Lattice studies of charmonia and exotics

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in collaboration with:

C. B. Lang, D. Mohler, L. Leskovec

G. Bali, S. Collins, D. Mohler, M. Padmanath, S. Piemonte, S. Wieshaeupl

Outline

- this is not a review talk

(1) Lattice search for exotic X(5568) in $B_s\,\pi^+$ scattering [Lang, Mohler, S.P., PRD 2016]

(2) "conventional" chamonium resonances above open charm threshold

in particular vector $\psi(2S)$ and scalar "$\chi_{c0}(2P)$"

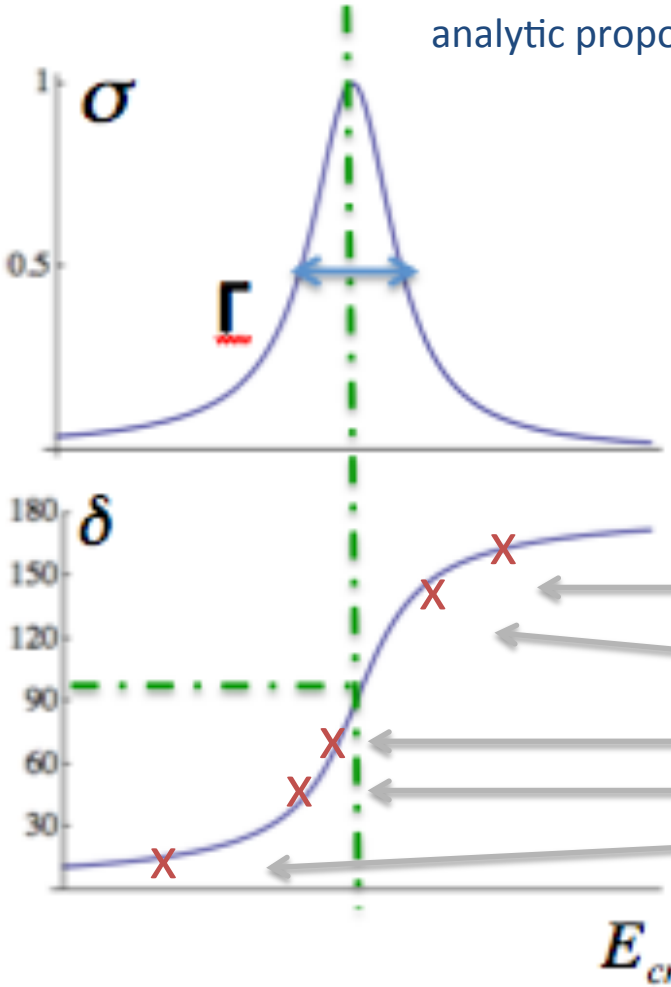
- lattice post-diction of $\psi(2S)$ and pre-diction of "$\chi_{c0}(2P)$" [Lang, Leskovec, Mohler, S.P., JHEP 2015]
- Belle observation of alternative candidate for "$\chi_{c0}(2P)$" [Belle, PRD 2017]
- ongoing lattice simulation of vector and scalar resonances
  [Regensburg QCD, G. Bali, S. Collins, D. Mohler, M. Padmanath, S. Piemonte, S.P., S. Wieshaeupl]

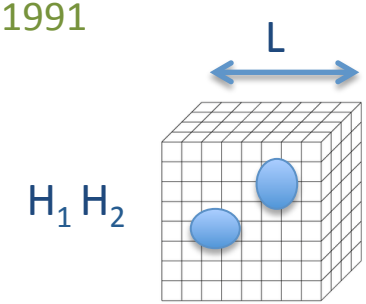
Rigorous treatment of hadrons near or above threshold:

scattering of two mesons in elastic channel

analytic proposal: Luscher 1991

$H_1 H_2 \rightarrow R \rightarrow H_1 H_2$





two mesons in a lattice box

$E_{cms}(L)$ energy of the system in center-of-momentum fr.

for one-channel scattering

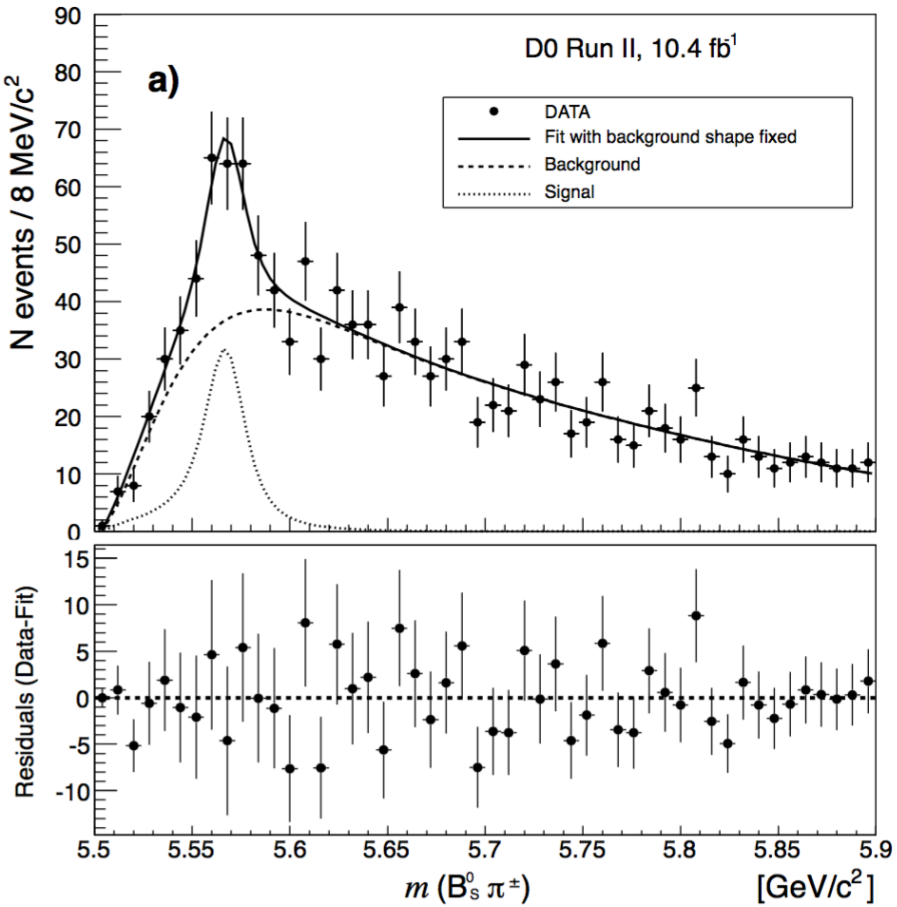
$$T = \sin\delta \, e^{i\delta}$$

$$\sigma \propto |\sin\delta|^2$$

scattering phase shifts at infinite volume $\delta(E_{cms})$ ← $E_{cms}(L)$ energies from lattice with spatial extent L

Search for resonance X(5568) in B_s π^+ scattering

D0 coll. found resonance X(5568) in $B_s\ \pi^+$ scattering



$B_s\ \pi^+$ invariant mass

D0 collaboration

february 2016: 1602.07588,

july 2016: PRL

- Γ=22 MeV
- J^P not measured
- The only hadron with 4 different flavors ?!

$$B_s\ \pi^+$$

$$\bar{b}s\ \bar{d}u$$

Search for X(5568) in $B_s\ \pi^+$ scattering

$$B_s\ \pi^+$$
$$\bar{b}s\ \bar{d}u$$

- soon after D0 result, several phenomenological studies appeared
- those who could find support, suggested it has $J^P=0^+$
- if X(5568) is $J^P=0^+$:

  - the only strong decay channel is $B_s\ \pi^+$

  - the next threshold is BK and it is 210 MeV above X(5568) !

