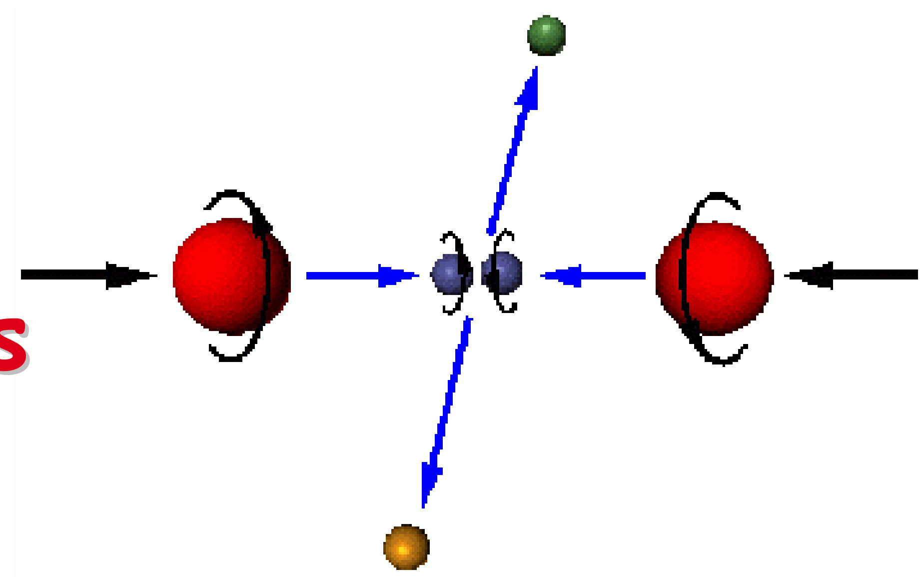
PHENIX Spin Program: recent results and prospects



Kenneth N. Barish

SPIN-Praha-2003
12-19 July, 2003

Questions RHIC hopes to address

- What makes up the spin of the proton?
  - ⇒ polarized proton collisions
- Why are quarks confined inside protons?
  - ⇒ heavy-ion collisions
- What makes up most of the mass around us?
  - ⇒ recreate "simple" vacuum

Outline

Introduction to PHENIX and RHIC

PHENIX Spin Physics

» Sensitivity to gluon contribution to proton spin (ΔG)
  - Leading hadrons, prompt γ production, heavy flavor production

» Quark and anti-quark helicity distributions

» Transversity

Introduction to heavy ion physics

Experimental Status

» Heavy ion physics
  - "hard probes" in Au+Au, p+p, and d+Au collisions

» Spin physics
  - p+p spin-averaged measurements
  - Establishment of polarized protons
  - Status of asymmetry measurements

Future Prospects

PHENIX

12 Countries; 57 Institutions; 460 Participants

Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
France	LPC, University de Clermont-Ferrand, Clermont-Ferrand
	Dapnia, CEA Saclay, Gif-sur-Yvette
	IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
	LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
	SUBATECH, Ecòle des Mines at Nantes, Nantes
Germany	University of Münster, Münster
Hungary	Central Research Institute for Physics (KFKI), Budapest
	Debrecen University, Debrecen
	Eötvös Loránd University (ELTE), Budapest
India	Banaras Hindu University, Banaras
	Bhabha Atomic Research Centre, Bombay
Israel	Weizmann Institute, Rehovot
Japan	Center for Nuclear Study, University of Tokyo, Tokyo
	Hiroshima University, Higashi-Hiroshima
	KEK, Institute for High Energy Physics, Tsukuba
	Kyoto University, Kyoto
	Nagasaki Institute of Applied Science, Nagasaki
	RIKEN, Institute for Physical and Chemical Research, Wako
	RIKEN-BNL Research Center, Upton, NY
	University of Tokyo, Bunkyo-ku, Tokyo
	Tokyo Institute of Technology, Tokyo
	University of Tsukuba, Tsukuba
	Waseda University, Tokyo
S. Korea	Cyclotron Application Laboratory, KAERI, Seoul
	Kangnung National University, Kangnung
	Korea University, Seoul
	Myong Ji University, Yongin City
	System Electronics Laboratory, Seoul Nat. University, Seoul
	Yonsei University, Seoul
Russia	Institute of High Energy Physics, Protovino
	Joint Institute for Nuclear Research, Dubna
	Kurchatov Institute, Moscow
	PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
	St. Petersburg State Technical University, St. Petersburg
Sweden	Lund University, Lund
USA	Abilene Christian University, Abilene, TX
	Brookhaven National Laboratory, Upton, NY
	University of California - Riverside, Riverside, CA
	University of Colorado, Boulder, CO
	Columbia University, Nevis Laboratories, Irvington, NY
	Florida State University, Tallahassee, FL
	Georgia State University, Atlanta, GA
	University of Illinois Urbana Champaign, IL
	Iowa State University and Ames Laboratory, Ames, IA
	Los Alamos National Laboratory, Los Alamos, NM
	Lawrence Livermore National Laboratory, Livermore, CA
	University of New Mexico, Albuquerque, NM
	New Mexico State University, Las Cruces, NM
	Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
	Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
	Oak Ridge National Laboratory, Oak Ridge, TN
	University of Tennessee, Knoxville, TN
	Vanderbilt University, Nashville, TN

The PHENIX Detector

Philosophy:

- ✓ High rate capability & granularity
- ✓ Good mass resolution and particle ID
- ➢ Sacrifice acceptance

Central Arm Tracking
  Drift Chamber, Pad Chambers, Time Expansion Chamber

Muon Arm Tracking
  Muon Tracker

Calorimetry
  PbGl and PbSc

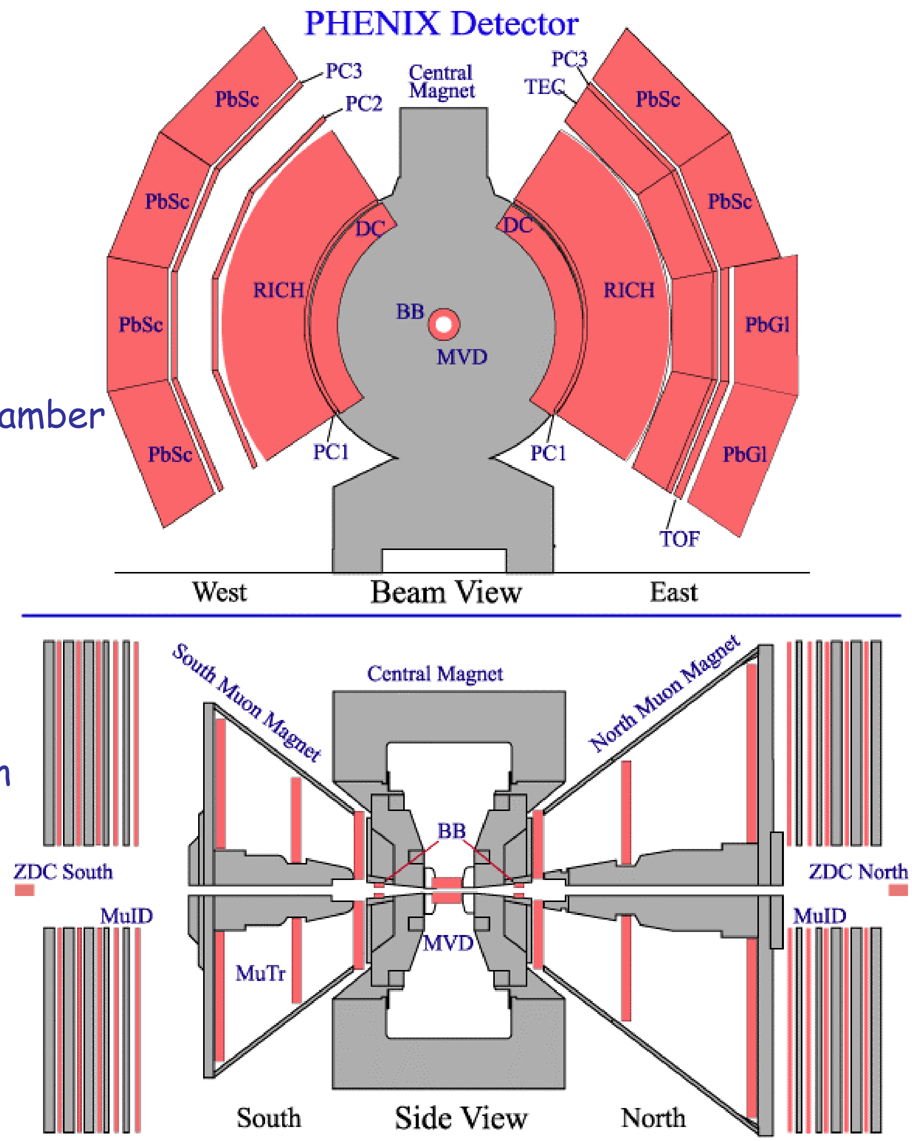
Particle Id
  Muon Identifier, RICH, TOF, TEC

Luminosity Counters/Vertex Detectors
  BBC, ZDC/SMD, Local Polarimeter, forward hadron calorimeters, NTC, MVD

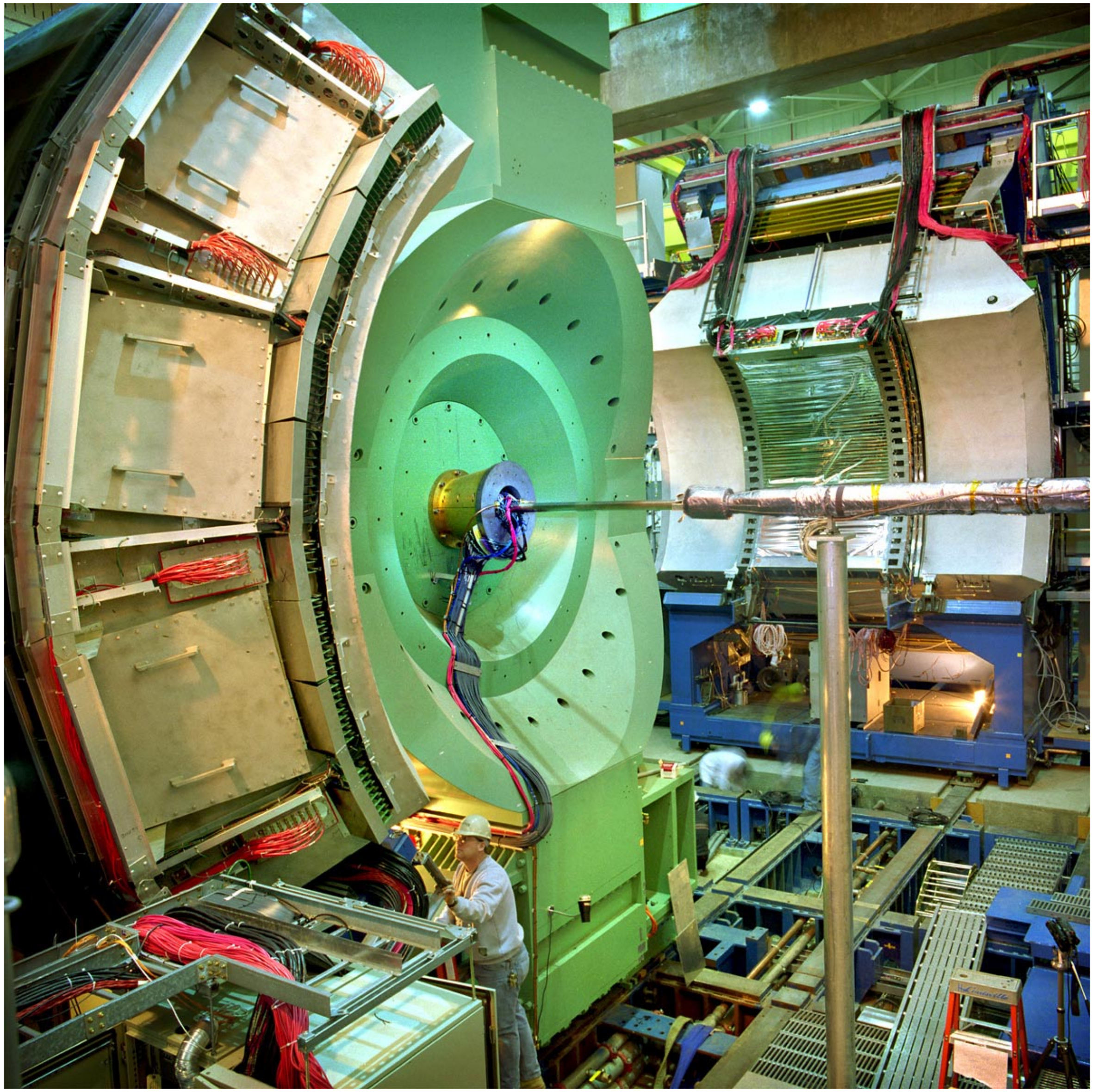
DAQ
  High bandwidth

Trigger
  Level 2
  Level 1 (GL1P, muId, EMC/RICH)

Online
  Calibration and production

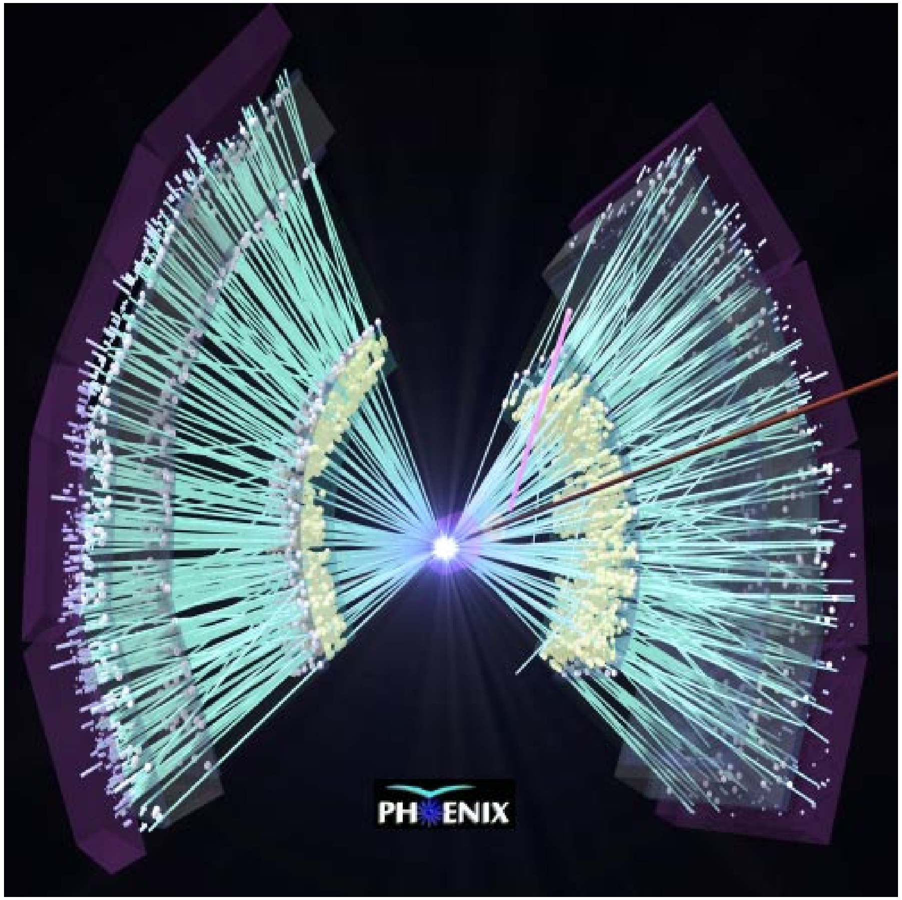


The PHENIX detector: central arms

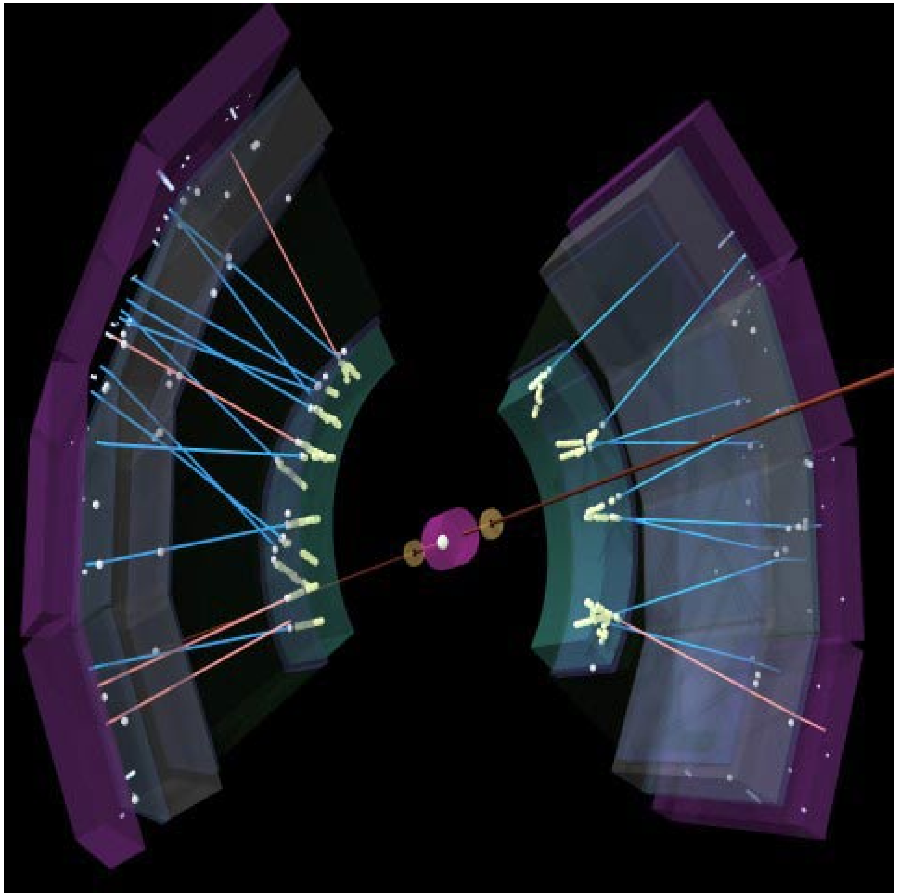


Two collisions in the central arms

2001/2002 Au-Au



2002/2003 d-Au



Relativistic Heavy Ion Collider

Design Parameters:

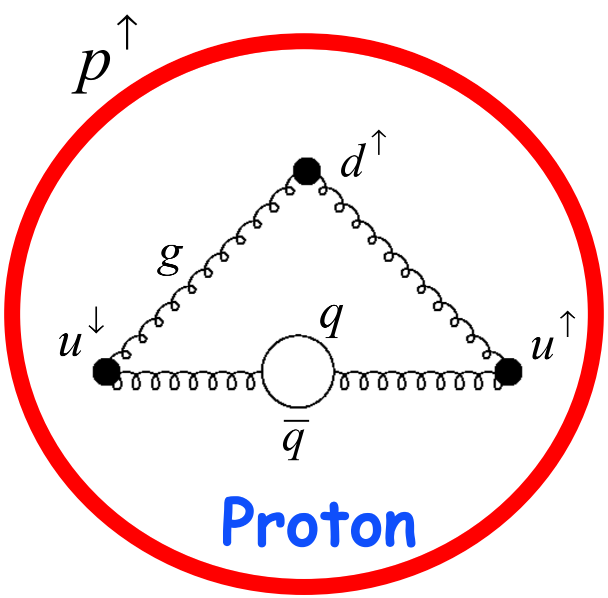
Performance	Au + Au	p+p
$\sqrt{s_{nn}}$	200 GeV	500 GeV
L [cm^{-2} s^{-1}]	2×10^{26}	2×10^{32}
Cross-section	7 barns	60 mbarn
Interaction rates	14 kHz	12 MHz

RHIC Capabilities

- ✓ Au + Au collisions at 200 GeV/u
- ✓ p + p collisions up to 500 GeV
- ✓ spin polarized protons (70%)
- ✓ lots of combinations in species and energy in between

What makes up the spin of the proton?

- Successful description of baryon μ_N in quark model
  - Quark carries all of proton spin
- Surprising data from polarized lepton-nucleon scattering
  - $\Delta\Sigma = \Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s} \approx 0.2 \rightarrow$ "spin crisis"
- Some possible resolutions for "spin crisis":
  - Gluons carry majority of proton spin
  - Anti-quark polarized



Quark Spin — Gluon Spin

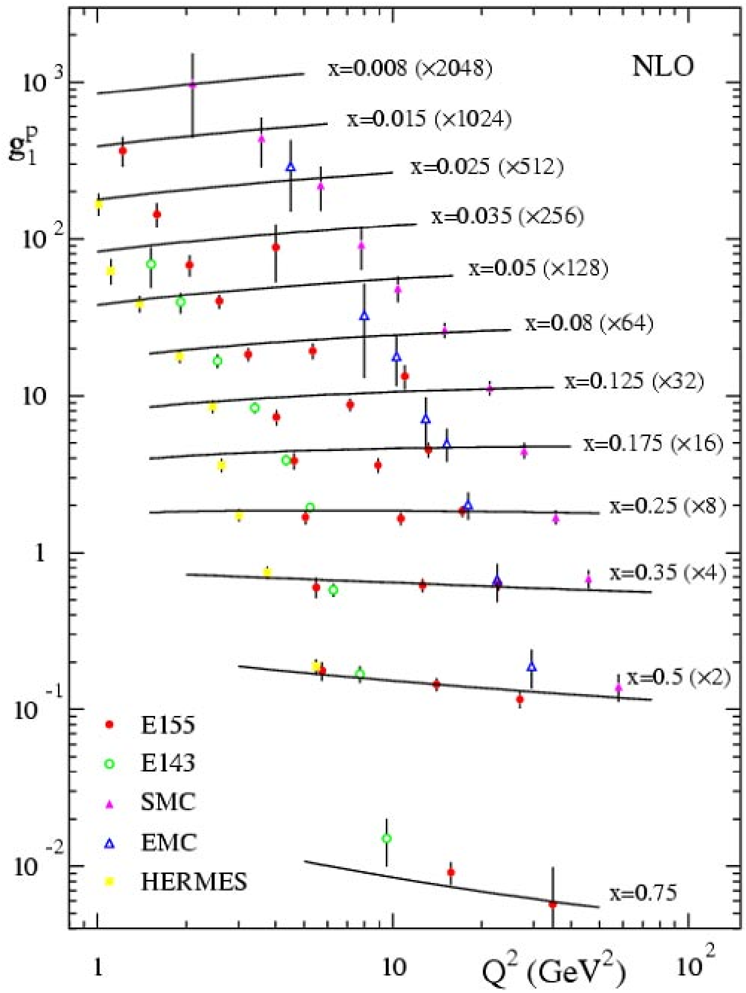
Spin $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

Orbital Angular Momentum

Experimental data on proton structure

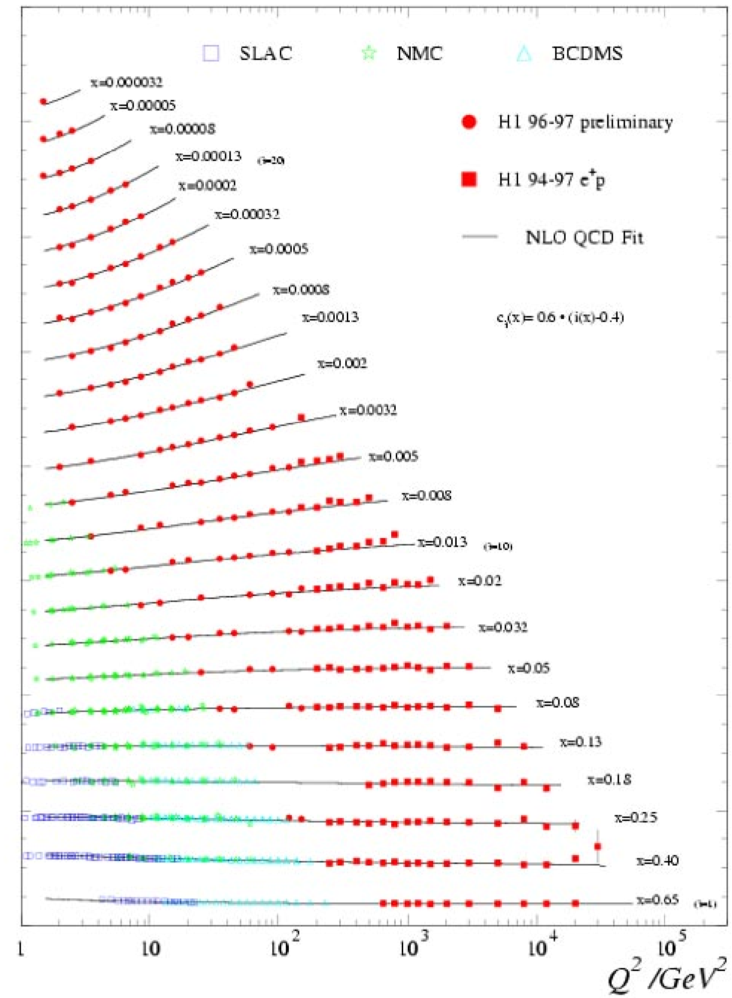
polarized

g_1



unpolarized

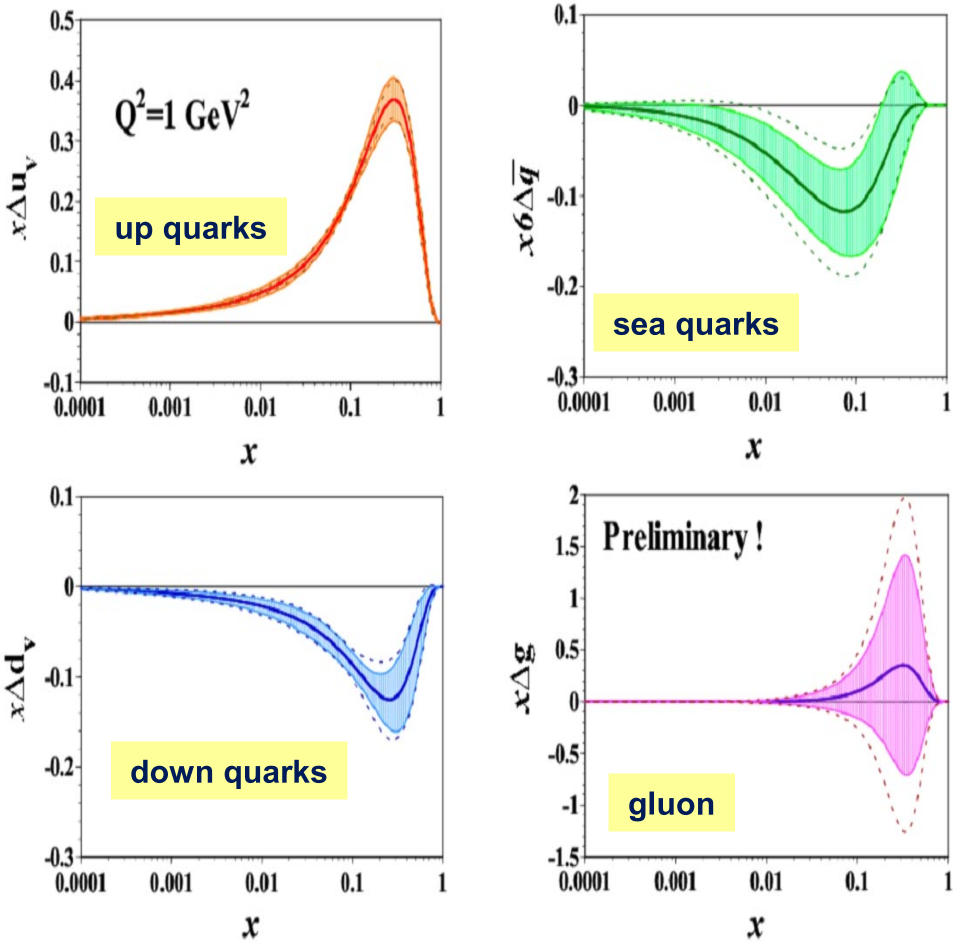
F_2



Gluon PDF's extracted through scaling violations

Polarized quark and gluon distributions

M. Hirai et al (AAC collab)



$$\Delta\Sigma = \int_0^1 \Delta\Sigma(x,Q^2)dx$$ is constrained

$$\Delta G = \int_0^1 \Delta g\left(x,Q^2\right)dx$$ is largely unknown

Proton Spin Structure at PHENIX

Gluon Polarization ΔG

π Production $A_{LL}(gg, gq \to \pi + X)$

Prompt Photon $A_{LL}(gq \to \gamma + X)$

Heavy Flavors $A_{LL}(gg \to c\bar{c}, b\bar{b} + X)$

Flavor decomposition

$$\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$$

W Production

$A_L(u + \bar{d} \to W^+ \to \ ^+ + \nu_l)$

$A_L(\bar{u} + d \to W^- \to \ ^- + \bar{\nu}_l)$

Transverse Spin

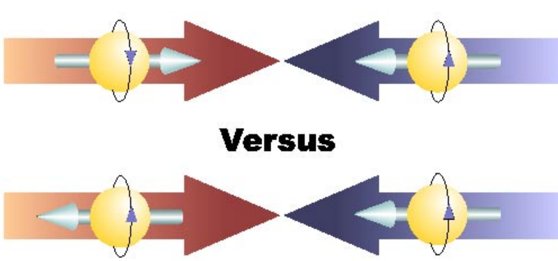
Transversity δq:

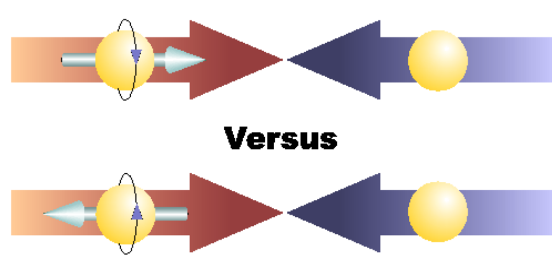
π^+, π^- Interference fragmentation:

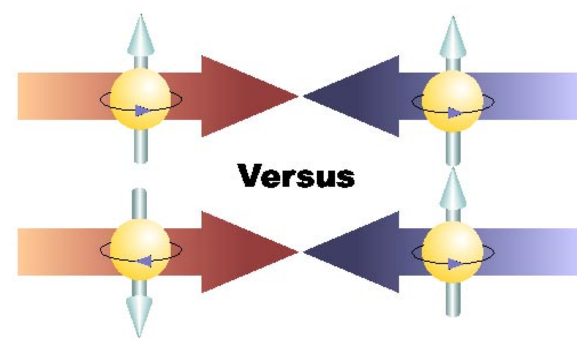
$A_T(p_\perp p \to (\pi^+, \pi^-) + X)$

Drell Yan A_{TT}

Single Asymmetries A_N





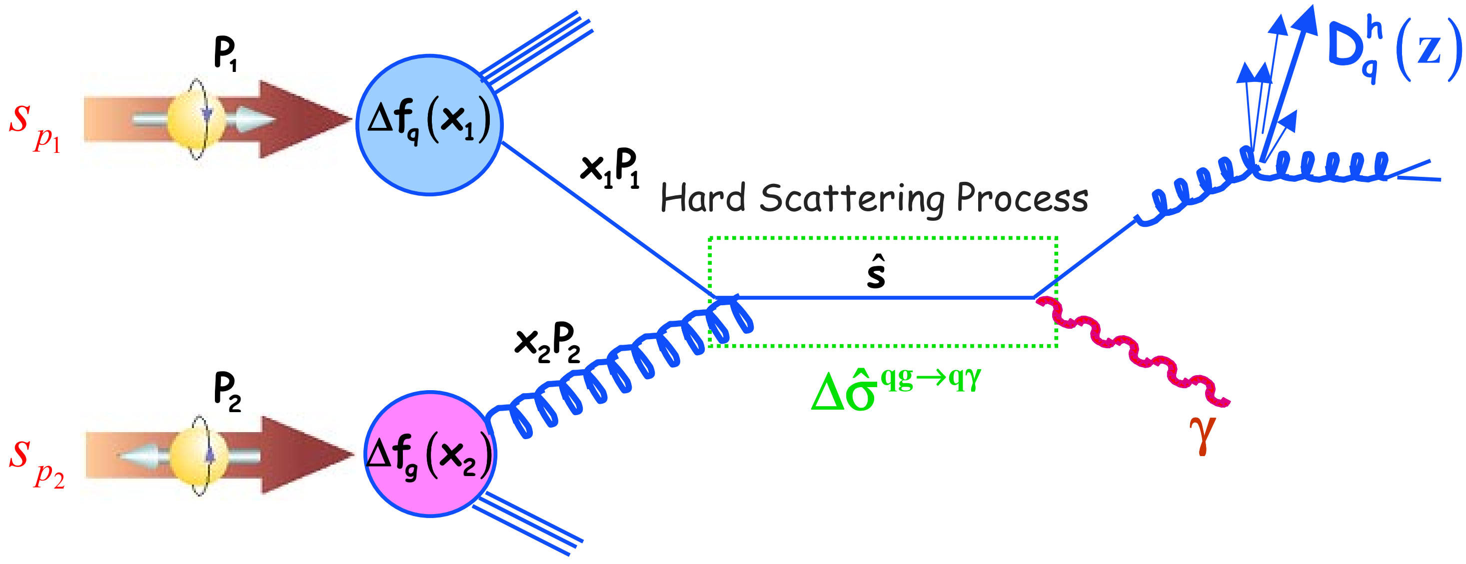


PHENIX

K. Barish

ΔG with a Polarized Proton Collider

Scattering processes in polarized p+p

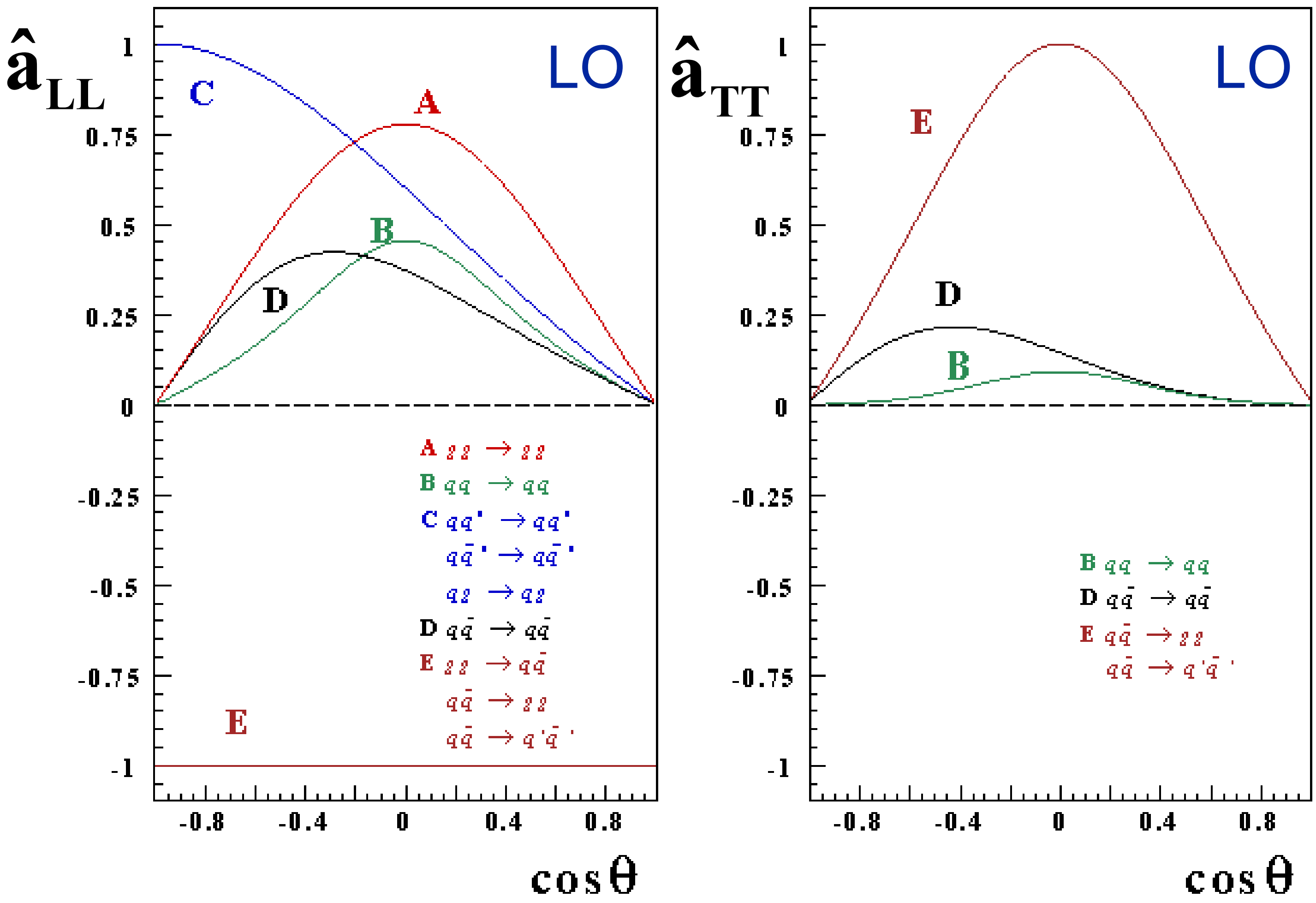


$$\Delta\sigma(pp\to\gamma X) \quad \Delta f_q(x_1)\otimes\Delta f_g(x_2)\otimes\Delta\hat{\sigma}^{qg\to q\gamma}(\hat{s})$$

$$A_{LL}=\frac{\sigma^{\uparrow\uparrow}-\sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow}+\sigma^{\uparrow\downarrow}}\equiv\frac{\Delta\sigma}{\sigma}=\hat{a}_{LL}(qg\to q\gamma)\otimes\frac{\Delta g(x_1)}{g(x_1)}\otimes\frac{\Delta q(x_2)}{q(x_2)}$$

