Physics Measurements with RHIC Detector and Luminosity Upgrades

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Red Team Review
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This talk

I have been asked to describe, as quantitatively as I can, the effects of the **detector upgrades** and **luminosity upgrade** on the physics program at RHIC.

Given the available time, I will be forced to focus on **only a few** of the key measurements. I will try to indicate as clearly as possible which measurements require **both** detector upgrades and the luminosity upgrade.

I will spend a little time trying to show how the RHIC II and LHC physics programs relate to each other.

Summary of RHIC upgrades and physics topics

Upgrades	High T QCD…. .....QGP				Spin			Low-x
PHENIX	e+e-	heavy flavor	jet tomog.	quarkonia	W	ΔG/G	Trans	
Hadron blind detector	X							
Vertex Tracker	X	X	O	O		X		O
Muon Trigger				O	X			
Forward cal. (NCC)			O	O	O		X	X
STAR								
Time of Flight (TOF)	X	O	X	X				
Heavy fl. tr. (HFT)	X	X		X				O
Forward Tracker		O			X	O	O	O
Forward Cal (FMS)						O	X	X
DAQ 1000	O	O	X	X	O	O	O	O
RHIC Luminosity	O	O	X	X	O	O	O	O

X upgrade critical for success
O upgrade significantly enhances program

Heavy Flavor

(What are the phases of QCD matter?)

(What is the nature of non-equilibrium processes in a fundamental theory?)

Future open charm and bottom

With detector upgrades (both PHENIX and STAR):

- Dramatically reduce backgrounds for all open charm, open beauty signals using **displaced vertex measurement** (PHENIX VTX, STAR HFT).
- Then can measure open charm directly via $D \rightarrow K\pi$ (STAR needs HFT, DAQ 1000)
- Separate open charm and beauty **statistically** using difference in displaced vertex distributions.

and with the luminosity upgrade (PHENIX and STAR):

- Extend **open charm and beauty R_{AA}** measurements to high p_T. What is the energy loss well above the thermalization region?
- Measure semileptonic charm and beauty decay **v_2 to high p_T**. See the transition from thermalization to jet energy loss for charm.
- Measure B directly: $B \rightarrow J/\psi$ independent of prompt J/ψ, using displaced vertex.
- Measure **open charm correlations** with open charm or hadrons.

Future charmonium and bottomonium

With detector upgrades:

- Large acceptance triggered J/ψ measurements in STAR with TOF, (EMC), DAQ-1000.
- Reduce J/ψ →μμ background with VTX and forward μ trigger upgrade in PHENIX.
- Improve mass resolution for charmonium and **resolve** Υ family (PHENIX).
- See γ in forward calorimeter (NCC) in front of muon arms (PHENIX).

And with the luminosity upgrade (PHENIX and STAR):

- **J/ψ R_{AA} to high p_T**. Does J/ψ suppression go away at high p_T?
- **J/ψ v_2 measurements versus p_T**. See evidence of charm recombination?
- **Υ R_{AA}**. Which Upsilons are suppressed at RHIC?
- Measure ψ', **χ_c → J/ψ+γ R_{AA}**. Ratio to J/ψ?
- Measure **B → J/ψ** using displaced vertex - independent B yield measurement, also get **background to prompt J/ψ measurement**.

Heavy flavor yields at RHIC II - PHENIX

200 GeV Au+Au for a 12 week physics run. Other species comparable.

Signal	$\lvert\eta\rvert$	Obtained	RHIC I (> 2008)	RHIC II
$J/\psi \rightarrow e^+e^-$	< 0.35	~ 800	3,300	45,000
$J/\psi \rightarrow \mu^+\mu^-$	1.2-2.4	~ 7000	29,000	395,000
$\psi' \rightarrow e^+e^-$	< 0.35		60	800
$\psi' \rightarrow \mu^+\mu^-$	1.2-2.4		520	7,100
$\chi_c \rightarrow e^+e^- \gamma$	< 0.35		220	2,900*
$\chi_c \rightarrow \mu^+\mu^- \gamma$	1.2-2.4		8,600	117,000*
$\Upsilon \rightarrow e^+e^-$	< 0.35		30	400
$\Upsilon \rightarrow \mu^+\mu^-$	1.2-2.4		80	1,040
$B \rightarrow J/\psi \rightarrow e^+e^-$	< 0.35		40	570
$B \rightarrow J/\psi \rightarrow \mu^+\mu^-$	1.2-2.4		420	5,700

* Large backgrounds, quality uncertain as yet.

Heavy flavor yields at RHIC II - STAR

200 GeV Au+Au for a 12 week physics run.

Signal	$\lvert\eta\rvert$	Obtained	RHIC I (> 2008)	RHIC II
$J/\psi \rightarrow e^+e^-$	< 1.0		16,200	220,000
$\psi' \rightarrow e^+e^-$	< 1.0		300	4,000
$\Upsilon \rightarrow e^+e^-$	< 1.0		830	11,200
$B \rightarrow J/\psi \rightarrow e^+e^-$	< 1.0		190	2,500
$D \rightarrow K\pi$	< 1.0		60,000*	60,000*

* From 200 Hz of minimum bias triggers (Thomas Ullrich).

Note: p+p yields are proportionately higher for J/ψ because trigger is more efficient.

Heavy flavor - relationship to the LHC program

Heavy flavor yield estimates by the LHC experiments

200 GeV Pb+Pb for 1M seconds data taking (ie. 1 month), 500 μb^{-1}.

Signal	ALICE[1]	$\lvert\eta\rvert$	CMS[2]	$\lvert\eta\rvert$	ATLAS[3]	$\lvert\eta\rvert$
$J/\psi \rightarrow \mu^+\mu^-$	740,000	2.5-4	24,000	< 2.4	8K-100K	< 2.5
$J/\psi \rightarrow e^+e^-$	9,500[4]	< 0.9				
$\psi' \rightarrow \mu^+\mu^-$	14,000	2.5-4	440	< 2.4	140-1800	< 2.5
$\psi' \rightarrow e^+e^-$	190[4]	< 0.9				
$\Upsilon \rightarrow \mu^+\mu^-$	8,400	2.5-4	26,000	< 2.4	15,000	< 2.0
$\Upsilon \rightarrow e^+e^-$	2,600	< 0.9				
$D \rightarrow K\pi$	8,000	< 0.9			**Prompt J/ψ only**	

1. Philippe Crochet, EPJdirect A1, 1 (2005), and private comm.
2. Bolek Wyslouch, PANIC LHC satellite workshop
3. Helio Takai, PANIC LHC satellite workshop
4. Minbias + central untriggered events - Philippe Crochet

RHIC II

Beams: **p to U**

All combinations $\sqrt{s}$ = **22-200 GeV**

Central Au+Au: **$T \sim 2\ T_c$**

Detectors:

PHENIX STAR eRHIC detector?

12 weeks / year physics (split runs)

Average luminosity $7 * 10^{27}\ cm^{-2}\ s^{-1}$

Au+Au lum/year 18,000 mb^{-1}

$Lint_{RHIC}/Lint_{LHC}$ = **36**

$N_{cc} \sim 10$ $N_{bb} \sim 0.05$ (central)

LHC

Beams: **p to Pb**

p+p $\sqrt{s}$ = **14 TeV**

p+Pb $\sqrt{s}$ = **8.8 TeV**

Pb+Pb $\sqrt{s}$ = **5.5 TeV**

Central Pb+Pb: **$T \sim 4\ T_c$**

Detectors:

ALICE ATLAS CMS

4 weeks / year physics

Average luminosity $5 * 10^{26}\ cm^{-2}\ s^{-1}$

Pb+Pb luminosity/year 500 mb^{-1}

$\sigma\ (J/\psi)_{LHC} = \sigma\ (J/\psi)_{RHIC} * 13$

$\sigma\ (\Upsilon)_{LHC} = \sigma\ (\Upsilon)_{RHIC} * 55$

$N_{cc} \sim 115$ $N_{bb} \sim 5$ (central)

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Pb+Pb luminosi

$\sigma\ (J/\psi)_{LHC}$ = σ (

$\sigma\ (\Upsilon)_{LHC}$ = σ (

Lots more charm and bottom coalescence and bottom feed-down to charm

$N_{cc} \sim 115$ $N_{bb} \sim 5$ (central)

High pT probes

(What are the phases of QCD matter?)

