Recent development in understanding of hadron spectra

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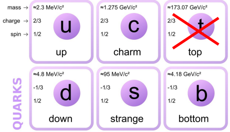
IWHSS 2022
CERN Globe

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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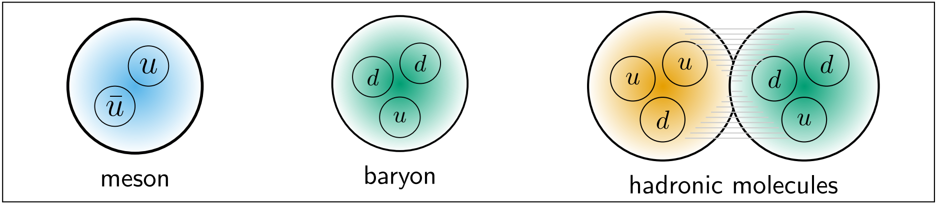

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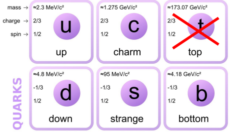

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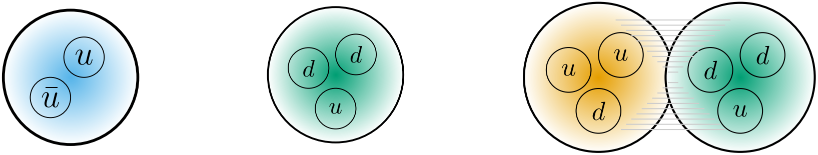
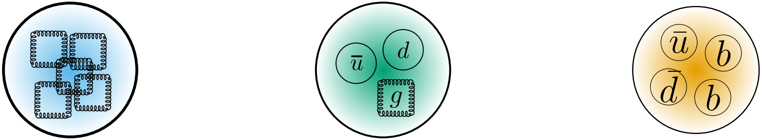


meson baryon hadronic molecules

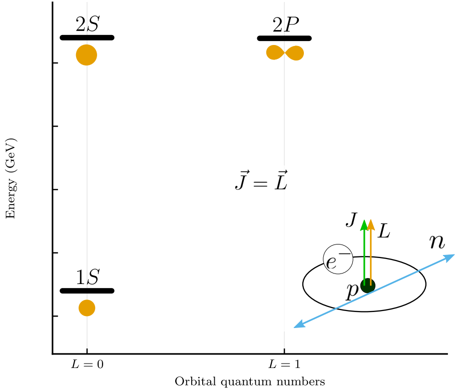
Exotic matter:



glueball hybrid tetraquark

Why there are so many hadrons?

QED



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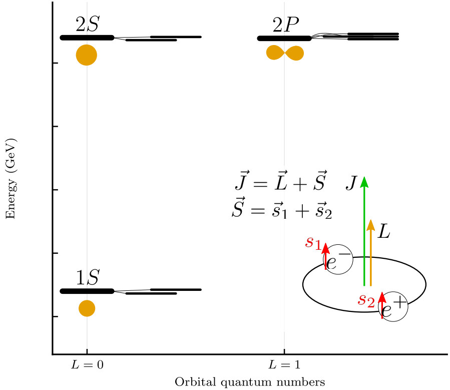

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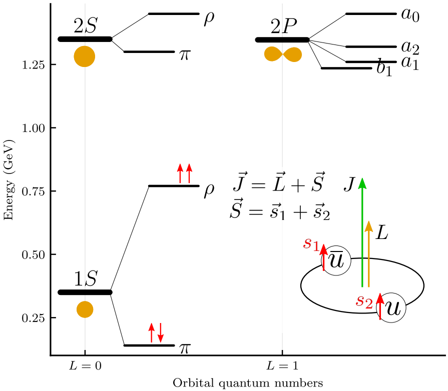

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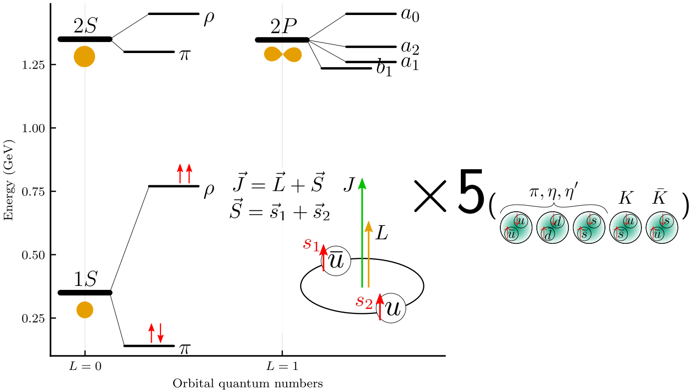

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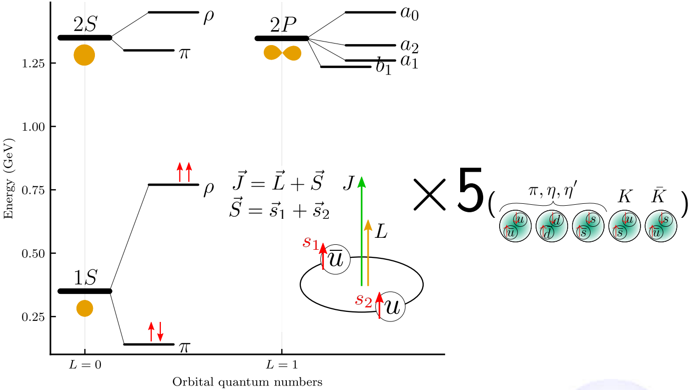
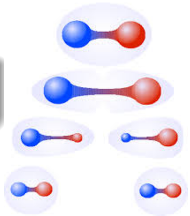
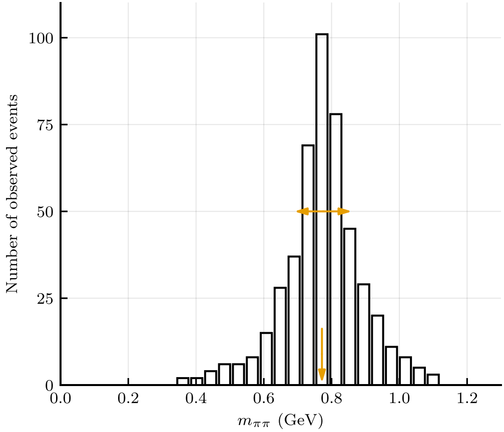


- (π, ρ), (K, K^*), $(\eta_c, J/\psi)$
  are the lowest $1S$ states $(\downarrow\uparrow, \uparrow\uparrow)$ of the families.



Goal: identify excitation of ordinary systems, find exotic formations

Invariant-mass distribution, resonances



Hadronic state is a particle

- charact. by **mass** (energy) and **width** (lifetime)

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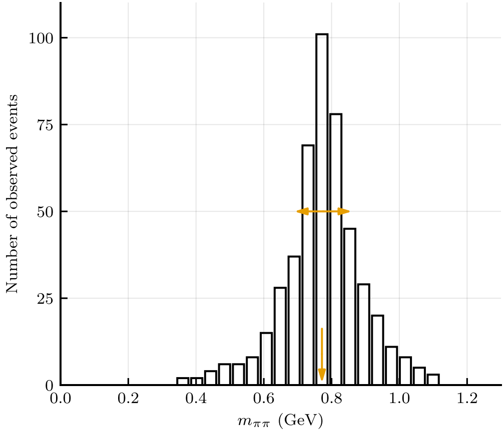

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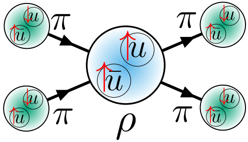

- Hadronic states are **resonances** of the hadronic system
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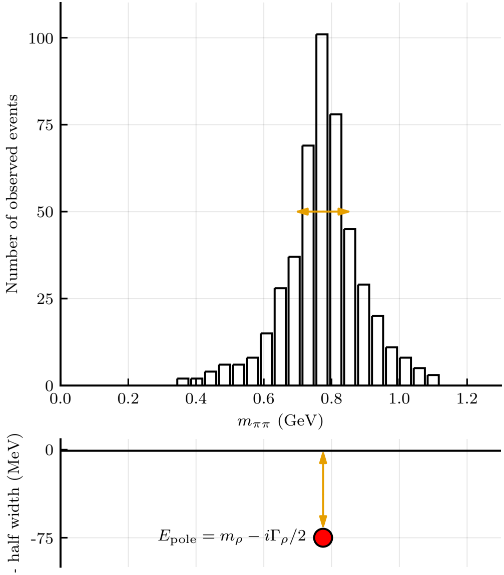

