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

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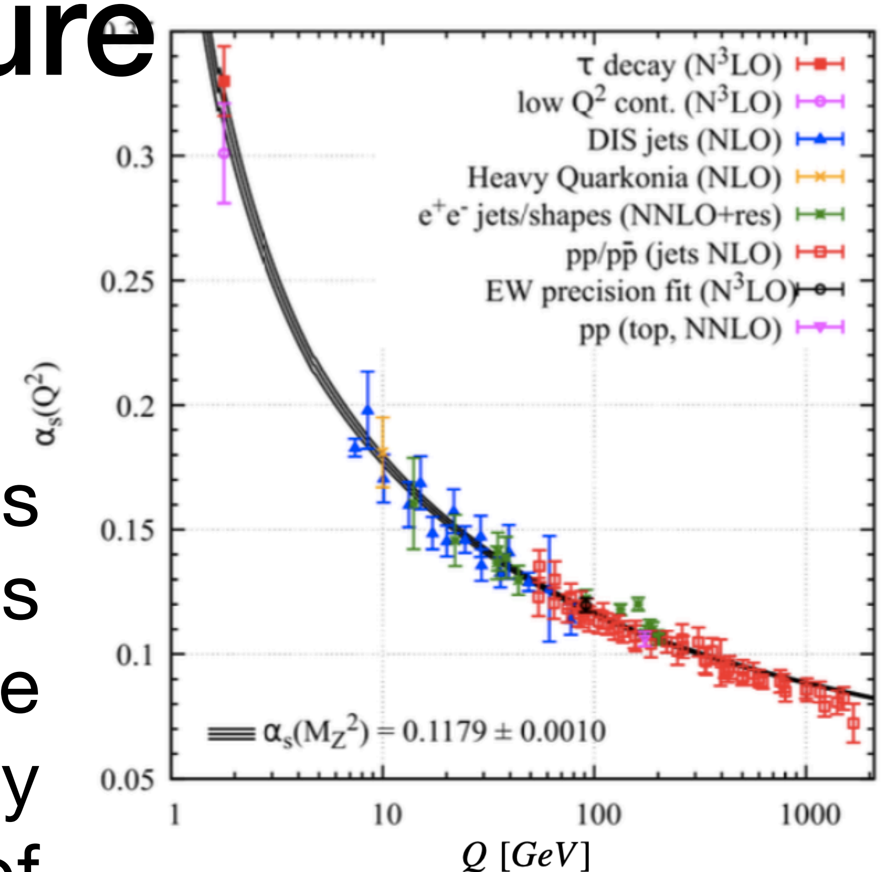
Hadron structure

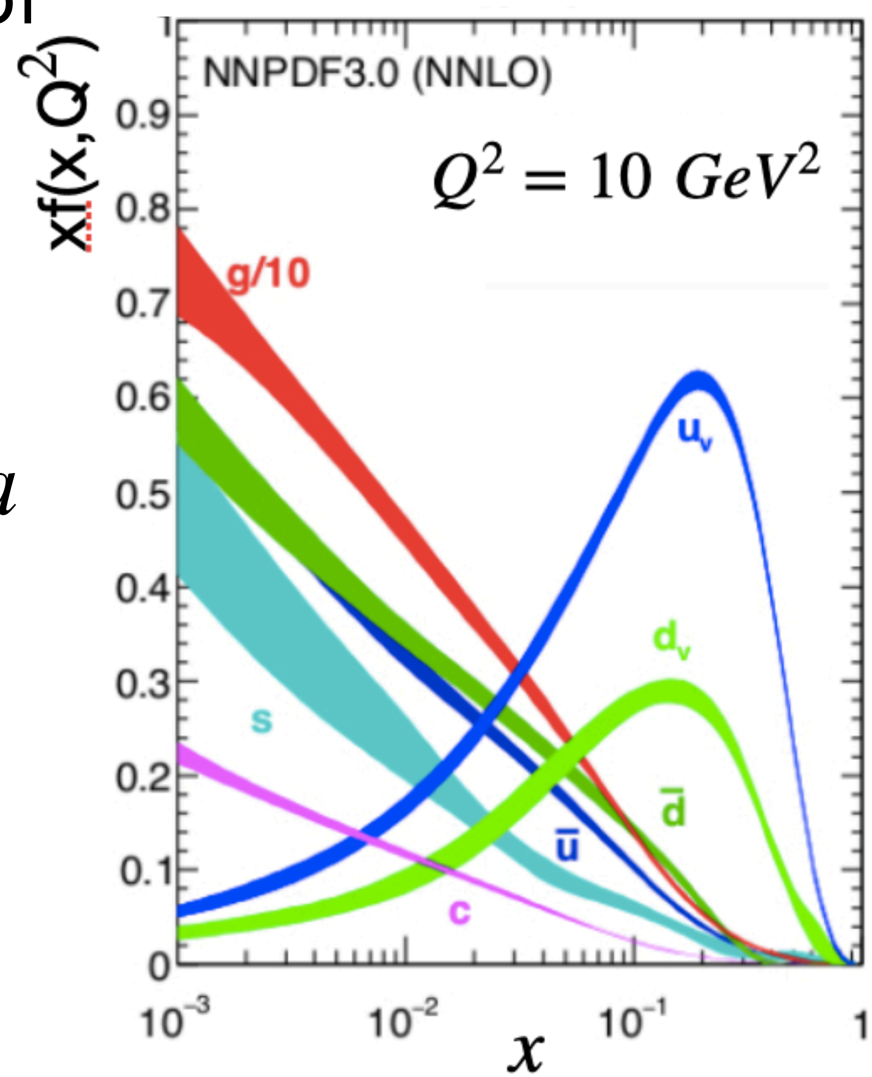
QCD is the theory of strong interaction between quarks and gluons, describes processes at $\alpha_S(Q^2) < 1$.

To desribe hadron interactions at high energies one can use factorization theorem: hard cross section of interaction of A and B hadrons could be written as a convolution of parton density functions (PDFs) with hard cross section of interaction of partons:

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

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





Intrinsic charm of a hadron

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

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

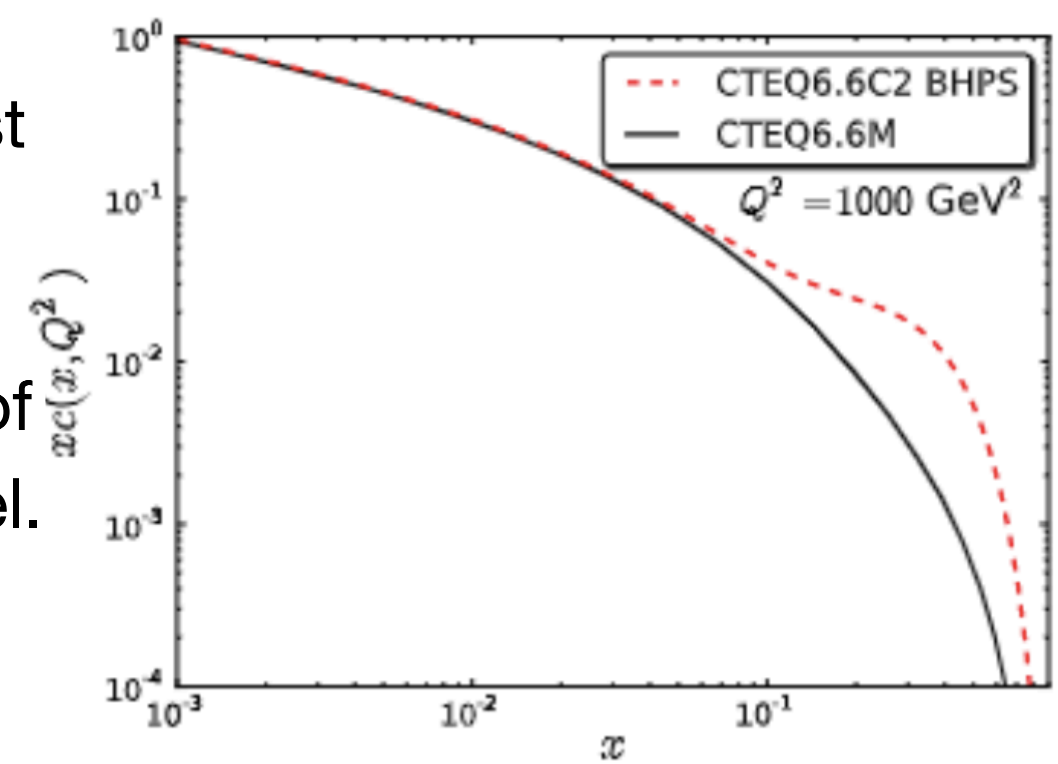
- Intrinsic charm contribution is generated non-perturbatively via $gg \to Q\bar{Q}$.
- Beside of intrinsic charm ($gg \to Q\bar{Q}$) there is extrinsic charm component in hadrons that arises from gluon splitting ($g \to Q\bar{Q}$).
- Valence-like intrinsic charm quarks carry the most part of hadron momentum.
- LHCb and EMC data were included into parton distribution functions NNPDF4.0. The existence of intrinsic charm of proton is established at 3σ level.

