A. Drutskoy

LPI, Moscow

Recent production and spectroscopy results from D0

QWG 2021 (virtual) – *The 14-th International Workshop on Heavy Quarkonium*

March 15-19, 2021, Davis, US

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

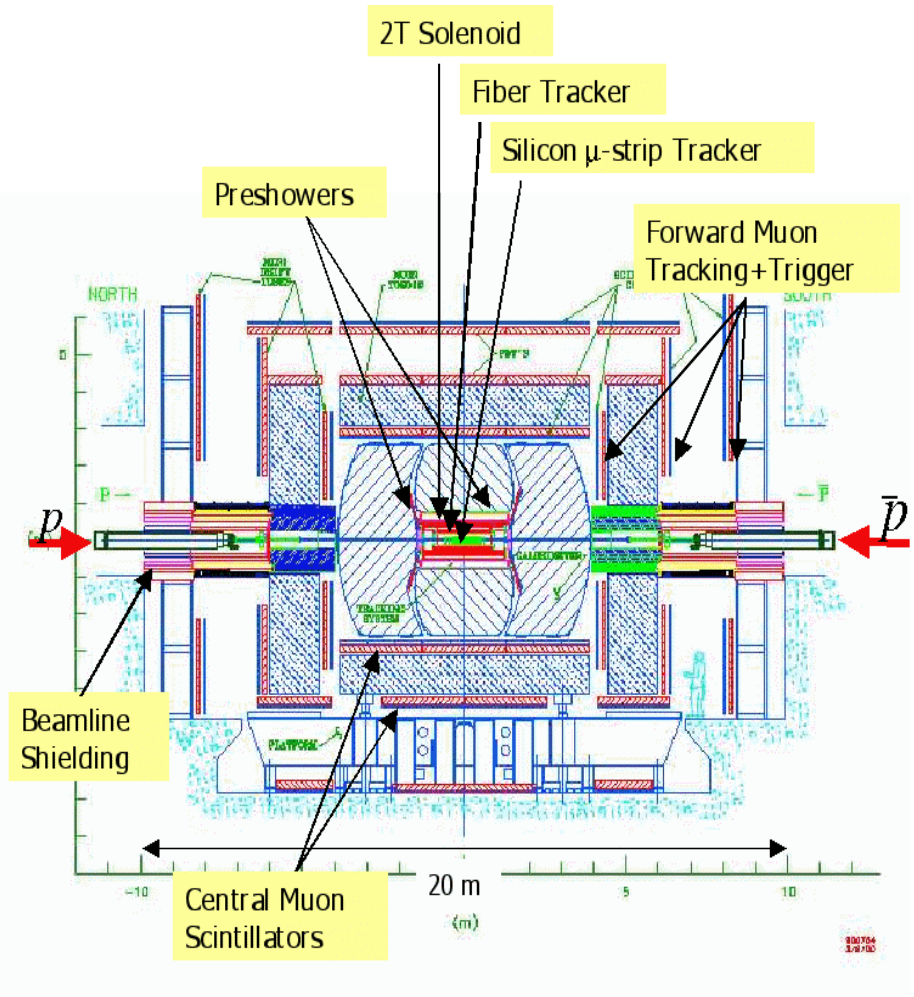
Tevatron $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV

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

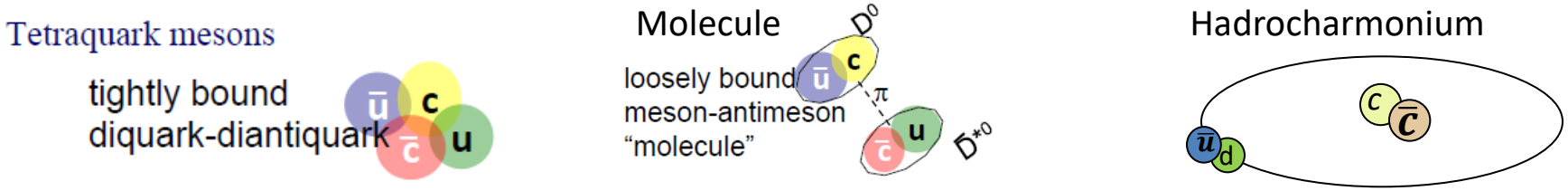
D0 detector: excellent μ-ID in wide rapidity range, forward muon system, solenoid and muon toroid magnets polarity flips (decreasing systematics)



