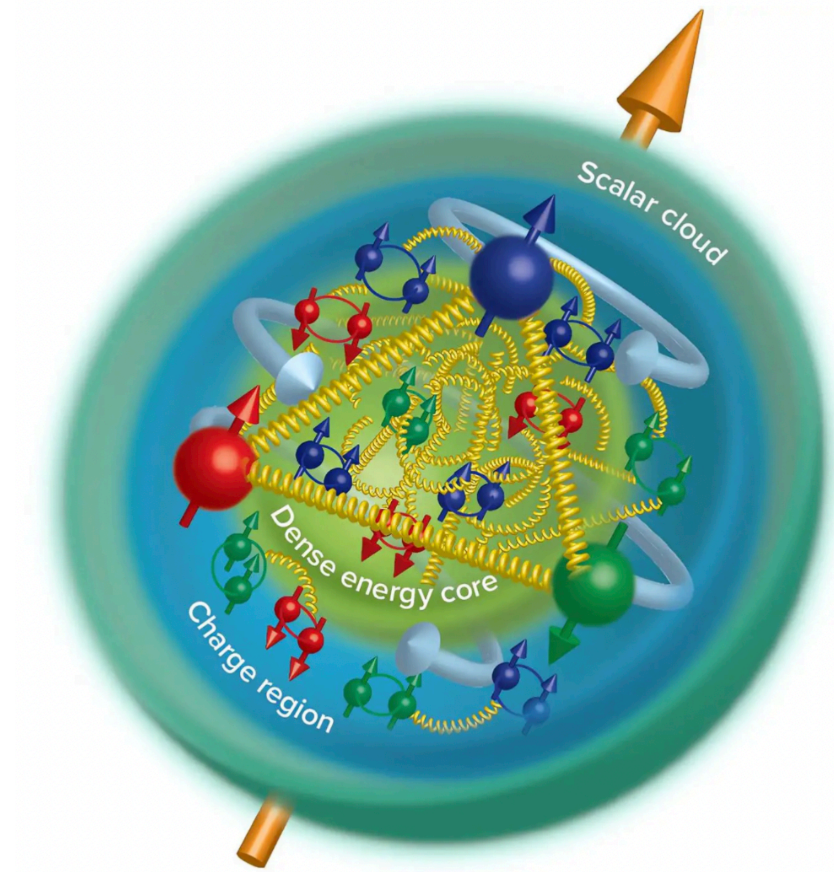
Spin Physics Detector project @ NICA

A. Guskov, JINR

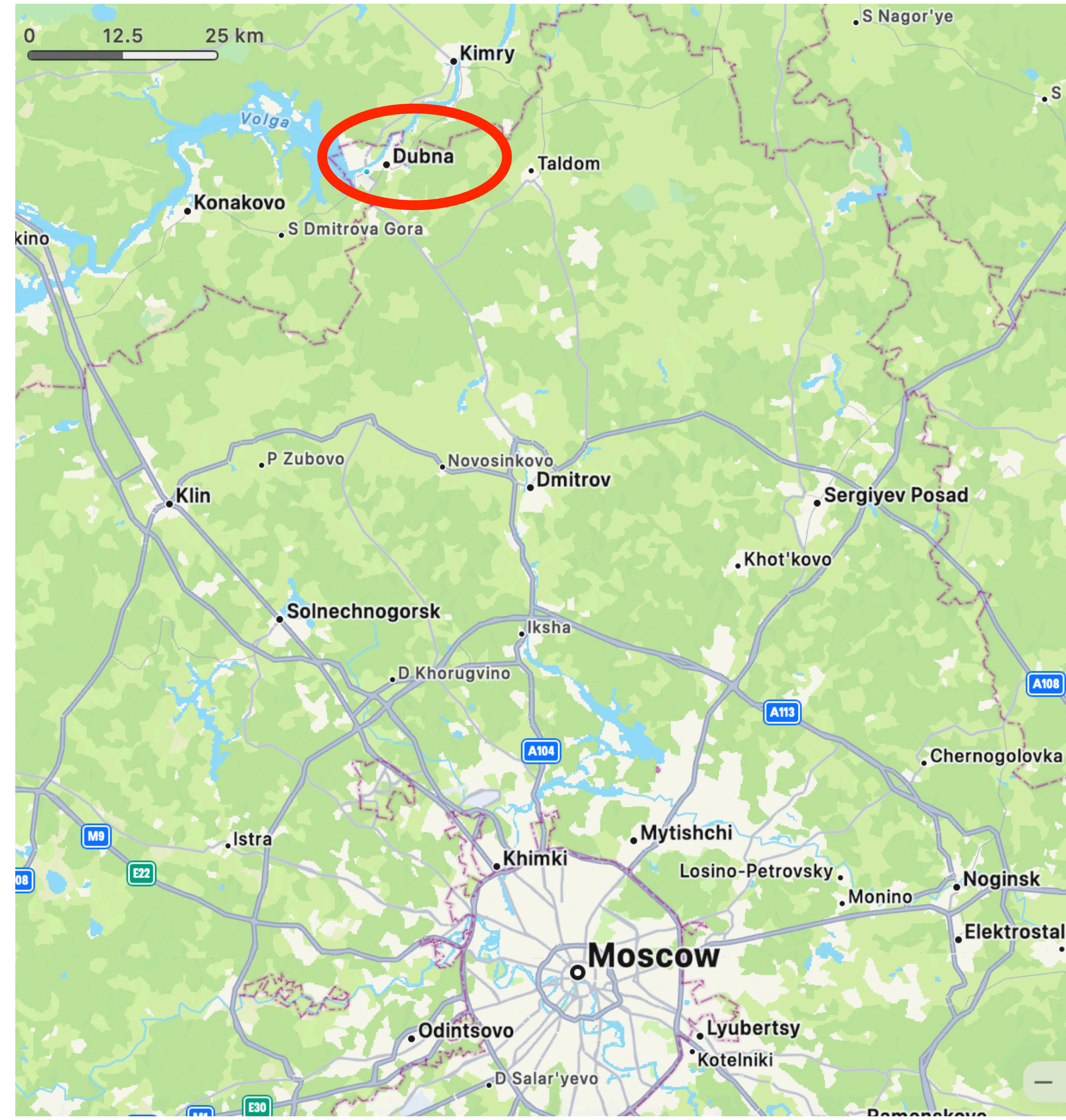
avg@jinr.int



中国科学技术大学
University of Science and Technology of China

25.03.2025

THE JOINT INSTITUTE FOR NUCLEAR RESEARCH, DUBNA, RUSSIA



The **Joint Institute for Nuclear Research** is an international intergovernmental scientific research organization in the science city Dubna of the Moscow region (Russia)

Spin Physic Detector @ NICA

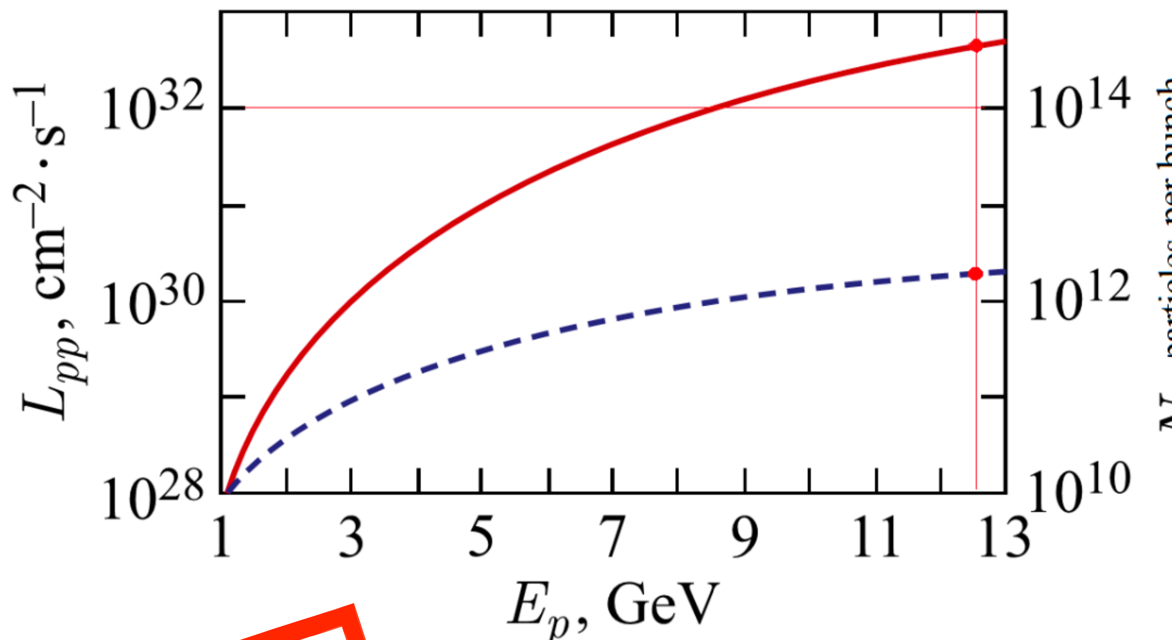
NICA - Nuclotron-based Ion Collider fAcility

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

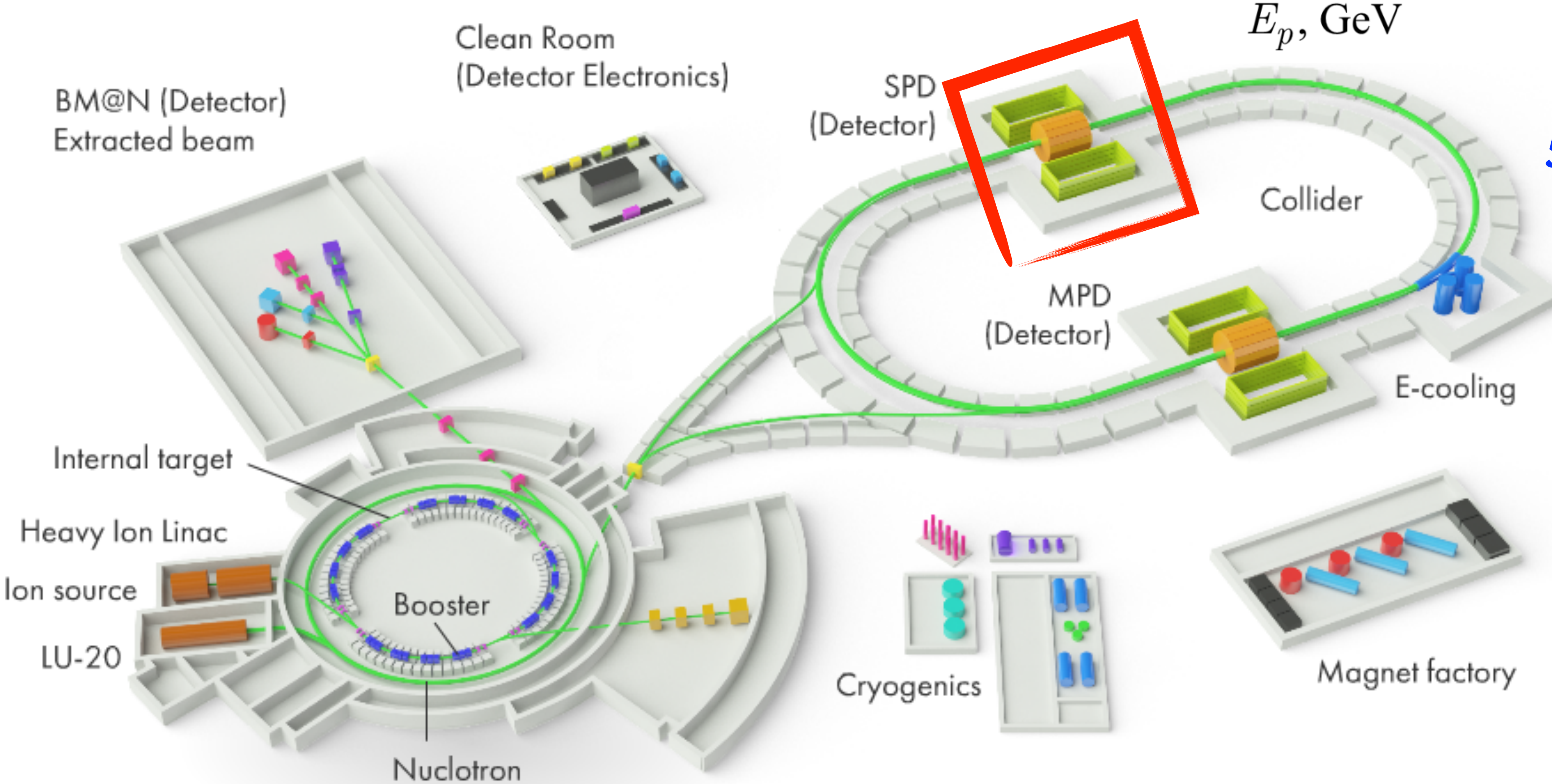
$d^{\uparrow}d^{\uparrow} : \sqrt{s} \leq 13.5\ GeV$

U, L, T

$|P| > 70\%$



503 m



D. Gross and NICA

2016

NICA landscape

NICA landscape

Strong pressure

➤ 13.6.24 - NICA technological launch

➤ Beam circulation - summer 2025

Polarized beams at NICA

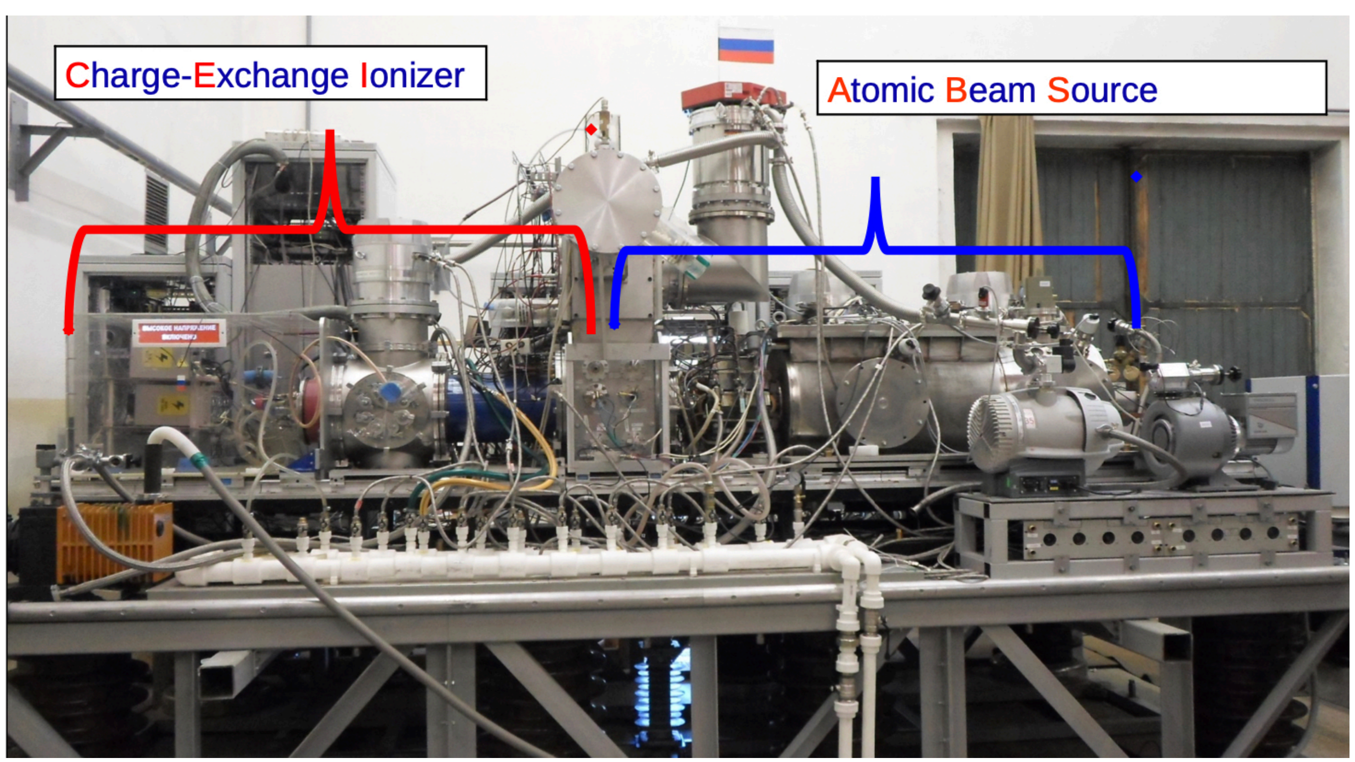
d↑- was accelerated in 1986 (Synchrophasotron) and 2002 (Nuclotron). It is quite simple procedure: there is just 1 depolarizing spin resonance at 5.6 GeV.

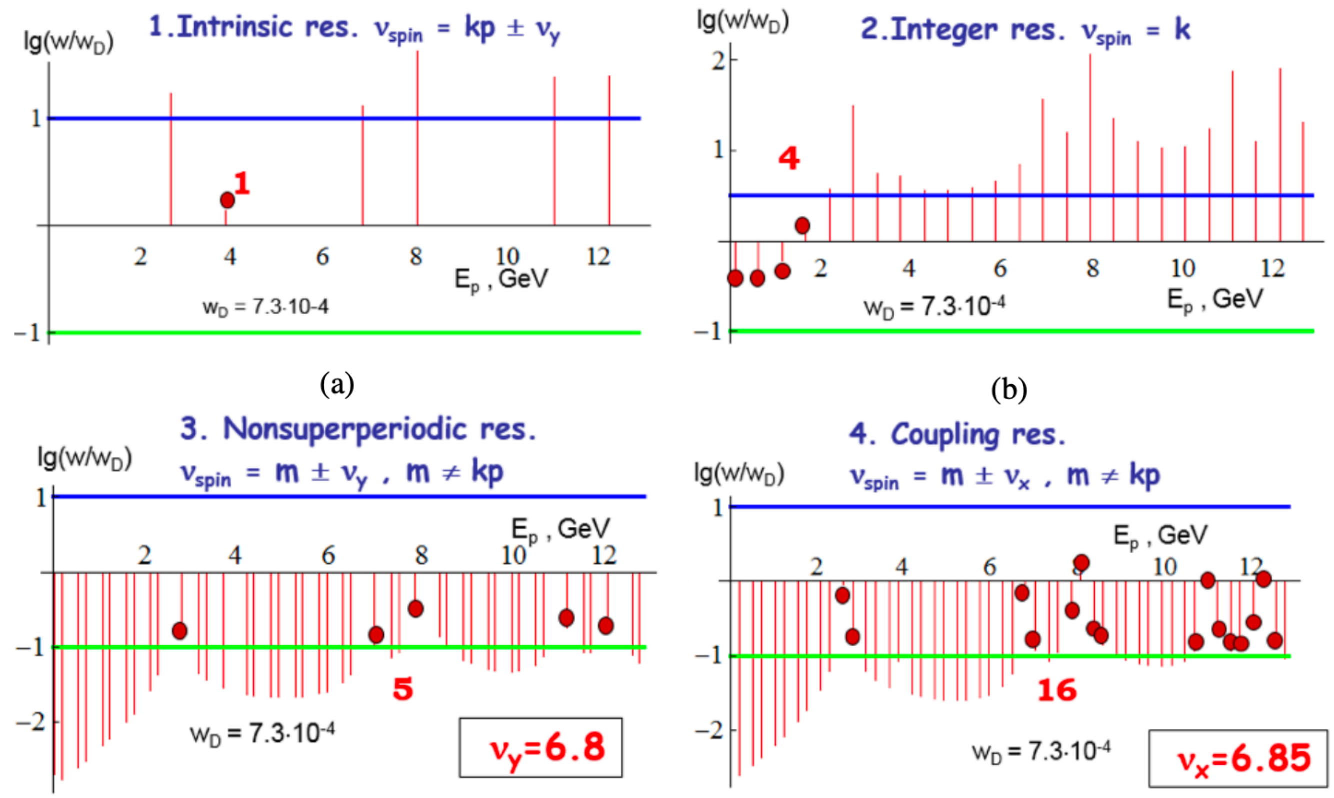
p↑- was first obtained only in 2017.

Source of Polarized Ions:

$$H^0\uparrow + D^+ \rightarrow H^+\uparrow + D^0$$

$$D^0\uparrow + H^+ \rightarrow D^+\uparrow + H^0$$

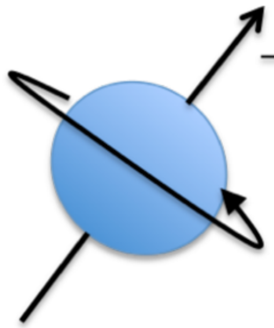




- Longitudinal polarization in the IP can be supported at the integer spin-resonances
  - For protons: E_{kin}=(0.108+0.523·n) [GeV]
  - For deuterons: E_{kin}=(5.62+6.56·n) [GeV/u]

- Transverse polarization at any energies

Proton as a composite object



$$\overrightarrow{\mu_S} = g_S \times \frac{e}{2m} \times \vec{S}$$

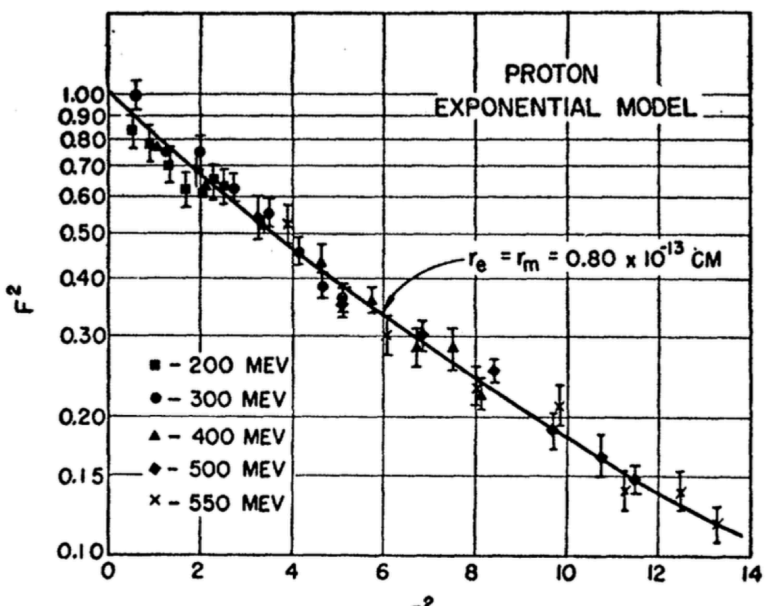
	gs (expected)	gs (measured)
e	-2	-2.0023
p	2	**5.58**
n	0	**-3.83**

1930-s

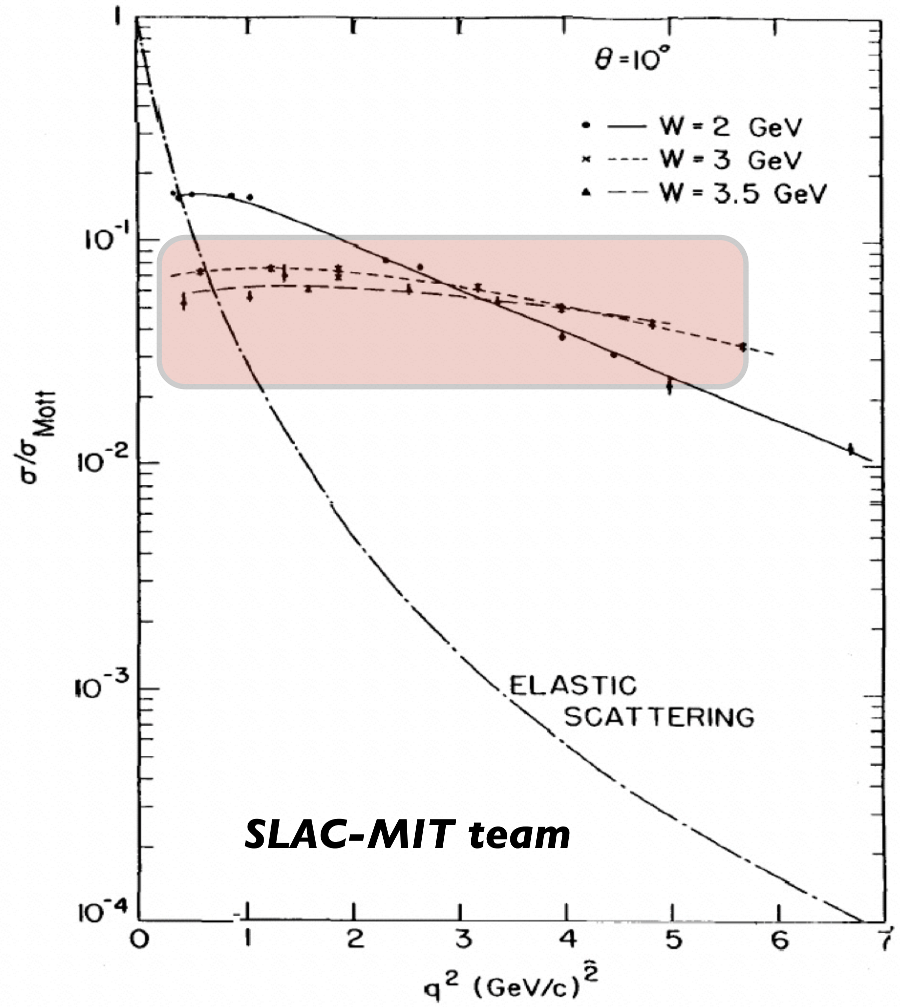
It seems that nucleons are not point-like structureless objects!

Proton size and structure

R. Hofstadter - Nobel Prize in 1961



:en from ref. [13]



J. Friedman, H. Kendall, R. Taylor - Nobel Prize in 1990

Partons - point-like objects inside the proton

Form-factor

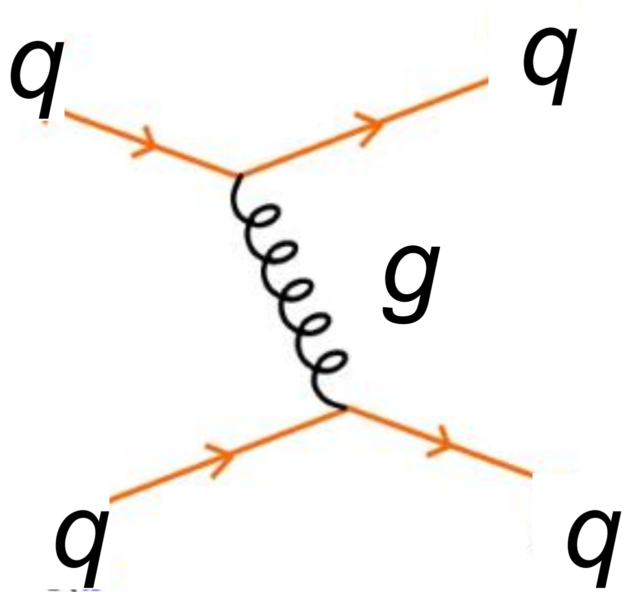
$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point-like}} \times F^2(q^2)$$

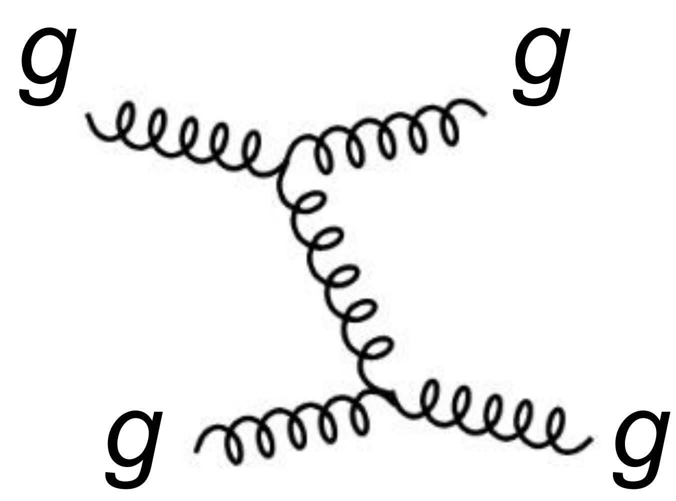
$$F(q^2) \approx 1 - \frac{q^2 < r^2 >}{6\hbar^2}$$

Partonic model - 1969

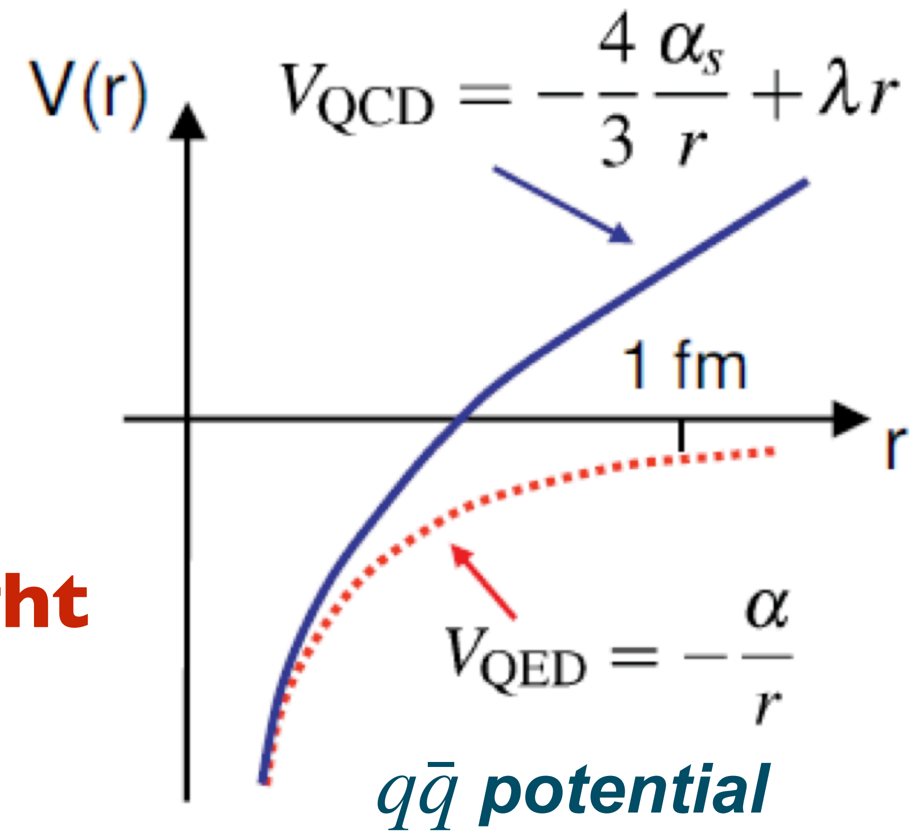
R. Feynman

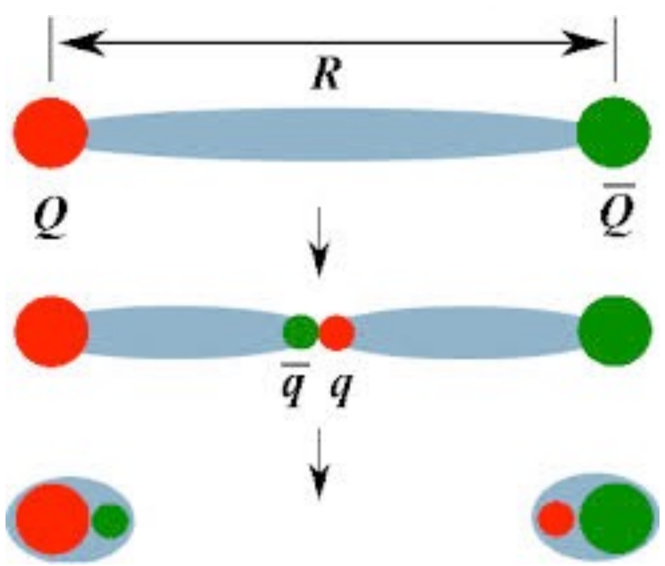
Quantum ChromoDynamics - QCD





Analog in electrodynamics: **light emitting light !**



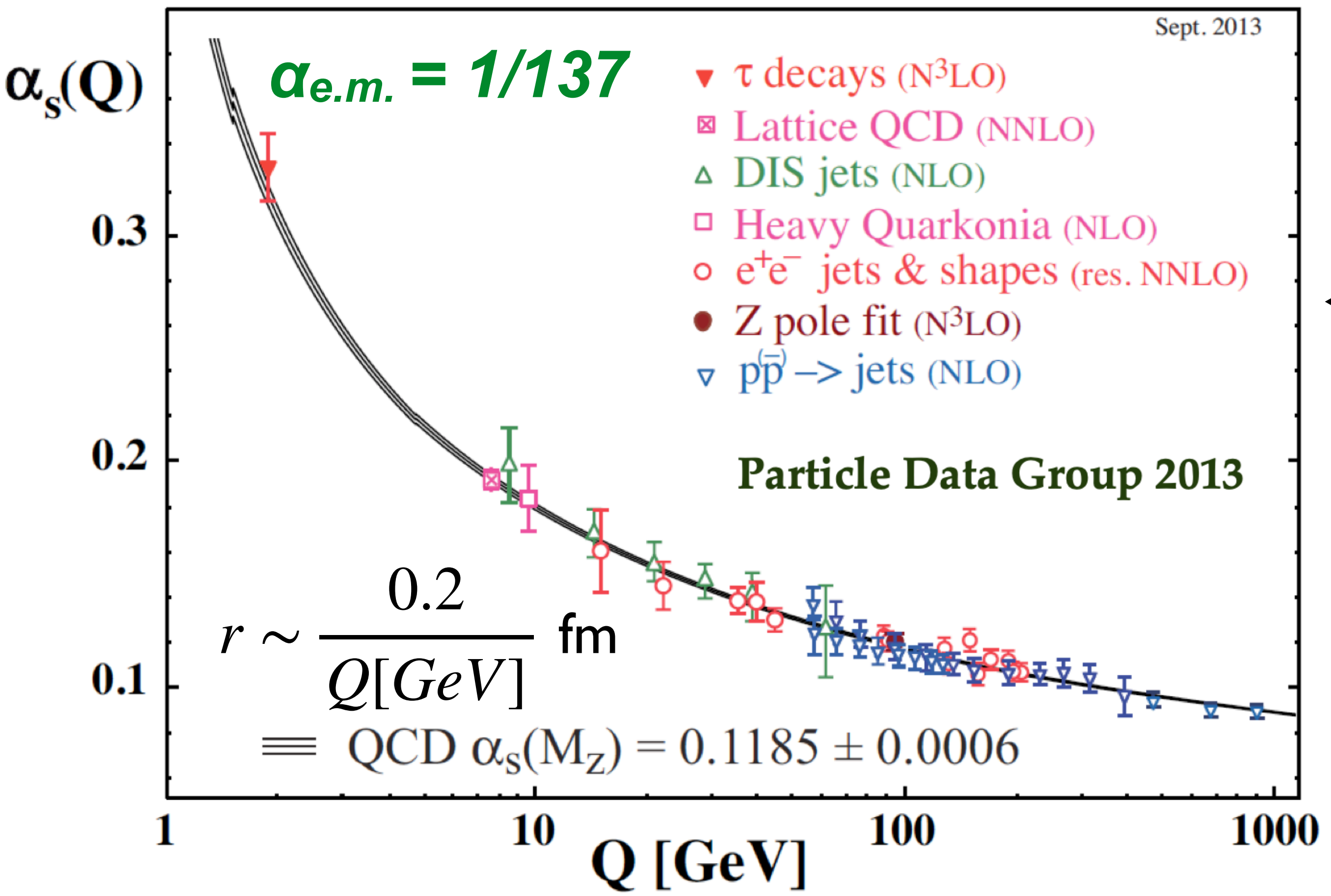


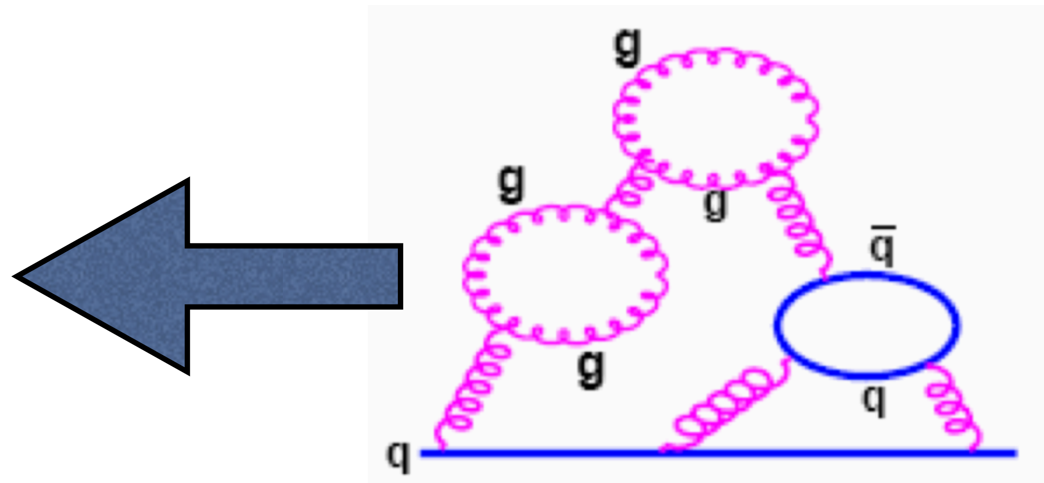
Quark confinement at large scale
but asymptotic freedom at below 1 fm

D.Gross, D. Politzer, F. Wilczek - Nobel Prize in 2004

Problem to describe hadrons ab initio

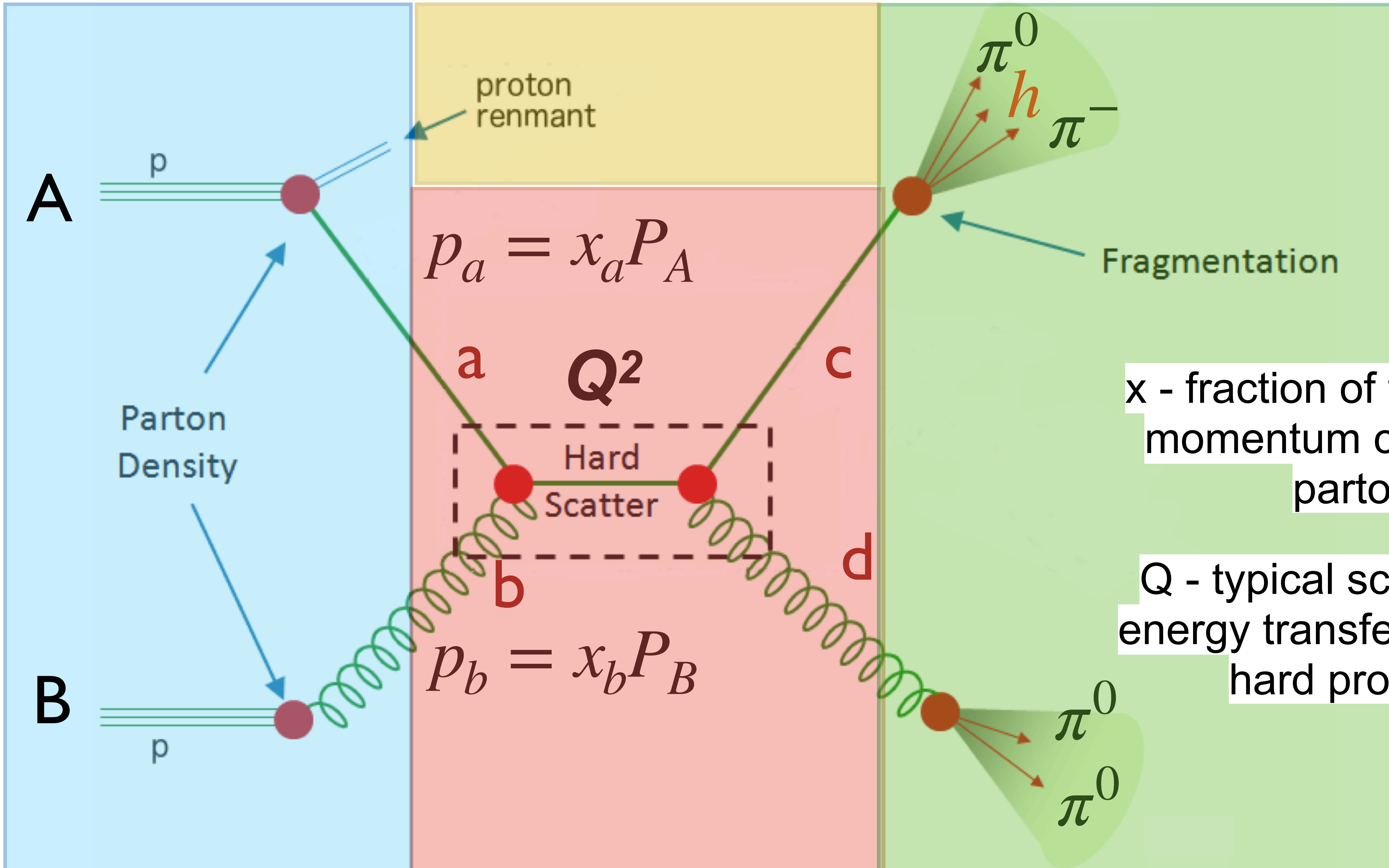
QCD is the true theory of the interaction between quarks and gluons. However, the possibilities to obtain quantitative predictions on its basis are **limited**.