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

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)



J/ψ pair events at NA3

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

	$P^{\psi}_{x_1}$	$P^{\psi}_{y_1}$	$P^{\psi}_{z_1}$	$P^{\psi}_{x_2}$	$P^{\psi}_{y_2}$	$P^{\psi}_{z_2}$	$M_{\psi_1\psi_2}$	$P^{T}_{\psi_1\psi_2}$
	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

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):

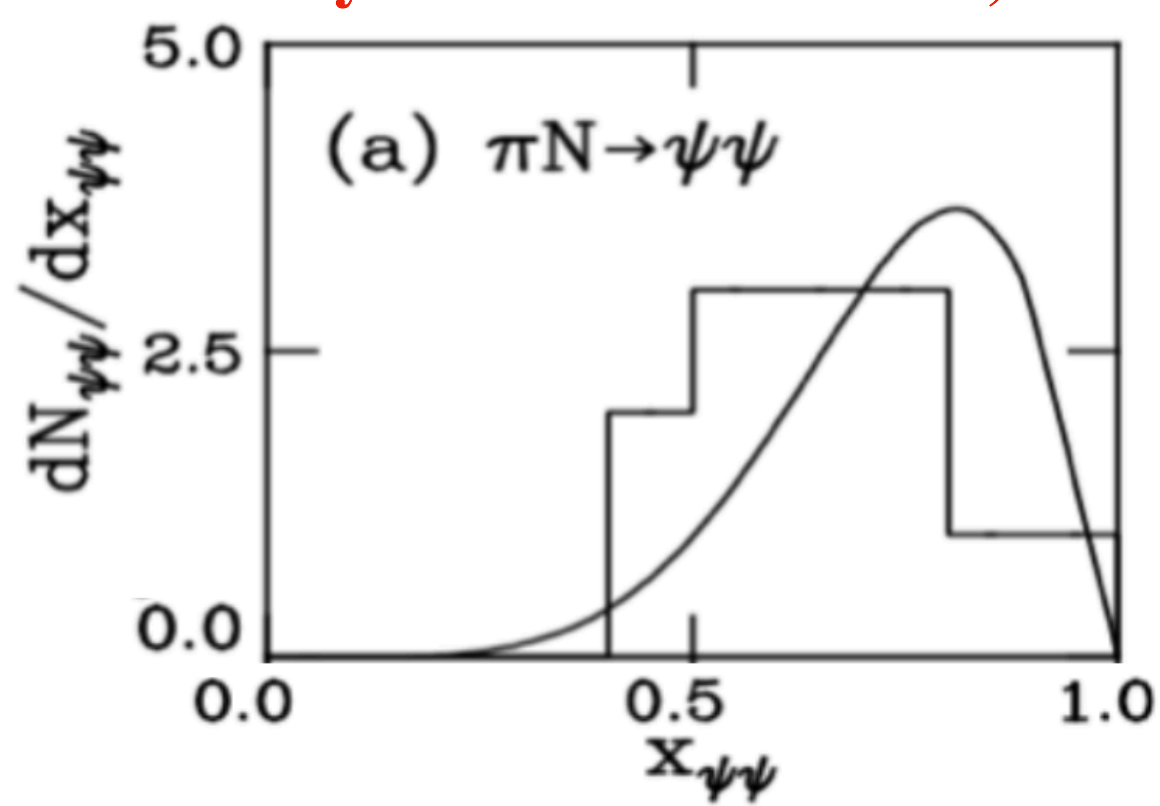
$\sigma_{2J/\psi}(p\ 400\ GeV/c) = 27 \pm 10\ pb/nucleon$

All J/ψ pair events observed by NA3 were interpreted using intrinsic charm hypothesis ($|d\bar{u}c\bar{c}c\bar{c}\rangle$ Fock component of pion).

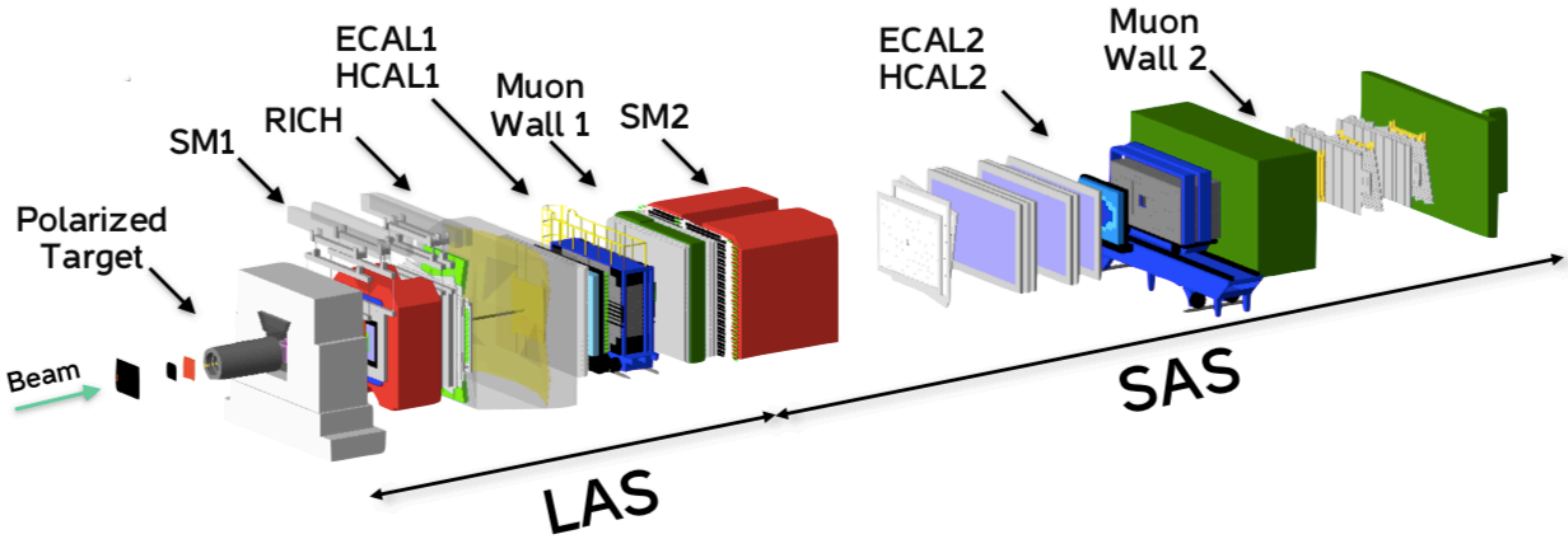
Kinematic distributions are not corrected for the acceptance;

The new measurement by COMPASS allows to estimate contribution of different production mechanisms (including IC) into double J/ψ production cross section.

