
Universe 5-IV-71 #200, Whanki Kim

Proton Spin

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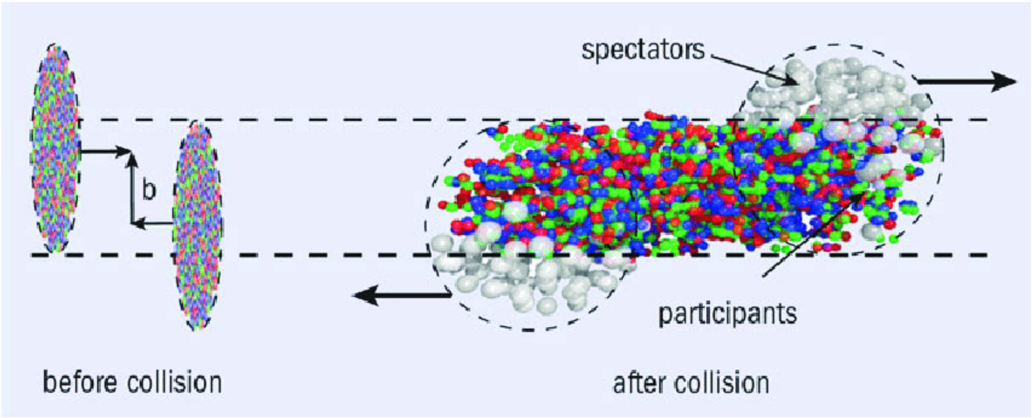
Seminar @Yonsei University

2022.Mar.21

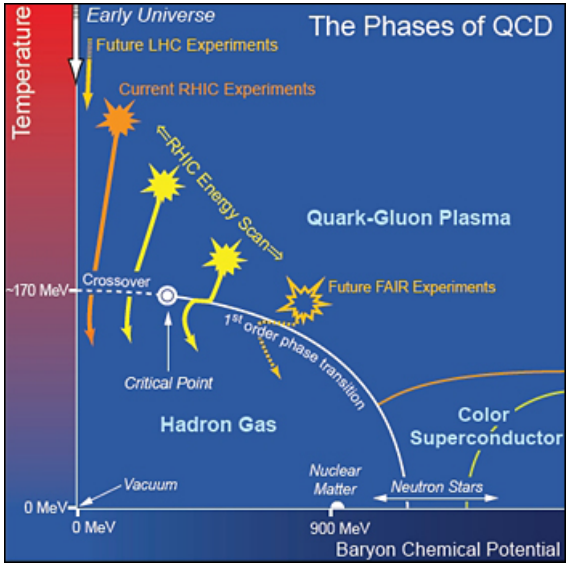
About me

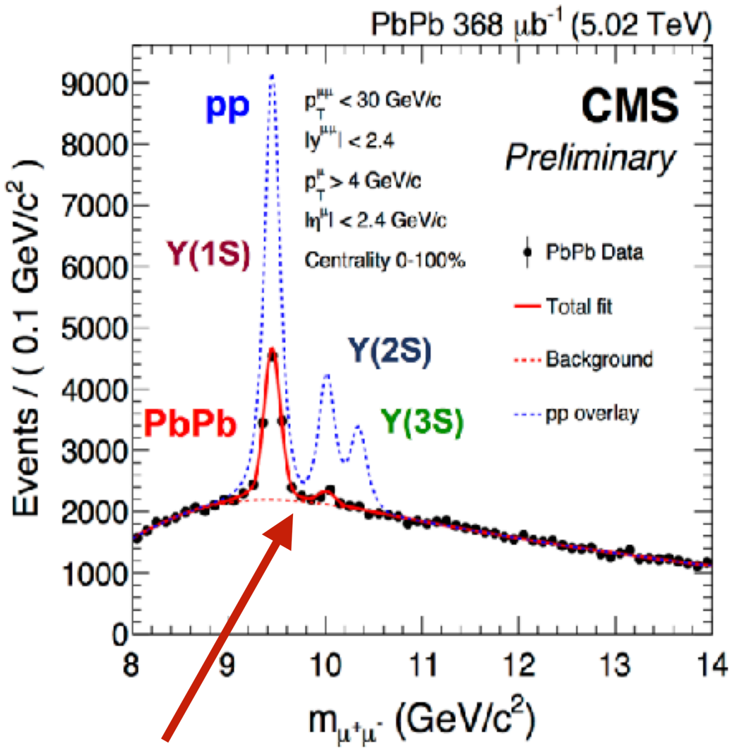
- CMS collaboration @ LHC (2008 — *present)*
  - MIT, Korea_U, Sejong_U
  - Heavy Ion Physics Analysis Group
  - CMS heavy ion group convener (Level 2) in 2020 — 2022
- LAMPS collaboration (2018 — *present*)
- ECCE collaboration at Electorn Ion Collider
- SHINCHON collaboration: Namer
- Faculty at Sejong_U (2018 — *present*)

My major expertise

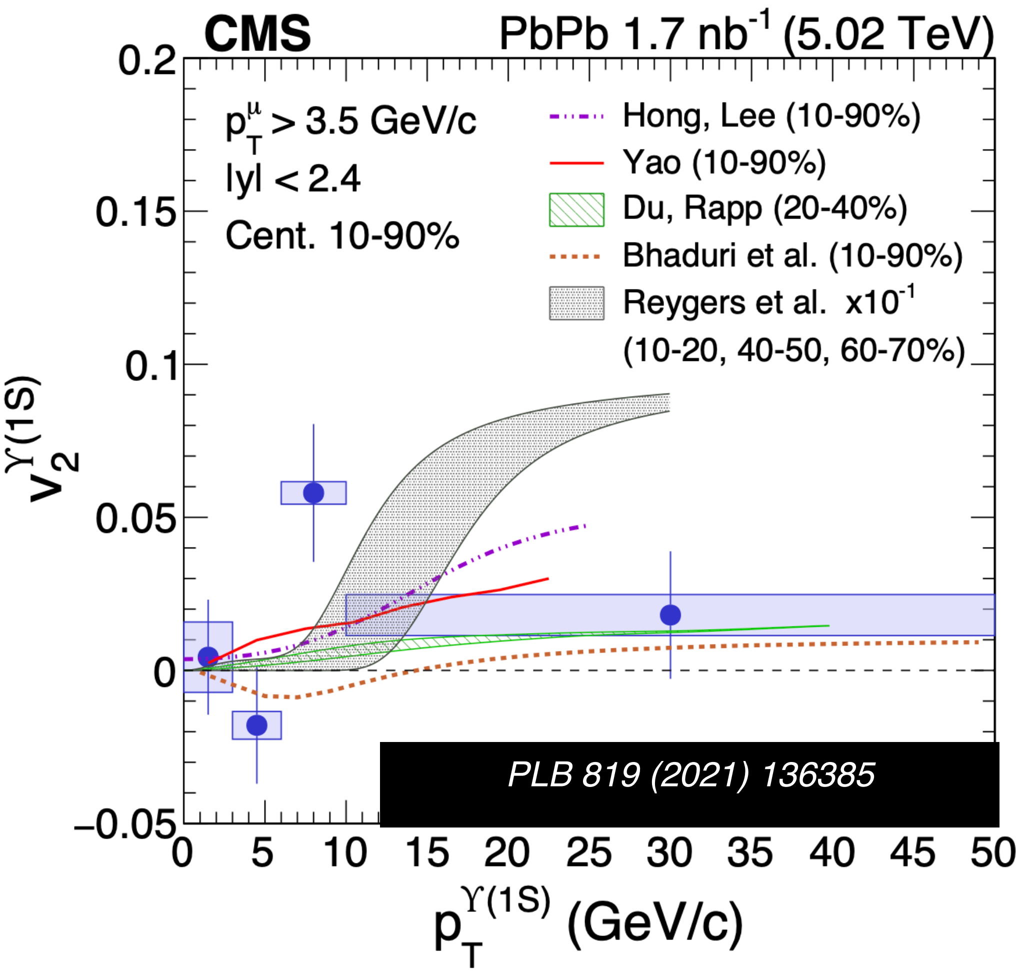


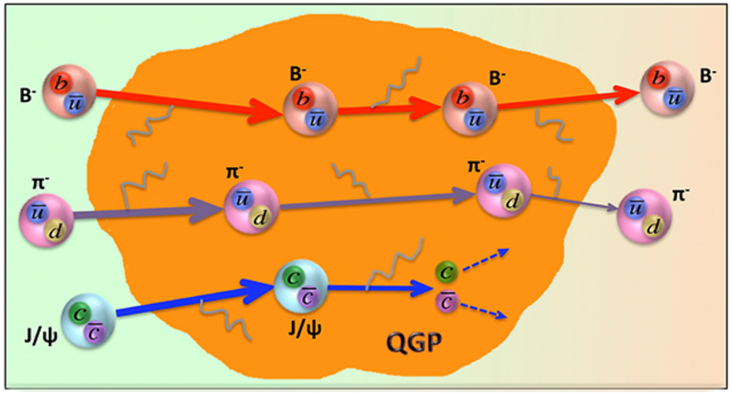
- Heavy Ion collision at LHC
  - CMS, ATALS experiments
- Neuron star, Bose-Einstein condensate in nuclei





몬테-카를로 시뮬레이터





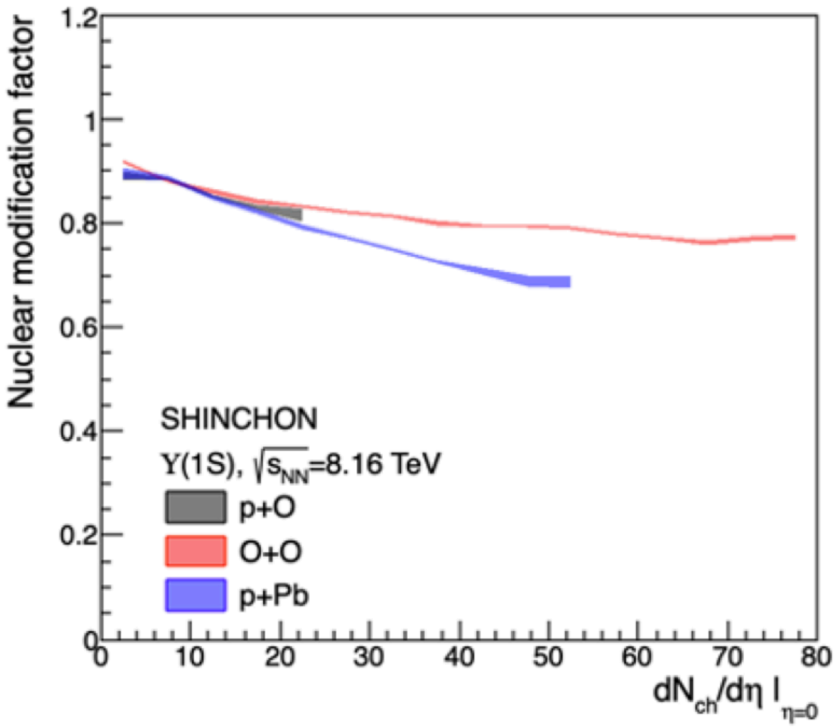
simulation,
heavy quark,
quarkonia,
heayv ion,
hydrodynamics

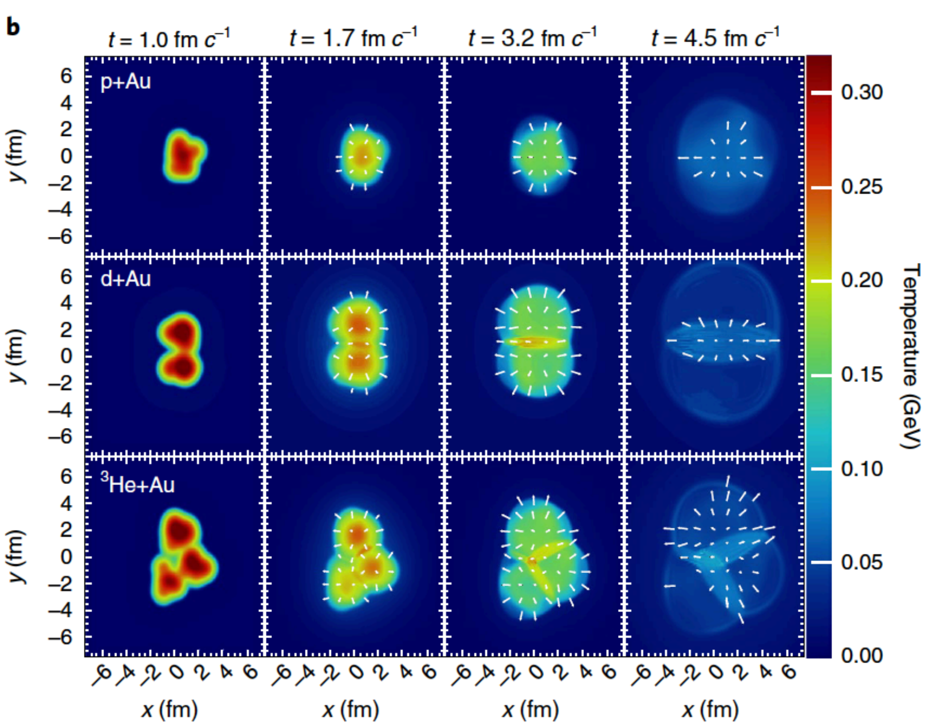
Upsilon Melting in heavy ion

ShinChon_MC

Simulation for **H**eavy **I**o**N** **C**ollision with **H**eavy-quark and **ON**ia

Collaboration of ~10 people from 5 universities (부산대, 인하대 ,연세대 ,고려대 ,세종대)





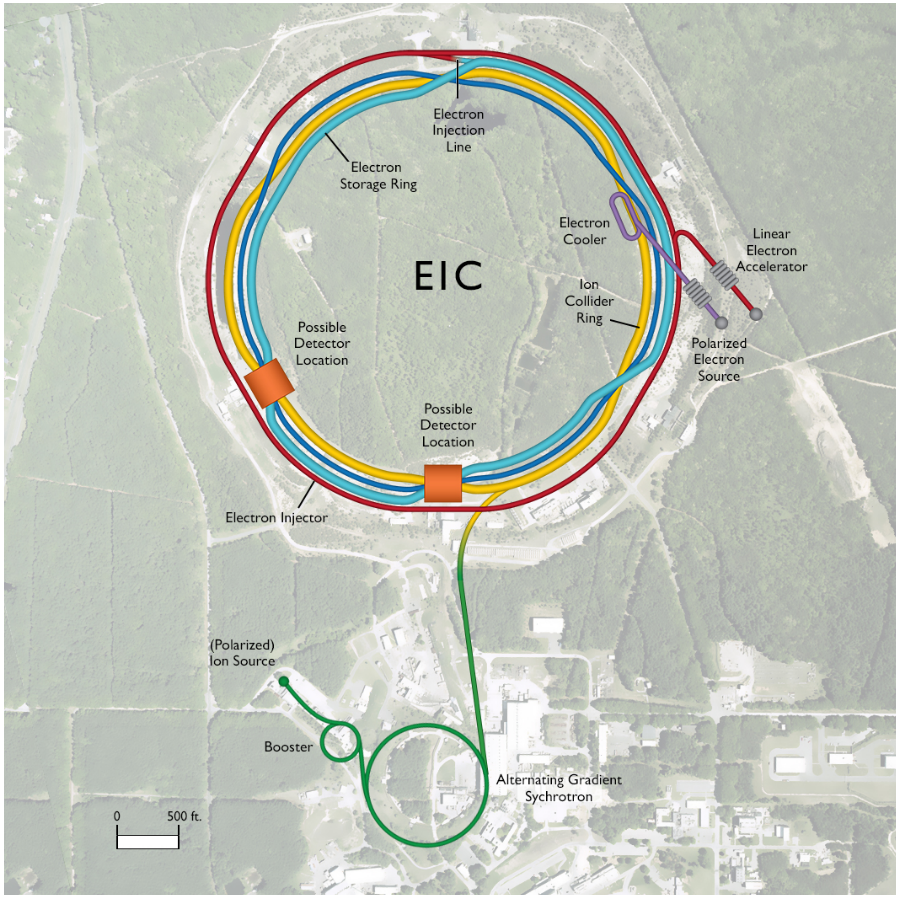
Q. So what does it have to do with

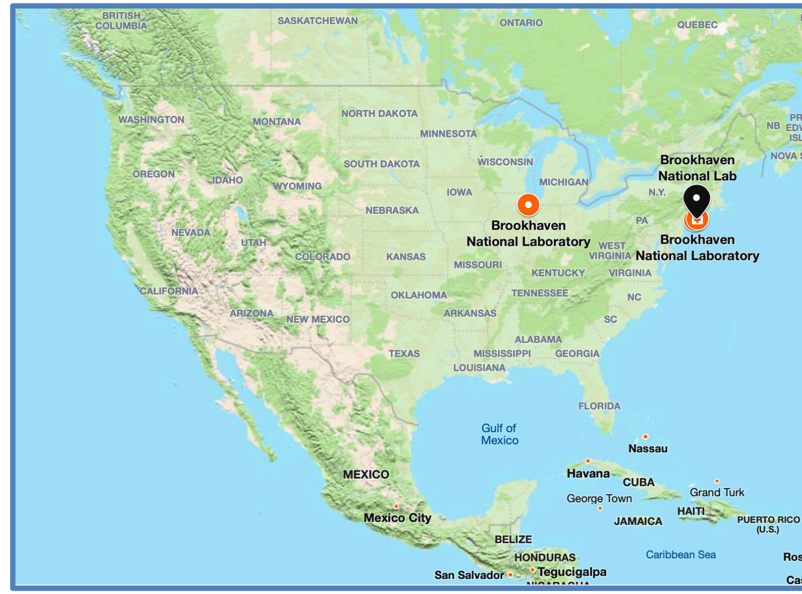
the proton spin?

A. Nothing so far

Starcraft Comics, S. Kim (2000)

EIC?





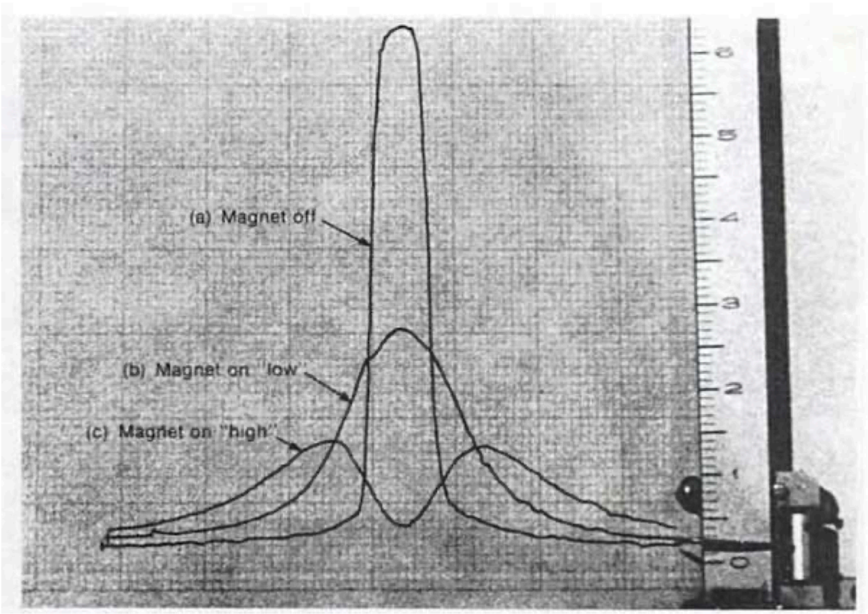
Electron Ion Collider **(EIC)**

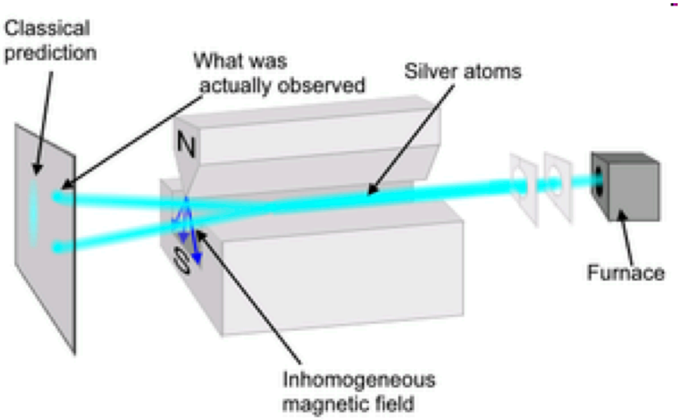
- To be built at Brookhaven National Lab in 2030s
- Collide polarized electron and p, d, He, and heavy ions

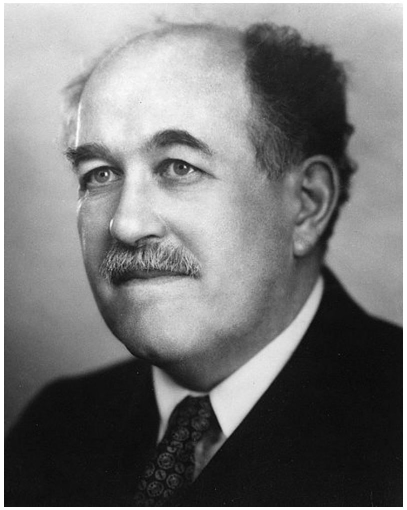
Key science questions that the EIC will address are:

- How do the nucleonic properties such as mass and spin emerge from partons and their underlying interactions?
- How are partons inside the nucleon distributed in both momentum and position space?
- How do color-charged quarks and gluons, and jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