Unlike the hydrogen atom, we cannot (yet?) describe from first principles the structure of hadrons and their interactions at low energies

Factorization theorem



x - fraction of the proton momentum carried by parton

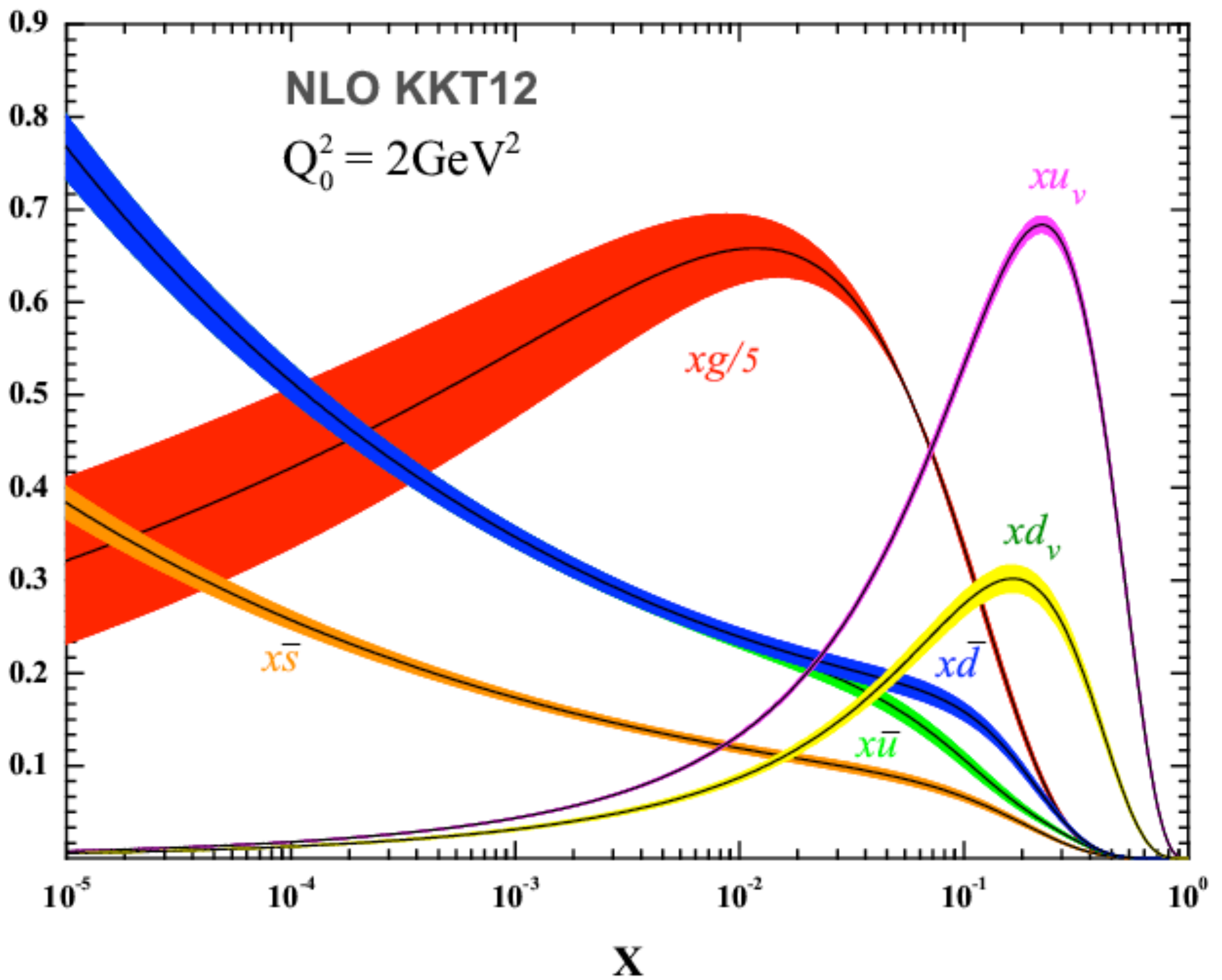
Q - typical scale of the energy transferred in the hard process

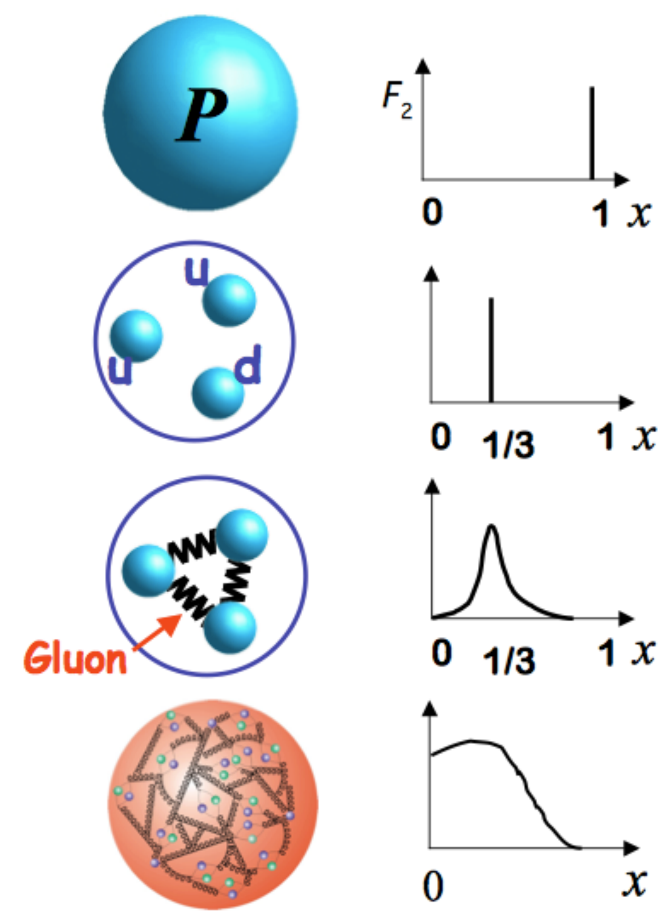
$$\sigma_{AB\to hX} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b \boxed{f(x_a, Q^2) f(x_b, Q^2)} \times \boxed{\hat{\sigma}_{ab\to cd}(x_a, x_b, Q^2)} \times \boxed{D_{cd\to h}}$$

$\boxed{Q^2 >> 1\ \mathrm{GeV}^2/c^2}$

Parton Distribution Functions

Parton Distribution Functions PDFs $f(x,Q^2)$ describes probability for given Q^2 to find inside the proton a parton carrying momentum fraction x

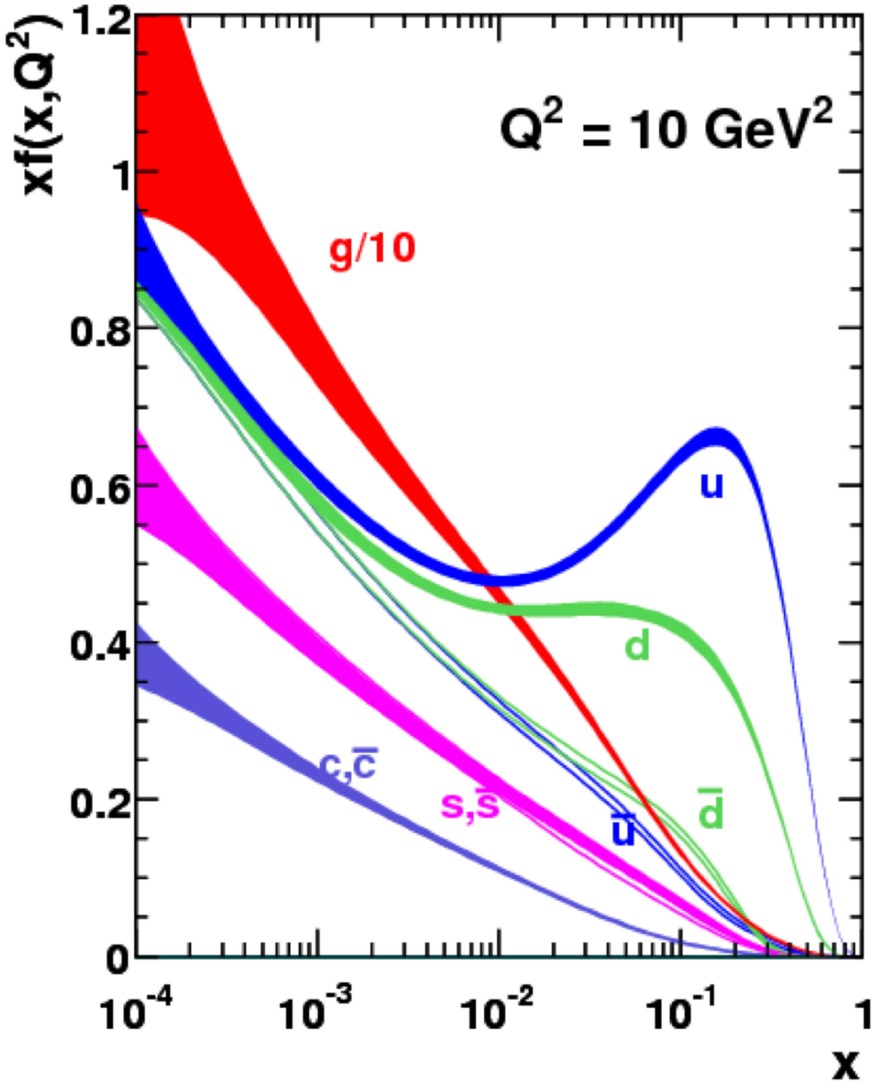


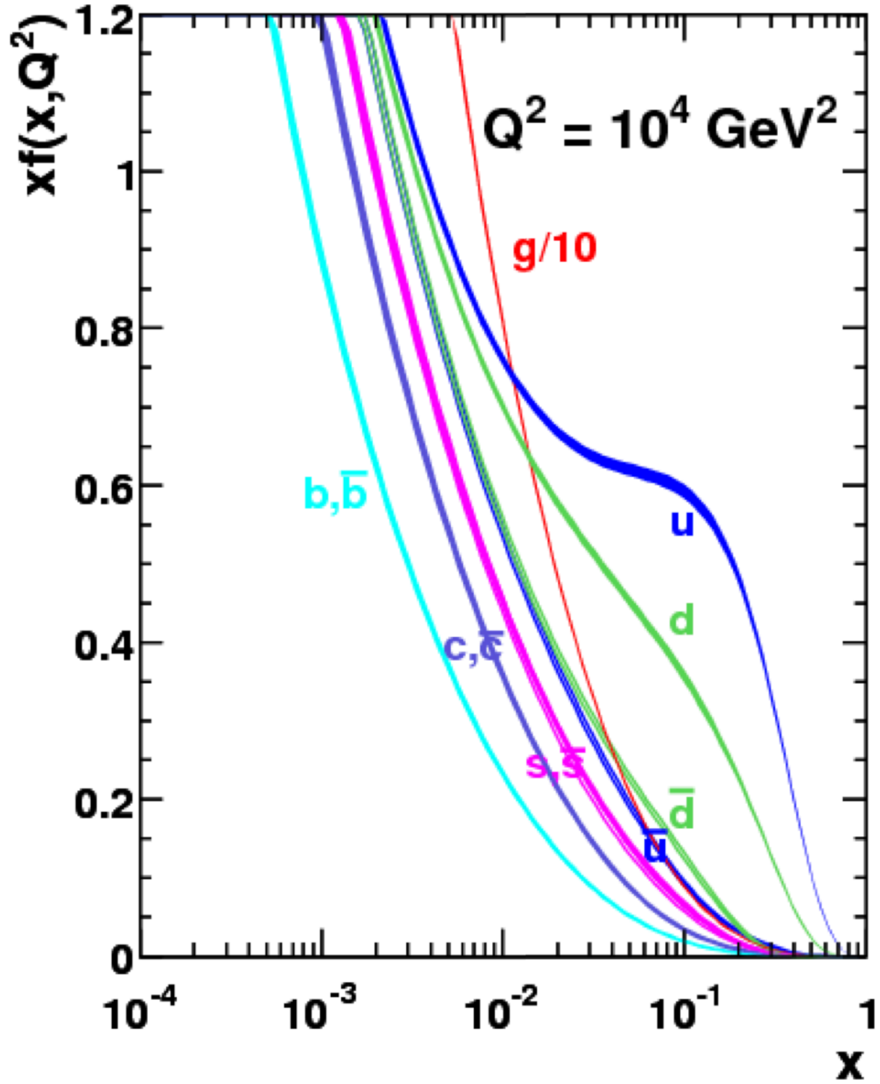


PDFs are universal, they are independent on the hard process

PDFs cannot be calculated in QCD from the first principles!

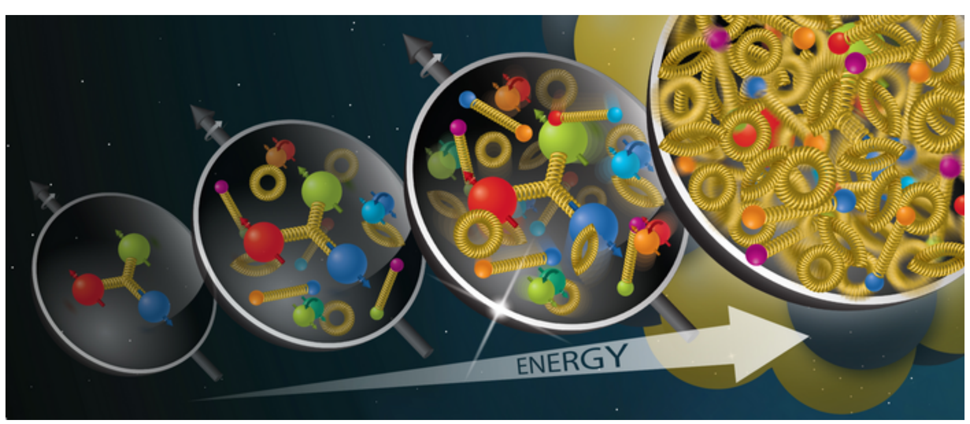
Parton Distribution Functions





$$\sum_i \int dx\, x q_i(x) = 1$$

q_i	momentum
d_V	0.111
u_V	0.267
d_S	0.066
u_S	0.053
s_S	0.033
c_S	0.016
total	0.546



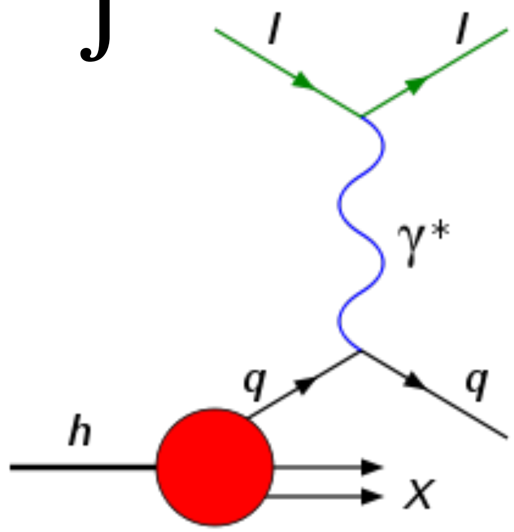
$$g = 1 - 0.546 = 0.454$$

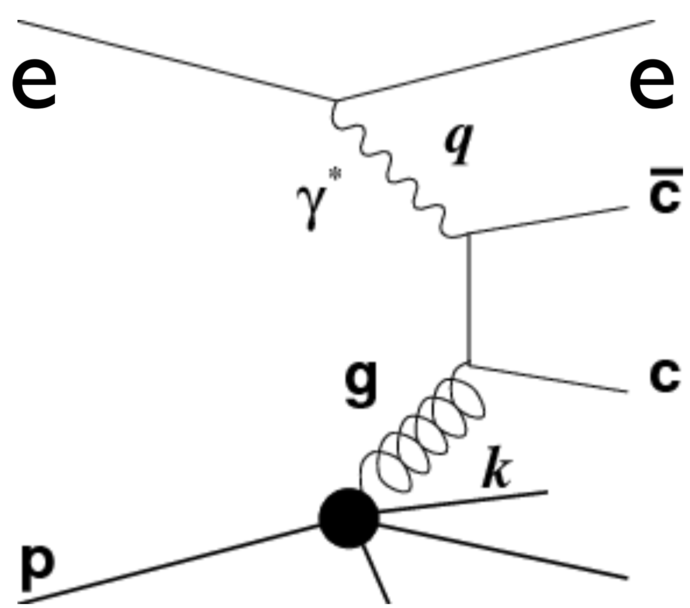
Sea partons becomes more important at high Q^2

How to access PDFs ?

Deep Inelastic Scattering

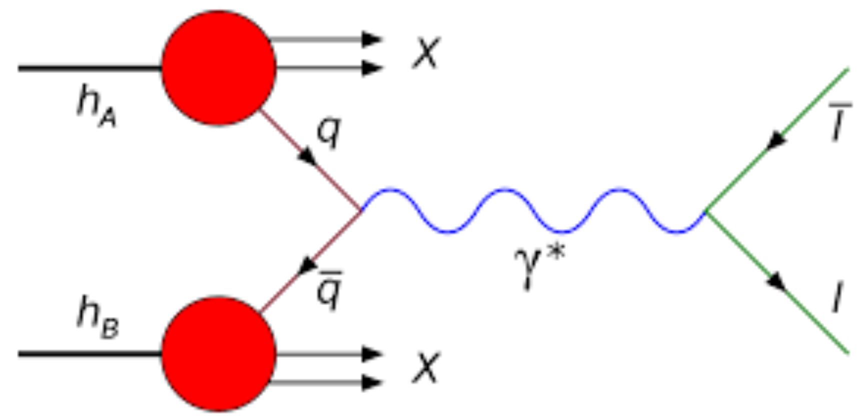
$$\sigma = \int \hat{\sigma} q(x) dx$$

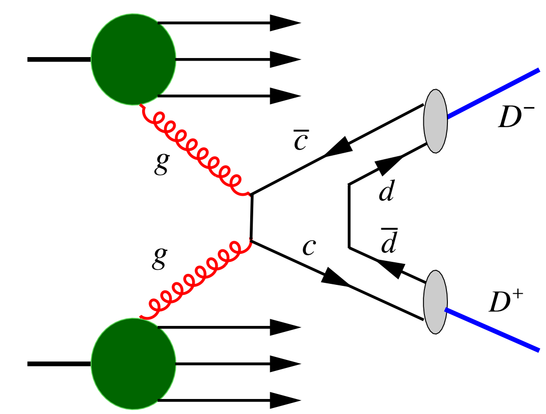




Hadronic interactions

$$\sigma = \int\int \hat{\sigma} q_A(x_A) q_B(x_B) dx_A dx_B$$

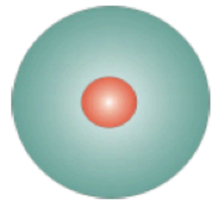




CTEQ Collaboration
JAM Collaboration
DSSV Collaboration
NNPDF Collaboration
…

Polarized proton

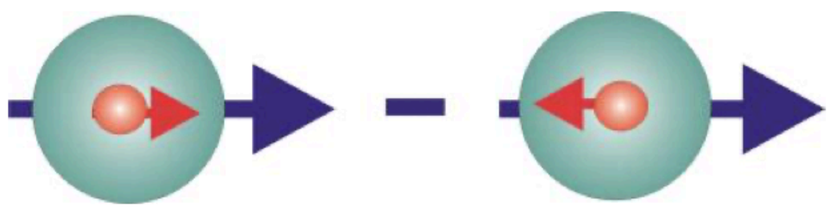
f(x)



Unpolarized PDF

unpolarized DIS

Δf(x)

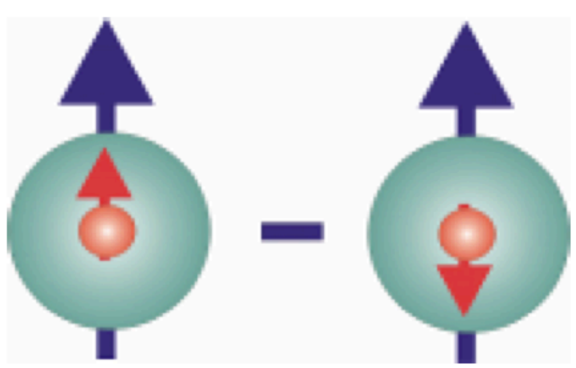


Helicity

polarized DIS

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

Δ_Tf(x)



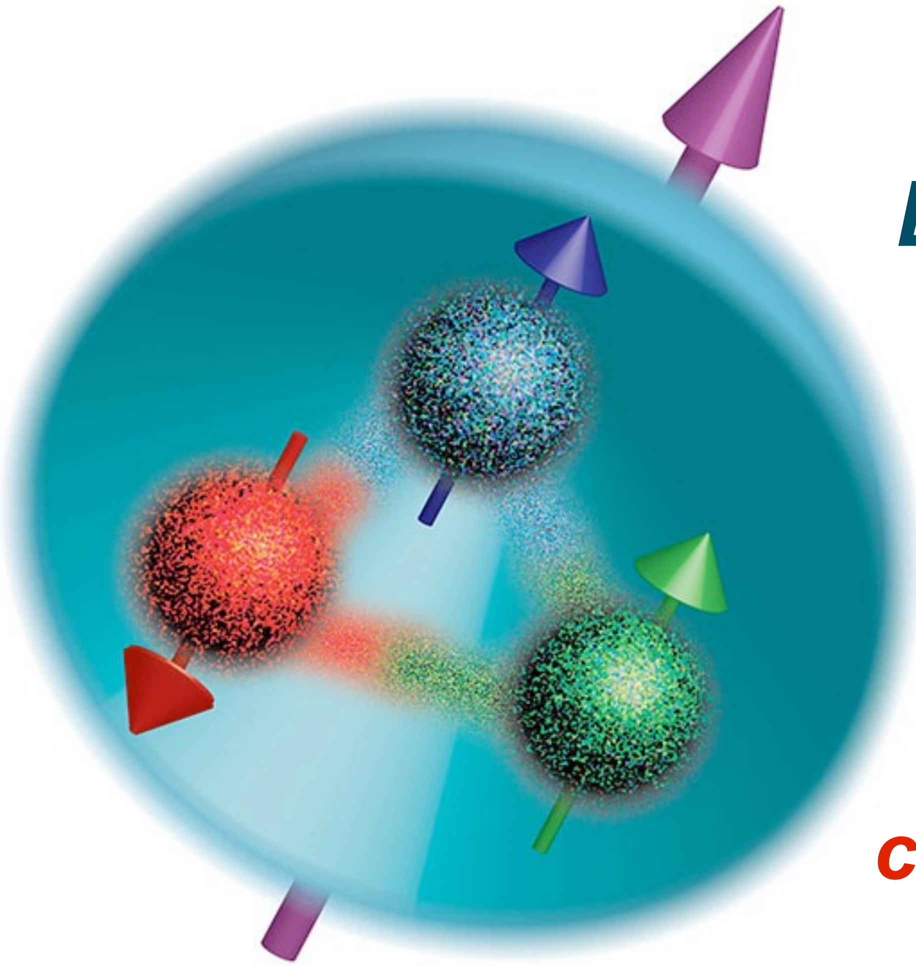
Transversity

polarized SIDIS

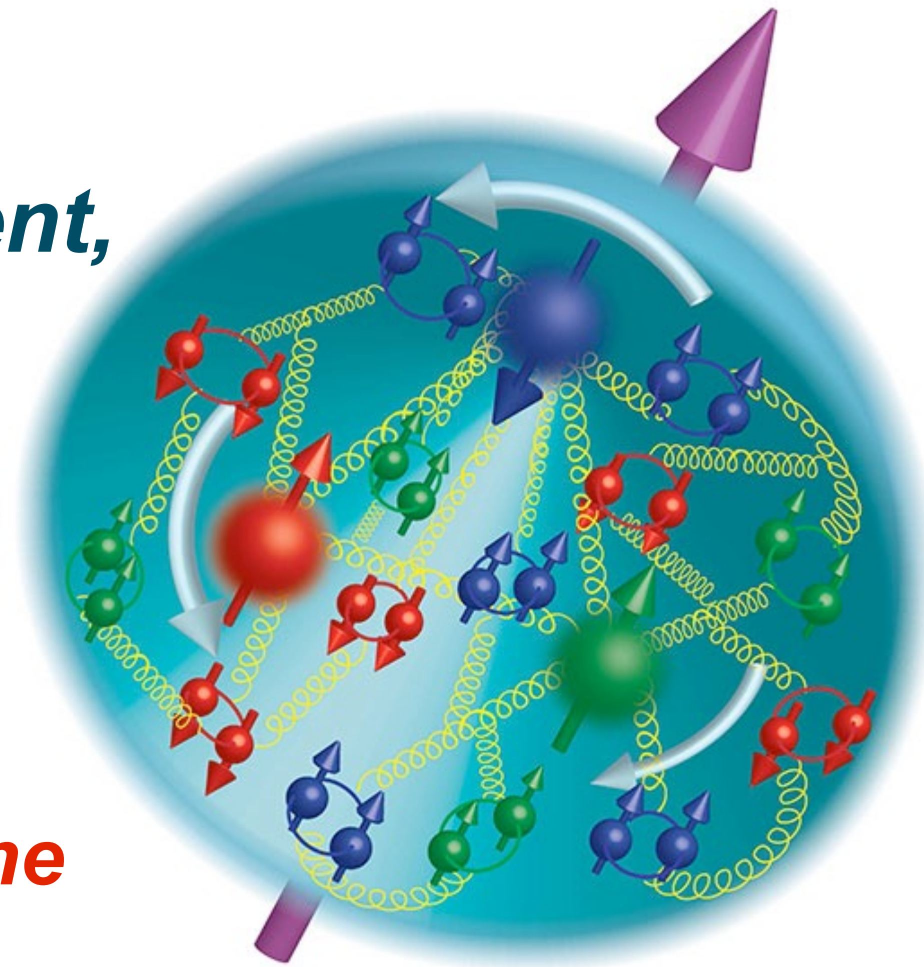
P

Azimuthal asymmetryes A_N

Spin crisis



EMC experiment, CERN 1988



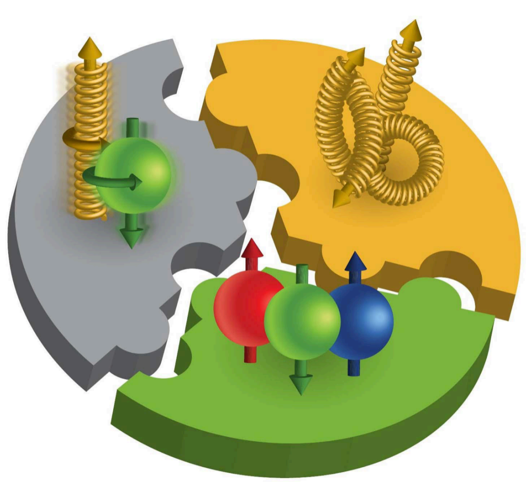
Quark contribution to the proton spin is below 30%!

Naive quark model

$$\frac{1}{2} = \sum_{q=u,u,d} \left(\frac{\vec{1}}{2}\right)$$

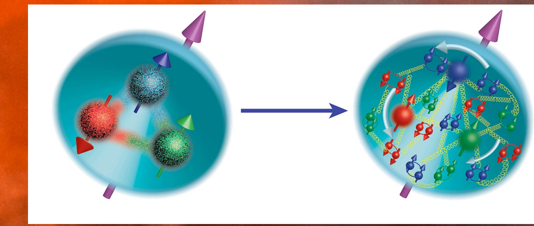
Real situation

L - orbital moments of quarks and gluons



$$S_N = \tfrac{1}{2} = \tfrac{1}{2}\,\Delta\Sigma + \Delta G + L$$

Gluon helicity

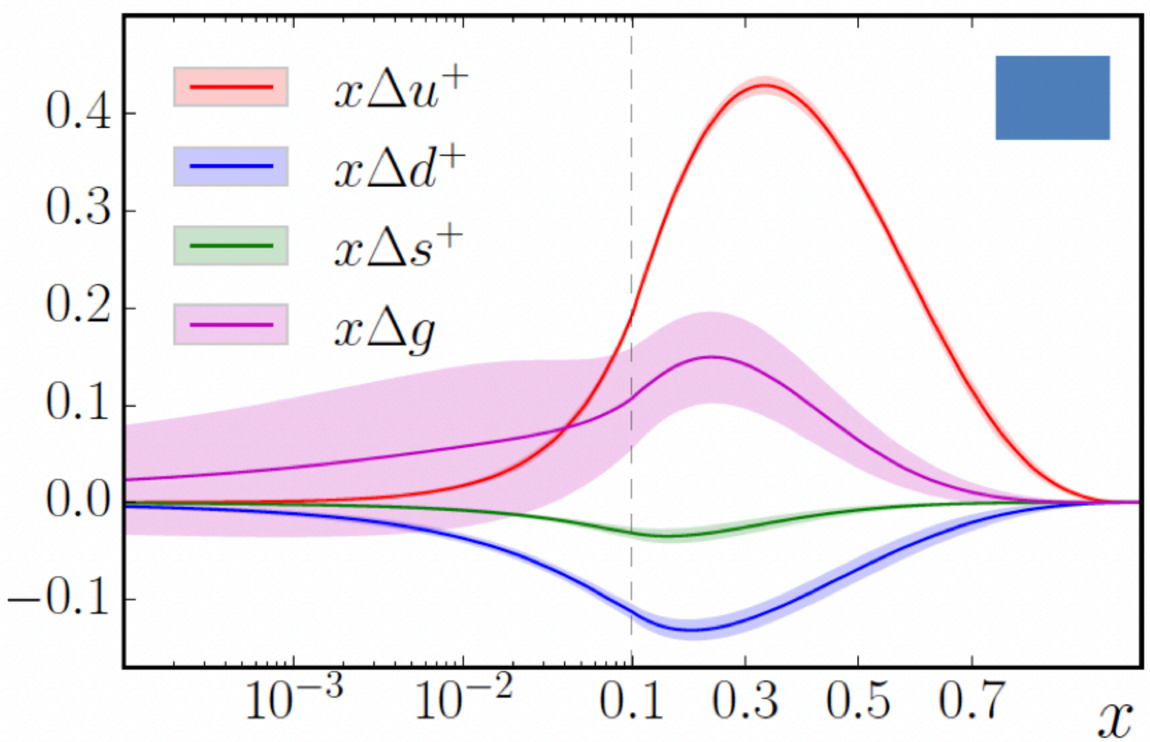


~30%

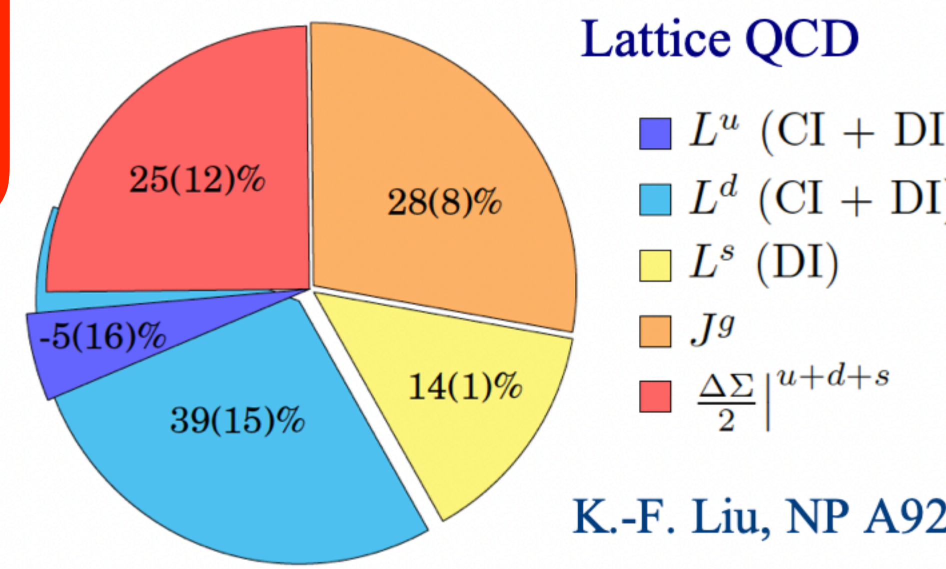
$$J = \frac{1}{2}\Delta\Sigma + \Delta G + \boxed{L_q + L_g}$$

~10-20%

? ?

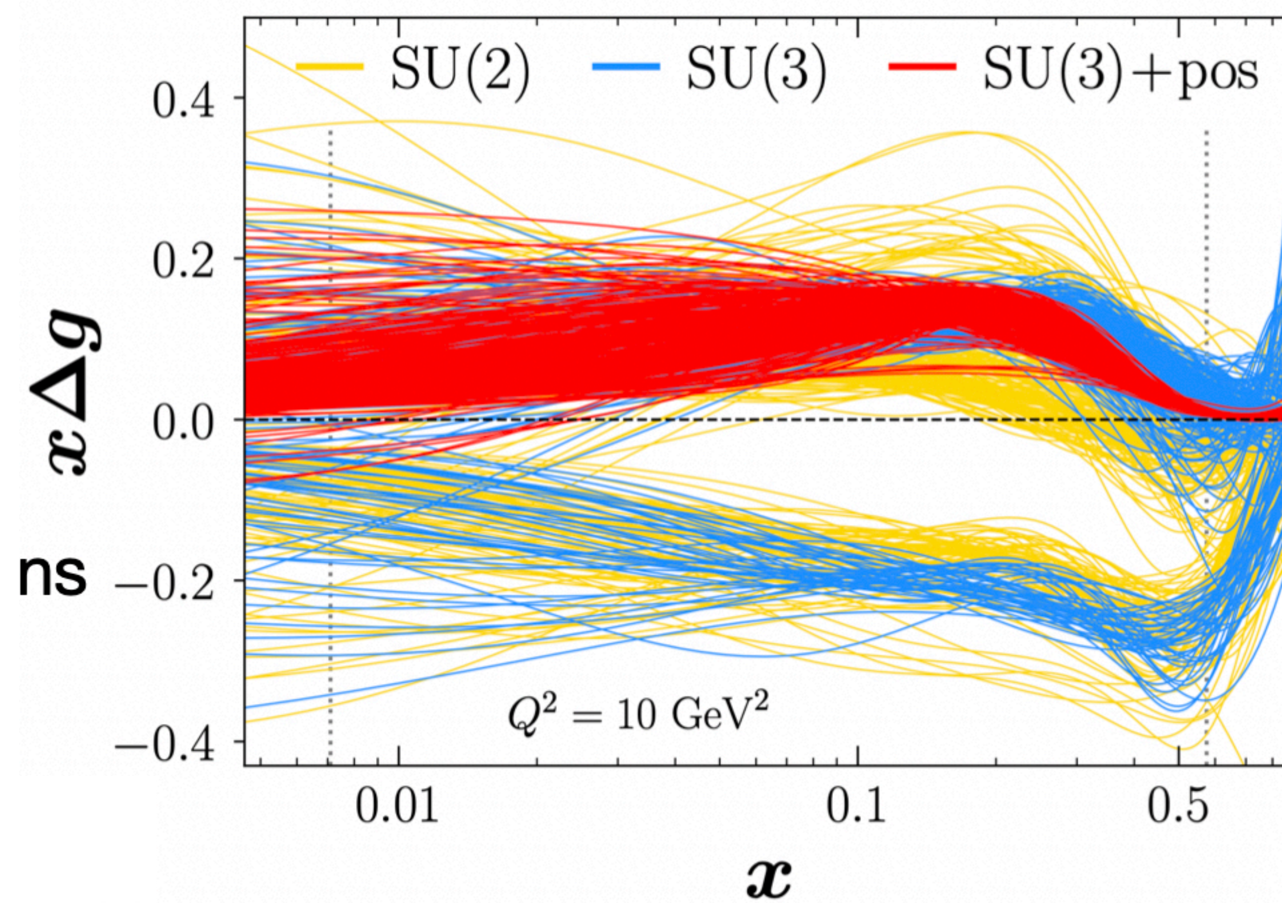


JAM Collaboration, PRD (2016).



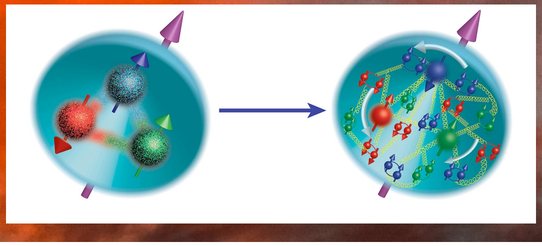
K.-F. Liu, NP A928, 99 (2014).

Y. Zhou et al (JAM) Phys. Rev. D 105, 074022 (2022)



To access angular momenta info about 3D structure is needed!

Gluon helicity

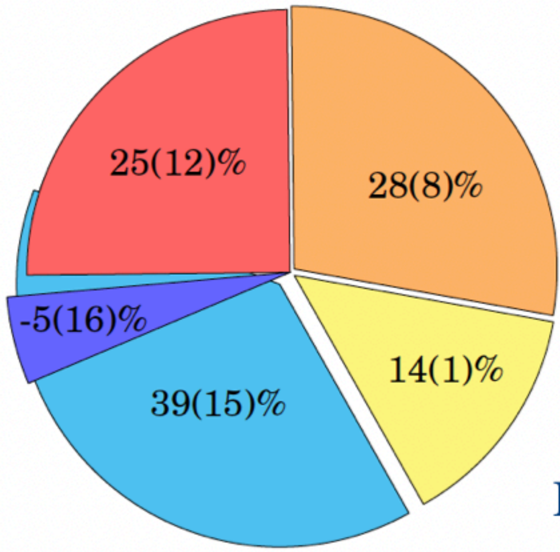


$$J = \frac{1}{2}\Delta\Sigma + \Delta G + \boxed{L_q + L_g}$$

~30%

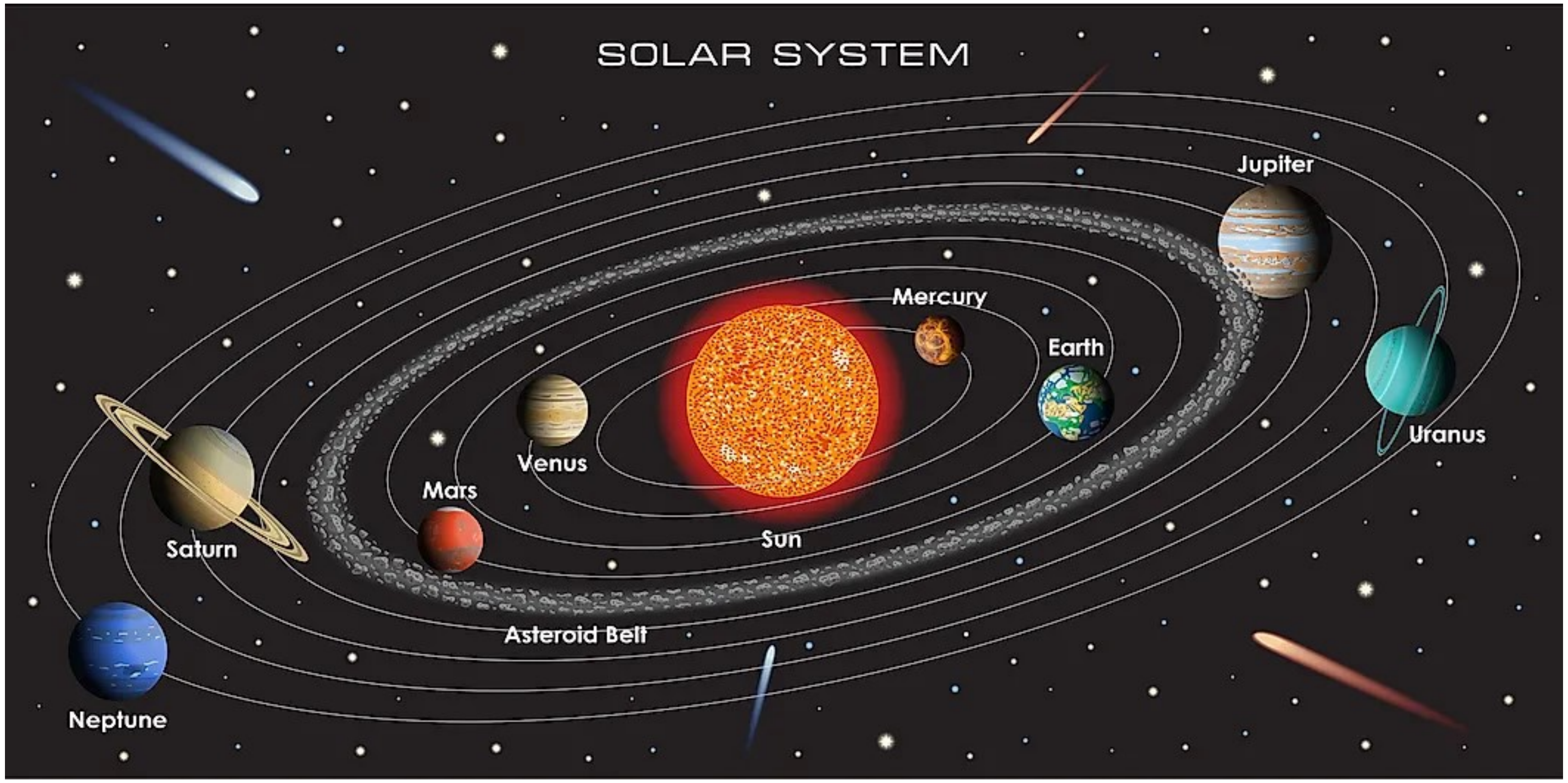
~10-20%

~50% !



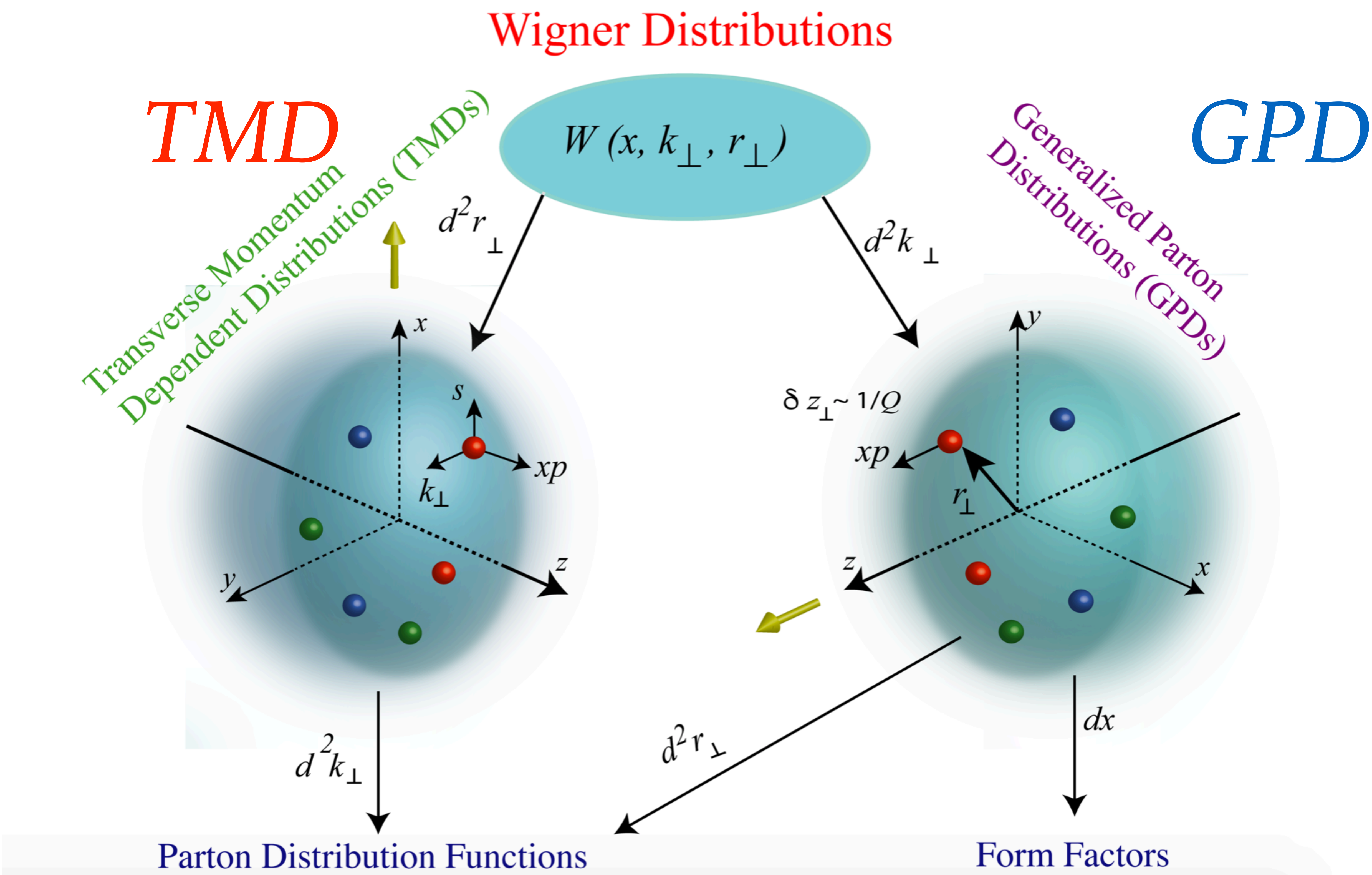
K.-F. Liu, NP A928, 99 (2014).

