Gluon Saturation and the "Color Glass Condensate" A new experimental direction for "QCD at RHIC"

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Workshop on pA Physics at RHIC/

Heavy Ion Physics for the Next Decade

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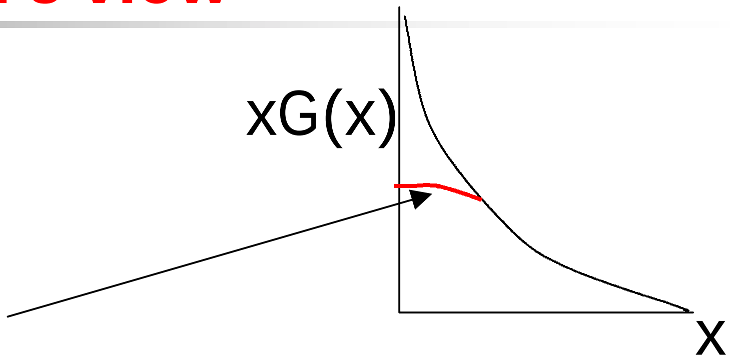
A new regime of calculable phenomena in QCD?

- QCD is the right theory of Strong Interactions (Wilczeck)
  - Notoriously hard to calculate
  - Regimes where QCD simplifies – Calculations can be done
    - High Q^2
      - Well Tested – pQCD
    - High Temperature/Baryon Density
      - RHIC and Lower energy Heavy Ion Physics
      - Observables often difficult to quantify and/or interpret
        - Hopes for a different situation at RHIC!
    - Cold high baryon density QCD - nice but not testable in the lab?
    - **High Gluon Densities at low-x**
      - Reliable non-perturbative calculations of experimental observables
      - Testable in the laboratory : lepton-A, **pA**

What is a color glass condensate?

A layman's view



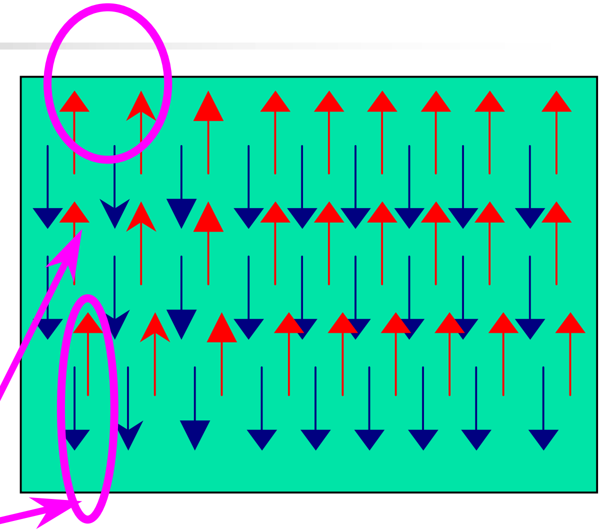
- gluons ~ $x^{-\delta}$,i.e. there are more of them as you go to lower x
  - violates unitarity
- Idea (many theorists) : Gluons saturate, and the distribution stops growing.
- Recently, a new way to look at this phenomena (McLerran, Venogopolan etc) Idea: at low x there are so many gluons, that the quantum occupation numbers gets so large that the situation looks classical.
- Can use renormalization group methods to do a calculation of this effect. Depends only on a "scale"

  $\Lambda_{CGC}^{2} = (1/\pi R^2)(dN_{gluon}/dy)$ ~ 2-D gluon density
- Gluons are bosons (interacting) – a bose condensate!
- Gluons fill up the available states, so putting more gluons in means they have to go into a higher energy state – higher pt
- Higher pt -> smaller transverse size
  - Probes of a particular Q^2 go blind to these small partons. Fixes up unitarity for a fixed Q^2.

Why the idea is attractive

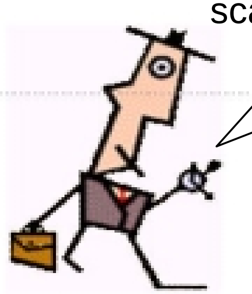
- Continues the theme of bulk matter, high density/temperature – a "gluon plasma"
- Condensed matter type many body phenomena – condensates
  - Gluons (bosons! Interacting bosons) are in a single quantum state
  - Gluons form a glass
    - Long time scale coming from "frustration"
- Robust calculations in QCD using reliable "renormalization group" methods
  - A method used (and trusted) in all branches of physics
  - Depends on a single scale
    - $\Lambda_{CGC}^{2} = (1/\pi R^2)(dN_{gluon}/dy)$ ~ 2-D gluon density

Why a glass?

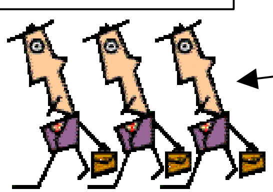


- Glass – ala condensed matter –

  A glass is a material with
  - long time scale
    - Think of Window glass, which is a liquid – years for it to “pour”
  - induced by “frustration”
    - E.g. Spin glass
    - Neighboring red and blue are “happy”
    - Neighboring red and red are “frustrated”
  - In Color Condensate we have “relativistic frustration”
  - Model Break Nucleus into Gluon Field, and Source
    - “Source” – quarks and gluons at high-x, ***Lorenz time dialated clock runs slow***
    - Gluon field at low-x. Clock runs fast, but motion is governed by “source”, and a long time scale governs the motion of the gluons. They are “frustrated”

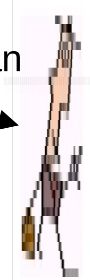


Work Work
Work Work

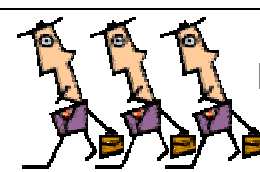


Happy
Hard working
Gluons

Lorentz Time
Dialated Spokesman



W….o…r… k … W . .



