Strangeness production and $\Lambda(1405)$ in pp collisions at HADES

Valentin Kladov on behalf of the HADES collaboration

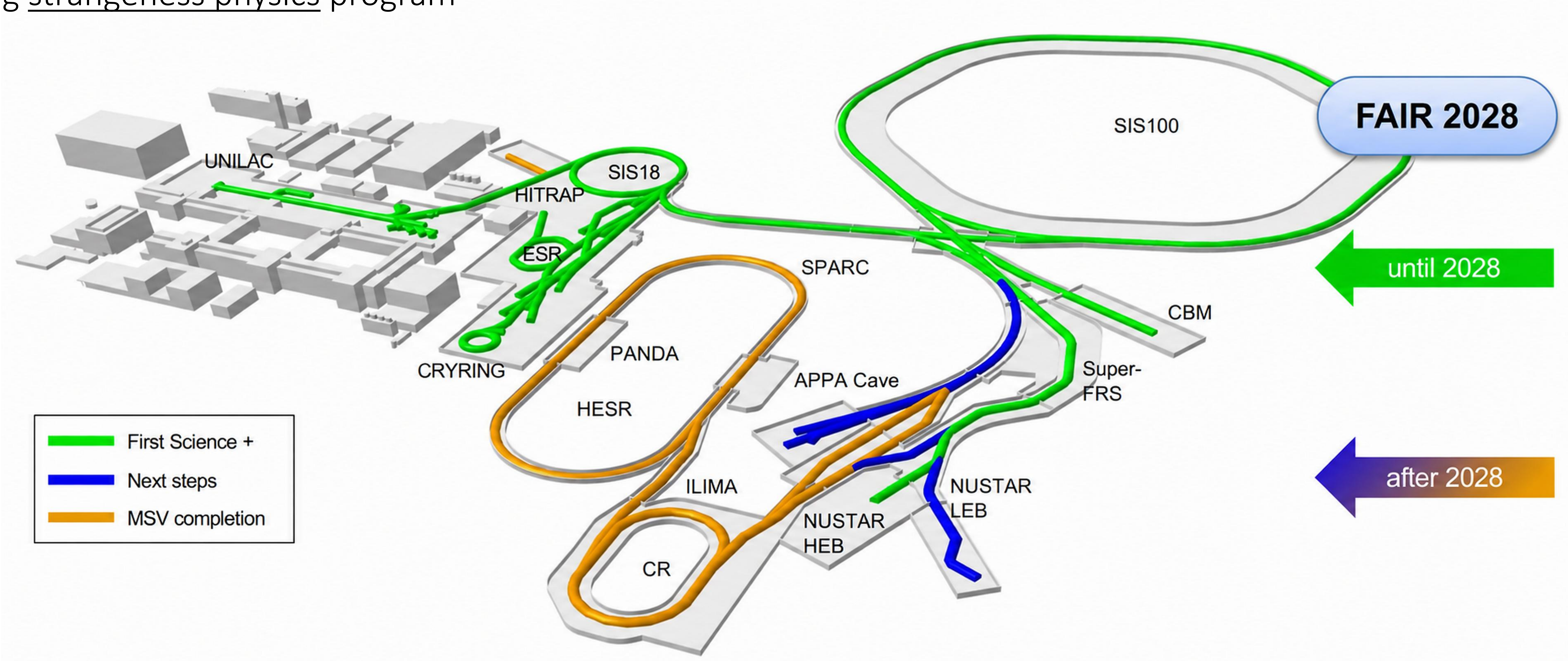
Ruhr-Universität Bochum
GSI Helmholtzzentrum

NSTAR 2026

10.09.2026

GSI & FAIR Experiments

- FAIR - Next generation strong interaction / atomic physics experiments
- Including strangeness physics program



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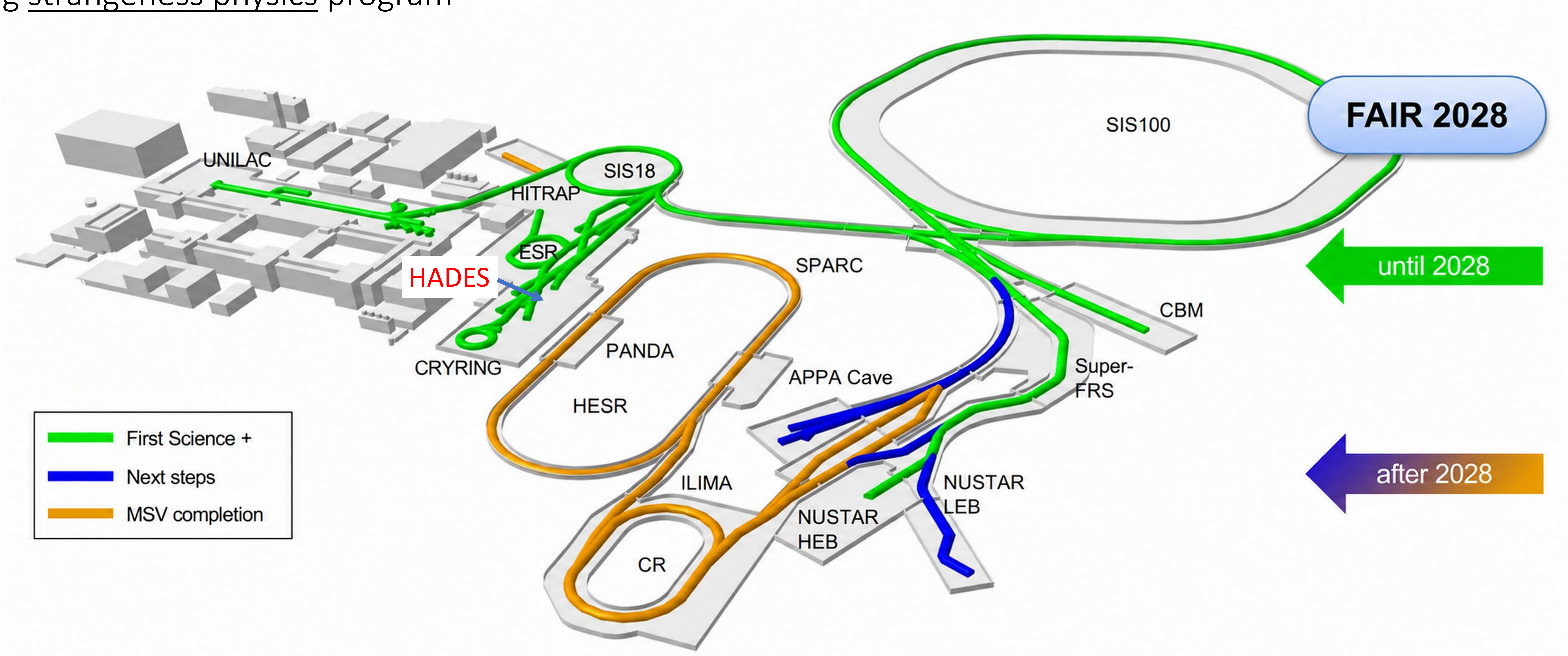
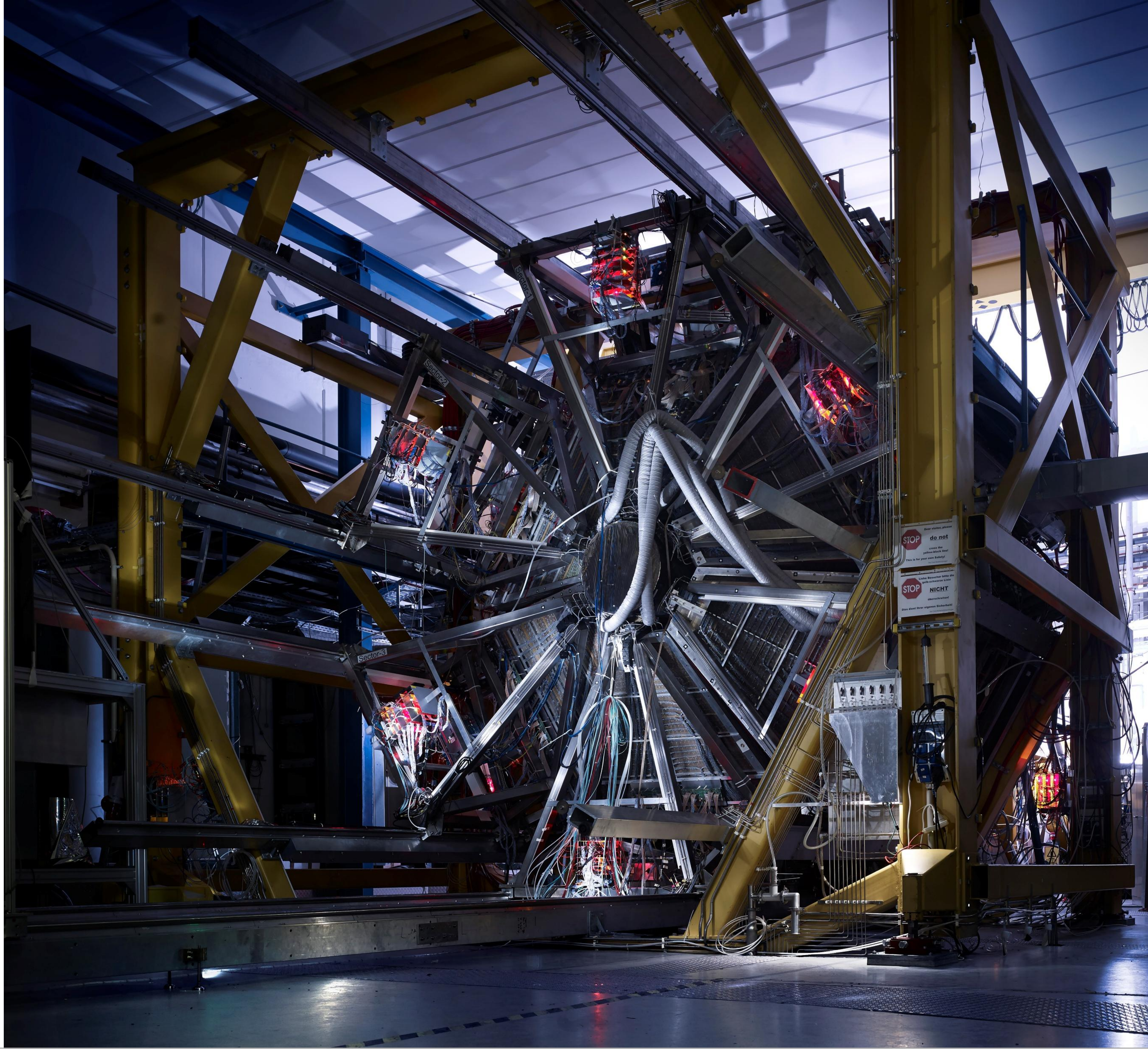


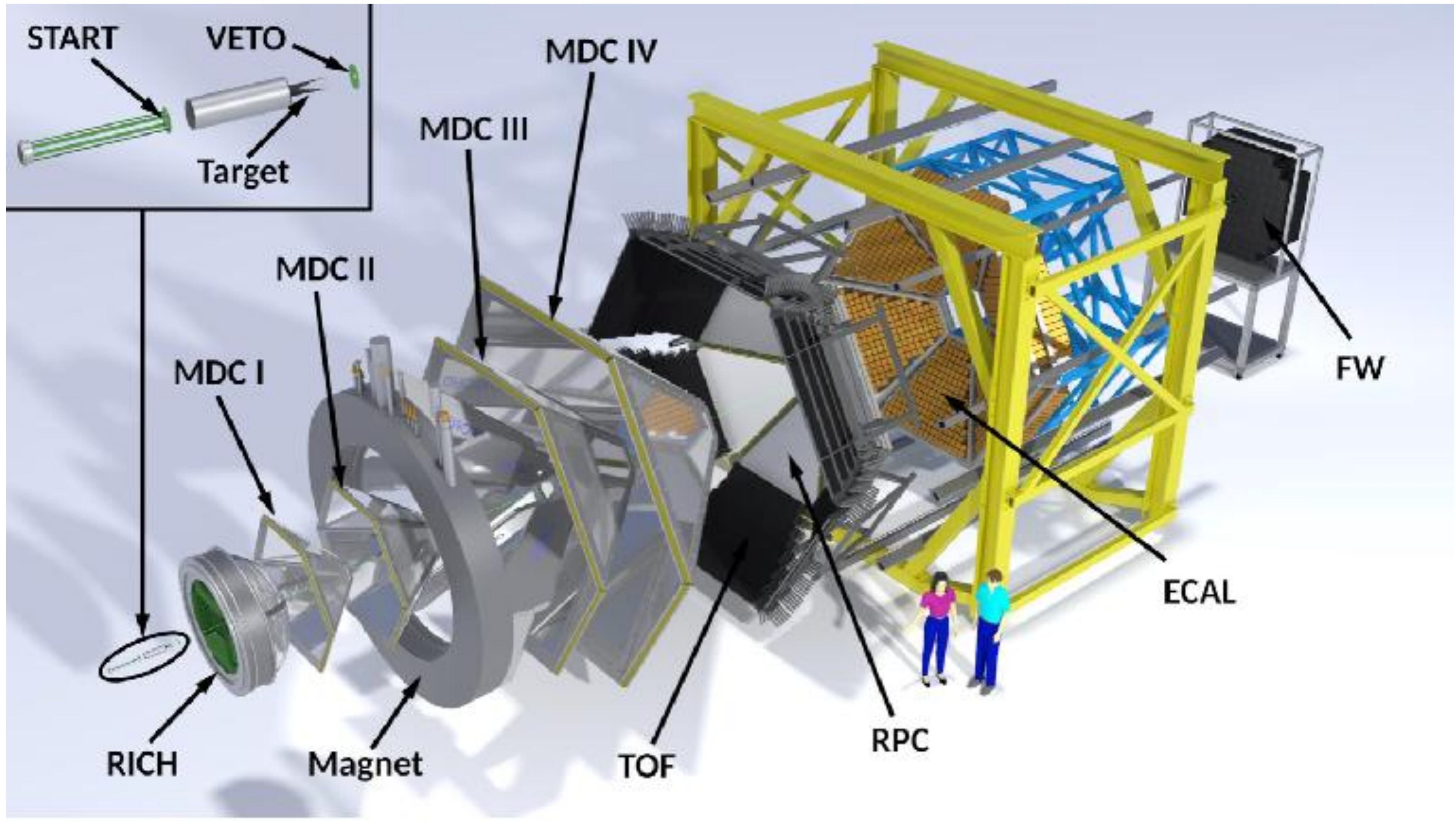
Physics at HADES

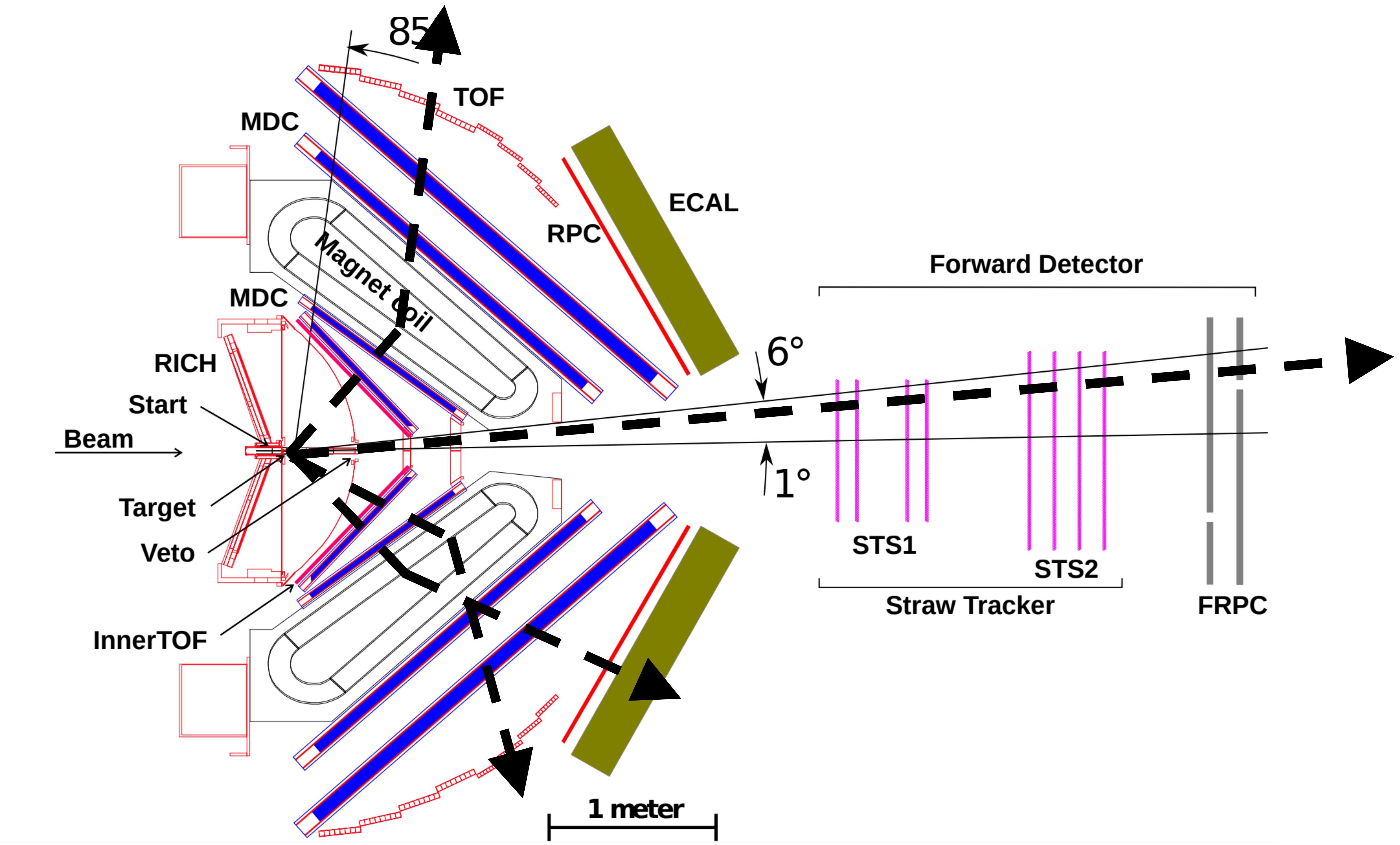
FAIR phase-0 experiment

- Heavy nuclei collisions
- Dilepton inclusive studies
- Flow dynamics
- <u>Hadron physics with hadron beams</u>
- ...



HADES Detector





- Fixed target
- Heavy ion, $\boldsymbol{p} + \boldsymbol{p}$, $\pi + p$, $d + p$
- Good momentum resolution, acceptance, PID
- RICH for electron identification
- Track, Q, $\vec{p}$, $\mathrm{d}E/\mathrm{d}x$ in drift chambers (MDC)
- β from Start and TOF/RPC

$\Lambda(1405)$ Study at HADES

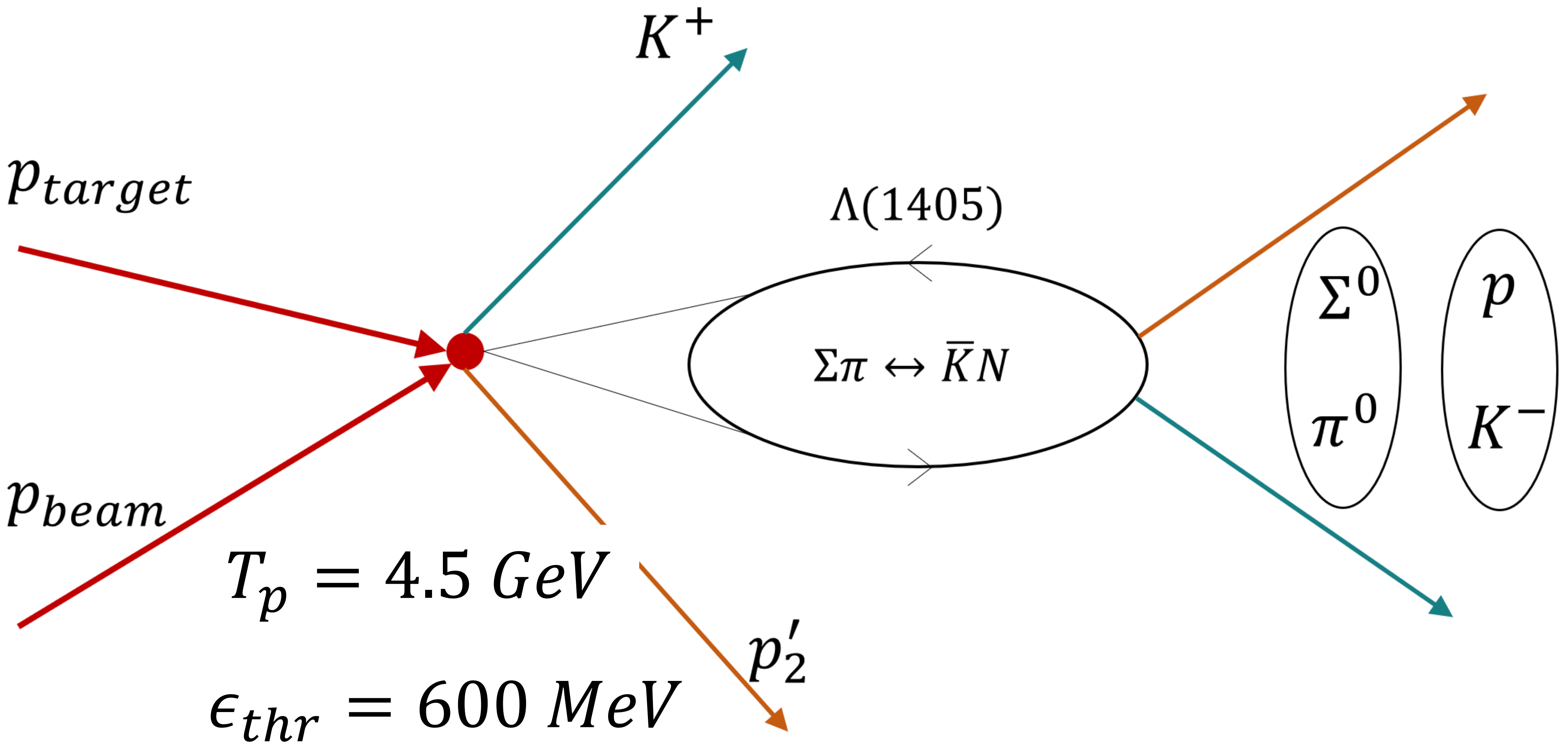
- Strangeness production in a non-strange system

- Nature of the $\Lambda(1405)$:

- Not yet fully established experimentally

- Two-pole structure emerging from coupled meson-baryon interactions?

