p-A Physics at the LHC

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1. **Overview and motivation**
2. **Physics issues**
3. **Practical considerations**
4. **Accelerator issues/performance**
5. **Jet rates**
6. **Summary**

See **http://wwwth.cern.ch/pAatLHC/pAworkshop2.html**
for program and slides for LHC p-A workshop in May

Why p-A @ LHC?

- Baseline
  - Show that effects observed in A-A are unique.
  - Calibrate “nuclear effects” in A-A
- Measure nuclear PDF’s at low x
  - Shadowing, leading twist vs higher twist
  - Saturation & color-glass condensate
- Study effects of multiple semi-hard scattering.
  - “Cronin” broadening (also saturation!)
- Test factorization (breakdown) in p-A
  - A-enhanced power corrections
- Study (final-state) interaction of various

p-A Collisions @ LHC

In summary, the pA program at the LHC serves a dual role. It is needed to calibrate the AA measurements for a sounder interpretation. It also has intrinsic merits in the framework of a more profound understanding of QCD (e.g. shadowing vs. diffraction, nonlinear QCD and saturation, higher twists...). Thus, one should foresee three key steps in this program: (1) (pp and) pPb runs with reliable determination of centrality at the same collision energy as PbPb interactions; (2) a systematic study of pA collisions, requiring a variety of collision energies and nuclei as well as a centrality scan; and (3) an interchange of p- and A-beams for asymmetric detectors. The expected physics output from measurements of hard and semi-hard probes in pA collisions at the LHC may be summarized as follows. We are able to

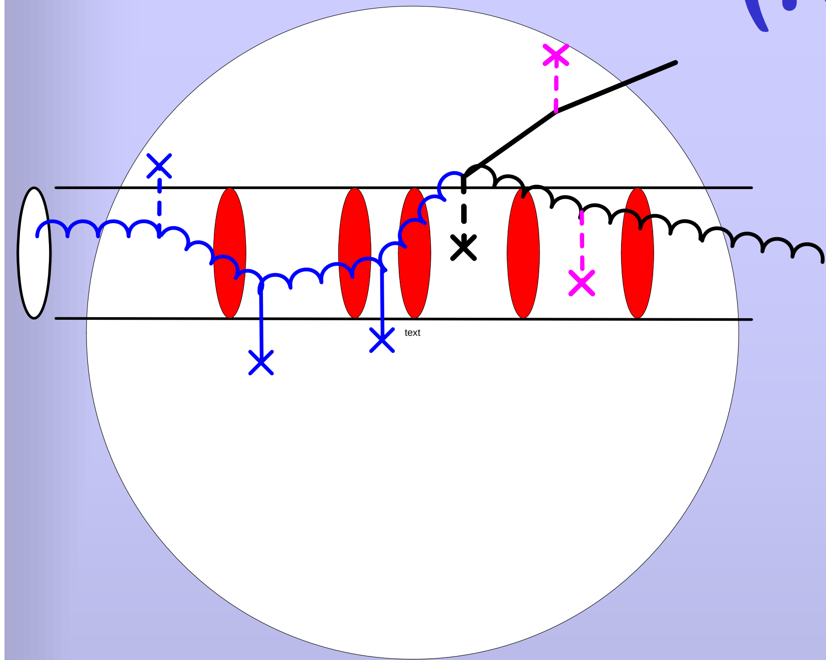
- test the predictive power of QCD perturbation theory in nuclear collisions by verifying the applicability of factorization theorems and the universality of the nPDFs through the hardest probes, only available at the LHC $\longrightarrow$ Secs. 3 and 5.
- measure the nuclear effects (internal to the nucleus) in the nPDFs over an unprecedented range of x and Q; investigate the interplay between the "EMC" effect, nuclear shadowing and saturation as well as the transverse-coordinate dependence of the nPDFs; and possibly, discover a new state of matter, the color glass condensate, by probing very soft gluons in heavy nuclei through the rapidity dependence $\longrightarrow$ Sec. 4.
- determine the nuclear dependence of the cross sections of the semi-hard probes in pA collisions and study QCD multiple parton scattering in nuclear matter and its corresponding dependences beyond the universal nuclear effects included in the nPDFs $\longrightarrow$ Sec. 6.
- extract excellent information on QCD dynamics in hadronization because normal nuclear matter acts like a filter for color neutralization and parton hadronization and explore potential new QCD phenomena in pA collisions, such as diffraction into three jets, double PDFs, etc. $\longrightarrow$ Sec. 7.
- use the hard and semi-hard probe cross sections as references for the QGP signals in AA collisions: the hard probes set the benchmark of the applicability of factorization while the semi-hard probes help to understand the size of the nuclear modifications not caused by the dense medium produced in AA collisions.

- **Summary of LHC "Yellow Report" on p-A**

p-A @ LHC: Not just a good idea …

- Particle production and hard scattering in A-A collisions dominated by low-x partons (gluons)
- Large gluon densities @ low x:
  - Large contributions from non-leading twist
  - Strong unitarity corrections to σ_{hard}
- BFKL evolution may dominate over DGLAP for moderate Q^2 (~ $[10\ \mathrm{GeV}]^2$) processes
- Initial conditions of Pb-Pb collisions will be determined by emission of multi-GeV gluons
  - Strongly affected by above (saturation, color-glass, ?)
- Even "hard" processes may be affected
- **Essential that we have p-A measurements to**

p-A @ LHC: Coherence (Naively)