For Solar System

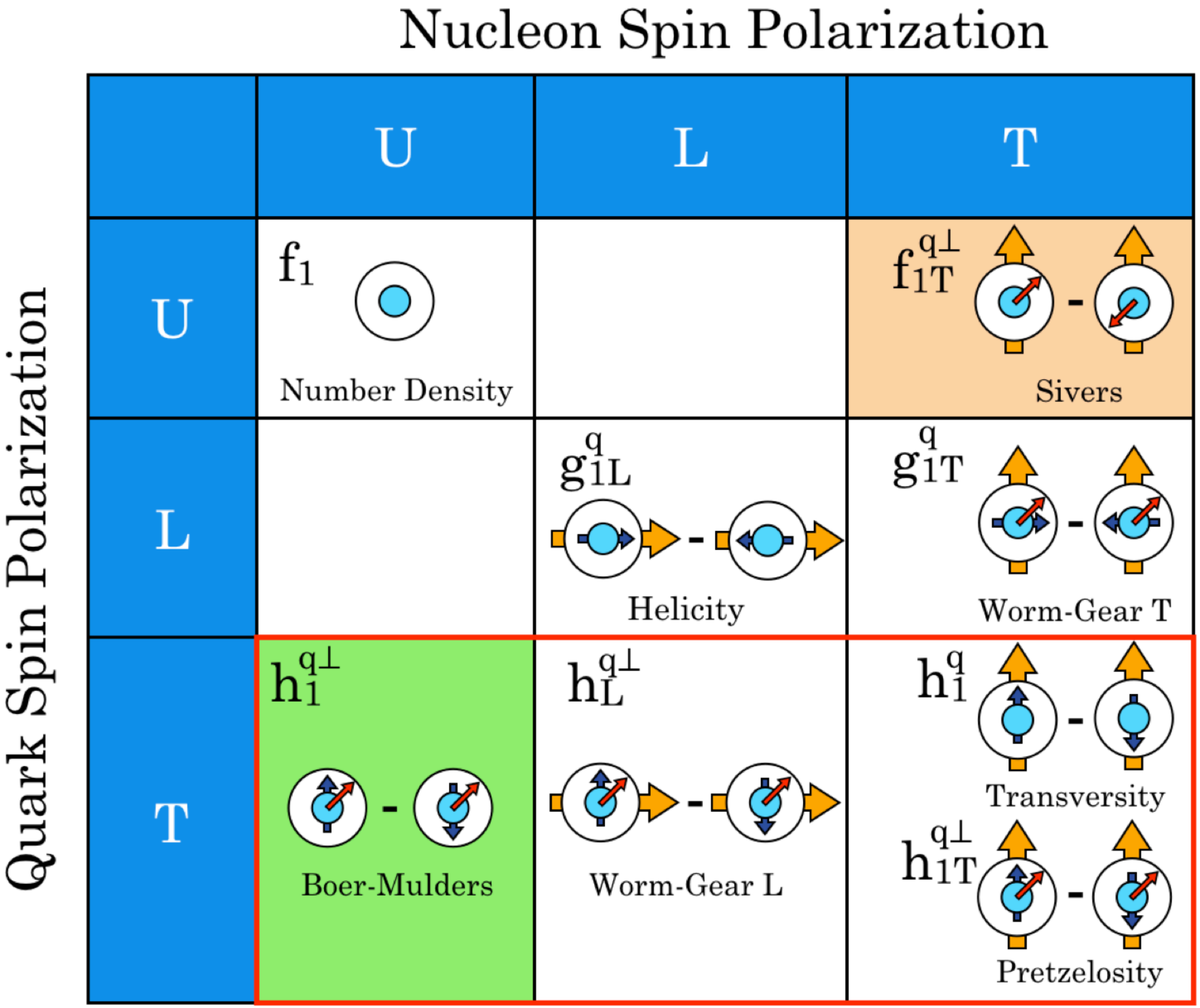


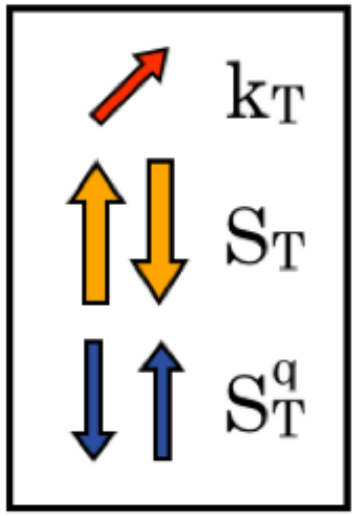
98% is angular moment!

3D-tomography of proton



TMD PDFs

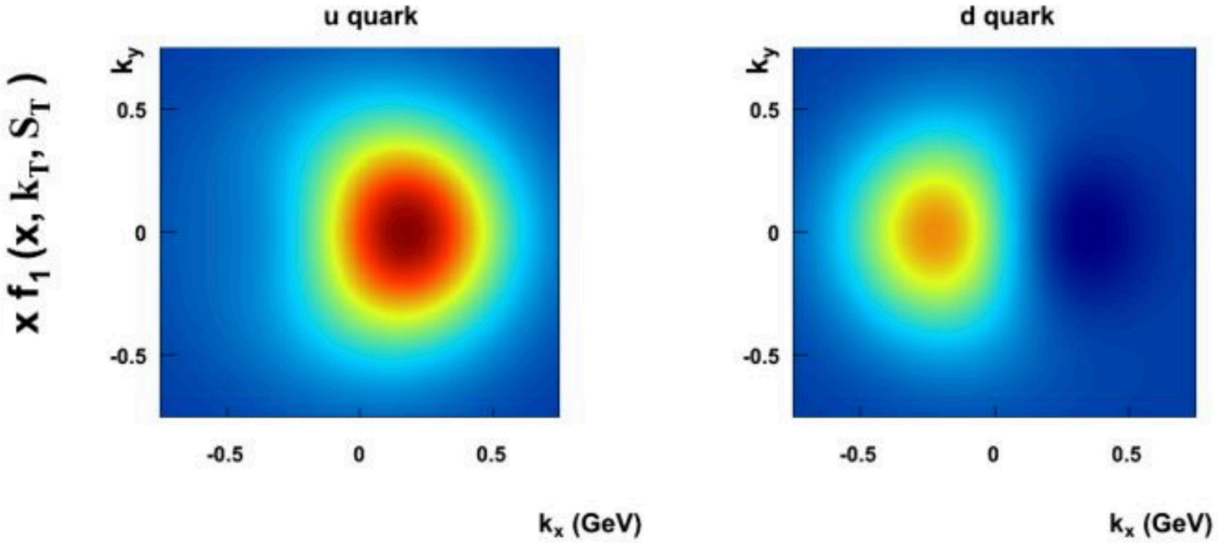




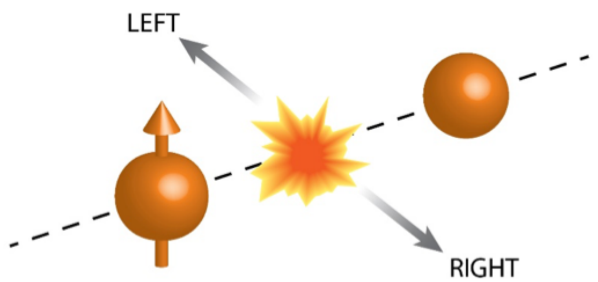
***5 additional (TMD) functions* describing the correlation between the nucleon spin, parton spin, and parton transverse momentum.**

TMD effects: Sivers effect

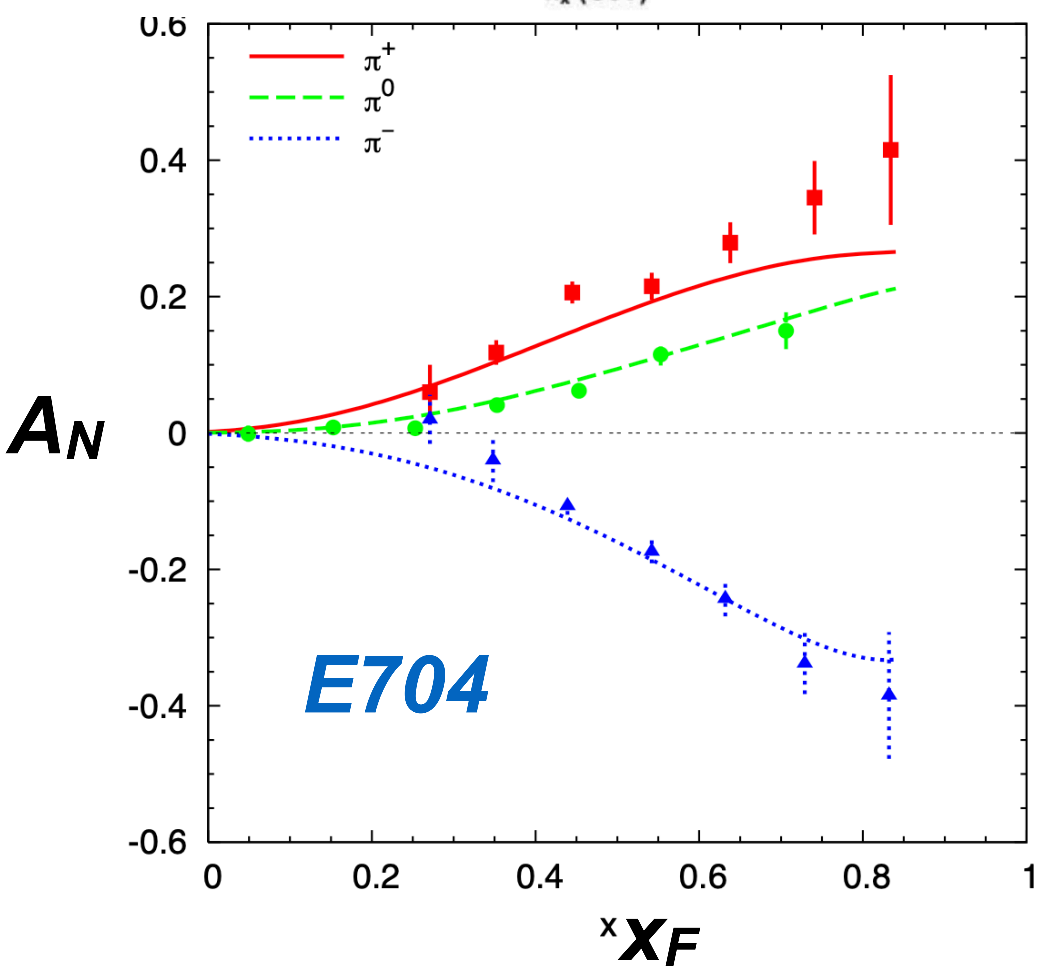
Probabilities to meet in a transversely polarized proton a parton moving to the left and to the right with respect to the $(\vec{S},\vec{p})$ plane are different!

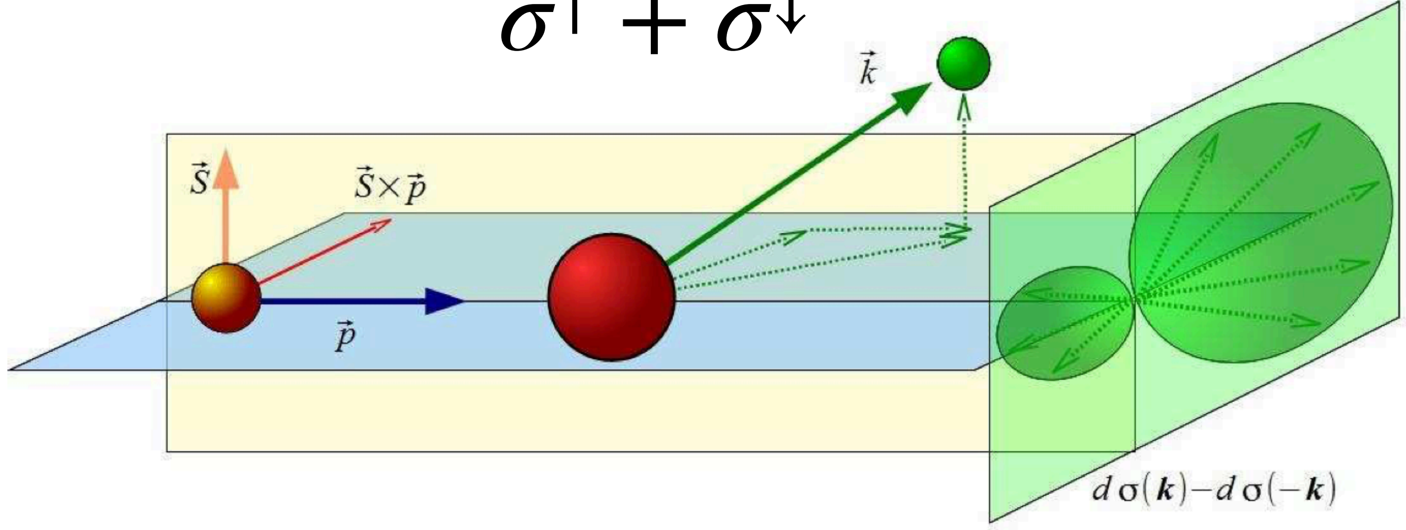


x=0.1



$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim f_{Sivers}$$

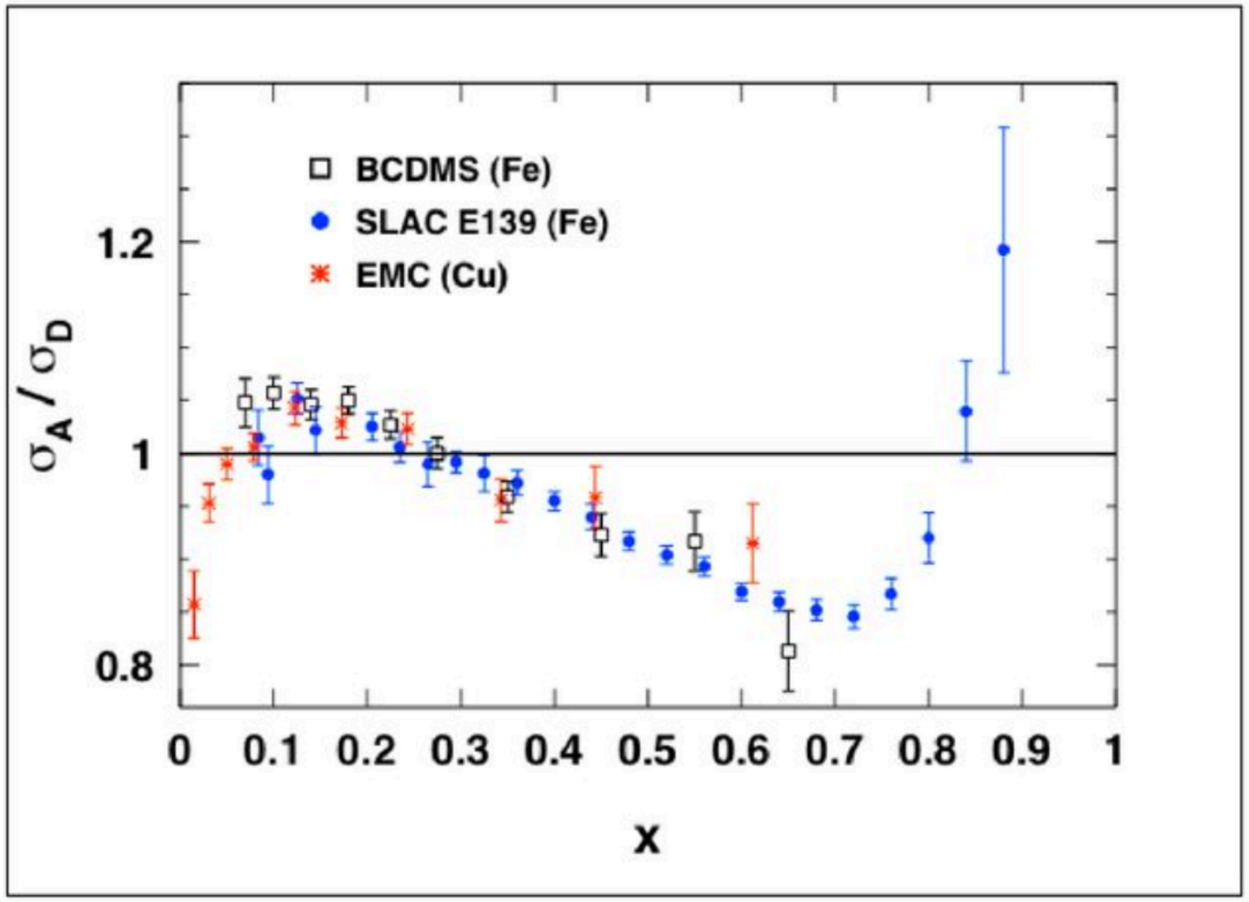




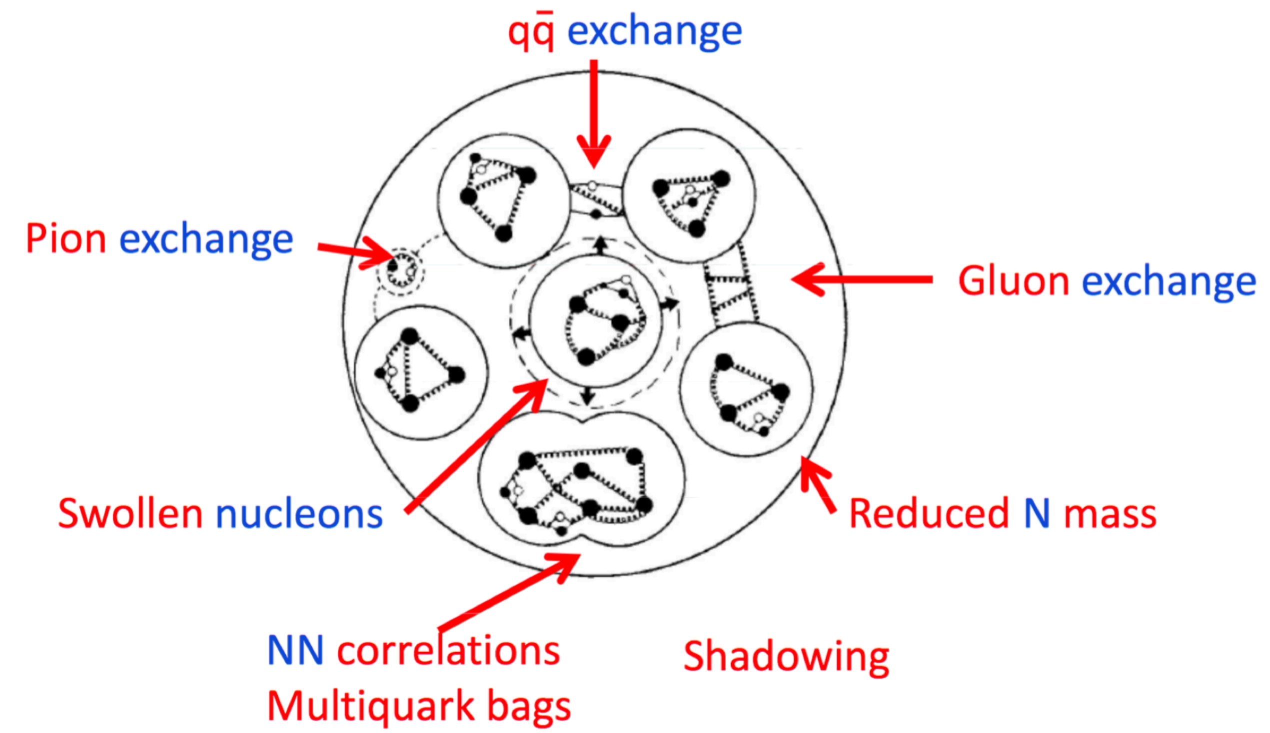
The Sievers effect is usually observed together with the Collins effect, an asymmetry arising from the fragmentation of the final state.

EMC-effect

EMC collaboration, 1982



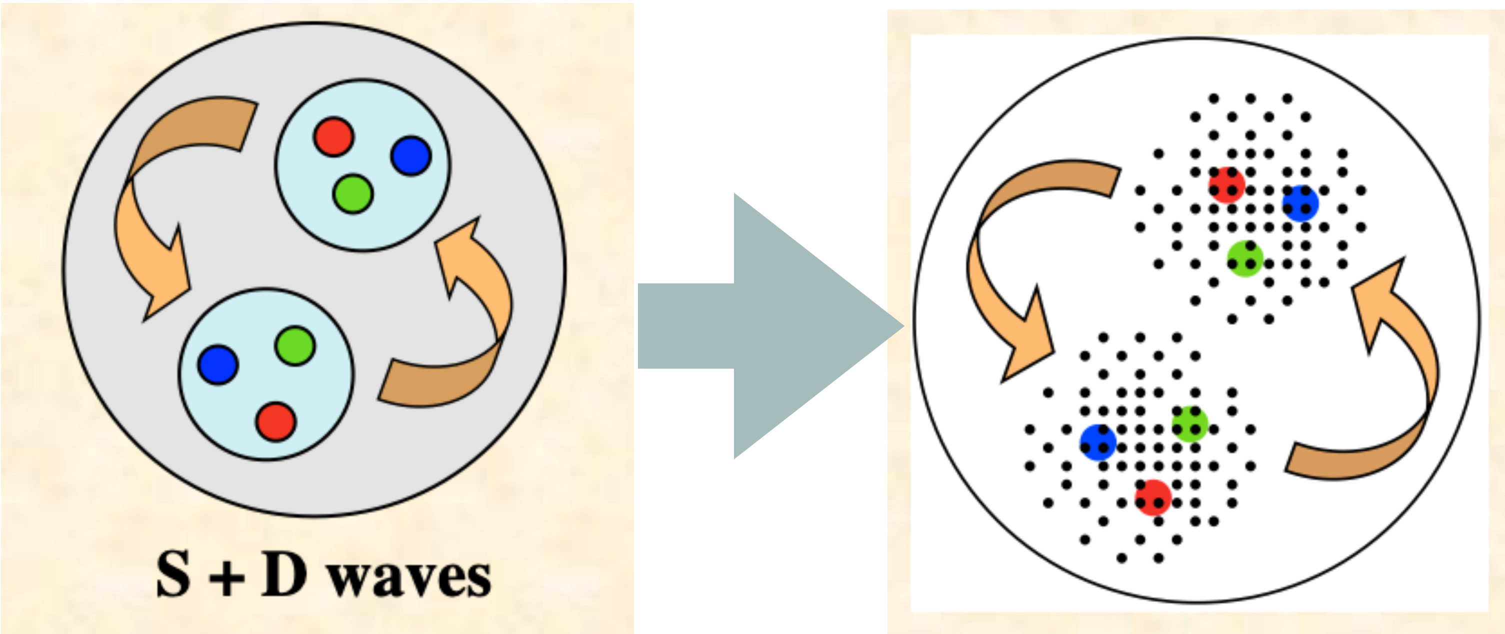
The nucleon "knows" which nucleus it is in!



Open questions:

- flavour-separated EMC-effect
- gluon EMC-effect
- polarized EMC effect

Deuteron

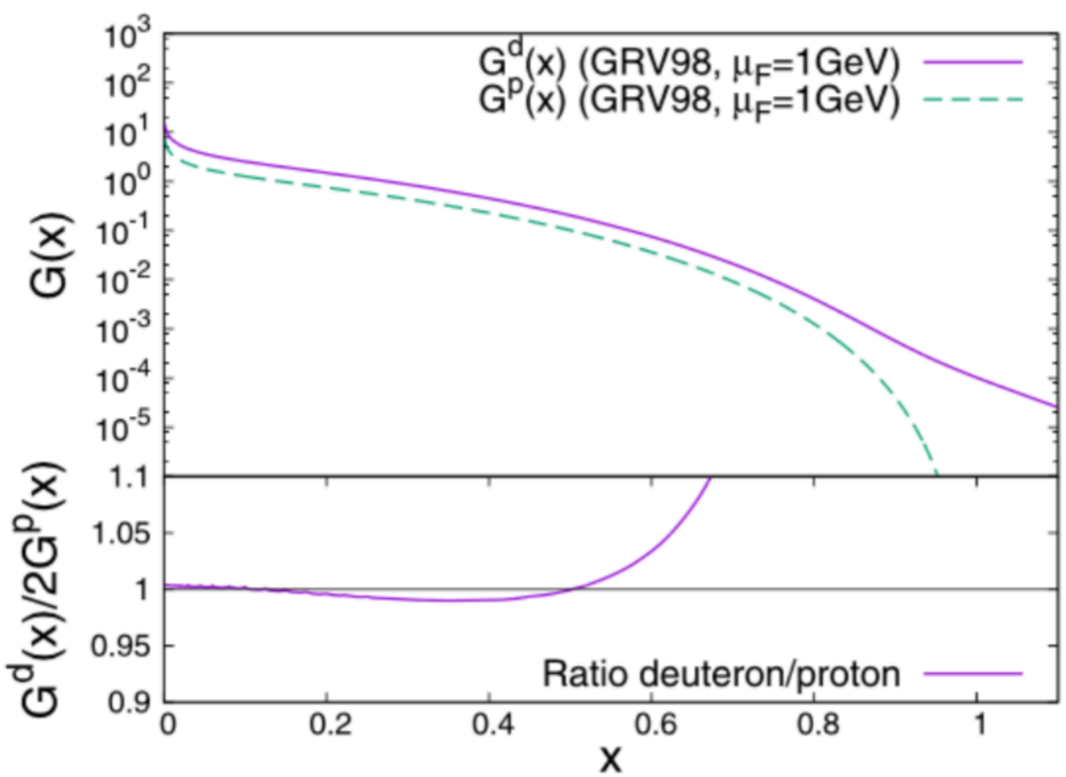


Deuteron is not just proton + neutron!

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

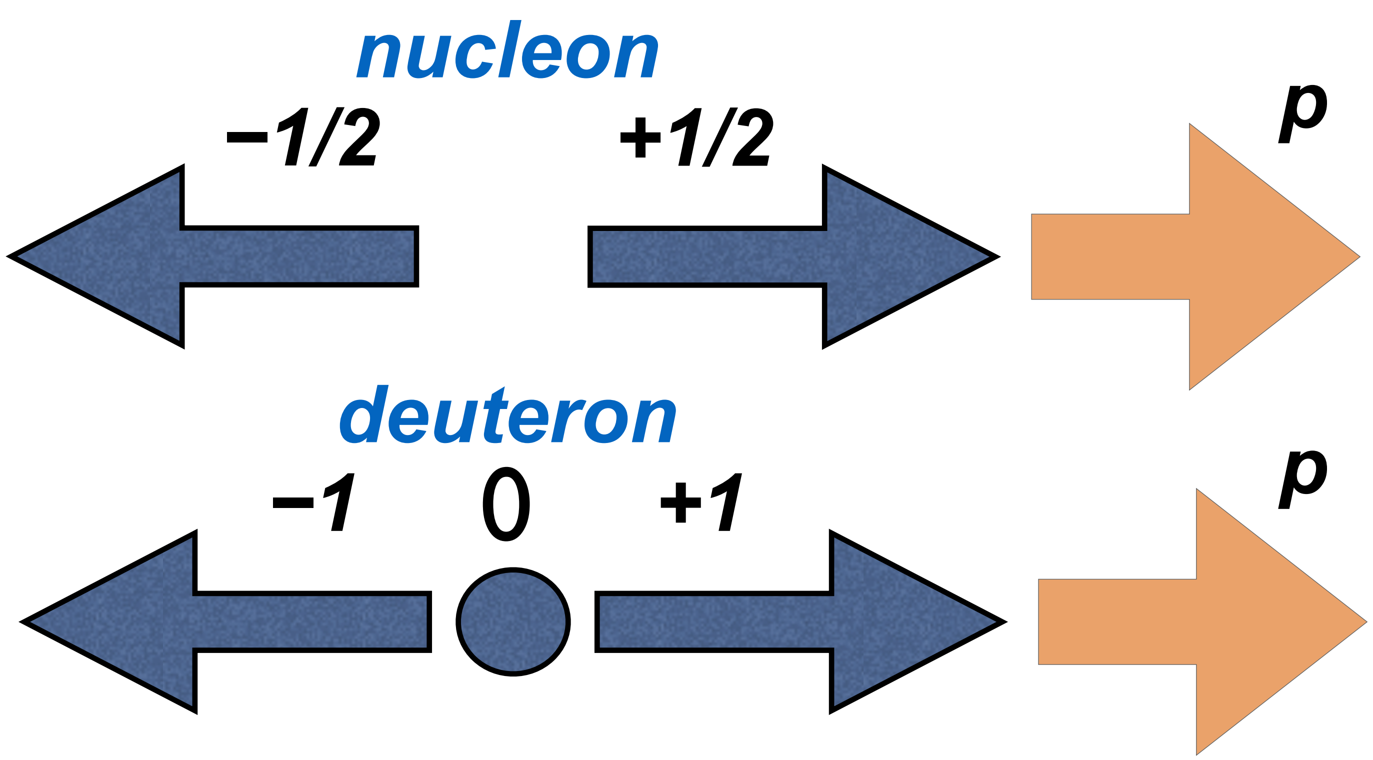
hidden color

In some models the HC fraction is up to 90%!



More gluons at large x with respect to nucleon?

Deuteron as spin-1 particle



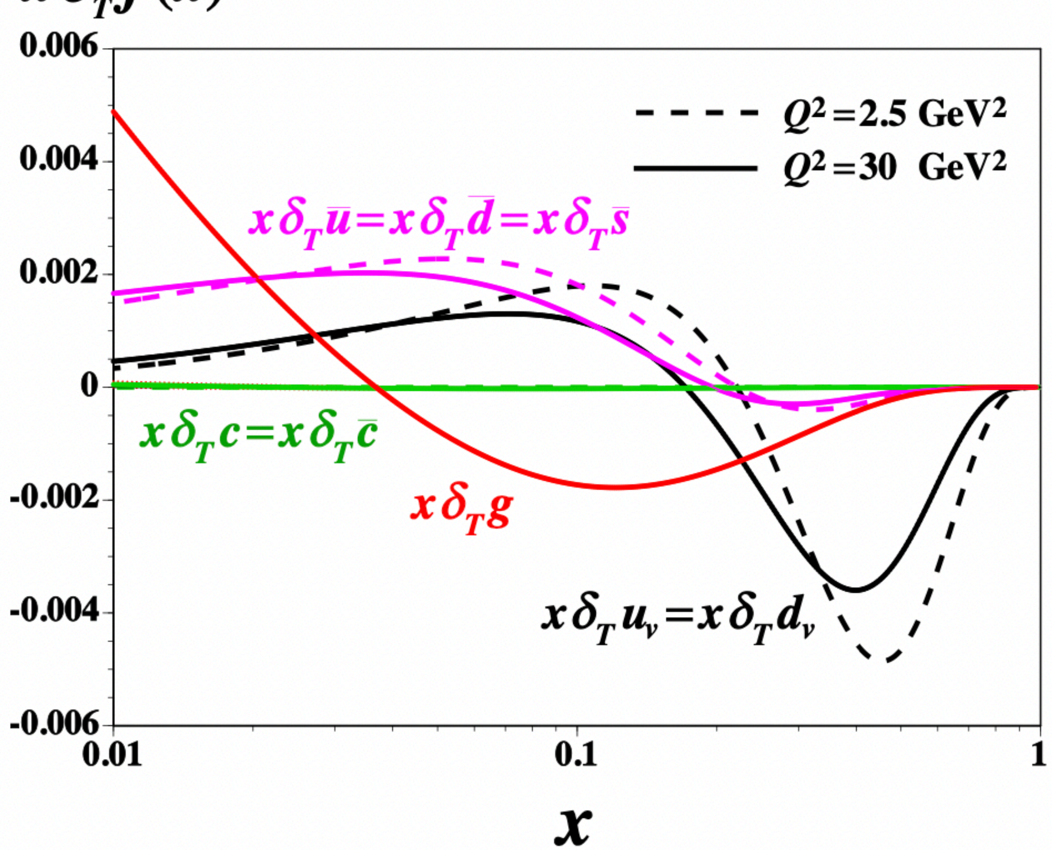
Vector polarization

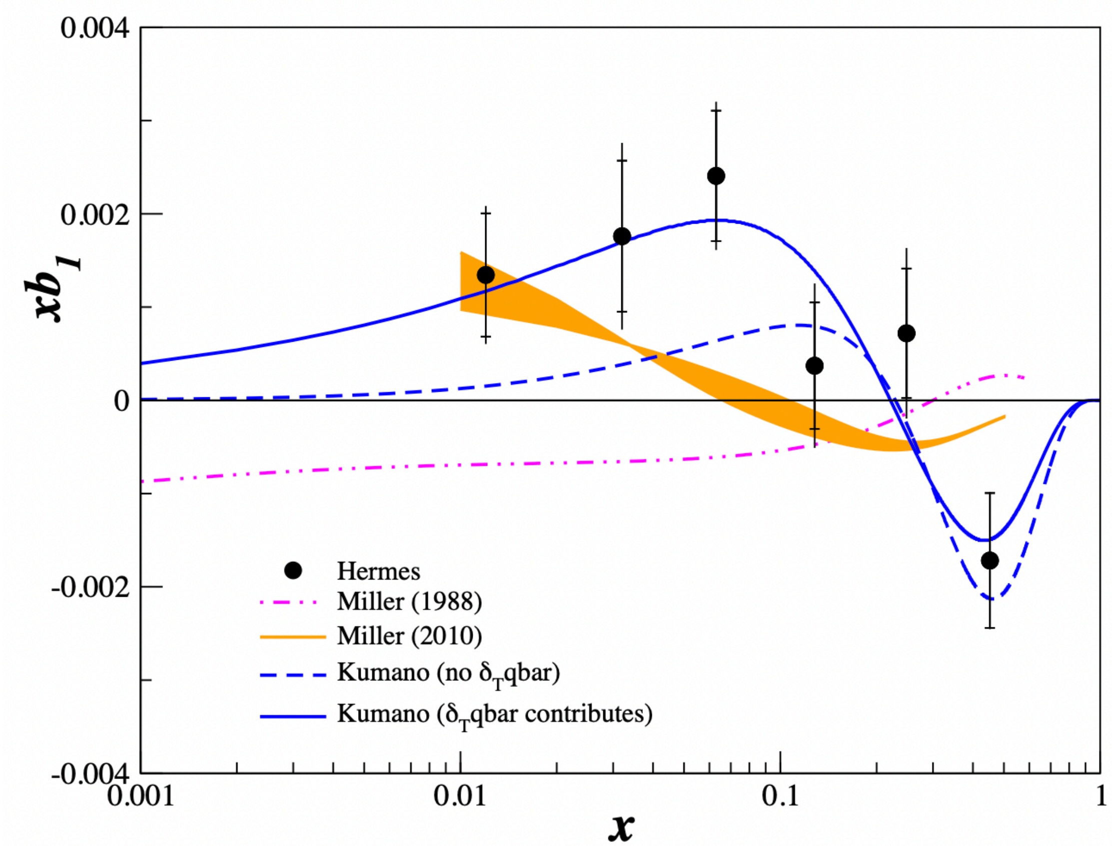
$$\frac{N_{1/2} - N_{-1/2}}{N_{1/2} + N_{-1/2}}$$

Tensor polarization

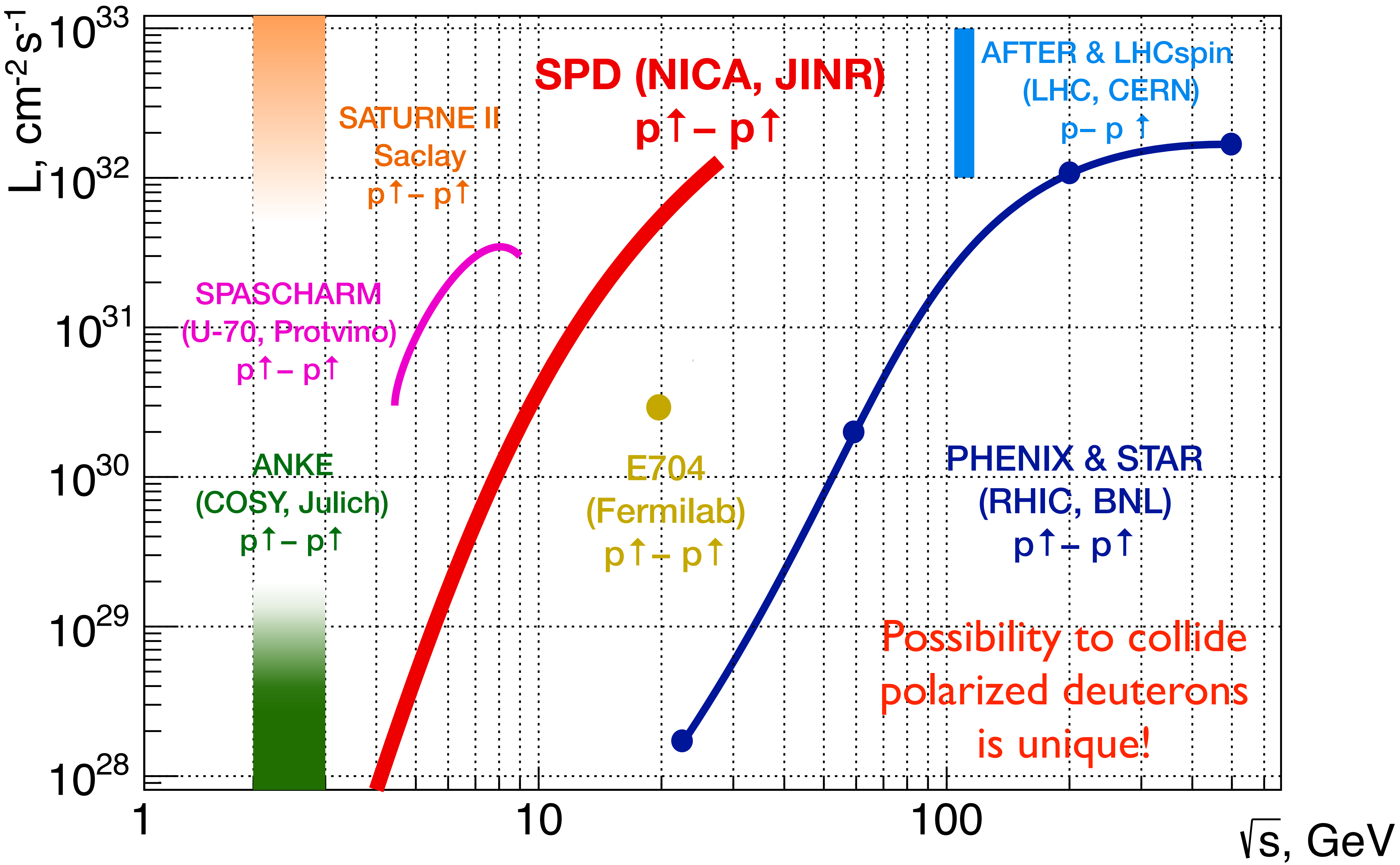
$$\frac{2N_0 - (N_{-1} + N_1)}{2N_0 + N_{1/2} + N_{-1/2}}$$

New 11 "tensor" PDFs, mostly unknown

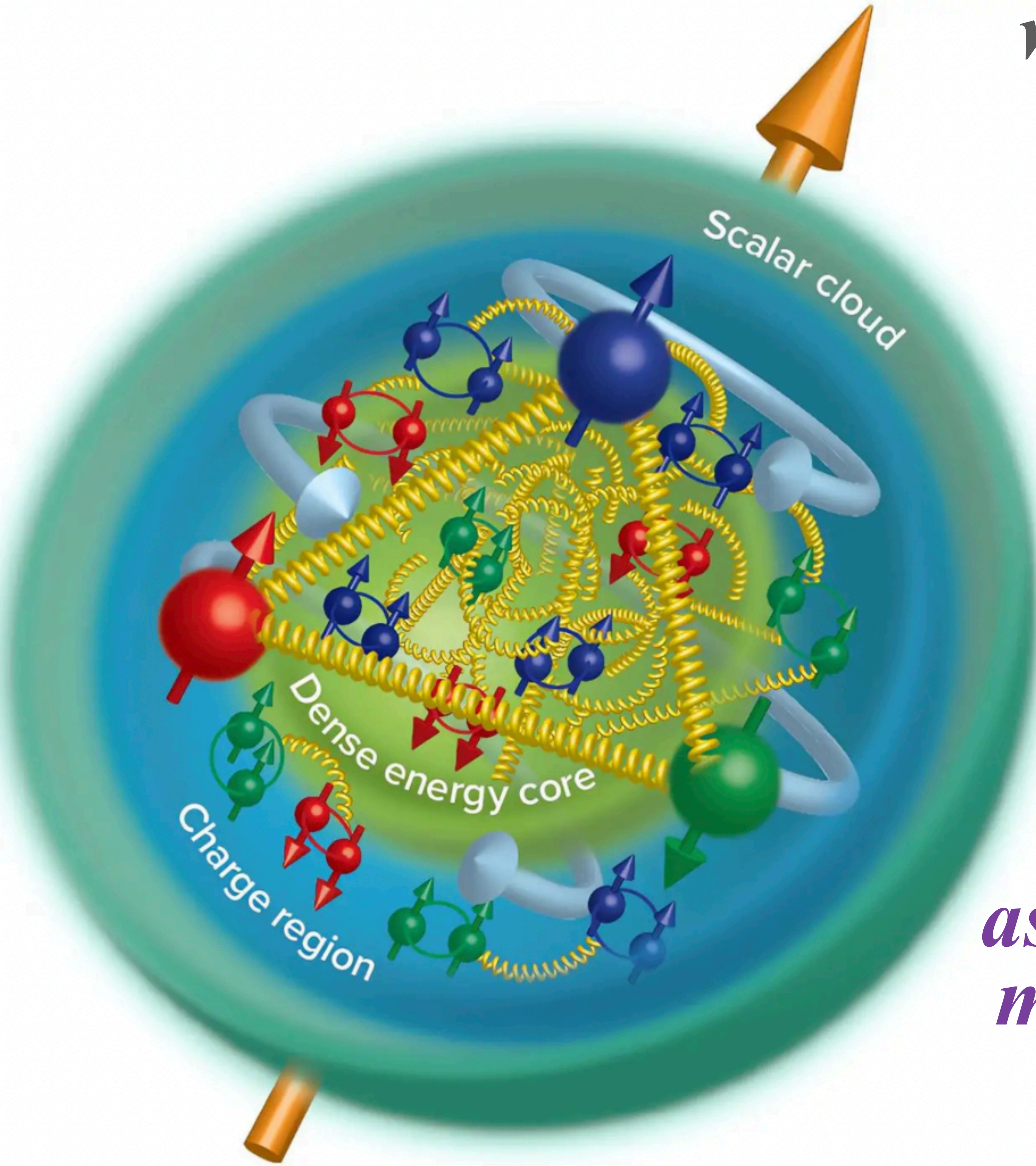




SPD and others



Spin Physics @ NICA



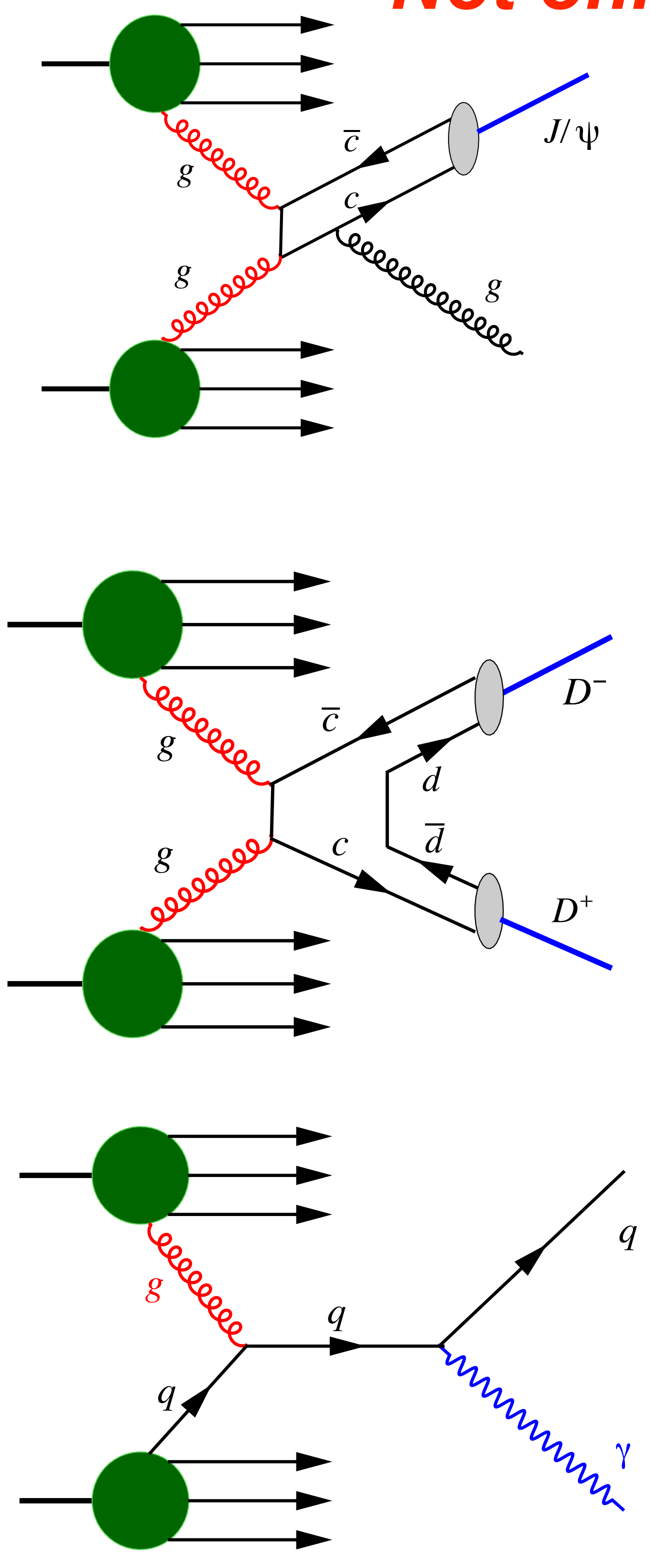
we plan to study how the proton and deuteron spin!

