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Latest D0 results on exotic hadrons produced in $p\bar{p}$ collisions

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Outline

- Introduction
- Recent D0 studies of exotic states
  - Prompt and nonprompt production of X(3872) and ψ(2S)
  - Associated production of X(3872) and soft-pion
  - Prompt and nonprompt production of Z_c^+(3900)
  - Evidence for inclusive nonprompt production of P_c states
- Conclusion

D0 detector

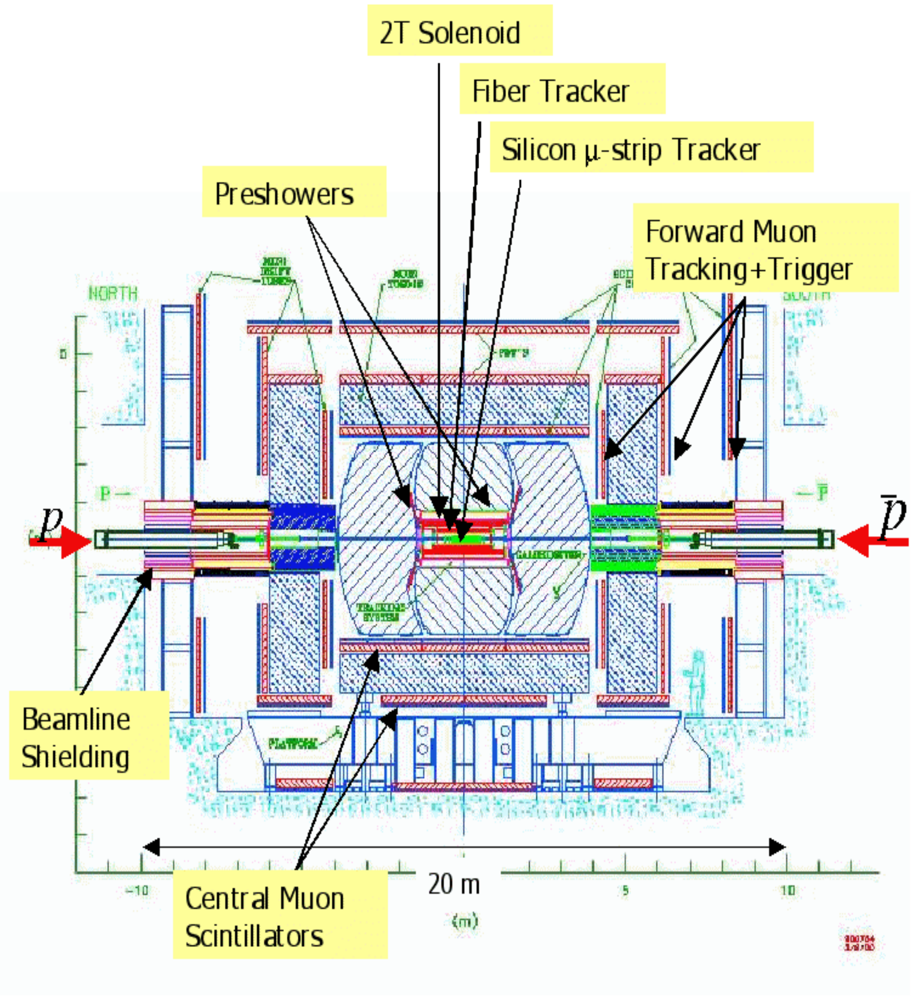
Tevatron $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV

Run II operation from 2001 to 2011

Run II : $\int \mathcal{L}\, dt$ ~ 10 fb^{-1}

D0 detector is multipurpose,
high acceptance detector with
good tracking and vertex systems

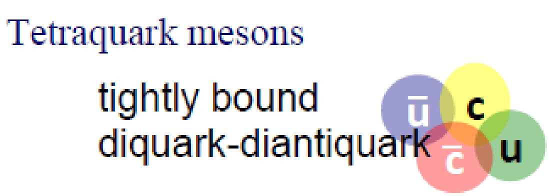
D0 detector: excellent μ-ID in wide rapidity range, forward muon system, solenoid and muon toroid magnets polarity flips (decreasing systematics)

