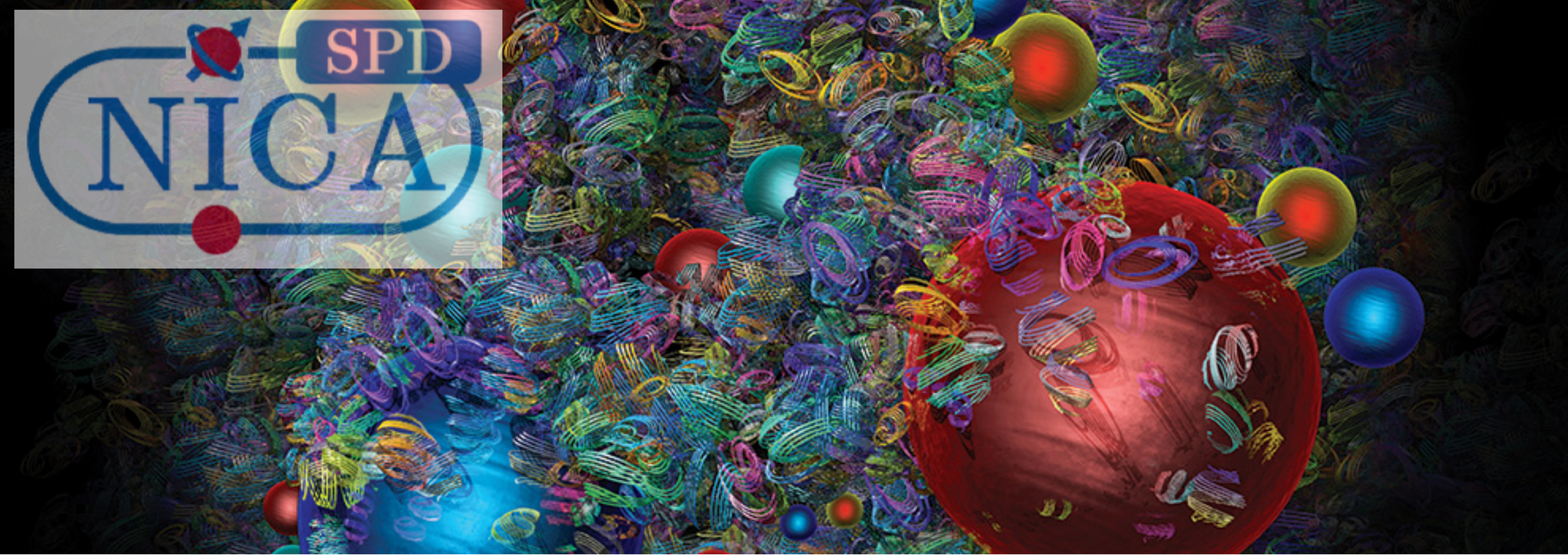


SPIN PHYSICS DETECTOR AT NICA

Alexey Guskov, JINR

XVIII MWPF

alexey.guskov@jinr.int

24.11.22

SPD AT NICA

NICA - Nuclotron-based Ion Collider fAcility

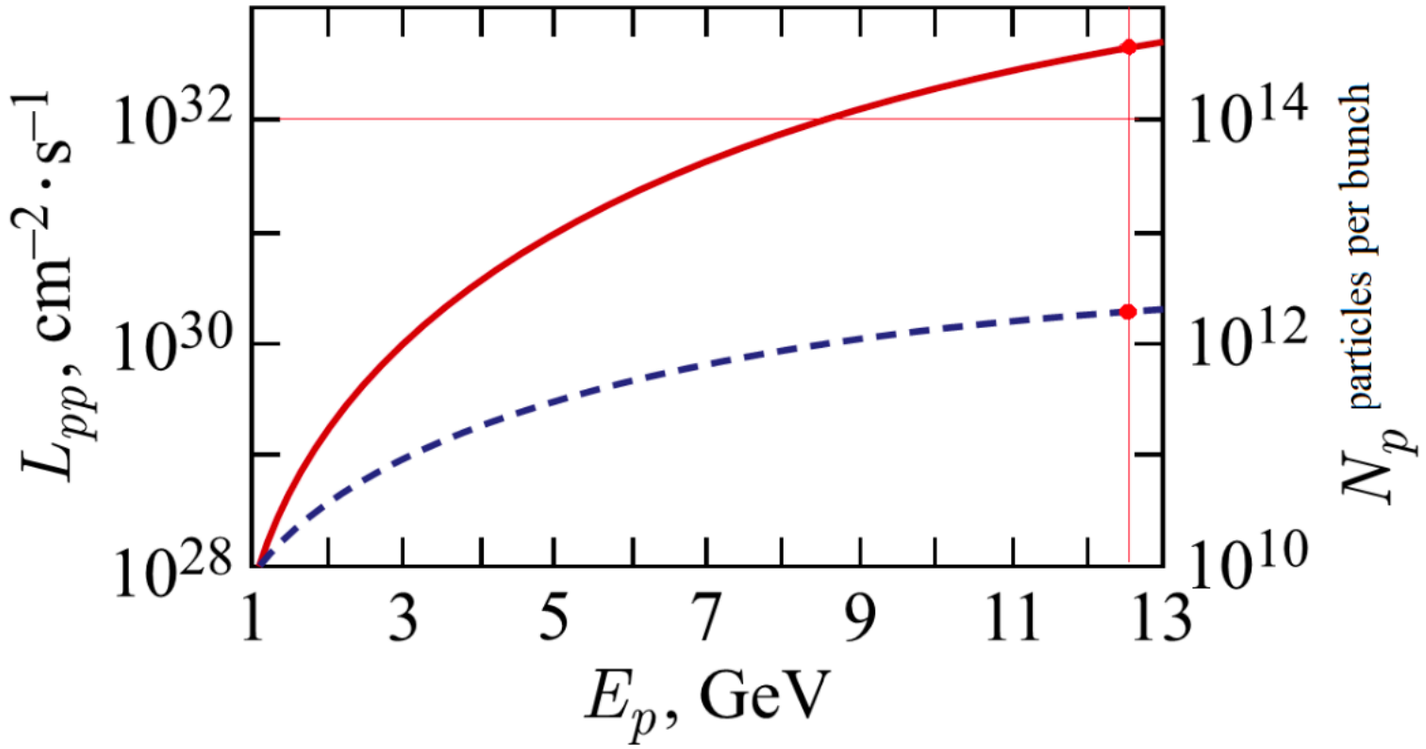
$p^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 27\ GeV$

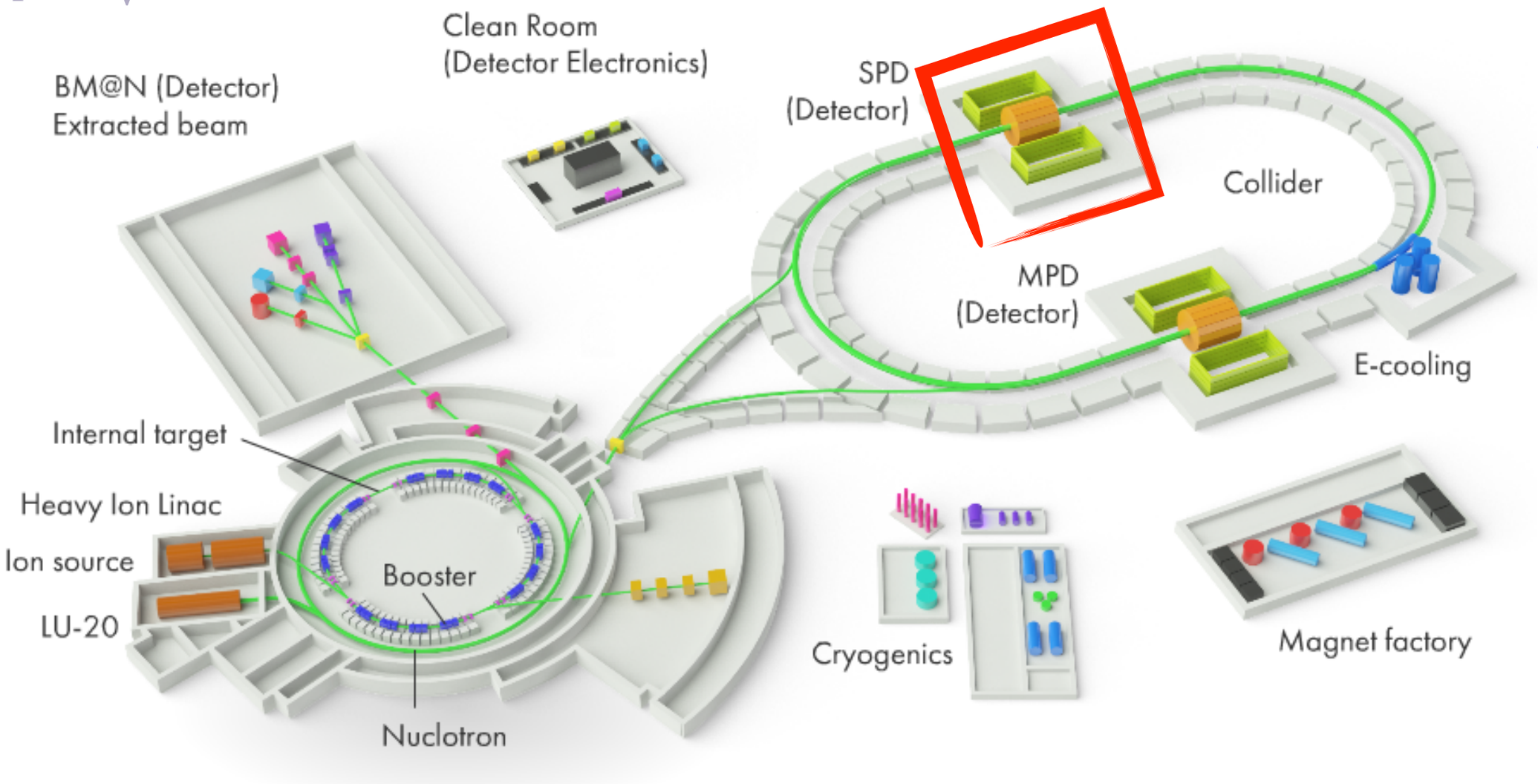
$d^{\uparrow}d^{\uparrow} : \sqrt{s} \leq 13.5\ GeV$

$d^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 19\ GeV$

U, L, T

|P|>70%

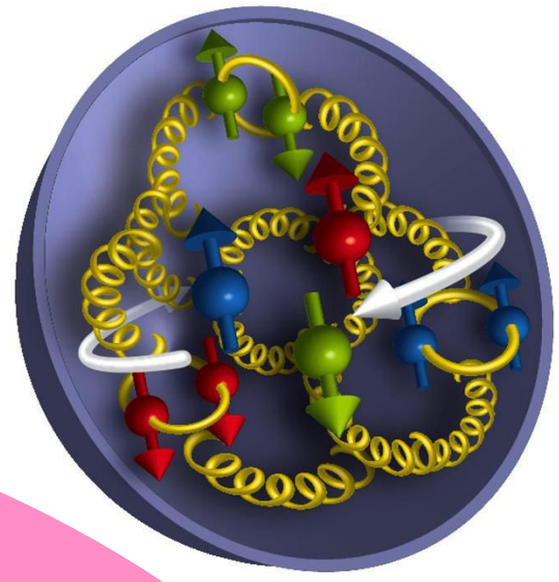




503 m

NICA

CONCEPT OF THE SPD PHYSICS PROGRAM



SPD - a universal facility for comprehensive study of gluon content in proton and deuteron at large x

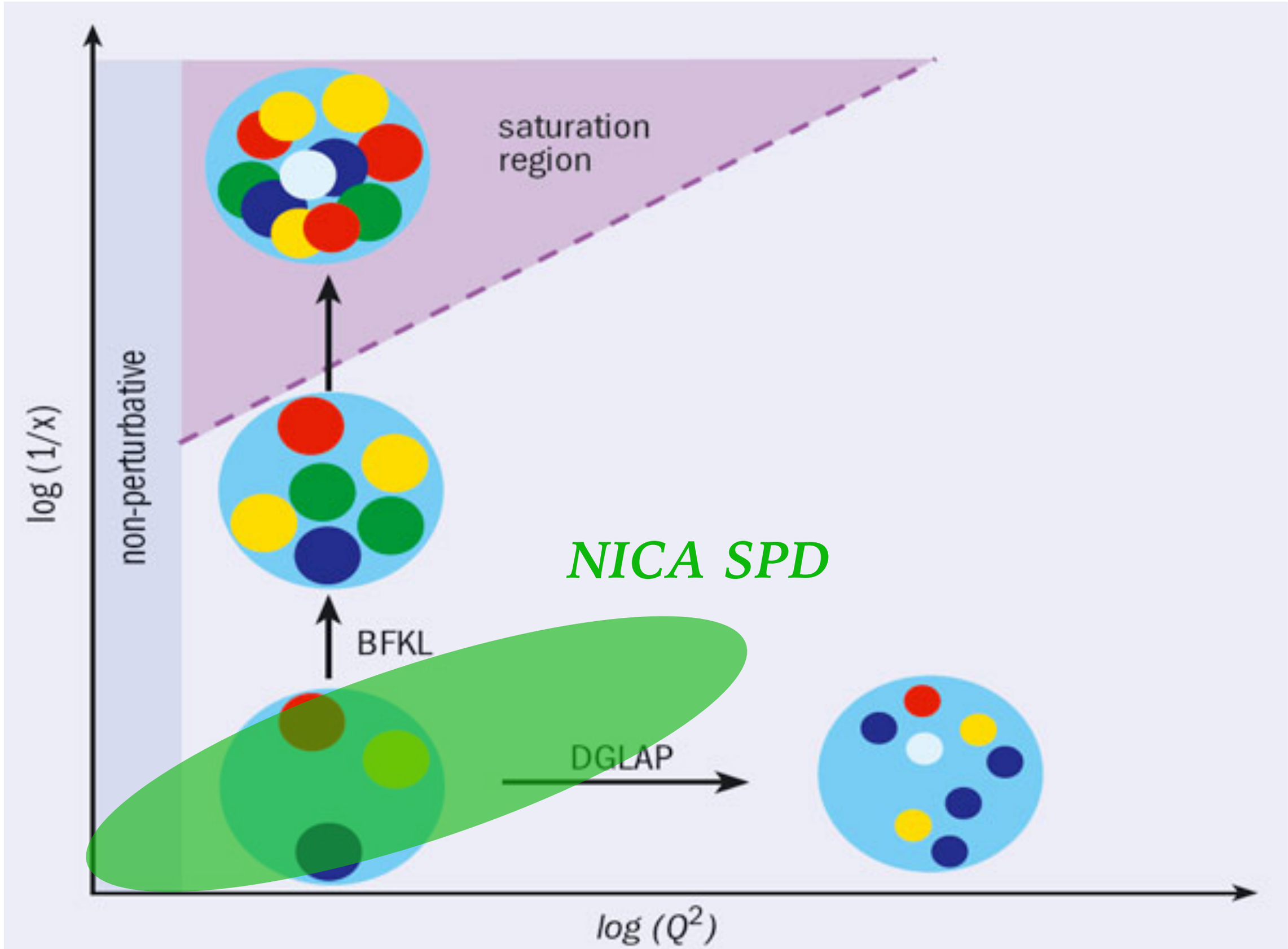
Charmonia

Prompt photons

Open charm

Other spin-related phenomena

Other physics


saturation
region
log (1/x)
non-perturbative
NICA SPD
BFKL
DGLAP
log (Q^2)

SPD Physics Program

JPPNP: 103858 | Model 3G | pp. 1–43 (col. fig: NIL)

ARTICLE IN PRESS

Progress in Particle and Nuclear Physics xxx (xxxx) xxx

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

On the physics potential to study the gluon content of proton and deuteron at NICA SPD

A. Arbuzov [a], A. Bacchetta [b,c], M. Butenschoen [d], F.G. Celiberto [b,c,e,f], U. D'Alesio [g,h], M. Deka [a], I. Denisenko [a], M.G. Echevarria [i], A. Efremov [a], N.Ya. Ivanov [a,j], A. Guskov [a,k,*], A. Karpishkov [l,a], Ya. Klopot [a,m], B.A. Kniehl [d], A. Kotzinian [j,o], S. Kumano [p], J.P. Lansberg [q], Keh-Fei Liu [r], F. Murgia [h], M. Nefedov [l], B. Parsamyan [a,n,o], C. Pisano [g,h], M. Radici [c], A. Rymbekova [a], V. Saleev [l,a], A. Shipilova [l,a], Qin-Tao Song [s], O. Teryaev [a]

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[d] II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
[e] European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), I-38123 Villazzano, Trento, Italy
[f] Fondazione Bruno Kessler (FBK), I-38123 Povo, Trento, Italy
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[h] INFN Sezione di Cagliari, I-09042 Monserrato, Italy

Prog.Part.Nucl.Phys. 119 (2021) 103858

arXiv:2011.15005

SPD Physics Program

Prepared for Physics of Elementary Particles and Atomic Nuclei. Theory

Possible studies at the first stage of the NICA collider operation with polarized and unpolarized proton and deuteron beams

V.V. Abramov[1], *A. Aleshko*[2], *V.A. Baskov*[3], *E. Boos*[2], *V. Bunichev*[2], *O.D. Dalkarov*[3], *R. El-Kholy*[4], *A. Galoyan*[5], *A.V. Guskov*[6], *V.T. Kim*[7,8], *E. Kokoulina*[5,9], *I.A. Koop*[10,11,12], *B.F. Kostenko*[13], *A.D. Kovalenko*[5], *V.P. Ladygin*[5], *A. B. Larionov*[14,15], *A.I. L'vov*[3], *A.I. Milstein*[10,11], *V.A. Nikitin*[5], *N. N. Nikolaev*[16,26], *A. S. Popov*[10], *V.V. Polyanskiy*[3], *J.-M. Richard*[17], *S. G. Salnikov*[10], *A.A. Shavrin*[18], *P. Yu. Shatunov*[10,11], *Yu.M. Shatunov*[10,11], *O.V. Selyugin*[14], *M. Strikman*[19], *E. Tomasi-Gustafsson*[20], *V.V. Uzhinsky*[13], *Yu.N. Uzikov*[6,21,22,*], *Qian Wang*[23], *Qiang Zhao*[24,25], *A.V. Zelenov*[7]

[1] NRC "Kurchatov Institute" - IHEP, Protvino 142281, Moscow region, Russia

[2] Skobeltsyn Institute of Nuclear Physics, MSU, Moscow, 119991 Russia

[3] P.N. Lebedev Physical Institute,Leninsky prospect 53, 119991 Moscow, Russia

arXiv:2102.08477

SPD Conceptual Design Report

CDR was presented on the meeting of the JINR Program Advisory Committee for particle physics in Jan, 2021 and approved in Jan, 2022

JOINT INSTITUTE FOR NUCLEAR RESEARCH

February 3, 2021

Conceptual design of the Spin Physics Detector

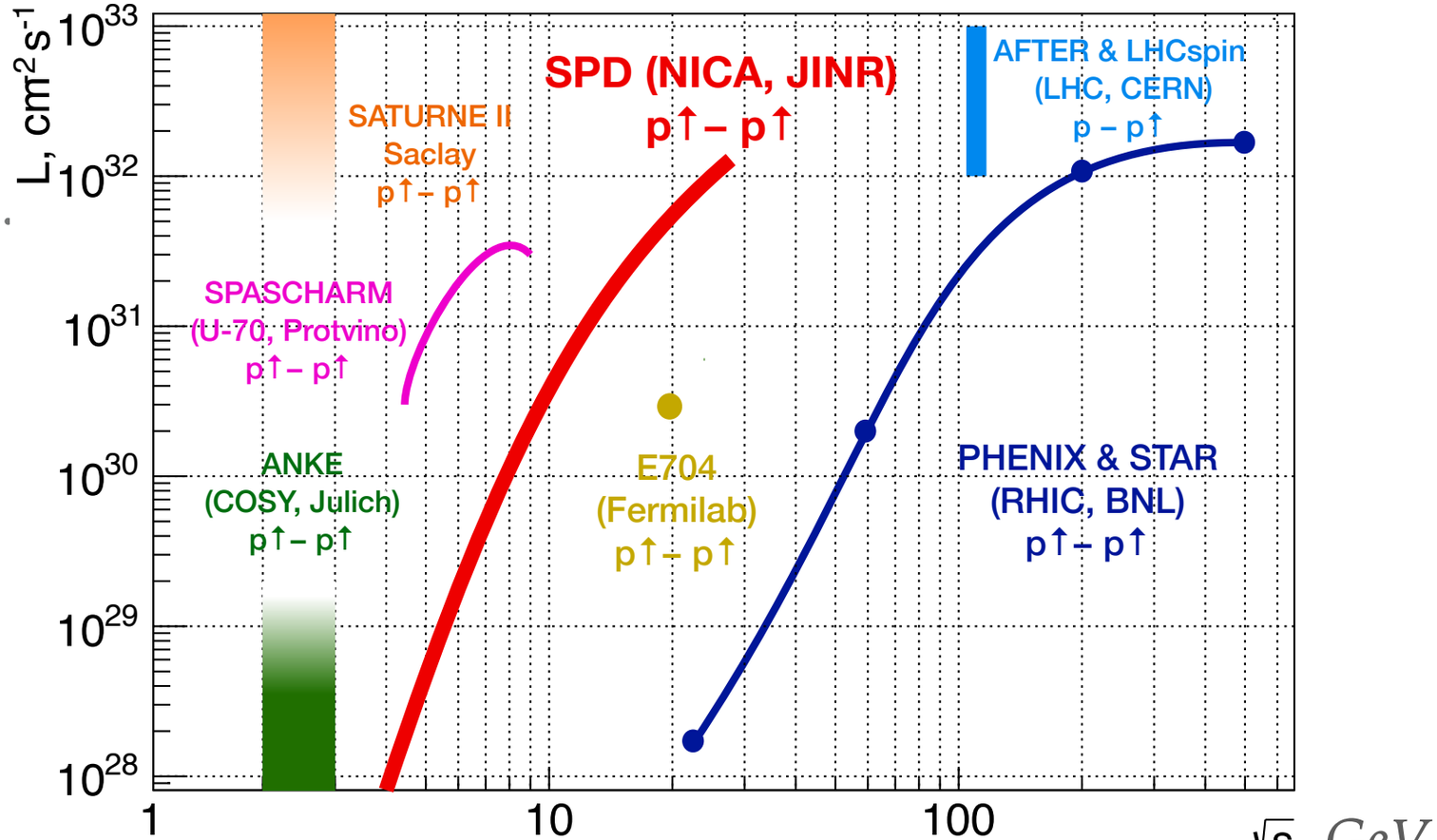
Version 1.0

The SPD proto-collaboration*

arXiv:2102.00442

SPD – VS OTHERS

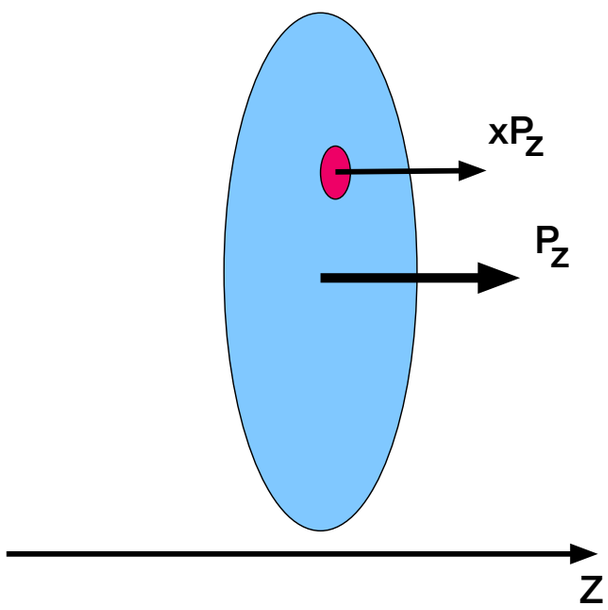
In the $p^{\uparrow}p^{\uparrow}$ mode:



Experimental facility	SPD @NICA	RHIC	EIC	AFTER @LHC	LHCspin
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	≤27 (p-p) ≤13.5 (d-d) ≤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

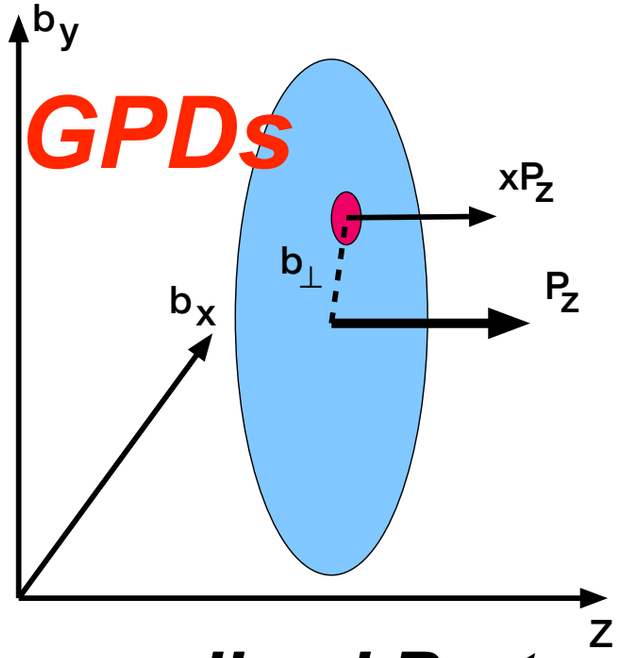
In the $d^{\uparrow}d^{\uparrow}$ mode we are unique

3D STRUCTURE OF THE PROTON

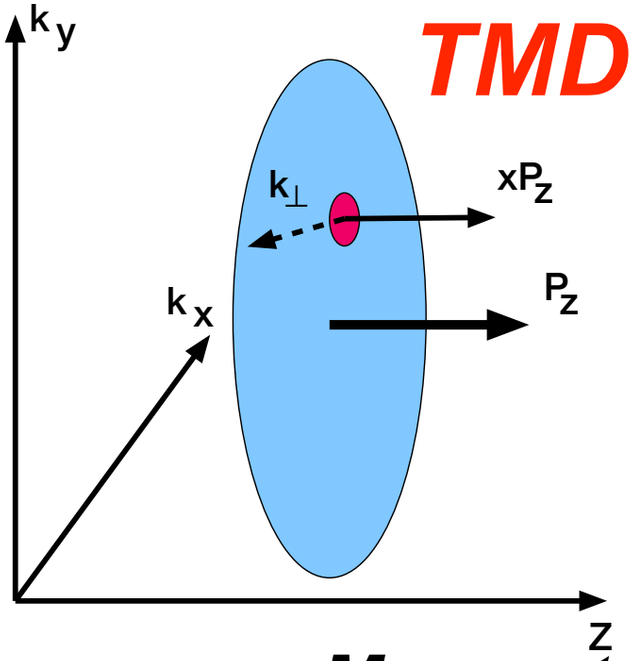


Collinear approximation

(common PDF)

