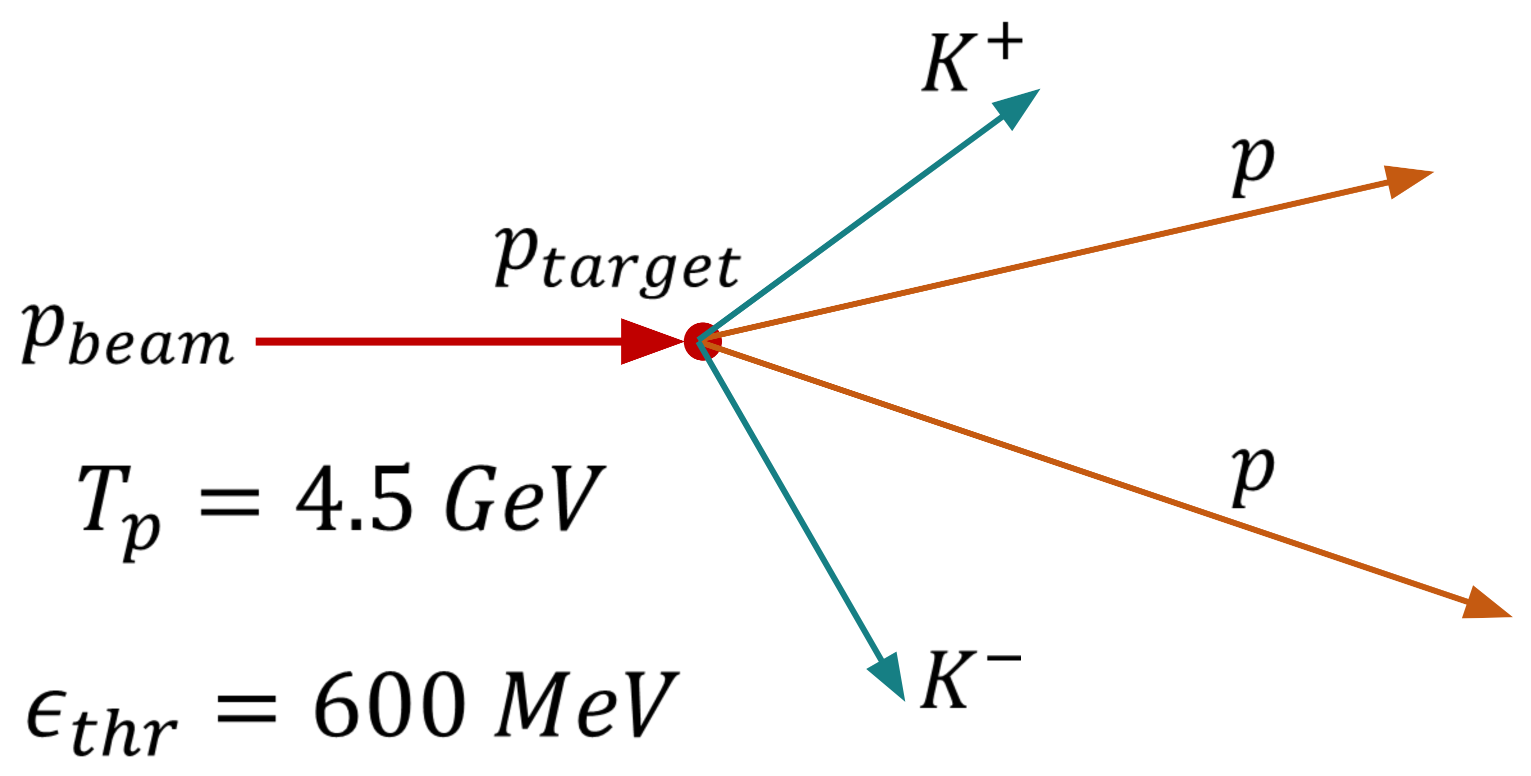
Quality checks for $pp \rightarrow ppK^+K^-$ reaction analysis

Valentin Kladov

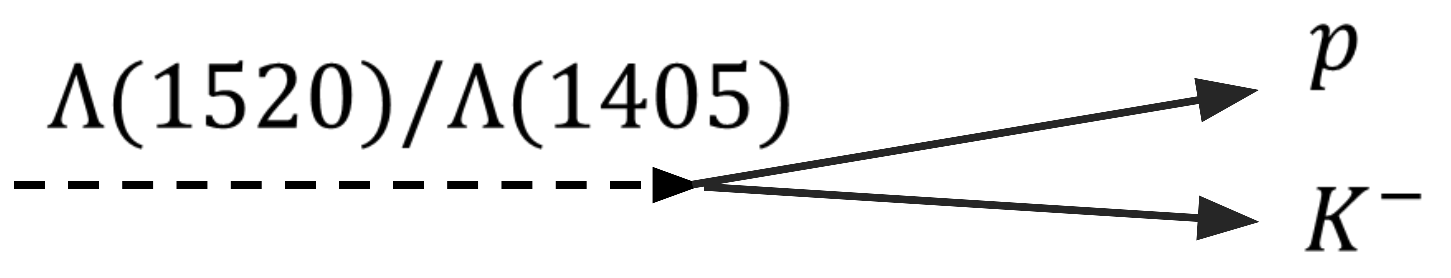
Ruhr-Universität Bochum
GSI Helmholtzzentrum

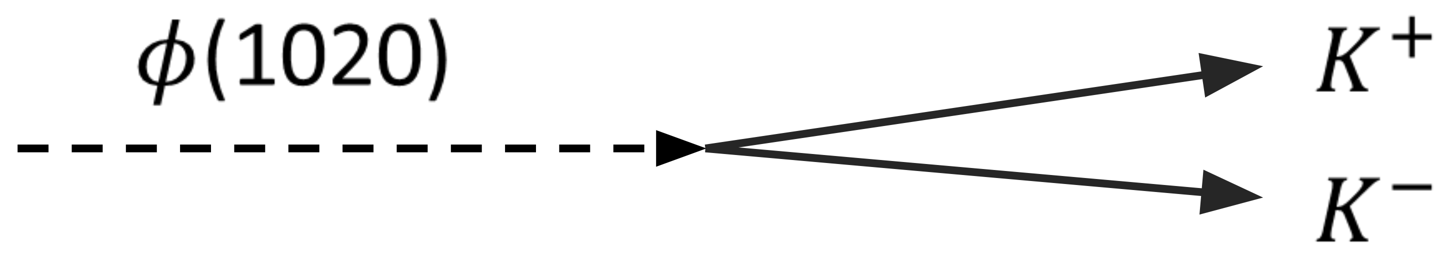
Motivation

- Strangeness production in a non-strange system?
- Final state interactions in pK^- and K^+K^- pairs?
- The role of baryon resonances? N^* or $\Lambda(1405)$

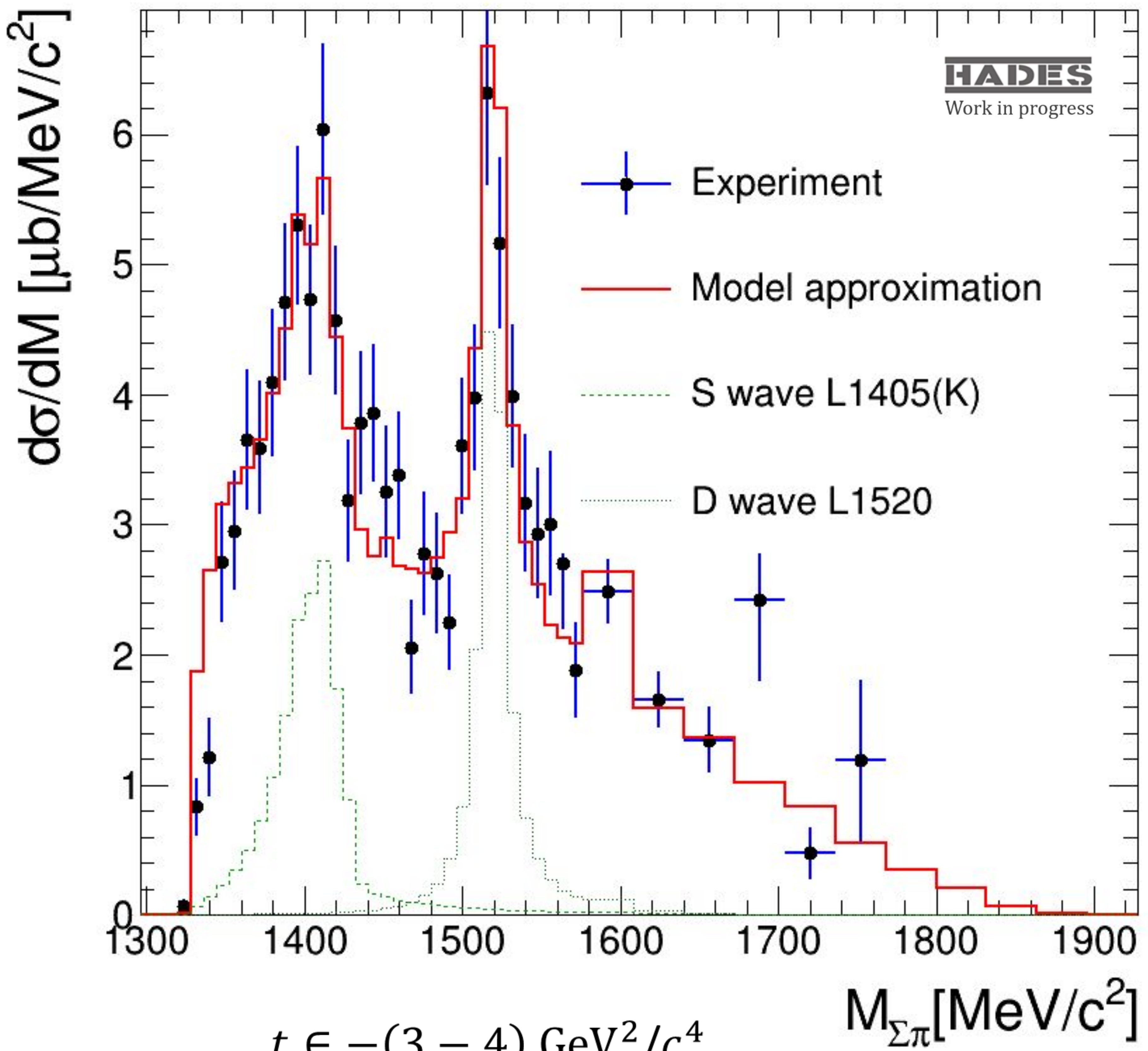


- Differential and total cross sections
- Resonance parameters, spin density matrix elements
- Scattering lengths from FSI
- K-matrix formalism pole positions for $\Lambda(1405)$

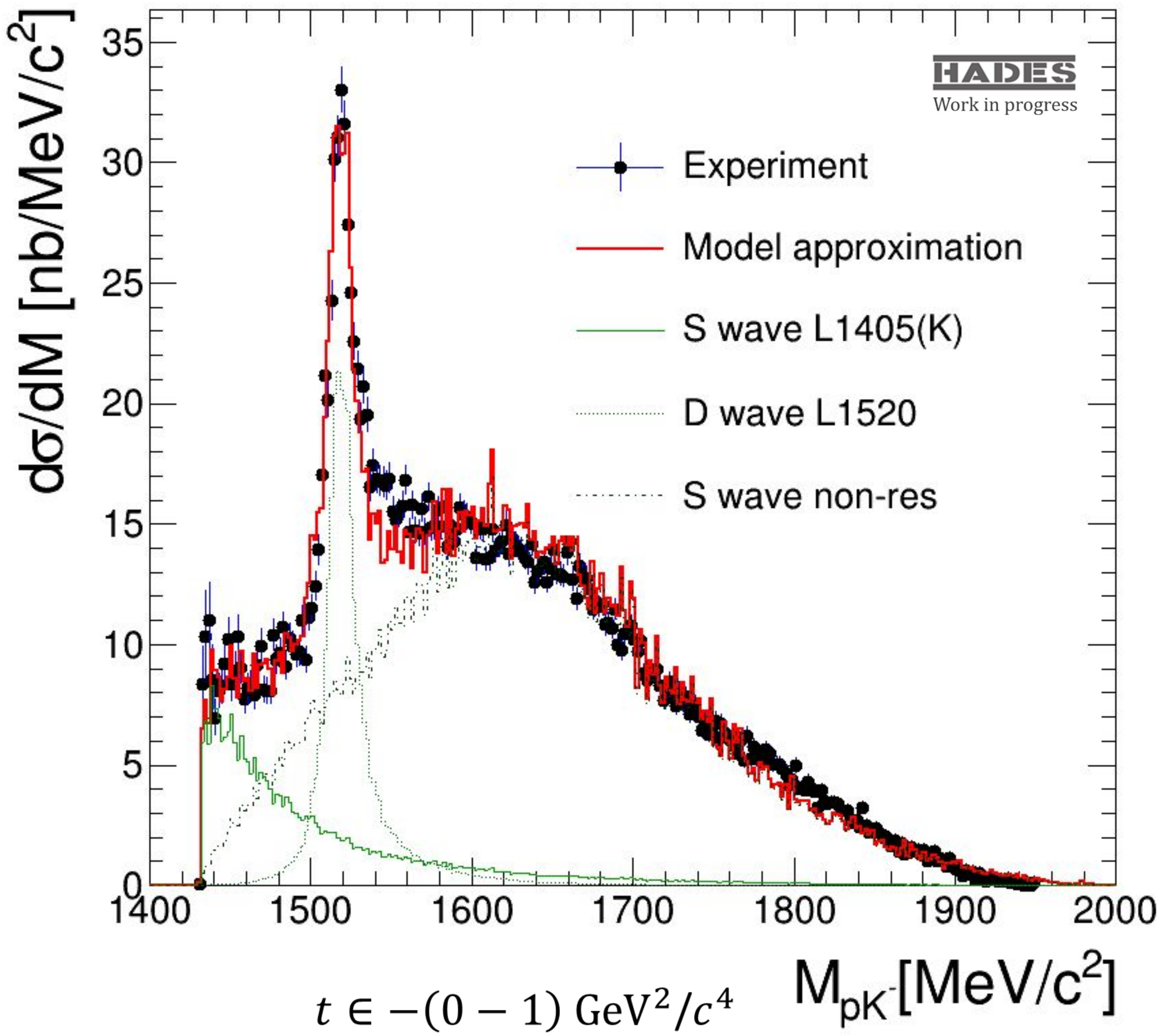




Λ(1405) Analysis in Progress



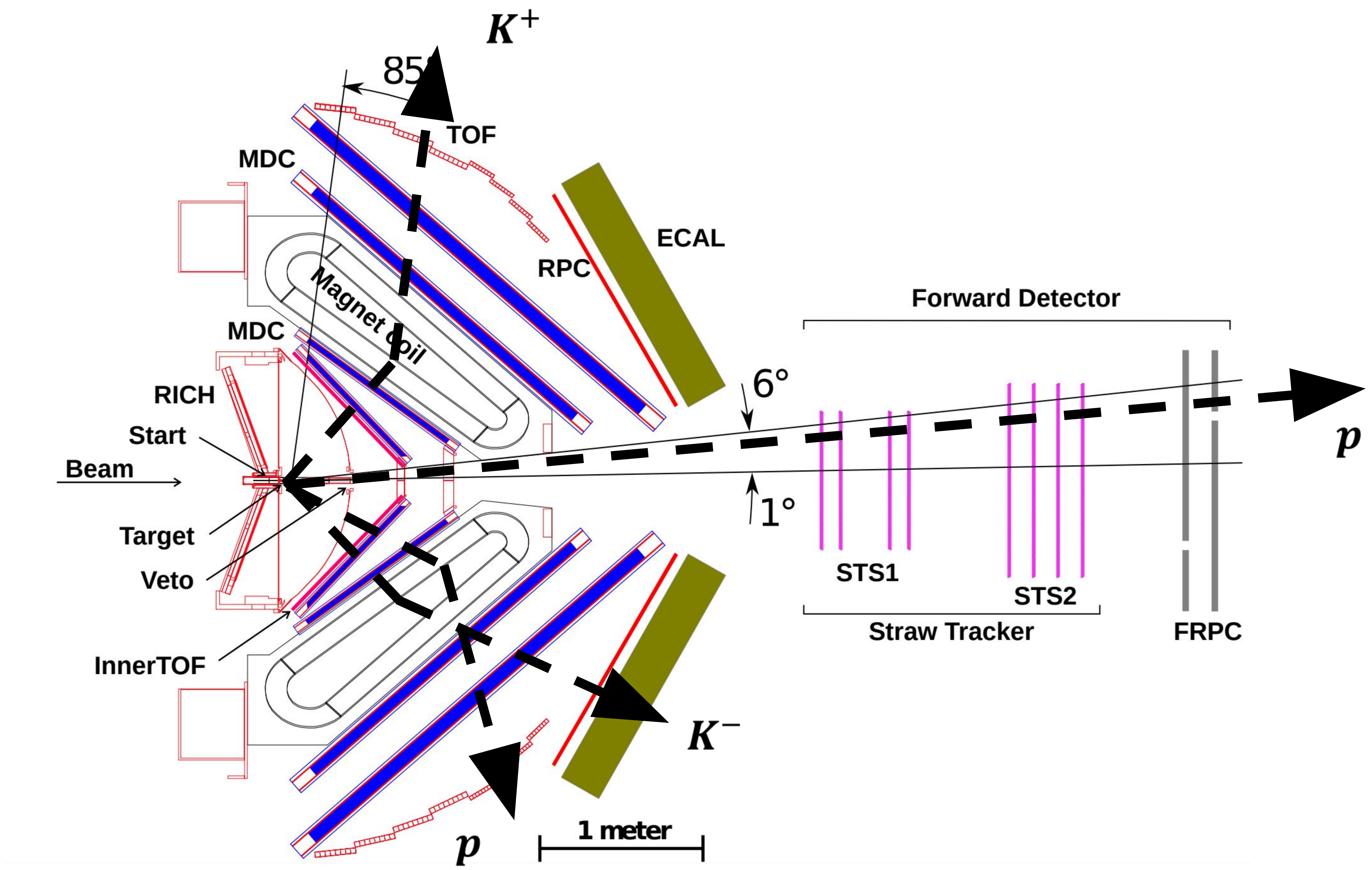
$t \in -(3-4)\ \mathrm{GeV}^2/c^4$



$t \in -(0-1)\ \mathrm{GeV}^2/c^4$

- Differential cross sections in momentum transfer bins t
- Fit within <u>2-pole K-matrix formalism</u> to approximate UchPT models
- Will present tomorrow at Meson 2026
- <u>Separate PWG discussion needed?</u>

Event Selection



- February 2022 beam time, HF topology

Topology: $2K^{\pm}$ & $1p$ in HADES, $1p$ in Forward

- *PID in HADES:* NN-based, $\pi^{\pm}, K^{\pm}, p$ classification
- *Kinematic refit:* $\chi^2_{KK} < 20$ & $\chi^2_{KK} < \chi^2_{\pi\pi \cdot}$, 4C refit

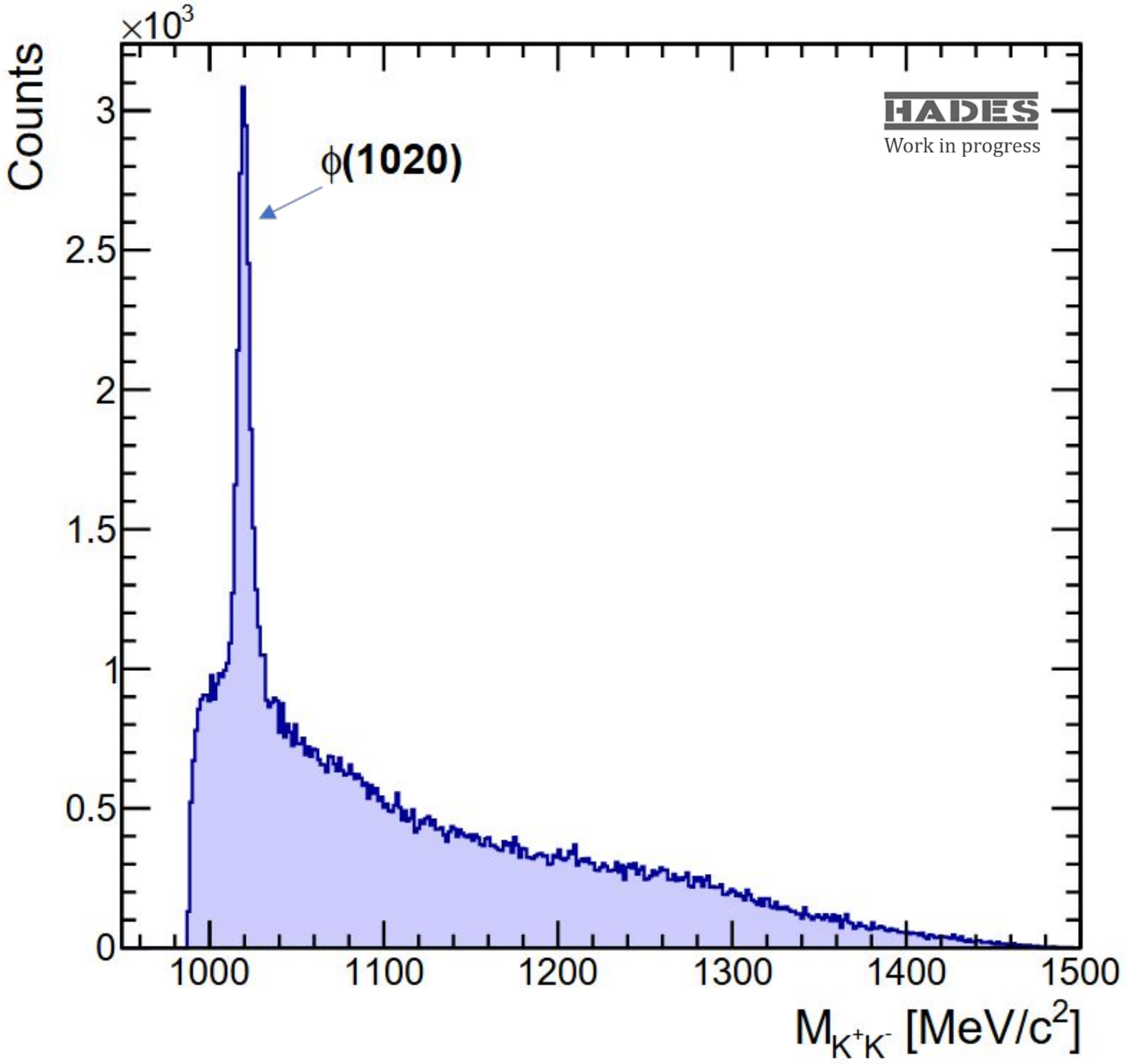
Signal: $pp \to ppK^+K^-$ ($\sim 5\ \mu b$)

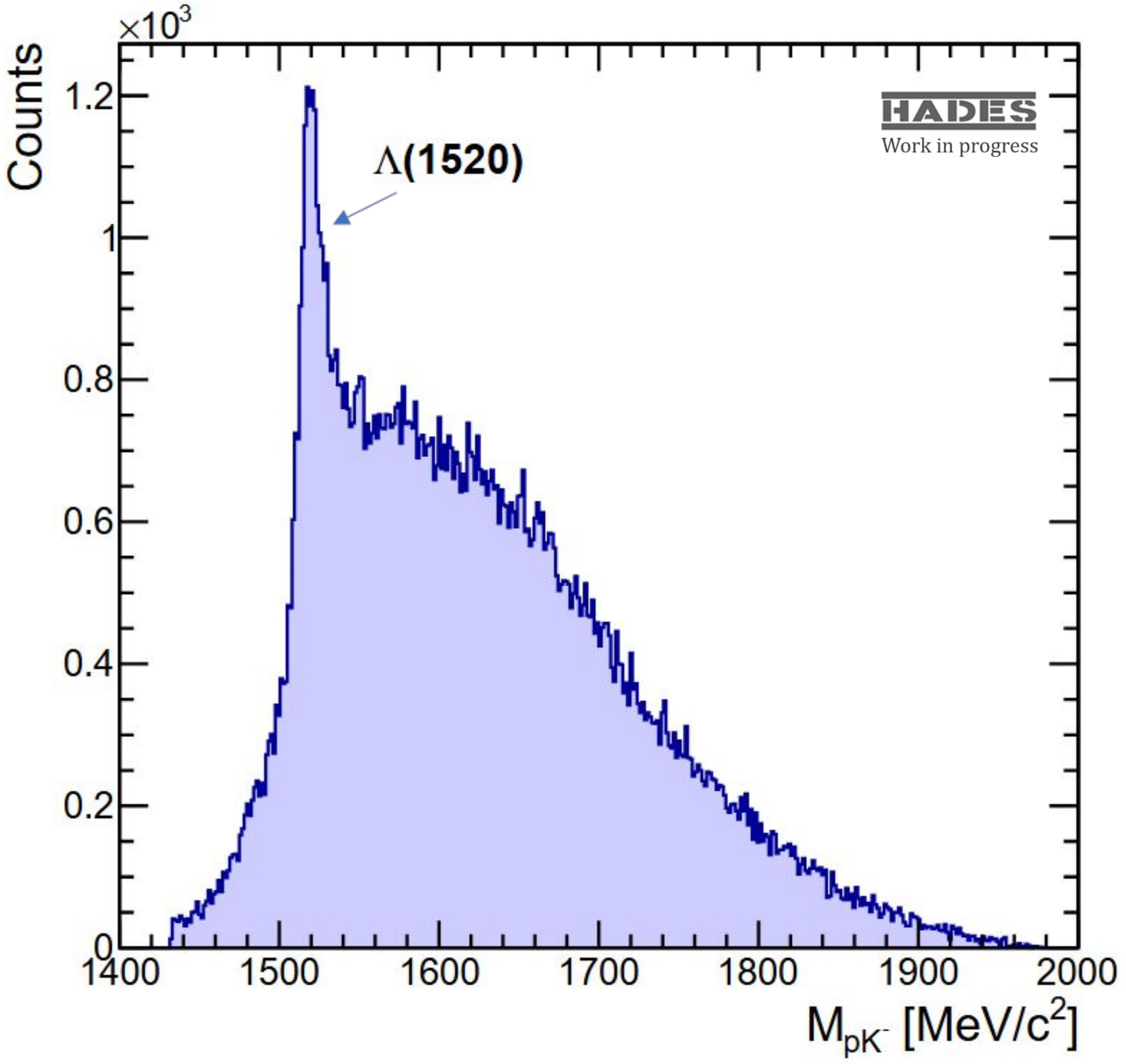
Background: $pp \to pp\pi^+\pi^-$ ($\sim 5000\ \mu b$)

$pp \to pK^+[\Lambda \to p\pi^-]$ ($\sim 50\ \mu b$)

...

Raw Distributions



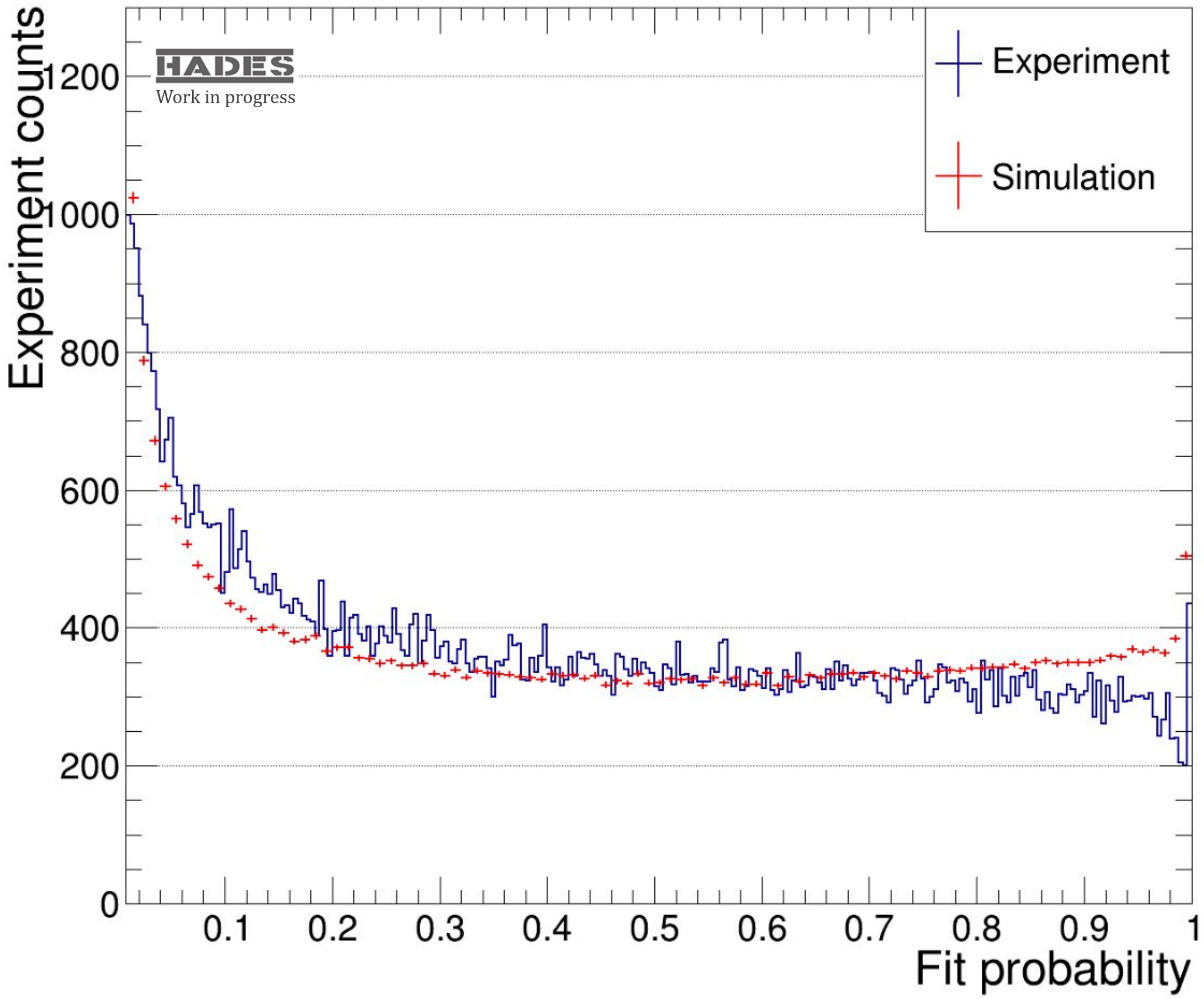


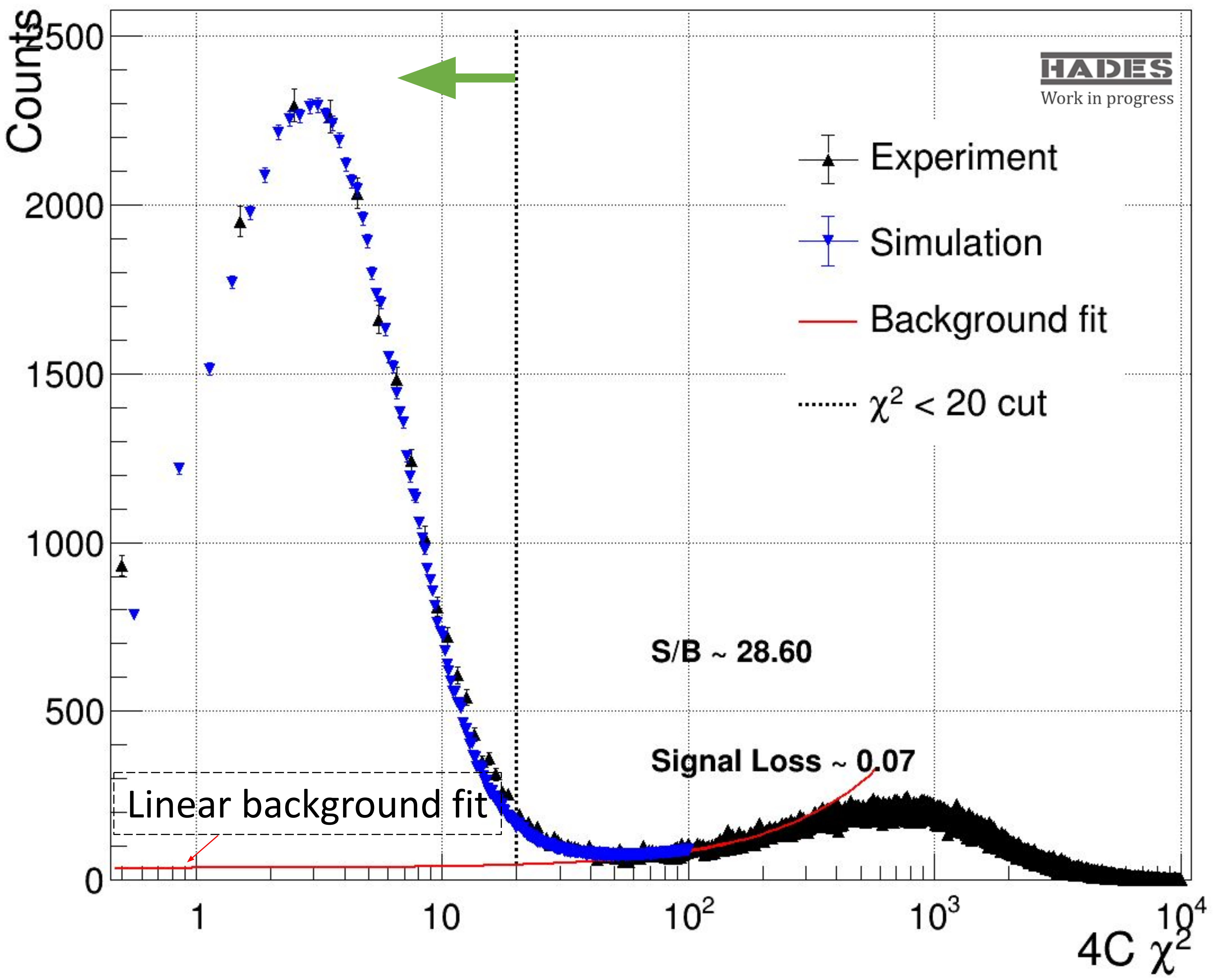
- Obtained after all selection cuts
- Filled with KR-shifted values

➢ Does kinematic refit (KR) work properly?