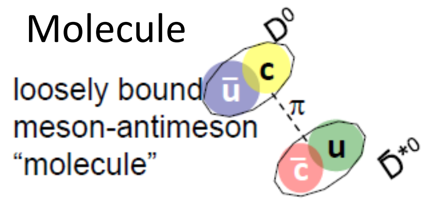


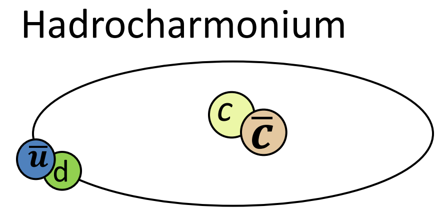
D0 detector

Production of four-quark states in hadron colliders

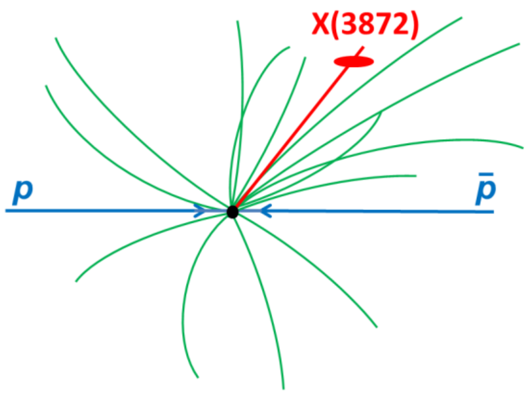
Dynamic configuration of four-quark states can be tightly bound (tetraquark, pentaquark), loosely bound (molecule, hadroquarkonium) or their mixture:



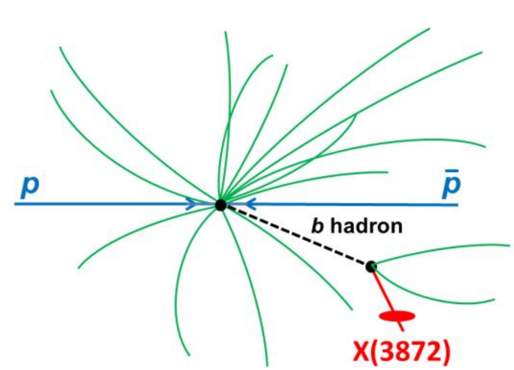




Many exotic states were observed experimentally, however theoretical interpretation is still unclear. State X(3872) is assumed to be a mixture of conventional χ_{c1}(2P) state and molecule. State Z_c^+(3900) is assumed to be molecule.



Prompt X(3872) production



Nonprompt X(3872) production

Can loosely bound and spatially large state survive after production in multi-track vertex?

Comparison of prompt and nonprompt ➔ important info about exotic states.

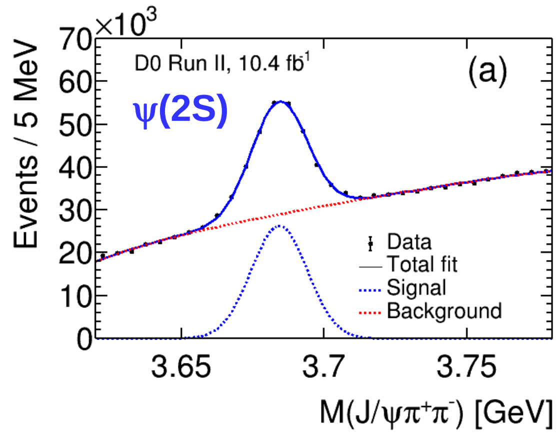
Prompt and nonprompt production of X(3872) and ψ(2S)

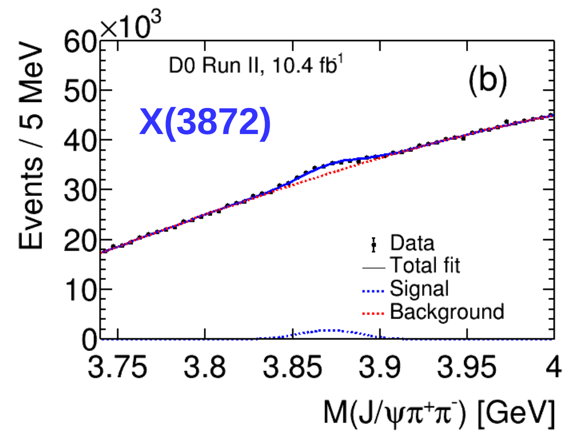
Study of X(3872) state in decays to $J/\psi\ \pi^+\pi^-$ using ψ(2S) as control sample

