Probing QGP with flow
(including system size and energy dependence)

An experimental overview

Katarína Křížková Gajdošová
Czech Technical University in Prague

7th November 2019
This talk ...

• ... is about an overview of the latest results and developments in the field
• ... is not about summary of Quark Matter 2019 parallel talks
  • Although we did see quite a lot of new results and interesting implications, which I cannot ignore
• ... has only 25 minutes, so I apologise in advance if I do not include your work

Pointers to talks / posters:

Speaker, day@time

Results that are currently on the slide

Speaker, day@time

Similar results that did not fit in

New result from this Quark Matter

New result since last Quark Matter

New at QM19
What do we know: from AA down to pp

$V_2 \sim 0.1 \text{ fm/c}$

"Pre-equilibrium"

Courtesy of Wei Li
What do we know: from AA down to pp

Initial state geometry (overlapping nucleons) → In-medium interactions → Final momentum anisotropy

$V_2 \approx 0.1 \text{ fm/c}$

Peripheral → Central

AuAu/PbPb

He$^3$Au, OO, ArAr?

LM → HM

“Pre-equilibrium”

Courtesy of Wei Li
What do we know: from AA down to pp

Initial state geometry (overlapping nucleons) → In-medium interactions → Final momentum anisotropy

He³Au, OO, ArAr?

Peripheral

Central

AuAu/PbPb

“Pre-equilibrium”

Initial state geometry (sub-nucleon fluctuations) / gluon field momentum correlations

In-medium interactions

Final momentum anisotropy

Courtesy of Wei Li
What do we know: from AA down to pp

Initial state geometry (overlapping nucleons) → In-medium interactions → Final momentum anisotropy

"Precision" measurements: constraints on initial state, transport coefficients (η/s, ζ/s, ...)

V2

Peripheral

Central

AuAu/PbPb

He\textsuperscript{3}Au, OO, ArAr?

pp, pA?

"Pre-equilibrium"

Initial state geometry (sub-nucleon fluctuations) / gluon field momentum correlations → In-medium interactions → Final momentum anisotropy

Courtesy of Wei Li
What do we know: from AA down to pp

Initial state geometry (overlapping nucleons) → In-medium interactions → Final momentum anisotropy

“Precision” measurements:
- constraints on initial state, transport coefficients ($\eta/s$, $\zeta/s$, …)

“Decision” measurements:
- what is the origin of collectivity,
- what kind of medium are we talking about (if there is any)?

Initial state geometry (sub-nucleon fluctuations) / gluon field momentum correlations → In-medium interactions → Final momentum anisotropy
Large collision systems

Gale et al., Int.J.Mod.Phys. A28 (2013) 1340011

• Significant improvements in our understanding of heavy-ion collisions
  • **Theory**: Ideal hydro $\rightarrow$ viscous hydro with constant $\eta/s$ $\rightarrow$ viscous hydro with $\eta/s(T)$
  • **Experiment**: $v_2 \rightarrow v_n$ $\rightarrow$ identified hadron $v_n$ $\rightarrow$ fluctuations, …

• Large amount of data allows us to measure **more differential experimental measurements** $\rightarrow$ precision era

![Graph showing increasing precision of key observables and techniques developed over time.]

J. Bernhard, et al., PRC 94, 024907 (2016)

J-F. Paquet, Tuesday@17:40
Large collision systems

\[ P(\varphi) = \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} V_n e^{-in\varphi} \]

\[ V_n = v_n e^{in\Psi_n} \]

Flow vector magnitude

Flow vector fluctuations

Flow vector correlations

Flow of identified hadrons

Flow coefficients \((v_n)\)

Flow de-correlations \((p_T, \eta)\)

Flow fluctuations

Event shape engineering

Symmetric cumulants

Non-linear flow modes

Light flavor flow

Heavy flavor flow

Energy dependence

System dependence
Large collision systems

\[ P(\varphi) = \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} V_n e^{-in\varphi} \]

\[ V_n = v_n e^{in\Psi_n} \]

Flow vector magnitude

Flow vector fluctuations

Flow vector correlations

Flow of identified hadrons

Flow coefficients \((v_n)\)

Flow de-correlations \((p_T, \eta)\)

