Particle production from e^-e^+ through pp to AA collisions
arXiv:1601.06001

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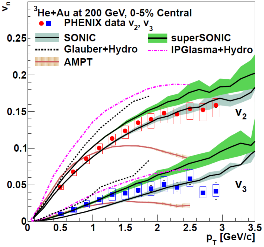
Particle production mechanisms

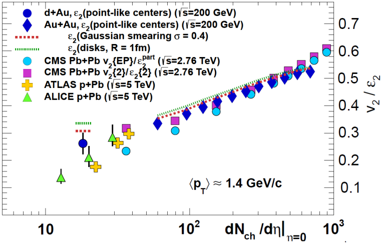
- A+A(B) collisions: frequently described with thermo/hydrodynamics
- Model ingredients: macroscopic variables (temperature, entropy)
  see e.g. W. Kittel and E. A. DeWolf, Soft Multihadron Dynamics, (World Scientic, 2005)
  or recent PHENIX, PHOBOS, STAR, ALICE, CMS and ATLAS papers
- Microscopic phenomenology used in $\mathrm{e}^- + \mathrm{e}^+$, $\mathrm{e}^\pm + \mathrm{p}$, p($\bar{\mathrm{p}}$)+p or p+A
- Perturbative gluon exchange, gauge fields, strings, parton hadronization
  see e.g. Kharzeev et al., NPA747; Armesto et al., PRL94, Dusling et al., PRD87
  and other references in arXiv:1601.06001
- Even for soft collisions and soft particle production
- Associated mechanisms: single-diffractive, double-diffractive, inelastic non-diffractive collisions
- These models don't use macroscopic variables
- What do the measurements tell us?

Similarities from p+p through p+A to A+A(B)

- Similar charged particle multiplicities (N_{ch})
- Similar pseudorapidity densities ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$)
- Azimuthal long range ($|\Delta\eta| \geq 4$) angular correlations, “ridge”
- Collective anisotropic flow in A+A collisions
- Also in p+p, p+Pb, d+Au and He+Au

ALICE PLB719, ATLAS PRL110, CMS PLB718, PHENIX PRL114, PHENIX PRL115





- Qualitative consistency achieved with hydro

See e.g. Bozek, PRC85, the Buda-Lund model from Csörgő et al., NPA661, JPhysG30, EPJA38, . . .

- Common underlying particle production mechanism dominating?

Our framework to capture underlying physics

- Macroscopic entropy (S) ansatz

$$S \sim (TR)^3 \sim \text{const.} \quad (1)$$

$$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \text{ and } \langle N_{\mathrm{ch}} \rangle \sim S \quad (2)$$

- Initial stage variable N_{pp} number of participant pairs
  - $N_{\mathrm{pp}} = 1$ for $\mathrm{e}^- + \mathrm{e}^+$, $\mathrm{e}^\pm + \mathrm{p}$ and p($\bar{\mathrm{p}}$)+p
  - Nucleon or quark participant pairs (N_{npp}, N_{qpp}) in p+A, A+A(B)
- Further assumption: $N_{\mathrm{pp}}^{1/3} \propto R \Rightarrow [(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)/N_{\mathrm{pp}}]^{1/3} \sim T \sim \langle p_T \rangle$
- Monte Carlo Glauber calculations performed to obtain N_{npp} and N_{qpp}.

Lacey et al. PRC83, Eremin et al. PRC67, Bialas et al. PLB649, Nouicer EPJC49, PHENIX PRC89

- Subset of initial particles become participants by an initial inelastic N+N or q+q interaction.
- $N_{\mathrm{np}} = 2N_{\mathrm{npp}}$ or $N_{\mathrm{qp}} = 2N_{\mathrm{qpp}}$
- N+N (q+q) cross sections taken from literature Fagunders et al, J. Phys. G40

Effective energy notation in $\mathrm{e}^- + \mathrm{e}^+$, p($\bar{\mathrm{p}}$)+p and $\mathrm{e}^\pm + \mathrm{p}$

- Similarity in particle production ⇔ $E_{\rm eff}$ available for particle production?