D0 collaboration,
arXiv:2007.13420
(this and next 2 slides)

Large X(3872) & ψ(2S) signals: detailed study of properties

$t_{pp} = \vec{L}_{xy}\, \vec{p}_T\, m\, /\, (p_T^2\, c)$





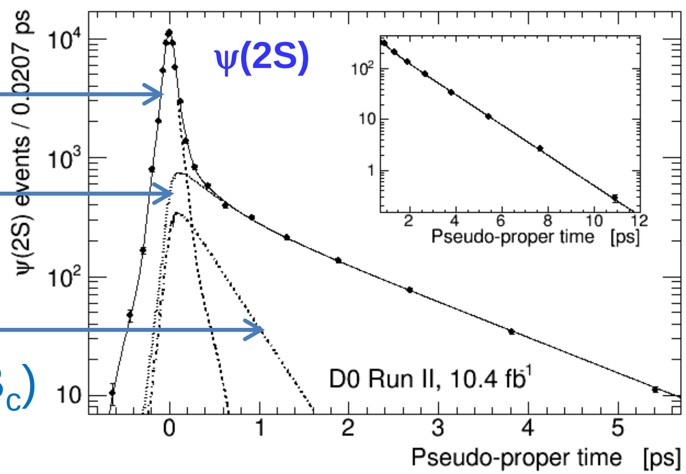
N_{ev} = 126,900 ± 800

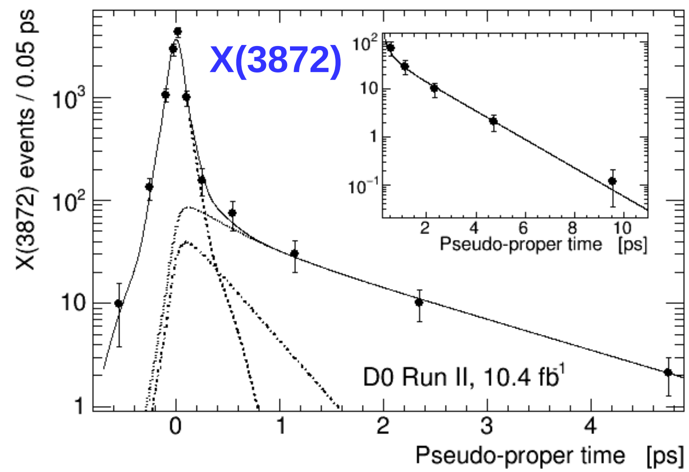
N_{ev} = 16,400 ± 1000

Prompt

Nonprompt

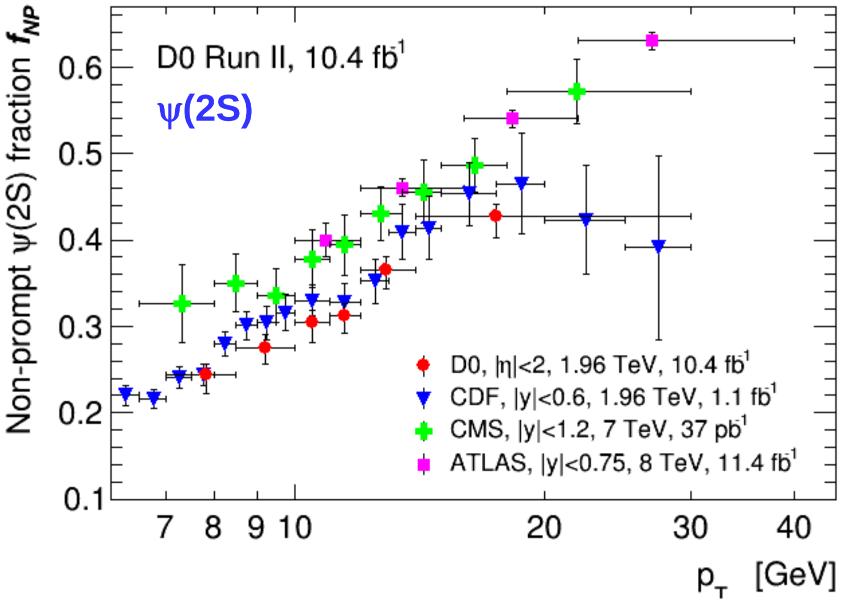
Nonprompt short-lived (B_c)

