The Quark Gluon Plasma: A Look Inside the Hottest Matter in the Universe

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March 12, 2019

how hot?

how hot?

80 ° F

how hot?

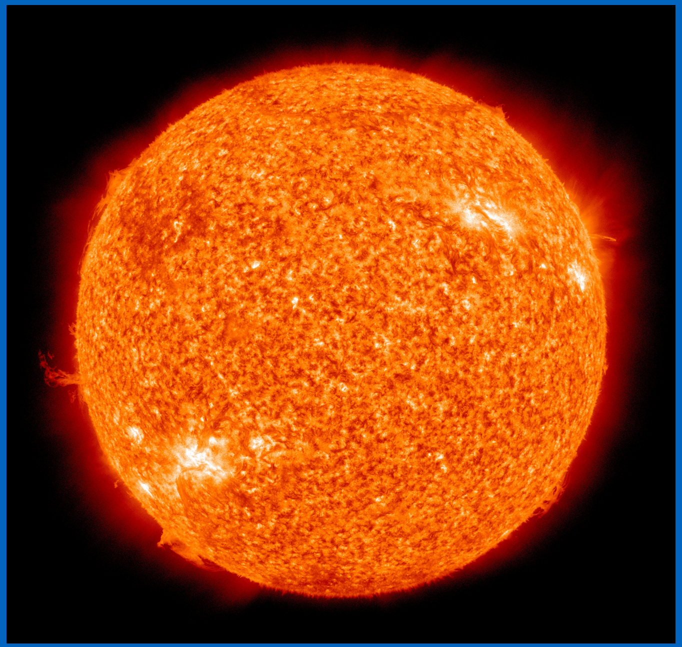
80 ° F

2000 ° F

how hot?

80 ° F

2000 ° F

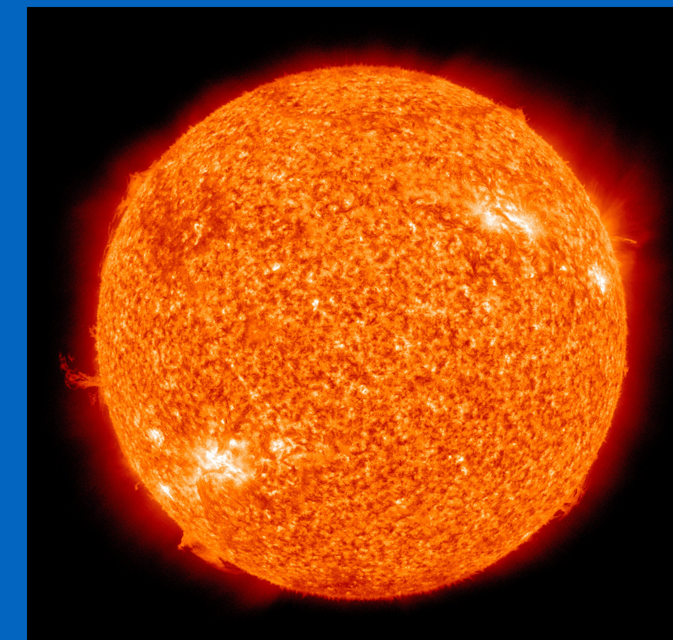


28M ° F

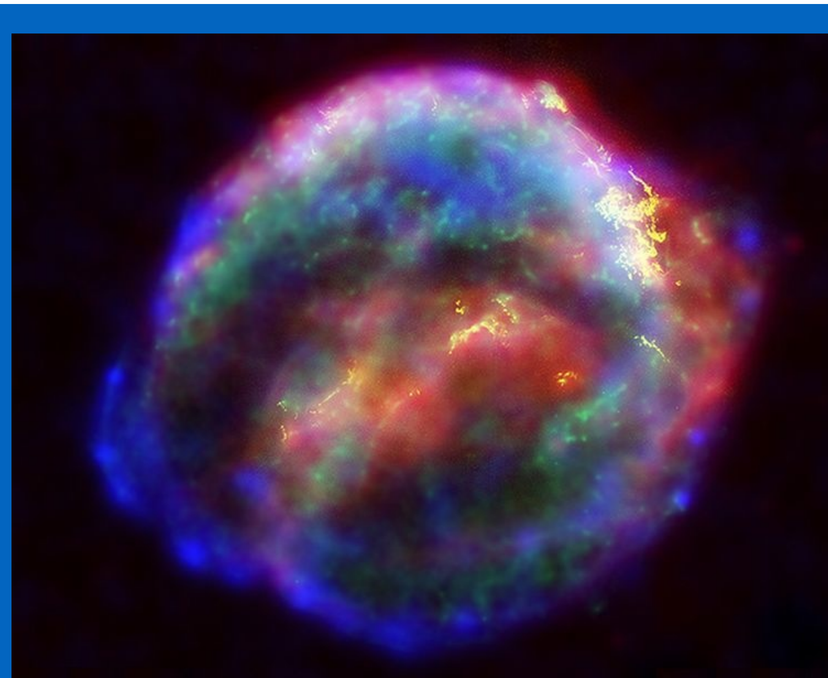
how hot?

80 ° F

2000 ° F



28M ° F

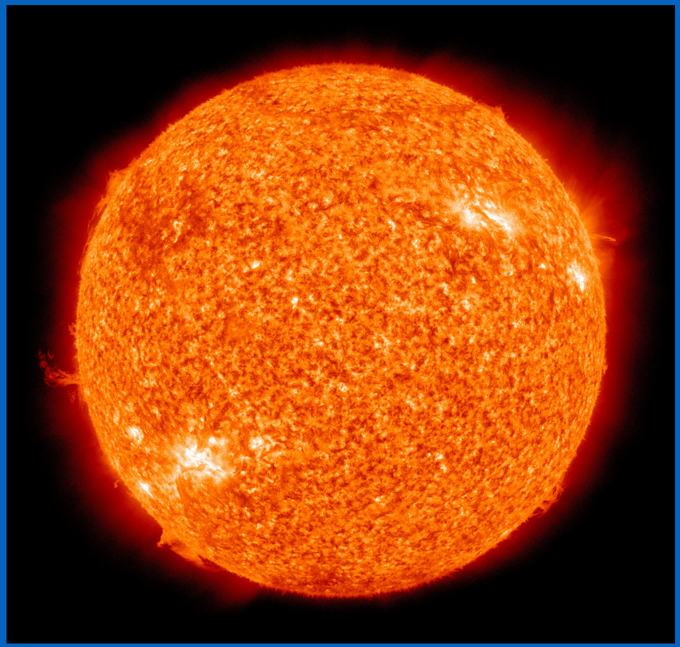


150B ° F

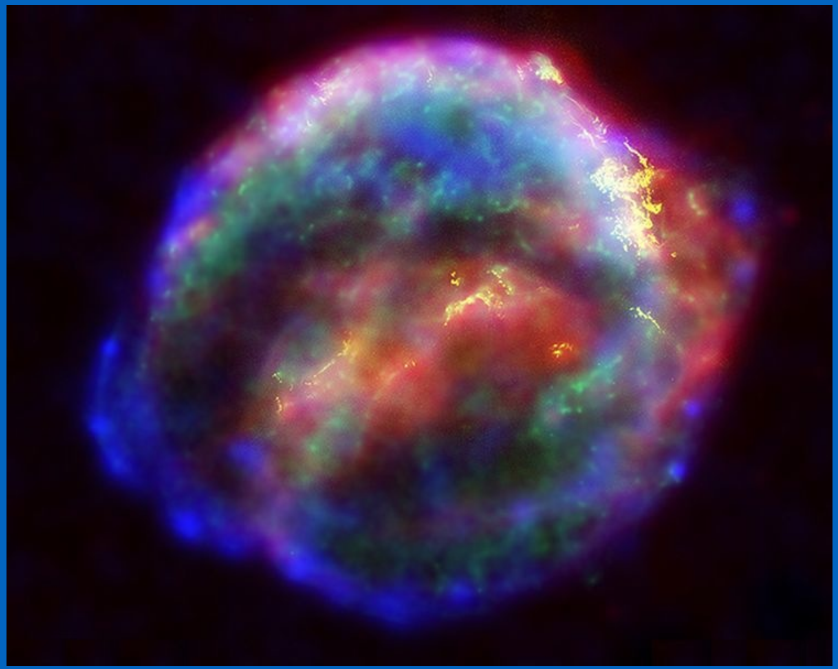
how hot?

80 ° F

2000 ° F



28M ° F



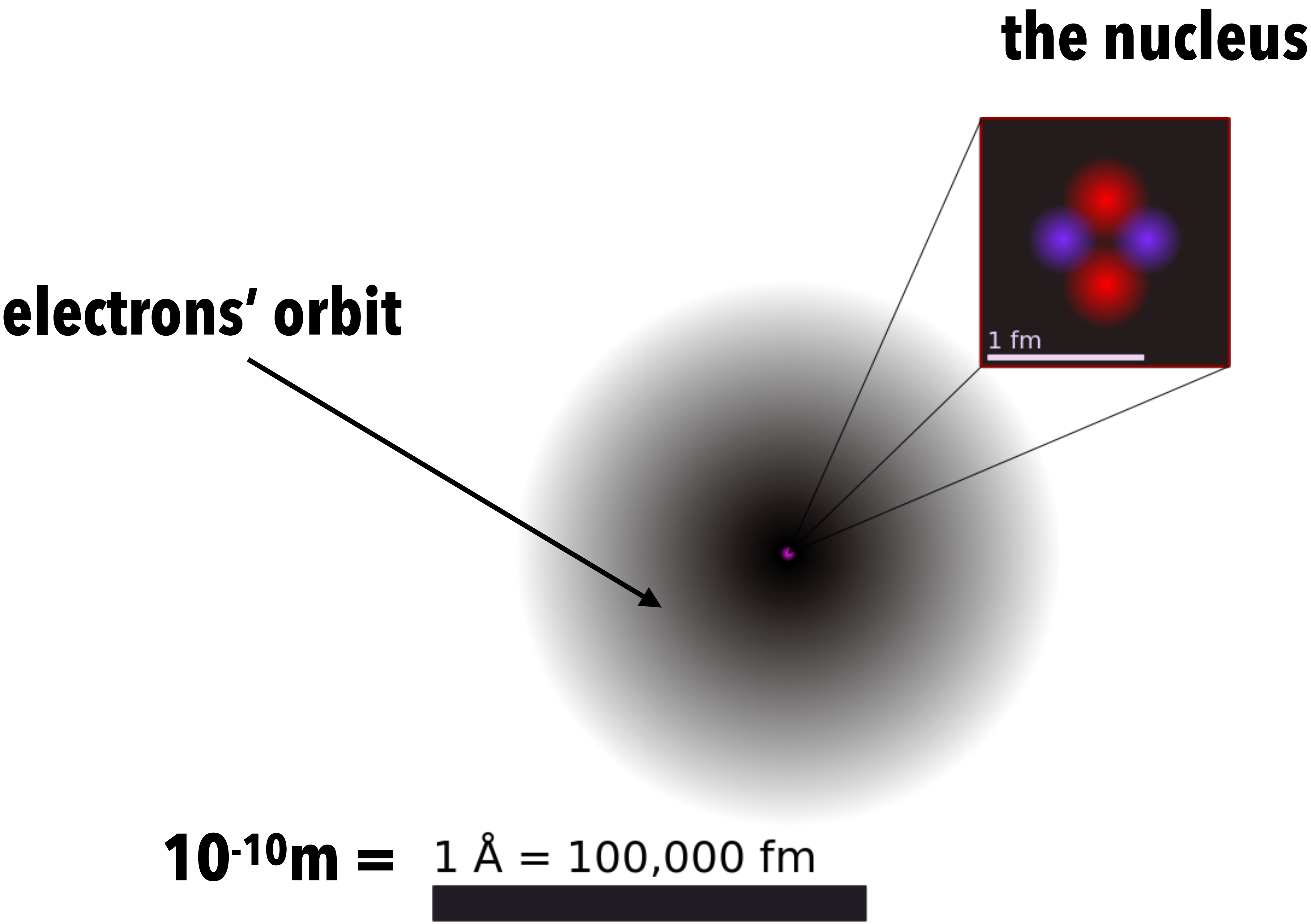
150B ° F

quark-gluon plasma

no photo available

5T ° F

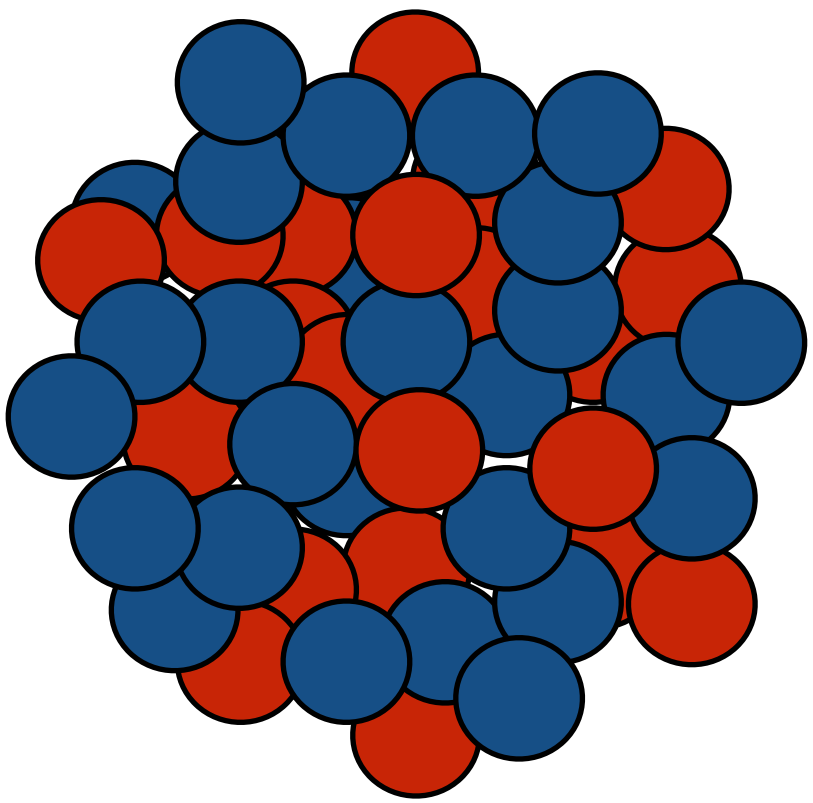
what is inside an atom?



10^{-10}m =

image: wikipedia

the nucleus

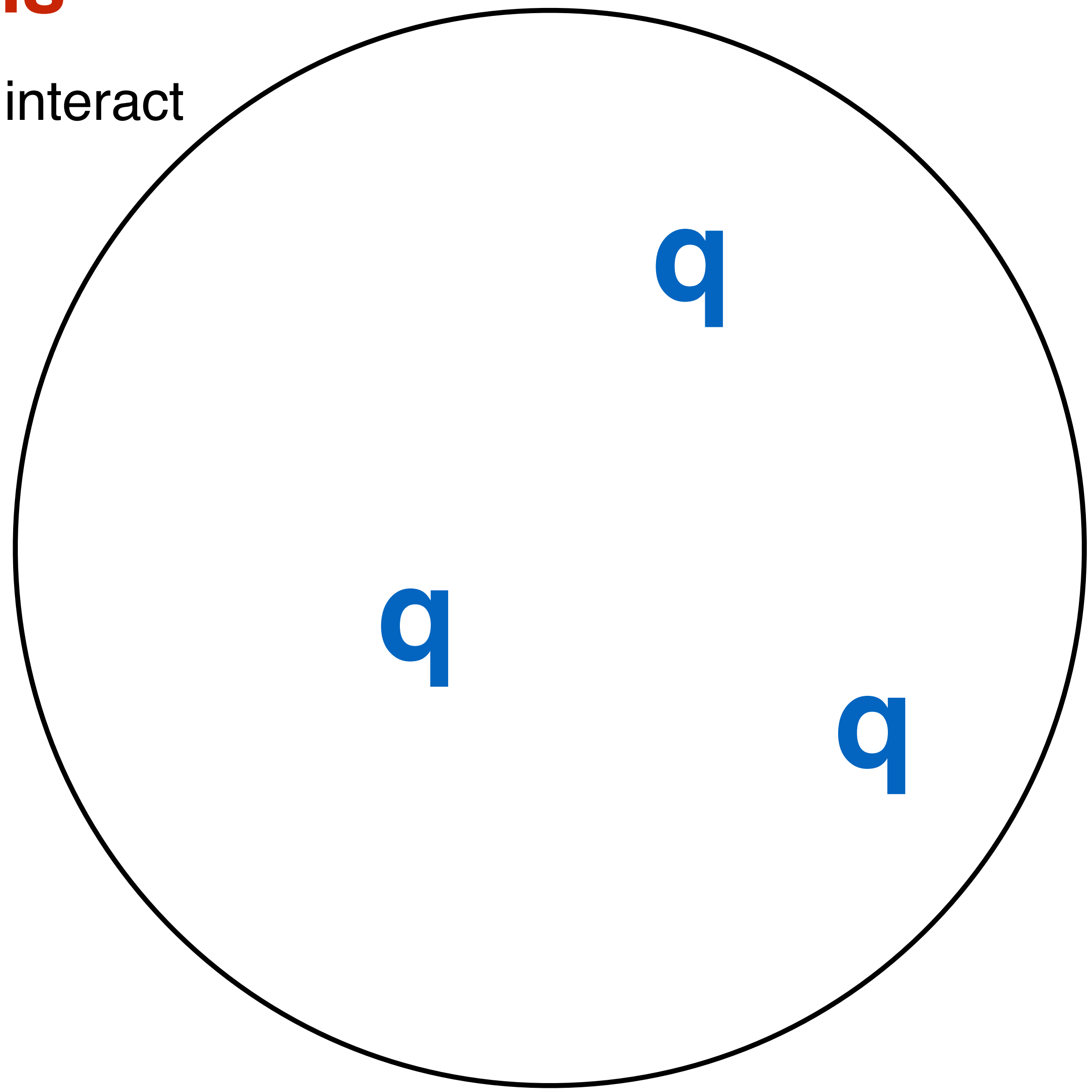


- >99% of the mass of atoms, and thus normal matter, is in the nucleus
- vary in size from hydrogen → uranium and larger
- composed of protons and neutrons
- the nucleus is held together by the strong force
  - one of the 4 fundamental forces
  - very strong & short range interactions

and what's inside protons and neutrons?

quarks and gluons

fundamental particles which interact via the strong force



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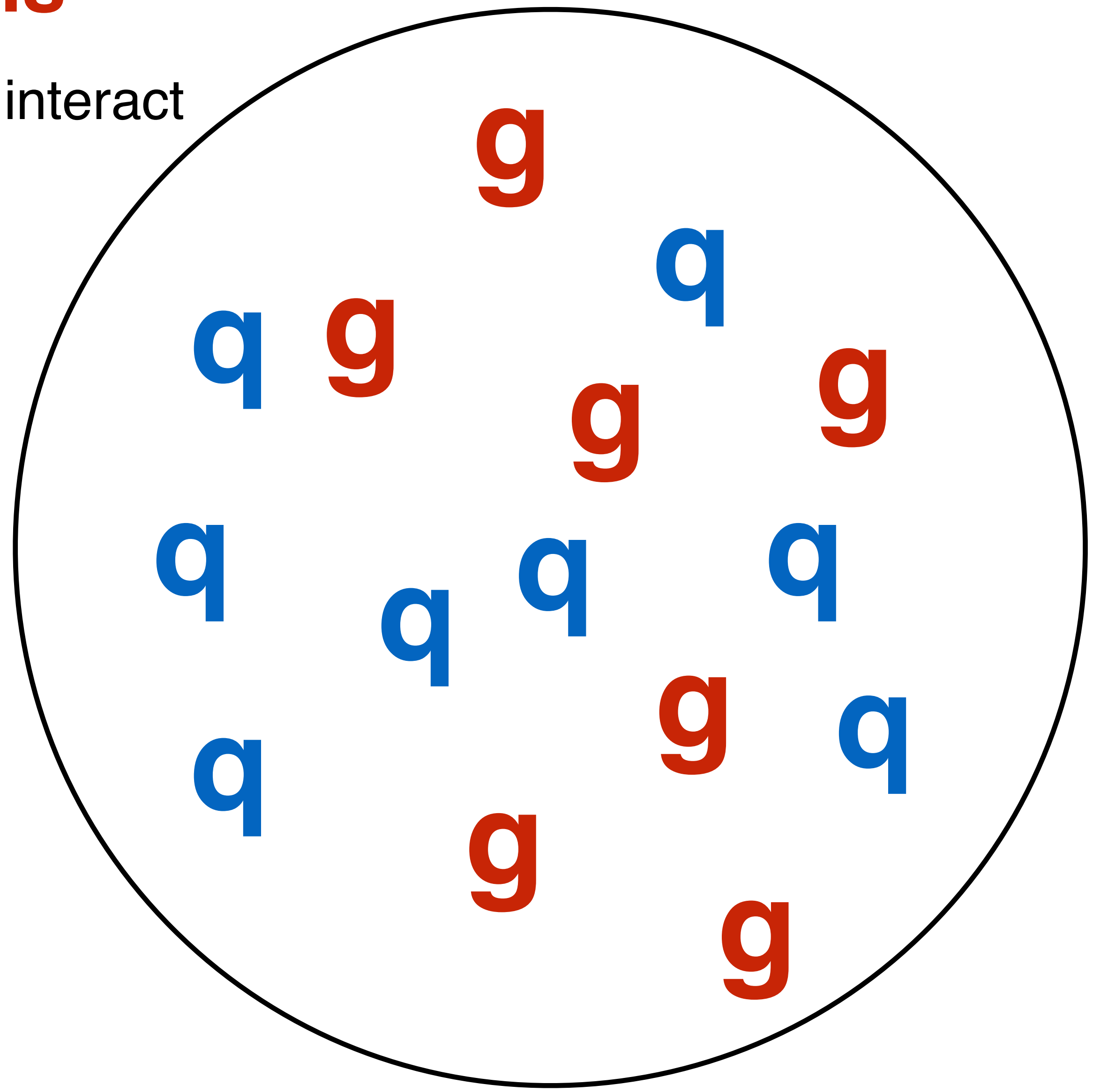

quarks and gluons

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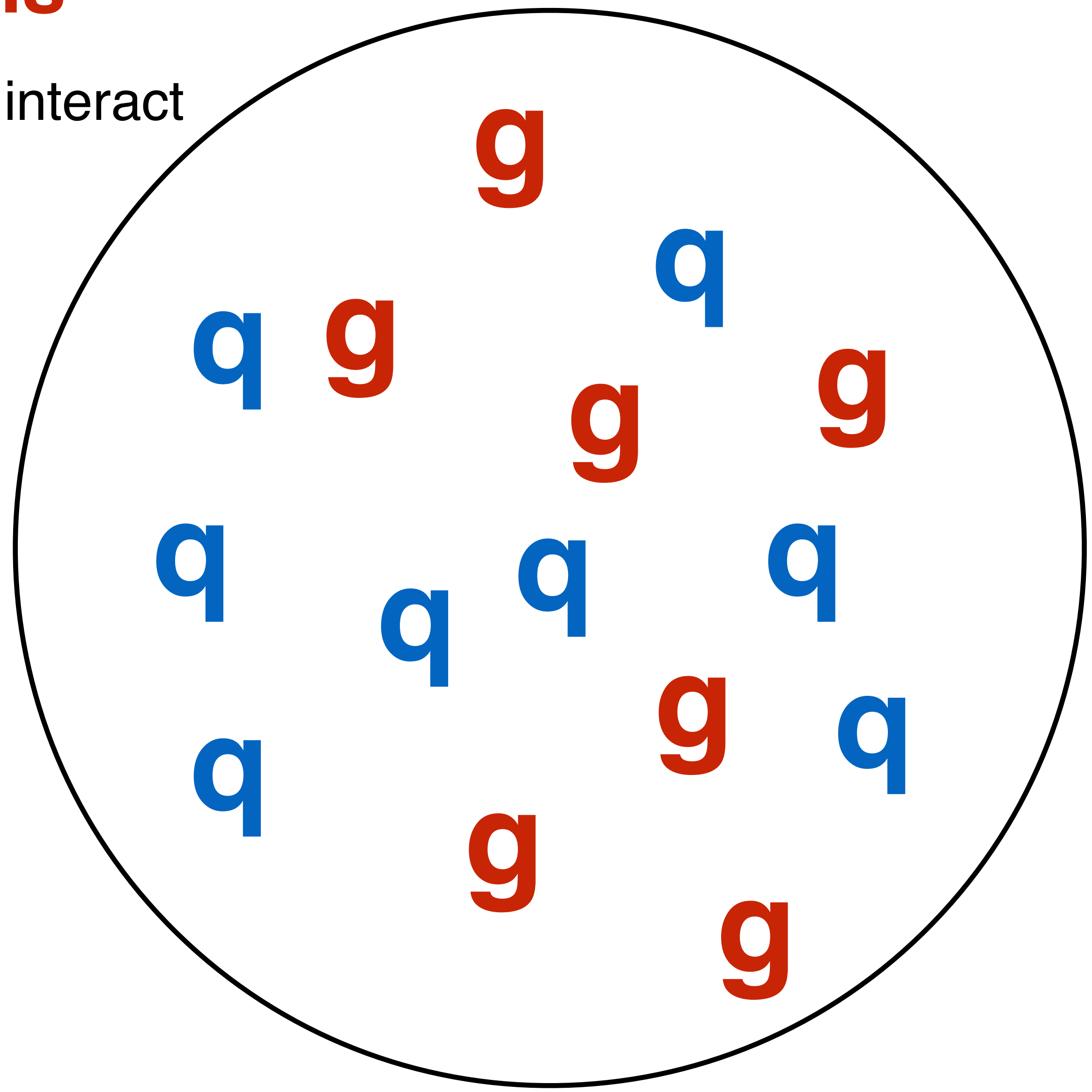
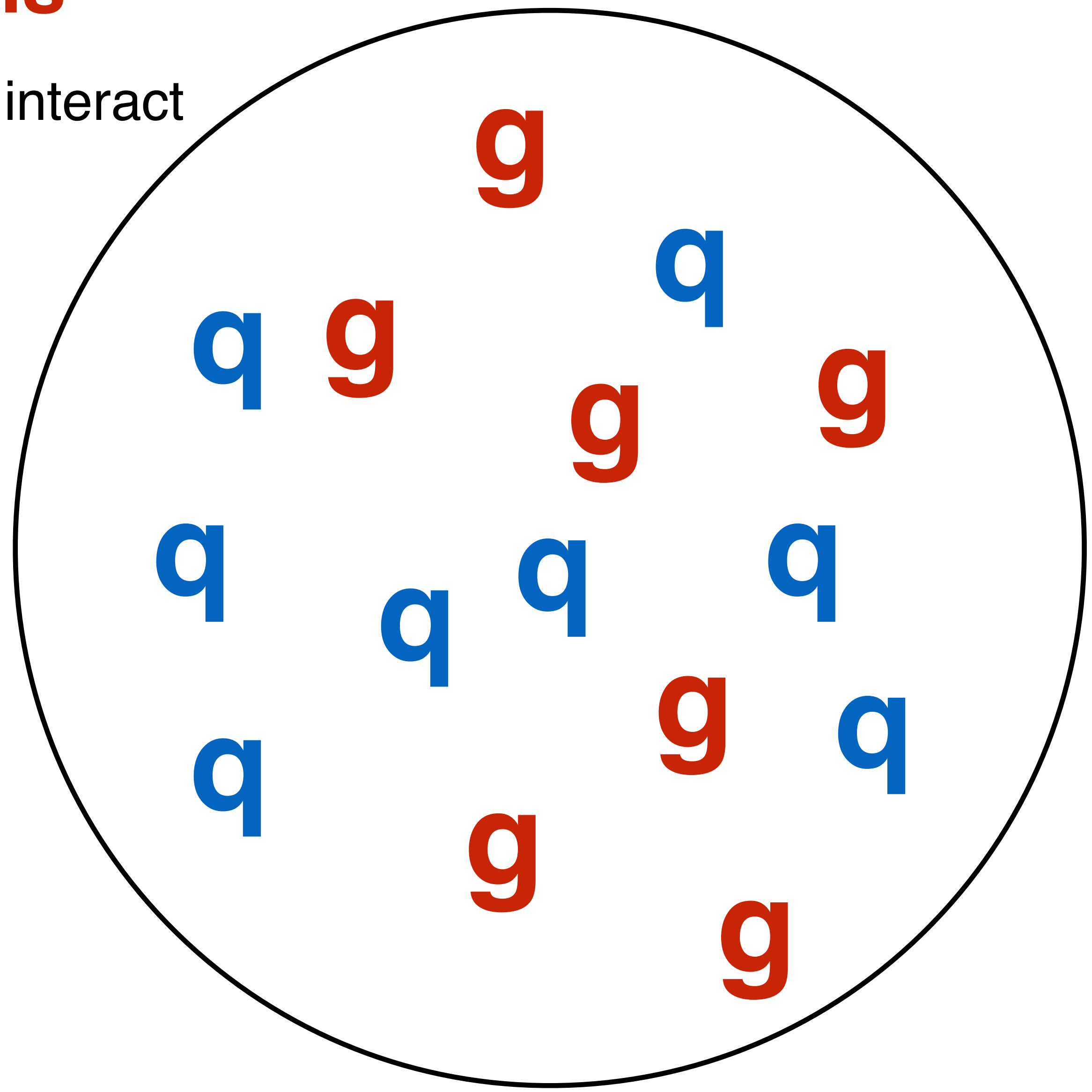


and what's inside protons and neutrons?

