Exotic Charmonium States @ LHC

Flavor Physics & CP Violation 2013
Buzios, Rio, Brasil

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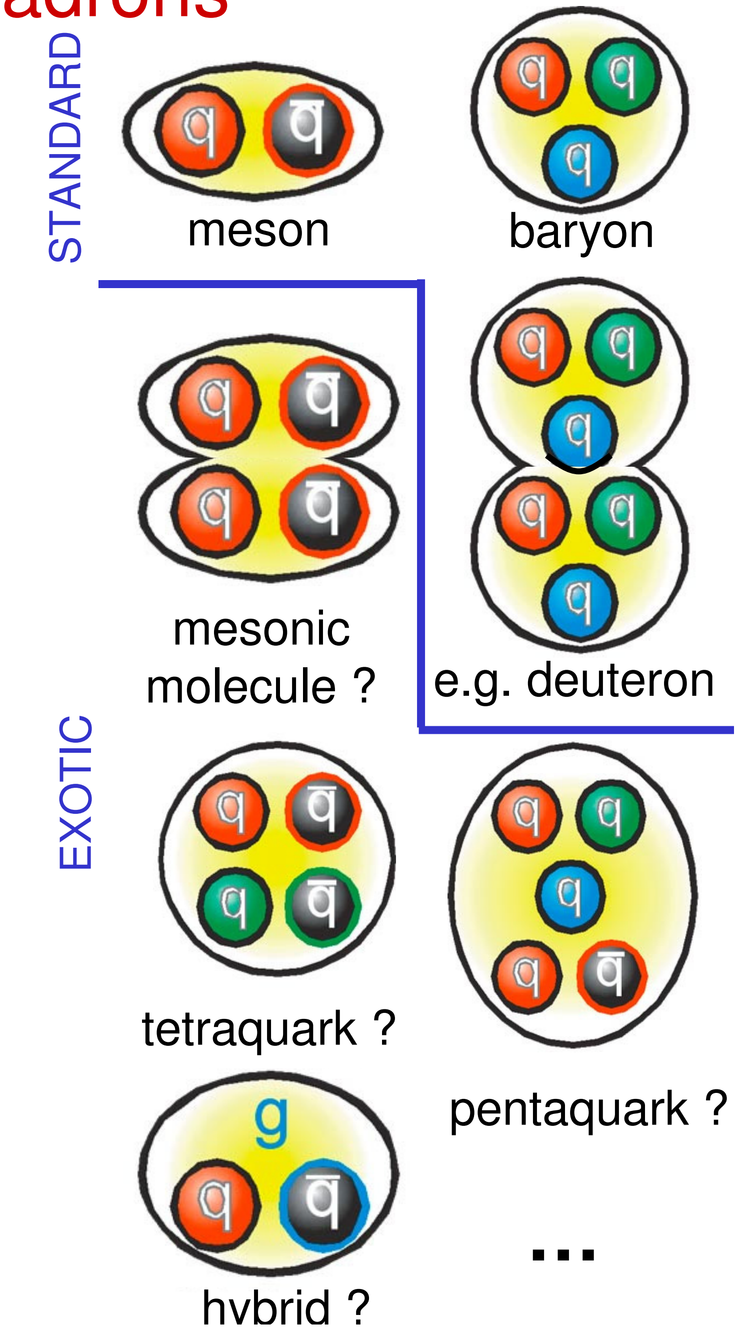
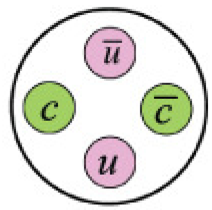
On behalf of the LHCb collaboration,
including results from CMS experiment

Standard and Exotic Hadrons

- Longstanding dispute in light meson spectroscopy if exotic states exist (too many scalar states?)
- No convincing experimental proofs for existence of elusive pentaquarks
- Recent discoveries in heavy quark states have revived hopes for conclusive proofs for existence of exotic mesons



X(3872)

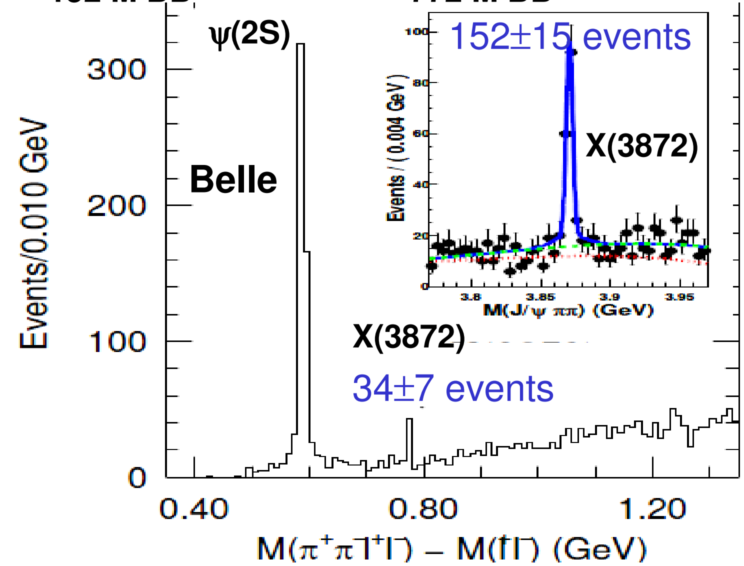


?

- Discovered by Belle in 2003 at e^+e^- B-factory in $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\, \pi^+\pi^-$
- Confirmed by CDF and D0 in 2004 at Tevatron, mostly prompt (~84%) production $pp \to X(3872)$+anything
- Also observed by BaBar in 2005. Later at LHC by LHCb and CMS.
- Its width, mass and decay modes disfavor a standard $c\bar{c}$ state.
- $D\bar{D}^*$ molecule, tetraquark, hybrid…?
- Even 10 years after the discovery some basic experimental questions are not answered:
  - Is its $J^{PC}=1^{++}$ or 2^{-+} ?
  - Is its mass below the $D\bar{D}^*$ threshold?
  - Prompt production mechanism ?

