Double J/ψ production in pion-nucleon scattering at COMPASS

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Motivation

J/ψ pair production process allows to study:

— production mechanisms: single parton scattering (SPS), double parton scattering (DPS);

— intrinsic charm of hadrons (IC);

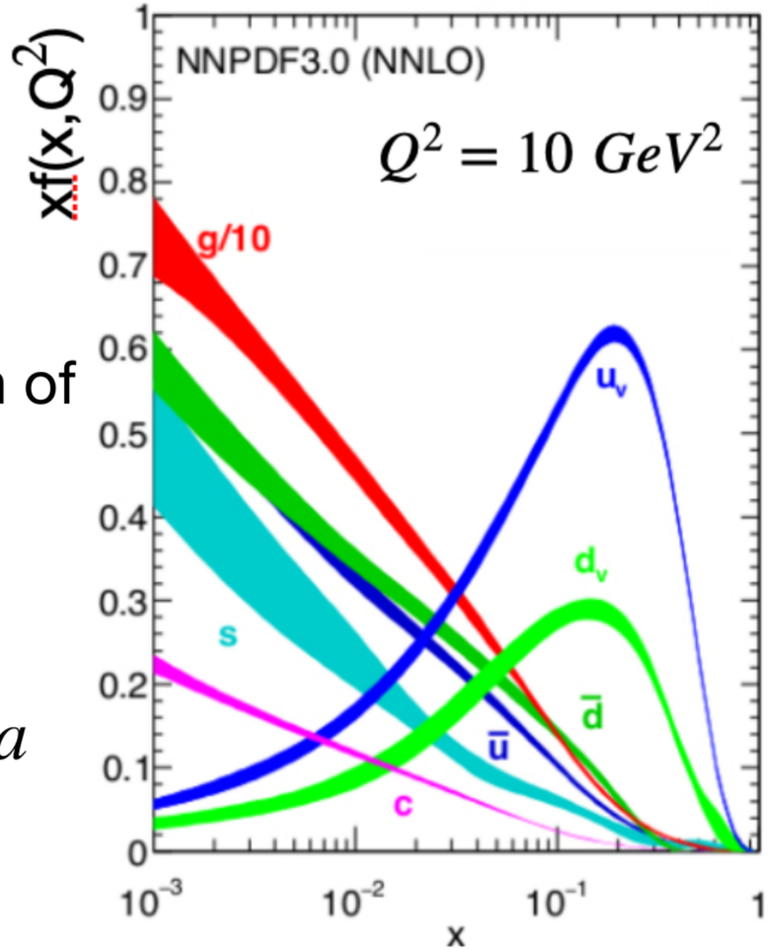
— decay of high mass states (η_b, $\chi_{b_{0,1,2}}$) to J/ψ pair;

— exotic states that decay to J/ψ pair.

Hadron structure

The quark-parton model: inside of a hadron there are

- valence quarks,
- gluons,
- sea quarks.



QCD describes the processes at $\alpha_S(Q^2) < 1$.

At large distances the cross section of interaction of A and B hadrons could be written as

$$\sigma_{AB} \sim \sum_{a,b} \int dx_a \int dx_b f_a^A(x_a) f_b^B(x_b) \hat{\sigma}_{ab},$$

where $\hat{\sigma}_{ab}$ — hard cross section of interaction of a and b partons.

Intrinsic charm of hadron

- The existence of non-perturbative (intrinsic) Fock component in a hadron with c-quarks is postulated:

$$|p\rangle \sim |uud\rangle + |uudg\rangle + |uudc\bar{c}\rangle + \ldots$$

- Intrinsic charm contribution is generated non-perturbatively via $gg \to Q\bar{Q}$.
- Beside of intrinsic charm ($gg \to Q\bar{Q}$) there is extrinsic charm component in hadrons that arises from gluon splitting ($g \to Q\bar{Q}$).
- Valence-like intrinsic charm quarks carry the most part of hadron momentum.
- The probability to find intrinsic charm in a proton was estimated to be $1\ \%$.

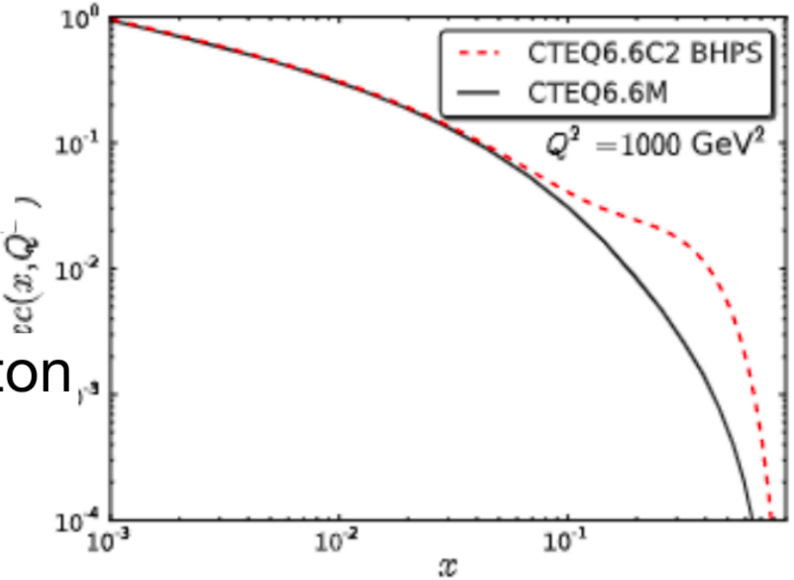
BHPS model:

S.J. Brodsky et al,

Phys. Lett. B 93, 451 (1980)

Phys.Rev.D 23 (1981) 2745

V.A. Bednyakov, G.I. Lykasov
Phys. Lett. B, 728, 602 (2014)

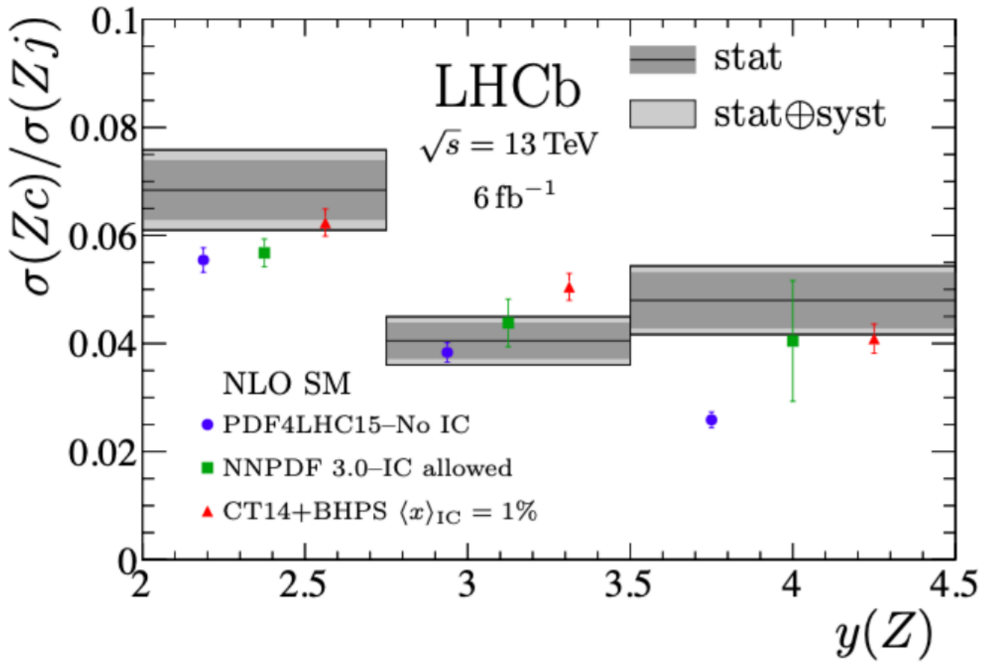


Intrinsic charm of a proton

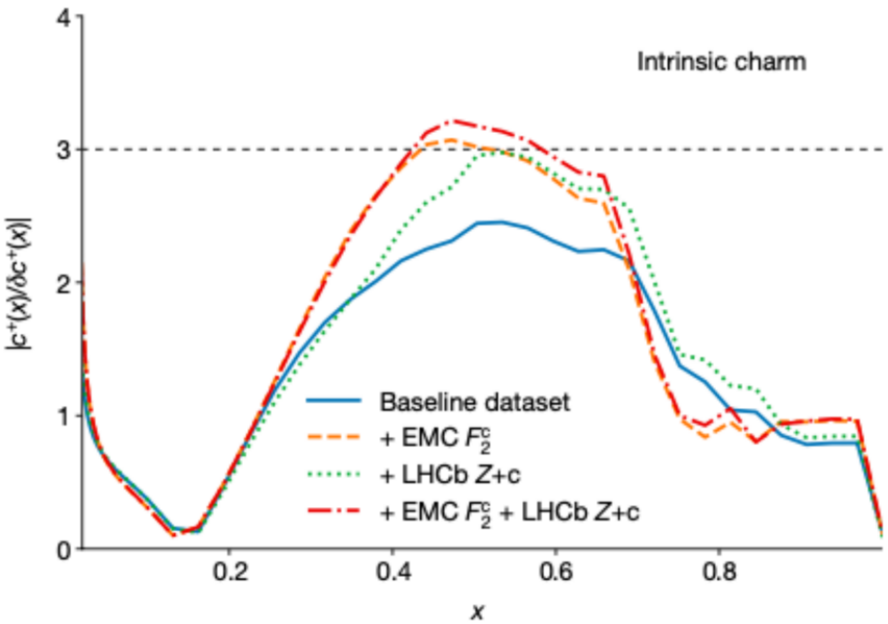
LHCb: Z + charm jet

Data are consistent with the effect expected if the proton wave function contains the $|uudc\bar{c}\rangle$ component predicted by BHPS.