quarks and **gluons**

fundamental particles which interact via the strong force

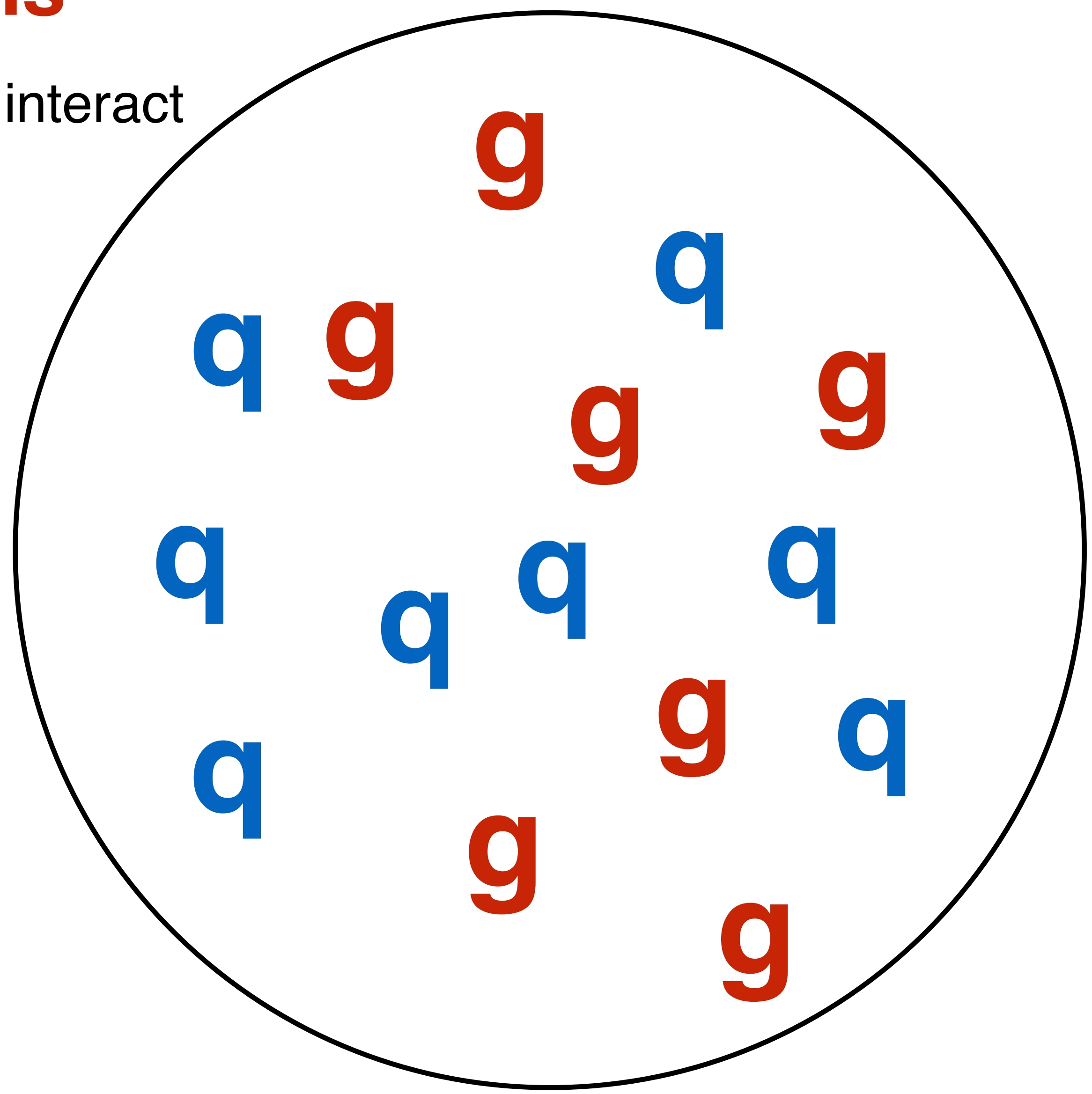


confinement

and what's inside protons and neutrons?

quarks and gluons

fundamental particles which interact via the strong force



confinement

confinement makes the strong force hard to study because the details are locked inside the protons and neutrons

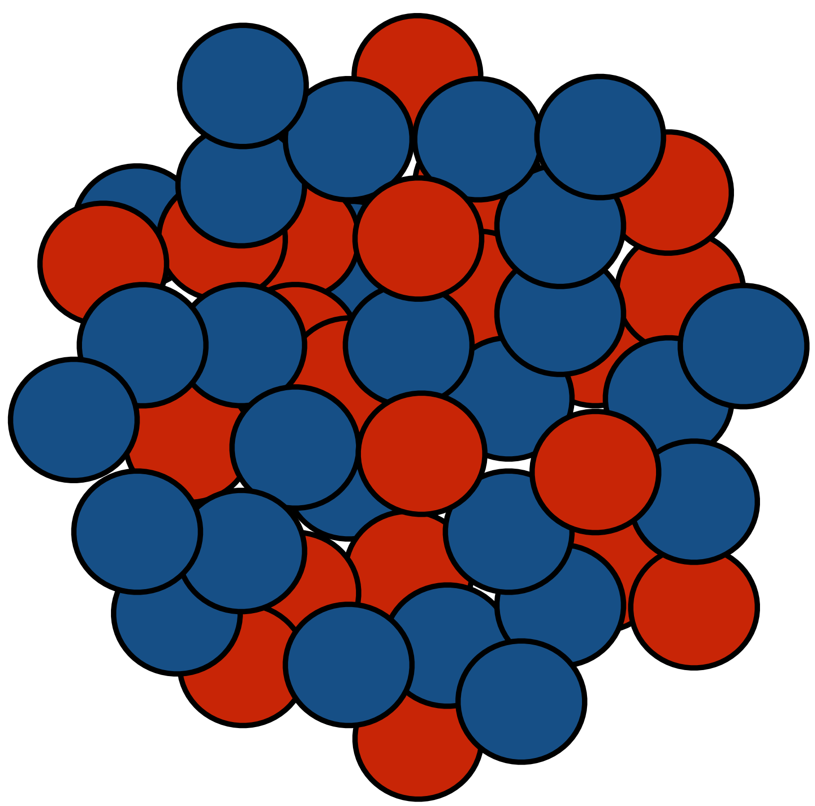
strong force at high temperature

a system that's hot and dense enough for the quarks and gluons to not be confined anymore

strong force at high temperature

a system that's hot and dense enough for the quarks and gluons to not be confined anymore

lead nucleus
(many protons & neutrons)



strong force at high temperature

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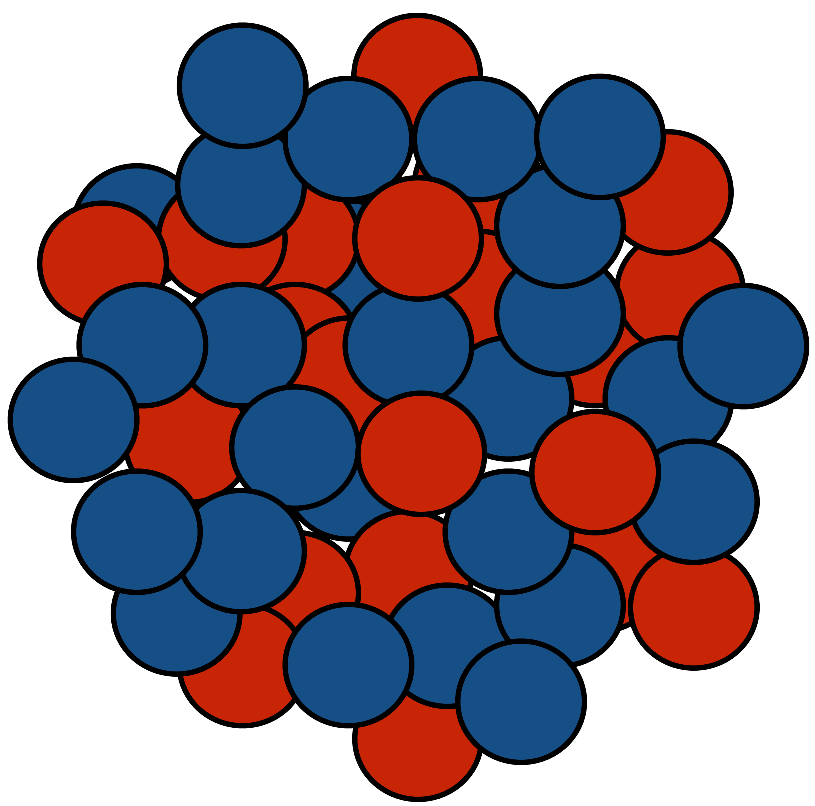
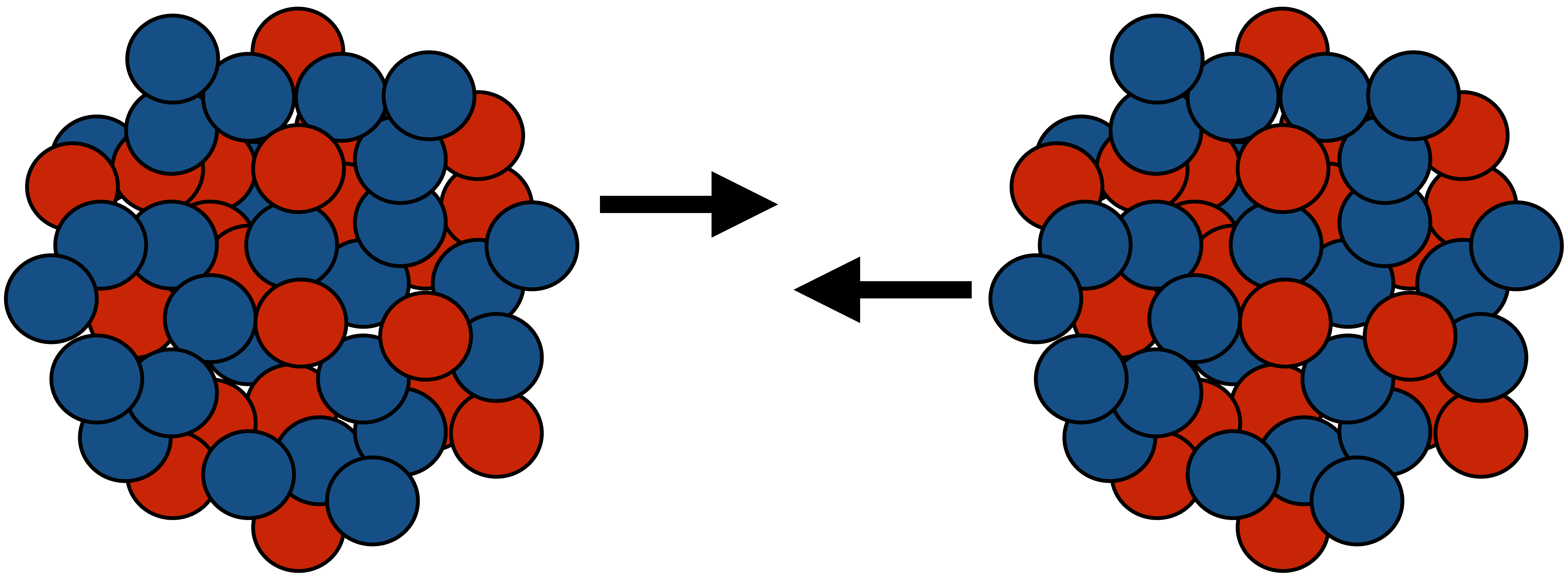


+ energy

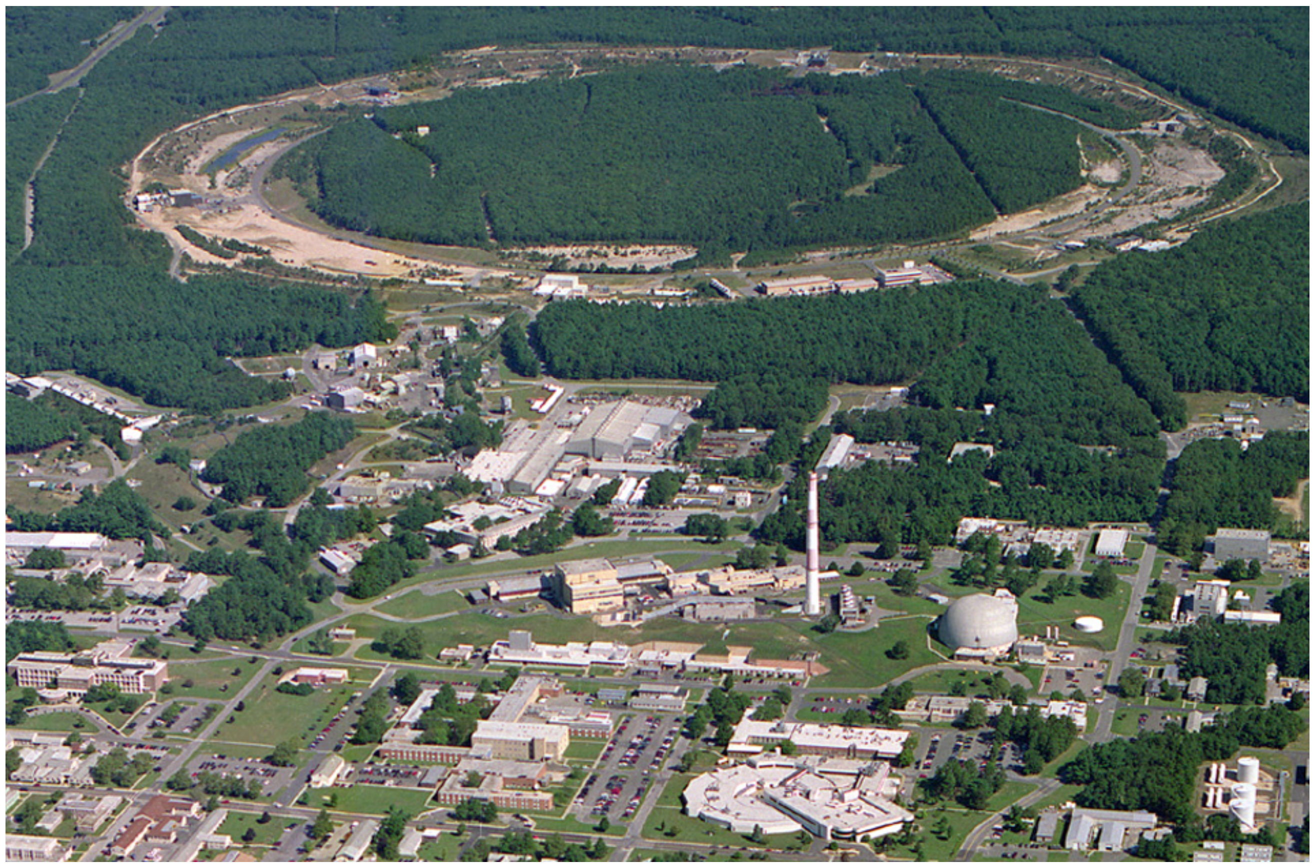
strong force at high temperature



to create a system that's hot and dense enough for the quarks and gluons to not be confined anymore: the **quark-gluon plasma**

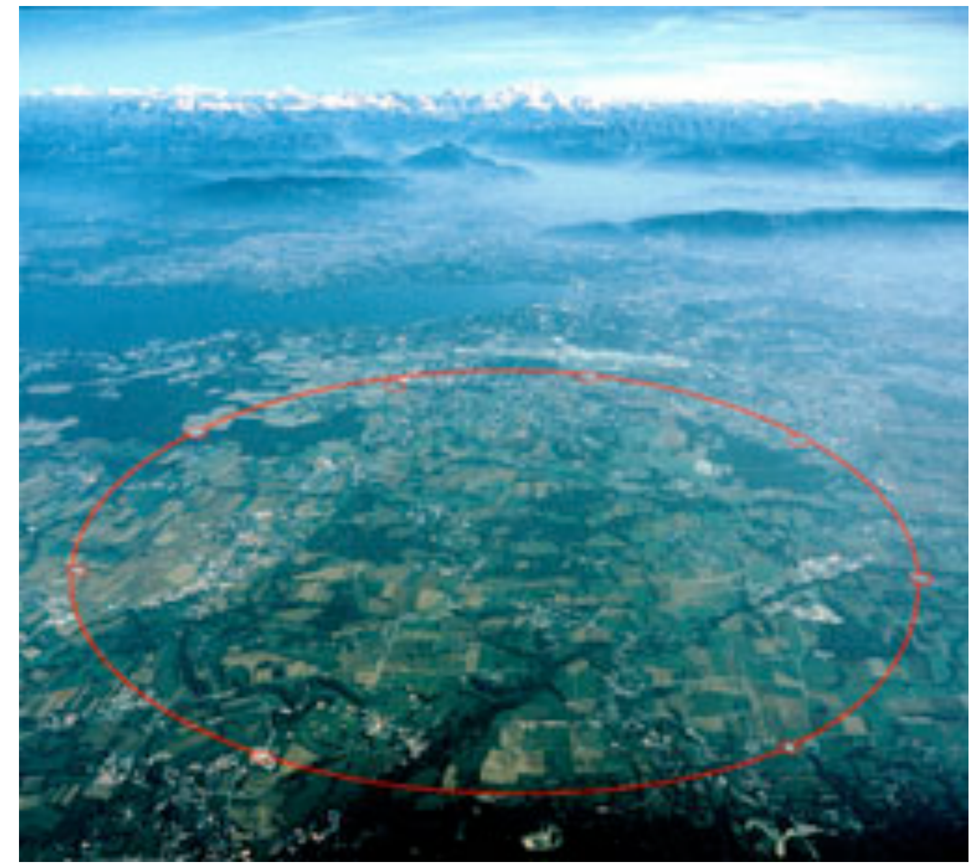
this is how the universe looked a millionth of a second after the Big Bang

Relativistic Heavy Ion Collider, New York



0.200 TeV collision energy

Large Hadron Collider, CERN



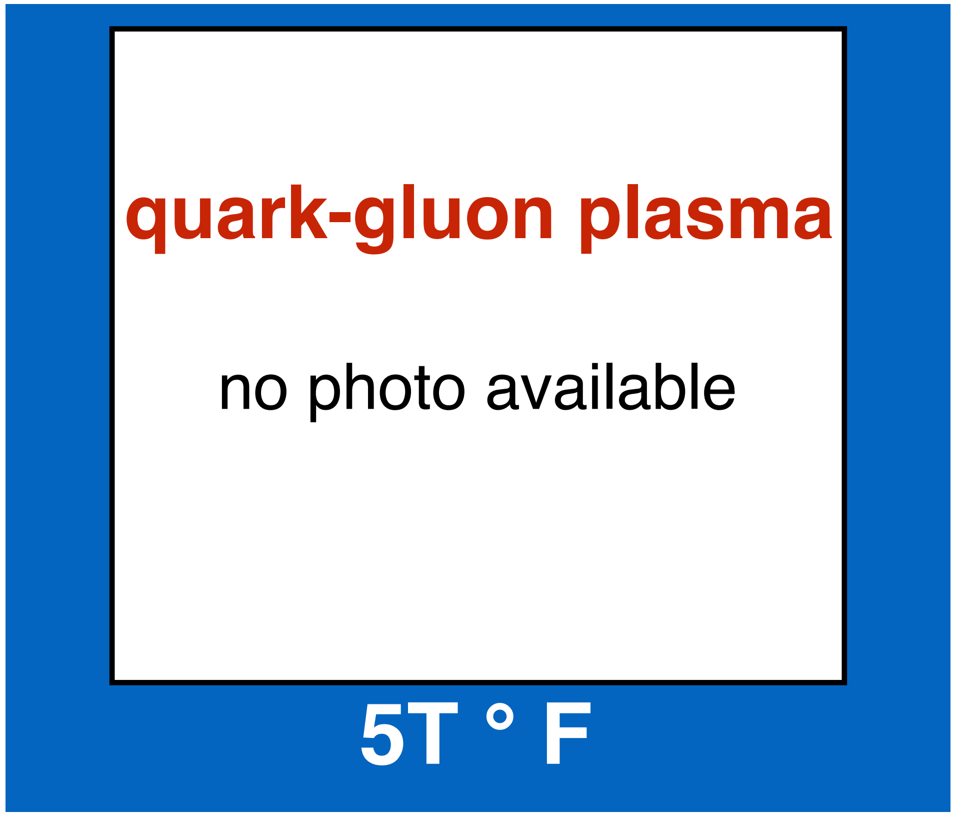
5.02 TeV collision energy

the world has two colliders capable of doing this
(check out CERN's youtube channel for videos about how colliders work)

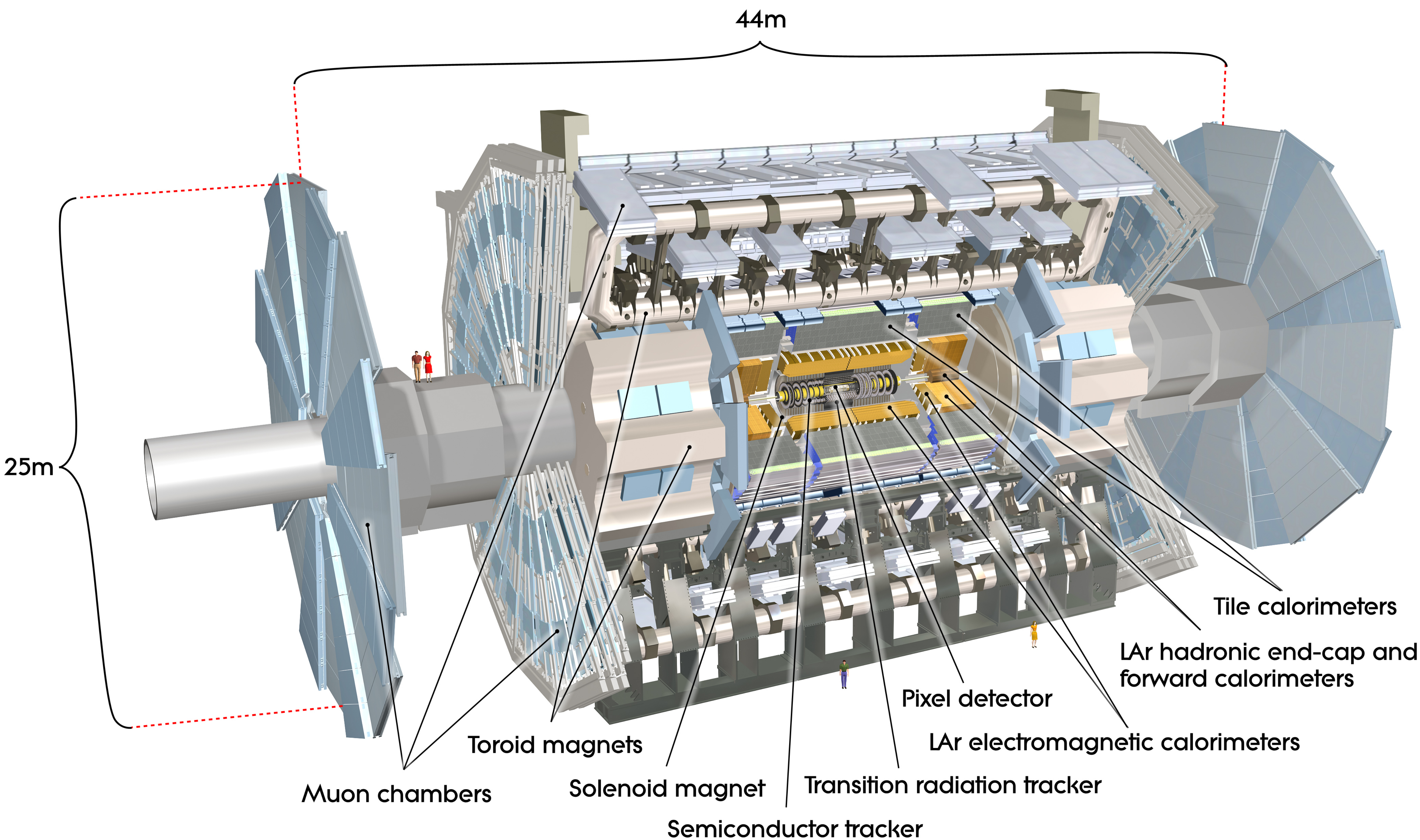
relativistic **heavy** ion collisions

quark-gluon plasma (QGP)