$\Delta\hat{\sigma}/\hat{\sigma}$

LO pQCD partonic level asymmetries

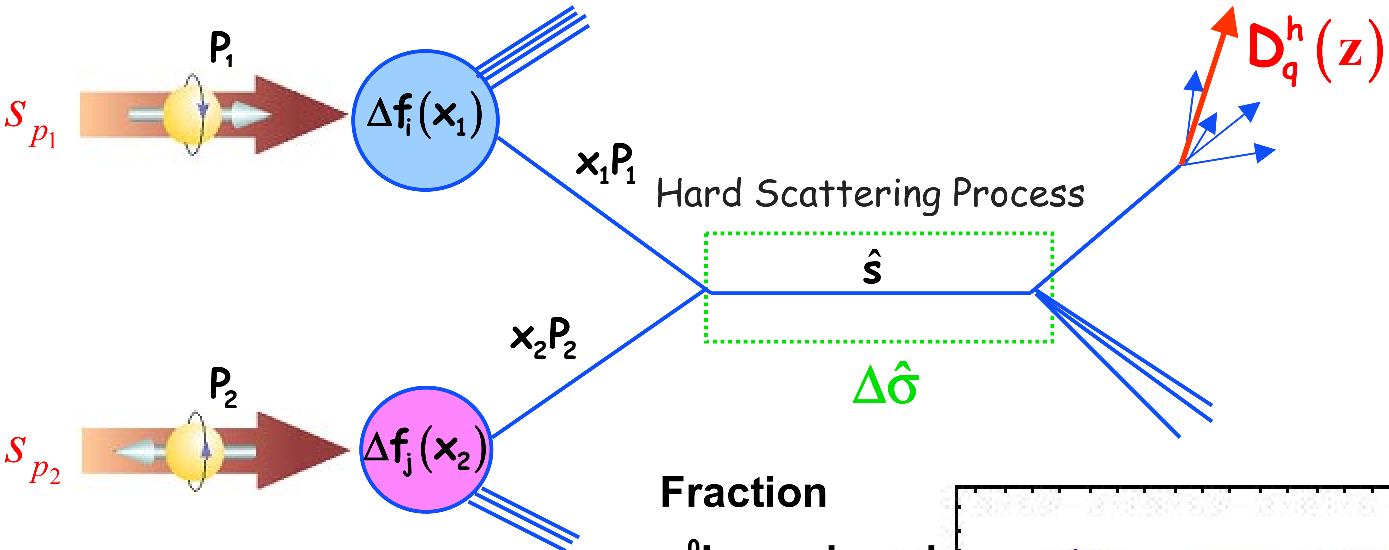


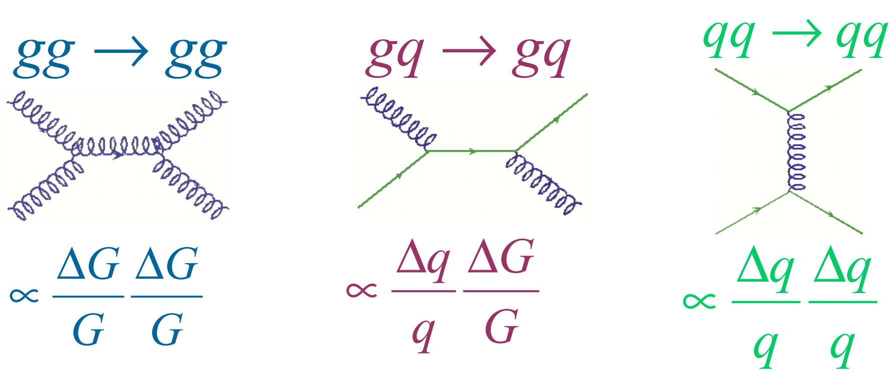
NLO corrections are now known for all relevant reactions

ΔG IN PHENIX (1)

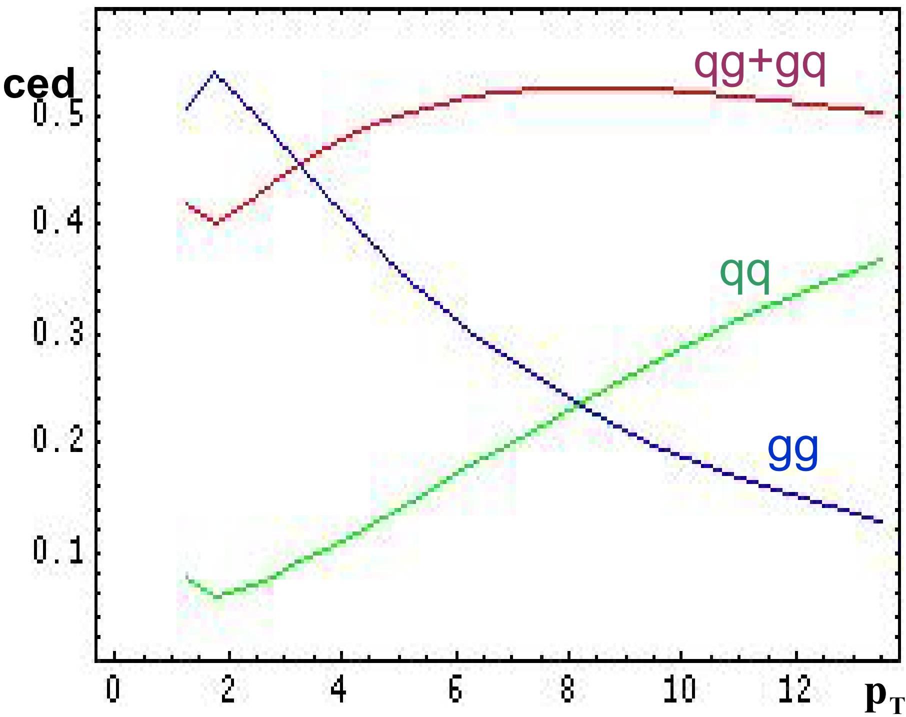
Leading Hadrons

Leading hadrons as jet tags



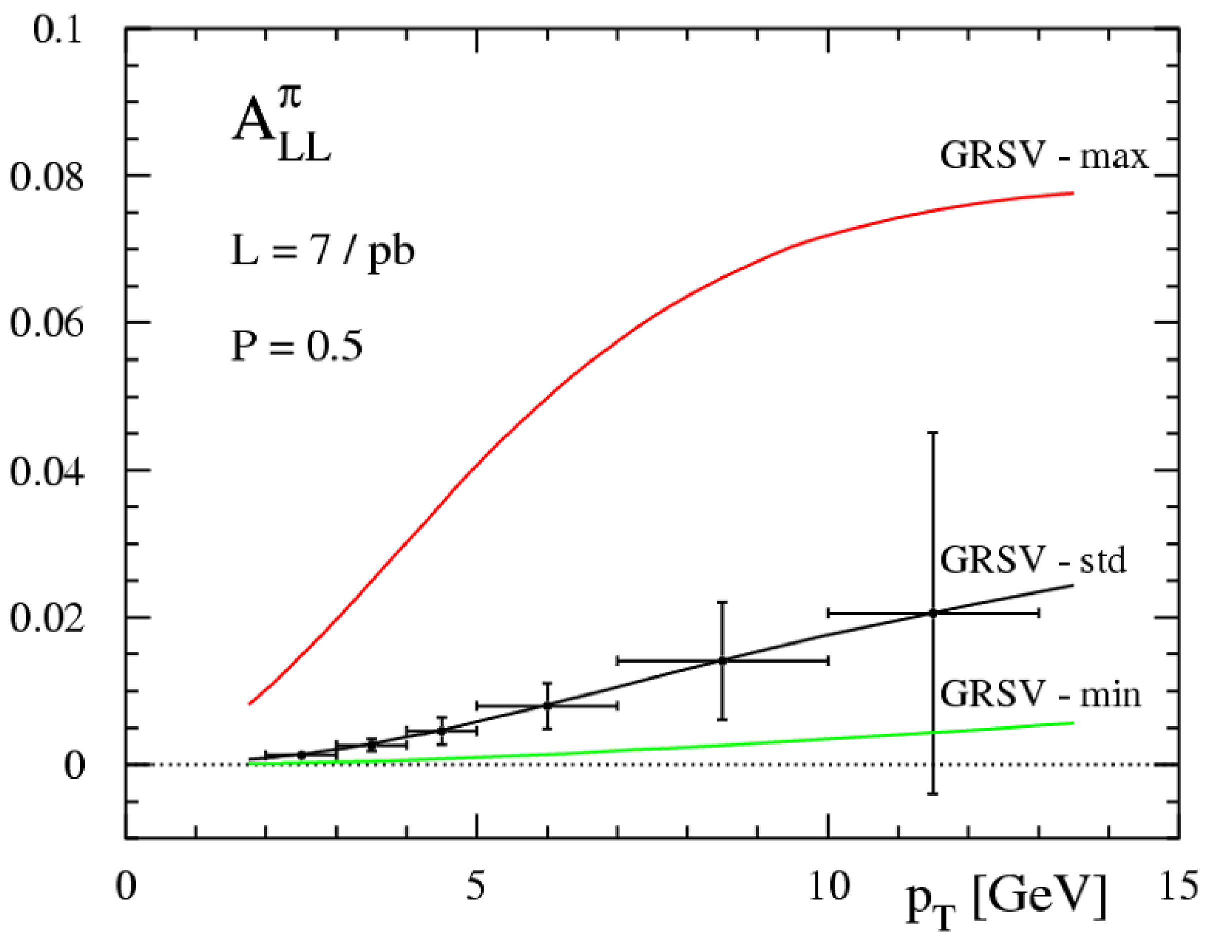


Fraction π^0's produced



π^0 Production and ΔG

π^0 can be used to determine ΔG with limited $\mathcal{L}$ & $\mathcal{P}$

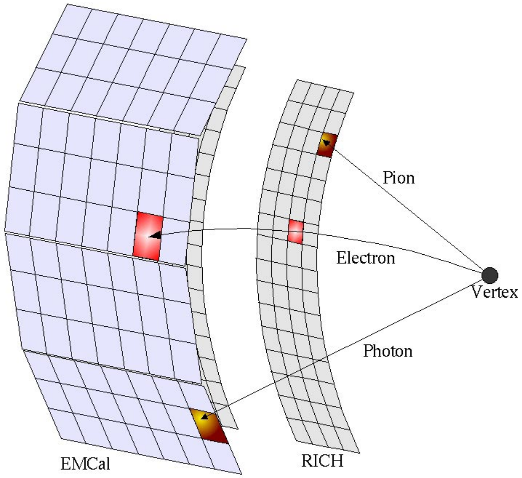


Jager, Schafer, Stratmann, Vogelsang

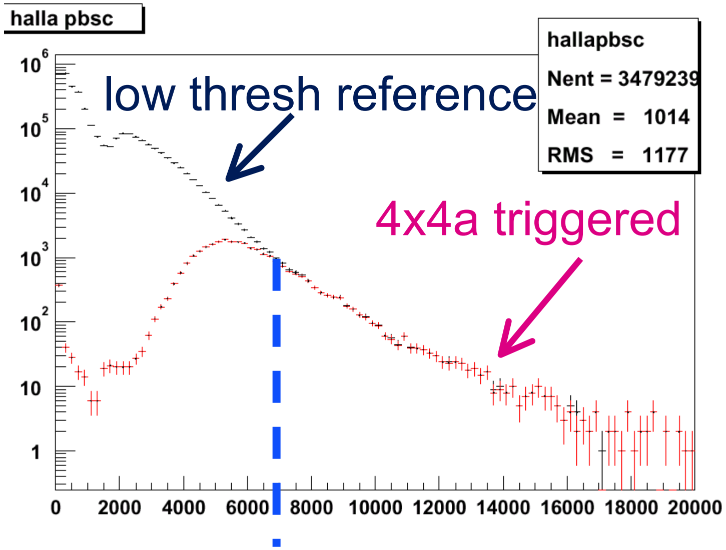
Central arm γ and π^0 trigger

» Trigger with a rejection power of > 100 at Level-1 needed in p+p
- Reduce the 12MHz interaction rate to 1 KHz

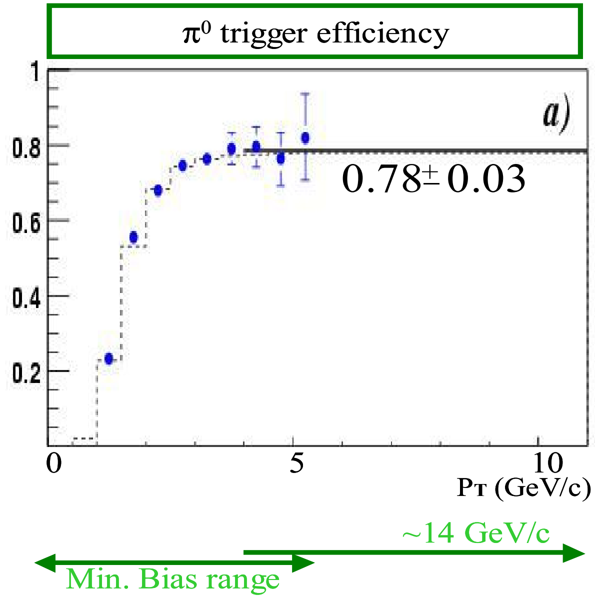
» EMCal part has two sums to collect photon showers
- 2x2 towers non-overlapping sum (low threshold ~ 0.8 GeV)
  - Used in conjunction with RICH to form an electron trigger
- 4x4 towers overlapping sum (higher thresholds at 2 and 3 GeV)
  - Used for γ trigger



4x4a in 2002-2003 run.



2x2 in 2001-2002 run.

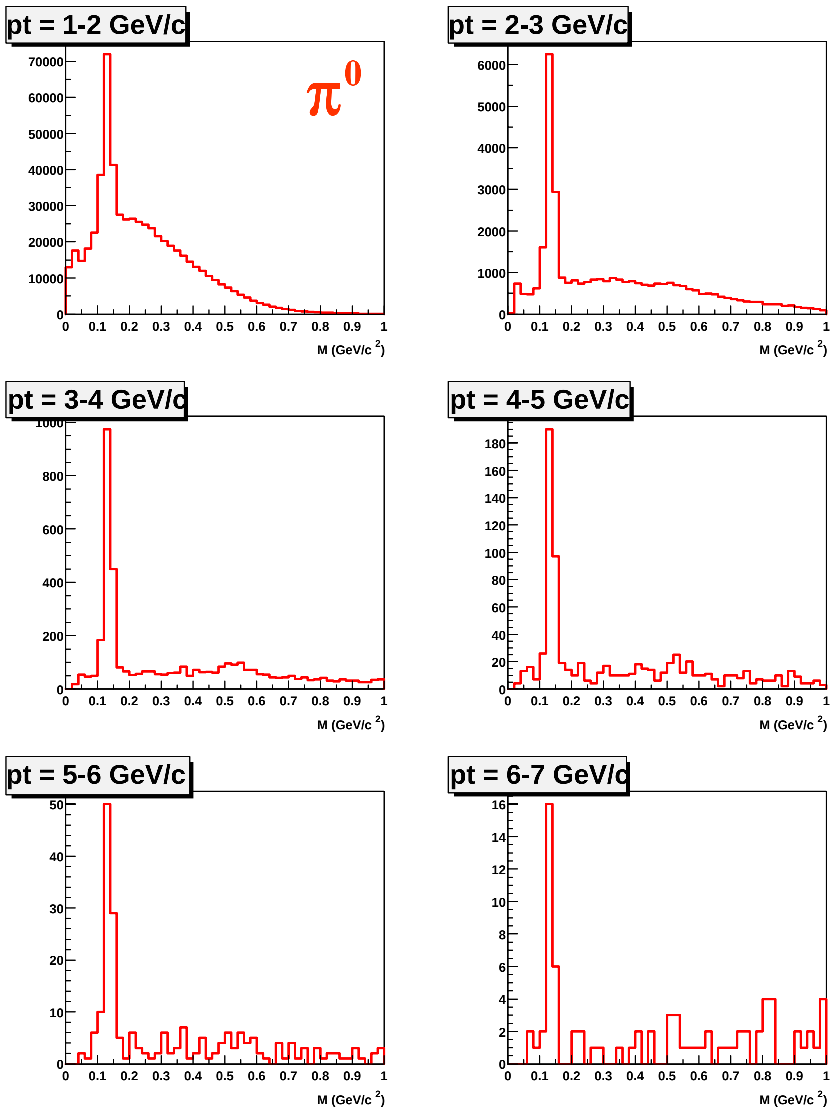


Neutral pions in PHENIX

PHENIX has a fine grained, high resolution EMCal

- $\Delta\phi\Delta\eta \approx 0.01\times0.01$ in $|\eta| \leq 0.35$
- $\pi^0\gamma$ separation up to 30 GeV/c

π^0's were reconstructed on-line during this past run.



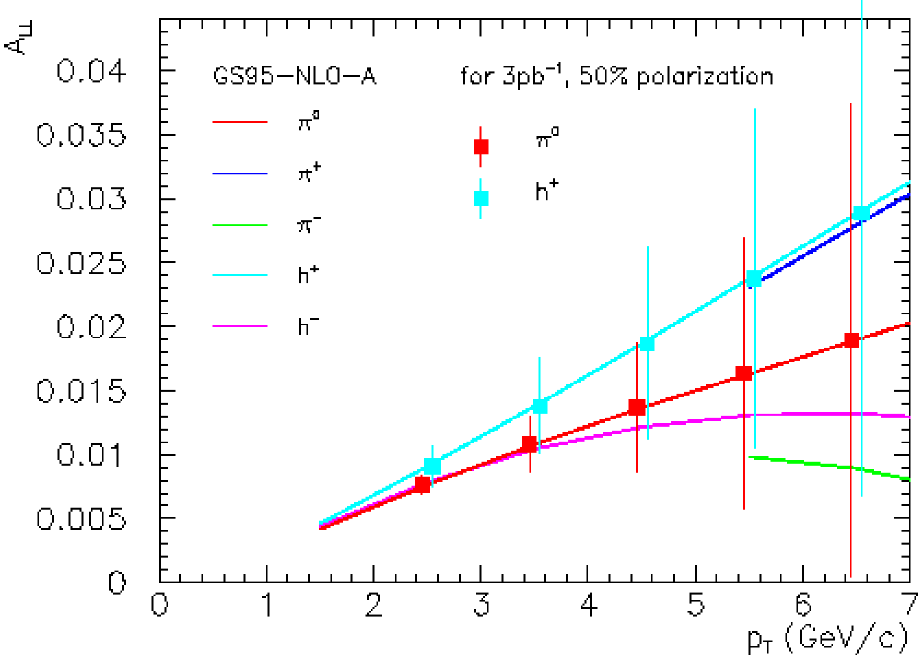
Gluon polarization measurement (π, h)

π^0 and charged hadrons

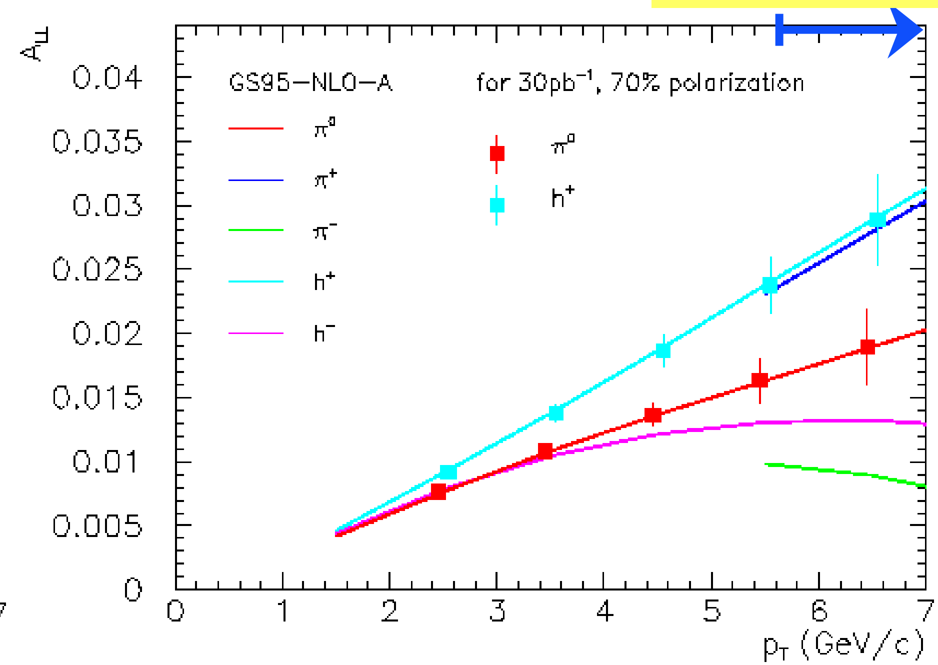
» alternative to jet measurement in the small acceptance
  - all channels are combined for the gluon polarization analysis

» quark polarization – flavor decomposition
  - π^+ from u-quark, π^0/π^- from u- and d-quark …

π-ID with RICH detector



Asymmetry



Asymmetry

ΔG IN PHENIX (2)

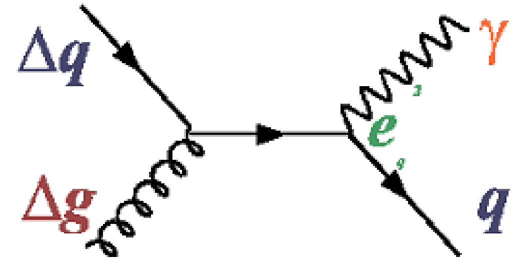
Prompt γ Production

Prompt photon production

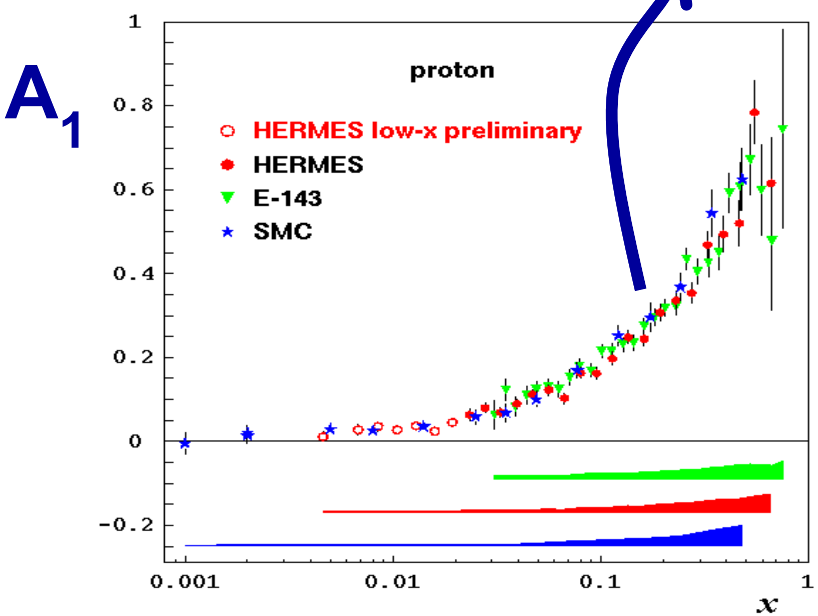
Gluon Compton Dominates

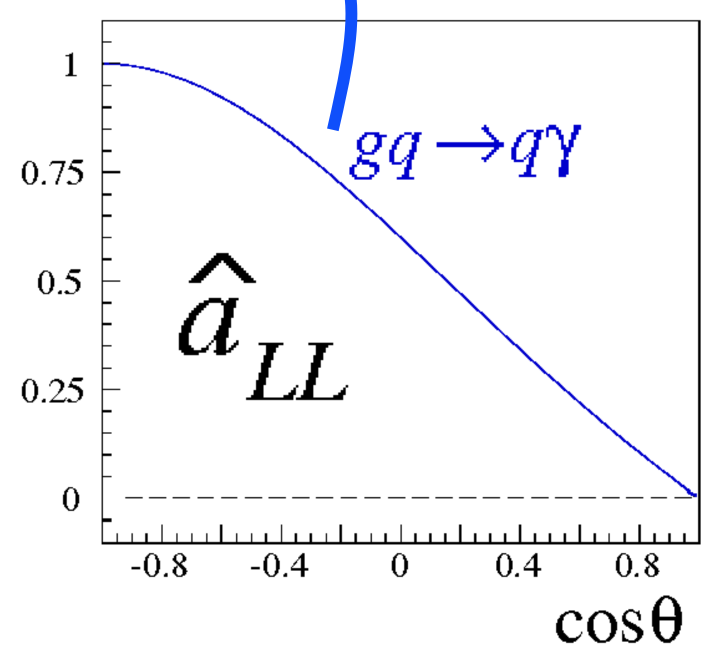
» At LO no fragmentation function

» Small contamination from annihilation



$$A_{LL} = \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\sum_{i=u,d,s} e_i^2 \Delta f_i(x_2)}{\sum_{i=u,d,s} e_i^2 f_i(x_2)} \otimes \hat{a}_{LL}(gq \to q\gamma)$$

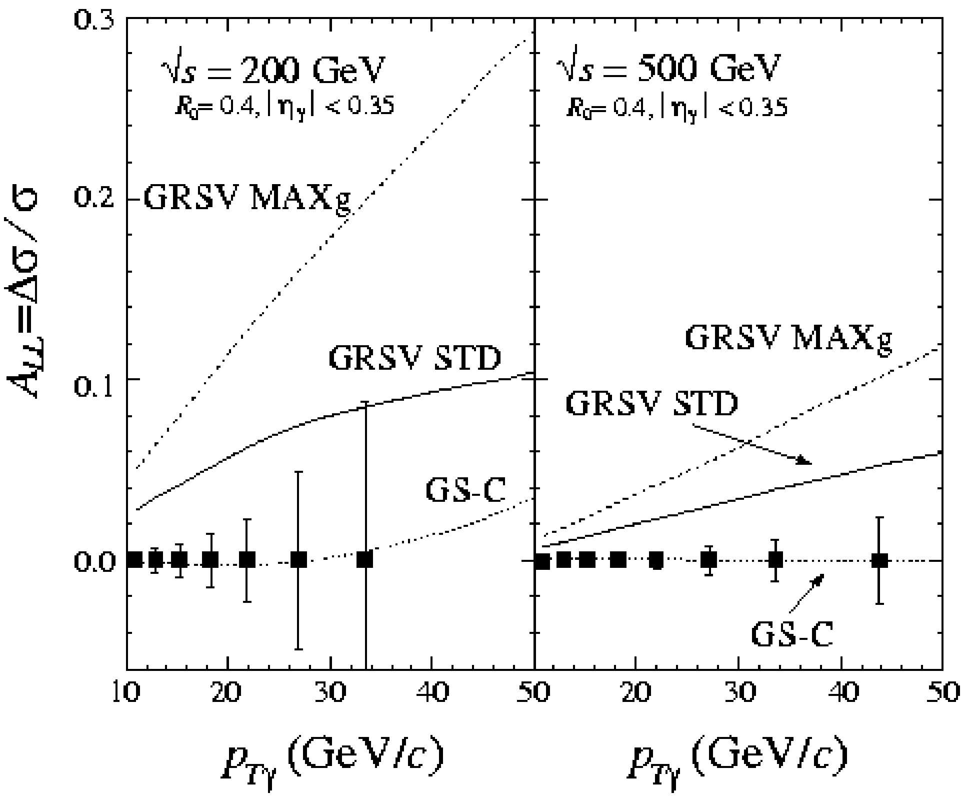




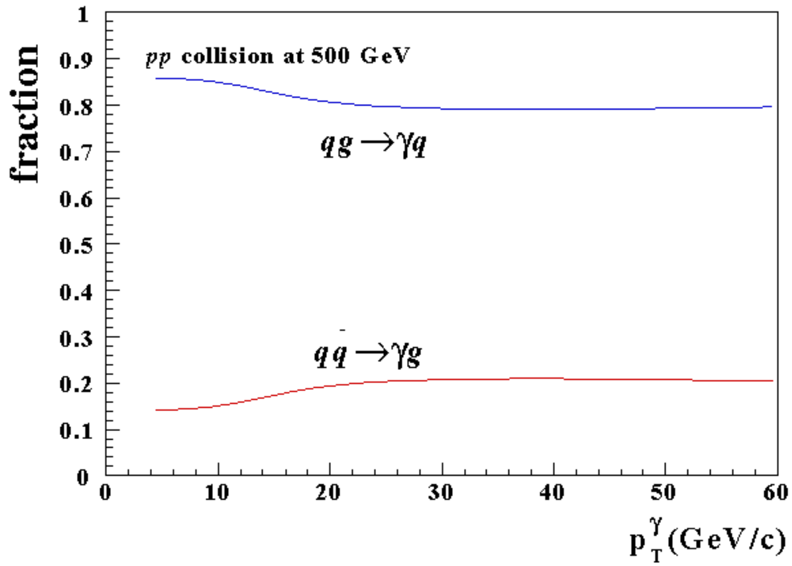
Prompt photon measurement

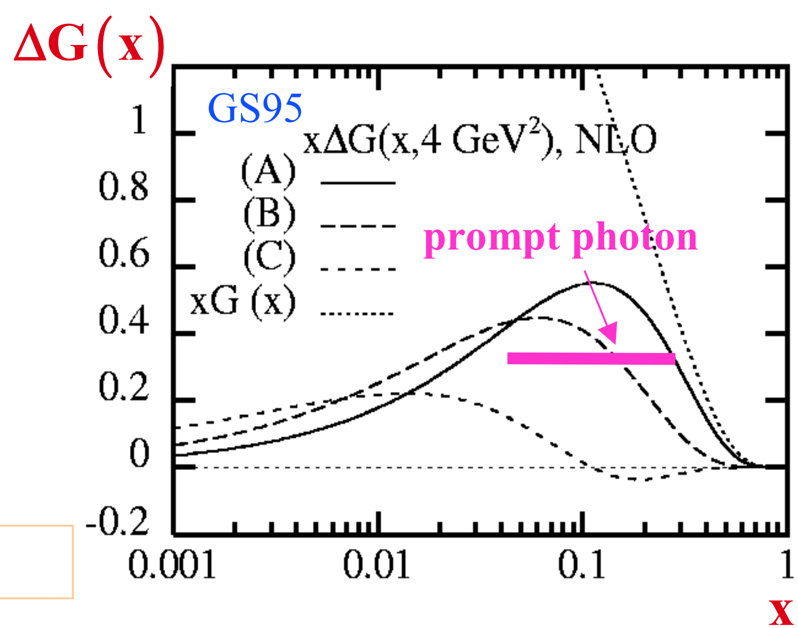
Prompt photon

- » clear interpretation
  - – gluon Compton process dominant



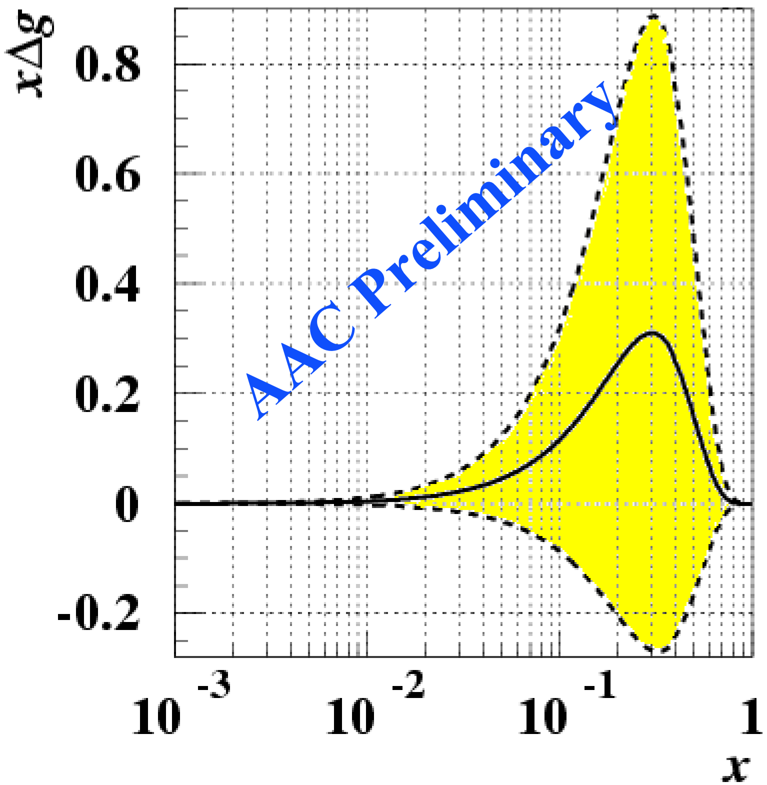
statistics with full design luminosity and polarization

