Physics with charmonia at SPD

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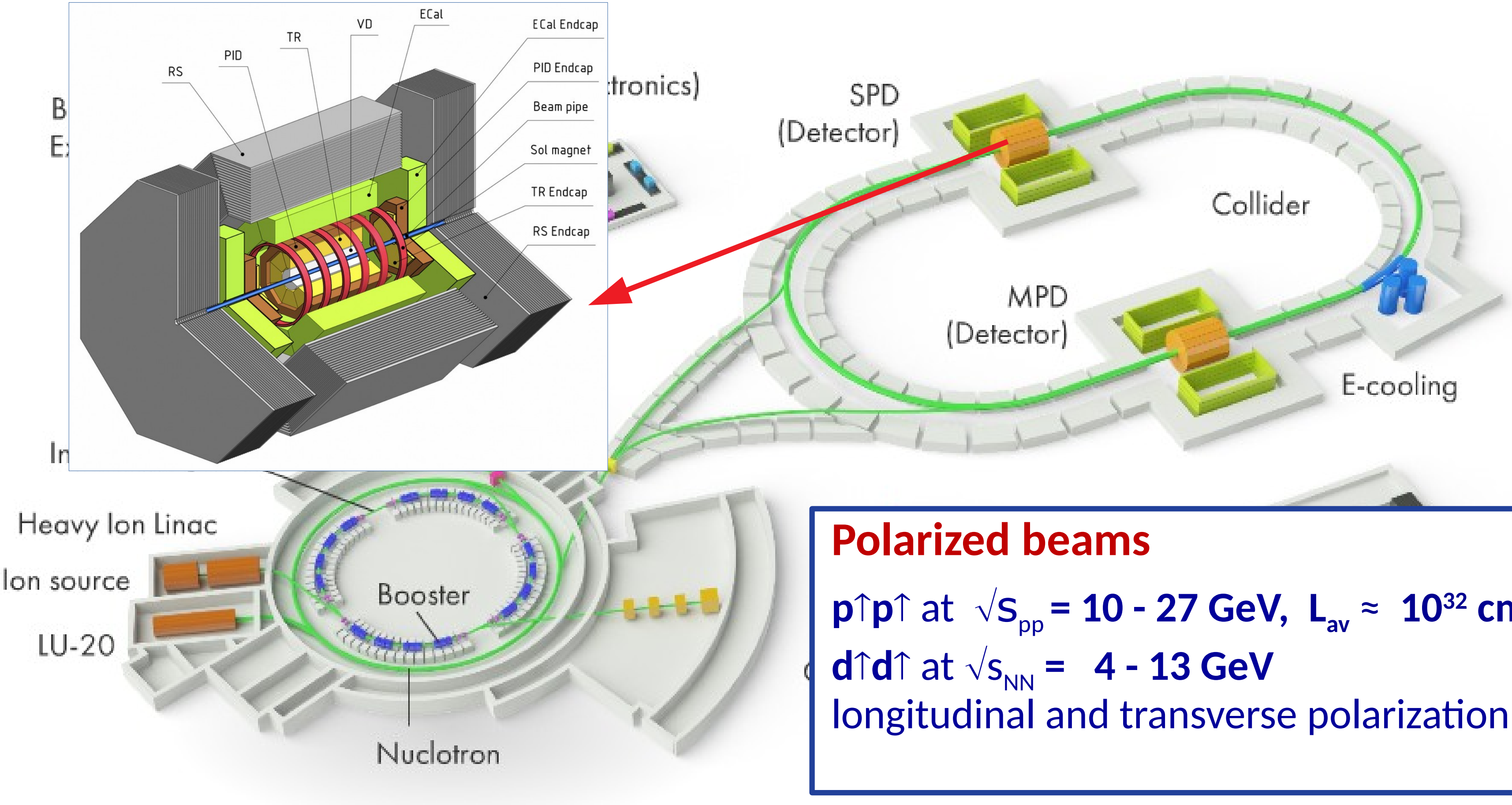
RFBR Grants for NICA
20-23 October 2020

