Light-Meson Spectroscopy at Lepto- and Hadroproduction Experiments

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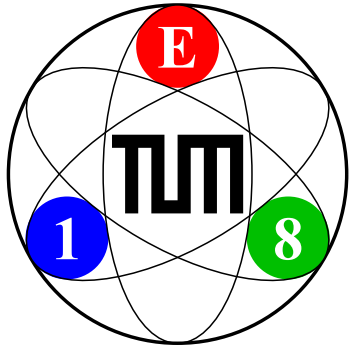
on Hadron Spectroscopy and Structure
Guilin, 18. August 2019



Constituent Quark Model

Light mesons

- $|q\bar{q}\rangle$ quantum states, with $q = u, d,$ or s
- Organized in $SU(3)_{\text{flavor}}$ nonets

Quantum numbers

- Quark spins couple to total intrinsic spin $S = 0$ or 1
- Relative orbital angular Momentum $\vec{L}$ and $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} + \vec{S}$
- Parity: $P = (-1)^{L+1}$
- Charge conjugation: $C = (-1)^{L+S}$
- Forbidden J^{PC} combinations: 0^{--}, even^{+-}, odd^{-+}

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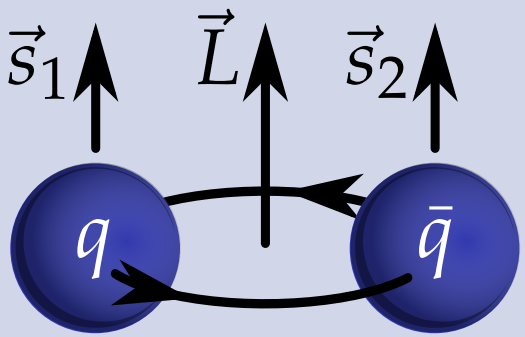

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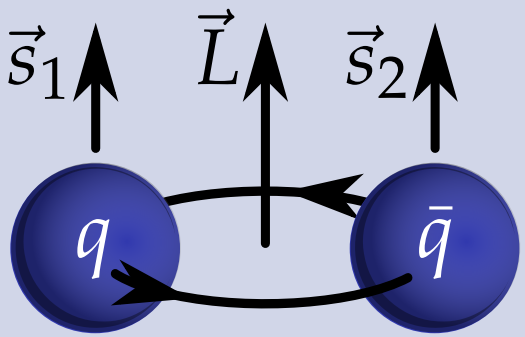

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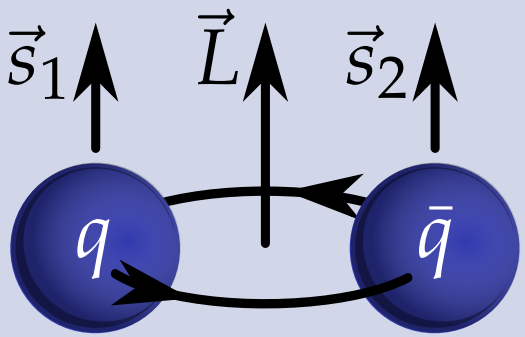
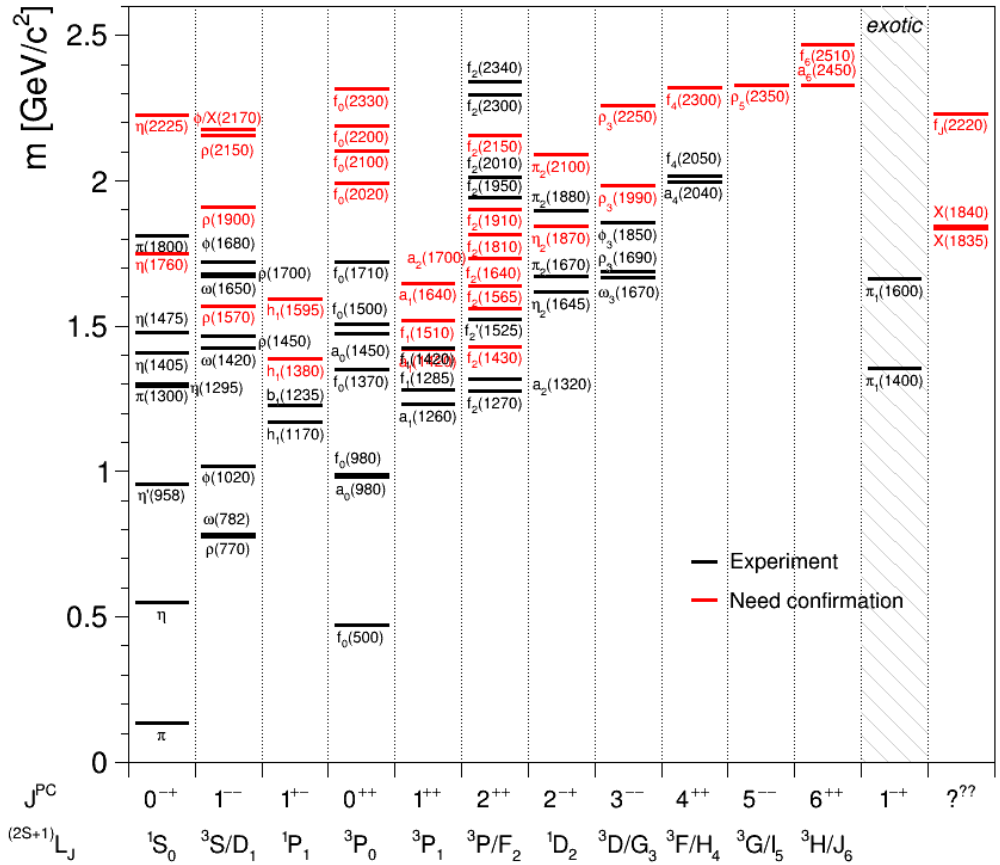


Spectrum of Light Non-Strange Mesons

Light-Meson Frontier



[Courtesy K. Götzen, GSI]

- Rich spectrum
- Many states in mass region $\gtrsim 2\,\mathrm{GeV}/c^2$ need confirmation
- Many wide states
  - Identification requires partial-wave analysis (PWA)
  - Overlap and mixing of states with same J^{PC}

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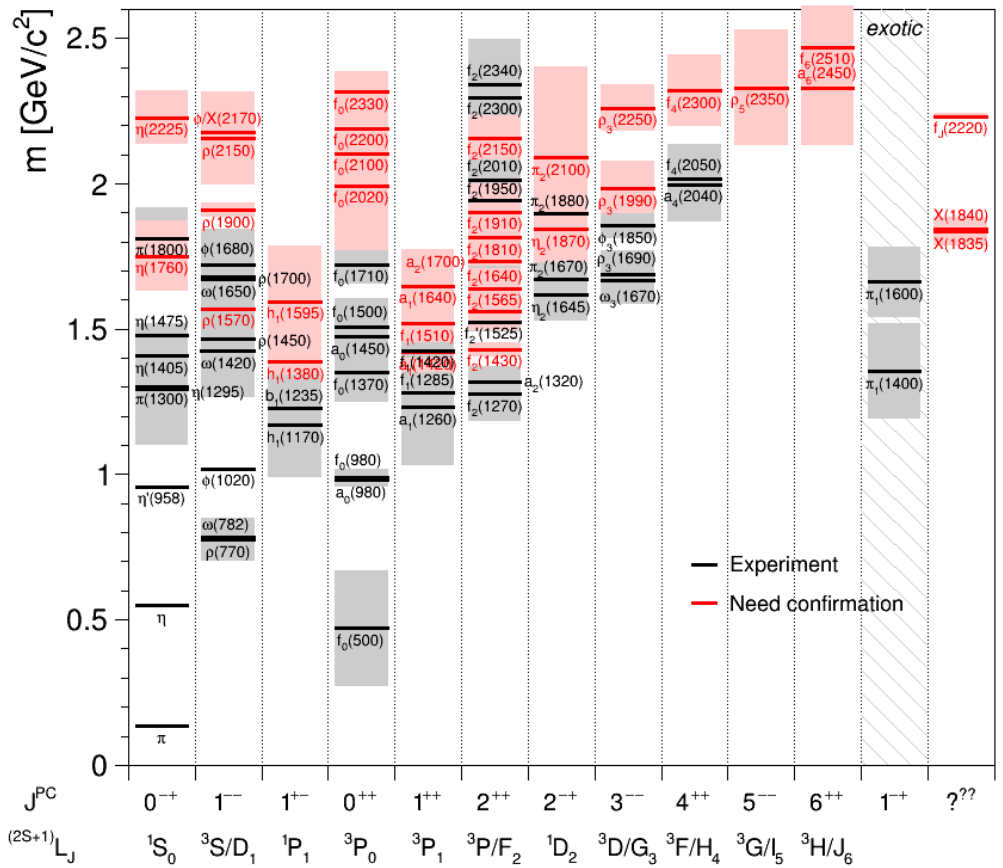

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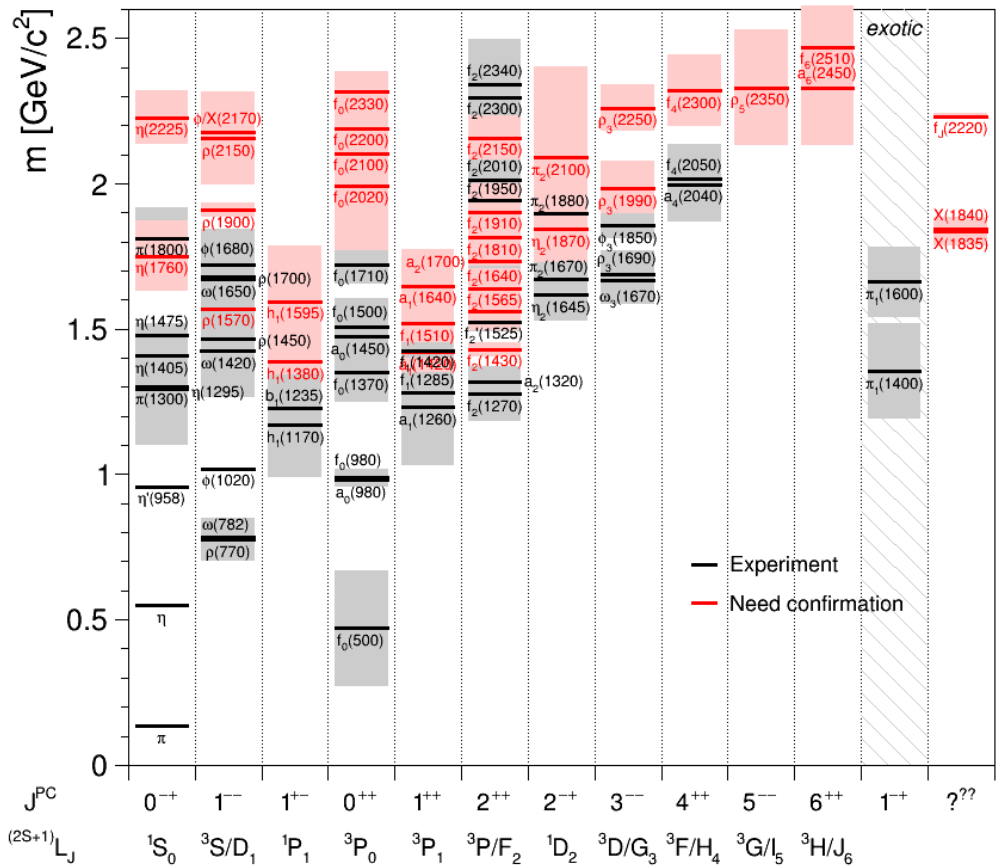

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Goal: precision measurement

- Confirm higher excitations
- Complete $SU(3)_{\mathrm{flavor}}$ nonets
- Search for exotic states

Spectrum of Light Non-Strange Mesons

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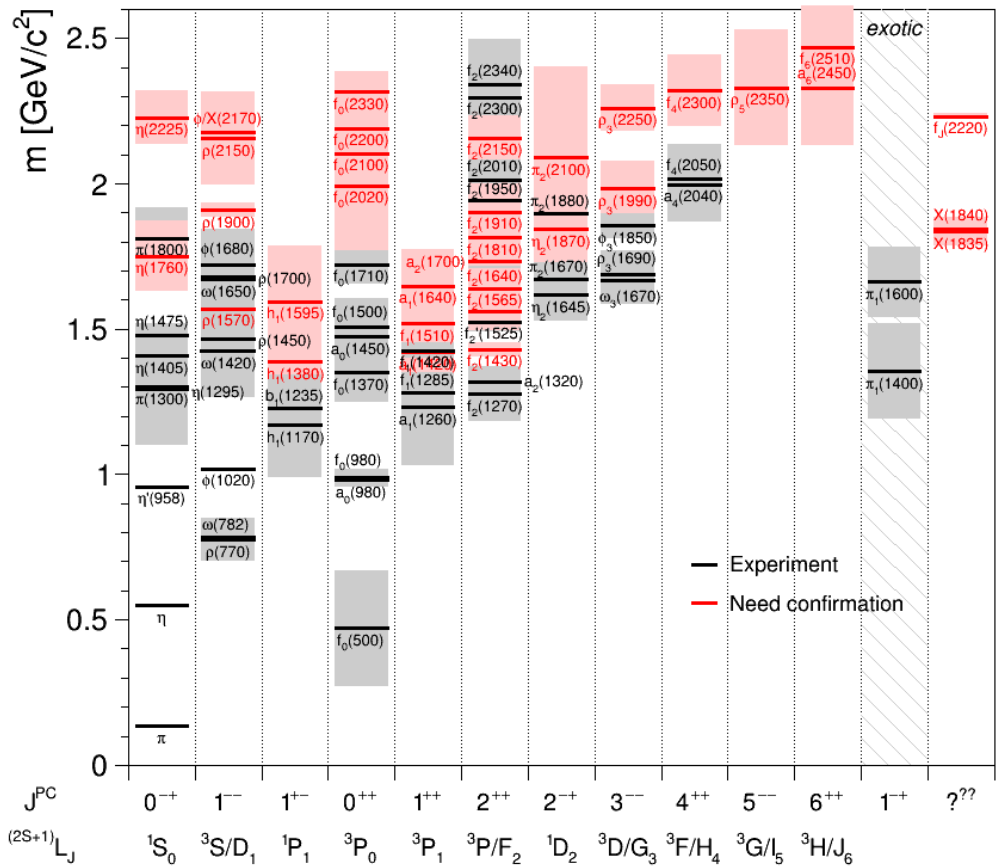

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Goal: precision measurement

- Important input for theory and phenomenology
- Understand QCD at low energies, i.e. nature of confinement

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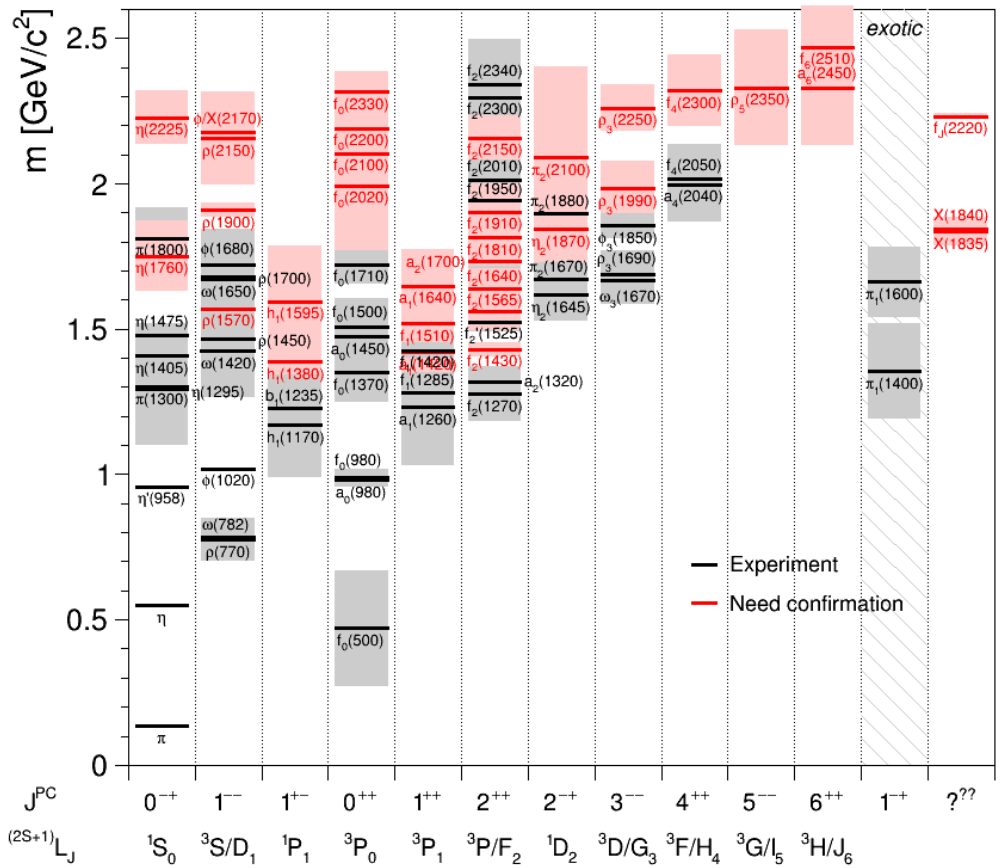
Light-Meson Frontier



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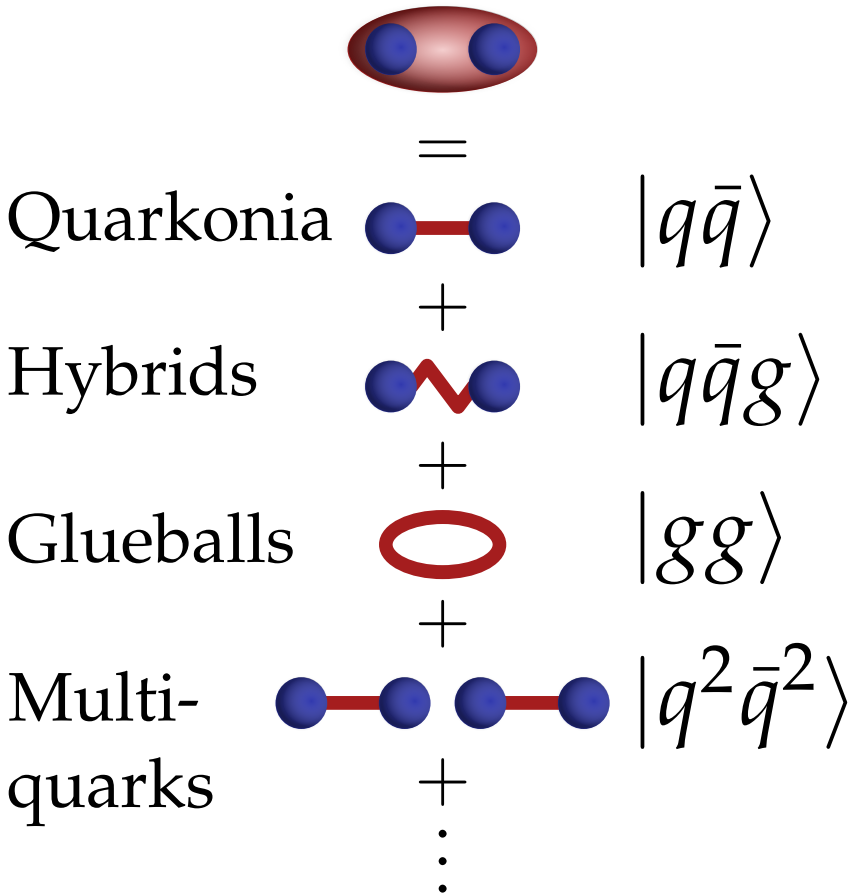
Analyses driven by

- High-quality data
- Advancements in analysis techniques
- More rigorous theoretical PWA models

Beyond the Constituent Quark Model

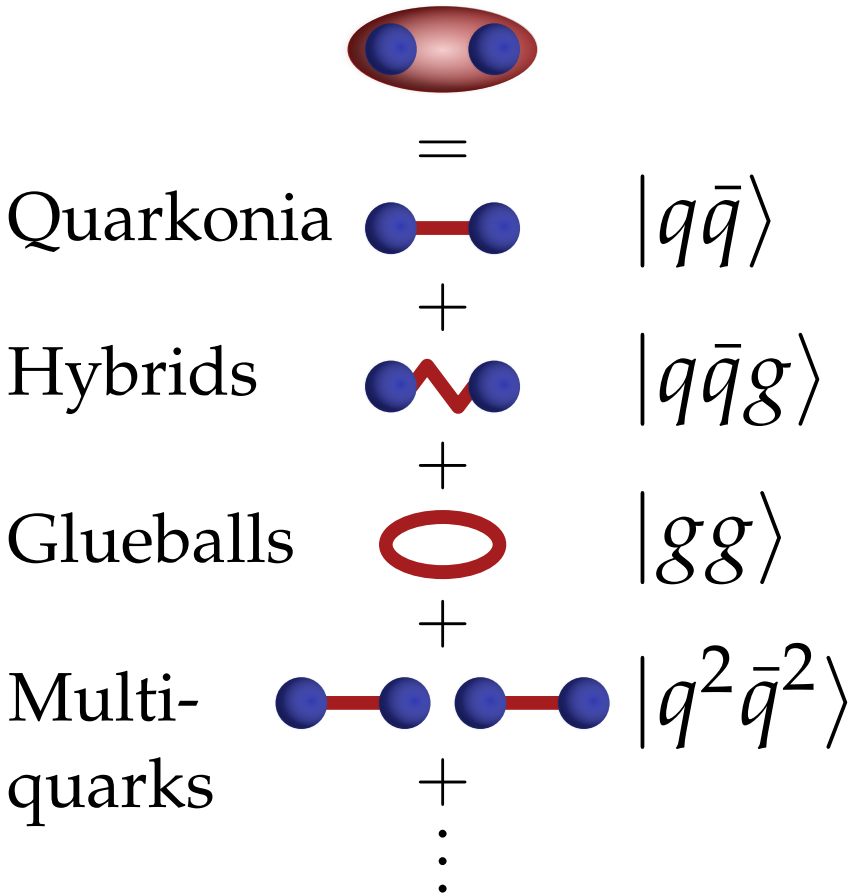
Exotic Mesons



QCD permits additional color-singlet mesonic configurations

Physical mesons

- Linear superpositions of *all* allowed basis states
- "Configuration mixing"
- Disentanglement of contributions difficult
  - Detailed information about couplings to production and decay channels required



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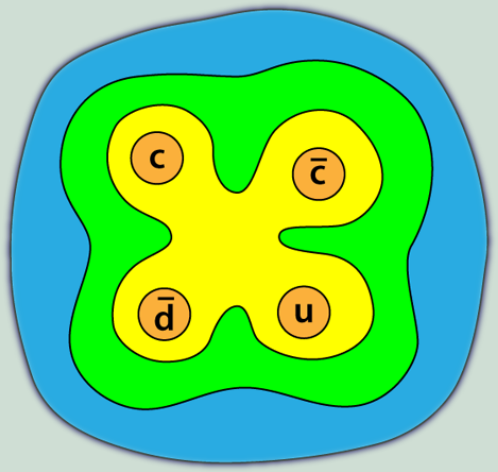
Exotic Mesons

So far clearest experimental evidence in heavy-quark sector

Tetraquark candidates $Z_{c,b}$

- Charged $|c\bar{c}\rangle$- and $|b\bar{b}\rangle$-like states
- E.g. $Z_c^{\pm}(3900) \rightarrow J/\psi + \pi^{\pm}$



Pentaquark candidates P_c^+

- Heavy baryon
- Decay mode $P_c^+ \rightarrow J/\psi + p$

Light-quark sector

- Model calculations suggest some states to be tetraquarks, hybrids, or glueballs
- Also lattice QCD calculations predict hybrids

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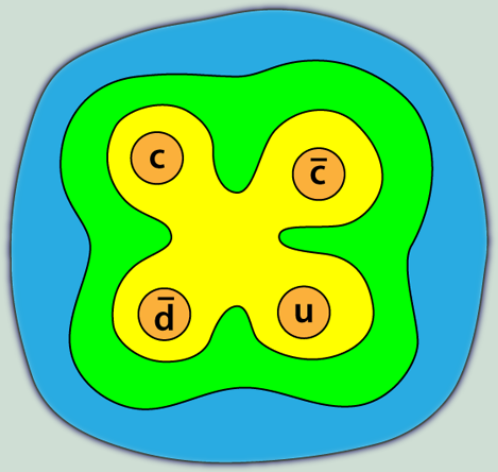

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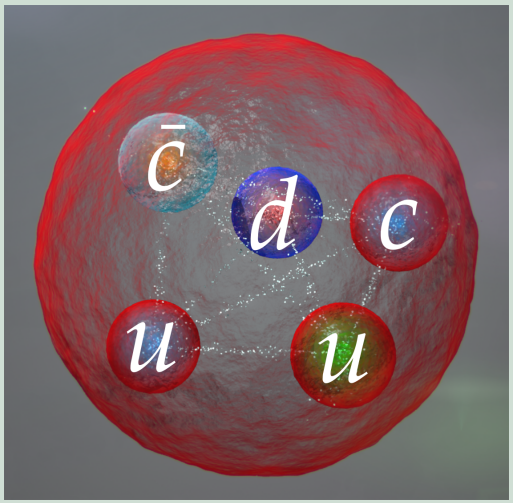

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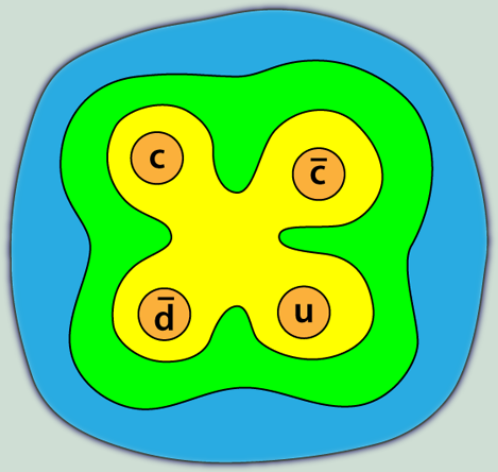

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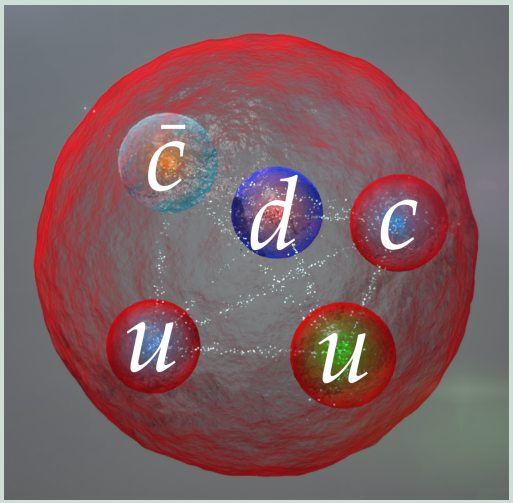

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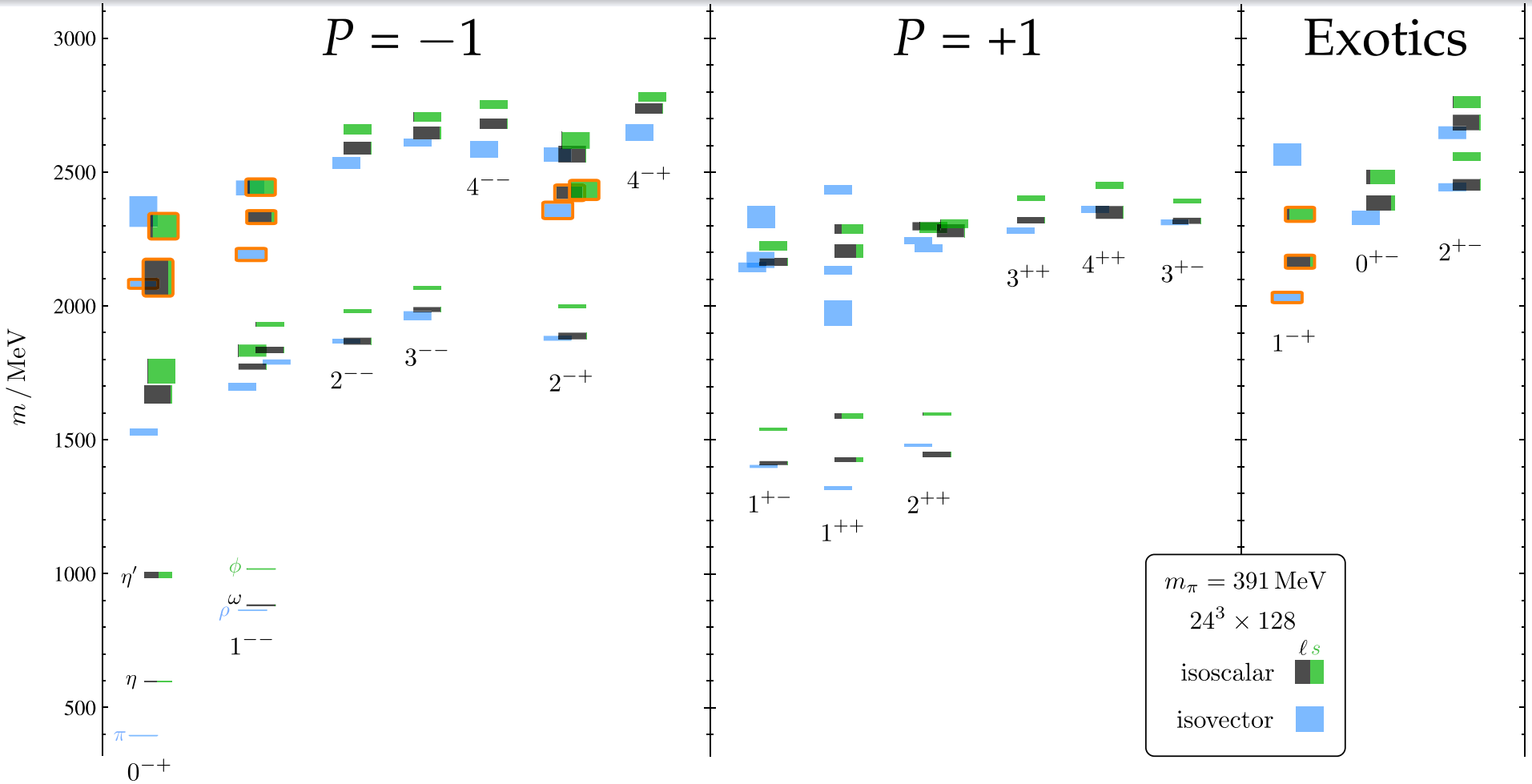
Light-Meson Spectrum from Lattice QCD