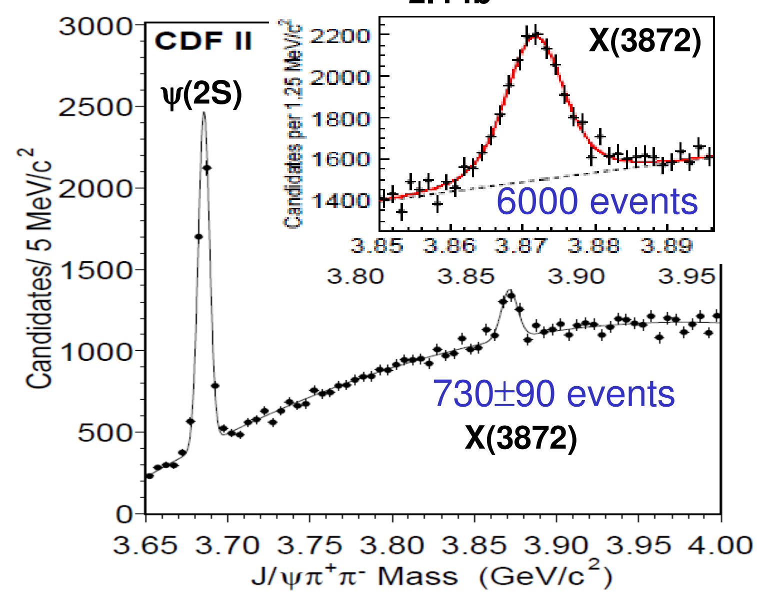
PRL 91, 262001 (2003) 152 M BB

PRD 84, 052004 (2011) 772 M BB

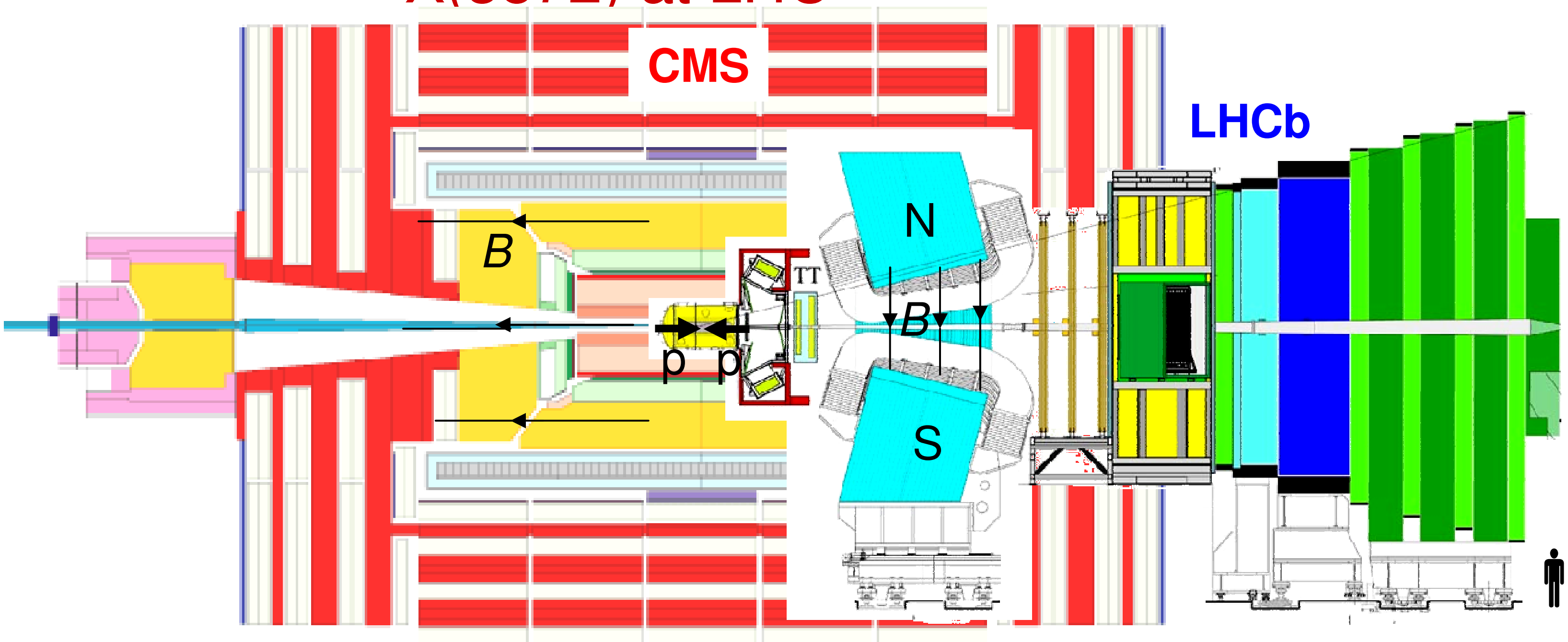


PRL 93, 072001 (2004) 0.22 fb^{-1}

PRL 103,152001 (2009) 2.4 fb^{-1}



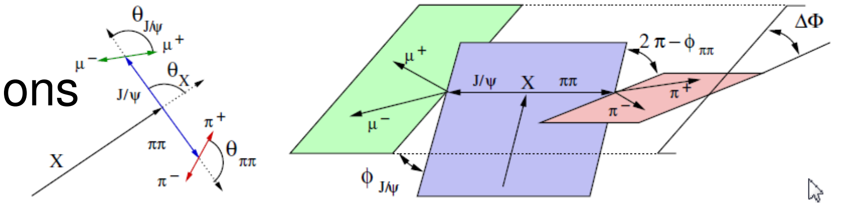
X(3872) at LHC



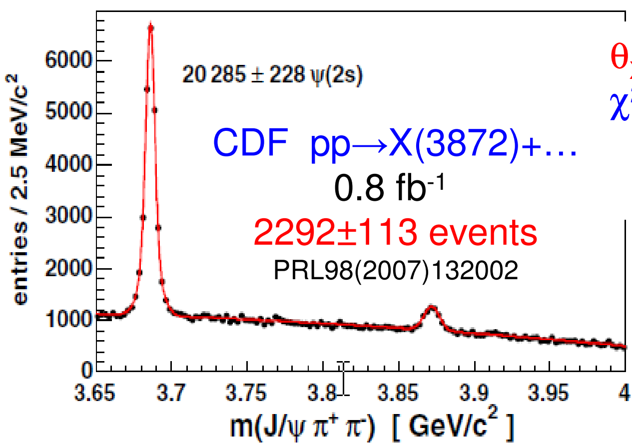
- Advantages of LHC vs e^+e^-:
  - Prompt production and orders of magnitude larger B-meson production rates
- Advantages of LHC vs Tevatron:
  - Higher cross-section thanks to higher energy
- Advantages of LHCb vs central detectors:
  - Large trigger bandwidth totally devoted to heavy flavor physics; higher trigger efficiencies
  - Can identify and trigger on lower p_T (di)muons
  - K/π separation (RICH detectors)
- Advantage of CMS vs LHCb:
  - Higher luminosity

X(3872) quantum numbers

- Key for narrowing down theoretical interpretations
- C = + since decay to $\gamma J/\psi$ was observed
  BaBar PRD74(2006)071101; Belle PRL107(2011)091803
- Best sensitivity to J^P via **angular correlations** among decay products in the most copiously observed decay mode $X(3872) \to (J/\psi \to \mu^+\mu^-)(\rho \to \pi^+\pi^-)$



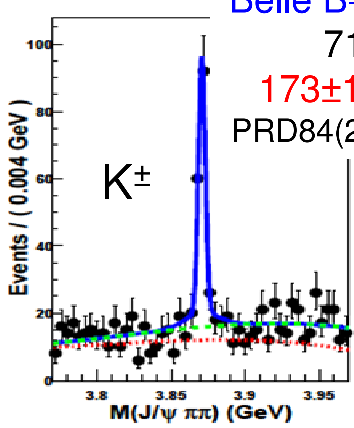
5 angles to work with e.g.:
3 helicity angles: θ_X, $\theta_{J/\psi}$, $\theta_{\pi\pi}$
2 independent angles between decay planes

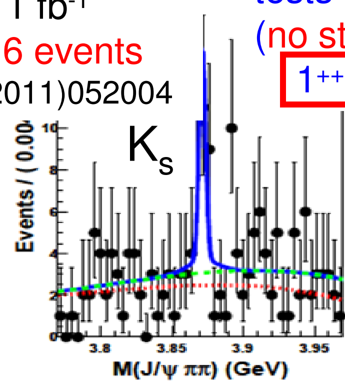


CDF $p\bar{p} \to X(3872)+\ldots$
0.8 fb^{-1}
2292±113 events
PRL98(2007)132002

θ_X unknown in prompt production
χ^2 tests on binned 3D-correlations:
disfavor all J^{PC} but $1^{++}, 2^{-+}$ which could not be distinguished