Can HADES data be described consistently within this picture?

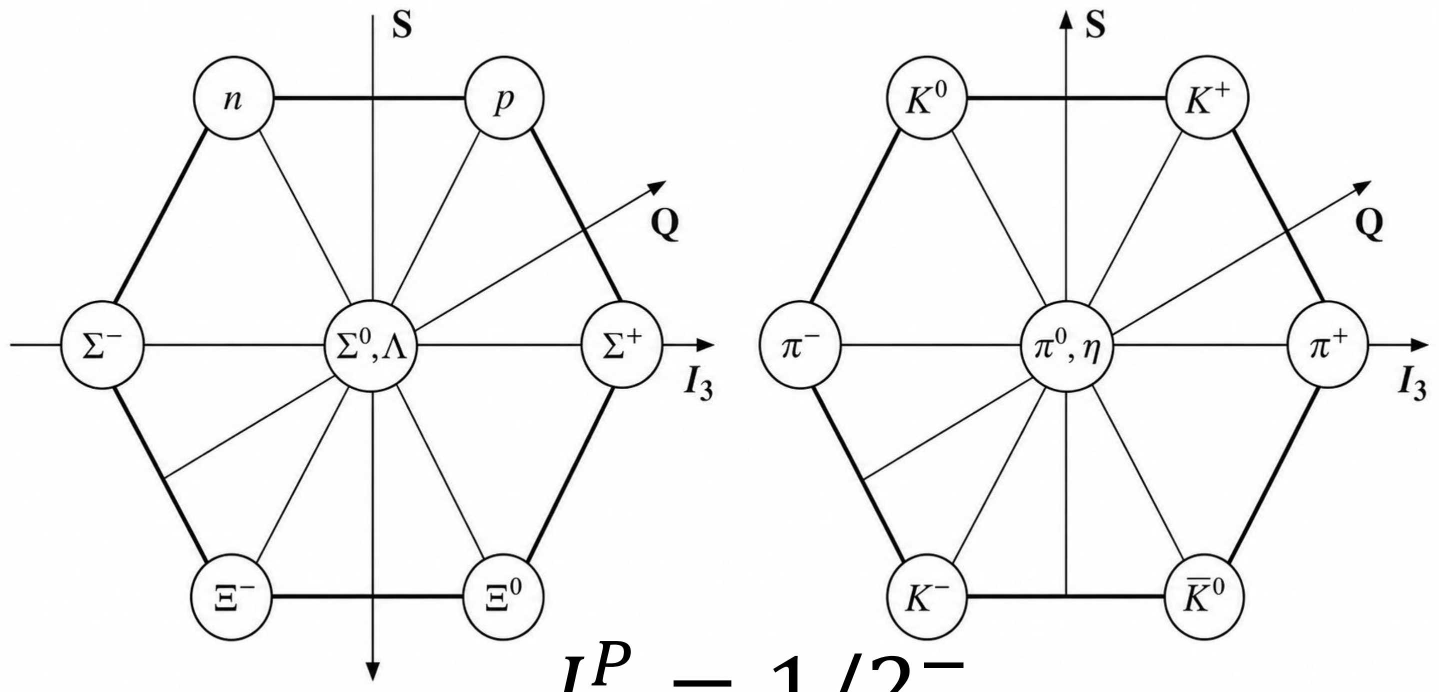


$\boldsymbol{pp \rightarrow pK^+[pK^-]}$ ⟵ I = 0, 1

$\boldsymbol{pp \rightarrow pK^+[\Sigma^0\pi^0]}$ ⟵ I = 0, (2) “golden channel”

$pp \rightarrow pK^+[\Sigma^\pm\pi^\mp]$ ⟵ I = 0, 1, 2

$pp \rightarrow pK^+[n\bar{K}^0]$ ⟵ I = 0, 1



$J^P = 1/2^-$

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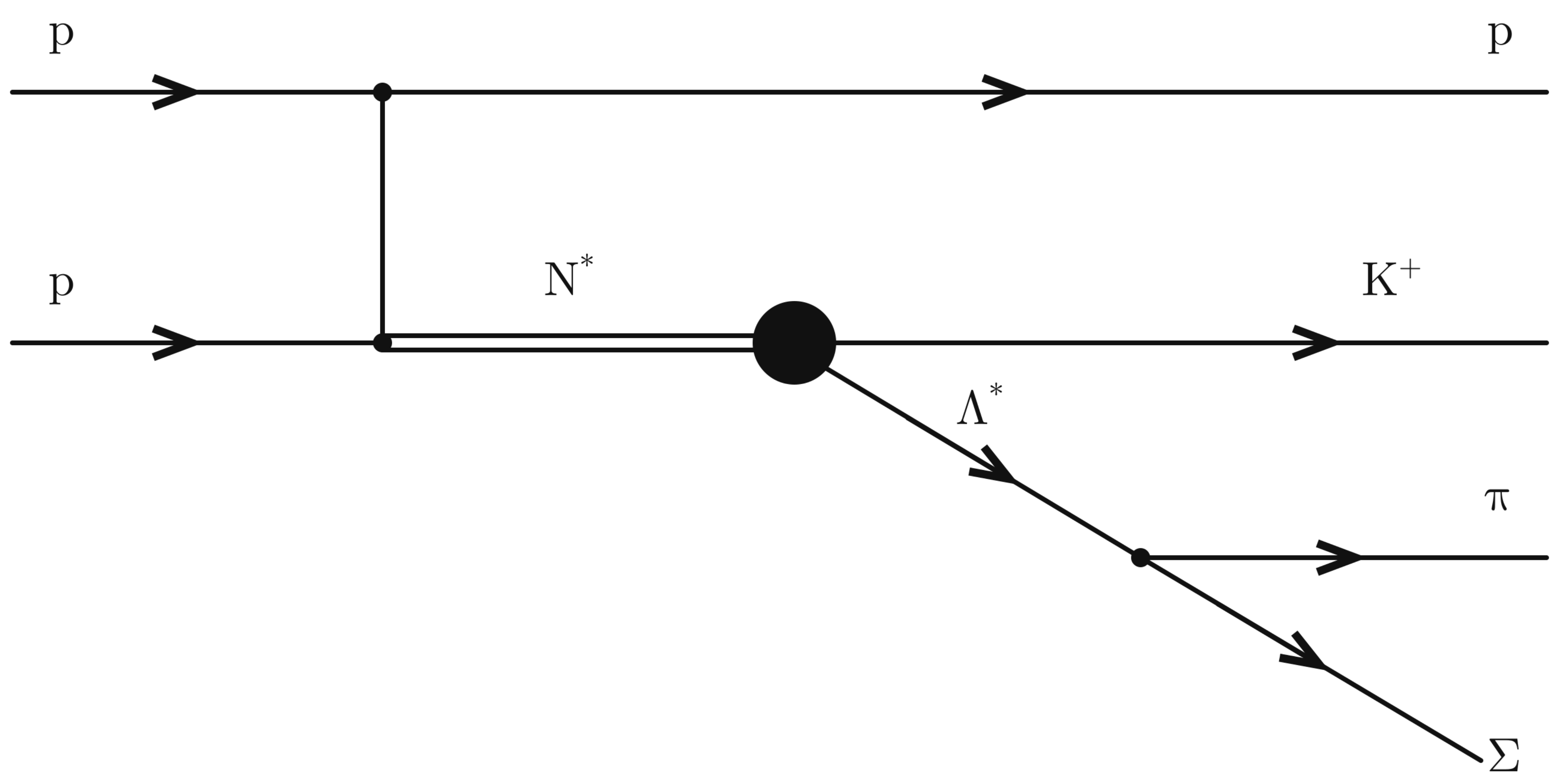

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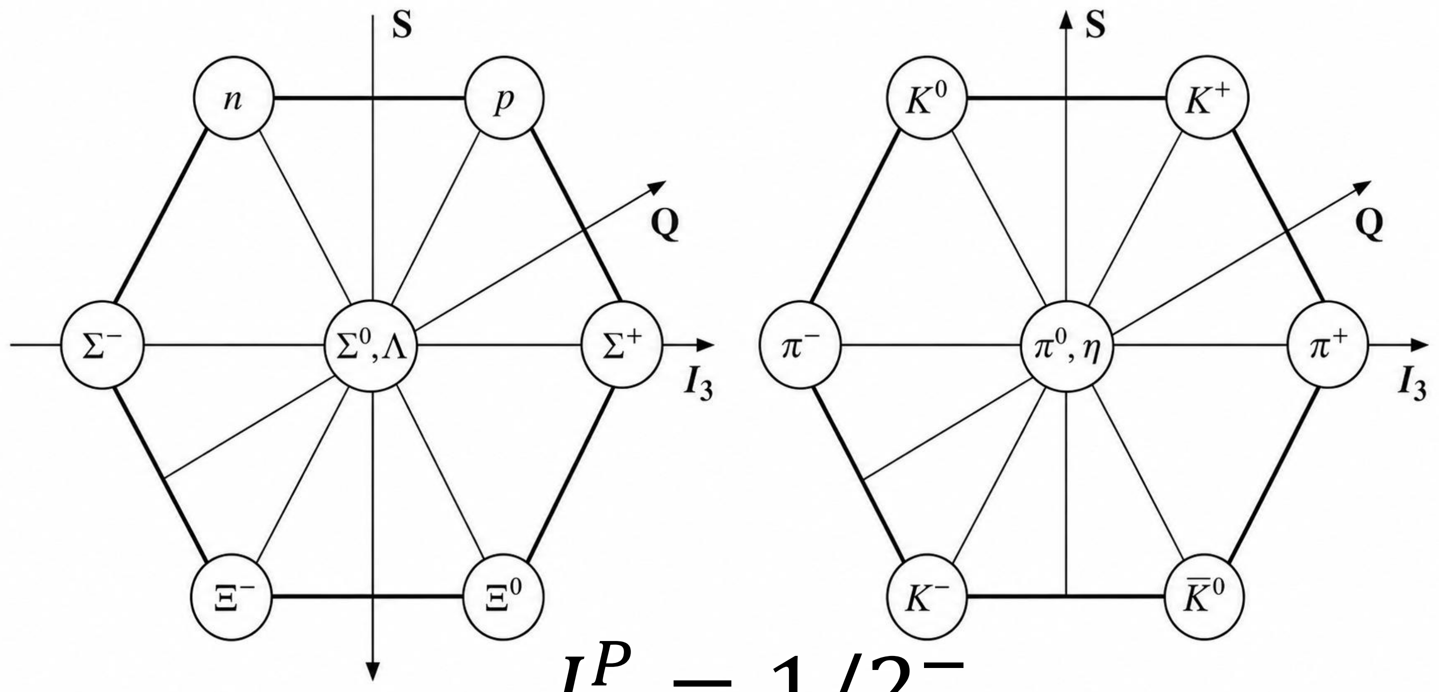
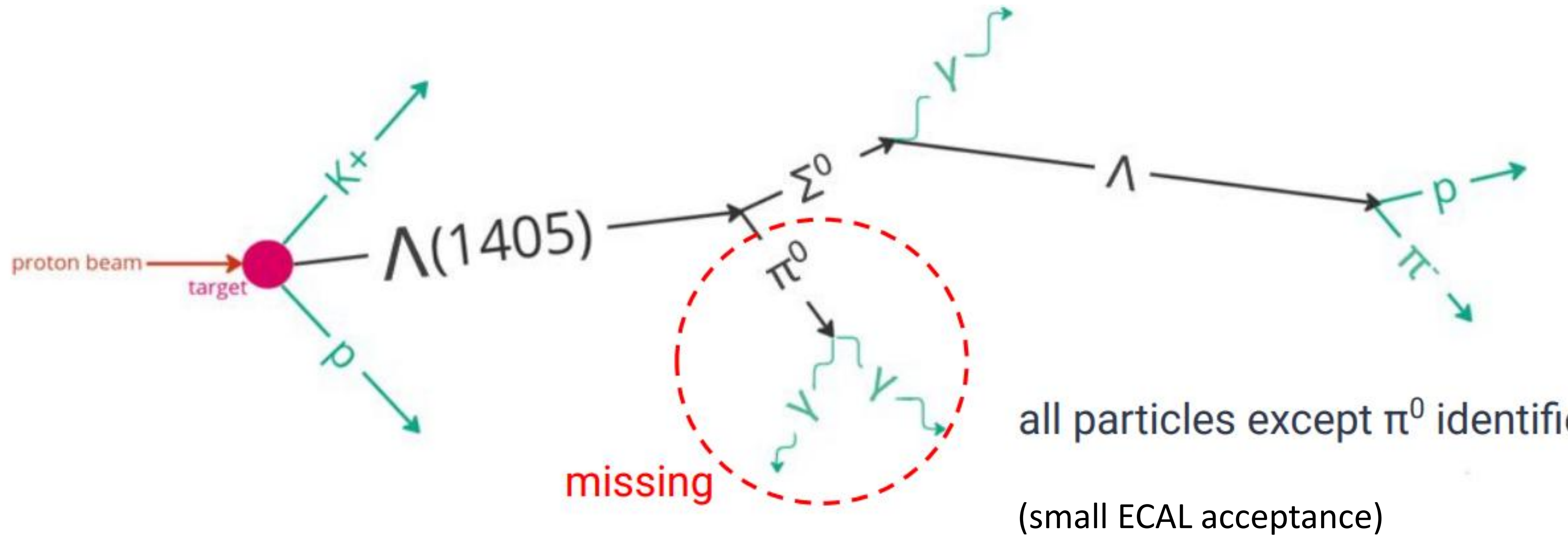


$J^P = 1/2^-$

Event Selection $\boldsymbol{\Sigma\pi}$

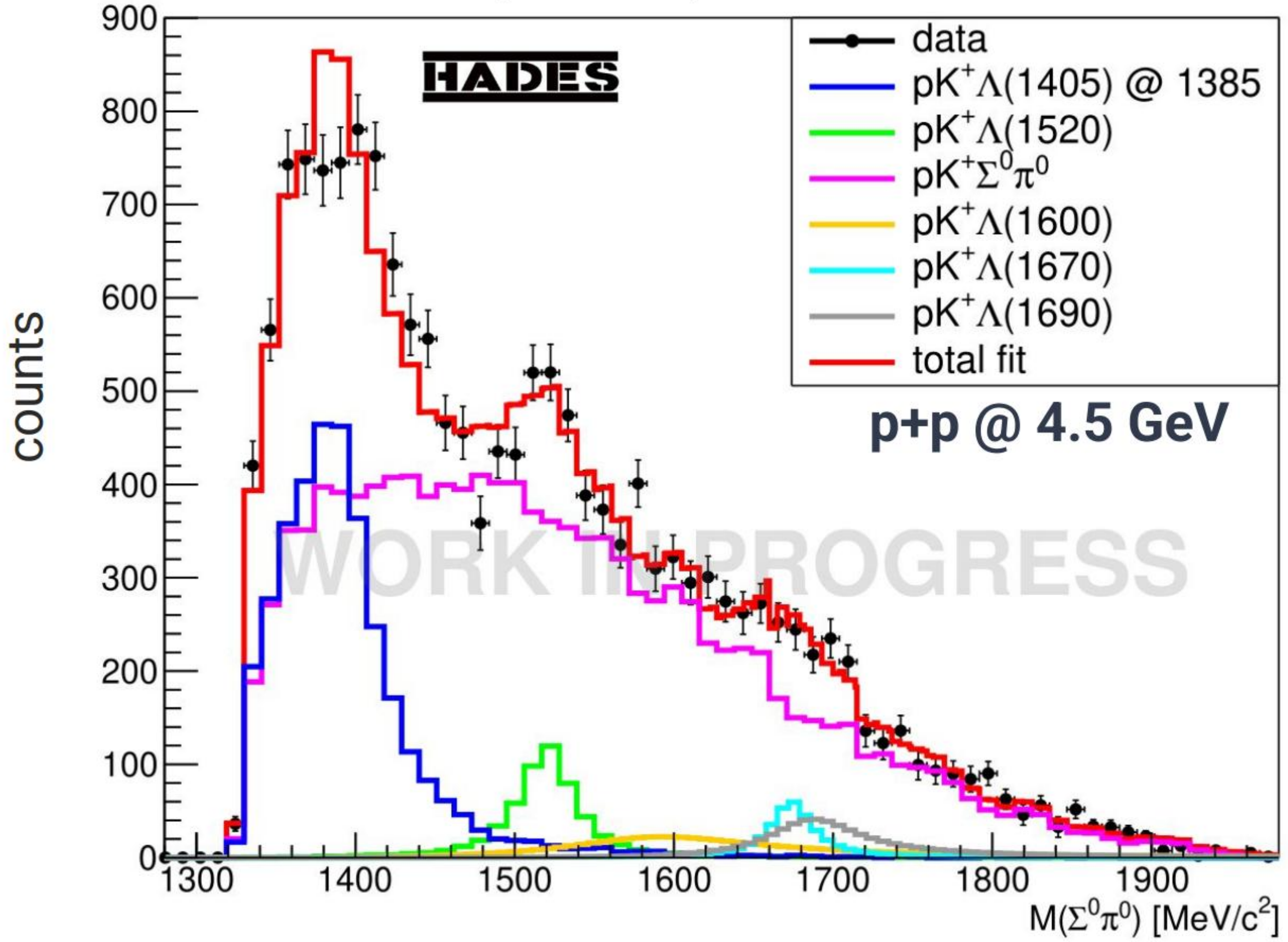


all particles except π^0 identified → 1C fit applied

(small ECAL acceptance)

1. Broad PID cuts
2. Topology cuts for Λ selection
3. Kinematic refit cuts for missing π^0 and $\Sigma^0 \rightarrow \gamma\Lambda$ mass
4. Missing π^0 mass sideband subtraction