Phys.Rev.Lett. 128 (2022) 8, 082001



Statistical significance



NNPDF collaboration
Nature 608 (2022) 7923, 483-487

LHCb and EMC data were included into parton distribution functions NNPDF4.0. The existence of intrinsic charm of proton is established at 3σ level.

J/ψ pair events at NA3

Phys Lett B, v114, No6 (1982):

$\sigma_{2J/\psi}(\pi^- \ 150 \ GeV/c) = 18 \pm 8 \ pb/nucleon$

$\sigma_{2J/\psi}(\pi^- \ 280 \ GeV/c) = 30 \pm 10 \ pb/nucleon$

Phys Lett B, v158, No1 (1985):

$\sigma_{2J/\psi}(p \ 400 \ GeV/c) = 27 \pm 10 \ pb/nucleon$

Kinematical properties of the 13 $\psi\psi$ events observed in our experiment. P_z is given in the laboratory frame.

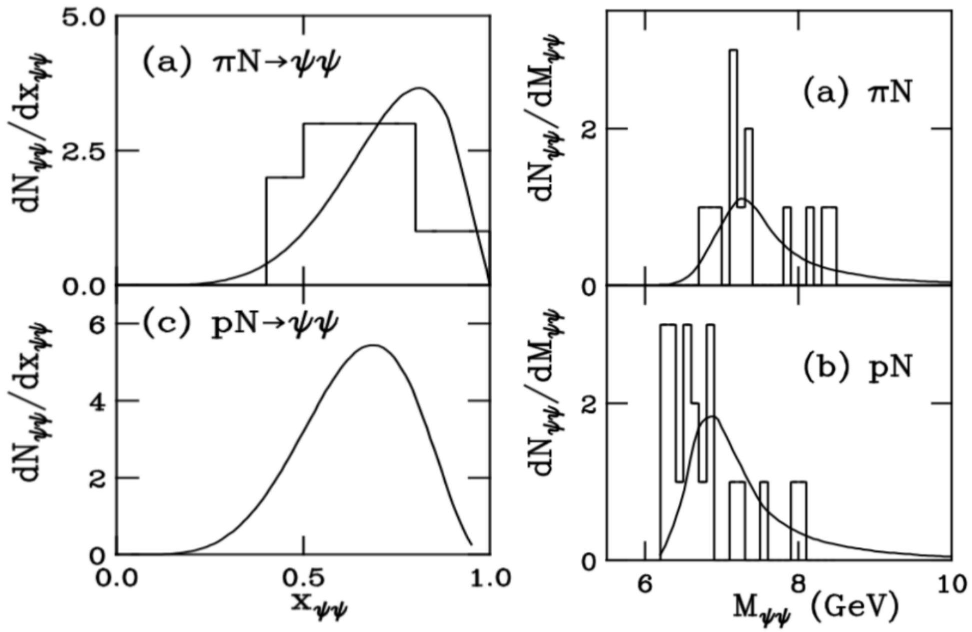
	$P^{\psi}_{x_1}$	$P^{\psi}_{y_1}$	$P^{\psi}_{z_1}$	$P^{\psi}_{x_2}$	$P^{\psi}_{y_2}$	$P^{\psi}_{z_2}$	$M_{\psi_1\psi_2}$	$P^{T}_{\psi_1\psi_2}$
π^- 280 GeV/c	0.90	−1.52	80.15	−0.398	1.67	44.89	7.39	0.52
	−1.41	−0.98	46.52	2.31	0.21	107.04	7.84	1.18
	−0.34	−0.48	43.49	1.01	1.79	105.96	7.18	1.47
	−0.55	−0.13	138.55	1.16	0.55	75.81	6.83	0.74
	1.37	0.58	41.38	−0.87	−0.91	151.79	8.31	0.60
	0.46	0.87	99.72	0.22	−0.49	36.14	7.14	0.78
	−1.27	1.20	78.14	0.09	−0.95	63.28	6.71	1.20
π^- 150 GeV/c	2.86	−1.14	58.15	−1.72	1.93	77.19	8.43	1.39
	0.13	0.36	28.17	−1.09	0.54	87.73	7.28	1.32
	1.59	1.11	48.59	−1.14	−1.19	53.73	7.17	0.46
	1.33	0.54	39.50	−0.61	0.18	78.89	6.99	1.02
	−0.52	1.56	46.78	0.60	−1.65	78.28	7.30	0.12
	0.60	0.49	75.49	−0.84	−1.67	23.62	8.17	1.20

S.J.Brodsky, R.Vogt

Phys.Lett.B349:569-575,1995

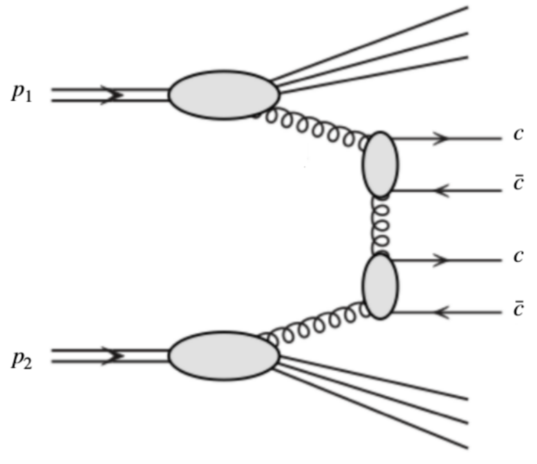
Data were interpreted using intrinsic charm hypothesis ($|d\bar{u}c\bar{c}c\bar{c}\rangle$ Fock component of pion).

Kinematic distributions are not corrected for the acceptance.



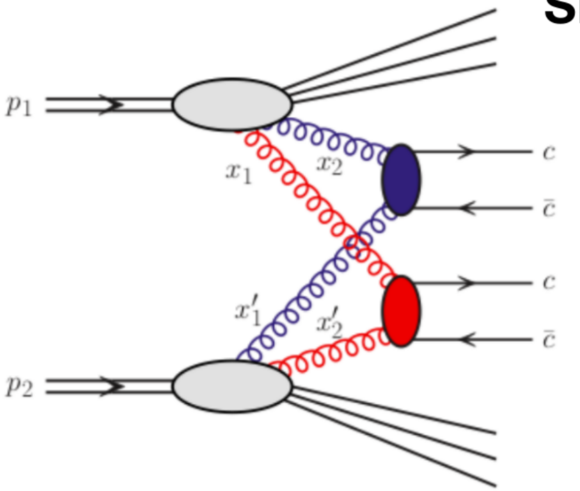
Associative production of J/ψ

Single parton scattering (SPS, $gg \to J/\psi J/\psi$, $q\bar{q} \to J/\psi J/\psi$) is one of the most important production mechanisms of J/ψ pairs.