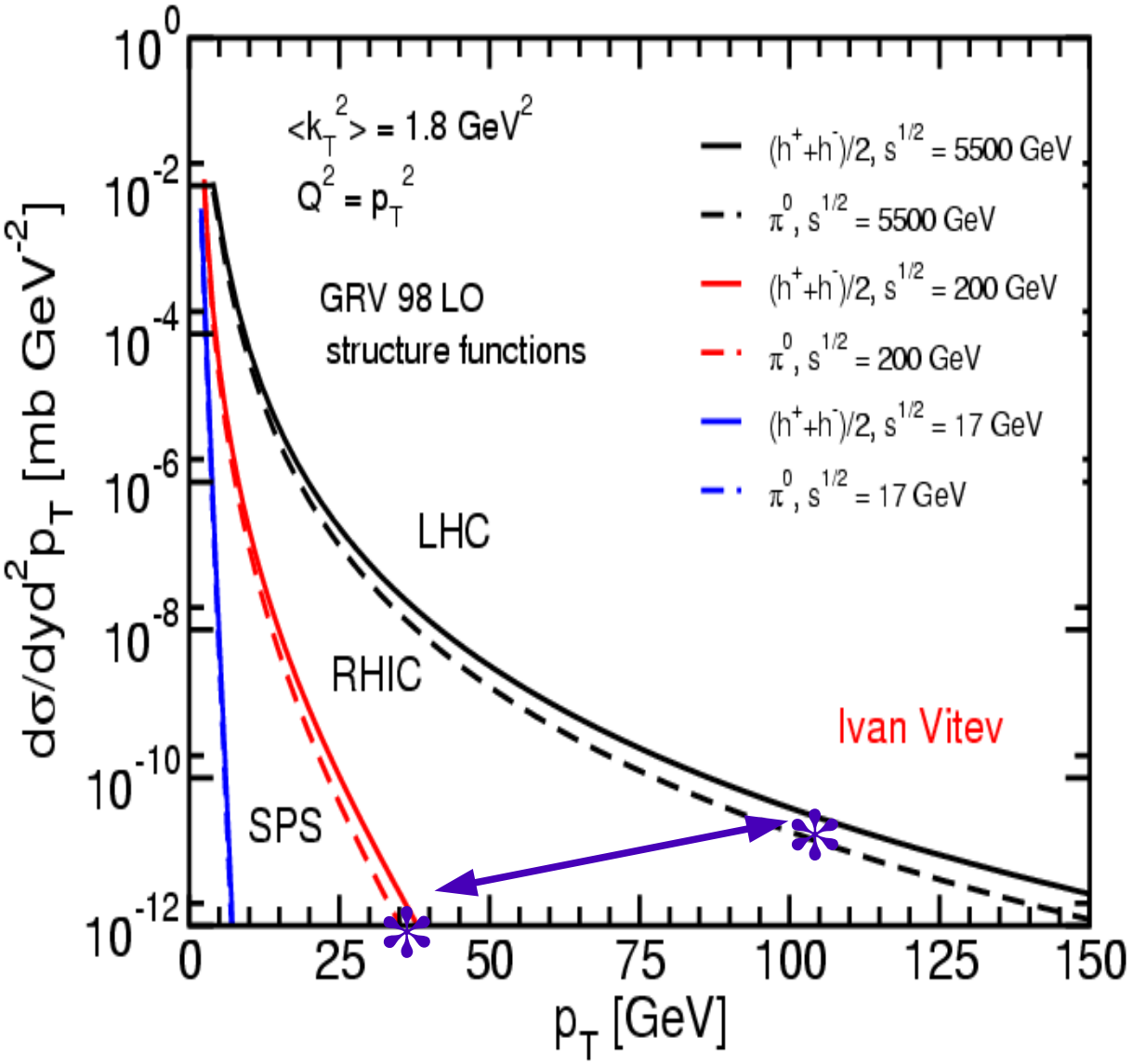
(What is the nature of non-equilibrium processes in a fundamental theory?)

The p_T reach at RHIC and LHC

Remember **integrated luminosity per year** at RHIC II is **x 36** larger than at LHC.

Asterisks show my rough estimate of where **$N/dydp_T \sim 800$** after **1 year running** (without acceptance correction).

So the LHC p_T reach is larger by a factor of ~ 3.



The p_T reach at RHIC and LHC

At the highest p_T, quark jets dominate at RHIC. Gluon jets dominate at all accessible p_T at LHC. Fractional E loss is larger at RHIC.

Remember **integrated luminosity per year** at RHIC II is **x 36** larger than at LHC.

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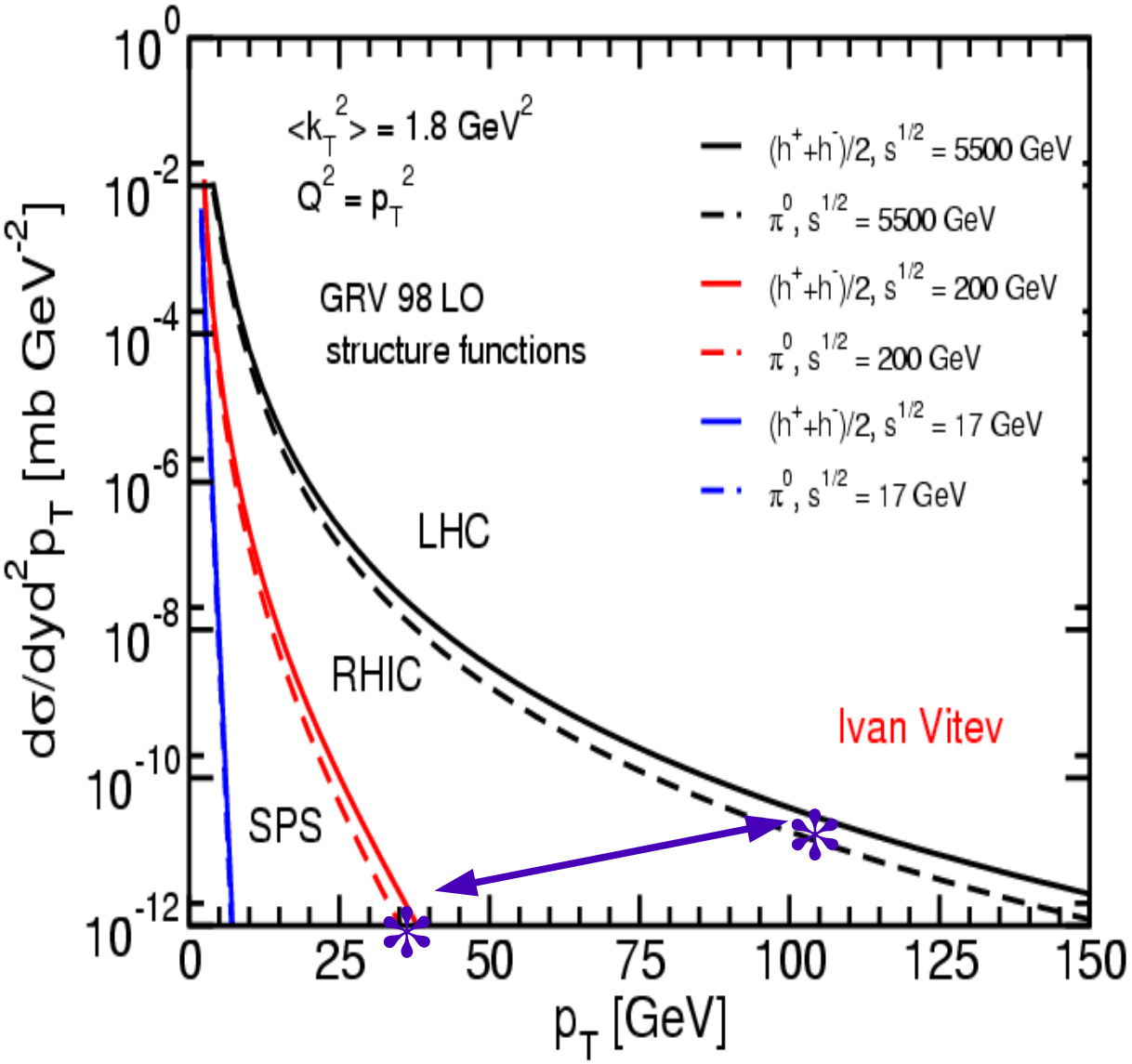


Future high p_T probes

With detector upgrades:

- Charm tagged jets. Requires PHENIX VTX, STAR HFT and DAQ 1000. PHENIX Nose Cone Calorimeter for jet energy measurements.
- Yields with particle ID of leading particle to high p_T.

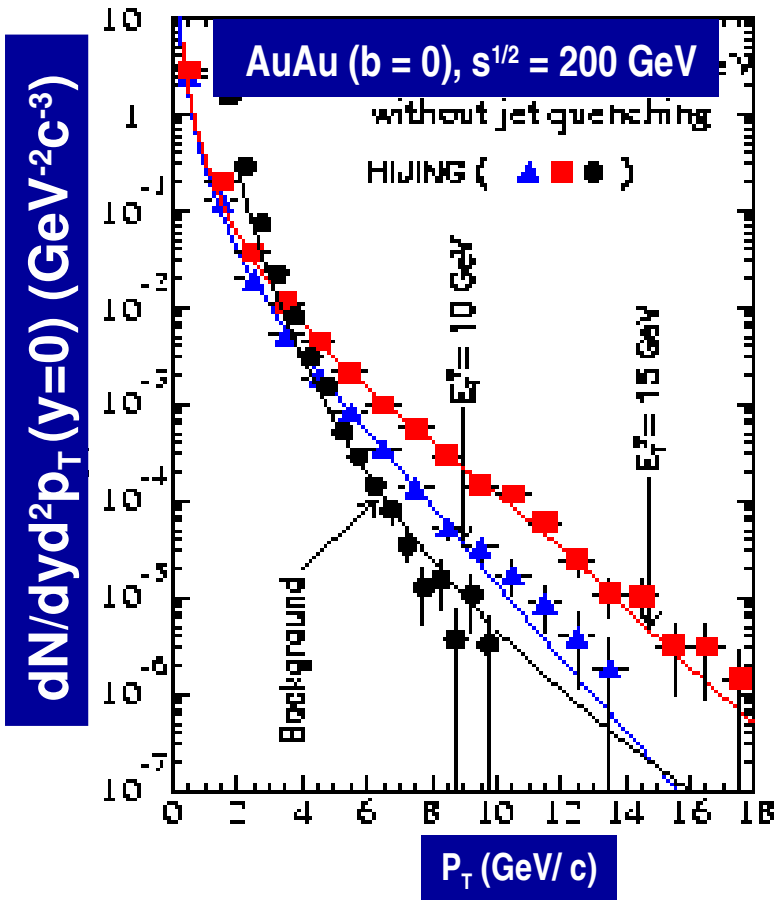
Future high p_T probes (cont.)

And with the luminosity upgrade:

- Tagged jets for **tomography to very high p_T**
  - **γ - jet correlations**. Clean tag of recoil gluon or quark jet gives energy: Study jet energy loss. Eliminates trigger bias.
  - **b and c tagged jets**. Study heavy quark jet energy loss.
  - **Gluon jets** (J/ψ-jet or cc/bb-jet correlations). High p_T cc/bb pairs from gluon splitting.
- **γ - leading hadron correlations**. Study bremstrahlung photons from jet interactions in medium. Cleaner at RHIC than LHC.
- **Identified particle v_2** to high p_T (30 GeV/c ?). Baryon/meson, light/heavy quarks. Test of how well energy loss is understood.
- Near and away side **jet cones**. Study eg. Mach Cones using high p_T jets. 3 particle correlations. Multi-dimensional tomography (p_T-ϕ-Ψ_{rp}). **Very statistics hungry at high p_T**.
- **U+U collisions.** Can we see stronger jet quenching?
- **Dileptons at high p_T** in and out of jets. Look for light vector meson (ρ) decays from earliest times and highest temperatures.
- **Jet conversion photons**. Control of uncertainties needs RHIC II. Difficult at LHC (except for virtual photons to low mass lepton pairs).