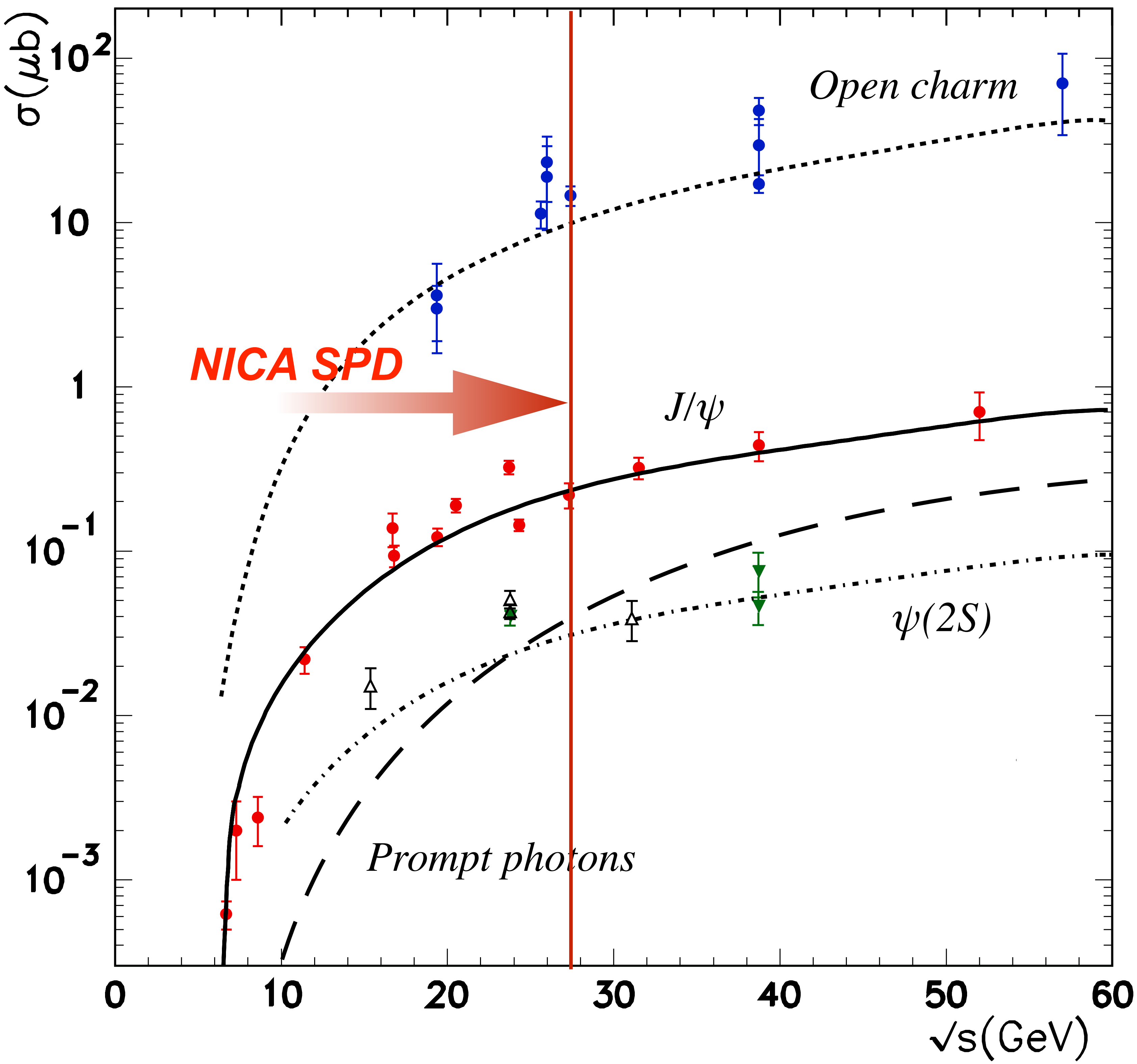
especially their gluon component!

Gluon TMD PDFs via asymmetries and angular modulations in the cross sections

SPD and gluon structure of nucleon

Not only J/ψ!





SPD gluon program

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

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Progress in Particle and Nuclear Physics xxx (xxxx) xxx

arXiv:2011.15005

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Review

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

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On the physics potential to study the gluon content of proton and deuteron at NICA SPD #1

A. Arbuzov (Dubna, JINR), A. Bacchetta (Pavia U. and INFN, Pavia), M. Butenschoen (Hamburg U., Inst. Theor. Phys. II), F.G. Celiberto (Pavia U. and INFN, Pavia and ECT, Trento and Fond. Bruno Kessler, Povo), U. D'Alesio (Cagliari U. and INFN, Cagliari) et al. (Nov 30, 2020)

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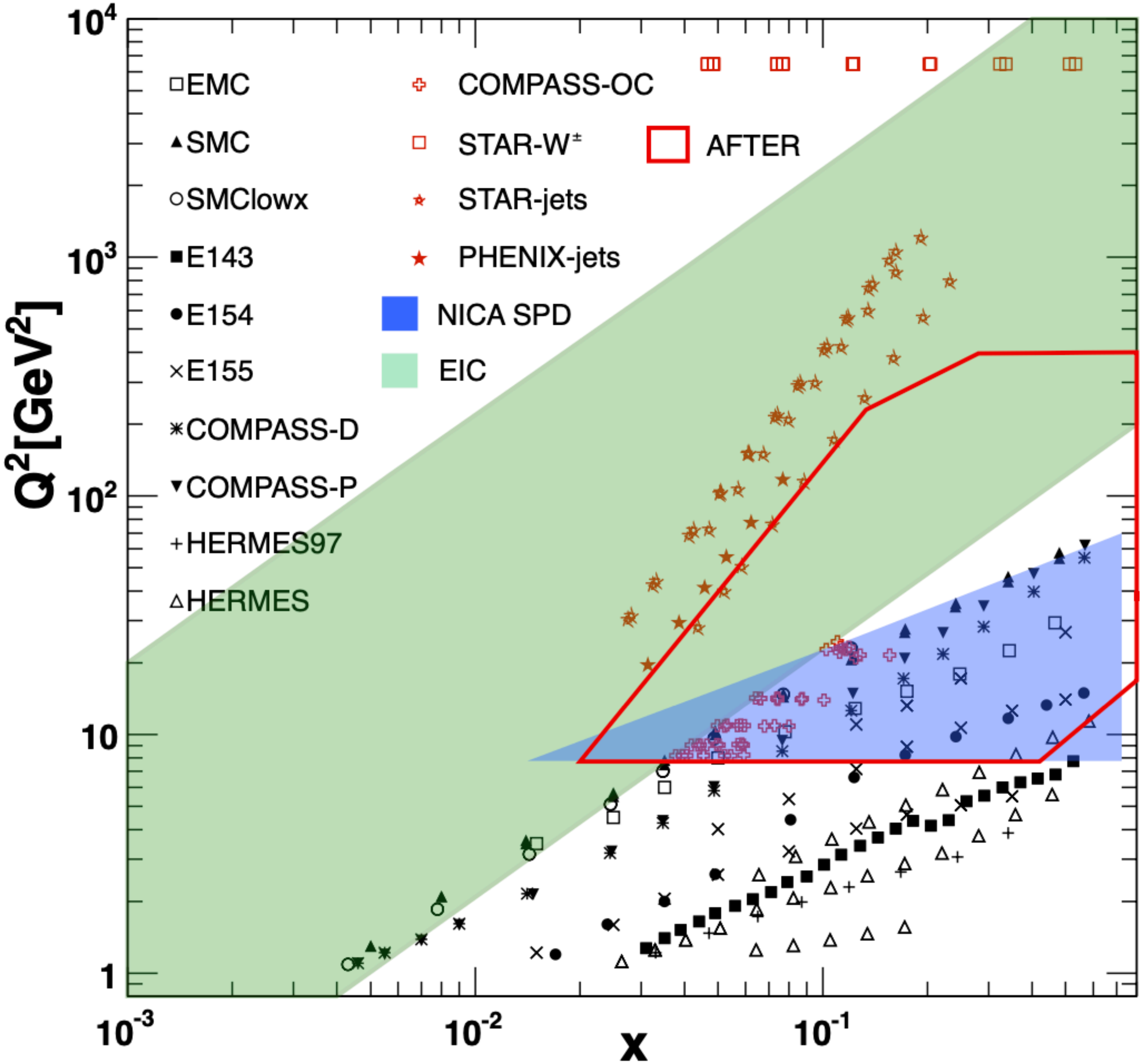
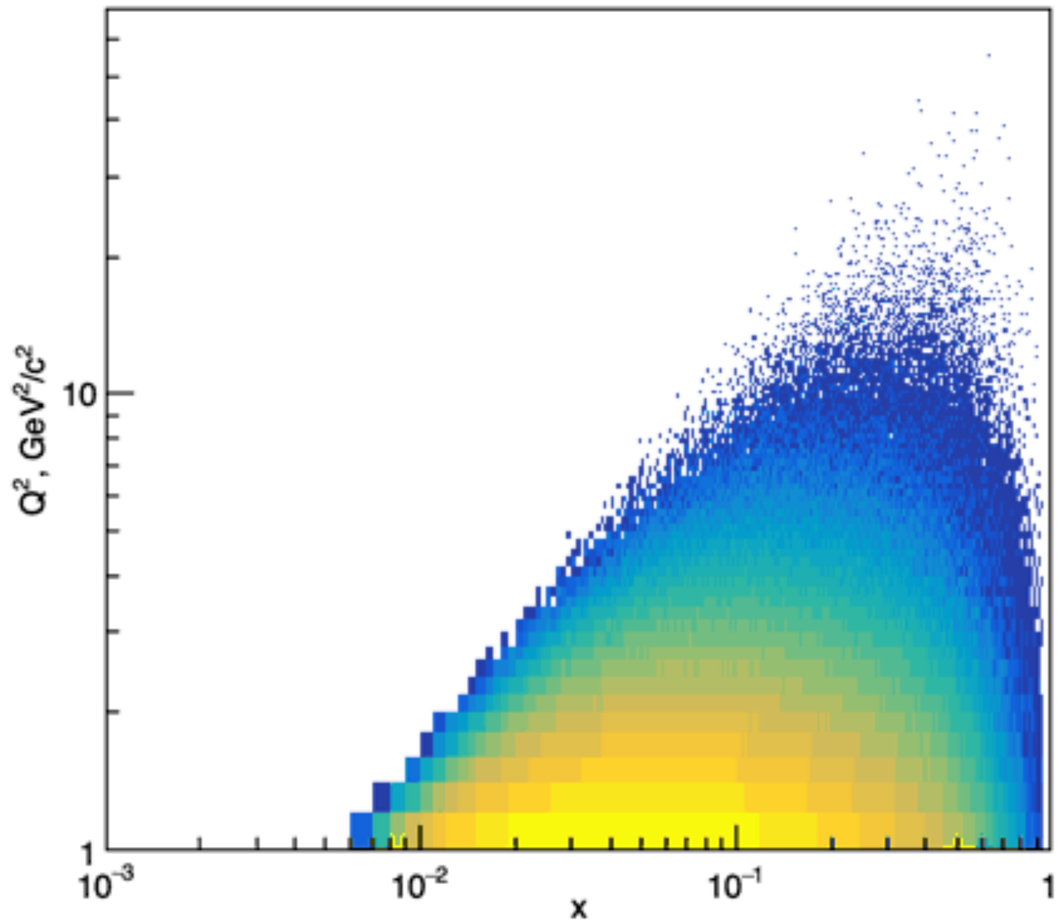
SPD and others

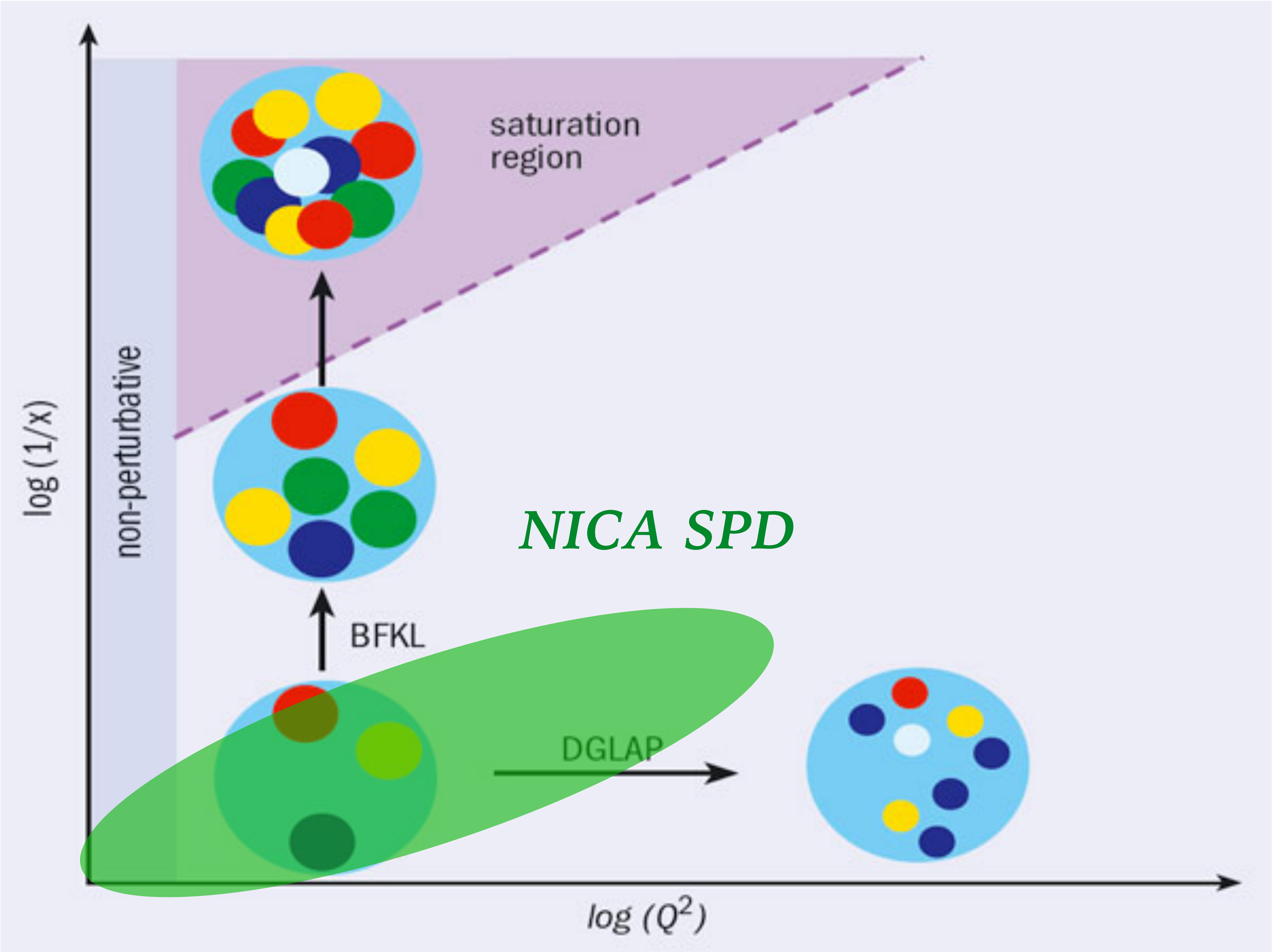




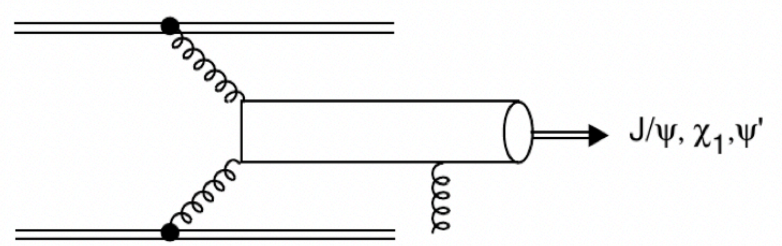
$Q^2 = 1\ GeV^2/c^2, < x > = 0.16$

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

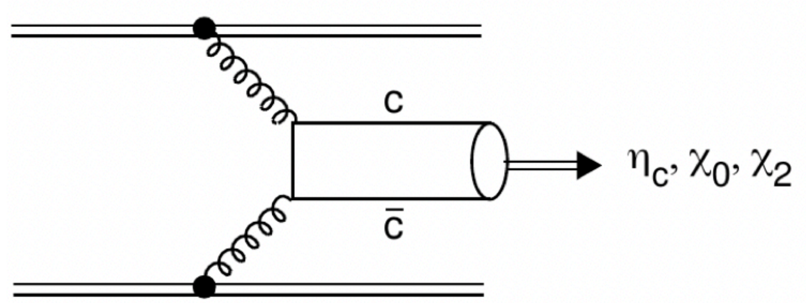
QCD landscape & SPD

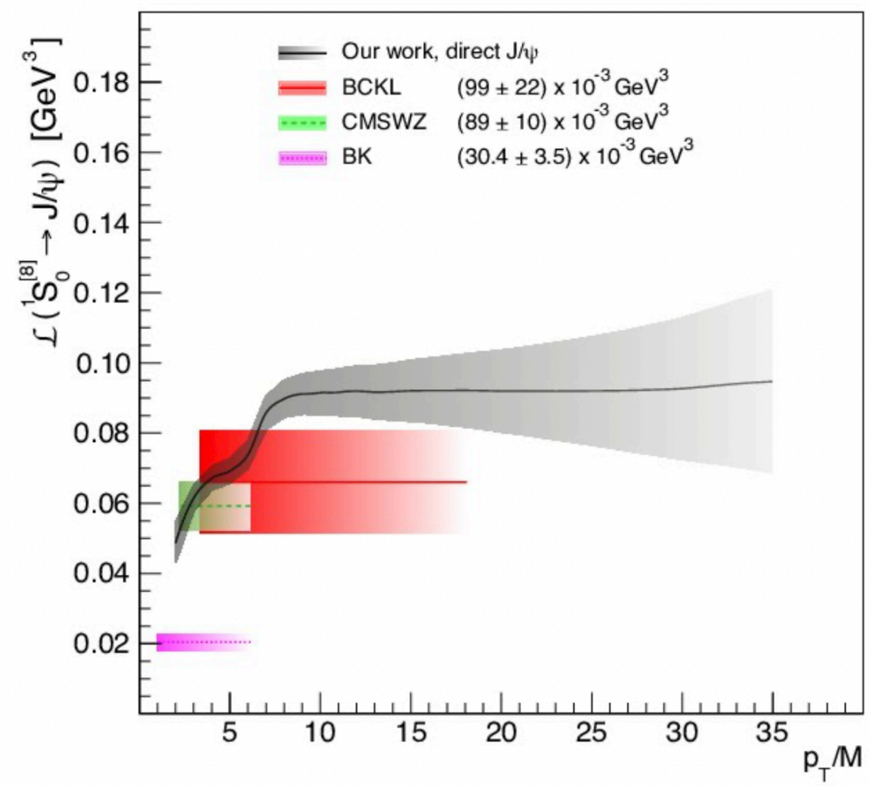


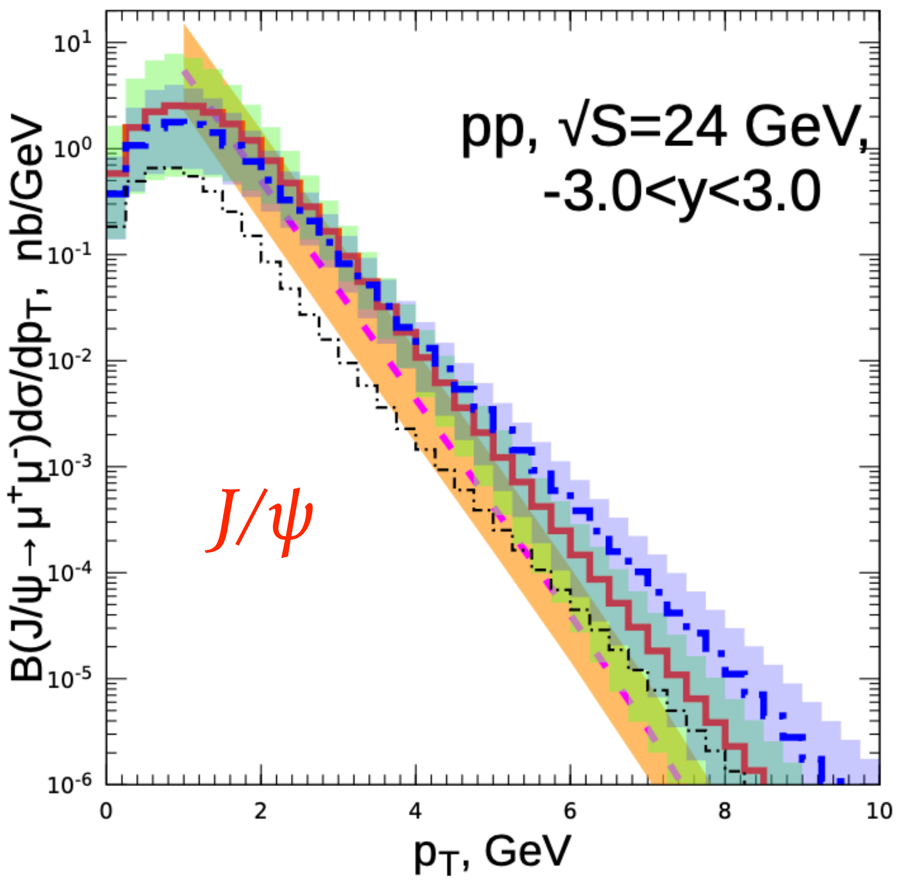
Charmonia production

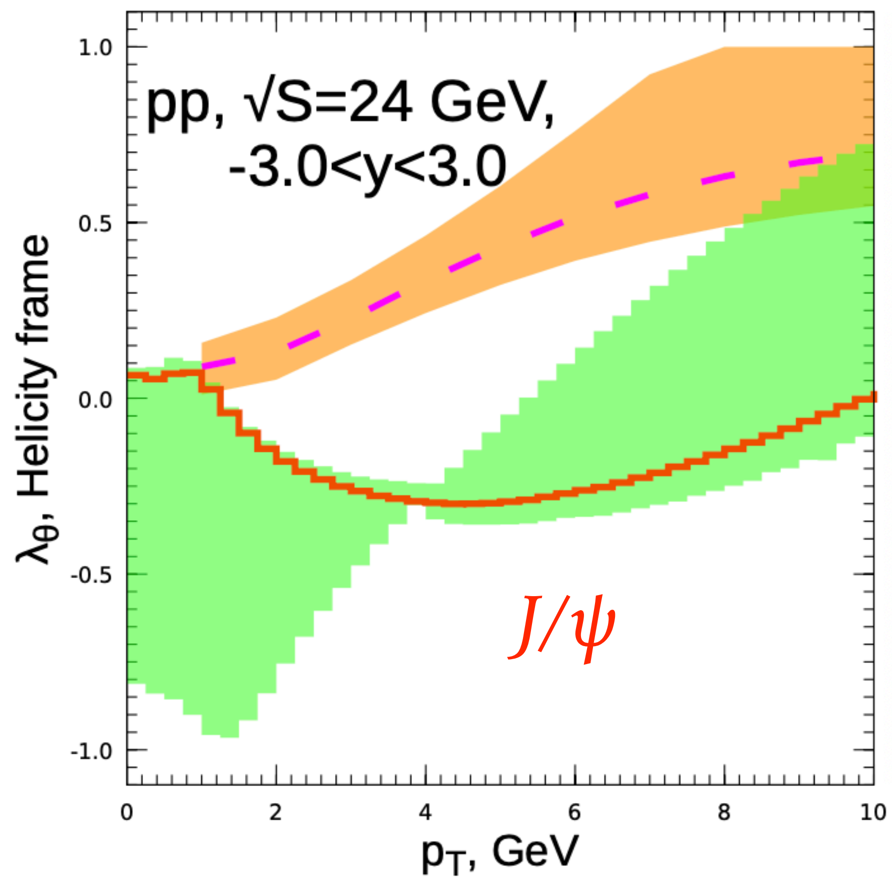


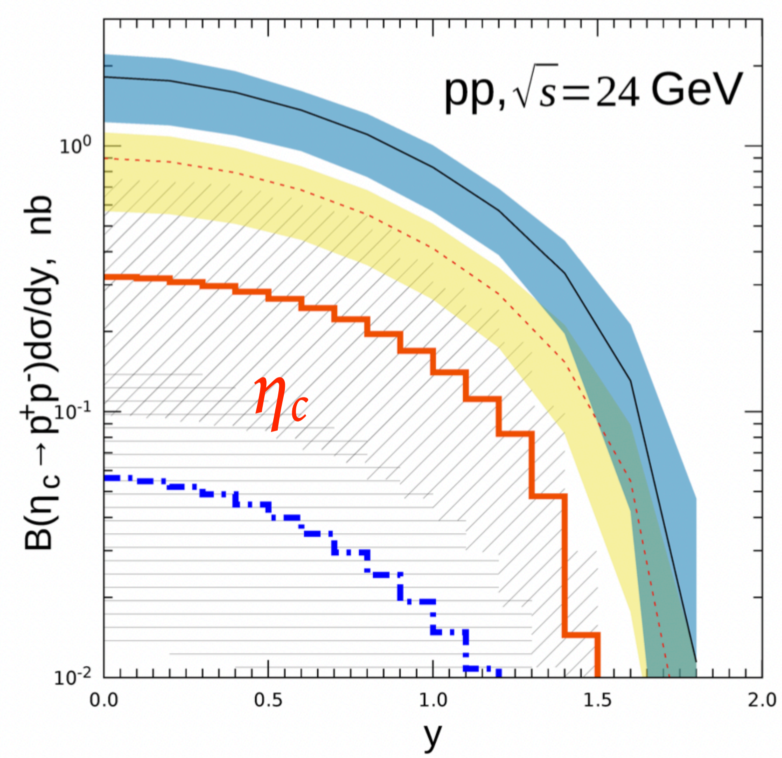
NRQCD — LDMEs



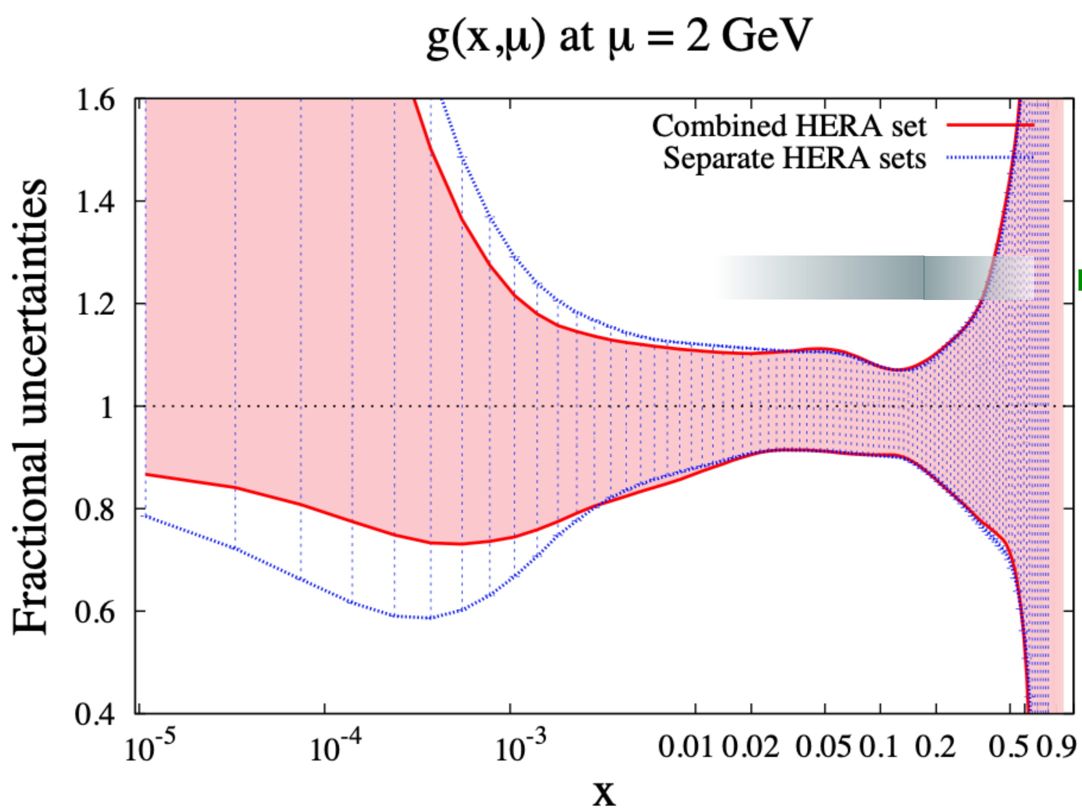




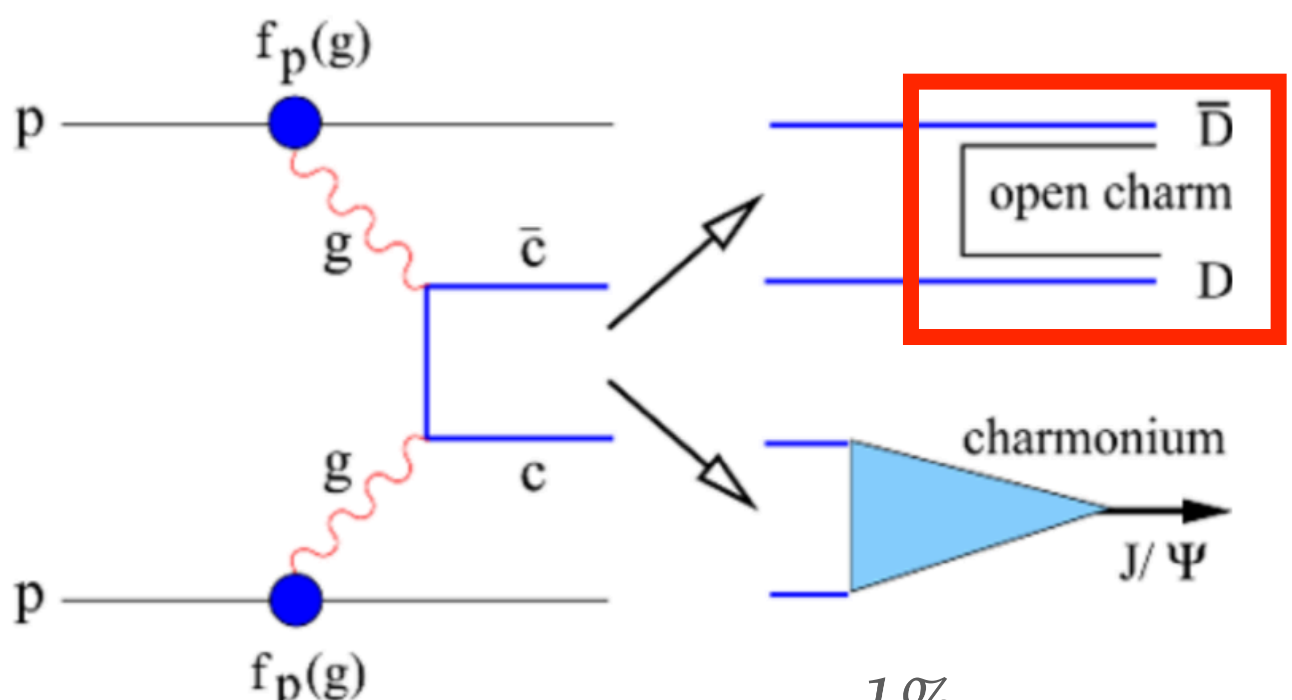




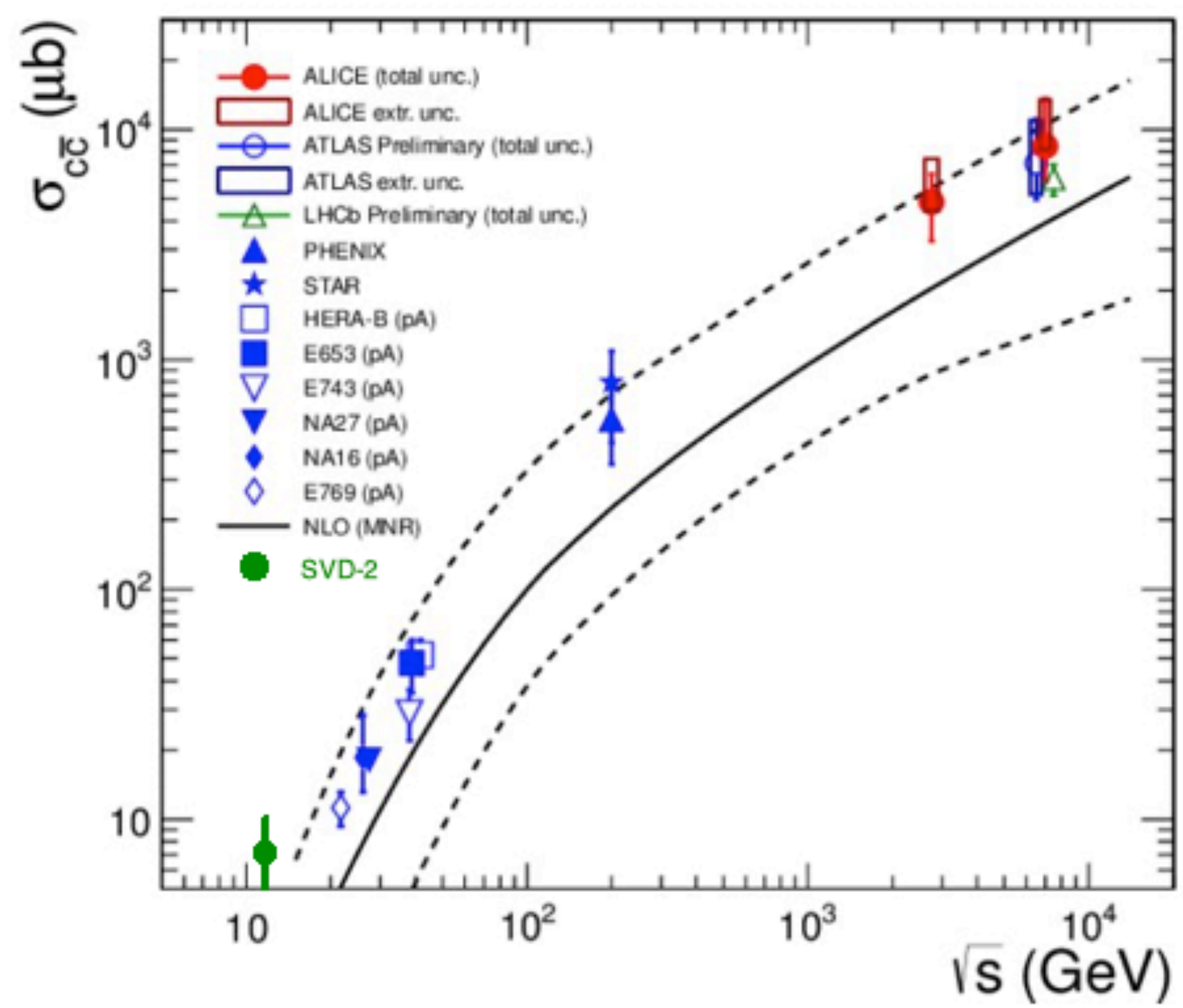
unpolarized gluons in proton at high x



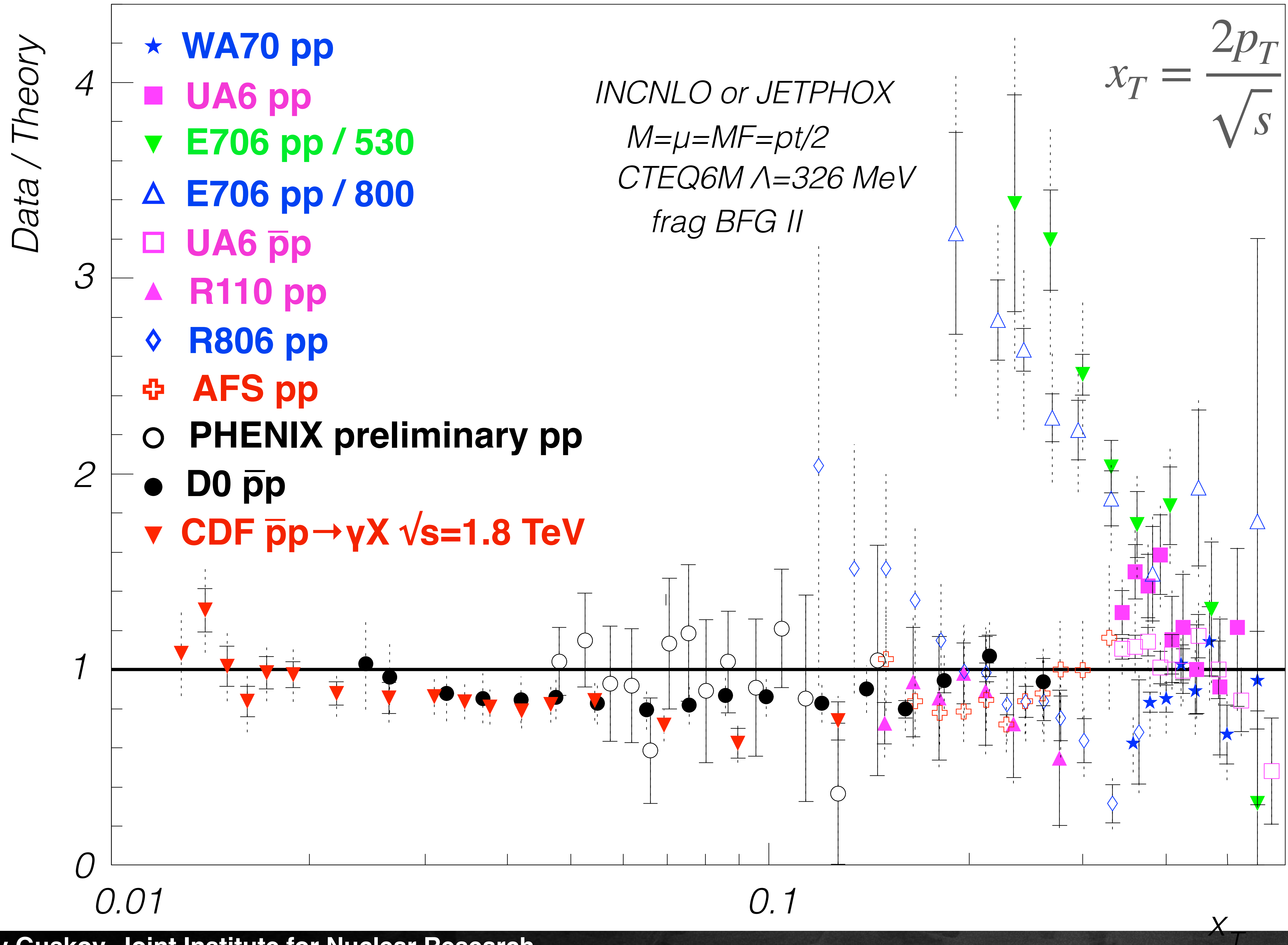
Good opportunity for SPD



∼1%



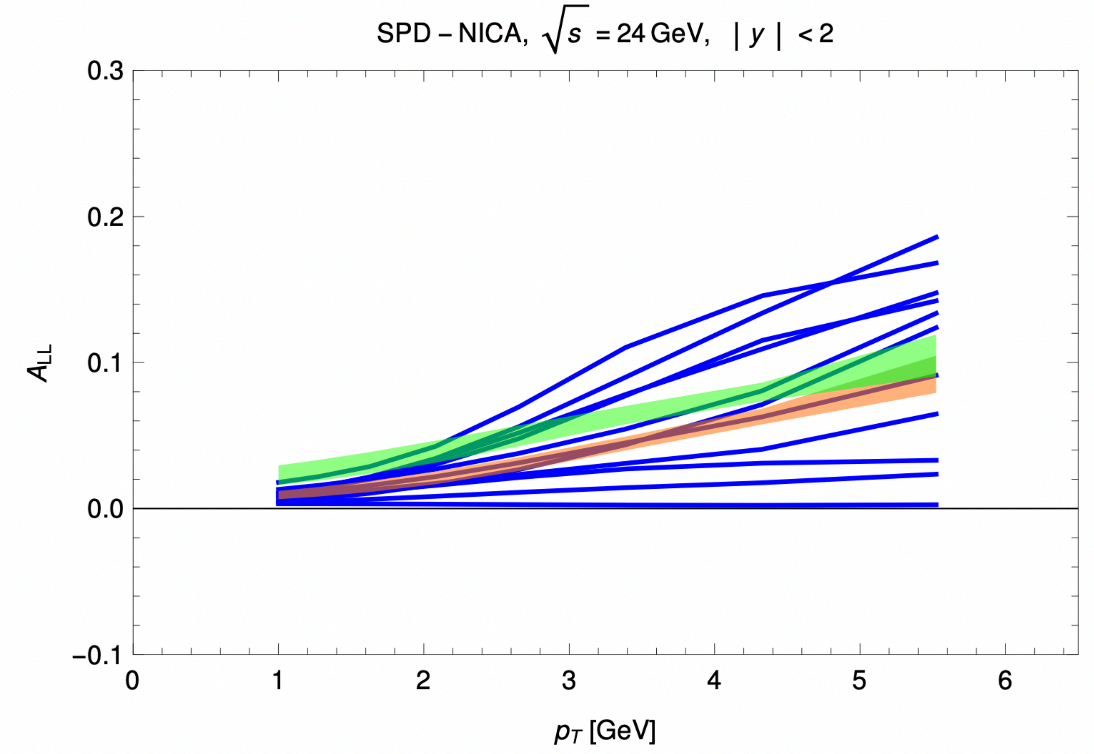
Prompt photon puzzle



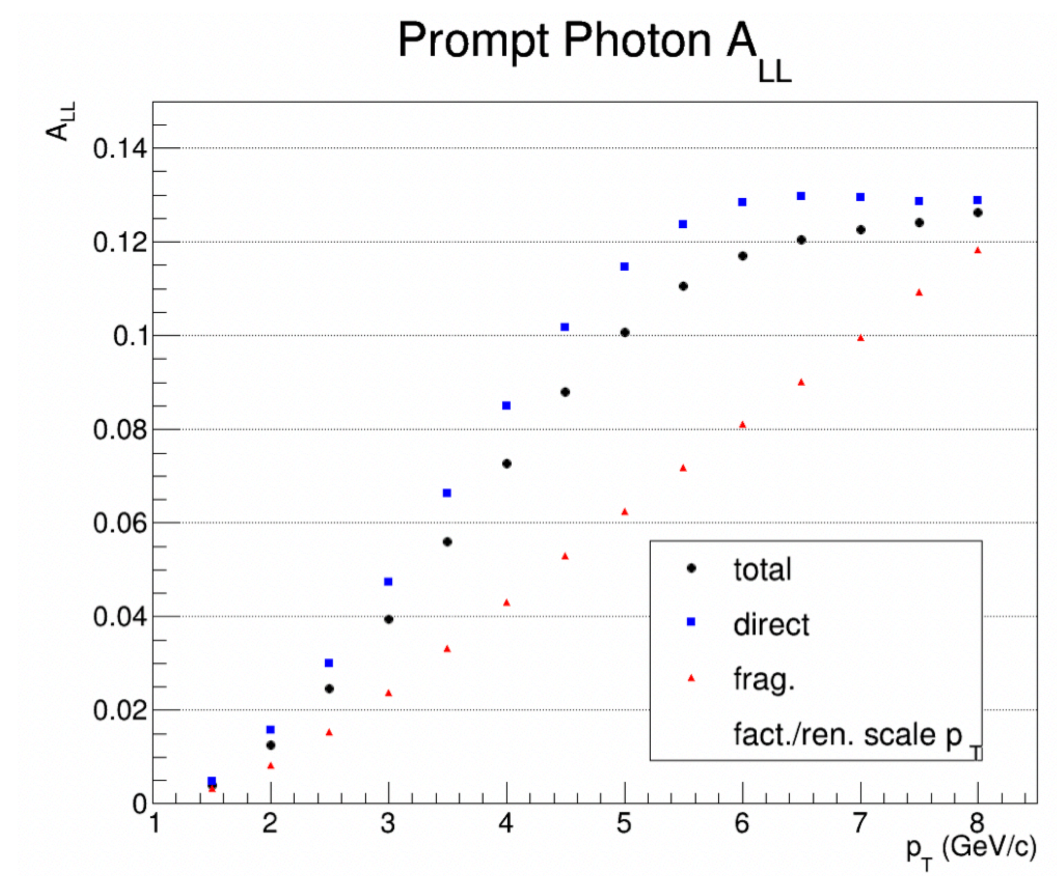
Gluon helicity function $\Delta g(x)$: expectations for A_{LL} at NICA energies

