Probing of the nature of the $\chi_{c1}(3872)$ state with radiative decays

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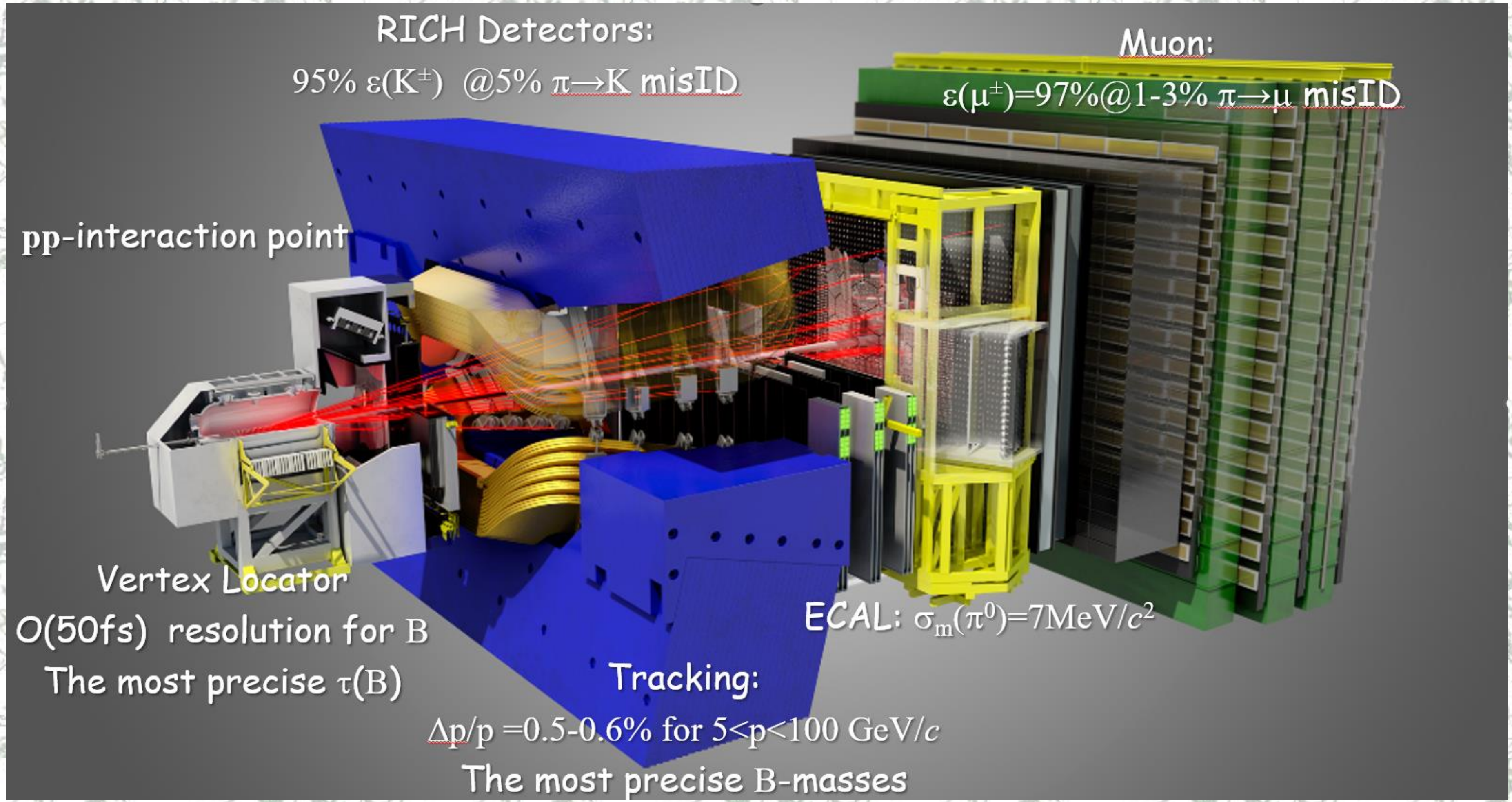
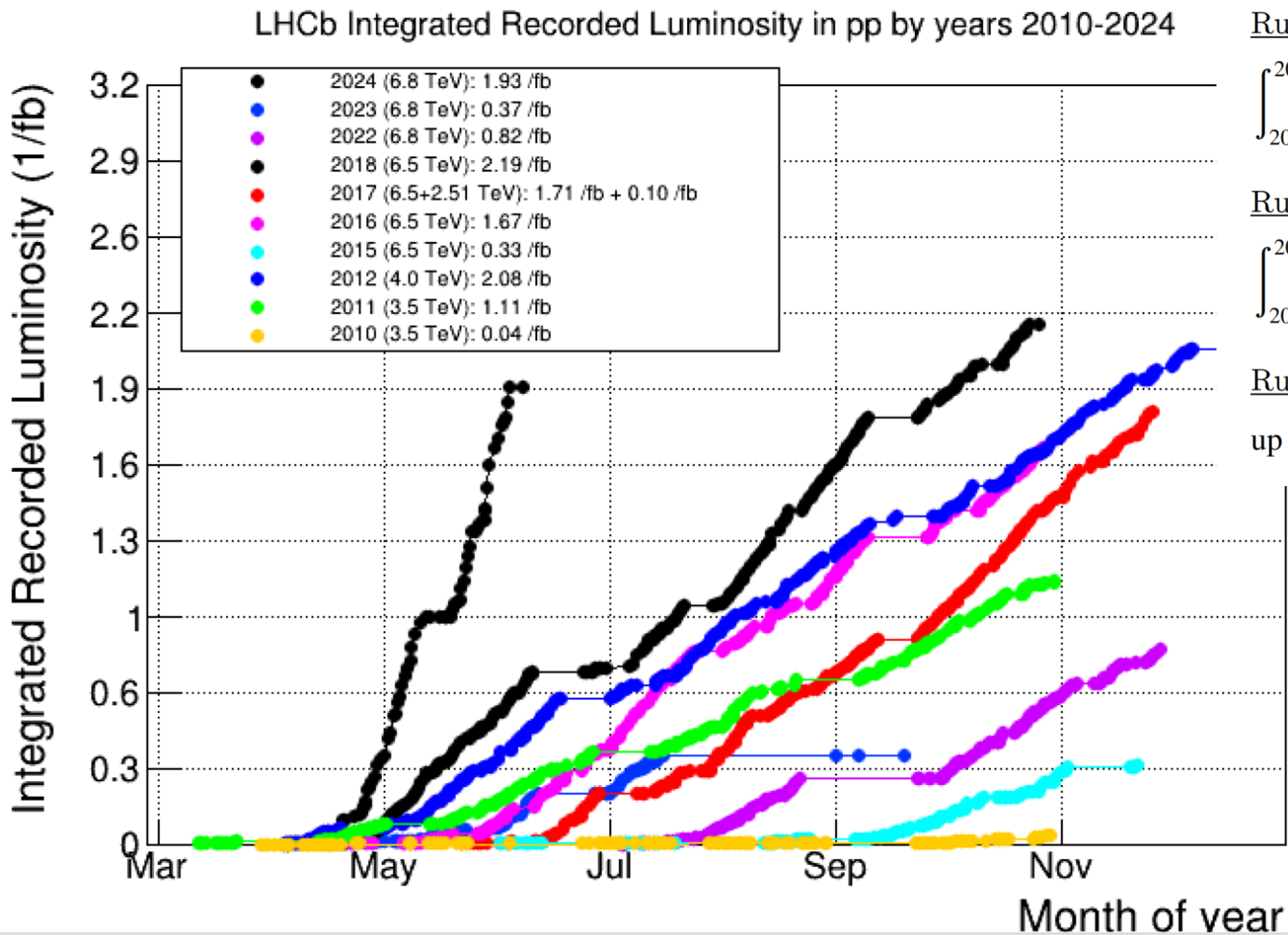
On behalf of the LHCb collaboration