➢ Is background really low?

Kinematic Refit





Sufficiently flat probability distribution

$S/B \sim 30, \qquad S = 1.5 \cdot 10^5$

KinFit package: https://doi.org/10.1007/s41781-023-00112-x

New

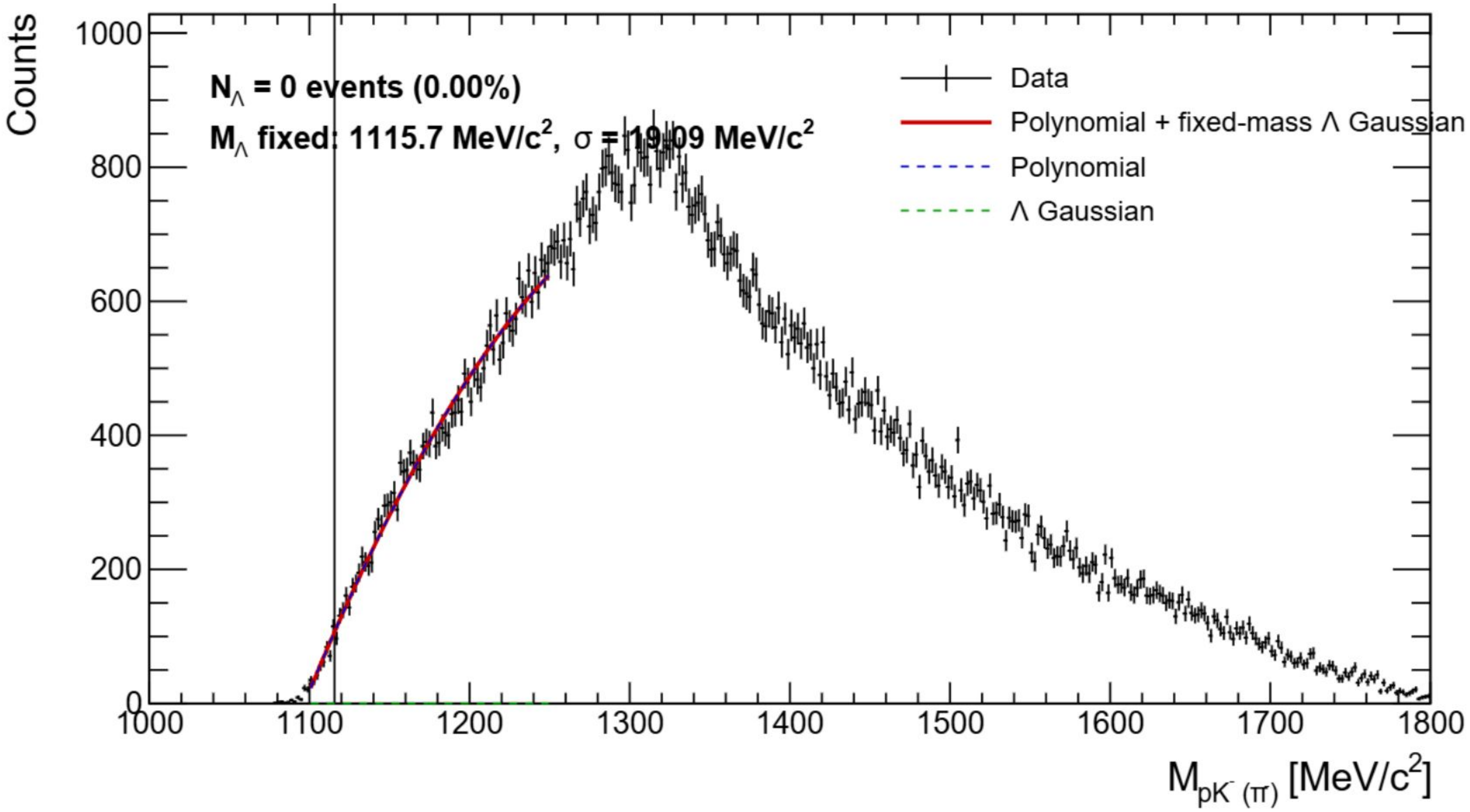
Remaining Background Studies 1

$$pp \to pK^{+}[\Lambda \to p\pi^{-}]$$

Lambda contribution,

Under the assumption of $\pi - K$ misidentification

No contribution visible



Old-New

Remaining Background Studies 2

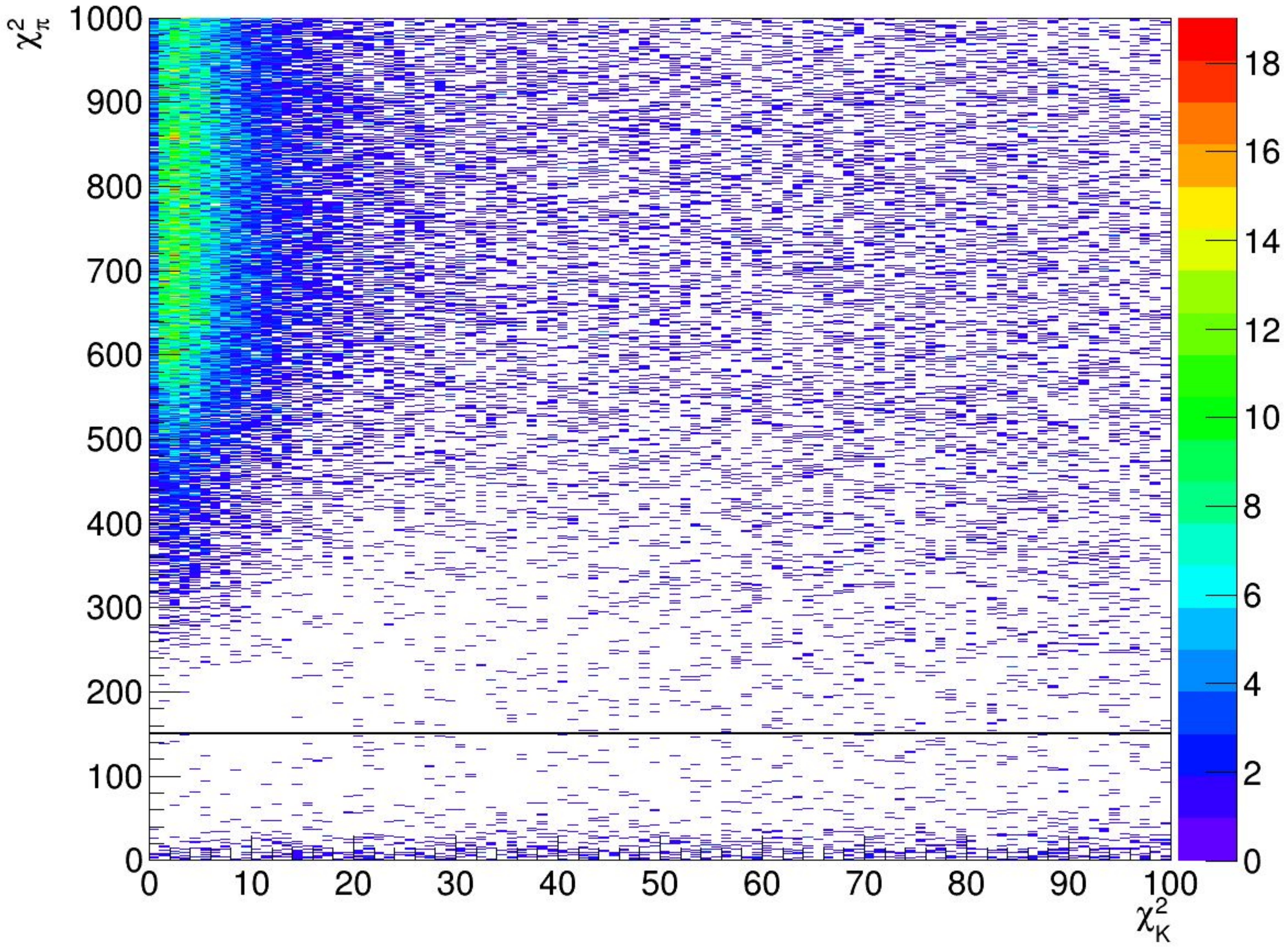
$$pp \to pp\pi^+\pi^-$$

4C fit in a mass hypothesis of double K

Against the fit with in a hypothesis of double π

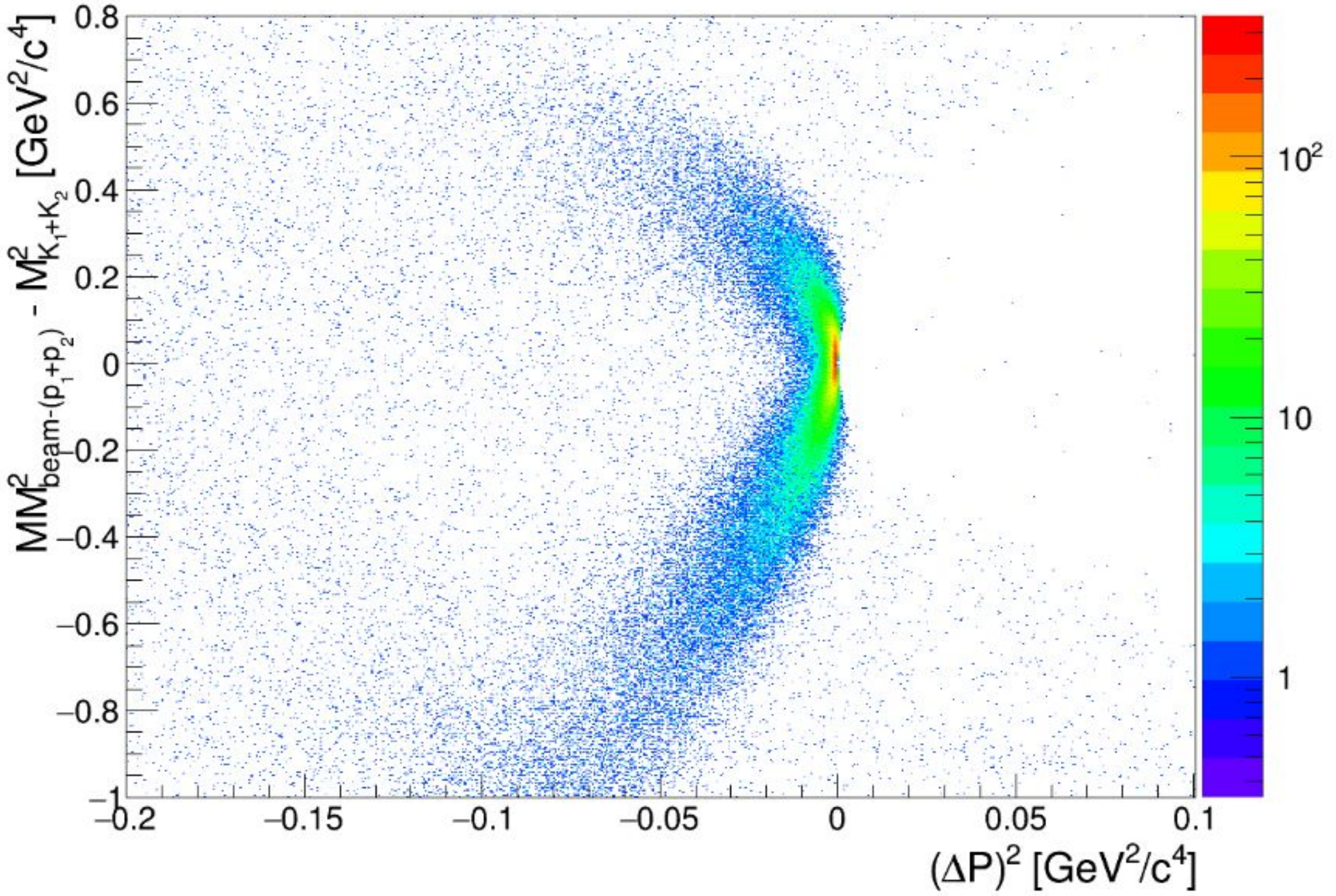
The line shows the cut that is currently used

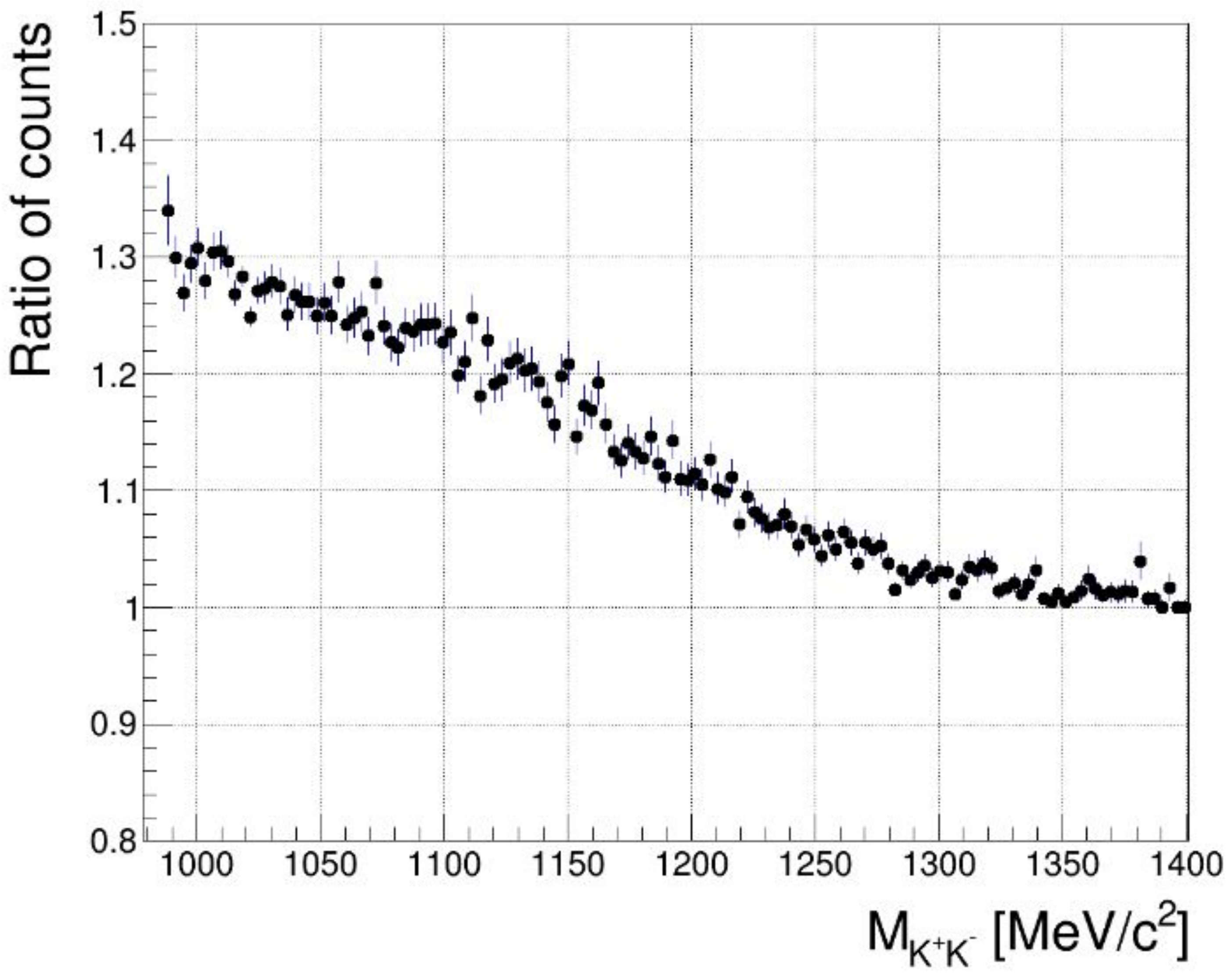
Clear contribution is almost completely removed

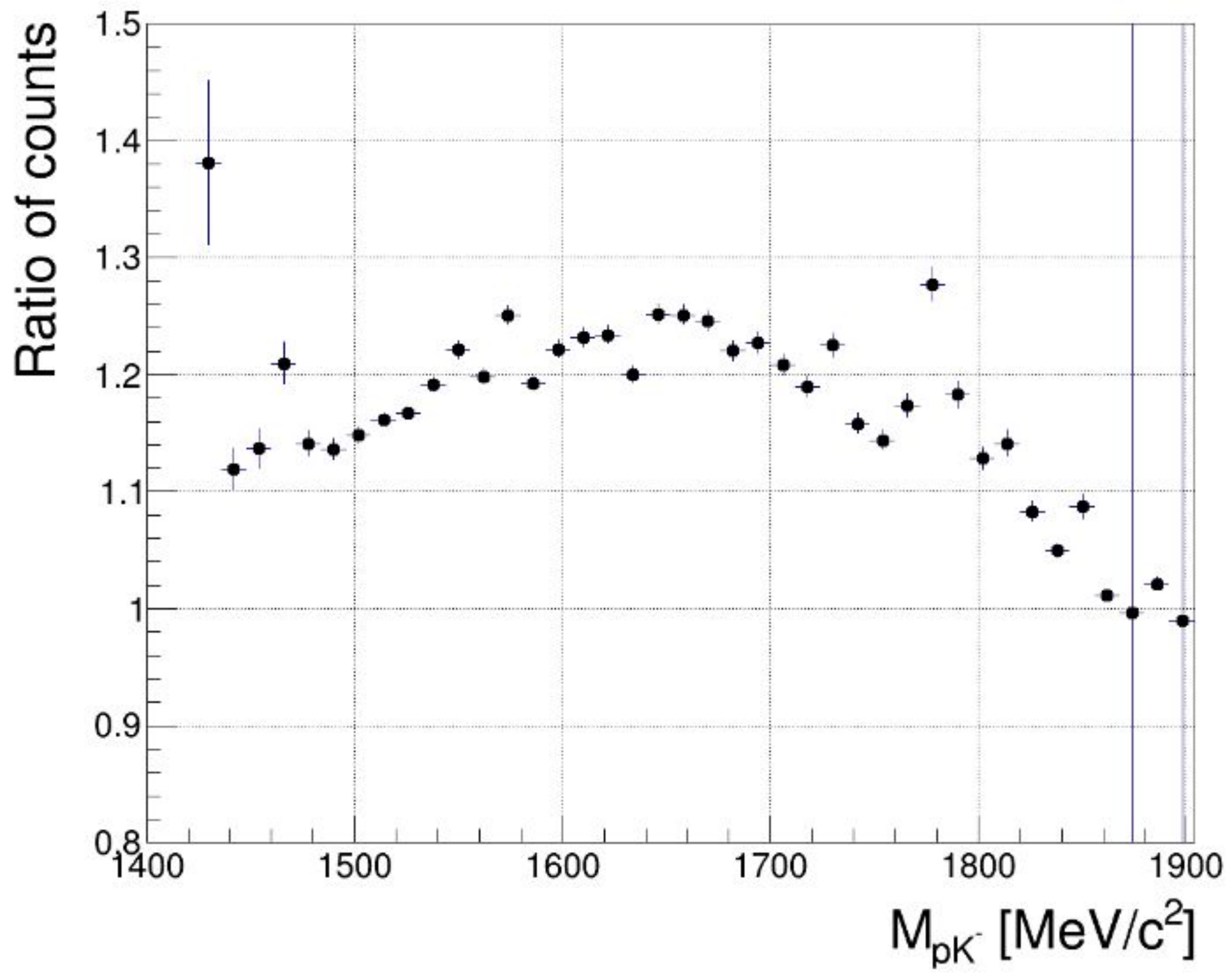


Old-New

Remaining Background Studies 3





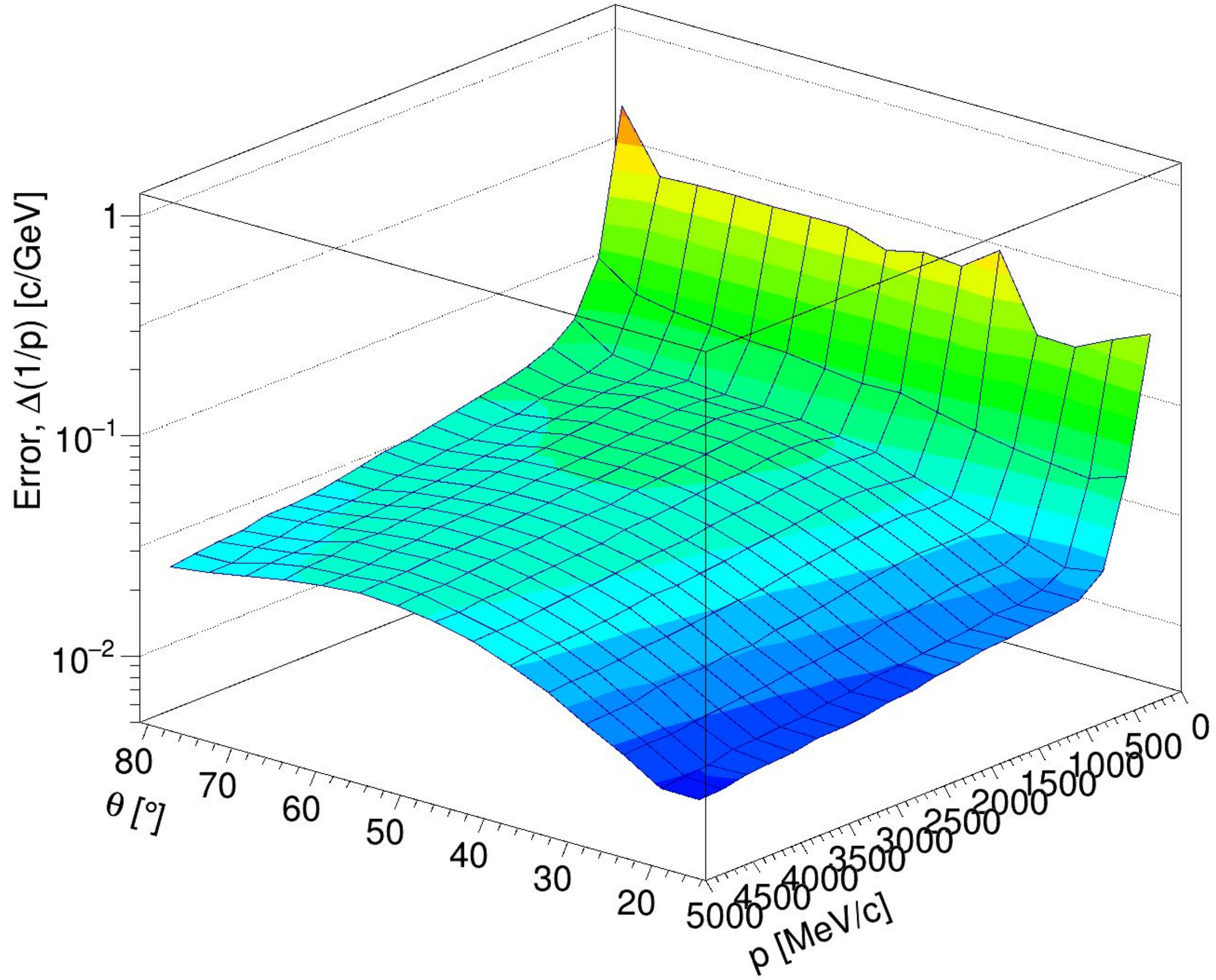


Study of extra kinematic variables

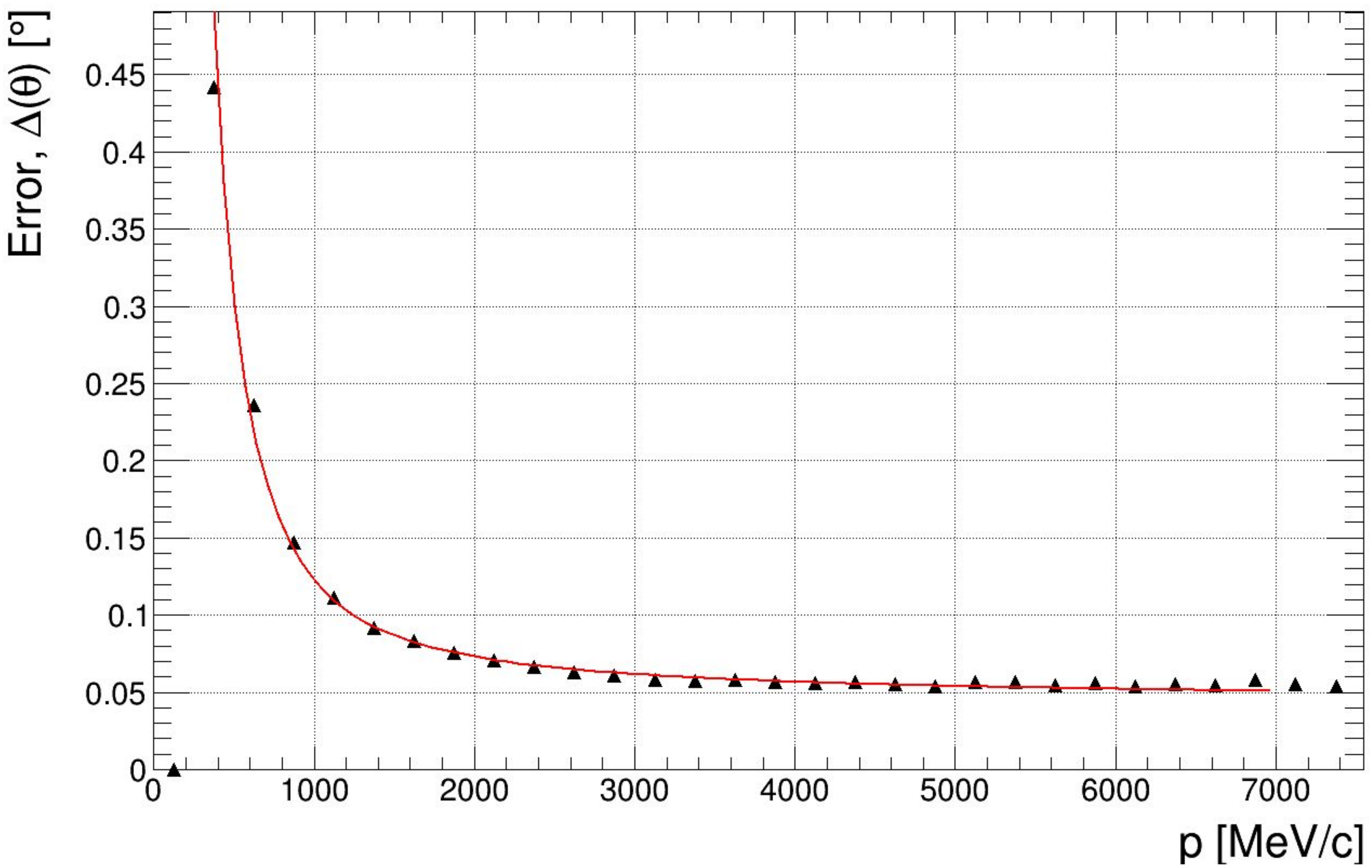
Shows that stricter cuts do not produce noticeable structures in the phi(1020) and lambda(1520) regions

