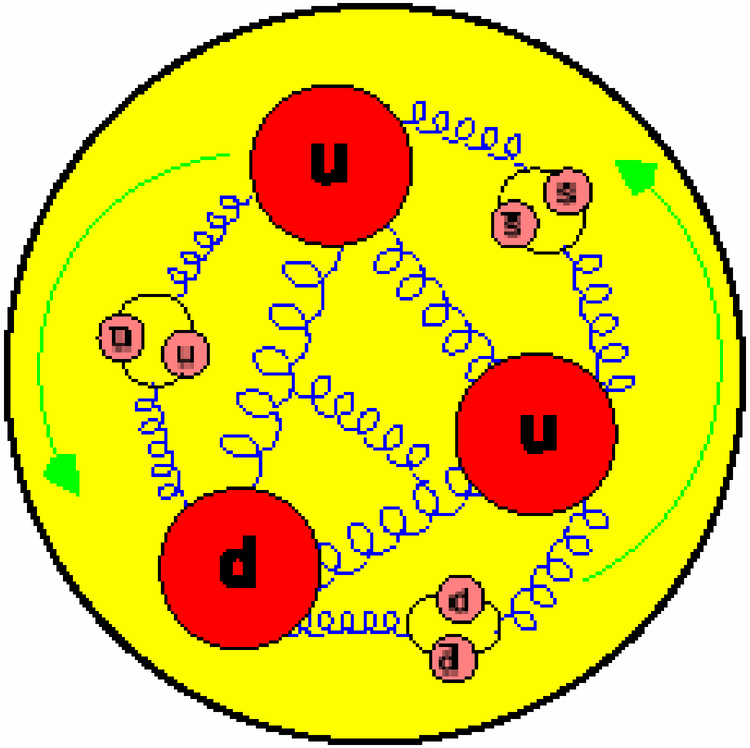
Quarks, Gluons and the Origin of the Proton Spin

403 Tuesday Seminar

Department of Physics, University of Illinois

April 3rd, 2012



M. Grosse Perdekamp, University of Illinois

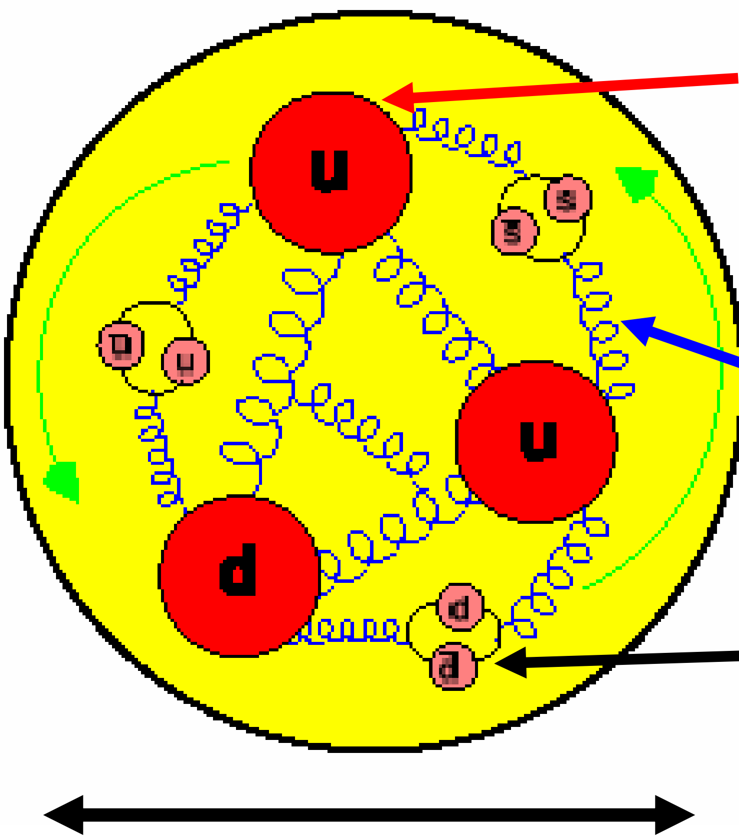
Overview

- **Motivation**
- **e-p Scattering and Proton Spin Structure**
  - Quark Spin vs e-p Cross Sections
  - The Spin Crisis
- **p-p Scattering**
  - Polarized Protons at High Energy: Instrumentation & Theory
  - The Gluon Spin from RHIC data
- **W-physics**
  - Accessing Anti-Quark Spin Structure through W-Bosons

Nucleon Spin Structure

➔ *Motivation*
& Results from e-p

The Proton: A complex system of quarks, anti-quarks and gluons!



valence quarks: 2 up-, 1 down-quark

gluons, the force carriers of the strong nuclear force.

“sea-quarks” : quark-anti-quark pairs that can be formed from a gluon for a short time and annihilate again.

1 Fm ~ 10^{-15}m

The Nucleon as QCD Laboratory ➔ Synthesis of Nuclear Matter from Quarks and Gluons

The proton is the fundamental bound state of QCD - quarks and gluons are the constituents:

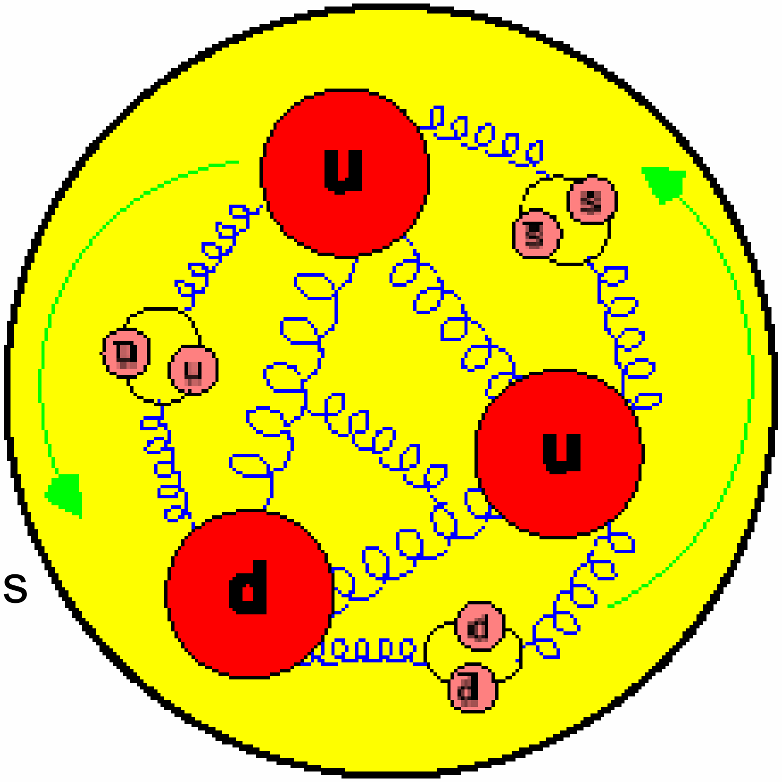
Can we understand the wave function of the nucleon from first principles QCD ?

Present (modest) status:

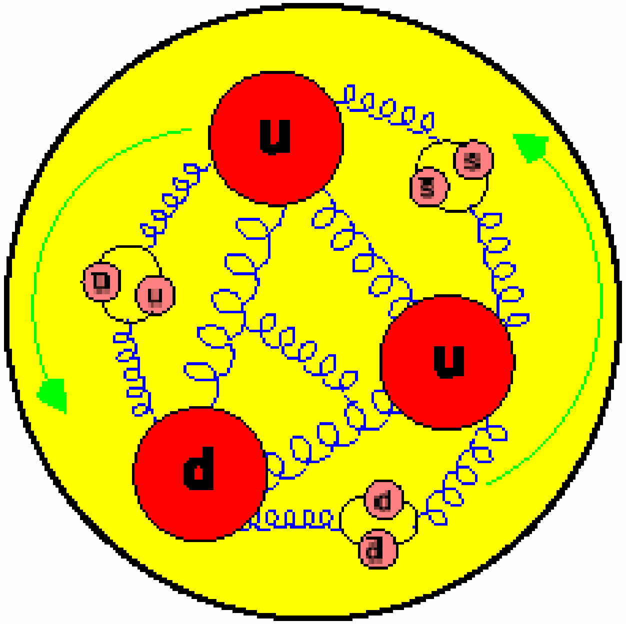
Description of proton in hard scattering processes with parton distribution functions (often model dependent!).

Two (of many) open questions:

Origin of the spin and mass of the proton ?



Proton Spin Structure: Quark and Gluon Spin



$$x = \frac{p_{quark}}{p_{proton}}$$

Constituents:

quarks = u, d, s and gluons

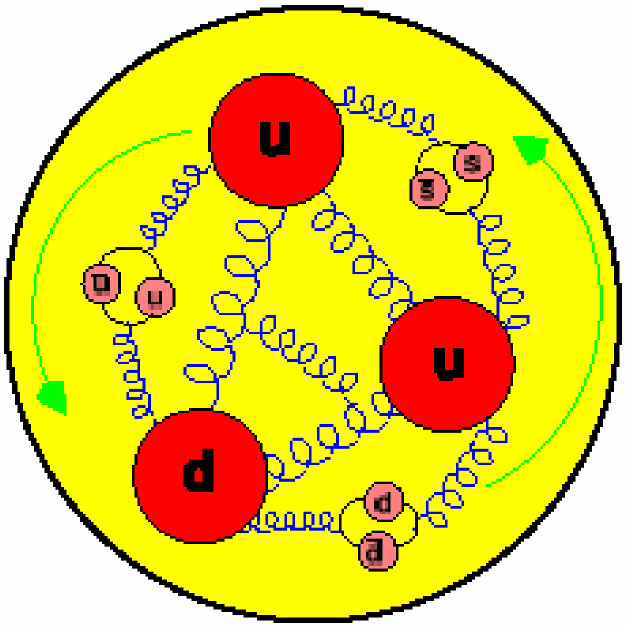
$\Rightarrow$ Total Quark Spin :

$$\Delta\Sigma = \sum_{q,\bar{q}} \int_{x=0}^{x=1} \Delta q(\mathrm{x})$$

$\Rightarrow$ Total Gluon Spin :

$$\Delta G = \int_{x=0}^{x=1} \Delta G(\mathrm{x})$$

Proton Spin: Quark Spin + Gluon Spin + Orbital Angular Momentum



$$x = \frac{p_{quark}}{p_{proton}}$$

De-composition of the Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

Quark Spin

Gluon Spin

Orbital Angular momentum

Proton Spin Structure from Inclusive Deep Inelastic Lepton-Nucleon Scattering

spin

el

m

ark

le

$, Q^2)$

Fraction of proton spin carried by quarks:

$\Delta\Sigma = 0.33 \pm 0.025(\text{exp}) \pm 0.030\ (\text{th})$

Extract spi
distribution
spin structu
(later SIDIS

(x)

$q,\bar{q}\quad 0$

Quark Spin Contributions now measured to about 10%.