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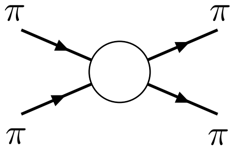

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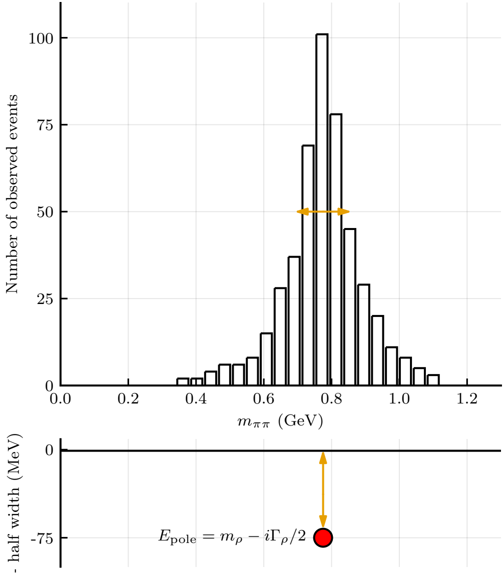

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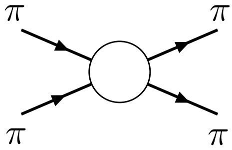

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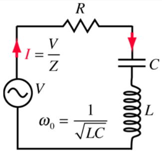
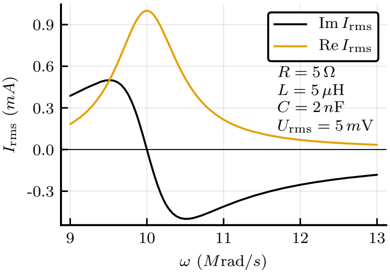
- resonances are **poles** of scattering amplitude.

Hadron resonances are resonances

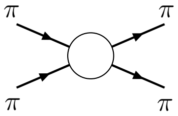
Electric circuit



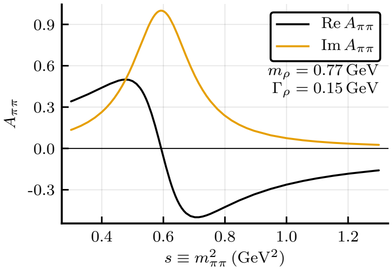
$$I_{\mathrm{rms}} = \frac{U}{R + iL\omega - \frac{i}{C\omega}}$$

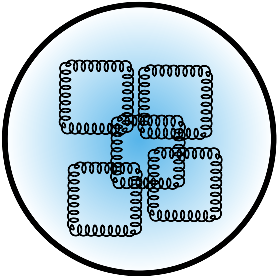


Scattering



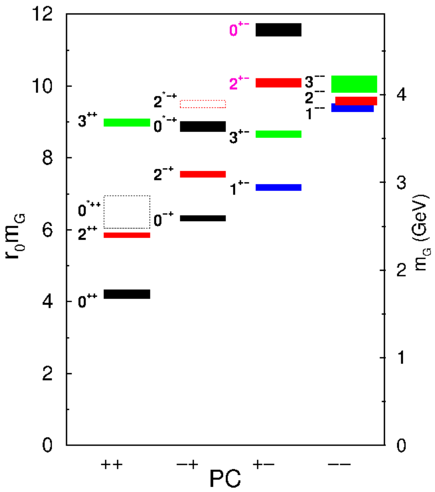
$$A_{\pi\pi} = \frac{m\Gamma}{m^2 - s - im\Gamma}$$





Glueballs

States in pure Yang-Mills



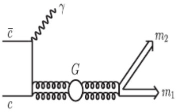
[Morningstar-Peardon, PRD60 (1999) 034509]

$$\mathcal{L}_{\mathrm{YM}} = -\frac{1}{4} F_{\mu\nu}^2$$

- The self-interaction between gluons leads to the prediction of glueballs
- 0^{++} is the lowest state, $m(G) \sim 1.7 - 2\,\mathrm{GeV}$
  [Chen et al., PRD73 (2006) 014516],
  [Huber et al., EPJC 80 (2020) 1077],
  [Szczepaniak-Swanson, PLB (2003) 577]
- The clearest sign of the confinement
- The worst state to search in real life due to large mixing with quark states

$J/\psi \to \gamma\pi^0\pi^0$ and $\to \gamma K^0_S K^0_S$

[JPAC, EPJC 82 (2022) 1, 80]



- Gluon-rich process, expected to be the golden channel for the search of the scalar glueball
- BESIII data [PRD98 (2018) 072003; PRD92 (2015) 052003]

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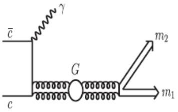

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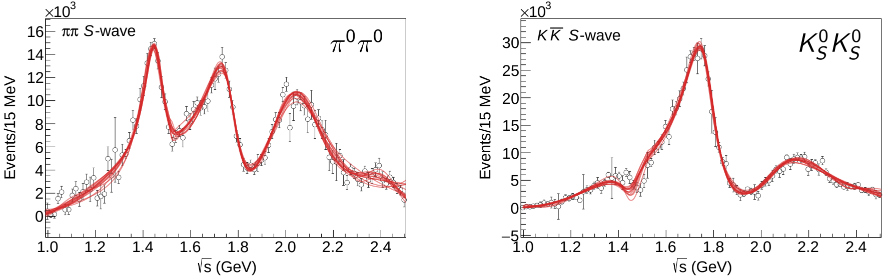

Large production coupling of $f_0(1710)$ suggests it to have sizable glueball components

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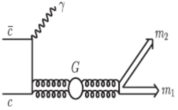

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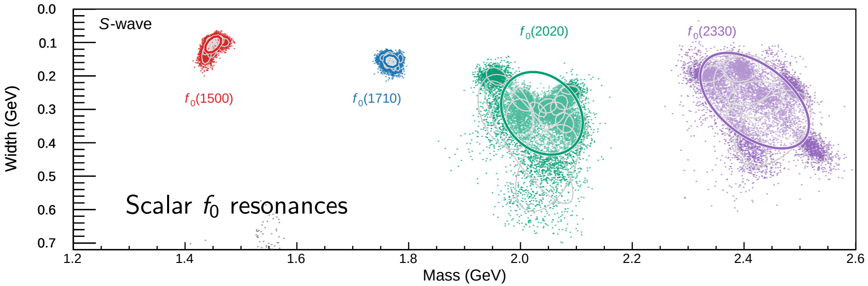

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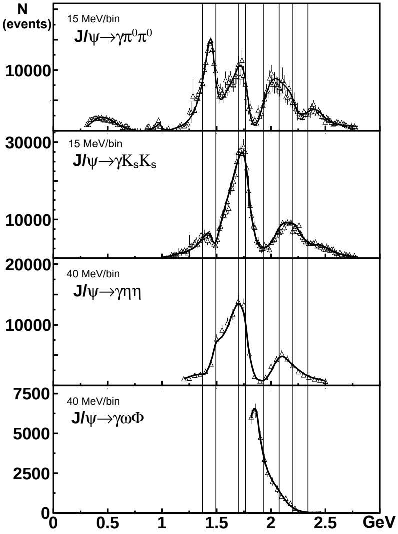
Production of scalar mesons via glueball compoment

[Bonn-Gatchina group, PLB816 (2021) 136227]



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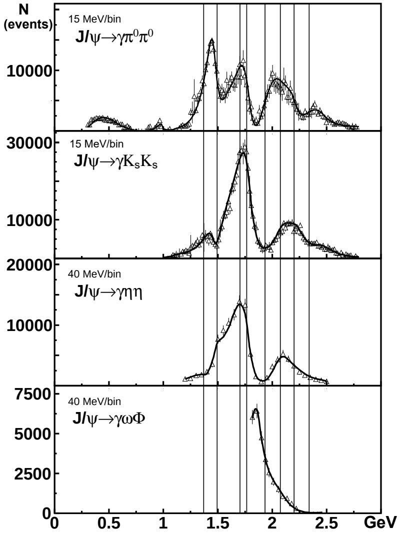