  - exotic resonance in one-channel scattering !? This is something lattice QCD can do!

- note: all other exotic candidates (Z_c, Z_b, ...) are resonances but lie

  - next to a higher threshold
  - above several thresholds

  } this is much more challenging that is why it is difficult to establish those exotic states on lattice

Employed operators: $B_s\ \pi^+$ and BK

$$O_{1,2}^{B_s(0)\pi(0)} = \left[\bar{b}\Gamma_{1,2}s\right](\mathbf{p}=0)\left[\bar{d}\Gamma_{1,2}u\right](\mathbf{p}=0)$$

$$O_{1,2}^{B_s(1)\pi(-1)} = \sum_{\mathbf{p}=\pm\mathbf{e}_{\mathbf{x},\mathbf{y},\mathbf{z}}\ 2\pi/L} \left[\bar{b}\Gamma_{1,2}s\right](\mathbf{p})\left[\bar{d}\Gamma_{1,2}u\right](-\mathbf{p})$$

$$O_{1,2}^{B(0)K(0)} = \left[\bar{b}\Gamma_{1,2}u\right](\mathbf{p}=0)\left[\bar{d}\Gamma_{1,2}s\right](\mathbf{p}=0)$$

$$\Gamma_1 = \gamma_5 \text{ and } \Gamma_2 = \gamma_5\gamma_t$$

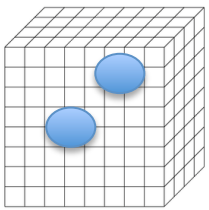
BK threshold 210 MeV higher;

the interpolators are employed just for completeness

[Lang, Mohler, S.P., 1607.03185, PRD 2016]

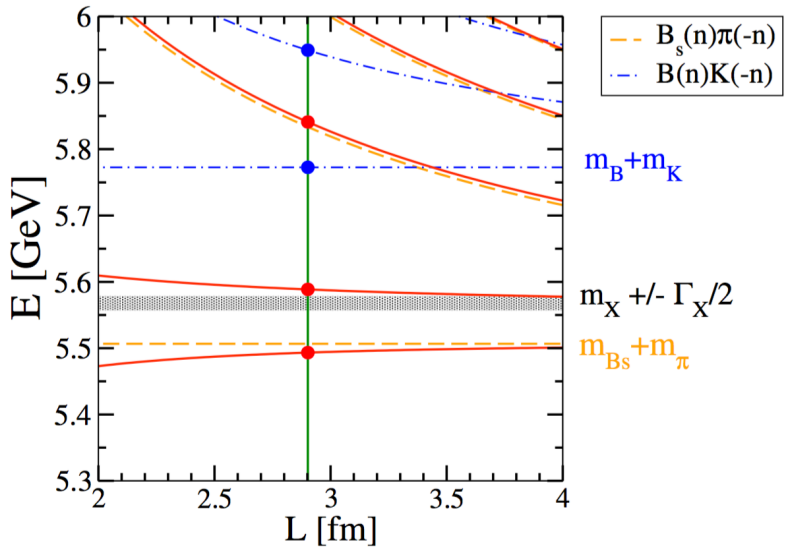
$B_s\ \pi^+$

$\bar{b}s\ \bar{d}u$



Analytic expectation for E_n if X(5568) exists

based on m_X and Γ_X as measured by D0 exp



$$\delta_{B_s\pi}(p) = \text{atan}\left[\frac{E\,\Gamma(E)}{m_X^2 - E^2}\right], \quad \Gamma(E) = \Gamma_X \frac{p(E)m_X^2}{p(m_X)E^2}$$

$$\delta_{B_s\pi}(p) = \text{atan}\left[\frac{\sqrt{\pi}pL}{2\,Z_{00}(1;(pL/2\pi)^2)}\right]$$

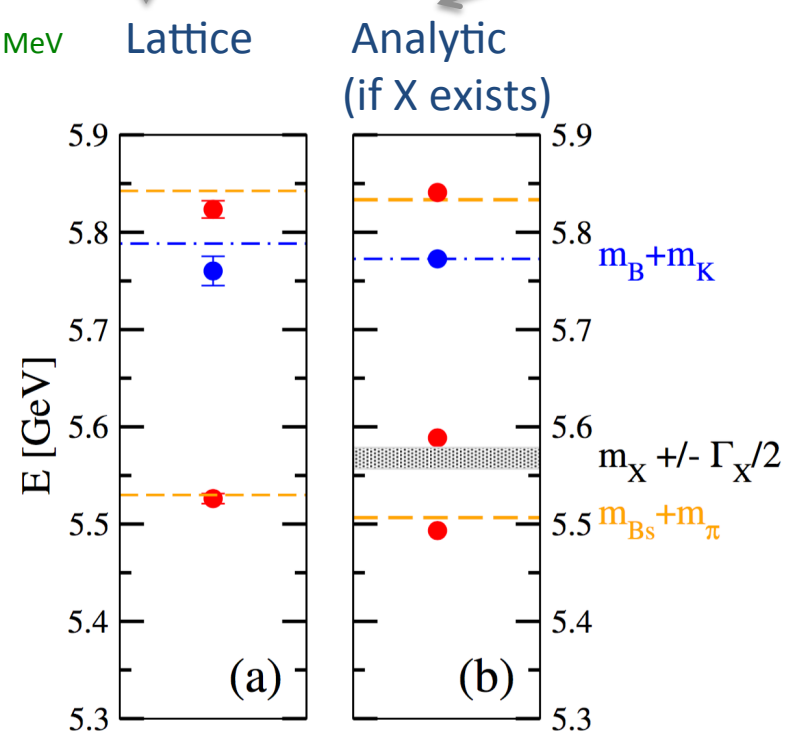
Results of E_n from actual lattice simulation

PACS-CS ens.