Frustrated
Gluons

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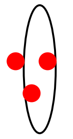
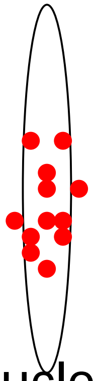


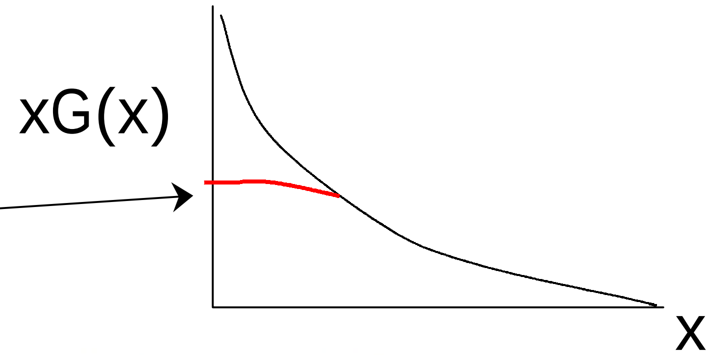
$$dN/dy \sim R^3 \sim A$$

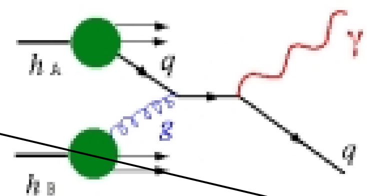


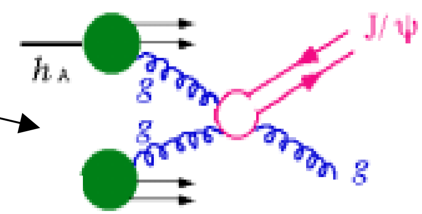
Saturation Region

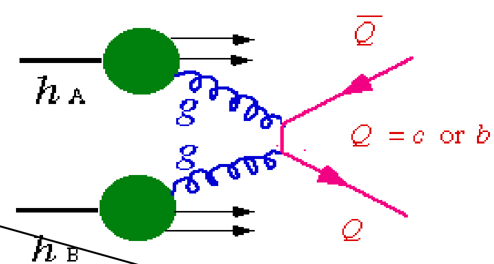
How do you experimentally see this?

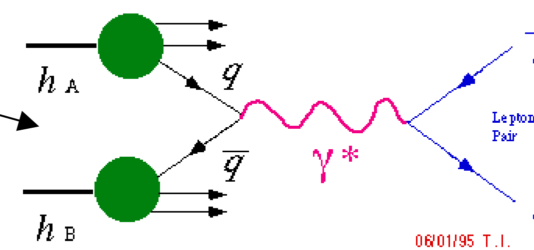
- Look at Gluon Structure Functions at low-x (M. Brooks)
  - At saturation it should turn over
  - Measure in pA
    - Direct photons (Paul)
    - J/ψ production
      - problems in interpretation
        - Production mechanisms
        - Suppression
    - Open Charm
    - Change of quark structure functions with Q^2 – use Drell-Yan as a probe
- Diffractive cross section
  - J.C Peng/S. White
- Other things?
  - Pt Broadening?
  - .....











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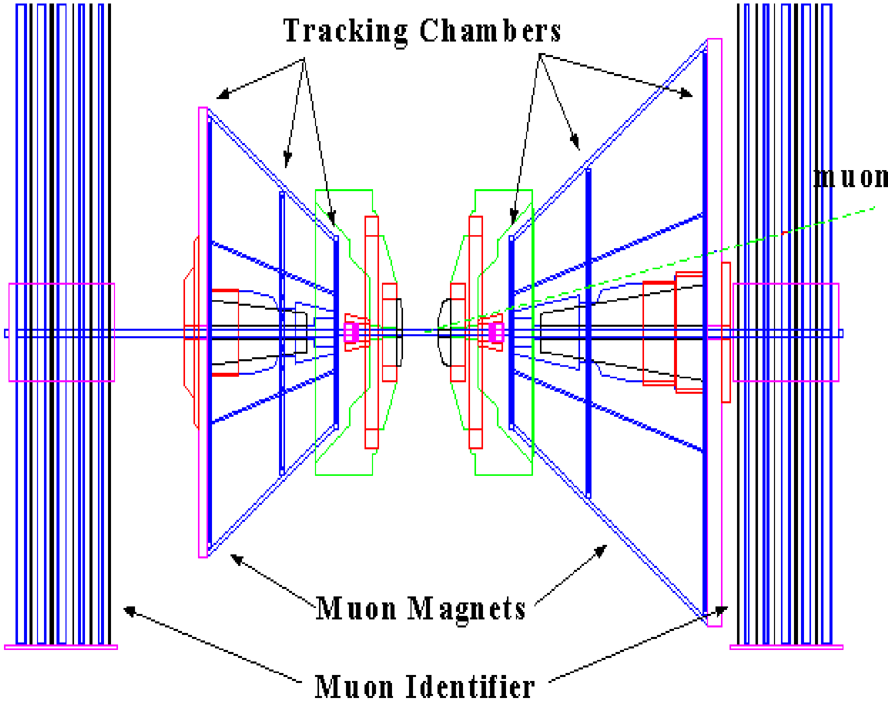
pA at RHIC

- Run Various Nuclei to chart out effects
  - Need pp to "Normalize"
  - pA Needed for heavy ion program
- pAu assume $L=\sqrt{L(pp)xL(AA)}$
  - 100(p) x 100(Au) or 250(p) x 100(Au)
- As Example – PHENIX
  - Would like to measure x_1, $x_{2,}$,Q^2
    - For 2→1 Process (Sea quarks) e.g. Drell Yan, $x_F=x_1-x_{2,,}$, $M^2=Sx_1x$
    - For 2 →2 Process, e.g. (gluon distribution) Direct Photon, Open Charm, J/ψ
      - Need to measure Outgoing Jet - Tough – Perhaps add a jet detector to PHENIX
    - For the purpose of this talk – assume present PHENIX, upgrades suggested at end