Proton spin in 1920s

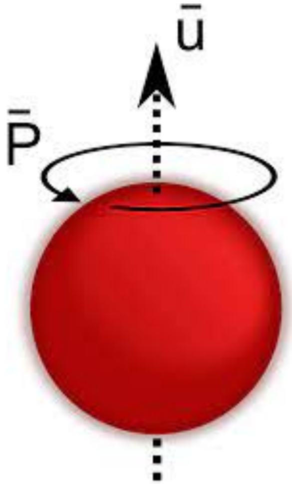




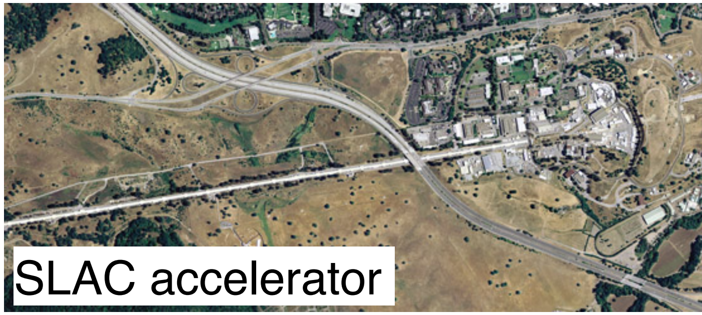


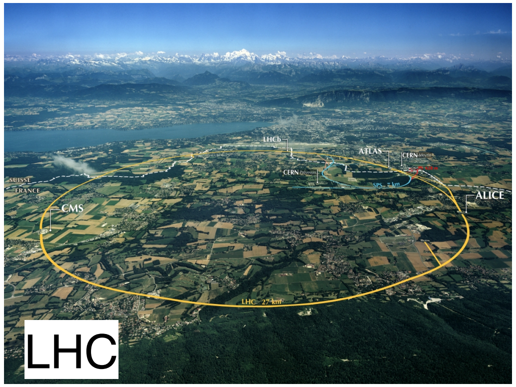
Stern-Gelarch experiment

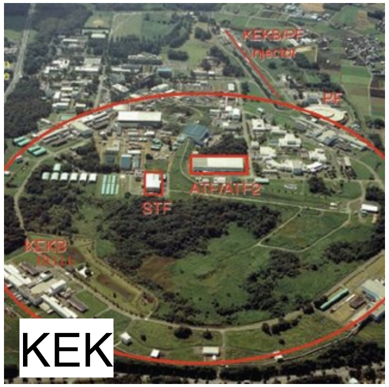
Proton has a spin-1/2

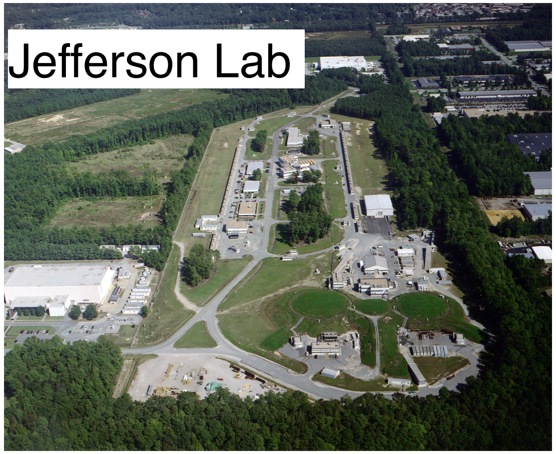


Zoo of accelerators and colliders

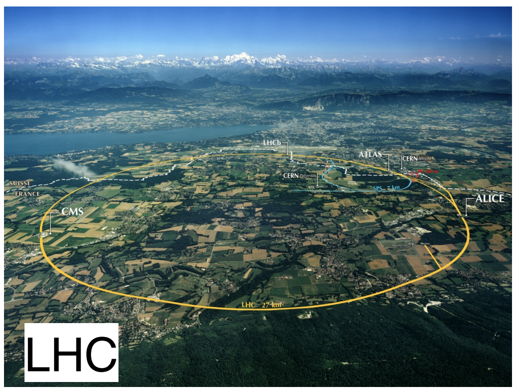


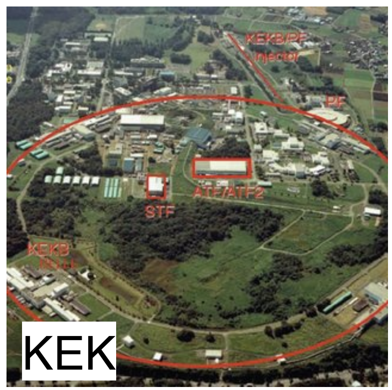






Zoo of accelerators and colliders

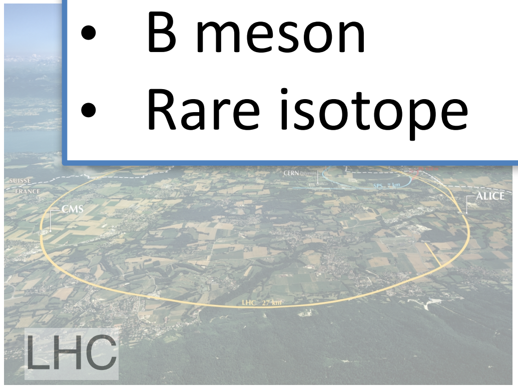




Zoo of accelerators and colliders

Matter factories

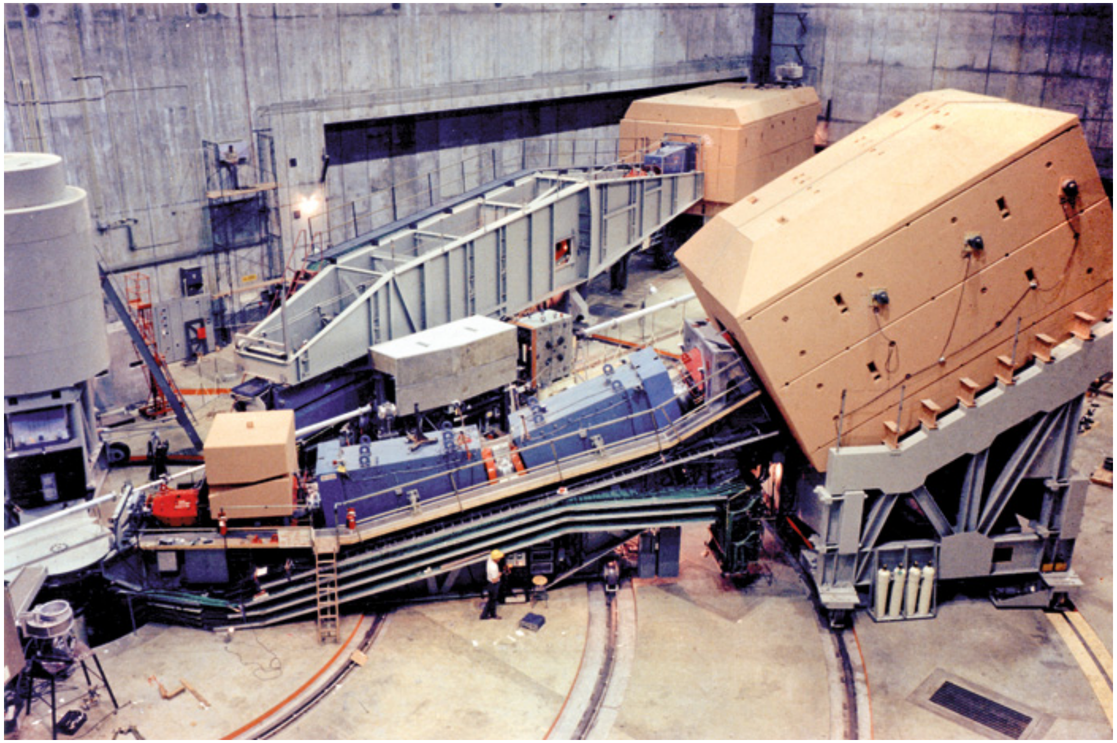
- Higgs
- B meson
- Rare isotope

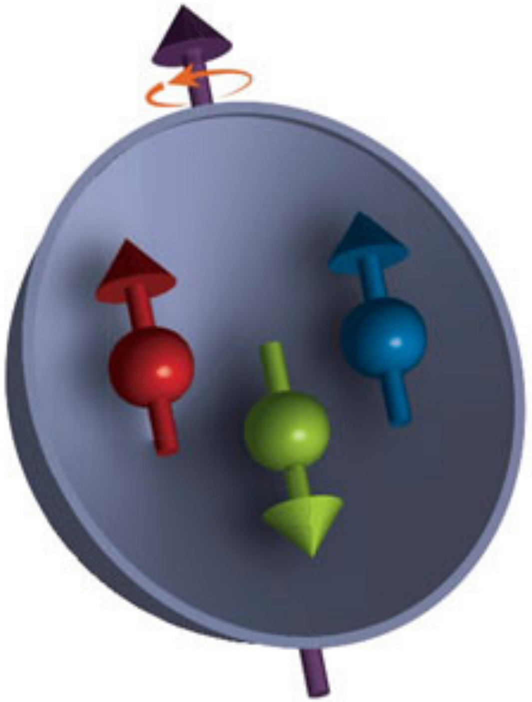


Microscopy of matter

- Photo interaction
- e and μ beams

Deep inelastic scattering

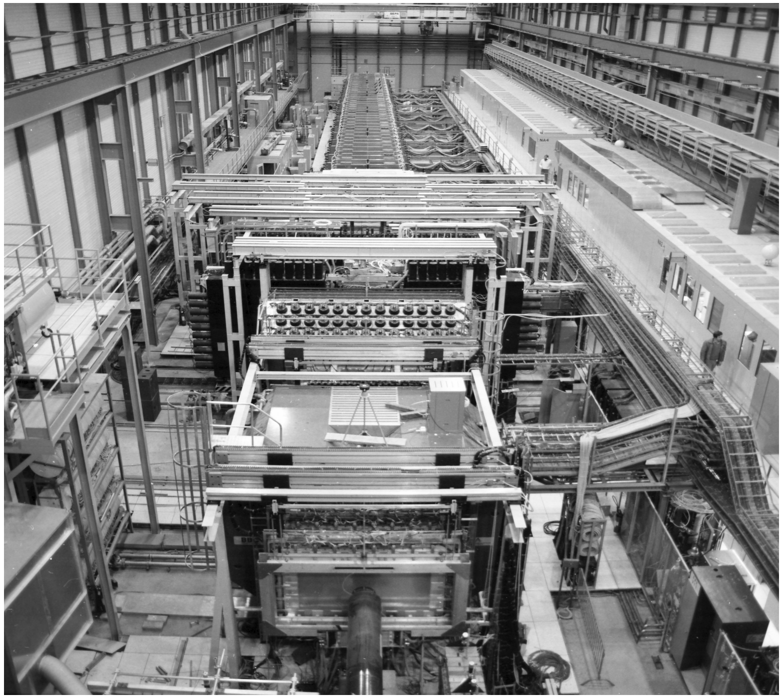




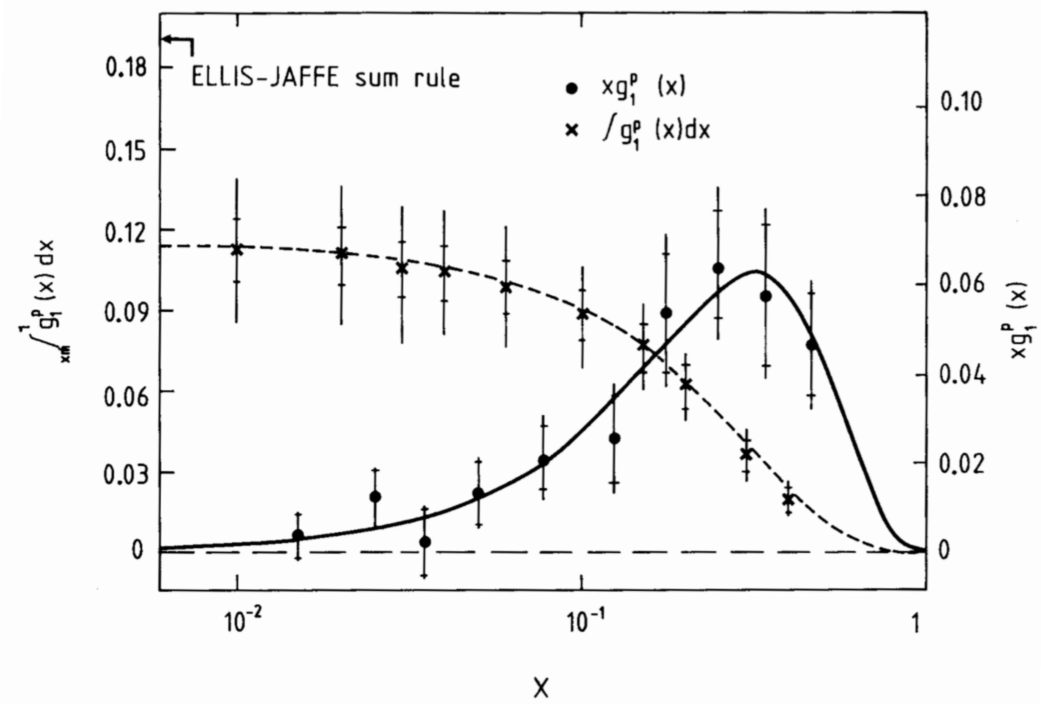
- Discovery of quarks in 1960s by DIS (deep inelastic scattering) at SLAC
- Good agreement with magnetic moment in quark model

Baryon	Magnetic moment of quark model	Computed (μ_N)	Observed (μ_N)
p	$4/3\ \mu_u - 1/3\ \mu_d$	2.79	2.793
n	$4/3\ \mu_d - 1/3\ \mu_u$	−1.86	−1.913

Proton spin **crisis**



PLB 206 (1988) 364



- **EMC** experiment @ CERN (late 1980s)
- Muon collides to polarized proton target
- The proton spin carried by quarks were only ~20% of 1/2
- Called proton spin crisis

Proton spin **crisis**

- New framework for proton spin

$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

- Latest value:
  - $\Sigma \sim 0.3$,
  - Δg ~ Non zero, large uncertainty
  - L_Q, L_G unknwon

now

Proton spin crisis

List of unsolved problems in physics

From Wikipedia, the free encyclopedia

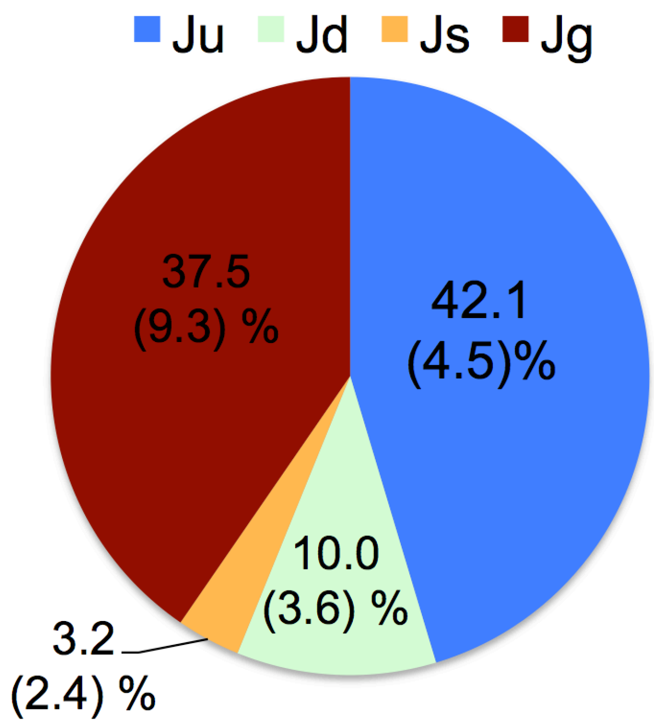
(Redirected from Unsolved problems in physics)

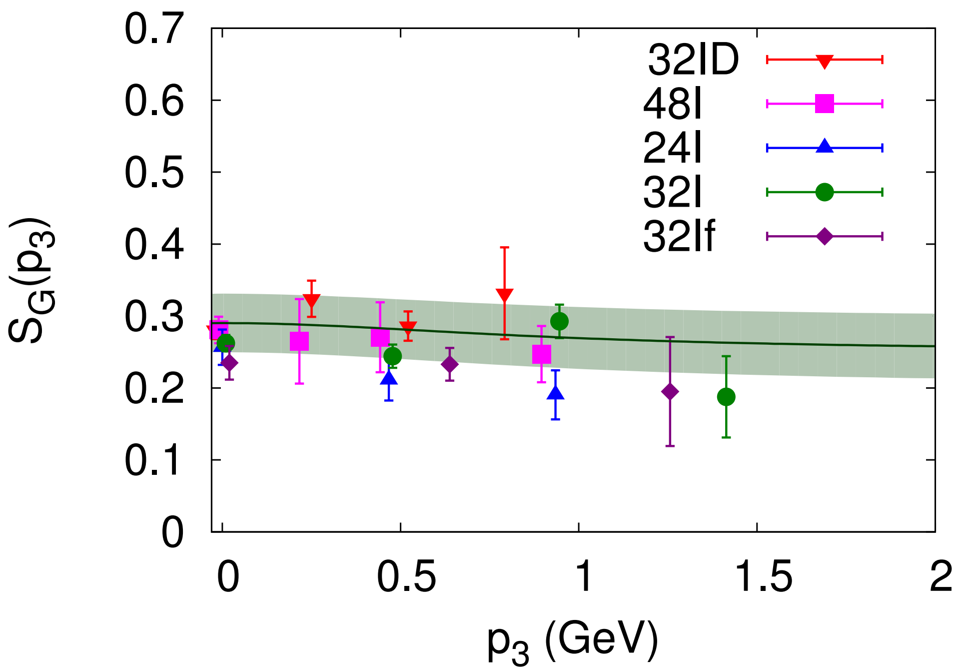
High-energy physics/particle physics [edit]

See also: Beyond the Standard Model

- Hierarchy problem: Why is gravity such a weak force? It becomes strong for particles only at the Planck scale, around 10^{19} GeV, much above the electroweak scale (100 GeV, the energy scale dominating physics at low energies). Why are these scales so different from each other? What prevents quantities at the electroweak scale, such as the Higgs boson mass, from getting quantum corrections on the order of the Planck scale? Is the solution supersymmetry, extra dimensions, or just anthropic fine-tuning?
- Magnetic monopoles: Did particles that carry "magnetic charge" exist in some past, higher-energy epoch? If so, do any remain today? (Paul Dirac showed the existence of some types of magnetic monopoles would explain charge quantization.)[24]
- Neutron lifetime puzzle: While the neutron lifetime has been studied for decades, there currently exists a lack of consilience on its exact value, due to different results from two experimental methods ("bottle" versus "beam").[25]
- Proton decay and spin crisis: Is the proton fundamentally stable? Or does it decay with a finite lifetime as predicted by some extensions to the standard model?[26] How do the quarks and gluons carry the spin of protons?[27]
- Supersymmetry: Is spacetime supersymmetry realized at TeV scale? If so, what is the mechanism of supersymmetry breaking? Does supersymmetry stabilize the electroweak scale, preventing high quantum corrections? Does the lightest supersymmetric particle (LSP) comprise dark matter?

Lattice QCD calculation





- Study by ETMC collaboration, *PRD 101, 094513*

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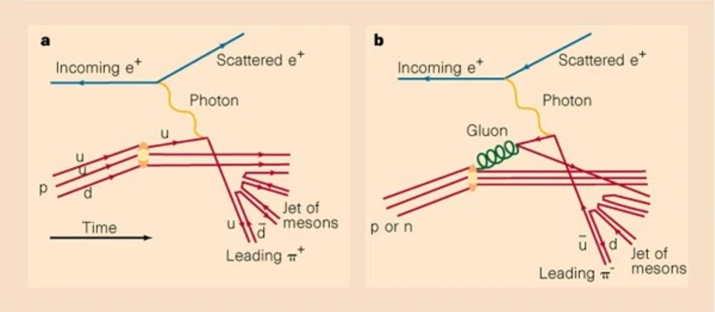
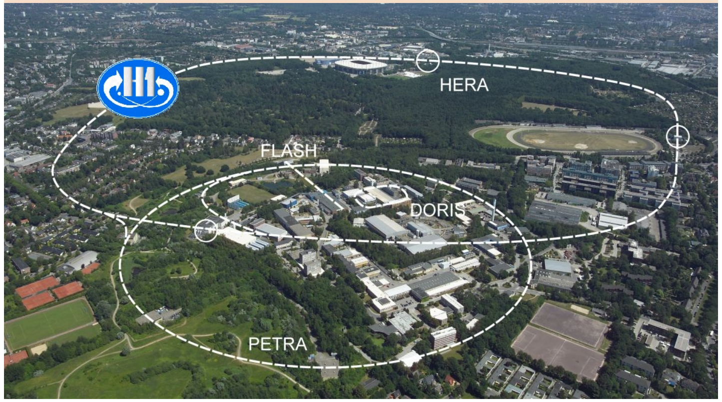
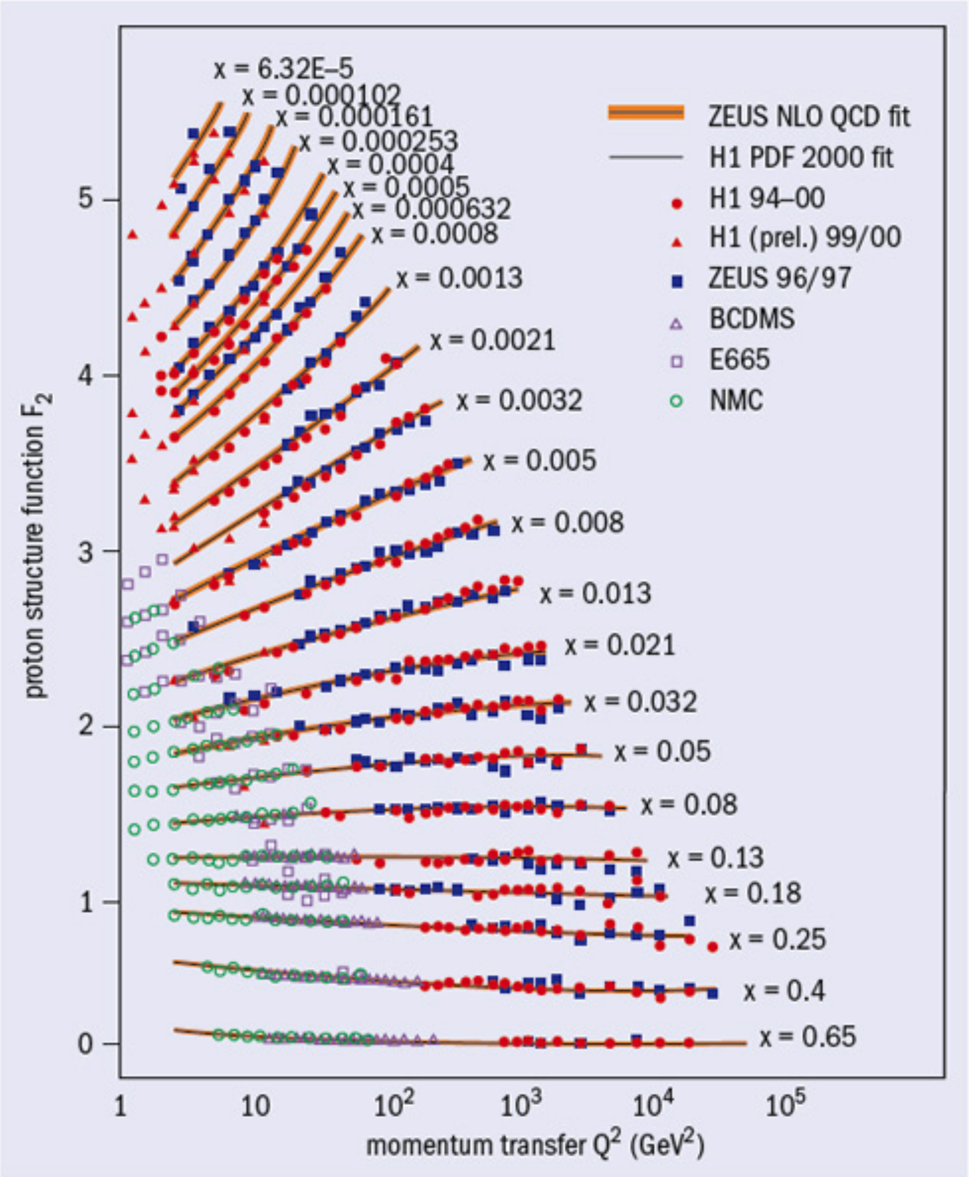
Semi inclusive deep inelastic scattering