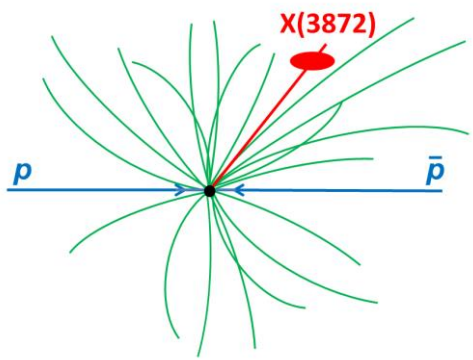
D0 detector

Production of four-quark states in hadron colliders

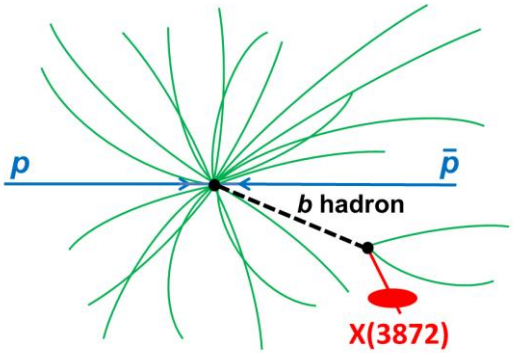
Dynamic configuration of four-quark states can be tightly bound (tetraquark, pentaquark), loosely bound (molecule, hadroquarkonium) or their mixture:



Many exotic states were observed experimentally, however theoretical interpretation is still unclear. State X(3872) is assumed to be a mixture of conventional $\chi_{c1}(2P)$ 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.

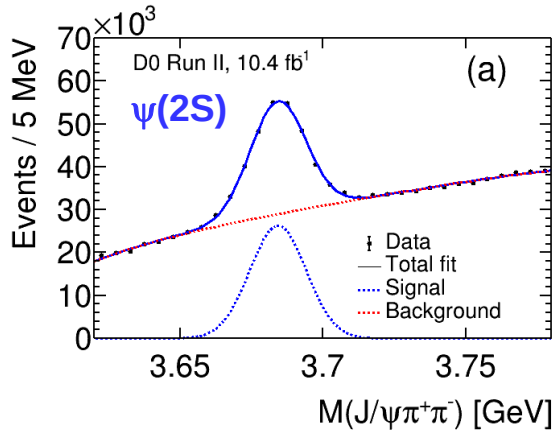
Prompt and nonprompt production of X(3872) and ψ(2S)

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

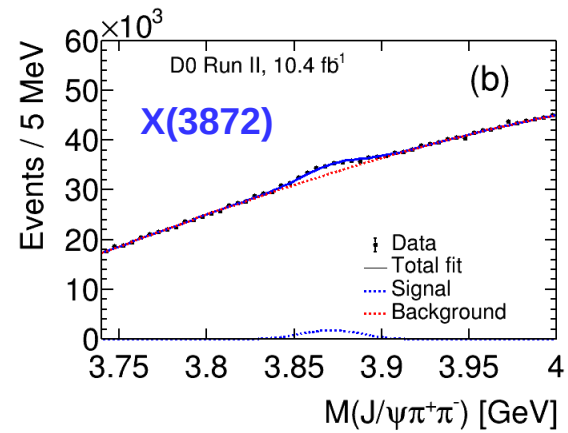
D0 collaboration,
PRD 102 (2020) 072005
(this and next 2 slides)

