Accessing The Gluon's Polarization

Advancement to Candidacy Qualifying Examination
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September 7, 2006

Spin is an **essential** and fascinating complication in the physics of elementary particles
-Elliot Leader

OUTLINE

1. BACKGROUND

2. QUANTUM CHROMODYNAMICS

3. SPIN and DIRECT PROCESSES

4. RHIC and PHENIX

BACKGROUND

Spin was first discovered in the context of the emission spectrum of alkali metals - "two-valued quantum degree of freedom" associated with the electron in the outermost shell.

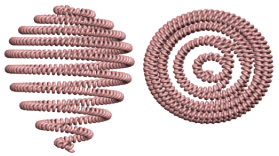
In trying to understand splitting patterns and separations of line spectra, the concept of spin appeared.

"*it is indeed very clever but of course has nothing to do with reality*". *W. Pauli*

Pauli finally formalized the theory of **Spin** in 1927

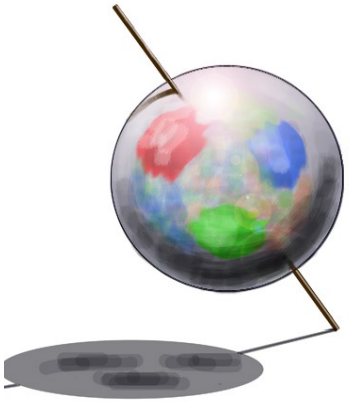
Intrinsic Spin Violates our intuition:

How can an elementary particle such as the e^- be point like and have perpetual angular momentum.?

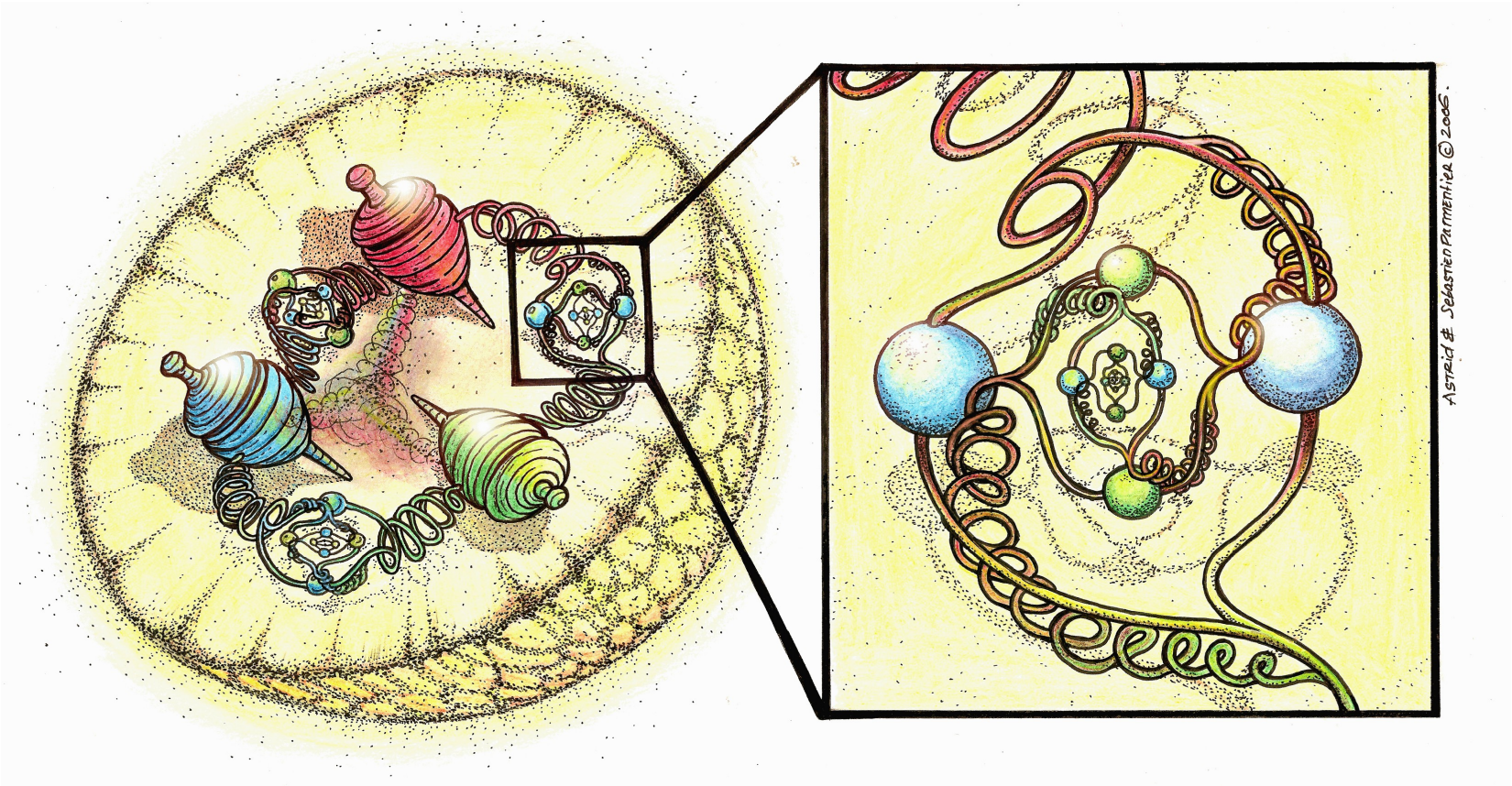


The Proton also violates our intuition.
The Proton is composed of quarks, gluons and anti quarks.

We should expect the proton's spin to be predominately carried by its 3 valence quarks



QUANTUM CHROMODYNAMICS

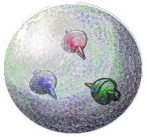


That nucleon has a large anomalous magnetic moment proves that this is not a ***fundamental*** spin1/2 Dirac particle.

Within the nucleon:
Quarks, gluons and their angular momentum caused by their high speed motion within the nucleon are contributors to the Nucleon's spin.

QCD SPIN PICTURE

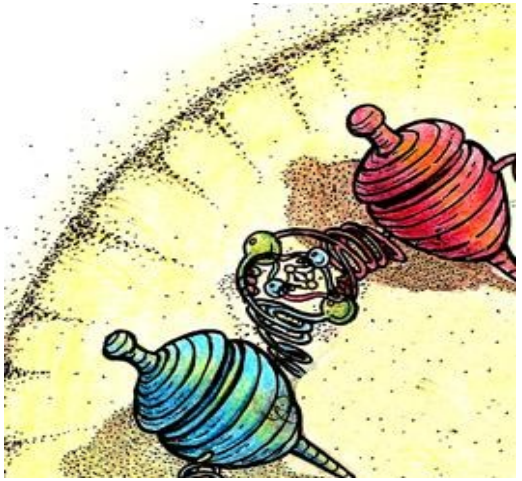
QCD is non-abelian gauge theory that describes the interaction of massless spin ½ objects that possess an internal degree of freedom called **color**.



The primary goal of **QCD** spin is to describe hadrons in terms of **quarks** and **gluons**

QCD PICTURE continued...

For interactions between quarks at very short distances (large momentum transfers) the theory looks more like a free-field theory, without interactions

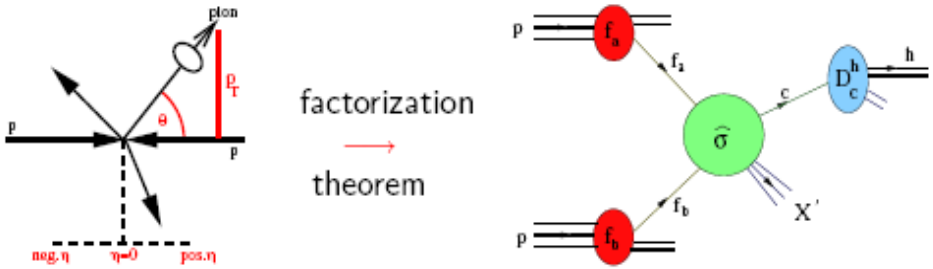


This is the justification for the Quark Parton Model (QPM) and the use of perturbative methods for large momentum reactions.