- **H**adron-**E**lektron-**R**ing**a**nlage
- DESY, Hamburg
- H1, ZEUS, HERMES, HERA-B

$$F_1(x, Q^2) \to \frac{1}{2}\sum_f Q_f^2\Big(q_f(x) + \overline{q}_f(x)\Big)$$



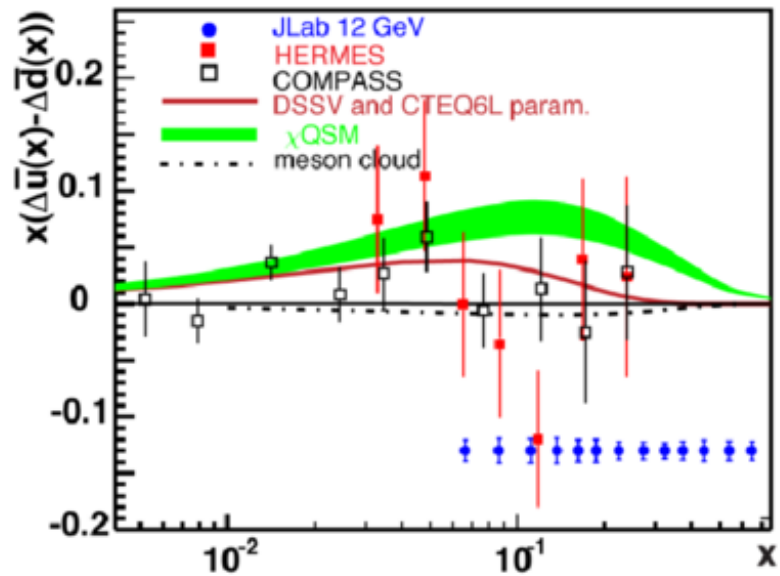




Polarized (SI)DIS

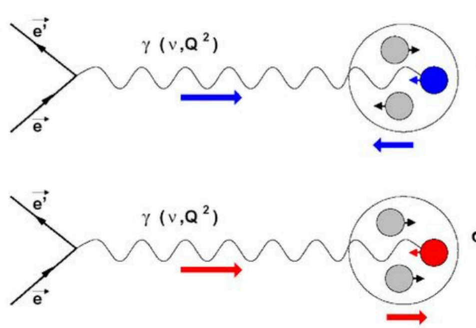
- Semi-inclusive deep inlastic scatteing (SIDIS) using polarized beam
- HERA, COMPASS, JLAB experiments

$$g_1 = \frac{1}{2}\sum_q e_q^2 (q^+ - q^-)$$



photon-nucleon asymmetry

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{\sum_q e_q^2 \Delta q(x)}{\sum_q e_q^2 q(x)} = \frac{g_1(x)}{F_1(x)}$$

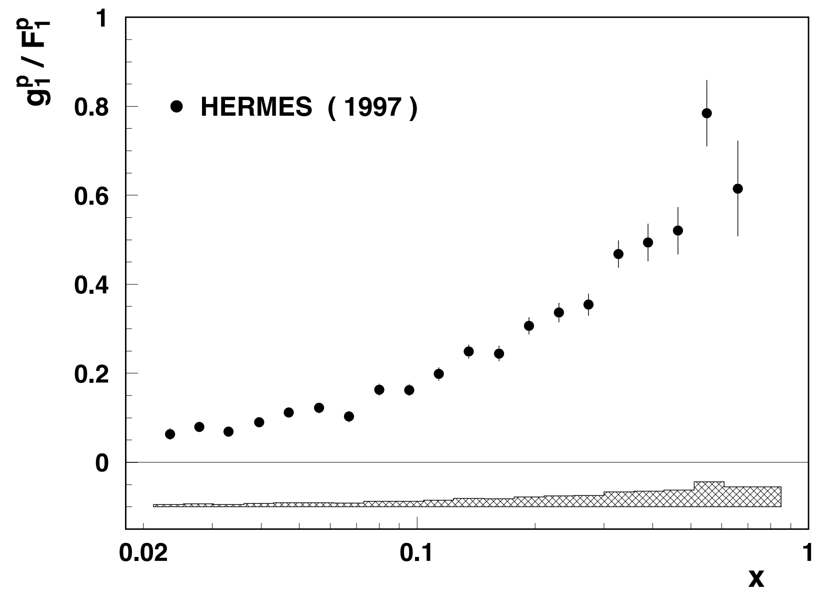


$\Delta q(x) = q(x)^+ - q(x)^-$

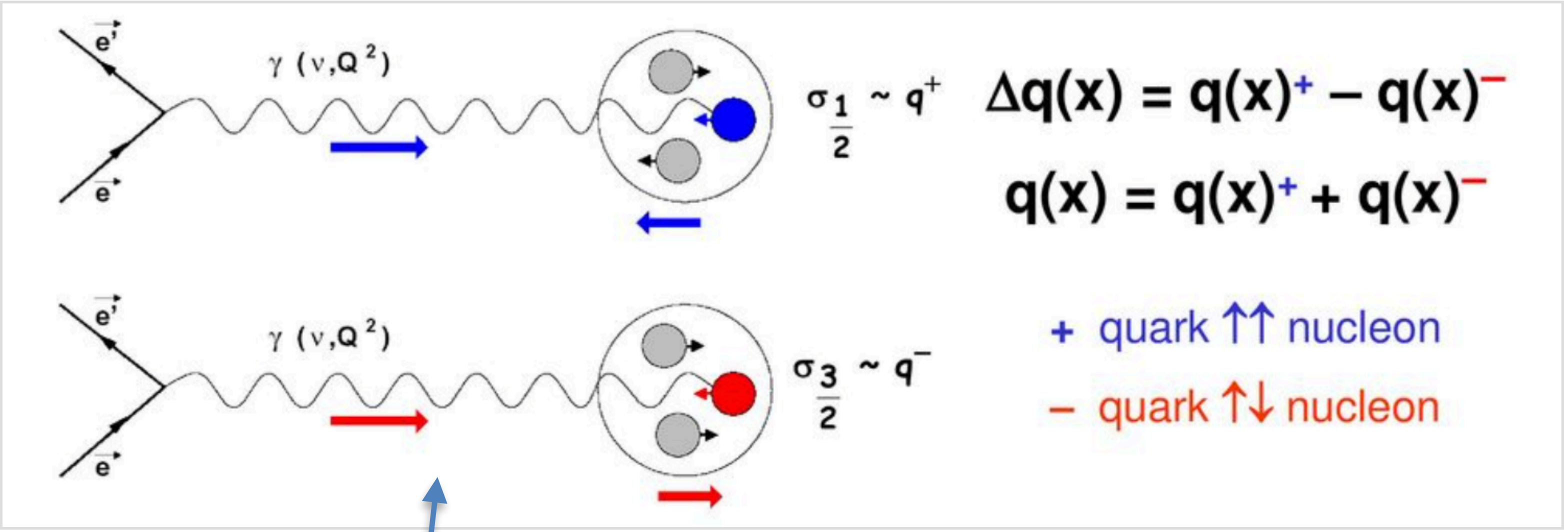
$q(x) = q(x)^+ + q(x)^-$

+ quark ↑↑ nucleon

− quark ↑↓ nucleon



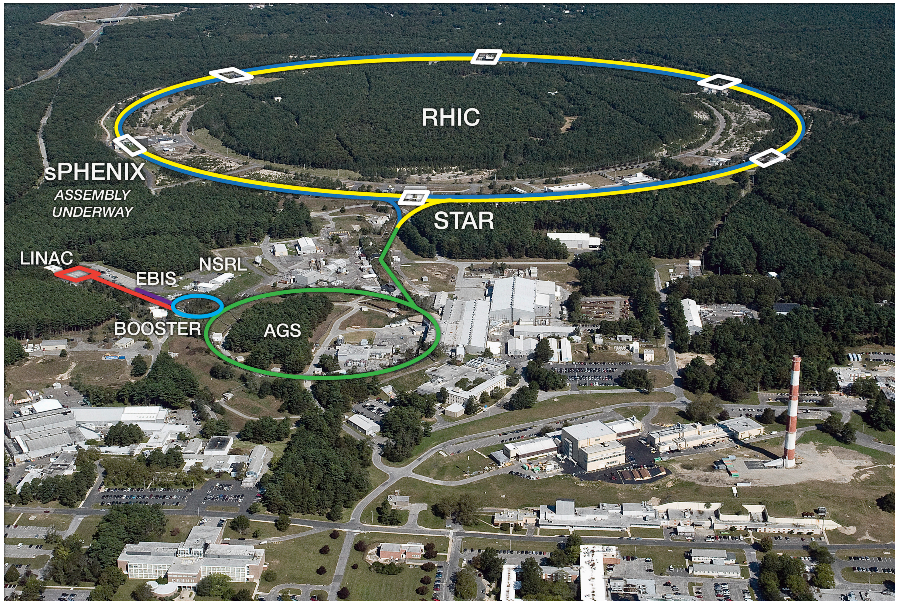
Polarized (SI)DIS

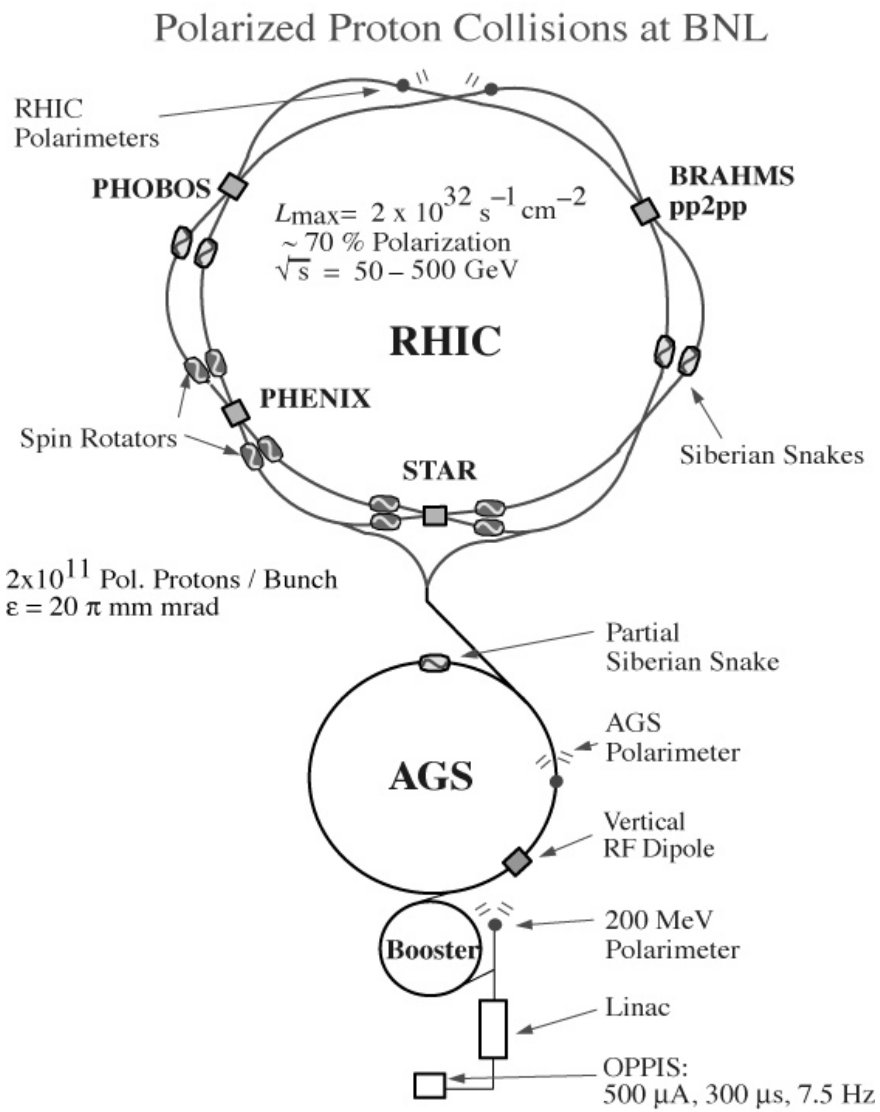


$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

- Can we separate the quark flavours in spin contribution?
- What about sea quarks?
- How can we measure the spin property of gluons (Δg)?
- What should we do to access L_Q and L_G ?

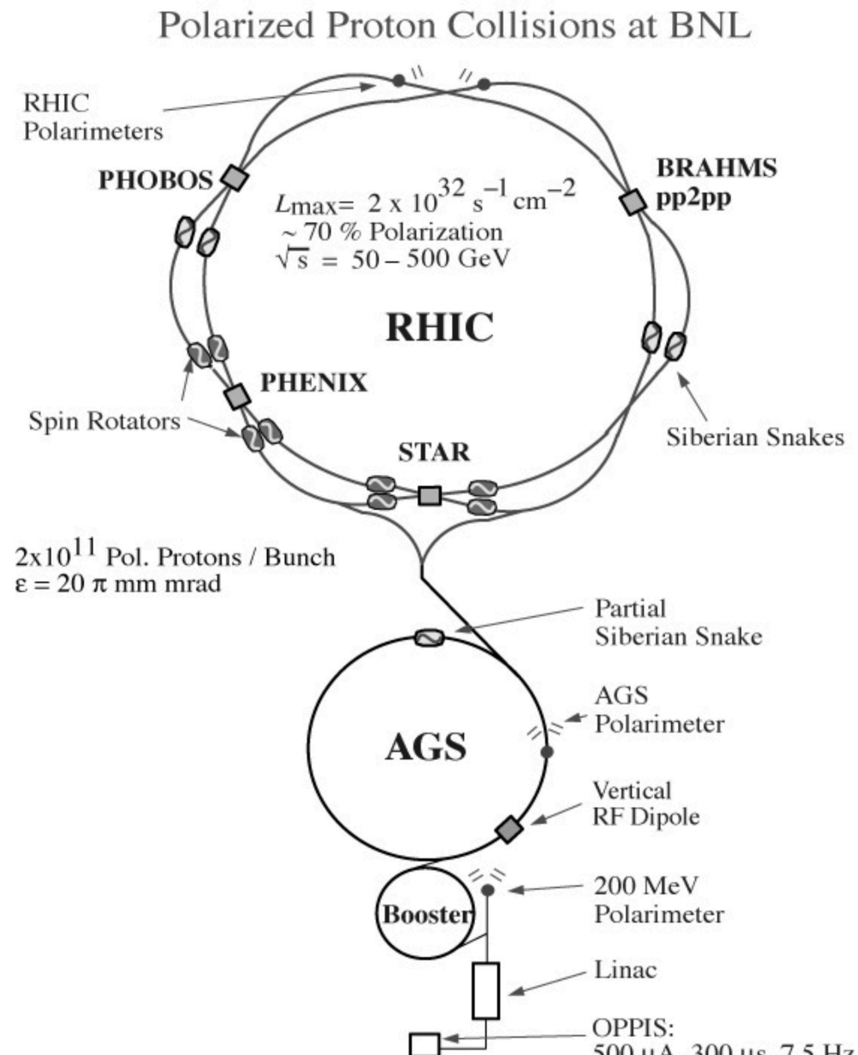
RHIC @ BNL





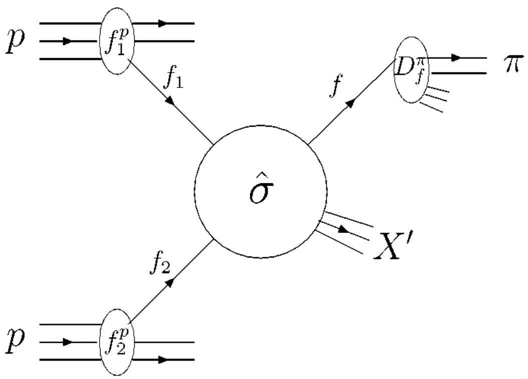
- Relativistic heavy iion collider
- Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV
- p+p collison at $\sqrt{s} = 510$ GeV
- Polarized proton beams are available with P_{beam} = 0.7

Beam polarization



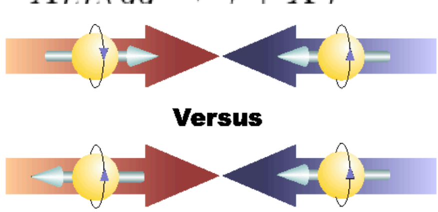
What a technology!

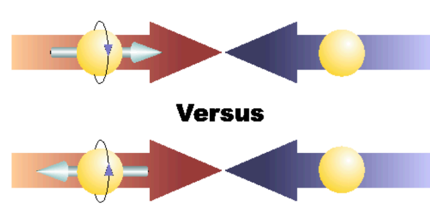
Spin Physics at RHIC

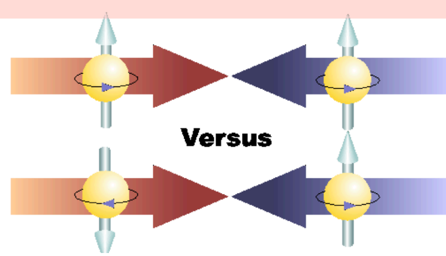


$$\frac{d\sigma^{pp\to\pi X}}{d\mathcal{P}} = \sum_{f_1,f_2,f}\int dx_1 dx_2 dz\, f_1^p(x_1,\mu^2)\, f_2^p(x_2,\mu^2) \times \frac{d\hat{\sigma}^{f_1 f_2\to f X'}}{d\mathcal{P}}(x_1\, p_1, x_2\, p_2, p_\pi/z, \mu)\, D_f^\pi(z,\mu^2)$$

Gluon Polarization ΔG	Anti-Quark Polarization $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse single/double Spin effects
$\pi^{0,+,-}$ Production $A_{LL}(gg, gq \rightarrow \pi^{0,\pm} + X)$ Heavy Flavors $A_{LL}(gg \rightarrow c\bar{c}, b\bar{b} + X)$ Prompt Photon $A_{LL}(gq \rightarrow \gamma + X)$	W physics $A_L(u + \bar{d} \rightarrow W^+ \rightarrow l^+ + \nu_l)$ $A_L(\bar{u} + d \rightarrow W^- \rightarrow l^- + \bar{\nu_l})$ Longitudinal single spin physics 500 GeV CM	Transversity: Sivers vs. Collins effects & physics of higher twists; Pion interf. Fragmentation Transverse single spin physics Phenix-Local Polarimetry







Spin Physics at RHIC

$$\frac{d\Delta\sigma^{pp\to\pi X}}{d\mathcal{P}} \equiv \frac{1}{4}\left[\frac{d\sigma_{++}^{pp\to\pi X}}{d\mathcal{P}} - \frac{d\sigma_{+-}^{pp\to\pi X}}{d\mathcal{P}} - \frac{d\sigma_{-+}^{pp\to\pi X}}{d\mathcal{P}} + \frac{d\sigma_{--}^{pp\to\pi X}}{d\mathcal{P}}\right]$$

$$= \sum_{f_1, f_2, f} \int dx_1 dx_2 dz\; \Delta f_1^p(x_1, \mu^2)\; \Delta f_2^p(x_2, \mu^2)$$

$$\times \frac{d\Delta\hat{\sigma}^{f_1 f_2\to f X'}}{d\mathcal{P}}(x_1, p_1, x_2, p_2, p_\pi/z, \mu)\; D_f^\pi(z, \mu^2), \qquad 3.$$

where

$$\frac{d\Delta\hat{\sigma}^{f_1 f_2\to f X'}}{d\mathcal{P}} \equiv \frac{1}{4}\left[\frac{d\hat{\sigma}_{++}^{f_1 f_2\to f X'}}{d\mathcal{P}} - \frac{d\hat{\sigma}_{+-}^{f_1 f_2\to f X'}}{d\mathcal{P}} - \frac{d\hat{\sigma}_{-+}^{f_1 f_2\to f X'}}{d\mathcal{P}} + \frac{d\hat{\sigma}_{--}^{f_1 f_2\to f X'}}{d\mathcal{P}}\right]. \qquad 4.$$

From Annu. Rev. Nucl. Part. Sci. 2000. 50:525–75

Spin Physics at RHIC

$$\frac{d\Delta\sigma^{pp\to\pi X}}{d\mathcal{P}} \equiv \frac{1}{4}\left[\frac{d\sigma_{++}^{pp\to\pi X}}{d\mathcal{P}} - \frac{d\sigma_{+-}^{pp\to\pi X}}{d\mathcal{P}} - \frac{d\sigma_{-+}^{pp\to\pi X}}{d\mathcal{P}} + \frac{d\sigma_{--}^{pp\to\pi X}}{d\mathcal{P}}\right]$$

$$= \sum_{f_1,f_2,f} \int dx_1 dx_2 dz\ \Delta f_1^p(x_1,\mu^2)\ \Delta f_2^p(x_2,\mu^2)$$

$$\times \frac{d\Delta\hat{\sigma}^{f_1 f_2\to f X'}}{d\mathcal{P}}(x_1,\ p_1,\ x_2,\ p_2,\ p_\pi/z,\ \mu)\ D_f^\pi(z,\mu^2), \qquad 3.$$

where

$$\frac{d\Delta\hat{\sigma}^{f_1 f_2\to f X'}}{d\mathcal{P}} \equiv \frac{1}{4}\left[\frac{d\hat{\sigma}_{++}^{f_1 f_2\to f X'}}{d\mathcal{P}} - \frac{d\hat{\sigma}_{+-}^{f_1 f_2\to f X'}}{d\mathcal{P}} - \frac{d\hat{\sigma}_{-+}^{f_1 f_2\to f X'}}{d\mathcal{P}} + \frac{d\hat{\sigma}_{--}^{f_1 f_2\to f X'}}{d\mathcal{P}}\right]. \qquad 4.$$

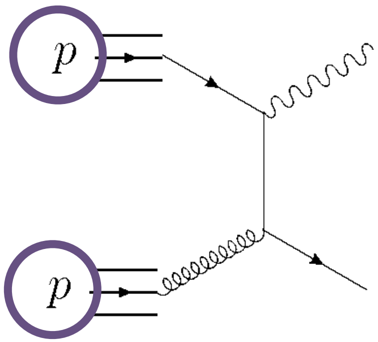
Double-helicity asymmetry A_{LL}

$$A_{LL}^{\pi} = \frac{d\Delta\sigma^{pp\to\pi X}/d\mathcal{P}}{d\sigma^{pp\to\pi X}/d\mathcal{P}} = \frac{\sum_{f_1,f_2,f} \Delta f_1 \times \Delta f_2 \times \left[d\hat{\sigma}^{f_1 f_2\to f X'}\ \hat{a}_{LL}^{f_1 f_2\to f X'}\right] \times D_f}{\sum_{f_1,f_2,f} f_1 \times f_2 \times [d\hat{\sigma}^{f_1 f_2\to f X'}] \times D_f}$$

