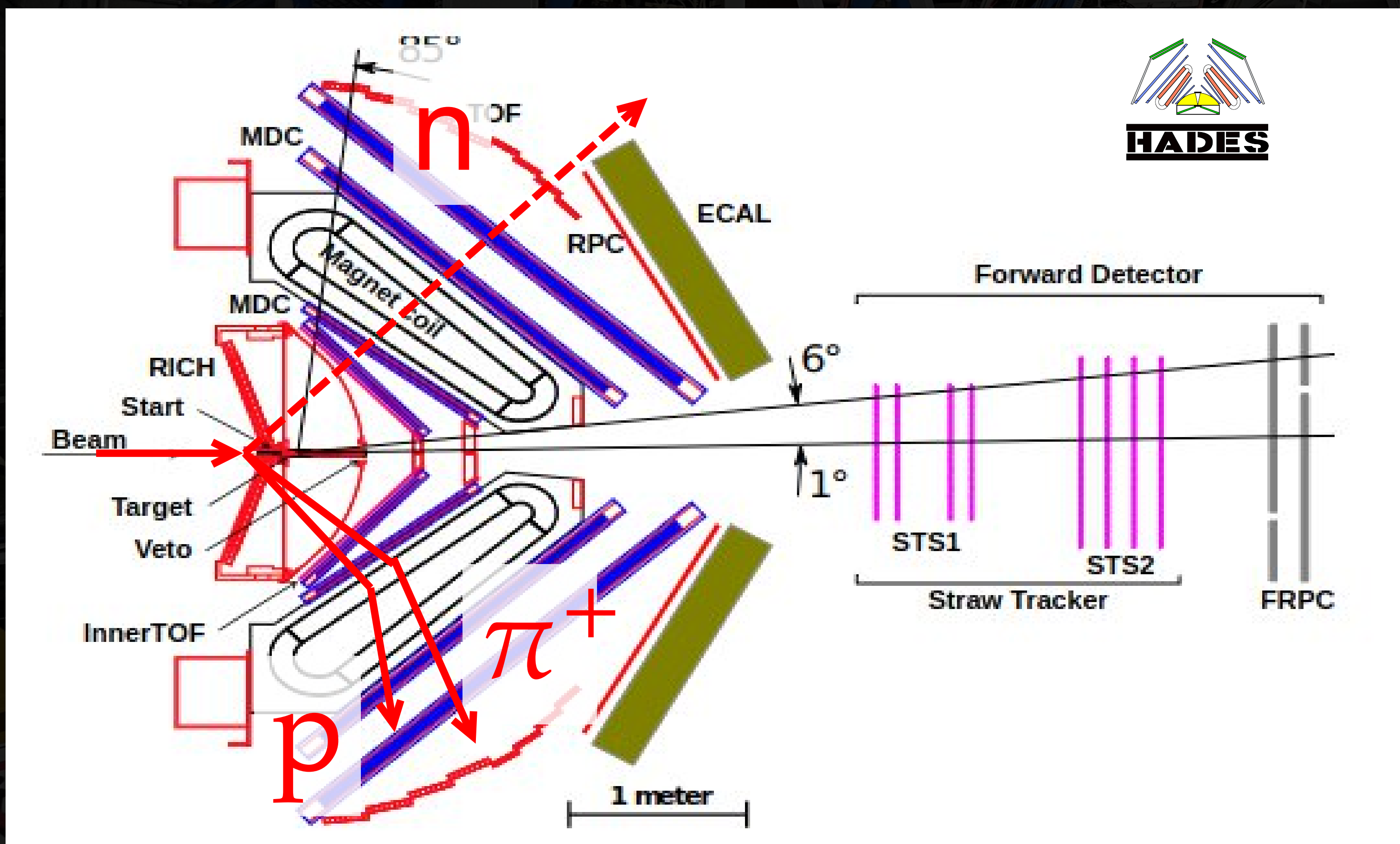
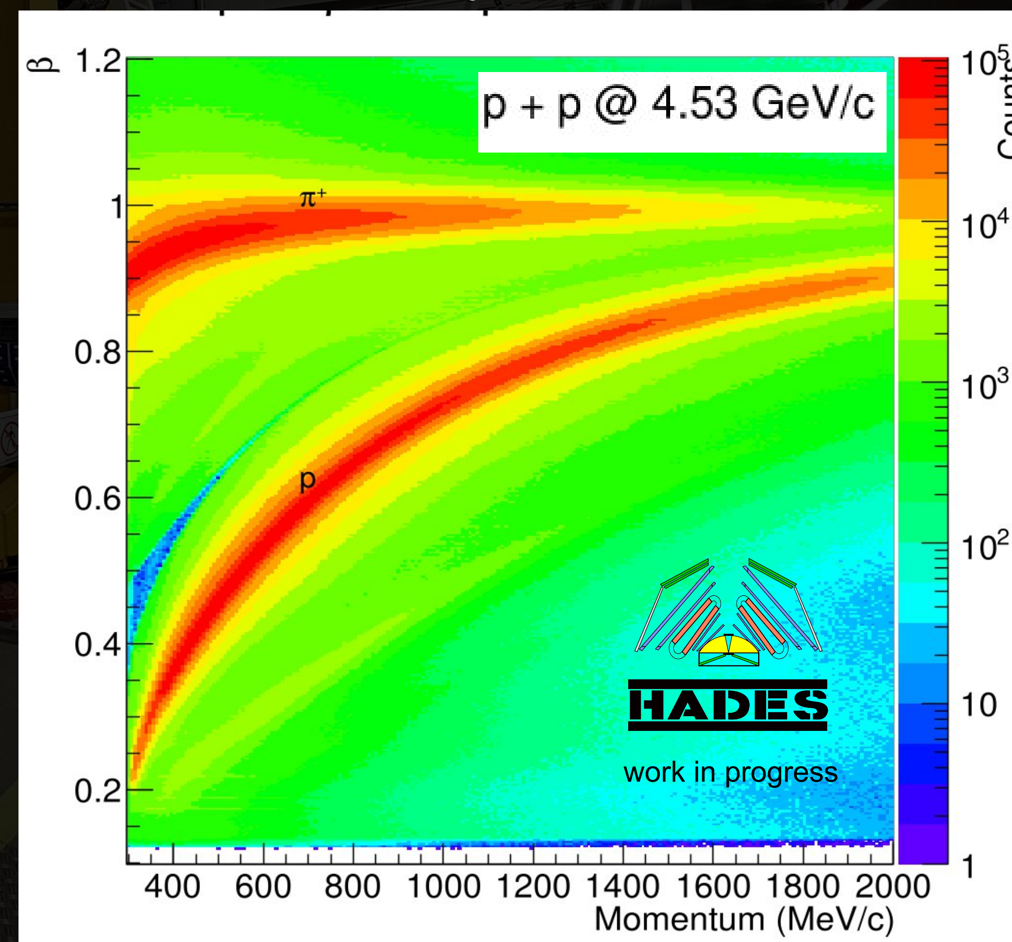
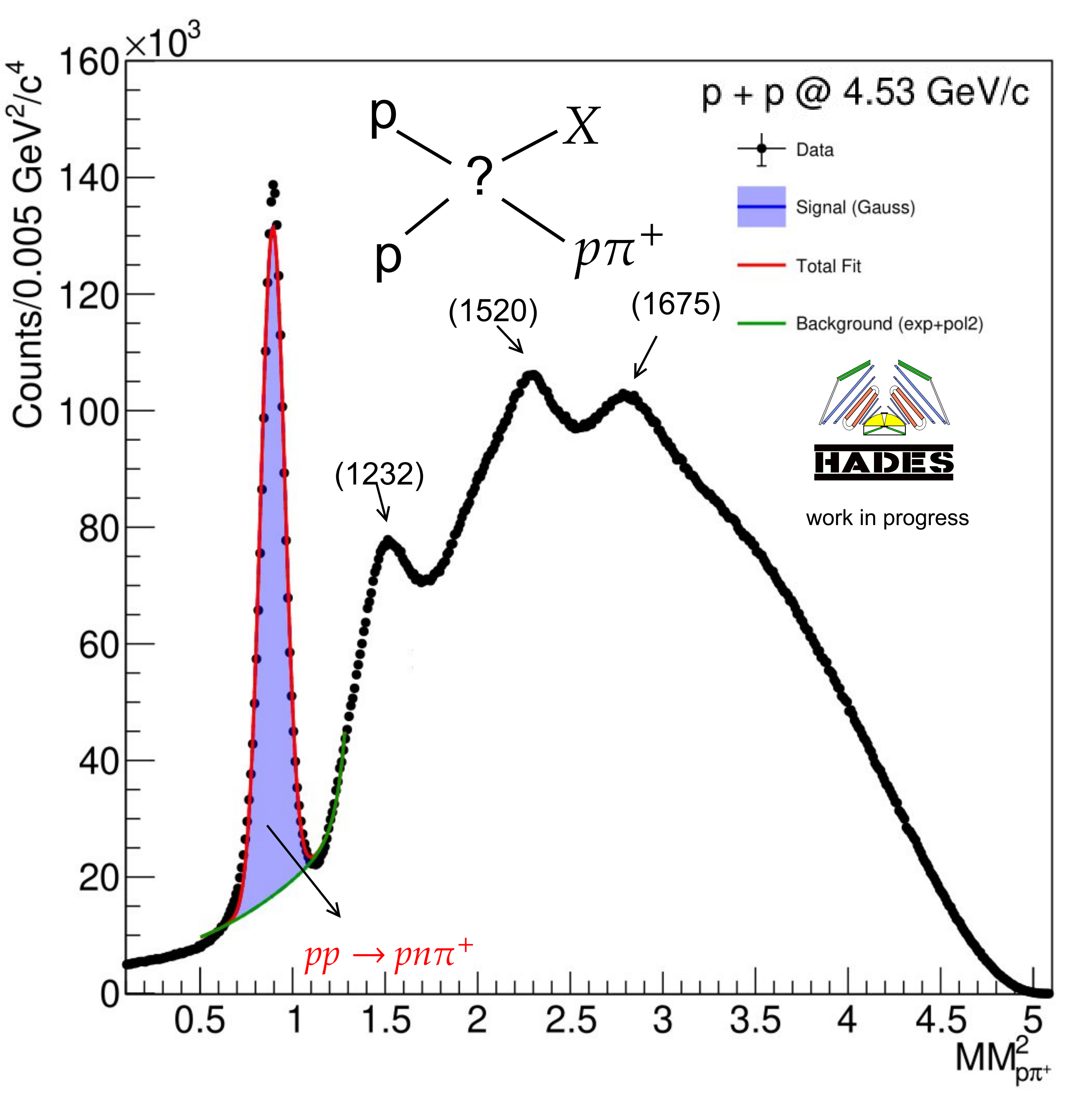


After Multiplicity and Vertex cuts



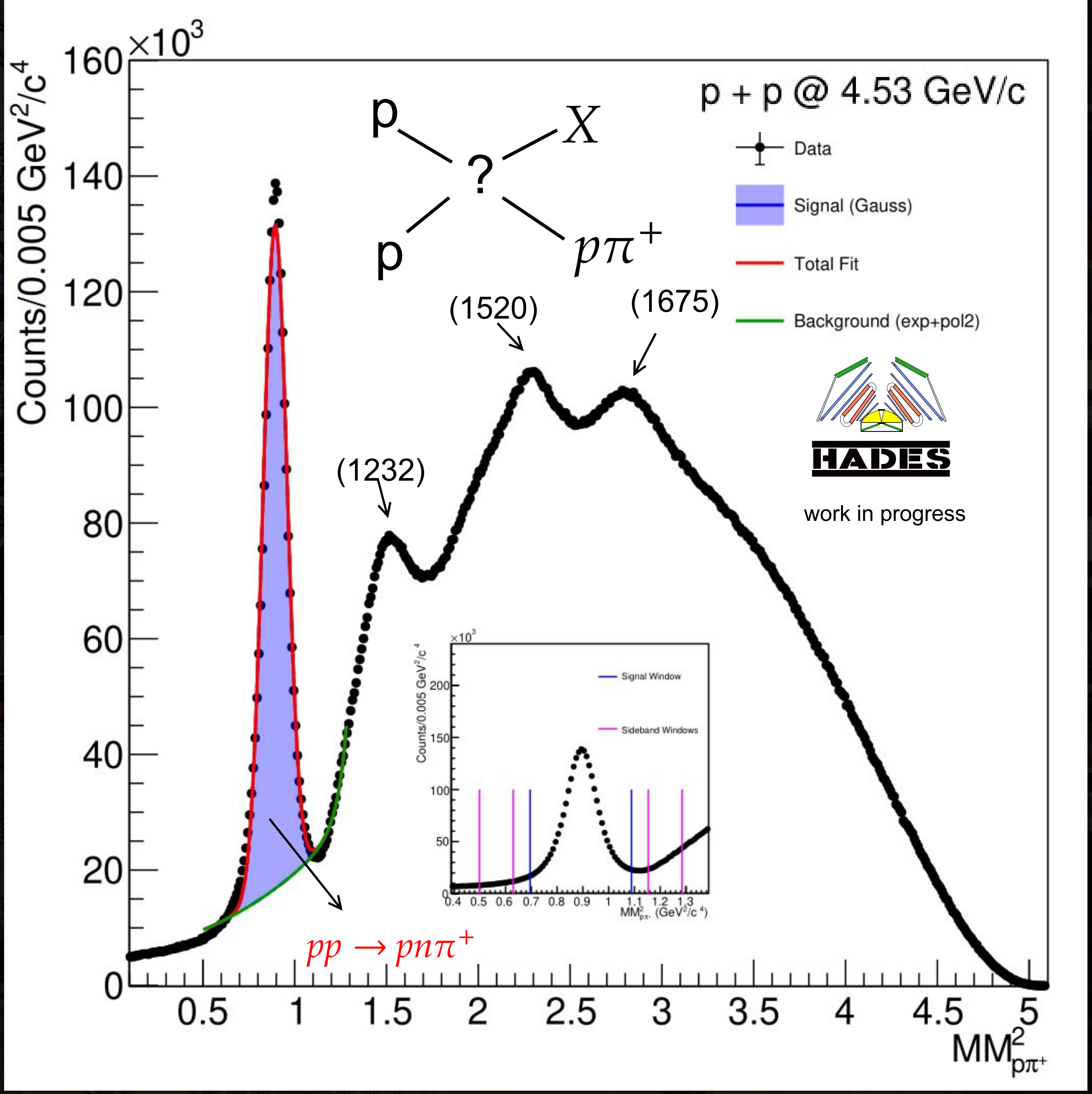
Missing Neutron Identification

- Select **missing neutron** by applying mass window for further analysis.

