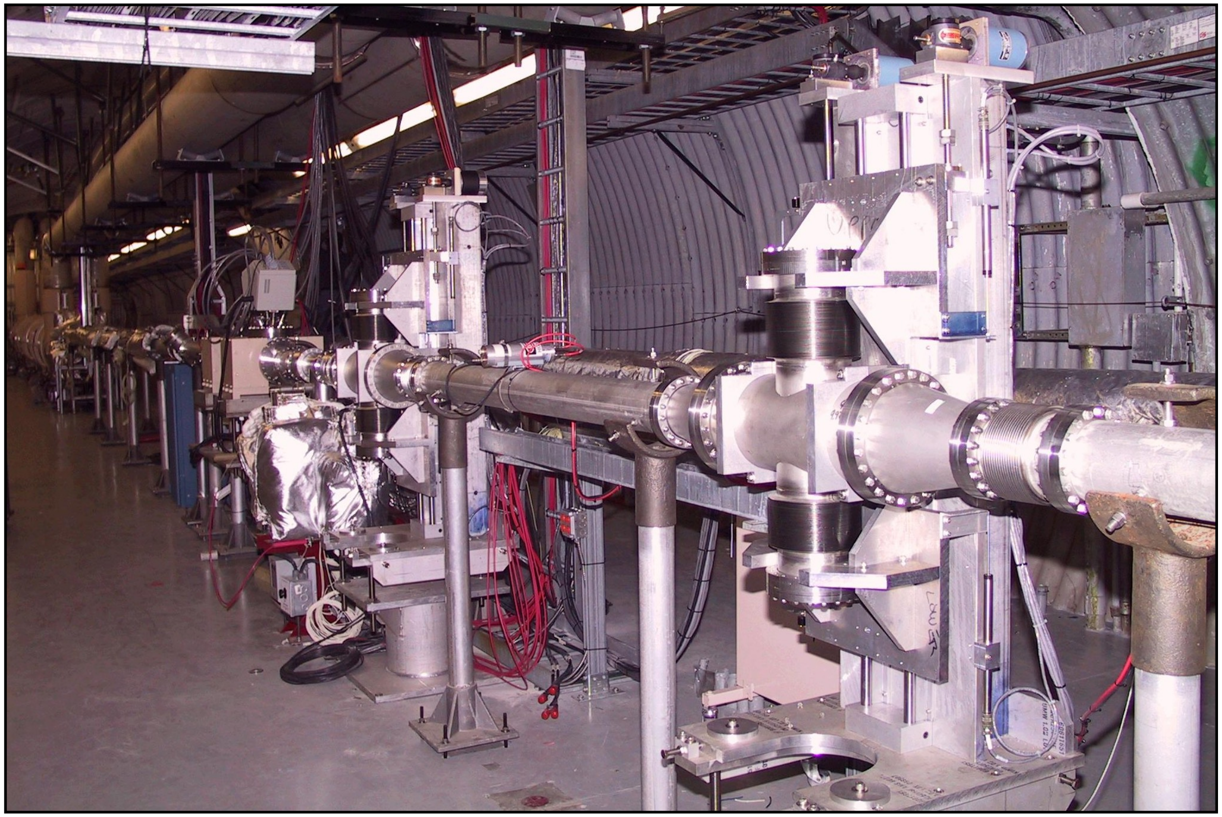


Hadronic Interactions

Nuclear Physics Group Seminar

April 9, 2015

S. Bültmann

Outline

- Elastic Scattering
- Polarized Proton-Proton Scattering at RHIC
- The Drell-Yan Process

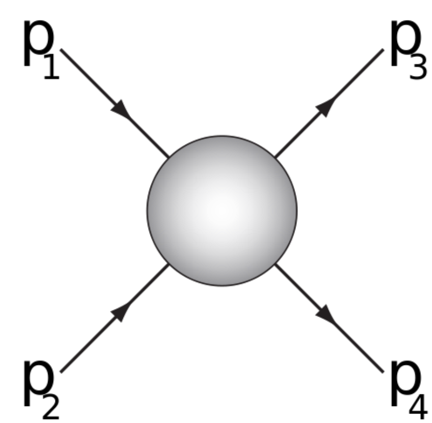
Elastic Scattering

- In elastic scattering protons interact via two fundamental interactions: EM (QED) and Hadronic (non-pQCD)
- May interact by exchanging a hypothetical Pomeron described as a color singlet combination of two gluons (for high *t*)
- Has quantum numbers of the vacuum, has mass, zero spin, neither electric nor color charge

Mandelstam variables:

$$t = (p_1 - p_3)^2 = -4p^2 \sin^2(\theta/2)$$

$$s = (p_1 + p_2)^2 = (p^2 + m^2)$$



Elastic Scattering at RHIC

Coulomb interaction for $|t| < 10^{-3}$ GeV^2

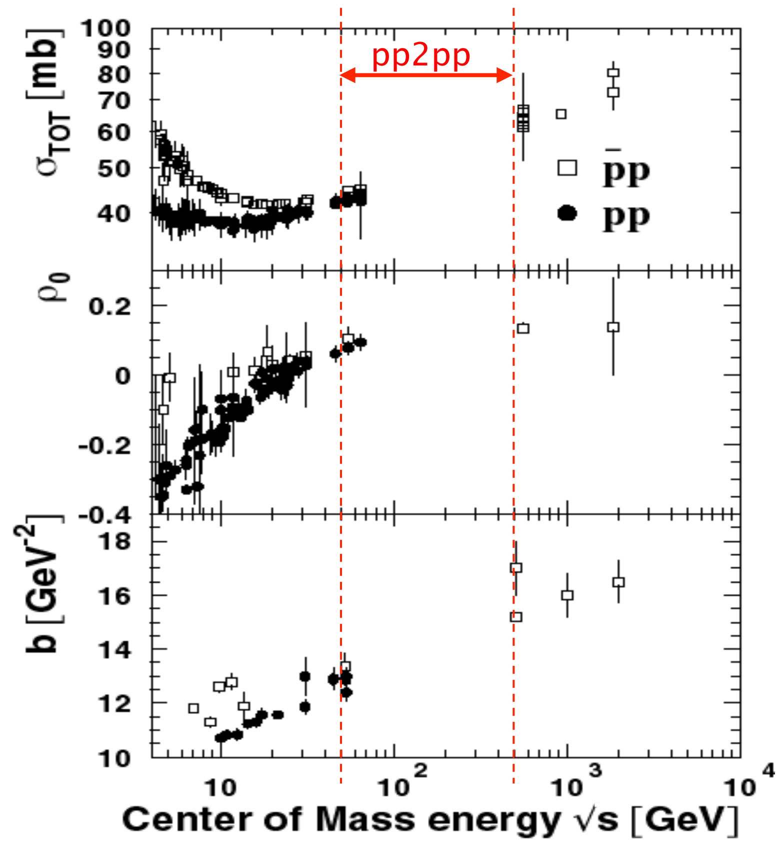
Measure total cross section σ_{tot} and access imaginary part of scattering amplitude via optical theorem

Hadronic interaction for $5 \cdot 10^{-3}$ GeV$^2 \leq |t| \leq 1$ GeV^2

Measure forward diffraction cone slope *b*

Interference between Coulomb and hadronic interaction (CNI-region)

Measure ratio of real and imaginary part of forward scattering amplitude ρ_0 and extract its real part using measured σ_{tot}



Differential Elastic Cross Section

For Proton–Proton Scattering

$$\frac{d\sigma}{dt} = \frac{4\pi\,(\alpha\, G_E^{\,2})^2}{t^2} + \frac{(1+\rho^2)\,\sigma_{tot}^{\,2}\; e^{+bt}}{16\pi} + \frac{(\rho + \Delta\Phi)\,\alpha\, G_E^{\,2}\,\sigma_{tot}\; e^{+\frac{1}{2}bt}}{t}$$

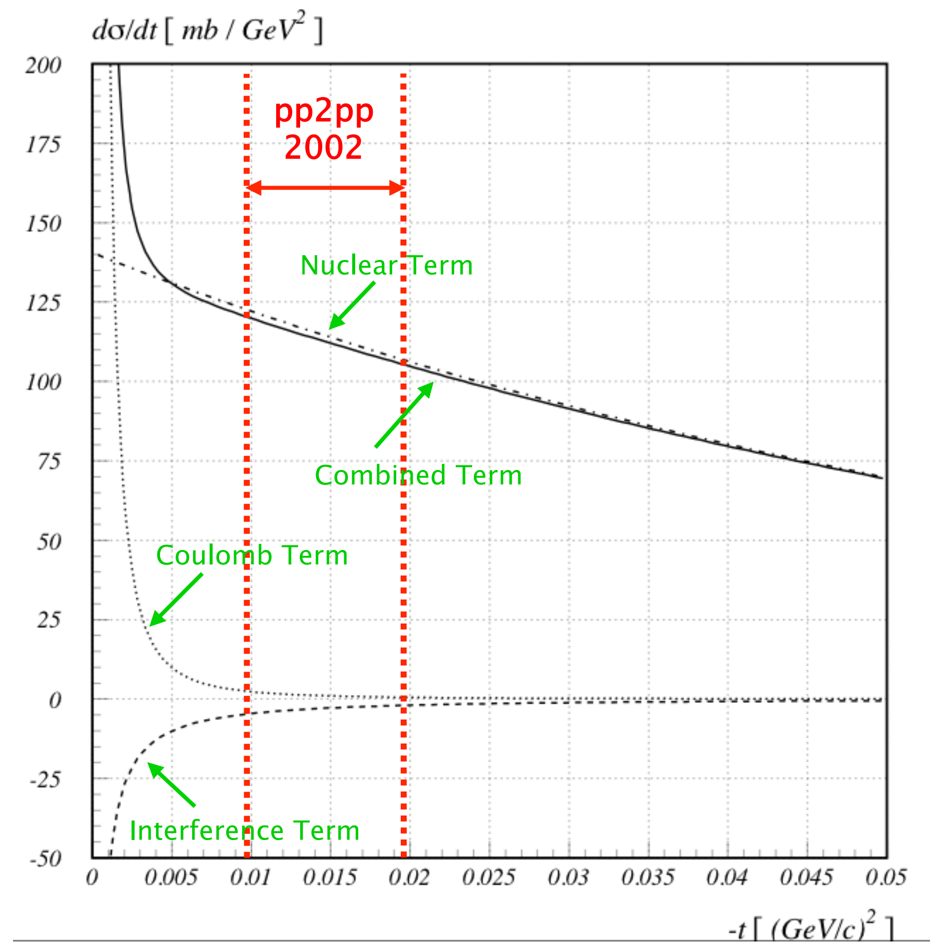
$\Delta\Phi$ = Coulomb Phase

G_E = Proton Electric Form Factor

Input : σ_{tot} = 52 mb

ρ = 0.13

b = 14 GeV^{-2}



Values for $\sqrt{s}$ = 200 GeV

pp Elastic Scattering Amplitudes

The helicity amplitudes describe elastic proton-proton scattering

$\phi_1(s,t) \propto <++|M|++>$

$\phi_2(s,t) \propto <++|M|-->$

$\phi_3(s,t) \propto <+-|M|+->$

$\phi_4(s,t) \propto <+-|M|-+>$

$\phi_5(s,t) \propto <++|M|+->$ $(= \phi_{flip})$

$\phi_n(s,t) \propto <h_3\, h_4\, |M| h_1\, h_2>$

with h_x = *s*–channel helicity

$p_1 = -p_2$ incoming protons

$p_3 = -p_4$ scattered protons

$$\phi_+(s,t) = \frac{1}{2}\left(\phi_1(s,t) + \phi_3(s,t)\right) = \phi_{no\text{-}flip}$$