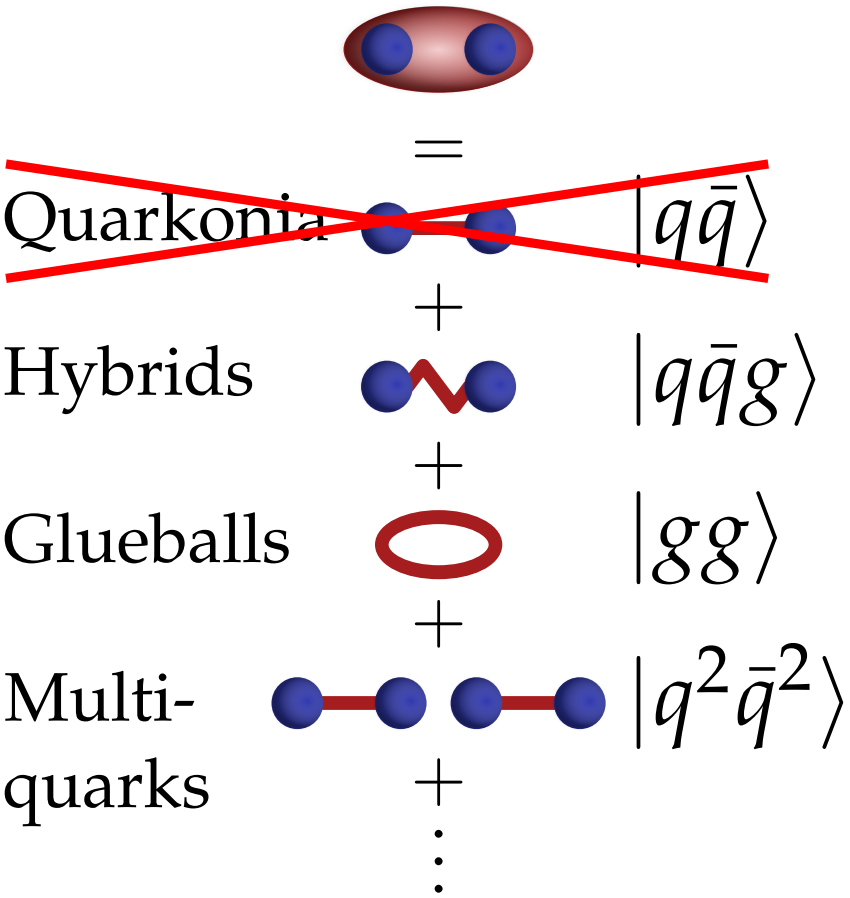
State-of-the-art calculation with $m_\pi = 391\,\mathrm{MeV}/c^2$

Dudek *et al.* [HadSpec], PRD **88** (2013) 094505



- High towers of excited states
- Essentially recovers quark-model pattern
- Additional hybrid-meson super-multiplet

Spin-Exotic Mesons



- States with $J^{PC} = 0^{--}$, even^{+-}, or odd^{-+} forbidden for $|q\bar{q}\rangle$
- Finding them would be unambiguous proof for configurations beyond $|q\bar{q}\rangle$

3 light-meson candidates

1. $\pi_1(1400)$: seen in $\eta\pi$
2. $\pi_1(1600)$: seen in $\rho(770)\pi$, $\eta'\pi$, $b_1(1235)\pi$, and $f_1(1285)\pi$
3. $\pi_1(2015)$ (needs confirmation): seen in $b_1(1235)\pi$, and $f_1(1285)\pi$

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- Some claims are controversial

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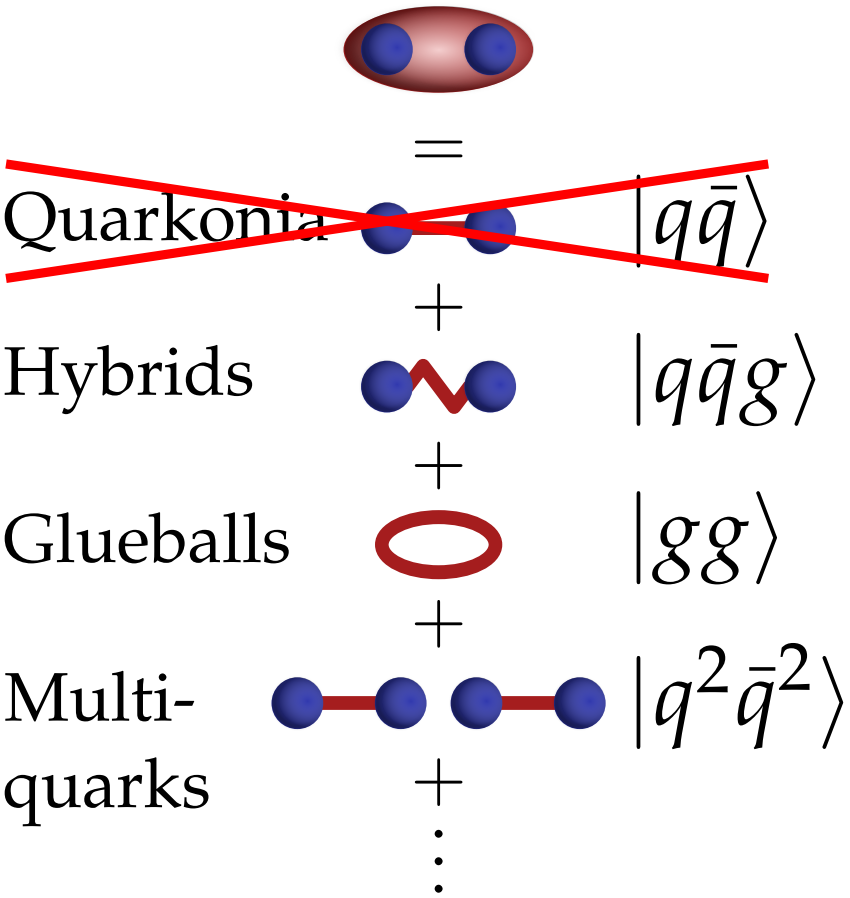

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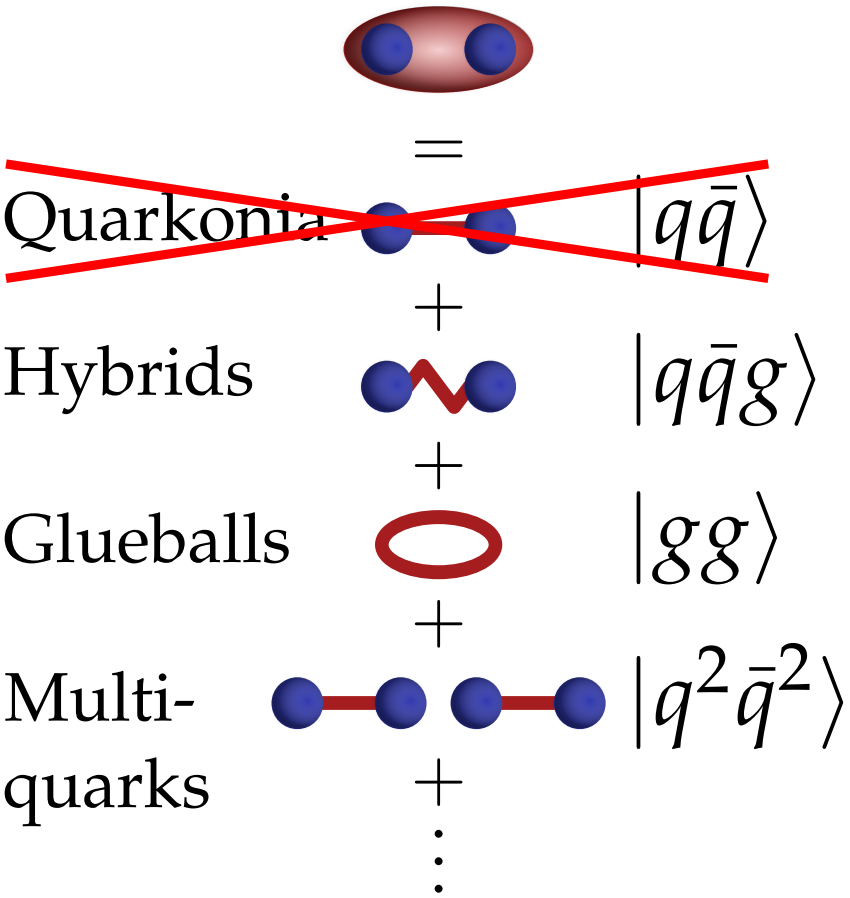

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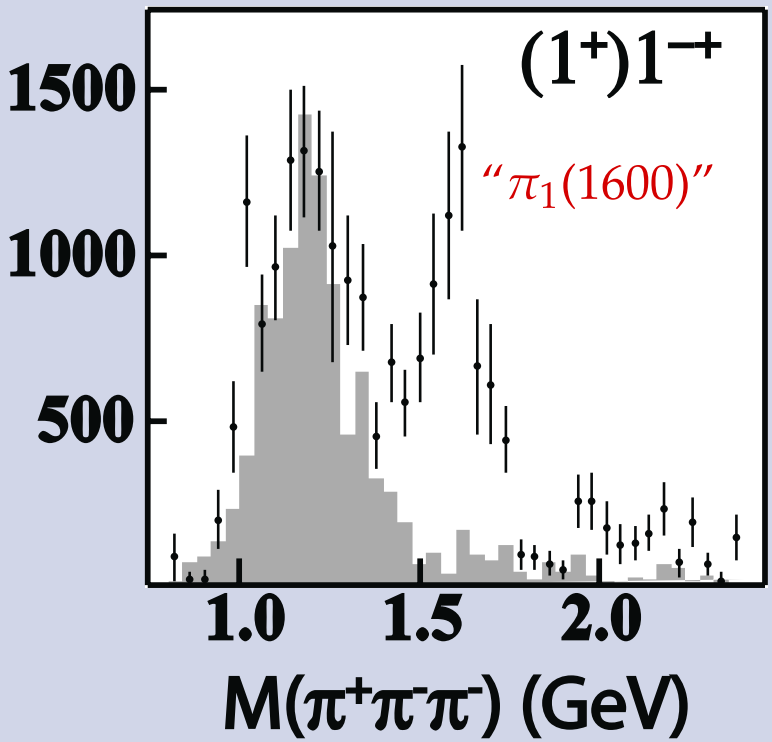
BNL E852 analyses: 18 GeV/c π^- beam on p target

PRL **81** (1998) 5760



- 2.5×10^5 events
- $0.1 < t' < 1.0\ (\mathrm{GeV}/c)^2$
- PWA: 21 waves

$J^{PC} = 1^{-+}$ Spin-Exotic Mesons

The Checkered History of $\pi_1(1600) \to \rho(770)\pi$

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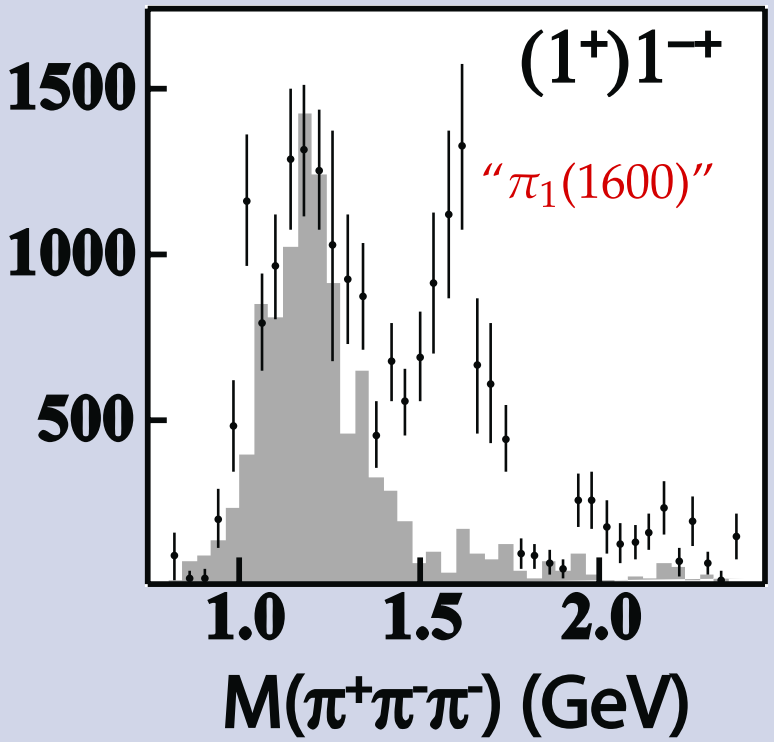

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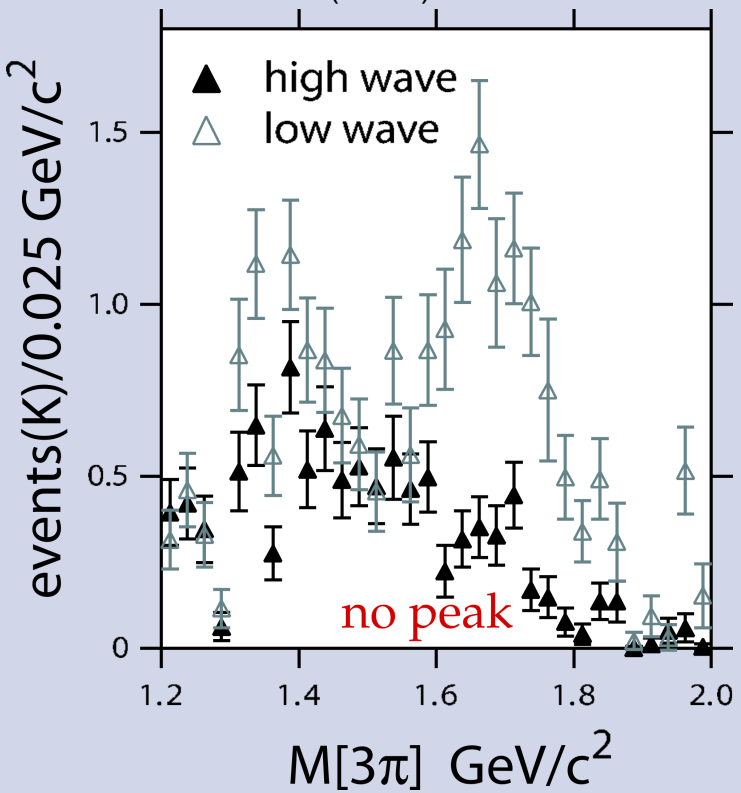
PRD **73** (2006) 072001

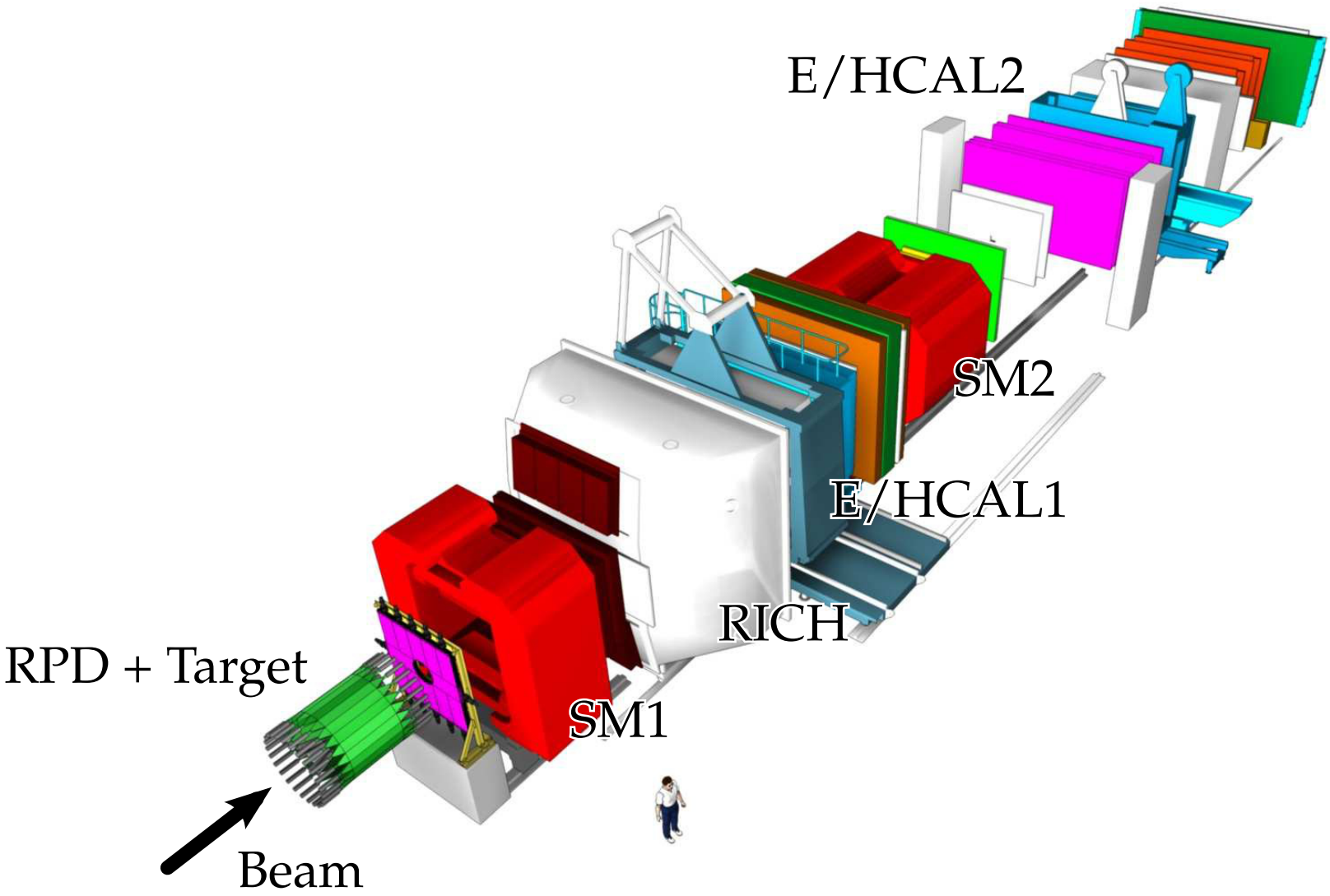


- 2.6×10^6 events
- $0.1 < t' < 0.5\ (\mathrm{GeV}/c)^2$
- PWA: 21 and 36 waves

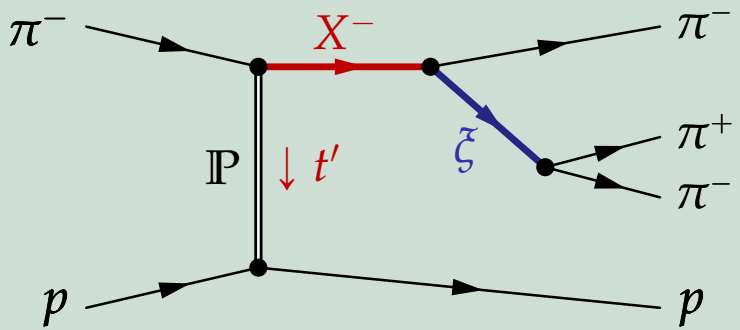
The COMPASS Experiment at the CERN SPS

Experimental Setup

Adolph *et al.*, NIMA **779** (2015) 69



190 GeV/c π^- beam on p target

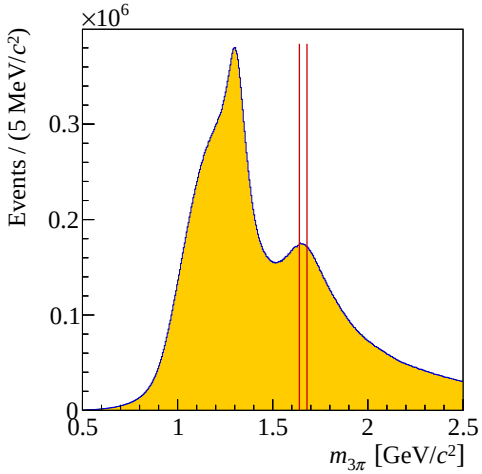


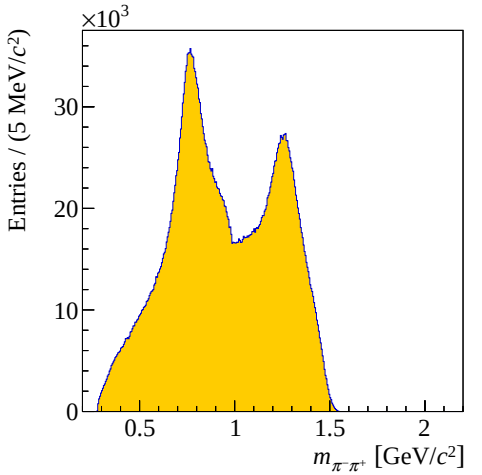
- 46×10^6 events
- $0.1 < t' < 1.0\ (\mathrm{GeV}/c)^2$
- PWA: 88 waves

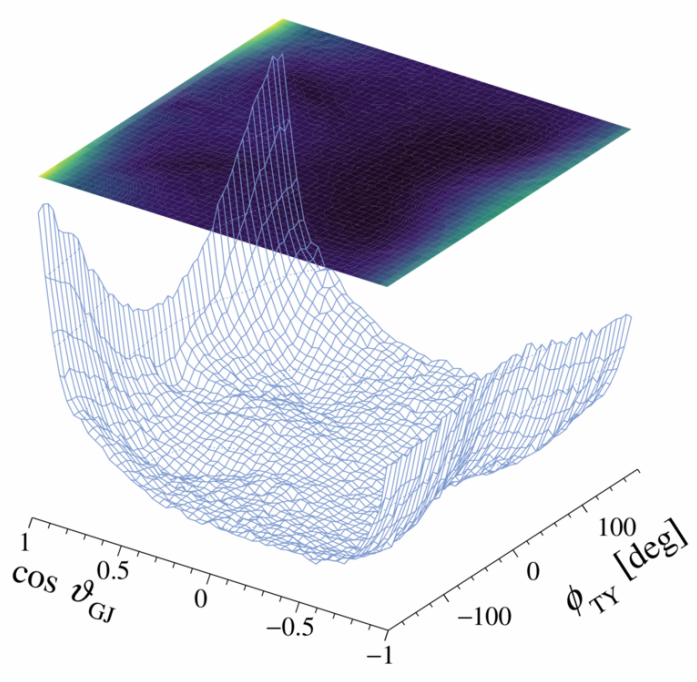
Kinematic Distributions for $\pi^-\pi^-\pi^+$ Final State

COMPASS, PRD **95** (2017) 032004

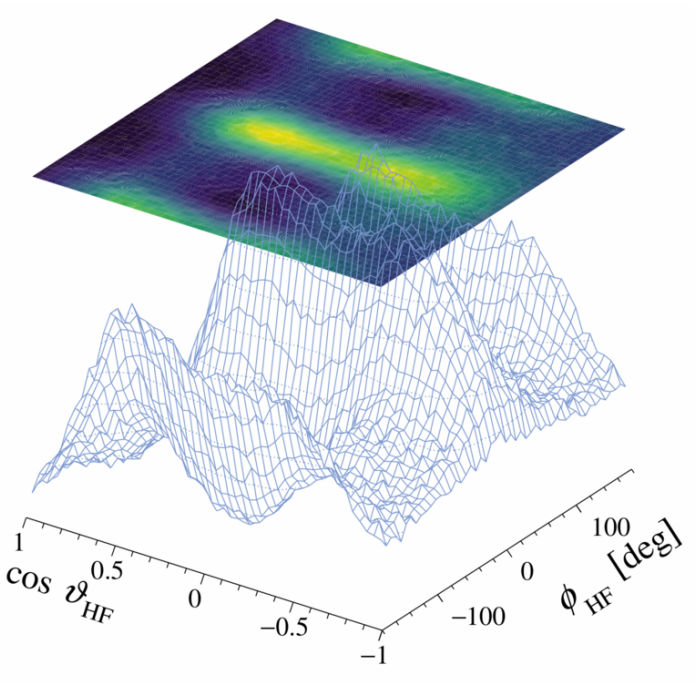
- **PWA input:** 6 variables that define kinematics of 3-body decay







$X^- \to \xi^0 + \pi^-$



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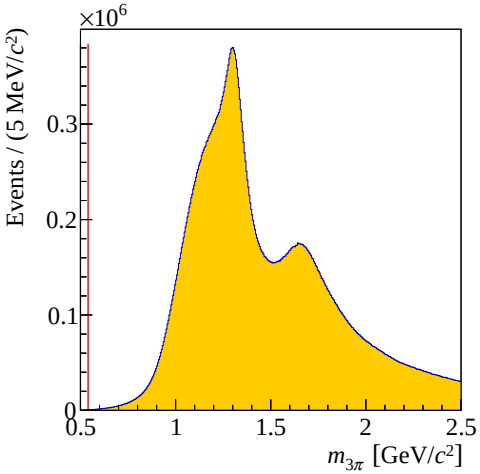

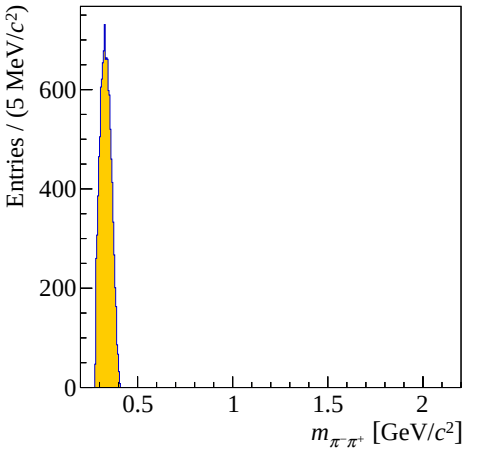

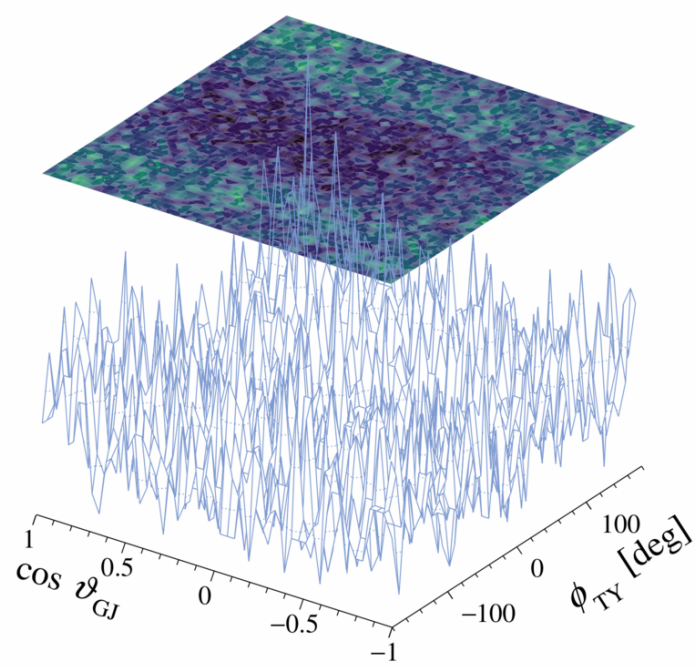

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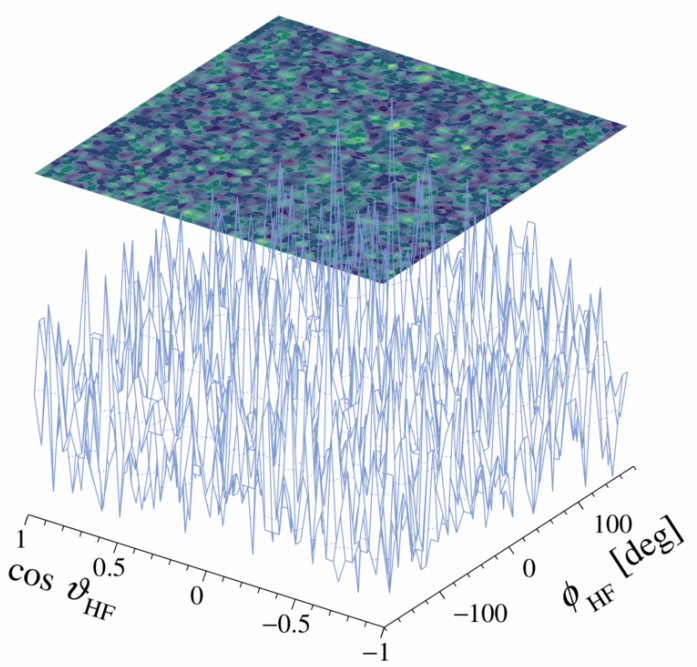


$\xi^0 \to \pi^- + \pi^+$

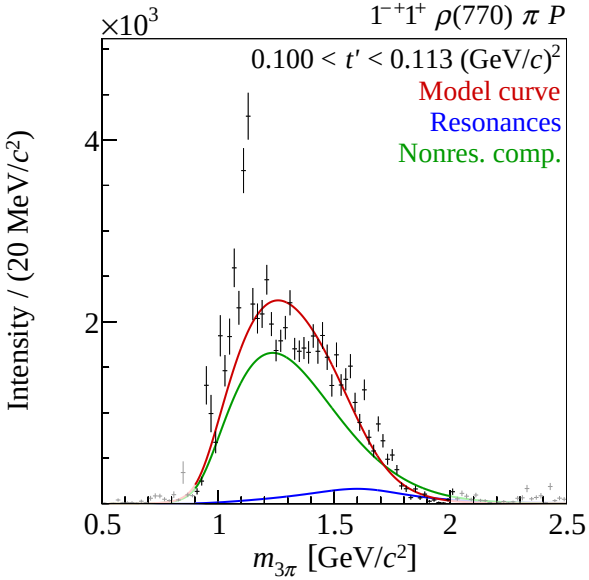
Spin-exotic $1^{-+} \to \rho(770)\pi\, P$ Wave