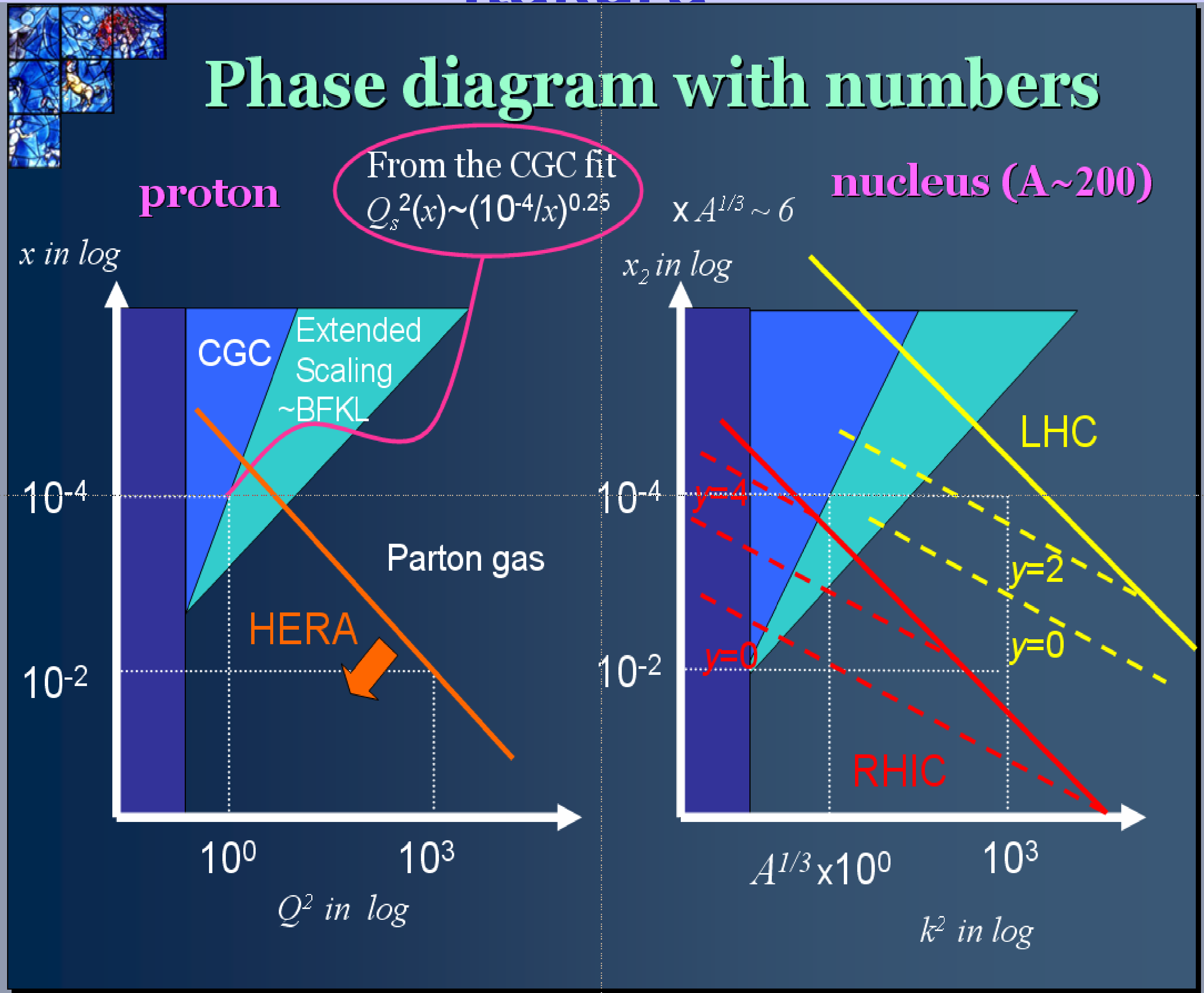
View in nucleus rest frame

- For mid-rapidity jet with M_T
  - Relative to nucleus, $\Delta y \approx 8$
  - $E \approx p_L = M_T \cosh(\Delta y) \approx 1500\, M_T$
  - Lorentz boost: $\gamma = \cosh(y) \approx 1500$
- Also, Jet formation time: $\tau \sim 1/m_T$
- Giving (jet) formation length (L_F)

$\Rightarrow L_F = 300\ \text{GeV fm} / m_T$

- From this simple analysis we can conclude:
  - Even for 100 GeV jet, formation length > nucleon spacing
  - For ~ 10 GeV jets, formation occurs over ~ full nucleus
    - So we should expect strong coherence effects
- But if we have ±5 units of acceptance we can change the formation length by factor of > 100!

Slide from QM 2005 Talk by K. Itakura

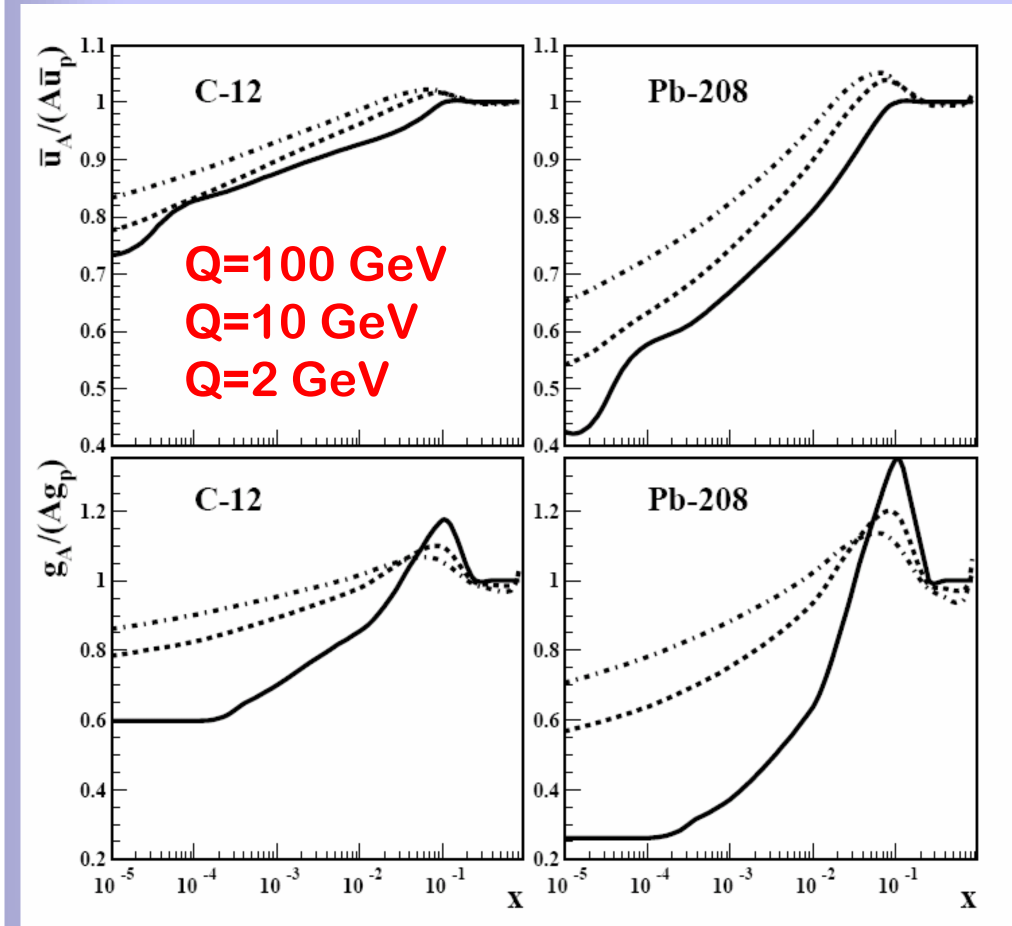


p-A @ LHC: Important Observables

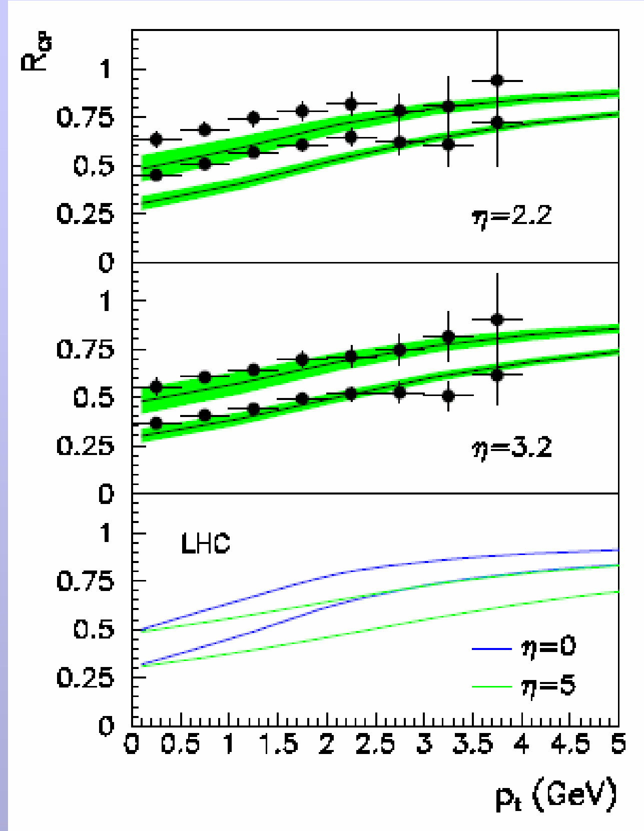
- Event properties: $dE_T/d\eta$, $dN_{chg}/d\eta$, …
- Single Jet production:
  - Rates: $d^2N/d\eta dE_T^{jet}$ min-bias and vs centrality
  - Fragmentation: D(z), hadron J_T, sub-jets
  - Above for b-tagged jets
  - How low in E_T can we go?
- Direct γ, Z, W production: $d^2N/d\eta dp_T$
- Di-jets/γ-jet/Z-jet/di-γ:
  - Rates vs E_{T1}/E_{T2}, (η_1, η_2)
  - Angular distributions $(\Delta\phi)$
- Heavy flavor: open charm, single leptons,