Measure

$$\sigma_{tot} = \frac{8\pi}{s}\, Im\,[\phi_+(s,t)]_{t=0}$$

$$\frac{d\sigma}{dt} = \frac{2\pi}{s^2}\left(|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 | + 4\,|\phi_5|^2 \right)$$

$$\Delta\sigma_T = -\frac{8\pi}{s}\, Im\,[\phi_2(s,t)]_{t=0} = \sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}$$

$$2\pi\frac{d^2\sigma}{dt\,d\varphi} = \frac{d\sigma}{dt}\left(1 + (P_B + P_Y)\, A_N \cos\varphi + P_B P_Y\,(A_{NN}\cos^2\varphi + A_{SS}\sin^2\varphi)\right)$$

Single Spin Asymmetry

Single spin asymmetry A_N of transversely polarized protons arises in CNI region from interference of hadronic non-flip with electromagnetic spin-flip amplitude

Measure dependence on $|t|$ to probe for interference contribution from hadronic spin-flip amplitude with electromagnetic amplitude

Disentangle Real and Imaginary part of hadronic spin flip contribution by measuring shift or slope change of A_N with possible zero crossing

$$A_N(t) = \frac{1}{P_Y \cdot \cos\varphi} \frac{N_{\uparrow\uparrow}(t) + N_{\uparrow\downarrow}(t) - N_{\downarrow\downarrow}(t) - N_{\downarrow\uparrow}(t)}{N_{\uparrow\uparrow}(t) + N_{\uparrow\downarrow}(t) + N_{\downarrow\downarrow}(t) + N_{\downarrow\uparrow}(t)}$$

$$\propto \frac{\mathcal{Im}\left(\phi^{\mathrm{em}\,*}_{\mathrm{flip}} \; \phi^{\mathrm{had}}_{\mathrm{no-flip}} + \phi^{\mathrm{had}\,*}_{\mathrm{flip}} \; \phi^{\mathrm{em}}_{\mathrm{noflip}} \right)}{d\sigma / dt}$$

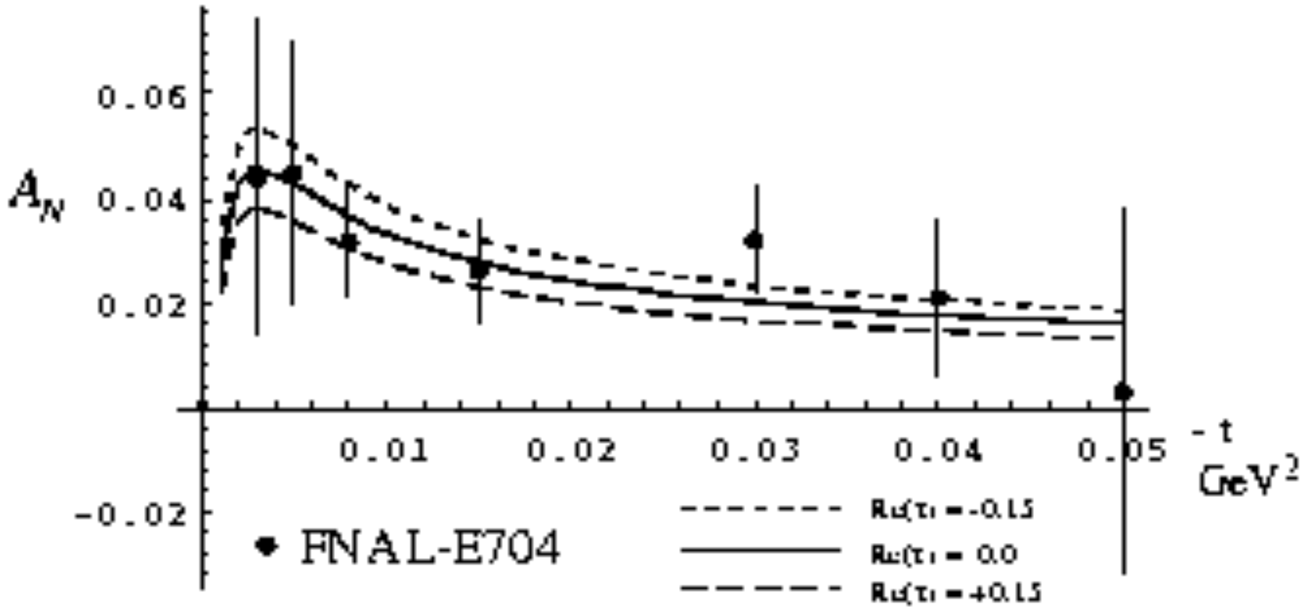
for small t

With $N(t) = \frac{dN}{dt}$

P_Y = beam pol.

φ = azimuth

Single Spin Asymmetry



N.H. Buttimore, B.Z. Kopeliovich, E. Leader, J. Soffer, T.L. Trueman, "The Spin Dependence of High-Energy Proton Scattering", PRD 59, 114010 (1999)

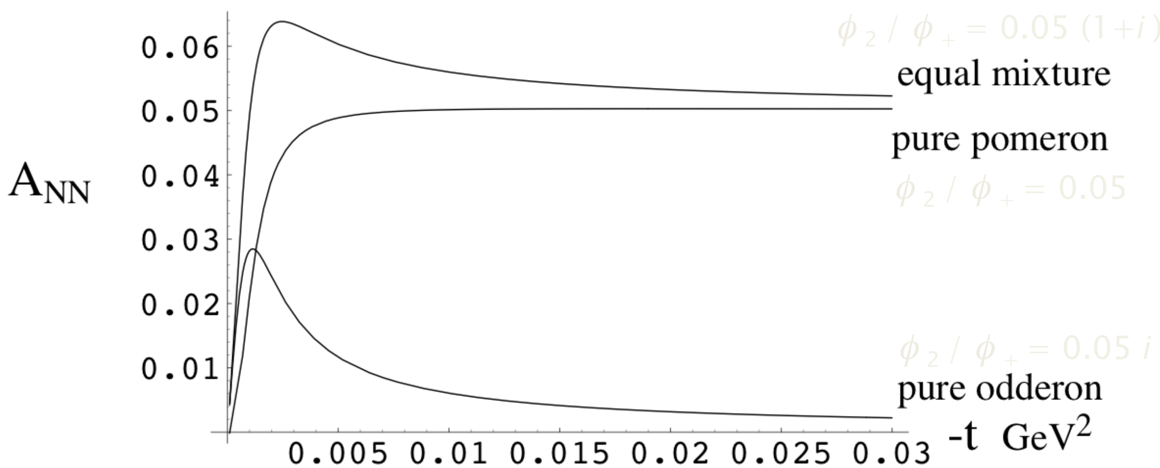
Double Spin Asymmetry

Measure A_{NN} with transversely polarized protons to find limit on detectable Odderon, $C = -1$ partner of the Pomeron, contribution to interference between ϕ_1 and ϕ_2

Pomeron and Odderon out of phase by about 90° at $t = 0$

$$A_{NN}(t) = \frac{1}{P_Y \cdot P_B \cdot \cos^2\varphi} \frac{N_{\uparrow\uparrow}(t) + N_{\downarrow\downarrow}(t) - N_{\uparrow\downarrow}(t) - N_{\downarrow\uparrow}(t)}{N_{\uparrow\uparrow}(t) + N_{\downarrow\downarrow}(t) + N_{\uparrow\downarrow}(t) + N_{\downarrow\uparrow}(t)} \propto \frac{\mathcal{R}e\,(\phi_{\text{no-flip}}\,\phi_2^{\,*})}{d\sigma / dt}$$

for small t



E. Leader, T.L. Trueman, "The Odderon and Spin Dependence of High-Energy Proton-Proton Scattering", PRD 61, 077504 (2000)

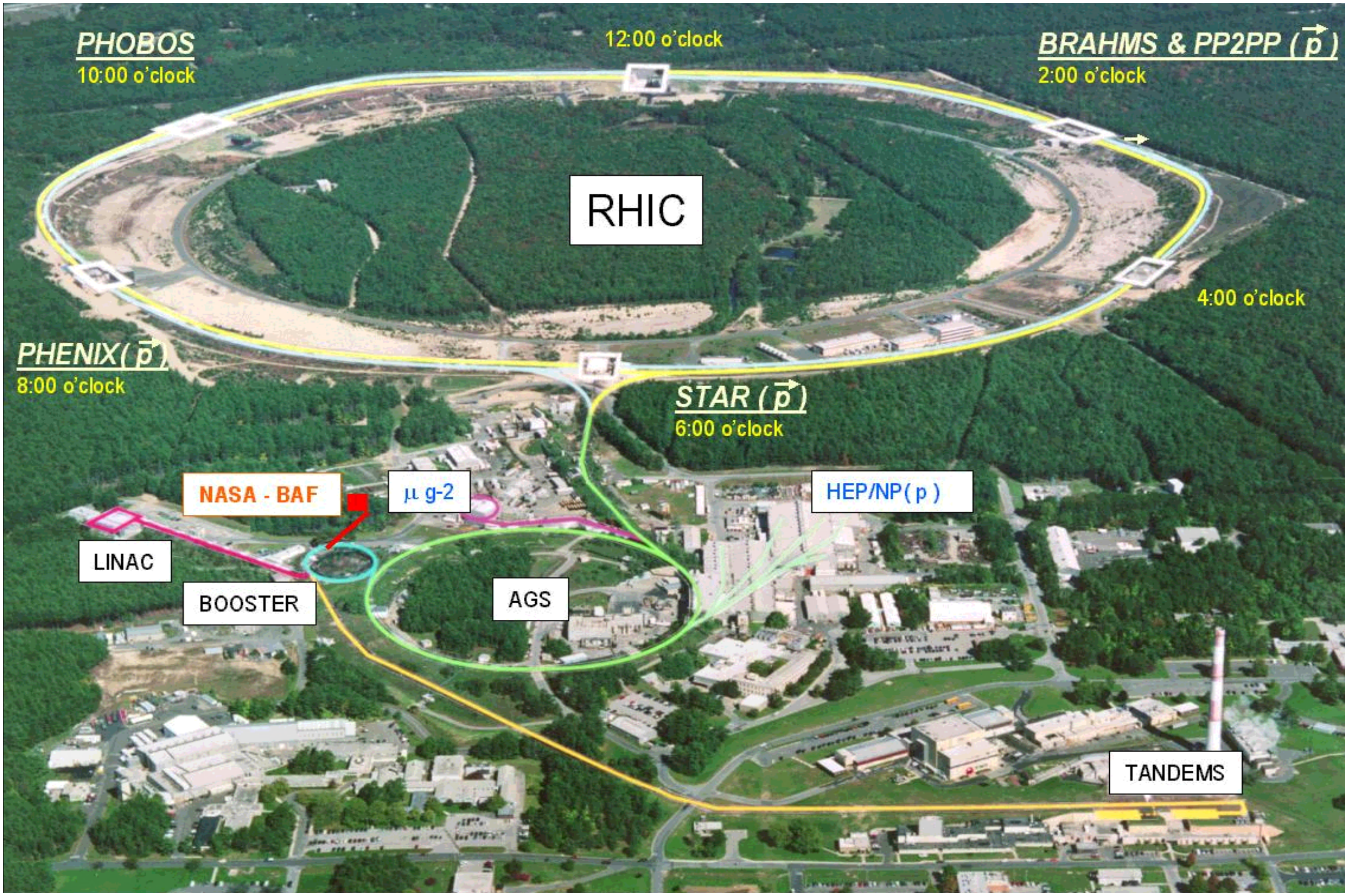
The RHIC Accelerator

Need two separate beam lines with individual transport magnets except in the interaction regions

To collide identical particles, like polarized protons, need

- Polarized proton source
- Magnets to maintain polarization as much as possible (vertically)
- Polarization measurement (to about 5%)
- Magnets to change polarization from transverse to longitudinal

Birds Eye View of RHIC



The RHIC Accelerator

55 proton bunches per beam (design 120)