From Annu. Rev. Nucl. Part. Sci. 2000. 50:525–75

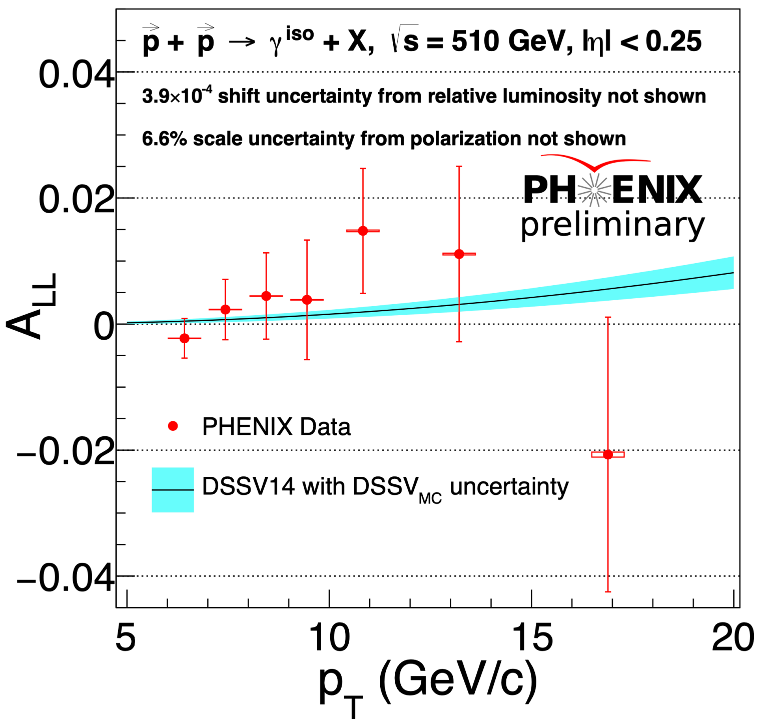
Gluon spin measured in hard scattering

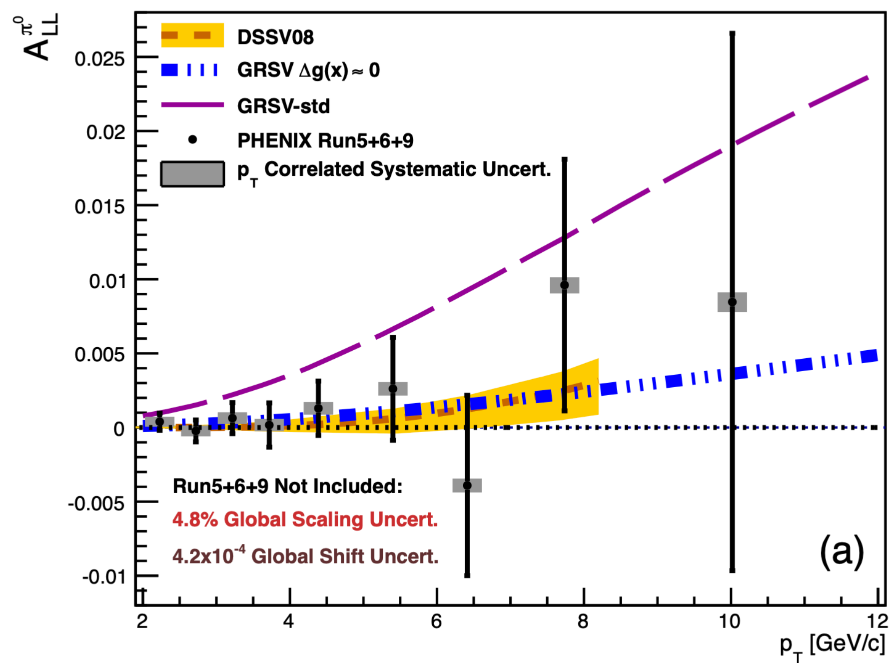
A_{LL} of direct photon from QCD compton scattering



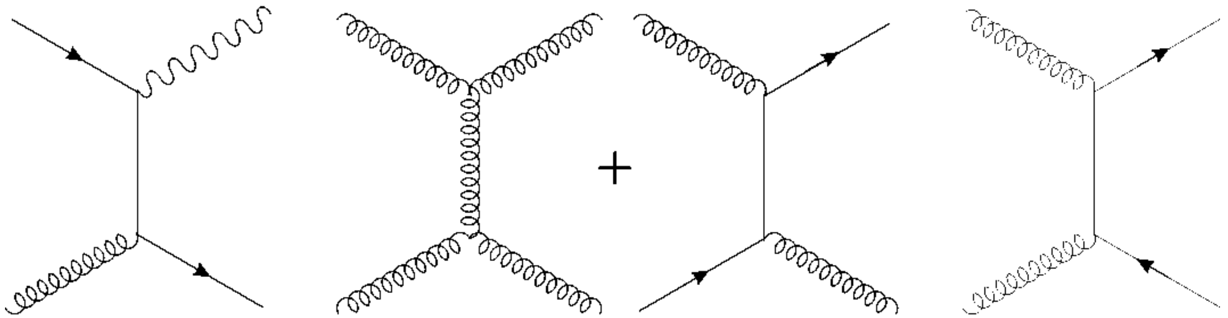
$$A_{LL} \approx \boxed{\frac{\Delta g(x_1)}{g(x_1)}} \cdot \left[\frac{\sum_q e_q^2 \left[\Delta q(x_2) + \Delta \bar{q}(x_2)\right]}{\sum_q e_q^2 \left[q(x_2) + \bar{q}(x_2)\right]} \right] \cdot \boxed{\hat{a}_{LL}(gq \to \gamma q)} + (1 \leftrightarrow 2)$$

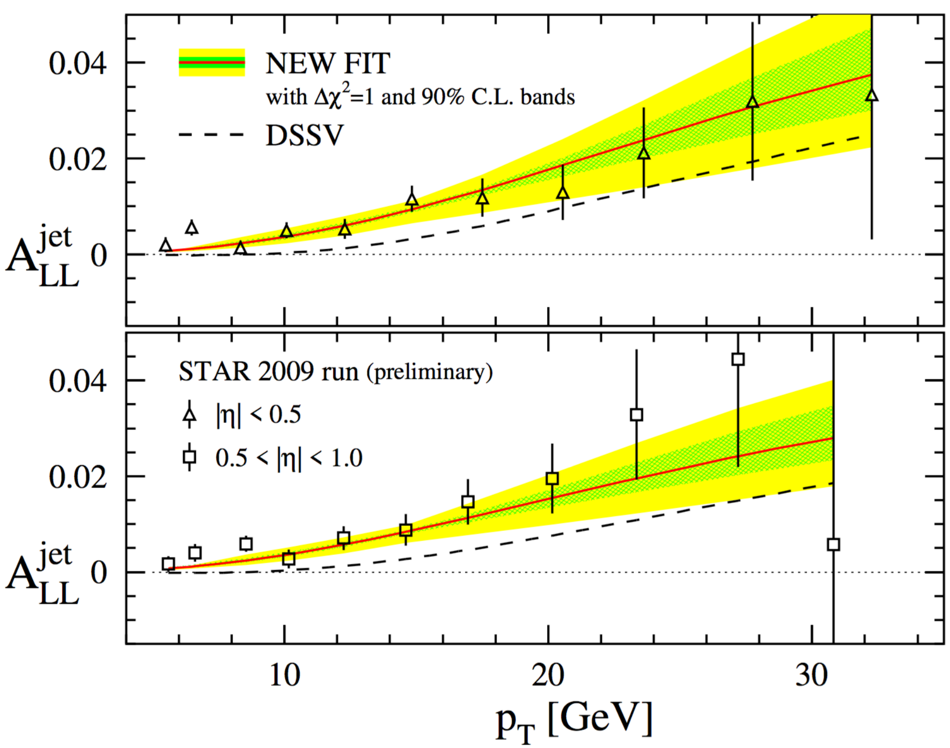
1

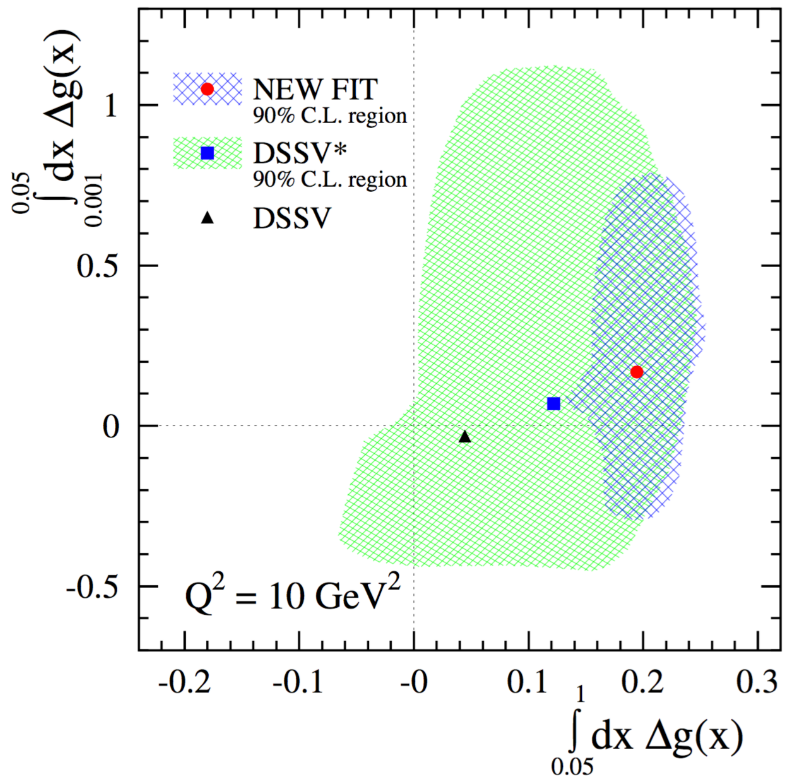




Gluon spin measured in hard scattering

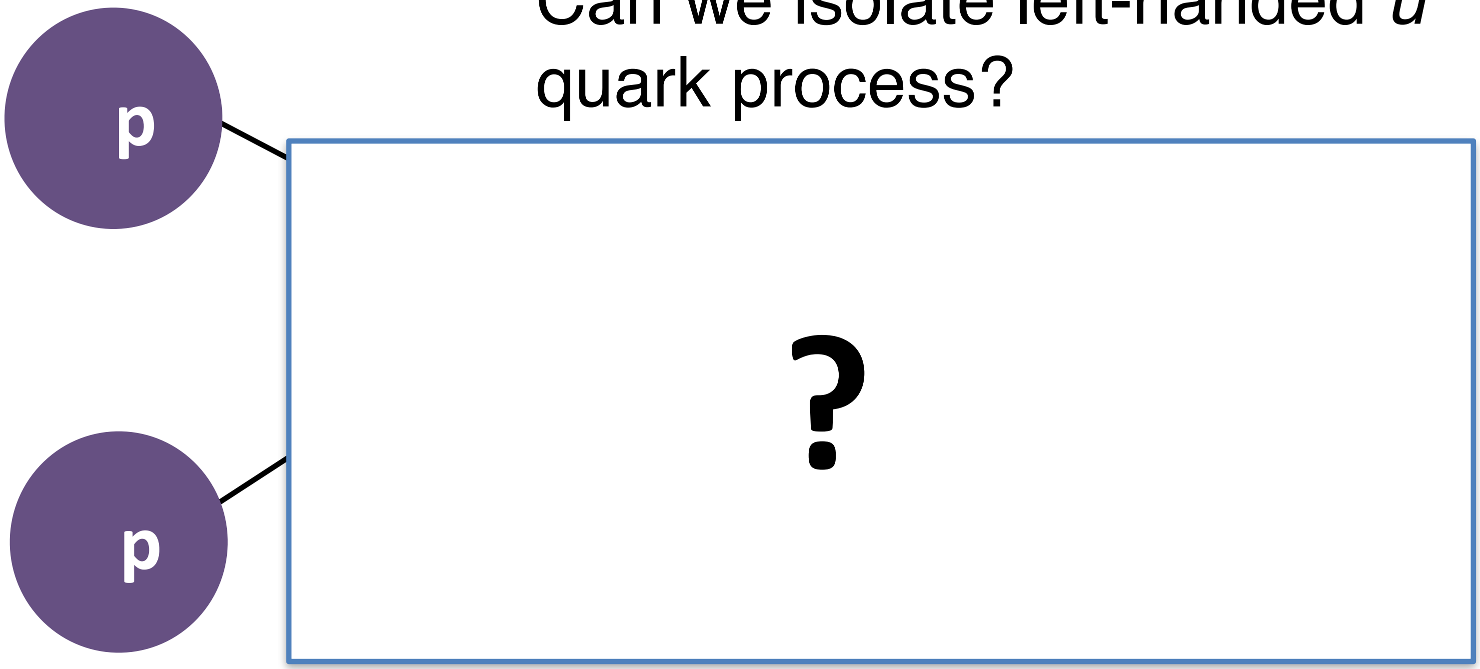




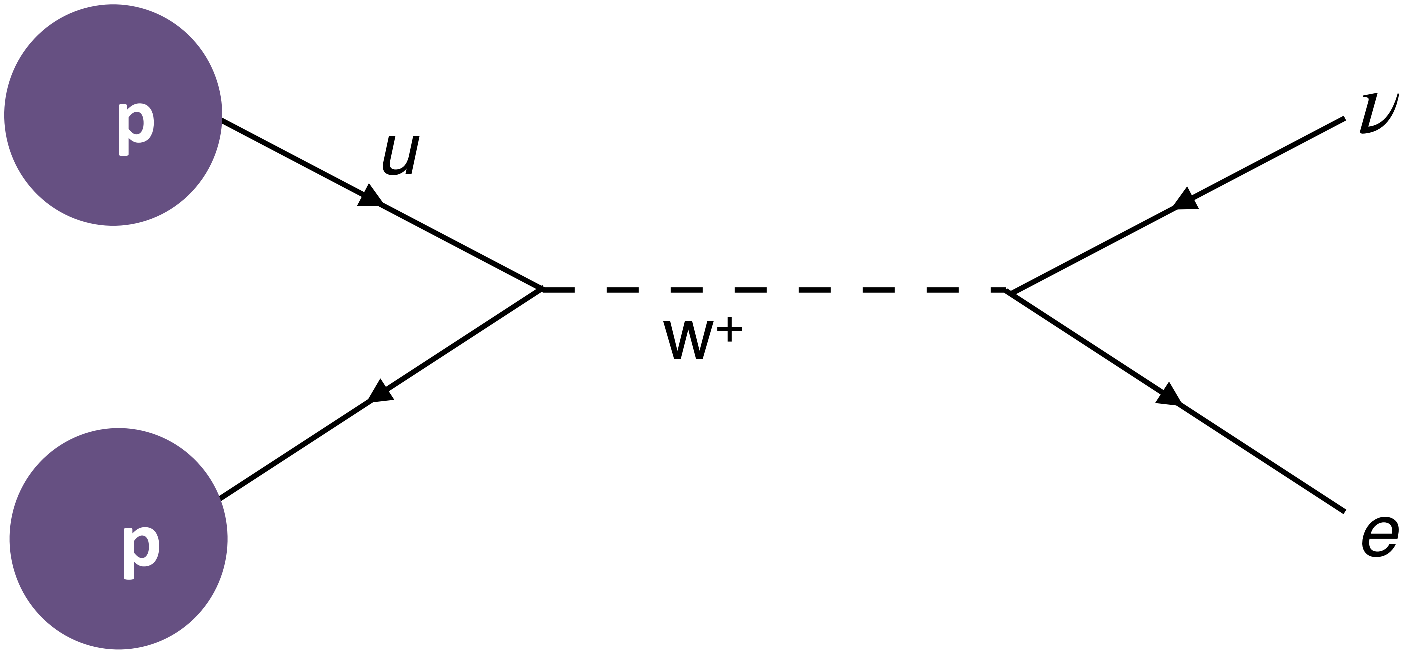


Flavor tagging

Can we isolate left-handed *u* quark process?

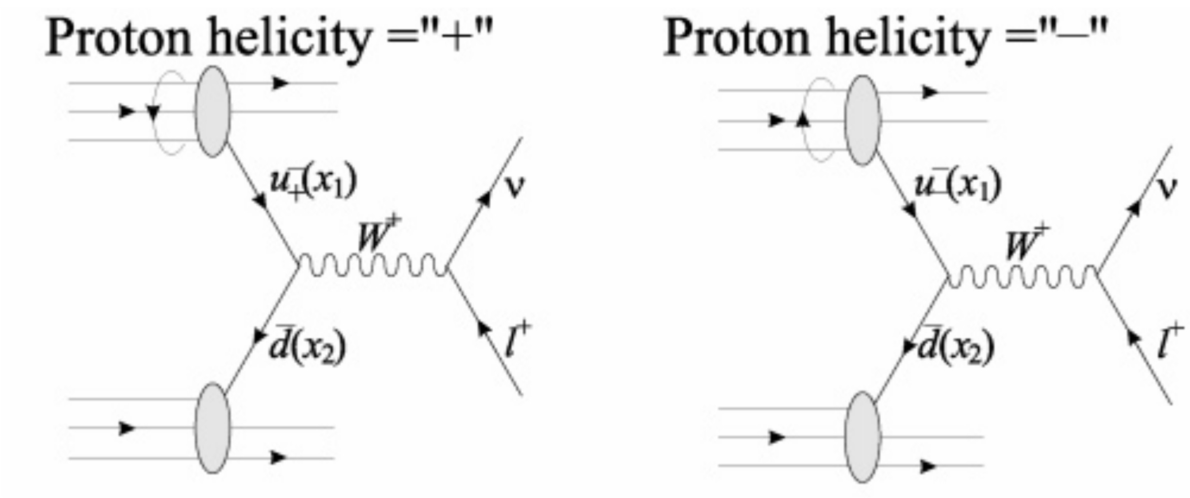


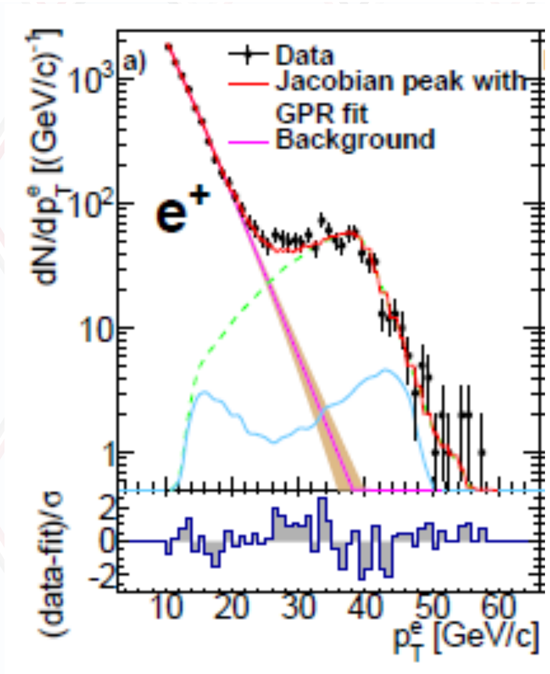
Flavor tagging



- V-A coupling of W boson selects LH quark and RH anti-quark
- Allows the probe of sea quarks as well

Flavor tagging



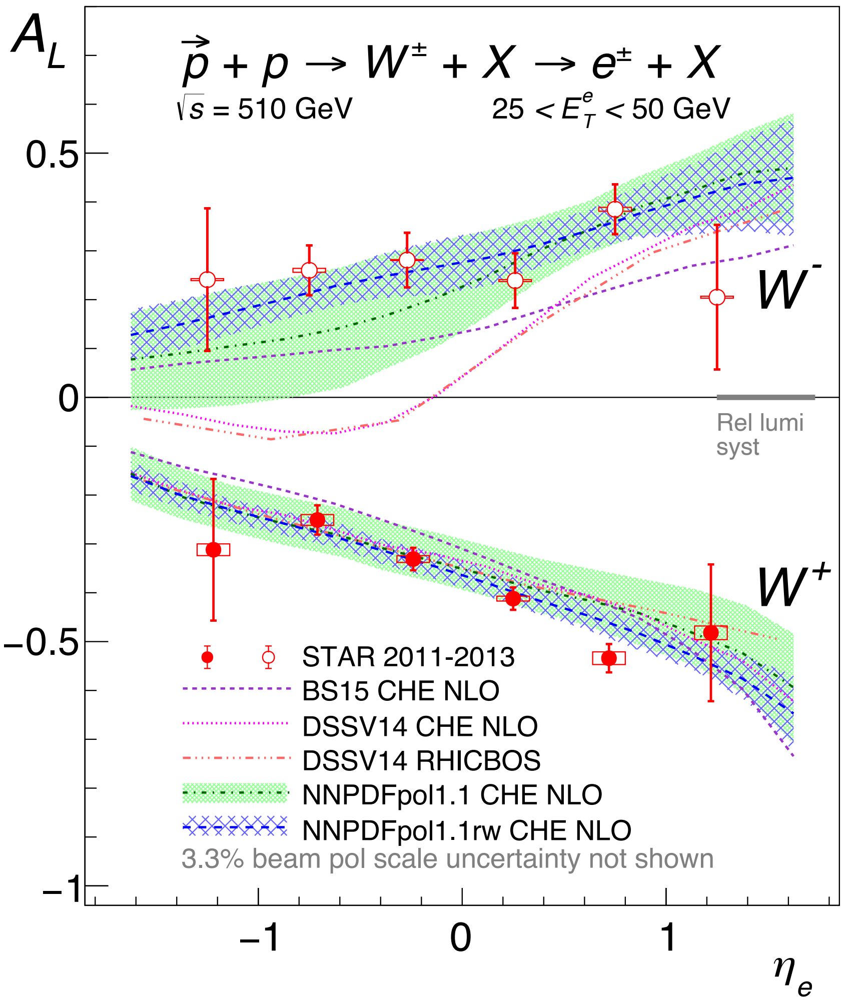


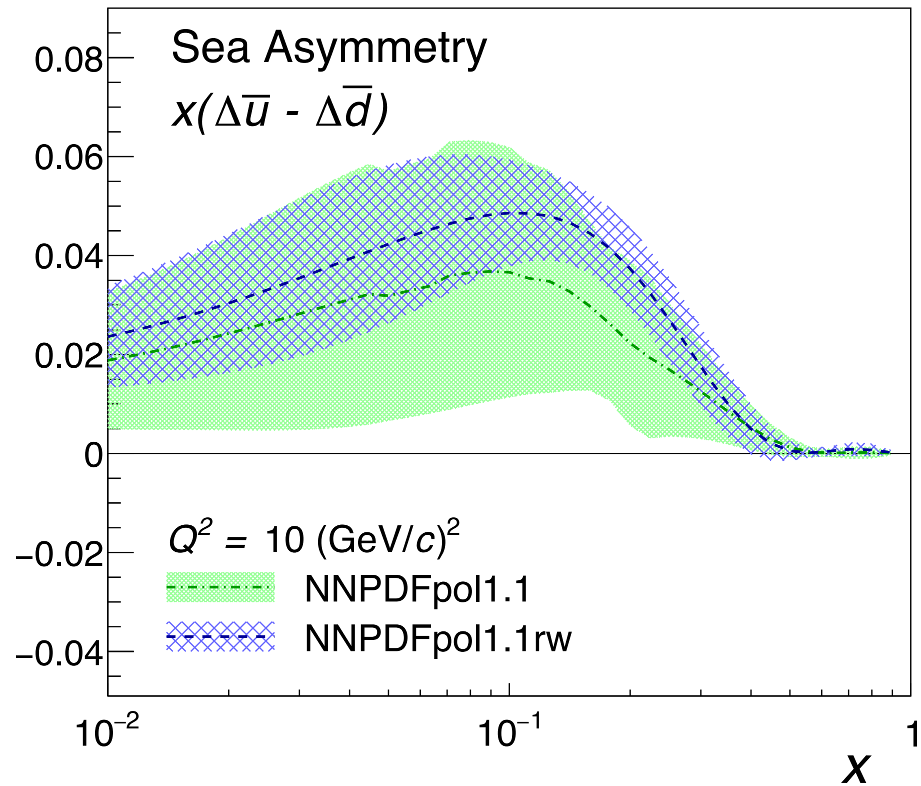
$$A_L^W = \frac{1}{P} \times \frac{N_-(W) - N_+(W)}{N_-(W) + N_+(W)}$$

- W is rare, thus demanding high energy and high luminosity
- RHIC $\sqrt{s} = 510$ for pp
- $\int^{1\ year} L\ dt = O(100)\ pb^{-1}$
- PHENIX and STAR experiments can measure high energy electrons at mid-rapidity and muons at forward

