Recent results on light-meson exotics from the COMPASS experiment

Mikhail Mikhasenko

Excellence Cluster ORIGINS, Munich, Germany
Joint Physics Analysis Center

August 6th, 2021

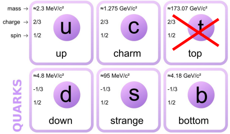
The plan of the talk

Variety of the hadronic states

QCD at low-energy regime:

- color interaction confined
- effective d.o.f. - **constituent** quarks (gluons?)

Variety of the hadronic states



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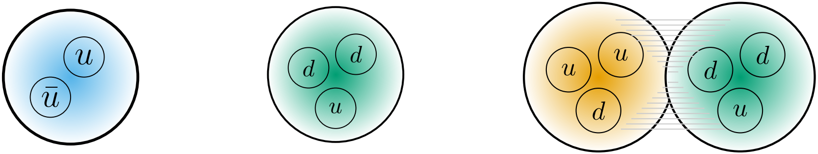

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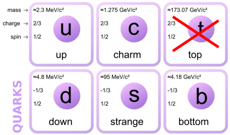

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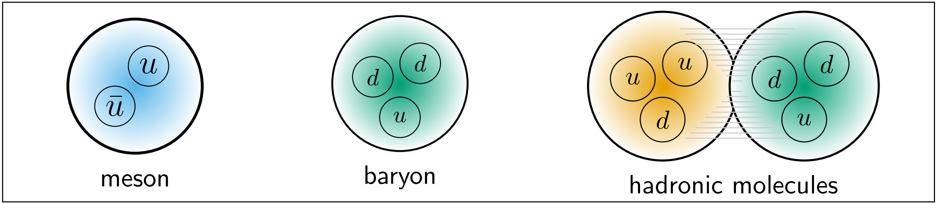
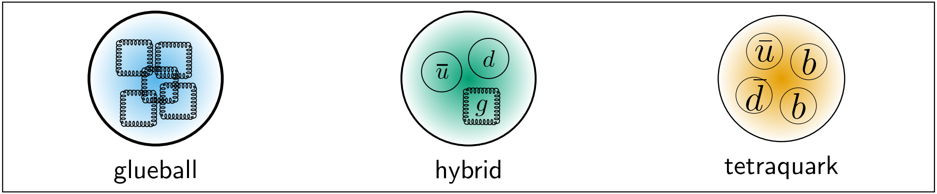
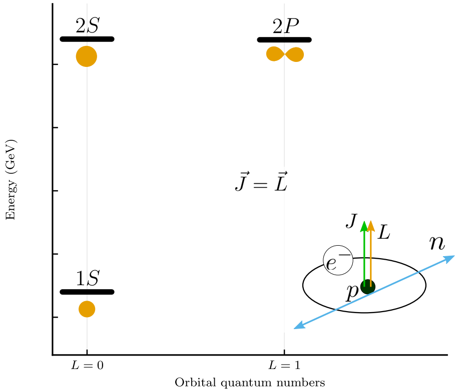


Exotic matter:



Excitation spectrum of a bound system

QED



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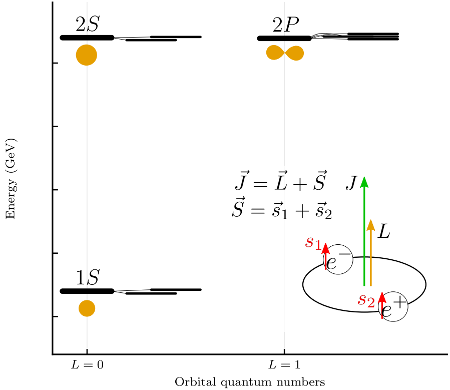

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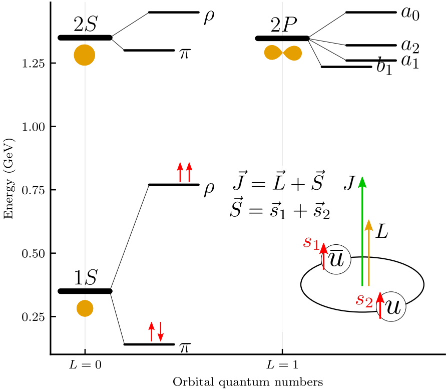

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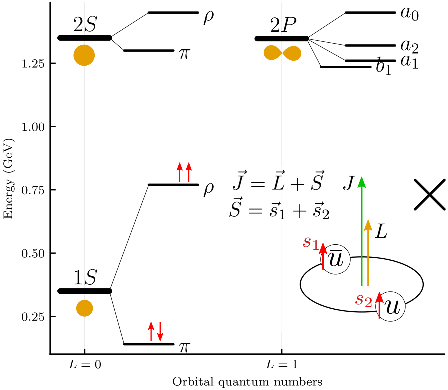
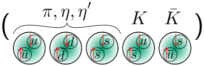


$\times 5$



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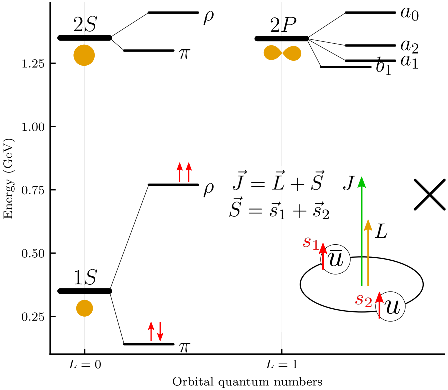

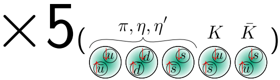

- QED: hyperfine splitting
- QCD: is far not hyperfine

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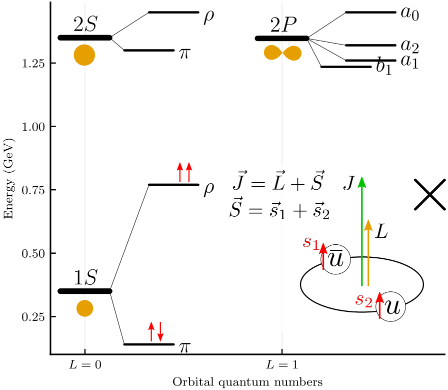
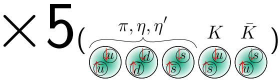
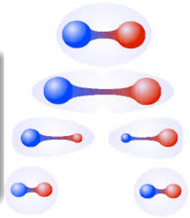