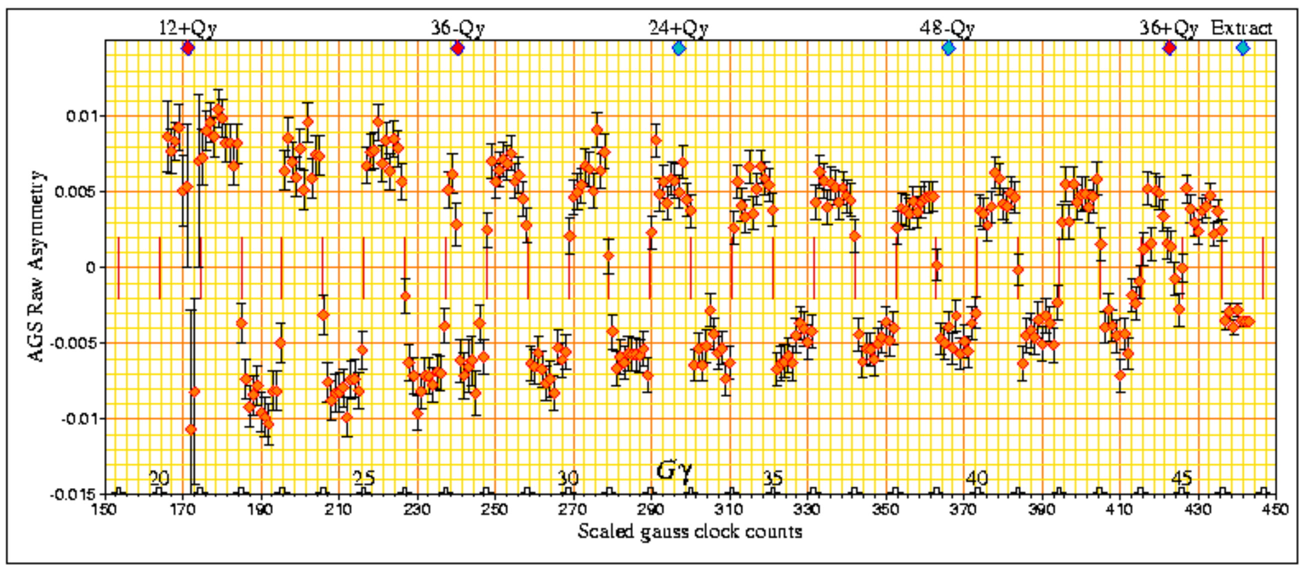
10^{11} protons per bunch (design $2\cdot10^{11}$)

Beam momentum 100 GeV/*c* (design up to 250 GeV/*c*)

Fill life time about one shift of eight hours

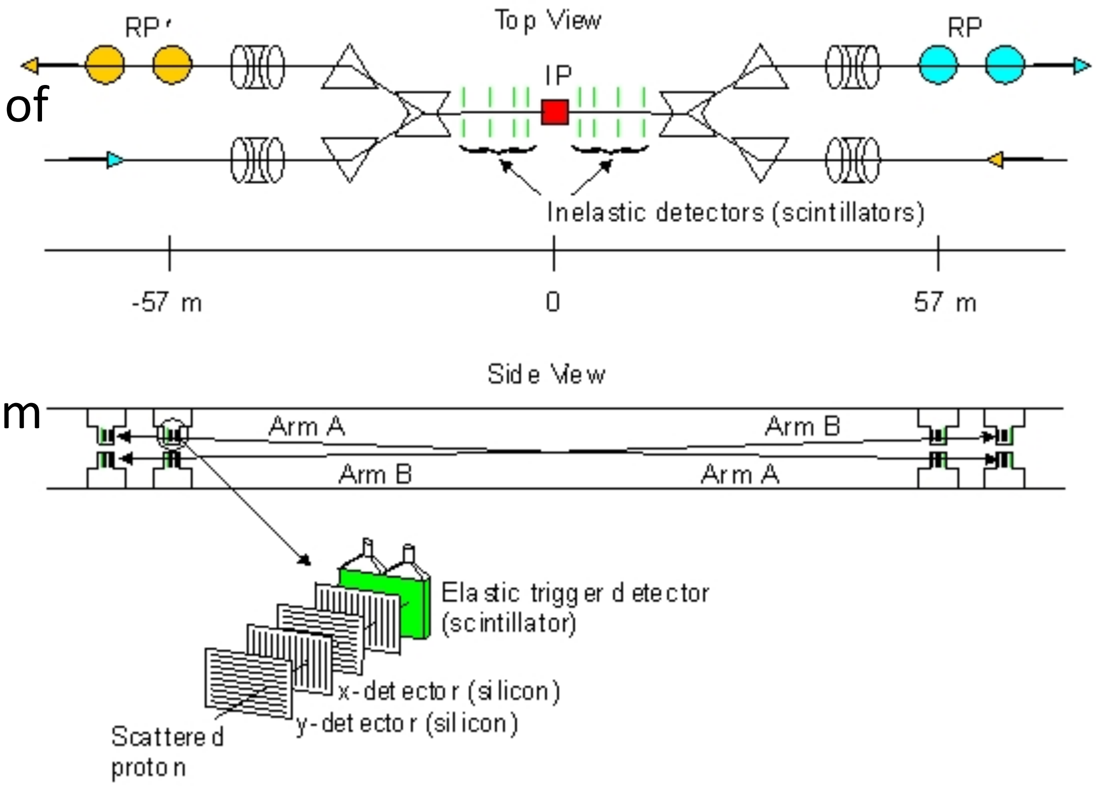
Polarization about 0.6 (design 0.7)

Polarization loss mostly in the AGS

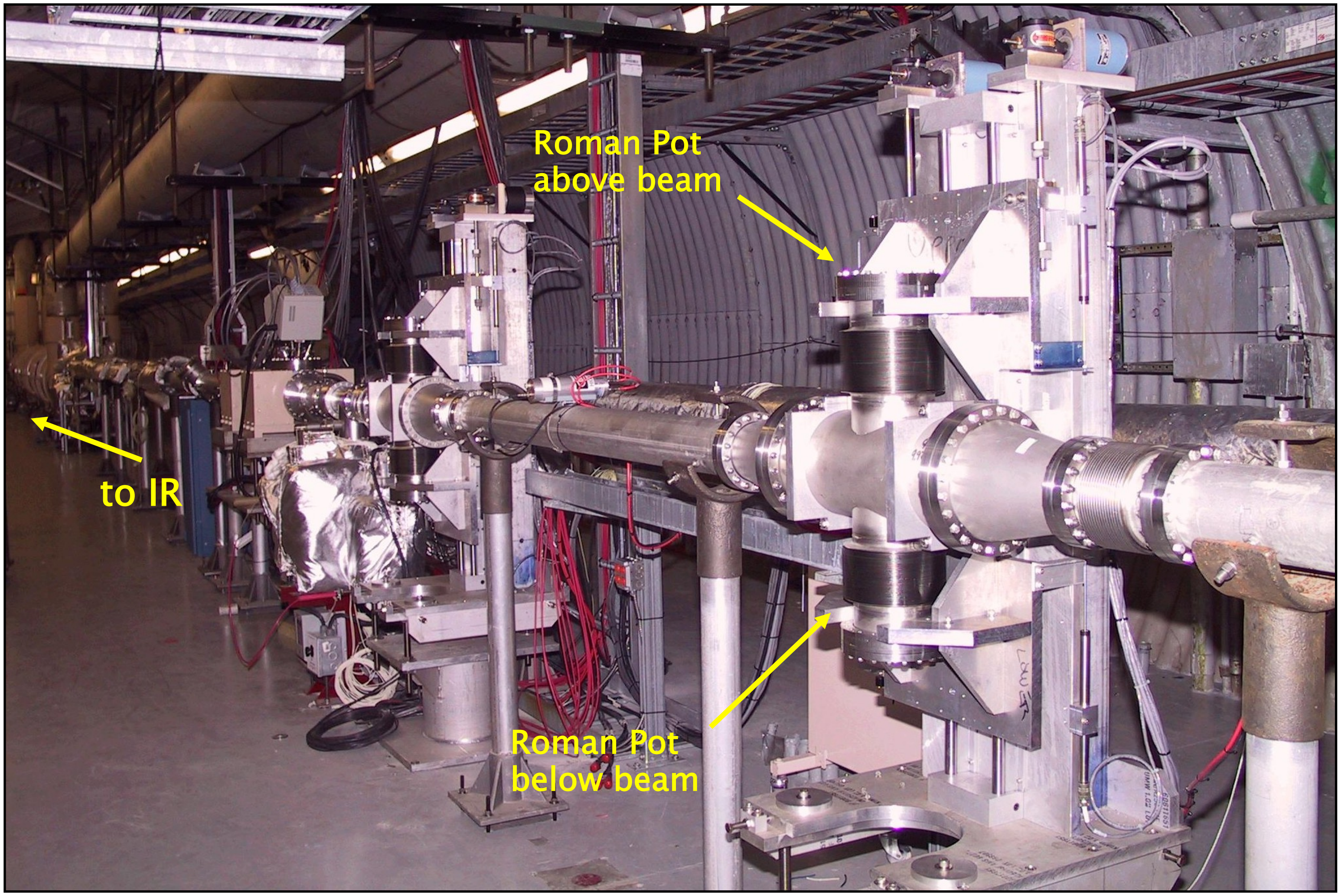


Polarized Elastic *pp*-Scattering

- Elastically scattered protons have very small scattering angle Θ^*, hence beam transport magnets determine trajectory of scattered protons
- The optimal position for the detectors is where scattered protons are well separated from beam protons
- Need Roman Pot to measure scattered protons close to the beam without breaking accelerator vacuum



RHIC Experimental Setup



Principle of Measurement

Elastically forward scattered protons have very small scattering angle θ^*

Beam transport magnets determine trajectory of beam and scattered protons

Scattered protons need to be well separated from the beam protons

Need Roman Pot to measure scattered protons close to beam

Beam transport equations relate measured position at detector to scattering angle

$x = a_{11} x_0 + L_{eff} \theta_x^*$ → Optimize so that a_{11} small and L_{eff} large

$\theta_x = a_{12} x_0 + a_{22} \theta_x^*$ → x_0 can be calculated by measuring θ_x (2^{nd} RP)

