CGC 2013 - A PERSPECTIVE.

Alex Kovner

University of Connecticut

p-A COLLISIONS A NATURAL HABITAT FOR SATURATION.

SO IS IT THERE? IS IT NOT THERE? CAN WE EVEN TELL IF IT IS THERE?

A WONDERFUL AND SIMPLE IDEA

IN A DENSE SYSTEM (HADRON OR NUCLEUS) THE AVERAGE DENSITY OF PARTONS (OR FIELDS OR WHAT NOT...) DEFINES A TRANSVERSE SCALE $Q_S^2 \propto \rho$.

AT DISTANCE SCALES $\Delta x^2 < Q_S^{-2}$ THE SYSTEM IS DILUTE PARTONIC: GLUON DENSITY AT HIGH MOMENTUM $\Phi(k) \propto 1/k^2$ (up to logarithmic corrections)

AT LOW RESOLUTION SCALES $\Delta x^2 > Q_S^{-2}$ THE SYSTEM IS SATURATED. THERE ARE MUCH LESS GLUONS THAN PERTURBATIVE EXPECTATION: AT $k < Q_S$, $\Phi(k) \propto const$, OR MAYBE EVEN $\Phi(k) \propto k^2$.

Q_S IS ALWAYS THERE - EVEN FOR A PROTON AT REST, BUT $Q_s^2 \sim 0.04 Gev^2$ - NONPERTURBATIVELY SMALL AND SATURATED REGIME IS INTRACTABLE.

BUT IT GROWS WITH ATOMIC NUMBER AND WITH ENERGY $Q_S^2 \propto A^{1/3} s^{\# \alpha_s}$

SO NATURALLY THE BEST WAY TO GET INTO "'PERTURBATIVE SATURATION REGIME"' (CGC ?) IS TO PROBE HEAVY NUCLEUS AT HIGH ENERGY.

TO MINIMIZE STRONG FINAL STATE EFFECTS THE PROBE BETTER BE SMALL, SO IN THE ABSENCE OF e-A MACHINE, THE BEST REACTION IS p-A.

WHAT DO WE EXPECT FORM CGC?

WITH WHAT LEVEL OF ACCURACY CAN WE CALCULATE INTERESTING OBSERVABLES?

MULTIPLICITES

k_T **SPECTRUM AND** R_{pA}

TWO PARTICLE CORRELATIONS - "THE RIDGE"

MULTIPLICITIES

THE SIMPLEST OBSERVABLE. ROUGHLY SPEAKING PROPORTIONAL TO THE SATURATION MOMENTUM

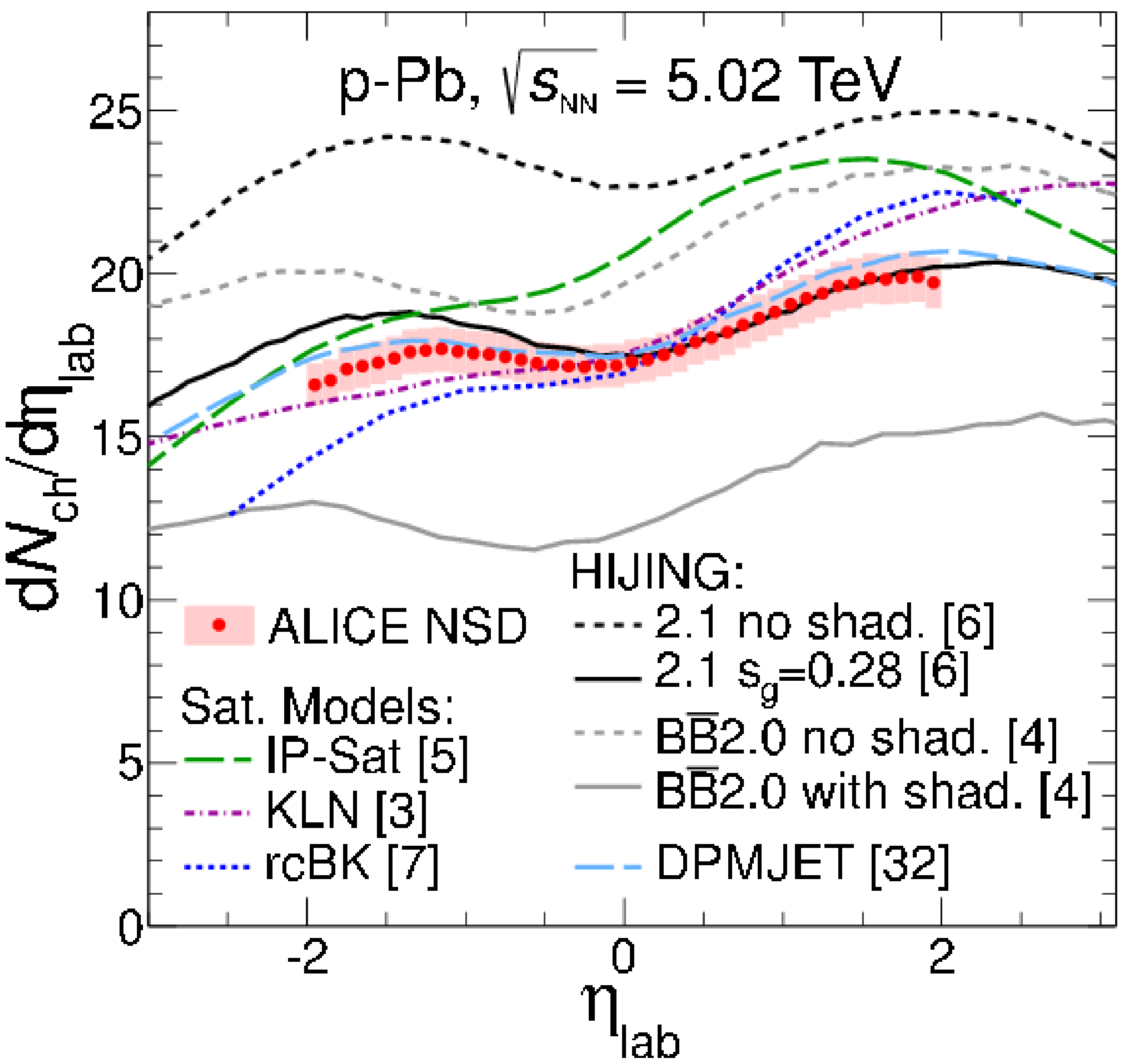
$$\frac{dN}{dy} \propto \frac{1}{\alpha_S(Q_S^2)} S Q_S^2 \times ln \frac{Q_S^2(1)}{Q_S^2(2)}$$