Resulting spectrum

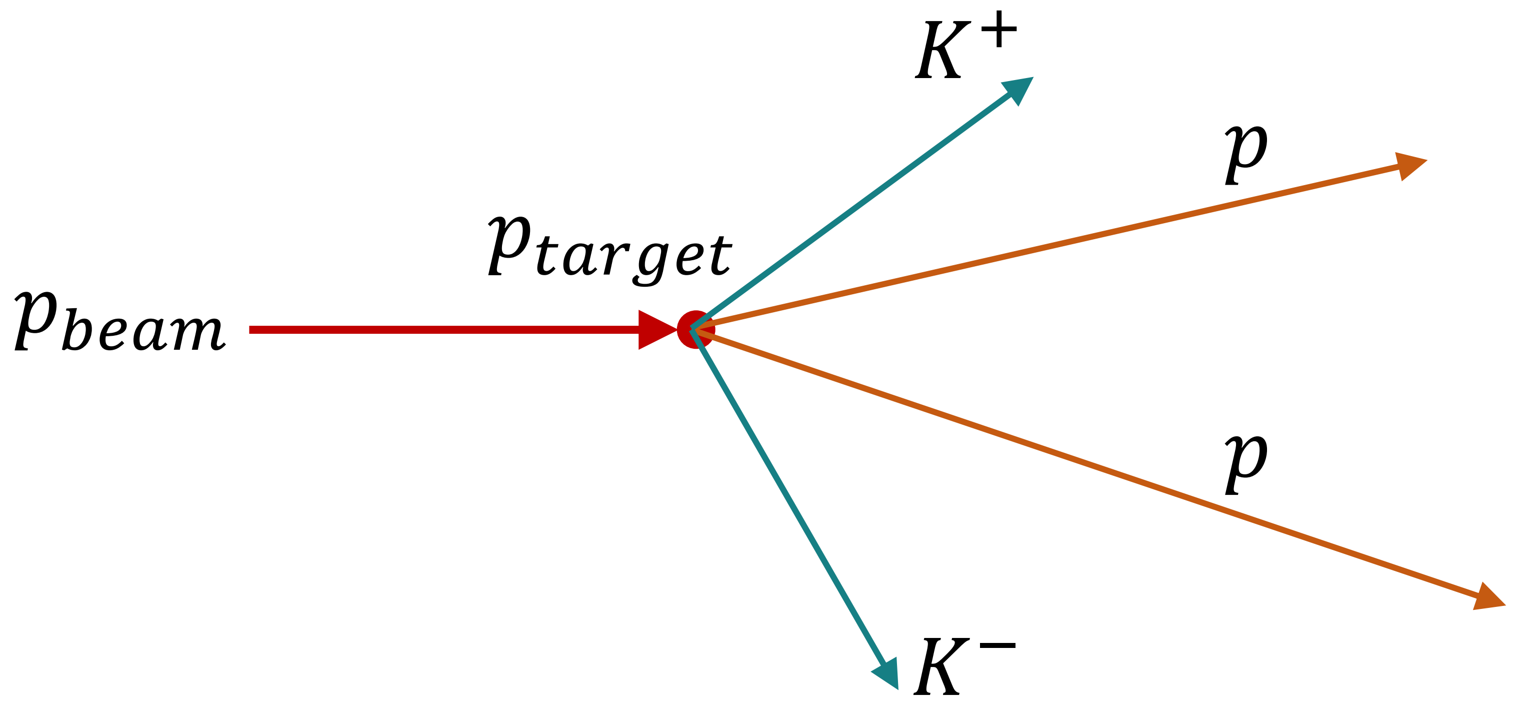


✓ $M_{\Sigma\pi}$ obtained with sideband subtraction

*$\Sigma\pi$ analysis done by Anna Władyszewska, presented on Wednesday, session B

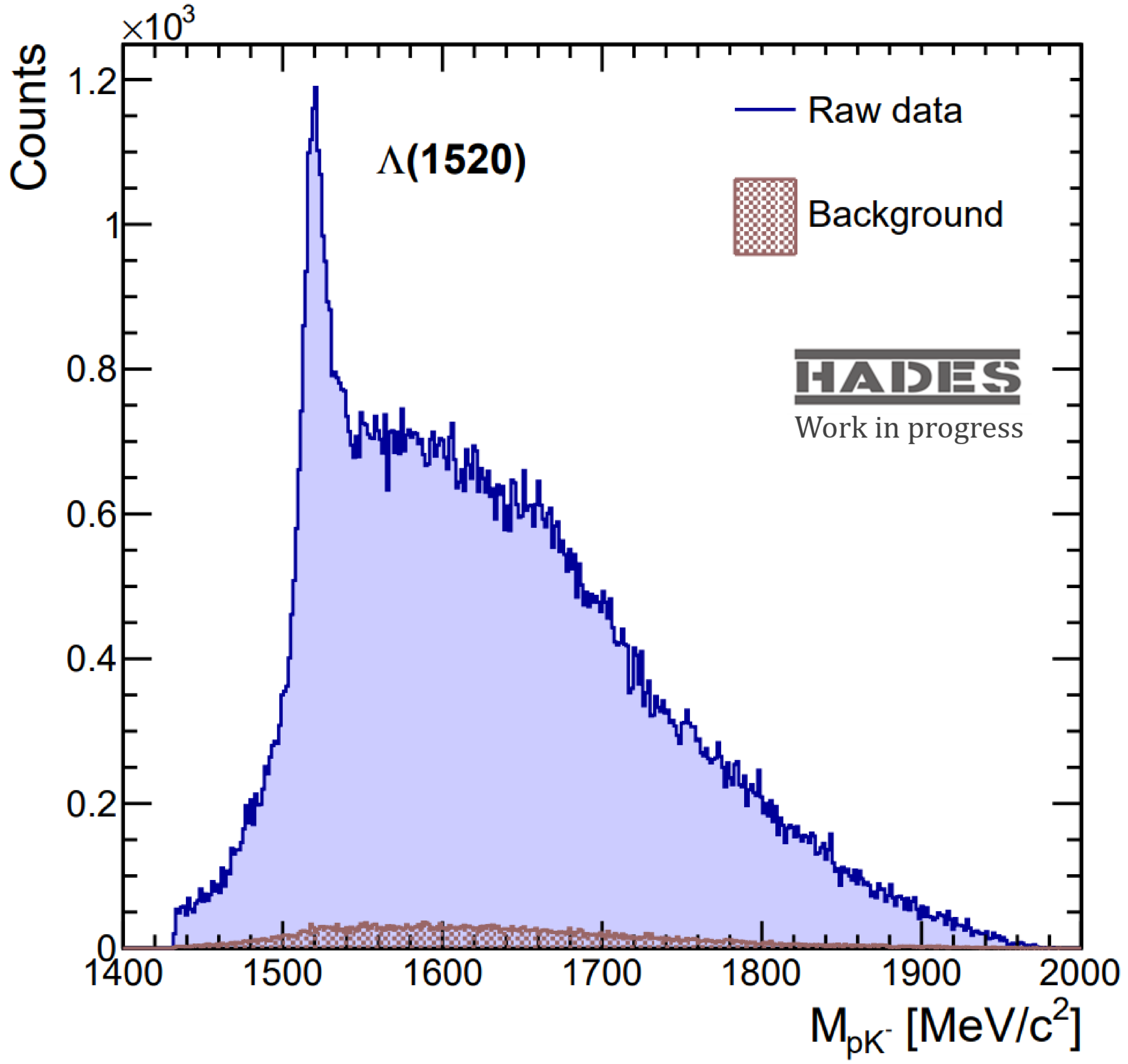
KinFit: Comput. Softw Big Sci 8, 3 (2024)

Event Selection pK



All particle identified → 4C fit applied

1. ML-based PID cuts for $\pi^\pm, K^\pm, p$ classification
2. 4C kinematic refit in different mass hypotheses

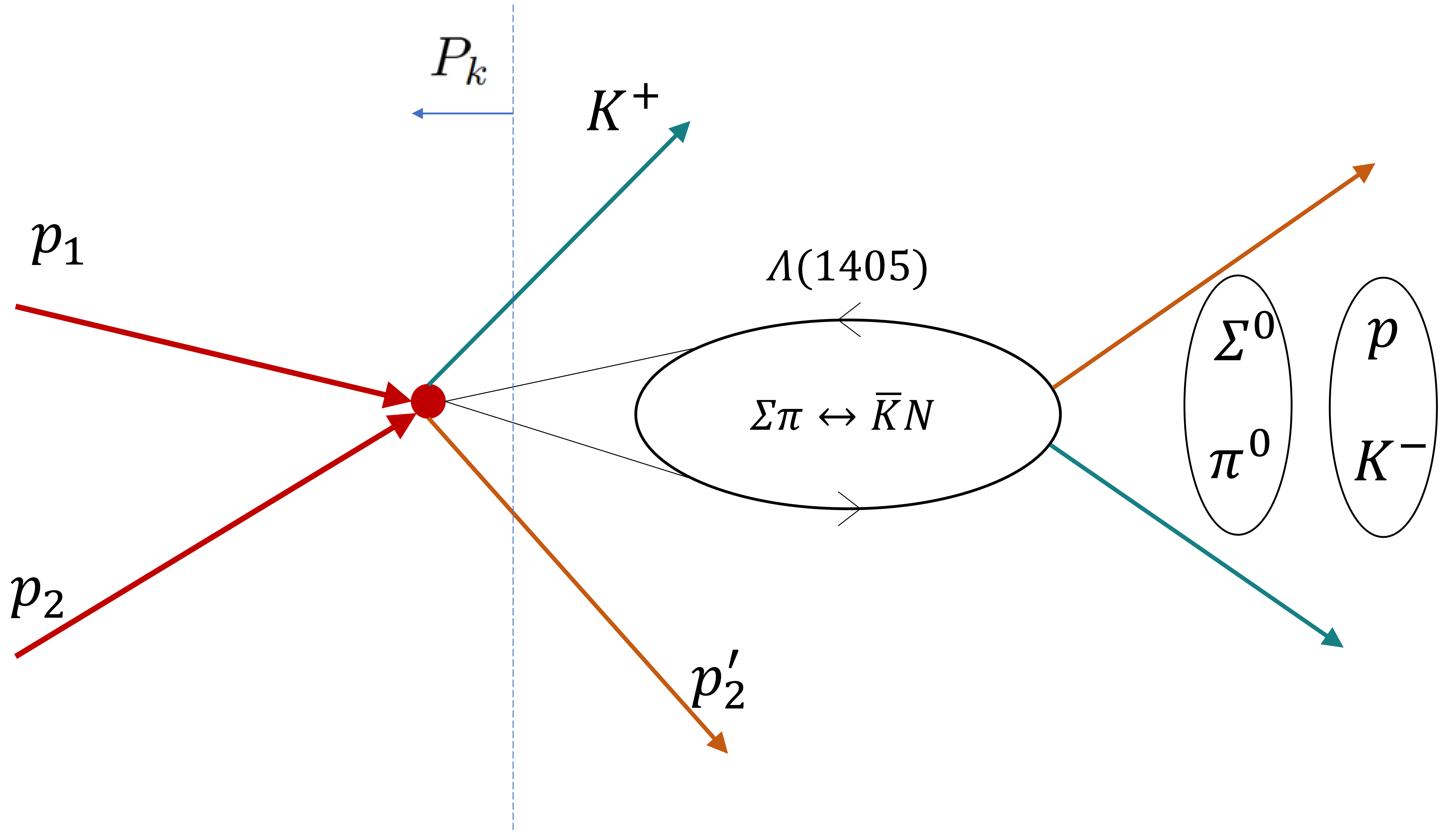


✓ $S/B \sim 30$ Clean dataset

✓ pK^- channel events as "pure" sample

KinFit: Comput. Softw Big Sci 8, 3 (2024)

Coupled Channels Analysis in K-Matrix Formalism



$$A(s) = [I - K(s)C(s)]^{-1}\,P(s)$$

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

$$P_k(s) = \sum_R \frac{g_{R,k}\,\beta_R}{m_R^2 - s}$$

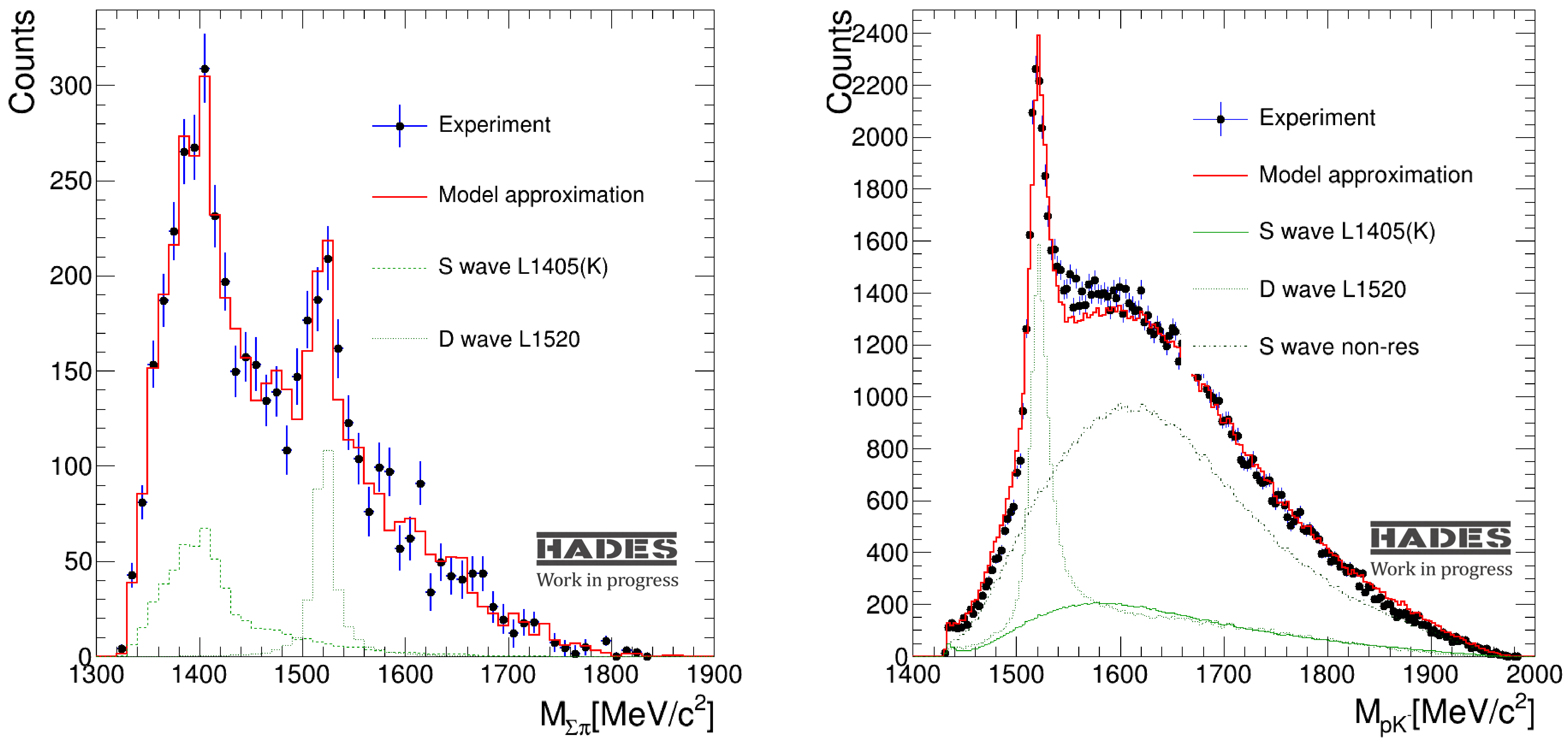
Two-pole description of $\Lambda(1405)$:

Dynamically generated $\Sigma\pi - \bar{K}N$ state?

(Poles of the amplitude)

- $J^p = \frac{1}{2}^-$, S wave
- $I = 0$ for $\Sigma\pi$; $I = 0|1$ for pK – incoherent terms
- 2 channels, 2x2 matrices

Raw Data Approximations

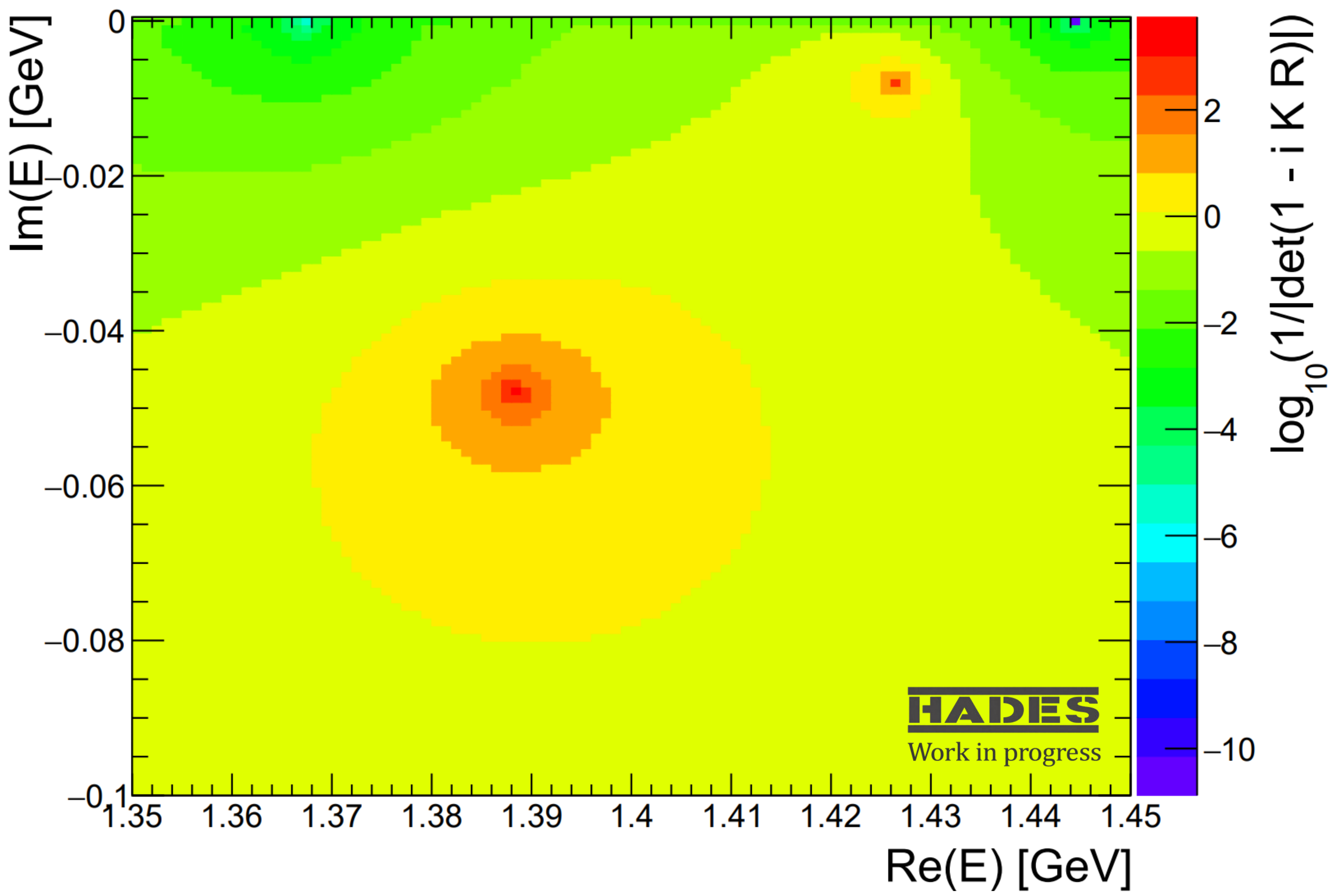


- Unbinned maximum likelihood fit
- Cross-channels included (e.g. $\phi \to KK$)
- Both final states fit simultaneously

✓ Fit consistent with two-pole K-matrix description

- $I_{pK} = \underbrace{f(s)}_{\text{non-res}} + \underbrace{c_1|((I-KC)^{-1}P)_1|^2}_{\Lambda(1405)} + \underbrace{|C^{\Sigma\pi}_{\Lambda(1520)}BW_{\Lambda(1520)}|2}_{\Lambda(1520)}$
- $I_{\Sigma\pi} = |1 + c_2((I-KC)^{-1}P)_2|^2 + |C^{pK}_{\Lambda(1520)}BW_{\Lambda(1520)}|2$

