First report on CCE subTask force with dedicated theorists

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CCE SubTask Force with theoreticians

- Started during the scrutiny process and in view of a future physics book
  → *sharpening the uniqueness and competetiveness of PANDA*

- FullSim physics analyses to be carried out
  → *New, up-to-date material for conferences, and*
  → *Set of physics paper planned ... (towards physics book)*

Charmonium-like exotics at PANDA

- uniquely gluon-rich process: ppbar
  → *high cross section for states with gluonic excitations / exotics*
- unique in precise measurement of widths
  → *sub-MeV range, needed to understand X,Y,Z nature*
- unique in discovery potential for high spins:
  → *no angular momentum barrier (and no restriction spin)*
- complementary production to e.m. induced process

=> Only PANDA will enable to explore complete multiplets and clarify nature of X,Y,Z

Publication / release issues

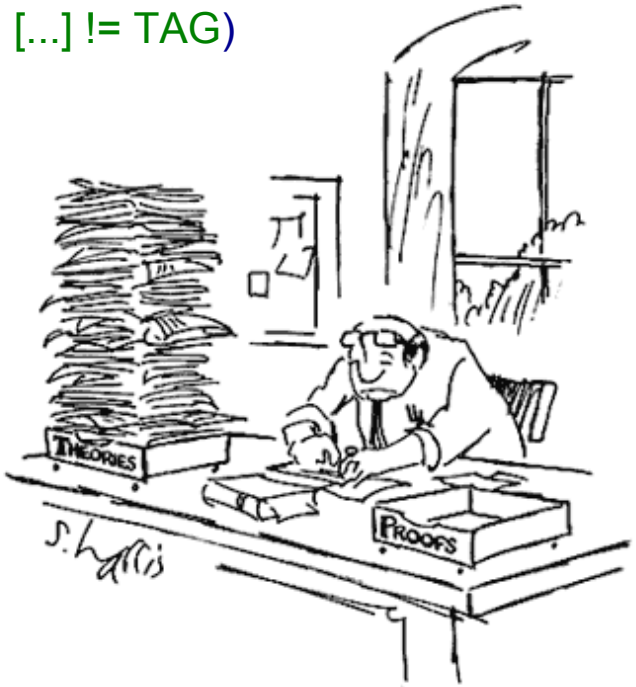
In collaboration with Christoph Hanhart, we set up a Task Force on CCE

List of involved theorists, expertise ([...] = TAG, [...] != TAG)

- Christian Fischer (U. Giessen) [P]
- Eric Swanson (U. Michigan) [P]
- Mikail Voloshin (U. Minnesota) [P]
- Antonio Polosa (U. Roma I) [P]

- Nora Brambilla (TU Munich) [EFT]
- Christoph Hanhart (FZJ) [P,EFT]
- Matthias Lutz (GSI) [P,EFT]
- Juan M.N. Pamplona (U. Valencia) [P,EFT]

- Gunnar Bali (U. Regensburg) [L]
- Sasa Prelovsek (U. Ljubljana) [L]
- Christopher Thomas (U. Cambridge) [L]
  (member of the Hadron Spectrum Collaboration)



Request to / common goal with theorists

- **Extend the list of channels**
  - Which ones to be added?
  - Especially in view of uniqueness/competitiveness by PANDA
  - Get right priorities

- **Strengthen analysis outcome with input/calculations from your side**

  - A good example of the resonance energy scan study using the example of X(3872)
    → *provided slides [talk given at QWG 2016]*

  - Hanhart et al. provided line-shape predictions for virtual vs. bound state
    => *Apart from simple BW shaped resonance assumption, dedicated study in addition for distinction between two line-shapes / types of states (detemine the pole location)*

Collection & summary of new input (floating, in progress)

New inputs – X(4014)

M.Voloshin: Apart from X(3872), the companion state $X_2(4014)$ at the $D^{*0}\,\bar{D}^{*0}$ threshold with $J^{PC} = 2^{++}$ is extremely likely to exist => PANDA can uniquely search for it!