Flow fluctuations

Event shape engineering

Symmetric cumulants

Non-linear flow modes

Light flavor flow

Heavy flavor flow

Energy dependence

System dependence

\[ P(\varphi) = \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} V_n e^{-in\varphi} \]

\[ V_n = v_n e^{in\Psi_n} \]
(Longitudinal) de-correlation of flow vector

J. Jia and P. Huo, PRC 90, 034905 (2014)

EbyE fluctuations in the initial state -> flow vector de-correlations

Constraints on fluctuation-driven longitudinal dynamics
Constraints on fluctuation-driven longitudinal dynamics

EbyE fluctuations in the initial state $\rightarrow$ flow vector de-correlations

$$r_n(\eta) = \frac{\langle V_n(-\eta)V_n^*(\eta_{ref}) \rangle}{\langle V_n(+\eta)V_n^*(\eta_{ref}) \rangle}$$

$$= \frac{\langle v_n(-\eta)v_n(\eta_{ref})\cos n(\Psi_n(-\eta) - \Psi_n(\eta_{ref})) \rangle}{\langle v_n(+\eta)v_n(\eta_{ref})\cos n(\Psi_n(+\eta) - \Psi_n(\eta_{ref})) \rangle}$$

EbyE fluctuations in the initial state $\rightarrow$ flow vector de-correlations

J. Jia and P. Huo, PRC 90, 034905 (2014)
(Longitudinal) de-correlation of flow vector

No de-correlation: \( r_n(\eta) = 1 \)

\[
v_n(-\eta) = v_n(+\eta) \\
\Psi_n(-\eta) = \Psi_n(+\eta)
\]

De-correlation: \( r_n(\eta) < 1 \)

EbyE fluctuations in the initial state -> flow vector de-correlations

\[
r_n(\eta) = \frac{\langle V_n(-\eta)V_n^*(\eta_{\text{ref}}) \rangle}{\langle V_n(+\eta)V_n^*(\eta_{\text{ref}}) \rangle}
= \frac{\langle v_n(-\eta)v_n(\eta_{\text{ref}})\cos n(\Psi_n(-\eta) - \Psi_n(\eta_{\text{ref}})) \rangle}{\langle v_n(+\eta)v_n(\eta_{\text{ref}})\cos n(\Psi_n(+\eta) - \Psi_n(\eta_{\text{ref}})) \rangle}
\]

Constraints on fluctuation-driven longitudinal dynamics
(Longitudinal) de-correlation of flow vector

- Strong energy dependence of $r_3(\eta)$

QM19 | 7th November 2019 | Wuhan, China
Katarina Krizkova Gajdosova | CTU in Prague
(Longitudinal) de-correlation of flow vector

- Strong energy dependence of $r_3(\eta)$
- XeXe vs. PbPb: sensitivity to initial geometry and viscous corrections

\[ \propto \frac{r_n(\eta)_{\text{XeXe}}}{r_n(\eta)_{\text{PbPb}}} \]

- Models tuned to describe $v_n$ cannot reproduce this measurement
Flow fluctuations

Constraints on initial state fluctuations

Parametrisation of $P(v_n)$:

Bessel-Gaussian

$$v_n\{4\} = v_n\{6\} = v_n\{8\}$$

$$\frac{v_n\{m\}}{v_n\{k\}} = 1$$

not Bessel-Gaussian

$$v_n\{4\} \neq v_n\{6\} \neq v_n\{8\}$$

$$\frac{v_n\{m\}}{v_n\{k\}} < 1$$

$$m > k$$

Reminder:

$$\sqrt[4]{-c_n\{4\}} = v_n\{4\}$$

$$\sqrt[6]{\frac{1}{4} c_n\{6\}} = v_n\{6\}$$

$$\sqrt[8]{-\frac{1}{33} c_n\{8\}} = v_n\{8\}$$
Flow fluctuations

Indication of a $p_T$ dependence of flow fluctuations \(-\) influence from the final state

