Physics with charmonia at the SPD experiment

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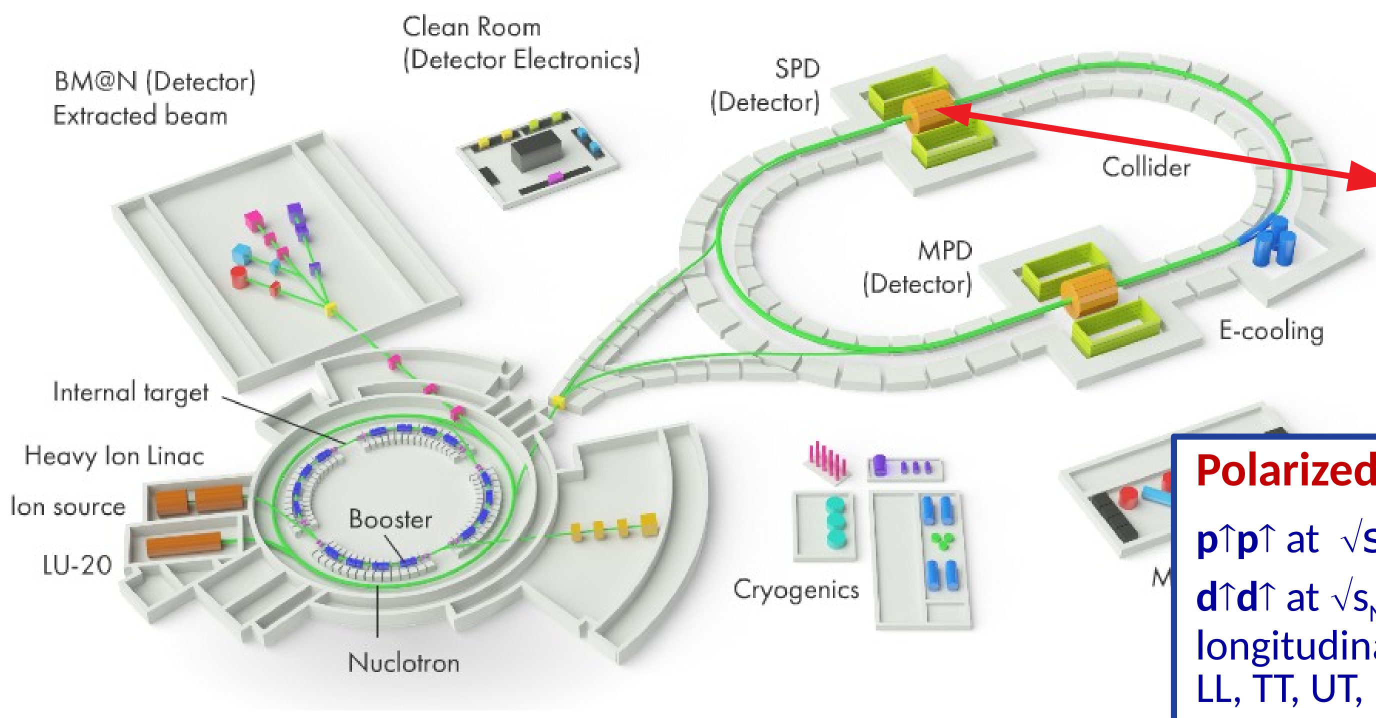
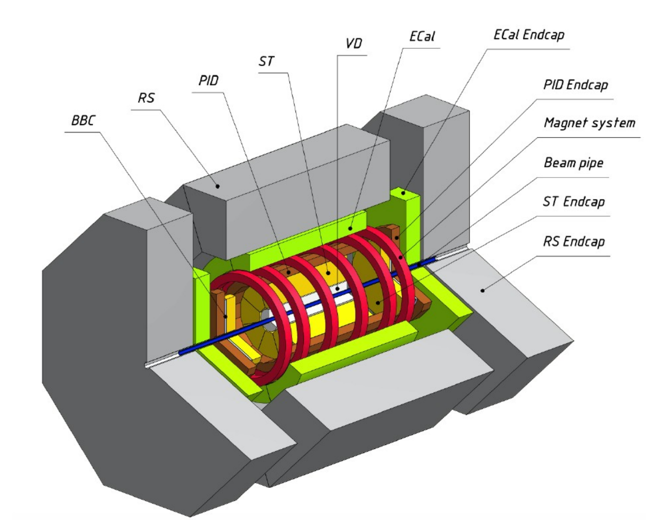
Quarkonia As Tools 2021
22-26 March 2021

Nuclotron-based Ion Collider fAcility (NICA)

Joint Institute for Nuclear Research (Dubna)





Spin Physics Detector (SPD)

Polarized beams

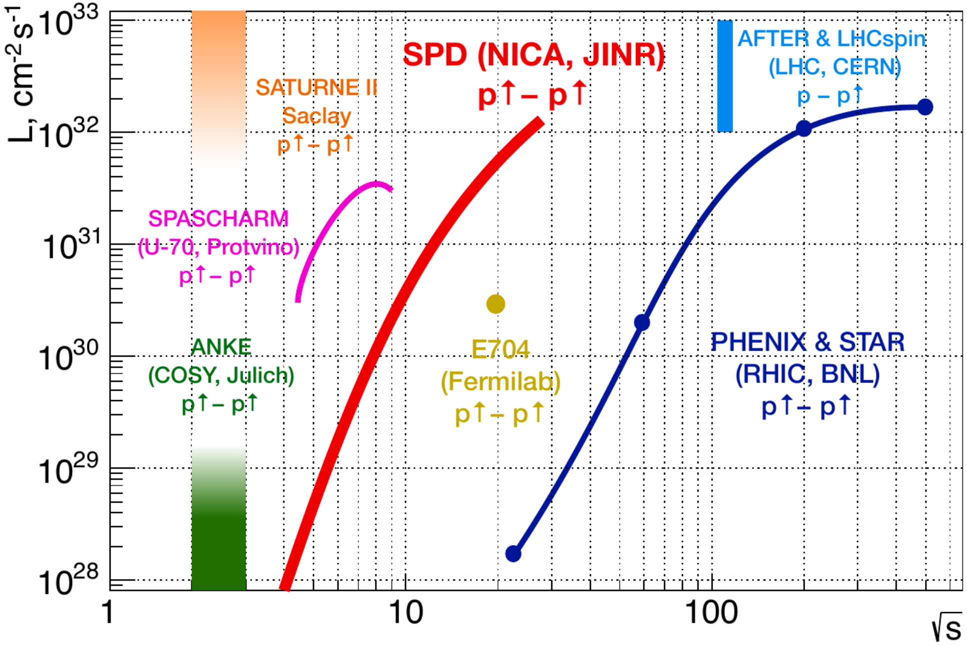
p↑p↑ at $\sqrt{s_{pp}}$ **= 10 - 27 GeV, $L_{av} \approx$ 10^{32} $cm^{-2}s^{-1}$**