- Muon Arms
  - (10°-30°) (12°-30°)
  - E>2GeV
- Central Arms (70°-110° not shown)
  - Electrons/Photons

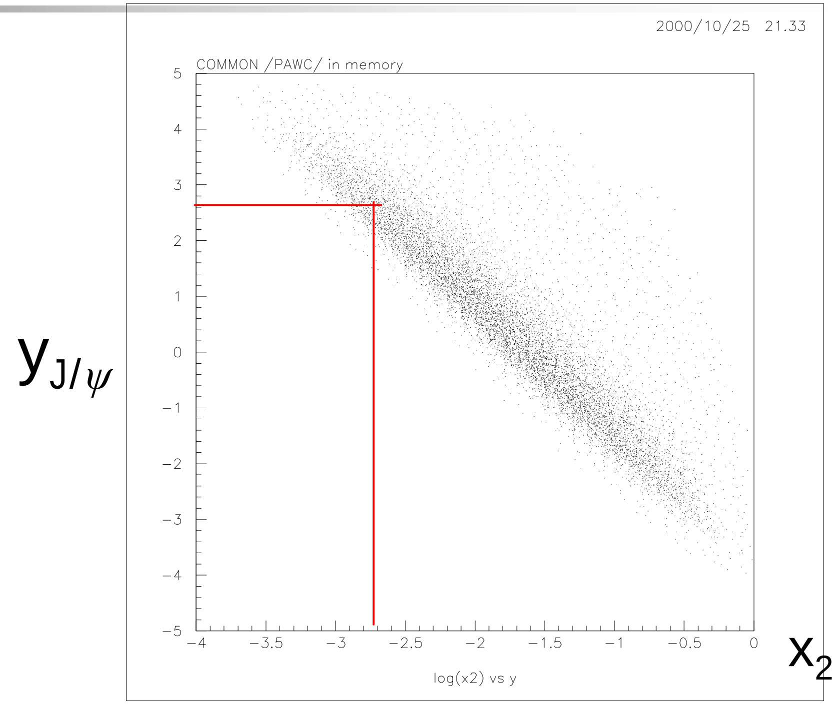
The Simulation (Pythia)

- Level of simulation work is primitive – only primary processes, perfect detector (I.e. only angle and energy cuts – note: for electron arm, I used full azimuth)
- For 2→2 Processes, since we only measure one of the outgoing partons, what do we do?

➔ Use correlation of x_2 with y.

Then compare to a model.

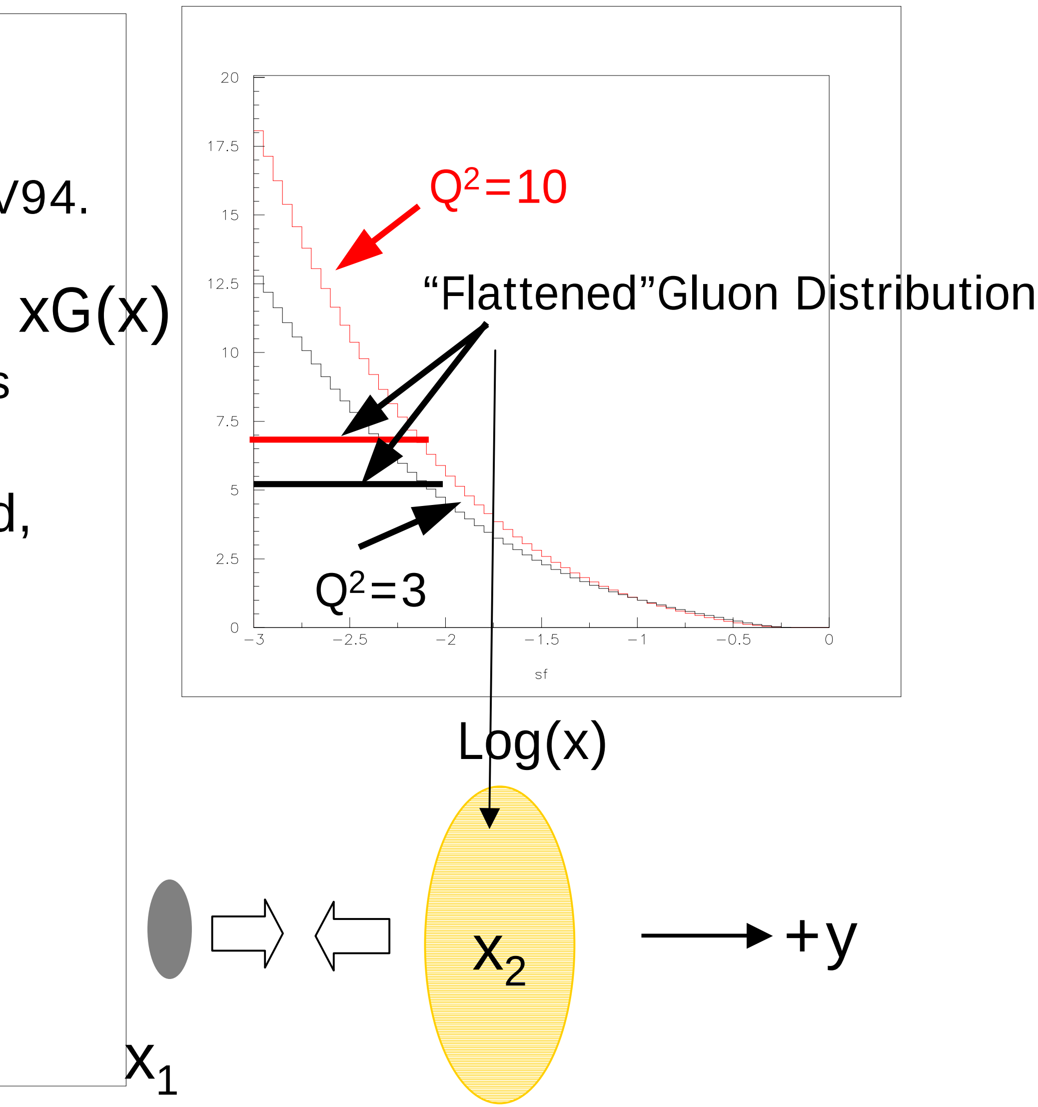
Note: correlation is not as good for open charm when detecting only the leptons