$\frac{v_2(6)}{v_2(4)}$

$\frac{v_2(8)}{v_2(4)}$
Flow fluctuations

Models: particle species dependence

Data: no particle species dependence observed

\[ F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle} \]

\[ \sigma_{v_n} \approx \sqrt{\langle v_n \{2\}^2 - v_n \{4\}^2 \rangle / 2} \]

\[ \langle v_n \rangle \approx \sqrt{\langle v_n \{2\}^2 + v_n \{4\}^2 \rangle / 2} \]
Non-linear flow modes

\[ V_2 \propto \epsilon_2 \quad V_n = V_n^{NL} + V_n^L \]
\[ V_3 \propto \epsilon_3 \]

\[ V_4 = \chi_{4,22}(V_2)^2 + V_4^L \]

\[ \propto \epsilon_2^2 \quad \propto \epsilon_4 \]

Sensitive to both initial conditions and transport coefficients

New at QM19

ALICE, PLB 773 (2017) 68-80

Pb-Pb \( \sqrt{s}_{NN} = 2.76 \) TeV

0.2 < \( p_T < 5.0 \) GeV/c

|\( n \)| < 0.8

Centrality percentile
Non-linear flow modes

$V_2 \propto \epsilon_2$

$V_3 \propto \epsilon_3$

$V_n = V_n^{NL} + V_n^L$

e.g. $V_4 = \chi_{4,22}(V_2)^2 + V_4^L \propto \epsilon_2^2 \propto \epsilon_4$

Sensitive to both initial conditions and transport coefficients

Strong constraint on theory

- Measurements of identified particles

J. Parkkila, Wednesday @ 9:20
Non-linear flow modes

\[ V_2 \propto \epsilon_2 \quad V_n = V_{n}^{NL} + V_{n}^{L} \]

\[ V_3 \propto \epsilon_3 \]

e.g. \[ V_4 = \chi_{4,22}(V_2)^2 + V_4^L \]
\[ \propto \epsilon_2^2 \quad \propto \epsilon_4 \]

Sensitive to both initial conditions and transport coefficients

Strong constraint on theory

- Measurements of identified particles
- Measurements of high-order harmonics
Non-linear flow modes

\[ V_2 \propto \epsilon_2 \quad V_n = V_n^{NL} + V_n^L \]
\[ V_3 \propto \epsilon_3 \]

\( \text{e.g.} \quad V_4 = \chi_{4,22}(V_2)^2 + V_4^L \propto \epsilon_2^2 \propto \epsilon_4 \)

Sensitive to both initial conditions and transport coefficients

Strong constraint on theory

- Measurements of identified particles
- Measurements of high-order harmonics
- Energy dependence vanishes for \( \chi_{4,22} \)
- Dependence on collision system size vanishes for \( \chi_{4,22} \)

\[ \chi_{4,22} = \frac{u_{4,22}}{\sqrt{\langle V_2^4 \rangle}} \]
Heavy (bottom) flavor flow

- Heavy quark $b \rightarrow e(\mu)$ flows (compatible with ALICE, ATLAS, STAR observations)

- Flow of charm > flow of beauty

Quarkonia summary: Z. Tang, Friday@15:30

Heavy quarks summary: J. Wang, Friday@14:00
Large collision systems

\[ P(\varphi) = \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} V_n e^{-in\varphi} \]

\[ V_n = v_n e^{in\Psi_n} \]

- **New constraints on theory**
  - Flow vector magnitude
  - Flow vector fluctuations
  - Flow vector correlations
  - Flow of identified hadrons
  - Flow coefficients (\(v_n\))
  - Flow de-correlations (\(p_T, \eta\))
  - Flow fluctuations
  - Event shape engineering
  - Symmetric cumulants
  - Non-linear flow modes
  - Light flavor flow
  - Heavy flavor flow
  - Energy dependence
  - System dependence

New at QM19
From large to small collision systems

• Is there collectivity in small systems?
• What is the origin of collectivity?

We need “decision / discovery” measurements.
From large to small collision systems

- Is there collectivity in small systems?
- What is the origin of collectivity?

We need “decision / discovery” measurements.

Decision: Is there collectivity or not?

Decision: Do we create similar medium as in large systems or not?

Long-range multi-particle correlations

Flow of identified hadrons
Response to initial geometry?
Symmetric cumulants
Heavy flavor flow
High-pT flow: jet quenching?
Novel geometric configurations

Energy dependence
System dependence
From large to small collision systems

• Is there collectivity in small systems?
• What is the origin of collectivity?

\{ We need “decision / discovery” measurements.