  Feinberg Phys Rept. 5, Albini et al. Nuovo Cim A32, Basile et al. PLB92&Nuovo Cim A67

- Remaining energy associated with leading particles

  PHOBOS nucl-ex/0301017

- Constituent quark picture: fraction of quarks contribute to $E_{\rm eff}$

  Nyiri, IJMP A18

- Thus a reduced $\sqrt{s}$ is expected to give similar values for $E_{\rm eff}$

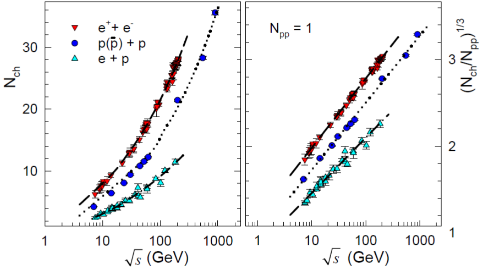
$$\kappa_1\sqrt{s}_{\rm ee} \approx \kappa_2\sqrt{s}_{\rm pp} \approx \kappa_3\sqrt{s}_{\rm ep} \text{ with } \kappa_1 \equiv 1 \tag{3}$$

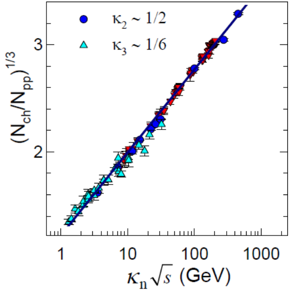
Sarkisyan and Sakharov, hep-ph/0410324

- $\kappa_{2,3}$: scale factors related to the number of quark participants
- Fraction of the available energy for particle production
- Comparable $\langle N_{\rm ch}\rangle$ in $\mathrm{e}^- + \mathrm{e}^+$, p($\bar{\mathrm{p}}$)+p and $\mathrm{e}^\pm + \mathrm{p}$ for reduced $\sqrt{s}$

$\langle N_{\rm ch}\rangle$ vs. $\sqrt{s}$ scaling

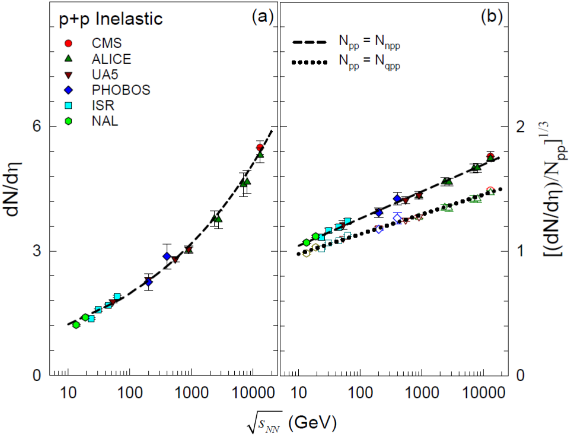
- $[N_{\rm ch}/N_{\rm pp}]^{1/3} \sim T \propto \log\sqrt{s}$
- Scaling versus $\kappa_n\sqrt{s}$
- $\kappa_1 = 1$ by definition
- $\kappa_2 \sim 1/2$: Half the pairs deposit their full energy
- $\kappa_3 \sim 1/6$:
  Half the pairs, 1/3 of the proton
- Fit result:
  $\langle N_{\rm ch}\rangle = \left[b_{\langle \rm N_{ch}\rangle} + m_{\langle \rm N_{ch}\rangle}\log(\kappa_n\sqrt{s})\right]^3$
  $b_{\langle \rm N_{ch}\rangle} = 1.22 \pm 0.01$
  $m_{\langle \rm N_{ch}\rangle} = 0.775 \pm 0.006$
- Can be used to predict $\langle N_{\rm ch}\rangle$ as a function of $\sqrt{s}$ for ee, ep and pp





$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\eta\approx 0}$ in inelastic p+p collisions

- Similar to $\langle N_{\mathrm{ch}}\rangle$
- $T \sim \langle p_T\rangle \propto \log\sqrt{s}$
- N_{qpp} scaling: similar trend
- Slow change of N_{qpp} vs $\sqrt{s}$
- Fit: dashed curve
- Recent 13 TeV inel. results by CMS, ALICE: good agreement with this scaling prediction

