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

LHCb-PAPER-2024-015, in prep.

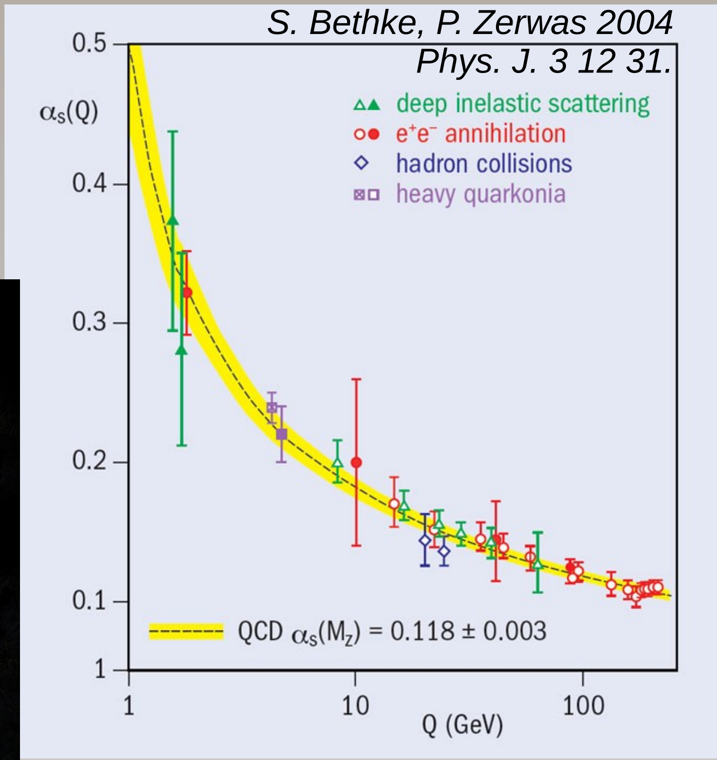
Ivan Polyakov

on behalf of the LHCb collaboration

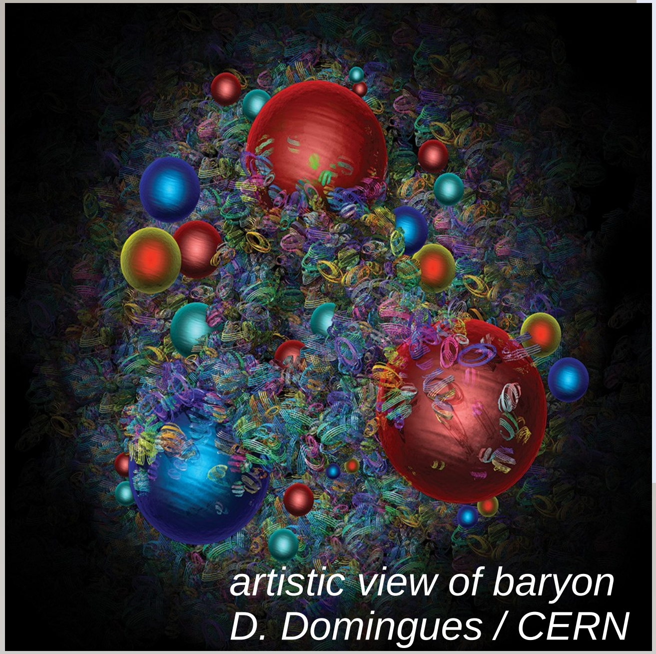
CERN LHC Seminar
11 June 2024

Non-perturbative QCD

- QCD is successful theory giving in precise predictions at high energies

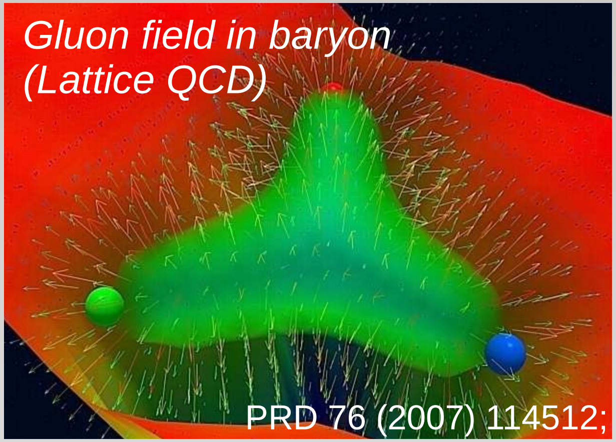


- However is highly non-perturbative at hadron/nuclei energy scale


artistic view of baryon
D. Domingues / CERN

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

  → knowledge limited by available quark configurations


Gluon field in baryon (Lattice QCD)
PRD 76 (2007) 114512;

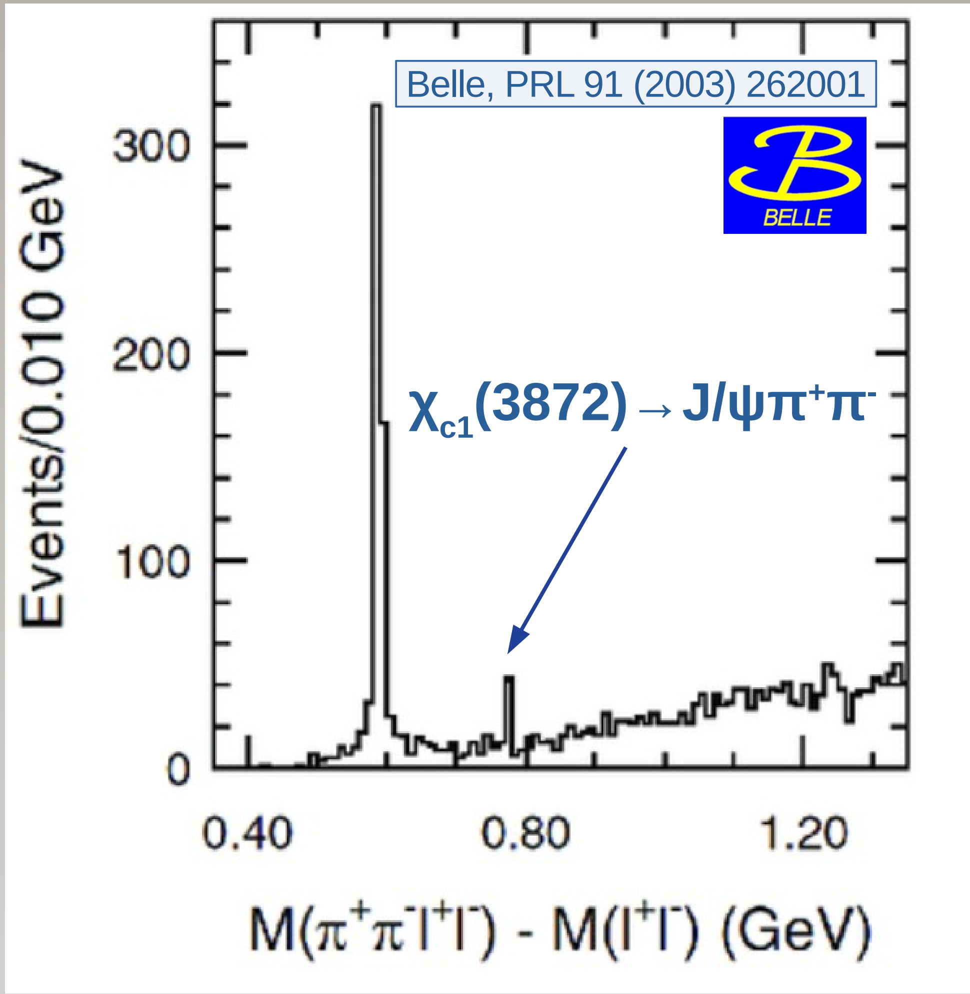
Exotic hadron spectroscopy

- In 2003 first exotic hadron was identified in particle discovered in $J/\psi\pi^+\pi^-$ by Belle

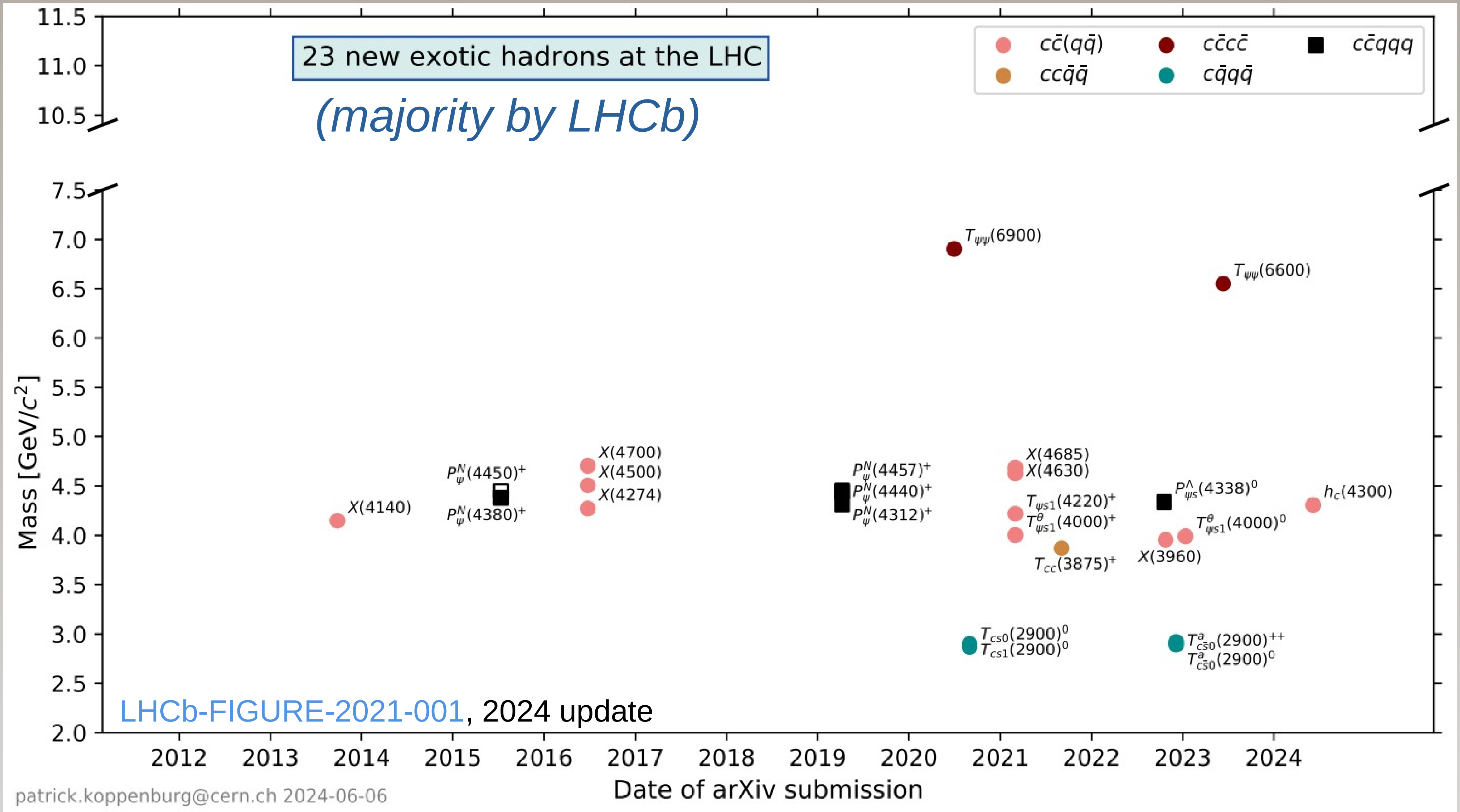
  - X(3872), *now known as $\chi_{c1}(3872)$*

    didn't fit conventional charmonium expectations

- Since then >50 exotic hadron candidates are discovered



23 new hadrons at the LHC



- The $\chi_{c1}(3872)$ remains the cornerstone for theory and experiment

The χ_{c1}(3872) career

N. Hüsken, E. S. Norella, I. Polyakov

4.2. *The $\chi_{c1}(3872)$* *(also known as $X(3872)$)*

MESON-LIKE/HIDDEN CHARM/ISOSCALAR

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

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

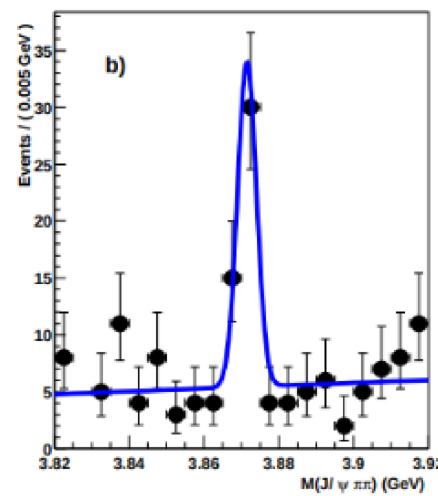
experiments: Belle, CDF, D0, BaBar, LHCb, CMS, ATLAS, BESIII (and potentially E705, COMPASS)

production: B^+, B^0, B_s^0 and Λ_b^0 decays, prompt pp, $p\bar{p}$, pPb (Pbp) and PbPb collisions, $e^+e^- \to \gamma\chi_{c1}(3872)$, $\omega\chi_{c1}(3872)$ potentially via ψ- or χ_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 ± 0.21 MeV *(Breit-Wigner)*

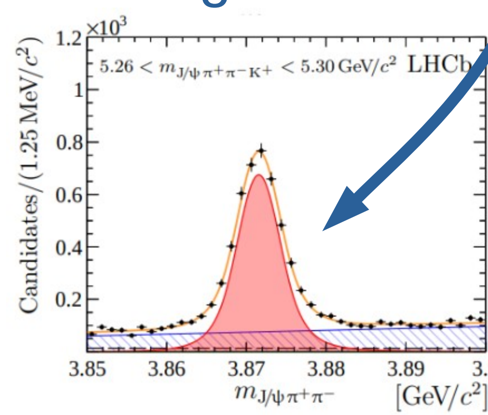


Belle, PRL 91 (2003) 262001

36 → 20x10^3 signal events

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

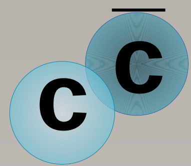
LHCb, JHEP 08 (2020) 123



LHCb, JHEP 08 (2020) 123

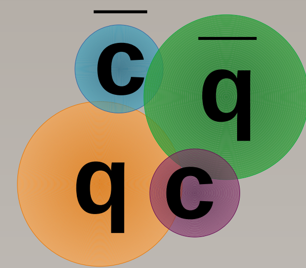
Theory models

** see references in Appendix*



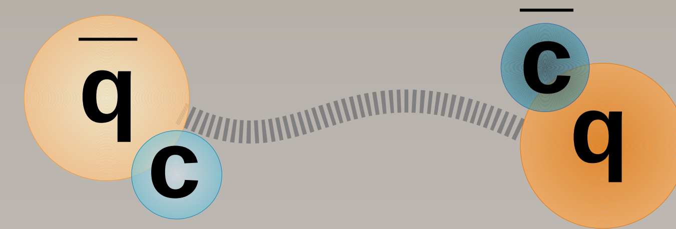
charmonium

Barnes, Godfrey, Swanson; Eichten, Lane, Quigg; Suzuki; ...



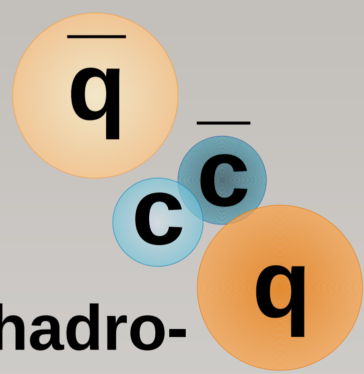
compact tetraquark

Maiani, Piccini, Polosa, Riquer; Matheus, Narison, Nielsen, Richard; ...



