Measurements of the exotic tetraquark candidate X(3872) in pp and pPb

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Quark Model of Hadrons

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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Received 4 January 1964

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G. Zweig *)
CERN - Geneva

8182/TH.401
17 January 1964

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

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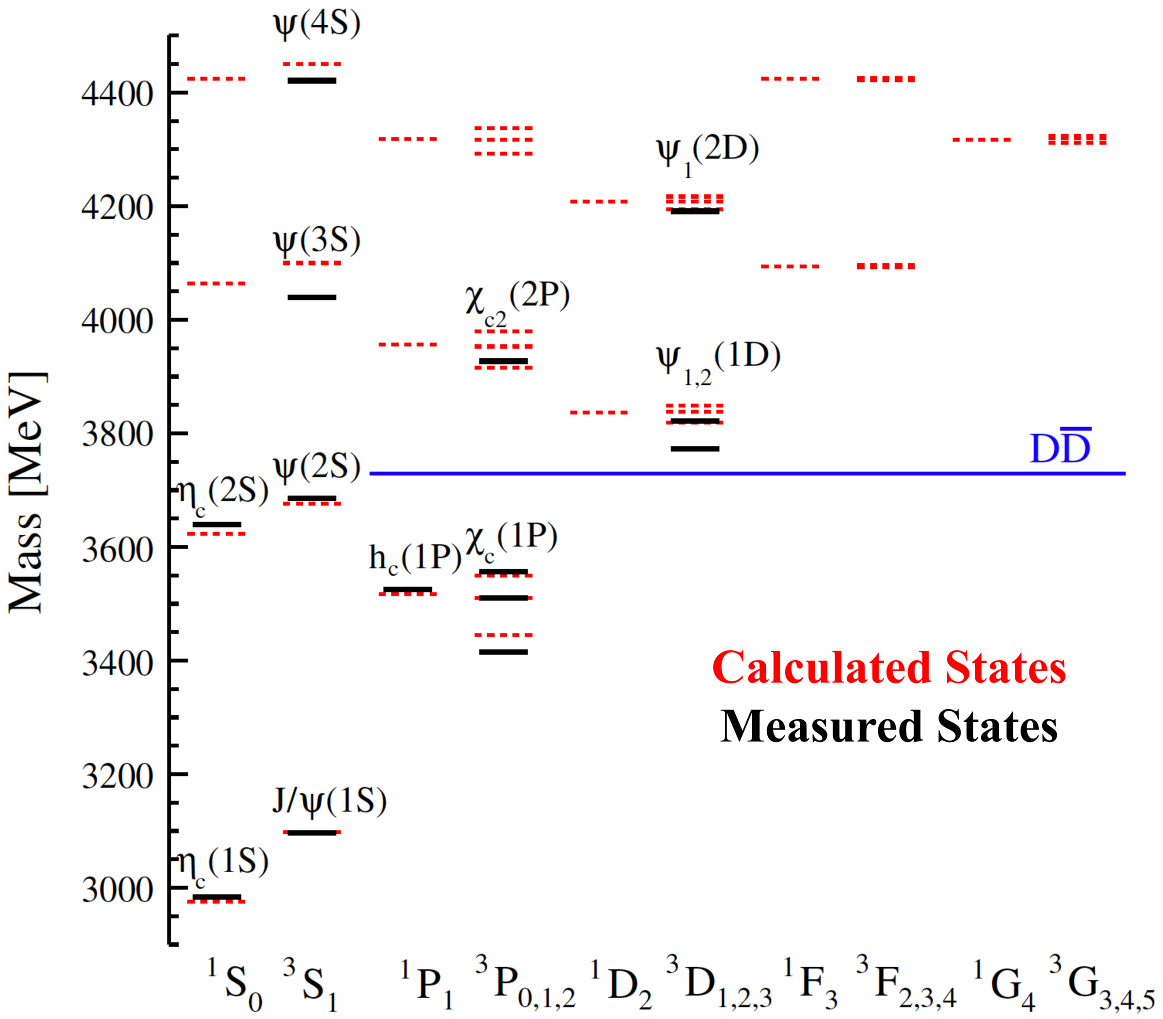
States with >3 quarks have been expected since the beginning of the quark model

Conventional $c\bar{c}$ States



Rev. Mod. Phys. 90, 015003 (2018)

Nonrelativistic potential model: solve Schrodinger equation with the potential

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

Barnes, Godfrey, Swanson,
Phys. Rev. D 72, 054026 (2005)

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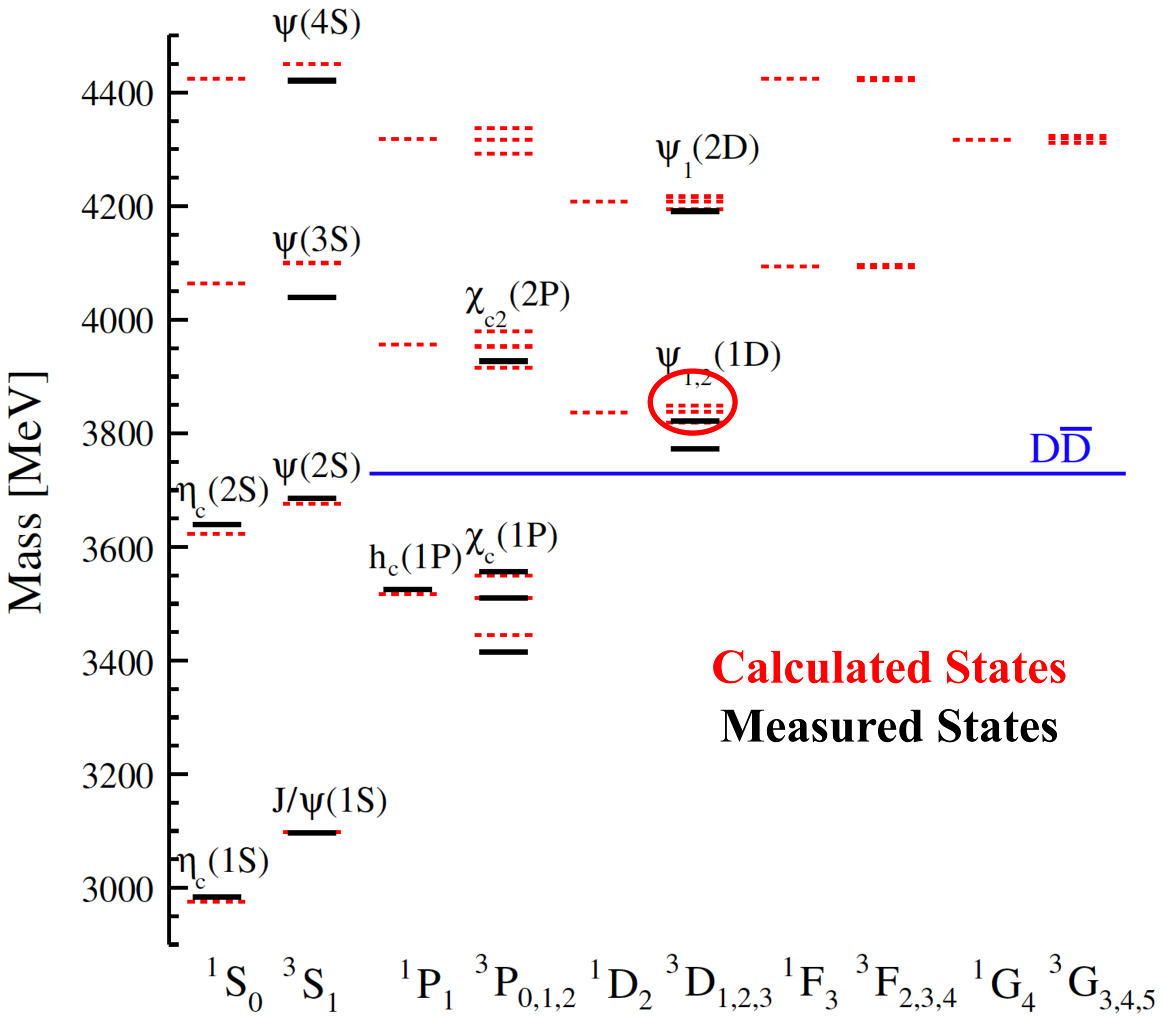

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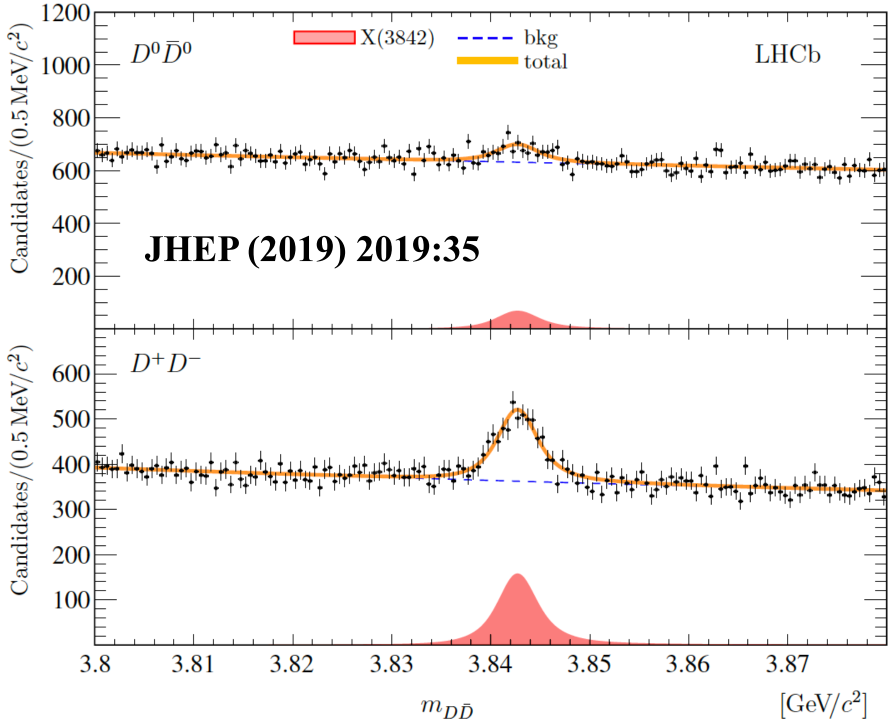
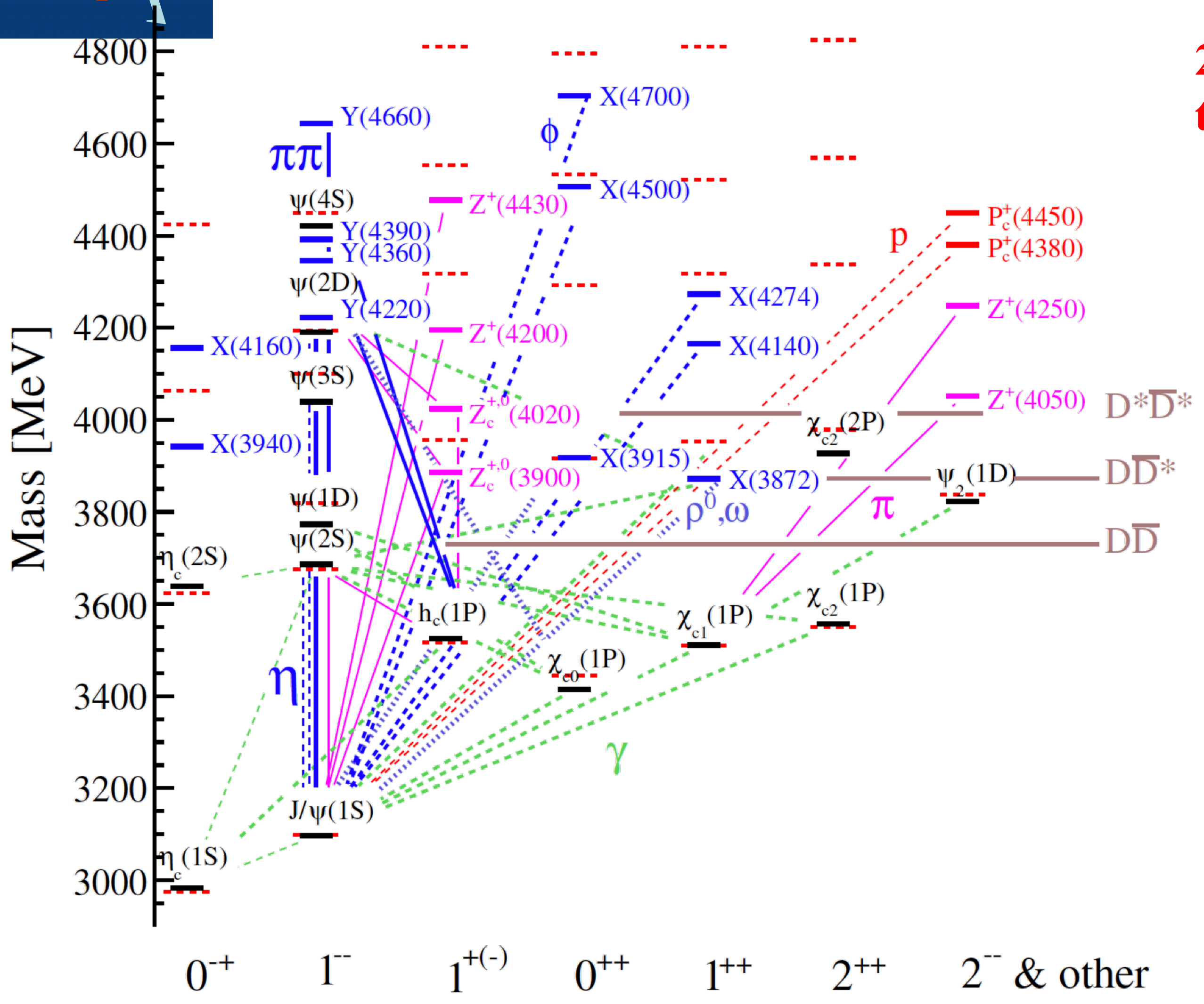