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

longitudinal and transverse polarization (UU, LL, TT, UT, LT) ~ 70%

Operation: after **2025**

NICA and other facilities



Experimental facility	SPD @NICA [30]	RHIC [29]	EIC [26]	AFTER @LHC [24]	SpinLHC [25]
Scientific center	JINR	BNL	BNL	CERN	CERN
Operation mode	collider	collider	collider	fixed target	fixed target
Colliding particles & polarization	$p^\uparrow$-$p^\uparrow$ $d^\uparrow$-$d^\uparrow$ $p^\uparrow$-d, p-$d^\uparrow$	$p^\uparrow$-$p^\uparrow$	$e^\uparrow$-$p^\uparrow$, $d^\uparrow$, ^{3}He$^\uparrow$	p-$p^\uparrow$, $d^\uparrow$	p-$p^\uparrow$
Center-of-mass energy $\sqrt{s_{NN}}$, GeV	$\leq$27 (p-p) $\leq$13.5 (d-d) $\leq$19 (p-d)	63, 200, 500	20-140 (ep)	115	115
Max. luminosity, 10^{32} cm^{-2} s^{-1}	~1 (p-p) ~0.1 (d-d)	2	1000	up to ~10 (p-p)	4.7
Physics run	>2025	running	>2030	>2025	>2025

arXiv:2102.00442

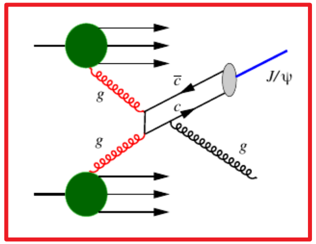
The SPD experiment

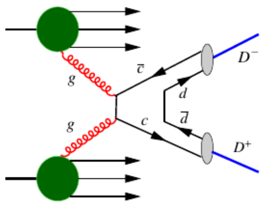
Primary physics goal – proton and deuteron spin-dependent gluon structure.

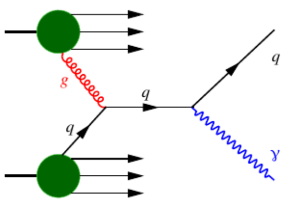
GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_{1T}^g, $h_{1T}^{\perp g}$

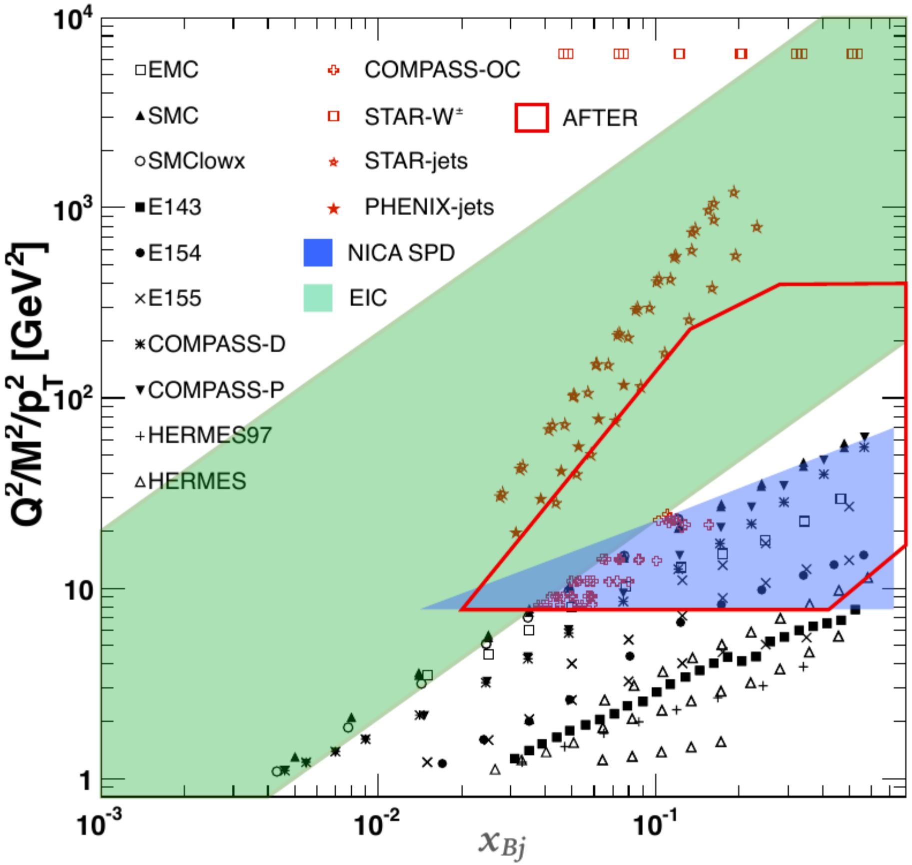
Acta Phys.Polon.B 46 (2015)

Theoretical paper arXiv:2011.15005 (accepted to PNPP)
(many thanks to all contributors!)
Complimentary probes:





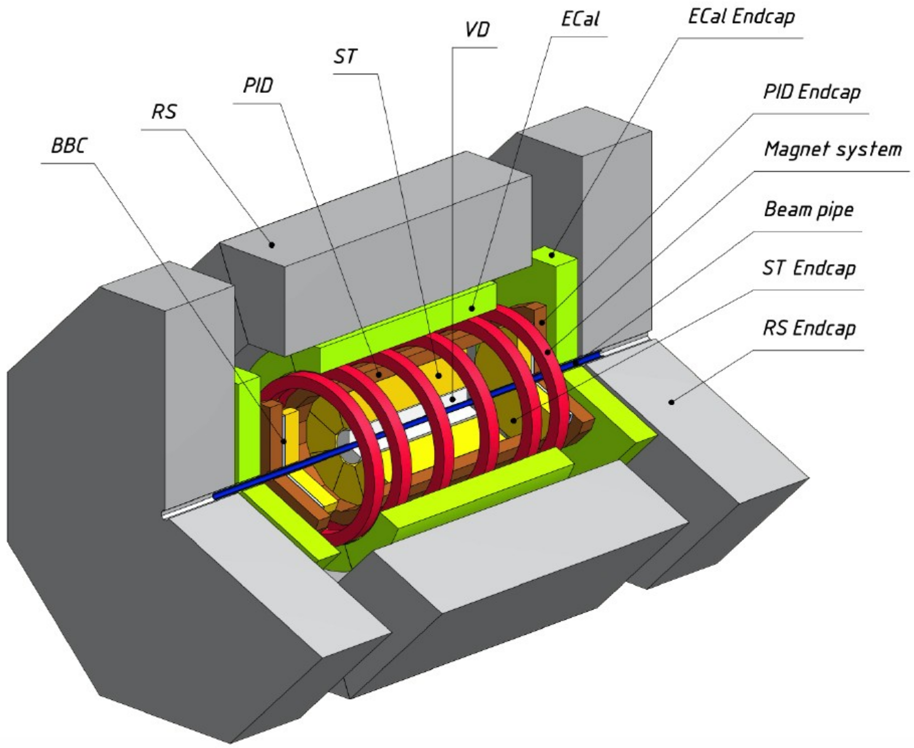




arXiv:2011.15005

Spin Physics Detector

6 s.c. coils: field up to 1T



SPD CDR: arXiv:2102.00442

Components

Vertex detector (VD): DSSD (5 layers) or MAPS (3 layers) + DSSD(2 layers)
$\sigma_{r\varphi}$ < 50 μm, σ_z < 100 μm