- Shape of intensity distribution changes dramatically with t'
- Low t': mostly non-resonant
- High t': mostly $\pi_1(1600)$

Resonance parameters

- $\pi_1(1600)$
  $m_0 = (1600\,^{+110}_{-60})\,\mathrm{MeV}/c^2$
  $\Gamma_0 = (580\,^{+100}_{-230})\,\mathrm{MeV}/c^2$
- Large systematic uncertainties

lowest t' bin



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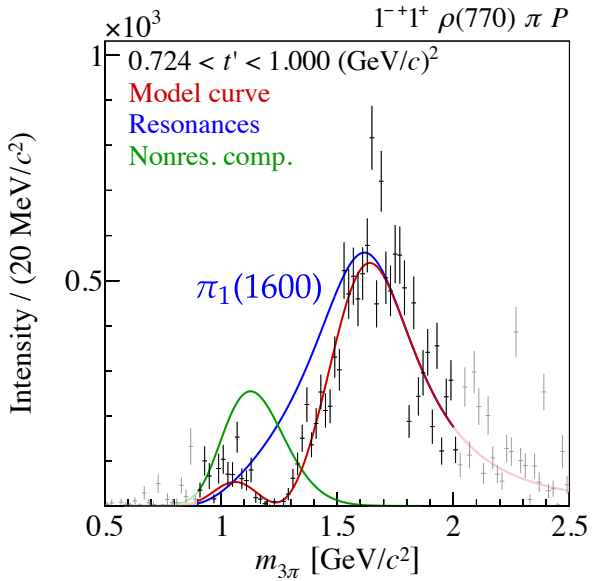

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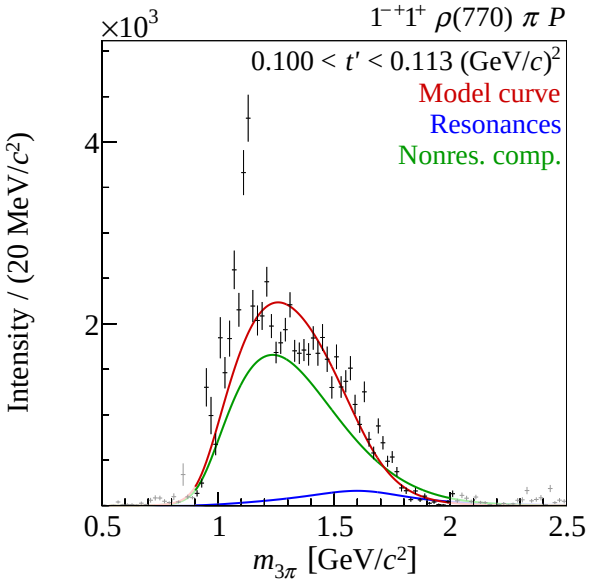
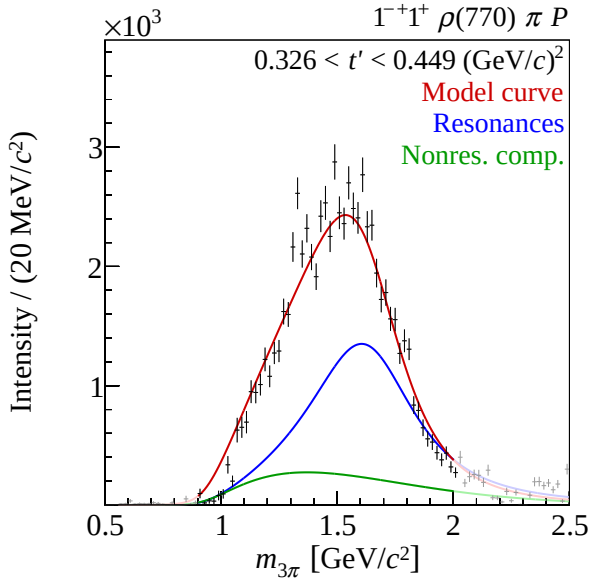
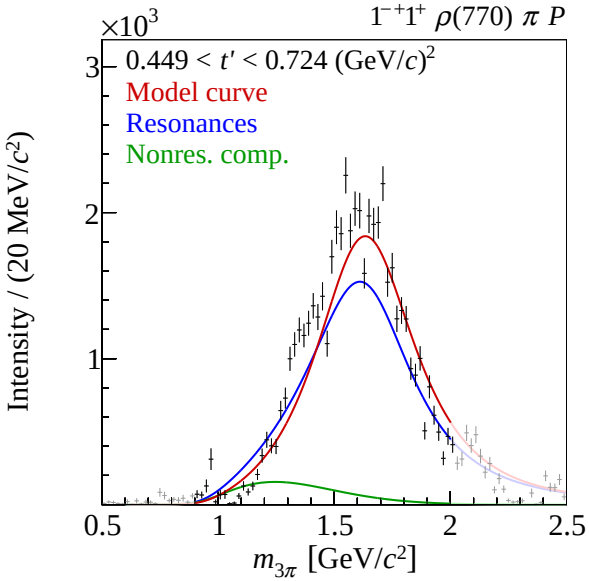
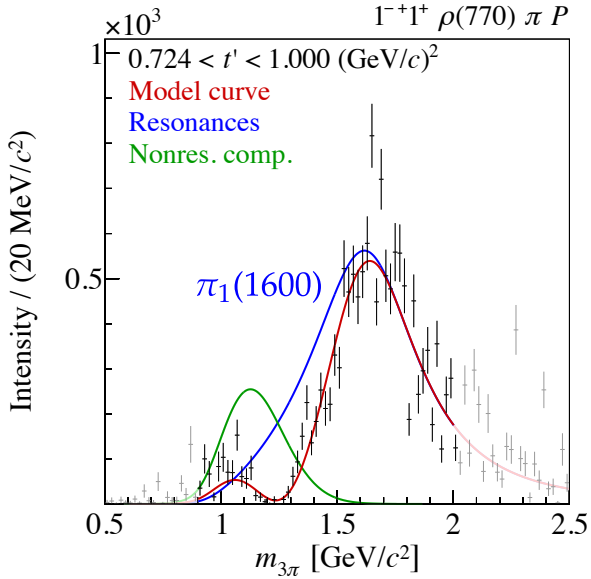






highest t' bin



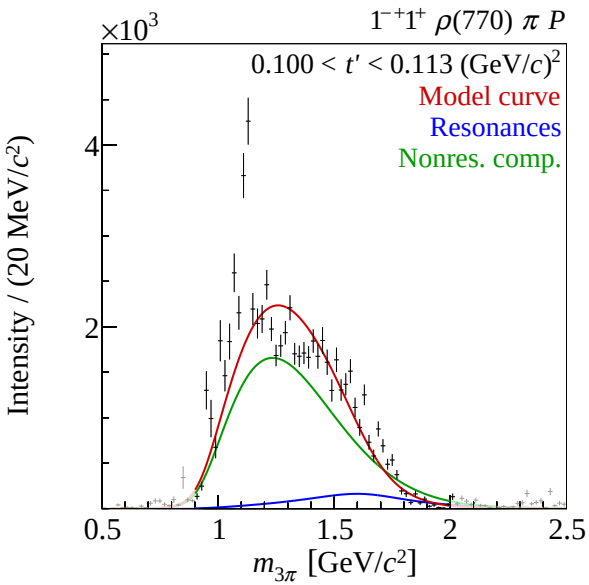
Spin-exotic $1^{-+} \to \rho(770)\pi\, P$ Wave

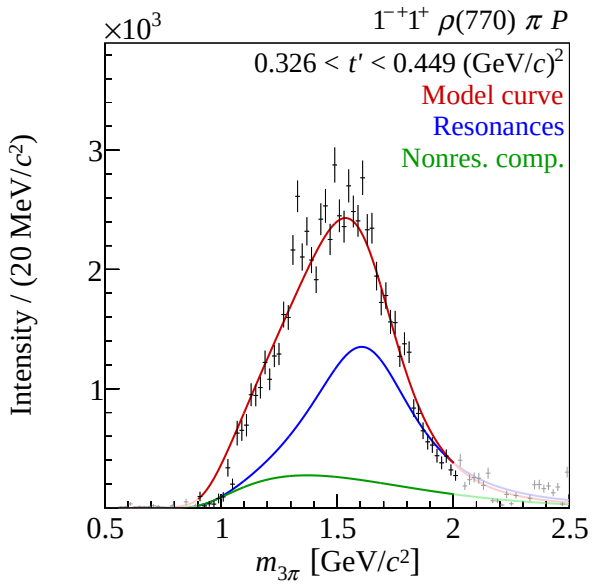
- Shape of intensity distribution changes dramatically with t'
- Low t': mostly non-resonant
- High t': mostly $\pi_1(1600)$

Resonance parameters

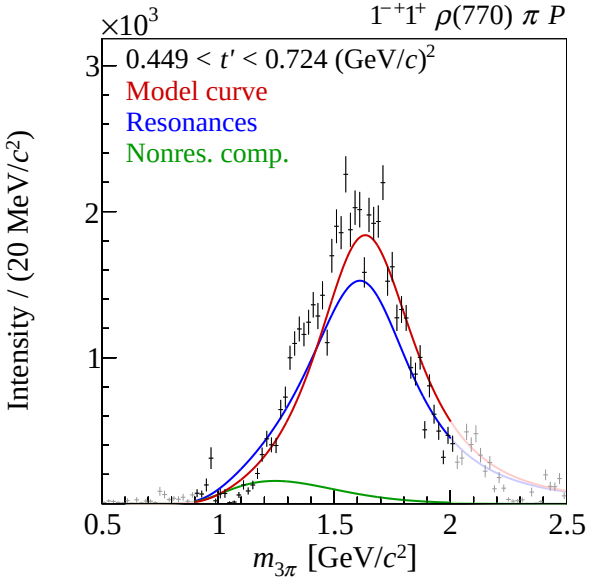
- $\pi_1(1600)$
  $m_0 = (1600\,^{+110}_{-60})\,\mathrm{MeV}/c^2$
  $\Gamma_0 = (580\,^{+100}_{-230})\,\mathrm{MeV}/c^2$
- Large systematic uncertainties

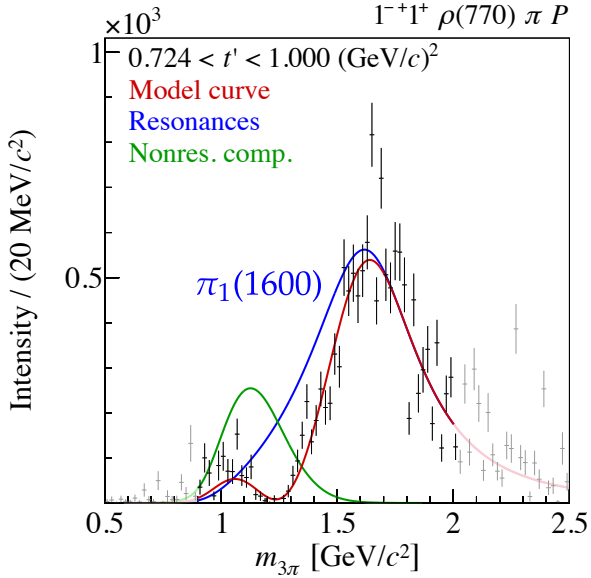
lowest t' bin





highest t' bin





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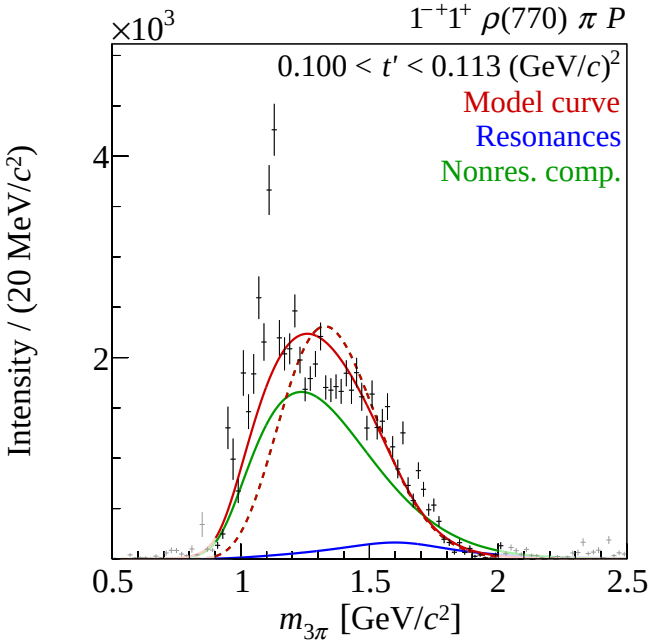


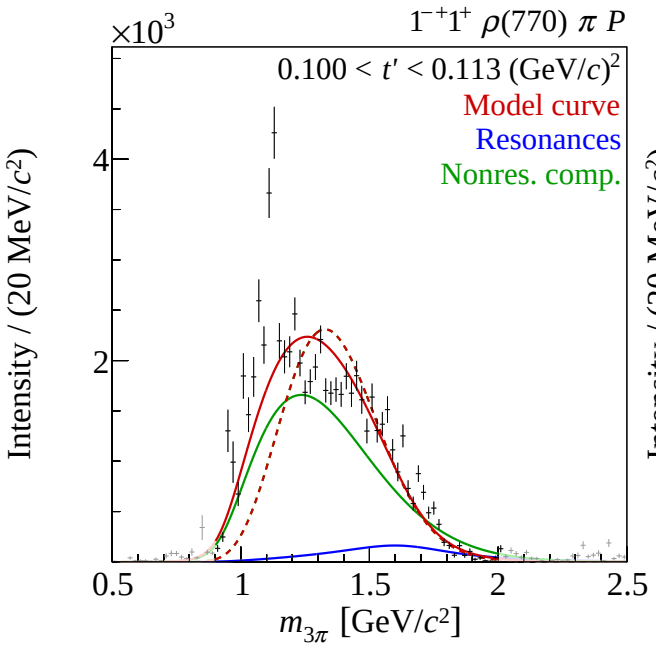
- Data at high t' cannot be described without $\pi_1(1600)$ component (dashed curves)

- t'-resolved analysis solves long-standing puzzle of seemingly contradictory BNL E852 results

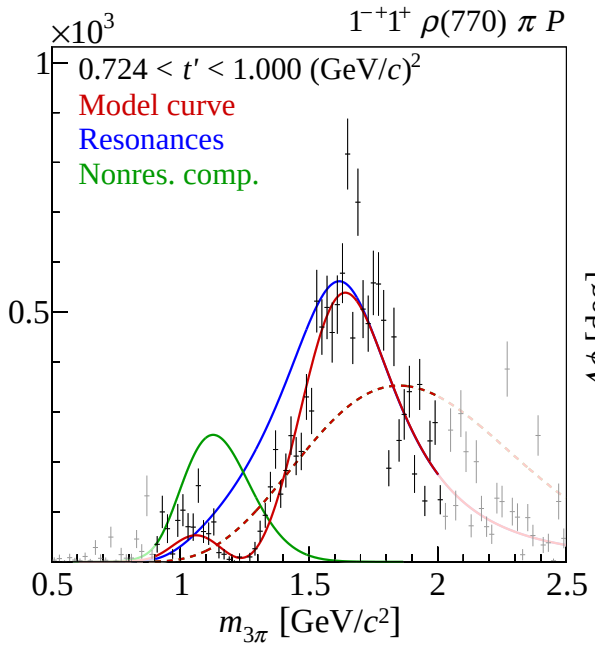
Spin-exotic $1^{-+} \to \rho(770)\pi\, P$ Wave

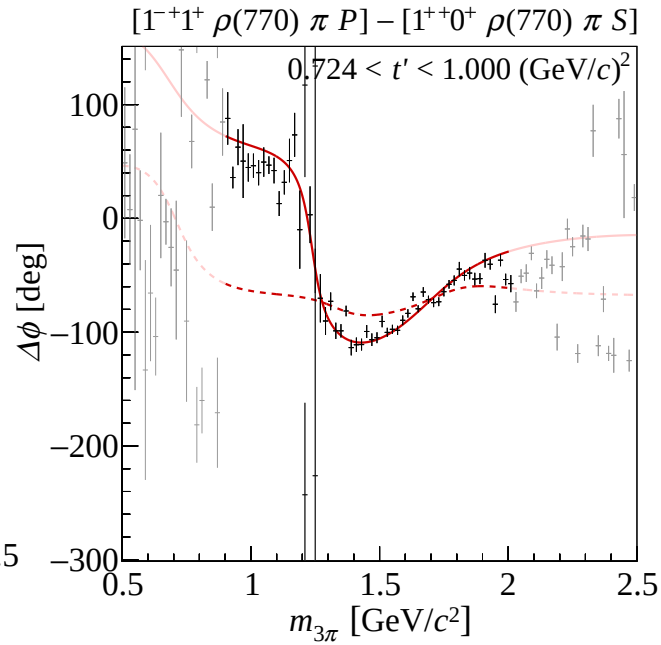
COMPASS, PRD **98** (2018) 092003

lowest t' bin



highest t' bin





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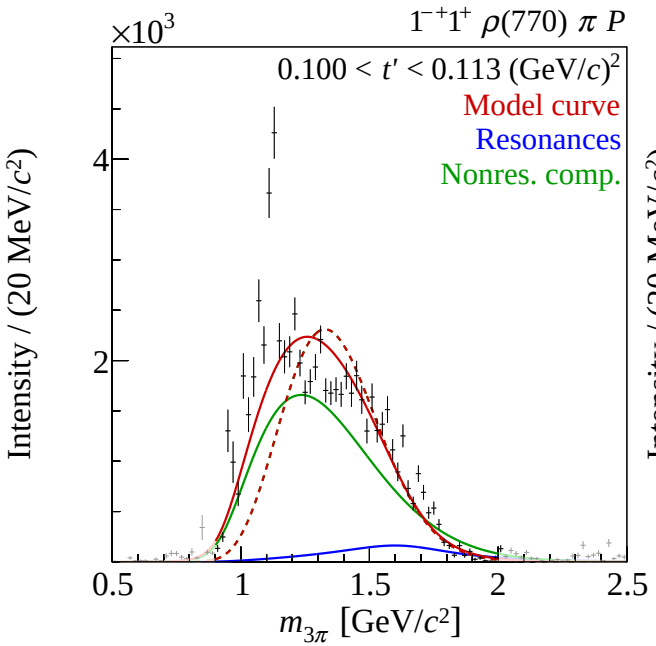

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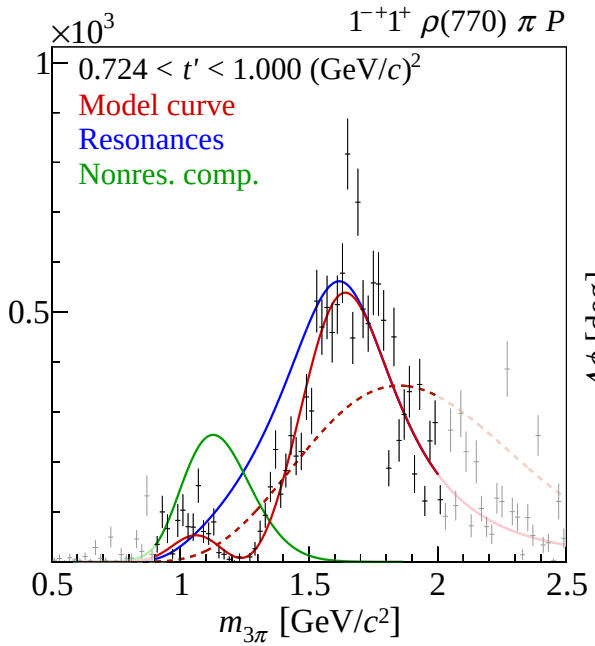

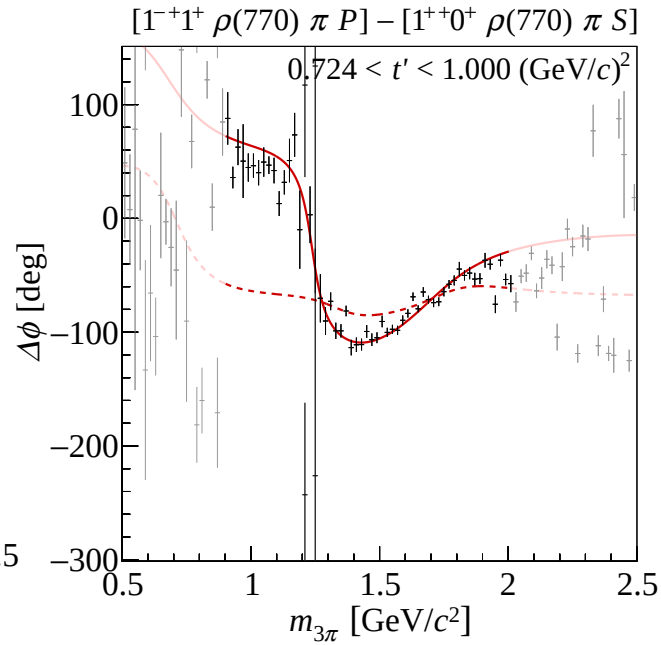

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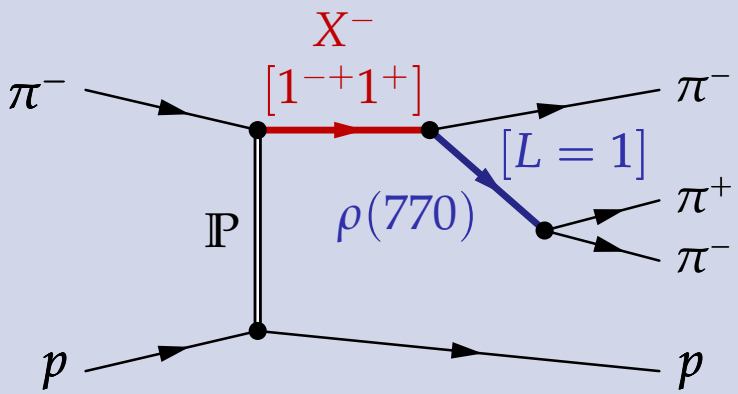
Model Dependence of the $\pi_1(1600)$ Signal?



- Conventional PWA requires complete knowledge of $\xi^0 \to \pi^-\pi^+$ amplitude
  - Employed parametrization for amplitudes of $\rho(770)$ isobar might deviate from data
- *Novel technique:* **"freed-isobar" PWA**

  Krinner *et al.*, PRD **97** (2018) 114008
  - Replace fixed isobar parametrizations by step-like functions
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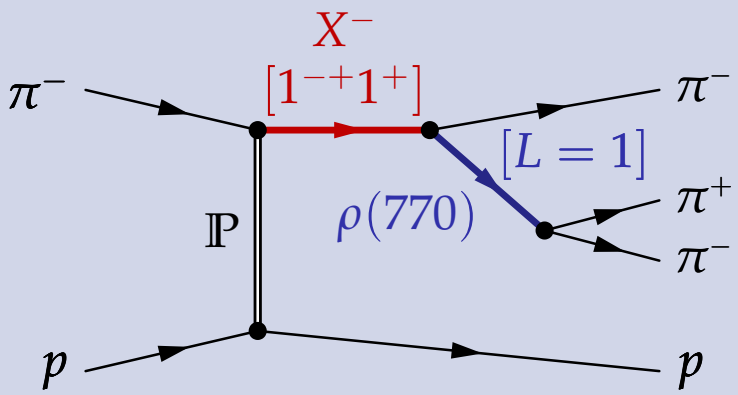

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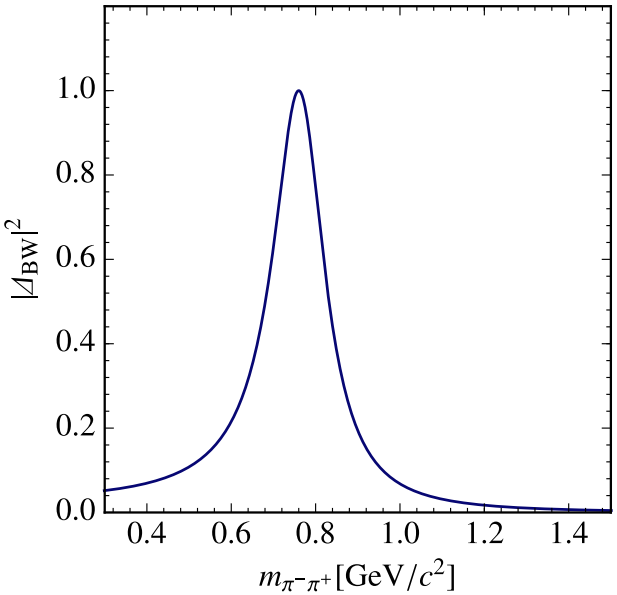

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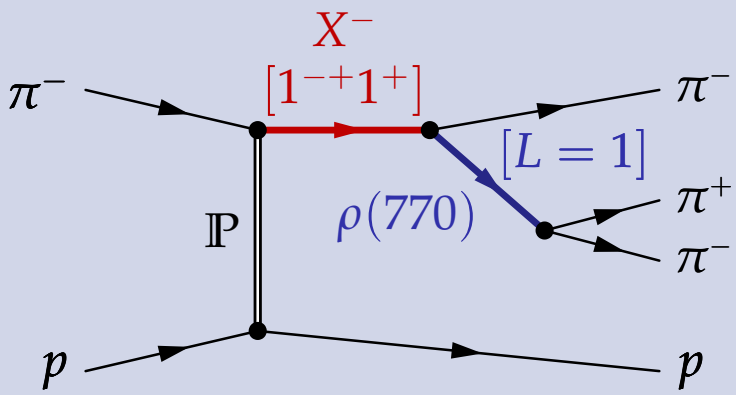

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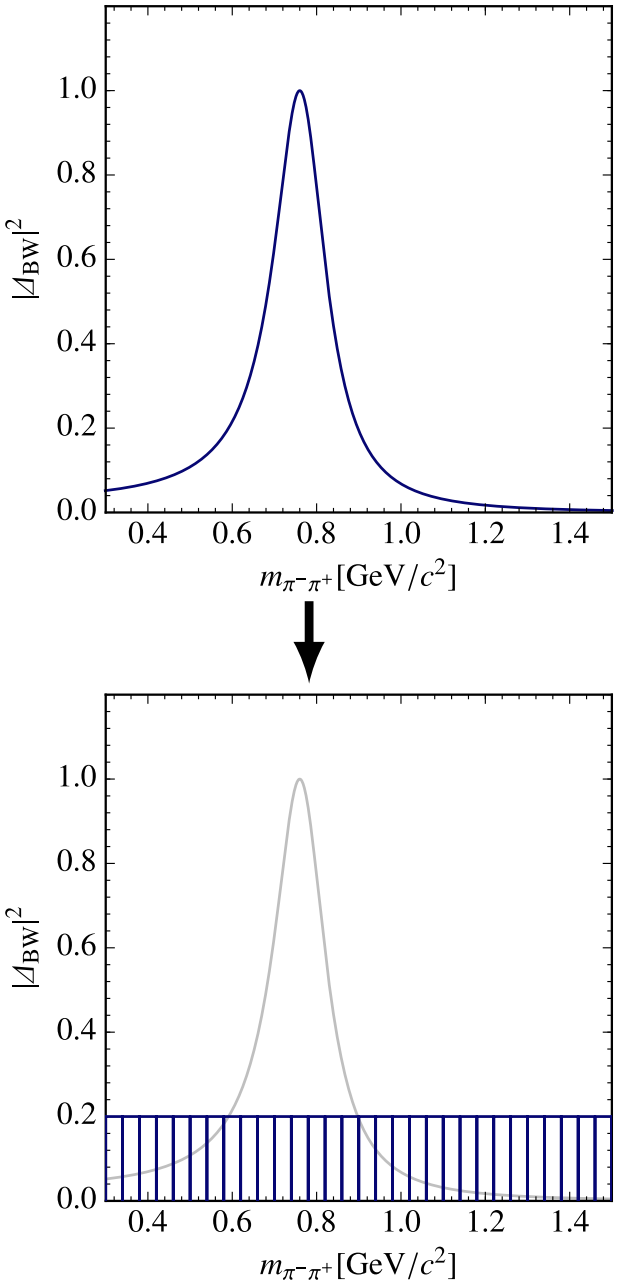

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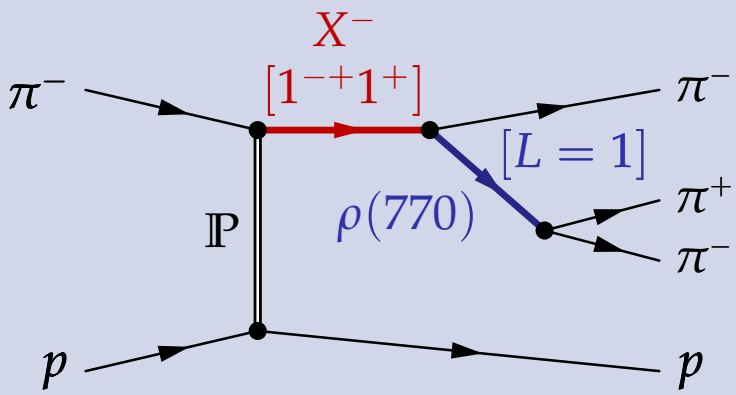