New charmonium states still being found: LHCb observed state consistent with $\psi_3(1^3D_3)$ found in $\boldsymbol{D\bar{D}}$ and $\boldsymbol{D^+D^-}$ mass spectra in 2019

Crucial to account for conventional states when searching for exotics

Exotic $c\bar{c}$ States



20+ states containing $c\bar{c}$ have been discovered since 2003 that do not fit in the picture of typical charmonium:

Collectively known as "*XYZ*" particles

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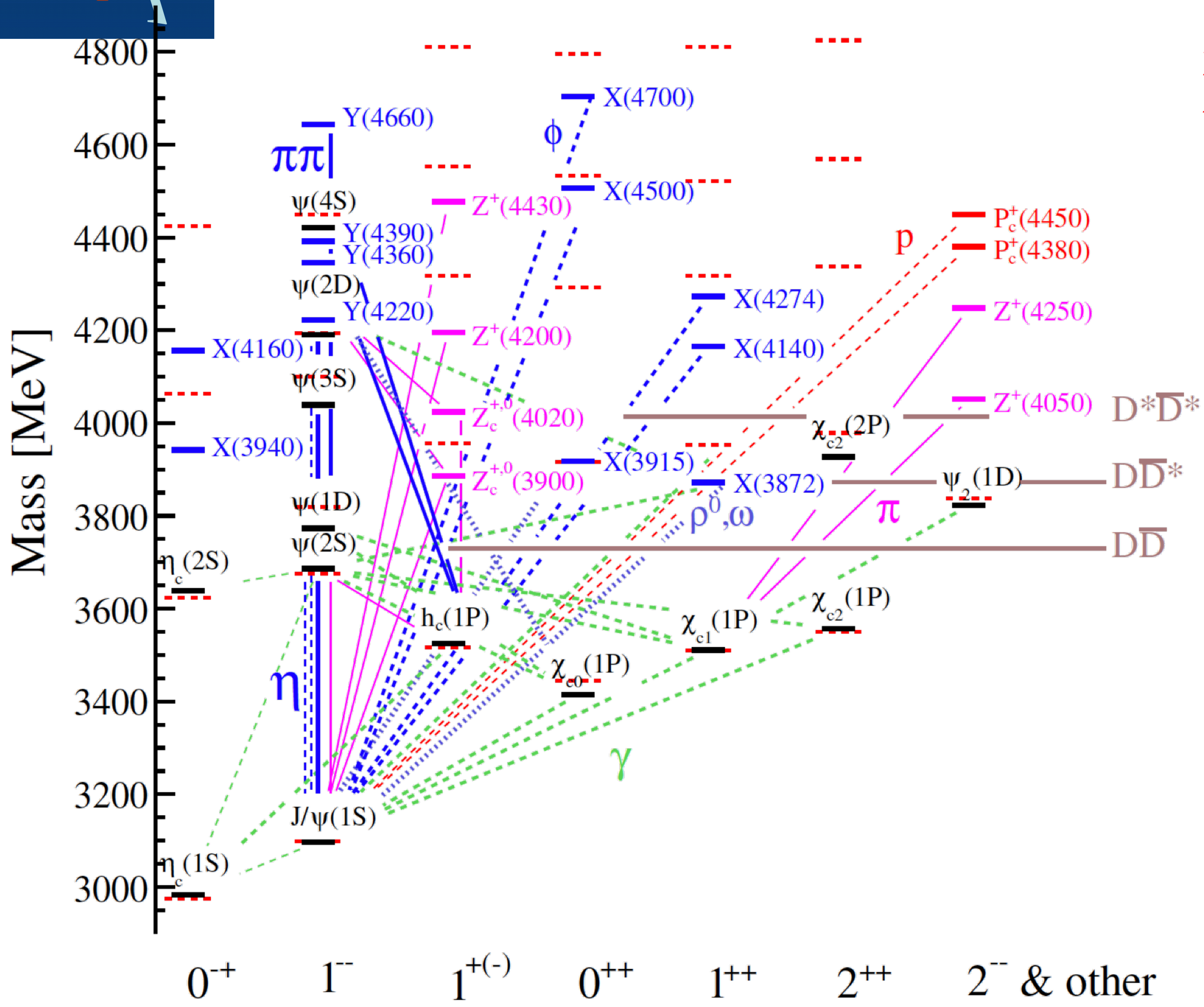

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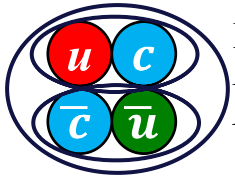
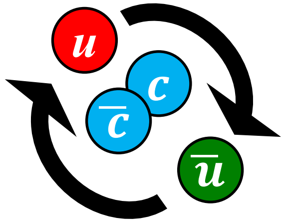
Multiple explanations explored in literature:

Compact tetraquark/pentaquark



Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/ adjoint charmonium
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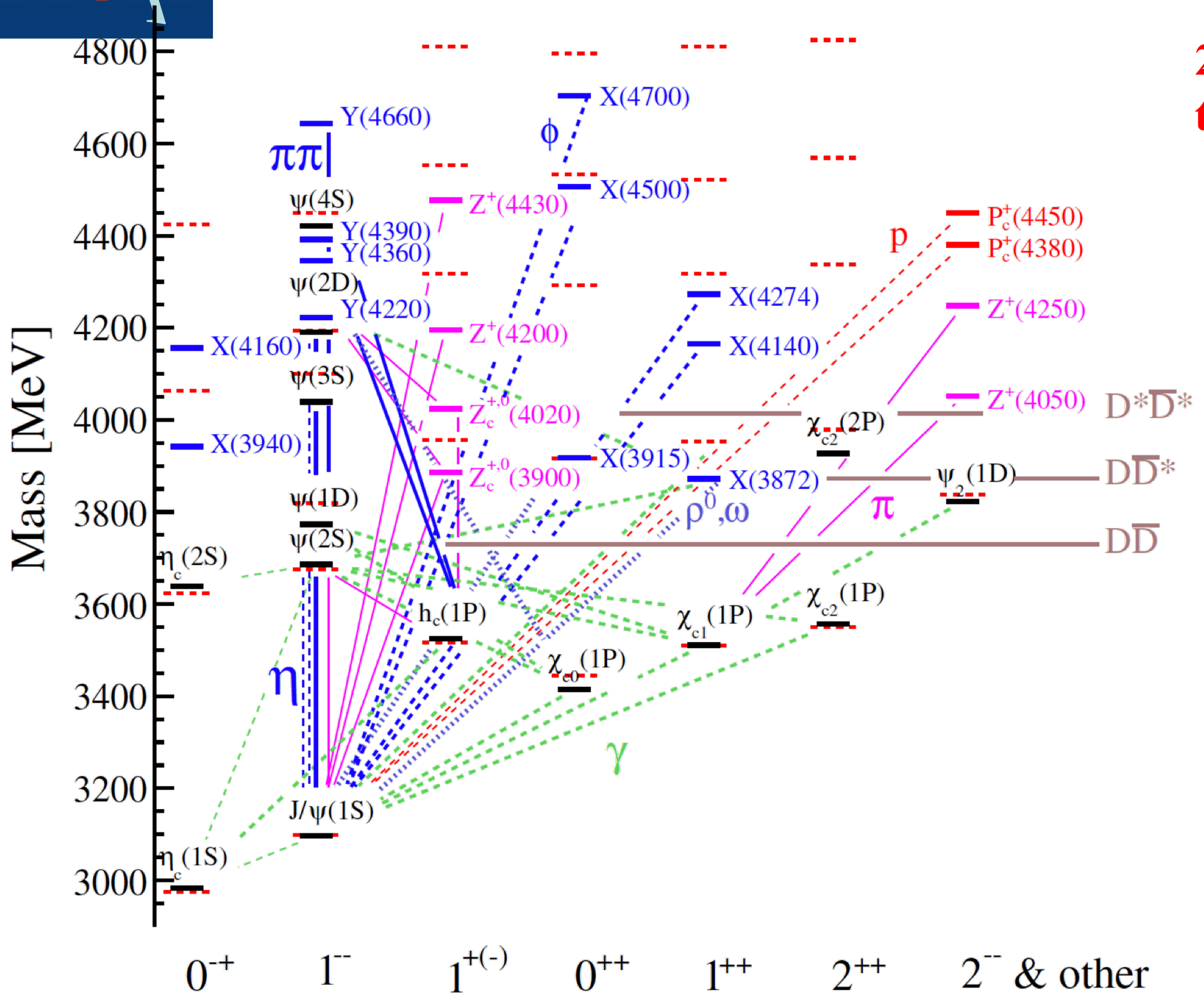

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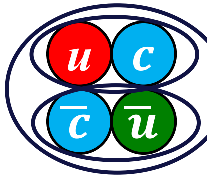

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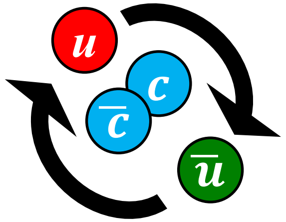

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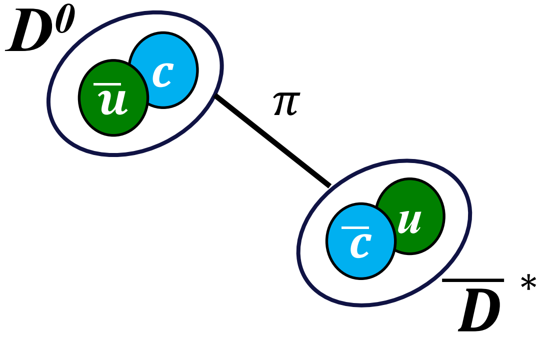
Hadronic Molecules

PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



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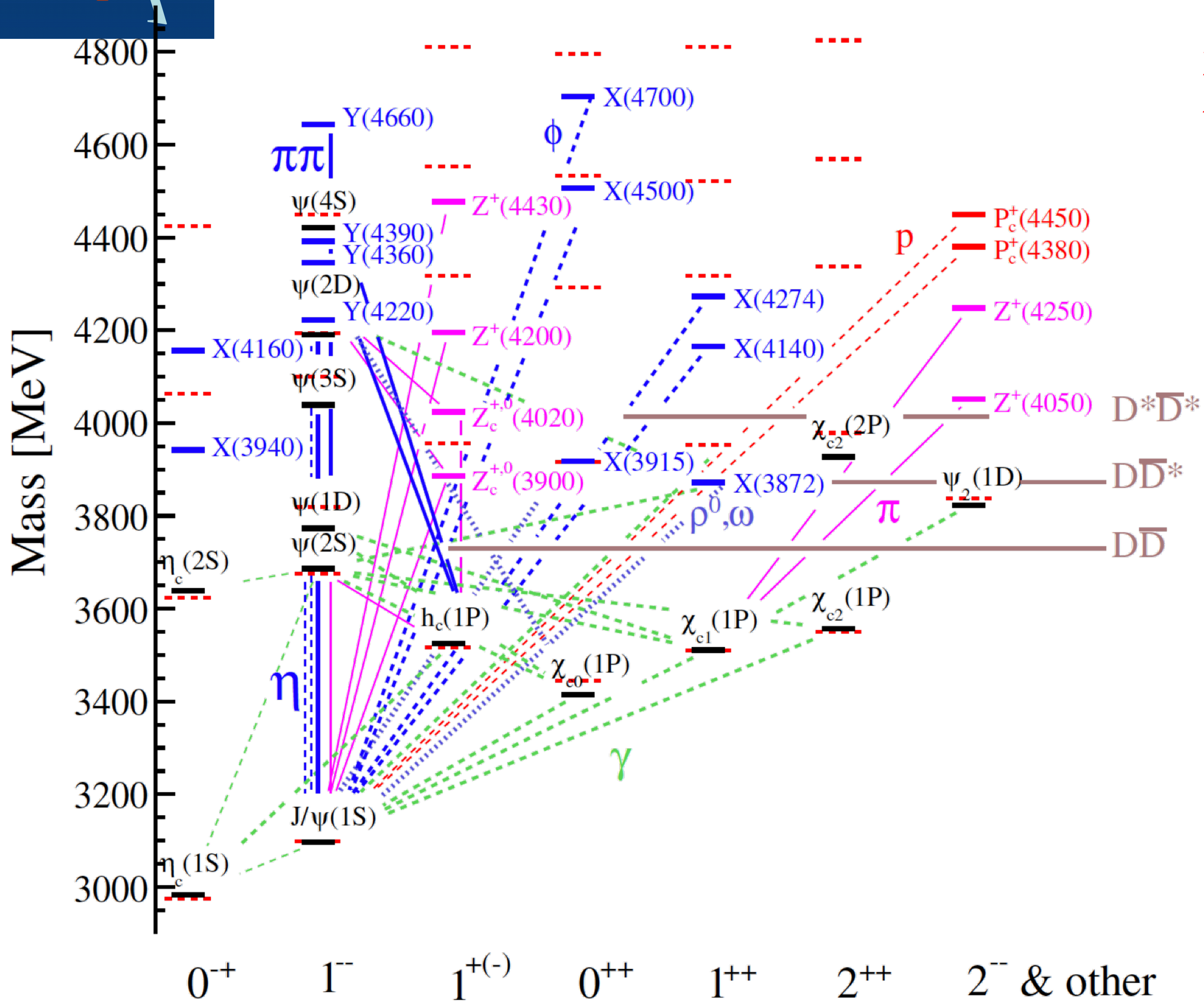

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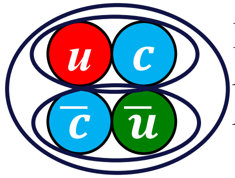

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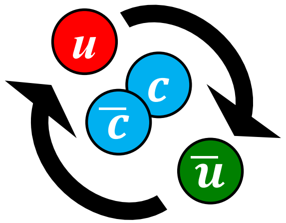

