Centrality dependence of particle production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE experiment at LHC

Alberica Toia (Frankfurt University) on behalf of the ALICE Collaboration

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Outline & Motivations

ALICE measured min bias $R_{pA}^\rightarrow$ Consistent with 1 for $p_T > 2\text{GeV/c}$

Average $p$-Pb overlap function $<T_{pA}>$ from total (geometric) $p$-$A$ cross-section:

$$\langle N_{coll} \rangle = 208 \cdot \sigma_{pN}/\sigma_{pA}$$
$$\sigma_{pN} = 70\text{mb}$$
$$\sigma_{pA} = 2100\text{mb}$$

Measurements at low and intermediate $p_T$, coherent and collective effects with a strong geometric collisions geometry dependence

p-A nuclear modifications: incoherent superposition of $p$-$N$ collisions?

1) how many collisions ($N_{coll}$)?

2) what is the bias?
Glauber + Slow Nucleon Model

- Glauber fits: good description of data
- SNM: heuristic model → remarkably good agreement!
- $\langle N_{coll}^{\text{Glauber}} \rangle$ similar for different estimators
- Sys. Err: varying Glauber par.
- MC closure test with HIJING

**ALICE p-Pb $|s_{NN}| = 5.02$ TeV**

- Data
- NBD-Glauber fit

$N_{coll}^{\text{Glauber}}$ similar for different estimators

**Glauber + Negative Binomial Distribution**
Origin of the Bias in pA

Looser correlation between \( N_{\text{part}} \) and impact parameter (b)

\[ \rightarrow \text{Fluctuations at the origin of physical bias} \]
Biases in pA

- **Multiplicity bias**: fluctuations sizable
  → Bias on $\text{Mult}/N_{\text{part}}$ at central and peripheral collisions

- MC models with multi-parton interaction (MPI) include fluctuations of particle sources (hard scatterings)
  HIJING (X.N. Wang, M. Gyulassy, nucl-th/9502021)

  → bias in mult ~ bias in hard scattering
**Biases in pA**

- **Multiplicity bias**: fluctuations sizable
  - Bias on $\text{Mult}/N_{\text{part}}$ at central and peripheral collisions
- MC models with multi-parton interaction (MPI) include fluctuations of particle sources (hard scatterings)
  - HIJING (X.N. Wang, M. Gyulassy, nucl-th/9502021)
  - $\rightarrow$ bias in mult $\sim$ bias in hard scattering

- Triggered di-hadron angular ($\Delta\phi$) correlations are an ideal tool to study mini-jets.
  - Separates overlapping particle sources on a statistical basis
  - Sensitivity to fragmentation properties and number of particle sources
  - Important deviations for low and high $N_{\text{coll}}$
  - $\rightarrow$ less / more semi-hard scatterings per p-N collision

Alberica Toia
Biases in pA

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  → Bias on $\text{Mult}/N_{\text{part}}$ at central and peripheral collisions

- MC models with multi-parton interaction (MPI) include fluctuations of particle sources (hard scatterings)
  HIJING (X.N. Wang, M. Gyulassy, nucl-th/9502021)
  → bias in mult ~ bias in hard scattering

- **Jet-veto**: multiplicity range in peripheral events represent an effective veto on hard processes

- **Geometry bias**:
  Mean nucleon-nucleon impact parameter ($b_{NN}$) increases in peripheral collisions
Scaling of particle production

\[\frac{\langle S \rangle_i}{\langle S \rangle_{MB}} \text{ vs } \frac{dN/d\eta}{dN/d\eta}_{MB} \] (-1<\eta_{lab}<0)

- PHOBOS d-Au: \( \eta \rightarrow 1.6^{*}\eta \) (beam rapidity)
- Similar dependence except A-going dir.