Straw tracker (ST):
σ~150 μm
de/dx

Particle identification (PID)
TOF: plastic scintillators or MRPC
σ < 70 ps
Aerogel counters

Sampling Ecal:
$\sigma_E/E = 5\%/\sqrt{E} \otimes 2\%$

Range System (RS):
muon identification and coarse hadron calorimetry

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

Status of the NICA SPD project

- Positive feedback from JINR PAC in January 2021
- DAC and the collaboration are being formed
- CDR published (arXiv:2102.00442)
- TDR is expected this year

Charmonia production as a probe of gluon TMD PDFs

Charmonia production

- dominated by gluon-gluon fusion
- high cross-section
- J/ψ can be easily reconstructed from the $\mu^+\mu^-$ decay, $\psi(2S)$ and χ_{cJ} can be reconstructed based on this decay
- hadronization of $c\bar{c}$ pair is not well understood theoretically:
  - CSM
  - Color Evaporation Model
  - NRQCD
- TMD factorization may be violated
- η_c might be the best probe, but its observation is challenging experimentally
- the J/ψ signal is "contaminated" by feed-down contributions

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, $h_{1T}^{\perp g}$

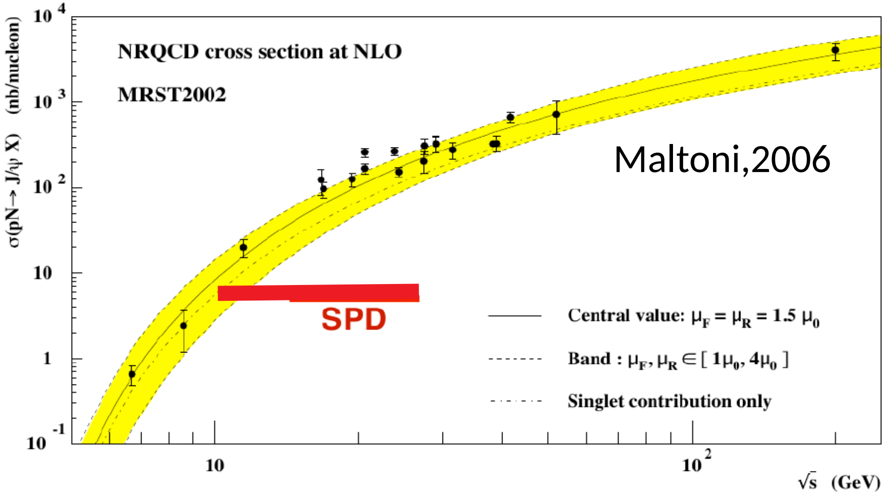
Acta Phys.Polon.B 46 (2015)

Some probes with charmonia production:

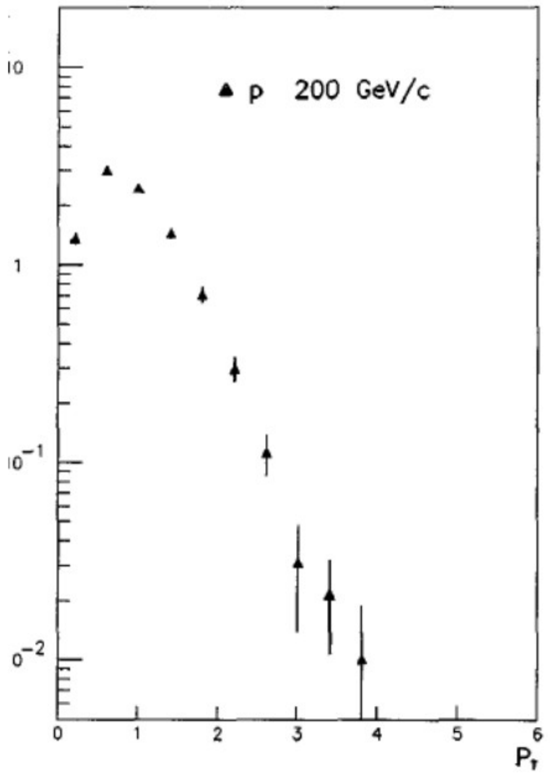
- f_1^g: $\eta_c X$, $\chi_{cJ} X$, $2J/\psi X$, $J/\psi\gamma X$…
- Sivers function ($p^\uparrow p$): $J/\psi X$, $\chi_{cJ} X$, $\eta_c X$, …
- Gluon polarization ($\vec{p}\vec{p}$): $J/\psi X$, …
- Boer-Mulders function: $\eta_c X$, $\chi_c X$, $2J/\psi X$, $J/\psi\gamma X$, …

Charmonia production at SPD

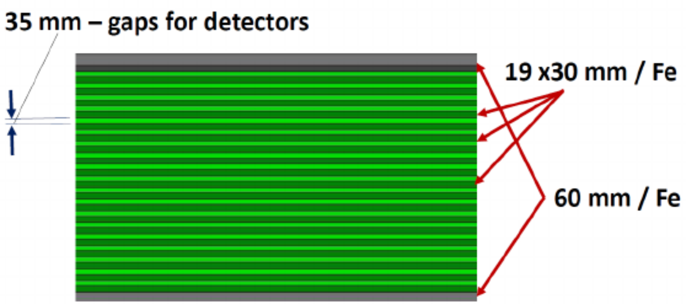
- High statistics: 12 million inclusive $J/\psi(\to\mu^+\mu^-)$ events per year
- Strategy is to obtain all possible measurements in the wide kinematic range
- Constrain both theoretical approaches and PDFs
- Our p_T are mostly below $M_{J/\psi}$
- LDME → shape functions (Echevarria,2019)?