- C-even states in terms of $S_H \times S_L$ de-composition

$$(2^+): \quad \left(1^-_H \otimes 1^-_L\right)\Big|_{J=2}\,, \quad D^*\bar{D}^*\,;$$

$$(1^+): \quad \left(1^-_H \otimes 1^-_L\right)\Big|_{J=1}\,, \quad D^*\bar{D} + \bar{D}^*D; (= X(3872))$$

$$(0^+): \quad \frac{\sqrt{3}}{2}\left(0^-_H \otimes 0^-_L\right) + \frac{1}{2}\left(1^-_H \otimes 1^-_L\right)\Big|_{J=0}\,, \quad D^*\bar{D}^*\,;$$

$$(0^+): \quad \frac{1}{2}\left(0^-_H \otimes 0^-_L\right) - \frac{\sqrt{3}}{2}\left(1^-_H \otimes 1^-_L\right)\Big|_{J=0}\,, \quad D\bar{D}\,;$$

- 2^{++}: $X_2(4014)$ relative to $D^*\bar{D}^*$ should be the same as 1^{++}: X(3872) rel. to $D\bar{D}^*$
- Similar isospin breaking pattern (D^{*+} -- D^{*0}) mass splitting; $2M(D^{*0}) = 4014$ MeV

See also:
[M.Albaladejo, F.-K.Guo, C.Hidalgo-Duque, J.Nieves, M.P.Valderrama,'EP J C 75 (2015) No.11, 547]
[V.Baru, E.Epelbaum, A.A.Filin, C.Hanhart, U.G. Meissner, A.V.Nefediev, Phys. Lett. B 763 (2016) 20]

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- Search for X(4014) (2^{++} partner of X(3872), possible hadronic molecule)
  - Width: 50-100 MeV, mass shift of up to 70 MeV beneath D*D* threshold
    (due to D-D mass difference, when assuming no form factor to be taken into account for pion exchange as expected from EFT)* [Q.Wang, V.Baru, A.A.Filin, C.Hanhart, A.V.Nefediev, J.L.Wynen, arXiv:1805.07453 [hep-ph]]
  - If decay dominantly to DDbar (in D-wave) => $\Gamma \leq 70$ MeV
  - Production rate: N(X(3872))/N(X(4014)) ~1 (HQSS)
  - Angular distribution for 2^{++}
  - For simulations
    => *Use Γ ~50 MeV (to fix effective coupling), and very narrow, Γ ~1 MeV)*

See also:
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- Search for X(4014) (2^{++} partner of X(3872), possible hadronic molecule)

  - Critical question:

    Form Factor to be taken into account, suppressing one-pion-exchange?

    → *only an experiment can tell us ...*
  - Special for PANDA:

    2^{++} state difficult to access at e^+e^- machines
  - Decays:

    $X_2(4014) \rightarrow \rho J/\psi,\ \omega J/\psi,\ \gamma J/\psi,\ \gamma\psi'$
  - Also decays to D-wave heavy meson pairs:

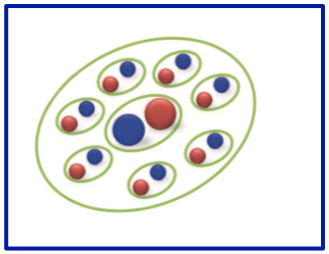
    $X_2(4014) \rightarrow D^*\bar{D}$, $D\bar{D}$ are allowed by HQSS
  - Not necessarily very narrow:

    $X_2(4014) \rightarrow \Gamma \sim 10$ MeV or more

See also:
[V.Baru, E.Epelbaum, A.A.Filin, C.Hanhart, U.G.Meissner and A.V.Nefediev, Phys. Lett. B 726 (2013) 537]

New inputs – Y states, Search for spin partners

C.Hanhart: Y(4660) etc. → e+e- predestined,
however, PANDA should search for spin partners



- Prediction/expectation from Hadrocharmonium interpretation

  - Extra states as compact QQbar surrounded by light quarks
  - Natural explanation why e.g. Y(4260) $\rightarrow \pi\pi J/\psi$
    but not to DDbar
  - HQSS demands spin of the QQbar core to be conserved in decay to charmonia
  - To explain e+e- $\rightarrow \pi\pi h_c$
    - mixing between $s_{ccbar} = 0$ and $s_{ccbar} = 1$ is needed
    - leading to Y(4260) and Y(4360)