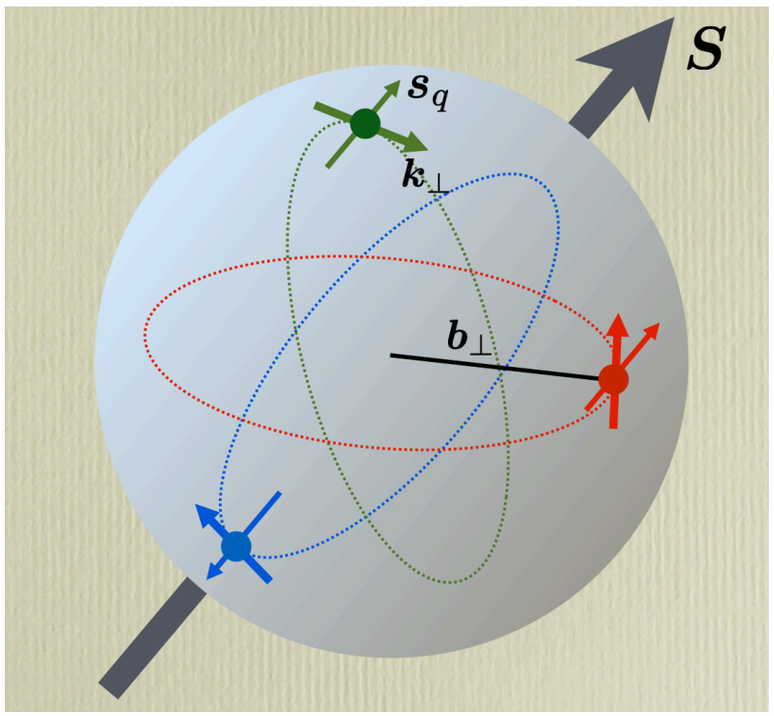


Generalized Parton Distributions



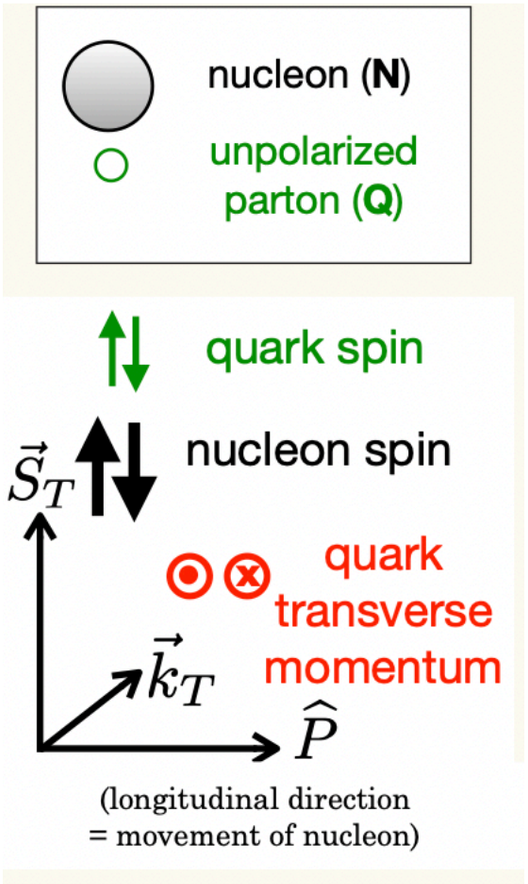
Transverse Momentum Dependent PDFs

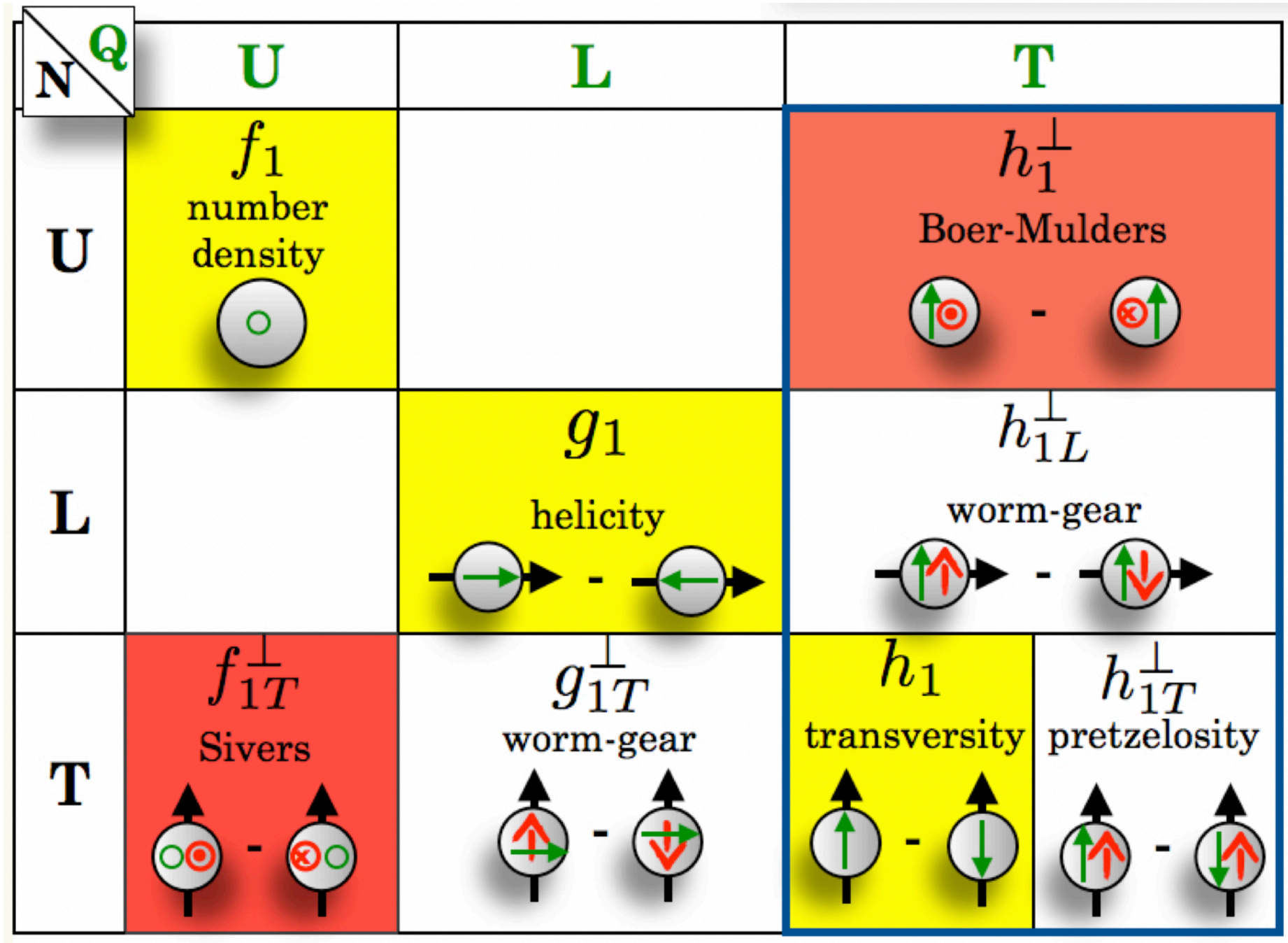
3D structure of nucleon



connection to orbital moment

TMD PDFS


nucleon (N)
unpolarized parton (Q)
quark spin
nucleon spin
$\vec{S}_T$
quark transverse momentum
$\vec{k}_T$
$\widehat{P}$
(longitudinal direction = movement of nucleon)


N
Q
U
L
T
U
f_1
number density
$h_1^\perp$
Boer-Mulders
L
g_1
helicity
$h_{1L}^\perp$
worm-gear
T
$f_{1T}^\perp$
Sivers
$g_{1T}^\perp$
worm-gear
h_1
transversity
$h_{1T}^\perp$
pretzelosity

GLUON PDFs

Unpolarized gluons at high x in proton and deuteron

Gluon helicity

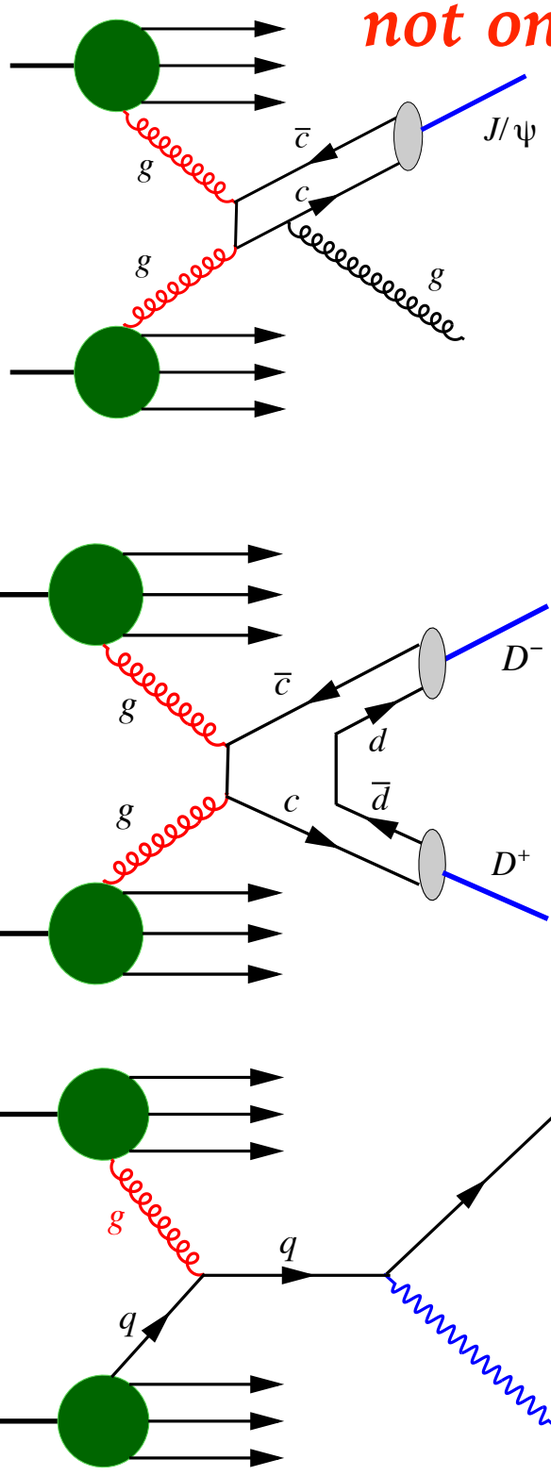
Gluon Boer-Mulders function

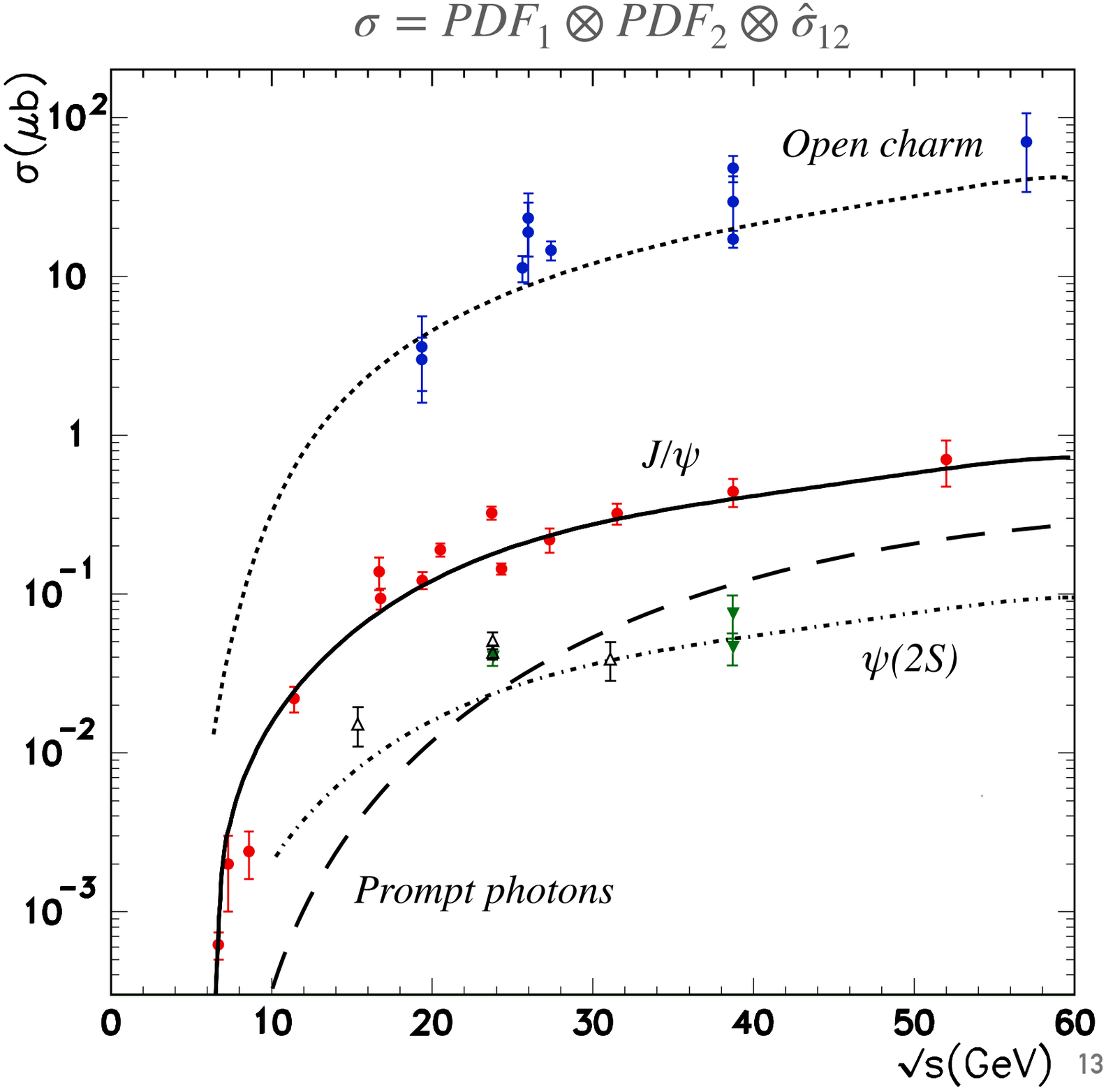
GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g, h_{1T}^{\perp g}$

