The Initial Stages of Colliding Nuclei and Hadrons

Prithwish Tribedy

September 12-17, 2016, on South Padre Island, TX, USA

Hot Quarks 2016, workshop for young scientist on the physics of ultra relativistic A-A collisions

A conventional picture of collisions A+A : fig:S.Bass

You have seen this before but let me add two more…

Λ states of Λ A conventional picture of collisions

Λ states of Λ A conventional picture of collisions

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Λ states of Λ A conventional picture of collisions

How can we possibly know about initial states ?

talk by Soumya

P^2 Long range correlations

P^2 Long range correlations

 r $irrelations$ Figure 1 shows dihadron azimuthal distributions nor-Long range correlations au colotiano *p*associety are shown. The height of the background of the

I ond rande medium. However, those correlation measurements required background subtraction, and \Box study of the properties of the away-side jet has been P^2 and baryon fraction exhibit substantial differences from jet

^T increases from left to right, and two

Long range correlations

P^2

Long range correlations

P^2

Signature of medium formation

Striking similarity

Is this signature of collectivity ?

Is this hydro or CGC ? Is this signature of QGP ?

Is this hydro or CGC ? Is this signature of collectivity ? Is this signature of QGP ?

Lets focus on the long range correlations

ations cannot be much affected by the sub-horizon sub-horizon sub-horizon scale processes allowable p ine ondin of fond range correlations in the postments provide extremely valuable information about the inflationary epoch of The origin of long range correlations causal influence on the particles and place inside the place inside the corresponding take place in side the corresponding take place in the corresponding take place in the corresponding take place in the corresponding tak

Causality argument tells it must have origin as very early stages

ations cannot be much affected by the sub-horizon scale processes allowable in the post-inflationary thermal universe. This explains why CMB measure-The origin of long range correlations

ality argument tells it must have origin as very a phenomena may provide important insights with regard \sim to the theoretical interpretation of the observed phenomenon of the observed phenomenon of the observed phenom hand soft particle production amidst large parton denit tells it must have origin as that the azimuthal anisotropy of say *p^T* . 1 GeV parti-Causality argument tells it must have origin as very early stages

Long range correlations

vation of sizable Fourier harmonic coecients *vn*(*p^T*) up to *its this que to initial state* m contration at the contration and a vation of sizable Fourier harmonic coecients *vn*(*p^T*) up **the IS in 18 and 20 and 10 and 10** correlation generally attributed to anisotropic flow. Most $\frac{1}{2}$ this dusta initial state mementum anger corr

or initial state position space correlations ? transformed into momentum space correlations due tum space cor or initial state position space correlations ? transformed into momentum space correlations due to momentum space correlations due to momentum space correlat
The correlations due to momentum space correlations due to momentum space correlations due to momentum space c m space correl Is this due to initial state momentum space correlation

For A+A collisions we know the answer

Nearly boost invariant initial state position space correlations + collective flow → ridge like structure in A+A

boost invariant initial state boost invariant hydro evolution

Still initial state drives the phenomenon

Initial state position space correlations

Same story for small systems ?

Bozek, Broniowski 1304.3044 K. Werner *et al* 1307.4379

Then we need to estimate the right initial conditions ?

Nearly boost invariant initial state position space correlations + collective flow → ridge like structure in A+A

Another piece of puzzle p+Pb

However it persist up to very large $p_{\perp} = 10$ GeV some semi-hard (short distance) QCD dynamics playing a role ?