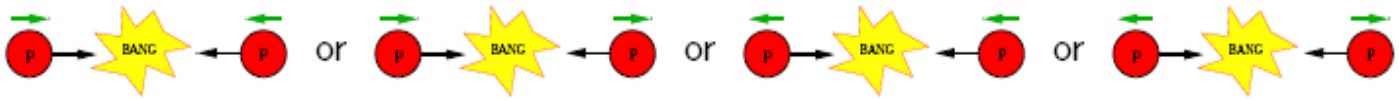
FACTORIZATION:

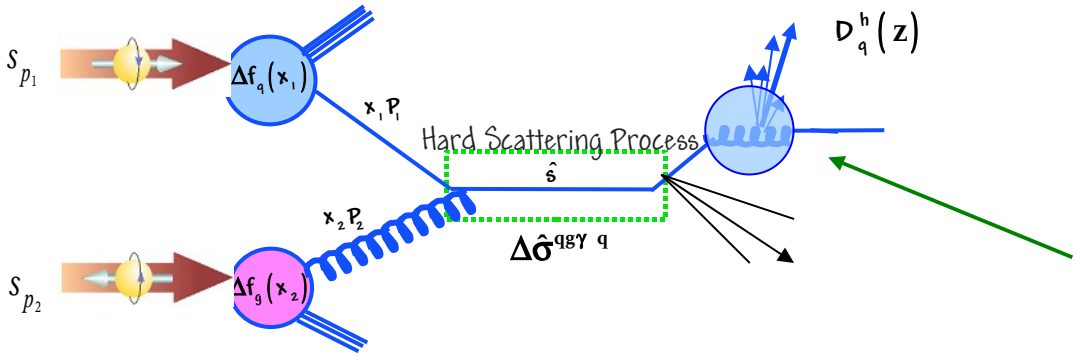
It is assumed that a differential cross section section can be written as the convolution of a parton density and a hard scattering process

$$d\sigma = f_a \times f_b \times d\hat{\sigma} \times D_c^h$$



With polarization we can perform four different types of experiments





– Fragmention of parton and creation of hadrons
- Fragmentation functions from data

Spin Dependant Parton Density Functions

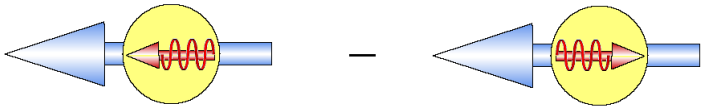
In a proton with helicity + we can find a parton:

$g(x,Q^2)=$

$q(x,Q^2)=$

•We then Define **Δf** as the probability of finding a quark(or gluon) or anti quark with spin parallel or anti parallel to the spin of the nucleon.

$\Delta q(x,Q^2)=$

$\Delta g(x,Q^2)=$ 

These integrals of Δ f multiplied by the spin of the parton f will give the amount of spin carried by each parton*.

*i.e for gluons : **Amount of carried spin ~ Δ g*1**

The Longitudinally polarized parton density functions can be separated from the unpolarized case:

$$\frac{d\Delta\sigma^{\vec{p}\vec{p}\to\pi X}}{dp_T d\eta} = \sum_{abc}\int dx_a\, dx_b\, dz_c\, \Delta f_a(x_a,\mu_f)\, \Delta f_b(x_b,\mu_f)\, D_c^{\pi}(z_c,\mu_f')$$
$$\times \frac{d\Delta\hat{\sigma}^{ab\to cX'}}{dp_T d\eta}(x_a P_a, x_b P_b, P^{\pi}/z_c, \mu_f, \mu_f', \mu_r) + \mathcal{O}(\frac{\lambda}{p_T})^n$$

$= \frac{1}{4}\ [d\sigma^{++} - d\sigma^{+-} - d\sigma^{-+} + d\sigma^{--}]$

The bottom line:

A longitudinally polarized cross section gives access to Δf

$d\sigma \sim \Delta f$

This longitudinally polarized cross section depends only on:
the parton densities (also product Fragmentation Functions) and sub-process cross-section.

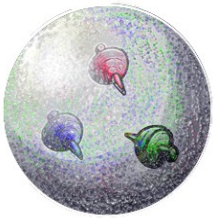
SPIN and Direct Processes

Spin Structure of the Proton

Quarks and Gluons carry about 50% (each) of the longitudinal momentum

What about *spin*?

Valence quarks(QPM)

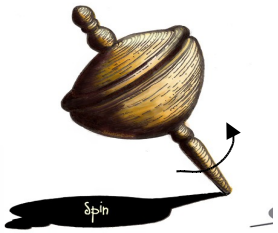


~30%

Illustration by Sebastien Pamentier & Astrid Morreale

Gluons, sea quarks (QCD)

~>=0?



~??

Orbital angular momentum contributions.

WHAT IS DELTA G :

•**DELTA G**: The spin contribution due to the gluons
•Contains Information on the **pQCD** picture of the nucleon.

While there may be indication of a non-zero contribution but we *need* more experiments/analysis to disentangle all the contributions to the nucleon spin.

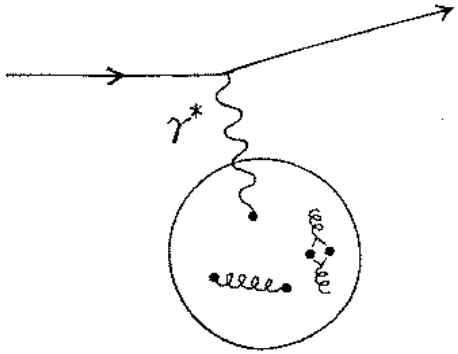
This is summarized by the **Helicity Sum Rule:**

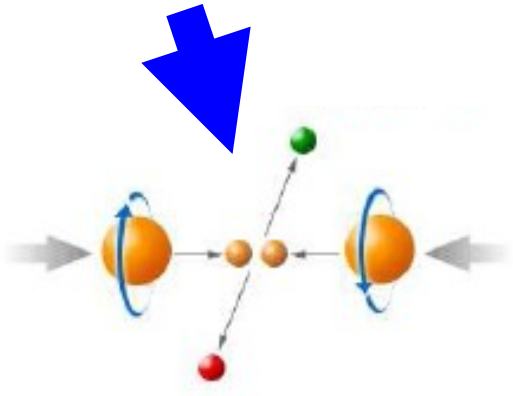
$$S_z = 1/2 = 1/2\,(\Delta u + \Delta d + \Delta s) + L_q + \Delta G + L_G.$$

•**Reminder: $\Delta q = q^+$ and q^-** are the probabilities of finding a quark or anti quark with spin parallel or anti parallel to the spin of the nucleon.

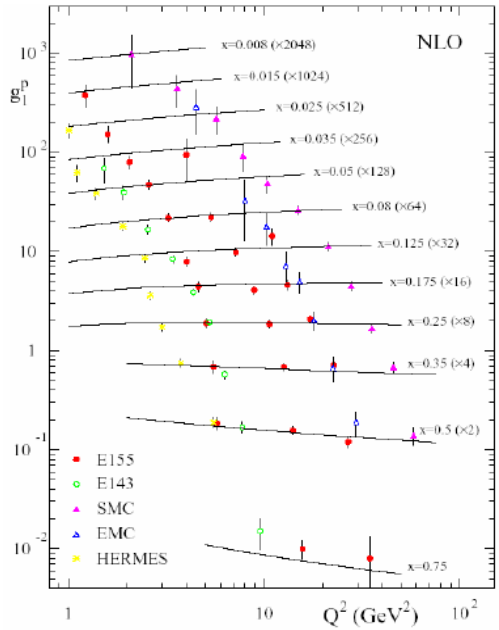
Proton Colliders are excellent tools to measure delta g.

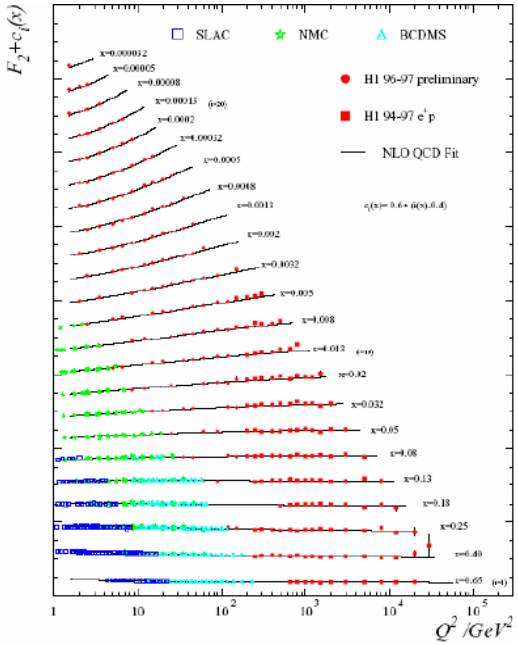
*DIS:Virtual photons do not couple directly to gluons.





We still need more data that will give more information on the gluon distribution functions.





Data of Q^2 at fixed x. Left:polarized, right Unpolarized.

HOW CAN WE MEASURE DELTA G :

S_z **sum rule** involves integrated densities!!

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

We measure **asymmetries.**

Asymmetries are a convolution of the unknown pdf's in both colliding protons w/the elementary scattering asymmetries summed over the different processes that contribute to the observed events.

