The $\chi_{c1}(3872)$ and study of its radiative decays at LHCb

Ivan Polyakov

on behalf of the LHCb collaboration

CERN LHC Seminar
11 June 2024
Non-perturbative QCD

- QCD is a successful theory giving precise predictions at high energies.

- However, it is highly non-perturbative at hadron/nuclei energy scale.

- Hence, (semi-) phenomenological approaches (or Lattice QCD) have to be used.

  → Knowledge limited by available quark configurations.
Exotic hadron spectroscopy

- In 2003 first exotic hadron was identified in particle discovered in $J/\psi\pi^+\pi^-$ by Belle
  - $X(3872)$, now known as $\chi_{c1}(3872)$
    
    didn’t fit conventional charmonium expectations

- Since then >50 exotic hadron candidates are discovered

Belle, PRL 91 (2003) 262001
23 new hadrons at the LHC

The $\chi_{c1} (3872)$ remains the cornerstone for theory and experiment
4.2. The $\chi_{c1}(3872)$ (also known as $X(3872)$)

MESON-LIKE/HIDDEN CHARME/ISOSCALAR

quantum numbers: $I^G(J^{PC}) = 0^+(1^{++})$

minimal quark content: $[c\bar{c}]$, more likely $[c\bar{c}(u\bar{u} + d\bar{d})]$ 

experiments: Belle, CDF, D0, BaBar, LHCb, CMS, ATLAS, BESIII (and potentially E705, COMPASS) 

production: $B^+, B^0, B_s^0$ and $\Lambda_b^0$ decays, 

prompt $pp, p\bar{p}, pPb$ (Ppb) and PbPb collisions, $e^+e^- \rightarrow \gamma\chi_{c1}(3872)$, $\omega\chi_{c1}(3872)$ potentially via $\psi$- or $\chi_c$-like states

decay modes: $\pi^+\pi^- J/\psi$, $\omega J/\psi$, $D^{*0}\bar{D}^0$, $\pi^0\chi_{c1}(1P)$, $\gamma J/\psi$, $\gamma\psi(2S)$

nearby threshold: $D^{*0}\bar{D}^0$

width: $1.19 \pm 0.21$ MeV (Breit-Wigner)

$$m(\chi_{c1}(3872)) - m(D^{0}\bar{D}^{*0}) = -0.07 \pm 0.12 \text{ MeV}$$
Theory models

- **charmonium**
  - Barnes, Godfrey, Swanson; Eichten, Lane, Quigg; Suzuki; ...

- **compact tetraquark**
  - Maiani, Piccini, Polosa, Riquer; Matheus, Narison, Nielsen, Richard; ...

- **DD* molecule**
  - Braaten, Kusunoki; Swanson; Wong; Tornquist; ...

- **hadro-charmonium**
  - Dubynskiy, Voloshin; ...

- **hybrid**
  - Close, Godfrey; Li; ...

- **admixture**
  - Suzuki; Close, Page; Dong, Faessler, Gutsche, Lyubovitskij; ...

*see references in Appendix*
Isospin violation

- $\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-$ decay is dominated by $\rho^0 \rightarrow \pi^+ \pi^-$ indicating strong isospin violation.

- LHCb has accessed $\omega \rightarrow \pi^+ \pi^-$ (BR~1.5%) admixture in the same final state ~10x larger than typical isospin violation in conventional charmonium.

- Likely related to 8 MeV splitting between $D^0 \overline{D}^{*0}$ and $D^+ D^{*-}$ thresholds.
**$\chi_{c1}(3872)$ partners**

- Partners with various $J^{PC}$ naturally arise in diquark-diquark model including $I=0$ and $I=1$ states with $J^{PC}=1^{++} ightarrow$ charged $X(3872)^\pm$

  \[\text{Maiani, Piccini, Polosa, Riquer, PRD 71 (2005) 014028}\]