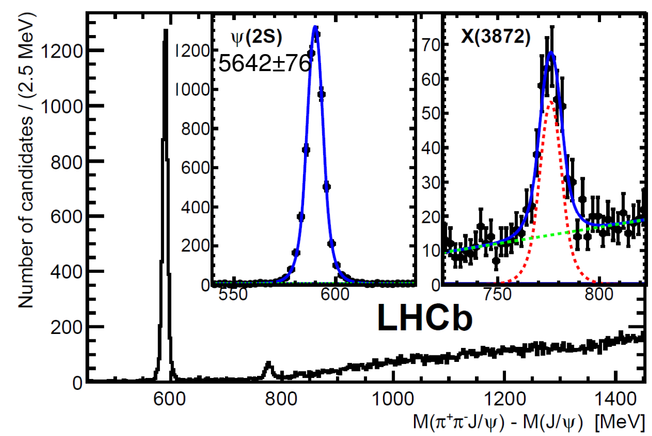
Belle $B \to X(3872)K$
711 fb^{-1}
173±16 events
PRD84(2011)052004





θ_X known in $B \to X(3872)K$
tests on binned 1D-distributions
(no study of correlations)
$1^{++}, 2^{-+}$ could not be distinguished

LHCb $B^+ \to X(3872)K^+$
1 fb^{-1}
new
313±26 events
arXiv:1302.6269
Accepted by PRL

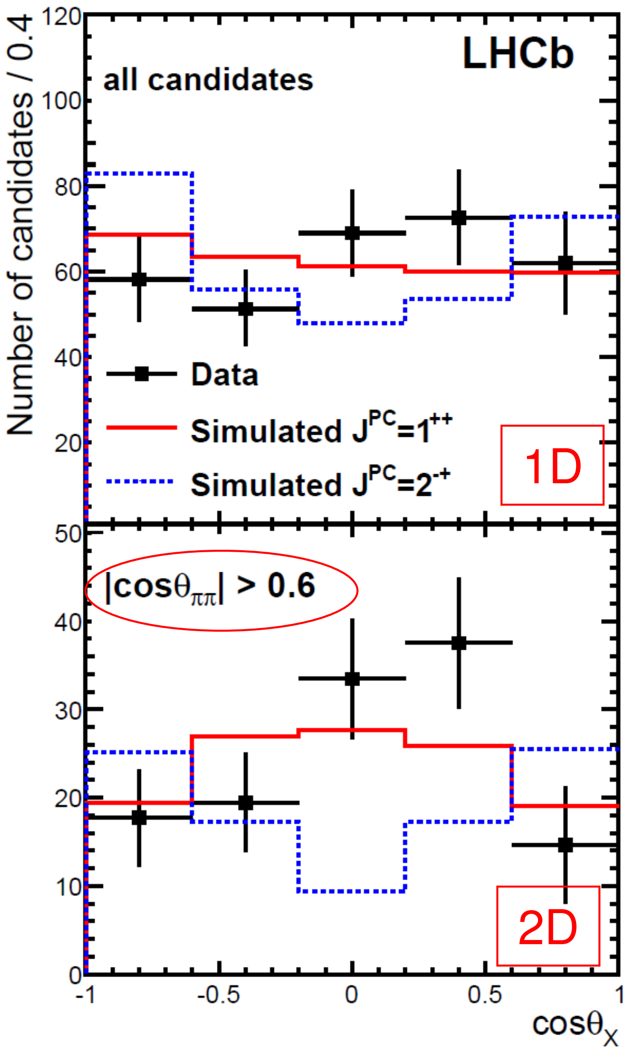


Quality of sample as good as at e^+e^-!

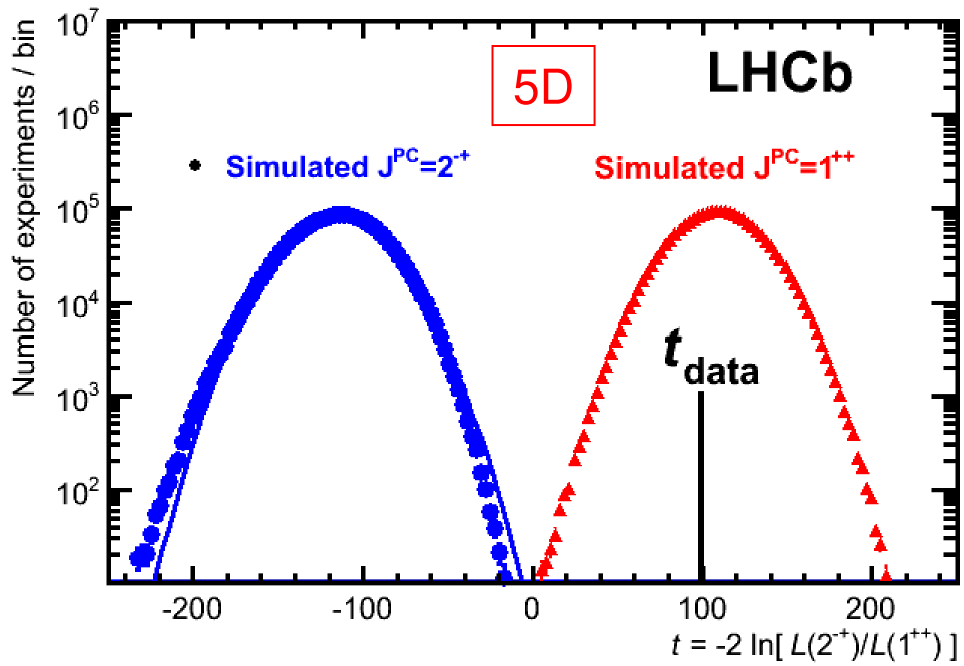
Likelihood-ratio test using 5D-correlations (unbinned data)

X(3872) quantum numbers

Projections of 5D likelihood fits



- Angular correlations increase spin sensitivity
- Best sensitivity using correlations among all 5 angles:
  - Best way to test them: **the likelihood-ratio test**



2^{-+} rejected at $>8\sigma$

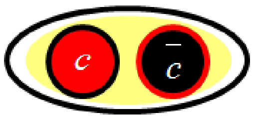
The data are consistent with 1^{++}

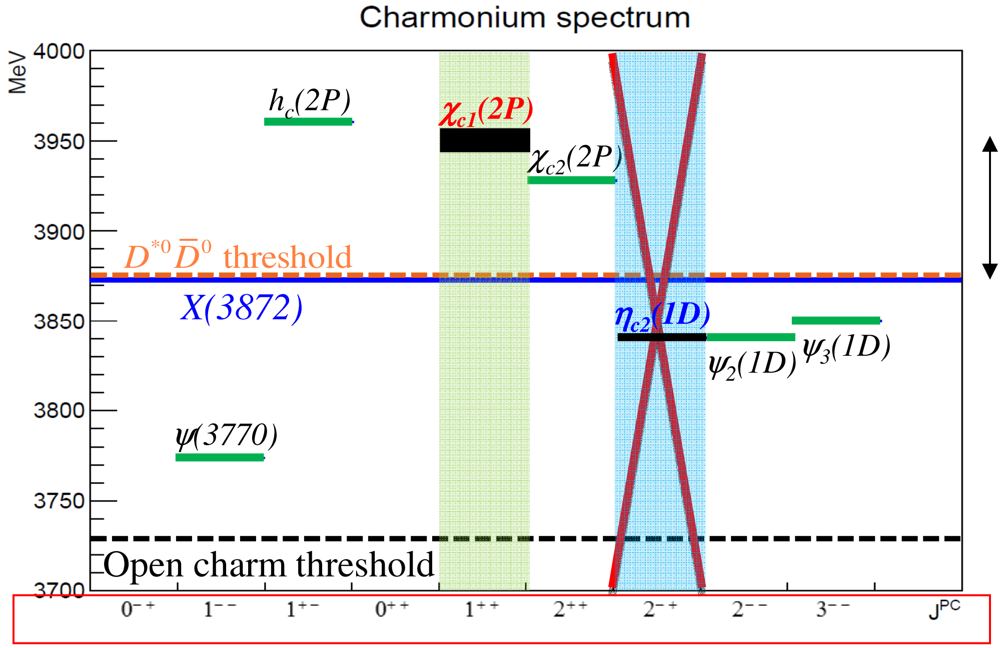
X(3872) interpretations

J^{PC} of X(3872) has been determined to be 1^{++}

$\eta_{c2}(1^1D_{2-+})$ is now ruled out!