Similar equations for y-coordinate

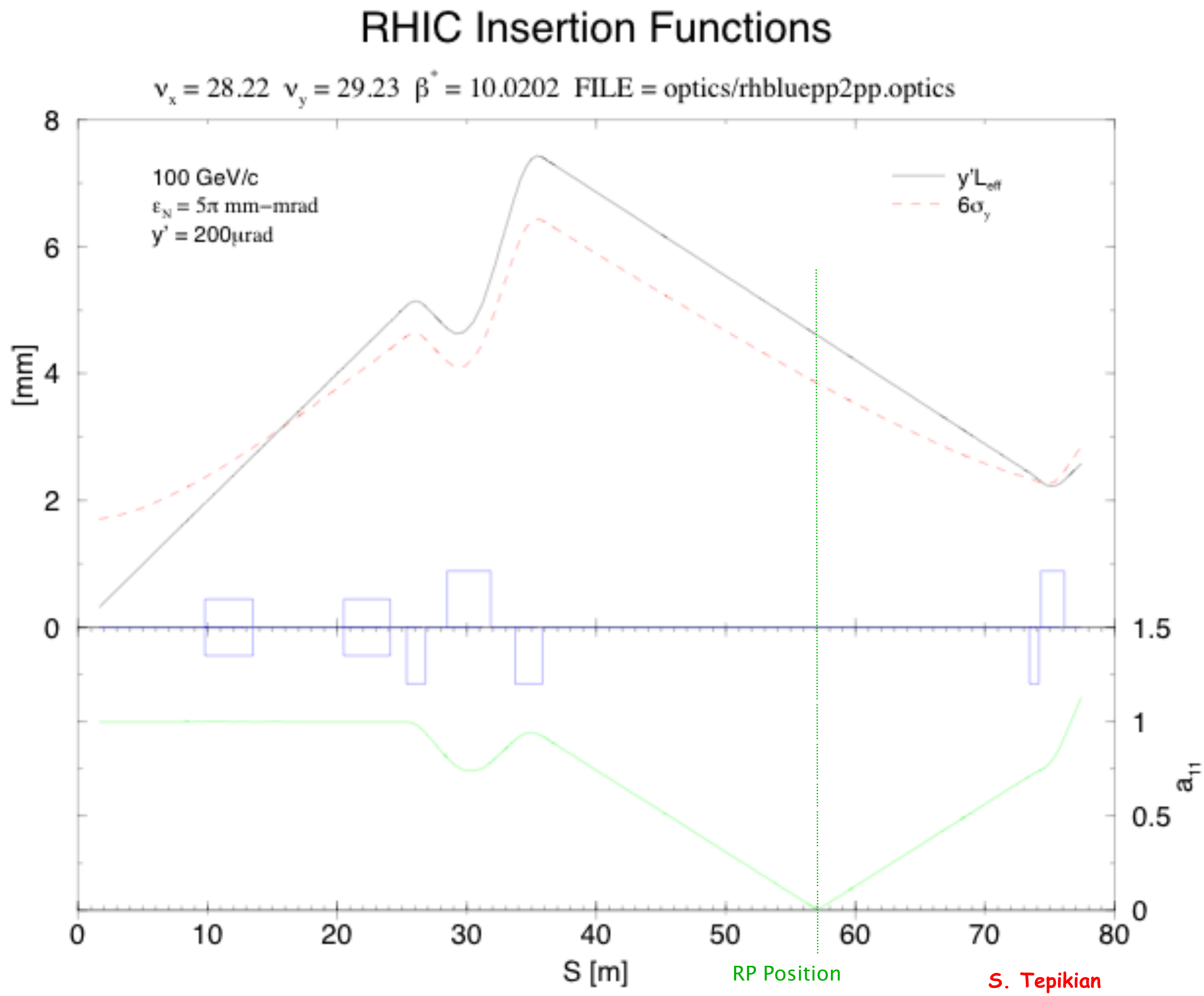
Neglect terms mixing x- and y-coordinate in above equations

x : Position at Detector

θ_x : Angle at Detector

x_0 : Position at Interaction Point

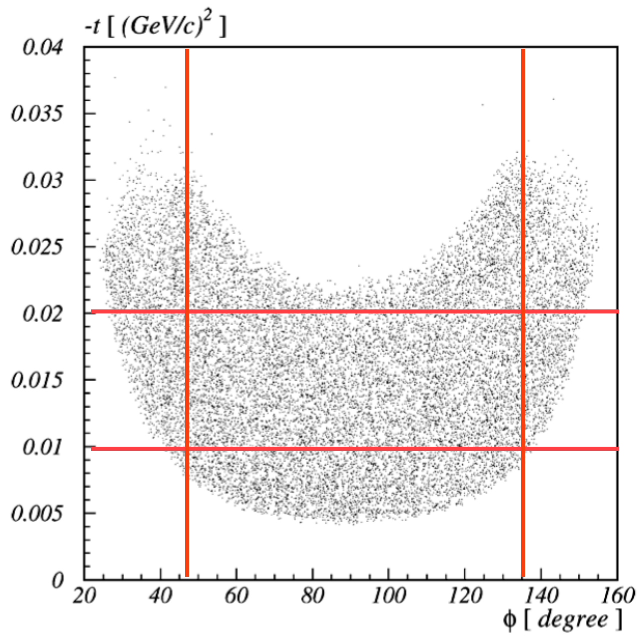
θ_x^* : Scattering Angle at IP

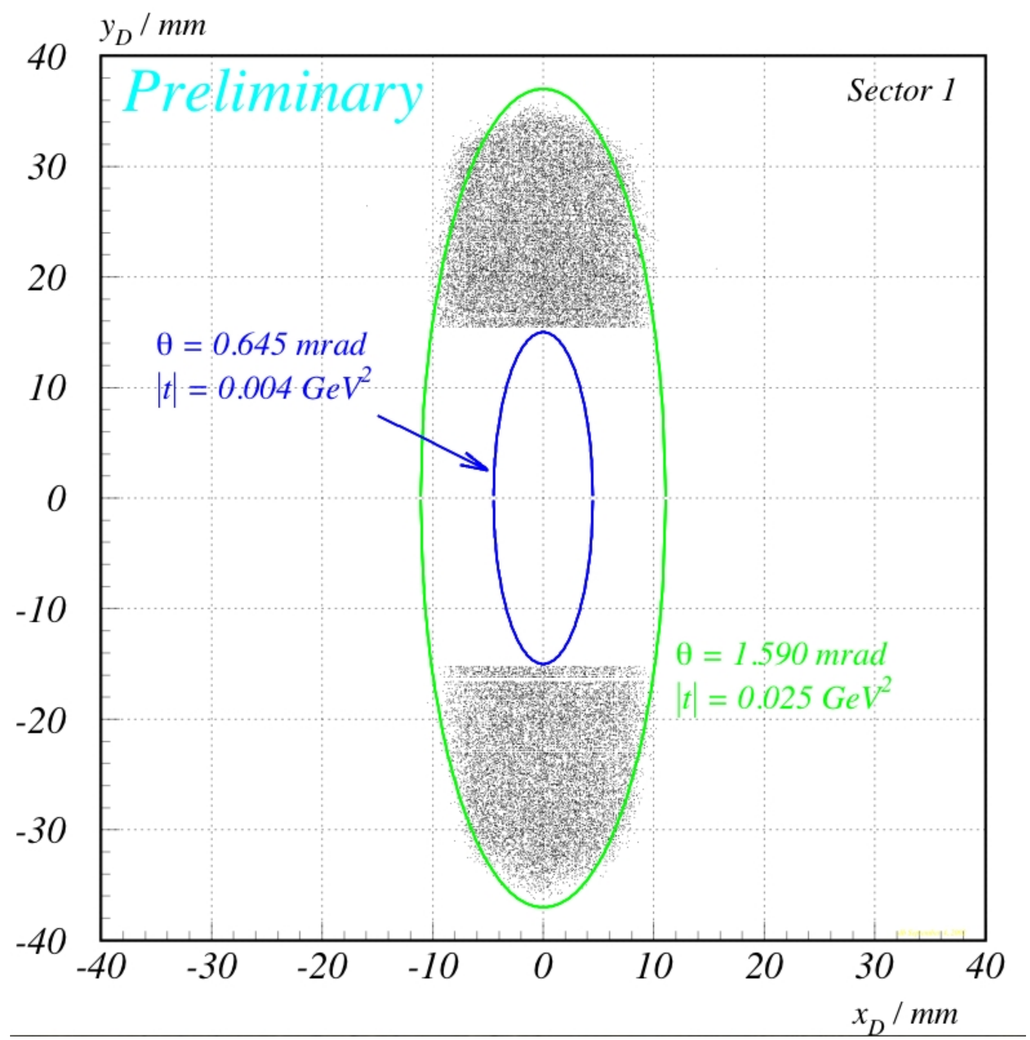


RHIC Insertion Functions
ν_x = 28.22 ν_y = 29.23 β^* = 10.0202 FILE = optics/rhbluepp2pp.optics
100 GeV/c
ε_N = 5π mm−mrad
y' = 200μrad
y'L_{eff}
6σ_y
[mm]
a_{11}
S [m]
RP Position
S. Tepikian

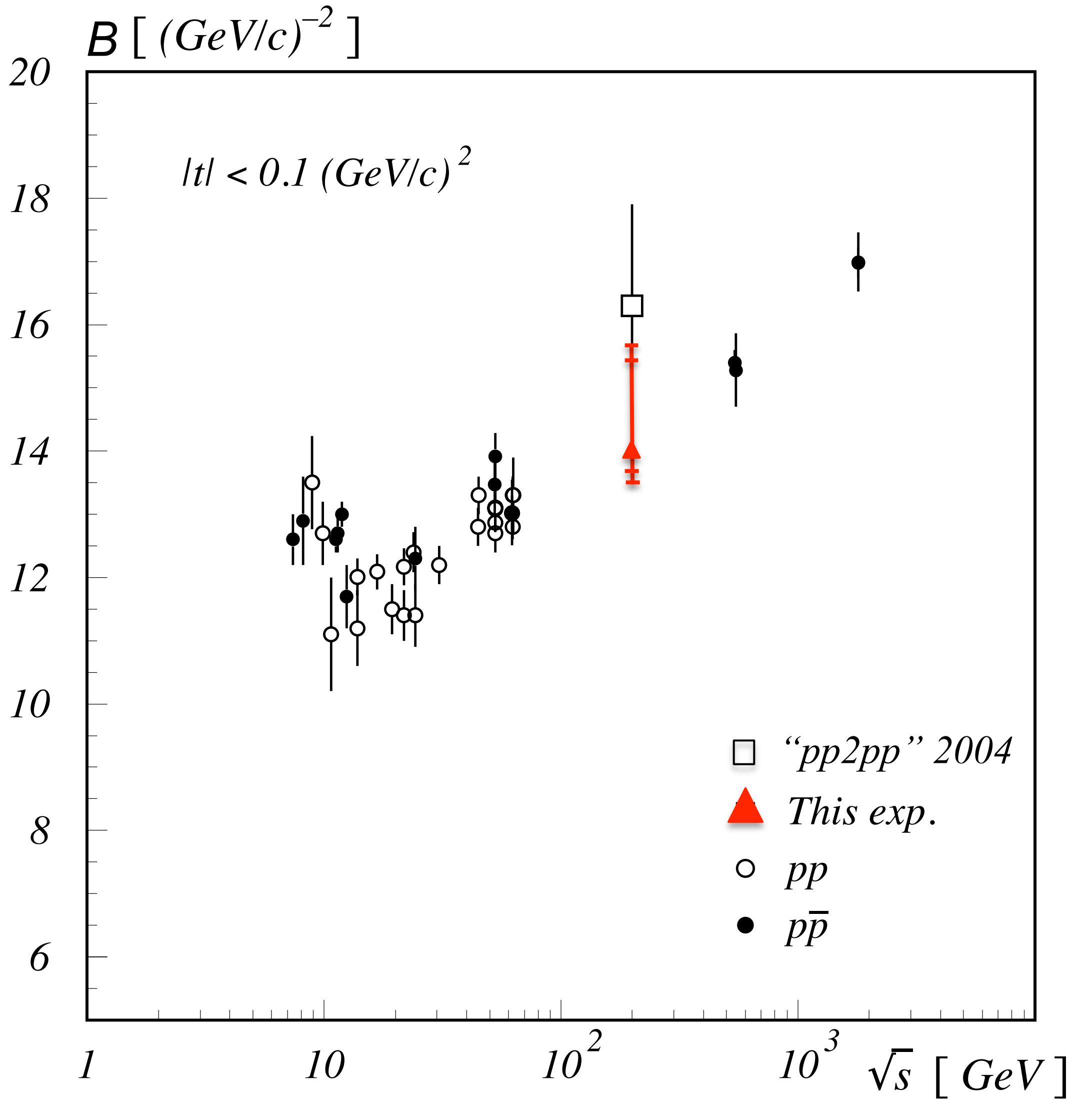
Elastic Hit Pattern

Hit distribution of scattered protons within 3σ - correlation cut reconstructed using the nominal beam transport