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

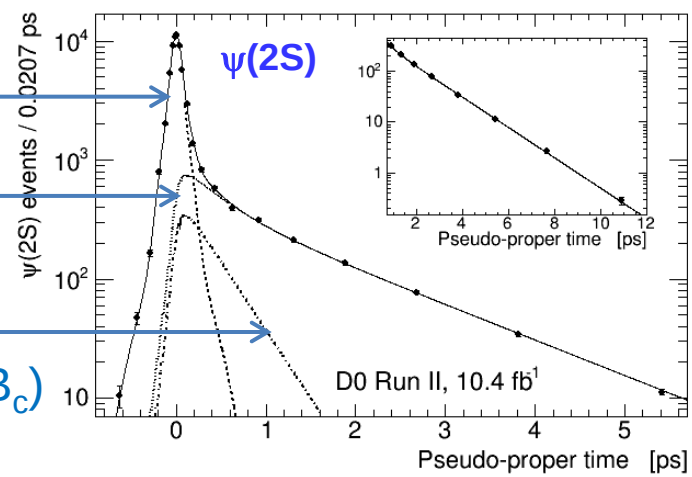


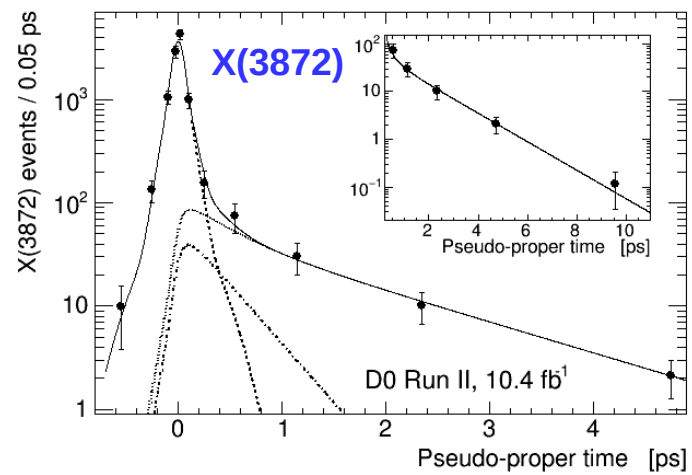
N_{ev} = 16,400 ± 1000

Prompt

Nonprompt

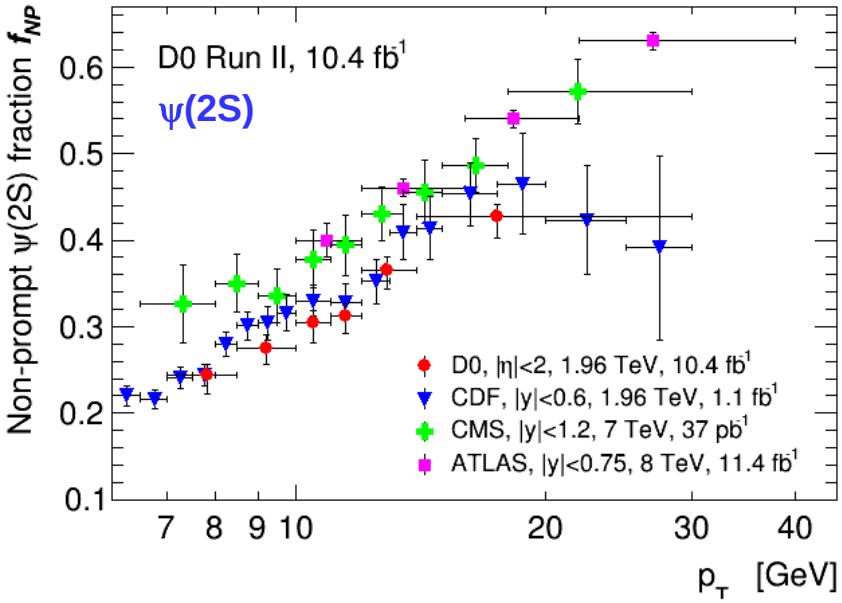
Nonprompt short-lived (B_c)