LHCb detector



Dataset



Run1 :

$$\int_{2011}^{2012} \mathscr{L} = 3\text{fb}^{-1}, \quad \sqrt{s} = 7-8\text{TeV}$$

Run2 :

$$\int_{2015}^{2018} \mathscr{L} = 6\text{fb}^{-1}, \quad \sqrt{s} = 13\text{TeV}$$

Run3 (on-going) :

up to $50\,\text{fb}^{-1}$, $\sqrt{s} = 13\text{TeV}$

$\mathscr{R}_{\psi\gamma}$

$$\mathscr{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$$

a probe for X(3272) nature

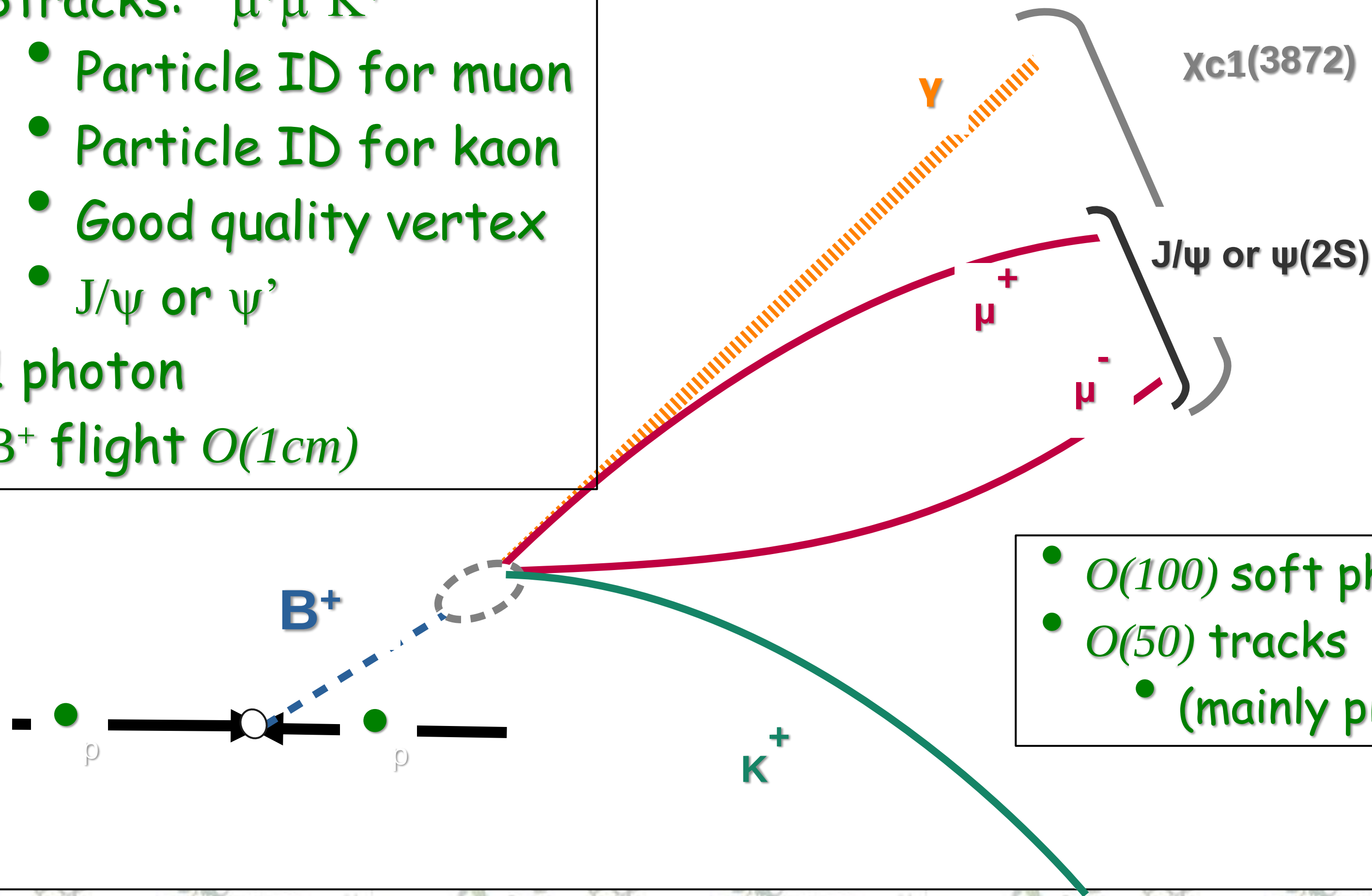
A way to measure:

$$\mathscr{R}_{\psi\gamma} = \frac{\mathcal{B}_{B^+\to(\chi_{c1}(3872)\to\psi(2S)\gamma)K^+}}{\mathcal{B}_{B^+\to(\chi_{c1}(3872)\to J/\psi\gamma)K^+}}$$

- Need to reconstruct $B^+\to(\chi_{c1}(3872)\to\psi\gamma)K^+$

Selection

- 3tracks: $\mu^+\mu^-K^+$
  - Particle ID for muon
  - Particle ID for kaon
  - Good quality vertex
  - J/ψ or ψ'
- 1 photon
- B^+ flight $O(1cm)$



- $O(100)$ soft photons
- $O(50)$ tracks
  - (mainly pions in PVs)

Selection

- 2014 analysis (Run 1) : Cut-based selection
- New analysis: MVA-based selection
  - For Run 2 background is larger (#soft photons)
- Variables:
  - Track reconstruction quality
  - Vertex quality, decay consistency
  - Track impact parameters, ..
  - B^+ lifetime
  - Kaon ID
  - Photon ID quality

Training:
- Signal: MC
- Background: sidebands +MC

16 variables in total

MC adjustments

Simulated samples are properly adjusted/corrected

- B^+ kinematics (p_T&y):
  - $B^+ \to J/\psi K^+$
- Track multiplicity
  - taken from data: $B^+ \to J/\psi K^+$
- Kaon ID:
  - taken from data: $D^{*+} \to (D^0 \to K^- \pi^+) \pi^+$
- Track reconstruction
  - corrected using $J/\psi \to \mu^+ \mu^-$
- Photon reconstruction
  - corrected using $B^+ \to J/\psi(K^{*+} \to K^- \pi^0)$

Standard candle: $B^+ \to (\chi_{c1} \to J/\psi\gamma)K^+$

- Same final state: $\mu^+\mu^-\gamma K^+$
- 170k events
- Low background

- Shapes, mass, mass resolution
- Efficiencies
- MC-data agreement

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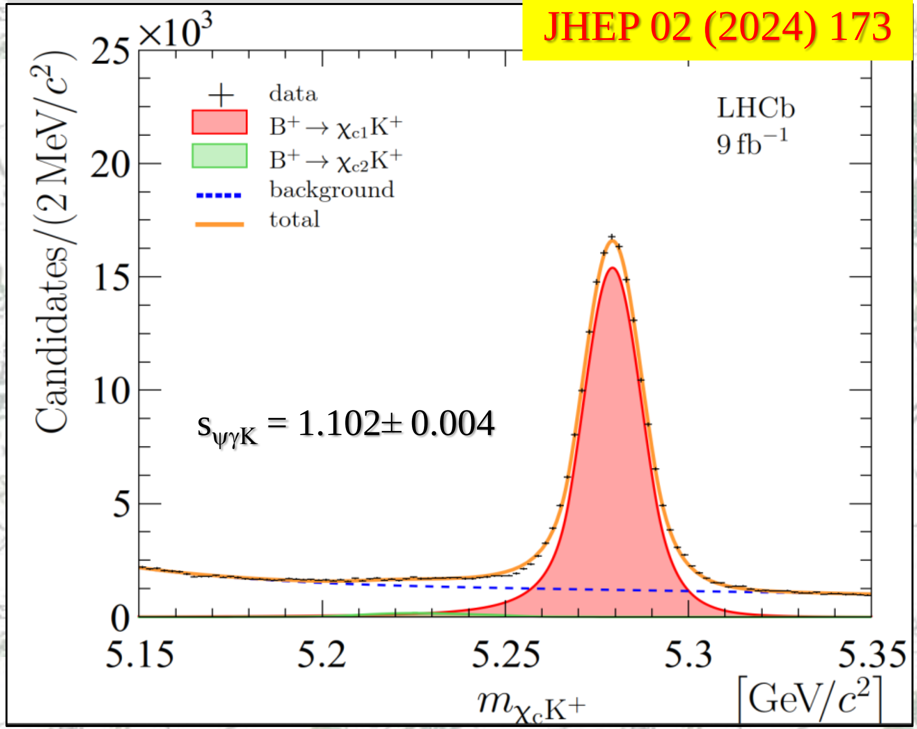