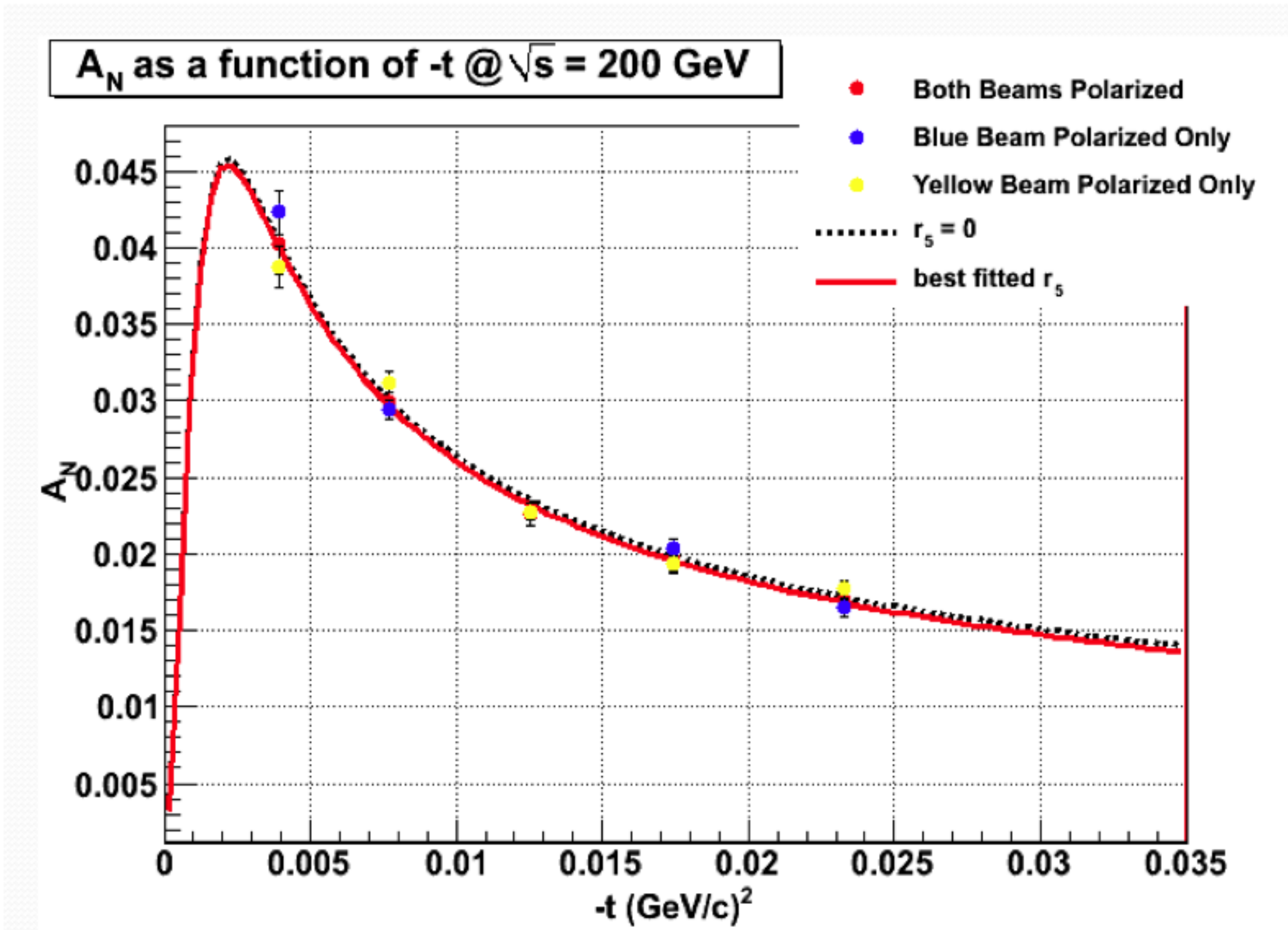
Comparison of Slope Values



$B = 14.0 \pm 0.3$ (stat.)

$\pm$ 1.1 (sys.) GeV^{-2}

Analyzing Power

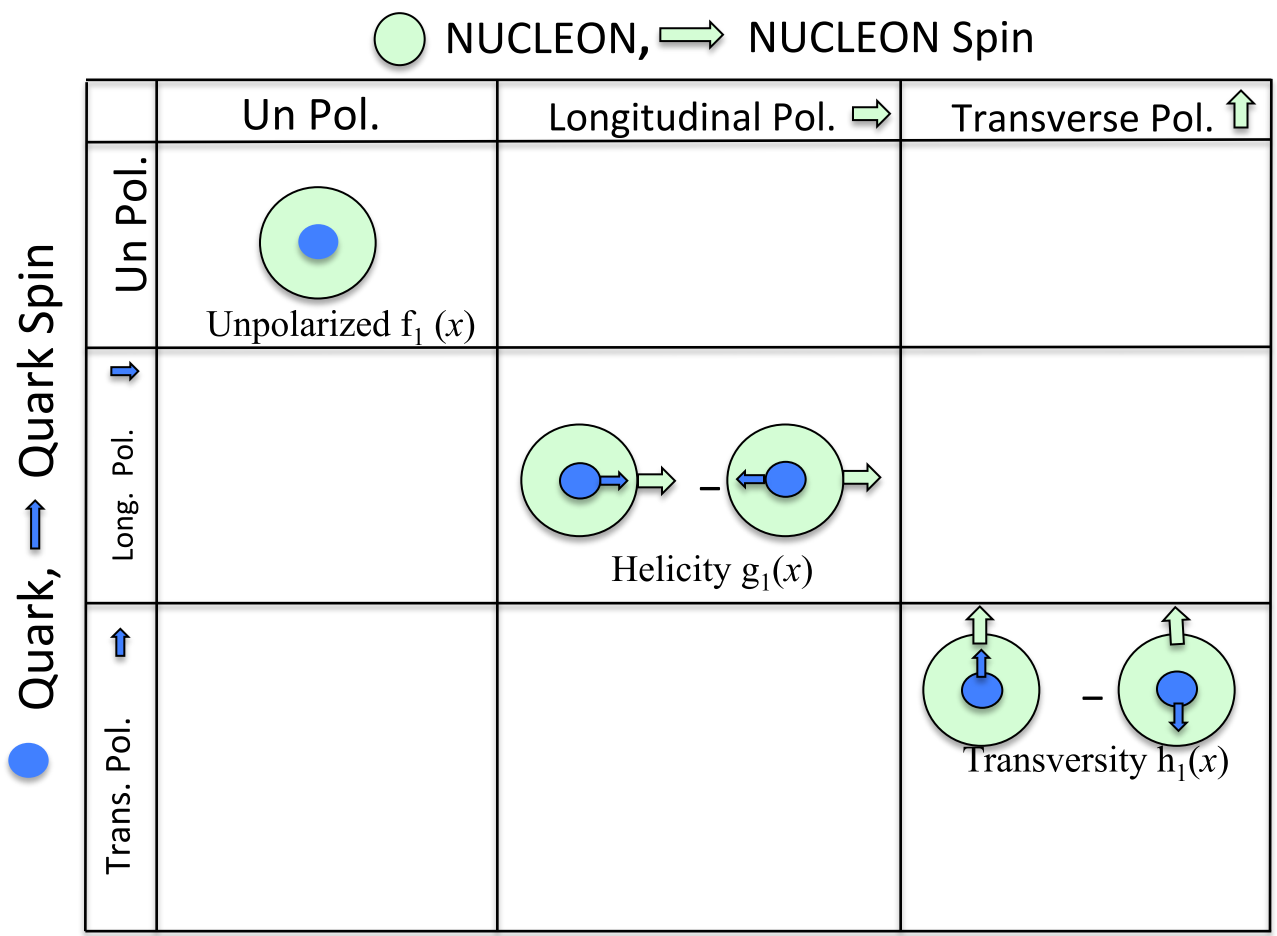


Hadron-Hadron Collisions and the Drell-Yan Process

- Annihilation of a quark and anti-quark in hadron-hadron collisions
- Timelike virtual photon creating lepton pair
- Related to deep-inelastic scattering of a lepton off a hadron with spacelike virtual photon exchange

Nucleon Spin Structure

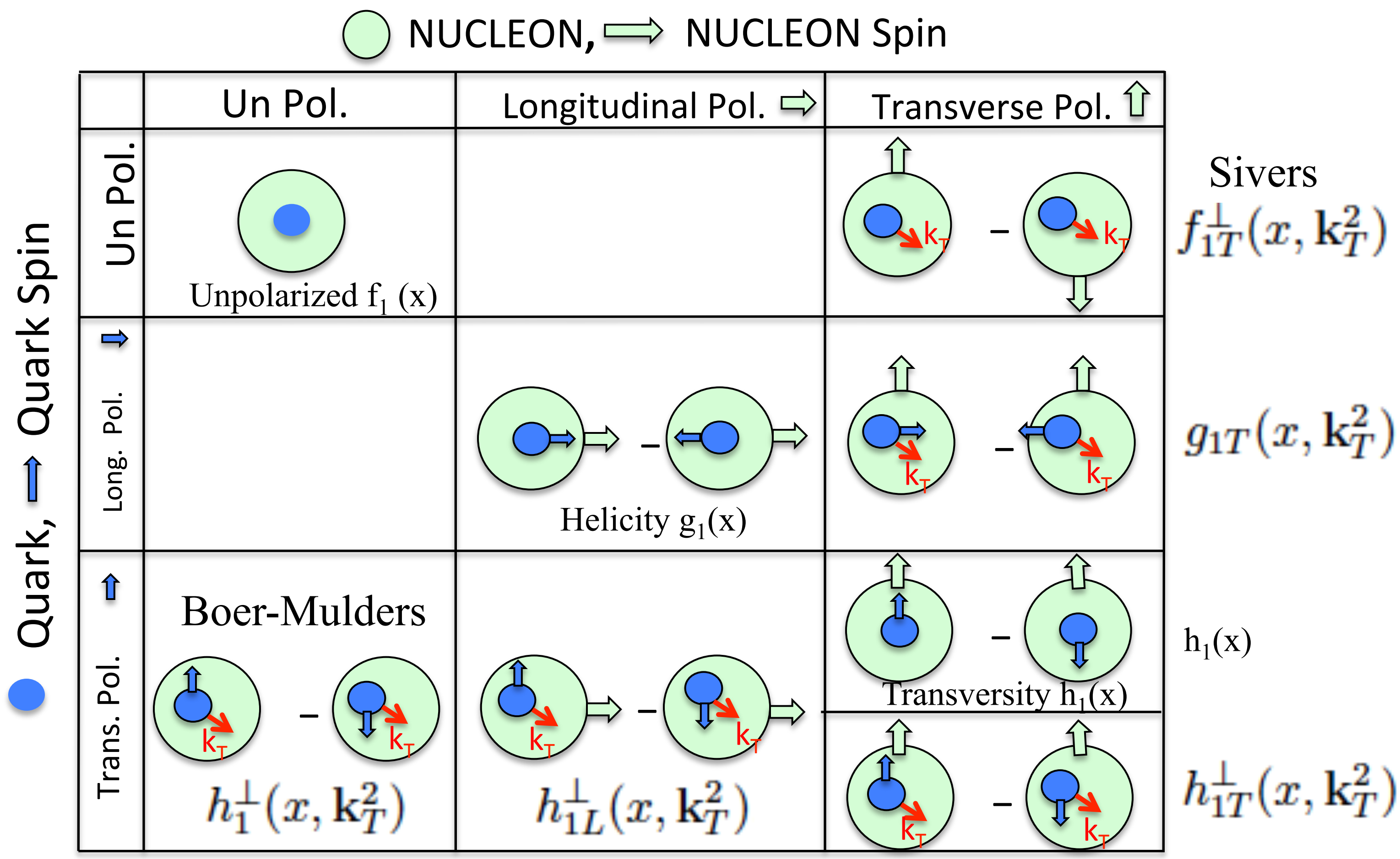
- Structure of the nucleon can be described in leading twist by three Parton Distribution Functions (PDFs)
- Depending on momentum fraction (x) carried by the struck quark