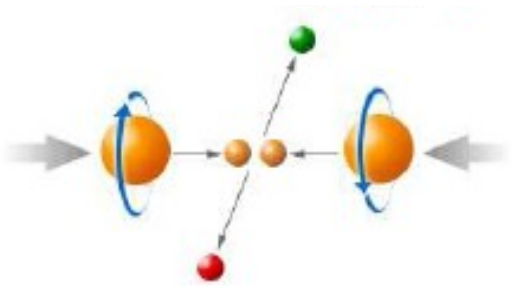
In practice what we look is the ratio of the polarized vs the unpolarized cross-section:

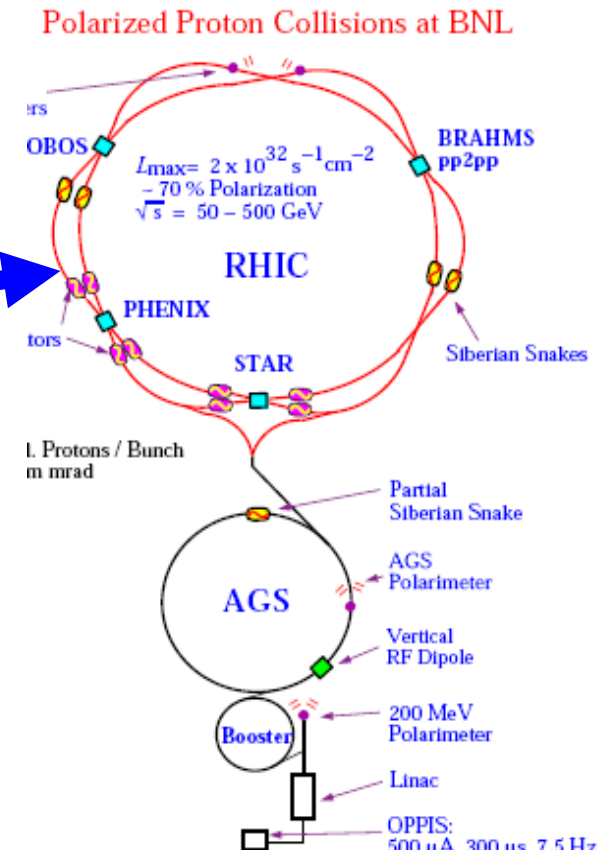
$$A_{LL} \equiv \frac{d\Delta\sigma}{d\sigma}$$

Its General Structure:

$$A_{LL} = \frac{\sum_{fq,fg} \frac{\Delta f_q}{f_q} \frac{\Delta f_g}{f_g} [d\Delta\sigma^{qg\to\pi X} \hat{a}_{LL}^{qg\to\pi X}] \times D_\pi}{\sum_{fq,fg} [d\sigma^{qg\to\pi X}] D_\pi} \sim \frac{\Delta f}{f}$$

AT the Relativistic Heavy Ion Collider:





Double Spin Asymmetries can be defined and measured for both polarized beams at RHIC as:

$$A_{LL} = \frac{(\sigma_{++}+\sigma_{--})-(\sigma_{+-}+\sigma_{-+})}{(\sigma_{++}+\sigma_{--})+(\sigma_{+-}+\sigma_{-+})}$$

Final state cross section with with initial proton helicities as subscripted.

BUT...
Since our proton beams are not in pure helicity states, we must weight by the polarization

$$P_{beam} = \frac{B_+ - B_-}{B_+ + B_-}$$

Finally what we end with is (doing the algebra, they are equivalent!):

$$A_{LL}(p_T)=\frac{\sigma_{++}-\sigma_{+-}}{\sigma_{++}+\sigma_{+-}} \rightarrow \frac{1}{P^2}\frac{N_{++}(p_T)-RN_{+-}(p_T)}{N_{++}(p_T)+RN_{+-}(p_T)} \quad ,R=\frac{L_{++}}{L_{+-}}$$

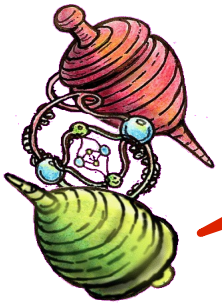
$$\sim \frac{\Delta f}{f}$$

Where the N $_{\text{subscripts}}$ are the observed particle yields when the beams are polarized in different configurations and normalized by the relative Polarization(for ++, -- vs +-, -+.) and the luminosity R

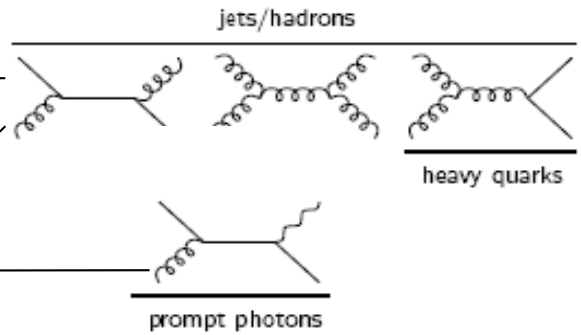
-As long as our detectors are stable our measurement of A_{LL} will be stable and our errors will be largely statistical!

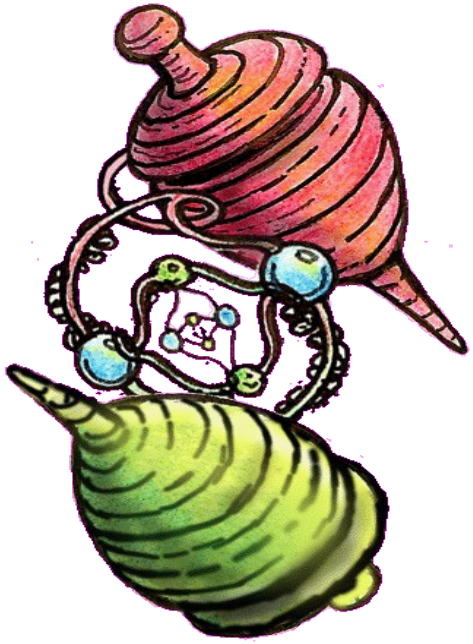
Measuring double spin asymmetries in certain final are the most valuable tool to measure polarized gluon (and quark) distribution functions in the proton.

The most accurate way to do so is the study of those processes which can be calculated in the framework of perturbative QCD.



reaction	LO subprocesses	partons probed
$pp \to \text{jets } X$	$q\bar{q}, qq, qg, gg \to \text{jet } X$	Δq, Δg
$pp \to \pi X$	$q\bar{q}, qq, qg, gg \to \pi X$	Δq, Δg
$pp \to \gamma X$	$qg \to q\gamma$, $q\bar{q} \to g\gamma$	Δg
$pp \to Q\bar{Q}X$	$gg \to Q\bar{Q}$, $q\bar{q} \to Q\bar{Q}$	Δg





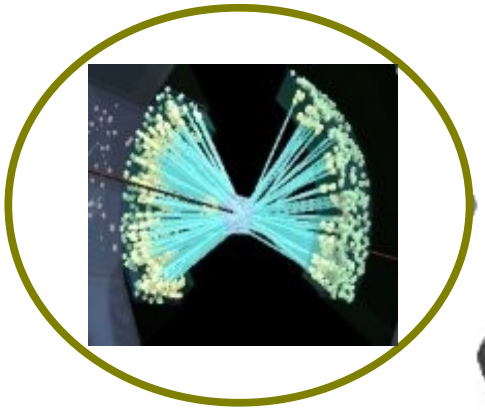
The **PI MESON** plays an important role in our quest:

- Zero spin and composed of first generation quarks
- Pseudo scalar under a parity transformation: pion currents couple to the axial vector current.
- Production of pions proceed from **g-g** and **g-q** initiated sub processes on proton-proton collisions

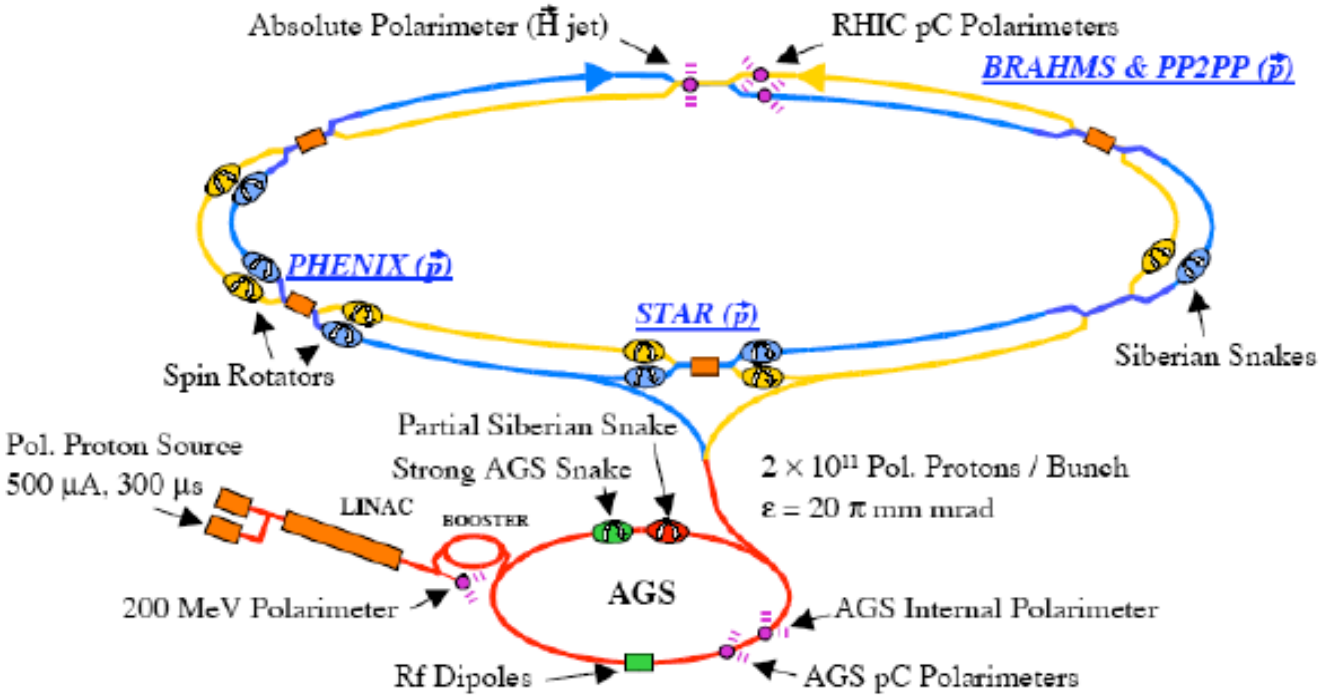
RHIC and PHENIX (Physics High Energy Experiment)

Shooting at polarized protons with polarized quarks.