- $X(3872)^\pm$ are not seen in experiment

  \[\frac{BR(B^+ \rightarrow X(3872)^+K^0)}{BR(B^+ \rightarrow X(3872)K^+)} < 0.5\]

  \[\text{Belle, PRD 84 (2011) 052004}\]

  can be easily accommodated by theory  \[\text{Maiani, Polosa, Riquer, PRD 102 (2020) 034017}\]

- **[New:]** In $DD^*$ EFT one also finds isovector partners $W_{c1}^0$ and $W_{c1}^{\pm}$ of the $\chi_{c1}(3872)$ as virtual states around 3867 MeV

  \[\text{Zhang, Ji, Dong, Guo, Hanhart, Meisner, Rusetsky, arXiv:2404.11215}\]
Production in hadron collisions

- \( \sigma(p\bar{p} \rightarrow \chi_{c1}(3872)[\rightarrow J/\psi \pi \pi]+...) > 3.1 \text{ nb at } \sqrt{s} = 1.98 \text{ TeV} \)

- while estimations for loosely bound (\( E_B \sim 0.25 \text{ MeV} \)) \( D\bar{D}^* \) molecule give only \( \sim 0.085 \text{ nb} \)

- in turn, argue that \( D\bar{D}^* \) re-scattering can raise it up to 4–200 nb

also see

- \( \sigma(pp \rightarrow \chi_{c1}(3872)+...) \) at high \( p_T \) at LHC

- Indication of non-molecular component

- or feature of charm?
Production vs multiplicity

- $\sigma_{\chi(3872)} / \sigma_{\psi(2S)}$ dependence on track multiplicity in pp measured by LHCb
  \[ \text{LHCb, PRL 126 (2021) 092001} \]

- can’t be explained with two (naive?) molecule models
  \[ \text{Esposito, Ferreiro, Pilloni, Polosa, Salgado, EPJC 81 (2021) 669} \]

- in turn, argue that it can after re-estimating $\pi X \rightarrow D\bar{D}^*$ break-up cross-section (geo) from $\pi r^2 \sim 1400$ mb to $\sim 3$ mb
  \[ \text{Braaten, He, Ingles, Jiang, PRD 103 (2021) L071901} \]
Pole position

- Accessing pole in low-energy $D\bar{D}^*$ scattering via lineshapes in different decay modes

- No firm conclusion yet, looking forward for larger statistics and combination of channels

LHCb, PRD 102 (2020) 092005

Belle, PRD 107 (2023) 112011

BESIII, arXiv:2309.01502
What we want vs. what we get

Theory

Experiment

* except for $T_{cc}$ [ccud]
Radiative decays. Short recap

\[ R_{\psi \gamma} \equiv \frac{\mathcal{B}(\chi_{c1}(3872) \rightarrow \psi(2S)\gamma)}{\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi\gamma)} \]

**Theory**

- \( R_{\psi \gamma} \sim 0.3\% \) for molecules,
- \( R_{\psi \gamma} \sim 1-6 \) for pure charmonia

**Experiment**

- **2004-2005**
  - \( R_{\psi \gamma} > 1 \) can be achieved for molecules as well
  - BaBar: Observation of \( \chi_{c1}(3872) \rightarrow J/\psi\gamma \)
  - \( R_{\psi \gamma} = 3.4 \pm 1.4 \)

- **2009**
  - BaBar: \( R_{\psi \gamma} < 2.1 \) (90% CL)

- **2011**
  - Belle: \( R_{\psi \gamma} < 0.59 \) (90% CL)

- **2014**
  - LHCb (Run1): \( R_{\psi \gamma} = 2.5 \pm 0.7 \)

- **2020**
  - BESIII: \( R_{\psi \gamma} < 0.95 \) (90% CL)

- **2024**
  - \( R_{\psi \gamma} > 0.95 \) for compact ccq\textsubscript{q}

References:

- Swanson, PLB 598 (2004) 197
- Eichten, Lane, Quigg, PRD 73 (2006) 014014
- Guo, Hanhart, Kalashnikova, Meissner, Nefediev, PLB 742 (2015) 394
- Grinstein, Maiani, Polosa, PRD 109 (2024) 074009