ASSUMES $\phi(k) \sim const; \quad k < Q_S$ AND k_T FACTORISED GLUON PRODUCTION, AND LOCAL GLUON-HADRON DUALITY - KLN MODEL

Q_S DEPENDS ON ENERGY, RAPIDITY AND CENTRALITY

$$Q_S^2 = Q_0^2 N_{part} \left[x_0 \frac{W}{Q_0} e^{\pm y} \right]^{\lambda}; \qquad Q_0 = 0.6\ Gev; \quad x_0 = 0.01; \quad \lambda = 0.205$$

THIS SIMPLE INPUT PLUS SOME MODELLING AT $x \to 1$ PLUS GLAUBER MONTE CARLO FOR FLUCTUATIONS OF N_{part} AND THEREFORE Q_S OF Pb PRODUCES VERY COMPELLING RESULTS.


p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
$dN_{ch}/d\eta_{lab}$
η_{lab}
0
5
10
15
20
25
-2
0
2
ALICE NSD
Sat. Models:
IP-Sat [5]
KLN [3]
rcBK [7]
HIJING:
2.1 no shad. [6]
2.1 s_g=0.28 [6]
$B\bar{B}$2.0 no shad. [4]
$B\bar{B}$2.0 with shad. [4]
DPMJET [32]

rc BK AND FRIENDS

BUT ONE WANTS TO DO MORE AND TO DO IT BETTER.

IN PRINCIPLE WE DO NOT HAVE TO MODEL THE DEPENDENCE OF Q_S ON W AND y. THIS DEPENDENCE SHOULD FOLLLOW FROM THE QCD EVOLUTION: BK/JIMWLK EQUATION.

LAST SEVERAL YEARS "rcBK" APPROACH HAS BEEN DEVELOPED AND VIGOROUSLY APPLIED.
ONE CHOOSES A "REASONABLE" INITIAL CONDITION FOR $\Phi(k)$ AT INITIAL x_0 AND EVOLVES IT IN RAPIDITY WITH THE BALITSKY-KOVCHEGOV EQUATION, WHERE THE COUPLING CONSTANT RUNS AT THE SCALE CHOSEN TO MINIMIZE SOME NEXT TO LEADING ORDER CONTRIBUTIONS.

NEED TO CHOOSE INITIAL CONDITIONS.

$$N(r,x_0) = 1 - \exp\Big[-\frac{(r^2 Q^2_{0S,\ proton})^\gamma}{4}\ln(\frac{1}{\Lambda r})\Big]; \qquad \Phi(k) \propto \frac{1}{\alpha_s(k)} k^2 N(k)$$

PARAMETERS Q_{0s} AND γ ARE CONSTRAINED TO A DEGREE BY FITS TO **DIS HERA** DATA (ANOTHER ADJUSTABLE PARAMETER OR TWO IN α_S)

NEED TO MODEL THE Q_S OF NUCLEUS.

TWO BASIC APPROACHES:

1. THE SIMPLEST IS FIX ONE $Q_{0S,\ nucleus}$ AND SOLVE BK EQUATION WITH THIS INITIAL CONDITION (REZAEIAN also TRIBEDY-VENUGOPALAN).

2. MORE ELABORATE: GLAUBER MONTE CARLO FOR DISTRIBUTION OF NUCLEONS IN THE NUCLEUS YIELDS TRANSVERSE POSITION DEPENDENT Q_S. CALCULATE PARTICLE PRODUCTION LOCALLY IN b AND INTEGRATE OVER b IN THE END (ALBACETE, DUMITRU, FUJII, NARA)

FINALLY: HOW DO WE CALCULATE HADRON PRODUCTION?

1. k_T FACTORIZATION:

$$\frac{dN}{dy d^2p_T d^2R} \propto \frac{1}{p_T^2}\int d^2k_T \int d^2b \alpha_S(Q)\Phi_P(k_T,x_1,b)\Phi_T(p_T-k_T,x_2,R-b)$$

R-NUCLEAR IMPACT PARAMTER, b TRANSVERSE COORDINATE IN THE PROTON. AT HIGH P_T CONVOLUTED WITH GLUON FRAGMENTATION FUNCTION. THIS IS DERIVED FOR PRODUCTION OF SOFT GLUONS - FAR IN RAPIDITY FROM VALENCE PARTONS.