R.Vogt, S.Brodsky
Phys.Lett.B349:569-575,1995



COMPASS Drell-Yan setup (2015, 2018)

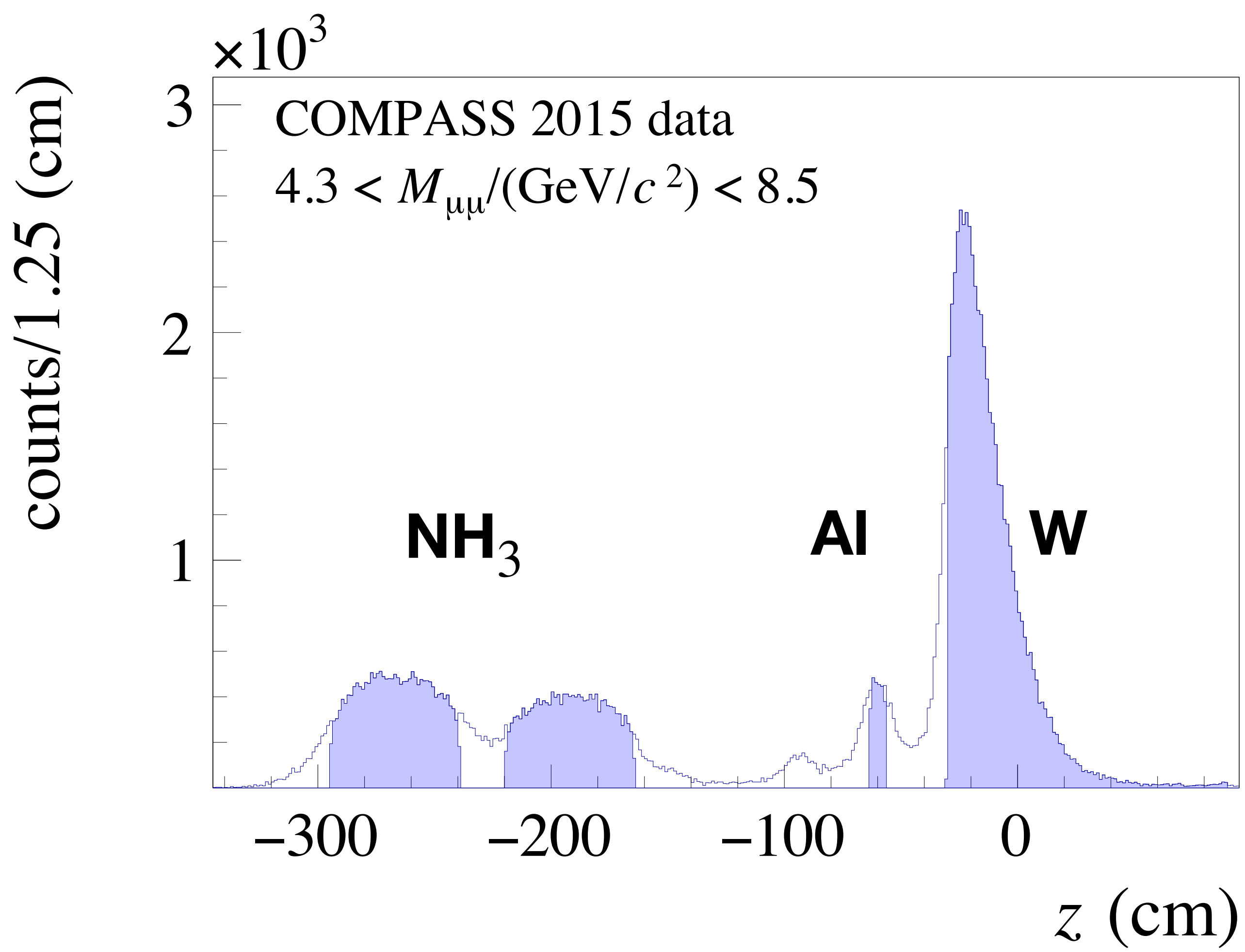


Beam dump configuration:

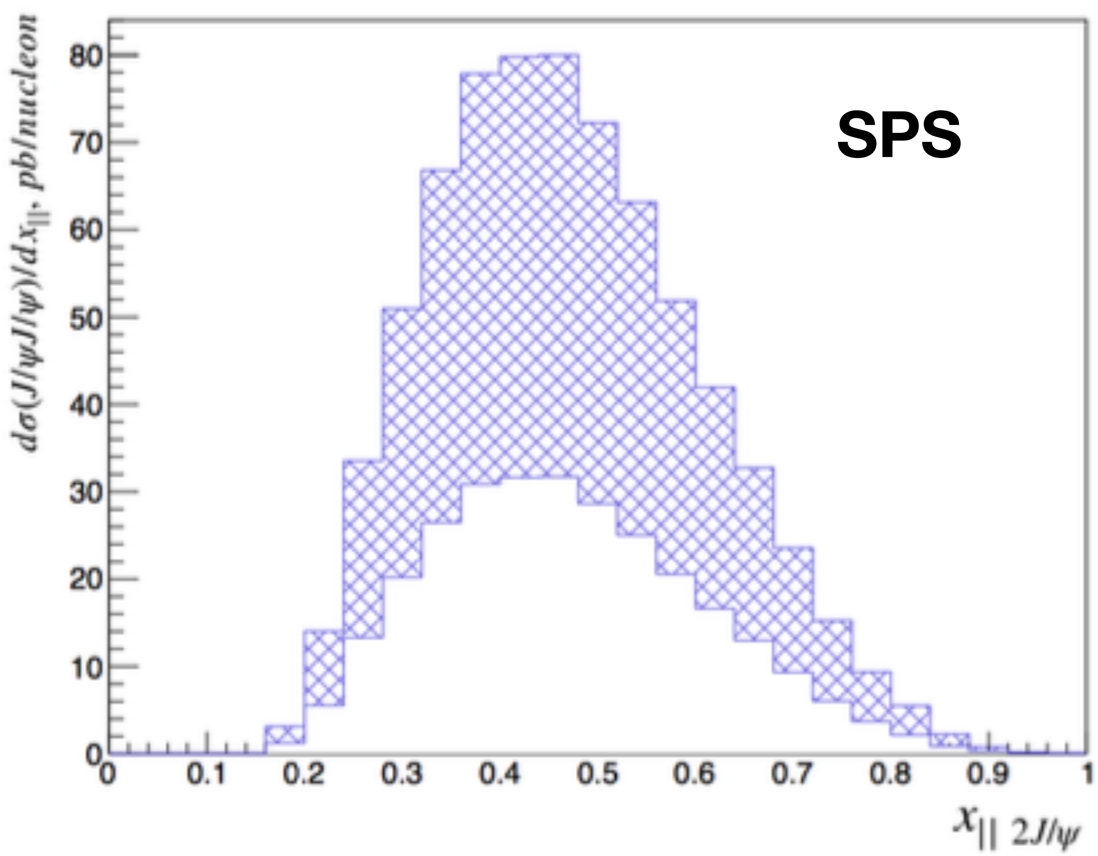
- Optimized for muon registration;
- > 6M J/ψ in NH_3 target;