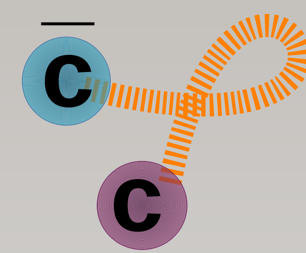
$D\bar{D}^*$ molecula

Braaten, Kusunoki; Swanson; Wong; Tornquist; ...



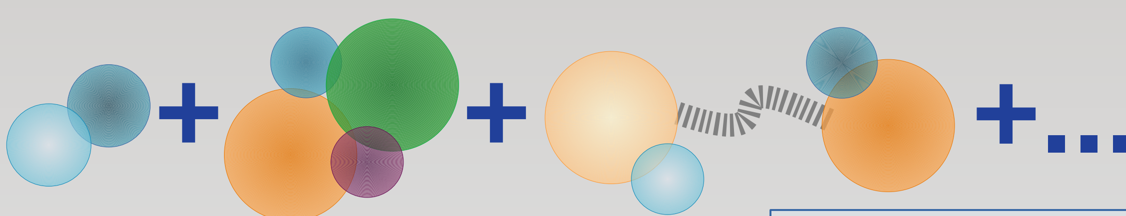
hadro-charmonium

Dubynskiy, Voloshin; ...



hybrid

Close, Godfrey; Li; ...



admixture

Suzuki; Close, Page; Dong, Faessler, Gutsche, Lyubovitskij; ...

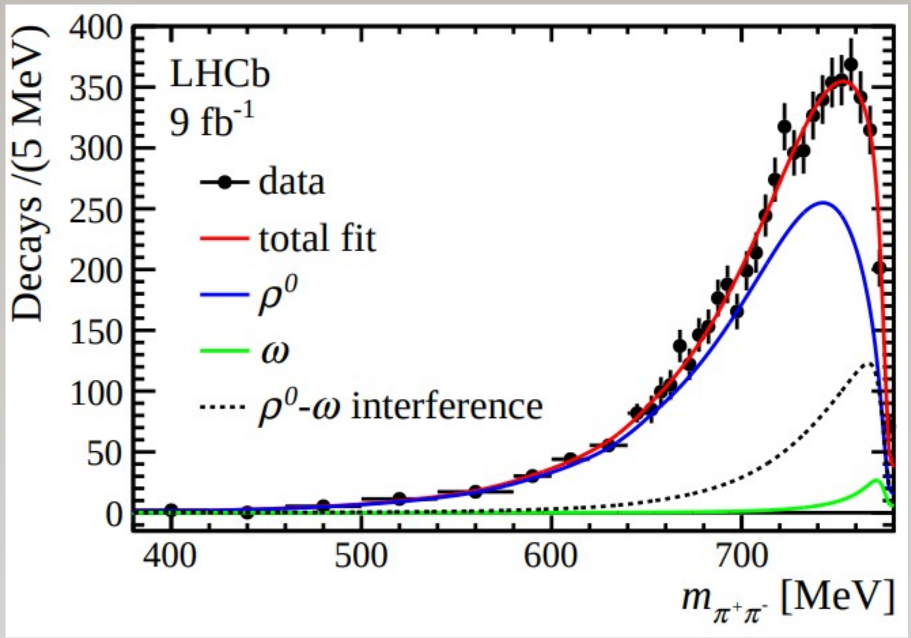
Isospin violation

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

- LHCb has accessed $\omega \to \pi^+ \pi^-$ (BR~1.5%) admixture in the same final state

LHCb, PRD 131 (2023) L011103

$$\frac{g_{\chi_{c1}(3872)\to\rho^0 J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = 0.29 \pm 0.04$$



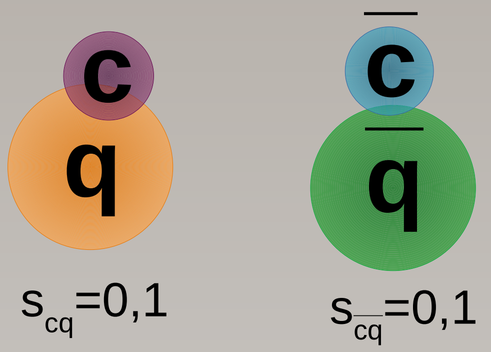
- ~10x larger than typical isospin violation in conventional charmonium

$$\frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = 0.045 \pm 0.001$$

- 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 $J^{PC}=1^{++}$
  → charged $X(3872)^{\pm}$ Maiani, Piccini, Polosa, Riquer, PRD 71 (2005) 014028



- $X(3872)^{\pm}$ are not seen in experiment
  $BR(B^{+}\to X(3872)^{+}K^{0})/BR(B^{+}\to X(3872)K^{+}) < 0.5$ Belle, PRD 84 (2011) 052004

  can be easily accommodated by theory Maiani, Polosa, Riquer, PRD 102 (2020) 034017

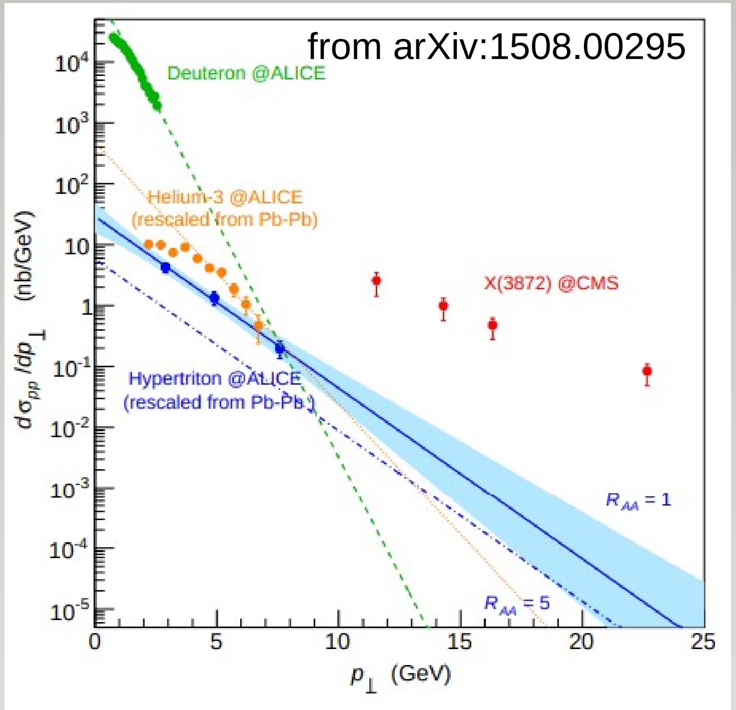
- [New:] In $D\bar{D}^{*}$ EFT one also finds isovector partners W_{c1}^{0} and $W_{c1}^{\pm}$ of the $\chi_{c1}(3872)$ as virtual states around 3867 MeV

Zhang, Ji, Dong, Guo, Hanhart, Meisner, Rusetsky, arXiv:2404.11215

Production in hadron collisions

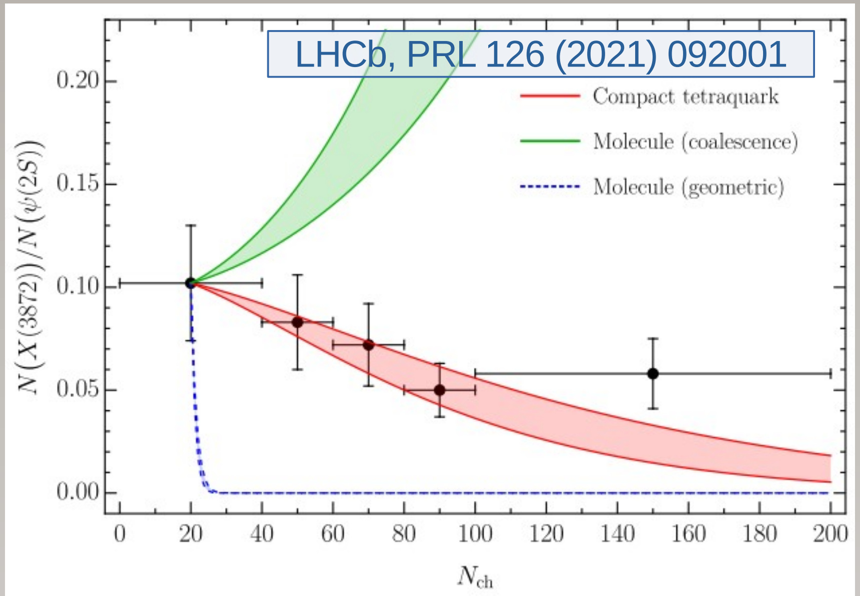
- $\sigma(p\bar{p} \to \chi_{c1}(3872)[\to J/\psi\pi\pi]+\ldots) > 3.1$ nb at $\sqrt{s}=1.98$ TeV
  CDF note 7159 (2004)
  - while Bignamini, Grinstein, Piccinini, Polosa, Sabelli, PRL 103 (2009) 162001 estimations for loosely bound ($E_B \sim 0.25$ MeV) $D\bar{D}^*$ molecule give only ~0.085 nb
  - in turn, Artoisenet, Braaten, PRD 81 (2010) 114018 argue that $D\bar{D}^*$ re-scattering can raise it up to 4–200 nb

    also see Albaladejo, Guo, Hanhart, Meißner, Nieves, Nogga, Yang, CPC 41 (2017) 121001
- $\sigma(pp \to \chi_{c1}(3872)+\ldots)$ at high p_T at LHC
  - Indication of non-molecular component
    Esposito, Guerrieri, Maiani, Piccinini, Pilloni, Polosa, Riquer, PRD 92 (2015) 034028
  - or feature of charm?

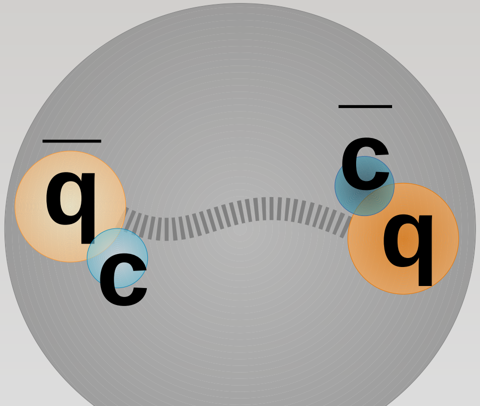


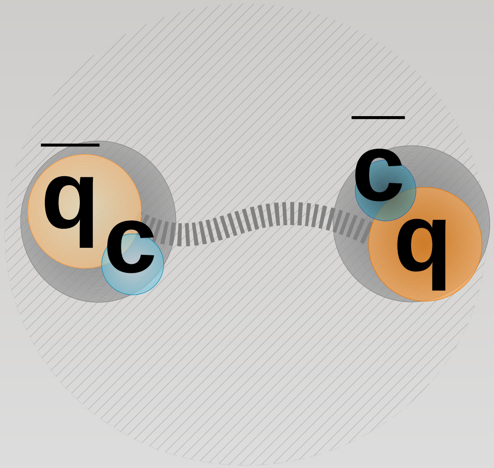
Production vs multiplicity

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



  - can't be explained with two (naive?) molecule models
    Esposito, Ferreiro, Pilloni, Polosa, Salgado, EPJC 81 (2021) 669
  - in turn, Braaten, He, Ingles, Jiang, PRD 103 (2021) L071901 argue that it can after re-estimating $\pi X \rightarrow D\bar{D}^*$ break-up cross-section (geo) from πr^2~1400 mb to ~3 mb

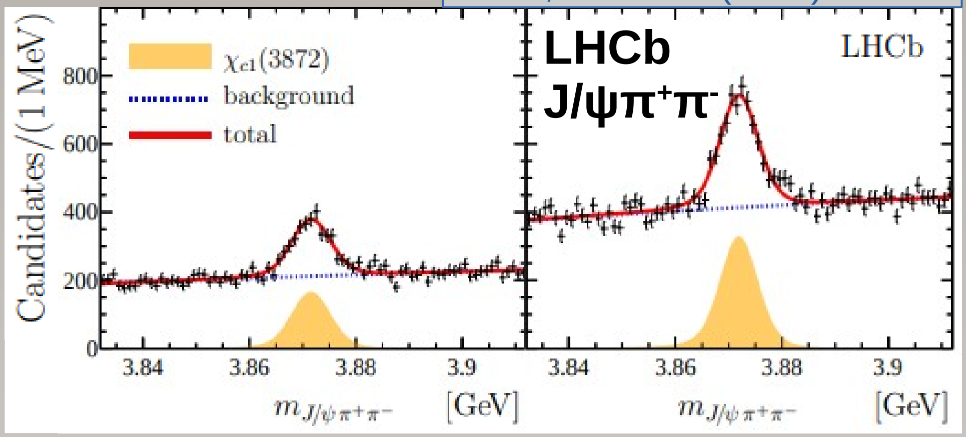




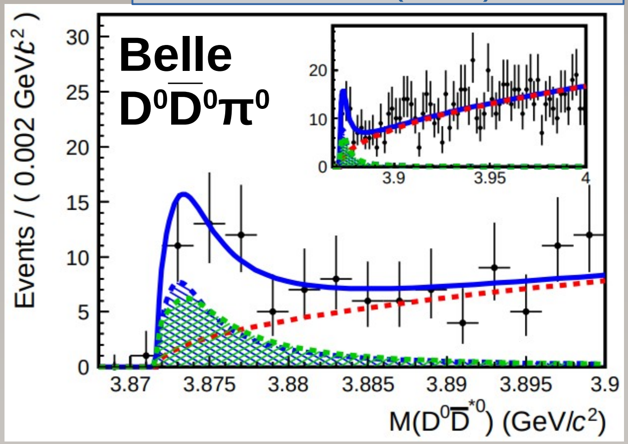
Pole position

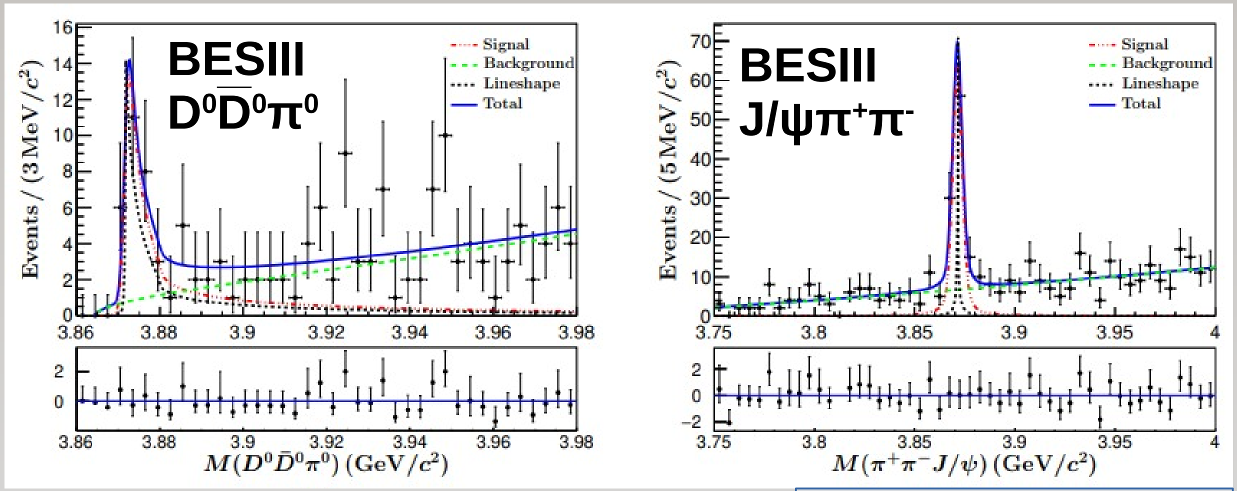
- Accessing pole in low-energy $D\bar{D}^*$ scattering via lineshapes in different decay modes