Gluon Sivers function

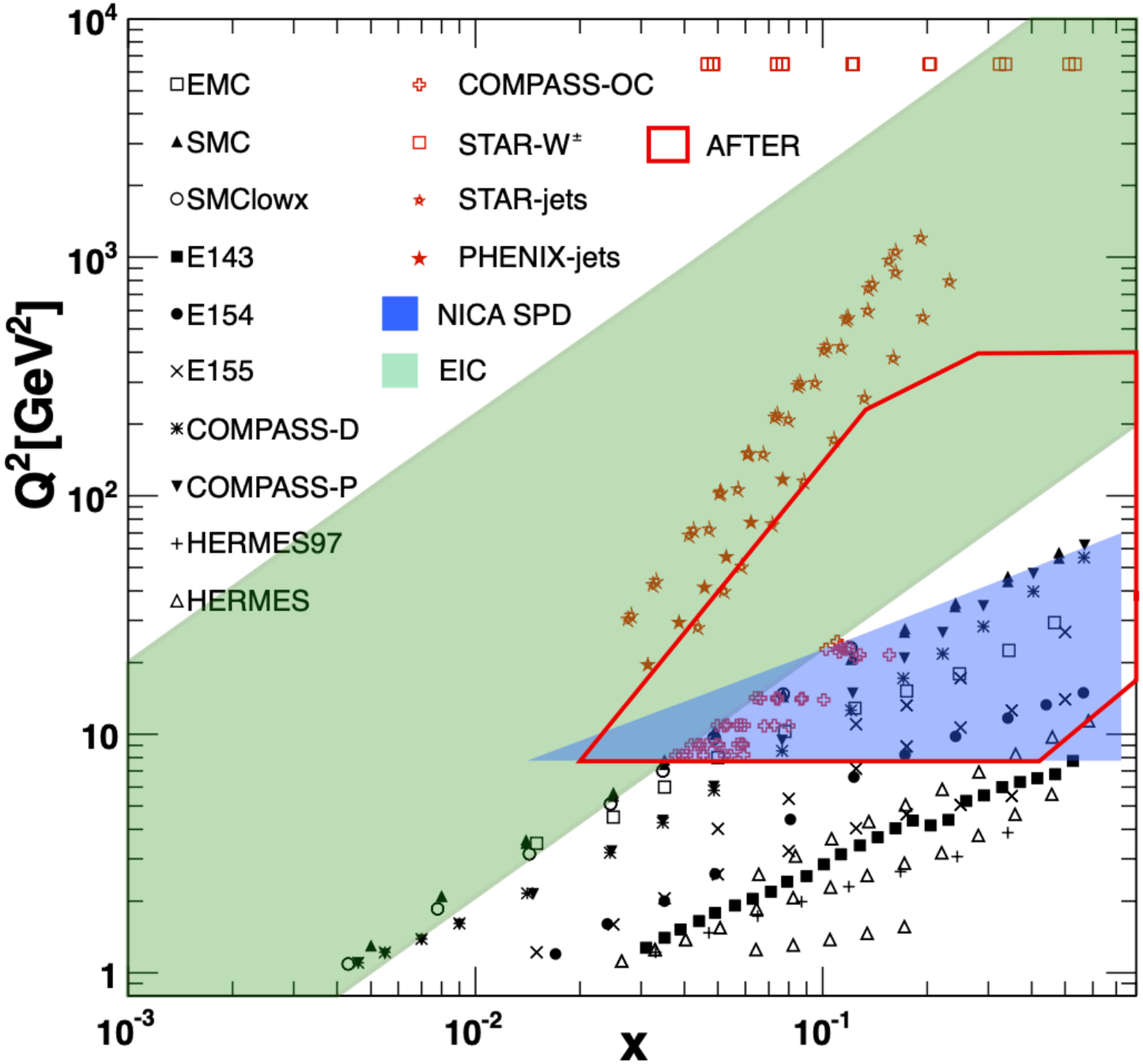
Gluon transversity in deuteron

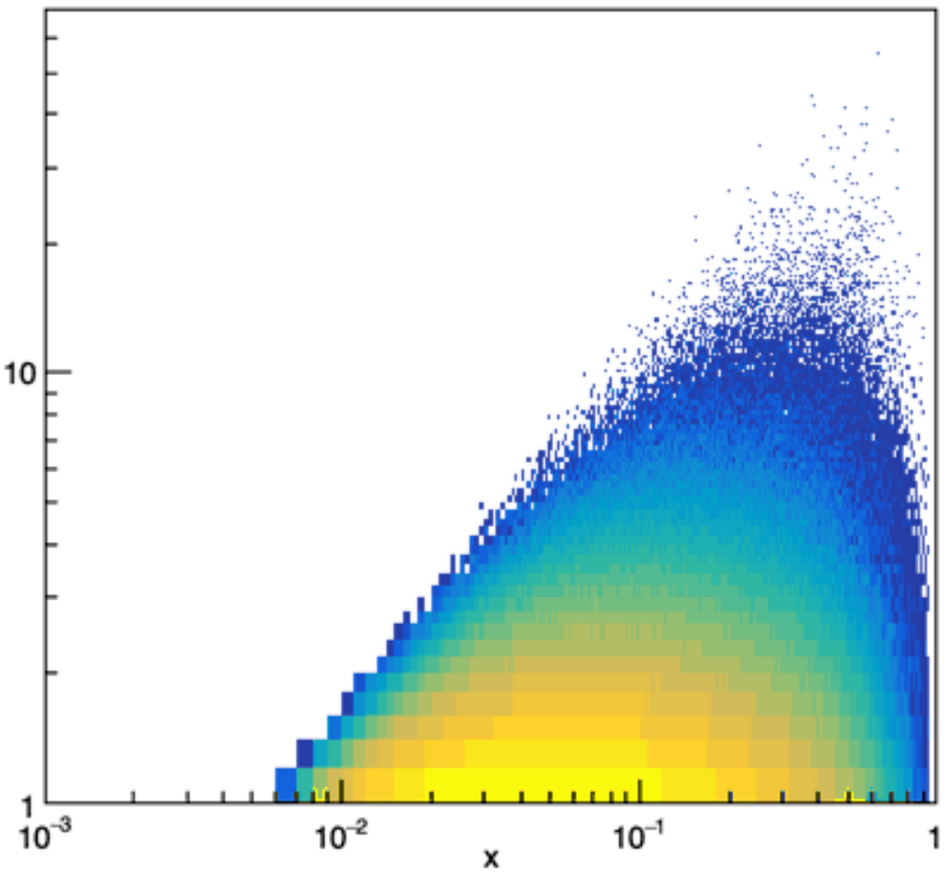
GLUON PROBES AT SPD





KINEMATIC RANGE

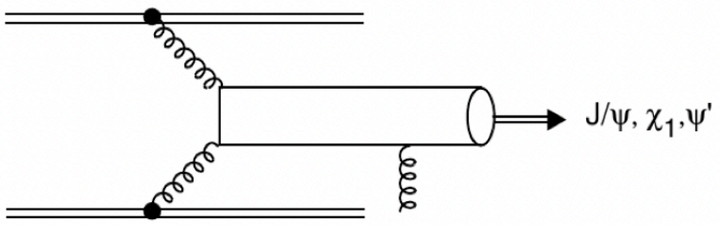




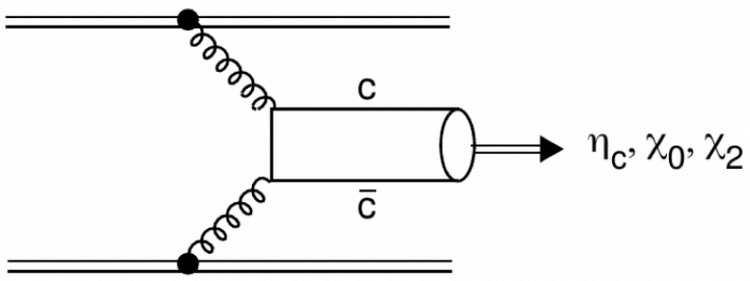
$Q^2 = 1\ GeV^2/c^2, < x > = 0.16$

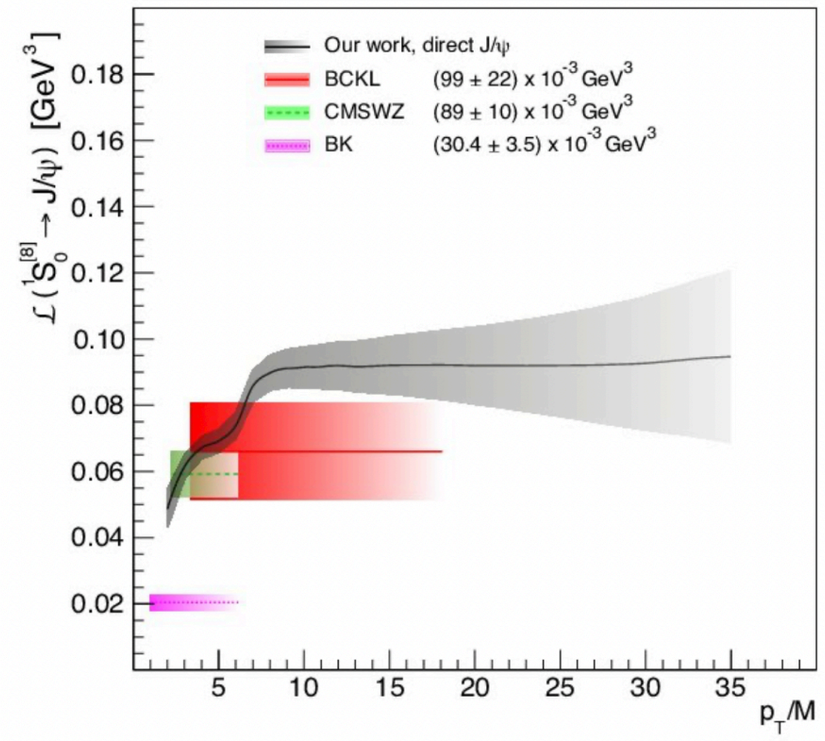
$Q^2 = 10\ GeV^2/c^2, < x > = 0.3$

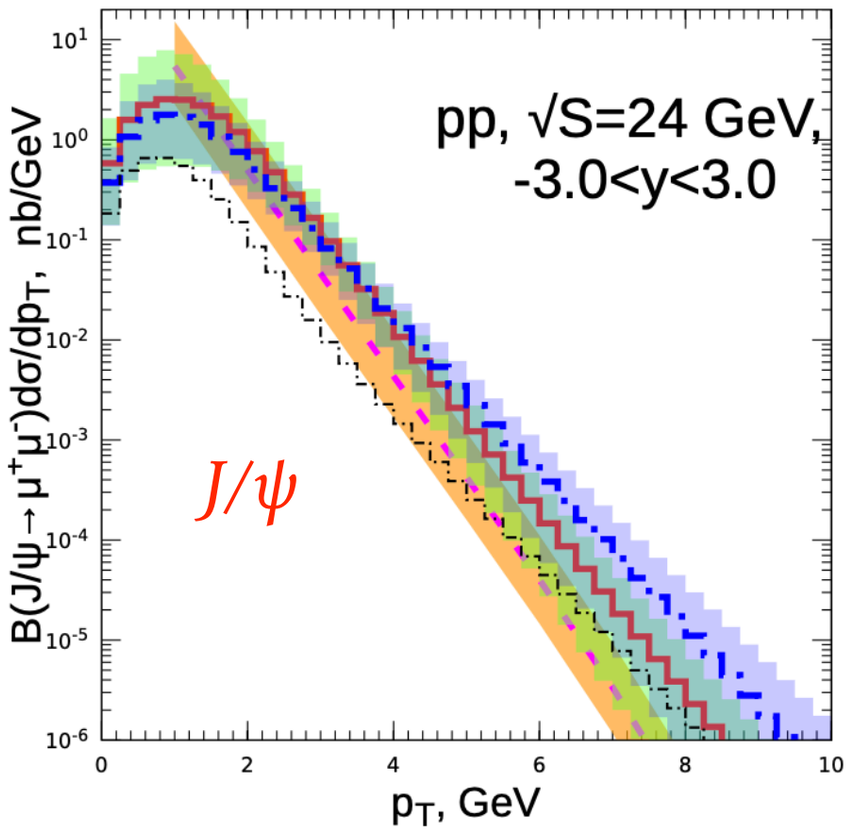
CHARMONIA PRODUCTION

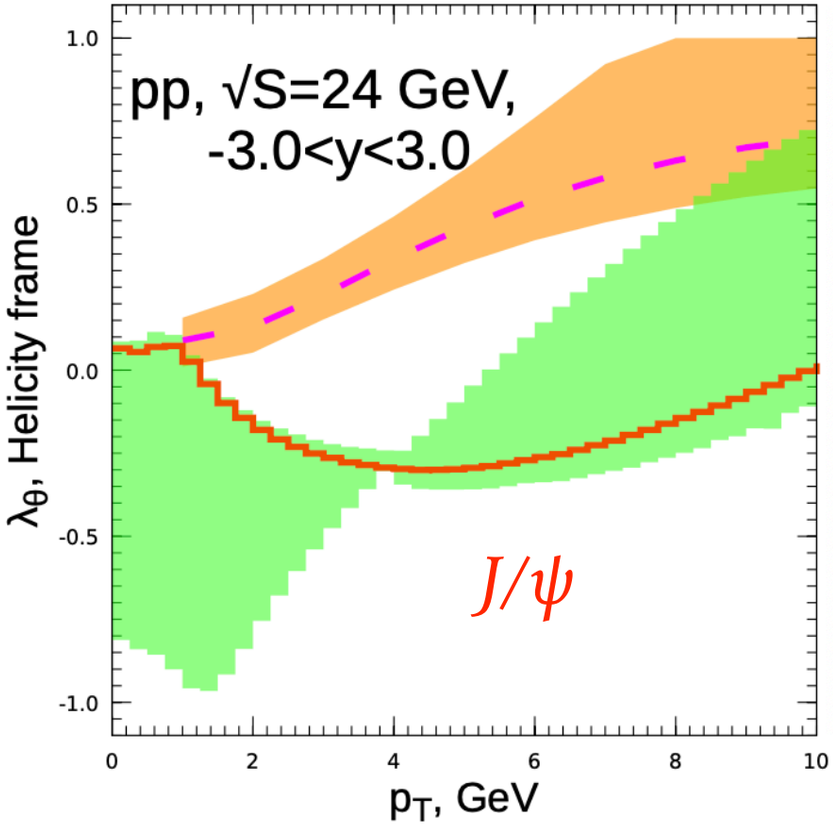


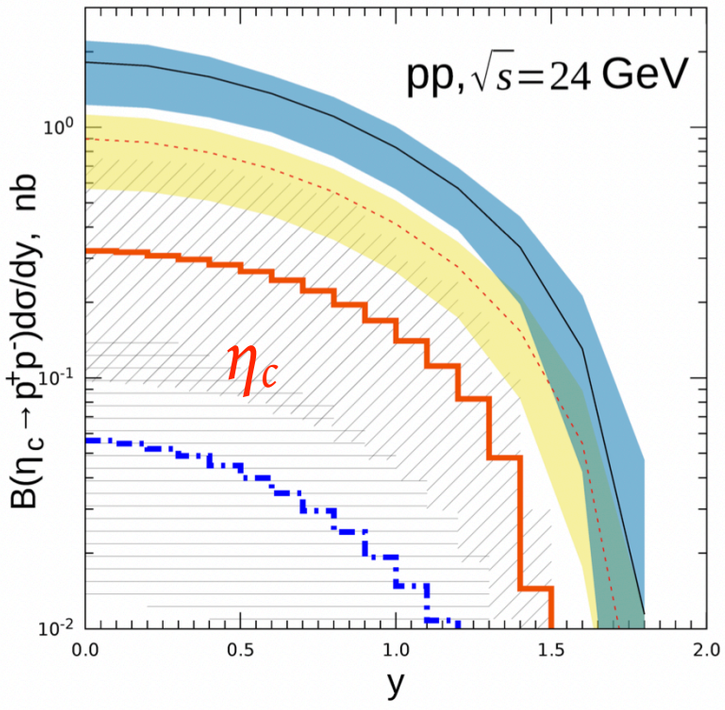
NRQCD — LDMEs



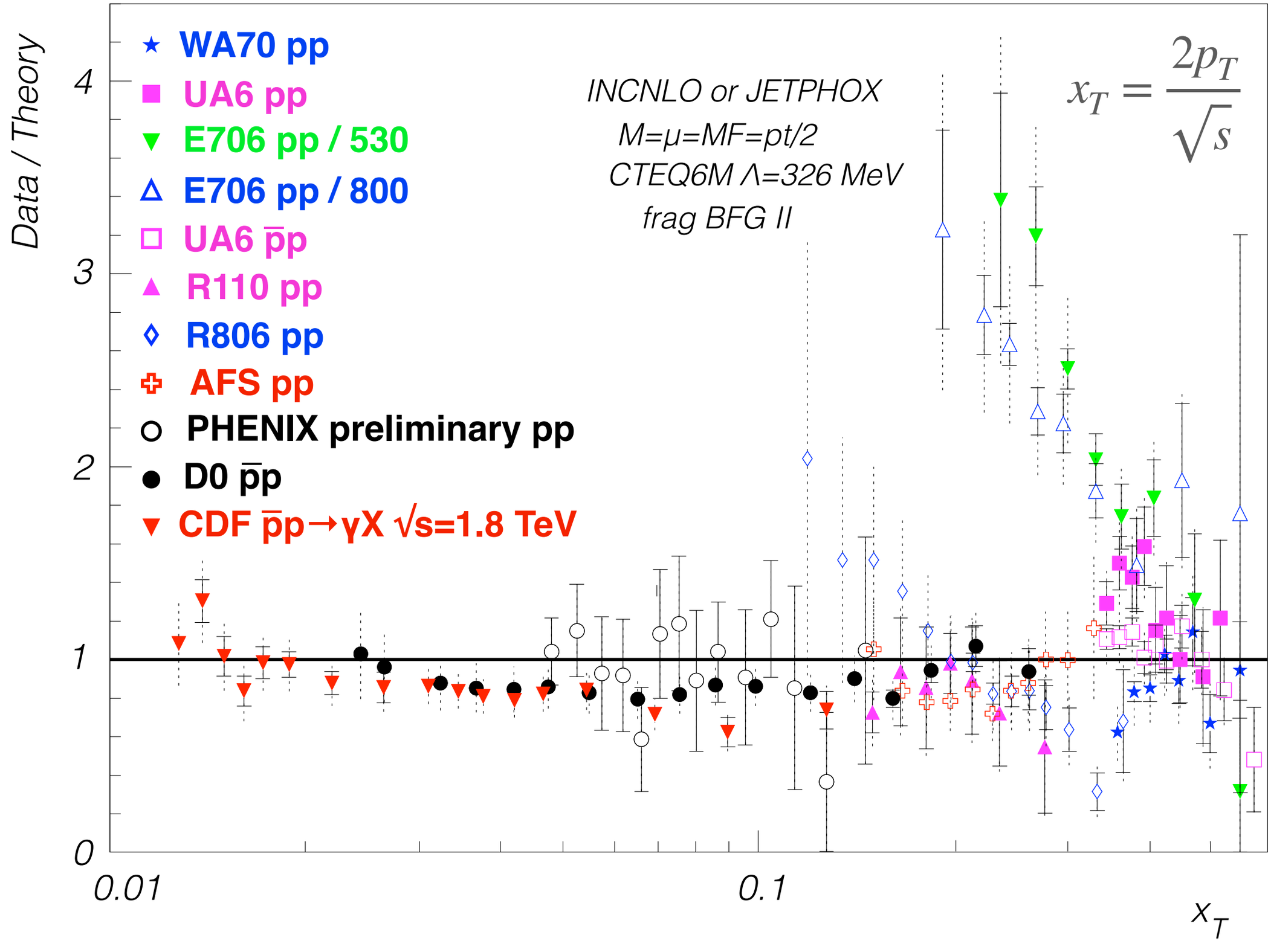




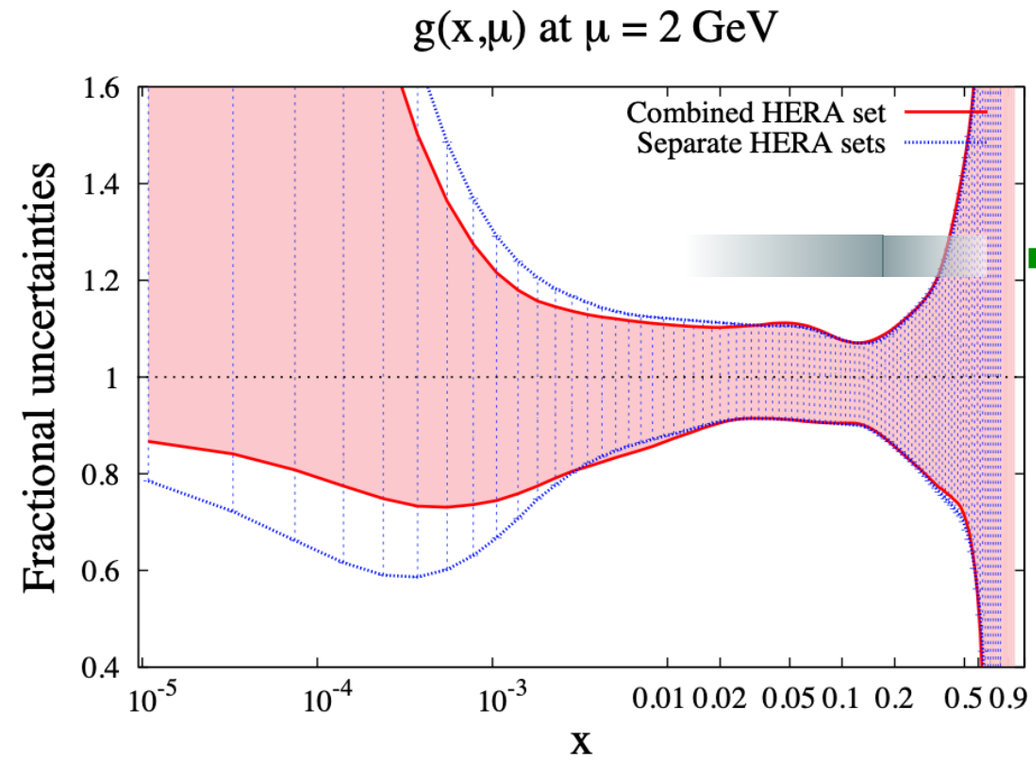




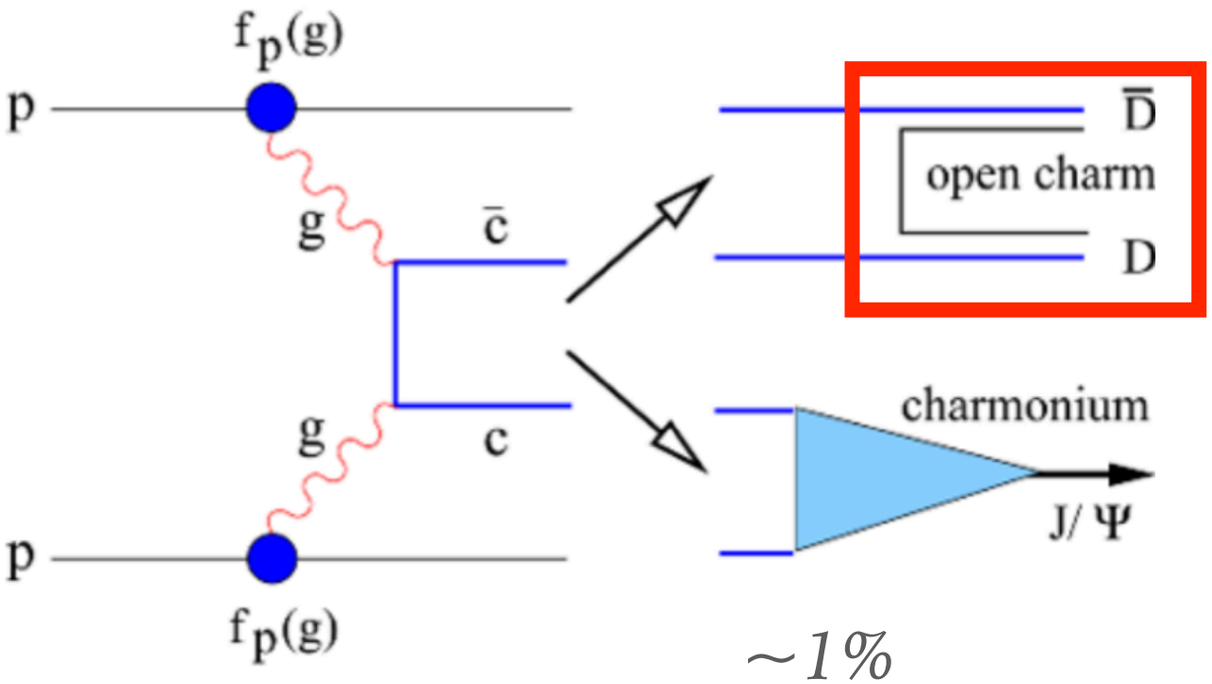
PROMPT PHOTON PUZZLE



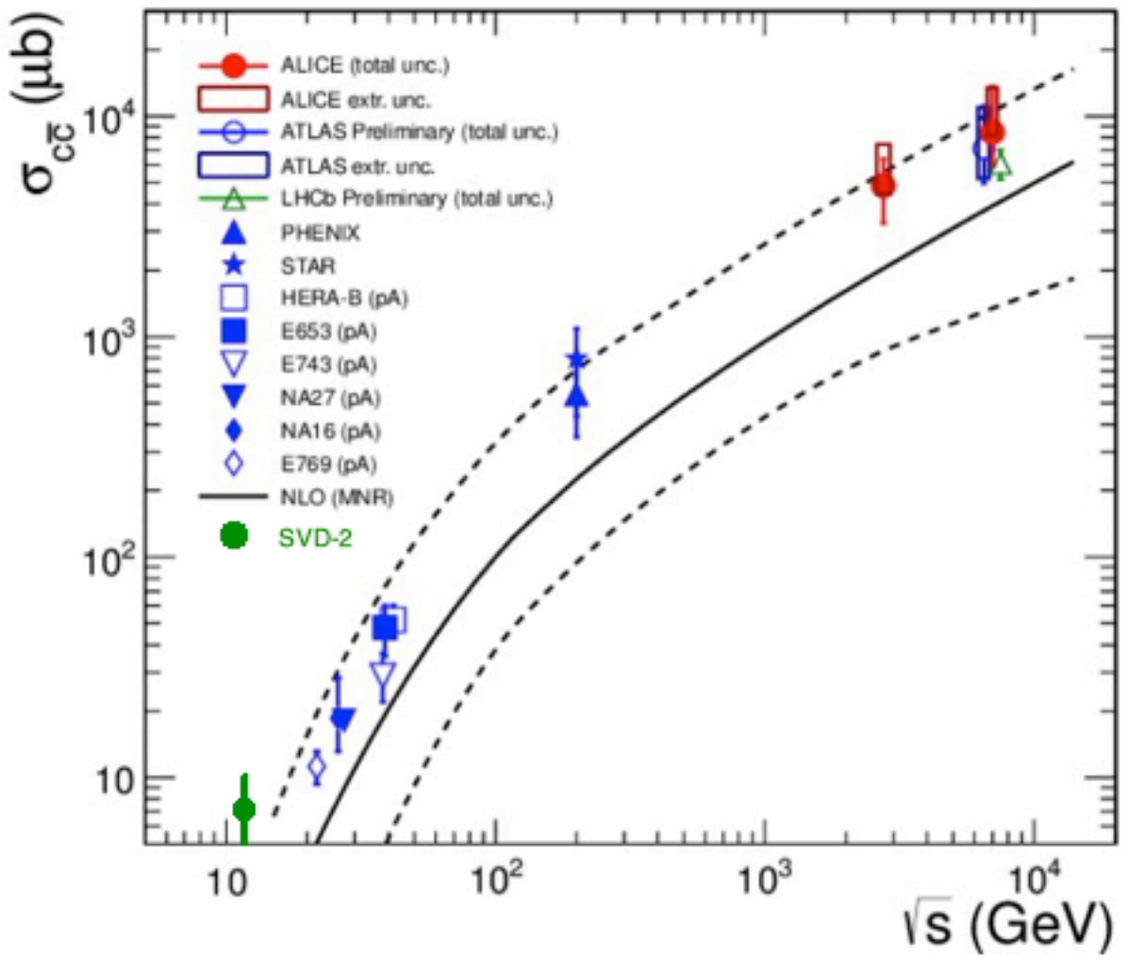
UNPOLARIZED GLUONS IN PROTON AT HIGH x



Good opportunity for SPD

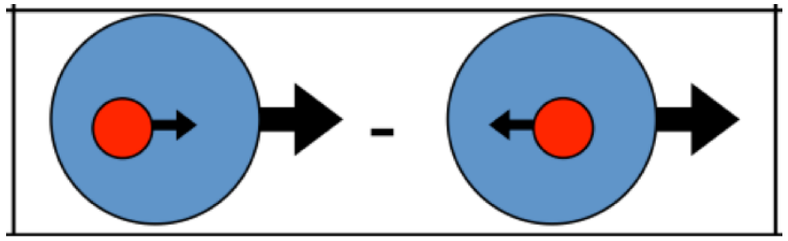


~1%

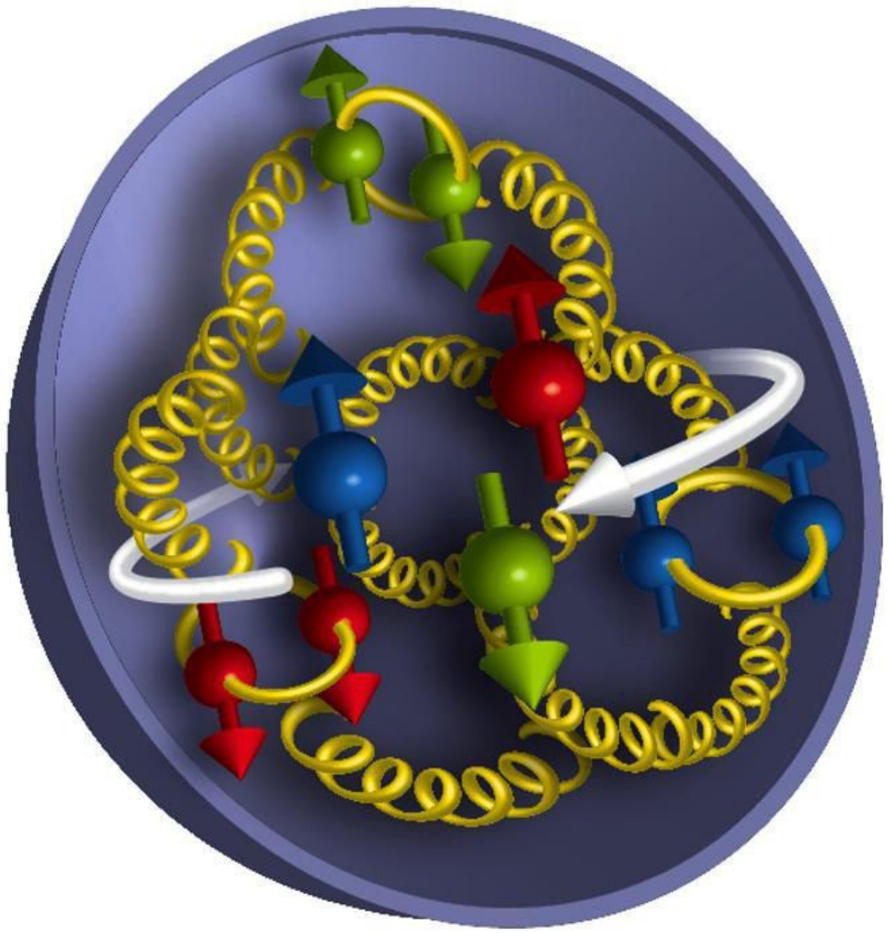


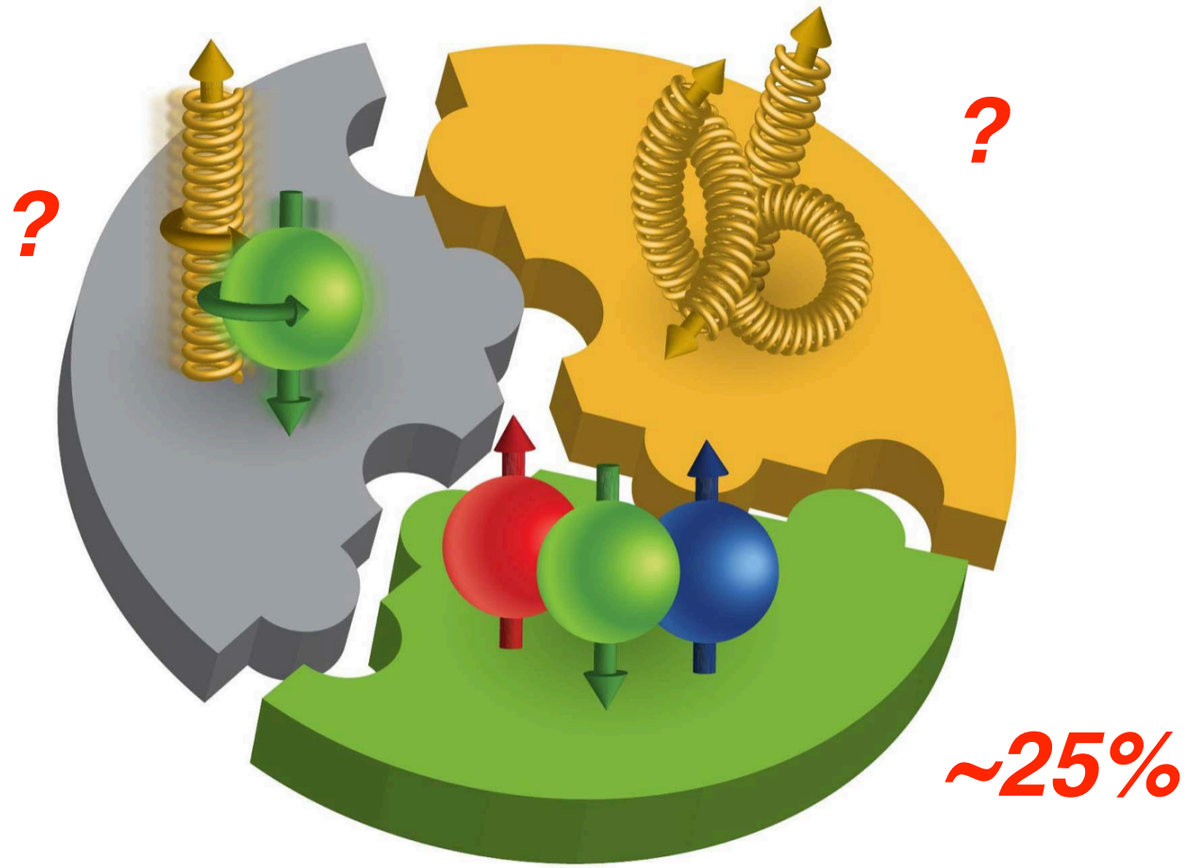
GLUON HELICITY FUNCTION Δg(x) : SPIN CRISIS

Δg(x) :



$$\Delta G = \int_0^1 \Delta g(x) dx$$



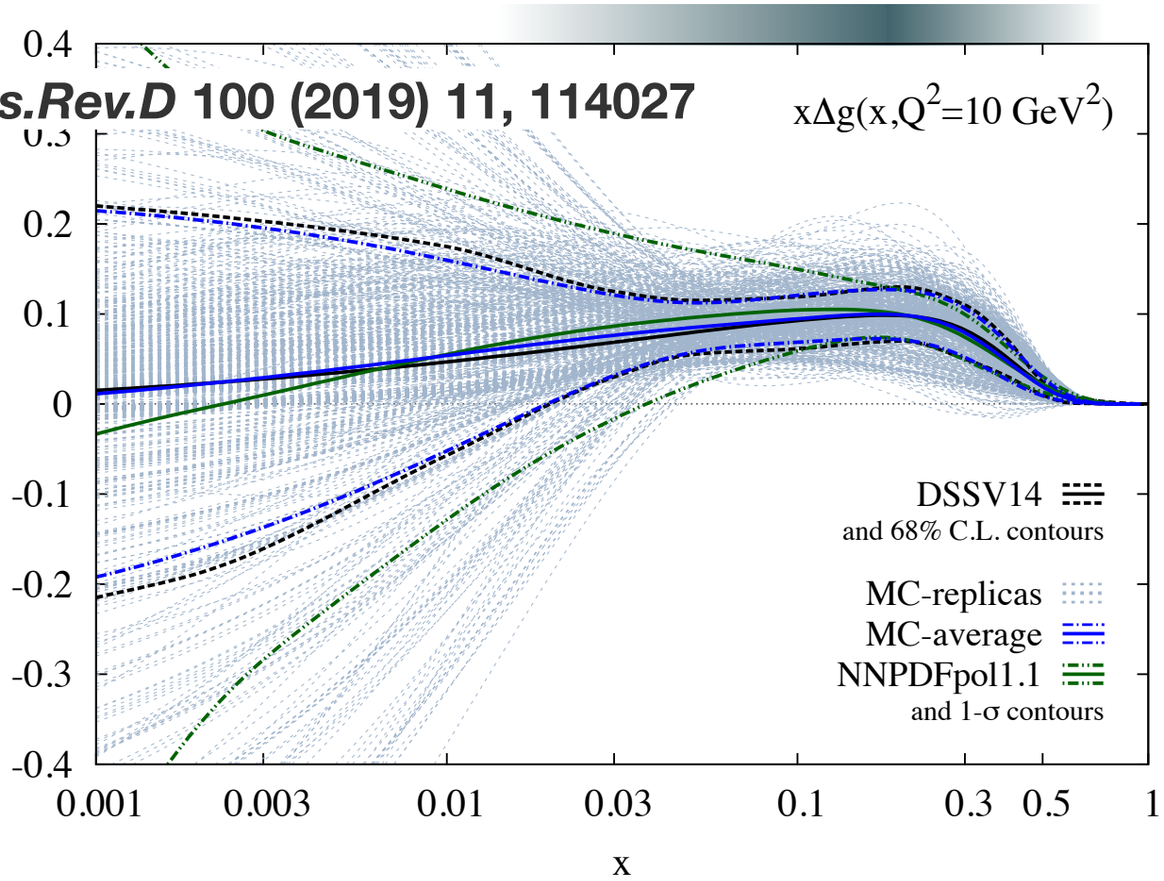


$$S_N = ½ = ½\,\Delta\Sigma + \Delta G + L$$

GLUON HELICITY FUNCTION Δg(x)