Charmonium



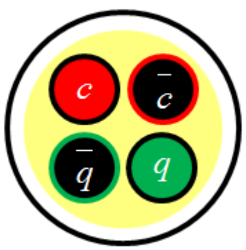


$\chi_{c1}(2^3P_{1++})$ possible but disfavored by mass

1^{++} was expected in both tetra-quark and molecular models

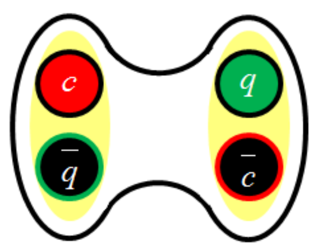
The four-quark models also favored by the coincidence of X(3872) mass with the $D^{*0}\overline{D^0}$ threshold

Tetra-quark



Nearly degenerate charged partners expected but not observed.

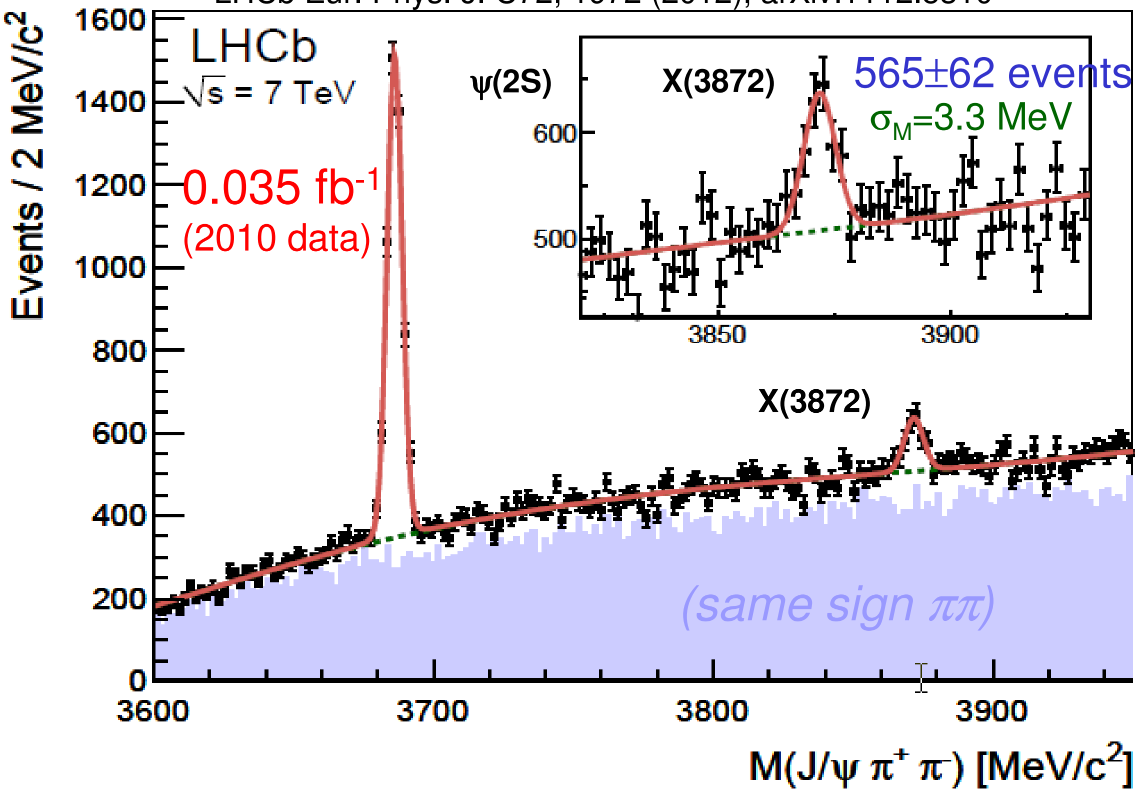
$D^{*0}\overline{D^0}$ molecule



Binding energy requires mass to be below $M(D^0)+M(D^{*0})$. Satisfied? (see next)

Inclusive X(3872) at LHCb (mostly prompt) - M[X(3872)]

LHCb Eur. Phys. J. C72, 1972 (2012), arXiv:1112.5310



Mass resolution and S/B similar to CDF.

Signal yield/fb^{-1} 6.5 times higher than in CDF.

M[ψ(2s)] = 3686.12±0.06±0.10 MeV
vs PDG 3686.09±0.04 MeV

M[X(3872)] = 3871.95±0.48±0.12 MeV

vs CDF 3871.61±0.16±0.19 MeV
Belle 3871.84±0.27±0.19 MeV

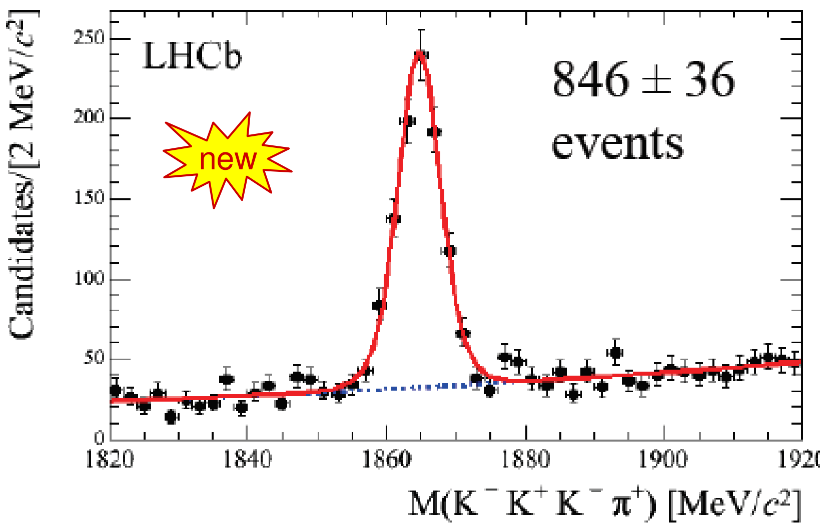
The statistical error on the mass measurement from 2010 data not competitive yet, but the systematic error is small.

Already have 3 fb^{-1} collected in 2011-12. Expected statistical error ~0.05 MeV.

Good determination of $M(D^0)+M(D^{0*})$ = **$2M(D^0)$** + $\Delta M(D^{0*}-D^0)$ also needed.