LHCb, PRD 102 (2020) 092005



Belle, PRD 107 (2023) 112011





BESIII, arXiv:2309.01502

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

What we want vs. what we get

Theory	Experiment
	
 	

** except for T_{cc} [$cc\overline{ud}$]* LHCb, Nature Phys 18 (2022) 751, Nature Comm. 13 (2022) 3351 LHC Seminar, 14 sep 2021 …

Radiative decays. Short recap

$$R_{\psi\gamma} \equiv \frac{\mathcal{B}(\chi_{c1}(3872) \to \psi(2S)\gamma)}{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\gamma)}$$

Theory

$R_{\psi\gamma}$ ~ 0.3% for moleculas,

$R_{\psi\gamma}$ ~ 1-6 for pure charmonia

Swanson, PLB 598 (2004) 197

Lahde, arXiv:hep-ph/0208110

Barnes, Godfrey, arXiv:hep-ph/0311162

Eichten, Lane, Quigg, PRD 73 (2006) 014014

$R_{\psi\gamma} > 1$ can be achieved for moleculas as well

Guo, Hanhart, Kalashnikova, Meissner, Nefediev, PLB 742 (2015) 394

$R_{\psi\gamma}$>0.95 for compact $c\bar{c}q\bar{q}$

Grinstein, Maiani, Polosa, PRD 109 (2024) 074009

Experiment

2004-2005

2006 BaBar: Observation of $\chi_{c1}(3872) \to J/\psi\gamma$

PRD 74 (2006) 071101

2009 BaBar: $R_{\psi\gamma} = 3.4 \pm 1.4$

PRL 102 (2009) 132001

2011 Belle: $R_{\psi\gamma} < 2.1$ (90% CL)

PRL 107 (2011) 091803

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

NPB 886 (2014) 665

2015

2020 BESIII: $R_{\psi\gamma} < 0.59$ (90% CL)

PRL 124 (2020) 242001

2024

Charmonium picture

- Radiative E1 transitions within charmonia states:

photon momenta — wave function projections

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

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

Barnes, Godfrey, arXiv:hep-ph/0311162

Initial state X(3872)	Final state	M_f (MeV)	ω (MeV)	$\langle f\|r\|i\rangle$ (GeV^{-1})	C_{fi}	Width (keV)
2^3P_1	$\psi'(2^3S_1)\,\gamma$	3686	182	2.723	$\frac{1}{3}$	63.9
	$J/\psi(1^3S_1)\,\gamma$	3097	697	0.150	$\frac{1}{3}$	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

1

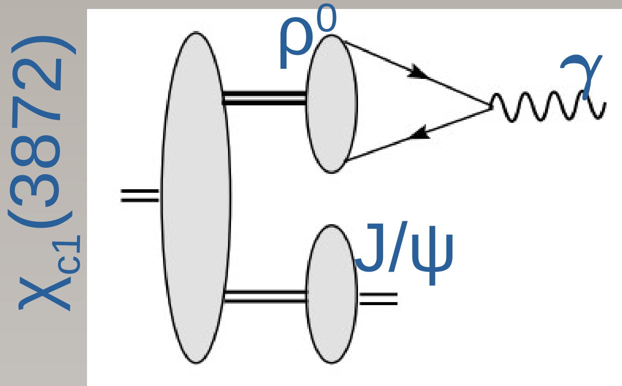
$R_{\psi\gamma} \sim 5.8$

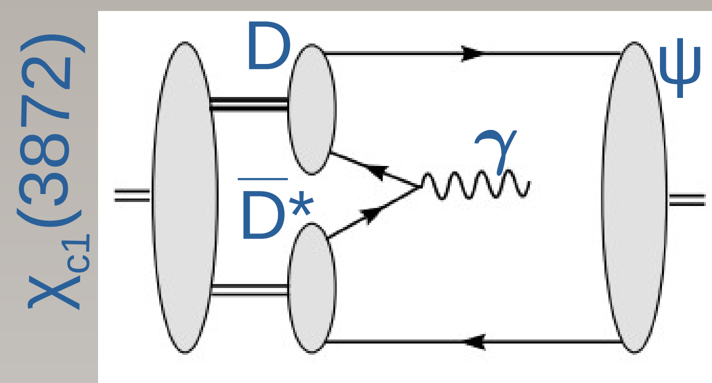
- With X(3872) as $\chi_{c1}(2P)$ + 2.3% $\chi_{c1}(1P)$ mixture

$R_{\psi\gamma} \sim 0.8 \pm 0.2$ Badalian, Orlovsky, Simonov, arXiv:1202.4882

(Naive?) Molecula picture

- 1. by Swanson, PLB 598 (2004) 197





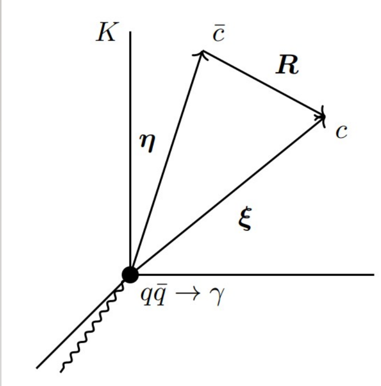
~12%

(dominant in J/ψγ mode)

~86%

$R_{\psi\gamma}$~0.4%

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



$$A(X \to \Psi\,\gamma) = \mathscr{F} \int d^3R\, d^3\xi\, d^3\eta\;\; \delta^3(\boldsymbol{\eta} + \boldsymbol{R} - \boldsymbol{\xi})\, e^{-i\frac{1}{2}\boldsymbol{k}\cdot(\boldsymbol{\xi}+\boldsymbol{\eta})}\, \psi(|\boldsymbol{R}|)\, \Psi(|\boldsymbol{R}|)\, \chi(|\boldsymbol{\xi}|)\, \chi(|\boldsymbol{\eta}|)$$

$$\Psi_{\text{mol.}}(R) = \frac{1}{\sqrt{2\pi R_0}} \frac{e^{-R/R_0}}{R}$$

R_0 ~ 10 fm

(E_B ~ 0.2 MeV)

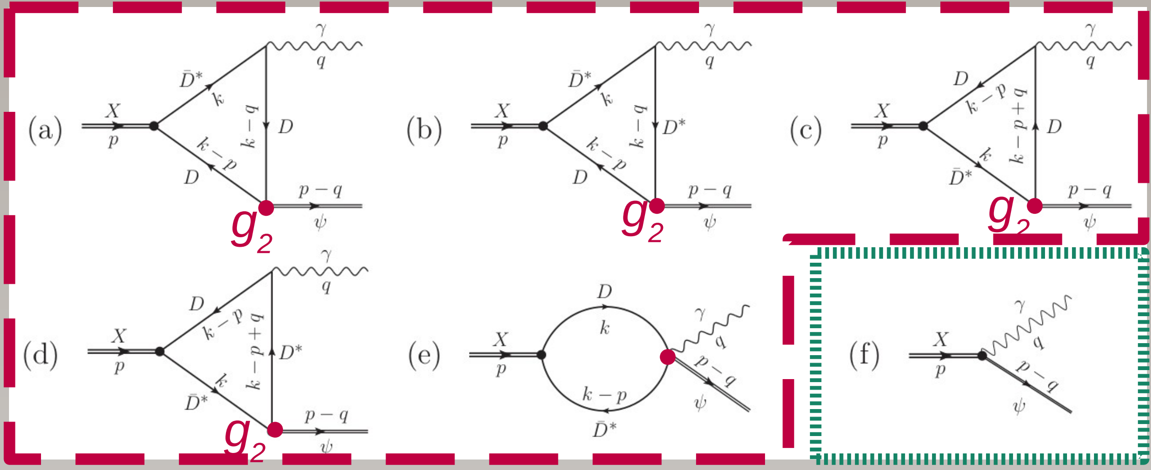
for R_{rms}(Mol)=17 fm, R_{rms}(D) = 0.68 fm

$$\mathscr{R} = \frac{\mathscr{B}(X \to \psi'\gamma)}{\mathscr{B}(X \to \psi\gamma)} = 0.036$$

~~Molecula~~ EFT picture

Guo, Hanhart, Kalashnikova, Meissner, Nefediev, PLB 742 (2015) 394

- EFT theory with
  “dimension regularisation with the $\overline{MS}$ subtraction scheme at the scale μ”



“loop” processes

“contact” process

$$R_{\psi\gamma} \equiv \frac{\Gamma(X \to \gamma\psi')}{\Gamma(X \to \gamma J/\psi)} = 0.21 \times \left(g_2'/g_2\right)^2 \text{ at } \mu = m_X$$

+?

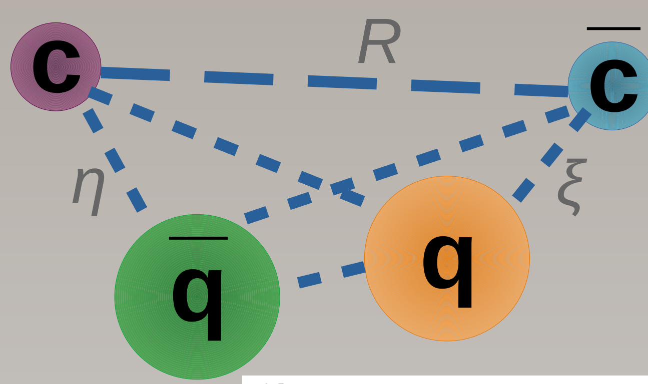
- Is $\mathbf{g_2^{\psi(2S)}/g_2^{J/\psi} \sim 1}$ a reasonable assumption?

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

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

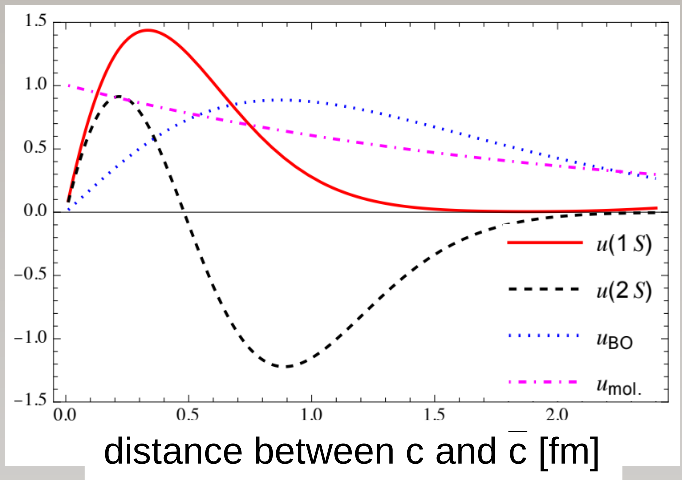
Compact tetraquark picture

Grinstein, Maiani, Polosa, PRD 109 (2024) 074009



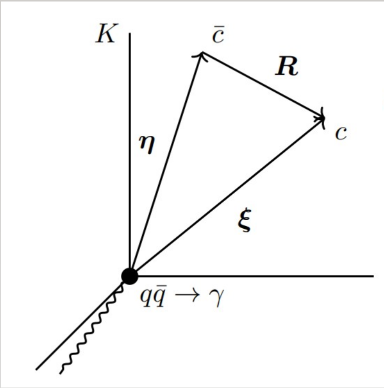
- Describe $c\bar{c}q\bar{q}$ bound state in Born-Oppenheimer (LO) approach

$$\Psi(\mathbf{r}_c, \mathbf{r}_{\bar{c}}, \mathbf{r}_u, \mathbf{r}_{\bar{u}}) \approx \chi_C(|\mathbf{r}_u - \mathbf{r}_c|)\chi_C(|\mathbf{r}_{\bar{u}} - \mathbf{r}_{\bar{c}}|)\Psi_{BO}(|\mathbf{r}_c - \mathbf{r}_{\bar{c}}|)$$



- Consider configuration with leading (?) contribution

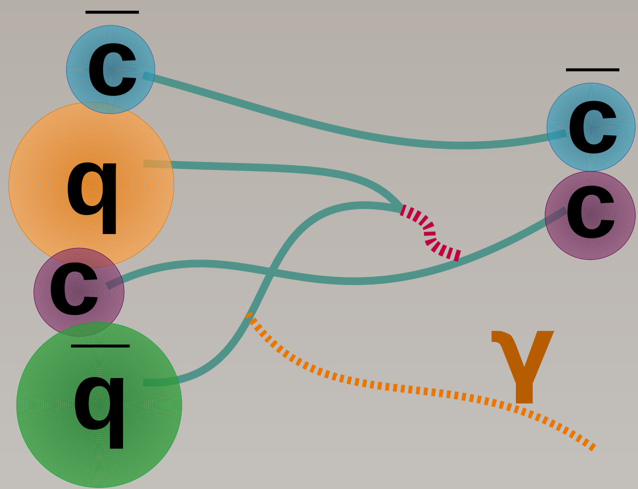
$$|(c\bar{c})_{\mathbf{8}}(q\bar{q})_{\mathbf{8}}\rangle = \sqrt{\frac{2}{3}}|(cq)_{\bar{\mathbf{3}}}(\bar{c}\bar{q})_{\mathbf{3}}\rangle - \sqrt{\frac{1}{3}}|(cq)_{\bar{\mathbf{6}}}(\bar{c}\bar{q})_{\mathbf{6}}\rangle$$