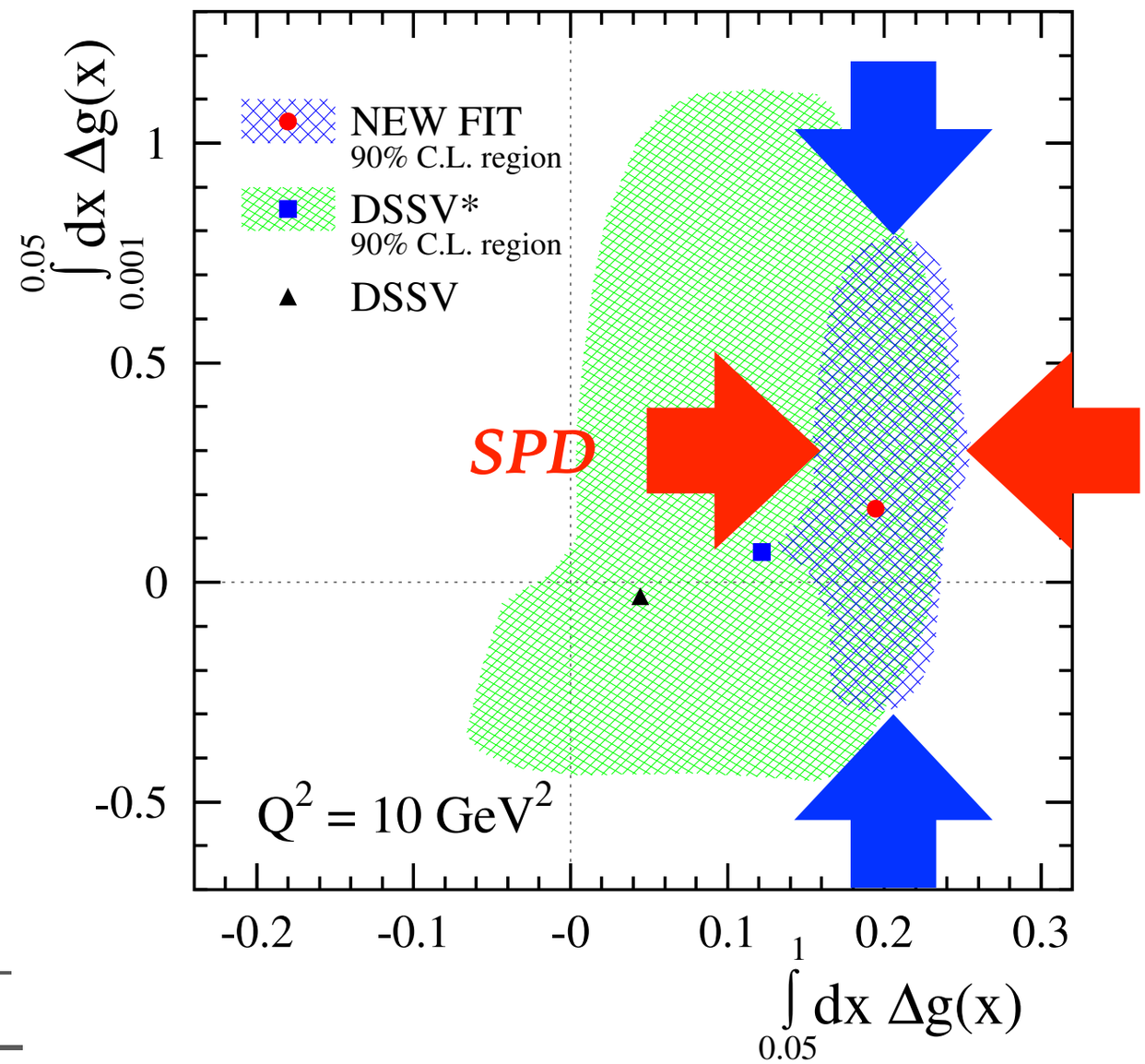
accessible with SPD

Phys.Rev.D 100 (2019) 11, 114027



Phys.Rev.Lett. 113 (2014) 1, 012001

EIC

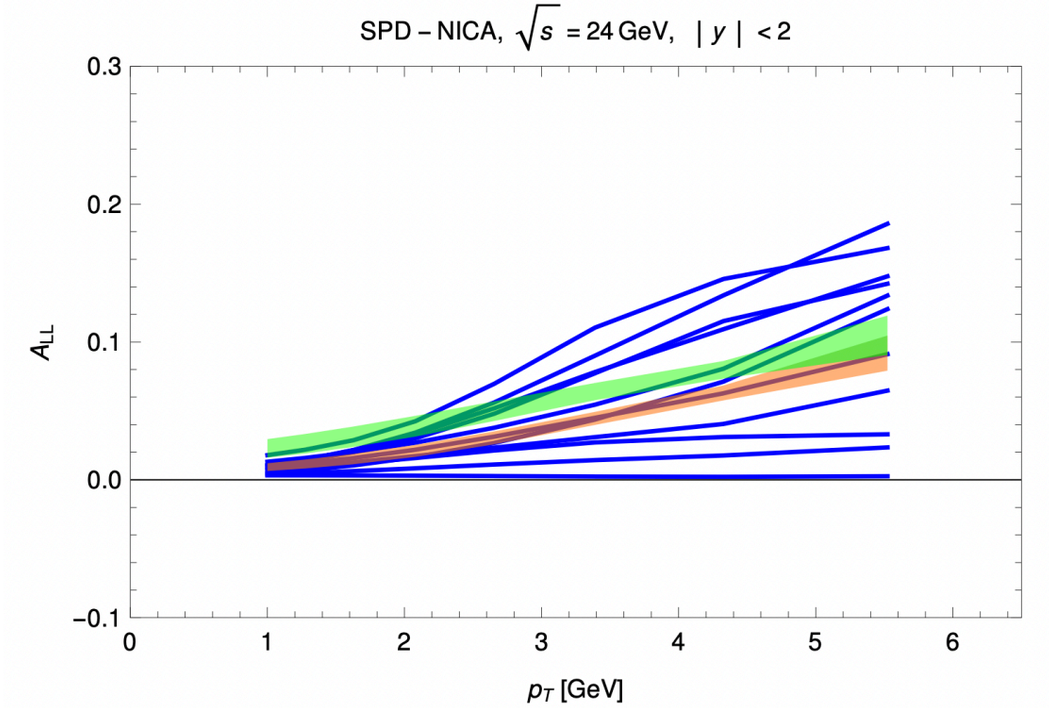


SPD could help to reduce uncertainty of ΔG at large x

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

$$A_{LL}^{c\bar{c}} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta g(x_2)}{g(x_2)} \otimes \hat{a}_{LL}^{gg \to c\bar{c}X} \qquad A_{LL}^{\gamma} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes A_{1p}(x_2) \otimes \hat{a}_{LL}^{gq(\bar{q}) \to \gamma q(\bar{q})} + (1 \leftrightarrow 2)\,.$$

GLUON HELICITY FUNCTION Δg(x) : EXPECTATIONS FOR A_{LL}



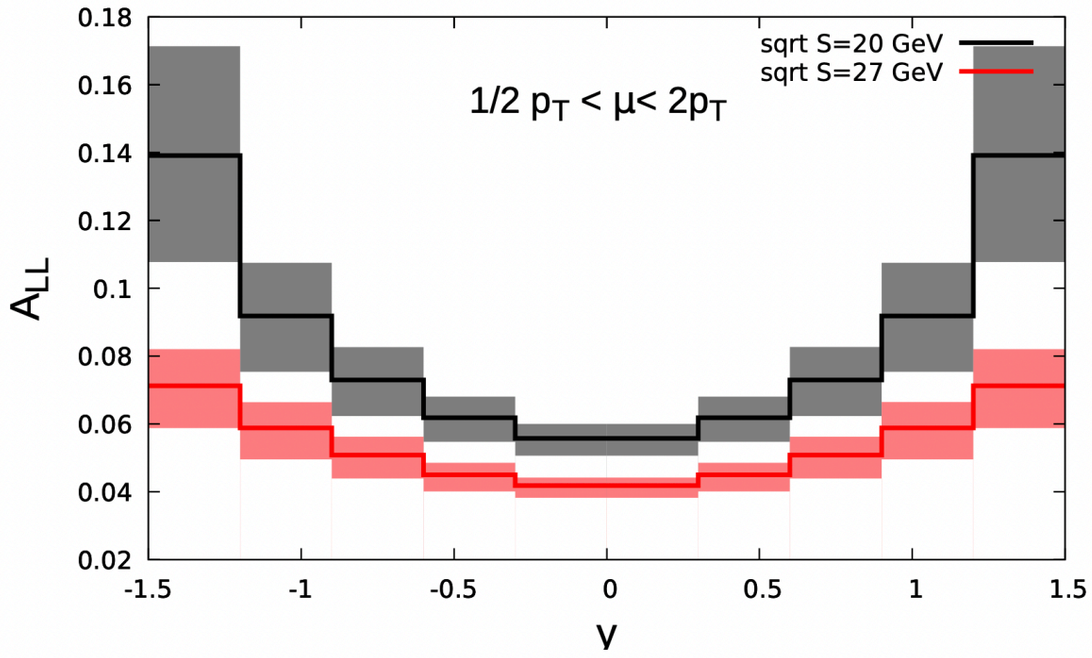
$gg \rightarrow J/\psi g$

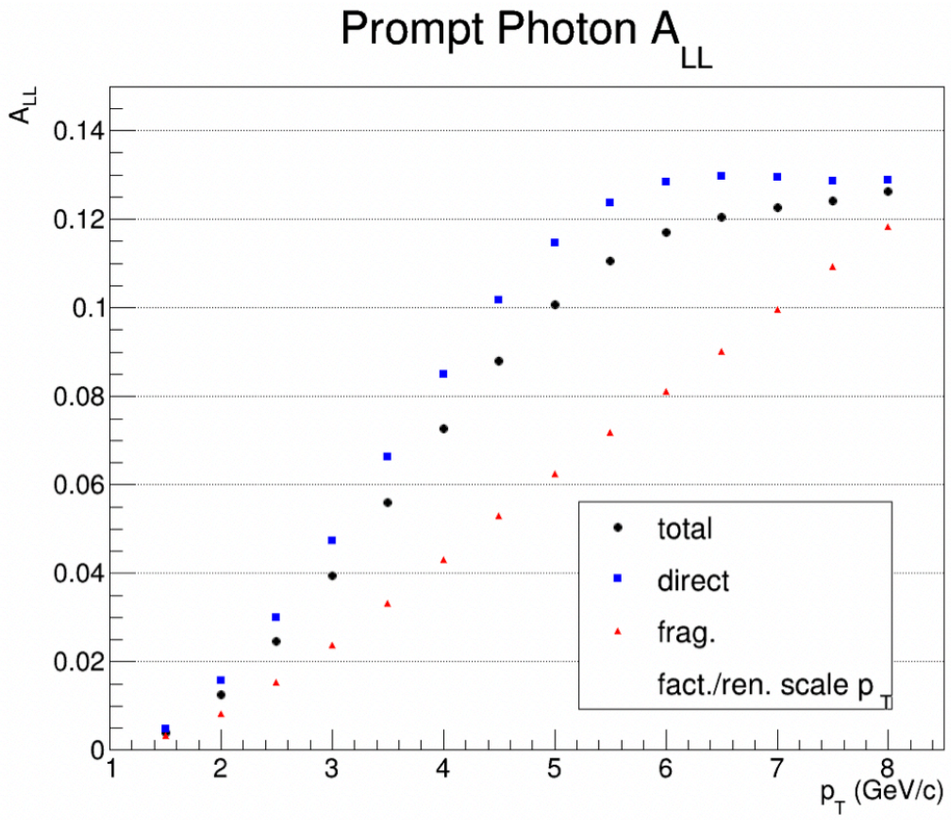
M. Nefedov

W. Vogelsang

A. Shipilova

$qg \rightarrow q\gamma$



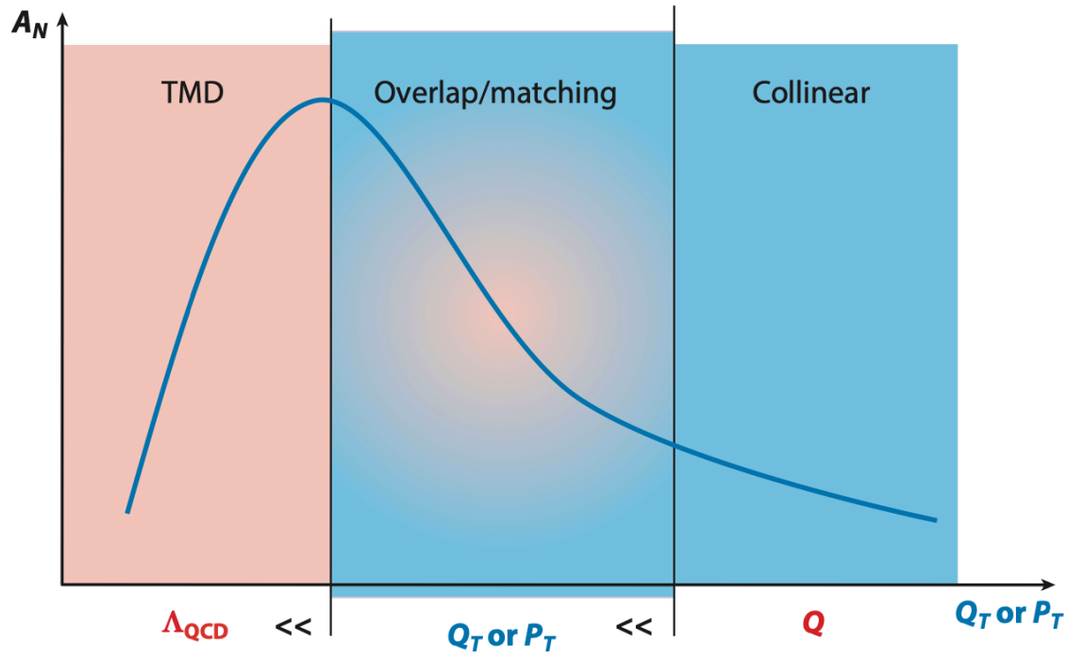


GLUON–INDUCED TMD EFFECTS : GLUON SIVERS FUNCTION $\Delta^g_N(x,k_T)$

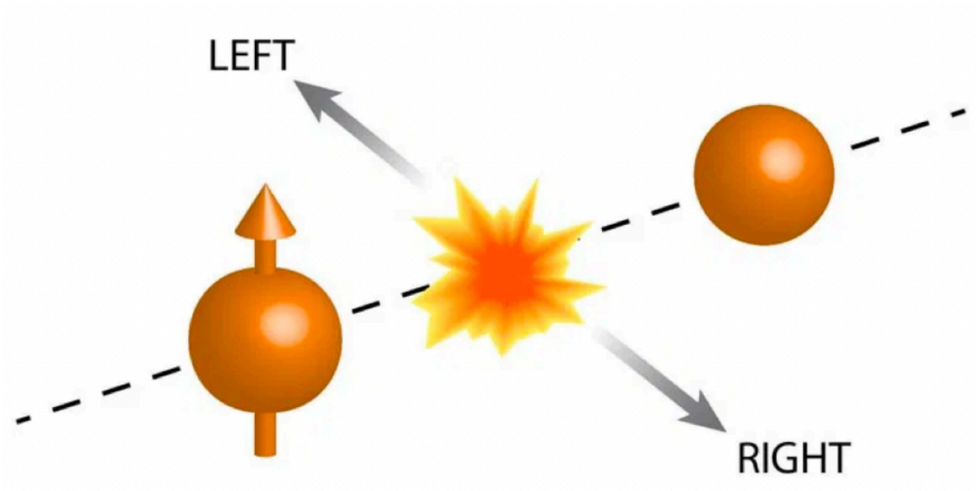
1) *Collinear factorization + three-parton correlations in twist-3*

2) *TMD factorization*

Different $<k_T>$ for quarks and gluons?



Sivers effect: *left-right asymmetry of unpolarized k_T distribution in transversely polarized nucleon*