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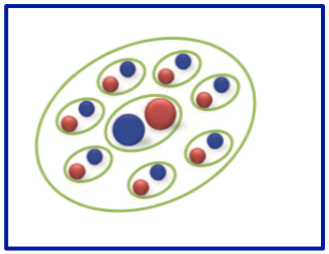
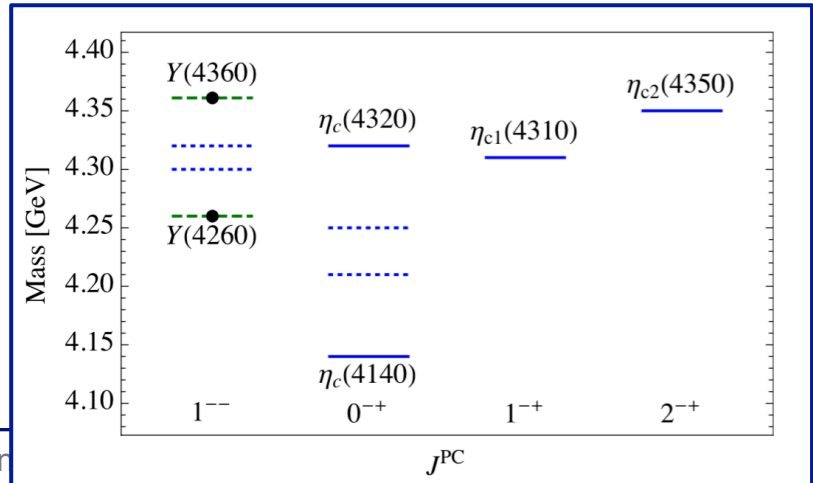


- Prediction/expectation from Hadrocharmonium interpretation
  - Special feature:
    Very light 0^{-+} state that should not decay to D*Dbar
  - Special for PANDA in general:
    Pseudoscalar 0^{-+} states not directly producable in e^+e^-
  - Decays:
    $\eta_c(4140) \rightarrow \chi_{c0}\pi\pi, \eta_c'\pi\pi$ *(ccbar with J=0 plus pions)*
  - Where sits the first potential exotic pseudoscalar?
    Somewhere 4.1 – 4.4 GeV → PANDA

- Mixing suggests for unmixed states:
  - $\Psi_3 \sim (1^{--})_{c\bar{c}} \otimes (0^{++})_{q\bar{q}} \qquad \Psi_1 \sim (1^{+-})_{c\bar{c}} \otimes (0^{-+})_{q\bar{q}}$
  - where heavy cores are ψ' and h_c

→ get spin partners via $\psi' \rightarrow \eta_c'$ and $h_c \rightarrow \{\chi_{c0}, \chi_{c1}, \chi_{c2}\}$

[Cleven et al., PRD 92 (2015) 014005]



New inputs – Y states, Search for spin partners

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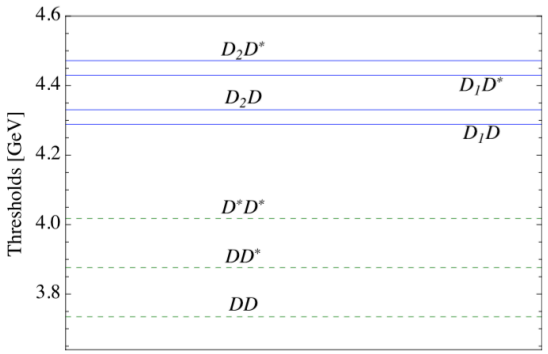
- Prediction/expectation from Hadronic molecule interpretation
  - $1/2^+$ multiplet (D,D*) and $3/2^-$ multiplet (D_1,D_2)

Example: $1/2^+$ multiplet $\{D, D^*\}$ and $3/2^-$ multiplet $\{D_1, D_2\}$ →



$3^{-\pm}$: D^*D_2
$0^{-\pm}$: D^*D_1
$2^{-\pm}$: $D^*D_1 - D^*D_2 - DD_2$
$1^{-\pm}$: $DD_1 - D^*D_1 - D^*D_2$ ($Y(4260), Y(4360)$ $(I=0)$)

2^{++}: D^*D^*
1^{++}: DD^* ($X(3872)$ $(I=0)$)
1^{+-}: $DD^* - D^*D^*$ ($Z_c(3900)^+, Z_c(4020)^+$ $(I=1)$)
0^{++}: $DD - D^*D^*$;