+ Variations of the primary χ^2 cut in the backup

Errors for KR

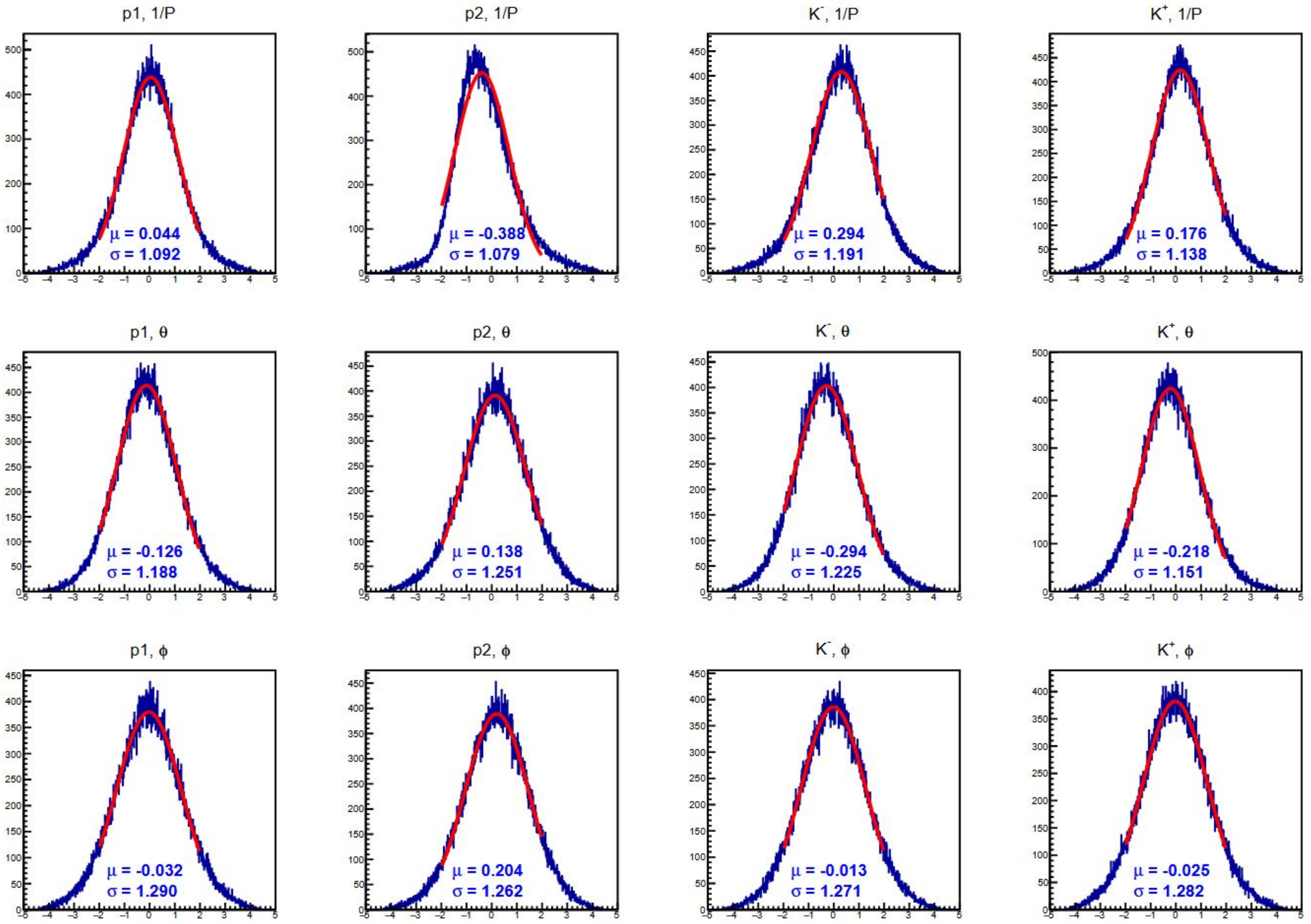


For main HADES particles

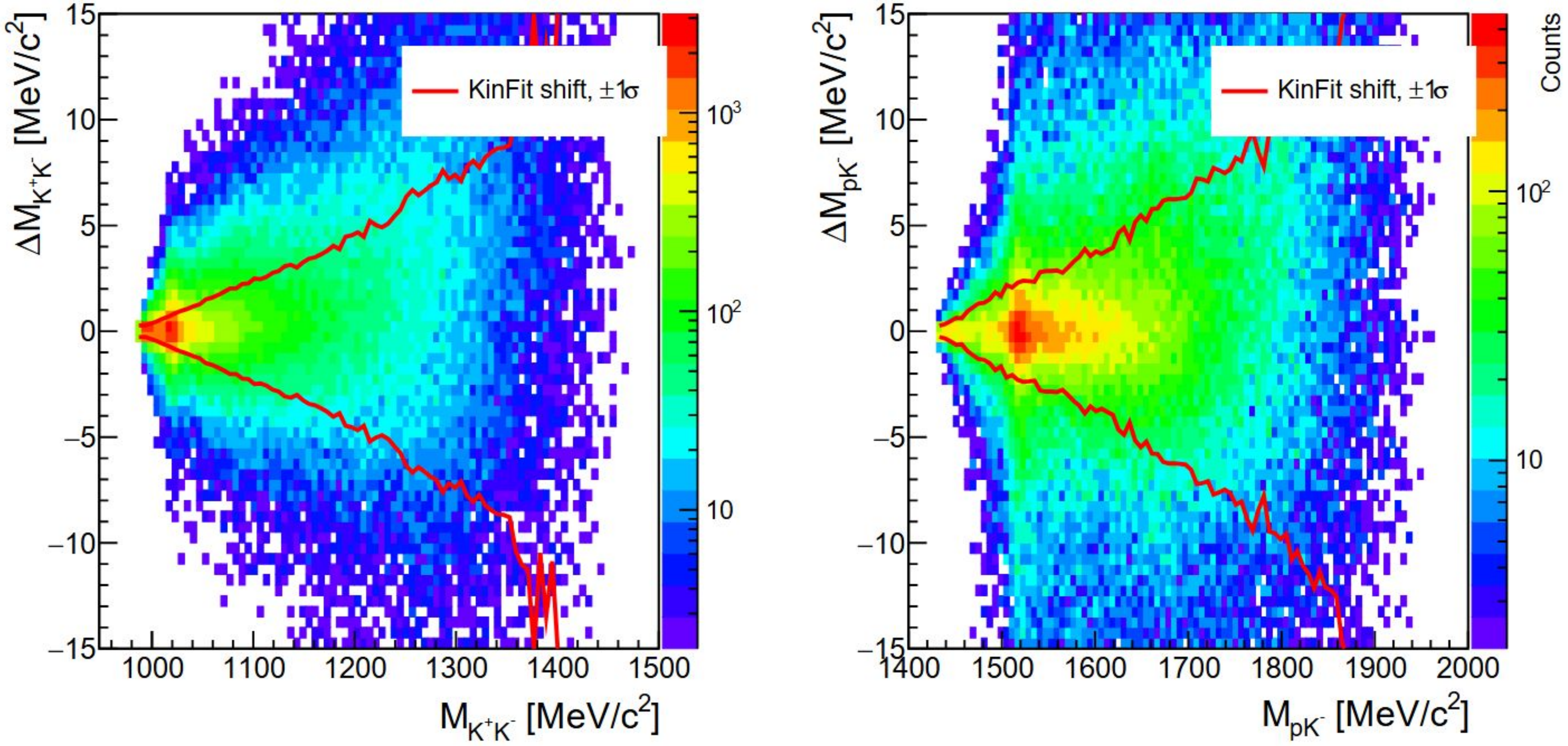


For Forward particles

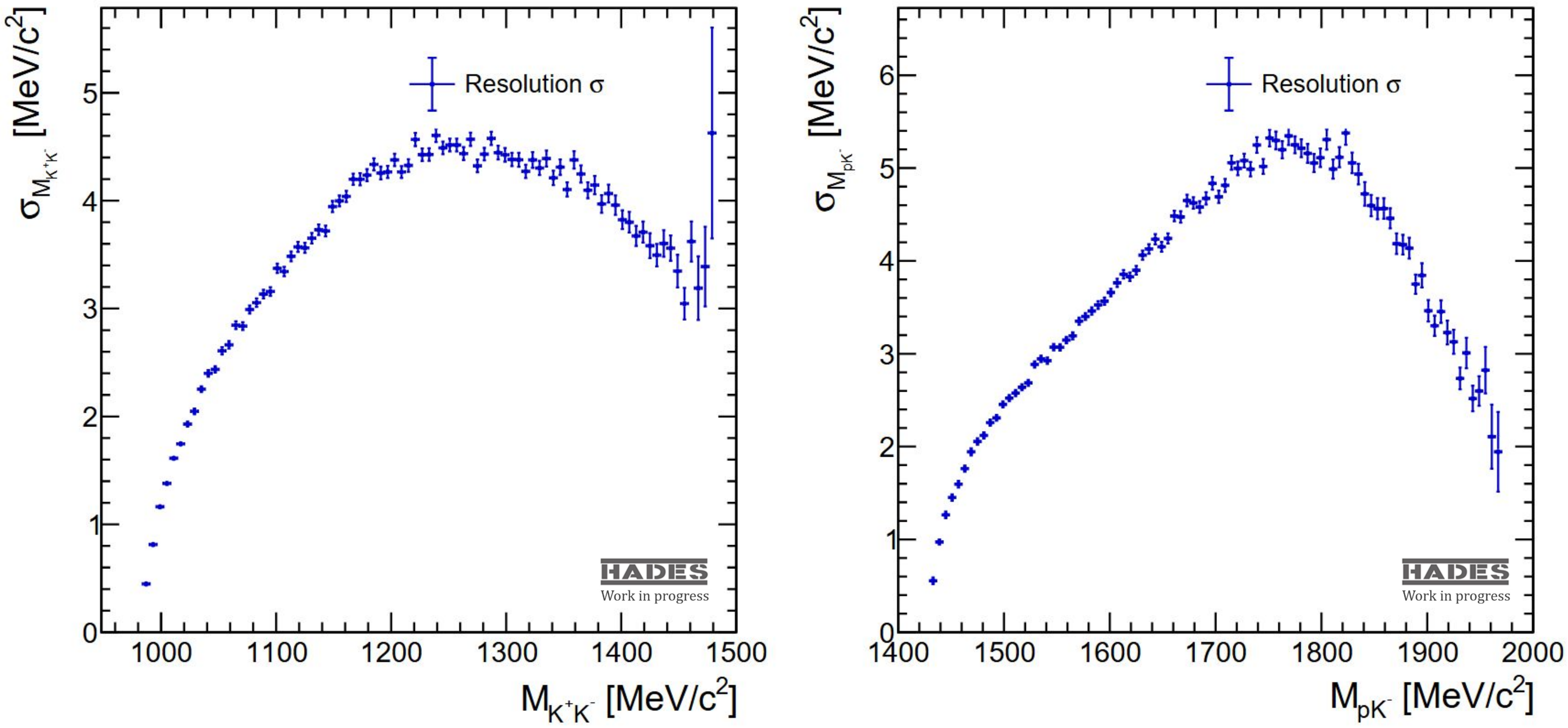
Experimental Pull Distributions



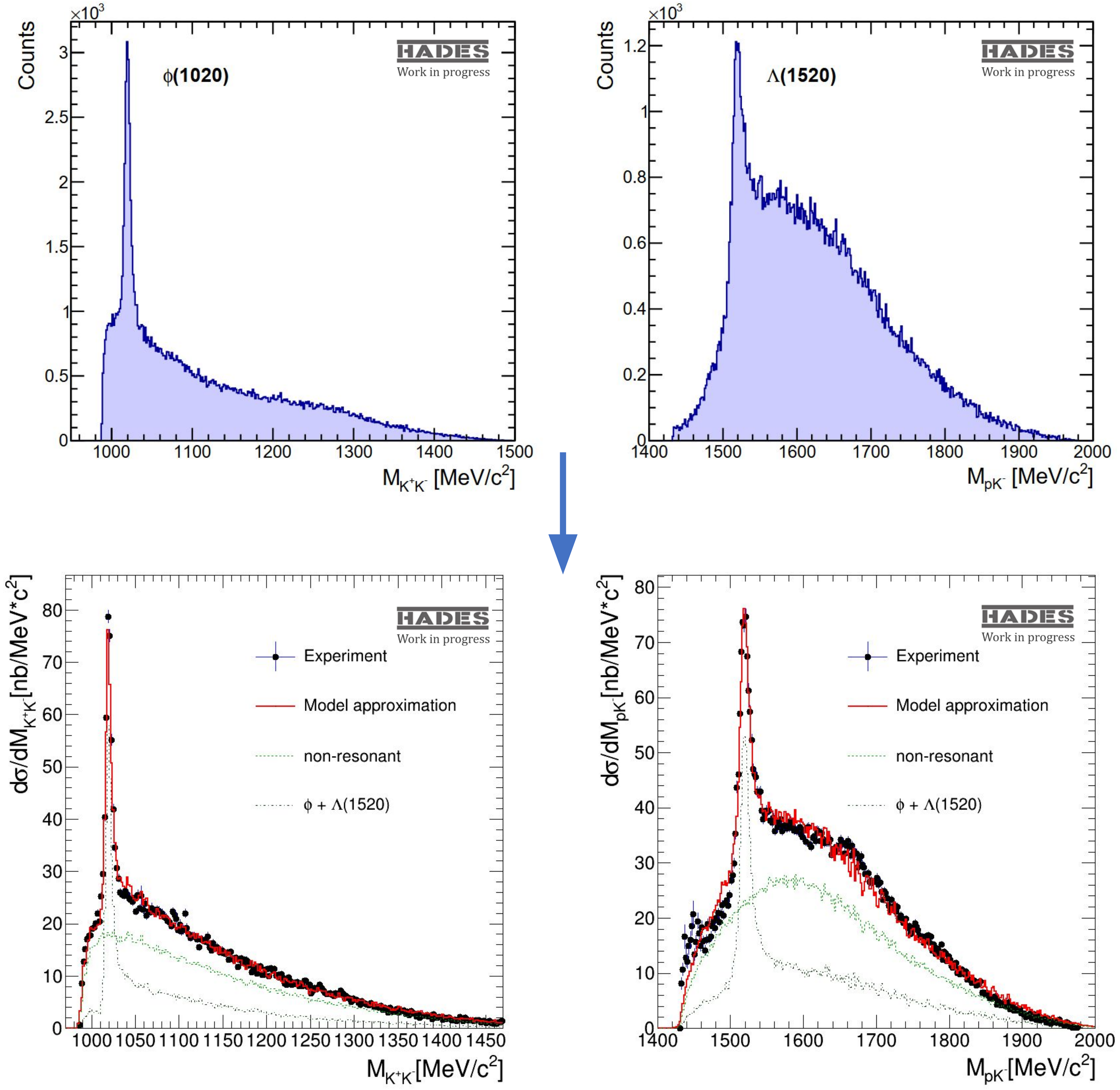
KR Shifts of Invariant Masses



Mass Resolutions



Efficiency Times Acceptance Correction



- *Method:*

Bin-by-Bin

Phase Space Simulation

- *Parameterization*:

Main resonances in 2D, 3D, or 4D:

$$M(K^+K^-) + M(pK^-)$$

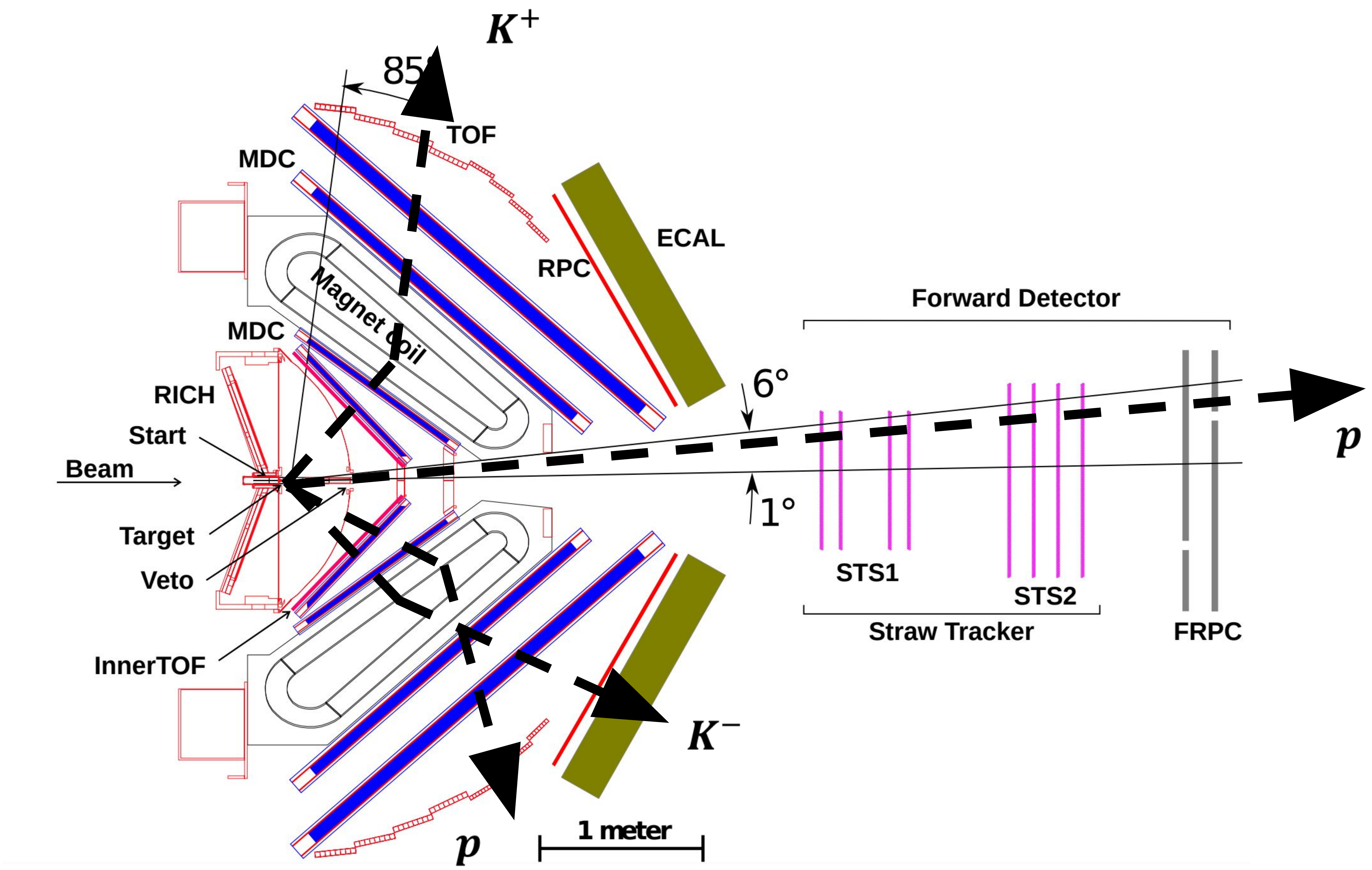
$$M(K^+K^-) + M(pK^-) + \theta^{GJ}_{\phi\to KK}$$

$$M(K^+K^-) + M(pK^-) + \theta^{GJ}_{\phi\to KK} + \varphi^{GJ}_{\phi\to KK}$$

➢ What are systematic uncertainties of this correction?

(from PID, acceptance, parameterization)

Event Selection



Topology: $2K^{\pm}$ & $1p$ in HADES, $1p$ in Forward

- *PID in HADES:* NN-based, $\pi^{\pm}, K^{\pm}, p$ classification
- *Kinematic refit:* $\chi^2_{KK} < 20$ & $\chi^2_{KK} < \chi^2_{\pi\pi}$., 4C refit

New

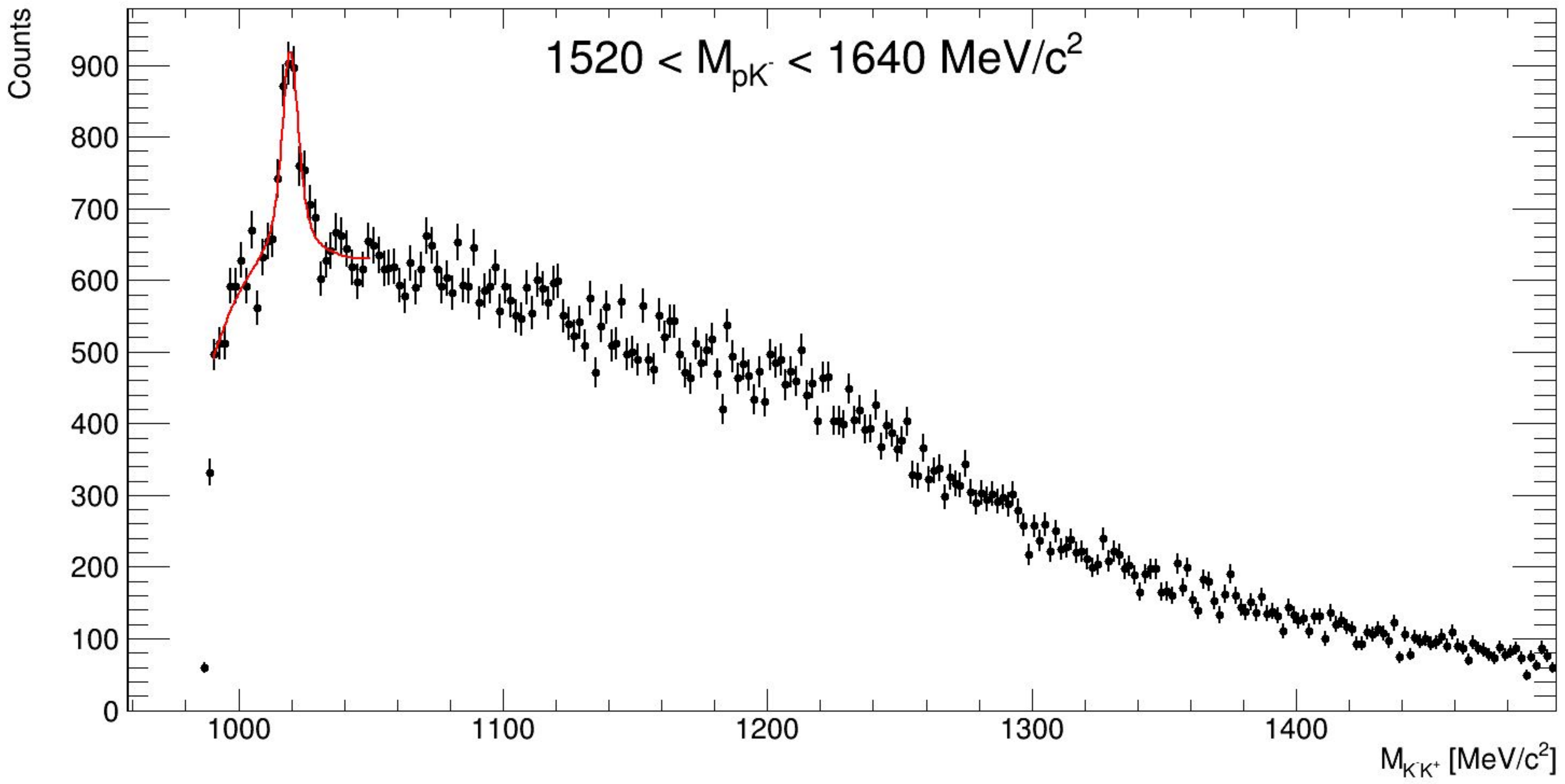
Test Without KR - ppϕ(1020) Cross Section

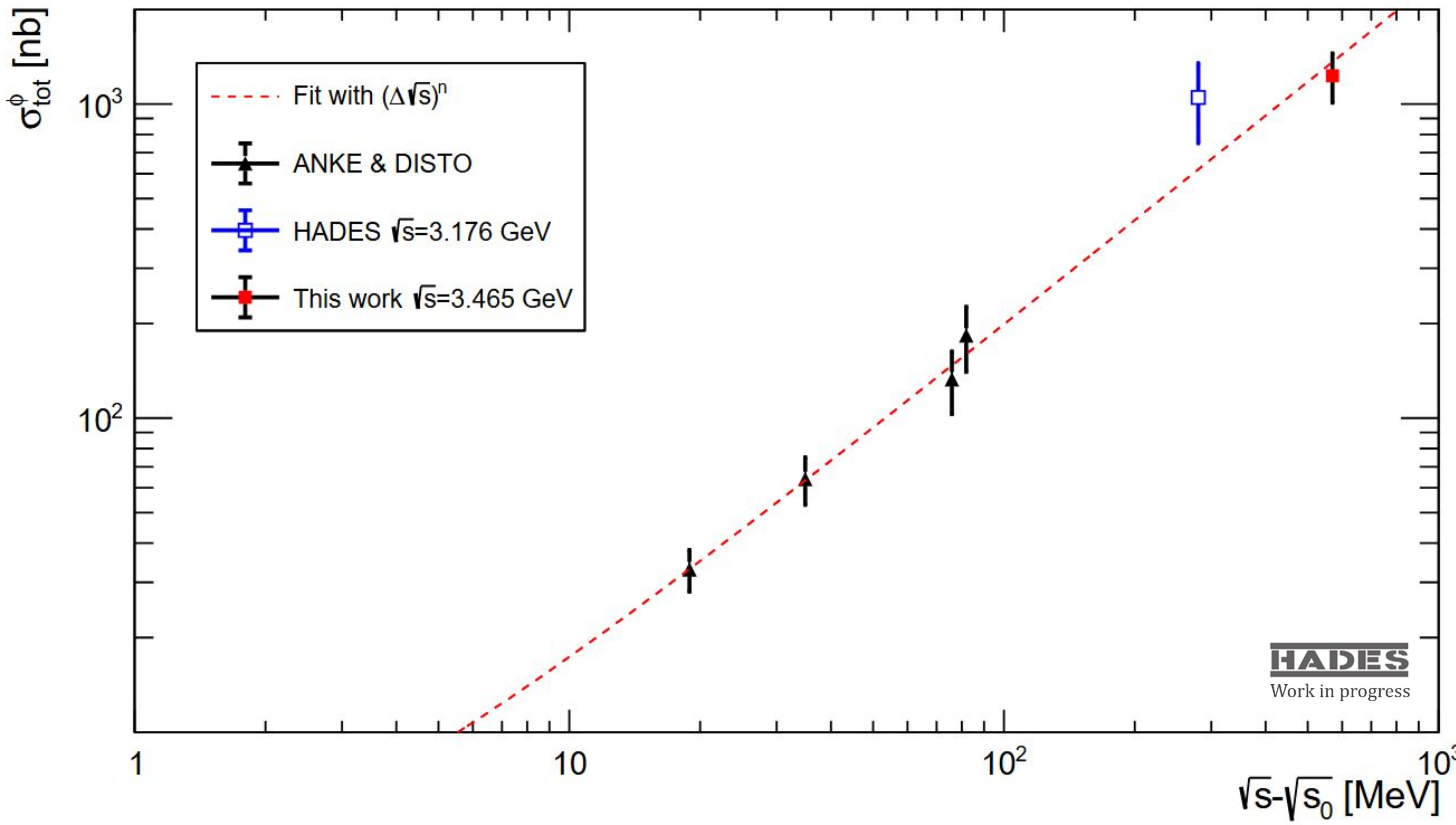
Selection:

1. Same as in the main analysis
2. Before KR
3. Total FS momentum not too small compared to IS

Calculation:

1. Phase space sim, bin-by-bin, 2D map, M(KK) vs M(pK)
2. Fit M(KK) in each bin of M(pK) for N(exp)
3. Weight efficiency with the Voigt shape from exp





Cross section normally = 1230 +- 150 nb

Cross section no KR = 1380 +- 175 nb

Particle Identification with DANN

- Traditional PID systematic uncertainties ~10%

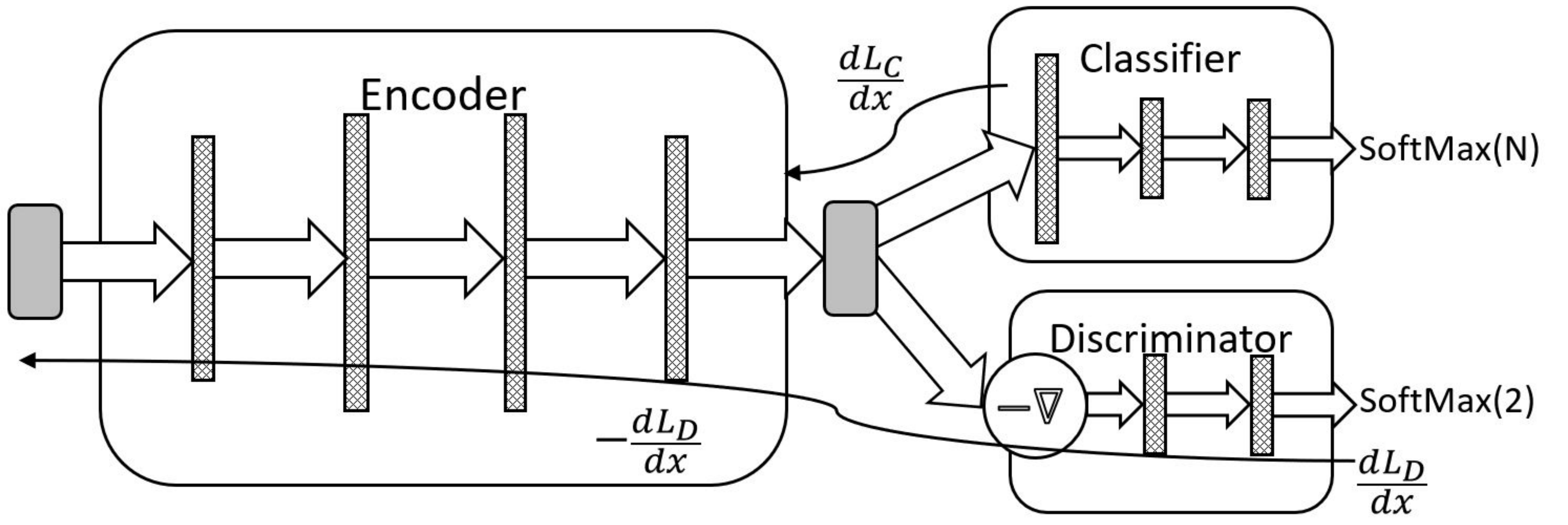
➢ Improve PID and reduce systematic error (Sim-Exp consistency)

Input parameters

- *Moment*
- *Charge*
- *Theta*
- dE/dx_{Ml}
- *Beta*

$+\ \beta^{i}_{theory}(p) - \beta^{i}_{exp}$ x3

5 Probabilities: $\pi^{\pm}, K^{\pm}, p$



2 Domain classes: sim, exp

✔ All information simultaneously, <u>better performance</u>

✔ Operates with probabilities, <u>flexible classification</u>

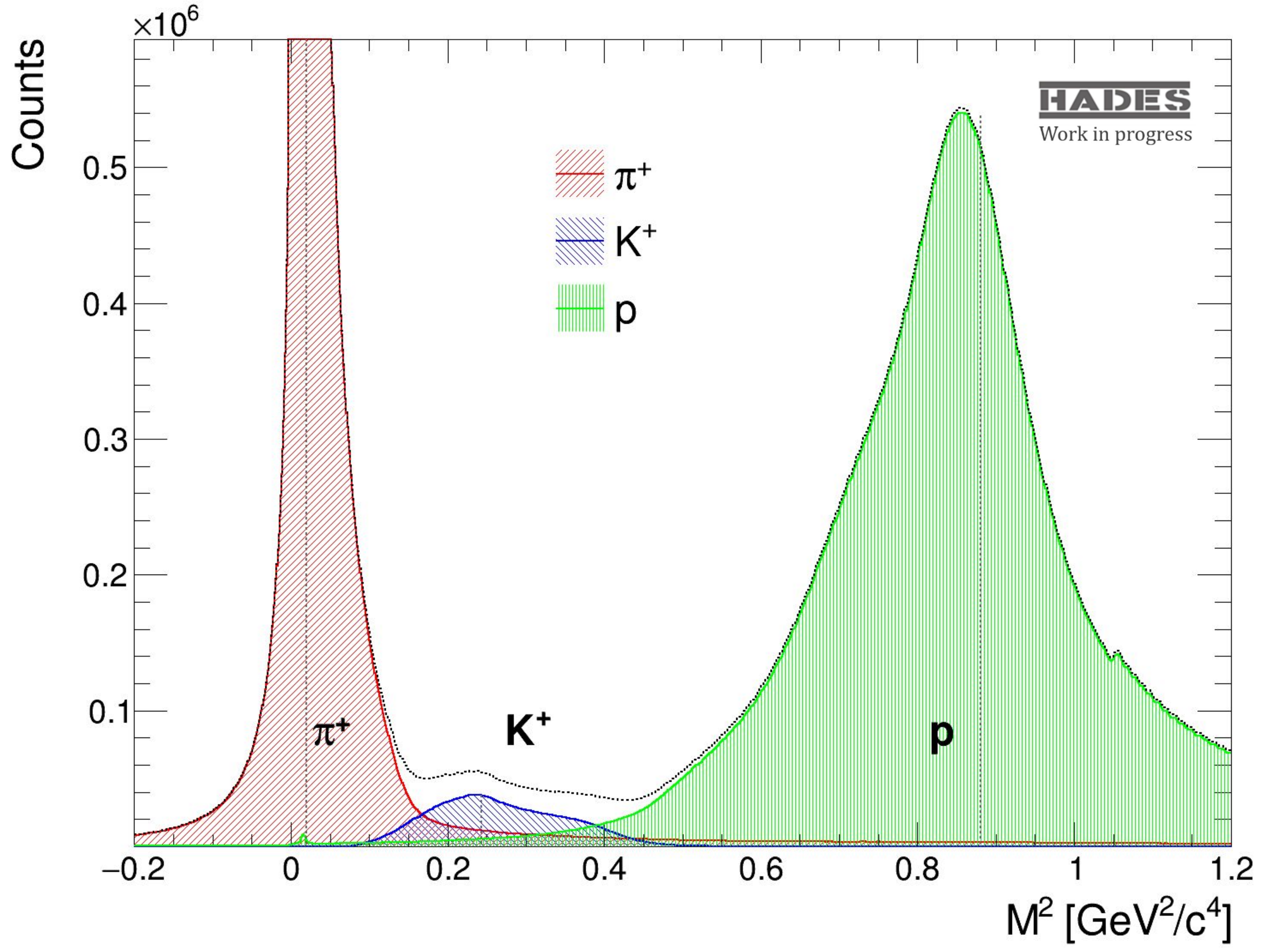
✔ <u>Less sim-exp difference</u>

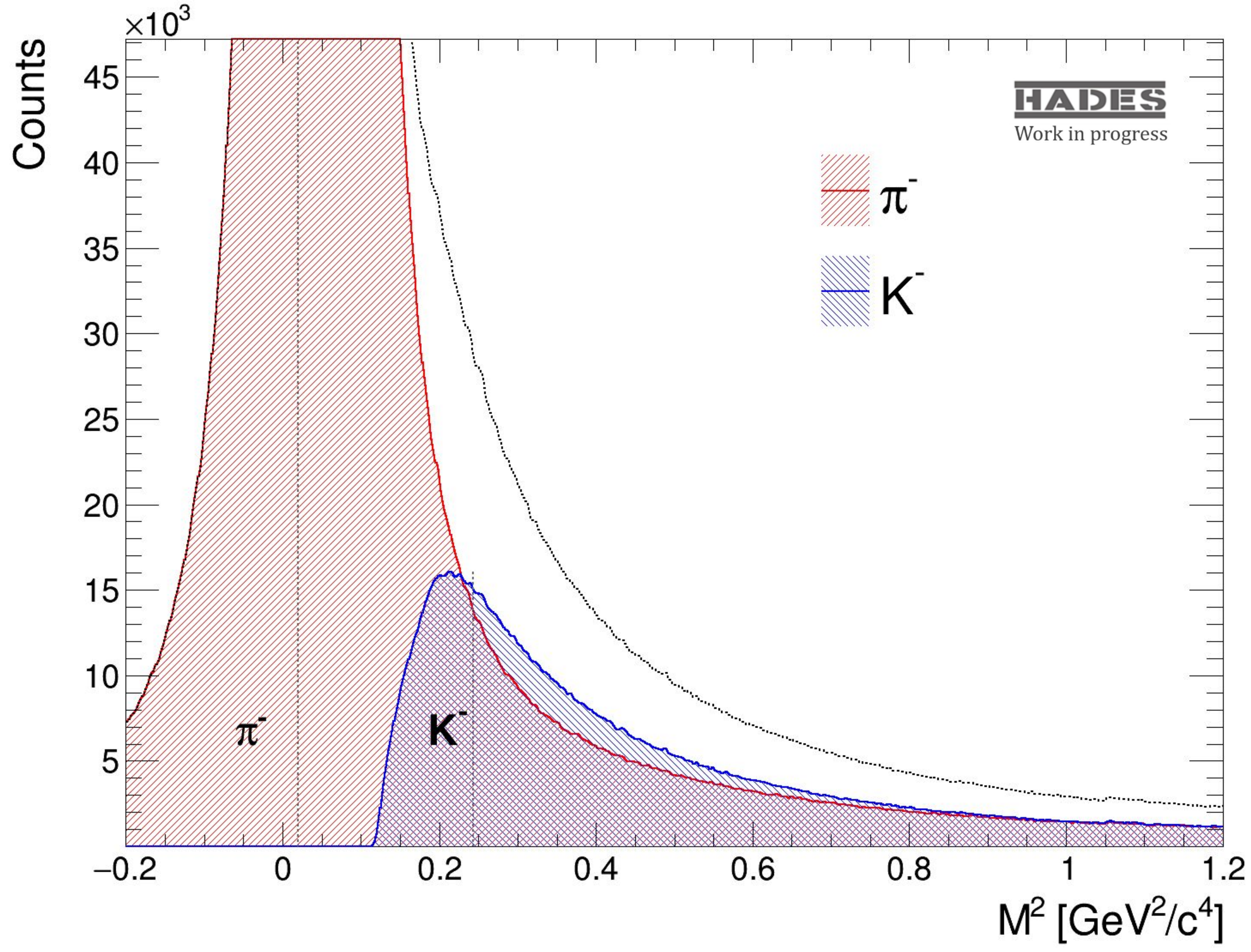
*Input features do not include m^2 because of <=0 problems

Mass Distributions

Mass distributions overlap, while keeping contaminations in K low.