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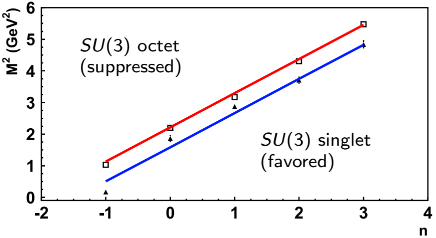

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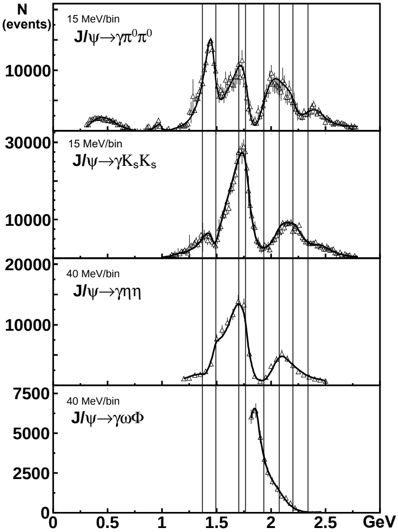

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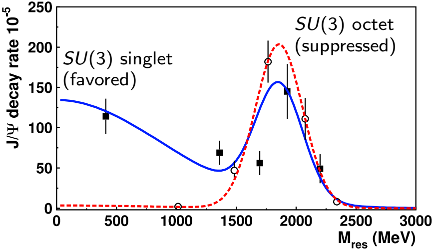
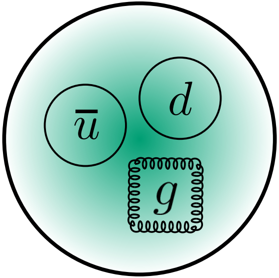


"Fragmented glueball":

- No extra state, shares scalar-resonance w.functions

Hybrids

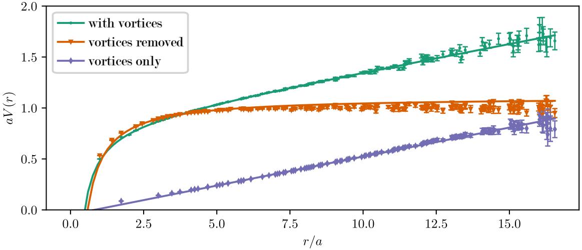


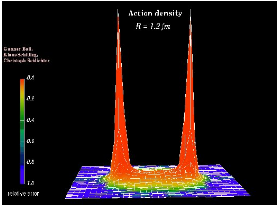
Hybrids

Vortices and QCD confinement

[Greensite, PPNP51 (2003) 1]

- The self-interactions of gluons cause formation of $q\bar{q}$ and g condensates
- Many strictures in QCD vacuum fields:
  - instantons, merons, abelian monopoles, **centre vortices**



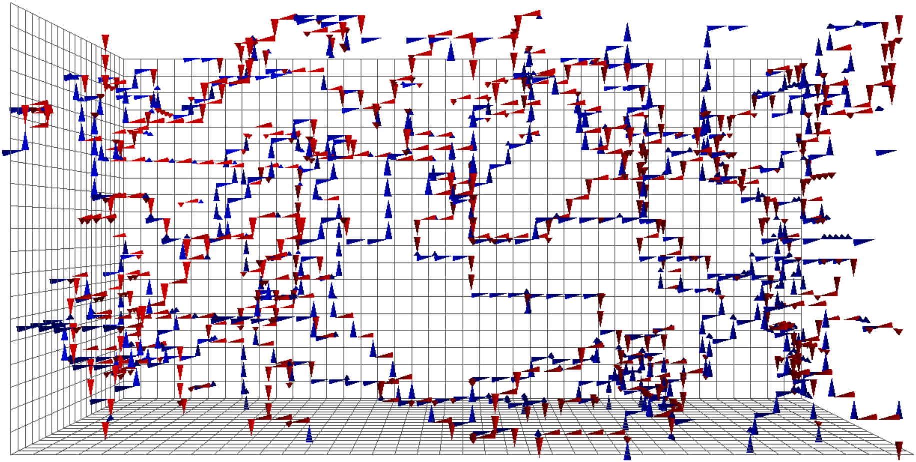


Centre vortices capture the essence of nonperturbative QCD:

- cause the confinement
- lead to dynamical generation of the mass

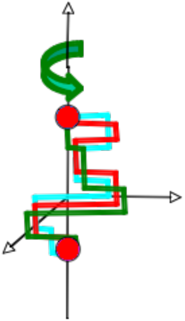
Vortices flow in QCD vacuum

[Adelaide group]

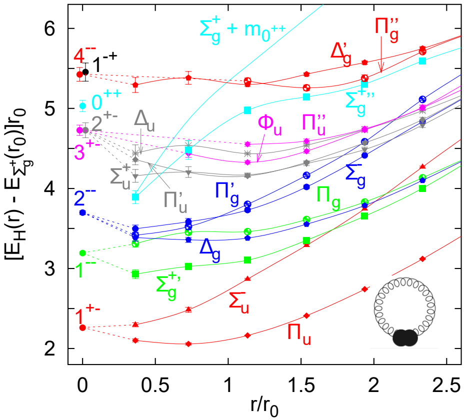


Constituent gluons

- Physical quarks appear to move in the gluon-field condensate
- The condensate can be **excited** leading to effective (constituent) gluons



[Bali et. al, PRD 69 (2004) 094001]



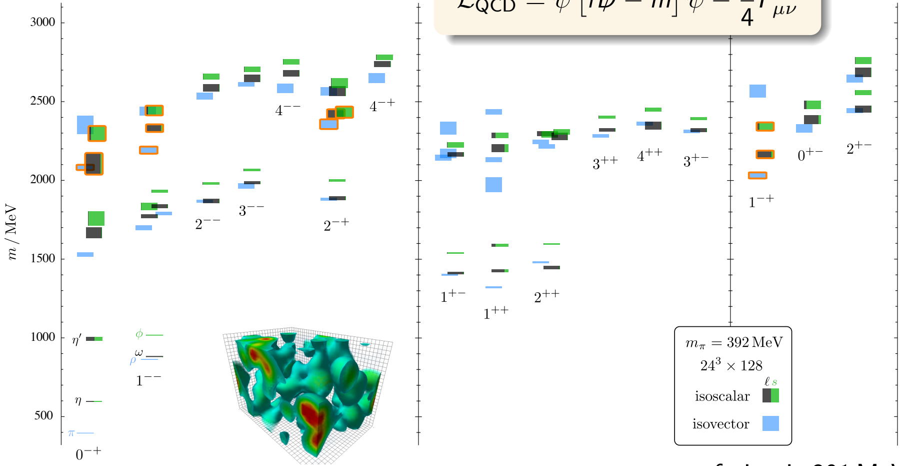
The lowest state is $J^{PC} = 1^{-+}$

Gluons behave as quasiparticles with 1^{+-} [Krupinski-Szczepaniak, PRD73 (2006) 116002]

Hybrid multiplets from Lattice

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

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



[D. Leinweber et al, CSSM Visualisation]

mass of pion is 391 MeV

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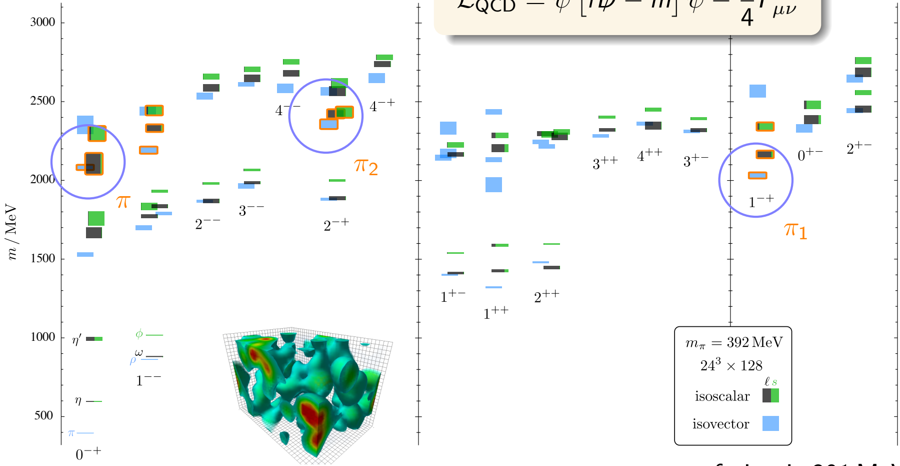