SPD at NICA



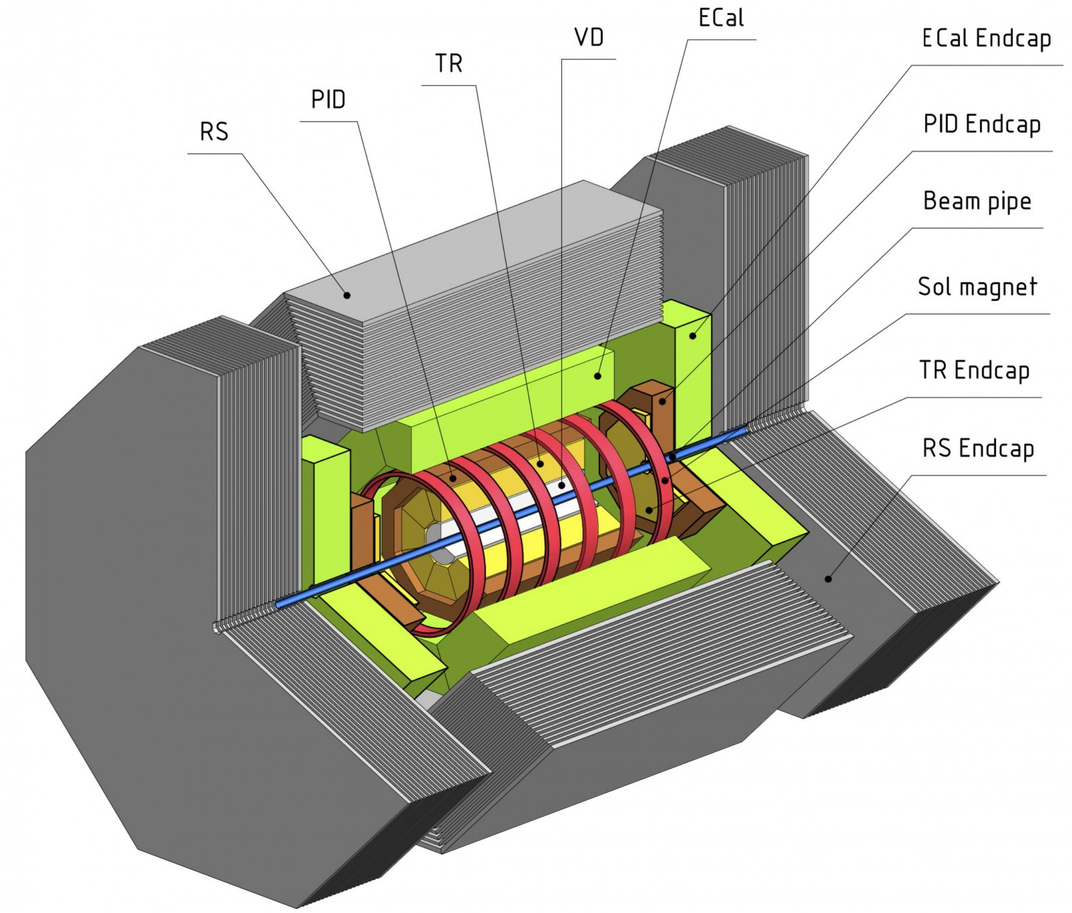
Polarized beams

p↑p↑ at $\sqrt{s_{pp}}$ **= 10 - 27 GeV, $L_{av} \approx 10^{32}$ cm^{-2}s^{-1}**

d↑d↑ at $\sqrt{s_{NN}}$ **= 4 - 13 GeV**

longitudinal and transverse polarization ~ 70%

SPD at NICA



Primary physics goal – proton spin-dependent gluon structure.

Complimentary probes:

- charm (D-mesons)
- **charmonium (J/ψ, χ_{cJ}, ψ(2S), η_c(?))**
- prompt photons

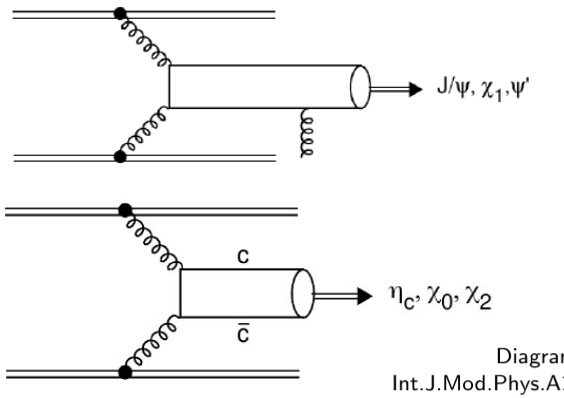
SPD advantages: 4π detector, open spectrometer (possibility to study not only J/ψ), high statistics

Charmonia production in hadron collisions

At SPD energies **dominated** by gluon-guon fusion → sensitive to gluon PDF

Experimentally

- High cross section (200-250 nb at √s=27 GeV)
- Clear experimental signature (in case of J/ψ, χ_c and ψ(2S) can be seen in related modes)



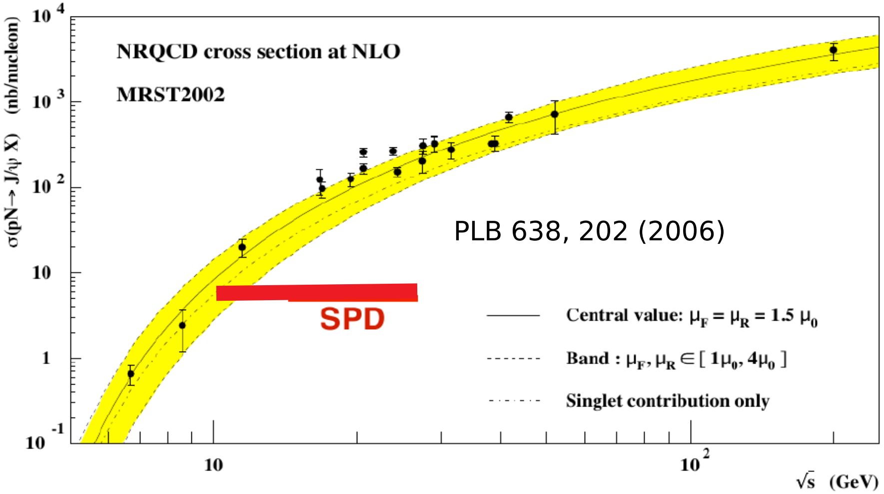
Diagrams from
Int.J.Mod.Phys.A10:3043-3070,1995

Problems:

- Model dependence
- Feed-down contribution (about 30% of J/ψ come from decays of χ and ψ(2S)

SPD can

- validate theoretical approaches
- use them to measure or constrain gluon PDF



Charmonia production and proton structure

Some probes with charmonia production:

- f_1^g: $\eta_c X$, $\chi_{cJ} X$, $2J/\psi X$, $J/\psi\gamma X$…
- Sivers function ($p^{\uparrow}p$): $J/\psi X$, $\chi_{cJ} X$, $\eta_c X$, …
- Gluon polarization ($\vec{p}\vec{p}$): $J/\psi X$, …
- Boer-Mulders function: $\eta_c X$, $\chi_c X$, $2J/\psi X$, $J/\psi\gamma X$, …

TMD factorization is broken for J/ψ production.