*Experiment





ML-PID Tag-and-probe Procedure

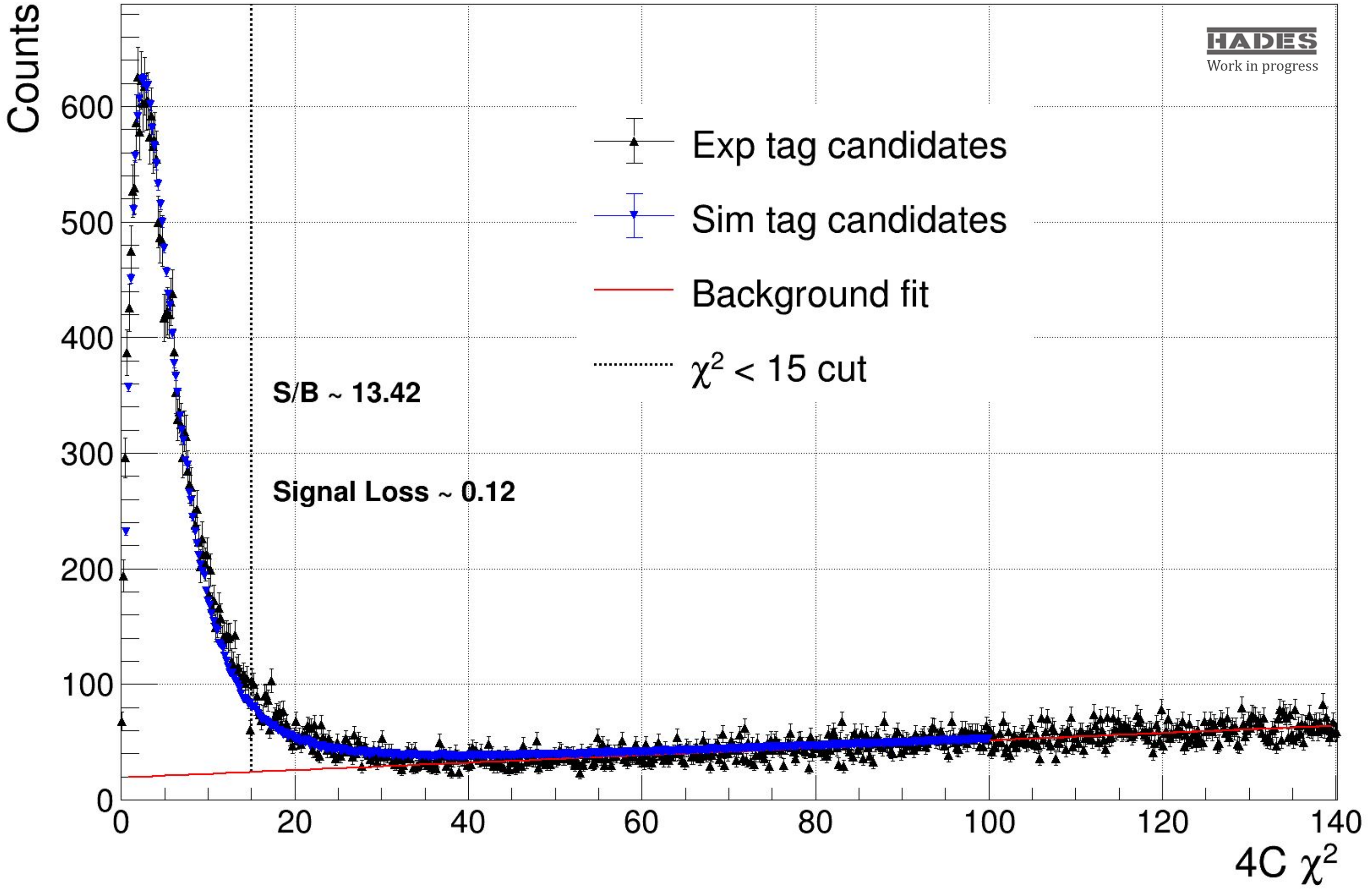
1. Do strict PID for all particles except one: $ppK^+/pp\pi^-$ (K^-/π^+).

2. Select a remaining particle with $\bar{q}$ as K^-/π^+.

3. Apply 4C kinematic refit ($ppK^+K^-/\ pp\pi^+\pi^-$).

4. Choose the lowest χ^2 combination, apply strict cut.

5. Apply PID to the tagged K^-/π^+.

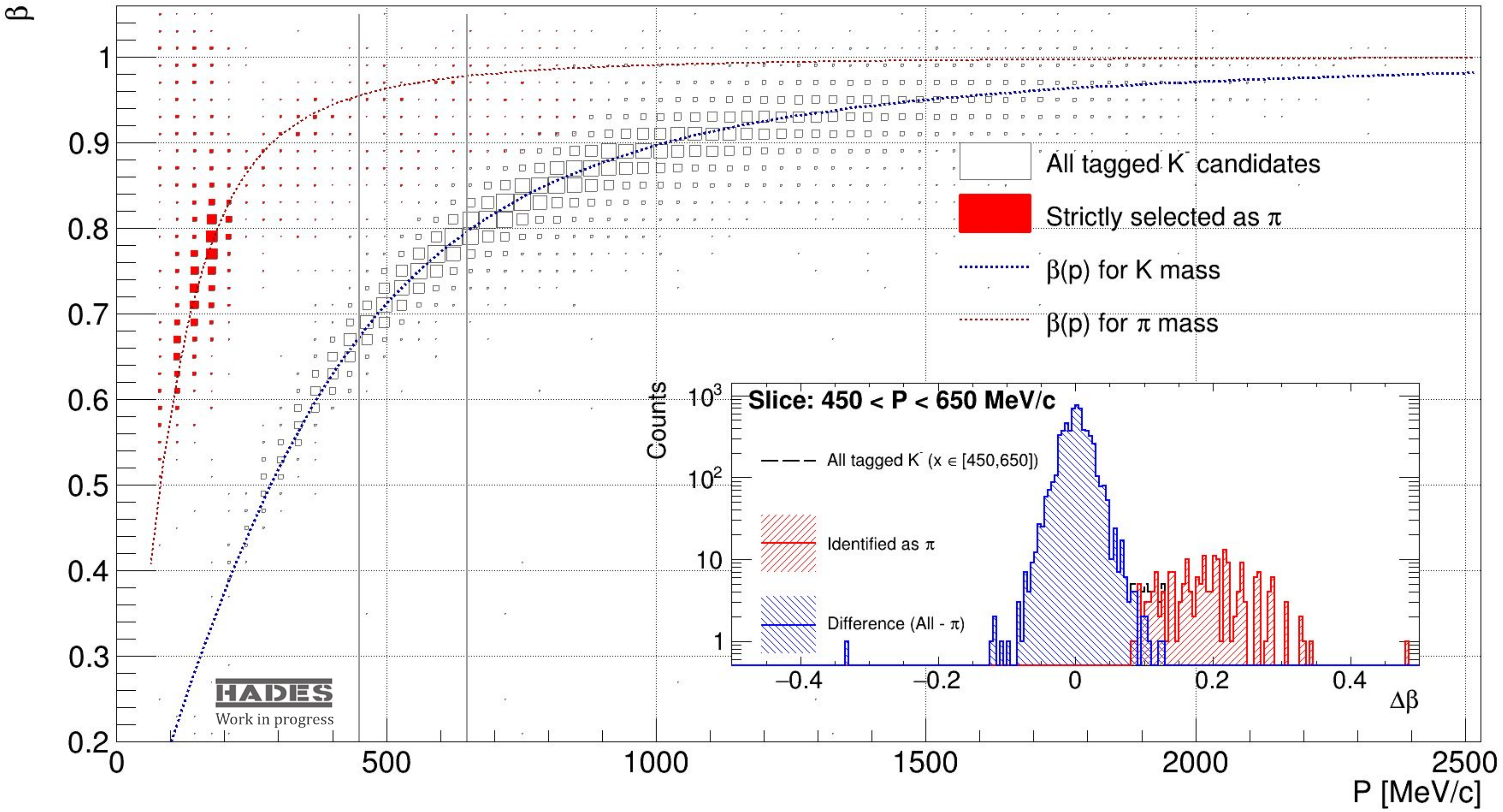


 Measure efficiency and purity (misidentification rates) vs P

ML-PID Tag-and-probe Procedure

- Remaining kaon tag contamination is efficiently removed (see the inset).
- The mainly background-populated area contains <<1% kaons (based on sim).

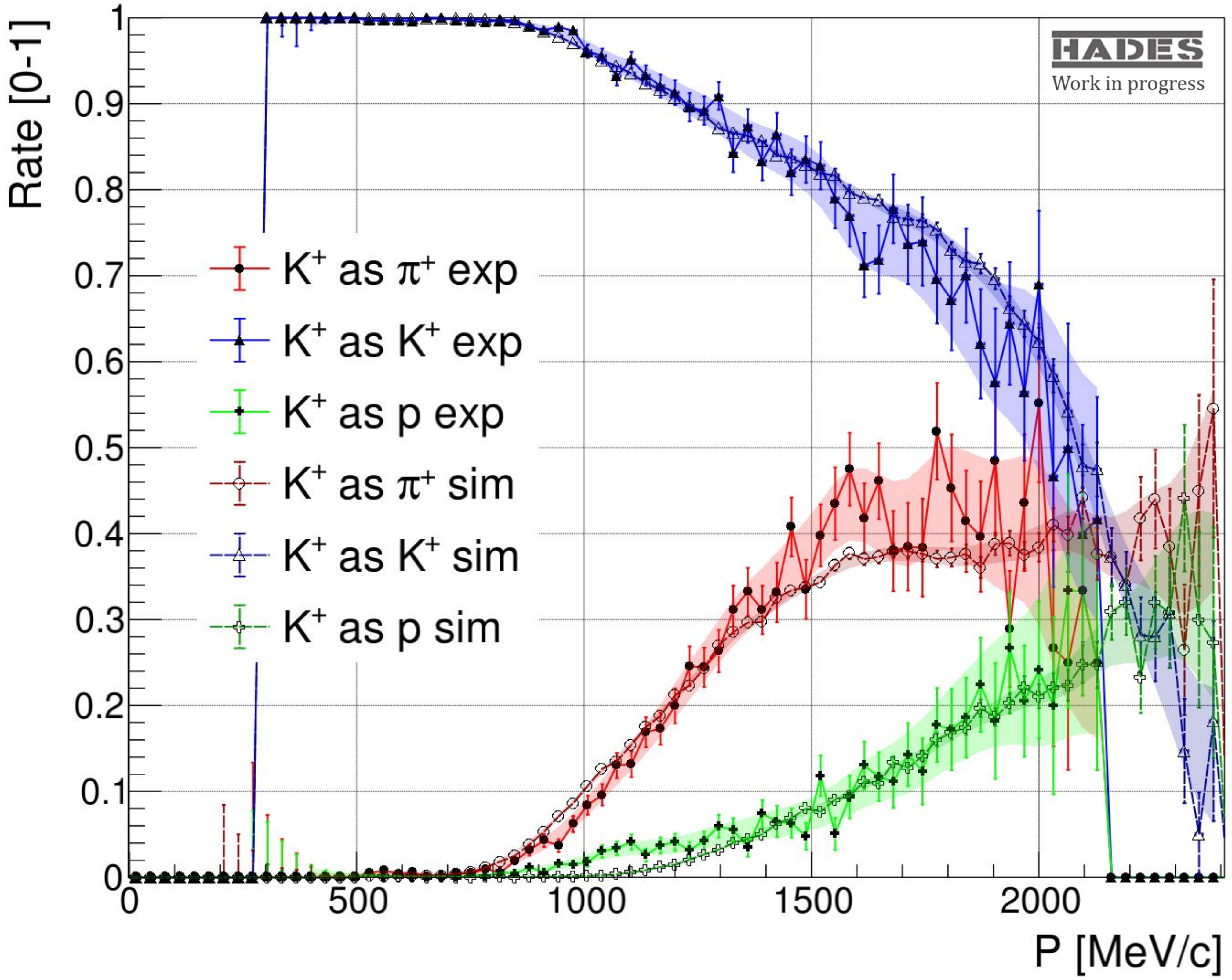
✓ Clean datasets for π, K, p obtained.

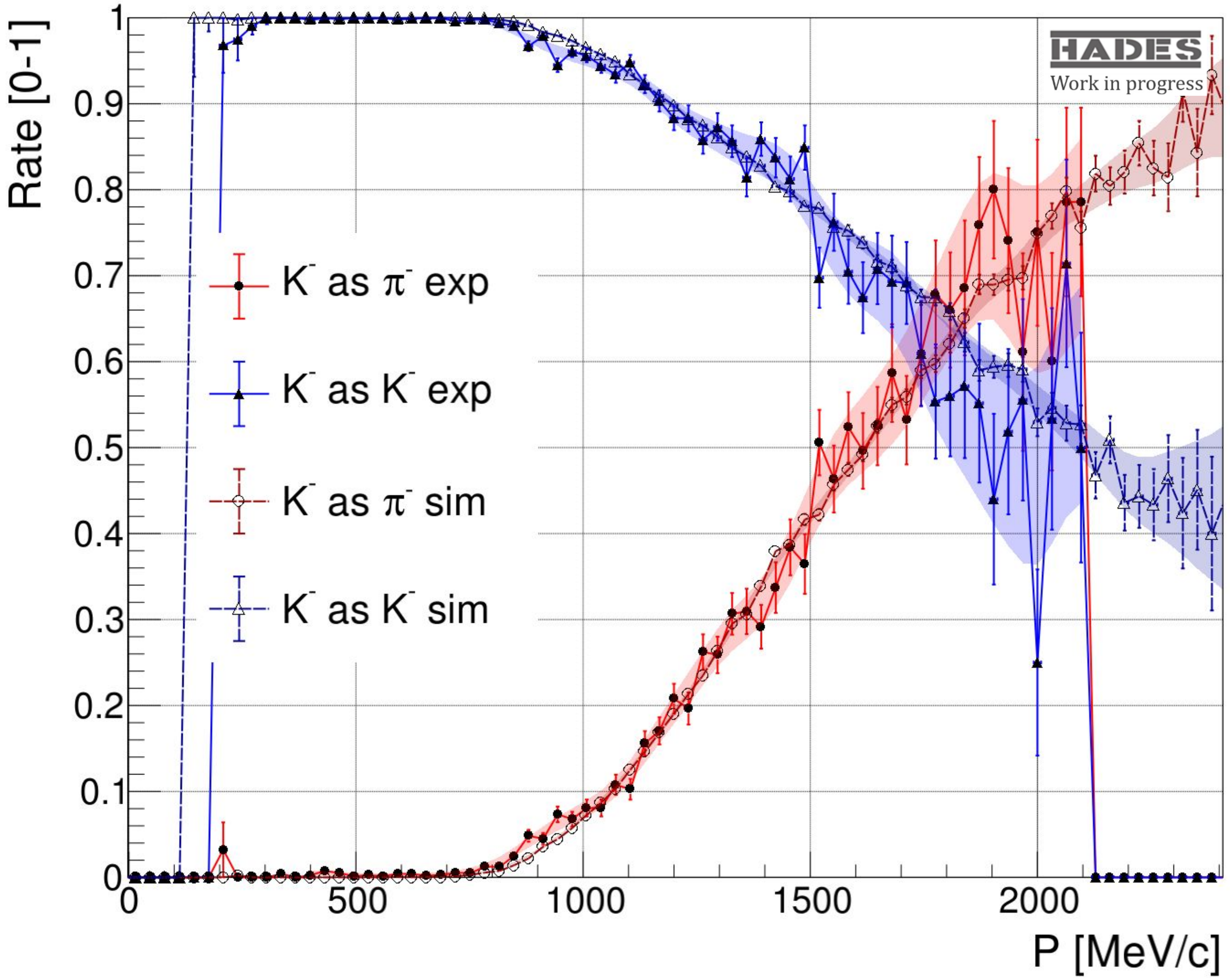


Momentum Dependence of Kaon Efficiency and Purity

Selection efficiency and “purity” vs momentum

*Share of particles being identified as C_i with <u>loose cuts</u> (prob > 35%) → Sum is more than 1

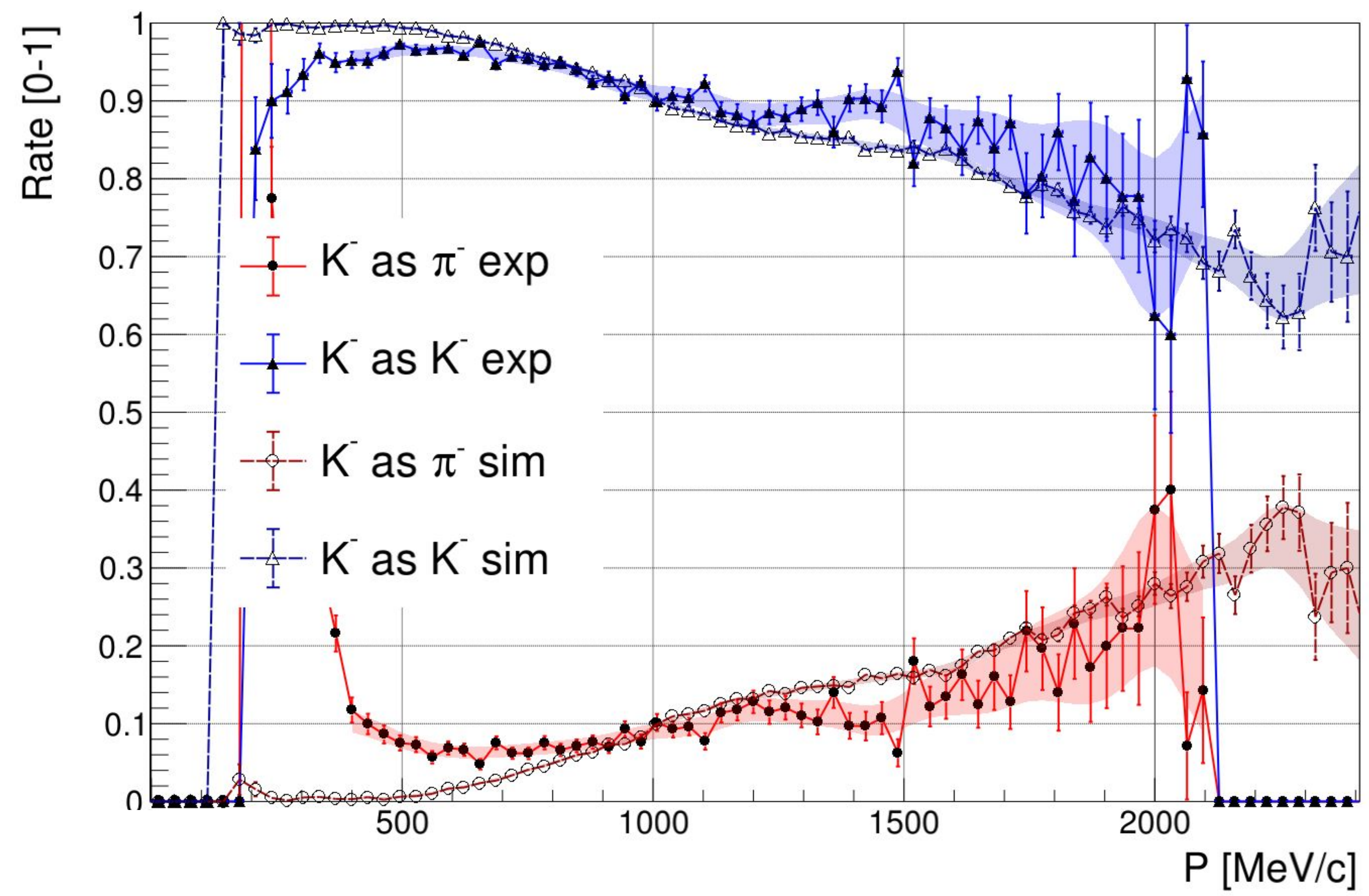




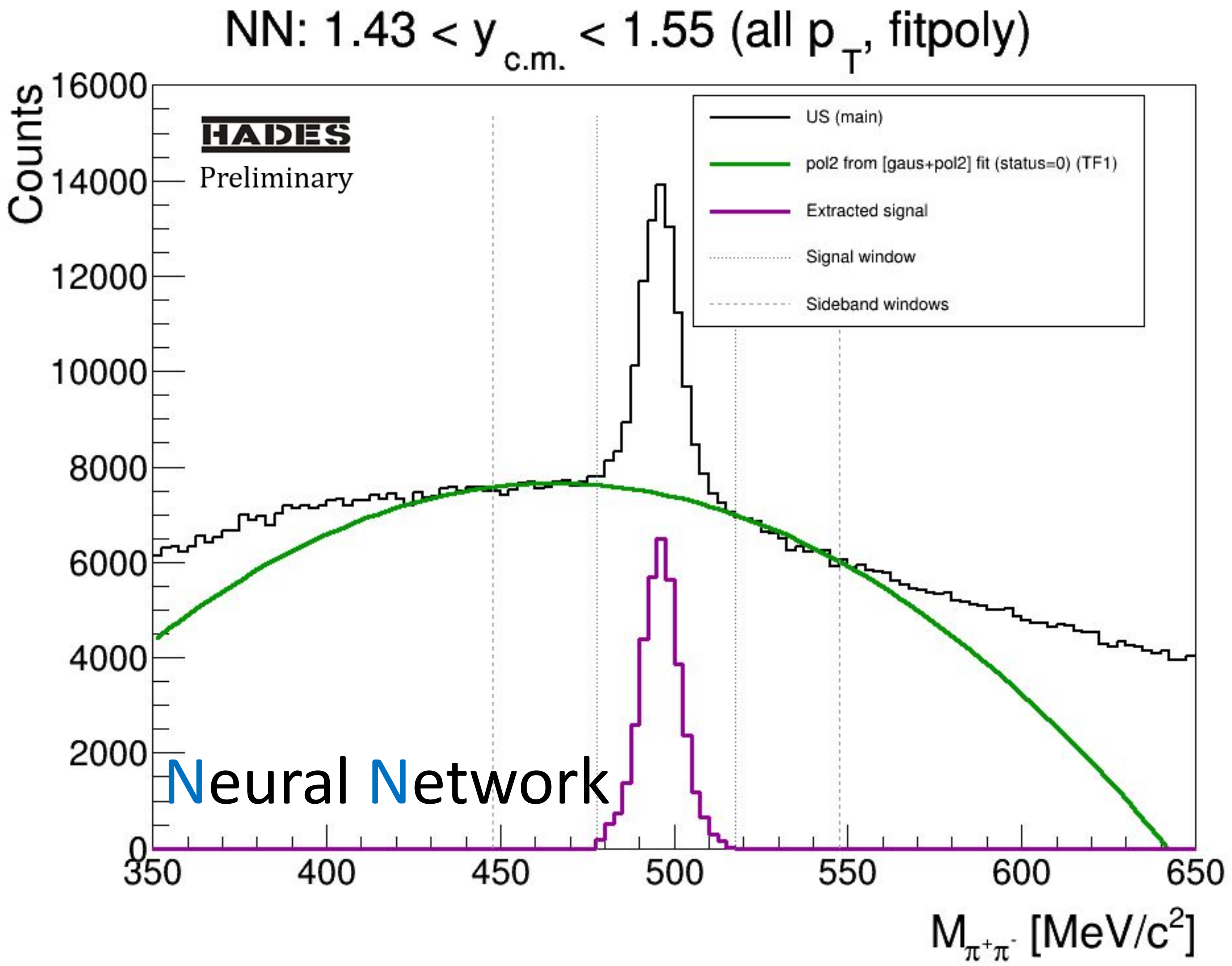
✓ *DANN sim-exp agreement (< 1% per particle)*

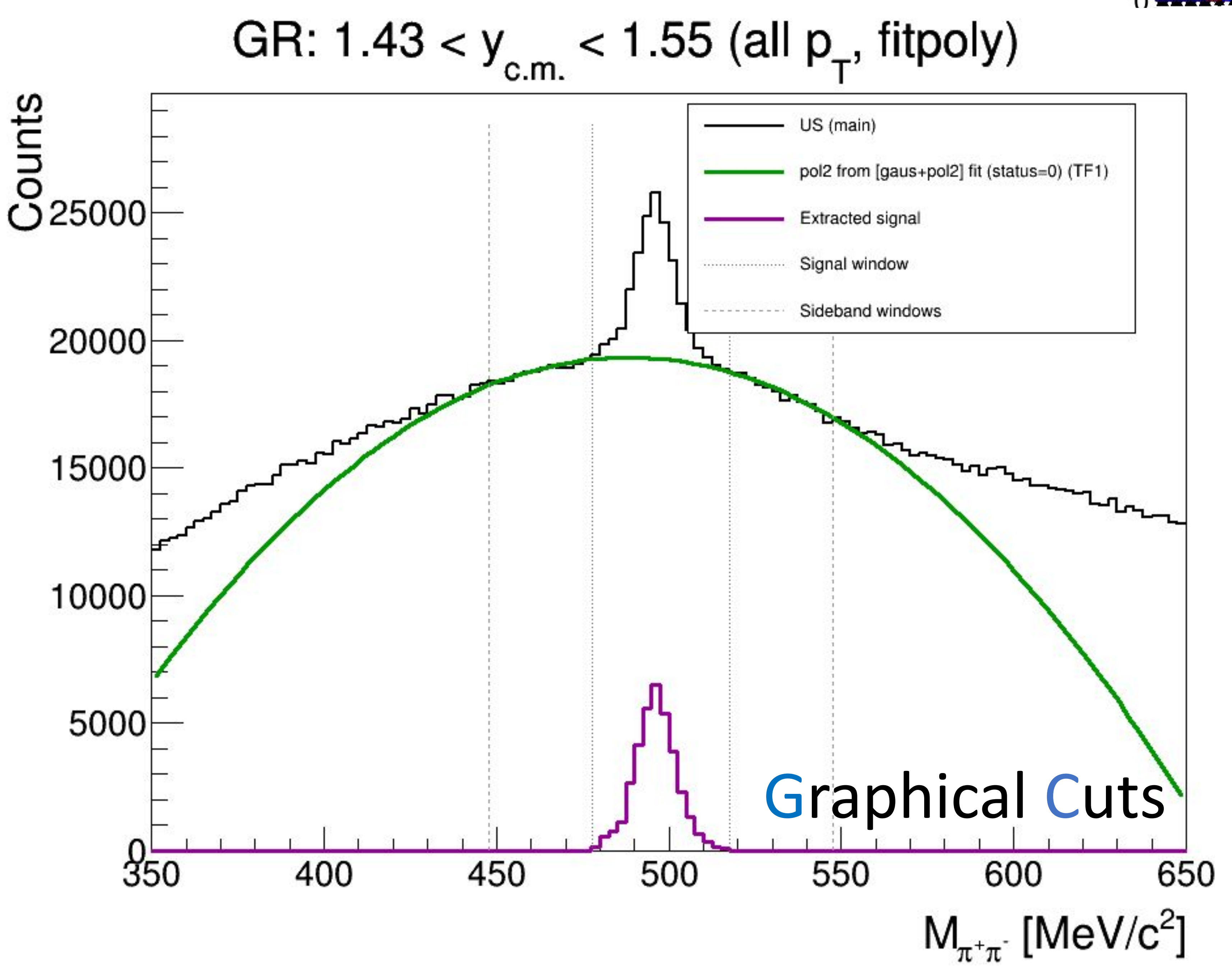
Comparison to Graphical Cuts: Direct + ρ

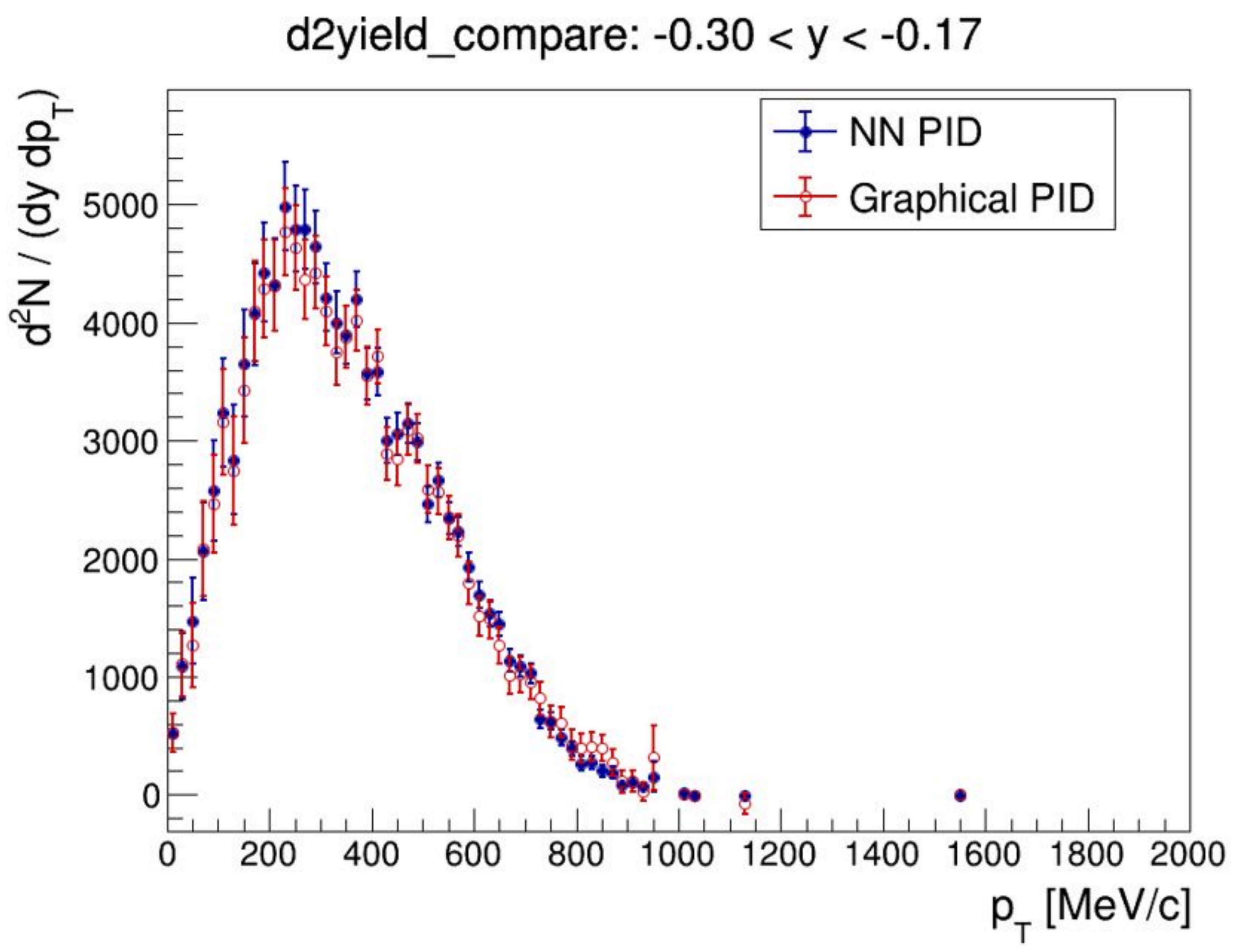
1. Tested graphical cuts systematic effects as well for DANN validation



2. Compared results for inclusive resonance analyses without KR (pions)





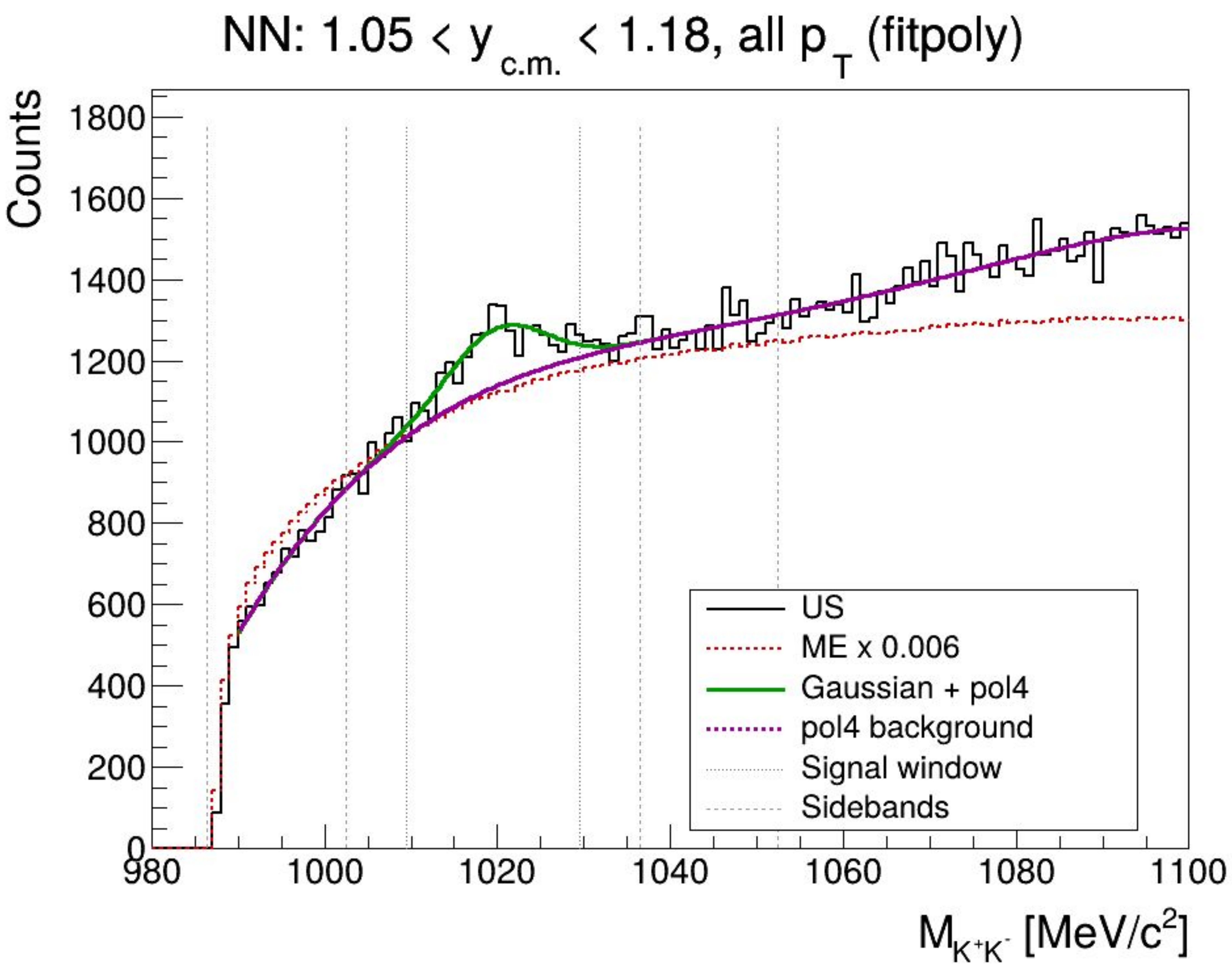


New

Comparison to Graphical Cuts: ϕ(1020)

Potential extensions

1. ϕ(1020) inclusive selection
2. kaon inclusive selection



They need a special treatment, because background is still too large.