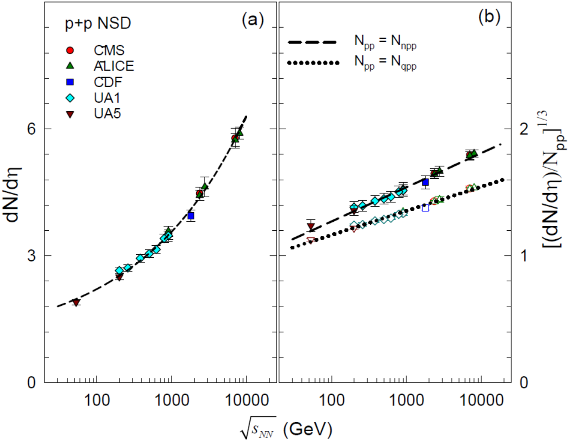


$$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\mathrm{INE}} = \left[b_{\mathrm{INE}} + m_{\mathrm{INE}}\log(\sqrt{s})\right]^3,$$

$$b_{\mathrm{INE}} = 0.826 \pm 0.008,\ \ m_{\mathrm{INE}} = 0.220 \pm 0.004$$

$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\eta\approx0}$ in NSD p+p collisions

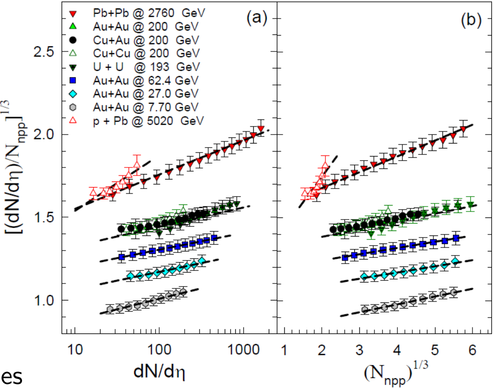
- Similar trends as for inelastic collisions
- Larger intercept
- Smaller slope
- Recall $\left[\frac{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta}{N_{\mathrm{pp}}}\right]^{1/3} \sim T \sim \langle p_T \rangle$
- $\langle p_T \rangle \propto T$ increases as $\log(\sqrt{s})$
- Can be used to predict $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$



$$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\mathrm{NSD}} = \left[b_{\mathrm{NSD}} + m_{\mathrm{NSD}} \log(\sqrt{s})\right]^3,$$

$$b_{\mathrm{NSD}} = 0.747 \pm 0.022, \;\; m_{\mathrm{NSD}} = 0.267 \pm 0.007$$

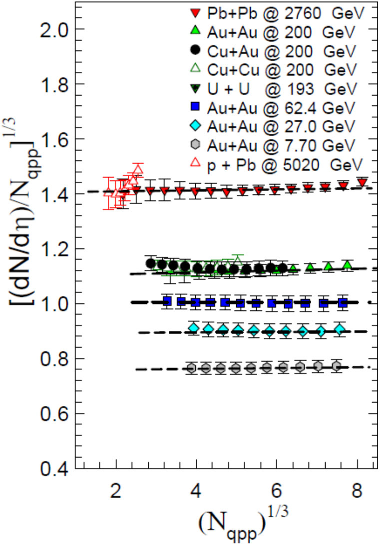
Nucleon participant scaling in A+A(B) collisions



- All systems: $\left[\frac{\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{|\eta|=0.5}}{N_{\mathrm{npp}}}\right]^{1/3} \sim T$
  (a): $\propto \log(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta) \sim \log S$,
  (b): $\propto N_{\mathrm{npp}}^{1/3} \sim R$
  - Logarithmic S-dependence
  - Linear size dependence (at a given $\sqrt{s_{\mathrm{NN}}}$)
  - $\langle p_T \rangle$ increases with $\sqrt{s_{\mathrm{NN}}}$ and $\log(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)$
  - Pseudorapidity density factorizes into contributions depending on $\sqrt{s_{\mathrm{NN}}}$ and $N_{\mathrm{npp}}^{1/3}$
- Slope increaseses with beam energy
- Lack of sensitivity to system type (Cu+Cu, Cu+Au, Au+Au, U+U), for fixed $\sqrt{s_{\mathrm{NN}}}$.