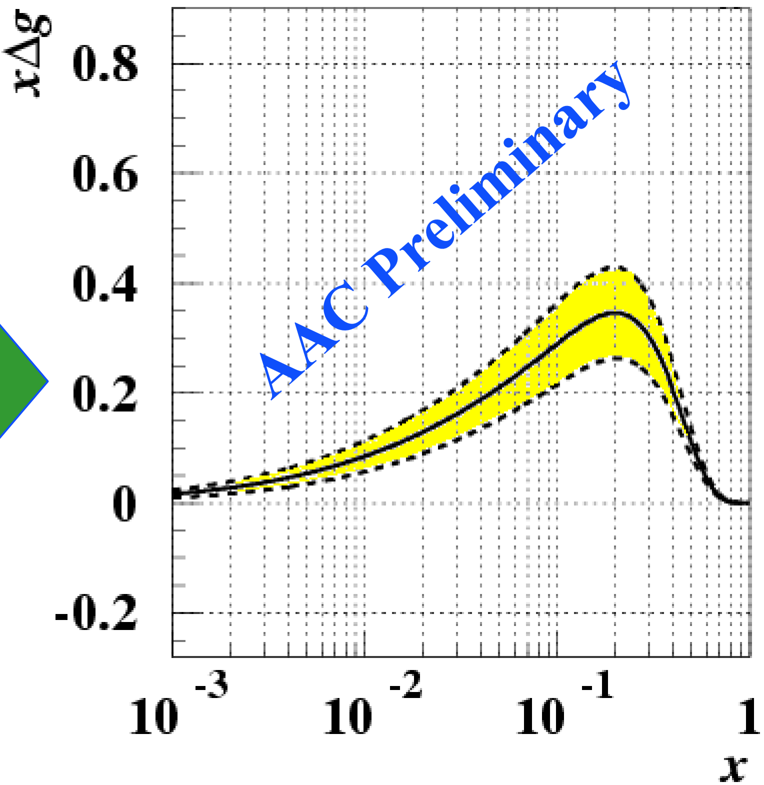




Prompt γ measurement: impact on ΔG

If the projected PHENIX Prompt Photon Data are included in a Global QCD Analysis:





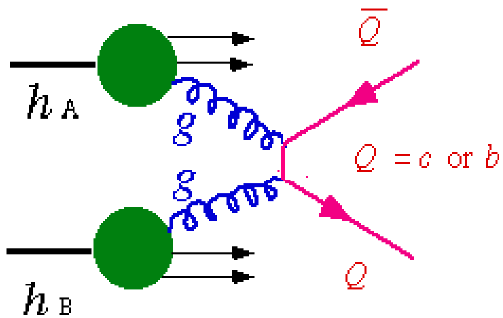
M. Hirai, H.Kobayashi, M. Miyama *et al.*

ΔG IN PHENIX (3)

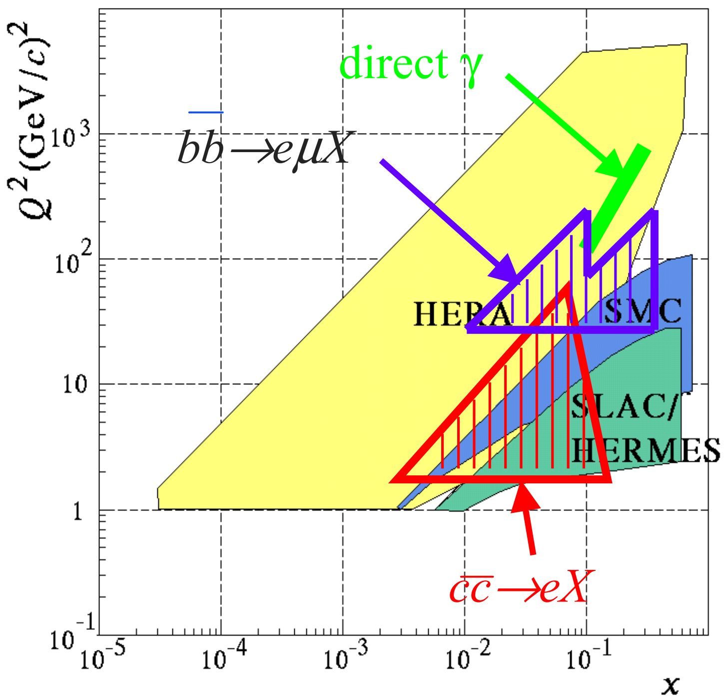
Heavy Flavor Production

Open heavy flavors in PHENIX

Open heavy flavor production



$$A_{LL} \propto \frac{\Delta G(x_A)}{G(x_A)} \otimes \frac{\Delta G(x_B)}{G(x_B)} \otimes \hat{a}_{LL}^{gg \to Q\bar{Q}}$$



H. Sato

Decay channels:

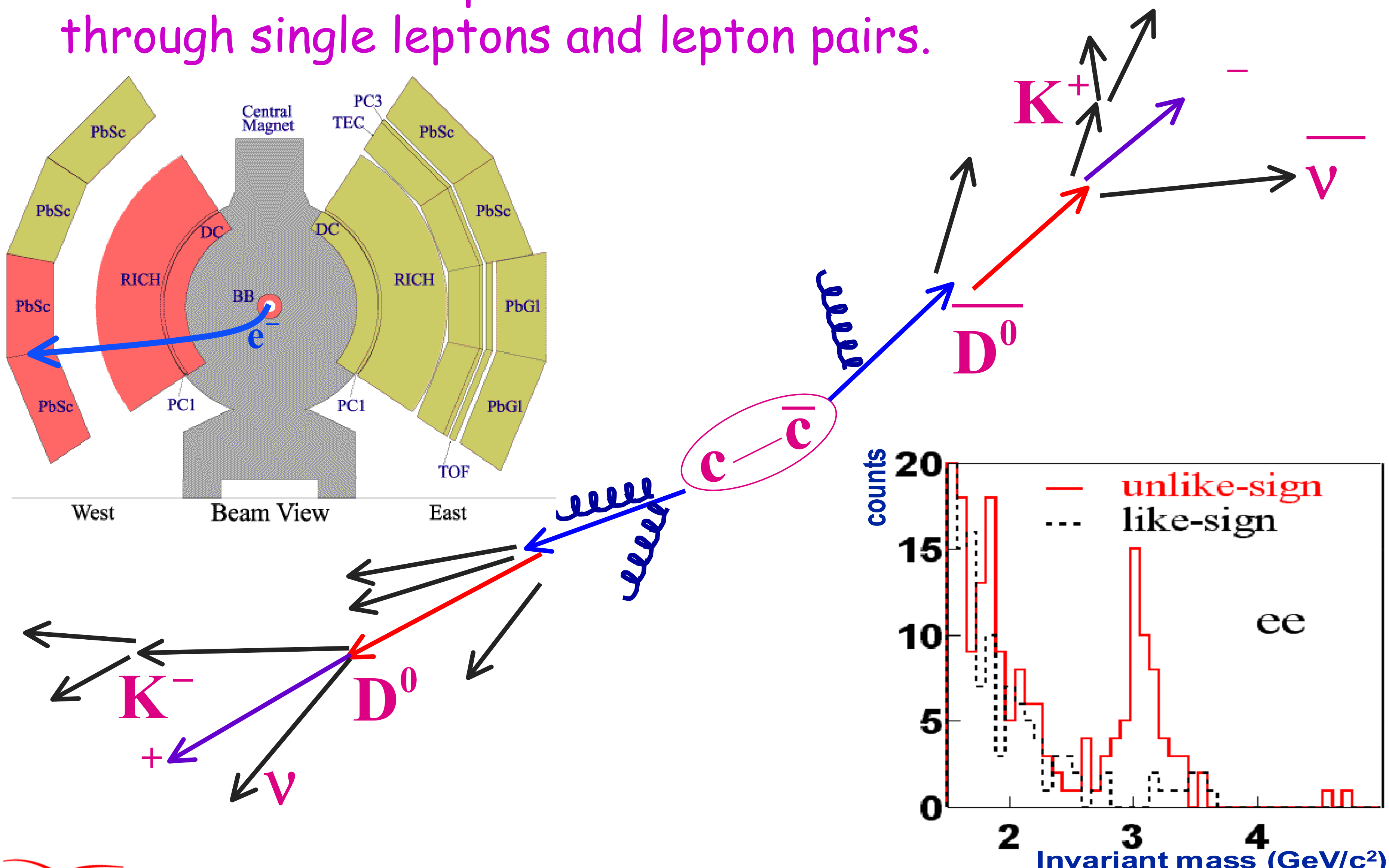
» e^+e^-, $\mu^+\mu^-$, eμ, e, μ, eD, μD

Provides more independent ΔG measurements in PHENIX

» Helps control experimental and theoretical systematic errors
» Different channels cover different kinematic regions

Electrons in PHENIX

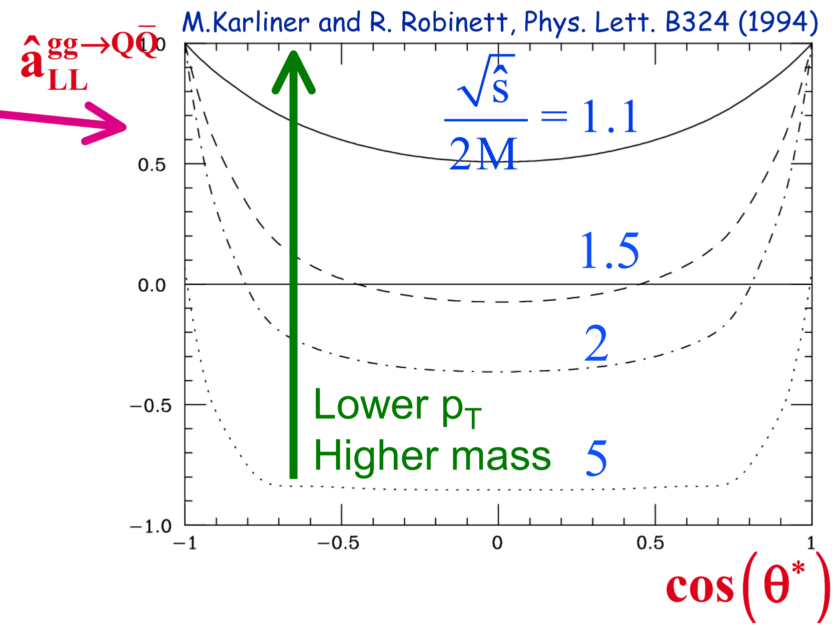
- ✓ We can measure open charm and bottom contributions through single leptons and lepton pairs.



A_{LL} for heavy quark production

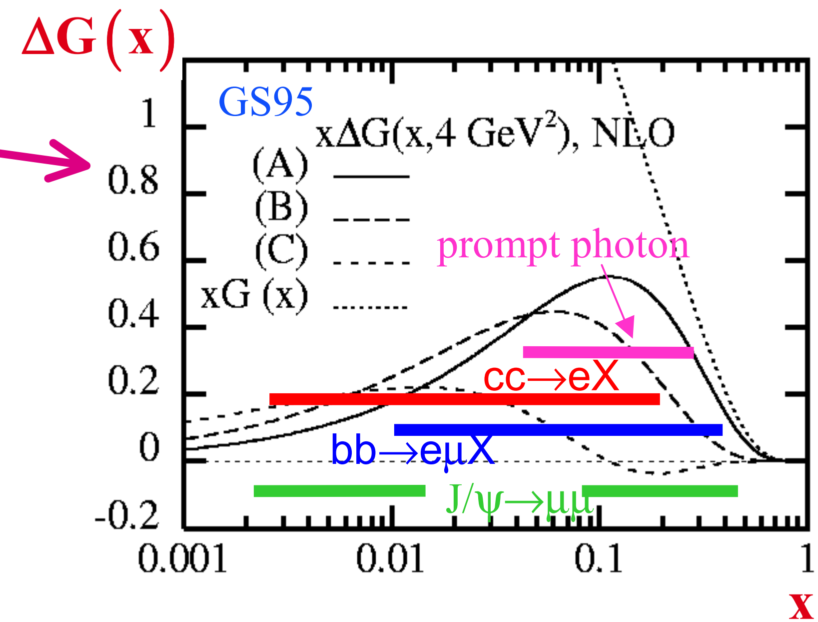
✓ **Analyzing Power**

- » Use LO analyzing power calculation
- » Charm and bottom will differ because of mass dependence
  - – Changes sign for large mass and low transverse momentum
- » NLO calculations are now available
  - – I.Bojak & M. Stratmann, hep-ph/0112276



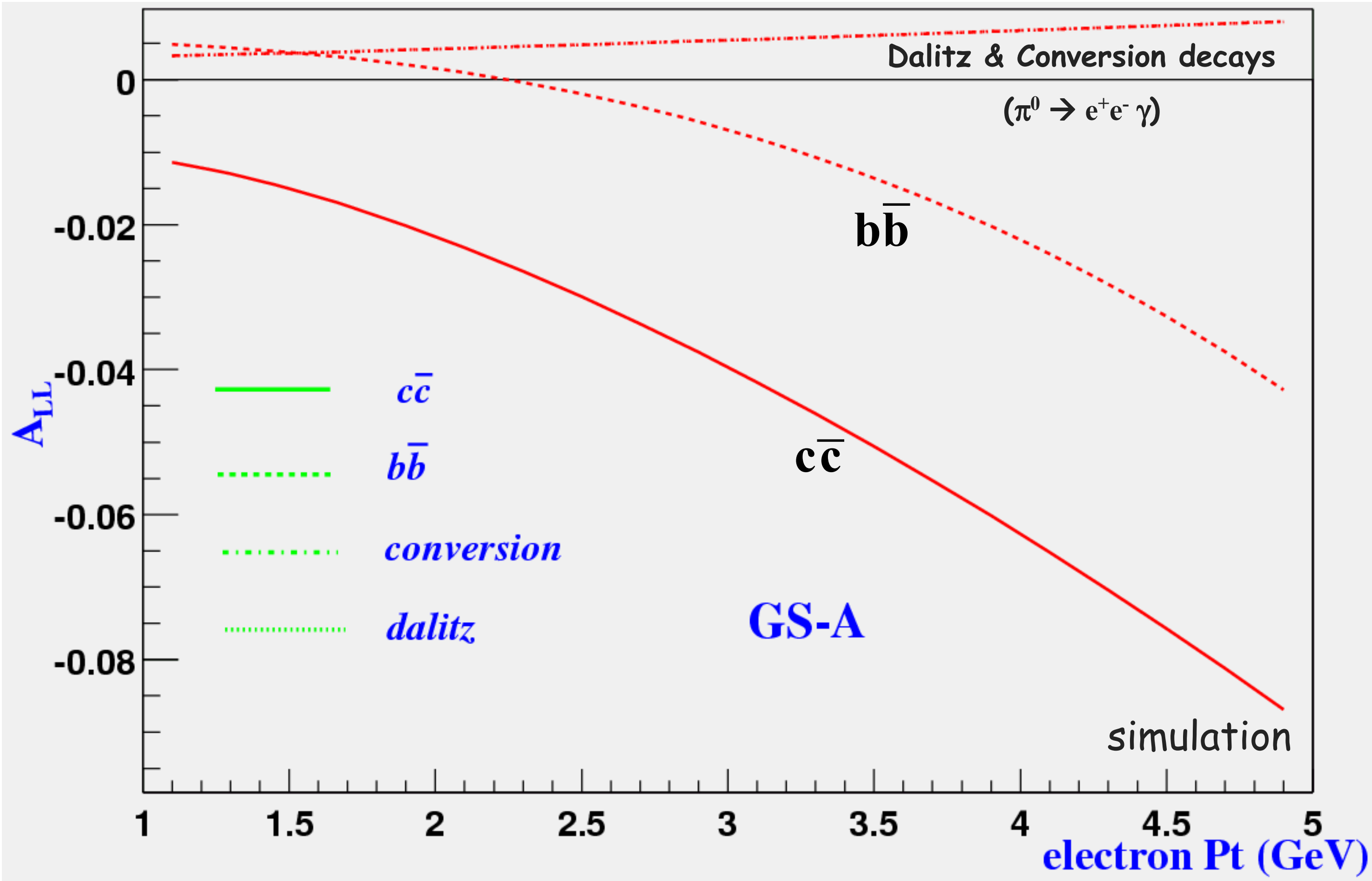
✓ **Gluon Polarization**

- » Use simple parameterized functions from Gehrmann & Stirling
  - – Phys.Rev.D52 6100 (1996)
- » x range for charm and bottom production different because of decay kinematics



A_{LL} from background & signal electrons

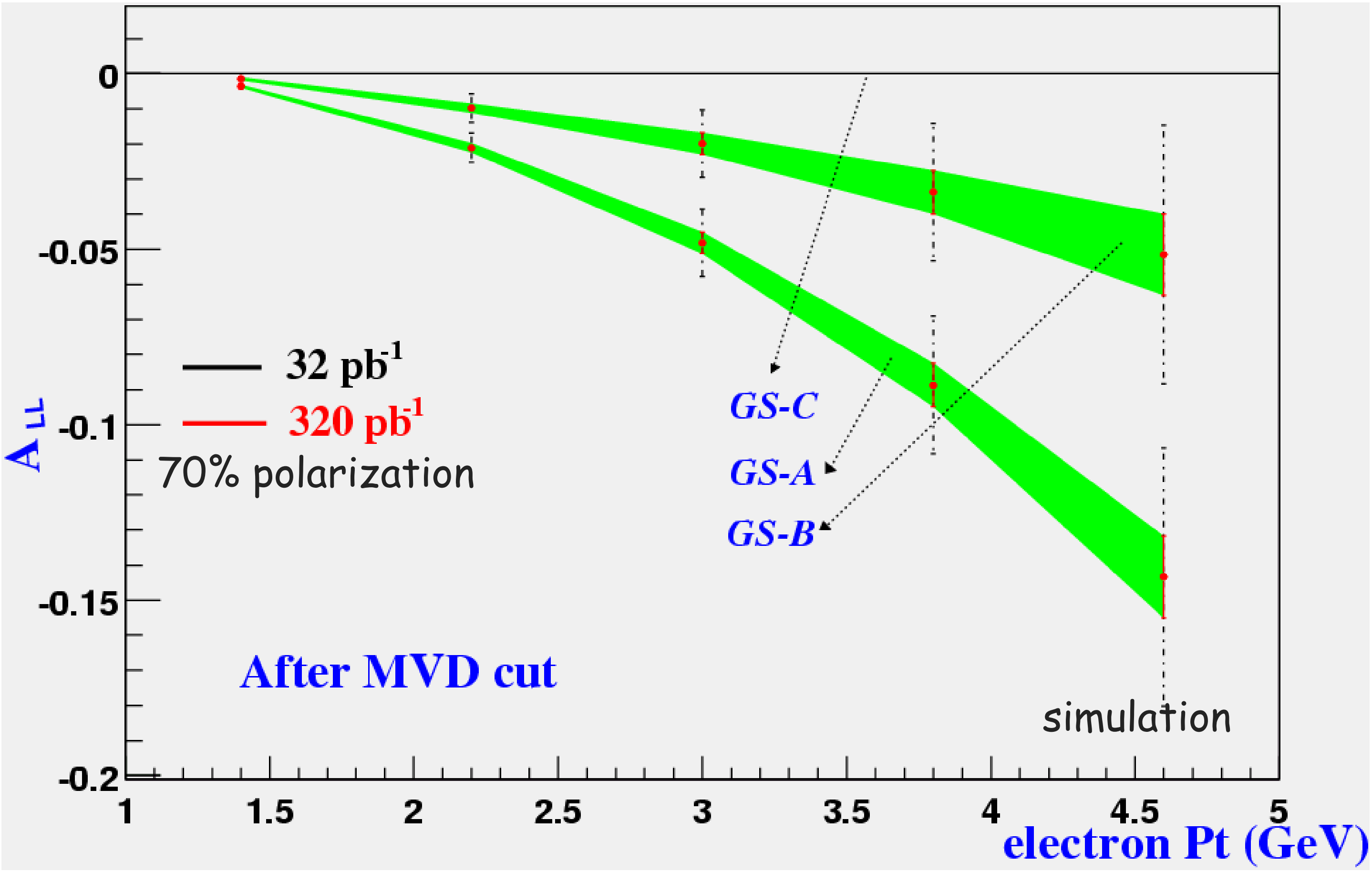
An electron A_{LL} measurement will include contributions from charm, bottom, photon conversions, & Dalitz decays.



W. Xie

A_{LL} in PHENIX using single electrons

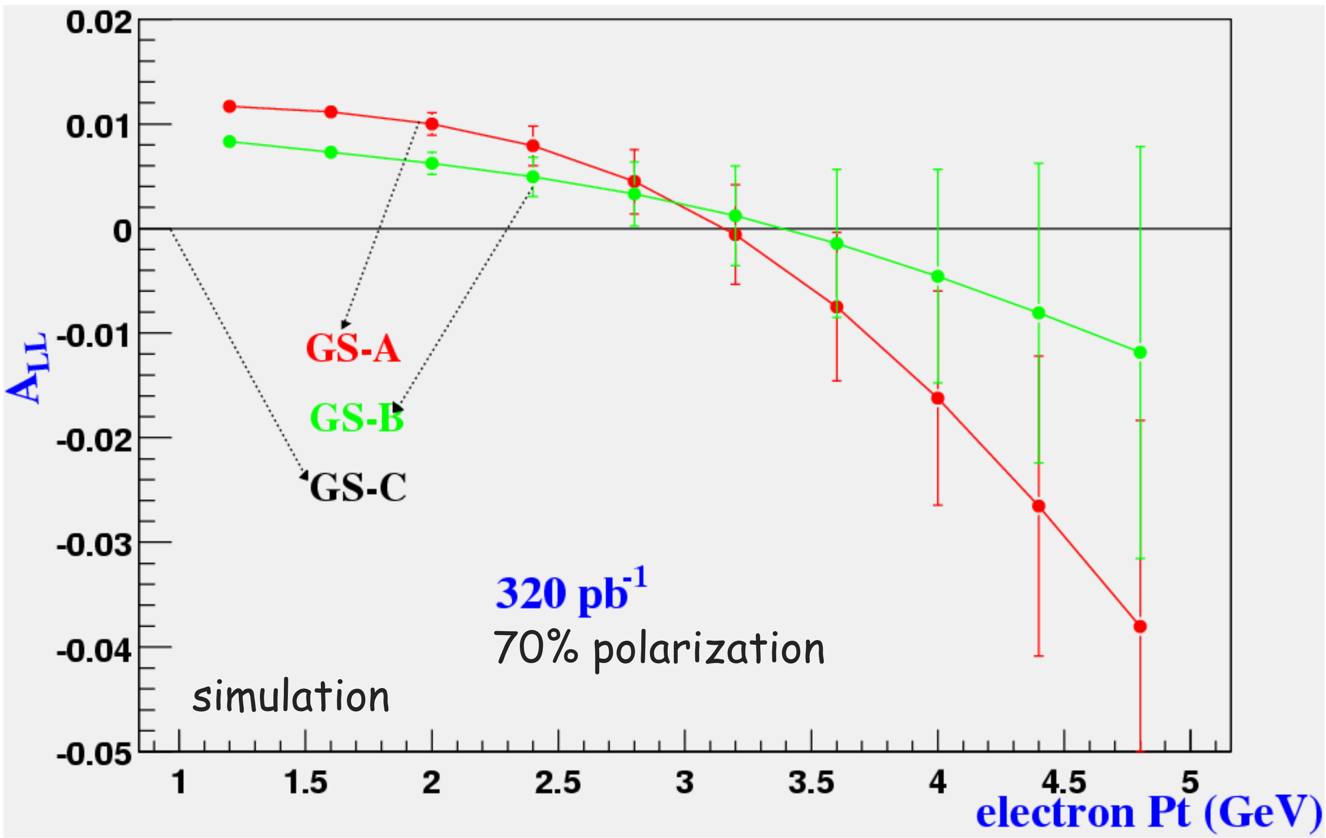
- ✓ Events have been tagged online by an electron with p_T>1GeV in the central arm
- ✓ An offline MVD (inner tracker) cut to reject Dalitz and conversion electrons has been applied



W. Xie

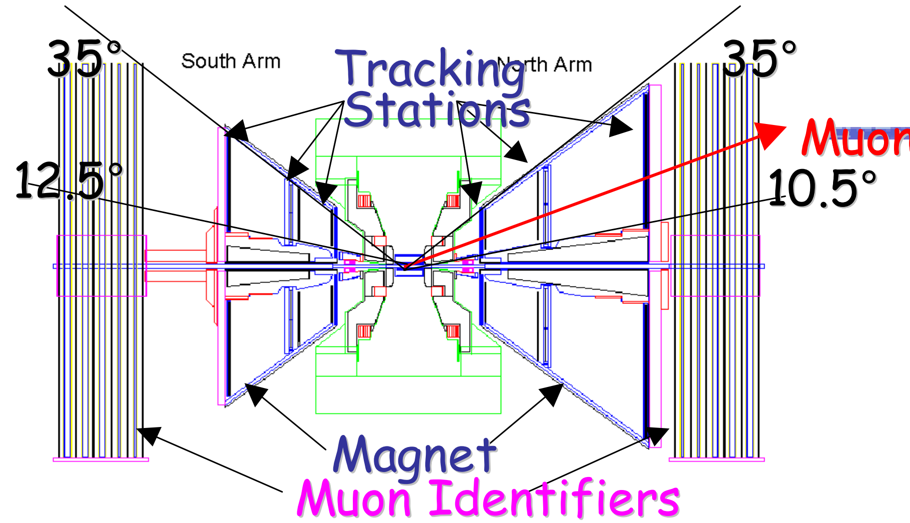
A_{LL} of identified conversions & Dalitz

- ✓ The MVD cuts can be inverted to produce a sample of events which contain electrons from conversions and Dalitz decays (from QCD jet events with π^0's).
- ✓ The asymmetry at low transverse momentum has flipped sign, giving us a handle on false asymmetries caused by acceptance effects.
- ✓ The asymmetry can also be used in conjunction with the direct π^0 measurement in a global analysis that will give us a handle on our systematic errors

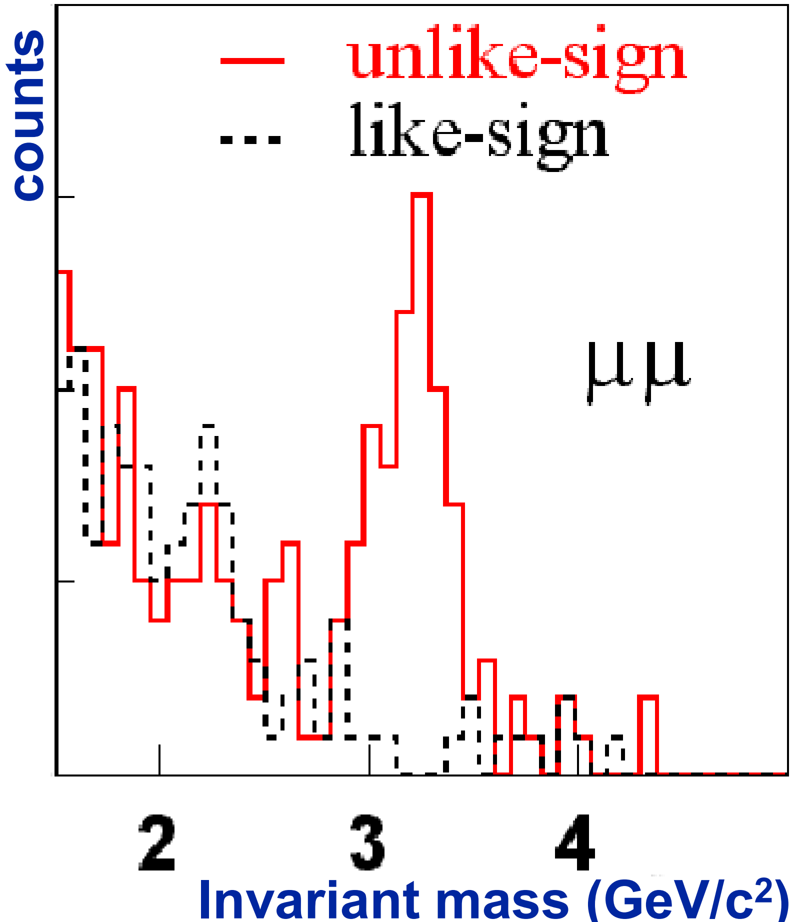


W. Xie
K. Barish

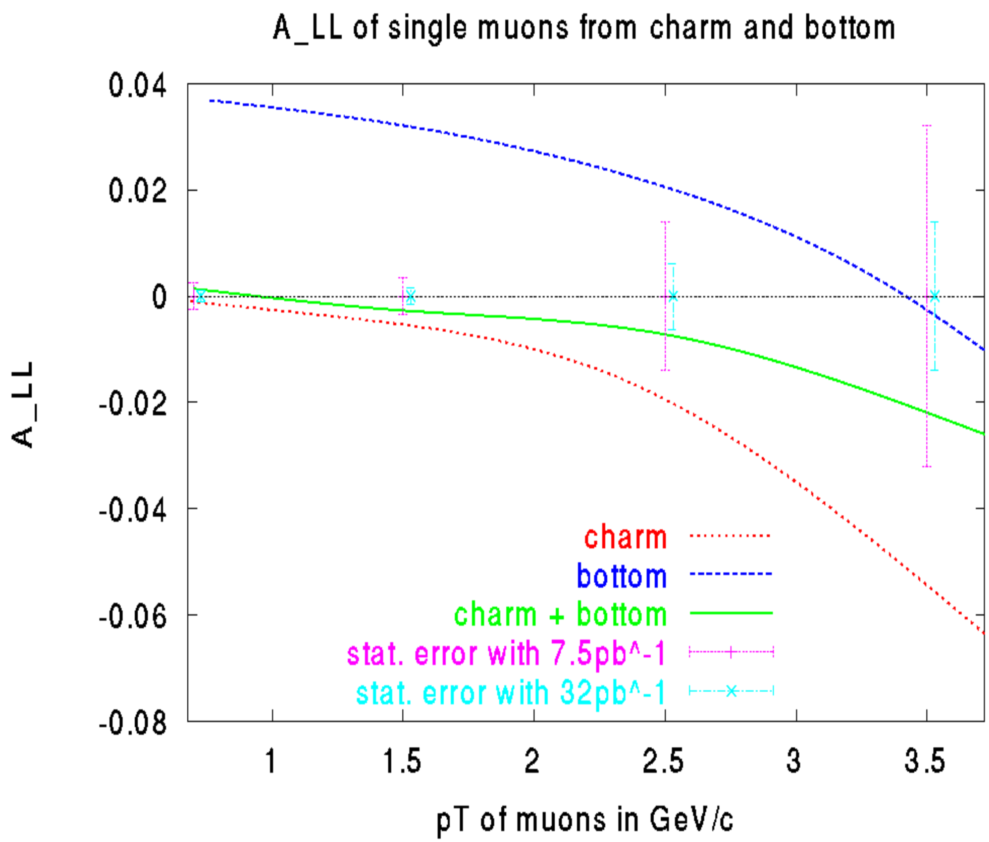
μ's in PHENIX



35°
South Arm
Tracking Stations
North Arm
35°
12.5°
Muon
10.5°
Magnet
Muon Identifiers



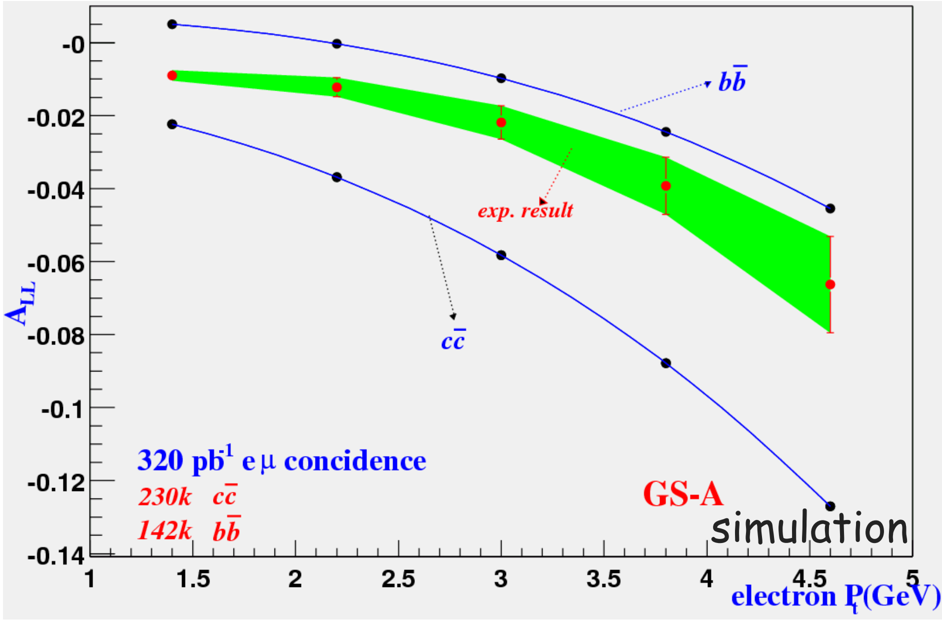
counts
unlike-sign
like-sign
μμ
2
3
4
Invariant mass (GeV/c²)