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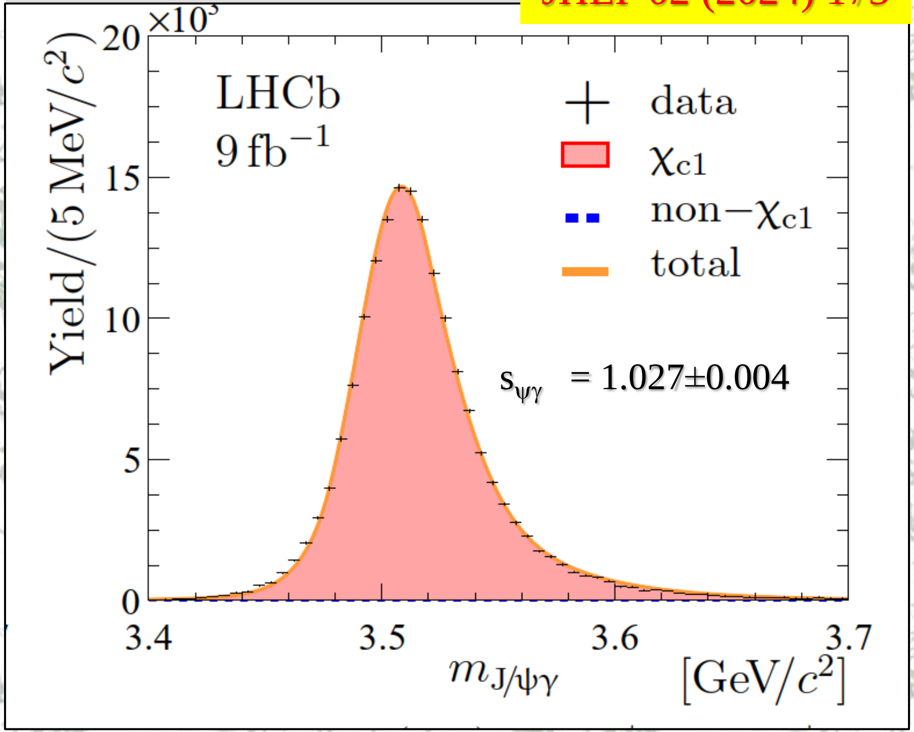


Signal determination

- Unbinned extended 2D fit: $m_{\psi\gamma}$ vs $m_{\psi\gamma K}$
- Simultaneously for four samples:
  - $B^+ \to \psi'\gamma K^+$, $B^+ \to J/\psi\gamma K^+$, Run 1 and Run 2 samples

- Signal components
- Background components
- Combinatorial background
  - 2D polynomials