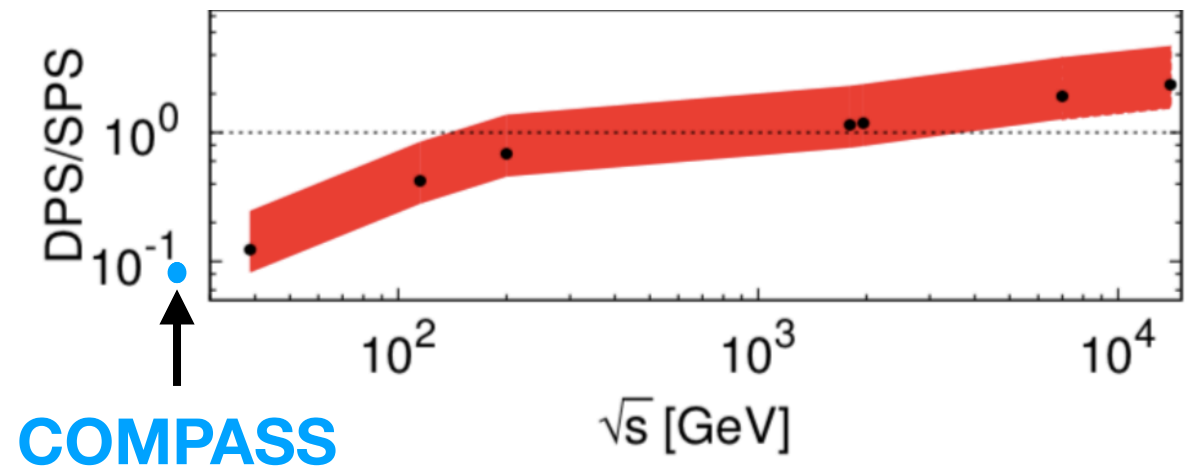
Unique hadron beam in DY runs :

- hadron beam composition: 96.80% π^-, 2.40% $\bar{K}$, 0.80% $\bar{p}$;
- beam momentum : **190 ± 3 GeV/c**;
- intensity: up to **7**x**10**[7] **hadrons / sec**;

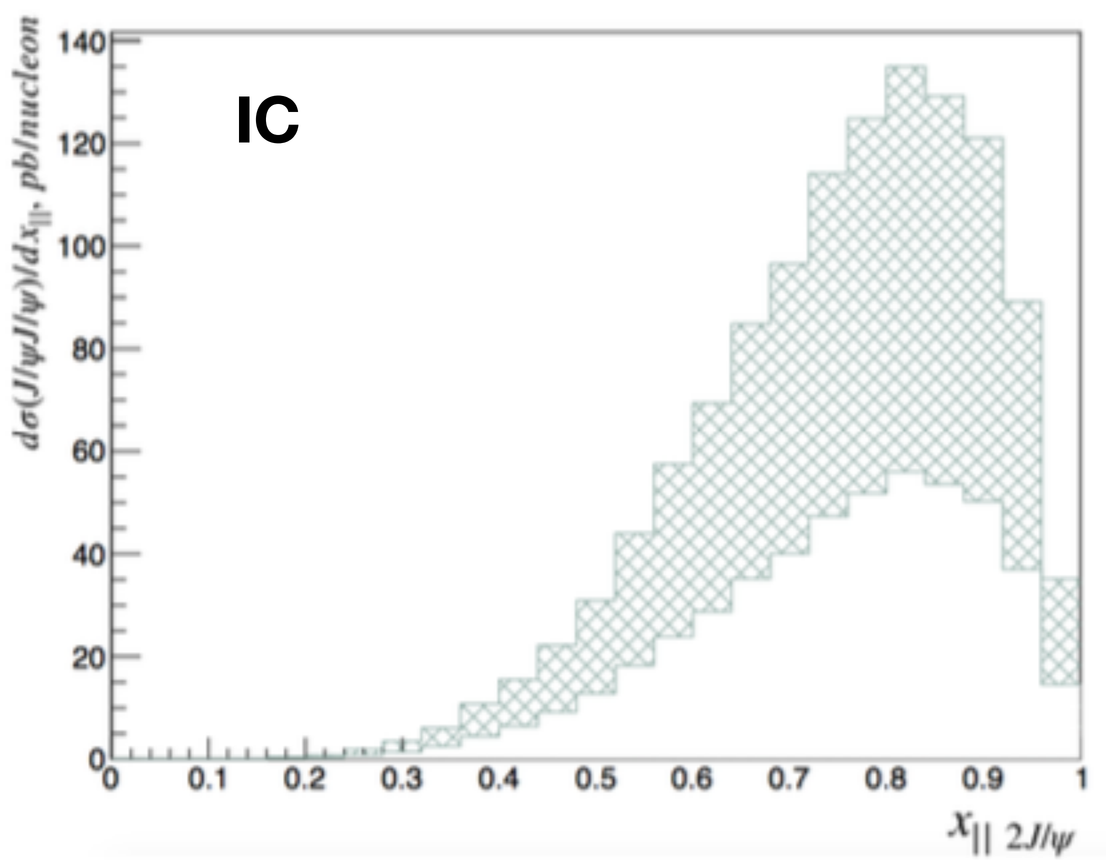


J/ψ pair production mechanisms at COMPASS





- At $\sqrt{s} = 19.7\ GeV$ the ratio $\sigma^{DPS}/\sigma^{SPS} \lesssim 0.1$.



- The distribution of $x_{||} = \dfrac{p_{Z\ 2J/\psi}}{p_{beam}}$ can be used to determine the relative weights of double J/ψ production mechanisms (IC, SPS).

Cross section of J/ψ pair production at nuclear targets

$$\frac{\sigma_{J/\psi J/\psi}}{\sigma_{J/\psi}} = \frac{1}{BR(J/\psi \to \mu\mu)} \cdot \frac{N_{J/\psi J/\psi}}{A_{J/\psi J/\psi}} \cdot \frac{A_{J/\psi}}{N_{J/\psi}}$$