How's do we...?



RHIC



2 counter rotating accelerator storage rings with collisions at six interaction points

Siberian Snakes: Depolarized resonances averaged out by rotating spin by 180 degrees each turn.

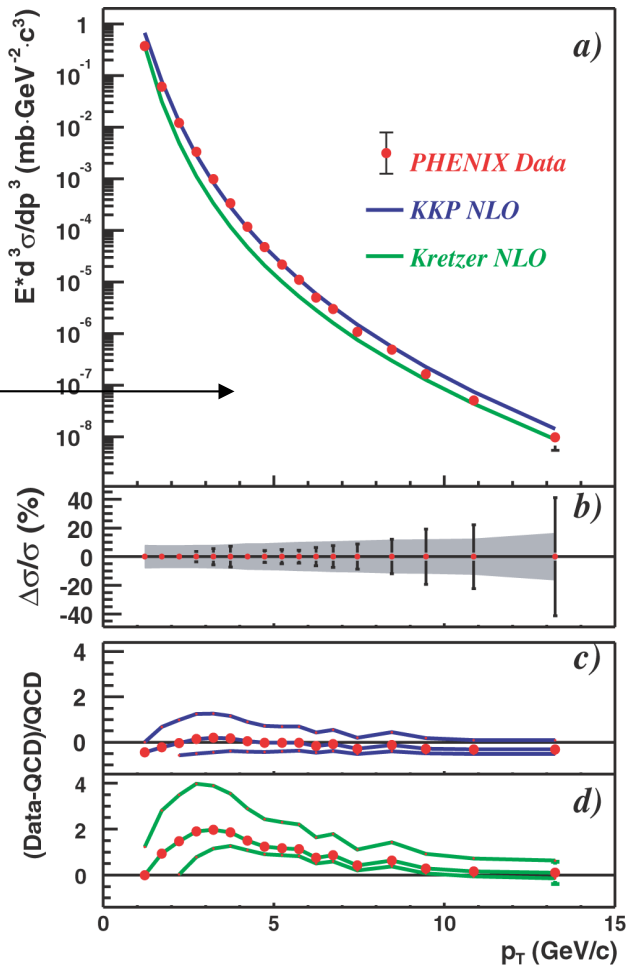
About RHIC:

-Highest energy nuclear collider in the world.
$\sqrt{s}$=200GeV, $\sqrt{s}$=500GeV.

-A QCD laboratory: Perturbative description of QCD is valid at RHIC energies

-Most versatile, capable of colliding any species on any species.

-Premier facility for studies of the spin content of the proton.



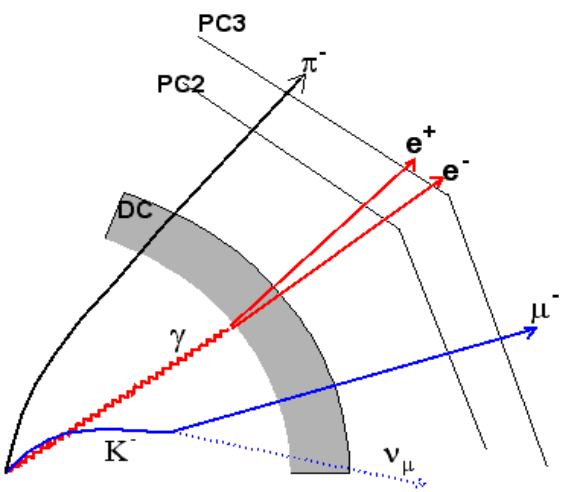
Central Spectrometers

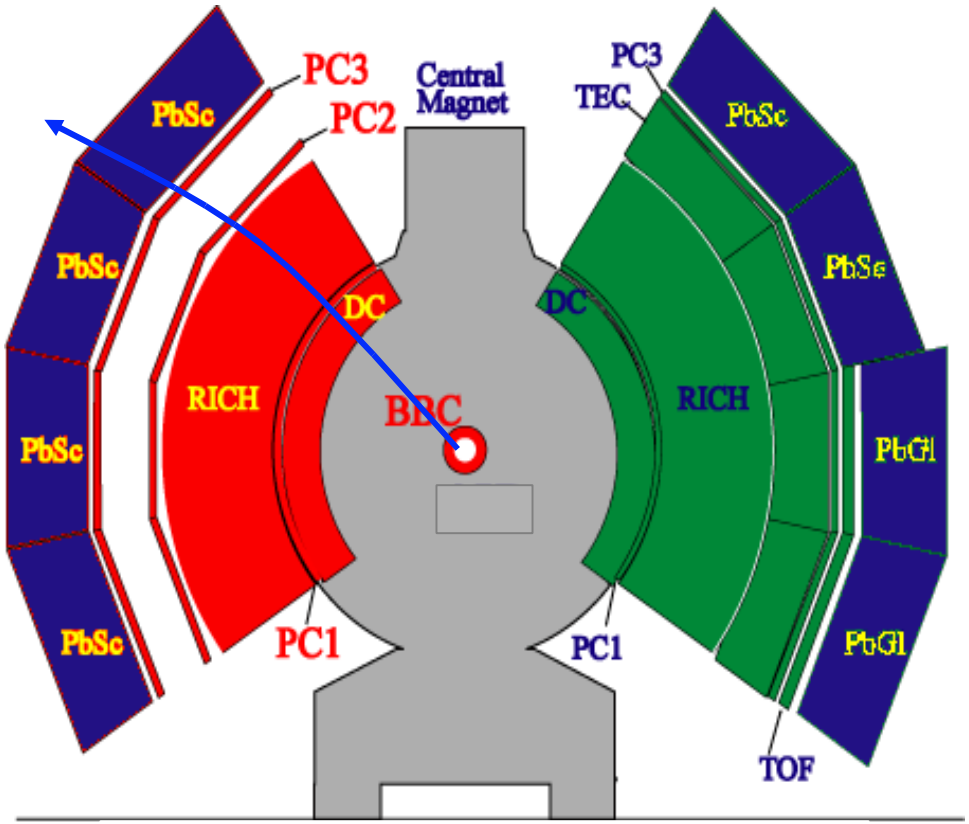
Electrons,
Photons,Hadrons

Tracking
-Drift Chamber(DC),
Pad Chambers(PC)

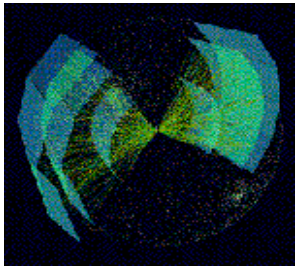
Electron and Hadron Identification
-Ring Imaging Cerenkov Counter(RICH
-ElectroMagnetic Calorimeter(EMCal)

Photons
-ElectroMagnetic Calorimeter (EMCal)





RHIC's Massive detector PHENIX has a fine-grained calorimetry 100 times finer than previous collider detectors.

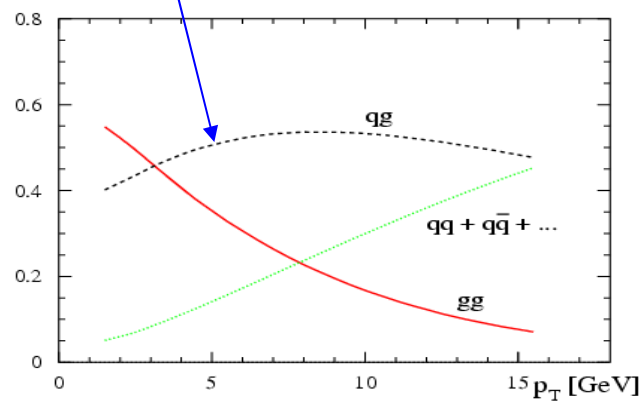


•Triggering in the central arms allow us select high PT photons, electrons and the charged pions. (Trigger funded by UCR)

• We select the Pion signal and clean up the background created by other high Pt Particles by looking at different sub detector cuts

•Identifying what kind of Fast Particles produced Čerenkov light in our sub detector (RICH) is also used for the charged pion selection process.

Since q-g starts to dominate for P_T>5GeV ,we can look for charged pions which come from a fragmenting parton.