- Coverage for Muon arms to y~2.5
  - ➔ $x_2 \sim 10^{-3}$
  - $Q^2 \sim 5\ GeV^2$

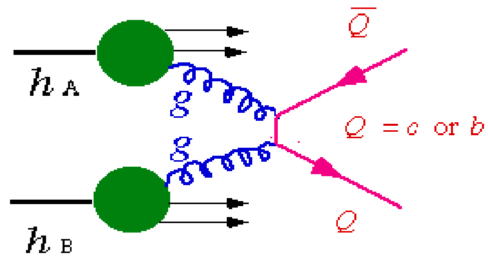
Faking up the saturation

- Model a gluon distribution
  - For proton use GRV94.
  - For Nucleus start with GRV94. For $x_2<10^{-2}$ flatten gluon distribution.
  - Note: the Nucleus side was modeled as a neutron
- In the exp't, compare pp, pd, pA.

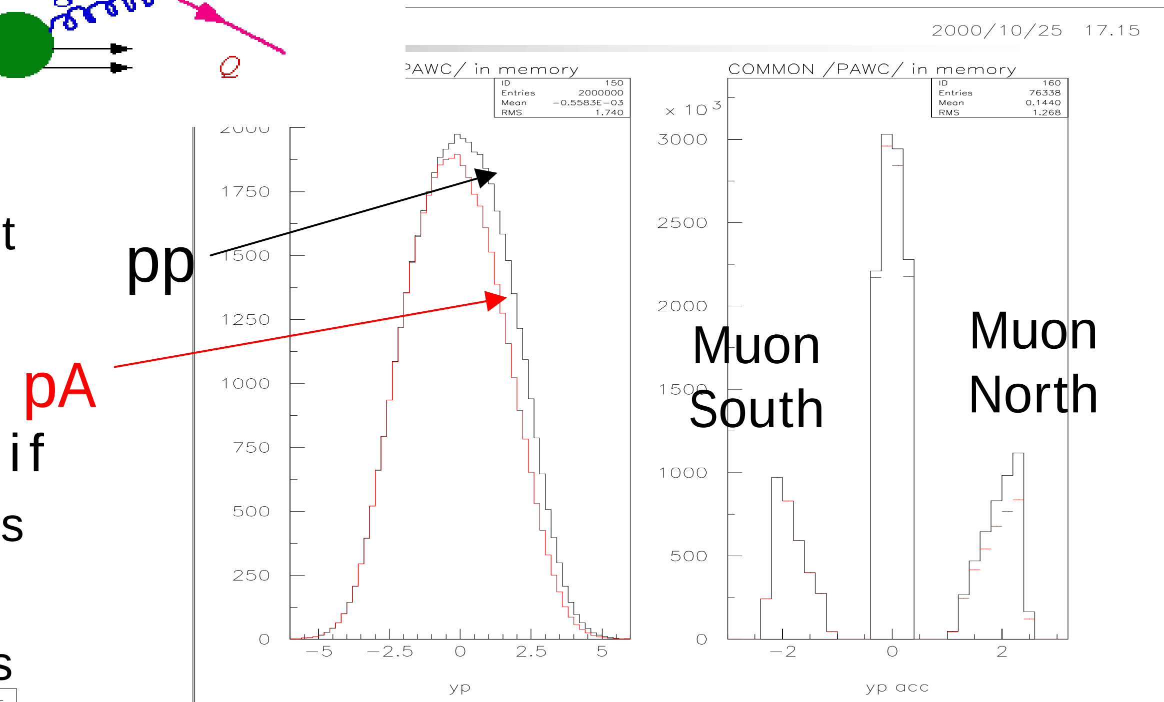


  - x_1, x_2 – fraction of nucleon momentum carried by parton
  - X_2 Refers to Nucleus
  - **Low x_2 will be at high y**

Charm



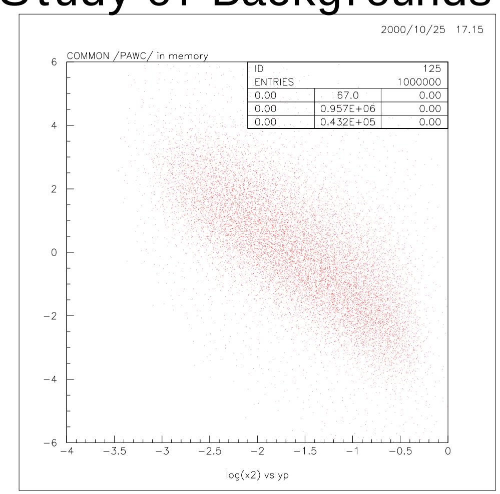
- Detect only leptons
  - Require $\mu^+ \mu^-$, μe in event
  - Look at y_{lepton}
- 1 Month running
- Plenty of statistics even if
  - Saturation effect is less
  - Hard cuts needed
- Need Study of Backgrounds