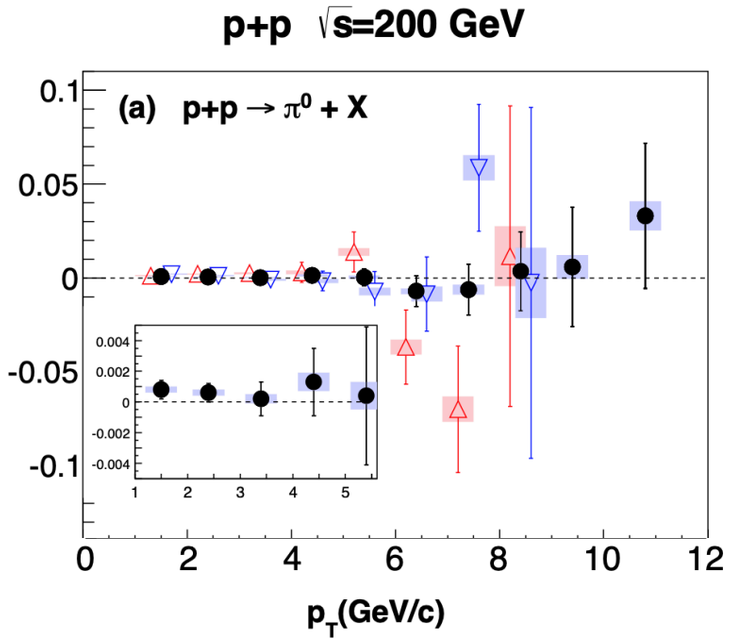
Sivers effect

A_N

Collins effect

- due to fragmentation of polarized quark

GLUON SIVERS FUNCTION $\Delta^{g}_{N}(x,k_T)$

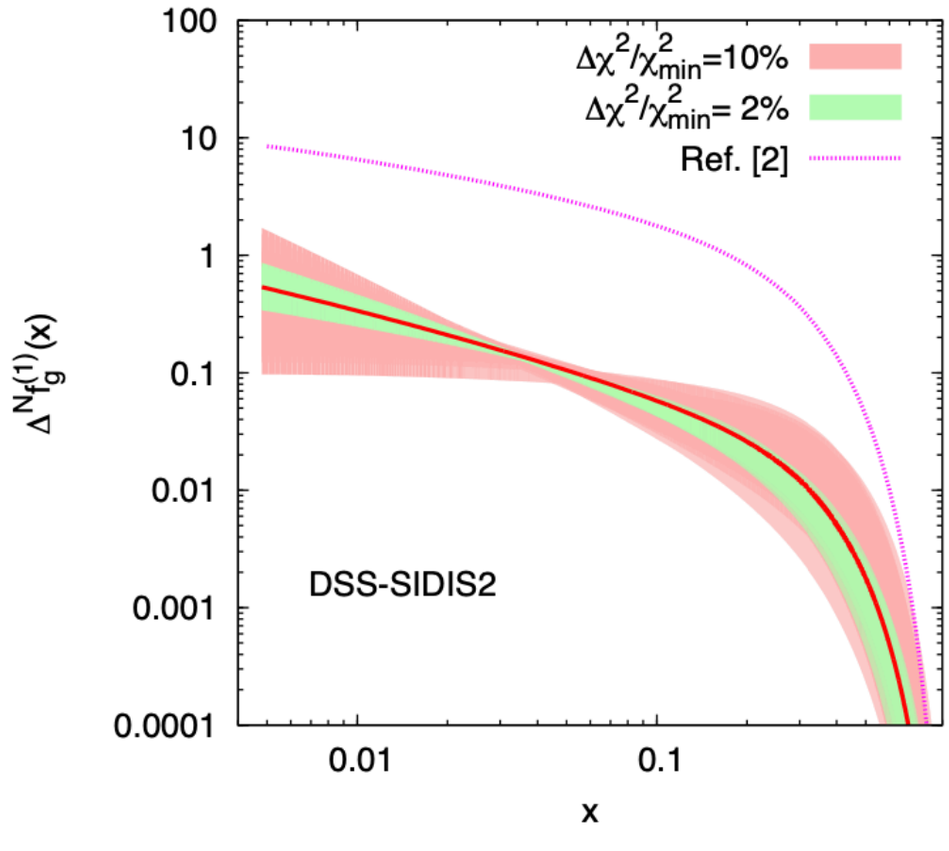


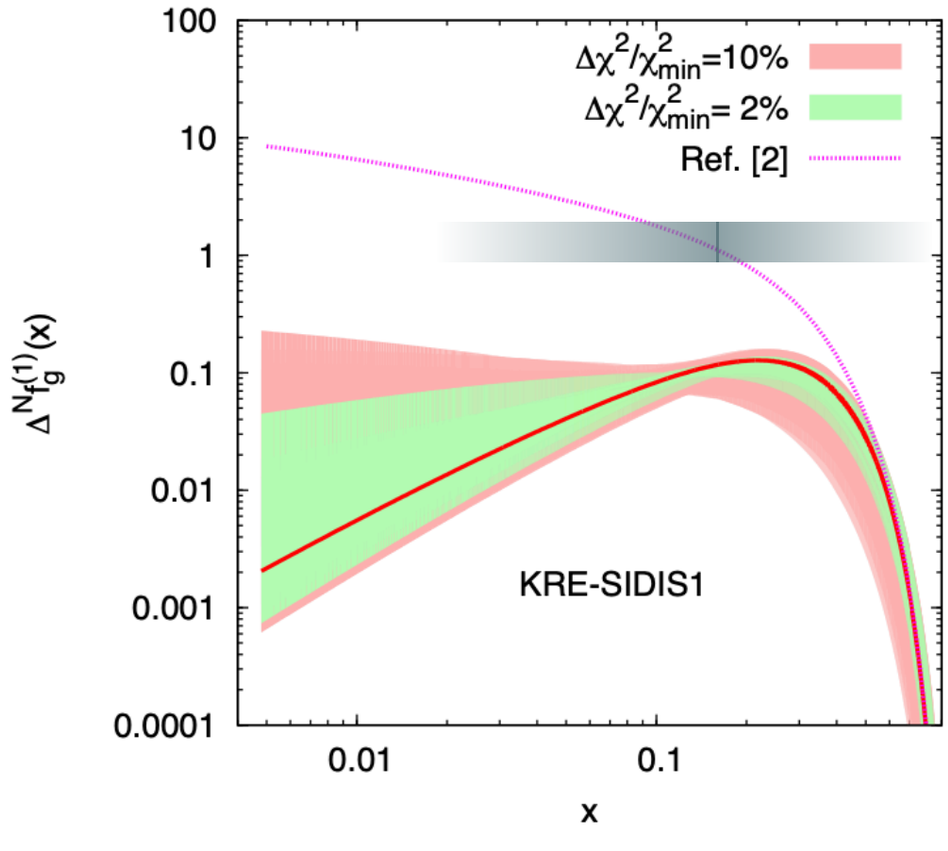
***Phys.Rev.D* 90 (2014) 1, 012006**

PHENIX

First $k_\perp$-moment of the gluon Sivers function

JHEP 09 (2015) 119

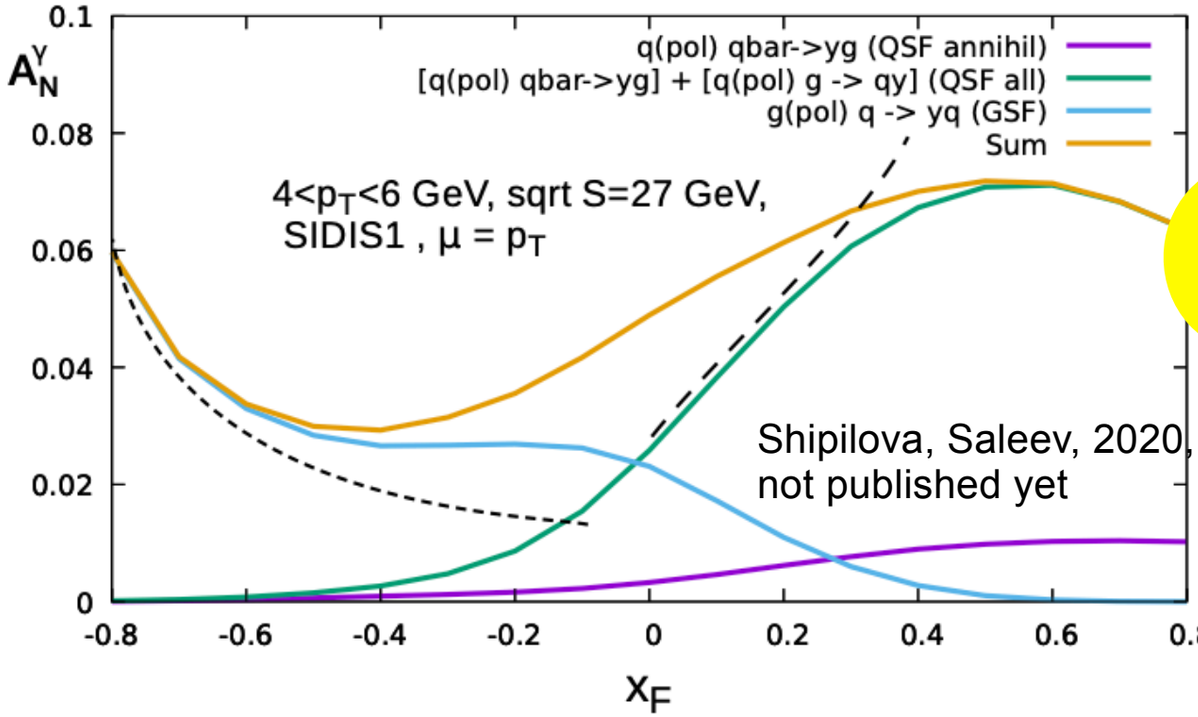




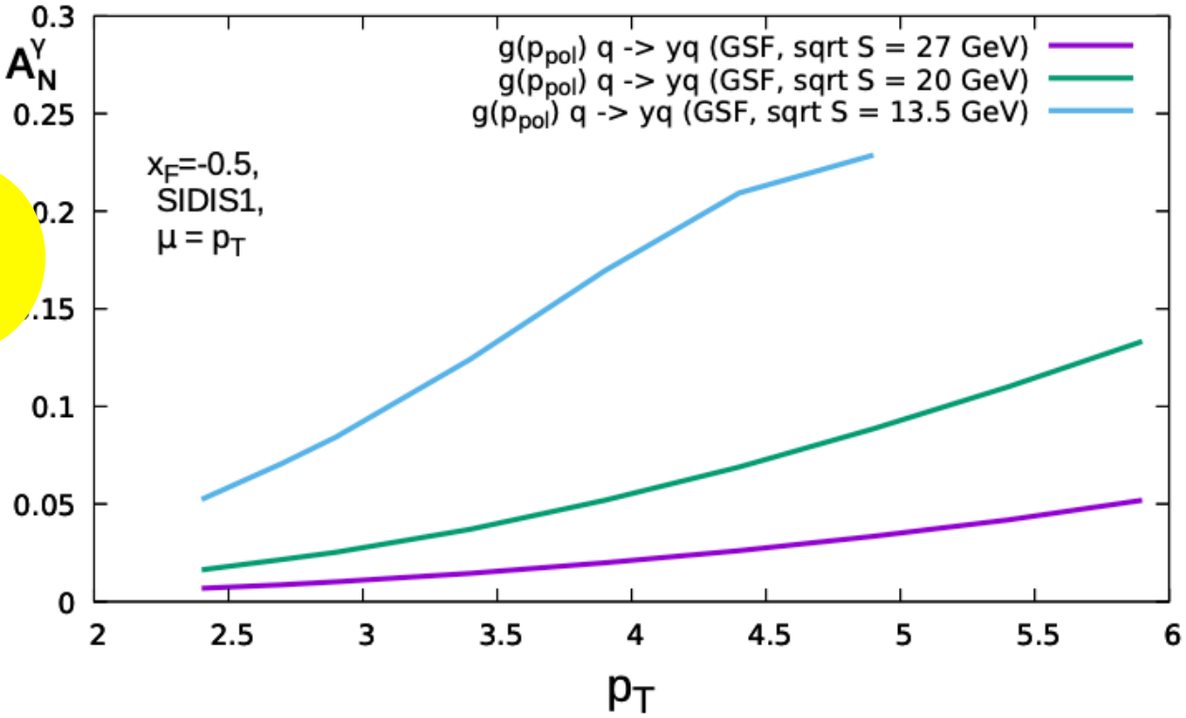
SPD

GLUON-INDUCED TMD EFFECTS: EXPECTATIONS FOR A_N

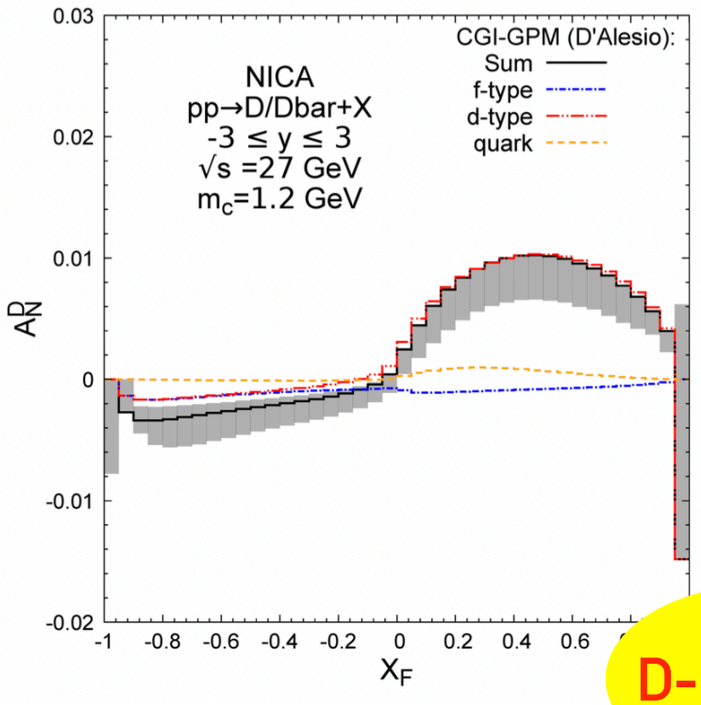
Sivers effect contribution

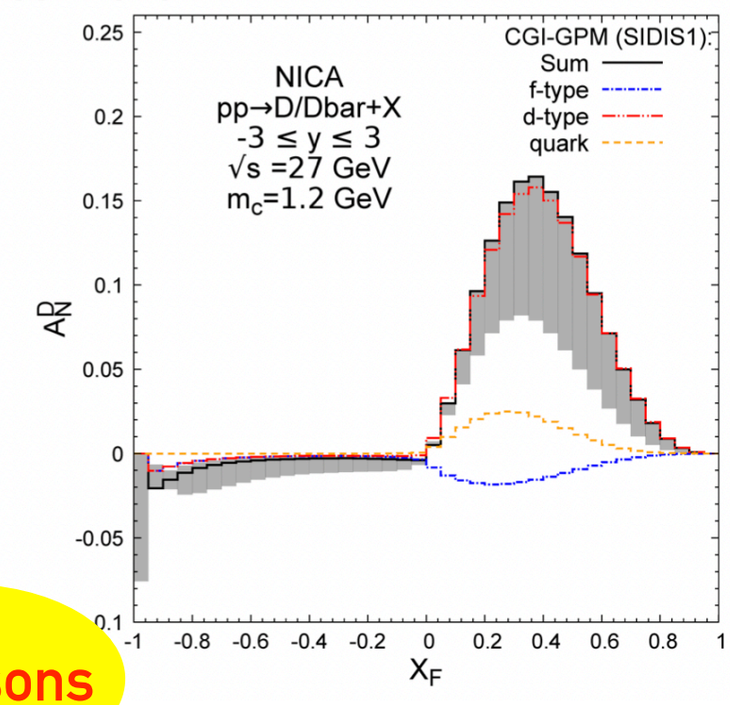


Y

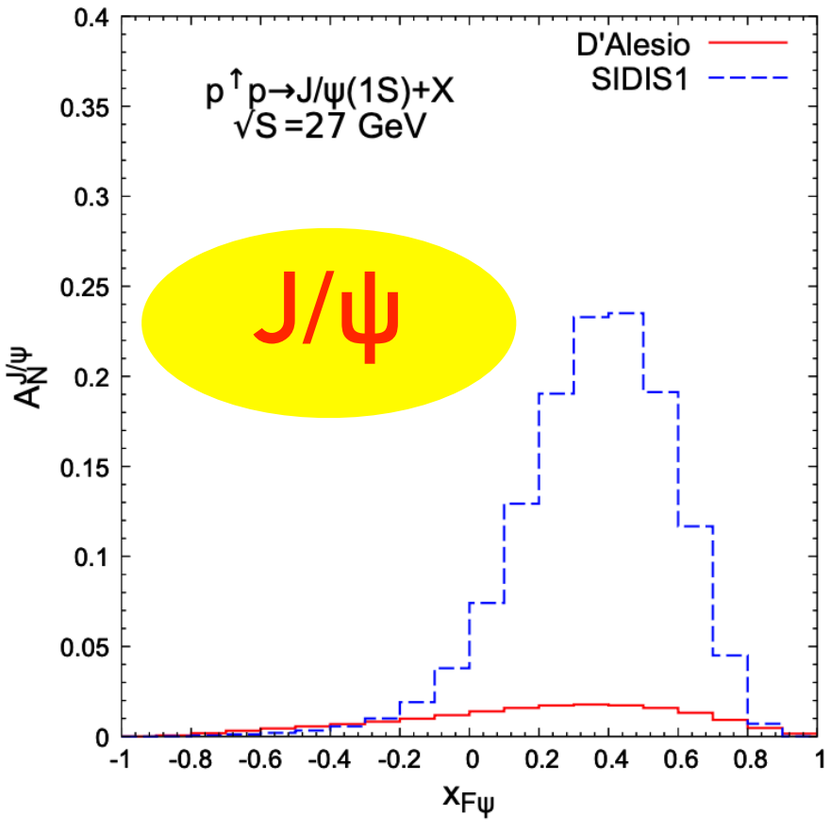


Saleev 2020



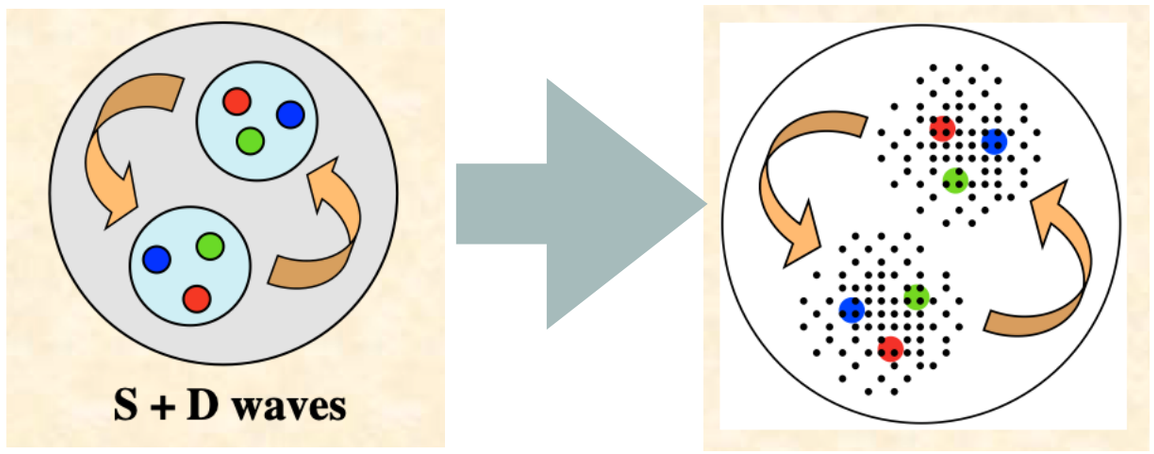


D-mesons



DEUTERON

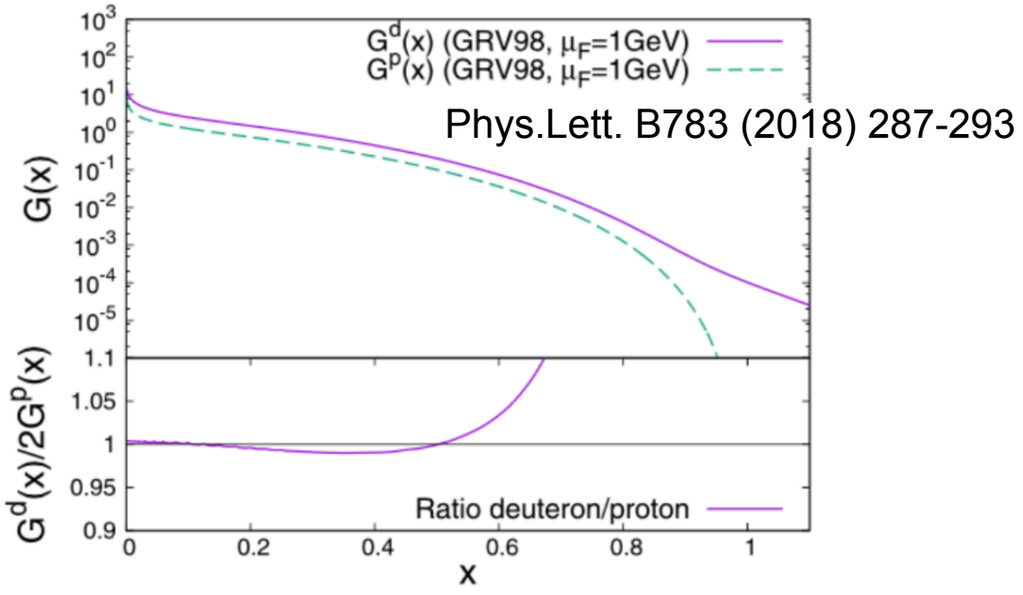
S. Kumano



$$|6q\rangle = c_1|NN\rangle + c_2|\Delta\Delta\rangle + c_3|CC\rangle$$

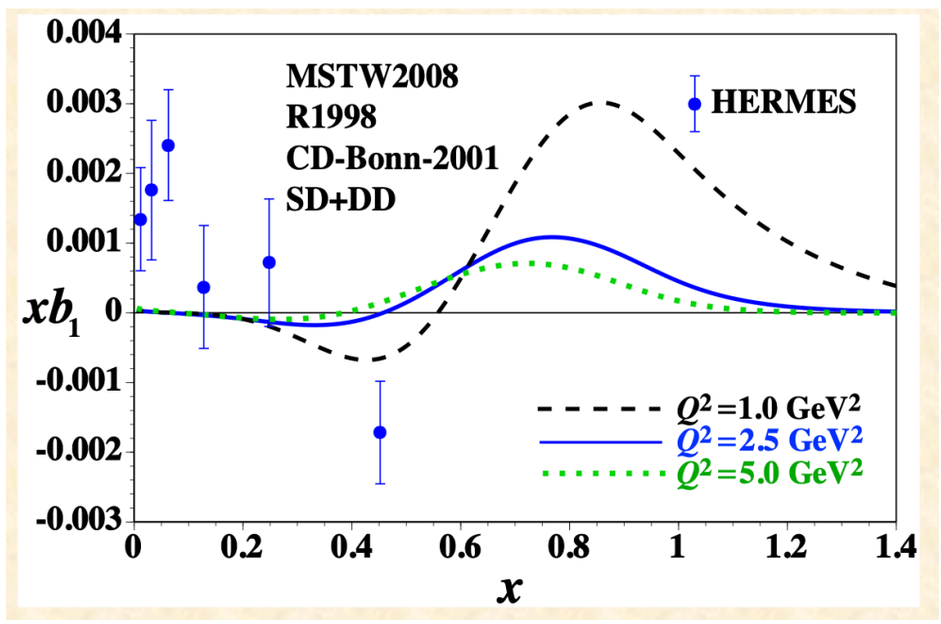
hidden color up to 90% at some models!

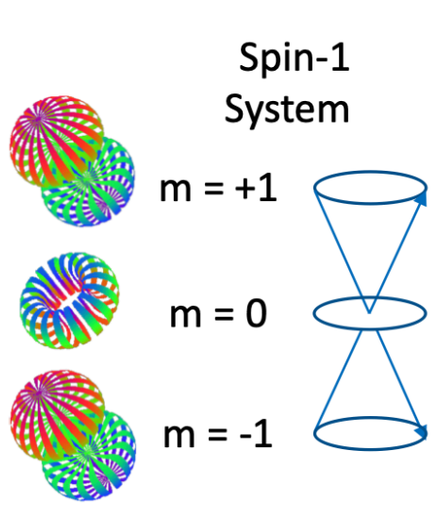
G. A. Miller, Phys.Rev. C89 (2014) no.4, 045203

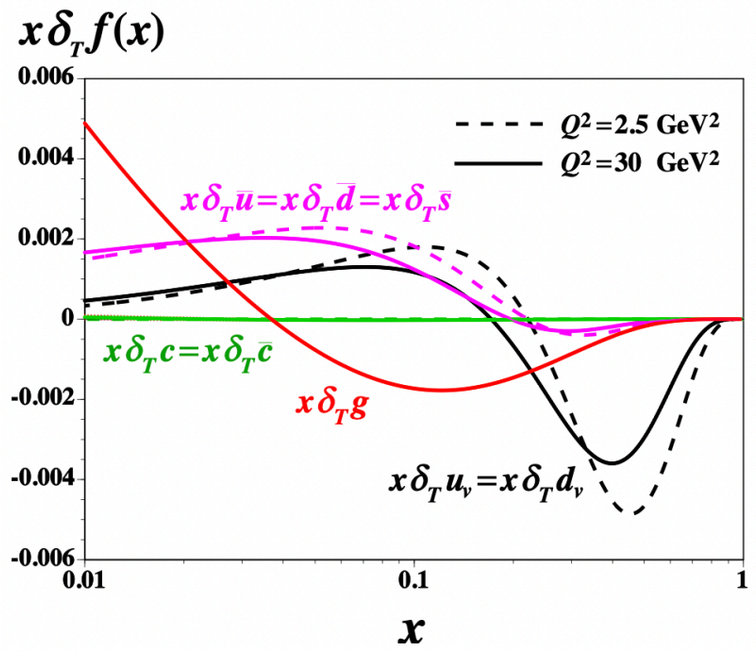


Phys.Lett. B783 (2018) 287-293

Fig. 6. Gluon PDF in the deuteron and in the nucleon.



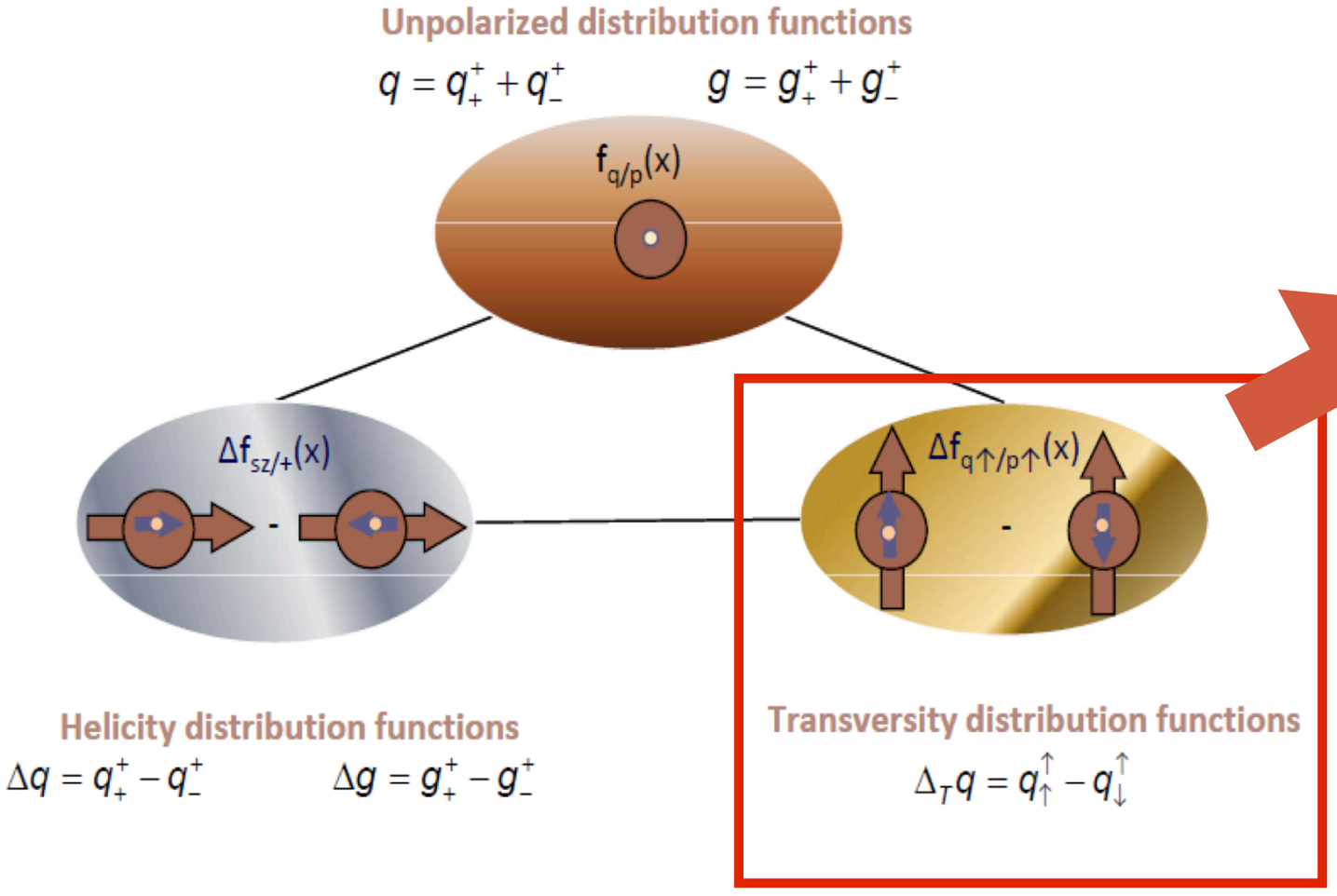




New structure functions: b_1, b_2, b_3, b_4

$$\int dx\, b_1(x)_{\mathrm{LO}} = -\frac{5}{24}\lim_{t\to 0} t\,F_Q(t) + \sum_i e_i^2 \int dx\,\delta_T\bar{q}_i(x),$$

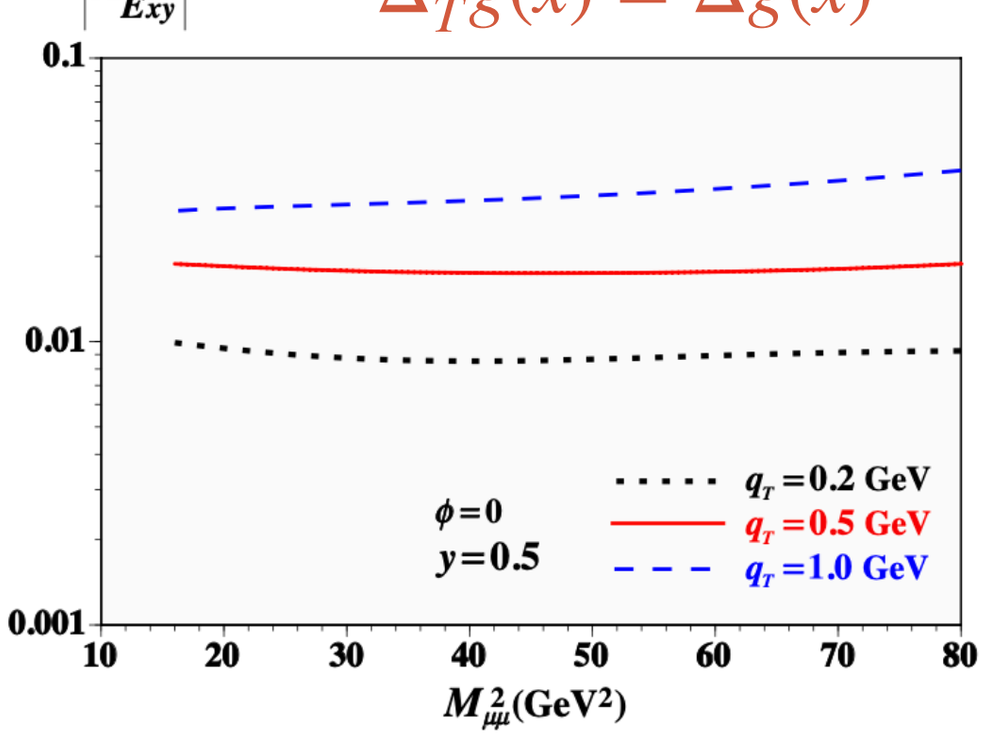
GLUON TRANSVERSITY $\Delta g_T(x)$ IN DEUTERON



Transversity function is related to spin-flip amplitude but $\Delta s=2$ is impossible in LO for spin-1/2 hadron.

But nonzero gluon transversity is possible already in LO in deuteron due to non-nucleonic gluon component! It could be accessed via double transverse spin asymmetry!

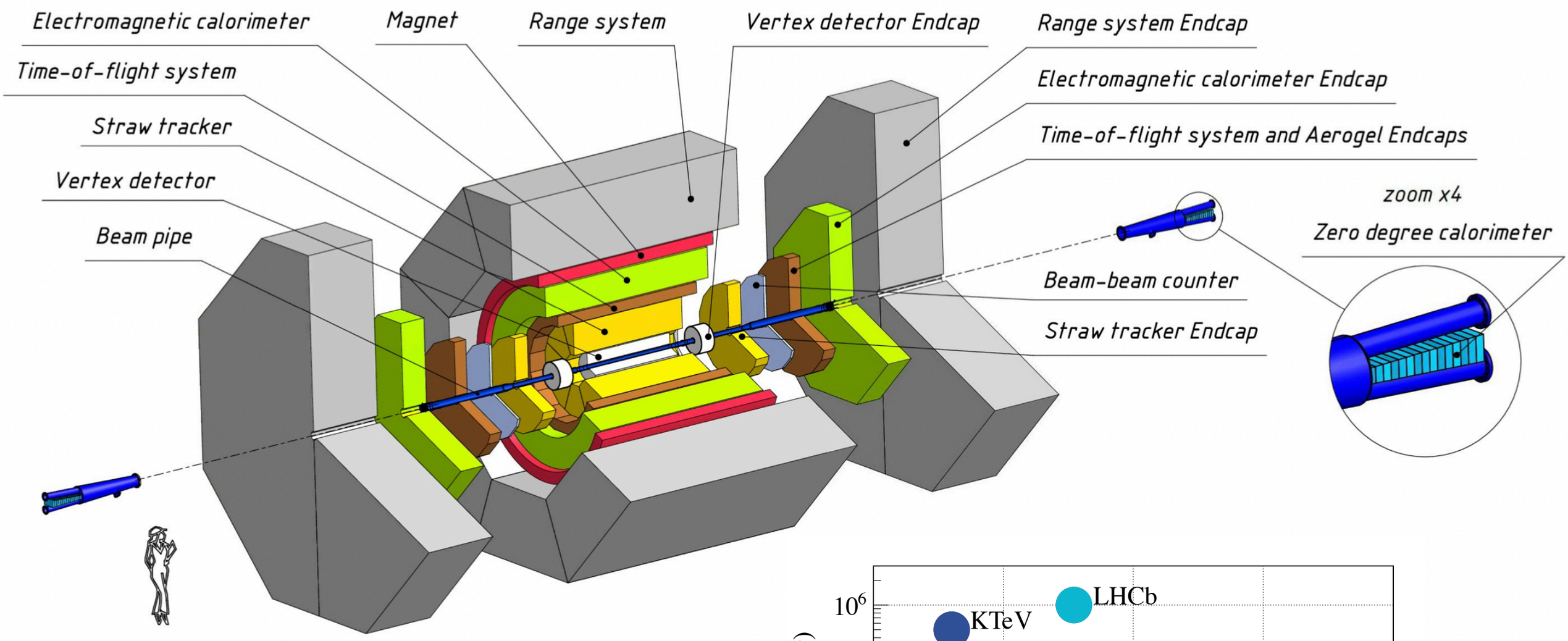
Sh. Kumano for DY:
$\Delta_T g(x) = \Delta g(x)$



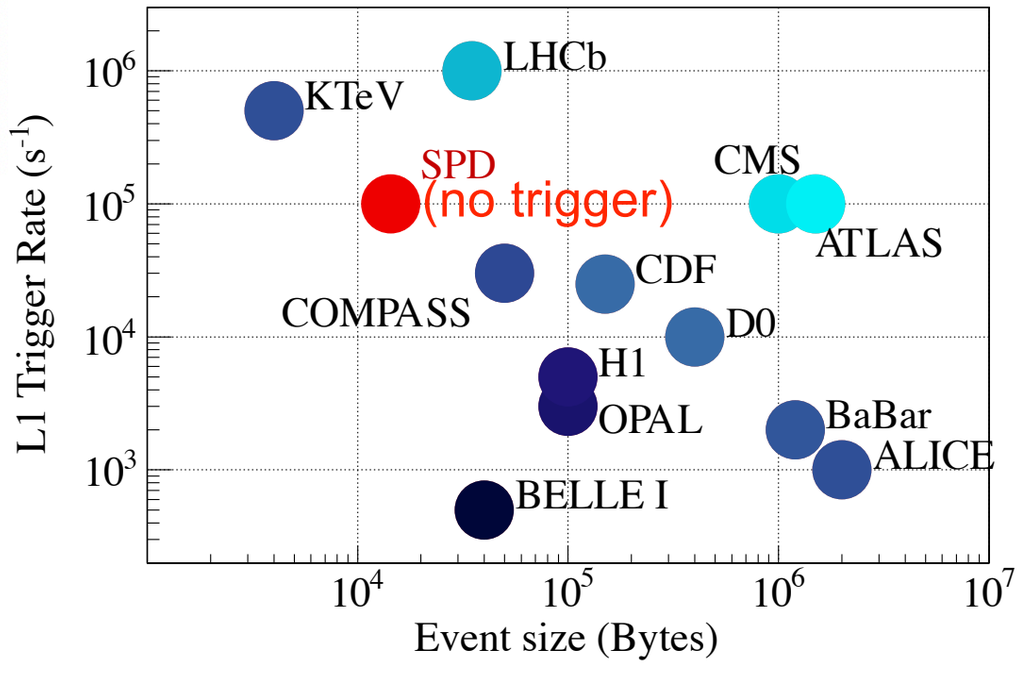
RATES FOR MAIN PROBES

Probe	$\sigma_{27\,\mathrm{GeV}}$, nb (×BF)	$\sigma_{13.5\,\mathrm{GeV}}$, nb (×BF)	$N_{27\,\mathrm{GeV}}$, 10^6	$N_{13.5\,\mathrm{GeV}}$ 10^6
Prompt-γ ($p_T > 3$ GeV/c)	35	2	35	0.2
J/ψ	200	60		
$\to \mu^+\mu^-$	12	3.6	12	0.36
$\psi(2S)$	25	5		
$\to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$	0.5	0.1	0.5	0.01
$\to \mu^+\mu^-$	0.2	0.04	0.2	0.004
$\chi_{c1} + \chi_{c2}$	200			
$\to \gamma J/\psi \to \gamma\mu^+\mu^-$	2.4		2.4	
η_c	400			
$\to p\bar{p}$	0.6		0.6	
Open charm: $D\overline{D}$ pairs	14000	1300		
Single D-mesons				
$D^+ \to K^-2\pi^+$ ($D^- \to K^+2\pi^-$)	520	48	520	4.8
$D^0 \to K^-\pi^+$ ($\overline{D}^0 \to K^+\pi^-$)	360	33	360	3.3

SPD DETECTOR



No hardware triggers to avoid possible bias!