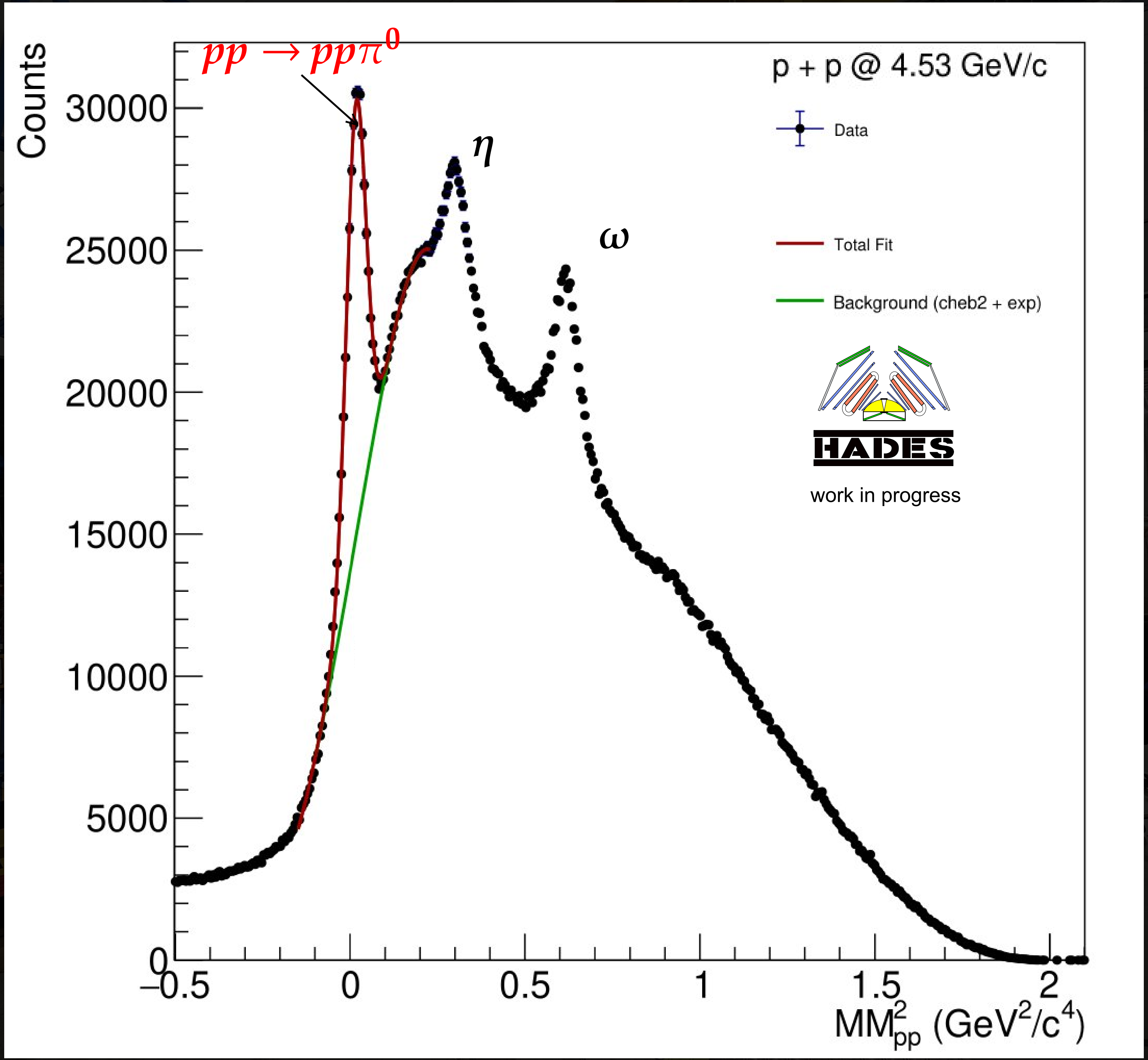


Missing Neutron Identification

- Select **missing neutron** by applying mass window for further analysis.
- Kinematic fit is applied to signal and sideband regions.



$pp \rightarrow pp\pi^0$



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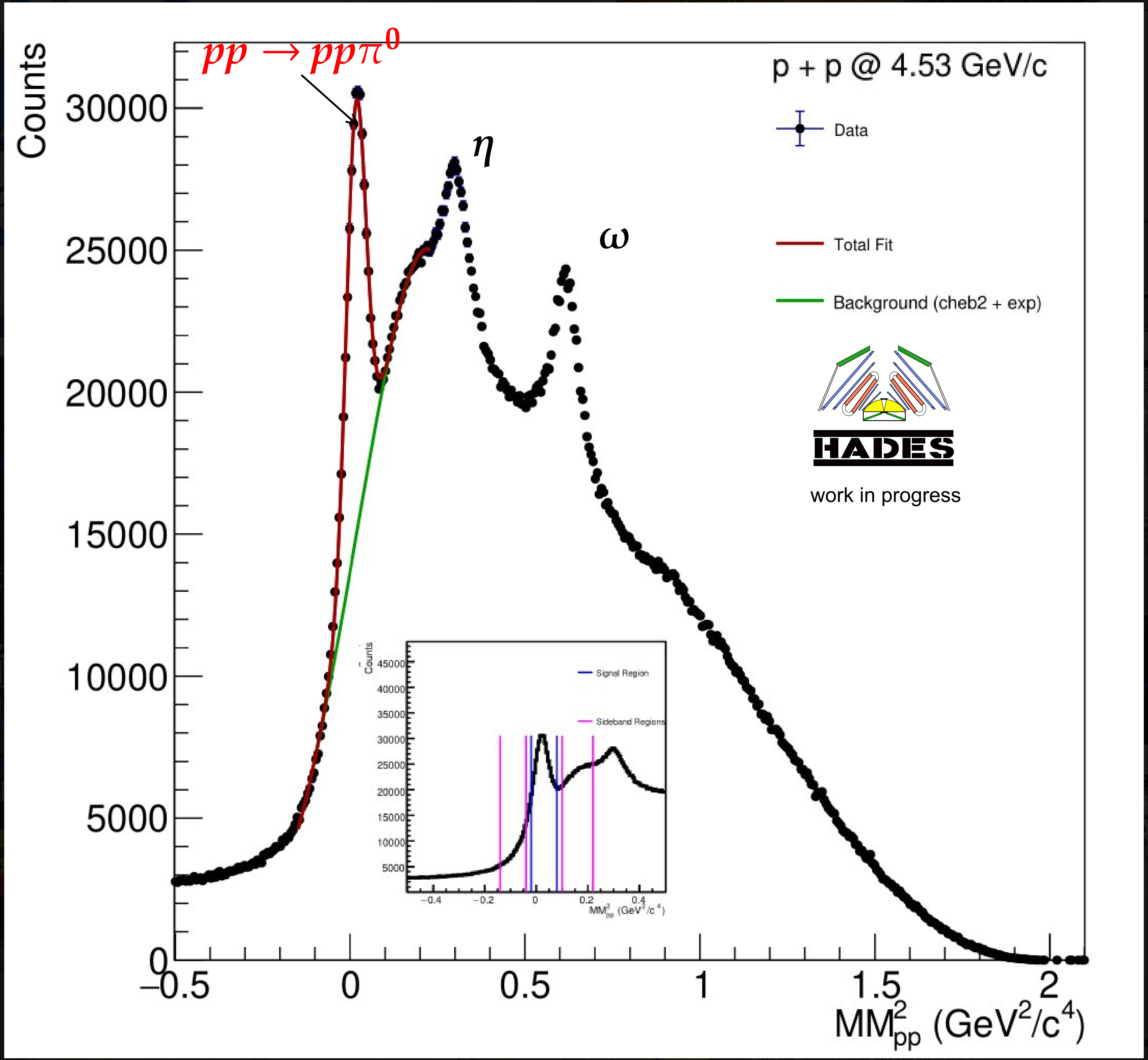
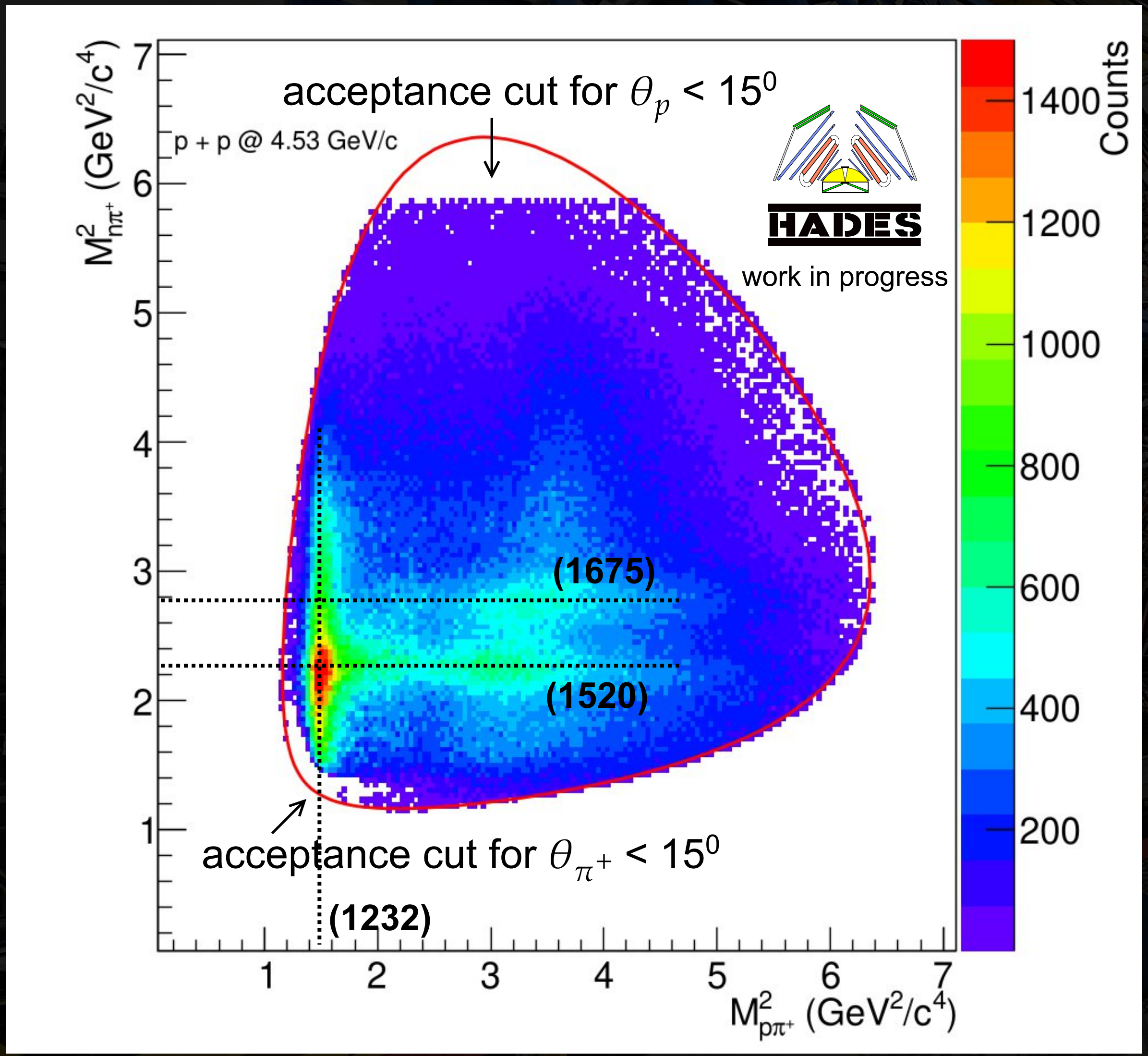
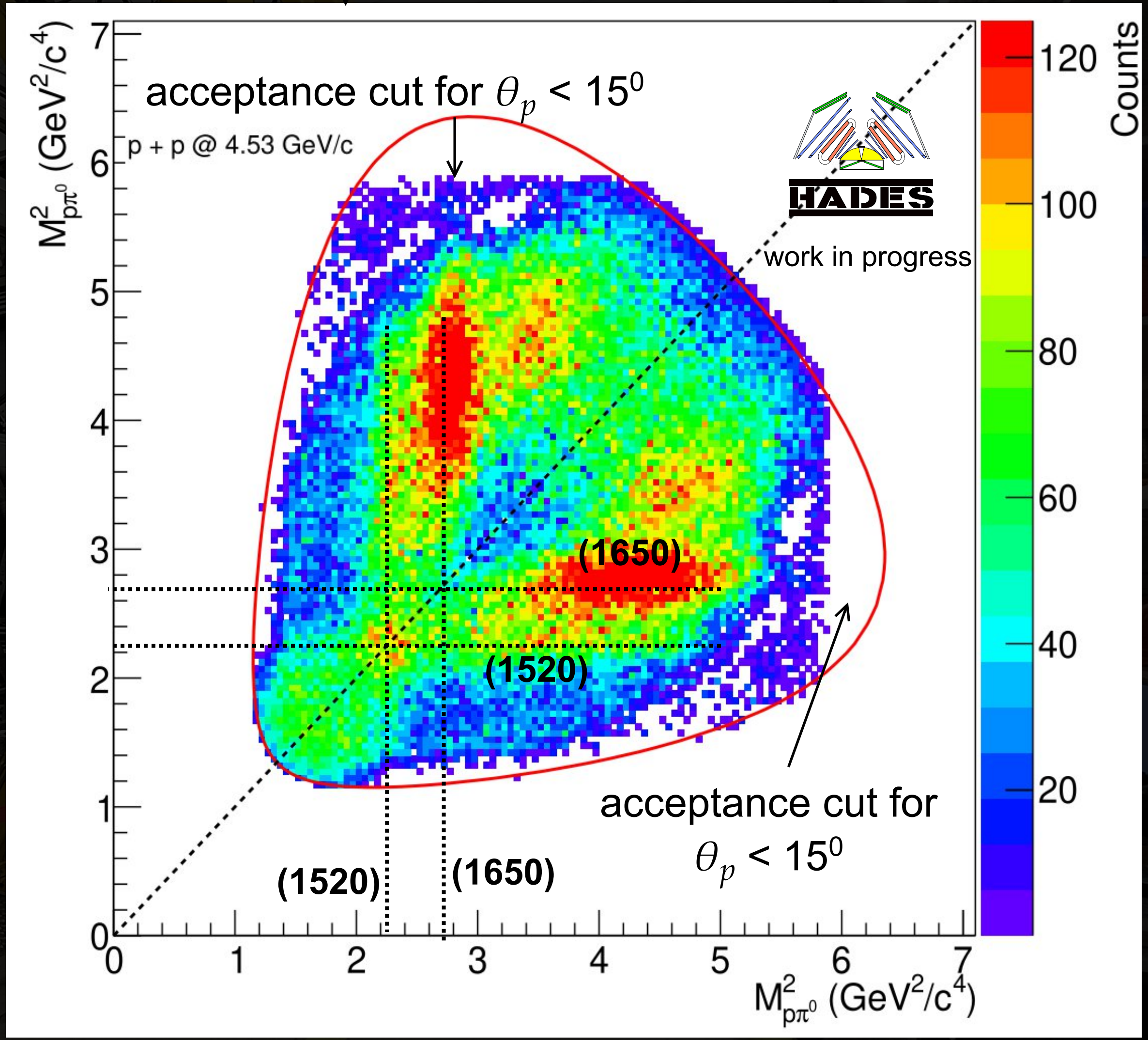


$pp \to pp\pi^0$
η
ω
p + p @ 4.53 GeV/c
Data
Total Fit
Background (cheb2 + exp)
HADES
work in progress
Counts
MM^2_{pp} (GeV^2/c^4)
Signal Region
Sideband Regions