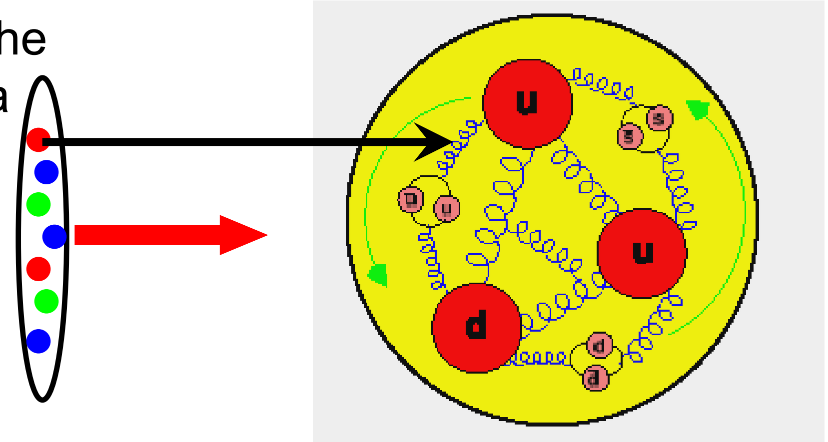
Next step: gluon spin contributions !

Polarized p-p at RHIC

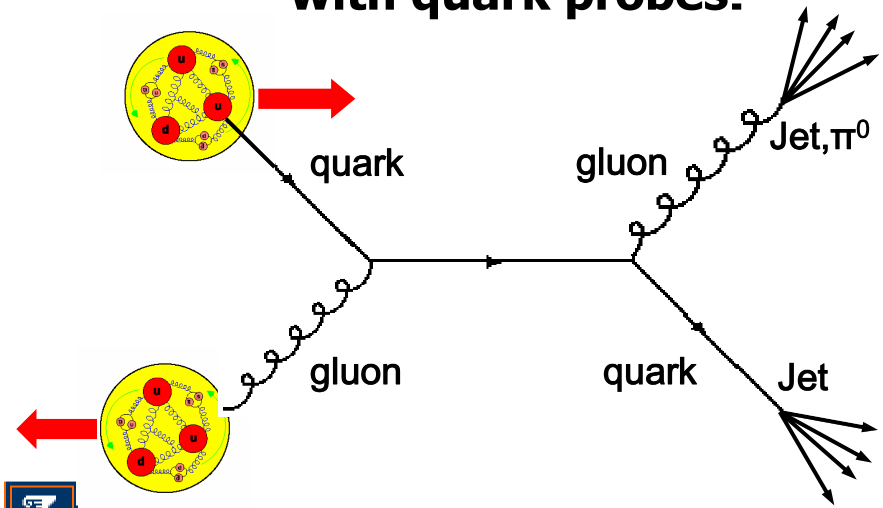
➔ Instrumentation,
Theory Frame Work

RHIC SPIN: Proton Structure with Quark and Gluon Probes

At ultra-relativistic energies the proton (roughly) represents a jet of quarks and gluons



Example: Production of neutral pions ~ probe gluon content with with quark probes!

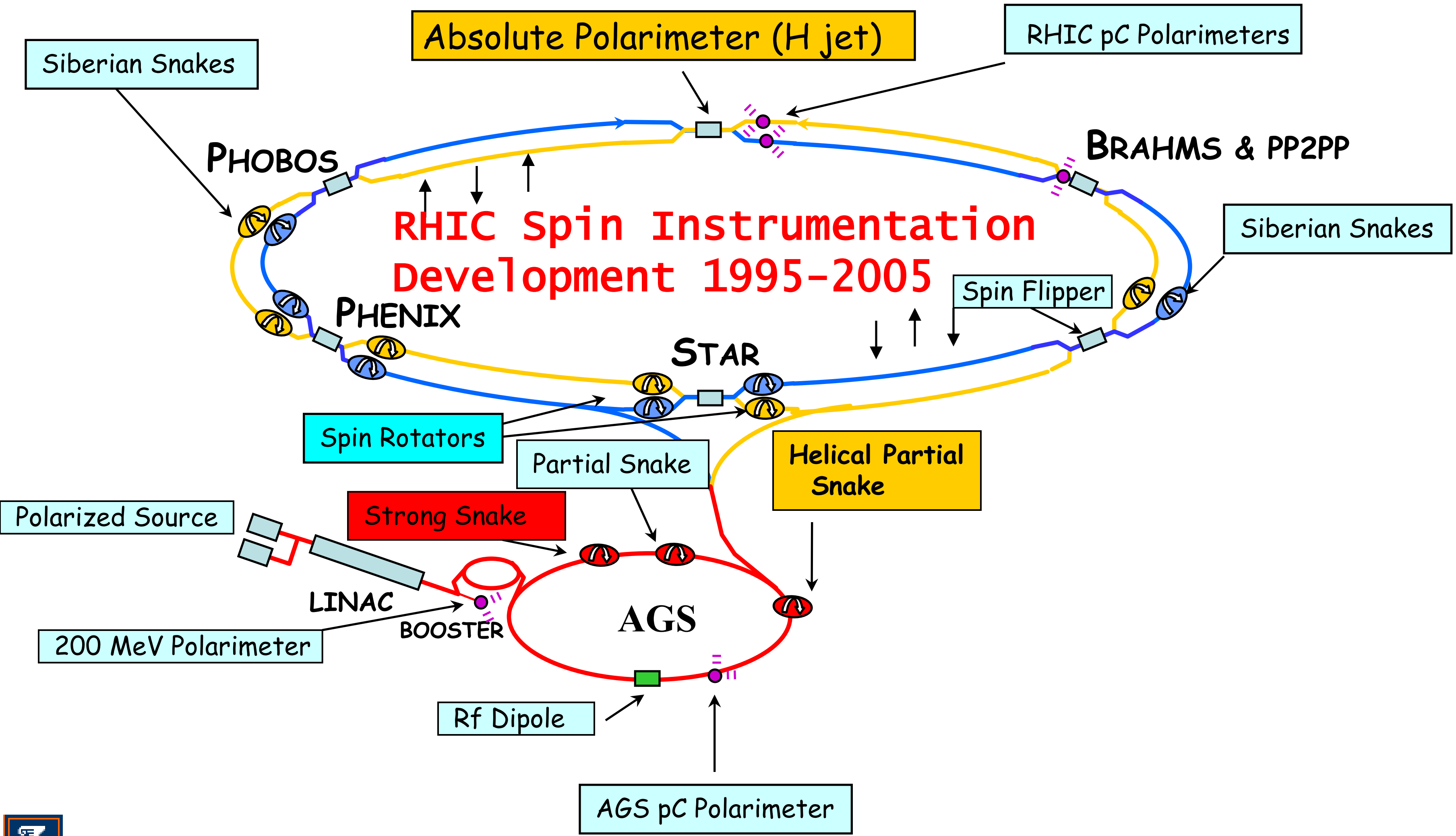


$$A_{LL}^{\pi^0} = \frac{N_{\pi^0}^{\uparrow\downarrow} - N_{\pi^0}^{\uparrow\uparrow}}{N_{\pi^0}^{\uparrow\downarrow} + N_{\pi^0}^{\uparrow\uparrow}}$$

measured double spin asymmetry

$$= \underbrace{a_{LL}(qg \to qg)}_{\text{QCD}} \cdot \underbrace{\frac{\Delta G(x_g)}{G(x_g)}}_{?} \cdot \underbrace{A_1(x_q)}_{\text{DIS}}$$

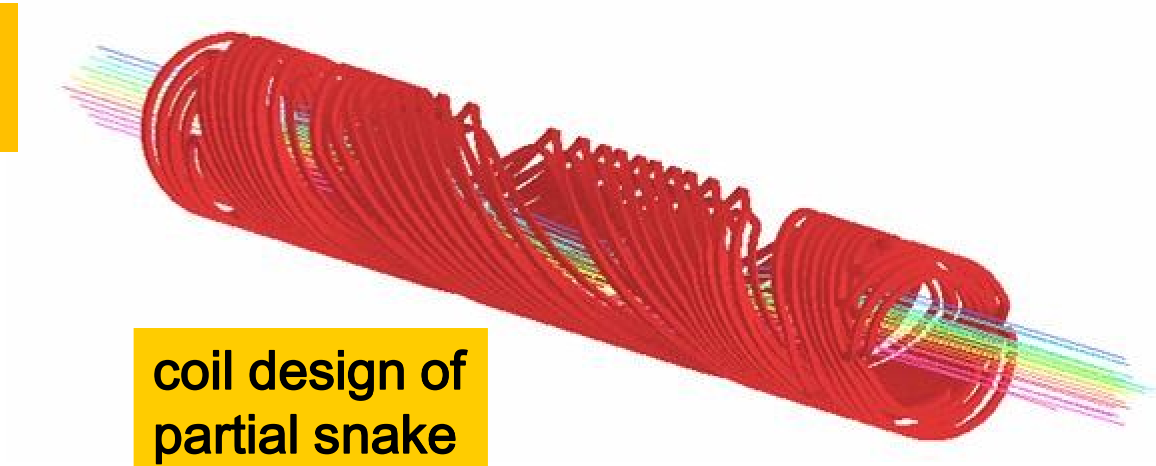
A novel experimental method: Probing Proton Spin Structure in High Energy Polarized Proton Collisions



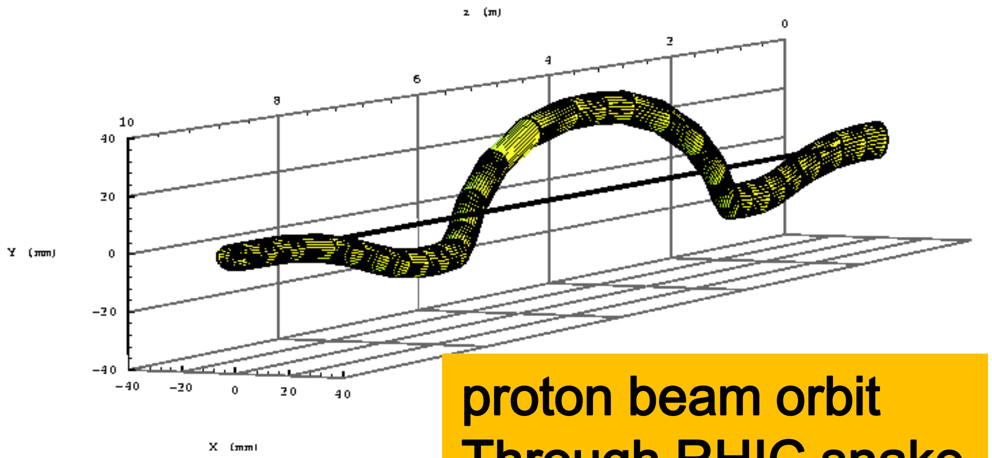
Siberian Snakes

Helical dipole magnets in the AGS and RHIC:
effects of depolarizing resonances are averaged out by rotating the proton spin by large angles on each turn