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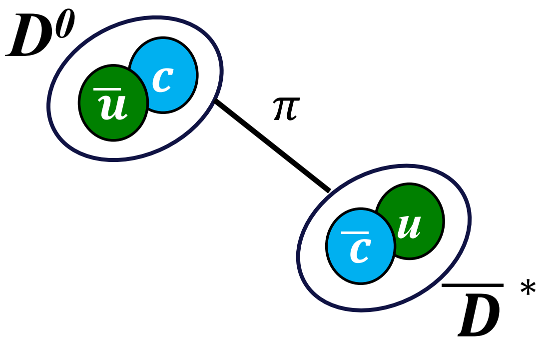


Mixtures of exotic + conventional states

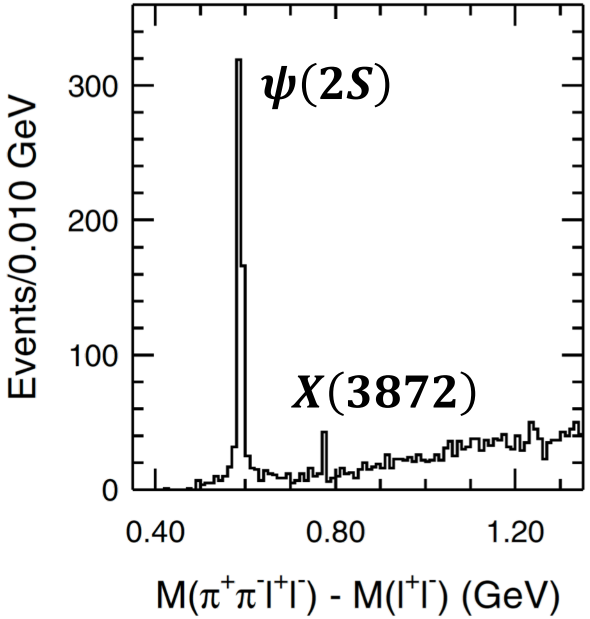
$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

PLB 578 365 (2004)
PRD 96 074014 (2017)

X(3872) - a puzzle

Recently renamed $\chi_{c1}(3872)$ by PDG

Belle Collaboration
PRL 91 262001 (2003)



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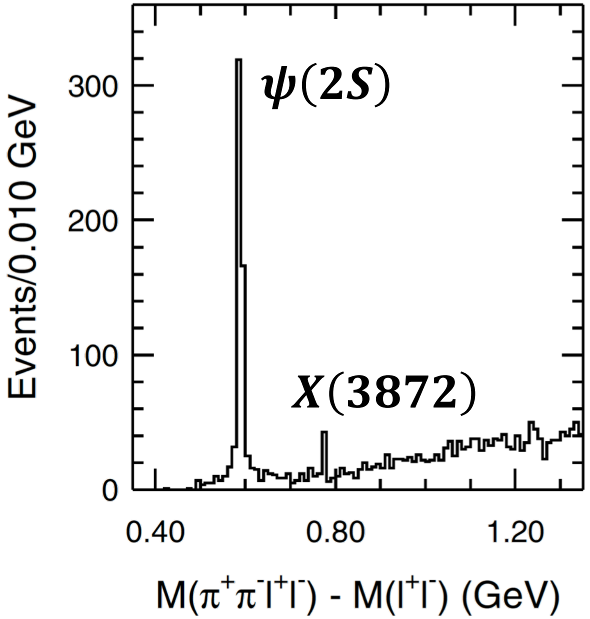

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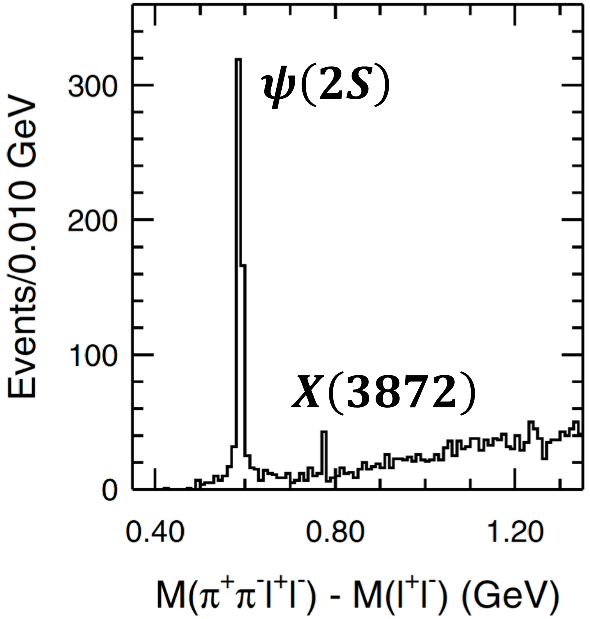

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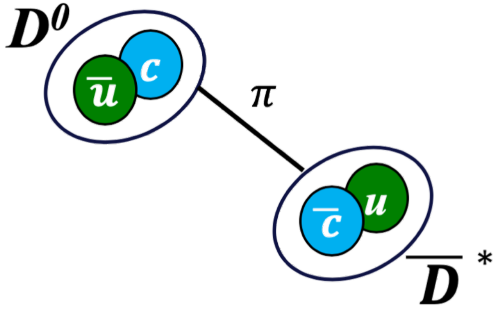

***VERY* small binding energy**
***VERY* large radius, ~7 fm**

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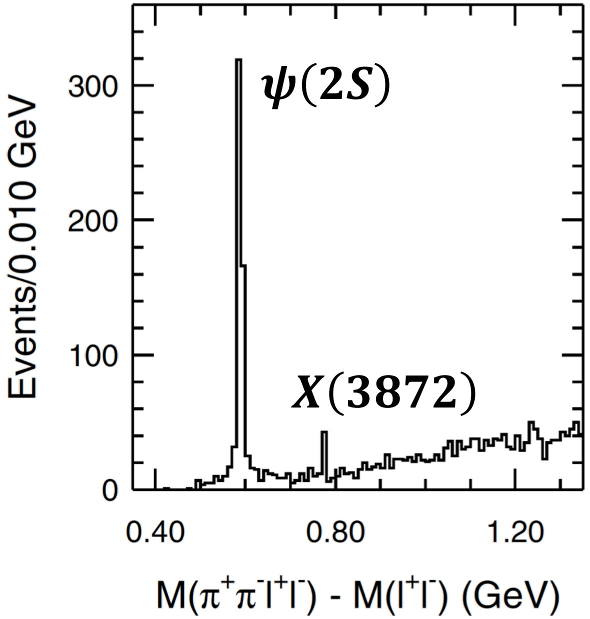

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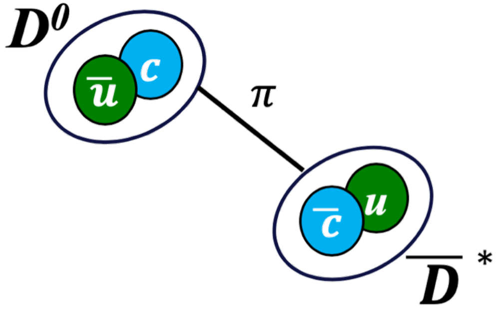

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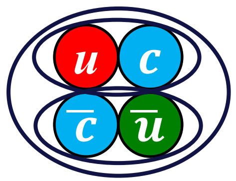
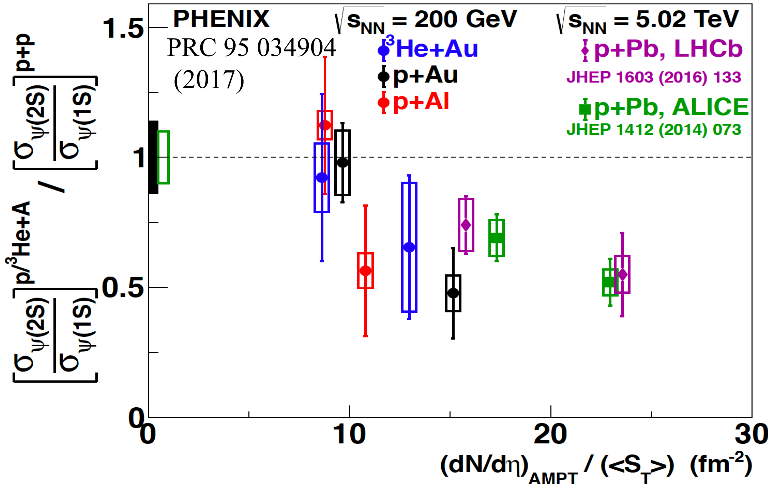
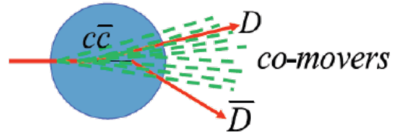


Tightly bound via color exchange between diquarks
Small **radius, ~1 fm**

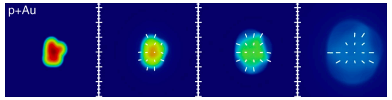
Effects of Binding Energy

- Suppression of weakly-bound quarkonia states has been studied for decades in pA collisions
  - Ratios of $\psi(2S)/_{J/\psi}$ and $\Upsilon(2S,3S)/_{\Upsilon(1S)}$





cf. PLB 749 98 (2015)



PHENIX, Nature Physics 15 214 (2019)

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Satz, J. Phys. G 32 (3) 2006

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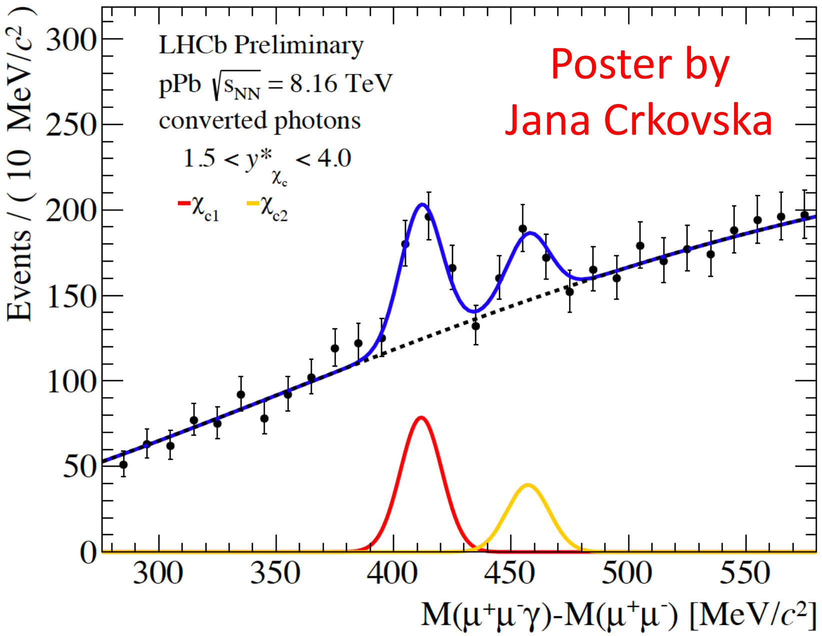

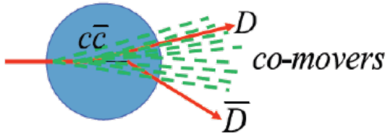

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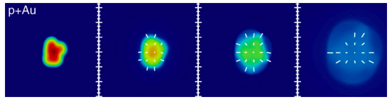

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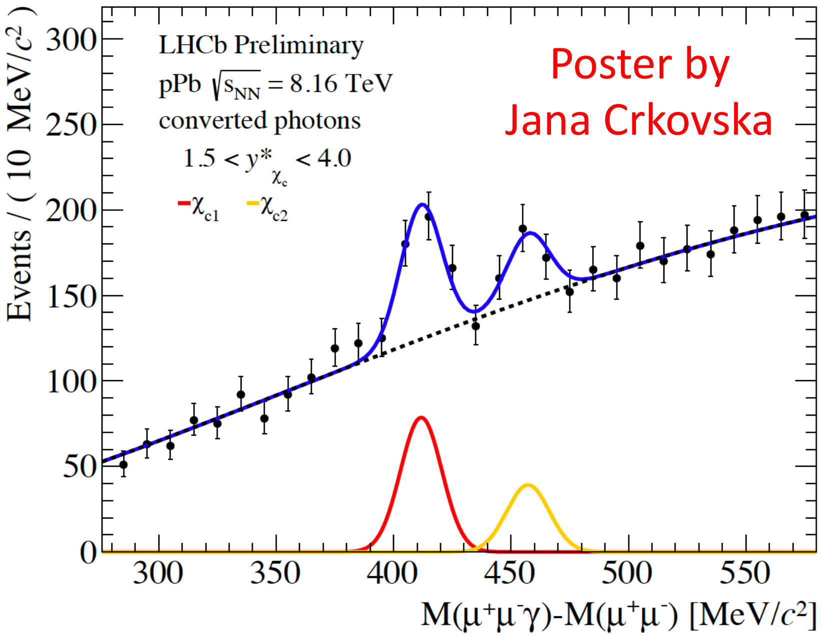

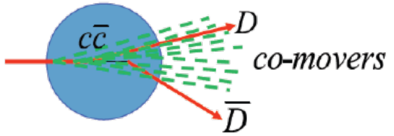

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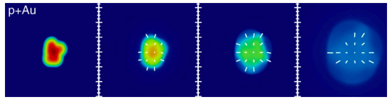

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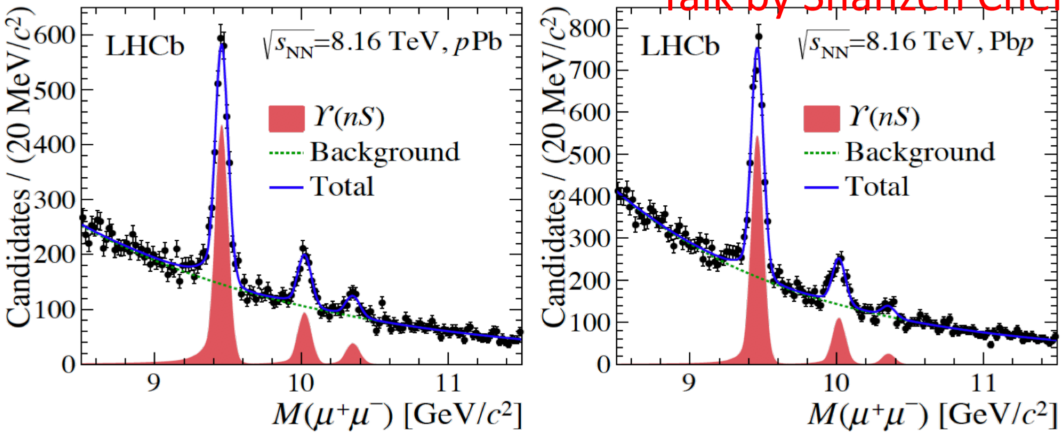
Talk by Shanzen Chen