Decision:
Is there collectivity or not?

\textbf{Long-range multi-particle correlations}

\begin{itemize}
  \item Flow of identified hadrons
  \item Response to initial geometry?
  \item Symmetric cumulants
  \item Heavy flavor flow
  \item High-pT flow: jet quenching?
  \item Novel geometric configurations
\end{itemize}

Energy dependence
System dependence
Long-range correlations

- Long-range correlations in pseudorapidity observed even at the smallest collision system

CMS, JHEP 09 (2010) 091
• Long-range correlations in pseudorapidity observed even at the smallest collision system
• Ridge persists up to very large $\Delta \eta$
  - $p$-Pb: $\Delta \eta \sim 8$
  - $pp$: $\Delta \eta \sim 6$
Collectivity down to pp collisions

Collectivity: long-range multi-particle correlations

CMS, PLB 765, 193 (2017)
Collectivity down to low energies

Collectivity: long-range multi-particle correlations

CMS, PLB 765, 193 (2017)

STAR, Quark Matter 2018

Efficiency Corrected TPC Multiplicity
What is the origin of collectivity?

**Initial State (IS)**
- Initial momentum correlations
- CGC

Not correlated to initial geometry

Color correlations between gluon domains

\[ V_2 \sim 0.1 \text{ fm/c} \]

- Peripheral: AuAu/PbPb
- Central: He\(^3\)Au, OO, ArAr?
- LM: \( pp, pA? \)
- HM: "Pre-equilibrium"

Courtesy of Wei Li
What is the origin of collectivity?

**Initial State (IS)**
- Initial momentum correlations
- CGC

**Final State (FS)**
- Initial spatial anisotropy + interactions in the final state
- Hydrodynamics
- Parton transport / escape

- Not correlated to initial geometry
- Color correlations between gluon domains

- Correlated to initial geometry
- Sub-nucleon fluctuations

**Notation:**
- $v_2 \approx 0.1 \text{ fm/c}$
- Peripheral and Central
- AuAu/PbPb
- He$^3$Au, OO, ArAr?
- pp, pA?
- LM and HM
- “Pre-equilibrium”

Courtesy of Wei Li
What is the origin of collectivity?

Initial State (IS)
- Initial momentum correlations
- CGC

Not correlated to initial geometry

Color correlations between gluon domains

Final State (FS)
- Initial spatial anisotropy + interactions in the final state
- Hydrodynamics
- Parton transport / escape

Correlated to initial geometry

Sub-nucleon fluctuations

Need to investigate with more experimental data and comparison to models.
✓ Mass-ordering
✓ Particle-type grouping

What do measurements tell us?

ALICE, QM18

CMS pp $\sqrt{s} = 13$ TeV CMS, PLB 765, 193-220 (2017)

PHENIX, PRC 97, 064904 (2018)
What do measurements tell us?

✓ Mass-ordering
✓ Particle-type grouping
✓ Geometry-driven

**What do measurements tell us?**

- Mass-ordering
- Particle-type grouping
- Geometry-driven

**Graphical Content:**

- Graph a: \( p + Au \) \( \sqrt{s_{NN}} = 200 \text{ GeV} \) 0–5%
- Graph b: \( d + Au \) \( \sqrt{s_{NN}} = 200 \text{ GeV} \) 0–5%
- Graph c: \( \text{He} + Au \) \( \sqrt{s_{NN}} = 200 \text{ GeV} \) 0–5%

**Equations:**

- PHENIX

**ArXiv:**

- 1904.11519

**Graphical Data:**

- CMS
- 0.3 < \( p_T < 3.0 \) GeV/c
- \( \eta | < 2.4 \)
- \( p \) \( \text{Pb} \)
- \( p \text{Pb} 5.02 \text{ TeV} \)
- \( p \text{Pb} 8.16 \text{ TeV} \)

**Analysis:**

- Fluctuation-Driven Eccentricities

**Table:**

<table>
<thead>
<tr>
<th>CMS</th>
<th>arXiv: 1904.11519</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 &lt; ( p_T &lt; 3.0 ) GeV/c</td>
<td></td>
</tr>
<tr>
<td>( \eta</td>
<td>&lt; 2.4 )</td>
</tr>
<tr>
<td>( p ) ( \text{Pb} )</td>
<td></td>
</tr>
<tr>
<td>( p \text{Pb} 5.02 \text{ TeV} )</td>
<td></td>
</tr>
<tr>
<td>( p \text{Pb} 8.16 \text{ TeV} )</td>
<td></td>
</tr>
</tbody>
</table>