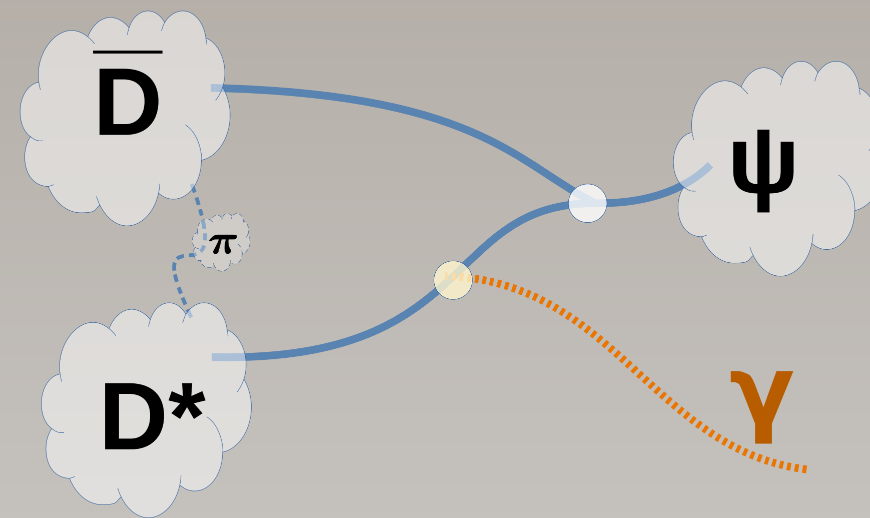


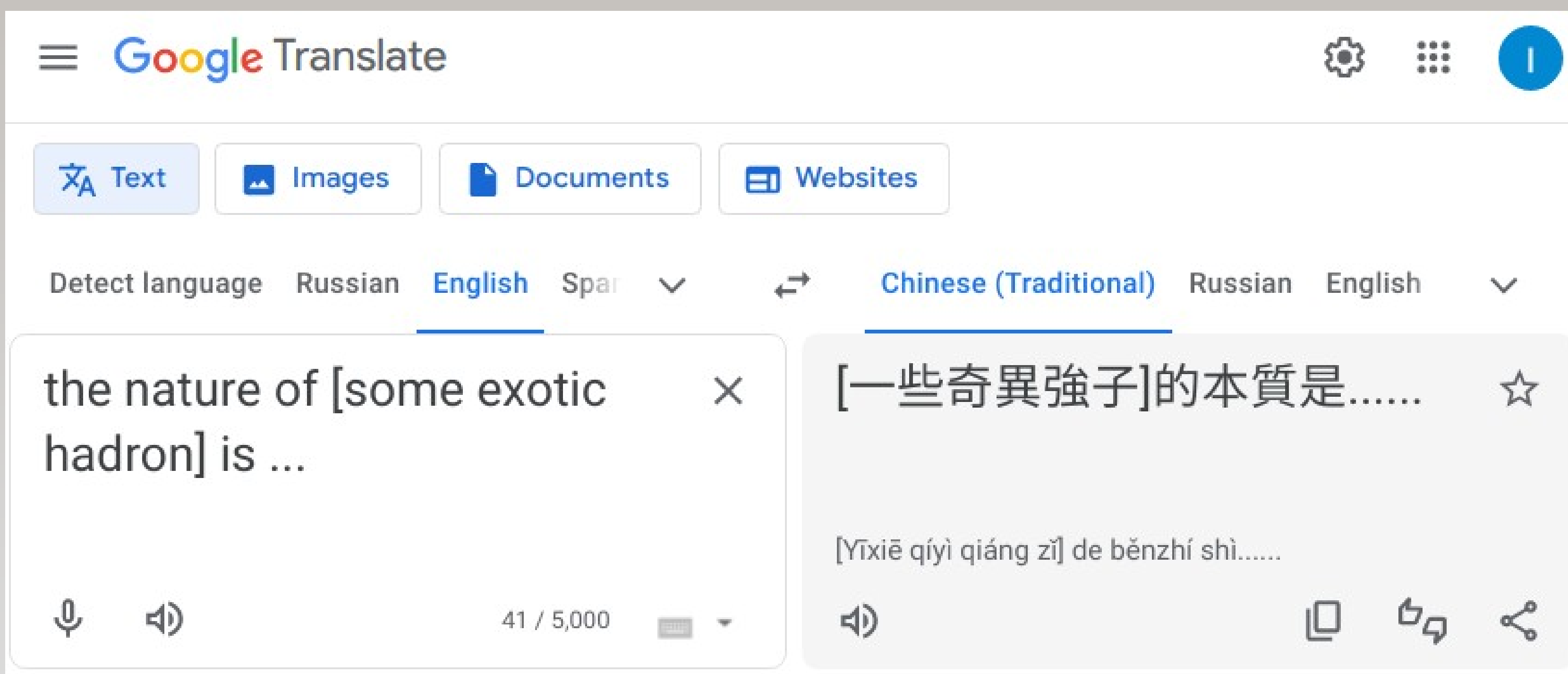
$$A(X \to \Psi\gamma) = \mathscr{F}\int d^3R\, d^3\xi\, d^3\eta\;\delta^3(\boldsymbol{\eta} + \boldsymbol{R} - \boldsymbol{\xi})e^{-i\frac{1}{2}\boldsymbol{k}\cdot(\boldsymbol{\xi}+\boldsymbol{\eta})}\,\psi(|\boldsymbol{R}|)\,\Psi(|\boldsymbol{R}|)\,\chi(|\boldsymbol{\xi}|)\,\chi(|\boldsymbol{\eta}|)$$

$R_{\psi\gamma}$>0.95 (up to 12)

Reflections







Summary of theory predictions

LHCb-PAPER-2024-015, in prep.

Reference		$\mathscr{R}_{\psi\gamma}$	
T. Barnes and S. Godfrey	[67]	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson	[69]	2.6	$c\bar{c}$
B.-Q. Li and K. T. Chao	[82]	1.3	$c\bar{c}$
Y. Dong *et al.*	[83]	$1.3 - 5.8$	$c\bar{c}$
A. M. Badalian *et al.*	[84]	(0.8 ± 0.2)	$c\bar{c}$
J. Ferretti, G. Galata and E. Santopinto	[85]	6.4	$c\bar{c}$
A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker	[86]	2.4	$c\bar{c}$
W. J. Deng *et al.*	[87]	1.3	$c\bar{c}$
F. Giacosa, M. Piotrowska and S. Goito	[71]	5.4	$c\bar{c}/\mathrm{vc}$
E. S. Swanson	[81]	3.8 ‰	$D\bar{D}^*$
Y. Dong *et al.*	[83]	3.3 ‰	$D\bar{D}^*$
D. P. Rathaud and A. K. Rai	[88]	0.25	$D\bar{D}^*$
R. F. Lebed and S. R. Martinez	[89]	3.3 ‰	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	[90]	3.6 %	$D\bar{D}^*$
S. Takeuchi, M. Takizawa and K. Shimizu	[91]	$1.1 - 3.4$	$D\bar{D}^*$
E. Cincioglu *et al.*	[92]	< 4	$D\bar{D}^*$
D. A.-S. Molnar, R. F. Luiz and R. Higa	[93]	$2 - 10$	$D\bar{D}^*$
F.-K. Guo *et al.*	[94]	$0.21(g_2'/g_2)^2$	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	[90]	$> \left(0.95^{+0.01}_{-0.07}\right)$	$c\bar{c}q\bar{q}$

$R_{\psi\gamma}>1$

$R_{\psi\gamma}\ll 1$

$R_{\psi\gamma}\sim 1$

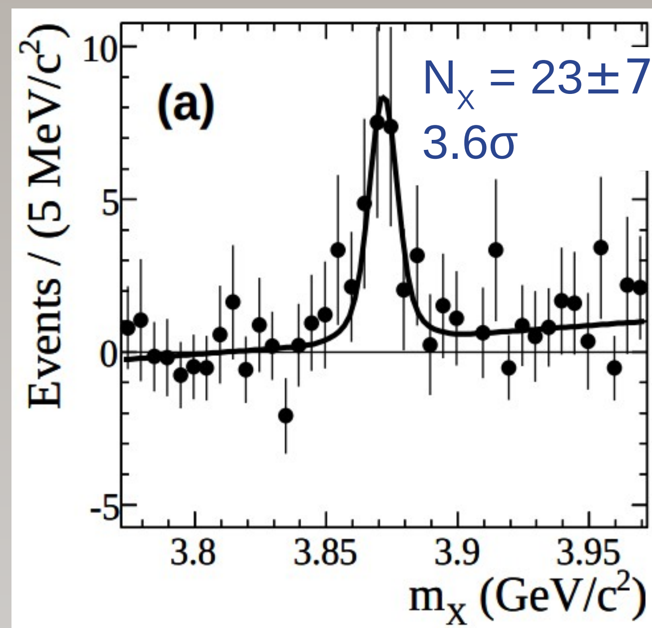
$R_{\psi\gamma}\gtrsim 1$

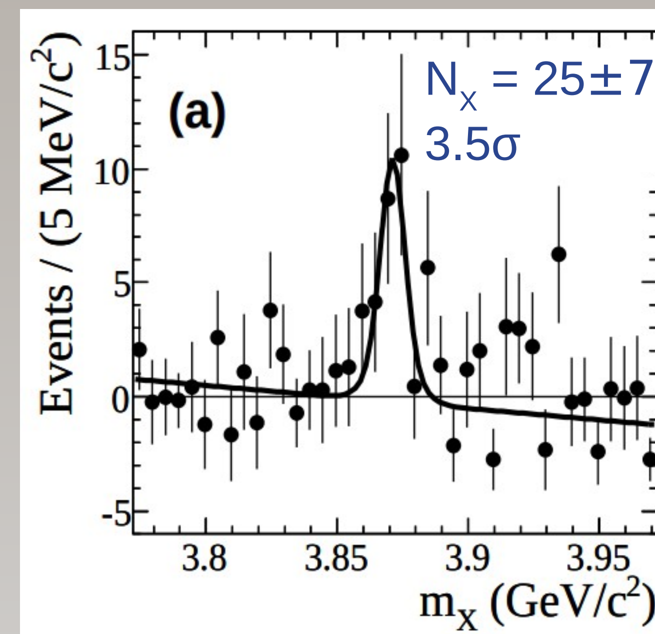
- $c\bar{c}$ + $D\bar{D}^*$ admixture can reproduce any value in between

Evidences for $\chi_{c1}(3872) \to \psi(2S)\gamma$

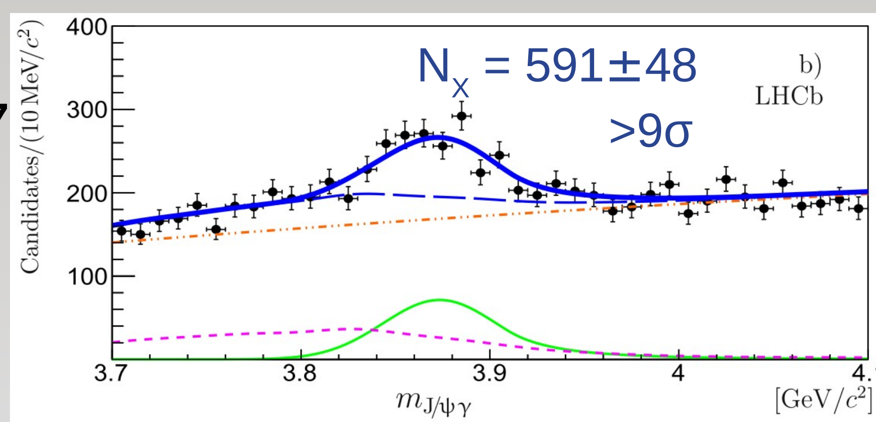
J/ψγ mode   ψ(2S)γ mode

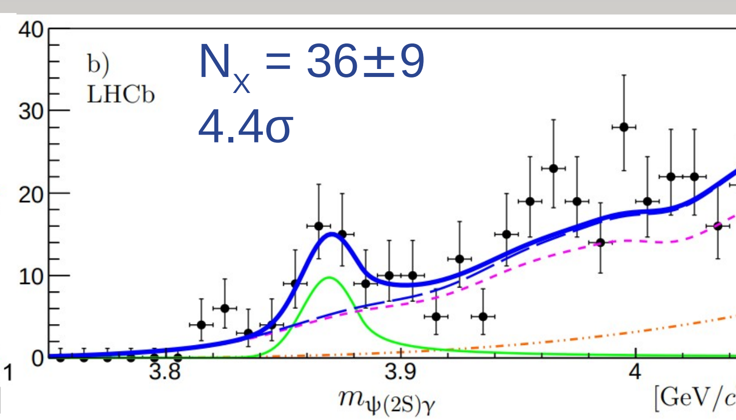
BaBar (2009)
$R_{\psi\gamma} = 3.4 \pm 1.4$
PRL 102 (2009) 132001





LHCb (2014)
$R_{\psi\gamma} = 2.5 \pm 0.7$
NPB 886 (2014) 665





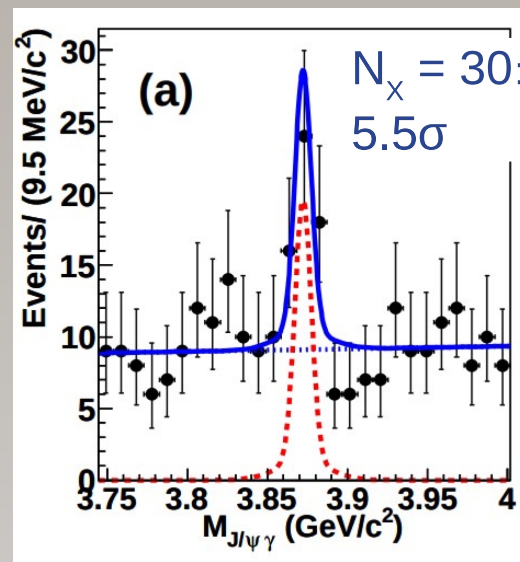
Non-observations of $\chi_{c1}(3872) \to \psi(2S)\gamma$

$J/\psi\gamma$ mode | $\psi(2S)\gamma$ mode

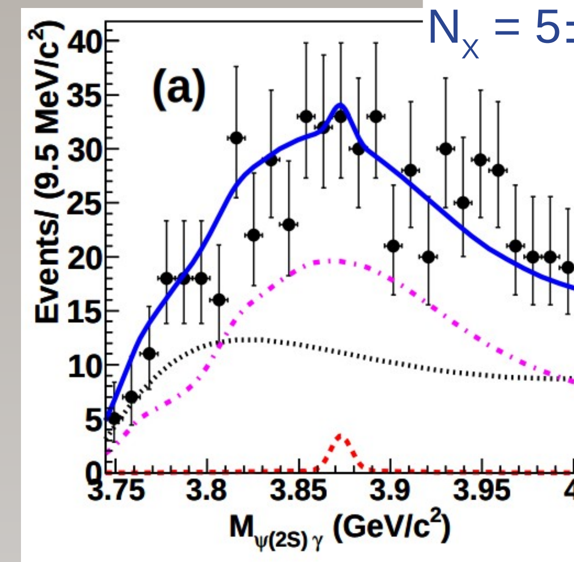
Belle (2011)

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

PRL 107 (2011) 091803



$N_X = 30 \pm 8$
5.5σ



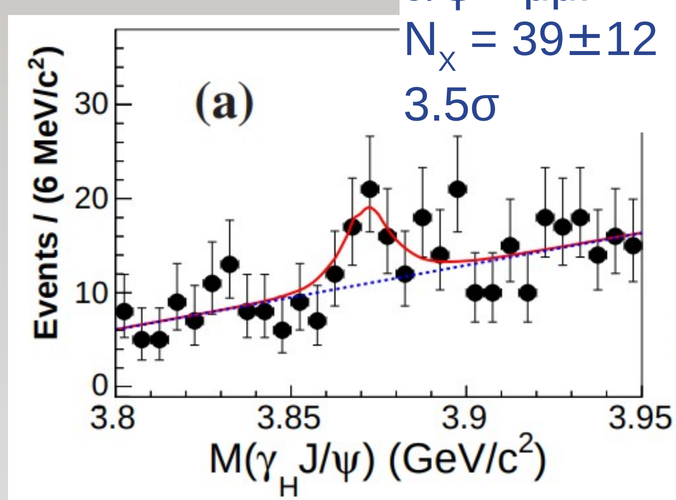
$N_X = 5 \pm 12$

BESIII (2020)

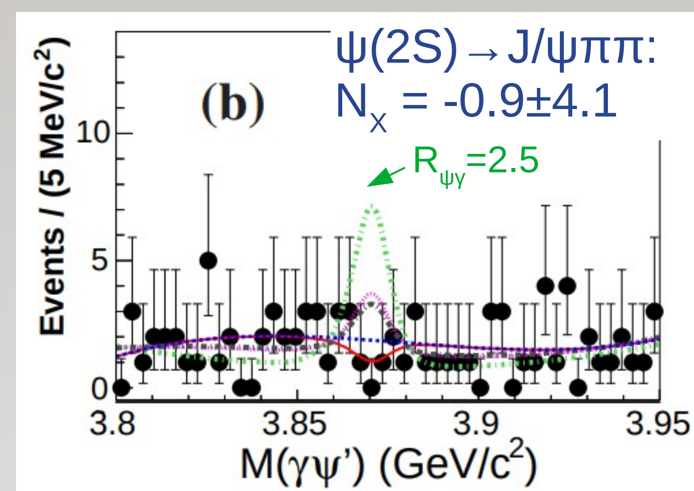
$R_{\psi\gamma} < 0.59$ (90% CL)