cut-out section of RHIC snake



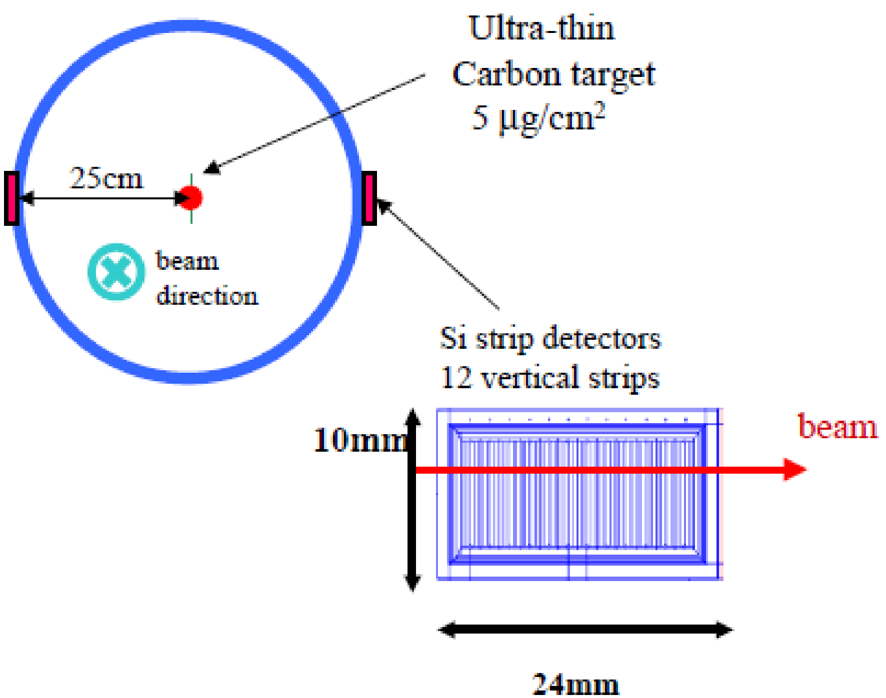
coil design of partial snake for the AGS

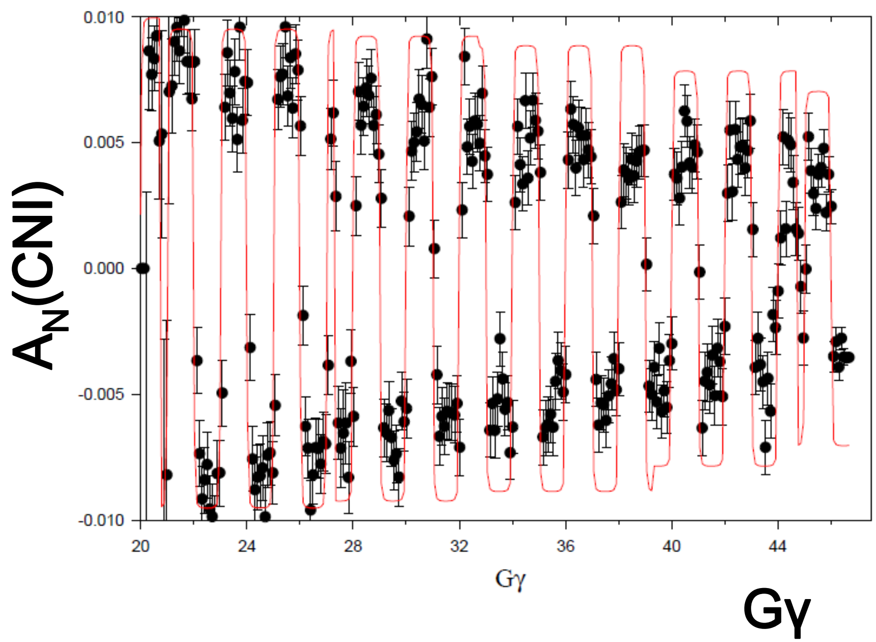


proton beam orbit Through RHIC snake

High Energy Beam Polarimeters: CNI Polarimeters in the AGS + RHIC

Carbon CNI polarimeter in the AGS: based on internal carbon target + observation of recoil carbon nuclei.





Observation of polarization in the AGS during ramp from 2 to 26 GeV !

Experiments at RHIC: Example PHENIX Detector

The experimental task:

Observe final state of ion-ion and proton-proton collisions

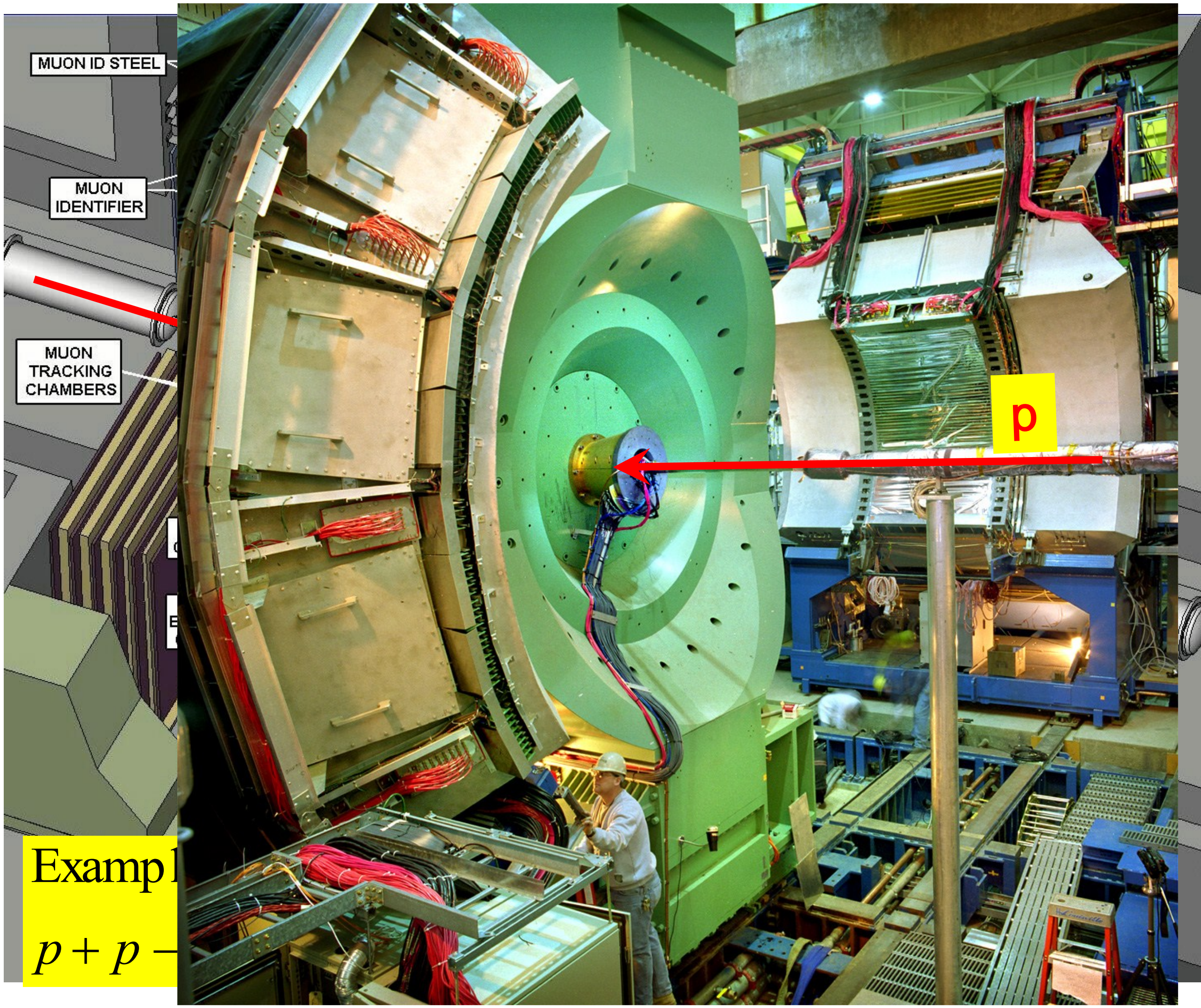
$$p + p \rightarrow$$

$$n \cdot \gamma + m \cdot e + o \cdot \pi^0 + \ldots$$

(a) measure momentum + energy of final state particles

(b) identify final state particles: eg. photons vs electrons

(c) select events of interest



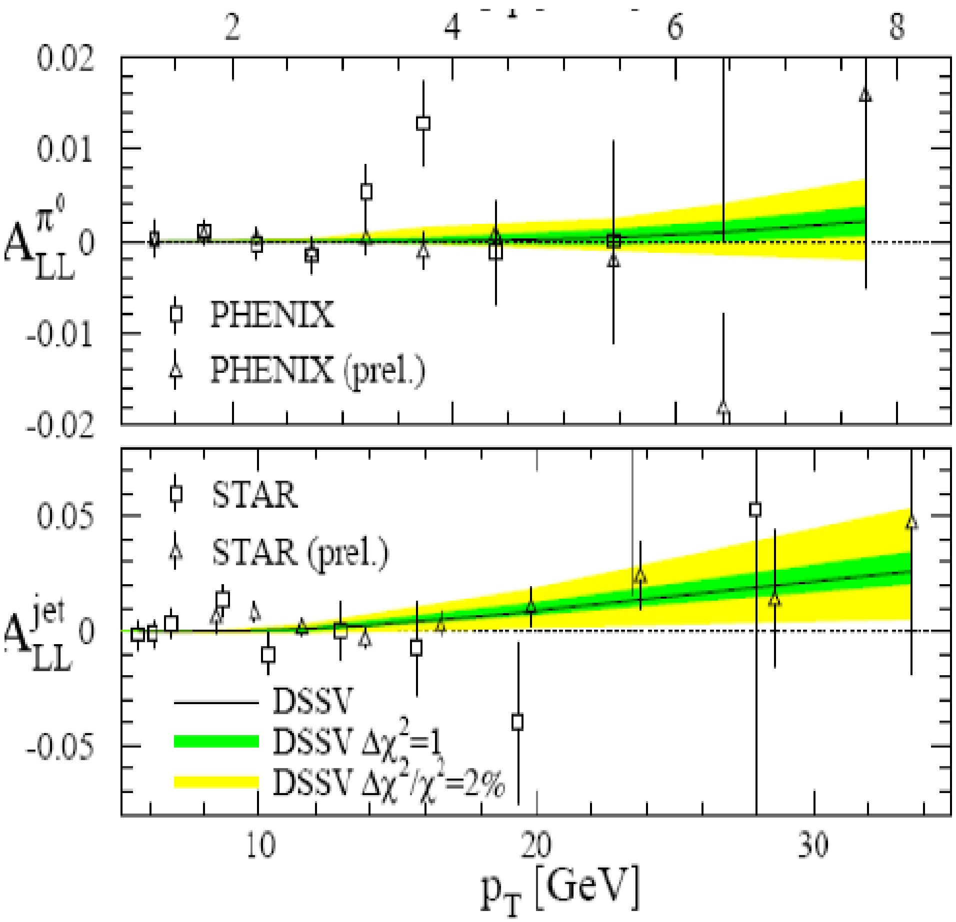
RHIC Results

➔ *A_{LL} for pion & jets*

Extraction of ΔG

RHIC data and QCD Theory Analysis

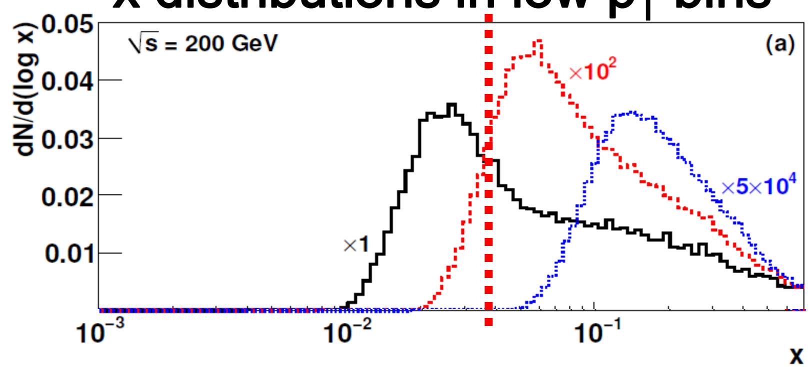
De Florian, Sassot, Stratmann and Vogelsang, Phys. Rev. D80 (2009) 034030



Good Agreement between data and QCD fits.