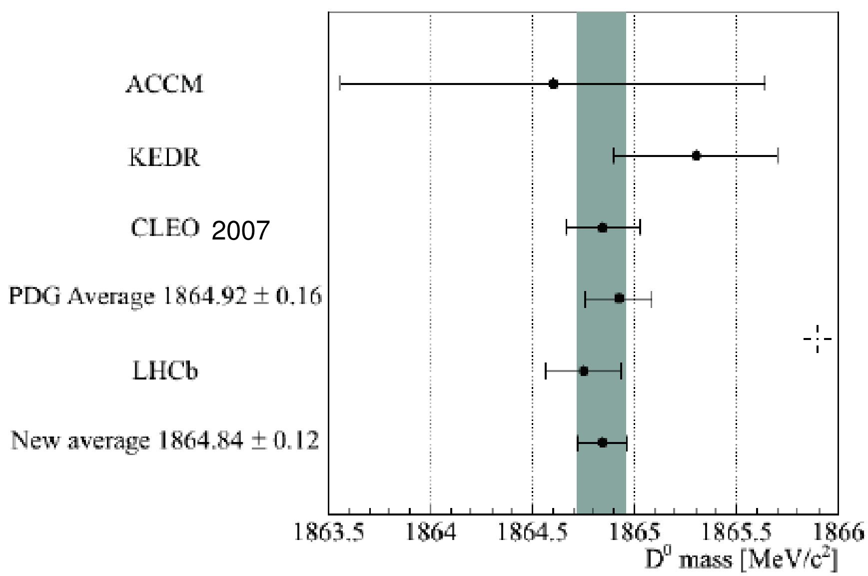
D^0 mass determination by LHCb

LHCb arXiv:1304.6865



- Use $D^0 \rightarrow K^- K^+ K^- \pi^+$ decays
- Low energy release → low systematic error
- Use D^0s produced in semileptonic b decays for good background suppression and high trigger efficiency

$M(D^0)$ = 1864.85±0.15±0.11 MeV



New average: $M(D^0)$=1864.84±0.12 MeV

+ using PDG averages:
$\Delta M(D^{*0}-D^0)$ =142.12±0.07 MeV
M[X(3872)] =3871.68±0.17 MeV

$M[X(3872)] - M(D^0+D^{*0})$= –0.12±0.30 MeV

If molecule then very loosely bound
→ large in size (>6 fm at 90% CL)

X(3872) production

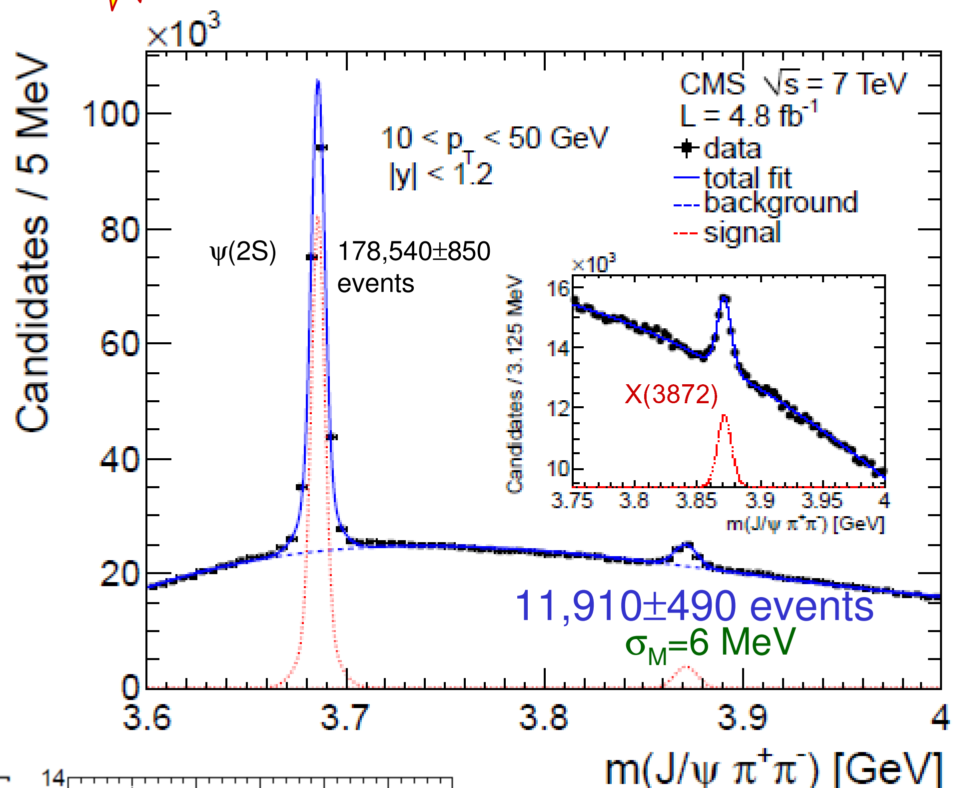
- Prompt X(3872) production cross-section measured at Tevatron:
  - Bignamini et al PRL103, 162001 (2009); PLB 684, 228 (2010)
    - orders of magnitude too large to be a $D\bar{D}^*$ molecule
  - Artoisenet, Braaten PRD81, 114018 (2010); PRD83, 014019 (2011):
    - can be reconciled with the molecular model when $D\bar{D}^*$ rescattering is considered
    - they also predicted X(3872) pp σ x BR(X(3872) $\to J/\psi\, \pi^+\pi^-$) at LHC scaling from the measurement at Tevatron using NRQCD approach
  - Esposito,Piccinini,Pilloni,Polosa arXiv:1305.0527:
    - Propose elastic scattering of D-meson pairs with co-moving pions as alternative mechanism for enhancement of molecular X(3872) in prompt production (no predictions yet) new

- The cross-section measured by the LHCb in the 2010 data (E_{CM}=7 TeV) a factor of 2.4 smaller than predicted:
  - 5.4±1.3±0.4 nb in 2.5< y <4.5 and 5 < p_T <20 GeV vs. 13.0±2.7 nb (Artoisenet, Braaten – error from the normalization to CDF)
  - This was based on very little data in the forward region.
- Need more measurements including differential cross-sections, separating prompt and B productions. Also in the central region.

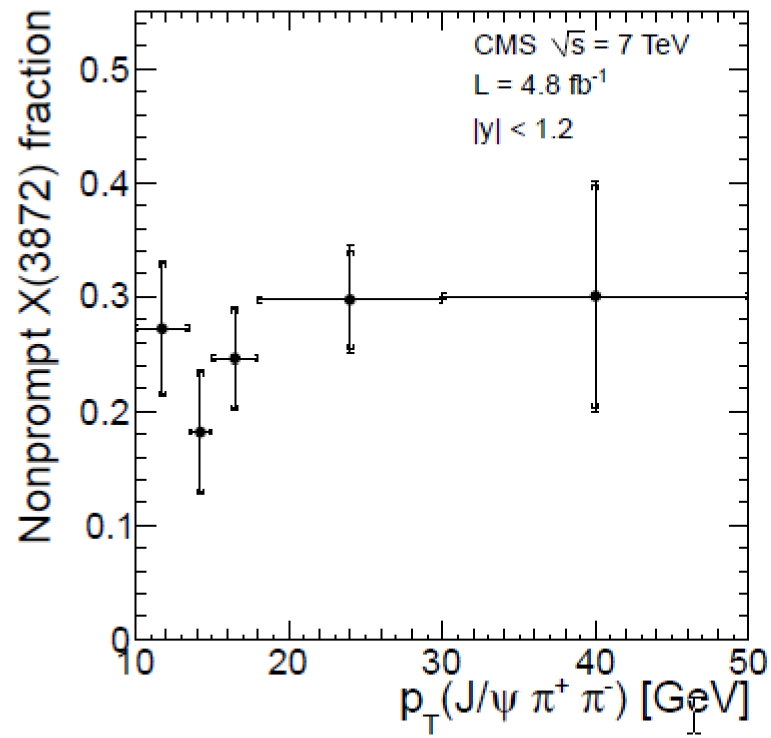
X(3872) production at the central region at LHC