γ- jet tomography

Detect both γ and leading hadron from recoil quark or gluon jet, get **initial** jet energy from γ energy.



- Leading hadrons are very rare: only ~0.1% of jets fragment hard enough that hadrons are above incoherent background

- **$(1/2\pi p_T)d^2N/dydp_T$ for γ + jet coincidences (central Au+Au):**
  - **E =10 GeV: 6 nb/GeV**
  - **E =15 GeV: 0.6 nb/GeV**

- 1 yr at RHIC I =1.8 nb^{-1} - 15 GeV get < **200 events** in STAR acceptance before efficiency factors.
- 1 yr at RHIC II = 18 nb^{-1}. 15 GeV get < **2000 events** in acceptance.
- **luminosity upgrade needed to access this physics!**

- The π^0 component of the inclusive γ has to be either suppressed **or** measured and subtracted. **Direct γ is ~60% of inclusive at 8 GeV/c.**

Forward physics

(What is the wave function of a heavy nucleus?)

Future pA / dA physics

With detector upgrades:

- Begin mapping gluon density vs x. **STAR FMS and PHENIX NCC** are crucial for forward rapidity π^0 measurements.
- **Monojet measurement** to test CGC theory. Needs STAR FMS or PHENIX NCC.

and with the luminosity upgrade:

- **γ-jet coincidences:** Measure gluon density vs x with complete kinematics.
- **Heavy flavor production vs x:** Measure gluon density to lower x.

Monojets

Forward suppression mechanisms that do not change the hard scattering mechanism:

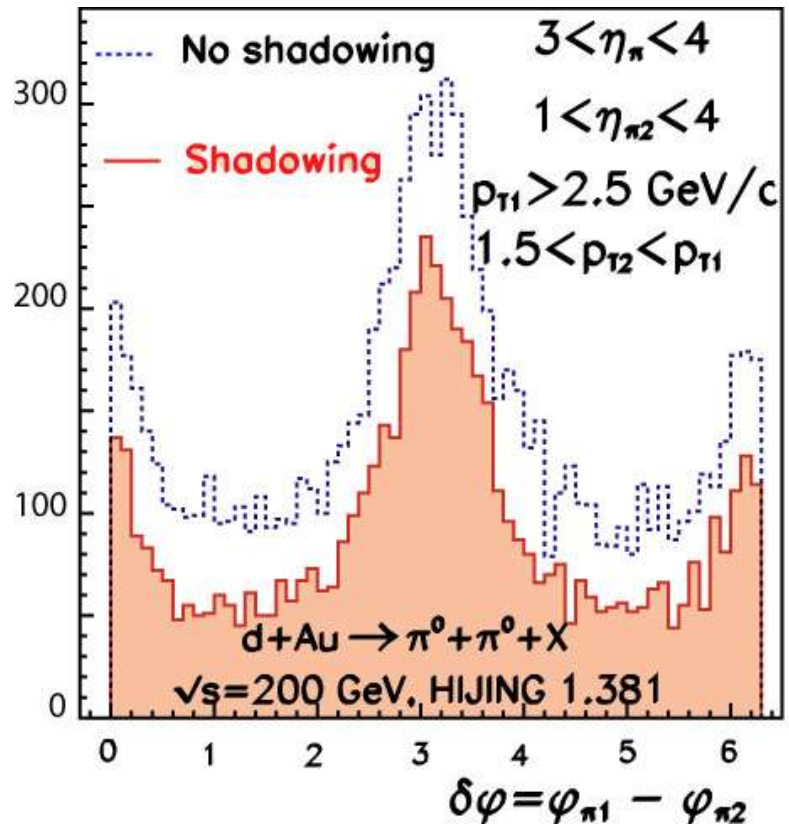
Leading twist shadowing

Initial state energy loss → **back-to-back jets**

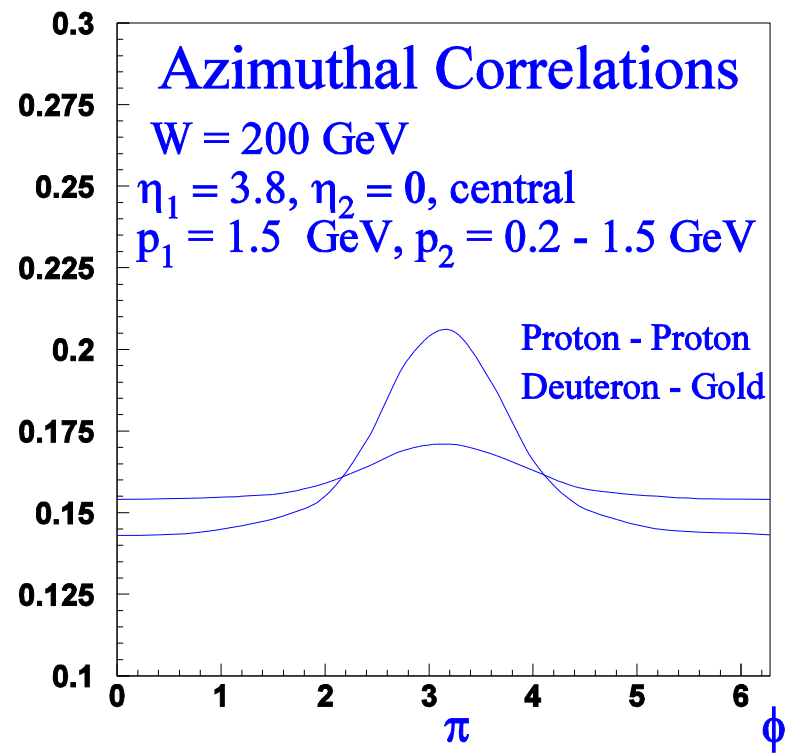
and a mechanism that does:

Coherent multiple scattering from saturated gluon fields → **monojets**

Leading twist shadowing: yield reduced, correlation still there.



CGC calculation showing monojet behavior.



π^0–π^0 needs STAR FMS, PHENIX NCC, luminosity upgrade not needed.

γ-jet requires detector upgrades **and** luminosity upgrades.

10 week d+Au run: Expect ~ 6K back to back coincidences in STAR.

If gluon saturation is observed at RHIC, then a critical follow-up question is:

What is the gluon density at the saturation scale? Address by:

- Heavy flavor production vs x
- γ-jet coincidences

which will benefit from both the upgraded detectors and the luminosity upgrade.

Relationship to LHC: Forward rapidity at RHIC samples similar x to mid rapidity at LHC. RHIC measurements will be important in separating initial state effects from final state effects at LHC.

Spin

(What is the wave function of the proton?)

Future spin physics

With detector upgrades:

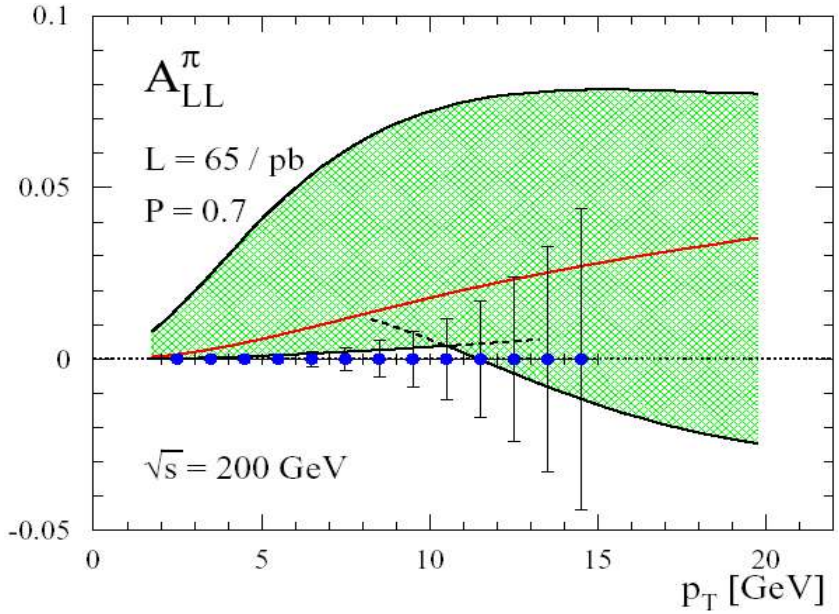
- Measure $\Delta G(x)$ over broad x, with as complete kinematics as possible:
  - **γ-jet coincidences:** STAR can do - **DAQ 1000 helps**, PHENIX **VTX**, **NCC**
  - **jet-jet coincidences:** STAR can do now, **better with DAQ 1000**.
  - **Open heavy flavor:** PHENIX needs **VTX**, STAR needs **HFT**.
- **$W^{\pm}$ production at 500 GeV:** Flavor separation of quark and anti-quark polarizations. PHENIX needs **muon trigger upgrade** to handle highest luminosity. STAR needs **forward tracking upgrade** for the charge of the W.
- **Transverse spin:** Measurement of transversity and Sivers (connection to orbital angular momentum?) parton distribution functions. STAR needs **Forward Meson Spectrometer**. PHENIX needs **VTX**, **Nose Cone Calorimeter**