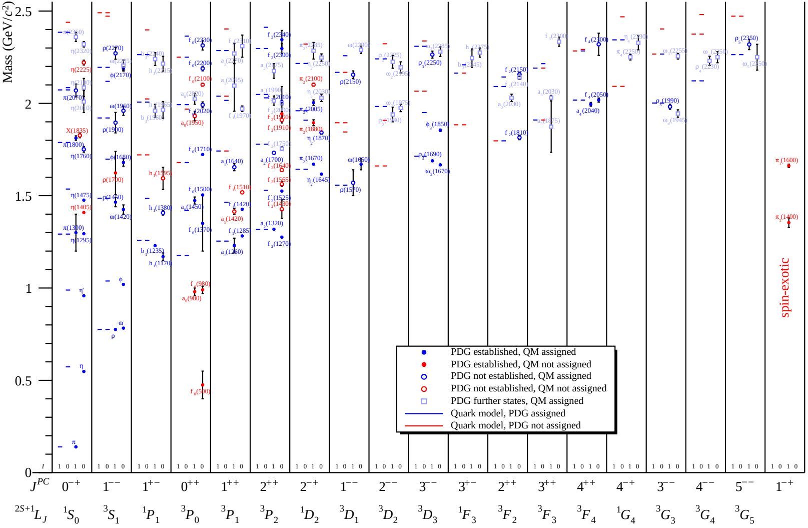




- QED: hyperfine splitting
- QCD: is far not hyperfine
- Example of spin-flip transition:
  $\rho(\uparrow\uparrow) \to \pi(\uparrow\downarrow)$ transition is a "QCD-cell division"

Experimental situation on (non-strange) Light mesons

[B. Ketzer, B. Grube, D. Ryabchikov, PPNP, arXiv:1909.06366]



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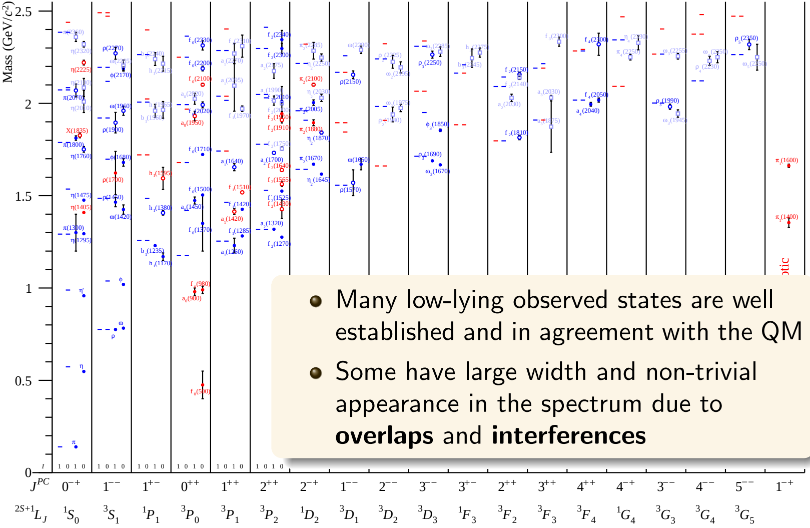
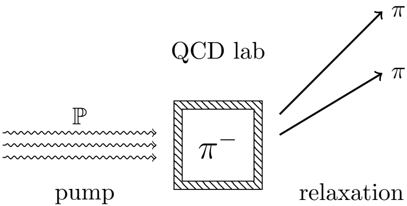


- Many low-lying observed states are well established and in agreement with the QM
- Some have large width and non-trivial appearance in the spectrum due to **overlaps** and **interferences**

Laboratory to study hadronic excitations



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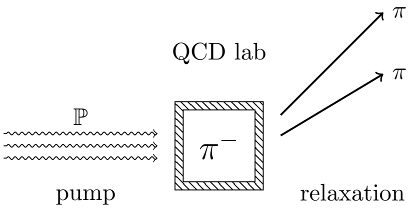
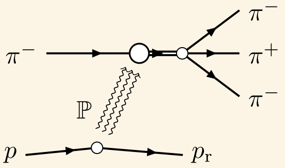


Diffractive reaction



- Pion beam scattered off the proton target
- High energy guarantees t-channel process.
- The target provide the gluonic field
- 3π production has the largest cross section (inelastic)

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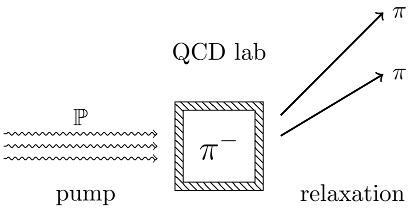

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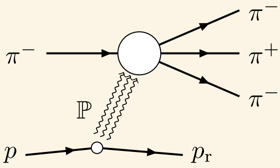

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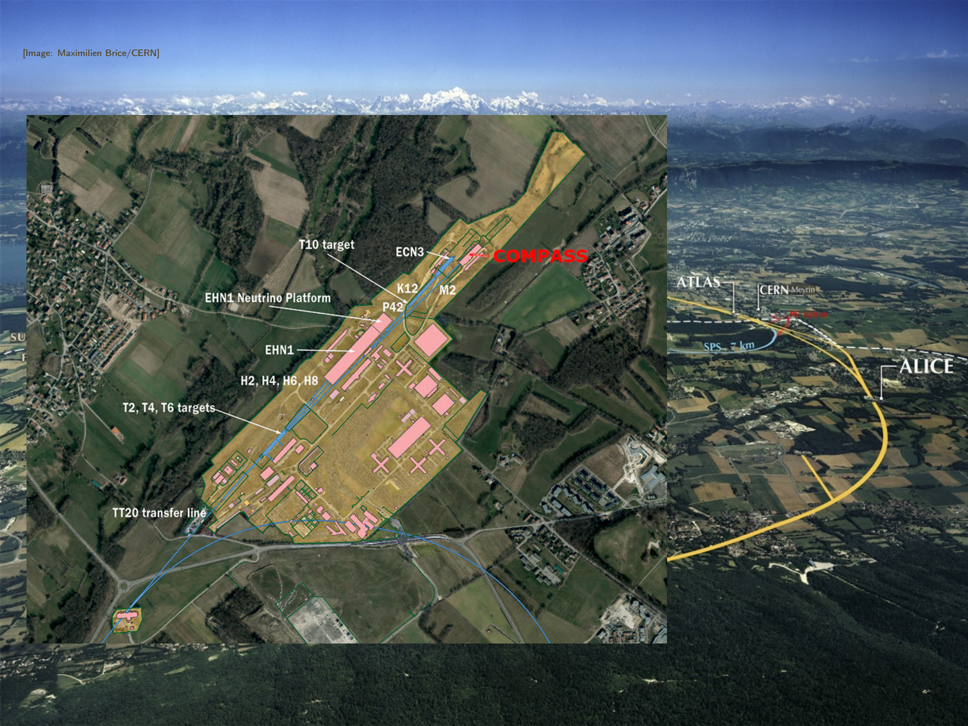
[Image: Maximilien Brice/CERN]