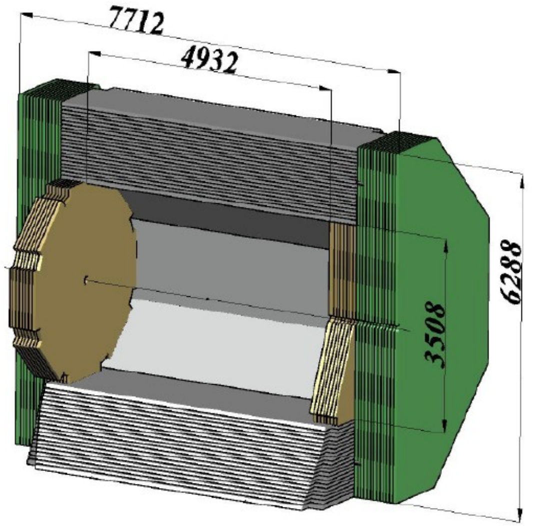


The J/ψ p_T distribution from NA3 at $\sqrt{s} = 19.4$ GeV



Reconstruction of J/ψ → $\mu^+\mu^-$ at SPD



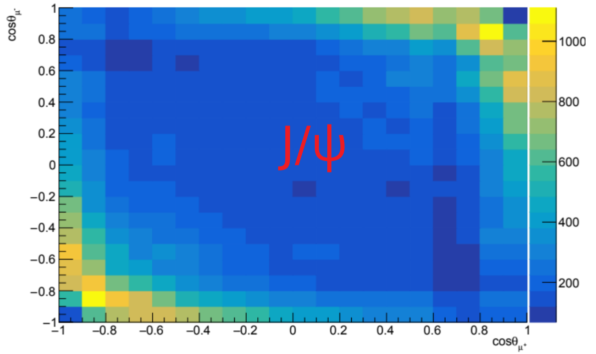


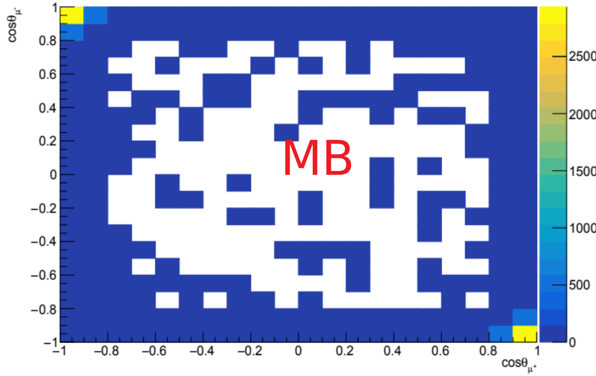
Muon/pion separation will be based on **patterns** in RS (standard algorithms + ML).

Background
- pion 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, t=10^7s
- muon candidate must **pass more than 3λ**
- additional cuts on polar angle



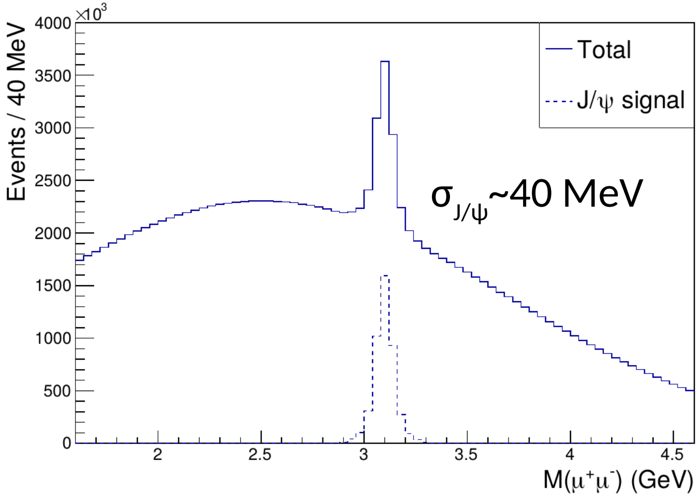


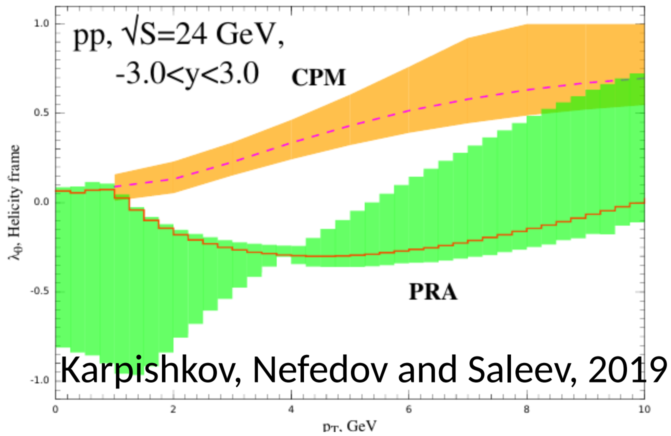
Inclusive J/ψ measurements

- Reconstruction efficiency: 35-45%
- Statistics: ~4.6 M (selected events) per year
- Large background
- Errors are estimated using the LSM method

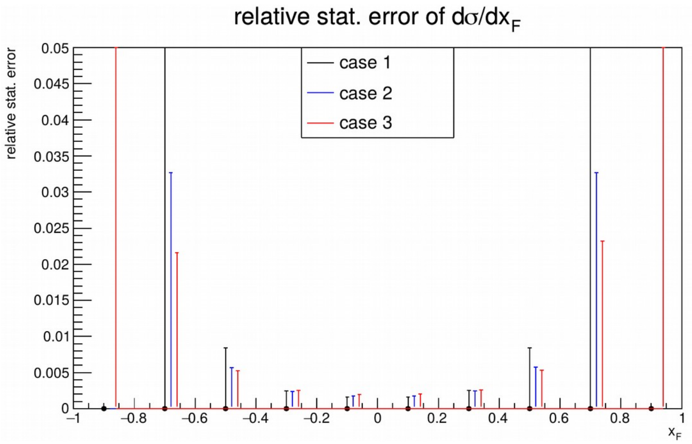
Observables:

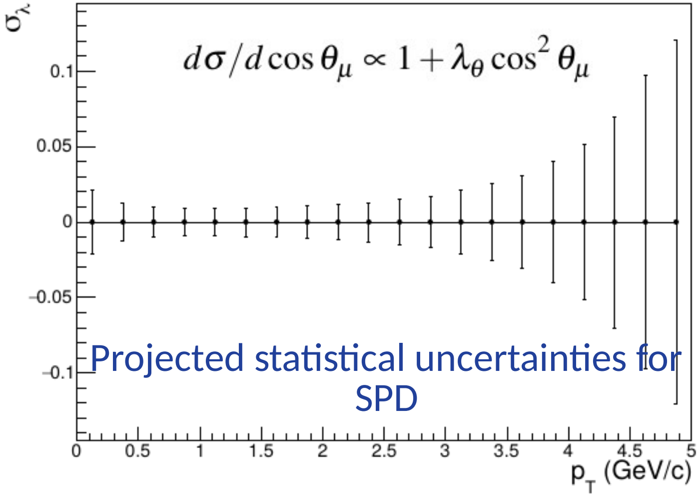
- cross-section, p_T-, x_F-dependencies
- polarization
- asymmetries