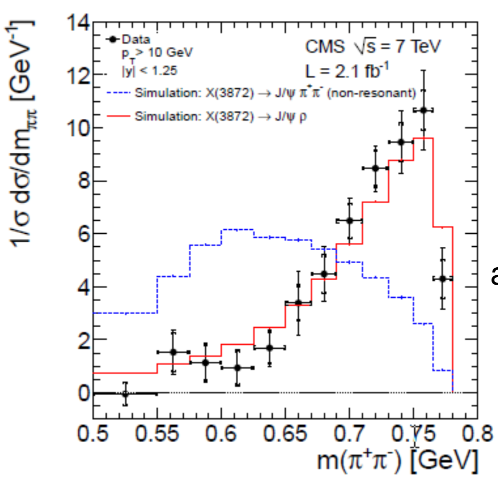
new

CMS JHEP 1304(2013)154 arXiv:1302.3968



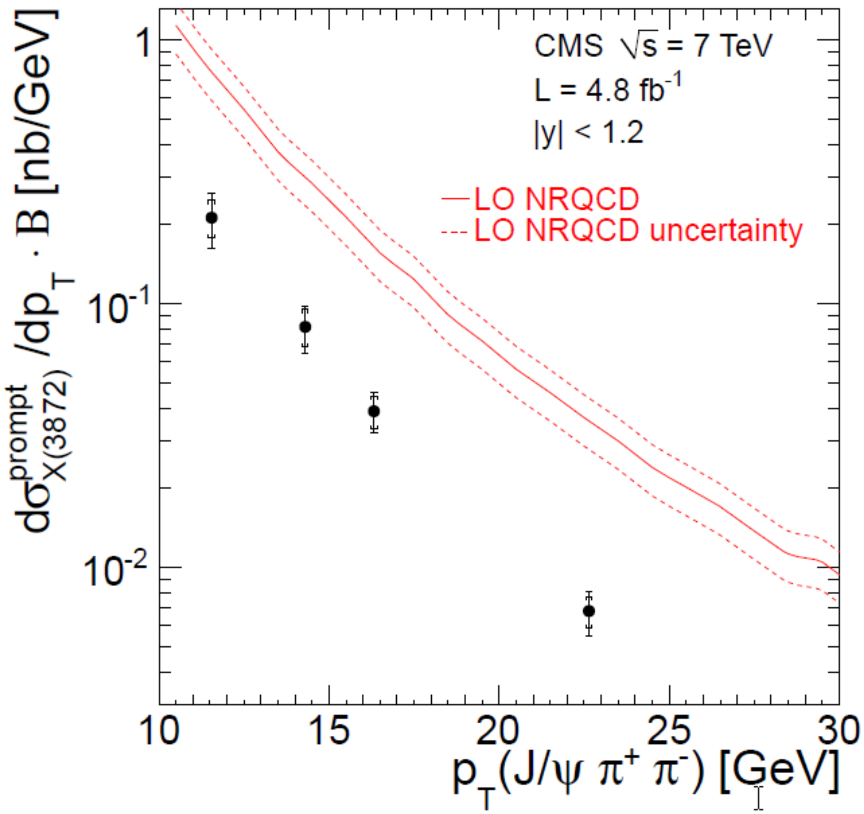
- Use $\psi(2S)$ for normalization
- Huge statistics:
  - study integrated and differential cross-section in p_T
  - determine non-prompt fraction:





Data consistent with
$X(3872) \rightarrow \rho J/\psi$
as previously observed
with smaller statistics

X(3872) production at the central region at LHC



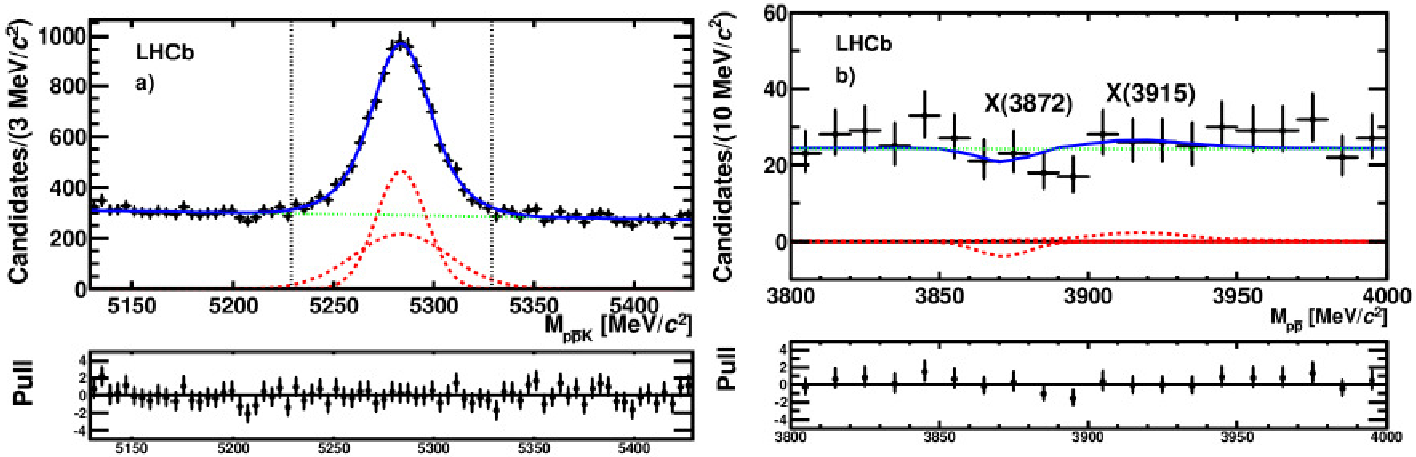
- Total cross-section $\sigma(pp \rightarrow X(3872)\text{+anything}) \times BR(X(3872) \rightarrow J/\psi\pi^+\pi^-)$ factor of 3.8 smaller than predicted:
  - $1.06 \pm 0.11 \pm 0.15$ nb in $|y|<1.2$ and $10< p_T<30$ GeV vs. 4.0 ± 0.9 nb (Artoisenet, Braaten – error from the normalization to CDF)

Looking for new decay mode of X(3872)

new

Search for $X(3872) \to p\bar{p}$ arXiv:1303.7133

- Search for $B^+ \to X(3872)K^+$ In the $B^+ \to p\bar{p}K^+$ decay channel with 1 fb^{-1}
- $B^+ \to p\bar{p}K^+$ signal yield: 6951 ± 176
- $X(3872) \to p\bar{p}$ signal yield: -9 ± 8



- No signal, but upper limit on the ratios:

$$\frac{BR(B^+ \to X(3872)K^+, X(3872) \to p\bar{p})}{BR(B^+ \to p\bar{p}K^+)} < 0.017$$