RHIC data constrain $\Delta G(x)$ significantly for $0.05 < x < 0.2$

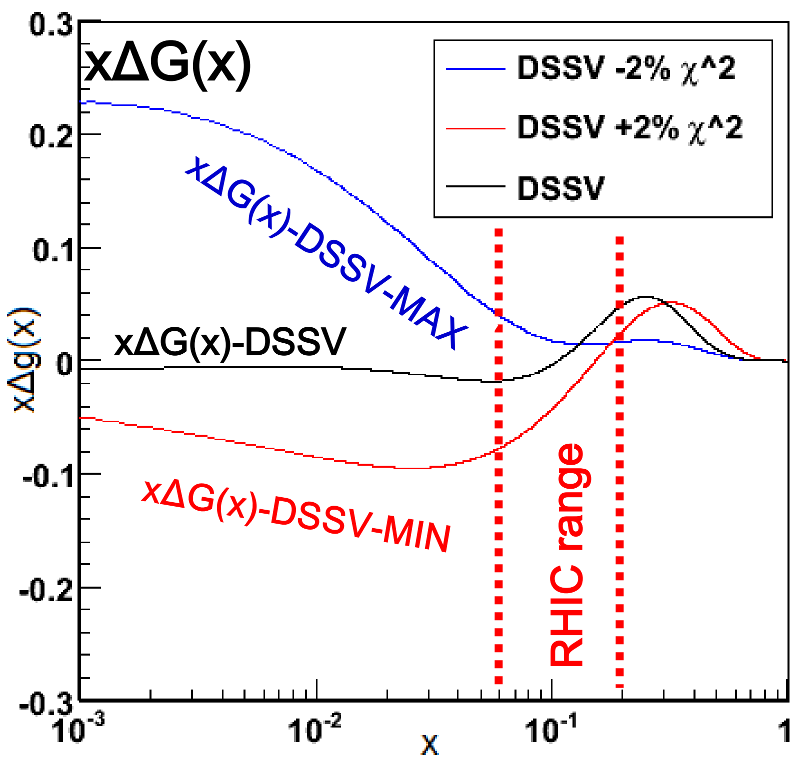
x distributions in low p_T bins

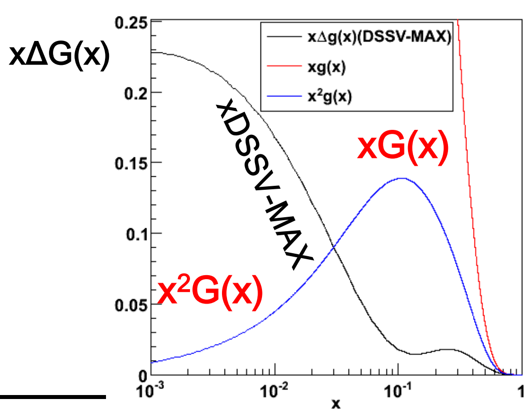


x=0.05

$x=2p_T/\sqrt{s}$

Result for the Gluon Spin Distribution ➔ ΔG(x)





Gluon Spin Distribution: ΔG(x)

- ➔ node at x ~ 0.1
- ➔ data constrain 0.05<x<0.2
- ➔ uncertainties indicated by DSSV-MIN and MAX
- ➔ Uncertainties not constrained by data for x<0.05

Gluon Spin Contribution: $\int \Delta G(x)dx$ remains uncertain!

Truncated moment constrained by data small due to node!

$$\Gamma_{0.05}^{0.2} = \int_{0.05}^{0.2} \Delta G(x)dx \approx 0$$

High x truncated moment bound by G(x)

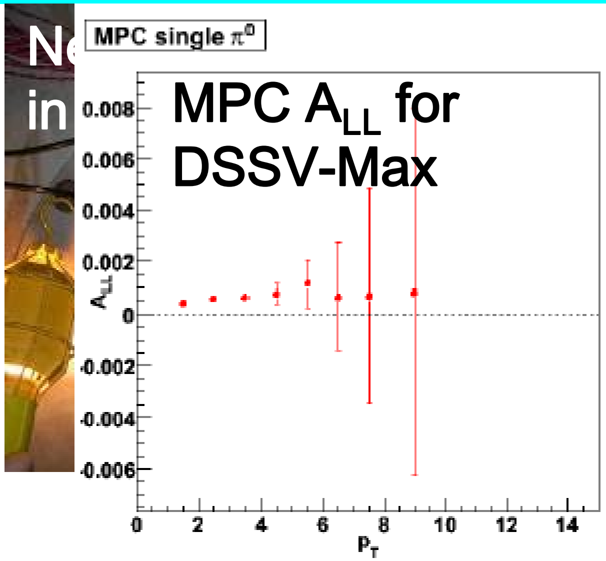
$$\Gamma_{0.2}^{1.0} = \int_{0.2}^{1} \Delta G(x)dx \leq \int_{0.2}^{1} G(x)dx \approx 0.05$$

Low x truncated moment can be large!

$$\Gamma_{0.0}^{0.05} = \int_{0.0}^{0.05} \Delta G(x)dx \leq \int_{0.0}^{0.05} G(x)dx \longrightarrow \text{Large!}$$

Next Steps: Extend Measurement to low x !

Measurement of inclusive hadrons and back-to-back hadron or jet pairs at forward rapidity tags low x_{gluon}!



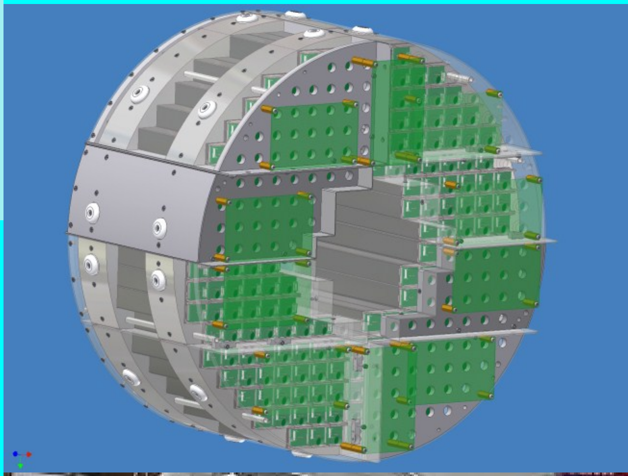
PHENIX MPC : $3.1 < \eta < 3.9$ and x ➔ 0.001

Goal: $\Gamma_{0.0001}^{0.5} = \int_{0.0001}^{0.5} \Delta G(x) dx$ leaving extrapolation uncertainties sufficiently small for the determination of the gluon spin contribution!

PHENIX Muon Piston Calorimeter

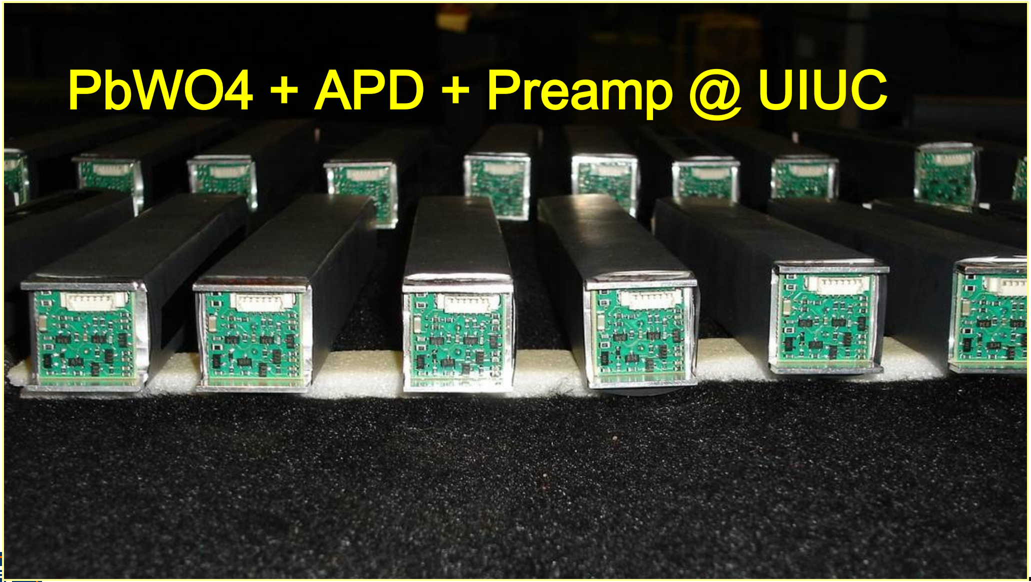
Technology → ALICE(PHOS)

$PbWO_4$
avalanche photo diode readout
$3.1 < \eta < 3.9, \; 0 < \varphi < 2\pi$
$-3.7 < \eta < -3.1, \; 0 < \varphi < 2\pi$



Data Sampled

Both detector were fully installed and commissioned for run 2009 and saw $\int L dt \sim 15\ pb^{-1}$.