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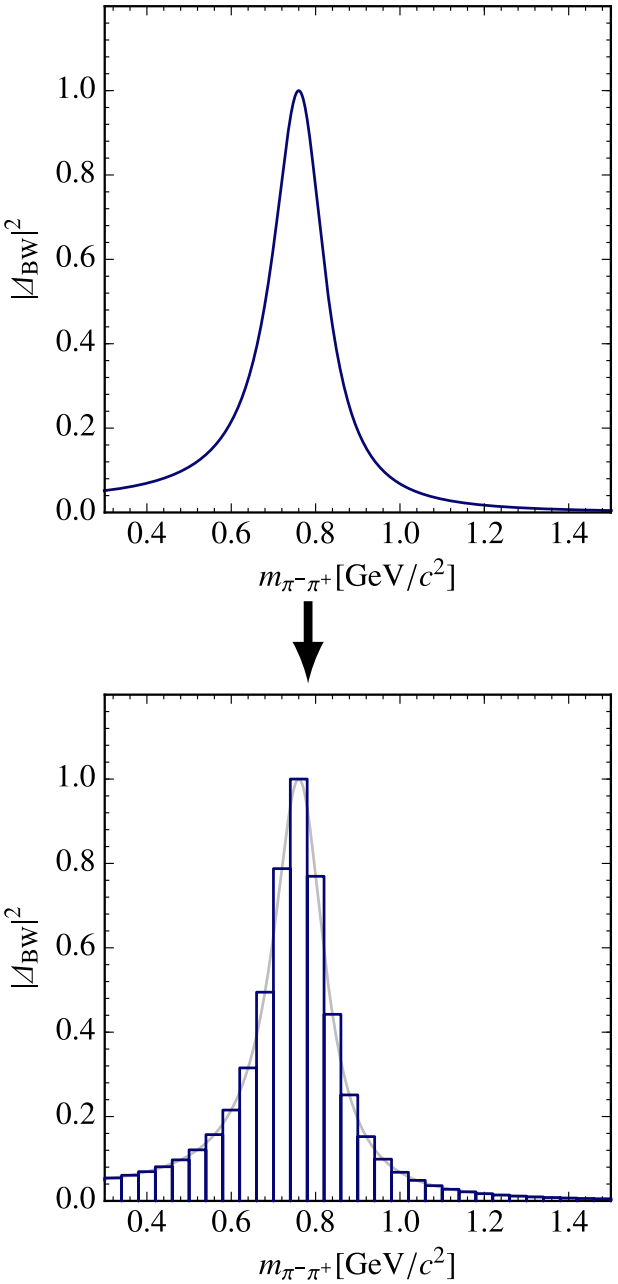
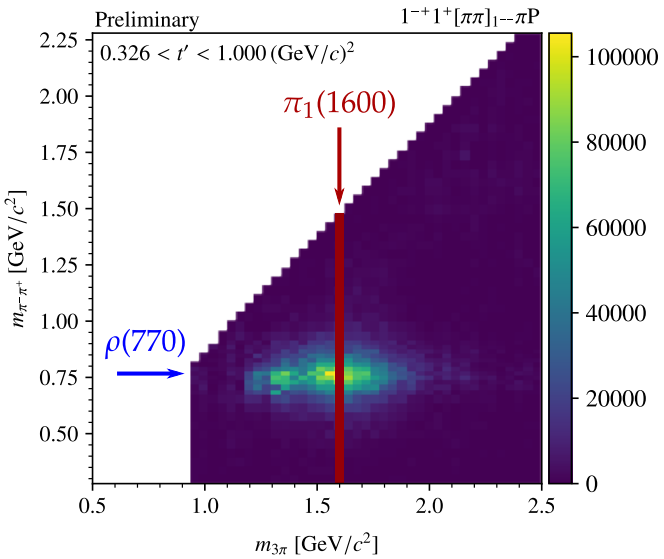


$\pi^-\pi^+$ Amplitude in $1^{-+} \to [\pi\pi]_{1^{--}} + \pi^-$ P Wave

$0.326 < t' < 1.000\,(\mathrm{GeV}/c)^2$



- Intensity peak at $m_{3\pi} \approx 1.6\,\mathrm{GeV}/c^2$ and $m_{\pi^-\pi^+} \approx 0.8\,\mathrm{GeV}/c^2$
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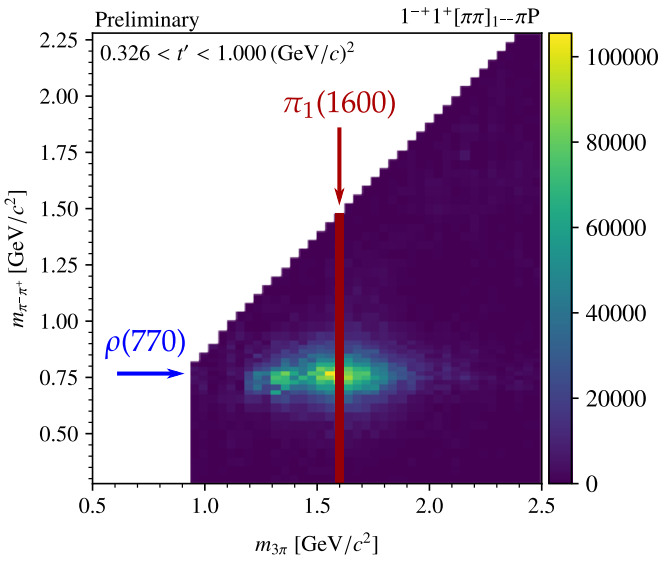

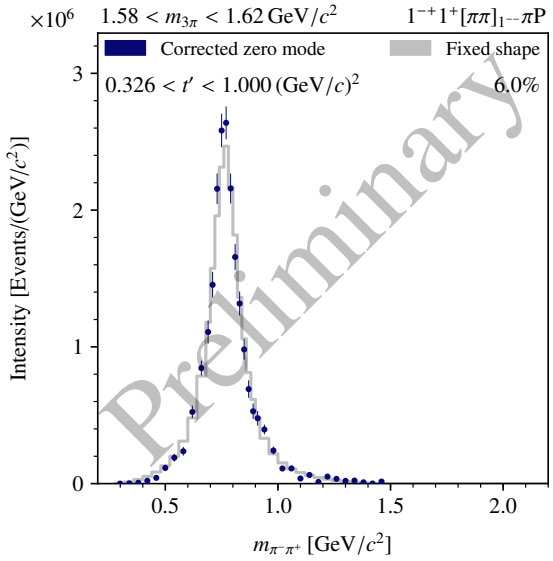

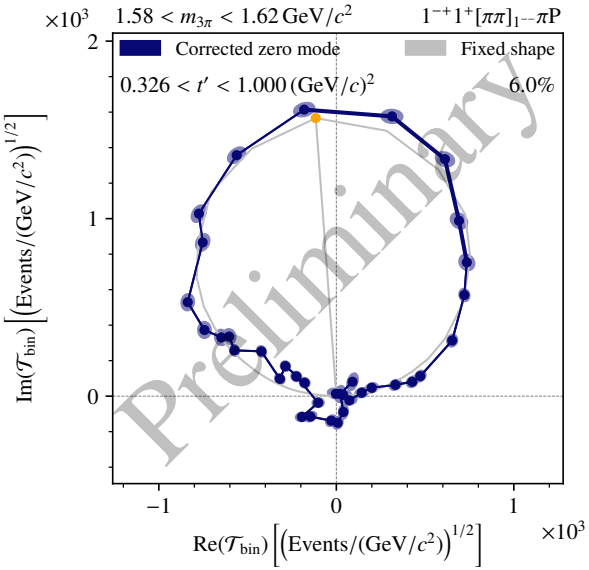

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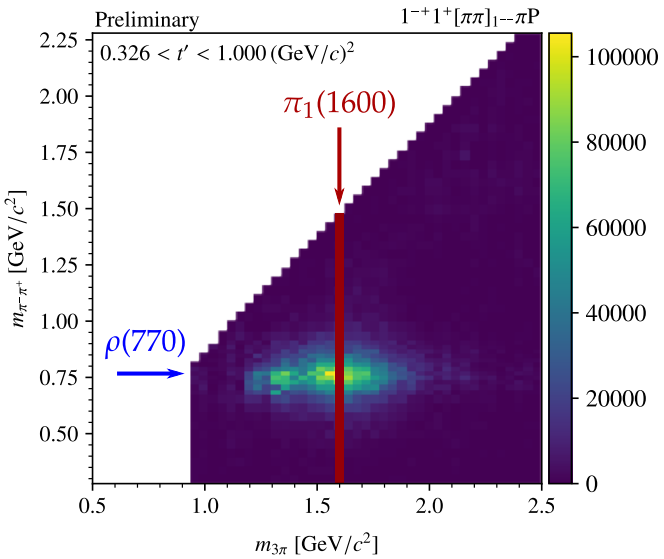

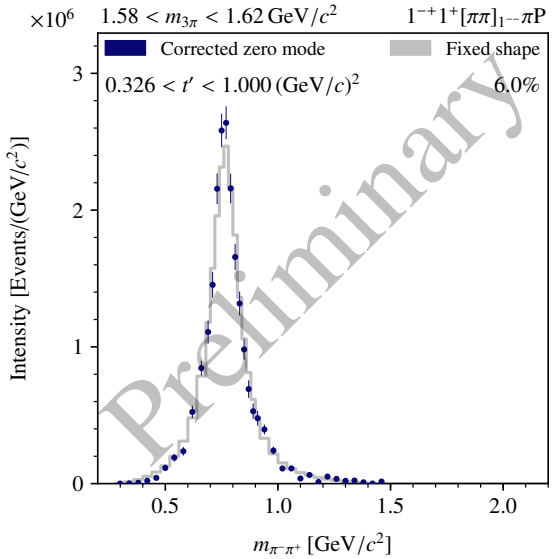

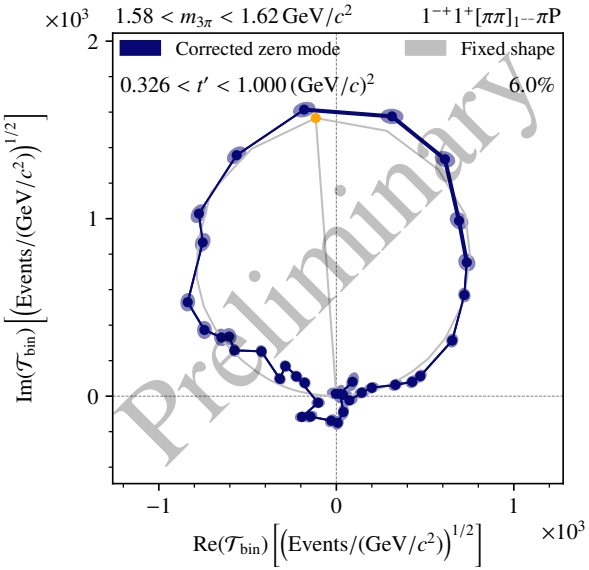

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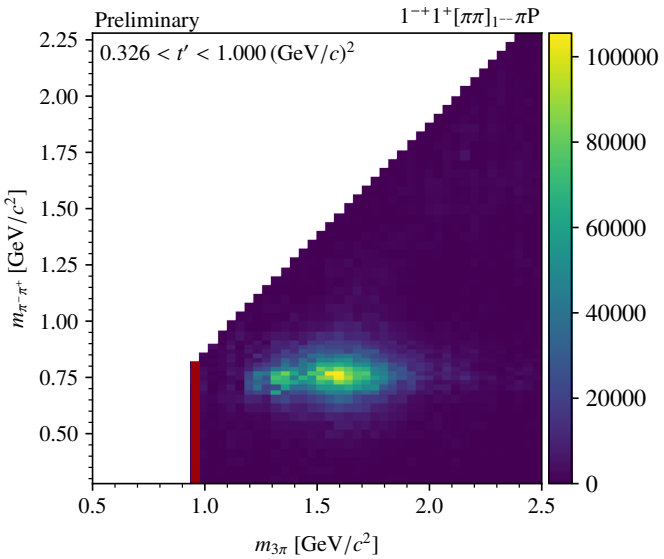

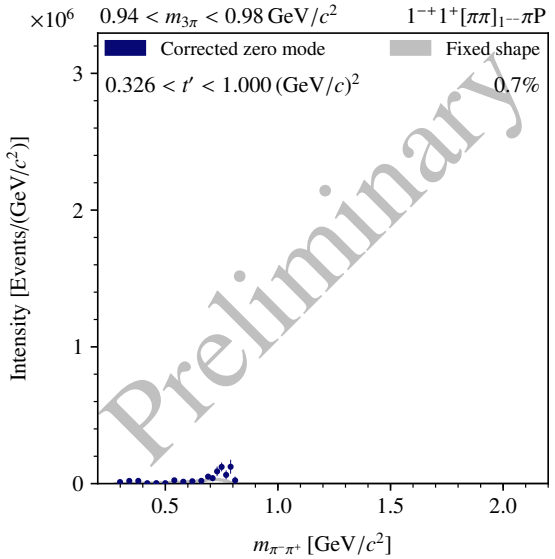

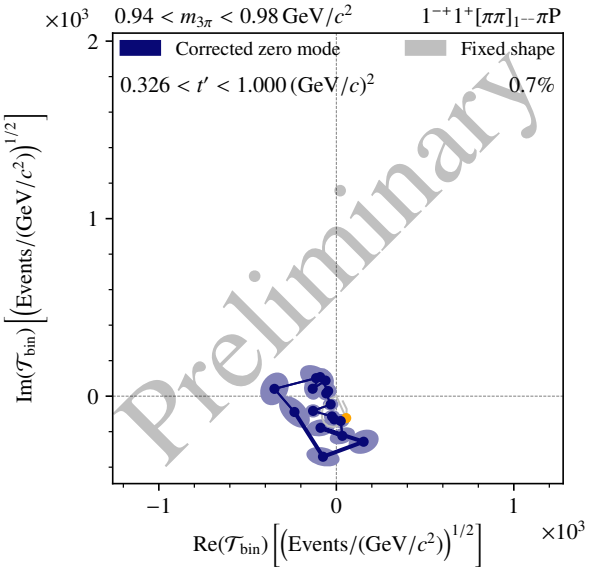

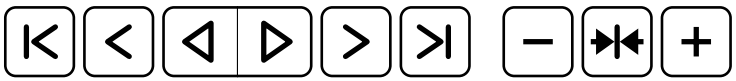

Comparison with Conventional PWA

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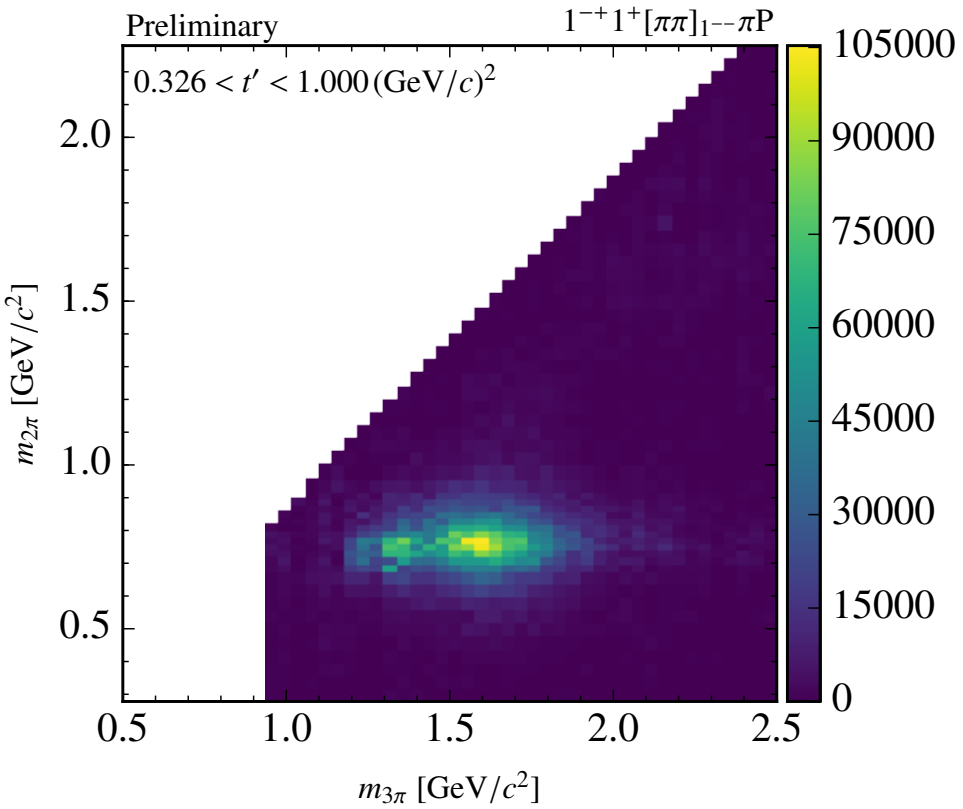
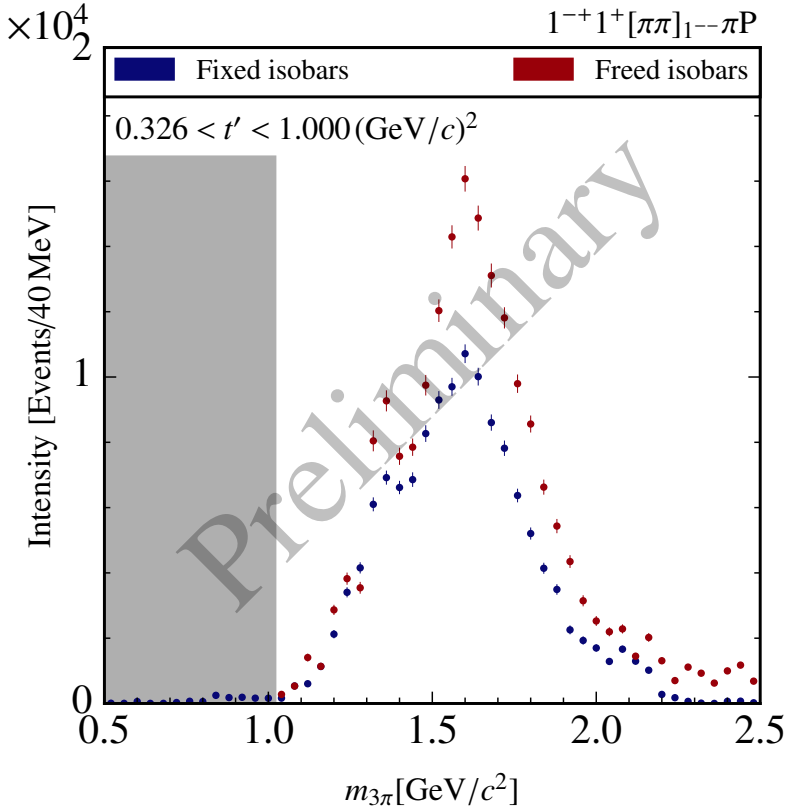
Coherent sum over $m_{\pi^-\pi^+}$





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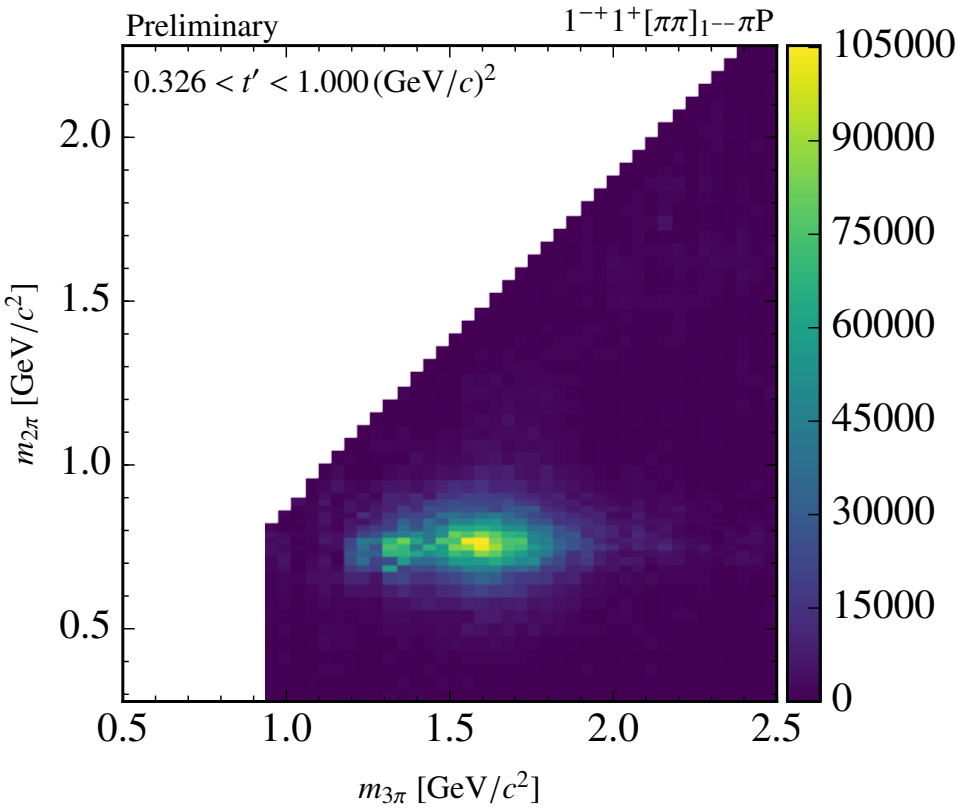

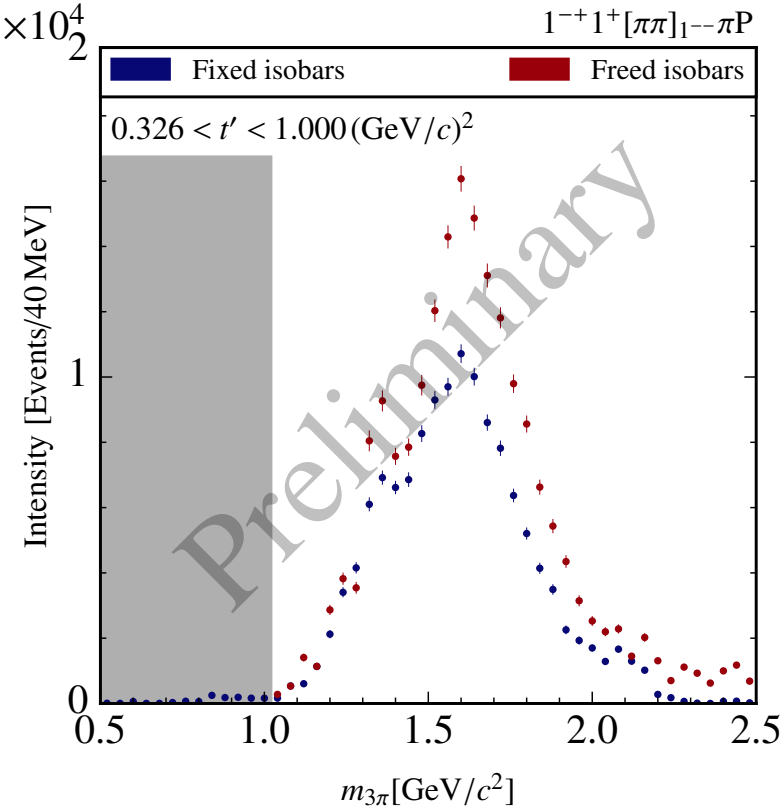

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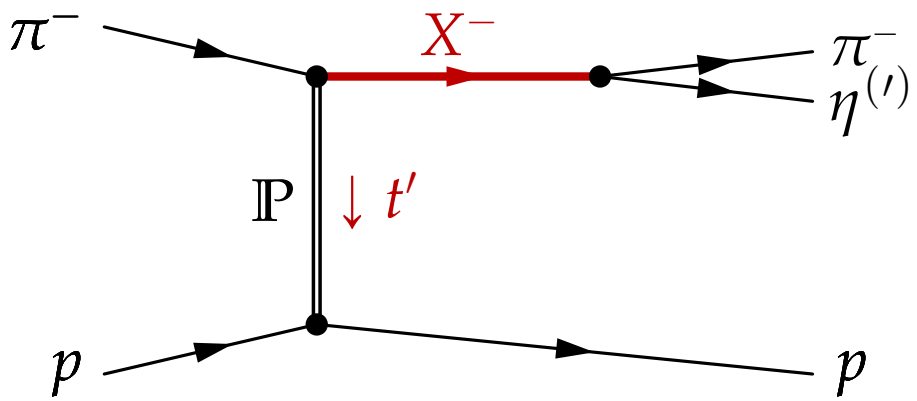
See talk by Fabian Krinner, Sat at 14:30

JPAC Coupled-Channel Analysis of $\eta\pi$ and $\eta'\pi$

Rodas *et al.* [JPAC], PRL **122** (2019) 042002



- Partial-wave amplitudes from COMPASS PLB **740** (2015) 303
- Analytical and unitary model based on S-matrix principles

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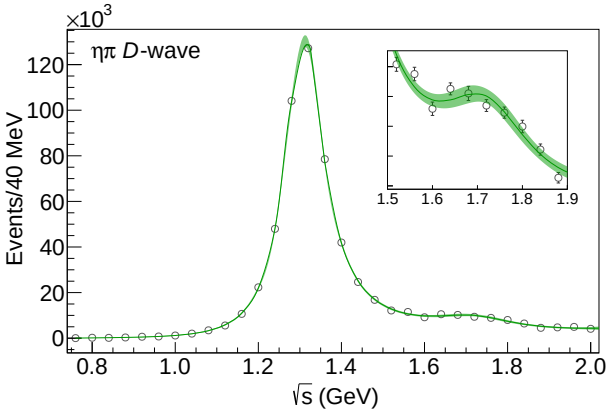
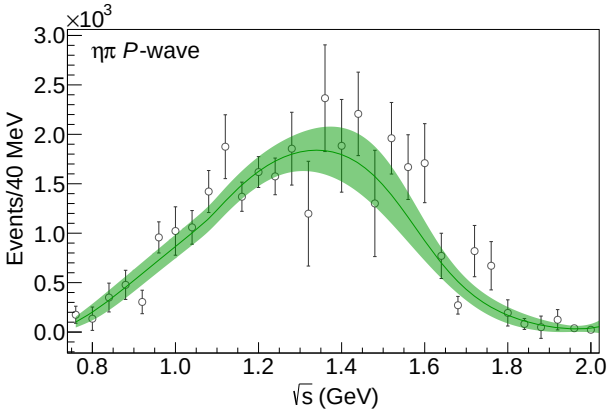
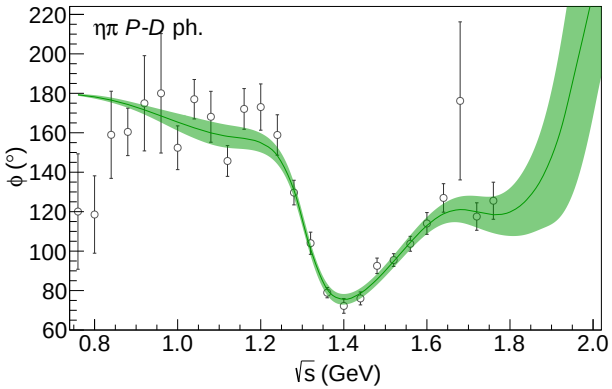
$\eta\pi$: 2^{++}



1^{-+}



$\Delta\phi(1^{-+} - 2^{++})$



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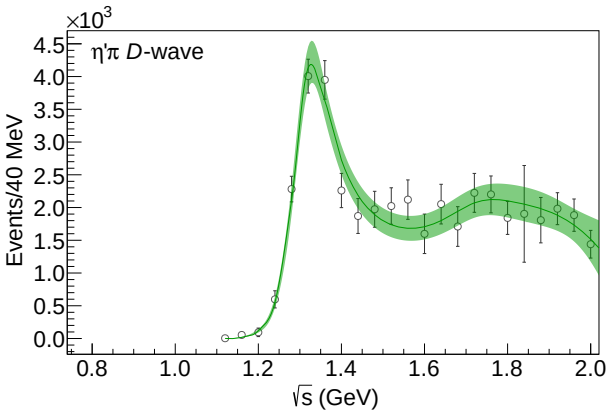

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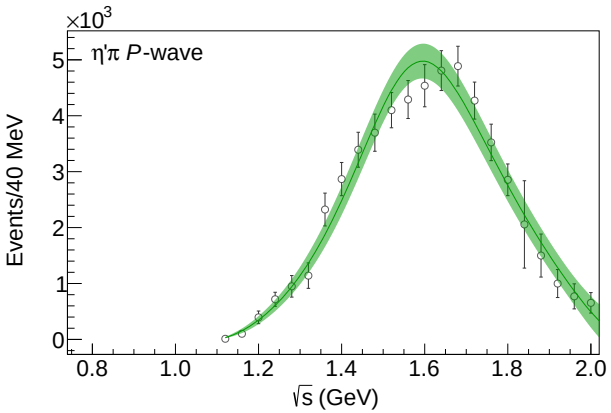

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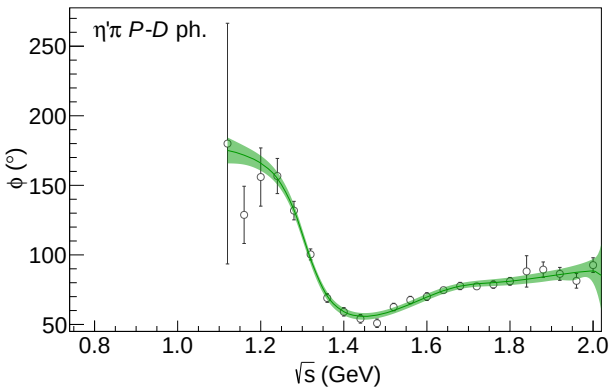