**Graphical Representation:**

- Graph a: \( p + Au \) \( \sqrt{s_{NN}} = 200 \text{ GeV} \) 0–5%
- Graph b: \( d + Au \) \( \sqrt{s_{NN}} = 200 \text{ GeV} \) 0–5%
- Graph c: \( \text{He} + Au \) \( \sqrt{s_{NN}} = 200 \text{ GeV} \) 0–5%

**Graphical Analysis:**

- PHENIX
What do measurements tell us?

- Mass-ordering
- Particle-type grouping
- Geometry-driven
- Described by hydrodynamics

What is the origin of collectivity?

**Initial State (IS)**
- Initial momentum correlations
- CGC

**Final State (FS)**
- Initial spatial anisotropy + interactions in the final state
- Hydrodynamics
- Parton transport / escape

Data seem to favor the final state description (origin similar to large systems)

- Peripheral
- AuAu/PbPb
- He³Au, OO, ArAr?
- Central
- LM
- pp, pA?
- HM

**Sub-nucleon fluctuations**

- Not correlated to initial geometry
- Color correlations between gluon domains

- Correlated to initial geometry

**Initial State (IS)**

**Final State (FS)**

Sub-nucleon fluctuations

Data seem to favor the final state description (origin similar to large systems)

Initial momentum correlations

CGC
Beware of gaps in the FS description

Hydrodynamics fails to describe the negative $c_2\{4\}$ no matter what the $\varepsilon_2\{4\}$ is.

Zhao et al., PLB 780, 495 (2018)
What is the origin of collectivity?

Initial State (IS)
- Initial momentum correlations
- CGC

Final State (FS)
- Initial spatial anisotropy + interactions in the final state
- Hydrodynamics
- Parton transport / escape

Not correlated to initial geometry
Color correlations between gluon domains

There is still a lot to understand. -> We need more measurements.

Courtesy of Wei Li
Small systems scan @ RHIC

\[ v_2(\text{STAR}) \approx v_2(\text{PHENIX}) \]
\[ v_3(\text{STAR}) \neq v_3(\text{PHENIX}) \]

- STAR measurements of \( v_3 \) are system independent
- Large difference between \( v_3 \) needs to be understood
• STAR measurements of $v_3$ are system independent
  • Large difference between $v_3$ needs to be understood
  • STAR measurements consistent with the important role of sub-nucleonic fluctuations
Jet quenching: is there, or is not there?

K. Keys Hill, Tuesday@11:20

\[ v_2(p_T) > 0 \quad \text{and} \quad v_2(p_T) > 0 \]

**EXPERIMENT**

**THEORY**
Jet quenching: is there, or is not there?

No evidence for jet quenching yet.

### EXPERIMENT

<table>
<thead>
<tr>
<th>$v_2(p_T)$</th>
<th>$R_{pPb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; 0$</td>
<td>$\approx 1$</td>
</tr>
</tbody>
</table>

### THEORY

<table>
<thead>
<tr>
<th>$v_2(p_T)$</th>
<th>$R_{pPb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; 0$</td>
<td>$&lt; 1$</td>
</tr>
</tbody>
</table>

- Do we really observe no jet quenching in small systems?
- Biases coming from event selection (ALICE, PLB 793 (2019) 420-432)
Flow of heavy flavor quarks

- Bottom quark **doesn’t flow** in small systems (Note: In large systems bottom quark flows)
- While charm quark does

---

**ATLAS**

\( pp, \sqrt{s} = 13 \text{ TeV}, 150 \text{ pb}^{-1} \)

- 4<\( p_T \)<6 GeV
- 1.5<\( |\Delta\eta| \)<5

\[ c\rightarrow\mu \]
\[ b\rightarrow\mu \]

**CMS Preliminary**

pPb 186 nb\(^{-1}\) (8.16 TeV)

- \( v_{2\,\{2\}} \)
- \( p_T \) (GeV)