Low-x Effects @ LHC

Frankfurt, Guzey, Strikman:
Leading twist Shadowing



Armesto, Salgado, Wiedemann,
Phys. Rev. Lett. 94:022002 (2005)

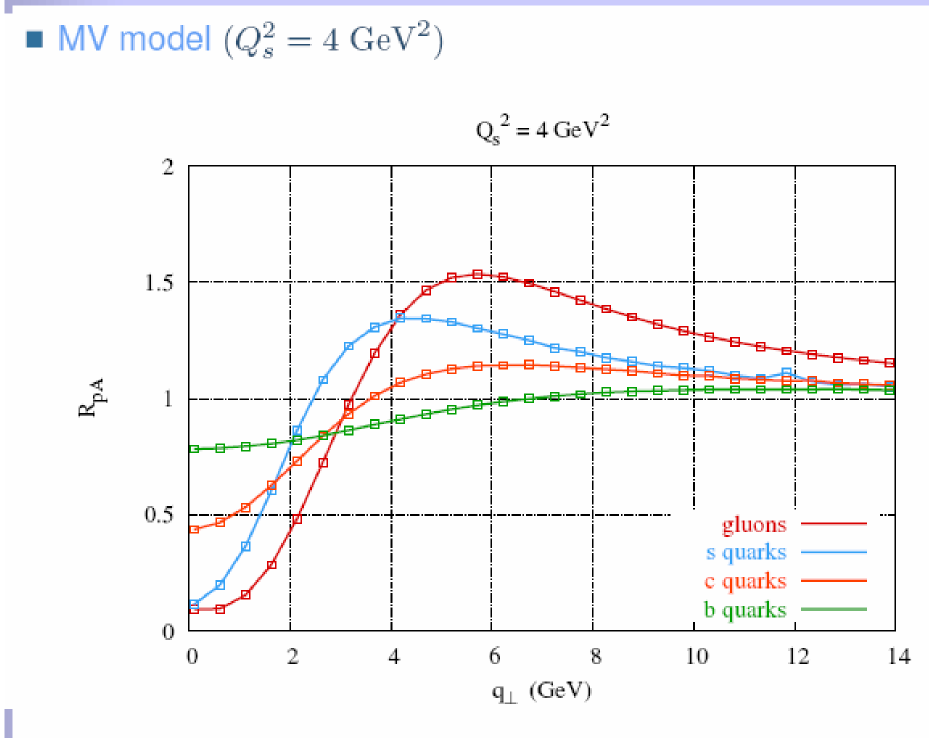


- **Measurable shadowing even at 100 GeV.**
- **Modest effects at mid-rapidity (but going away slowly)**

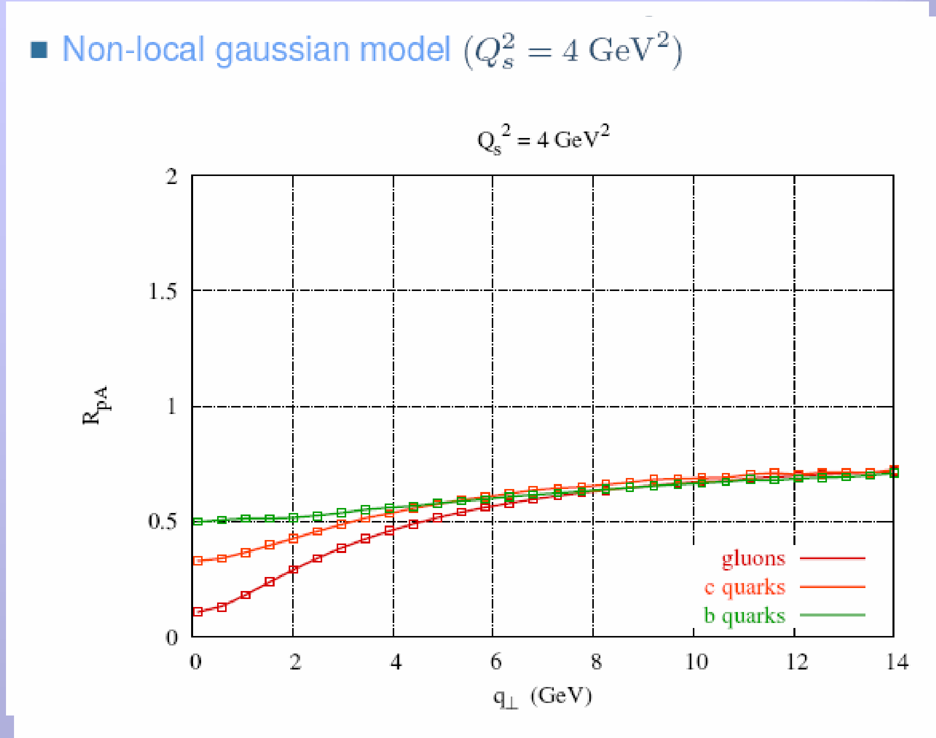
Saturation: Heavy Quark Production

F. Gelis, LHC: p-A workshop

Broadening Only



Including Quantum Evolution

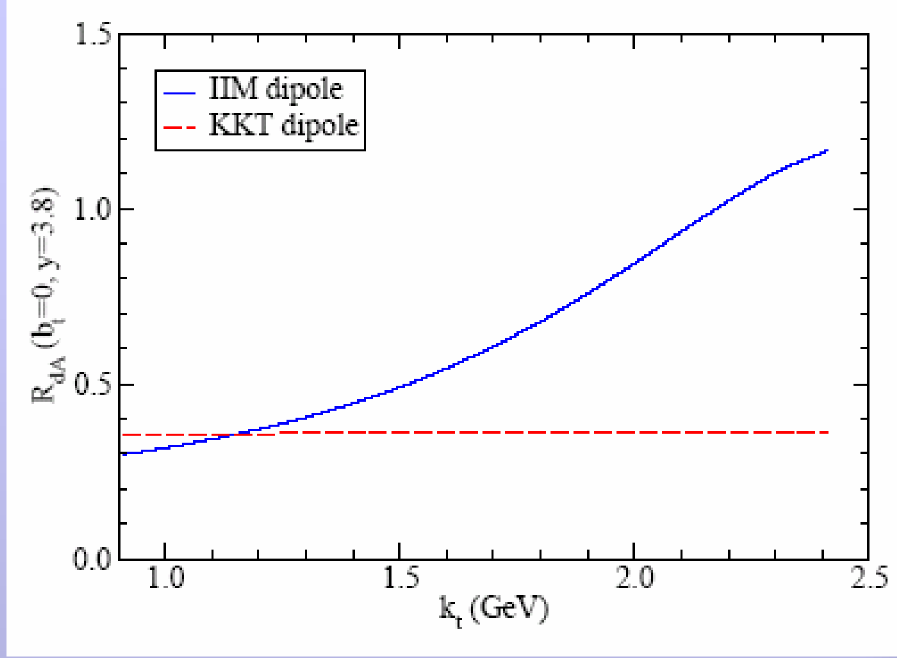


- **MV saturation produces large Cronin effect**
- **But incorporation of BFKL evolution:**
  - **Kills Cronin effect**
  - **Suppressed quark/gluon yields over large p_T range**