Our key ingredients:

$$\sigma(pp \to hX) : f_q(x_1) \otimes f_g(x_2) \otimes \hat{\sigma}^{qg \to \pi X}(\hat{s}) \otimes D_q^h(z)$$

- Structure functions (needs experimental input)
- pQCD hard scattering rates (calculable in pQCD)
- Fragmentation functions (needs experimental input)

The pions Fragmentation functions contain all long-distance interactions, they are not calculable but they are universal:

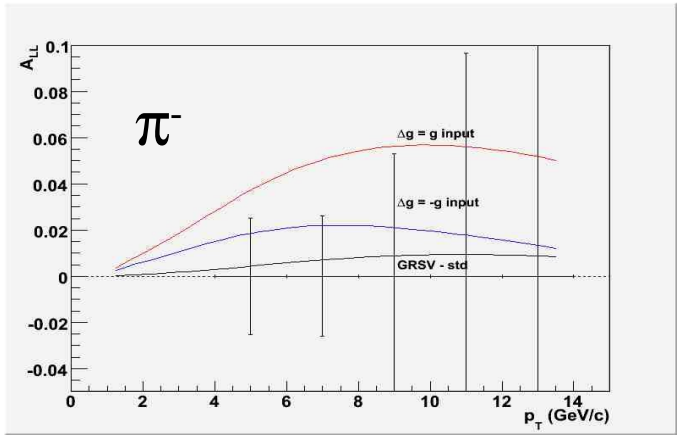
$$D^{\pi^+}_u > D^{\pi^0}_u > D^{\pi^-}_u \,,\; D^{\pi^+}_g = D^{\pi^-}_g$$

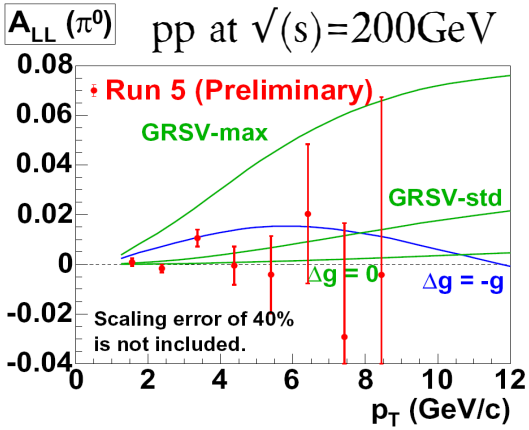
Charged Pion A_{LL} has sensitivity to the sign of Δg

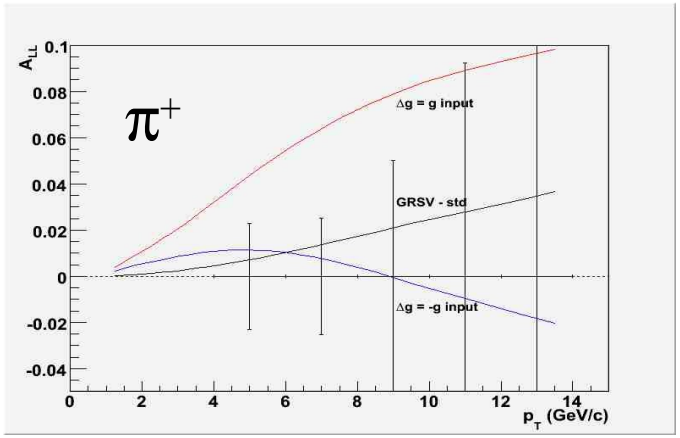
Just like in the pion's fragmentation functions

the size of the asymmetries are ordered.

e.g, if $\Delta g>0$, then: $A^{\pi+}_{LL} > A^{\pi 0}_{LL} > A^{\pi-}_{LL}$







Projections for A_{LL} of pi+ and pi- for Run5 with 3.8 pb^{-1} and 48% polarization and preliminary neutral pion double asymmetries result

Tracks can be divided into different categories according to RICH response, i.e.:

- RICH Hit: $e^{\pm}$ background and high-p_T $\pi^{\pm}$
- No RICH Hit: decay background and high-p_T K,p

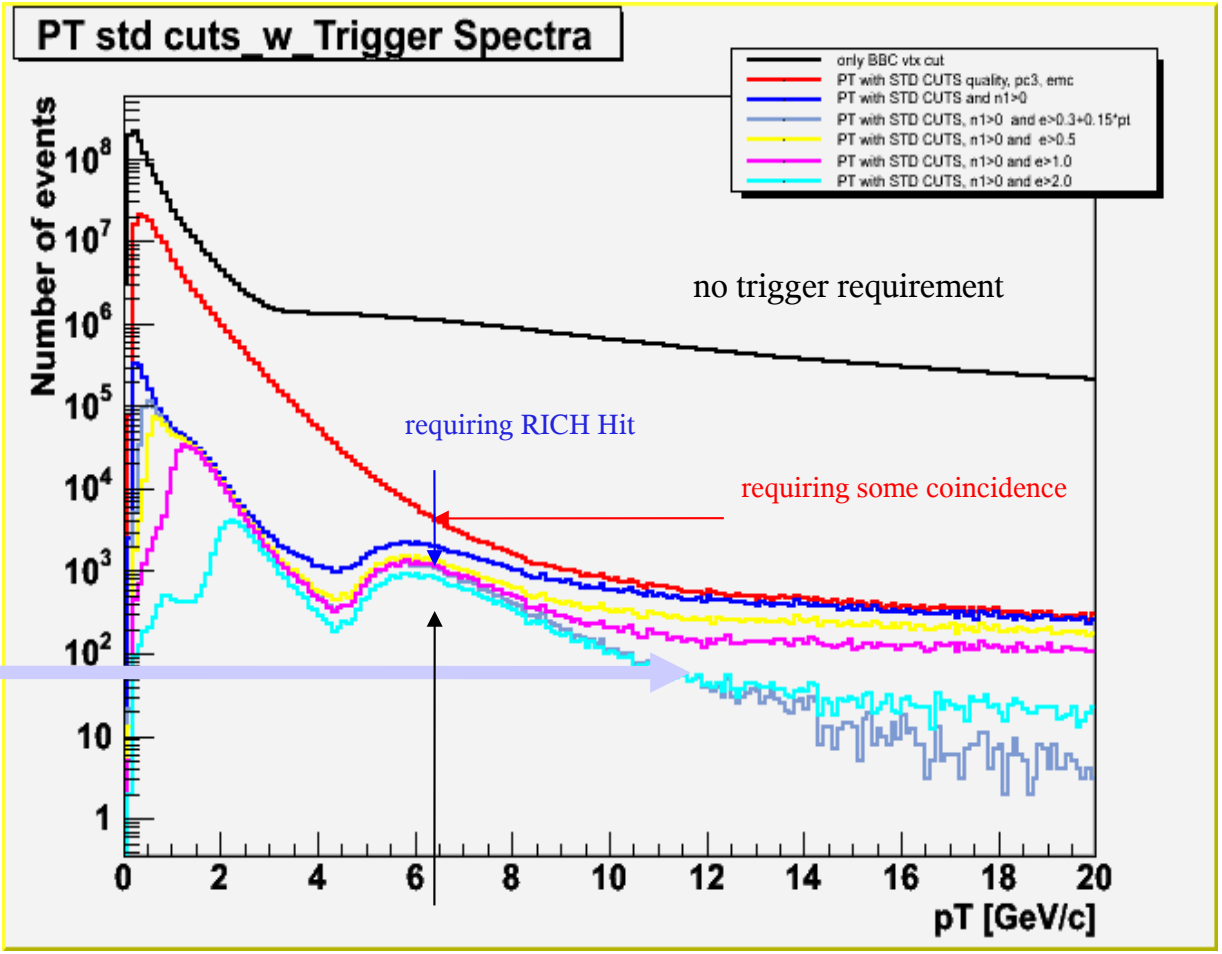
Particle	Electron	Pion	Kaon	Proton
Threshold	30 MeV	4.7 GeV	16 GeV	30 Gev

The trigger used is a coincidence hit in the RICH(Ring Imaging Cerenkov Counter) and a shower in the Electro-Magnetic Calorimeter.

EMCal Energy Cut Study

Std Cuts with Quality>7

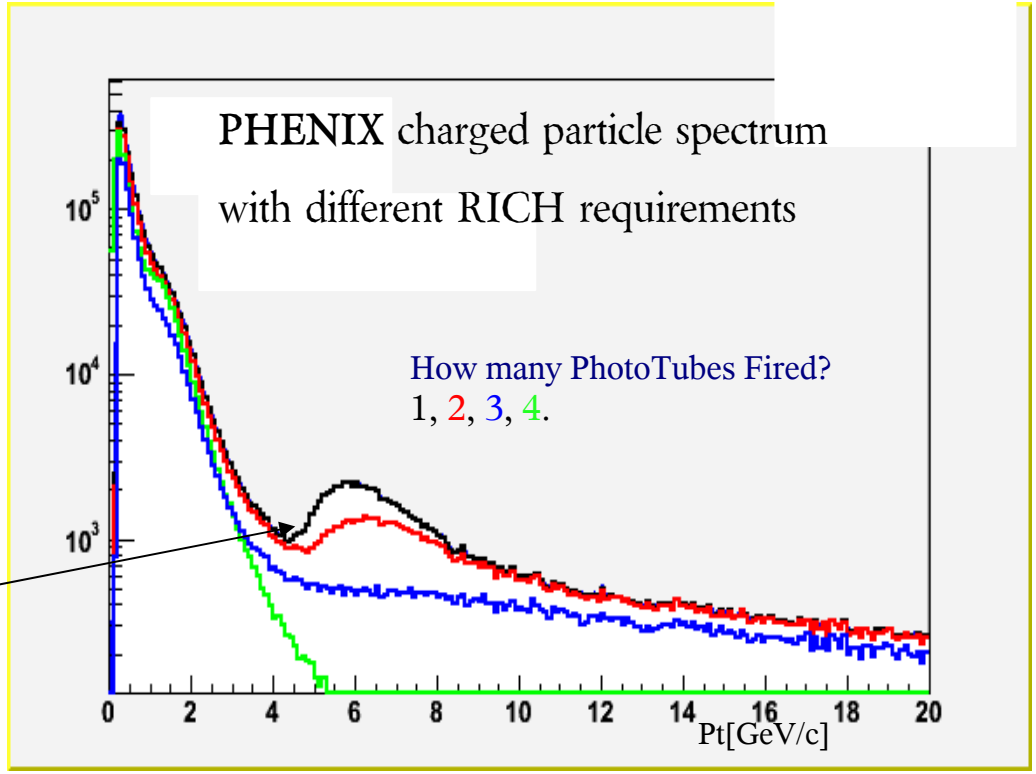
PT dependent Energy cut greatly reduces background