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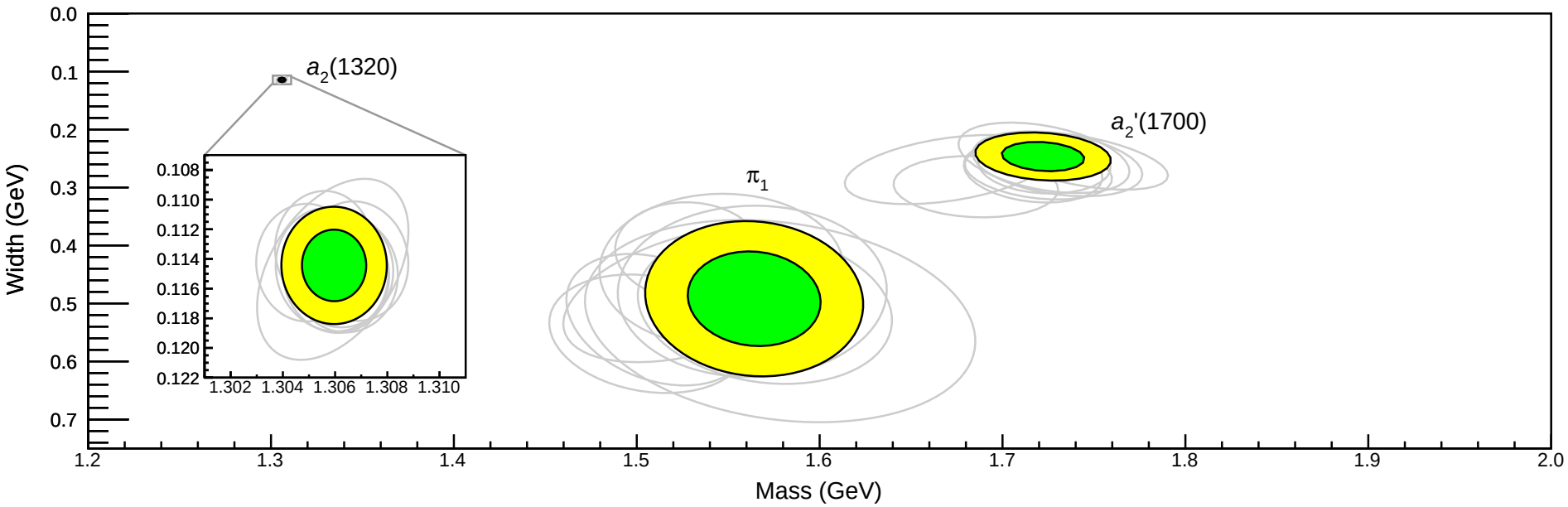
JPAC Coupled-Channel Analysis of $\eta\pi$ and $\eta'\pi$

Resonance Pole Parameters

Rodas *et al.* [JPAC], PRL **122** (2019) 042002



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  - $\Gamma_0 = (492 \pm 54_{\text{stat.}} \pm 102_{\text{sys.}})\,\text{MeV}/c^2$
  - Consistent with $\pi_1(1600)$
  - First measurement of pole parameters of $\pi_1(1600)$
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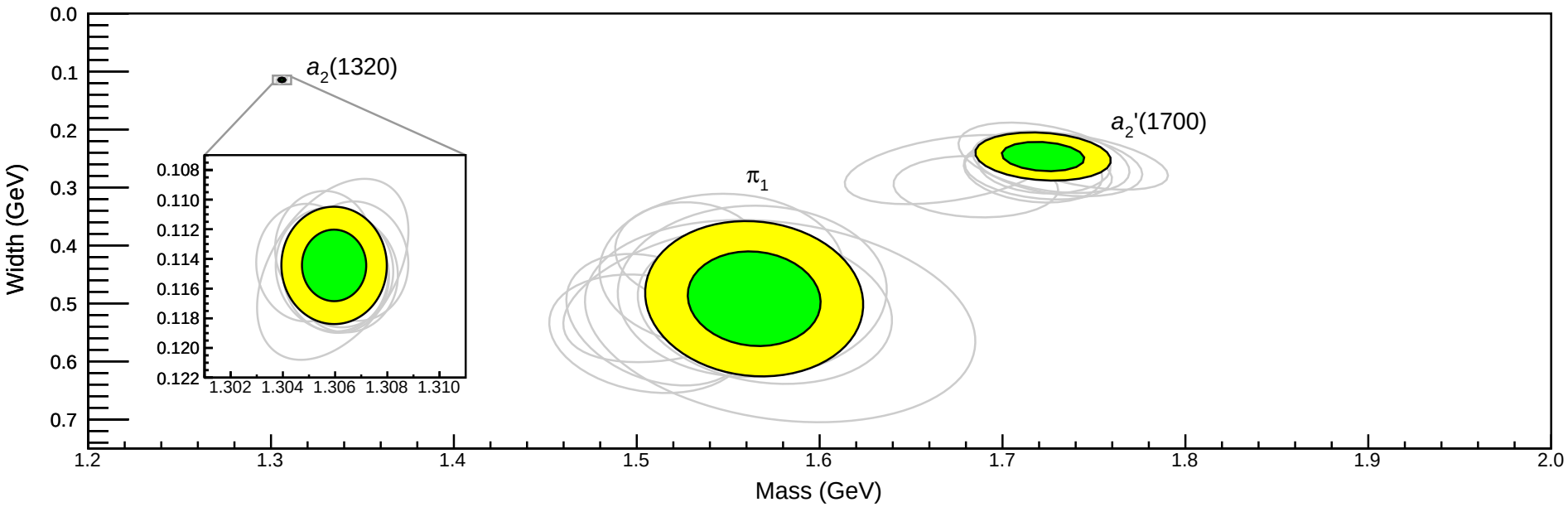

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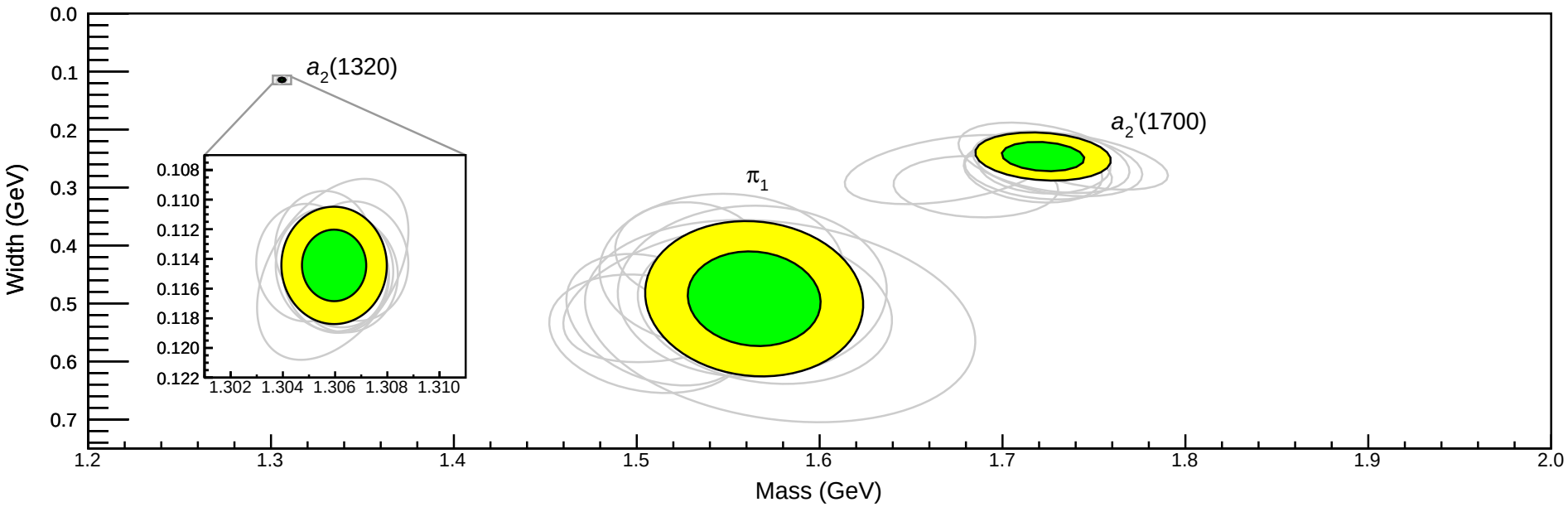
JPAC Coupled-Channel Analysis of $\eta\pi$ and $\eta'\pi$

Resonance Pole Parameters

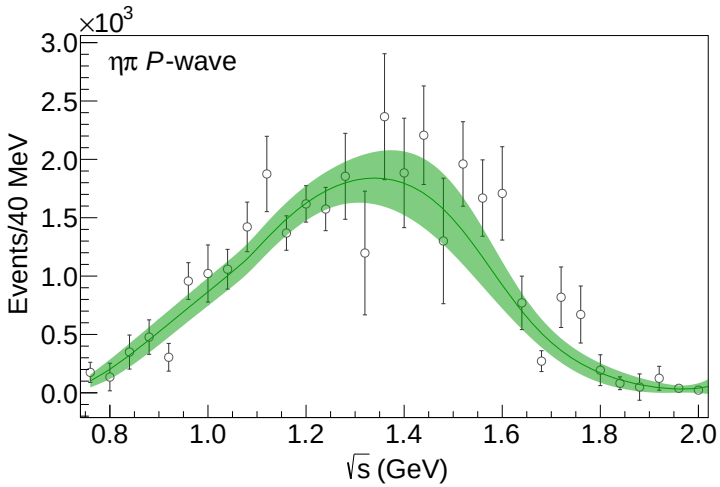
Rodas *et al.* [JPAC], PRL **122** (2019) 042002



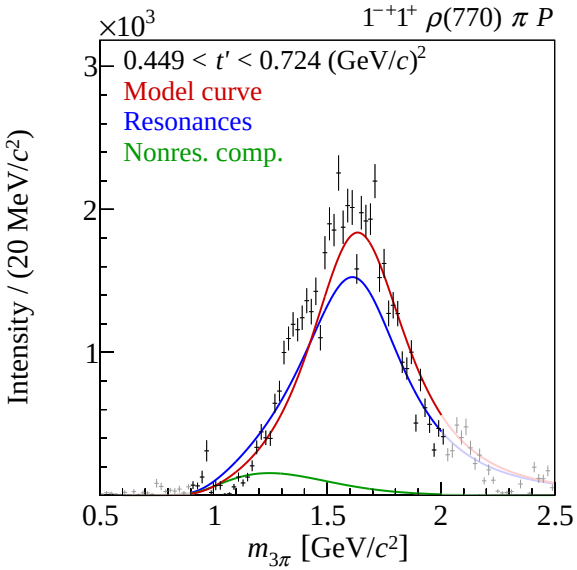
- Only single 1^{-+}-wave pole required to describe peaks at 1.4 and 1.6 GeV/c^2
  - $m_0 = (1564 \pm 24_{\text{stat.}} \pm 86_{\text{sys.}})\,\text{MeV}/c^2$
  - $\Gamma_0 = (492 \pm 54_{\text{stat.}} \pm 102_{\text{sys.}})\,\text{MeV}/c^2$
  - Consistent with $\pi_1(1600)$
  - First measurement of pole parameters of $\pi_1(1600)$
- Raises doubts about existence of $\pi_1(1400)$

The $\pi_1(1600)$: Three Sides of the Same Coin

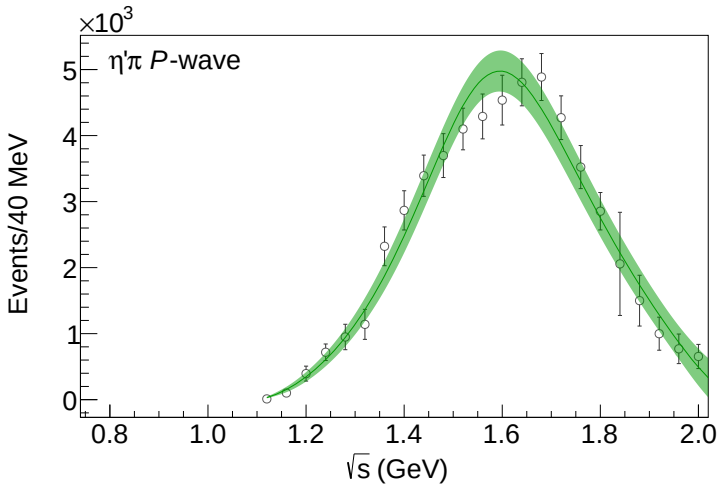
$\eta\pi$: $0.1 < t' < 1.0\,(\mathrm{GeV}/c)^2$



3π: $0.449 < t' < 0.724\,(\mathrm{GeV}/c)^2$



$\eta'\pi$: $0.1 < t' < 1.0\,(\mathrm{GeV}/c)^2$



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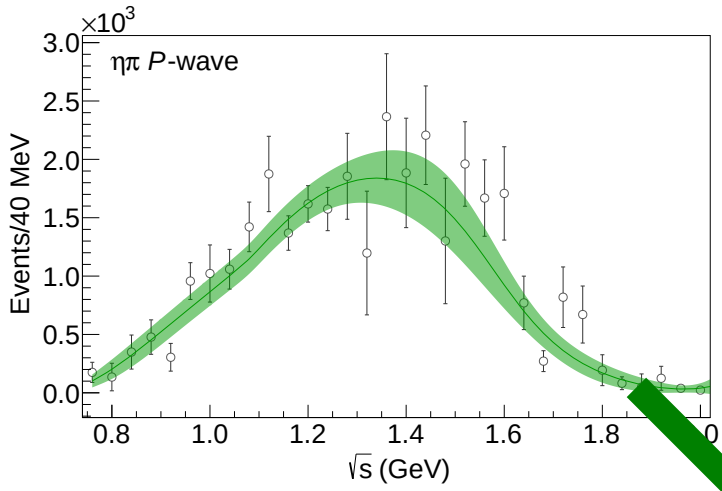

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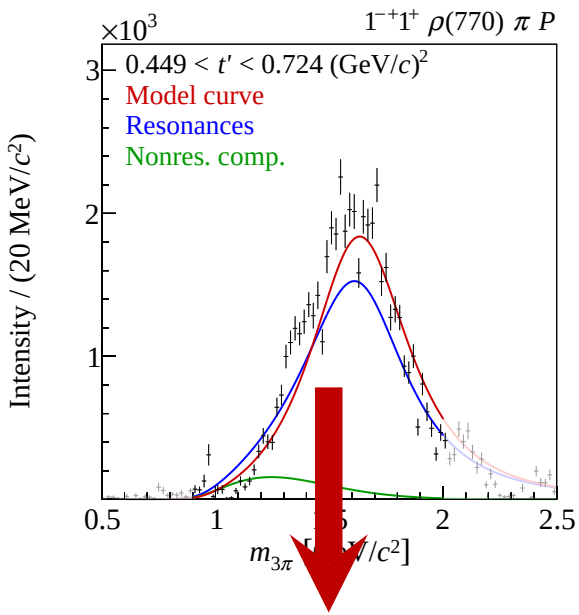
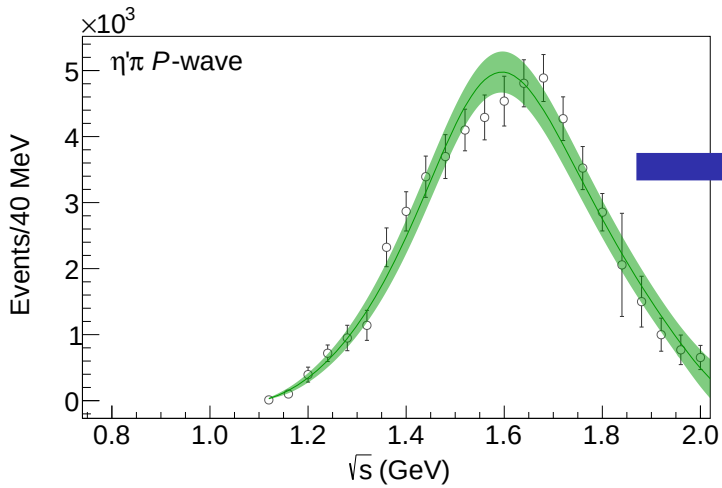
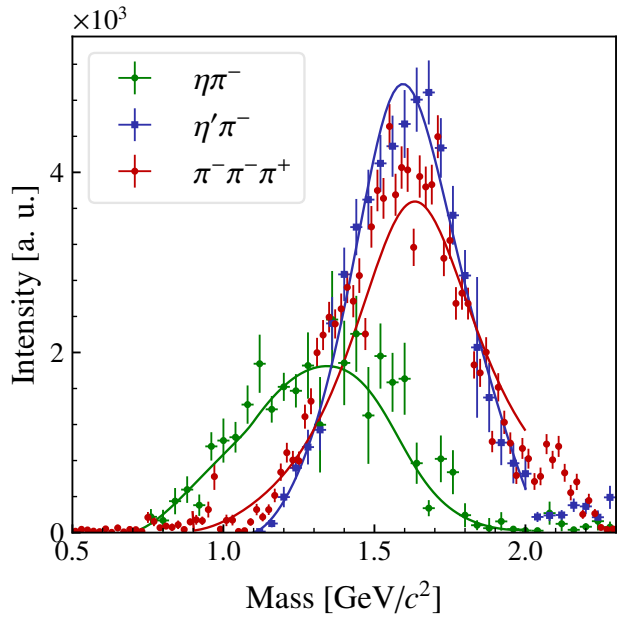


$\eta'\pi$: $0.1 < t' < 1.0\,(\mathrm{GeV}/c)^2$

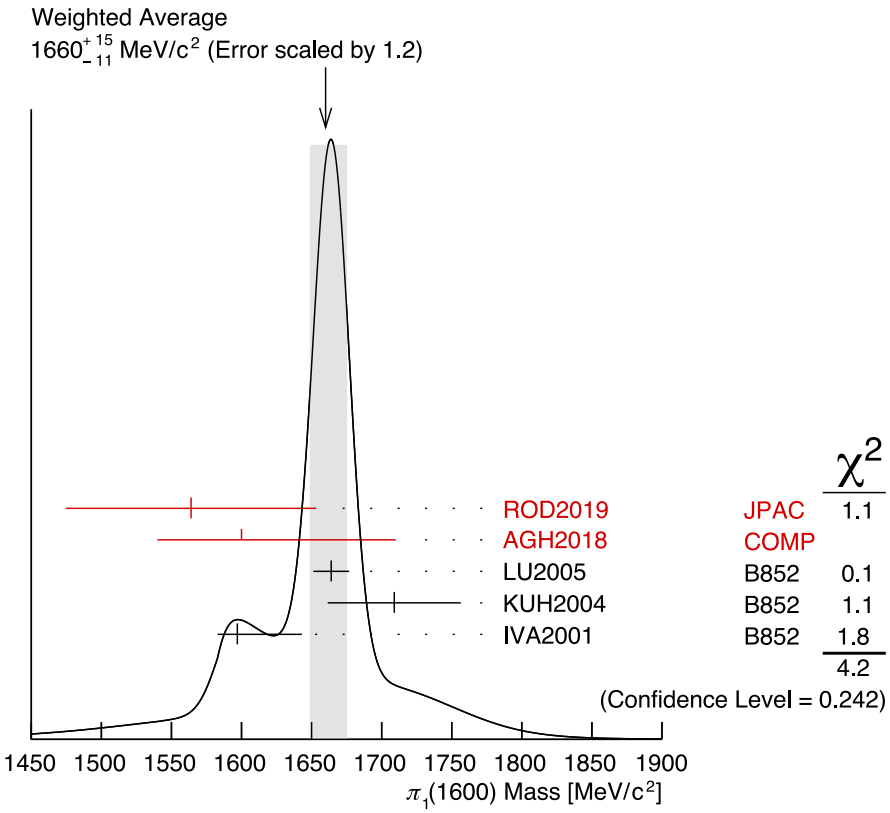




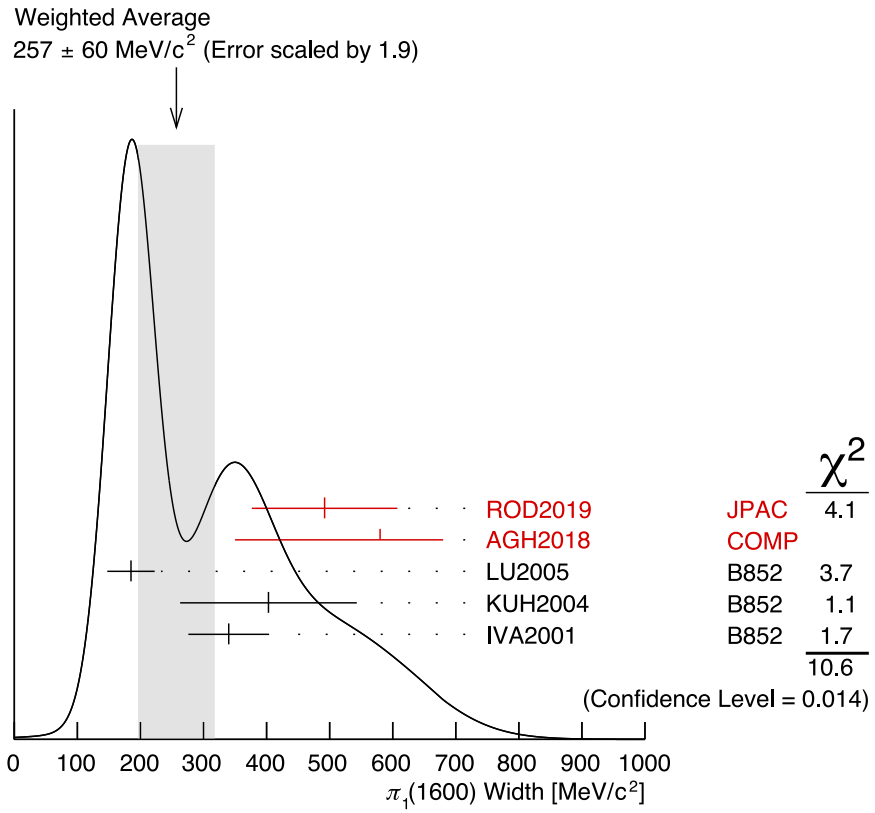
The $\pi_1(1600)$ Resonance Parameters

PDG 2019

$$m_0 = (1660\,^{+15}_{-11})\,\mathrm{MeV}/c^2$$



$$\Gamma_0 = (257 \pm 60)\,\mathrm{MeV}/c^2$$

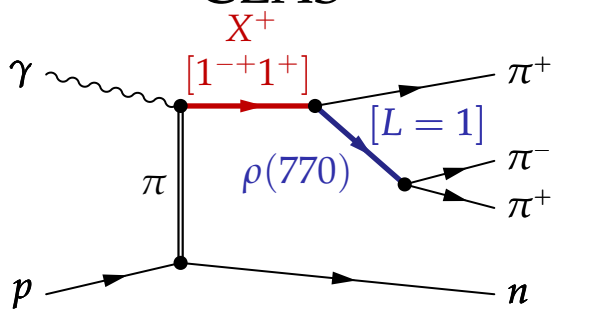


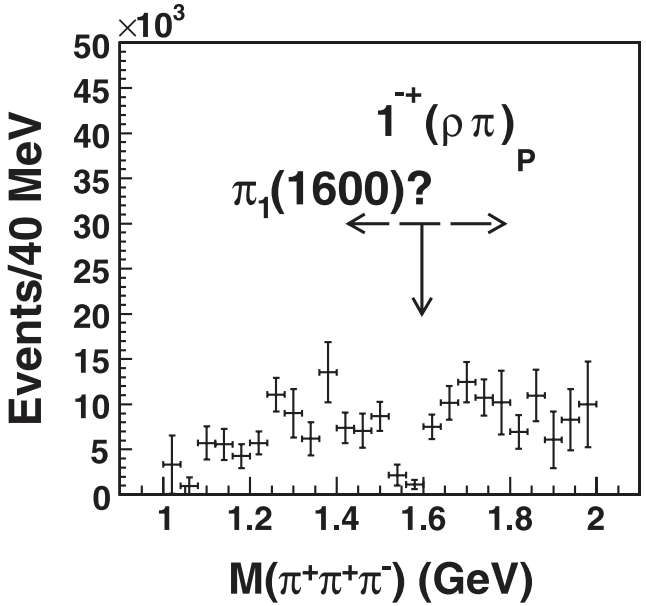
- Most measurements prefer width $> 300\,\mathrm{MeV}/c^2$
- Breit-Wigner parameters in fair agreement with pole parameters
- Still large uncertainties, mostly systematical

A Remaining Puzzle

Spin-exotic $1^{-+}\,1^{+}\,\rho(770)\,\pi\,P$ Wave from $\pi\gamma$ Interactions

CLAS





PRL **102** (2009) 102002

COMPASS

- We observe $\pi_1(1600) \to \rho(770)\pi$ but not $\pi\gamma \to \pi_1(1600)$?

A Remaining Puzzle

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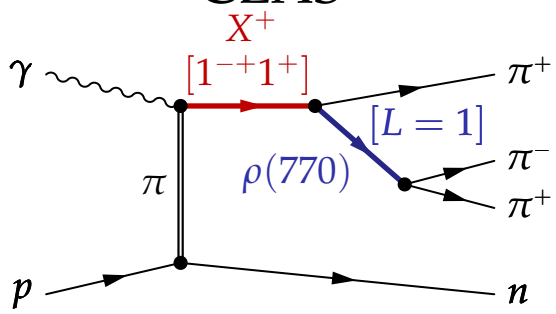

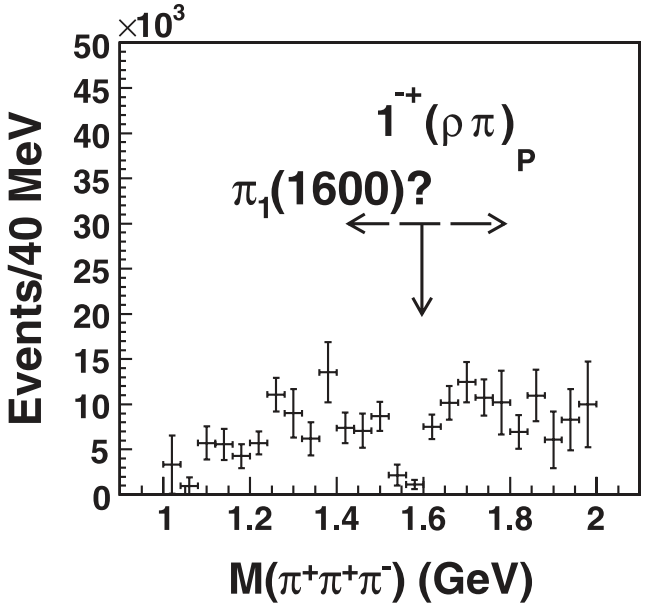

PRL **102** (2009) 102002

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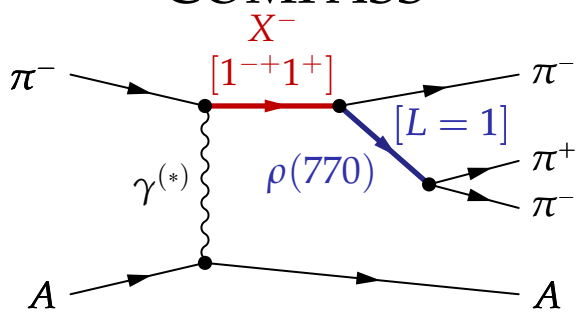

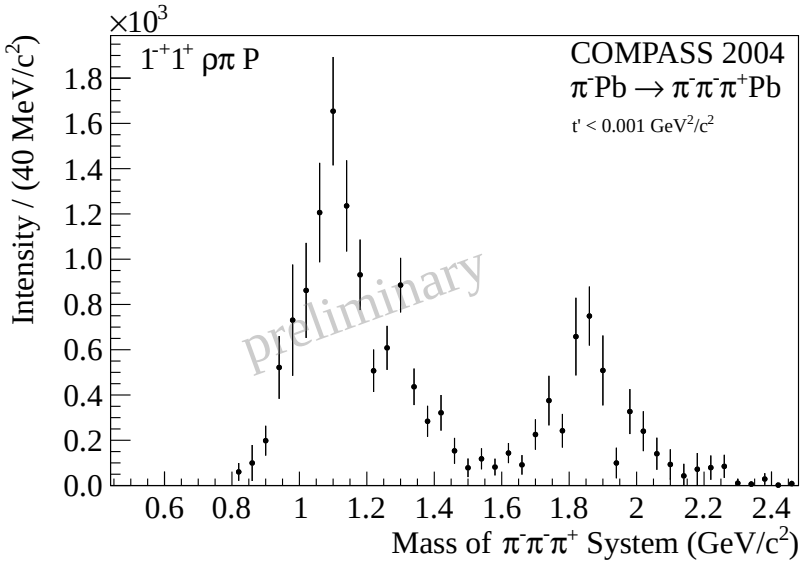

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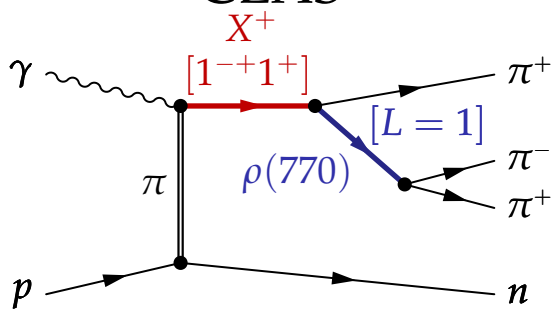
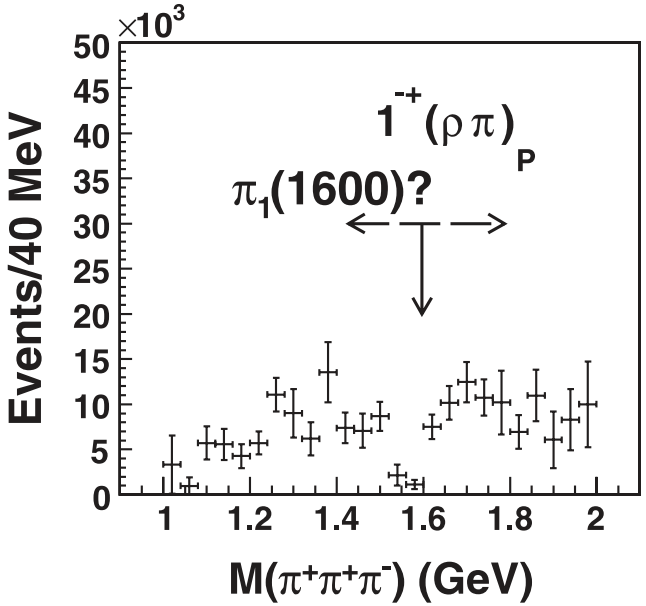
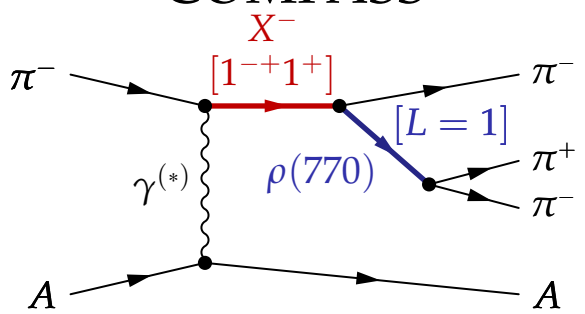
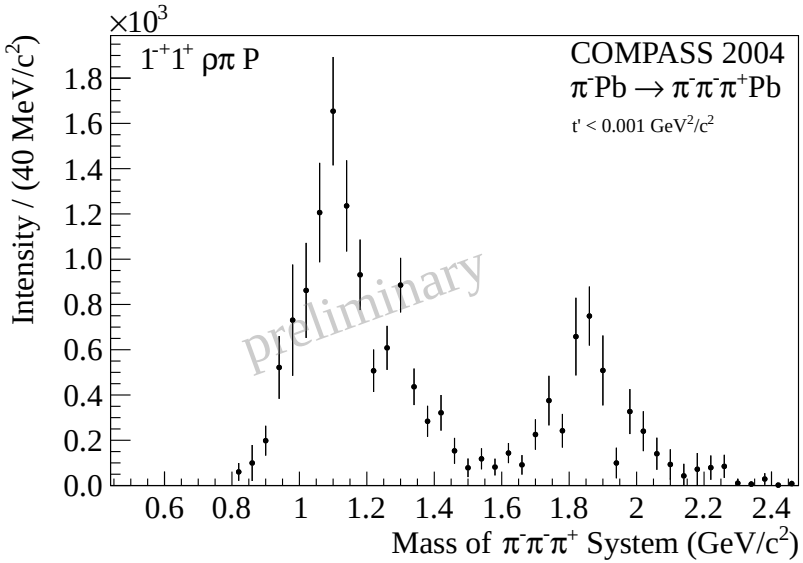