L=2.9 fm

$m_\pi \approx 156$ MeV

Nf=2+1



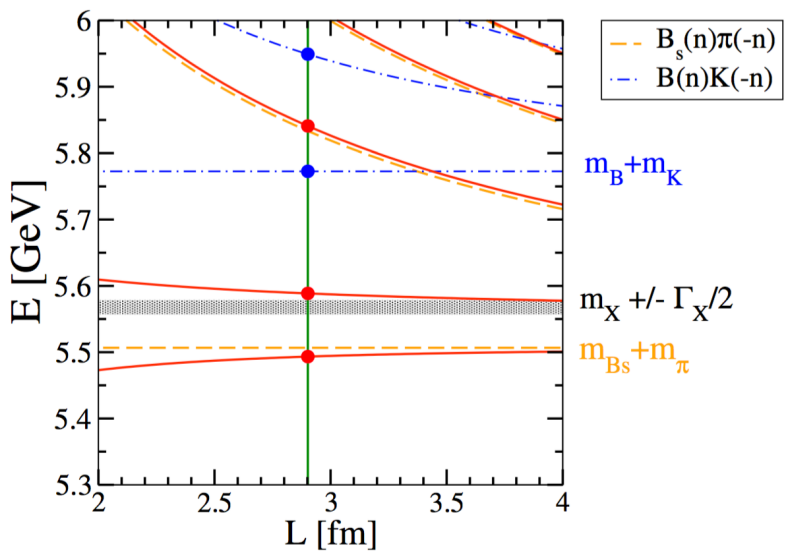
Lattice result (obtained before march 22nd 2016 – see next slide):

- no indication of X(5568)
- interactions in $B_s\,\pi^+$ and BK system are small

[Lang, Mohler, S.P., 1607.03185, PRD 2016]

Analytic expectation for E_n if X(5568) exists

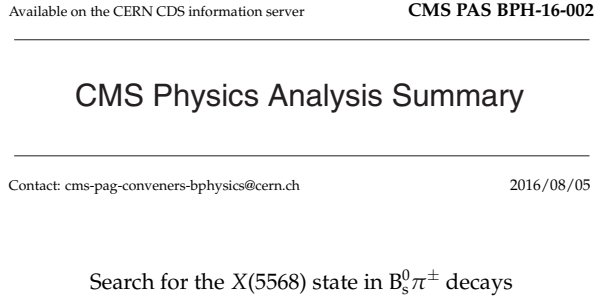
based on m_X and Γ_X as measured by D0 exp



$$\delta_{B_s\pi}(p) = \mathrm{atan}\left[\frac{E\,\Gamma(E)}{m_X^2 - E^2}\right], \quad \Gamma(E) = \Gamma_X \frac{p(E)m_X^2}{p(m_X)E^2}$$

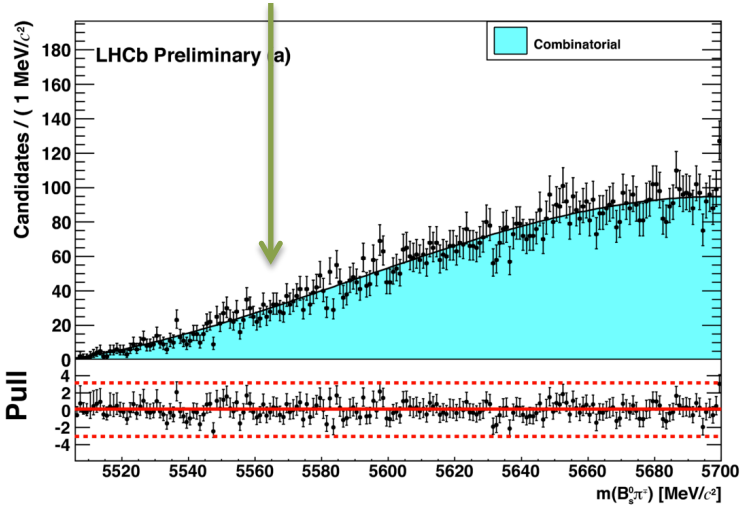
$$\delta_{B_s\pi}(p) = \mathrm{atan}\left[\frac{\sqrt{\pi}pL}{2\,Z_{00}(1;(pL/2\pi)^2)}\right]$$

LHCb, march 2017



CMS, august 2017

position of claimed D0 state



$B_s\ \pi^+$ invariant mass

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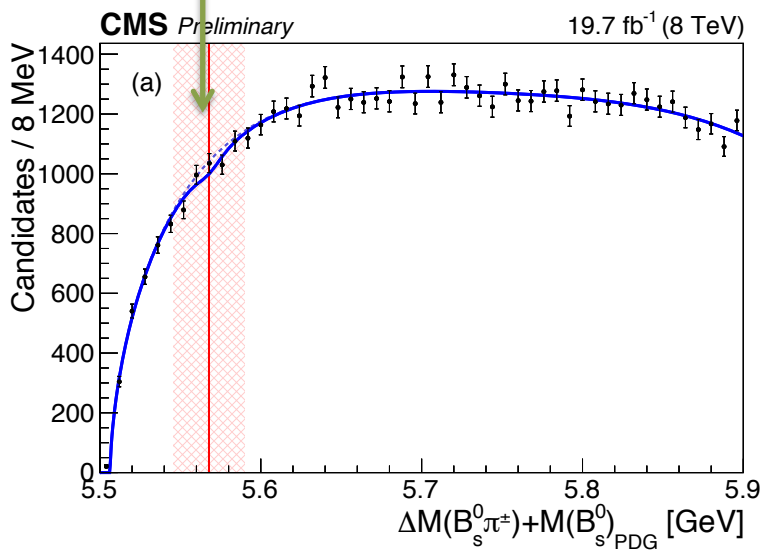


