RHIC II Physics in the LHC era

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This talk

I have been asked to discuss how the RHIC II heavy ion physics program compares with, and complements, the LHC program.

I will focus on the **heavy ion programs** at the two facilities and, through necessity, on a limited number of physics topics. Bill Zajc has already given an overview of the physics program at RHIC II, and there have been talks on the forward physics and spin programs at RHIC II by Carl Gagliardi and Steve Vigdor.

Where possible, I will try to be quantitative. Please keep in mind that these quantitative estimates are not to be taken more seriously than **a factor of two or so** (or, in the case of unexpected physics effects, worse than that) for signals that have not been seen yet at RHIC.

What is RHIC II?

RHIC II is a **luminosity upgrade** to RHIC that will produce the following improvements in performance:

		---- Luminosity Delivered / week ---		
Species	**units**	**Obtained**	**RHIC 2008**	**RHIC II**
p+p	pb^{-1}	0.9	26	33
d+Au	nb^{-1}	4.5	--	62
Cu+Cu	nb^{-1}	2.4	--	25
Au+Au	μb^{-1}	160	327	2500

Note: Because the collision diamond has σ = 20 cm at RHIC and σ = 10 cm at RHIC II, the gain in **usable luminosity** is larger than the ratio of delivered luminosity when going to RHIC II.

There are also a number of planned detector upgrades for PHENIX and STAR that are crucial to the RHIC II physics program.

Detector upgrades before RHIC II

PHENIX and STAR have extensive upgrade plans that will be completed in the mid near term - **about 5 years**. These will be described later by Tom Ludlam, so I will not spend a lot of time on them.

These detector upgrades are crucial to the RHIC program both before and after the luminosity upgrade.

STAR:

- DAQ upgrade increases rate to 1 KHz, triggered data has ~ 0 dead time.
- Silicon tracking upgrade for heavy flavor, jet physics, spin physics.
- Barrel TOF for hadron PID, heavy flavor decay electron PID.
- EMCAL + TOF J/ψ trigger useful in Au+Au collisions.

PHENIX:

- Silicon tracker for heavy flavor, jet physics, spin physics.
- Forward muon trigger for high rate pp + improved pattern recognition.
- Nose cone calorimeter for heavy flavor measurements.
- Aerogel + new MRP TOF detectors for hadron PID.
- Hadron-blind detector for light vector meson e^+e^- measurements.

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 μb^{-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: $T \sim 3.5\ T_c$

Detectors:
ALICE ATLAS CMS

4 weeks / year physics
Average luminosity $5 * 10^{26}$ cm^{-2} s^{-1}
Pb+Pb luminosity/year 500 μb^{-1}

$\sigma(J/\psi)_{LHC} = \sigma(J/\psi)_{RHIC} *$ **13**
$\sigma(Y)_{LHC} = \sigma(Y)_{RHIC} *$ **55**

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

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RHIC II

Beams: **p to U**
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Central Au+Au: T ~ 2 T_c

Detectors:
PHENIX STAR eRHIC detector?

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What does RHIC II buy us?

Increased luminosity + more powerful upgraded detectors - we go to the next level of model testing for:

- Open charm and beauty as probes of heavy quark energy loss and thermalization in A+A collisions.
- Charmonium and Y family as probes of deconfinement.
- Light parton jets as probes of nuclear matter.
- Light vector mesons as probes of chiral symmetry restoration.
- Low x (gluon shadowing) physics - see Talk by Carl Gagliardi.
- Spin physics - see talk by Steve Vigdor.

Open Charm and beauty

With detector upgrades (both PHENIX and STAR):

• Dramatically reduce backgrounds for all open charm, open beauty sigmals using displaced vertex measurement.

• Separate open charm and beauty statistically using displaced vertex.

• Separate B $\rightarrow$ J/ψ from prompt J/ψ using displaced vertex.

And with the luminosity upgrade:

• 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 **open charm correlations** with open charm or hadrons.