Nucleon Spin Structure

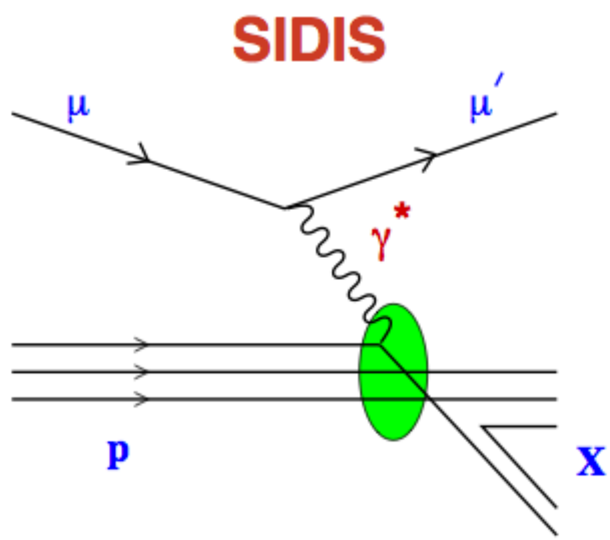
- For a complete description five additional Transverse Momentum Dependent Parton Distribution Functions (TMDs) are needed
- These account for the intrinsic transverse momentum (k_T) of the quarks
- Correlations between spin and transverse momentum of quarks and nucleons might not be negligible

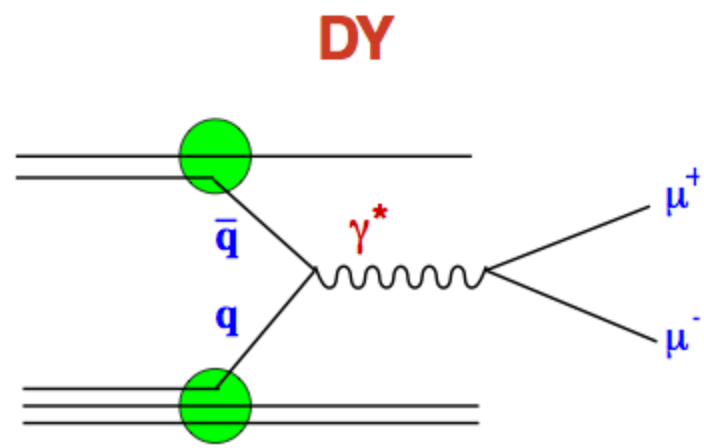
Nucleon Spin Structure



TMDs

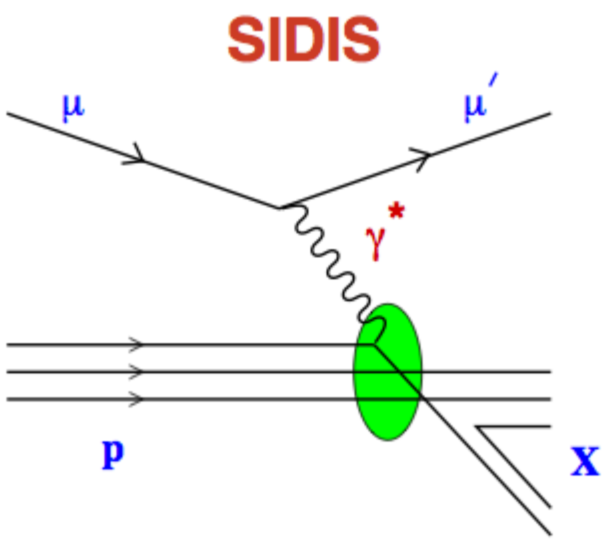
- TMDs can be accessed through the measurement of Transverse Single Spin Asymmetries (TSSAs) in Semi-Inclusive Deep Inelastic Scattering (SIDIS) or the Drell-Yan (DY) process with a transversely polarized nucleon target

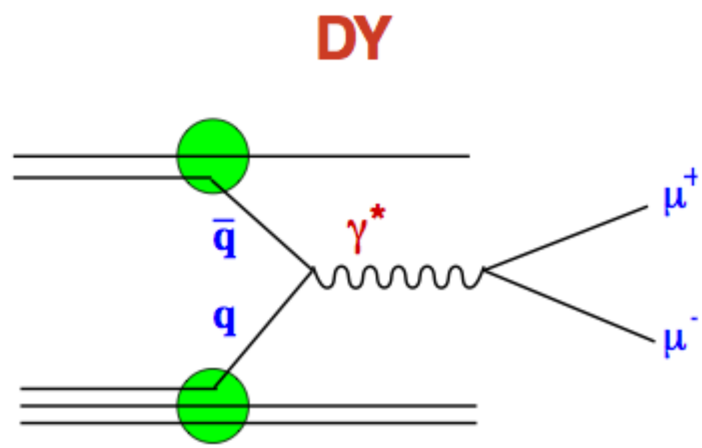




TMDs

- SIDIS: TSSA prop. to TMD (quark) ⊗ FF (quark → hadron)
- DY: TSSA proportional to TMD (quark) ⊗ TMD (anti-quark)

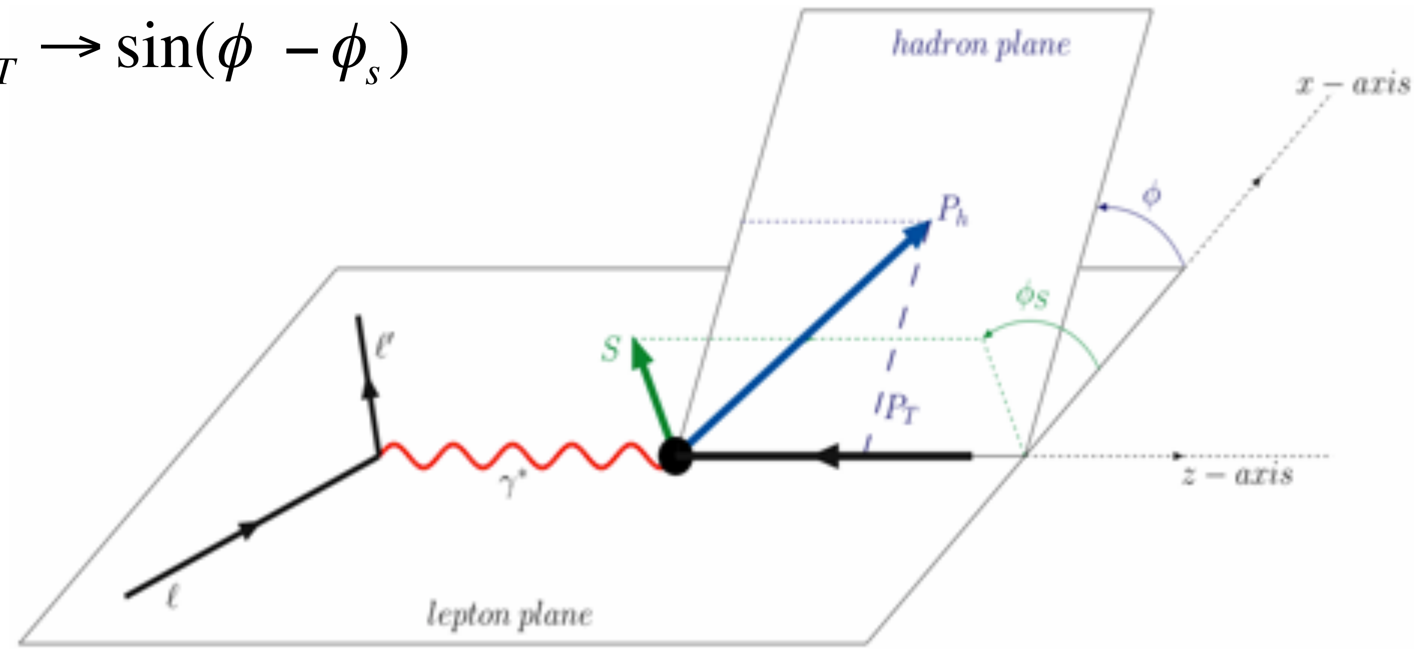




Sivers Function in SIDIS

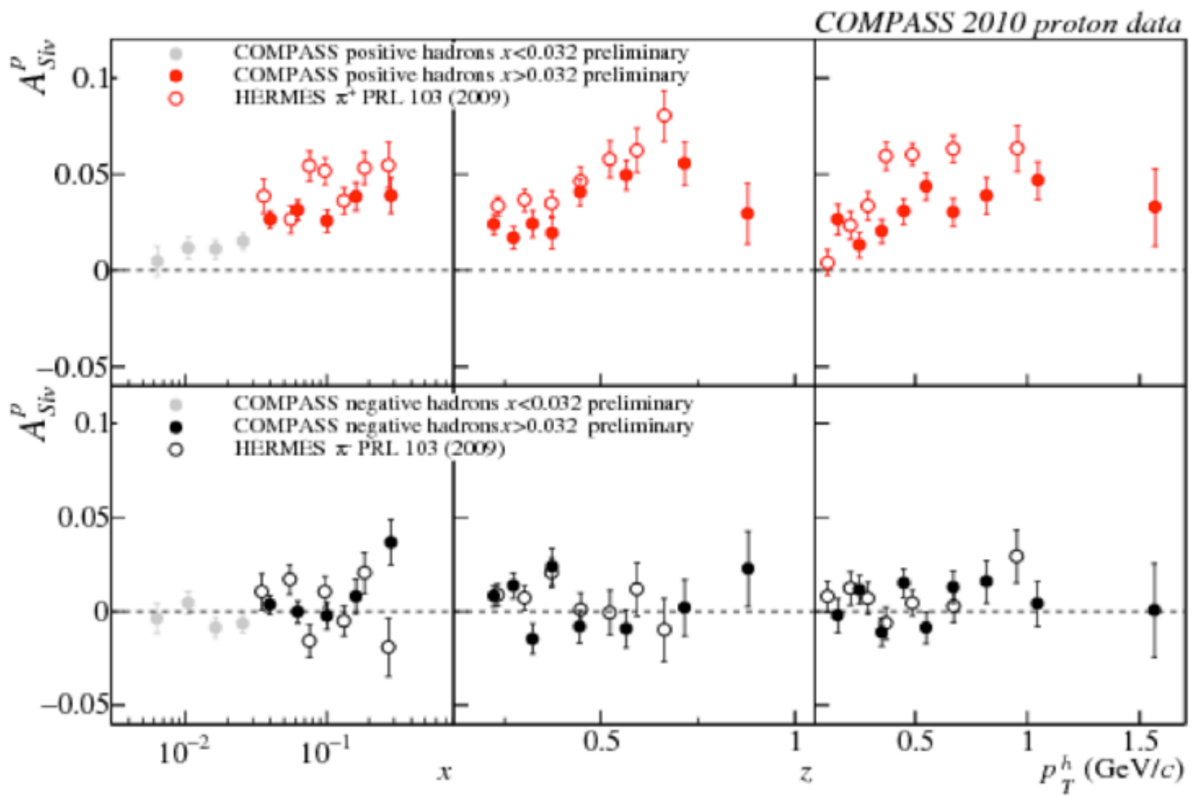
- TMDs measured in azimuthal Sivers asymmetry of produced hadron and nucleon spin