Signal component: S×S

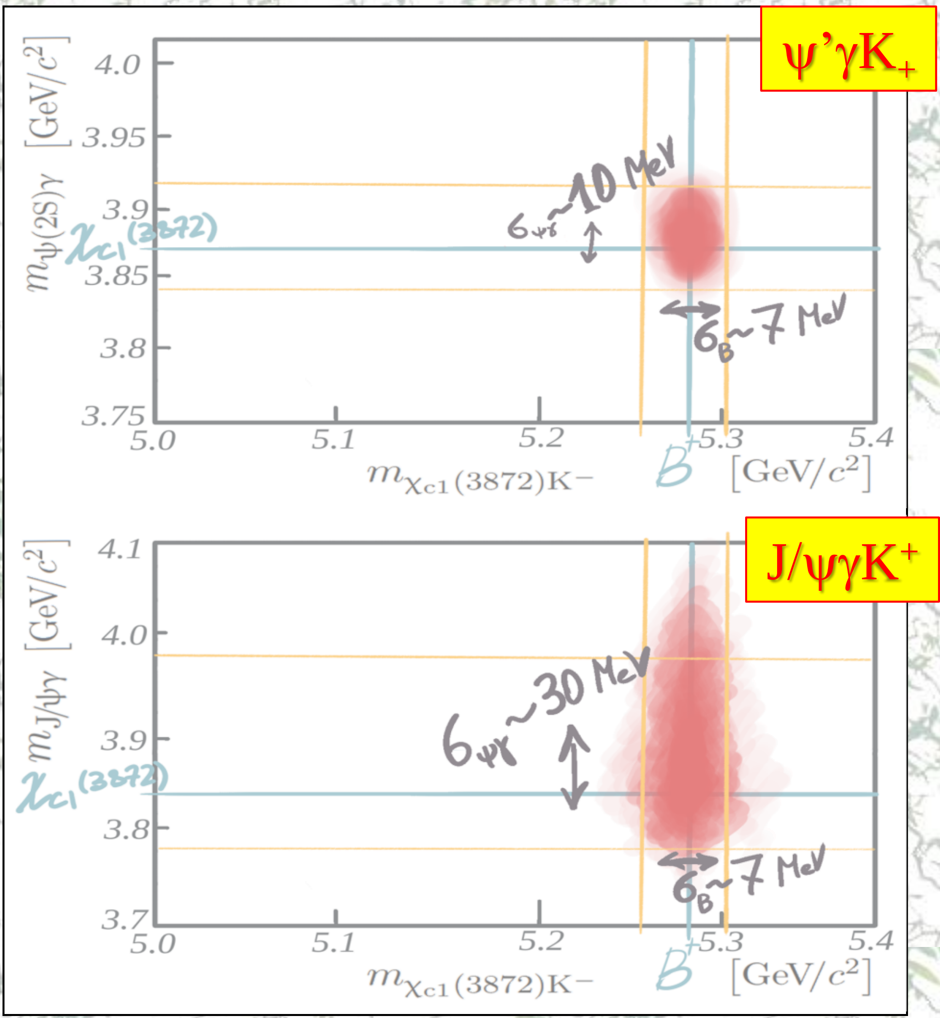
- Shapes: from MC

  Checked with $B^+ \to (\chi_{c1} \to J/\psi\gamma)K^+$
  - MC uncertainties are included into the fit
- Resolution corrections from $B^+ \to (\chi_{c1} \to J/\psi\gamma)K^+$

  $s_{\psi\gamma} = 1.027 \pm 0.004$

  $s_{\psi\gamma K} = 1.102 \pm 0.004$

  Uncertainties are included into the fit
- Masses are shared for 4 samples



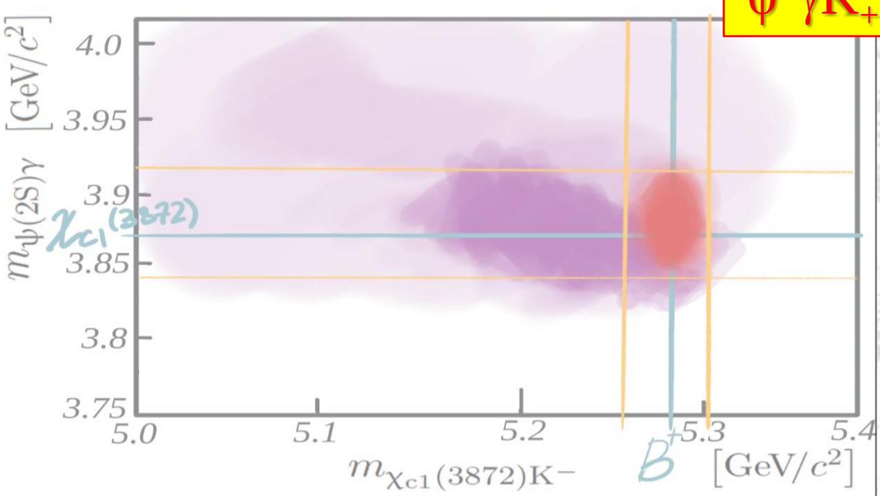
Background components (1)

$B \to \psi' K^+X + \gamma$

- MC sample of decays with K^*, $K_0^*(700)$, $K_1(1270)$, $K^*(1410)$, $K_2^*(1430)$, $K^*(1680)$ and non-resonant decays $\psi' K^+\pi$, $\psi' K^+\pi\pi$, $\psi' K^+\eta$, $\psi' K^{*+}\eta$, $\psi' K^+\omega$

Many other contributions are studied and found to be negligible

$\psi'\gamma K_+$

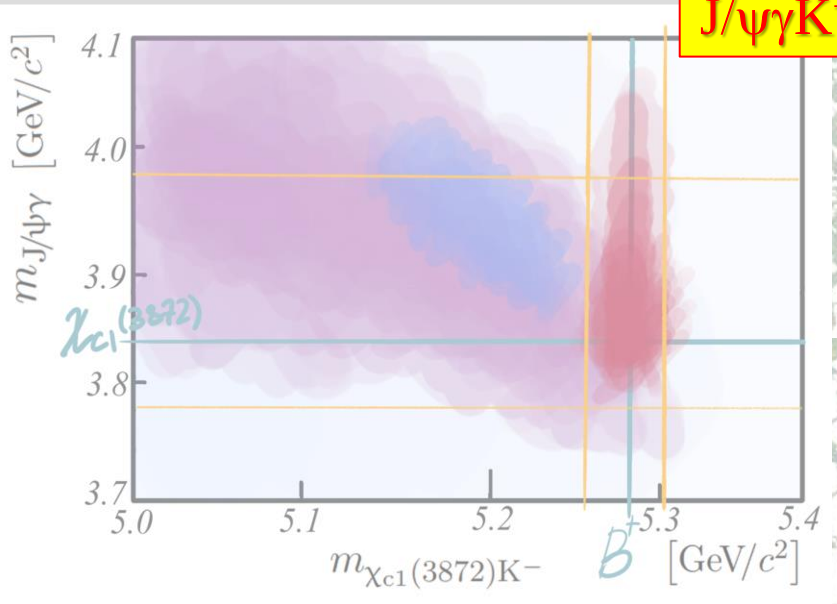


Various parameterisations are probed:
- Legendre polynomials
- 2D-histograms, …

Background components (2)

$B^+ \to J/\psi\ (K^{*+} \to K^+\pi^0)$

- From simulation
- Various parametersations
- Legendre polynomials
- 2D histograms, .
- ….