Charmonium and Bottomonium

With detector upgrades:

- J/ψ from B decays with displaced vertex measurement (both).
- Reduce J/ψ →μμ background with forward μ trigger in PHENIX.
- Improve mass resolution for charmonium and **resolve** Υ family (both).
- See γ in forward calorimeter in front of muon arms (PHENIX).

And with the luminosity upgrade:

- **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 χ_c → **J/ψ+γ R_{AA}**. Ratio to J/ψ?
- Measure ψ' **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.

High p_T probes

With detector upgrades:

- STAR EMCal jet trigger.
- Particle ID to high p_T.

High p_T probes (cont.)

And with the luminosity upgrade:

- Tagged jets
  - **γ - jet correlations**. Clean tag of recoil gluon or quark jet gives energy: Study jet energy loss.
  - **b and c tagged jets**. Study heavy quark jet energy loss.
  - **Gluon jets** (J/ψ-jet or cc/bb-jet correlations). High p_T J/ψ are from gluon splitting, as are high p_T cc and bb pairs.
- Full jet reconstruction.
- **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.
- 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).

Light vector meson dielectron physics

With detector upgrades:

- Factor of 100 reduction in combinatorial background for ω, ϕ, ρ $\rightarrow e^+e^-$ with PHENIX HBD.

And with the 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 with the HBD. Have to measure with silicon vertex and subtract.
- Elleptic flow vs p_T for resonances, continuum?
- Measurements at lower energy with usable luminosity?

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

Quantitative estimates

In the next few slides I will show some quantitative estimates of the **heavy flavor signal yields** that we can expect at RHIC II, and I will also give a few examples of the corresponding yields for the LHC detectors. I will focus mostly on quarkonium measurements - these are generally the most statistics starved.

Assumptions for Au+Au at RHIC II:

- J/ψ cross sections from PHENIX data.
- Υ and open bottom cross sections from hep-ph/9502270 (agrees with PHENIX preliminary Υ measurement)
- Pair reconstruction efficiency 40%
- Trigger efficiency ~ 80%
- PHENIX & STAR coll. vertex cut 80% (central bucket)*70% in ± 10 cm.
- Displaced vertex cut (open charm, bottom) 40% efficient.

LHC estimates provided by LHC experiments.

(But I also made some with more conservative efficiencies)

But first - 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 $\rightarrow$ e and B $\rightarrow$ 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$\rightarrow$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.**

Heavy flavor yields at RHIC II - PHENIX

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

Signal	$\|\eta\|$	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	$\|\eta\|$	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		30,000*	30,000*

* From 100 Hz of minimum bias triggers (Thomas Ullrich).

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

Heavy flavor yields at LHC - from 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]	$\lvert\eta\rvert$
$J/\psi \to \mu^+\mu^-$	740,000	2.5-4	24,000	< 2.4	8K-100K	< 2.5
$J/\psi \to e^+e^-$	9,500[4]	< 0.9				
$\psi' \to \mu^+\mu^-$	14,000	2.5-4	440	< 2.4	140-1800	< 2.5
$\psi' \to e^+e^-$	190[4]	< 0.9				
$\Upsilon \to \mu^+\mu^-$	8,400	2.5-4	26,000	< 2.4	15,000	< 2.0
$\Upsilon \to e^+e^-$	2,600	< 0.9				
$D \to K\pi$	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

The yields on the previous slide are from estimates by the LHC experiments. I made some estimates of my own for some signals using published acceptances for ALICE and CMS, with the **same trigger and reconstruction efficiencies** that I used for the RHIC II estimates (80% and 40% respectively).

The p+p cross sections used in my estimates are from **hep-ph/0311048**.

The cold matter corrections (**shadowing+"normal" absorption**) at 5.5 TeV are from recent calculations from R. Vogt (LHC satellite meeting talk).