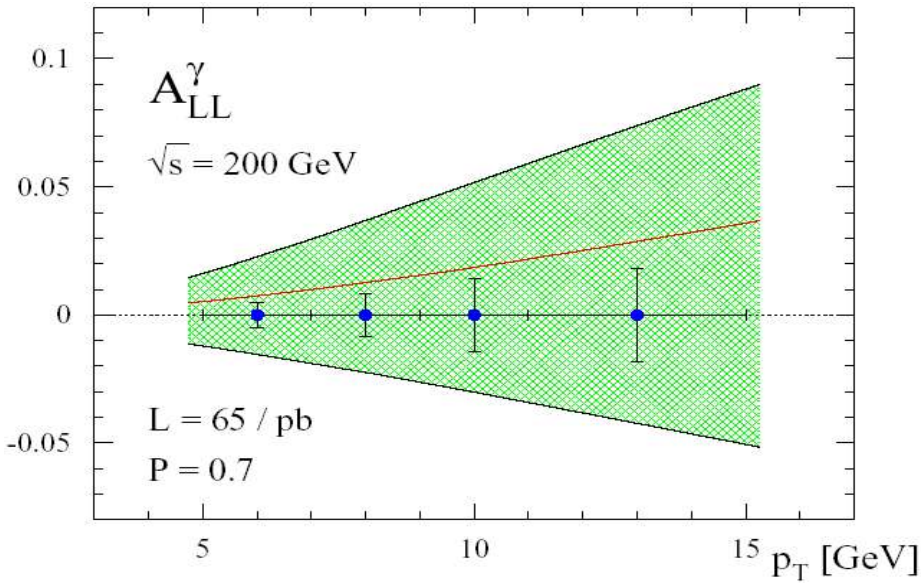
and with the luminosity upgrade:

- Factor of three luminosity makes the three spin programs practical in a reasonable time.
- **W + charm, inclusive $\bar{\Lambda}$:** Measure polarization of strange quark sea.
- **A_{TT} in Drell-Yan:** Explore transversity (**dedicated interaction region?**)

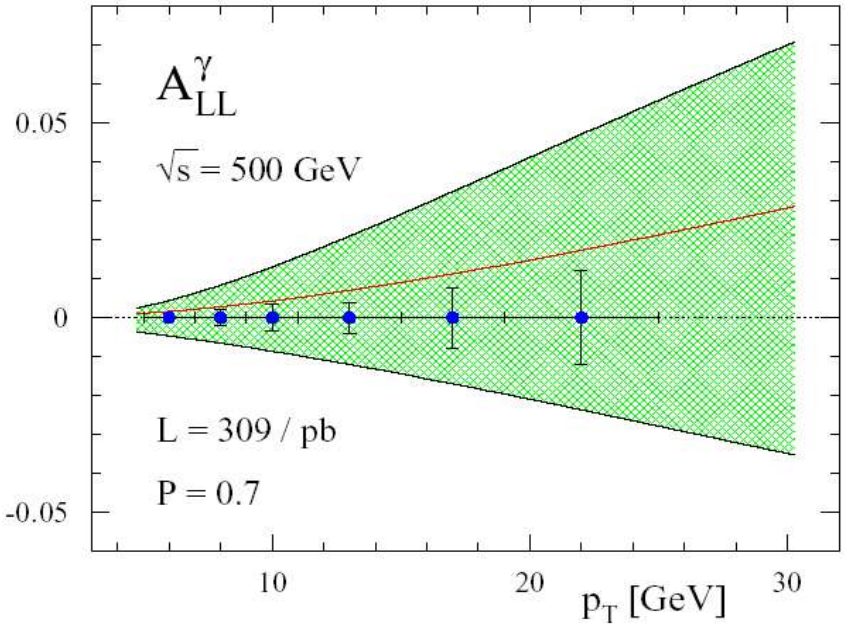
Gluon polarization measurements that just need run time

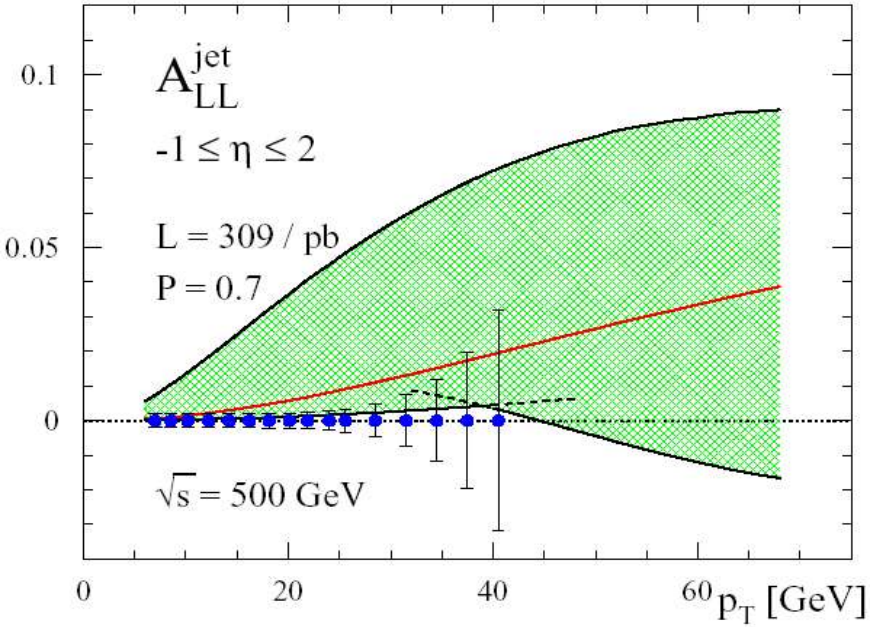
π^0 and direct photon at PHENIX $|\eta| < 0.35$, $\sqrt{s}$ = 200 GeV 2005 – 2009 runs





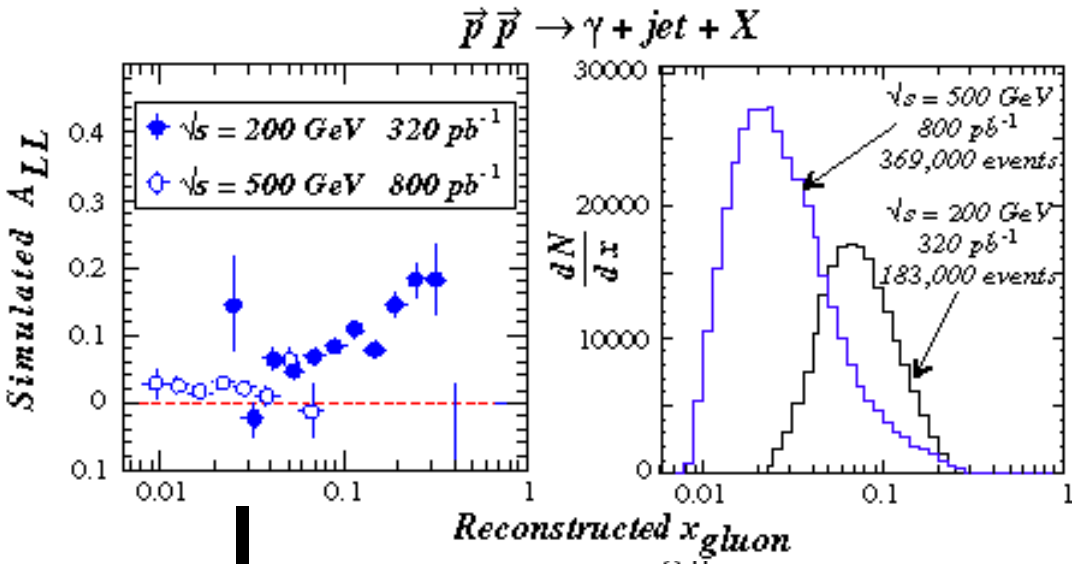
Direct photon (PHENIX) and jet (STAR) $\sqrt{s}$ = 500 GeV 2009 – 2012 runs