Direct Photon Production

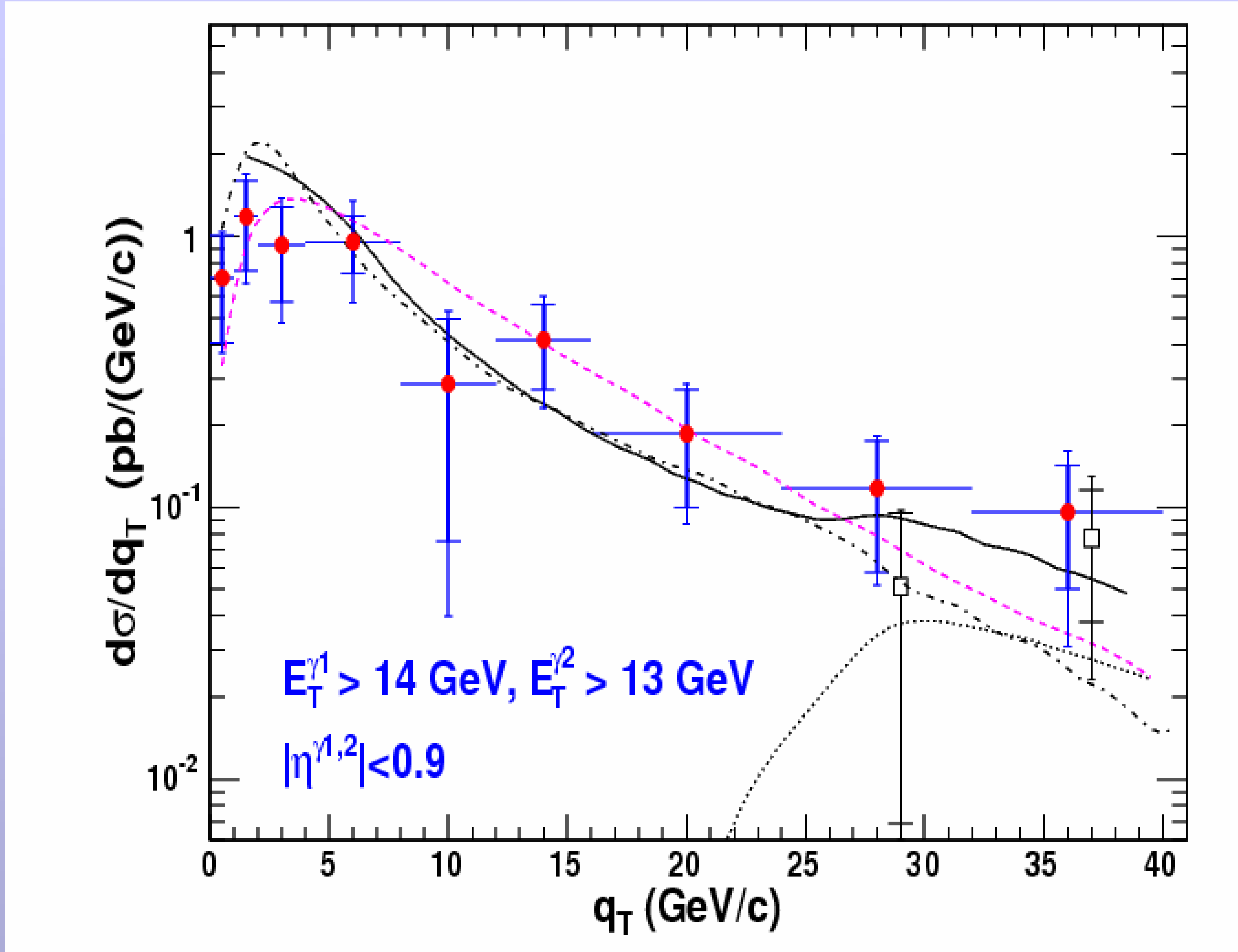
- k_T broadening, evolution of parton distributions will modify prompt γ spectrum.
- Calculation for forward prompt γ @ RHIC
- If there are mono-jets, are there mono-photons??

J. Jalilian-Marian, hep-ph/0501222



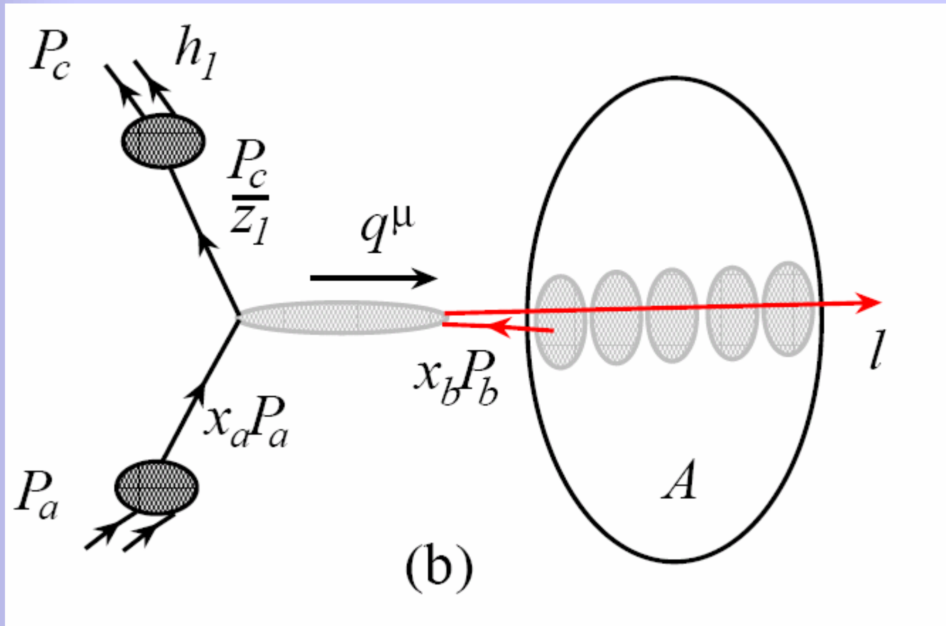
- γ-jets more sensitive than di-jets to initial state because less broadening from jet.
- di-γ production even more interesting – kinematics completely determined.
  - Need good photon isolation!