$B_s\ \pi^+$ invariant mass

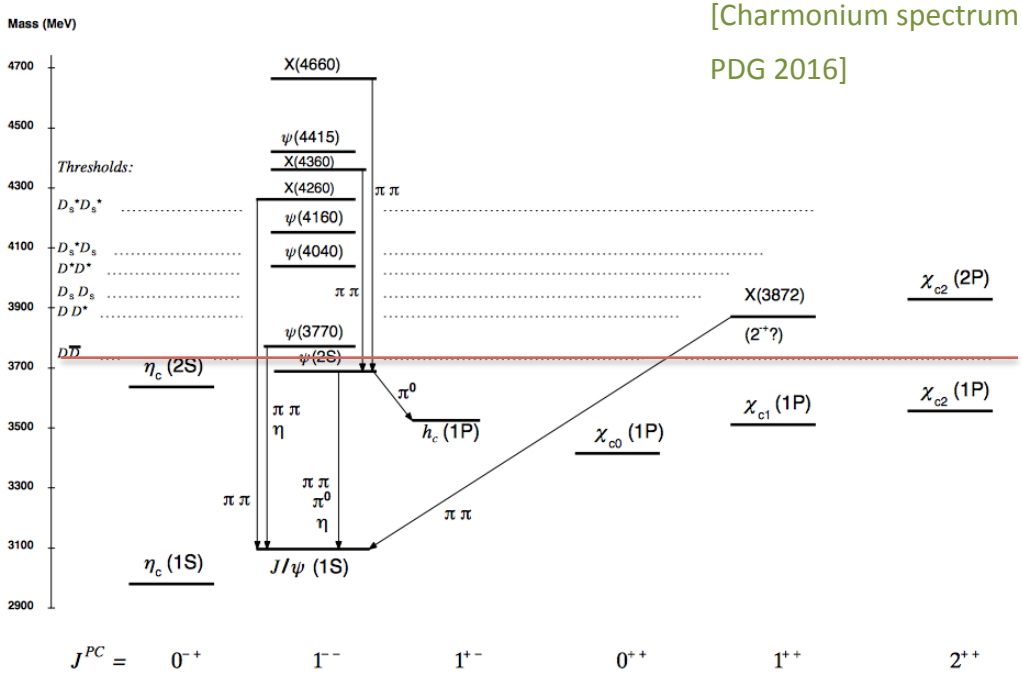
LHCb data published in

1608.00435: PRL 2016

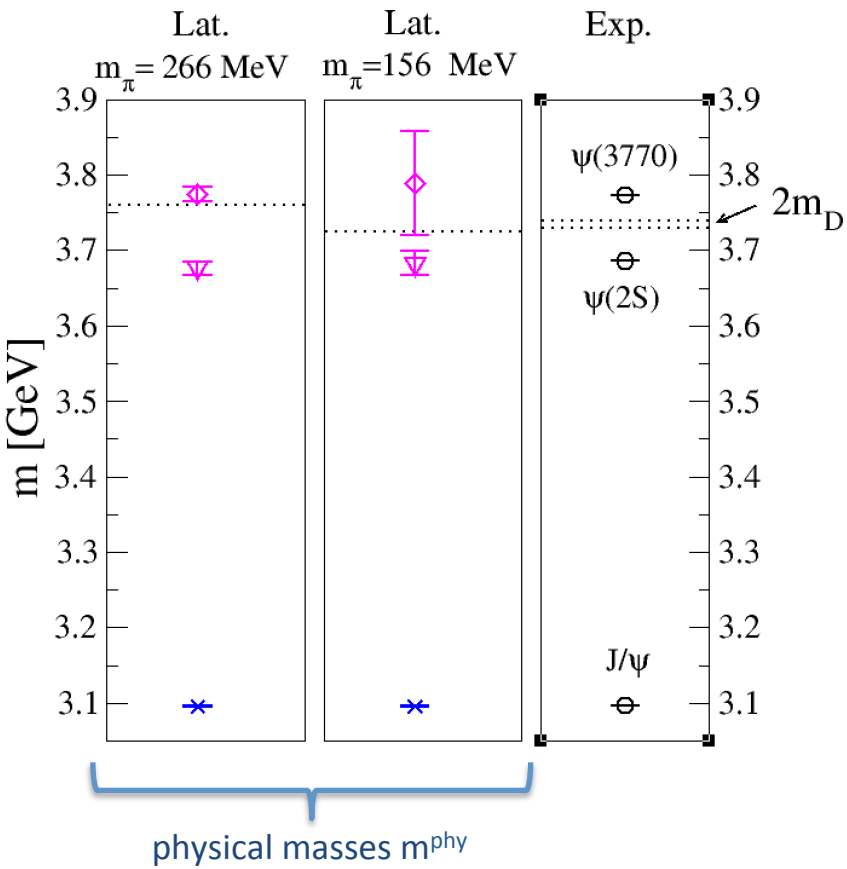
Charmonium resonances above open-charm threshold

[Charmonium spectrum PDG 2016]

before 2015
all charmonium resonances
above open charm threshold
were treated on the lattice
as strongly stable



Vector resonance ψ(3770) and bound st. ψ(2S) from DD scattering in p-wave



$$\mathcal{O}: \bar{c}\, c,\ D\bar{D}, \quad J^{PC} = 1^{--}$$

DD scat. in p-wave is simulated

$$E_n \ \rightarrow\ \delta(E_n)$$

T-matrix is determined from E_n

and interpolated near threshold:

Bound state ψ(2S) from pole in T:

cot $\delta(p_B)$ = i

m_B (triangles)

$$T \propto \frac{1}{\cot\delta - i}$$

Resonance ψ(3770): $\delta(m_R)=90^o$

m_R (diamonds), Γ (given below)

$\eta_c(1S)$
$J/\psi(1S)$
$\chi_{c0}(1P)$
$\chi_{c1}(1P)$
$h_c(1P)$
$\chi_{c2}(1P)$
$\eta_c(2S)$
$\psi(2S)$
$2m_D$
$\psi(3770)$
$X(3872)$
$\chi_{c0}(2P)$wa
$\chi_{c2}(2P)$
$X(3940)$
$\psi(4040)$
$X(4050)^{\pm}$
$X(4140)$
$\psi(4160)$
$X(4160)$
$X(4250)^{\pm}$

ψ(3770)	Mass [MeV]	g (no unit)
Lat (m_π=266 MeV)	3774 ±6±10	19.7 ±1.4
Lat (m_π=156 MeV)	3789 ±68±10	28 ± 21
Exp.	3773.15± 0.33	18.7 ± 1.4

$$\Gamma = \frac{g^2}{6\pi}\frac{p^3}{s}$$

Lang, Leskovec, Mohler, S.P., 1503.05363, JHEP 2015]

Scalar charmonium resonances above open-charm threshold

- still not settled which exp candidate corresponds to first excited scalar charmonium $\chi_{c0}(2P)$

- **X(3915)** as $\chi_{c0}(2P)$ not supported:

  - since X(3915) → DD not observed although this is expected to be dominant decay mode of $\chi_{c0}(2P)$ [Meissner & Guo 1208.1134] , Olsen 1410.6534]

  - instead X(3915) →J/Ψ ω observed

  - $\Gamma^{exp}_{X(3915)} \approx 20$ MeV, $\chi_{c0}(2P)$ expected to be wide

  - reanalysis [Zhou et al, PRL 2015] of BaBar data shows that $J^{PC}=2^{++}$ assignment for X(3915) could be possible

  - mass difference $\chi_{c2}(2P)$-$\chi_{c0}(2P)$ would be much smaller than in potential models and smaller than for bottomonium

I will present :

- our lattice "pre-diction" of $\chi_{c0}(2P)$ [JHEP 2015]
- discovery of an alternative candidate for $\chi_{c0}(2P)$ by Belle [april, PRD 2017]
- our ongoing lattice simulations of this channel [RQCD, 2017]

Lattice simulation [Lang et al, 2015]: scalar charmonia from DD scattering in s-wave, $J^{PC}=0^{++}$

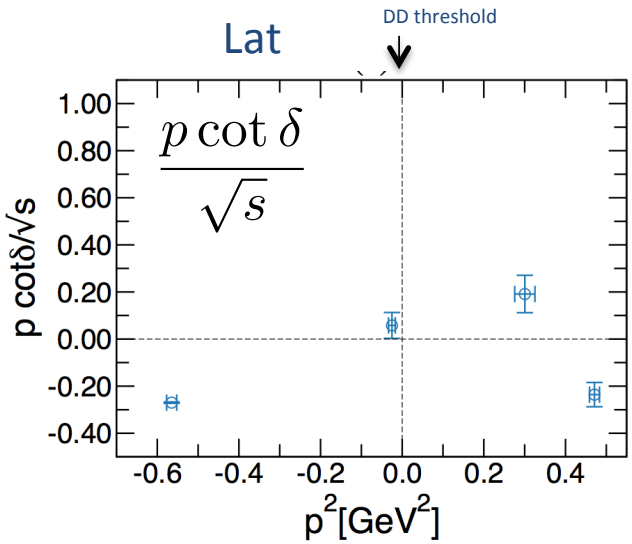
- m_π=266 MeV, V=16^3x 32, Nf=2, only total momentum P=0
- δ = phase shift for DD scattering in s-wave
- δ from lattice only for few energy points
- p cot δ shown, which can be presented also below threshold
- comparison of lattice results (black points) to several hypothesis made

resonance:

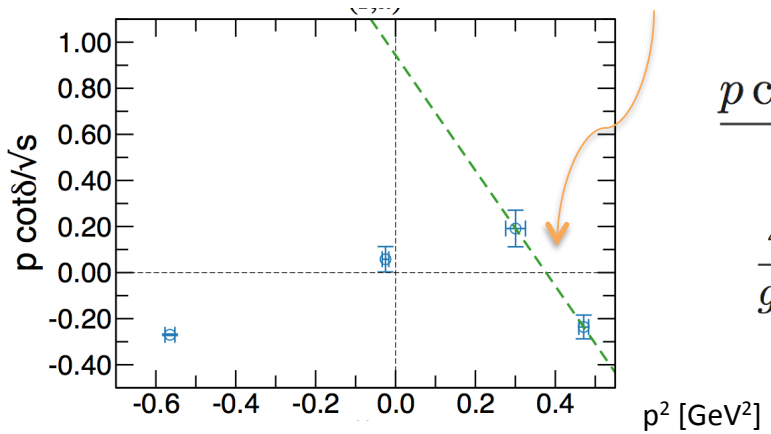
δ=90 → cotδ=0

$\mathcal{O}: \bar{c}\, c, D\bar{D}$

Lat



one resonance BW fit in its vicinity



$$\frac{p \cot \delta(s)}{\sqrt{s}} = \frac{4}{g^2}(p_R^2 - p^2)$$

"pre-dicted" $\chi_{c0}(2P)$: m_R= 3966 ± 20 MeV Γ= 67 ± 18 MeV

does not describe our results near or below threshold

Lang, Leskovec, Mohler, S.P., 1503.05363, JHEP 2015, m_π=266, 156 MeV

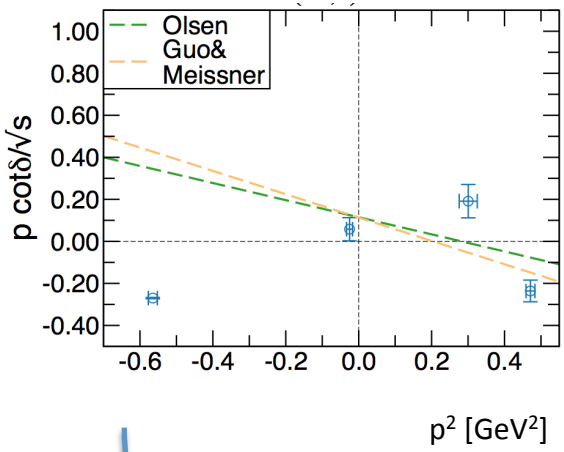
Lattice simulation [Lang et al, 2015] cont'd

$\mathcal{O}$: $\bar{c}\ c, D\bar{D}$

- various hypothesis versus lattice results
- one of the conclusions: more detailed DD lineshape needed from lattice

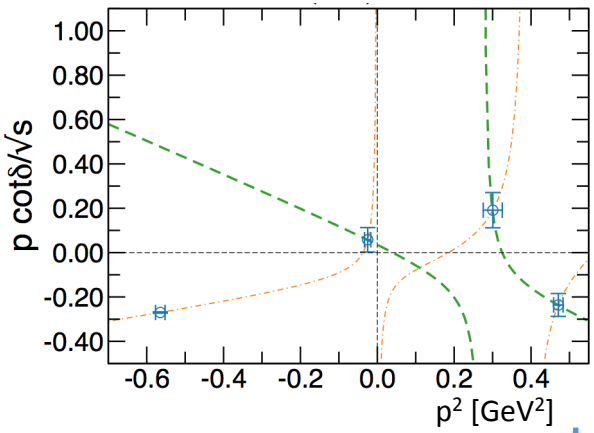
Hypothesis:

one very broad BW reson.



Hypothesis:

two BW resonances

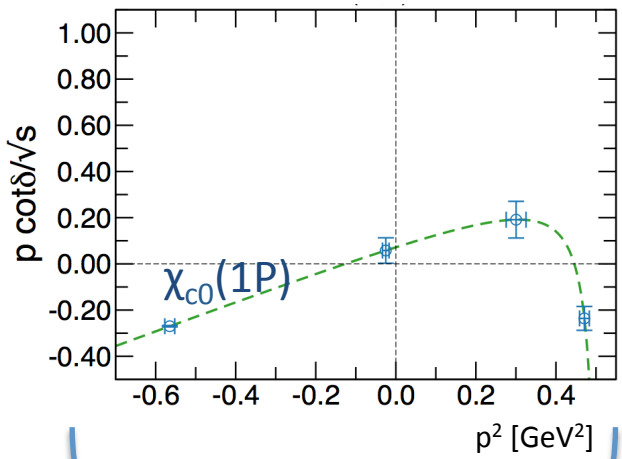


not supported by lat. data near and above th.

Hypothesis:

one narrowish resononance &

bound state pole at $\chi_{c0}(1P)$



supported by lat.

narrow resonance in D$\underline{\bar{D}}$:

m_R= 4002 ± 24 MeV

$\Gamma^{predict}$= 32 ± 48 MeV

Lang, Leskovec, Mohler, S.P.,

1503.05363, JHEP 2015, m_π=266, 156 MeV

Belle experiment [Chilikin et al, 2017]
Observation of alternative $\chi_{c0}(2P)$ candidate

double charm production $e^+e^- \to J/\psi\, D\, \bar{D}$

New charmoniumlike state observed

X*(3860)

- significance 6.5 σ

$$m = 3862^{+26+40}_{-32-13}\ \text{MeV}$$

$$\Gamma = 201^{+154+88}_{-67-82}\ \text{MeV}$$

- decays to D D̲

- $J^{PC}=0^{++}$ hypothesis favored over 2^{++} hypothesis at the level 2.5 σ

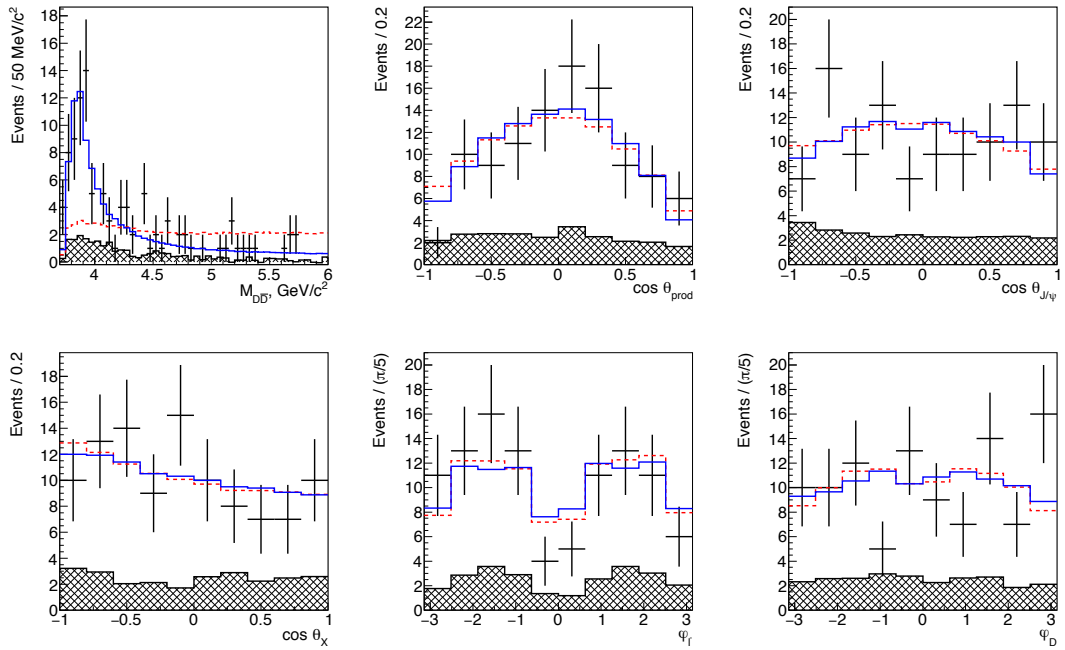


FIG. 6. Projections of the signal fit results in the default model onto $M_{D\bar{D}}$ and angular variables. The points with error bars are the data, the hatched histograms are the background, the blue solid line is the fit with a new X^* resonance ($J^{PC} = 0^{++}$) and the red dashed line is the fit with nonresonant amplitude only.