**Fit:** assuming \( dN/d\eta \) scales with \( N_{part} \)

\[
\frac{\langle S \rangle_i}{\langle S \rangle_{MB}} = \frac{\left(\frac{N_{part}}{MB}\right)}{\left(\frac{N_{part}}{MB} - \alpha\right)} \cdot \left(\frac{\langle dN/d\eta \rangle_i}{\langle dN/d\eta \rangle_{MB}}\right)^{-1<\eta<0} - \frac{\alpha}{\left(\frac{N_{part}}{MB} - \alpha\right)}
\]

- \( \alpha = 0 \) – perfect \( N_{part} \) scaling
- \( \alpha = 1 \) – perfect \( N_{coll} \) (or \( N_{part} \) target) scaling
- \( \alpha \) has clear meaning (\( N_{part} \) vs \( N_{coll} \) scaling)

Correlation between causally disconnected observables (eg: slow neutrons - multiplicity) → connection to geometry.
Hybrid Method

1) assumption: ZN insensitive to dynamical biases → slice events in ZN

2) assumption:
   a) Mid-rap $dN/d\eta$ scales with $N_{part}$
   b) Pb-side $dN/d\eta$ scales with $N_{part}$ (target)
      ($= N_{coll}$ in pA)
   c) Yield at high-$p_T$ scales with $N_{coll}$

\[
\langle N_{part}\rangle_i^{\text{mult}} = \langle N_{part}\rangle_{MB} \cdot \frac{\langle S \rangle_i}{\langle S \rangle_{MB}}
\]
\[
\langle N_{coll}\rangle_i^{\text{mult}} = \langle N_{part}\rangle_i^{\text{mult}} - 1
\]
\[
\langle N_{coll}\rangle_i^{\text{Pb-side}} = \langle N_{coll}\rangle_{MB} \cdot \frac{\langle S \rangle_i}{\langle S \rangle_{MB}}
\]
\[
\langle N_{coll}\rangle_i^{\text{high}-p_T} = \langle N_{coll}\rangle_{MB} \cdot \frac{\langle S \rangle_i}{\langle S \rangle_{MB}}
\]

- All values within at most 10% → consistency of assumptions
- This does not yet prove the validity of any (or all) of these assumptions 2a), b), c)
\[ Q_{pA} \left( p_T; \text{cent} \right) = \frac{\frac{d N^{pA}}{d p_T}}{\frac{d N^{pp}}{d p_T}} = \frac{d N^{pA}}{d p_T} \frac{T_{pA}^{Glauber}}{T_{pA}^{Glauber}} \frac{d \sigma^{pp}}{d p_T} \neq 1 \]

- \( Q_{pPb} \) widely spread between centrality classes
- Negative slope in 80-100%
  (jet contribution increases with \( p_T \))
  → “jet veto bias”
- Good agreement with G-PYTHIA
  (Pythia + p-Pb Glauber MC)
  - In 80-100%
  - High-\( p_T \)
  → incoherent superposition of pN
- Deviations at low-\( p_T \)
  (soft particles: no scale with \( N_{\text{coll}} \))
- Deviations at intermediate \( p_T \)
  → nuclear effects?
$Q_{pA}(p_T; \text{cent}) = \frac{d N_{pA}/d p_T}{N_{\text{coll}}^{\text{Glauber}}} = \frac{d N_{pA}/d p_T}{T_{pA}^{\text{Glauber}}} \neq 1$

- $Q_{pPb}$ spread between centrality
- Reduces with increasing rapidity gap: CL1→V0M→V0A
- Negative slope in 80-100% → “jet veto bias”
- Reduces in V0M and absent in V0A
- Good agreement with G-PYTHIA (Pythia + p-Pb Glauber MC)
- Worse in V0M and V0A
- Deviations at intermediate $p_T$
- ZNA: spectra more similar high-$p_T$ values → bias in $N_{\text{coll}}$

**NEW!**

**CL1:** SPD cluster $|\eta|<1.4$

**V0M:** V0A+C Mult.
(-3.7<|$\eta$|<−1.7, 2.8<|$\eta$|<5.1)

**V0A:** V0A Mult (2.8<|$\eta$|<5.1)

**ZNA:** $0^\circ$ Neutron Energy
QpA

\[ Q_{pA}(p_T; \text{cent}) = \frac{\frac{d N^{pA}}{d p_T}}{N^{\text{Glauber}}_{\text{coll}}} = \frac{\frac{d N^{pA}}{d p_T}}{T^{\text{Glauber}}_{pA}} \neq 1 \]

**NEW!**

Hybrid: nearly perfect scaling with \( N_{\text{coll}} \) at high-\( p_T \)

**NEW!**
NEW!

Multiplicity density

CL1

V0M

VOA

ZNA

ALICE p-Pb $|s_{NN}|=5.02$ TeV

PRELIMINARY
Multiplicity vs Centrality

Asymmetry Evolution with $N_{\text{ch}}$

Increasing excess of particles in the direction of the Pb beam with respect to the proton-going direction.