PRL 124 (2020) 242001

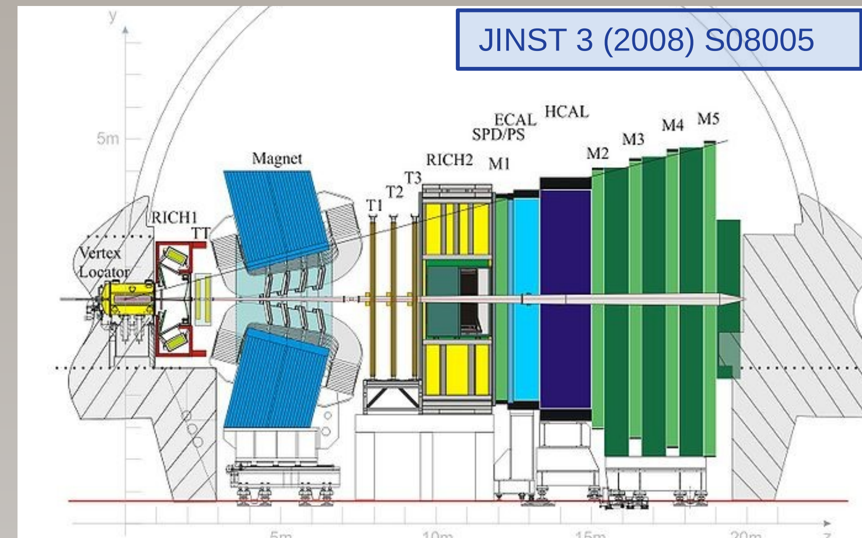
$J/\psi \to \mu\mu$:
$N_X = 39 \pm 12$
3.5σ



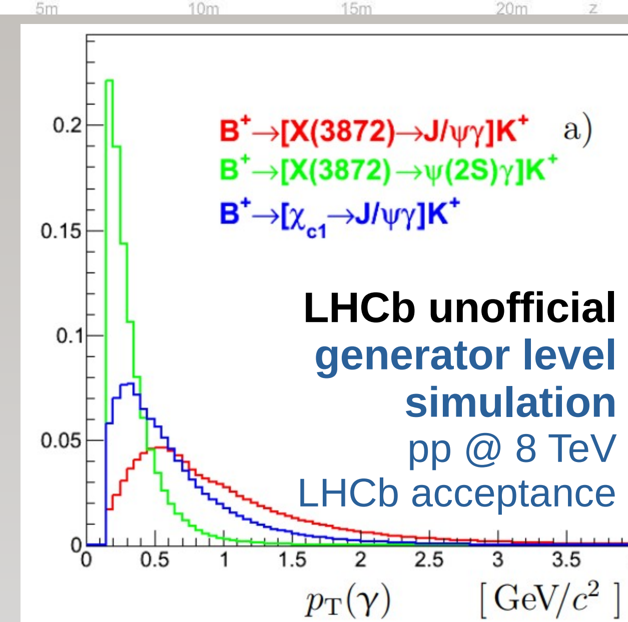
$\psi(2S) \to J/\psi\pi\pi$:
$N_X = -0.9 \pm 4.1$



Specifics of LHCb



- Excellent in reconstructing B-decays, ECAL resolution: $1\,\% \oplus \frac{10\,\%}{\sqrt{E/GeV}}$
- Use $B^+ \to \chi_{c1}(3872)[\to \psi\gamma]K^+$ decay
- High background from prompt $\pi^0 \to \gamma\gamma$: O(100) photons per event
  - Especially critical for $\chi_{c1}(3872) \to \psi(2S)\gamma$ mode due to softer photon
  - Noticeably enhanced with 7 TeV (2011) $\to$ 8 TeV (2012) $\to$ 13 TeV (2015-2018) increase in pp collision energy



New measurement

LHCb-PAPER-2024-015, in prep.

	Run 1	Run 2	Total Lumi
LHCb 2014 measurement	7 TeV (1 fb^{-1}) + 8 TeV (2 fb^{-1})		3 fb^{-1}
New measurement	7 TeV (1 fb^{-1}) + 8 TeV (2 fb^{-1})	13 TeV (6 fb^{-1})	9 fb^{-1}

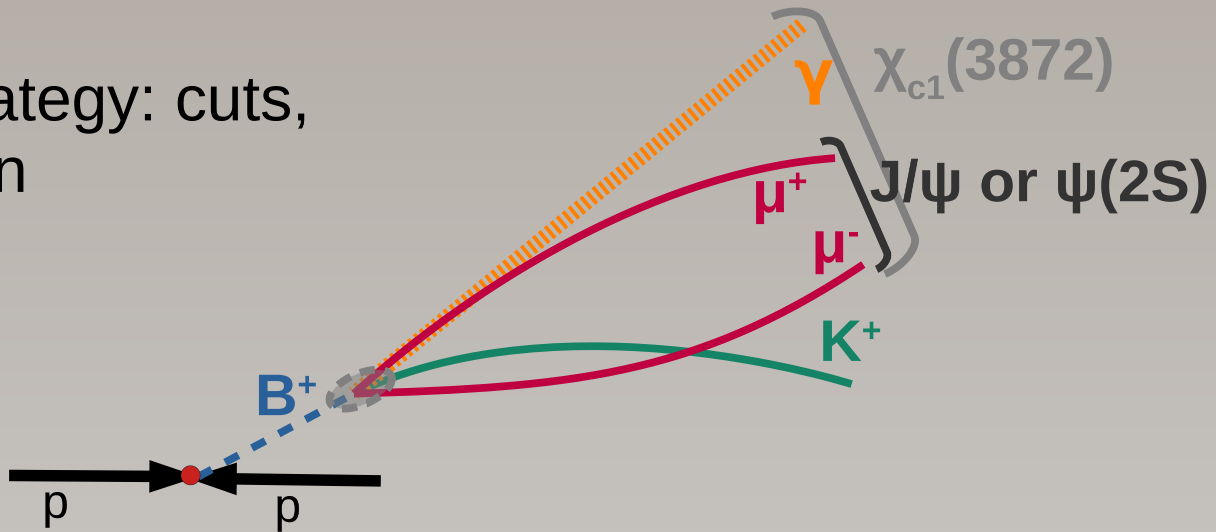
same data sample

~2x higher B production cross-section

but also higher backgrounds

Selection

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



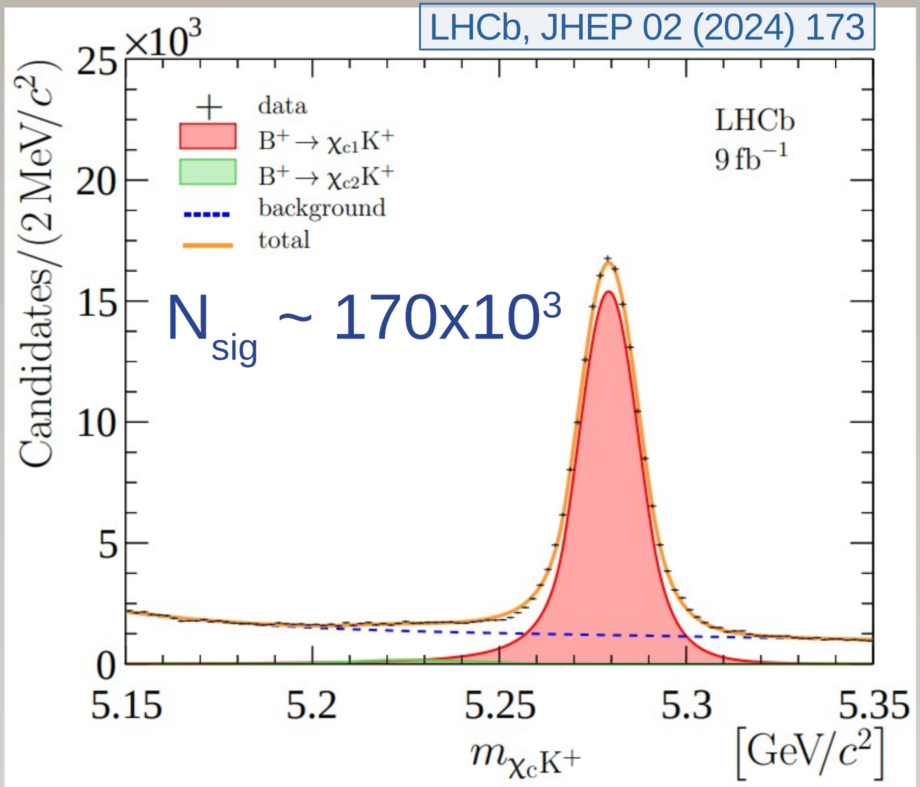
- New strategy: loose cut preselection + MLP *(Multi-Layered Perceptron)* separate for J/ψ and $\psi(2S)$ modes, Run1 and Run2
  - kinematics & geometry [8 vars]
  - decay chain & vertex quality [5 vars]
  - track reconstruction & identification quality [2 vars]
  - photon reconstruction quality [1 var]

  → 16 variables, $p_T(\gamma)$ is of highest importance

- Optimize $S/\sqrt{S+B}$ using simulation for signal and sideband data for background

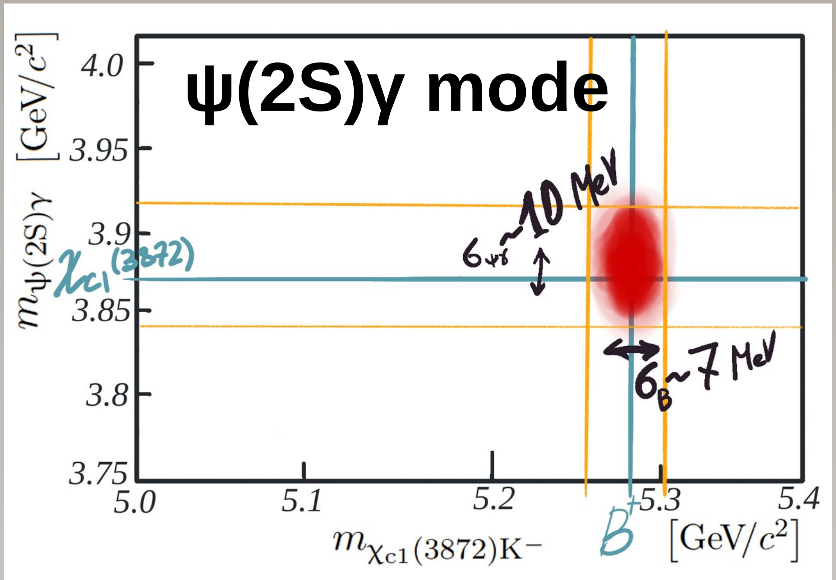
$B^+ \to \chi_{c1}[\to J/\psi\gamma]K^+$ as standard candle

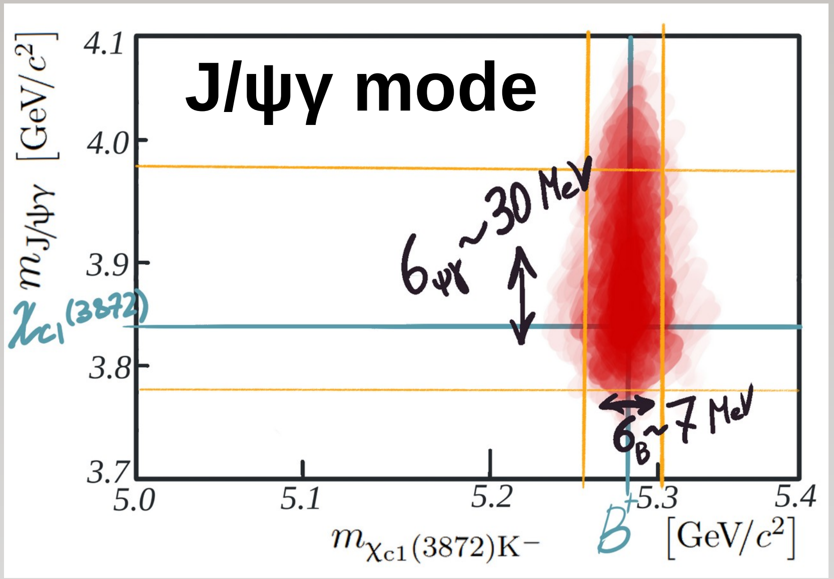
- Same decay topology, similar kinematics, huge statistics
- Cross-check performance for reconstruction and selection
- Calibrate mass resolution and mass scale
- Investigate data-MC agreement for efficiency



Signal (fit function)

- Signal: S_B x S_X
  - *S_B – Double Sided Crystall Ball (DSCB)*
  - *S_X – DSCB + split (asymmetric) Gaussian*
- Use kinematic fit with vertex and $\psi \to \mu^+\mu^-$ mass constraints to improve $m_{\psi\gamma}$ mass resolution
- Use additional $X \to \psi\gamma$ mass constraint for $m_B = m_{\psi\gamma K}$
- Correction factors on mass resolution from the $B^+ \to \chi_{c1}[\to J/\psi\gamma]K^+$ channel:
  - 1.102±0.004 for σ_B
  - 1.027±0.004 for $\sigma_{\psi\gamma}$



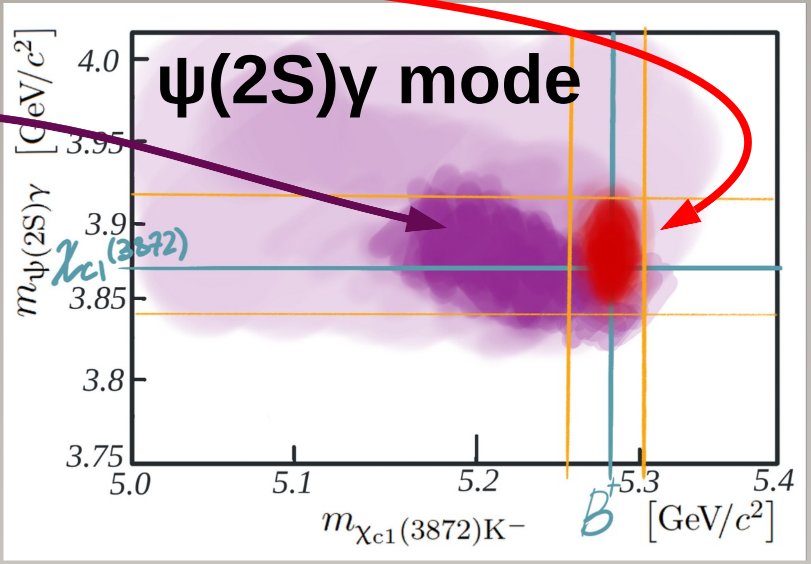


Backgrounds

- Signal final state: **$\psi\gamma K^+$**
- $\psi(2S)$ mode:
  - $B \to$ **$\psi(2S)K^+$**X + **γ**