- No convincing evidence for mini-jet quenching seen in data
- The away side is almost un-modified, even used for subtraction
- approach towards thermalization \rightarrow mini-jets must be fully quenched

Flow like patten but how about jet-quenching ?

arXiv: 1011.5531

One more thing we shouldn't forget

Ridge appears only in high multiplicity events in small systems

Similar underlying dynamics must drive these phenomenon

Origin of high multiplicity events \longleftrightarrow Systematics of Δ η- Δ φ correlations

One more thing we shouldn't forget

Ridge appears only in high multiplicity events in small systems

Initial state correlations

Initial state correlations

Initial stages of colliding hadrons/nuclei

At high energies in Regge Gribov limit $\sqrt{s}\to\infty, x\to 0$: gluon saturation $\sqrt{s} \rightarrow \infty, x \rightarrow 0$

• Non-linear processes stop growth of gluons, emergence of a scale $\ Q_S(x) > \Lambda_{QCD}$

Initial stages of colliding hadrons/nuclei

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At high energies in Regge Gribov limit $\sqrt{s}\to\infty, x\to 0$: gluon saturation $\sqrt{s} \rightarrow \infty, x \rightarrow 0$

• Non-linear processes stop growth of gluons, emergence of a scale $\ Q_S(x) > \Lambda_{QCD}$ • Gluon dominated wave function, high occupancy \sim $\frac{1}{\sqrt{2\pi}}$ peaked at $Q_S(x)$ ∼ 1 α_S

Proton fluctuation : Saturation momentum

p+p collisions are asymmetric

Distribution of Partons are driven by stochastic process

The wave function of a hadron $|H\rangle = |qqq\rangle + |qqqg\rangle + \cdots + |qqqgg \cdots gg\rangle$

Quark structure Essential for description of Incoherent DIS data

The nuclear scattering matrix is obtained as Nucleus multiple proton target

p+p collisions are eccentric *^r* ²*Q*² *sp/*2

Proton fluctuation : Intrinsic shape

$$
\mathcal{S}^A_{\mathrm{dip}}(\mathbf{r}_\perp, \mathsf{x}, \mathbf{b}_\perp) = \prod_{i=0}^A \mathcal{S}^p_{\mathrm{dip}}(\mathbf{r}_\perp, \mathsf{x}, \mathbf{b}_\perp)
$$

Schenke, Mantysaari 1603.04349

Initial state momentum correlation

Correlations already present among partons in projectile wave function survive after scattering off the color fields of target

Intrinsic momentum space correlations collimated emission of particles

ΔΦ

$$
\langle n^2 \rangle - \langle n \rangle^2 \sim \frac{1}{Q_S^2 S_\perp}
$$

Initial state momentum correlation

n-particle correlations \rightarrow negative binomial distributions (NBD) $NBD + Qs$ -fluctuations + collision geometry \rightarrow multiplicity distributions

Classical Yang-Mills : Numerical solutions *A*⁺ = 0 Classical Vancouver on 2019
19 *A*⁺ = 0

IP-Glasma model in a nutshell

B (11) *^A* (12)

- \rightarrow classical color charge $\rho(x_{\perp})$
- → classical color field solving

$$
[D_\mu, F_{\mu\nu}] = J_\nu
$$

Talk by Steven

Colliding nuclei

Classical Yang-Mills : Numerical solutions *A*⁺ = 0 Classical Vancouver on 2019
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IP-Glasma model in a nutshell

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$$
[D_\mu,F_{\mu\nu}]=J_\nu
$$

$$
\longrightarrow \frac{dN}{d\mathbf{p}_{T1}dy_1 \dots d\mathbf{p}_{Tn}dy_n}
$$

$$
\longrightarrow \ T_{\mu,\nu}(\tau,x_\perp,\eta)
$$

Talk by Steven

Colliding nuclei

- \rightarrow classical color charge $\rho(x_{\perp})$
- \rightarrow classical color field solving
- Field after collisions \rightarrow combination of colliding fields

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Colliding nuclei

- \rightarrow classical color charge $\rho(x_{\perp})$
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- Field after collisions \rightarrow combination of colliding fields

Purely momentum space correlations of gluons produce ridge after fragmentation

Mass ordering can come from initial state correlations + fragmentations

Initial state correlations

Common Initial conditions

fig: Gale, Jeon, Schenke, Int.J.Mod.Phys. A28 (2013) 1340011

Energy densities from these models are input to hydrodynamic simulations

neXus, EPOS : Parton-Based Gribov Regge Theory

Pierog, Karpenko, Katzy, Yatsenko, Werner, 1306.0121

$DIPSY$: saturation + BFKL cascade [Flensburg](http://arxiv.org/find/hep-ph/1/au:+Flensburg_C/0/1/0/all/0/1), [Gustafson](http://arxiv.org/find/hep-ph/1/au:+Gustafson_G/0/1/0/all/0/1),

Kharzeev, Levin, Nardi, hep-ph/0111315, Drescher, Nara 0707.0249, Albacete, Dumitru 1011.5161

A few other models of initial conditions $\mathbf{u} \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{v}$ is a good alternative model for p-p and p-A minimum bias analysis.