Similar trend in common $N_{\text{ch}}$-range.

$N_{\text{ch}}/N_{\text{part}}$ vs $N_{\text{part}}$

- CL1, V0M and V0A: increases more than linearly (multiplicity bias)
- Not for Glauber-Gribov model
- ZNA: saturation above $N_{\text{part}} \approx 13$

Hybrid: nearly perfect scaling with $N_{\text{part}}$
Summary

- **Multiplicity Estimators**: bias on the hardness of the pN collisions (quantified by the number of hard scatterings per pN collision).
  - For $Q_{pA}$: include full dynamical bias (incoherent superposition of pN collisions) → Glauber + pp

- **ZDC Estimator**: expected to be insensitive to bias
  Establish a geometry-related particle scaling with a better than 10% precision entirely data-driven approach!
Assumptions on particle scaling:
  - Mid-Mult $\sim N_{\text{part}}$, Forward-Mult $\sim N_{\text{part}}^{\text{target}}$, High-$p_T$ $\sim N_{\text{coll}}$
    → one implies the other two!
  → Unbiased centrality determination in pA collisions!

- Centrality dependence of particle production measured:
  → $N_{\text{ch}}$ scales with $N_{\text{part}}$
  → $Q_{pA}$ consistent with 1 at high-$p_T$

- **Strong constrains on the models describing particle production in HI collisions**
Extra
<table>
<thead>
<tr>
<th>Event Activity</th>
<th>$N_{\text{coll}}$</th>
<th>Method</th>
<th>$Q_{p\text{Pb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL1</td>
<td>$N_{\text{CL1 coll}}^\text{CL1}$</td>
<td>Glauber+NBD fit</td>
<td>$Q_{p\text{Pb}}^{\text{CL1}}$</td>
</tr>
<tr>
<td>V0M</td>
<td>$N_{\text{Glauber coll}}^{\text{V0M}}$</td>
<td>Glauber+NBD fit</td>
<td>$Q_{p\text{Pb}}^{\text{Glauber}}$</td>
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<tr>
<td>V0A</td>
<td>$N_{\text{coll}}^{\text{V0A}}$</td>
<td>Glauber+SNM fit</td>
<td>$Q_{p\text{Pb}}^{\text{V0A}}$</td>
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<tr>
<td>ZNA</td>
<td>$N_{\text{coll}}^{\text{ZNA}}$</td>
<td>Glauber+SNM fit</td>
<td>$Q_{p\text{Pb}}^{\text{ZNA}}$</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{coll}}^{\text{mult}}$</td>
<td>assuming $(dN/d\eta)<em>{-1&lt;\eta&lt;0} \propto N</em>{\text{part}}$</td>
<td>$Q_{p\text{Pb}}^{\text{mult}}$</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{coll}}^{\text{Pb-side}}$</td>
<td>assuming V0A ring $1 \propto N_{\text{target part}}$</td>
<td>$Q_{p\text{Pb}}^{\text{Pb-side}}$</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{coll}}^{\text{high-pt}}$</td>
<td>assuming $(dN/dp_T)<em>{p_T&gt;10\text{GeV/c}} \propto N</em>{\text{coll}}$</td>
<td>$Q_{p\text{Pb}}^{\text{high-pt}}$</td>
</tr>
</tbody>
</table>
- **Nuclear density profile: Woods–Saxon (2pF)**
  - Radius = 6.62 ± 0.06 fm
  - Skin depth = 0.546 ± 0.01 fm
  - Intra-nucleon distance = 0.4 ± 0.4 fm
- **Cross-section** $\sigma_{NN} = 70 \pm 5$ mb
- **Proton radius** $R_p = 0.6 \pm 0.2$ fm
Slow Nucleon Model