Ivan Polyakov
Charmonium picture

- Radiative E1 transitions within charmonia states:

\[ \Gamma(n^{2S+1}L_J \rightarrow n'^{2S'+1}L'_{J'}, \gamma) = \frac{4}{3} e_c^2 \alpha \omega^3 C_{fi} \delta_{SS'} \langle n'^{2S'+1}L'_{J'} | r | n^{2S+1}L_J \rangle^2 \]

- Consider X(3872) as \( \chi_{c1}^{(2P)} \) state

| Initial state X(3872) | Final state | \( M_f \) (MeV) | \( \omega \) (MeV) | \( \langle f|r|i\rangle \) | \( C_{fi} \) | Width (keV) |
|------------------------|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( 2^3P_1 \) \( \psi'(2^3S_1) \gamma \) | \( J/\psi(1^3S_1) \gamma \) | 3686 | 182 | 697 | 2.723 | 1.150 | 63.9 | 11.0 |

\( (w_{\psi(2S)}/w_{J/\psi})^3 \sim 0.018 \)

\[ |\langle f|r|i\rangle_{\psi(2S)} / |\langle f|r|i\rangle_{J/\psi}|^2 \sim 330 \]

2P has much larger overlap with 2S than with 1S

- With X(3872) as \( \chi_{c1}^{(2P)} + 2.3\% \chi_{c1}^{(1P)} \) mixture

\[ R_{\psi_Y} \sim 0.8 \pm 0.2 \]
(Naive?) Molecula picture

1. by Grinstein, Maiani, Polosa, PRD 109 (2024) 074009

\[ R_{\text{rms}} \approx 10 \text{ fm} \]  
(\( E_B \approx 0.2 \text{ MeV} \))

2. by Swanson, PLB 598 (2004) 197

\[ R_{\psi\gamma} \approx 0.4\% \]
Molecuła EFT picture

- EFT theory with "dimension regularisation with the MS subtraction scheme at the scale $\mu$"

\[ R_{\gamma \psi} \equiv \frac{\Gamma(X \rightarrow \gamma \psi)}{\Gamma(X \rightarrow \gamma J/\psi)} = 0.21 \times \left(\frac{g'_{2}/g_{2}}{g_{2}}\right)^2 \text{ at } \mu = m_X \]

- Is $g^\psi_{2}/g^{J/\psi}_{2} \sim 1$ a reasonable assumption?

- What is correspondence between loop/contact and molecular/compact for given $\mu=m_X$?

- Molnar, Luis, Higa, arXiv:1601.03366 obtain different results while using ~ same method
Compact tetraquark picture

- Describe $c\bar{c}q\bar{q}$ bound state in Born-Oppenheimer (LO) approach

$$\Psi(r_c, r_{\bar{c}}, r_u, r_{\bar{u}}) \approx \chi_c(|r_u - r_c|)\chi_c(|r_{\bar{u}} - r_{\bar{c}}|)\Psi_{BO}(|r_c - r_{\bar{c}}|)$$

- Consider configuration with leading (?) contribution

$$|(c\bar{c})_8(q\bar{q})_8) = \sqrt{\frac{2}{3}}|(cq)_3(c\bar{q})_3) - \sqrt{\frac{1}{3}}|cq)_6(c\bar{q})_6$$

$$A(X \rightarrow \Psi \gamma) = \mathcal{F} \int d^3R d^3\xi d^3\eta \delta^3(\eta + R - \xi) e^{-i\frac{1}{2}k(|\xi + \eta|)}\psi(|R|) \Psi(|R|) \chi(|\xi|) \chi(|\eta|)$$

$$R_{\psi Y} > 0.95 \, \text{(up to 12)}$$
Reflections

the nature of [some exotic hadron] is ...