Sideband Subtracted Dalitz Plots

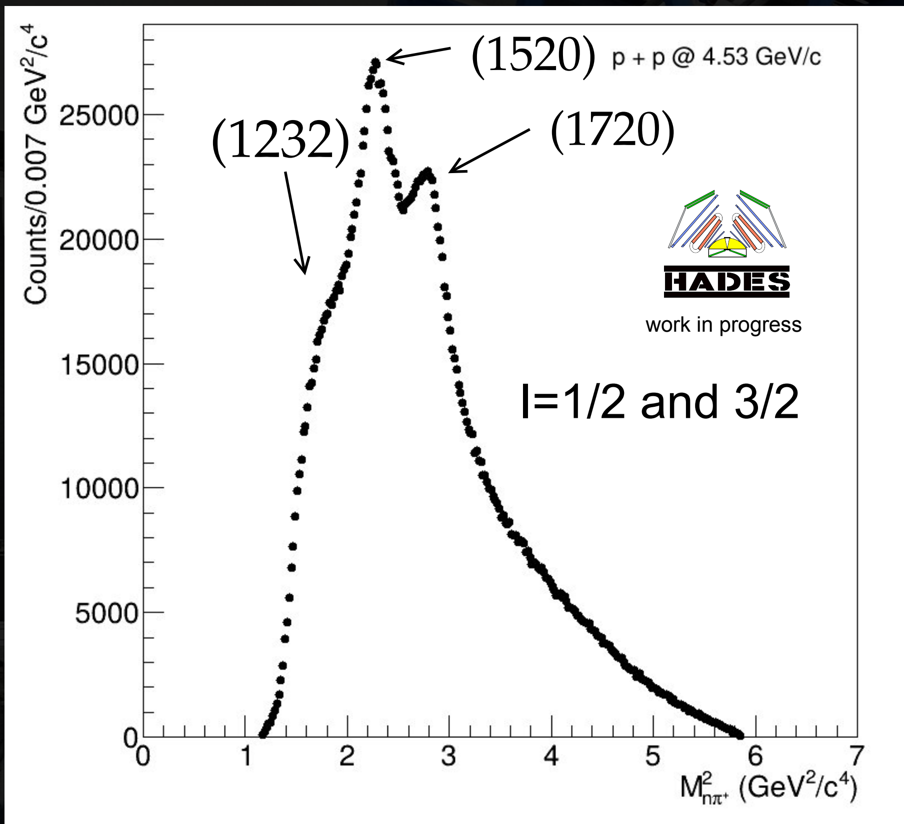


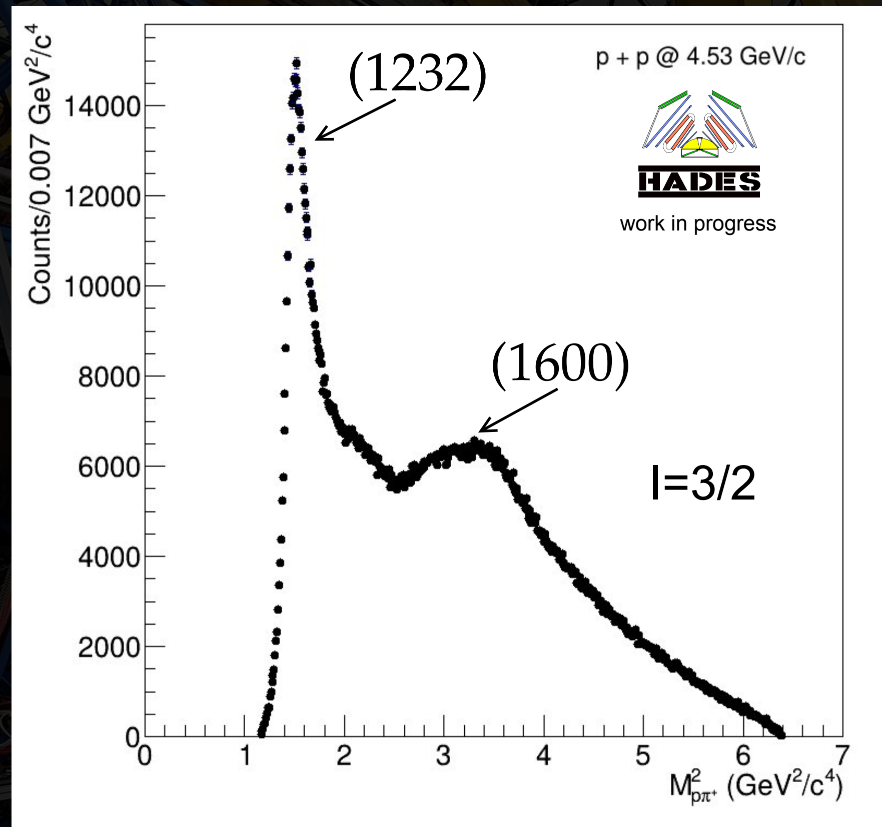


$pn\pi^+$

$pp\pi^0$

Dalitz Plot Projections





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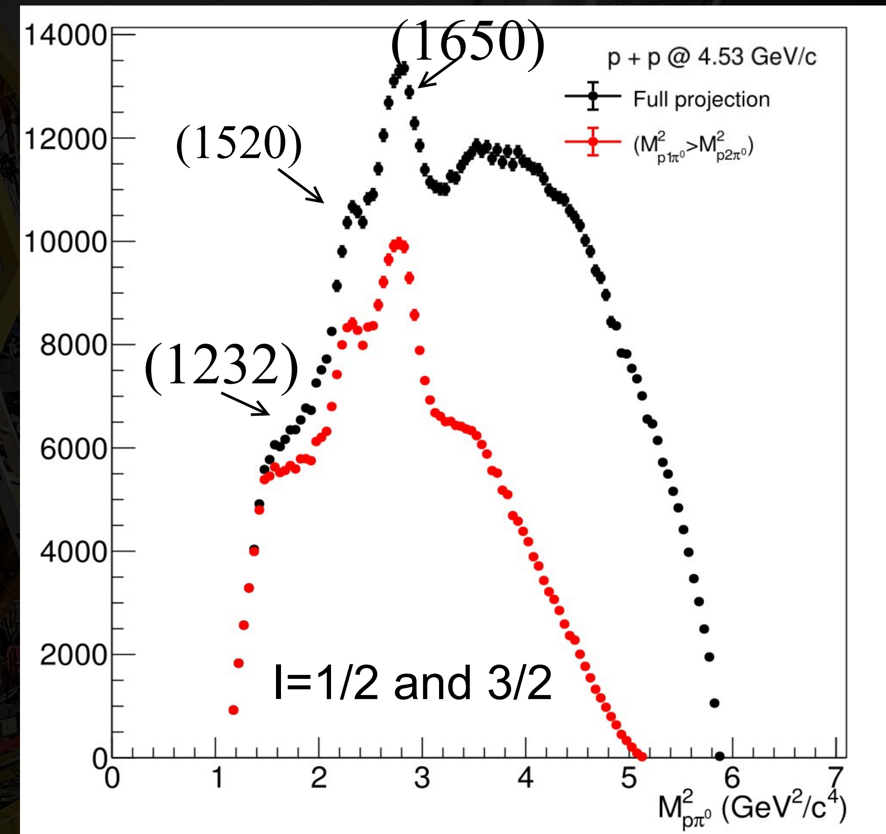
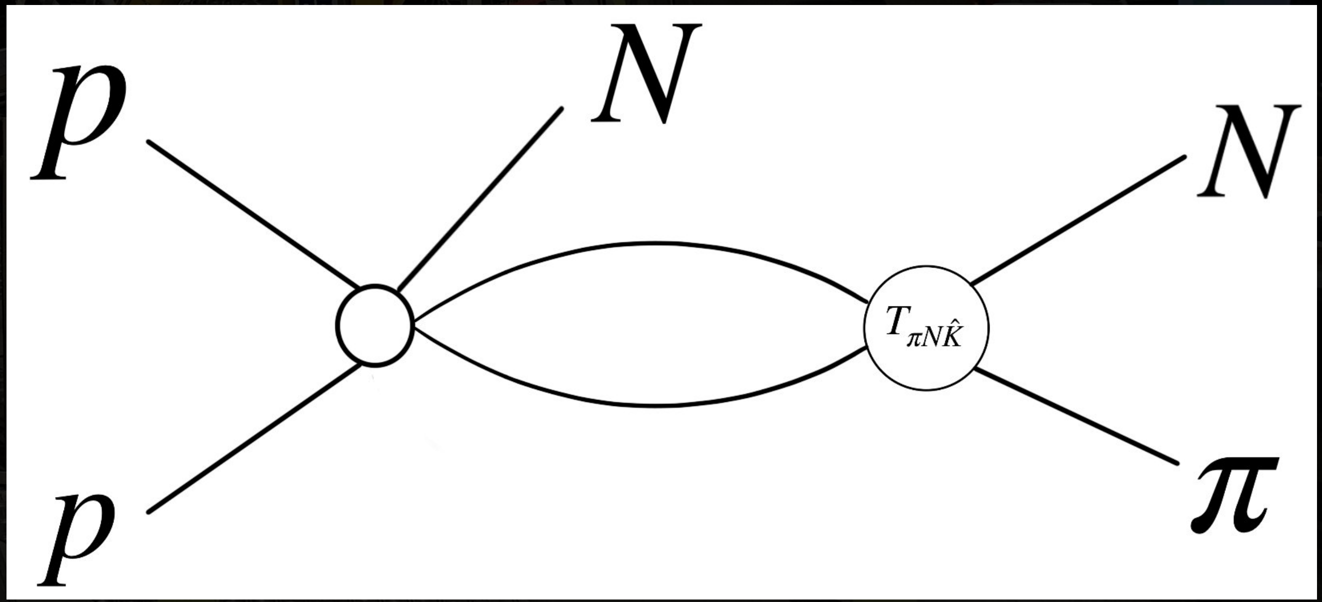


$pp\pi^0$

$pp \to NN\pi$ with **Jülich-Bonn Dynamic Coupled Channel Approach**

- Dynamical Coupled Channel (DCC) [4] approach : simultaneous analysis of different reactions.

- Allows for extracting the coupling strength of the resonances to final states.



4. D. Rönchen *et al.*, *Photocouplings at the pole from pion photoproduction. Eur. Phys. J. A 50 (6) 101 (2014) DOI: 10.1140/epja/i2014-14101-3*

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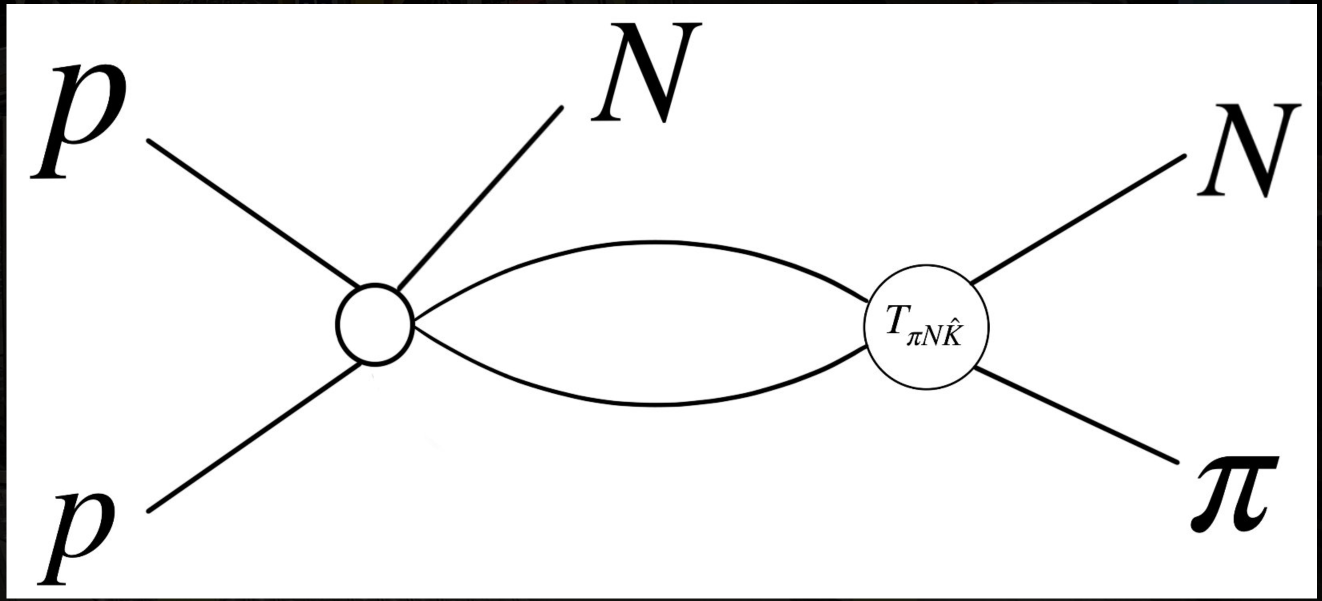
- $\mathcal{M}$ is the invariant matrix element for calculating the invariant mass distribution and $T_{\pi p \hat{K}}$ is the full JüBo T-Matrix for different channels ($\hat{K} \to \pi N$), includes s-channel and dynamically generated resonances.



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- $\mathcal{M}$ is the invariant matrix element for calculating the invariant mass distribution and $T_{\pi p \hat{K}}$ is the full JüBo T-Matrix for different channels ($\hat{K} \to \pi$N), includes s-channel and dynamically generated resonances.

$$\mathcal{M}_{\mu\nu}(q,p',\epsilon) = V_{\mu\nu}(q,p',\epsilon) + \sum_{\hat{K}} \int_0^\infty dp\, p^2 T_{\mu\hat{K}}(q,p,\epsilon) G_{\hat{K}}(p,\epsilon) V_{\hat{K}\nu}(p,p',\epsilon)$$

Kernel which contains the coupling information of the resonances to the final state

all possible meson baryon channels

ϵ - C.M energy of $pp \to pn\pi^+$

- $\text{MB} \to \text{MB}$ interactions (e.g. FSI) are incorporated by Jülich-Bonn model (fitted through lots of data) within SU(3) dynamics.

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*Plenary talk (Monday) Deborah Rönchen

$pp \rightarrow NN\pi$ with **Jülich-Bonn Dynamic Coupled Channel Approach**

- Dynamical Coupled Channel (DCC) [4] approach : simultaneous analysis of different reactions.

- Allows for extracting the coupling streng[redacted] final states.

- $\mathcal{M}$ is the invariant matrix [redacted] ass distribution and T_π [redacted] els ($\hat{K} \rightarrow \pi$N), includes s-c[redacted] ces.

Can we decouple final-state interactions from the production mechanism?

$$\mathcal{M}_{\mu\nu}(q \ldots [redacted] \ldots {}_{\mu\hat{K}}(q,p,\epsilon)G_{\hat{K}}(p,\epsilon)V_{\hat{K}\nu}(p,p',\epsilon)$$

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AmpTools – Framework for Amplitude Analysis

Purpose:

- Toolkit for performing Partial Wave Analysis (PWA)[5].
- Fits complex amplitudes for exclusive reactions.

Key Features:

- Flexible physics model definitions (resonances, backgrounds).
- Coherent and incoherent amplitude combinations.
- Event-based maximum likelihood fitting.

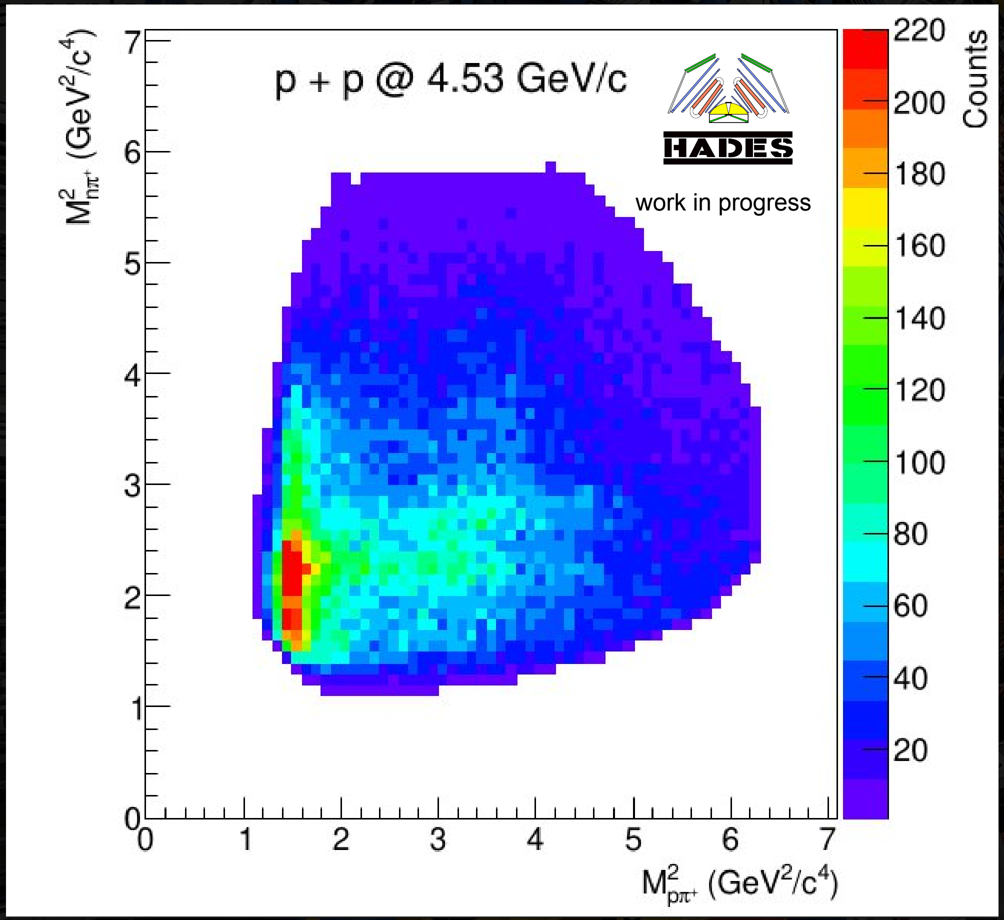
$$-2\ln\mathcal{L}(\theta) = -2\left(\sum_{i=1}^{N}\ln I(x_i;\theta) - \int I(x;\theta)\eta(x)\,dx\right) + c_1$$

- GPU acceleration for fast computations.
- Interfaces with ROOT.