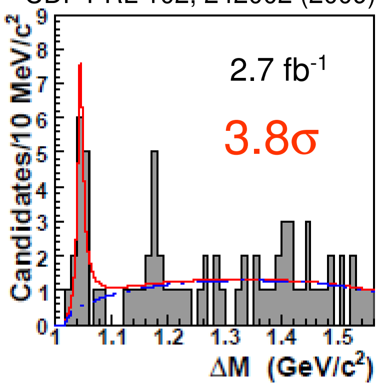
$$\frac{BR(X(3872) \to p\bar{p})}{BR(X(3872) \to J/\psi\pi^+\pi^-)} < 2.0 \times 10^{-3}$$

X(4140)

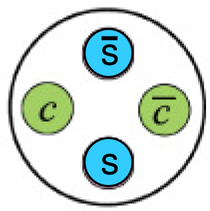
$B^+ \to J/\psi\phi\, K^+$ $(\phi \to K^+ K^-)$

superseded →

CDF PRL 102, 242002 (2009)



115±12 $B^+ \to J/\psi\phi K^+$ events



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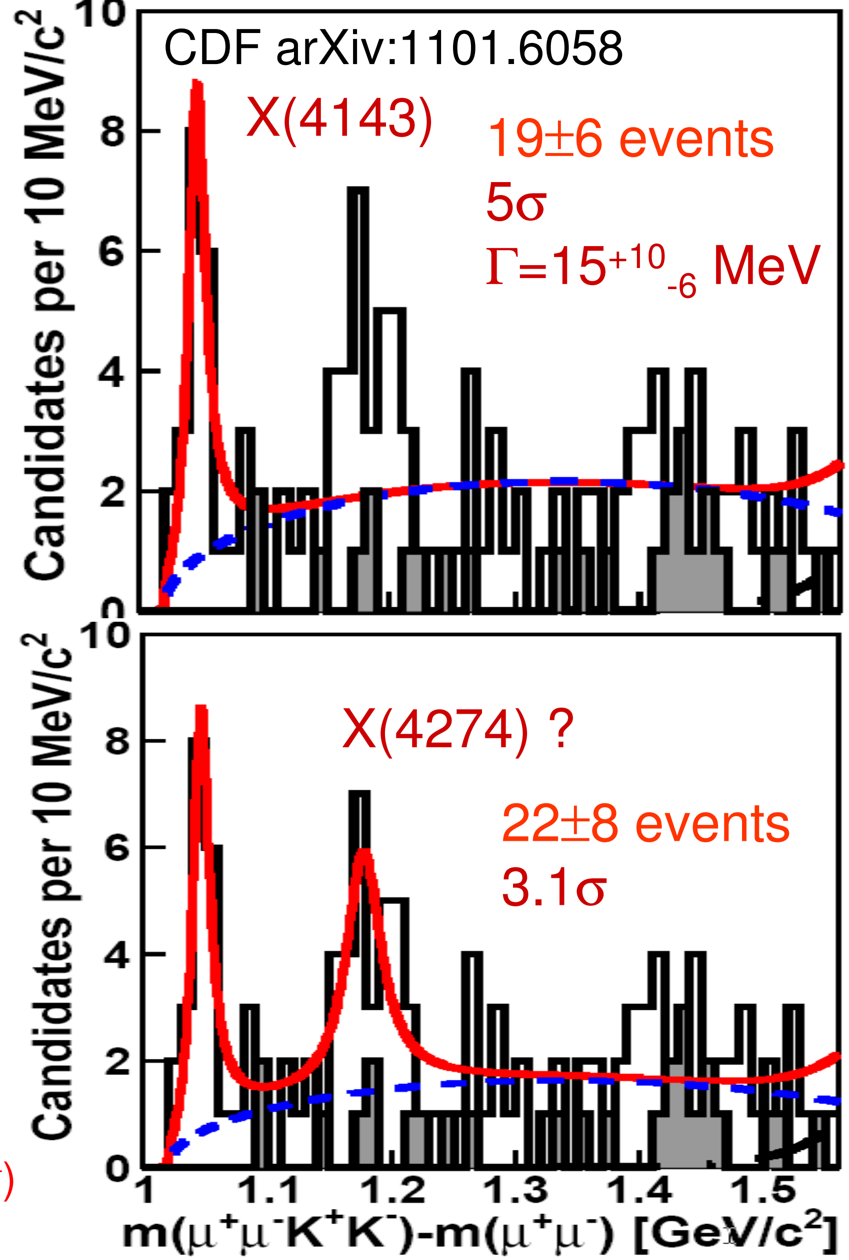
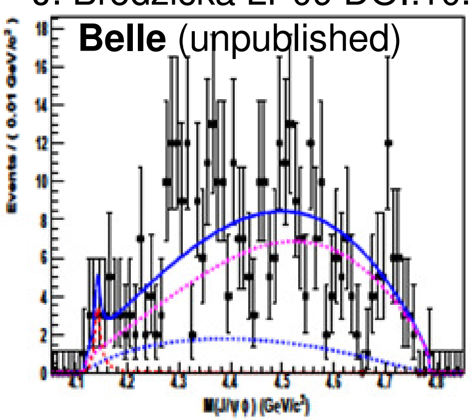
CDF data 6 fb^{-1}



A **narrow** state at this mass decaying to $J/\psi\phi$ necessarily exotic!

J. Brodzicka LP09 DOI:10.3204/DESY-PROC-2010-04/38

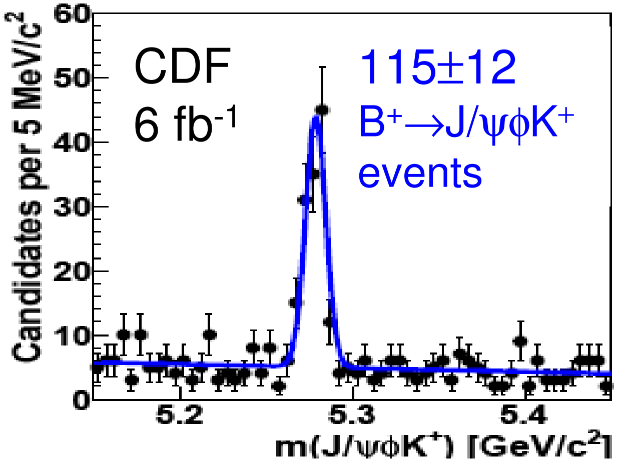


325±21 $B^+ \to J/\psi\phi K^+$ events but low efficiency near the $J/\psi\phi$ threshold

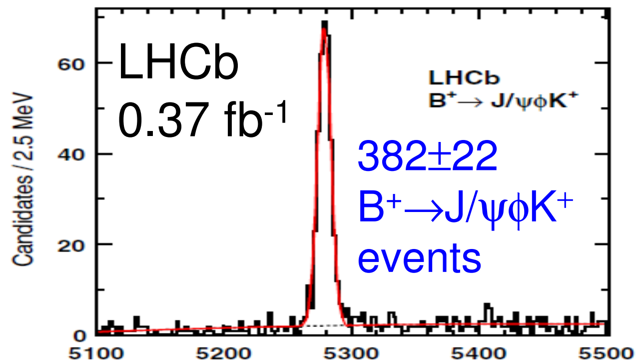
$BR(B^+ \to X(4140)K^+, X \to J/\psi\phi)$ $< 6 \times 10^{-6}$ (90%CL)