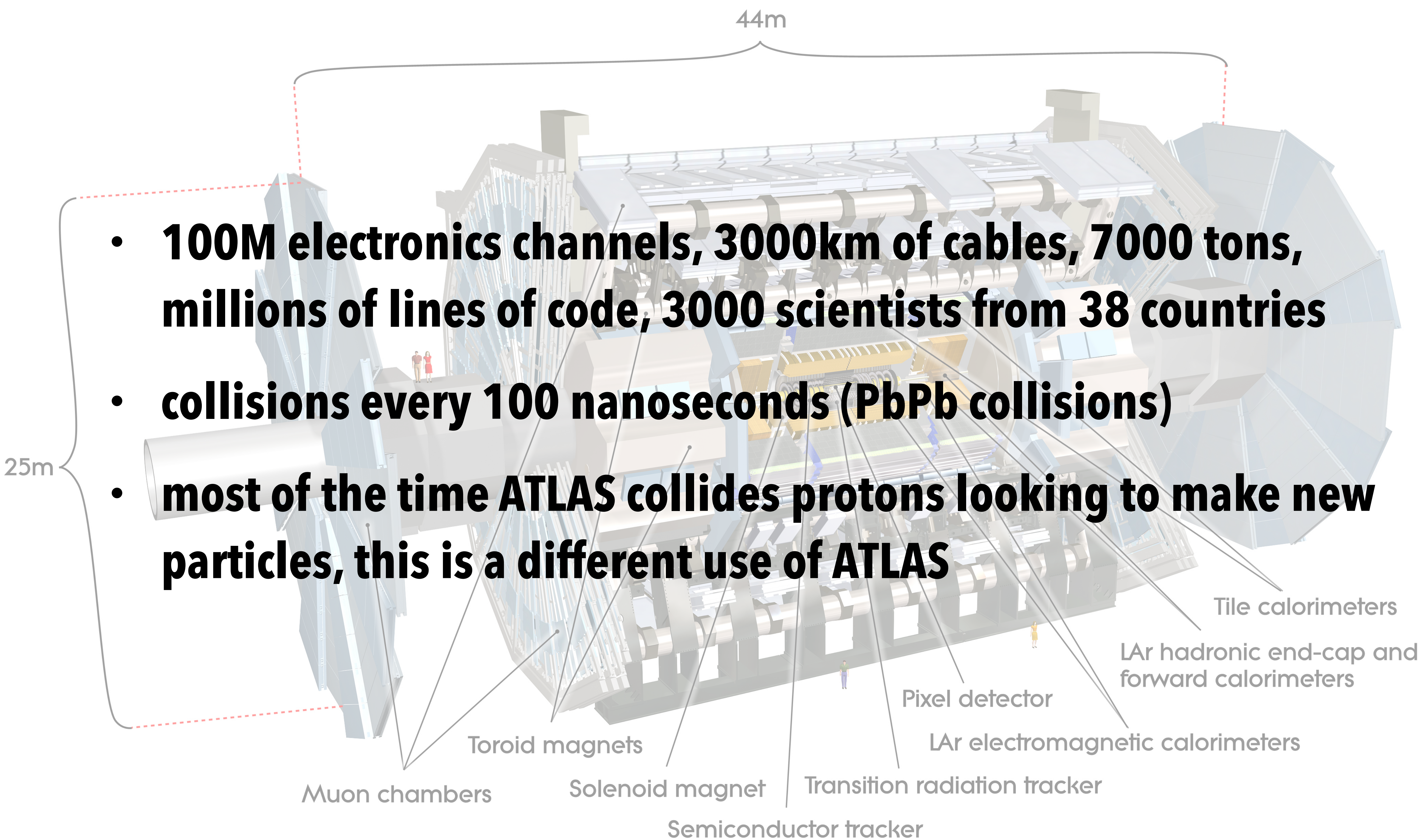
lasts for a billionth of a trillionth of a second (10^{-23} sec)
and billion times smaller than a pixel on an iPhone display (10^{-14}m)



ATLAS detector at CERN



some ATLAS statistics

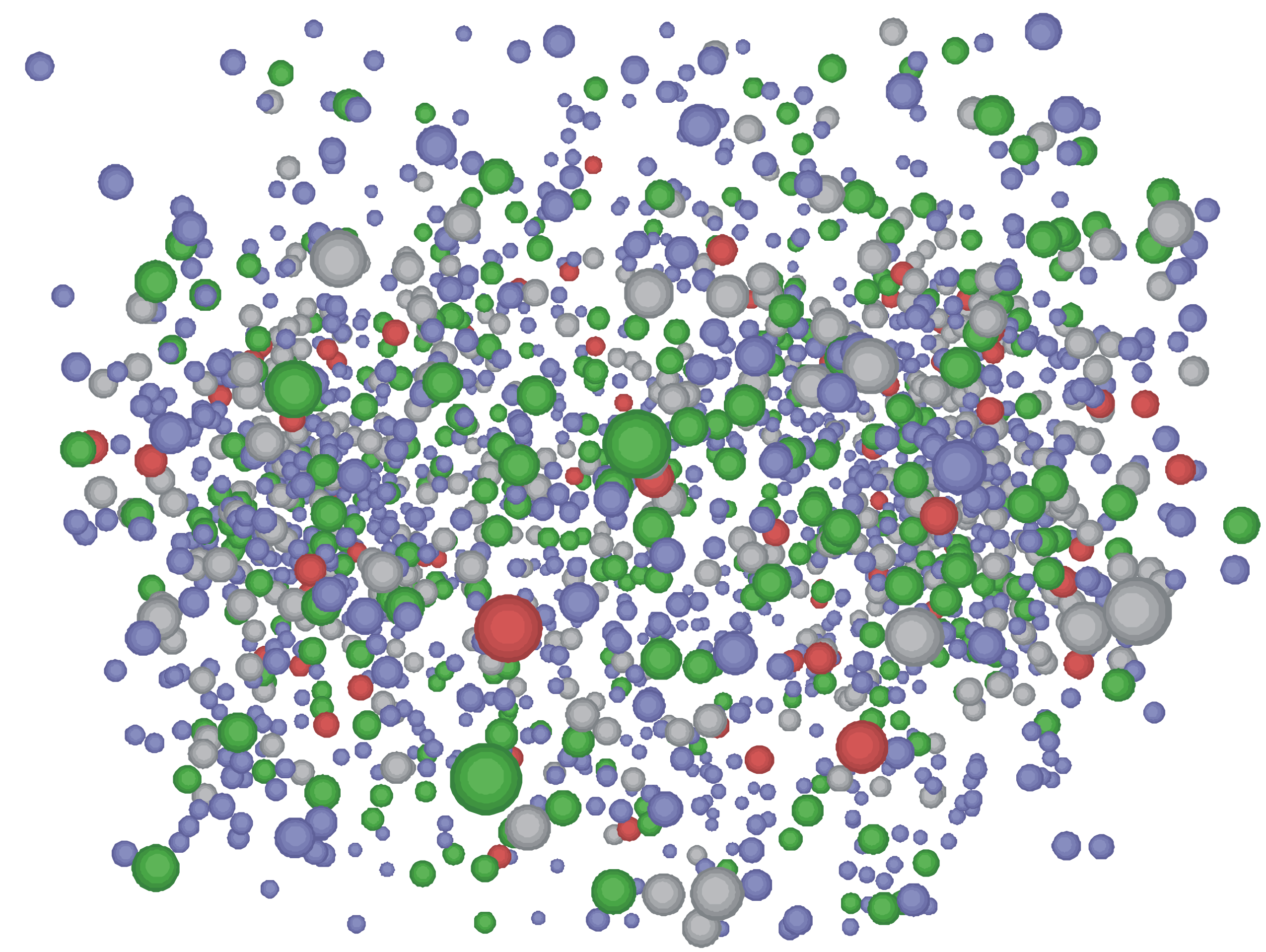


- **100M electronics channels, 3000km of cables, 7000 tons, millions of lines of code, 3000 scientists from 38 countries**
- **collisions every 100 nanoseconds (PbPb collisions)**
- **most of the time ATLAS collides protons looking to make new particles, this is a different use of ATLAS**

output so far: ~ 800 science papers

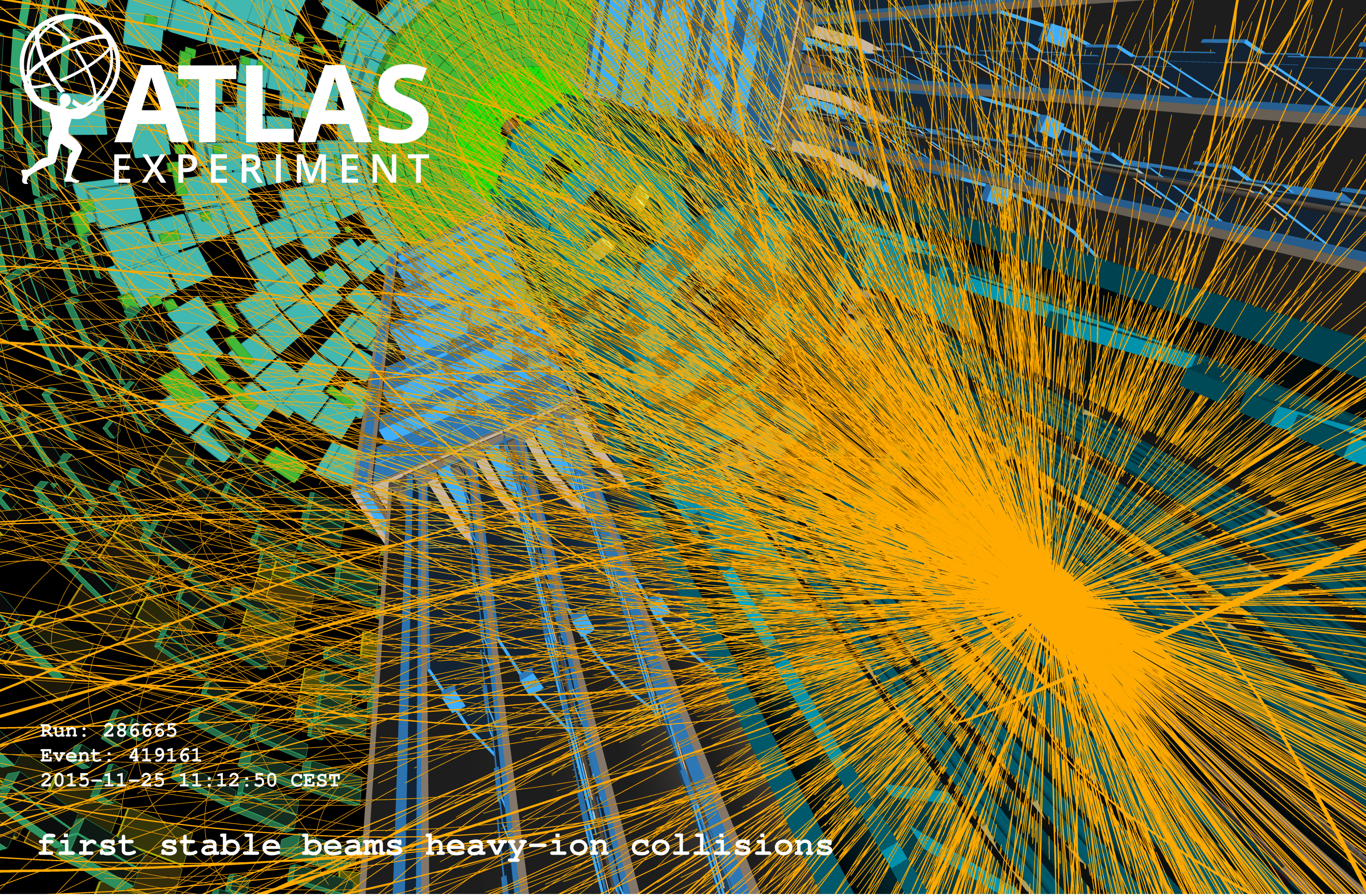
hundreds or thousands of **new** particles are created in each collision

$$E = mc^2$$



these particles provide the only window into the earlier stages of the collision

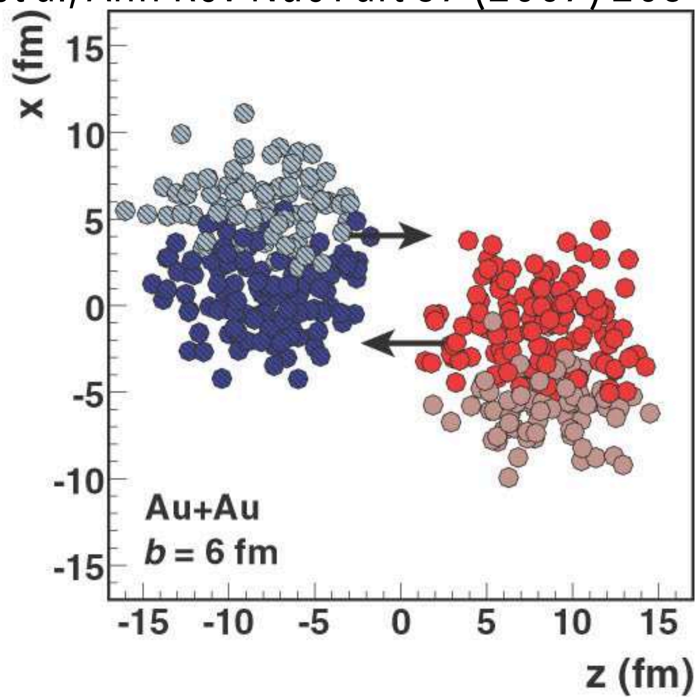
we look at each collision individually, but measure billions of collisions!



up to 10000 particles created in the most head on collisions

what do nuclear collisions look like?

Miller, et al, Ann Rev Nuc Part 57 (2007) 205



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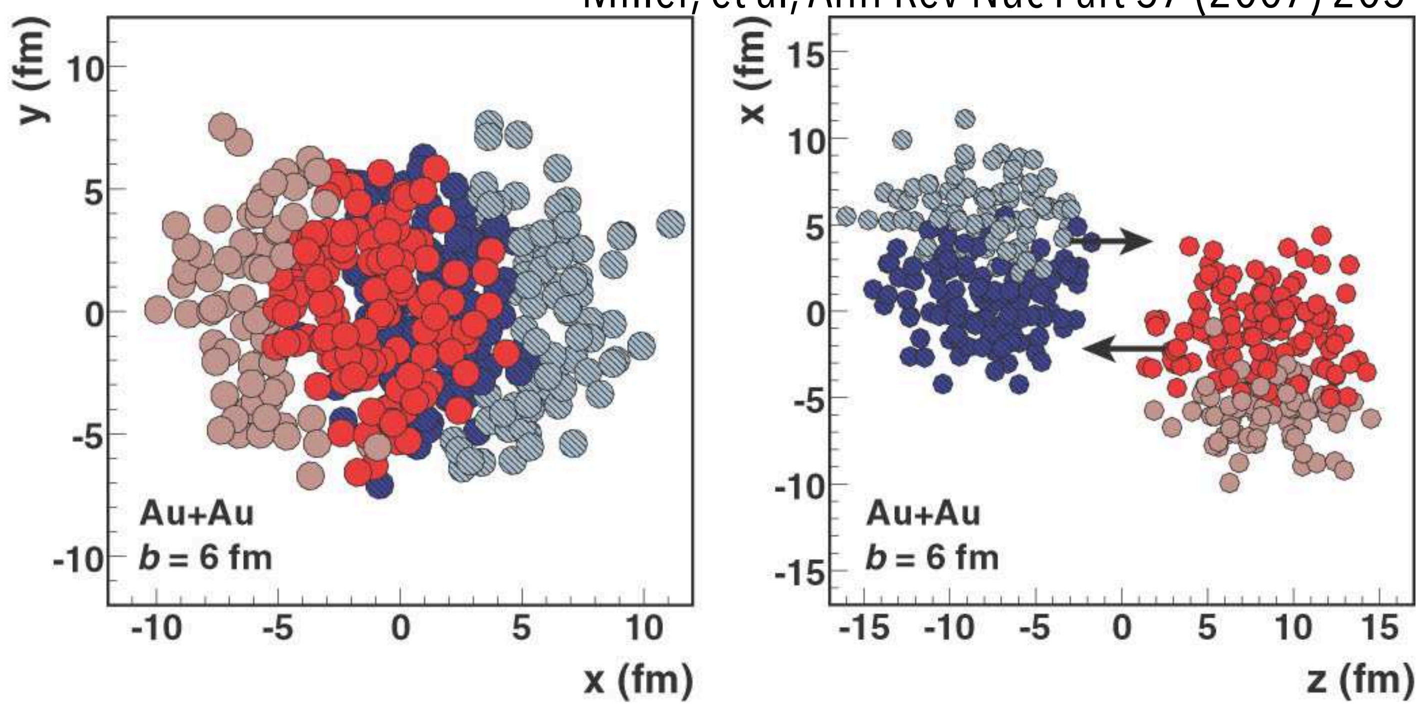

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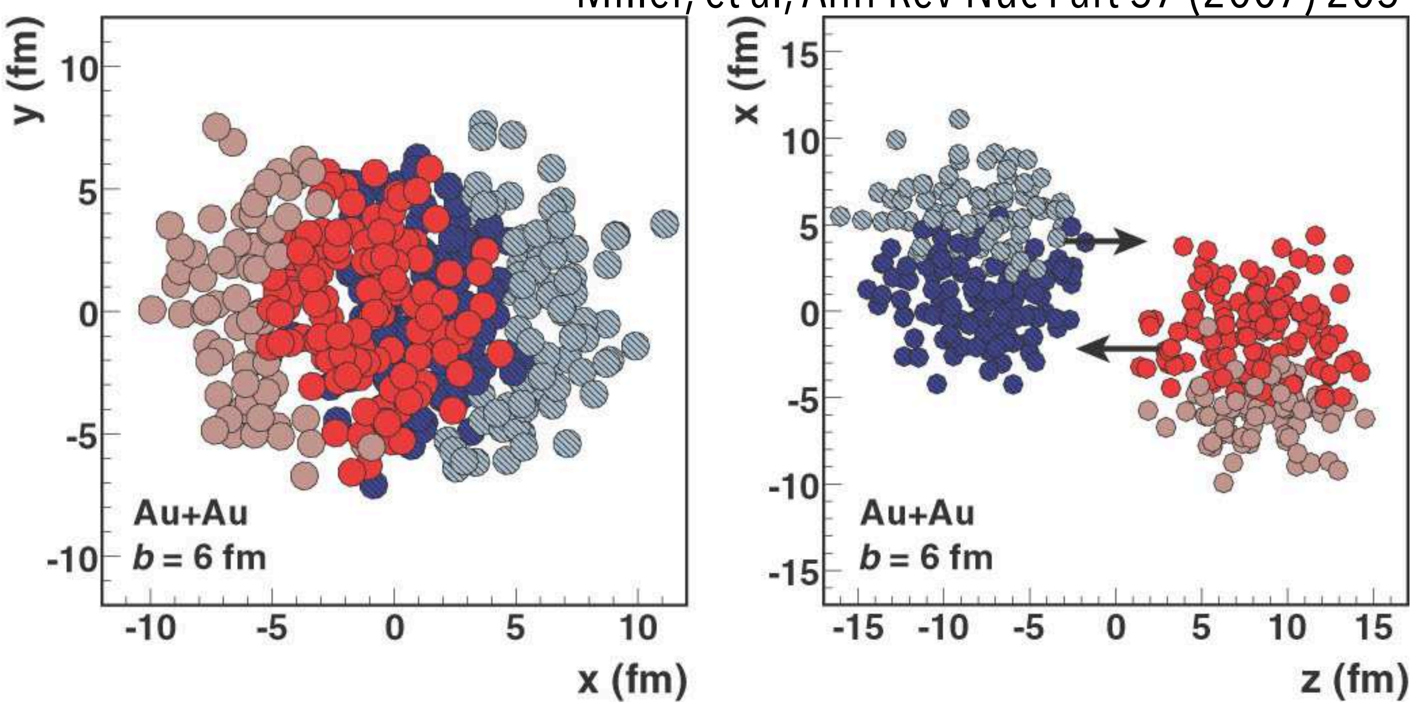
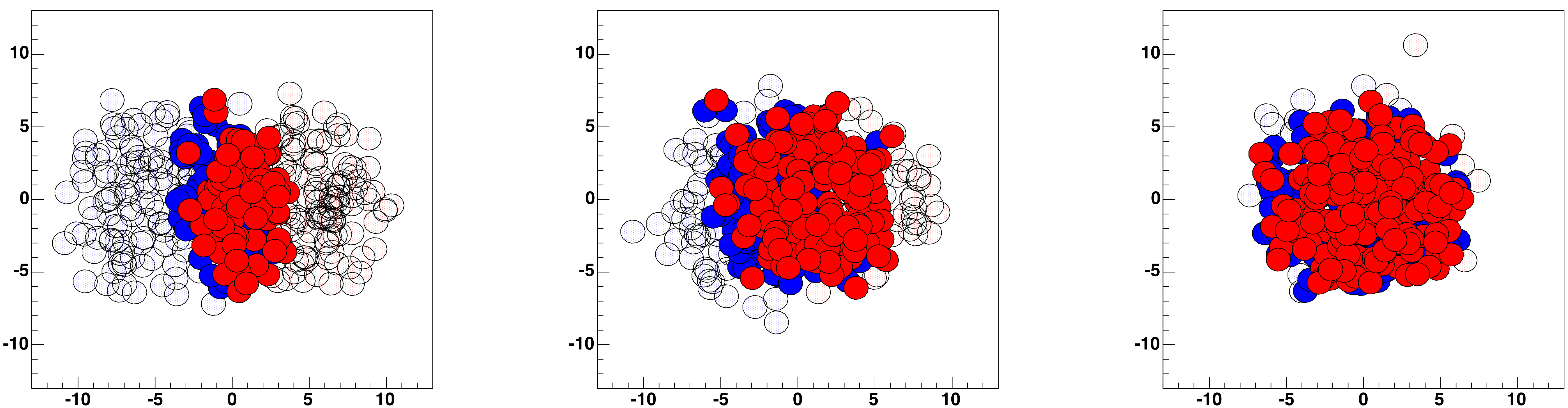
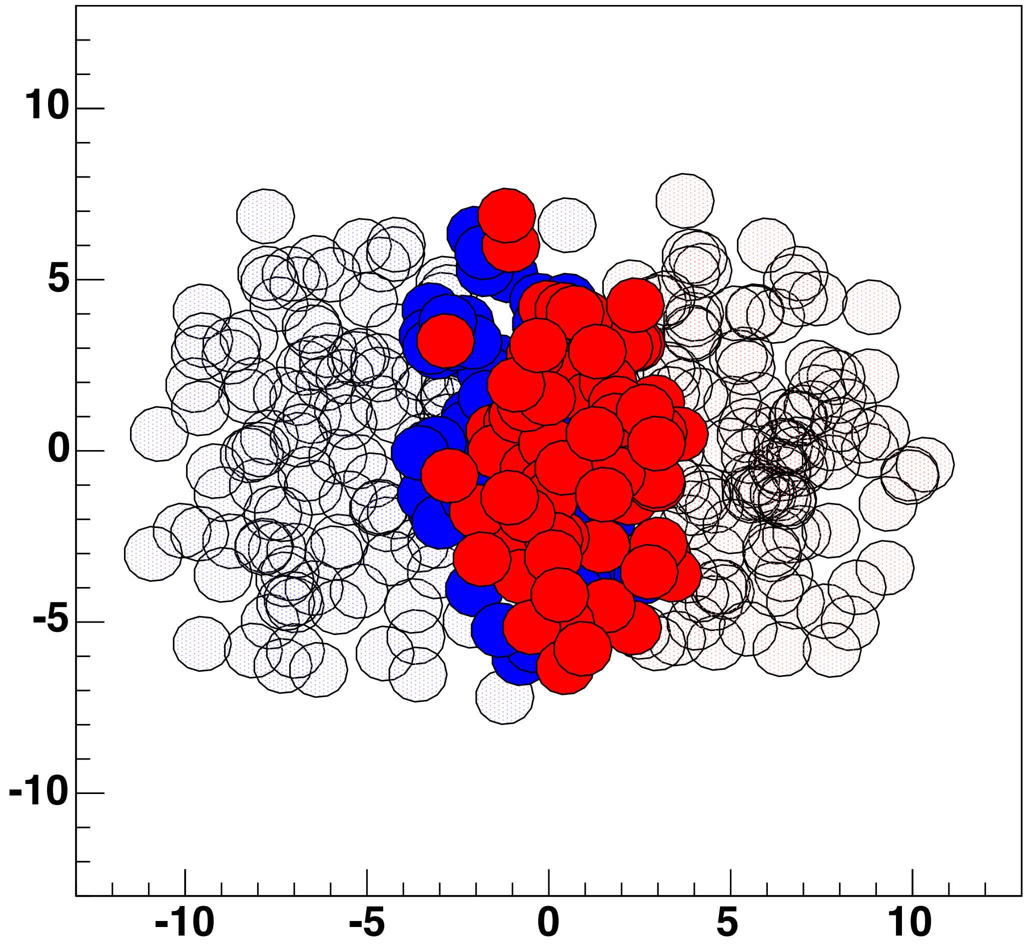


view: one nuclei going into the screen and one coming out



counting particles



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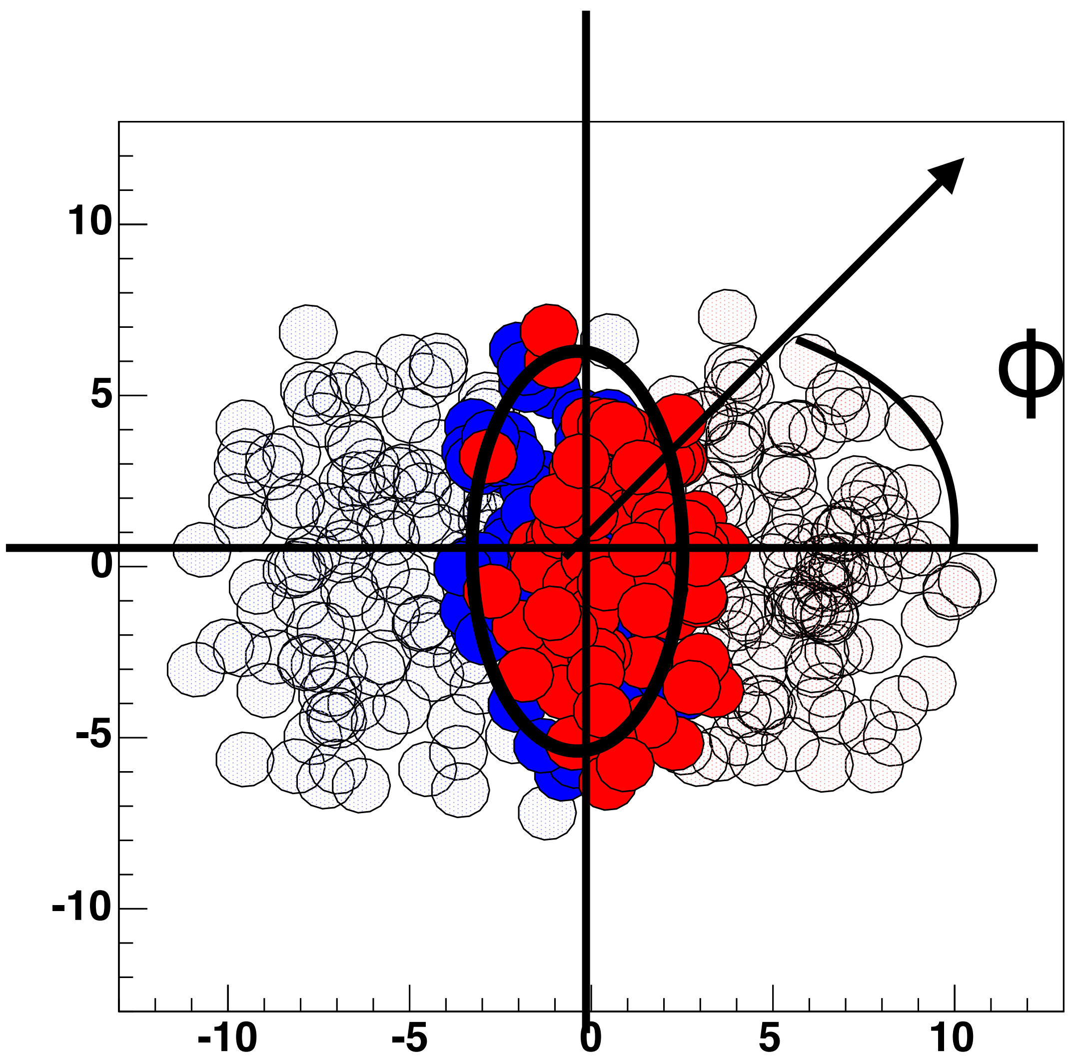