PRL **102** (2009) 102002

COMPASS





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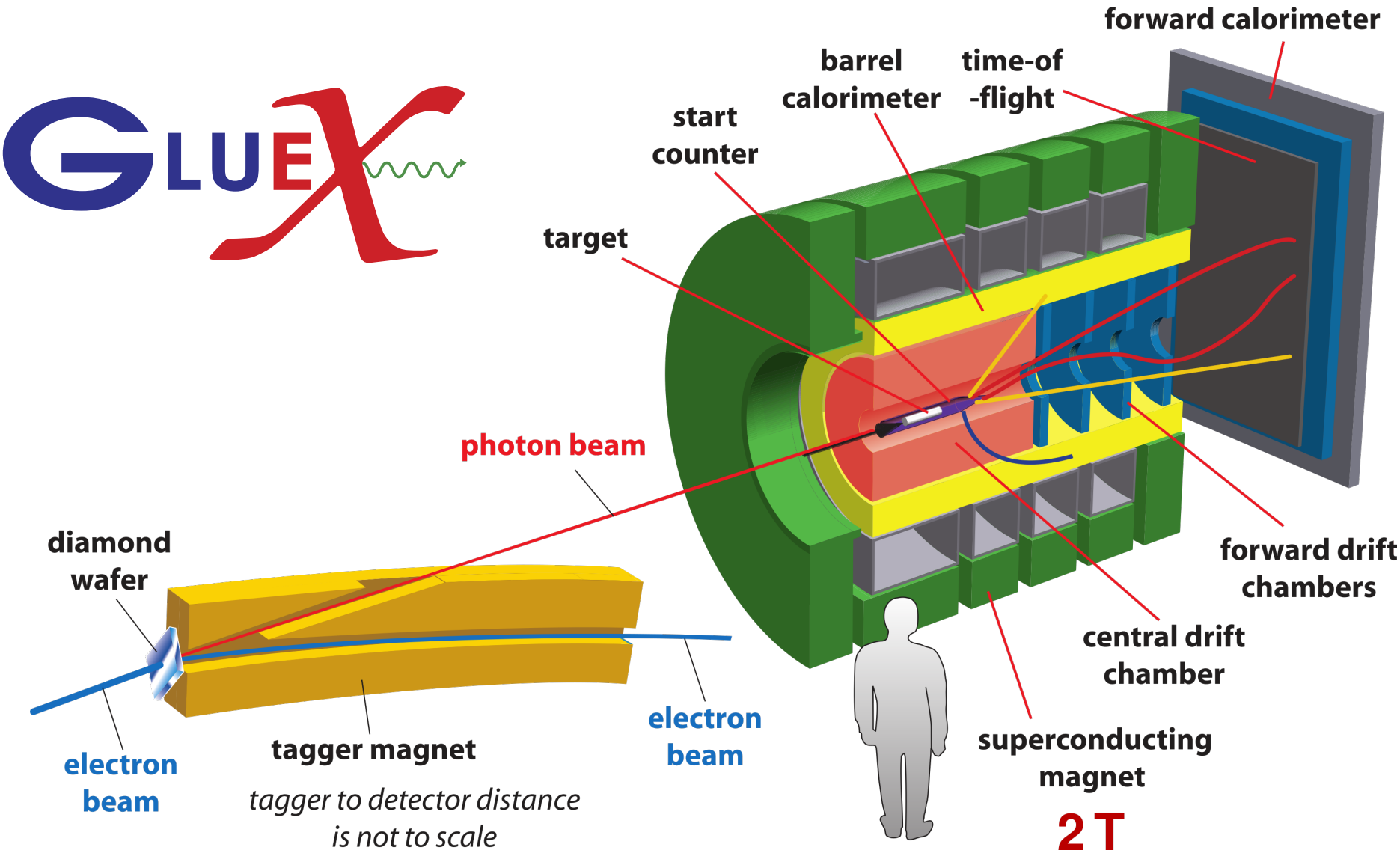
The GlueX Experiment at the JLab CEBAF

Experimental Setup

Al Ghoul *et al.* [GlueX], AIP Conf. Proc. **1735** (2016) 020001



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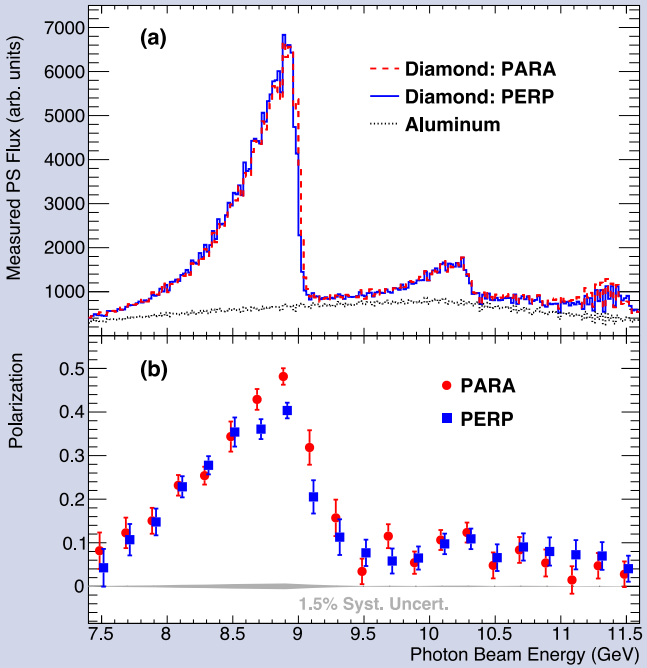
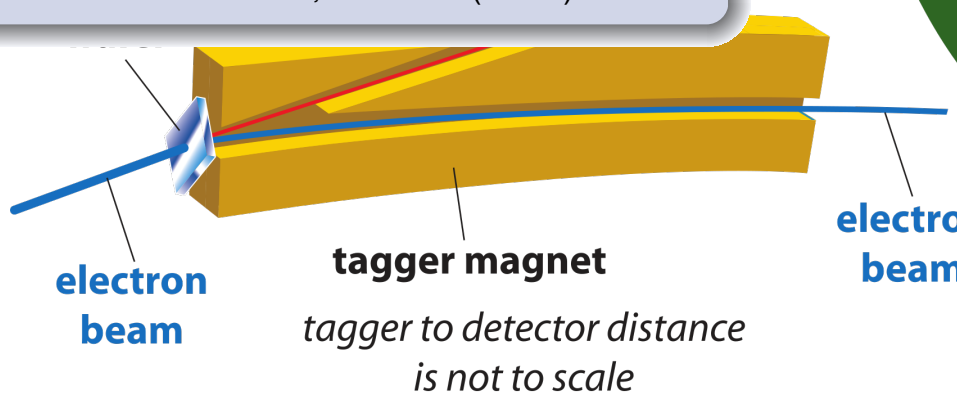
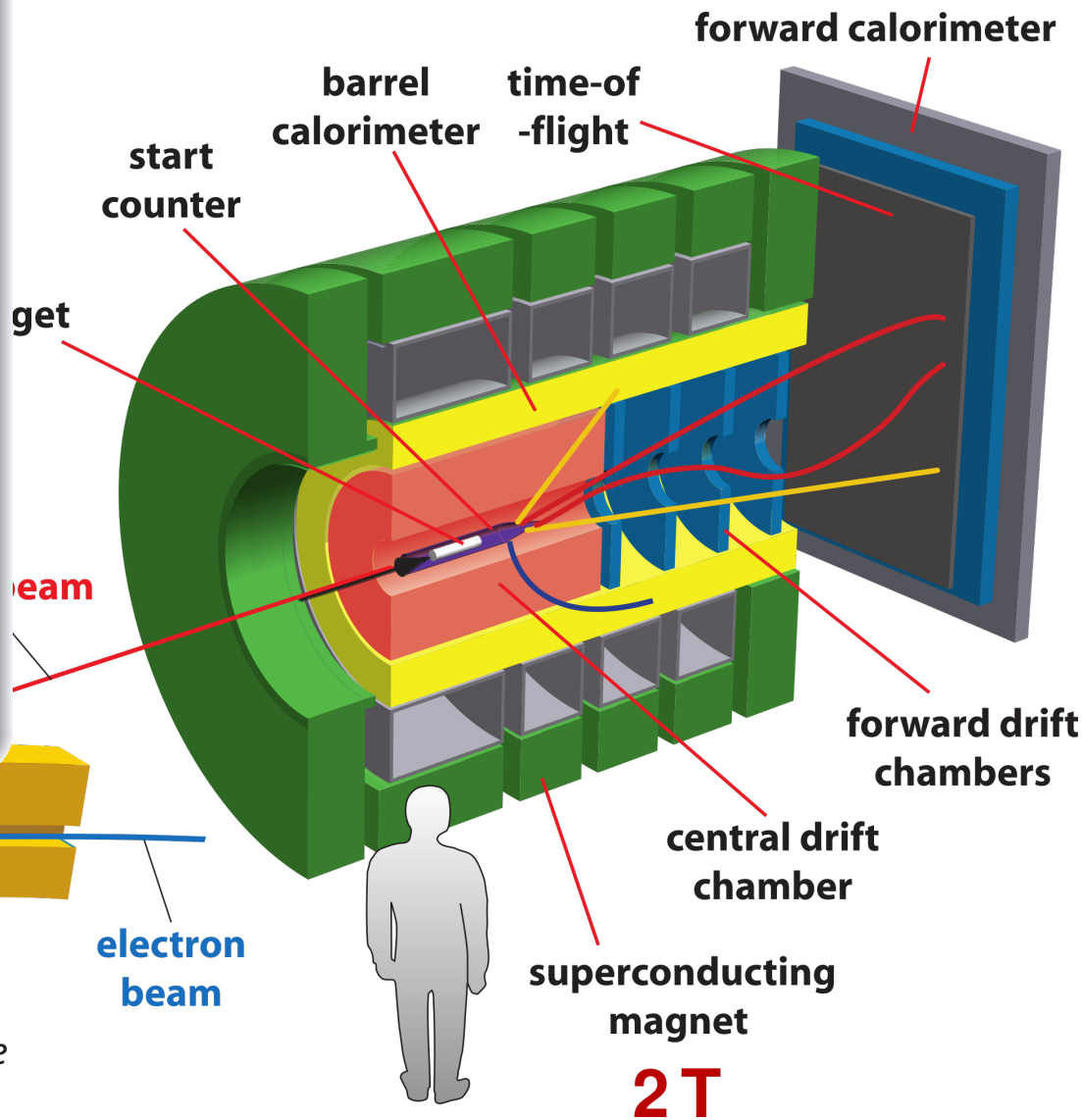
Lin. polarized γ beam on p target



GlueX, PRC **95** (2017) 042201





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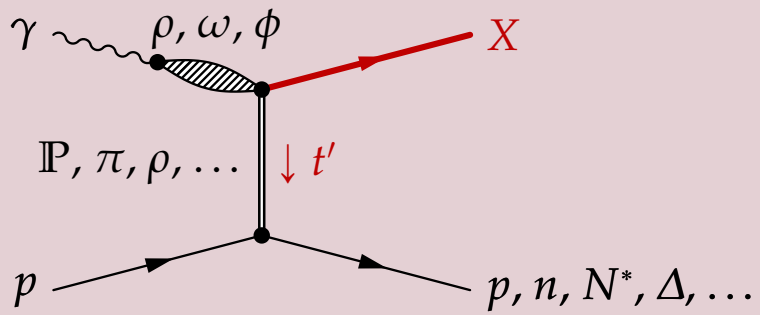


- Wide variety of $I^G\ J^{PC}$ accessible
- γ polarization constraints production processes
- Complementary to π beam (COMPASS, VES)

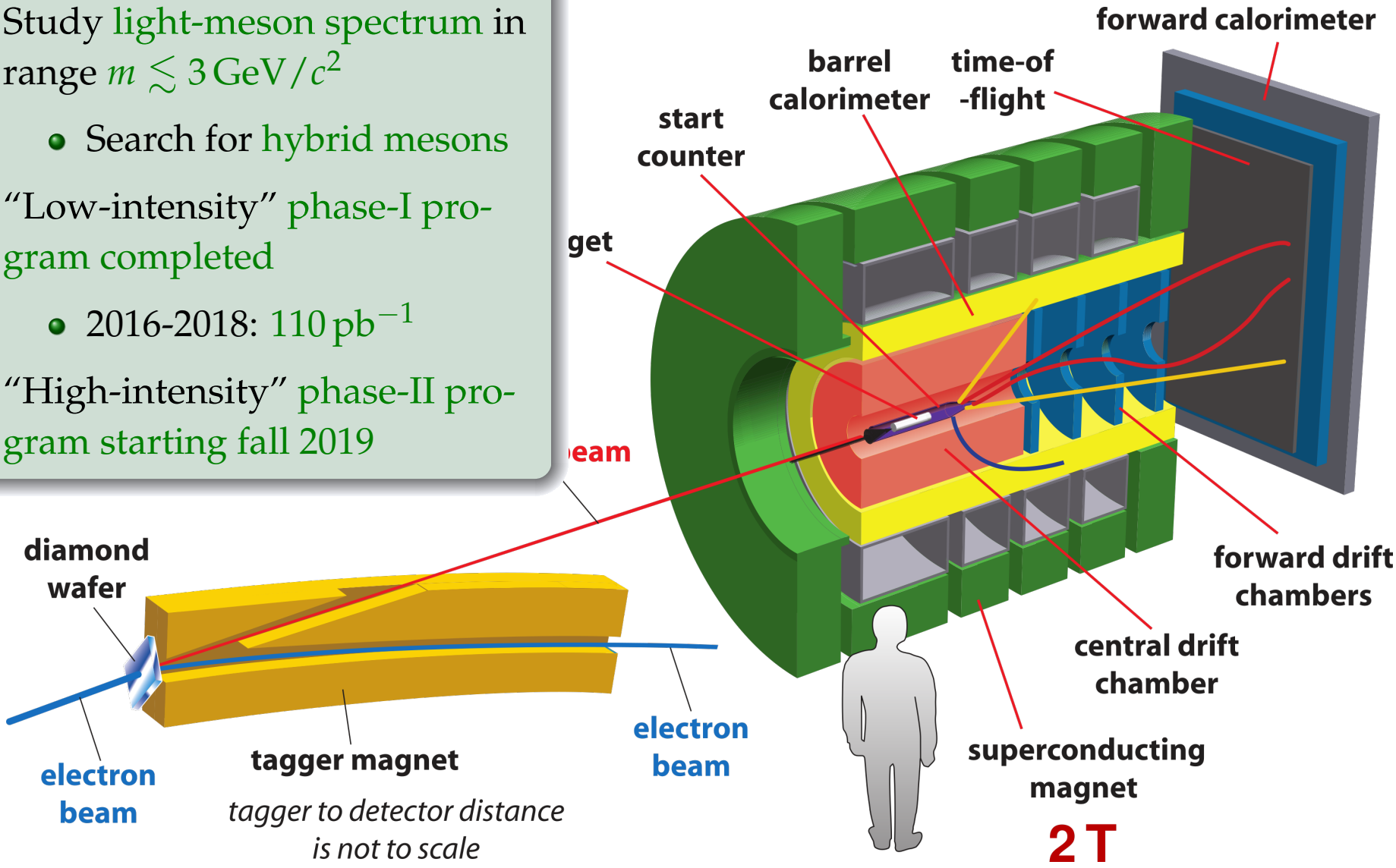
The GlueX Experiment at the JLab CEBAF

Experimental Setup

Al Ghoul *et al.* [GlueX], AIP Conf. Proc. **1735** (2016) 020001

Lin. polarized γ beam on p target

- Study light-meson spectrum in range $m \lesssim 3\,\mathrm{GeV}/c^2$
  - Search for hybrid mesons
- "Low-intensity" phase-I program completed
  - 2016-2018: $110\,\mathrm{pb}^{-1}$
- "High-intensity" phase-II program starting fall 2019



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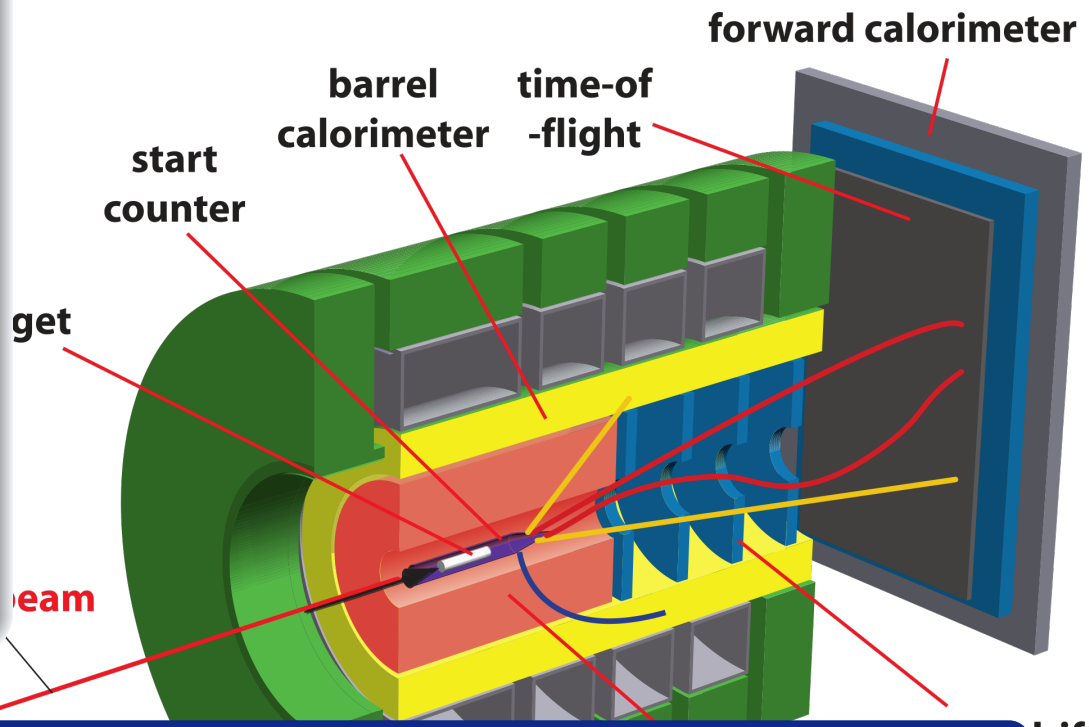
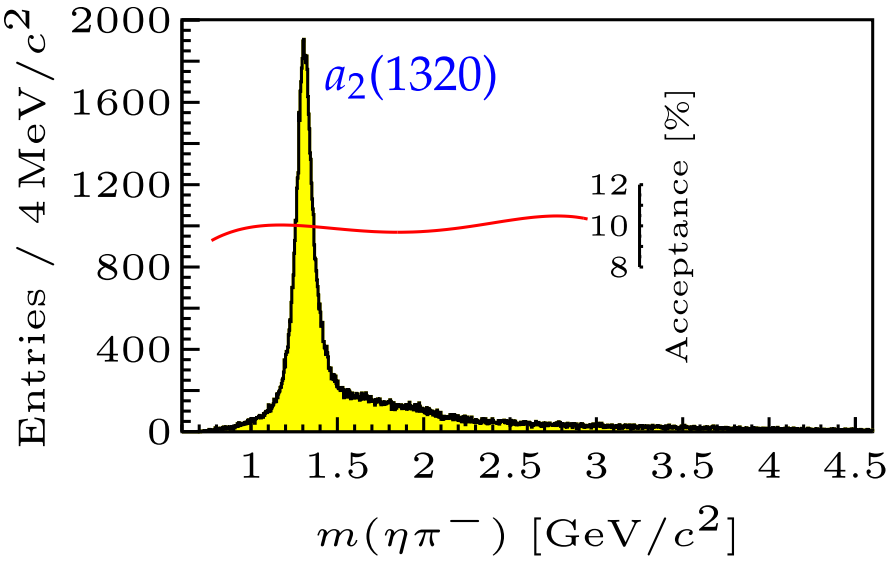


See talks

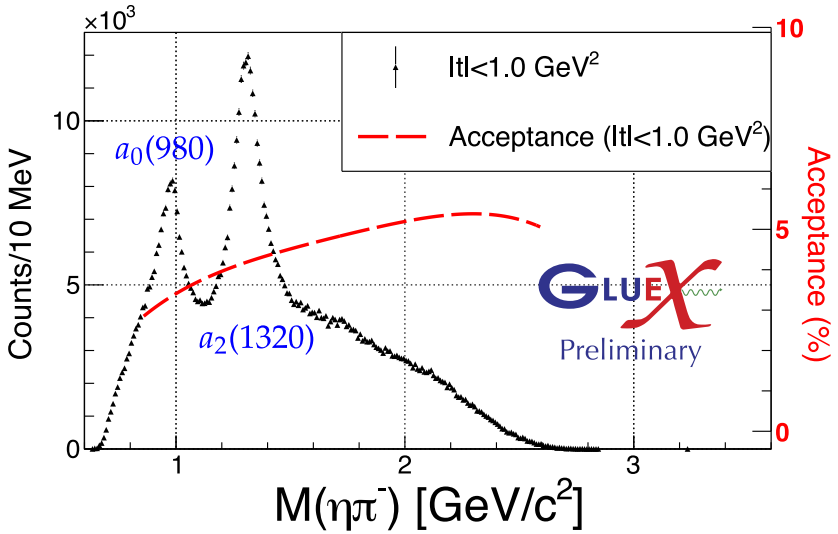
- *"Overview of the GlueX physics program"* by Matthew Shepherd, today at 14:00
- *"Overview of Light Meson Results from the GlueX Experiment"* by David Mack, today at 16:15

$\eta\pi$ and $\eta'\pi$ Final States at GlueX

COMPASS $\pi^- p \to \eta\pi^- p, \eta \to \pi^+\pi^-\pi^0$: 116×10^3 events



GlueX $\gamma p \to \eta\pi^-\Delta^{++}, \eta \to \gamma\gamma$: 10^6 events expected (phase I)



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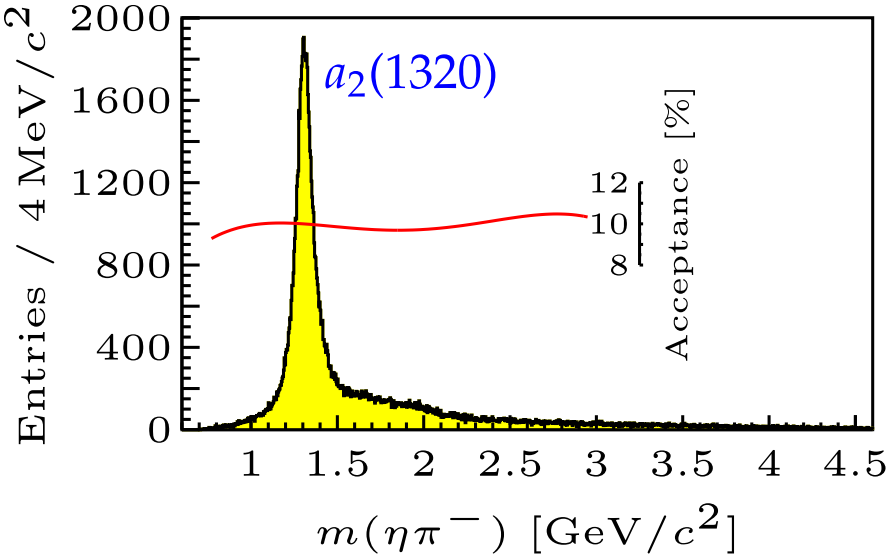

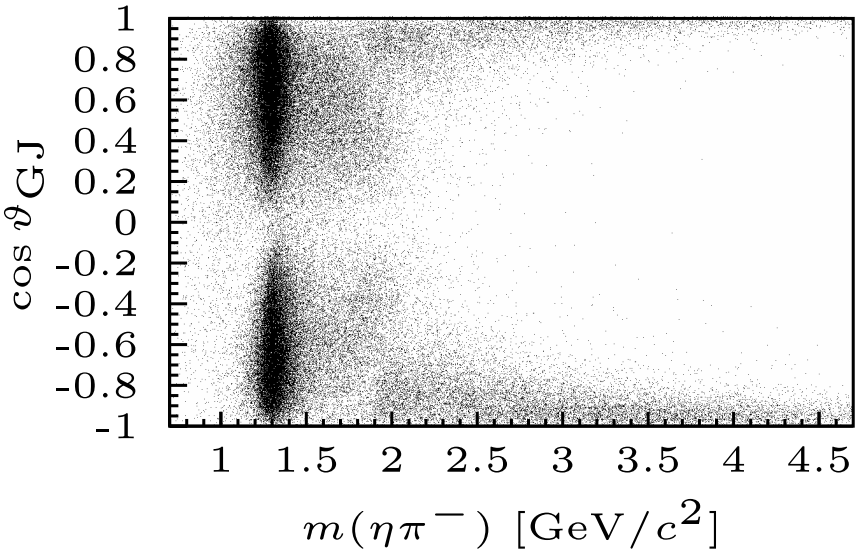

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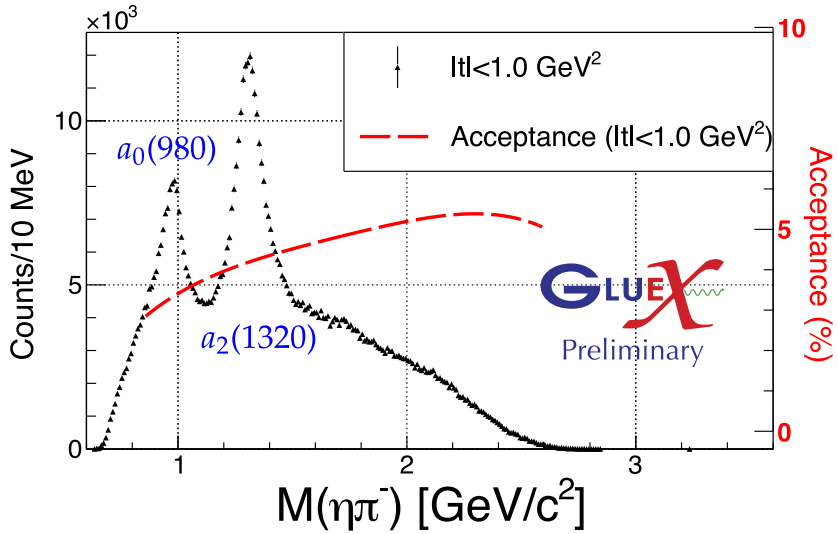
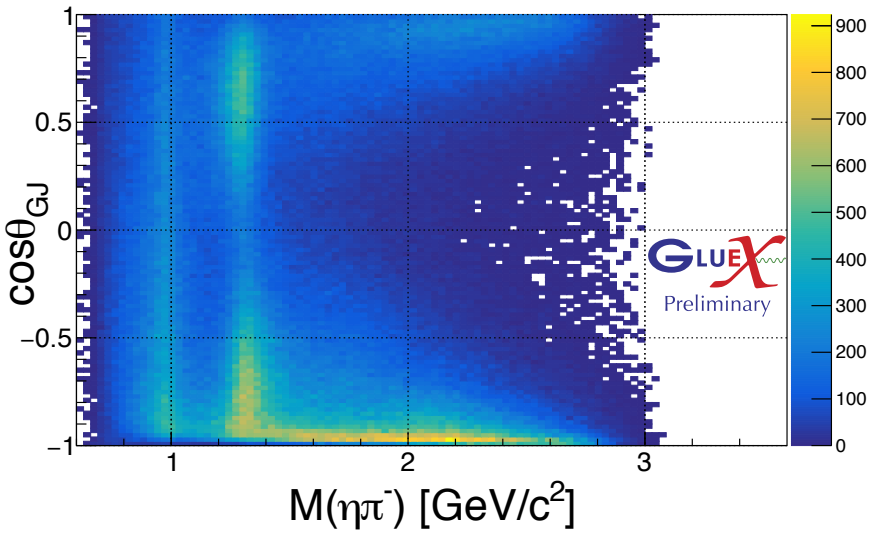
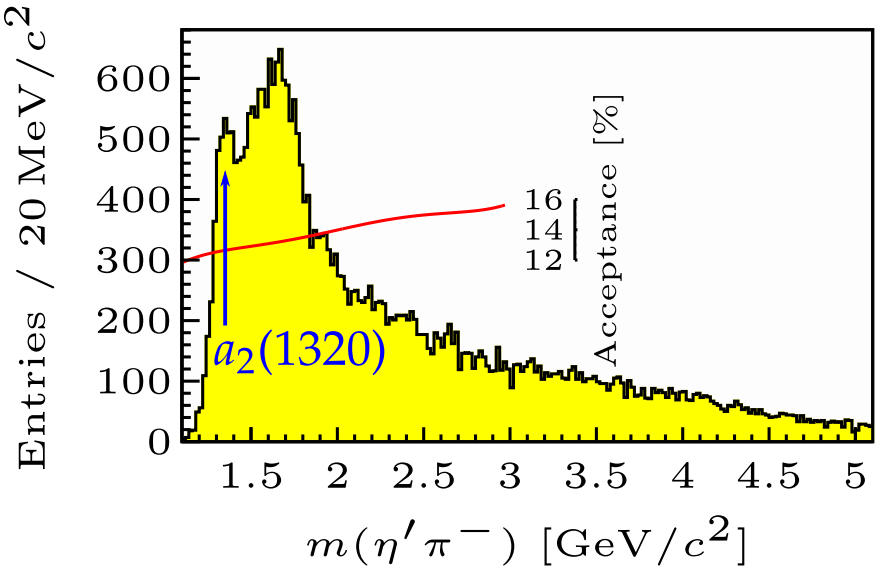