Gluon TMD PDFs

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_{1T}^g, $h_{1T}^{\perp g}$

Acta Phys.Polon.B 46 (2015)

Charmonium production is complimentary to prompt photons and open charm.

Theoretical approaches

Approaches to charmonia production:

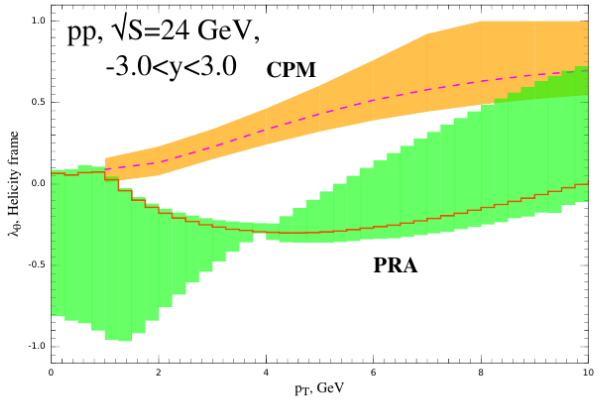
- Color Singlet Model
- Color Evaporation Model
- NRQCD

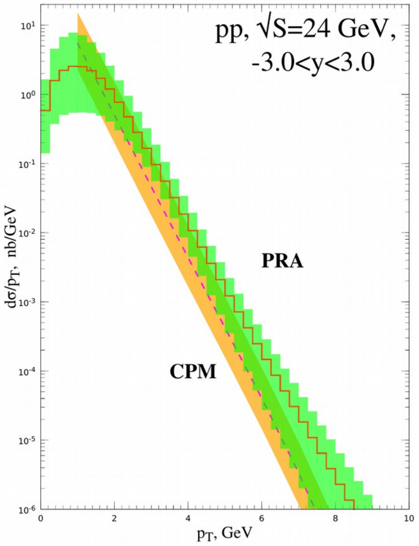
Our p_T are mostly below $M_{J/\psi}$:

- collinear factorization is not applicable
- TMD
- Parton Reggeization Approach (PRA)
- k_T-factorization approach by Baranov and Lipatov (?)

Observables for validation of models:

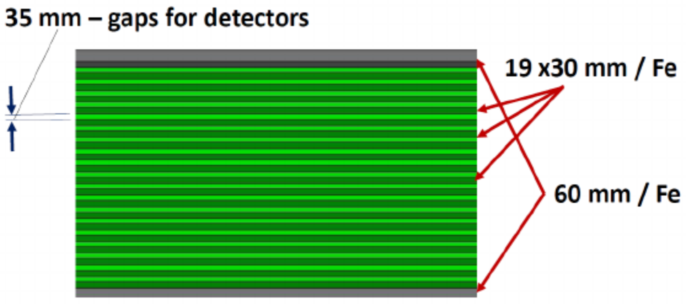
- cross-section, p_T-, x_F-dependecies
- polarization(!)
- J/ψ feed down fractions
- asymmetries

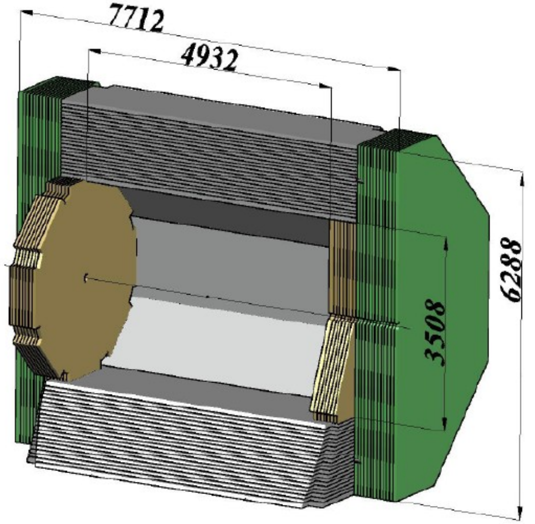




Karpishkov, Nefedov and Saleev, 2019

$J/\psi \to \mu^+\mu^-$





Muon/pion separation will be based on **paterns** in RS (standard algorithms + ML).

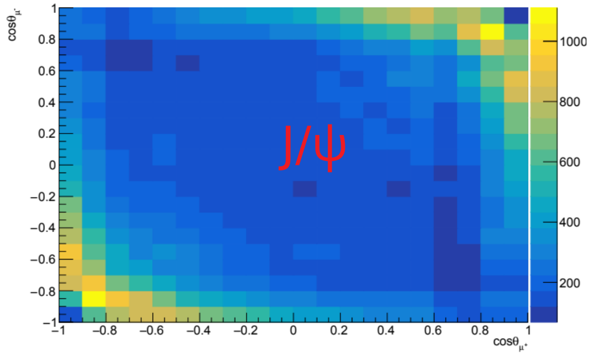
Background

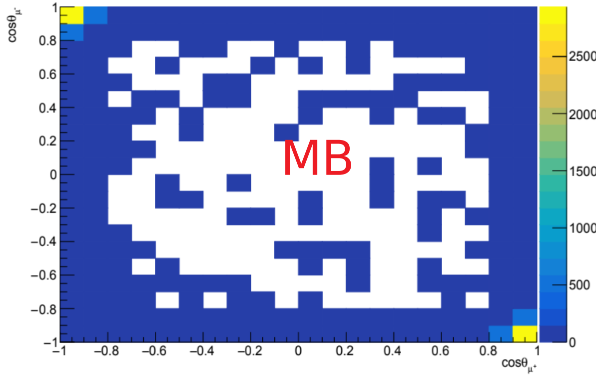
- Decay muons
- Pions passing significant distance in RS
- Combination