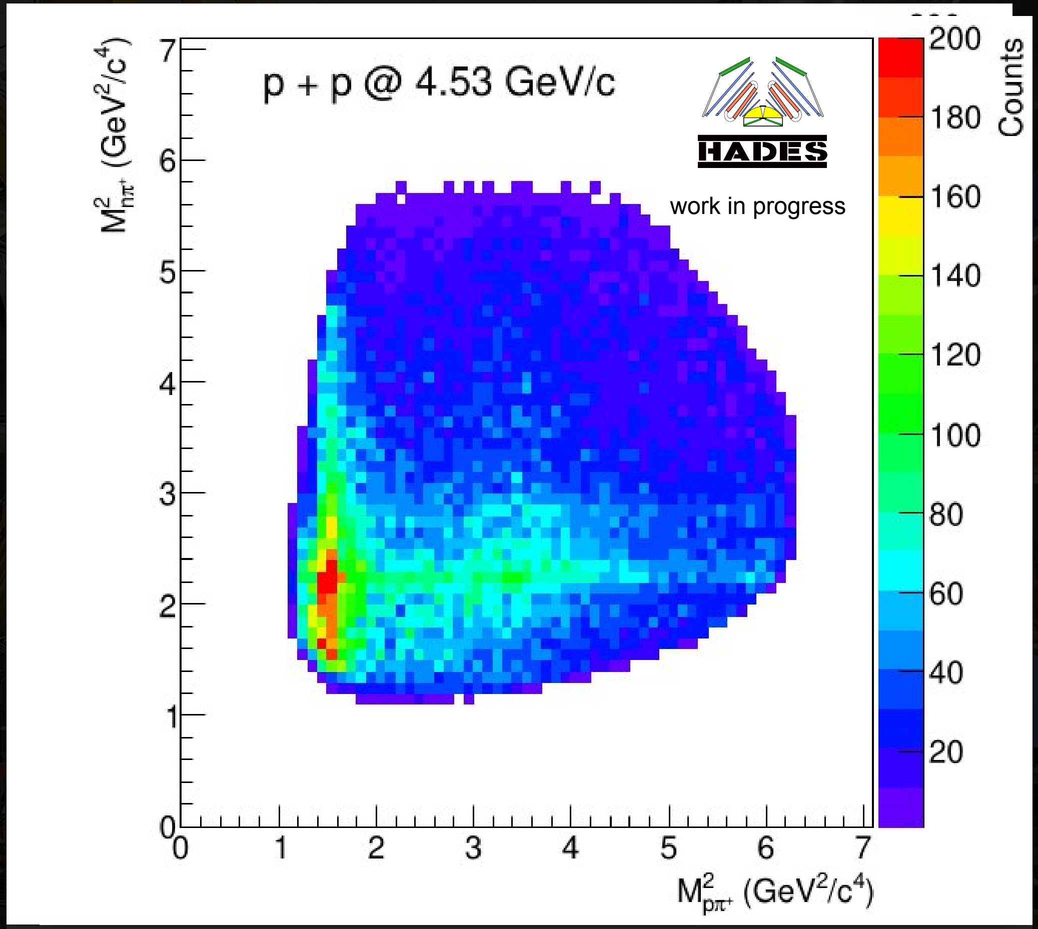
Talk by Ahmed Foda

5. doi.org/10.5281/zenodo.5039377

Preliminary Fit Results



Data



Fit Result (P33,P31,S11 and P11)

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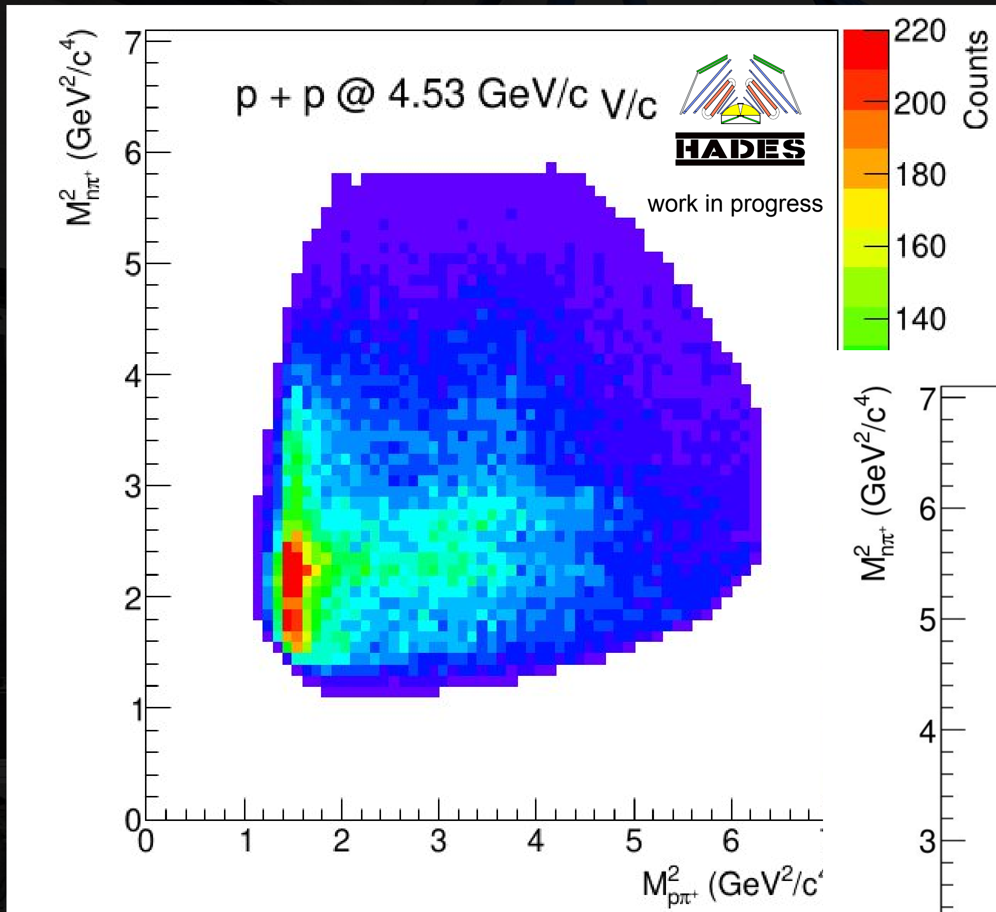
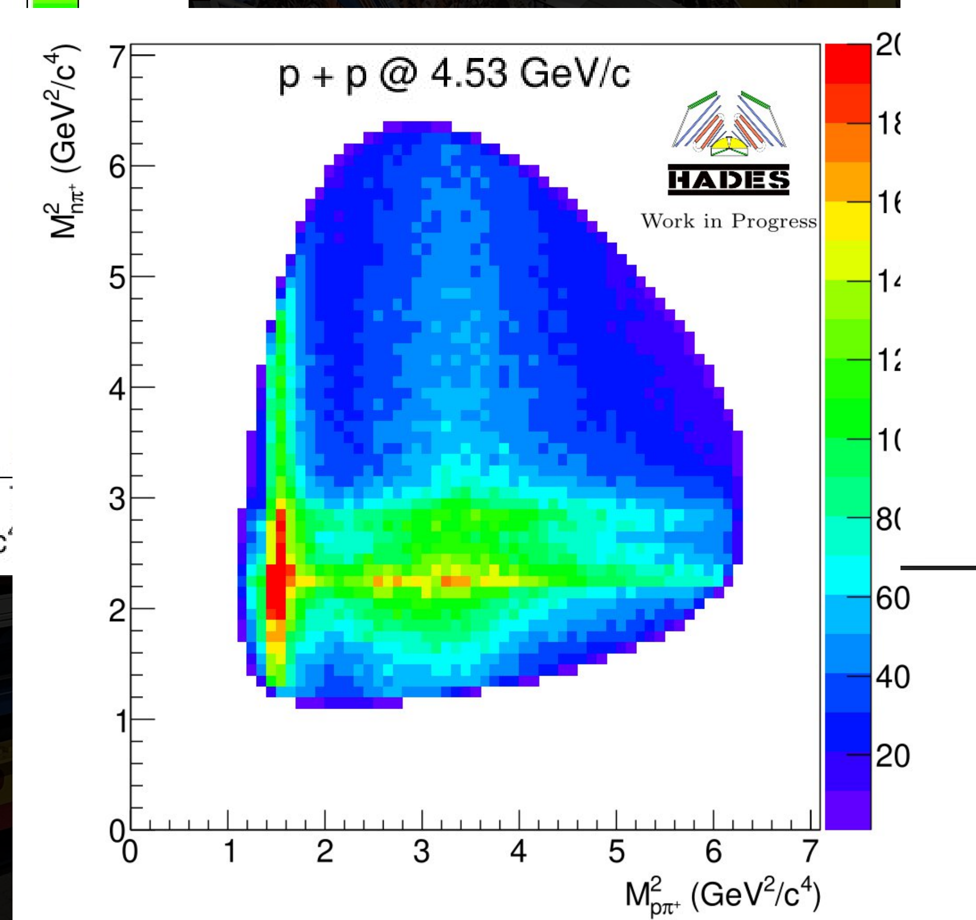
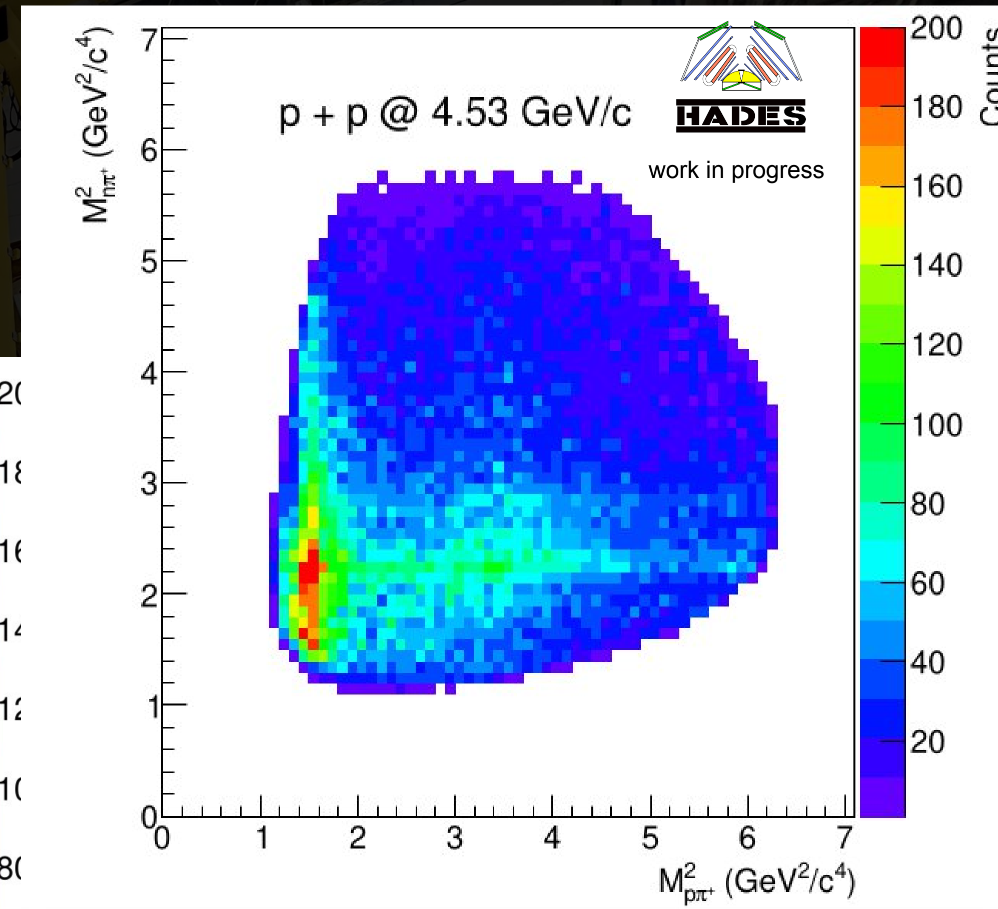