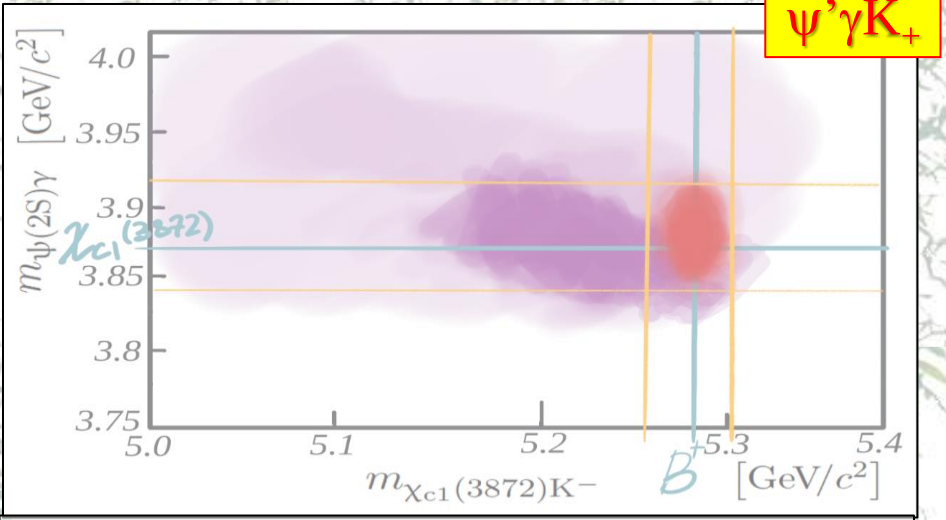
- Other (unidentified) $B \to J/\psi X$ decays
  - 2D Gaussian

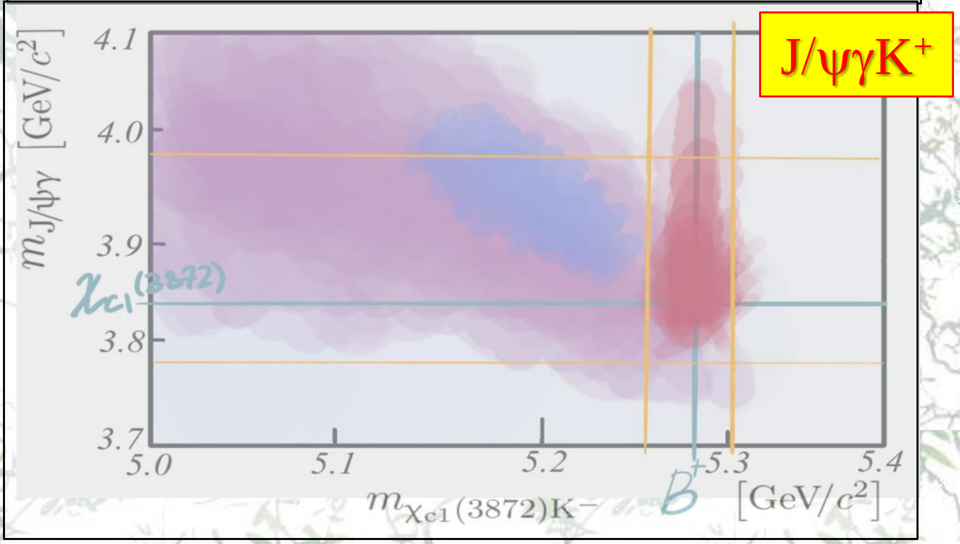
Overall fit function

- Signal components
- Background components
- (for J/ψ channel: *non-B* background:

  const × $S_{\psi\gamma}$
- Combinatorial
  - 2D polynomials

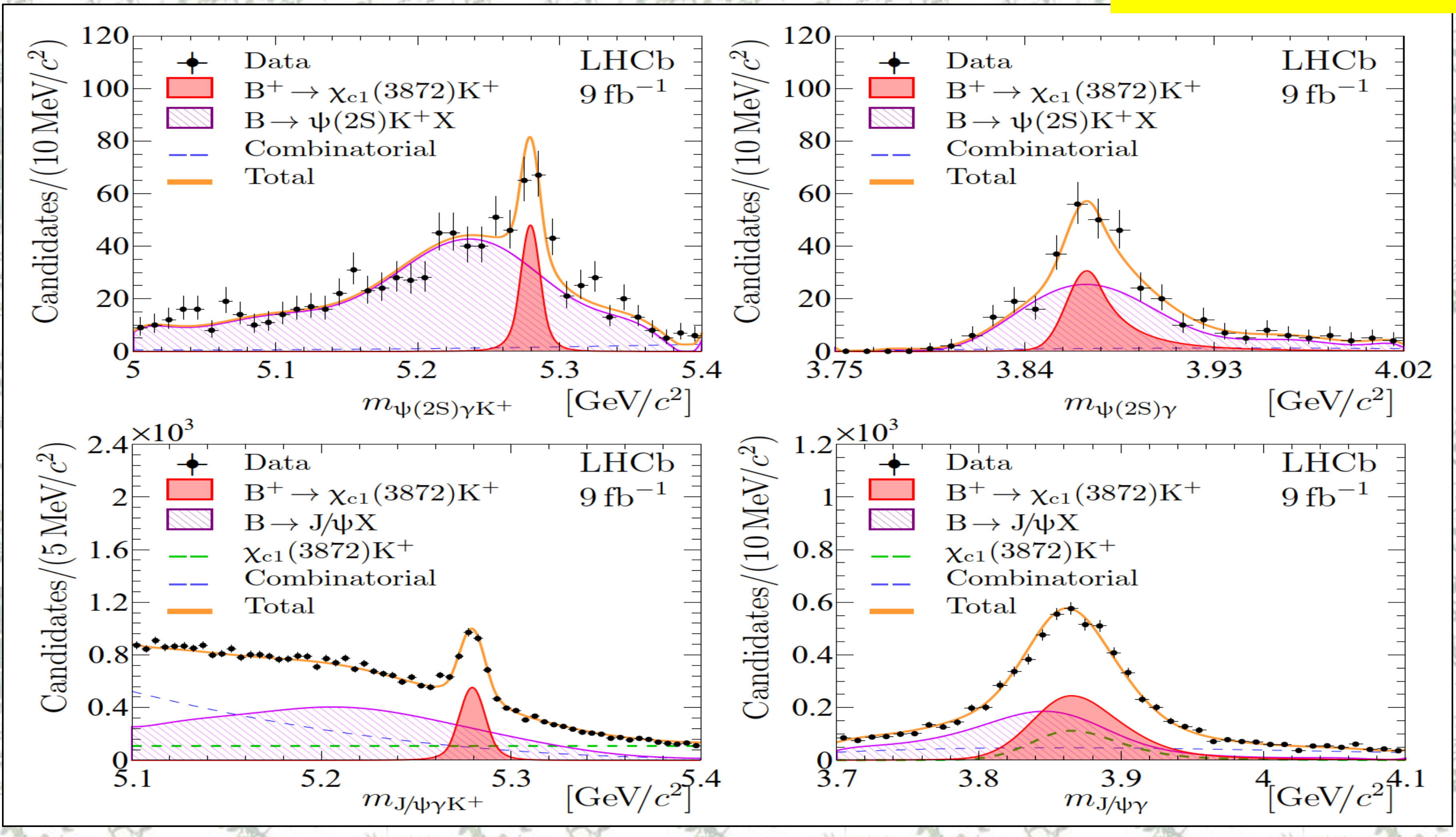
  (9/16 parameters)