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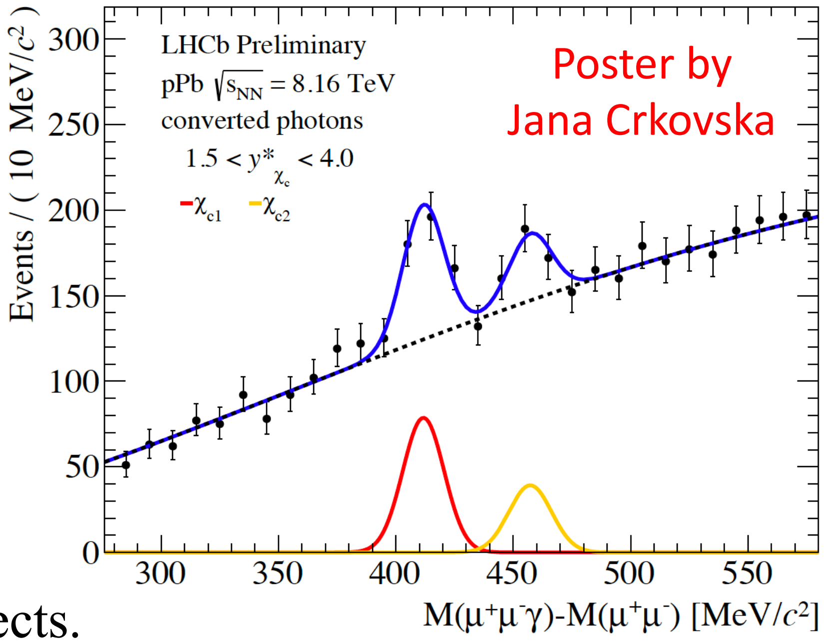
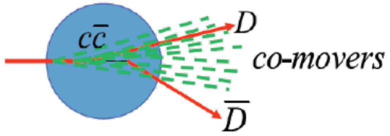
- Weakly bound hadronic molecules may show similar effects.





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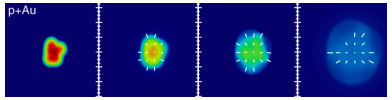

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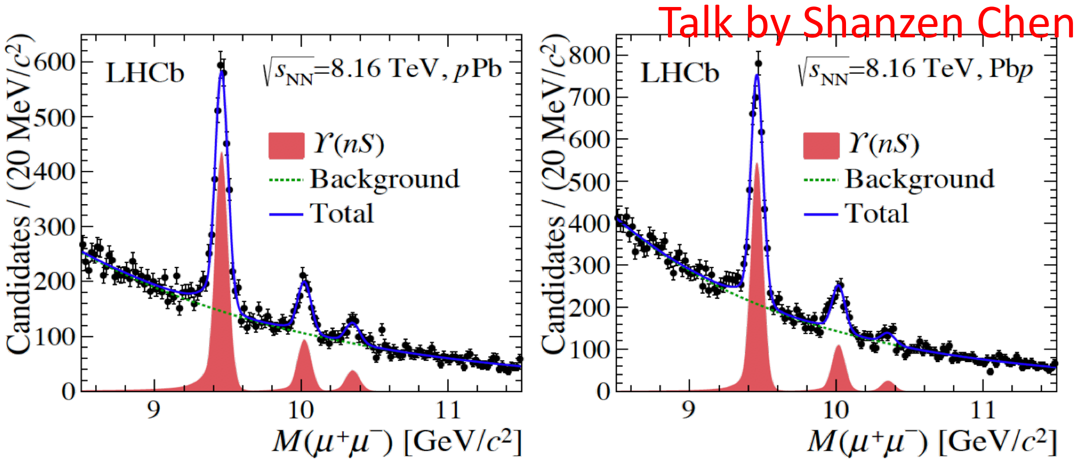
Satz, J. Phys. G 32 (3) 2006

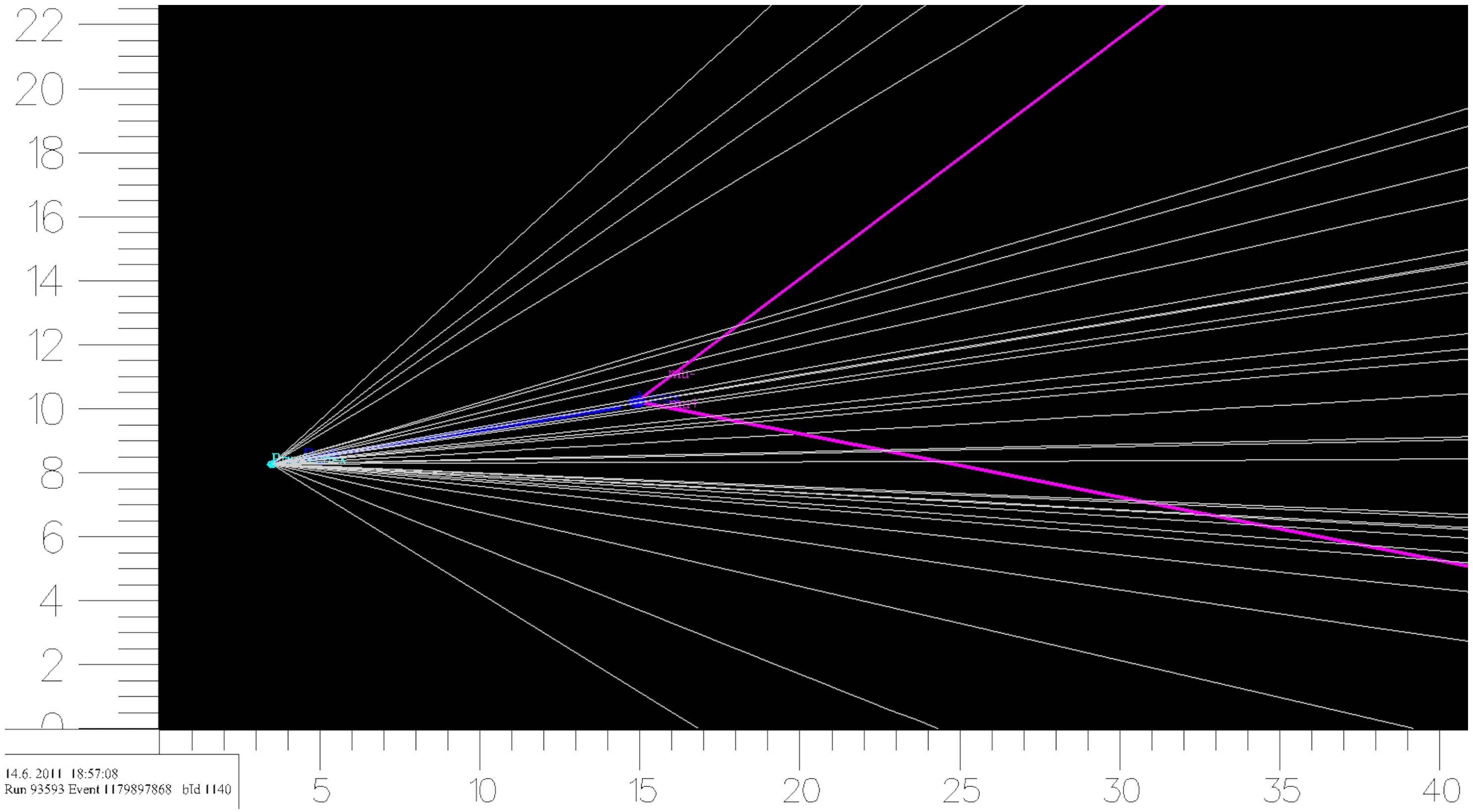


Probing X(3872) structure via interactions with the underlying event

Prompt production:

- X(3872) produced at collision vertex can be subject to further interactions with co-moving particles (medium?) produced in the event
- Potentially subject to breakup effects

Event display of $B_s^0 \rightarrow \mu^+\mu^-$ candidate, PRL 118 191801 (2017)



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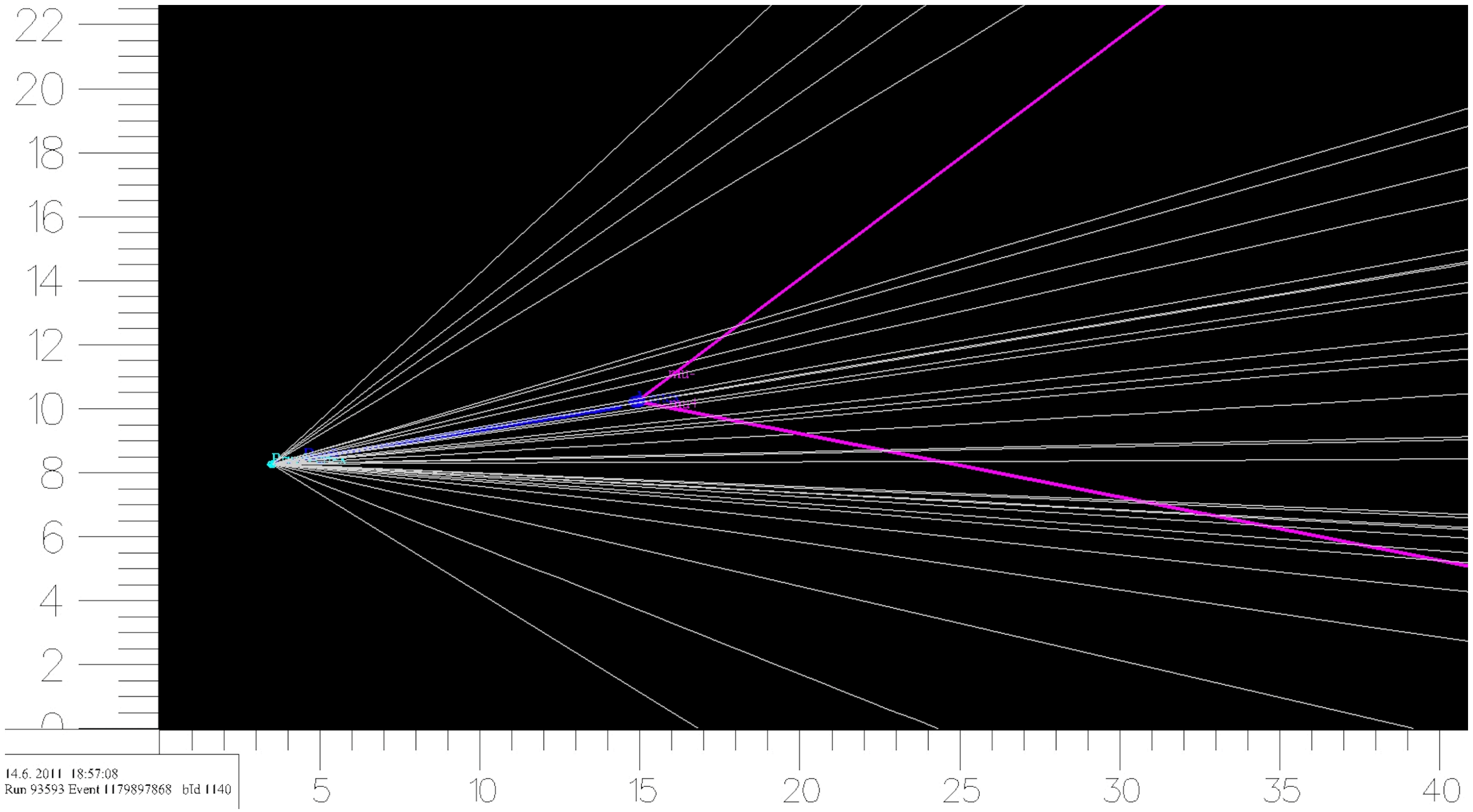
Production in ***b***-decays:

- Hadrons containing ***b*** travel down the beampipe and decay away from the primary vertex and decay in vacuum
- X(3872) from decays not subject to further interactions
- Control sample

Event display of $B_s^0 \to \mu^+\mu^-$ candidate, PRL 118 191801 (2017)