Chilikin et al, Belle, 1704.01872, PRD 2017

Compatibility of

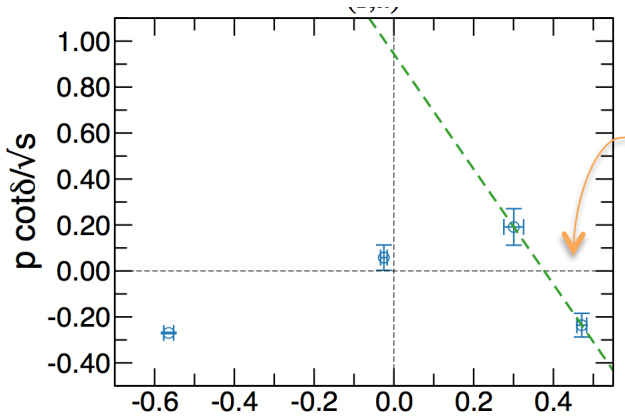
X*(3860) [Belle 2017] & lattice [Lang et al, 2015] ?

$\chi_{c0}(2P)$ provided in Ref. [41]. The parameters $M = 3966 \pm 20$ MeV$/c^2$ and $\Gamma = 67 \pm 18$ MeV are used. The comparison is performed in the same way as those for the experimentally known states with $J^{PC} = 0^{++}$; the results are shown in Table III. The difference of the $X^*(3860)$ and predicted $\chi_{c0}(2P)$ parameters is at 2.7σ level. Note that the systematic errors have not been determined in Ref. [41]; thus, the actual level of disagreement should be less than 2.7σ.

[41] C. B. Lang, L. Leskovec, D. Mohler, and S. Prelovsek, J. High Energy Phys. 09 (2015) 089.

Hypothesis: one "narowish" resonance

- BW fit in vicinity of the resonance
- omitting the points away from it
- does not describe our results near threshold



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Chilikin et al, Belle,

1704.01872, PRD 2017

m= 3966 ± 20 MeV

Γ= 67 ± 18 MeV

"pre-dicted"

Lang, Leskovec, Mohler, S.P.,

1503.05363, JHEP 2015, $m_\pi \approx 266$ MeV

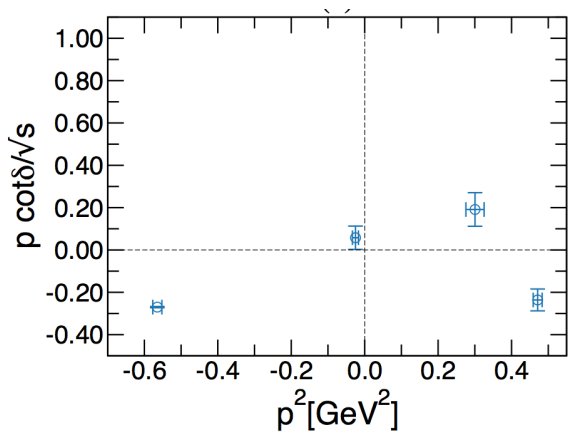
agreement not ideal, but not completely incompatible

clearly more work needed, at least on ab-inito theory side

Ongoing lattice simul. [RQCD 2017] vs. previous simul. [Lang et al, 2015]

	CLS ensembles	
	dyn flavors: u/d, s	dyn flavors: u/d
	$m_\pi \approx$ 280 MeV	$m_\pi \approx$ 266 MeV
	a ≈ 0.0854 fm	a ≈ 0.124 fm
	currently two m_c	one m_c
	total mom. P=0 and P≠0	only P=0
	$V=24^3 \times 128$, $32^3 \times 96$	$V=16^3 \times 32$
incorporated channels for $J^{PC}=1^{--}$	$D\bar{D}$	$D\bar{D}$
incorporated channels for $J^{PC}=0^{++}$	$D\bar{D}, \quad J/\psi\,\omega, \quad D_s\bar{D}_s, \quad D^*\bar{D}^*$	$D\bar{D}, \quad J/\psi\,\omega$

2015 simulation was done also on PACS-CS ensemble with $m_\pi \approx$ 156 MeV but the results were (much) noisier than for $m_\pi \approx$ 266 MeV



Regensburg QCD

G. Bali, S. Collins, D. Mohler, M. Padmanath,

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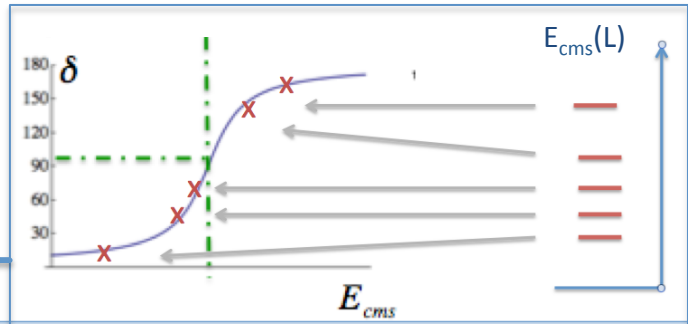
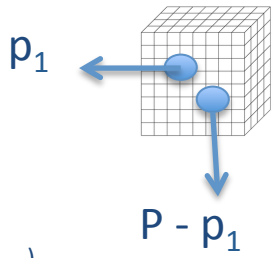


$\delta(E_{cms}) \longleftarrow E_{cms}(L)$

$$E_{cms}^{non-int} = \sqrt{\vec{p}_1^{\,2} + m_1^2} + \sqrt{(\vec{P} - \vec{p}_1)^2 + m_2^2}$$

$$\vec{p}_1 = \frac{2\pi}{L}\vec{n}_1$$



using more P and L renders values of δ (E_{cms}) at more values of E_{cms}

Regensburg QCD

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incorporated channels for $J^{PC}=0^{++}$	$D\bar{D}$, $J/\psi\,\omega$, $D_s\bar{D}_s$, $D^*\bar{D}^*$	$D\bar{D}$, $J/\psi\,\omega$