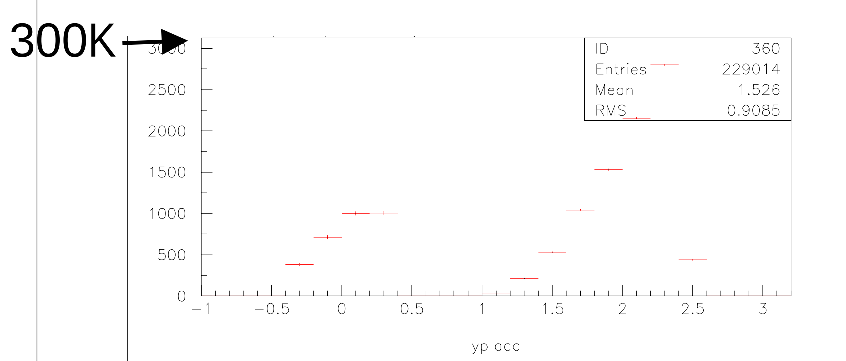
All leptons from Charm

Detected leptons

y_{lepton}



x_2



pp-pA

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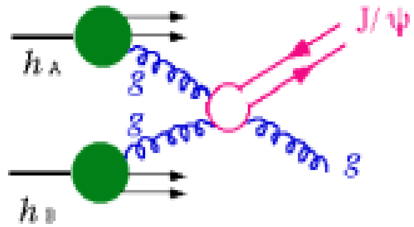
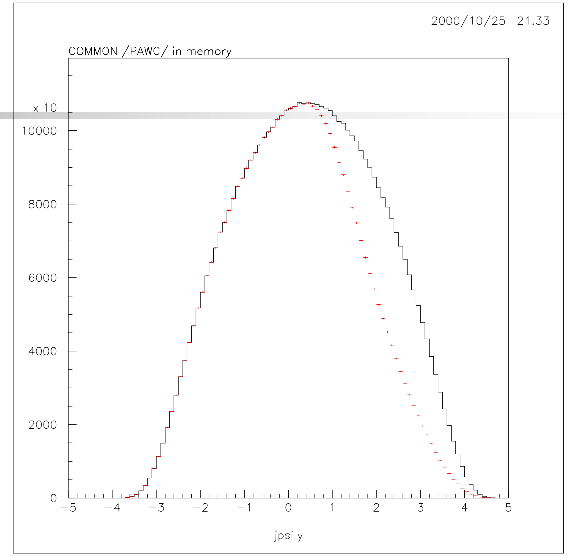
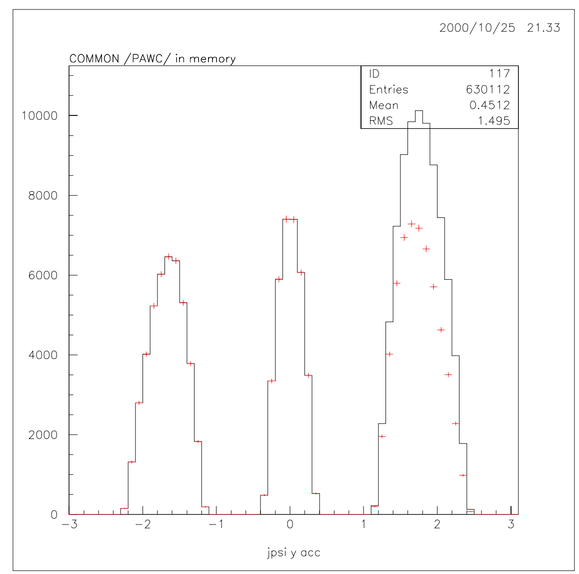
J/ψ



- 250x100
- Look at $y_{J/\psi}$
- Turns out going to 250 doesn't help much unless one extends y coverage of detector





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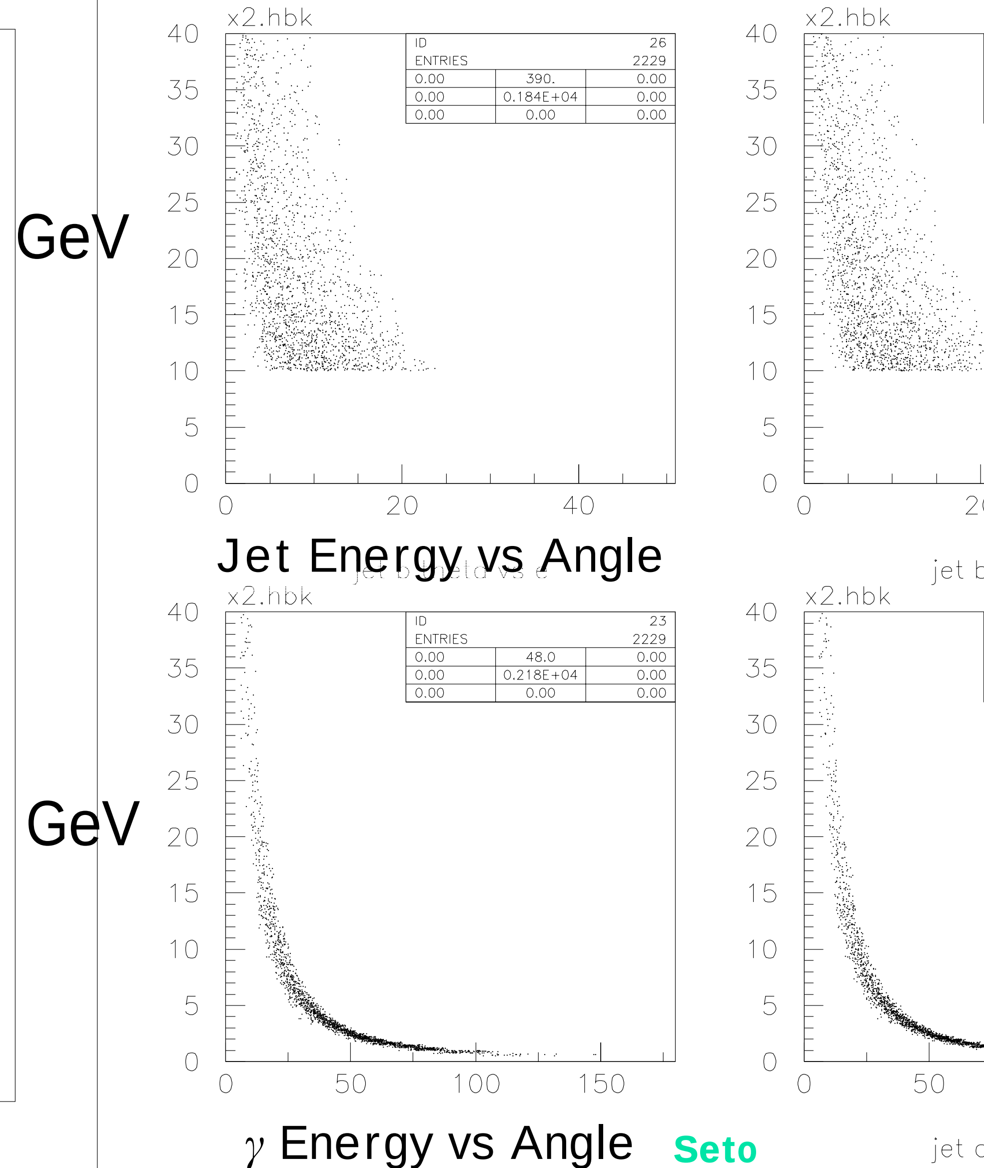
Improving the situation