- J/ψ: 40% at $\eta \sim 0$ 50% at $\eta \sim$ 2-4
- Υ : 60% at $\eta \sim 0$ 65% at $\eta \sim$ 2-4

My estimates are generally within a factor of 2 of those from the LHC experiments.

Heavy flavor yields at LHC - my numbers in bold black using conservative reconstruction efficiencies

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

Signal	ALICE	$\|\eta\|$	CMS	$\|\eta\|$	ATLAS[3]	$\|\eta\|$
$J/\psi \rightarrow \mu^+\mu^-$	**380,000**	2.5-4	**40,000**	< 2.4	8K-100K	< 2.5
$J/\psi \rightarrow e^+e^-$	9,500[4]	< 0.9				
$\psi' \rightarrow \mu^+\mu^-$	**6850**		**731**	< 2.4	140-1800	< 2.5
$\psi' \rightarrow e^+e^-$	190[4]					
$\Upsilon \rightarrow \mu^+\mu^-$	**4,150**	2.5-4	**8,200**	< 2.4	15,000	< 2.0
$\Upsilon \rightarrow e^+e^-$	**1,940**	< 0.9				
$D \rightarrow K\pi$	8,000[1]	< 0.9				

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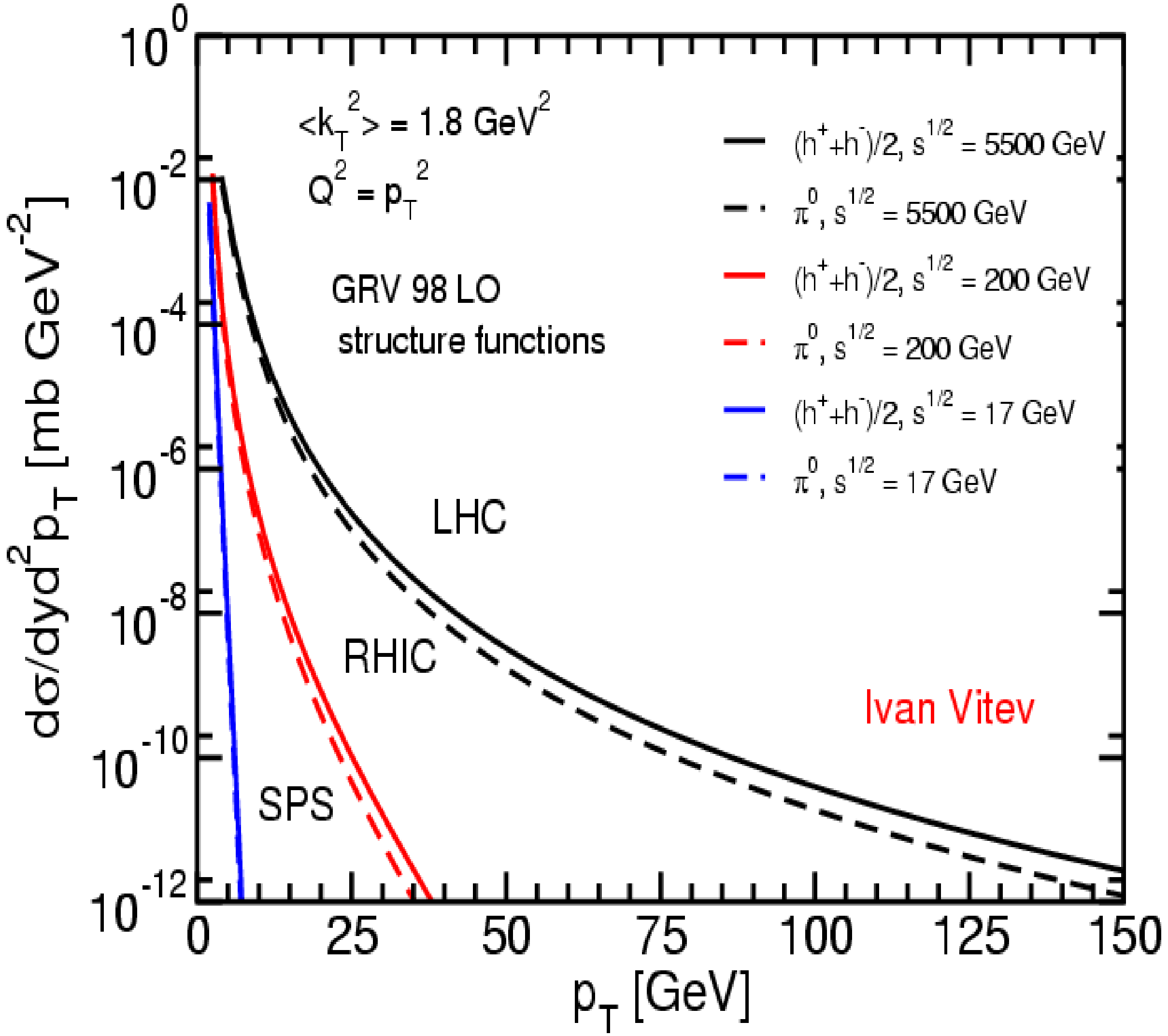
The p_T reach at RHIC and LHC