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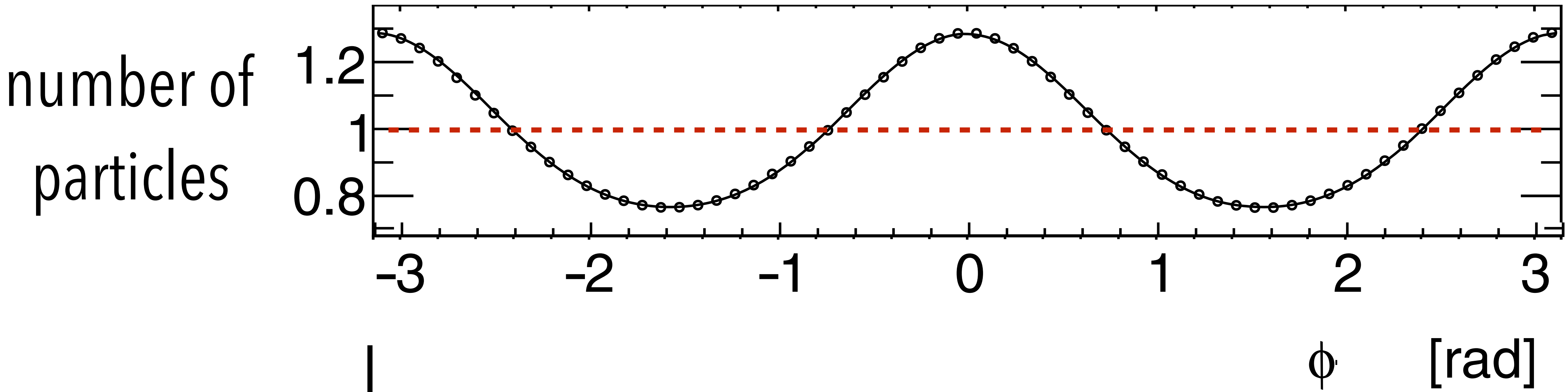
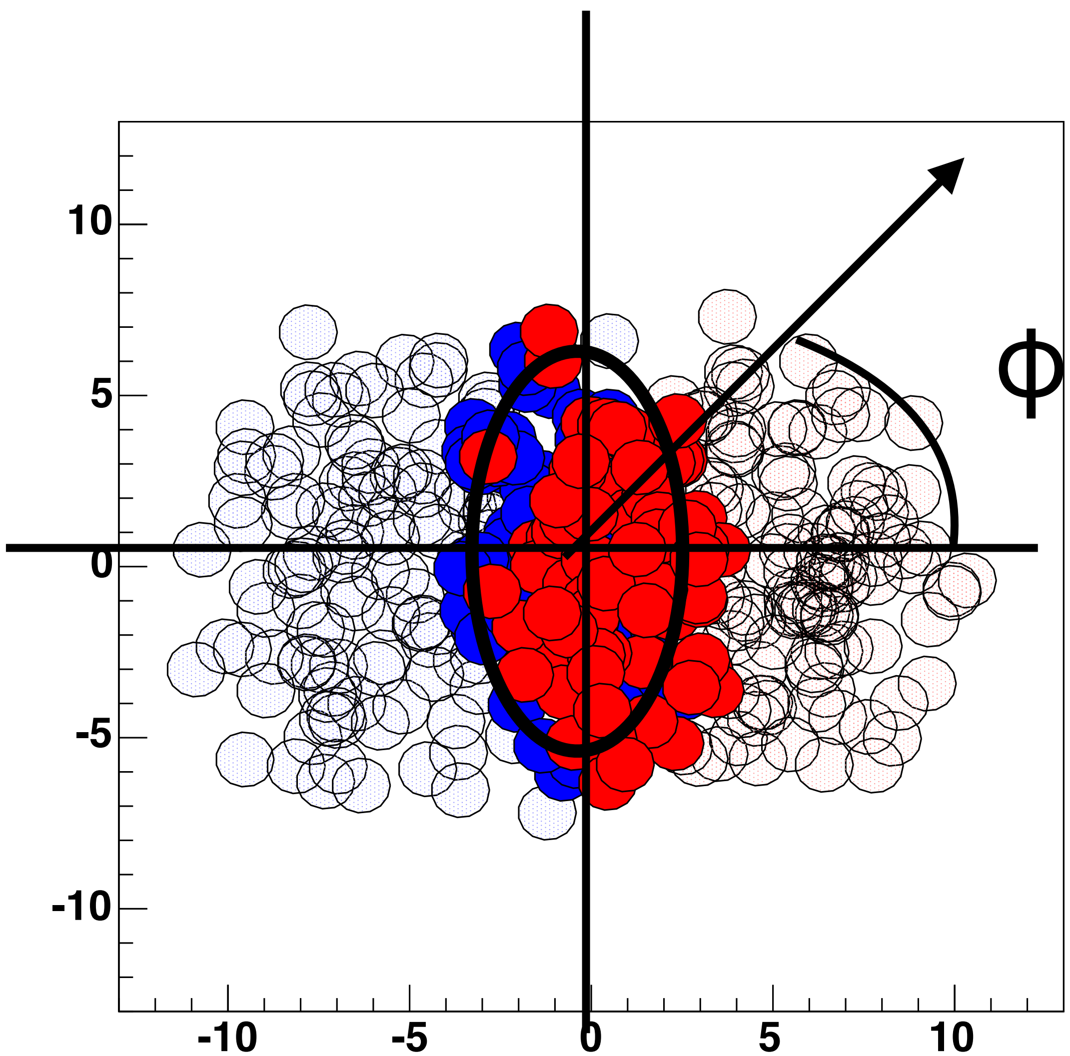
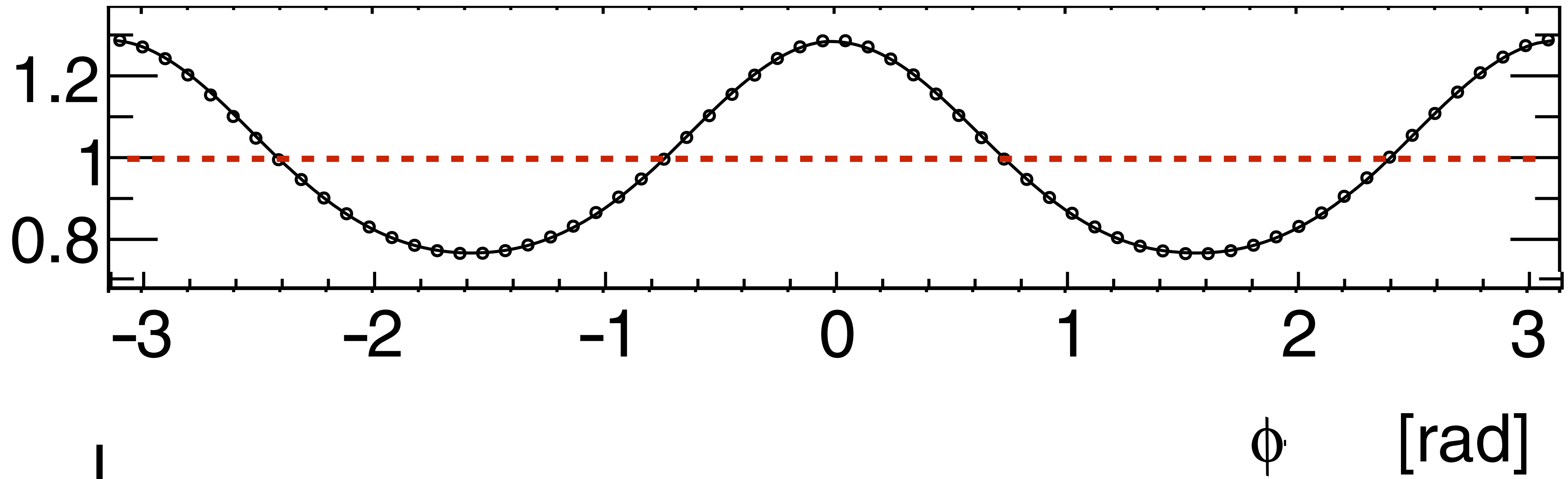
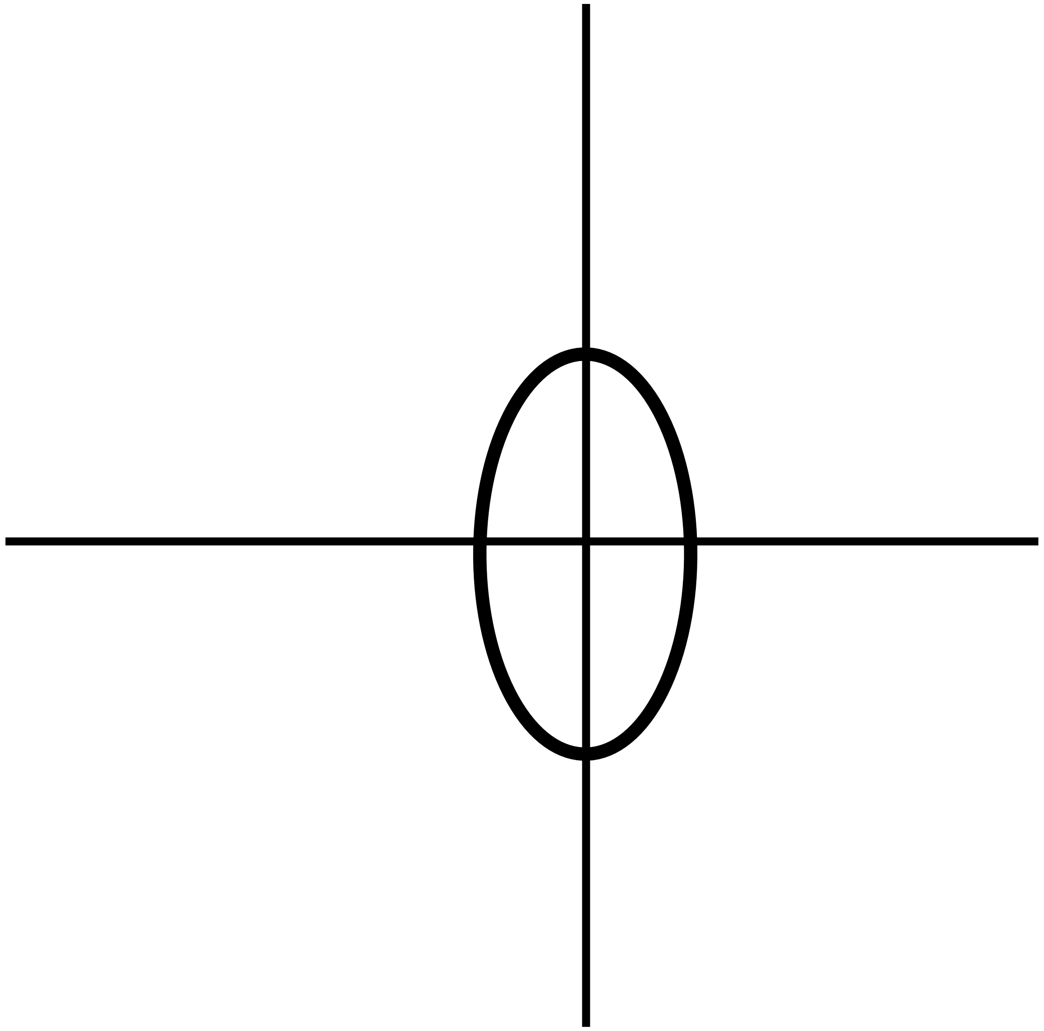
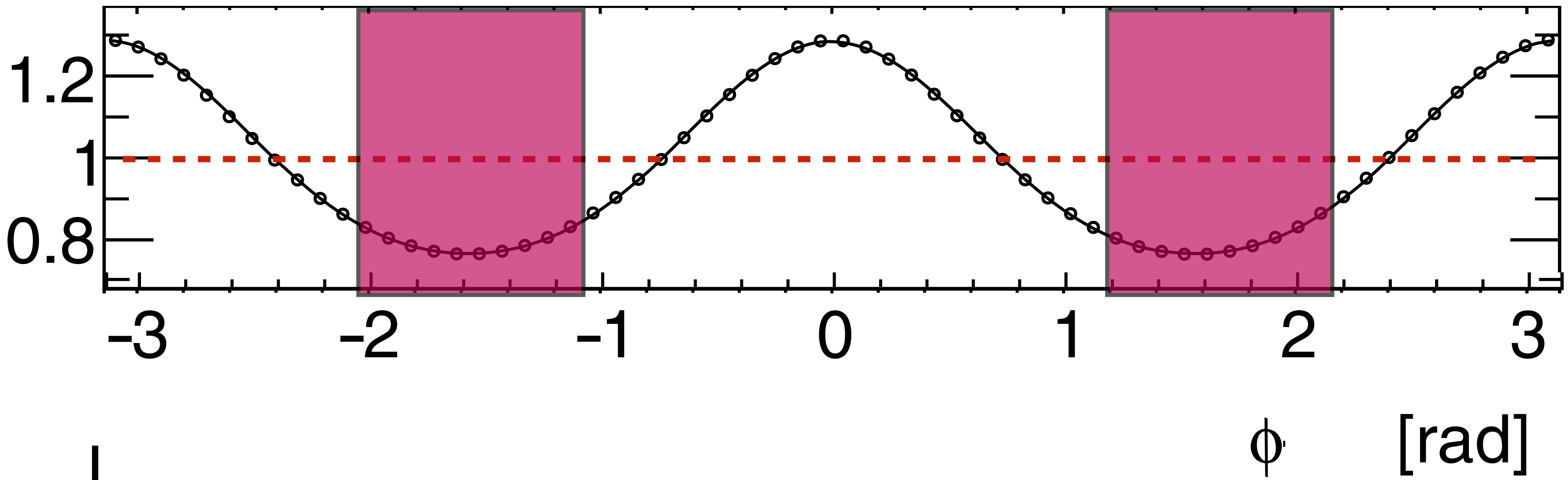


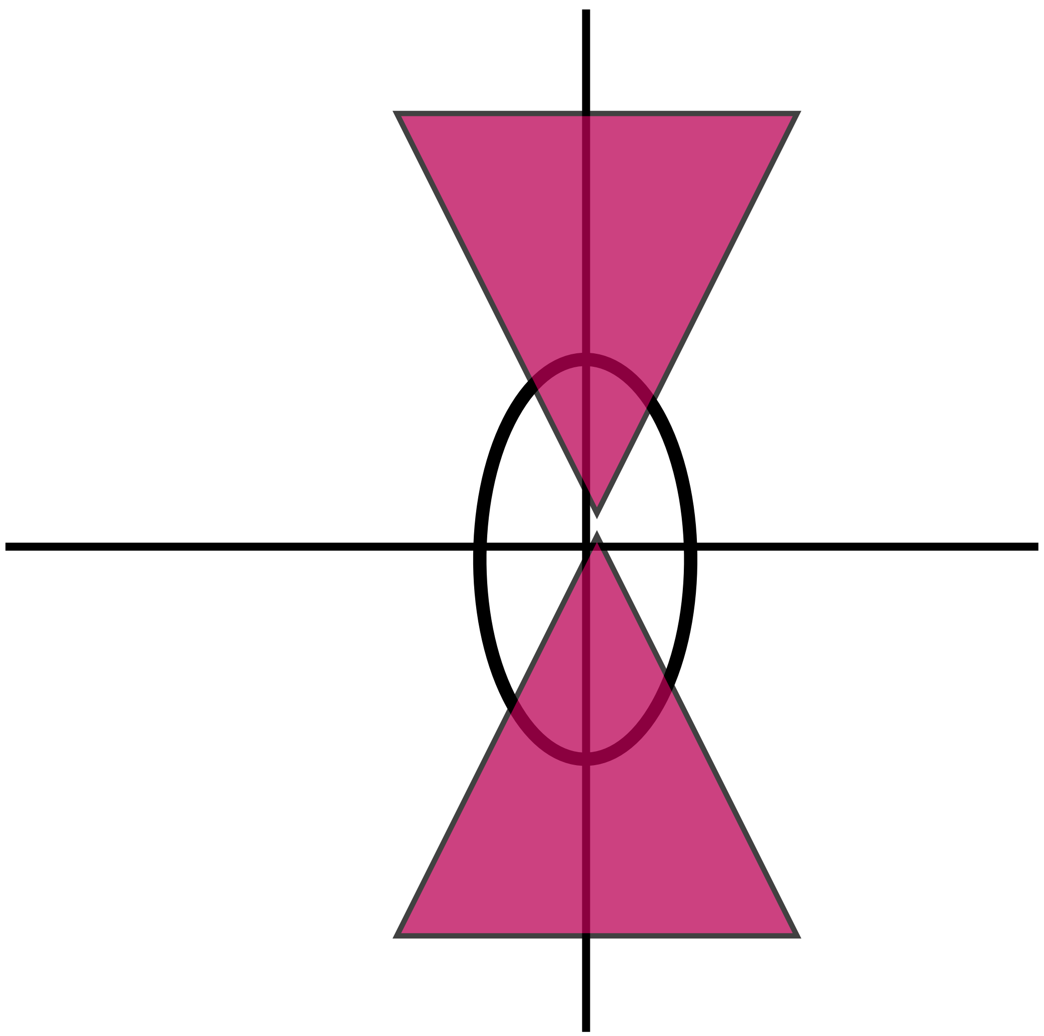


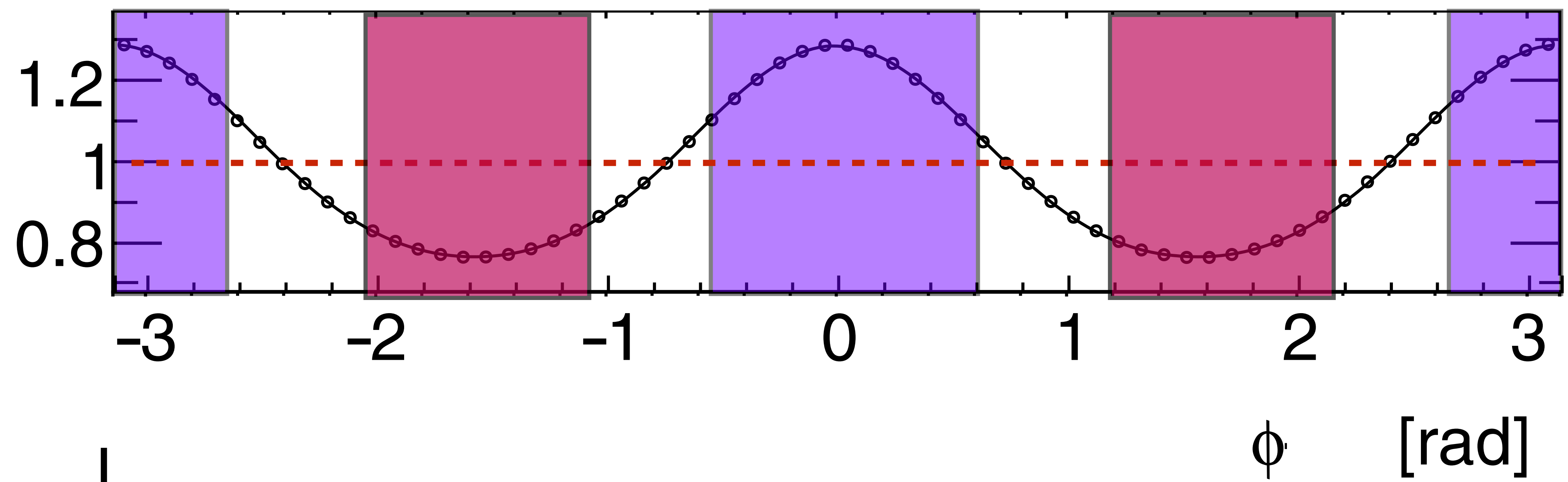
collision geometry

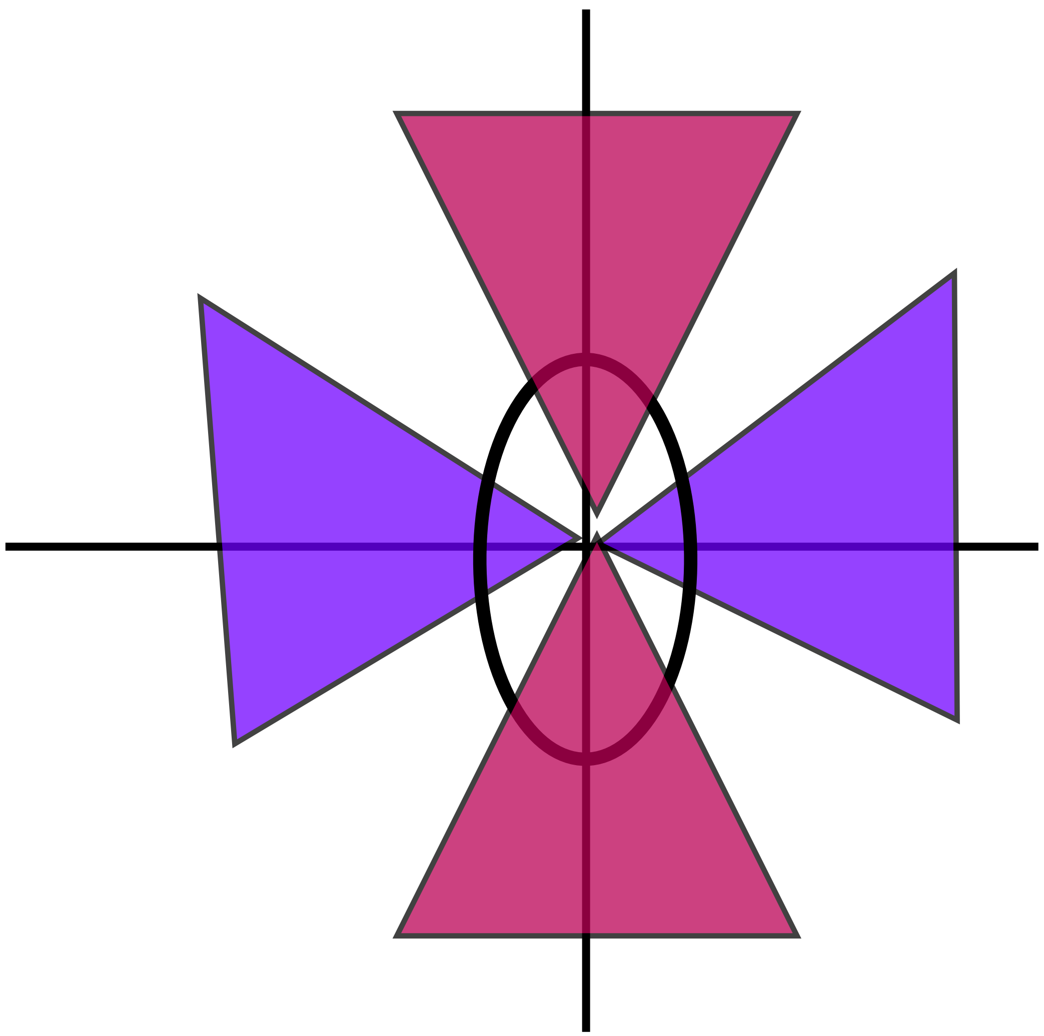





1.2
1
0.8
-3
-2
-1
0
1
2
3
ϕ [rad]

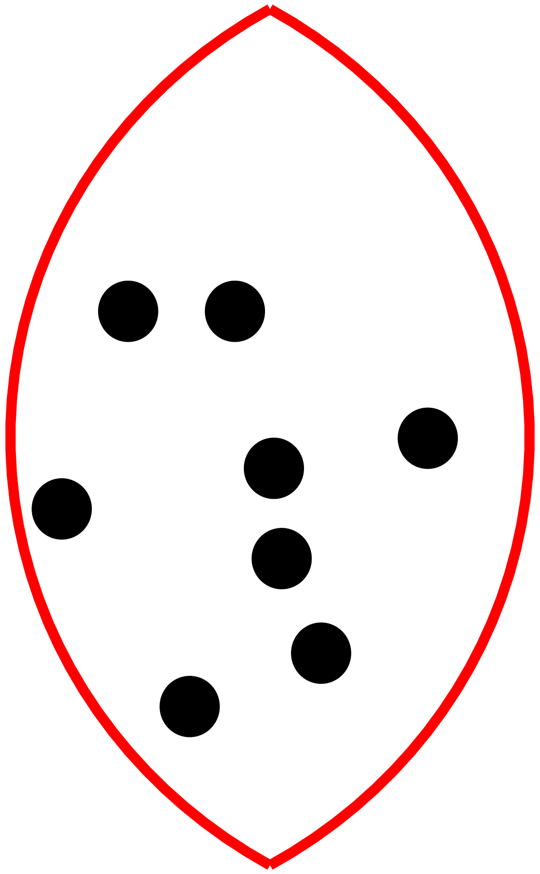






more particles come out the long side
than the short side!

what's going on inside the collision?