Results from RHIC

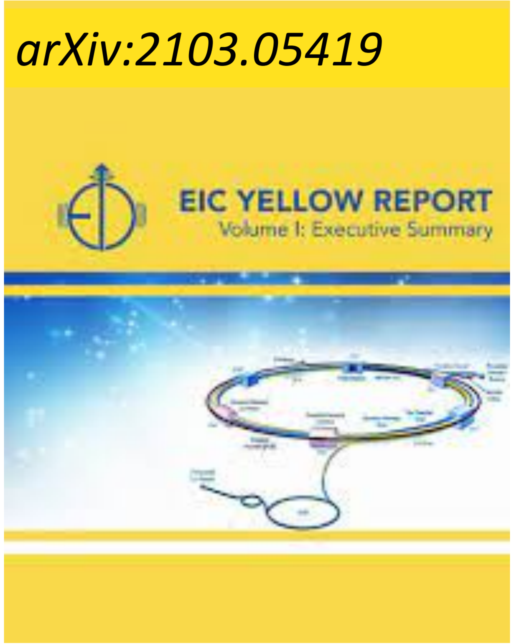
PRD 99, 051102 (2019)






"THE WAY OF THE FUTURE"
- THE AVIATOR

- 2002: eRHIC community formed and submitted a white paper to NSAC Long Range Plan(NRP) review
- 2021: Yellow Report defines Science Requirements and Detector Concepts



Légion étrangère effrayant, Vol 1. 이현세

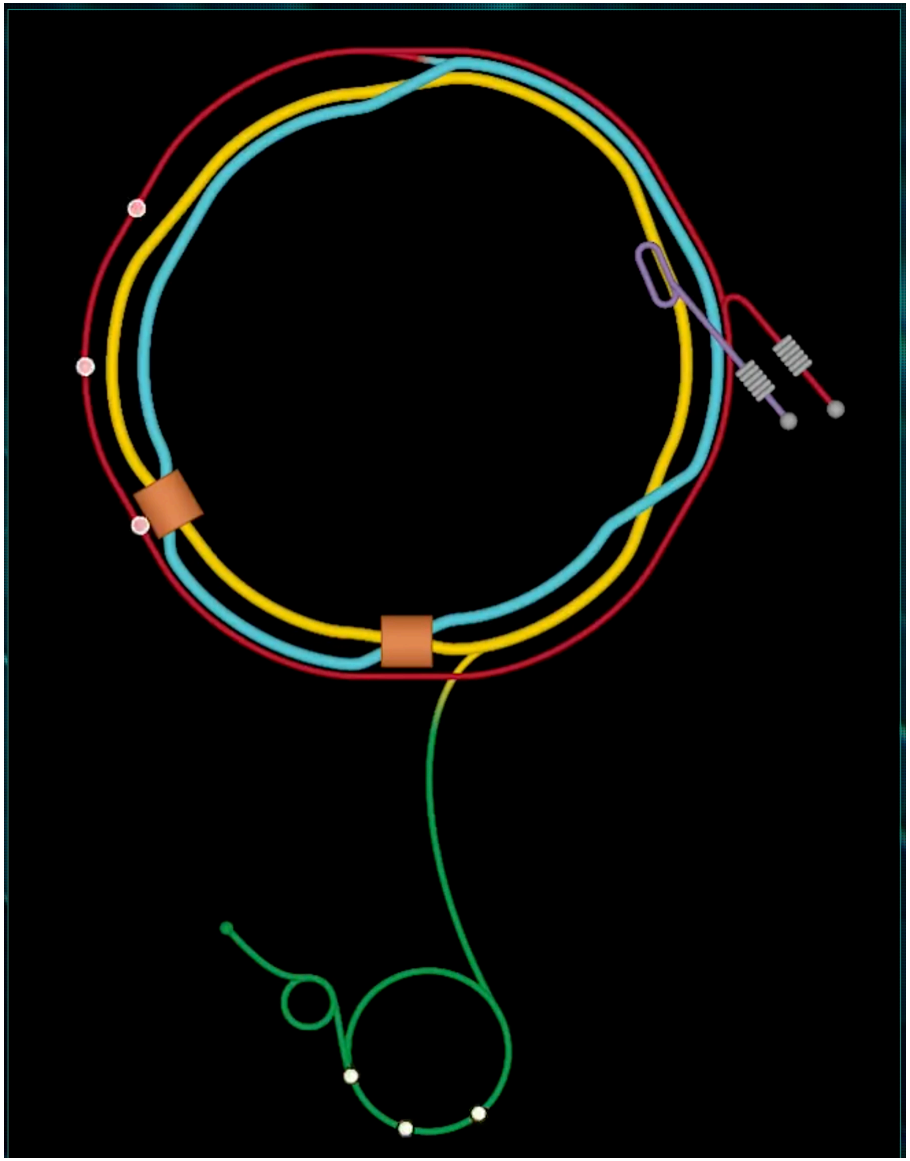
Science mission

World's first collider for polarized e+p and e+A collider

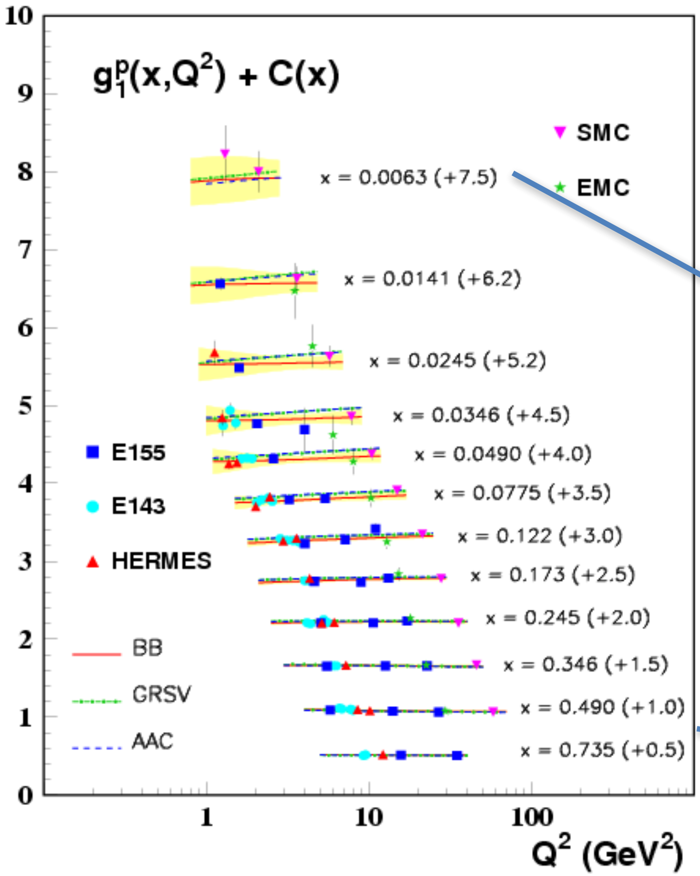
- High luminosity ~ 10^{34} $cm^{-2}s^{-1}$
- E_{cm} : Up to ~140 GeV
- Highly polarized electron (~70%) and proton (~70%) beams
- To be constructed at BNL in ~2030

Answer to Ultimate QCD questions

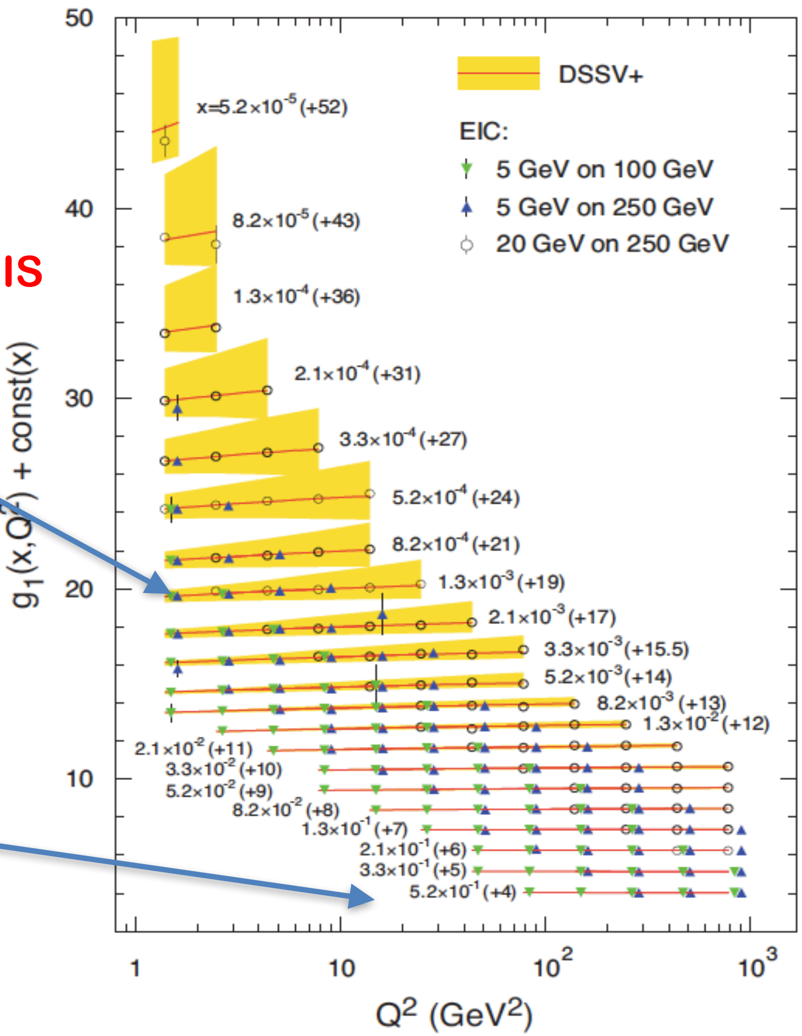
- How mass and spin of nucleons emerge from partons?
- How are partons distributed in momentum and position space?
- How do quarks and gluons interact with nuclear medium?
- Where does confinement come from?



Unprecedented precision for proton spin structure



Polarized DIS at EIC



EIC Yellow Report arXiv:2103.05419

Gluon spin and 3-d tomography

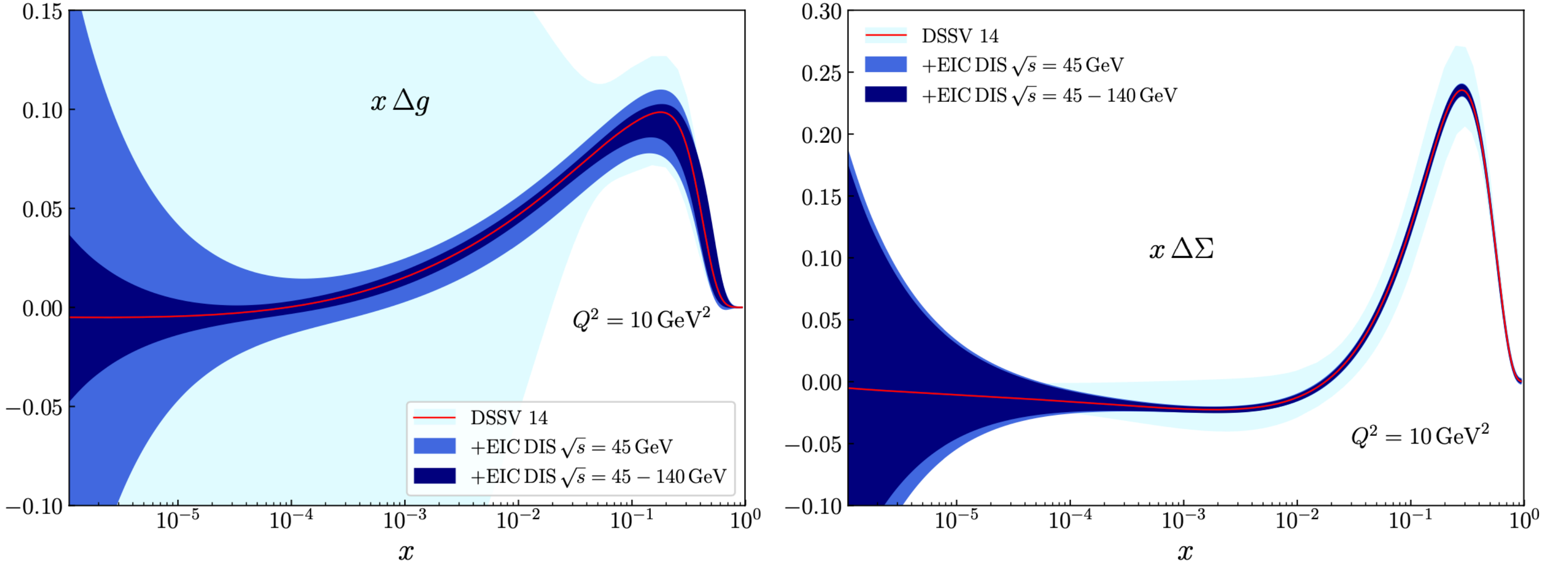
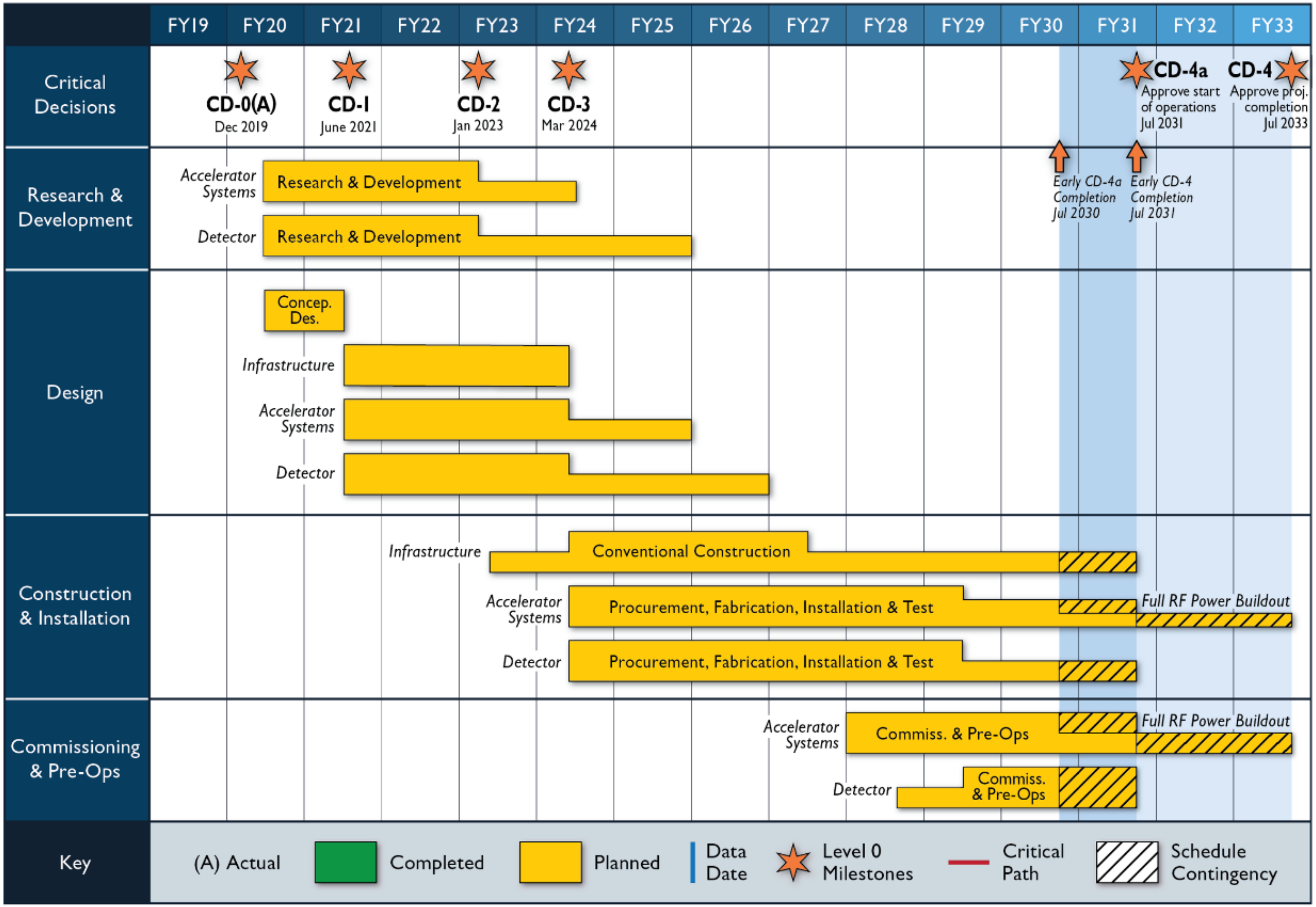


Figure 7.12: Impact of the projected EIC A_{LL} pseudoda on the gluon helicity (left panel) and quark singlet helicity (right panel) distributions as a function of x for $Q^2 = 10\,\mathrm{GeV}^2$. In addition to the DSSV14 estimate (light-blue), the uncertainty bands resulting from the fit including the $\sqrt{s} = 45$ GeV DIS pseudodata (blue) and, subsequently, the reweighting with $\sqrt{s} = 140$ GeV pseudodata (dark blue), are also shown.

EIC Yellow Report arXiv:2103.05419

Construction Timeline

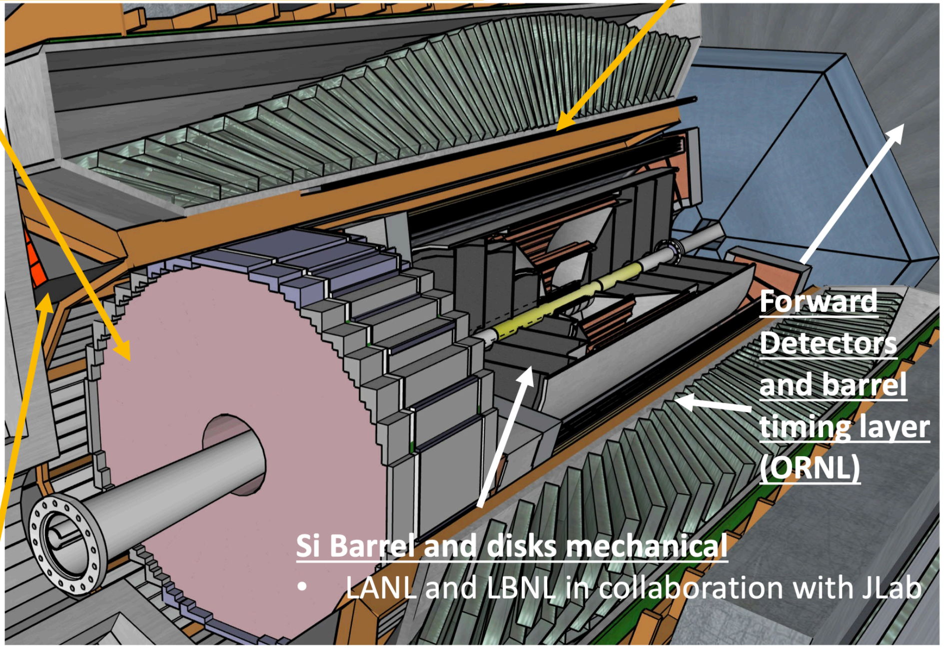


Participation in ECCE consortium

Design/Engineering Activities and Integration

Electron Endcap EMCal
- Initial concept (Josh Crafts, CUA)
- Frame and cooling system (IJCLab-Orsay)

Barrel EMCal Support
- Various options EMCal (Josh Crafts, CUA)
- Impact on support structure and frame (MIT)



Evaluate available space and detector placement and supports

Work started on integration of MPGD between Si and DIRC (e.g. https://userweb.jlab.org/~jfast/EIC/Hybrid_ECCE/Hybrid_Tracker-ECCE.pdf)

DIRC
- Re-use concept (CUA, GSI)
- Support structure (GSI)

EIC Project :
- Support for barrel EMCal and a universal frame that holds the DIRC and detectors "within" (backward EMCAl, mRICH, etc.)
- support of forward Hadron Calorimeter, and how to split it for maintenance mode, looking at similar for the backward HCal side.

arXiv > hep-ph > arXiv:2202.11631

Search...

Help | Advance

High Energy Physics – Phenomenology

[Submitted on 23 Feb 2022]

Production of $P_c(4312)$ state in electron-proton collisions

In Woo Park, Su Houng Lee, Sungtae Cho, Yongsun Kim

We study the cross sections for the electro-production of $P_c(4312)$ particle, a recently discovered pentaquark state, in electron-proton collisions assuming possible quantum numbers to be $J^P = \frac{1}{2}^{\pm}, \frac{3}{2}^{\pm}$. $\sqrt{s}$ is set to the energy of the future Electron Ion Collider at Brookhaven National Laboratory, in order to asses the possibility of the measurement in this facility. One can discriminate the spin of $P_c(4312)$ by comparing the pseudorapidity distribution in two different polarization configurations for proton and electron beams. Furthermore, the parity of $P_c(4312)$ can be discerned by analyzing the decay angle in the $P_c \rightarrow p + J/\psi$ channel. As the multiplicity of P_c production in our calculation is large, the EIC can be considered as a future facility for precision measurement of heavy pentaquarks.