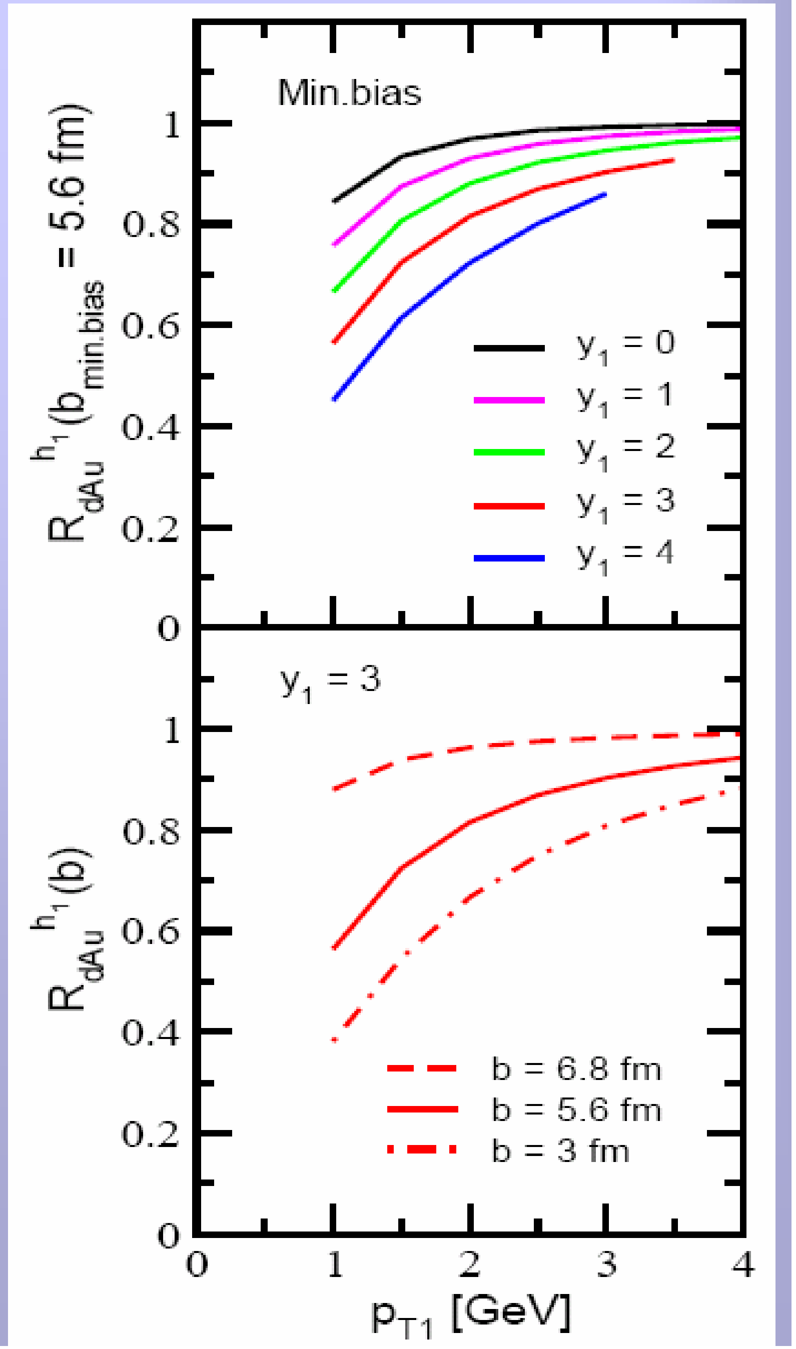
Example: $\gamma\gamma$ from CDF



- Cross-section is small (< 10^{-4} of di-jet)
- But even 10^{-5} of di-jet rate is OK (below)

Vitev and Qiu: Higher Twist





- **"Higher Twist":**
  - **multiple exchanges between projectile & target.**
- **Vitev & Qiu: coherent multiple scattering**
  - **Effective rescaling of x of parton from deuteron.**

p-A in LHC: Jowett @ p-A Workshop

Summary and Outlook

- p-Pb upgrade of the LHC appears feasible.
  - Some, but not all, of the Pb-Pb problems
  - Some, but not all, of the p-p problems
  - Some specifically p-Pb beam dynamics problems deserve further study.
  - Modest investment in LHC Main Rings hardware
- d-Pb only slightly easier (from Main Ring beam dynamics point of view) but would require investment
  - See talk on injector chain by C. Carli
- p-(lighter A) seems not to be more difficult than p-Pb.
- Priorities and planning to be promulgated.
- Some experience with the LHC will clarify many things!

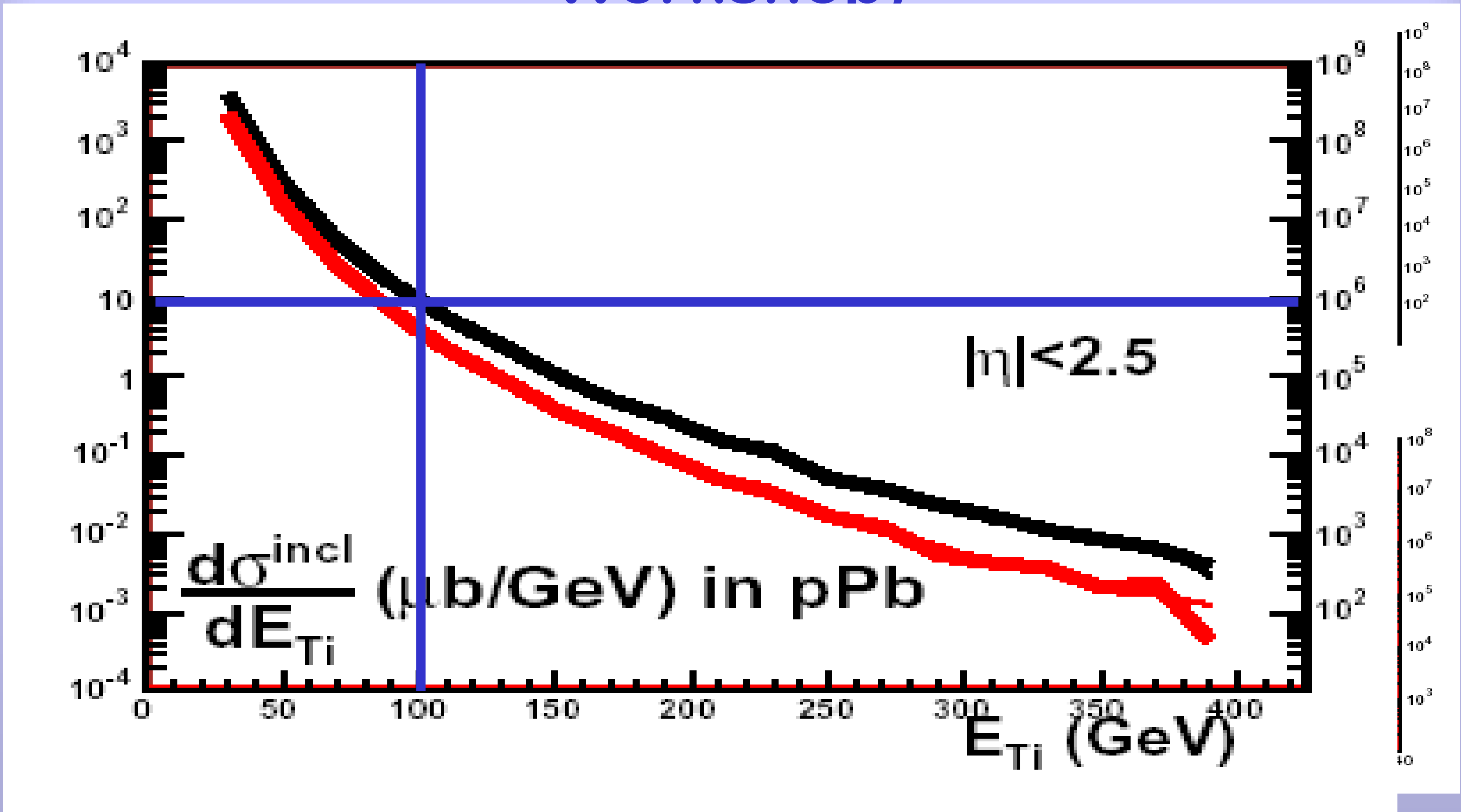
p/d/A-A Collision Energies

From Jowett's talk @ LHC p-A workshop

	p-p	Pb-Pb	p-Pb	d-Pb
E / TeV	7	574	(7,574)	(7,574)
E_N / TeV	7	2.76	(7,2.76)	(3.5,2.76)
$\sqrt{s}$ / TeV	14	1148	126.8	126.8
$\sqrt{s_{NN}}$ / TeV	14	5.52	8.79	6.22
y_{CM}	0	0	2.20	2.20
y_{NN}	0	0	-0.46	-0.12