Charged Pions begin to emit light in the RICH, different EMC energy cuts show how we can begin to separate background

Influence of Cerenkov Detector Cuts

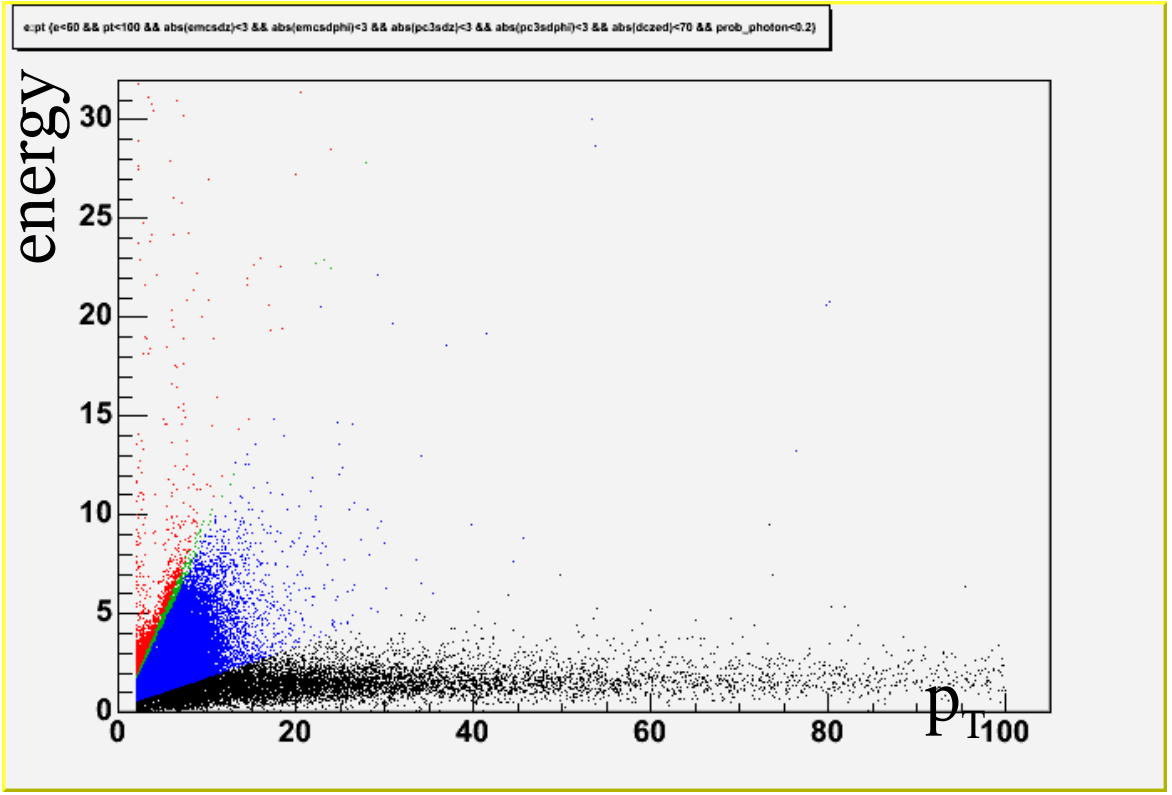
$\pi^{\pm}$



Triggered tracks and different PMT firing requirements

also show a well defined charged pion signal

Energy cuts



p_T

Black: Removed by "e>0.3 + 0.15*pt"

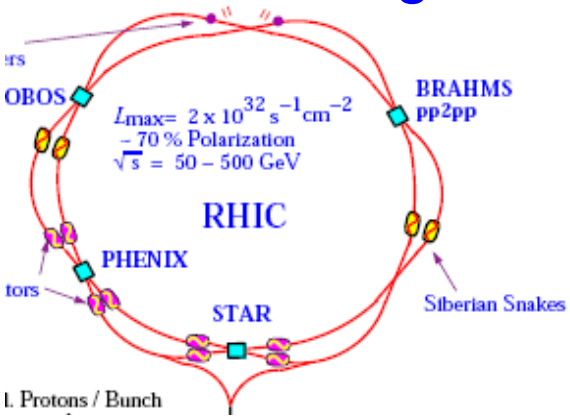
Red: removed by "e/mom < 1"

Green: removed by "e/mom < 0.9"

Blue: Remaining sample

After intense detector studies,
we then look require that all candidate particles match these cuts

We then look at the number of particles detected with the polarized proton beams in different configurations

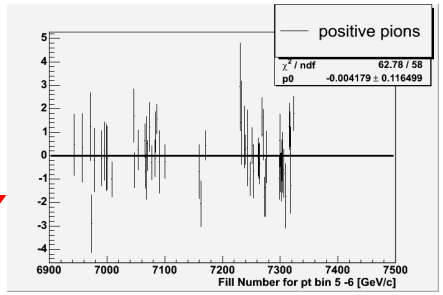


There are 120 bunch crossings, each bunch crossing has luminosity information, and the spin pattern in each beam.

$$A_{LL} = \frac{1}{P^2} \frac{N_{++}(p_T) - RN_{+-}(p_T)}{N_{++}(p_T) + RN_{+-}(p_T)}, R = \frac{L_{++}}{L_{+-}}$$

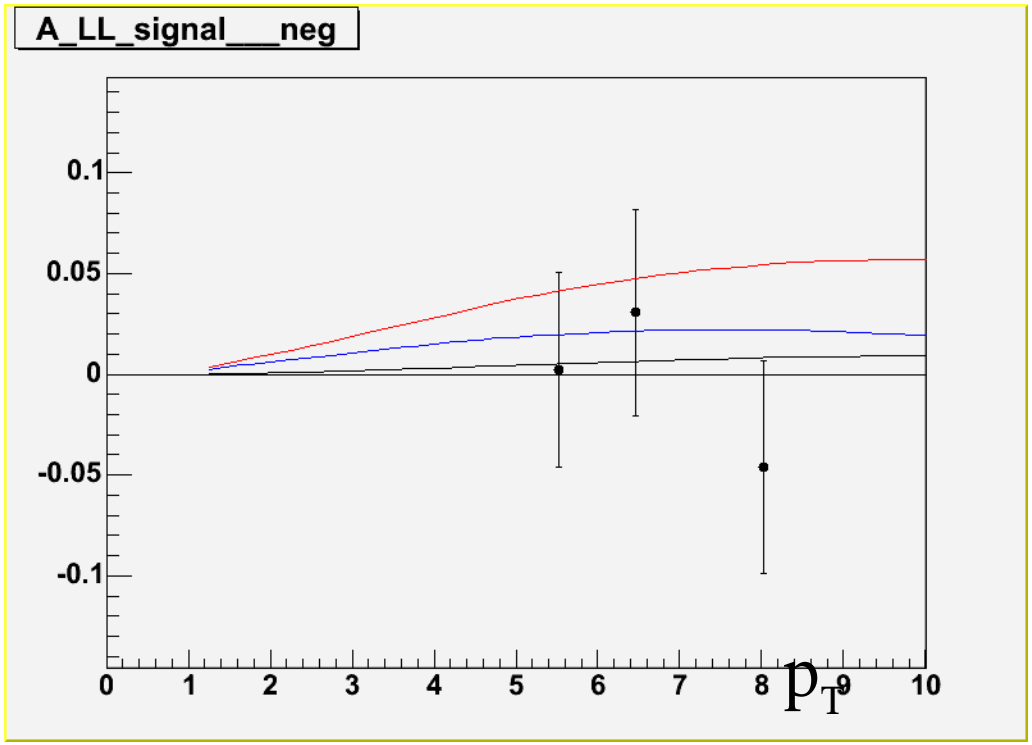
The charged pion yields are thus calculated:
By Transverse Momentum range(PT Bin)
By Bunch Crossing