Fit results

arXiv:2406.17006



Fit results

arXiv:2406.17006

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
Significance		5.3σ	6.7σ

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Systematics for $\mathscr{R}_{\psi\gamma}$

arXiv:2406.17006

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

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	$^{+8.0}_{-9.2}$	$^{+8.7}_{-7.9}$

Many cross-checks, including 1D fits; conservative variations

$B^+\to J/\psi K^+$

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

$B^+\to J/\psi(K^{*+}\to K^+\pi^0)$

$D^{*+}\to(D^0\to K^-\pi^+)p+$

$B^+\to J/\psi K+$ & $\psi' K+$

$B^+\to(\chi_{c1}\to J/\psi\gamma)K^+$

Results

arXiv:2406.17006

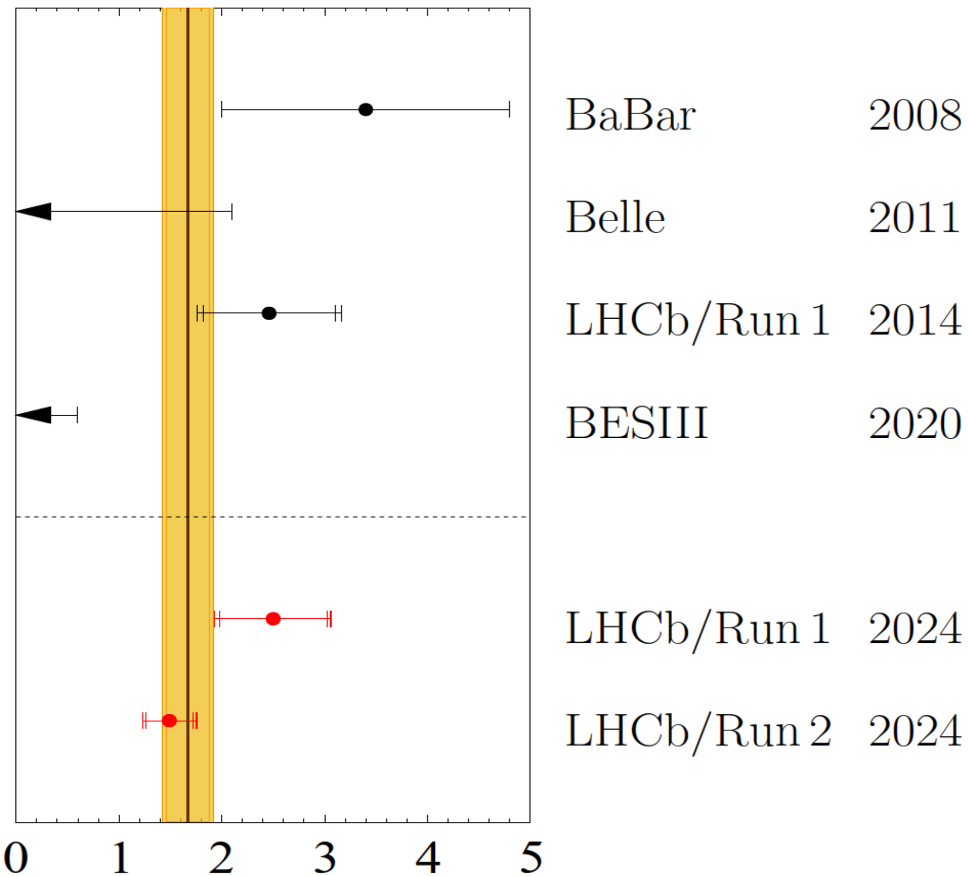
New results

$$\mathcal{R}^{\mathrm{Run\,1}}_{\psi\gamma} = 2.50 \pm 0.52\,^{+0.20}_{-0.23} \pm 0.06$$

$$\mathcal{R}^{\mathrm{Run\,2}}_{\psi\gamma} = 1.49 \pm 0.23\,^{+0.13}_{-0.12} \pm 0.03$$