**New at QM19**

S. Tang, Tuesday@16:40

Heavy quarks summary: J. Wang, Friday@14:00

ATLAS, arXiv:1909.01650

---

Katarina Krizkova Gajdosova | CTU in Prague
Summary

Large systems

• Exhaustive number of detailed measurements
• New constraints on theoretical calculations, new inputs for Bayesian analysis, …

Small systems

• Many new measurements available to challenge our understanding of small systems
• Final state seems to be important to describe data, but the influence from the initial state cannot be ignored (especially at low multiplicities)
• What is the relative contribution of IS and FS?
• Joined experimental (and theoretical) effort to …
  • … define observables that allow us to answer the above question
  • … define a precise event class selection common to all experiments and reproducible by theory
  • … properly deal with non-flow effects

Many thanks to: Y. Zhou, M. van Leeuwen, J. Jia, S. Esumi, W. Li, K. Safarik, B. Trzeciak, C. Loizides
• Sign change of multi-particle cumulants -> **Influence from centrality fluctuations within a fixed centrality bin**, M. Zhou, J. Jia, PRC 98, 044903 (2018)

• “Wrong” sign of cumulants is not necessarily incorrect -> hint for new parametrisation of $P(v_n)$ in ultracentral collisions?

**Normalized cumulant:**

$$ nc_2\{4\} = \frac{c_2\{4\}}{c_2\{2\}^2} = \frac{\langle v_2^4 \rangle - 2\langle v_2^2 \rangle^2}{\langle v_2^2 \rangle^2} $$

**Reminder:**

$$ 4 \sqrt{-c_n\{4\}} = v_n\{4\} \quad \text{real-valued flow coefficient} $$

**ATLAS, arXiv:1904.04808**
Event-shape engineering

Reduced flow vector:

\[ q_n = \frac{|Q_n|}{\sqrt{M}} \]

EbyE fluctuations in the initial state -> flow fluctuations within a fixed centrality

<table>
<thead>
<tr>
<th>Centrality 0-1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-0.1</td>
</tr>
</tbody>
</table>

-> select events based on initial (geometrical) shape

-> further opportunity to constrain the initial conditions

ATLAS, PRC 92, 034903 (2015)
Event-shape engineering

No $p_T$ dependence: same source of flow fluctuations (geometrical)

No dependence on particle species found

ALICE Preliminary

Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV

30–40% $|\eta| < 0.8$

$2\times v_{2}(\Delta\eta|>2)$ (q$_2$/unbiased)

$P_T$ (GeV/c)

- $h^+$
- $h^+ |\eta| < 0.8$
- PID $|y| < 0.5$

Full markers: 0–10% $q_{2}^{VOC}$

Open markers: 90–100% $q_{2}^{VOC}$

ALI–PREL–336302

ALI–PREL–335418
Where do observations of collectivity stop?

- **Photo-nuclear (≈ meson-nuclear) collisions**
  - Collision energy depends on the photon energy

- **ep collisions**
  - \( c_2(2, |\Delta \eta| > 2.0) \approx 0 \)
  - Large statistical fluctuations, still room for small flow signal

- **e^+e^- collisions**
  - No ridge observed

---

**ATLAS-CONF-2019-022**

**ZEUS, Quark Matter 2018**

Relative contribution from IS and FS

- Correlation of $v_n$ with geometry
  - Increases with multiplicity

- Correlation of $v_n$ with initial momentum anisotropy
  - Decreases with multiplicity
• Proposal for new collision systems: OO

### Year | Systems, $\sqrt{s_{NN}}$ | Time | $L_{int}$ | @LHC
--- | --- | --- | --- | ---
2022 | Pb–Pb 5.5 TeV | 5 weeks | 3.9 nb$^{-1}$ | 
2022 | O–O, p–O | 1 week | 500 $\mu$b$^{-1}$ and 200 $\mu$b$^{-1}$ | 

<table>
<thead>
<tr>
<th>Single-Beam Energy (GeV/n)</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>Run Time</th>
<th>Species</th>
<th>Events (MinBias)</th>
<th>Priority</th>
<th>Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>200</td>
<td>1 week$^2$</td>
<td>O–O</td>
<td>400M</td>
<td>3</td>
<td>8</td>
</tr>
</tbody>
</table>