[一些奇異強子]的本質是......
### Summary of theory predictions

<table>
<thead>
<tr>
<th>Reference</th>
<th>Reference</th>
<th>$R_{\psi\gamma}$</th>
<th>Admixture</th>
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<tbody>
<tr>
<td>T. Barnes and S. Godfrey</td>
<td></td>
<td>5.8</td>
<td>$c\bar{c}$</td>
</tr>
<tr>
<td>T. Barnes, S. Godfrey and S. Swanson</td>
<td></td>
<td>2.6</td>
<td>$c\bar{c}$</td>
</tr>
<tr>
<td>B.-Q. Li and K. T. Chao</td>
<td></td>
<td>1.3</td>
<td>$c\bar{c}$</td>
</tr>
<tr>
<td>Y. Dong et al.</td>
<td></td>
<td>$1.3 - 5.8$</td>
<td>$c\bar{c}$</td>
</tr>
<tr>
<td>A. M. Badalian et al.</td>
<td></td>
<td>$0.8 \pm 0.2$</td>
<td>$c\bar{c}$</td>
</tr>
<tr>
<td>J. Ferretti, G. Galata and E. Santopinto</td>
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<td>6.4</td>
<td>$c\bar{c}$</td>
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<td>A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker</td>
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<td>$c\bar{c}$</td>
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<td>W. J. Deng et al.</td>
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<td>F. Giacosa, M. Piotrowska and S. Goito</td>
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<td>5.4</td>
<td>$c\bar{c}/\psi\gamma$</td>
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<td>E. S. Swanson</td>
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<td>3.8 %</td>
<td>$D\bar{D}$*</td>
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<tr>
<td>Y. Dong et al.</td>
<td></td>
<td>3.3 %</td>
<td>$D\bar{D}$*</td>
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<td>D. P. Rathaud and A. K. Rai</td>
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<td>$D\bar{D}$*</td>
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<tr>
<td>R. F. Lebed and S. R. Martinez</td>
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<td>3.3 %</td>
<td>$D\bar{D}$*</td>
</tr>
<tr>
<td>B. Grinstein, L. Maiani and A. D. Polosa</td>
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<td>3.6 %</td>
<td>$D\bar{D}$*</td>
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<tr>
<td>S. Takeuchi, M. Takizawa and K. Shimizu</td>
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<td>E. Cincioğlu et al.</td>
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<td>&lt; 4</td>
<td>$D\bar{D}$*</td>
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<td>D. A.-S. Molnar, R. F. Luiz and R. Higa</td>
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<tr>
<td>F.-K. Guo et al.</td>
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<td>$0.21(q'/q_2)^2$</td>
<td>$D\bar{D}$*</td>
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<tr>
<td>B. Grinstein, L. Maiani and A. D. Polosa</td>
<td></td>
<td>&gt; $(0.95^{+0.01}_{-0.07})$</td>
<td>$c\bar{c}q\bar{q}$</td>
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</table>

- $c\bar{c} + D\bar{D}$* admixture can reproduce any value in between
Evidences for $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$

**J/ψγ mode**

**BaBar (2009)**

$R_{\psi\gamma} = 3.4 \pm 1.4$

**LHCb (2014)**

$R_{\psi\gamma} = 2.5 \pm 0.7$

**ψ(2S)γ mode**

$N_\chi = 591 \pm 48$

$N_\chi = 36 \pm 9$

**PRL 102 (2009) 132001**

**NPB 886 (2014) 665**
Non-observations of $\chi_{c1}(3872) \to \psi(2S)\gamma$

**J/$\psi\gamma$ mode**

Belle (2011)

$R_{\psi\gamma} < 2.1$ (90% CL)

**PRL 107 (2011) 091803**

$N_x = 30 \pm 8$

5.5$\sigma$

**ψ(2S)γ mode**

BESIII (2020)

$R_{\psi\gamma} < 0.59$ (90% CL)

**PRL 124 (2020) 242001**

$N_x = 39 \pm 12$

3.5$\sigma$

$J/\psi \to \mu\mu$

$N_x = -0.9 \pm 4.1$

BESIII (2020)

$R_{\psi\gamma} = 2.5$

$\psi(2S) \to J/\psi\pi\pi$

$N_x = 5 \pm 12$
Specifics of LHCb

- Excellent in reconstructing B-decays, ECAL resolution: $1\% \oplus \frac{10\%}{\sqrt{E/\text{GeV}}}$

- Use $B^+ \rightarrow \chi_{c1}(3872)[\rightarrow \psi \gamma]K^+$ decay

- High background from prompt $\pi^0 \rightarrow \gamma \gamma$: $O(100)$ photons per event
  - Especially critical for $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$ mode due to softer photon

- Noticeably enhanced with $7 \text{ TeV (2011) } \rightarrow 8 \text{ TeV (2012)} \rightarrow 13 \text{ TeV (2015-2018)}$ increase in pp collision energy
## New measurement

LHCb-PAPER-2024-015, in prep.