- Multi-differential analysis will require additional selection methods

Only limited amount of good bins

New

Comparison to Graphical Cuts: Kaons

Potential extensions

1. ϕ(1020) inclusive selection
2. kaon inclusive selection →

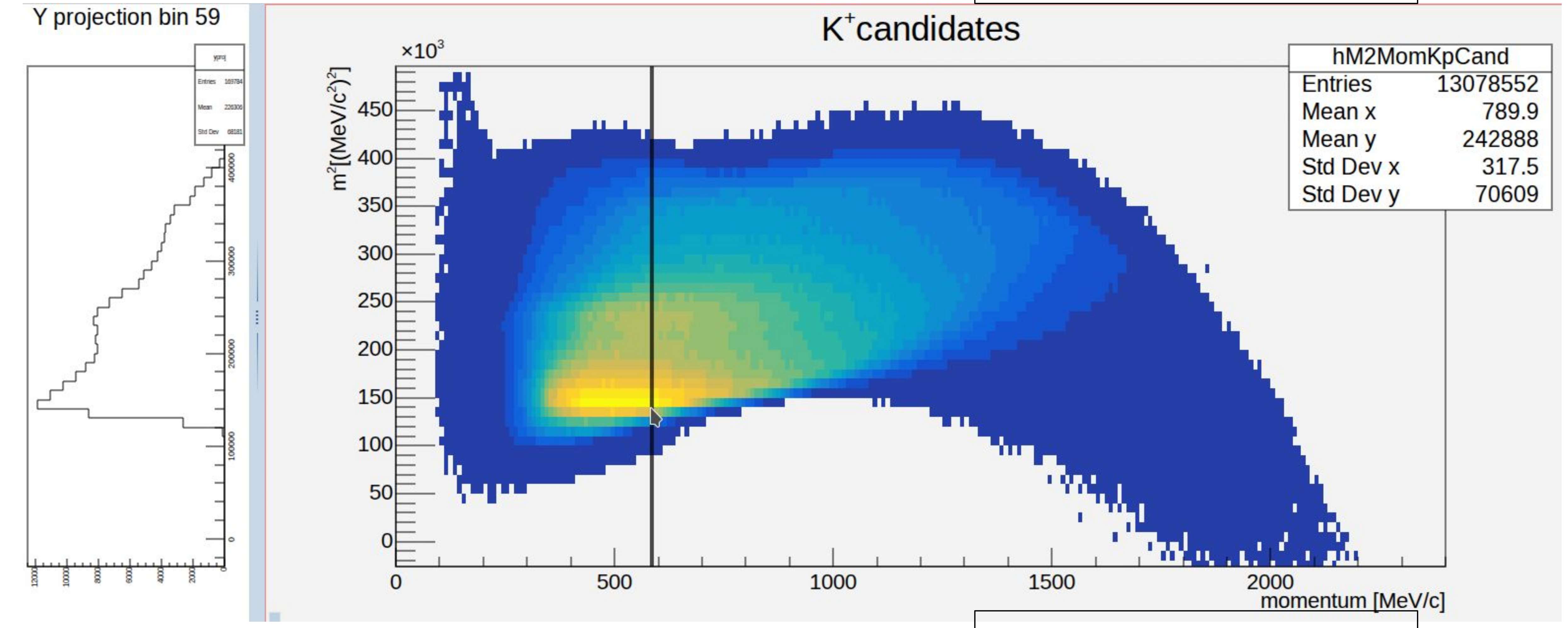
They need a special treatment, because background is still too large.

➢ Multi-differential analysis will require additional selection methods

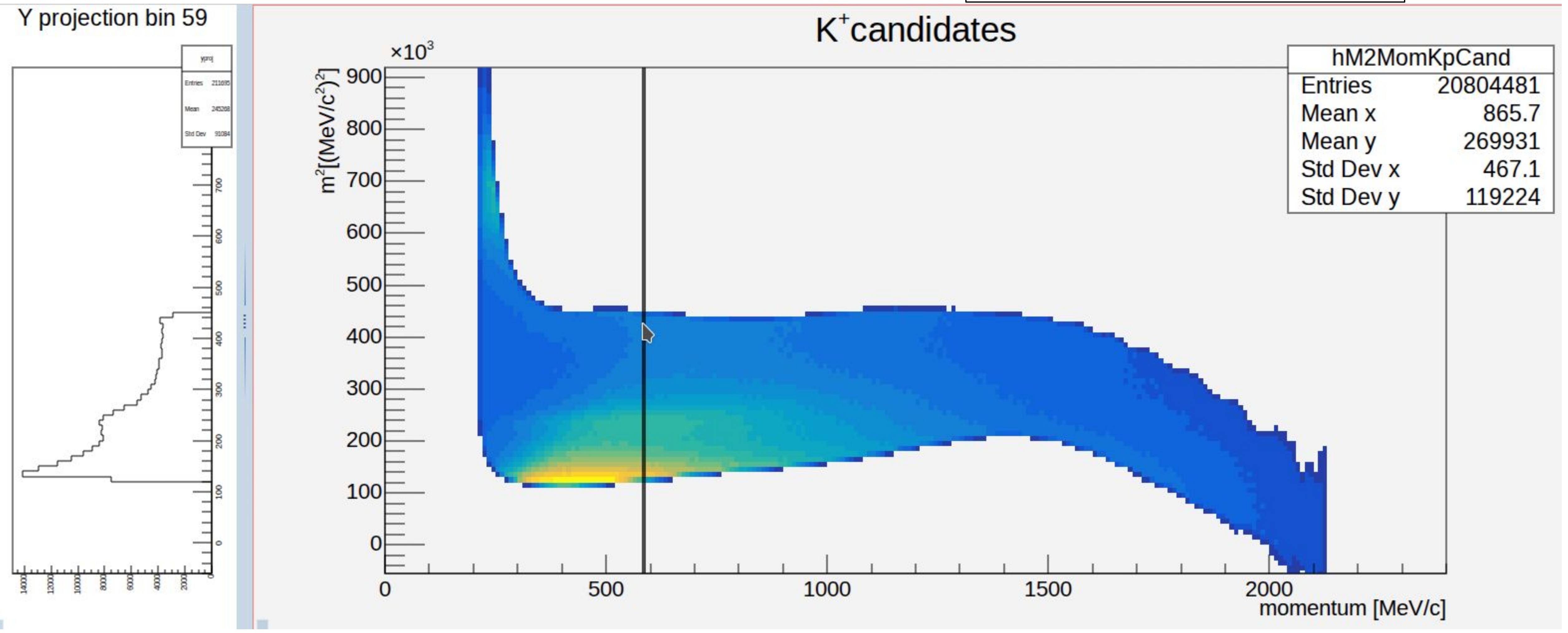
Graphical cuts = no cut at all

➢ Can try Carl's selection

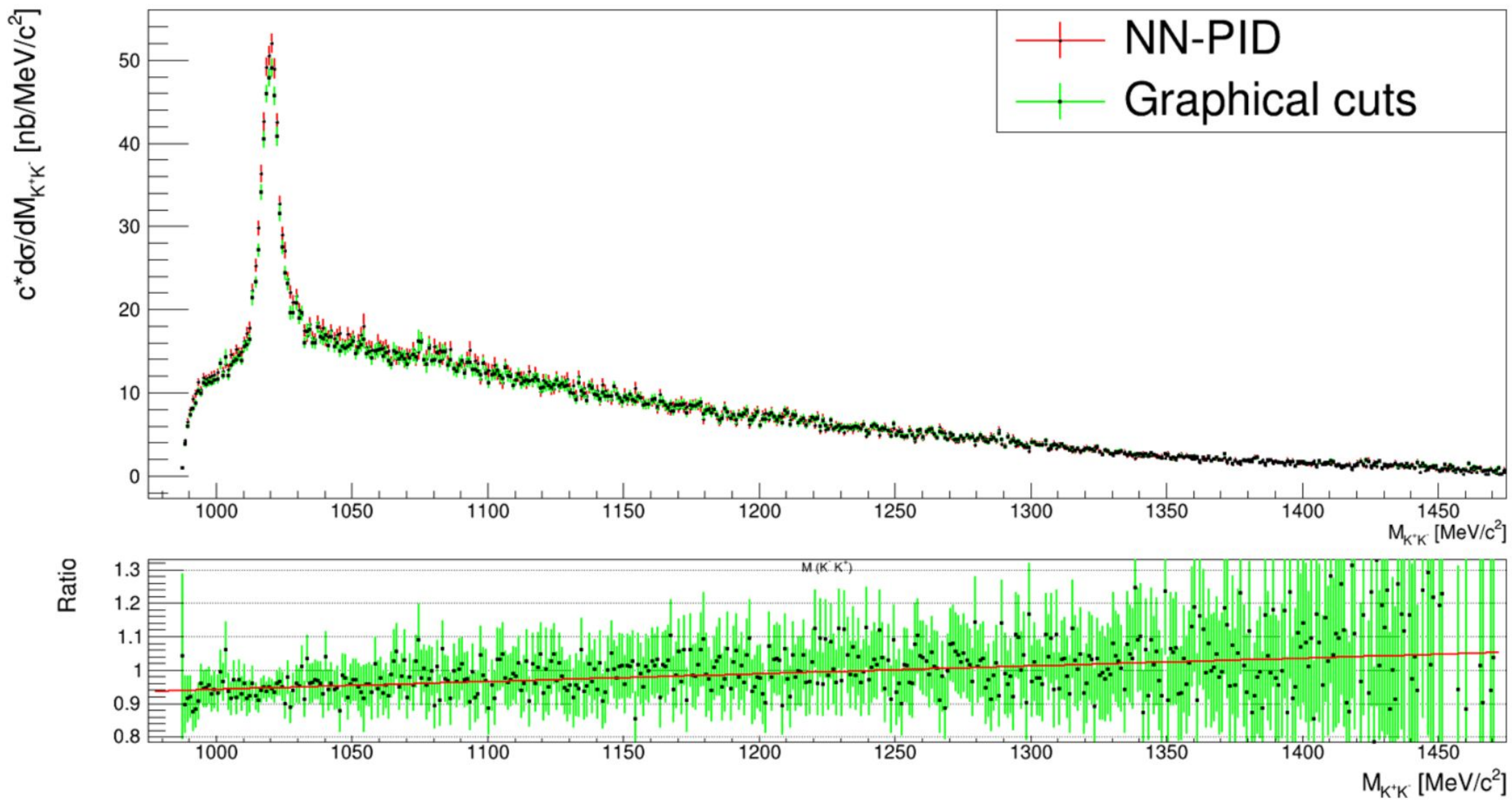
ML-based PID



Graphical Cuts

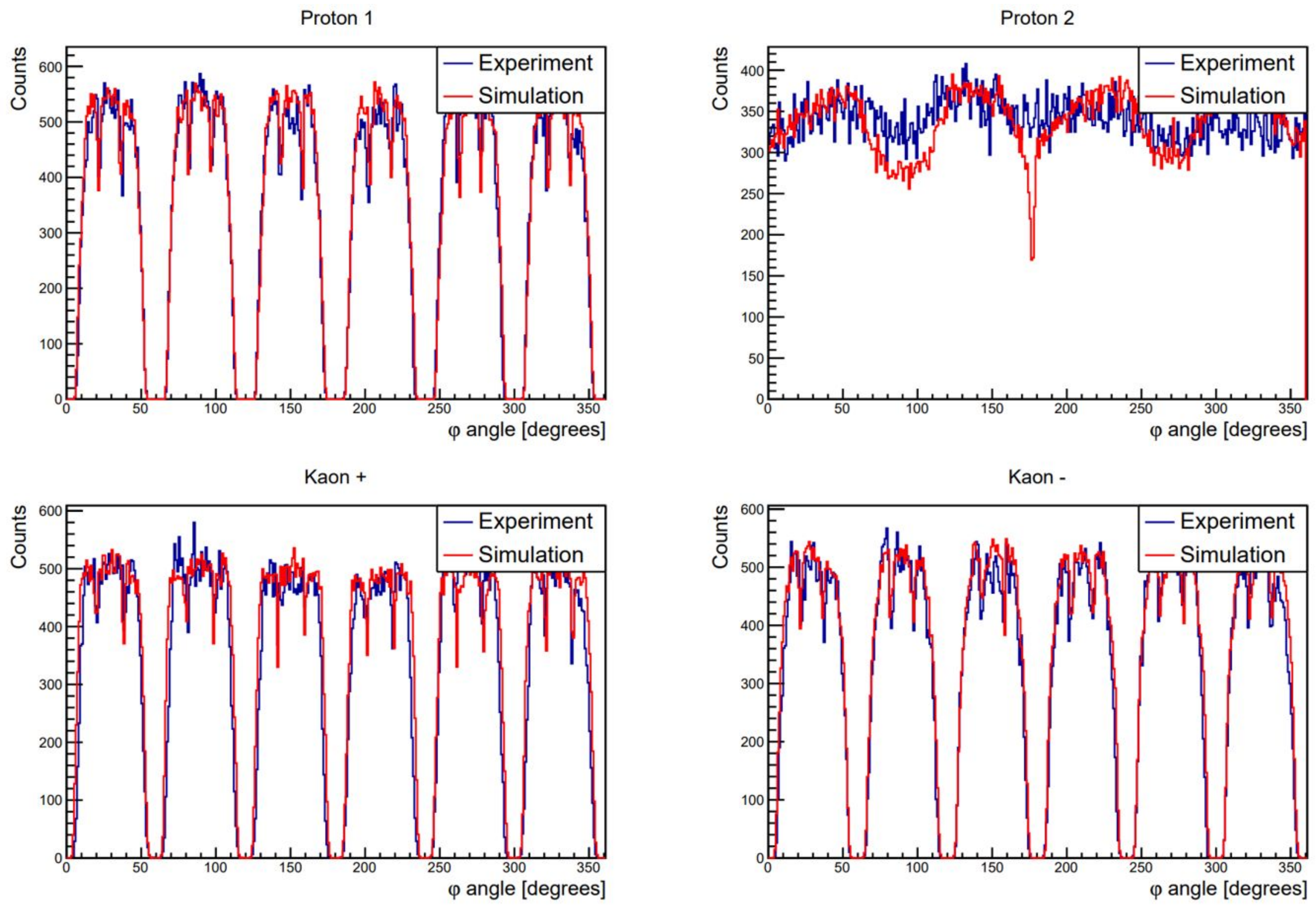


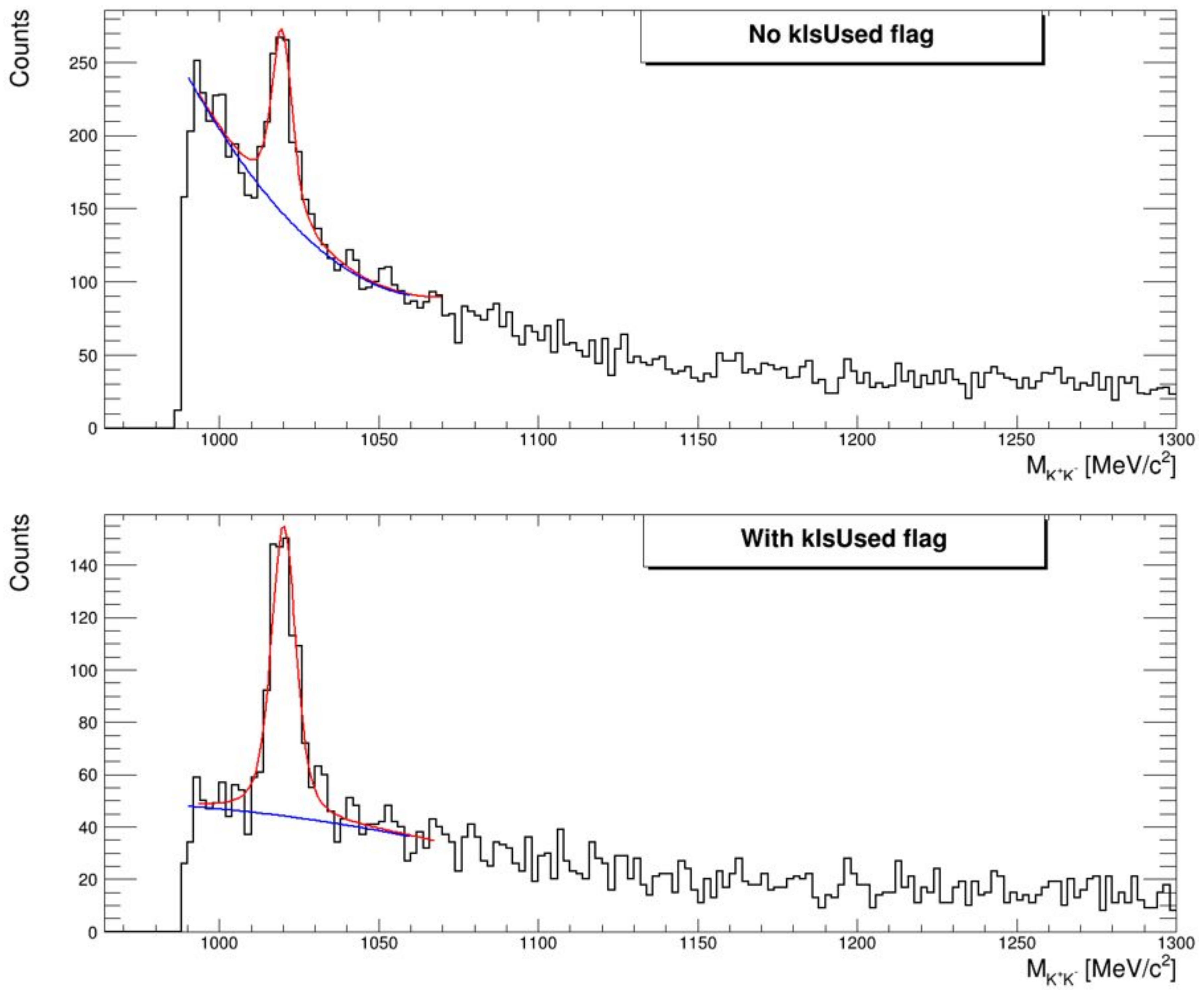
Systematic Uncertainties: PID



Variations of the systematic bias correction calculation + comparison with the graphical cuts

Systematic Uncertainties: Acceptance and Global Cuts

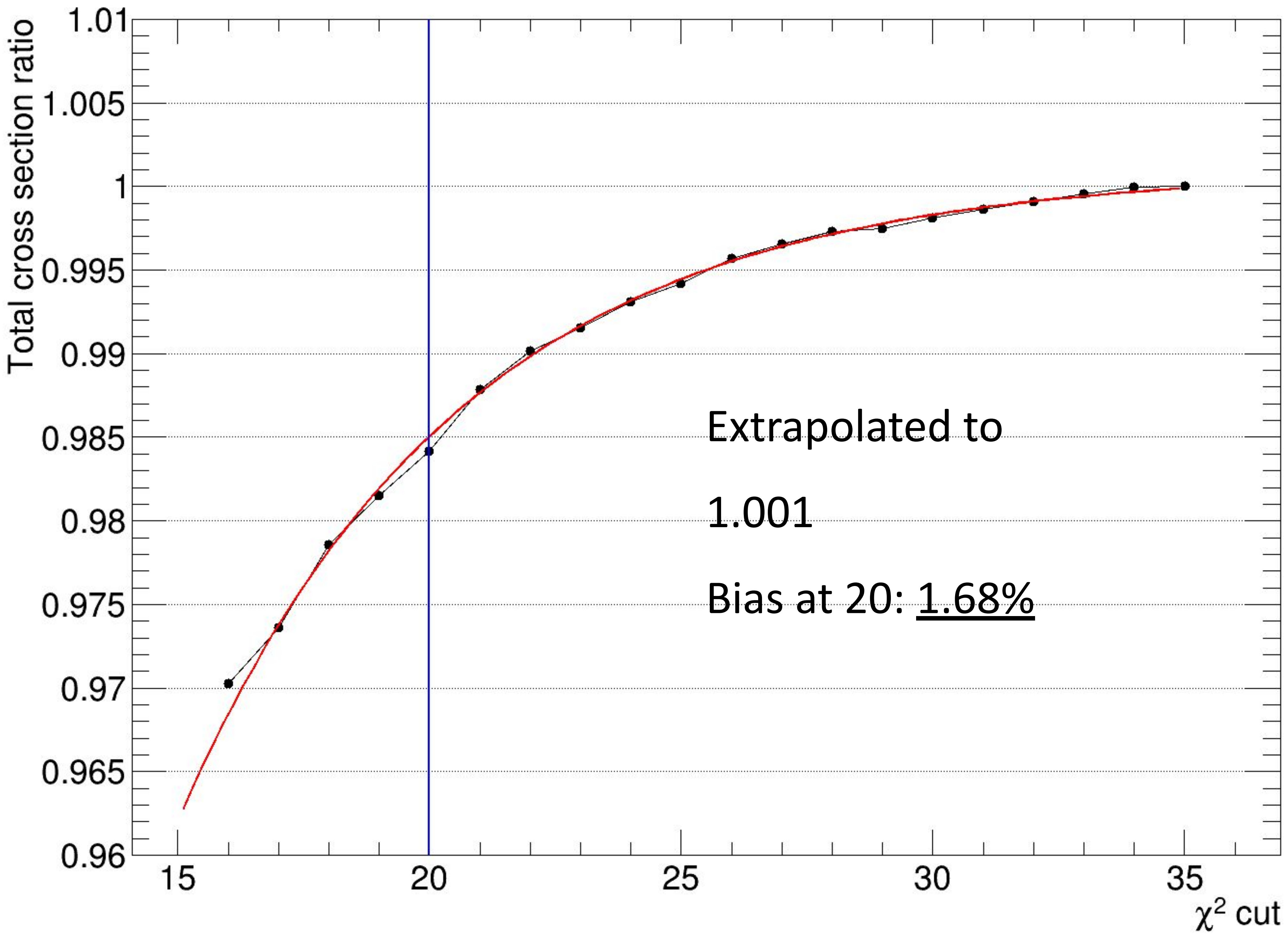




Estimated via

- Varying the methods, selection cuts, and models
- Comparing Sim to Exp efficiencies

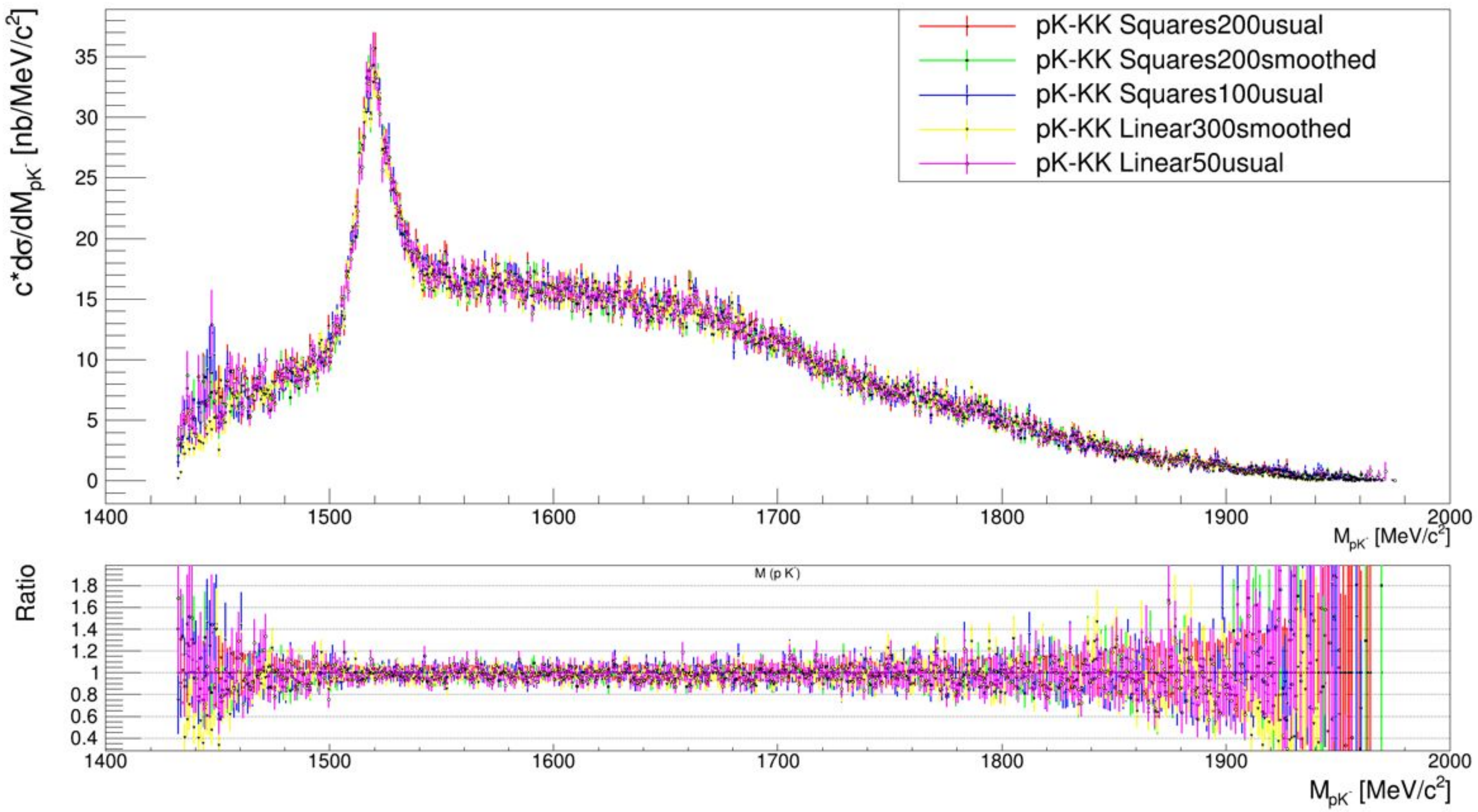
Systematic Uncertainties: KR cuts



Estimated via

- Varying the methods, selection cuts, and models
- Comparing Sim to Exp efficiencies

Systematic Uncertainties: Efficiency Correction



Estimated via

- Varying the methods, selection cuts, and models
- Comparing Sim to Exp efficiencies

Systematic Errors and Uncertainties

Source	Correction [Y/N]	Uncertainty [%]
Start detector	Y	1.5
`kIsUsed` flag	N	5
NN–PID	Y	2
Kinematic refit and χ^2 cuts	Y	3
Efficiency parametrization	N	5
Acceptance	Y	10
Remaining background	Y	3
Integrated luminosity	N	7
Total	-	~ 15

Estimated via

- Varying the methods, selection cuts, and models
- Comparing Sim to Exp efficiencies

Summary:

- Clean dataset S/B = 30, refined over the years
- A number of physics results obtained
- Kinematic refit works properly
- ML-based PID works properly
- Background and efficiency correction under control
- Systematic Uncertainties ~ 15%

Outlook:

- ➢ Gen4 - Gen3 difference
- ➢ Further work on inclusive analyses
- ➢ Improvements of PID
- ➢ Improvements of physics analysis

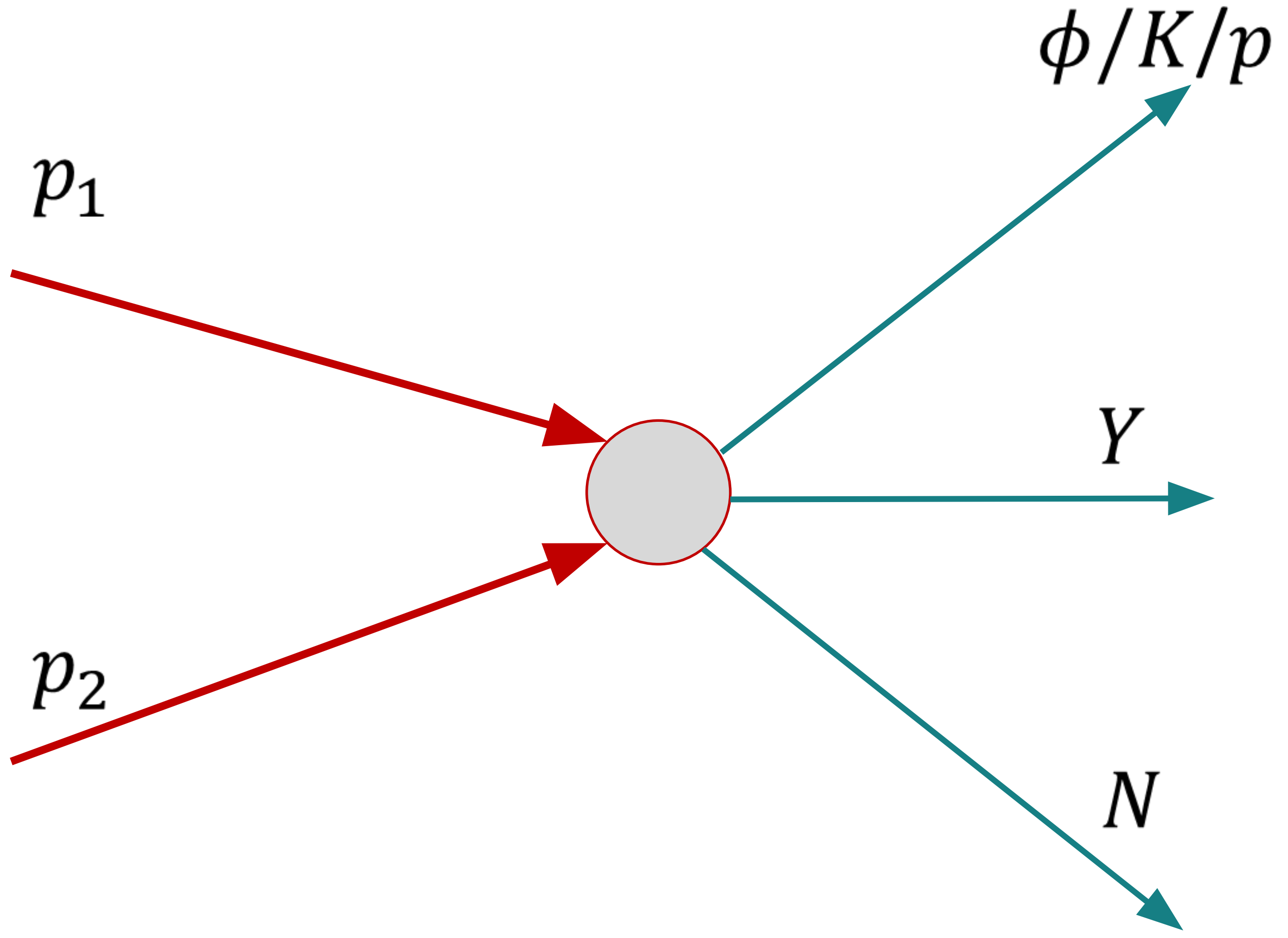
Thank you for your attention

Backup

Strangeness Production

Studies of strangeness in p-p collisions
Up to a few GeV above thresholds:

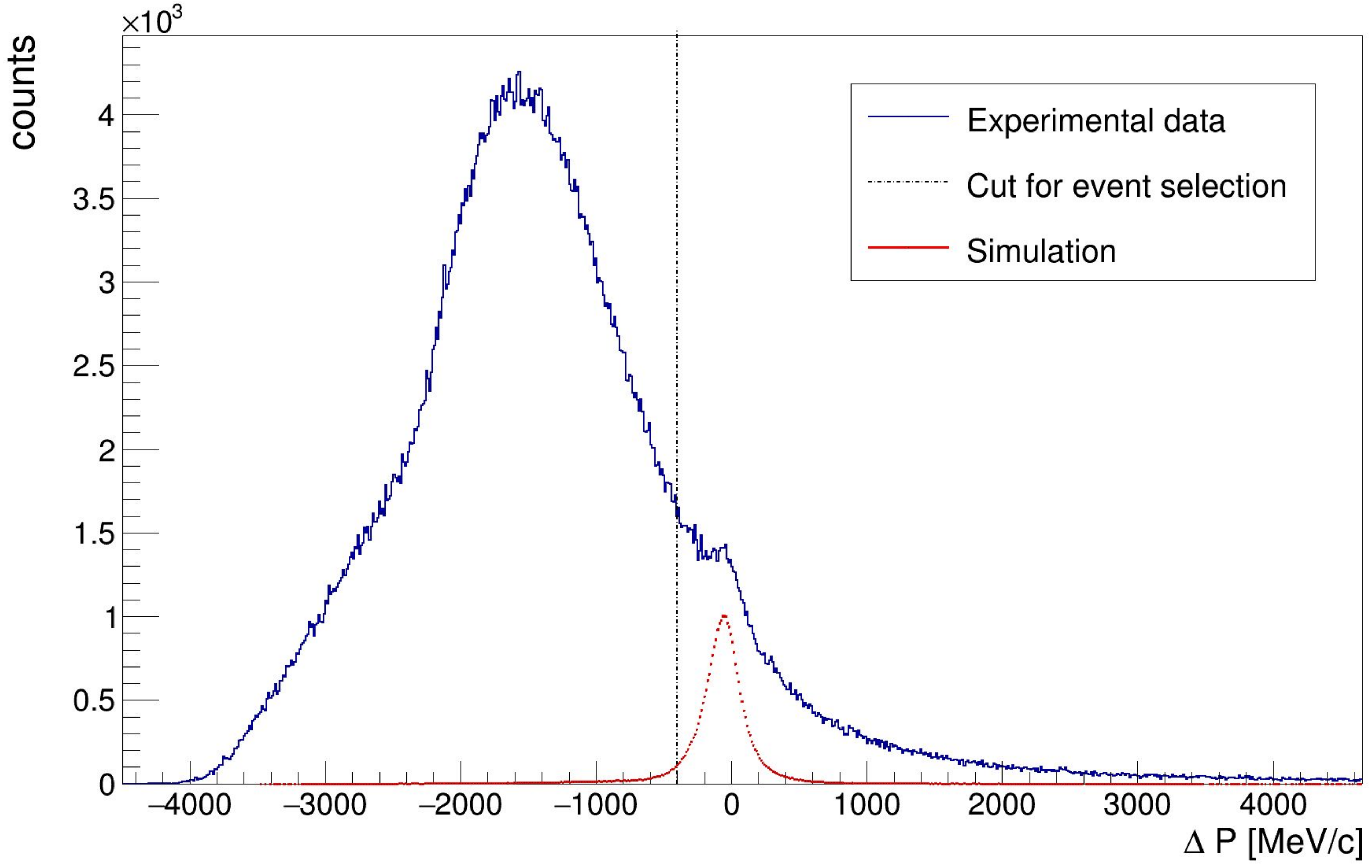
- Production mechanism in nonperturbative regime
- Spectroscopy of baryons with strangeness
- Hadron-hadron interactions
- Exotic states and resonances
- …