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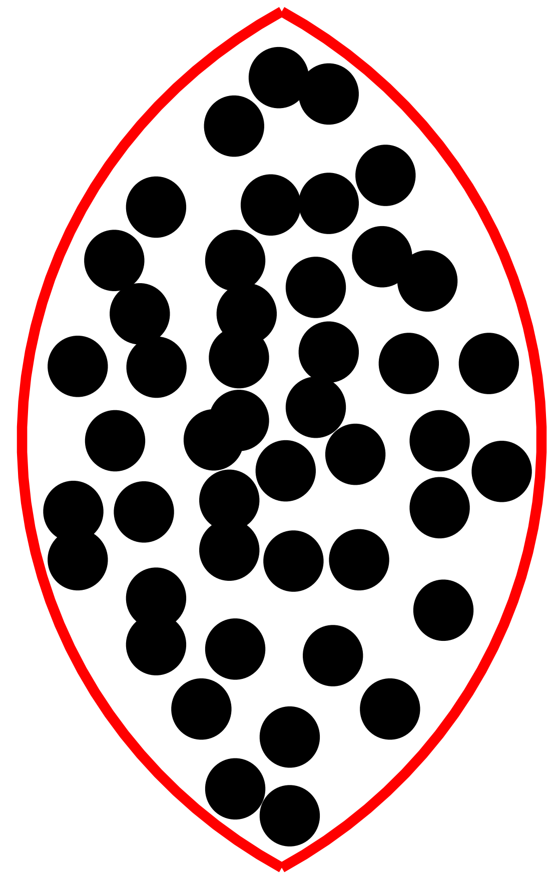
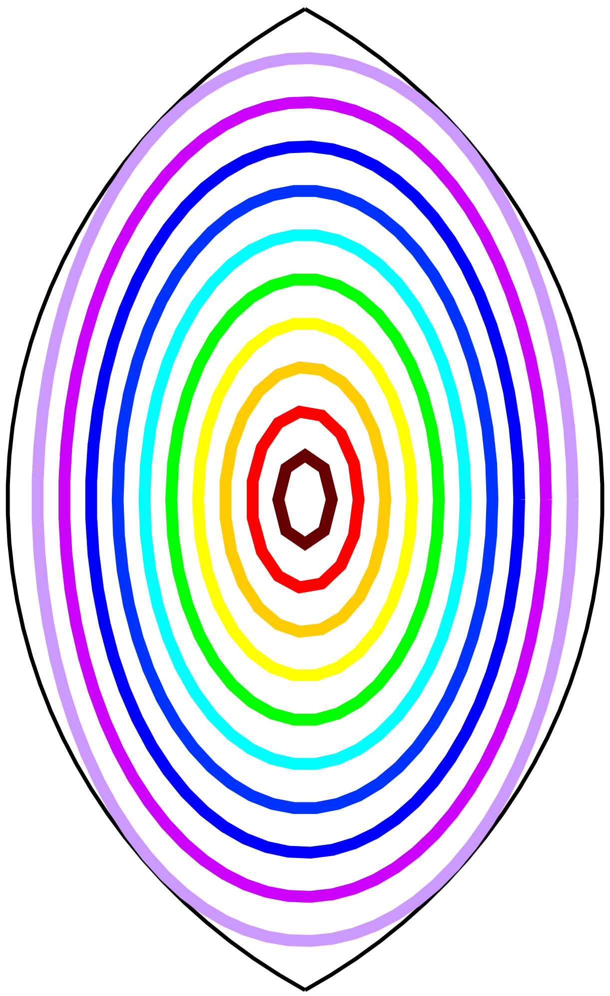


lots of interactions



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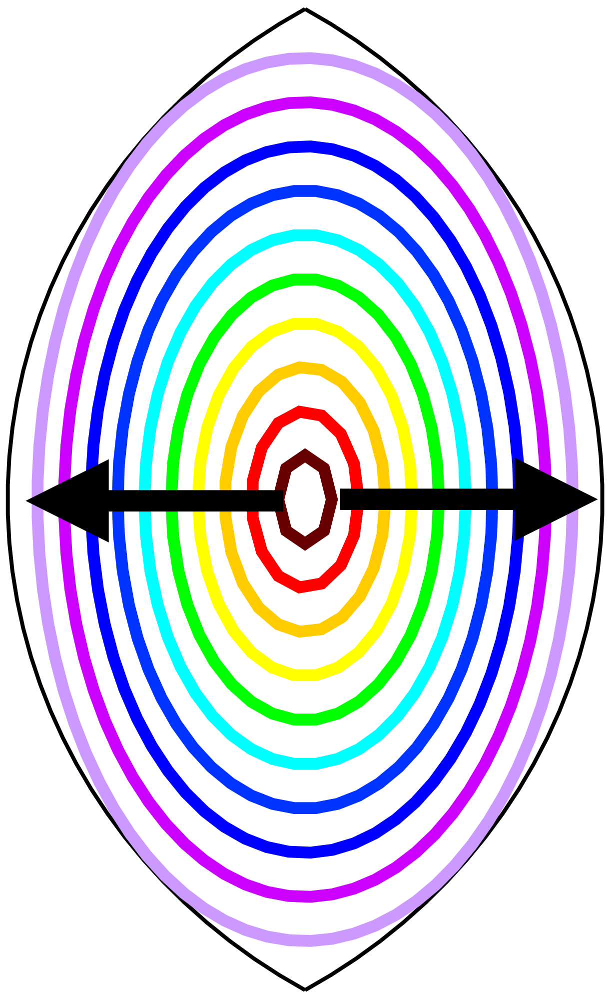
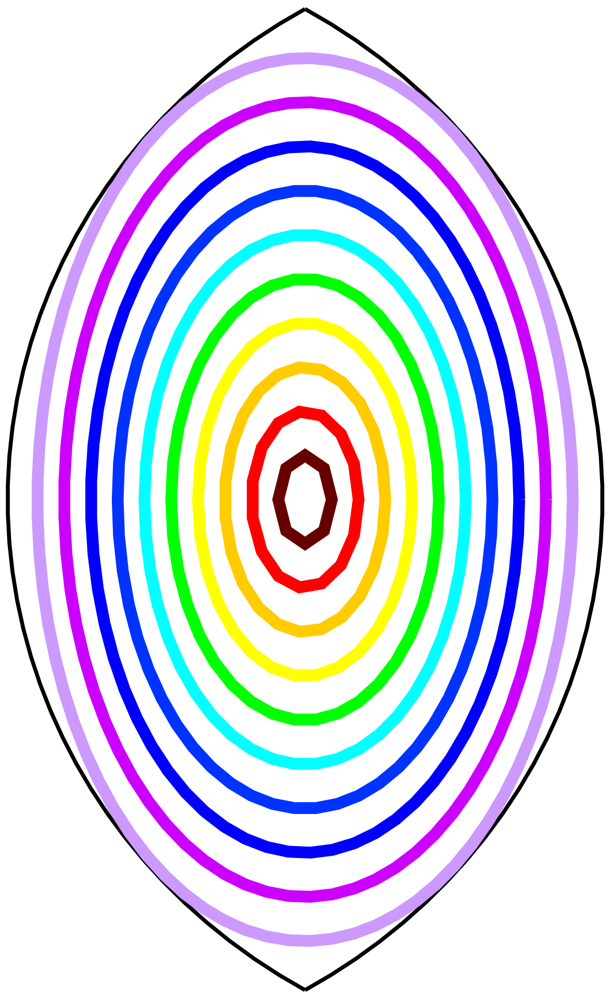


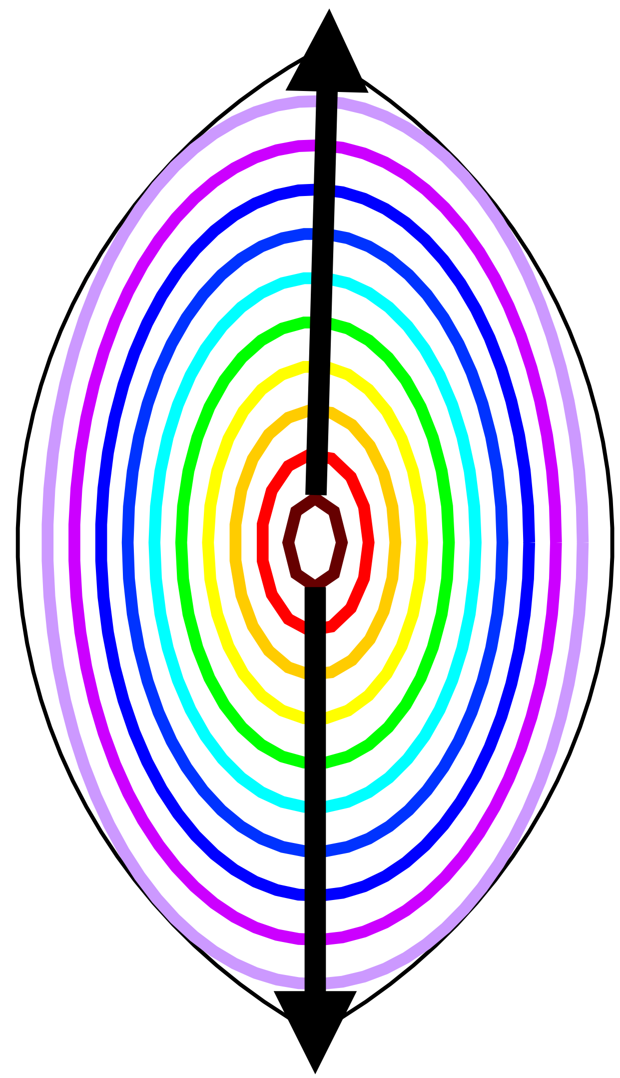
steep pressure change

lots of interactions

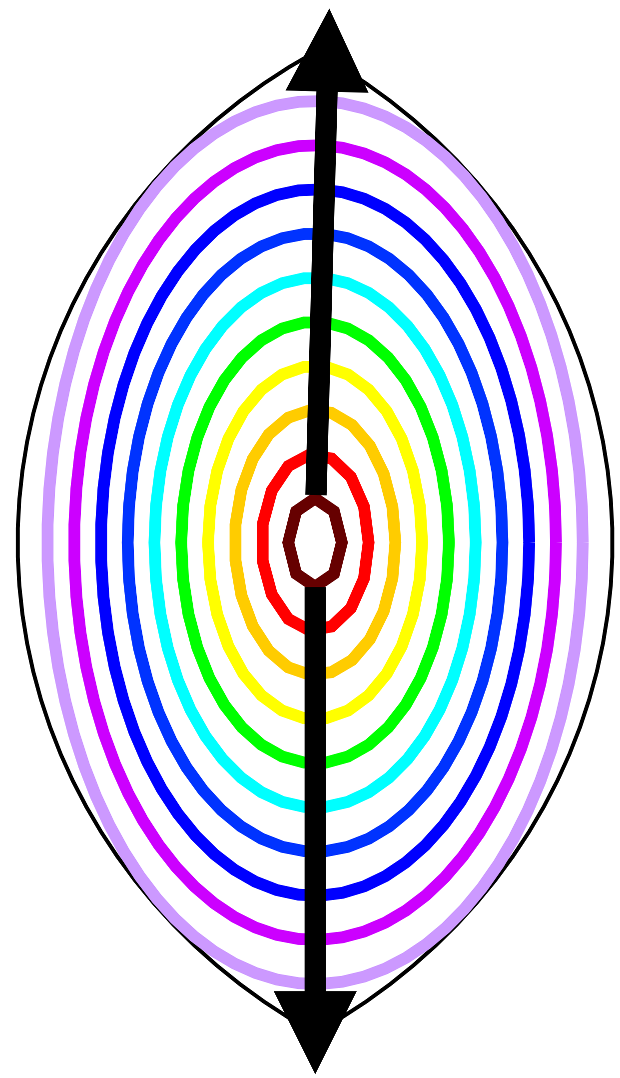


lots of interactions

gradual pressure change



gradual pressure change



this is how a liquid works!

characterizing a liquid

characterizing a liquid

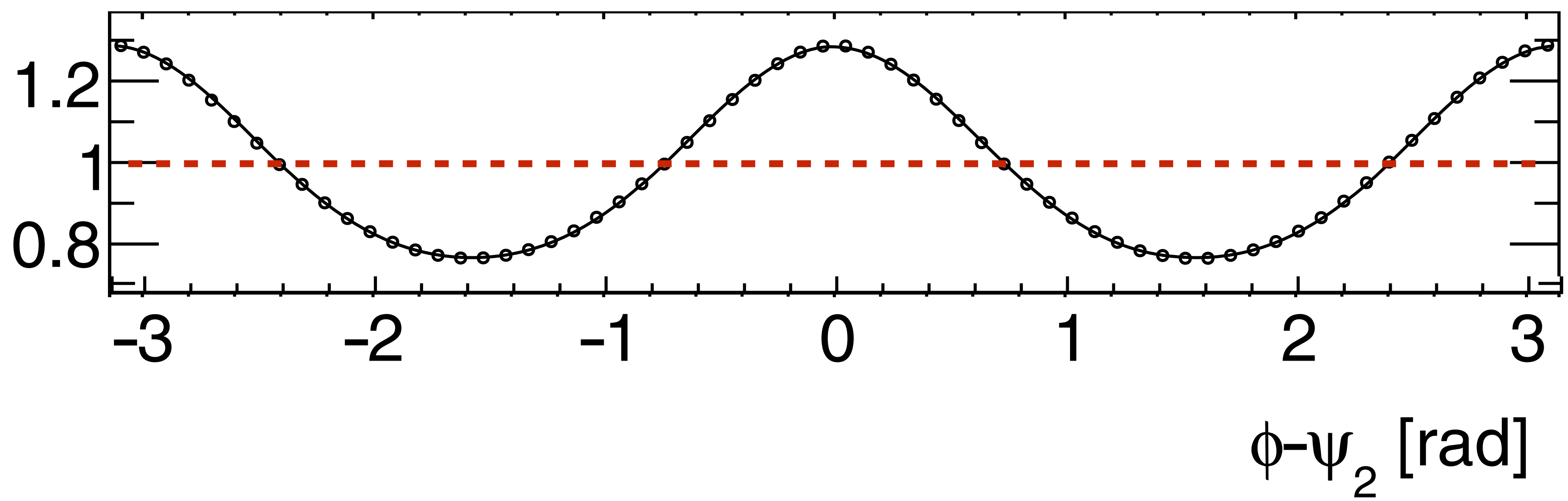
low viscosity

characterizing a liquid

low viscosity

high viscosity

QGP flows well!



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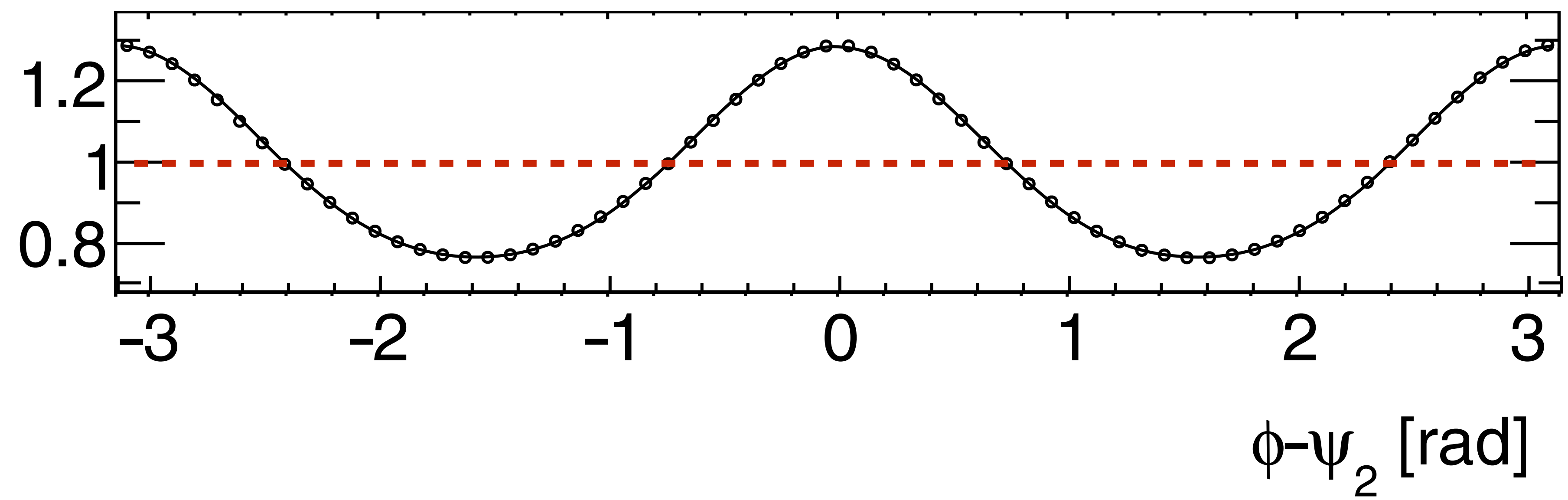
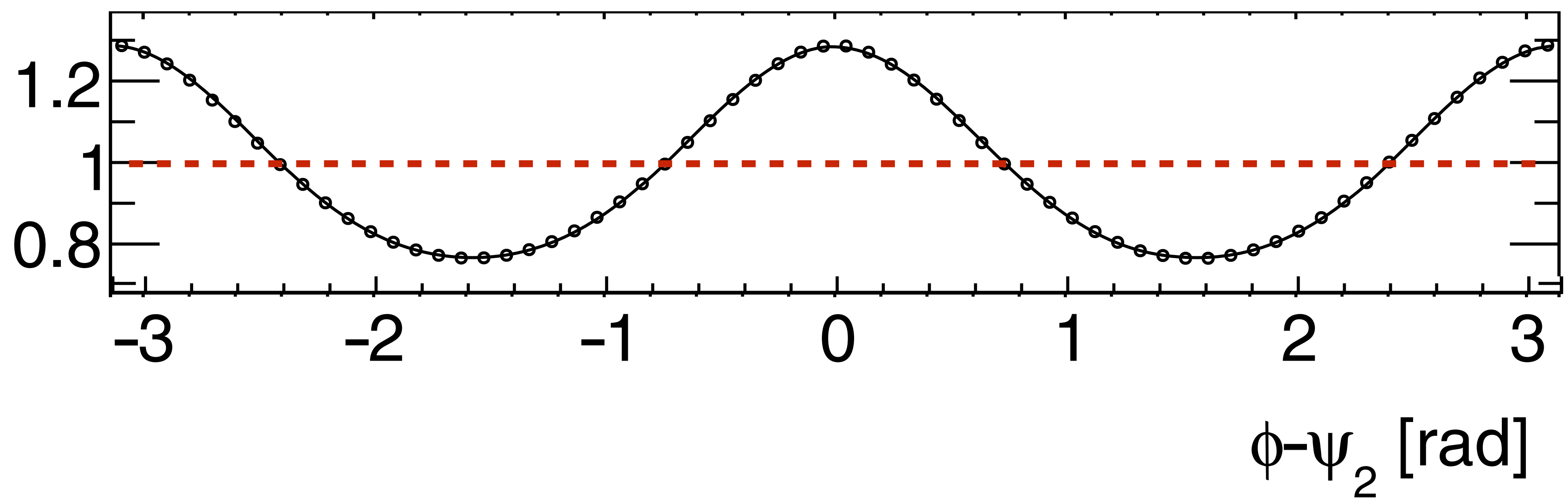


low viscosity (small η/s)

$\eta/s > 25\ (1/4\pi)$

QGP flows well!



low viscosity (small η/s)

η/s > 25 (1/4π)

η/s(QGP) < 5 (1/4π)

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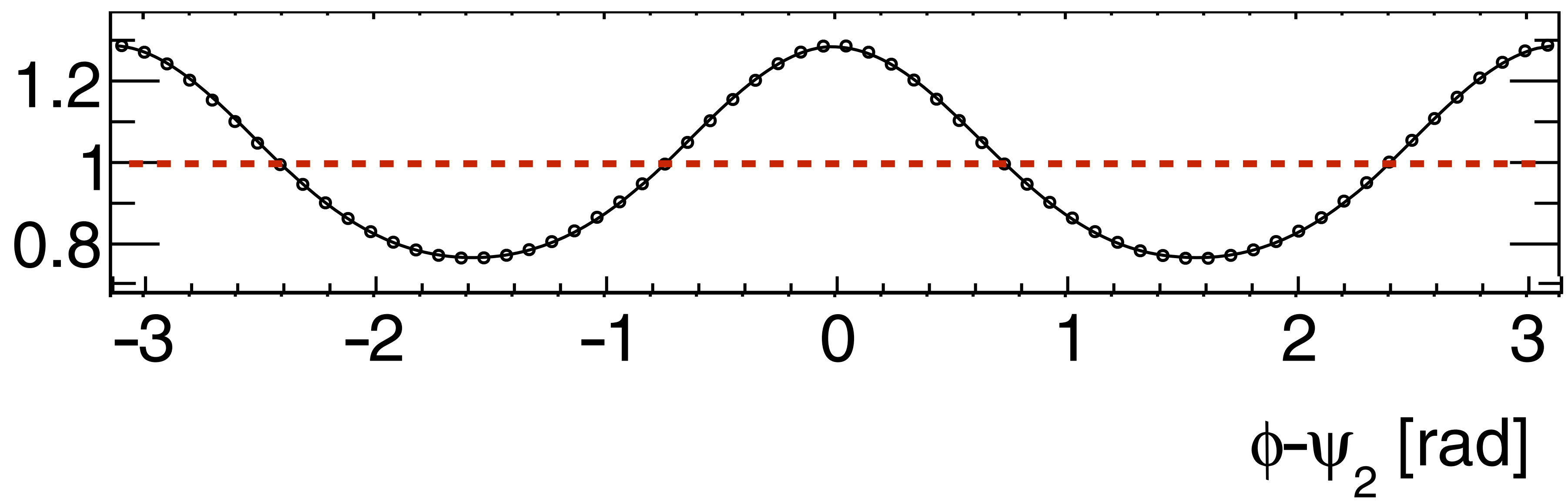

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string theory calculation:
universal minimum
η/s > 1/4π

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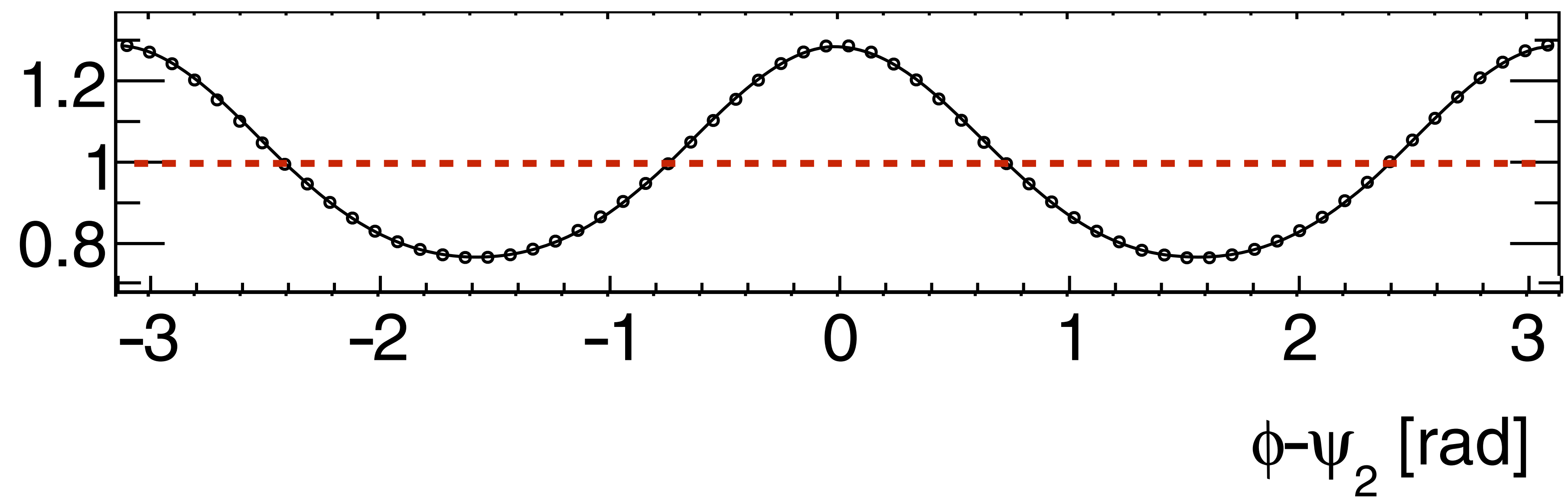

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η/s > 25 (1/4π)

η/s(QGP) < 5 (1/4π)

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η/s > 1/4π

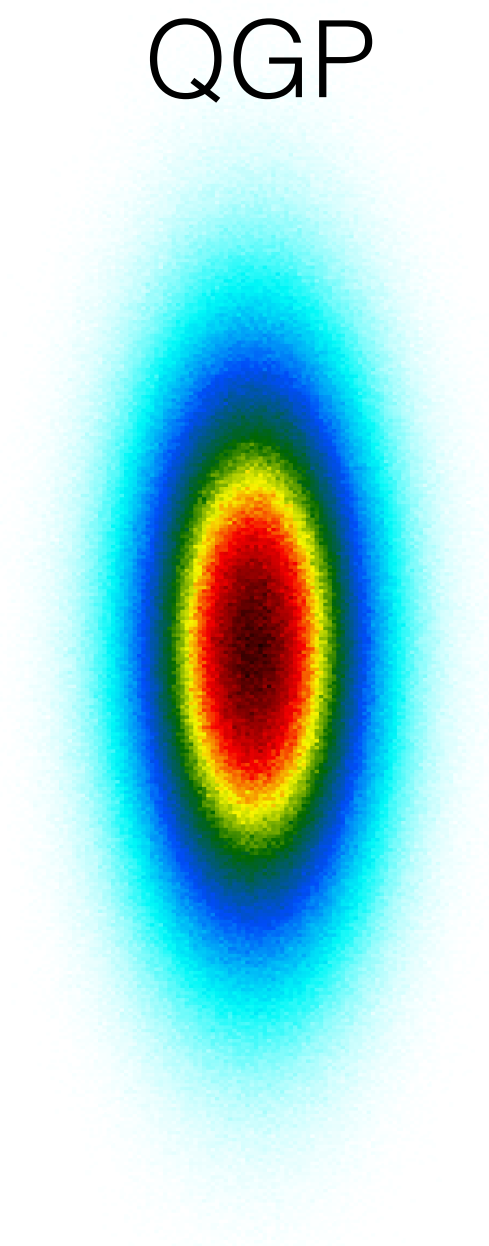
determining η/s(QGP)
is very important

why does the strong force at high temperature lead to fluid behavior?

why does the strong force at high temperature lead to fluid behavior?

to answer that, we need a picture of the microscopic interactions between the quarks and gluons inside the QGP

how we'd like to measure the QGP



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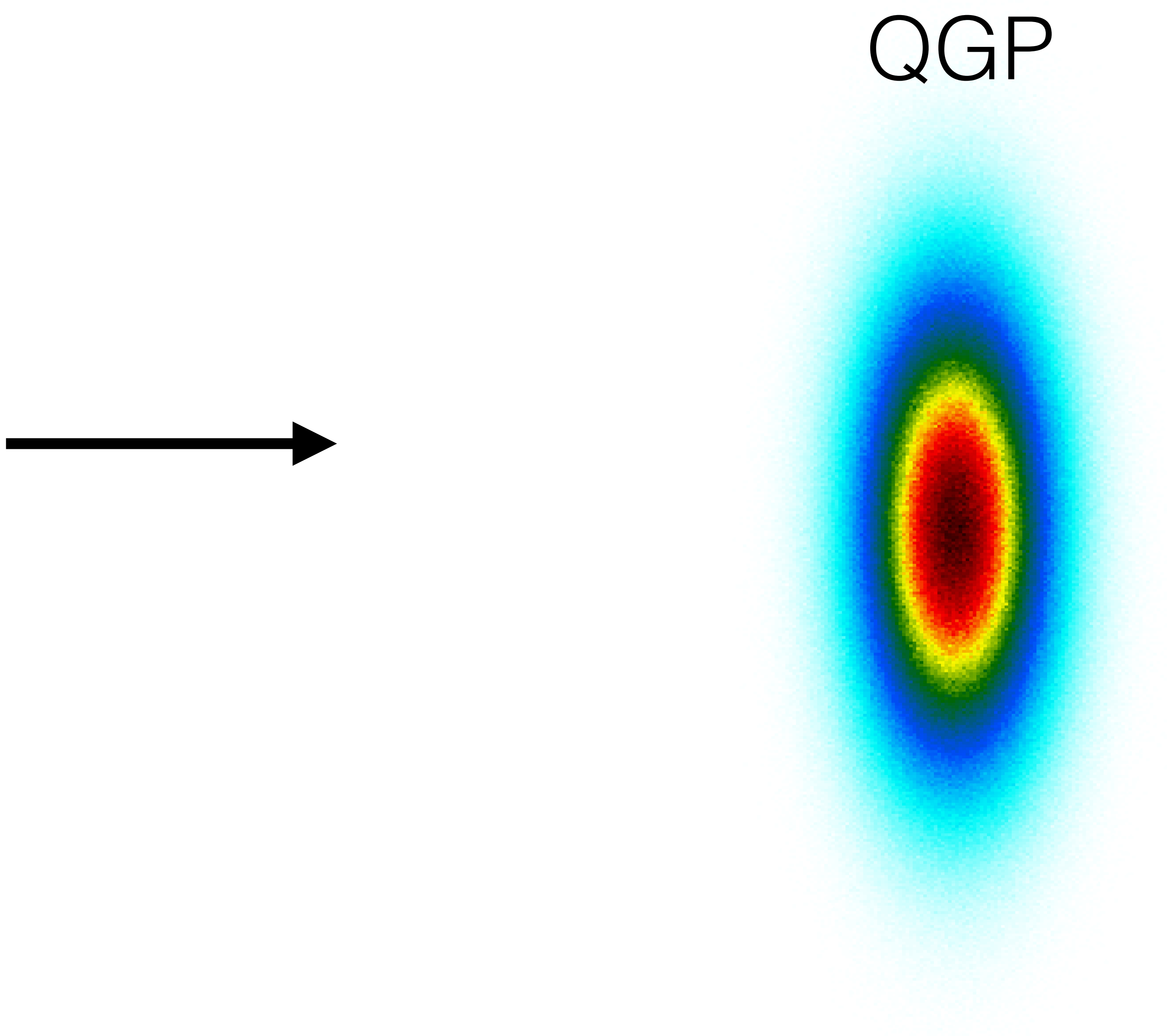