2. FOR MORE FORWARD RAPIDITIES - HYBRID FORMALIZM:

$$\frac{dN}{d\eta d^2k} = \left[\frac{dN}{d\eta d^2k}\right]_{elastic} + \left[\frac{dN}{d\eta d^2k}\right]_{inelastic}$$

$$\left[\frac{dN}{d\eta d^2k}\right]_{elastic} \propto \Sigma_{q,g} x_1 f_{q,g/p}(x_1) N_{q,g}(x_2,k_T)$$

$$\left[\frac{dN}{d\eta d^2k}\right]_{inelastic} \propto \alpha_S(Q)\frac{1}{k^4}\int d^2p\, p^2 N(x_2,p)\int \frac{d\zeta}{\zeta}\omega_j(\zeta) f_j(\frac{x_1}{\zeta},Q^2)$$

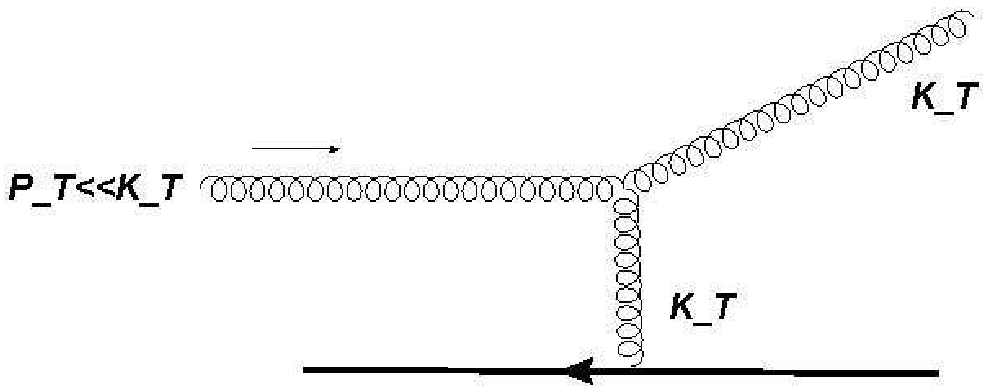


Figure 1: Elastic contribution to particle production.

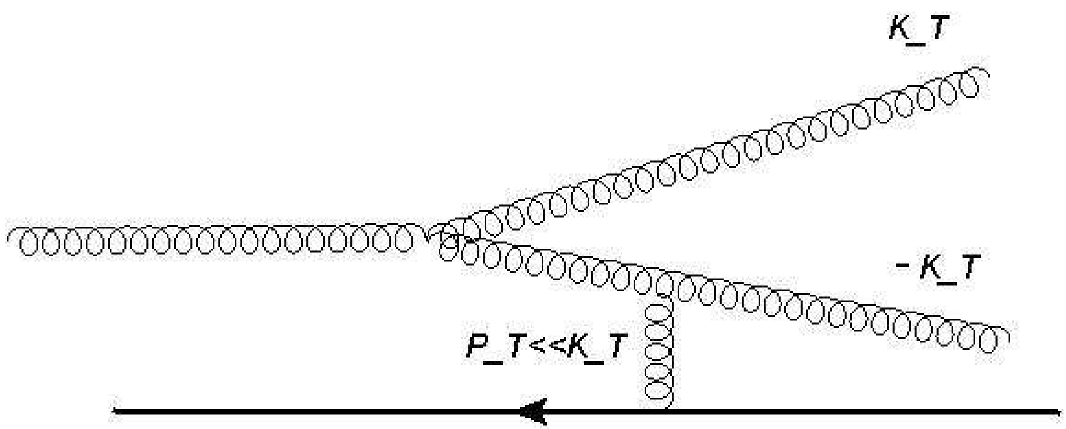


Figure 2: Inelastic contribution to particle production.

INELASTIC CONTRIBUTION FORMALLY A PERTURBATIVE CORRECTION, BUT IS OF THE SAME ORDER AS DGLAP EVOLUTION OF PARTONIC DISTRIBUTIONS IN THE ELASTIC PART.