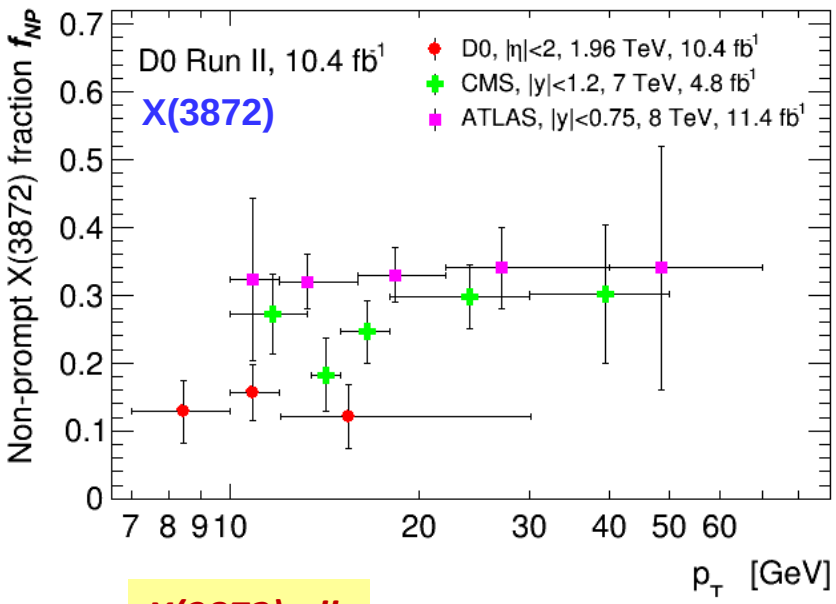




Pseudo-proper time t_{pp} distributions obtained using mass fits in t_{pp} bins

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

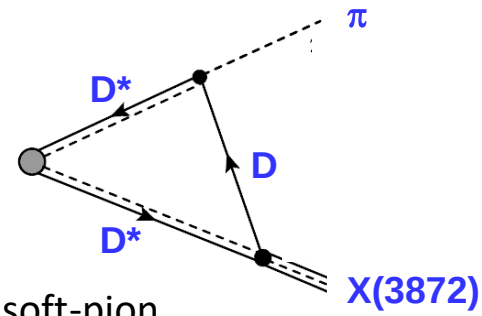
X(3872) all p_T: R_{D0} / R_{ATLAS} = (0.861/0.139) / (0.672/0.328) = 3.0 $\sim^{+0.8}_{-0.6}$ *(not gaussian)*

➡ 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).

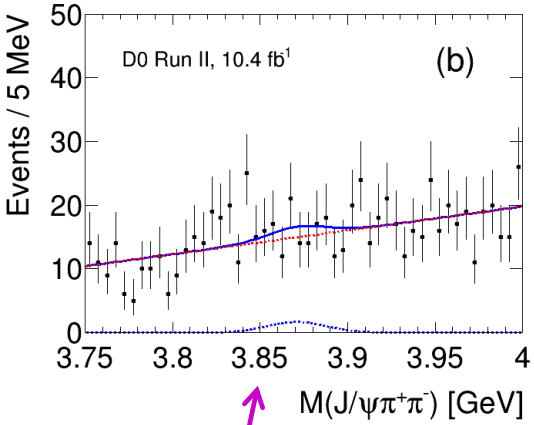


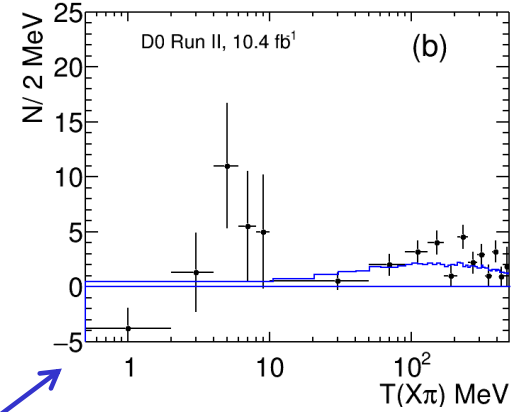
Braaten *et al* predict production of X(3872) molecule accompanied by soft-pion

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 (Xπ) < 11.8 MeV ➔ N_{sig} = 18±16 ev, bgr.~6 ev., ➔ expected 245-730 ev.

Nonprompt & T(Xπ) < 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 relative to *b*-hadron production suppressed at LHC comparing with Tevatron?

Is it effect of dissociation of spatially large object by many other tracks produced in primary vertex (LHCb, PRL 126, 092002, 2021)? Number of particles produced in primary vertex at 7-8 TeV LHC is about twice larger than in Tevatron 1.96 TeV.