<table>
<thead>
<tr>
<th></th>
<th>Run 1</th>
<th>Run 2</th>
<th>Total Lumi</th>
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<tr>
<td>LHCb 2014 measurement</td>
<td>7 TeV (1 fb$^{-1}$) + 8 TeV (2 fb$^{-1}$)</td>
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<td>3 fb$^{-1}$</td>
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<tr>
<td>New measurement</td>
<td>7 TeV (1 fb$^{-1}$) + 8 TeV (2 fb$^{-1}$)</td>
<td>13 TeV (6 fb$^{-1}$)</td>
<td>9 fb$^{-1}$</td>
</tr>
</tbody>
</table>

- ~2x higher B production cross-section
- but also higher backgrounds

same data sample
Selection

- 2014 analysis (Run1) strategy: cuts, small differences between $J/\psi$ and $\psi(2S)$ modes

- New strategy: loose cut preselection + MLP (Multi-Layered Perceptron) separate for $J/\psi$ and $\psi(2S)$ modes, Run1 and Run2
  - kinematics & geometry [8 vars]
  - decay chain & vertex quality [5 vars]
  - track reconstruction & identification quality [2 vars]
  - photon reconstruction quality [1 var]
  → 16 variables, $p_T(\gamma)$ is of highest importance

- Optimize $S/\sqrt{S+B}$ using simulation for signal and sideband data for background
$B^+ \rightarrow \chi_{c1}[ \rightarrow J/\psi \gamma]K^+$ as standard candle

- Same decay topology, similar kinematics, huge statistics
- Cross-check performance for reconstruction and selection
- Calibrate mass resolution and mass scale
- Investigate data-MC agreement for efficiency

$LHCb, JHEP 02 (2024) 173$

$N_{\text{sig}} \sim 170 \times 10^3$
Signal (fit function)

- **Signal**: $S_B \times S_X$
  - $S_B$ – Double Sided Crystall Ball (DSCB)
  - $S_X$ – DSCB + split (asymmetric) Gaussian

- Use kinematic fit with vertex and $\psi \rightarrow \mu^+\mu^-$ mass constraints to improve $m_{\psi\gamma}$ mass resolution

- Use additional $X \rightarrow \psi\gamma$ mass constraint for $m_B = m_{\psi\gamma}K$

- Correction factors on mass resolution from the $B^+ \rightarrow \chi_{c1}[\rightarrow J/\psi\gamma]K^+$ channel:
  - $1.102 \pm 0.004$ for $\sigma_B$
  - $1.027 \pm 0.004$ for $\sigma_{\psi\gamma}$
Backgrounds

- Signal final state: $\psi\gamma K^+$
- $\psi(2S)$ mode:
  - $B \rightarrow \psi(2S)K^+X + \gamma$
  - with intermediate $K^*$, $K_0^*(700)$, $K_1(1270)$, $K^*(1410)$, $K_2^*(1430)$, $K^*(1680)$
  - and non-resonant $\psi(2S)K^+\pi$, $\psi(2S)K^+\pi\pi$, $\psi(2S)K^+\eta$, $\psi(2S)K^{*+}\eta$, $\psi(2S)K^+\omega$

- $J/\psi$ mode:
  - $B^+ \rightarrow J/\psi K^{*+}(K^+\pi^0(\rightarrow \gamma\gamma))$

- Additional unidentified $B^+ \rightarrow J/\psi K^+X$

- Investigate shape with simulation
Overall fit function

- Components:
  - Signal: $S_B \times S_X$

- Partially reconstructed
  $B \rightarrow \psi(2S)KX$ or $B \rightarrow J/\psi K^{*+}$ decays
    (simulation, 2D Legendre pol.)