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

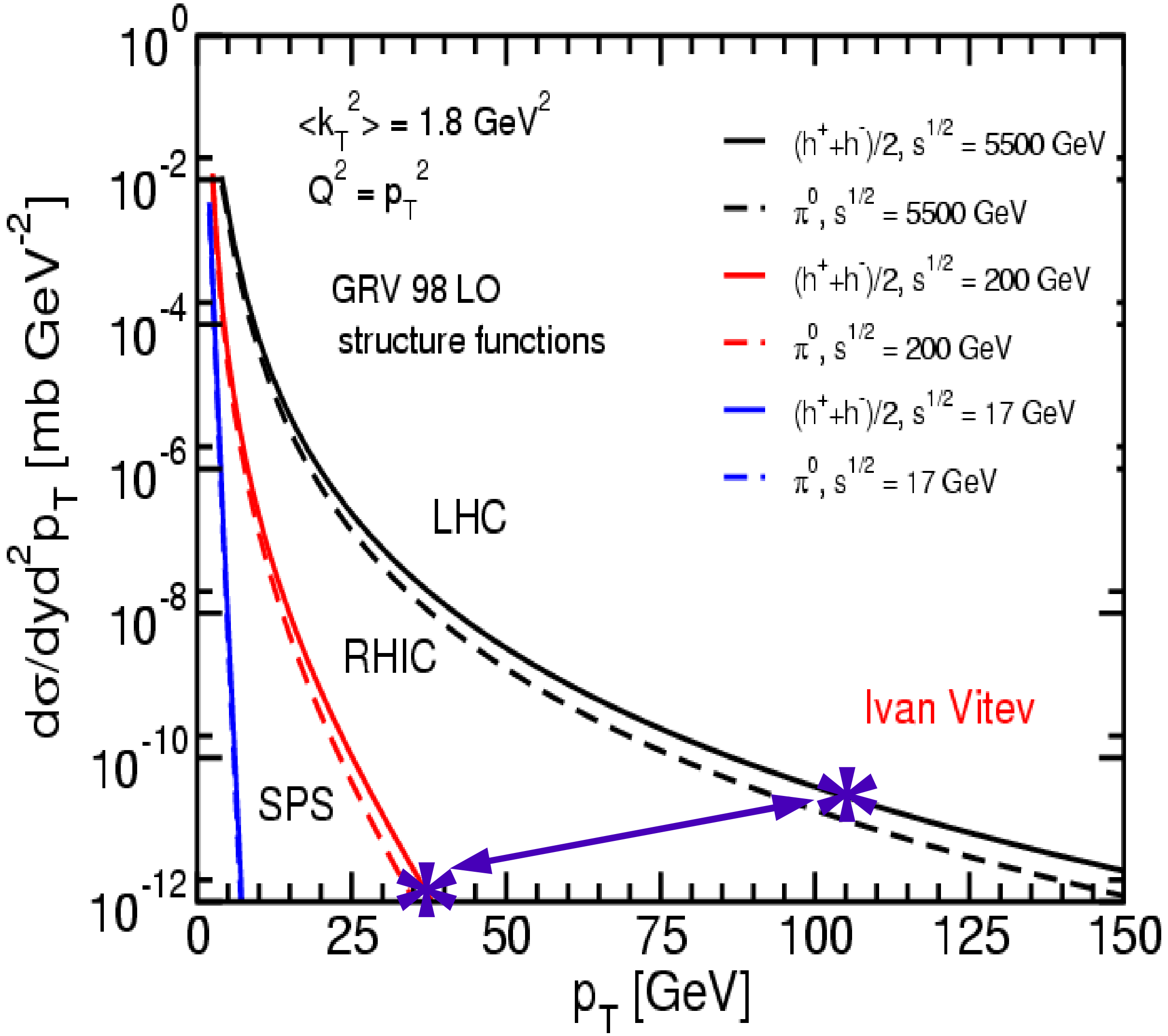


The p_T reach at RHIC and LHC

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

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

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