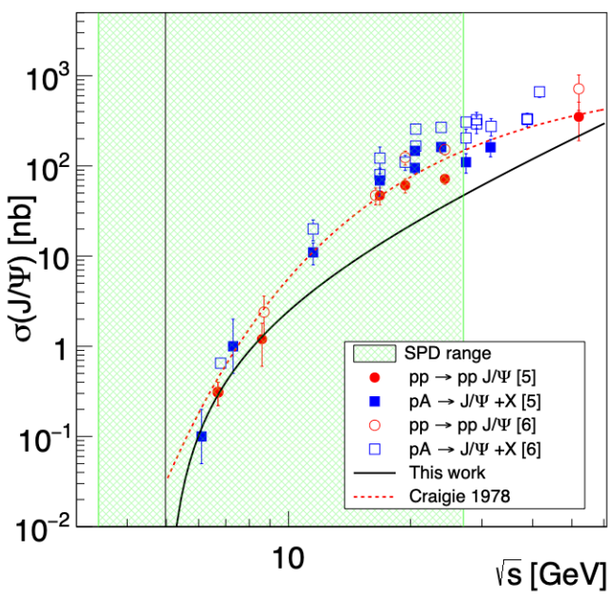
Phys.Part.Nucl. 52 (2021) 6, 1044-1119 arXiv:2102.08477

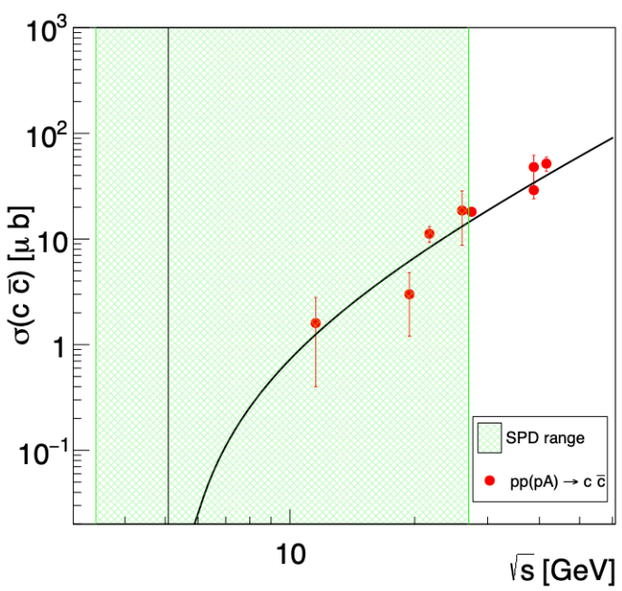
PHYSICS OF THE FIRST STAGE OF SPD RUNNING

Non-perturbative QCD — *Perturbative QCD*

$\sqrt{s}$

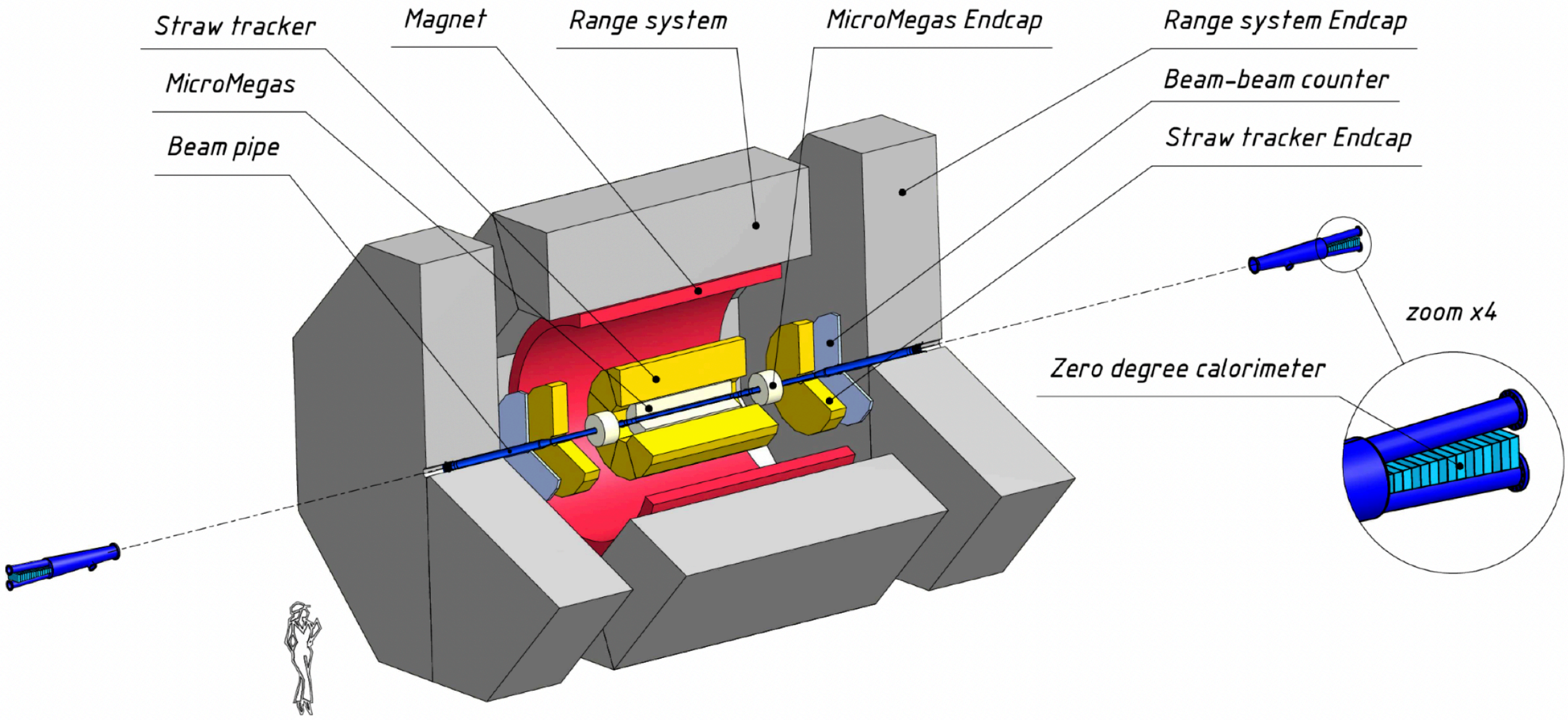
- Spin effects in p-p, p-d and d-d elastic scattering
- Spin effects in hyperons production
- Multiquark correlations $pp \to (6q)^* \to N\,N\,Mesons,$
- Dibaryon resonances
- Physics of light and intermediate nuclei collision
- Exclusive reactions
- Hypernucei $dd \to K^+\,K^+\,{}^{4}_{\Lambda\Lambda}\mathrm{n},$
- Open charm and charmonia near threshold





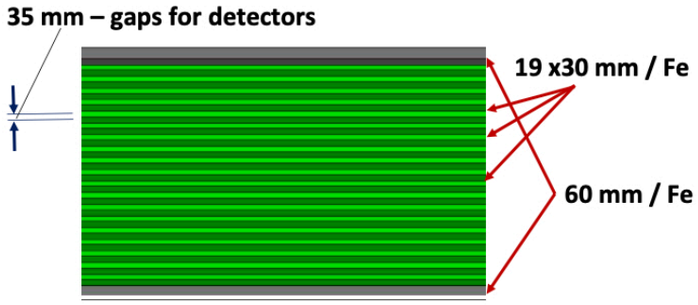
- Auxiliary measurements for astrophysics
- …

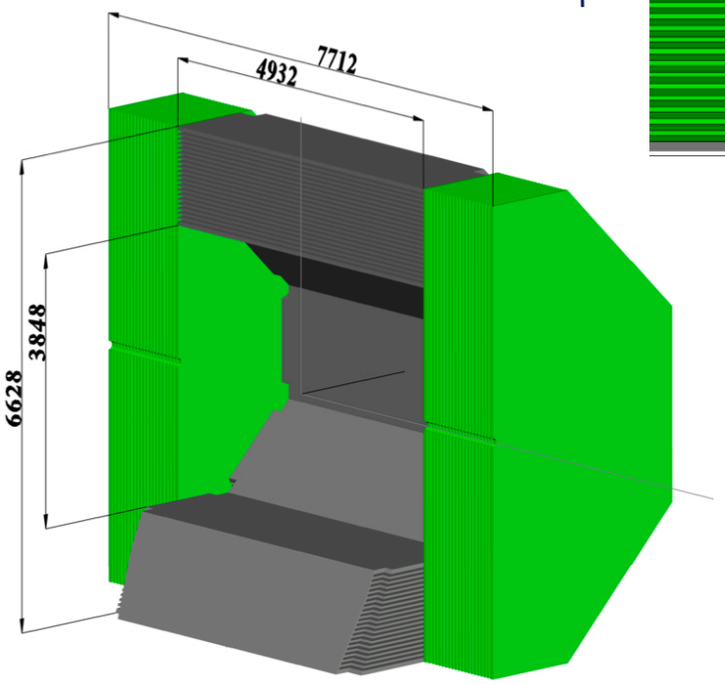
SPD: PHASE-I



Running with reduced beam energy and luminosity

RANGE (MUON) SYSTEM



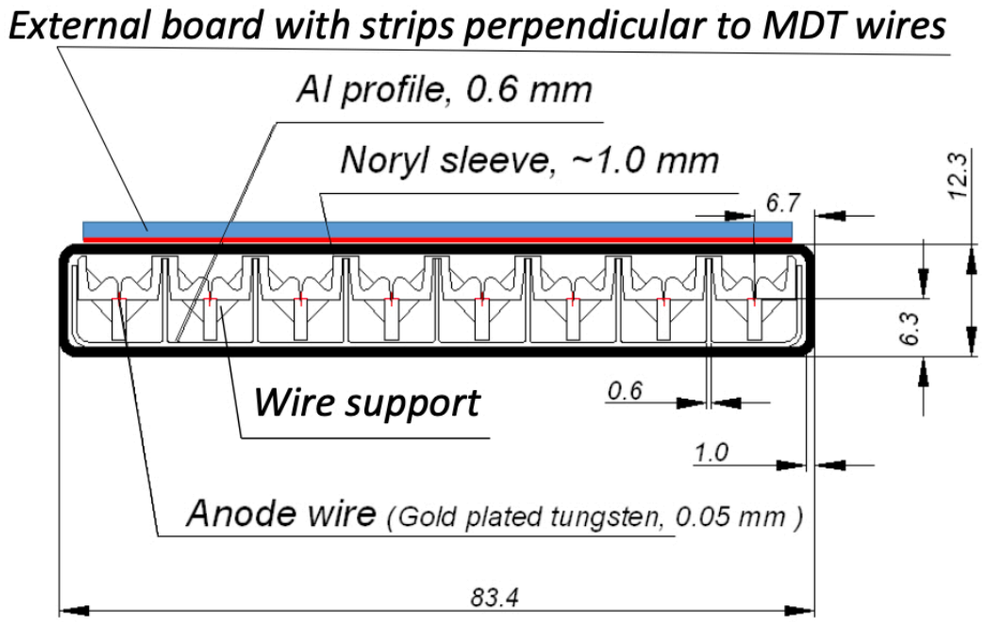


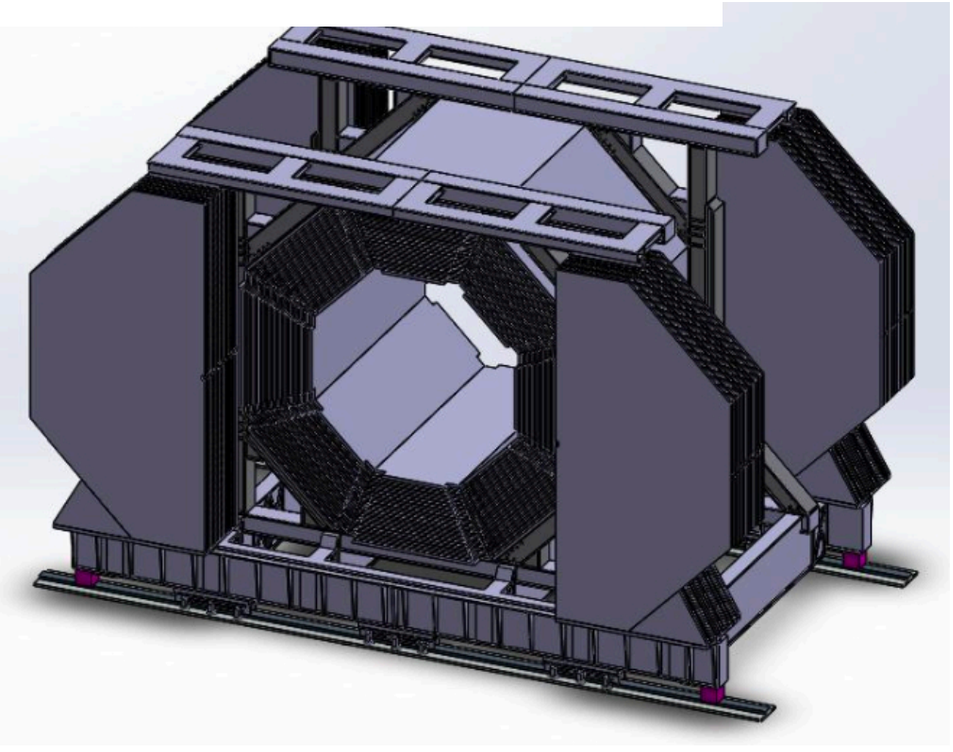
Goals:

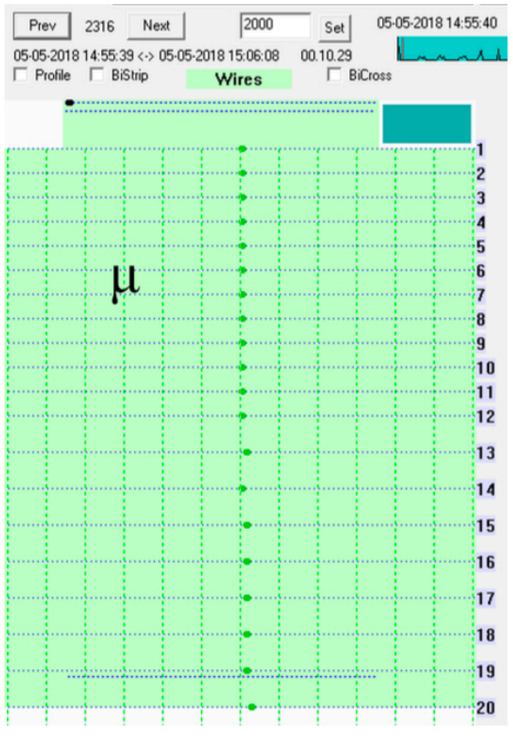
- *Muon identification*
- *Rough hadron calorimetry*
- *Yoke of the magnetic system*

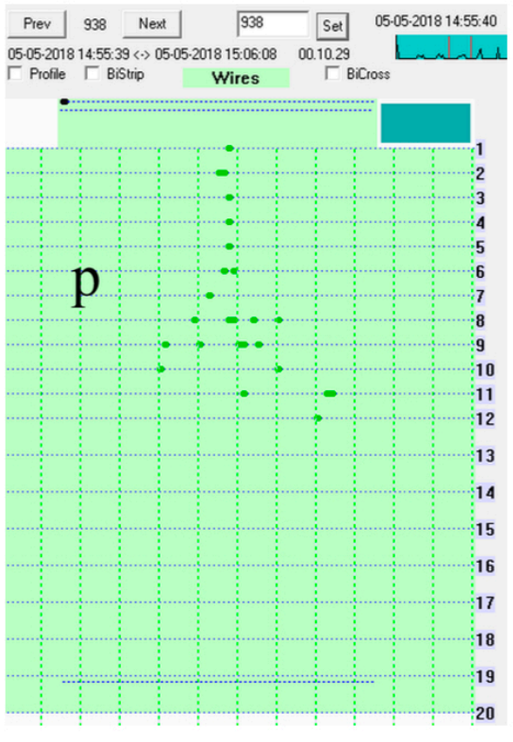
Requirements:

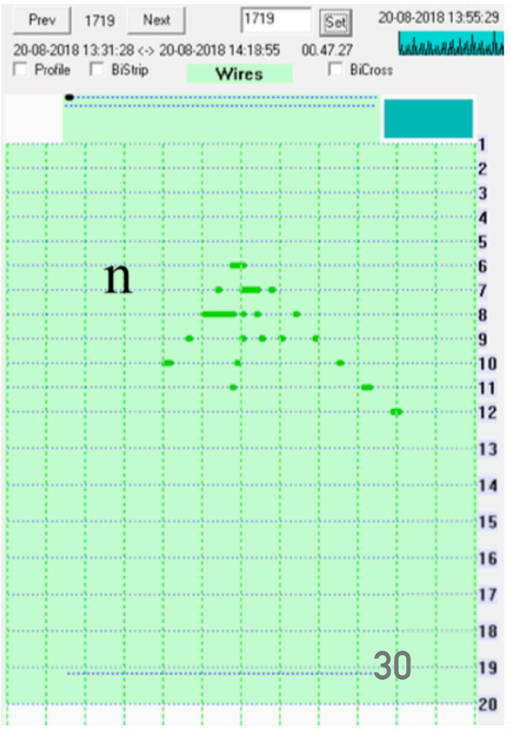
- *should have at least $4\lambda_I$*



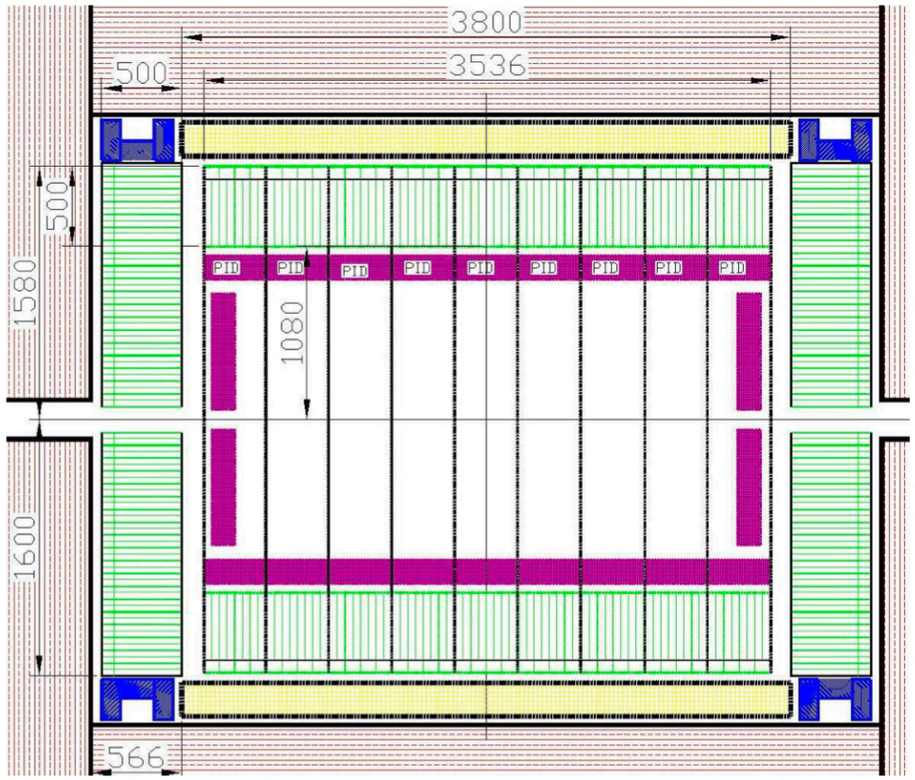








ELECTROMAGNETIC CALORIMETER



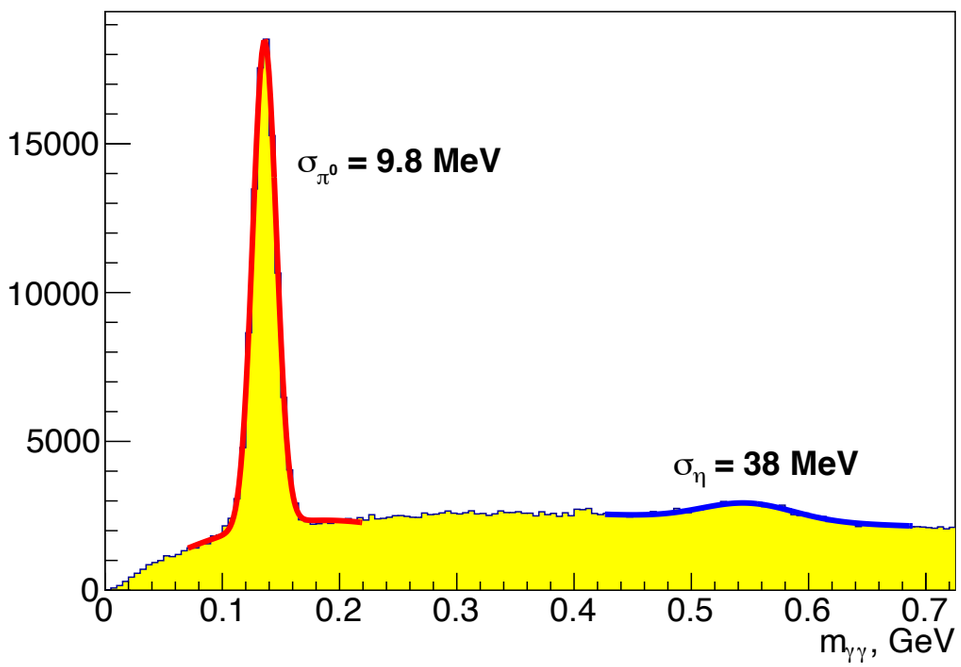
190 layers Sc/Pb =1.5/0.5 mm

Goals:

- *Detection of prompt photons, photons from π^0, η and χ_c decays*
- *Identification of electrons and positrons, participation in muon identification*

Requirements:

- *Granularity ~4 cm*
- *Low energy threshold (~50 MeV)*
- *Energy resolution* $\sim 5\,\%/\sqrt{E}$



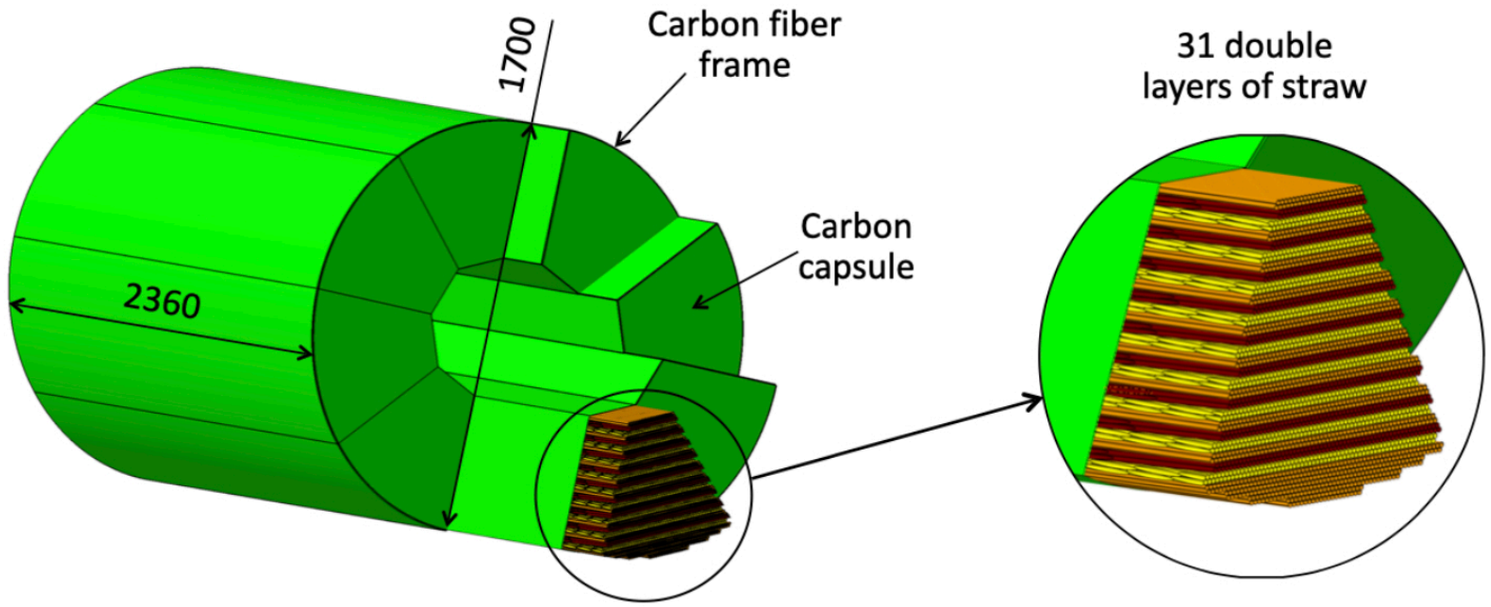
STRAW TRACKER

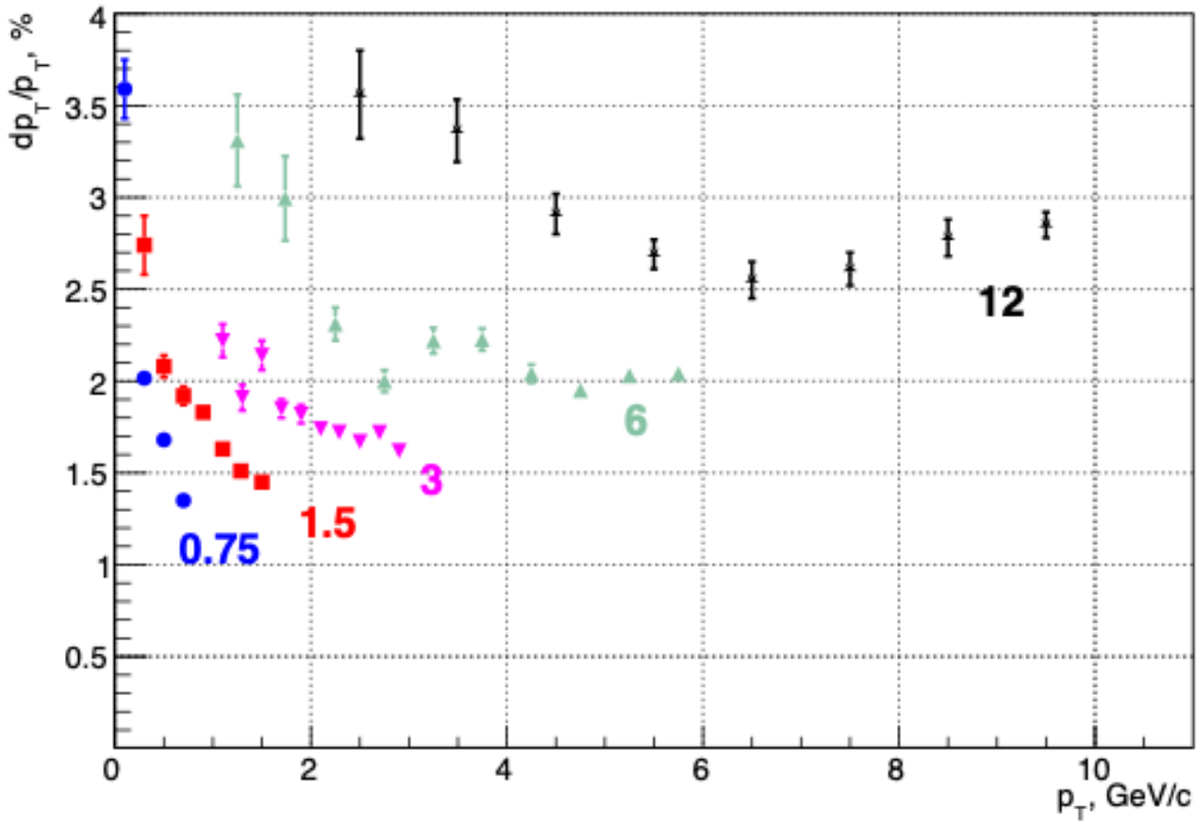
Goals:

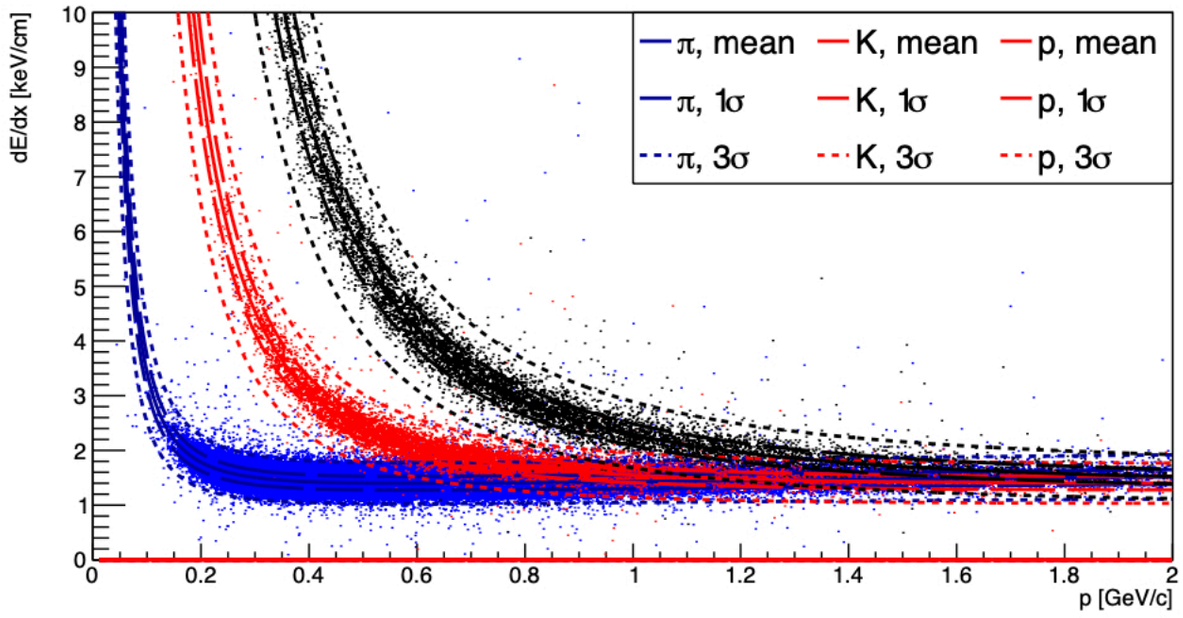
- *Track reconstruction and momentum measurement*
- *Participation in PID via dE/dx measurement*