$gg \rightarrow J/\psi g$

M. Nefedov

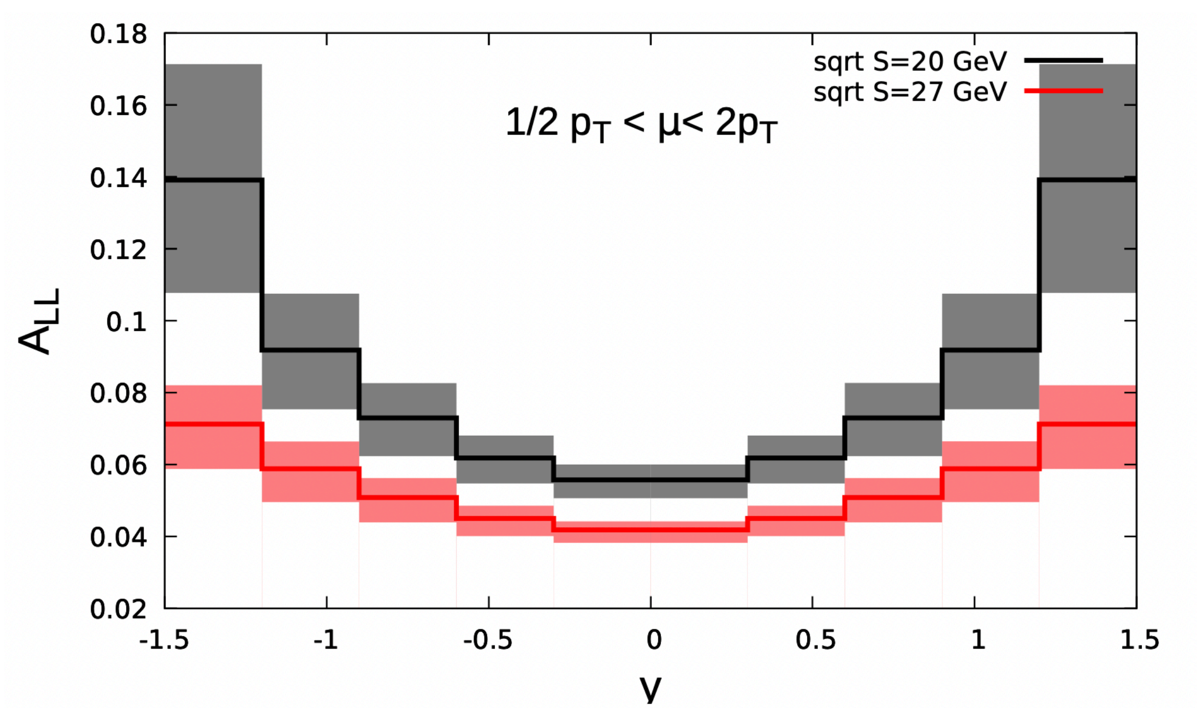


W. Vogelsang



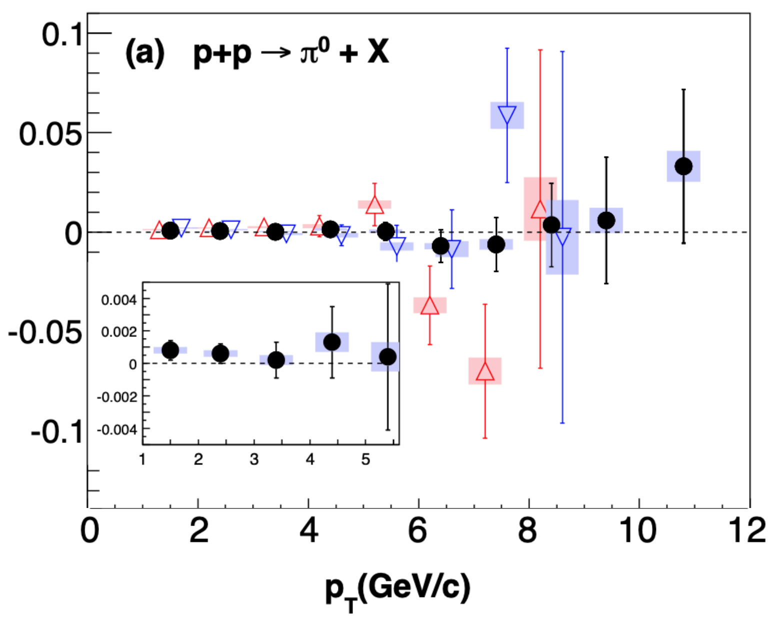
A. Shipilova

$qg \rightarrow q\gamma$



Gluon Sivers function $\Delta^g_N(x,k_T)$

p+p $\sqrt{s}$=200 GeV



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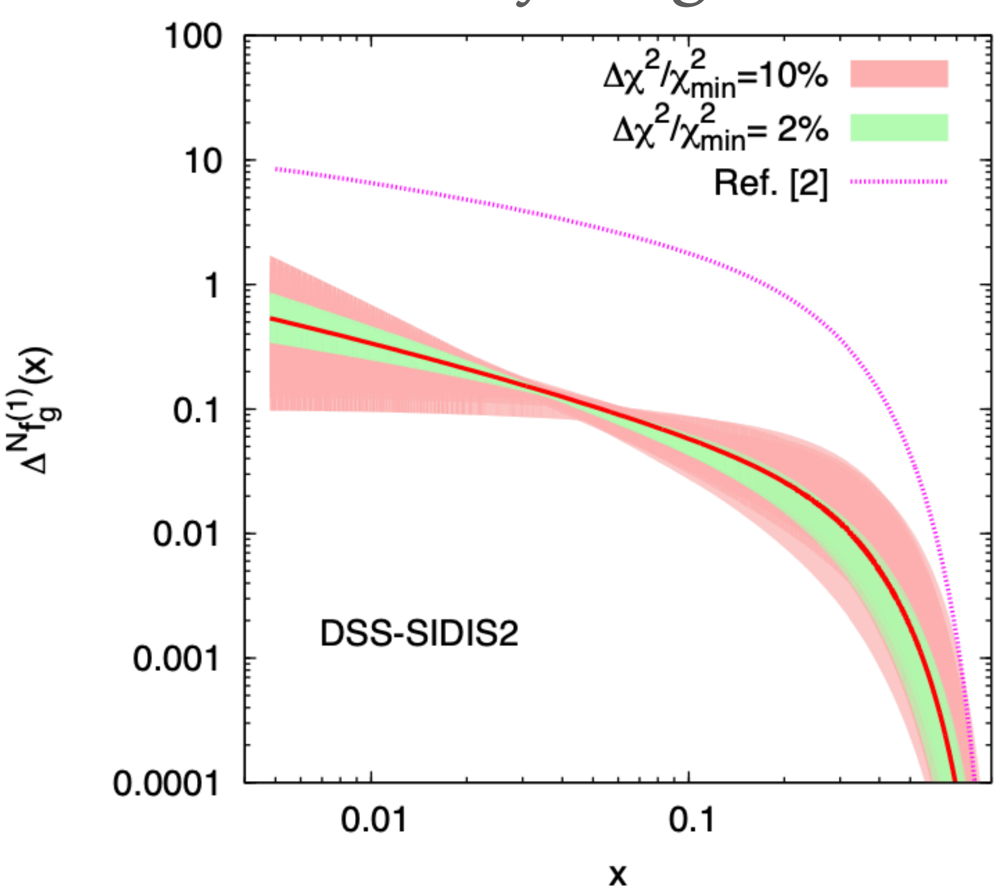
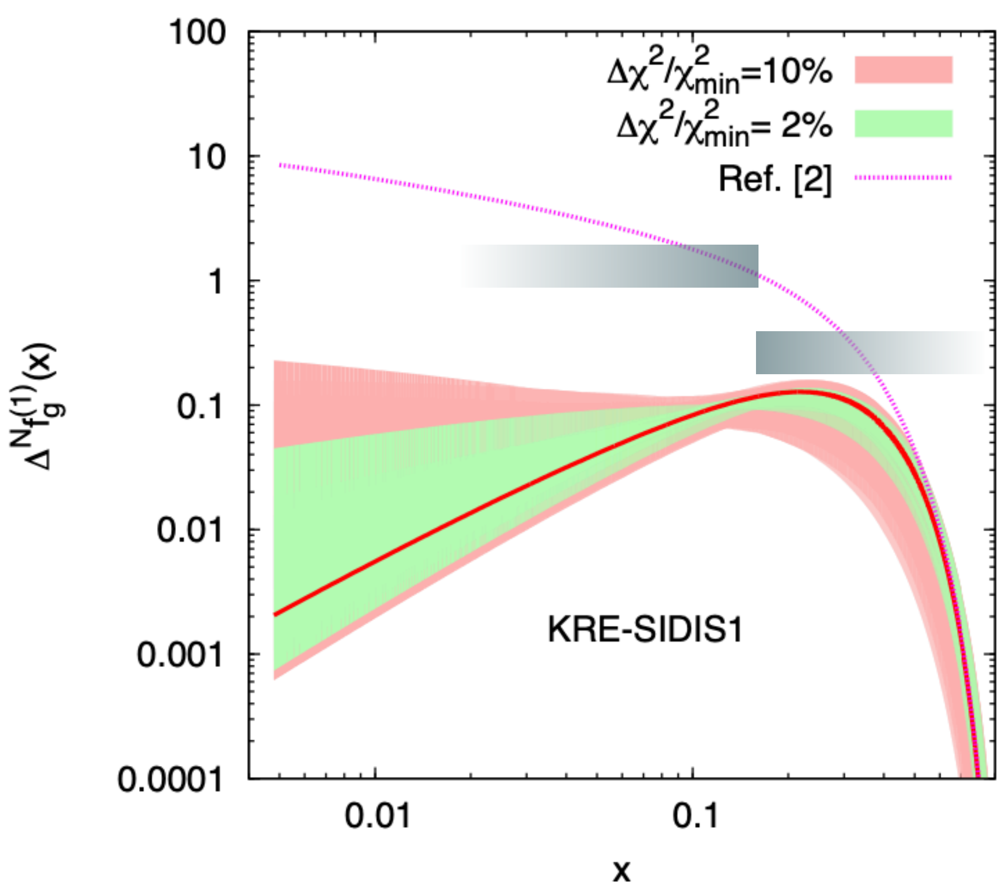
PHENIX

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

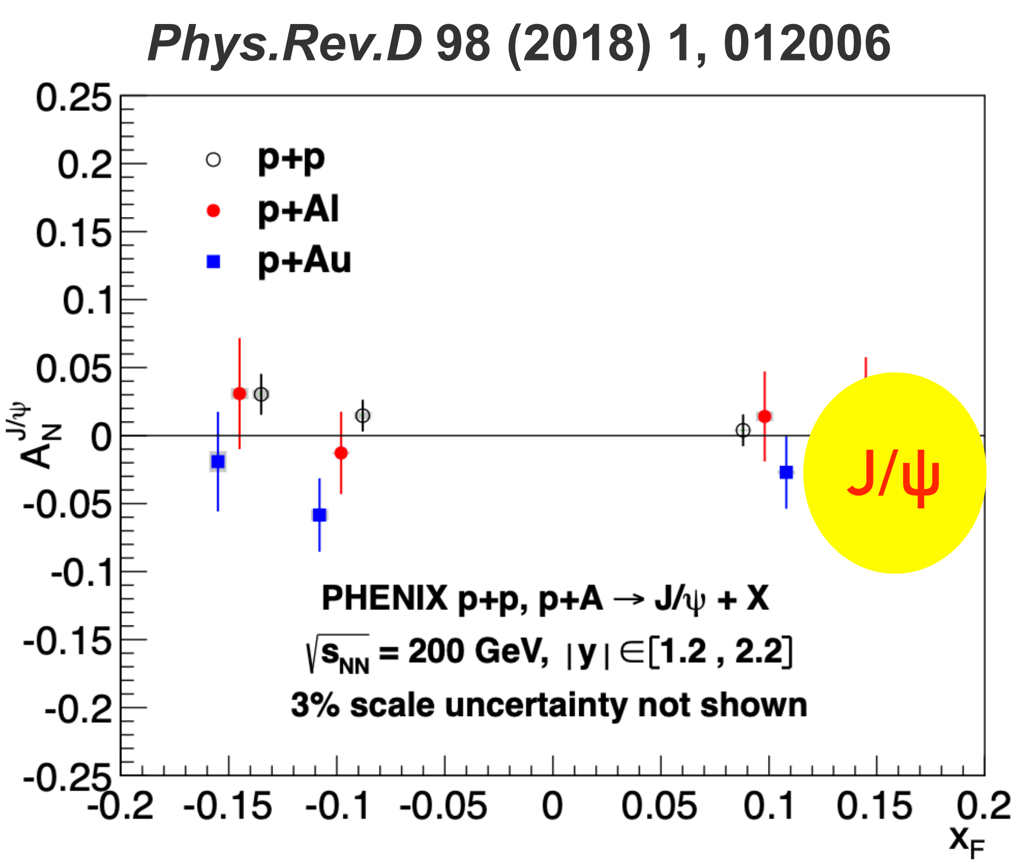


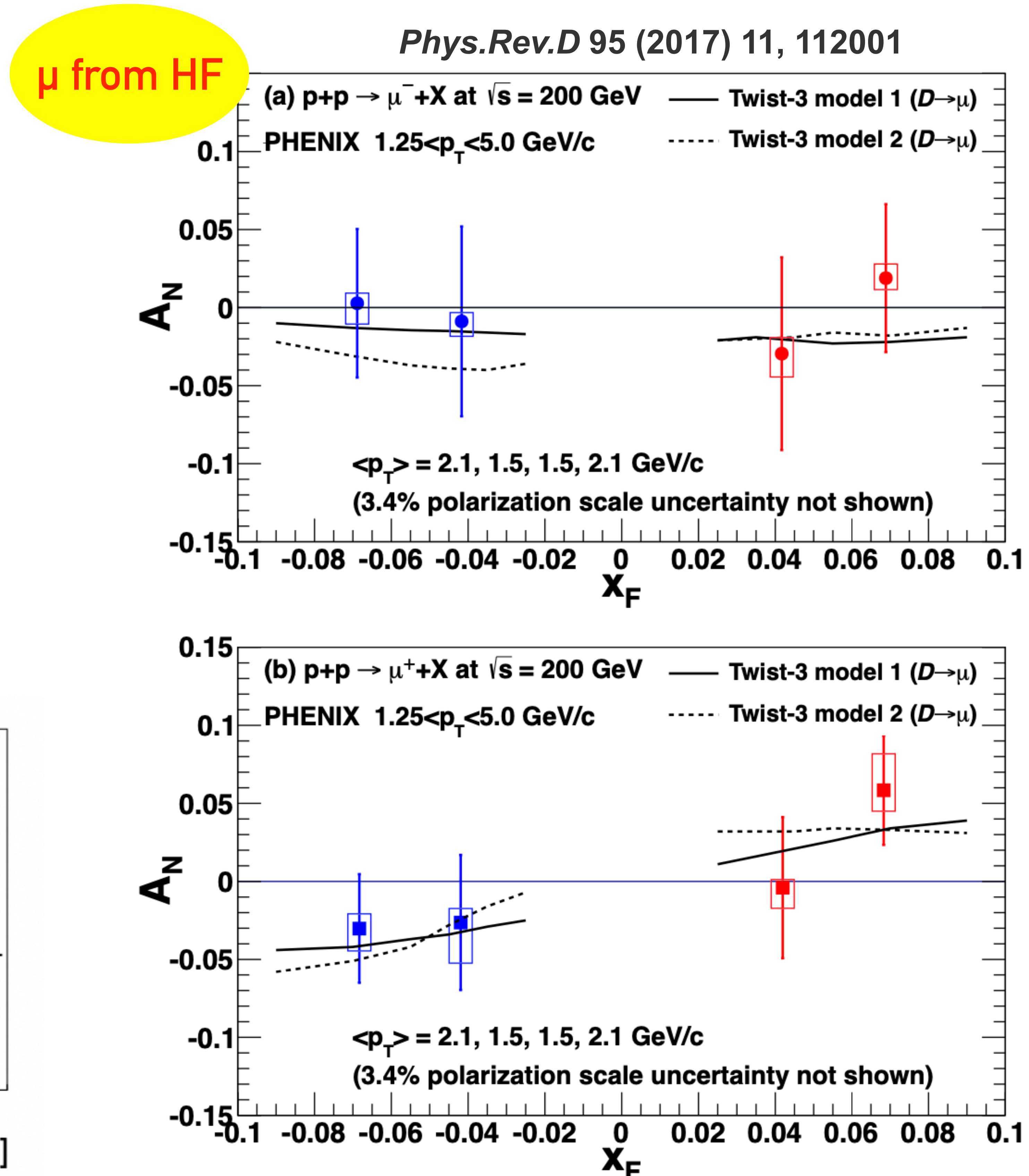
JHEP 09 (2015) 119

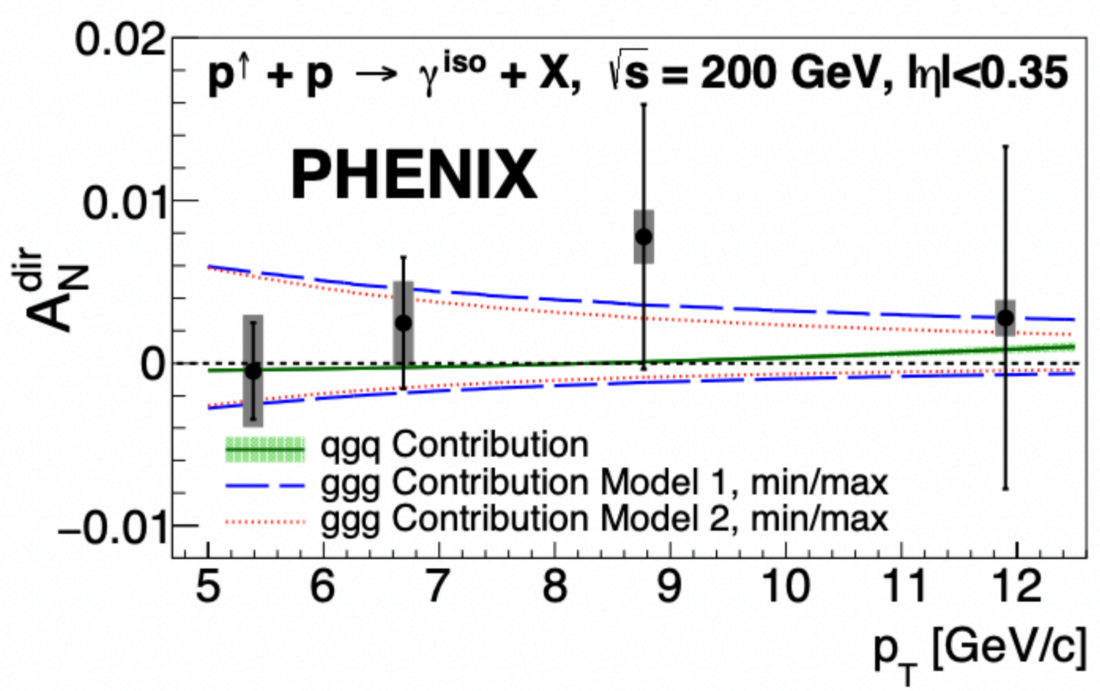


SPD

Gluon-induced TMD effects : existing results for A_N

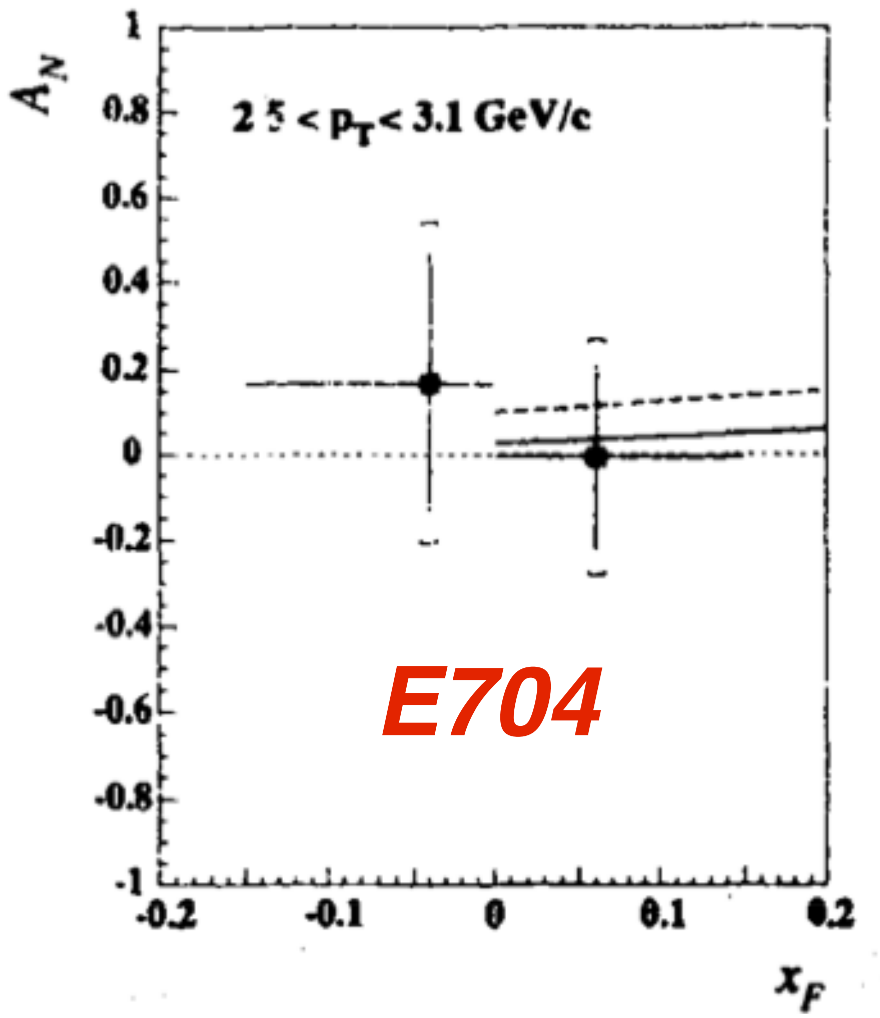






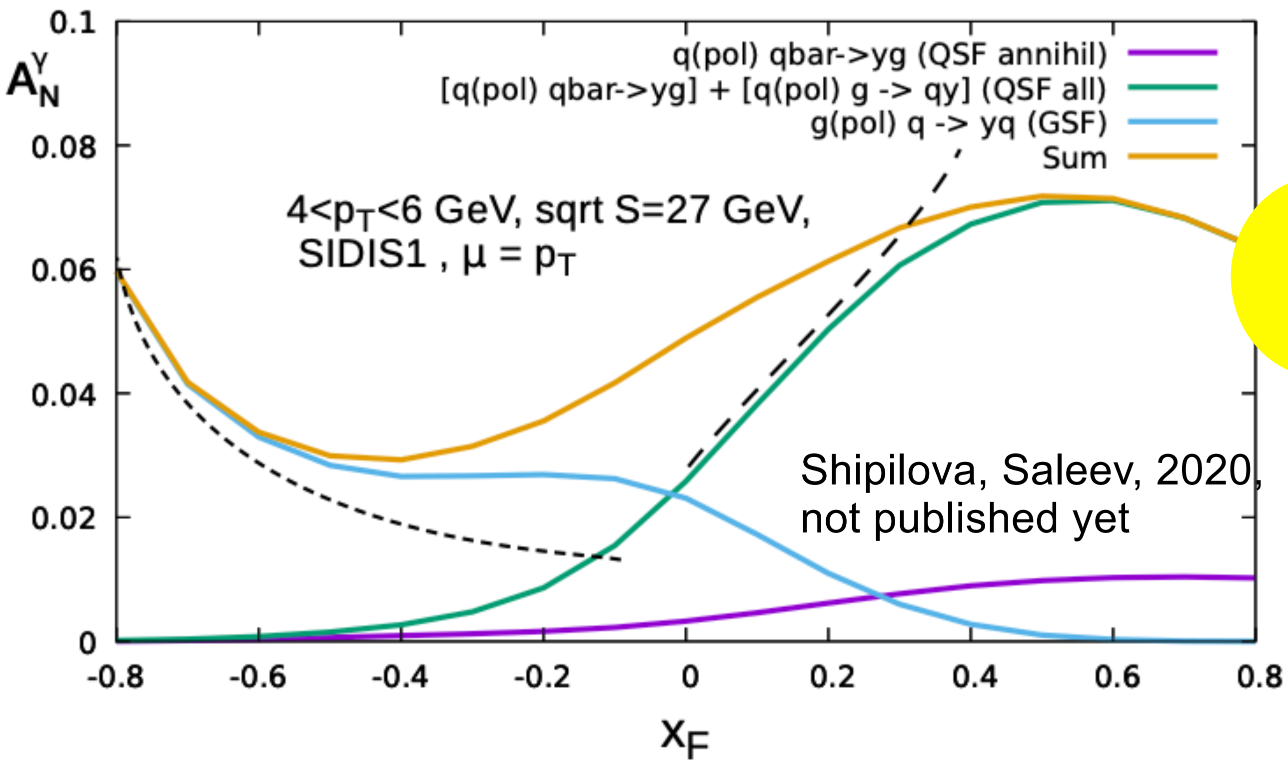
… and At NICA energies

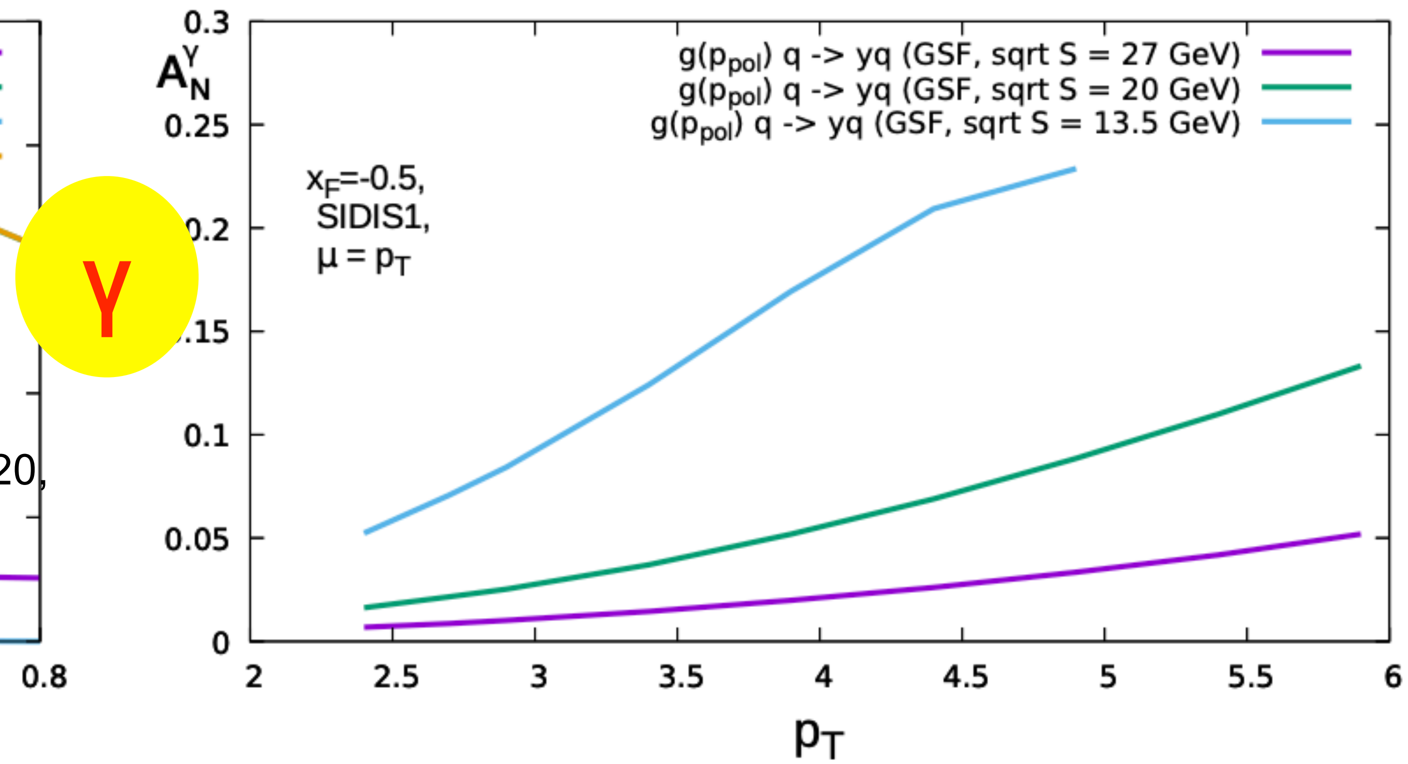
Phys. Lett. B 345 (1995)



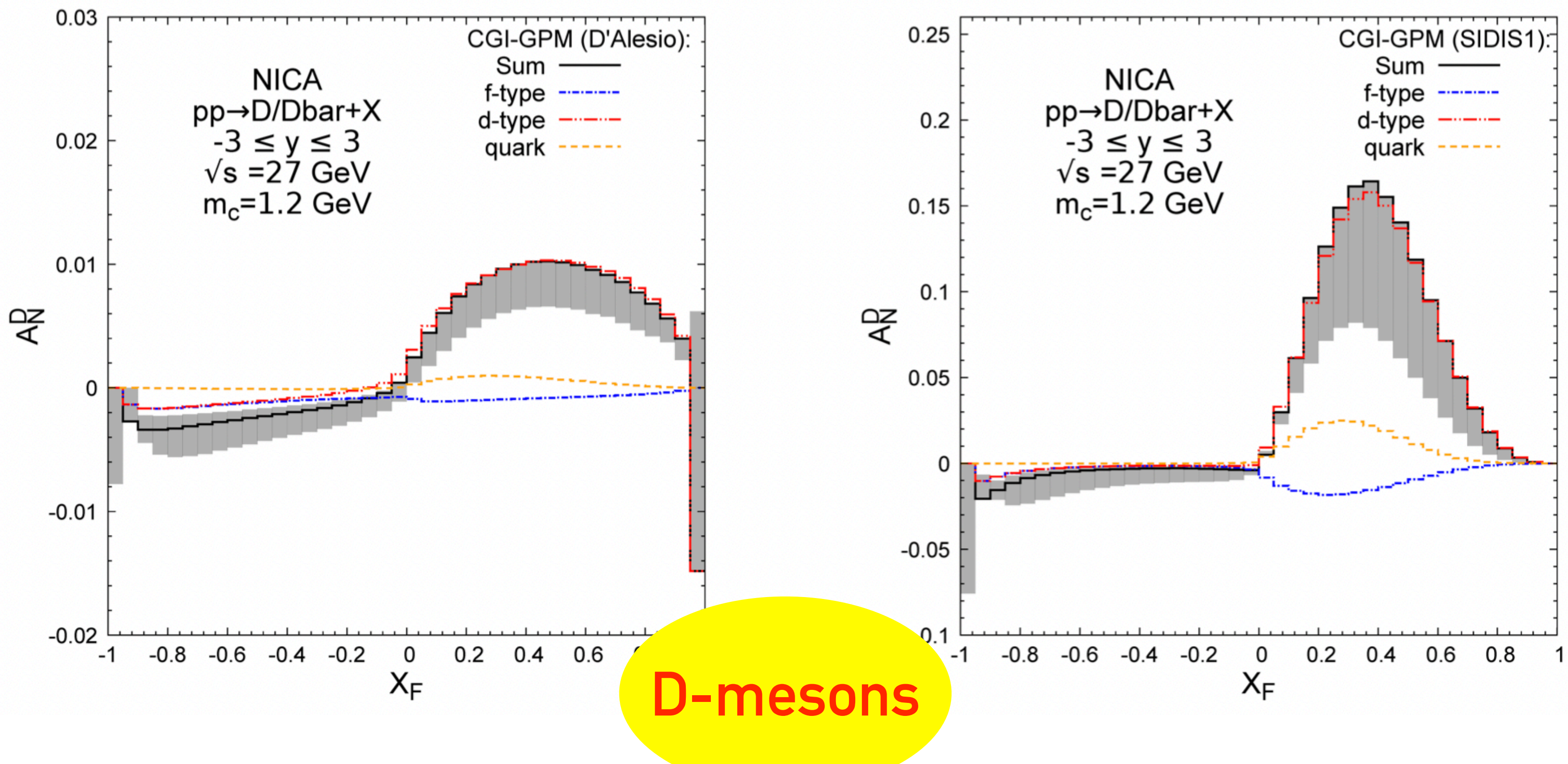
Gluon-induced TMD effects: expectations for A_N

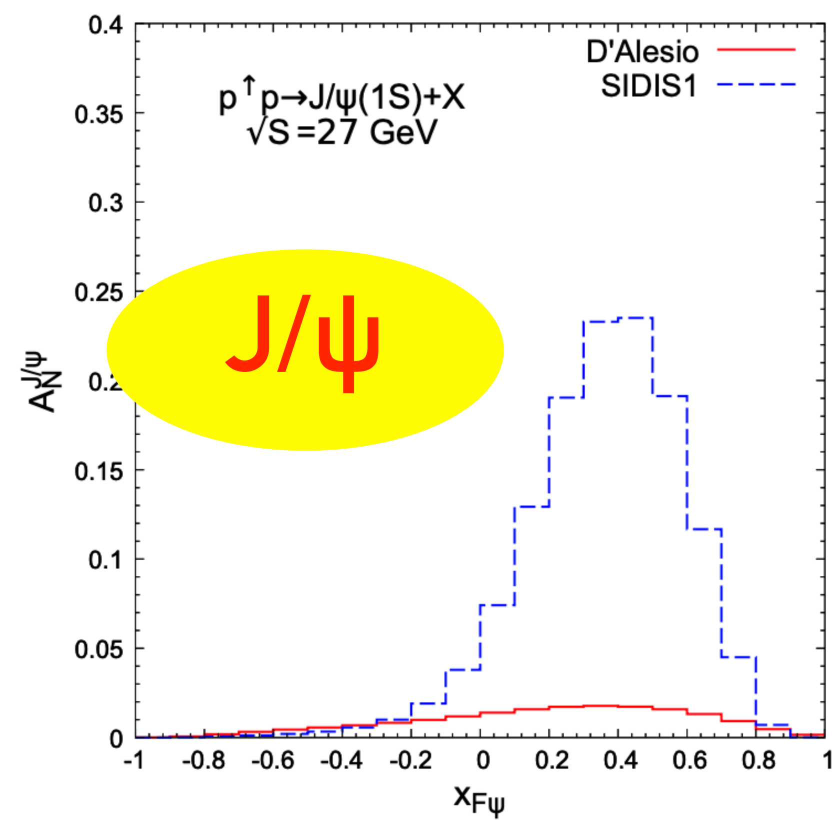
Sivers effect contribution



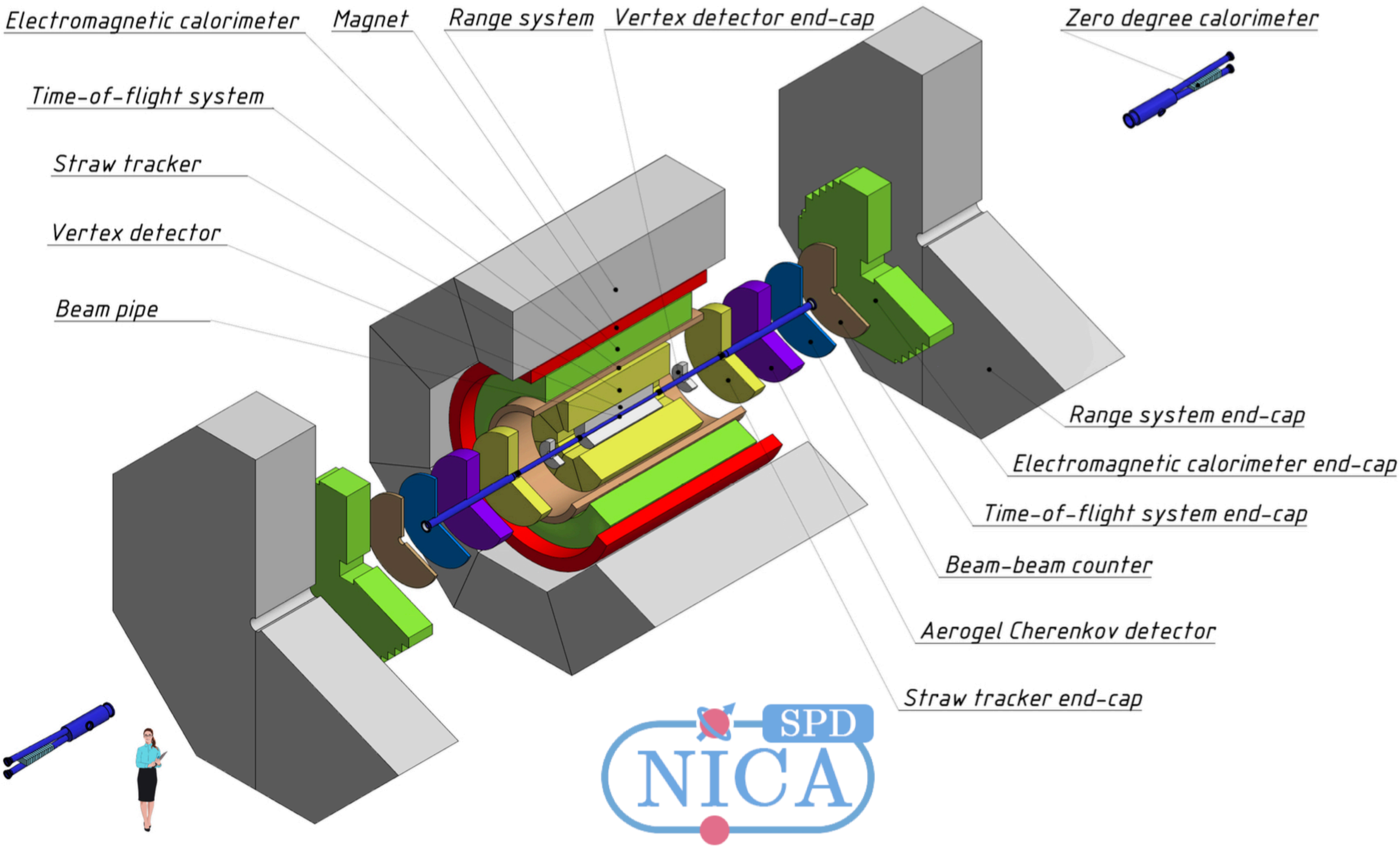


Saleev 2020



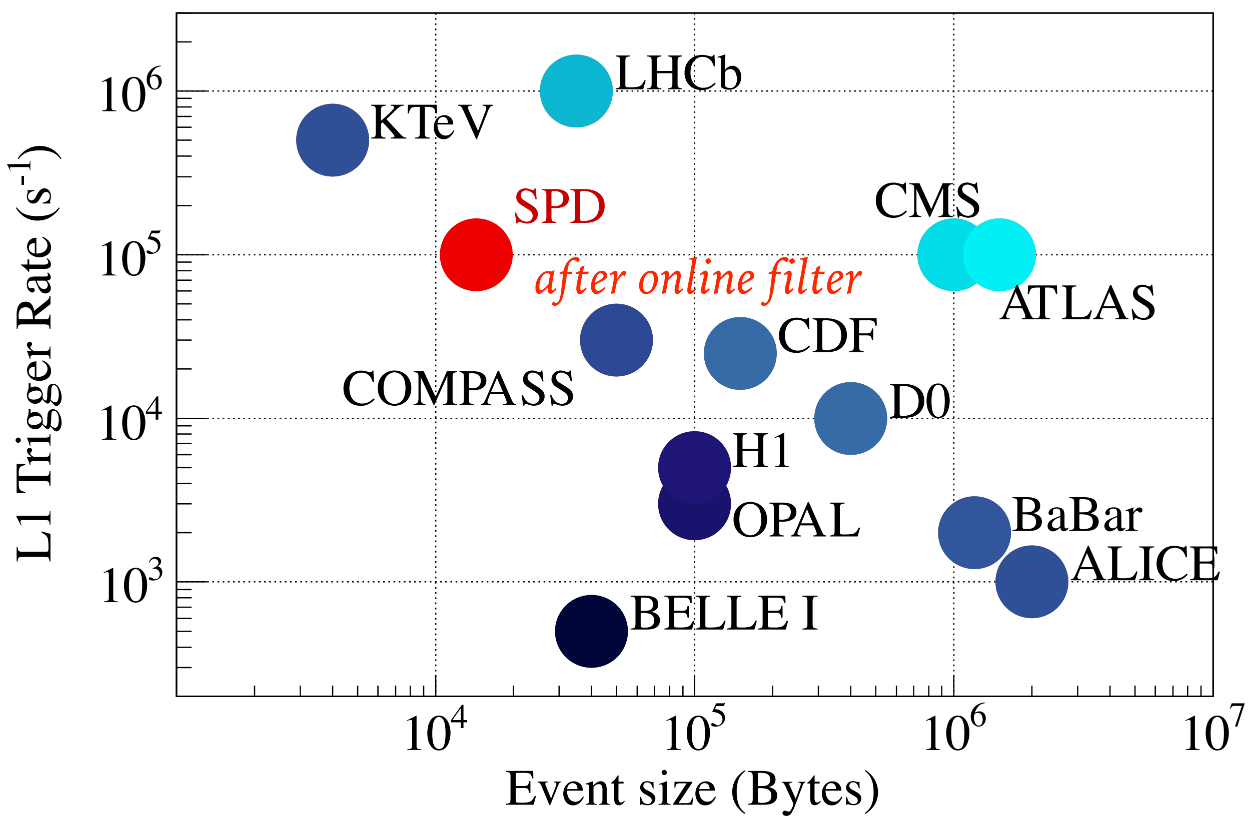


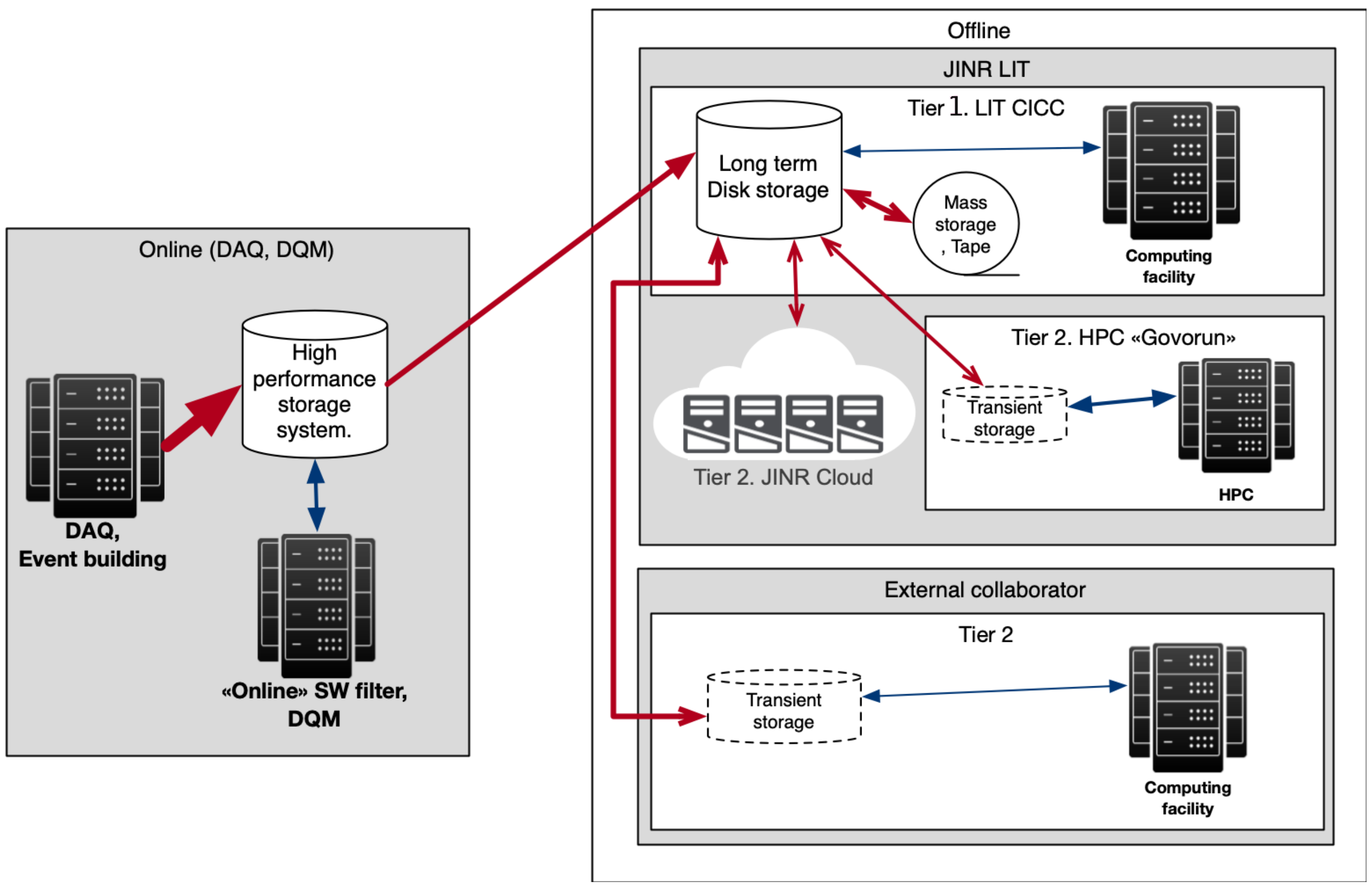
SPD setup


Electromagnetic calorimeter
Magnet
Range system
Vertex detector end-cap
Zero degree calorimeter
Time-of-flight system
Straw tracker
Vertex detector
Beam pipe
Range system end-cap
Electromagnetic calorimeter end-cap
Time-of-flight system end-cap
Beam-beam counter
Aerogel Cherenkov detector
Straw tracker end-cap

SPD DAQ

Free running (triggerless) mode !