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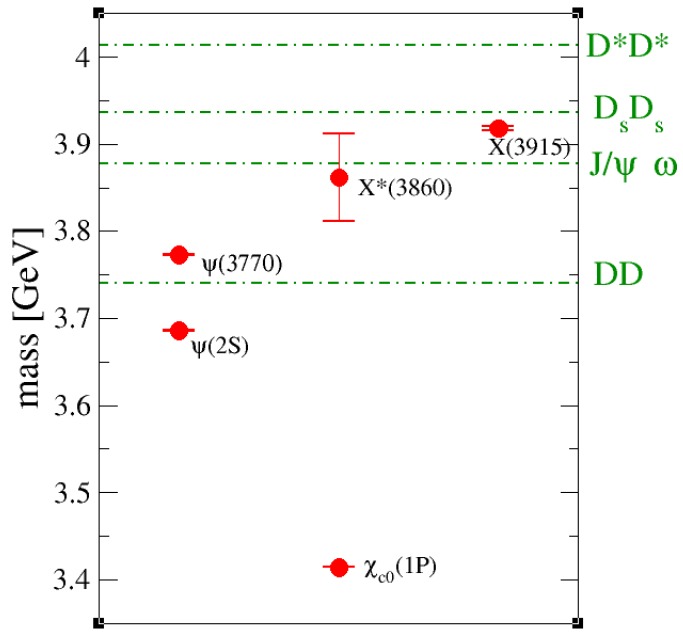
[PDG 2016]



Regensburg QCD

G. Bali, S. Collins, D. Mohler, M. Padmanath,

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Wick contractions

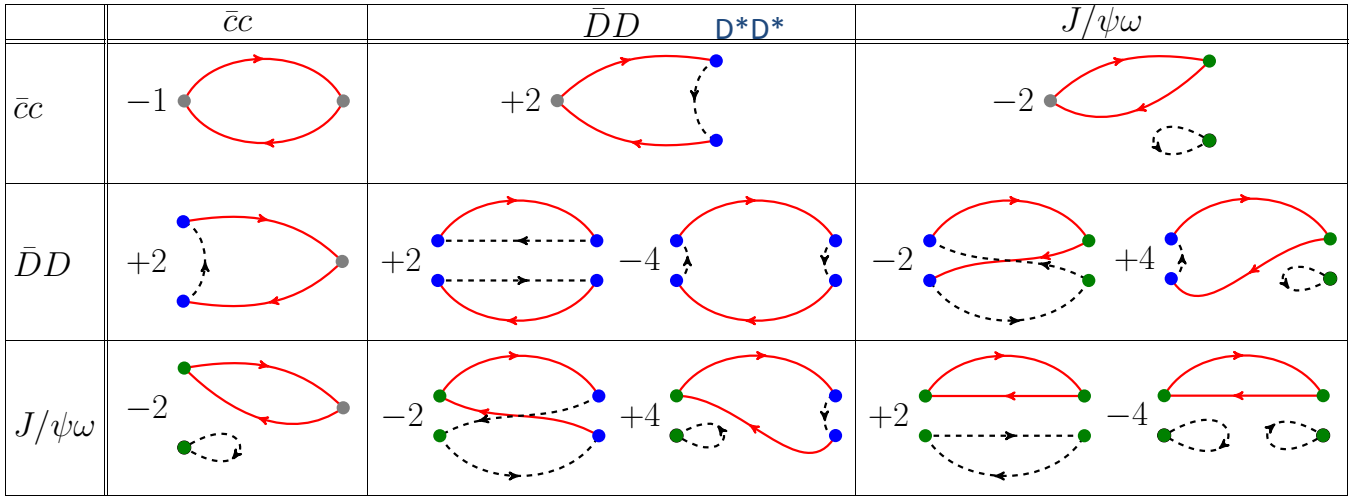
- coupled channels; interpolators: $\bar{c}c, \quad D\bar{D}, \quad D^*\bar{D}^*, \quad J/\psi\,\omega, \quad D_s\bar{D}_s$

- charm annihilation omitted

- the Figure shows just a part of the Wick contractions (without C C S S)

c quark

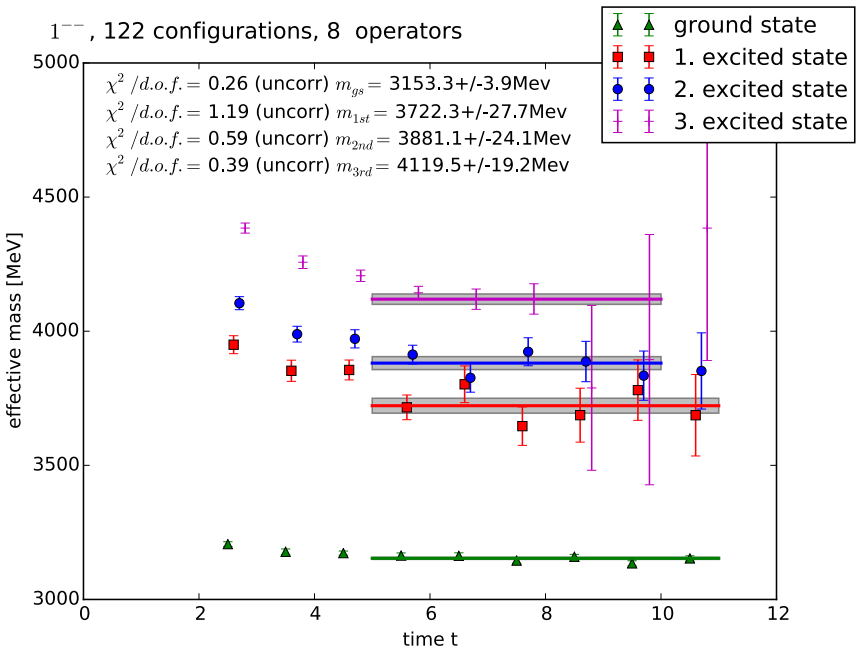
u,d quarks



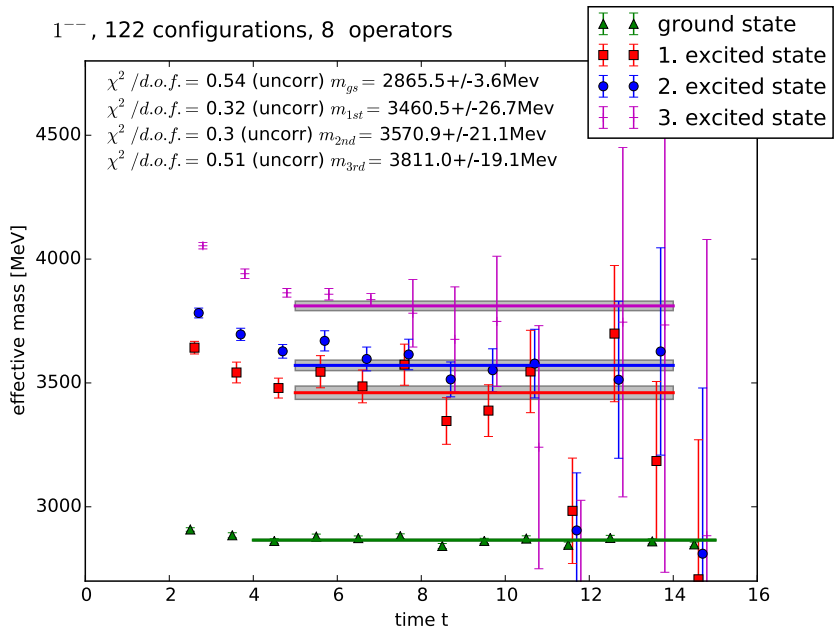
Some intermediate results for eigen-energies: $J^{PC}=1^{--}$ channel