However, DPS cross section is increasing with the energy:

$$\sigma_{AB}^{DPS} = \frac{m}{2}\int \underbrace{dx_1 dx_1' f^i(x_1) f^k(x_1') \hat{\sigma}^A(x_1, x_1')}_{\text{SPS(A)}}\ \underbrace{dx_2 dx_2' f^j(x_2) f^l(x_2') \hat{\sigma}^B(x_2, x_2')}_{\text{SPS(B)}} \underbrace{F_j^i(b) F_l^k(b) d^2b}_{\text{Transverse component}}$$



$\sigma_{eff} = \left[\int d^2b (F(b))^2\right]^{-1}$ - characterizes effective area of parton-parton interactions.

$$\sigma_{AB}^{DPS} = \frac{m}{2}\frac{\sigma_A^{SPS}\sigma_B^{SPS}}{\sigma_{eff}}$$

J.R. Gaunt et. al.
Eur.Phys.J.C 69 (2010) 53-65

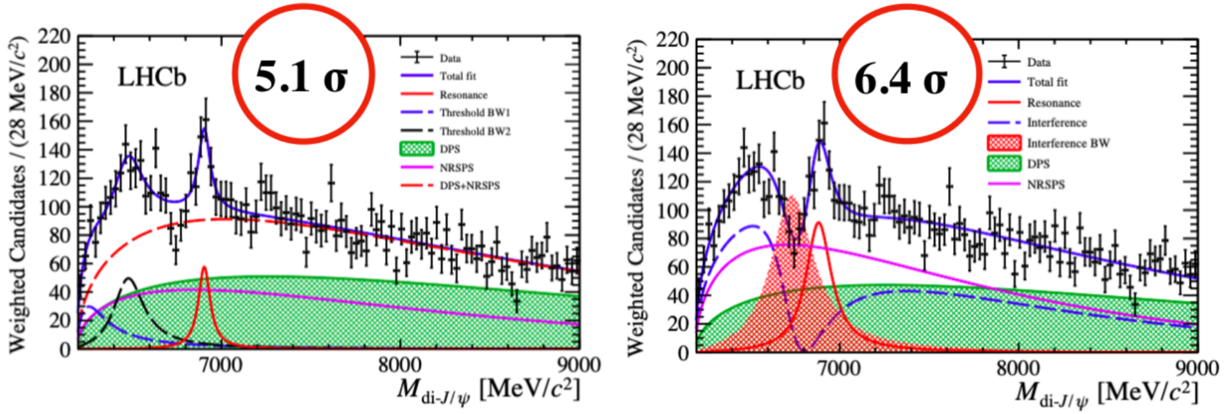
Exotic $|c\bar{c}c\bar{c}\rangle$ states

- 1975: first prediction of $|c\bar{c}c\bar{c}\rangle$ tetraquark states.
- 2020: LHCb reported the X(6900) structure in the $M_{2J/\psi}$ spectrum.
- 2022: ATLAS has proved the resonance with the mass of 6.9 GeV, and has shown the $J/\psi\psi'$ spectrum.
- 2022: CMS has proved the resonance with the mass of 6.9 GeV and announced two more resonances:

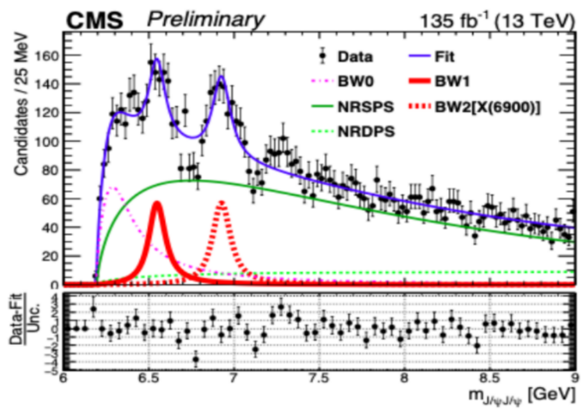
$M(X(6600)) = 6552 \pm 10_{stat} \pm 12_{syst}$ MeV

$M(X(7300)) = 7287 \pm 19_{stat} \pm 5_{syst}$ MeV.

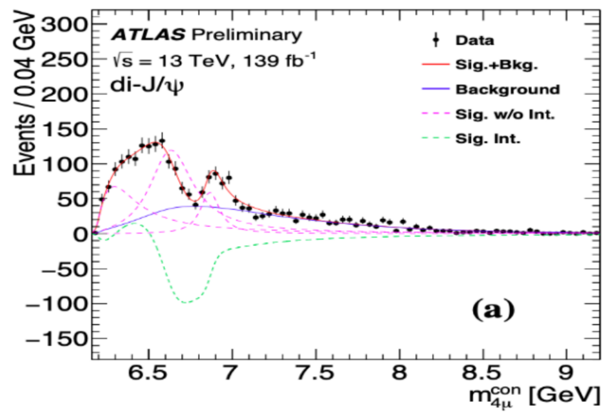
Sci. Bull., V65, №23, p1983-1993, 2020



CMS PAS BPH-21-003



ATLAS-CONF-2022-040



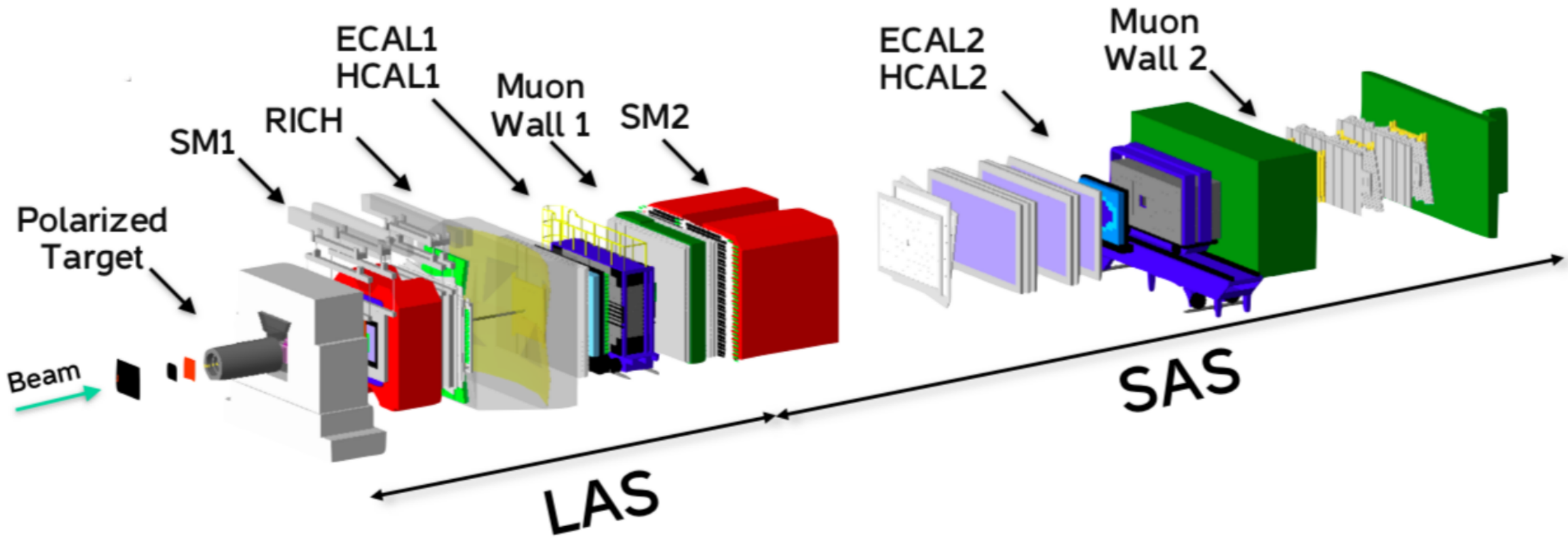
J/ψ pair production at COMPASS

The only experimental observation of J/ψ pair production in pion-nucleon interactions was done by the NA3 experiment more than 40 years ago.

The new measurement by COMPASS allows:

- To estimate contribution of different production mechanisms (including IC) into double J/ψ production cross section.
- To check the hypothesis that intrinsic charm of pion is dominant J/ψ pair production mechanism in the NA3 data.
- To search for exotic states that decay to J/ψ pair.