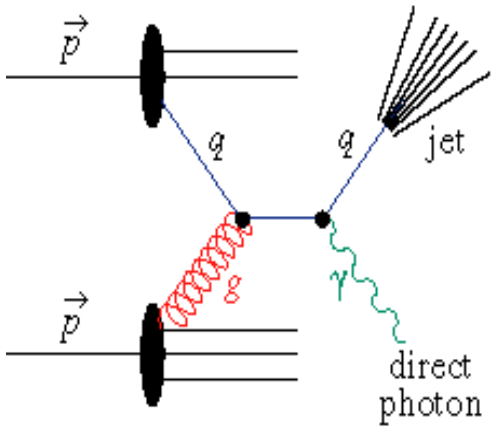




STAR Sensitivity to ΔG(x) using γ-jet coincidences to pin down x

Needs run time only



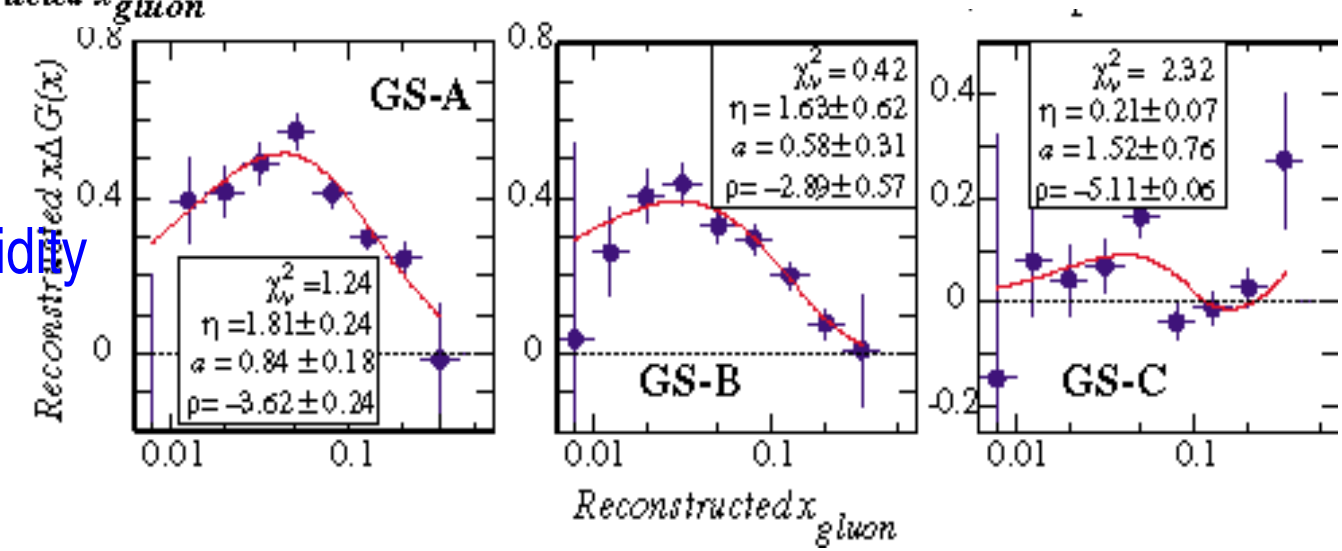


200 and 500GeV

Going to forward rapidity

Better sensitivity

Wider x range



$$\Delta G(Q^2) = \int_0^1 \Delta G(x, Q^2)\, dx$$

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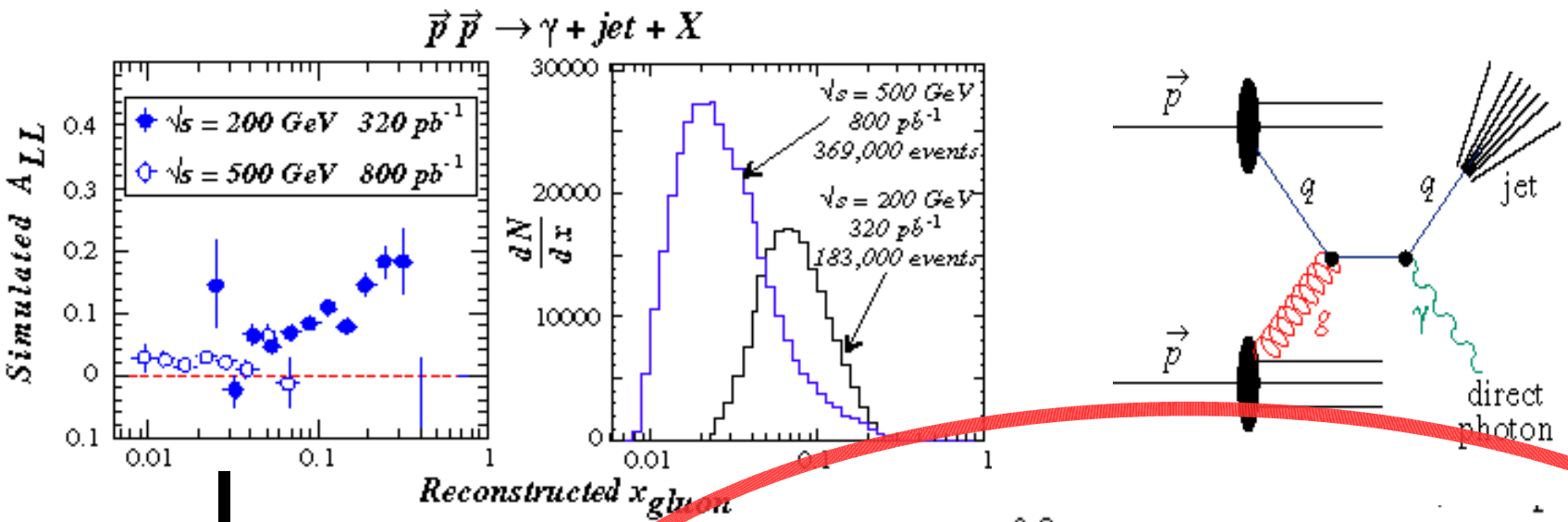
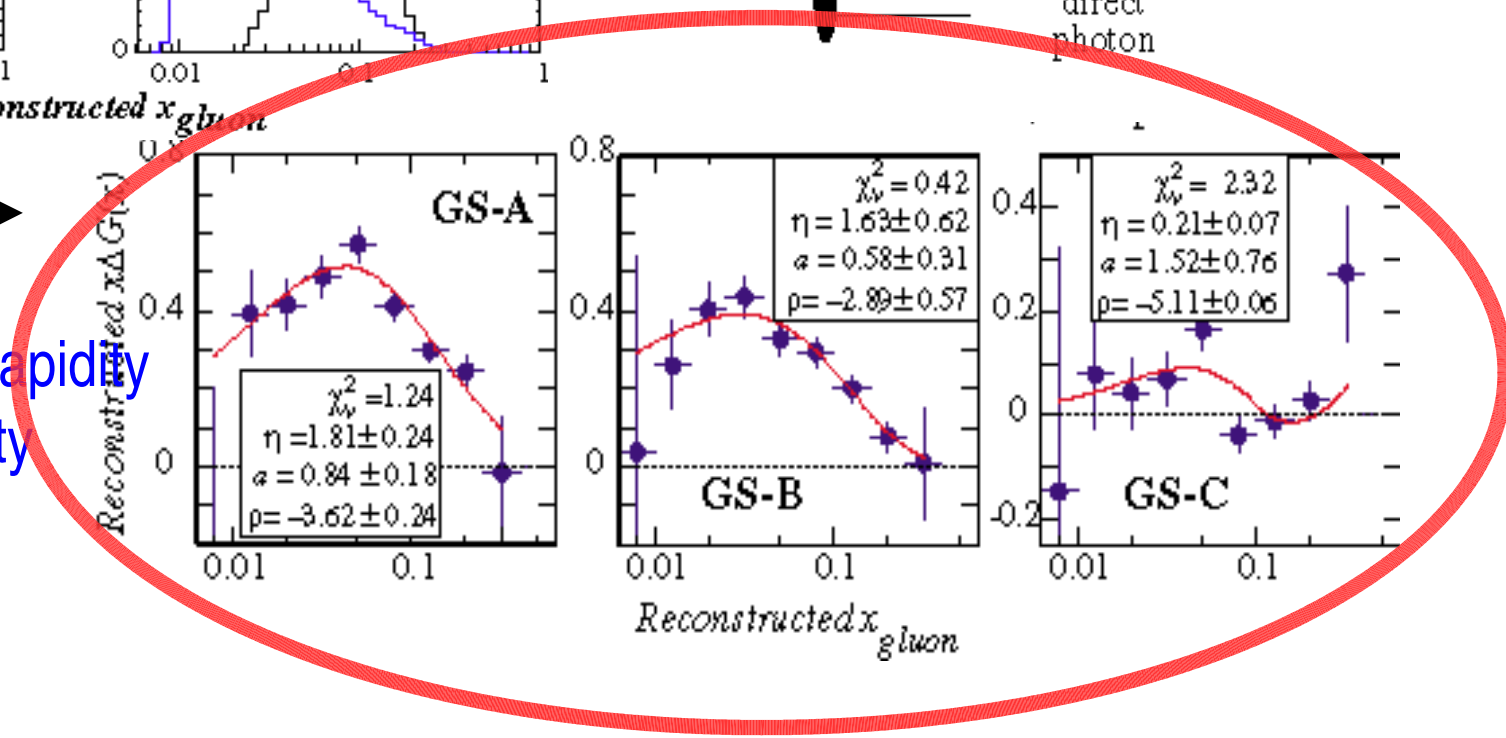