- Presented at Lattice 2017 (Piemonte, Weishaeupl)
- $V=24^3 \times 128$ (U101 CLS ensemble)
- just total momentum P=0
- low statistics

E_n [GeV]



(a) $\kappa_c = 0.123147$



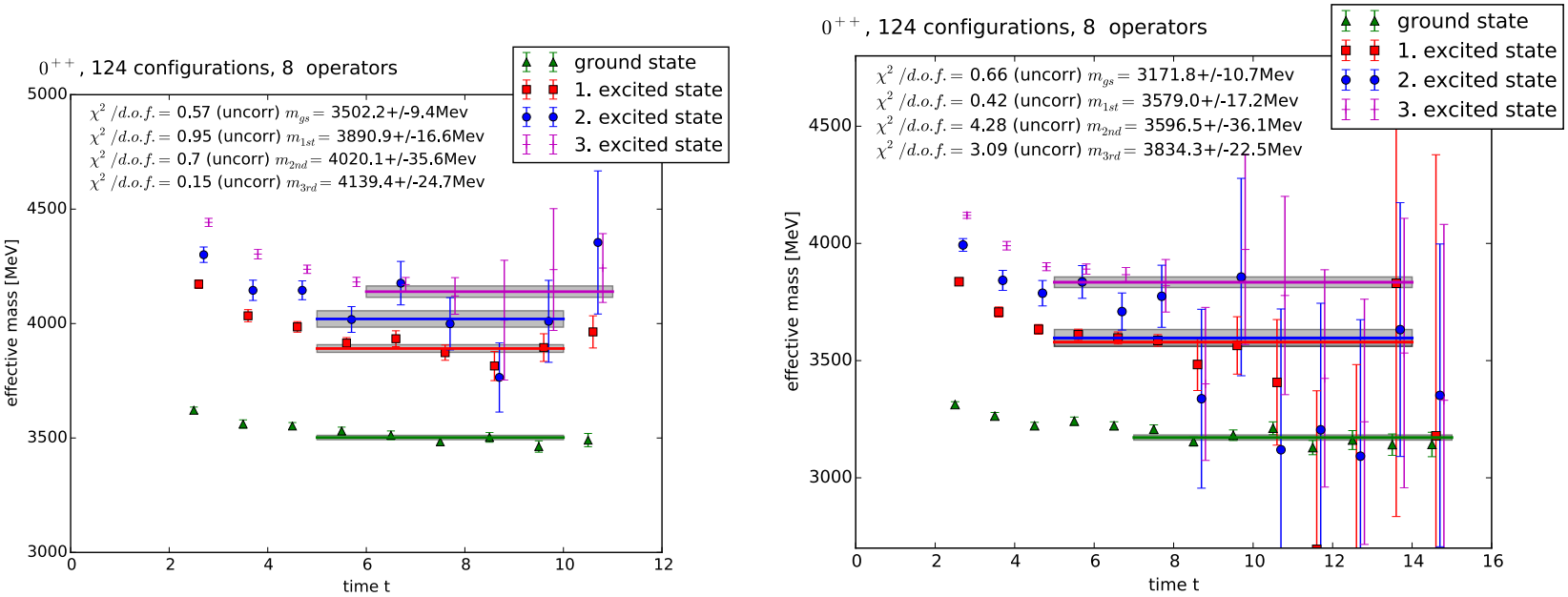
(b) $\kappa_c = 0.125220$

two values of m_c

Some intermediate results for eigen-energies: $J^{PC}=0^{++}$ channel

- Presented at Lattice 2017 (Piemonte, Weishaeupl)
- $V=24^3 \times 128$ (U101 CLS ensemble)
- just total momentum P=0
- **c <u>c</u> s <u>s</u>** not yet coupled to the rest (meanwhile this has been done)

E_n [GeV]

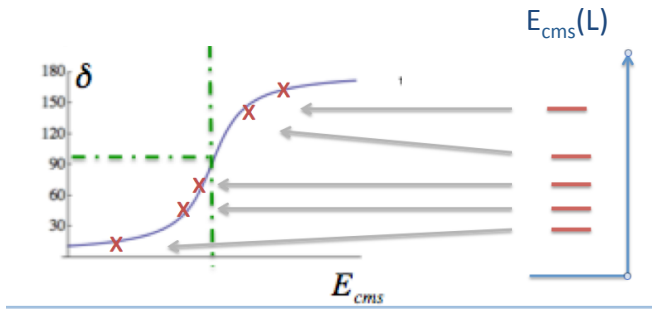


(c) $\kappa_c = 0.123147$ (d) $\kappa_c = 0.125220$

two values of m_c

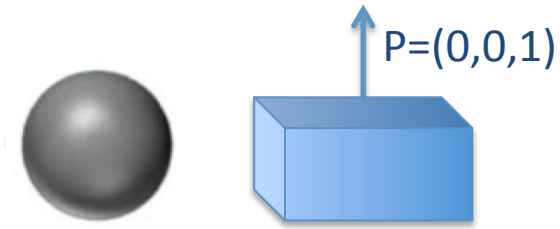
Ongoing lattice simul. [RQCD 2017] cont'd

- meanwhile we have significantly increased the statistics
- have some results also for P≠0
- have coupled c c̲ s s̲ to the rest
- have calculated quark props also 32^3 x 96 (H105)



- scattering phase shifts and scattering matrices have not been extracted yet
- therefore physics conclusions can not be drawn yet

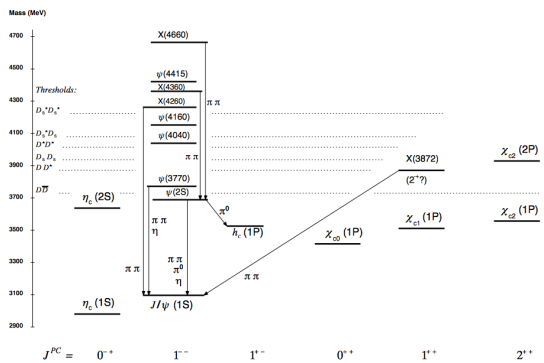
One of the challenges for total mom. P≠0



J → irrep of discrete group

SO(3) D_{4h}

- J is not good quantum number on lattice
- parity is not good quantum number; only helicity is
- example: irrep=A_1 that contains J=0 states
  contains also J=2 states
- general: given irrep contains a number of different J^{PC}
- particularly challenging for dense charmonium spectrum



S. Prelovsek, Hadron 2017

Conclusions

- if exotic hadrons were
  - strongly stable or
  - resonances that can strongly decay only to one final state H_1H_2

  then lattice QCD could reliably establish them

  D0 exotic X(5568) in one-channel $B_s\,\pi^+$ scattering ? Our lattice simulation did not find evidence for it

- experimental exotic candidates can decay to more H_1H_2 .. more challenging

- charmonium resonances above open charm threshold were (roughly) extracted for the first time together with their decay width [2015]

- alternative candidate for first excited scalar charmonium resonance was discovered this year difference with respect to our "pre-diction" at 2.7 σ level (agreement not ideal, but not completely incompatible)

- much more detailed extraction of scattering matrix is needed and is on the way ...