COMPASS Drell-Yan setup (2015, 2018)

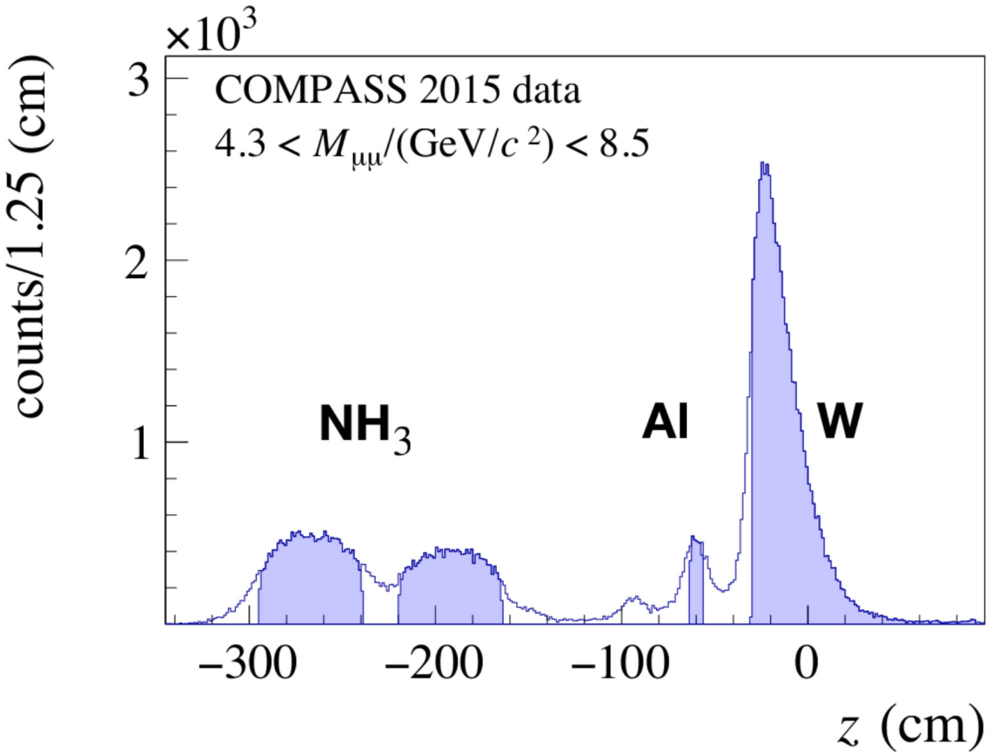


Beam dump configuration:

- Optimized for muon registration;
- > 6M J/ψ in NH_3 target;

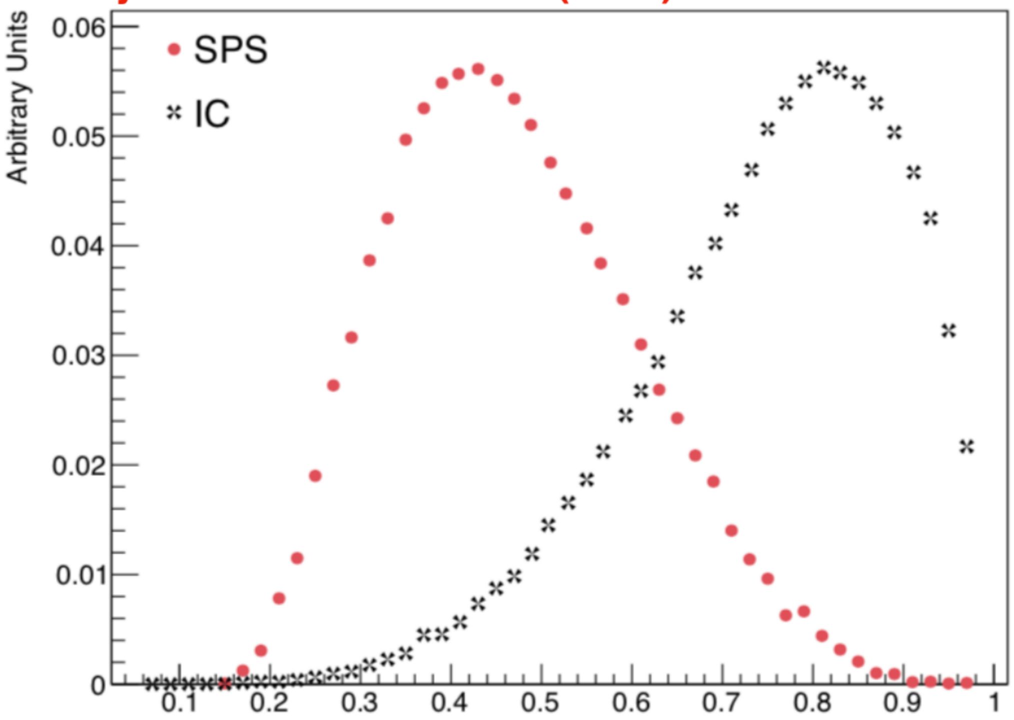
Unique hadron beam in DY runs :

- hadron beam composition: 96.80% π^-, 2.40% $\bar{K}$, 0.80% $\bar{p}$;
- beam momentum : **190 ± 3 GeV/c**;
- intensity: up to **7x10[7] hadrons / sec**;

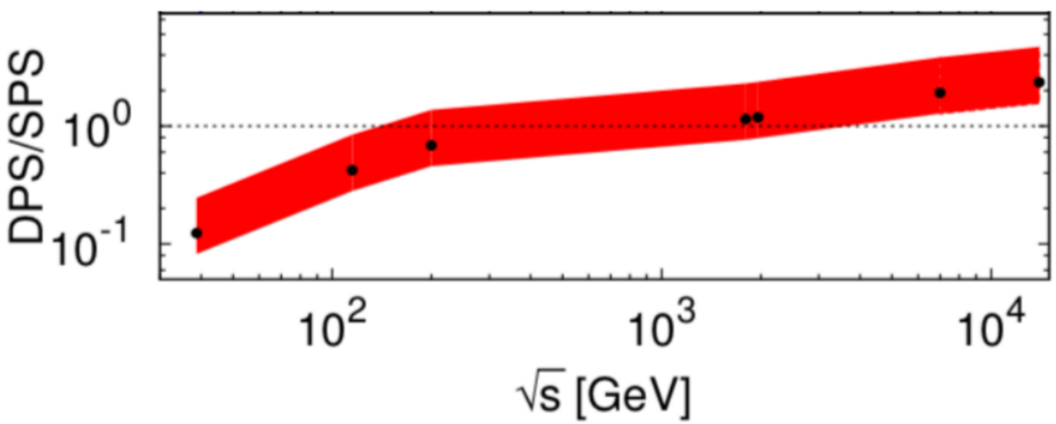


J/ψ pair production at COMPASS

A.Gridin, S.Koshkarev,
Phys. Part. Nucl. Lett. 17 (2020) 826-833



$$x_{||\ 2J/\psi} = \frac{p_{Z\ 2J/\psi}}{p_{beam}}$$

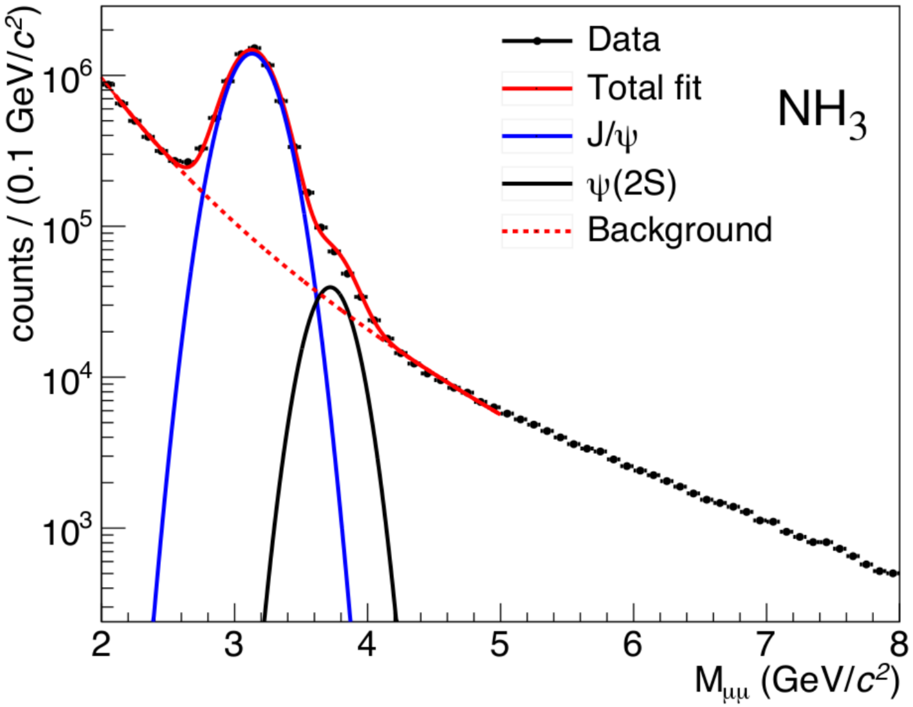


SPS and IC are the leading J/ψ pair production mechanisms at COMPASS energies.

The ratio of $\sigma^{DPS}/\sigma^{SPS} \approx 0.1$ at $\sqrt{s} = 19.7\ GeV$.

The distribution of longitudinal momentum fraction of J/ψ pair in the lab frame can be used to determine the relative weights of double J/ψ production mechanisms (IC, SPS).