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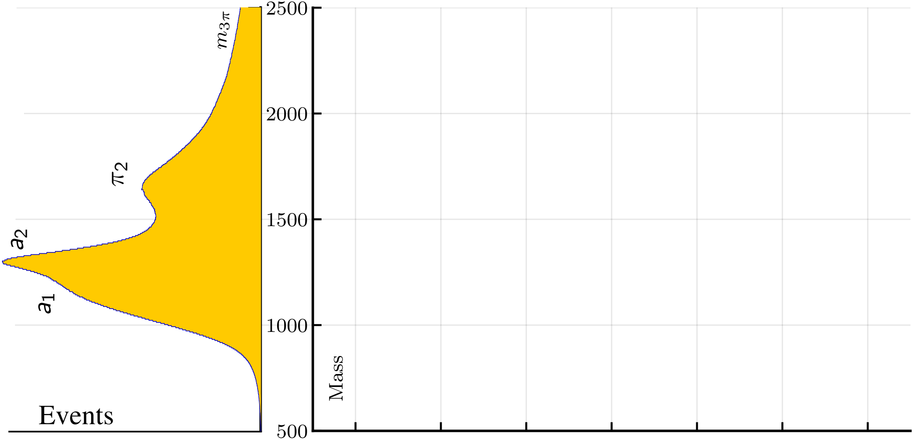
Diffractive production of 3π states [COMPASS, PRD95 (2017) 032004]

The results of the 3π PWA at COMPASS
— 14 interfering waves × 11 t'-slices simultaneously.



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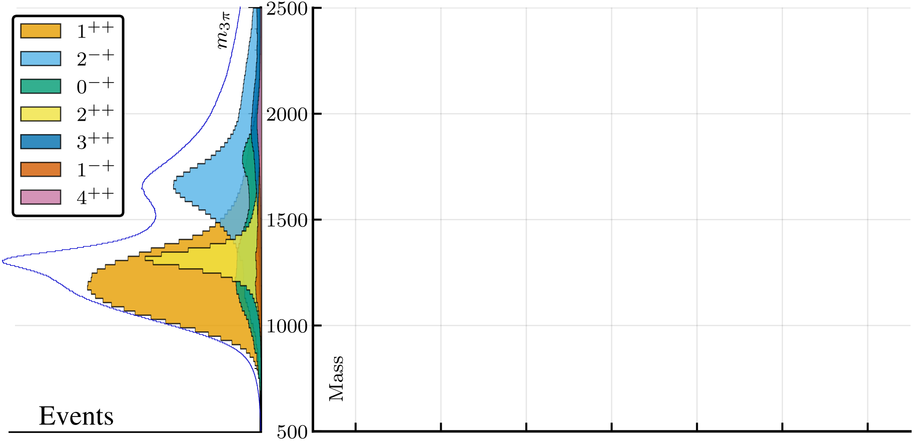

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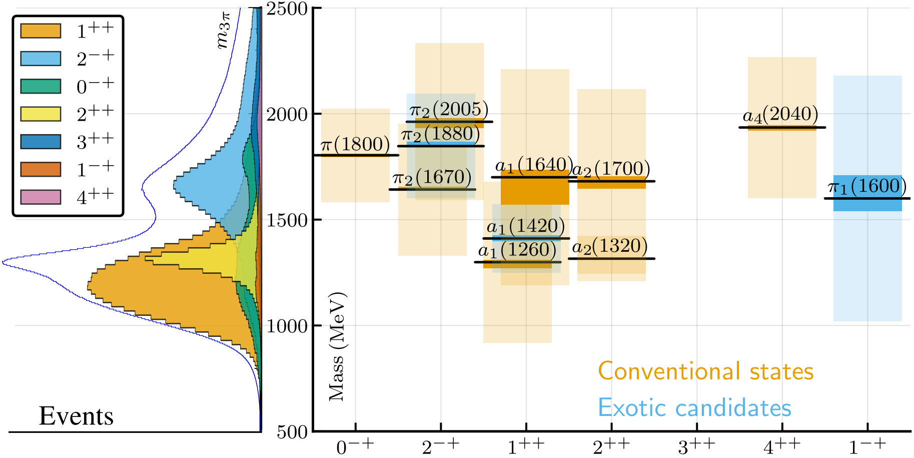


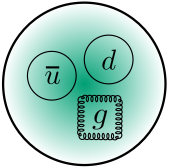
- Simultaneous fit for 11 resonances including hybrid candidates, $\pi_1(1600)$ and $\pi_2(1880)$.

Experimental evidence for the hybrid mesons

Evidence for 1^{-+} hybrid

- Established in decays to $\eta^{(\prime)}\pi$ by COMPASS [COMPASS, JPAC]
- Established in decays to 3π by COMPASS [COMPASS]
- See in $\bar{p}N$ annihilation with the Crystal Ball data [Kopf et al.,]

More details in Stephan's talk (today), Vincent's talk (tomorrow)



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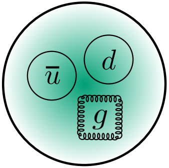
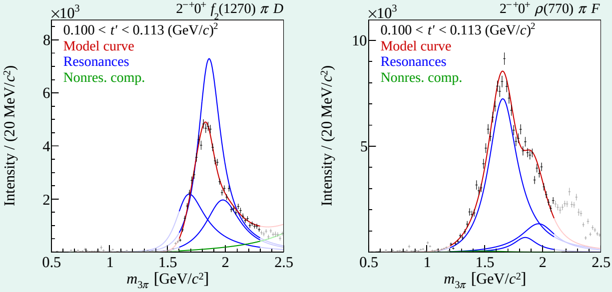


Hits for 2^{-+} hybrid

- $\pi_2(1880)$ is required in COMPASS fits [COMPASS, PRD95 (2017) 032004]
- **Challenge:** overlapping resonances!



Towards more theory-sound model

[JPAC, PPNP (2022) 103981]

JPAC: tight collaboration between theory and experiment

- How to model 3-body resonances?
  [JPAC, JHEP 08 (2019) 080]
- How to incorporate spin?
  [JPAC, PRD101 (2020), 034033]
- How to add background?
- Test case: $a_1(1260) \to 3\pi$
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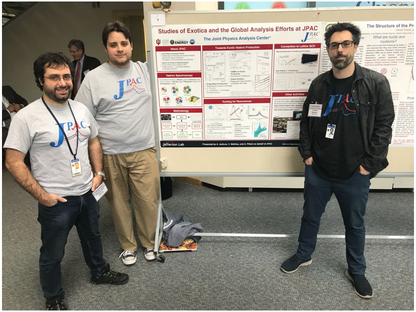

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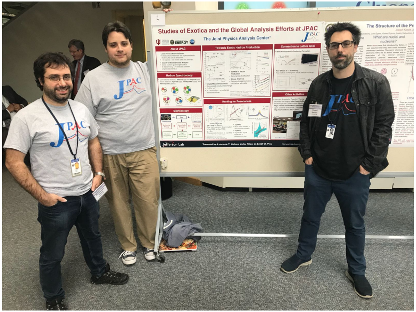

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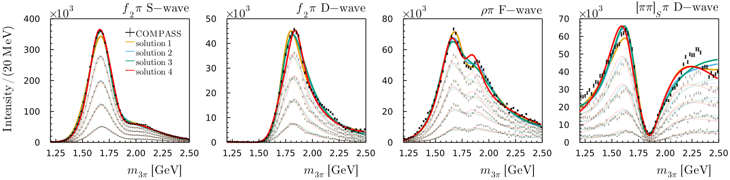
2^{-+} fits require $\pi_2(1880)$