LHCb average

$$\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04\,.$$



$$\mathcal{R}_{\psi\gamma} = \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$$

Conclusions

- The first observation of $X(3972) \to \psi'\gamma$ decay
- New measurement of $\mathscr{R}_{\psi\gamma}$ ratio
  - Good agreement with previous Run 1 LHCb-2014 measurement
  - Large tension with BESIII
  - Ratio is not compatible with simple molecular models
  - Ratio is well compatible with charmonium, tetraquark and mixture models

What are conclusion about X(3872) nature?

Future of X(3872) at LHCb

- Run 3 is going well
- Run 3&4: x10 in statistics
- Run 5&6: x100(?) in statistics

☹ but largely increased background will make the analyses with (soft) photons very hard. No straightforward linear improvement with integrated luminosity.

Upgrade in calorimeter: improved granularity, timing, … with hope to keep good performance for soft photons even in very hard conditions.

What else?

Other channels?

Combined line shape analyses $J/\psi\pi\pi$ vs $D^{*}D$ with Belle II & BESIII ?

… ?

THANK YOU!

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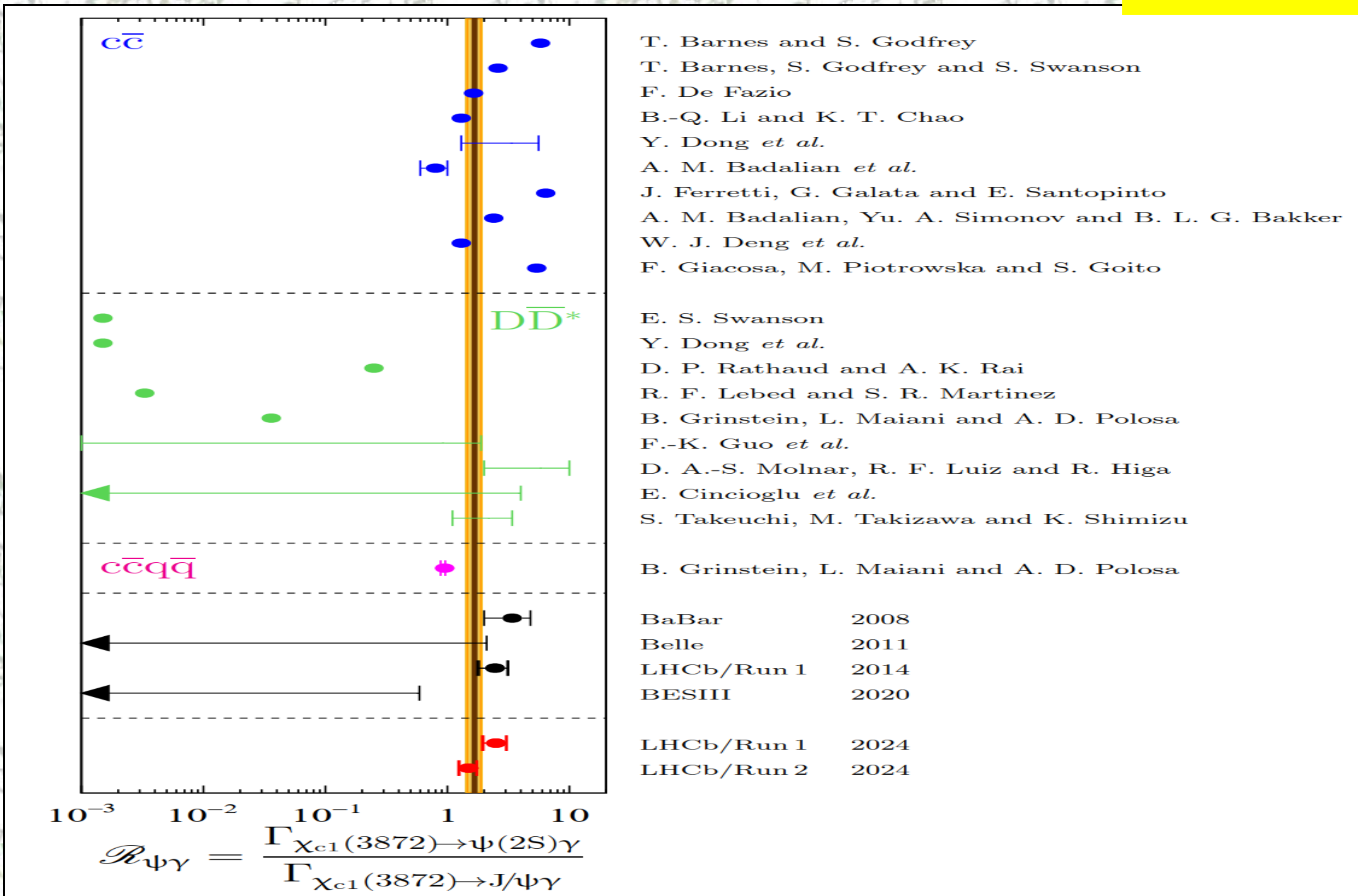

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