Comments: 7 pages, 6 figures

Subjects: **High Energy Physics – Phenomenology (hep-ph)**; Nuclear Experiment (nucl-ex); Nuclear Theory (nucl-th)

Cite as: arXiv:2202.11631 **[hep-ph]**

(or arXiv:2202.11631v1 **[hep-ph]** for this version)

https://doi.org/10.48550/arXiv.2202.11631

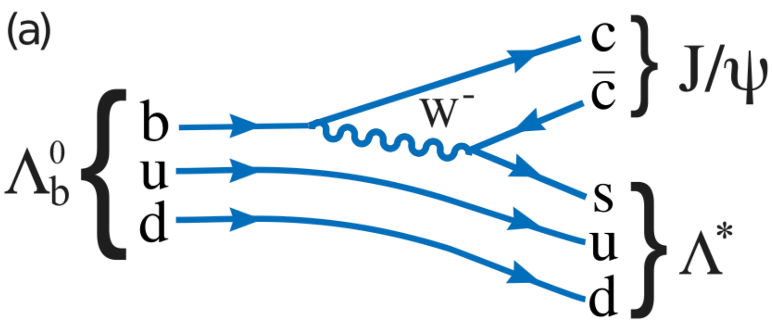
Submission history

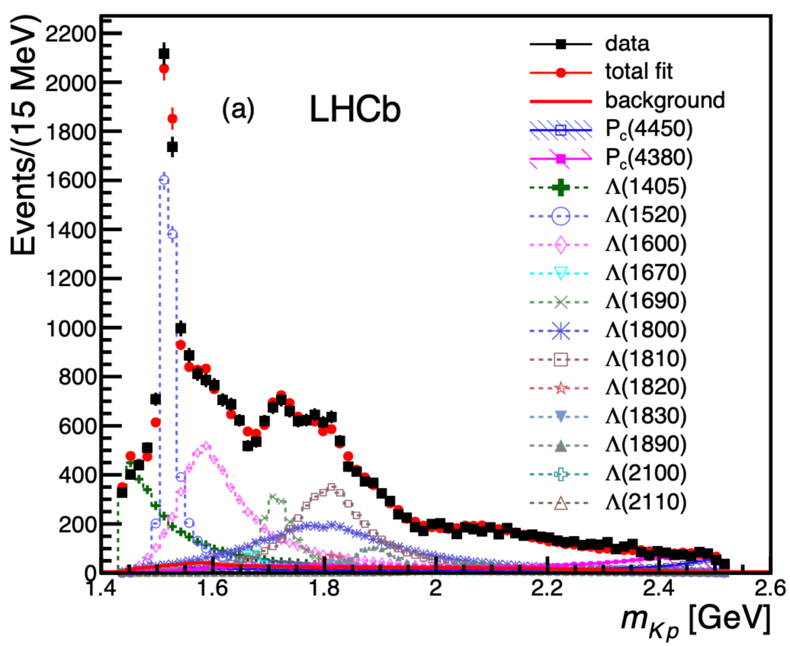
From: Yongsun Kim [view email]

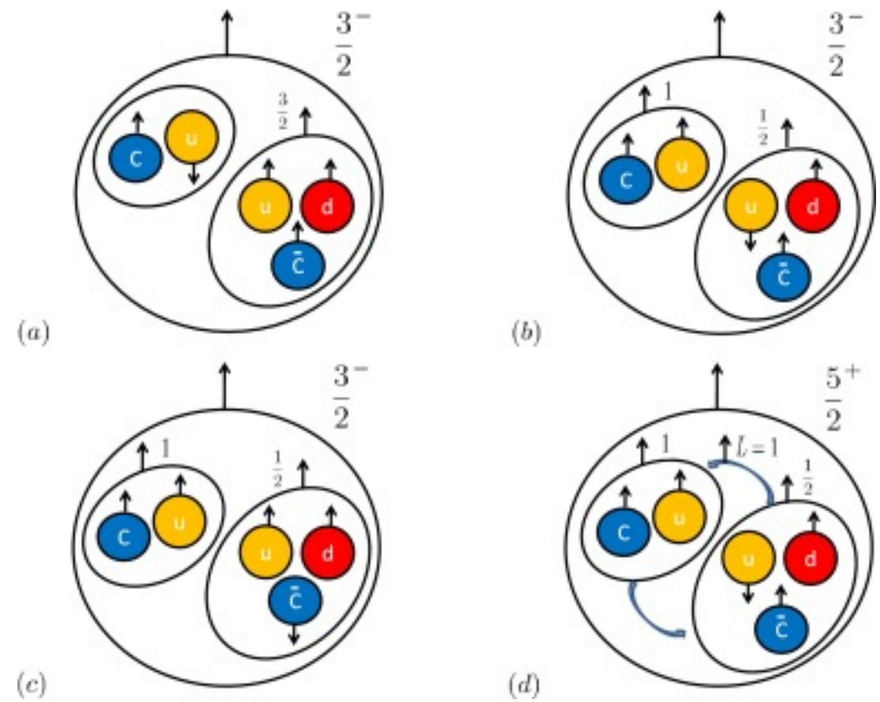
[v1] Wed, 23 Feb 2022 17:07:42 UTC (557 KB)

Heavy penta-quark discovered by LHCb

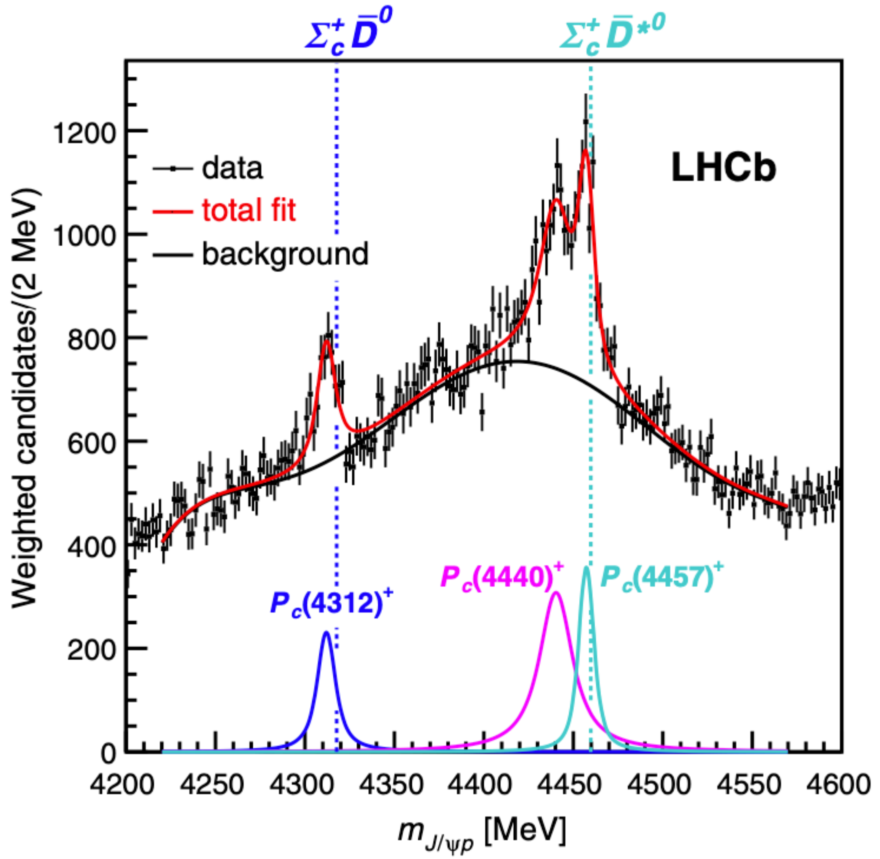
P_c (4380), P_c (4450) observed in 2015 *arxiv:1507.03414*





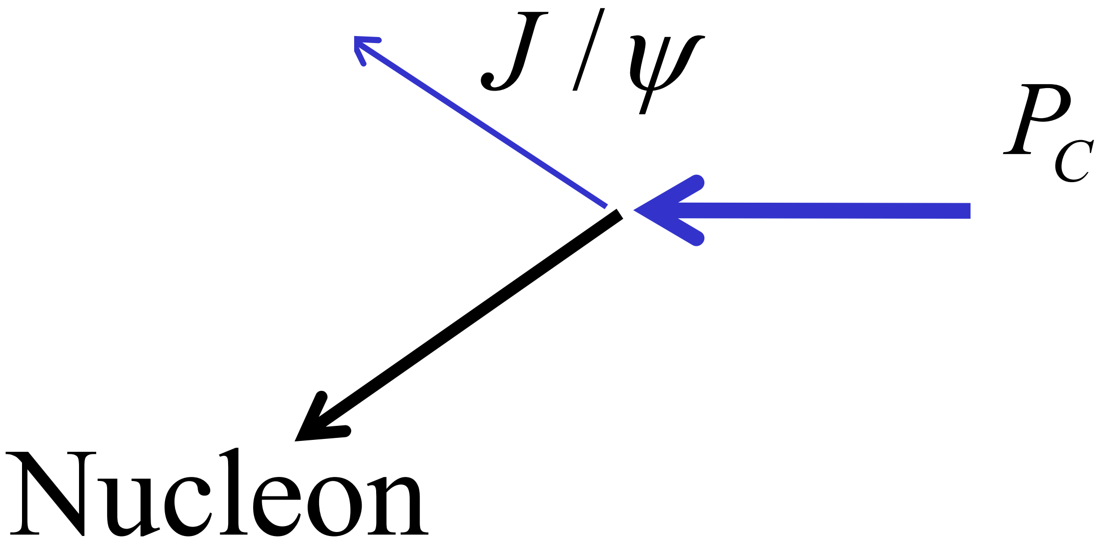


Update by 2018 data

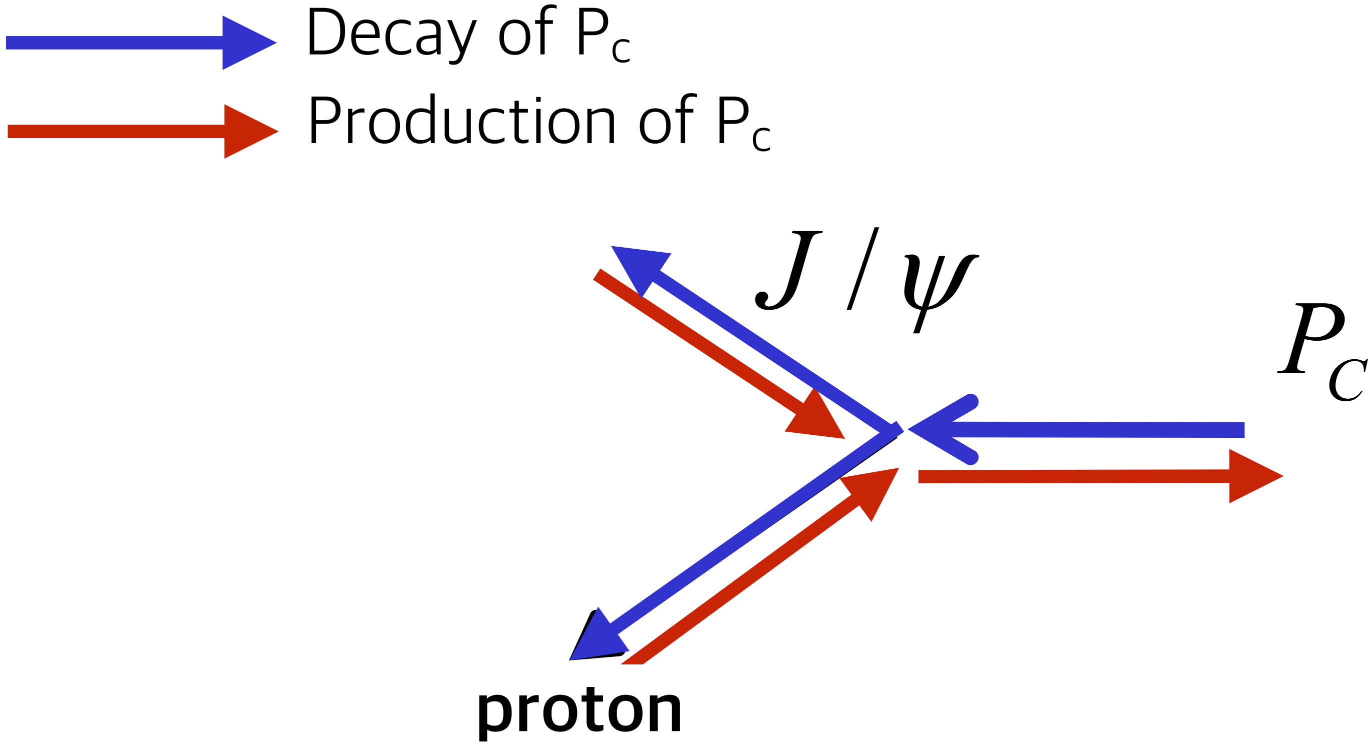


State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Production of Pc in some other place?

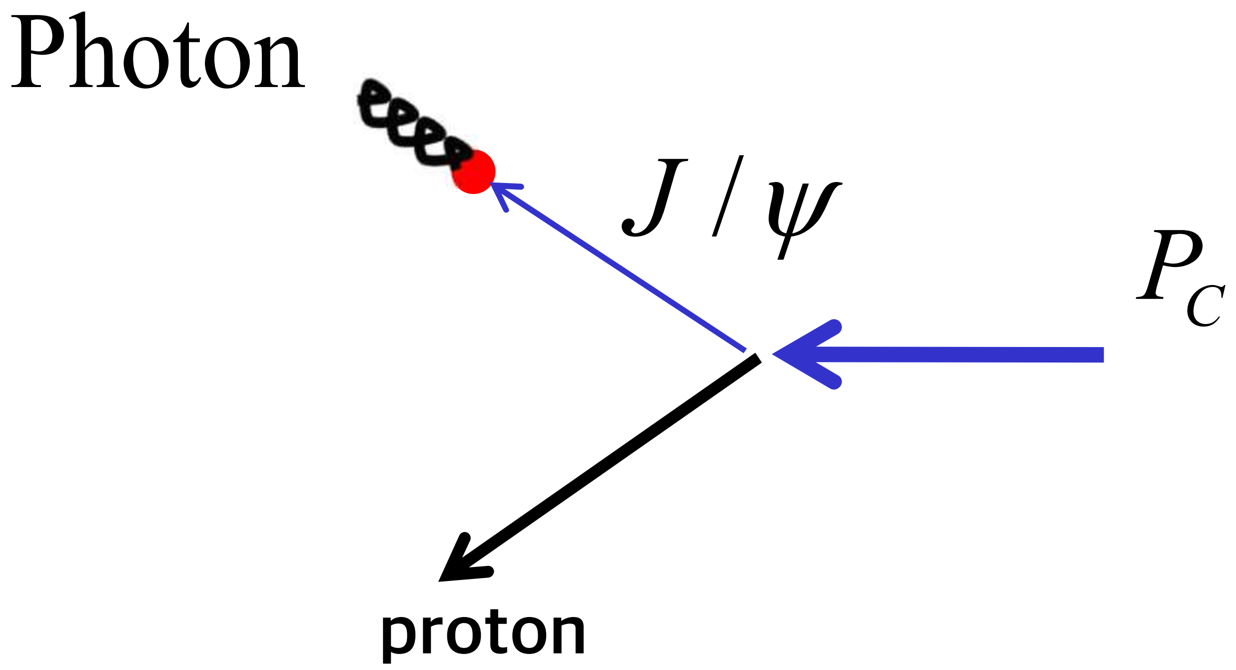


Production of Pc in heavy ion collision?

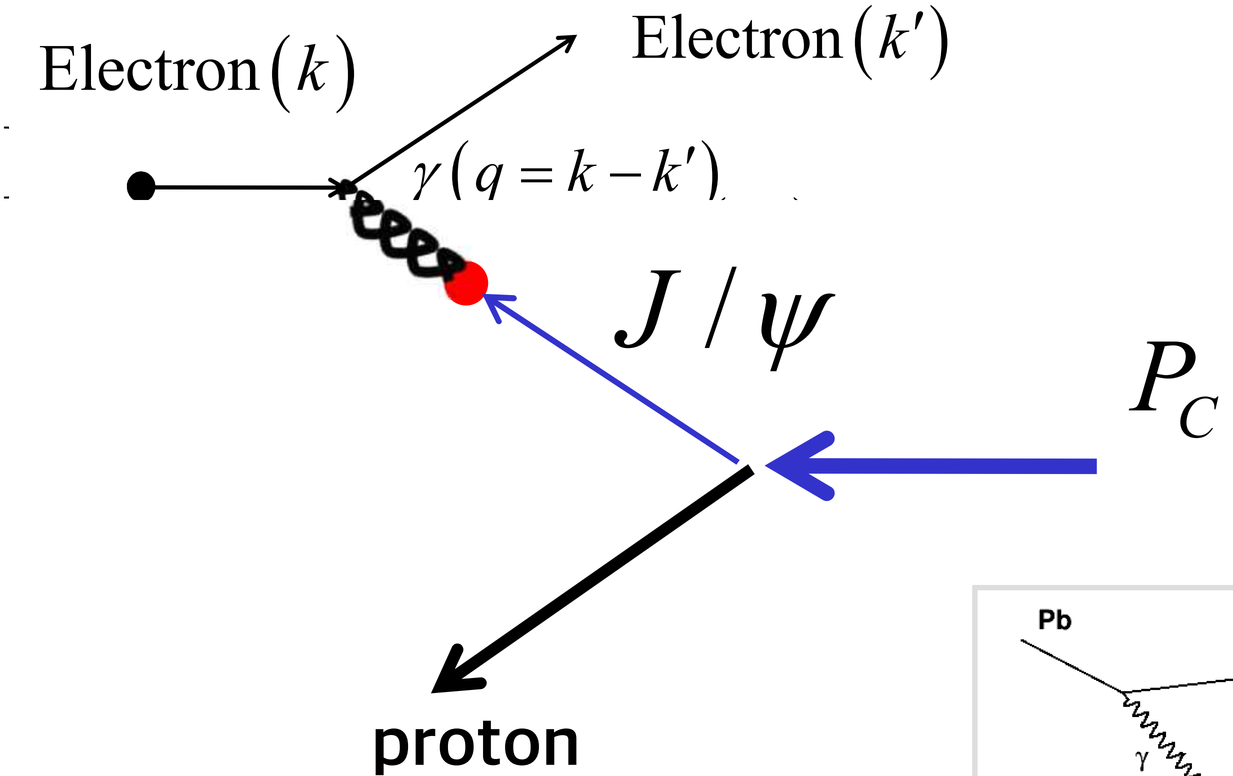


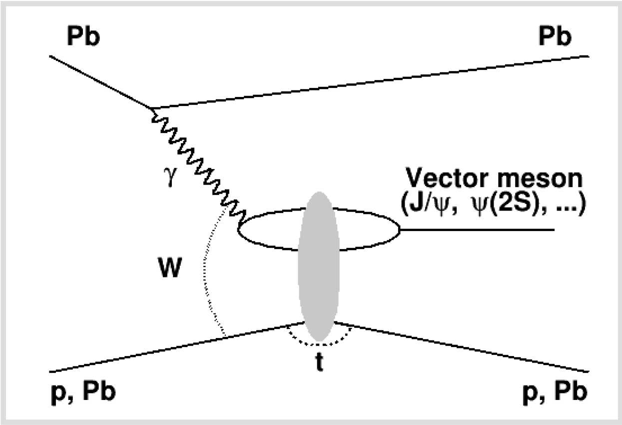
Creation of pentaquark by coalescnece?

Production of Pc in EIC?

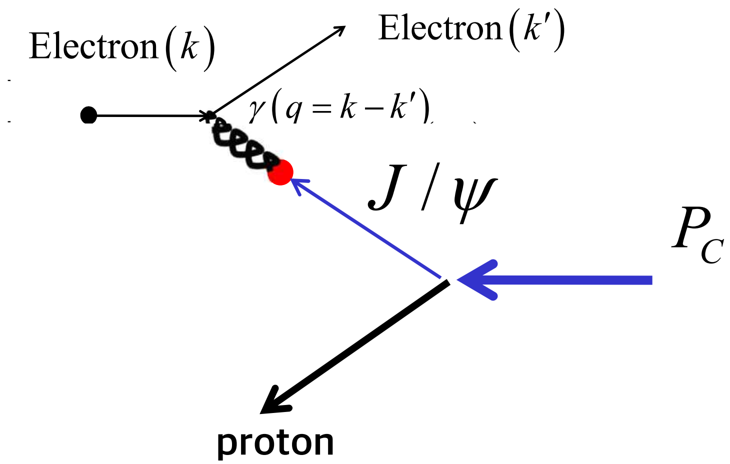


Production of Pc in EIC?





Production of Pc in EIC?



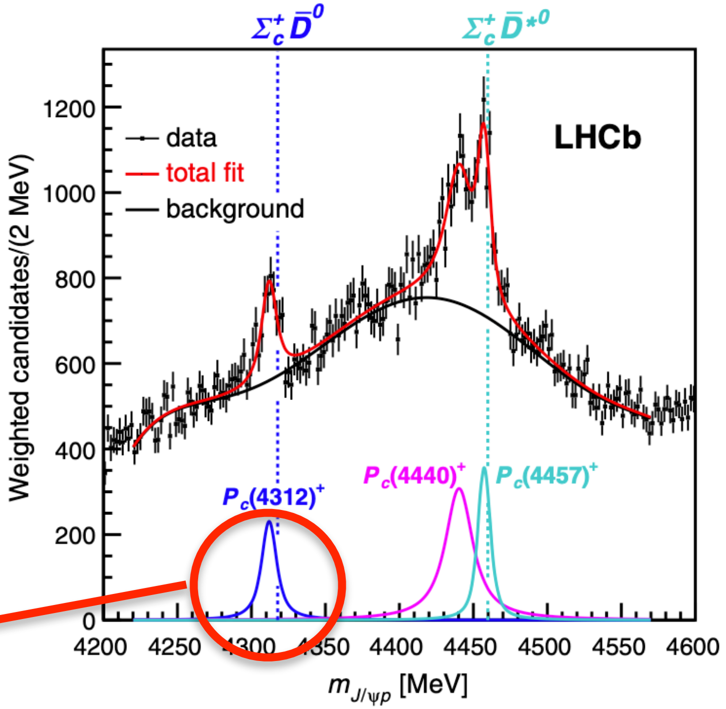
Vector meson dominance model

Z.Phys. A356 (1996) 193-206, Klingl et al.

Currents and Mesons (1969), Sakurai

$$\mathcal{L}_{\text{int}} = \begin{cases} \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \sigma^{\mu\nu} F^J_{\mu\nu} \psi_{P_c} & J^P = \frac{1}{2}^+, \\ \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \gamma_5 \sigma^{\mu\nu} F^J_{\mu\nu} \psi_{P_c} & J^P = \frac{1}{2}^-, \\ \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \gamma_5 \gamma^\mu F^J_{\mu\nu} \psi^\nu_{P_c} & J^P = \frac{3}{2}^+, \\ \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \gamma^\mu F^J_{\mu\nu} \psi^\nu_{P_c} & J^P = \frac{3}{2}^-. \end{cases}$$

J^P	$\frac{1}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$
g_{JpP_c}	0.379	0.169	1.47	0.599



EIC capacity

	e	p	$^{3}He^{2+}$	$^{197}Au^{79+}$
Energy, GeV	15.9	250	167	100
CM energy, GeV		122.5	81.7	63.2
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	0.33	0.3	0.6	0.6
Bunch charge, nC	5.3	4.8	6.4	3.9
Beam current, mA	50	42	55	33
Hadron rms norm. emittance, μm		0.27	0.20	0.20
Electron rms norm. emittance, μm		31.6	34.7	57.9
Beta*, cm (both planes)	5	5	5	5
Hadron beam-beam parameter		0.015	0.014	0.008
Electron beam disruption		2.8	5.2	1.9
Space charge parameter		0.006	0.016	0.016
rms bunch length, cm	0.4	5	5	5
Polarization, %	80	70	70	none
Peak luminosity, 10^{33} $cm^{-2}s^{-1}$		1.5	2.8	1.7

10 fb^{-1} per month!