[Cleven et al., PRD 92 (2015) 014005]

Explains mass gab between $J^P=1^+$ and 1^- states:

- $\Delta m(Y(4260) - X(3872)) = 388$ MeV ~ $\Delta m(D_1(2420) - D^*) = 410$ MeV
- If it exists, for hadrocharmonium: $\Delta m = M(0^-) - M(1^-) = \sim 100$ MeV

New inputs – Y states, Search for spin partners

S.Prelovsek: Several XYZ analysis topics,
PANDA should look at

- Search for strange partner Z_c with (cbarcsbaru), i.e. Z_{cs}
  - ppbar $\rightarrow Y(4xxx) \rightarrow Z_{cs}^{+} K^{-}$ (ccbar), e.g. KK J/ψ (I=1/2)

  => Of course in our mind, lets think on it more (Priority)

- Search for Charmonium hybrid with non-qqbar J^{PC}
  - Indeed important, looked at in Panda performance report (2009), and somebody revisiting (M.Moritz)

  => Yes, let's think on it more, especially since newer work has been done as quoted by you [JHEP (2016) 089] (Priority)

- Determination of X(3915) J^{PC}: 0^{++} or 2^{++}

  => Certainly of interest, but not really unique for PANDA (Low(er) priority)

New inputs – Y states, Search for spin partners

S.Prelovsek: Several XYZ analysis topics,
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- Confirmation of X(3860) with $J^{PC} = 0^{++}$ (Belle 2017)
  => Certainly of interest, but not really unique for PANDA (Low(er) priority)

- Exploration: Any $J^{PC} = 1^{++}$ isospin zero state above X(3872)
  => Not unique for PANDA, but certainly very interesting,
  especially when 'married' with new theoretical/lattice
  work from your side! Time scale? "I guess about 2 years"

- Establishing any of J = 3 states in charmonium spectrum
  - the lowest conventional one is 3^{--}, expected at ~3.9 GeV
  - We thought on such "feasibility studies" since long
    (definitely and absolutely unique for PANDA)

  => It would really be great to work out something together! (Priority)

  NB: Polosa et al.: EPJC 78 2018 pg. 29 --> Tetraquark (Polosa) vs molecule (Hanhart)

New input

S.Prelovsek: Several
PANDA

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  => Certainly of int
- Exploration: Any J^PC
  => Not unique for
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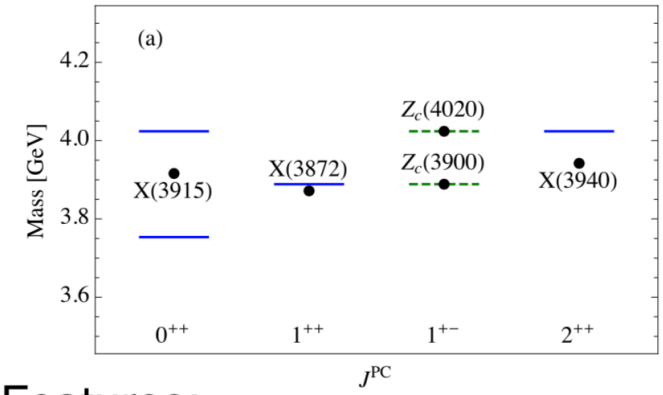
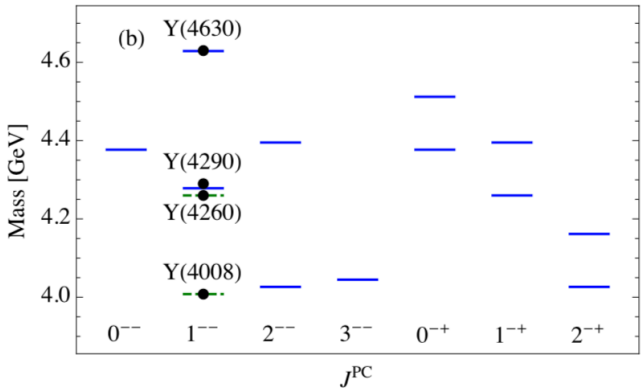
Cleven et al., PRD 92(2015)014005





Features:

→ very light $J = 3$ state

→ lightest vector state 'only' 100 MeV above $X(3872)$

... however: $Y(4008)$ not seen by BESIII PRL118(2017)092001

→ Many more states predicted than observed!