Data

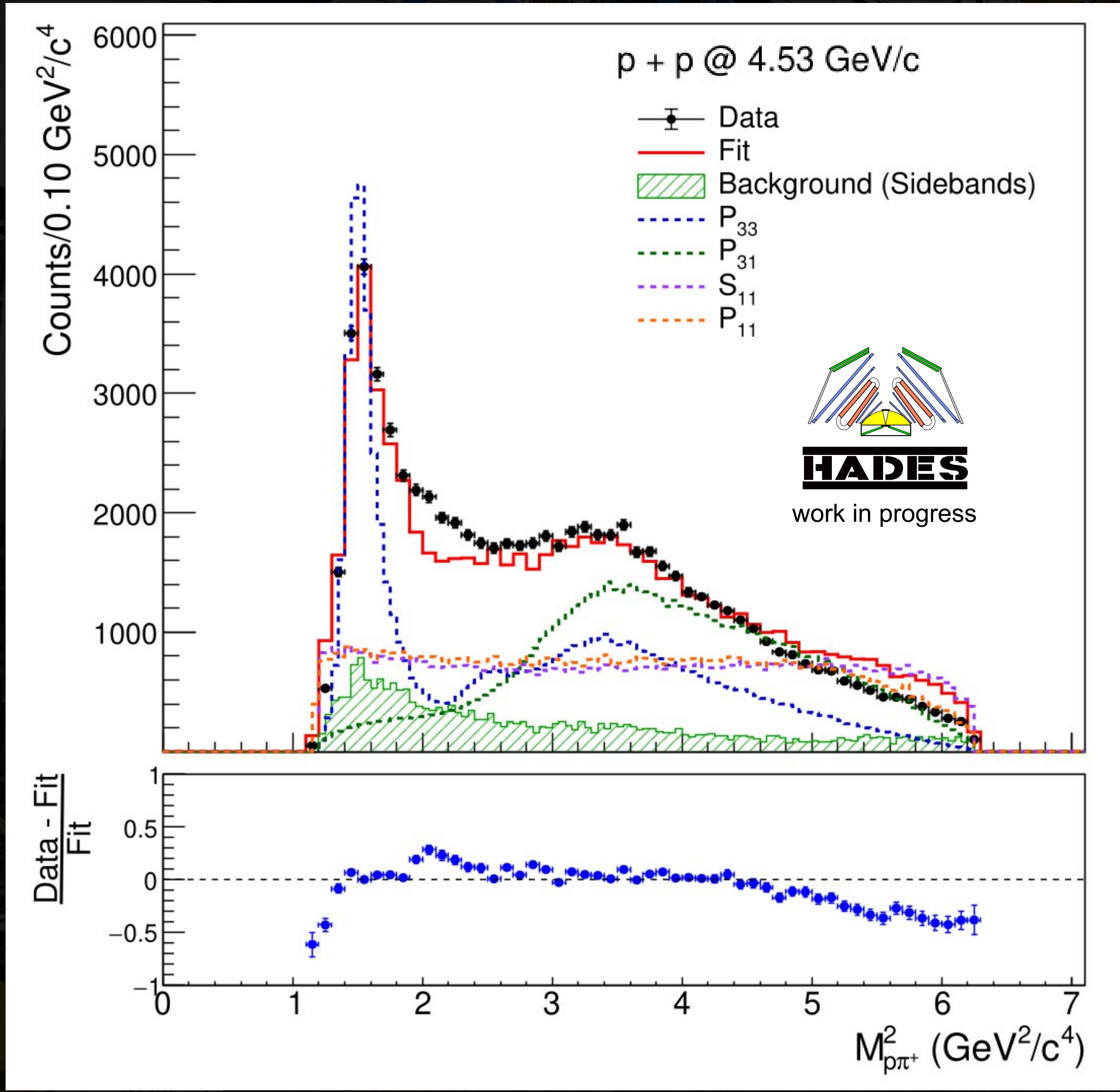


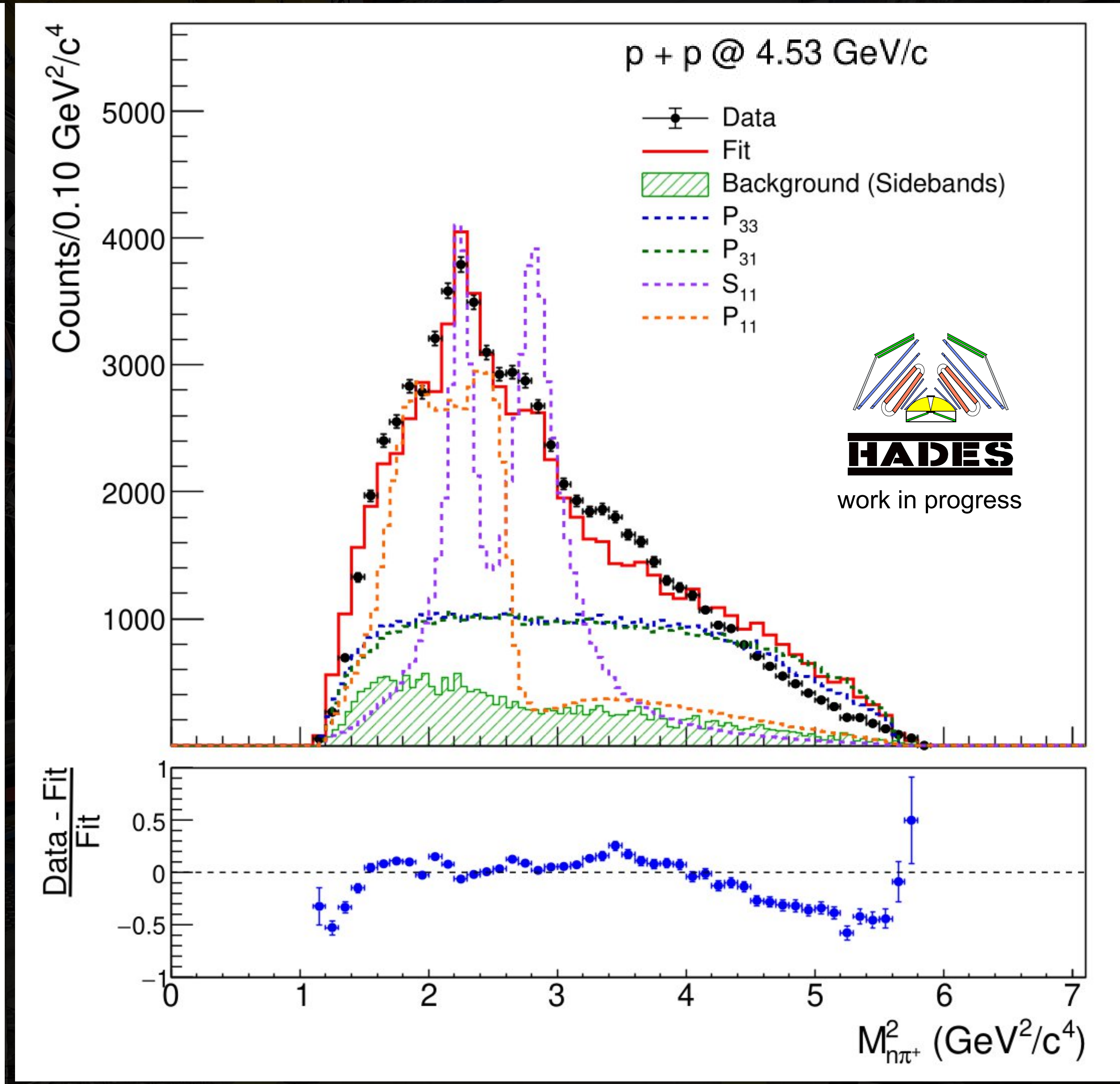


Acceptance Corrected

Fit Result (P33,P31,S11 and P11)

Preliminary Fit Results





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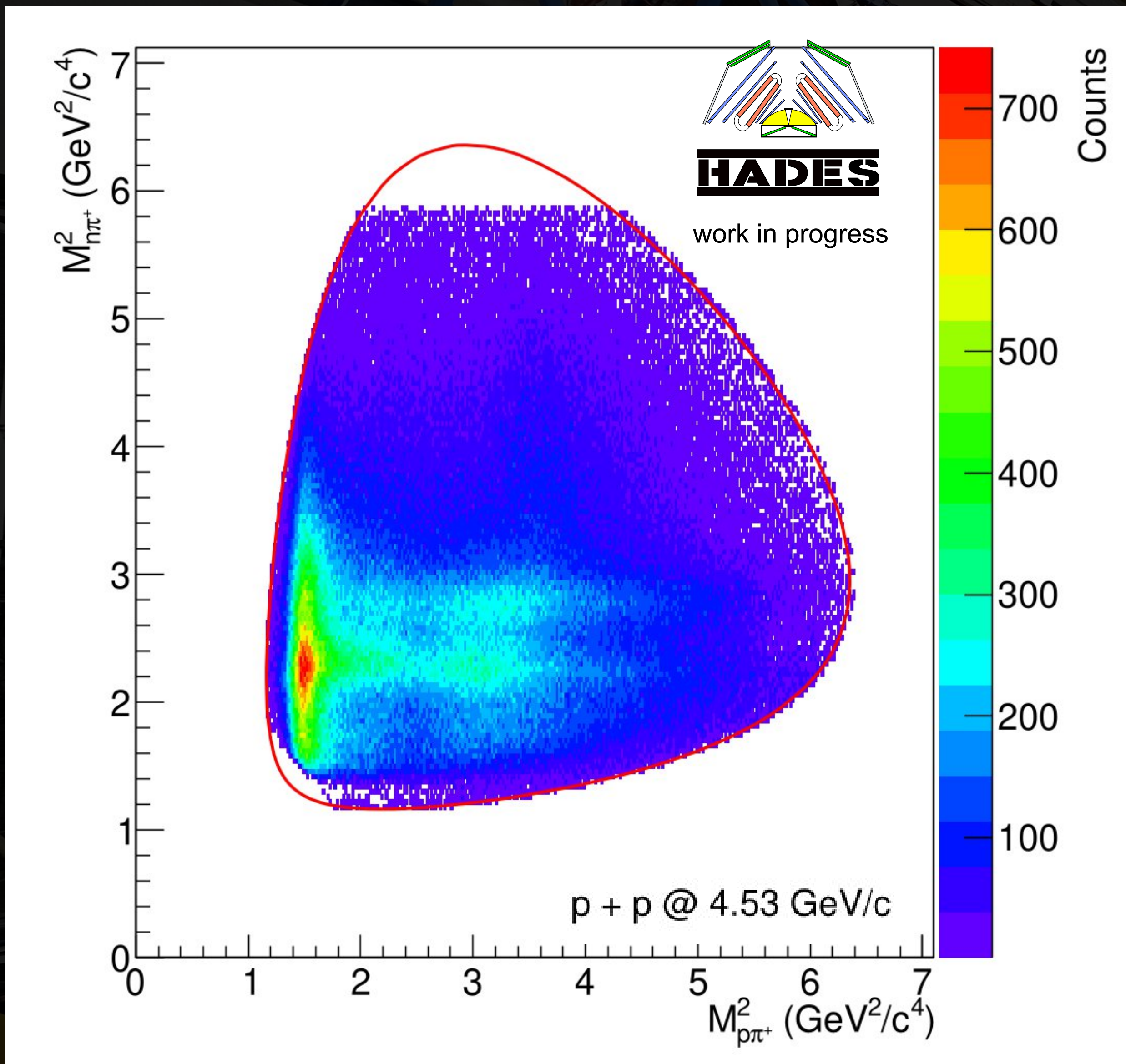
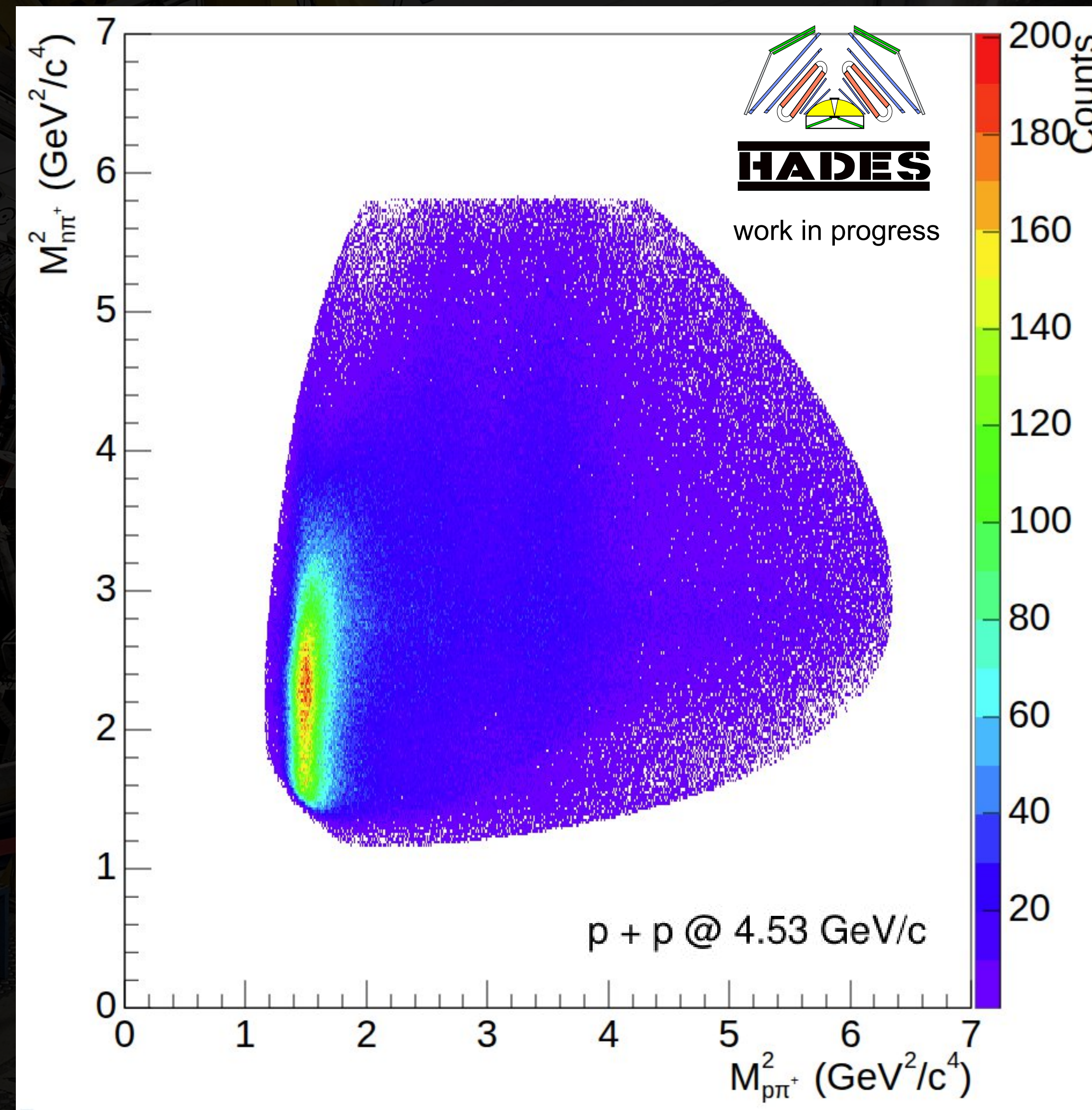
Comparision to Transport Models



Data



SMASH[6]

6. Weil, J., et al. Smash-transport/smash: SMASH-3.3. SMASH-3.3, Zenodo, 10 Dec. 2025, https://doi.org/10.5281/zenodo.17878251.

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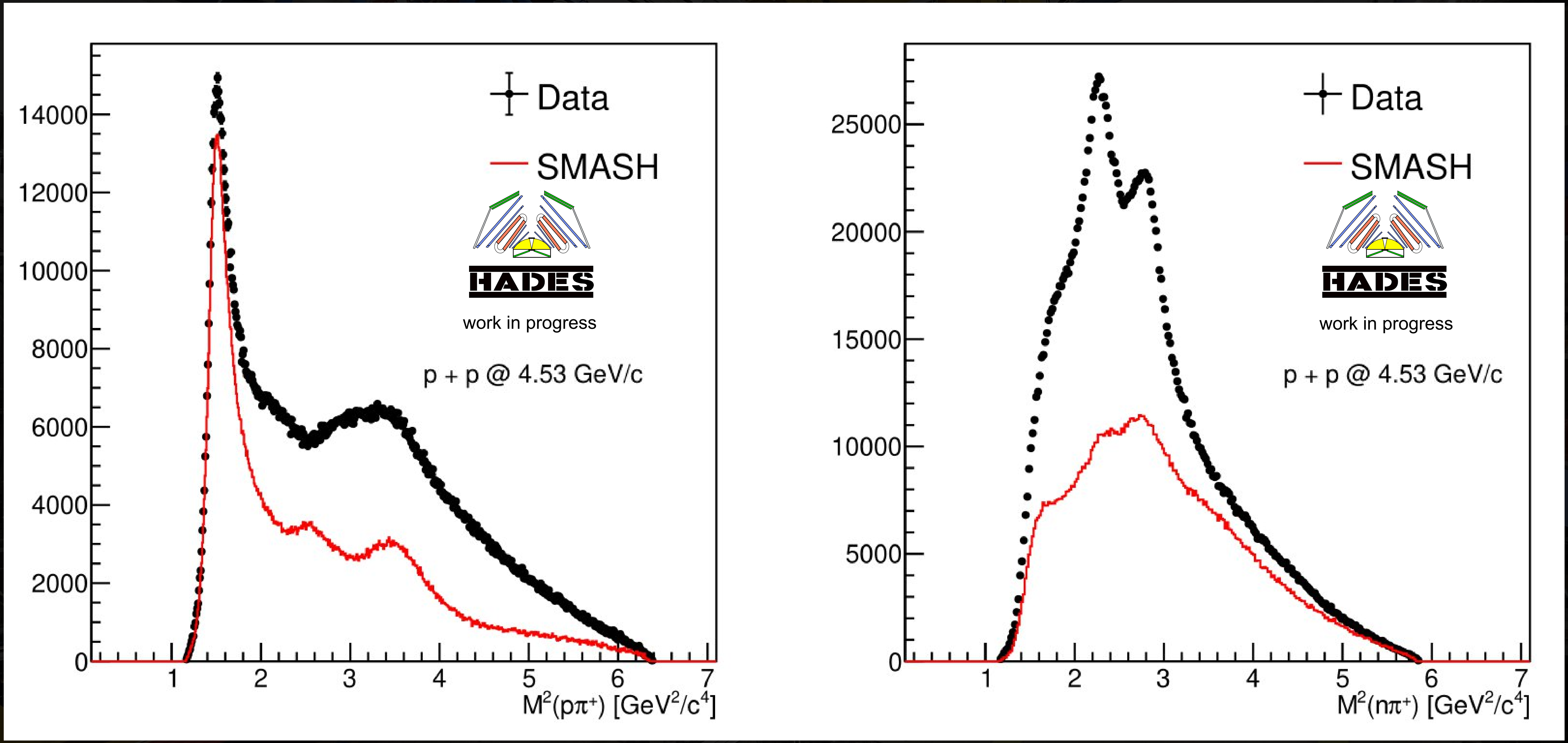

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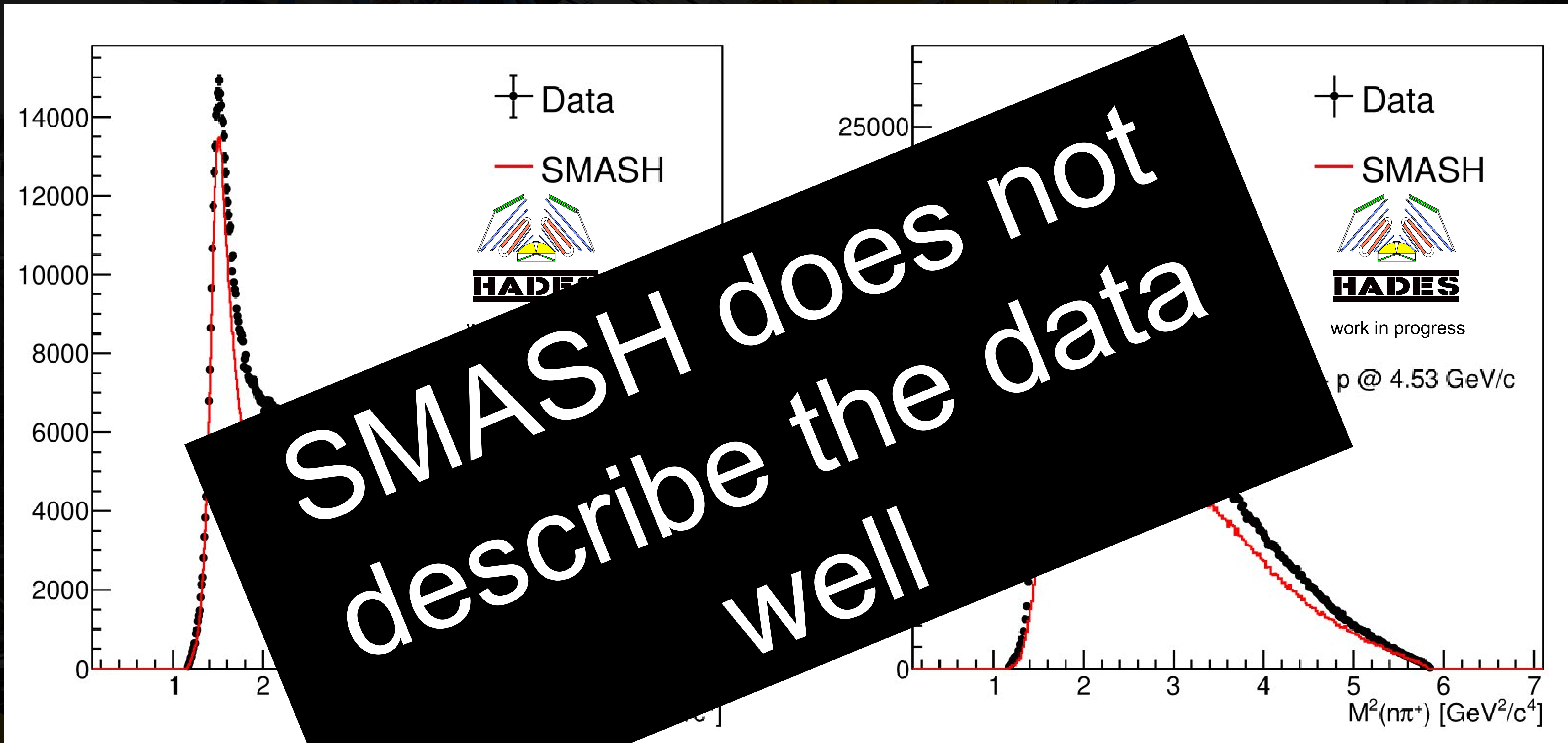