Requirements:

- *Spatial resolution ~150 μm*
- *Low material budget*
- *Operation in magnetic field of about 1 T*







CENTRAL DETECTOR

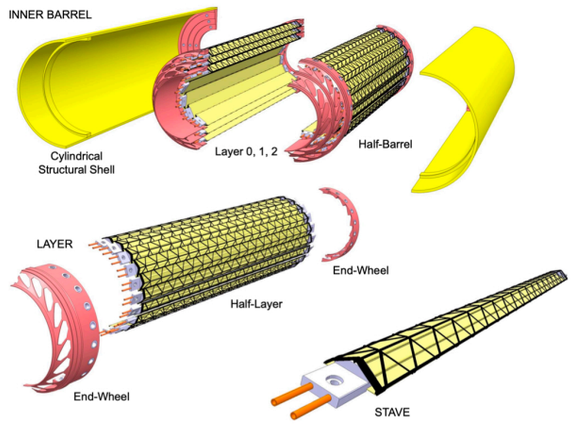
Goals:

- *Reconstruction of secondary vertices for D-mesons decay*
- *Participation in track reconstruction and momentum measurement*

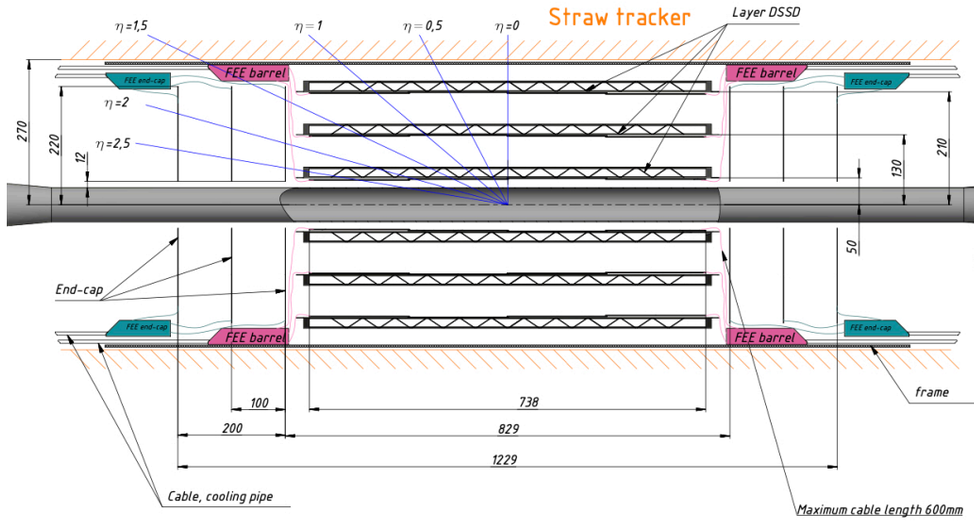
Requirements:

- *Spatial resolution <100 μm*
- *Low material budget*
- *Has to be installed as close as possible to the IP*

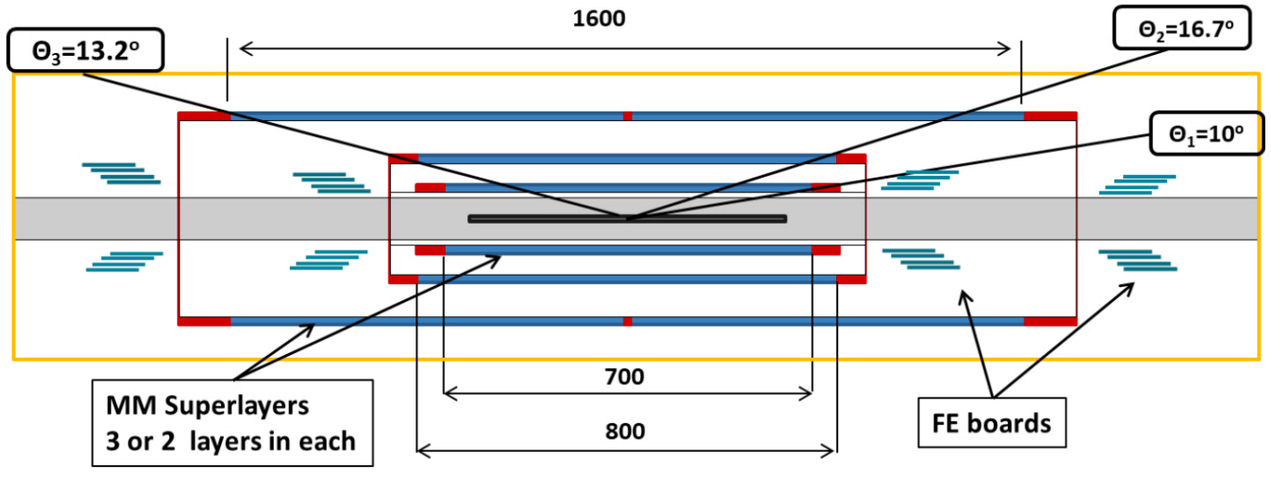
MAPS option

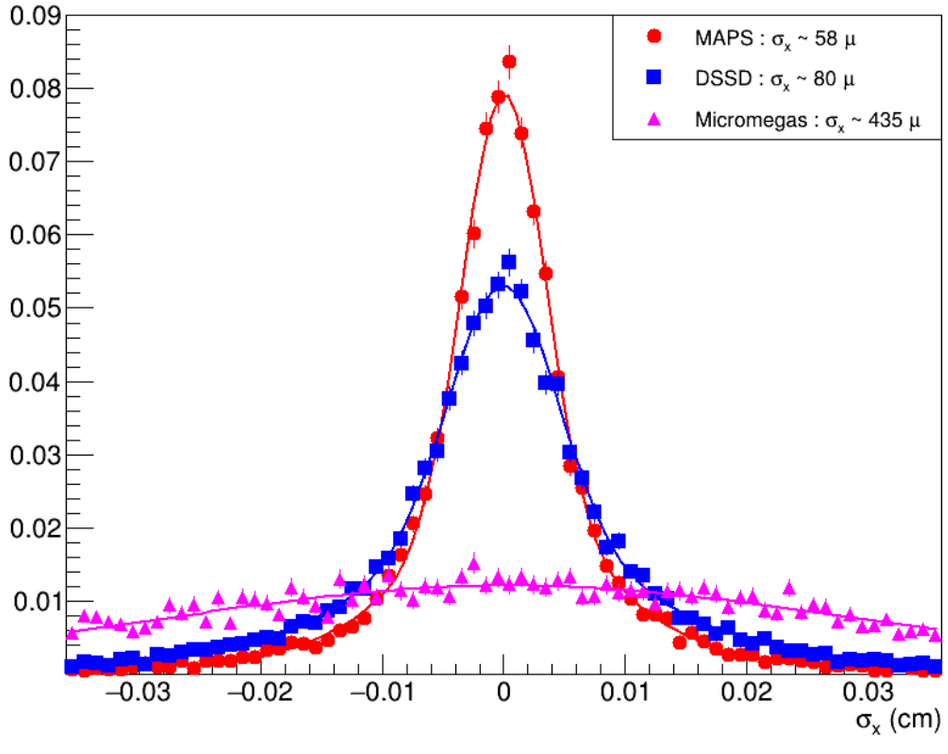


DSSD option

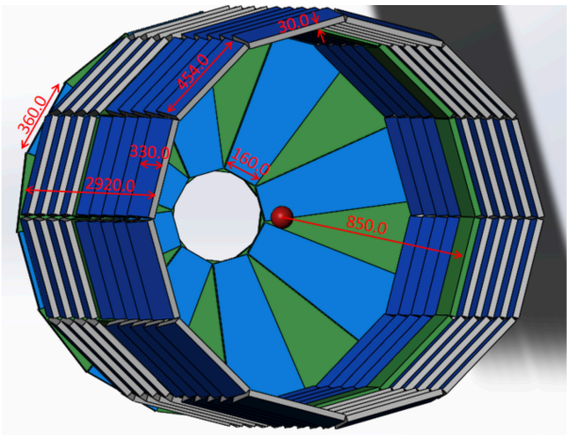


Micromegas-based central tracker for stage-1





PID



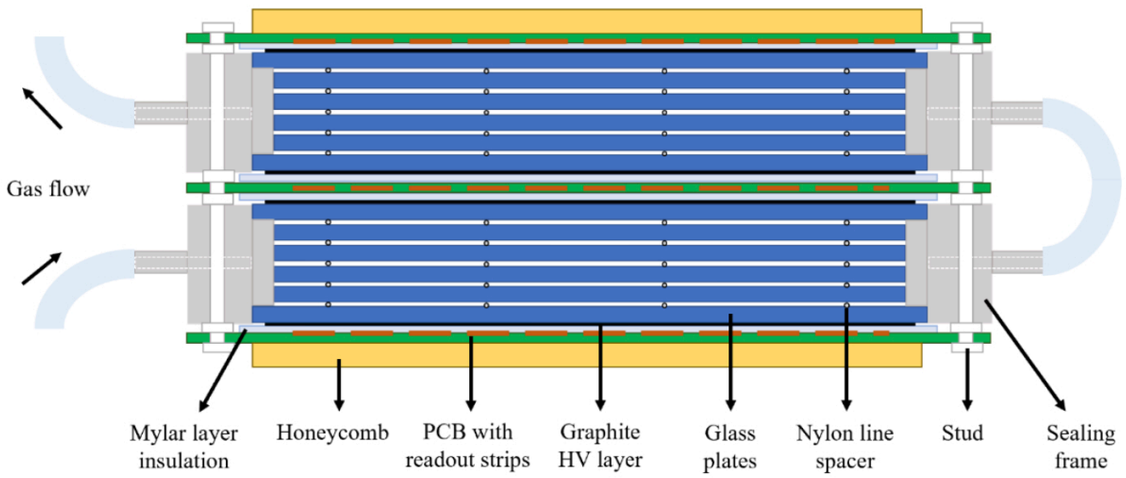
MRPC-based TOF

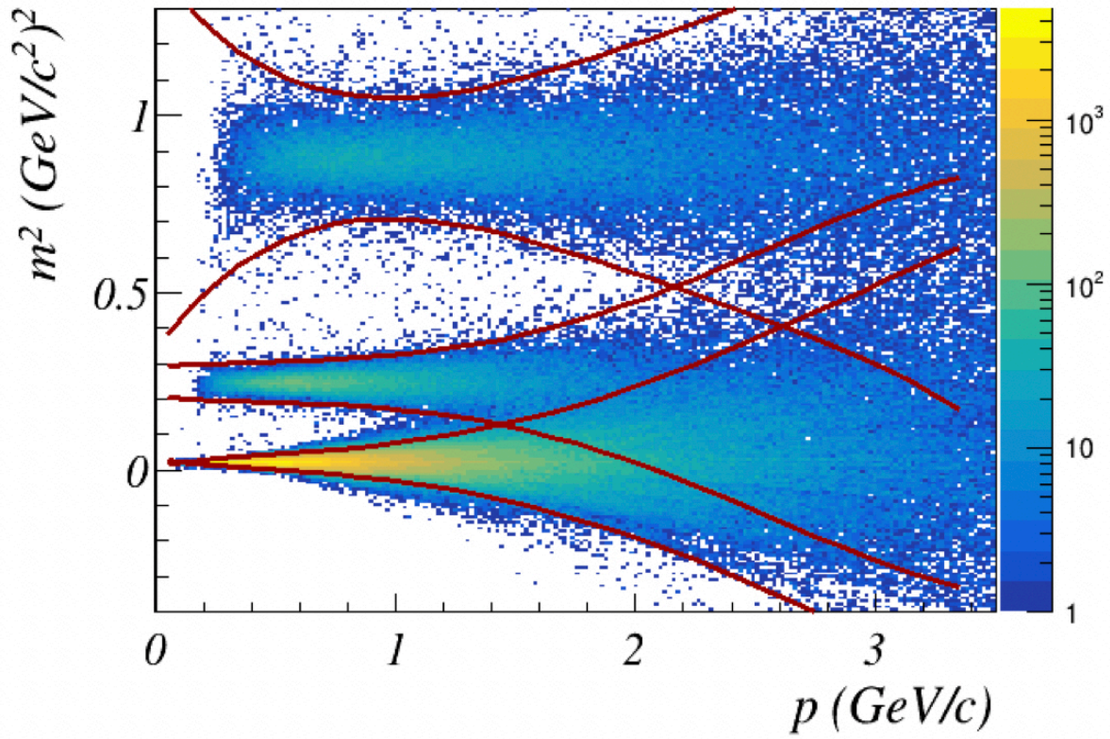
Goals:

- *π/K separation up to ~1.5 GeV*
- *K/p separation*
- *t_0 determination*

Requirements:

- *Time resolution <60 ps*





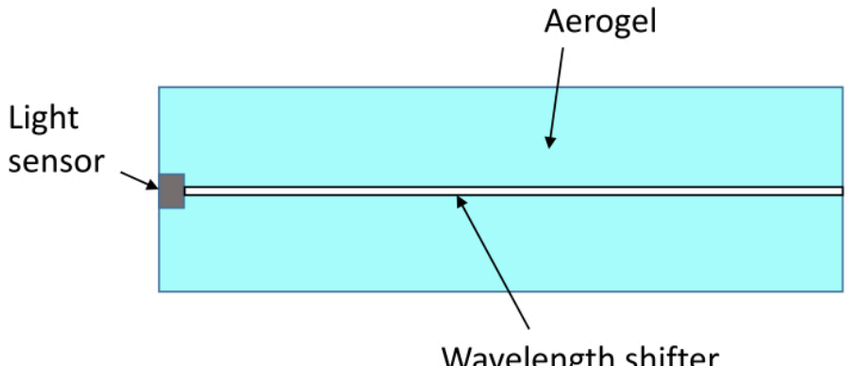
Aerogel counter in End-Caps

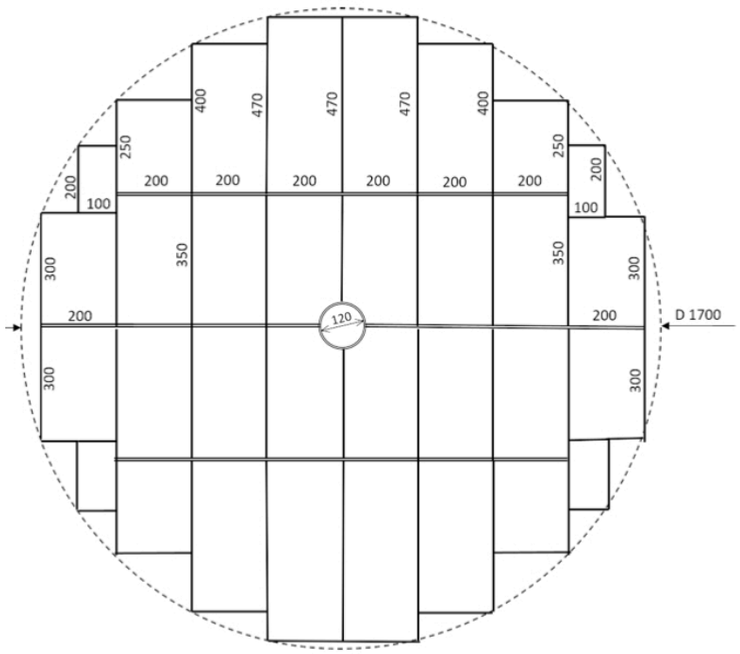
Goals:

- *π/K separation up to 2.5 GeV range*

Requirements:

- *We should have enough light!*





LOCAL POLARIMETRY AND LUMINOSITY CONTROL

Local polarimetry

- *Charged particles in BBC*
- *π^0 in the end-cap part of ECAL*
- *Neutrons in ZDC*

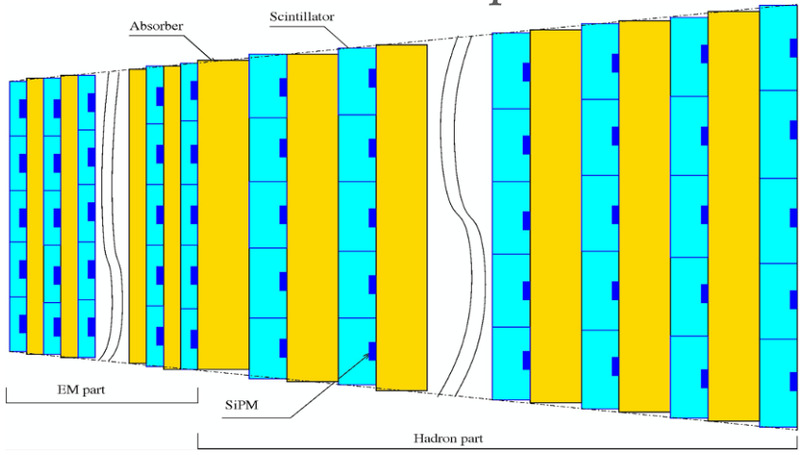
Zero-Degree Calorimeter

Goals:

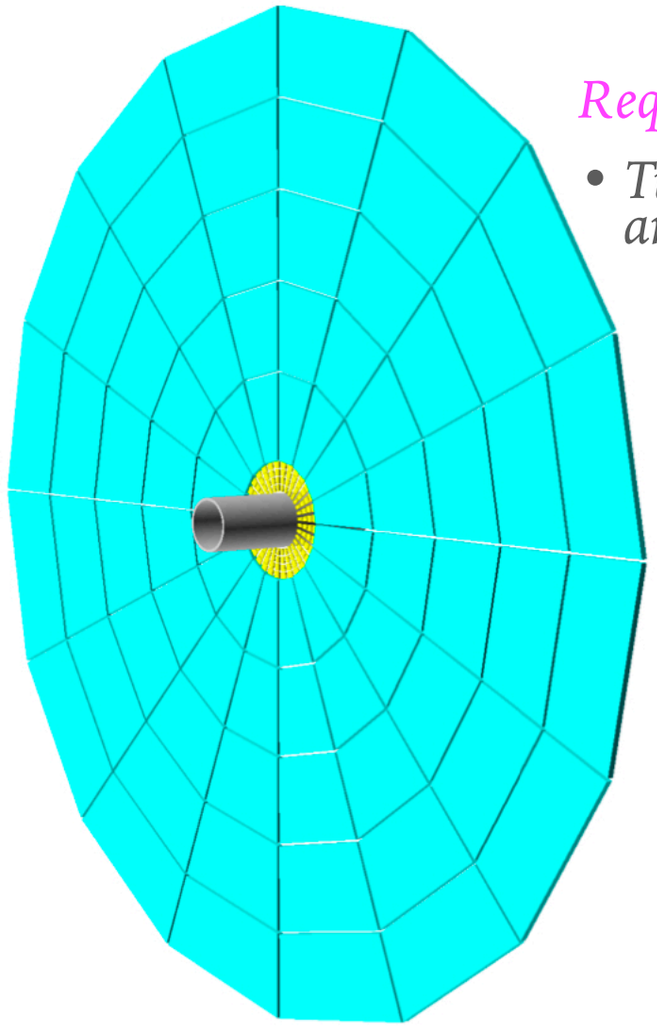
- *Luminosity monitor*
- *n/γ detection*

Requirements:

- *$13X_0$ for EM-part and $2.9\lambda_I$ for hadron part*
- *Energy resolution $50\,\%/\sqrt{E} \oplus 30\,\%$ for hadrons and $20\,\%/\sqrt{E} \oplus 9\,\%$ for γ*
- *Time resolution ~150 ps*



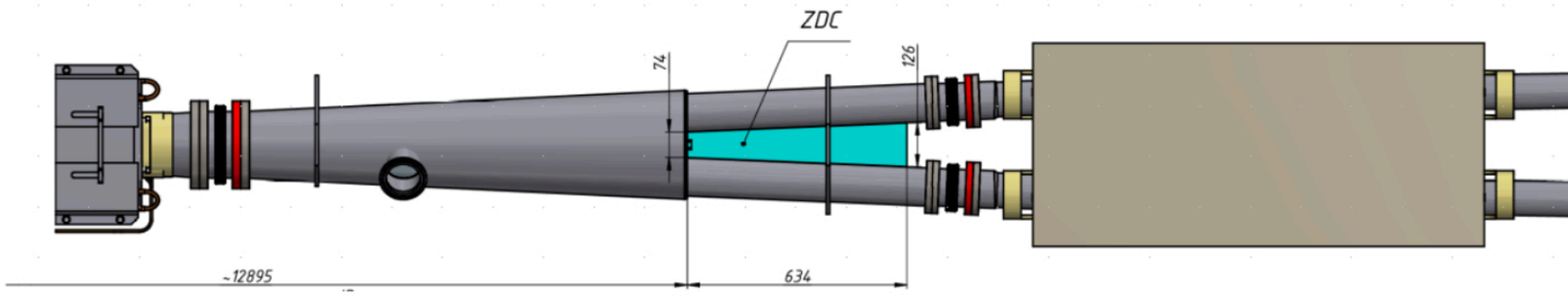
Beam-Beam Counter



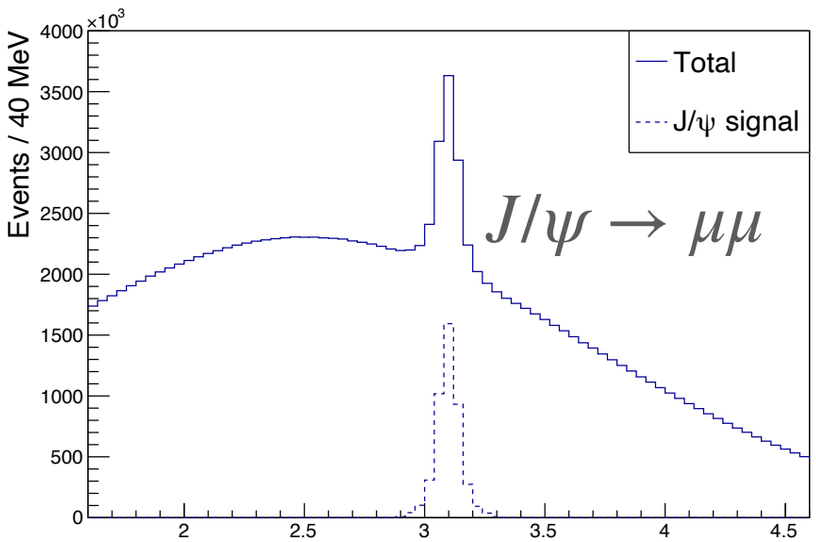
Requirements:

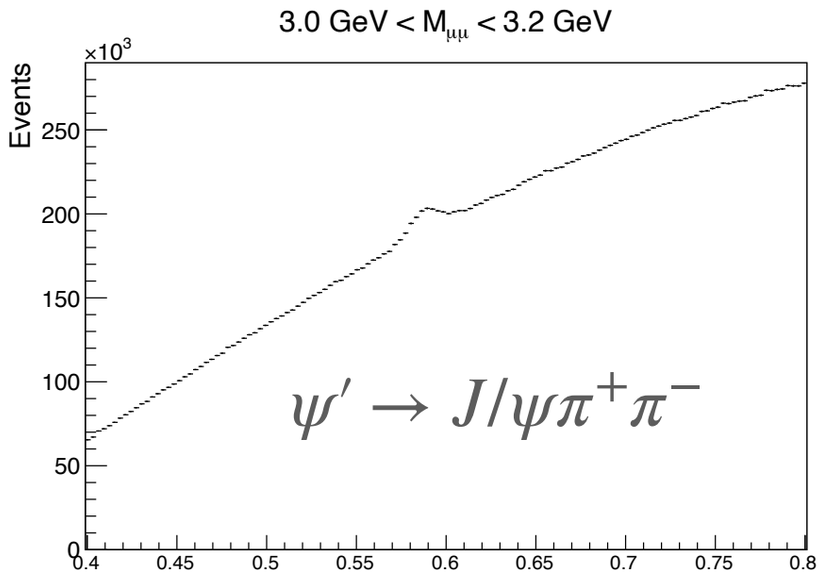
- *Time resolution ~1 ns (MPC) and ~400 ps (scintillator)*