Maybe since di-quark picture too restrictive/constraining?

Richard et al., PRD95(2017)054019

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New inputs – Y states, S

S.Prelovsek: Several XYZ analysis topics
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  => Certainly of interest, but not real
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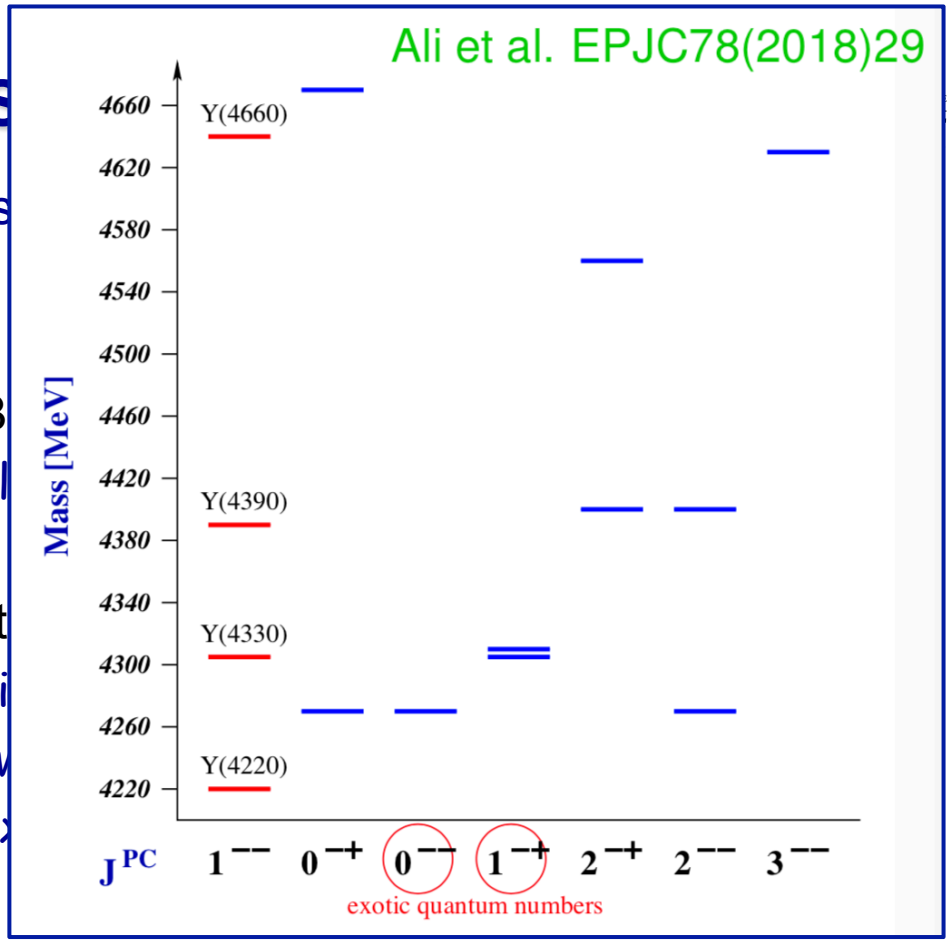

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New inputs – Y states, Search for spin partners

S.Prelovsek: Several XYZ analysis topics (4660), PANDA should look at

- Search for heavy-quark spin partners of discovered Z_c
  - the discovered ones seems to have $J^P = 1^+$
  - Z_b spectrum <=> similar expected for Z_c states

  => Yes, lets think/work on it more! (Priority?),
  Already on plan ... (CH, somehow question of priority (SU(3), Z_b end 2018, then ..)

- Further investigation of 4 resonances found by LHCb in $J/\psi\varphi$
  - search for them in open charm

  => Certainly quite interesting, unfortunately, not really unique for PANDA (Low(er) Priority)

Conclusion & outlook

CCE subTask force succesfully launched:

- Group of dedicated theoreticians built
  - First inputs and discussions (via Email so far)
- First report given
  - already a few concrete examples
  - and a further prioritised list of proposals
- Continue to collect and discuss
  - Next report foreseen for next CM
  - Important:

    → *Go for concrete input/team work with colleagues from theory*

Outlook:

Wikipage with topic-wise connections, and a summarising note