MB events simulated with Pythia6 and Pythia8. Inclusive J/ψ – Pythia8

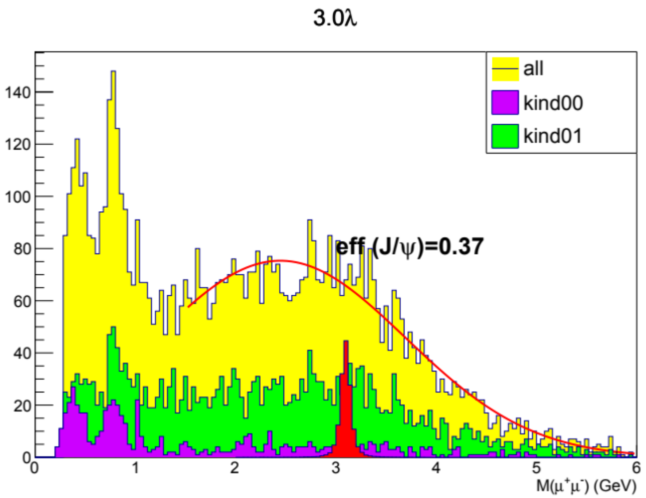
For the results below:

- E_{CMS}= 27 GeV
- muon candidate must **pass more than 3λ**,
- additional cuts on polar angle.



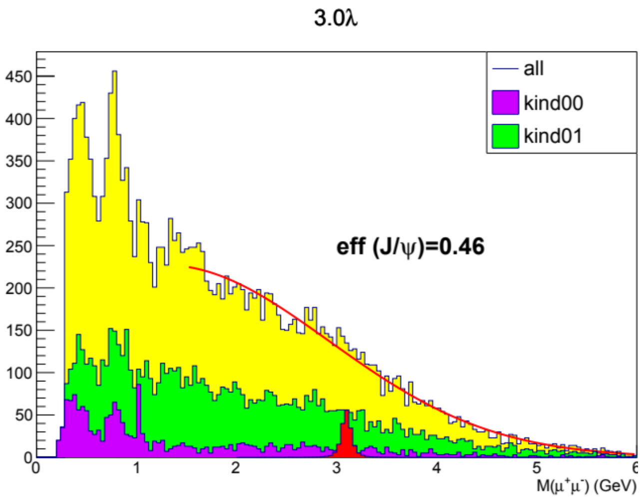


Dimuon mass spectrum



case 1

$|\cos\theta_{\mu}|<0.9$

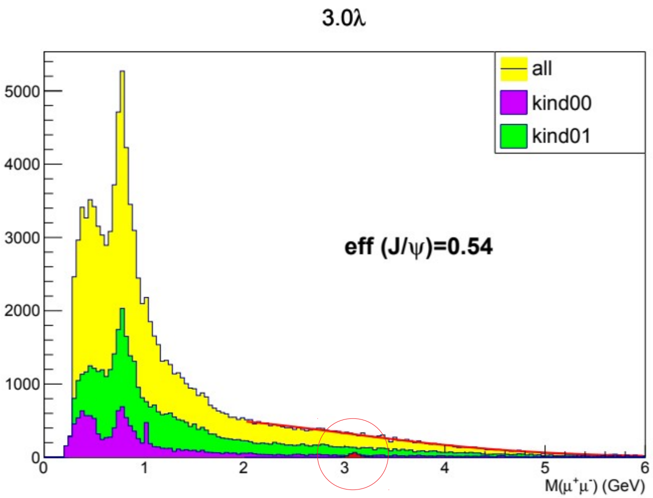


case 2

$|\cos\theta_{\mu}| < 0.95$

$\cos\theta_{\mu+} > 0.8$ and $\cos\theta_{\mu-} < -0.8$ or

$\cos\theta_{\mu+} < -0.8$ and $\cos\theta_{\mu-} > 0.8$



case 3

$\theta_{\mu} > 0.1$

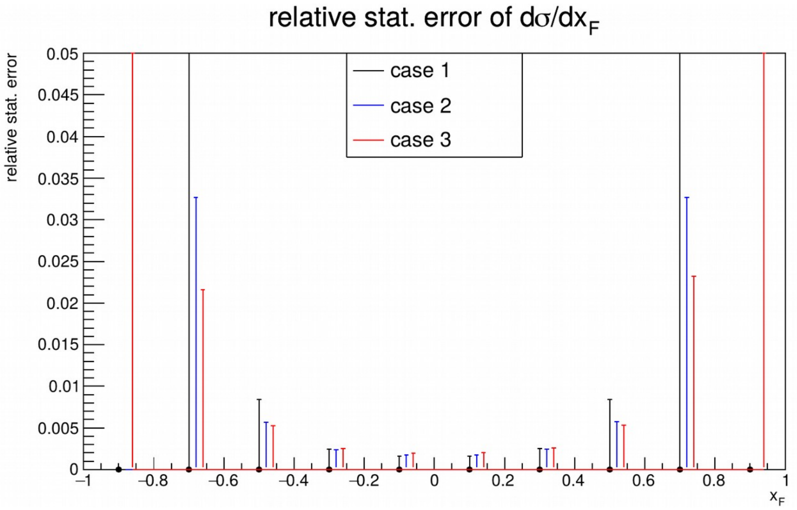
$\cos\theta_{\mu+} > 0.8$ and $\cos\theta_{\mu-} < -0.8$ or