	CPU [cores]	Disk [PB]	Tape [PB]
Online filter	6000	2	none
Offline computing	30000	5	9 per year

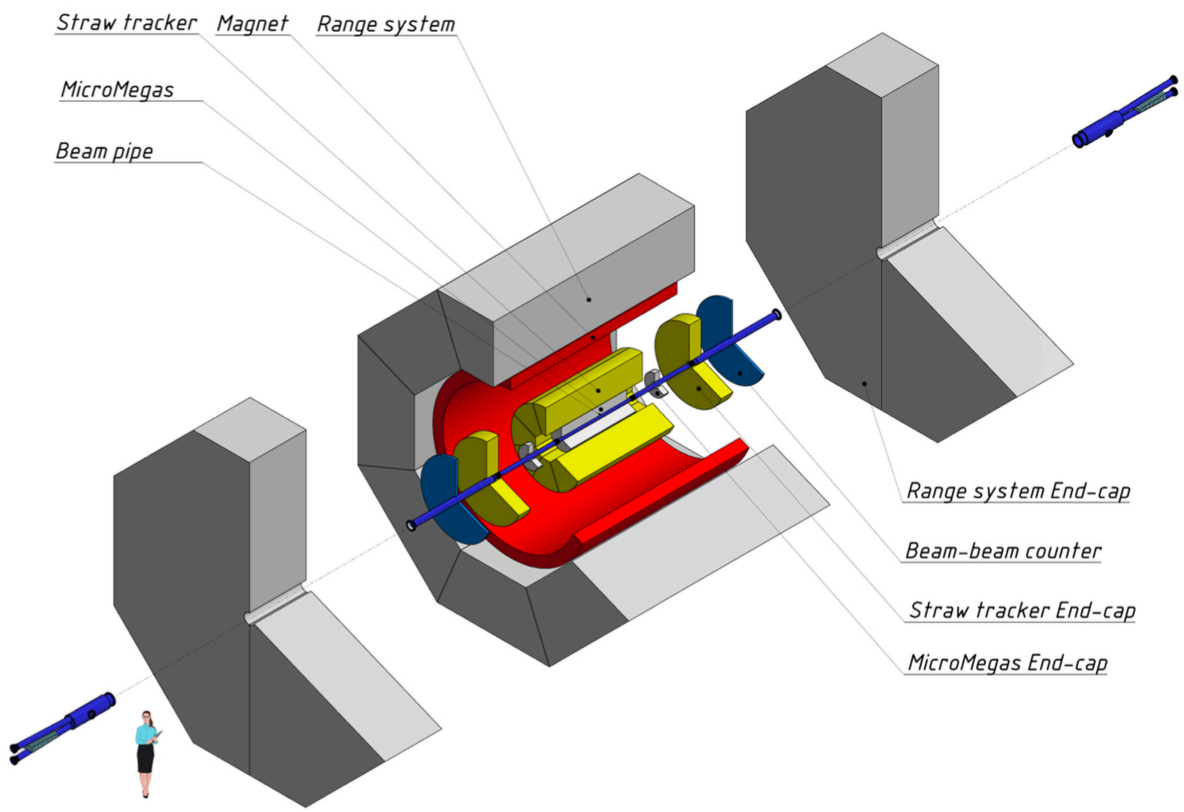
Alexey Guskov, Joint Institute for Nuclear Research

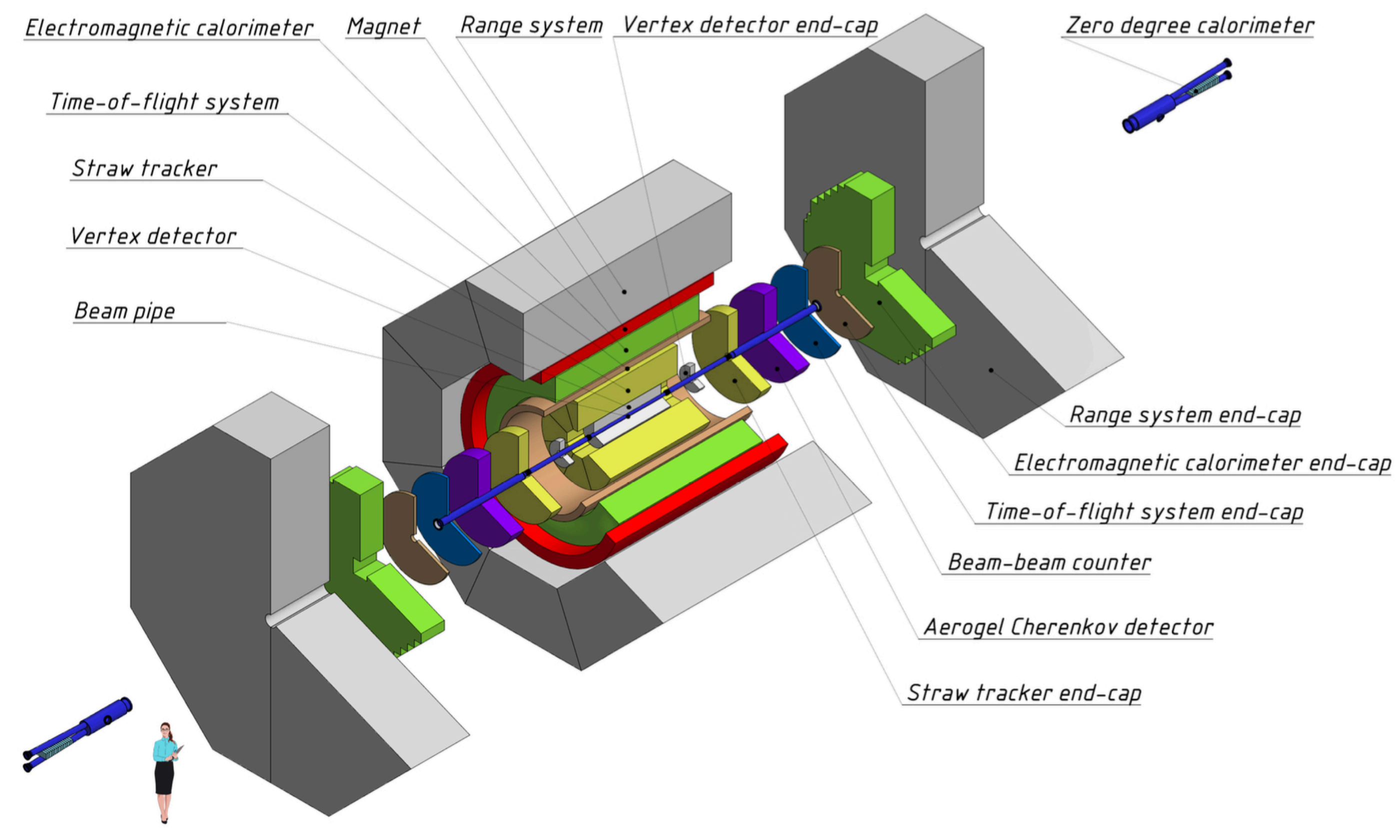
SPD: two stages

Creating of polarized infrastructure | **Upgrade of polarized infrastructure**

Start of NICA operation | *+4 years* | *+6 years* | *+8 years*

SPD construction | **1st stage of operation** | **SPD upgrade** | **2nd stage of operation**





SPD setup: basic properties

	Stage I	Stage II
Maximum luminosity, 10^{32} cm^{-2} s^{-2}	up to 0.1	1
Interaction rate, MHz	up to 0.4	4
Magnetic field at IP, T	up to 1.0	1.0
Track momentum resolution $\frac{\delta p}{p}$ at 1 GeV/c, %	$\sim$1.7	$\sim$1.0
Photon energy resolution, %		$5/\sqrt{E} \oplus 1$
$D^0 \to K\pi$ vertex spatial resolution, μm		60 for MAPS
		80 for DSSD
PID capabilities	dE/dx, RS	dE/dx, ECal, RS, TOF, FARICH
Number of channels, 10^3	170	294 for MAPS)
	210	397 for DSSD
Raw data flow, GB/s	up to 1	up to 20
Total weight, t	1236*	1240
Power consumption, kW	77	113 for MAPS
		90 for DSSD

Detector	Spatial resolution	Time resolution	Energy resolution	Signal length
RS	3 mm (wires), 1 cm (strips)	150 ns	$90\%/\sqrt{E}$ (p, n)	250÷500 ns
ECal	5 mm (γ, 1 GeV)	1 ns	$5\%/\sqrt{E} \oplus 1\%$	
TOF	10 cm	50 ps	–	
FARICH		<1 ns	$d\beta/\beta < 10^{-3}$	10 ns
Straw	150 μm	1 ns	$8.5\%(dE/dx)$	120 ns
SVD MAPS	5 μm	–	–	
SVD DSSD	27.4 μm (ϕ)	–	–	
	81.3 μm (z)			
MCT	150 μm	10 ns	–	$\sim$ 300 ns
BBC inner	1.5 mm	50 ps	–	
BBC outer	$\sim$ 10 cm	400 ps	–	
ZDC	$\sim$ 1 cm	150 ps at 0.4 GeV	$50\%/\sqrt{E} \oplus 30\%$ (n)	
			$20\%/\sqrt{E} \oplus 9\%$ (γ)	

Alexey Guskov, Joint Institute for Nuclear Research

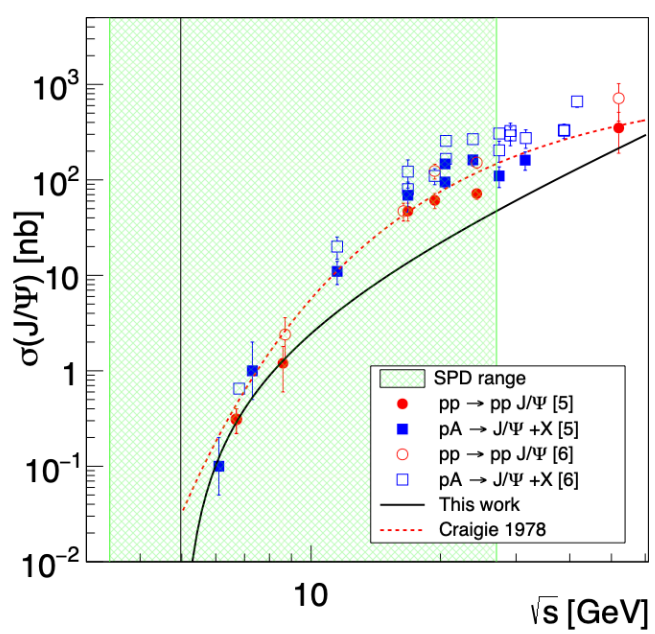
Physic of the first stage

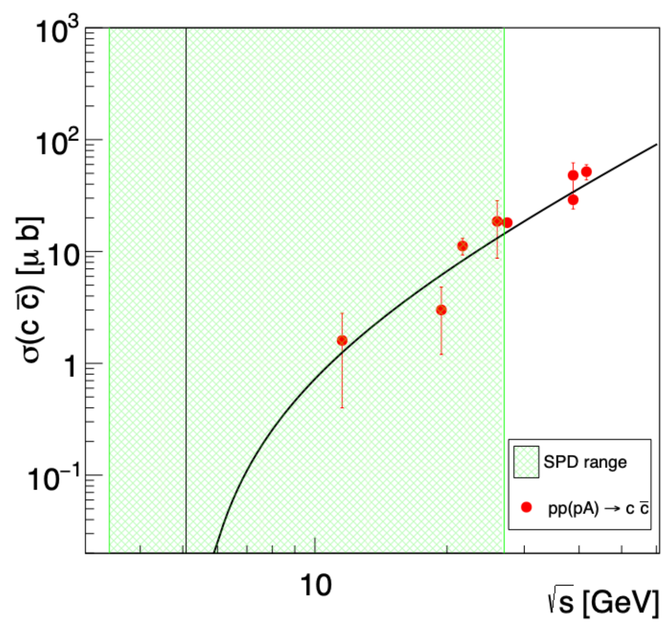
Non-perturbative QCD	Perturbative QCD

$\sqrt{s}$

- 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

arXiv:2102.08477

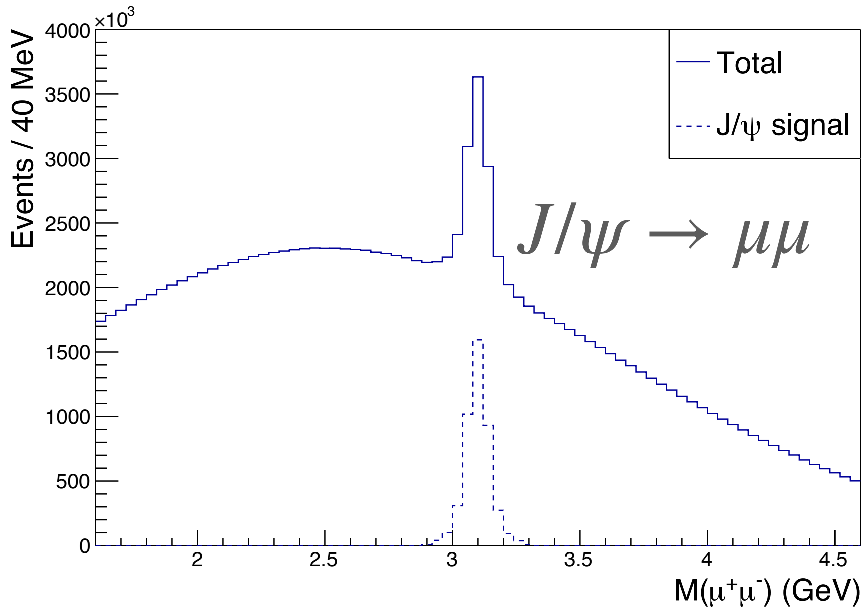


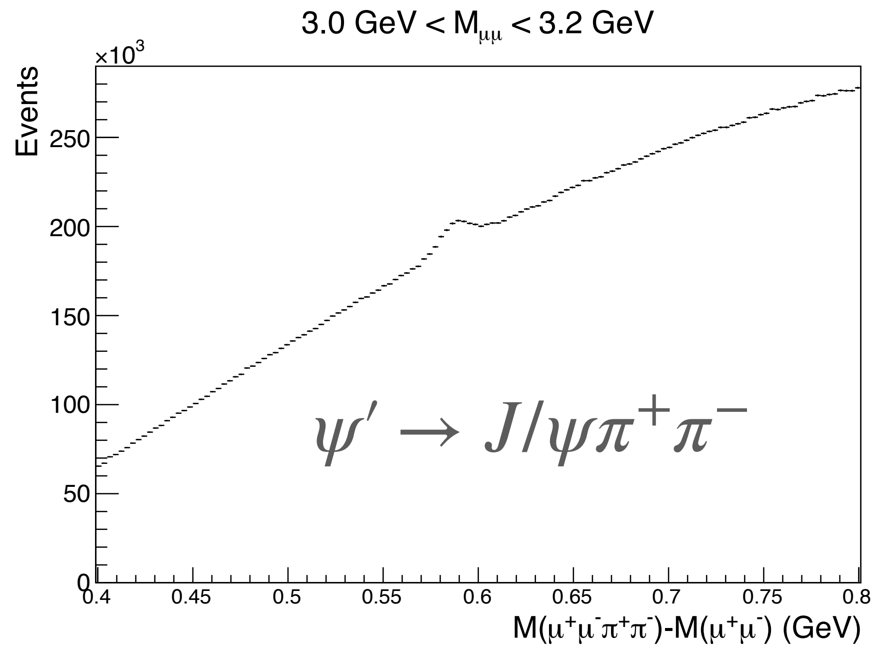


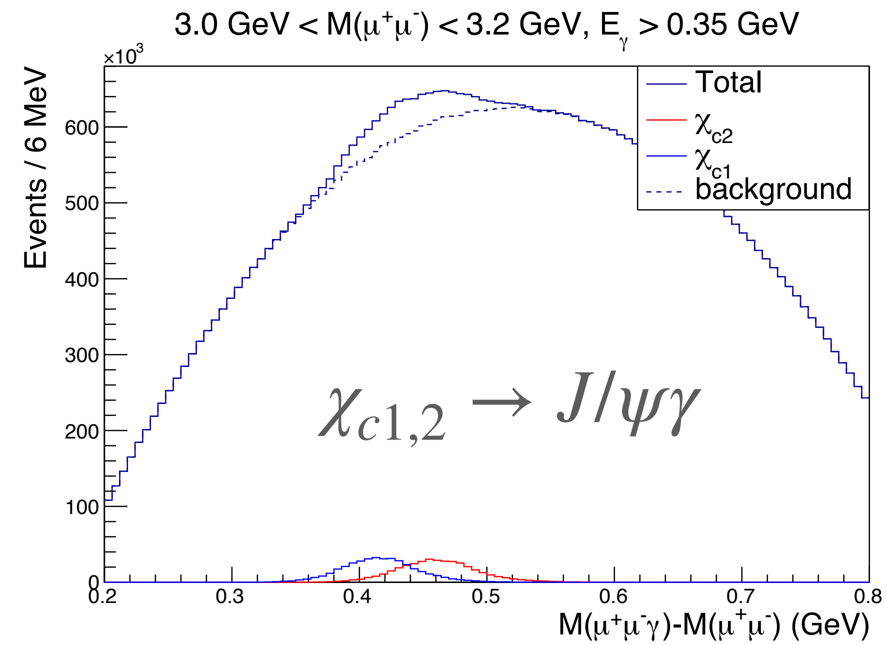
- Auxiliary measurements for astrophysics
- …

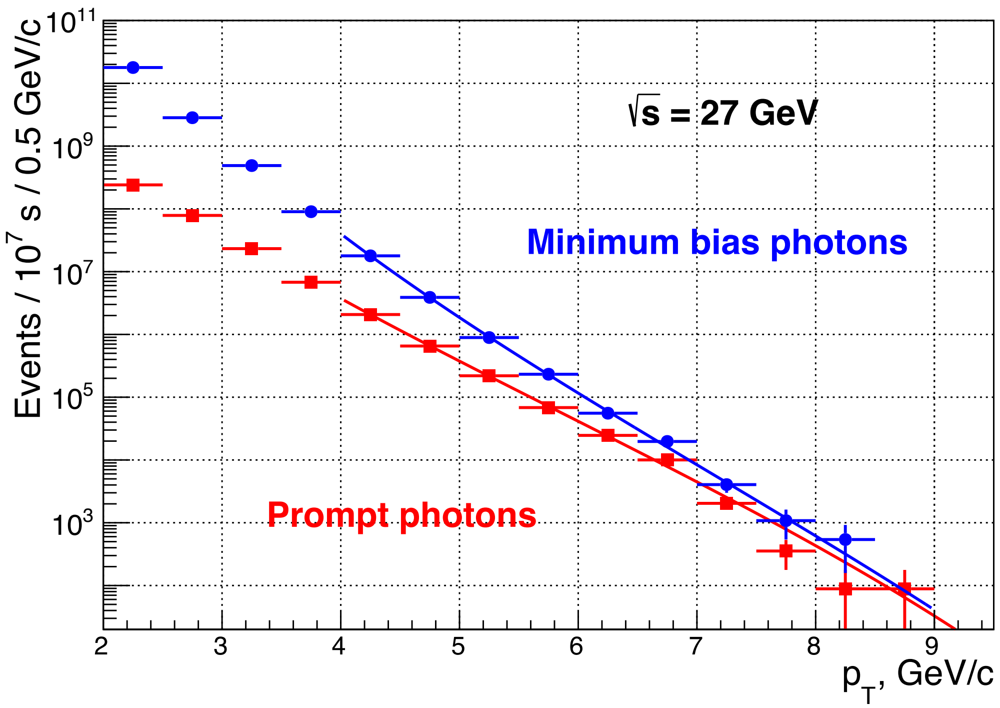
Physics performance for gluon probes

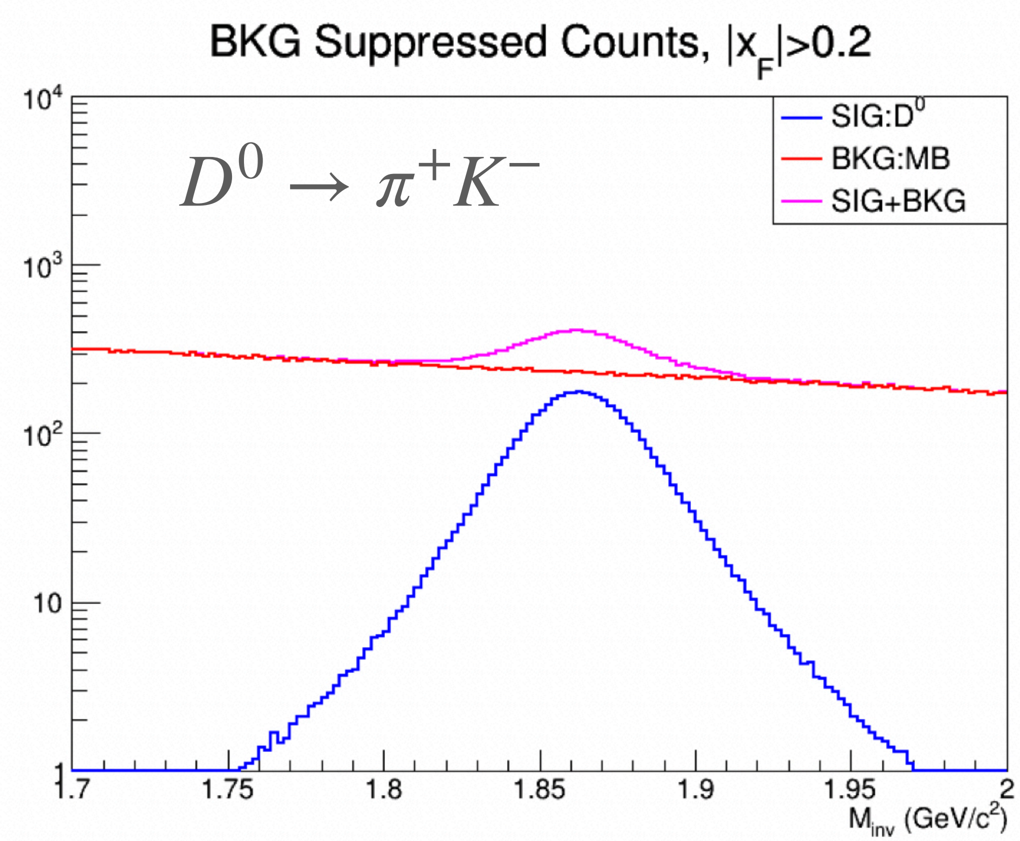
(1 year=10^7 s)