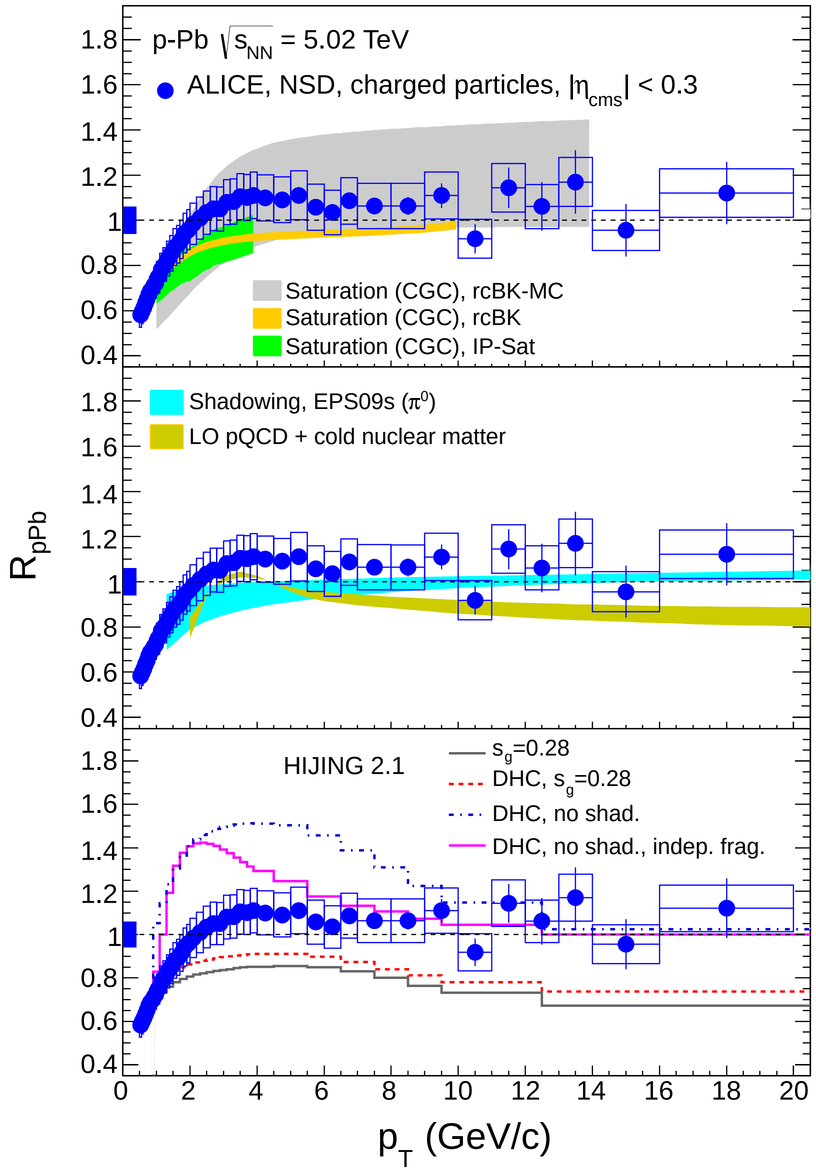


Figure 3: ALICE data: NO CRONIN PEAK (check), SUPPRESSION UP TO 2 Gev (check), VERY FLAT $R_{pA} \sim 1$ ABOVE 2-3 Gev (kh-m, check)