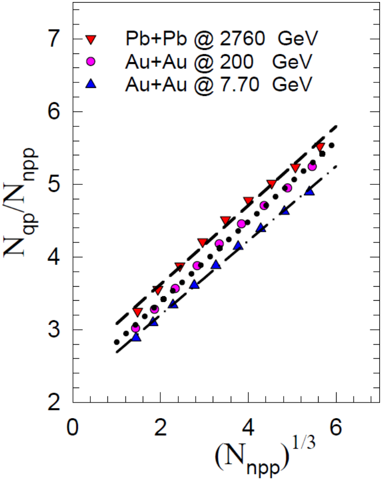
Quark participant scaling

- If N_{qpp} instead of N_{npp}: size dependence suppressed
- Clear $\sqrt{s_{\mathrm{NN}}}$ dependence
- Can be attributed to the linear dependence of $N_{\mathrm{qp}}/N_{\mathrm{npp}}$ on initial size (see next slide)
- Central to mid-central p+Pb: $N_{\mathrm{qp}}/N_{\mathrm{npp}}$ decreases with $N_{\mathrm{npp}}^{1/3}$
- Reduction of the energy deposited in these collisions, large multiplicity fluctuations.



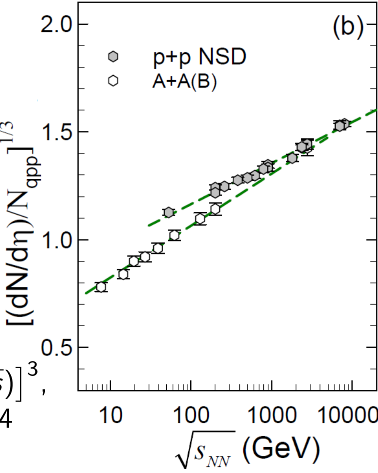
$N_{\mathrm{qp}}/N_{\mathrm{npp}}$ scaling

- $N_{\mathrm{qp}}/N_{\mathrm{npp}}$ scales with $N_{\mathrm{npp}}^{1/3} \sim R$
- N_{qpp} scales roughly with volume
- Slight increase over broad $\sqrt{s}$ range.



Similarity between p+p and A+A(B)

- Strikingly similar trends for NSD p+p and A+A(B) collisions
- Common particle production mechanism?
- Deviation for $\sqrt{s_{\rm NN}} \lesssim 2$ TeV
  - Larger T or $\langle p_T \rangle$ for same $\sqrt{s}$ p+p
- Centrality and $\sqrt{s}$ dependent values of $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta|_{|\eta|=0.5}$ scale with $N_{\rm qpp}$ and $\log(\sqrt{s_{\rm NN}})$.
- AA fit:
  $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta|_{|\eta|=0.5} = N_{\rm qpp}\left[b_{\rm AA} + m_{\rm AA}\log(\sqrt{s})\right]^3$,
  $b_{\rm AA} = 0.530 \pm 0.008,\ m_{\rm AA} = 0.258 \pm 0.004$
- Basis for robust predictions.
- E.g. $\sim 20\%$ increase of $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta|_{|\eta|=0.5}$ for Pb+Pb at 5.02 TeV compared to 2.76 TeV.



Summary

- Performed a systematic study of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ and $\langle N_{\mathrm{ch}}\rangle$
- $\mathrm{e}^- + \mathrm{e}^+$, $\mathrm{e}^\pm + \mathrm{p}$, and p($\bar{\mathrm{p}}$)+p, p+A and A+A(B)
- Several orders of magnitude in $\sqrt{s}$
- Scaling patterns for both $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ and $\langle N_{\mathrm{ch}}\rangle$
- Validation of leading particle effect
- Importance of quark participants in A+A(B)
- Strikingly similar terms for NSD p+p and A+A(B)
- Pseudorapidity factorizes with $\log(\sqrt{s})$ and N_{pp}
- Quantification: systematization and prediction of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ and $\langle N_{\mathrm{ch}}\rangle$ measurements

Thank you for your attention!

And let me invite you to the 16th Zimanyi School in Budapest

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