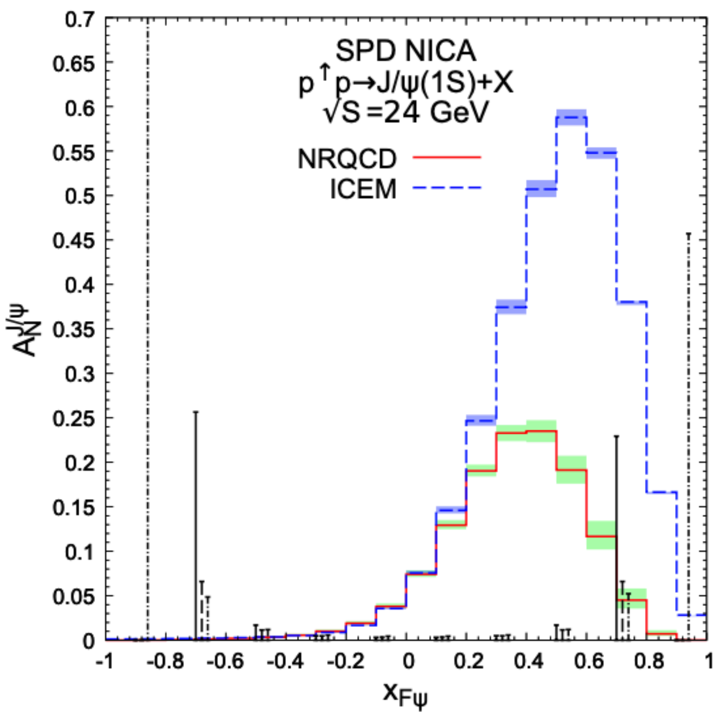




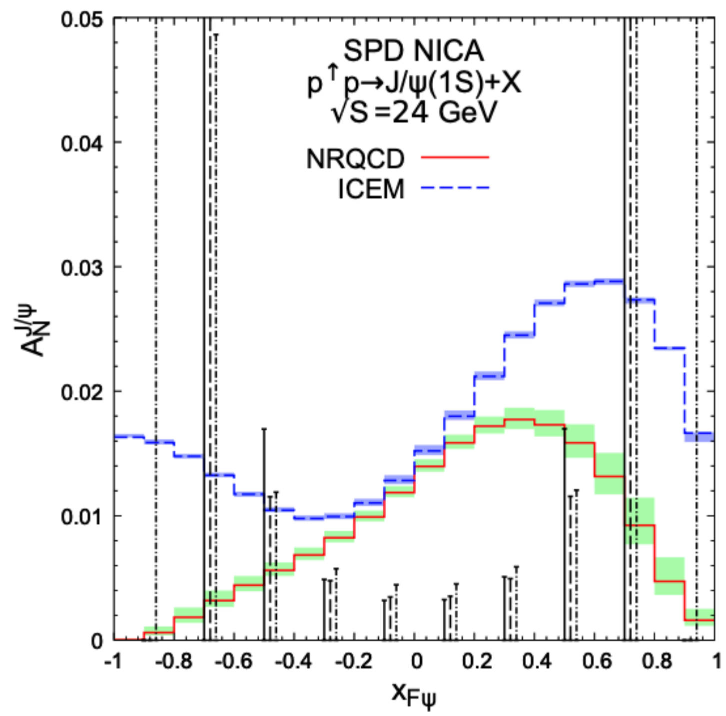


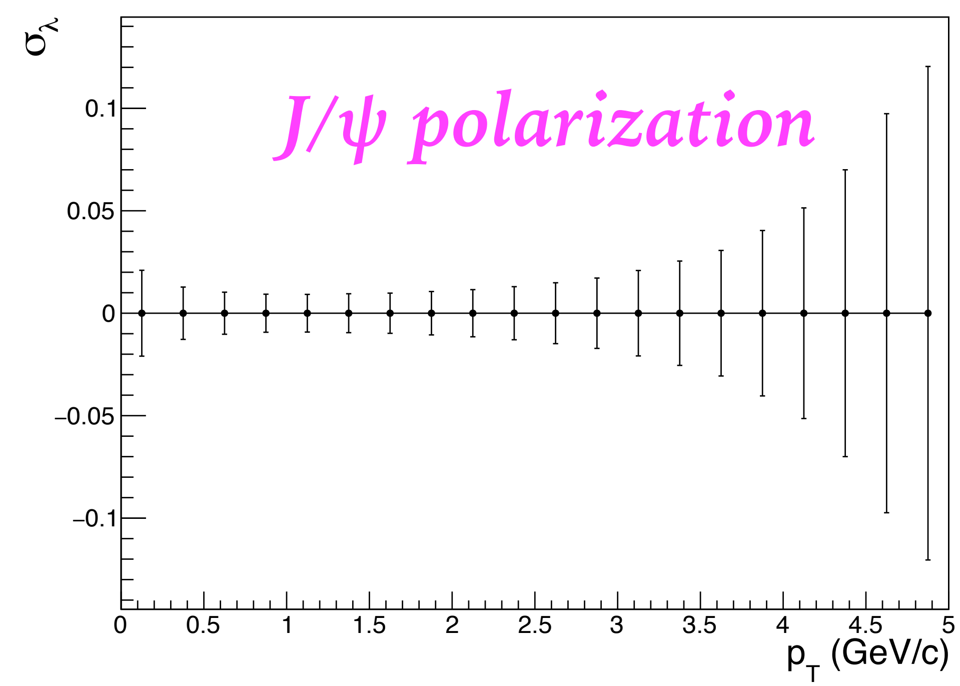


Physics performance: accuracies



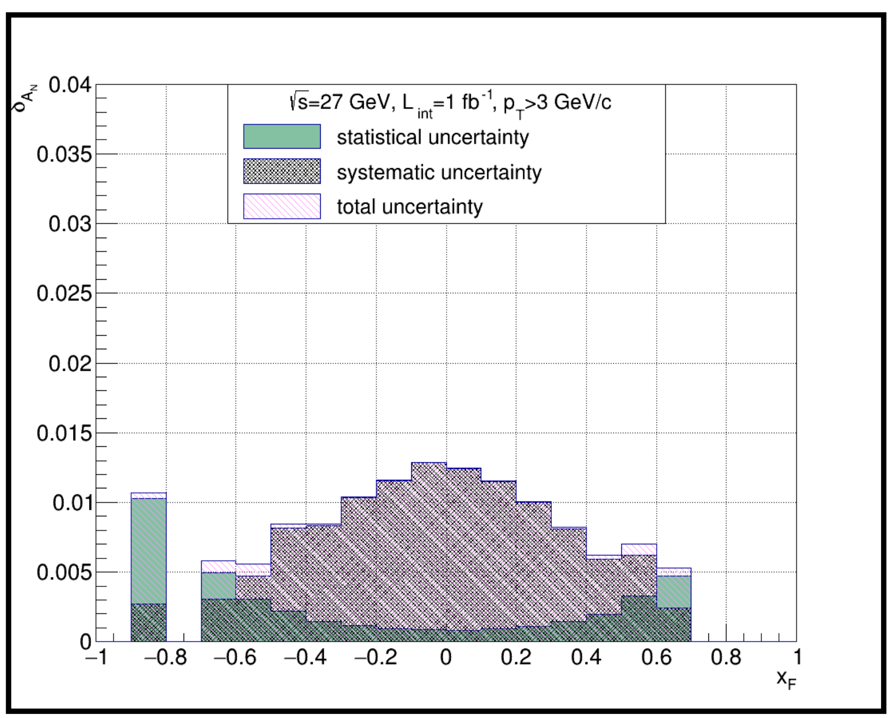
J/ψ



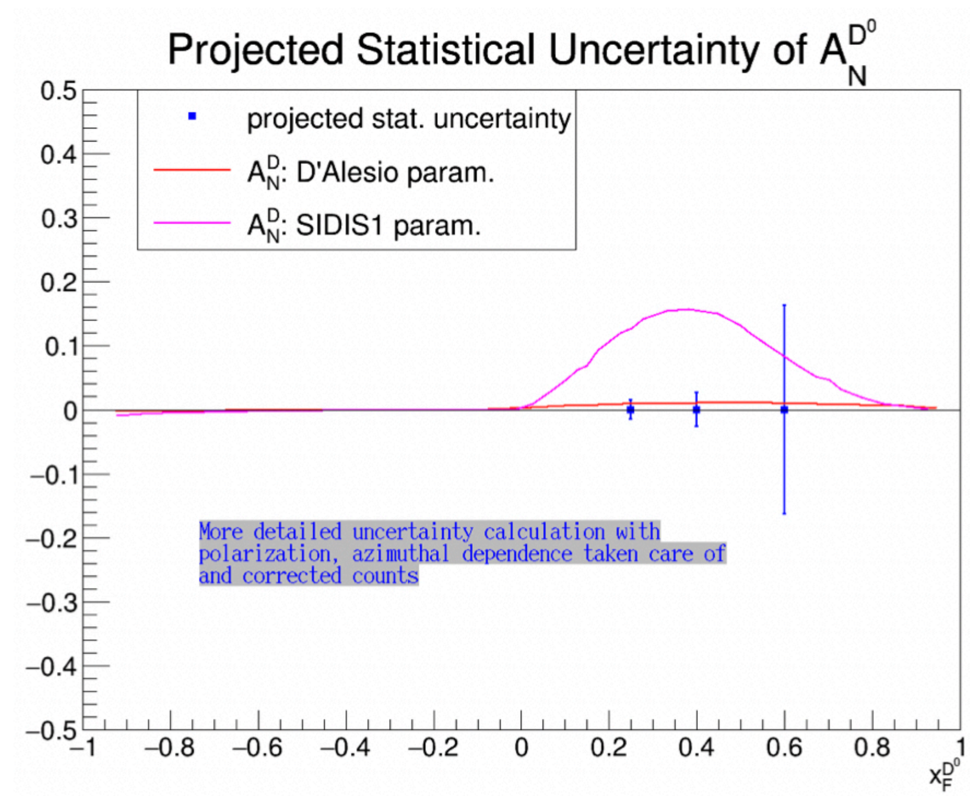


J/ψ polarization

Different inputs for gluon Sivers function

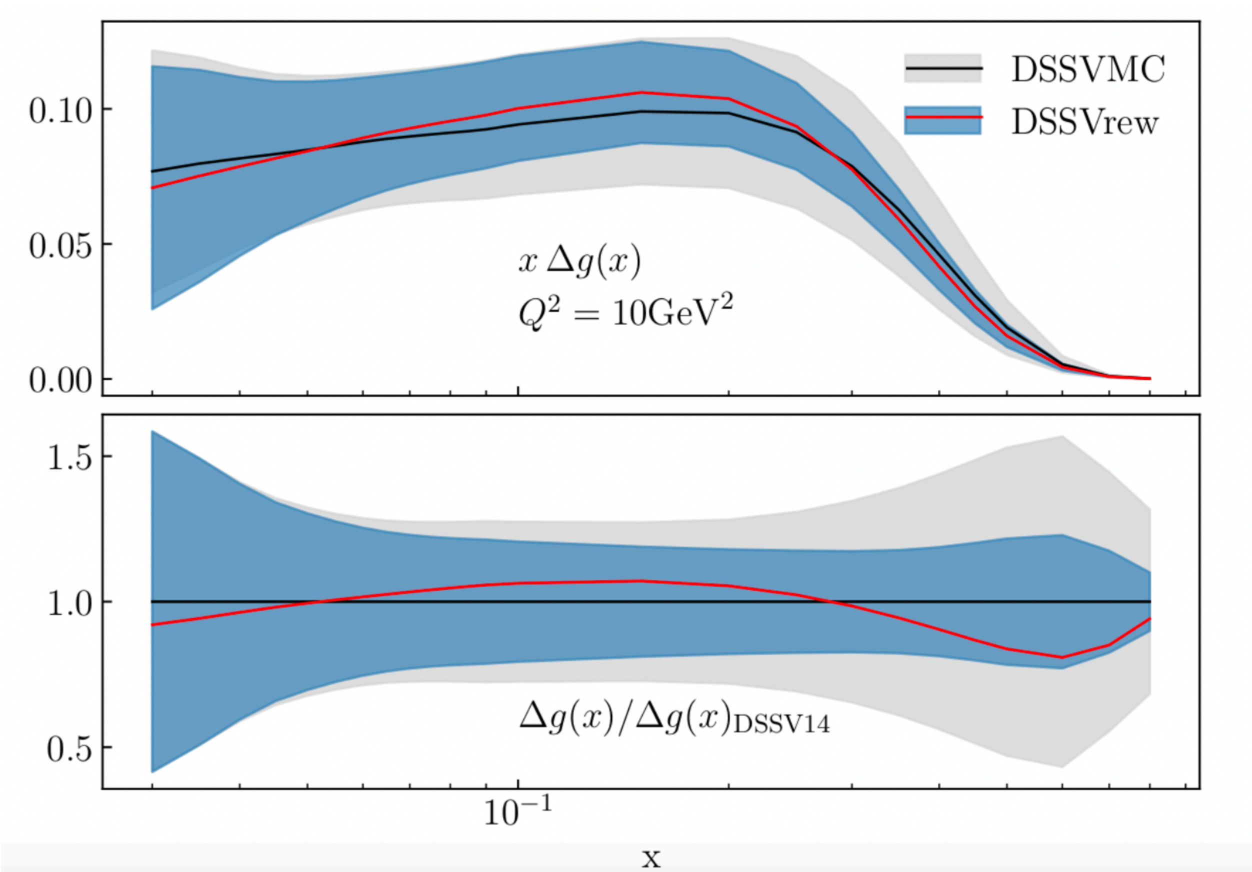


prompt-γ

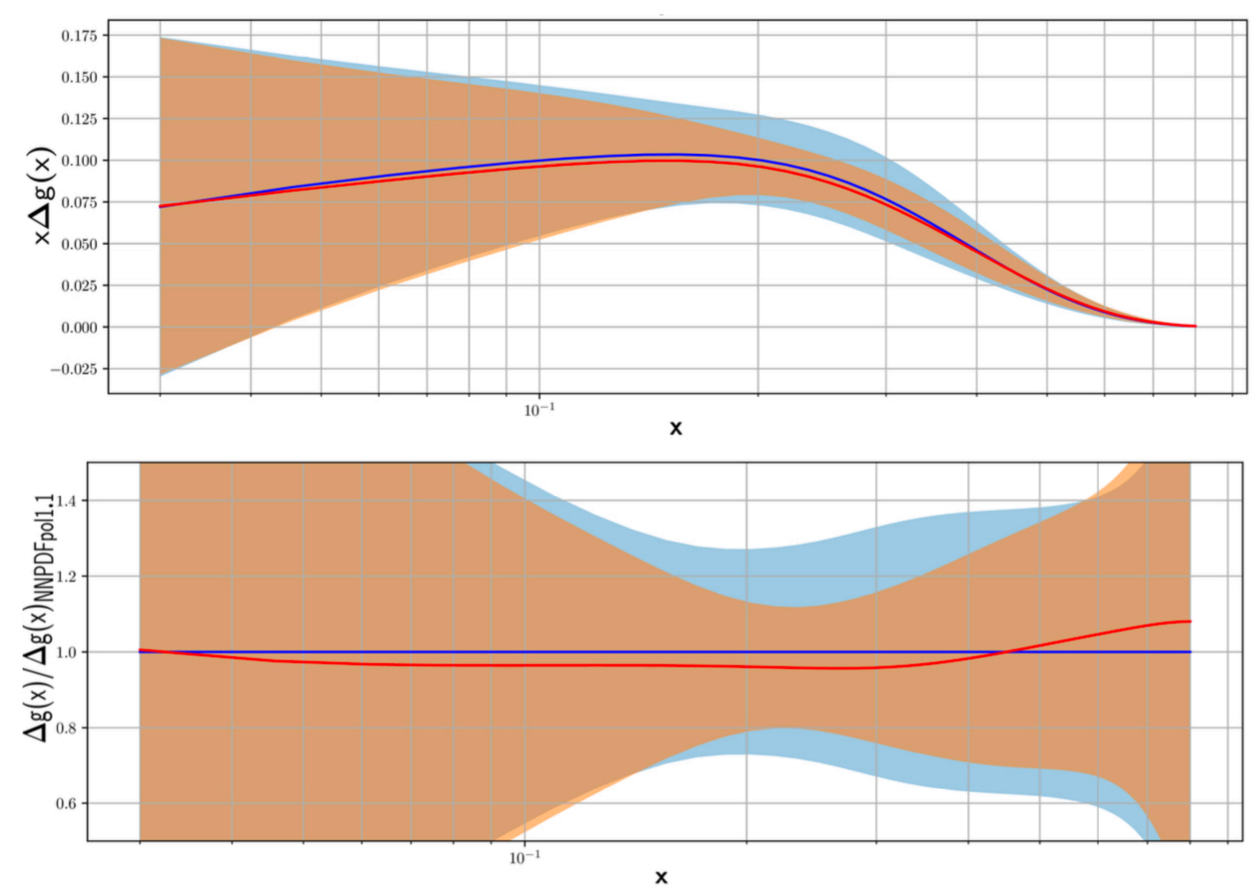


D^0

Impact of SPD measurements to the world data for $\Delta g(x)$

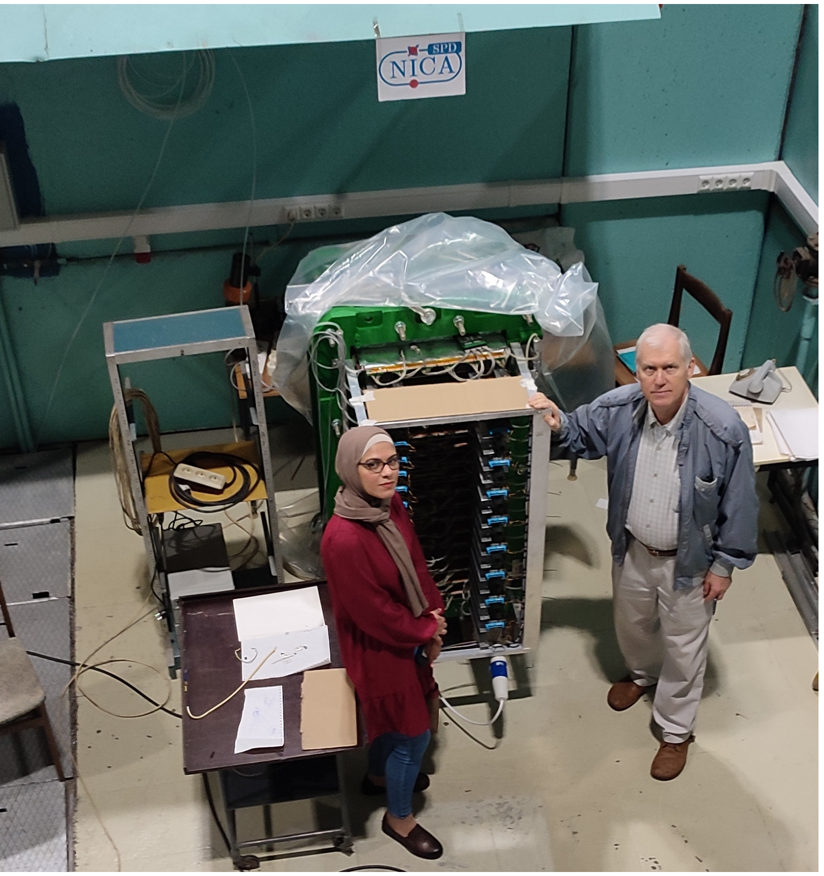


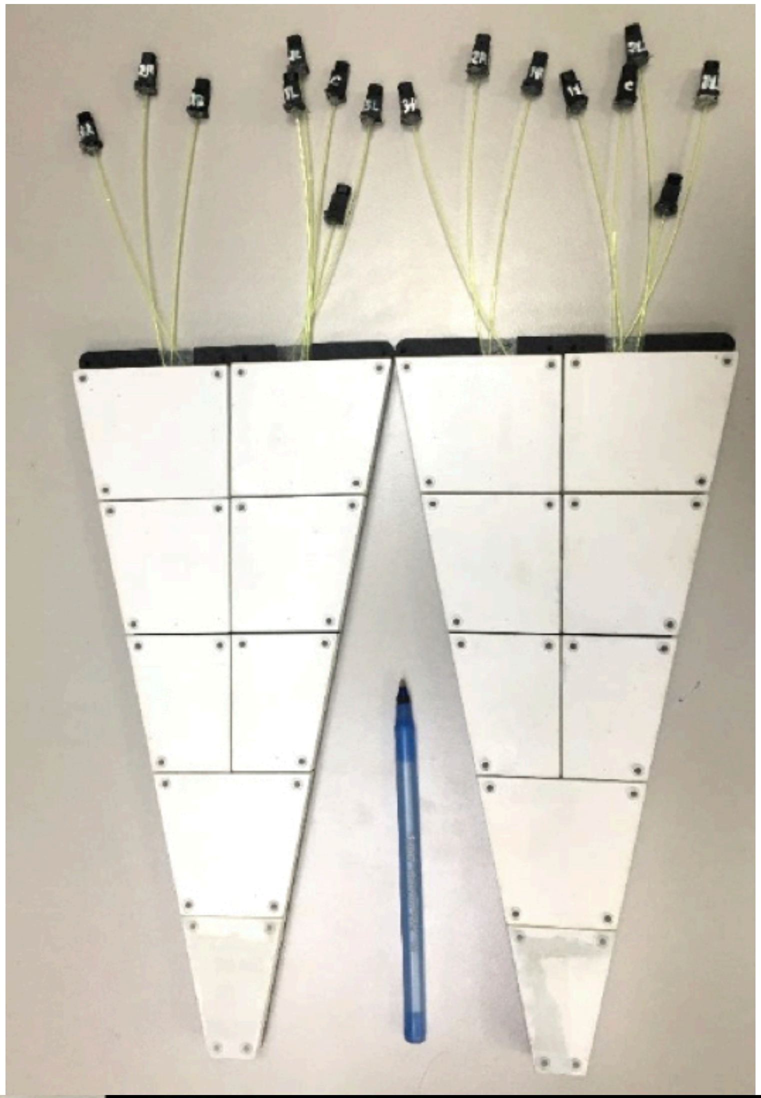
A_{LL} *for prompt photons*

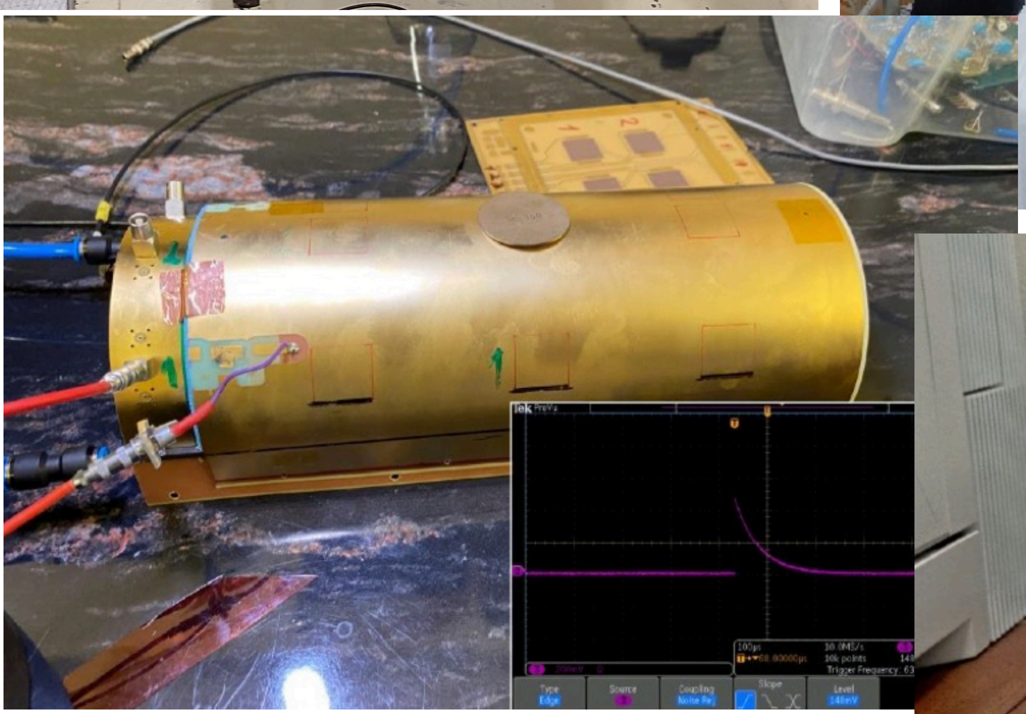


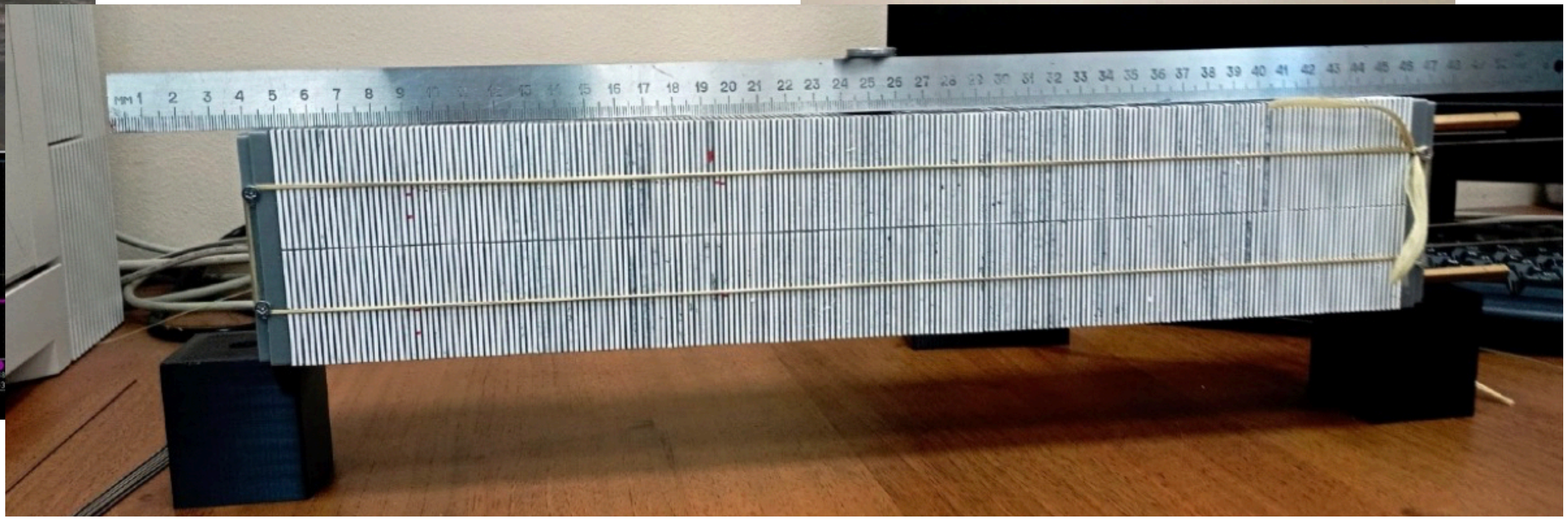
A_{LL} *for* J/ψ

Hardware









SPD experimental hall

Status of the SPD project

SPD **Conceptual Design Report** was presented firstly in Jan 2021 and approved by the JINR PAC for Particle physics after an international expertise in Jan 2022

https://arxiv.org/abs/2102.00442

SPD **Technical Design Report** was presented firstly in Jan 2023, then was updated in 2024 and passed international expertise this year.

https://arxiv.org/abs/2404.08317

The **first phase** of the SPD project is included into the JINR's 7-year plan (2024-2030)

The **SPD international collaboration** established in 2021. Currently it consists of 35 institutes from 15 countries and more than 400 participants

SPD map

SPD ~~vs~~ + STCF !

Hadron collisions:

$$\sigma_{AB\to hX} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b \boxed{f(x_a, Q^2)}\boxed{f(x_b, Q^2)} \times \boxed{\hat{\sigma}_{ab\to cd}(x_a, x_b, Q^2)} \times \boxed{D_{cd\to h}}$$

e^+e^- collisions:

$$\sigma_{e^+e^-\to hX} = \sum_{q} \boxed{\hat{\sigma}_{e^+e^-\to q\bar{q}}(Q^2)} \times \boxed{D_{q\bar{q}\to h}}$$

Information about fragmentation functions from e^+e^- colliders is needed to account correctly the hadron production!

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 high-x in proton and deuteron;
  - gluon transversity in deuteron;
  - …
- Comprehensive physics program for the first period of data taking: spin effects in p-p, p-d and d-d elastic scattering, spin effects in hyperon production, multiquark correlations, dibaryon resonances, physics of light and intermediate nuclei collisions, exclusive reactions, hypernuclei, open charm and charmonia near threshold, etc.;
- **The SPD gluon physics program is complementary to the other intentions to study the gluon content of nuclei (RHIC, AFTER, LHC-Spin, EIC, JLab experiments, EICC, …)**
- More information including **SPD CDR** and **TDR** can be found at http://spd.jinr.ru .

Summary

We wait from theorists:

- *new brilliant ideas!*
- *predictions for SPD kinematics*
  - *polarized* ***p-p*** *collisions,* $\sqrt{s_{pp}} \leq 27\ GeV$
  - *polarized* ***d-d*** *collisions,* $\sqrt{s_{NN}} \leq 13.5\ GeV$
  - unpolarized **p-p**, **d-d**, and **light ions** collisions

… from experimentalists:

- *joining the* ***SPD project*** *with their experience and enthusiasm*

You are welcome!

Hadron structure: main actors

DESY

hermes

BNL

PHENIX

STAR

sPHENIX

EICC

EIC

ECCE

JLAB

CLAS12

SoLID

GlueX

Fermilab

SeaQuest
E906

SPIN QUEST

JINR

SPD

NICA

CERN

COMPASS

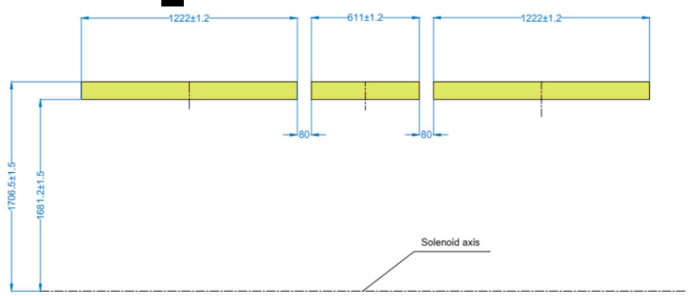
AMBER

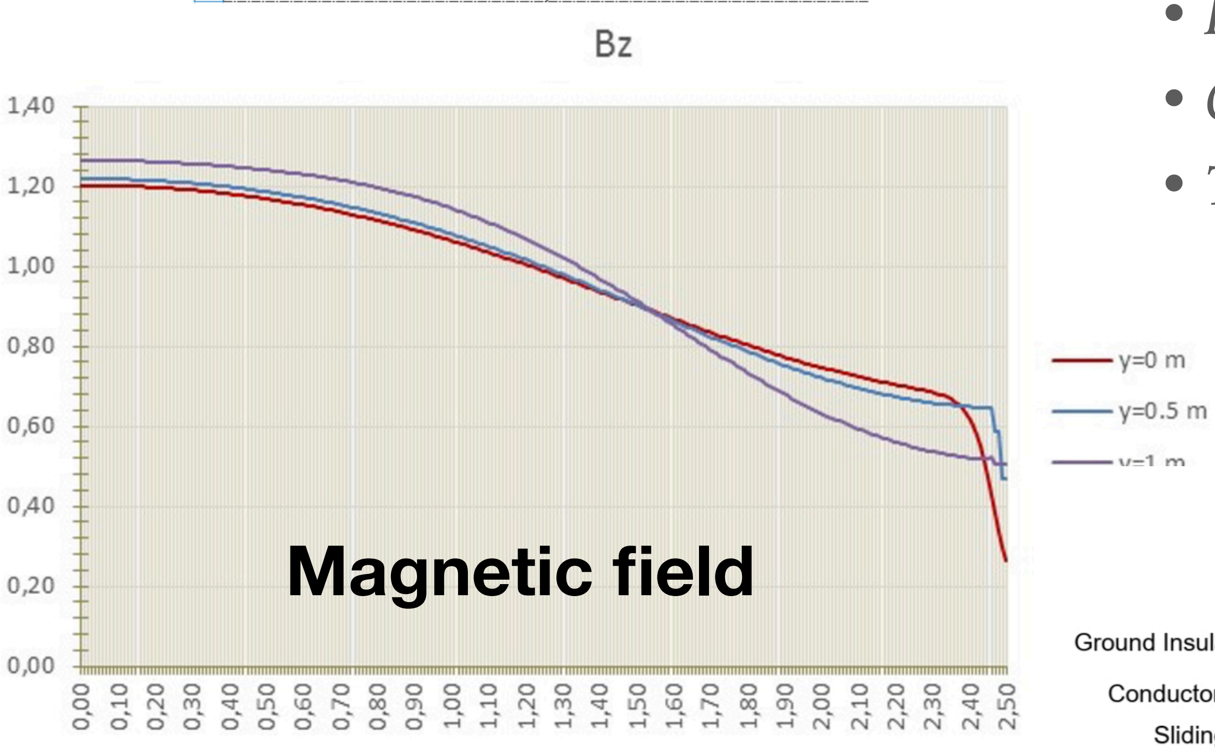
LHC spin

AFTER

BACKUP SLIDES

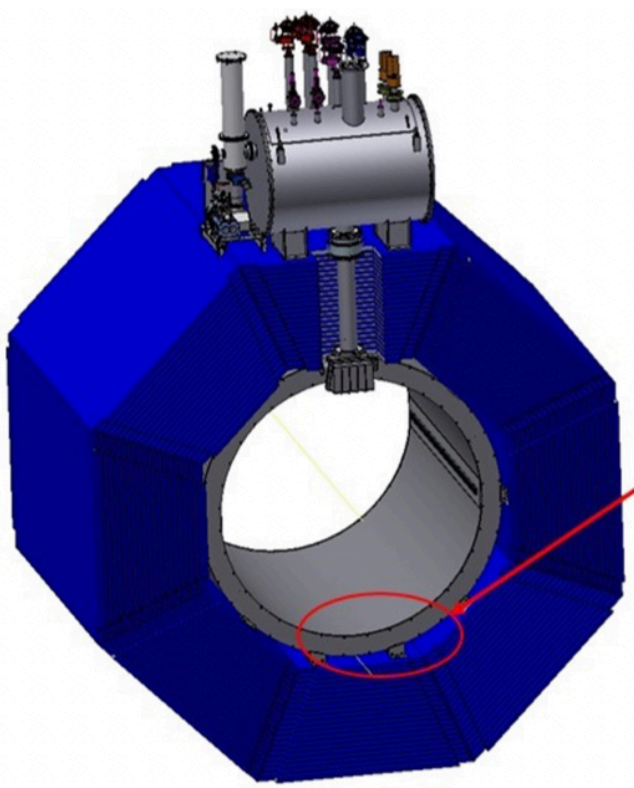
Superconducting magnet



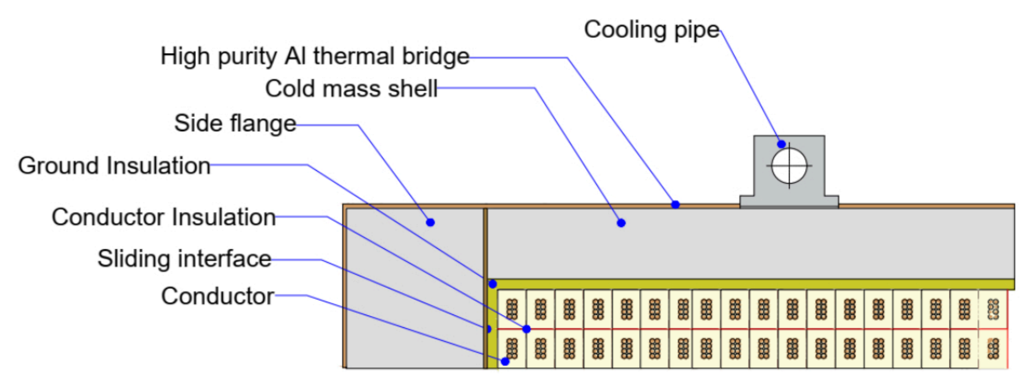


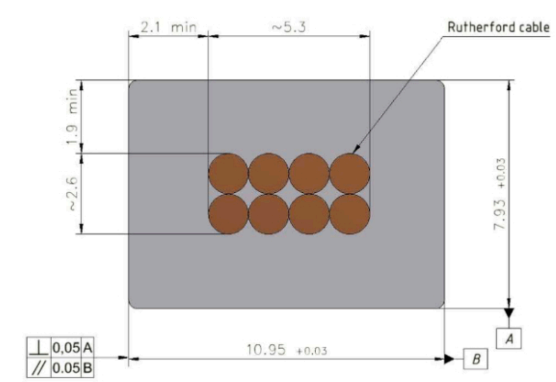
Magnetic field

- *PANDA technology*
- *Field at axis: 1.0 T*
- *Operating current: 4.4 kA*
- *Total stored energy: 19.3 MJ*



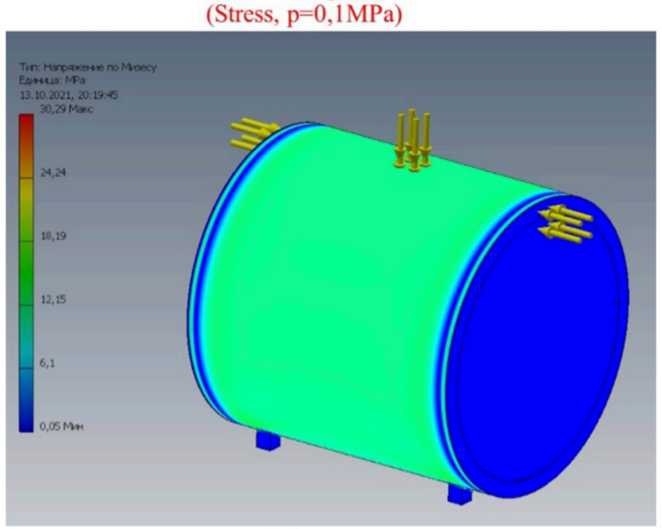
Cross section of the cold mass and cable



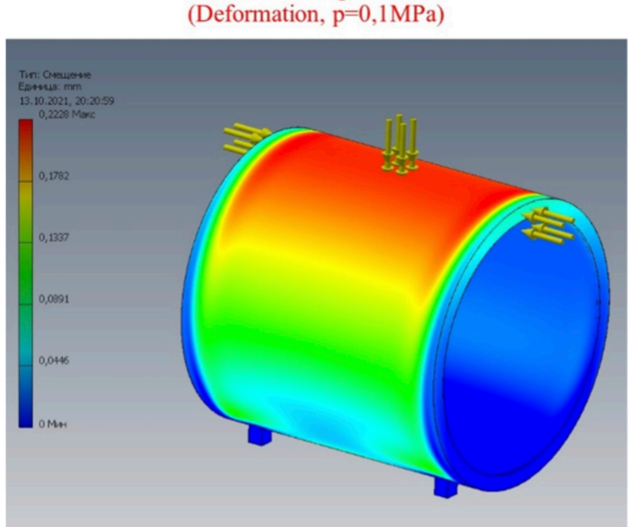


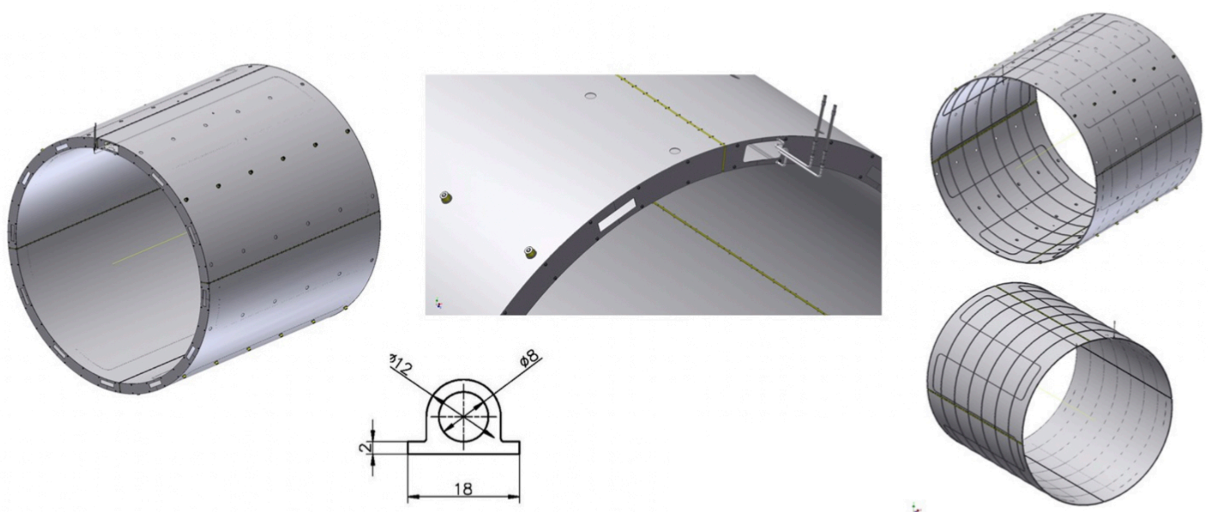
Mechanical properties

SPD Magnet
(Stress, p=0,1MPa)



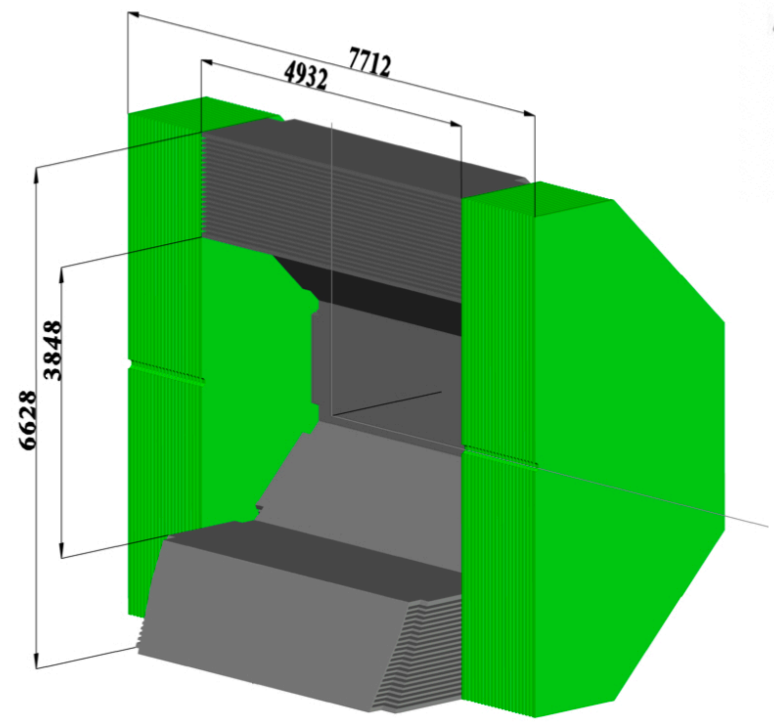
SPD Magnet
(Deformation, p=0,1MPa)

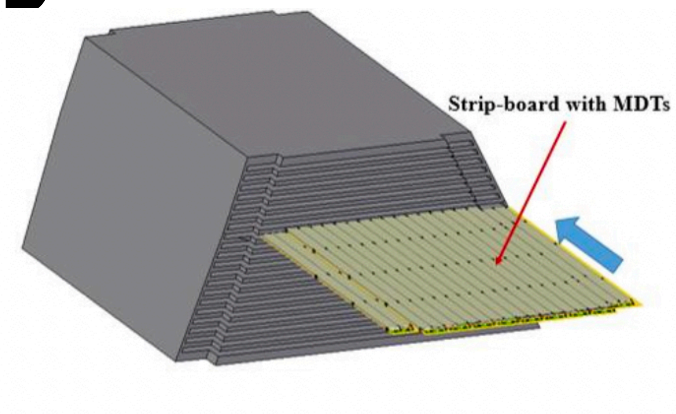




Thermal shield of cryostat

Range system



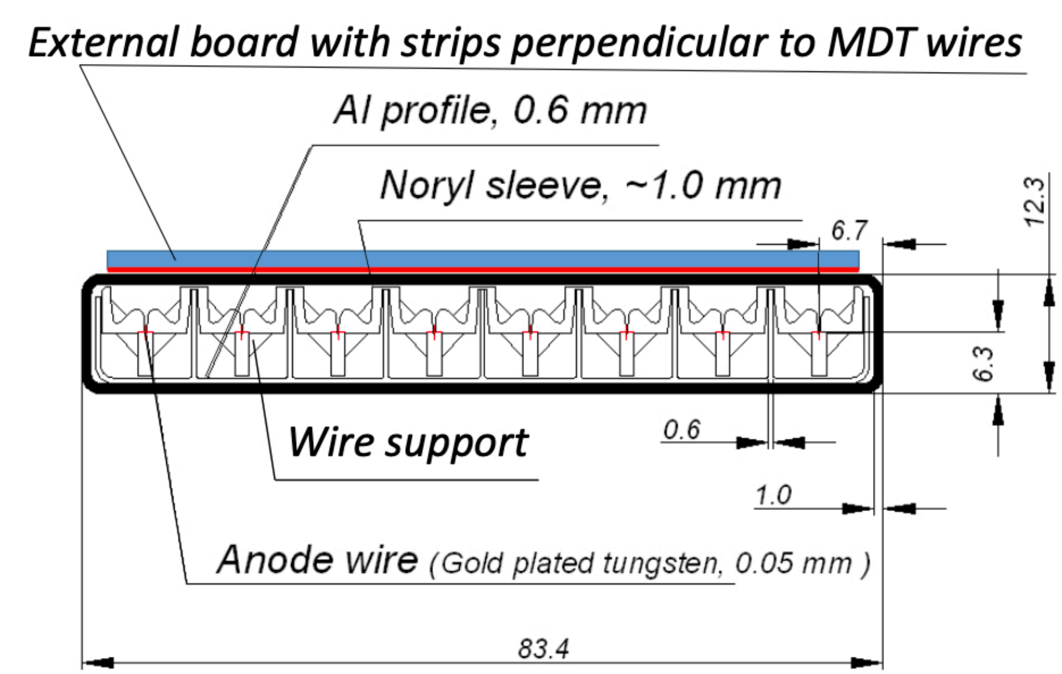


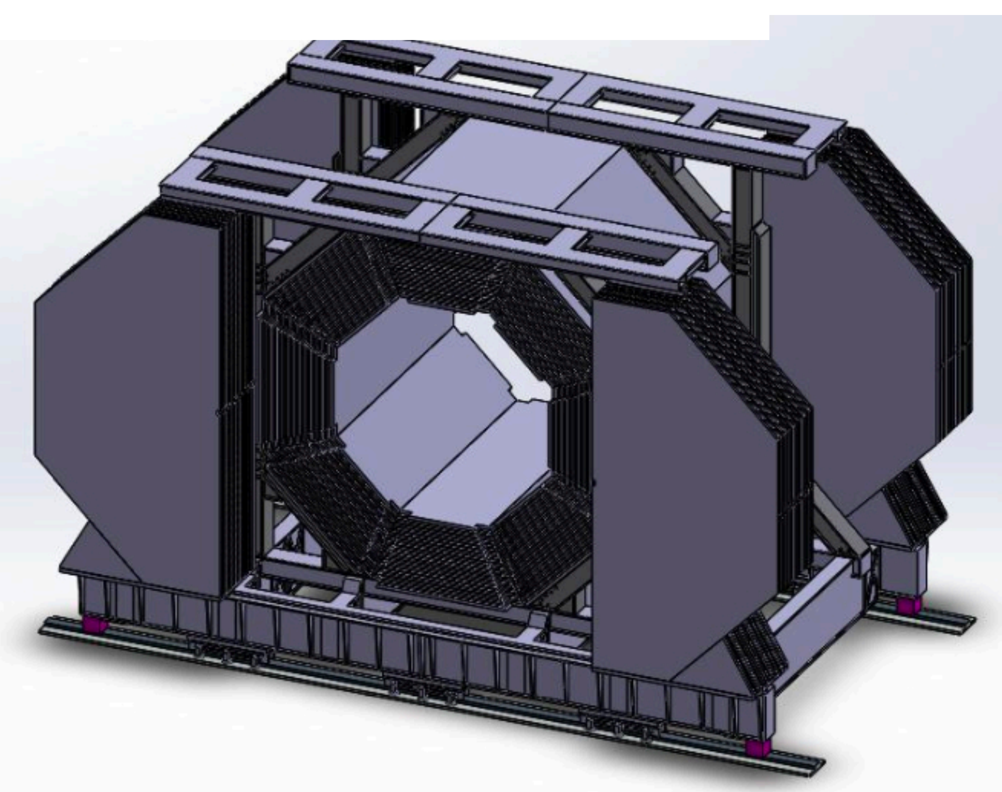
Goals:

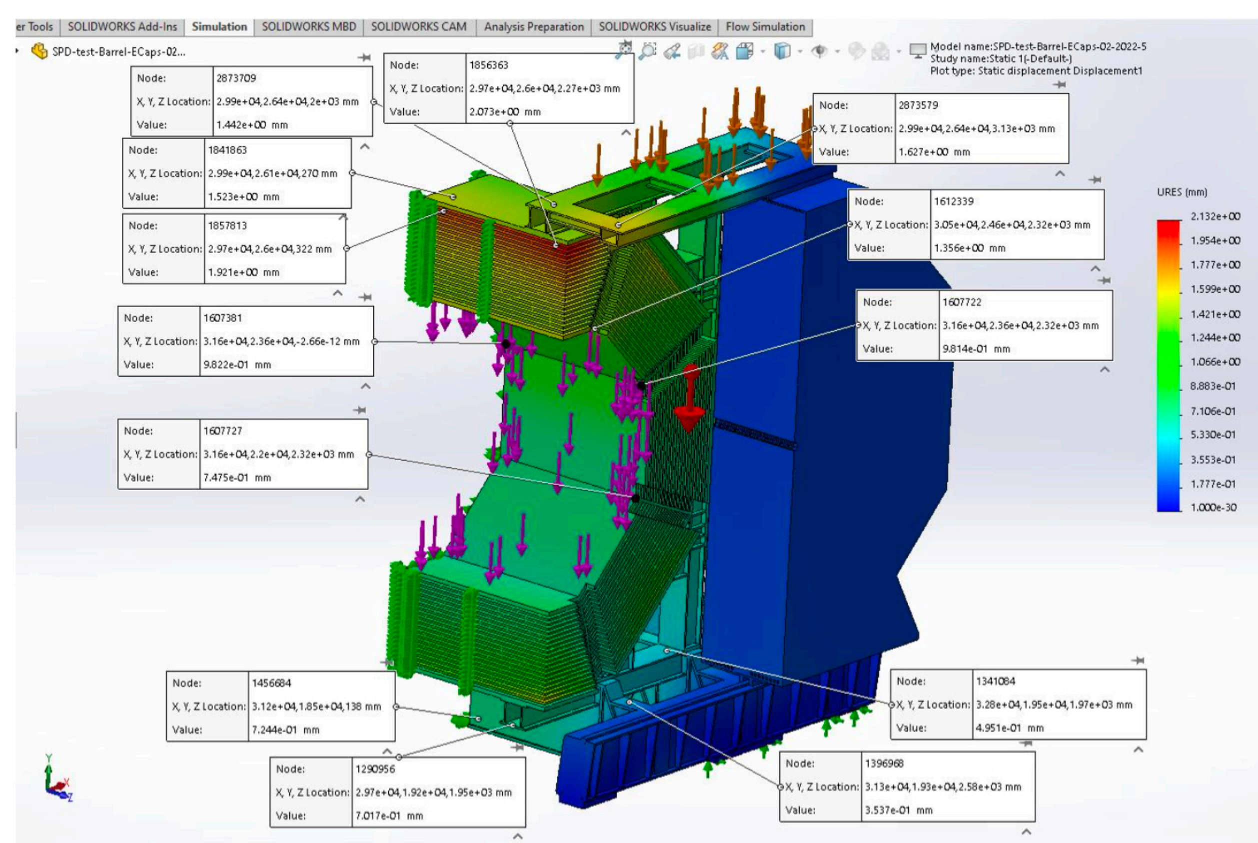
- *Muon identification*
- *Rough hadron calorimetry*
- *Yoke of the magnetic system*

Requirements:

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

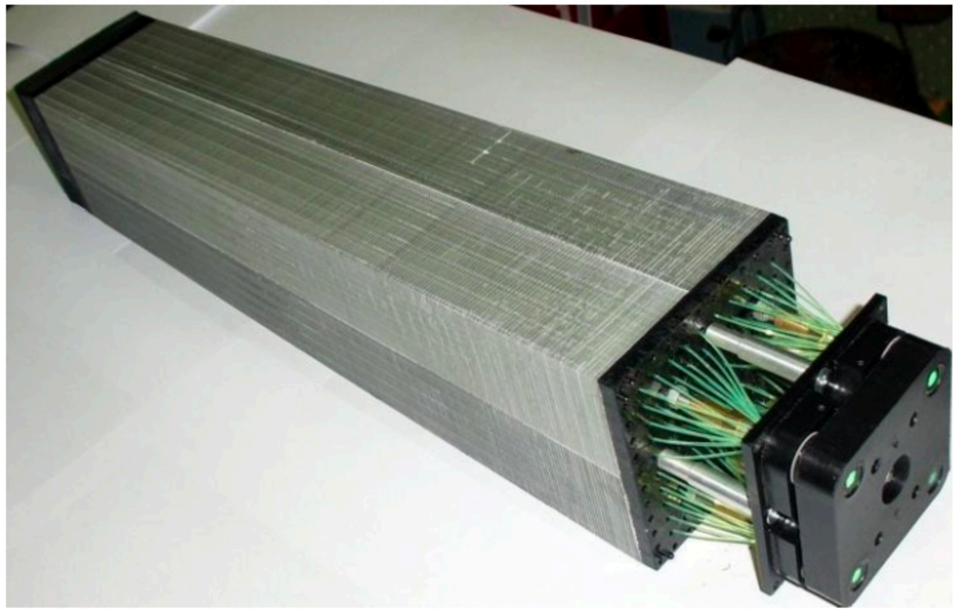




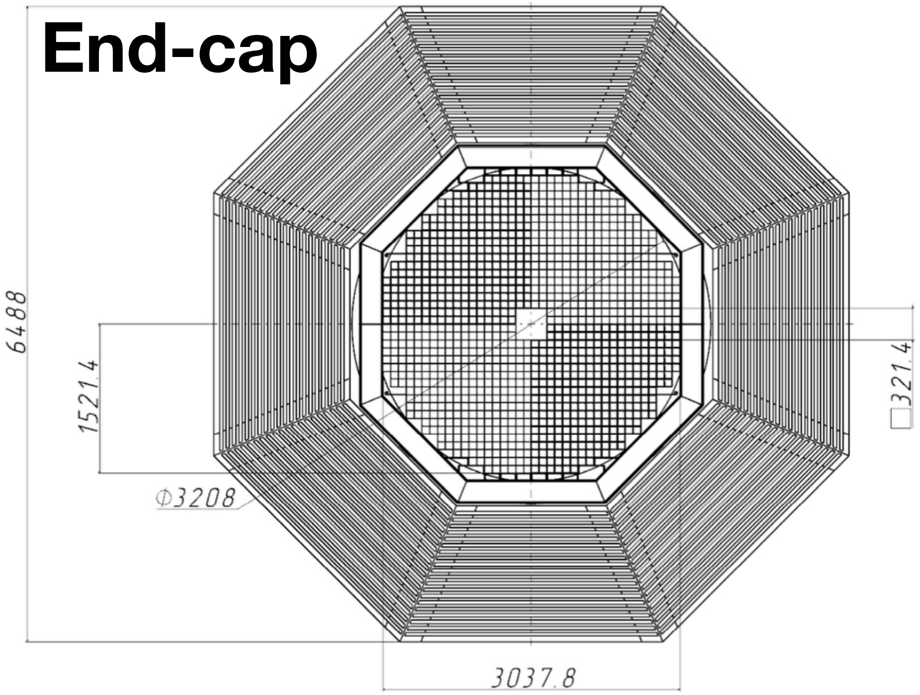


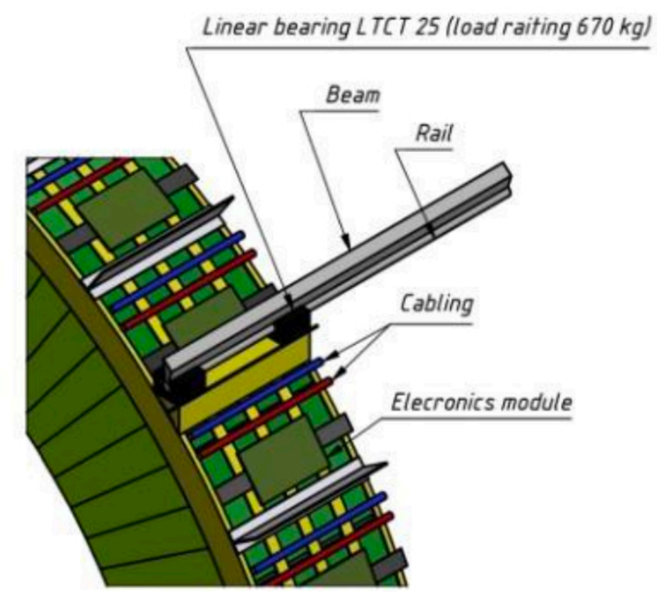

SPD
NICA
CMS RPC
PAT
VVS
NICA
2
2
3
22.2

Electromagnetic calorimeter



End-cap





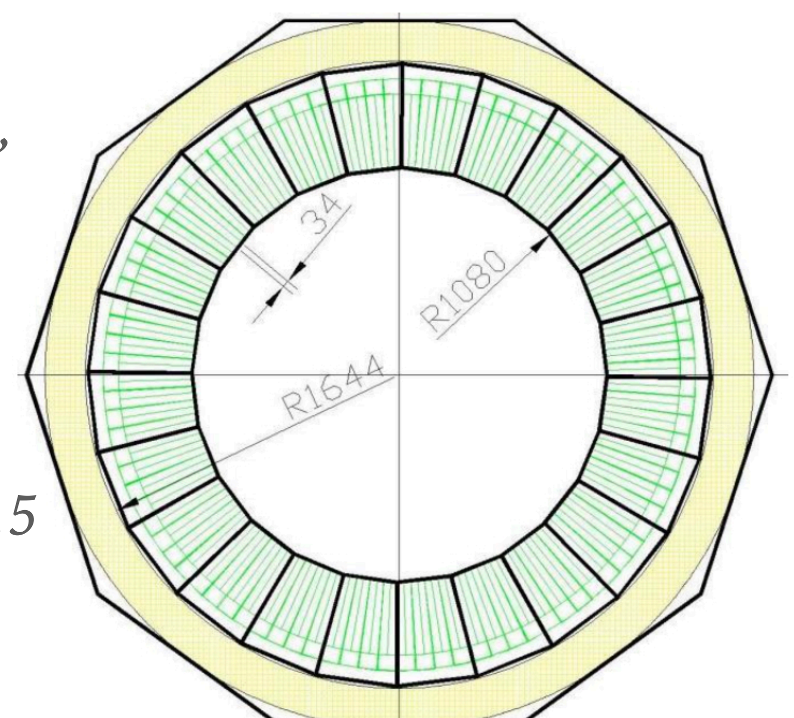
Goals:

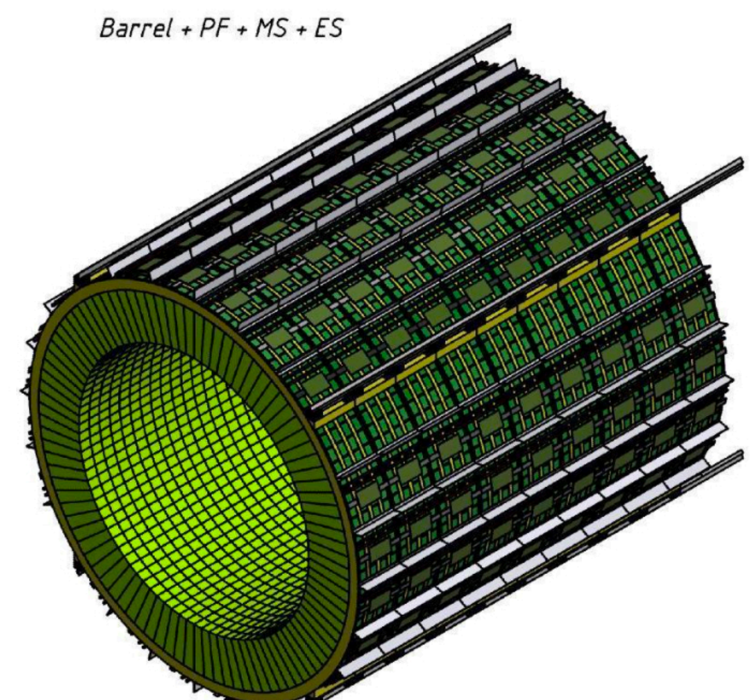
- *Detection of prompt photons, photons from π^0, η and χ_c decays*
- *Identification of electrons and positrons, participation in muon identification*
- *Local polarimetry with π^0*

Requirements:

- *Granularity ~4 cm*
- *Sampling: 190 layers (1.5 mm Sc. + 0.5 mm Pb), X/X_0=17.6*
- *Low energy threshold (~50 MeV)*
- *Energy resolution $\sim 5\,\%/\sqrt{E}$*