SMASH does not describe the data well

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Conclusion and Outlook

- The data provides valuable constraints for improving the implementation of baryon-resonance dynamics in transport models such as SMASH.
- Preliminary fit to the $pp \rightarrow pn\pi^+$ case shows the coupled channel machinery works.
- A good benchmark case to validate this machinery and assess whether it can be used to compute the FSI for other channels involving $\mathrm{K}\Lambda$ and $\mathrm{K}\Sigma$.
- Once the fit for $pp \rightarrow pn\pi^+$ case is finalised, quantify the different MB contribution.
- Also do a combined fit of the $pp \rightarrow pn\pi^+$ and $pp \rightarrow pp\pi^0$ channels.
- Extract cross-sections for $pp \rightarrow pn\pi^+$ and $pp \rightarrow pp\pi^0$ channels

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Δ Thank You Δ

Particle Identification via TOF

- For each event, four track PID hypotheses are evaluated:
  pp, pπ^+, π^+p, $\pi^+\pi^+$

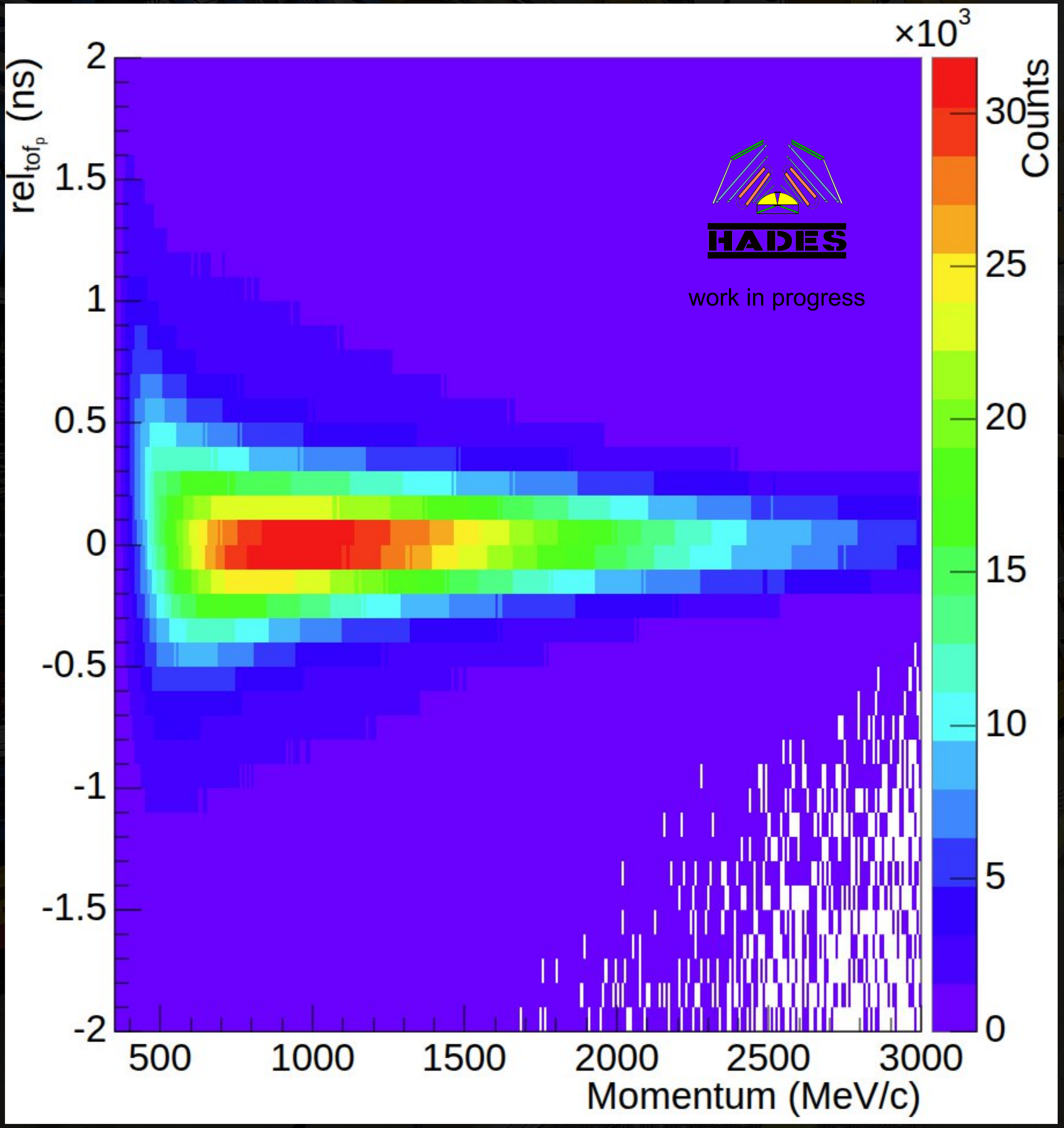
- For each hypothesis Δt_i is calculated, where Δt_i = measured-expected TOF for track i.

- For each event, the four possible values of χ^2 are calculated corresponding to all four possible track combinations.

$$\chi^2 = (\Delta t_1)^2 + (\Delta t_2)^2$$

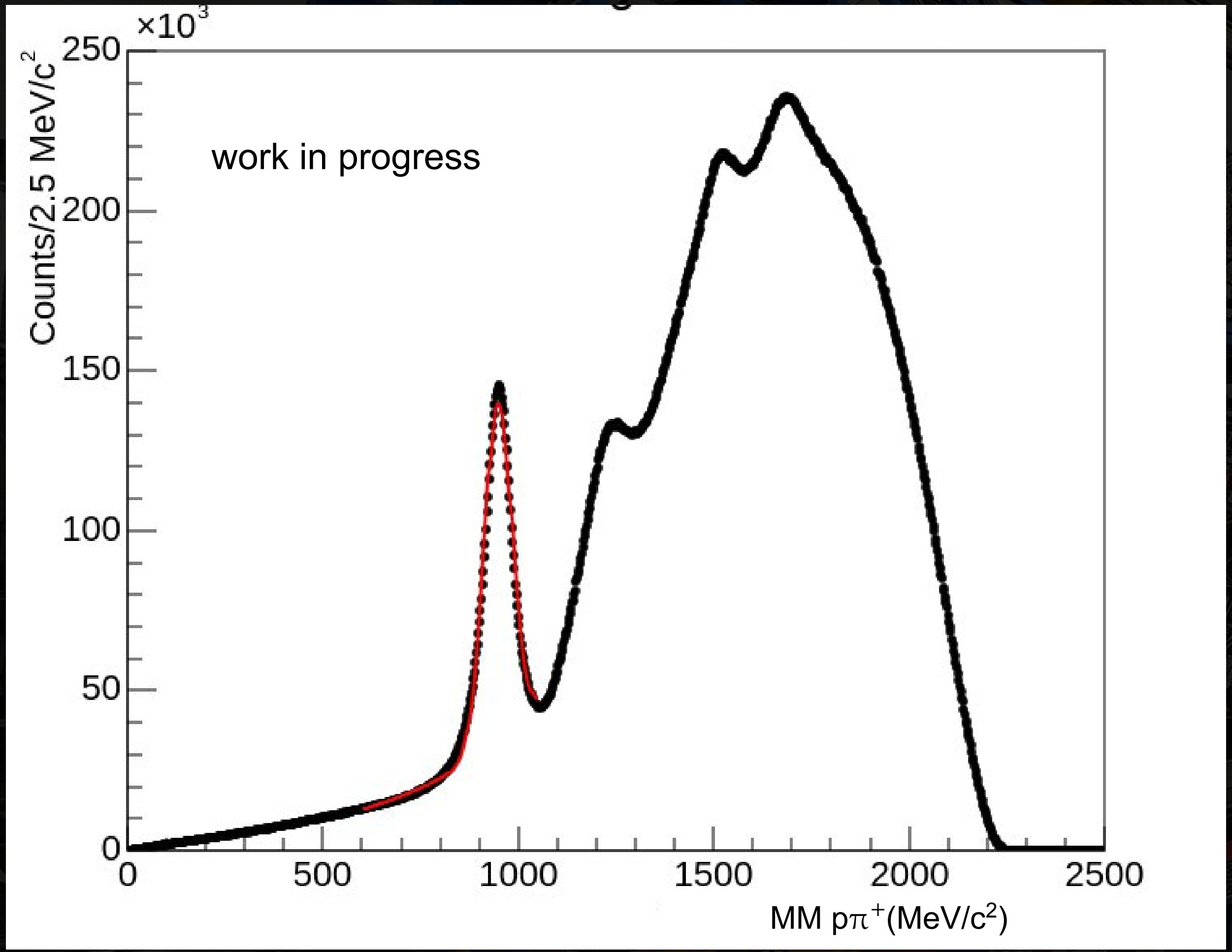
- The track PID hypothesis with the smallest χ^2 value is chosen to identify the PID of the two tracks.

Particle Identification

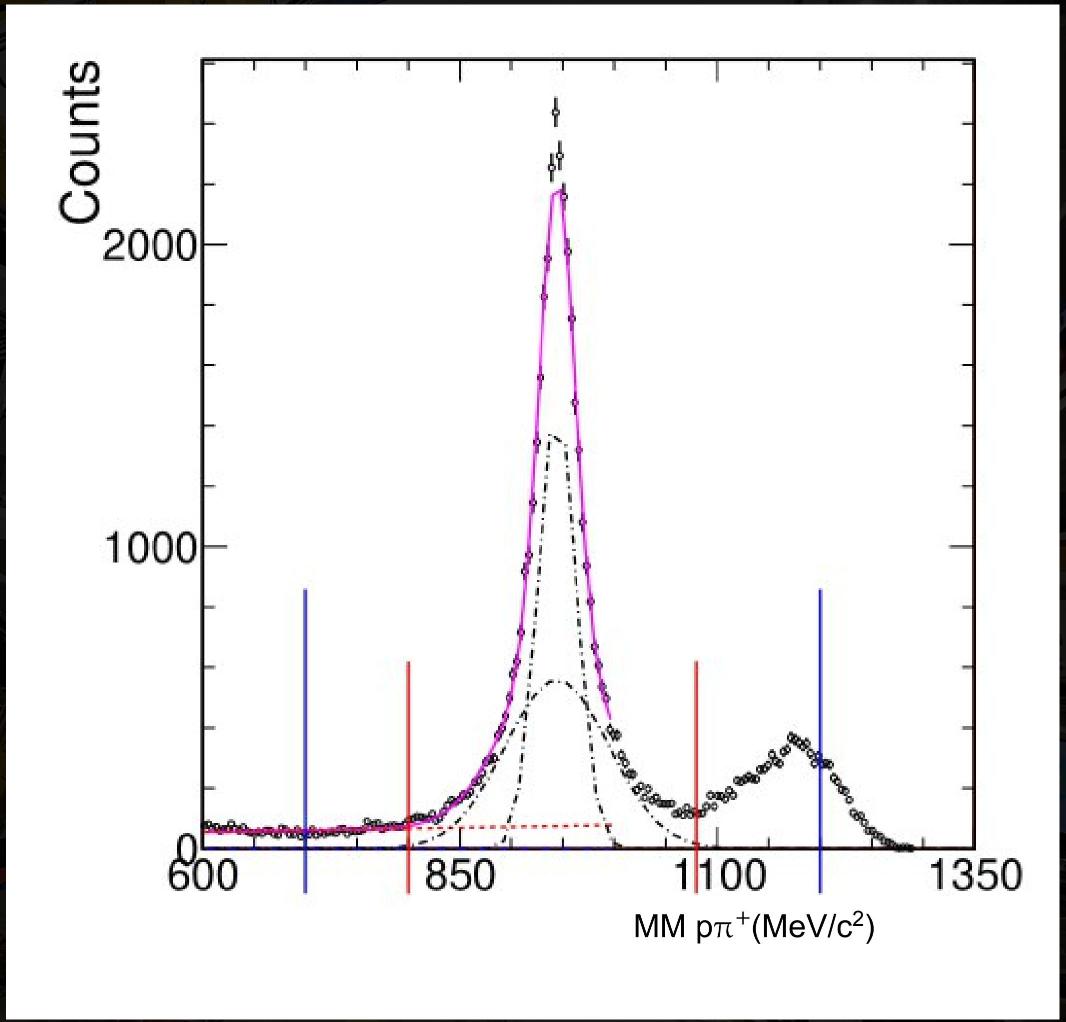


proton

Missing Mass Resolution



Neutron Peak Resolution ~ 35 MeV/c^2



pp at T = 1.25 GeV
T. Liu, PhD Thesis 2010.

Neutron Peak Resolution ~ 12 MeV/c^2

Normalization and Barrier Factors

- The amplitude is normalized and multiplied by a barrier factor:

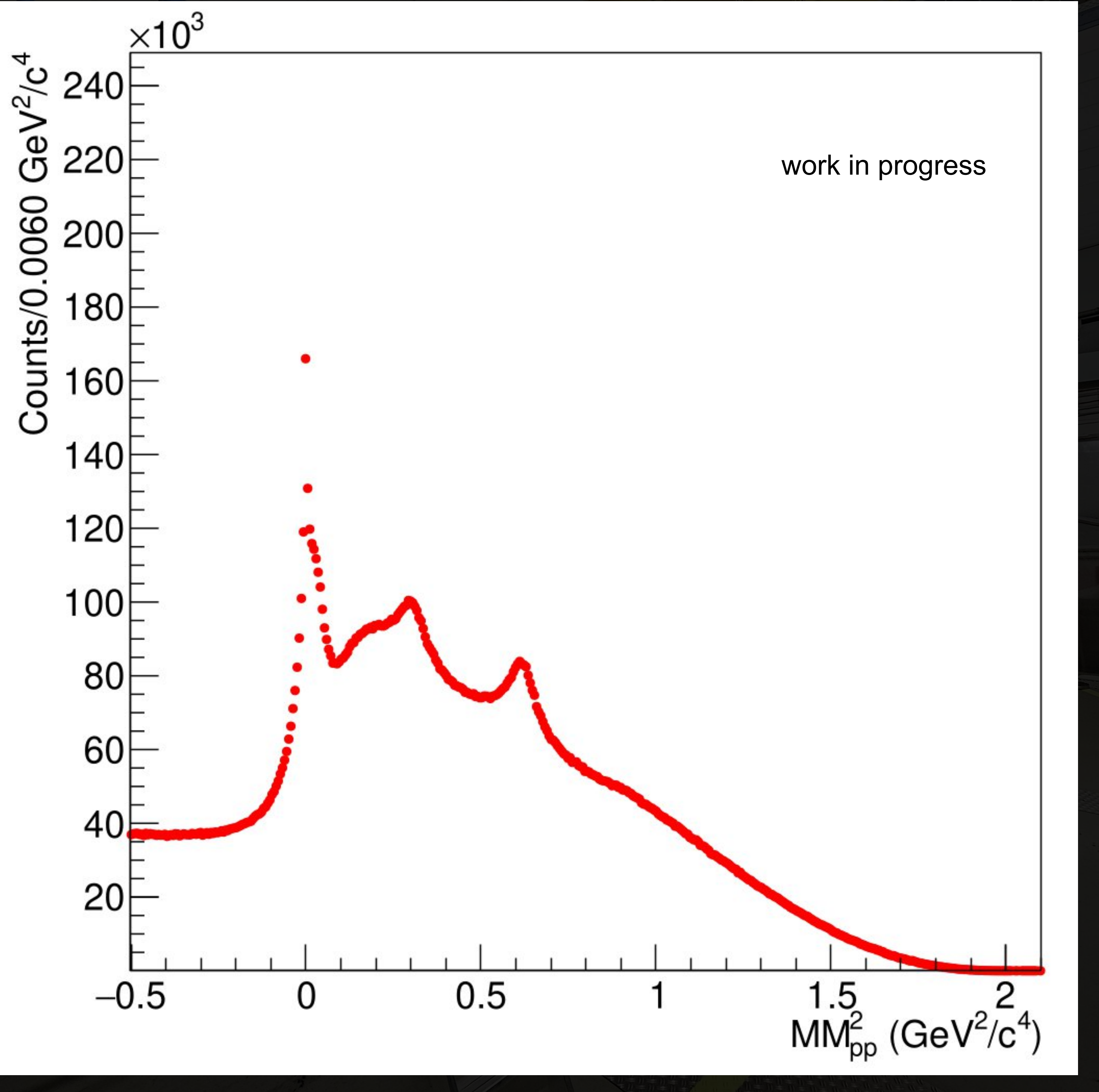
$$A_{JuBo}(L, I, J) = B_L(q)\sqrt{\frac{\rho(s, m_1, m_2)\, K_f}{K_i}}\, A_{L,I,J}(\alpha, \gamma)$$

- B_L(q) is the Blatt-Weisskopf barrier factor for a spectator with the orbital angular momentum L.