200 and 500GeV

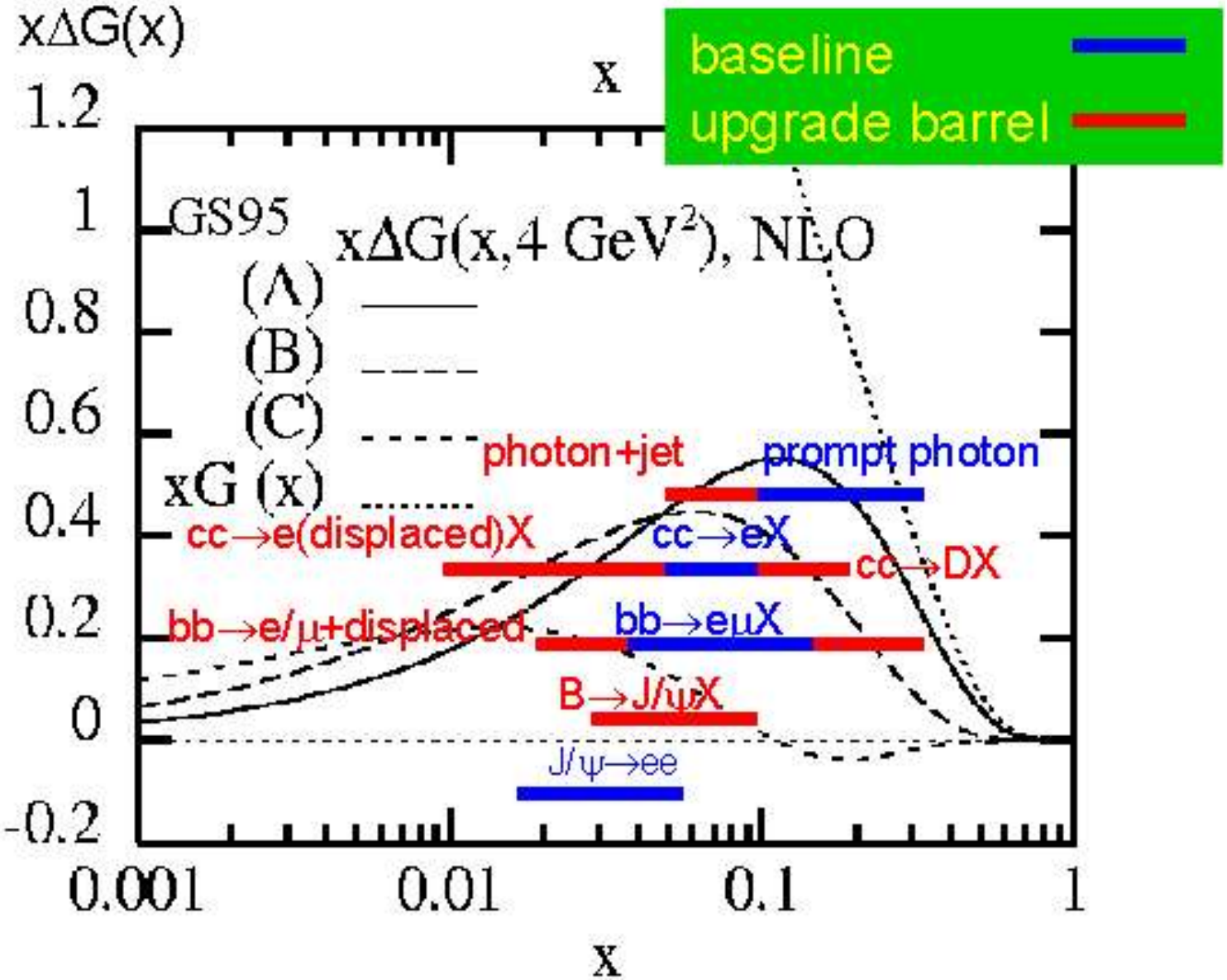
Going to forward rapidity

- Better sensitivity
- Wider x range

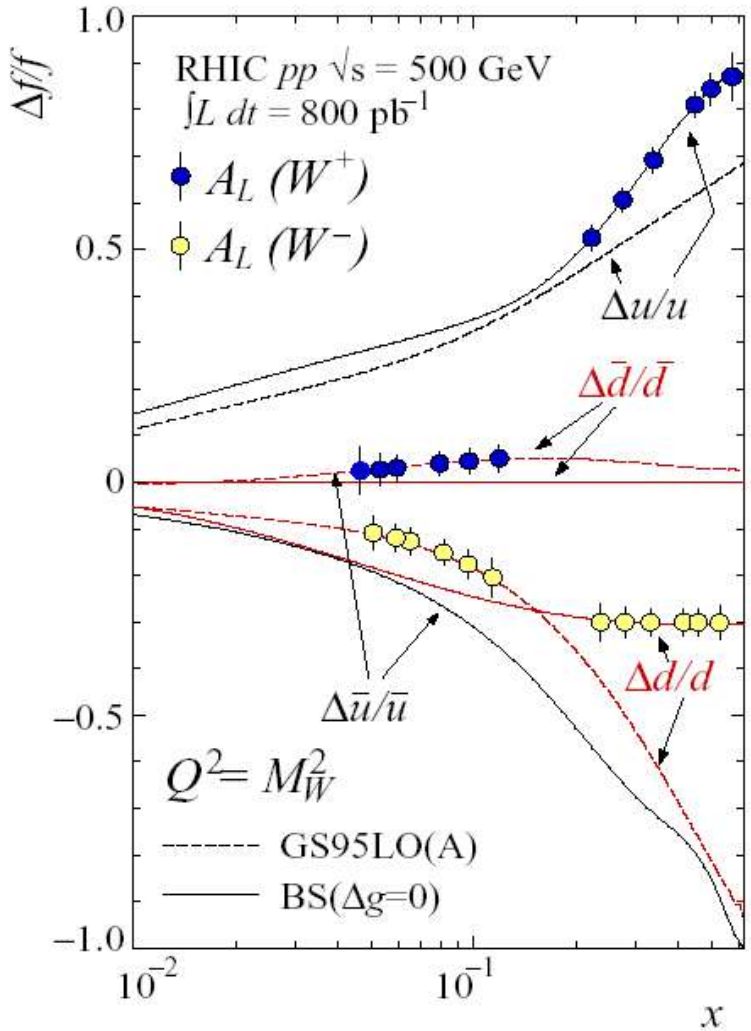
$$\Delta G(Q^2) = \int_0^1 \Delta G(x, Q^2)\, dx$$

Example of x range increase from upgrades:

PHENIX VTX Barrel upgrade



Example: Δq, $\Delta\bar{q}$ with detector upgrades accumulating statistics 2009 -2012



- Machine and detector requirements:
  - $\int Ldt \sim 800 pb^{-1}$, P=0.7 at $\sqrt{s}$=500 GeV
  - **Upgrades: Muon trigger (PHENIX)**
    forward tracking (STAR)

2009 to 2012 running at $\sqrt{s}$=500 GeV
CAD projects to yield $\int Ldt \sim 950 pb^{-1}$

Clean measurement of quark- and antiquark polarizations!

Luminosity at RHIC II adds W production with associate charm!
➔ access to strange quark polarization!

Low mass lepton pairs

(What are the phases of QCD matter?)

Future low mass lepton pair measurements

With detector upgrades:

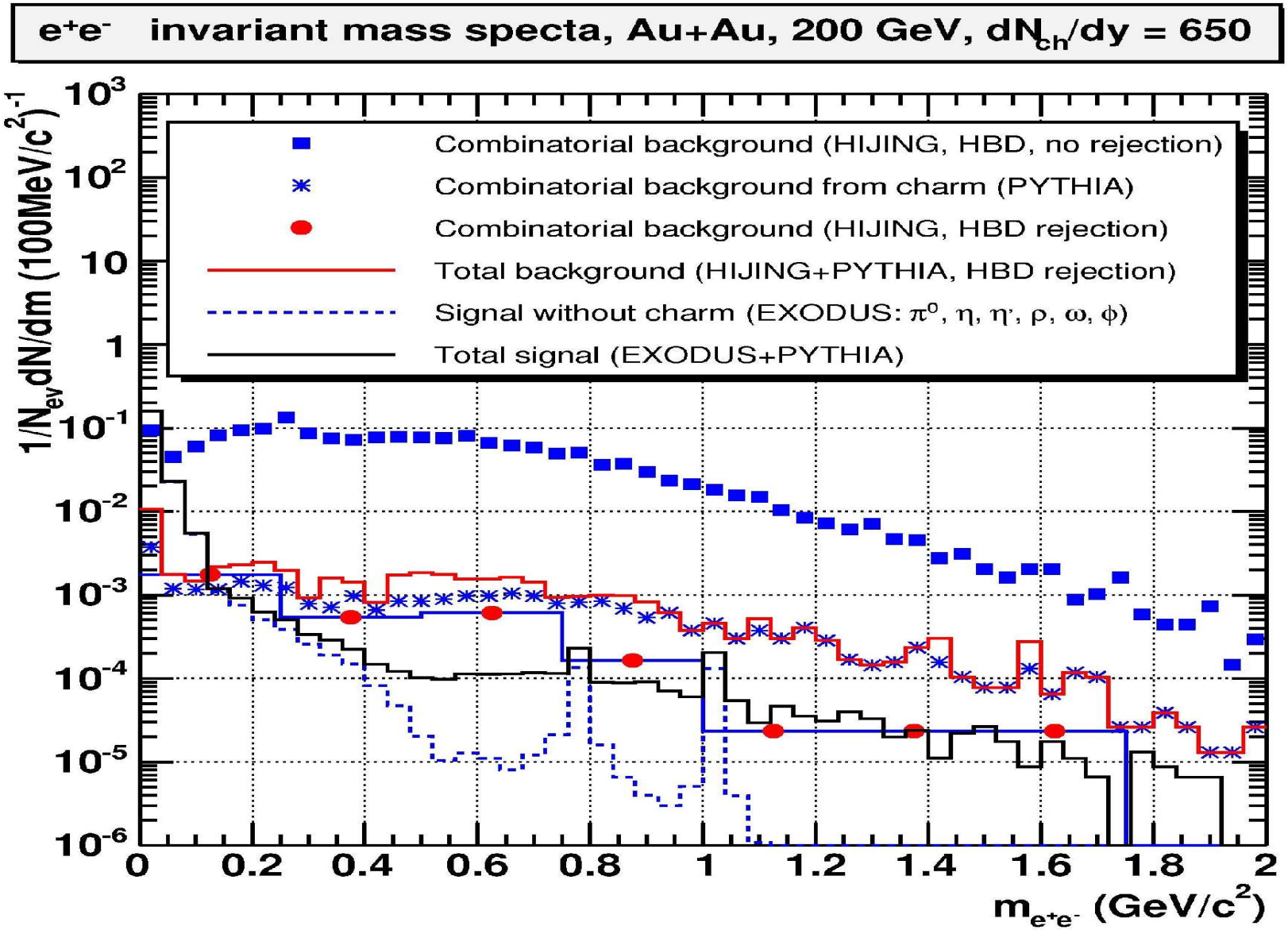
- can cleanly measure ω, ϕ, $\rho \rightarrow e^+e^-$. in 200 GeV Au+Au collisions in PHENIX and STAR.

And with the luminosity upgrade:

- Triggers needed at **full energy** to take advantage of luminosity upgrade.
- High statistics resonance yields, masses, shapes to high p_T.
- Is the ρ enhanced, broadened? Dependence on p_T?
- Open charm dileptons major remaining background. Phenix and STAR have to measure charm dileptons with SVT and HFT and subtract.
- Elleptic flow vs p_T for resonances, continuum?
- Luminosity upgrade enables measurements at lower energy with usable luminosity.