Selection of events for no KR tests

Particle identification with strict PID

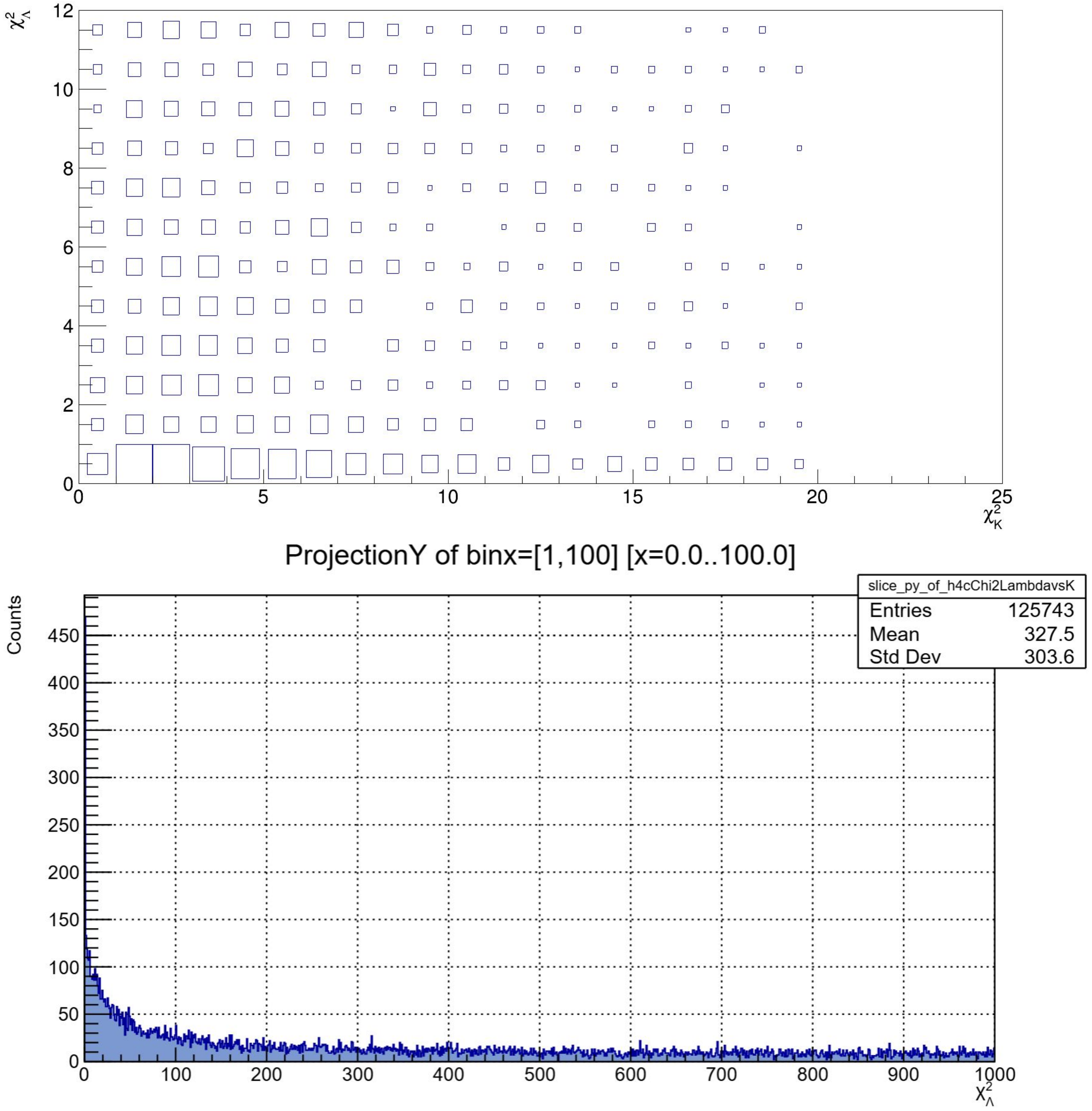
Total momentum of final state is not significantly lower than that of initial state



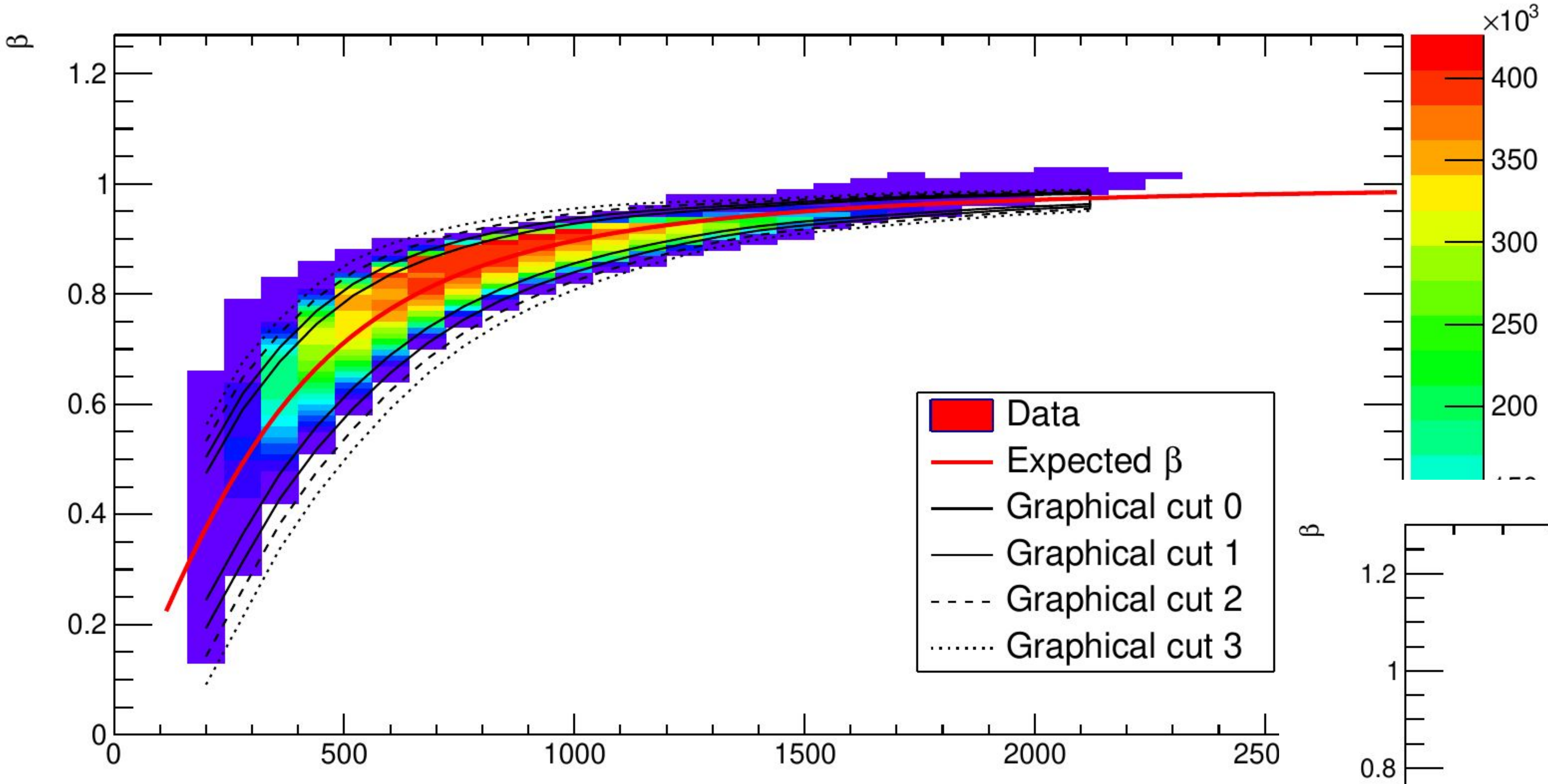
Remaining Background Studies 2

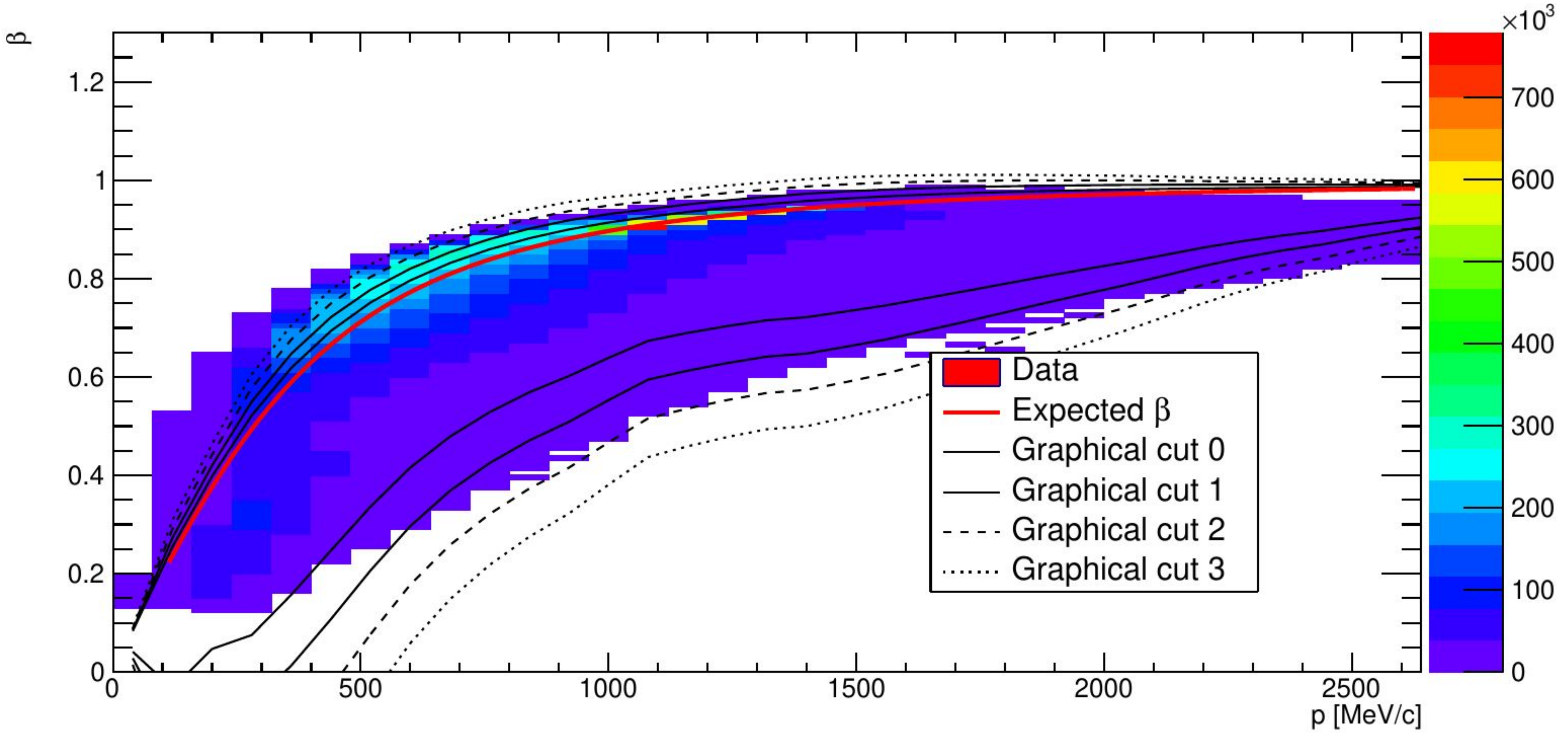
3C fit for Lambda candidate.

(no peak, consistent numbers)



Graphical cuts windows





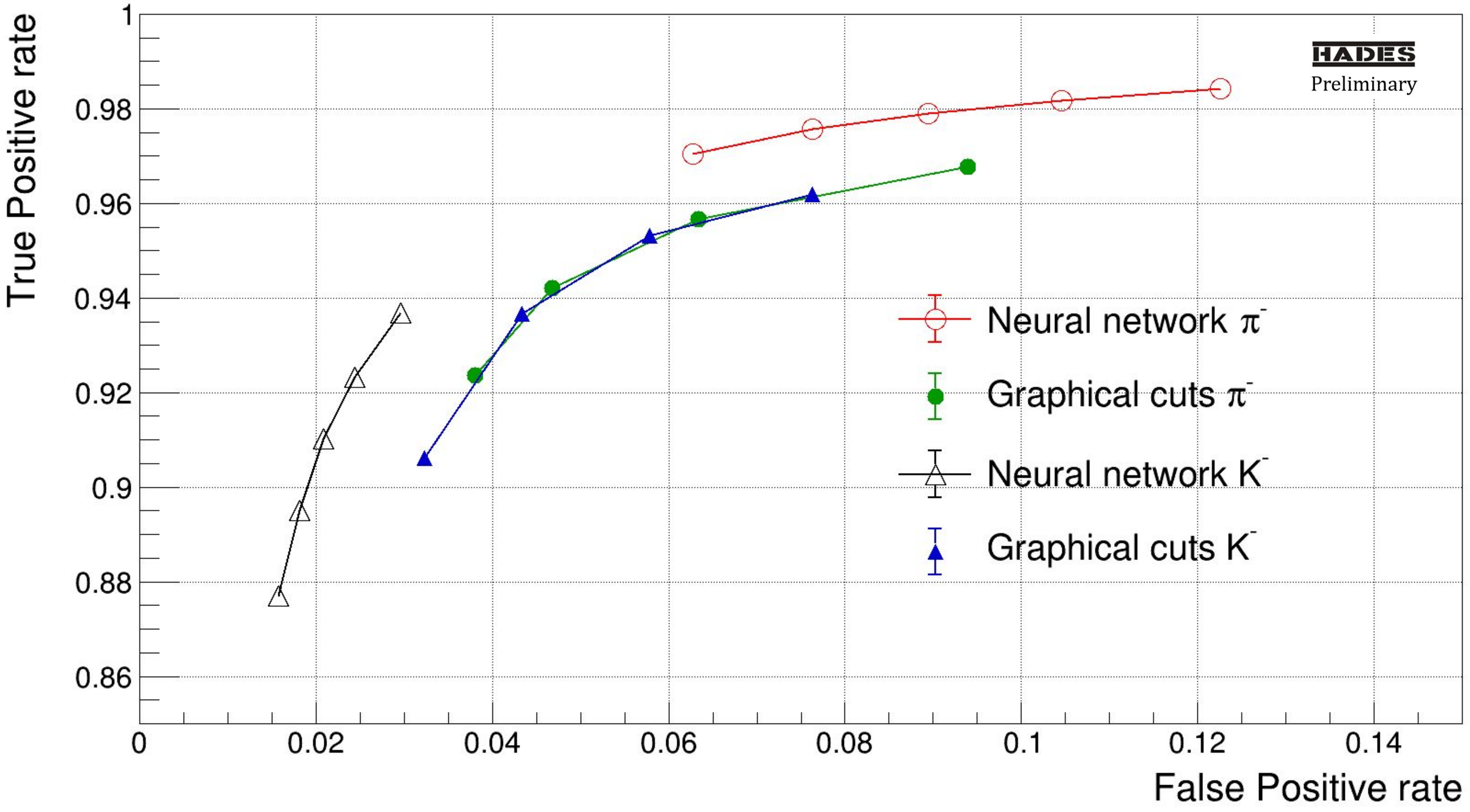
Comparison With the Graphical Cuts ($\beta - P$)

DANN PID has ~1.5 times better

purity at the same efficiency:

$$\mathrm{TPR}_i \equiv \frac{N(\text{true } i \text{ selected as } i)}{N(\text{true } i)}^{*}$$

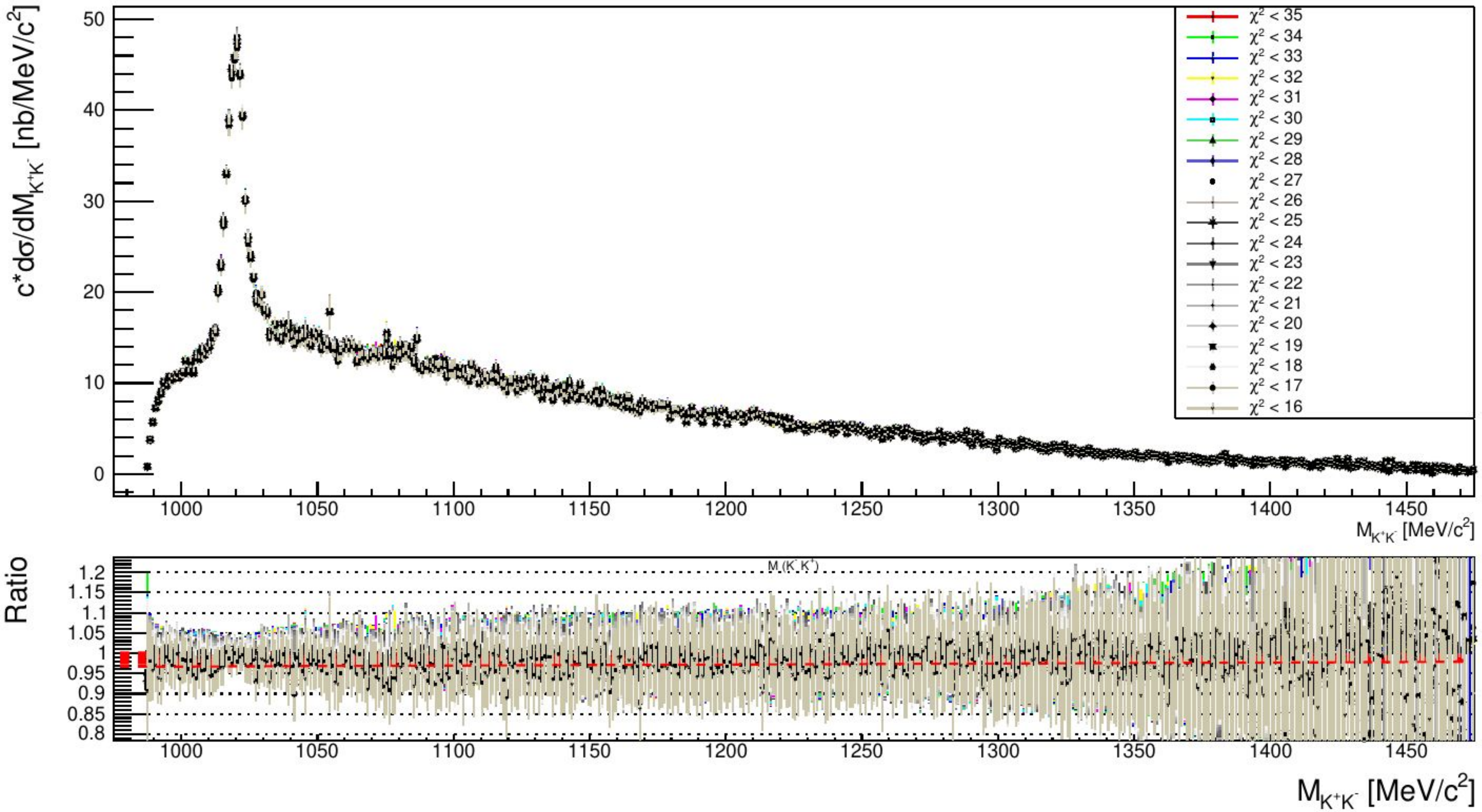
$$\mathrm{FPR}_i \equiv \frac{N(\text{true } j \neq i \text{ selected as } i)}{N(\text{true } j \neq i)}^{*}$$



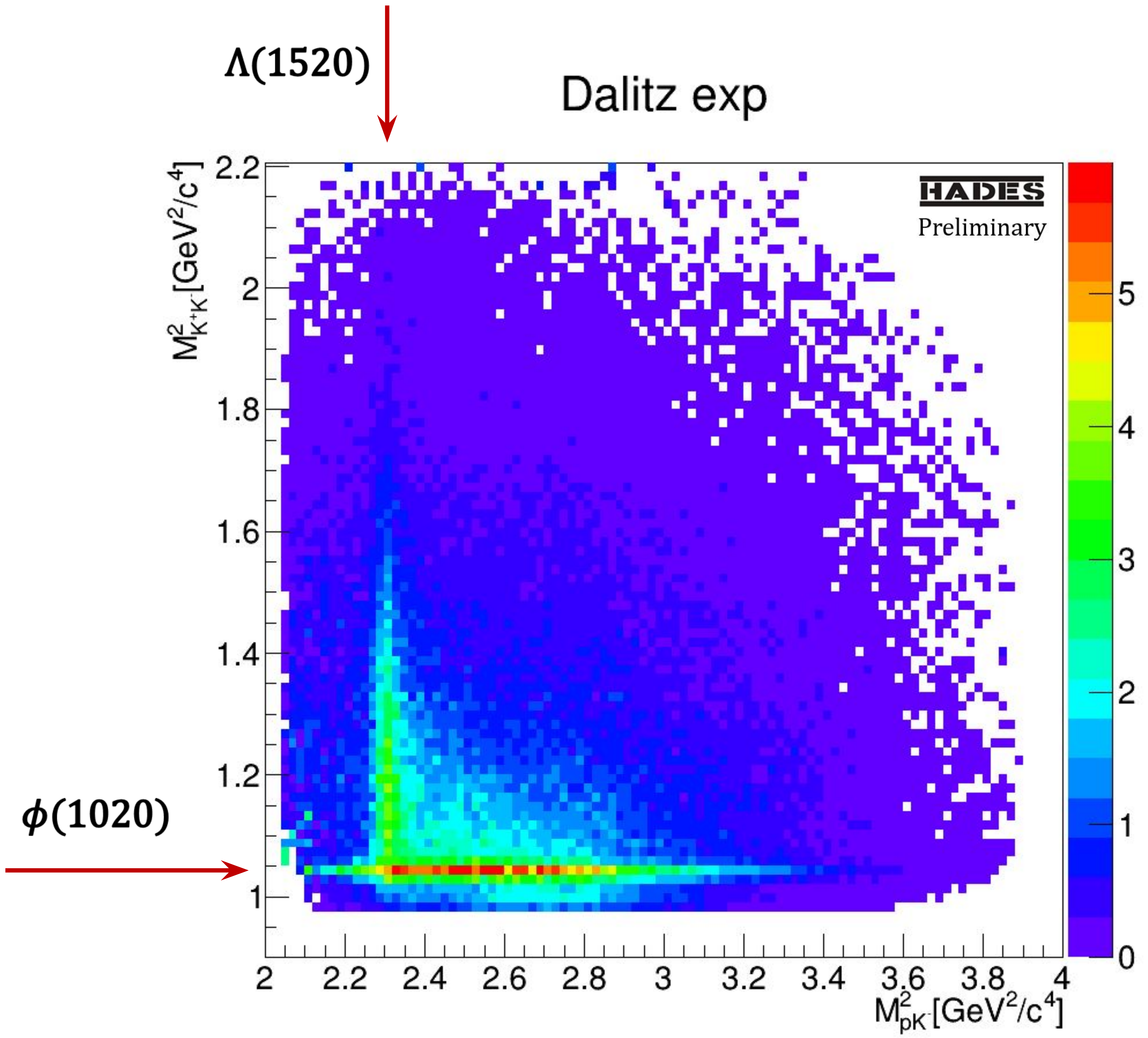
✔ *Performance improvements*

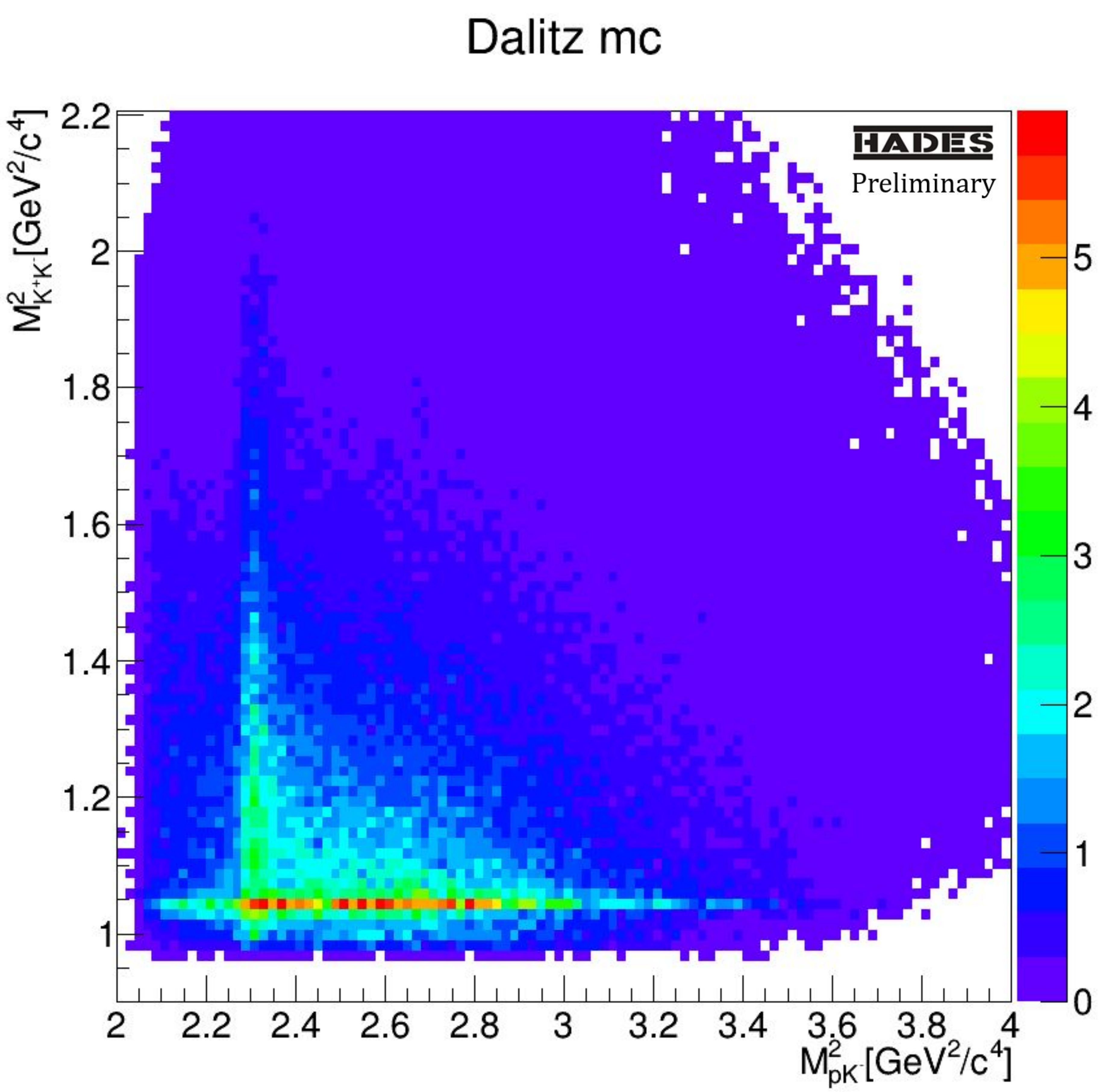
*Both TPR and FPR are self-contained for the case of two classes and thus insensitive to the fractions of events

Varying the chi2 cut



Mass Distributions and Model Approximations





- Efficiency and luminosity corrected counts
- 2 combinations per event (2 protons)

- MC events based on phase space distribution reweighted by a model

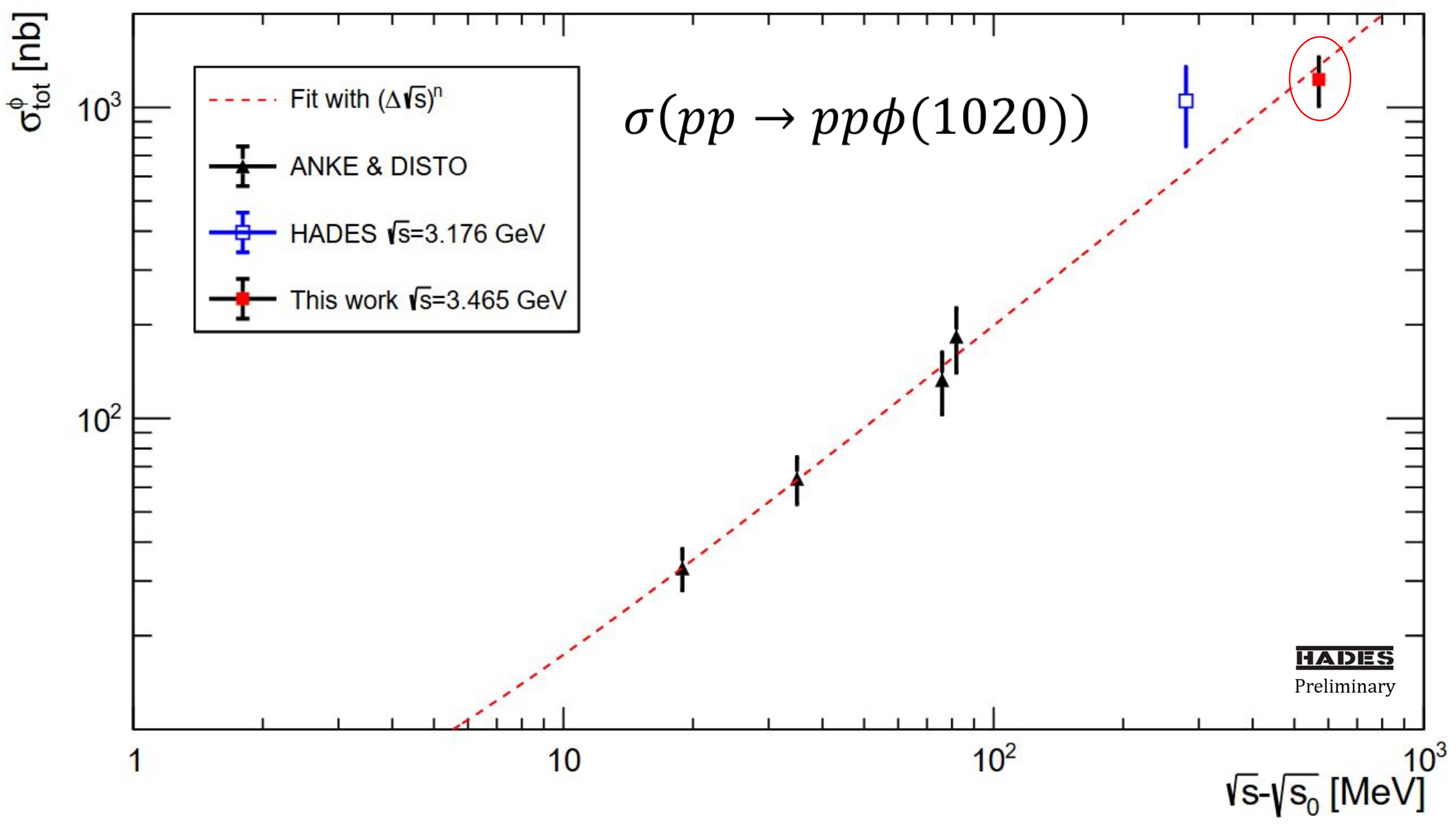
Total and Resonance Cross Sections

- $\sigma(pp \rightarrow ppK^+K^-) \quad = \quad 2800 \pm 400 \text{ nb}$
- $\sigma(pp \rightarrow pp\phi(1020)) \quad = \quad 613 \pm 90 \text{ nb}$
- $\sigma(pp \rightarrow pK^+\Lambda(1520)) = 1372 \pm 200 \text{ nb}$

At $\sqrt{s} = 3465 \pm 5$ MeV

Systematic uncertainty $\sim 15\%$

mainly from global acceptance



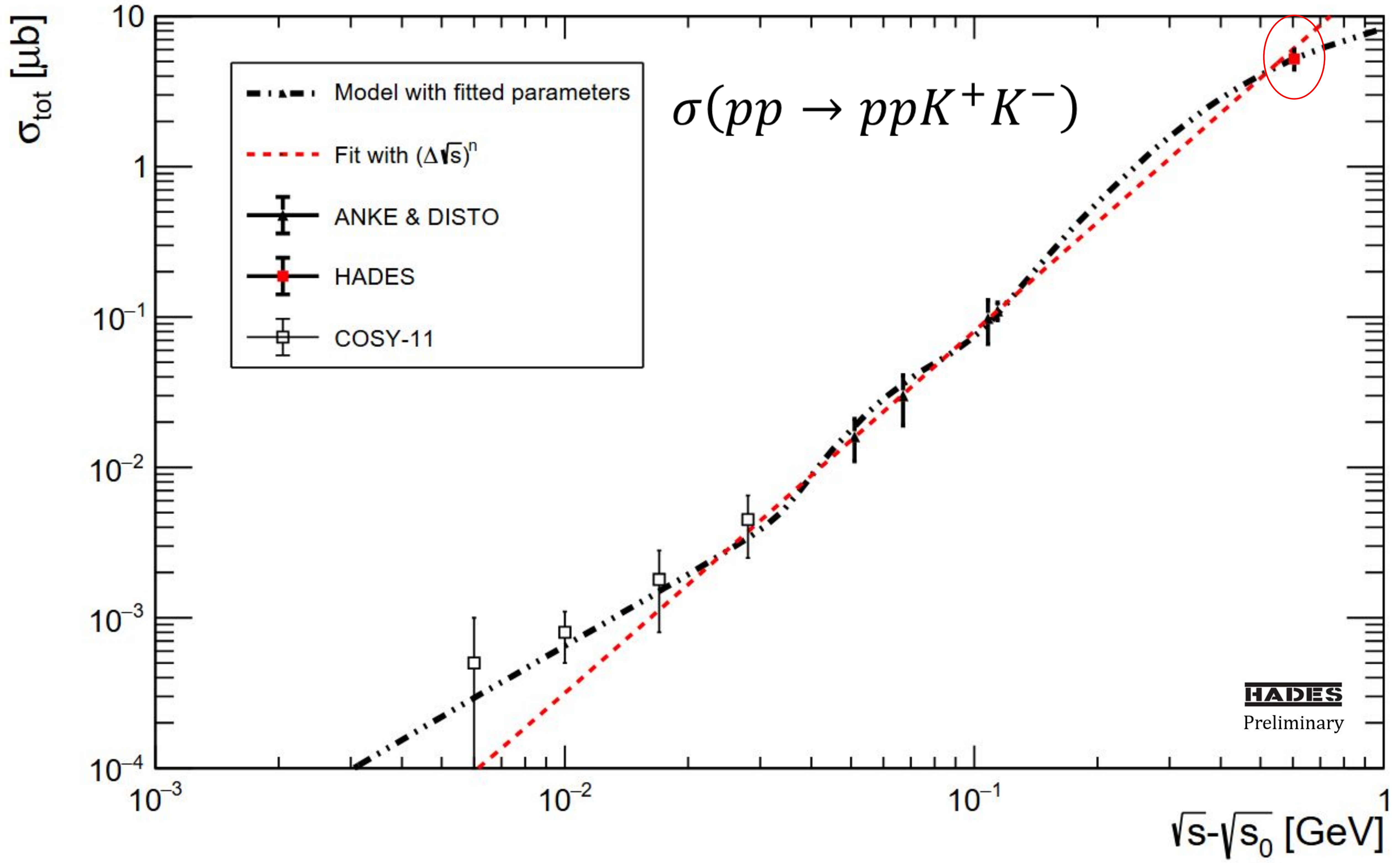
Total and Resonance Cross Sections

- $\sigma(pp \to ppK^+K^-) \quad = \quad 2800 \pm 400 \text{ nb}$
- $\sigma(pp \to pp\phi(1020)) \quad = \quad 613 \pm 90 \text{ nb}$
- $\sigma(pp \to pK^+\Lambda(1520)) = 1372 \pm 200 \text{ nb}$