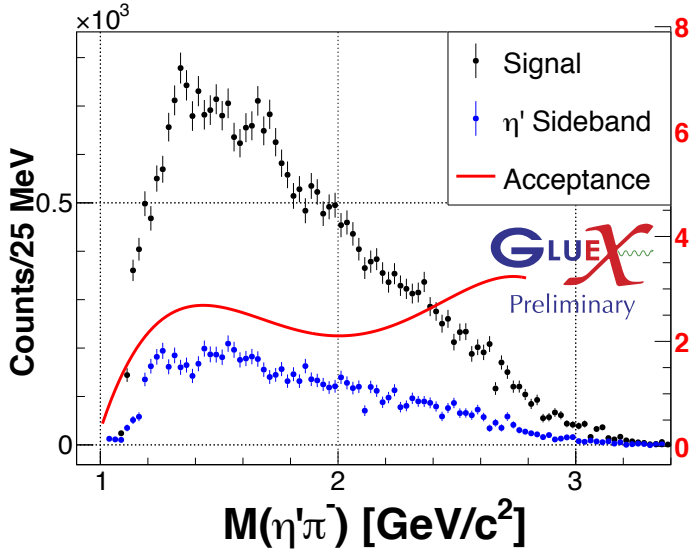


$\eta\pi$ and $\eta'\pi$ Final States at GlueX

COMPASS $\pi^- p \to \eta'\pi^- p, \eta' \to \pi^+\pi^-\eta$: 39×10^3 events



GlueX $\gamma p \to \eta'\pi^-\Delta^{++}, \eta' \to \pi^+\pi^-\eta$: 40 to 45 $\times 10^3$ events expected (phase I)



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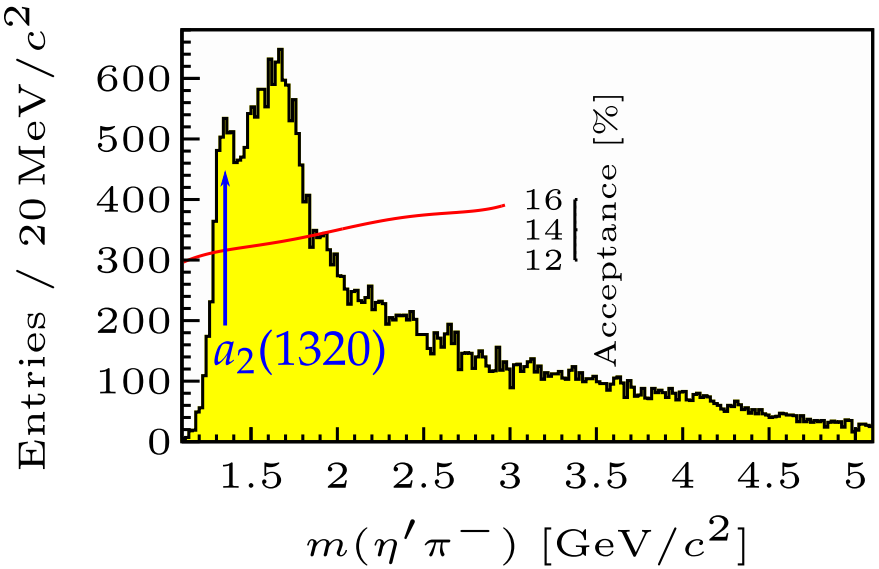

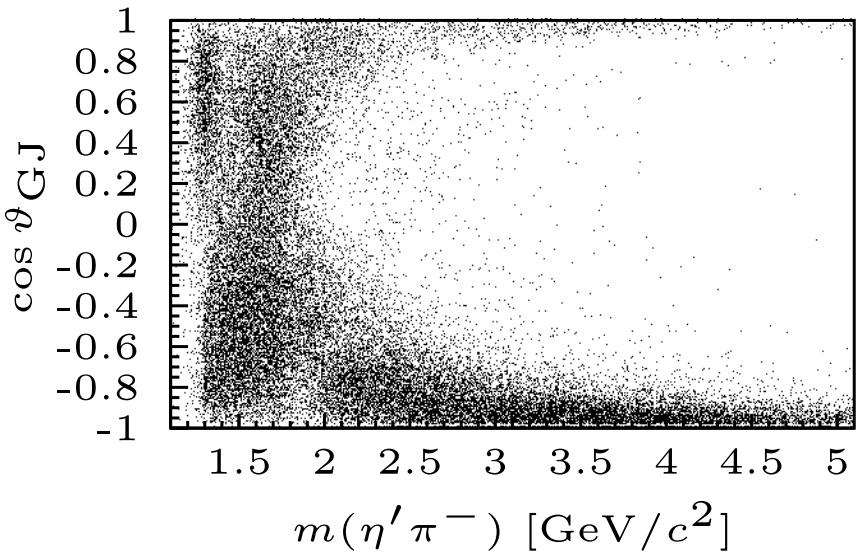

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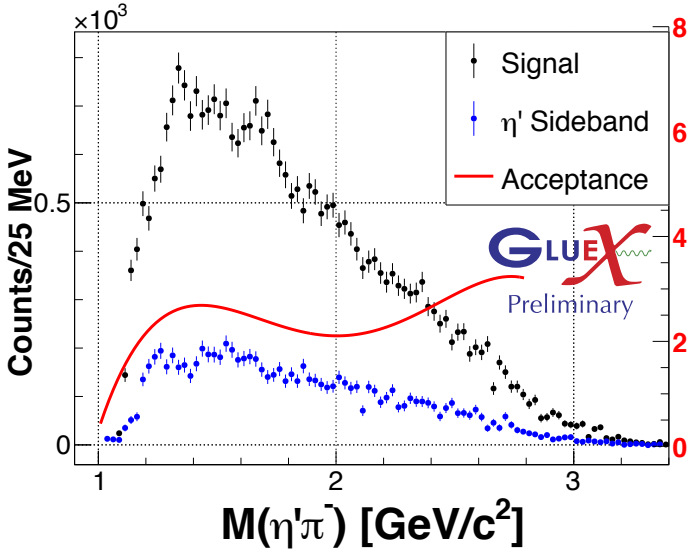

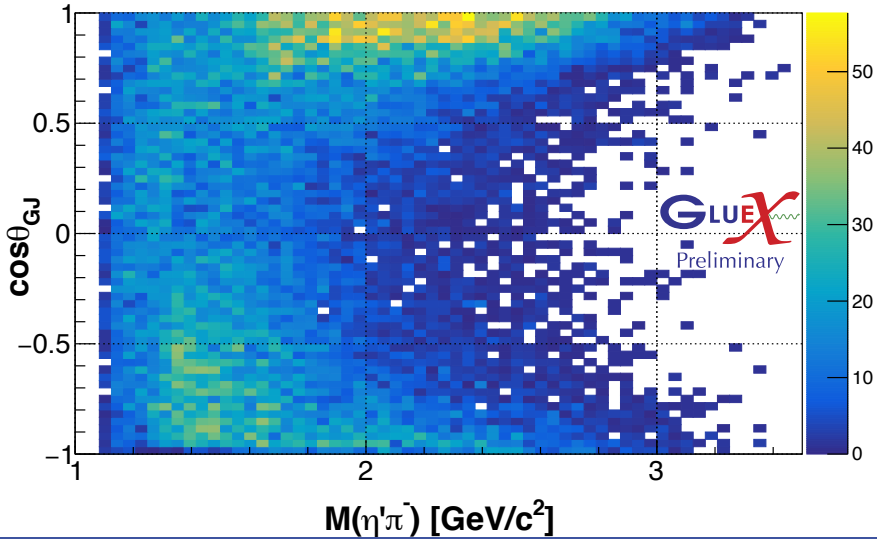

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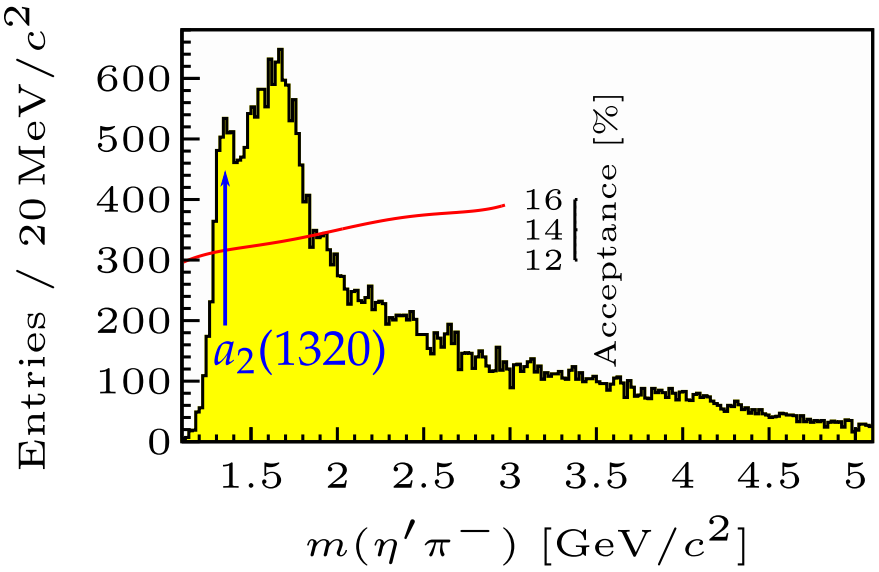

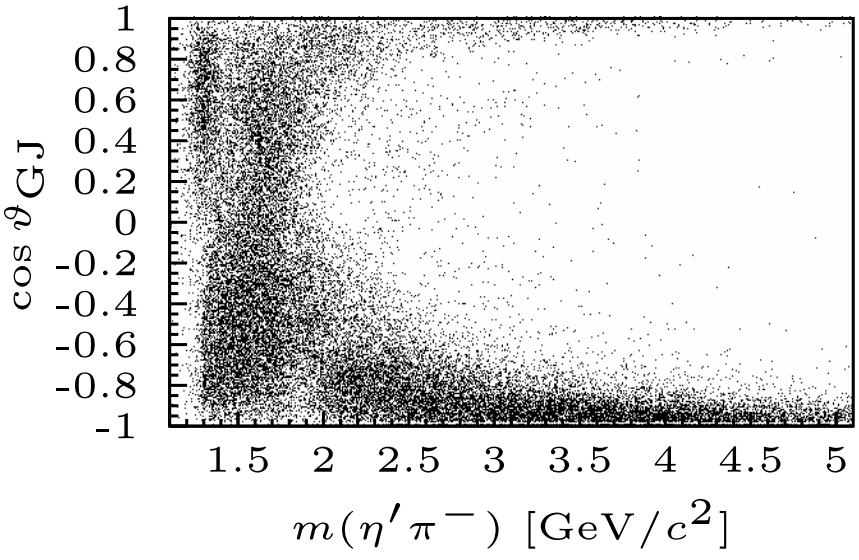

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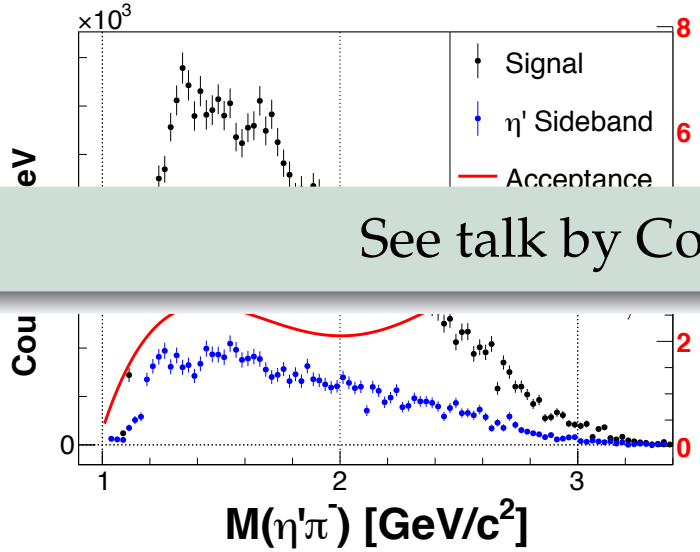
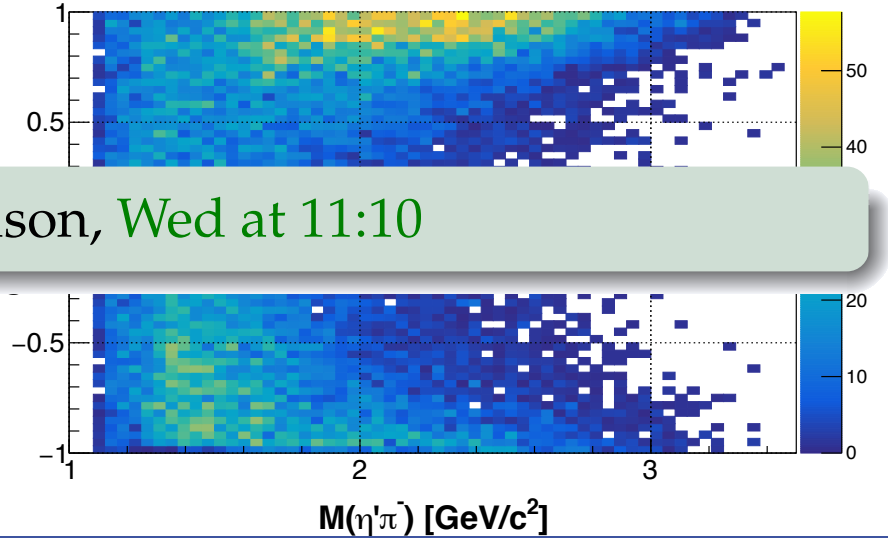
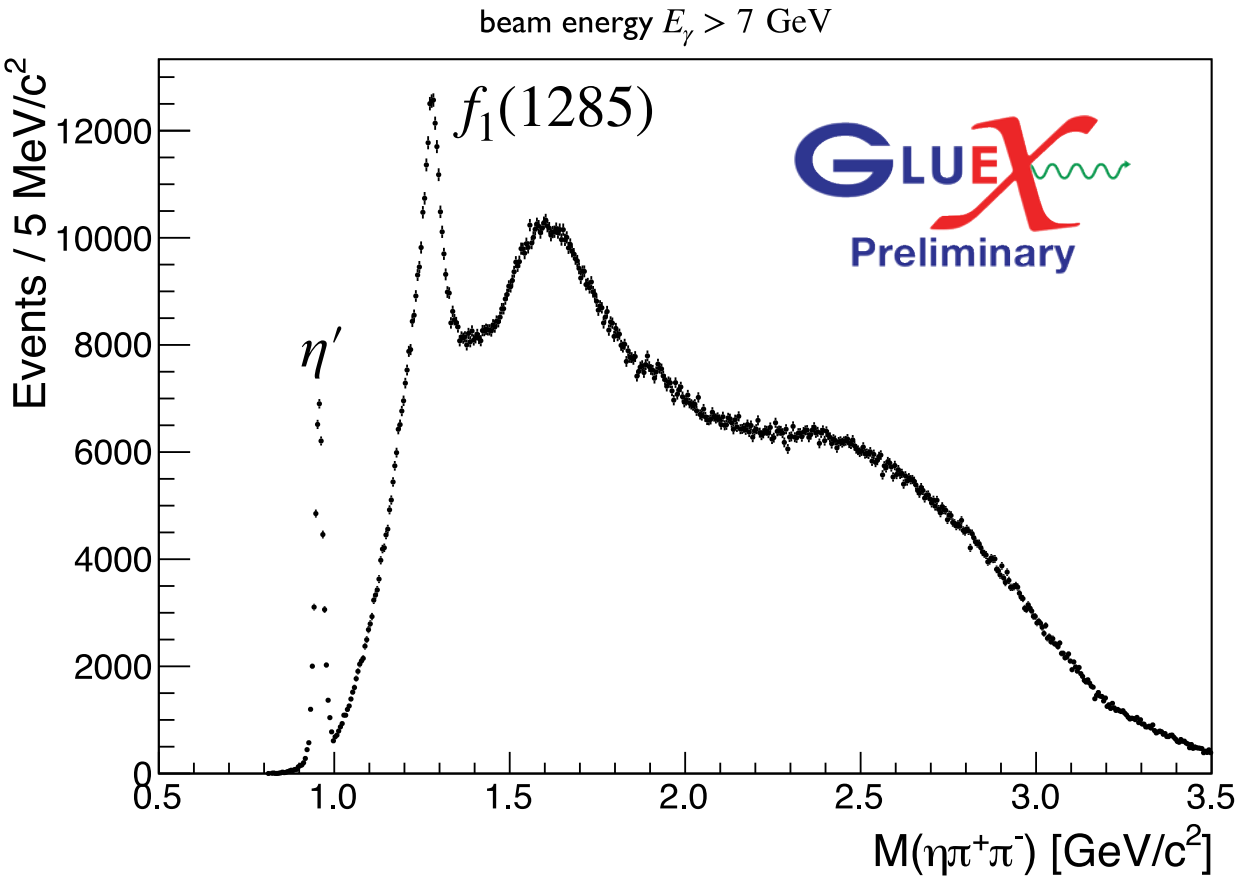




See talk by Colin Gleason, Wed at 11:10

Search for $J^{PC} = 1^{-+}$ and 2^{+-} Spin Exotics at GlueX

Example: $\gamma + p \to \eta\pi^+\pi^- + p$



- $\approx 20\,\%$ of phase-I data
- Search for
  - Isoscalar partner of $\pi_1(1600)$: $\eta_1 \to \eta f_2(1270)$ and $a_2(1320)\pi$
  - $b_2 \to \eta\rho(770)$

Search for $J^{PC} = 1^{-+}$ and 2^{+-} Spin Exotics at GlueX

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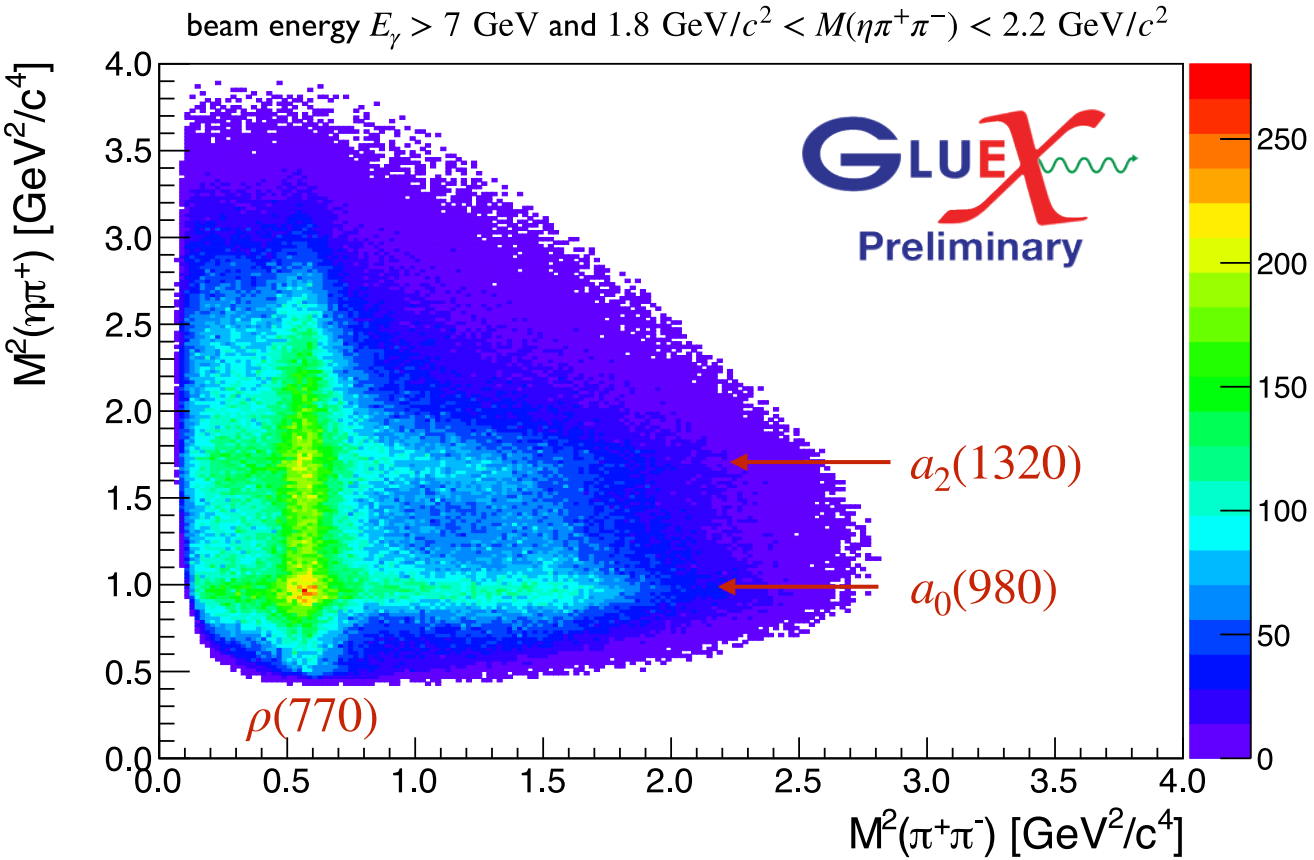

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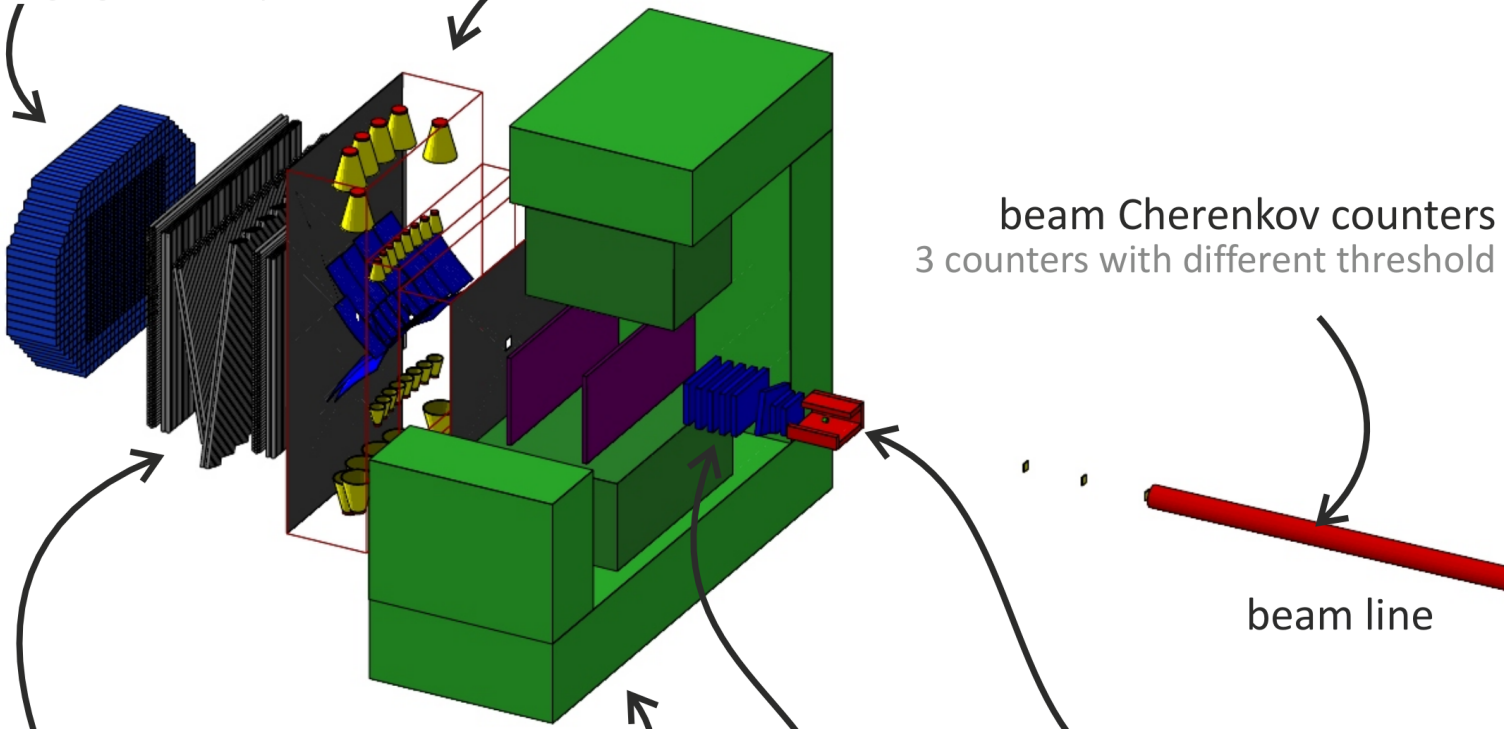
The VES Experiment at the IHEP U-70

Experimental Setup

Khokhlov *et al.*, EPJ Web Conf. **37** (2012) 01029



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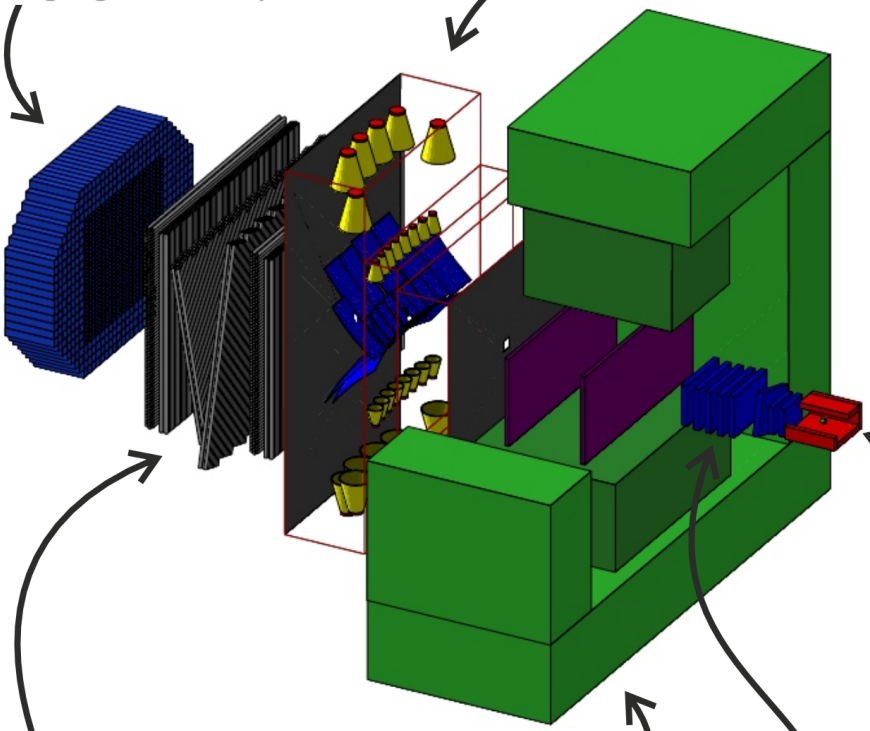
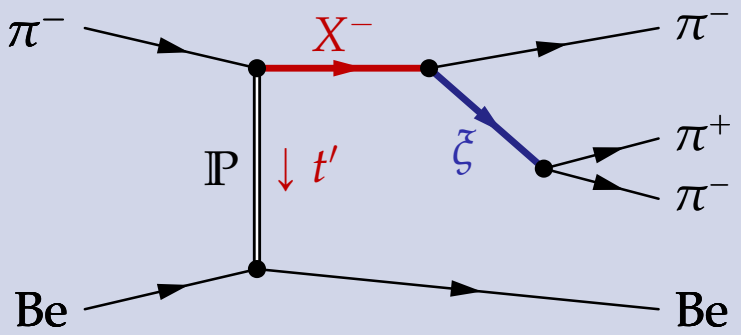
Experimental Setup

Khokhlov *et al.*, EPJ Web Conf. **37** (2012) 01029



29 GeV/c π^- beam on Be target



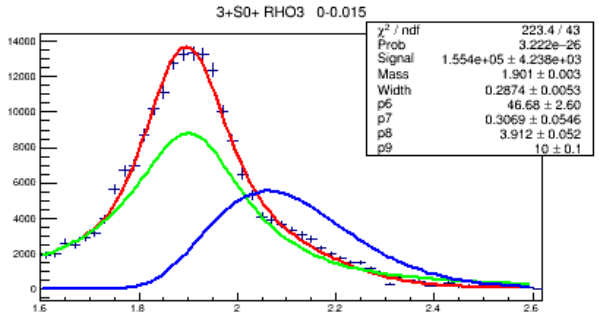
- 87×10^6 $\pi^-\pi^-\pi^+$ events
- 32×10^6 $\pi^-\pi^0\pi^0$ events
- $0 < t' < 1.0\,(\mathrm{GeV}/c)^2$