The p_T reach at RHIC and LHC

Remember that the y range is much larger at LHC, increasing total yields. But that only helps if the physics is independent of y!

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

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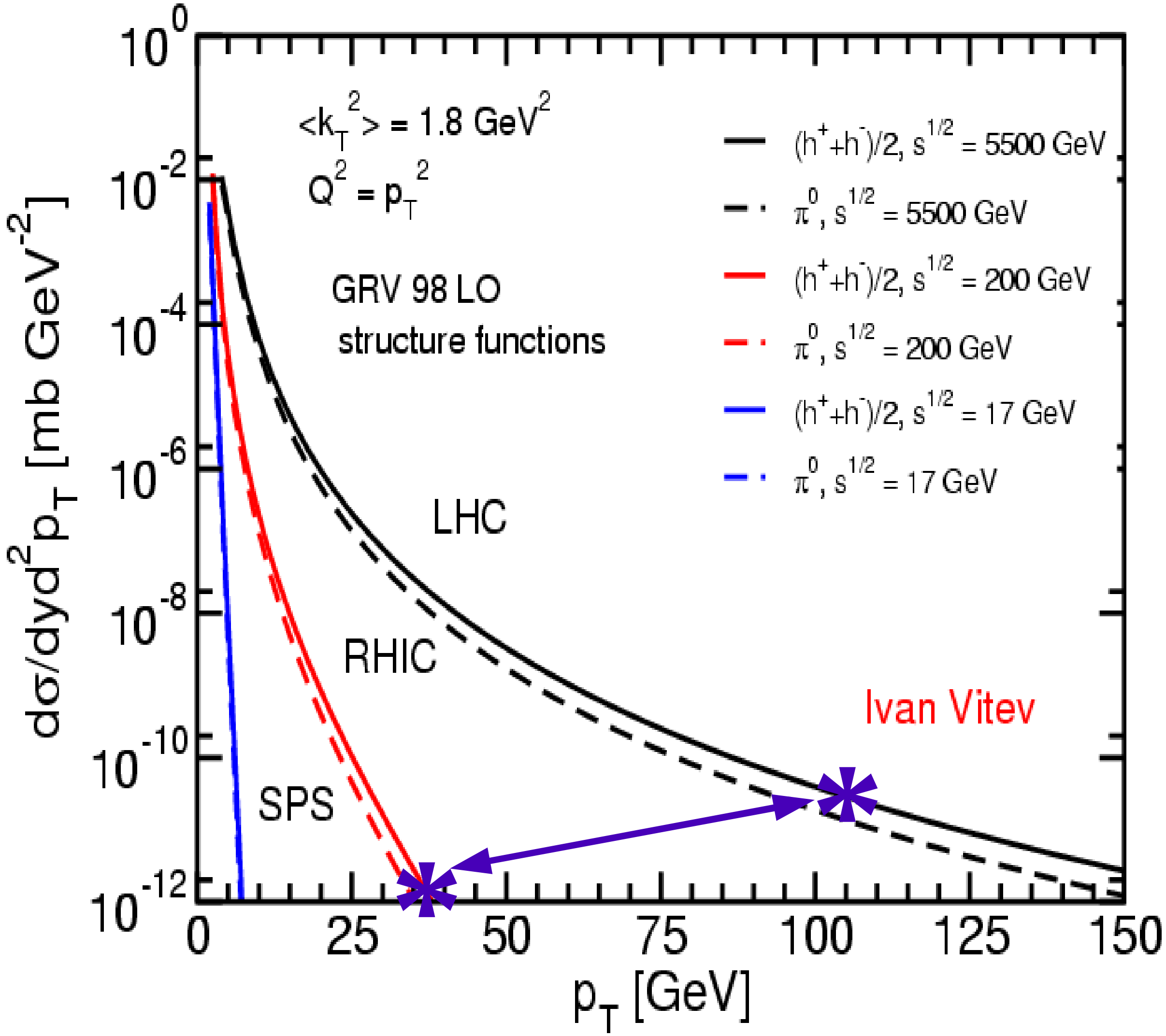