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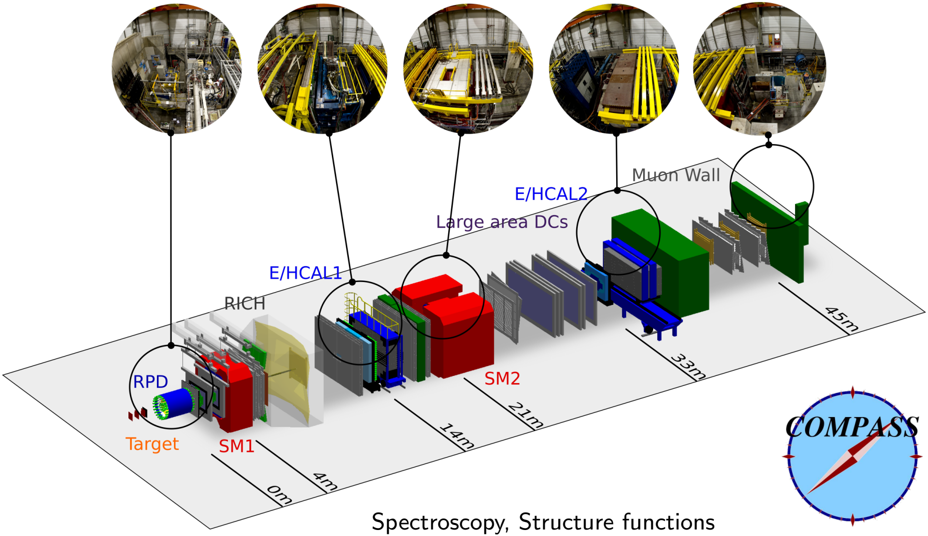
COMPASS Experiment

[NIM A779 (2015) 69-115]

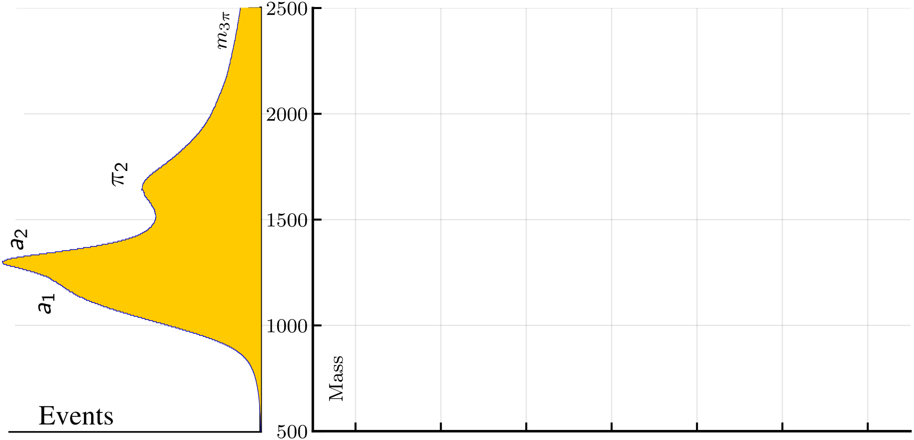


Spectroscopy, Structure functions

π/μ beam, 10^7 particles per $10s$ spill

Understanding of the 3π spectrum [COMPASS, PRD95 (2017) 032004]

The results of the main big fit
— 14 interfering waves × 11 t'-slices simultaneously.



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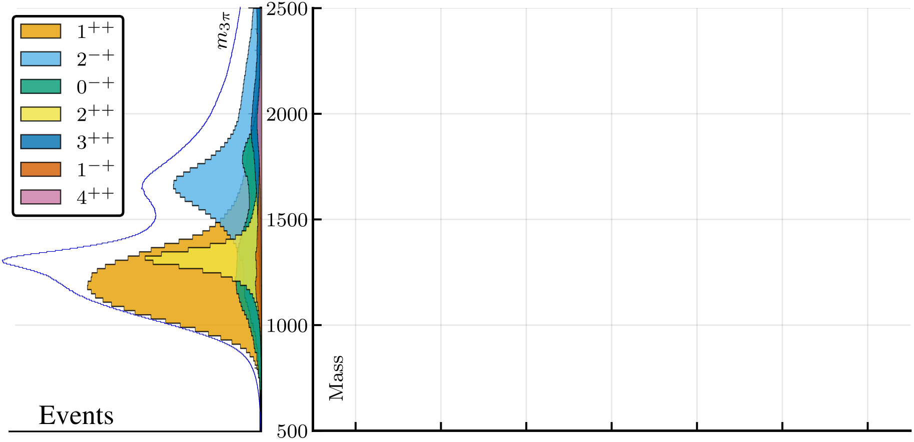

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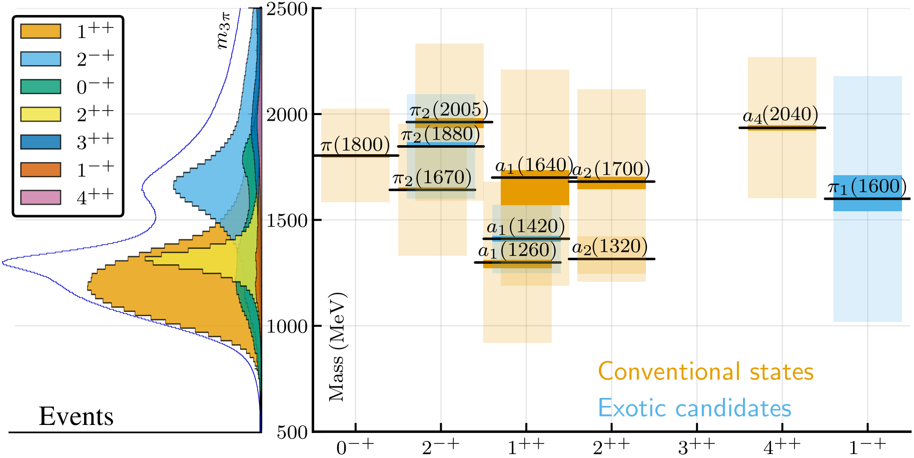


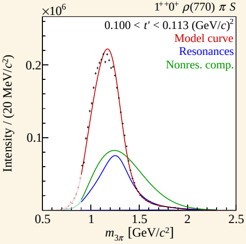
- 11 resonances are established including a new $a_1(1420)$

Resonance model fit

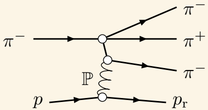
[COMPASS, PRD98 (2018) 092003]

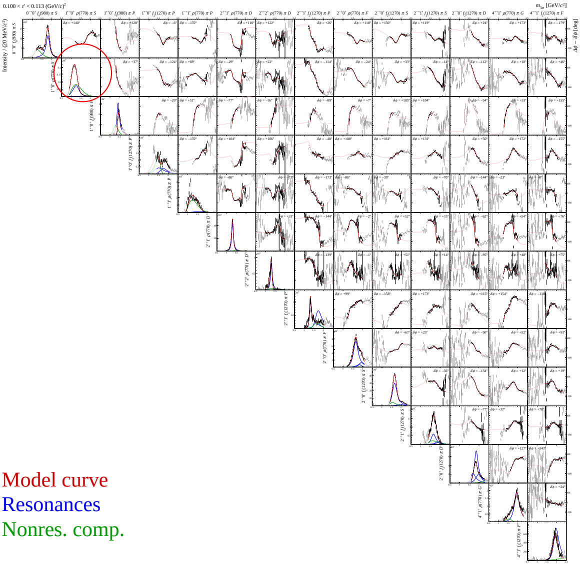
The main mass-dependent fit

Axial vector 1^{++}



- Non-resonant coherent background





Model curve
Resonances
Nonres. comp.