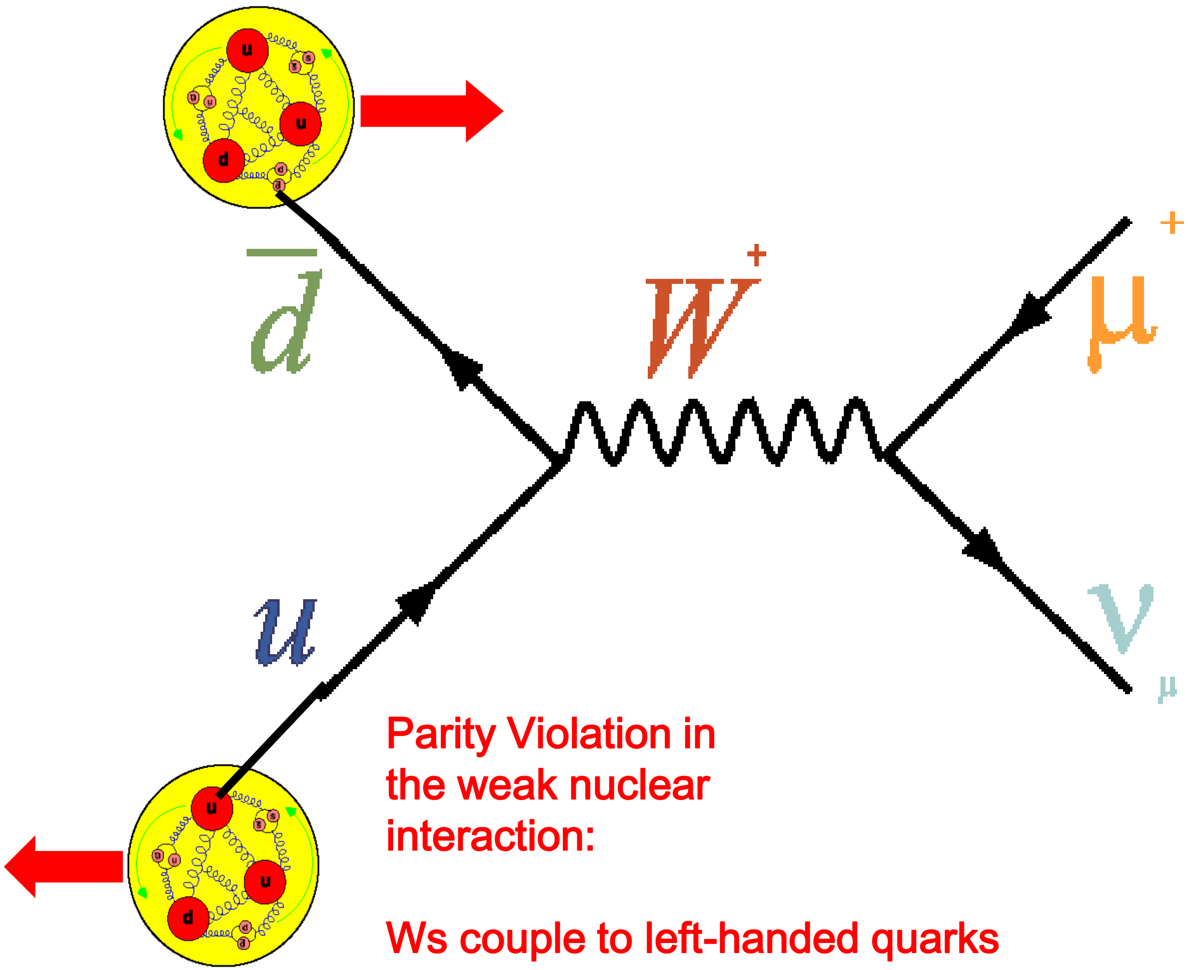


RHIC

➔ A_L *for W-Bosons*

W→ interact with quarks from virtual quark-anti-quark loops !!

W-Physics: Find Sea Quark Contributions to the Proton Spin



Proton Structure Info:

(1)
u-quarks have their spin (mostly) aligned with the proton spin.

(2)
d-quarks have their spin (mostly) anti-aligend with the proton spin.

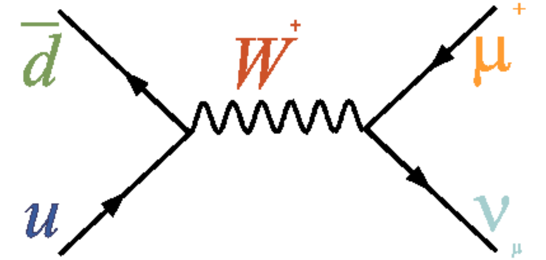
➔probe anti-d-quark
(1) need right handed anti-d-quark
(2) need proton p and spin parallel

➔ turns of u-contribution and anti-d quark will come from polarized proton

Parity Violation in the weak nuclear interaction:

Ws couple to left-handed quarks
Ws couple to right –handed anti-quarks

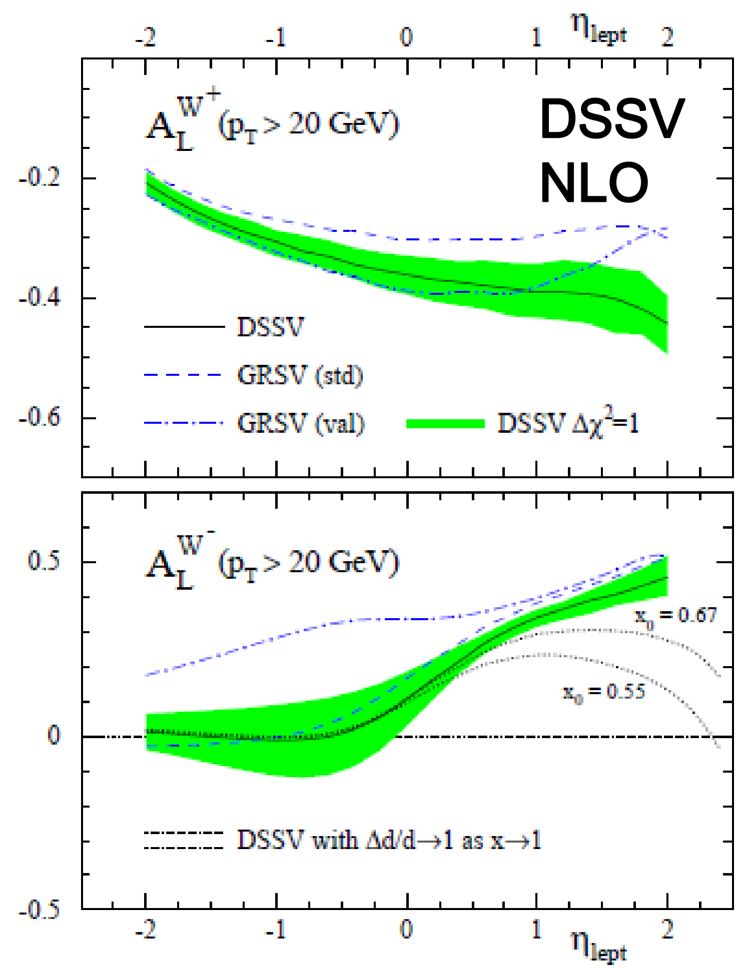
W Production in Polarized pp Collisions



Single Spin Asymmetry in the naive Quark Parton Model

$$A_L^{W^+} = \frac{\Delta u(x_1, M_W^2)}{u(x_1, M_W^2)}$$

DSSV projections for A_L for W^+ and W^- for different scenarios for $\Delta\bar{u}$ and $\Delta\bar{d}$. The asymmetries also have good sensitivity for the unknown behavior of $\Delta d(x)/d(x) \rightarrow 1$ for x -> 1 ?



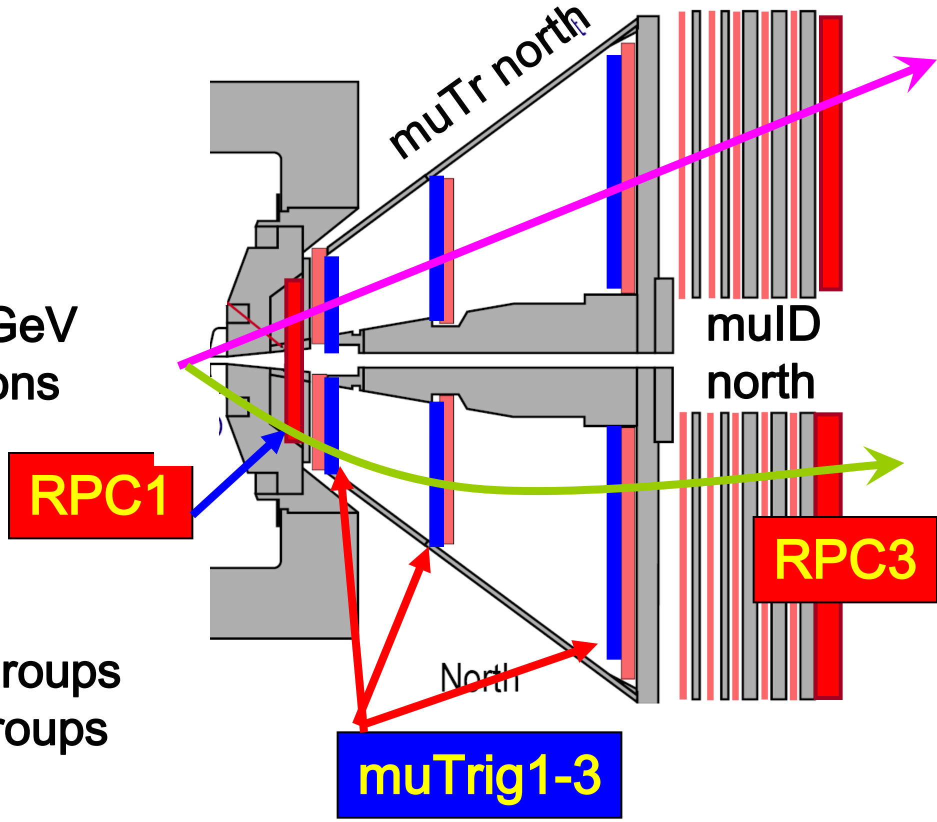
Muon Trigger Upgrade

Idea

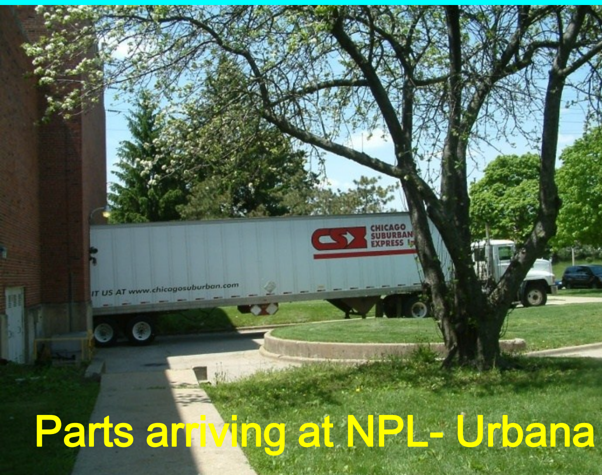
(1) Background of muons from pion + kaon decay is about 50 KHz in present muID trigger; max allowed is about 2kHz
(2) The momentum of the decay muons is mostly less than 10 GeV
(3) Muon from W-decay have mostly p > 20 GeV
(4) Feed information from muon tracker stations and newly built RPCs to fast trigger processors to reject low momrentum muons

(5) muTr electronics upgrade by Japanese groups
RPC upgrade by US+Korean+Chinese groups