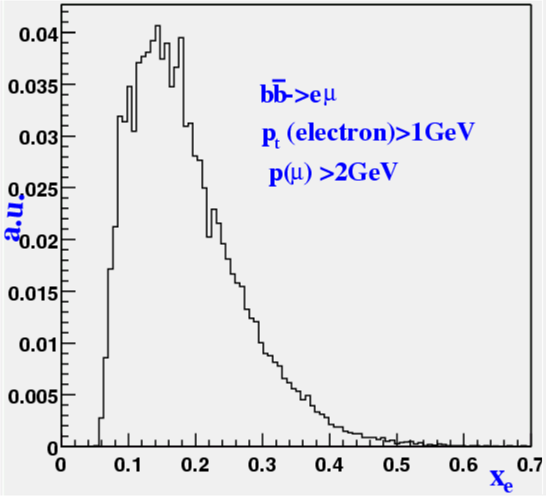


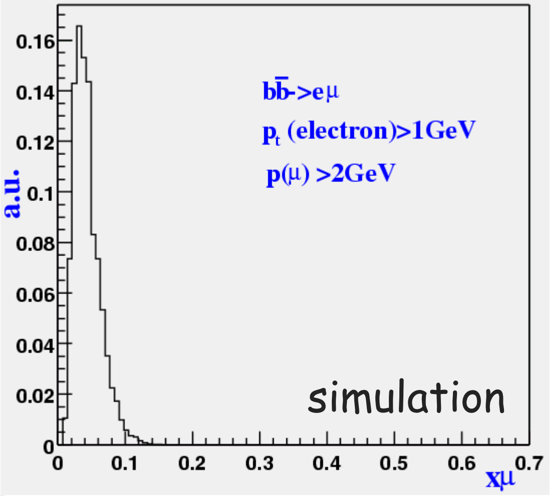
A_LL of single muons from charm and bottom
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
A_LL
1
1.5
2
2.5
3
3.5
pT of muons in GeV/c
charm
bottom
charm + bottom
stat. error with 7.5pb^-1
stat. error with 32pb^-1

Tagged μ-e coincidences

- ✓ We can require a muon detected in one of the forward muon arms in coincidence with an electron in the central arm
  - This requirement removes the background from conversions and Dalitz decays and it enhances the bottom yield in the event sample



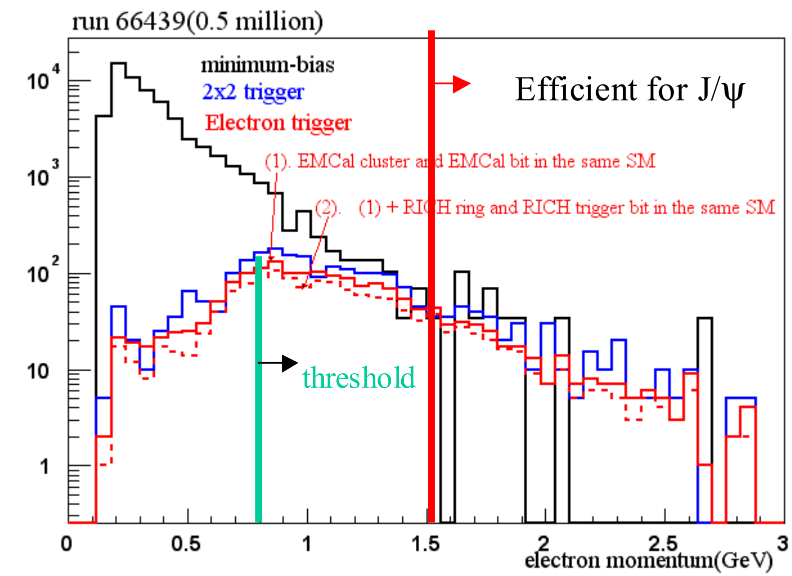


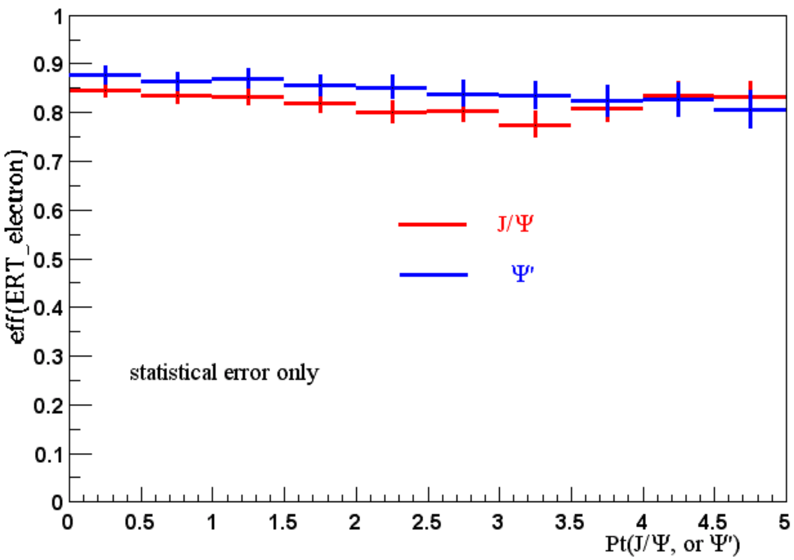


- ✓ In the μ-e channel the kinematic range reaches down to x_g~ 0.02.

W. Xie & H Sato

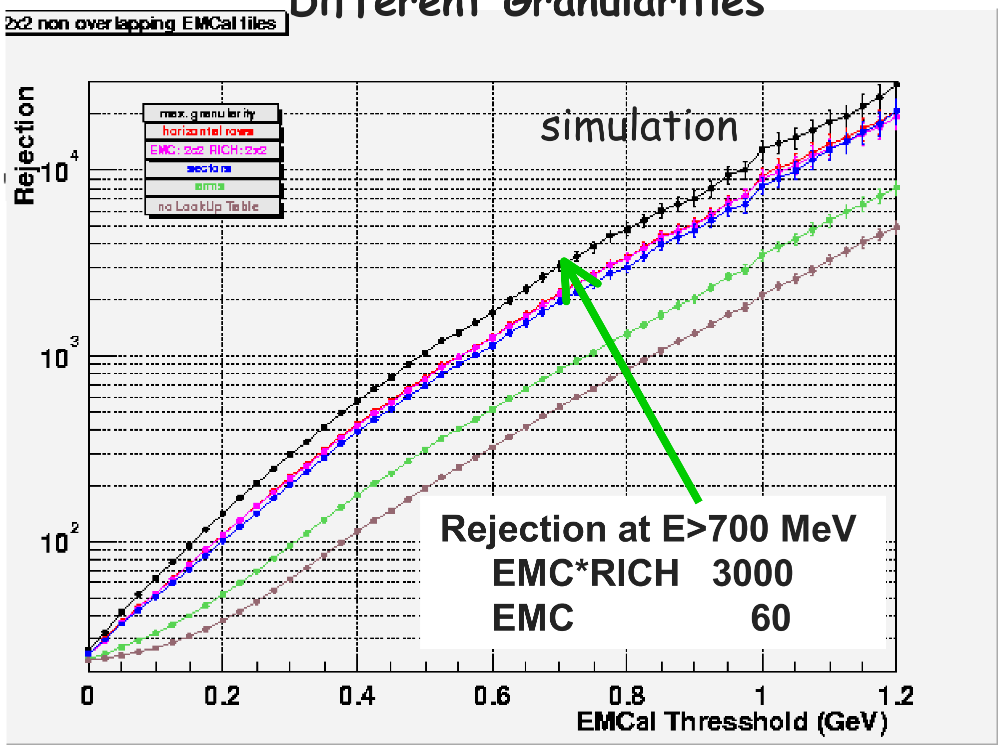
Electron Trigger





EMCal/RICH electron trigger in 2002-2003 d+Au and p+p runs!

EMCal/Rich Trigger rejection: Different Granularities

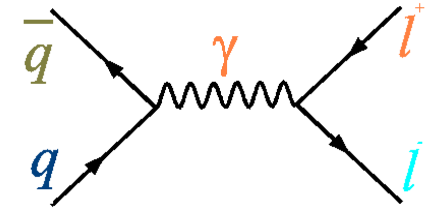


D. Galanakis and W. Xie

Antiquark helicity distributions in PHENIX

Anti-quark helicity distribution

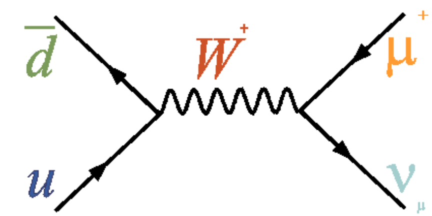
Drell-Yan production of lepton pairs



» Maximal parton level asymmetry: a_{LL}= -1
» Possible severe background from semi-leptonic decays of open charm productions

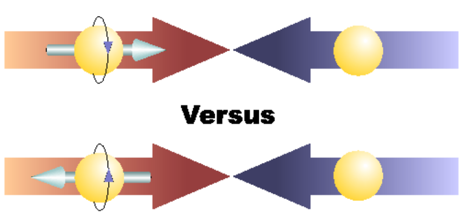
$$A_{LL}^{q\bar{q}\to\ -} = \frac{\Delta q(x_A)}{q(x_A)} \otimes \frac{\Delta \bar{q}(x_B)}{\bar{q}(x_B)} \otimes \hat{a}_{LL}^{q\bar{q}\to\ -}$$

W production



» Produced in parity violating *V-A* process
  – Chirality / helicity of quarks defined
» Couples to weak charge
  – Flavor almost fixed: flavor analysis possible
  – Flavor ID reduces uncertainty in current pol-PDF models.
» PHENIX-Muon Arms

$$A_L^{W^+\to\mu^+\nu_\mu} = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta \bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$



W kinematics and background

x can be determined directly if

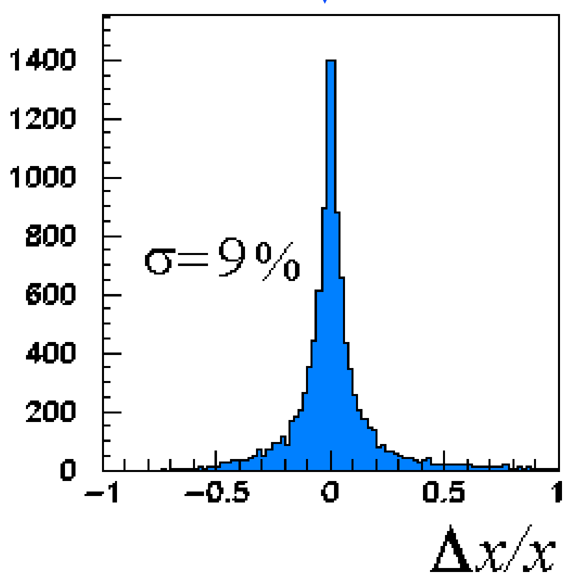
- W has no p_T
- W mass is δ-function

$$x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}; x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

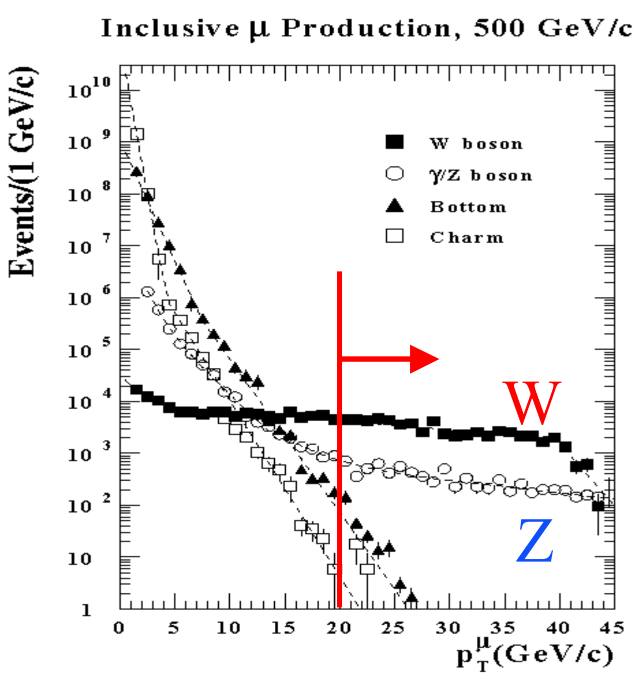
$$y_\mu = y_\mu^* + y_W; y_\mu^* = \frac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right)$$

$$\cos\theta = \pm\sqrt{1 - 4p_{T\mu}^2/M_W^2}$$

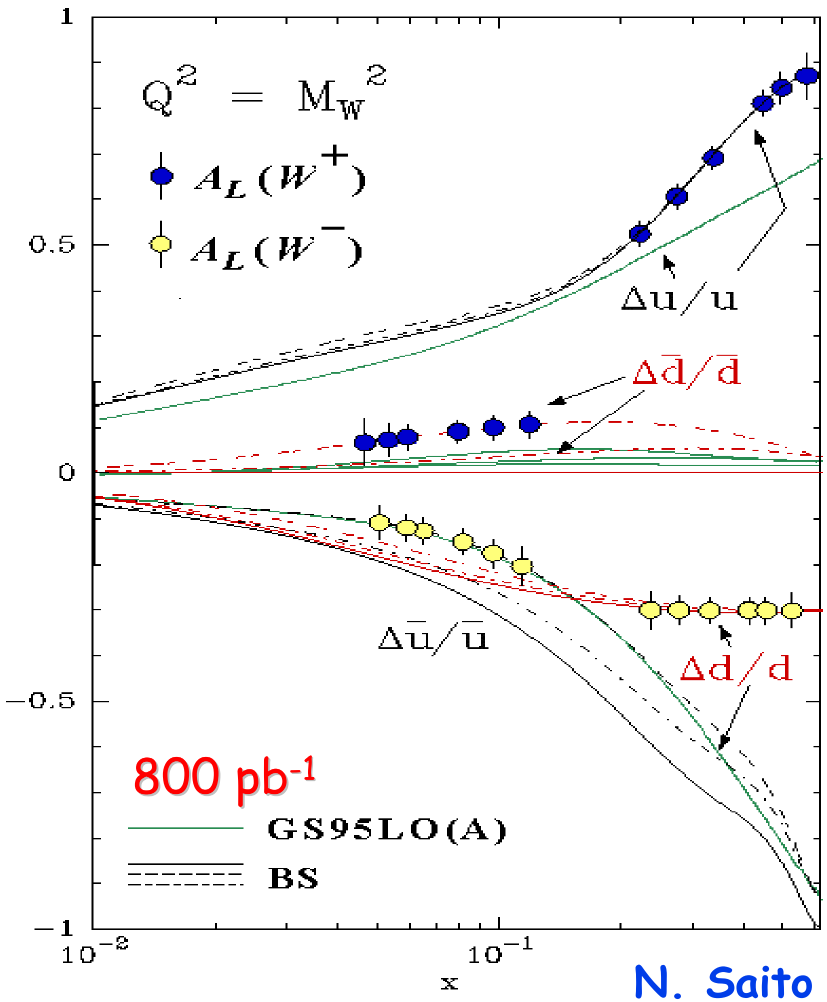
With realistic p_T and M_W the resolution is $\Delta x/x = 9\%$



For $p_T > 20$ GeV W dominates with a smaller contribution from Z^0



Sensitivity goal: flavor decomposition



N. Saito

$A_L(W^+) \rightarrow \Delta u/u(x_1)$ @$x_1 >> x_2$

$A_L(W^+) \rightarrow -\Delta d/d(x_1)$ @$x_2 >> x_1$

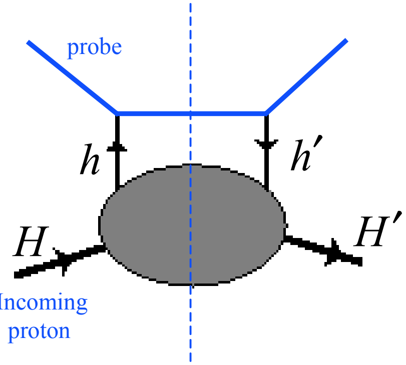
Note: there is a more recent treatment by Nadolsky and Yuan where they use resummation and NLO techniques.

Note: W^+ and W^{--} have a different acceptance In PHENIX.

Transversity

Transversity distributions

Hard Scattering Amplitudes



$H \equiv$ proton helicity
$h \equiv$ quark helicity

H	h		H'	h'
$\frac{1}{2}$	$\frac{1}{2}$	$\rightarrow$	$\frac{1}{2}$	$\frac{1}{2}$
$\frac{1}{2}$	$-\frac{1}{2}$	$\rightarrow$	$\frac{1}{2}$	$-\frac{1}{2}$

$\Rightarrow q(x,Q^2)\,,\, F_{1,2}(x,Q^2)$ (helicity av.)

$\Delta q(x,Q^2),\, g_1\,(x,Q^2)$ (helicity diff.)

$\frac{1}{2}$	$-\frac{1}{2}$	$\rightarrow$	$-\frac{1}{2}$	$\frac{1}{2}$

$\Rightarrow \delta q(x,Q^2)$ (helicity flip!)

On Transversity:

Transversity distributions $\delta q(x,Q^2)$ remain last unmeasured leading twist distributions

For non-relativistic quarks: $\delta q(x,Q^2) = \Delta q(x,Q^2)$

➡ Differences provides information on relativistic nature of quarks inside the proton

Soffer's bound: $\left|2\,\delta q_i(x,Q^2)\right| \le q_i(x,Q^2) + \Delta q_i(x,Q^2)$

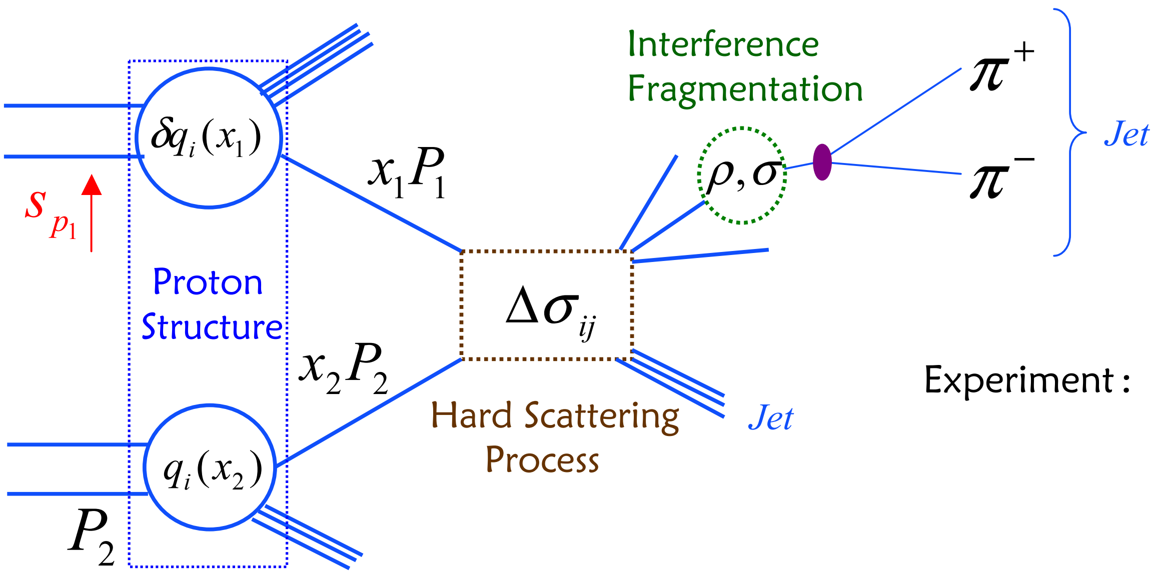
➡ Not small! Possibly $\left|\delta q_i\right| \approx \left|\Delta q_i\right|$!

$\delta q(x,Q^2)$ does not mix with gluons under evolution

First lattice QCD result: $\delta u + \delta d + \delta s = 0.56 \pm 0.09$

S. Aoki, M. Doui, T. Hatsuda and Y. Kuramashi Phys.Rev. D56 (1997)433
More recently: S. Capitani et.al. Nucl. Phys. B (Proc. Suppl.) 79 (1999) 548

Transversity via final state interactions



Jian Tang , Thesis MIT, June 1999
R. Jaffe, X.Jin, J. Tang Phys. Rev. D57 (1999)5920
X. Ji, Phys. Rev. D49 (1994)114
J. Collins, S. Heppelmann, G. Ladinsky, Nucl.Phys. B420 (1994)565

Experiment: $A_\perp = \dfrac{1}{P_{beam}} \dfrac{N^{\rightarrow} - N^{\leftarrow}}{N^{\rightarrow} + N^{\leftarrow}}$

Currently unknown: b-Factories,LEP

measured parton dis.

pQCD

$$\frac{d^7\sigma_H\left(pp^{\uparrow} \rightarrow \pi^+\pi^- X\right)}{dx_1 dx_2 dt dz dm^2 d\cos\theta d\varphi} \propto \delta q(x_1)\cdot q(x_2) \times \frac{d^3\sigma(q_1 q_2 \rightarrow q_3 q_4)}{dx_1 dx_2 dt} \times \frac{d^2\mathcal{M}}{dz dm^2 d\cos\theta d\varphi}$$

Model Calculations

Interference fragmentation

$$\frac{d^2\mathcal{M}}{dz\,dm^2} \propto \sin\delta_0 e^{i\delta_0}\left(\kappa\cdot\hat{q}_I(z)+\lambda\cdot\delta\hat{q}_I(z)\right)\sin\delta_1 e^{-i\delta_1}+\ldots$$

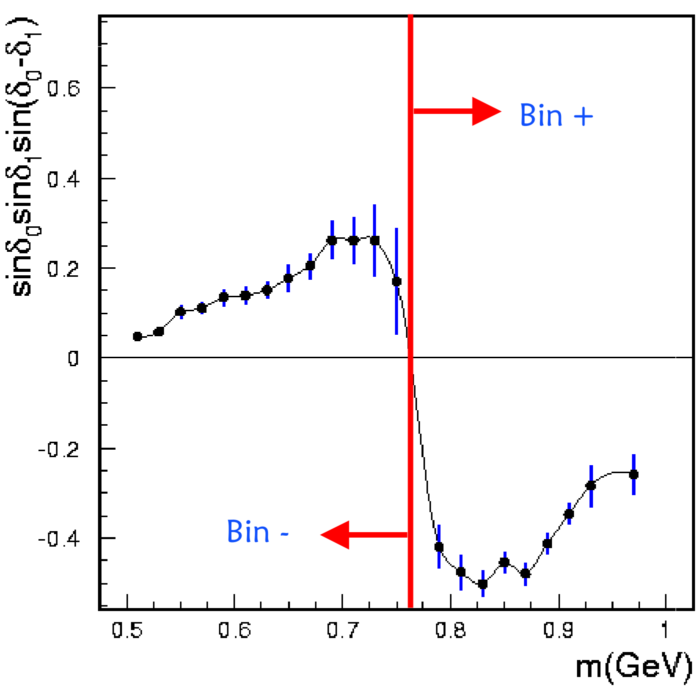
s-wave

p-wave

Strong interaction π,π phase shifts

Where: $\kappa = I\otimes\overline{\eta}_0,\ \ \lambda=\sigma_+\otimes\overline{\eta}_- + \sigma_-\otimes\overline{\eta}_+$

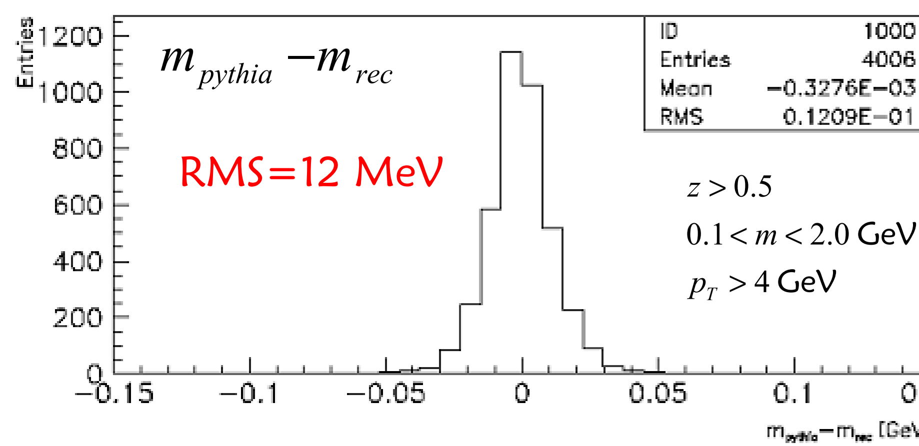
$\hat{q}_I(z), \delta\hat{q}_I(z)$: spin average and dif - ference fragmentation functions



P. Estabrooks and A.D. Martin, Nucl. Phys. B79 (1974)301

Non-vanishing "support" only in the ρ mass region!

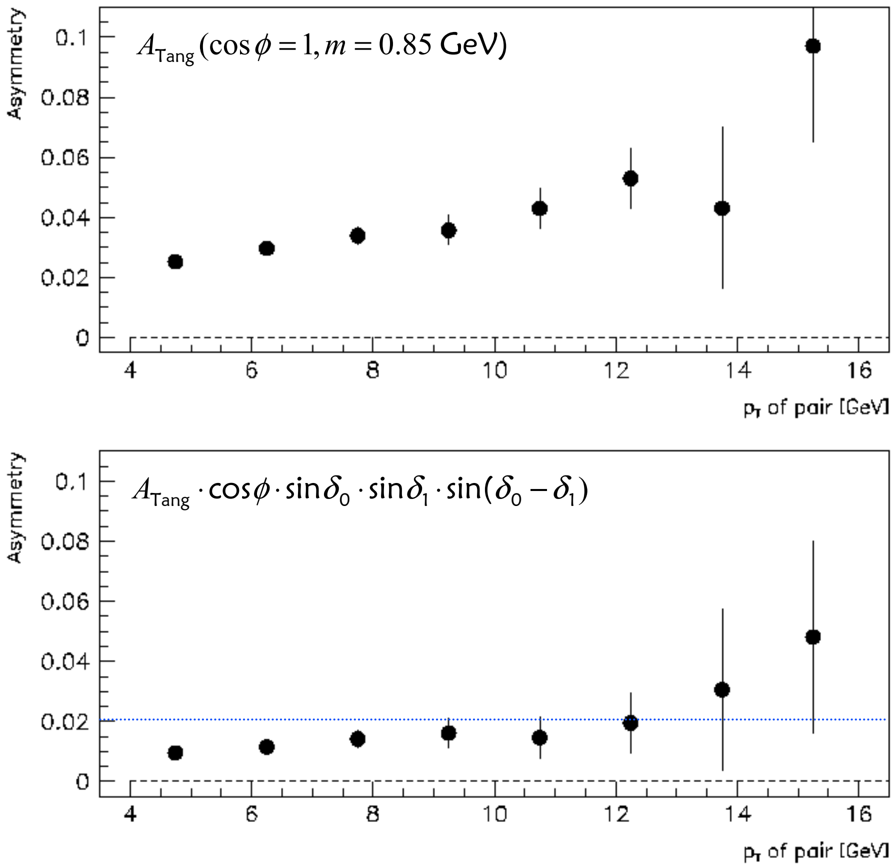
- Sufficient mass Resolution?
- Great for systematics!



Projected asymmetry

(For 1 week of running)

$A_T(p_\perp \rightarrow \pi^+\pi^- + X)$ vs p_T^{pair}



$\int L dt = 32\, pb^{-1}$

$E_{\pi_1,\pi_2} > 4$ GeV

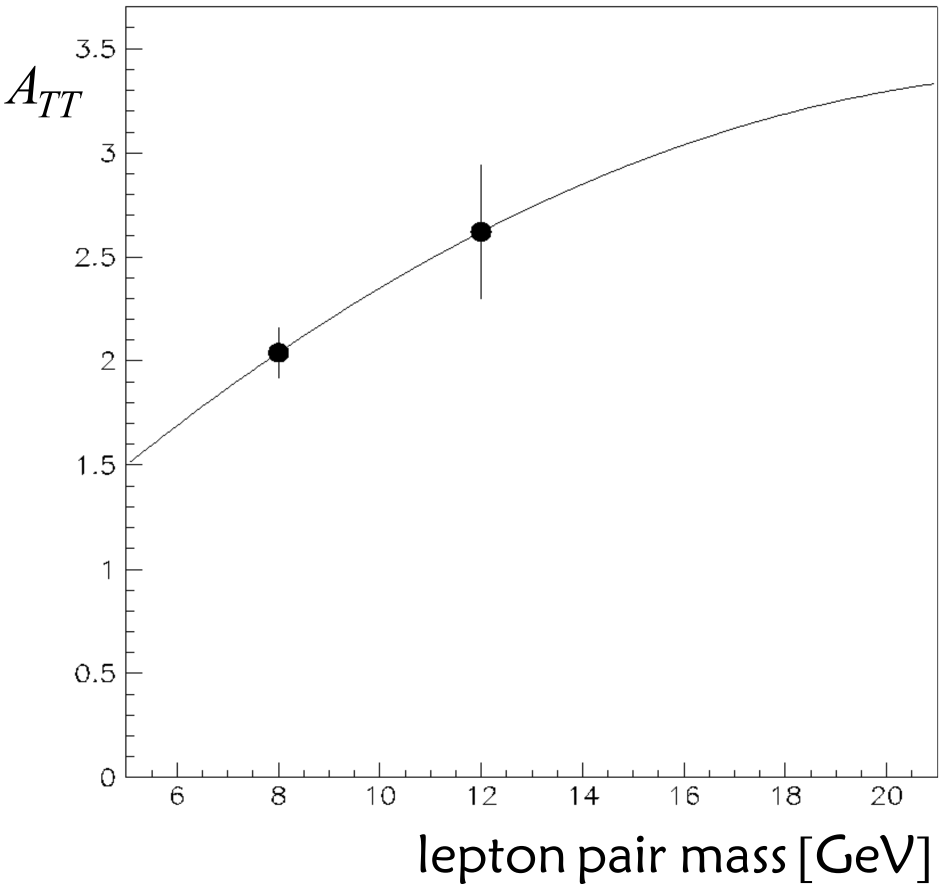
$\sqrt{p_{1T}^2 + p_{2T}^2} > 4$ GeV

800 MeV $< m <$ 950 MeV

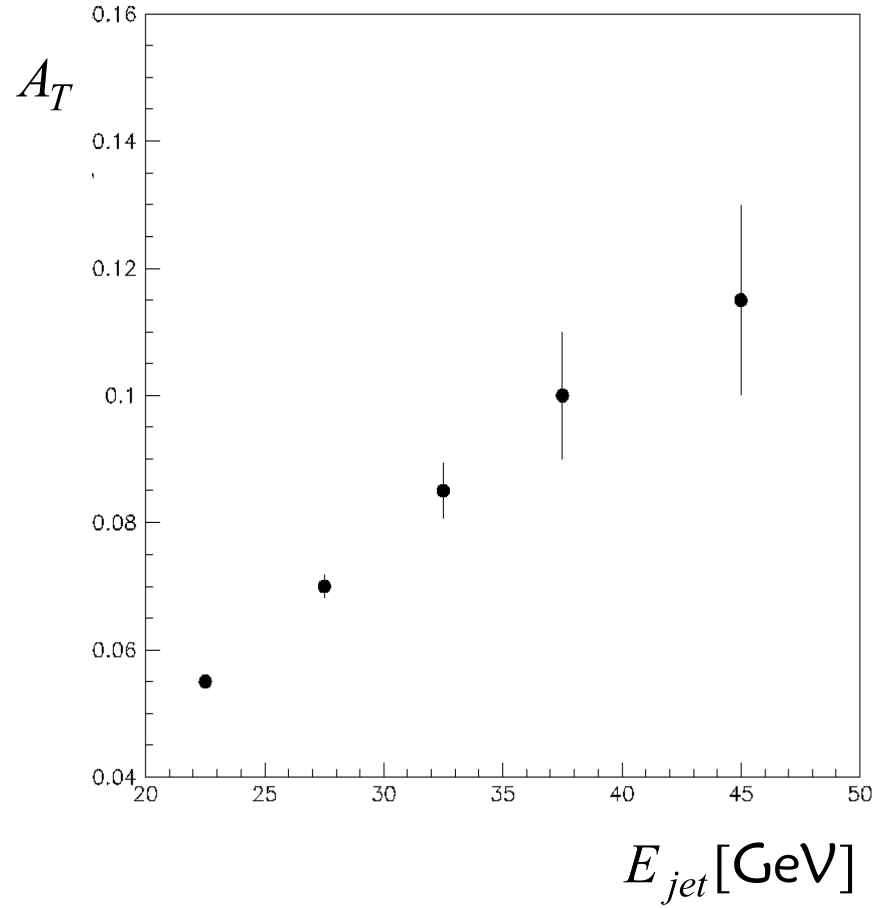
Small asymmetry below 5% but good rate!

RHIC luminosity upgrade

Drell Yan: Martin et al.