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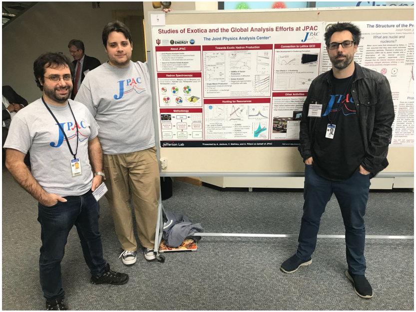

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  [JPAC, PRD101 (2020), 034033]
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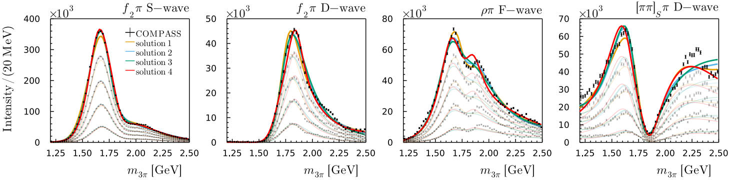
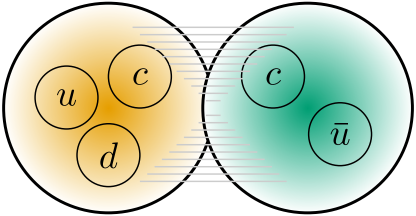
- Test case: $a_1(1260) \to 3\pi$
  [JPAC, PRD98 (2018), 096021]

2^{-+} fits require $\pi_2(1880)$

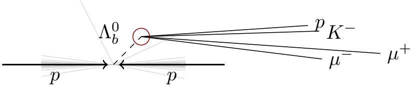


See talk of Vincent tomorrow.

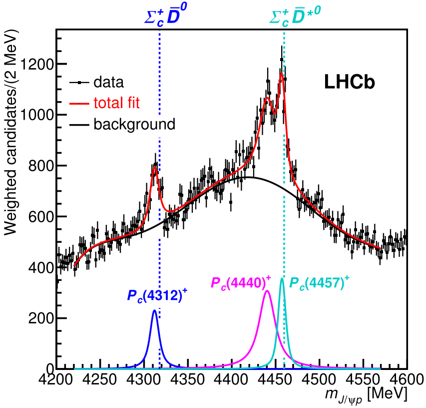


Exotic molecules

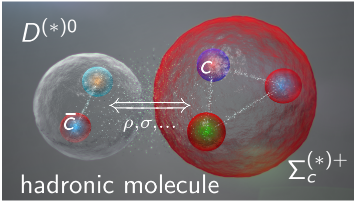
Pentaquarks in $p^{(uud)} J/\psi^{(c\bar{c})}$ mass spectrum [PRL 122 (2019) 22]



$$\Lambda_b^0 \to (pJ/\psi)\, K^-$$



- Narrow peaks in $\to pJ/\psi$
- Right near $\Sigma_c^{*+}\bar{D}^{*0}$ threshold
- The most plausible interpretation is hadronic molecules



- Would be an exotic nuclei
- No analogue of the Meson-Baryon system in nuclear physics

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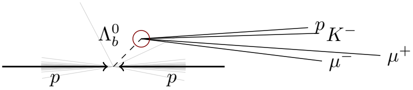

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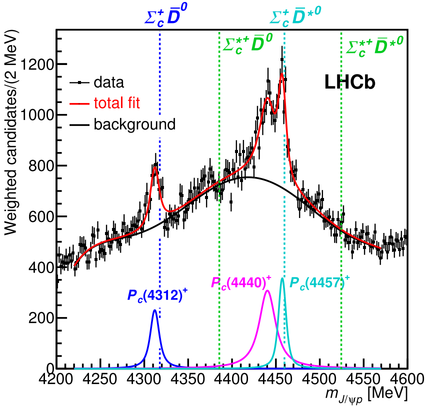

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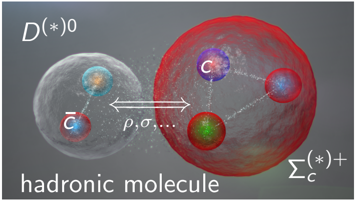

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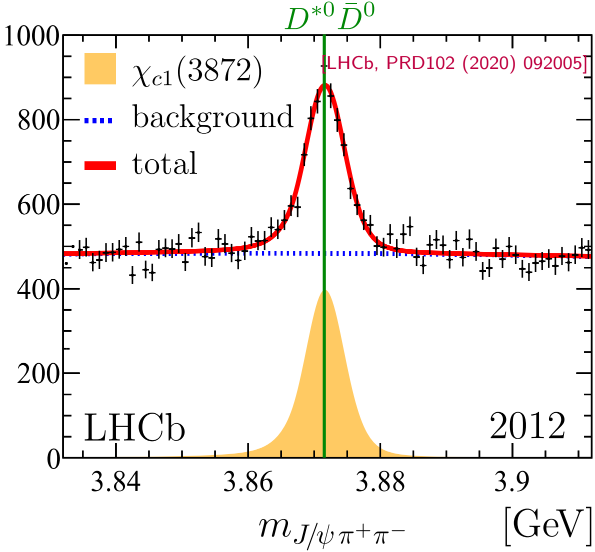
[Du et al., PRL 124 (2020) 7], [Liu et al., PRL 122 (2019) 24]

$\chi_{c1}(3872)$: charmonium state right at the $D^{*0}\bar{D}^0$ mass

Nature is highly debated from 2003 [Belle, PRL91 (2003), 262001]

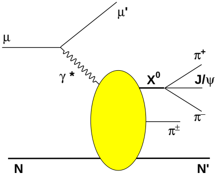
- Charmonium state ($c\bar{c}$), $\chi_{c1}(2P)$ is expected 70 MeV above
- The peak right at the $D^{*0}\bar{D}^0$ threshold
- Large isospin violation in the strong decays to $J/\psi\pi^+\pi^-$ [LHCb 2022, 2204.12597]

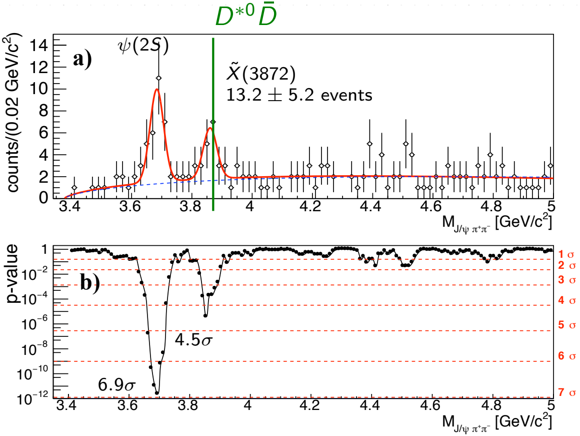


Puzzles from the muoproduction of $\chi_{c1}(3872)$

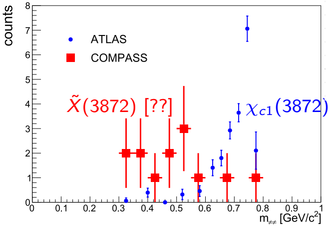
[COMPASS, PLB 783 (2018) 334]

- Exclusive production





- In association with $\pi^{\pm}$
- Large rate w.r.t. $\psi(2S)$



$\chi_{c1}(3872) \to J/\psi\rho$

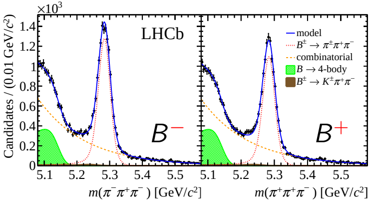
- $\pi\pi$ spectrum should show be the tail of the ρ
- The signal in 4.7σ tension with $\chi_{c1} \to J/\psi\rho$ decay