Single and double J/ψ events at COMPASS



2015+2018: large statistics of single J/ψ events collected

NH_3: $6.23 \cdot 10^6$

Al: $0.46 \cdot 10^6$

W: $2.51 \cdot 10^6$

	NH_3	Al	W
$M_{J/\psi}$, GeV/c^2	3.141 ± 0.009	3.138 ± 0.010	3.078 ± 0.009
$\Delta_{J/\psi}$, GeV/c^2	0.182 ± 0.008	0.202 ± 0.009	0.299 ± 0.011

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

COMPASS double J/ψ data:

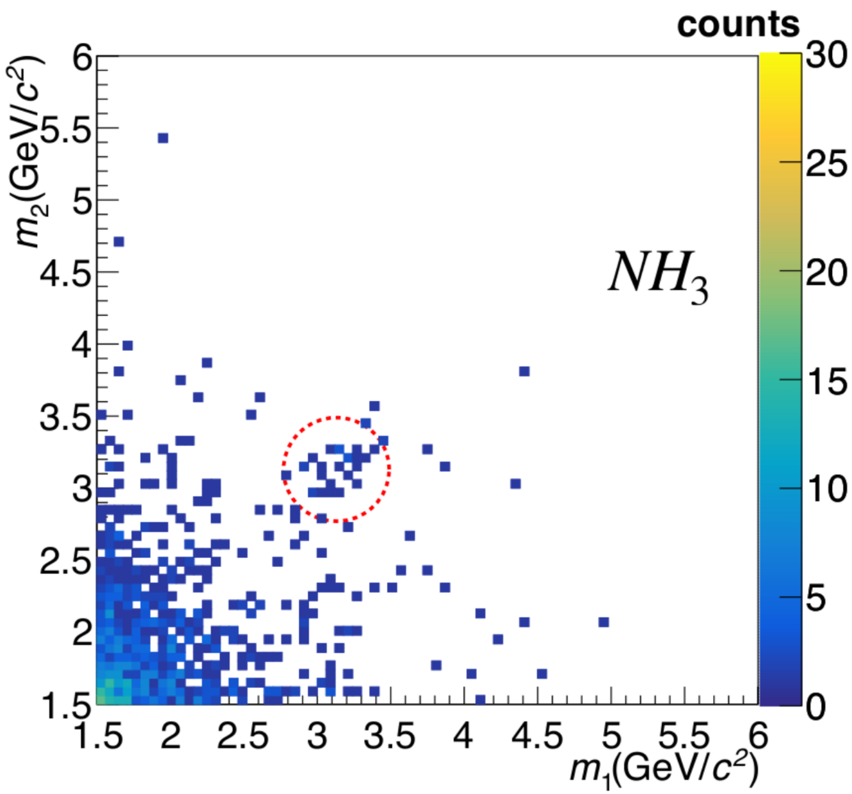
NH_3: 28 events

Al: 2 events

W: 13 events

All the events are selected in kinematic region:

$$x_{F\ J/\psi} = 2p_L^*/\sqrt{s} > 0$$



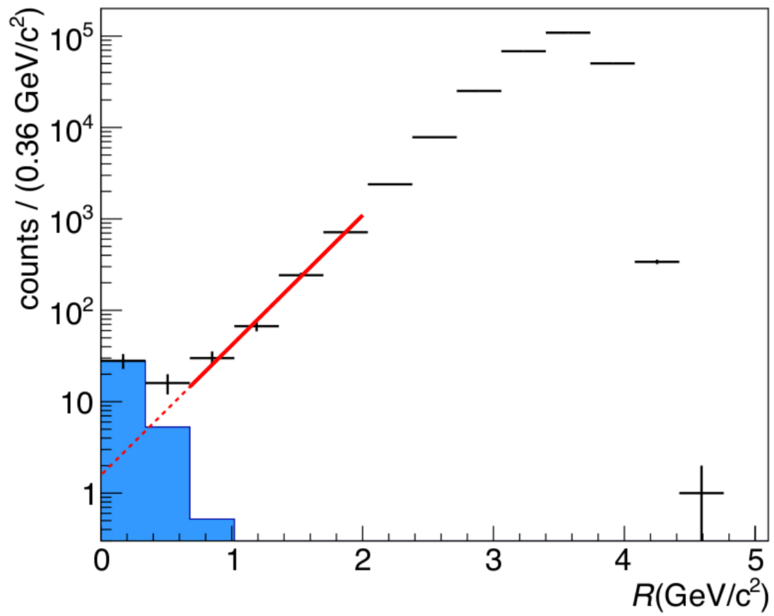
Signal and background events

Signal events: two J/ψ reconstructed in the same vertex, these 2J/ψ should appear as a result of a process: $\pi^- N \rightarrow J/\psi J/\psi + X$

Background events:

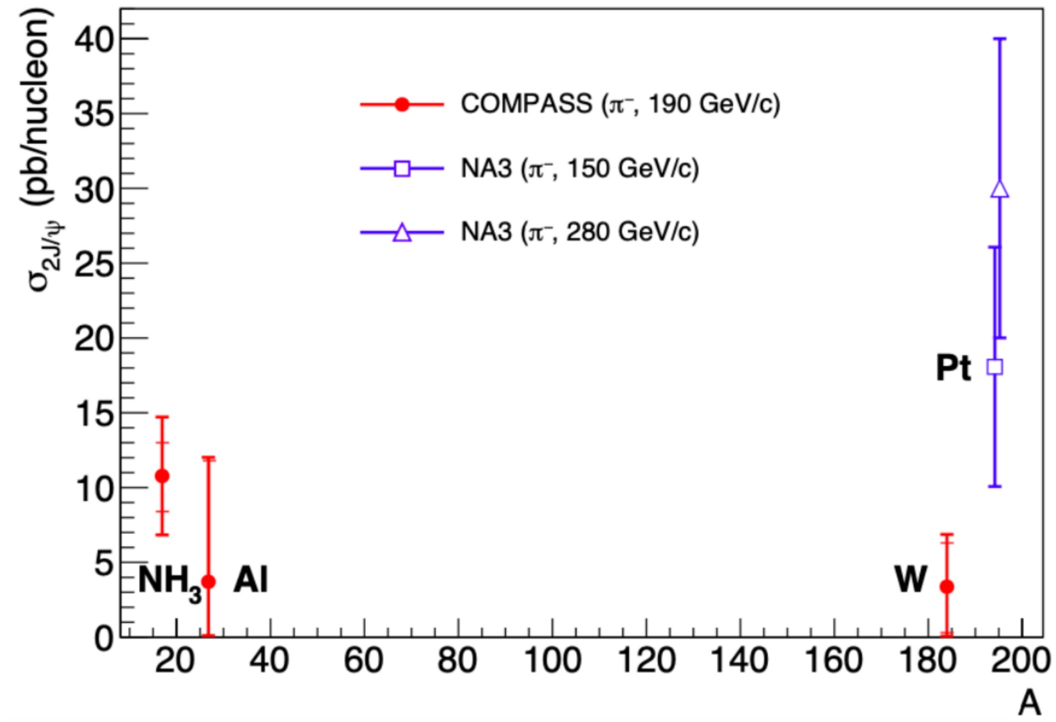
- **Pileup:** two J/ψ reconstructed in the same vertex, but produced in different interactions - estimated to be negligible;
- **Combinatorial background:** J/ψ**+**2μ **or** 4μ**;**
- B**-meson pair decay:** $B\bar{B} \rightarrow J/\psi J/\psi + X$

	NH_3	Al	W
$N_{J/\psi}/10^6$	6.23	0.46	2.51
$N_{2J/\psi\ candidates}$	28	2	13
$N_{2J/\psi\ background}$	2.9 ± 0.5	1.4 ± 0.4	8.5 ± 2.0
$N_{2J/\psi}$	25.1±0.5	0.6±0.4	4.5±2.0



Statistics of J/ψ pair events in NH_3 target at COMPASS approximately two times higher than NA3 statistics.