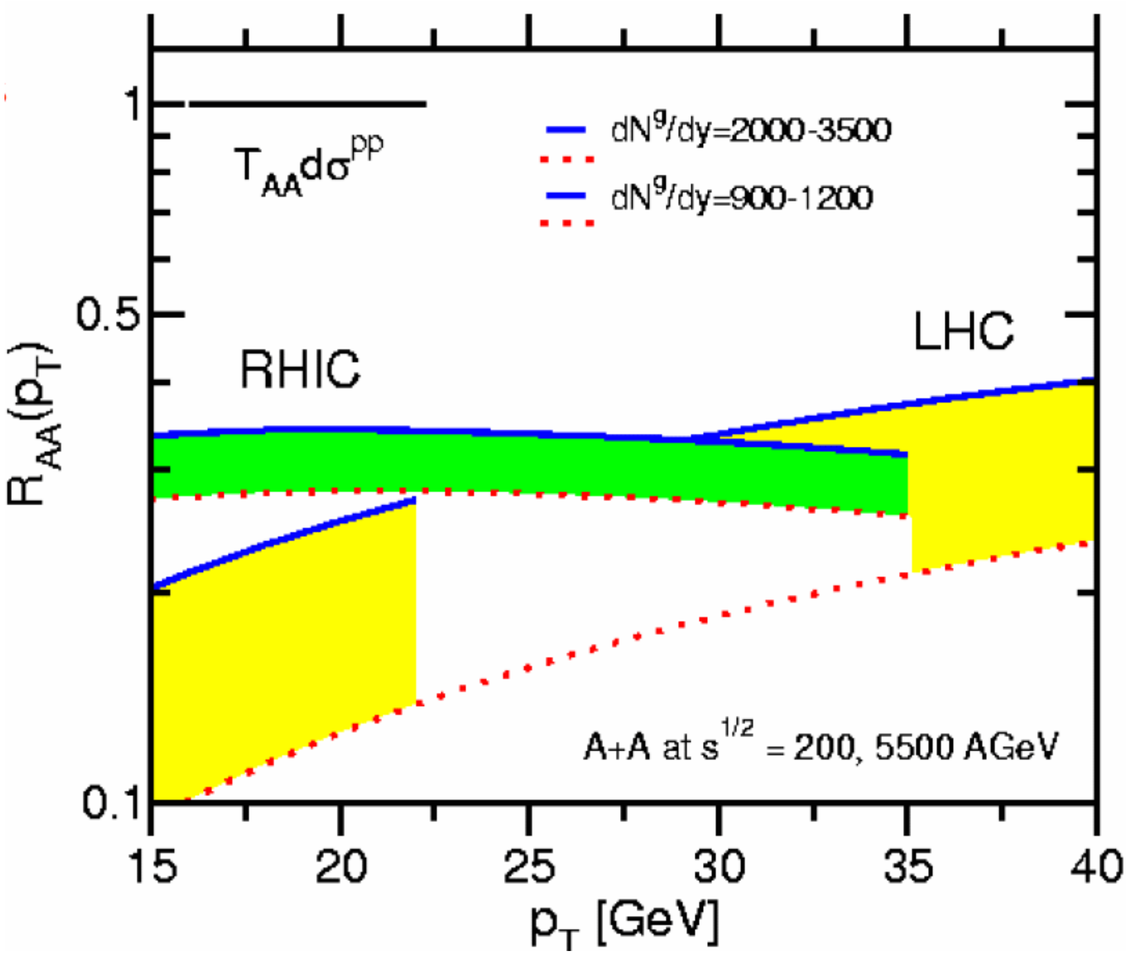
Conditions are different at RHIC and LHC