Comparison of f_{NP} at 13 TeV and 7-8 TeV at LHC will allow to clarify this question.

Many exotic states are observed in *B* decays and in low energy e^+e^- collisions, however only a few states are observed in prompt $p\bar{p}$ (pp) high energy collisions.

State X(3872) is maybe produced via 2-quark component and therefore it's production in $p\bar{p}$ collisions is not strongly suppressed.

If exotic state X(3872) prompt production is suppressed at LHC, it is possible to get even stronger suppression for other exotic states in LHC, in particular for X(5568). Tetraquark X(5568) includes 3 light quarks ⇨ large size ~(2-4) fm.

Then comparison of production ratio R(X5568/B_s) at Tevatron and LHC has no sense.

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

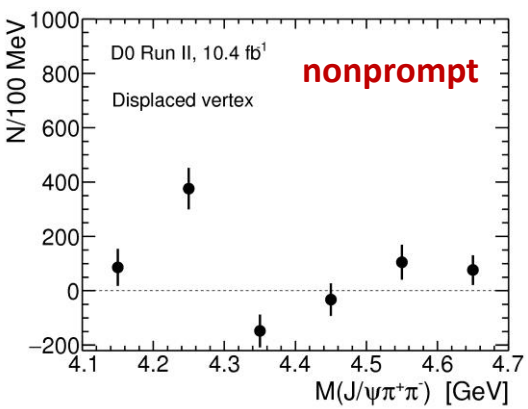
D0 collaboration, "Properties of $Z^{\pm}_c$ (3900) produced in $p\bar{p}$ collisions", Phys. Rev. D 100, 012005 (2019).

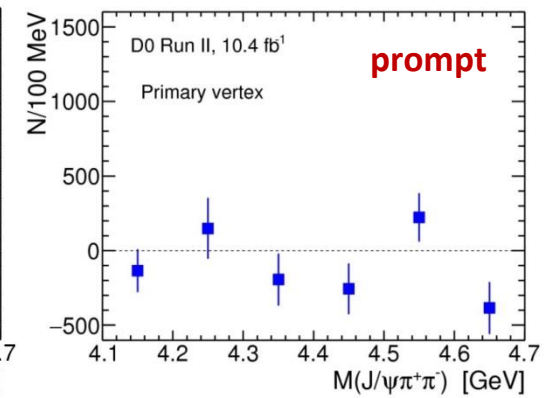
Semi-inclusive *b*-hadron decays are studied

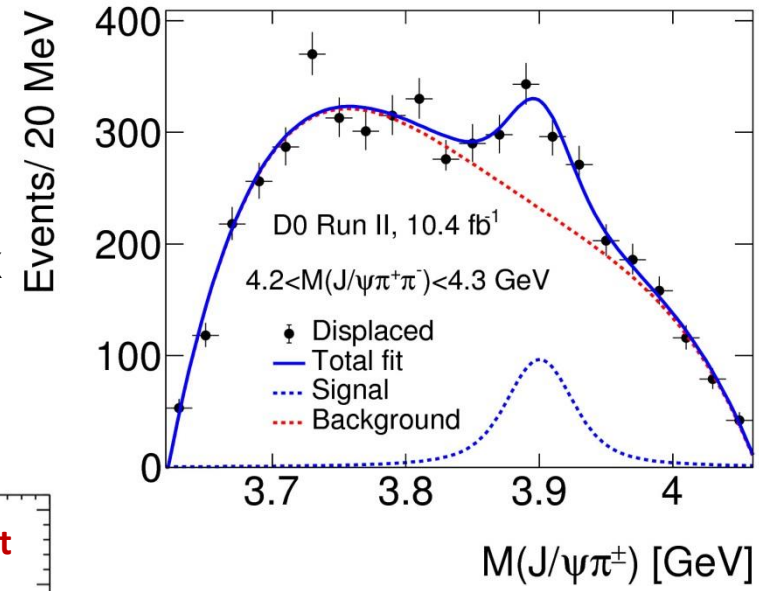
Selection: $J/\psi\ \pi^+\pi^-$, 4-tracks from same vertex