At $\sqrt{s} = 3465 \pm 5$ MeV

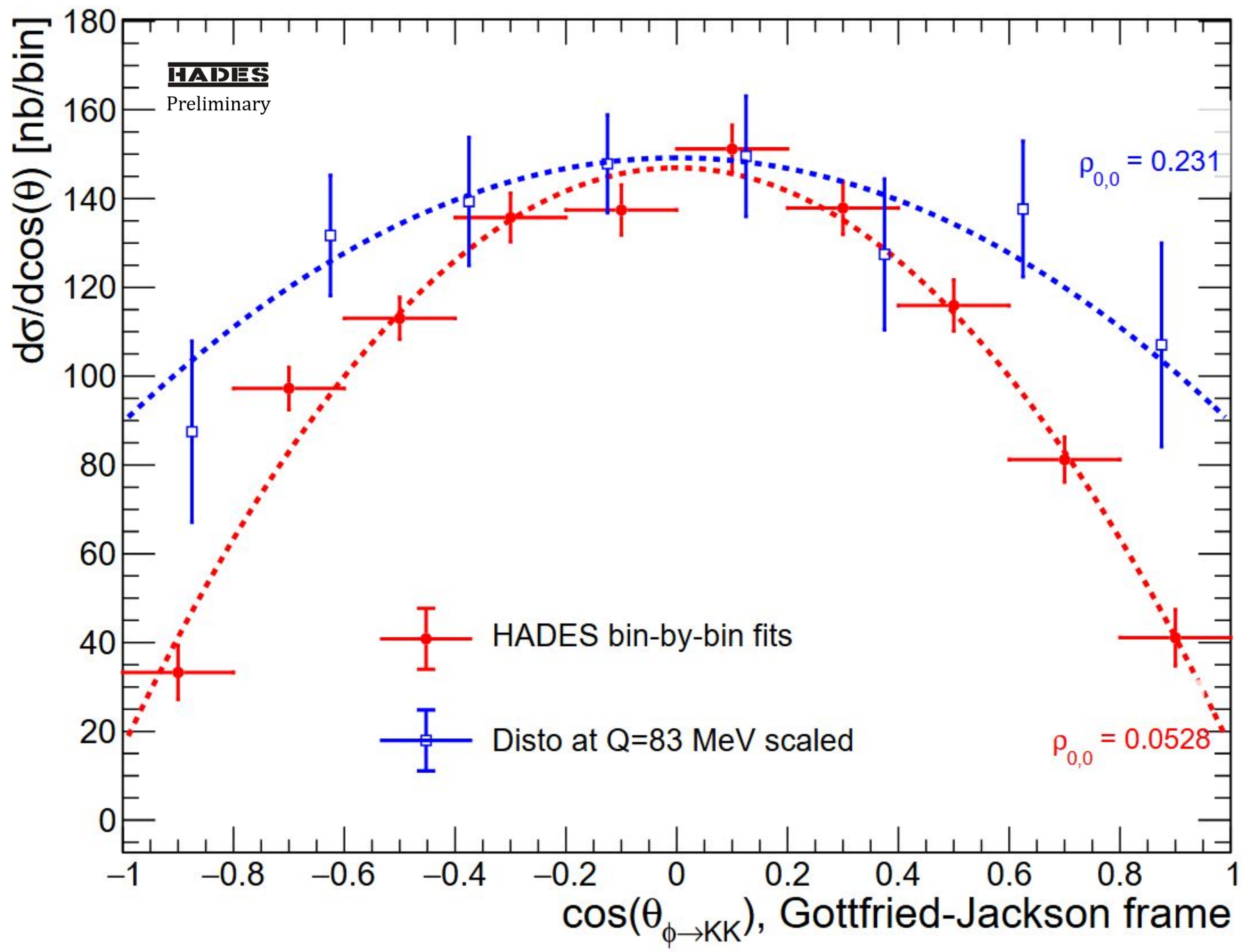
Systematic uncertainty $\sim 15\%$

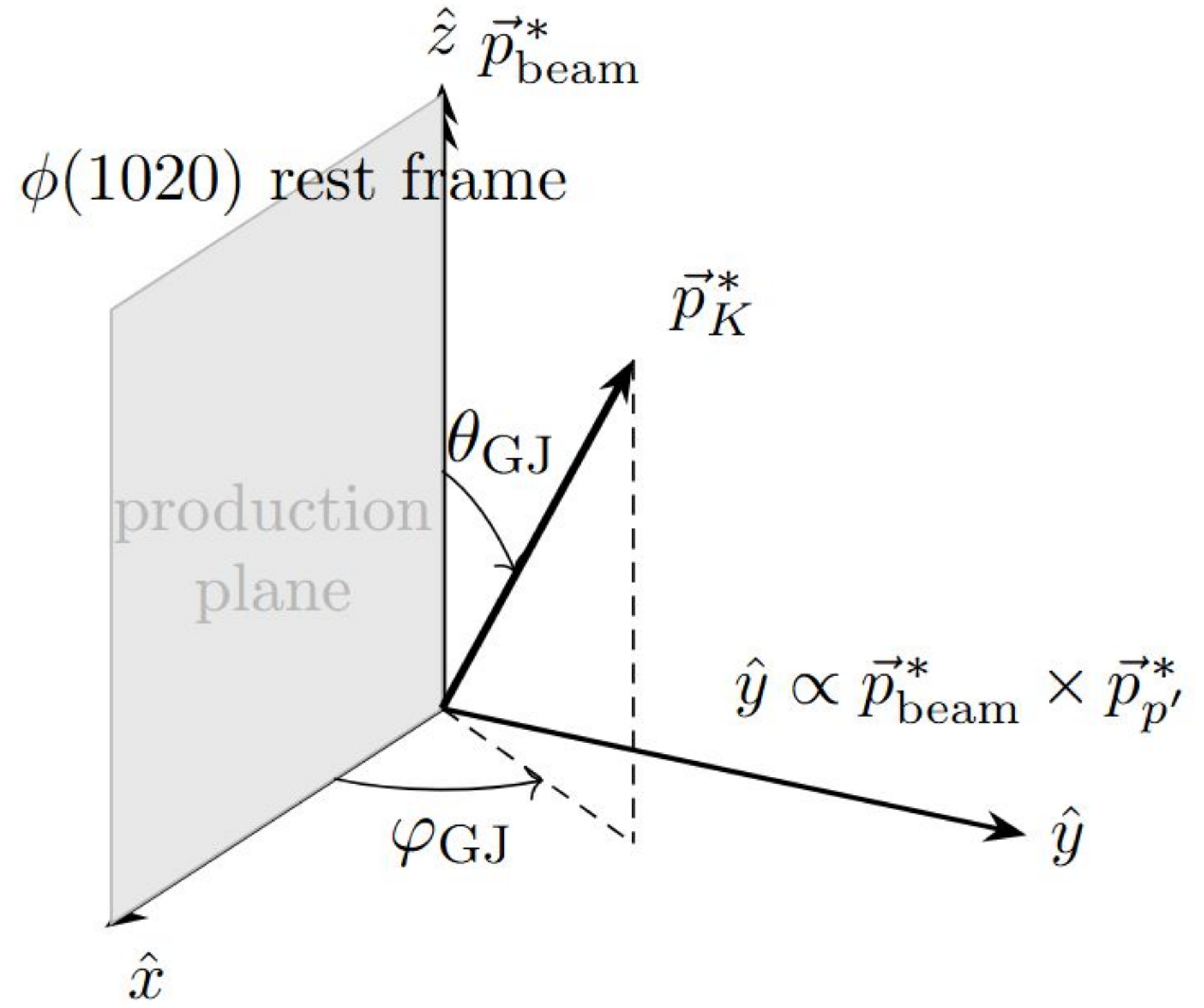
mainly from global acceptance



✔ Inclusion of FSI increases the low-energy cross section, and the measurements align.

Angular Analysis for $\phi(1020)$ spin





$\boldsymbol{\rho_{00} = 0.04 \pm 0.02}$ - This measurement at 600 MeV

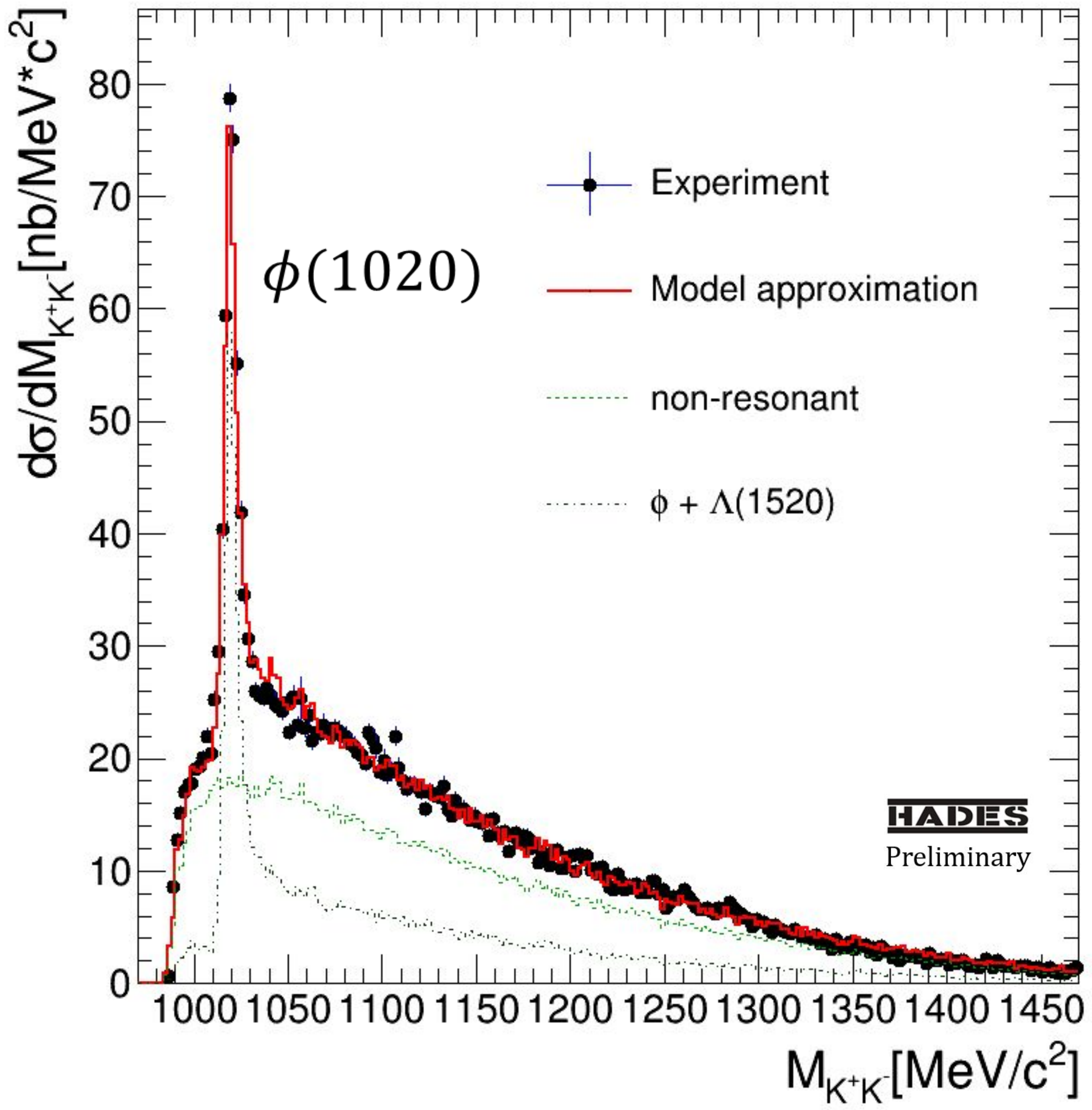
$\rho_{00} = 0.23 \pm 0.04$ – DISTO at ~100 MeV above E_{thr}

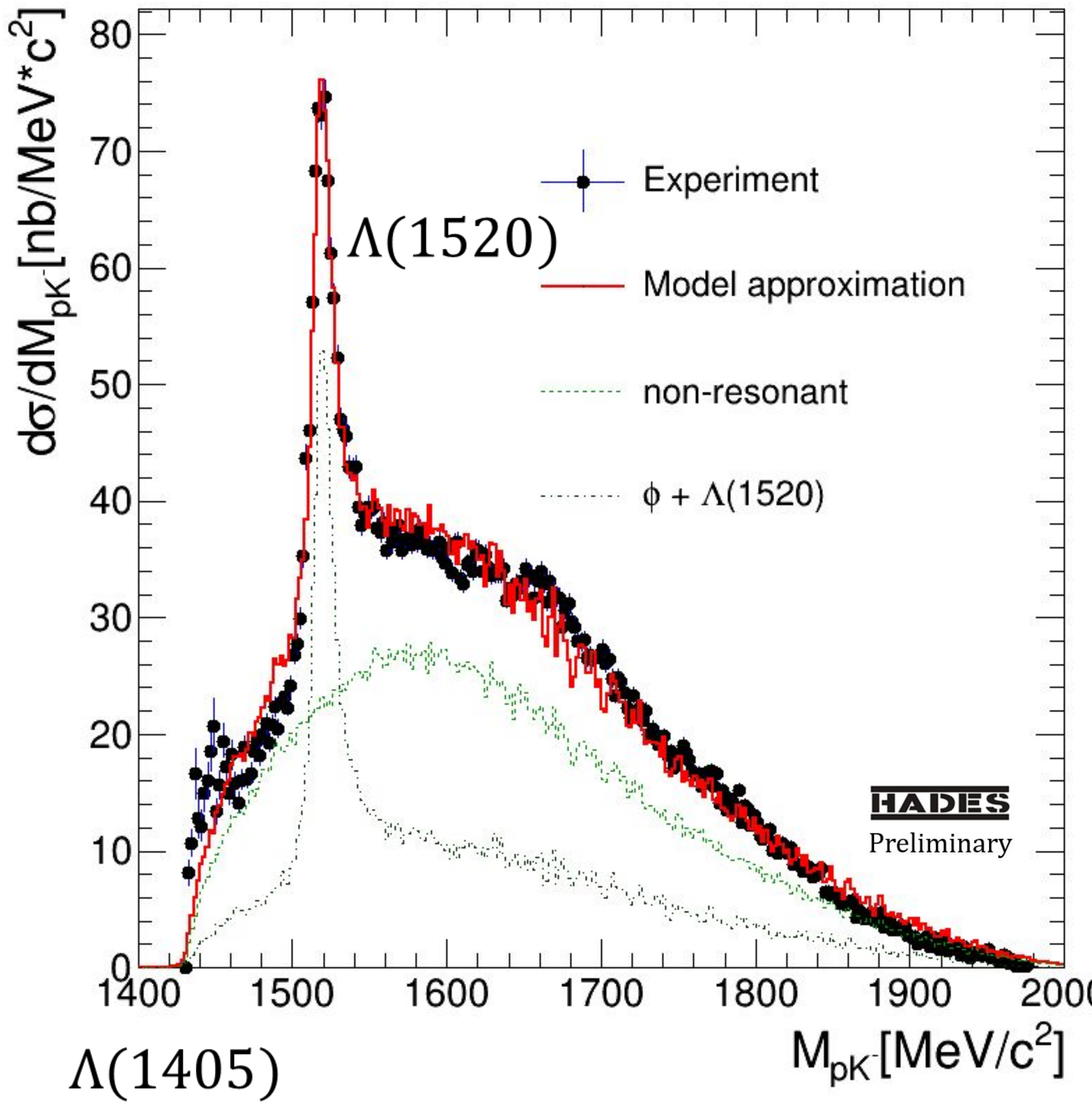
Longitudal polarization (1/3 for unpolarized)

$$\frac{dN}{d\Omega} = \frac{3}{4\pi}\left[\frac{1}{2}(1-\rho_{00}) + \left(\frac{3}{2}\rho_{00} - \frac{1}{2}\right)\cos^2\theta - \rho_{1-1}\sin^2\theta\cos 2\varphi - \sqrt{2}\,\mathrm{Re}(\rho_{10})\sin 2\theta\cos\varphi - \sqrt{2}\,\mathrm{Im}(\rho_{10})\sin 2\theta\sin\varphi\right].$$

- ✓ A transition from unpolarized to transverse production?
- ➢ Inclusion of φ diagonal elements is underway

Amplitude Analysis

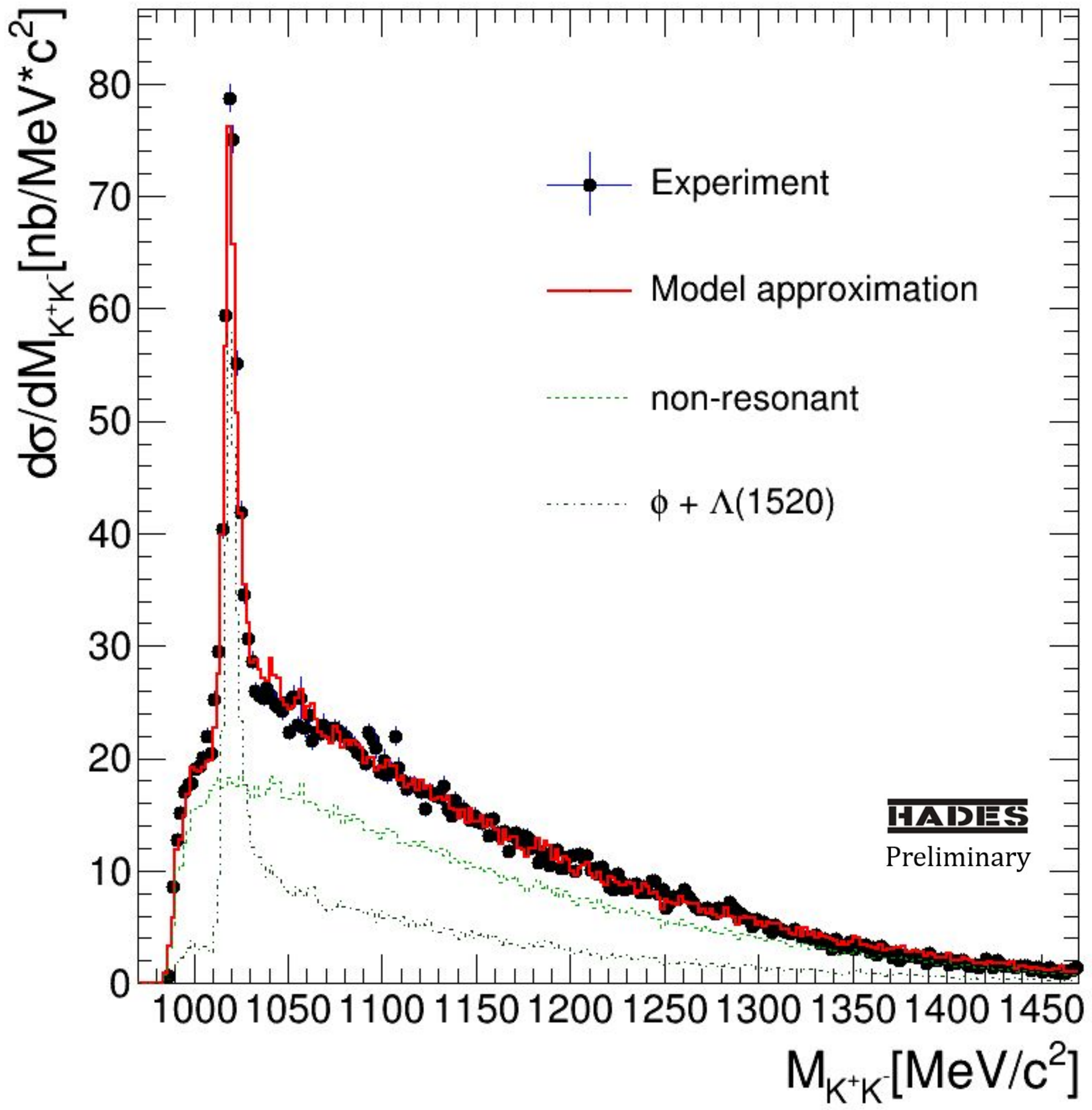


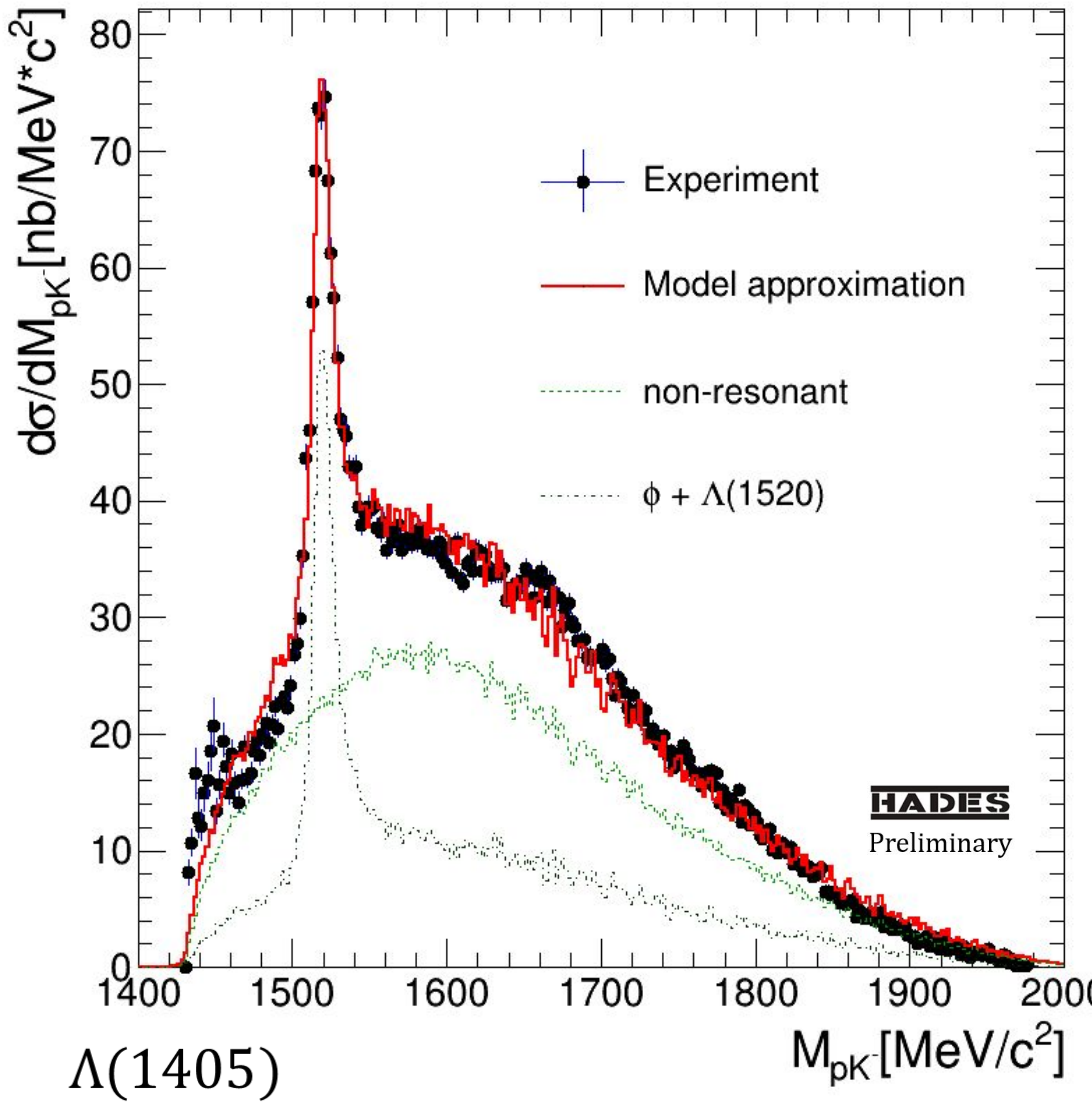


- MC phase space simulation, reweight events with the complex “amplitude” squared:
- $A = \frac{1}{1-iq_1 a_{pK}} \cdot \frac{1}{1-iqa_{KK}} \cdot$
  $\cdot\,(1 + c_1 BW_{\phi(1020)} + c_2 BW_{\Lambda(1520)})$
- Simultaneous fit of $M_{K^+K^-}$ and M_{pK^-}
- Fit parameters: c_1, c_2, c_3 and phases,
  Λ/ϕ parameters,
  a_{pK}, a_{KK} scattering lengths

✔ Valid description of the experiment with FSI encapsulating different effects

Amplitude Analysis





$\Lambda(1405)$

- $a_{KK} = (0.47 \pm 0.05) + i(0.0 \pm 0.1)$ fm
  - previous results* poorly constrained:

  $a_{KK} = (0.50^{+4}_{-0.5}) + i(3.0^{+3.0}_{-3.0})$ fm

- $a_{pK} = (0.09 \pm 0.02) + i(-0.22 \pm 0.05)$ fm

$M_\phi = (1019.5 \pm 0.1)$ MeV

$\Gamma_\phi = (4.5 \pm 0.1)$ MeV

$M_\Lambda = (1519 \pm 0.5)$ MeV

$\Gamma_\Lambda = (14 \pm 0.5)$ MeV

✓ The best fit includes $\Lambda(1405) \to pK$ subthreshold production

$M_\phi^{PDG} = (1019.461 \pm 0.016)$ MeV

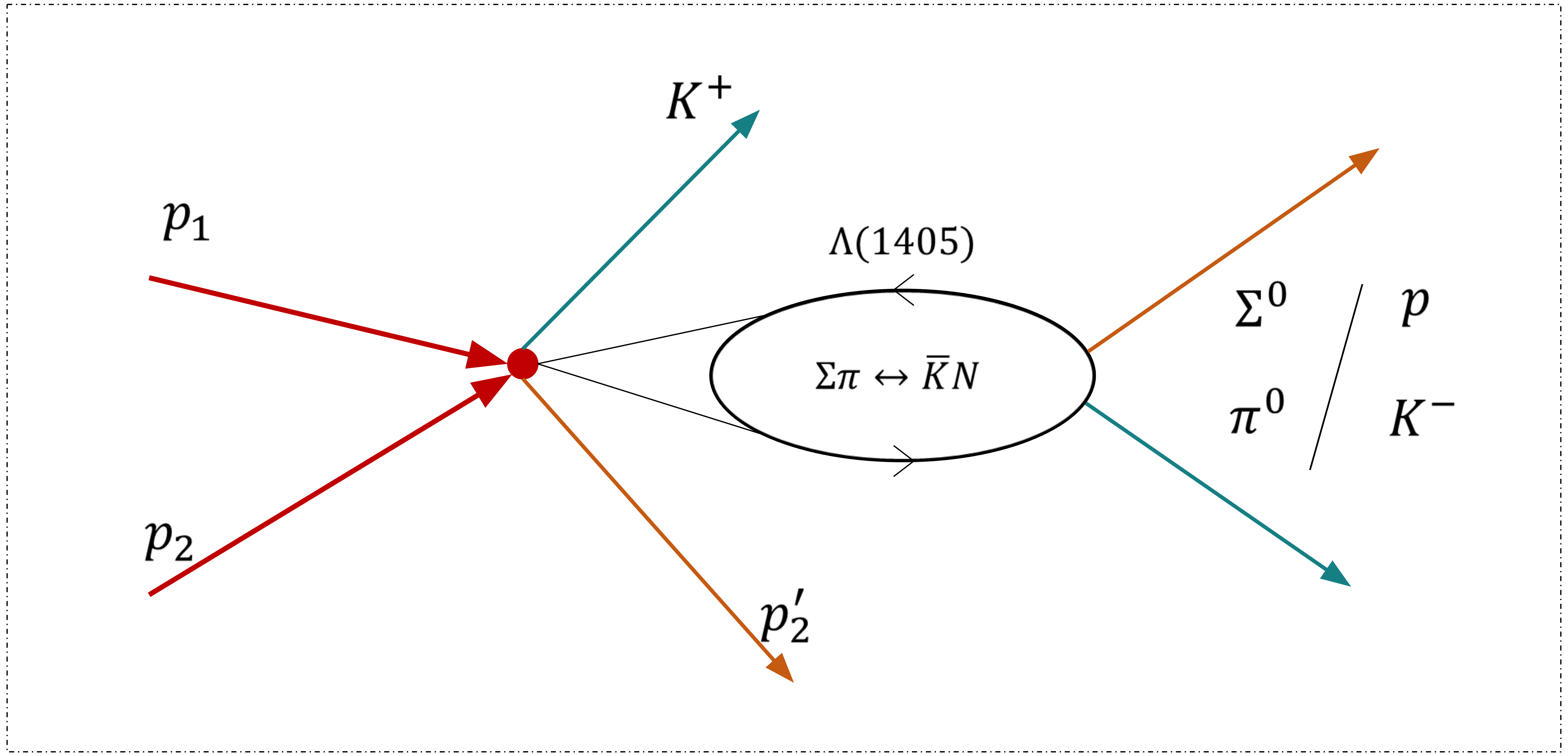
$\Gamma_\phi^{PDG} = (4.249 \pm 0.013)$ MeV

$M_\Lambda^{PDG} = (1519 \pm 1)$ MeV

$\Gamma_\Lambda^{PDG} = (15 \pm 1)$ MeV

*https://arxiv.org/abs/1003.4504

Coupled Channels Analysis in K-Matrix Formalism



$\Sigma\pi$ analysis described in the previous talk, done by Anna Władyszewska ($\Sigma^0 \to \gamma[\Lambda \to p\pi^-]$)

Simplified procedure:

1. Measure <u>two raw distributions</u>:

   M_{pK^-} & $M_{\Sigma^0\pi^0}$

2. Re-weight Phase Space simulation within a <u>common coupled amplitude</u>

3. Fit $M_{\Sigma\pi}$ and M_{pK^-} simultaneously

$$K_{ij}(s) = \sum_R \frac{g_{R,i}g_{R,j}}{m_R^2 - s}$$

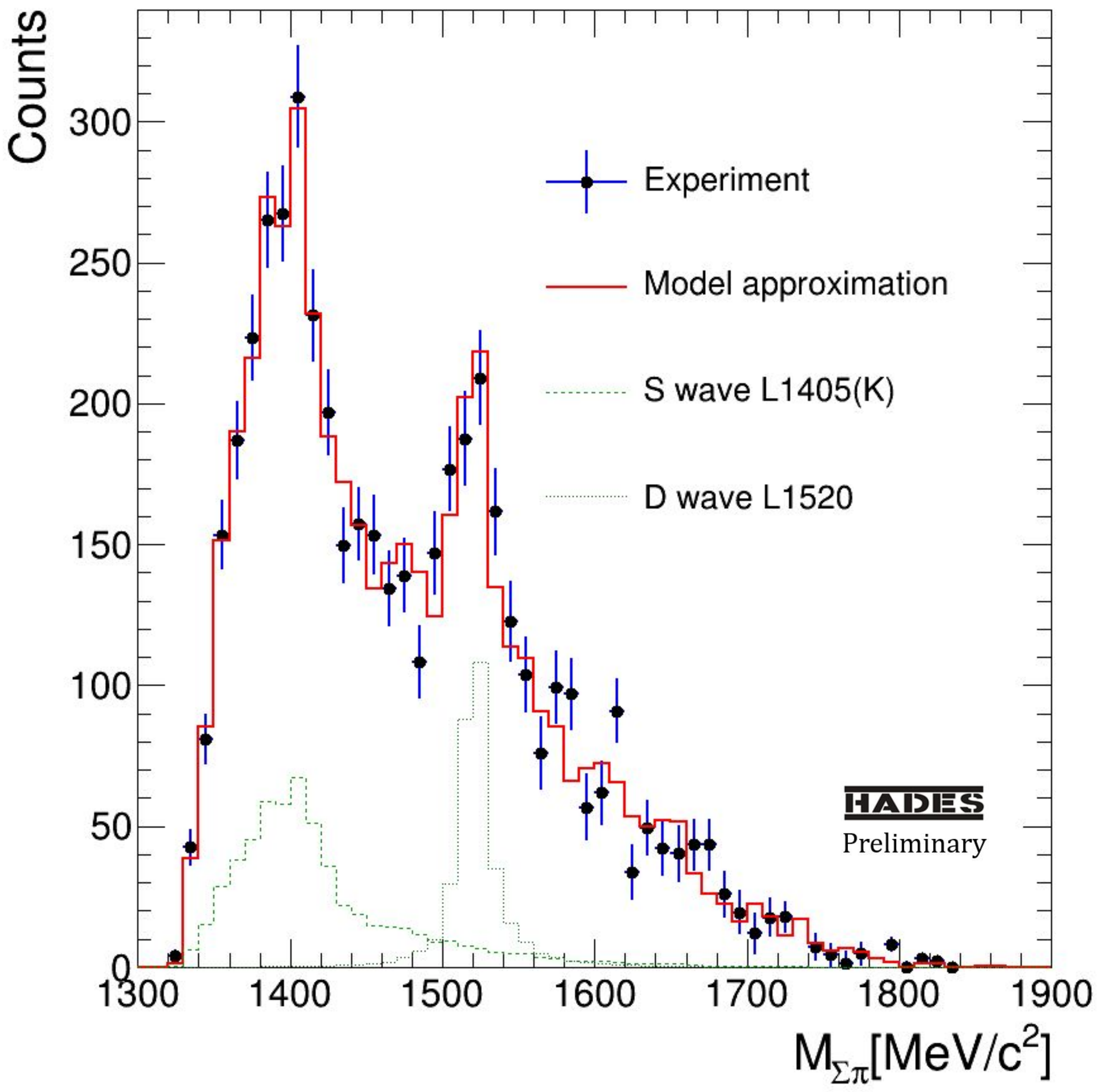
$$A_i(s) = \left[(I - iK\rho)^{-1}\right]_i^k P_k$$