PROTONS

⇒ E910 (p-Au @ 18 GeV/c) fit to $N_{\text{gray}}$ vs. $N_{\text{coll}}$ to determine the average number of gray protons

\[ \langle N_{\text{gray}} \rangle = (c_0 + c_1 N_{\text{coll}} + c_2 N_{\text{coll}}^2) \left( \frac{A_{\text{Pb}}}{A_{\text{Au}}} \right)^{2/3} \]

⇒ COSY (p-Au @ 2.5 GeV) measured the fraction of black over gray protons for the average number of black protons

\[ \langle N_{\text{black}} \rangle = f_{\text{blackovergray}} \times \langle N_{\text{gray}} \rangle \]

\[ f_{\text{blackovergray}} = 0.65 \]

⇒ $N_{\text{gray}}$, $N_{\text{black}}$ extracted from binomial distributions

NEUTRONS

⇒ from COSY: Light Charged Particle ($Z\leq 7$)

\[ \text{LCP} = \left( \langle N_{\text{gray}} \rangle + \langle N_{\text{black}} \rangle \right)/\alpha \]

\[ \alpha = 0.585 \quad (\text{COSY is left free}) \]

\[ \langle N_{\text{slow}} \rangle = \langle N_{\text{black}} \rangle + \langle N_{\text{gray}} \rangle = a + b/(c-\text{LCP}) \quad a, b, c \text{ can be finely tuned} \]

⇒ results from p induced spallation reactions (0.1-10 GeV) for the fraction of black/gray neutrons

\[ \langle N_{\text{black}} \rangle = 0.9 \times \langle N_{\text{slow}} \rangle \]

⇒ $N_{\text{gray}}$, $N_{\text{black}}$ extracted from binomial distributions
Slow Nucleon Model

- Features of $N_{ch} \sim$ independent of $E_{\text{projectile}}$ (1GeV $\rightarrow$ 1 TeV)

- **Slow nucleons** emission dictated by collision geometry $\rightarrow$ Maxwell-Boltzmann (independent statistical emission) classified from emulsion experiments
  - Gray: soft nucleons knocked out by wounded nucleons
  - Black: low energy target fragments from de-excitation, evaporation

- Glauber model $\rightarrow$ distribution of $N_{\text{coll}}$

- implemented model used a parameterization of results from low energy experiments
  C. Oppedisano https://edms.cern.ch/document/682801/1
  F. Sikler, hep-ph/0304065
Insights from Monte Carlo

$N_{\text{coll}}$ scaling: $n_{\text{hard}}/N_{\text{coll}} = \text{const.}$

Number of hard scatterings per p-N collision
- vs $N_{\text{coll}}$ (no multiplicity bias here!)
- Deviation from $N_{\text{coll}}$ scaling
  - at low $N_{\text{coll}}$: geometry $b_{\text{NN}}$
  - at high $N_{\text{coll}}$: energy conservation (break down of factorization)

p-Pb collisions described as incoherent superposition of nucleon-nucleon
- vs centrality from multiplicity $|\eta| < 1.4$
- only multiplicity bias
- strong deviation from $N_{\text{coll}}$-scaling at low and high centralities.
ZNA correlations

![ZNA correlations graph](image)
Detectors used for Centrality

Particle production modeled by Negative Binomial Distribution (NBD)

Nucleus fragmentation model:
Black nucleons: evaporation
Grey nucleons: knock-out
(eg C.Oppedisano https://edms.cern.ch/document/682801/1
F. Sikler arXiv: 0304.065)

Slow Nucleons
Detectors used for Centrality

**MID-RAPIDITY**

- TPC+ITS Tracks $|\eta| < 0.9$
- 2 layers Si Pixel $|\eta| < 2$ ; $|\eta| < 1.4$

**ZERO-DEGREE**

- Quartz-Fiber “Spaghetti” Zero Degree Calorimeters
- $z = \pm 112.5$ m

VZERO Scintillators

$z = 340$ cm $2.8 < \eta < 5.1$

$z = -90$ cm $-3.7 < \eta < -1.7$

Particle production modeled by Negative Binomial Distribution

Pb-fragmentation more relevant at forward rapidity

Centrality Estimators:

- **CL1**: Clusters in 2nd Pixel Layer
- **V0M**: VZERO-A+C Multiplicity
- **V0A**: VZERO-A Multiplicity
- **ZNA**: ZDC-A Neutron Energy

ZDC sensitive to slow nucleons

Nucleus fragmentation model:
- Black nucleons: evaporation
- Grey nucleons: knock-out
Glauber Fit

Glauber + Negative Binomial Distribution

- Centrality classes: Multiplicity distribution sliced into percentiles of cross-section
- Obtain $P(N_{\text{coll}})$ from Glauber MC
- For each $N_{\text{coll}}$ obtain
  - Multiplicity from NBD
  - Slow nucleons from SNM
- Obtain $\langle N_{\text{coll}} \rangle$ for each centrality class

Glauber MC Parameters

$$\rho(r) = \rho_0 \frac{1}{1 + \exp \left( \frac{r - R}{a} \right)}$$

- $R = 6.62 \pm 0.06$ fm
- $a = 0.546 \pm 0.01$ fm
- Minimum NN distance: $0.4 \pm 0.4$ fm
- pN Cross-section: $\sigma_{pN} = 70 \pm 5$ mb
- Proton radius: $R_p = 0.6 \pm 0.2$ fm
Ncoll from Glauber Fits

- \( <N_{\text{coll}}^{\text{Glauber}} > \) similar for different estimators
- Except for peripheral events, also similar to b-slicing
- Systematic error estimated by varying Glauber MC parameters.
- MC closure test performed with HIJING
Multiplicity Bias in pA

- **Multiplicity bias**: fluctuations sizable → Bias on Mult/\(N_{\text{part}}\) at central and peripheral collisions

- MC models with multi-parton interaction (MPI) include fluctuations of particle sources (hard scatterings)
  HIJING (X.N. Wang, M. Gyulassy, nucl-th/9502021)

→ bias in mult ~ bias in hard scattering

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Bias in pA -- peripheral

- **Jet-veto**: multiplicity range in peripheral events represent an effective veto on hard processes

- **Geometry bias**
  Mean nucleon-nucleon impact parameter \( b_{NN} \) increases in peripheral collisions

- Due to MPI, mult. fluctuations depend on fluctuations in particle sources (hard scatterings)
  - Mean number of scatterings per event obtained from impact parameter \( b_{NN} \)-dependent proton-nucleon overlap function \( T_N(b_{NN}) \)

\[
\rightarrow \text{bias in mult} \sim \text{bias in hard scattering emphasized at peripheral}
\]
Scaling of particle production

- Scaling studied by defining so called self-normalized signals $\langle S \rangle_i / \langle S \rangle_{MB}$ vs self-normalized mid-rapidity $dN/d\eta(-1<\eta_{lab}<0)$

  - Fit: assuming mid-rapidity $dN/d\eta$ scales with $N_{part}$
    
    $\alpha = 0$ – perfect $N_{part}$ scaling
    $\alpha = 1$ – perfect Ncoll (or $N_{target\_part}$) scaling
    $\alpha$ has clear meaning ($N_{part}$ vs Ncoll scaling)

\[ \frac{\langle S \rangle_i}{\langle S \rangle_{MB}} = \frac{\langle N_{part} \rangle_{MB} - \alpha}{\langle N_{part} \rangle_{MB}} \cdot \left( \frac{\langle dN/d\eta \rangle_i}{\langle dN/d\eta \rangle_{MB}} \right)_{-1<\eta<0} - \frac{\alpha}{\langle N_{part} \rangle_{MB} - \alpha} \]

\[ \frac{\langle S \rangle_i}{\langle S \rangle_{MB}} = \frac{\langle N_{part} \rangle_{MB}^\beta}{\langle N_{part} \rangle_{MB}} \cdot \left( \frac{\langle dN/d\eta \rangle_i}{\langle dN/d\eta \rangle_{MB}} \right)^\beta_{-1<\eta<0} \]

\[ \beta = 0 \] – perfect $N_{part}$ scaling
Scaling vs $\eta_{\text{CMS}}$

- PHOBOS d-Au dN/deta(eta) data, $\eta \rightarrow 1.6 \times \eta$ (beam rapidity RHIC $\rightarrow$ LHC)
- Similar dependence between our and PHOBOS data, except forward nucleus-going direction
- High-pT and inner VZERO-A ring quite similar, delta(alpha)$\sim$0.2
- Mid-rapidity vs inner VZERO-A is not perfect Npart vs Ncoll scaling, delta(alpha)$\sim$1.2