- Measure associated jet to get x_1 , x_2 , Q^2
  - Very tough. Associated current jet is often at small angles and must me disentangled from the fragmentation jet which heads down the beampipe.
- Improve muon acceptance with a very forward detector located in the tunnel. $x_2 \sim 10^{-4}$ for $\theta > 1^{\circ}$
- Large acceptance photon detector in the forward region
- Q. Can we use the D-Y to get the gluon distribution?

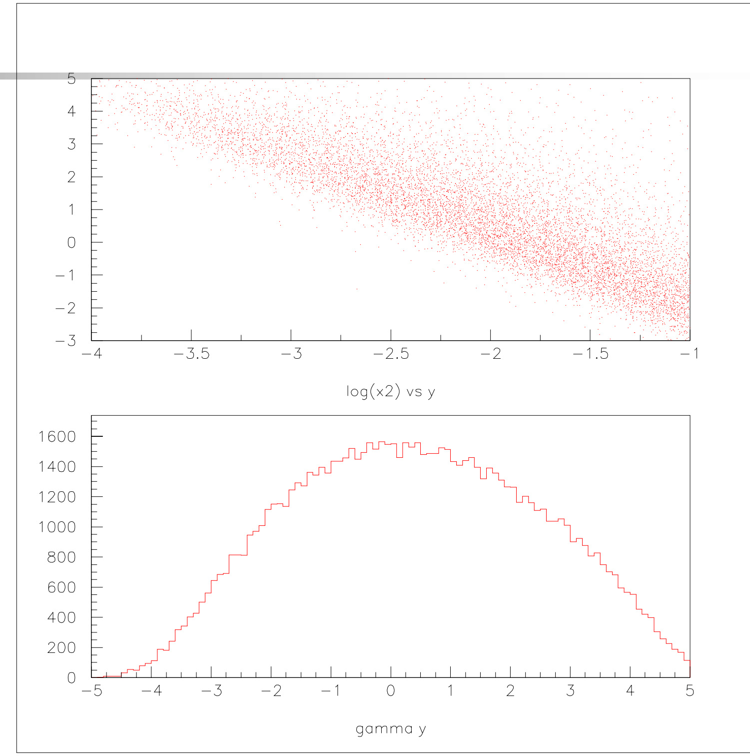
Detecting Jet w/ Direct photon

- For $x_2 = 5\times10^{-3}$
- Require Jet w/ direct γ to be > 10 GeV.
  - ➔ Jet angle < 20 degrees
  - Can we reconstruct a 10 GeV Jet?
  - Can we separate it from the beam fragments?

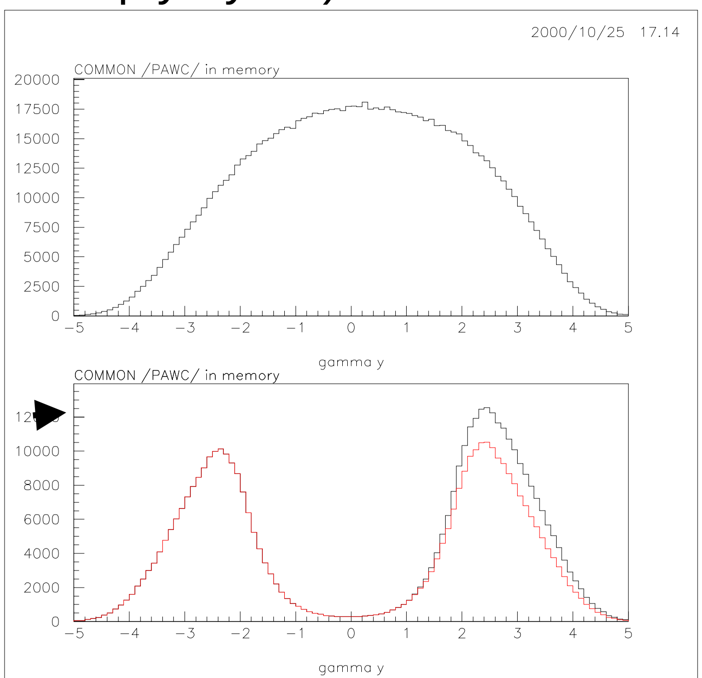


Direct Photons

- forward calorimeter (STAR?)
- Reguire Eγ>5GeV
- 100x100
- (note- to get counts/month, multiply by 35)