Karpishkov, Nefedov and Saleev, 2019





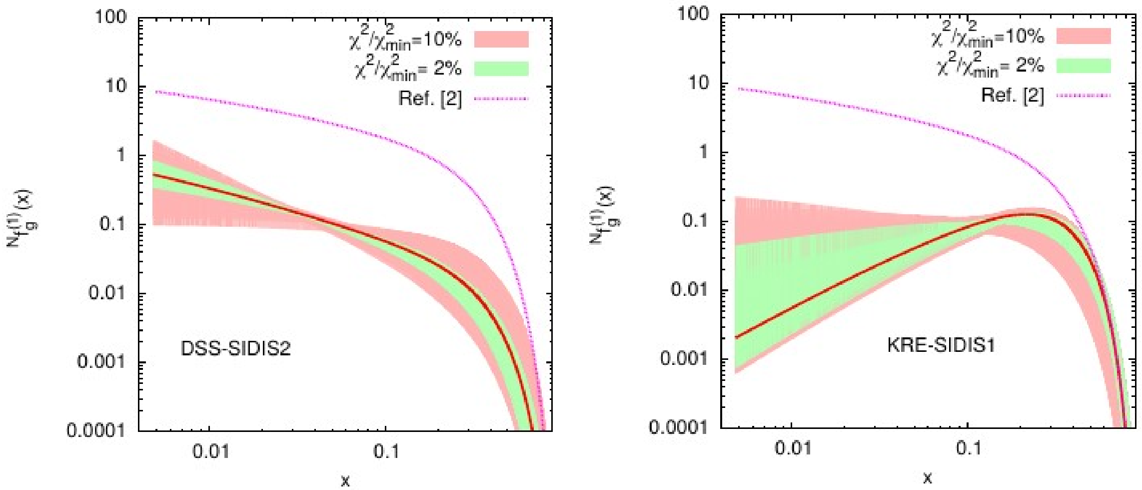
Projected statistical uncertainties for SPD

A_N for inclusive J/ψ production

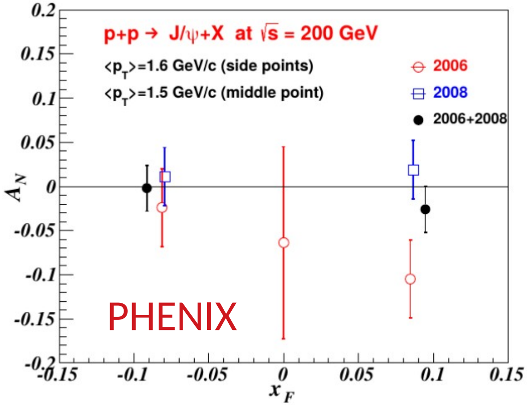
$$\sigma(\phi) \propto 1 + P \cdot A_N \sin(\phi_{\rm pol} - \phi)$$

Here and in the following P ~ 0.7 and is constant during the run.

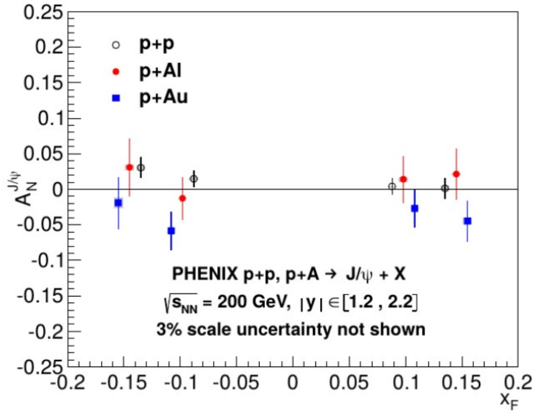
Probes $f_{1T}^{\perp g}$. For GPM (JHEP09(2015)119):



For CGI GPM see PRD99, 036013 (2019)



PRD82, 112008 (2010)

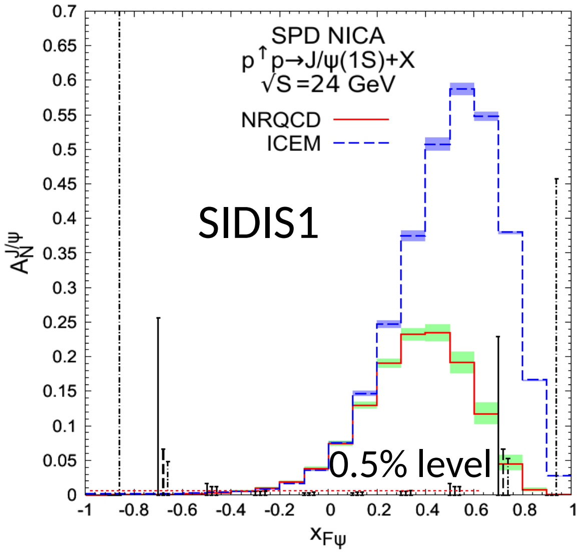


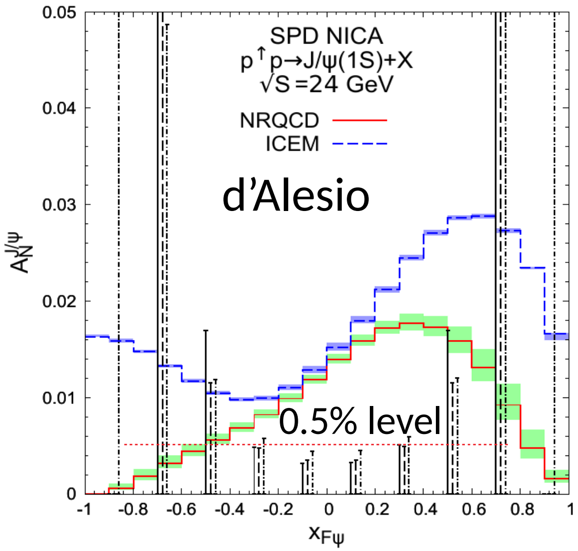
PRD98, 012006 (2018)

A_N for inclusive J/ψ production

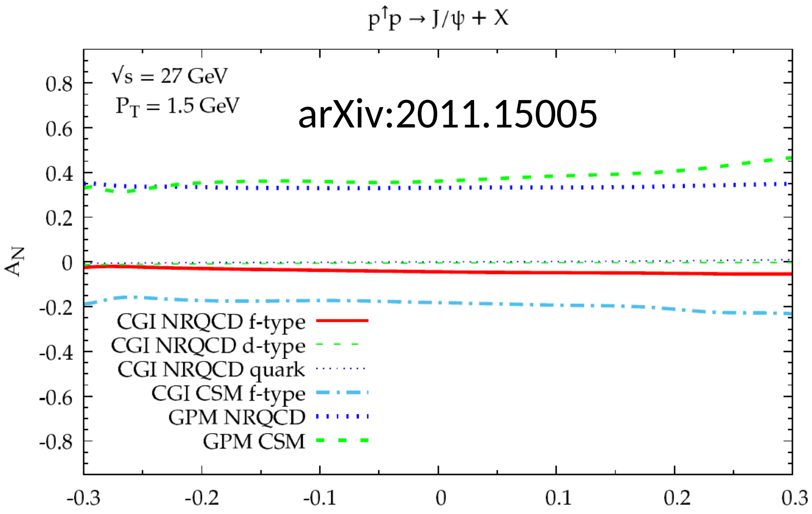
- GPM predictions for SIDIS1 and d'Alesio PDFs (see talk by A. Karpishkov)
- for CGI GPM asymmetry is smaller (see talk by A. Karpishkov)
- statistical errors given assuming a single polarized beam
- 3 different cuts on |cosθ| are shown
- SPD measurements in **wide kinematic range** should probe/constrain GSF and discriminate theoretical approaches to charmonia production