Unpolarized beam

Electron energy = 16 GeV

Proton energy = 250 GeV

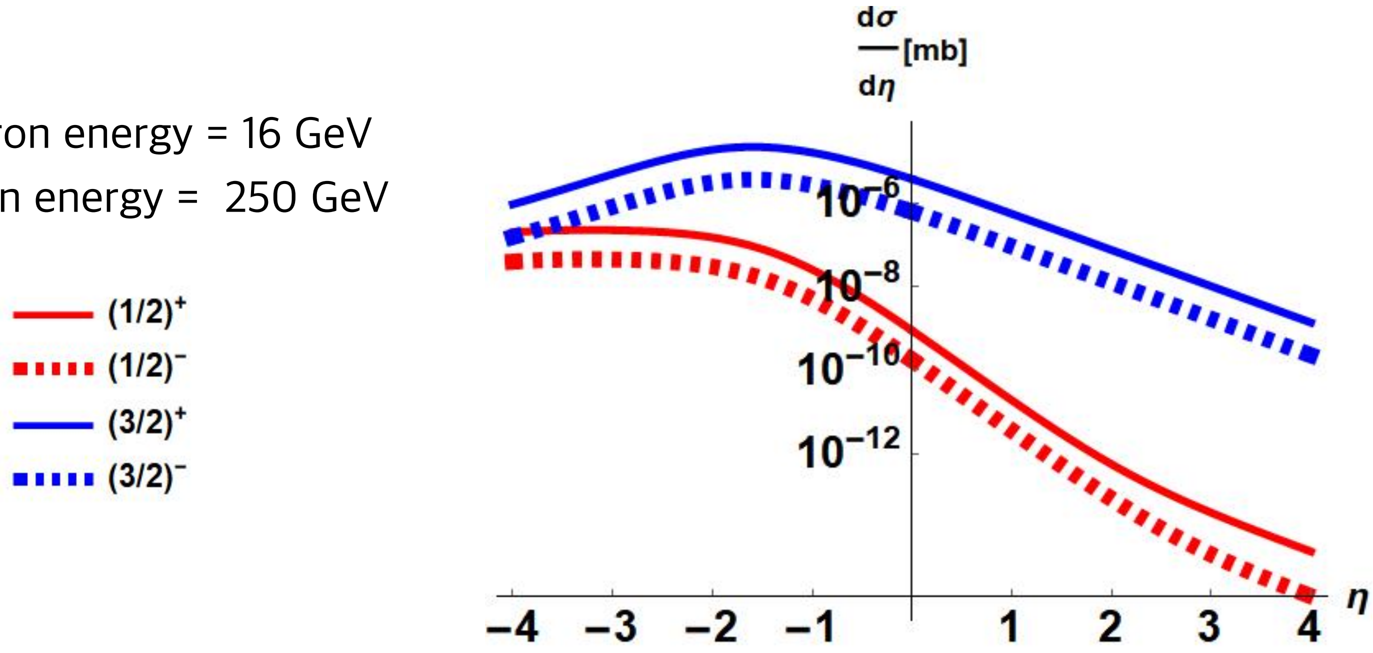


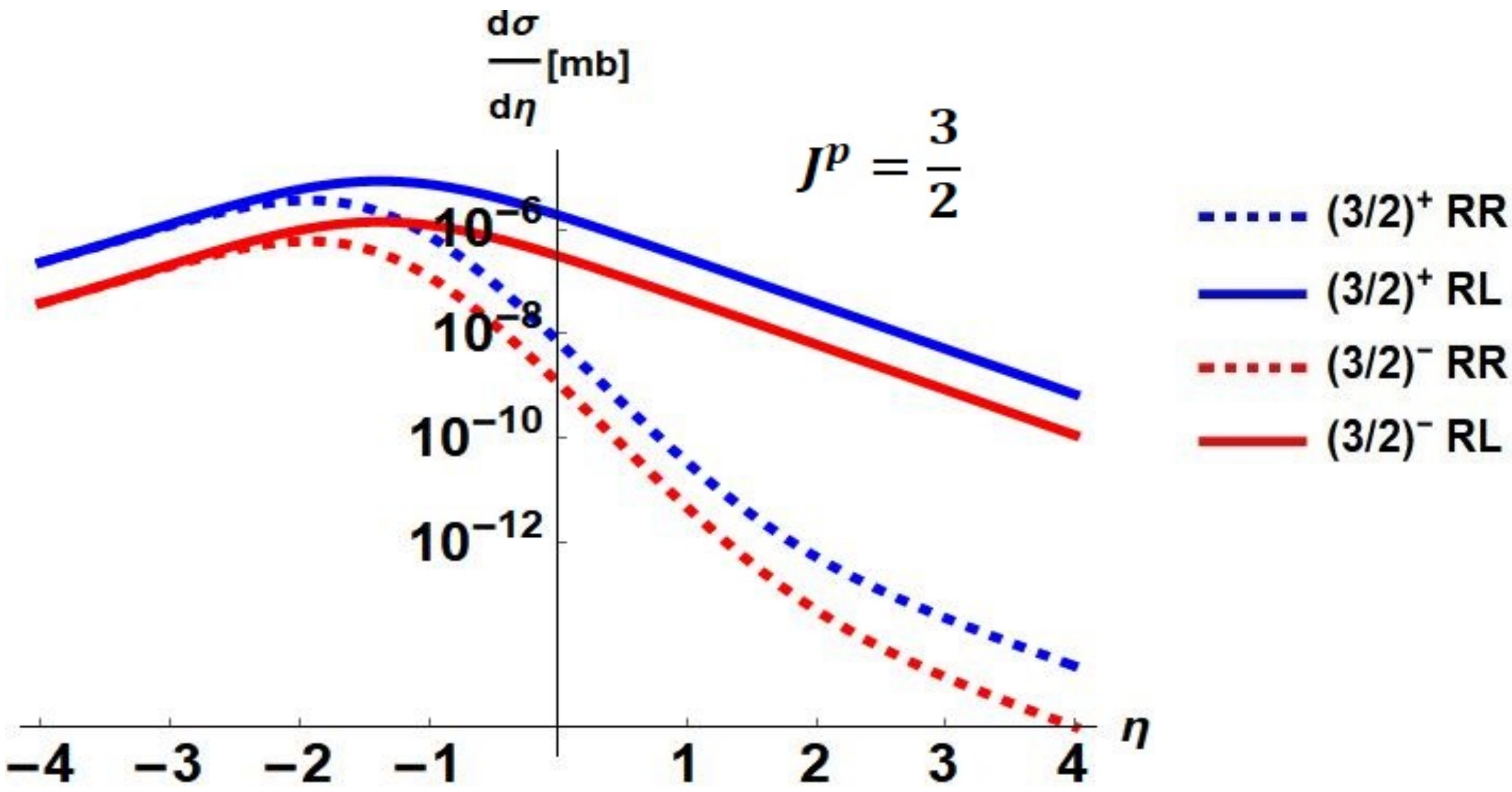
TABLE II. Expected number of $P_c(4312)$ produced at the EIC with 10 fb^{-1}.

J^P of P_c	$\frac{1}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$
Yield	5.09×10^6	1.01×10^6	4.51×10^8	7.46×10^7

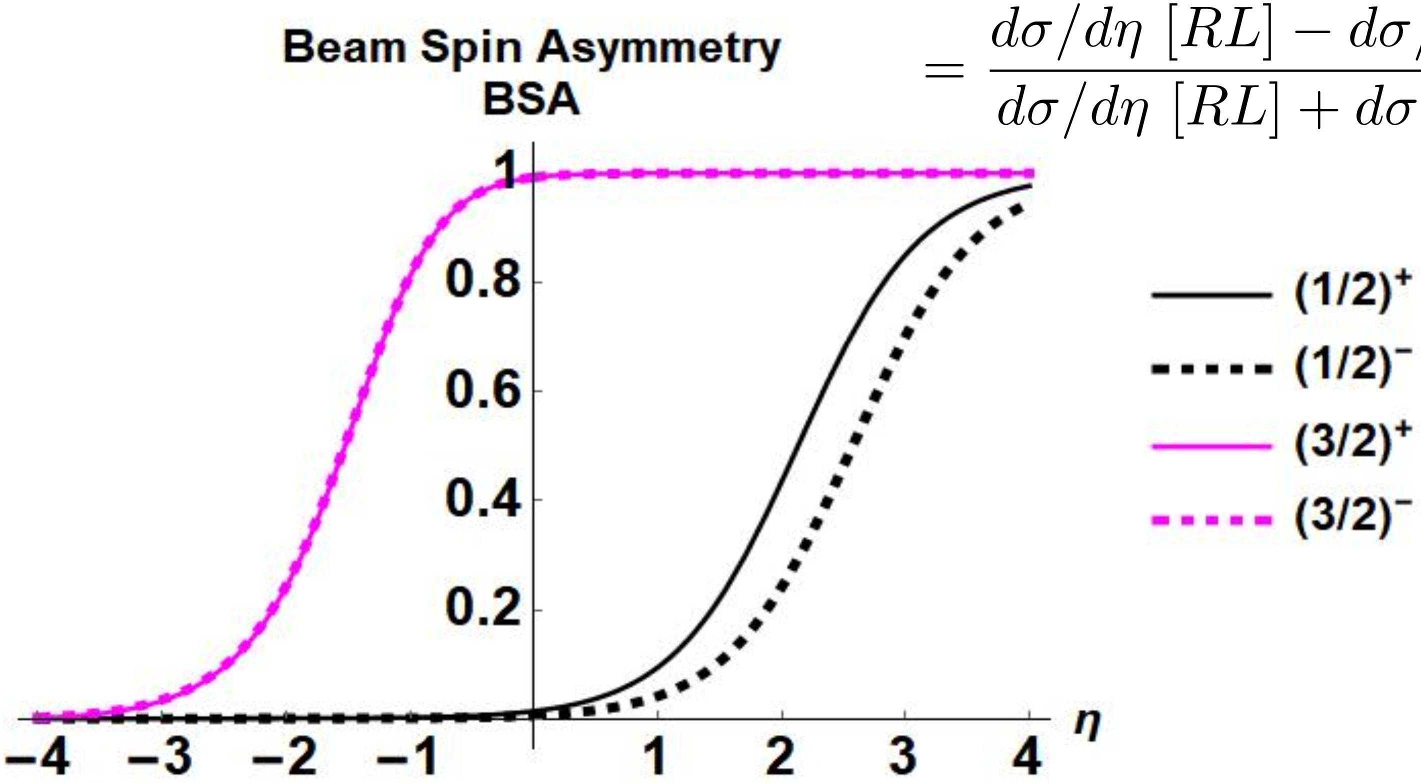
Millions of P_c produced in a year.

EIC being a penta quark factory?!

Polarized beam



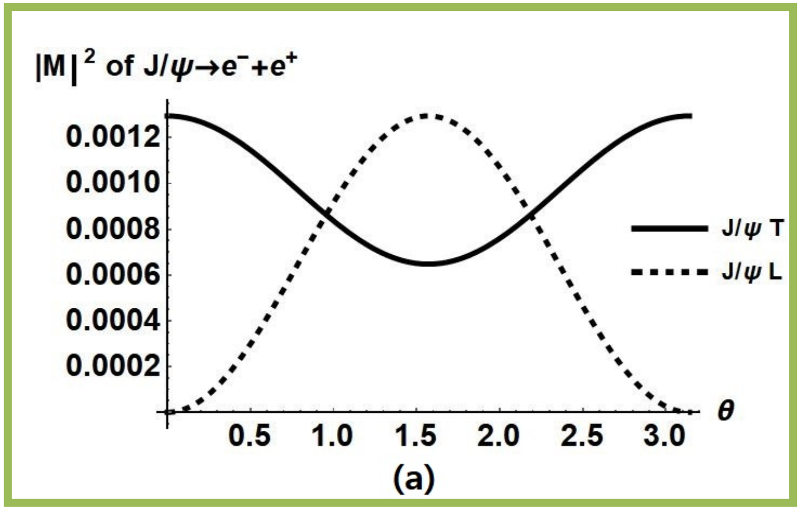
Polarized e+p beam

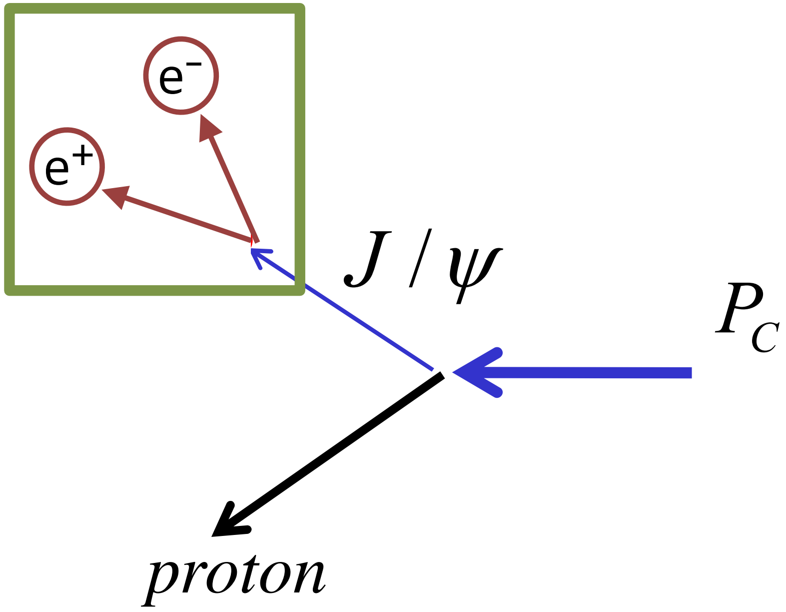


$$= \frac{d\sigma/d\eta\;[RL] - d\sigma/d\eta\;(RR)}{d\sigma/d\eta\;[RL] + d\sigma/d\eta\;[RR]}$$

The spin can be unambiguously determined by measuring BSA

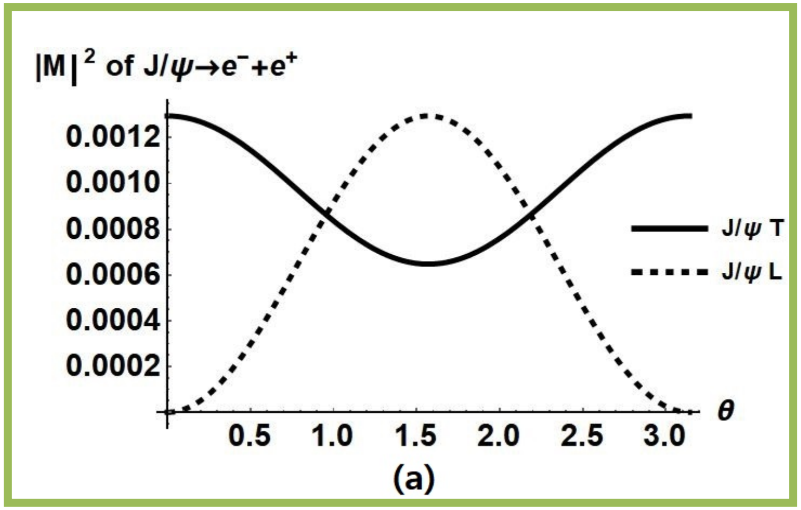
How about parity?

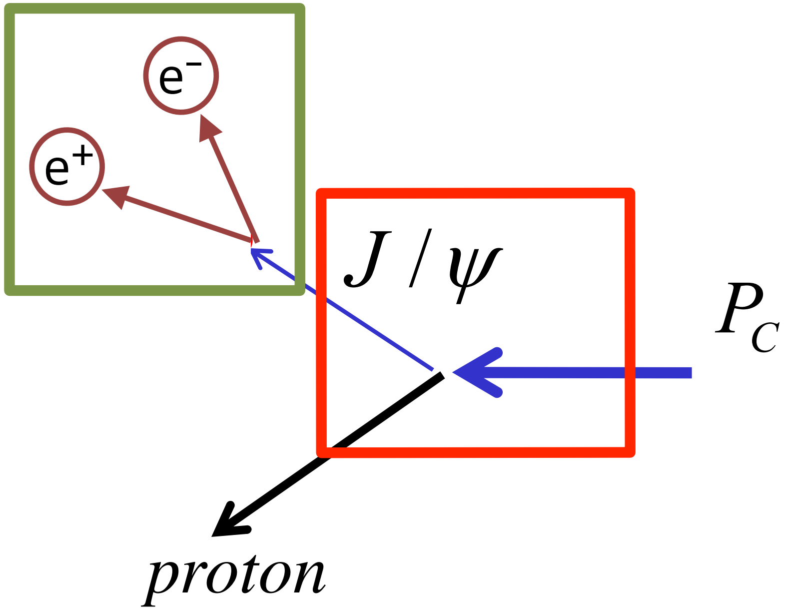


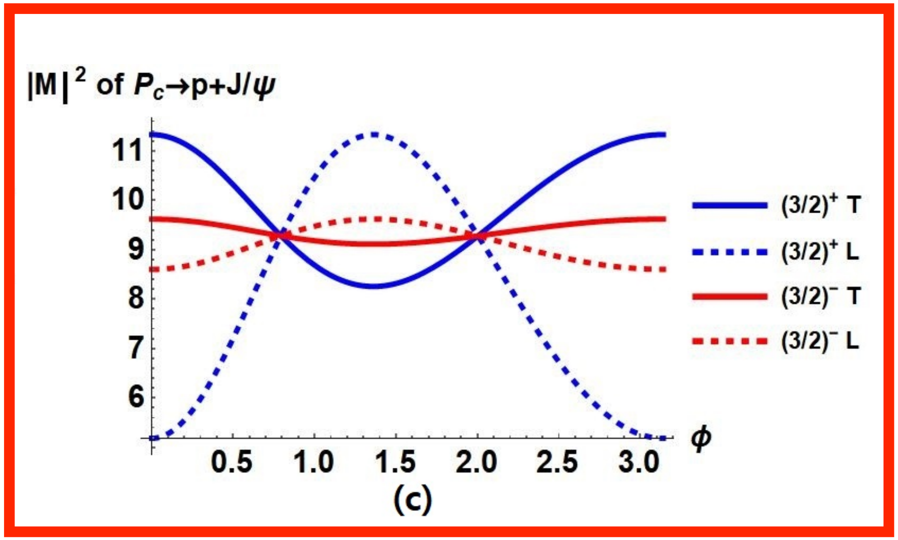


J/ψ has spin-1 and its polarity can be measured from the decay kinematics

How about parity?





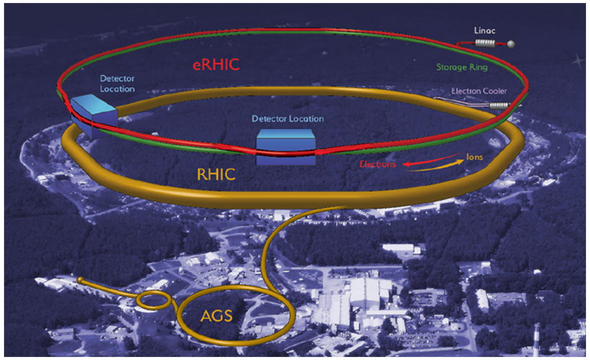


Parity can be experimenally determined by measuring the angle between the proton and P_c !

Summary

- Proton spin, WE KNOW NOTHING
- EIC will be the synomym for spin research
- Great opportunity for breakthrough in QCD
- Lots of phenomenology studies are available at EIC
- Local Collaboration is very imporant

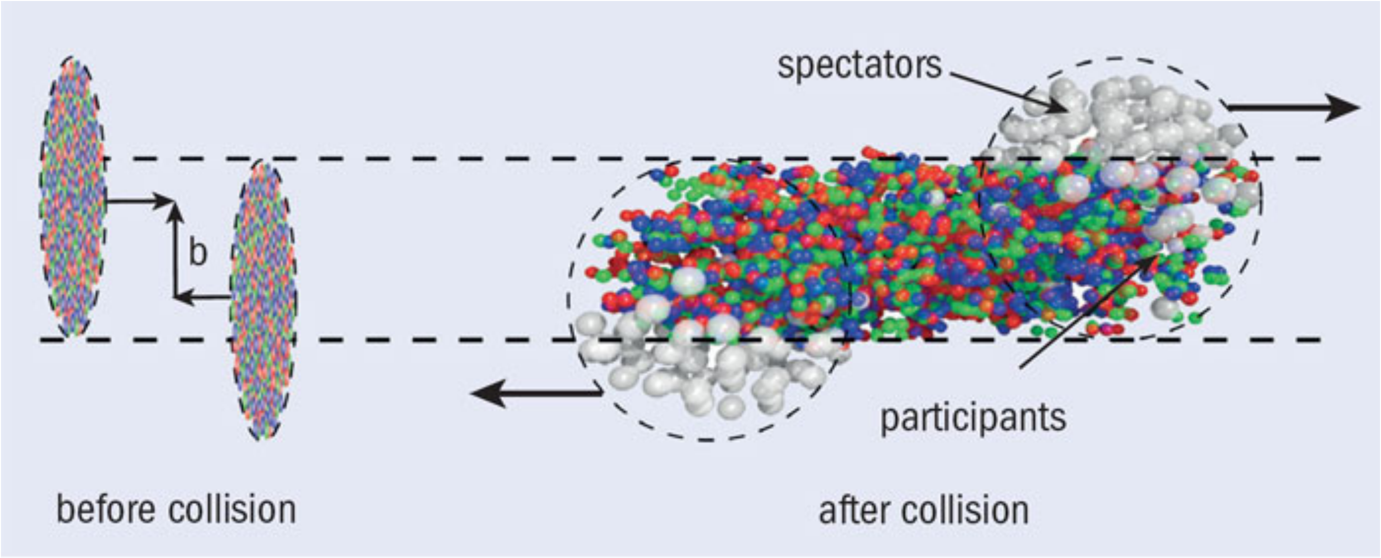
SLAC (1960s)



EIC (2030s)

BACKUP

Separation of initial state and final state effect…



Initial state effects

- nPDF
- Isospin effect

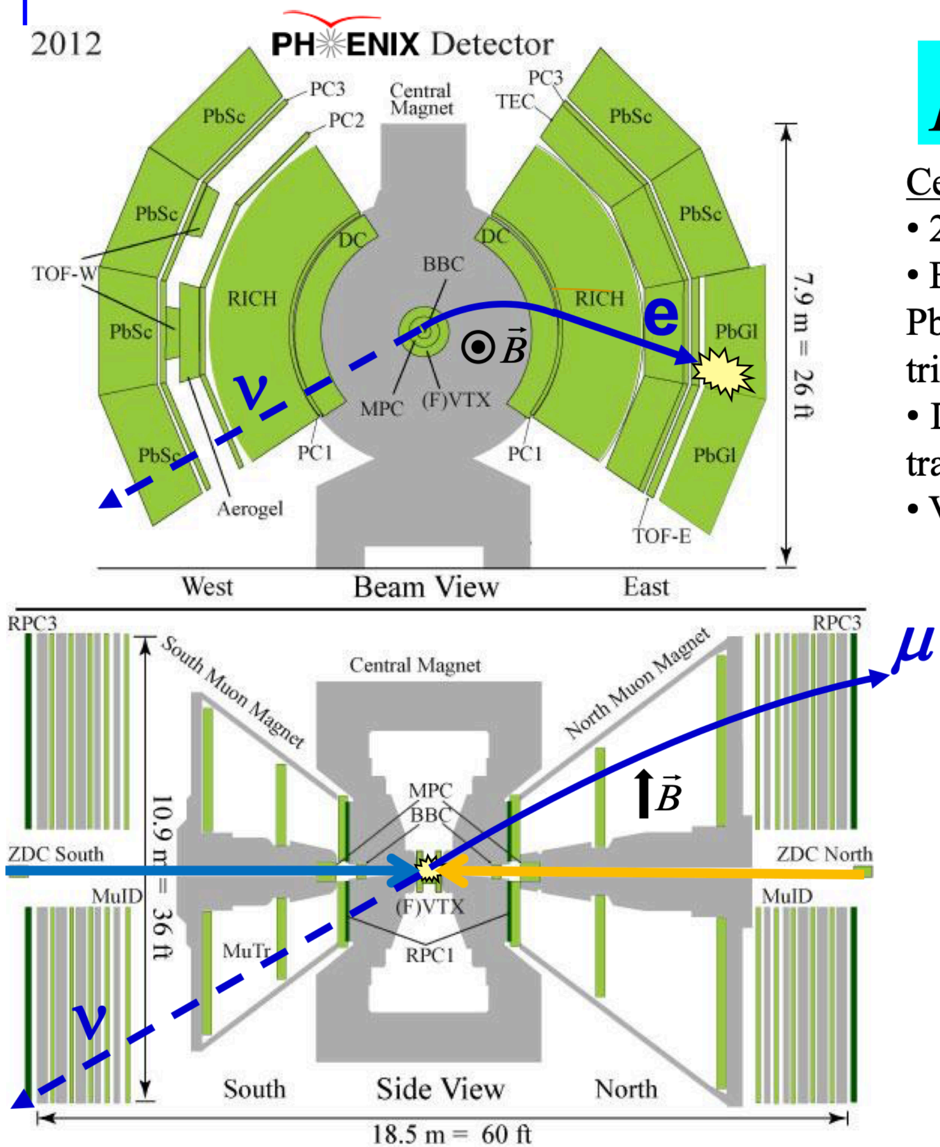
Final state effects

- Comover effect
- Nuclear absorption
- Elastic collision inside nucleus
- Debye screening
- Recombination

p+Pb collision

Pb+Pb collision

$W^{\pm}$ Measurements in PHENIX



$$p + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$$

Central arm spectrometers:

- 2 arms: $|\eta|<0.35$, each $\Delta\phi = \pi/2$
- Electromagnetic Calorimeter (EMCal: PbSc, PbGl) with fine segmentation $\Delta\varphi \times \Delta\eta \sim 0.01 \times 0.01$: triggering
- Drift Chamber (DC) and Pad Chamber (PC): tracking charged tracks and charge separation
- VTX detector (commissioned in 2011)

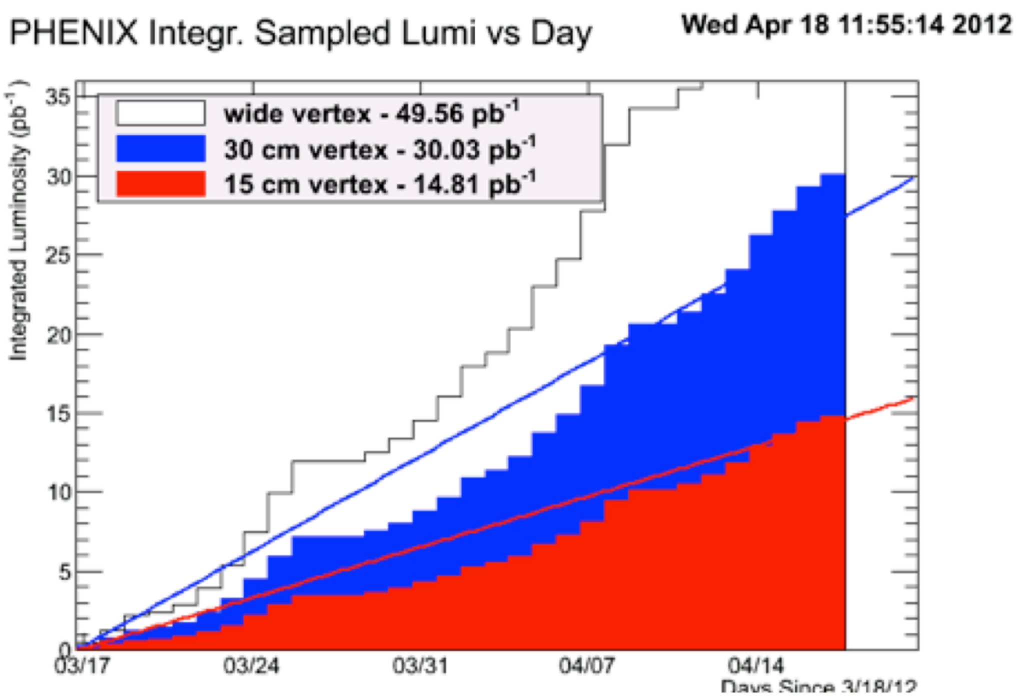
$$p + p \rightarrow W^{\pm} \rightarrow \mu^{\pm} + \nu$$

Forward (Muon) arm spectrometers:

- $1.2 < \eta < 2.4$ (North)
  $-2.2 < \eta < -1.2$ (South), $\Delta\phi = 2\pi$
- Muon Tracker (MuTr): tracking, triggering
- Muon Identifier (MuID): particle ID, triggering
- Resistive Plate Chamber (RPC): particle ID, triggering

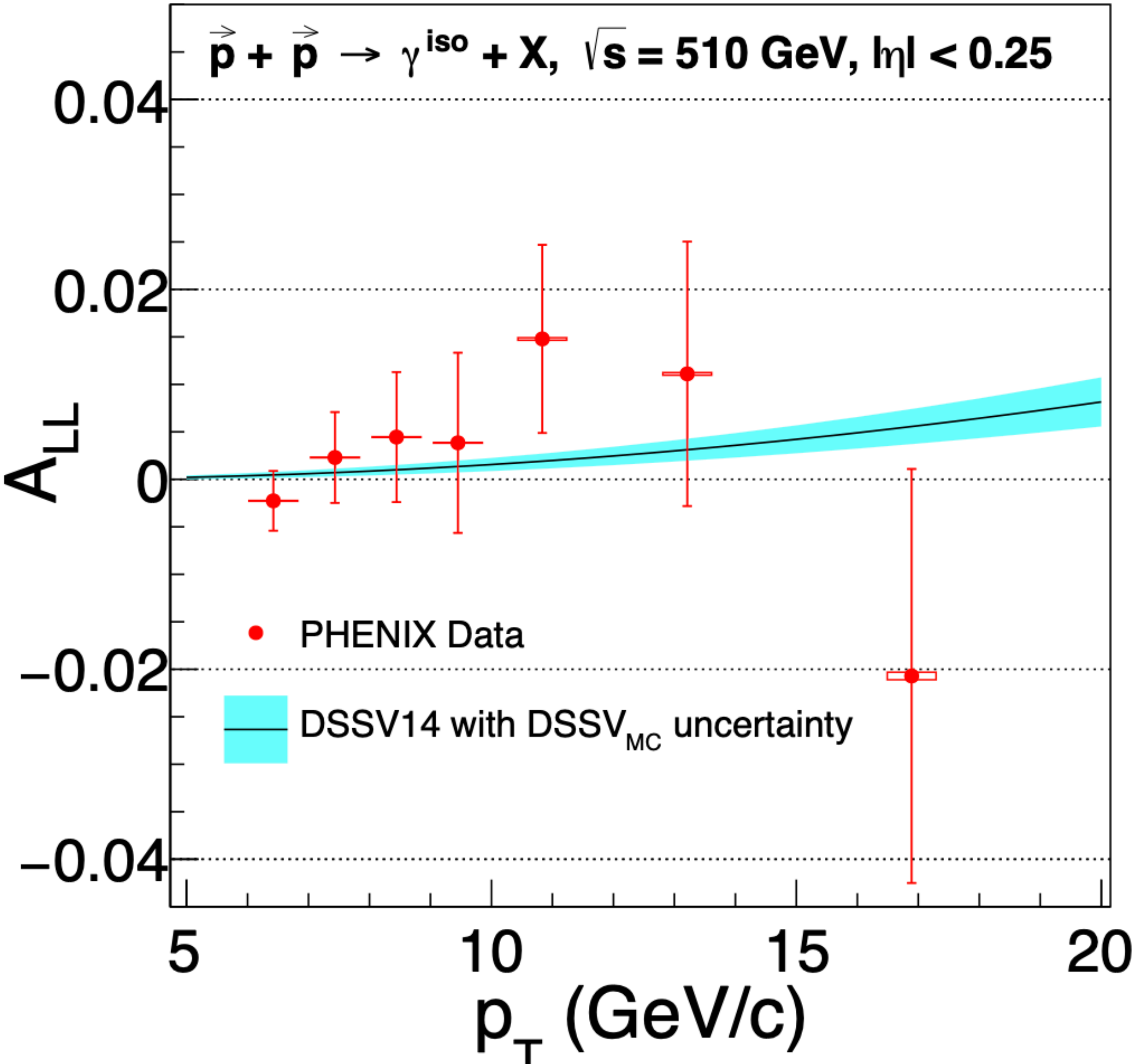
Spin Physics at RHIC

Year	√s (GeV)	∫Ldt (pb⁻¹)	Pol. (%)	LP² (pb⁻¹)
2009	500	8.6	39	1.3
2011	500	16	48	3.7
2012	**510**	**30**	**55**	**9.1**



(Note: recorded luminosity within |z-vertex|<30 cm)

In Run 2012 510 GeV longitudinally polarized *p*+*p* collisions, PHENIX recorded larger data sample with improved polarization in comparison to Run 2011 and Run 2009 hep-ex > arXiv:2202.08158



We present the measurement of the cross section and double-helicity asy
photon production in $\vec{p}+\vec{p}$ collisions at $\sqrt{s} = 510$ GeV. The measurement
midrapidity ($|\eta| < 0.25$) with the PHENIX detector at the Relativistic Hea
photons are dominantly produced by the quark-gluon scattering at relati
photons are produced from the initial partonic hard scattering and do not
force. Therefore, this measurement provides a clean and direct access to the
proton in the gluon-momentum-fraction range $0.02 < x < 0.08$.

FIG. 2. Double-helicity asymmetry A_{LL} *vs* p_T for isolated direct-photon production in polarized p+p collisions at $\sqrt{s} =$ 510 GeV at midrapidity. Vertical error bars (boxes) represent the statistical (systematic) uncertainties. Not shown are $3.9{\times}10^{-4}$ shift uncertainty from relative luminosity and 6.6% scale uncertainty from polarization. The NLO pQCD calculation is plotted as the solid curve with 1σ uncertainty band via MC replicas [11, 38, 39].

Run 2012 Measured W^+ and W^- Spectra (Mid-rapidity)

- 30-50 GeV/c – Signal Region
- 10-20 GeV/c – Background Dominated

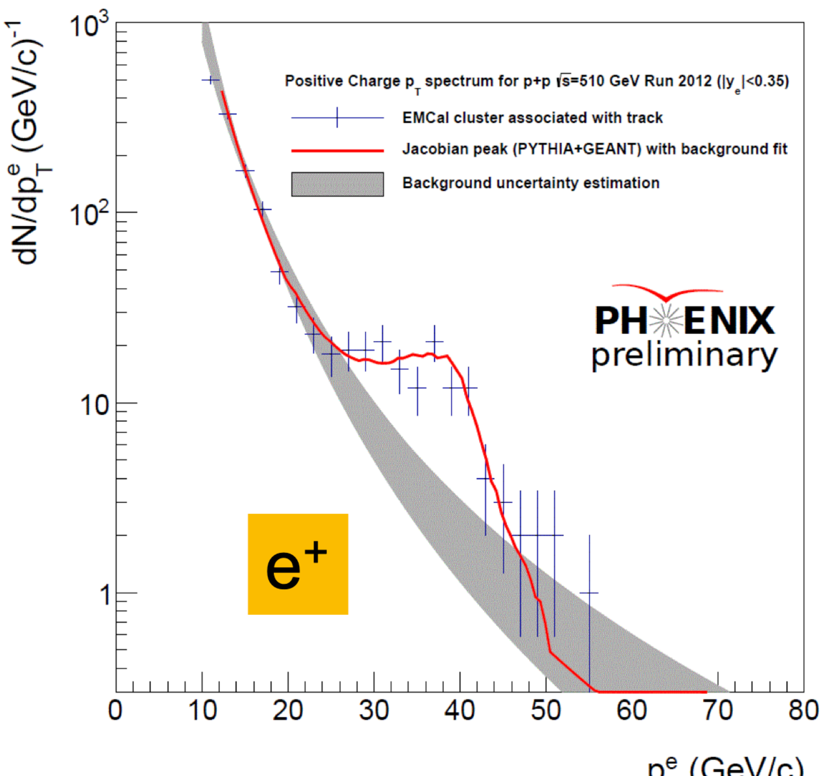
W^+ and W^- signal:

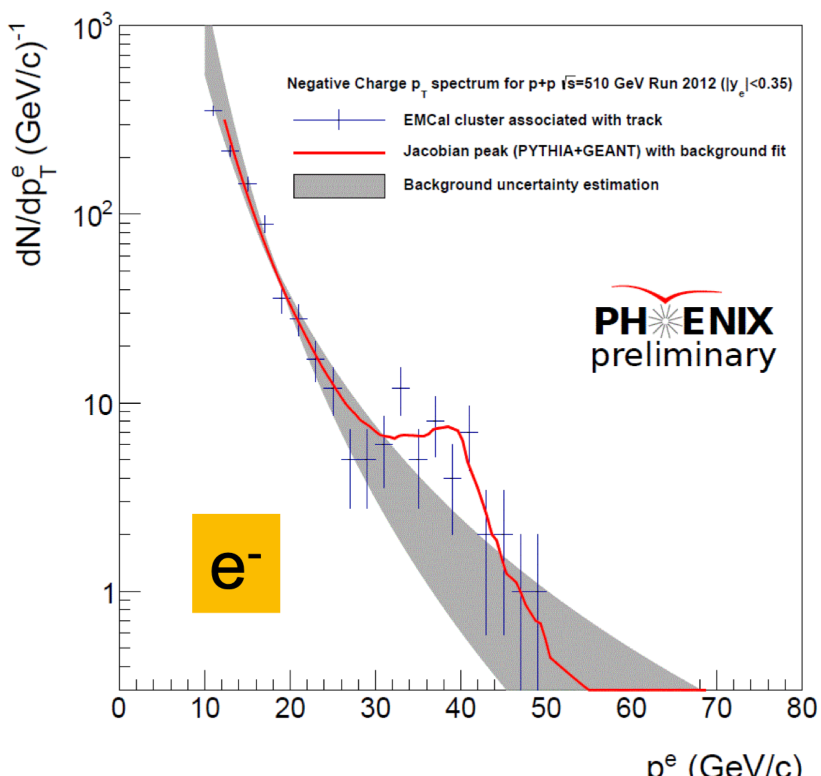
Jacobian peaks

- Background estimation:

Fit region 10 to 69 GeV/c with a power law

Fit region 20 to 50 GeV/c with a power law + Jacobian peak (simulation)





- After all cuts, we have 25% background in the signal region for W^+
- After all cuts, we have 42% background in the signal region for W^-

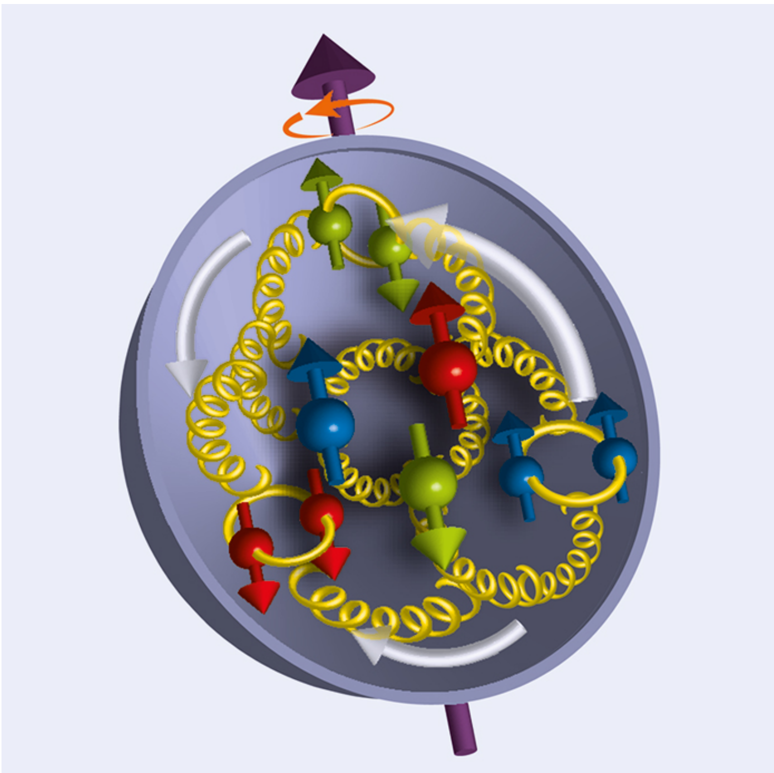
Coupling of J/psi + photon -> Pc

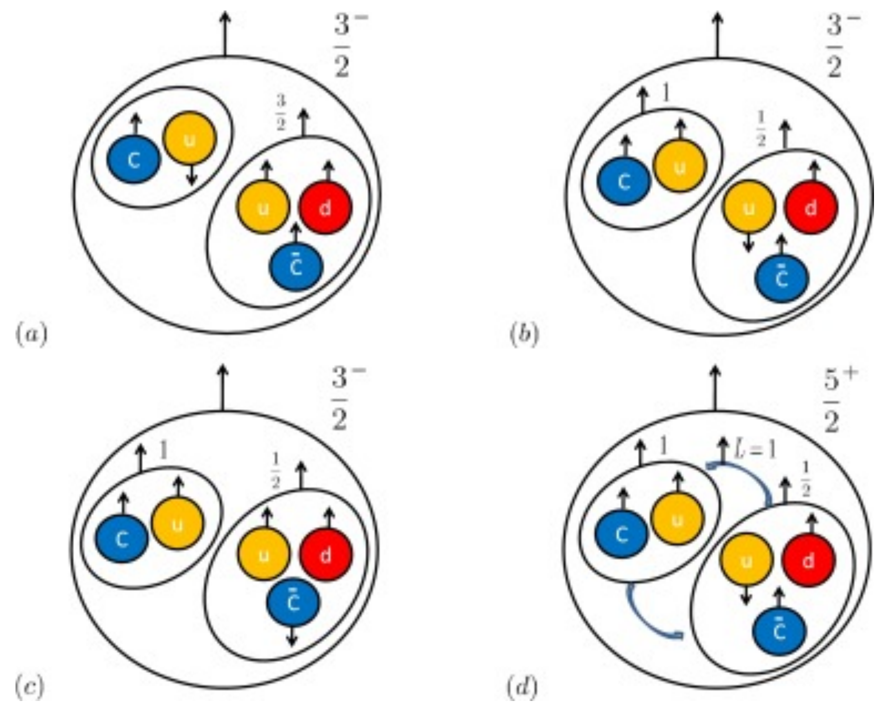
$$
J^p = \frac{1}{2}^+ \begin{cases} |\mathcal{M}|^2_T &= \frac{32 g^2_{JpP_c}}{m^2_{J/\psi}} \left(2(q\cdot p)(q\cdot p') + \frac{m^2_{J/\psi}}{\vec{q}^2}(\vec{q}\cdot\vec{p})(\vec{q}\cdot\vec{p'}) - m^2_{J/\psi}(E_{\vec{p}}E_{\vec{p'}} + m_p m_{P_c}) \right), \\ |\mathcal{M}|^2_L &= \frac{16 g^2_{JpP_c}}{m^2_{J/\psi}} \left(- m^2_{J/\psi}(p\cdot p' + m_p m_{P_c}) + 2m^2_{J/\psi}E_{\vec{p}}E_{\vec{p'}} - \frac{2m^2_{J/\psi}}{\vec{q}^2}(\vec{q}\cdot\vec{p})(\vec{q}\cdot\vec{p'}) \right), \end{cases} \tag{A6}
$$

$$
J^p = \frac{1}{2}^- \begin{cases} |\mathcal{M}|^2_T &= \frac{32 g^2_{JpP_c}}{m^2_{J/\psi}} \left(2(q\cdot p)(q\cdot p') + \frac{m^2_{J/\psi}}{\vec{q}^2}(\vec{q}\cdot\vec{p})(\vec{q}\cdot\vec{p'}) - m^2_{J/\psi}(E_{\vec{p}}E_{\vec{p'}} - m_p m_{P_c}) \right), \\ |\mathcal{M}|^2_L &= \frac{16 g^2_{JpP_c}}{m^2_{J/\psi}} \left(- m^2_{J/\psi}(p\cdot p' - m_p m_{P_c}) + 2m^2_{J/\psi}E_{\vec{p}}E_{\vec{p'}} - \frac{2m^2_{J/\psi}}{\vec{q}^2}(\vec{q}\cdot\vec{p})(\vec{q}\cdot\vec{p'}) \right), \end{cases} \tag{A7}
$$

$$
J^p = \frac{3}{2}^+ \begin{cases} |\mathcal{M}|^2_T &= \frac{8 g^2_{JpP_c}}{3m^2_{P_c} m^2_{J/\psi}} \Big(2m^2_{P_c}(q\cdot p)(q\cdot p') + 2(p\cdot p')(q\cdot p')^2 - 2m_p m^3_{P_c} m^2_{J/\psi} - m^2_{P_c}(p\cdot p')m^2_{J/\psi} \\ & \quad + \frac{m^2_{J/\psi}(p\cdot p')}{\vec{q}^2}(\vec{q}\cdot\vec{p'})^2 + \frac{m^2_{J/\psi}}{\vec{q}^2} m^2_{P_c}(\vec{q}\cdot\vec{p})(\vec{q}\cdot\vec{p'}) - m^2_{J/\psi}\vec{p'}^2(p\cdot p') - m^2_{P_c}E_{\vec{p}}E_{\vec{p'}}m^2_{J/\psi} \Big), \\ |\mathcal{M}|^2_L &= \frac{8 g^2_{JpP_c}}{3m^2_{P_c} m^2_{J/\psi}} \Big(- m_p m^3_{P_c} m^2_{J/\psi} - m^2_{P_c}(\vec{q}\cdot\vec{p})(\vec{q}\cdot\vec{p'})\frac{m^2_{J/\psi}}{\vec{q}^2} - (p\cdot p')(\vec{q}\cdot\vec{p'})^2\frac{m^2_{J/\psi}}{\vec{q}^2} \\ & \quad + m^2_{J/\psi}\vec{p'}^2(p\cdot p') + m^2_{P_c}E_{\vec{p}}E_{\vec{p'}}m^2_{J/\psi} \Big), \end{cases} \tag{A8}
$$

$$
J^p = \frac{3}{2}^- \begin{cases} |\mathcal{M}|^2_T &= \frac{8 g^2_{JpP_c}}{3m^2_{P_c} m^2_{J/\psi}} \Big(2m^2_{P_c}(q\cdot p)(q\cdot p') + 2(p\cdot p')(q\cdot p')^2 + 2m_p m^3_{P_c} m^2_{J/\psi} - m^2_{P_c}(p\cdot p')m^2_{J/\psi} \\ & \quad + \frac{m^2_{J/\psi}(p\cdot p')}{\vec{q}^2}(\vec{q}\cdot\vec{p'})^2 + \frac{m^2_{J/\psi}}{\vec{q}^2} m^2_{P_c}(\vec{q}\cdot\vec{p})(\vec{q}\cdot\vec{p'}) - m^2_{J/\psi}\vec{p'}^2(p\cdot p') - m^2_{P_c}E_{\vec{p}}E_{\vec{p'}}m^2_{J/\psi} \Big), \\ |\mathcal{M}|^2_L &= \frac{8 g^2_{JpP_c}}{3m^2_{P_c} m^2_{J/\psi}} \Big(m_p m^3_{P_c} m^2_{J/\psi} - m^2_{P_c}(\vec{q}\cdot\vec{p})(\vec{q}\cdot\vec{p'})\frac{m^2_{J/\psi}}{\vec{q}^2} - (p\cdot p')(\vec{q}\cdot\vec{p'})^2\frac{m^2_{J/\psi}}{\vec{q}^2} \\ & \quad + m^2_{J/\psi}\vec{p'}^2(p\cdot p') + m^2_{P_c}E_{\vec{p}}E_{\vec{p'}}m^2_{J/\psi} \Big). \end{cases} \tag{A9}
$$





Proton spin mystery

Probe for exotic partices