400K



- Running at 250x100 allows one to get to x_2~10^{-4} if calorimeter coverage to y=5

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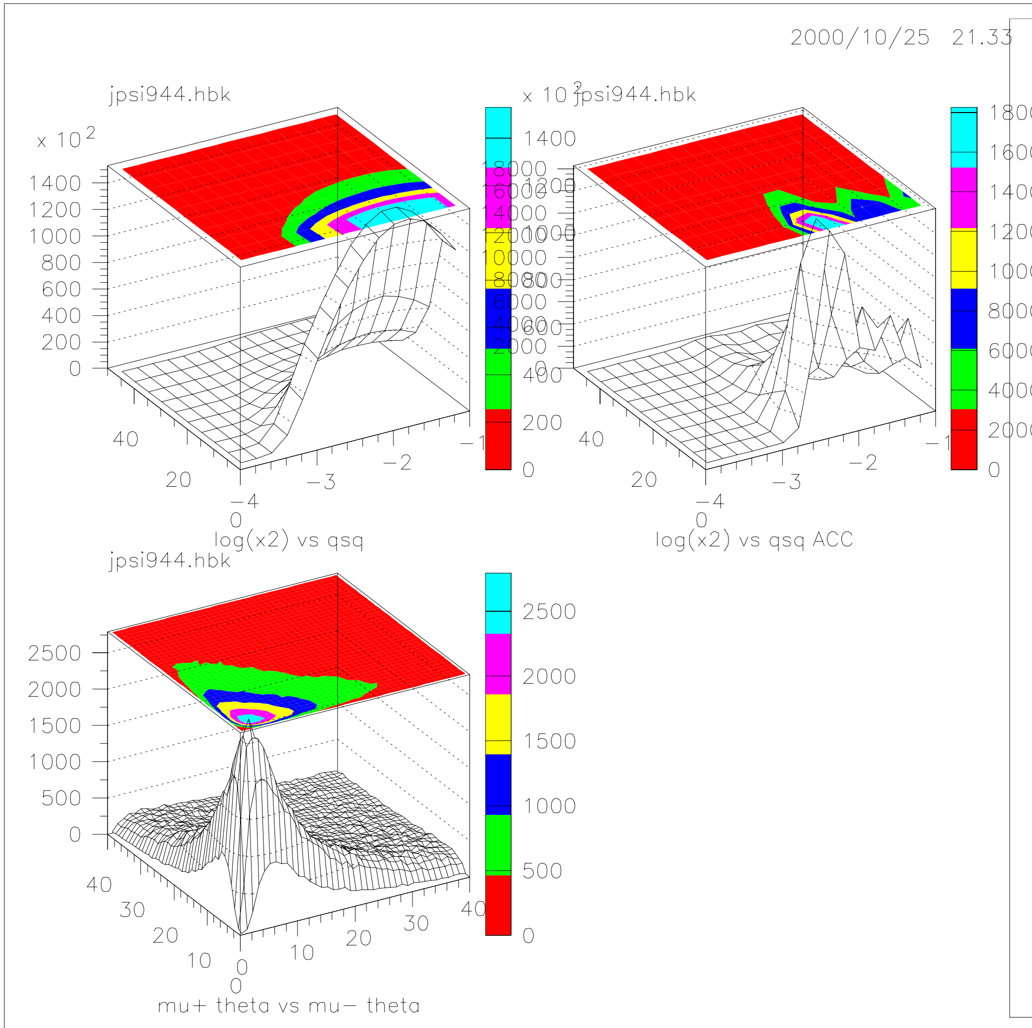
Conclusions