arXiv:2008.07232





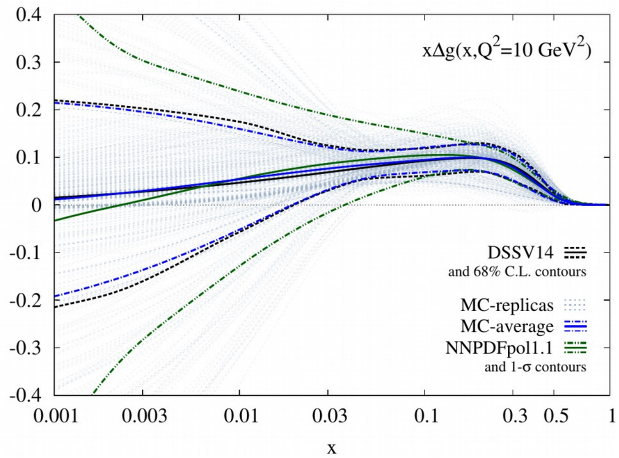
Maximized A_N for SPD, GPM and CGI GPM



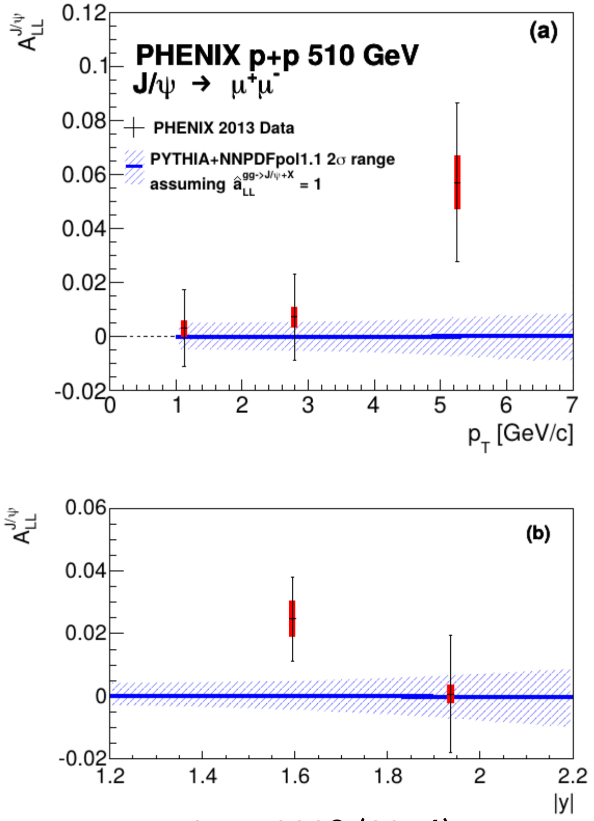
$$A_{LL}^{J/\psi} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

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

Probe for $g^g_1(\Delta g)$

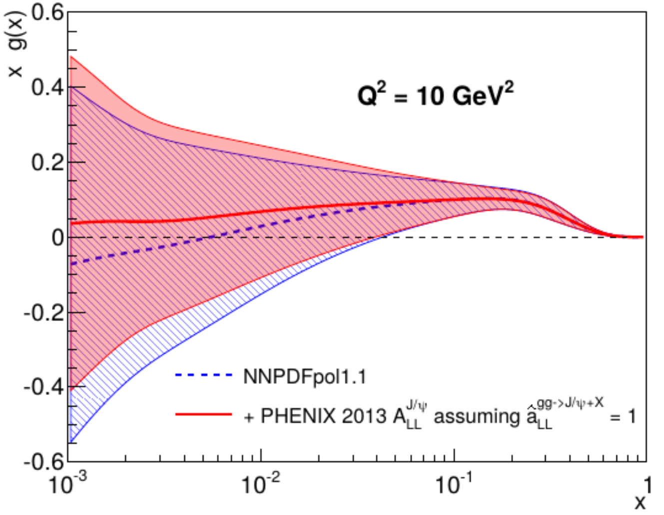


PRD100 114027 (2019)

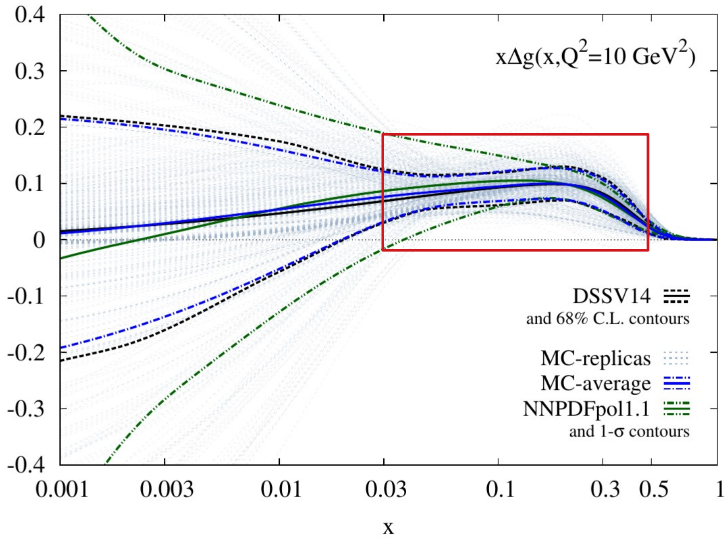


PRD94 112008 (2016)

For PHENIX
$x_1 \sim 5\times10^{-2}$
$x_2 \sim 2\times10^{-3}$



A_{LL} for inclusive J/ψ production at SPD

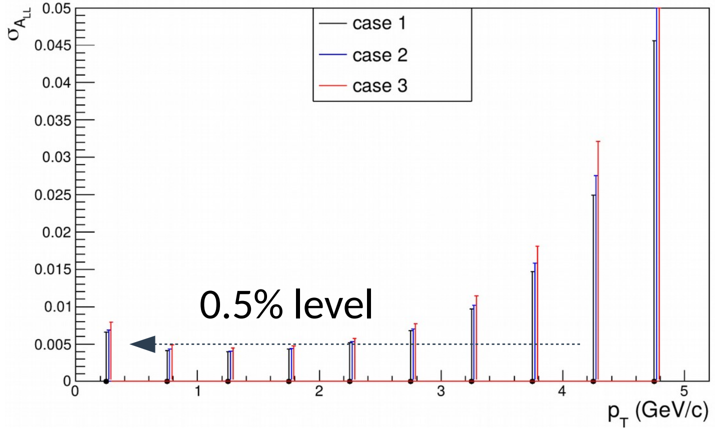


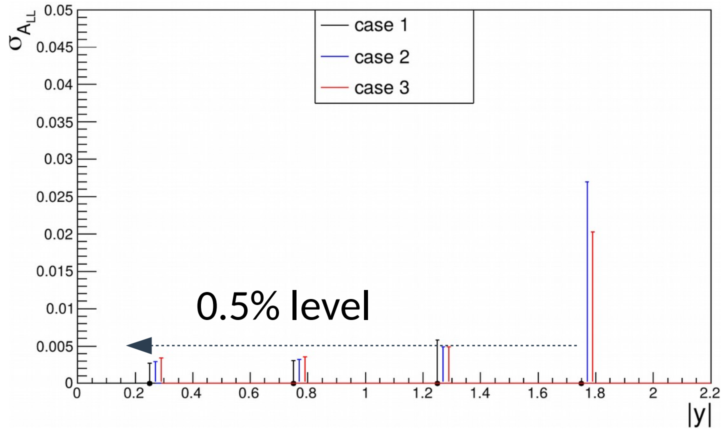
$$A_{LL}^{J/\psi} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta g(x_2)}{g(x_2)} \otimes \hat{a}_{LL}^{gg\to J/\psi+X}$$