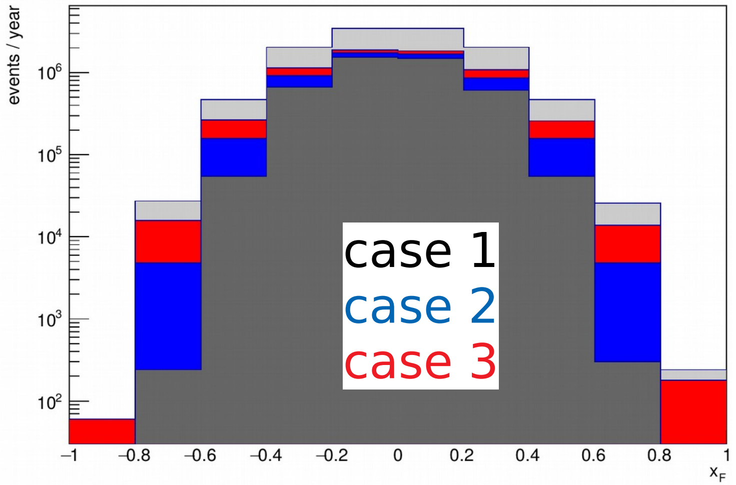
$\cos\theta_{\mu+} < -0.8$ and $\cos\theta_{\mu-} > 0.8$

Statistical errors estimated using formula for a linear fit in LSM:

$$\mu(x_i;\boldsymbol{\theta}) = \sum_{j=1}^{m} \theta_j h_j(x_i)$$

$$(U^{-1})_{ij} = \sum_{k=1}^{N} \frac{h_i(x_k)h_j(x_k)}{\sigma_k^2}$$





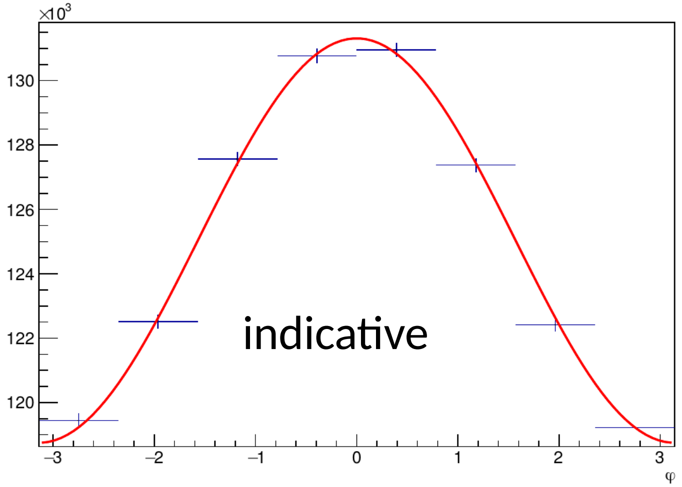
- The same shape (shown above) and signal/background ratio are assumed for all bins.
- In some regions acceptance is more important than signal to background ratio.
- Precision for **polarization measurement** is not shown, but can be also expected to be quite high too.

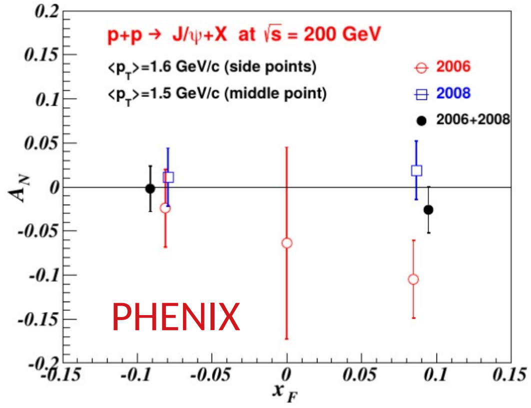
A_N for inclusive J/ψ production

$$\sigma(\phi) \propto 1 + P \cdot A_N \sin(\phi_{\rm pol} - \phi)$$

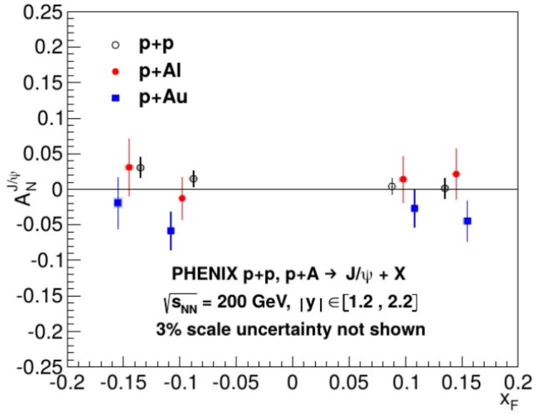
Assuming P ~ 0.7 and is constant during the run.

8 bins in ϕ. Fits with A + B cosϕ, A_N = B/(AP), relative uncertainty of A can be neglected.