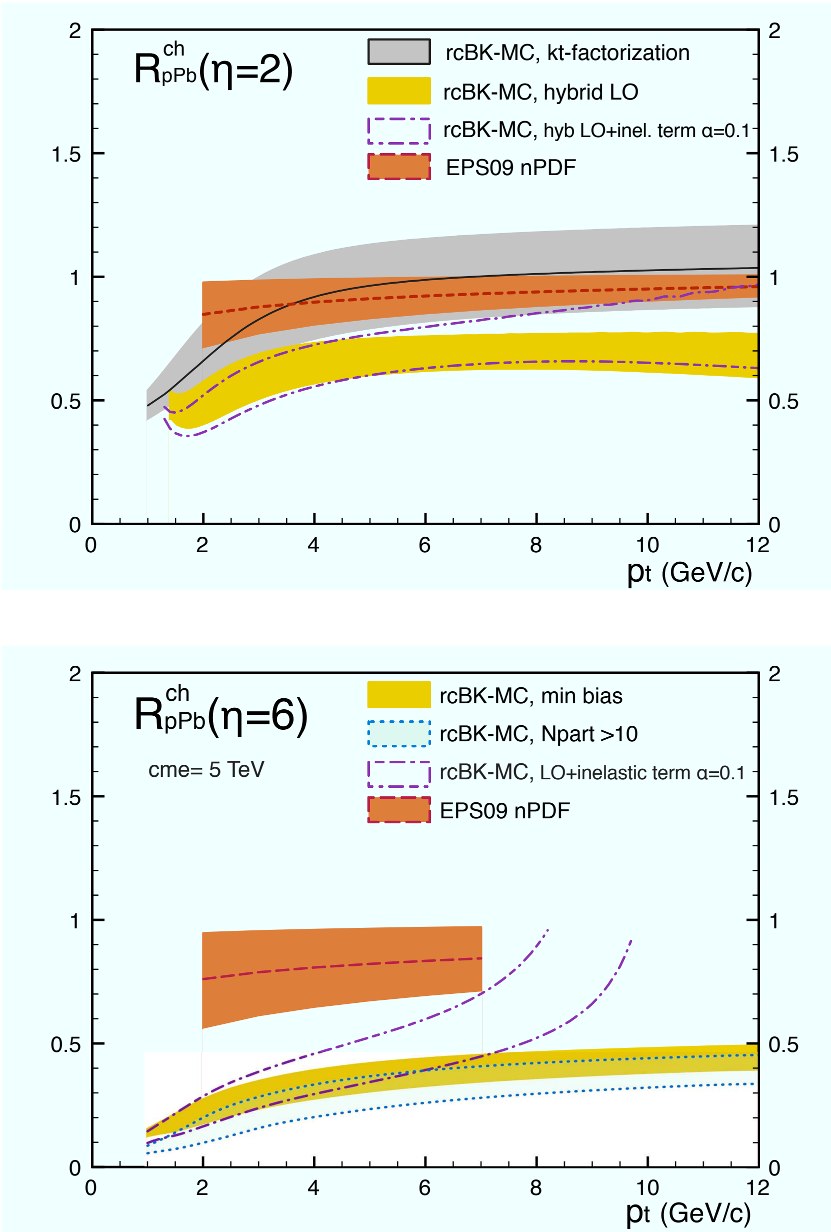


Figure 4: Albacete et.al. - predictions for p-Pb at 5 Tev

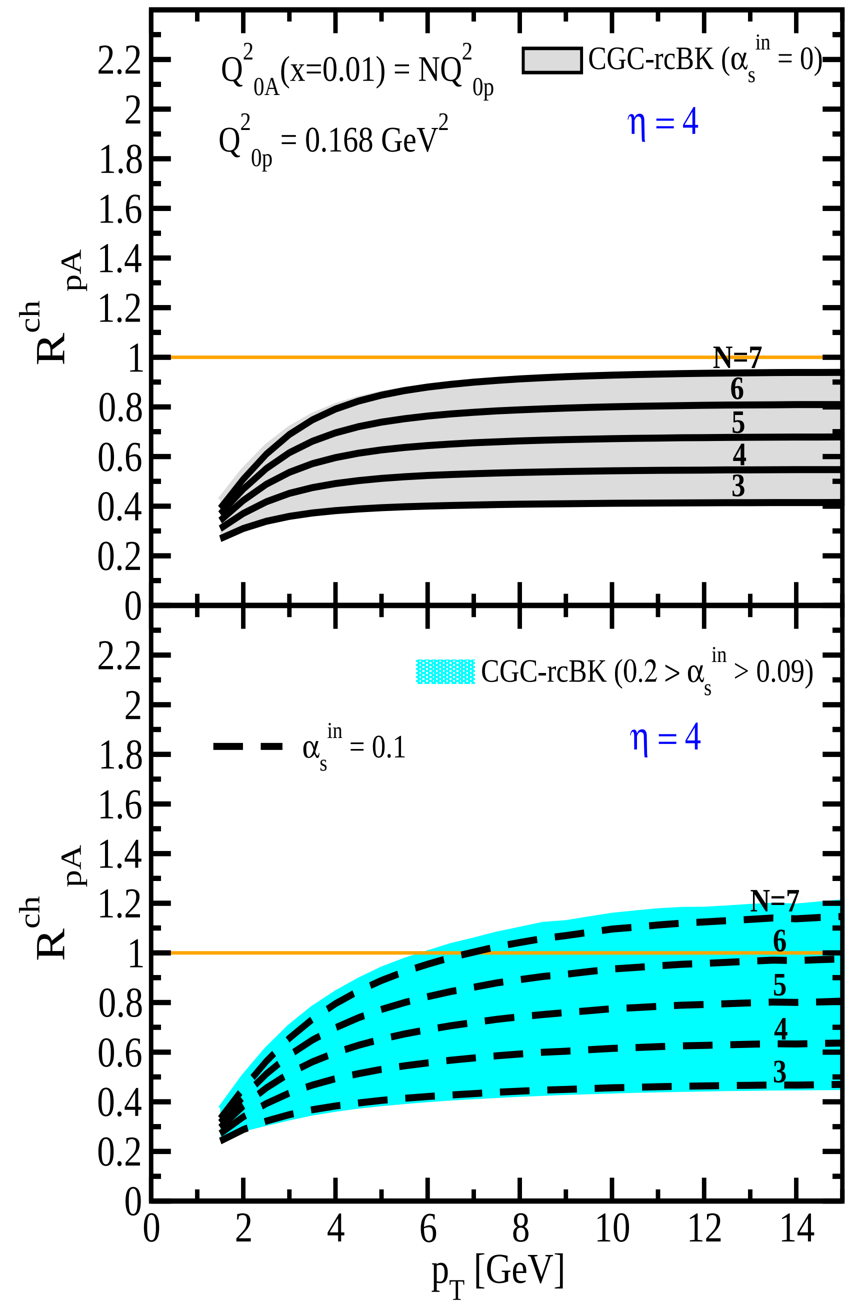


Figure 5: Rezaeian - predictions for p-Pb at 5 Tev

CLEARLY THE PREDICTION BAND IS VERY WIDE

CLEARLY THE EFFECT OF THE PERTURBATIVE CORRECTION - THE INELASTIC TERM IS VERY LARGE.

SO WE NEED TO UNDERSTAND THINGS BETTER.

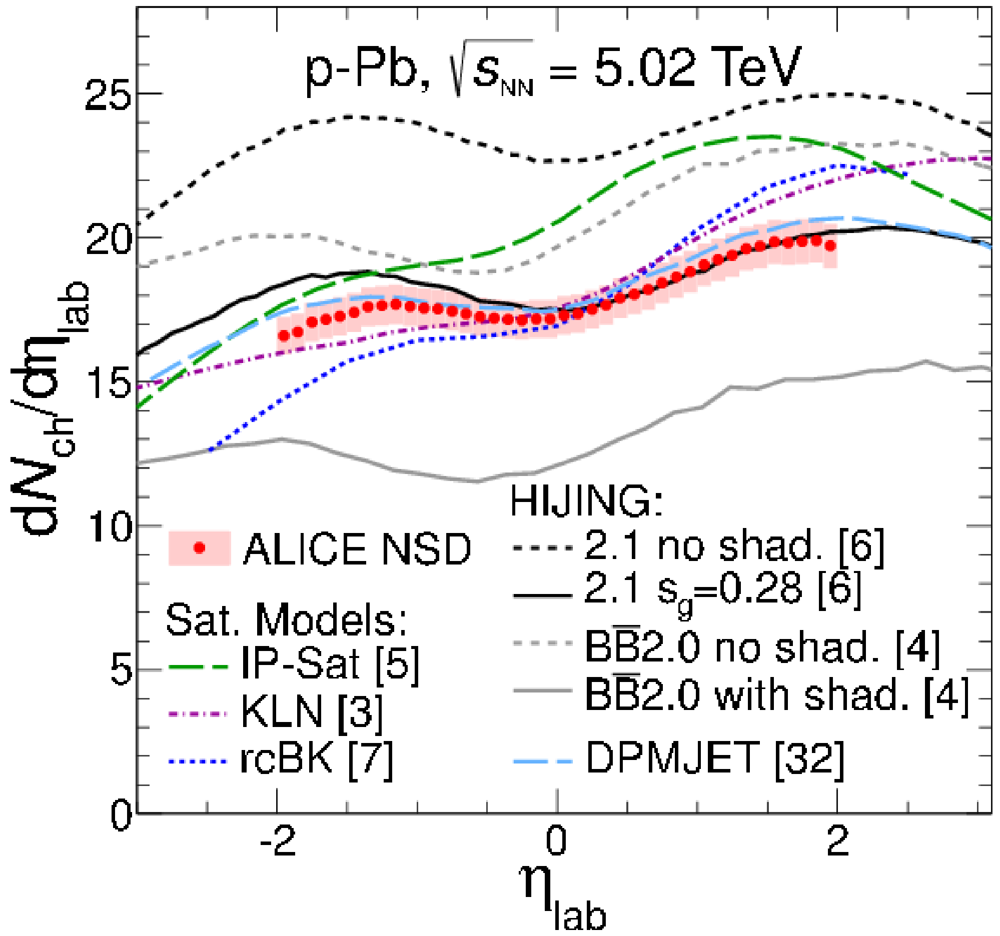
IS PERTURBATION THEORY UNSTABLE? POSSIBLY. THEN WE ARE IN TROUBLE.