The LHCb Detector

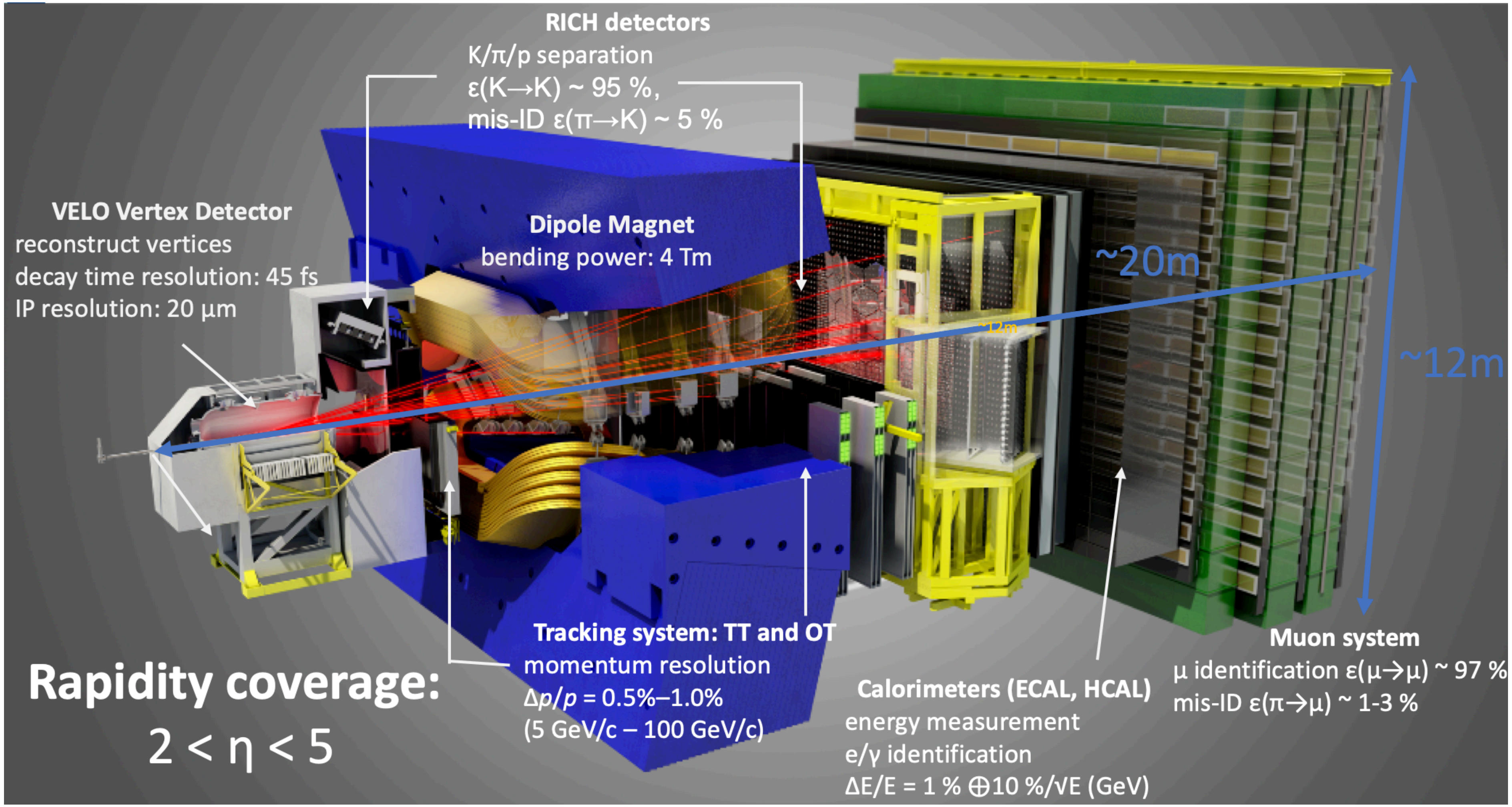
JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30, 1530022 (2015)

$X(3872) \to J/\psi\pi^+\pi^-$

Vertex detector (VELO):
-Separation of prompt and ***b***-decay production
-Number of VELO tracks gives measure of event activity

Two RICH detectors:
-Pion identification

Muon System:
-Layers of absorber/tracking
-Muon hardware trigger



X(3872) selection

LHCb-CONF-2019-005

Reconstruct the $\boldsymbol{\mu^+\mu^-\ \pi^+\pi^-}$ final state from the decays:

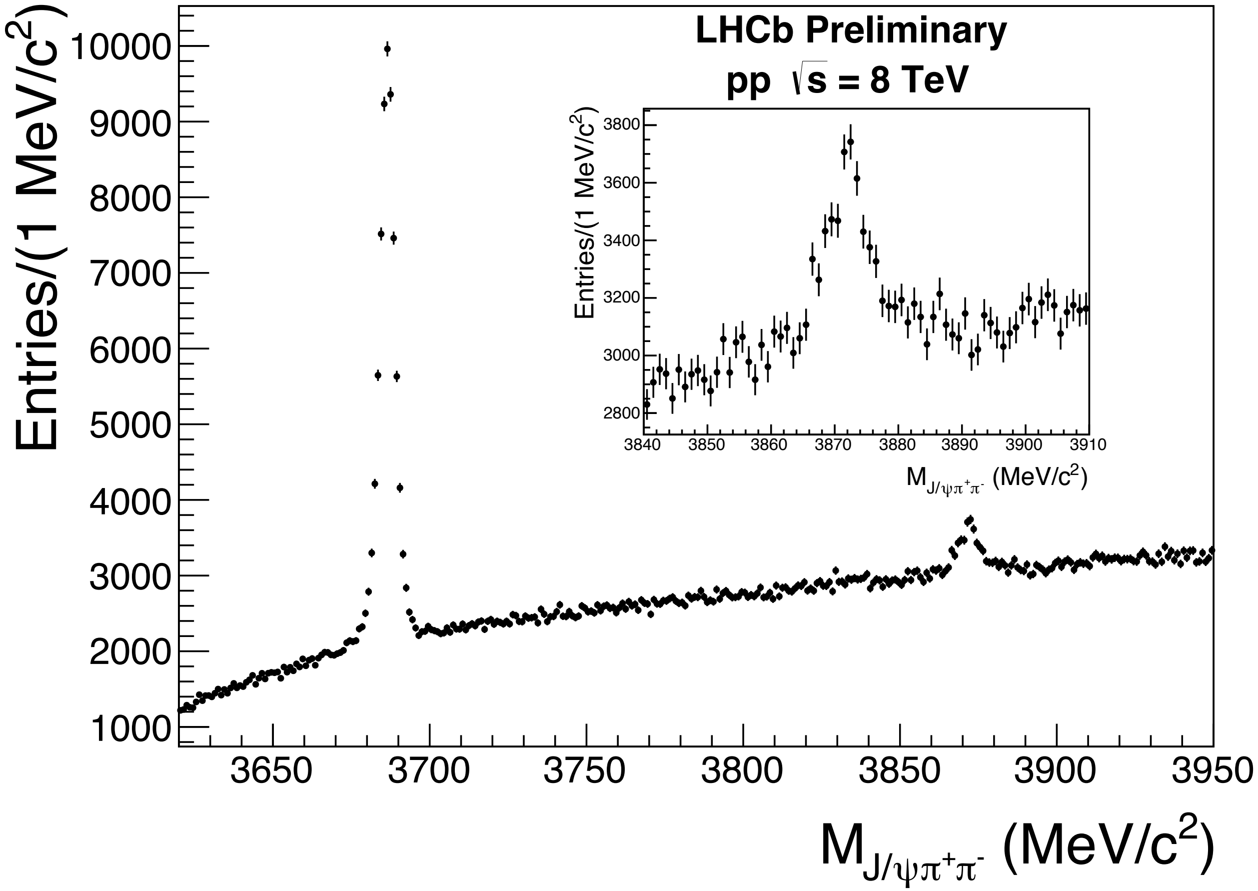
$$X(3872) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\rho(\rightarrow \pi^+\pi^-)$$

$$\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$$

Select $\boldsymbol{J/\psi}$ from dimuons, combine with two identified pions. Perform kinematic refit, constraining $\boldsymbol{J/\psi}$ mass to known value and all four tracks to identical vertex.

Direct comparison between conventional charmonium $\boldsymbol{\psi(2S)}$ and exotic $\boldsymbol{X(3872)}$ via ratio of cross sections:

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \rightarrow J/\psi\pi^+\pi^-]}$$



Prompt / *b*-decay separation

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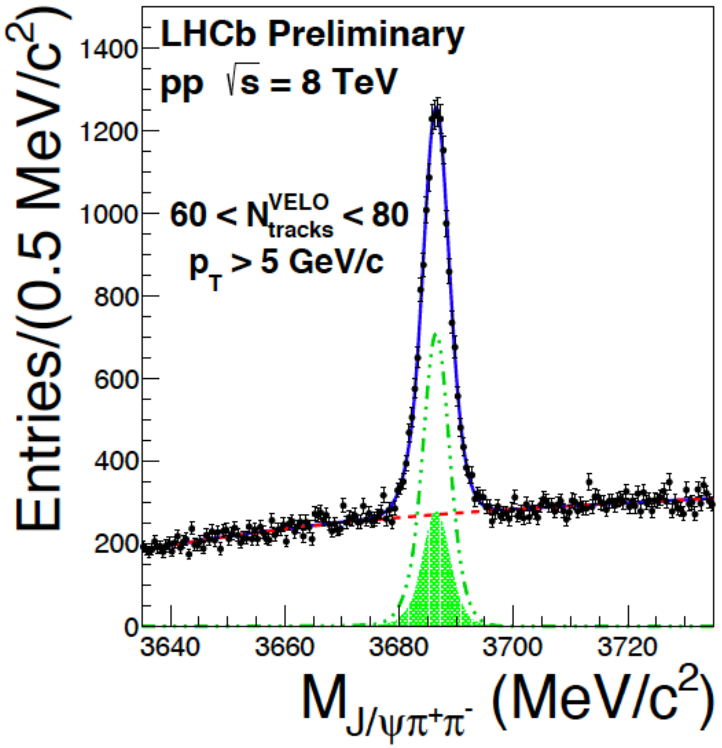
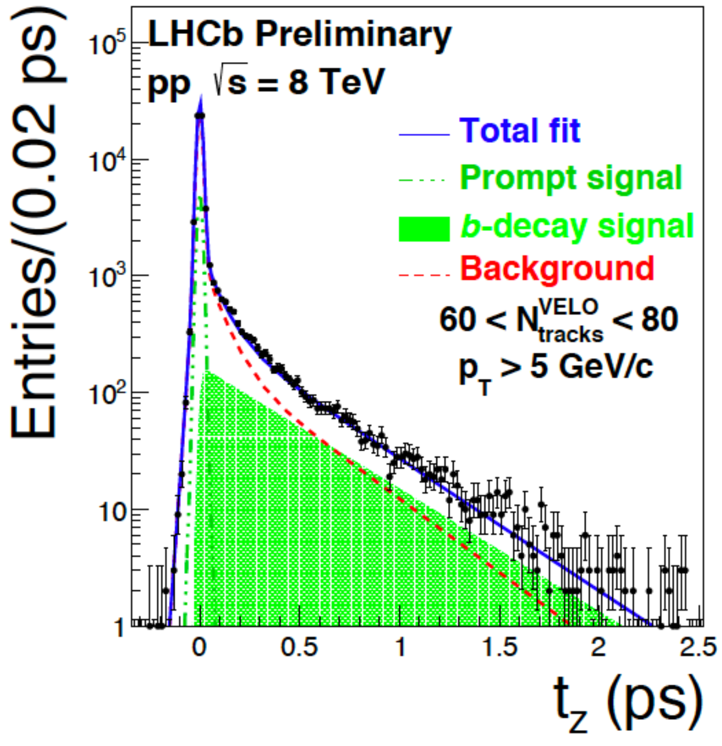
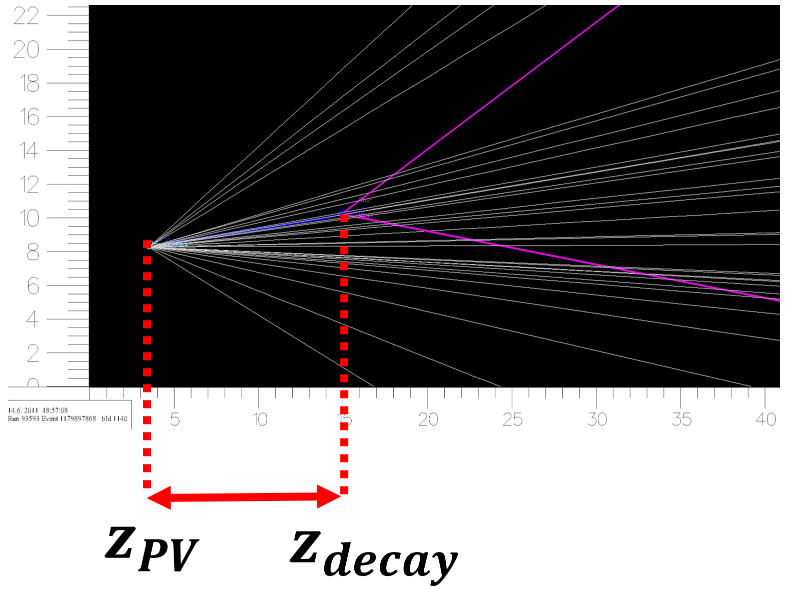