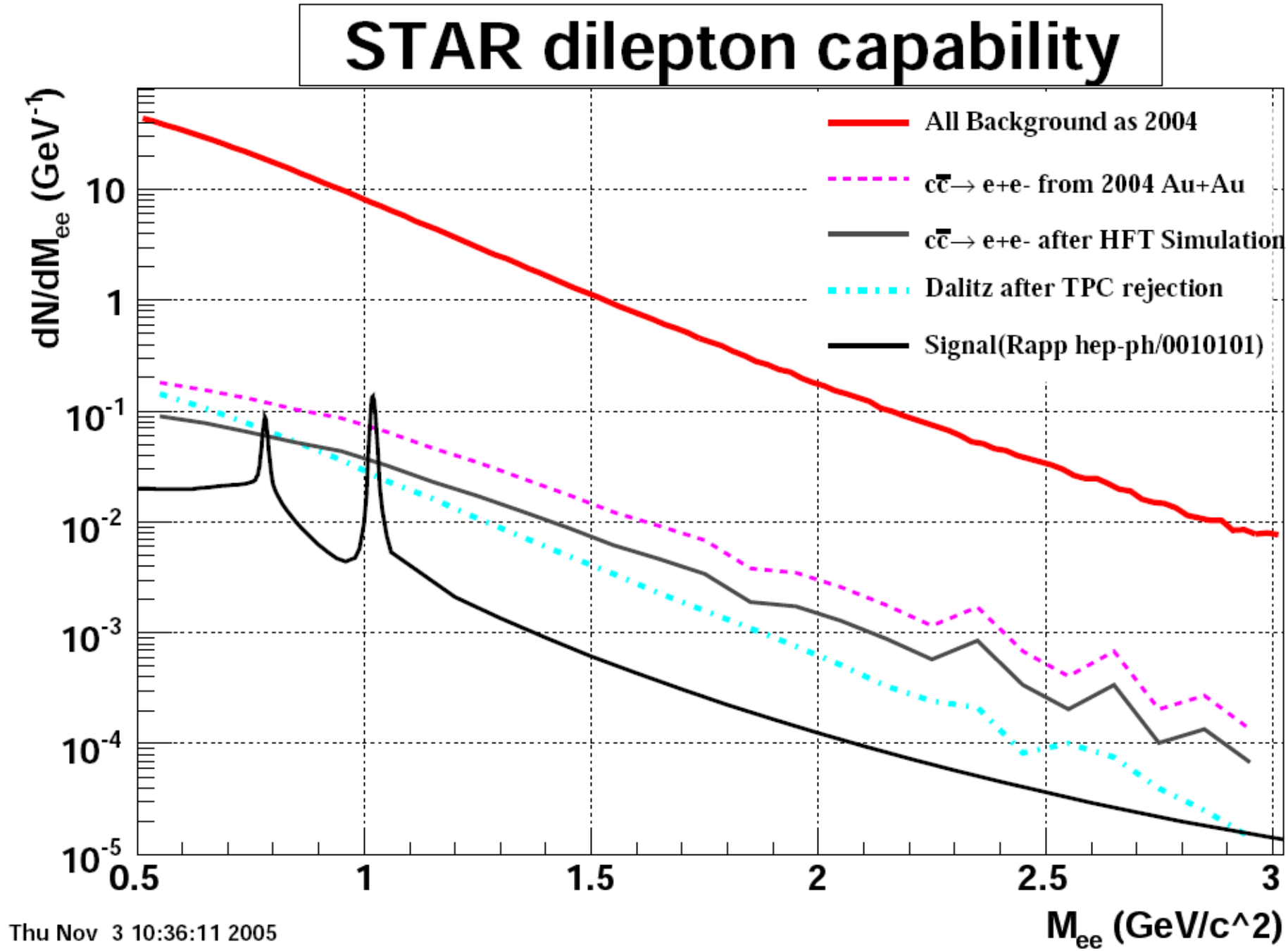
PHENIX dileptons with the HBD

PHENIX HBD gives **factor of 100** reduction in combinatorial background for ω, ϕ, ρ →e^+e^-



The low-mass pair measurement is ultimately limited by the combinatorial background from open charm, which has to be measured and subtracted to get the continuum.

STAR HFT upgrade **reduces conversion, charm background**, DAQ upgrade needed for rate



Low mass dilepton rates

Yields in a 200 GeV AuAu run **without** low mass dilepton triggers.

STAR: ϕ 6K ω 22K

PHENIX: ϕ 84K

To take advantage of the luminosity upgrade at full energy, both experiments need **low mass dilepton triggers** – under investigation.

The luminosity upgrade will be **essential** for efficient energy scans of low mass dilepton spectra. The luminosity will drop by ~ x 40 from 200 GeV to 30 GeV.

This physics is probably not feasible at LHC due to their very large charm yields.

What is special about RHIC/RHIC II?

Energy scans from 20(or lower?)-200 GeV - Species scans pp to UU:

- Access temperatures T_c – $2T_c$ with energy, species scans.
- Vary location in baryon density vs temperature space
- Vary geometry vs number of participants easily.

Asymmetric systems at same energy as symmetric systems.

Charm and bottom multiplicity/event **very** different from LHC.

Quarkonium mechanisms are considerably different from LHC.

Unique polarized proton collider for Spin.

Low mass dilepton physics possible at RHIC, not at LHC.

Onset of saturation effects likely occurs at RHIC energy.

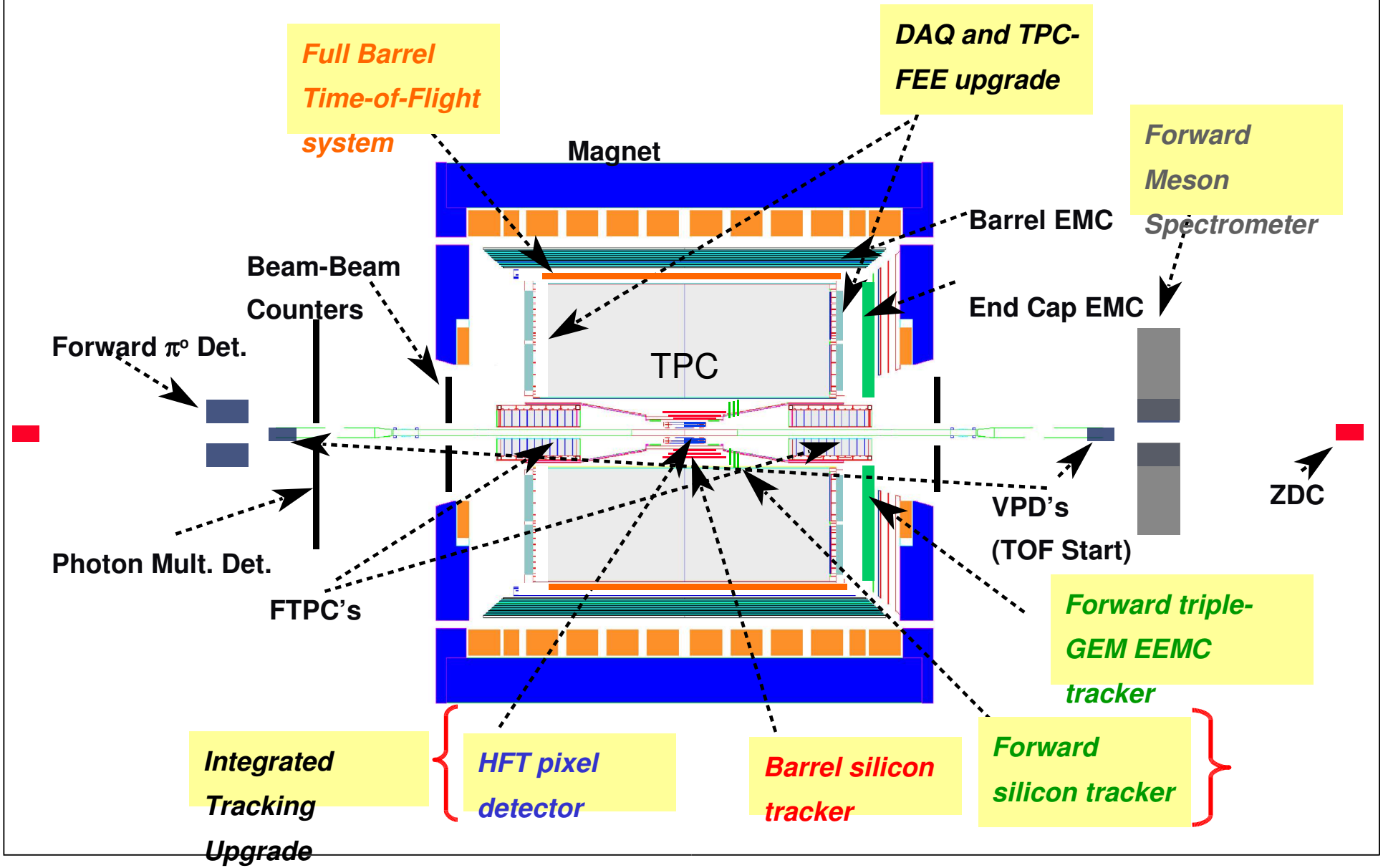
Highest (accessible) p_T jets dominated by gg at LHC, qq at RHIC.

Backup slides

Key future measurements

Open heavy flavor	v_2 and R_{AA} to high p_T
Quarkonium	Charmonium excited states Upsilons J/ψ kinematic distributions
Spin	W (quark spin structure) Heavy flavor and γ-jet correlations (gluon spin structure)
Jets	γ-tagged jets
Temperature	Intermediate mass dileptons Photons and low mass dileptons at intermediate p_T
EOS	Species scans (U+U and asymmetric collisions) QCD critical point scan (3 energies inside 20-62 GeV)
Low mass pairs	dileptons
pA	monojets

STAR Upgrades



The Upgraded PHENIX Detector

Charged Particle Tracking:

- Drift Chamber
- Pad Chamber
- Time Expansion Chamber/TRD
- Cathode Strip Chambers(Mu Tracking)
- Forward Muon Trigger Detector
- Si Vertex Tracking Detector- Barrel (Pixel + Strips)
- Si Vertex Endcap (mini-strips)

Particle ID:

- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)
- Aerogel Cerenkov Counter
- Multi-Resistive Plate Chamber Time of Flight
- Hadron Blind Detector

Calorimetry:

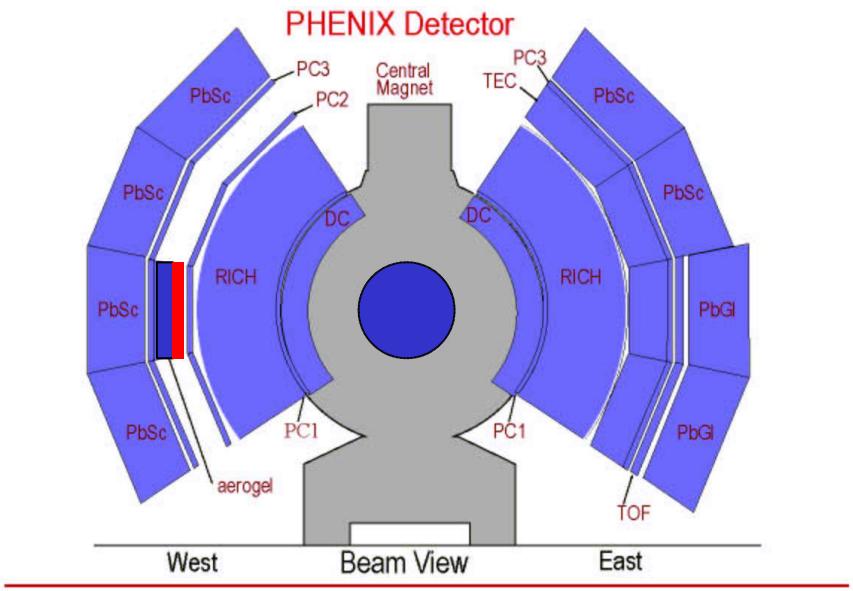
- Pb Scintillator
- Pb Glass
- Nose Cone Calorimeter

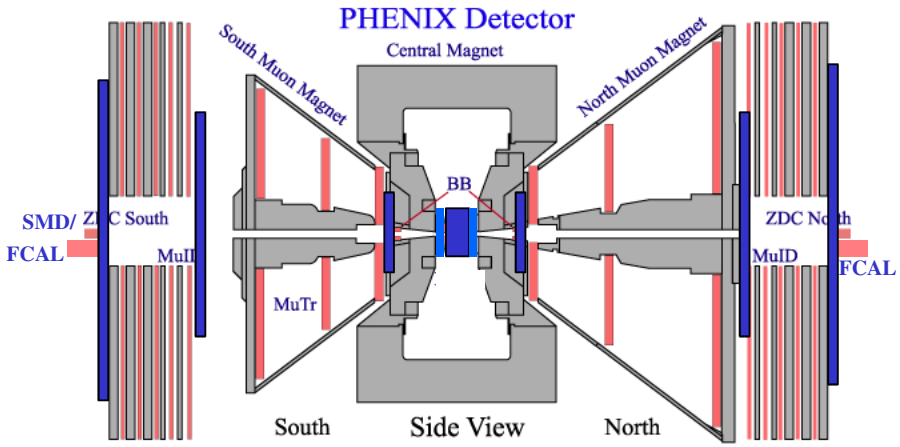
Event Characterization:

- Beam-Beam Counter
- Zero Degree Calorimeter/Shower Max Detector
- Forward Calorimeter

Data Acquisition:

- DAQ Upgrade





p_T reach for open and closed charm and beauty

Both STAR and PHENIX have heavy flavor semileptonic decay spectra from Run 4 Au+Au data. The STAR data appear to extend to ~ 7.5 GeV/c with good statistics. PHENIX has J/ψ spectra that extend beyond 5 GeV/c with good statistics.

RHIC II will produce about 2 orders of magnitude (x75) more integrated luminosity.

- According to FONLL calculations of p_T distributions for **D →e and B →e** by Ramona Vogt, this will extend the p_T reach by **~ 5 GeV/c**.

- The same calculations indicate that the p_T distributions for **D→Kπ** will be extended by **~ 5 GeV/c**.

- A simple extrapolation of the existing Run 4 PHENIX **J/ψ data** suggests that the p_T reach will increase by **~ 3 GeV/c.**

Polarized DIS

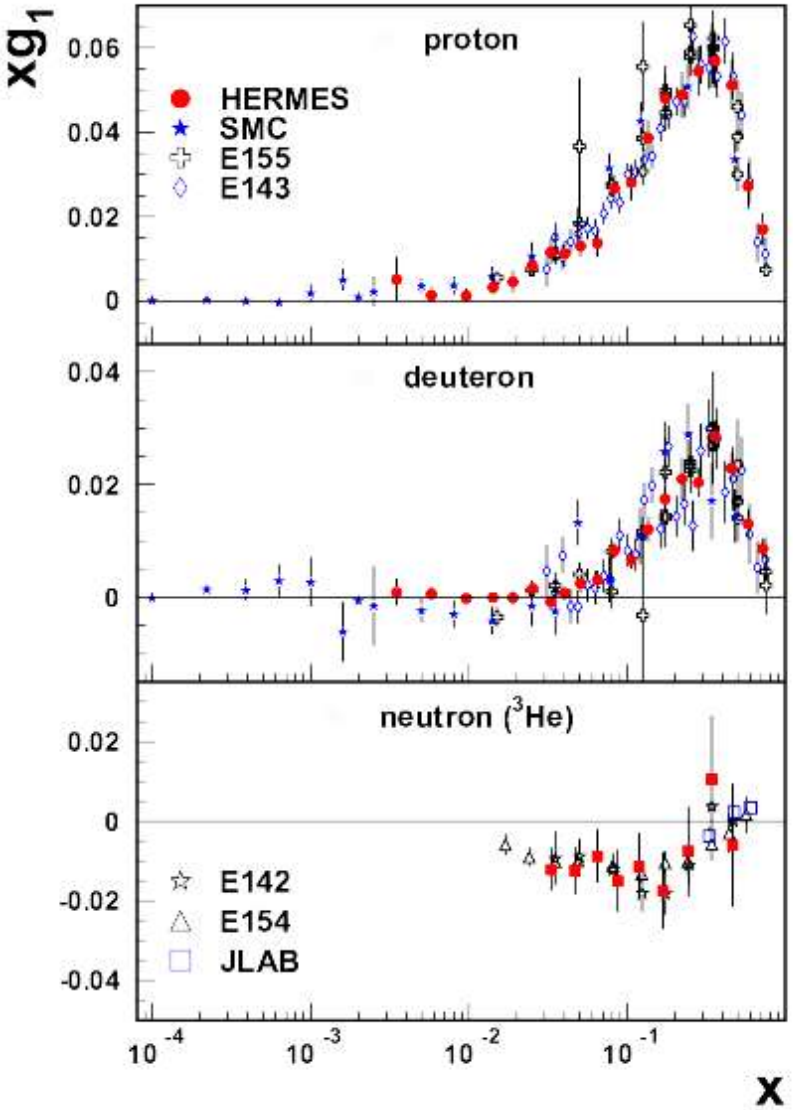
- quark contribution

$$\Delta\Sigma = 0.1 \sim 0.3$$

- origin of the nucleon spin 1/2 ?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

  - gluon contribution ?
  - orbital angular momentum ?



A RHIC II Example:

Sivers-Asymmetries, A_T in Drell Yan

STAR for 125pb^{-1}

Dedicated DY experiment 1250 pb^{-1} at high luminosity IR with mini-quads

Resulting in the first precise measurement of the Sivers function; access to orbital angular momentum?!

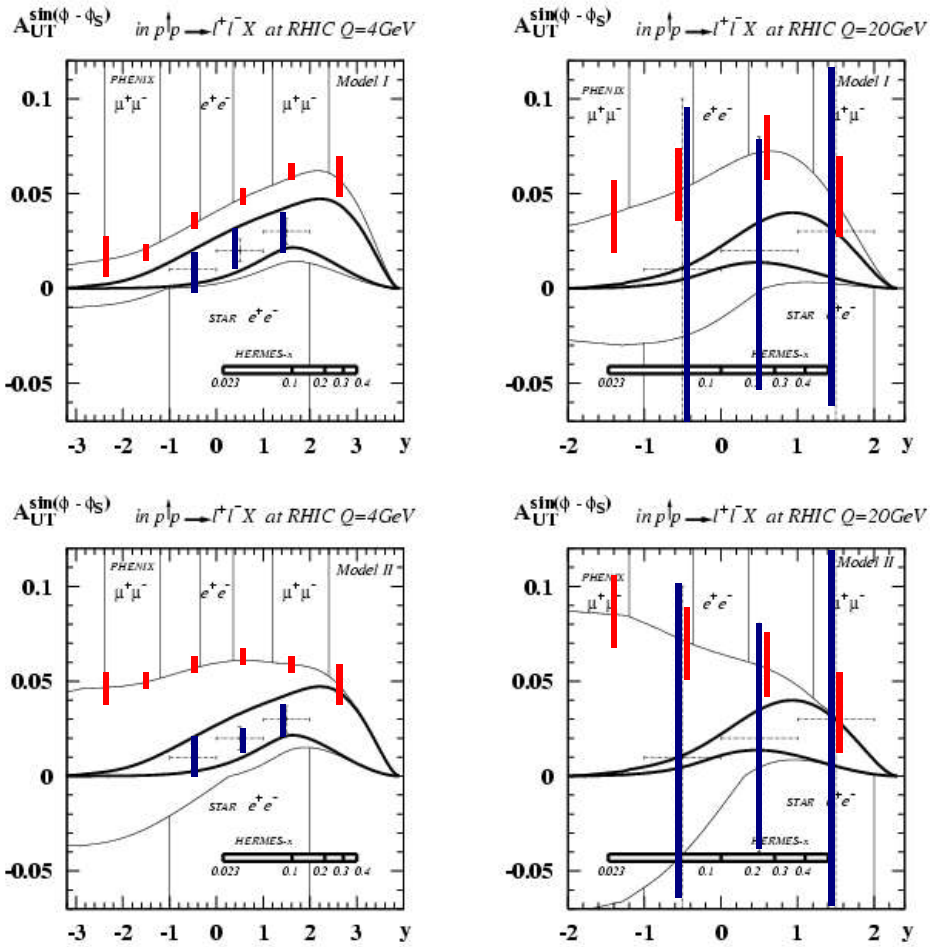


FIG. 1: *The azimuthal SSA $A_{UT}^{\sin(\phi-\phi_S)}$ in Drell-Yan lepton pair production, $p^\uparrow p \to l^+l^-X$, as function of y for the kinematics of the RHIC experiment with $\sqrt{s} = 200$ GeV, and $Q^2 = (4\,\mathrm{GeV})^2$ and $Q^2 = (20\,\mathrm{GeV})^2$ for the two different models for Sivers antiquarks distribution functions. The errors are estimated for STAR for $\int Ldt = 125pb^{-1}$. More detailed information can be found in section III.*