Different initial temperature gives ~ 3 times gluon density at LHC. High p_T at RHIC is dominated by quarks, but same p_T at LHC dominated by gluons.

Different underlying parton p_T spectrum produces this different R_{AA} behaviour.

RHIC and LHC give different handles, **and combine into a stiffer test of models of energy loss**.

From Ivan Vitev's talk at LHC satellite meeting, October 23, 2005.



Light vector meson dielectron physics at RHIC II

I do not (yet) have any quantitative estimates of yields for low mass dielectrons.

The basic measurements will be done at RHIC in the next few years, they do not require RHIC II luminosity.

But I think that the case will be made that RHIC II luminosity will make these measurements far more powerful. It may also allow lower energy measurements to be made with adequate luminosity.

Conclusions - RHIC II

RHIC II and the detector upgrades bring us dramatically expanded capabilities in heavy ion collisions, including:

• Separated open charm and beauty, R_{AA} and v_2 measurements to high p_T. Clean measurements of heavy quark energy loss.

• J/ψ R_{AA} to high p_T. J/ψ v_2 versus p_T. J/ψ $\langle p_T^2 \rangle$ vs centrality. Precise J/ψ rapidity dependence. All are strong tests of production models.

• Excited charmonium: $\chi_c \rightarrow J/\psi + \gamma$ and ψ' R_{AA}.

• Y R_{AA}. Which Upsilons are suppressed at RHIC?

• $B \rightarrow J/\psi$. Independent B yield measurement, background to prompt J/ψ.

• Jets tagged with γ, J/ψ, b, c, bb, cc - many clean handles on jet properties.

• Full jet reconstruction, studies of fragmentation of jets in medium.

• Clean measurements of light vector mesons, with high statistical precision, to probe chiral symmetry restoration effects.

and many others.

RHIC II / LHC Complementarity

RHIC II and LHC, because of their large difference in initial energy density and temperature, explore deconfined matter under substantially different conditions. **To be considered successful, models will have to describe data from both facilities.**