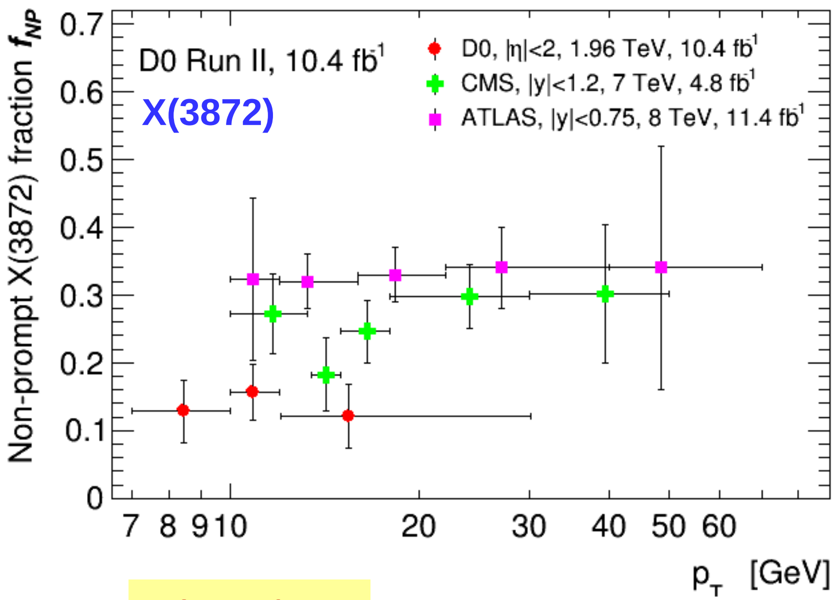




Pseudo-proper time t_{pp} distributions obtained using mass fits in t_{pp} bins

p_T distributions for nonprompt fraction f_{NP} for X(3872) and ψ(2S)





D0 data show same f_{NP} tendencies as at LHC: decreasing with p_T for ψ(2S), flat for X(3872)

X(3872) all, (stat+syst) :

D0: f_{NP} = 0.139 ± 0.027

ATLAS: f_{NP} = 0.328 ± 0.026

CDF (*unpubl*): f_{NP} = 0.161 ± 0.049 ± 0.02

We can compare production ratios for R(prompt/nonprompt) at Tevatron and LHC.

ψ(2S) at 10 GeV: $R_{D0/CDF}$ / $R_{CDF/ATLAS}$ = (0.7/0.3) / (0.65/0.35) = 1.26

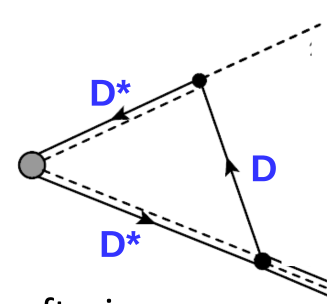
X(3872) all p_T: R_{D0} / R_{ATLAS} = (0.861/0.139) / (0.672/0.328) = 3.0 $\sim^{+0.8}_{-0.6}$ *(not gaussian)*

➡ relative X(3872) to *b*-hadron production suppressed 3 times from D0 to ATLAS

D0: |η|<1: f_{NP} = 16.4 ± 3.5 $^{+0.9}_{-1.6}$ % ; 1<|η|< 2: f_{NP} = 11.6 ± 3.2 $^{+0.9}_{-1.0}$ % - maybe small η effect

Associated production of X(3872) and soft-pion

E. Braaten, L.-P. He, K. Ingles, "Production of *X*(3872) accompanied by a soft pion at hadron colliders"', Phys. Rev. D, **100**, 094006 (2019).
E. Braaten, L.-P. He, K. Ingles, "Production of *X*(3872) accompanied by a pion in *B* meson decay", Phys. Rev. D, **100**, 074028 (2019).