PRD82, 112008 (2010)

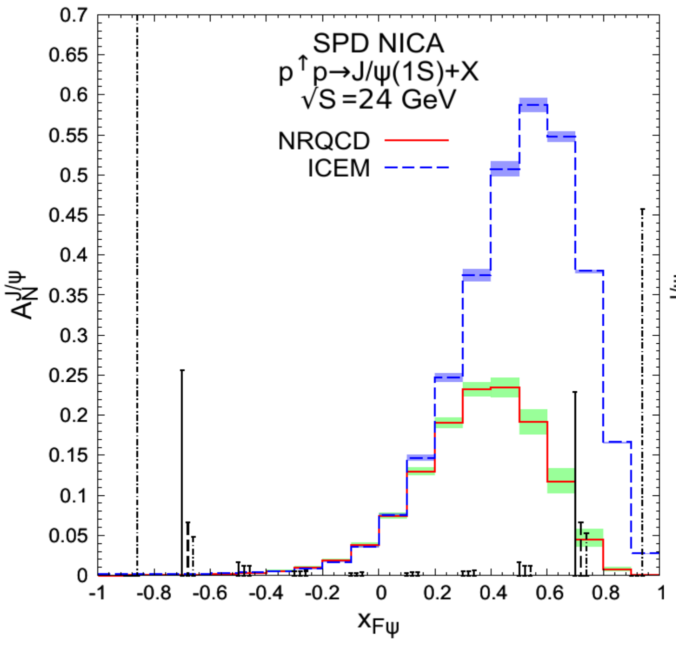


PRD98, 012006 (2018)

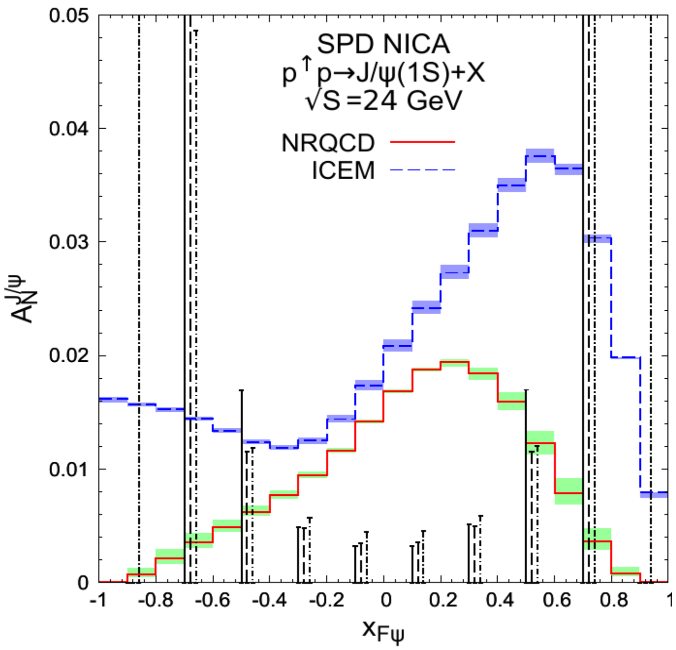
A_N for inclusive J/ψ production

GPM, Karpishkov, Saleev and Nefedov, 2020:
- d'Alesio and SIDIS1 – arXiv:2008.07232
- SIDIS2 – private communications

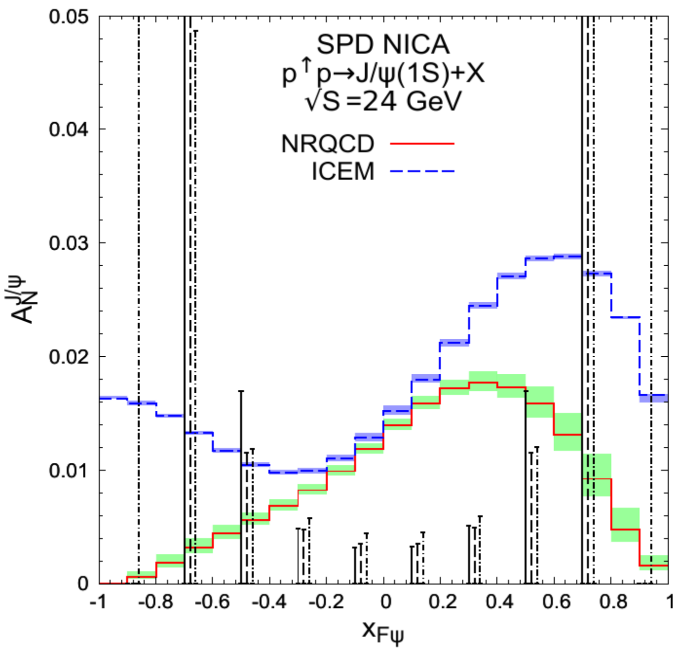
SIDIS1



SIDIS2



d'Alesio



A_{LL} for inclusive J/ψ production

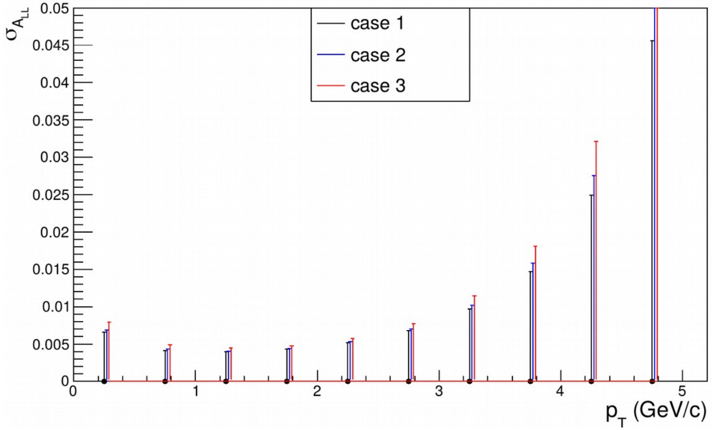
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{1}{P_1 P_2} \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}$$