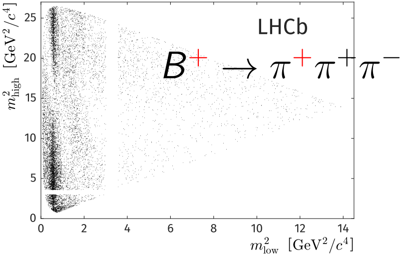
Precision studies of resonance line shapes

CP violation in $B \to 3\pi$

[PAPER-2019-017 (LHCb), PAPER-2019-018 (LHCb)]

Model-independent analysis





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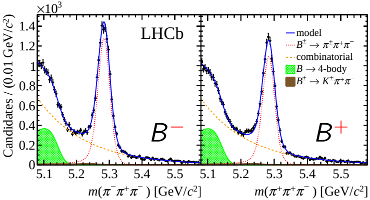

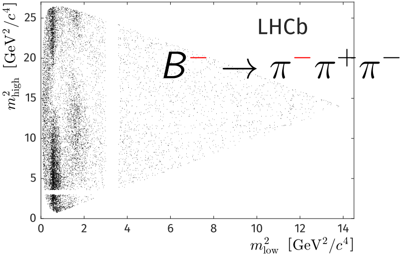

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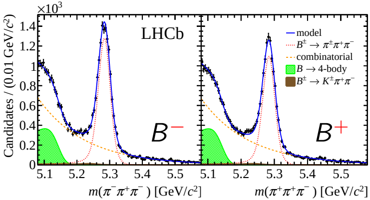

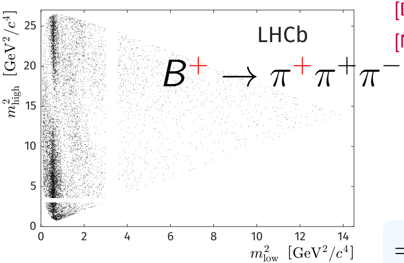

- $\mathrm{Br}(B^\pm \to \pi^\pm\pi^+\pi^-)$ are significantly different
- However, CPT implies same lifetime of B^+ and B^-

The main mechanism of CPV is **final-state interaction**

[Dedonder et al., APPB42 (2011), 2013]

[Nogueira et al., PRD92, 054010 (2015)]

- Decay probability is distributed between various channels.
- $\pi\pi \leftrightarrow K\bar{K}$ ensures distribution of CP between $B \to 3\pi$ and $B \to \pi K\bar{K}$

$\Rightarrow$ Precise studies of $\pi\pi/K\bar{K}$ amplitudes are needed

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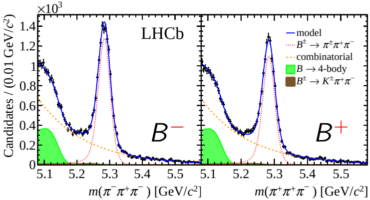

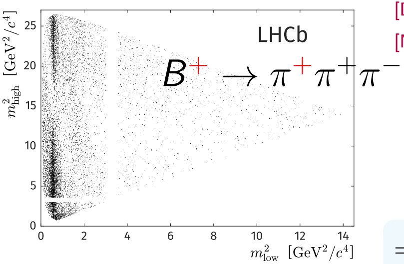

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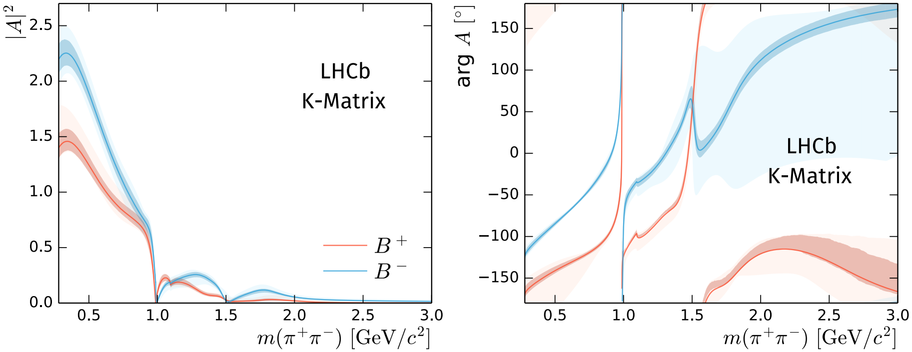
Recent results of $\pi\pi$ amplitude in D decays [PAPER-LHCb-2022-0XX], see Liupan's talk.

Extracted $(\pi\pi)_S$ production amplitude

[PAPER-2019-017 (LHCb)]



- Clear difference in $(\pi\pi)_S$ amplitude in B^+ and in B^-

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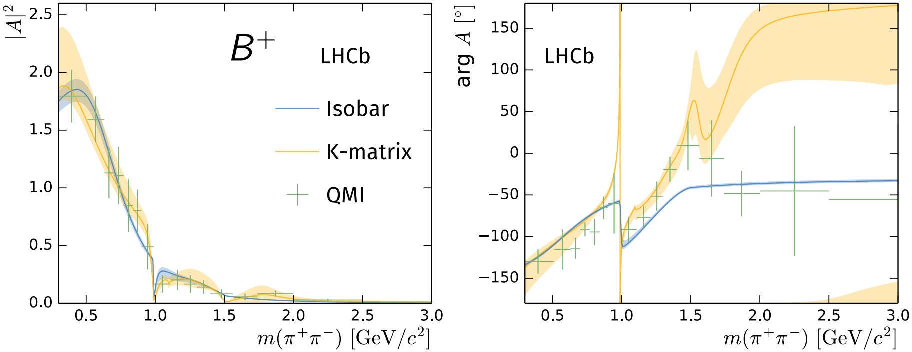

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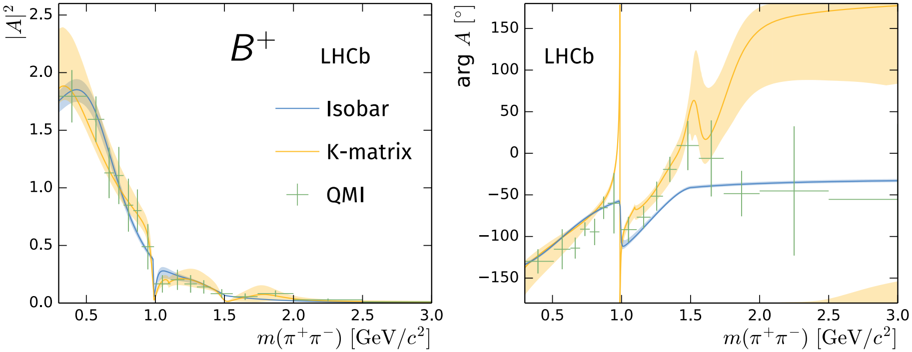

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- Different parametrizations are broadly consistent to each other

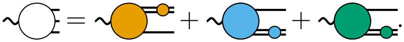
Many sources of the CP violation:

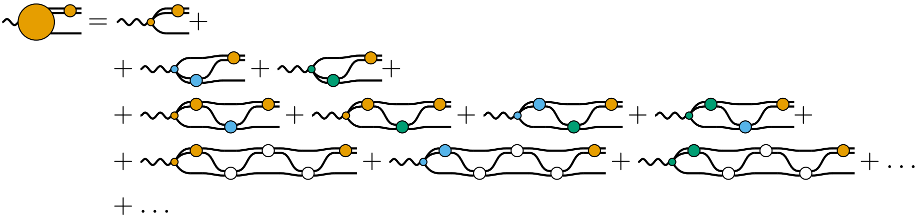
- $(\pi\pi)_S$-wave
- $\rho(770)/(\pi\pi)_S$ interference
- $f_2(1260)$

Convoluted with three-body dynamics

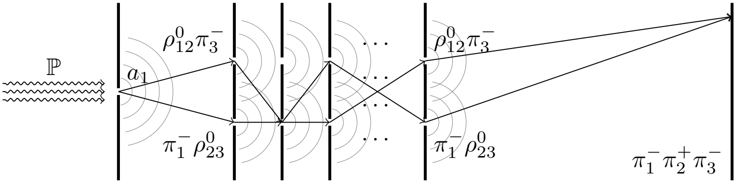
Three-body final-state interaction

For multibody decays, several decay chains lead to the same final state





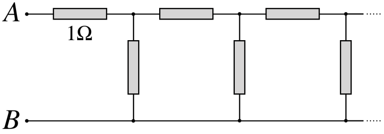
Hadronic double-slit experimental with infinite # of barriers