Interference FF in direct photon production



Beyond the standard model

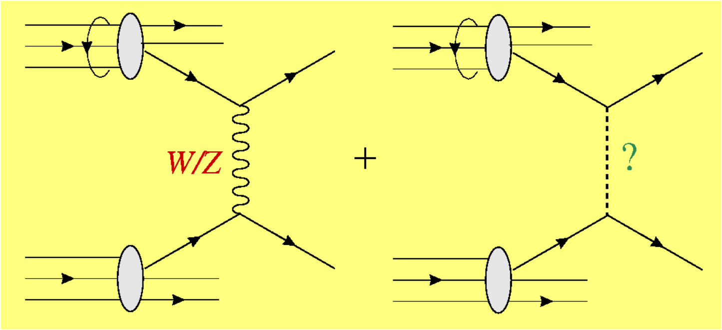
Searches for new physics

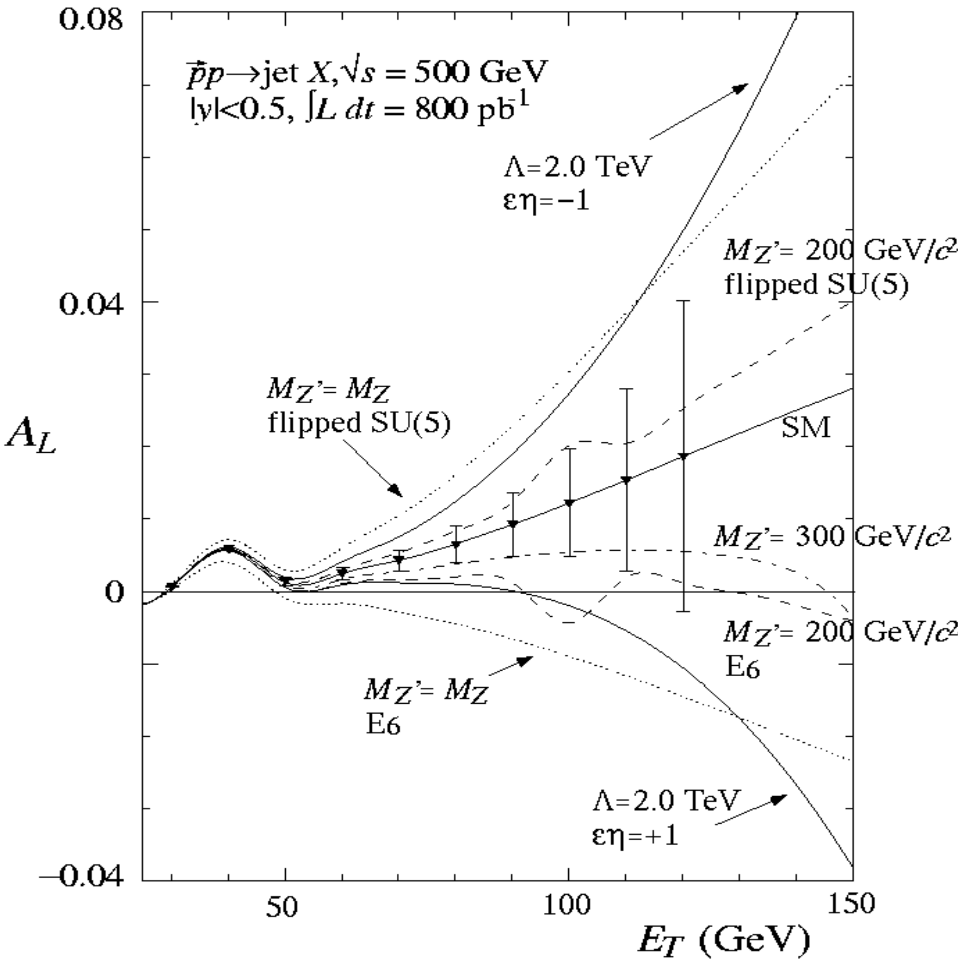
Anomalous parity violation in jet production

» Contact Interaction (Scale Λ)

- RHIC Spin Reach Λ~3.3 TeV

» New gauge boson Z'

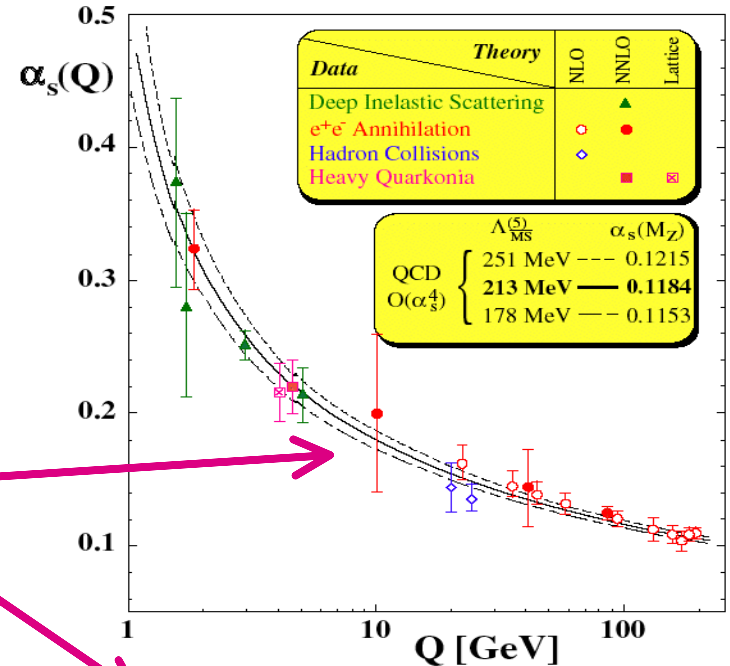


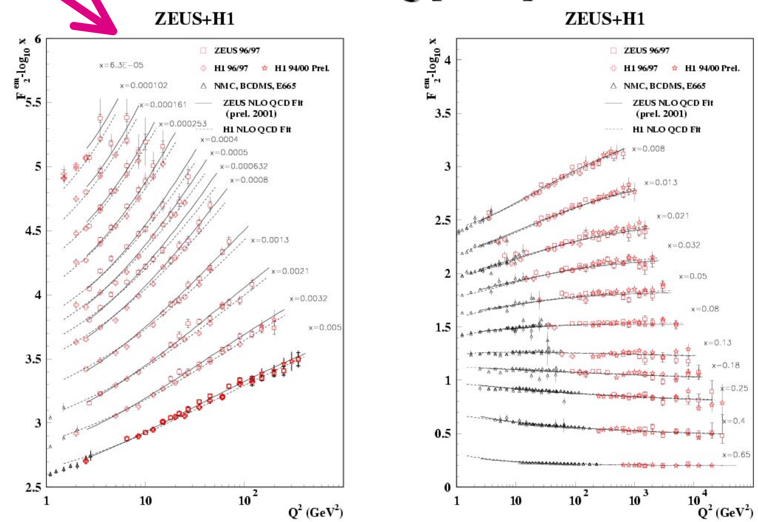


Introduction to heavy ion physics

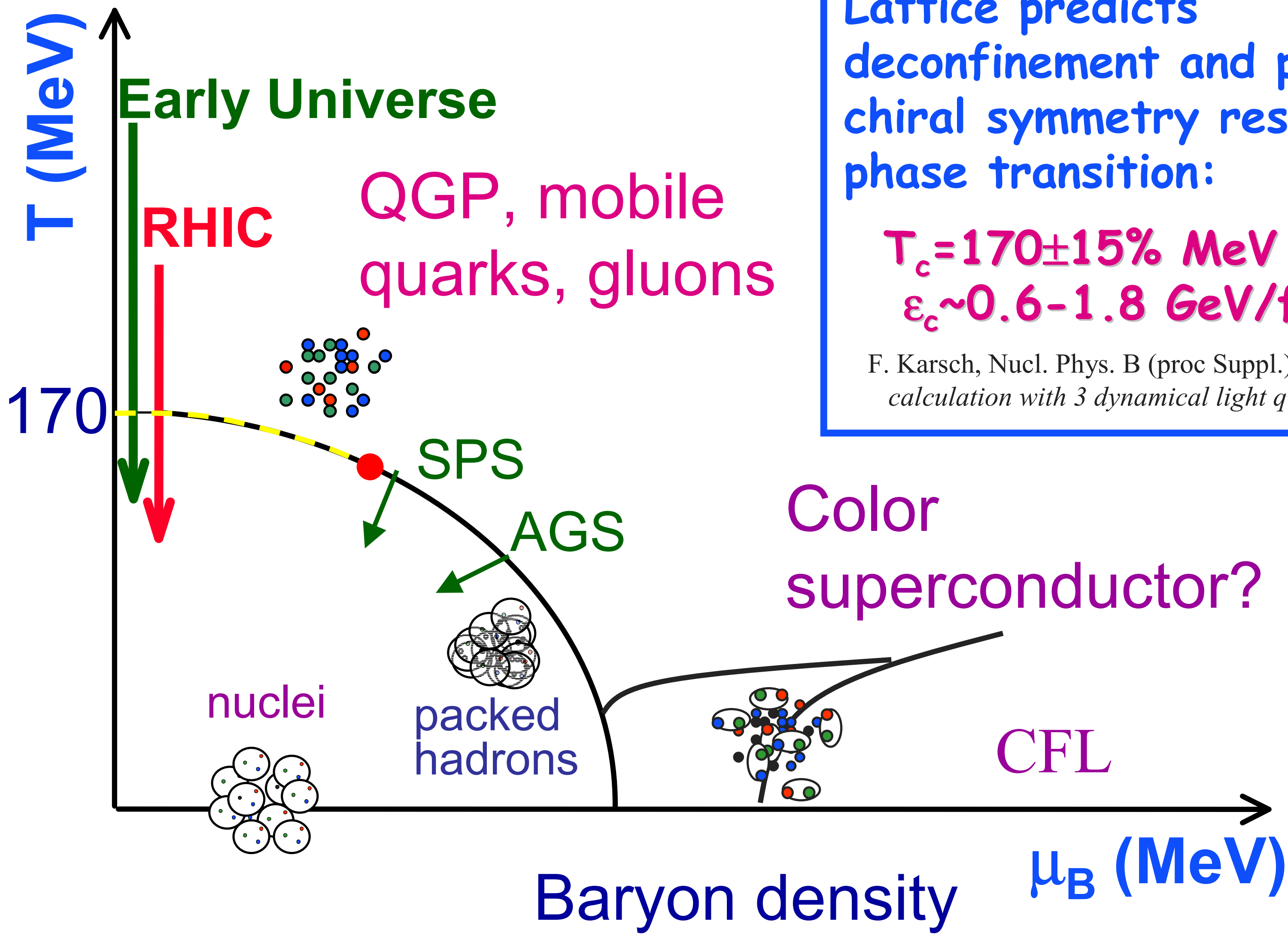
Heavy ions physics and QCD

- Assume QCD is the correct theory of strong interactions. Great success:
  - » α_s scaling
  - » Evolution of structure functions
- But only special cases can currently be calculated, e.g.
  - » High Q^2 where $\alpha_s \ll 1$ (pQCD)
  - » High T, Low μ_B (lattice)
  - » High μ_B, Low T (color superconductor)
  - » High gluon density (CGS)
- Experiment is needed to help guide theory in the difficult-to-calculate regions.
  - » Is there a new set of theoretical tools that need to be developed??





Phases of nuclear matter



Lattice predicts deconfinement and partial chiral symmetry restoration phase transition:

T_c=170±15% MeV (10^{12} °F)

ε_c~0.6-1.8 GeV/fm^3

F. Karsch, Nucl. Phys. B (proc Suppl.) 83-84 (2000) 14.
calculation with 3 dynamical light quarks

Deconfinement

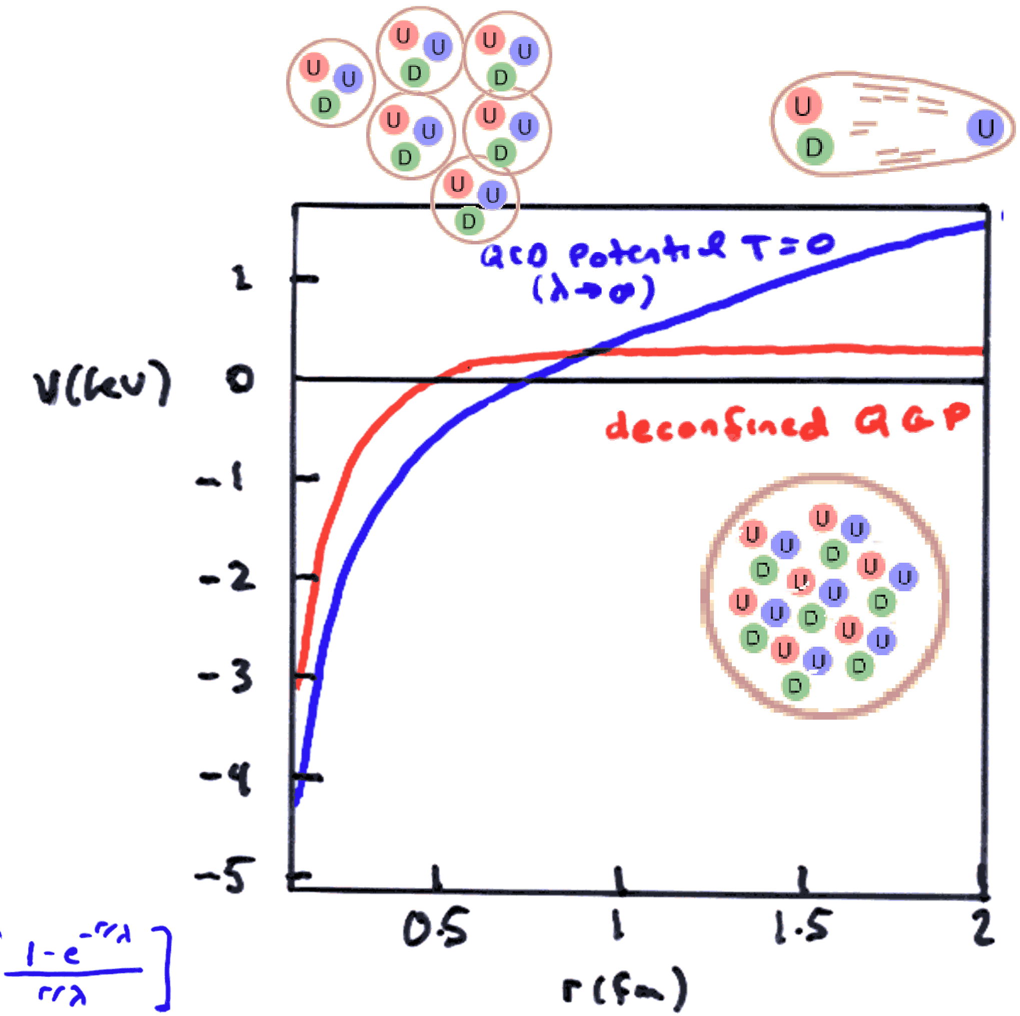
QCD potential:

in vacuum

- » linear increase with distance from color charge
- » strong attractive force
- » **confinement of quarks** to hadrons baryons (qqq) and mesons ($q\bar{q}$)

in dense and hot matter

- » screening of color charges
- » potential vanishes for large distance scales
- » **deconfinement of quarks!**



confinement

$$V(r) = -\frac{\alpha}{r} + kr \rightarrow -\frac{\alpha}{r}e^{-r/\lambda} + kr\left[\frac{1-e^{-r/\lambda}}{r/\lambda}\right]$$

"Coulomb" potential

Early universe ➨ Different Vacuum?

In the early universe this Vacuum was very different than it is now.

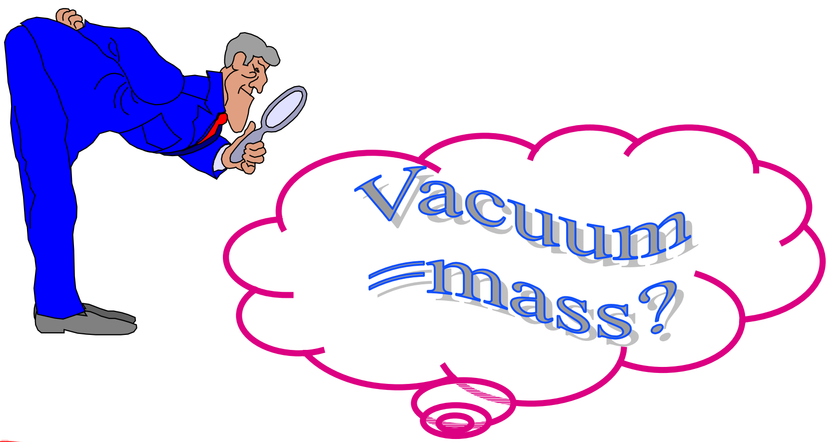
» Particles (hadrons) had different (~zero) masses!

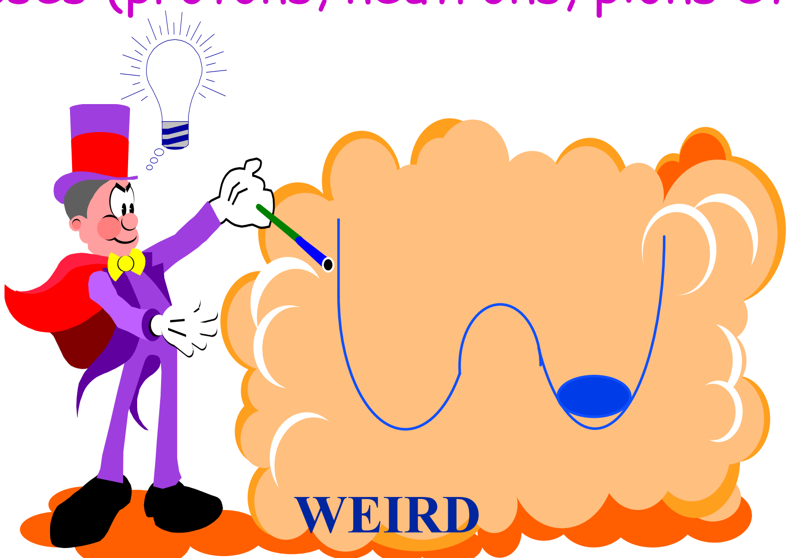
Present theories (well tested ones!) indicate that the vacuum is NOT empty but is filled with a quark condensate "goo"

» This is a very weird idea - "wilder than many crackpot theories, and more imaginative than most science fiction"-F. Wilczek

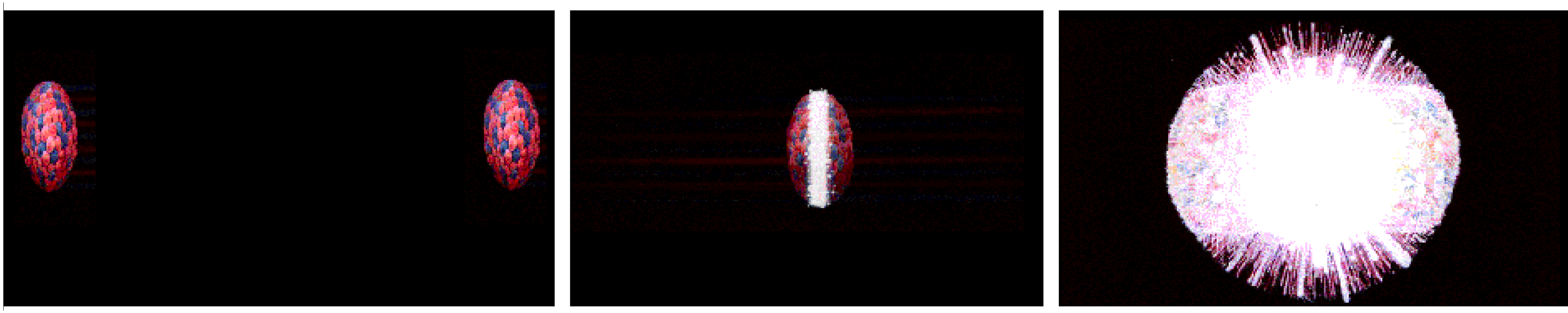
» Explains why particles (quarks) stick together -"confinement"

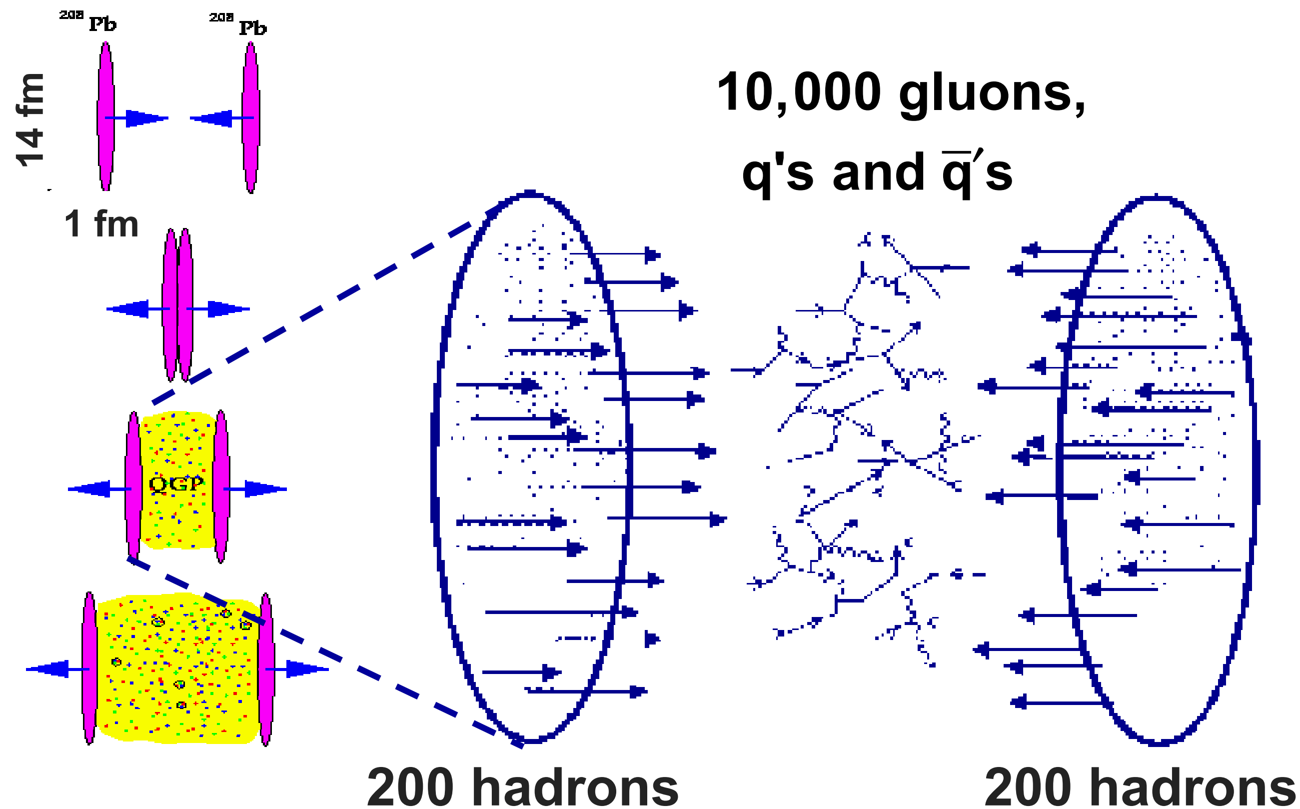
» is the origin of hadronic particle masses (protons, neutrons, pions etc)





How can we create in the lab?



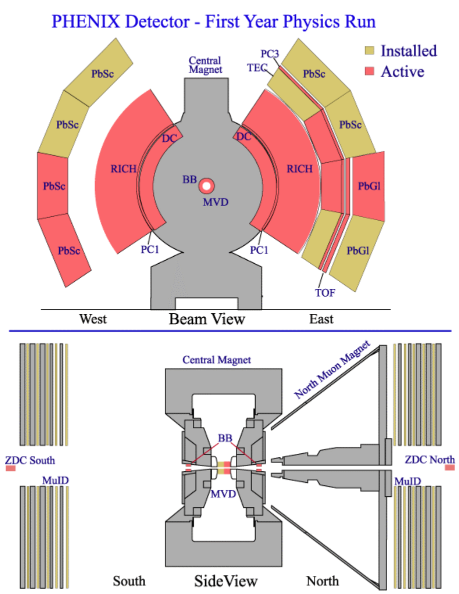


PHENIX experimental status

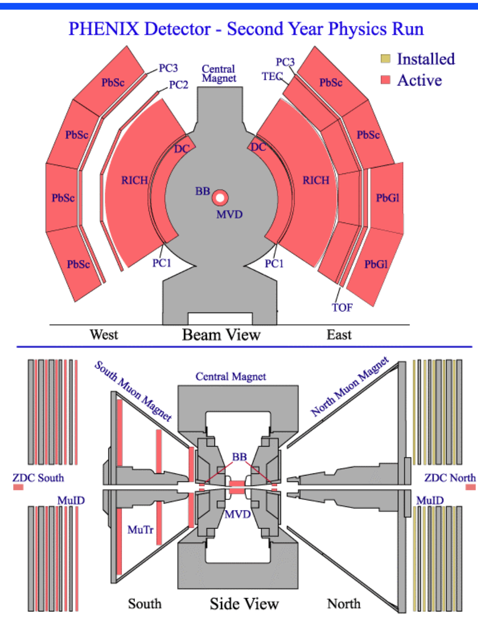
PHENIX Run History

Run	Year	Species	$s^{1/2}$ [GeV]	$\int Ldt$	N_{tot}	P
01	2000	Au-Au	130	1.0 mb^{-1}	10M	
02	2001/2002	Au-Au	200	24 mb^{-1}	170M	
		p-p	200	0.15 pb^{-1}	3.7G	~15%
03	2002/2003	d-Au	200	2.74 nb^{-1}	5.5G	
		p-p	200	0.35 pb^{-1}	6.6G	~27%

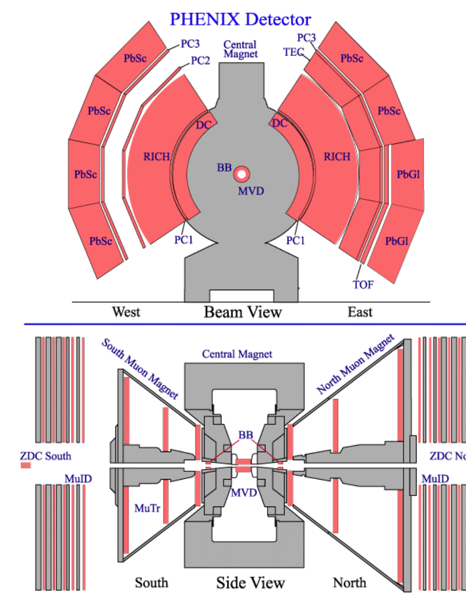
2000



2001/2002



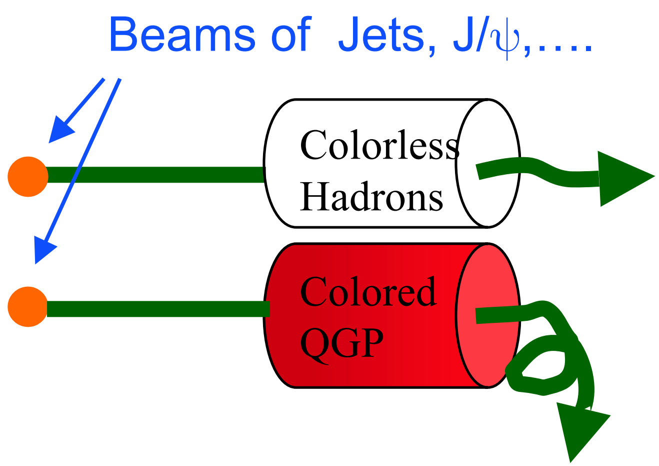
2002/2003



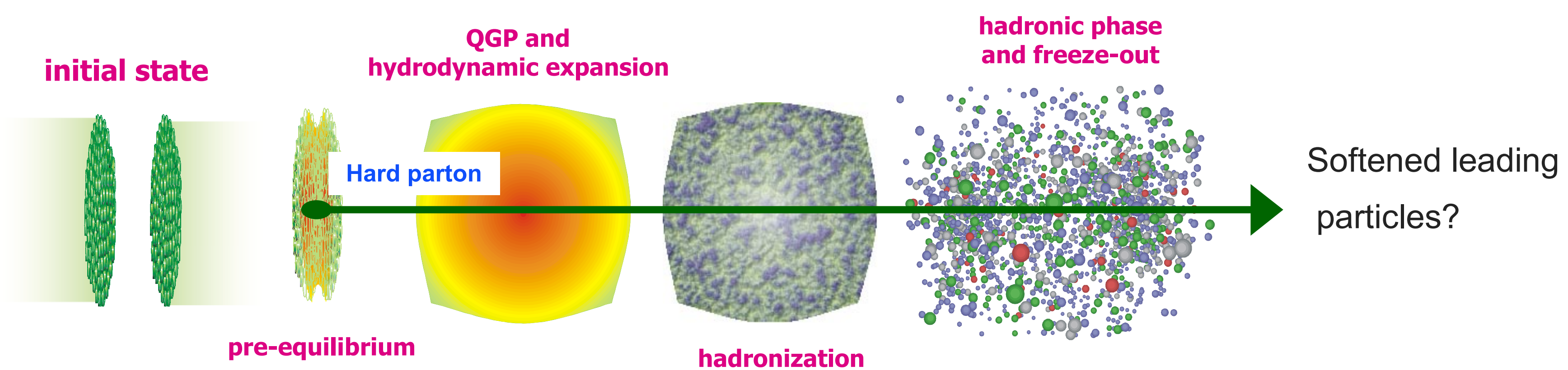
Primary Heavy Ion results

How can we probe deconfined matter?

We expect quarks and quarkonium states to ***respond differently*** to a plasma compared to ordinary nuclear matter



All probes must be auto-generated

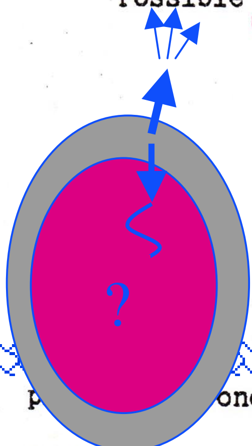


Can we look directly at jets?

20 YEARS AGO

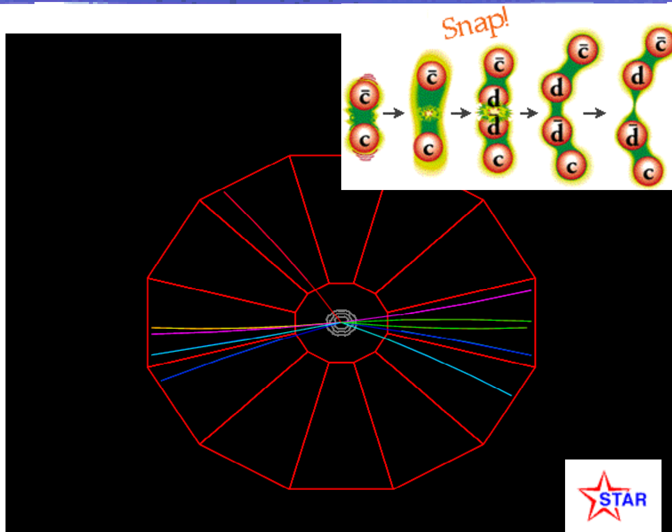
FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

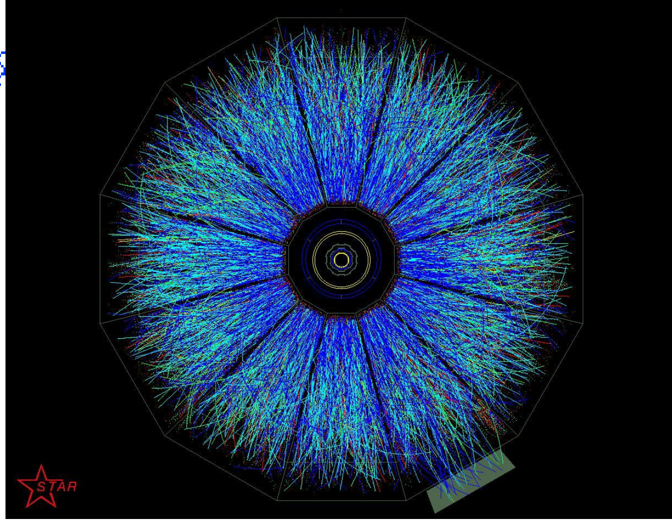


J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

p ondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



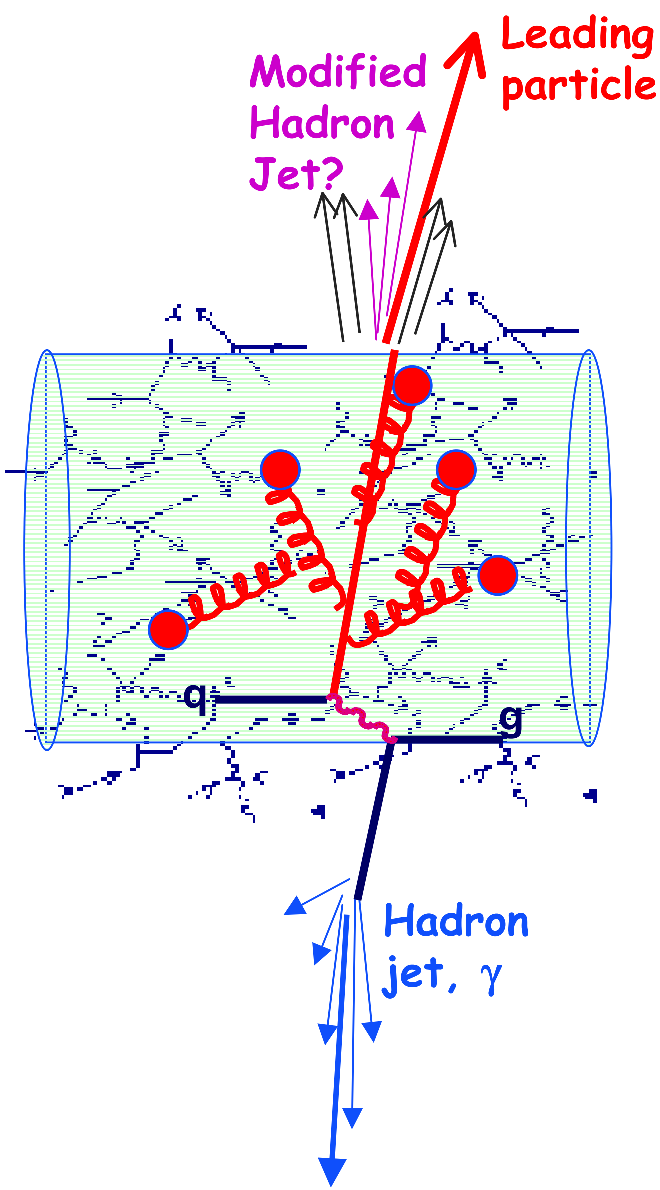
Au+Au event at 200 GeV



Leading particles as a probe

Advantage

- ✓ Can avoid soft background in a jet cone by letting $R \rightarrow 0$
- ✓ Best to measure using a fine grained calorimeter
  - Can identify neutral pions in PHENIX calorimeter $\delta\phi=\delta\eta=.01$
  - Fractional energy resolution improves with increasing energy
  - Relatively easy to trigger on



Disadvantage

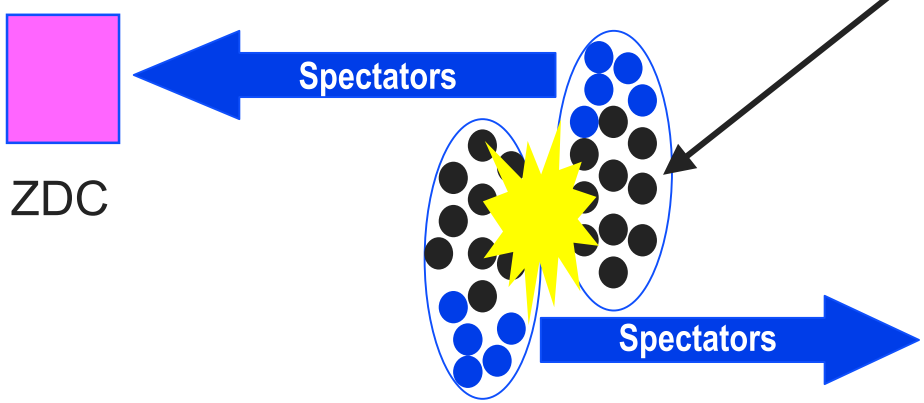
- ➢ Parent parton energy uncertain
  - Will dilute determination of the properties of the created state of matter

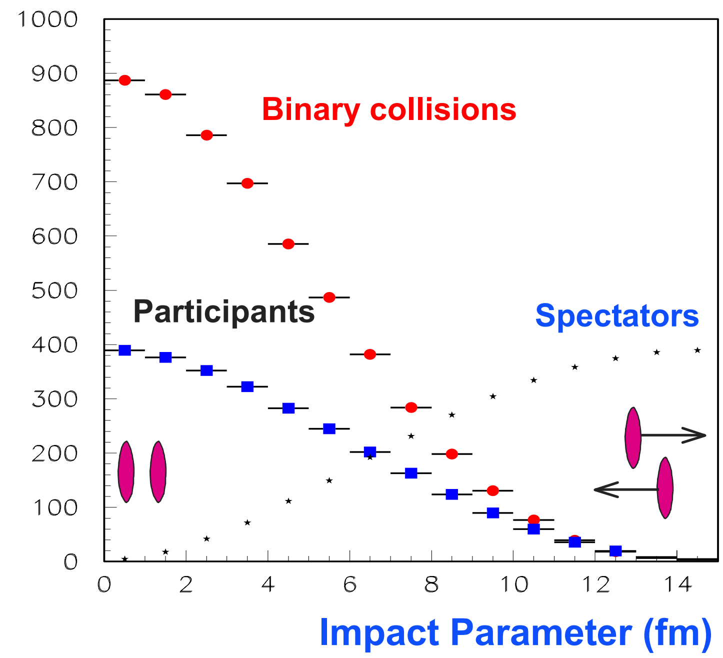
Collision Characterization

In Run 1 & 2, we only collided one nuclear species (Gold).