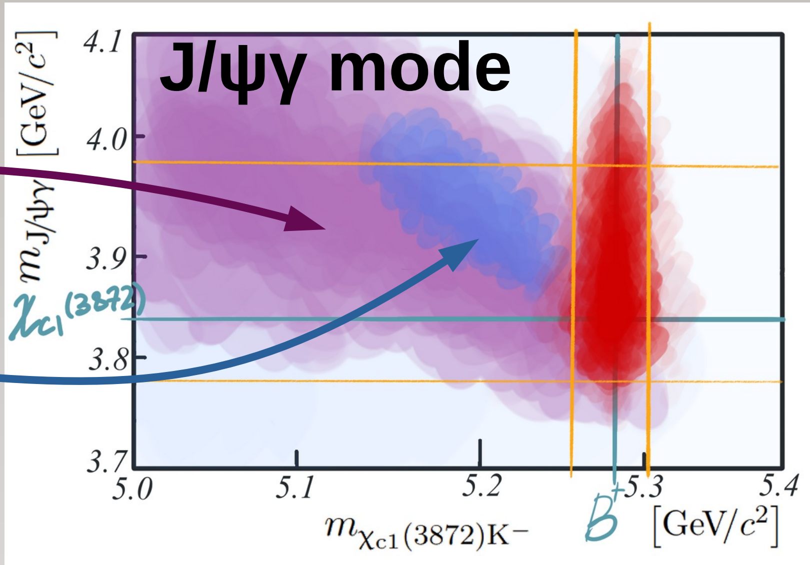
    with intermediate K^*, $K_0^*(700)$, $K_1(1270)$, $K^*(1410)$, $K_2^*(1430)$, $K^*(1680)$
    and non-resonant $\psi(2S)K^+\pi$, $\psi(2S)K^+\pi\pi$, $\psi(2S)K^+\eta$, $\psi(2S)K^{*+}\eta$, $\psi(2S)K^+\omega$

    improved model



- J/ψ mode:
  - $B^+ \to$ **J/ψ**K^{*+}(**K^+**$\pi^0(\to$ **γ**γ))
  - Additional unidentified $B^+ \to$ **J/ψ**K^+X

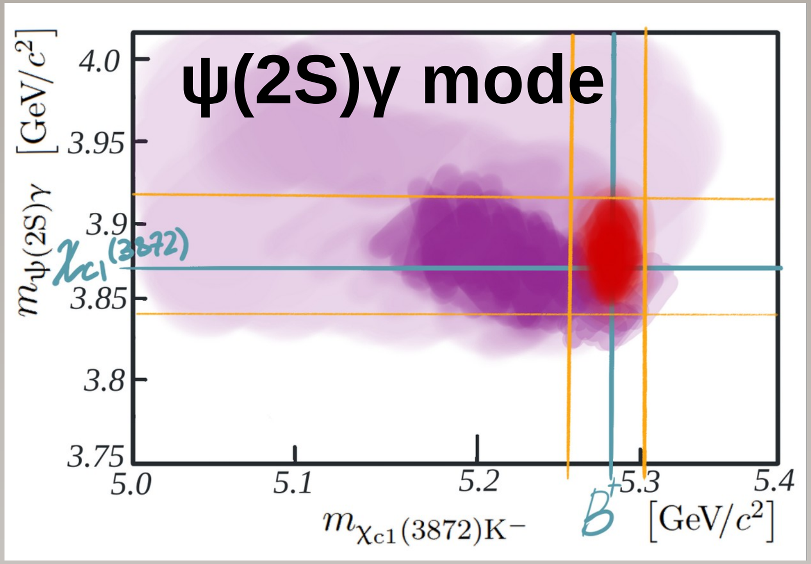
    new

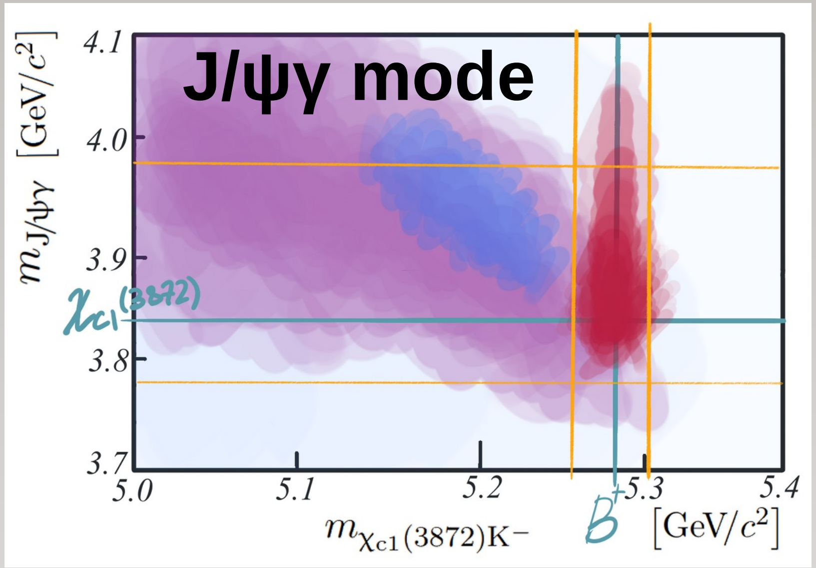


- Investigate shape with simulation

Overall fit function

- Components:
  - Signal: S_B x S_X
  - Partially reconstructed $B \to \psi(2S)KX$ or $B \to J/\psi K^{*+}$ decays (simulation, 2D Legendre pol.)
  - In J/ψ mode:
    - additional $B \to J/\psi KX$ (2D Gaussian function)
    - non-B background: $const_B$ x S_X
  - Combinatorial background – 2D polynomial (9/16 parameters)





- Simultaneous fit to 4 samples: Run1/2 ⊗ J/ψ / ψ(2S) shared B and $\chi_{c1}(3872)$ mass position and resolution

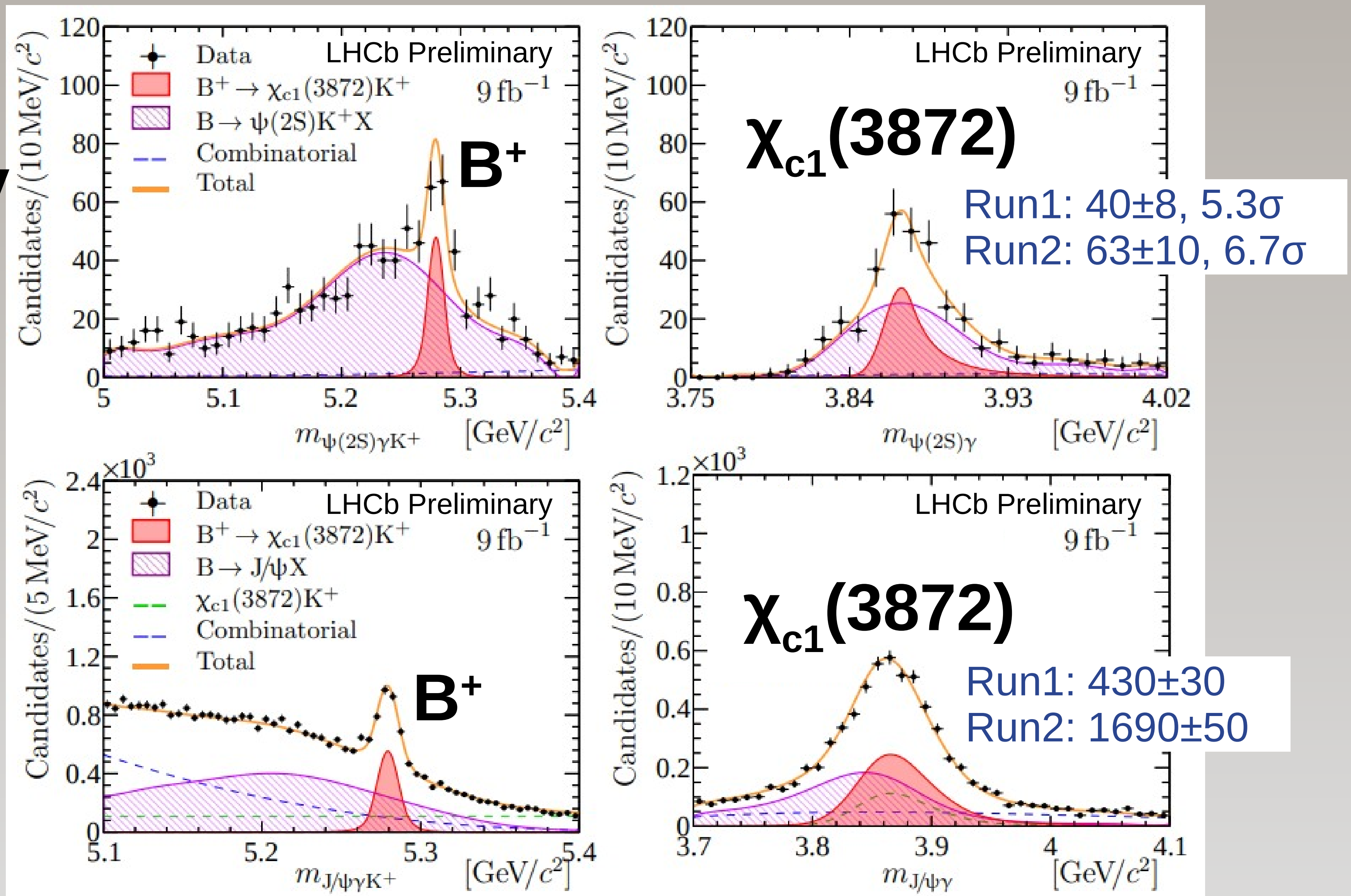
First observation of $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$

- Projections in signal regions

LHCb-PAPER-2024-015, in prep.

ψ(2S)γ mode

J/ψγ mode



Systematic uncertainties

- Cancel in the ratio to a large extent

Source	Data-taking period Run 1	Run 2
Fit model		
Signal and combinatorial background	$^{+5.7}_{-0.1}$	$^{+4.4}_{-2.0}$
$B \to \psi(2S)K^+X$ background		
Parameterisation	$^{+1.6}_{-4.9}$	$^{+5.0}_{-2.9}$
Composition	0.9	1.9
Simulation sample size	4.2	4.3
Additional components	$^{+0.6}_{-4.4}$	$^{+1.2}_{-2.6}$
B^+ meson kinematics	< 0.1	< 0.1
Track reconstruction	< 0.1	< 0.1
Photon reconstruction	1.1	1.1
Kaon identification	1.0	1.3
Trigger	1.1	1.1
Data-simulation (dis)agreement	1.0	$^{+1.0}_{-1.5}$
Simulation sample size for efficiency	2.3	1.4
Total	$^{+8.0}_{-9.2}$	$^{+8.7}_{-7.9}$

Understanding of background sources and shapes

checked on data:
$B^+ \to J/\psi K^+$
$J/\psi \to \mu^+\mu^-$
$B^+ \to J/\psi K^{*+}[\to K^+\pi^0]$
$D^{*+} \to D^0[\to K^-\pi^+]\pi^+$
$B^+ \to J/\psi(\psi(2S))K^+$
$B^+ \to \chi_{c1}[\to J/\psi\gamma]K^+$

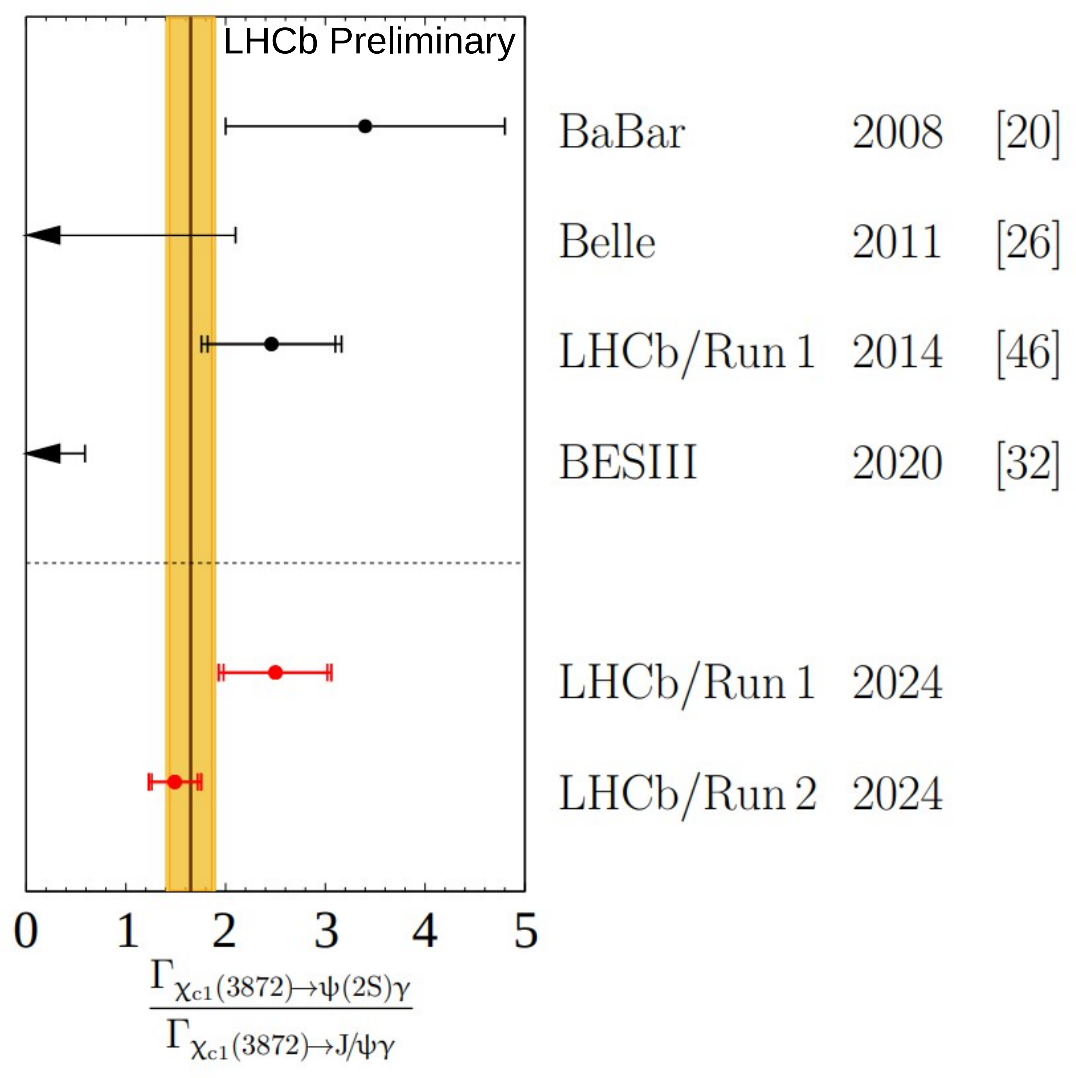
LHCb-PAPER-2024-015, in prep.