Resonance model fit

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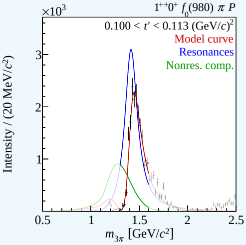
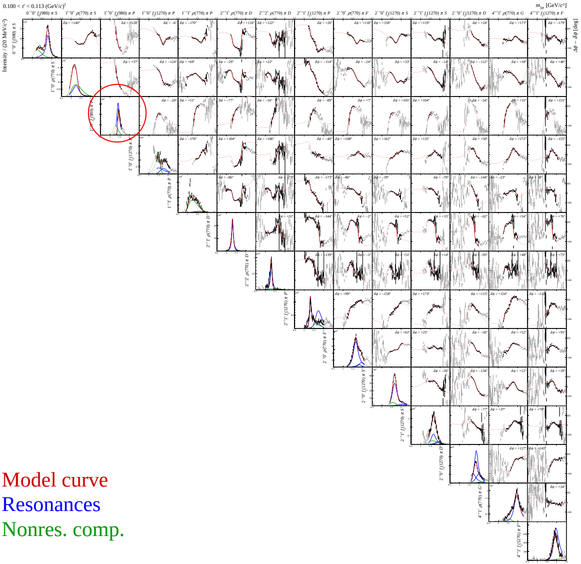
Axial "?" 1^{++}



- Exotic candidate!



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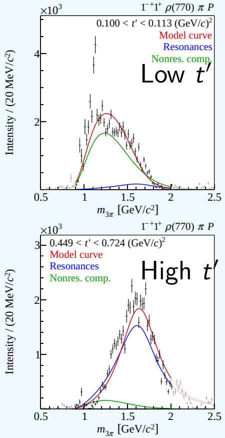

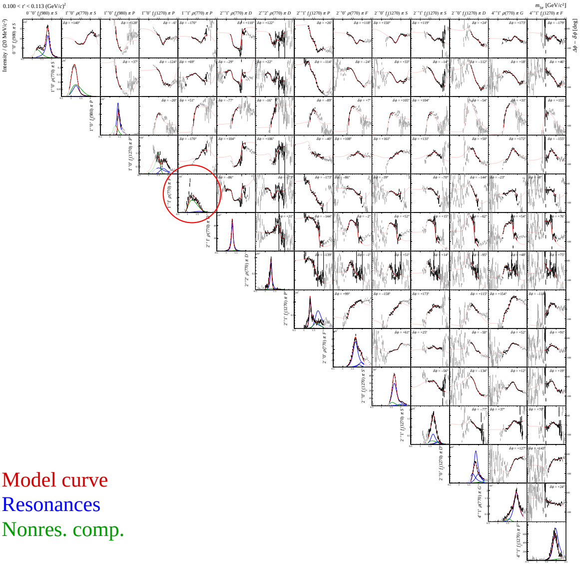

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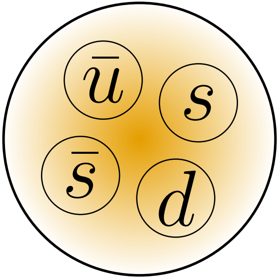
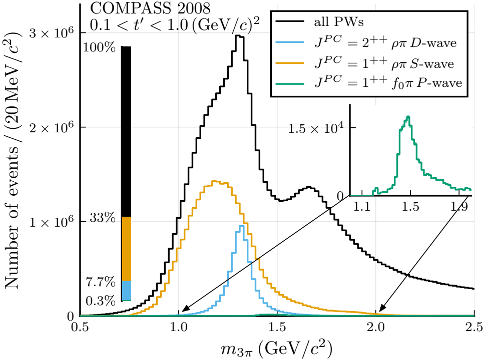
$a_1(1420)$ tetraquark candidate



Observation of the $a_1(1420)$

[COMPASS, PRL 115 (2015) 082001]



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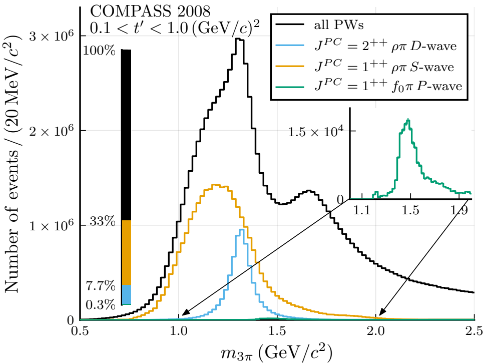

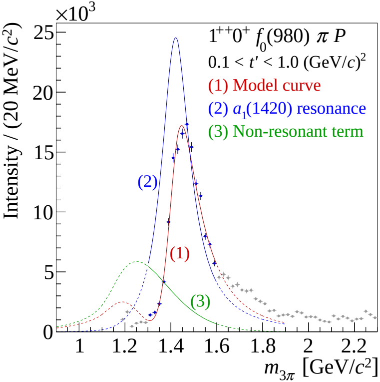

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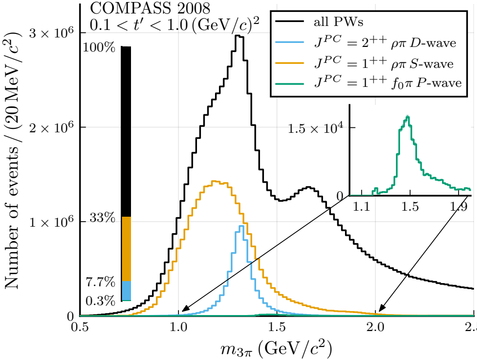

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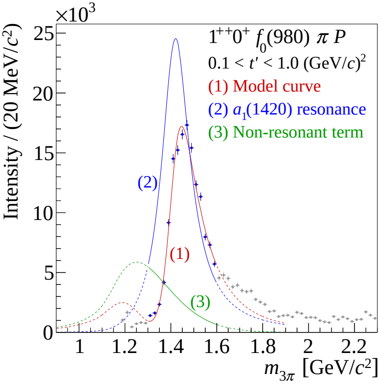

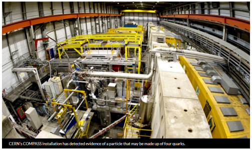

SCIENCE TICKER PARTICLE PHYSICS

New particle may be made of four quarks

BY ANDREW GRANT 4:48PM, FEBRUARY 2, 2015

CERN's COMPASS installation has detected evidence of a particle that may be made up of four quarks.