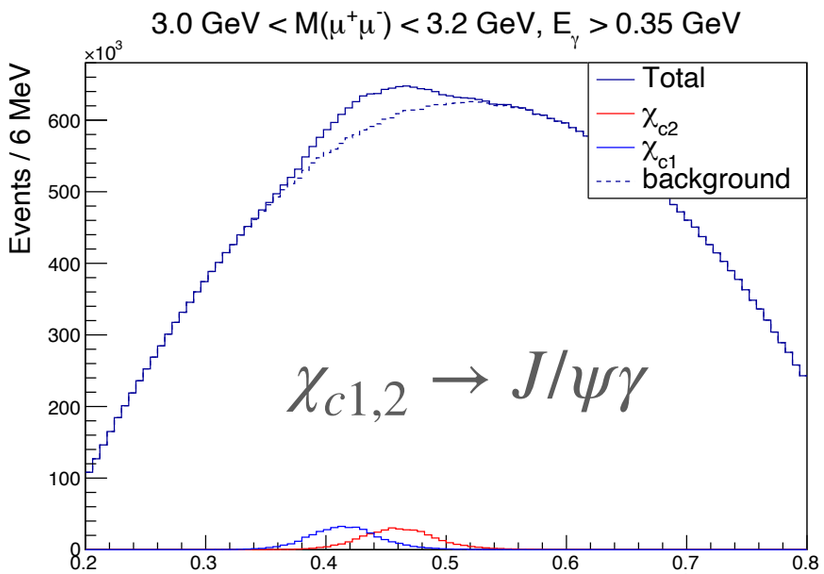
MCP-based FBBC

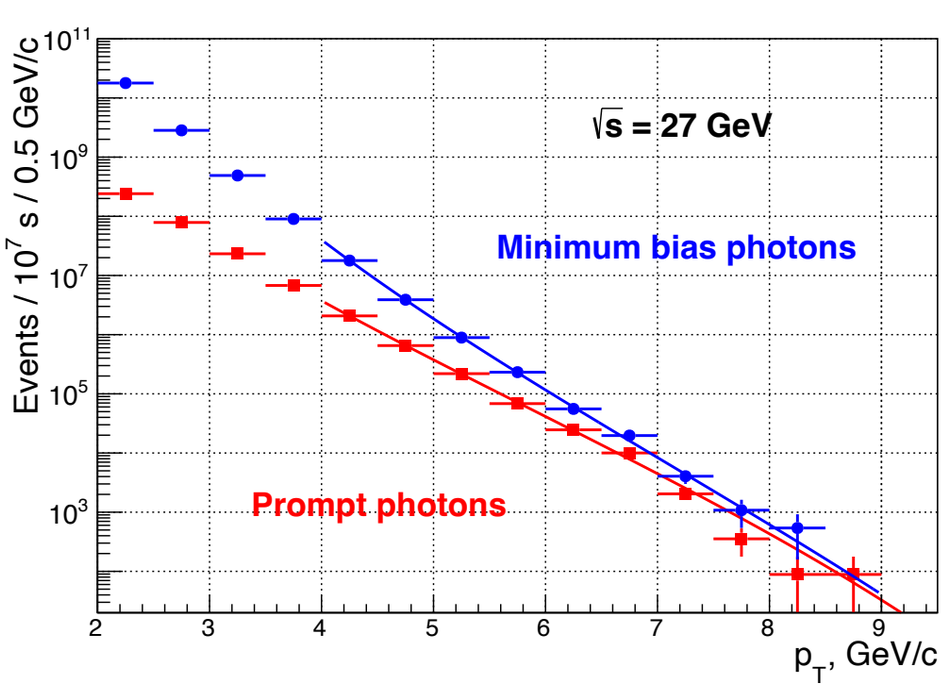


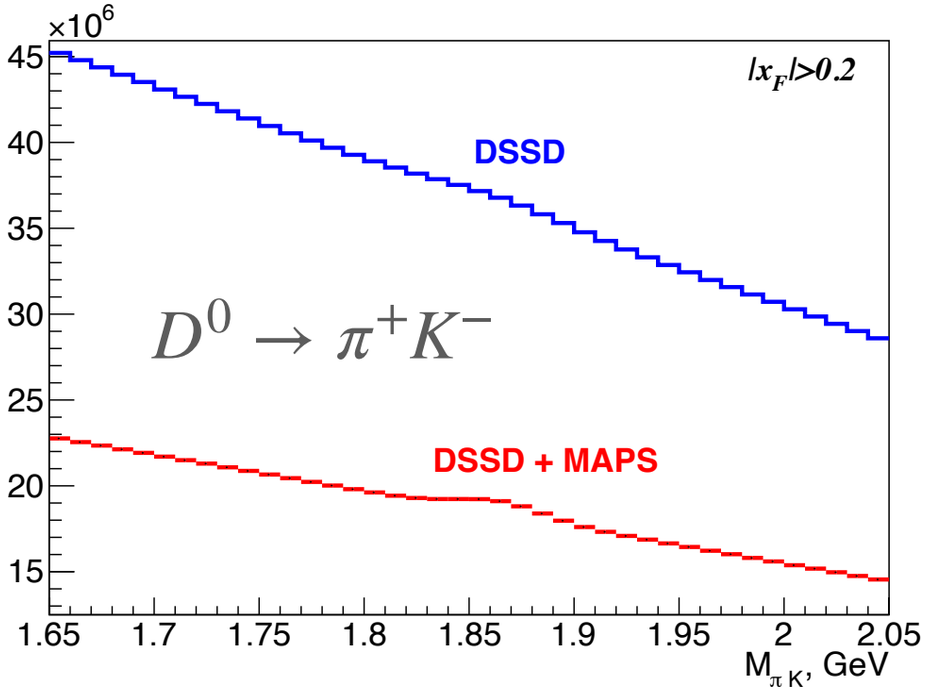
PHYSICS PERFORMANCE: GLUON PROBES (1 YEAR=10^7 S)



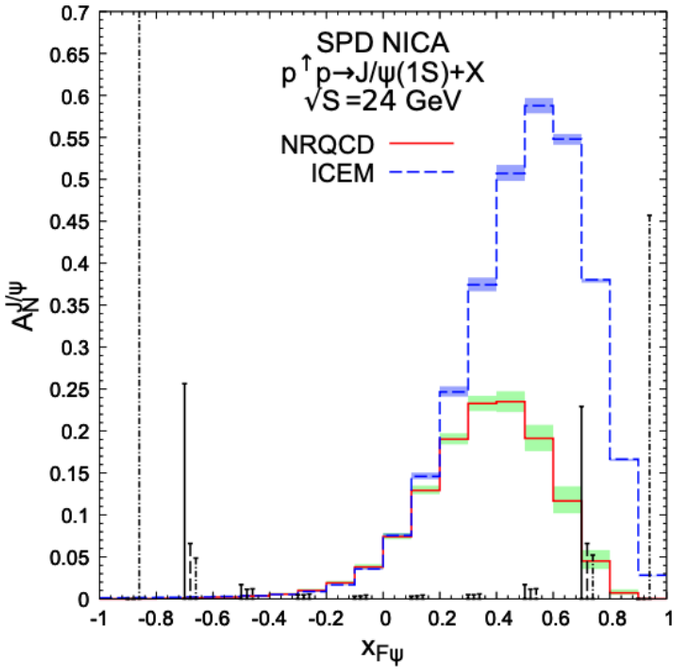




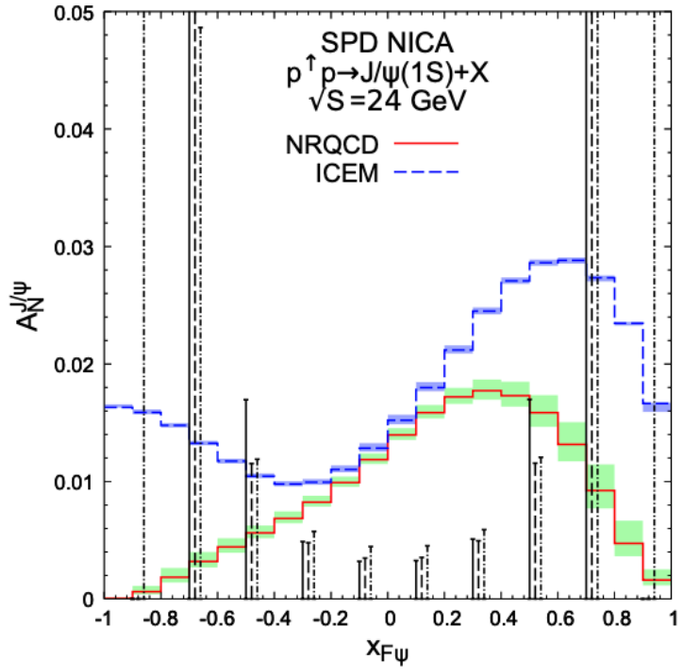


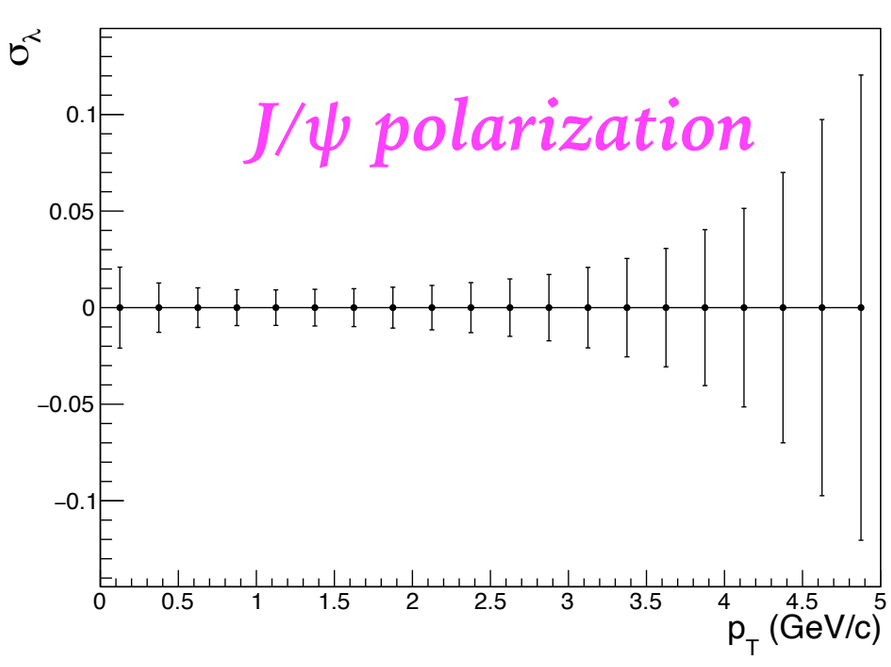


PHYSICS PERFORMANCE: ACCURACIES



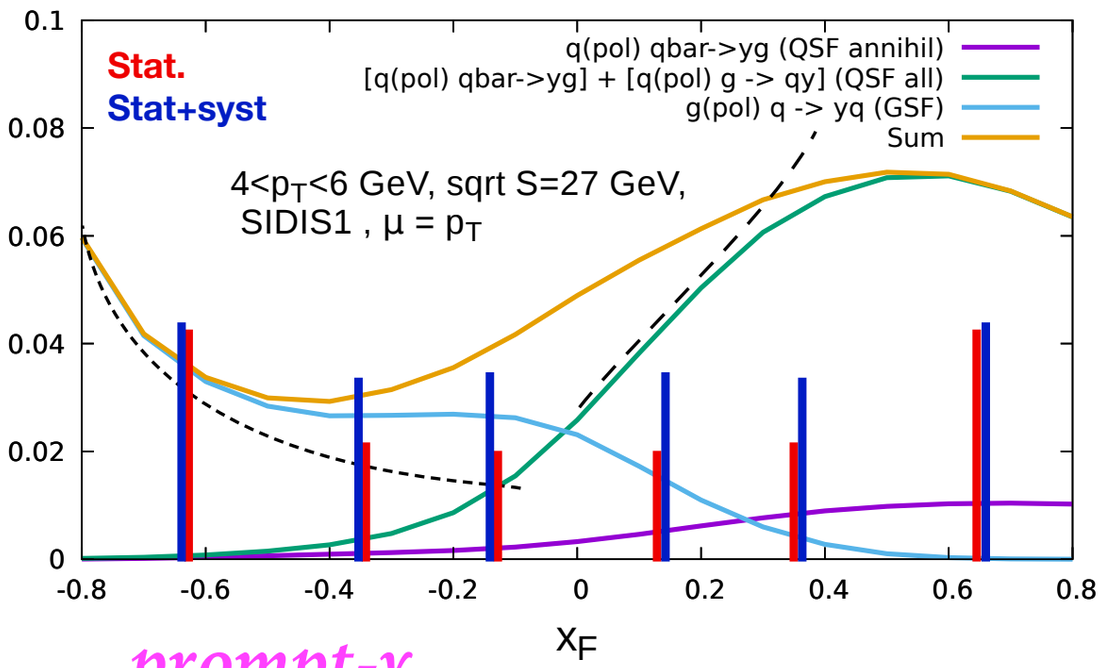
J/ψ



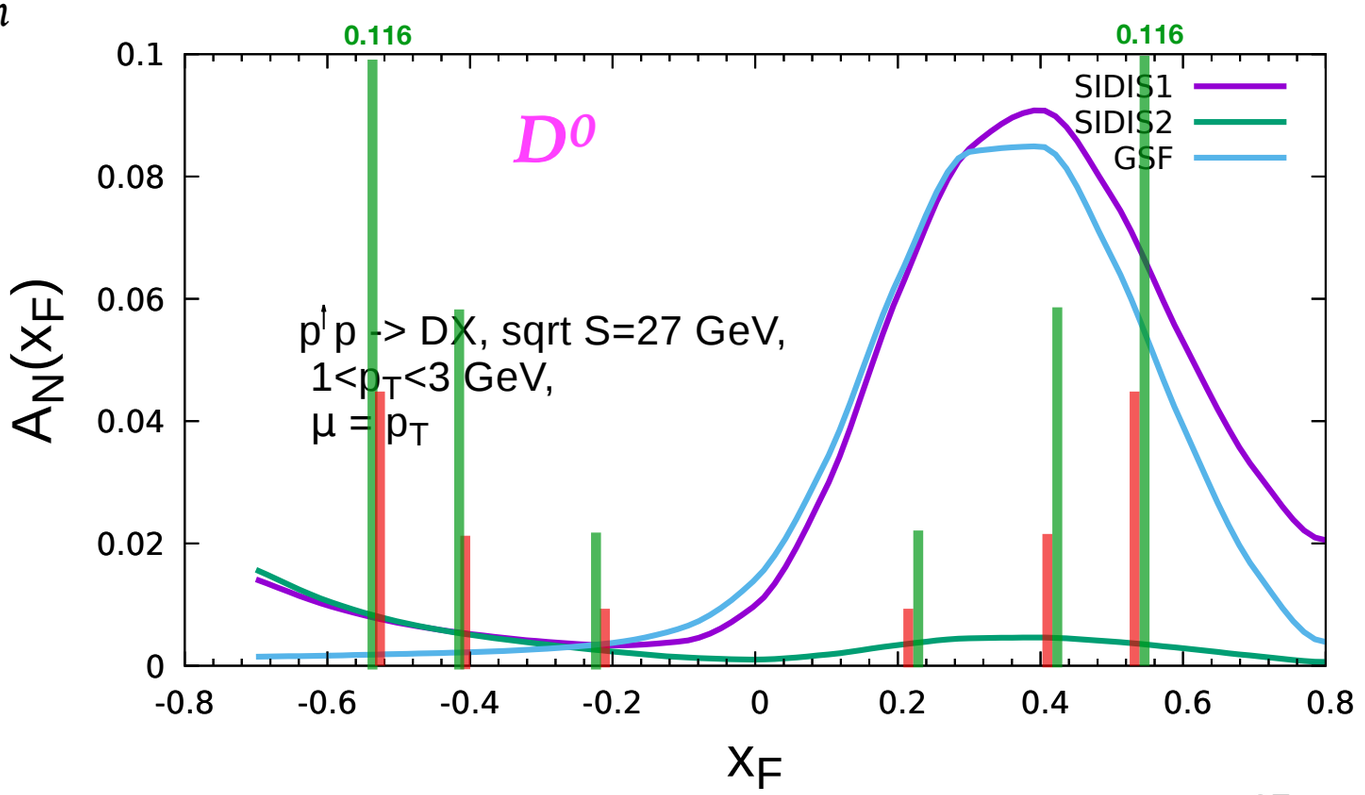


J/ψ polarization

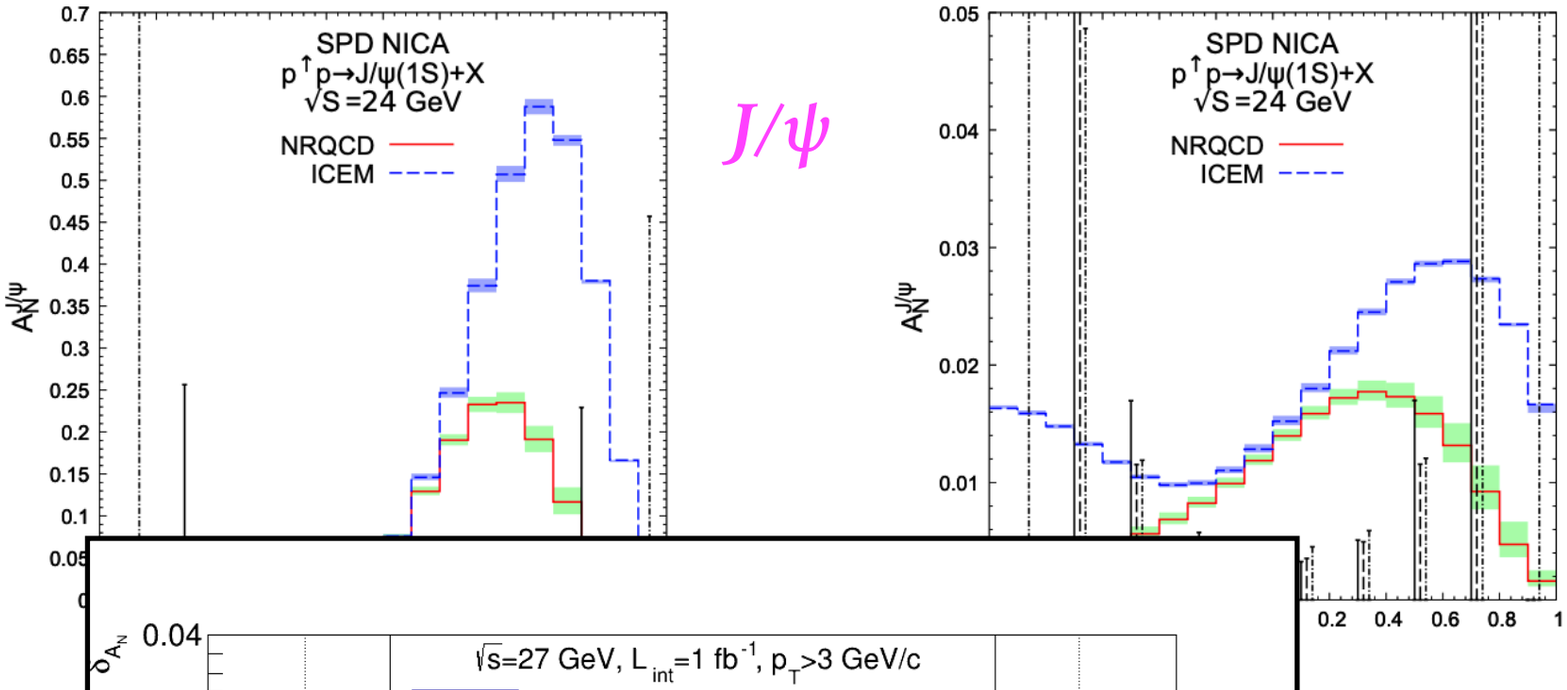
Different inputs for gluon Sivers function



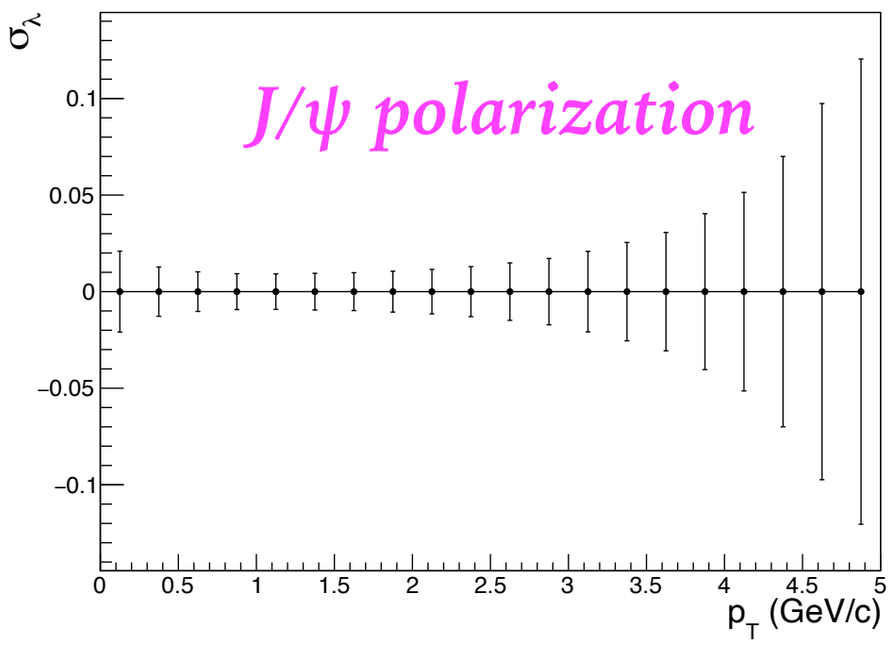
prompt-γ



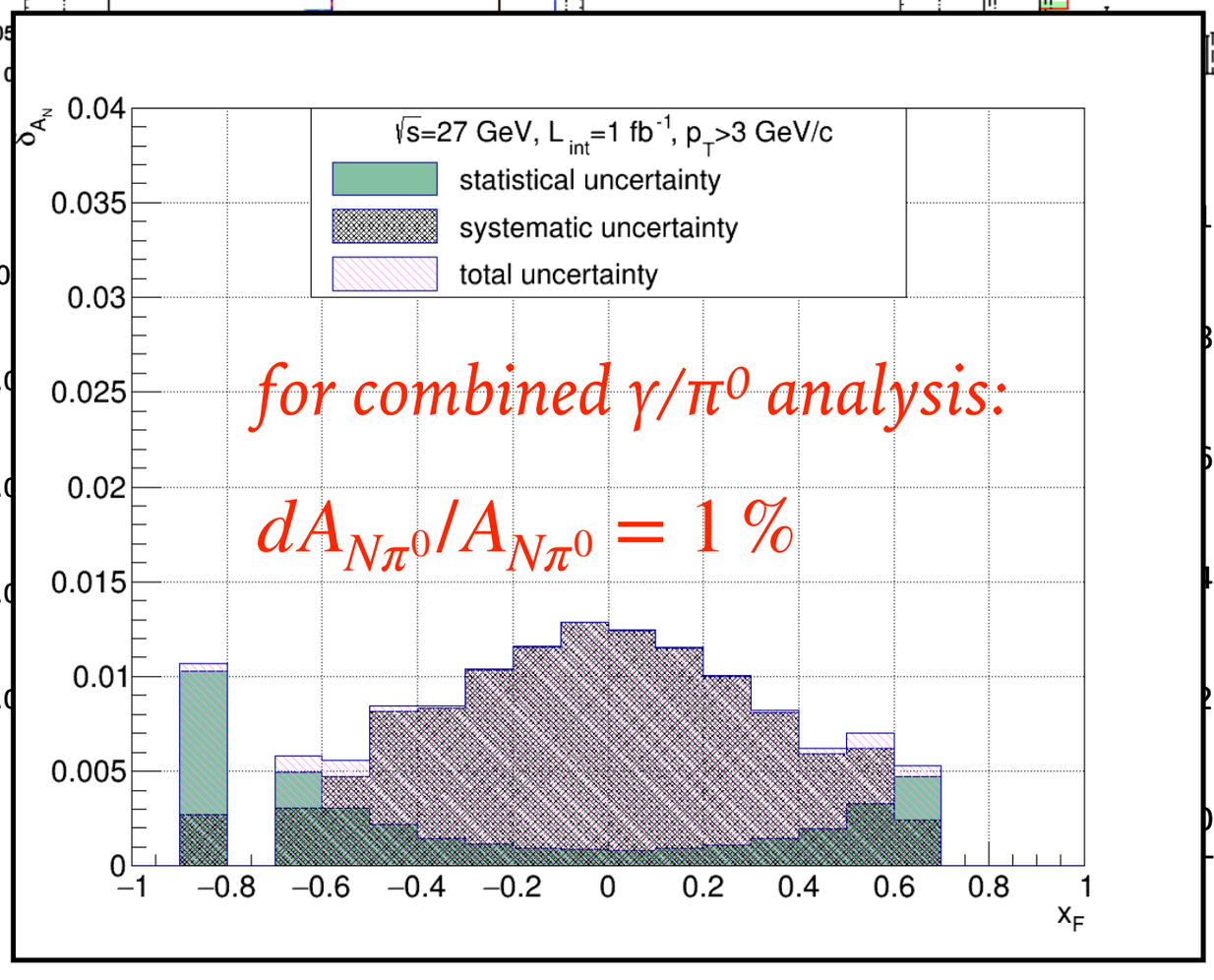
PHYSICS PERFORMANCE: ACCURACIES



J/ψ

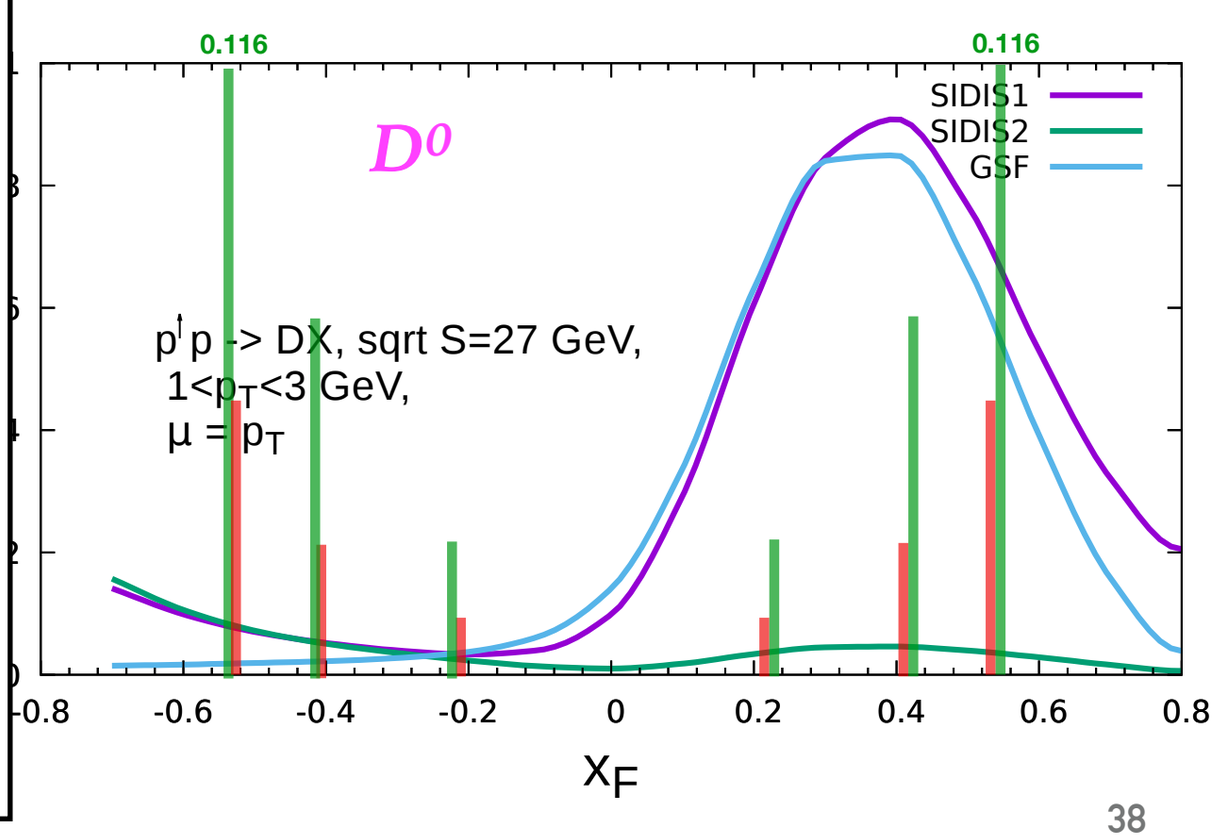


J/ψ polarization



for combined γ/π^0 analysis:

$$dA_{N\pi^0}/A_{N\pi^0} = 1\ \%$$



D^0

SPD international collaboration

32 institutes from 14 states,
~300 members

SUMMARY

- The **Spin Physics Detector** at the NICA collider is a universal facility for comprehensive study of polarized and unpolarized **gluon content of proton and deuteron**; in polarized high-luminosity **p-p** and **d-d** collisions at $\sqrt{s} \leq 27\ GeV$
- Complementing main probes such as **charmonia** (J/ψ and higher states), **open charm** and **prompt photons** will be used for that;
- SPD can contribute significantly to investigation of
  - gluon helicity;
  - gluon-induced TMD effects (Sivers and Boer-Mulders);
  - unpolarized gluon PDFs at moderate and high-x in proton and deuteron;
  - gluon transversity in deuteron.
  - …

➤Dedicated physics program for Stage-I with reduced luminosity and beam energy.

➤ **The SPD gluon physics program is complementary to the other intentions to study the gluon content of nuclei (RHIC, AFTER, EIC) and mesons (AMBER, EIC).**

- SPD CDR is available as arXiv:2102.00442 for more details.
- SPD TDR is about to be completed.
- More information could be found at http://spd.jinr.ru