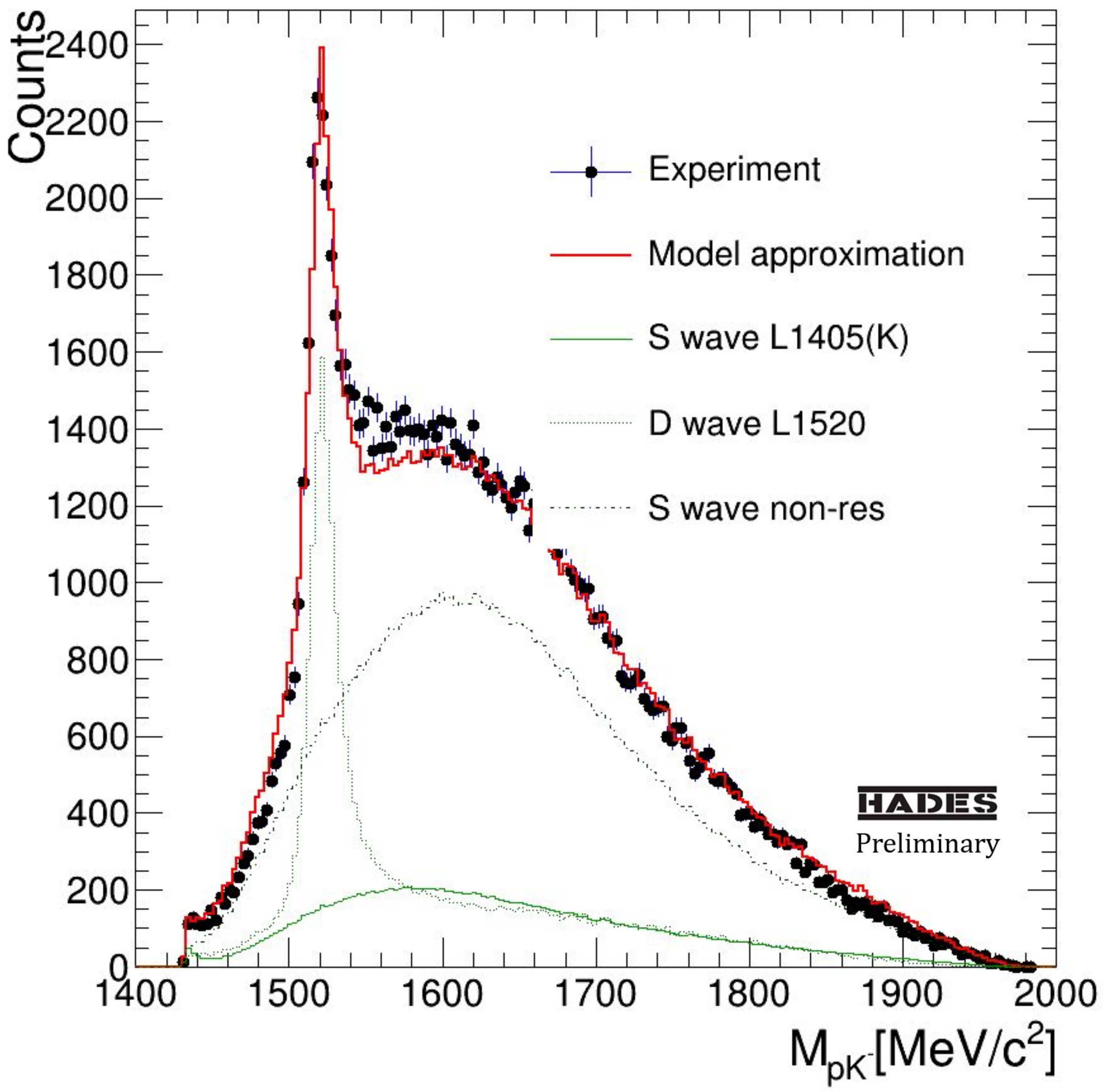
Two-pole description of $\Lambda(1405)$ – Dynamically generated $\Sigma\pi - \bar{K}N$ state?

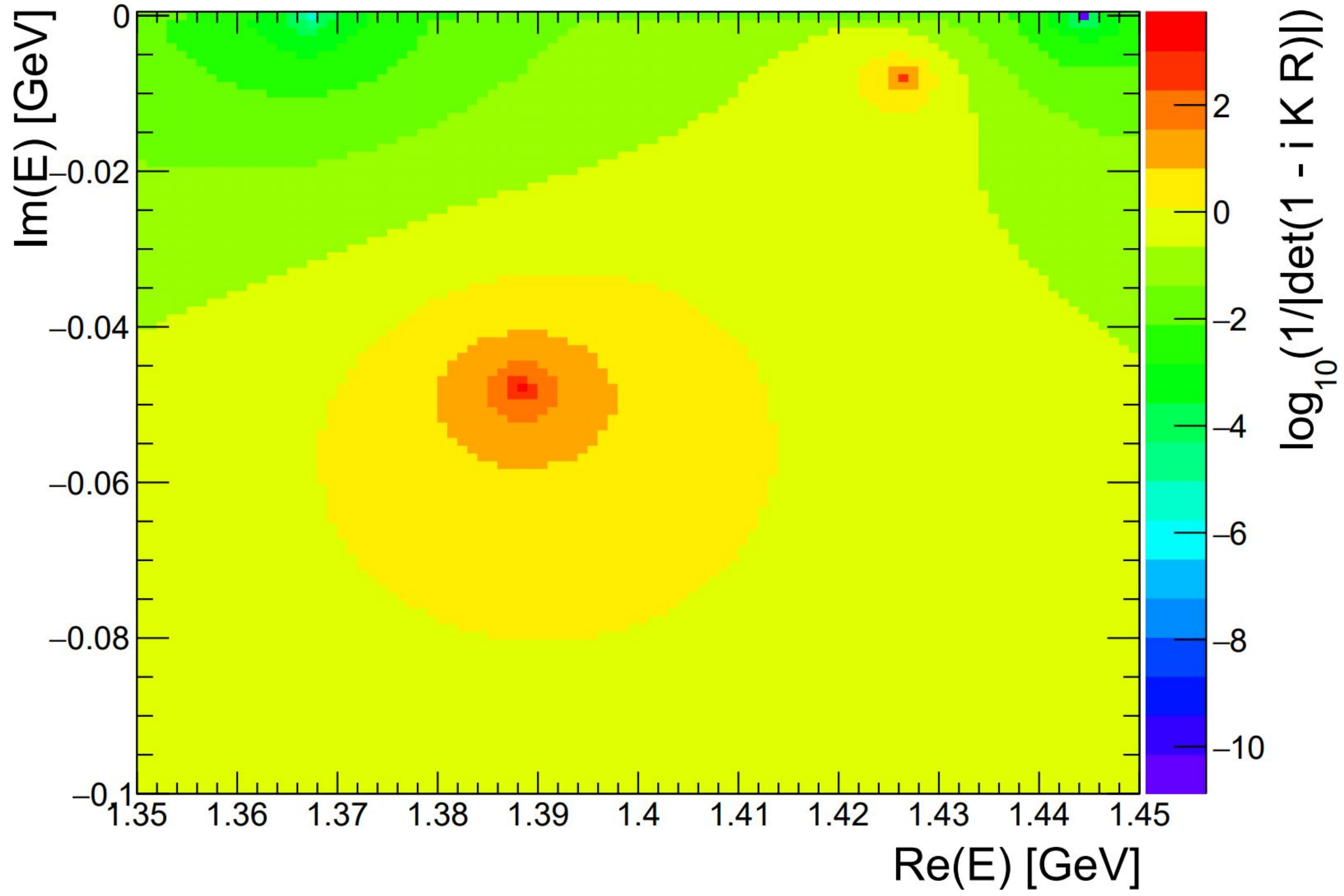
(Poles of the amplitude)

*Efficiency is encoded in the approximation model (phase space simulated, reconstructed and reweighted)

Raw Data Averaged over Momentum Transfer





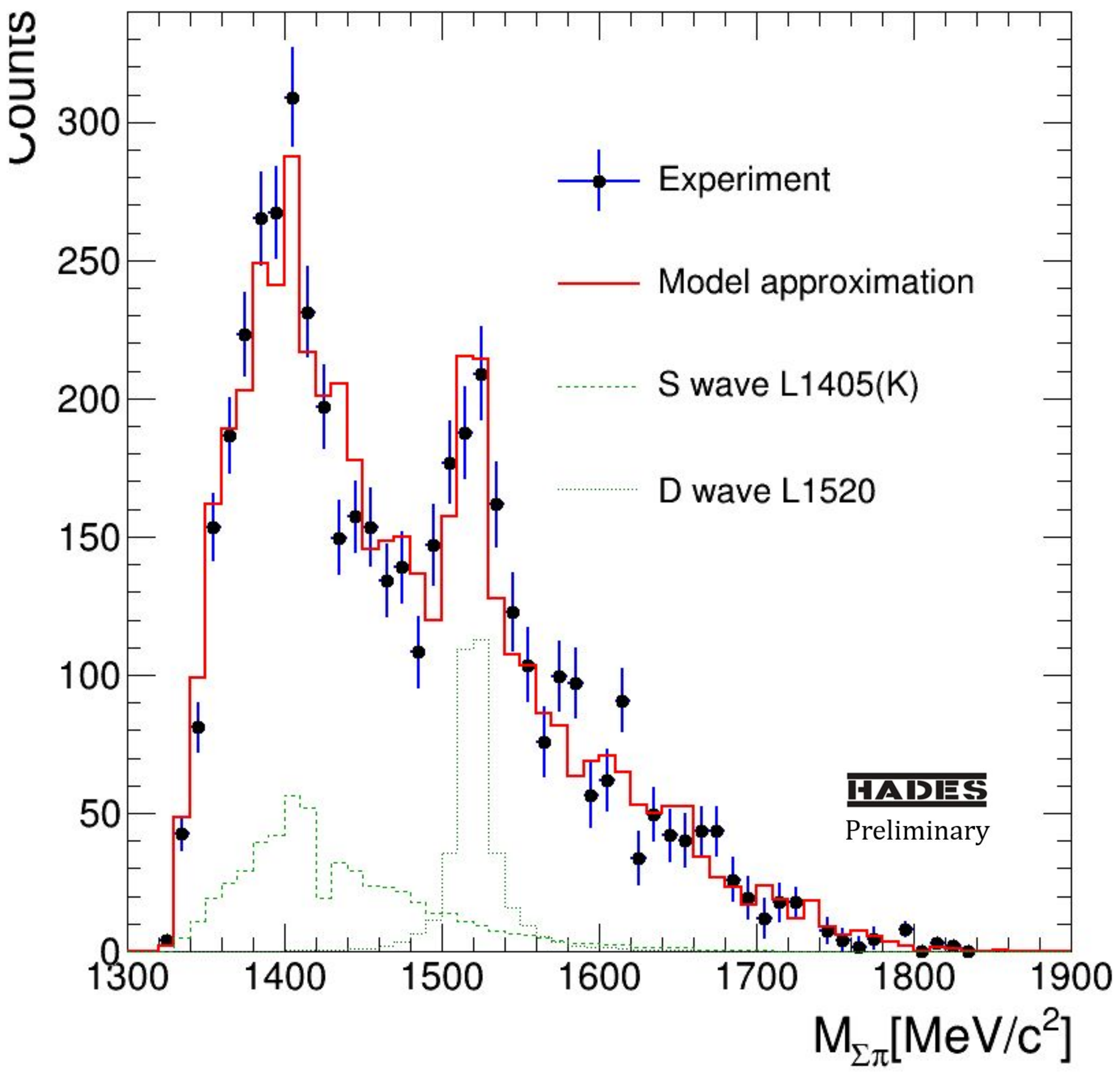


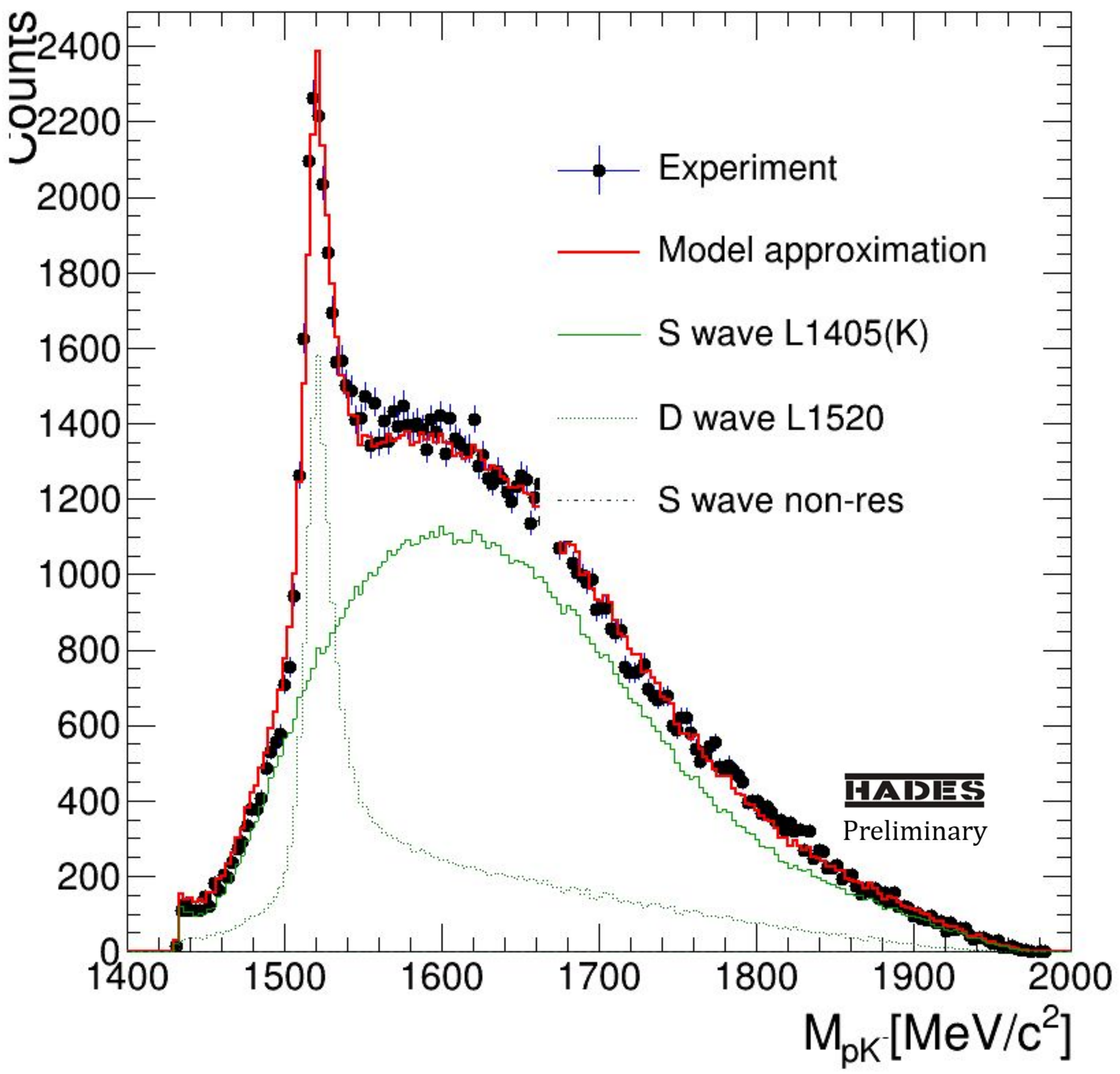
Total intensities with $\Lambda(1405)$ contribution:

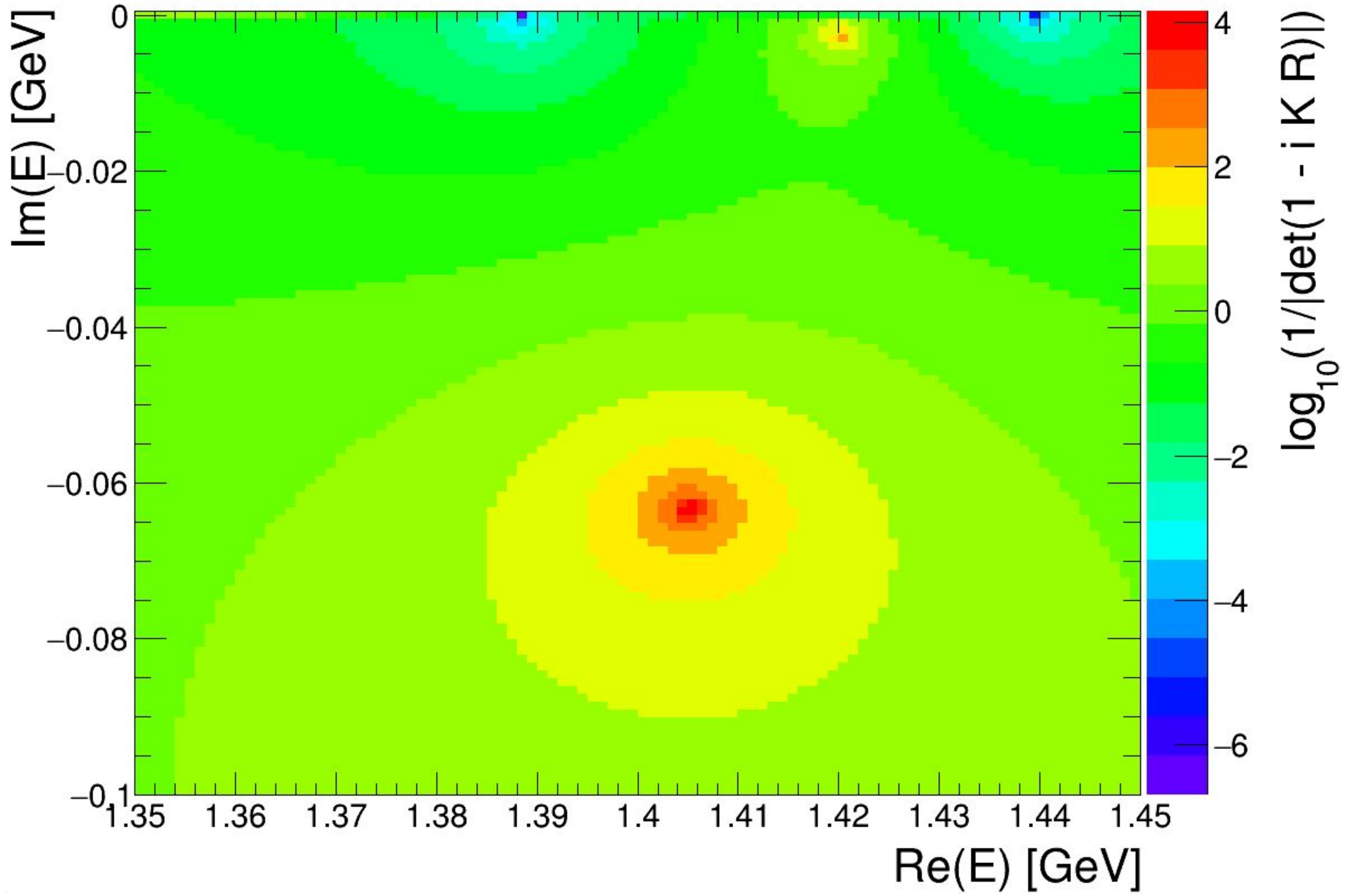
- $I_{pK} = \left|\frac{1}{1-iq_1 a_{pK}}\right|^2 + c_1|((1-IKR)^{-1}P)_1|^2 + |C^{\Sigma\pi}_{\Lambda(1520)} BW_{\Lambda(1520)}|^2$
- $I_{\Sigma\pi} = |1 + c_2((1-IKR)^{-1}P)_2|^2 + |C^{pK}_{\Lambda(1520)} BW_{\Lambda(1520)}|^2$

✔ Fit consistent with this hypothesis

Raw Data Averaged over Momentum Transfer







- $I_{pK} = \left|\frac{1}{1-iq_1 a_{pK}}\right|^2 + c_1|((1-IKR)^{-1}P)_1|^2 + |C^{\Sigma\pi}_{\Lambda(1520)} BW_{\Lambda(1520)}|^2$
- $I_{\Sigma\pi} = |1 + c_2((1-IKR)^{-1}P)_2|^2 + |C^{pK}_{\Lambda(1520)} BW_{\Lambda(1520)}|^2$

✔ Fit consistent with this hypothesis

Pole Positions and Theory

Pole positions, *Recent theory predictions (2000+)

!Not directly comparable (calculations vs parametrization)

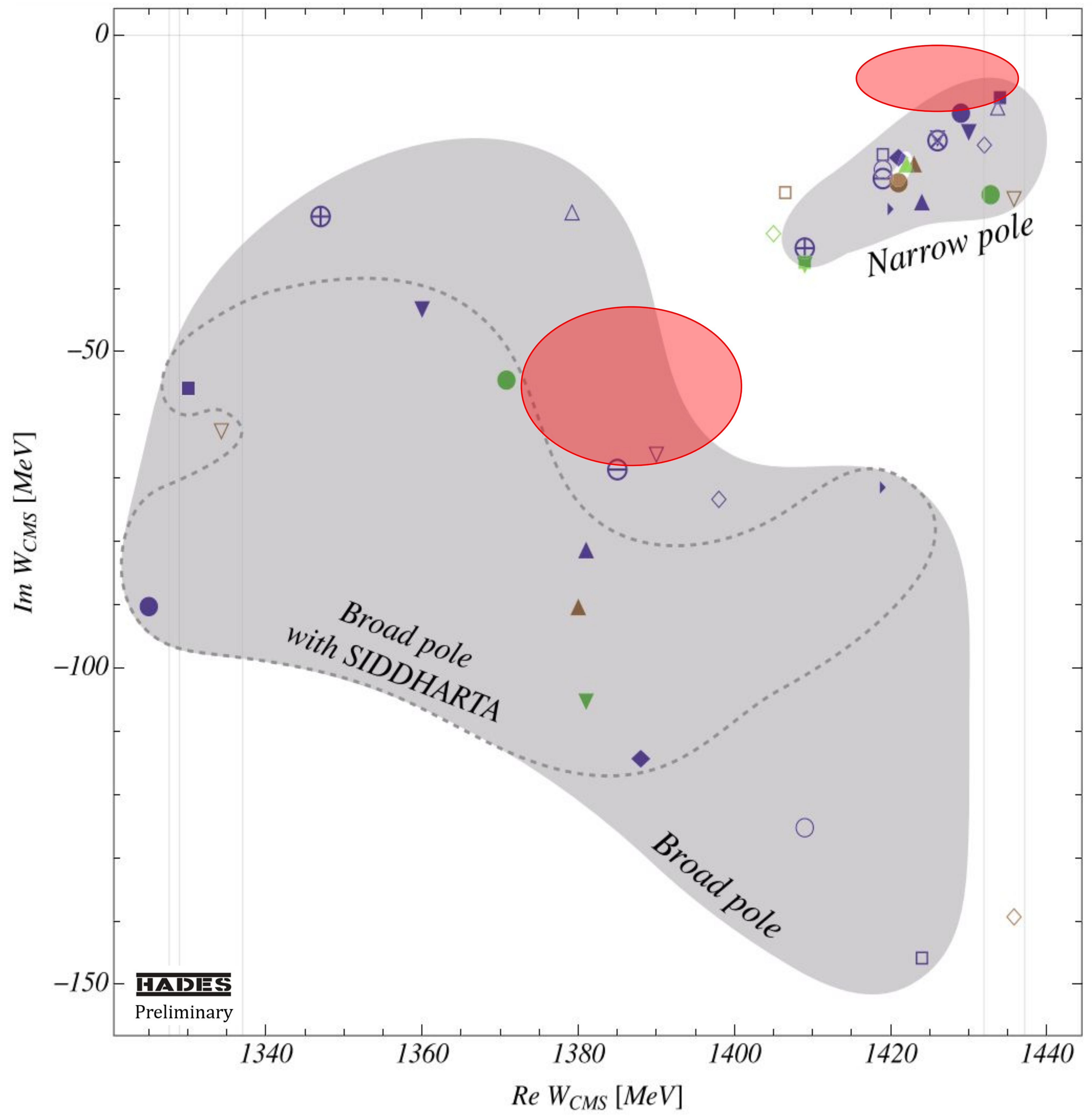
Red areas – poles from this work

Obtained by varying:

- Global amplitude model
- Production vector
- Fit procedure

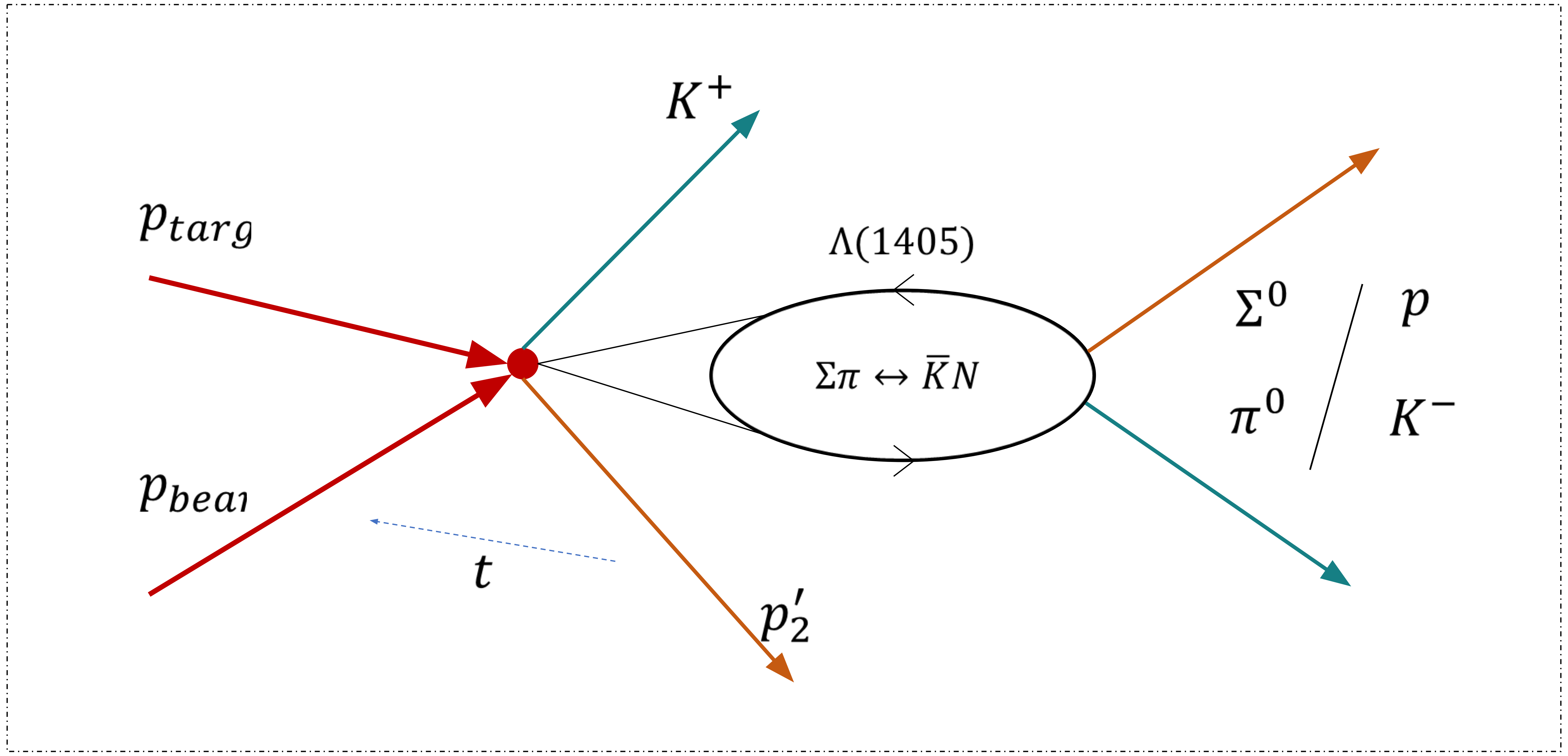
Compared to single pole and no Lambda(1405)

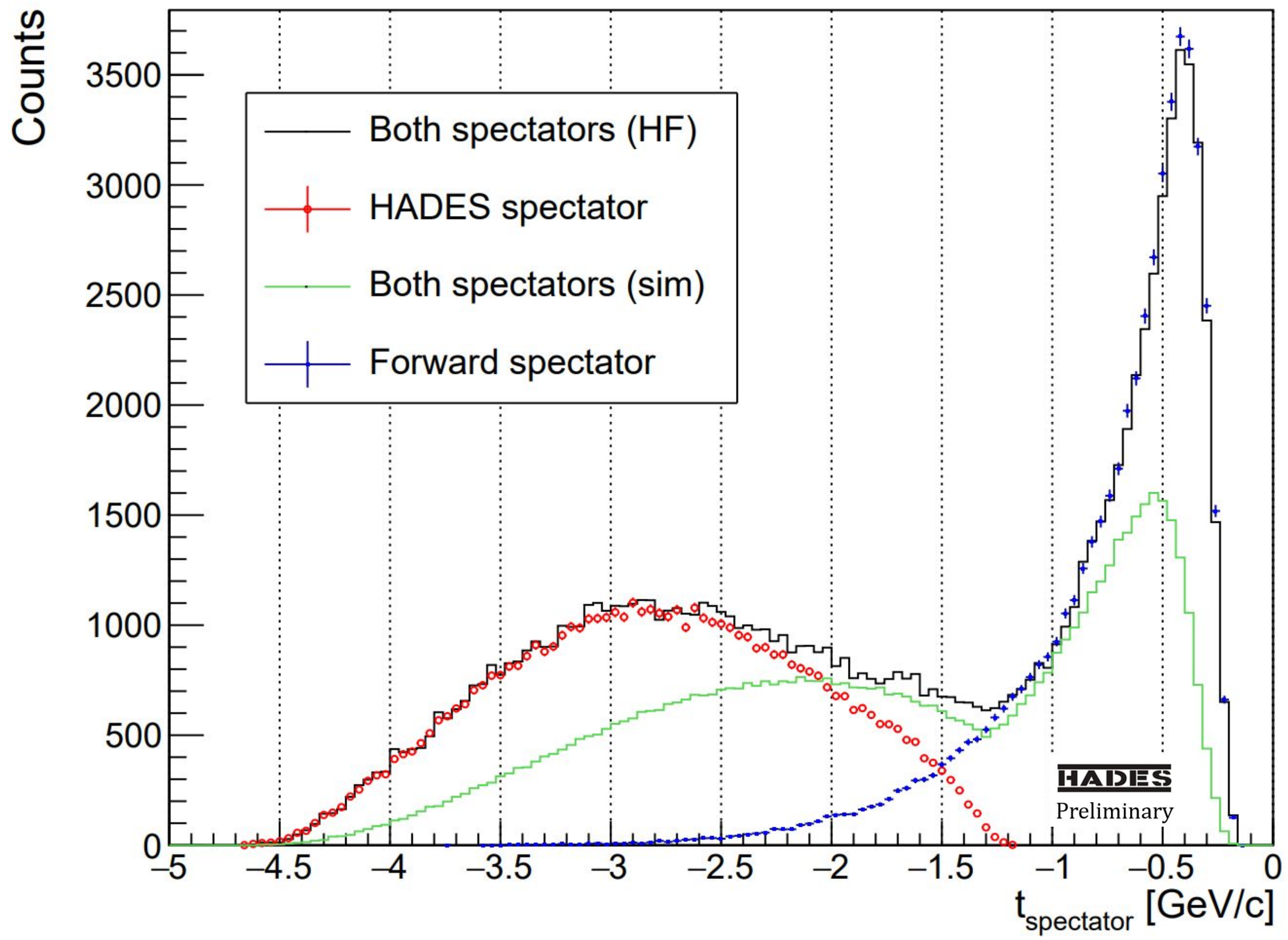
✔ Clear fit improvements



*https://doi.org/10.1140/epjs/s11734-021-00144-7

Cross Sections in Momentum Transfer bins





- ✔ Solves proton ambiguity for efficiency correction
- ✔ Can enhance Lambda(1405) visibility
- ✔ Access to branching ratios