- In $J/\psi$ mode:
  - additional $B \rightarrow J/\psi KX$
    (2D Gaussian function)
  - non-B background: $\text{const}_B \times S_X$

- Combinatorial background –
  2D polynomial (9/16 parameters)

- Simultaneous fit to 4 samples: Run1/2 $\otimes$ $J/\psi / \psi(2S)$
  shared $B$ and $\chi_{c1}(3872)$ mass position and resolution
First observation of $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$

- Projections in signal regions

$\psi(2S)\gamma$ mode

$\frac{3872}{\chi_{c1}}$

- Run1: 40±8, 5.3σ
- Run2: 63±10, 6.7σ

$\psi(2S)$ mode

- Run1: 430±30
- Run2: 1690±50

$J/\psi\gamma$ mode
## Systematic uncertainties

- Cancel in the ratio to a large extent

<table>
<thead>
<tr>
<th>Source</th>
<th>Data-taking period</th>
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<tbody>
<tr>
<td></td>
<td>Run 1</td>
</tr>
<tr>
<td>Fit model</td>
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<td>Signal and combinatorial background</td>
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<td>B → ψ(2S)K^+X background</td>
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<td>Parameterisation</td>
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<td>B^+ meson kinematics</td>
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<td>Data-simulation (dis)agreement</td>
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<td>Total</td>
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<td>-9.2</td>
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</tbody>
</table>

Understanding of background sources and shapes:

checked on data:

- B^+ → J/ψK^+
- J/ψ → μ^+μ^-
- B^+ → J/ψK^{*+}[→ K^+π^0]
- D^{*+} → D^0[→ K^−π^+]π^+
- B^+ → J/ψ(ψ(2S))K^+
- B^+ → χ_{c1}[→ J/ψγ]K^+
Results

- LHCb/Run1 2014 measurement:
  \[ R_{\psi \gamma} = 2.46 \pm 0.64 \pm 0.29 \]

- New measured BR ratios:
  \[ R_{\psi \gamma}^{\text{Run 1}} = 2.50 \pm 0.52^{+0.20}_{-0.23} \pm 0.06 \]
  \[ R_{\psi \gamma}^{\text{Run 2}} = 1.49 \pm 0.23^{+0.13}_{-0.12} \pm 0.03 \]

- Run1&2 average:
  \[ R_{\psi \gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04 \]
- $R_{\psi_{y}} \sim 1.7$ carries information about the $\chi_{c1}(3872)$ nature

- Likely sign of pure charmonium or compact ccqq component

… but ambiguities in theory interpretations need to be clarified first
- $R_{\psi y} \sim 1.7$ carries information about the $\chi_{c1}(3872)$ nature

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... waiting for model unification

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Ivan Polyakov
Future of the $\chi_{c1}(3872)$

- Run1&2 → Run3&4: 10x gain in statistics
  → Run5&6: 100x

- Radiative decays
  - ECAL enhancement in LS3 (granularity, timing, ...)

- New decay modes ($\chi_{c1}\pi\pi, p\bar{p}, ...$)