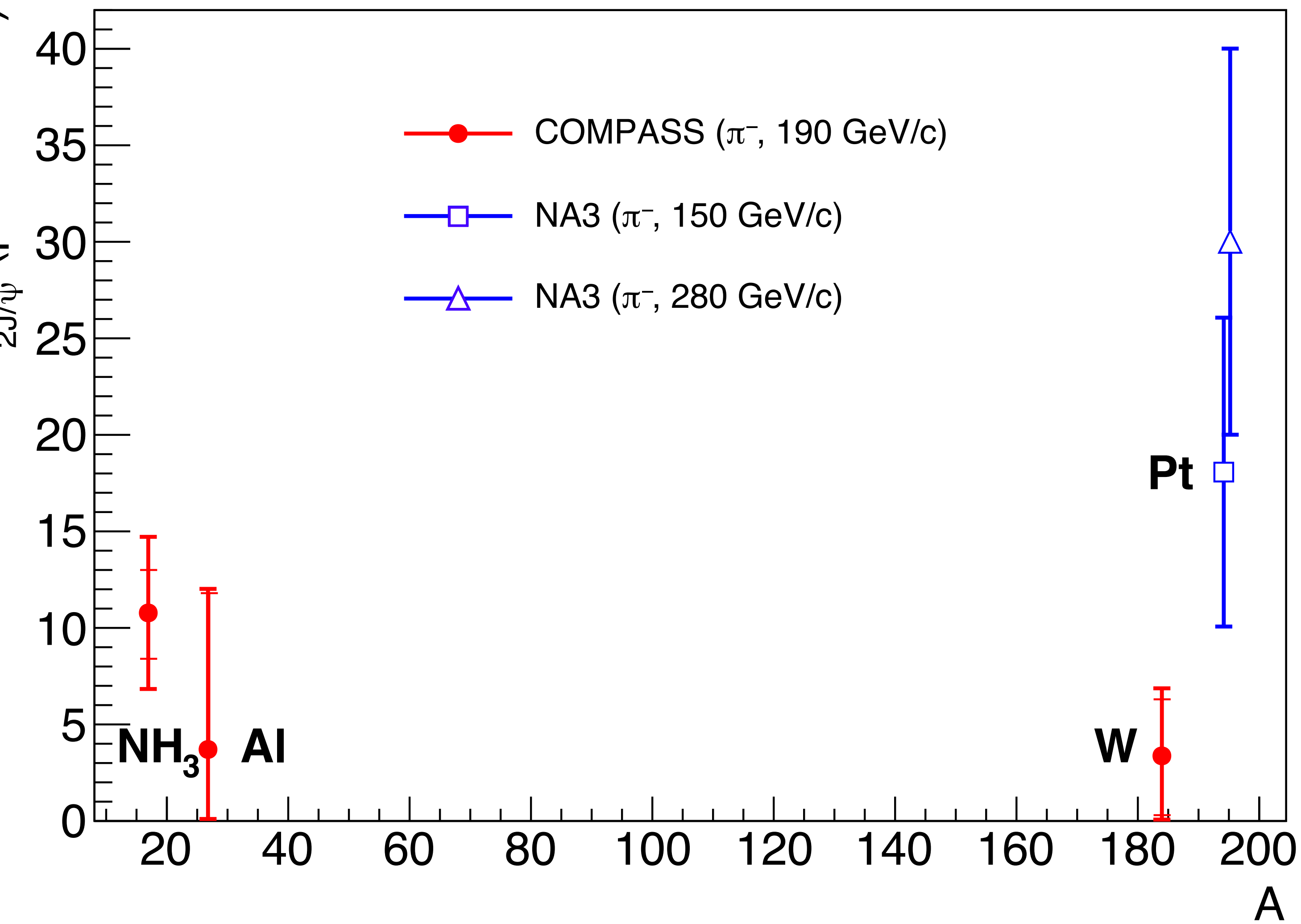
COMPASS:

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

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

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

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



NA3:

$$\frac{\sigma_{2J/\psi}}{\sigma_{J/\psi}} = (3 \pm 1) \cdot 10^{-4}$$

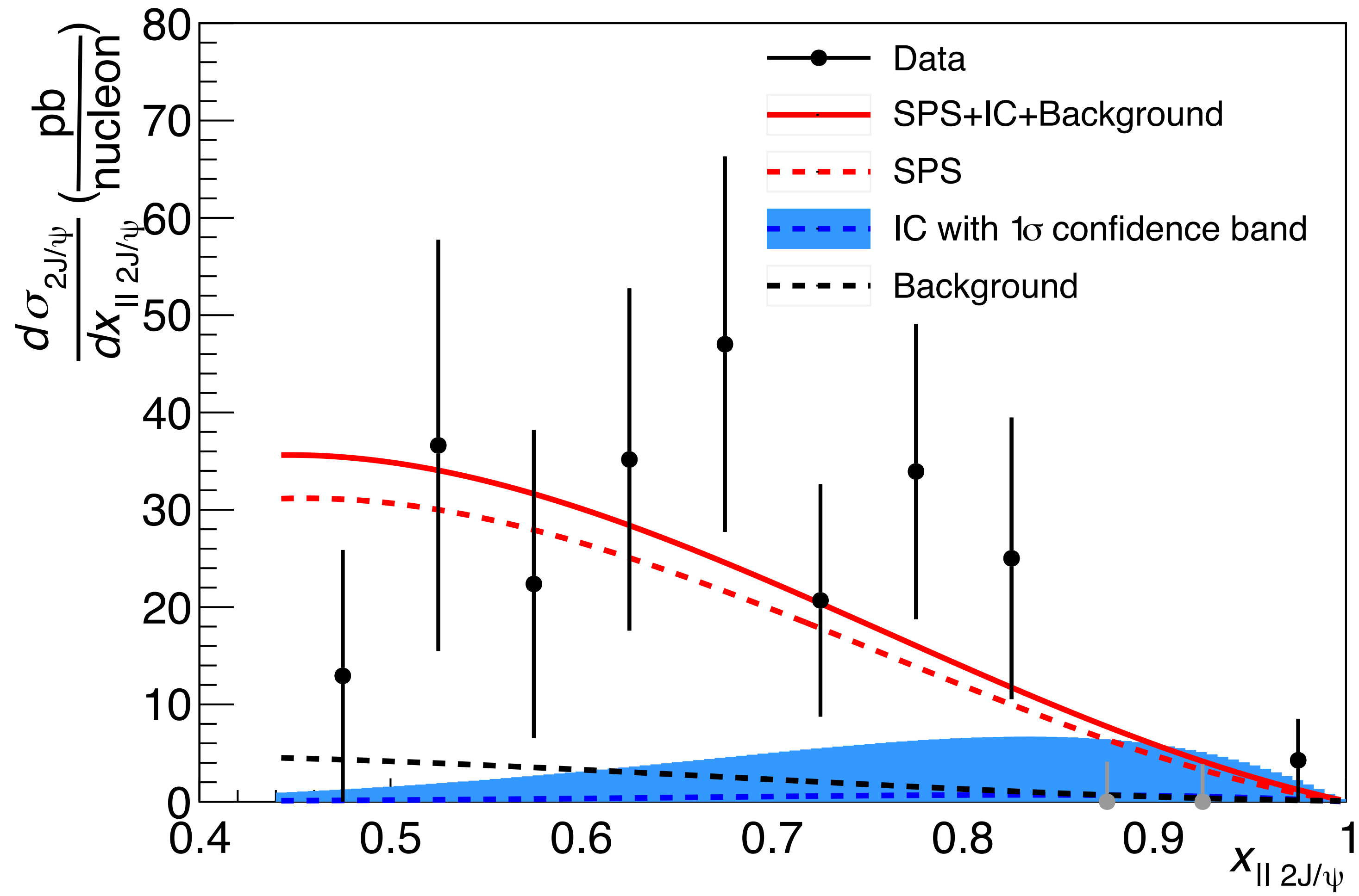
$$\sigma^{Pt}_{J/\psi J/\psi}(150\ GeV) = 18 \pm 8\ \frac{pb}{nucleon}$$

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

Within uncertainties, no significant evidence of nuclear effects in J/ψ pair production is observed.