$a_3(1875)$

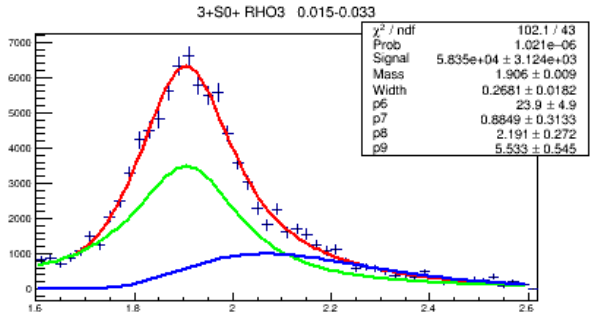
- "Further state" seen by BNL E852 in $\rho(770)\pi$, $f_2(1270)\pi$, and $\rho_3(1690)\pi$ BNL E852, PRD **65** (2002) 072001
  - $m_0 = (1874 \pm 43_{\text{stat.}} \pm 96_{\text{sys.}})\,\text{MeV}/c^2$
  - $\Gamma_0 = (385 \pm 121_{\text{stat.}} \pm 114_{\text{sys.}})\,\text{MeV}/c^2$

$a_3(1875)$ in $3^{++}\,0^+\,\rho_3(1690)\,\pi\,S$ Wave at VES

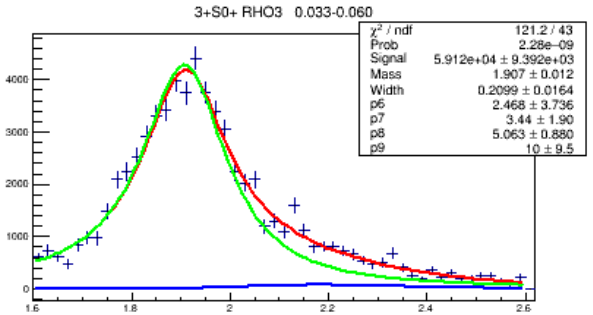
$0.000 < t' < 0.015\,(\mathrm{GeV}/c)^2$



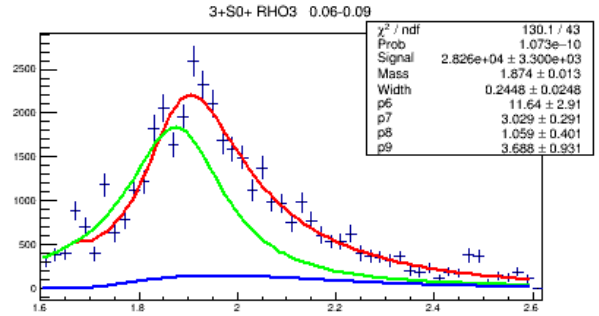
$0.015 < t' < 0.033\,(\mathrm{GeV}/c)^2$



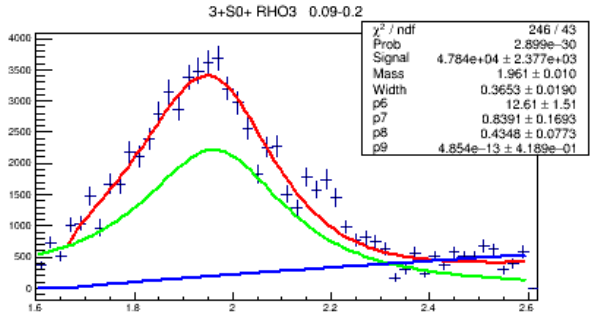
$0.033 < t' < 0.060\,(\mathrm{GeV}/c)^2$



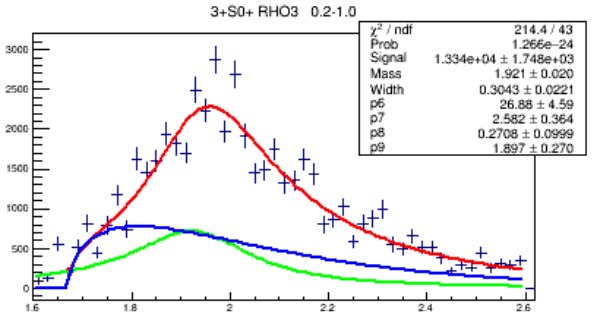
$0.060 < t' < 0.090\,(\mathrm{GeV}/c)^2$



$0.090 < t' < 0.200\,(\mathrm{GeV}/c)^2$



$0.200 < t' < 1.000\,(\mathrm{GeV}/c)^2$

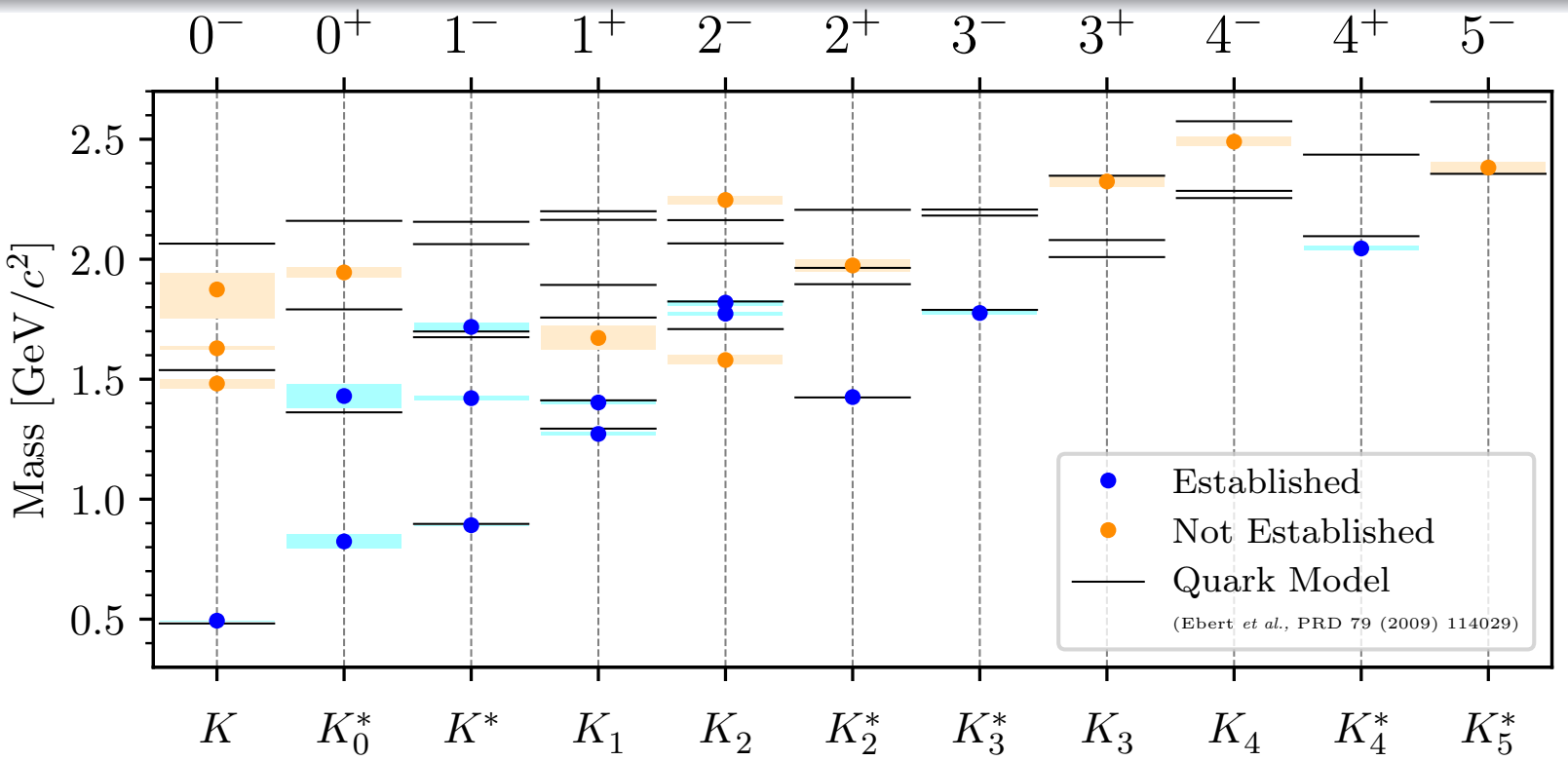


Resonance-model fit

Kachaev *et al.* [VES], EPJ Web Conf. **199** (2019) 02025

- $a_3(1875)$ confirmed by VES with parameters consistent with BNL E852 (combined $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$ data)
  - $m_0 = (1905 \pm 15)\,\mathrm{MeV}/c^2$
  - $\Gamma_0 = (250 \pm 30)\,\mathrm{MeV}/c^2$

Kaon Spectroscopy



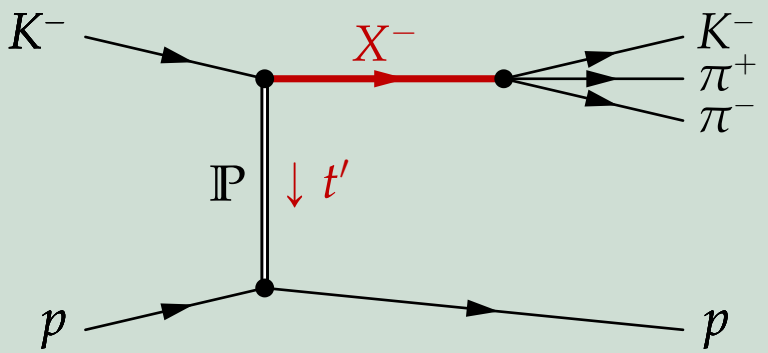
[Courtesy S. Wallner, TUM]

PDG 2019: 25 kaon states below 3.1 GeV/c^2

- Only 13 kaon states well established, 12 need confirmation
- Many predicted quark-model states still missing
- Little progress in past 30 years

Diffractive Production of $K^-\pi^-\pi^+$ at COMPASS

190 GeV/c K^- beam on p target



- 2.4 % K^- in beam
- 720 000 events
- $0.1 < t' < 1.0\ (\mathrm{GeV}/c)^2$
- Various potential resonance signals
- $\approx 3.5\times$ larger data sample than WA03
- Structures in $K^-\pi^+$ and $\pi^-\pi^+$ subsystems

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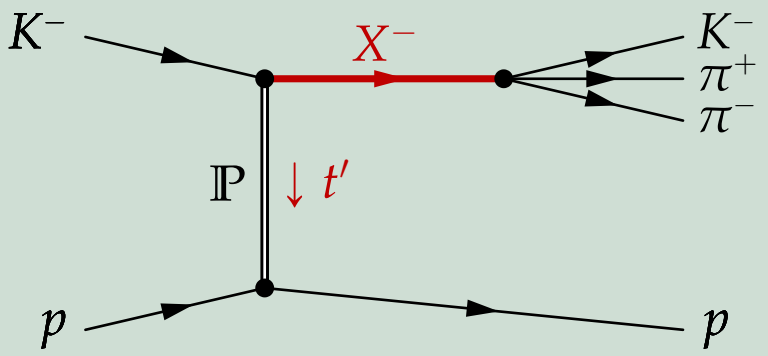

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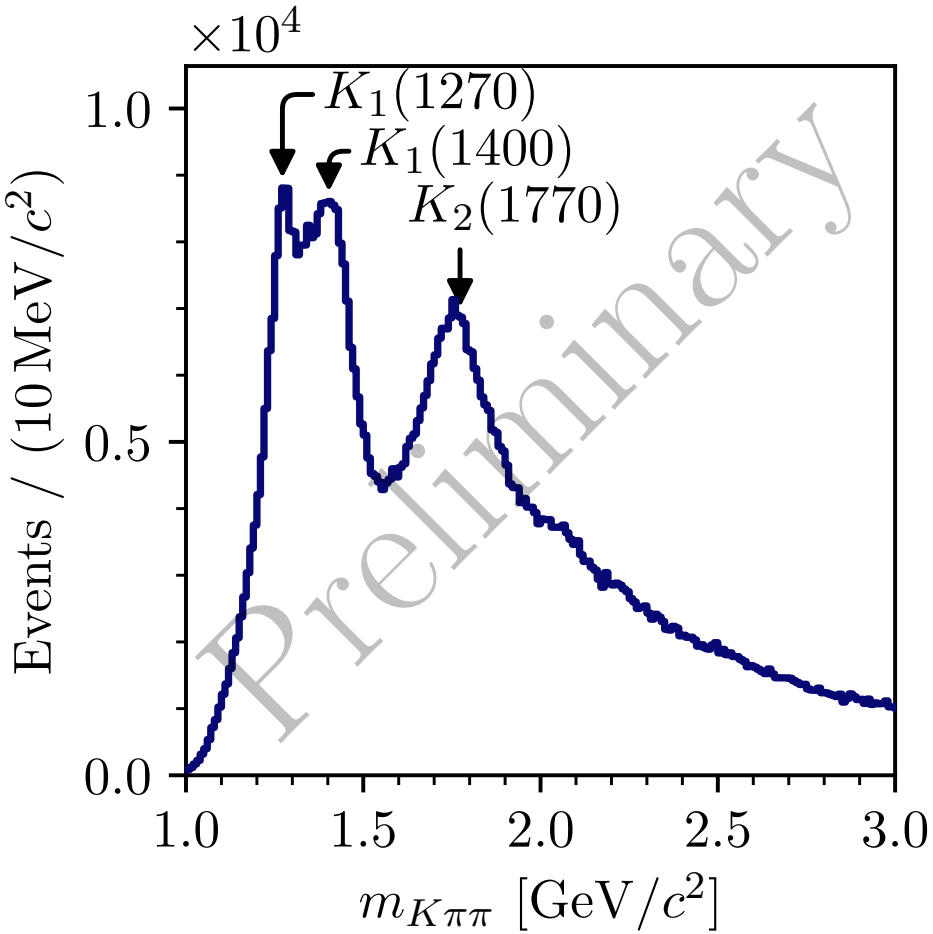

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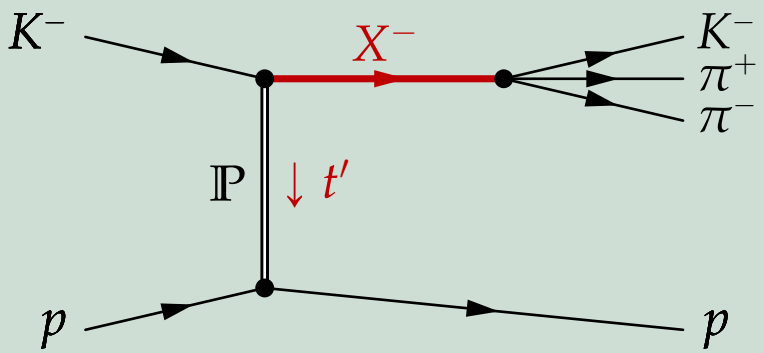

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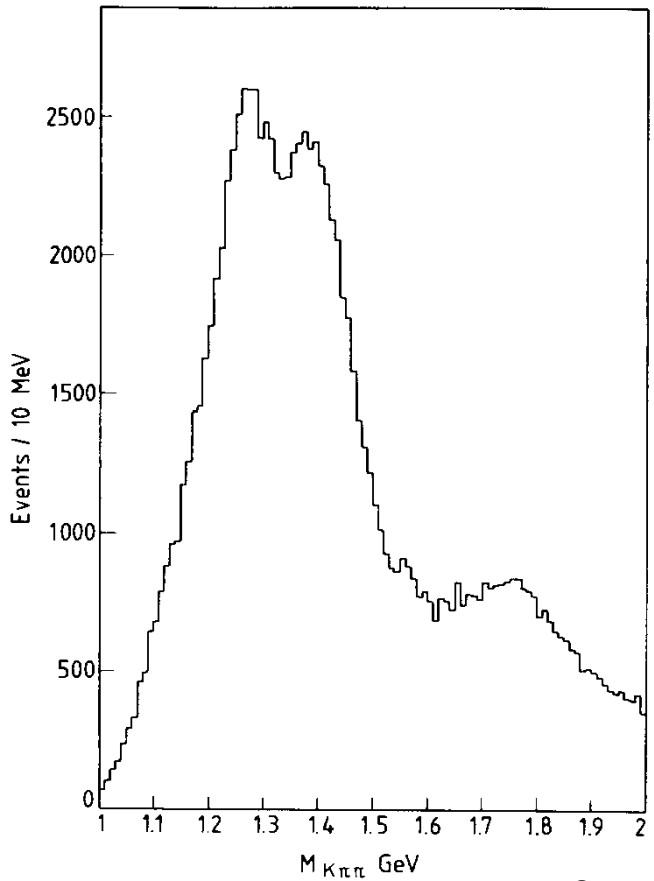
WA03 (CERN)



$0 < t' < 0.7\,(\mathrm{GeV}/c)^2$

200 000 events

ACCMOR, NPB **187** (1981) 1

Diffractive Production of $K^-\pi^-\pi^+$ at COMPASS

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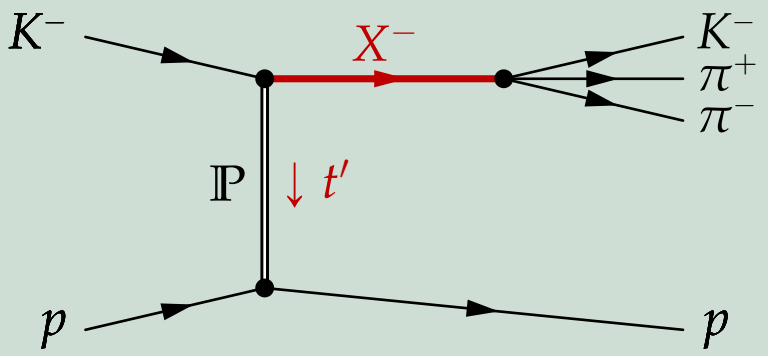

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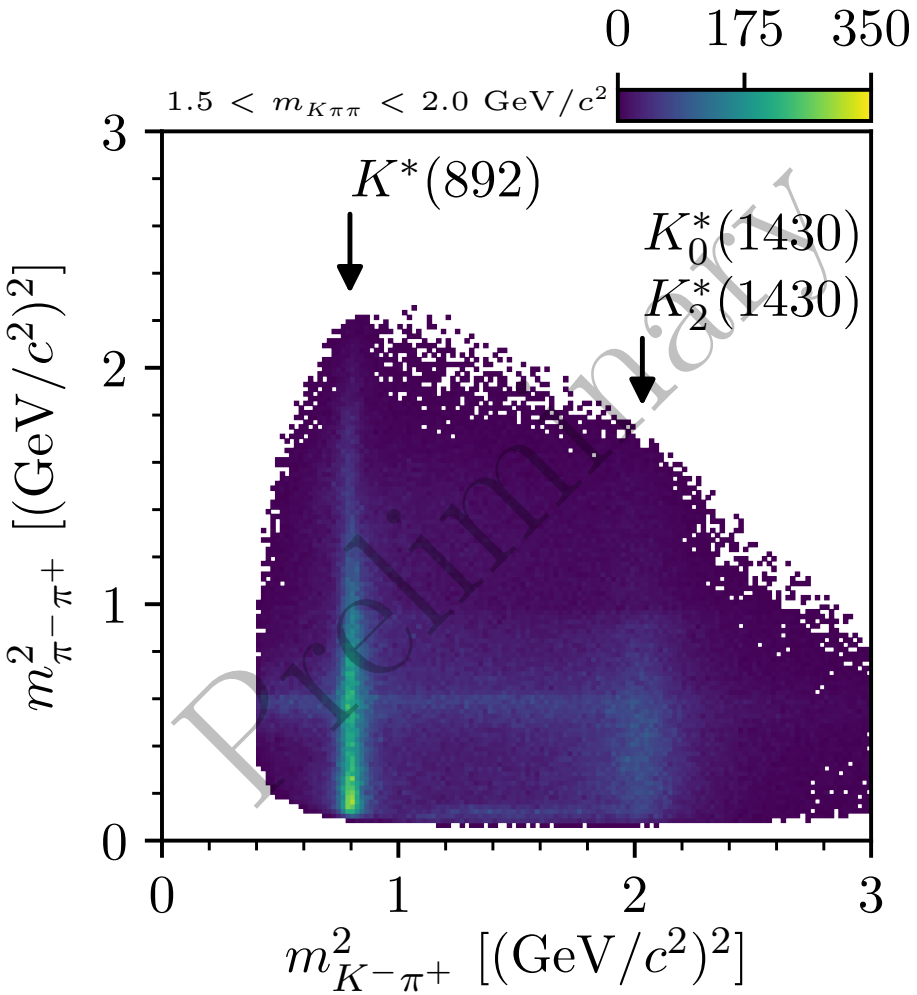
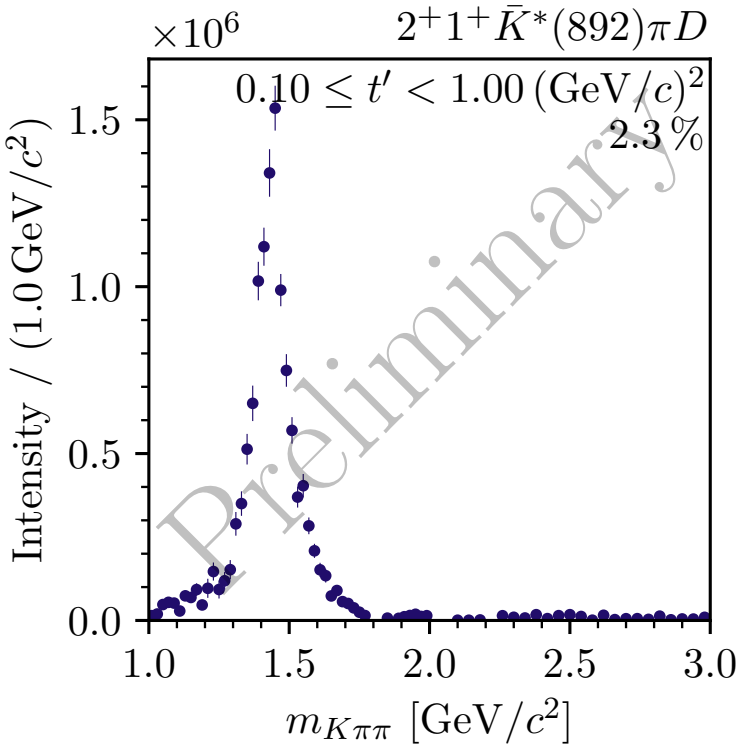


PWA of $K^- + p \to K^- \pi^- \pi^+ + p$

Example: $2^+\,1^+\,K^*(892)\,\pi\,D$ Wave

COMPASS



WA03

ACCMOR, NPB **187** (1981) 1

- Clear signal from $K_2^*(1430)$
- In agreement with WA03 result
- Cleaner signal in COMPASS data
- *Work in progress:* resonance-model fit

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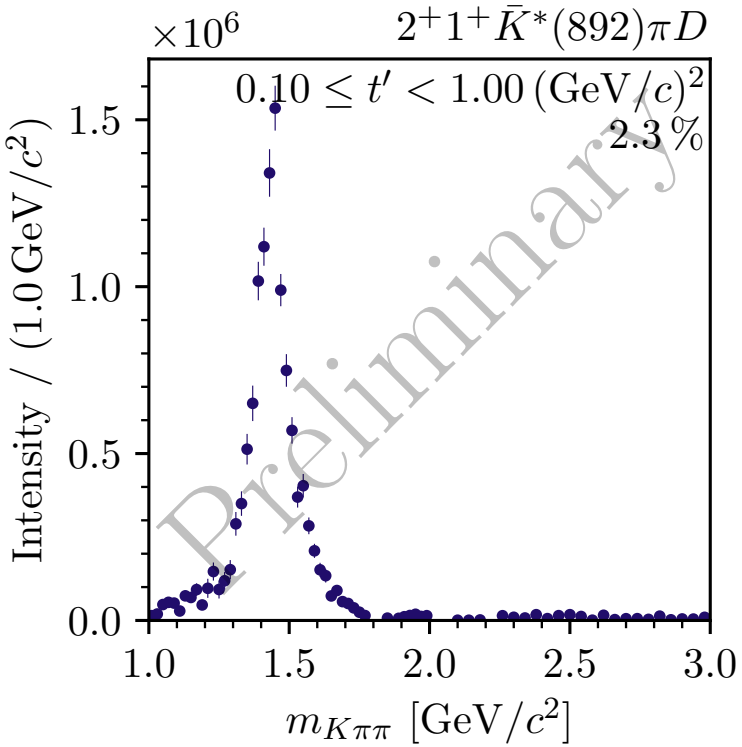
COMPASS



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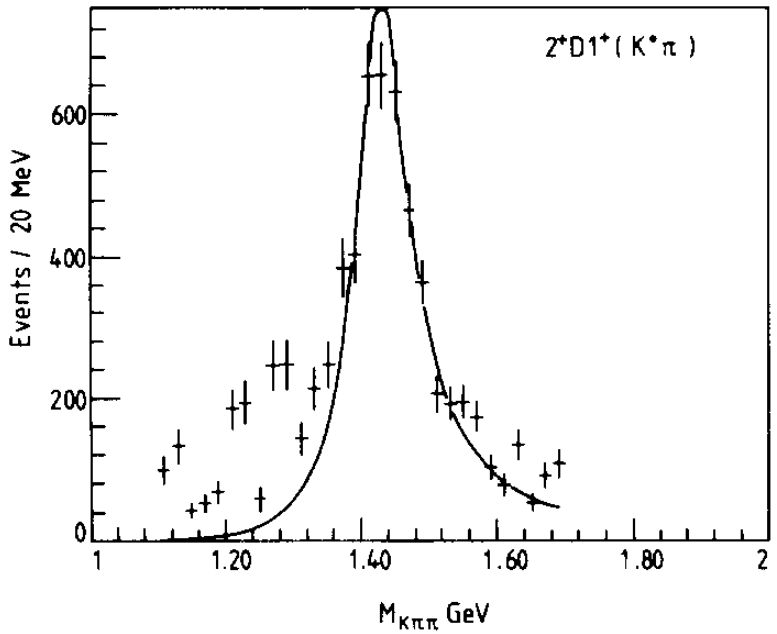

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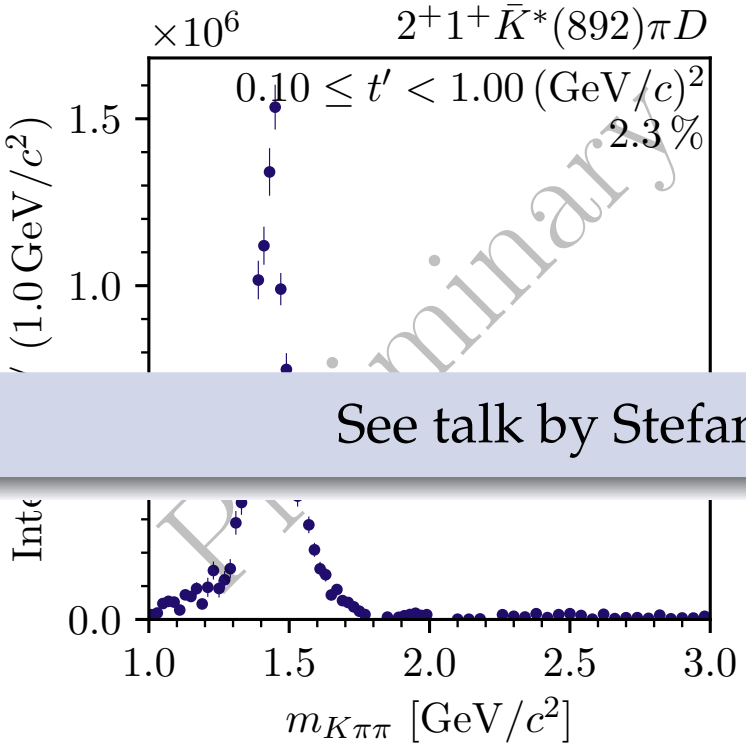

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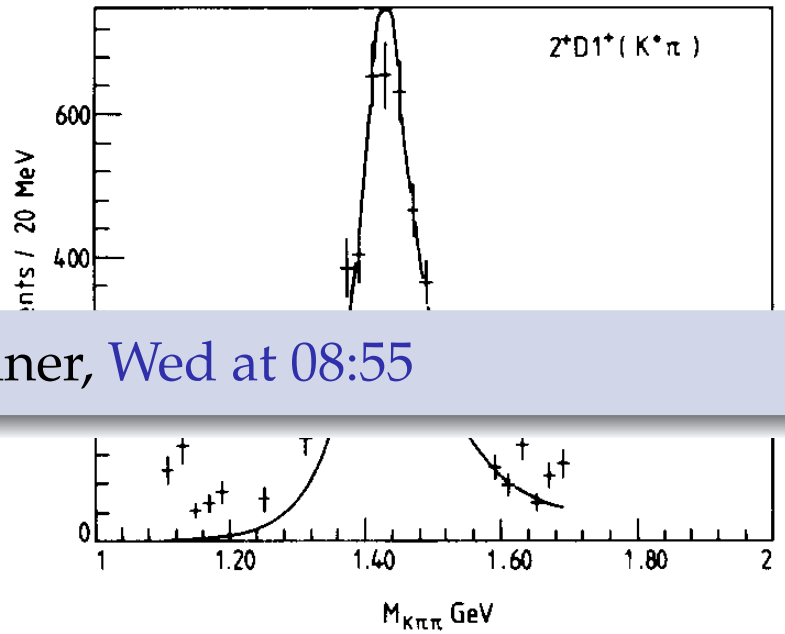

ACCMOR, NPB **187** (1981) 1

See talk by Stefan Wallner, Wed at 08:55

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Summary

Light-meson spectroscopy enters era of high-precision data

- Hadroproduction
  - COMPASS: finished data taking
  - VES: running
- Lepto/photoproduction
  - GlueX: finished phase-I campaign, starting phase II
  - CLAS12: MesonEx program
- Further future
  - $p\bar{p}$ at PANDA
  - COMPASS++/AMBER LoI: kaon spectroscopy *[arXiv:1808.00848]*

Common challenges

- Analyses dominated by systematic model uncertainties
- Requires
  - Refined analysis techniques
  - More accurate PWA models $\Rightarrow$ tight collaboration with theory

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