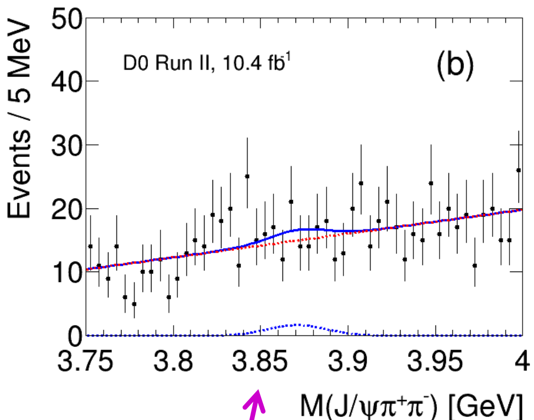


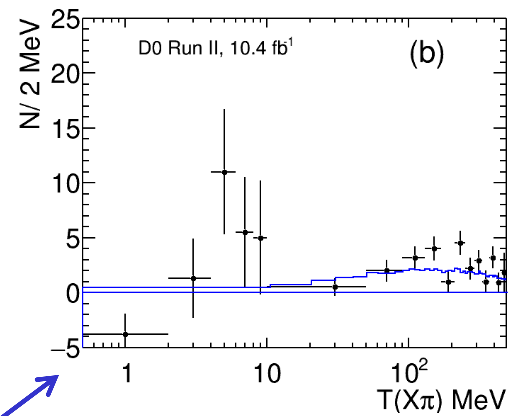
Braaten *et al* predict production of X(3872) molecule accompanied by soft-pion

Prompt:
$L_{xy} < 0.25$ mm & $L_{xy}/\sigma(L_{xy}) < 3$

Nonprompt:
$L_{xy} > 0.25$ mm & $L_{xy}/\sigma(L_{xy}) > 3$

Kinetic energy of soft-pion:
~1/7 of all X(3872) events predicted to have soft-pion at T (Xπ) < 11.8 MeV





X(3872) fit in T(Xπ) intervals

Prompt & $T(X\pi) < 11.8$ MeV ➔ N_{sig} = 18±16 ev, bgr.~6 ev., ➔ expected 245-730 ev.

Nonprompt & $T(X\pi) < 11.8$ MeV ➔ N_{sig} = 27±12 ev, bgr.~2 ev., ➔ expected 31-87 ev.

➡ observed 2σ effect in nonprompt production is not enough for definite conclusion

Questions to be addressed

Why is X(3872) prompt production suppressed relative to *b*-hadron production at LHC?

Is it effect of dissociation of spatially large object by many other tracks produced in primary vertex (LHCb-CONF-2019-005)? Number of particles produced in primary vertex at 7-8 TeV LHC is about twice larger than in Tevatron 1.96 TeV.

LHC measurements of f_{NP} ratio at 13 TeV are needed to understand tendency.

If exotic state X(3872) prompt production is suppressed at LHC, is it possible to get even stronger suppression for other exotic states in LHC, in particular for X(5568)?
State X(3872) probably has large 2-quark component and maybe not much suppressed.

Prompt and nonprompt production of $Z_c^+(3900)$

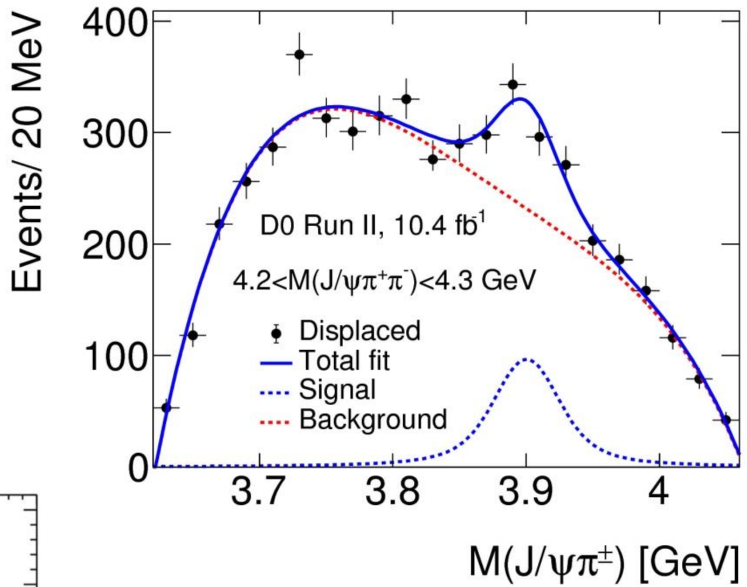
D0 collaboration, "Properties of $Z^{\pm}_c$ (3900) produced in $p\bar{p}$ collisions", Phys. Rev. D 100, 012005 (2019).