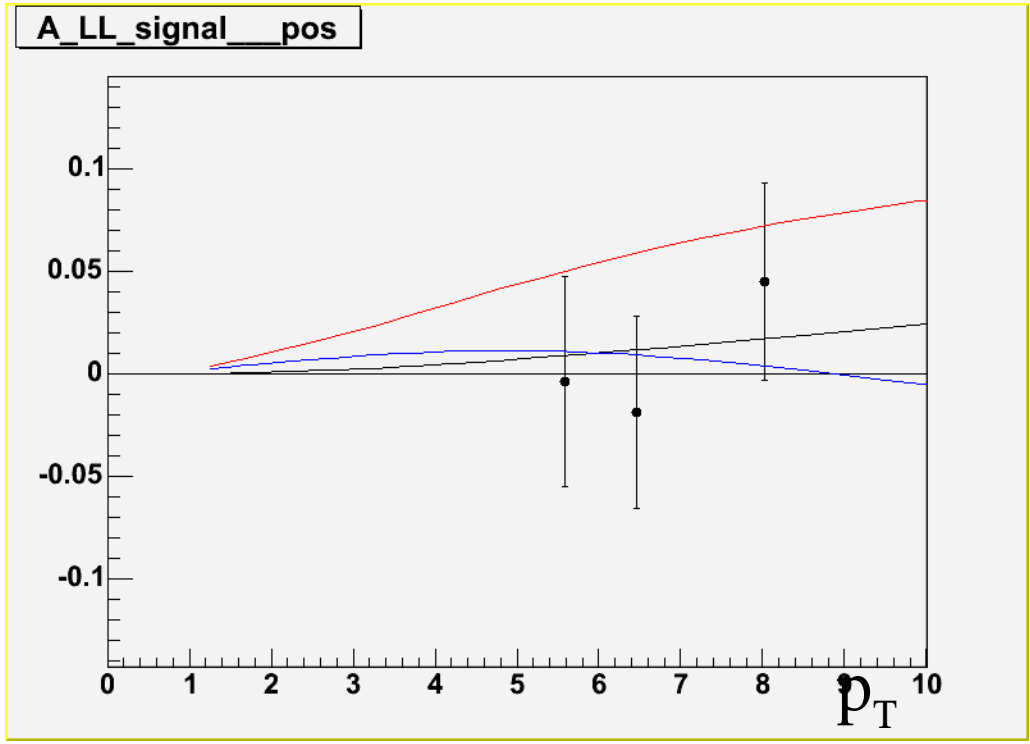
ALL is Finally calculated by Fill.



Measured Double Spin Longitudinal Asymmetries
Results with only Statistical Errors-A_{LL}

$\pi-$ $\pi+$





TO DO:

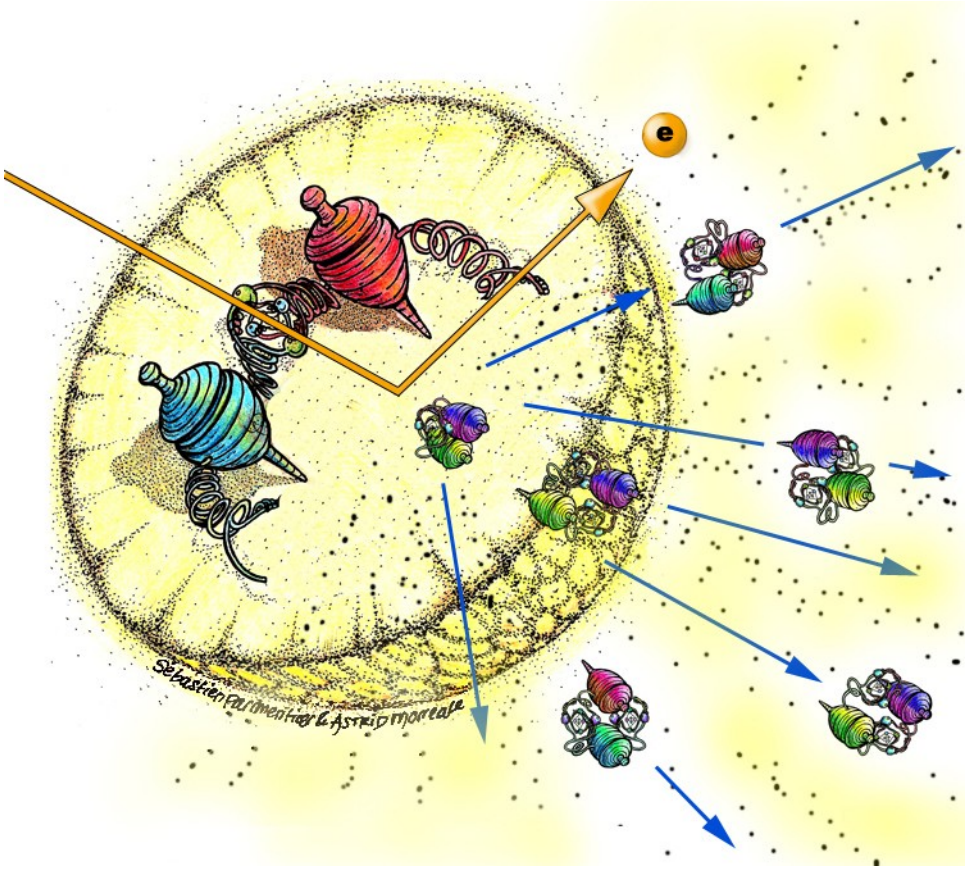
Combine run 6 statistics(twice the luminosity obtained in Run5)

Montecarlo Simulation to understand the efficiencies of the detector

Calculate the cross section.

Thank You!

BACKUP SLIDES


Sébastien Fourmentier & Astrid Moreale
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A General Note on Systematic errors:

COLLIDER:

False asymmetries:

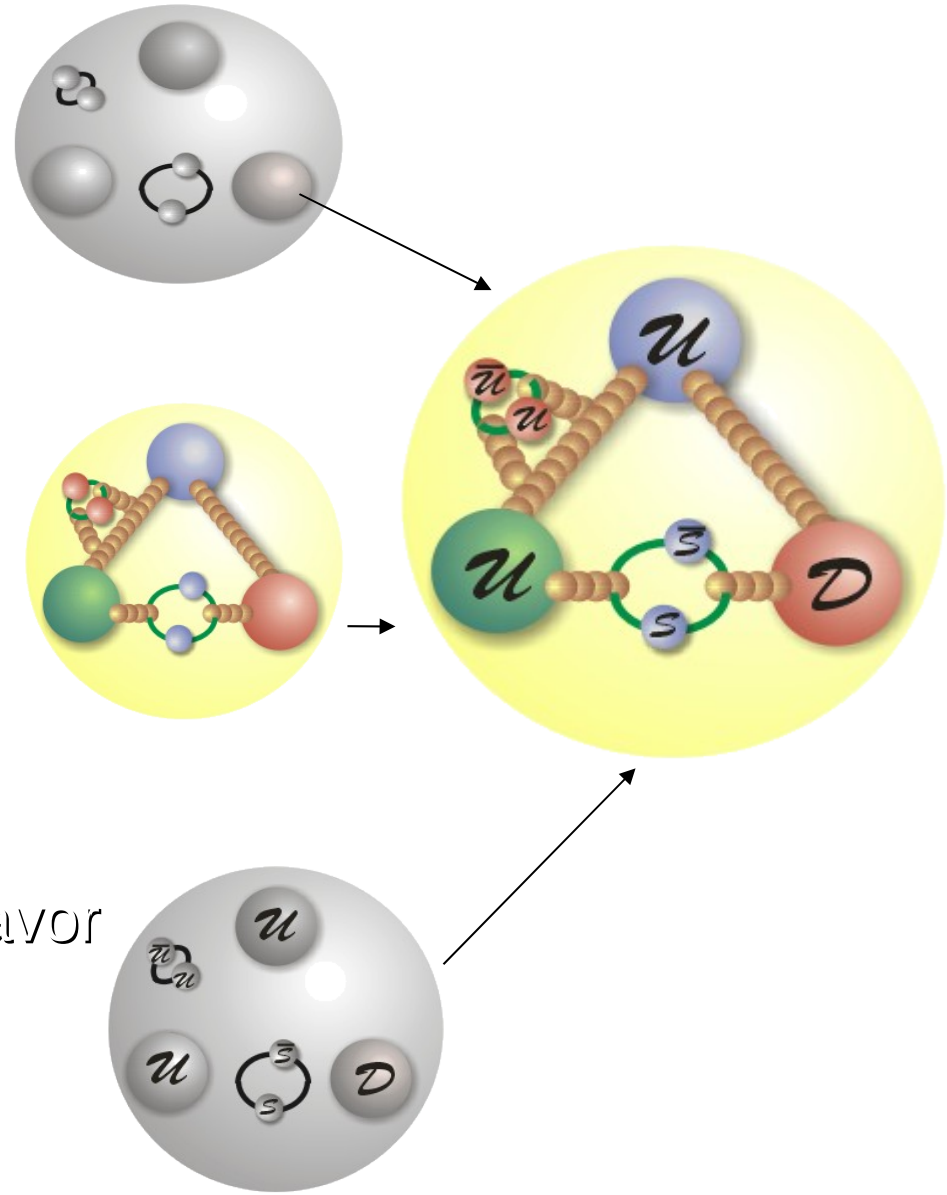
incorrect measurements of relative luminosities (PHENIX measures its own luminosity for each crossing and compares it to the other experiments)

Scale errors:

If the polarization is also not measured correctly the scale of our A_{LL}'s is modified.

Probing the Proton Structure

- EM interaction
  - Photon
    - Sensitive to electric charge^2
    - Insensitive to color charge
- Strong interaction
  - Gluon
    - Sensitive to color charge
    - Insensitive to flavor
- Weak interaction
  - Weak Boson
    - Sensitive to weak charge ~ flavor
    - Insensitive to color



Why Spin ?