Infinite Resistor Ladder Puzzle

[arXiv:2105.03690]

Equivalent resistance of the infinite ladder of the chains:



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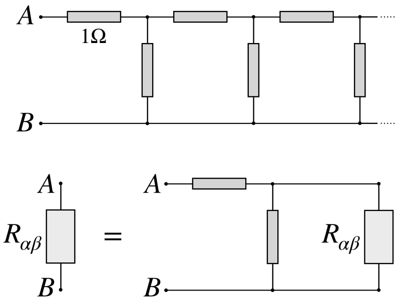

Equivalent resistance of the infinite ladder of the chains:

- Solved by adding one more unit cell

$$R_{\alpha\beta} = 1 + \frac{R_{\alpha\beta}}{1 + R_{\alpha\beta}}$$

- The answer is the golden ratio

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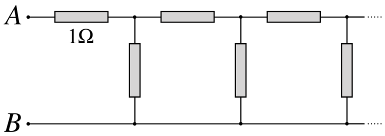
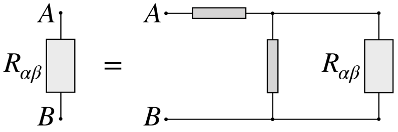
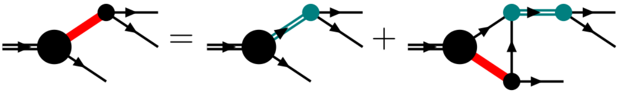




Infinite Rescattering Ladder



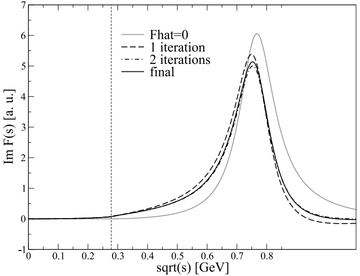
- Unitarity and analyticity are imposed (Khuri-Treiman equations)
- Solved by one more cell (a virtual loop integral)

One applications of the rescattering equations

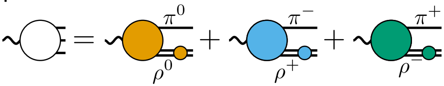
$$\phi/\omega \to 3\pi$$

[Niecknig et al., EPJC72 (2012) 2014]

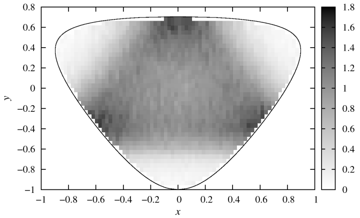
[I. Danilkin et al., PRD91 (2015), 094029]



- proceeds via three coherent chains



- KT to sum the infinite ladder
- The solution converges with three iterations



- 2×10^6 decays $\phi \to \pi^+\pi^-\pi^0$ by KLOE
- Excellent agreement with the data: $\chi^2/\text{ndf} = 1.02$
- Proves importance of the 3b rescattering corrections.

Probability re-distribution

$$\boxed{X \to \pi\pi\pi} \quad \xleftrightarrow{\pi\pi \leftrightarrow K\bar{K}} \quad \boxed{X \to \pi K\bar{K}}$$

- Plays nicely for B decays making CPV consistent with CPT
- What is tuning the mass of X to light-meson sector?

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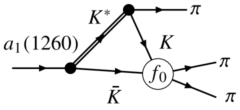

- Couplings between 3π and $\pi K\bar{K}$ is enhanced at 1.42 GeV
- Resonance-like effect, however, not exotic state
- Long-thought theoretical concept
- Observed by COMPASS for the first time
  [COMPASS, PRL 115 (2015) 082001]
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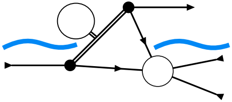

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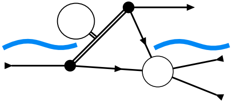

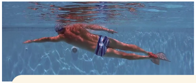

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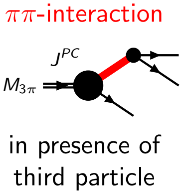
Ongoing effort to compute the effect in the KT approach.

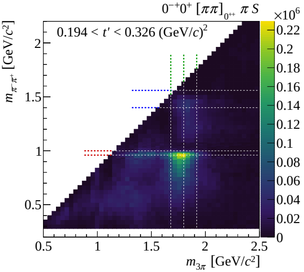
Mode precise data on $\pi\pi$ scattering

freed-isobar analysis in COMPASS



Large set of different $\pi\pi$ S-waves:

- The lineshape depends on:
  - Total invariant mass $M_{3\pi}$
  - Cross channel amplitudes (other waves in sector J^{PC})
  - Total quantum numbers J^{PC}



Several ongoing efforts to interpret the data, calibrate th. frameworks

Mode precise data on $\pi\pi$ scattering

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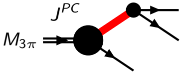
$\pi\pi$-interaction



in presence of third particle

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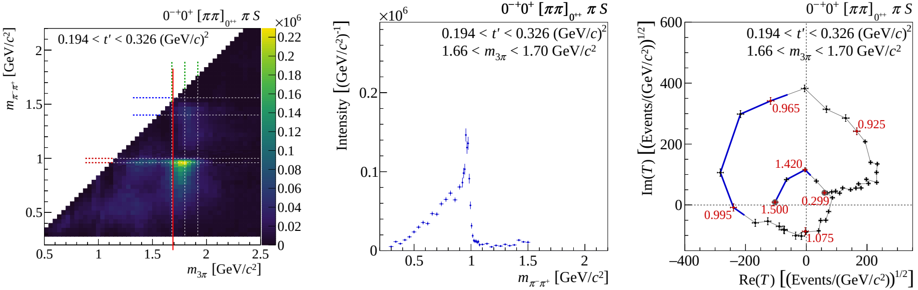

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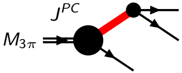

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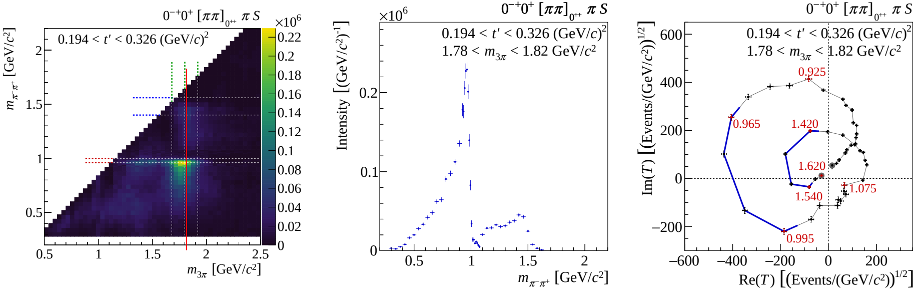

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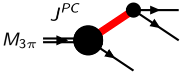

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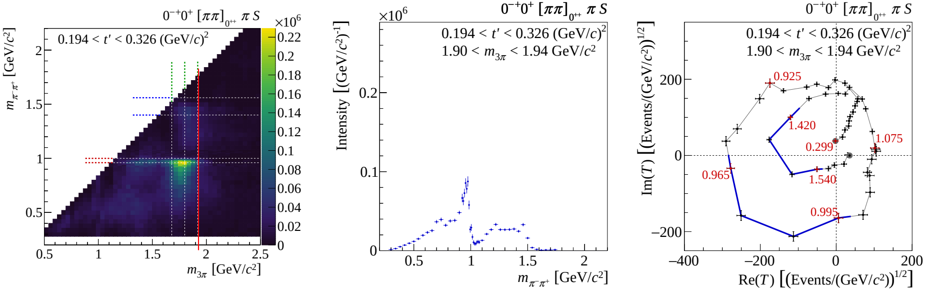