Simultaneous fit to invariant mass and pseudo proper time spectrum:

$$t_z = \frac{z_{decay} - z_{PV}}{p_z} M$$



Fit to mass constrains S/B while fit to t_z constrains prompt fraction

Prompt fraction

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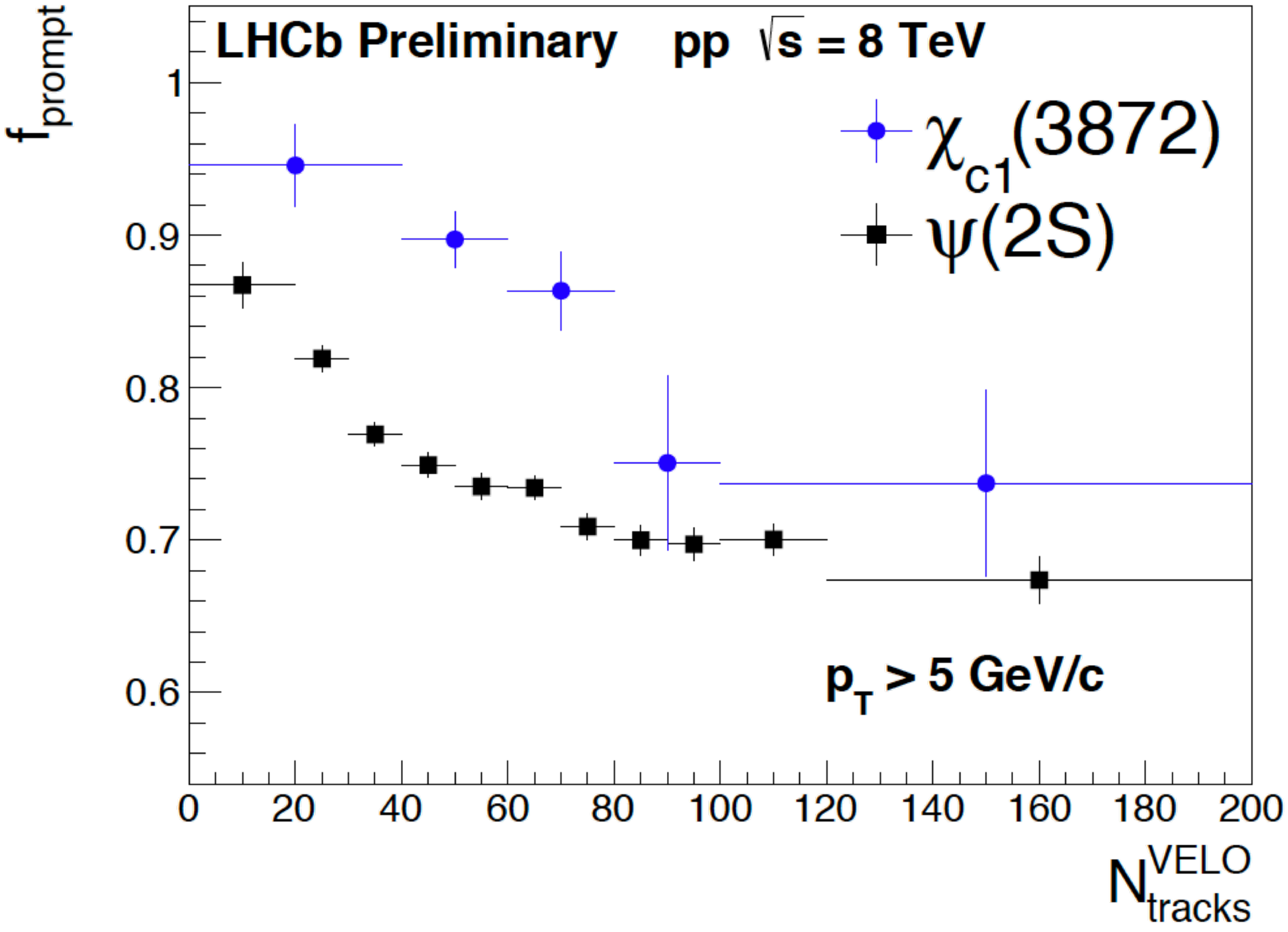

$$f_{prompt} = \frac{N_{prompt}}{N_{prompt} + N_{b-decay}}$$

- Significant decrease in prompt fraction of both $X(3872)$ and $\psi(2S)$ as event activity increases:

Prompt fraction

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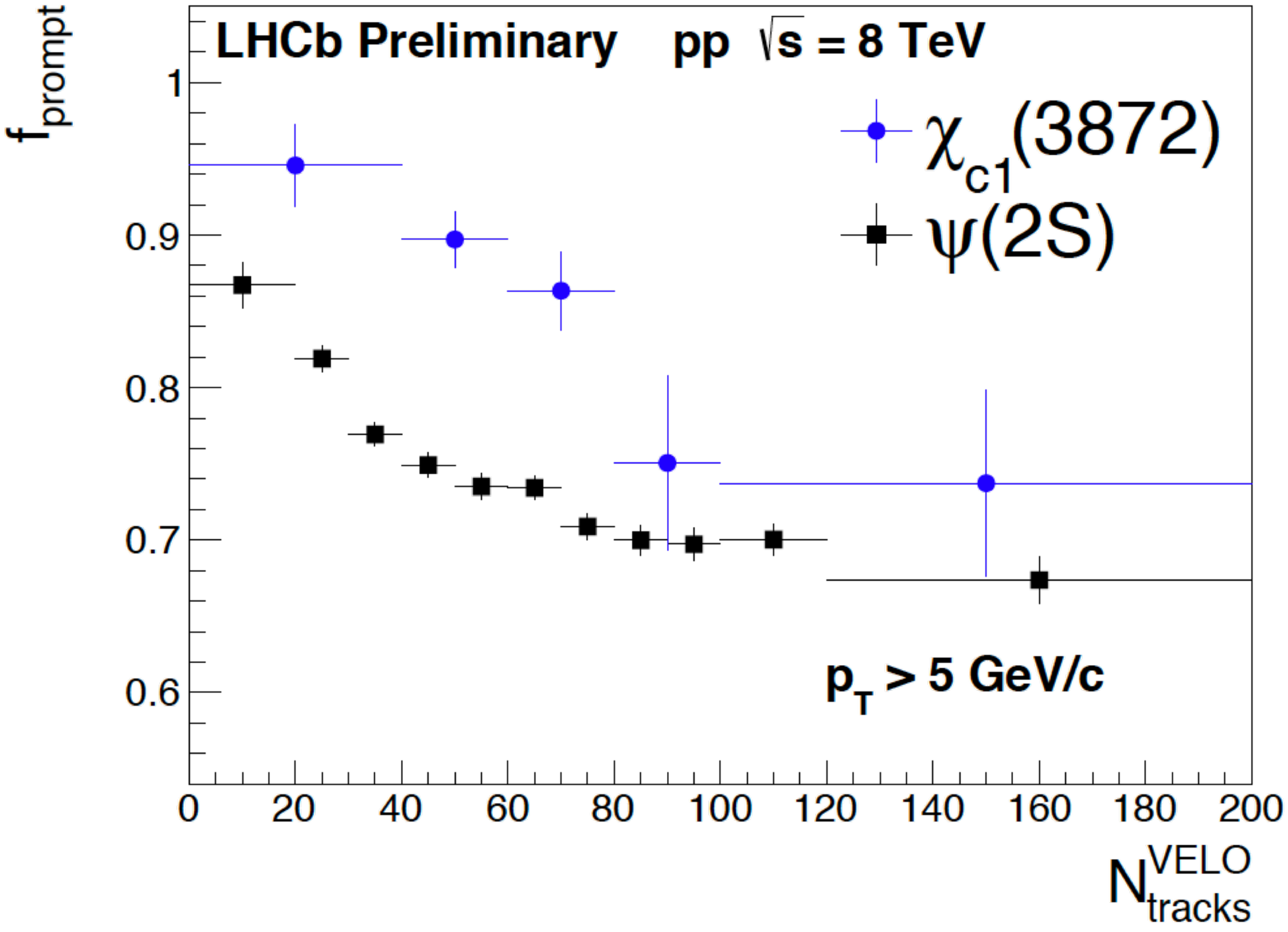

$$f_{prompt} = \frac{N_{prompt}}{N_{prompt} + N_{b-decay}}$$

- Significant decrease in prompt fraction of both $\boldsymbol{X(3872)}$ and $\boldsymbol{\psi(2S)}$ as event activity increases:
- Events with $\boldsymbol{b\bar{b}}$ production naturally have higher multiplicity, due to fragmentation and decays
  - OPAL, PLB 550 33 (2002)

Prompt fraction

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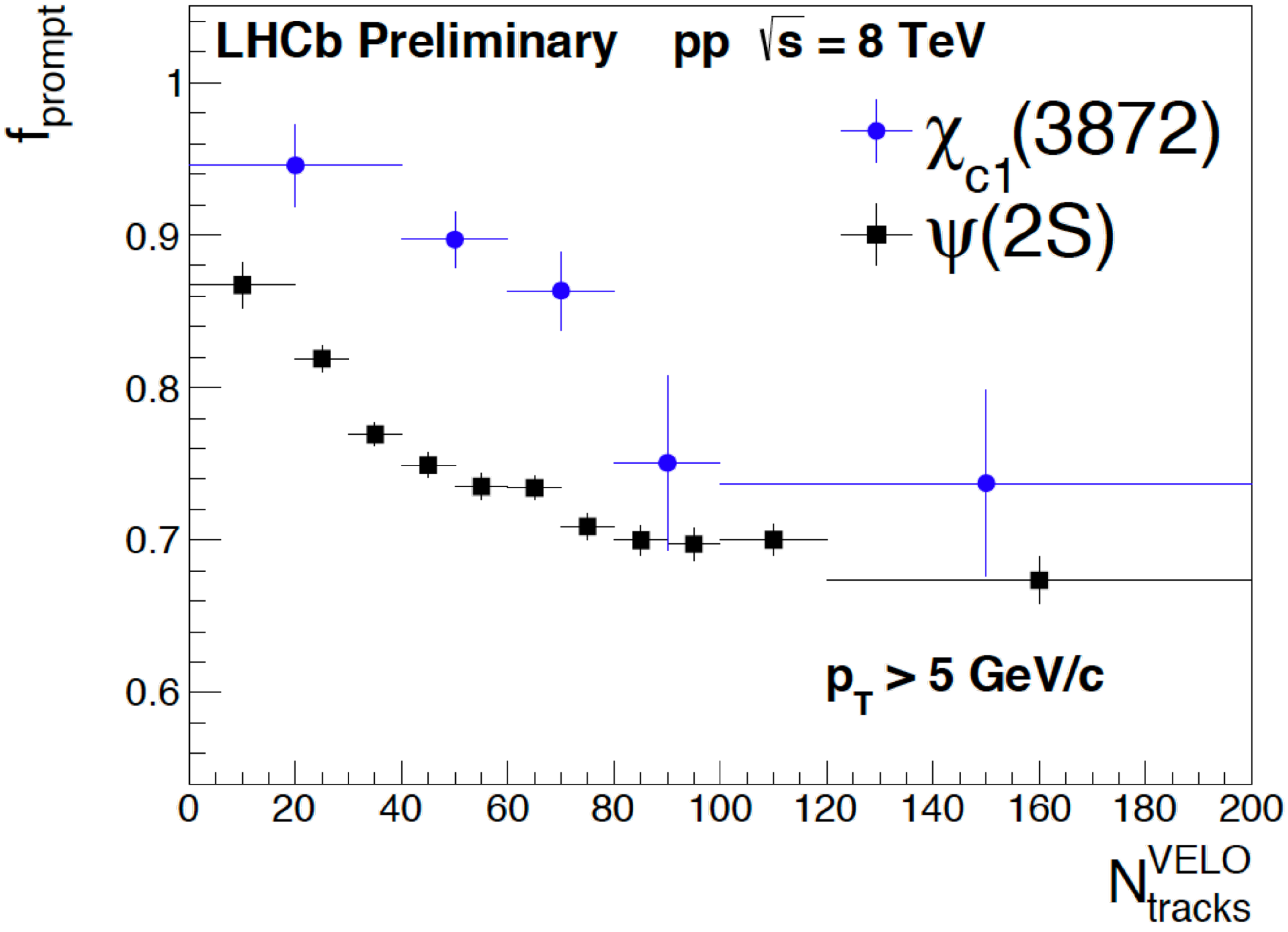


$$f_{prompt} = \frac{N_{prompt}}{N_{prompt} + N_{b-decay}}$$

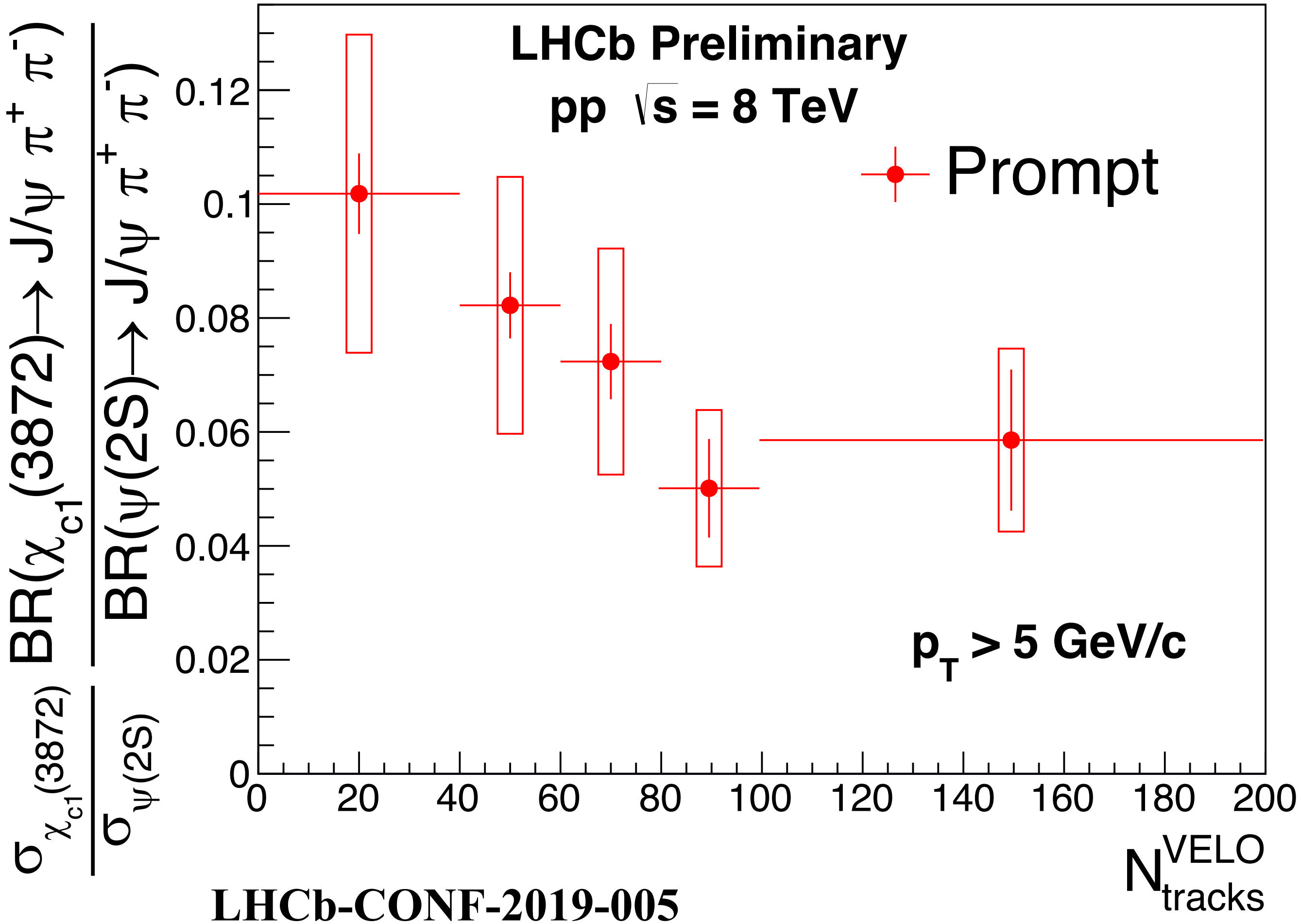
- Significant decrease in prompt fraction of both $X(3872)$ and $\psi(2S)$ as event activity increases:
- Events with $b\bar{b}$ production naturally have higher multiplicity, due to fragmentation and decays
    - OPAL, PLB 550 33 (2002)
- Formation of prompt $X(3872)$ and $\psi(2S)$ may be disrupted at the vertex, which cannot affect production via b decays in vaccum.