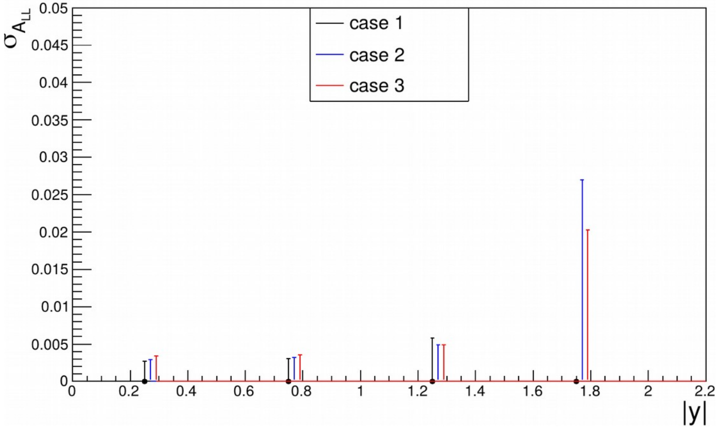
$$\sigma_{A_{LL}} \approx \frac{1}{P^2} \frac{\sigma_N}{N}$$

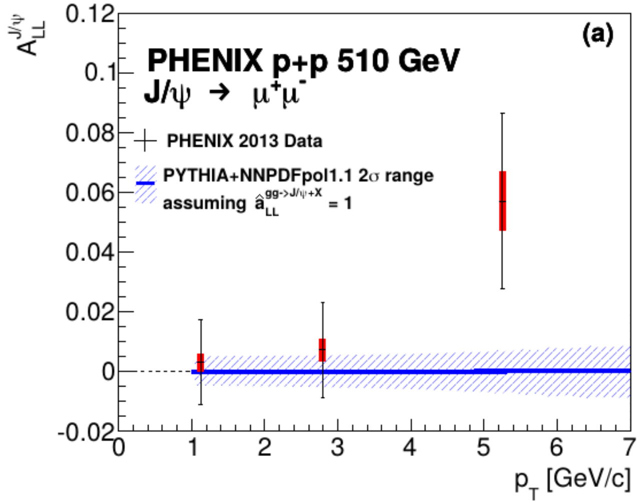
$$A_{LL}^{J/\psi} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta g(x_2)}{g(x_2)} \otimes \hat{a}_{LL}^{gg \to J/\psi + X}$$

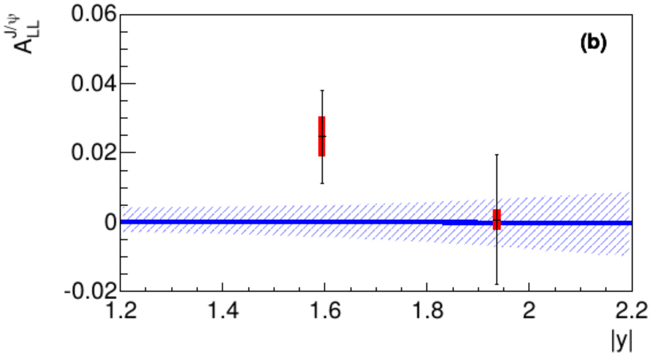
Naively, A_{LL} of the order of at least several percents can be expected.

We will constrain polarized PDF and check its universality.









On measurements of χ_{cJ},$\chi_{cJ} \to \gamma J/\psi$

χ_{cJ} production at low energy experiments (table extracts from PRD79,012001 (2009))

Exp.	beam/ target	$\sqrt(s)$ GeV	$N_{J/\psi}$	N_{χ_c}	$R\chi_c$	$\frac{\sigma(\chi_{c1})}{\sigma(\chi_{c2})}$	$\sigma(\chi_{c1})$ (nb/n)	$\sigma(\chi_{c2})$ (nb/n)
ISR [6]	pp	< 55 >	658	31 ± 11	0.43 ± 0.21			
R702 [7]	pp	52.4,62.7	975		$0.15^{+0.10}_{-0.15}$			
ISR [8]	pp	62			0.47(8)			
E610 [9]	pBe	19.4,21.7	157 ± 17	11.8 ± 5.4	0.47(23)	0.24(28)	39(49)	162(81)
E705 [10]	pLi	23.8	6090 ± 90	250 ± 35	0.30(4)	0.09(29)(17)	24(48)(2)	244(83)(16)
E771 [12]	pSi	38.8	11660 ± 139	66	0.76(29)(16)	0.61(24)(4)	488(128)(56)	805(231)(92)
HERA-B [14]	pC,Ti	41.6	4420 ± 100	370 ± 74	0.32(6)(4)			
CDF [11],[13]	$p\bar{p}$	1800	$\{^{88000}_{32642 \pm 185}$	$\{^{119 \pm 14}_{1230 \pm 72}$	0.297(17)(57)	1.19(33)(14)		

$$R_{12} = \frac{\sigma(\chi_{c1})B(\sigma(\chi_{c1}) \to \gamma J\psi)}{\sigma(\chi_{c2})B(\sigma(\chi_{c2}) \to \gamma J\psi)}$$

	R_{12}
C	$1.06 \pm 0.21_{st} \pm 0.37_{sys}$
Ti	$0.67 \pm 0.67_{st} \pm 0.23_{sys}$
W	$0.98 \pm 0.36_{st} \pm 0.34_{sys}$
Tot	$1.02 \pm 0.17_{st} \pm 0.36_{sys}$

Also HERA-B PRD79,012001 (2009): 15000 χ_{cJ} events

Both the feed-down contribution and relative contributions of χ_{c1} and χ_{c2} are important for validation of theoretical models!