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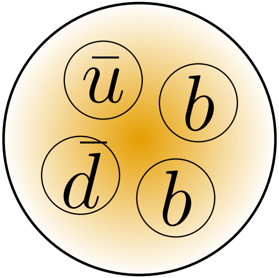
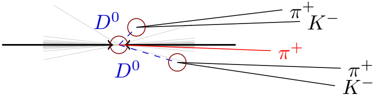
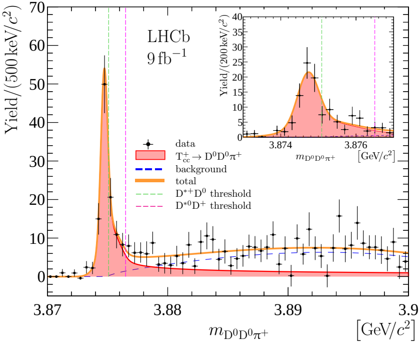


Tetraquarks

The landmark of 2021 – double-charm tetraquark, T_{cc}^{+}

[NP 18 (2022) 7, 751-754, NC 13 (2022) 1, 3351]





Two models: Native & Th.-motivated

- The peak position is well constrained.
- The width is not, limit to the coupling: $|g| > 7.7(6.2)\,\mathrm{GeV}$ at 90(95)% CL

Parameter	Value
N	117 ± 16
δm_{BW}	-273 ± 61 keV/c^2
Γ_{BW}	410 ± 165 keV

Naive BW

Parameter	Value
N	186 ± 24
δm_{U}	-359 ± 40 keV/c^2
$\lvert g\rvert$	3×10^4 GeV (fixed)

Advanced Model (developed for 3π at COMPASS)

Excellent agreement with the data. Reaction amplitude is fully fixed.

Fundamental parameters of T_{cc}^{+} [interactive]

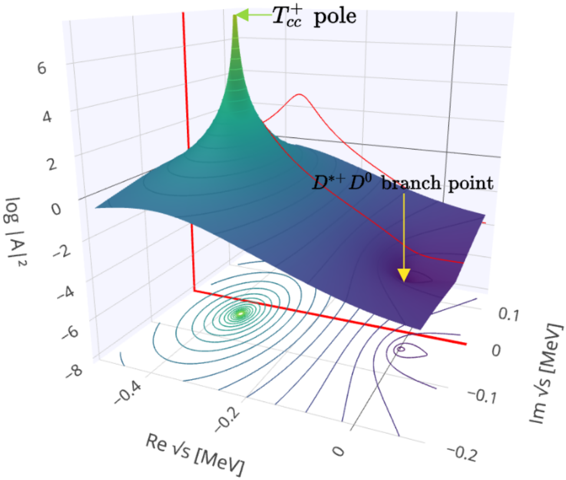
Mass and width – position of the complex pole of the reaction amplitude

- Analytic continuation is non-trivial due to three-body decays [MM et al. (JPAC), PRD 98 (2018) 096021]

The pole parameters:

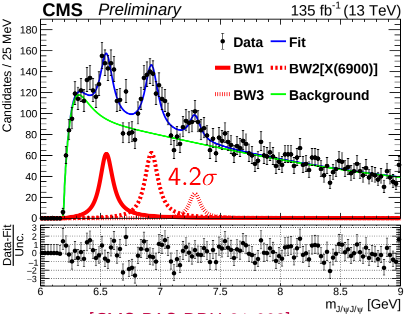
$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}\,\text{keV}\,,$$

$$\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14}\,\text{keV}\,.$$

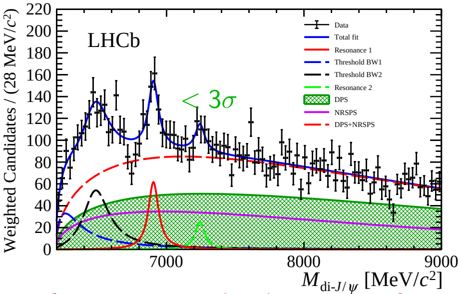


States in $J/\psi J/\psi$ spectrum – four-charm tetraquarks, $T_{\psi\psi}$

[LHCb(2020), CMS(2022), ATLAS(2022)]



[CMS-PAS-BPH-21-003]



[LHCb, Sci.Bull. 65 (2020) 23, 1983-1993]

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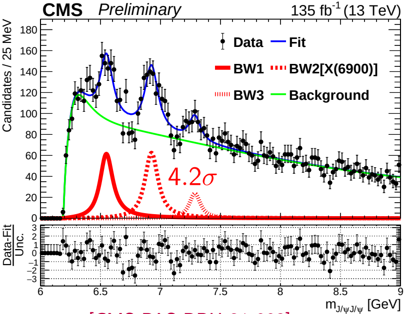

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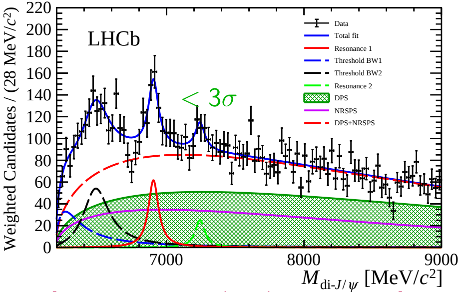

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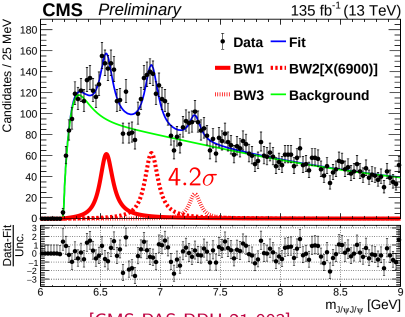

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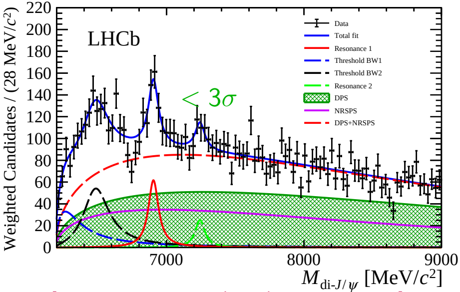

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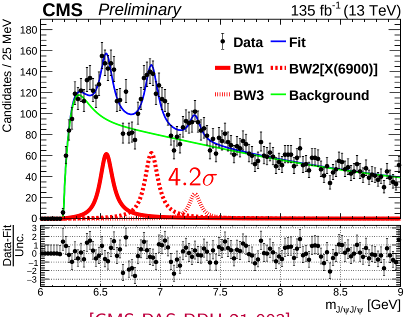

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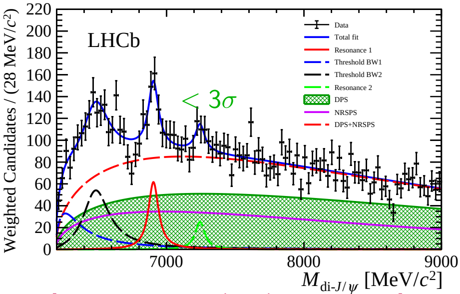

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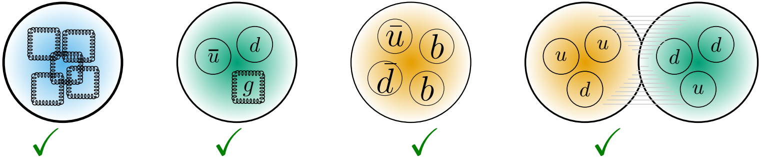
- Rapid raise at the threshold followed by the three peaks.
- Clear dips at 6.8 GeV makes the fit struggle
- Background is a continuum production process with many J^{PC}.
  Similar to Deck process in diffractive reactions
- Ideas to improve the analysis adding angular variables
  [MM, L. An, R. McNulty, arXiv:2007.05501]

Summary

- Spectroscopy is one of the most developing field of fundamental physics
- New large data samples from modern experiments
- Great effort of exp. and th groups
- Am amazing rate of discoveries:
  - New clues for the scalar glueball
  - Hybrid meson is established in several decay modes
  - Long-thought triangle singularity is observed
  - New classes of hadrons, $QQ\bar{q}\bar{q}'$ and $QQ\overline{QQ}$
  - New types of atoms, hadronic molecules.



Thank you for the attention