Not something ordinary

- Too close to the ground state $a_1(1260)$
- Its width is narrower than the ground state
- Close to threshold $K^*\bar{K}$, i.e. $(d\bar{s}) + (\bar{u}s)$, $E_{\text{th}} = 1.39\,\text{GeV}$.

$a_1(1420)$ interpretations

Possible scenaria

- **Pole** in the amplitude – Genuine resonance
- Singularity of the **non-pole** type

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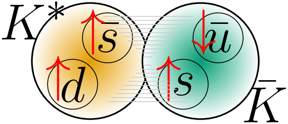

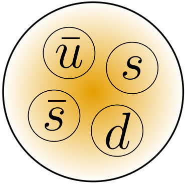

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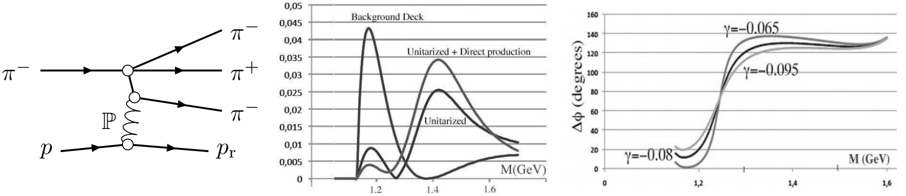

[J.-L. Basdevant, Ed. Berger, PRL114 (2015) no.19, 192001]

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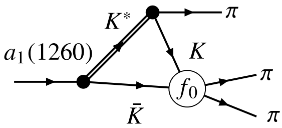

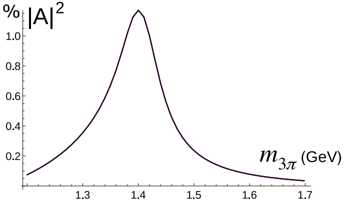

[MM, A. Sarantsev, B. Ketzer, PRD 91, 094015 (2015)], confirmed by [Aceti et al, PRD 94, 096015 (2016)]

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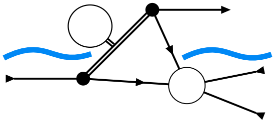

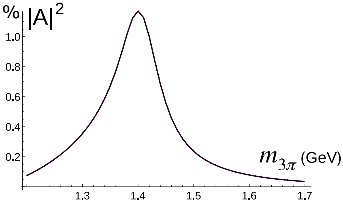

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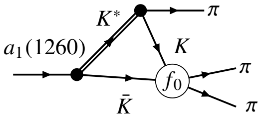
The key effect - the triangle rescattering graph



- f_0 is a resonance in $(K\bar{K})$ and also in $(\pi\pi)$ system.
- Ordinary a_1 decays to $K\bar{K}\pi$ via $K^*\bar{K}$
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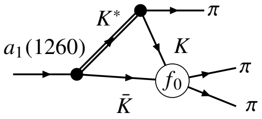

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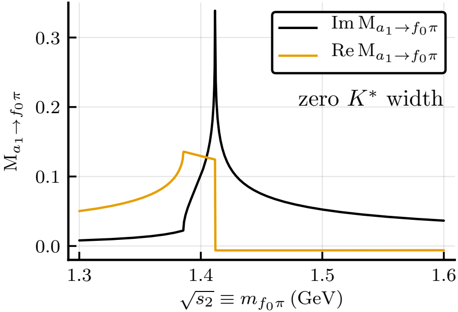

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- $A \sim \log(s_0 - m_{3\pi}^2)$ with s_0 determined by masses of involved particles.

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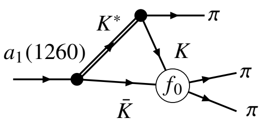

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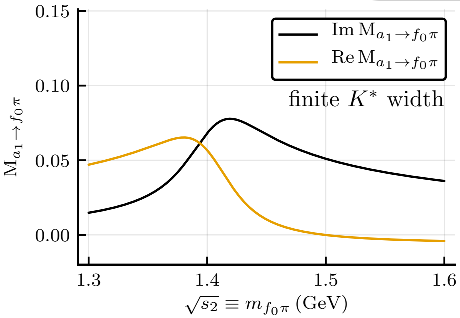

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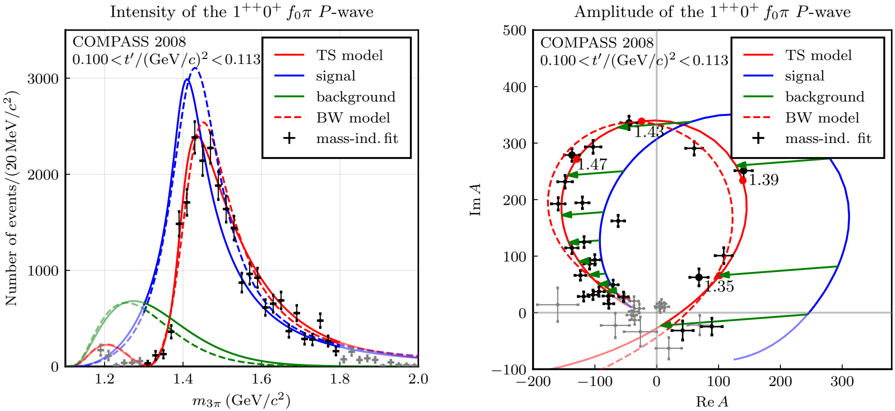
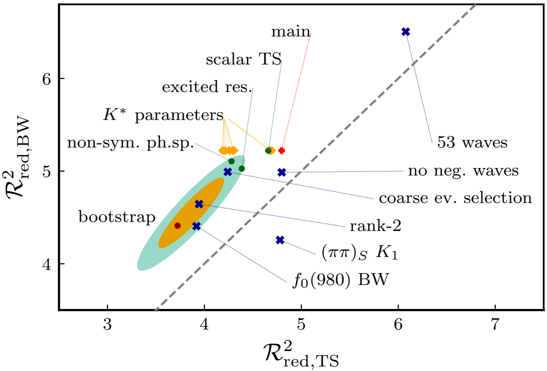
Fit with the rescattering model [COMPASS, PRL(2021)]