MORE LIKELY, I THINK, THE INELASTIC CORRECTION IS NOT AS BIG AS IT LOOKS. AT FORWARD RAPIDITIES AND LARGE TRANSVERSE MOMENTA THE PARTON PAIR ONLY EXIST FOR A SHORT TIME AND SHOULD NOT BE ABLE TO SCATTER COHERENTLY OFF THE TARGET. COHERENT SCATTERING APPROXIMATION MAY WELL BE AT FAULT.

MORE COMPLETE PERTURBATIVE CORRECTION EXISTS: CHIRILLI, XIAO, YUAN - BUT THE SCATTERING IS STILL TREATED THERE AS COHERENT.

rcBK ALSO PRODUCES PARTICLE MULTIPLICITIES. SO DO OTHER PHENOMENOLOGICAL SATURATION ANSATZE FOR THE GLUON DENSITY (IP-SAT, b-CGC)

IRONICALLY THE "OF THE SHELF" KLN MODEL STILL DOES THE BEST JOB.



THE RIDGE

CMS OBSERVATION OF RIDGE IN p-p FOLLOWED BY ALICE AND ATLAS OBSERVATION IN p-Pb

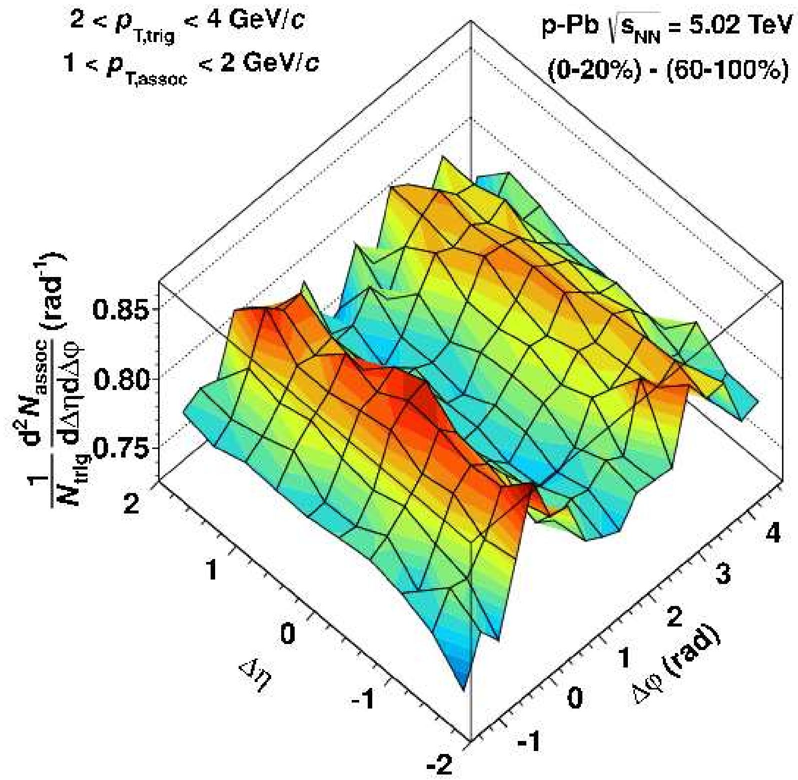


Figure 6: ALICE RIDGE

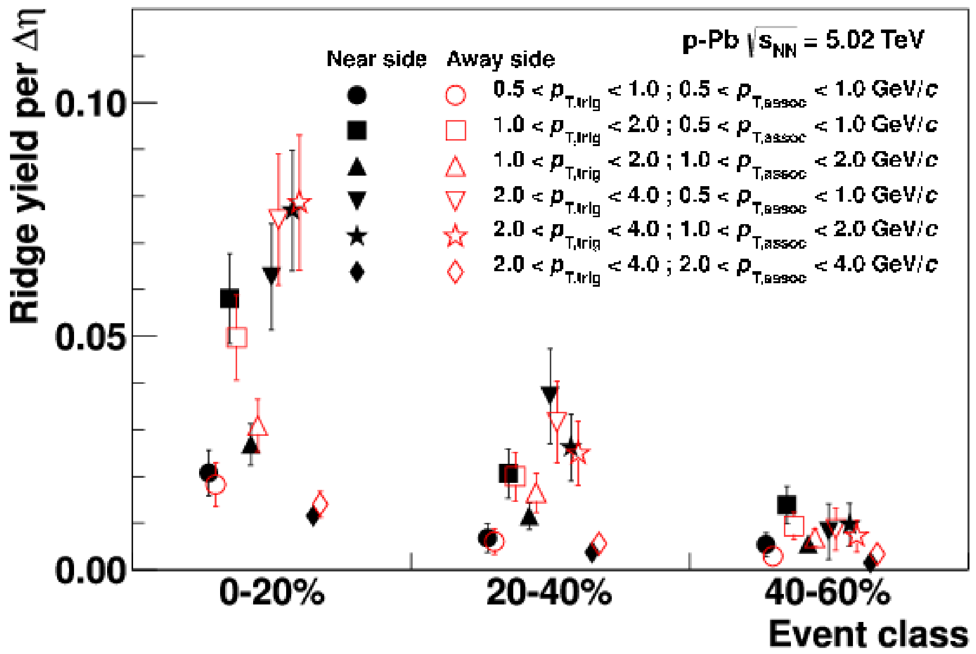


Figure 7: ALICE ridge at different p_T

QUALITATIVELY SIMILAR STRUCTURE: TWO PARTICLE CORRELATIONS LONG RANGE IN RAPIDITY (> 4 UNITS); AND COLLIMATED IN AZYMUTHAL ANGLE. p-Pb SIGNAL IS STRONGER (ABOUT A FACTOR OF 2.5-3 FOR CORRELATED YIELD). THE PLOTS ARE FOR ASSOCIATED YIED $R(\Delta\eta) \sim \frac{N_{correlated\ pairs}}{N_{trigger\ particles}}$