PHENIX Muon Spectrometer



PHENIX RPC-3 Half Octant Structure

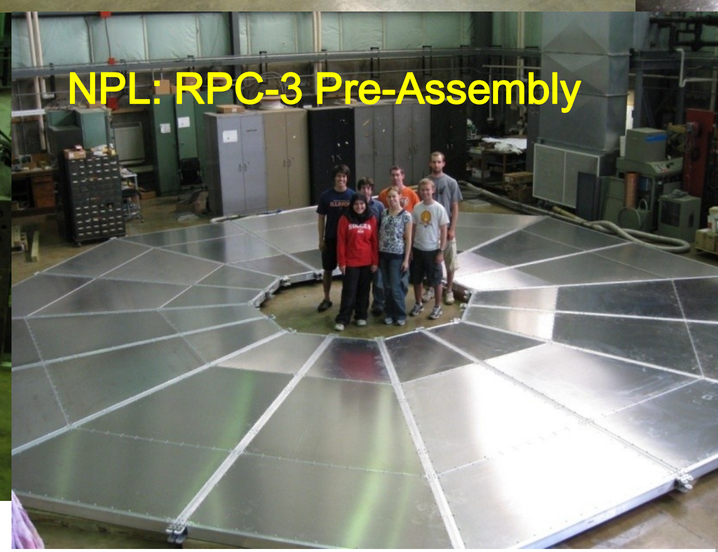


Parts arriving at NPL- Urbana

NPL: skins, cross-bars, brackets

NPL: Half octants to BNL

NPL: RPC-3 half octant storage



NPL: RPC-3 Pre-Assembly

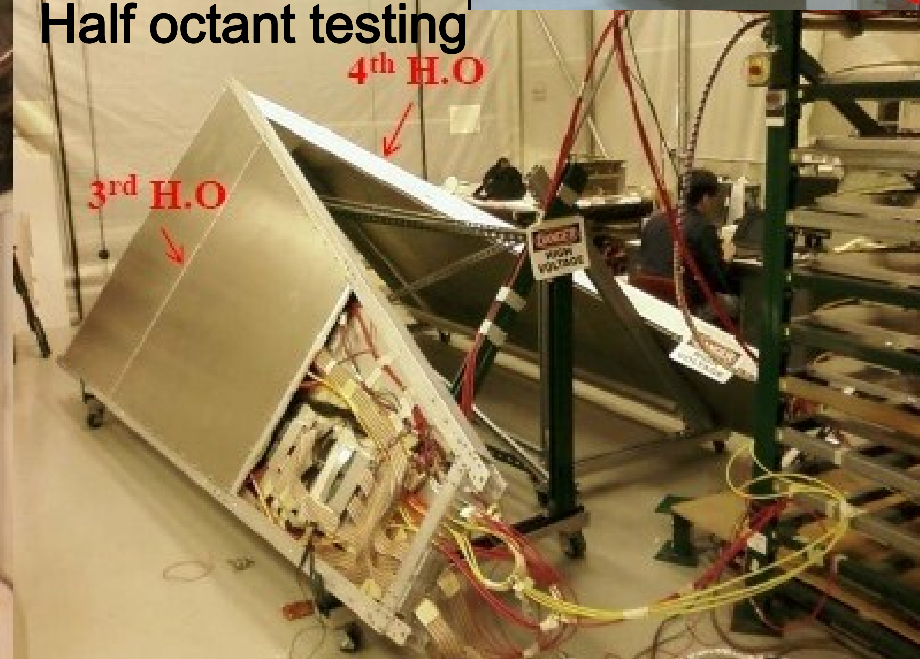
RPC-factory at BNL:
Half Octant Storage

RPC-3 North Assembly in the PHENIX RPC Factory at Brookhaven National Laboratory

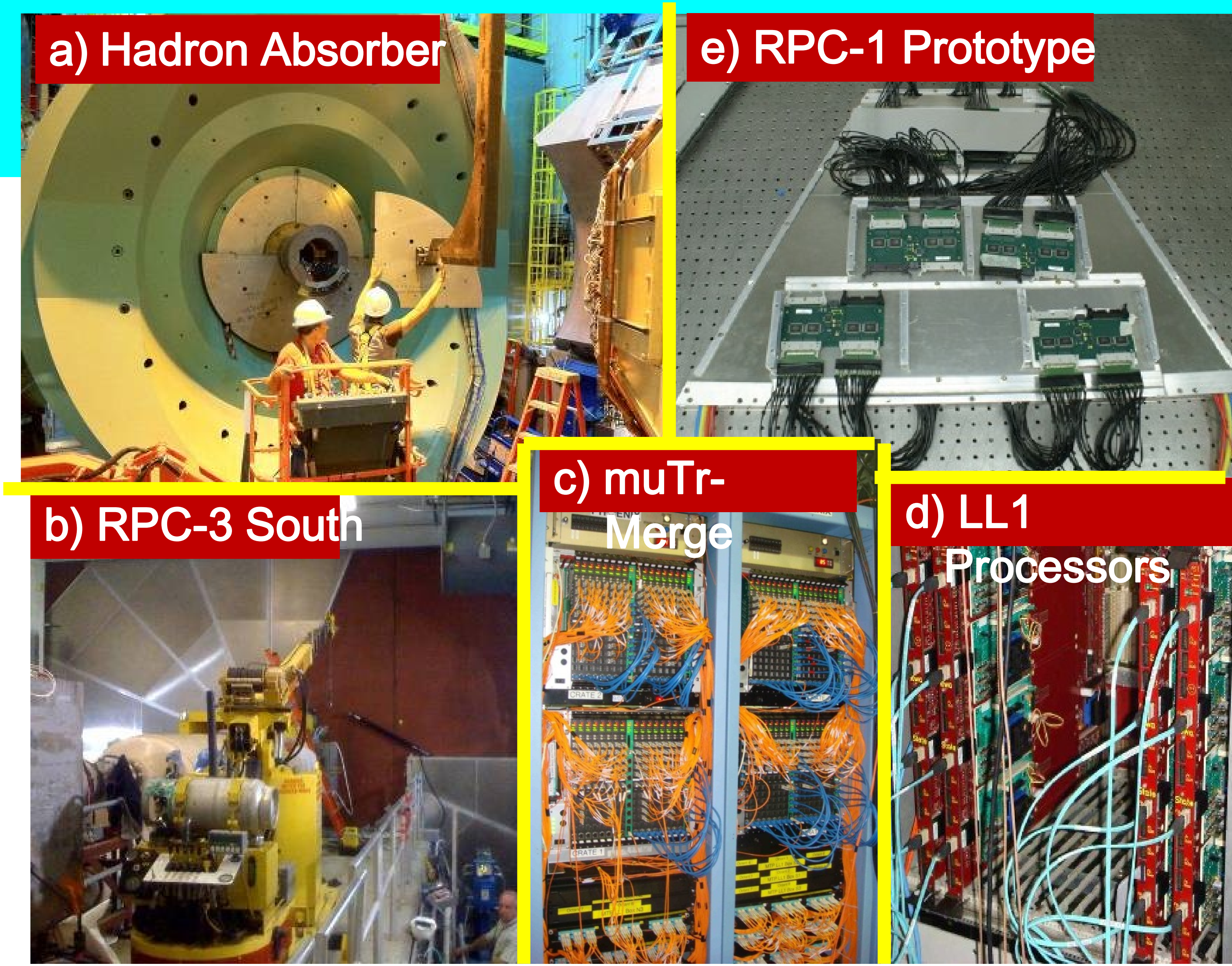
First fully assembled RPC half octants.

Tent for half octant burn in

RPC-factory: Half octant transfer

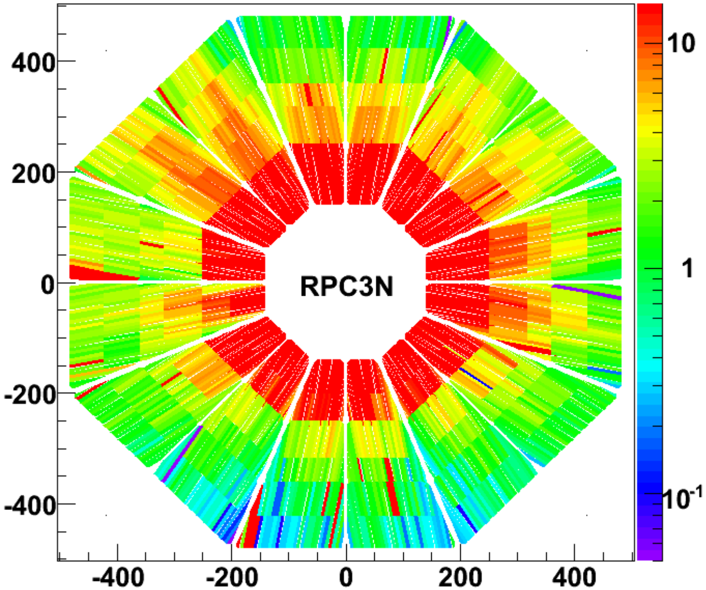


Half octant testing

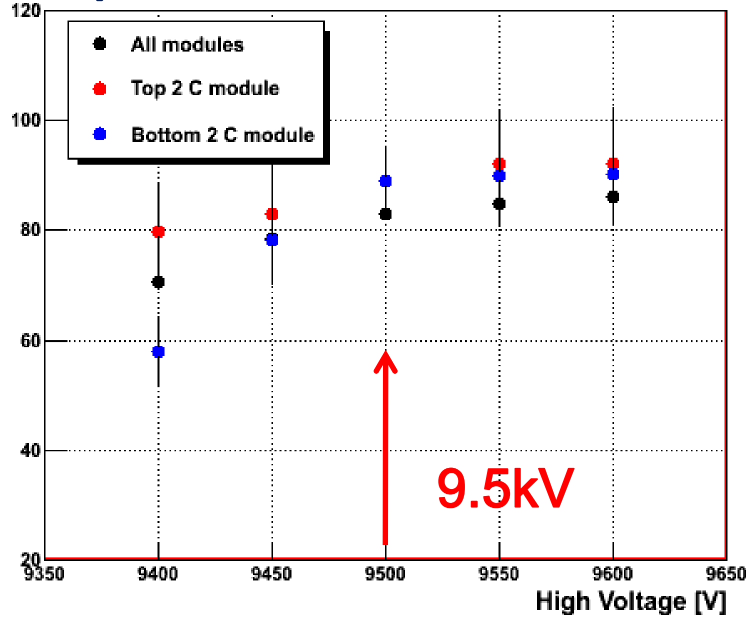

a) Hadron Absorber
e) RPC-1 Prototype
b) RPC-3 South
c) muTr-Merge
d) LL1 Processors