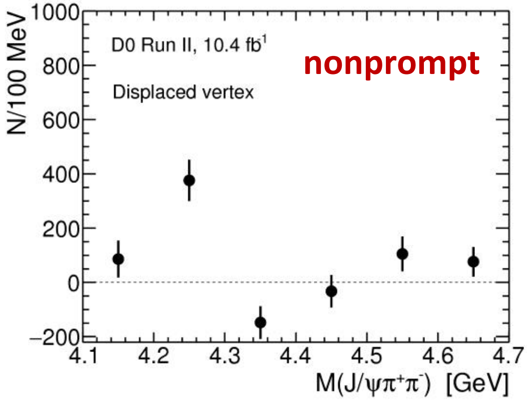
Semi-inclusive *b*-hadron decays are studied

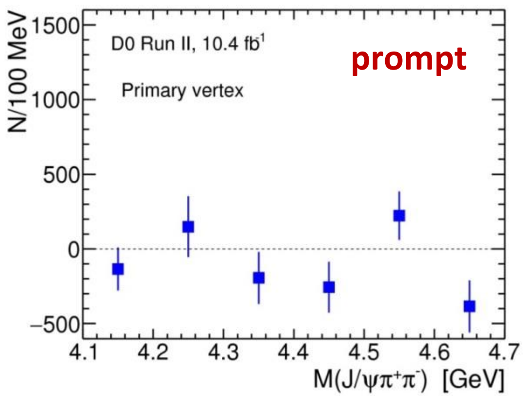
Selection: $J/\psi\ \pi^+\pi^-$, 4-tracks from same vertex

Nonprompt: $L_{xy}/\sigma(L_{xy}) > 5$ & $IP_{xy}(\pi)/\sigma(IP_{xy}(\pi)) > 2$

Prompt: rest of sample







Nonprompt: signal 376±76ev (5.2σ) is found in $M(J/\psi\pi^{\pm})$ distribution at $4.2 < M(J/\psi\pi^+\pi^-) < 4.3$GeV range

Indicates that $\psi(4260)\rightarrow Z_c^+(3900)\,\pi^-$

Fit $M(J/\psi\pi)$ to get $Z_c^+(3900)$ signal in $M(J/\psi\,\pi\pi)$ intervals for prompt and nonprompt ev.

➡ Significant signal only in nonprompt sample at $4.2 < M(J/\psi\pi^+\pi^-) < 4.3$GeV range

Evidence for inclusive nonprompt production of P_c states

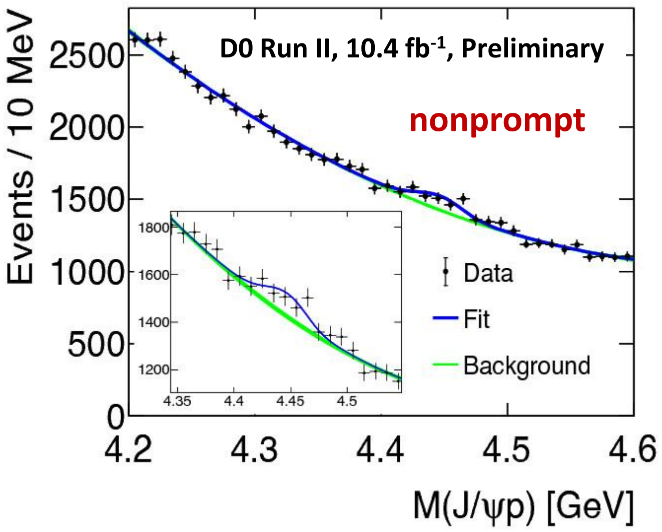
D0 collaboration, "Inclusive production of the P_c resonances in $p\bar{p}$ collisions", arXiv: 1910.11767.