Werner, Liu, and Pierog, hep-ph/0506232 Drescher, Hladik, Ostapchenko, Pierog, Werner, hep- ph/0007198.

Flensburg, Gustafson, Lönnblad 1103.4321

 P_a

 k_0

 k_1

 k_2

 q_1

 q_2

 q_3

ln s

CGC factorization : KLN model, f-KLN, MC-KLN, MC-rcBK

Data that nailed it down nailed it down rialied it down 0.2 Ê 0.2 u lat Hanca Ú Ù Á · at nailed it a · · ‡ Ú Á **Data that nailed it down** along earlier freeze-out. Both een die staatsland van die stelling van die stelling van die stelling van die s
Both een die stelling van 0.1 0.2 0.3 $\overline{}$ Ê nat nalled it dov Ú Ù Á **S** Á $\mathbf n$ Ê ‡ Ï 0.5 U o o U o o U o o U <u>**IUL HUILUU I**</u> Ú **</u></u>** · t nailed it de · · ‡ 10-20% Ú Á **Data that nailed it dowr** 0.1 0.2 0.3 \overline{a}

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10-20 10-20 10-20 10-20 10-20 10-20 10-20 10-20 10-20 10-20 10-20 10-20 10-20 10-20 10-20 10-20 10-20 10-<u>Li</u> m, Ollitrault ‡ Ï Ù · **Retinskaya, Luzun** Kaya, Luzum, Ollitra
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The freeze-out temperature is adjusted by the freeze-out temperature is adjusted by the freeze-out temperature unskáya, 1.000a Ï $\overline{}$)
ا Retinskaya, Luzum, C ya, Luzum, Ollitrault

 $\frac{1}{2}$ McCrabk RHIC and LHC v_n data highly constrains initial state models HaL RHIC HbL LHC **RHIC and LHC v_n data highly constrains initial state models** Ê \overline{a} Ê <u>ب</u> Ï \Box RHIG and LHG v_n data nighty constrains initial state model energies: in die less sent-al-less sender argumy somouremme minimen stelle mission. te models increases increases in the distance between the distribution of the distribution o energy and entropy weighting. The minimum and maxiincreases, which is mostly due to the dierence between RHIC and LHC v_n data highly constrains initial state models and LHC, respectively. In the same centrality range, the same centrality range, the same centrality range, the
In the same centrality range, the same centrality range, the same centrality range, the same contract of the s allowed band at LHC is sinitual state models in the set of \mathcal{L} ata highly constrains initial state models **FIFIG. AND AND LETTU VALGE RESULTS COLORED IN THE STATE THUGGIS** FIG. 2. (Color online) Shaded bands are root-mean-square models and at LHC is supported by the models *i* constrains initial state models

RHIC-AGS meet 2015, BNL 10/23/2015, BNL 10/23/2015, BNL 10/23/2015, BNL 10/23/2015, BNL 10/23/2015, BNL 10/23/
Rhic-Ags meet 2015, BNL 10/23/2015, BNL 10/23/2015, BNL 10/23/2015, BNL 10/23/2015, BNL 10/23/2015, BNL 10/23/
 $10-20$