Results from Run 2011: January - May

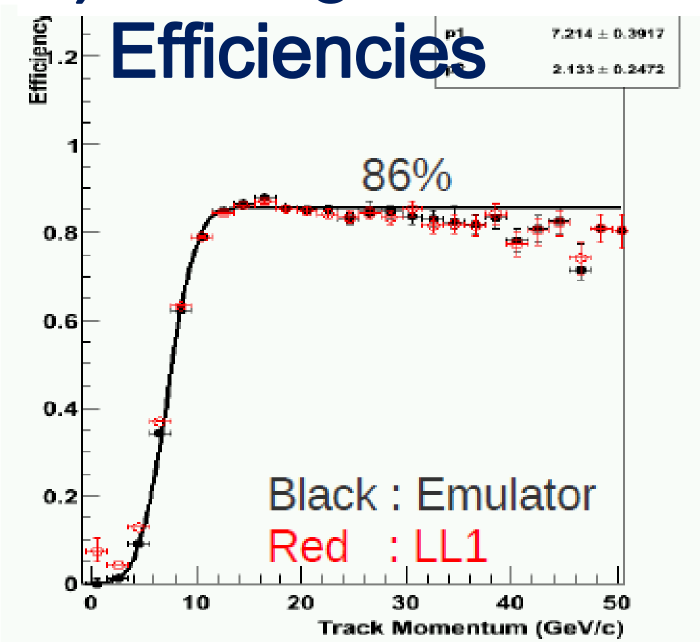
a) RPC Hit Map



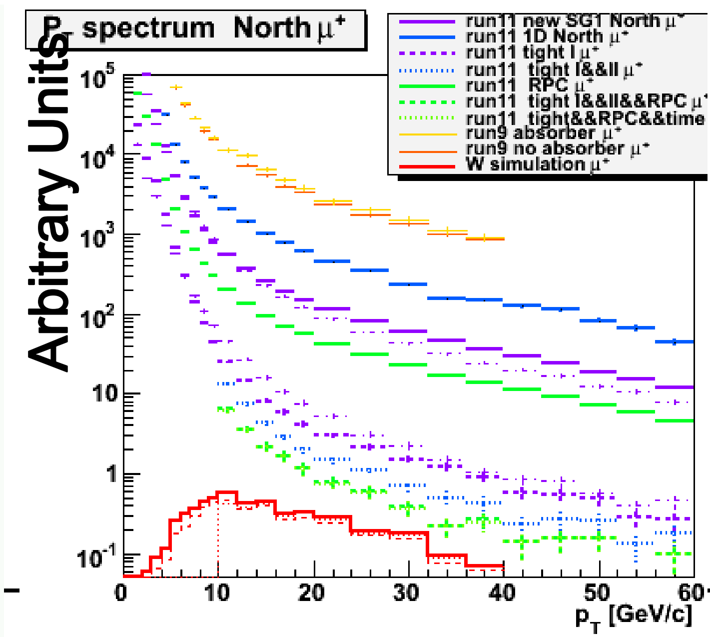
b) RPC-3 Efficiencies



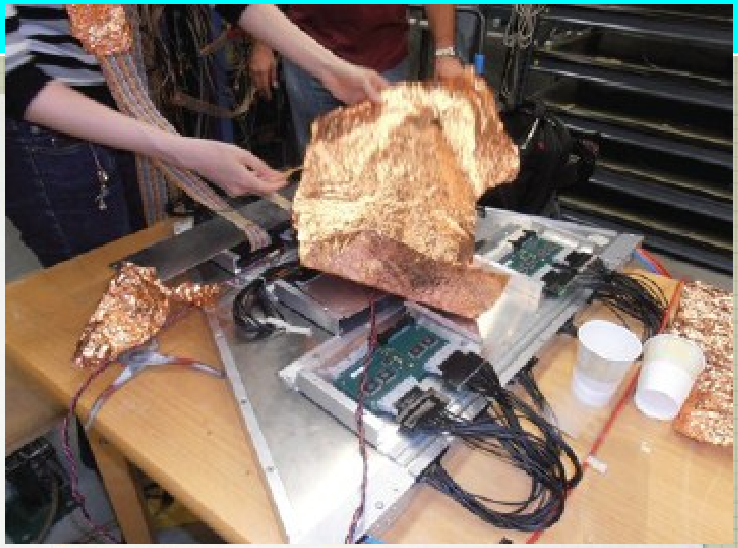
c) MuTrig-Efficiencies

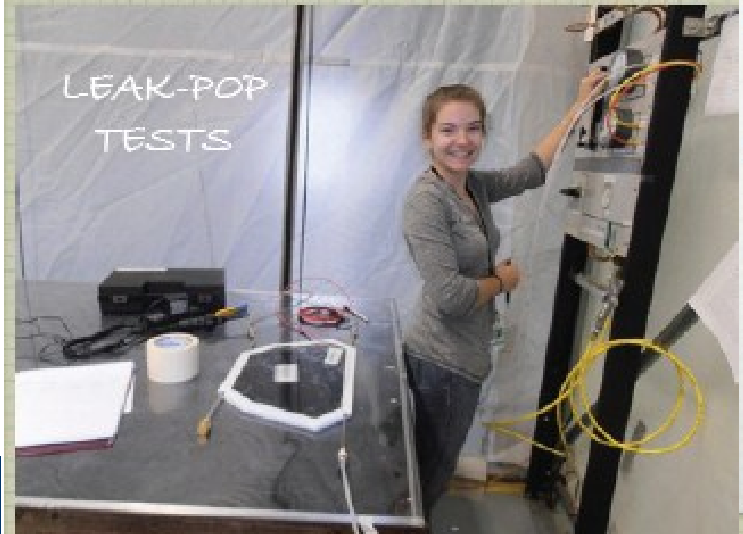


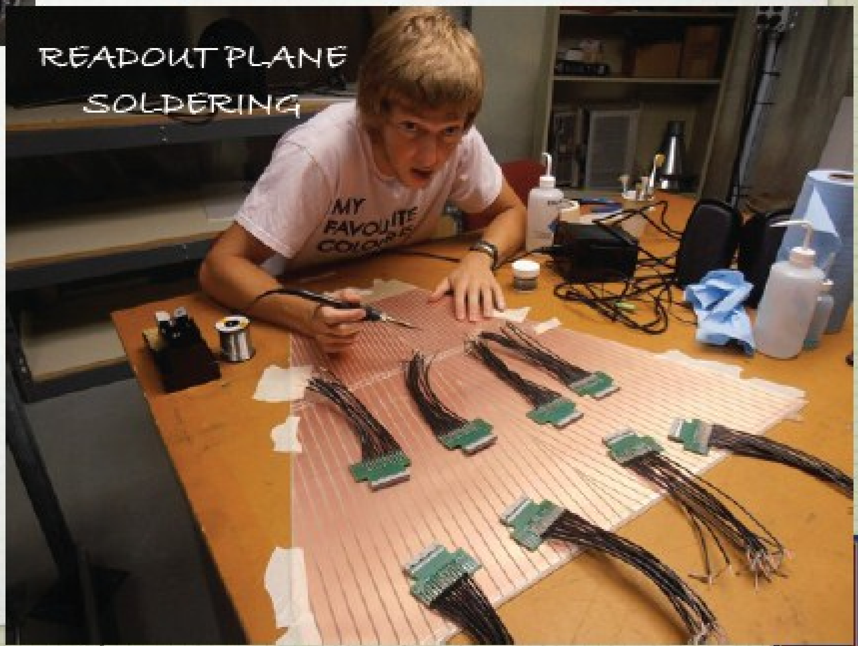
d) High p_T Background



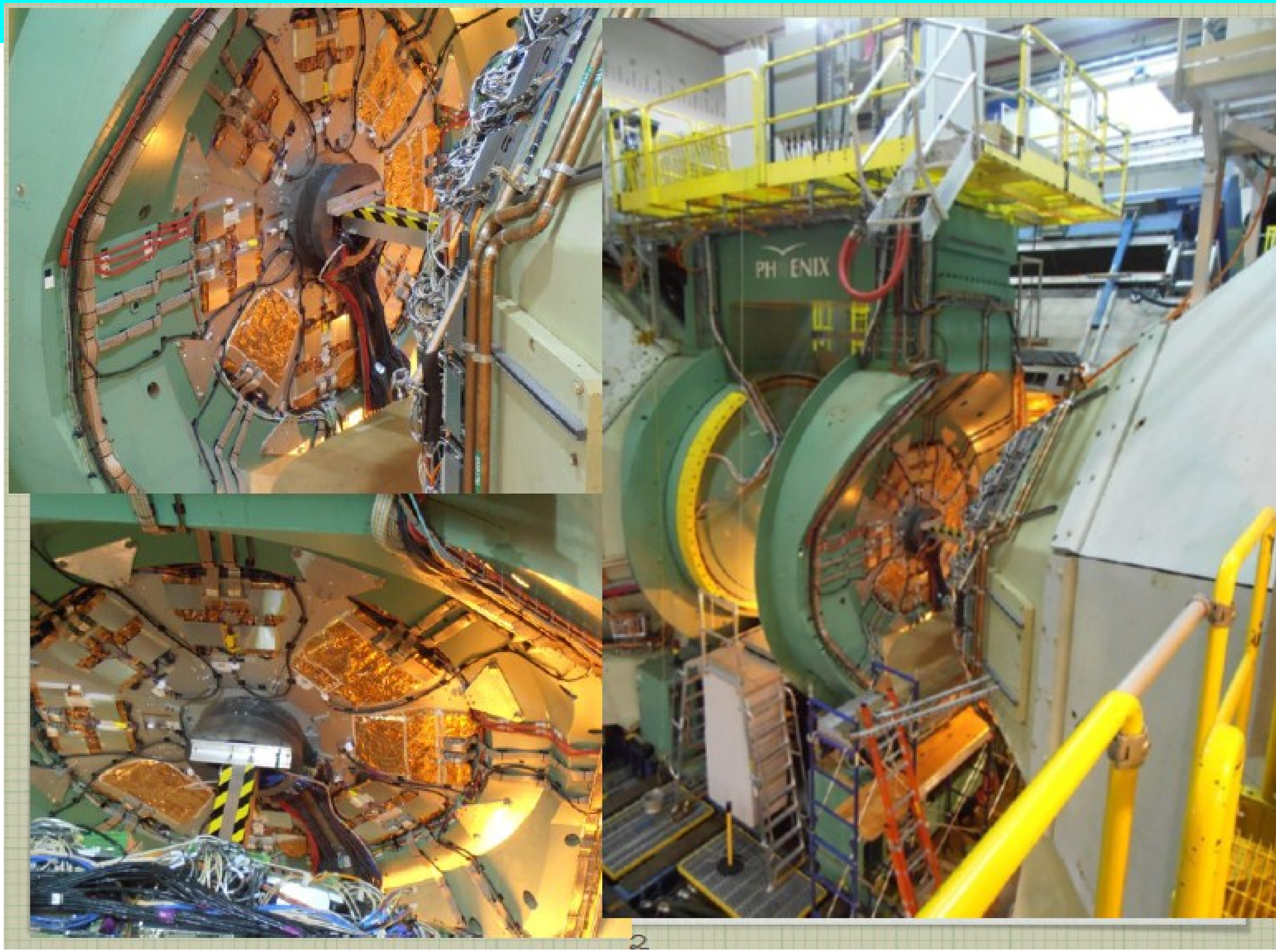
RPC-1 Assembly







RPC-1 Installation



Summary

A large experimental effort in polarized e-p and p-p is underway to determine the spin structure of the proton.

In deep inelastic e-p scattering the quark spin contribution has been found to be 1/3.