$$A_{UT} \rightarrow \sin(\phi - \phi_s)$$



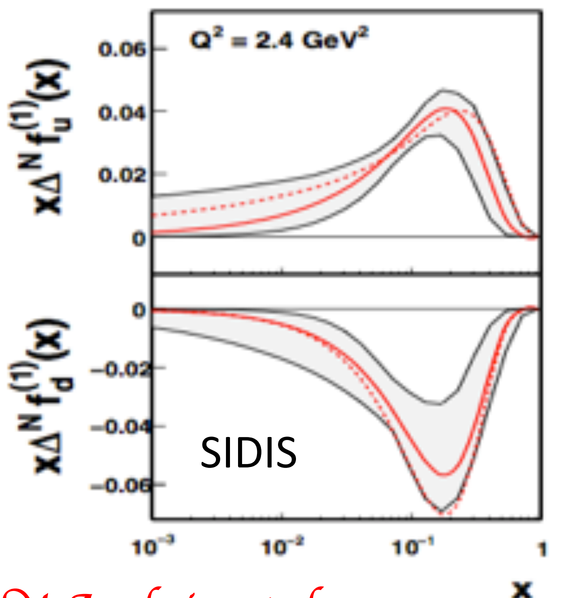
Sivers Function in SIDIS

- Positive Sivers asymmetry measured by Hermes and COMAPSS for positive hadrons

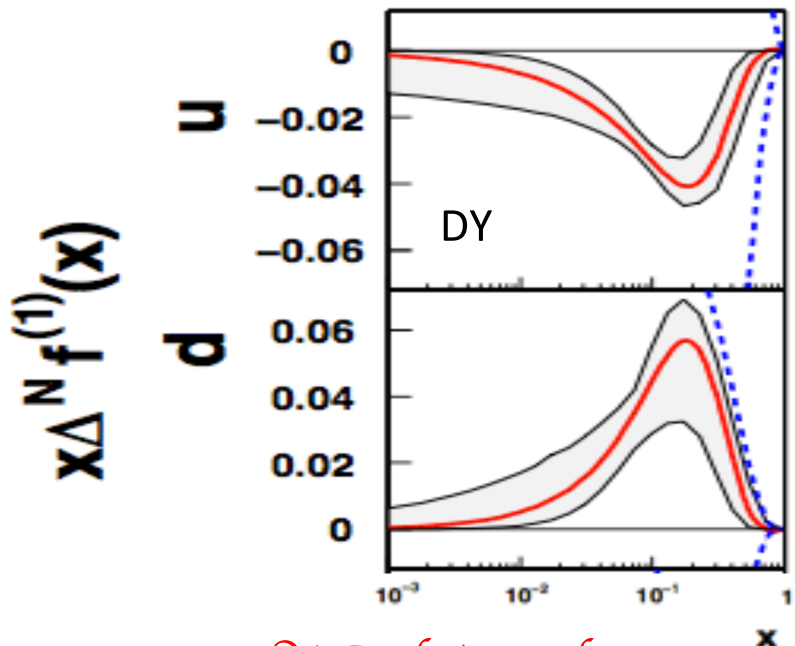


Sivers Function

- The resulting Sivers function is positive for u quarks and negative for d quarks in SIDIS, but predicted to be sign-reversed in Drell-Yan



M. Anselmino, et al., Eur. Phys. J. A 39, 89 - 100 (2009)



M. Anselmino, et al., Phys. Rev. D79, 054010 (2009)

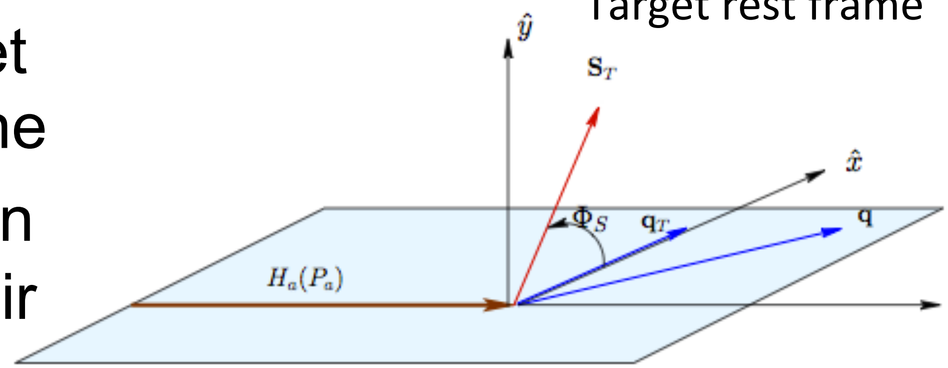
Angular Dependence of Polarized Drell-Yan Cross-Section

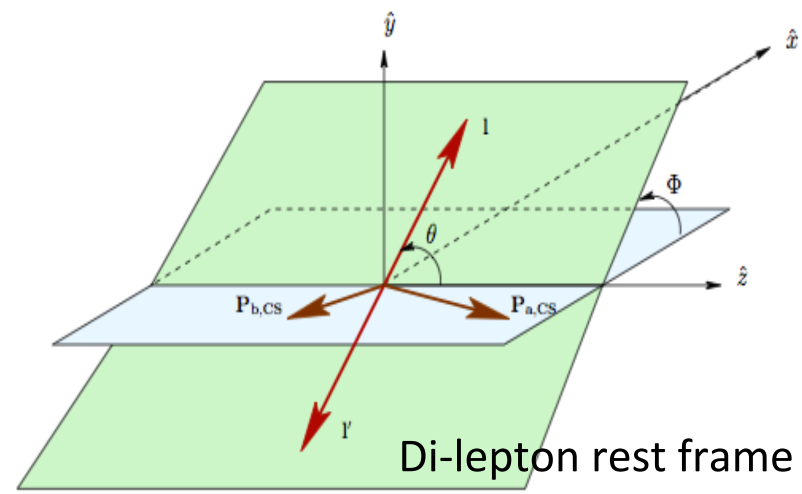
- Φ_S angle between target spin and lepton pair plane
- Φ angle between hadron pair plane and lepton pair plane
- θ polar angle of lepton pair
- If k_T of quarks non-zero

$$q_{\mathrm{T}} = k_{\mathrm{Ta}} + k_{\mathrm{Tb}}$$

of di-lepton

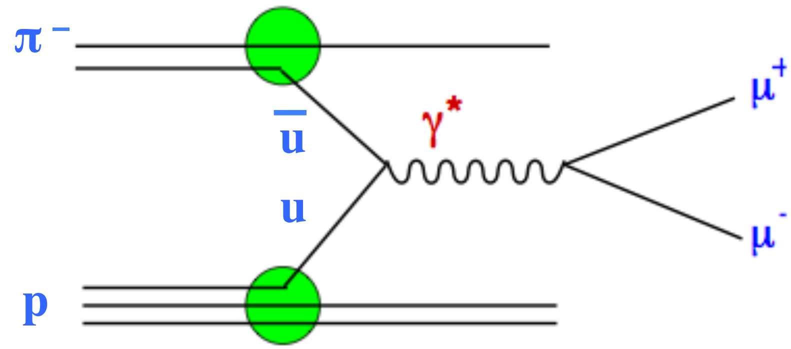
Target rest frame





Pion Induced Polarized Drell-Yan Cross-Section

- Negative pions scattering off polarized protons
- Dominated by u u-bar annihilation



$$
\begin{aligned}
d\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) = 1 &+ \bar{h}_1^\perp \otimes h_1^\perp \cos(2\phi) && (BM)_\pi \otimes (BM)_p \\
&+ |S_T| \Big[\bar{f}_1 \otimes \bar{f}_{1T}^\perp \sin\phi_S && (f_1)_\pi \otimes (Sivers)_p \\
&+ \bar{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi + \phi_S) && (BM)_\pi \otimes (Pretzelosity)_p \\
&+ \bar{h}_1^\perp \otimes h_1 \sin(2\phi - \phi_S) \Big] && (BM)_\pi \otimes (Transversity)_p
\end{aligned}
$$

Drell-Yan Cross-Section

- For a transversely polarized nucleon target

$$
\begin{aligned}
\frac{d\sigma}{d^4q\, d\Omega} \overset{\text{LO}}{=} & \frac{\alpha_{em}^2}{F\, q^2} \hat{\sigma}_U \Big\{ \Big(1 + D_{[\sin^2\theta]}\, A_U^{\cos 2\phi} \cos 2\phi \Big) \\
+ & |\mathbf{S}_T| \Big[A_T^{\sin\phi_S} \sin\phi_S + D_{[\sin^2\theta]} \Big(A_T^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) \\
+ & A_T^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) \Big) \Big] \Big\} ,
\end{aligned}
$$

S. Arnold et al., Phys. Rev. D79, 034005 (2009)

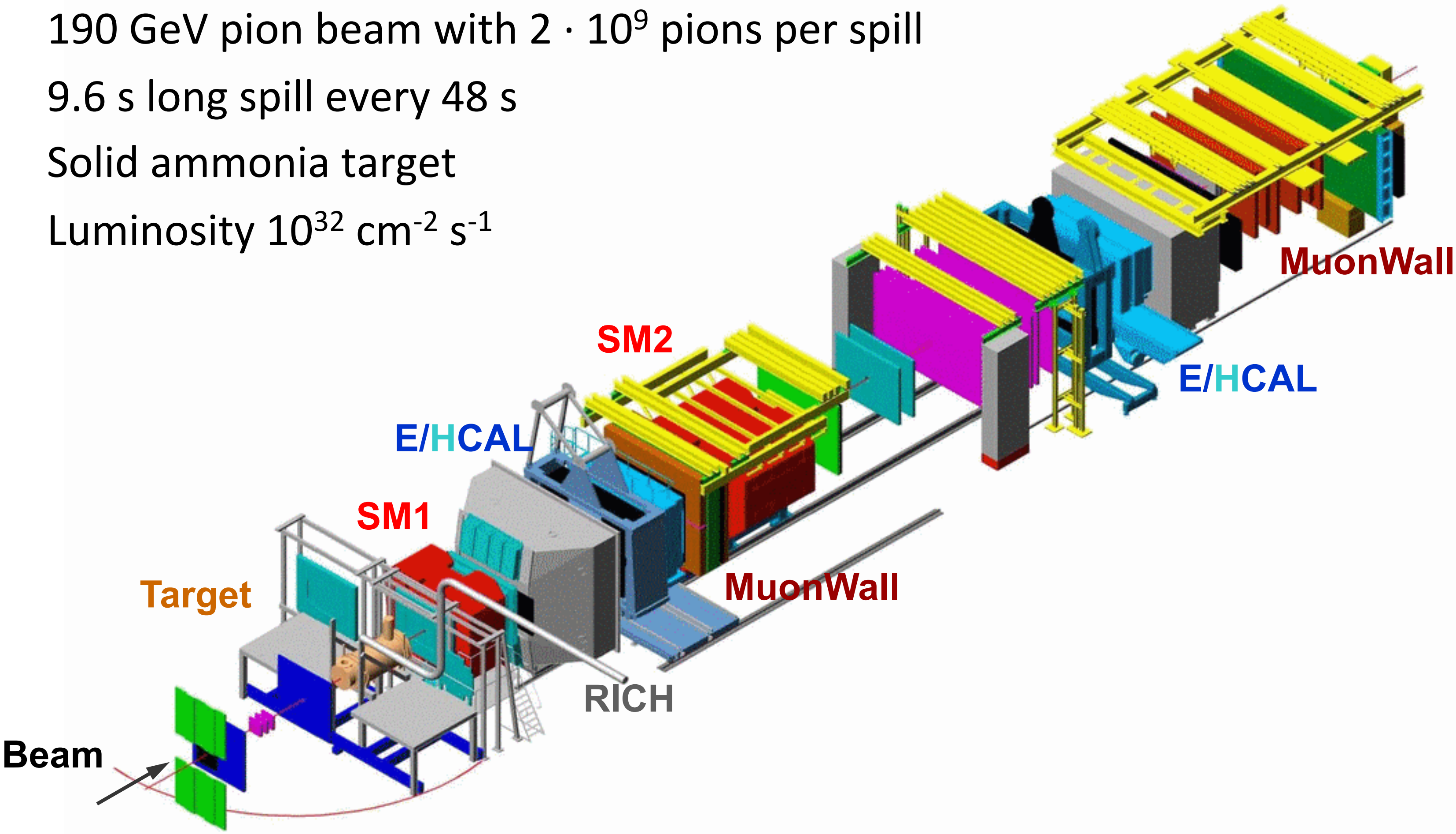
Sivers Asymmetry expected to be sizeable in valence quark region

F : flux of incoming hadrons
$D_{[]}$: depolarization factor
q : virtual photon momentum