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Hybrid Method

1) assumption: ZN insensitive to dynamical biases $\rightarrow$ slice events in ZNA

2) assumption:
   a) Mid-rap (-1<$\eta_{lab}$<0) $dN/d\eta$ scales with $N_{\text{part}}$
   b) Forward multiplicity in Pb-going direction scales with $N_{\text{part target}}$ (= $N_{\text{coll}}$ in pA)
      innermost ring of VZERO-A as a proxy
   c) Mid-rap $dN/d\eta$ at high-$p_T$ (10<$p_T$<20 GeV/c) scales with $N_{\text{coll}}$ all values within at most 10%
      $\rightarrow$ assumptions consistent within some good approximation
      Of course, this does not prove the validity of any (or all) of these assumptions

\[
\langle N_{\text{coll}} \rangle_i = \langle N_{\text{coll}} \rangle_{MB} \cdot \frac{\langle dN/d\eta \rangle_i}{\langle dN/d\eta \rangle_{MB}}^{-1 < \eta < 0}
\]
\[
\langle N_{\text{coll}} \rangle_i = \langle N_{\text{part}} \rangle_i - 1
\]
**Mean $Q_{pPb}$ at $p_T > 10$ GeV**

- $p$-Pb collisions described as incoherent superposition of nucleon-nucleon
  - vs centrality from multiplicity $|\eta| < 1.4$
  - only multiplicity bias
  - strong deviation from $N_{coll}$-scaling at low and high centralities.

- from multiplicity bias (Glauber + NBD fit)
- from Toy-MC (Glauber + Pythia)
Shape flattens with increasing rapidity gap
CL1→V0M→V0A
$Q_{pA}$ flat for hybrids
Bias from different estimators

• Different centrality estimators → different deviations from Ncoll scaling

  • **CL1 (Clusters Pixel Layer 2):** strong bias due to full overlap with tracking region.
    
    – Additional bias in peripheral event from “Jet veto effect”
    
    – Jets contribute to the multiplicity and shift events to higher centralities ($p_T$ - dependent)

  • **V0M (V0A+V0C Multiplicity):** reduced bias since outside tracking region

  • **V0A Multiplicity:** reduced bias because of important contribution from Pb fragmentation region.

  • **ZNA:** small bias slow nucleon production independent of hard processes

\[
Q_{pA}(p_T; \text{cent}) = \frac{d N^{pA}/d p_T}{N^{Glauber}_{\text{coll}}} = \frac{d N^{pA}/d p_T}{T^{Glauber}_{pA} d \sigma^{pp}/d p_T} \neq 1
\]

At high $p_T$

In general $N_{\text{coll}}$ for a given centrality class can not be used to scale the pp cross-section!
# Glauber-Gribov

<table>
<thead>
<tr>
<th>Centrality (%)</th>
<th>( N_{\text{part}} \times \text{NBD} )</th>
<th>( N_{\text{coll}} \times \text{NBD} )</th>
<th>( N_{\text{part}} \times \text{NBD} )</th>
<th>( N_{\text{coll}} \times \text{NBD} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5</td>
<td>14.8</td>
<td>14.9</td>
<td>17.8</td>
<td>19.2</td>
</tr>
<tr>
<td>5 - 10</td>
<td>13.0</td>
<td>13.2</td>
<td>14.4</td>
<td>15.2</td>
</tr>
<tr>
<td>10 - 20</td>
<td>11.7</td>
<td>11.8</td>
<td>12.0</td>
<td>12.5</td>
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<td>9.36</td>
<td>9.49</td>
<td>8.82</td>
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<td>6.42</td>
<td>6.49</td>
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<td>3.81</td>
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<td>1.94</td>
<td>1.85</td>
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<td>1.43</td>
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<td>0 - 100</td>
<td>6.87</td>
<td>6.87</td>
<td>6.73</td>
<td>6.75</td>
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