vs CDF x $BR_{PDG}(B^+ \to J/\psi\phi K^+)$ $= (8 \pm 2 \pm 3) \times 10^{-6}$

B samples used in analyses of X(4140) at hadronic machines

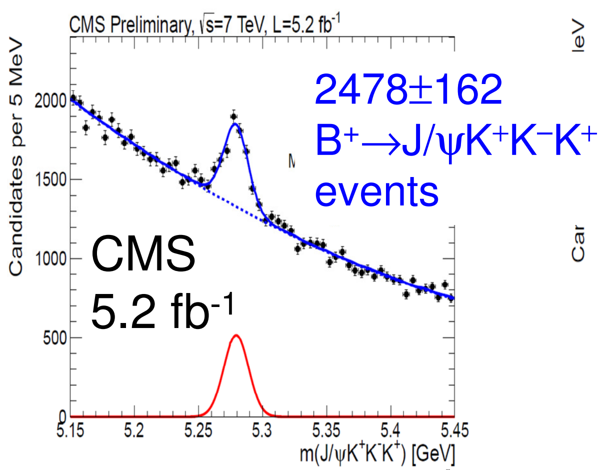


CDF arXiv:1101.6058

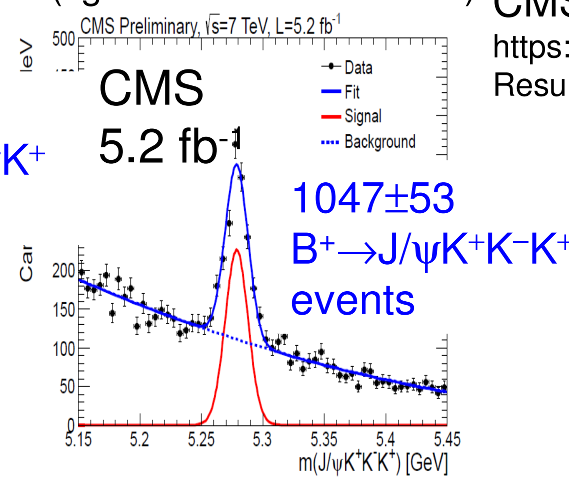


LHCb PRD85,091103(R)(2012)

~$^1/_8$ of the total LHCb sample



(tighter cuts: cross-check)



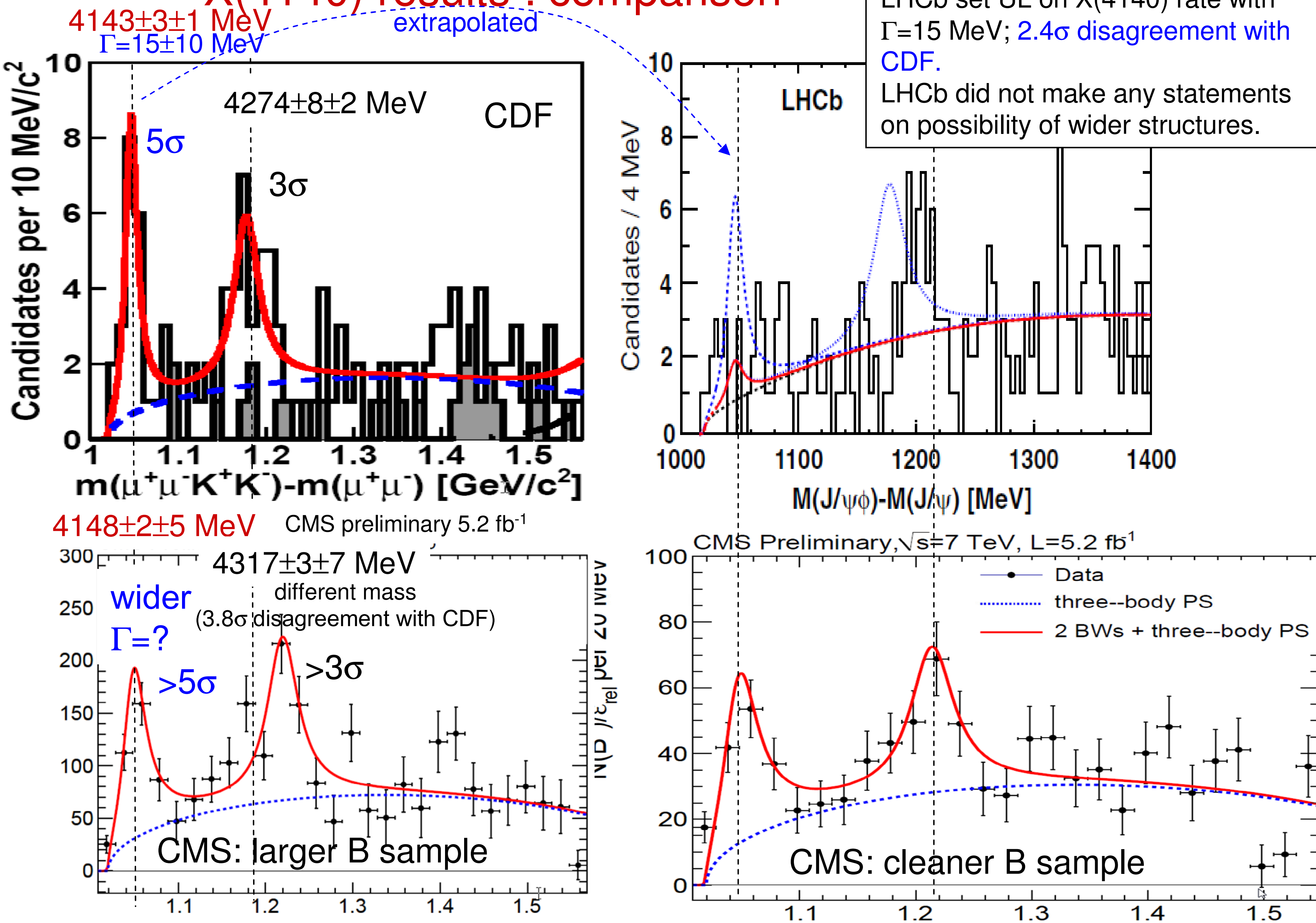
CMS preliminary (2011 data)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11026

- CMS has analyzed biggest statistics

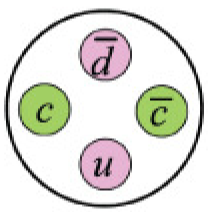
X(4140) results : comparison

LHCb set UL on X(4140) rate with Γ=15 MeV; 2.4σ disagreement with CDF.
LHCb did not make any statements on possibility of wider structures.



Summary

- LHC is having impact on X(3872):
  - LHCb has settled its quantum numbers to be $J^{PC}=1^{++}$
    - This favors exotic explanations of X(3872)
  - The cross-section measured by LHCb and CMS lower than predicted for LHC by Artoisenet-Braaten from the Tevatron data.
    - Prompt production mechanism for molecular X(3872) subject of theoretical controversy
  - Potential for the most precise determination of X(3872) mass
- $M(J/\psi\phi)$ structures in $B\to J/\psi\phi K$ decays:
  - Mild inconsistency (2.4σ) about existence of the narrow X(4140) peak in $M(J/\psi\phi)$ between CDF and LHCb
  - CMS is reporting a significant but wider peak at $4148\pm2\pm5$ MeV (and a wide peak at $4317\pm3\pm7$ MeV)
  - Nature of these structures needs to be studied. Both CMS and LHCb have much larger data samples than analyzed so far.
- LHC should impact studies of other exotic states in B-decays:
  - E.g. $Z(4430)^+\to\psi(2S)\pi^+$ state claimed by Belle, but not confirmed by BaBar in $B^0\to\psi(2S)\pi^+K^-$



$Z(4430)^+$
?