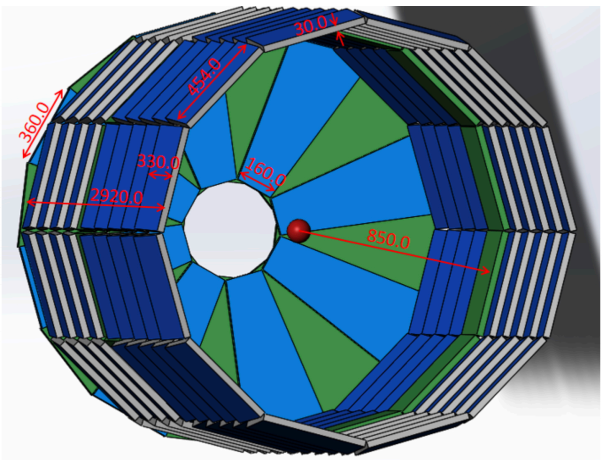
Barrel





Time-of-Flight system and Aerogel counters

MRPC-based TOF

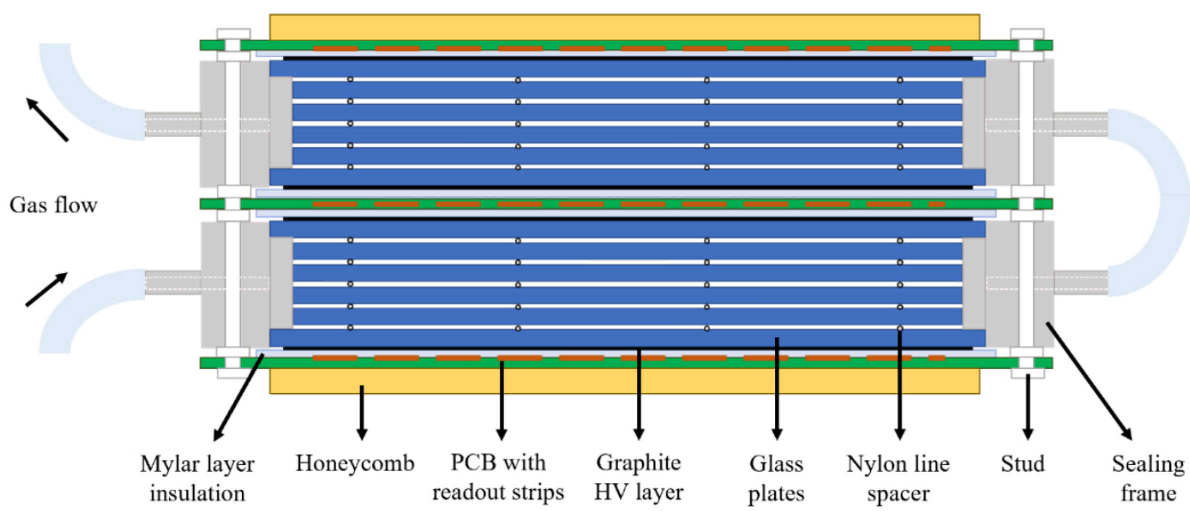


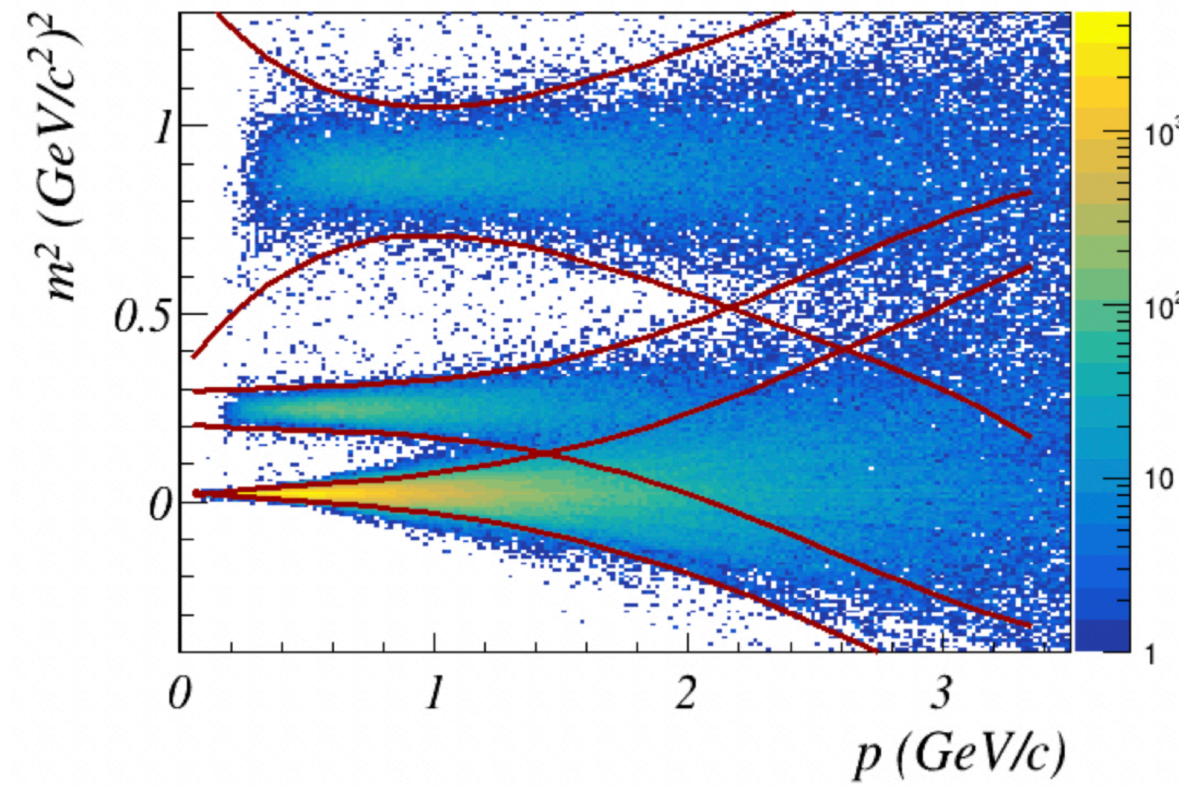
Goals:

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

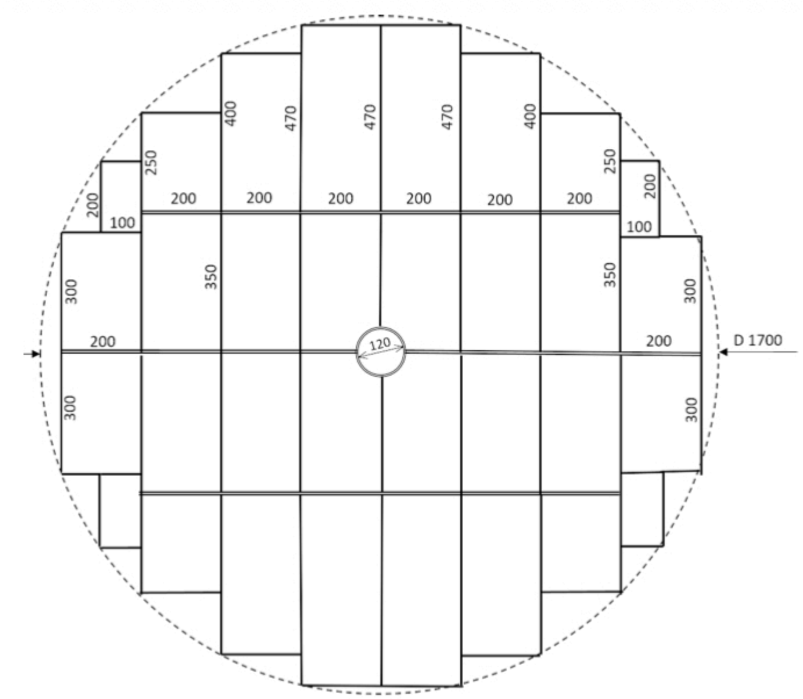
Requirements:

- *Time resolution <60 ps*





Aerogel counter in End-Caps

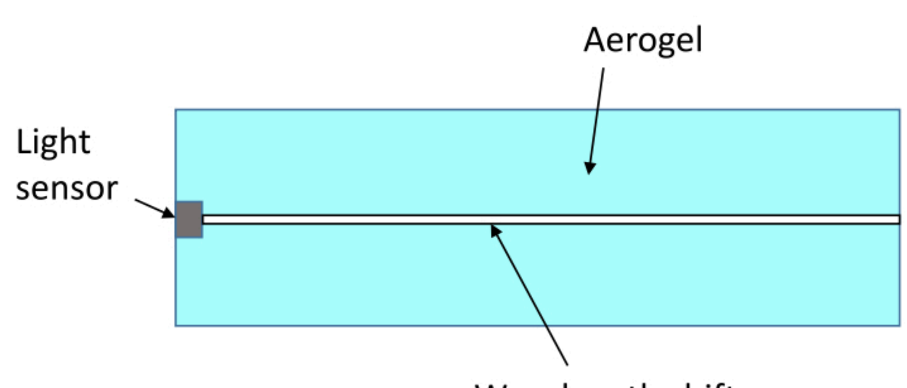


Goals:

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

Requirements:

- *We should have enough light!*



Straw Tracker

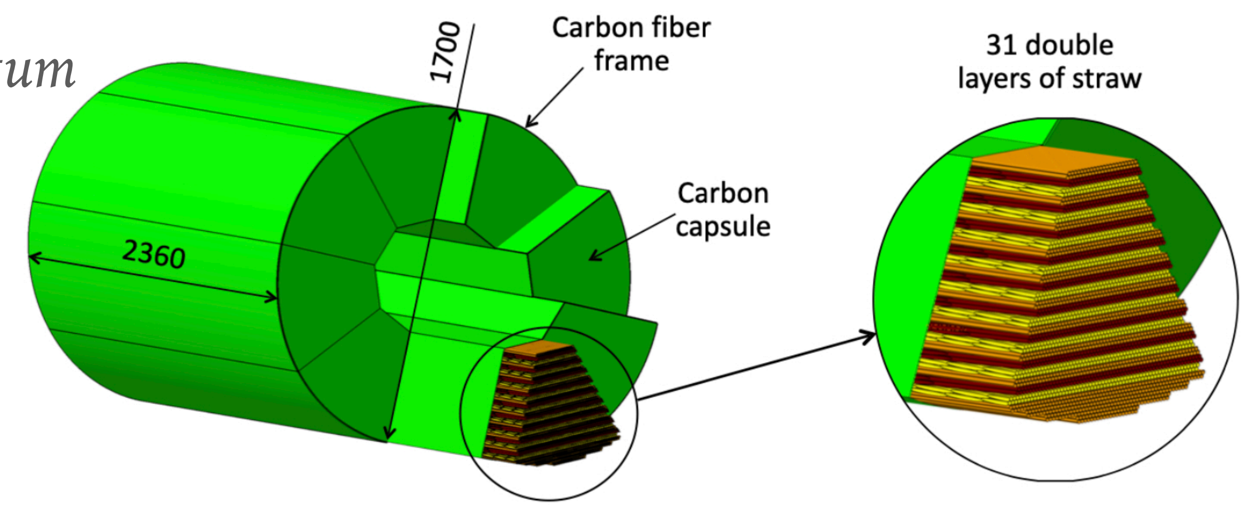
Goals:

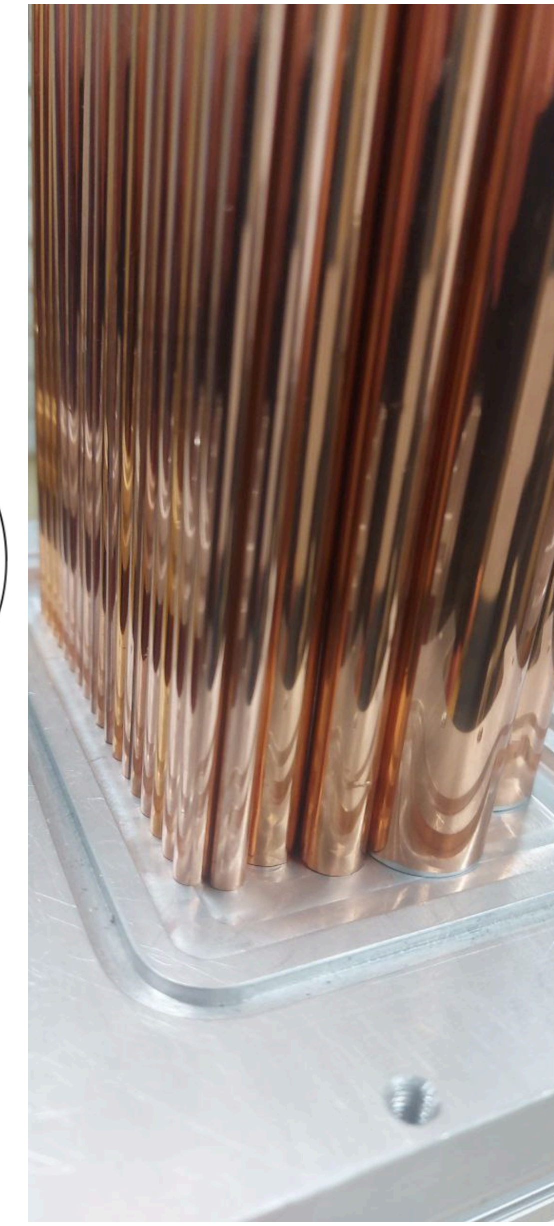
- *Track reconstruction and momentum measurement*
- *Participation in PID via dE/dx measurement*

Requirements:

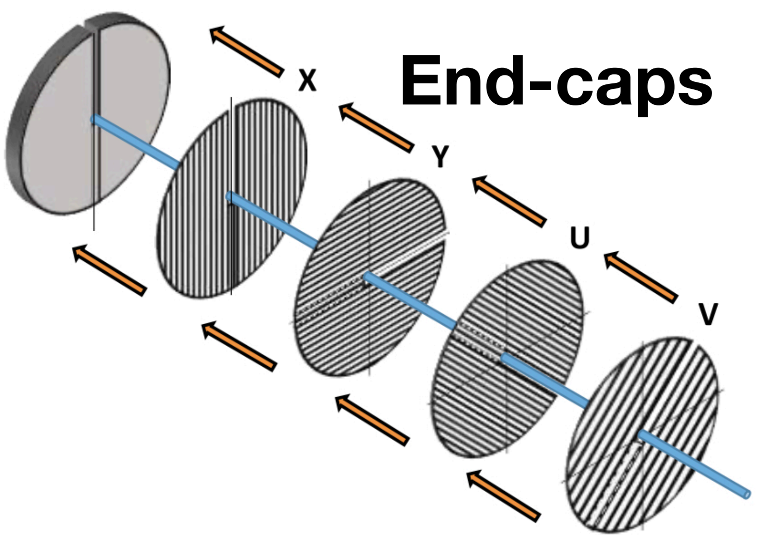
- *Spatial resolution ~150 μm*
- *Low material budget*
- *Operation in magnetic field of about 1 T*

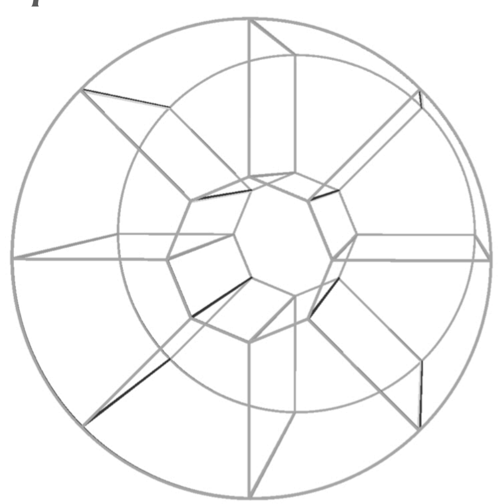
Barrel

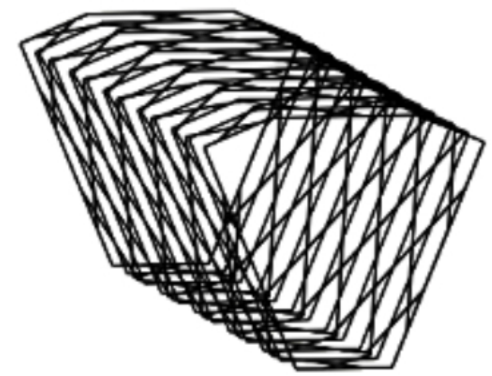


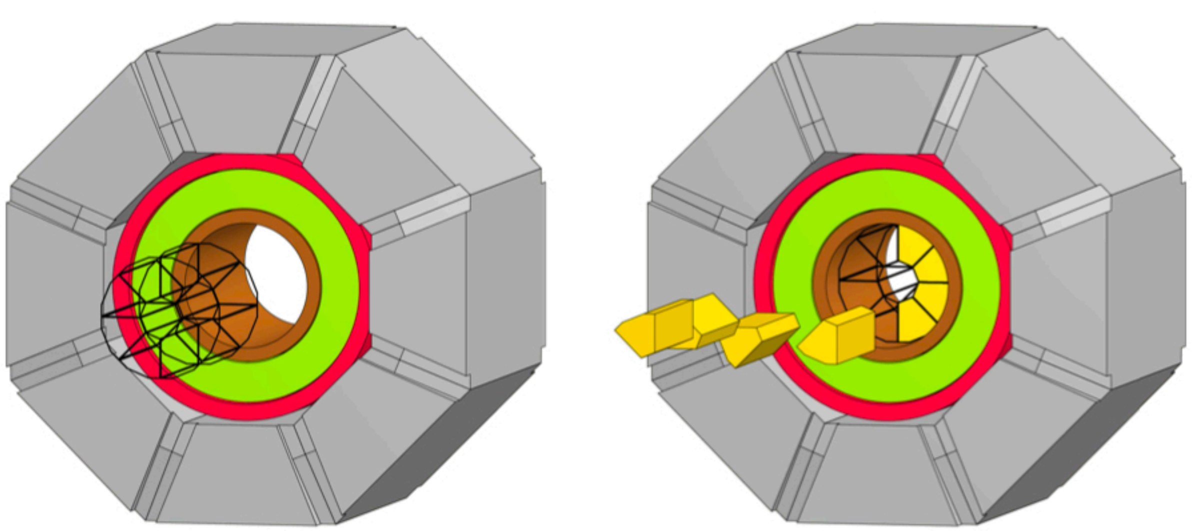


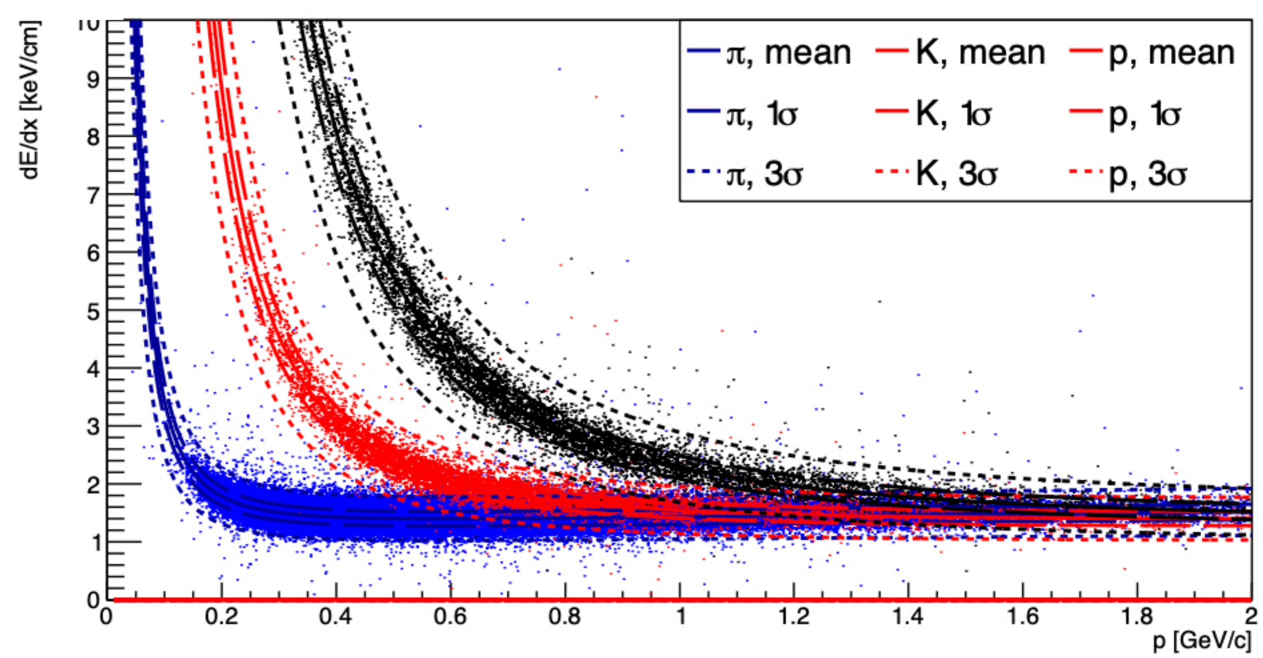
End-caps











Silicon Vertex Detector

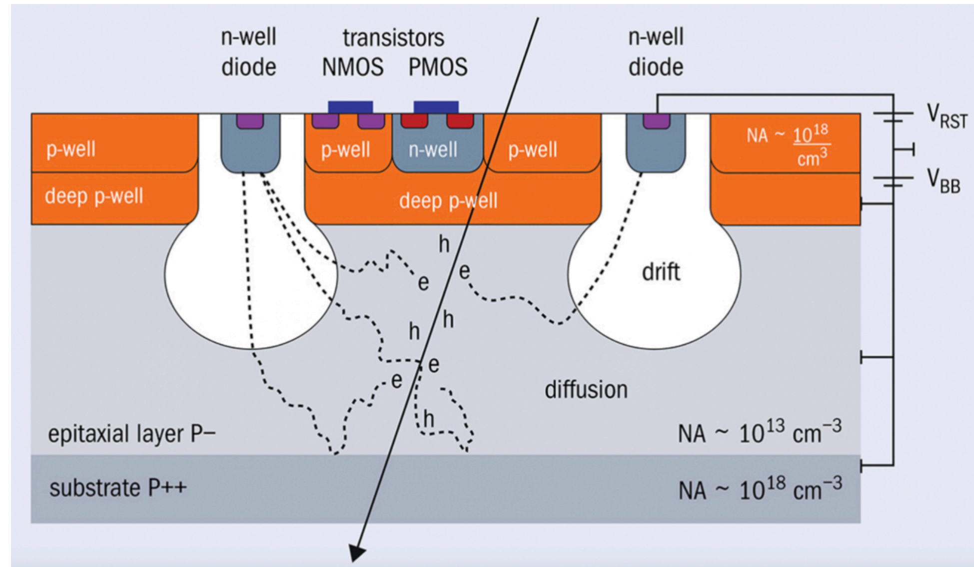
Goals:

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

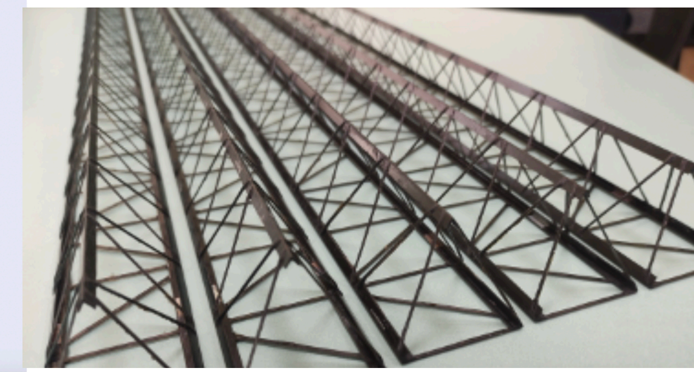
Requirements:

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

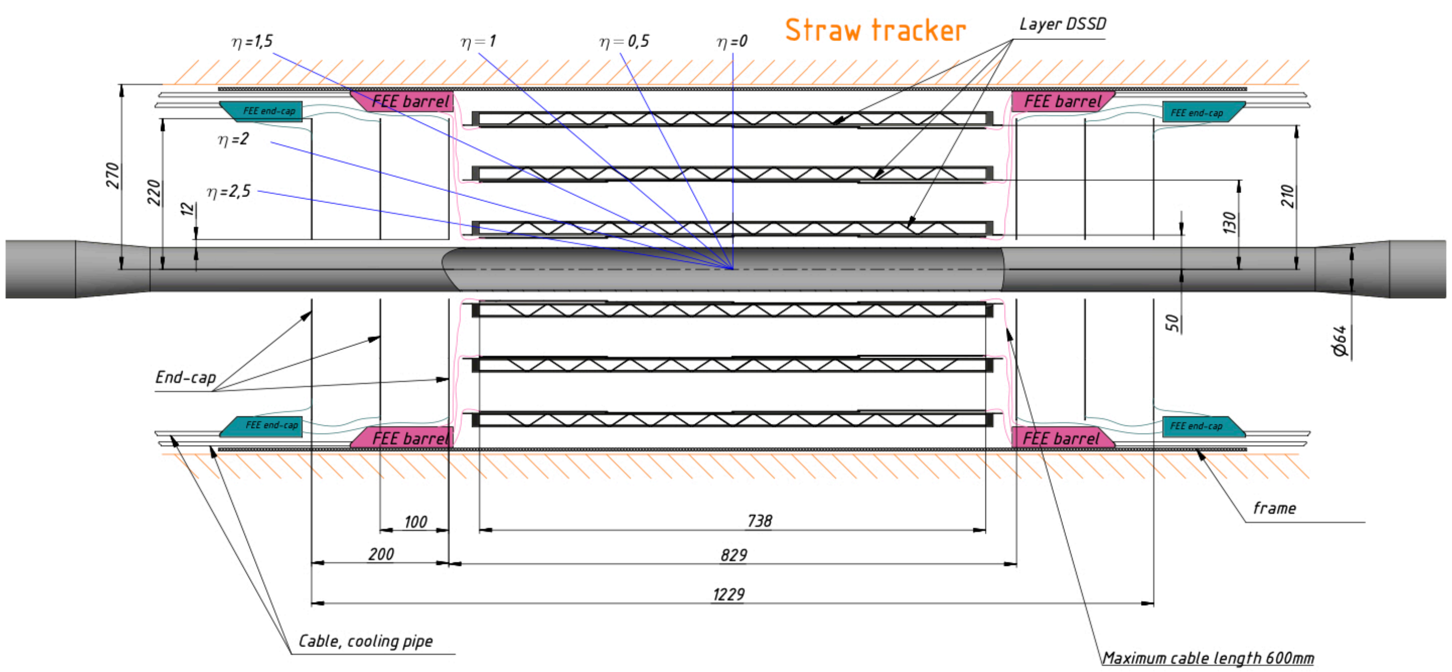
MAPS option: 4 layers

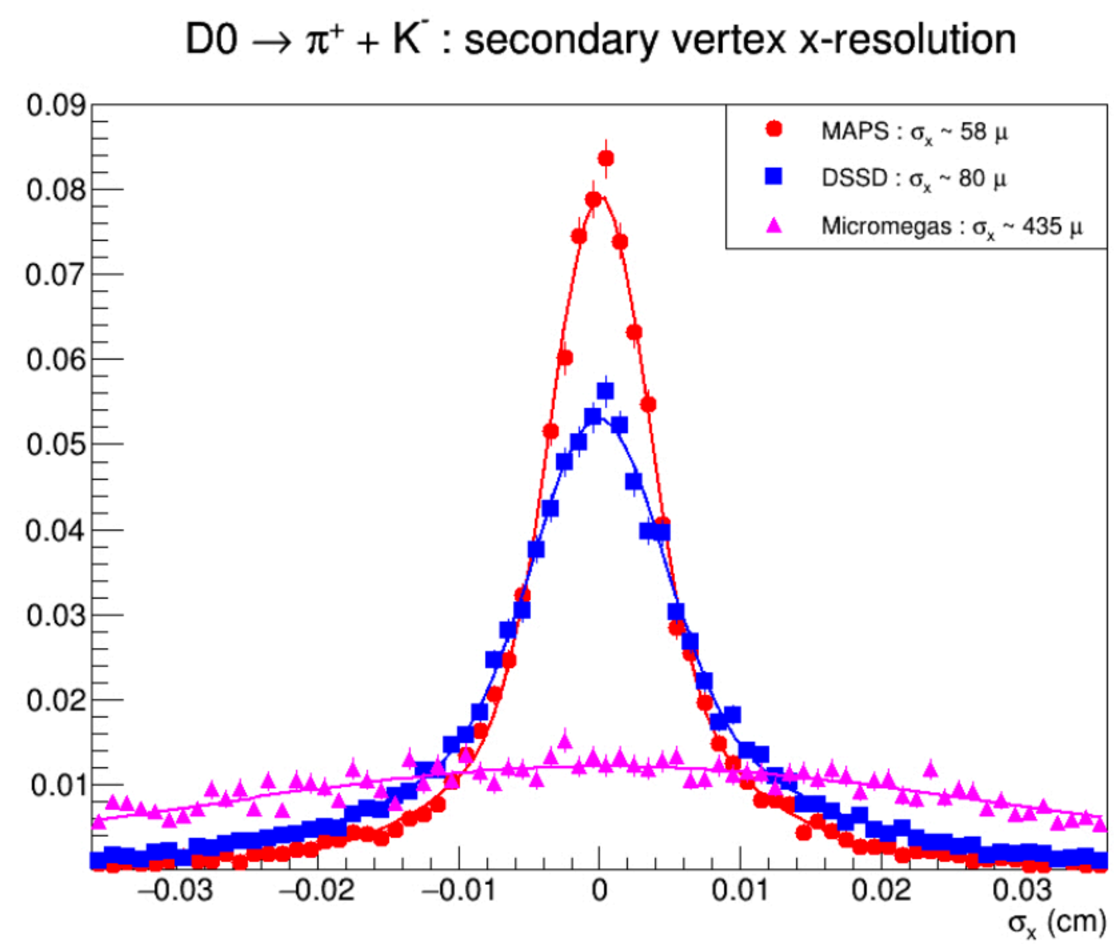


Carbon supports



DSSD option: 3 layers





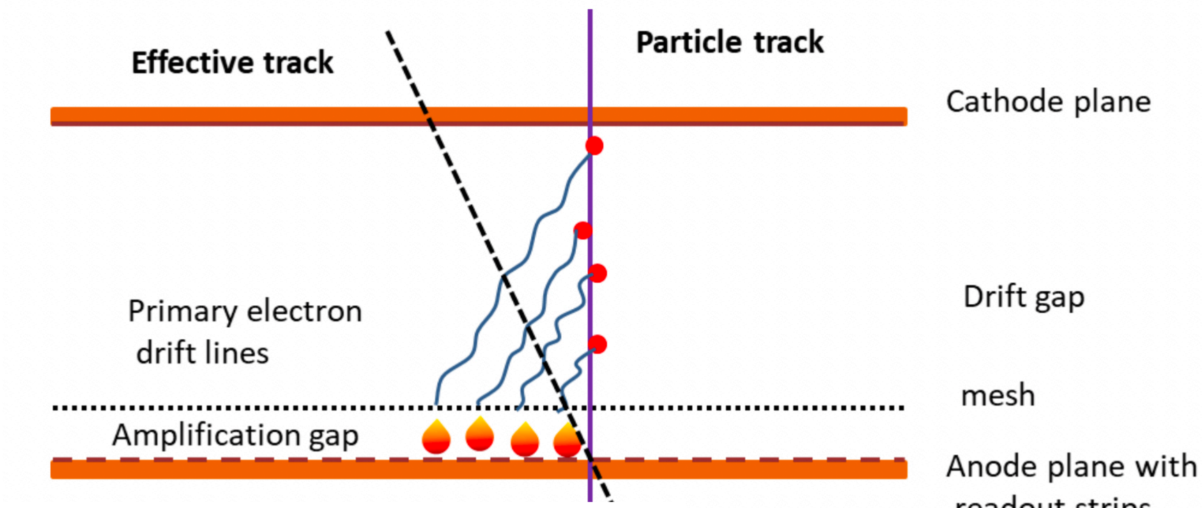
Micromegas-based Central Tracker

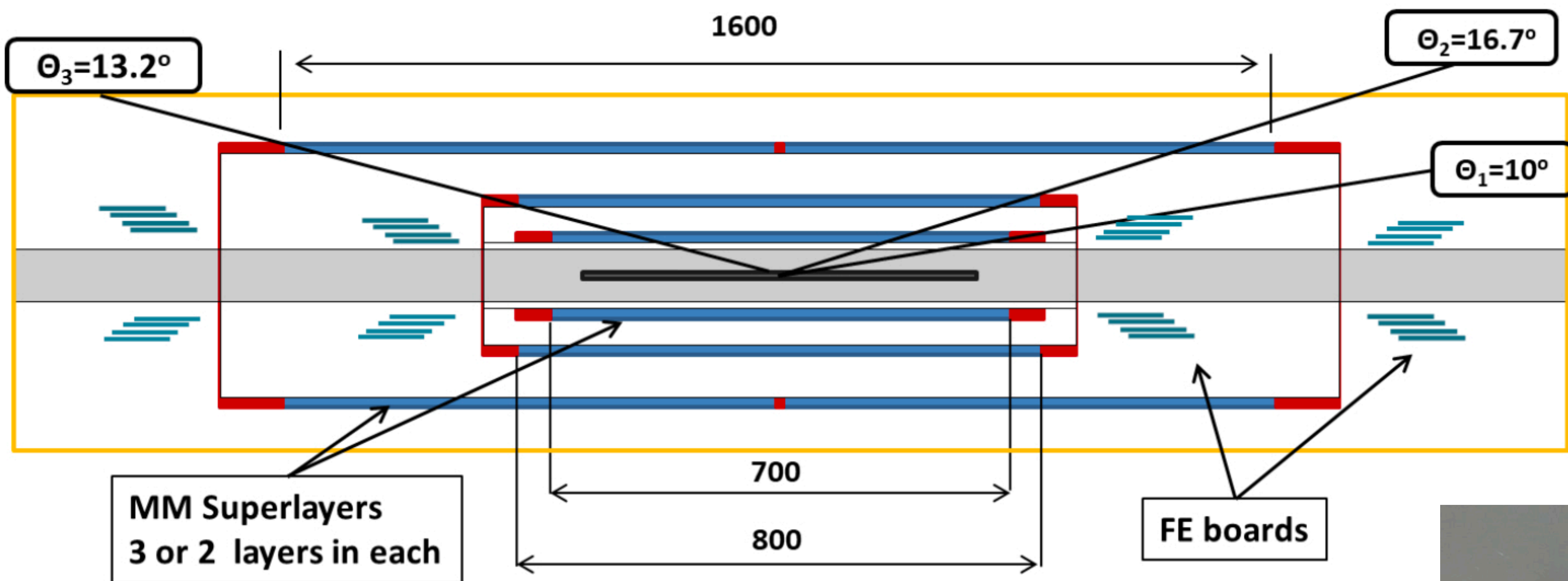
Goals:

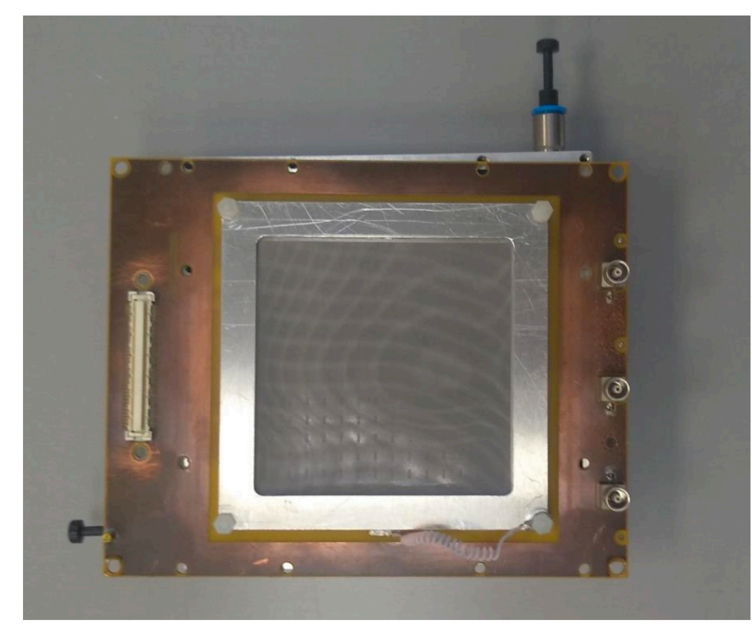
- *Improvement of the momentum resolution*

Requirements:

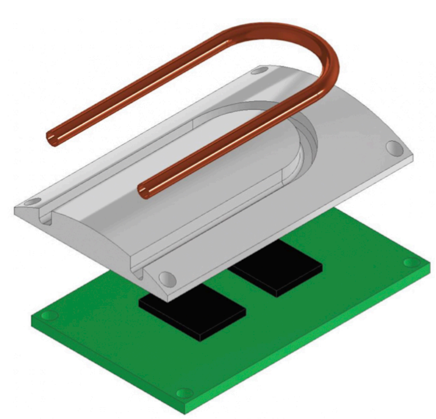
- *should operate in 1 T magnetic field*

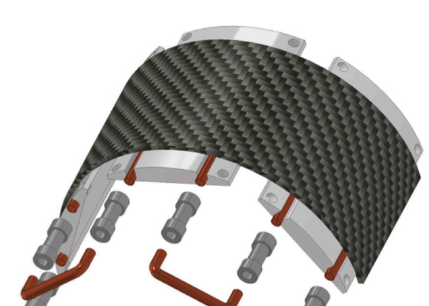






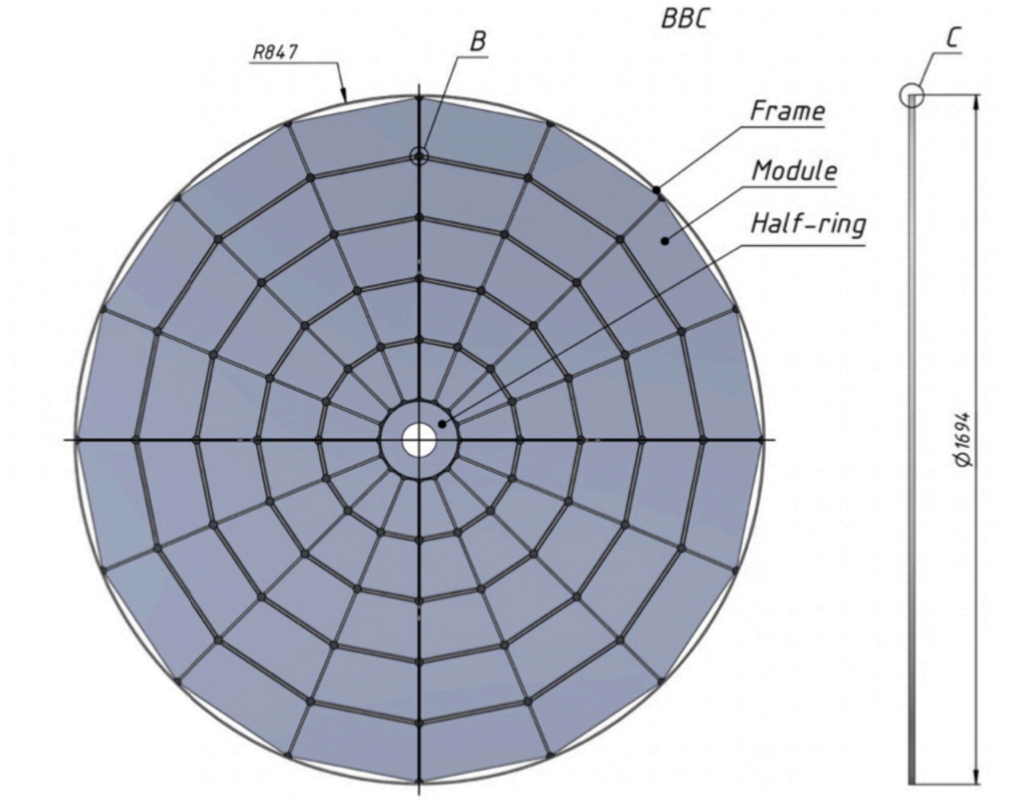
Water cooling





Beam-Beam Counters

Plastic scintillator-based outer part

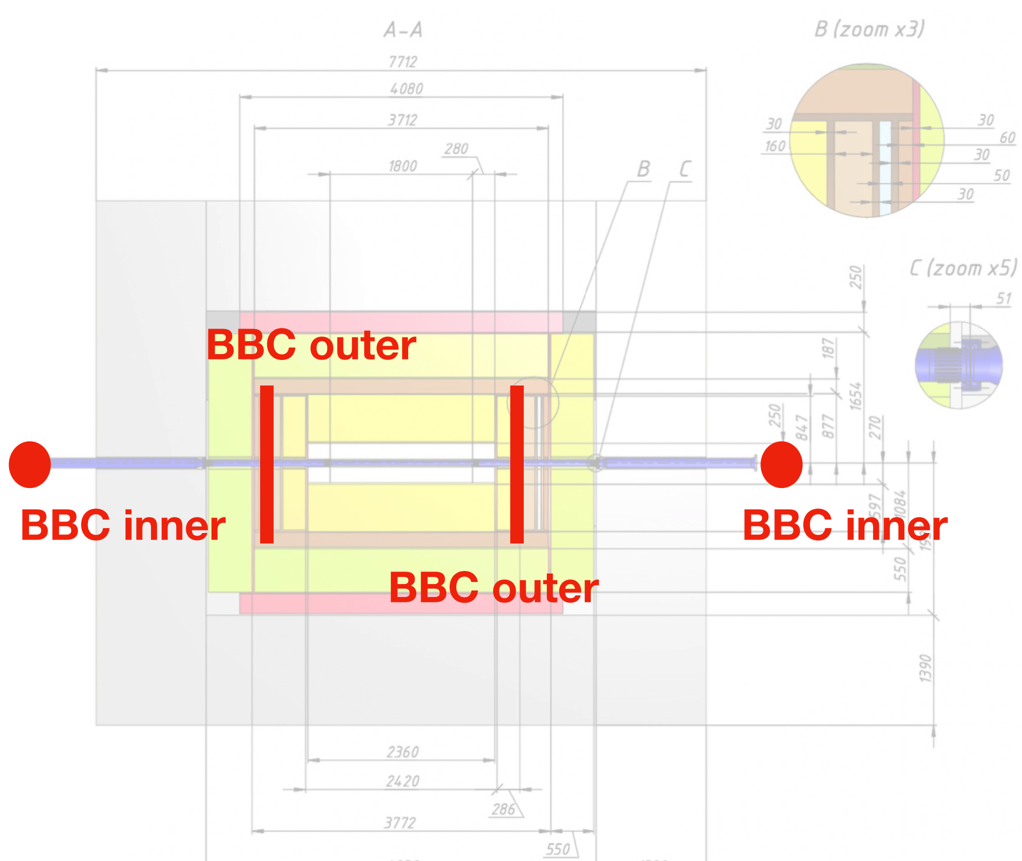


Goals:

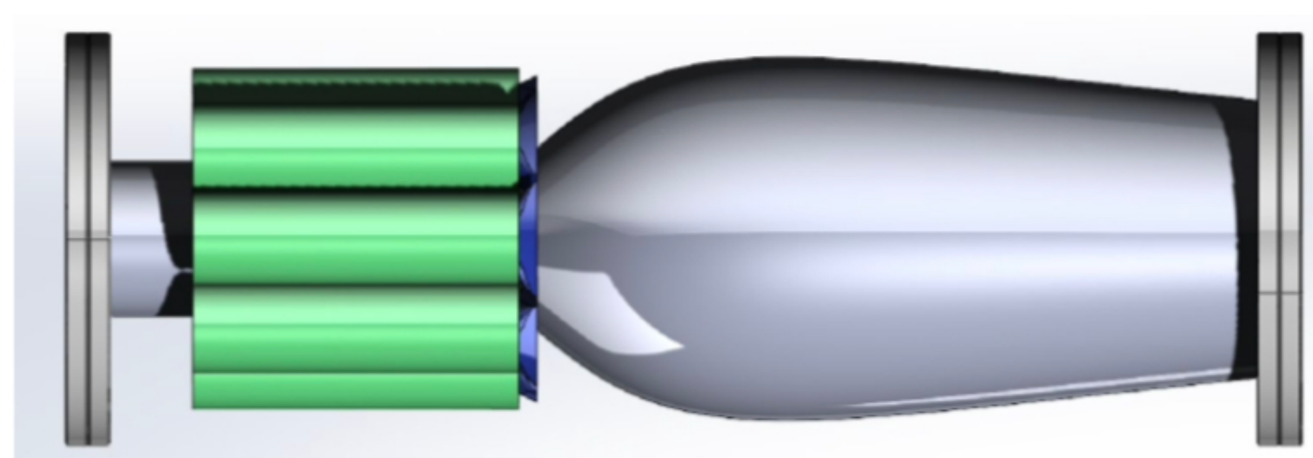
- *Local polarimetry*
- *Luminosity control*
- *Timing*

Requirements:

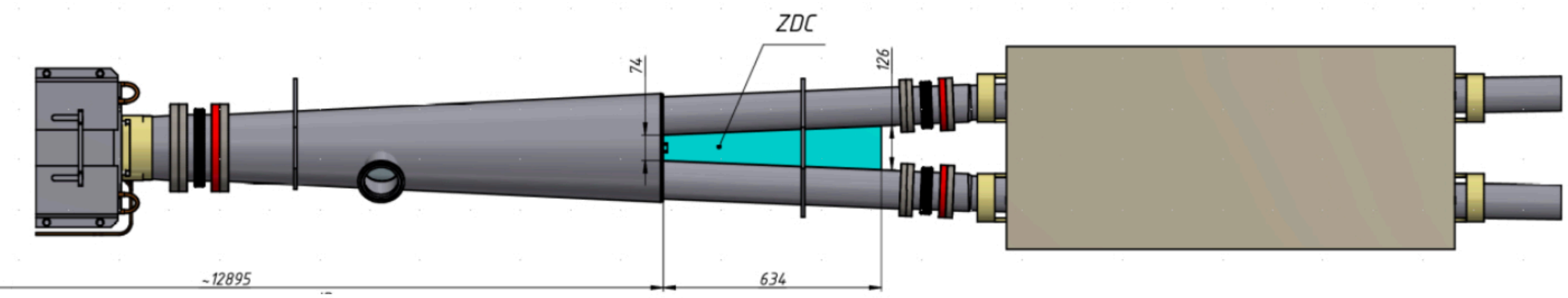
- *Operation close to the beam pipe (inner part)*
- *Time resolution ~1 ns (inner) and ~400 ps (outer part)*



MCP-based inner part



Zero Degree Calorimeters



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*