area between two curves of the type (5) with *C* = *C*min and

linear-response approximation itself: weighting with en-

L H C Vn range 0*.*2 *< p*^t *<* 5*.*0 GeV/*c* as a function of event centrality, with the more central collisions with the leftsate each other at RHIC and LHC v_n da along earlier freeze-out. Both eects essentially compensate each other who has resulted at RHIC and LHC v_n da **9** ‡ Ú such that all hydro points lie within the band. **RHIC and LHC v_n data highly constrains initial state** were instructed to the situation is the situation in the situation is different at LHC α $\overline{\text{D}}$ **THE 2019 LETTU VALIS** \blacksquare the uncertainty band comes not from properties of the Ω and H $\overline{\mathsf{C}}$ and $\mathsf{L}\mathsf{r}$ MC-Glauber 1ld II C and H $\overline{}$ can be $\overline{}$ ata hi $\frac{1}{\sqrt{2}}$ the uncertainty band comes not for the uncertainty band computer of the uncertainty of the uncertainty of the u energies: in die volks sender de less sena-syl voor online mean-square results are root-mean-square root-mean- \mathbf{R} were insensitive to the situation insensitive to \blacksquare RHIC and LHC v_n data highly constra In the largest contribution to the largest contribution to the third the third the third the third the third t were insensitive to *t*0. The situation is dierent at LHC were instant to **the situation in the situation in the situation is defined and LHC** v_n RHIC and LHC μ data highly constrains initial sl THE SAME LITTLE VILLAGE. In fact, the largest contribution to the thickness of the uncertainty band composition band comes not from properties of the uncertainty of the set of the

implied by hydrodynamic calculations in combination with ALICE data for the 5% most central Pb-Pb collisions at ∂ $s = 2$.76 TeV. Squares: $s = 2$.76 TeV. Squares: $s = 1$ fm **. 4** $i \in \mathbb{N}$ ALICE data for the 5% most central Pb-Pb collisions at ∂2 model dependent ! flow for a given value of ⌘*/s*, resulting in smaller values 0-10% $\mathbf 1$ Ï Ù · $\overline{\mathbf{C}}$ Ï Ú Ù · ud ‡ Ï Ù dia trial rialiet Ê ‡ Ï Ù ala trial nand flow for a given value of ⌘*/s*, resulting in smaller values P *ald* that nanve *C* = *C*max, where the values of *C*min and *C*max are chosen model dependent ! flow for a given value of ⌘*/s*, resulting in smaller values

40-50%

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vata that nail

 $\overline{}$ contracts the set of $\overline{}$ [−]¹ 10 1 ϵ −20 Γ MC-Glauber (correlation between shape and multiplicity) ad many modole of initial conditiv These data constrained many models of initial conditions like MC-KLN & These data constrained many models of initial conditions like MC-KLN & \mathcal{L}

Data that nailed it down

Improved Glauber Models Sandeep Chatterjee,∗ Sushant K. Singh,† Snigdha Ghosh, Md Hasanujjaman, Jane Alam, Alam, and Sourav Sarkar, Sa
Sarkar, Sarkar, Md Hasanujjaman, Jane Alam, and Sourav Sarkar, Sarkar, Sarkar, Sarkar, Sarkar, Sarkar, Sarkar, Theoretical Giauper Ividaels Division, 1200064, 1720064, Indianagar, 1980

the case of top ZDC events. However, none of these features have been observed in data. We address these discrepancies by including the effect of the two component Monte-Carlo Glauber model. All shadowing successfully successfu

Moreland, Bernhard, Bass 1412.4708 Eremin, Voloshin nucl-th/0302071, PHENIX 1509.06727 Chatterjee et al 1510.01311, 1601.03971

FIG. 1. The relative weight factors of each participant for each participant for each participant for each par
The relative weight for each participant for each participant for each participant for each participant of the Shadowed Glauber Normal Glauber

Modification of Glauber : additional coherence to be introduced

TRENTO Quark-Glauber Shadowed Glauber

EKRT : pQCD (shadowing) + saturation

NLO pQCD cross section of mini-jets with nPDF

Implementation of saturation when $2 \rightarrow 2 \sim 2 \rightarrow 3$

Very successful phenomenology at RHIC and LHC

Time evolution → Bjorken like expansion

Niemi, Eskola, Paatelainen 1505.02677

transverse plane and a conditions of the conditions

(LeXUS + Glauber)