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

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

Projected statistical uncertainties for SPD





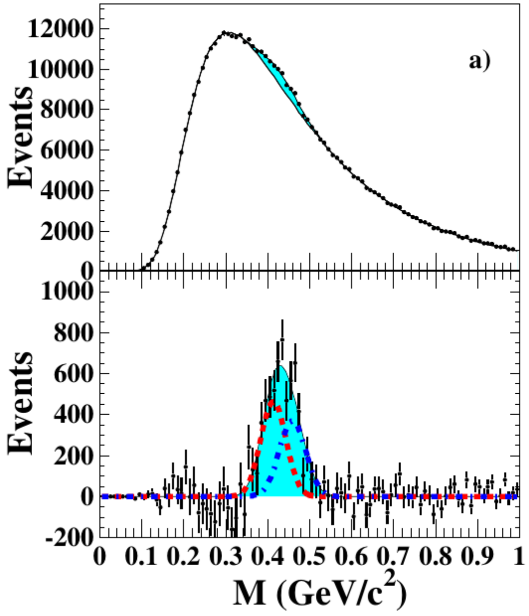
- |y|<2 is covered
- At SPD both $\Delta g(x_1)$ and $\Delta g(x_2)$ are expected to be close to the maximum
- A measurable A_{LL} of the order of 1-10% can be expected
- The measurements should constrain Δg and J/ψ production models

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)		

From HERA-B (Phys. Rev. D 79, 012001)



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

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

	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	$1.02 \pm 0.17_{st} \pm 0.36_{sys}$

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

- Reconstruction via $\gamma J/\psi$
- χ_{c1} and χ_{c2} mass difference ~45 MeV
- Expected statistics: **~500K** selected events for both states (30% feed-down assumed)
- Relative production rate of χ_{c1} and χ_{c2} validates models
- LO CS NRQCD [Boer, Pisano, 2012]:

$$\frac{d\sigma(\chi_{Q2})}{dy\, d^2\boldsymbol{q}_T} = \frac{32}{9}\frac{\pi^3\alpha_s^2}{M^5\, s}\langle 0|\mathcal{O}_1^{\chi_{Q2}}(^3P_2)|0\rangle\, \mathcal{C}\left[f_1^g\, f_1^g\right]$$

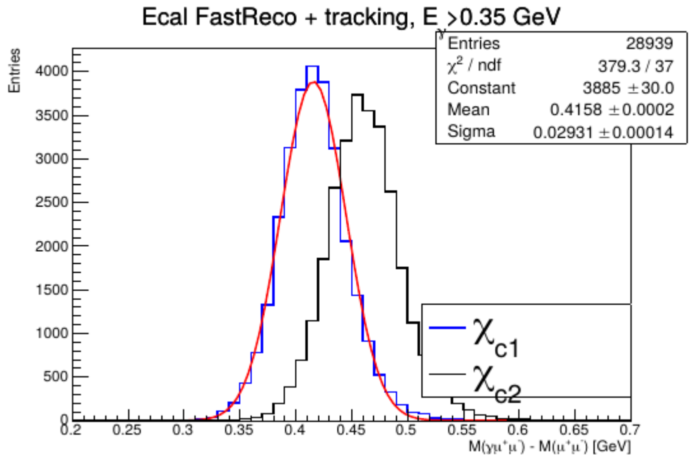
$$\frac{d\sigma(\chi_{Q0})}{dy\, d^2\boldsymbol{q}_T} = \frac{8}{3}\frac{\pi^3\alpha_s^2}{M^5\, s}\langle 0|\mathcal{O}_1^{\chi_{Q0}}(^3P_0)|0\rangle\, \mathcal{C}\left[f_1^g\, f_1^g\right]\left[1 + R(\boldsymbol{q}_T^2)\right]$$

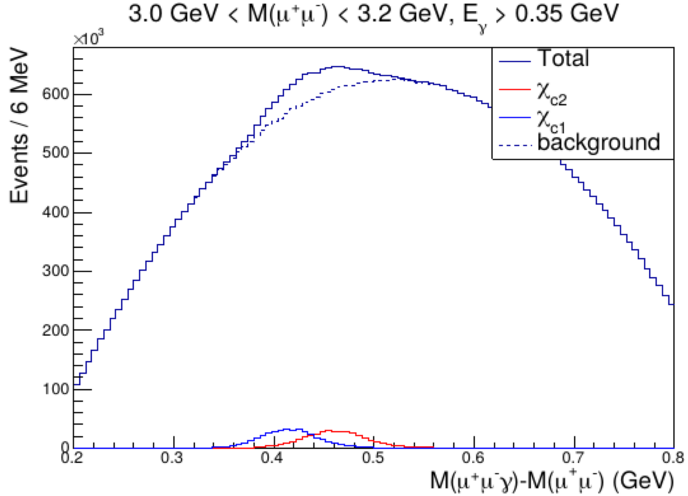
$$R(\boldsymbol{q}_T^2) \equiv \frac{\mathcal{C}\left[w\, h_1^{\perp g}\, h_1^{\perp g}\right]}{\mathcal{C}\left[f_1^g\, f_1^g\right]}$$

- For χ_{c0} and χ_{c2} TMD factorization holds only for one loop level (Ma,Wang, Zhao, 2014)

SPD measurements:

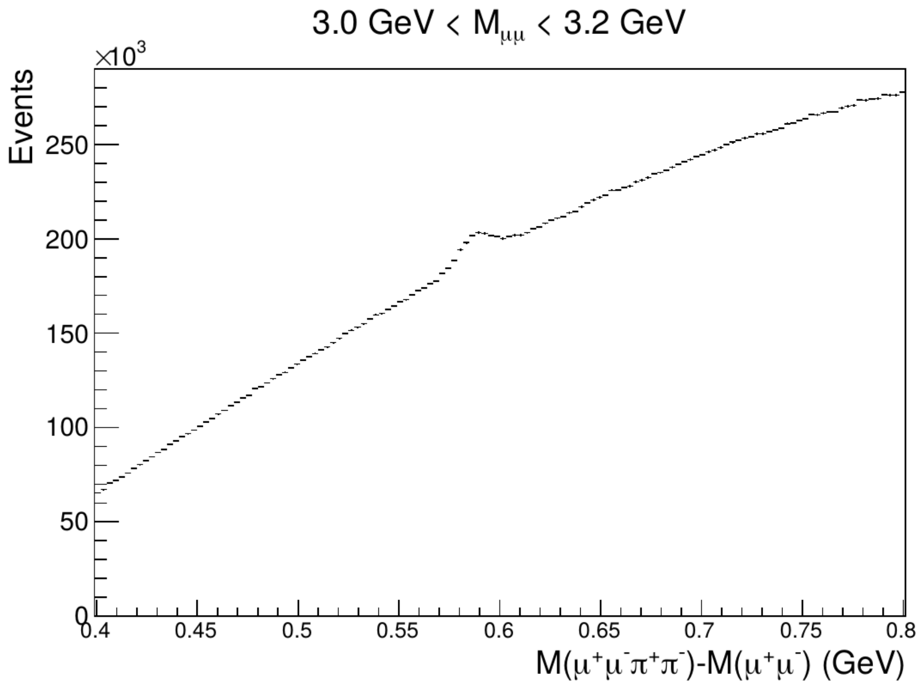
- differential cross-section as function of p_T and x_F
- relative contribution of the χ_{c1} and χ_{c2}