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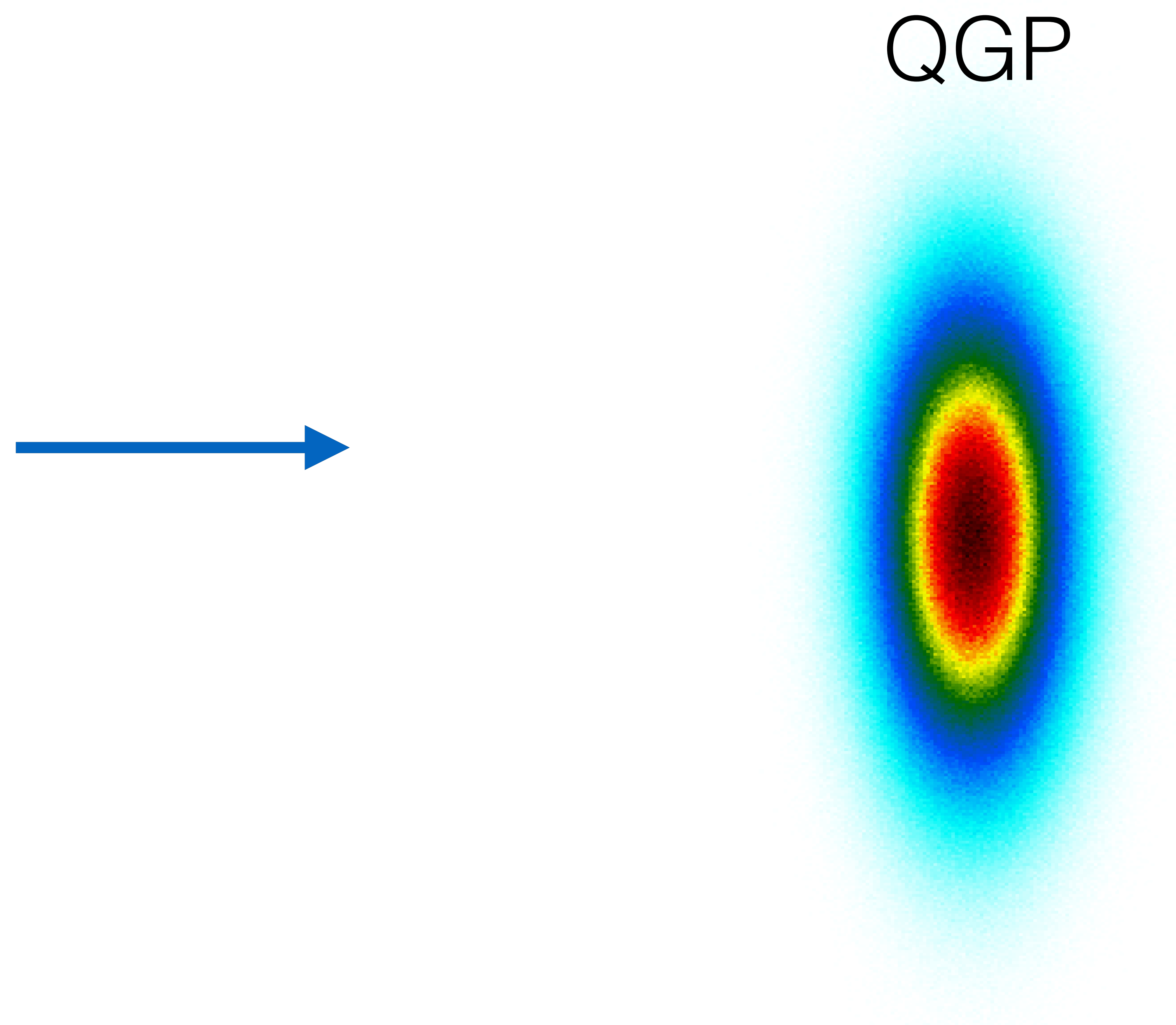

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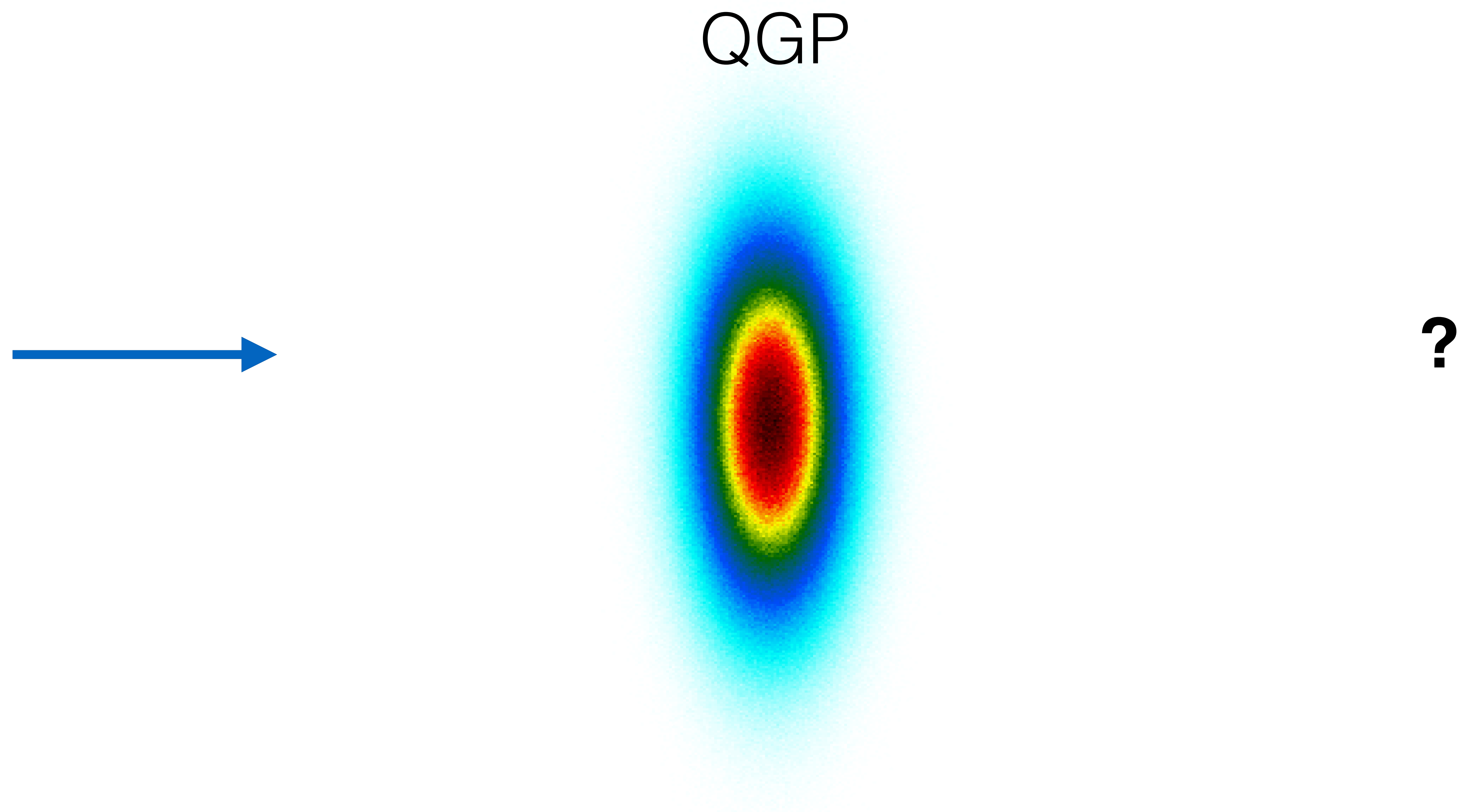
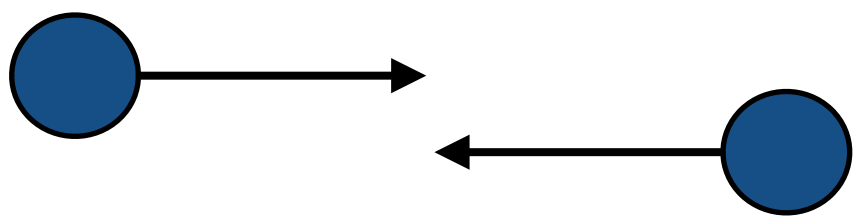
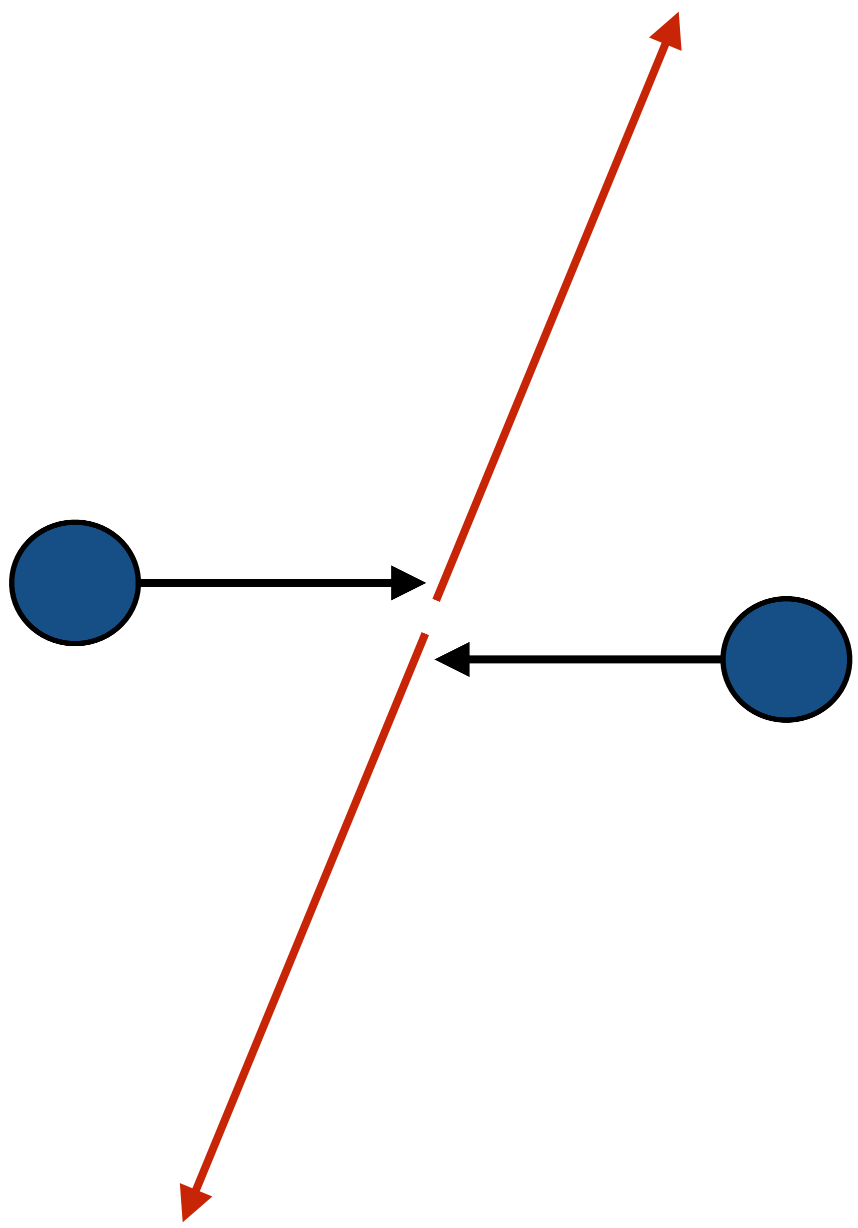


a proton is like a beam of incoming quarks & gluons



sometimes a quark from one proton hits a quark from the other head on

a proton is like a beam of incoming quarks



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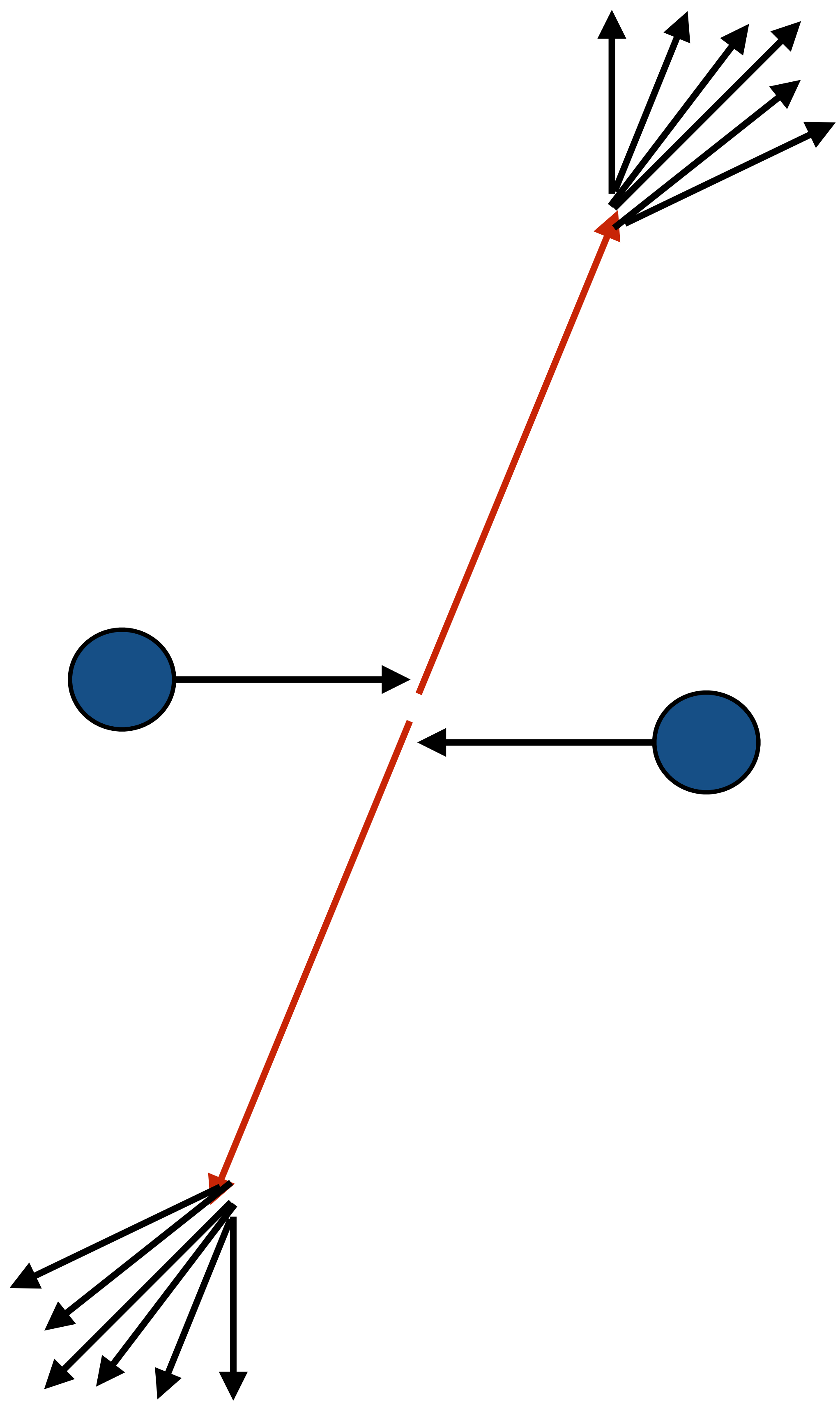
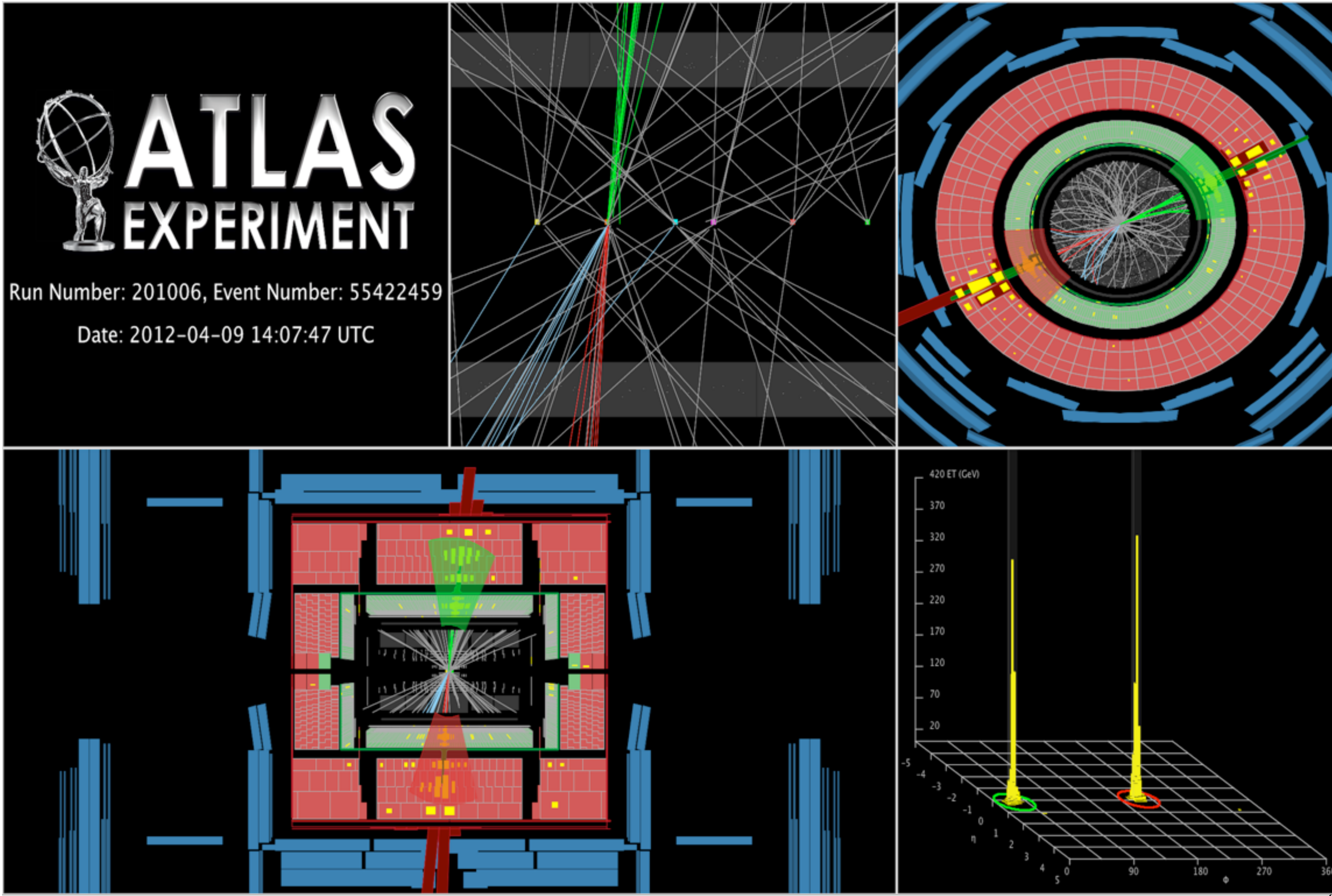


a pair of jets



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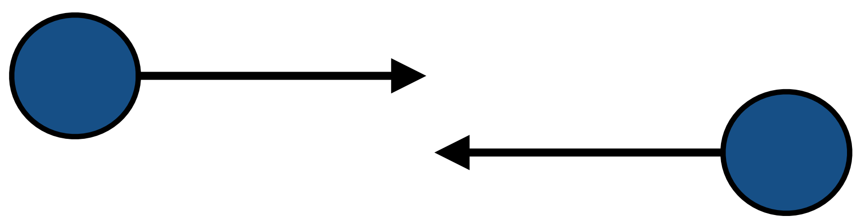

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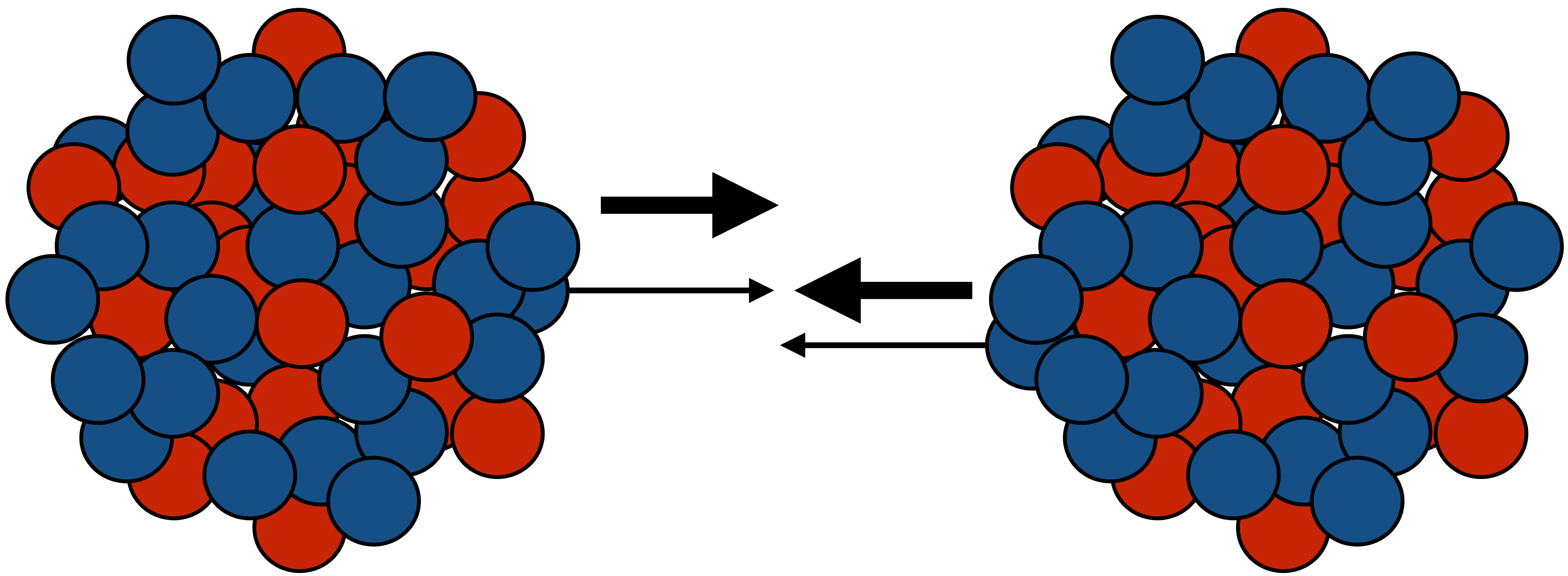