Fit perfectly describes the intensity and the phase motion



- No shape parameters for the signal component (TS)
- Background with constant phase is needed to shift the amplitude
- TS model shows a comparable quality to the resonance model (BW-model)

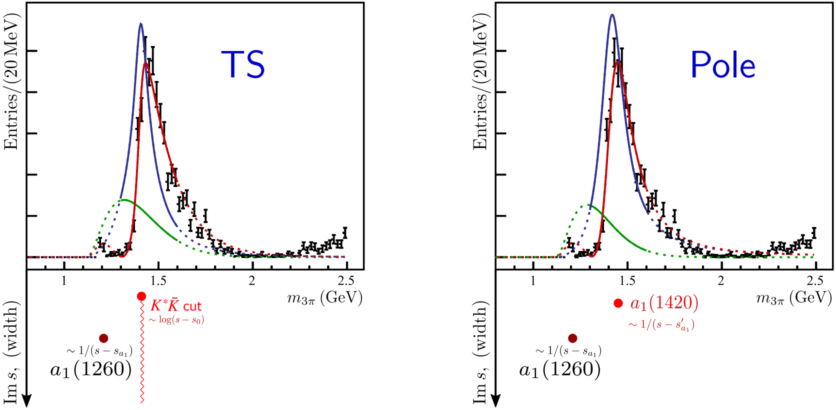
Systematic studies



TS model systematically yields a similar $\mathcal{R}^2_{\mathrm{red}}$ as the BW model.

- Neglecting interference of the conjugated decay chains,
- Neglecting the spins of the particles involved,
- Including the excitations $a_1(1640)$ and $a_2(1700)$
- Varying mass and width of the K^* resonance

Emerging interpretation [COMPASS, PRL (2021)]



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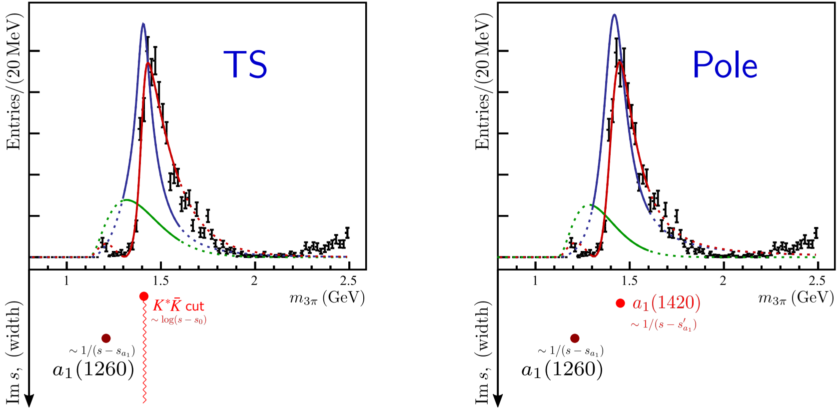

- $a_1(1420)$ signal can be described with $a_1(1260)$ as source for the **rescattering** via the triangle diagram ⇒ the first clear observation of the TS
- An additional pole is not needed, although, not excluded

Summary on $a_1(1420)$

- Peak and phase motion are not unique sign of a resonance!
- $a_1(1420)$ signal can be described with ordinary a_1 as source for the rescattering via the triangle diagram
- Old theoretical concept, but clearly observed for the first time!
- Intensity of signal $\sim 1\%$, in agreement with experiment

Signal in $f_0\pi$ P-wave $\Rightarrow$ established Triangle Singularity,
no need for the tetraquark

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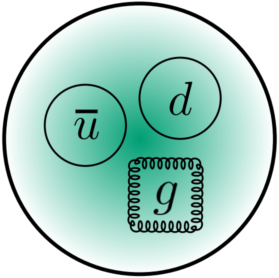
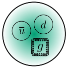
Outlook

- Solve consistent KT equations
  (five coupled systems: $\pi^-\pi^-\pi^+$, $\pi^-\pi^0\pi^0$, $K^+K^-\pi^-$, $K^0\overline{K}^0\pi^-$, and $K^0K^-\pi^0$)
- Observe the $a_1(1420)$ TS effect in τ decays [see e.g. Phys.Rev.D 99 (2019) 1, 016021]

$\pi_1(1600)$ hybrid candidate



Note on the history of $\pi_1(1600)$



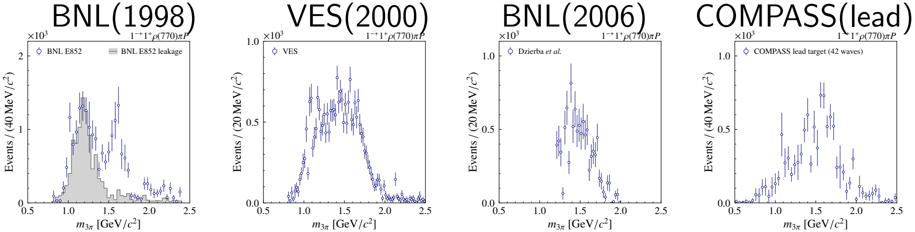
a resonance with non-$q\bar{q}$ quantum numbers, $J^{PC} = 1^{-+}$.

Two states in PDG: $\pi_1(1400)$ and $\pi_1(1600)$

- $\pi_1(1400) \to \eta\pi$
- $\pi_1(1600) \to \eta'\pi$ and $\to \rho\pi$ P-wave [solved in PRL122 (2019) 4, 042002]

Contradictions on $\pi_1(1600) \to \rho\pi$ P-wave (PWA)

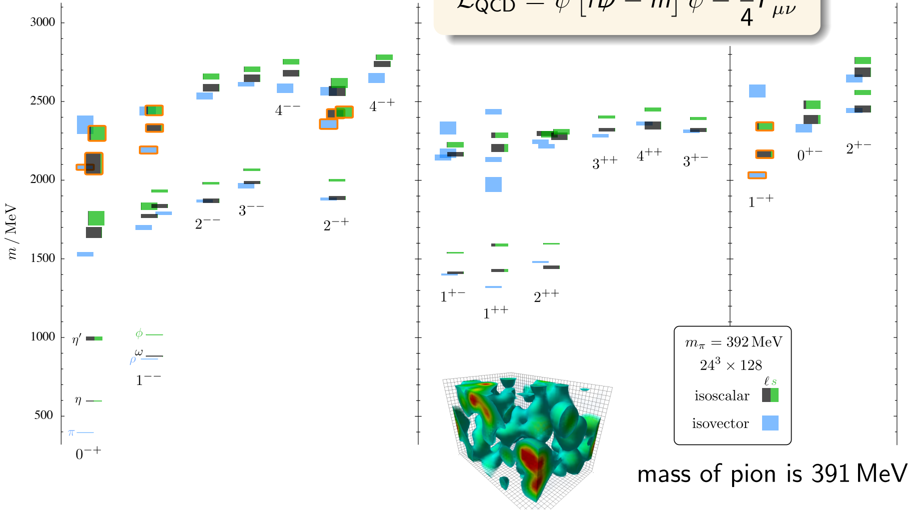
- Four analyses in the past arrive to different conclusions on **existence** and parameters of $\pi_1(1600)$