- At this point there is great difficulty constructing a theory that gives good descriptions of both the neutron and proton structure.

- **Spin** provides one of the most precise measurements of the **standard model.**
    - Polarized beams gave us a 25% gain in statistics

  $\mathrm{Sin}^2[\theta_w]=0.23031\pm0.000047$

- **Spin** measurements have helped understand the role of the V-A form of the weak Lagrangian.

- **A**ctive study of spin phenomena has led to numerous applications on other fields outside of collider physics experiments.

  – Nuclear Magnetic Resonance (NMR), Magnetic Resonance Imaging(MRI) , Giant Magneto-Resistive Effect,(GMR) (drive head technology), Spintronics.

- Parity invariance :
  helicity $\vec{J}\cdot\vec{p}/|\vec{p}|$ is pseudoscalar under space reflection

$$\hat{\mathrm{P}}\,|\,\vec{p},\,\lambda\,\rangle \;=\; \eta\,|\,-\vec{p},\,-\lambda\,\rangle \qquad (\,\eta \;=\; \text{intrinsic parity} \times \text{phase}\,)$$

- one can show that for our amplitudes :

$$\boxed{h_{-\lambda,-\lambda';-\Lambda,-\Lambda'}(\theta) \;=\; (-1)^{(\lambda-\lambda'-\Lambda+\Lambda')/2}\; h_{\lambda\lambda';\Lambda,\Lambda'}(\theta)}$$

- therefore,

$$\begin{aligned} h_{--;--} &= h_{++;++}(\theta) \\ h_{-+;-+} &= h_{+-;+-}(\theta) \\ h_{-+;--} &= -\,h_{+-;++}(\theta) \qquad \text{etc.} \end{aligned}$$

- Time reversal invariance :
  relates $A + B \to C + D$ to $C + D \to A + B$
  Here we have elastic reaction $A + B \to A + B$

- one can show that for our amplitudes :

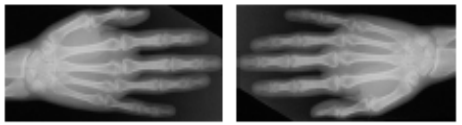
$$\boxed{h_{\Lambda,\Lambda';\lambda,\lambda'}(\theta) \;=\; (-1)^{(\lambda-\lambda'-\Lambda+\Lambda')/2}\; h_{\lambda\lambda';\Lambda,\Lambda'}(\theta)}$$

- therefore,

$$\begin{aligned} h_{+-;--} &= -h_{--;+-}(\theta) \\ h_{+-;++} &= -h_{++;+-}(\theta) \end{aligned}$$

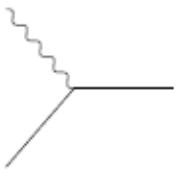
Chirality (or helicity-conservation) :

- saw that at high energies helicity = chirality



$$\Psi_{R,L} = \frac{1}{2}\left[\mathbb{1} \pm \gamma_5\right]\Psi$$

- preserved in all vector and axial-vector current interactions
- preserved by all perturbative QCD and electroweak interactions



$$\gamma,\, W^{\pm},\, Z^0 : \quad \begin{cases} \bar{\Psi}\gamma^\mu\Psi = \bar{L}\gamma^\mu L + \bar{R}\gamma^\mu R \\ \bar{\Psi}\gamma^\mu\gamma^5\Psi = \bar{L}\gamma^\mu L - \bar{R}\gamma^\mu R \end{cases}$$

$$g : \quad \bar{\Psi}\gamma^\mu\frac{\lambda}{2}\Psi = \bar{L}\gamma^\mu\frac{\lambda}{2}L + \bar{R}\gamma^\mu\frac{\lambda}{2}R$$

- violated for non-standard ((pseudo)scalar,tensor) interactions

- Parity invariance (if it holds) forbids
  - single-longitudinal spin asymmetries of the form

$$A_L = \frac{\sigma_{\rightarrow} - \sigma_{\leftarrow}}{\sigma_{\rightarrow} + \sigma_{\leftarrow}} \equiv \frac{\sigma_{+} - \sigma_{-}}{\sigma_{+} + \sigma_{-}}$$

  - certain azimuthal-angular dependences for transverse polarization
- single-transverse spin asymmetries of the form

$$A_N = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}}$$

  are allowed, but require helicity flips and complex amplitudes
  (actually, require "Im{ non-flip $\times$ single-flip* }")

- double-longitudinal spin asymmetries,

$$A_{LL} = \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+}}$$

  are allowed. Reduce under parity to

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

- double-transverse spin asymmetries,

$$A_{TT} = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}}$$

  are allowed, but require helicity flip or annihilating fermion lines

- [occasionally may use symmetry constraints for identical particles (e.g., $pp \to pp$)]

USEFUL TERMINOLOGY:

Figure of merit:

Product of luminosity and the squared values of the polarization of beam &target.

Inclusive measurement:

A partial measurement. Only a few produced particles, sometimes only one, are singled out for identification and measurement, ignoring the details of all other interaction products.

Semi-inclusive:

Measurements that detect final state hadrons in coincidence with the scattered probe.

Factorization theorem:
High-energy QCD processes involve both perturbative and non-perturbative dynamics. The two dramatically different dynamics (characterized by Q and by a hadronic scale ,respectively) factorize.

Universality of pdf's:They are the same regardless of the process involved.

Pseudorapidity:

Spatial coordinate describing the angle of a particle relative to the beam axis.

It is defined as $\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right),$ where theta is the angle relative to the beam axis.

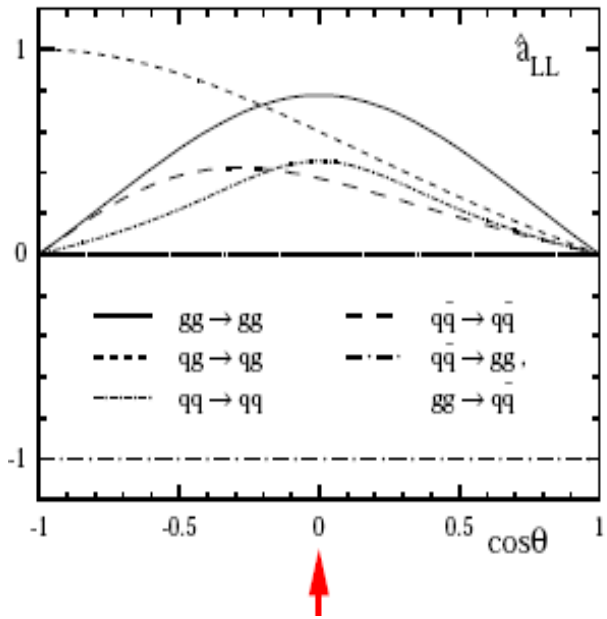
$$y = \frac{1}{2}\ln\left(\frac{E + p_L}{E - p_L}\right)$$

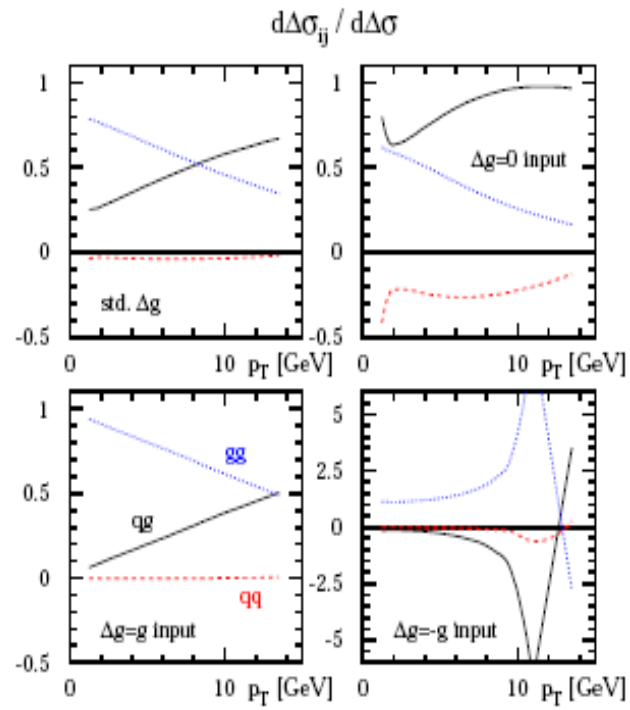
Rapidity: p_L is the component of the momentum along the beam direction.

Pseudo rapidity does not depend on the energy of the particle, only on the polar angle of its trajectory.

The rapidity is used in some hadron colliders(not in PHENIX) over the polar angle because particle production is constant as a function of rapidity.

The difference in the rapidity of two particles is independent of Lorentz boosts along the beam axis.





subprocess contributions:

fairly independently on what we assume about Δg we find:

gg processes:
dominate for $p_T \lesssim 10\,\mathrm{GeV}$

qg processes:
take over for $p_T \gtrsim 10\,\mathrm{GeV}$

qq processes:
always small unless p_T very large

→ even for $\hat{a}_{\mathrm{LL}} > 0$ we can have $A_{\mathrm{LL}} < 0$ *if* $\Delta f_a(x_a)\Delta f_b(x_b) < 0$