Polarized proton-proton Collisions at RHIC provide unique sensitivity to the gluon spin contribution. However, present measurements at RHIC only constrain $\int \Delta G(x)\,dx$ for $0.05 < x < 0.2$. Detector upgrades are underway to extend the x-range to x=0.001

Detector upgrade in STAR and PHENIX will make it possible to measure the spin distribution for anti-quarks through W-production

PHENIX Attempt at ΔG(x) at lower x: $A_{LL}(2\pi^0)$

from Les Bland (for STAR FMS)

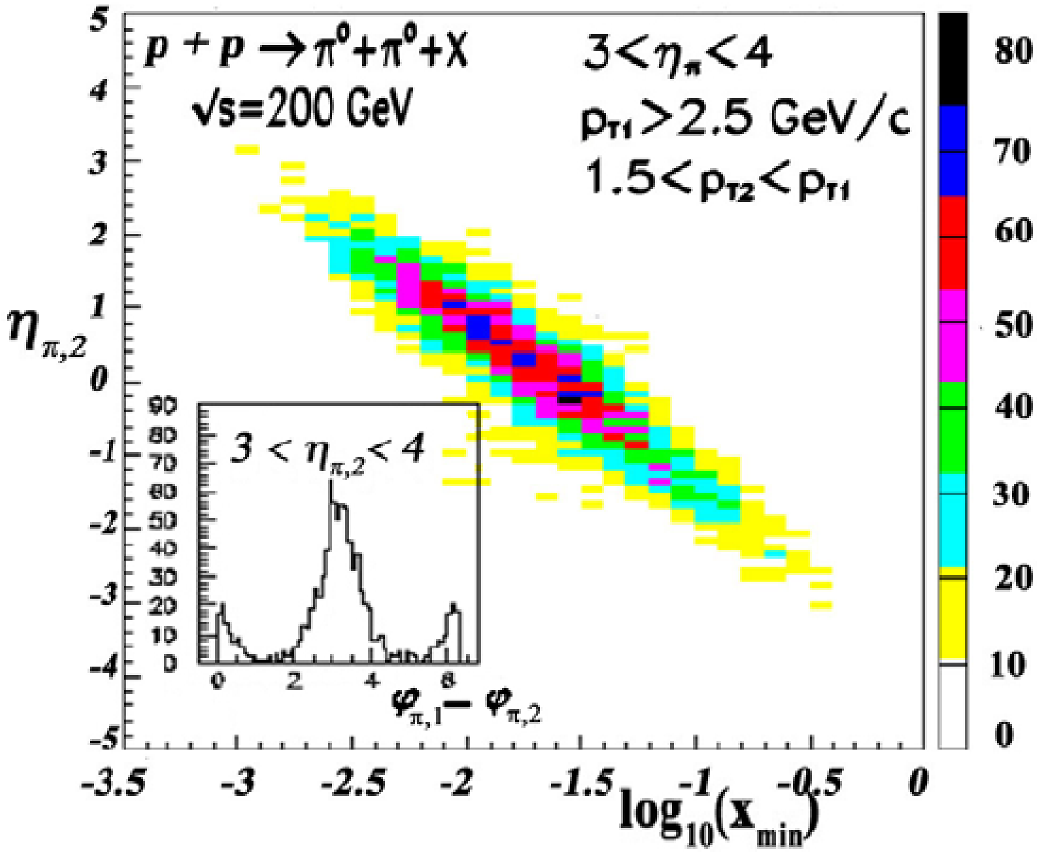
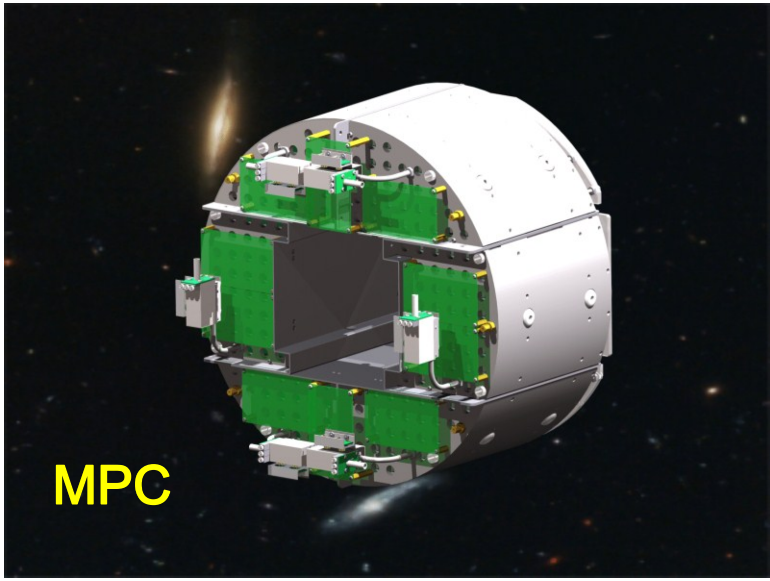


Fig. 2.4: The correlation between x and η for pion 2 in events triggered by a forward pion [5].

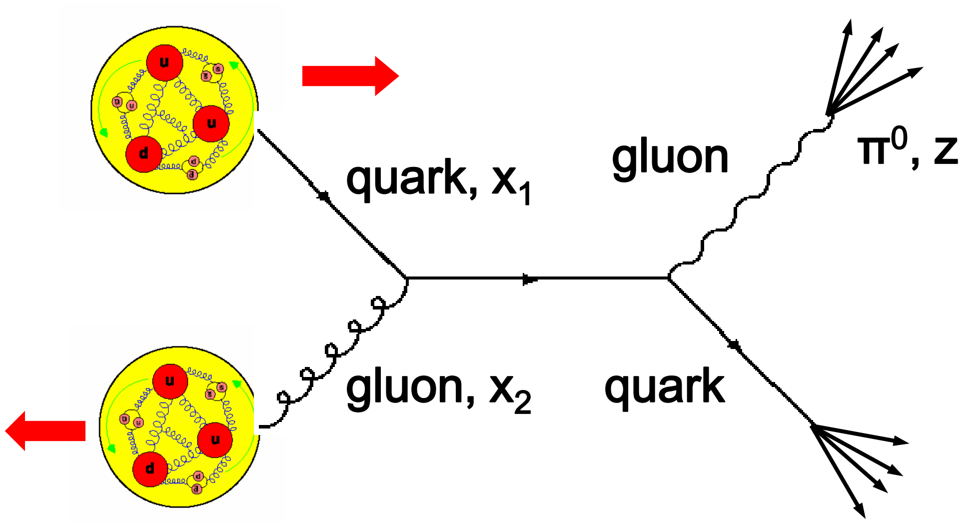
Measure A_{LL} for neutral pion pairs: one in the central arm the second in the MPC

➔ $0.1 > x_{gluon} \rightarrow 0.002$

Theory Framework available from Marco Stratmann



Relation between ΔG *and* Spin-Dependent p-p Cross Sections: Multiple Processes !



Inclusive pion production: many sub-processes contribute!

$$ij \to k \propto gg \to gg$$
$$qq \to qq$$
$$qg \to qg$$
$$(qg \to q\gamma)$$

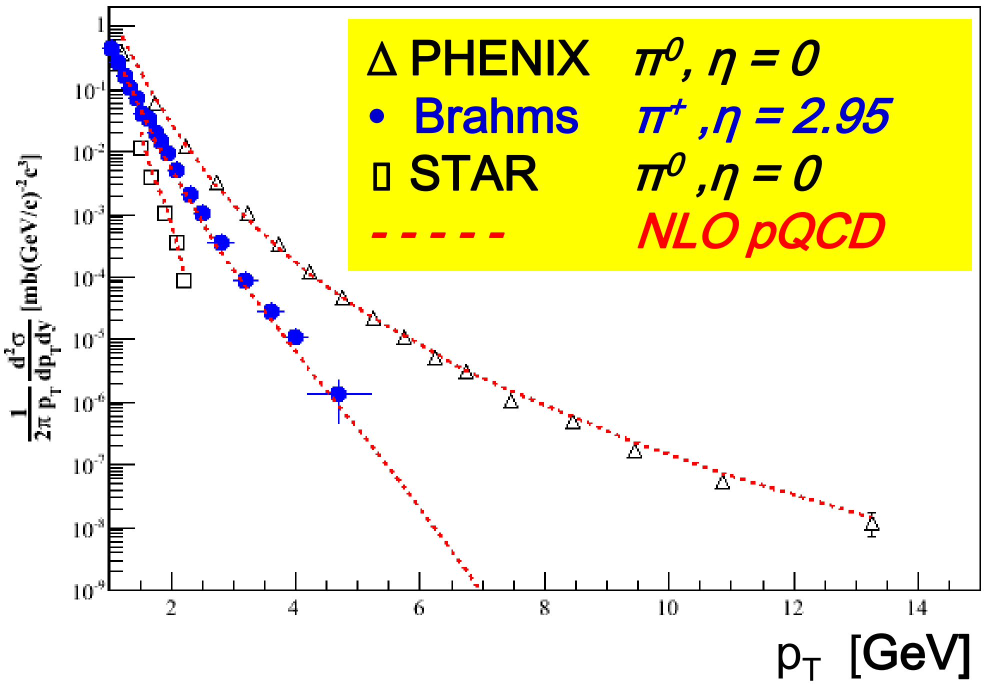
$$d\sigma^P \propto \sum_{i,j,k} \iiint_{x_1,x_2,z} dx_1 dx_2 dz f_i^P(x_1) f_j^P(x_2) d\hat{\sigma}(ij \to k) D_k^h(z)$$

in order to solve for ΔG: need to know all other $f_i^P(x)$ from DIS, SIDIS and $D_K^h(z)$ from e^+e^-, SIDIS and pp.

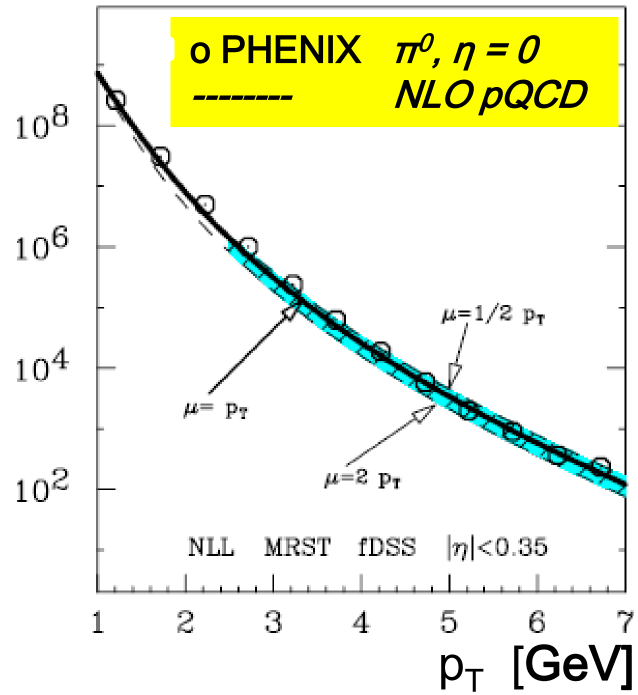
Need experimental verification of QCD-Theory at RHIC !

Cross Sections: QCD Theory vs RHIC data for Different √s and Rapidity Intervals

√s = 200 GeV



√s = 62.4 GeV



Good agreement between inclusive hadron cross sections from RHIC data and pQCD calculations !

See analysis in De Florian, Vogelsang, Wagner PRD 76,094021 (2007) and Bourrely and Soffer Eur.Phys.J.C36:371-374 (2004)