However, we can vary the collision size by selecting different impact parameter events

Different number of participating nucleons

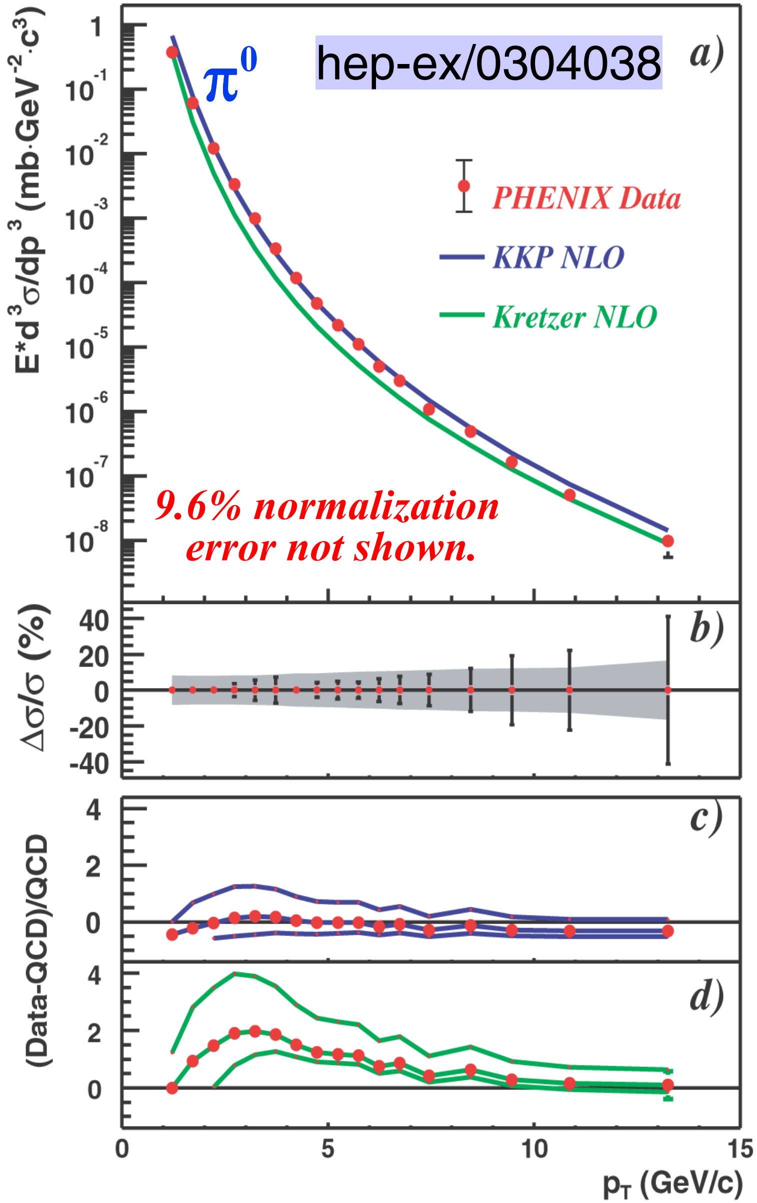




Participants = 2 x 197 - Spectators

PHENIX π^0 spectrum in p+p collisions

- ✓ What should we compare these results with?
  - Start with baseline that Au+Au is incoherent superposition of N+N collisions
  - Scale p+p collisions with number of binary collisions
- ✓ p+p comparison data was the largest systematic error for run 1 results
  - No data at 130GeV
- ✓ In run 2 PHENIX measured the neutral pion spectrum in p+p at 200 GeV.
- ✓ Results consistent with pQCD NLO calculation



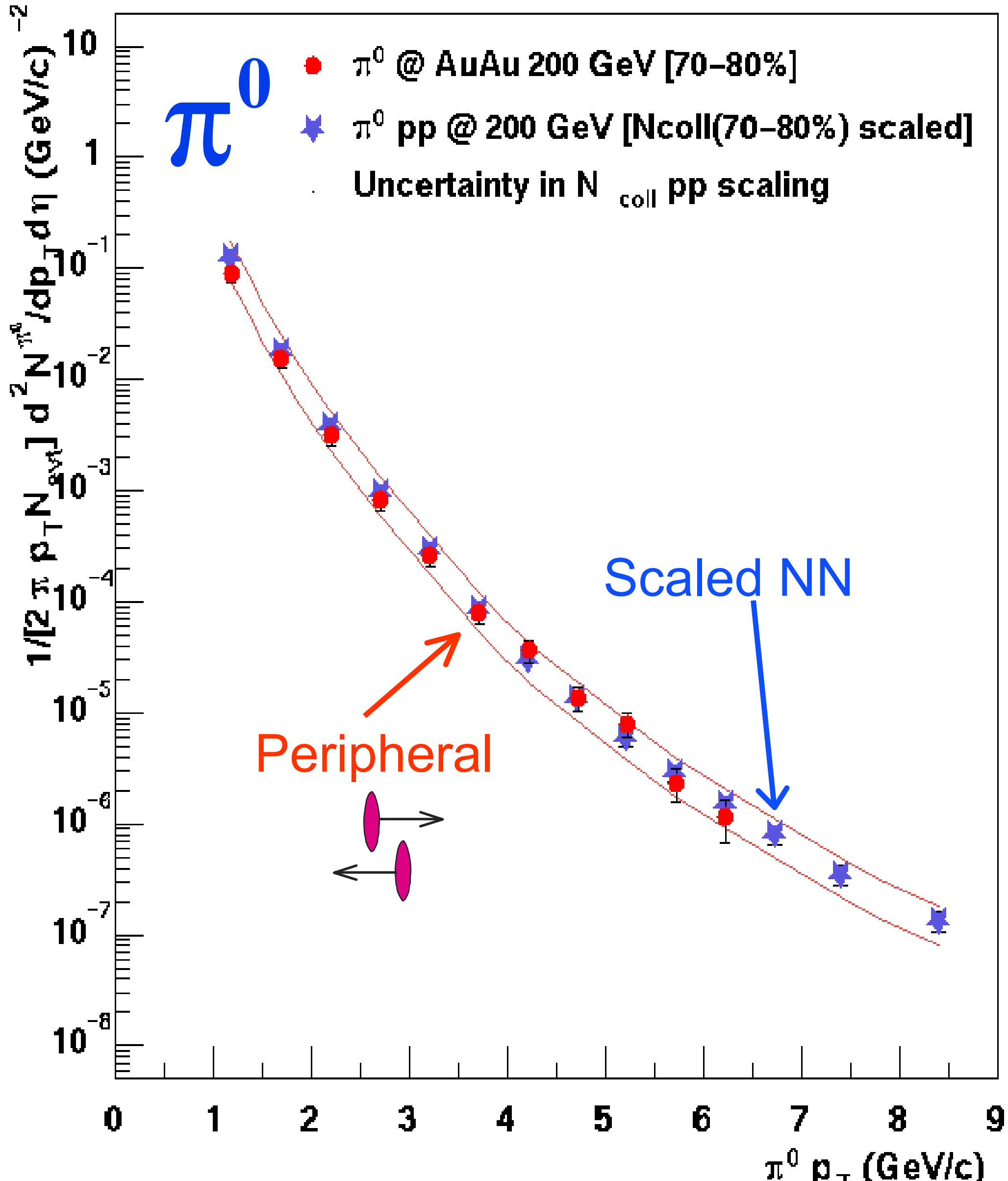
π^0 spectra in Au+Au at 200GeV

Peripheral Collisions

- ✓ PHENIX (Run-2) data on π^0 production in peripheral (70-80%) collisions
- ✓ Consistent with N+N, as measured by PHENIX, scaled by number of binary collisions

Scale p-p data by the number of binary collision in central peripheral collisions.

$$N_{collisions}^{70-80\%} = 12.4 \pm 4.2$$



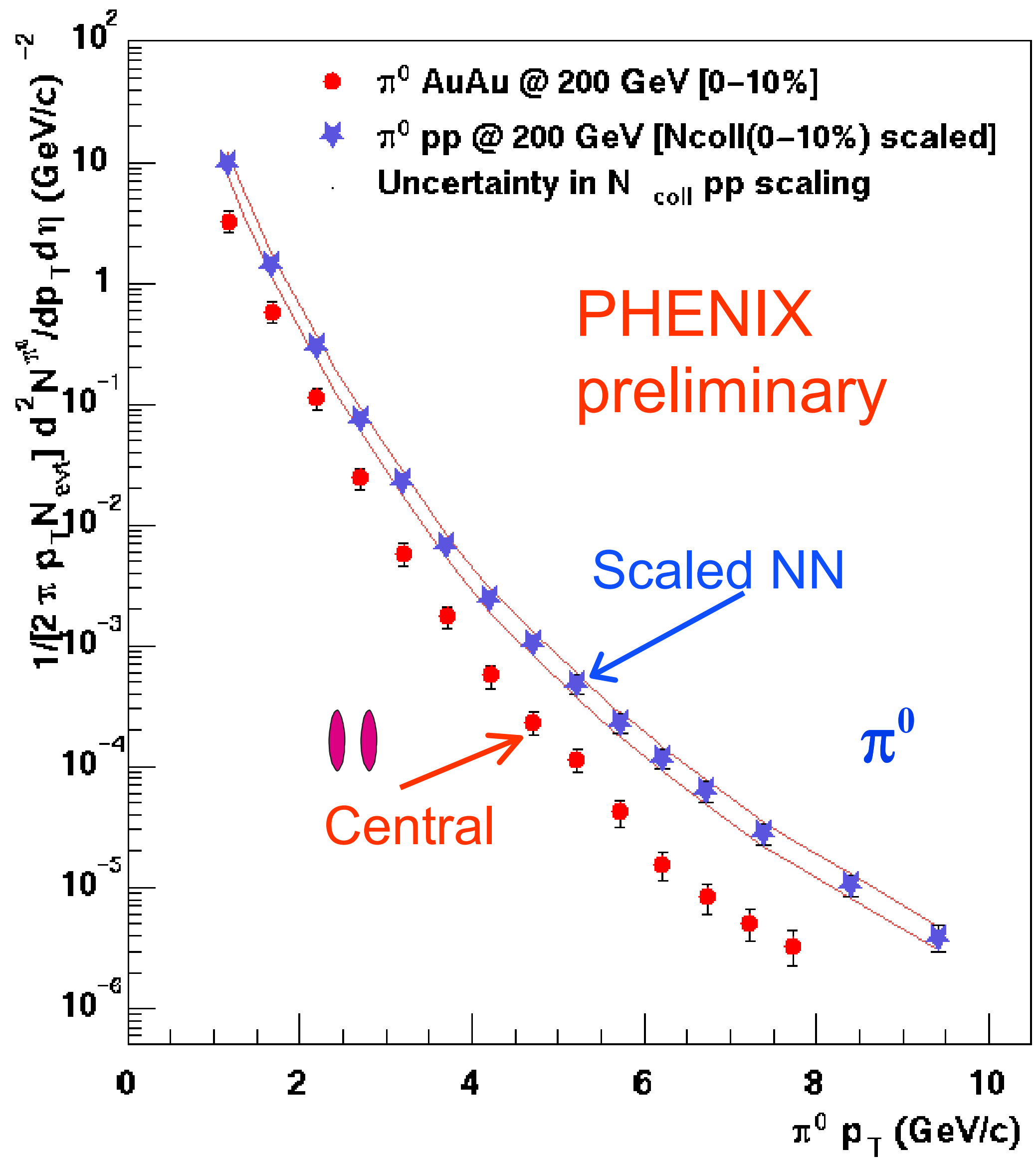
π^0 spectra in Au+Au at 200GeV

Central Collisions

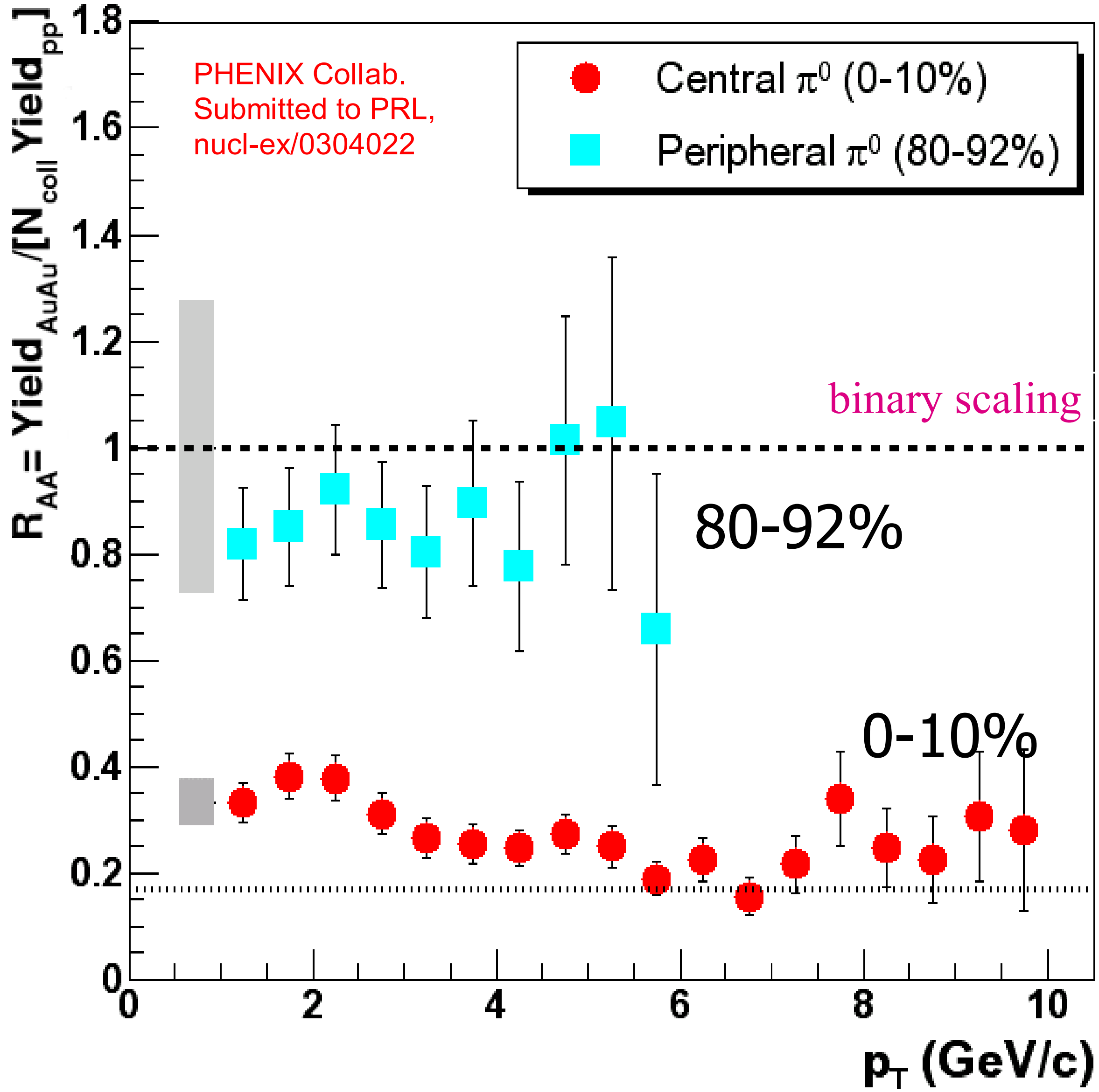
- ✓ PHENIX (Run-2) data on π^0 production in central (0-10%) collisions
- ✓ Clearly lower than the scaled N+N collisions
  - Factor 6 at p_T=6-8GeV/c.
- ✓ *At least qualitatively this is what we expect from energy loss in a dense medium.*

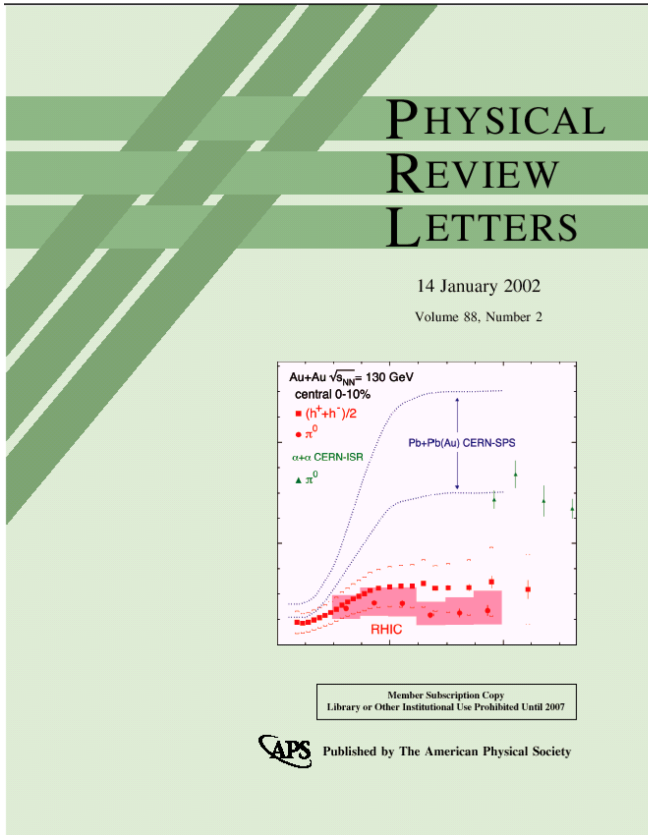
Scale p-p data by the number of binary collision in central and peripheral collisions.

$$N^{0-10\%}_{collisions} = 955.4 \pm 93.6$$



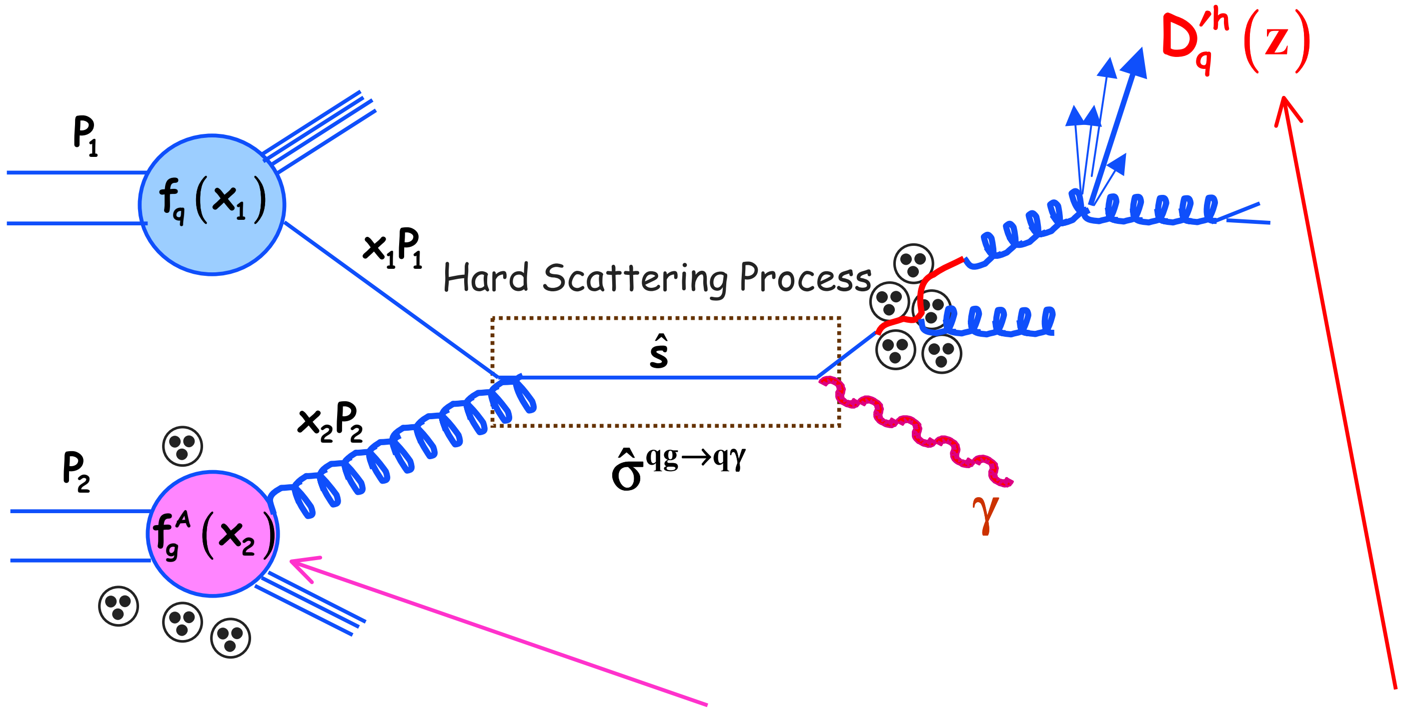
π^0 yield in Au+Au vs. p+p collisions





Discovery of high p_T suppression

Hard scattering processes in p+A

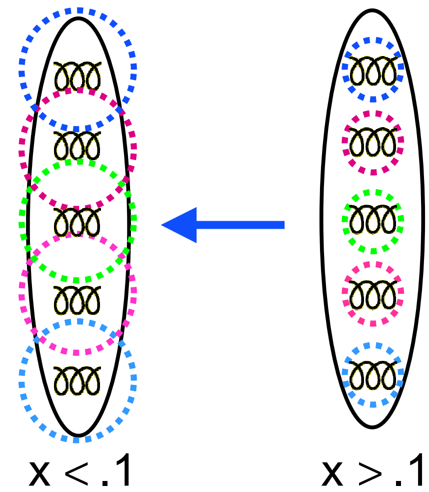


$$\sigma(pA \rightarrow hX) \quad f_q(x_1) \otimes f_g^A(x_2) \otimes \hat{\sigma}^{qg\rightarrow q\gamma}(\hat{s}) \otimes D_q'^h(z)$$

The structure functions and fragmentation function can be modified due to nuclear effects such as: "Cronin", "shadowing", saturation, and re-scattering.

Nuclear Shadowing of quarks and gluons

- ✓ Nucleon structure functions are known to be modified in nuclei.
- ✓ Can be modeled as a recombination effect due to high gluon # density at low x (in frame where nucleon is moving fast)

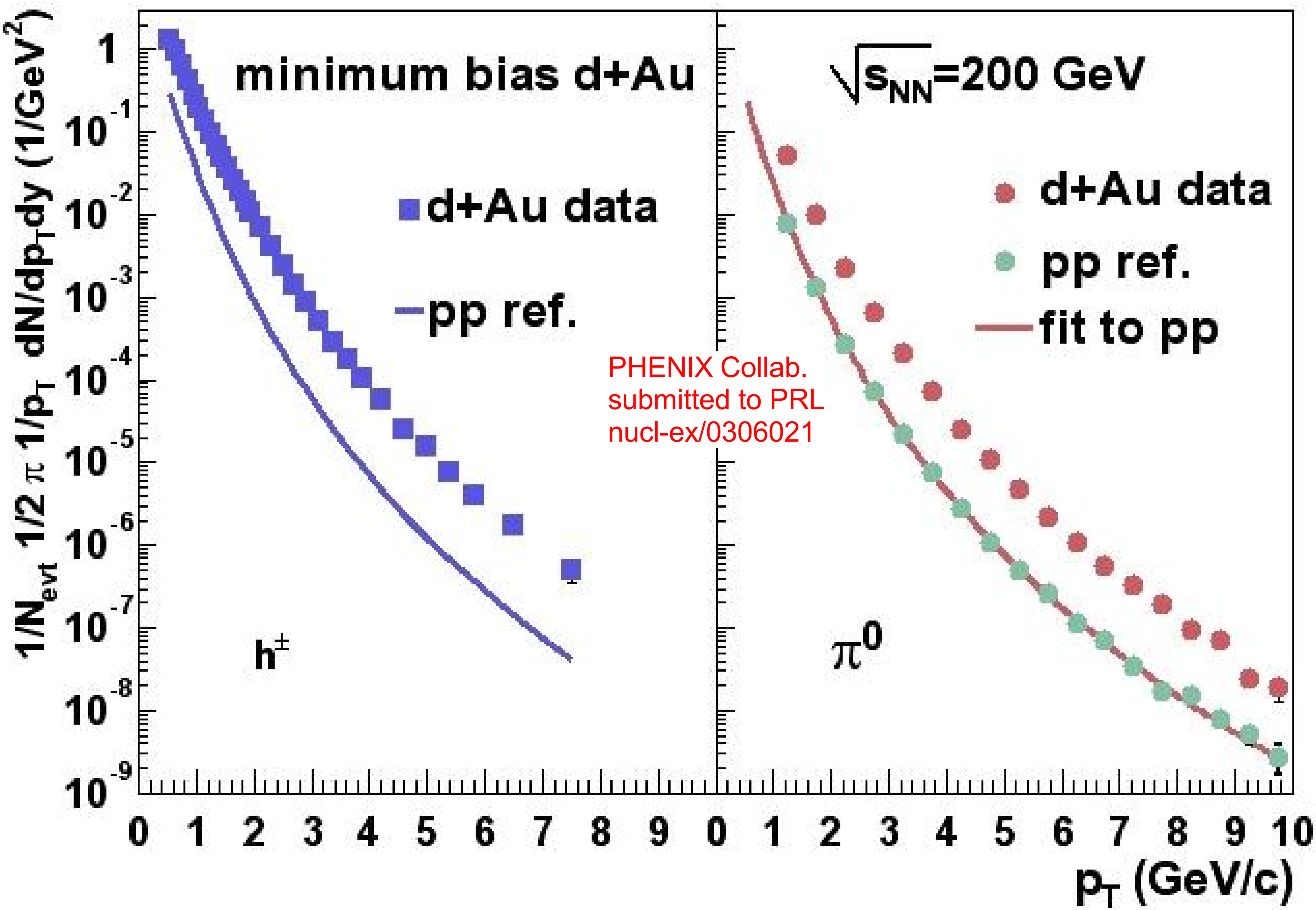


$x \;\; \frac{1}{2m_c}$

≈ 0.1

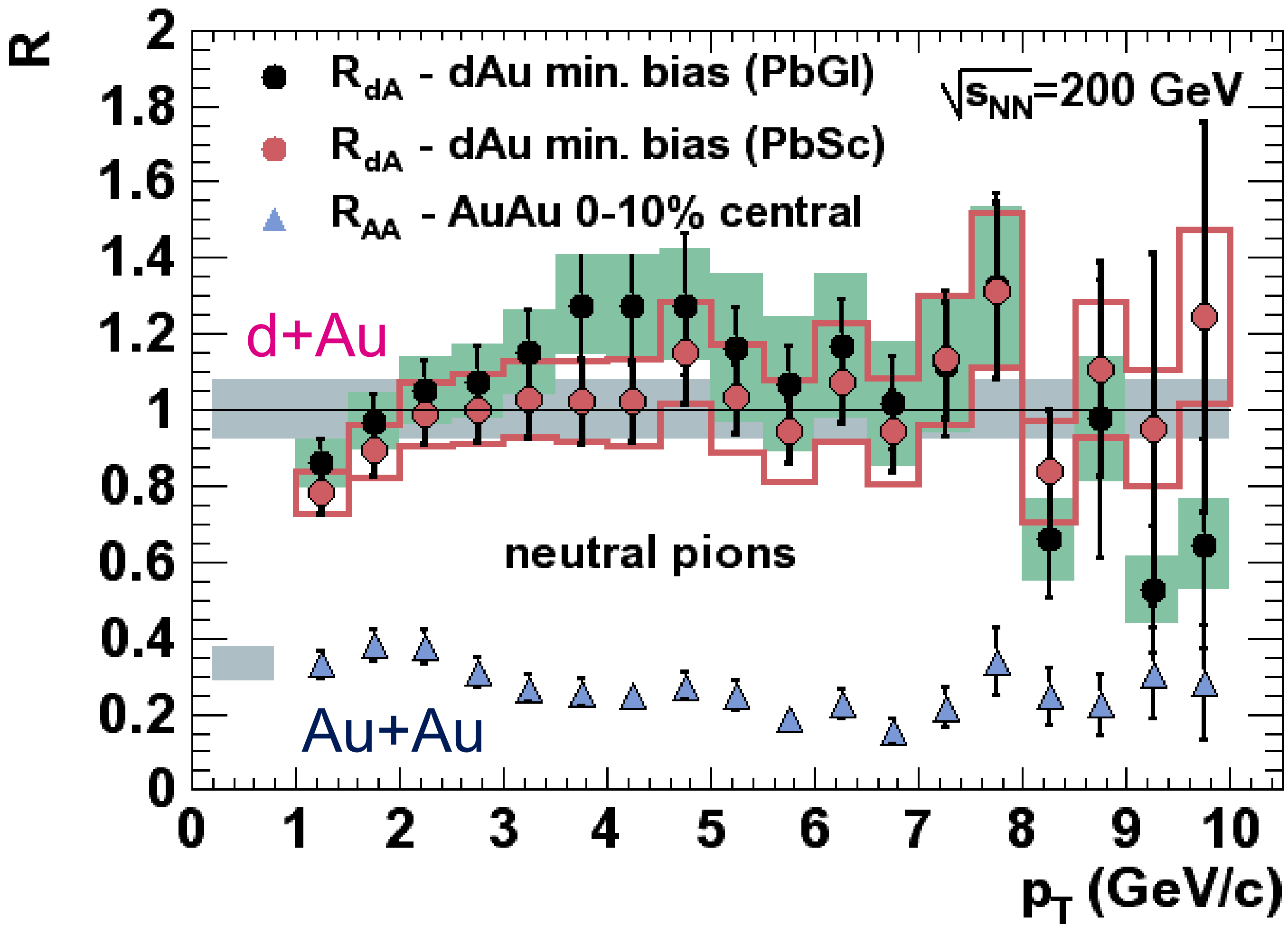
- ✓ Quark shadowing is measured and is expected to be a small (~10%) effect at RHIC energies.
- ✓ Gluon shadowing is not measured, but will clearly play a role at RHIC. It is not expected to be a large effect in the central region.
  - "super-shadowing" from a saturated state could produce a larger effect
- ✓ Run 3 included a long d+A run to address these issues.

d+Au Spectra



1/N_evt 1/2π 1/p_T dN/dp_T dy (1/GeV²)
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
minimum bias d+Au
d+Au data
pp ref.
h±
√s_NN=200 GeV
d+Au data
pp ref.
fit to pp
π0
PHENIX Collab.
submitted to PRL
nucl-ex/0306021
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 10
p_T (GeV/c)

R_{AA} vs. R_{dA} for Identified π^0



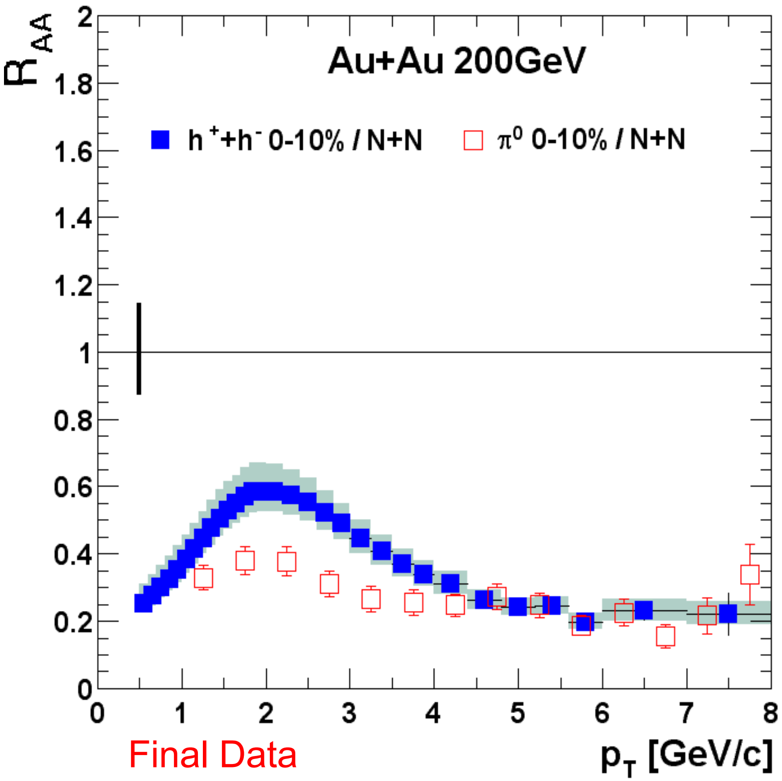
Initial State Effects Only

Initial + Final State Effects

d-Au results rule out CGC as the explanation for Jet Suppression at Central Rapidity and high p_T

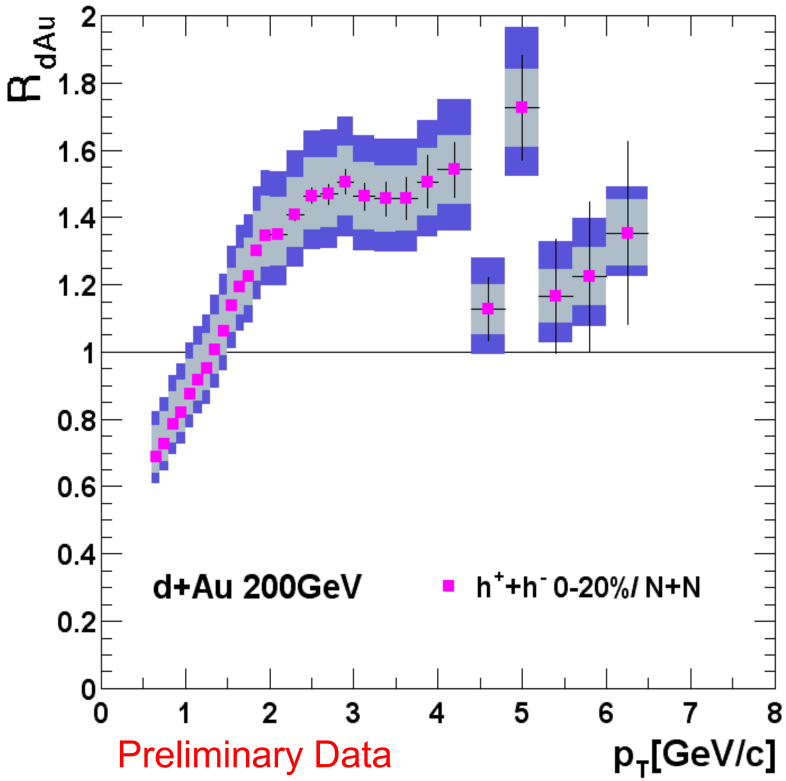
Centrality Dependence

Au + Au Experiment



Final Data

d + Au Control Experiment



Preliminary Data

"PHENIX Preliminary" results, consistent with PHOBOS data in ***submitted paper***

Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.