On inclusive ψ(2S) production at SPD

- No feed-down contributions
- ψ(2S) → $\mu^+\mu^-$ does not look promising (compared to J/ψ yield is suppressed by approximately 50)
- ψ(2S) → $\pi^+\pi^-$J/ψ, J/ψ → $\mu^+\mu^-$ according to preliminary studies:
  - **is feasible**, a narrow peak (~10 MeV) in M($\pi^+\pi^-\mu^+\mu^-$) - M($\mu^+\mu^-$) can be seen on a significant background
  - about 100K selected events per year are expected.



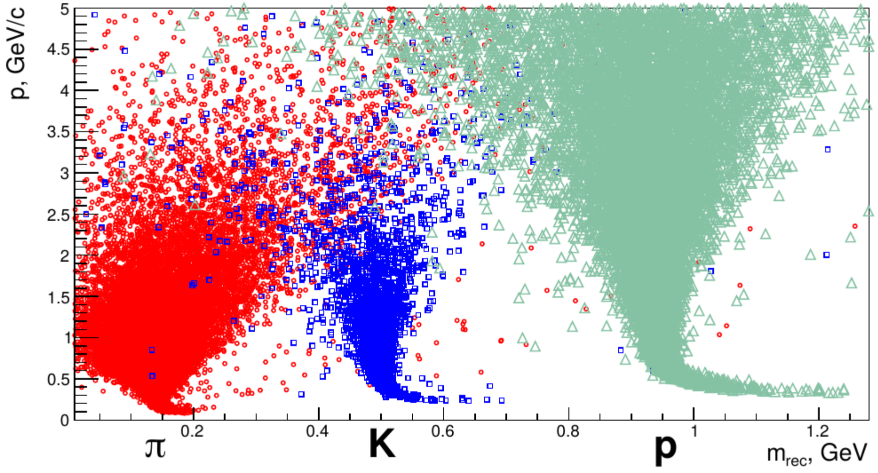
On η_c production

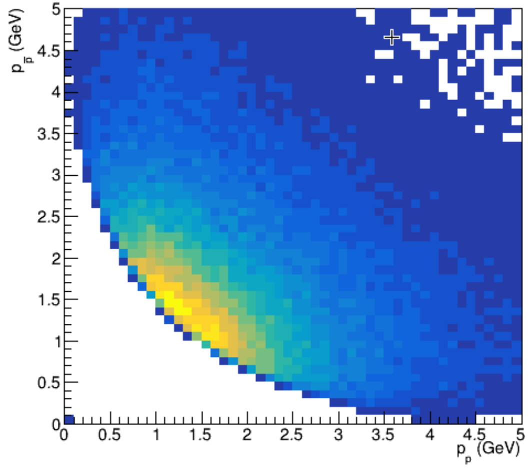
- The theoretically cleanest probe of gluon structure:
  - CS production
  - TMD factorization is proven
  - probes f_1^g and $h_1^{\perp g}$

$$\frac{d\sigma(\eta_Q)}{dy\, d^2\boldsymbol{q}_T} = \frac{2}{9}\frac{\pi^3\alpha_s^2}{M^3\, s}\langle 0|\mathcal{O}_1^{\eta_Q}({}^1S_0)|0\rangle\, \mathcal{C}\left[f_1^g\, f_1^g\right]\left[1 - R(\boldsymbol{q}_T^2)\right]$$

Boer, Pisano, 2012

- Experimentally challenging
- For SPD two modes, $p\bar{p}$ and $\Lambda\bar{\Lambda}$, can be used
- Expected statistics is **600K** for $p\bar{p}$ (conservative estimate) before the event selection.

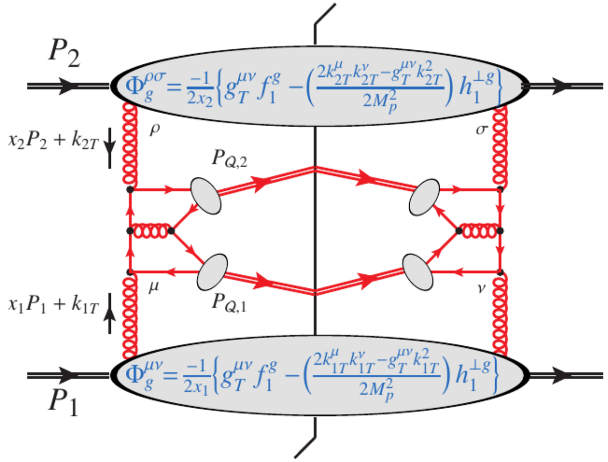




Double J/ψ production is promising:

- CS production, avoids TMD-factorization breaking effects
- In unpolarized collisions probes f_1^g and $h_1^{\perp g}$

$$\frac{1}{2\pi}\int d\phi_{CS}\frac{d\sigma}{dM_{QQ}dY_{QQ}d^2\boldsymbol{P}_{QQ_T}d\Omega} = F_1\,\mathcal{C}\Big[f_1^g f_1^g\Big] + F_2\,\mathcal{C}\Big[w_2 h_1^{\perp g} h_1^{\perp g}\Big]$$



EPJC80, 87 (2020)

At SPD:

- The cross-section is **27±10 pb** at √s=27 GeV (NA3, PLB158,85)
- Yield: 50-100 selected events for both dimuon and dielectron modes
- $d\sigma/dp_T$ for low-p_T, complimentary to “big” experiments
- probing evolution effects, x-dependence?

Ideas from JPL talk at the workshop “Gluon content of proton and deuteron with SPD at NICA”

Summary

- The SPD experiment is expected to provide important high-precision measurements of charmonia production (kinematic distributions, polarization and asymmetries) with unique high-statistics polarized data for √s between 10 and 27 GeV (4 – 13 GeV for dd).
- The measurement will constrain charmonia production models and probe gluon TMD PDFs (the latter will be complimented by other probes).
- These measurements should also allow the study of QCD factorization and factorization-breaking effects.
- We are very open to new ideas and suggestions.
- Adding our energy point (√s=27 GeV) in your future predictions would be extremely important for us.