Results

- LHCb/Run1 2014 measurement:

  $R_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29$

  NPB 886 (2014) 665



- New measured BR ratios:

$$\mathscr{R}_{\psi\gamma}^{\mathrm{Run\,1}} = 2.50 \pm 0.52\,^{+0.20}_{-0.23} \pm 0.06$$
$$\mathscr{R}_{\psi\gamma}^{\mathrm{Run\,2}} = 1.49 \pm 0.23\,^{+0.13}_{-0.12} \pm 0.03$$

- Run1&2 average:

$$\mathscr{R}_{\psi\gamma} = 1.67 \pm \underbrace{0.21}_{stat} \pm \underbrace{0.12}_{syst} \pm \underbrace{0.04}_{BR(\psi\to l^+l^-)}$$

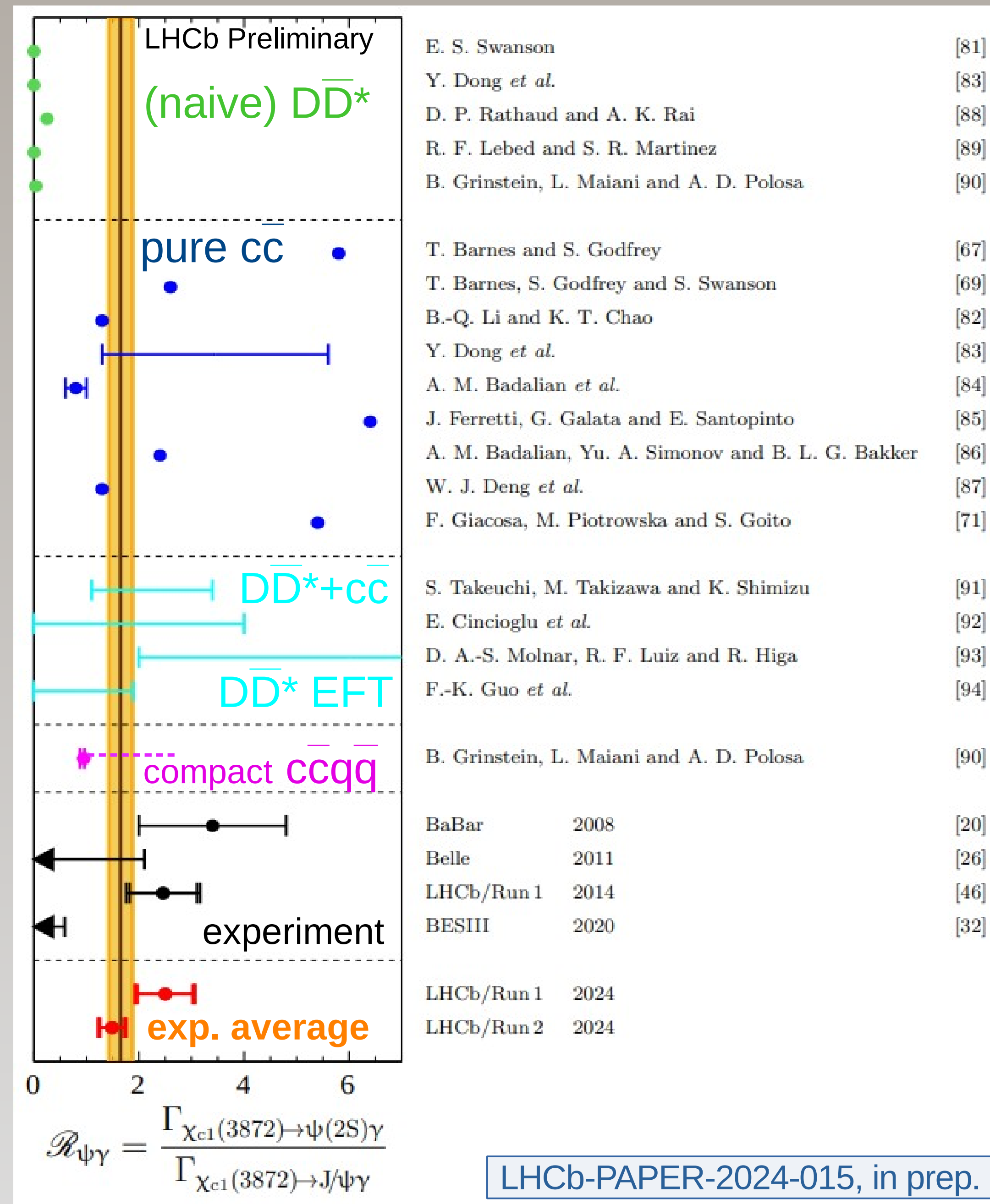
LHCb-PAPER-2024-015, in prep.

Carry-on message

- $R_{\psi\gamma}$~1.7 carries information about the χ_{c1}(3872) nature

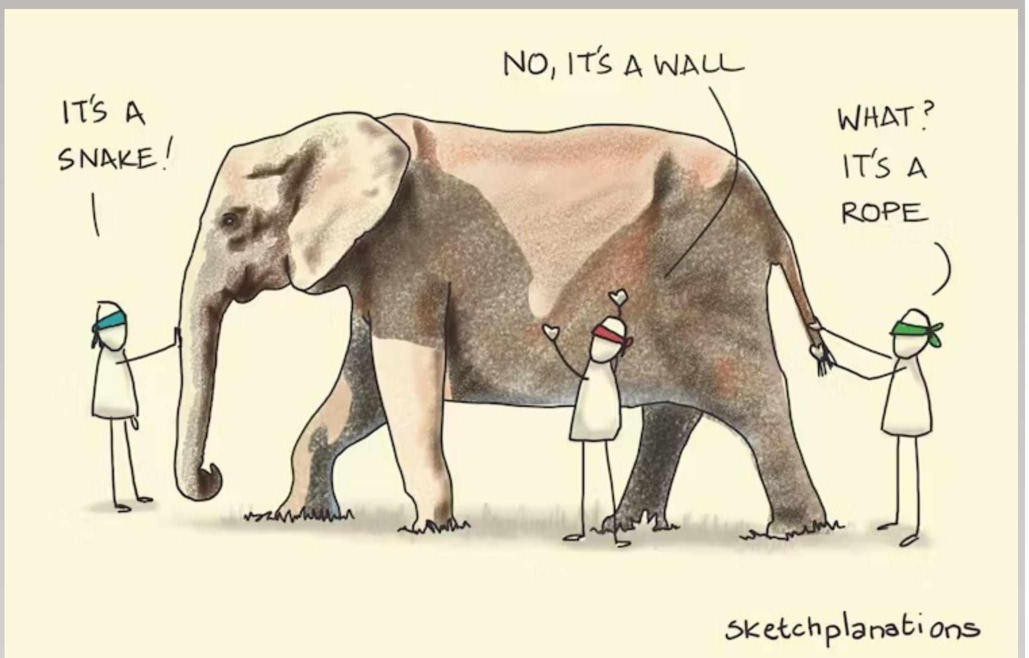
- Likely sign of pure charmonium or compact $c\bar{c}q\bar{q}$ component

  … but ambiguities in theory interpretations need to be clarified first

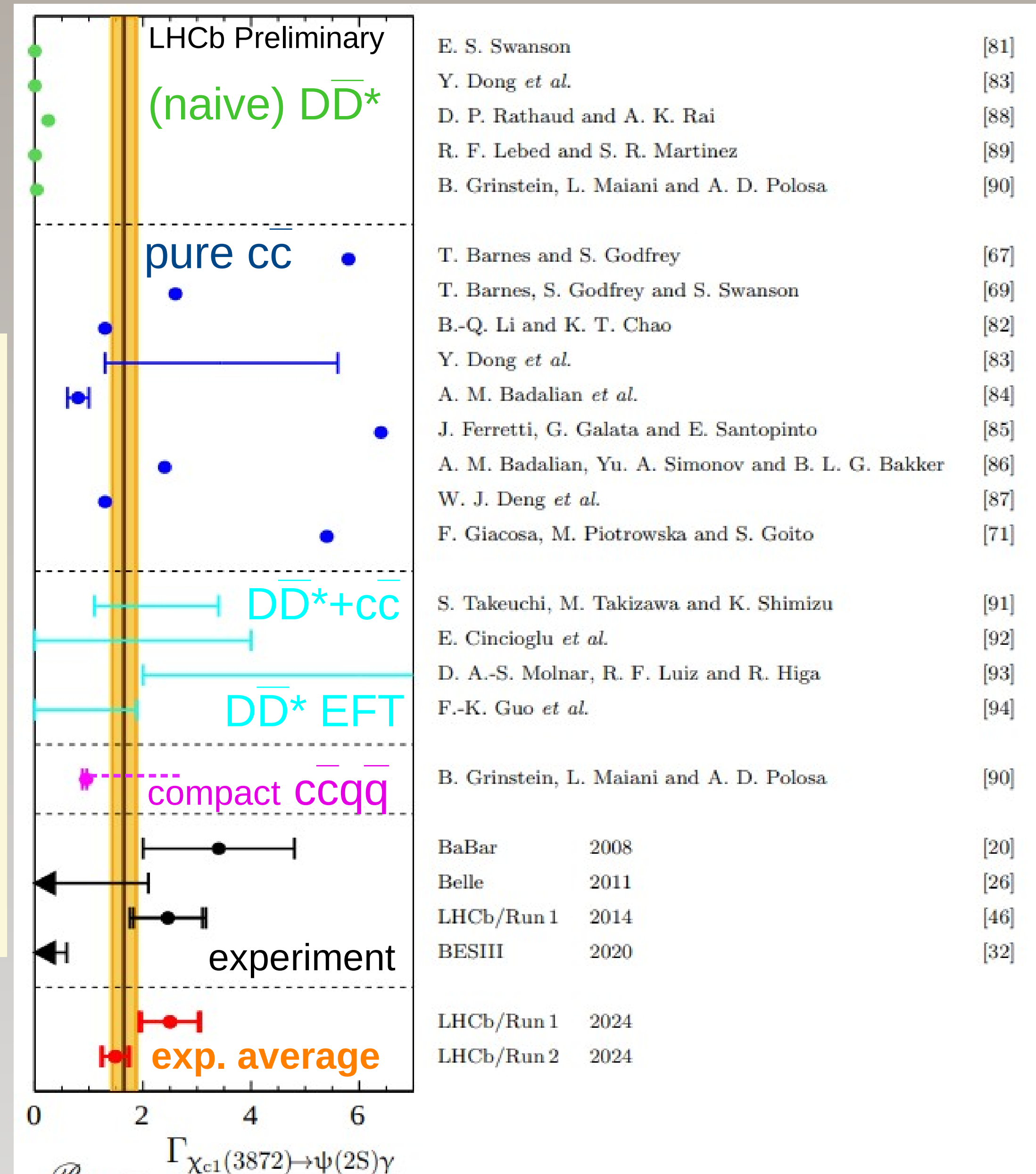


Carry-on message

- $R_{\psi\gamma}$~1.7 carries information about the $\chi_{c1}(3872)$ nature



… waiting for model unification



LHCb-PAPER-2024-015, in prep.

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

LHCb-TDR-023

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

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

  LHCb-TDR-024

- 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

LHCb meets Theory: Probing the nature of the $X(3872)$ state using radiative decays

Thursday 27 Jun 2024, 09:30 → 19:30 Europe/Zurich

17/1-007 (CERN)

Lorenzo Capriotti (Universita e INFN, Ferrara (IT)), Mengzhen Wang (Università degli Studi e INFN Milano (IT)), Vanya Belyaev (Sapienza Universita e INFN, Roma I (IT))

Description

This is a traditional mini-worshop "LHCb meets Theory". Previous editions of this workshop were devoted to studies of charm abd beauty baryons,, double-heavy baryons, lineshape of the X(3872) state, double open charm tetraquark T^+_{cc}, prospects for the T_{bc} and T_{bb} tetraquarks and many other hot items, interesting both for the LHCb and Theory.

This edition is devoted to probing of the nature of the $X(3872)$ state using radiative decays. The nature of the $X(3872)$ state is a subject of hot discussinon and intensive studies for more than twenty years. Radiative decays, namely the ratio of the partial widths of the $X(3872)$ decays into the $\psi'\gamma$ and $J/\psi\gamma$ final state potentially could shed light on the nature of the $X(3872)$ state, since the predicted ratio of radiative width is very sensitive to the assumed $X(3872)$ structure. The experimental situation (May 2024) is rather controversial, and there is no theory consensus. This worskhop provide the opportunity to discuss both theoretical and experiemtnal issues.

The agenda is being evolving and the talk titles, timeslots, durations and speakers are indicative only.

Workshop is planned to be in the hybrid format. For those who is in person at CERN the room is booked, Please register - it wil lhelp us to rebook the room if needed.

Videoconference

zoom Workshop on radiative decays of the X(3872) Join

Registration

Participants 13 Register

Participants

E Eric Swanson, J Jingqing Zhang, L Lorenzo Capriotti, L luciano maiani, M Makoto Takizawa, M Mengzhen Wang, R Richard Lebed, S Sachiko Takeuchi, S Sourabh Chutia, V Vanya Belyaev, +3

Appendix

Fit results

Parameter		Data-taking period Run 1	Run 2
$\psi(2S)\gamma K^+$			
$N_{B^+\to(\chi_{c1}(3872)\to\psi(2S)\gamma)K^+}$		40 ± 8	63 ± 10
$N_{B\to\psi(2S)K^+X}$		567 ± 24	885 ± 29
N_{comb}		55 ± 17	132 ± 19
$J/\psi\gamma K^+$			
$N_{B^+\to(\chi_{c1}(3872)\to J/\psi\gamma)K^+}$	$[10^3]$	0.43 ± 0.03	1.69 ± 0.05
$N_{B\to J/\psi X}$	$[10^3]$	3.61 ± 0.11	18.72 ± 0.26
$N_{\chi_{c1}(3872)K^+}$	$[10^3]$	1.18 ± 0.06	5.53 ± 0.23
N_{comb}	$[10^3]$	4.05 ± 0.11	17.46 ± 0.21
$\mathscr{S}_{\chi_{c1}(3872)\to\psi(2S)\gamma}$		5.3σ	6.7σ

LHCb-PAPER-2024-015

Efficiencies

LHCb-PAPER-2024-015

$$\mathscr{R}_{\psi\gamma} = \frac{N_{B^+\to(\chi_{c1}(3872)\to\psi(2S)\gamma)K^+}}{N_{B^+\to(\chi_{c1}(3872)\to J/\psi\gamma)K^+}} \times \frac{\varepsilon_{B^+\to(\chi_{c1}(3872)\to J/\psi\gamma)K^+}}{\varepsilon_{B^+\to(\chi_{c1}(3872)\to\psi(2S)\gamma)K^+}} \times \frac{\mathcal{B}_{J/\psi\to\mu^+\mu^-}}{\mathcal{B}_{\psi(2S)\to\mu^+\mu^-}}\,, \qquad (5)$$

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/ψ case

- Peaking backgrounds:
  2D Legendre with n=12&13,
  2D histograms with various interpolations

  - variate BR's of $B \to \psi(2S)KX$ composition

  - pseudo-experiment to access finite sample size effect

- Additional $B \to X[\to \psi(2S)\gamma] + K$ or $B \to J/\psi\gamma K$ components

First exotic hadrons

- Were anticipated since 60's
- No success in light sector
  - First candidates for tetraquarks in 90's: $f_0(500)$, $K^*_0(800)$, … later $D^*_{sJ}(2317)$, ...
  - Pentaquark Θ^+ [$uudd\bar{s}$] in 2003

no clear conclusion reached due to large widths & theoretical ambiguities

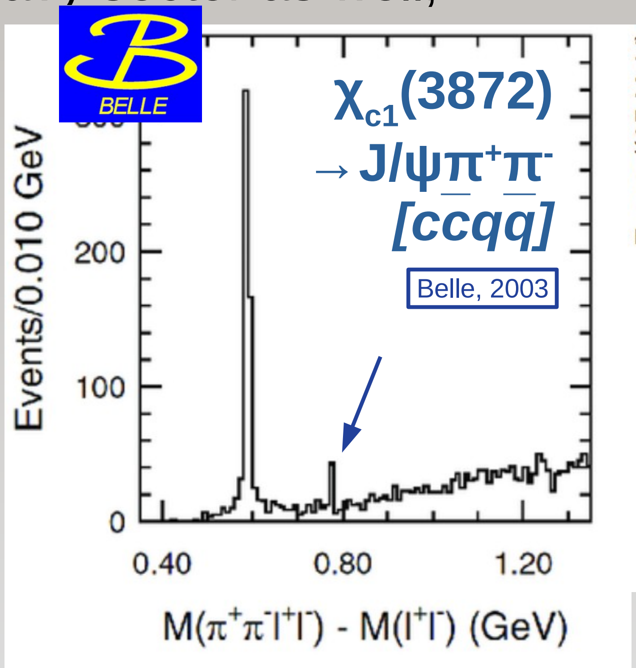
Fazio, 2004 | Eidelman, Gutsche, Hanhart, Mitchell, Spanier, 2020 (PDG)