Ratio of cross sections

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \to J/\psi\,\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \to J/\psi\,\pi^+\pi^-]} = \frac{N_{\chi_{c1}(3872)}\, f_{\text{prompt}}^{\chi_{c1}(3872)}}{N_{\psi(2S)}\, f_{\text{prompt}}^{\psi(2S)}} \times \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{\chi_{c1}(3872)}}$$

Ratio of cross sections

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \rightarrow J/\psi\pi^+\pi^-]} = \frac{N_{\chi_{c1}(3872)}\, f^{\chi_{c1}(3872)}_{\text{prompt}}}{N_{\psi(2S)}\, f^{\psi(2S)}_{\text{prompt}}} \times \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{\chi_{c1}(3872)}}$$



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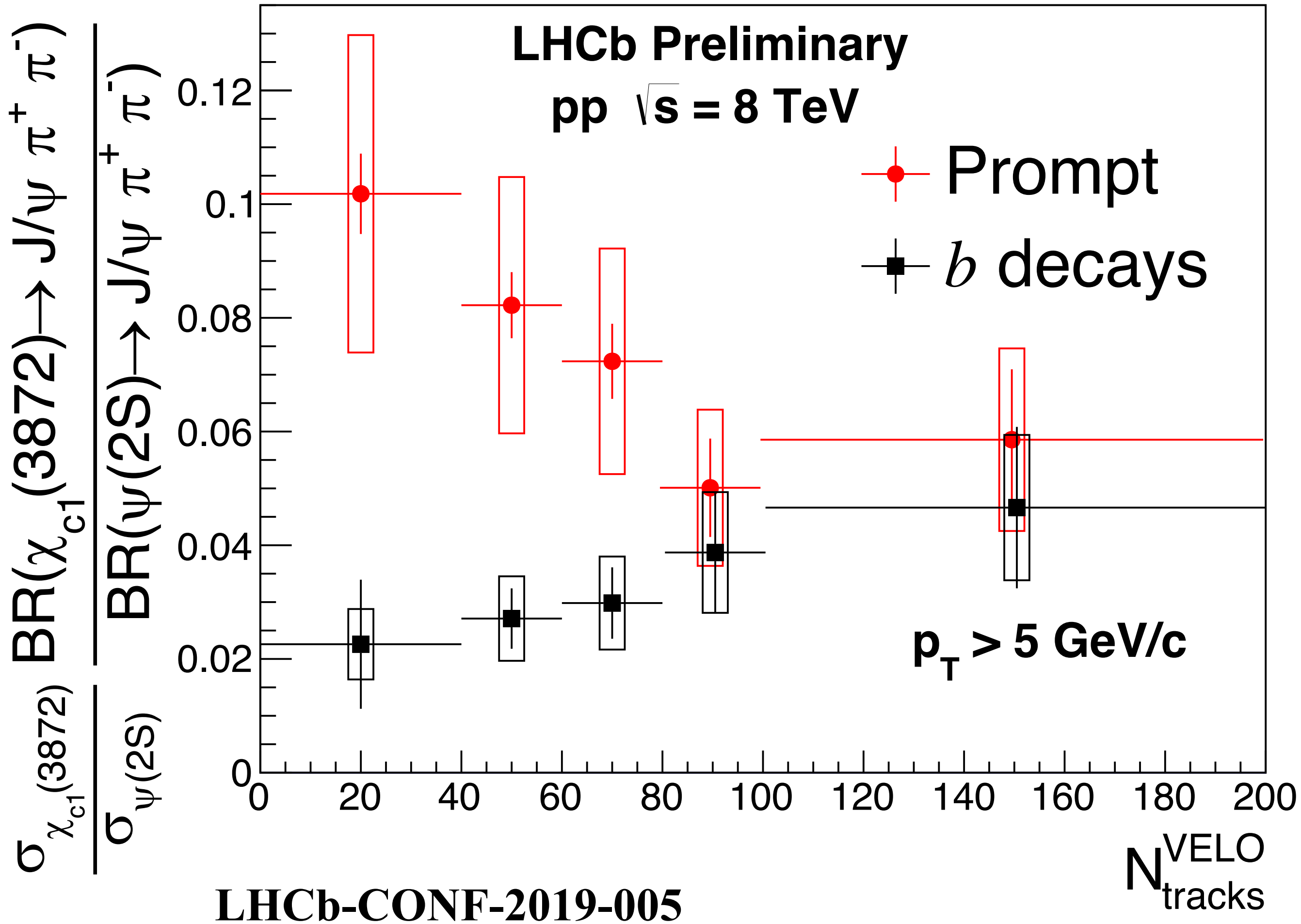
Prompt Component:
Increasing suppression of $\boldsymbol{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as event activity increases

Ratio of cross sections

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]} = \frac{N_{\chi_{c1}(3872)}\, f^{\chi_{c1}(3872)}_{\text{prompt}}}{N_{\psi(2S)}\, f^{\psi(2S)}_{\text{prompt}}} \times \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{\chi_{c1}(3872)}}$$



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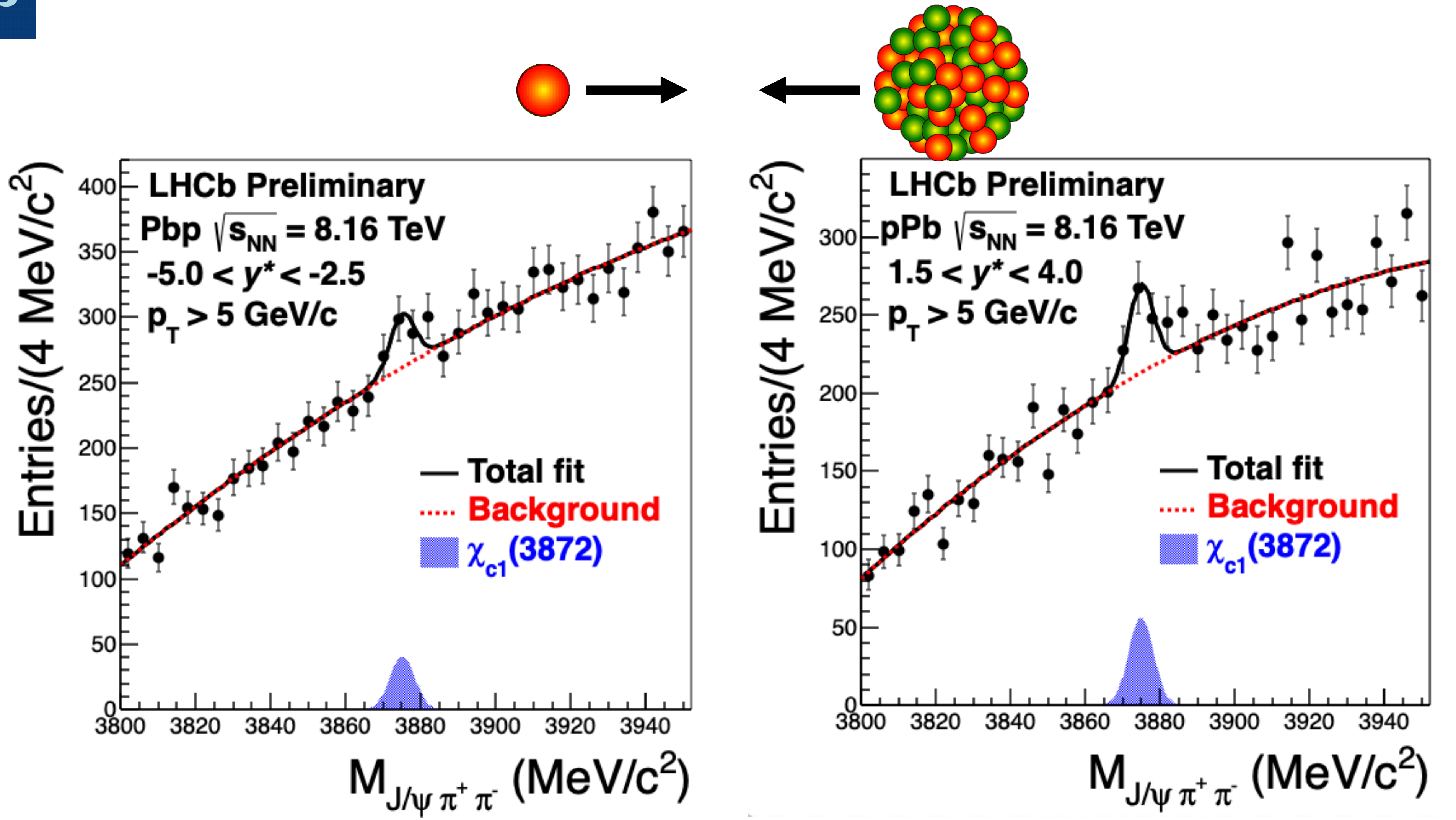
Prompt Component:
Increasing suppression of $X(3872)$ production relative to $\psi(2S)$ as event activity increases

***b*-decay component:**
No significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching fractions.
Consistent with ATLAS measurement
$R = 0.0395 \pm 0.0032 \pm 0.0008$ (p_T>10GeV/c)
JHEP 2017:117 (2017)

X(3872) in pPb collisions



Theorists: predictions welcome

Summary

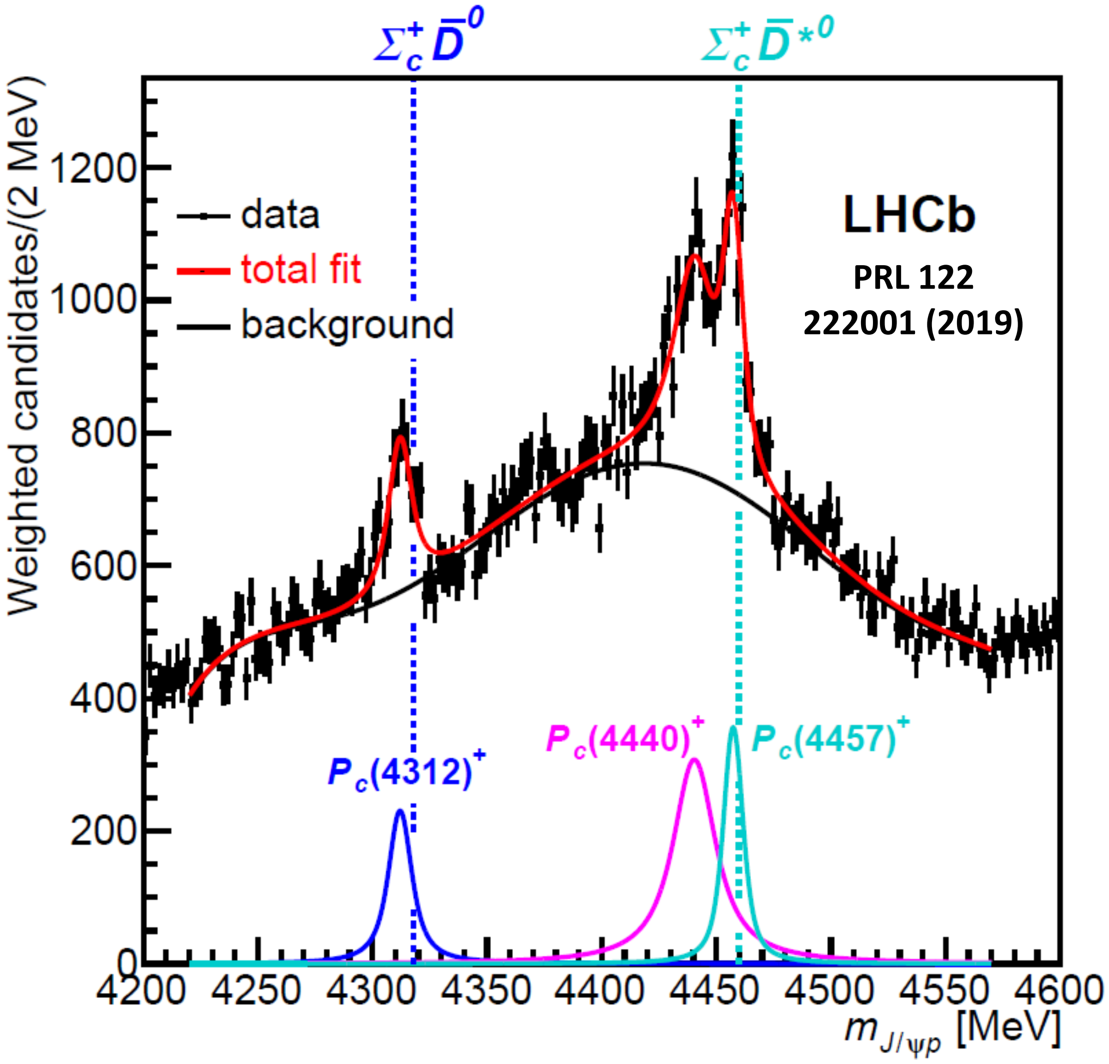
- The study of exotic hadrons is an active area of discovery in QCD