Light-meson excitations from Lattice QCD

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

$$\mathcal{L}_{\text{QCD}} = \overline{\psi}\left[i\not{D} - m\right]\psi - \frac{1}{4}F_{\mu\nu}^2$$



mass of pion is 391 MeV

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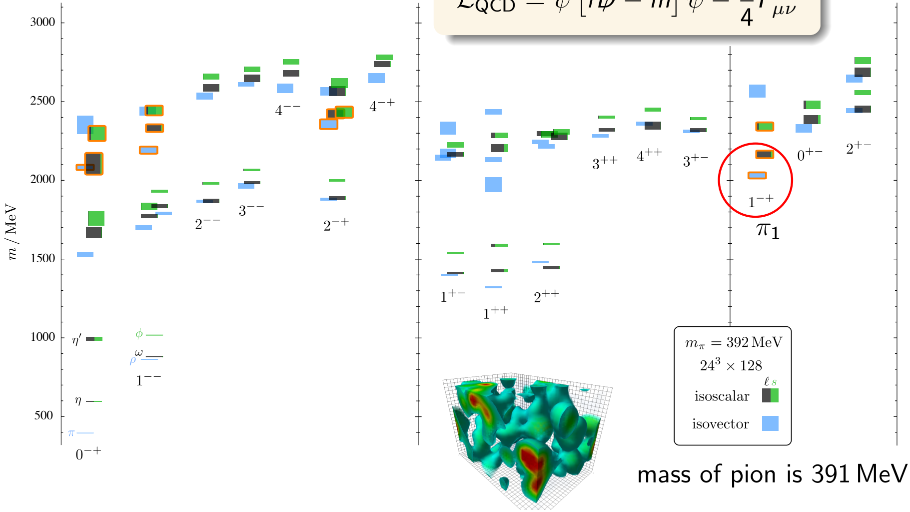

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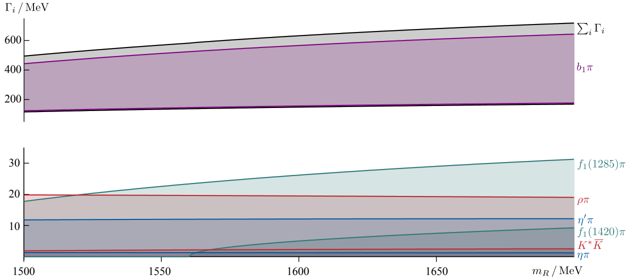
Exotic mesons in two-body **scattering** on lattice

[A.Woss et al., PRD 103, 054502 (2021)] (see the talk of Jo Dudek on Monday, 17h40)



Setup:

- $SU(3)$: $m_u = m_d = m_s$
- $m_\pi \approx 700\,\text{MeV}$
- 8 coupled two-body channels
- Wide range of operators

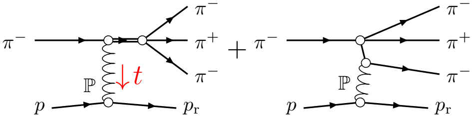
Conclusions:

- Strong coupling to $b_1\pi$
- Much smaller to $\rho\pi$, $f_1\pi$, $\eta^{(\prime)}\pi$
- Extrapolated width roughly agrees with experimental analysis

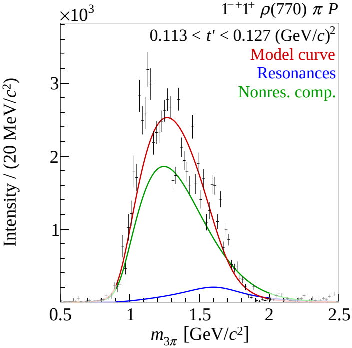
Parameters of the $\pi_1(1600)$ in 3π

[COMPASS, PRD98 (2018) 092003]

$\rho\pi$ *P*-wave from the 14-waves fit.



- Background changes with virtuality of $\mathbb{P}$ (t')
- The resonance mass and width are constrained to be the same for all t'



$$m(\pi_1) = 1550\,^{+110}_{-60}\,(\text{syst.})\,\text{MeV}, \quad \Gamma(\pi_1) = 580\,^{+100}_{-230}\,(\text{syst.})\,\text{MeV}$$

Consistent with measurements in $\eta'\pi$

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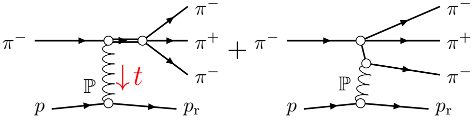

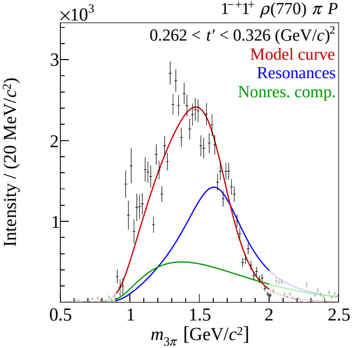

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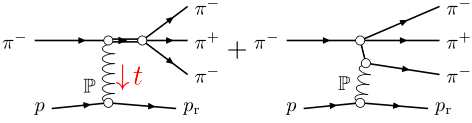

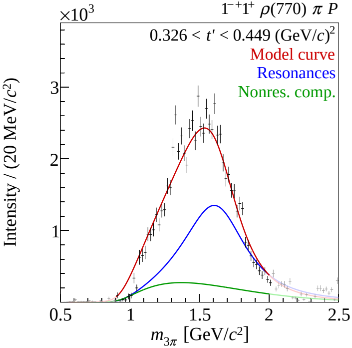

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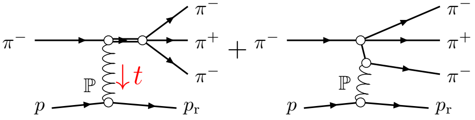

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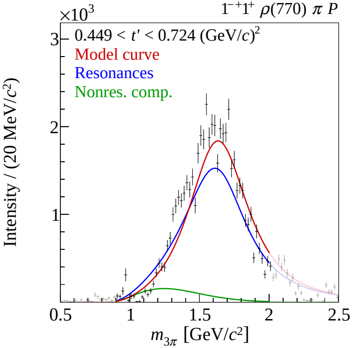