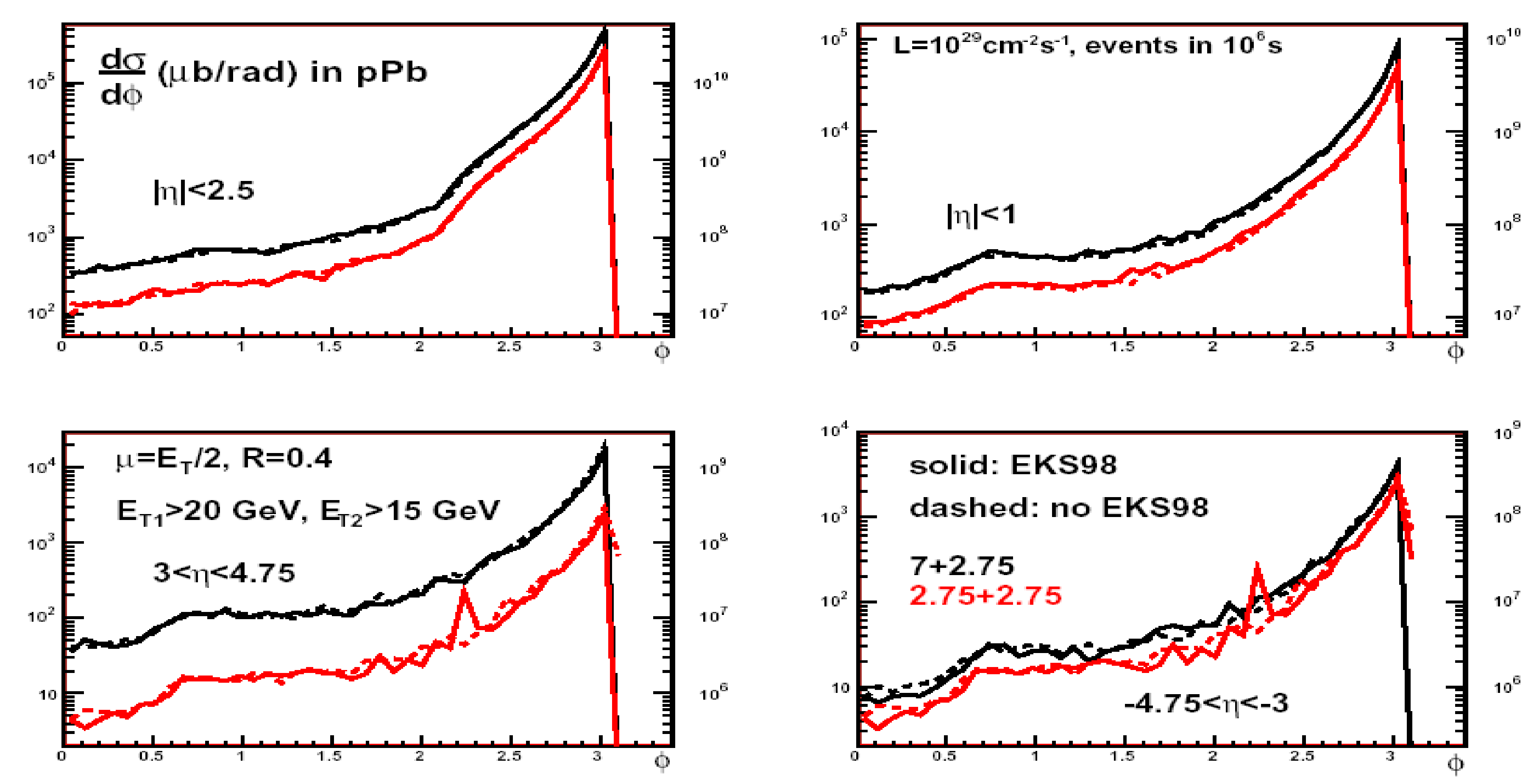
- **Due to LHC magnet design (shared field)**
  - **beams must operate @ equal rigidity**
  - **y_{NN} shifted by ≈ ½ unit in proton direction**
- **Nominally, different energies for p-p, p-A, A-A**
- **p-Pb Luminosity: ~ 1.5×10^{29} $cm^{-2}s^{-1}$ (higher?)**

Jet Rates (Armesto @ LHC p-A Workshop)



- Rate estimates (right scale) for $L = 1.5\times10^{29}$ $cm^{-2}s^{-1}$ and 10^6 s (~ 3 weeks @ 50% efficiency)
- ~ million jets above 100 GeV in |η|<2.5 in one LHC run

Jet Pair Rates (Armesto)

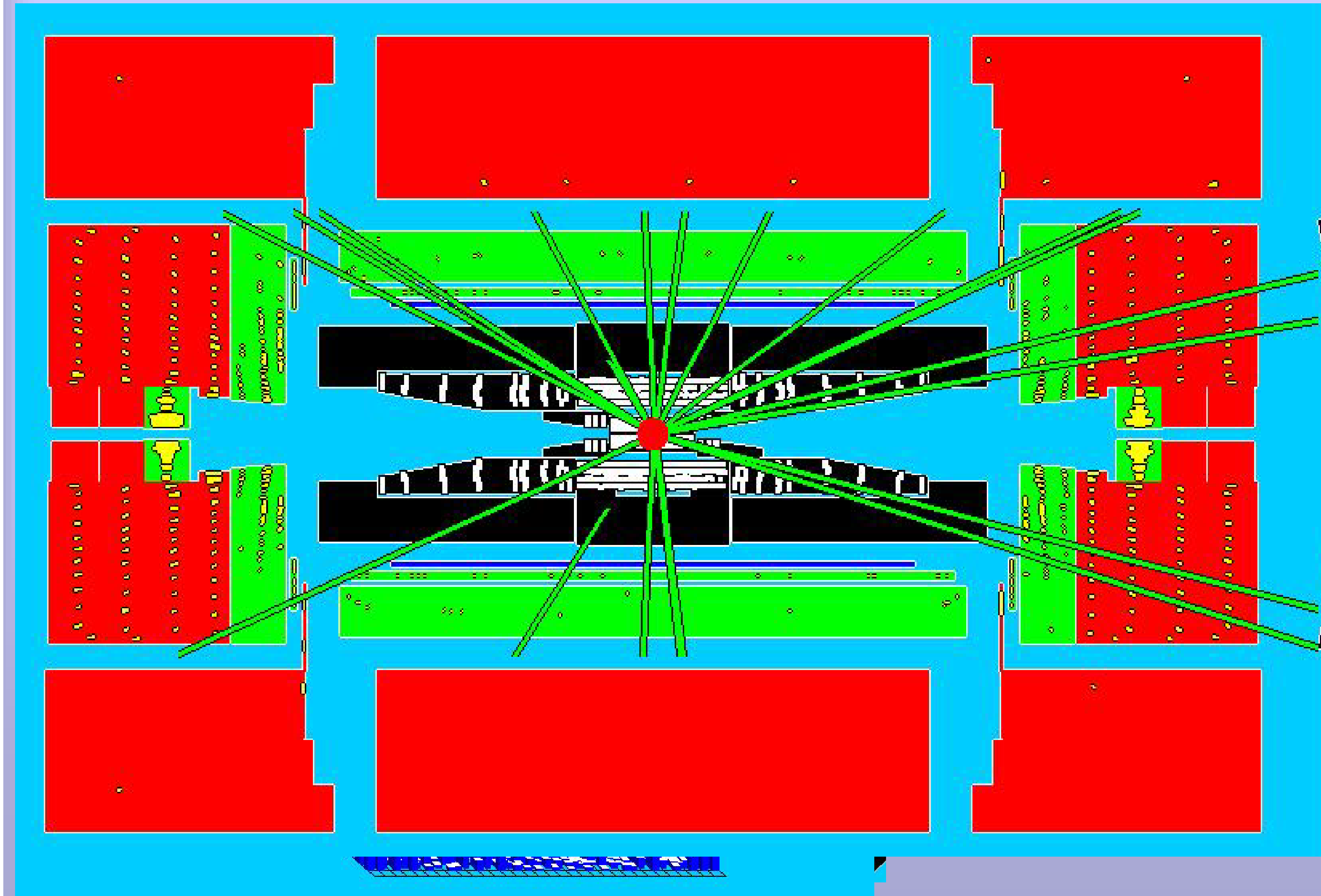


- Differential yield of jet pairs vs $\Delta\phi$ (p_{T1} > 20, p_{T2} >15)
  - Very little scale sensitivity
  - Very little sensitivity to nuclear PDF
- Rates are enormous (10 million w/ $\Delta\phi$ < 1 in

p-A Collisions: Soft "Background"

- **Some numerology:**
  - @ LHC energies, p-Pb collisions $\langle \nu \rangle \sim 7$
  - Due to coherence (wounded-nucleon scaling) $\langle \nu \rangle \sim 7 \rightarrow$ 4 times soft multiplicity (on average)
  - In p-p @ high-luminosity, ~ 25 collisions/crossing
  - Typical p-Pb collision has 1/6 the soft background of high-luminosity p-p collision.
- **Conclusion: for high-p_T measurements p-Pb detector performance better than p-p.**
- **Beware: this argument neglects rapidity dependence of soft p-Pb/p-p.**
  - Observe: best performance in low X_A direction.