Raw Data Approximations

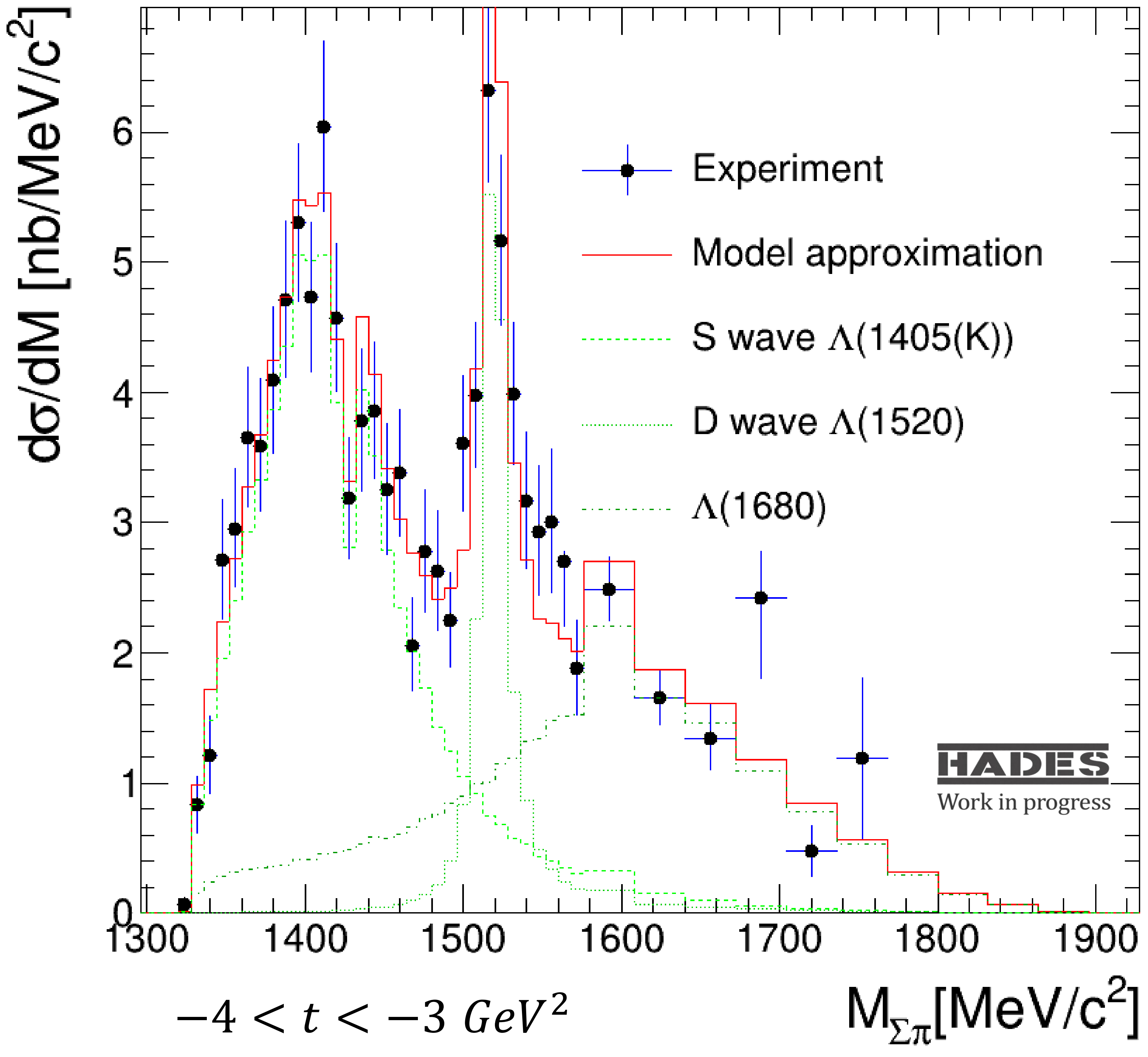


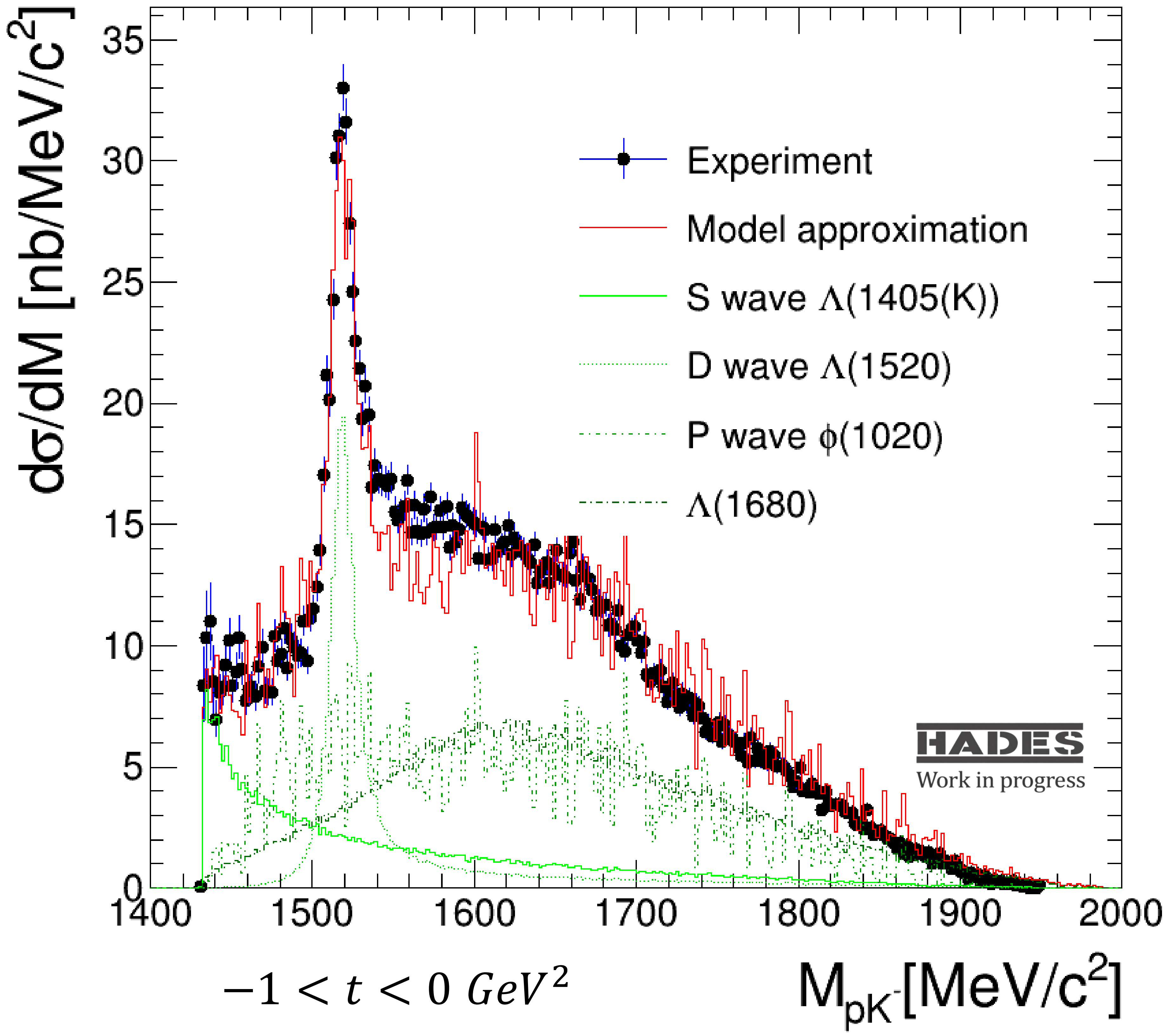
- Pole search with a 2D Newton's method
- $\det[I - K(s)C(s)] = 0$
- On unphysical Riemann sheets
- With Chew-Mandelstam analytic continuation

✓ Fit consistent with two-pole K-matrix description

- $I_{pK} = \underbrace{f(s)}_{\text{non-res}} + \underbrace{c_1|((I - KC)^{-1}P)_1|^2}_{\Lambda(1405)} + \underbrace{|C^{\Sigma\pi}_{\Lambda(1520)} BW_{\Lambda(1520)}|2}_{\Lambda(1520)}$
- $I_{\Sigma\pi} = |1 + c_2((I - KC)^{-1}P)_2|^2 + |C^{pK}_{\Lambda(1520)} BW_{\Lambda(1520)}|2$

Different Fit Example





- Approximating data differentially
- With different models and data types

Pole Positions and Theory

Pole positions, *Recent theory predictions (2000+) →

Not directly comparable (calculations vs parameterization)

$$\sqrt{s_0^{(1)}} = [(1390 \pm 10) - i(55 \pm 10)]\ \mathrm{MeV}$$

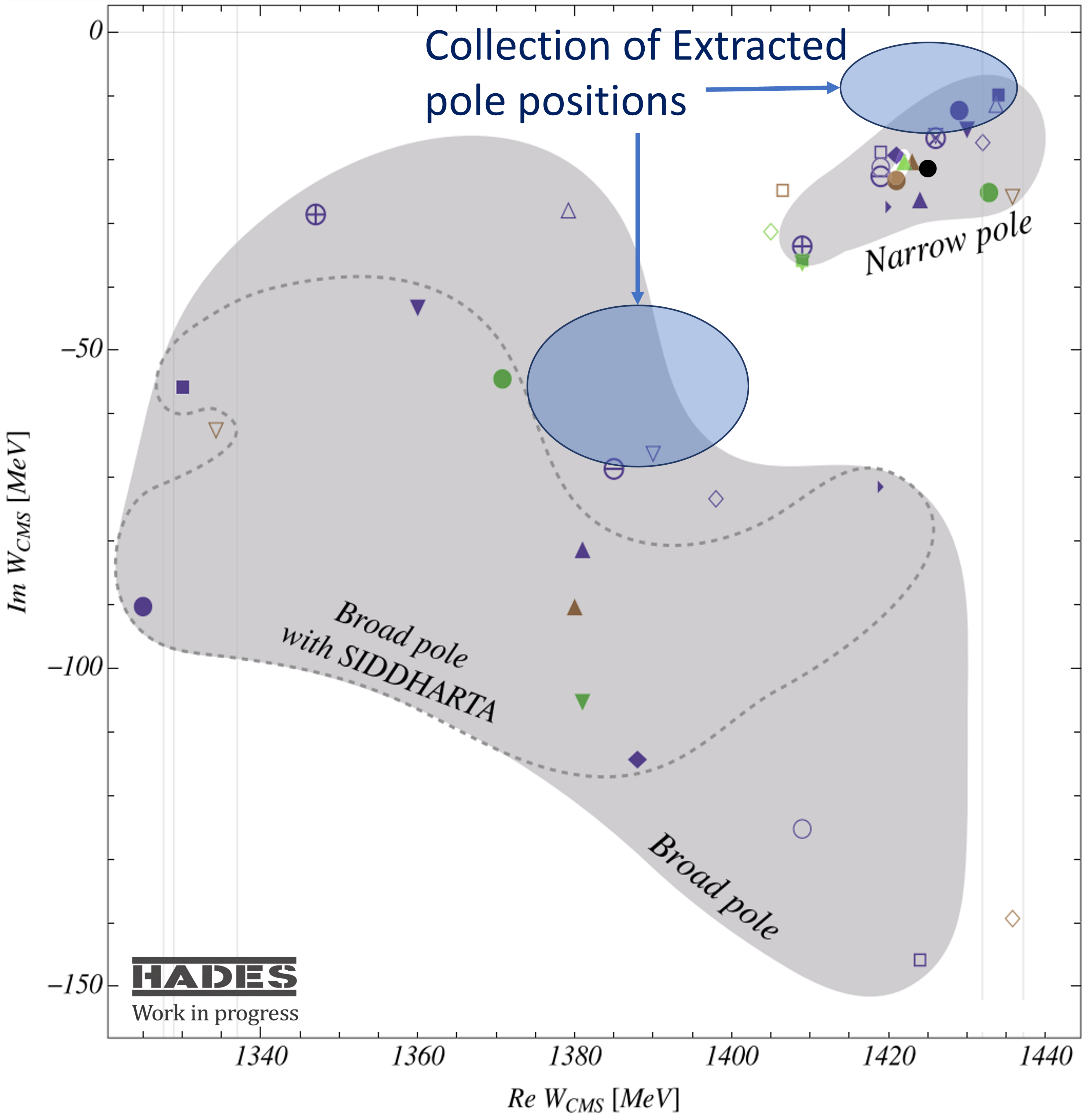
$$\sqrt{s_0^{(2)}} = [(1425 \pm 7) - i(8 \pm 5)]\ \mathrm{MeV}$$

Uncertainties estimated from ~50 fits, varying:

- Base amplitude details
- Production vector
- Fit procedure
- Raw / efficiency corrected data

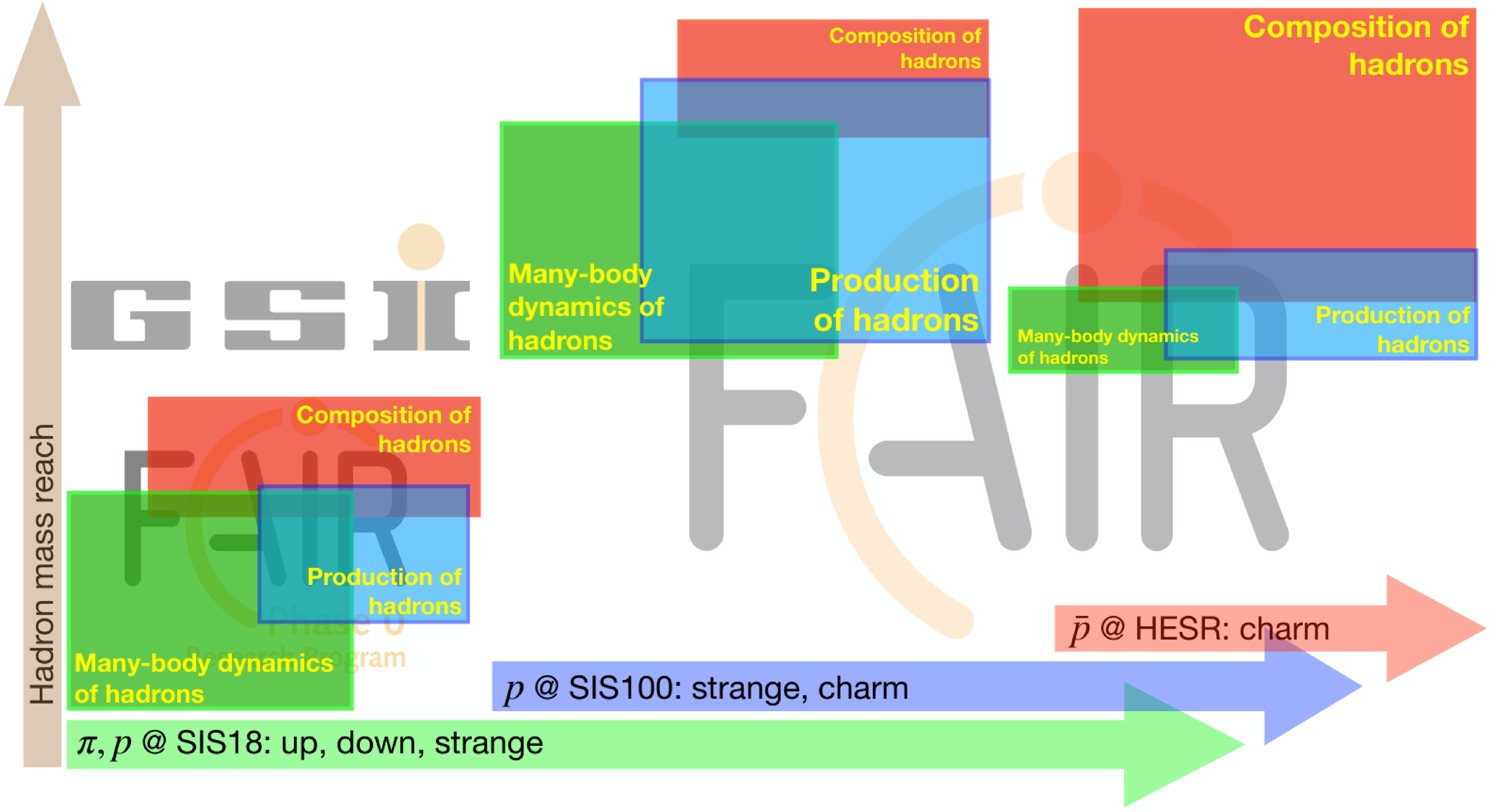
Compared to no $\Lambda(1405)$

✓ Fit improvements, not yet exact structure-deterministic



*Mai, M. Eur. Phys. J. Spec. Top. 230, 1593–1607 (2021)

Future Perspectives



QCD at FAIR - Frank Nerling, Friday 09:30

- π - beam program at HADES:
  - → 2 or 3 body final states
  - → PW decomposition of the N* spectrum
  - → Cleaner $\Lambda(1405)$ study
- p - beam at CBM:
  - → Double strangeness and charm
- Unify existing datasets:
  - → HADES, BESIII, LHCb, J-PARC, INSIGHT, GlueX..

Hadron Physics Opportunities at FAIR: arXiv:2512.15986

Summary

- High-statistics clean datasets for both $\Sigma\pi$ and pK
- The data are well-described with two-bare-pole coupled channel *K*-matrix for $\Lambda(1405)$ contribution
- Two nearby amplitude poles found consistently

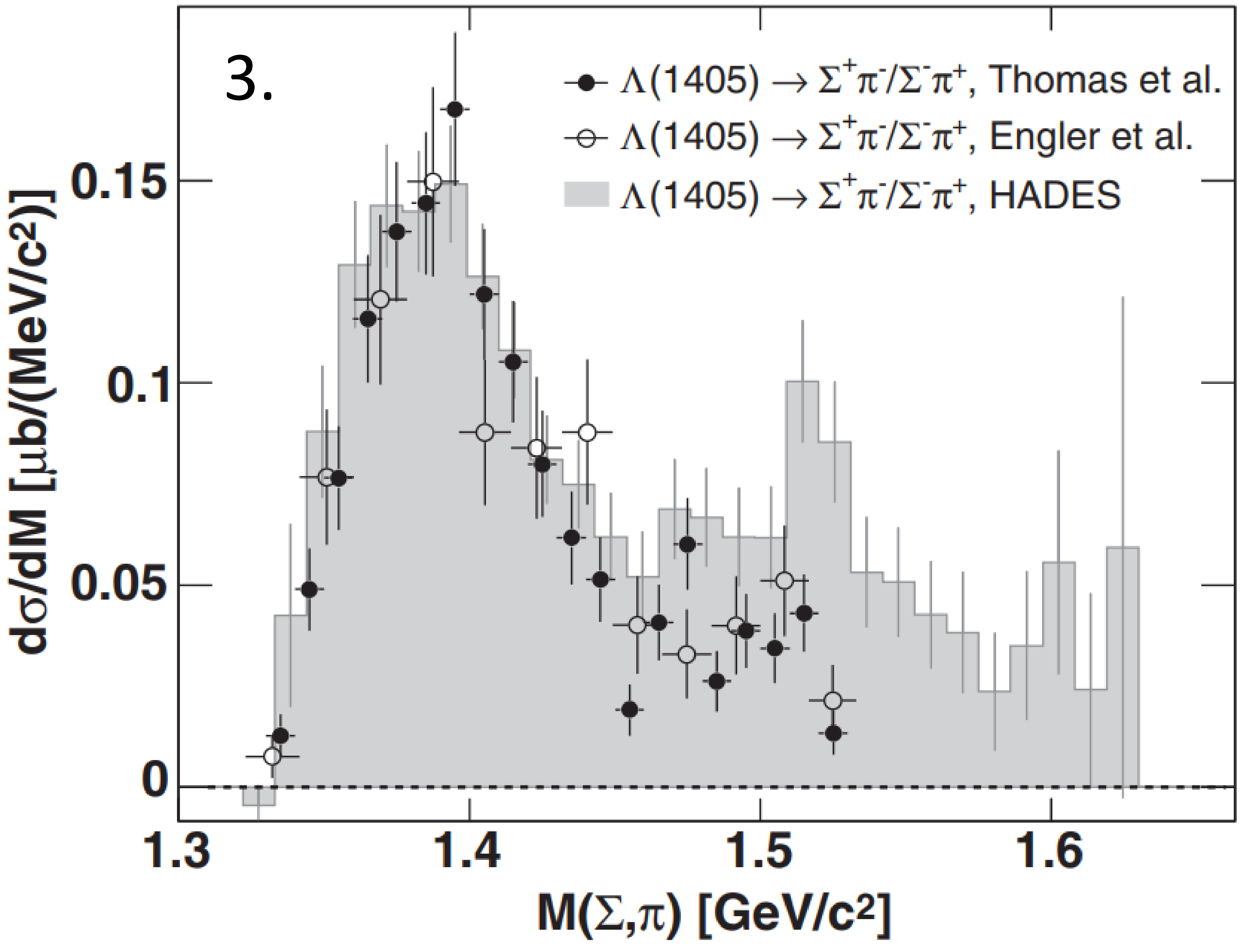
Questions to answer

- What specific $\Lambda(1405)$ hypotheses are preferrable?
- Can we constrain relative $\pi\Sigma/\bar{K}N$ couplings?
- How to compare with chiral unitary models?
- …