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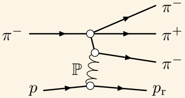
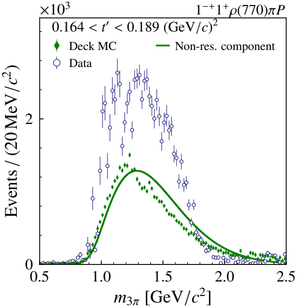
Two reasons of troubles with $\rho\pi$ P-wave [COMPASS, hep-ex:2108.01744]

Two effects:

- Non-resonant background depends on t' (Deck [PRL 13 (1964) 169-173])



$$= t_{\pi p} \frac{e^{-bt_1}}{m_\pi^2 - t_1} t_{\pi\pi}$$



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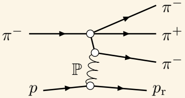

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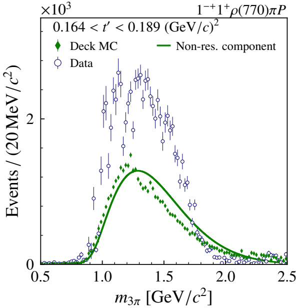
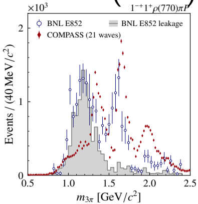
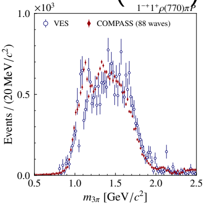
- Wave set (leakage to $\rho\pi$ P-wave) and consistency



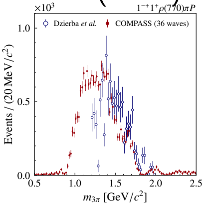
BNL(1998)



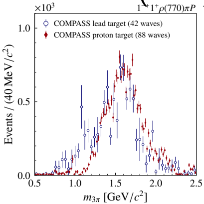
VES(2000)



BNL(2006)



COMPASS(lead)



Wrap up on $\pi_1(1600)$

- Analysis of $\eta^{(\prime)}\pi$ (not shown in this talk):
  - [COMPASS, PLB 740 (2015) 303]
  - [JPAC/COMPASS, PLB 779, 464-472]
  - [JPAC, PRL122 (2019) 4, 042002]

  establish $\pi_1(1400)/\pi_1(1600)$ is the same resonance with

$$\eta^{(\prime)}\pi: \quad m_{\text{pole}}(\pi_1) = 1567 \pm 24 \pm 86\,\mathrm{MeV} \quad \Gamma_{\text{pole}}(\pi_1) = 492 \pm 54 \pm 102\,\mathrm{MeV}$$

- Analysis of 3π:
  - [COMPASS, PRD95 (2017) 032004]
  - [COMPASS, PRD98 (2018) 092003]
  - [COMPASS, hep-ex:2108.01744]

  solved the long-standing puzzle on inconsistency of past analyses

$$3\pi: \quad m_{\text{pole}}(\pi_1) = 1630\,^{+110}_{-60}(\text{syst})\,\mathrm{MeV} \quad \Gamma_{\text{pole}}(\pi_1) = 570\,^{+100}_{-230}(\text{syst})\,\mathrm{MeV}$$

$\Rightarrow$ $\pi_1(1600)$ is lightest meson with exotic quantum numbers $J^{PC} = 1^{-+}$

Conclusions and outlook

- Hadron **spectroscopy** is a unique tool for understanding the QCD, the theory of matter formation
- **Diffractive** reaction is a clean setup for measurements of the excitation spectrum
- **COMPASS** leads the effort of large combined light-quark meson studies
- Many new surprises with new data (GlueX, BESIII, AMBER(?))
- Lattice QCD already provides quantities accessible at COMPASS, we should catch up
- Strengthen the TH+EXP collaboration

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Outlook for hadron spectroscopy at COMPASS

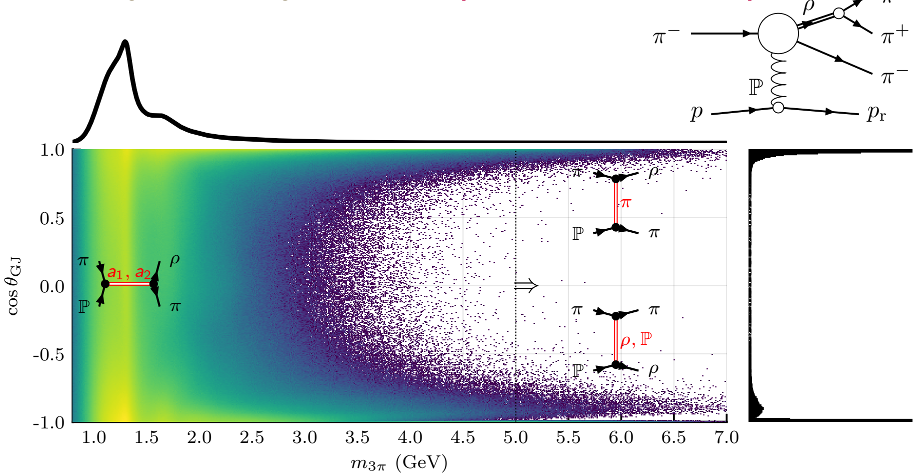
- $\pi_1(1600) \to b_1\pi$ and $\pi_1(1600) \to f_1\pi$ are under study in COMPASS
- Kaon diffraction reaction $K^- p \to K^-\pi^+\pi^- p$ is under study
  The first results are coming soon
- Extensive kaon spectroscopy program with AMBER at CERN is proposed

Thank you for the attention

Interfering background

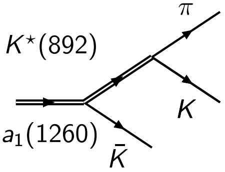
Forward-background scattering

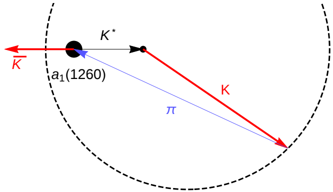
[COMPASS data, MM, PhD thesis]



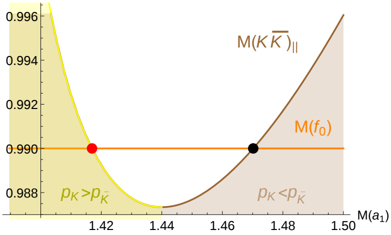
The high-energy exchange processes penetrate to the low energy and make resonance characterization difficult

Classical picture of near-mass-shell rescattering





Imagine cascade reaction $a_1(1260) \to K^\star(892)\bar{K}$, then $K^\star \to K\pi$, and calculate invariant mass of K and $\bar{K}$ for the case when K is parallel to $\bar{K}$.



Partial form of Landau conditions
[[Nucl. Phys. **13**, 181 (1959)]]:

- All particles in loop are on mass shell.
- The alignment of moments $\vec{p}_K \uparrow\uparrow \vec{p}_{\bar{K}}$.
- K is faster then $\bar{K}$.