Semi-inclusive analysis

Selection: $J/\psi\, p$, 3-tracks from same vertex

Nonprompt: $L_{xy}/\sigma(L_{xy}) > 5$

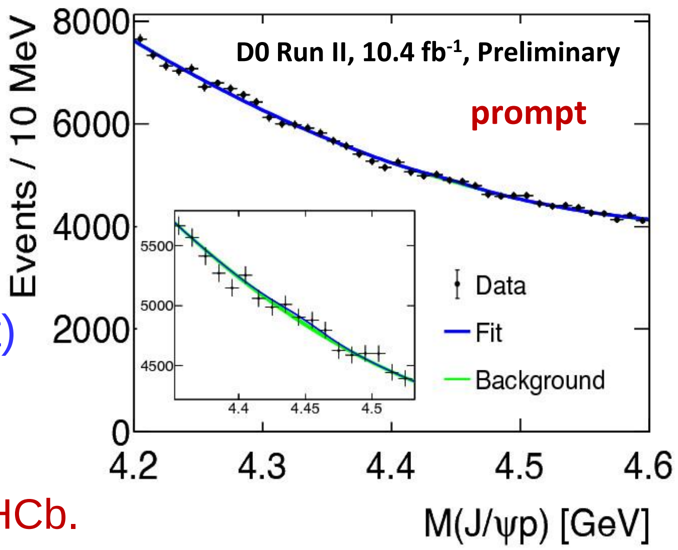
Prompt: rest of sample



Signal around 4450 MeV in nonprompt sample. Resolution does not allow to separate $P_c(4440)$ and $P_c(4457)$. Their sum is free parameter in fit. The signal shape is fixed using LHCb results.

Fit nonprompt: $N=830\pm206$ ev., signif. 3.2σ (stat+syst)

No signal in prompt sample.



First confirmatory evidence of P_c states observed by LHCb.

Conclusions

- Prompt and nonprompt production of X(3872) and $\psi(2S)$ states are studied. Dependencies of nonpompt fraction f_{NP} vs p_T demonstrate similar trends to those found in LHC measurements. Production ratio nonprompt/prompt decreases for $\psi(2S)$ by only ~25% from D0 to LHC conditions, whereas it decreases about 3 times for X(3872).

- Associated production of X(3872) and soft-pion is studied. This study is motivated by Braaten *et al* proposal of triangle diagram mechanism for X(3872) molecular production. No effect is found in prompt production. In nonprompt production excess of 2σ is found, that does not allow to make definite conclusion.

- Semi-inclusive method is used to study prompt and nonprompt production of $Z_c^+(3900)$.Signal of 5.2σ is found in nonprompt sample indicating to $Z_c^+(3900)$ production in chain $\psi(4260) \to Z_c^+(3900)\pi^-$. No signal is seen in prompt sample.

- Evidence of 3.2σ (stat+syst) is found in inclusive studies of nonprompt production of P_c states in channel $J/\psi\ p$. No signal is seen in prompt sample.

Additional material

Nonprompt fractions f_{NP} for X(3872) and ψ(2S)

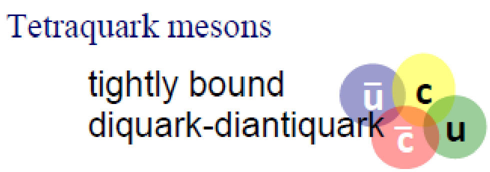
	$\psi(2S)$		$X(3872)$
all	$0.328 \pm 0.006\,^{+0.010}_{-0.013}$		$0.139 \pm 0.025 \pm 0.009$
p_T, GeV		p_T, GeV	
7 - 8.5	$0.244 \pm 0.008\,^{+0.010}_{-0.021}$	7 - 10	$0.128 \pm 0.046\,^{+0.009}_{-0.008}$
8.5 - 10	$0.275 \pm 0.007\,^{+0.013}_{-0.016}$		
10 - 11	$0.304 \pm 0.009\,^{+0.011}_{-0.020}$	10 - 12	$0.156 \pm 0.038\,^{+0.016}_{-0.014}$
11 - 12	$0.312 \pm 0.010\,^{+0.010}_{-0.017}$		
12 - 14	$0.365 \pm 0.008\,^{+0.013}_{-0.021}$	12 - 30	$0.121 \pm 0.047\,^{+0.010}_{-0.006}$
14 - 30	$0.427 \pm 0.007\,^{+0.013}_{-0.024}$		