Simulated (& Recon) Hijing p-Pb Event #2



- **Jet at forward (actually backward) rapidity**

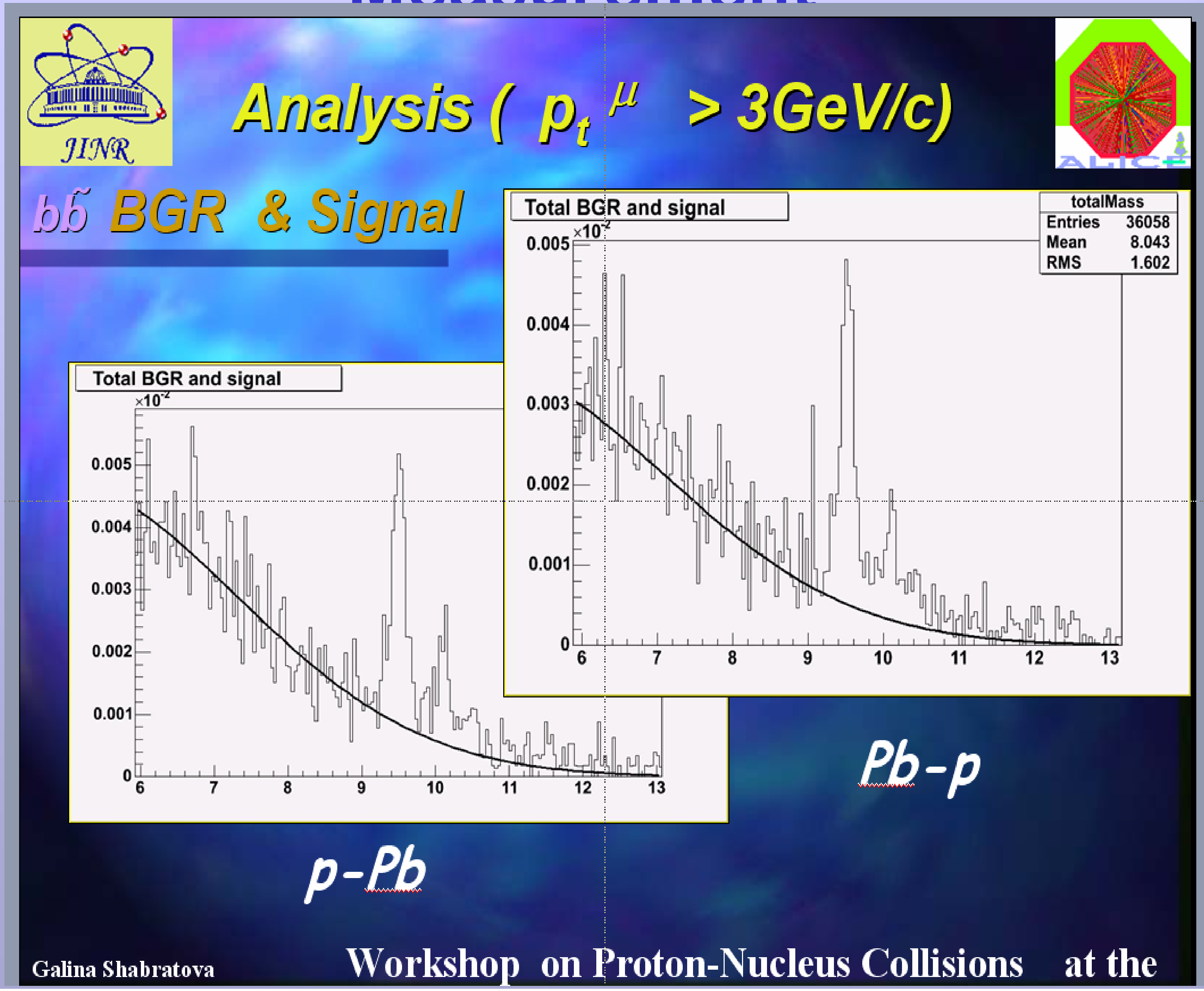
Centrality Measurement

- Problem w/ centrality measurement:
  - Measurements at mid-rapidity are biased
    - By hard processes
    - By the very low-x physics we want to study
  - At RHIC, measurements @ $|\eta| > 3$ are “safe”
    - Hard processes suppressed by phase space.
  - How far out in η is “safe” at LHC (6, 7, 9?)
- Zero-degree calorimeter(s) are useful
  - But evaporation neutron yield saturates.
  - Can distinguish peripheral from central but …
- p-A Centrality determination @ LHC needs careful study by all experiments.

Summary

- p-A collisions @ LHC provide laboratory for studying:
  - Strong field effects in QCD
  - Long-range evolution in QCD
  - Strong coherence in QCD scattering processes
  - Approach to unitarity limit in QCD scattering.
- This physics is all there in Pb-Pb collisions
  - We had better understand it.
- It is interesting in its own right !
- p-A @ LHC is an “upgrade”
  - But it is VERY likely to happen (> 2010?)
  - Much work is needed to study expt.