Results: Differential cross section of J/ψ pair production

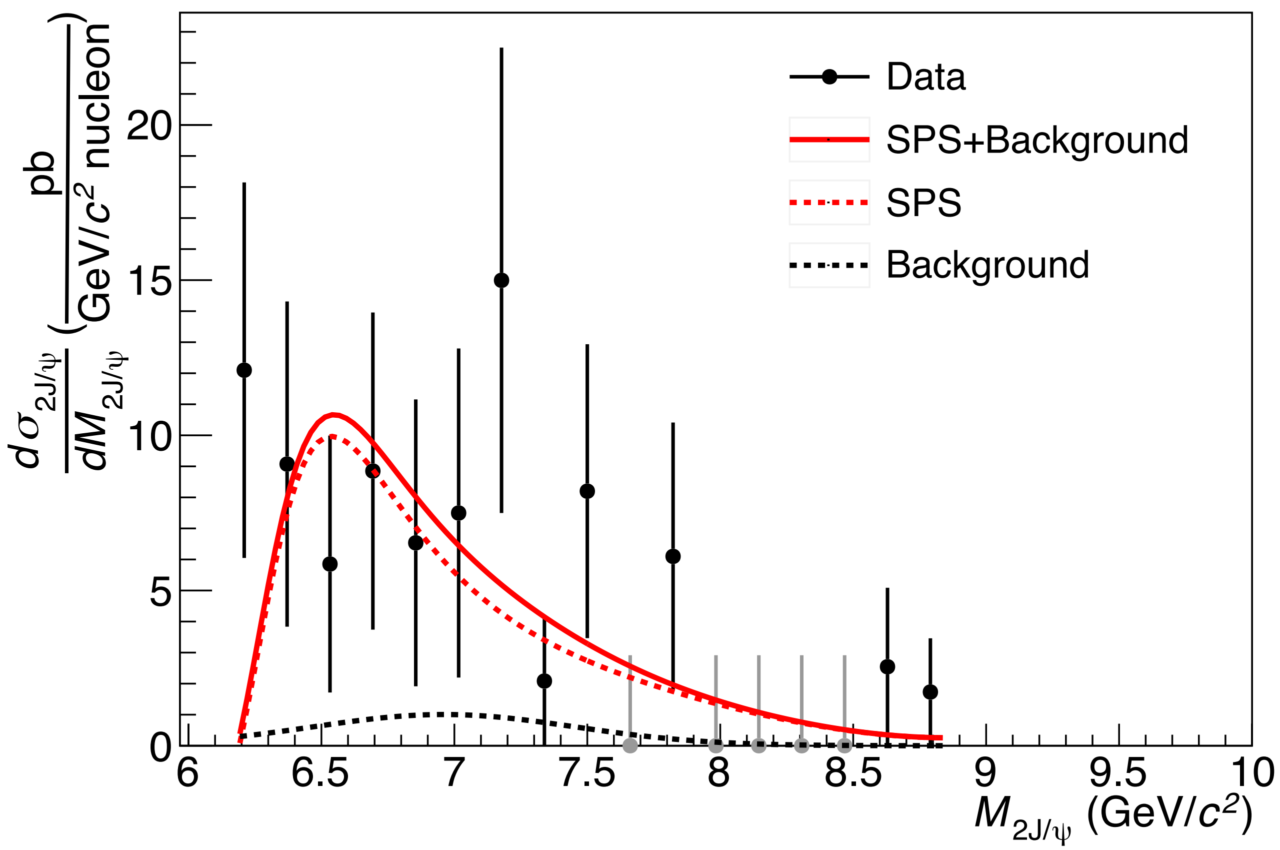
$$x_{F\ J/\psi} = \frac{2p_L^*}{\sqrt{s}} > 0$$



The function $f(x_{||\ 2J/\psi}) = a \cdot f_{SPS}(x_{||\ 2J/\psi}) + b \cdot f_{IC}(x_{||\ 2J/\psi}) + f_{bkg}(x_{||\ 2J/\psi})$ is fitted to the data assuming that SPS and IC are the leading production mechanisms. The DPS contribution is not considered in the fit;

The results are consistent with pure SPS hypothesis. An upper limit on IC production mechanism is established: $\sigma^{IC}_{2J/\psi}/\sigma_{2J/\psi}\Big|_{x_F>0} < 0.24\ (CL = 90\%)$.