- pA presents this community with a new vista of QCD research
  - More specifically – the realm of high gluon density
  - this region has the potential to give experimentalists, firm, experimentally verifiable non-perturbative predictions
    - The simplest of these can be tested with the present machine/experiments
  - There may be a host of new phenomena (ala condensed matter, many body physics) associated with this regime of QCD, which will become understandable as experiments progress.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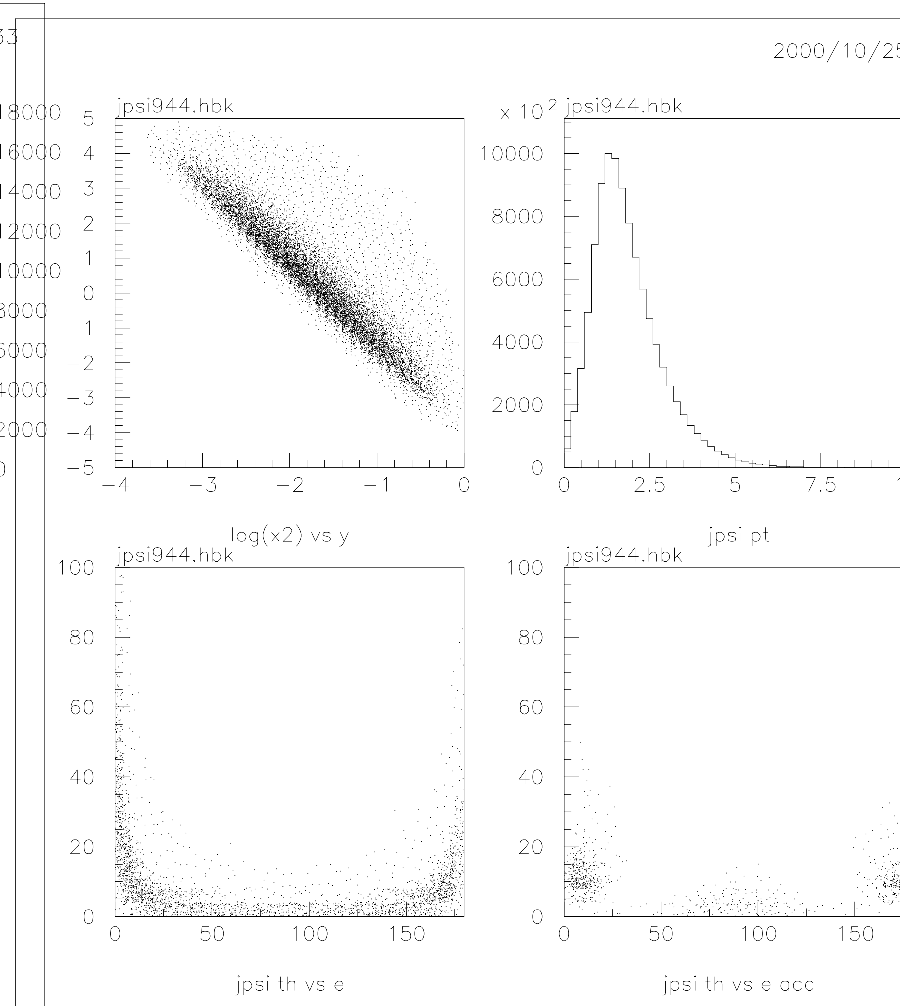
log(x2) vs qsq
log(x2) vs qsq ACC
mu+ theta vs mu− theta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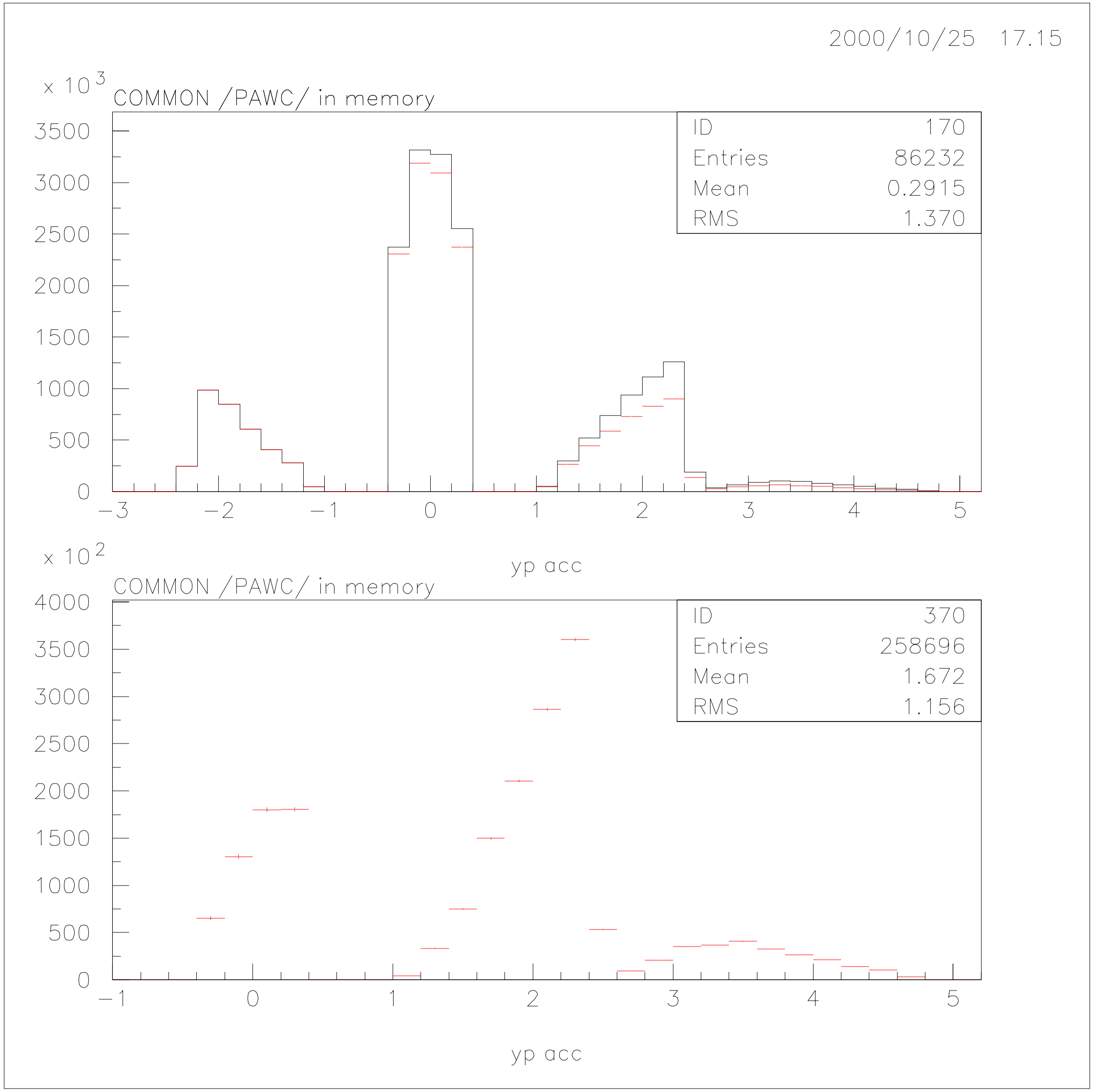
jpsi944.hbk
log(x2) vs y
jpsi pt
jpsi th vs e
jpsi th vs e acc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yp acc
x 10^2
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0
−1 0 1 2 3 4 5
yp acc

Nucleus