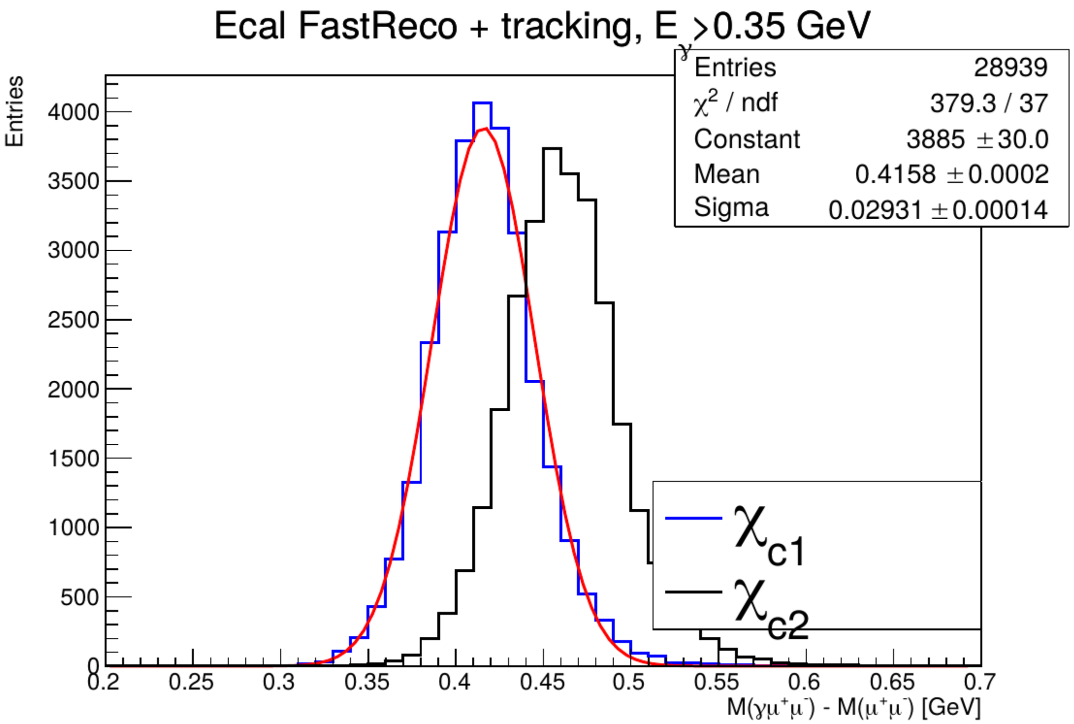
On measurements of χ_{cJ}, $\chi_{cJ} \to \gamma J/\psi$ at SPD

We can expect about 0.5M χ_{c1} and χ_{c2} events.
We will **not be able to separate these states** but measurements of

- feed-down fractions from χ_{c1} and χ_{c2},
- relative contributions of χ_{c1} and χ_{c2}

can be expected as a function of kinematic variables (p_T, x_F)

Large background is expected.



On ψ(2S)

- $\psi(2S) \rightarrow \mu^+\mu^-$ does not look promising
- $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \mu^+\mu^-$ according to preliminary studies:
  - **is feasible**, a narrow peak in $M(\pi^+\pi^-\mu^+\mu^-)$ - $M(\mu^+\mu^-)$ can be seen on a significant background
  - about 200K selected events per year are expected.

Double J/ψ production

Ideas are based on the talk by J.P. Lansberg at the "Gluon content of proton and neutron with SPD at NICA"

- Colorless final state
- $\frac{d\sigma}{dP_T^{\psi\psi}} \propto F_1 \mathcal{C}[f_1^g f_1^g] + F_2 \mathcal{C}[w_2 \times h_1^{\perp g} h_1^{\perp g}]$
- SPD can study low p_T J/ψJ/ψ production (complementary to ATLAS and CMS)
- DPS and SPS have different feed-down fractions. Search for J/ψψ(2S) and J/ψχ_{cJ}
- No x dependence yet for f_1^g. SPD can contribute?

But

- NA3: the cross-section of pN → J/ψJ/ψX is 27±10 pb at √s~27 GeV
- Can expect 50-100 events with both $\mu^+\mu^-$ and e^+e^- modes

Summary

- Charmonia production is a powerful probe of polarized and unpolarized proton gluon structure.
- In addition, the SPD experiment can provide important and precise measurements to validate theoretical approaches to charmonia production (like J/ψ polarization, feed-down fractions and relative production strength of χ_{c1} and χ_{c2}).
- SPD can be expected to provide the most precise measurements of J/ψ A_N and A_{LL} in the wide kinematic range at low energies, constraining (hopefully probing) gluon Sivers function and gluon polarized gluon PDF.
- It will be possible to have measurements with χ_{cJ} and $\psi(2S)$, the precision is being estimated. Feasibility of any physics with η_c is unclear. Other probes like $J/\psi D\bar{D}$, $2J/\psi$ or $\gamma J/\psi$ might be of some interest.
- SPD physics program with charmonia states is rich and promising.