- K_i,K_f are initial and final momenta in the CM frame.

- ρ is the Meson-Baryon phase space volume.

$pp \rightarrow pp\pi^0$

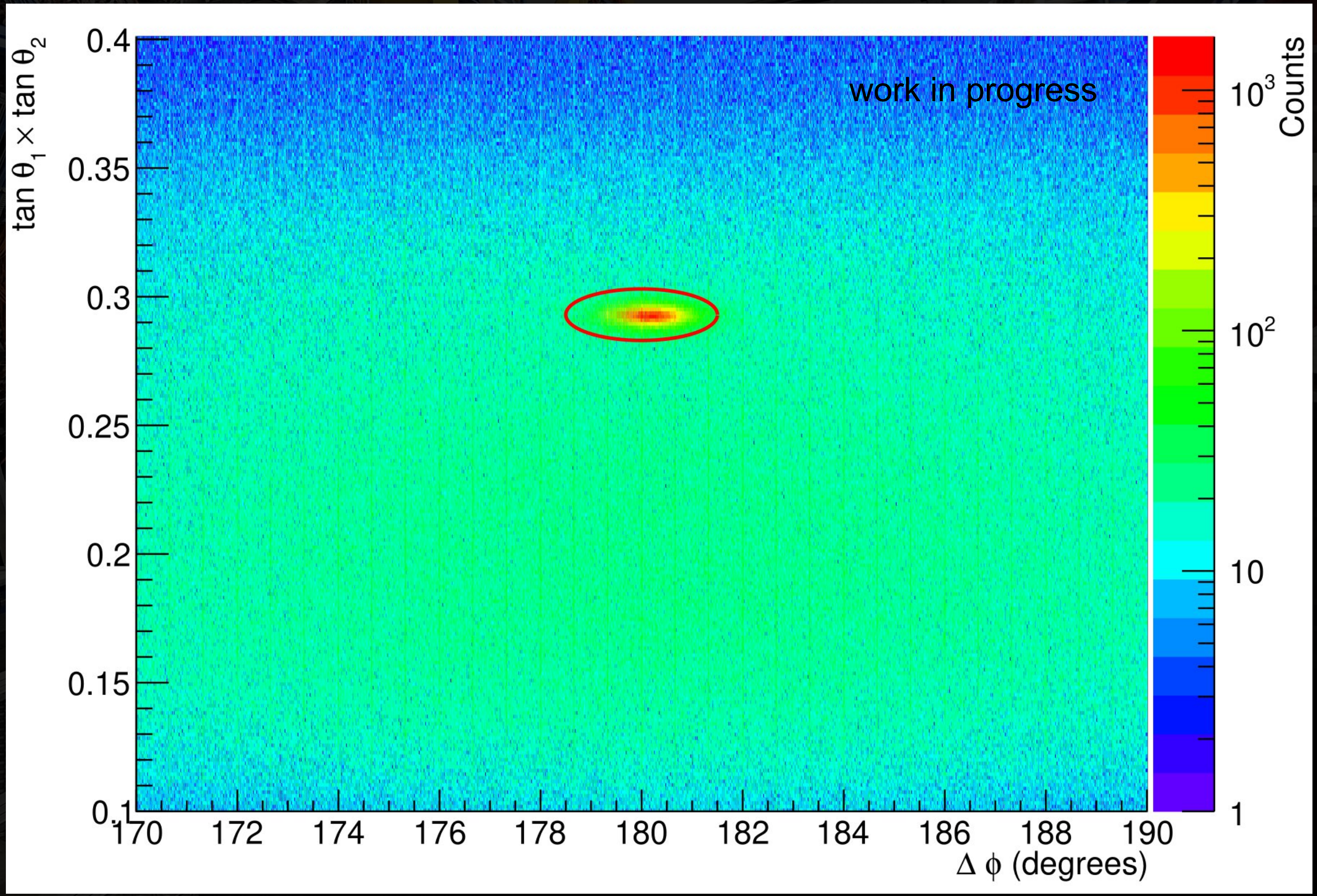


Elastic Cut

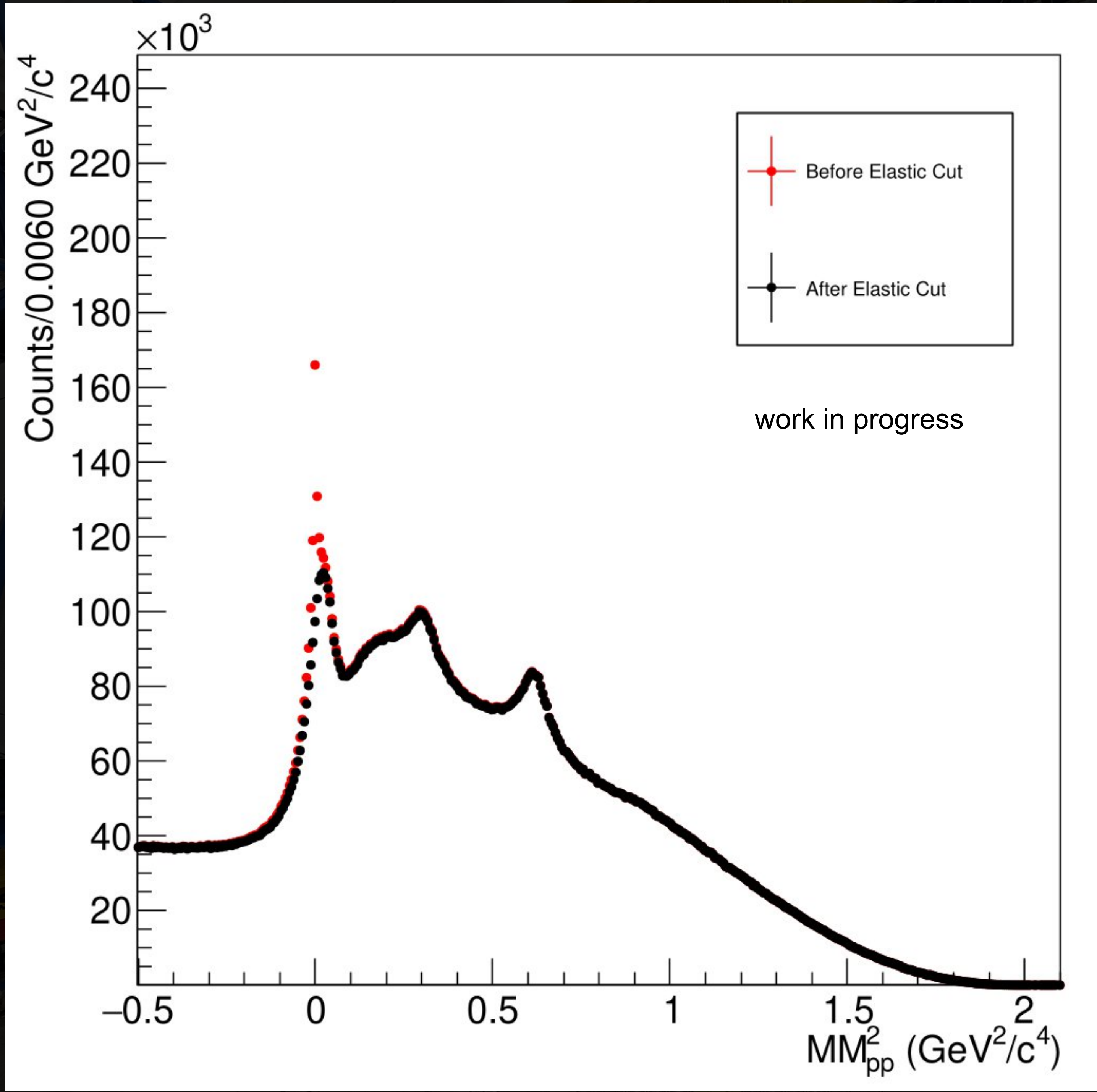
- Inelastic events are selected by applying cuts based on the expected kinematics of elastic scattering.

$$\Delta\phi = |\phi_1 - \phi_2| = 180^\circ$$

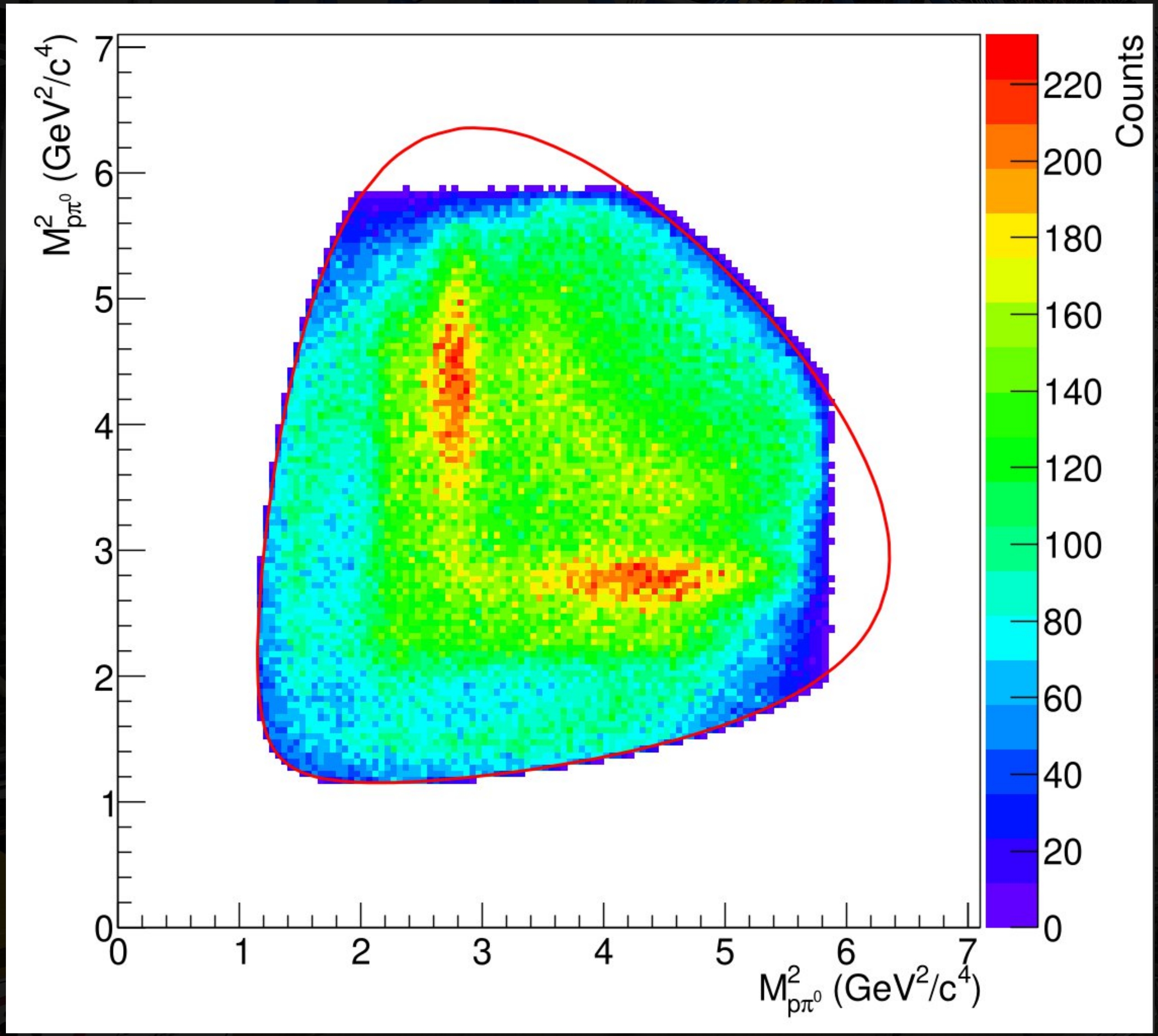
$$\tan\theta_1 \times \tan\theta_2 = \frac{1}{\gamma_{CM}^2}$$