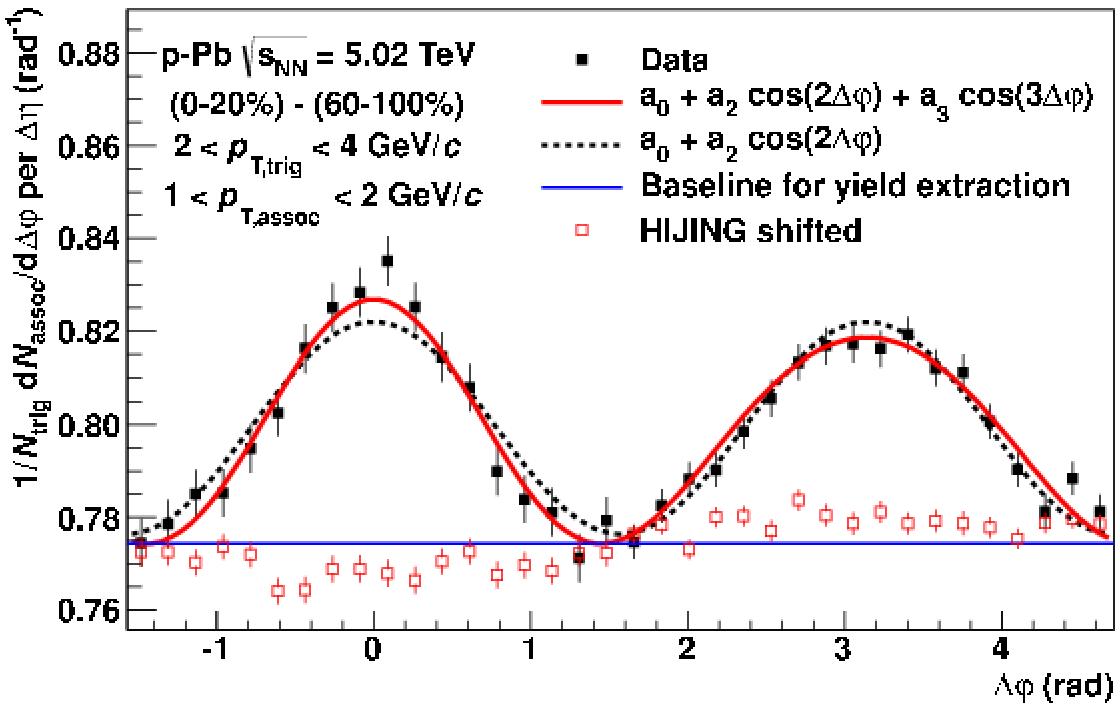


Figure 8: ALICE RIDGE IS SYMMETRIC

ALSO THE p-Pb SIGNAL IS SYMMETRIC IN $\Delta\phi \to \Delta\phi + \pi$.

VIGOROUS ACTIVITY TO DESCRIBE THE RIDGE WITHIN CGC APPROACH - **DUSLING AND VENUGOPALAN**

IT IS CERTAINLY CGC INSPIRED.
INVOLVES QUITE A BIT OF MODELING. E.G. REQUIRES A CHOICE OF Q_S FOR EVERY MULTIPICITY CLASS (NOT UNREASONABLE).
MOST IMPORTANT LIMITATION IN MY VIEW IS THAT IT TAKES AN ANSATZ FOR TWO PARTICLE PRODUCTION PROBABILITY FROM DILUTE LIMIT (HIGH p_T), AND APPLIES IT TO ALL MOMENTA.
THE VALIDITY IS NOT UNDER THEORETICAL CONTROL.
SOME IMPORTANT LEADING IN N_C EFFECTS ARE NOT INCLUDED. THE RESULTS OF DV ARE BASED ON A SUBLEADING IN N_C CONTRIBUTION.

A SHORT RUNDOWN OF EFFECTS THAT LEAD TO COLLIMATION.

1. DIRECTED COLOR FIELDS IN THE TARGET (KOVNER, LUBLINSKY). COLOR FIELDS IN THE TARGET HAVE FINITE CORRELATION LENGTH GIVEN BY $Q_{S,TARGET}$. WHEN TWO GLUONS FROM THE PROJECTILE SCATTER OFF THE SAME FIELD, THEY PICK UP THE SAME MOMENTUM TRANSFER. THIS LEADS TO POSITIVE ANGULAR CORRELATIONS. THIS IS LEADING N_C EFFECT. AT PRESENT WE DO NOT UNDERSTAND ITS ENERGY DEPENDENCE.
THIS EFFCT IS NOT INCLUDED IN DV

2. VARIATION OF COLOR FILED DENSITY IN THE TARGET (LEVIN AND REZAEIAN). IF THE SIZE OF THE INCOMING TWO GLUON STATE IS COMPARABLE TO THE SIZE OF THE REGION OVER WHICH Q_S VARIES, THERE IS A PREFERRED DIRECTION FOR SCATTERING - ALONG THE GRADIENT OF Q_S. THIS IS ALSO A LEADING N_C EFFECT AND HAS LEADING BEHAVIOR AT HIGH ENERGY. THE RELEVANT MOMENTUM RANGE HOWEVER IS NOT Q_S, BUT "THE CORRELATION LENGTH OF Q_S". STILL, GIVEN THAT Q_S FLUCTUATES IN IMPACT PARAMETER, IT MAY BE QUITE IMPORTANT.
THIS EFFCT IS NOT INCLUDED IN DV

3. BOSE CORRELATIONS BETWEEN THE GLUONS OF PROJECTILE. (DUMITRU, DUSLING, GELIS, JALILIAN MARIAN, LAPPI, MCLERRAN, VENUGOPALAN) DENSITY OF PROJECTILE GLUONS WITH THE SAME QUANTUM NUMBERS (TRANSVERSE MOMENTUM AND COLOR) IS ENHANCED DUE TO BOSE CORRELATIONS. THE GLUONS IN THIS CORRELATED CONFIGURATION PREFER TO SCATTER IN THE SAME DIRECTION. SINCE THE INCOMING GLUONS HAVE TO BE IN THE SAME COLOR STATE, THIS IS A SUBLEADING IN N_C CONTRIBUTION RELATIVE TO GENERIC SITUATION WHERE THE COLOR OF INCOMING GLUONS IS INDEPENDENT.
THIS EFFCT IS INCLUDED IN DV AND GIVES ALL THE CORRELATED CONTRIBUTION.