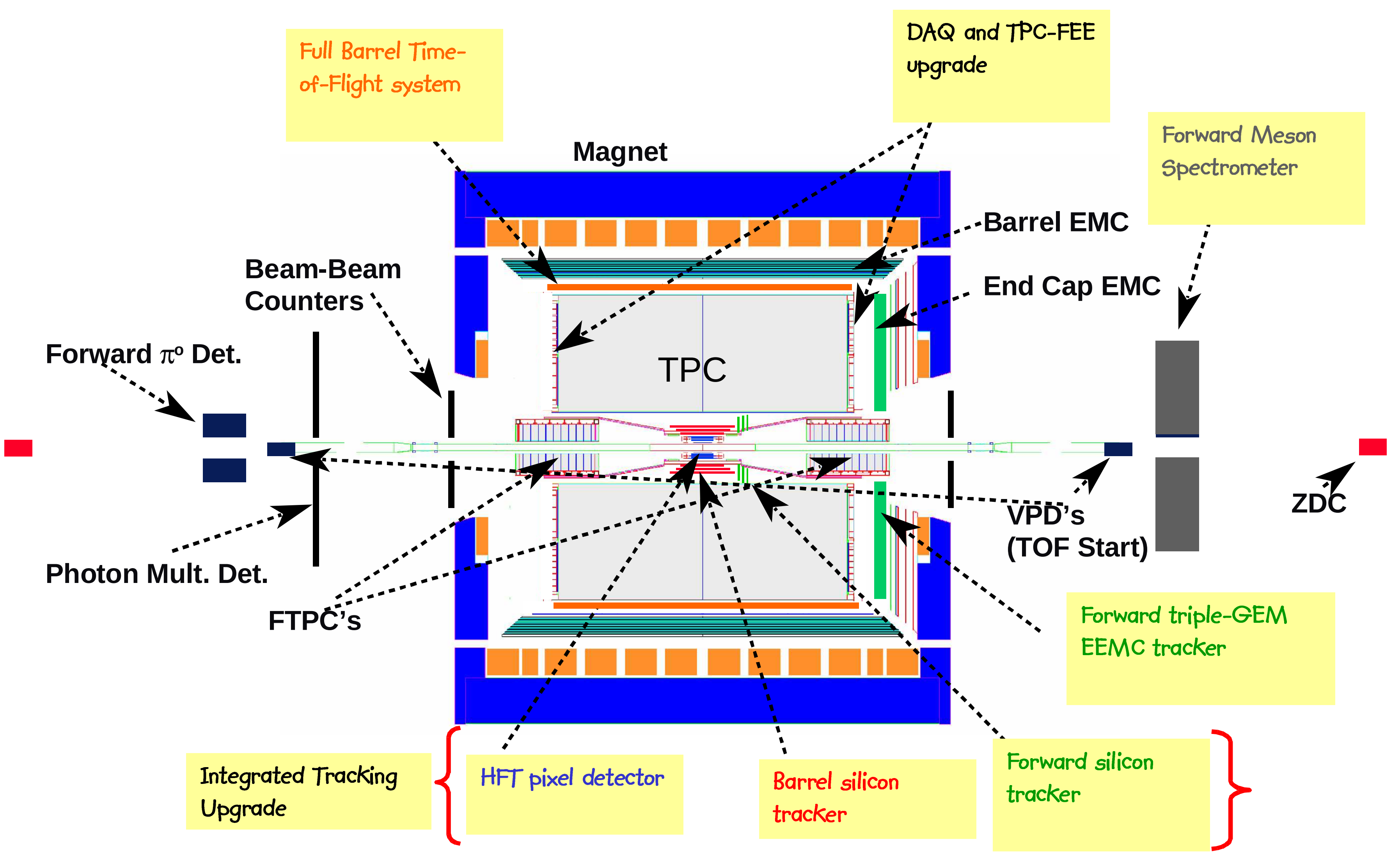
Although the heavy quark cross sections at LHC are much larger than those at RHIC, the much greater RHIC II integrated luminosities cause the heavy flavor yields **per year** to be similar at the two facilities.

The same is **not** true for jet yields. The LHC has far higher jet cross sections, and several times the p_T reach of RHIC II. But conditions are different, and that gives different handles on the physics. And some measurements are expected to be easier at RHIC II.

High precision studies of light vector mesons to look for effects of chiral symmetry restoration will be feasible at RHIC II. They will be very difficult, if not impossible, at LHC.

Backup slides

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