Double J/ψ cross-section measurement



$$\frac{\sigma_{2J/\psi}}{\sigma_{J/\psi}} = (1.02 \pm 0.22_{stat} \pm 0.27_{syst}) \cdot 10^{-4} (NH_3)$$

$$\sigma_{2J/\psi}^{NH_3} = 10.7 \pm 2.3_{stat} \pm 3.2_{syst} \ \ pb/nucleon$$

$$\sigma_{2J/\psi}^{Al} = 3.6 \pm 8.2_{stat} \pm 1.4_{syst} \ \ pb/nucleon$$

$$\sigma_{2J/\psi}^{W} = 3.3 \pm 3.0_{stat} \pm 1.8_{syst} \ \ pb/nucleon$$

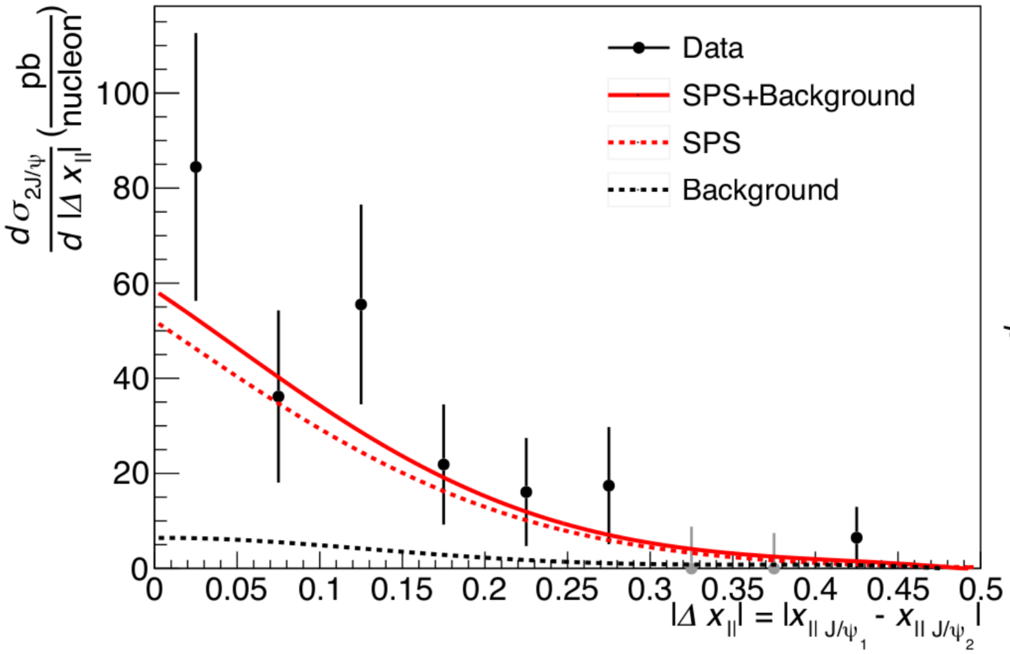
- COMPASS results do not contradict to NA3 measurement.
- Within uncertainties, no significant evidence of nuclear effects in J/ψ pair production is observed.

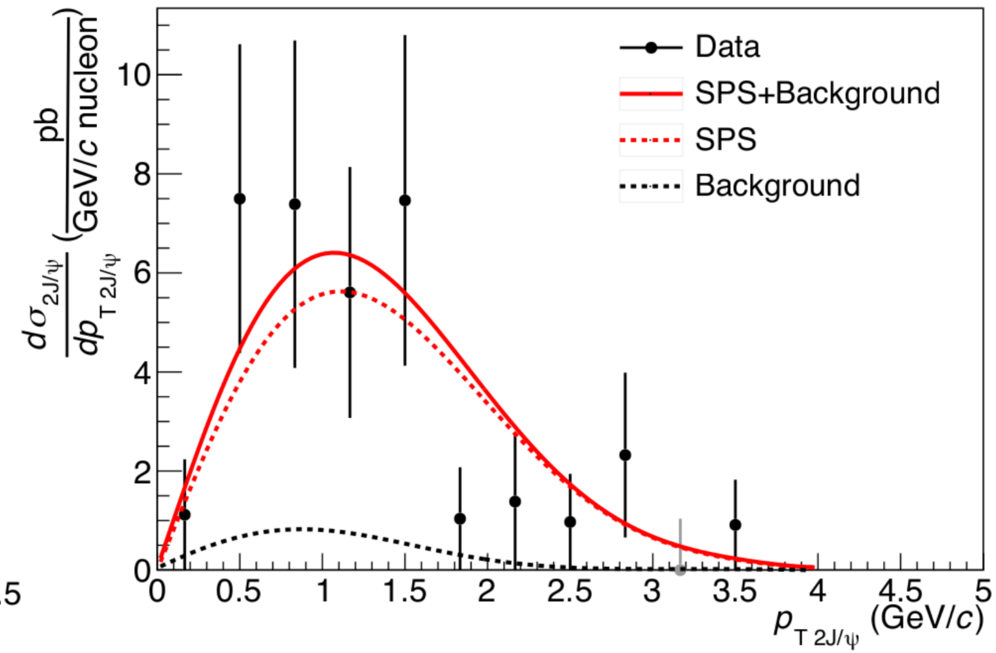
Main sources of systematics:

- uncertainty of $\sigma_{J/\psi}$
- background estimation
- acceptances of single and double J/ψ
- uncertainty of the number of single J/ψ

The measured by the NA3 $\sigma_{J/\psi} = 4.9 \pm 0.77 \dfrac{nb}{nucleon}$ was used for the estimation of $\sigma_{2J/\psi}$.

Differential cross section of J/ψ pair production

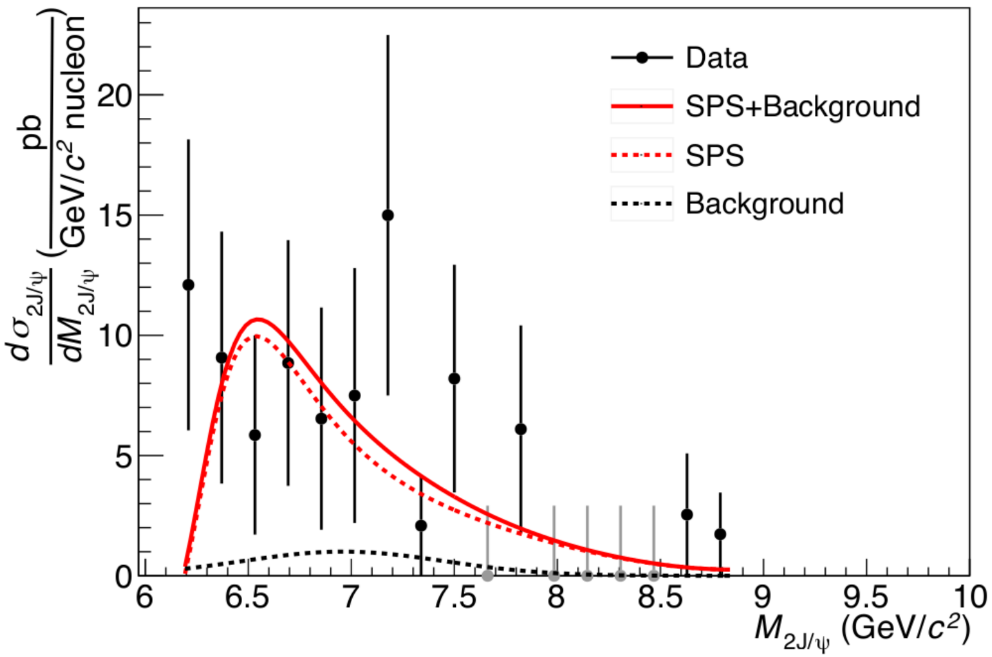


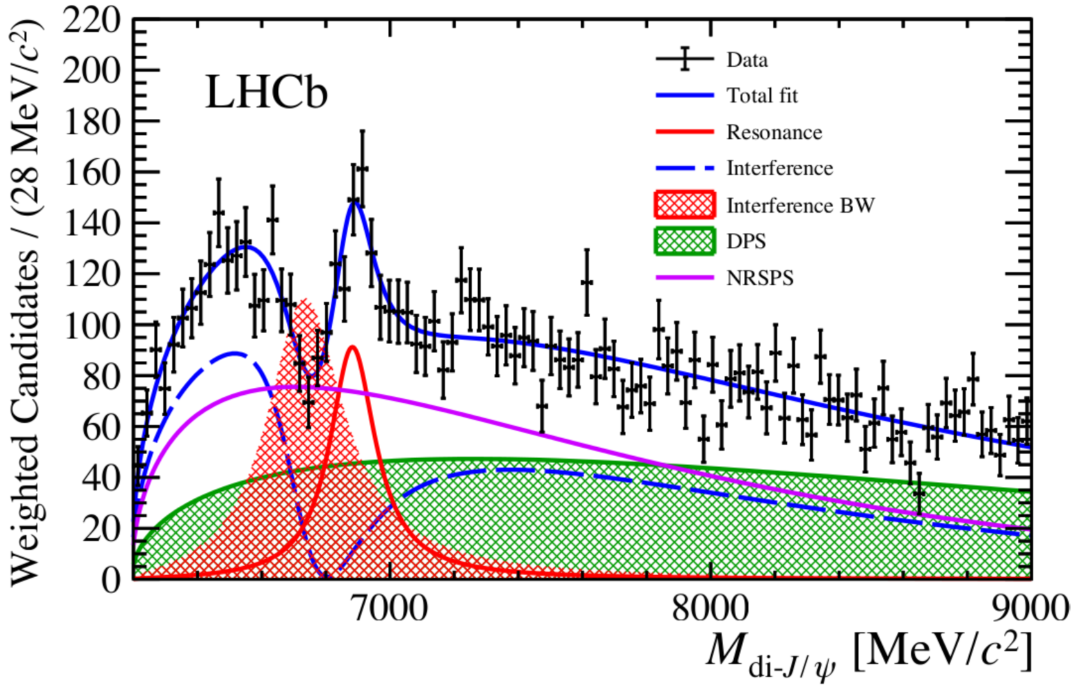


The function with one free parameter (SPS amplitude) is fitted to the data. The background contribution is fixed.