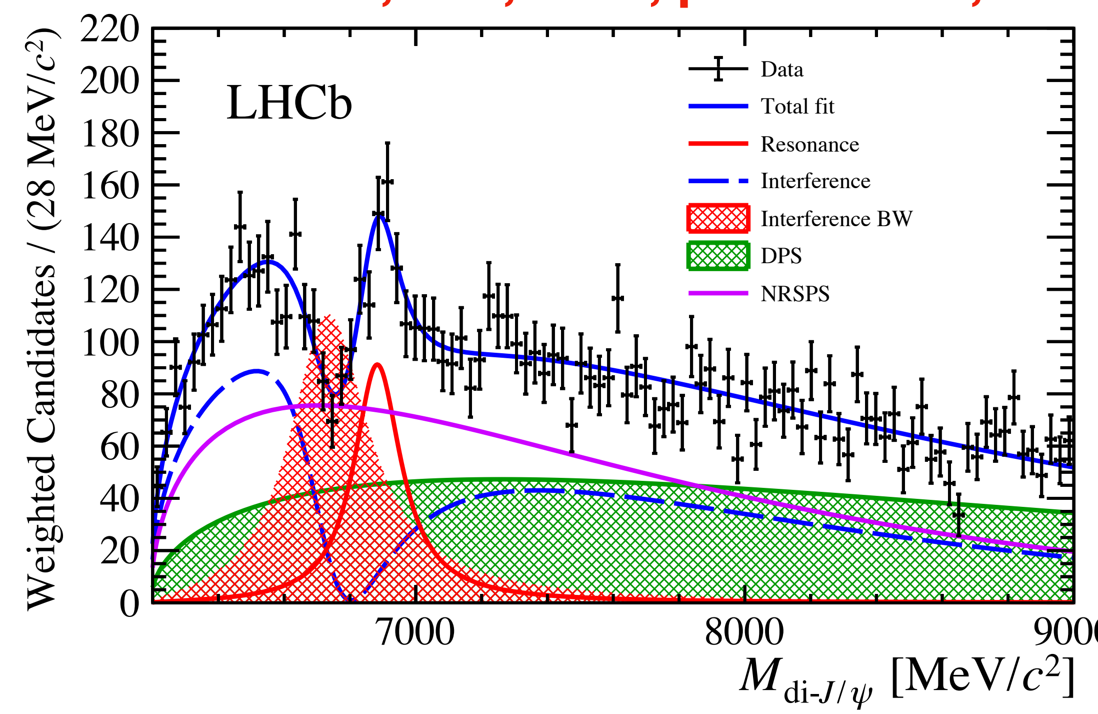
Results: the $M_{2J/\psi}$ spectrum



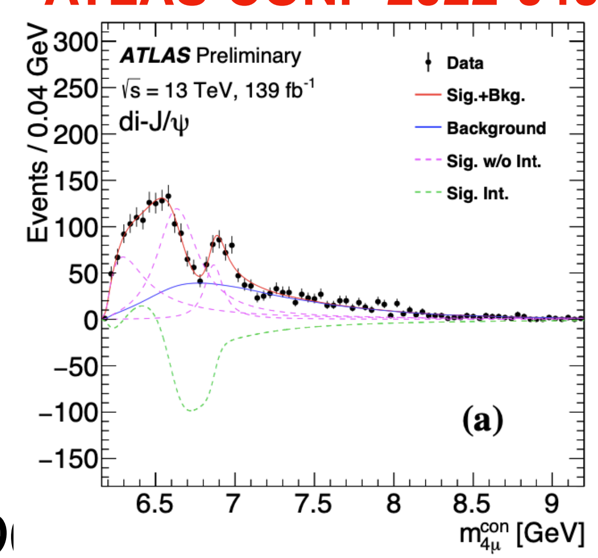
$m[X(6900)] = 6886 \pm 11 \pm 11$ МэВ

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

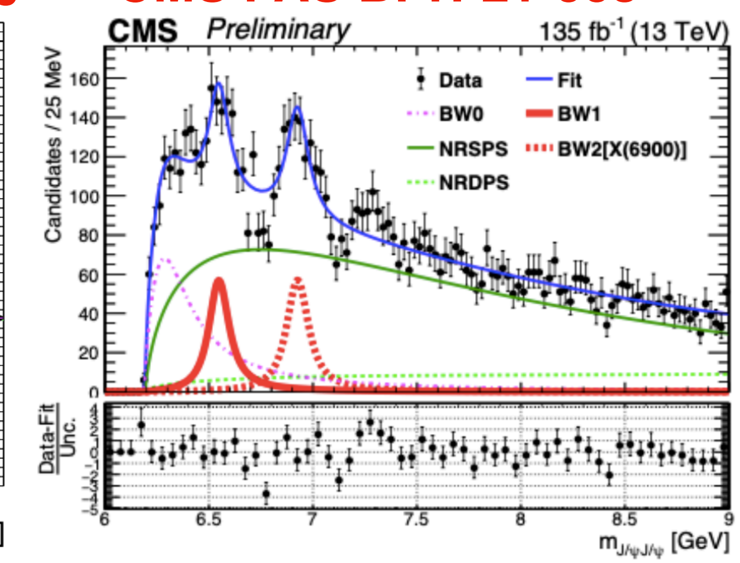
Sci. Bull., V65, №23, p1983-1993, 2020



ATLAS-CONF-2022-040



CMS PAS BPH-21-003



The $M_{2J/\psi}$ spectrum does not contain any evident signal from exotic states observed by LHCb.
An upper limit on the number of X(6900) in the COMPASS data is established:

$N_{X(6900)} < 6.7\ (CL = 90\%)$ and

$$\frac{\sigma_{X(6900)} \cdot BR(X(6900) \to J/\psi J/\psi)}{\sigma_{2J/\psi}} < 0.27\ (CL = 9$$

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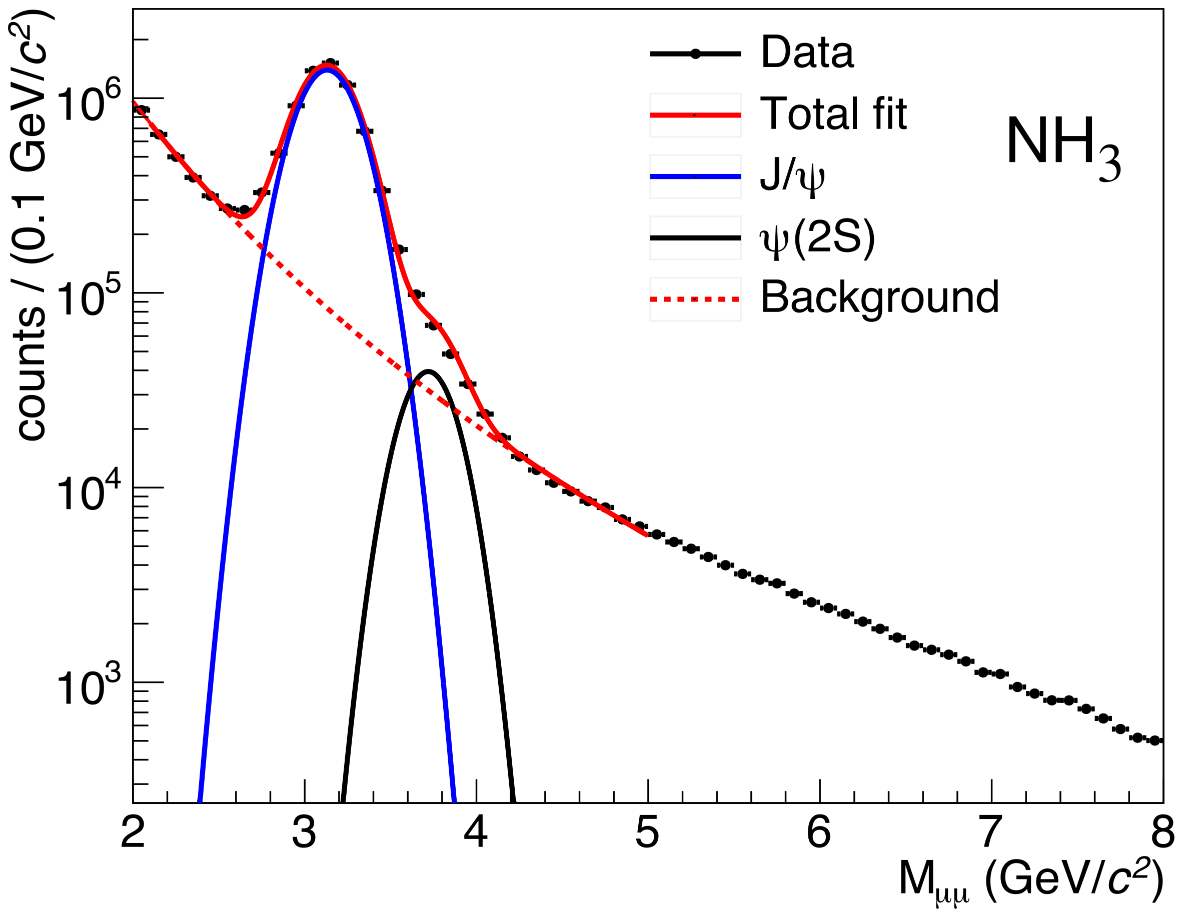
Results of the work are published in Phys.Lett.B 838 (2023) 137702

Backup slides

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

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

COMPASS double J/ψ data:

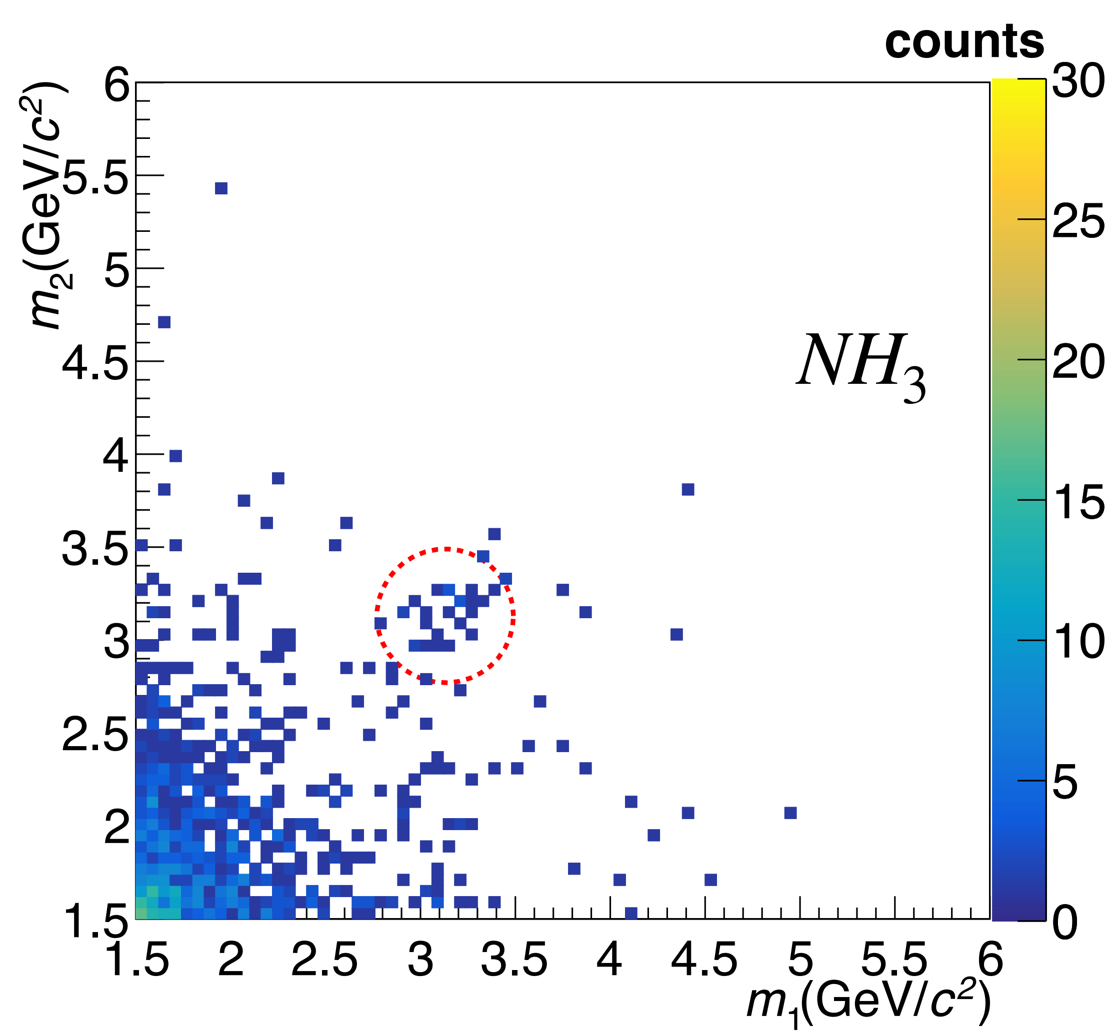
NH_3: 28 events

Al: 2 events

W: 13 events

All the events are selected in kinematic region:

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



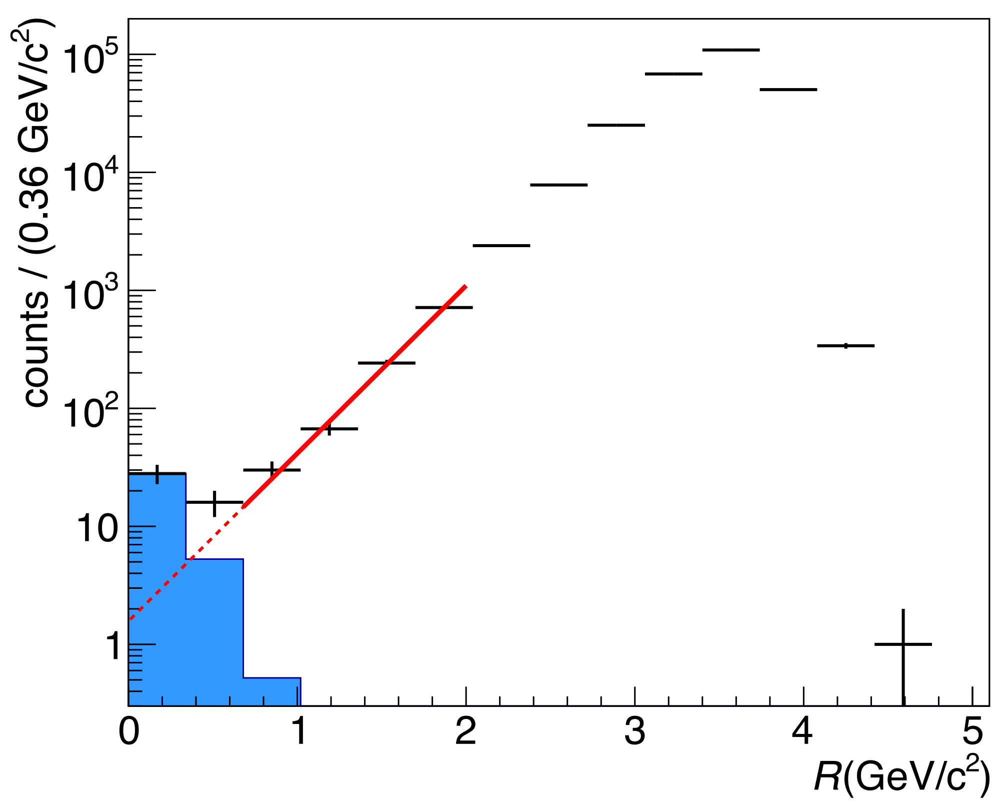
Signal and background events

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

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: $B\bar{B} \to J/\psi J/\psi + X$**

	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.

Systematic uncertainties

Main sources of systematics:

- **Uncertainty of $\sigma_{J/\psi}$:** is taken from NA3 measurement:
  $\sigma^{p}_{J/\psi} \cdot BR(J/\psi \rightarrow \mu\mu) = 6.3 \pm 0.8$ nb/nucleon (NH_3, Al)
  $\sigma^{Pt}_{J/\psi} \cdot BR(J/\psi \rightarrow \mu\mu) = 4.9 \pm 0.77$ nb/nucleon (W);

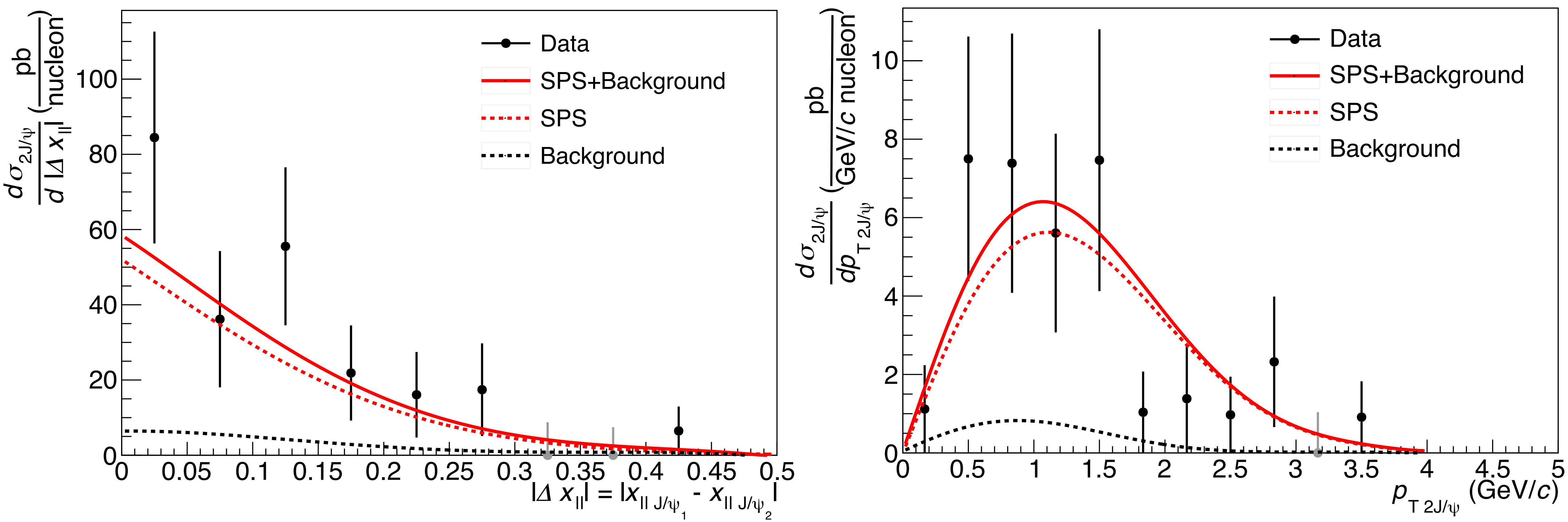
- J/ψ **pair acceptance:** takes into account uncertainty of $\frac{q\bar{q} \rightarrow J/\psi J/\psi}{gg \rightarrow J/\psi J/\psi}$, uncertainty of detector and trigger efficiencies;

- J/ψ **acceptance:** takes into account uncertainty of detector and trigger efficiencies and uncertainty of PDF selection;

- **combinatorial background:** estimated with a toy MC;

- **Number of single J/ψ:** was estimated from the fit of dimuon mass distribution by different functions (modified Gaussian, Crystall Ball).

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,