- Data and techniques from heavy ion physics give us a new window into dynamics of exotic states in a dense QCD environment:
  - Prompt fraction of **X(3872)** and $\boldsymbol{\psi(2S)}$ decreases with multiplicity in pp
  - Relative production in ***b***-decays shows no significant change with multiplicity
  - Indications that prompt **X(3872)** may be suppressed more than prompt $\boldsymbol{\psi(2S)}$ as multiplicity increases

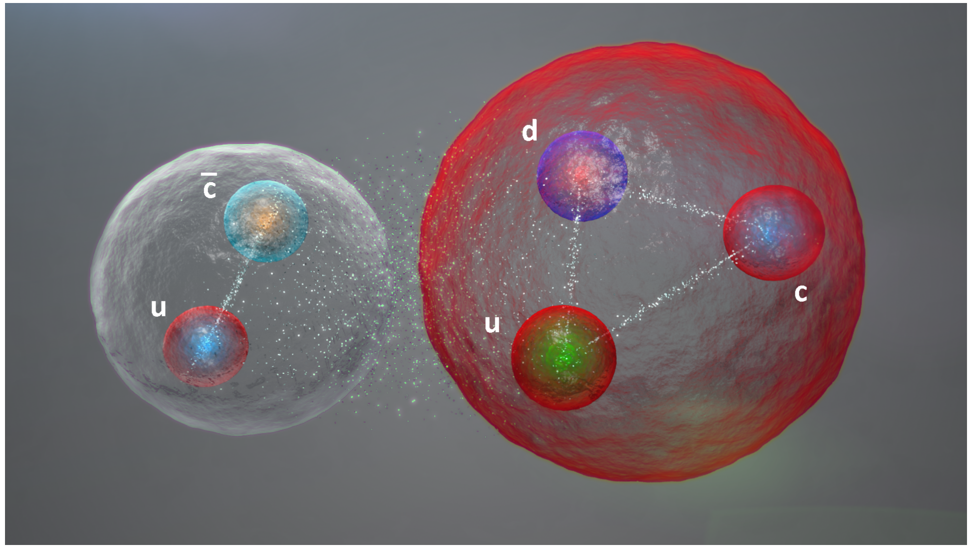
- Consistent with the interpretation of **X(3872)** as a large, weakly bound state such as a hadronic molecule.

This work is supported by the US Dept. of Energy/Office of Science/Nuclear Physics Division

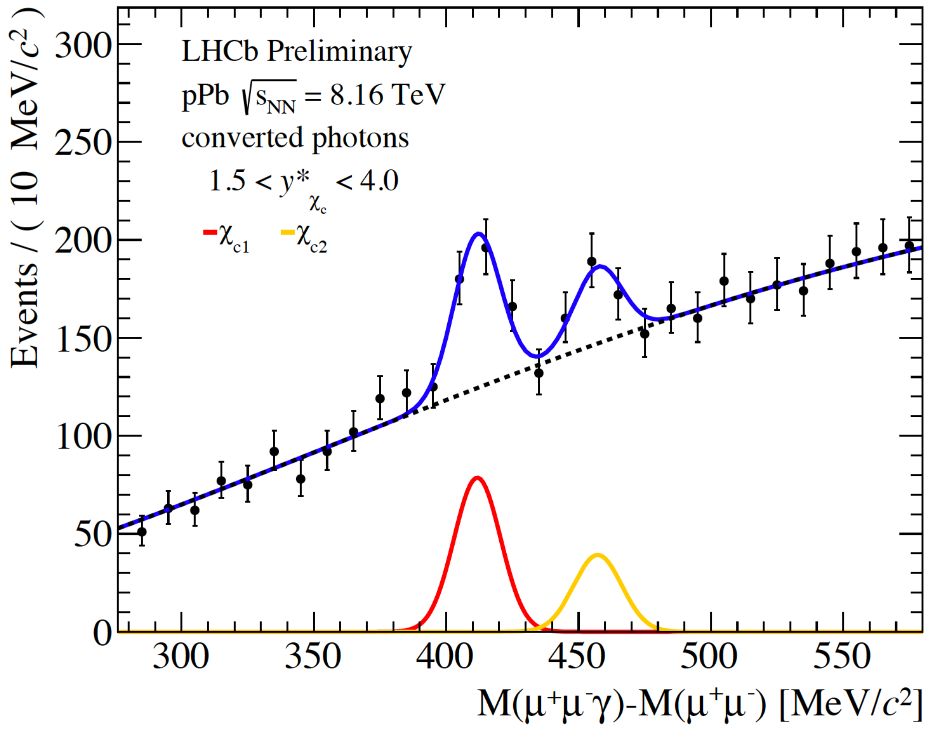
Recent Hadronic Molecule Candidates

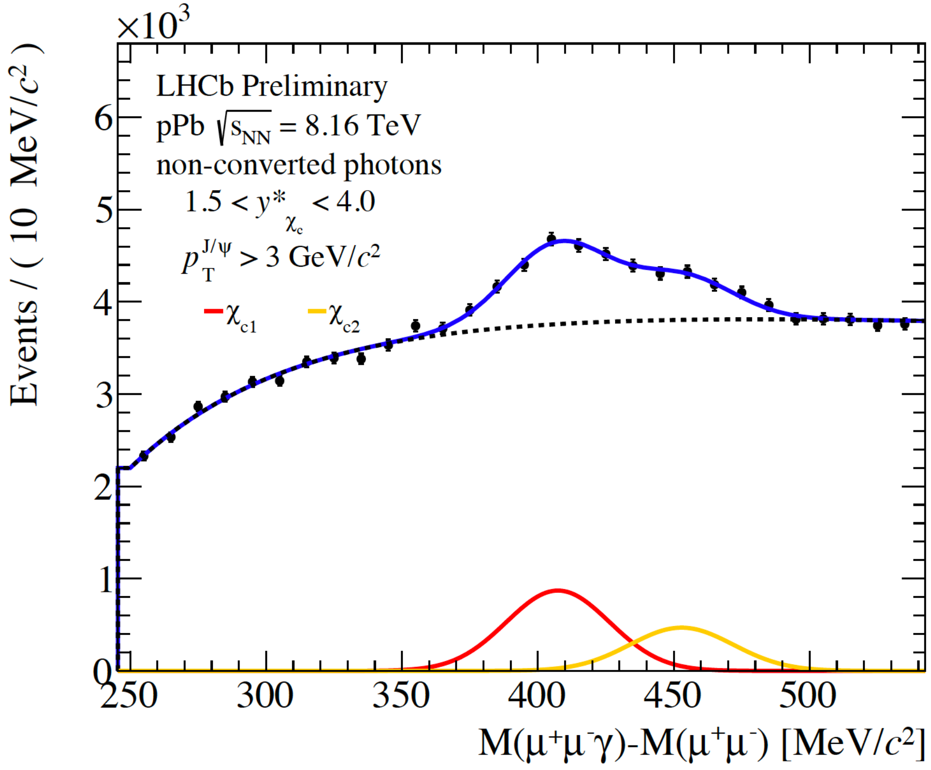


P_c pentaquark states recently discovered by LHCb are very close to mass thresholds for hadronic molecules.

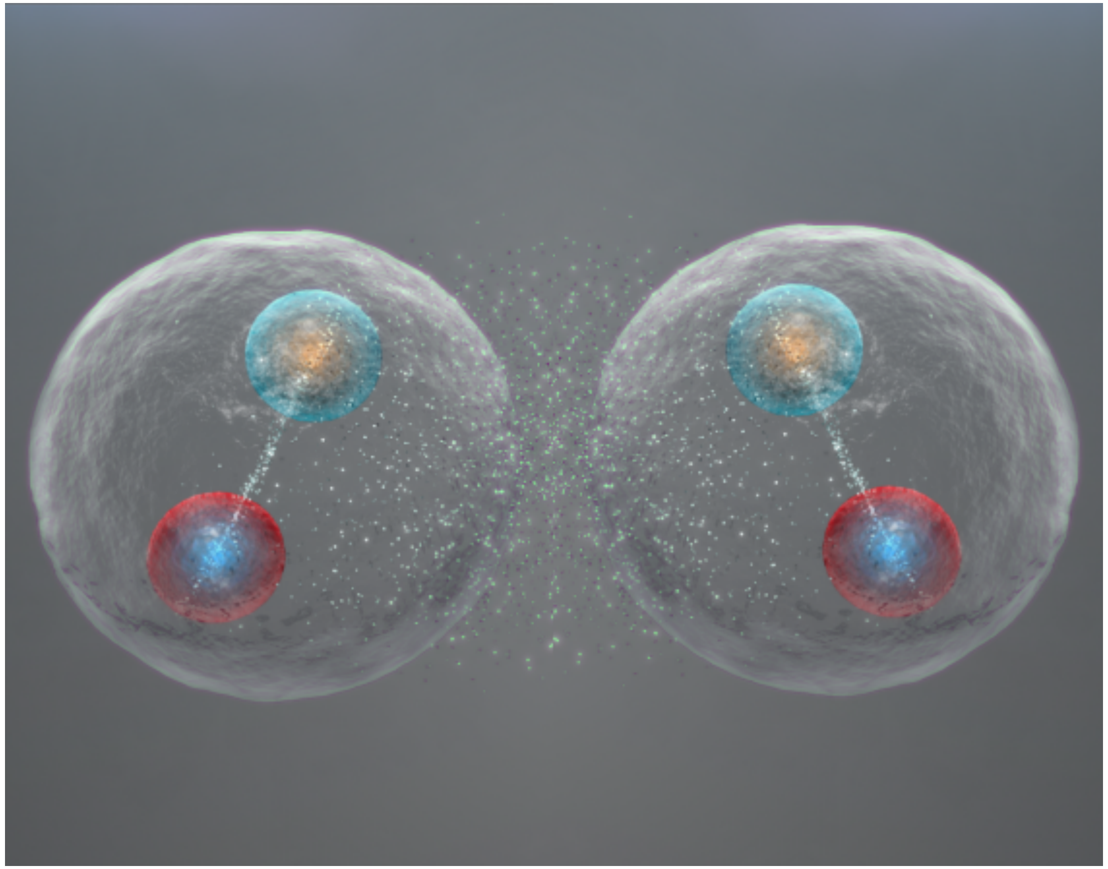


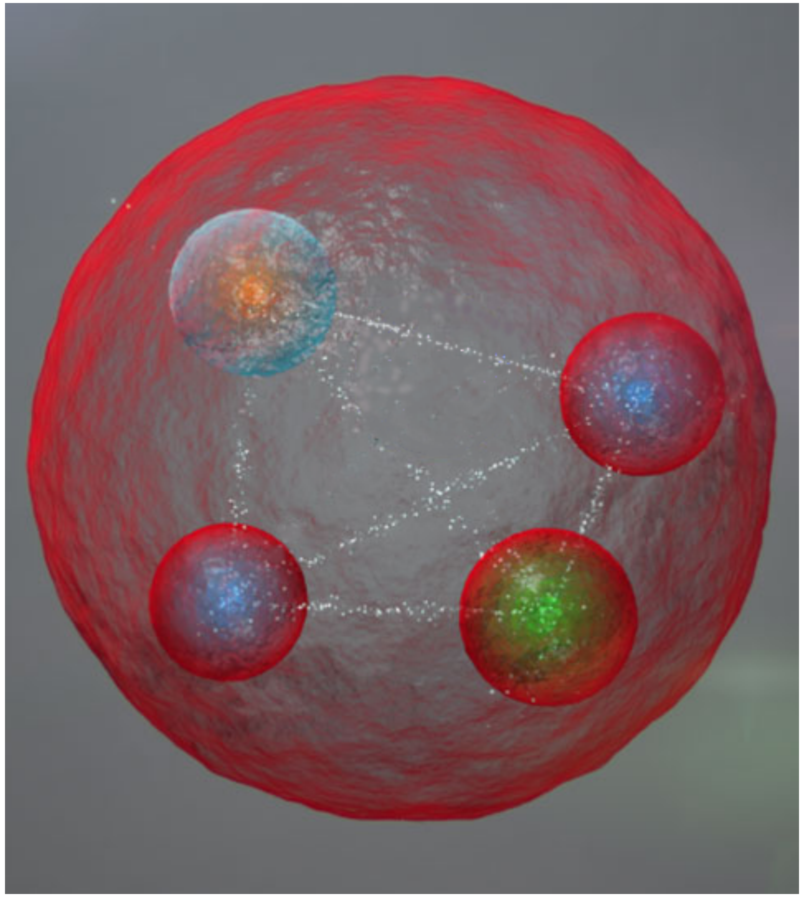
χ_c States in pPb





See Poster by Jana Crkovska





Observation of the $\Lambda_b^0 \to \chi_{c1}(3872)pK^-$ decay

The LHCb collaboration

E-mail: Ivan.Belyaev@itep.ru

Abstract: Using proton-proton collision data, collected with the LHCb detector and corresponding to 1.0, 2.0 and 1.9 fb^{-1} of integrated luminosity at the centre-of-mass energies of 7, 8, and 13 TeV, respectively, the decay $\Lambda_b^0 \to \chi_{c1}(3872)pK^-$ with $\chi_{c1}(3872) \to J/\psi\,\pi^+\pi^-$ is observed for the first time. The significance of the observed signal is in excess of seven standard deviations. It is found that $(58 \pm 15)\%$ of the decays proceed via the two-body intermediate state $\chi_{c1}(3872)\Lambda(1520)$. The branching fraction with respect to that of the $\Lambda_b^0 \to \psi(2S)pK^-$ decay mode, where the $\psi(2S)$ meson is reconstructed in the $J/\psi\,\pi^+\pi^-$ final state, is measured to be:

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1}(3872)pK^-)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)pK^-)} \times \frac{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\,\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\,\pi^+\pi^-)} = (5.4 \pm 1.1 \pm 0.2) \times 10^{-2}\,,$$

where the first uncertainty is statistical and the second is systematic.

Keywords: B physics, Branching fraction, Exotics, Hadron-Hadron scattering (experiments)

ArXiv ePrint: 1907.00954

JHEP09(2019)028