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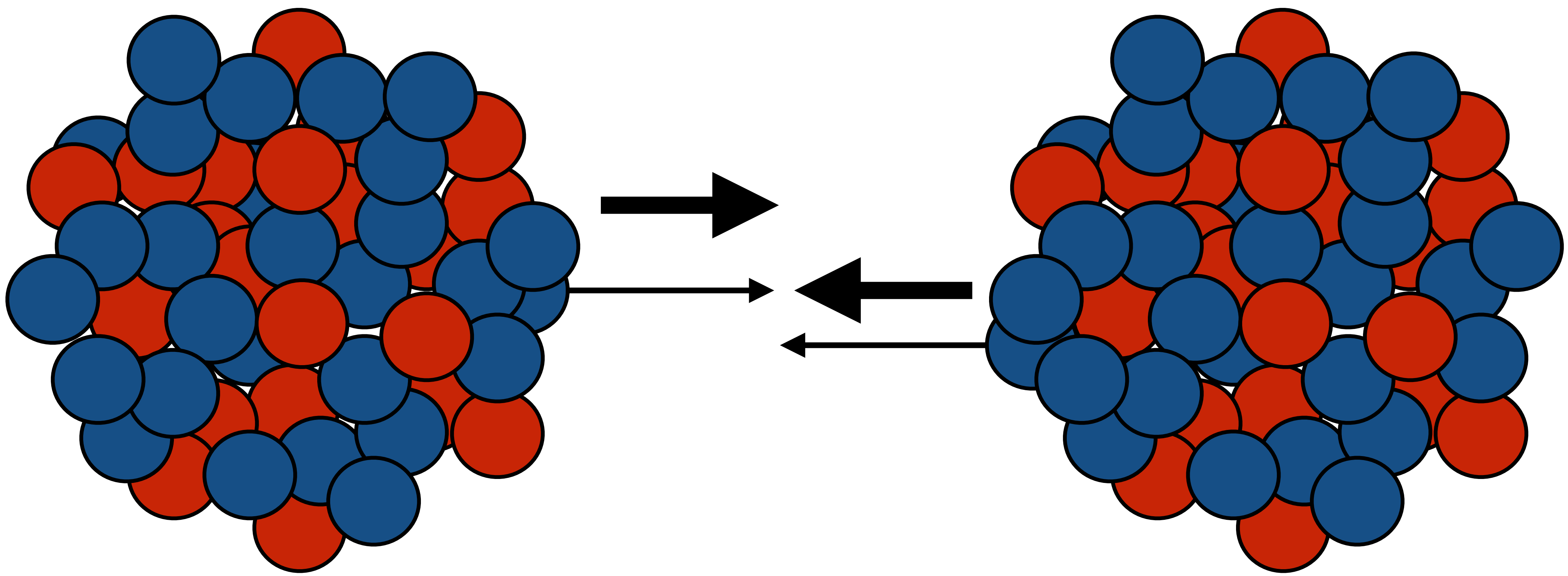
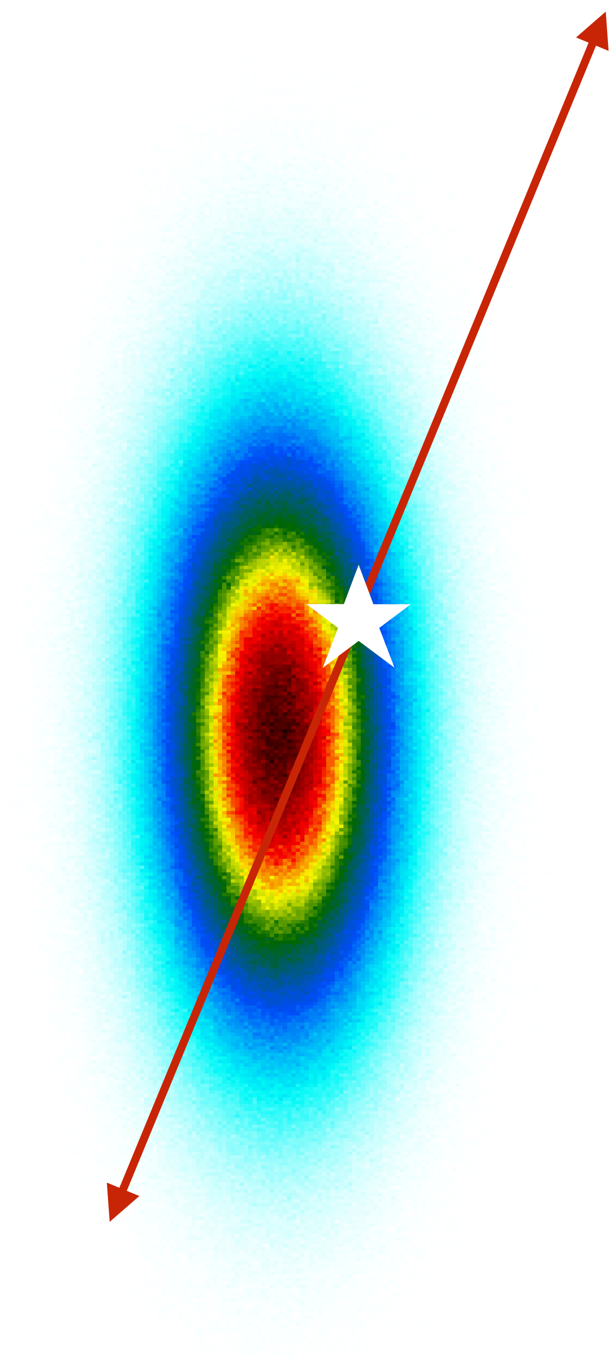
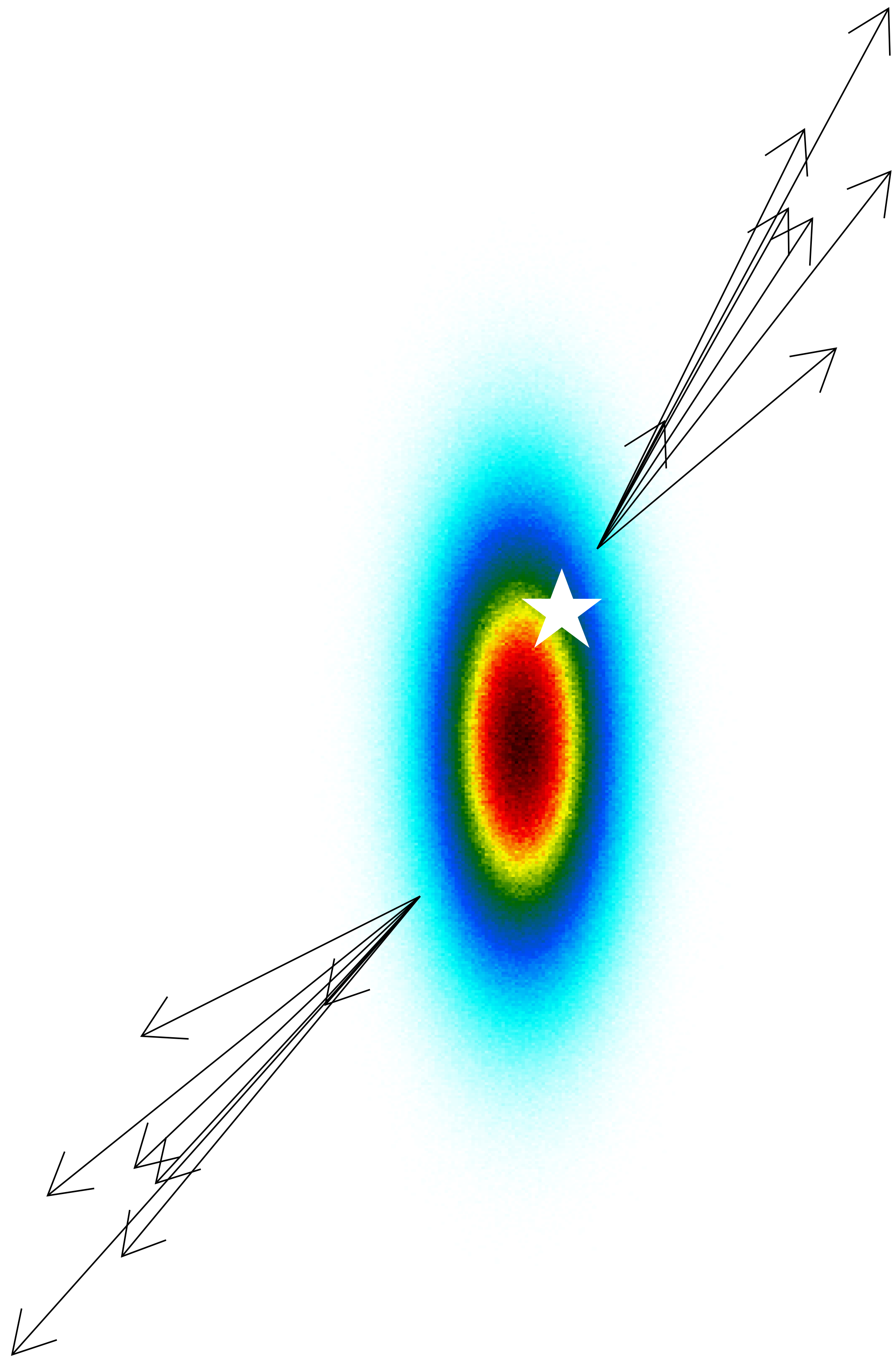


a jet created at the same time as the quark gluon plasma functions as a microscope

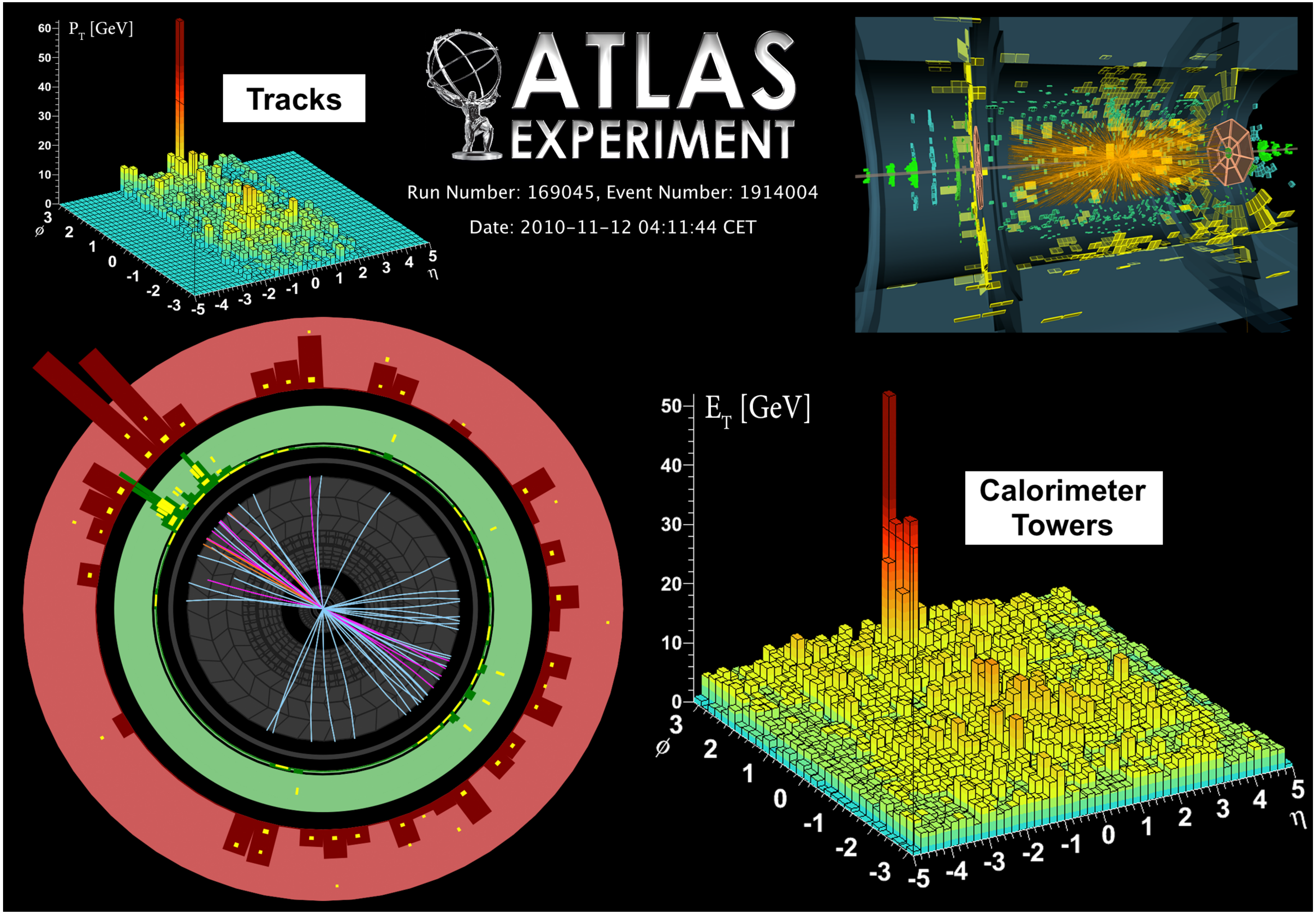
a proton is like a beam of incoming quarks



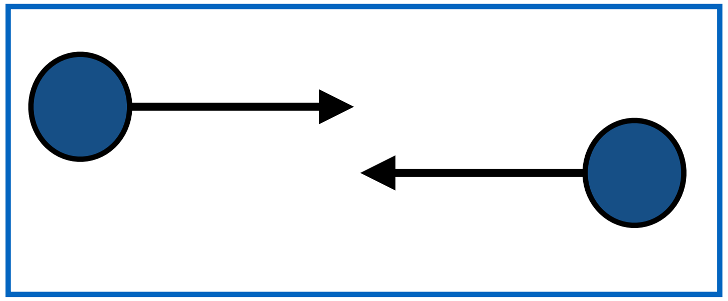
jets going through the QGP

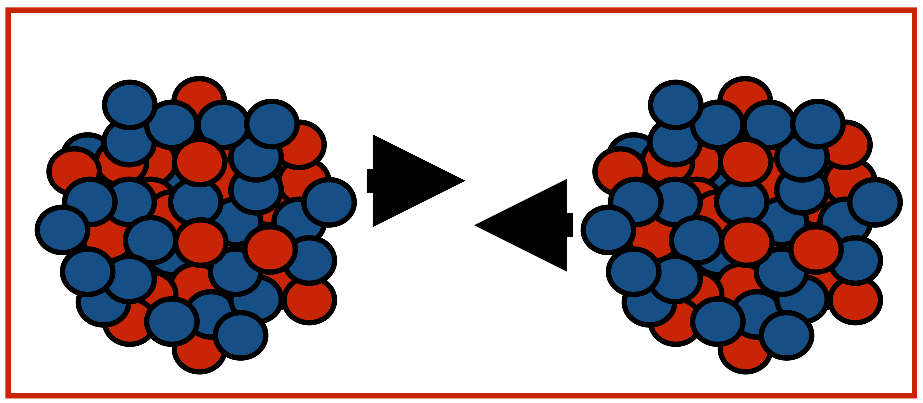


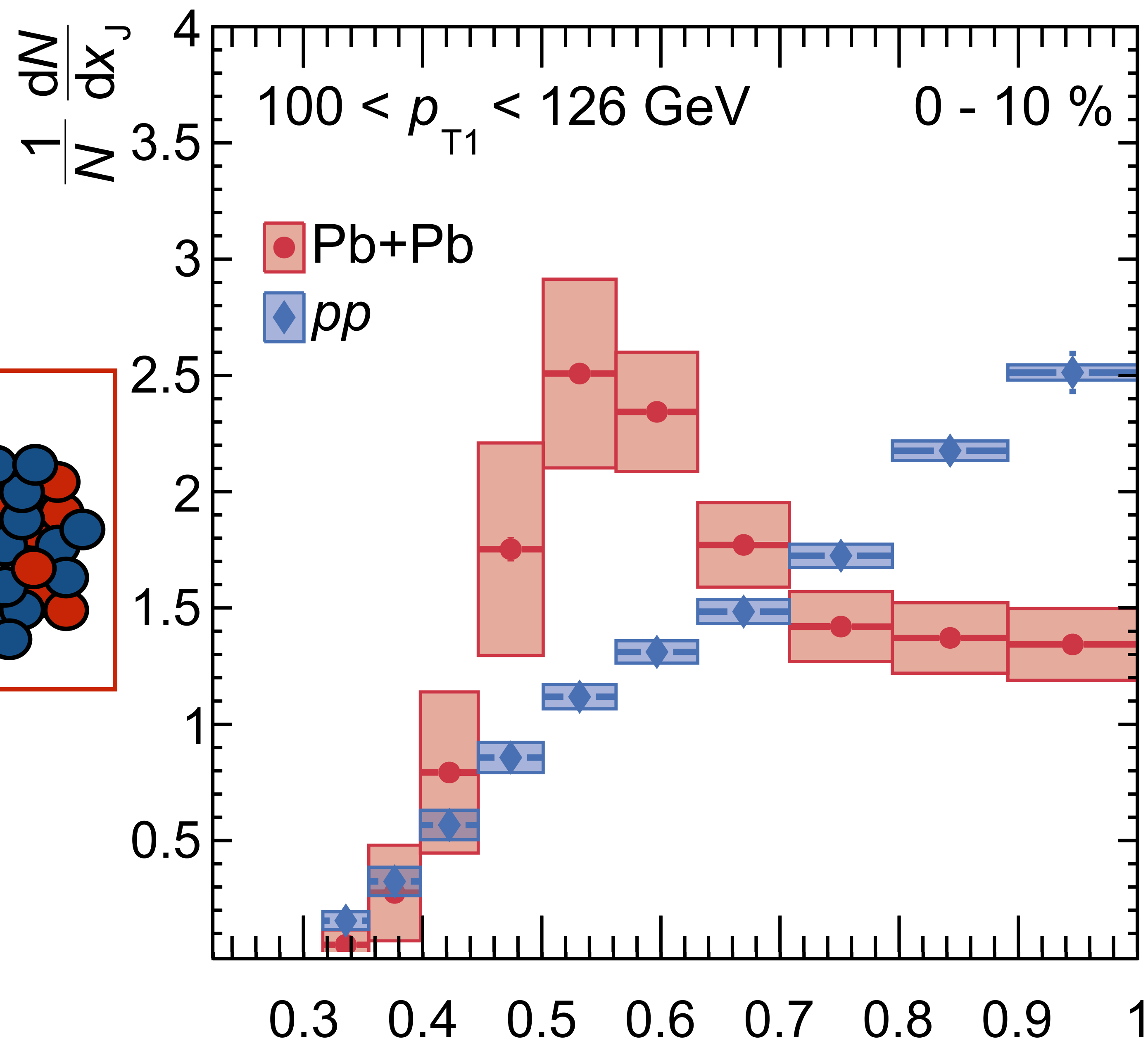
lead-lead collisions: not every jet survives