The $p_{T\ 2J/\psi}$ and $|\Delta x_{||}|$ distributions are in agreement with SPS model,

Differential cross section of J/ψ pair production



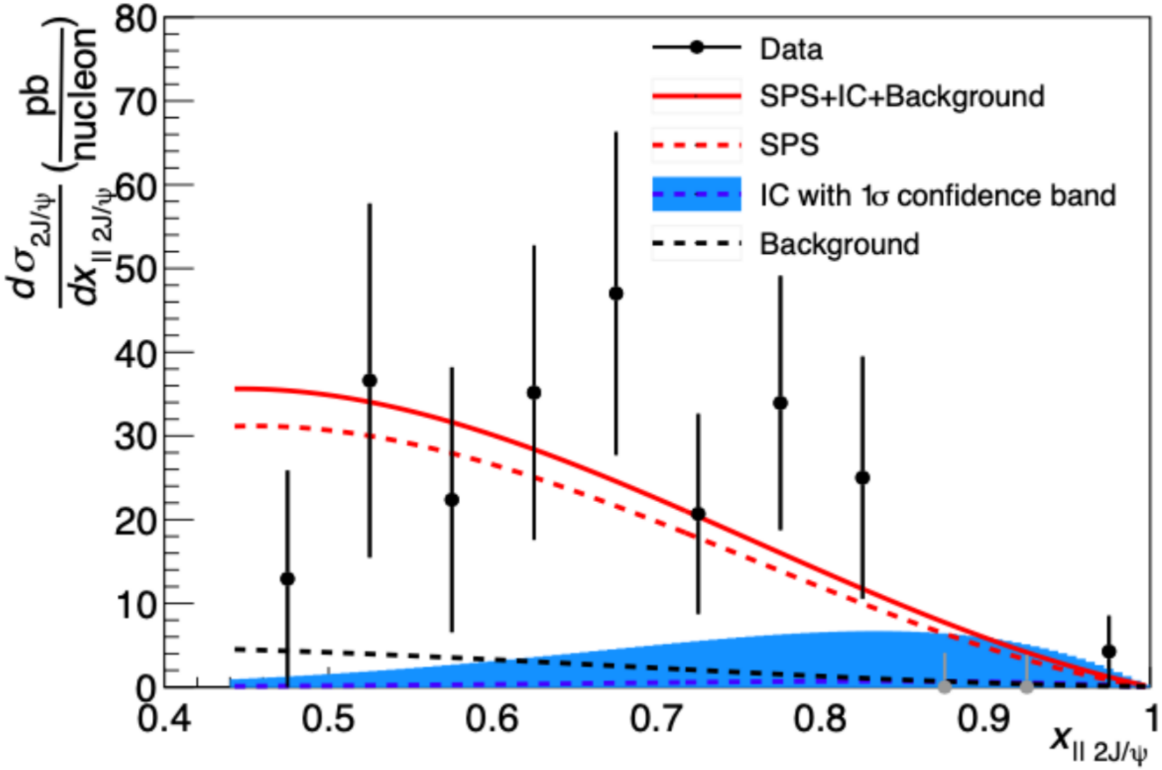


$m[X(6900)] = 6886 \pm 11 \pm 11$ МэВ

$\Gamma[X(6900)] = 168 \pm 33 \pm 69$ МэВ

Given the restricted statistics the $M_{2J/\psi}$ spectrum does not contain any evident signal from exotic states observed by LHCb.

Double J/ψ production mechanisms



SPS curve:

- HELAC-Onia generator: **H.S.Shao, Comput. Phys. Commun., Vol.198, p. 238-259, 2016;**
- Color Singlet J/ψ production model.

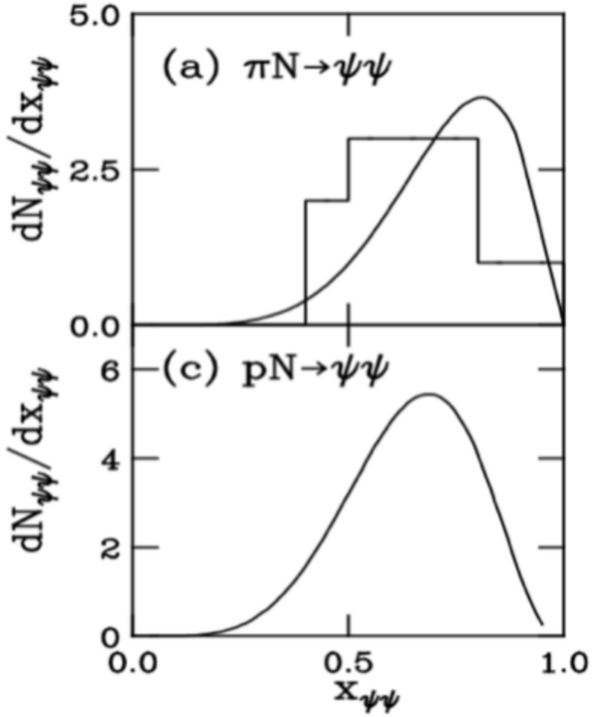
IC curve:

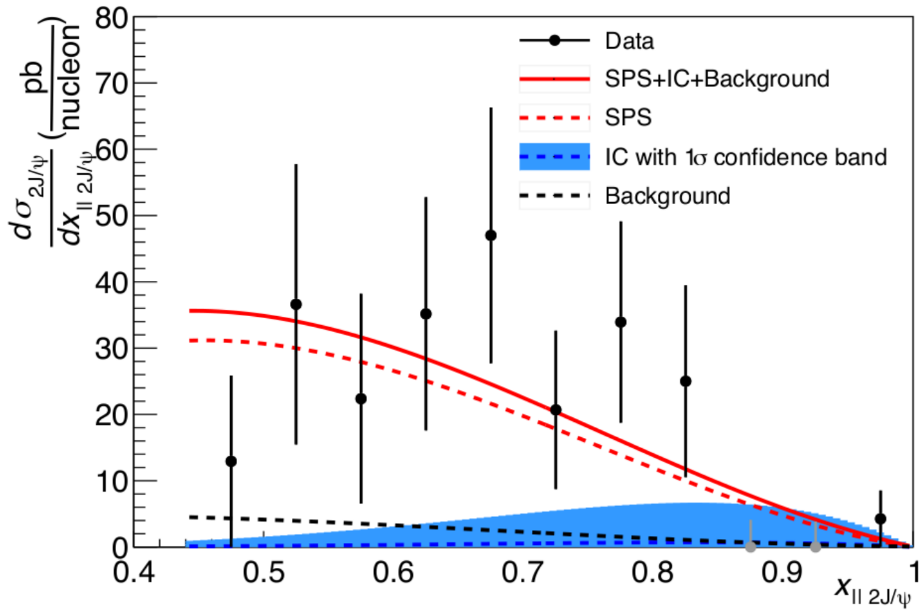
- predictions for COMPASS from **Phys.Part.Nucl.Lett. Vol17, No6, 2020**.

$$f(x_{||\ 2J/\psi}) = a \cdot f_{SPS}(x_{||\ 2J/\psi}) + b \cdot f_{IC}(x_{||\ 2J/\psi}) + f_{bkg}(x_{||\ 2J/\psi})$$

- the double parton scattering (DPS) is not considered in the fit;
- the data are consistent with pure SPS hypothesis
- $\sigma_{IC}/\sigma_{2J/\psi} < 0.24\ (CL = 90\%)$

J/ψ pair events at NA3 and COMPASS





NA3 (π^-, 150, 280 GeV): provided distributions are not corrected for the acceptance. Data were interpreted by S.Brodsky using intrinsic charm hypothesis ($|d\bar{u}c\bar{c}c\bar{c}\rangle$ Fock component of pion): **Phys.Lett.B349:569-575,1995**.