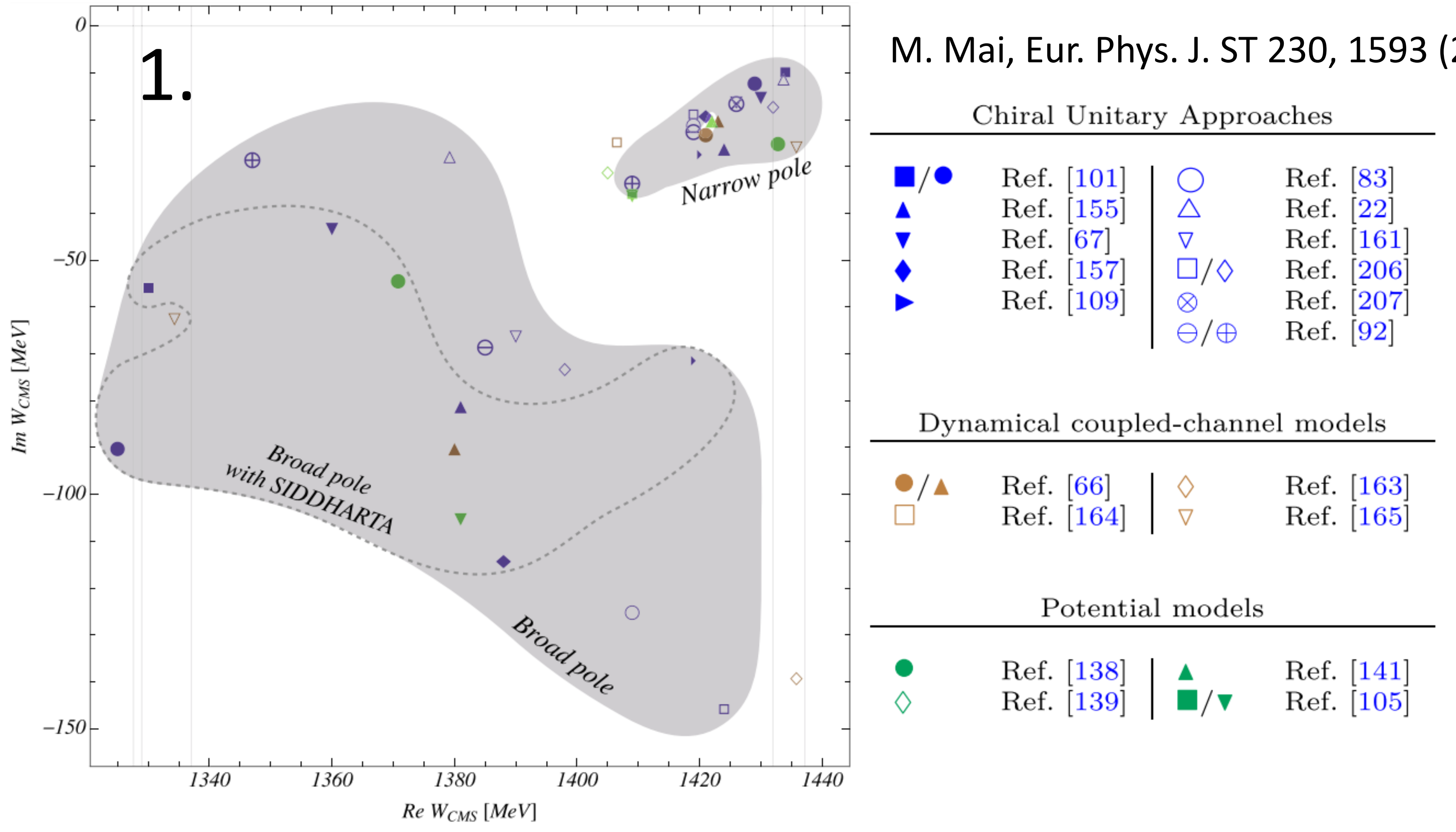
Backup

Previous Studies

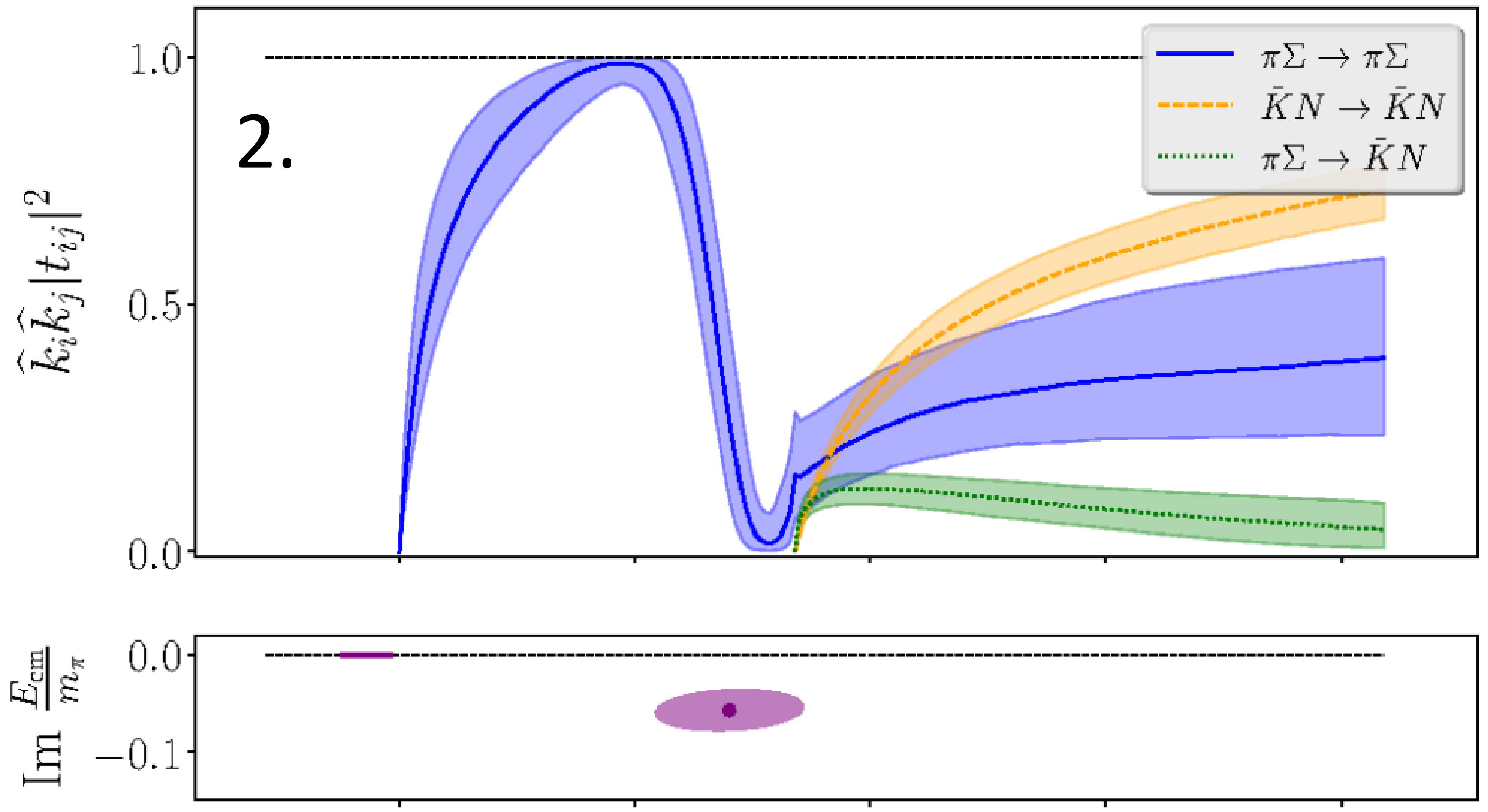
1. Effective field estimations
2. Lattice calculations
3. Previous HADES with 3.5 GeV beam



J. Siebenson and L. Fabbietti, Phys. Rev. C 88, 055201 (2013)



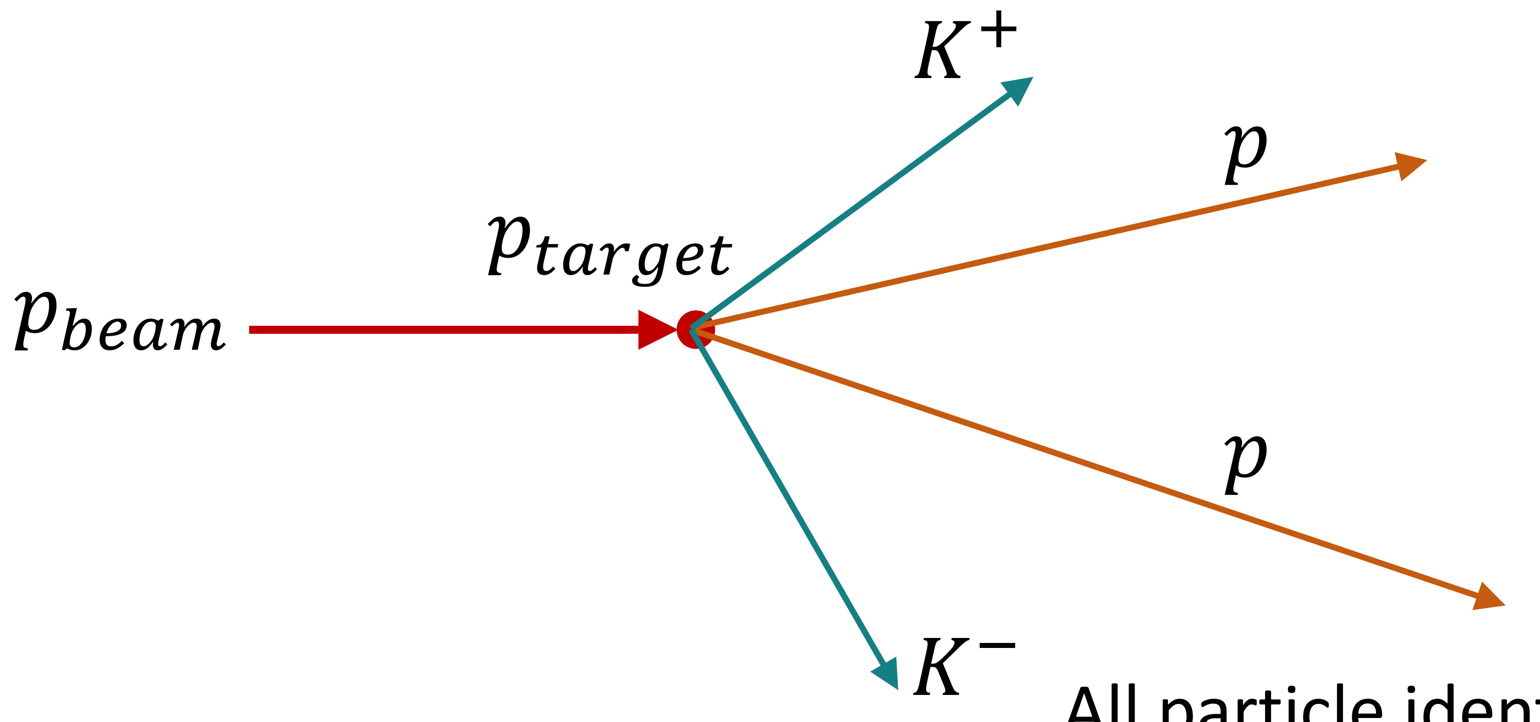
M. Mai, Eur. Phys. J. ST 230, 1593 (2021)



Bulava et al., arXiv:2307.13471 (2023)

$pp \to ppK^+K^-$

Background Estimation pK



All particle identified → 4C fit applied

1. ML-based PID cuts for $\pi^{\pm}, K^{\pm}, p$ classification

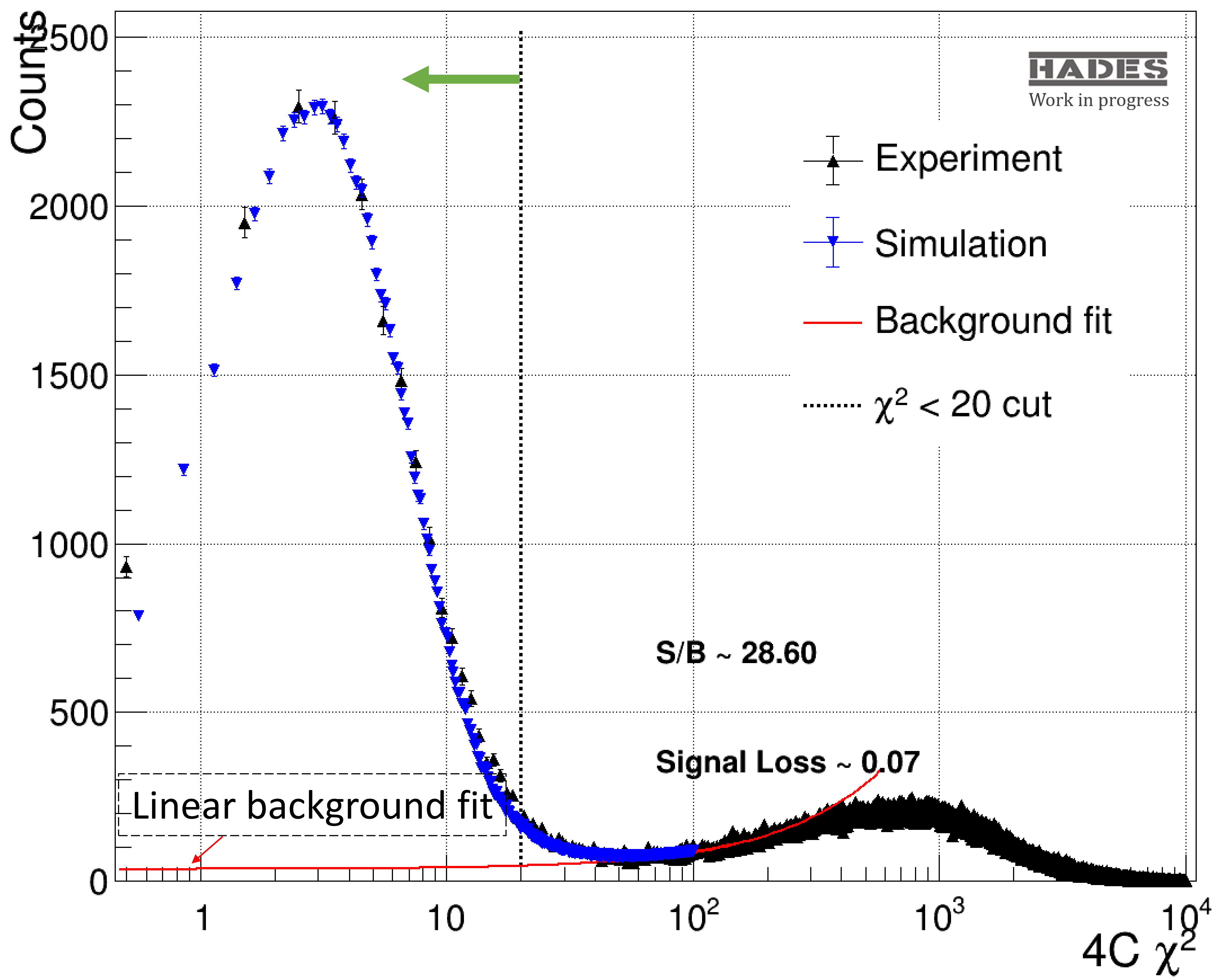
2. 4C kinematic refit in different mass hypotheses