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 $\psi(4260) \to Z_c^+(3900)\ \pi^-$

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

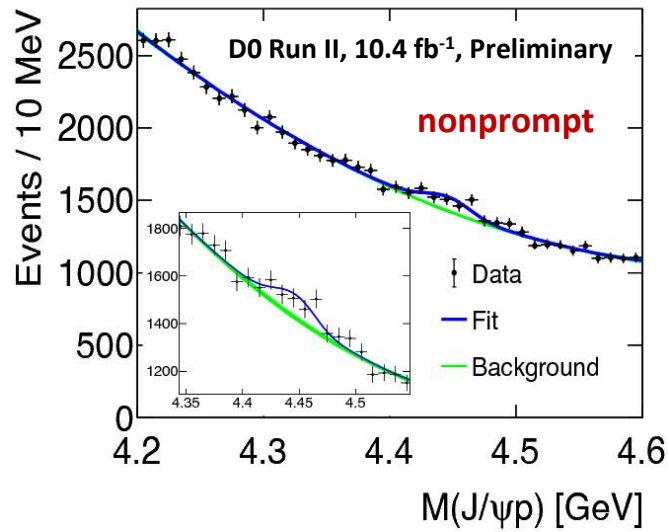
D0 collaboration, "Inclusive production of the P_c resonances in $p\bar{p}$ collisions", arXiv: 1910.11767.

Semi-inclusive analysis

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

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

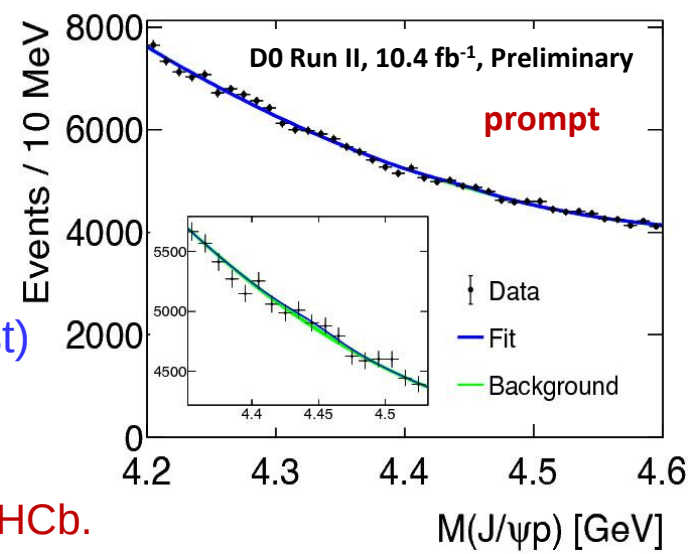
Prompt: rest of sample



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 ± 206 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 ψ(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 ψ(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 $\psi(4260) \rightarrow Z_c^+(3900)\pi^-$. 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/ψ *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	$0.427 \pm 0.007^{+0.013}_{-0.024}$		
	$\psi(2S)$		$X(3872)$
$\lvert\eta\rvert < 1$	$0.344 \pm 0.007^{+0.014}_{-0.020}$		$0.164 \pm 0.035^{+0.009}_{-0.016}$
$1 < \lvert\eta\rvert < 2$	$0.303 \pm 0.008^{+0.017}_{-0.020}$		$0.116 \pm 0.032^{+0.009}_{-0.010}$

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.

Production of X(3872) and ψ(2S) at Tevatron and LHC

ATLAS at 8 TeV, JHEP 01 (2017) 117: 470K ψ(2S) and 30K X(3872) , R ≈ 15.7

CMS at 7 TeV, JHEP 04 (2013) 154: 178,5K ψ(2S) and 11,9K X(3872) , R ≈ 15.0 ± 0.6

CDF at 1.96 TeV, PRL 96 (2006) 102002: 11500±220 ψ(2S) and 1260±130 X(3872), R=9.1±1.0

This analysis:

D0 at 1.96 TeV, PRD 102 (2020) 072005: 126.9±0.8K ψ(2S) and 16.4±1.0K X(3872), R=7.7±0.5