COMPASS (π^-, 190 GeV): data are corrected for the acceptance. Results do not contradict to the SPS production mechanism. An upper limit on double IC of pion production mechanism is established: $\sigma^{IC}_{2J/\psi}/\sigma_{2J/\psi}\Big|_{x_F>0} < 0.24\ (CL = 90\%)$.

Results

1) COMPASS has measured J/ψ pair cross section in $\pi^- N$ interactions. Differential cross sections as functions of $p_{T\ 2J/\psi}$, $x_{||\ 2J/\psi}$, $\Delta x_{||\ 2J/\psi}$ are obtained for NH_3 target.

2) The COMPASS double J/ψ data are consistent with SPS production mechanism. An upper limit on IC production mechanism is established in $x_{||\ 2J/\psi} > 0.4$ region: $\sigma^{IC}_{2J/\psi}/\sigma_{2J/\psi} < 0.24\ (CL = 90\%)$.

3) The double J/ψ mass spectrum does not contain any evident signal from exotic charmonium-like states observed by LHCb.

4) It is shown, that the interpretation of NA3 double J/ψ data (π^-, 150 and 280 GeV) using intrinsic charm of pion model is not correct. Kinematics of J/ψ pair events at COMPASS (π^-, 190 GeV) do not contradict to the SPS production mechanism.

Results of the work are published in Phys.Lett.B 838 (2023) 137702

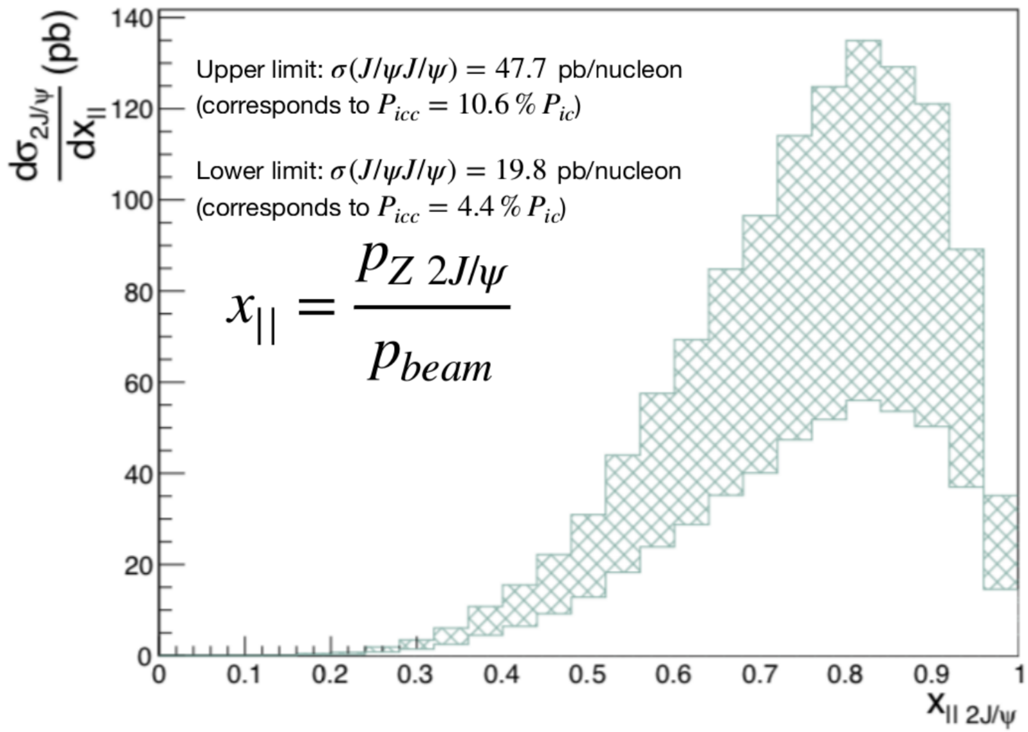
Thank you for attention

Intrinsic charm of pion at COMPASS

$|d\bar{u}c\bar{c}c\bar{c}\rangle$ Fock component of pion could be materialized into J/ψ pair;

$\sigma^{NA3}_{2J/\psi}(150\ GeV/c) = 18 \pm 8$ pb/nucleon

$\sigma^{NA3}_{2J/\psi}(280\ GeV/c) = 30 \pm 10$ pb/nucleon



$$\sigma_{2J/\psi} = f^2_{\psi/\pi}\frac{P_{icc}}{P_{ic}}\sigma_{ic}$$

To estimate J/ψ pair production cross section at COMPASS the values of $P_{icc} = 4.4\,\%\,P_{ic}$ and $P_{icc} = 10.6\,\%\,P_{ic}$ (probabilities to obtain Fock states with $c\bar{c}c\bar{c}$ and $c\bar{c}$) were taken from **Phys.Lett.B349:569-575,1995**.

Double J/ψ production cross section at COMPASS energy estimated to be 19.8 - 47.7 pb/nucleon.

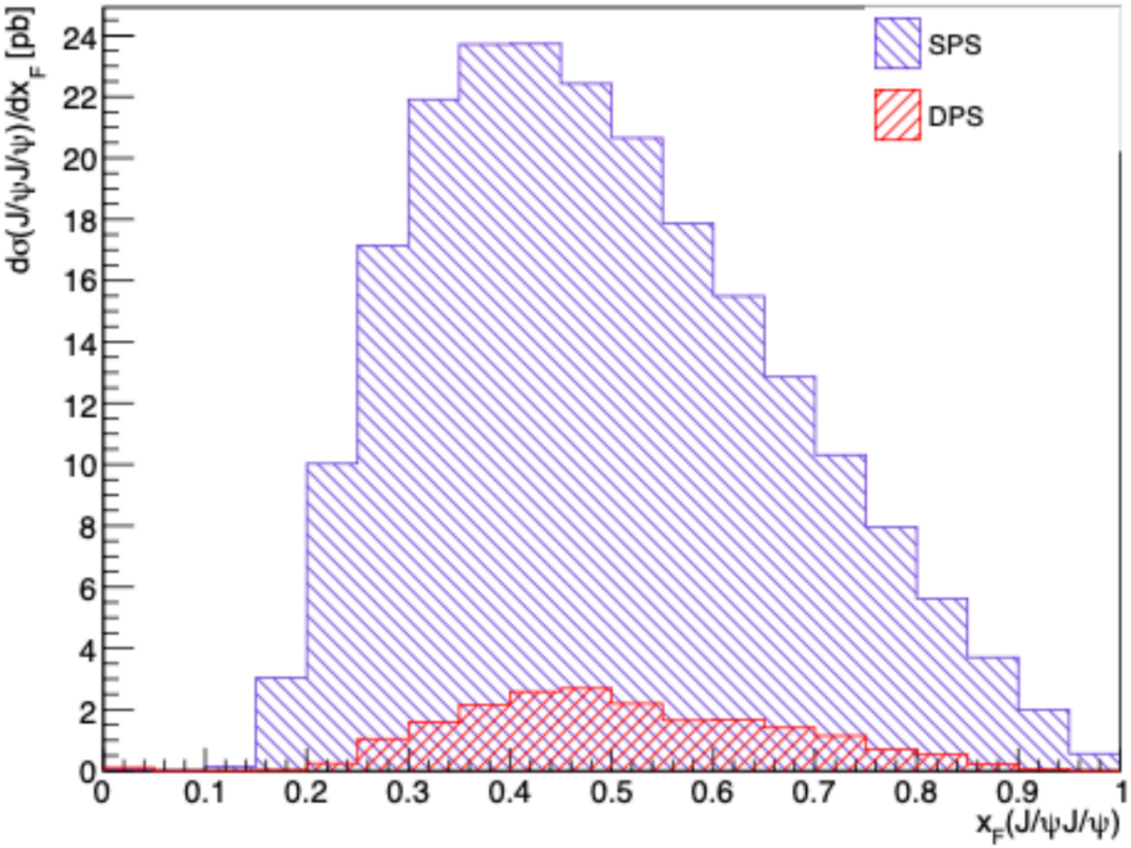
$\sigma_{ic} = 0.5\ mb$ - **IC cross section for π^- at 200 GeV/c.**

$f_{\psi/\pi} \approx 0.03$ - **fraction of $c\bar{c}$ quark pairs producing J/ψ**

SPS and DPS at COMPASS

S. Koshkarev, Proceedings of: DSPIN-19:

arXiv:1909.06195 [hep-ph]



$$\sigma_{J/\psi J/\psi} = 12\ pb/nucleon$$

σ_{eff} at different experiments