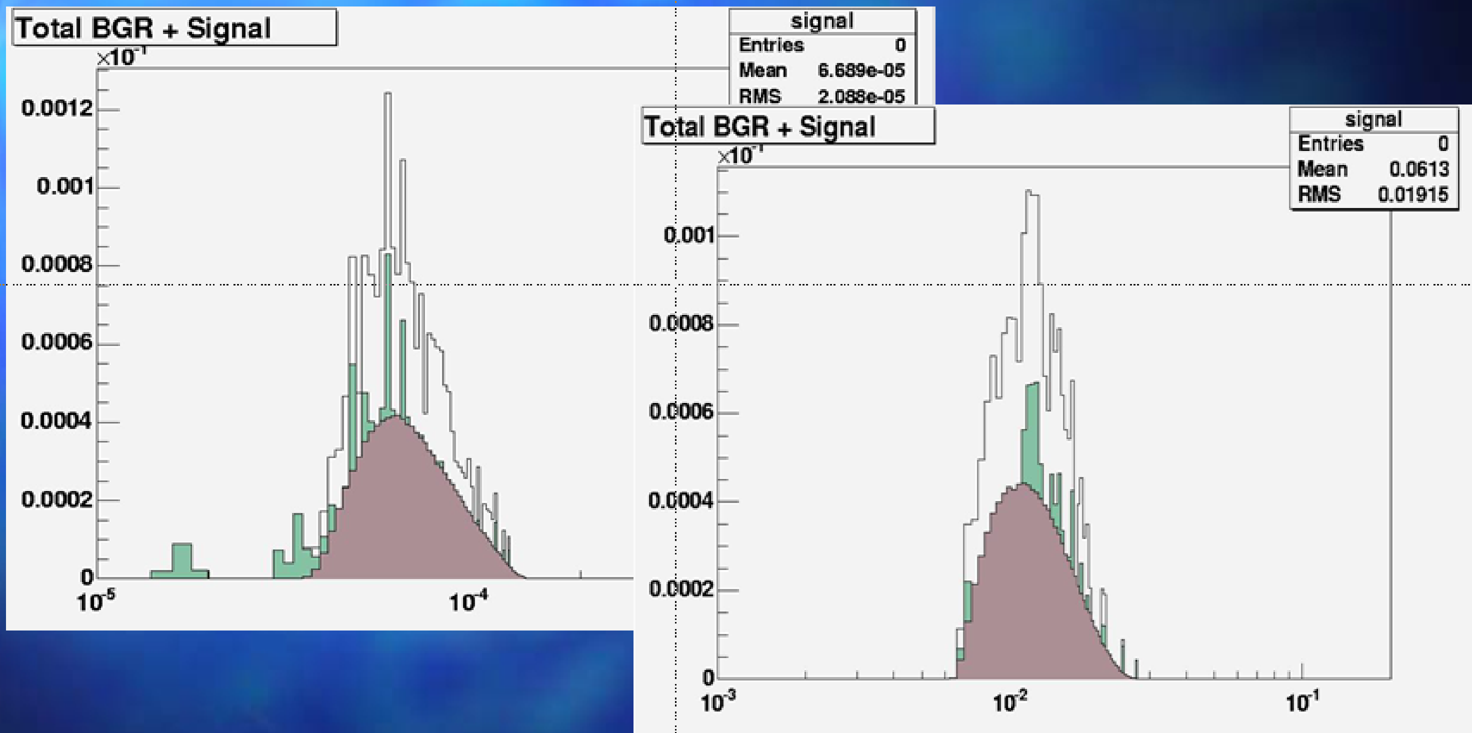
Alice: Forward Upsilon Measurement



Alice: Forward Upsilon x coverage

x_1 , x_2 at p_t^{μ} > 3GeV/c & 9.2 GeV<M_{eff}<10.7 GeV

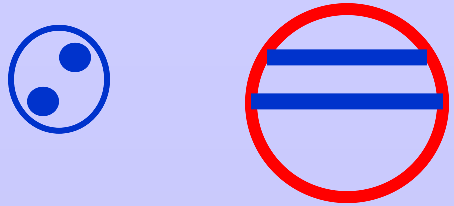
x_1 x_2



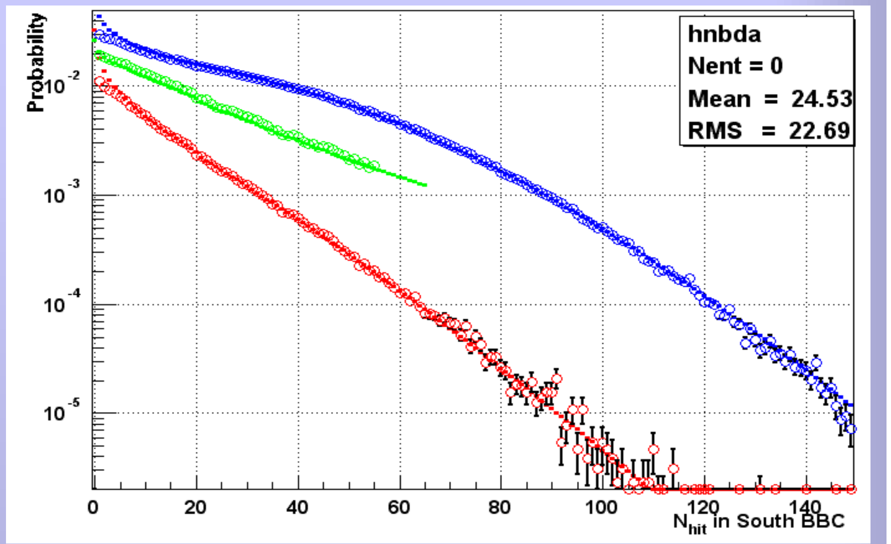
Pb-p

d-Au "Centrality"

- # soft scatters of n/p:
  - $\nu_{n/p} = T_{Au}(b_{n/p})\sigma_{NN}$



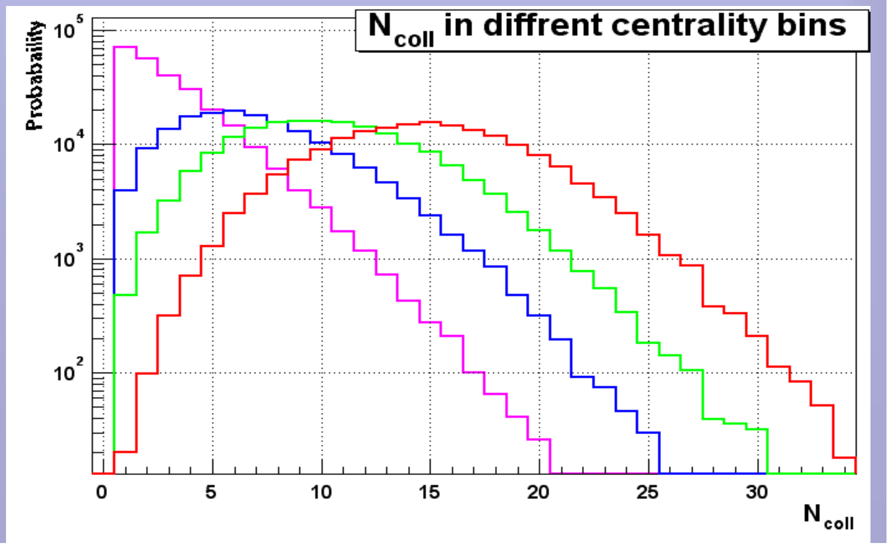
- **Parameterize multiplicity at large η vs ν_n, ν_p.**
  - Cut data according to fraction of total σ_{dA}.
  - For each, determine T_{dAu}
  - e.g for PHENIX (in %)
    - 0-20, 20-40, 40-60, 60-88



- Define:

$$R_{dA} = \frac{1}{T_{dA}} \frac{dn^{dA}_{hard}}{dp^2_\perp} \Big/ \frac{d\sigma^{NN}_{hard}}{dp^2_\perp}$$

$$R_{cp} = \frac{T^{periph}_{dA}}{T^{cent}_{dA}} \frac{dn^{cent}_{hard}}{dp^2_\perp} \Big/ \frac{dn^{periph}_{hard}}{dp^2_\perp}$$



Centrality in d(p)-A

- The ability to select on centrality in d(p)-A collisions is NEW and very important.
- Potentially the first opportunity to measure the impact parameter dependence of:
  - Initial-state broadening, Shadowing, …
- Observations of centrality dependence have already been important.
- But, there are some limitations:
  - Rely on Glauber model to indirectly relate "centrality" observables to impact parameter.
  - Kopeliovich: Flaw in Glauber models due to neglect of diffraction – which I think is a real issue.
  - May be important for understanding R_{CP}.

Di-jet / γ-jet / γ-γ Acoplanarity (2)

- d-A measurements @ RHIC limited by
  - Luminosity and Acceptance
- Both of these limitations are removed in (e.g.) ATLAS @ LHC
- Isolate initial-state radiation effects (modified in p-A) by comparing:
  - Di-jets, (isolated) γ -jets, (hard) di-photon
- Prediction from saturation:
  - "disappearance" of di-jet signal at $p_T \sim Q_s$
  - But, presumably measurable (calculable?) effects at higher p_T?? (precision vs "discovery")

p-A in ATLAS: Studies Needed

- Basically everything ! But specifically:
  - Real simulations of mult. and E_T measurement
  - Centrality determination.
  - Forward jet measurement @ moderate p_T
  - Measurement of < 20 GeV jets at mid-rapidity.
  - γ isolation efficiency and rejection vs p_T
  - Analysis of γ-jet kinematic (x_1, x_2) reconstruction
  - Sensitivity to changes in di-jet/ γ-jet/ … acoplanarity.
  - Double b-tag efficiency, rate (moderate p_T).
  - Jet overlap, double parton scattering events.
  - …