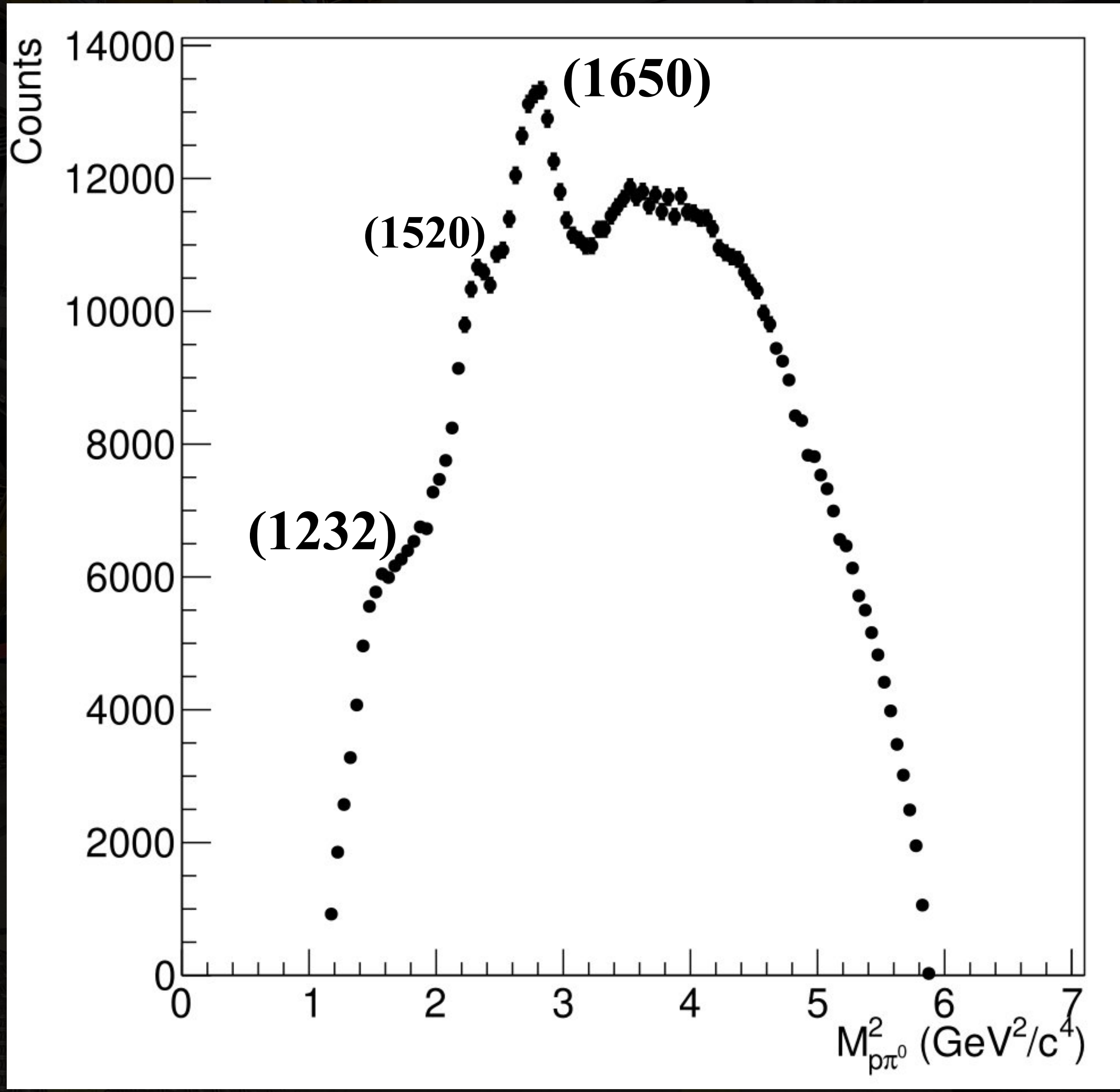


$pp \rightarrow pp\pi^0$

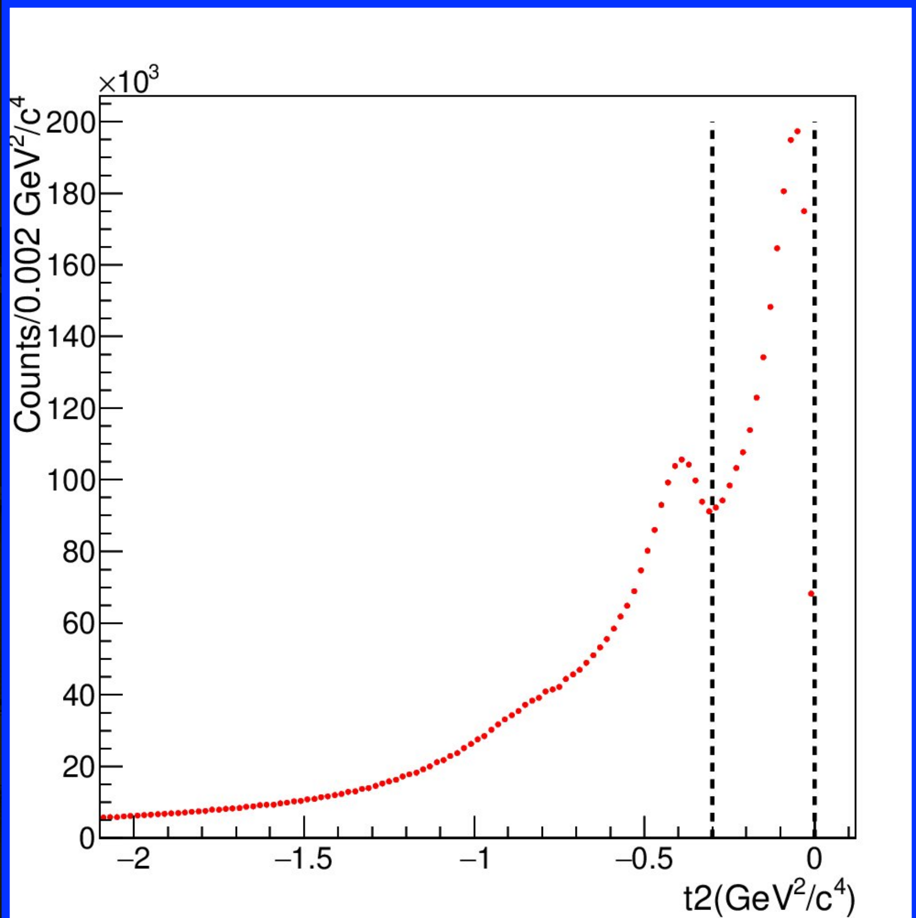


$pp\pi^0$ Dalitz Plot

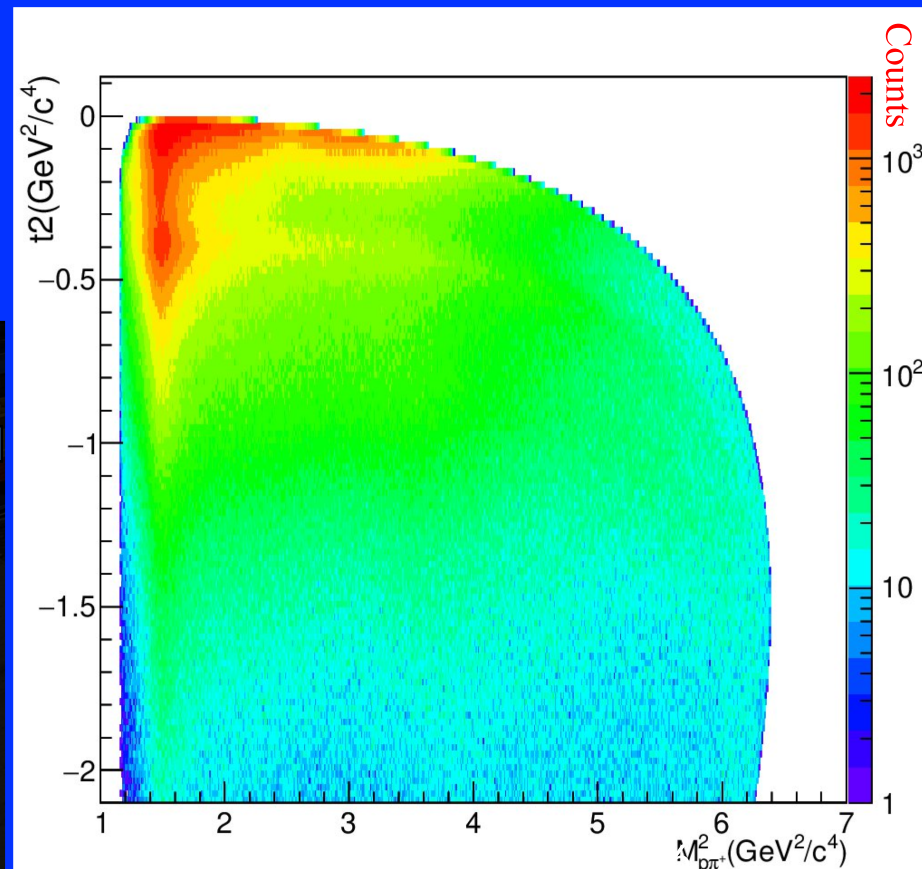


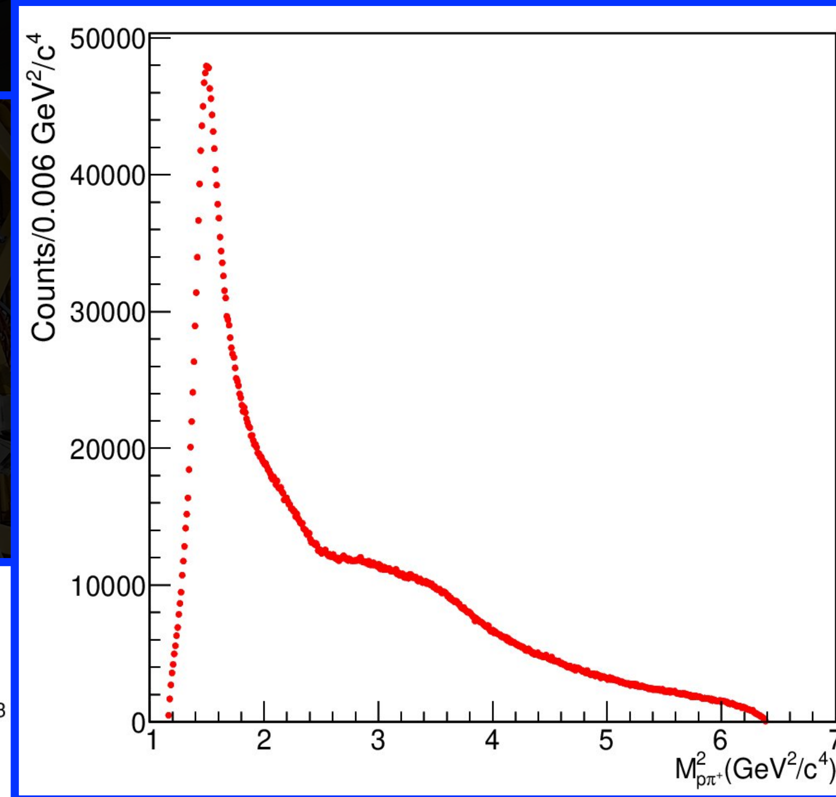


$M^2_{p\pi^+}$ vs t_2



Y projection

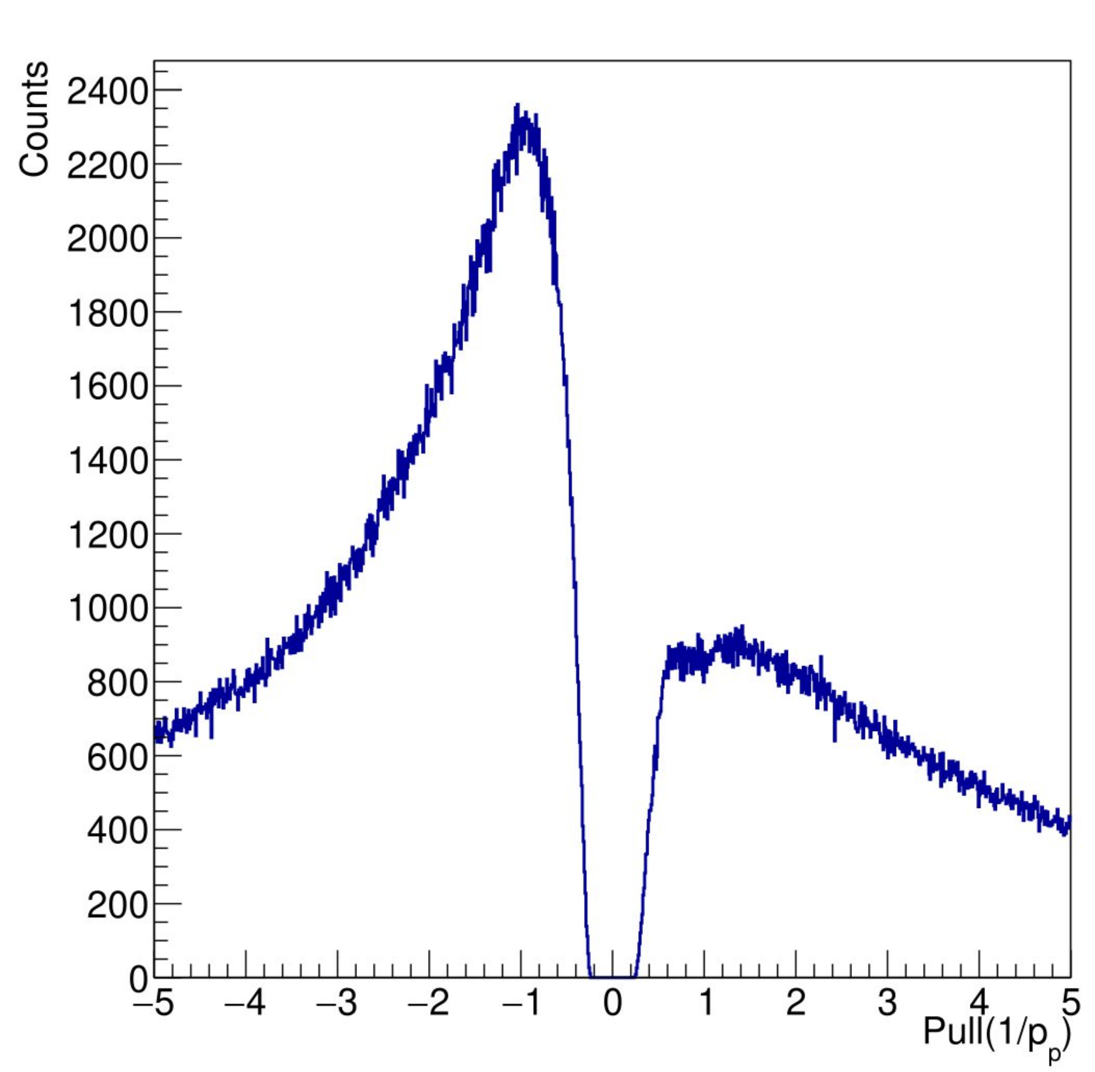




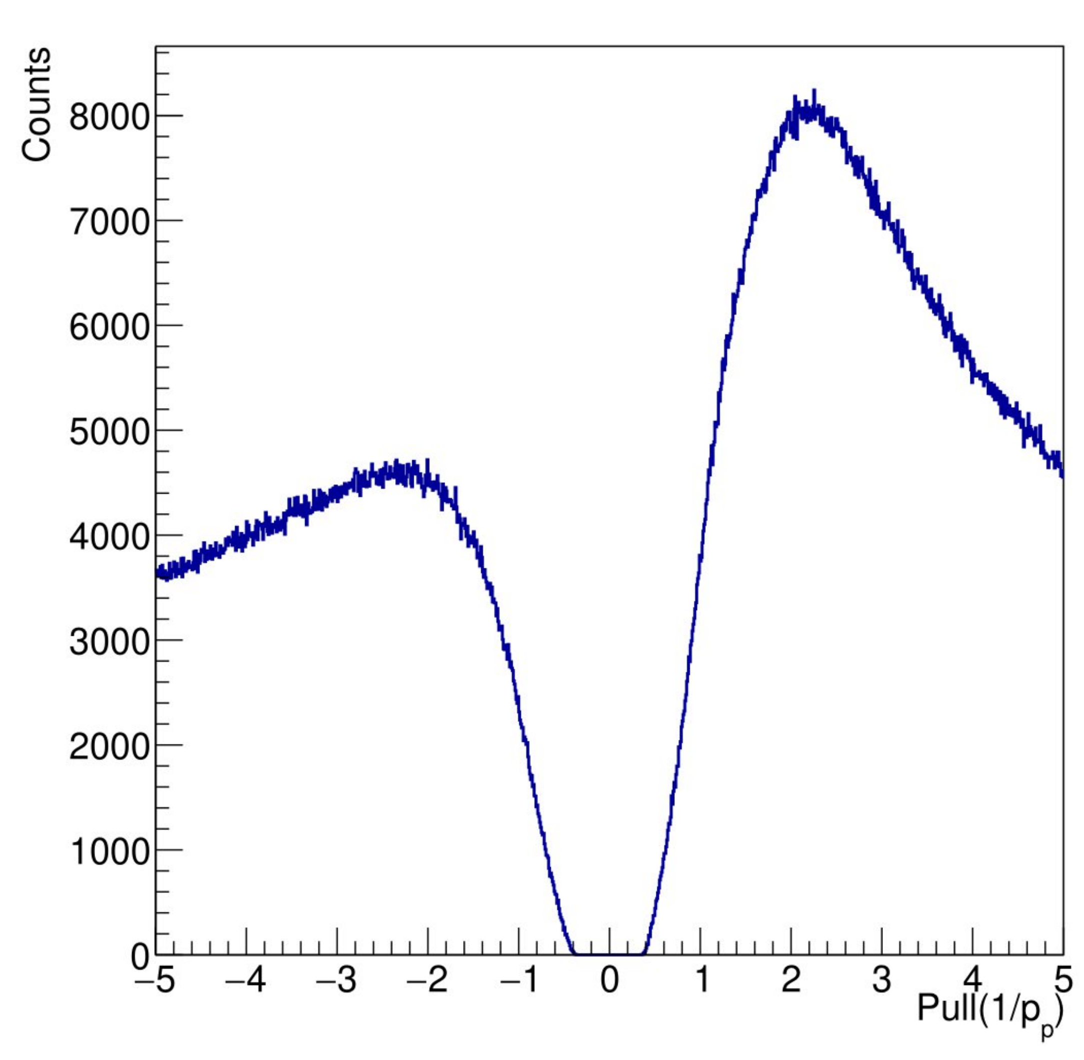
X projection

Kinfit Missing Mass Constraint

Can be thought as the 1C fit is shrinking the momentum of lower sideband to lower values and stretching the momentum of the upper sideband to higher values.



lower sideband



upper sideband