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

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

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

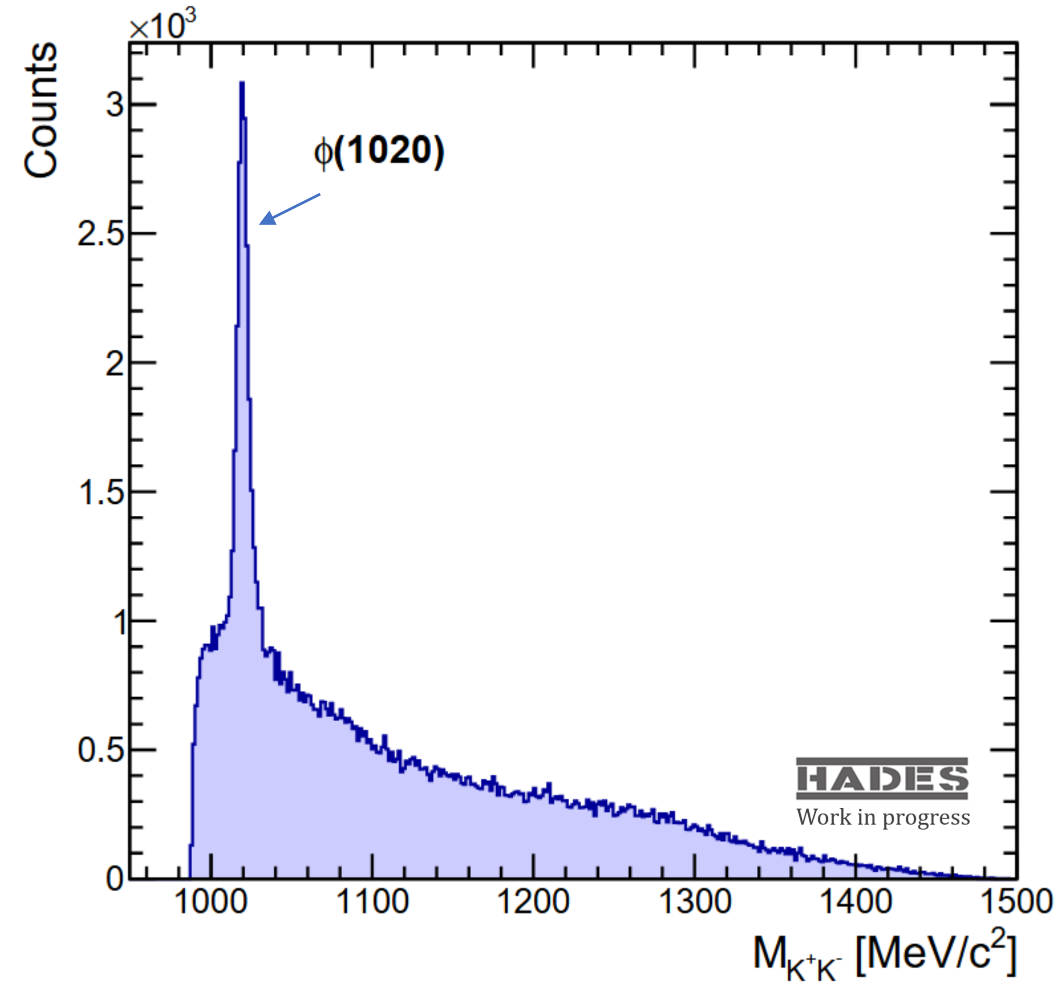
…

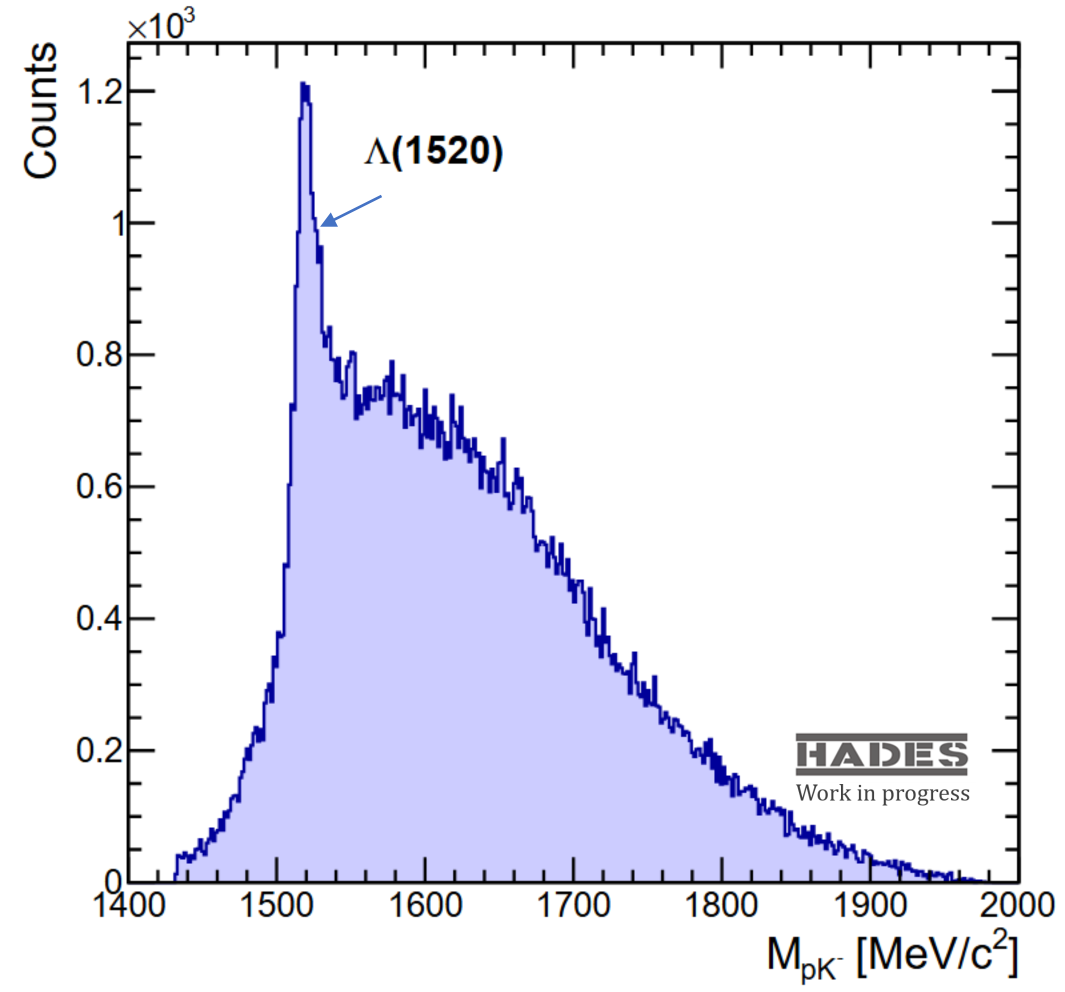


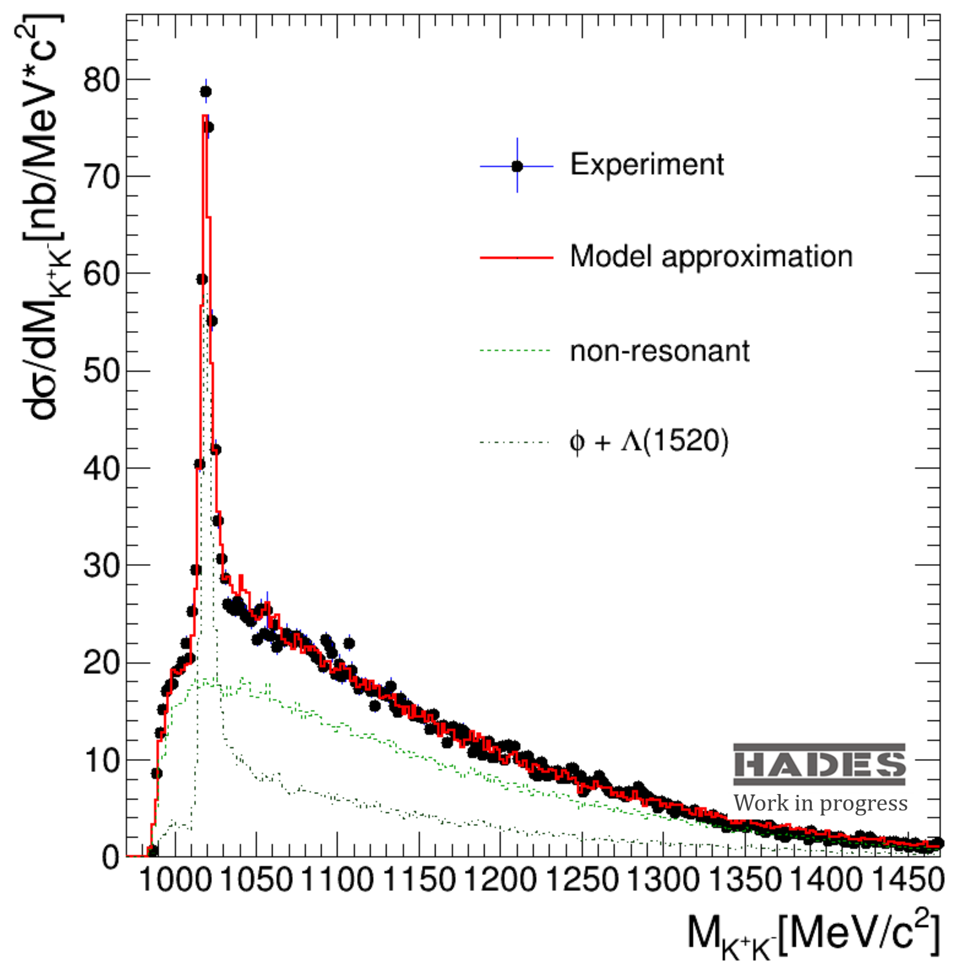
* Eur. Phys. J. A 50, 82 (2014), ** Phys. Lett. B 742, 242–248 (2015)

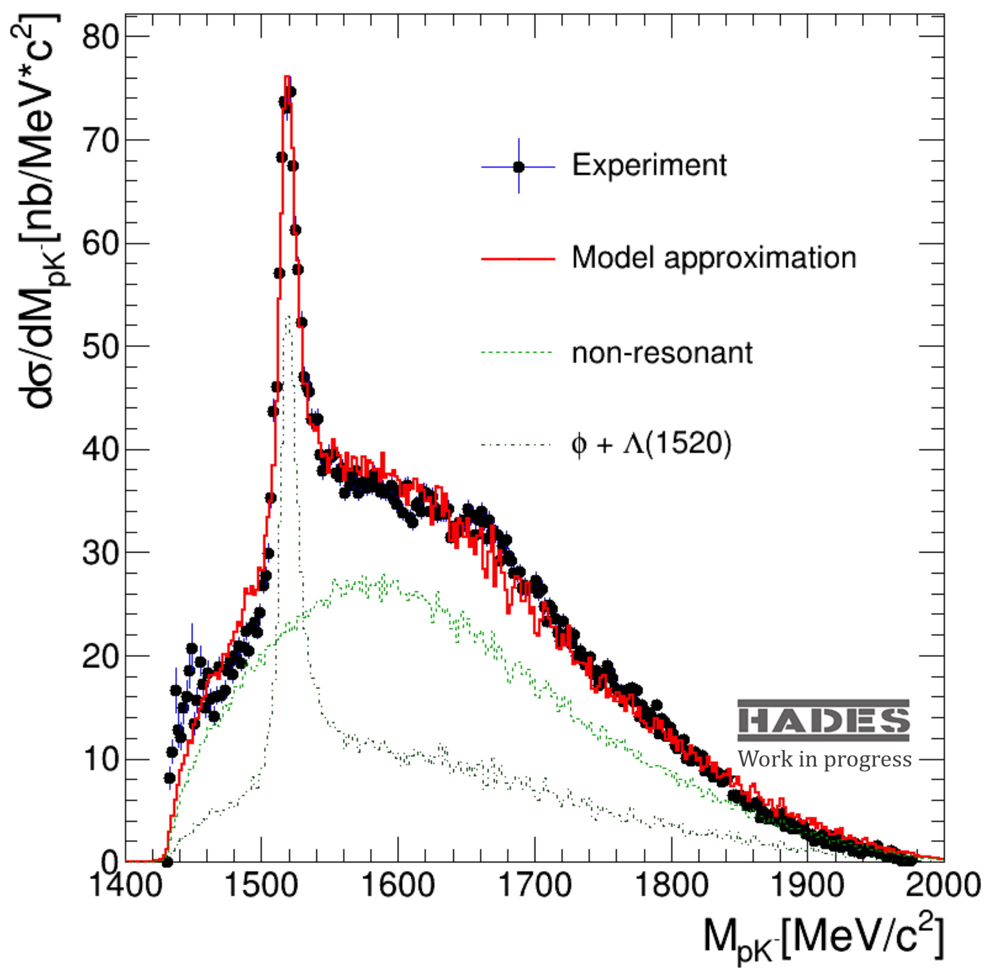
$pp \rightarrow ppK^+K^-$

Efficiency and Acceptance Correction









- *Method:*

  Bin-by-Bin

  Phase Space Simulation

- *Parametrization*:

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

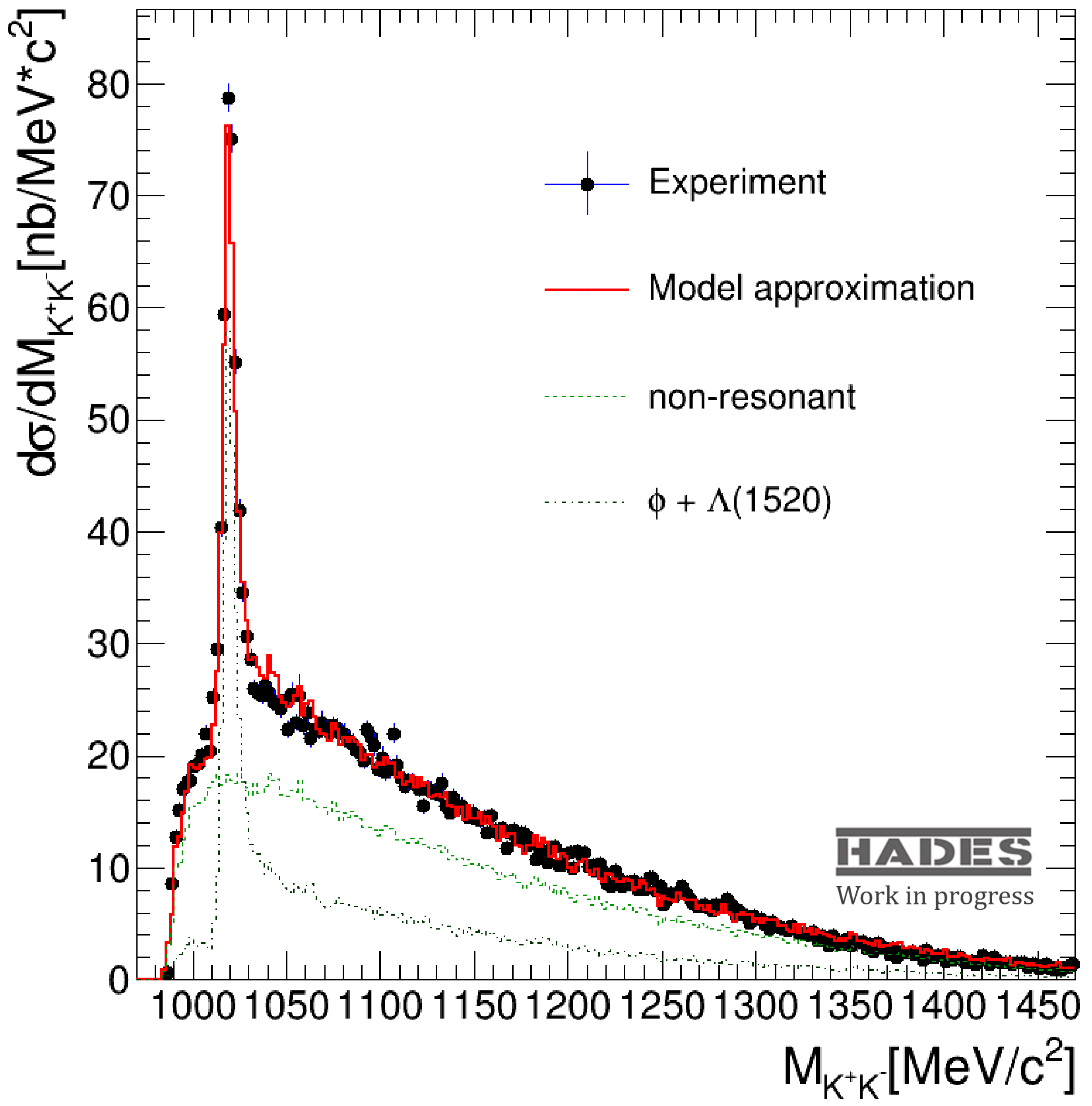
  $M(K^+K^-) + M(pK^-)$

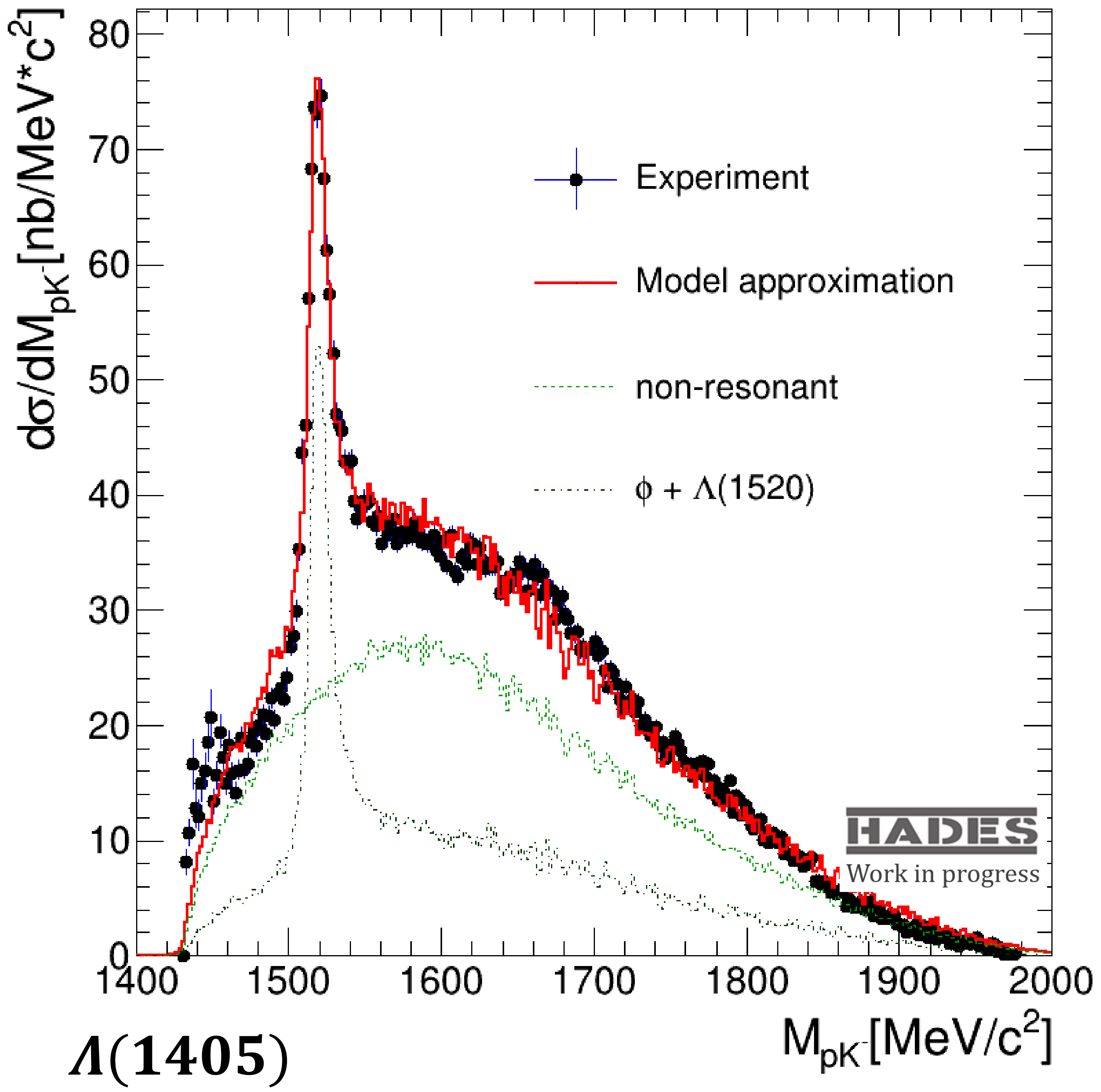
  $M(K^+K^-) + M(pK^-) + \theta^{GJ}_{\phi\rightarrow KK}$

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

- Eff.-corrected spectra are approximated by simple models → *total cross sections, SDMEs, resonance parameter values*

Breit-Wigner Amplitude Description





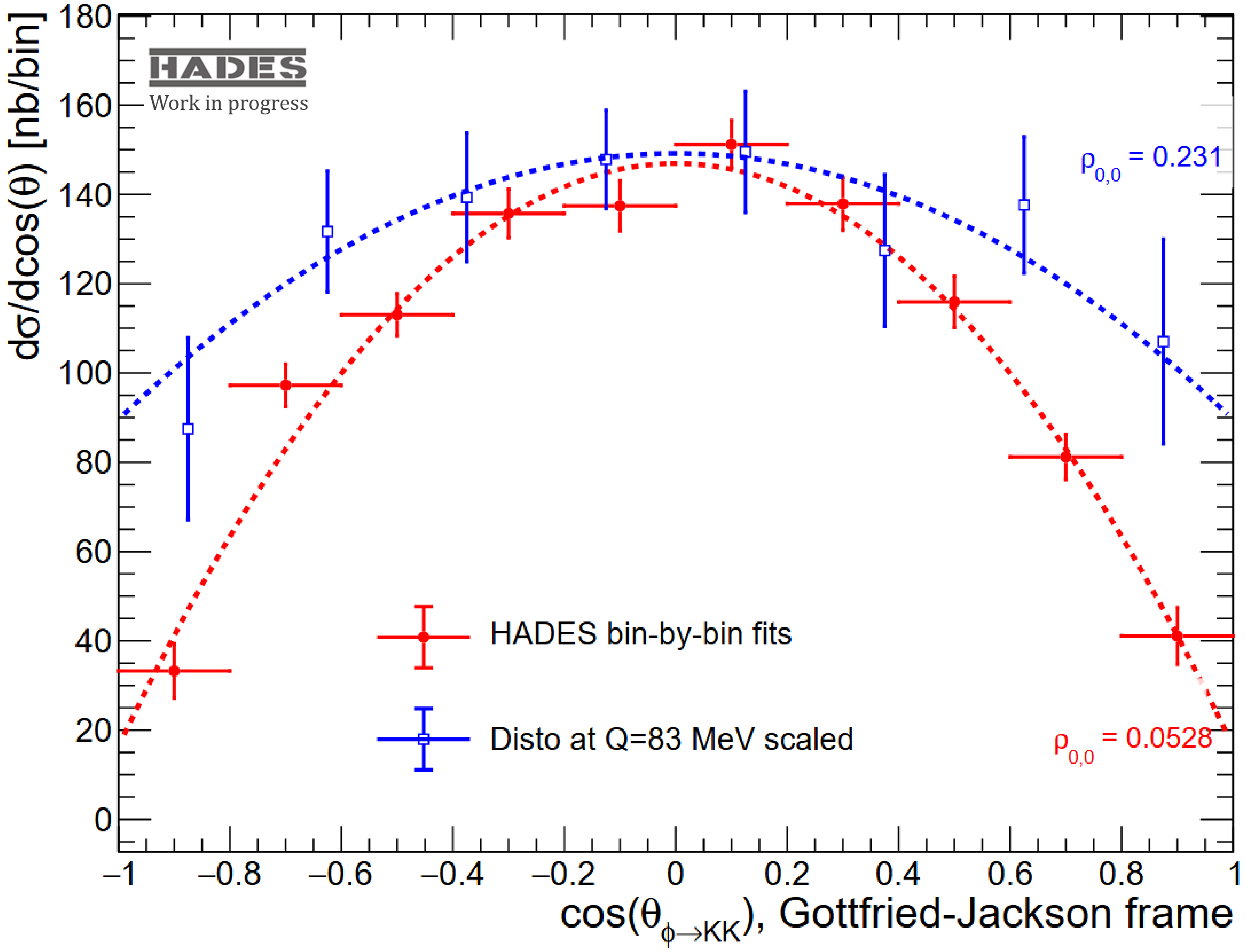
$\boldsymbol{\Lambda(1405)}$

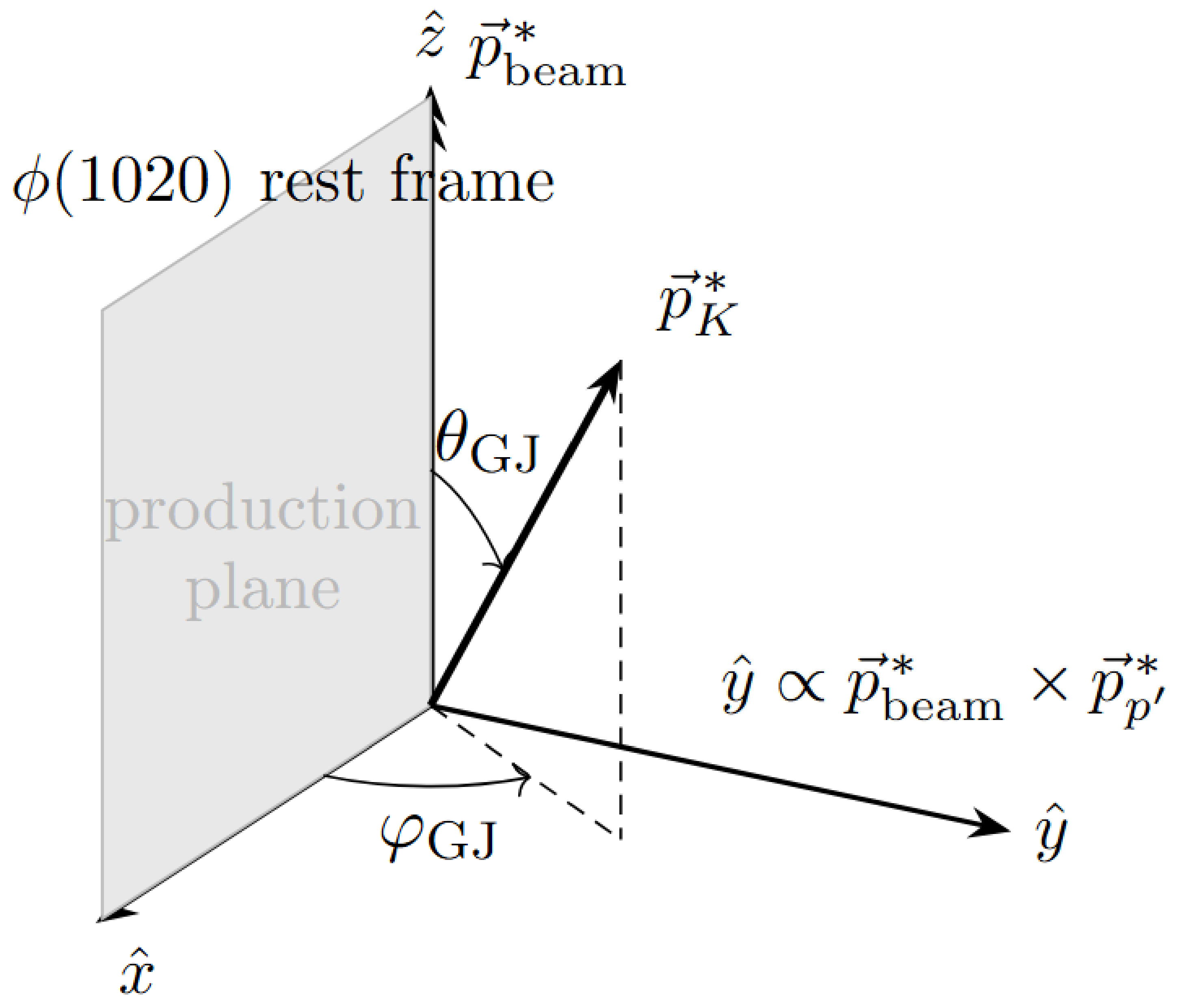
- $a_{KK} = [(0.47 \pm 0.05) + i(0.0 \pm 0.1)]$ fm
- $a_{pK} = [(0.09 \pm 0.02) + i(-0.22 \pm 0.05)]$ fm
- Resonance parameters consistent with PDG:

$M_\Lambda = (1519 \pm 0.5)$ MeV $\quad M_\phi = (1019.5 \pm 0.1)$ MeV

$\Gamma_\Lambda = (14 \pm 0.5)$ MeV $\quad \Gamma_\phi = (4.5 \pm 0.1)$ MeV

Angular Analysis for $\phi(1020)$ spin





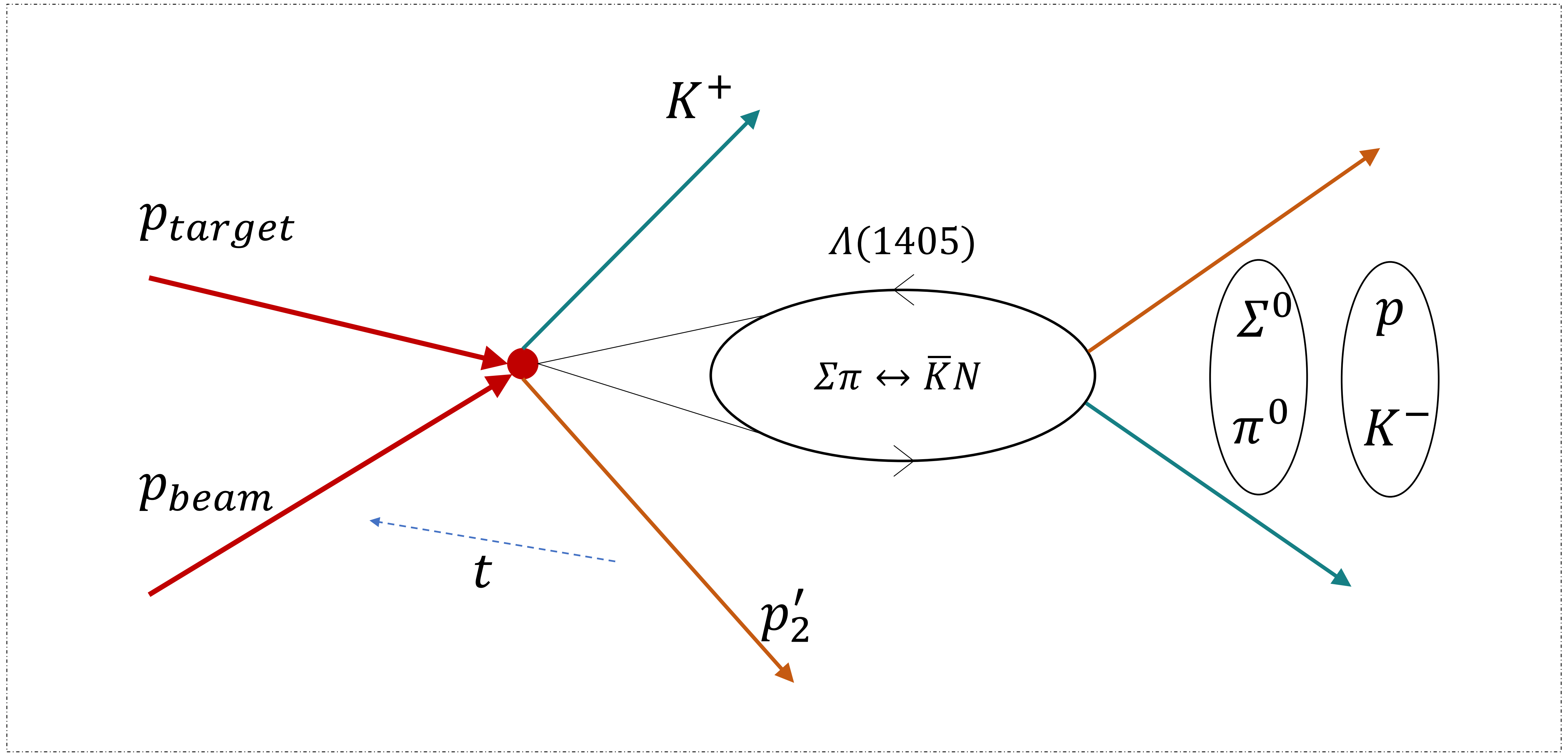
$\boldsymbol{\rho_{00} = 0.05 \pm 0.02}$ -This measurement at Q=600 MeV

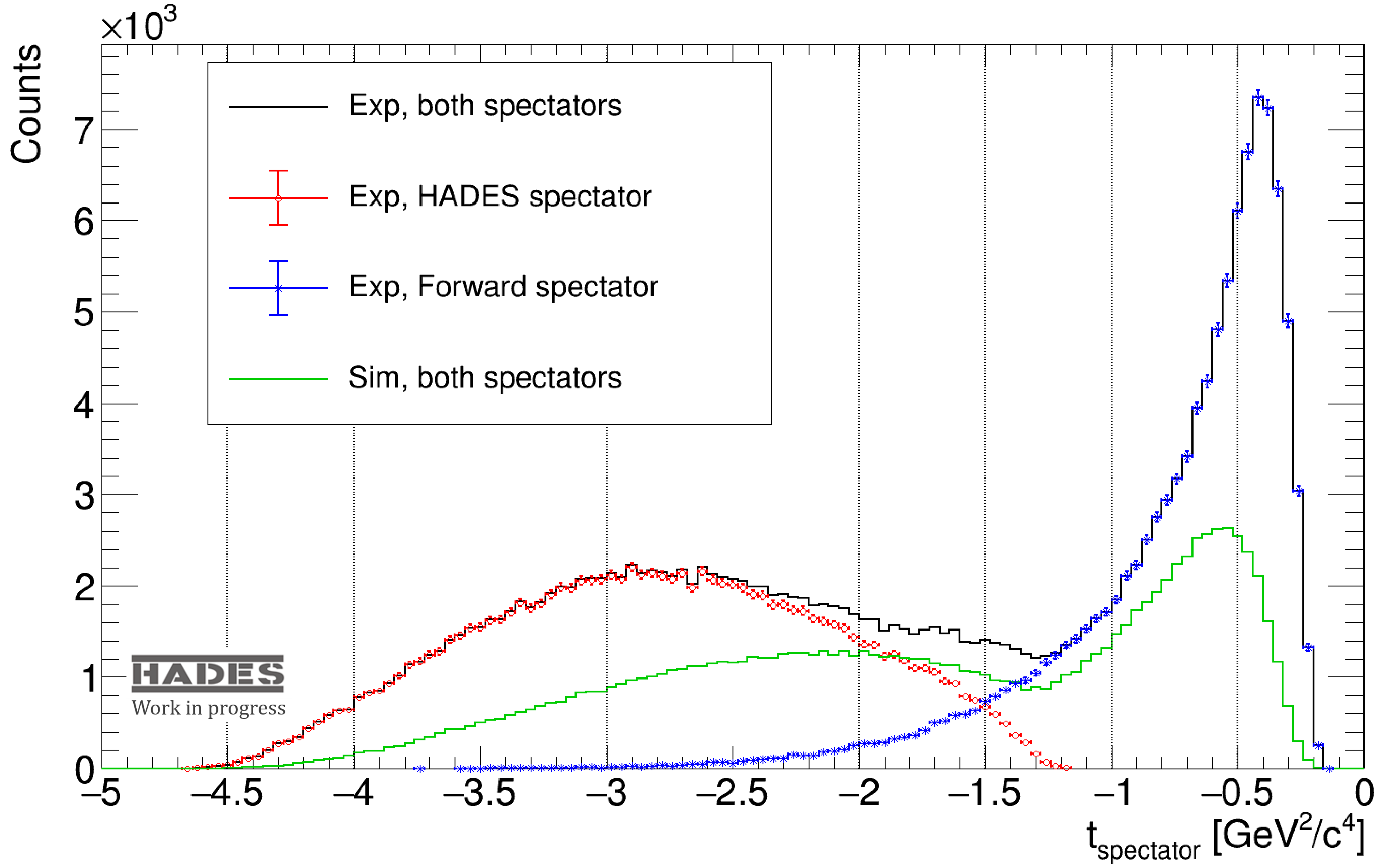
ρ_{00} = Longitudinal polarization (1/3 for unpolarized)

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

- ✓ Using this information for P-wave constraint
- ➢ Inclusion of nondiagonal elements is underway