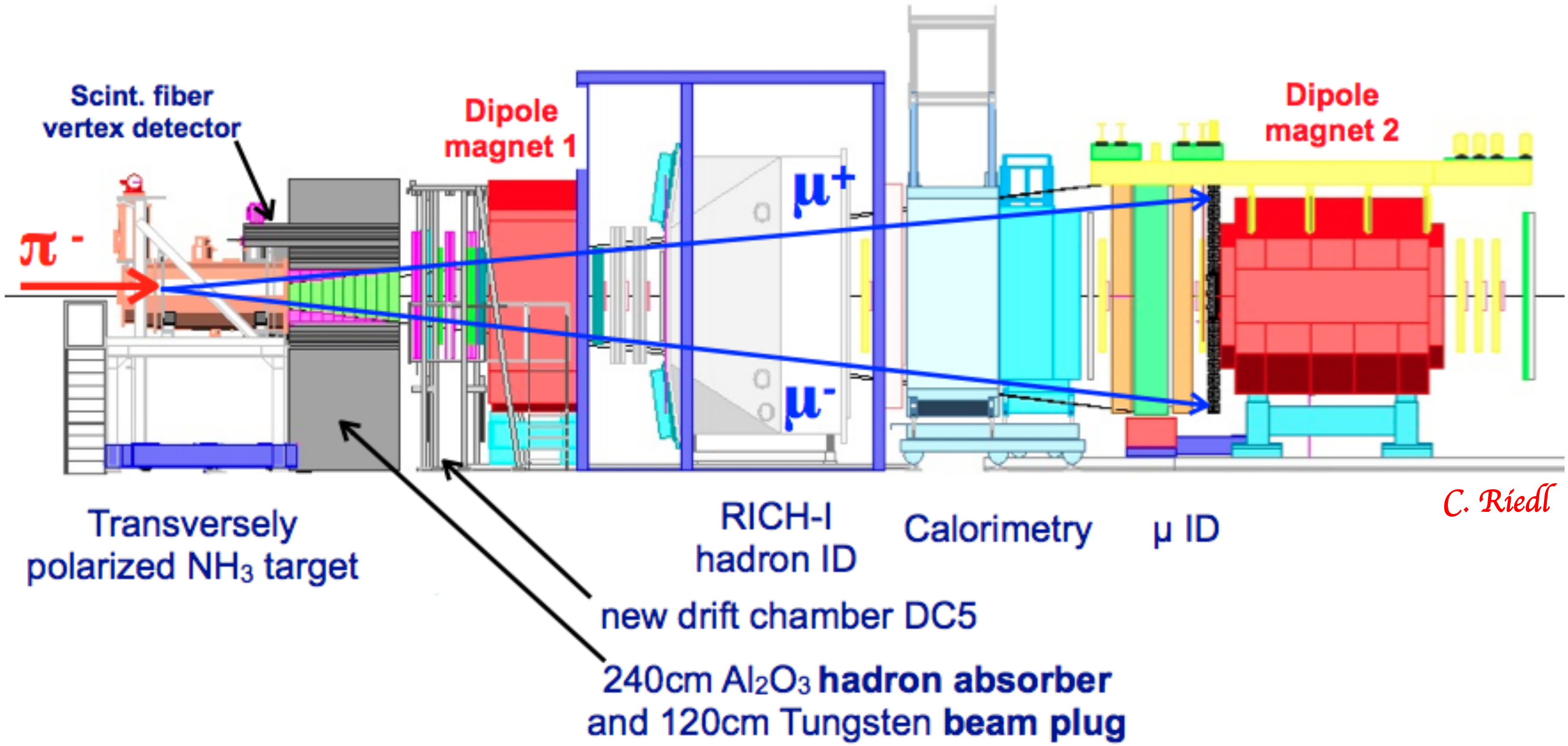
COMPASS

COMPASS

- 190 GeV pion beam with $2 \cdot 10^9$ pions per spill
- 9.6 s long spill every 48 s
- Solid ammonia target
- Luminosity 10^{32} cm^{-2} s^{-1}

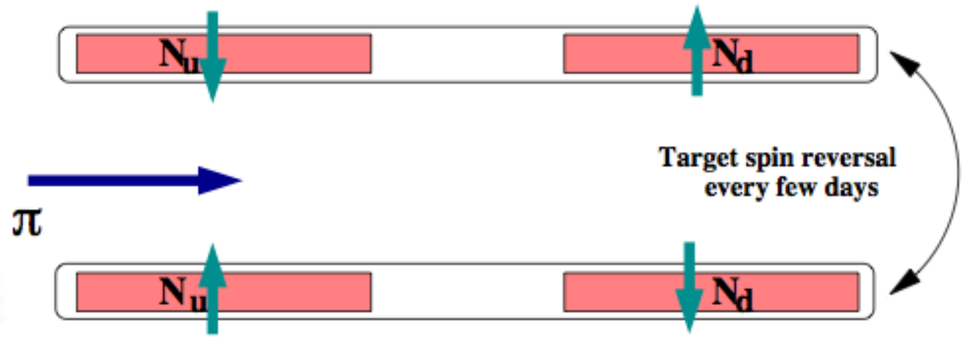


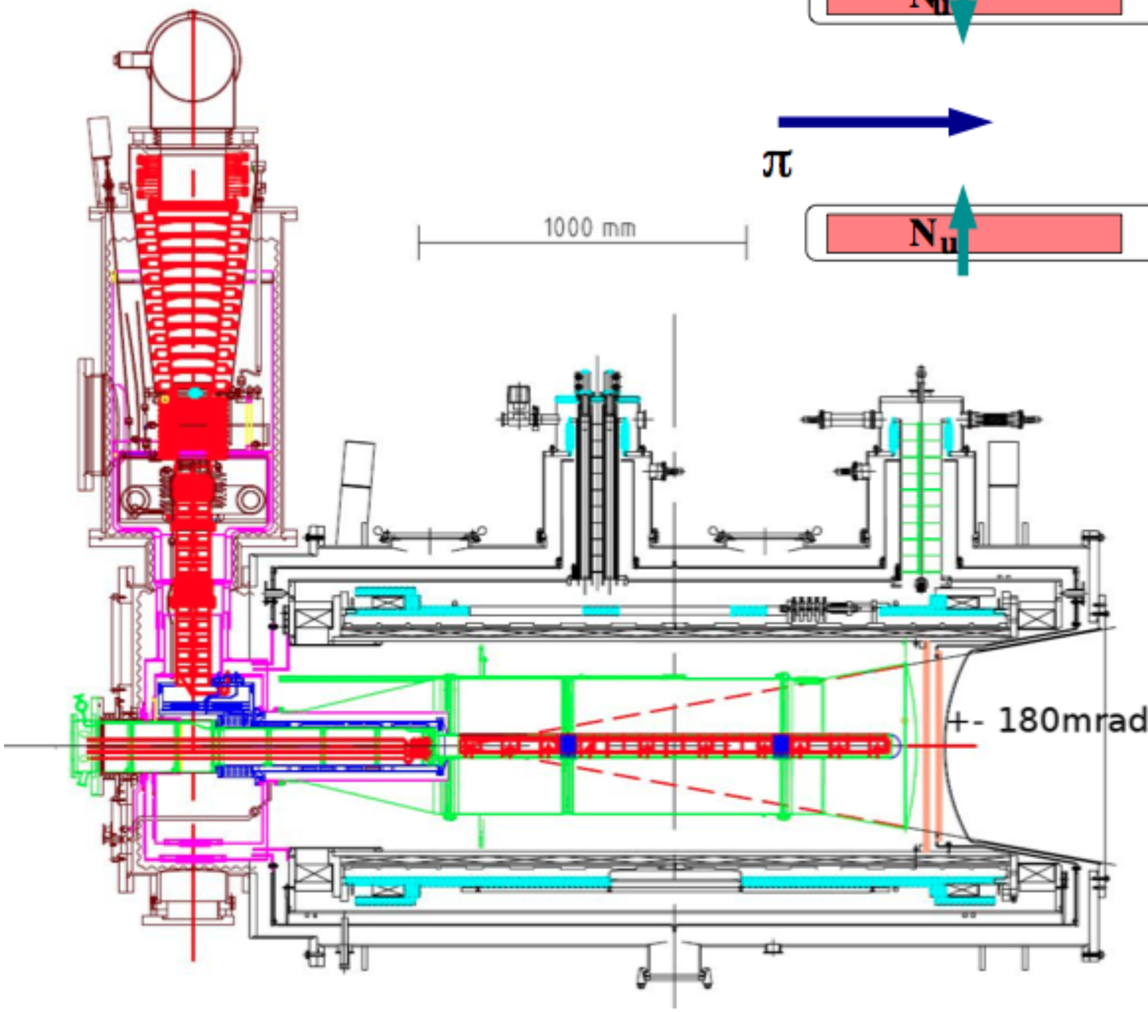
COMPASS



Scint. fiber
vertex detector
Dipole
magnet 1
Dipole
magnet 2
π -
μ+
μ-
C. Riedl
Transversely
polarized NH3 target
RICH-I
hadron ID
Calorimetry
μ ID
new drift chamber DC5
240cm Al2O3 hadron absorber
and 120cm Tungsten beam plug

COMPASS Polarized Target

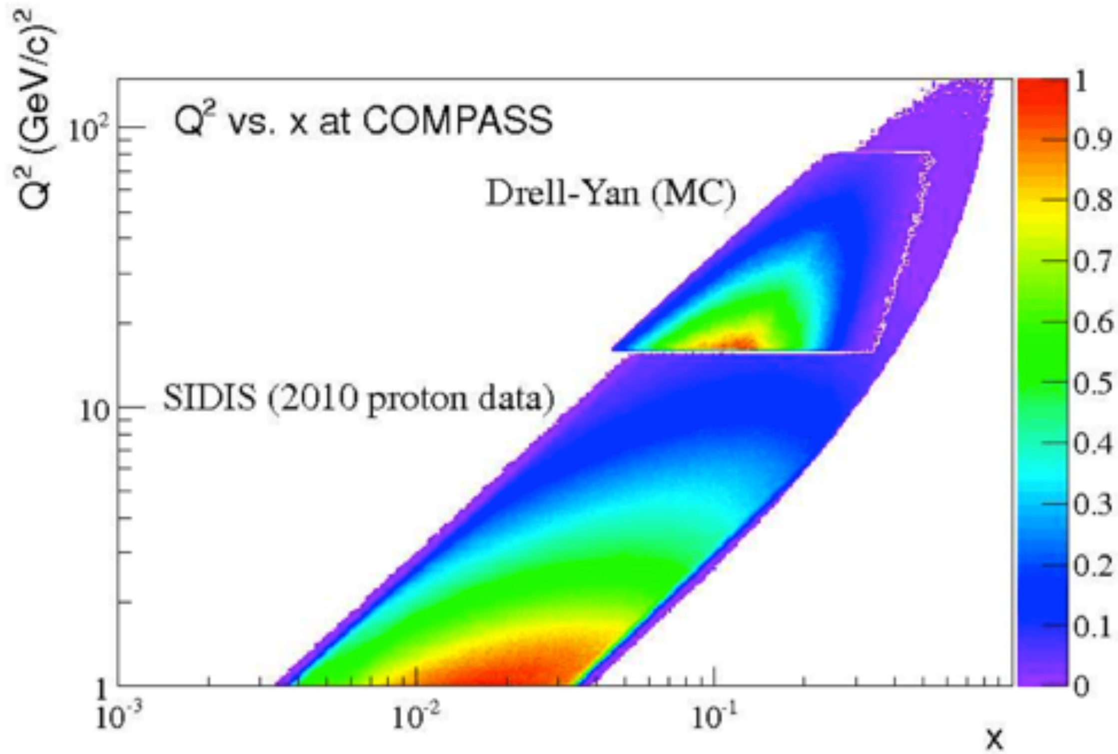




- 2.5 T longitudinal field for polarization build-up via DNP
- 0.6 T transverse field for data taking

Simulation of Kinematics

- Very good overlap between SIDIS and Drell-Yan



Estimates

- 140 days of running resulting in 285,000 DY events ($4 < M_{uu} < 9$ GeV/c^2)
- < 2% statistical precision on asymmetry