Jet Suppression is clearly a final state effect.

First results from polarized proton running

2001-2002 p+p run

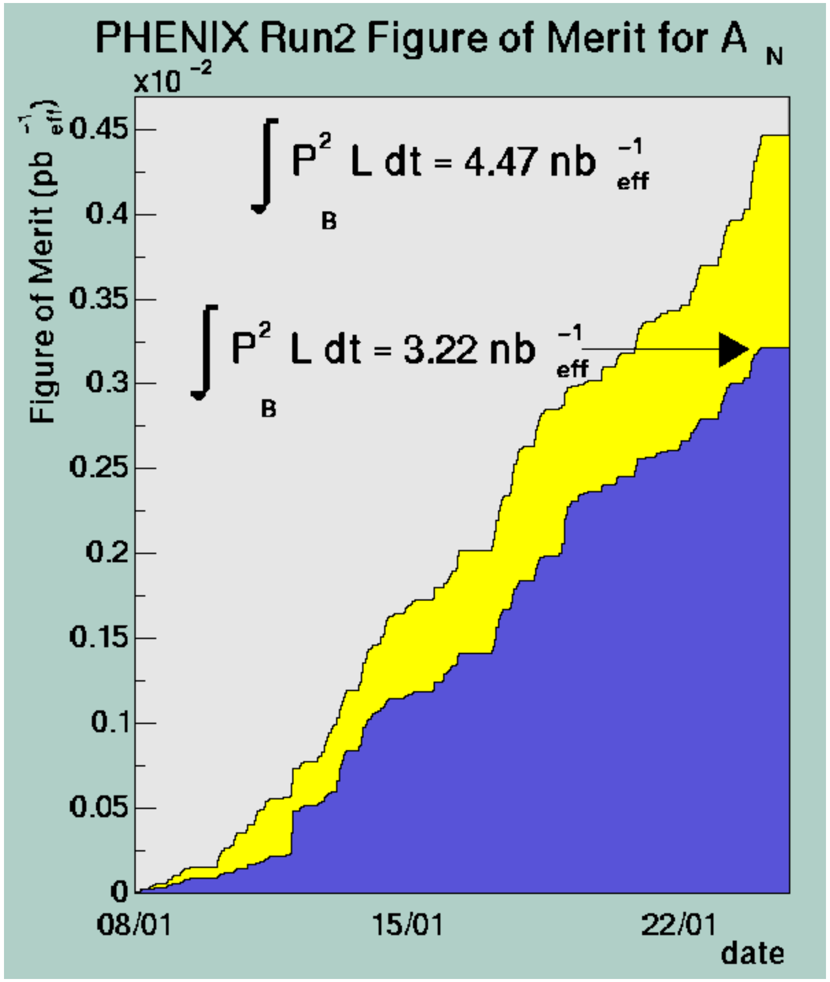
Luminosity
- » integrated luminosity 0.15 pb^{-1}
- » $L = 1.5\times10^{30}\ cm^{-1}sec^{-1}$ at max

Polarization – transverse
- » $\langle P_{yellow}\rangle$=17 %, $\langle P_{blue}\rangle$=14 %

Cross section measurement
- » π^0, J/ψ, …

A_N measurement (analysis ongoing …)
- » central arm (mid-rapidity, $x_F \sim 0$)
  - – π^0, charged hadrons, J/ψ, …
- » muon arm ($1.2 < \eta < 2.4$)
  - - single-μ, J/ψ, …

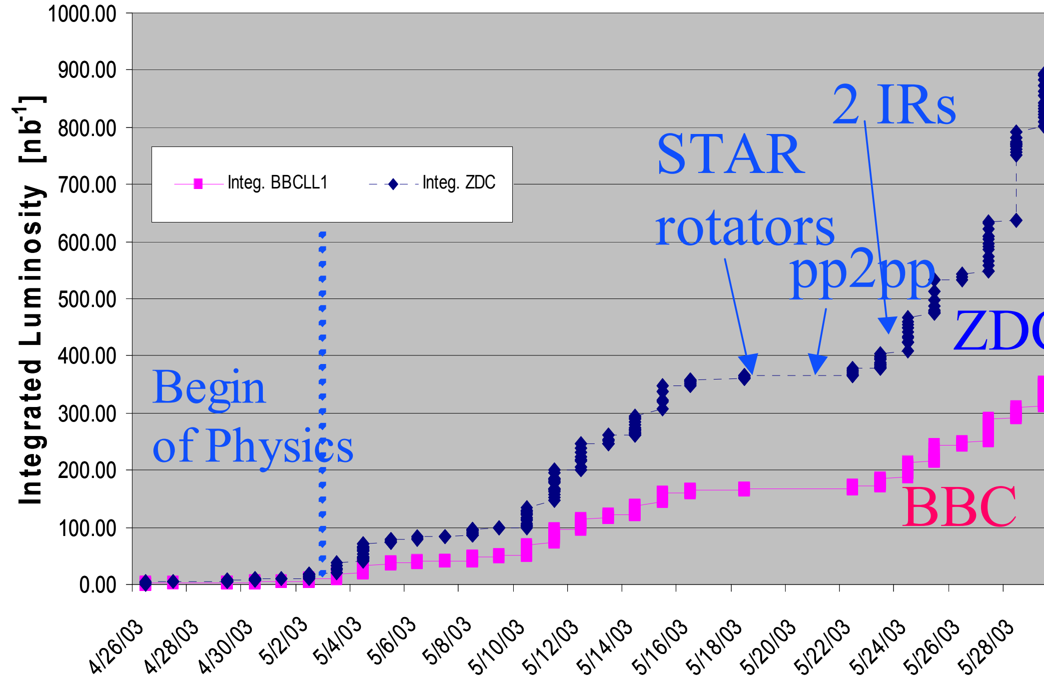
Systematic studies
- » relative luminosity study
- » local polarimeter development at IP12
  - - A_N measurement of neutron, photon, π^0 at very forward-rapidity

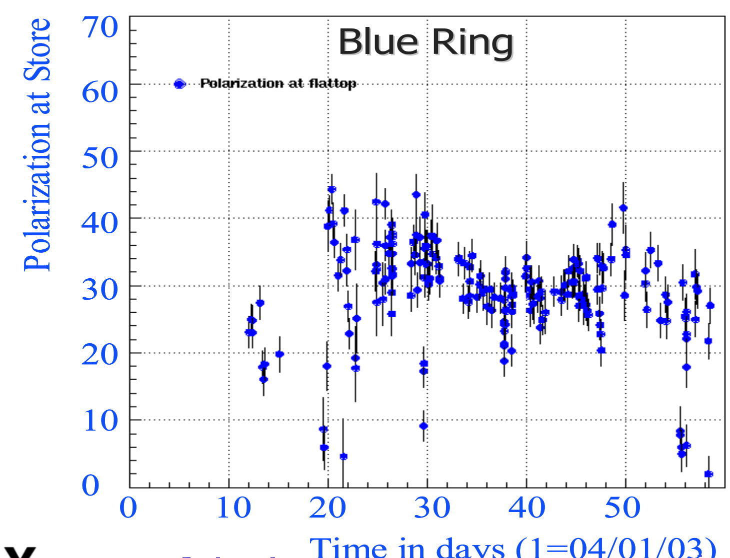


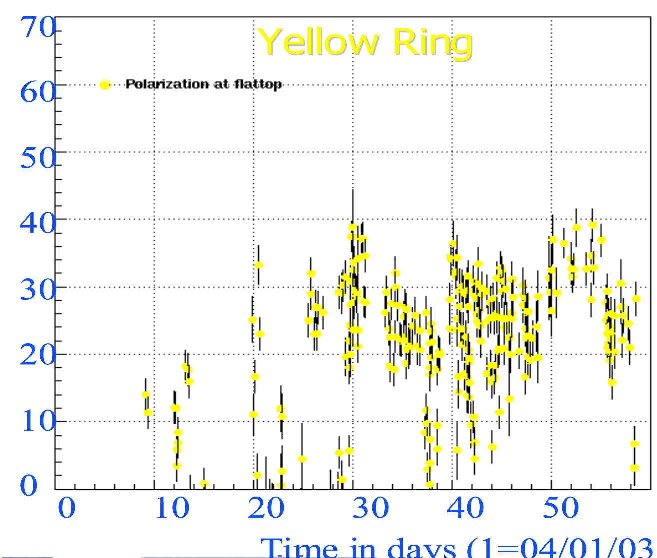
2002-2003 p+p run

- Integrated luminosity $350 nb^{-1}$ from 6.6×10^{9} BBCLL1 triggers
- Average polarization ~27%
- Figure of merit

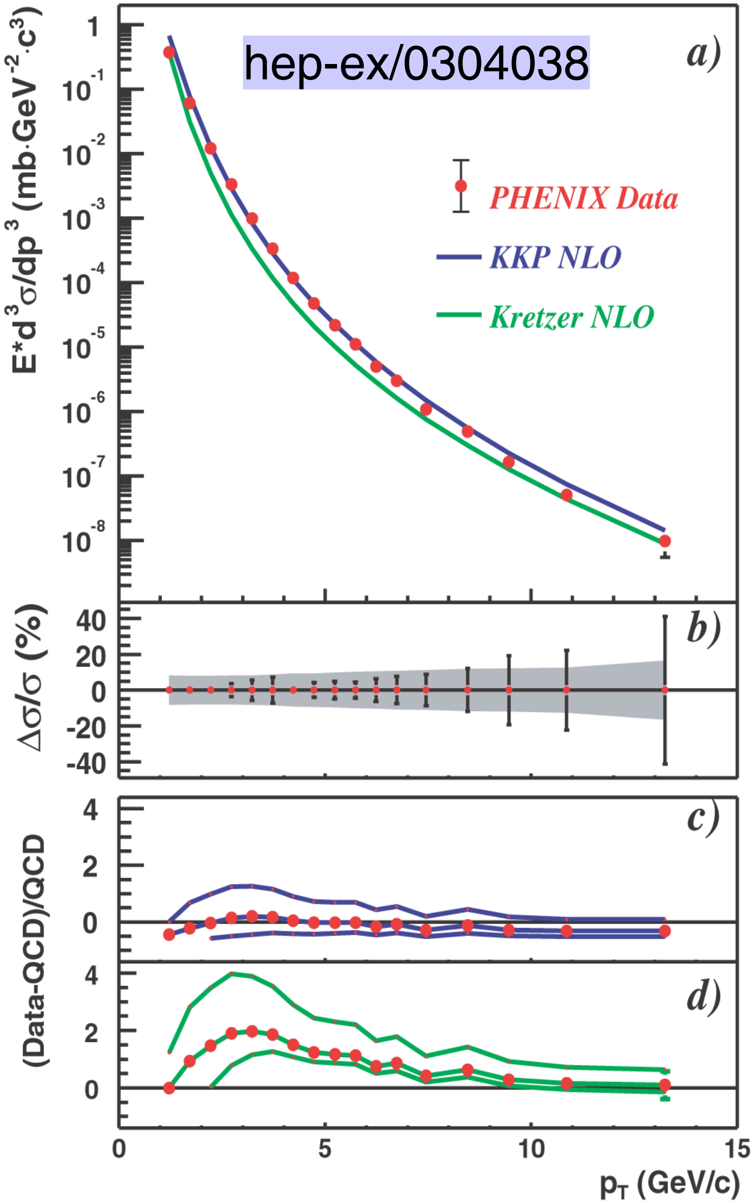
$$\int P_Y^2 P_B^2 L dt = 1.8\ nb^{-1}$$







π^0-Production in p+p at $\sqrt{s}$ = 200 GeV



Corrected π^0 spectrum

- » Trigger-Counter: BBC
  - sees ~50% of the inelastic p+p events
  - EmCal measures ~75% of the total number of π^0 in inelastic events
- » BBC trigger bias corrected for

Physics:

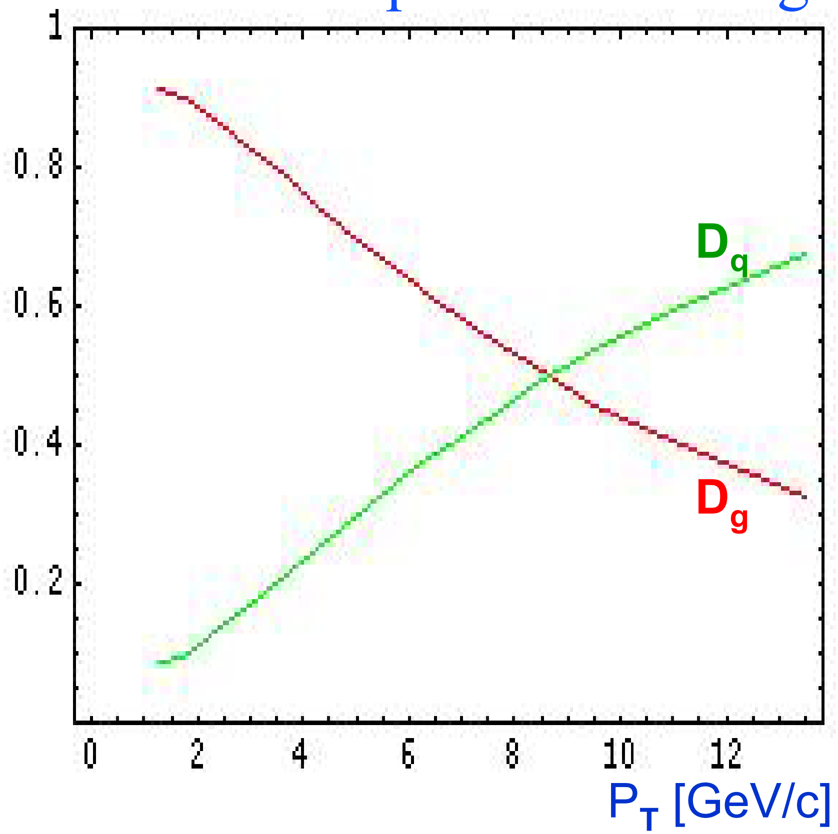
- » NLO pQCD consistent with data within scale ($\mu_N=\mu_F=p_T/2, p_T, 2p_T$) dependence.
  - pdf : CTEQ5M
  - fragmentation functions:
    [c] Kniehl-Kramer-Potter (KKP)
    [d] Kretzer
  - Spectrum constrains D(gluon→π) fragmentation function

F. Aversa *et al.*, NP**B327**, 105 (1989)
B.A. Kniehl *et al.*, NP**B597**, 337 (2001)
S. Kretzer, PR**D62**, 054001 (2000)

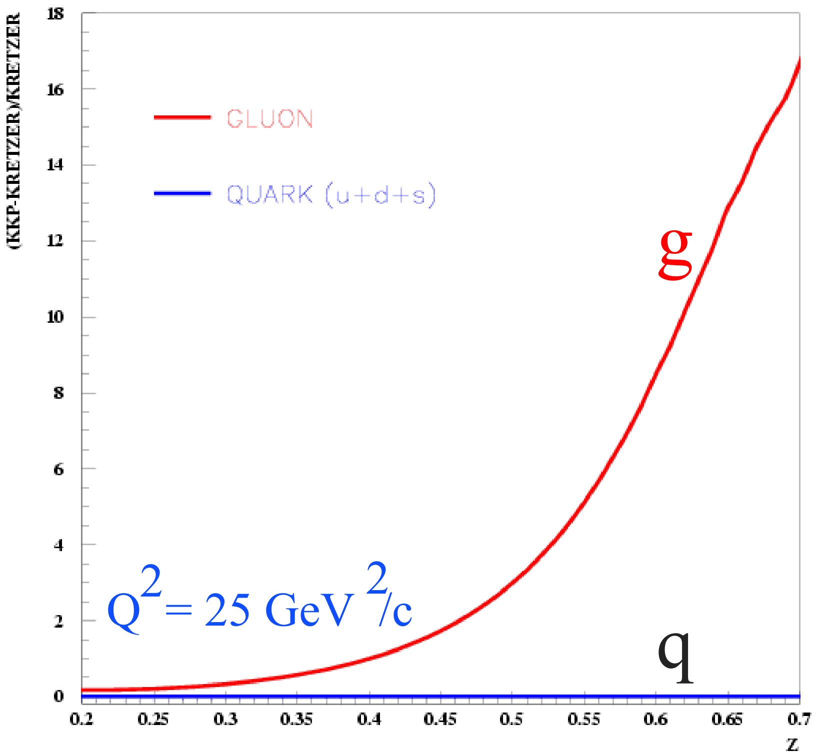
- » Important confirmation of theoretical foundations for spin program.
- » Result needed as reference for interpretation of Au+Au-Spectra

Why Kretzer & KKP Differ?

Relative Importance of Frag.



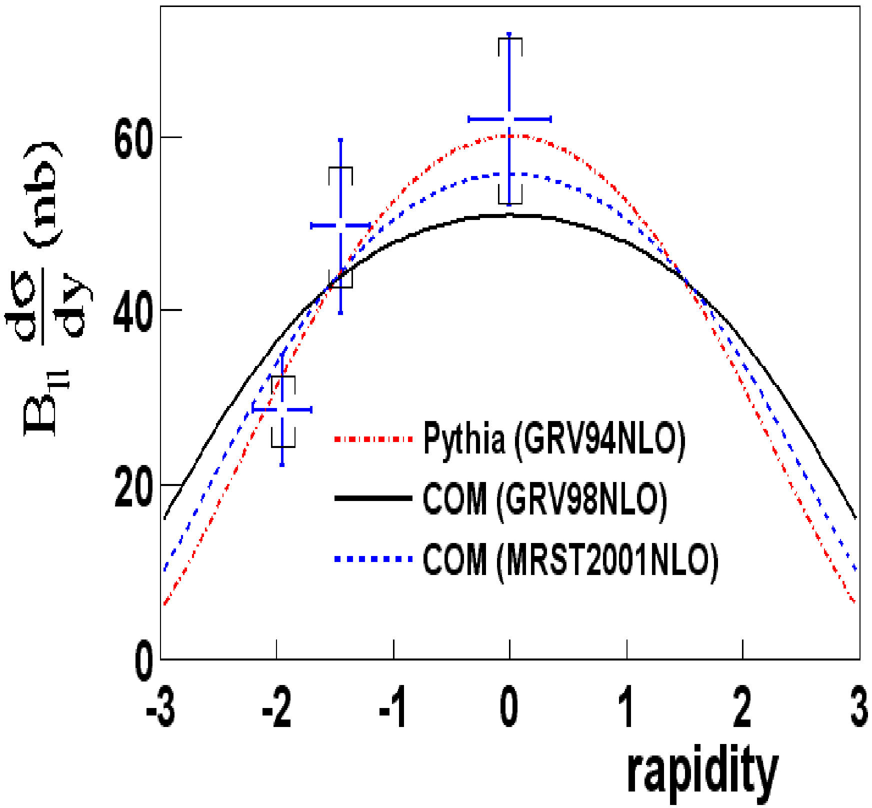
(KKP-Kretzer)/Kretzer -vs- z

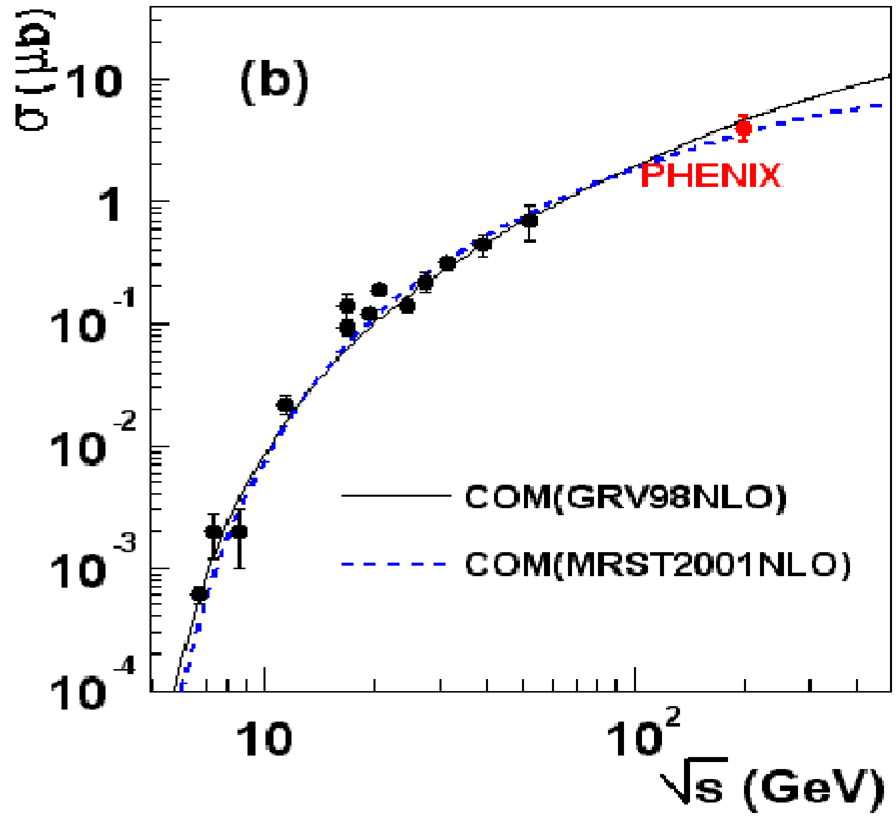


S. Kretzer, W. Vogelsang, private comm.

…$D_{g\rightarrow\pi}$ likely gives rise to low p_T difference

J/ψ production in p+p at √s = 200 GeV





Single-spin asymmetries (A_N)

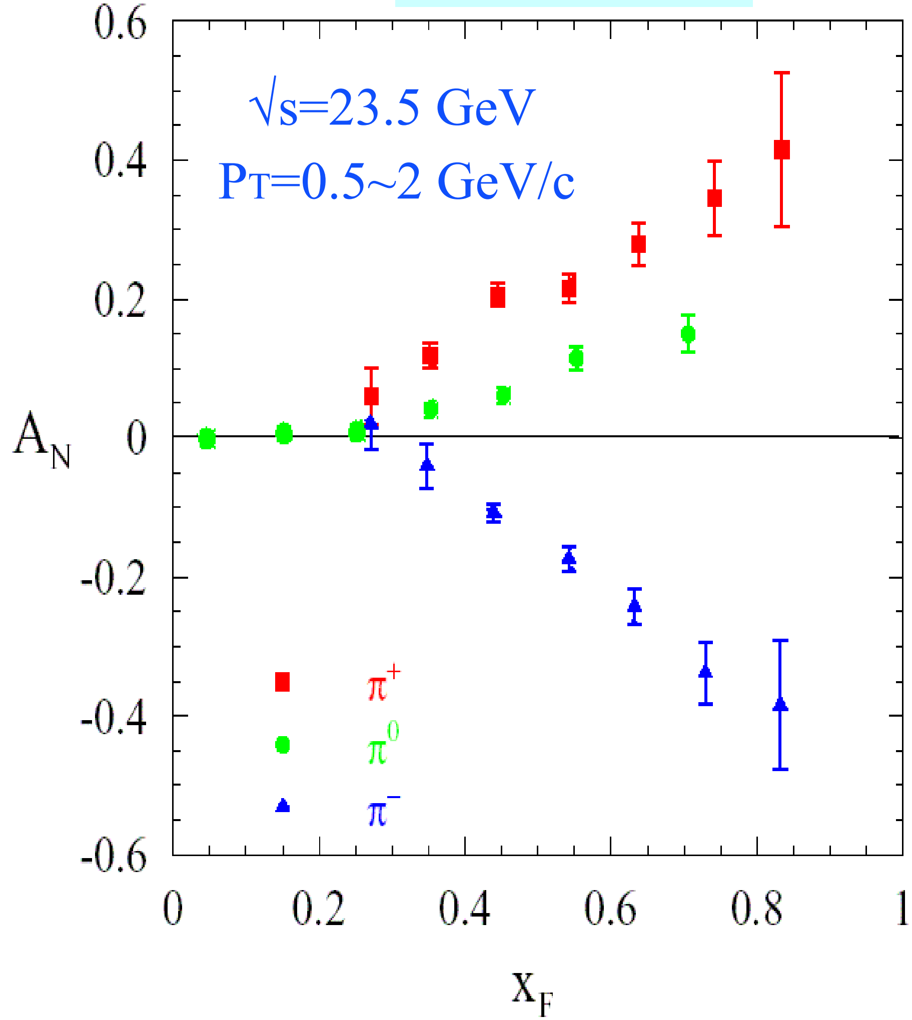
$$A_N = \frac{1}{P} \cdot \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

» Motivated by large A_N measured by the FNAL-E704 experiment at high-x_F at $\sqrt{s}$ = 19.4 GeV

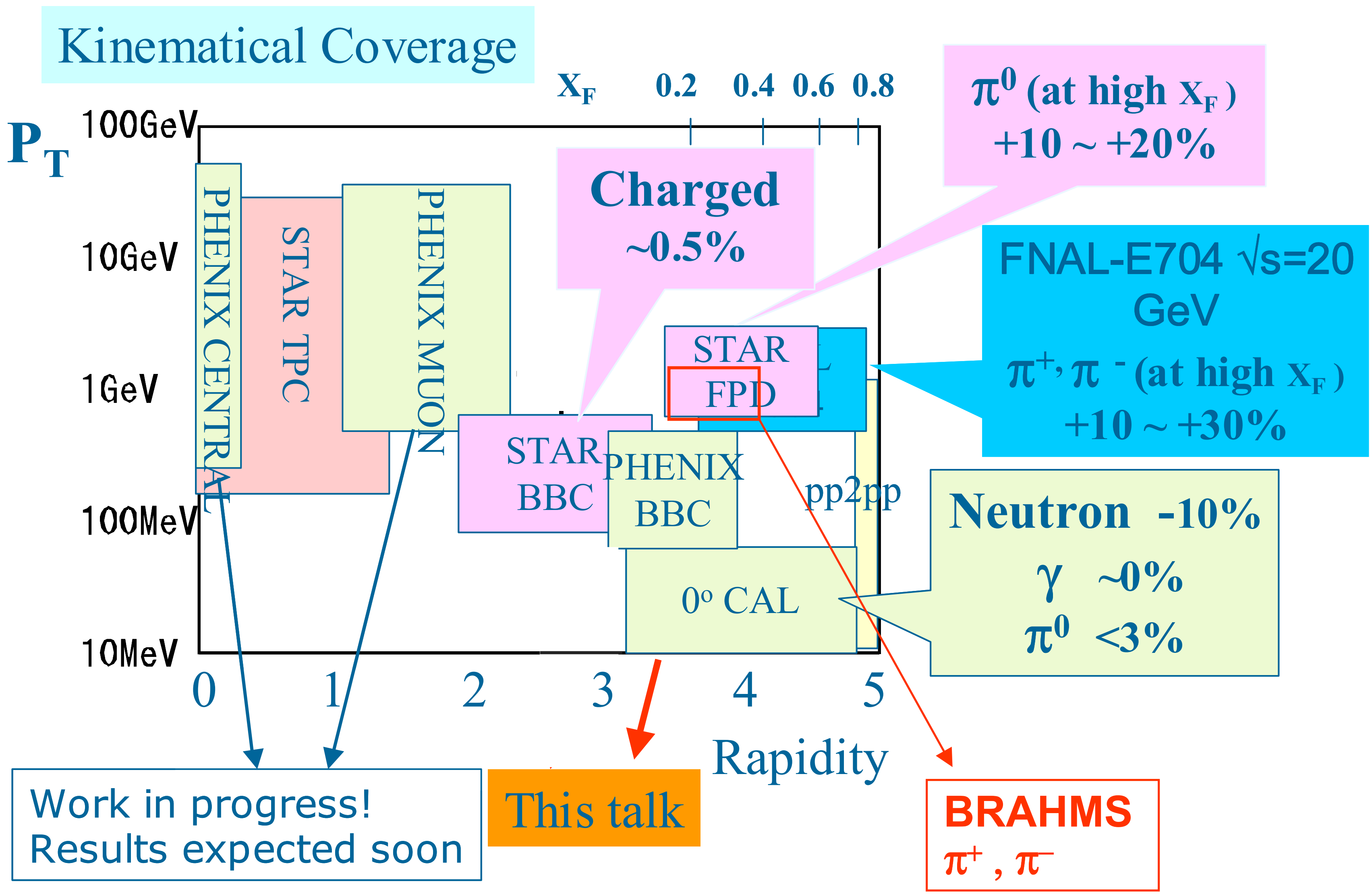
» Origin not well understood theoretically

» Application for high-energy polarized proton polarimetry

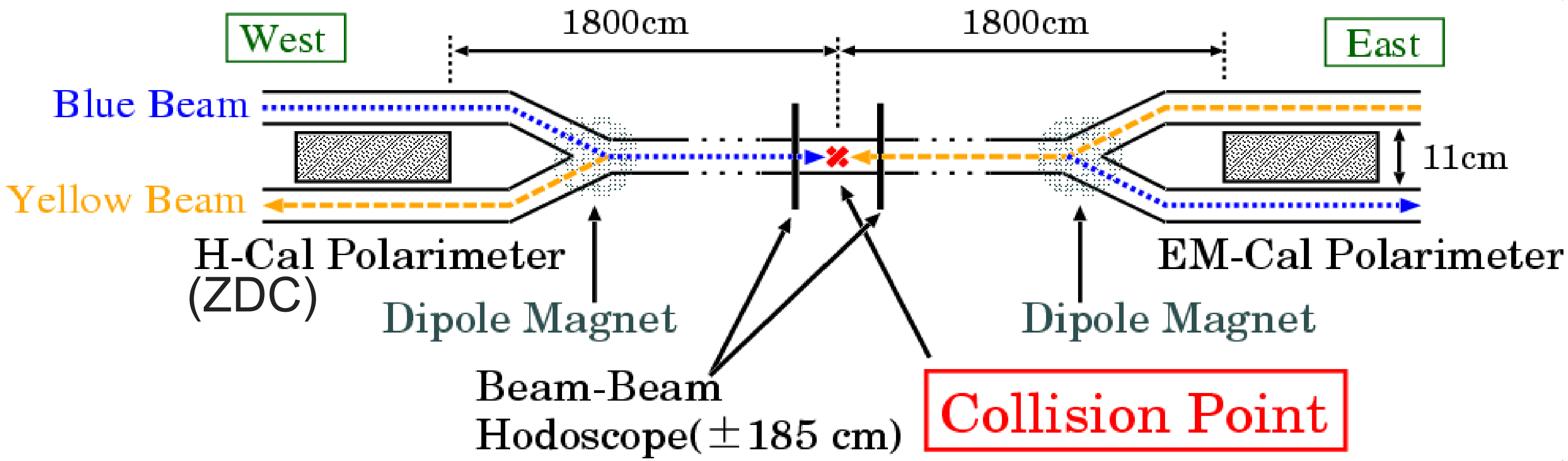
FNAL E704



A_N from RHIC $\sqrt{s}$=200 GeV

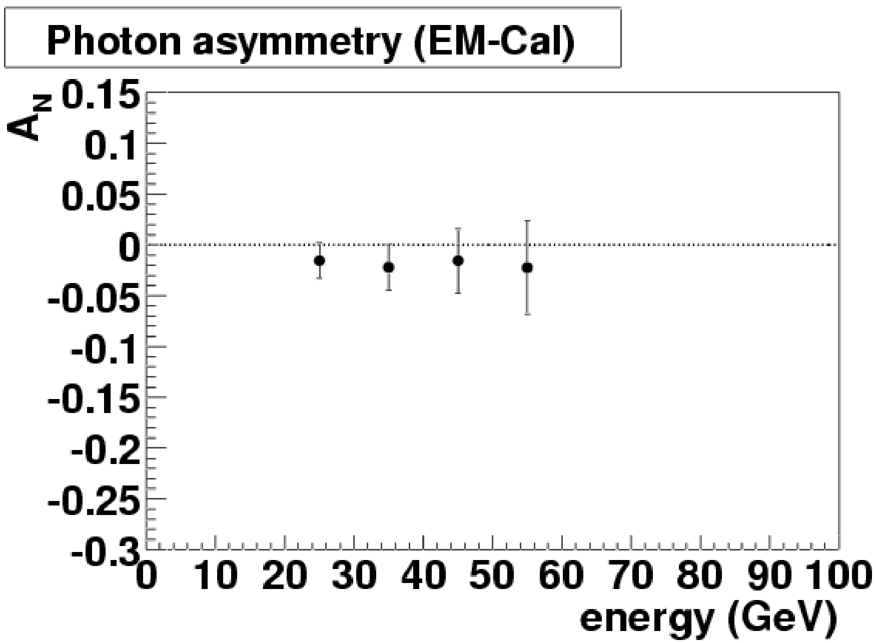


Very-Forward γ and n



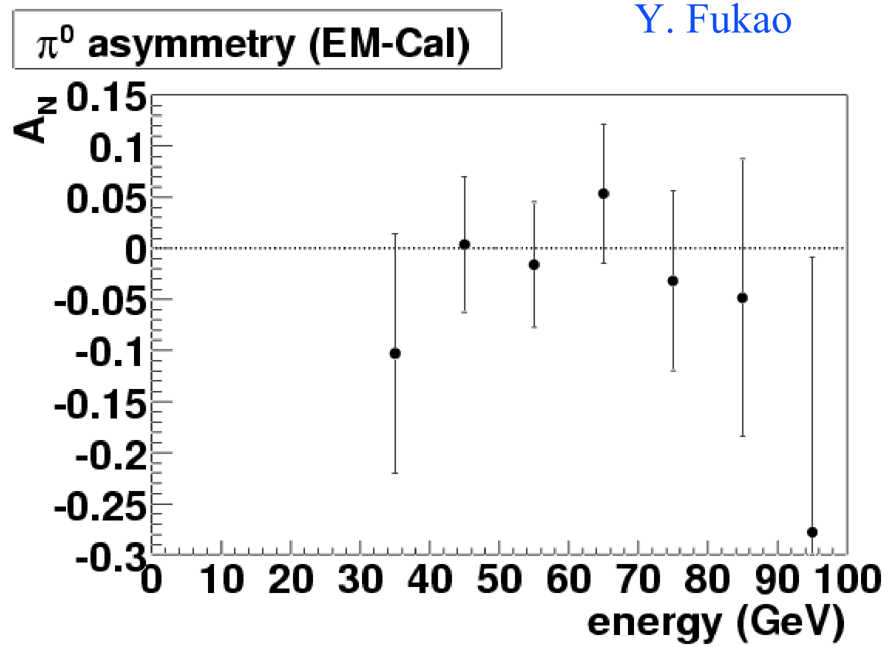
- Introduced as a polarized proton polarimeter at interaction region ("Local" polarimeter) to confirm spin dynamics in the RHIC ring
- Measure very-forward ($|\eta|$>6.5, x_F>0.2) photon and neutrons with low p_T (p_T<0.3 GeV/c)
- In Run-2, used ZDC in IP-12 region. In Run-3, used upgraded ZDC in IP-8 (PHENIX)