ALL THE ABOVE MECHANISMS LEAD TO SYMMETRIC CONTRIBUTIONS AT ϕ AND $\phi + \pi$.

DV CALCULATION IS AN INTERESTING MODEL, BUT IT IS HARD TO SEE HOW IT CAN BE THE LAST WORD. TANTALIZING THAT IT GIVES SUCH GOOD QUANTITIVE AGREEMENT WITH THE DATA. COULD BE AN ACCIDENT, OR COULD BE THAT THE OTHER EFFECTS ARE FOR SOME REASON SUPPRESSED.

IT IS IMPORTANT THAT THIS CALCULATION IS OUT THERE AS A BASELINE FOR FUTURE, HOPEFULLY MORE COMPLETE ONES

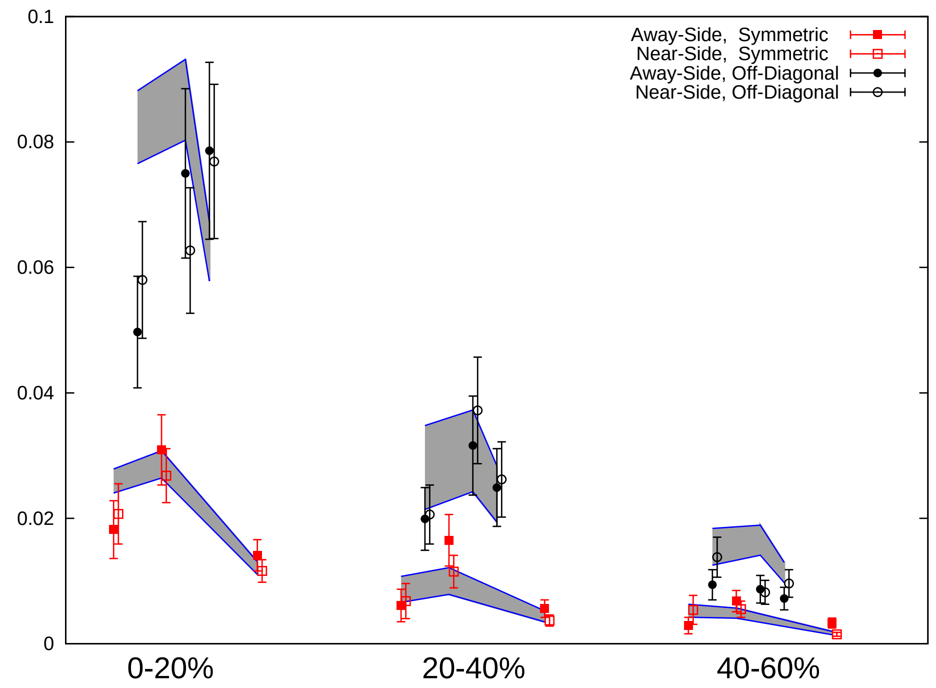


Figure 9: DUSLING-VENUGOPALAN FIT TO ALICE (LARGE FLUCTUATIONS IN Q_S?)

CONCLUSIONS

A MIXED BAG: QUALITATIVELY THINGS WORK QUITE WELL - A LOT OF FEATURES OF THE DATA ARE REPRODUCED.

IS IT A **THEORY** AS OPPOSED TO **MODEL**? NOT YET. STILL MANY AD HOC APPROXIMATIONS WITH NO OBVIOUS CONTROL ON THEIR VALIDITY PLUS A LOT OF FREEDOM IN FITTING (CHANGING) PARAMETERS.

THE USUAL ANNOYING THING. HERE IS A GOOD, SIMPLE IDEA. YOU MAKE THE SIMPLEST POSSIBLE ESTIMATE INSPIRED BY IT, AND IT WORKS BETTER THAN IT HAS THE RIGHT TO WORK. YOU IMPROVE IT BY MAKING REAL CALCULATION (INCLUDING PERTURBATIVE CORRECTIONS AND SUCH) AND THINGS GET ONLY WORSE. USUALLY ONE HAS TO WORK REALLY HARD TO GET BACK THE ACCURACY OF THE ORIGINAL BACK-OF-THE ENVELOPE ESTIMATE FROM THE REAL CONTROLLABLE CALCULATION.

TYPICAL TEENAGER: SHOOTS UP A FOOT IN HIGHT IN A YEAR, BUT DOES NOT QUITE KNOW WHAT TO DO WITH HIS LONG ARMS, PLUS HAS TONS OF PIMPLES. IT WILL TAKE TIME AND EFFORT TO GROW HIM INTO A PROFESSIONAL ATHLETE WITH SMOOTH SKIN (OR ALTERNATIVELY INTO A RESPECTED UNIVERSITY PROFESSOR). BUT IN THE END IT MAY HAPPEN.

SO I HOPE THAT WE ARE AT THIS STAGE IN THE CHAIN - MOVING FROM BACK OF THE ENVELOPE STUFF TO REAL CALCULATIONS, ALTHOUGH NOT QUITE THERE YET.