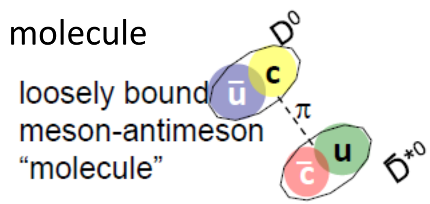
	$\psi(2S)$	$X(3872)$
$\lvert\eta\rvert < 1$	$0.344 \pm 0.007\,^{+0.014}_{-0.020}$	$0.164 \pm 0.035\,^{+0.009}_{-0.016}$
$1 < \lvert\eta\rvert < 2$	$0.303 \pm 0.008\,^{+0.017}_{-0.020}$	$0.116 \pm 0.032\,^{+0.009}_{-0.010}$

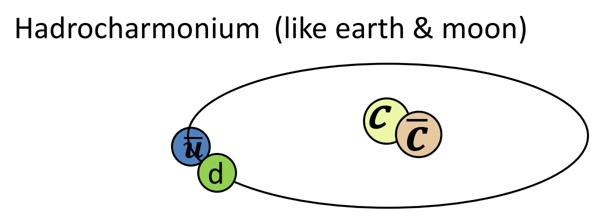
Retrospective to four-quark states

Four-quark states are not forbidden *theoretically*.
These states can be separated using information about masses, widths, charges, quantum numbers, production and decay modes (and their rates).

Exotic four-quark states can be theoretically described as tightly bounded (tetraquark) or loosely bounded (molecule, hadroquarkonium):







Observed with high stat significance four-quark states: **Z(4430)$^+$** $\rightarrow \Psi' \pi^+$, **X(4140)** $\rightarrow J/\psi\, \phi$, **$Z_b(10610)^+$** $\rightarrow \Upsilon\pi^+$, **$Z_b(10650)^+$** $\rightarrow \Upsilon\pi^+$, not well established **Z(4050)$^+$** $\rightarrow \chi_{c1}\, \pi^+$, **Z(4250)$^+$** $\rightarrow \chi_{c1}\, \pi^+$. Probably **X(3872)** is mixture of four- and two-quark states. Molecular interpretation works well for the states. Other exotic states: pentaquarks **P_c(4450)$^+$** $\rightarrow J/\psi\, p$, **P_c(4380)$^+$** $\rightarrow J/\psi\, p$

More information about exotic multiquark states is required to build explicit theory.

World Comparison

Analysis	Production ratio (X(5568) / B_s)	Reference
D0 ($J/\psi\ \phi$)	8.6 ± 1.9 ± 1.4%	PRL 117,022003(2016)
D0 ($\mu\ D_s$)	**$7.3^{+2.8}_{-2.4}{}^{+0.6}_{-1.7}\%$**	PRD 97, 092004 (2018)
LHCb	$< 2.4\%$ ($p_T(B_s^0) > 10$ GeV)	PRL 117,152003 (2016)
CMS	$< 1.1\%$ ($p_T(B_s^0) > 10$ GeV)	PRL 120, 202005 (2018)
ATLAS	$< 1.5\%$ ($p_T(B_s^0) > 10$ GeV)	PRL 120, 202007 (2018)
CDF	**< 6.7% (2.3 ± 1.9 ± 0.9%)**	PRL 120, 202006 (2018)

If X(5568) production is suppressed in LHC, interval R ~ 4-6 is not ruled out.

Prompt X(3873) production relative to *b*-hadron production is suppressed by factor ~2.5-3.0 in LHC relative to Tevatron conditions. It has to be taken into account, that X(3872) is probably produced as conventional 2-quark state.