Very forward γ and π^0 asymmetry



$$A_N = -0.018 \pm 0.012 \pm 0.023$$

Y. Fukao

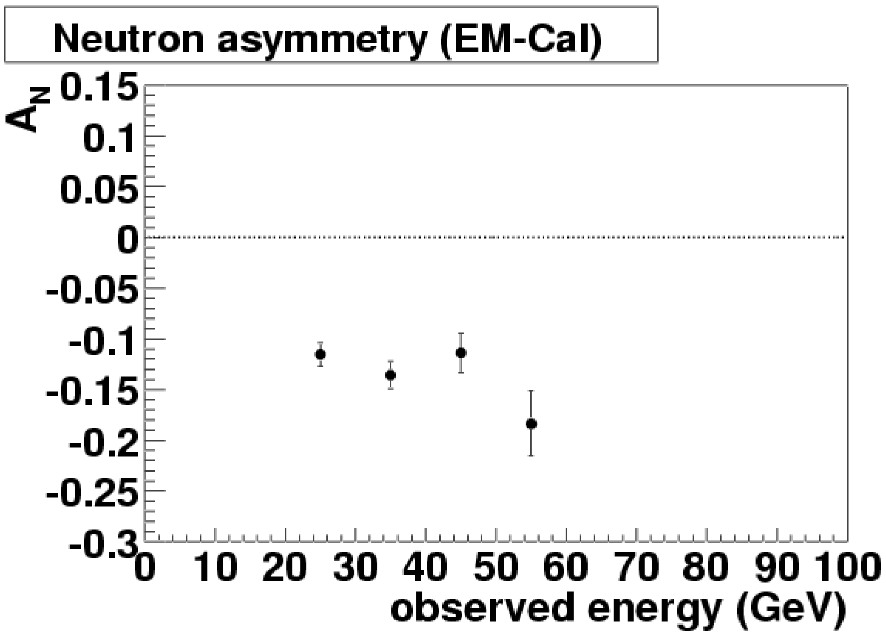


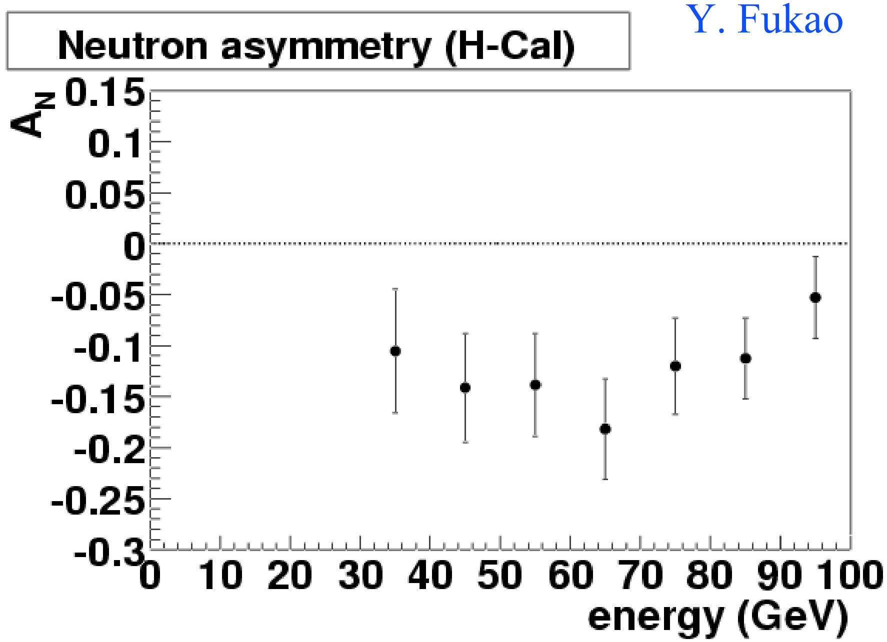
$$A_N = -0.010 \pm 0.032 \pm 0.002$$

A_N is consistent with 0

Neutron asymmetry

Y. Fukao



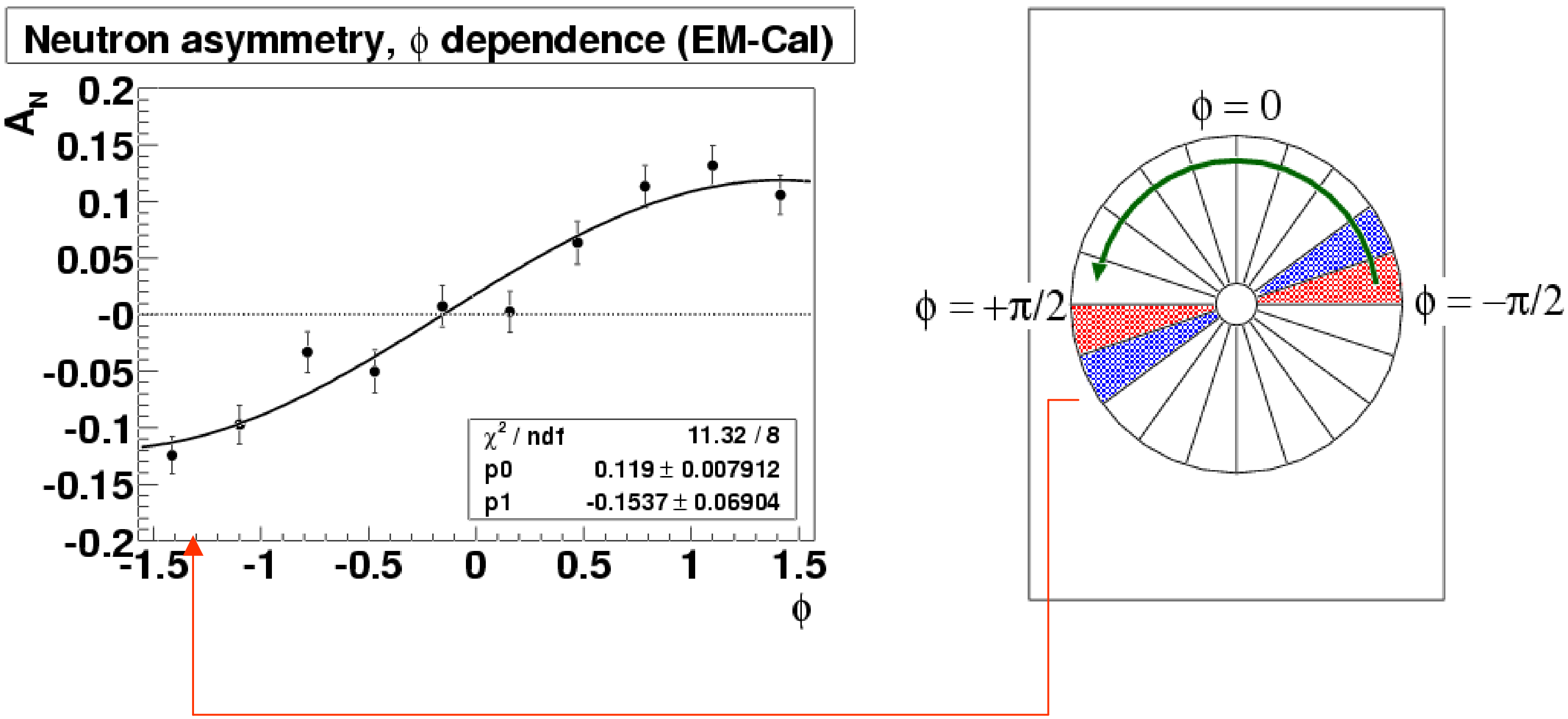


$$A_N = -0.126 \pm 0.008 \pm 0.041 \qquad A_N = -0.116 \pm 0.018 \pm 0.020$$

» Unexpectedly large asymmetry found

» EMCal & ZDC results are consistent

Neutron asymmetry phi dependence



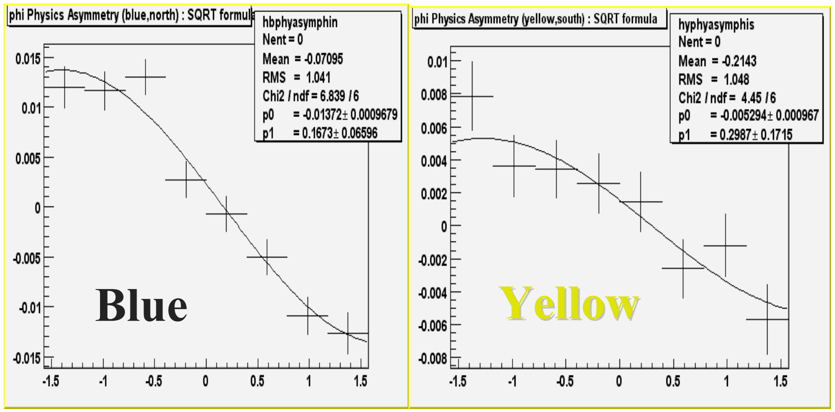
Very clear azimuthal asymmetry

Large asymmetry gives good figure of merit for local (PHENIX) polarimetry.

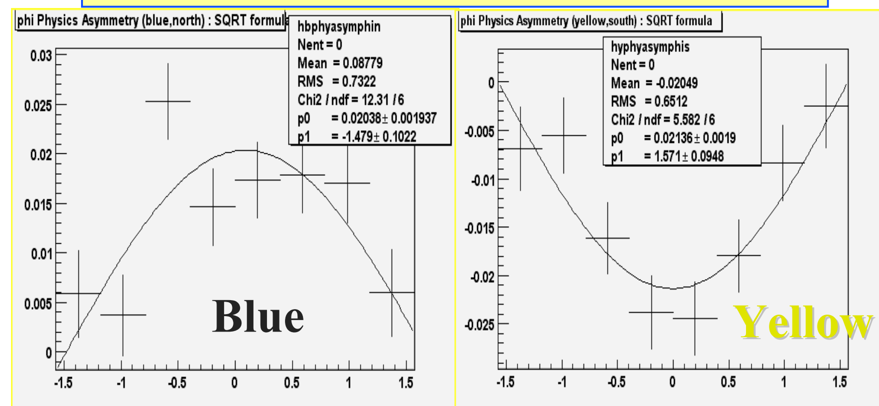
Local Polarimeter at PHENIX

Run-03

Spin Rotators OFF

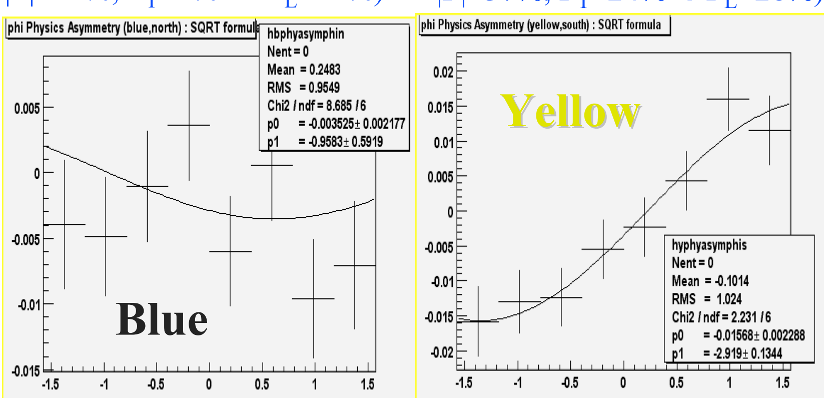


Spin Rotators ON, Current Reversed



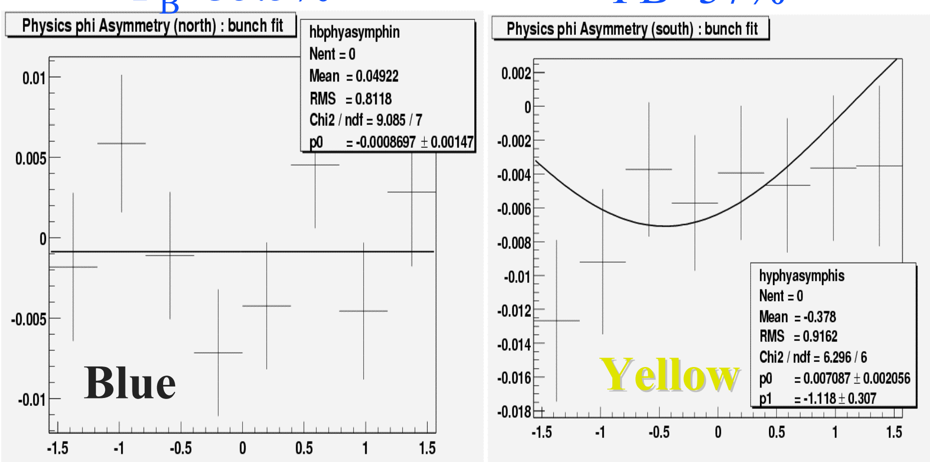
Spin Rotators ON, Almost…

|P|=30%, P_T=0% → P_L=30%) |P|=37%, P_T=24% → P_L=28%)



Spin Rotators ON, Correct!

P_B=35.5%   PB=37%



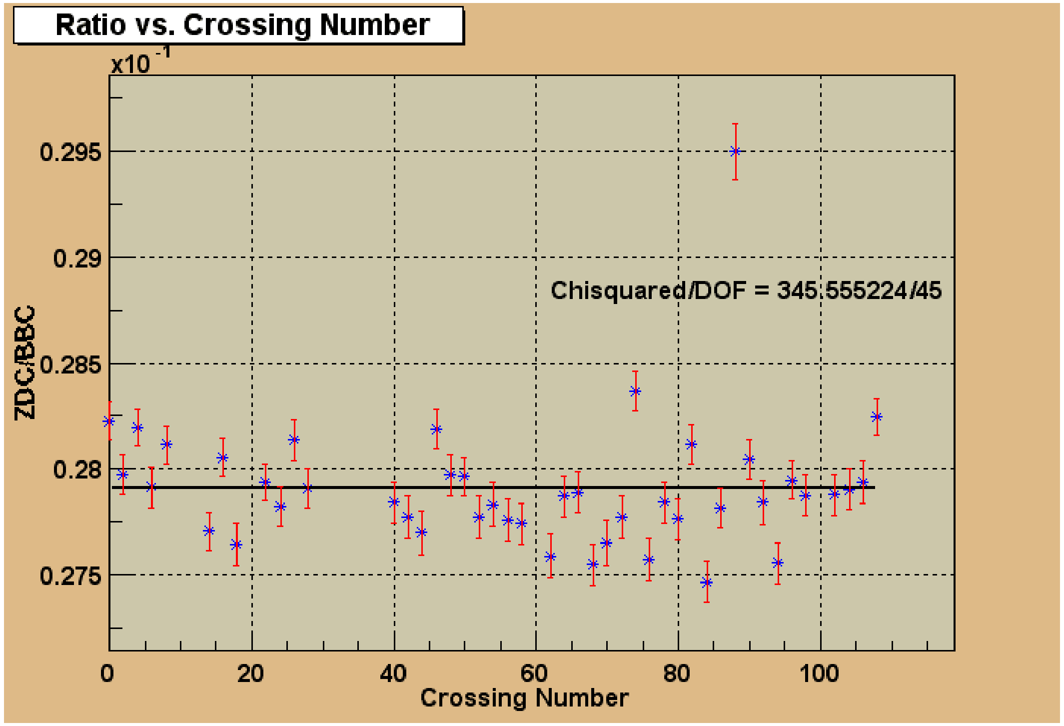
Upgraded ZDC with two component X-Y shower max detector

Relative luminosity (2001-2002 run)

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

$$= \frac{1}{P_1 P_2} \cdot \frac{N_{++} - R \cdot N_{+-}}{N_{++} + R \cdot N_{+-}}$$

$$R = \frac{L_{++}}{L_{+-}}$$



Relative luminosity measurement

» δA_{LL} < 0.3% measurement requires $\delta R/R$ < 0.1% measurement

Crossing-sorted scalers

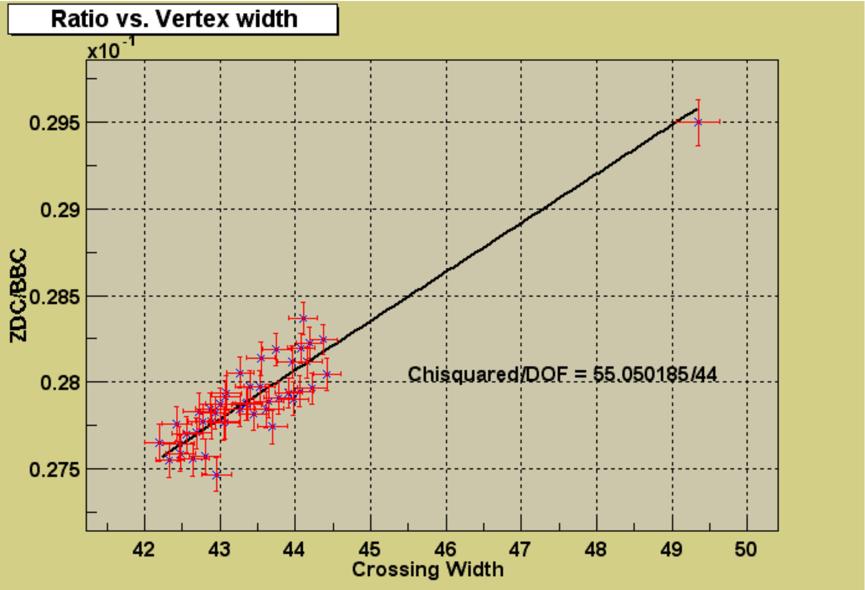
» 4 scalers × 120 crossings
- Min.Bias = BBC ⊕ NTC, BBC, NTC, ZDC

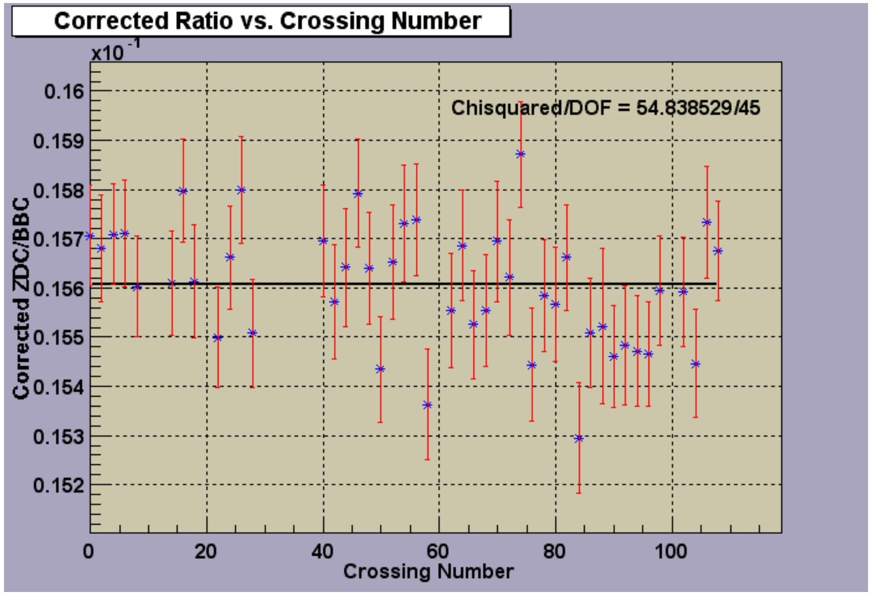
Limit on relative luminosity measurement

» Correct for (measured) vertex width
  - Ratio of counts in the two detectors is consistent with constant up to our level of statistics

» This means that if we apply correction for this the precision on R goes from:

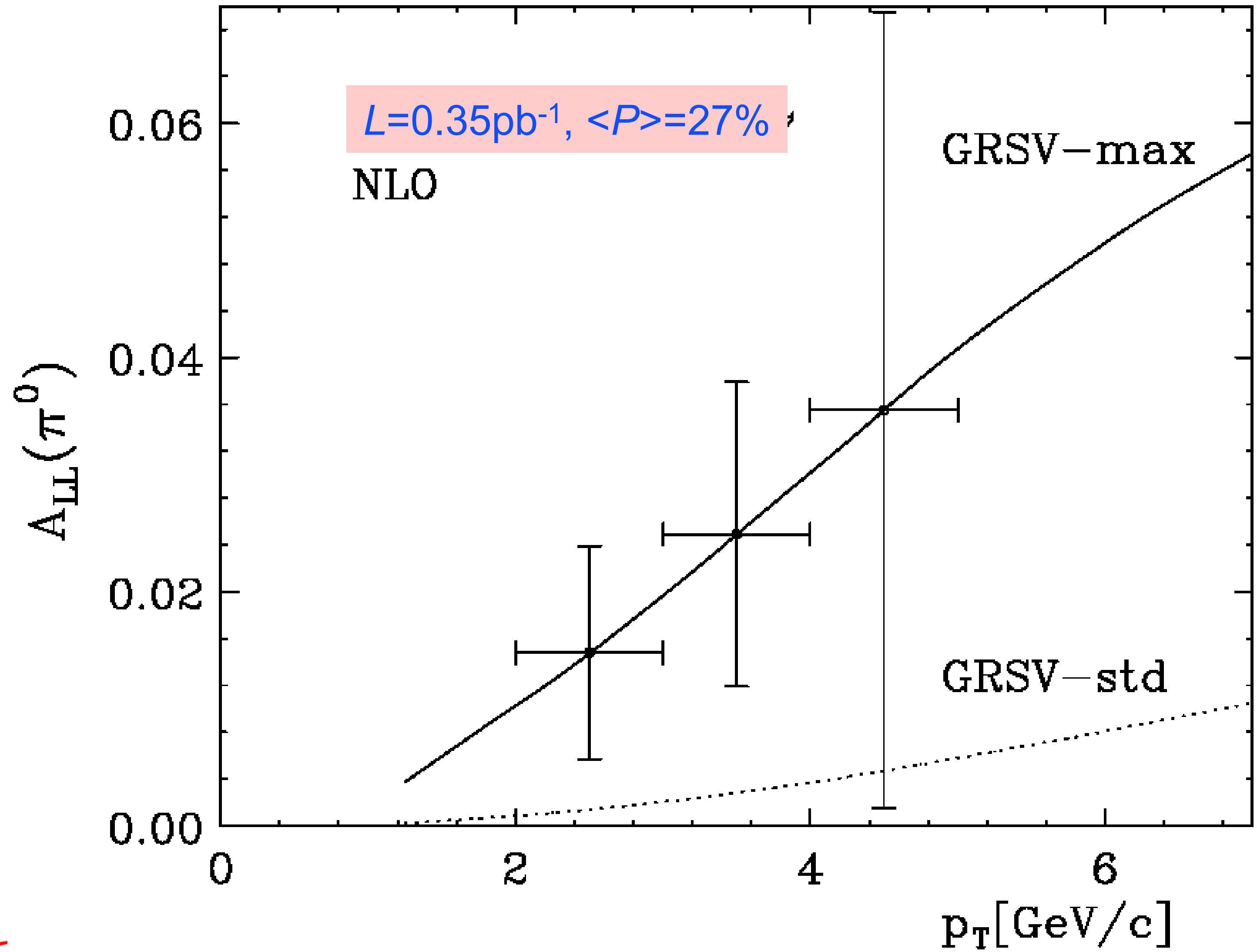
0.11% → 0.06%
(syst. limited) (stat. limited)





Projected A_{LL} sensitivity (2002-2003)

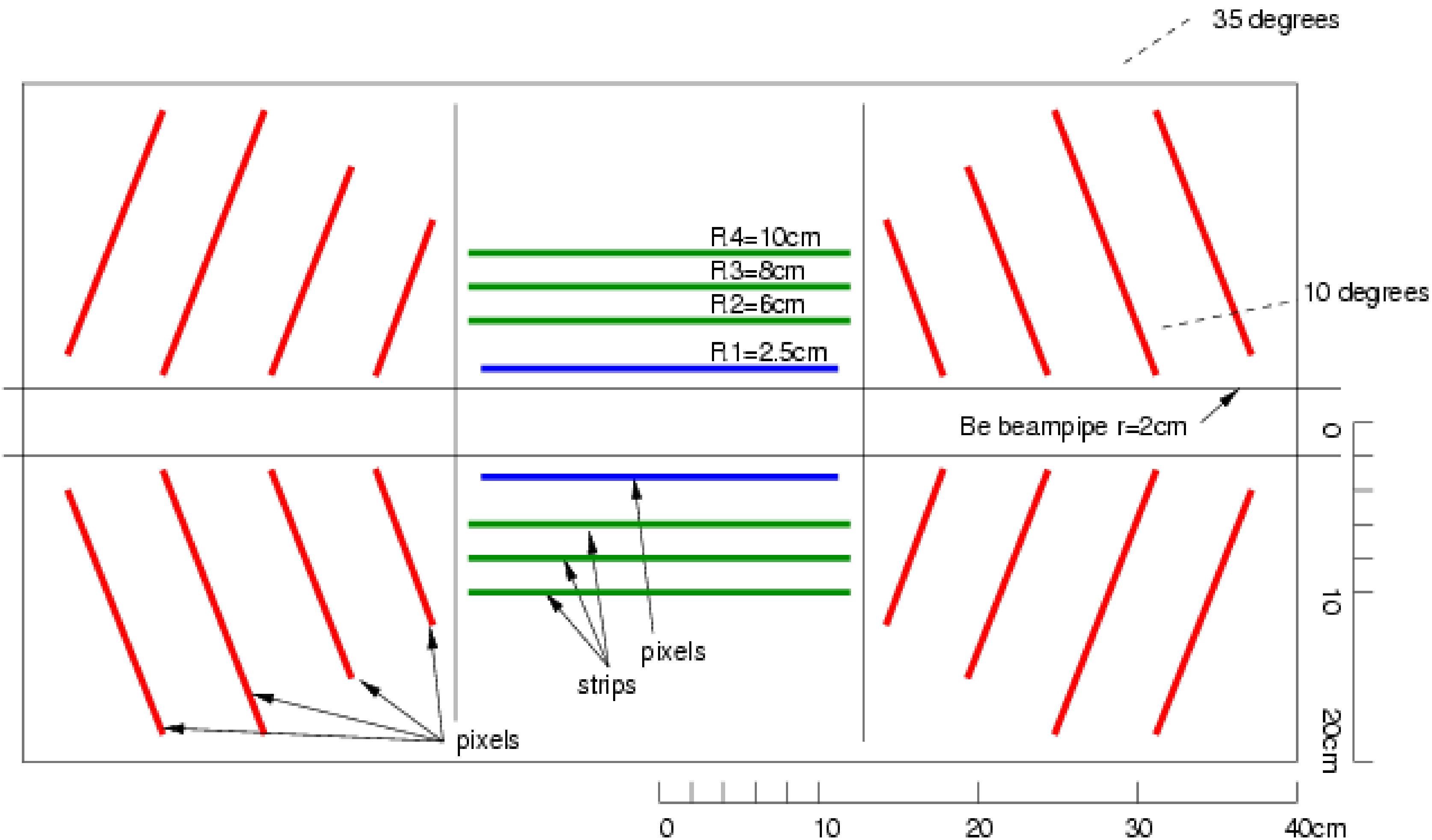
π^0 A_{LL} expectation



Future Prospects

Plans for PHENIX upgrade

Detection of heavy flavors (charm,bottom)
→ Silicon strip/pixel detectors

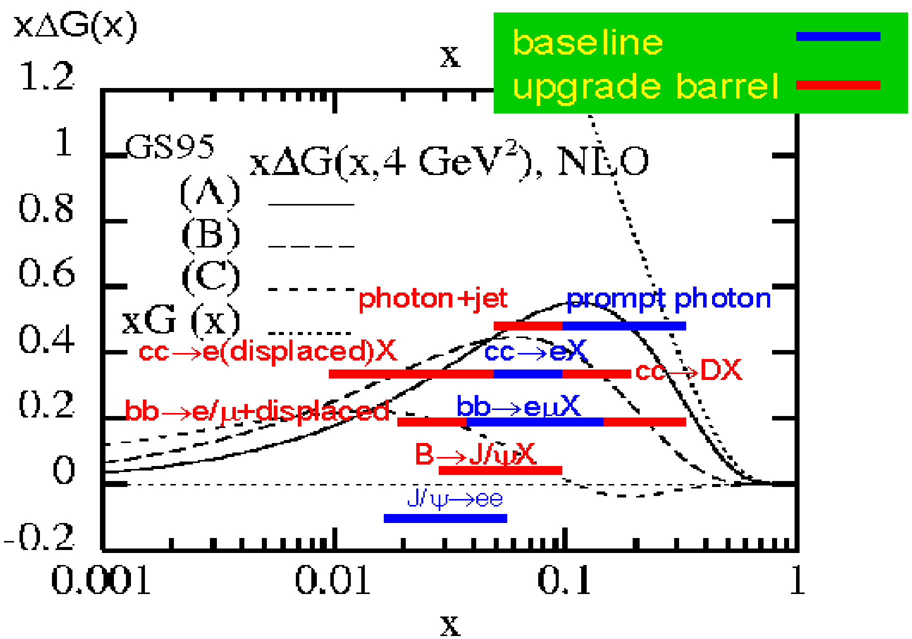


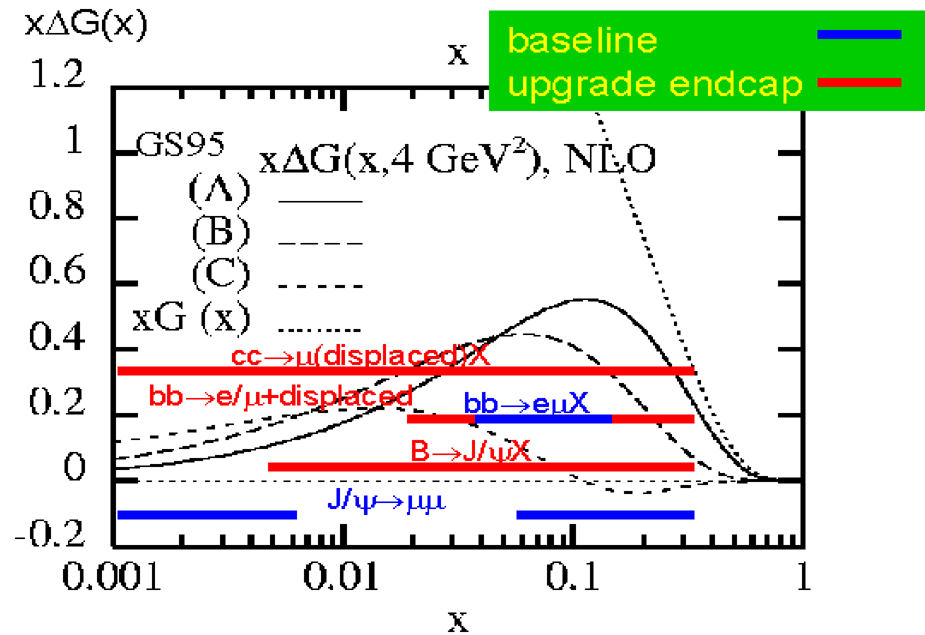
Spin Physics with Vertex Upgrade

Jet-axis for photon+jet-axis ➔ constraint on x

$c \rightarrow e, \mu$ displaced vertex low-x S/B, $D \rightarrow K\pi$ high-x

$b \rightarrow$ displaced J/ψ low/high-x, $b \rightarrow e$, displaced vertex high -x





Summary

- PHENIX is well suited to the study of spin physics with a wide variety of probes.
  - ΔG with prompt γ, heavy flavor via electrons, light hadrons
  - Anti-quark helicity distribution via W decay
  - Transversity
  - Physics beyond the standard model
- Run-02 gave us a baseline for transverse spin asymmetry and cross-sections.
- In Run-03, we commissioned with longitudinal polarized protons (successful spin rotators) and took data for our first A_{LL} measurements using π^0.
- We have studied our relative luminosity systematics and can make an A_{LL} measurement that is statistics limited.
- We have an upgrade plan that will give us the triggers and vertex information that we need for precise future measurements of ΔG, Δq and new physics at higher luminosity and energy.