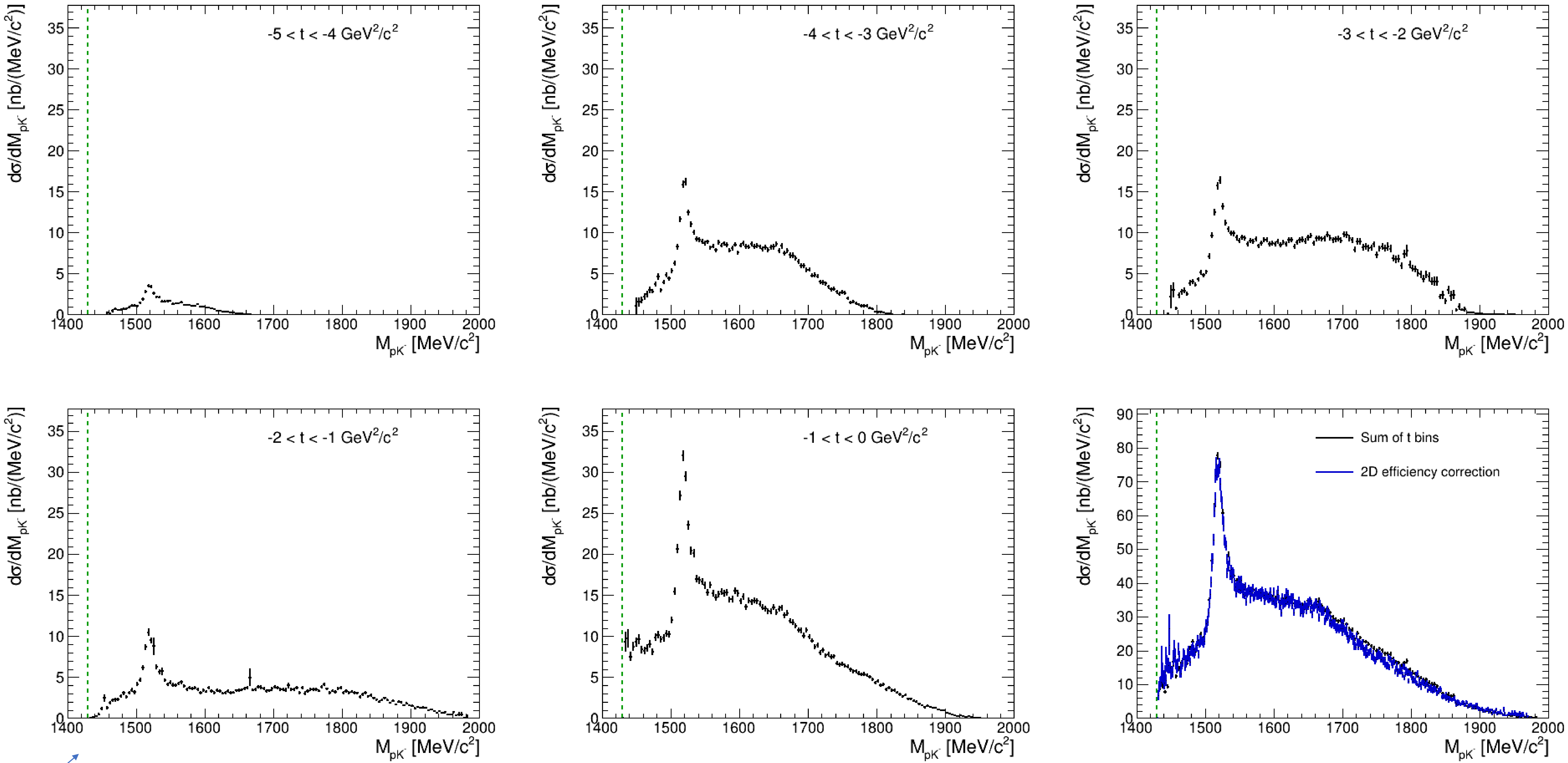
Momentum-Transfer Bins





Enhances $\Lambda(1405)$ threshold sensitivity

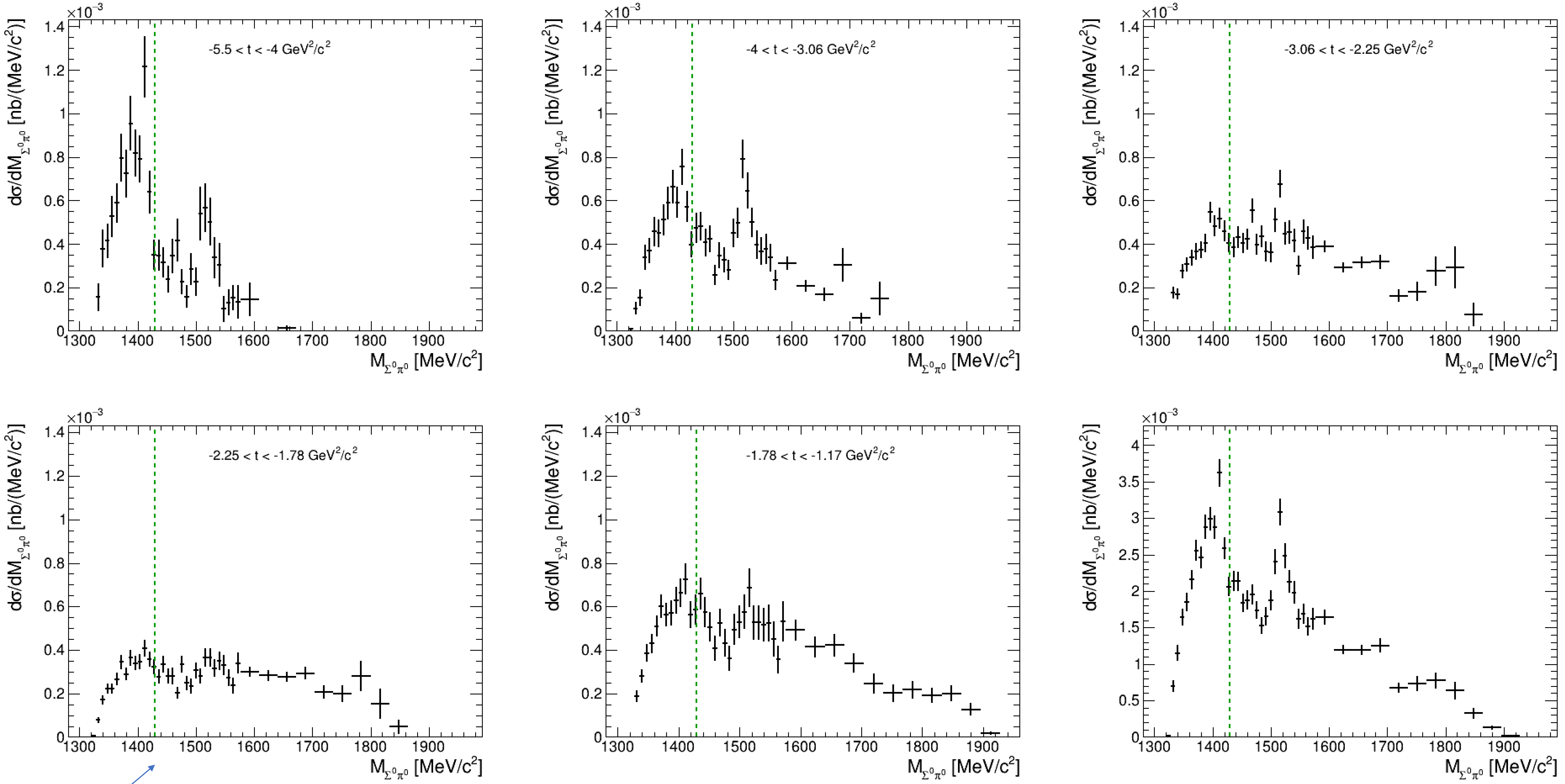
Momentum-Transfer Bins



$N\bar{K}$ threshold

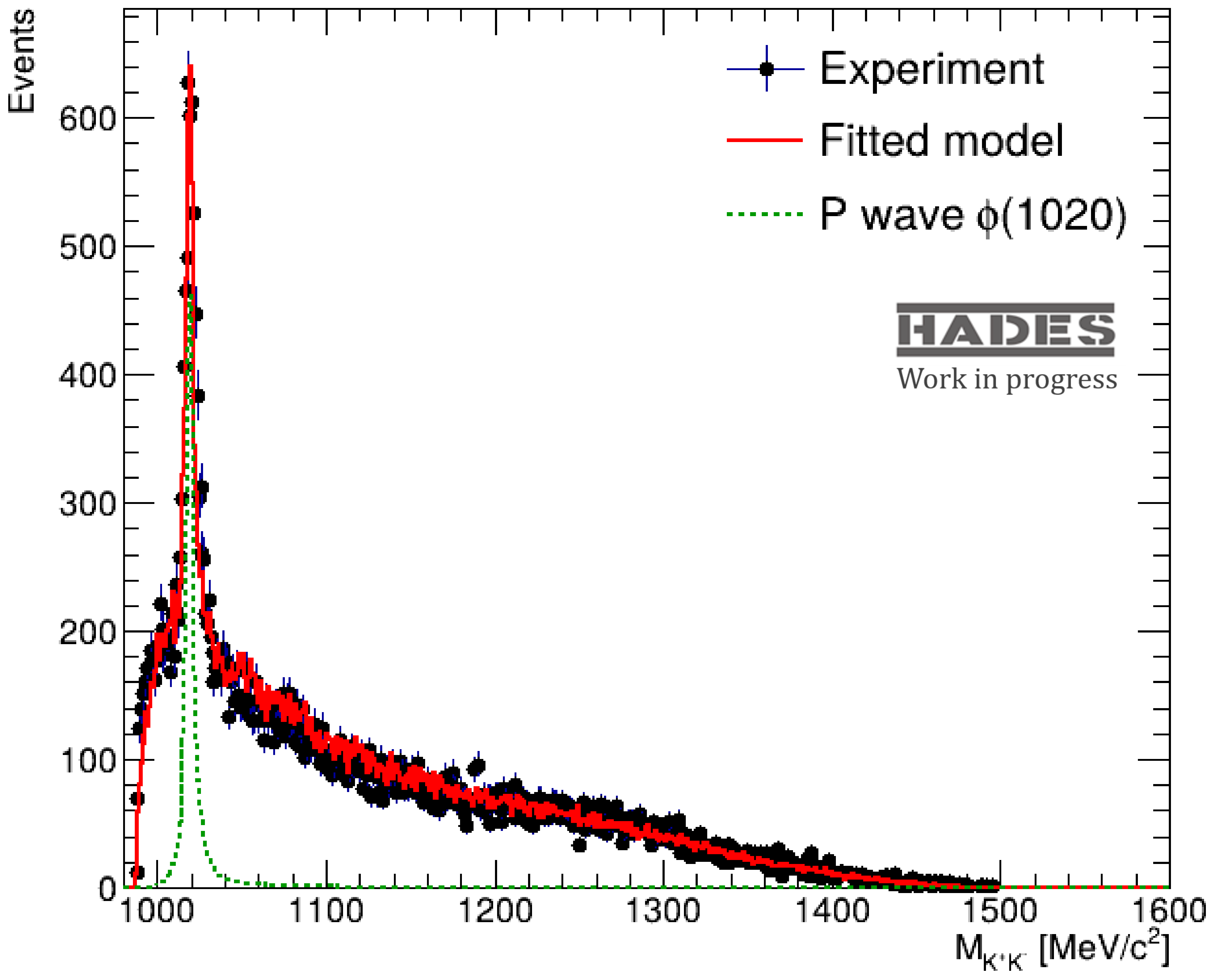
$pp \to pK^+\Sigma^0\pi^0$

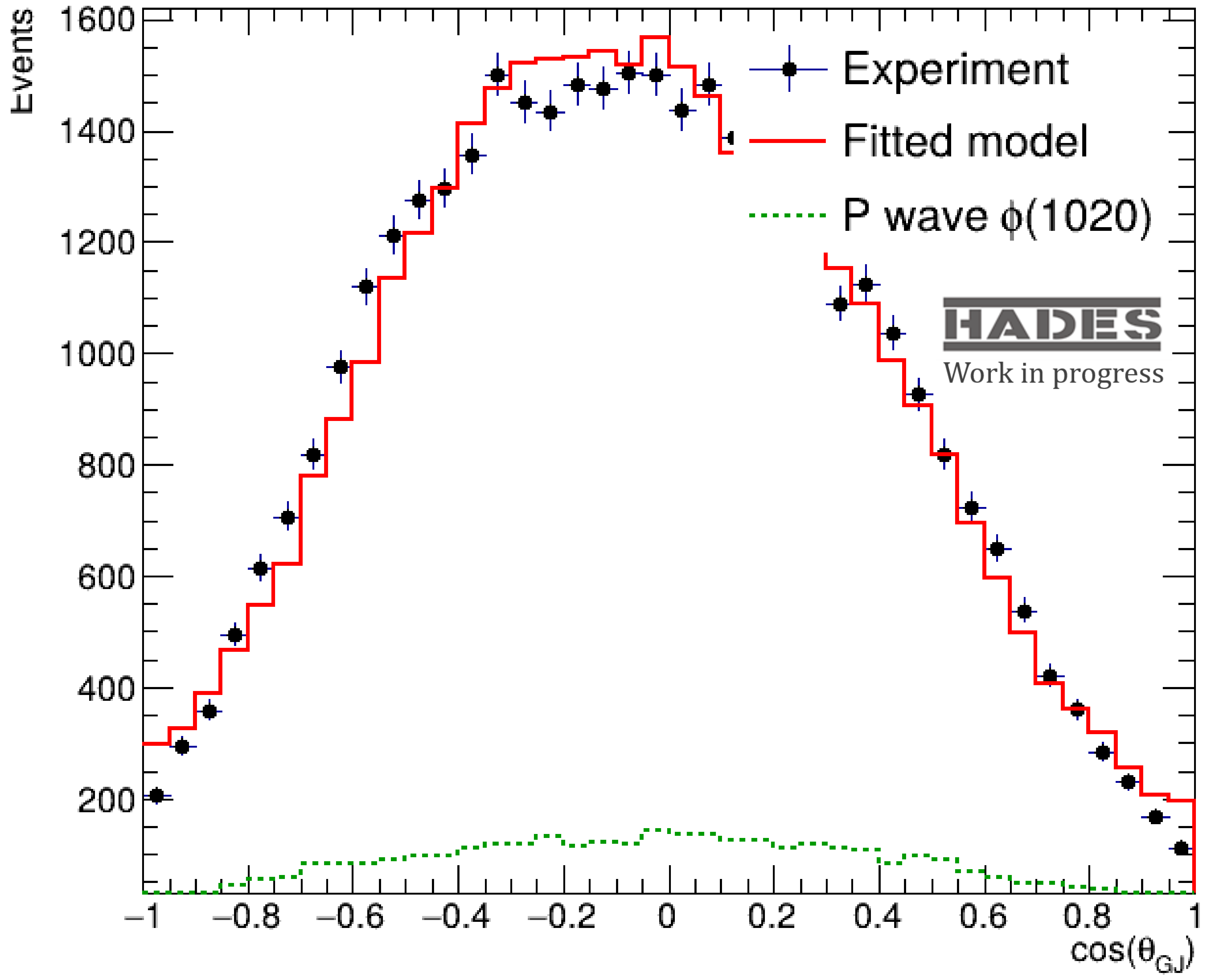
Momentum-Transfer Bins



$N\overline{K}$ threshold

Cross Channel $\phi \rightarrow KK$





Fixed P-wave angular dependency

Code on github

Additional Details about Intensities

1. P-wave $\phi(1020) \to KK$ decay is included with fixed parameters: ρ_{00} from SDME fits,

   BW depending on M_{KK} with energy-dependent width

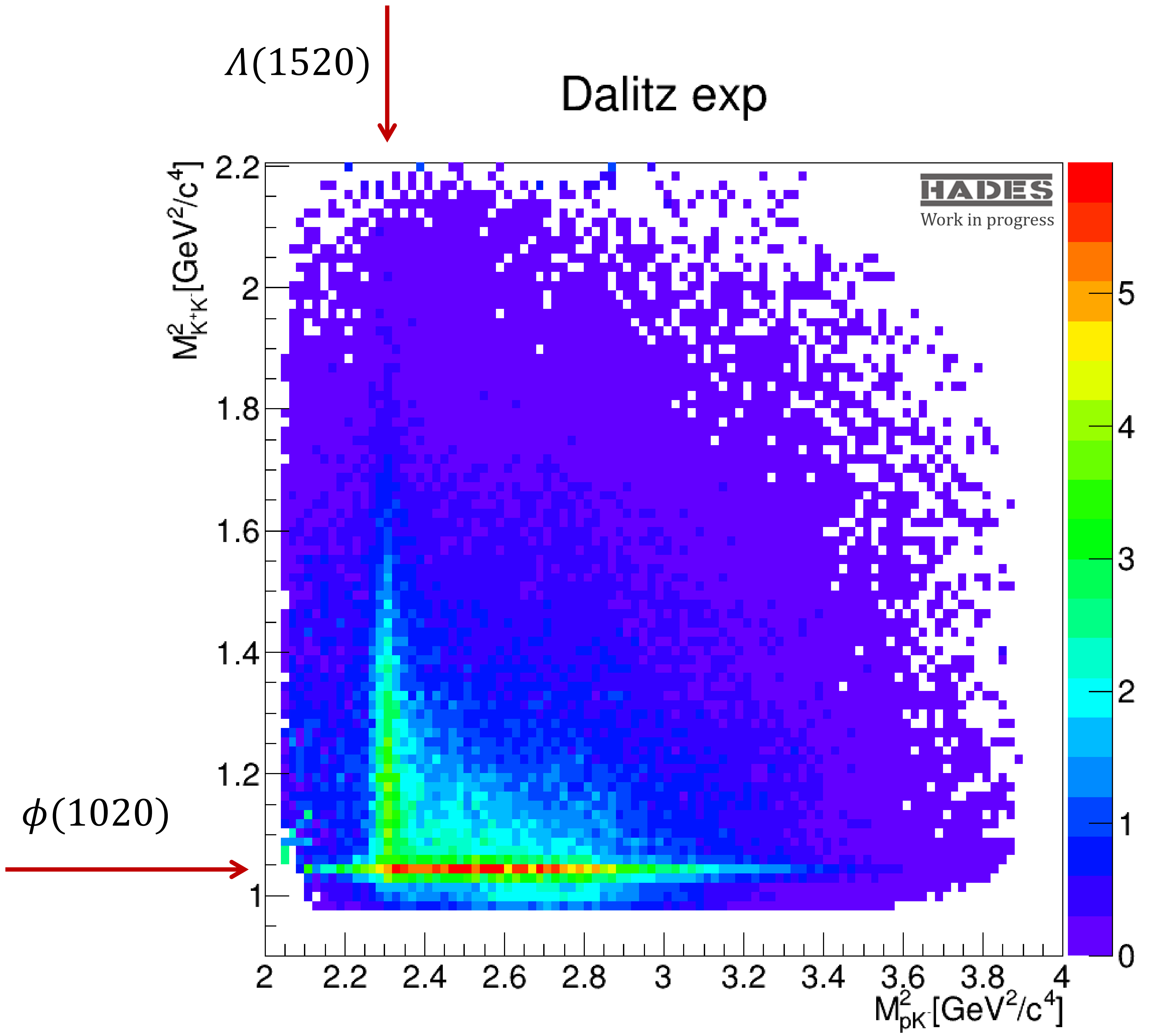
2. Both pK^- combinations are included without interference in the mainly used models

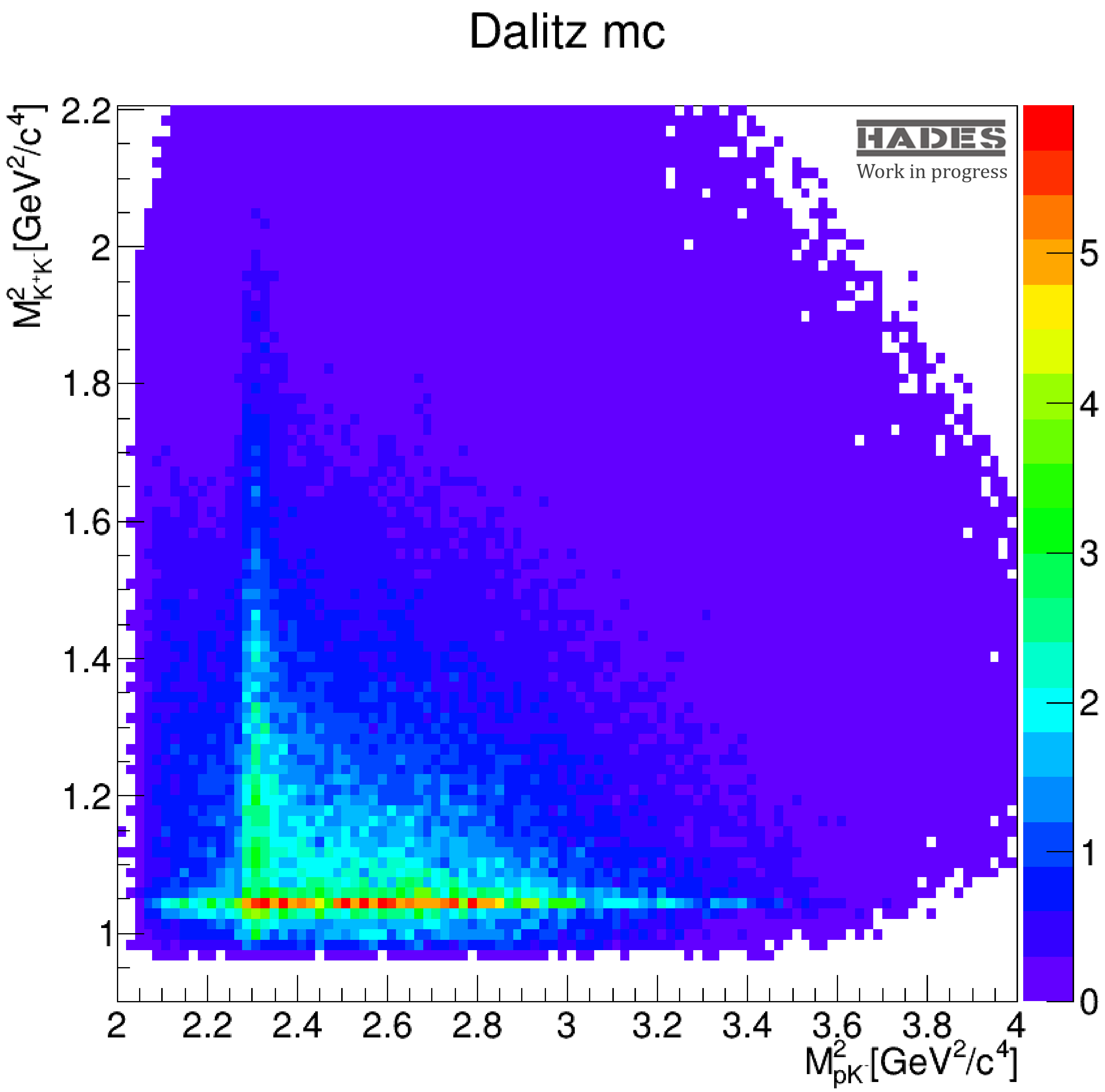
3. t-dependence in production vector strength

4. S-wave nonresonant contributions added as diagonal K-matrix terms

$pp \rightarrow ppK^+K^-$

Dalitz Distributions





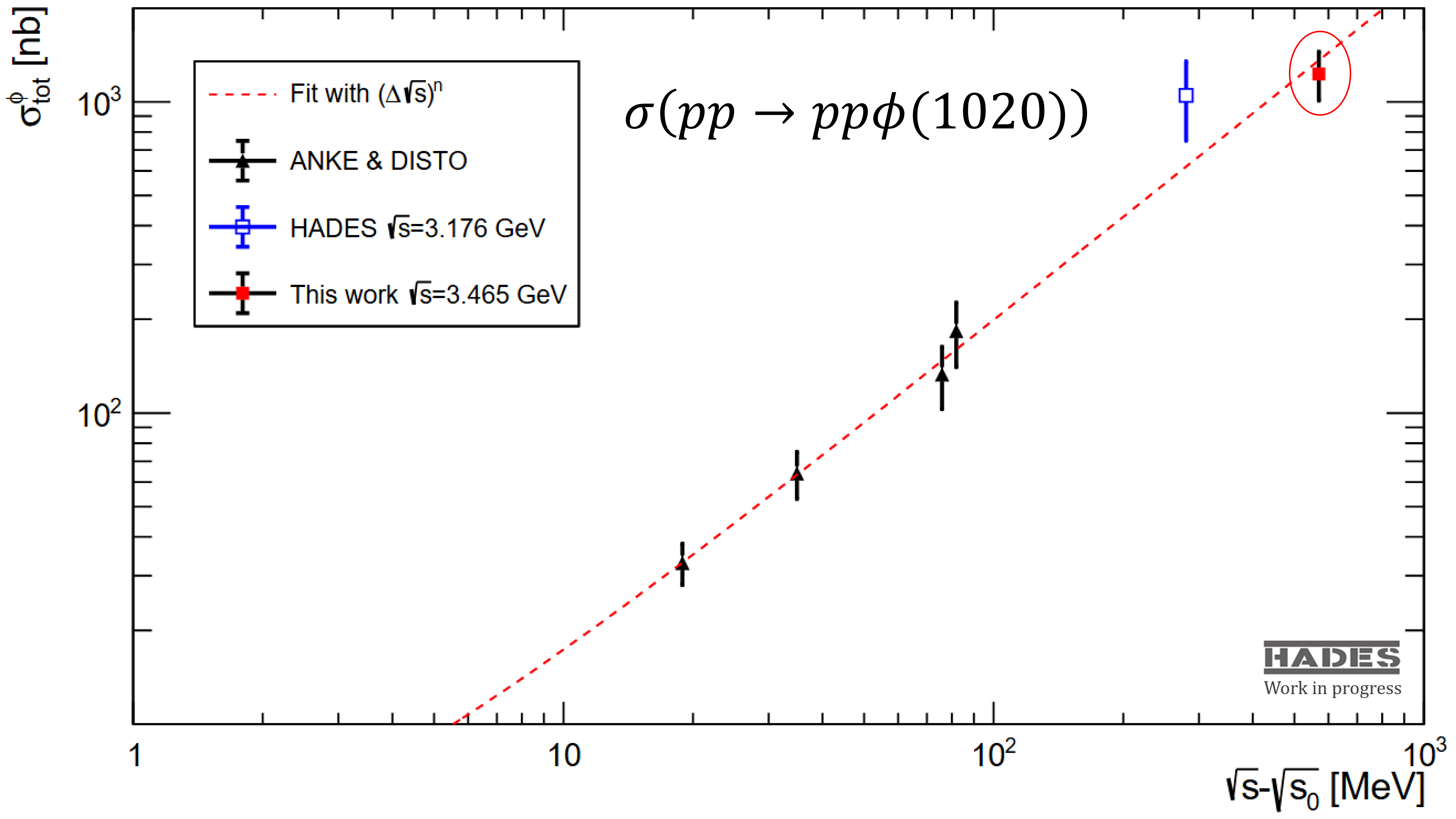
- Efficiency and luminosity corrected counts
- 2 combinations per event (2 protons)

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

Total and Resonance Cross Sections

- $\sigma(pp \to ppK^+K^-) \quad = \quad 5600 \pm 400\, nb$
- $\sigma(pp \to pp\phi(1020)) \quad = 1220 \pm 90\, nb$
- $\sigma(pp \to pK^+\Lambda(1520)) = 2740 \pm 200\, nb$

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



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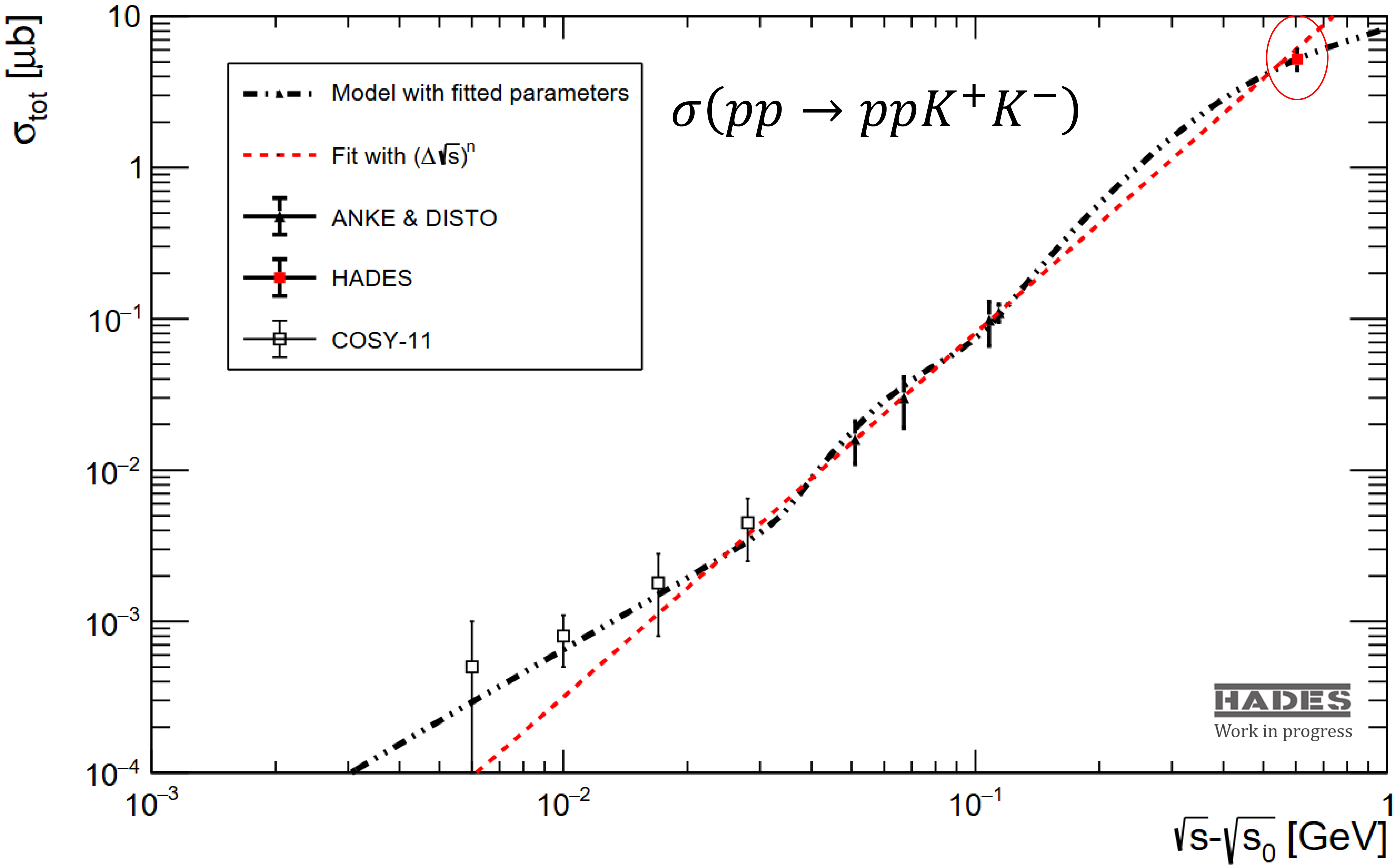

Systematic Errors and Uncertainties

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