- Combinations with Belle, BESIII, Belle-II
Post-Script

- “LHCb meets Theory” on the topic. 27 June 2024, CERN.
  https://indico.cern.ch/event/1423946/
  5 theory talks + BelleII, BESIII
Appendix
## Fit results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data-taking period</th>
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<tbody>
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<td>Run 1</td>
</tr>
<tr>
<td>( \psi(2S)\gamma K^+ )</td>
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<tr>
<td>( N_{B^+ \to (\chi_{c1}(3872) \to \psi(2S)\gamma)K^+} )</td>
<td>40 ± 8</td>
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<tr>
<td>( N_{B \to \psi(2S)K^+X} )</td>
<td>567 ± 24</td>
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<tr>
<td>( N_{\text{comb}} )</td>
<td>55 ± 17</td>
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<tr>
<td>( J/\psi\gamma K^+ )</td>
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<tr>
<td>( N_{B^+ \to (\chi_{c1}(3872) \to J/\psi\gamma)K^+} )</td>
<td>([10^3]) 0.43 ± 0.03</td>
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<tr>
<td>( N_{B \to J/\psi X} )</td>
<td>([10^3]) 3.61 ± 0.11</td>
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<tr>
<td>( N_{\chi_{c1}(3872)K^+} )</td>
<td>([10^3]) 1.18 ± 0.06</td>
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<td>( N_{\text{comb}} )</td>
<td>([10^3]) 4.05 ± 0.11</td>
</tr>
<tr>
<td>( \mathcal{L}<em>{\chi</em>{c1}(3872) \to \psi(2S)\gamma} )</td>
<td>5.3( \sigma )</td>
</tr>
</tbody>
</table>

LHCb-PAPER-2024-015
Efficiencies

\[ \mathcal{R}_{\psi\gamma} = \frac{N_{B^+ \to (X_{c1}(3872) \to \psi(2S)\gamma) K^+}}{N_{B^+ \to (X_{c1}(3872) \to J/\psi\gamma) K^+}} \times \frac{\mathcal{B}_{B^+ \to (X_{c1}(3872) \to J/\psi\gamma) K^+}}{\mathcal{B}_{B^+ \to (X_{c1}(3872) \to \psi(2S)\gamma) K^+}} \times \frac{\mathcal{B}_{J/\psi \to \mu^+\mu^-}}{\mathcal{B}_{\psi(2S) \to \mu^+\mu^-}}. \]  

Run1: 3.51 ± 0.08
Run2: 5.15 ± 0.07

PDG for $e^+e^-$: 7.53 ± 0.17
Alternative fit models

- **Signal:**
  Apollonios, Student-t, mod. Novosibirsk, split. DSCB

- **Combinatorial background:**
  2D pol with order 1&3 for $\psi(2S)$ case and 2 for J/$\psi$ case

- **Peaking backgrounds:**
  2D Legendre with n=12&13,
  2D histograms with various interpolations
  - variate BR’s of $B \rightarrow \psi(2S)KX$ composition
  - pseudo-experiment to access finite sample size effect

- **Additional** $B \rightarrow X[\rightarrow \psi(2S)\gamma] + K$ or $B \rightarrow J/\psi\gamma K$ components
First exotic hadrons

- Were anticipated since 60’s
- No success in light sector
  - First candidates for tetraquarks in 90’s:
    - $f_0(500)$, $K^*(800)$, ... later $D_{sJ}^*(2317)$, ...
  - Pentaquark $\Theta^+ [uudds]$ in 2003
- First one uniquely identified as exotic was $\chi_{c1}(3872)$ discovered in heavy sector in 2003;
  - First pentaquark in 2015 in heavy sector as well;

much smaller widths and clearer understanding of $c\bar{c}$ allowed to exclude conventional interpretations
## Theory models (References)

<table>
<thead>
<tr>
<th>charmonium</th>
<th>compact tetraquark</th>
<th>DD* molecule</th>
</tr>
</thead>
</table>
- Eichten, Lane, Quigg, Phys. Rev. D69 (2004) 094019;  
| hadro-charmonium | hybrid | admixture |
\( \chi_{c1}(3872) \) partners

- Partners with various \( J^{PC} \) naturally arise in diquark-diquark model

\[ \begin{align*}
\text{Overall possibilities for } J^{PC} \\
\text{s}_{cq} = 0 & \quad \text{and } \text{s}_{cq} = 0: \; 0^{++} \\
\text{s}_{cq} = 0 & \quad \text{and } \text{s}_{cq} = 1: \; 1^{++}, \; 1^{-+} \\
\text{s}_{cq} = 1 & \quad \text{and } \text{s}_{cq} = 1: \; 0^{++}, \; 1^{++}, \; 2^{++}
\end{align*} \]