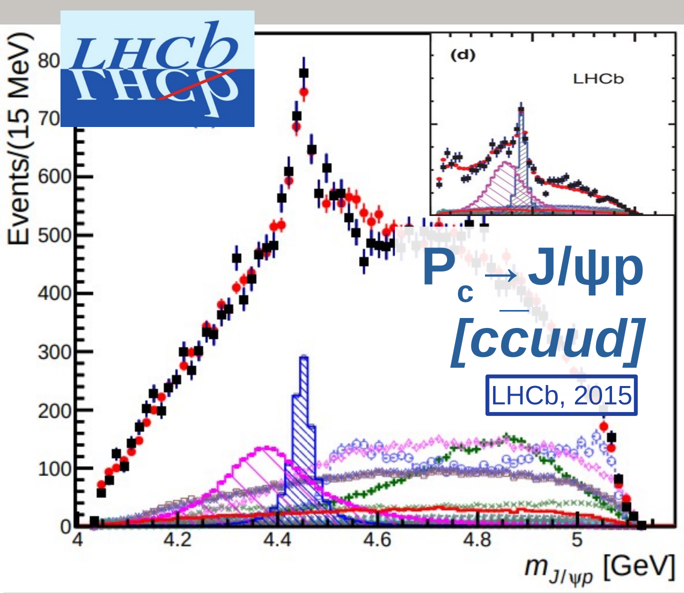
later shown to be false

Trilling, 2006 (PDG)

- 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)

charmonium

- Barnes, Godfrey, Swanson, Phys. Rev. D 69 (2004) 054008 & Phys. Rev. D 72 (2005) 054026;
- Eichten, Lane, Quigg, Phys. Rev. D69 (2004) 094019;
- Suzuki, Phys. Rev. D72 (2005) 606 114013;

compact tetraquark

- Maiani, Piccini, Polosa, Riquer, Phys. Rev. D71 (2005) 014028;
- Matheus, Narison, Nielsen, Richard, Phys. Rev. D75 (2007) 014005;

$D\bar{D}^*$ molecula

- Braaten, Kusunoki, Phys. Rev. D69 (2004) 074005;
- Swanson, Phys. Lett. B588 (2004) 189;
- Wong, Phys. Rev. C69 (2004) 055202;
- Tornquist, Phys. Lett. B590 (2004) 209;
- Hanhart, Kalashnikova, Kudryavtsev, Nefediev, Phys. Rev. D76 (2007) 034007

hadro-charmonium

- Dubynskiy, Voloshin, Phys. Lett. B666 (2008) 344;

hybrid

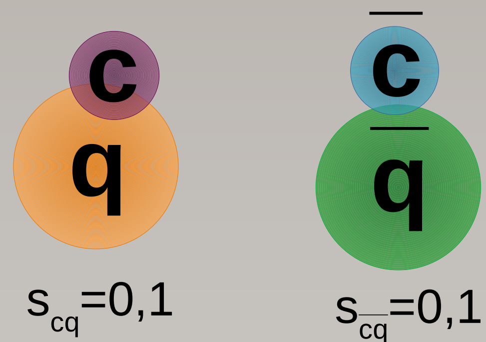
- Close, Godfrey, Phys. Lett. B574 (2003) 210;
- Li, Phys. Lett. B 605 (2005) 306;

admixture

- Suzuki, Phys. Rev. D72 (2005) 114013;
- Close, Page, Phys. Lett. B578 (2004) 119;
- Dong, Faessler, Gutsche, Lyubovitskij, J. Phys. G 38 (2011) 015001;

$\chi_{c1}(3872)$ partners

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



Overall possibilities for J^{PC}
$s_{cq}=0$ & $s_{\bar{c}\bar{q}}=0$: 0^{++}
$s_{cq}=0$ & $s_{\bar{c}\bar{q}}=1$: $\mathbf{1^{++}}$, 1^{+-}
$s_{cq}=1$ & $s_{\bar{c}\bar{q}}=1$: 0^{++}, 1^{+-}, 2^{++}

Maiani, Piccini, Polosa, Riquer, PRD 71 (2005) 014028

should be I=0 and I=1 states
→ charged $X(3872)^{\pm}$

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

$$BR(B^+ \to X(3872)^+ K^0)/BR(B^+ \to X(3872)K^+) < 0.5$$ Belle, PRD 84 (2011) 052004

can be easily accommodated by theory Maiani, Polosa, Riquer, PRD 102 (2020) 034017

$$0.05 < R^-_{2\pi} = \frac{\mathcal{B}(B^0 \to K^+ X(3872)^- \to K^+ J/\psi\ \pi^0\pi^-)}{\mathcal{B}(B^0 \to K^0 X(3872) \to K^0 J/\psi\ \pi^+\pi^-)} < 0.57$$

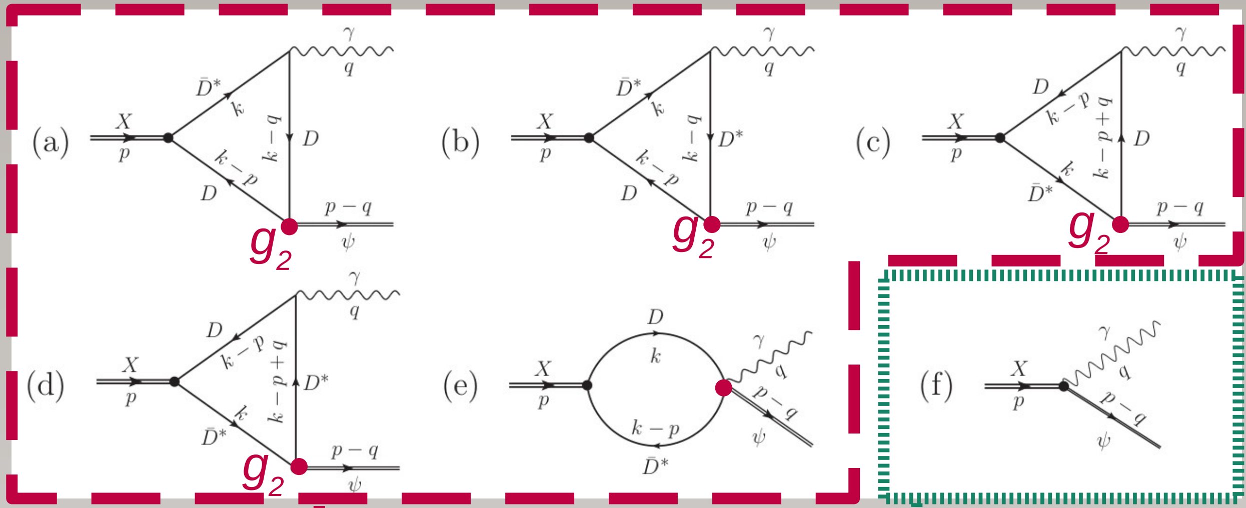
~~Molecula~~ EFT picture

- EFT theory with
  "dimension regularisation with the $\overline{MS}$ subtraction scheme at the scale μ"

Guo, Hanhart, Kalashnikova, Meissner, Nefediev, PLB 742 (2015) 394

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

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



+?

	$\mu = m_X/2$	$\mu = m_X$	$\mu = 2m_X$
$\Gamma(X \to \gamma J/\psi)$ [keV]	$9.7(r_x r_g)^2$	$23.5(r_x r_g)^2$	$43.2(r_x r_g)^2$
$\Gamma(X \to \gamma \psi')$ [keV]	$3.8(r_x r'_g)^2$	$4.9(r_x r'_g)^2$	$6.0(r_x r'_g)^2$
$R = \frac{\Gamma(X \to \gamma\psi')}{\Gamma(X \to \gamma J/\psi)}$	$0.39(g'_2/g_2)^2$	$0.21(g'_2/g_2)^2$	$0.14(g'_2/g_2)^2$

+ 200 keV
+ 10 keV

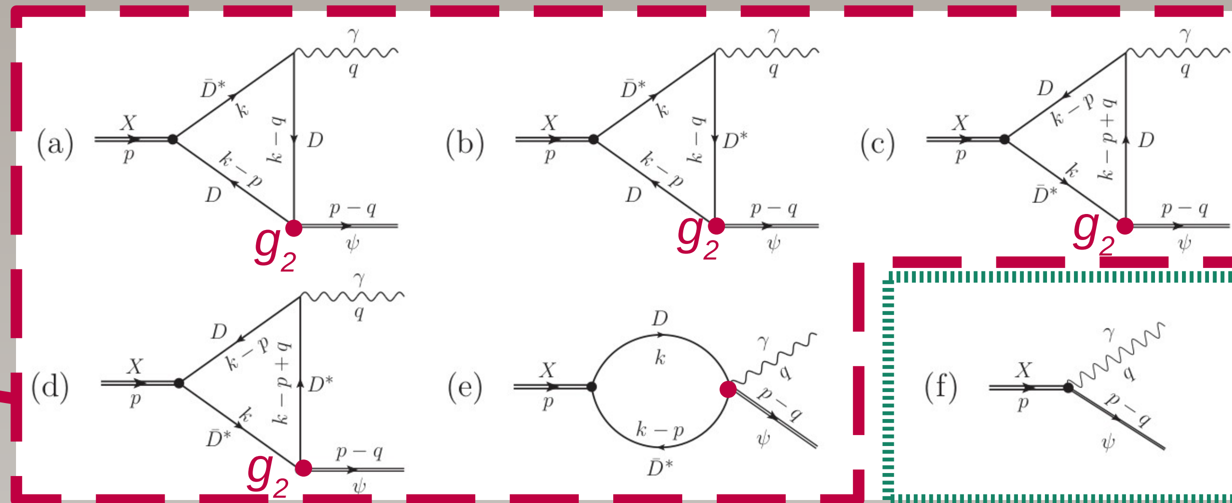
R = 0.07 ?

- Molnar, Luis, Higa, arxiv:1601.03366 get contradicting results while using ~ same method

g_2 in EFT picture

Guo, Hanhart, Kalashnikova, Meissner, Nefediev, PLB 742 (2015) 394

$R_{\psi\gamma} \sim 0.2\,(\mathbf{g_2^{\psi(2S)}/g_2^{J/\psi}})^2$



"loop" processes

"contact" process

- Is $\mathbf{g_2^{\psi(2S)}/g_2^{J/\psi} \sim 1}$ a reasonable assumption?
- According to Dong et al, arxiv:0909.0380 it is $\dfrac{g_{\psi(2S)DD}}{g_{J/\psi DD}} = \dfrac{g_{\psi(2S)D^*D^*}}{g_{J/\psi D^*D^*}} = \dfrac{m_{\psi(2S)}}{m_{J/\psi}}\,\dfrac{f_{J/\psi}}{f_{\psi(2S)}} \simeq 1.67$

$$g_{\psi_n DD} = g_{\psi_n D^* D^*}\frac{m_D}{m_{D^*}} = g_{\psi_n DD^*} m_{\psi_n}\sqrt{\frac{m_D}{m_{D^*}}} = \frac{m_{\psi_n}}{f_{\psi_n}}\,. \quad (13)$$

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

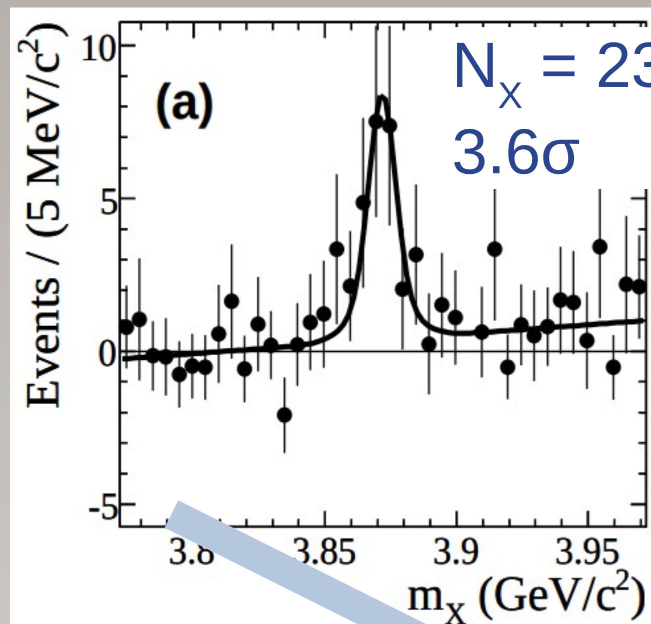
$$\Gamma(J/\psi \to e^+e^-) = \frac{16\pi}{27}\frac{\alpha^2}{m_{J/\psi}} f^2_{J/\psi} = 5.55 \text{ keV}\,,$$
$$\Gamma(\psi(2S) \to e^+e^-) = \frac{16\pi}{27}\frac{\alpha^2}{m_{\psi(2S)}} f^2_{\psi(2S)} = 2.38 \text{ keV}\,, \quad (14)$$

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

- but ~0.3 according to Grinstein, Maiani, Polosa, arXiv:2401.11623

$\chi_{c1}(3872) \to J/\psi\gamma$. BaBar & BESIII overlay

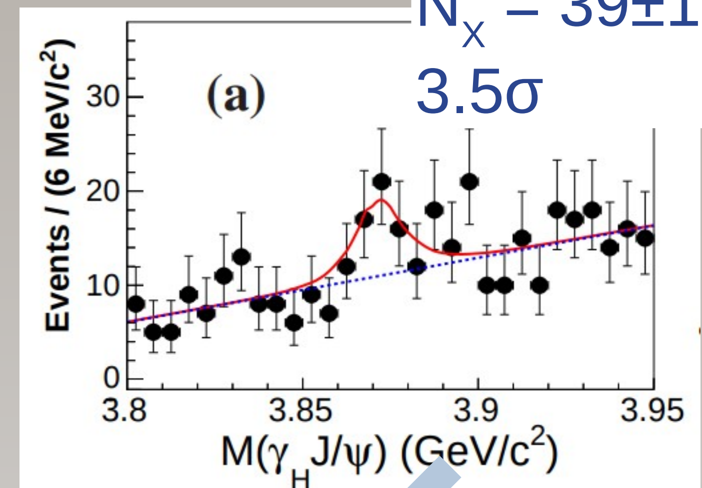
BaBar (2009)



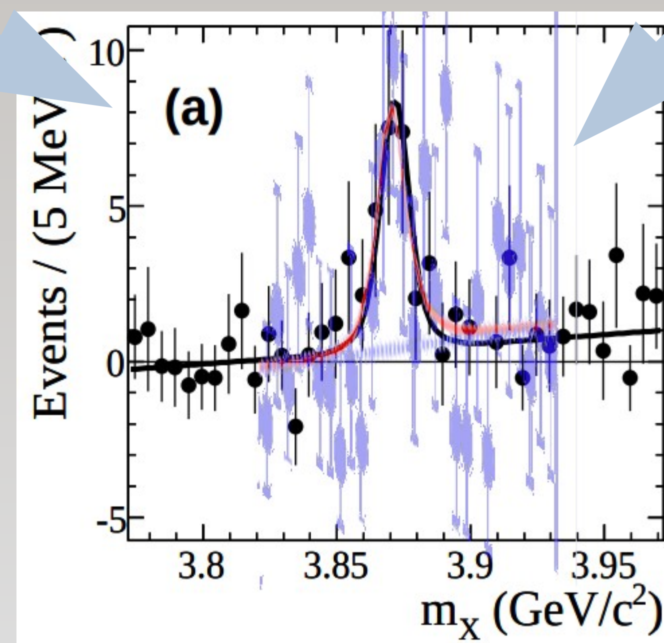
$N_X = 23 \pm 7$
3.6σ

BESIII (2020)

$J/\psi \to \mu\mu$:
$N_X = 39 \pm 12$
3.5σ



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



BaBar
BESIII