Schenke, Monnai 1509

- $\frac{1}{\sqrt{2}}$ Breaking of boost-invariance **→** due to longitudinal fluctuations **→** twist, torque, event-plane de-correlation \overline{a}
	- 3D initial state **→** More important at lower energies

3D-Glasma (JIMWLK + IP-Glasma)

Schenke, Monnai 1509.04103 Schenke, Schlichting 1605.07158

Includes `dynamical cross-over' (i.e. non-universal rapidity)

Chesler, Kilbertus, Van der Schee 1507.02548, Van der Schee, Schenke 1507.08195,

Holographic initial conditions

fig: W. Van der Schee QM'15

Initial state correlations

Pre-equilibrium dynamics - Classical Yang-Mills can not lead to isotropization or thermalization I.
II. The Early Search School is a can not lead to isotropize

Effective Kinetic Theory \rightarrow ab initio approach Effective Kinetic Theory \rightarrow ab initio approach

Arnold, Moore, Yaffe hep-ph/0209353 **Fig. 3. Classical Evolution of the System System evolution of the System S**

Approach to Isotropization /Thermalization distribution for the other discusses the other discusses the other discusses the connection between the formula approach to isotropization / I nermalization **/** 4 *A. Kurkela* / *Nuclear Physics A 00 (2016) 1–8*

$$
(\partial_t + \hat{\mathbf{p}} \cdot \nabla_{\mathbf{x}}) f_s(\mathbf{x}, \mathbf{p}, t) = -C_s^{2 \leftrightarrow 2}[f] - C_s^{``1 \leftrightarrow 2"}[f]
$$
\nArnold, Moore Kurkela, Zhu

\n

 Ω should be understood that fs(x, p, t) represents the phase space density of a single helicity Quasiparticle picture → Isotropization in weak coupling

talk by Aleksas

Qualitative Picture : Small systems

low multiplicity events

mini-jets escape

high multiplicity events

mini-jets quenched

Event-multiplicity

Schlichting's Phase Diagram of Correlation

 $|506.06647$

$$
Q_s \tau_{eq} \simeq 10(\eta/s)_{T_{eq}}^{4/3} (g^2 N_c)^{1/3} \simeq 10
$$

Number density $dN/dy \simeq \xi Q_s^2 \pi R^2$

mini-jets quenched

\mathbb{R} definal state take over ? parton in the solution is the soft thermal in the solution p be initial state take over from the crosspling corrected the time scale when γ particular version in the control of the soft tensor in the solution of the solution of \mathbb{R} pling corresponds to the time scale when a semi-hard particular state alle is the form α in the form and α

$$
\frac{\tau_{eq}}{R} \simeq \sqrt{\frac{100}{dN/dy}} \qquad \text{dN/dy \sim 100}
$$

to initial state and final state and final state e α ilibration time \sim system size verse momentum range e.g. 13 GeV. Based on our Equilibration time ~ system size ' Equilibration time ~ system size

Event-multiplicity

Summary

- Understanding Initial state from a first principle approach is essential
- Data in small systems provide unique opportunities and challenges
- Understanding of isotropization will improve complete modeling of HICs

Backup

Effect of running coupling \longrightarrow increase in $\langle p_T \rangle$

Mass ordering of average transverse momentum

A list of models of initial conditions

Kharzeev, Levin, Nardi, hep-ph/0111315, Drescher, Nara 0707.0249 KLN model, f-KLN, MC-KLN: k⊥-factorization (dilute-dense approximation) with UGDs dependent on $\mathsf{N}_{\mathsf{part}}$ $Q_S^2(x_\perp) \propto N_{part}(x_\perp)$ Albacete, Dumitru 1011.5161

MC-rcBK: Monte-Carlo implementation of k⊥-factorization with rc-BK UGDs constrained by HERA-data.

Schenke, PT, Venugopalan 1202.6646

IP-Glasma : IP-Sat initial condition (constrained by HERA data) and solutions of Classical Yang-Mill equations.