- \( \chi_{c1}(3872)^\pm \) are not seen in experiment

\[ \frac{BR(B^+ \to X(3872)^+ K^0)}{BR(B^+ \to X(3872) K^+)} < 0.5 \]

- \( \chi_{c1}(3872)^\pm \) should be \( I=0 \) and \( I=1 \) states

\( \rightarrow \) charged \( X(3872)^\pm \)

- Can be easily accommodated by theory

\[ 0.05 < R_{2\pi}^- = \frac{B(B^0 \to K^+ \chi_{c1}(3872)^- \to K^+ J/\psi \pi^0 \pi^-)}{B(B^0 \to K^0 \chi_{c1}(3872) \to K^0 J/\psi \pi^+ \pi^-)} < 0.57 \]
EFT theory with "dimension regularisation with the $\overline{\text{MS}}$ subtraction scheme at the scale $\mu$"

What is correspondence between loop/contact and molecular/compact for given $\mu=m_X$?

Is $g_2^{\psi(2S)}/g_2^{J/\psi} \sim 1$ a reasonable assumption?

<table>
<thead>
<tr>
<th></th>
<th>$\mu = m_X/2$</th>
<th>$\mu = m_X$</th>
<th>$\mu = 2m_X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma(X \rightarrow \gamma J/\psi)$ [keV]</td>
<td>$9.7(r_xr_g)^2$</td>
<td>$23.5(r_xr_g)^2$</td>
<td>$43.2(r_xr_g)^2$</td>
</tr>
<tr>
<td>$\Gamma(X \rightarrow \gamma J')$ [keV]</td>
<td>$3.8(r_xr'_g)^2$</td>
<td>$4.9(r_xr'_g)^2$</td>
<td>$6.0(r_xr'_g)^2$</td>
</tr>
<tr>
<td>$R = \frac{\Gamma(X \rightarrow \gamma J')}{\Gamma(X \rightarrow \gamma J/\psi)}$</td>
<td>$0.39(g'_2/g_2)^2$</td>
<td>$0.21(g'_2/g_2)^2$</td>
<td>$0.14(g'_2/g_2)^2$</td>
</tr>
</tbody>
</table>

get contradicting results while using ~ same method

Molnar, Luis, Higa, arxiv:1601.03366

Guo, Hanhart, Kalashnikova, Meissner, Nefediev, PLB 742 (2015) 394
Is $g_2^{(2S)}/g_2^{J/\psi} \sim 1$ a reasonable assumption?

According to Dong et al, arxiv:0909.0380 it is

$$\frac{g_{\psi(2S)DD}}{g_{J/\psi DD}} = \frac{g_{\psi(2S)D^*D^*}}{g_{J/\psi D^*D^*}} = \frac{m_{\psi(2S)}}{m_{J/\psi}} \frac{f_{J/\psi}}{f_{\psi(2S)}} \approx 1.67$$

The quantity $f_{\psi_n}$ is determined by the leptonic decay widths of $J/\psi$ and $\psi(2S)$ of

$$\Gamma(J/\psi \to e^+e^-) = \frac{16\pi}{27} \frac{\alpha^2}{m_{J/\psi}} f_{J/\psi}^2 = 5.55 \text{ keV},$$

$$\Gamma(\psi(2S) \to e^+e^-) = \frac{16\pi}{27} \frac{\alpha^2}{m_{\psi(2S)}} f_{\psi(2S)}^2 = 2.38 \text{ keV},$$

where $\alpha$ is the fine structure constant. From Eq. (14) we get $f_{J/\psi} = 416.4$ MeV and $f_{\psi(2S)} = 297.5$ MeV.

but $\sim 0.3$ according to Grinstein, Maiani, Polosa, arXiv:2401.11623
\( \chi_{c1}(3872) \to J/\psi \gamma \). BaBar & BESIII overlay

- Rescale BaBar and BESIII data points to same signal peak shape
  ... BESIII error bars are 1.5x larger, with 1.3x larger point density

\[ N_\chi = 23 \pm 7 \quad 3.6\sigma \]

\[ N_\chi = 39 \pm 12 \quad 3.5\sigma \]