energy balance of the jets

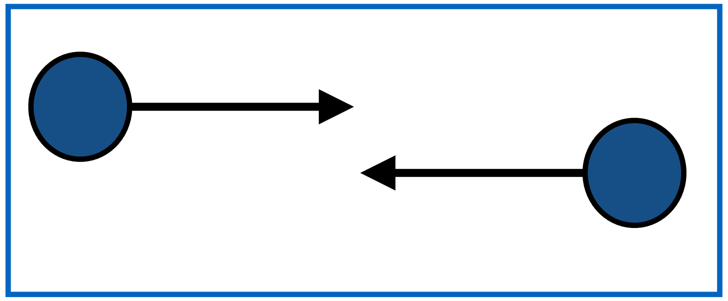


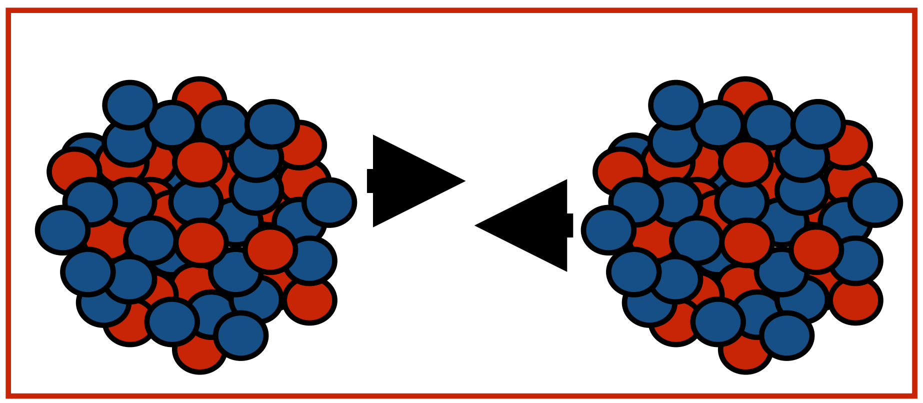


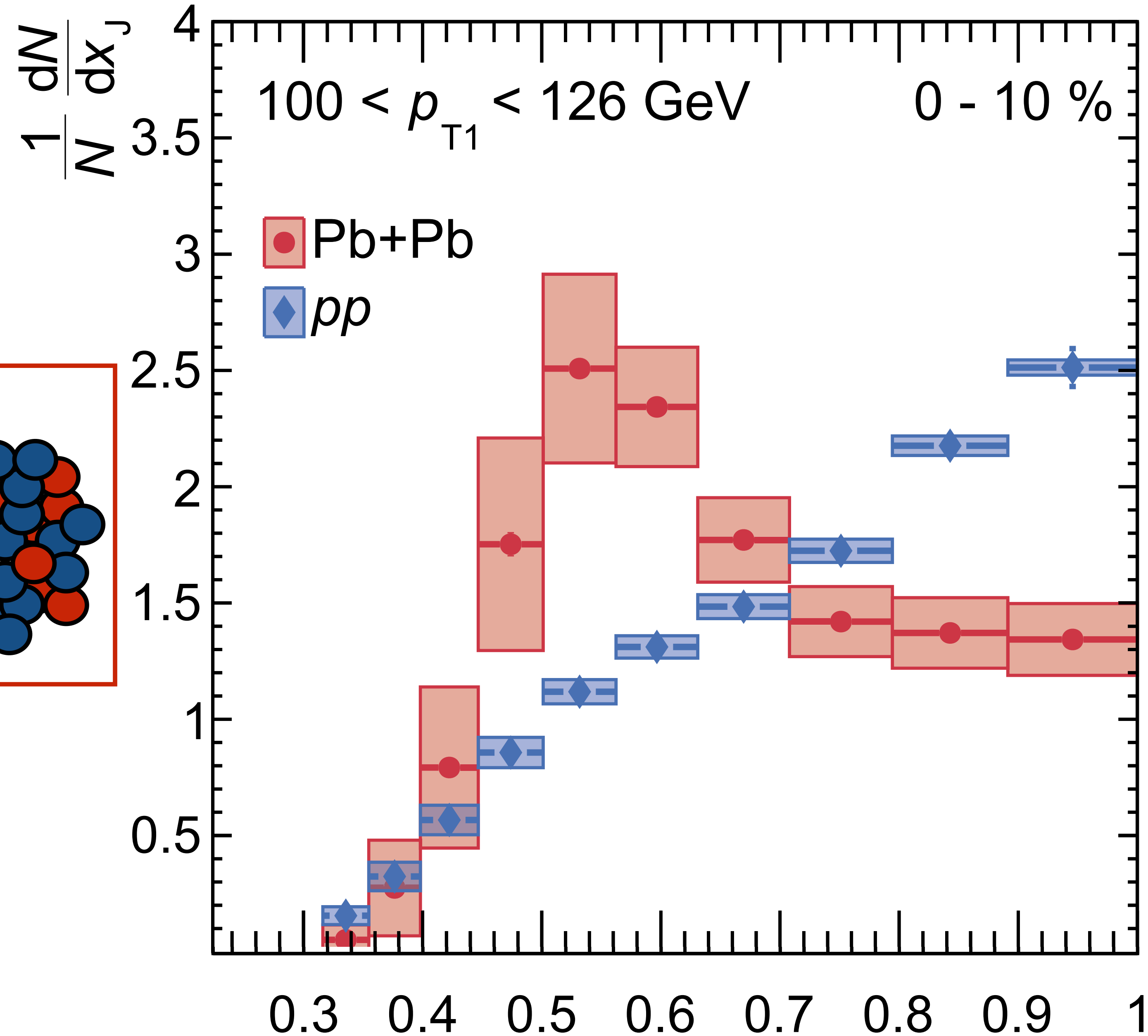


energy of jet 2 / energy of jet 1

energy balance of the jets



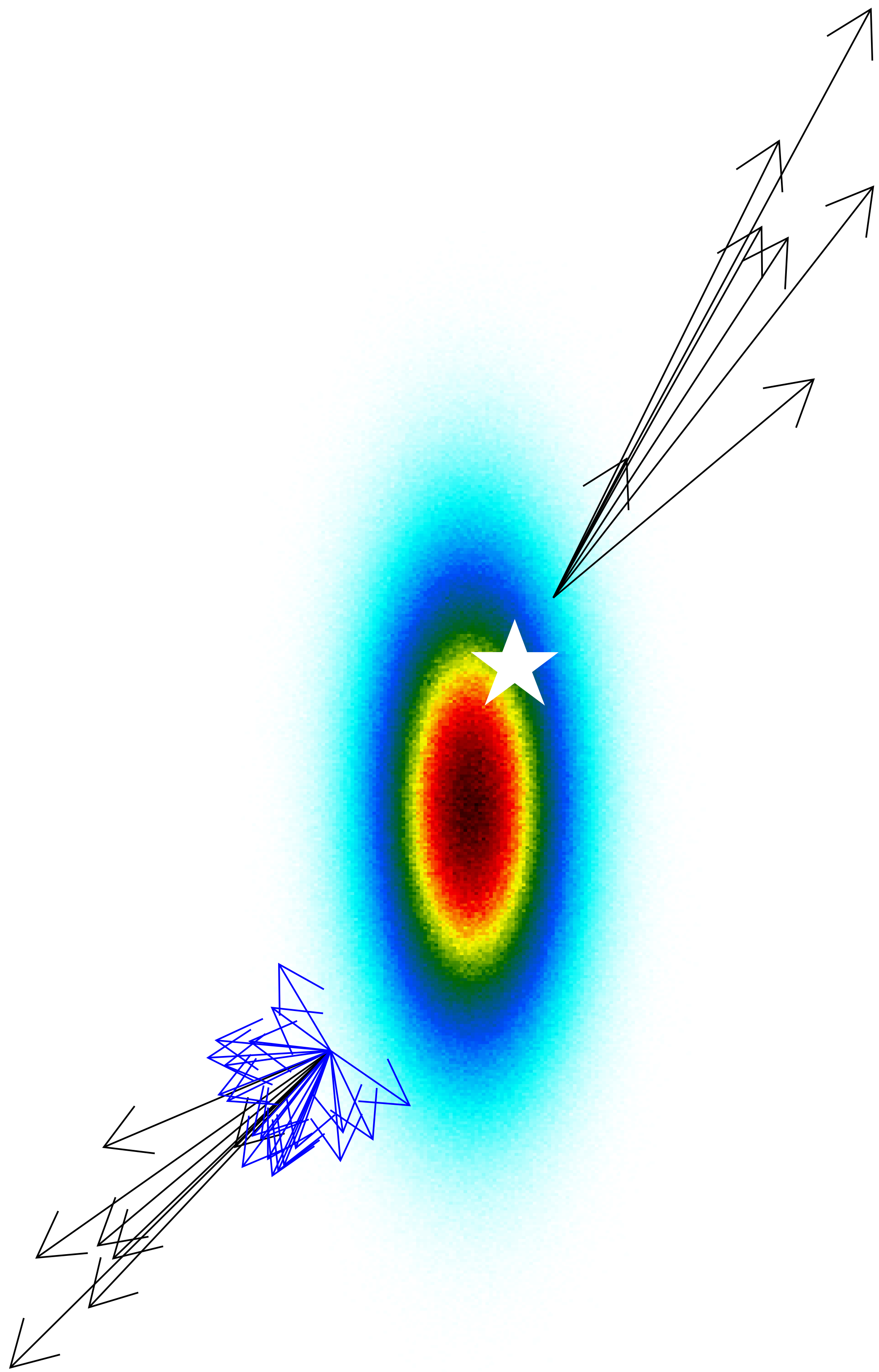




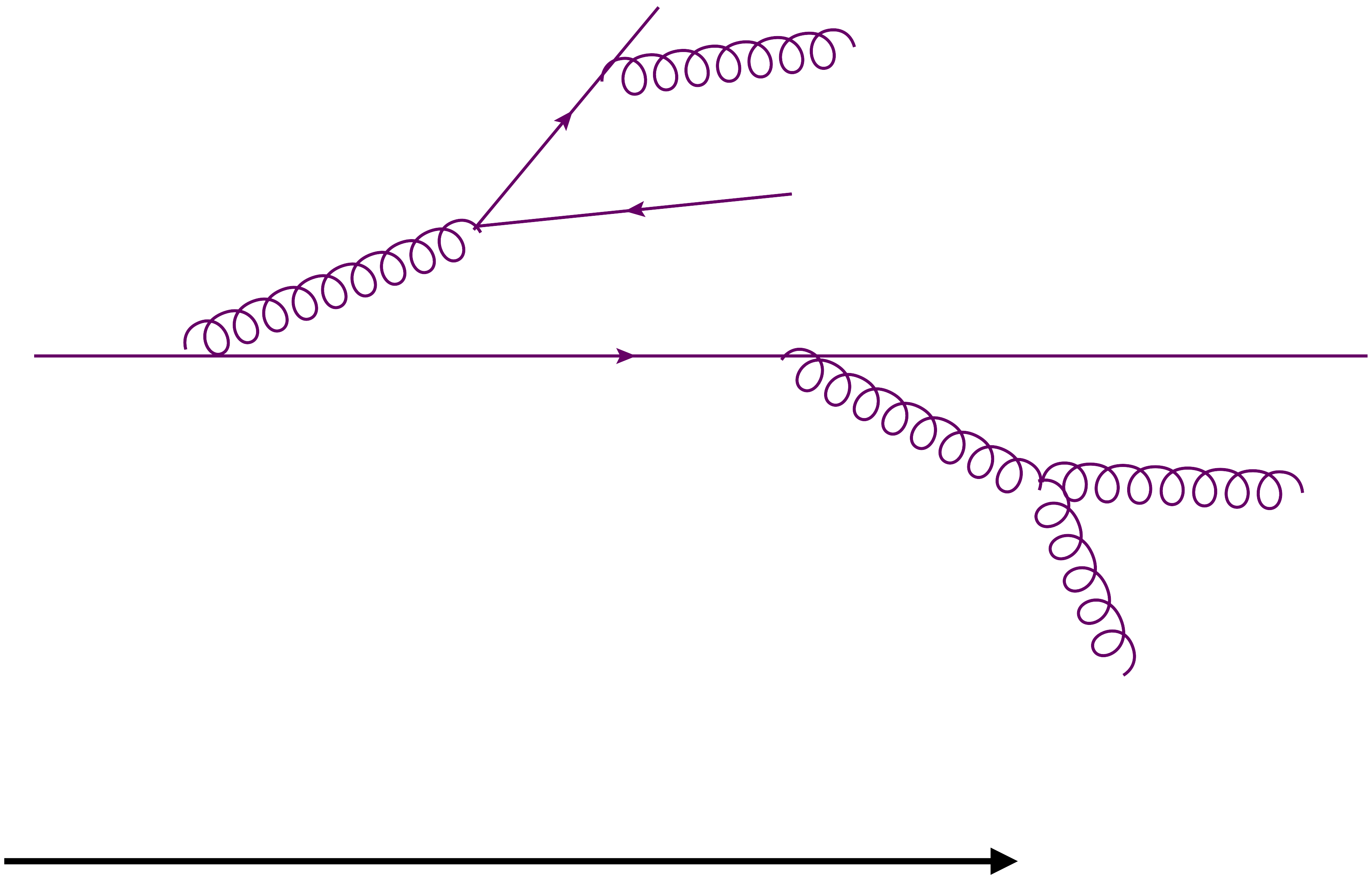
energy of jet 2 / energy of jet 1

a lot of energy is removed from jet 2

jets going through the QGP

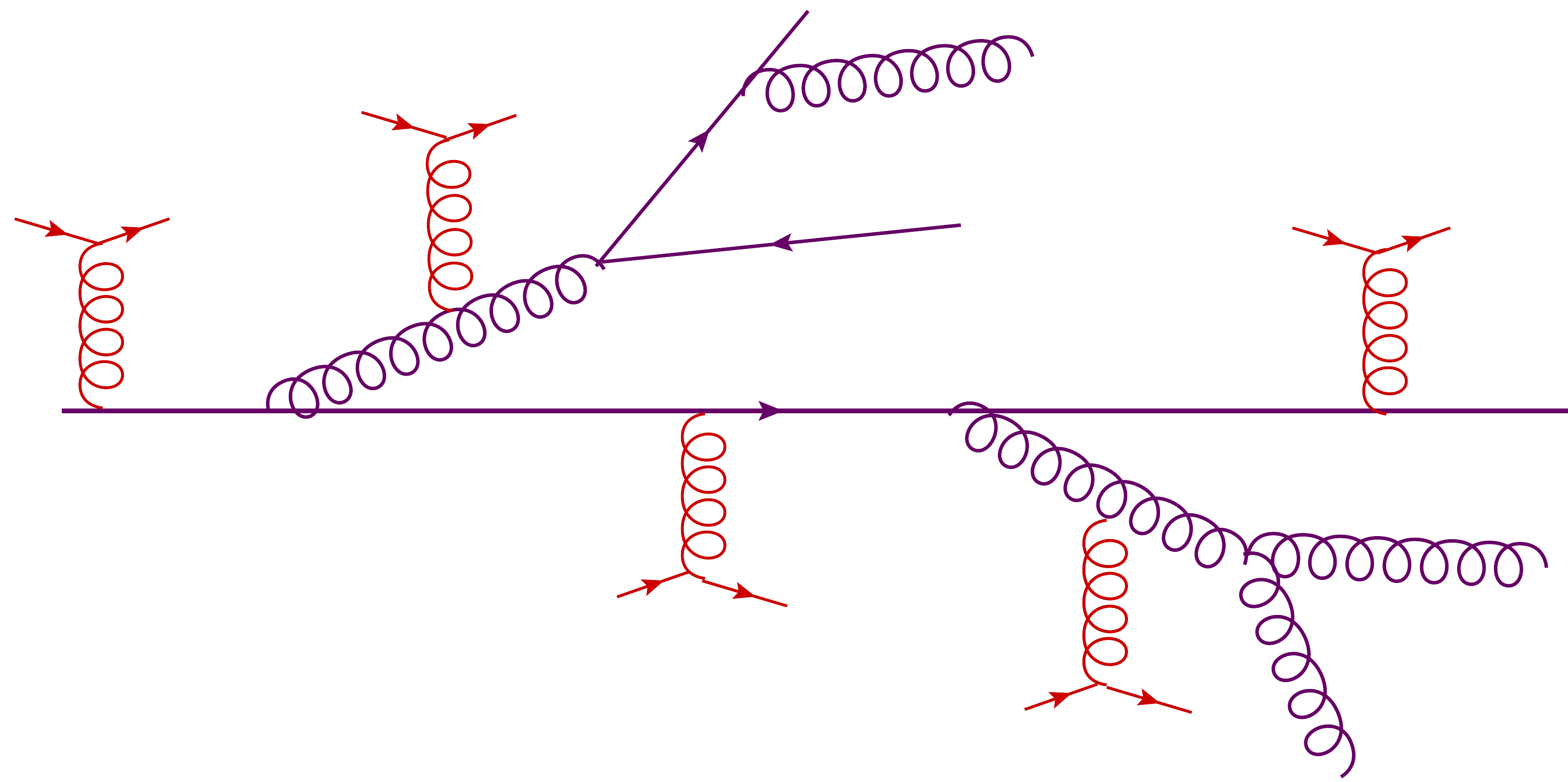


no QGP



time

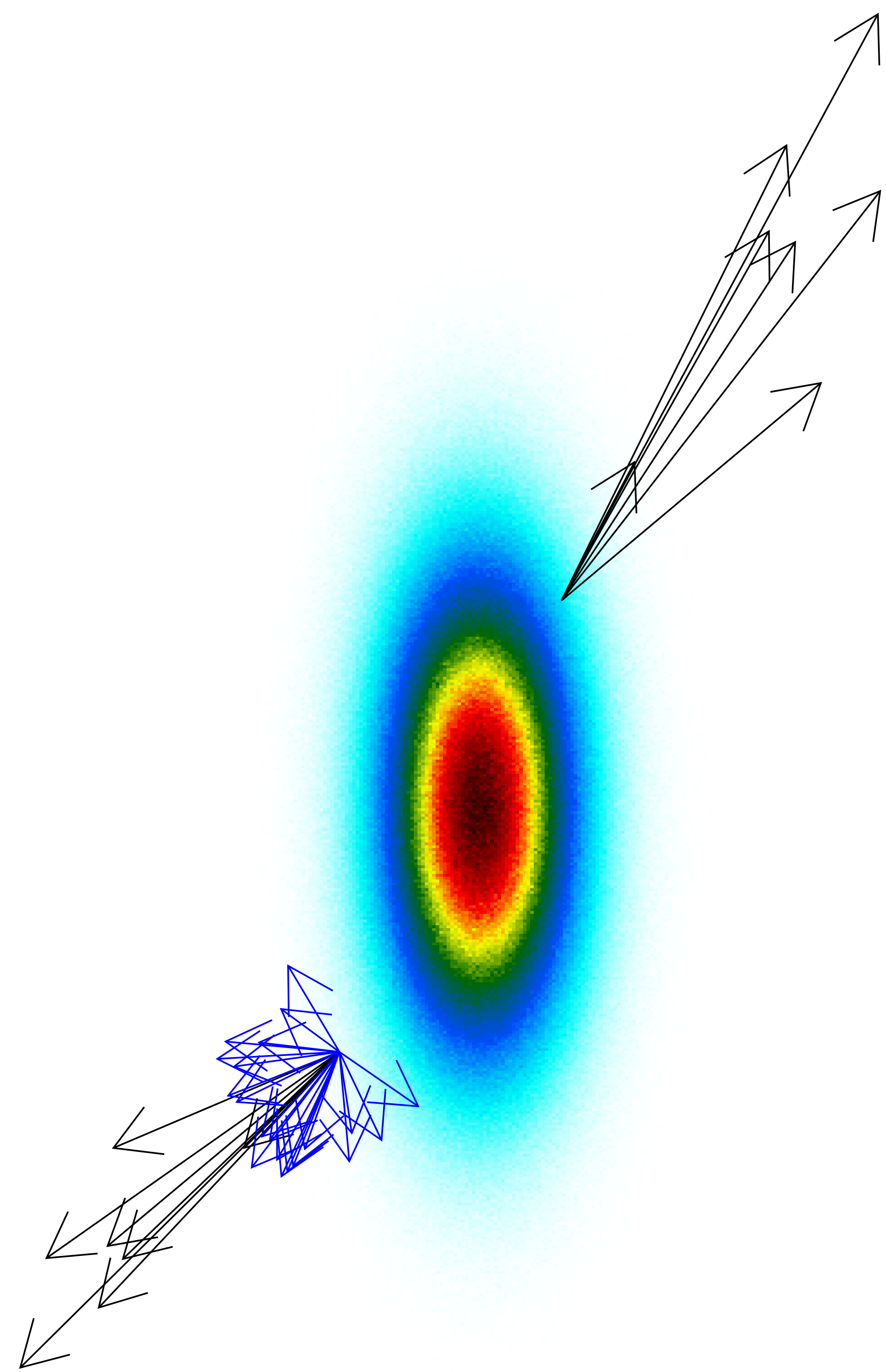
QGP



interactions with the **quark-gluon plasma** cause more particles

some of these particles are far from the jet

looking at the effects of the quark-gluon plasma



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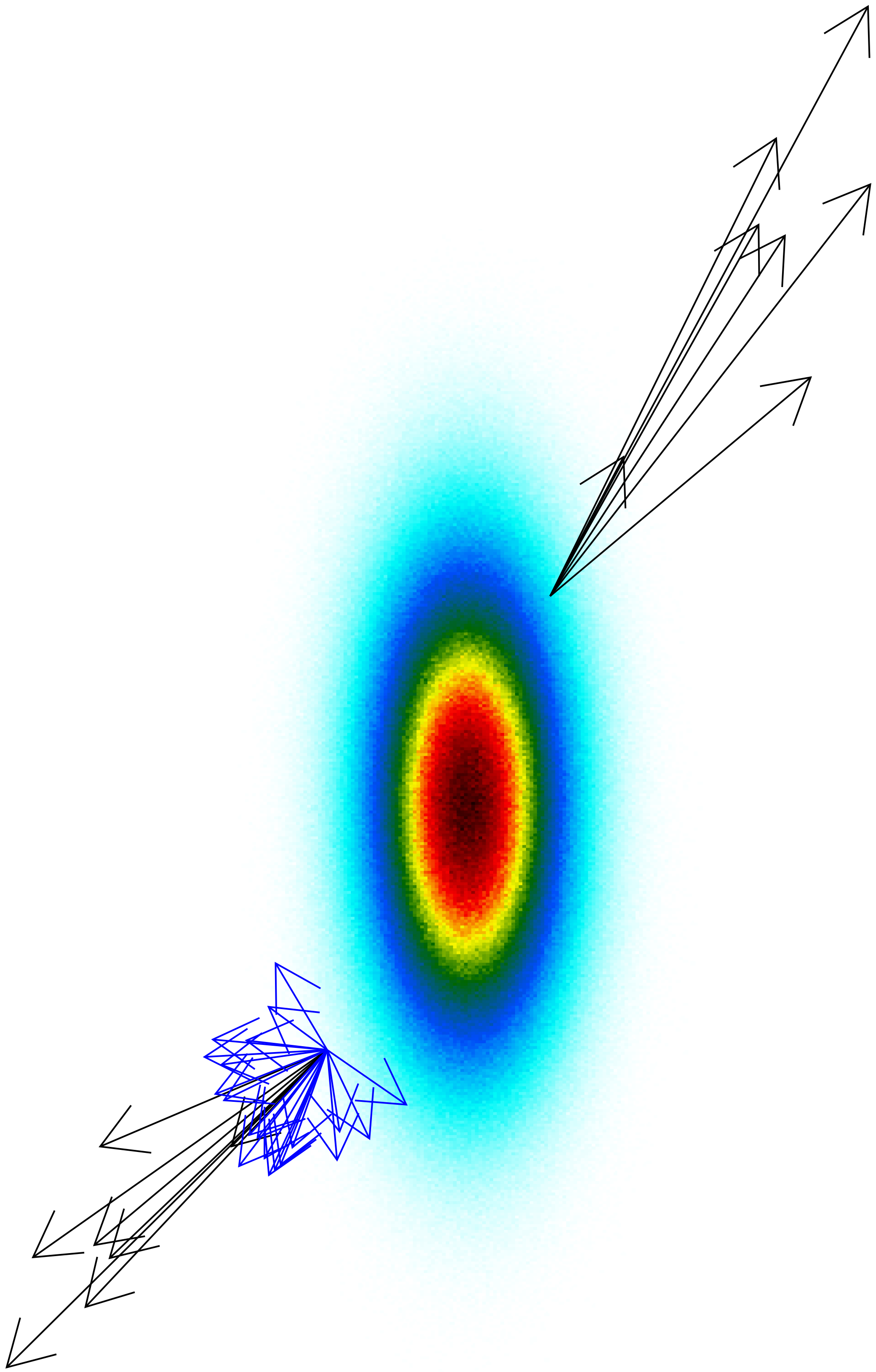
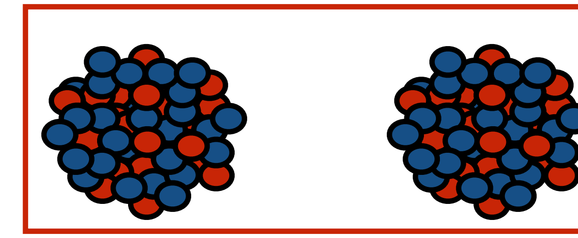
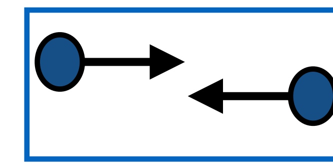
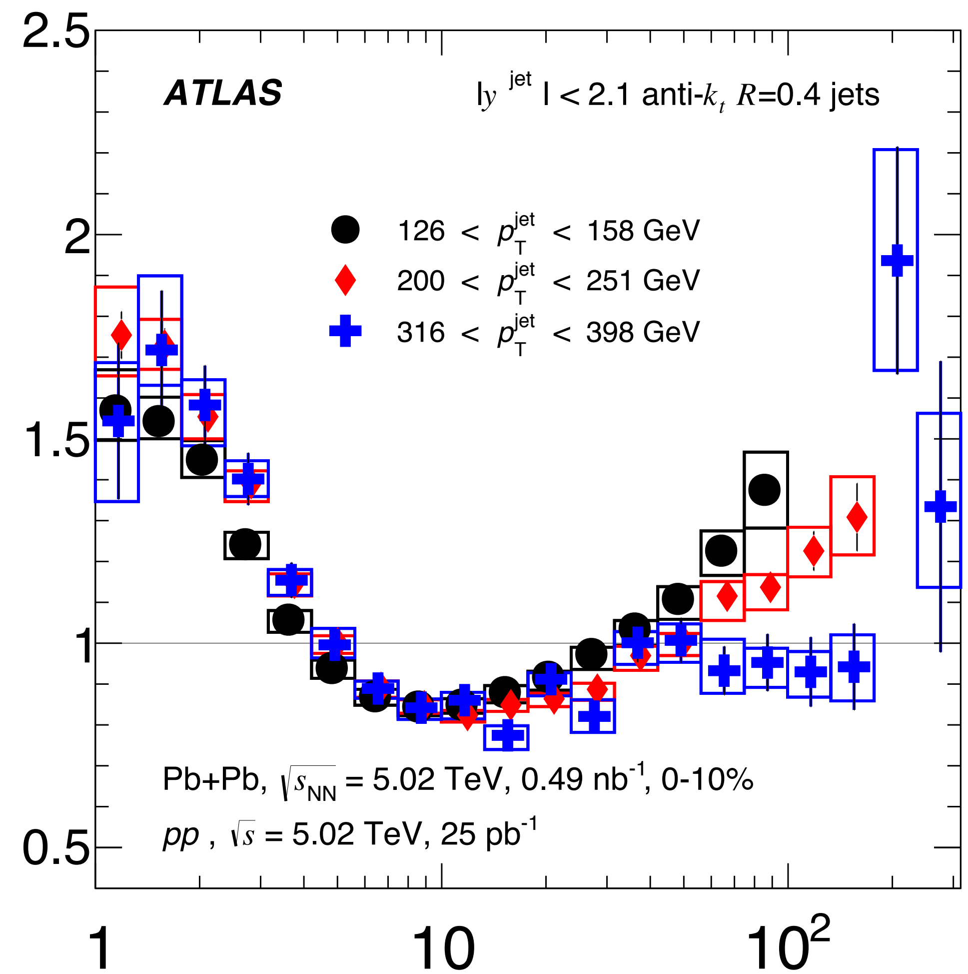


# of particle in jet



# of particle in jet





particle energy

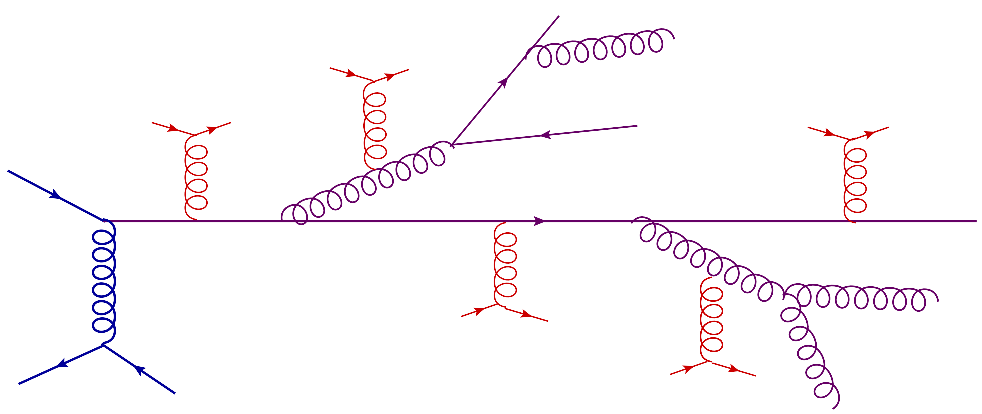
where next?

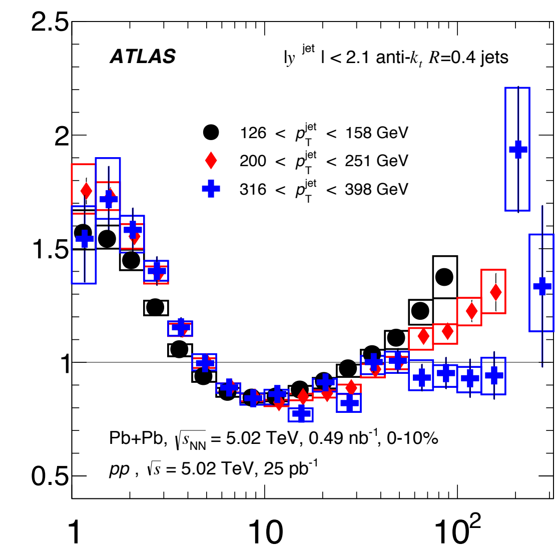
jets look different in the quark-gluon plasma

where next?

jets look different in the quark-gluon plasma

we work with theorists to build models which tell us how exactly





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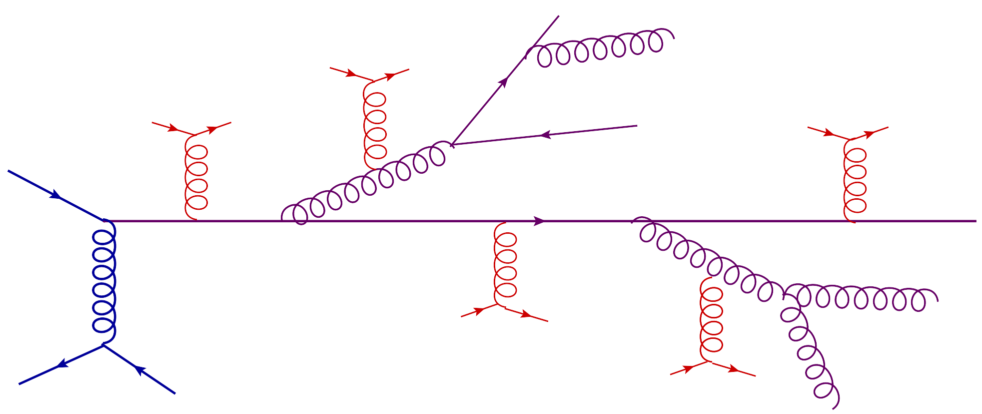

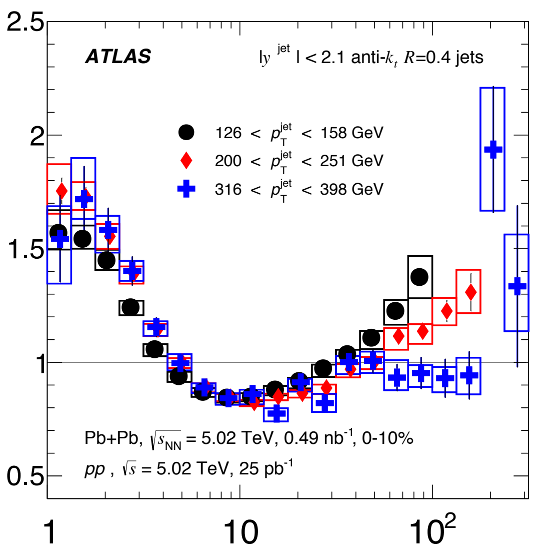

as an experimentalist, I try to figure out everything I can about how this depends on the size of the quark-gluon plasma, the energy of the jet, the type of quark, the temperature of the quark-gluon plasma,…

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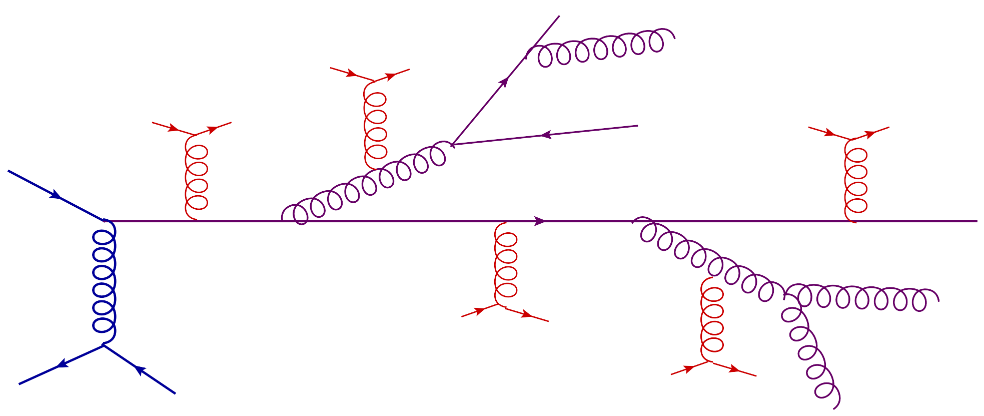

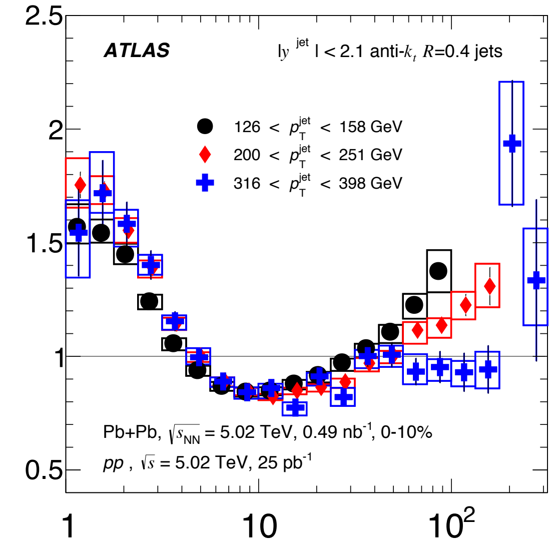

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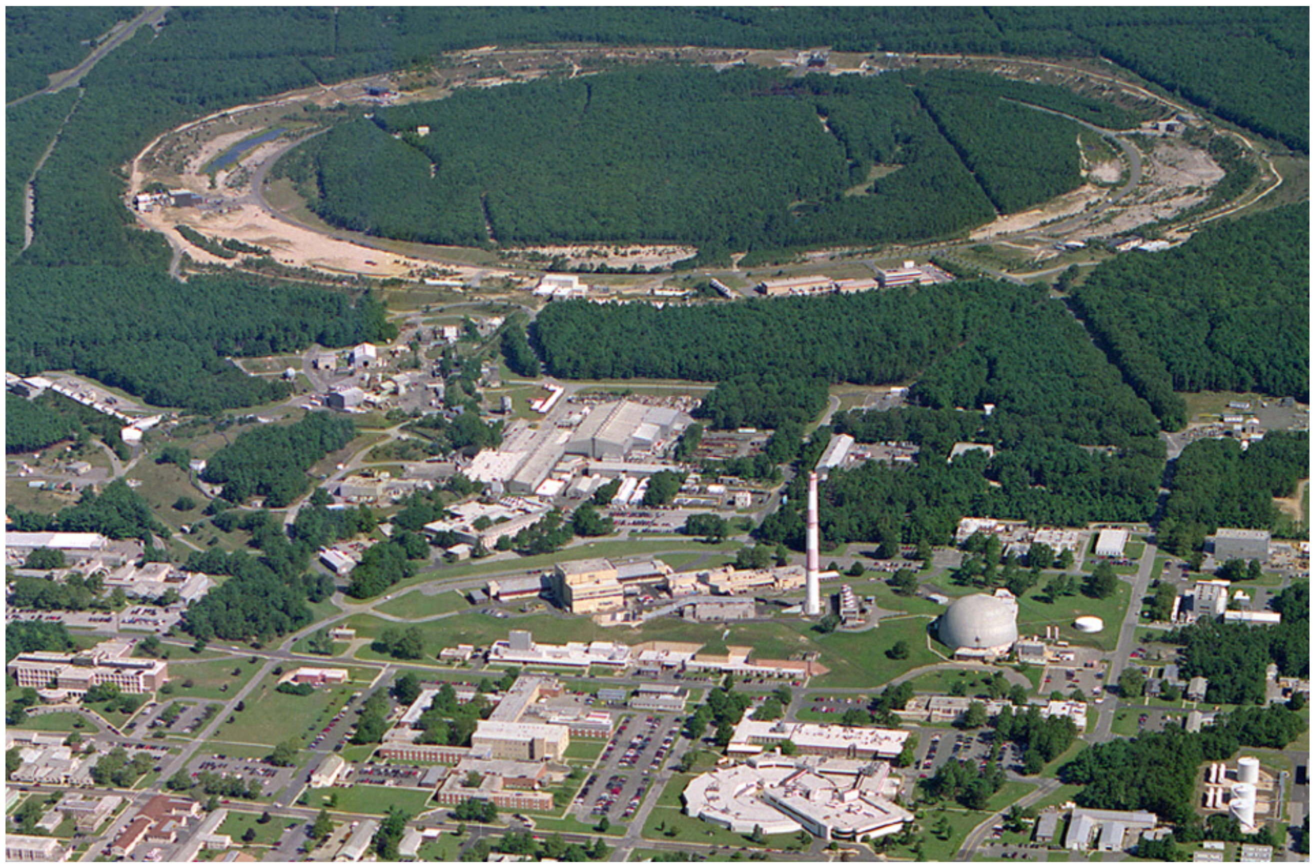
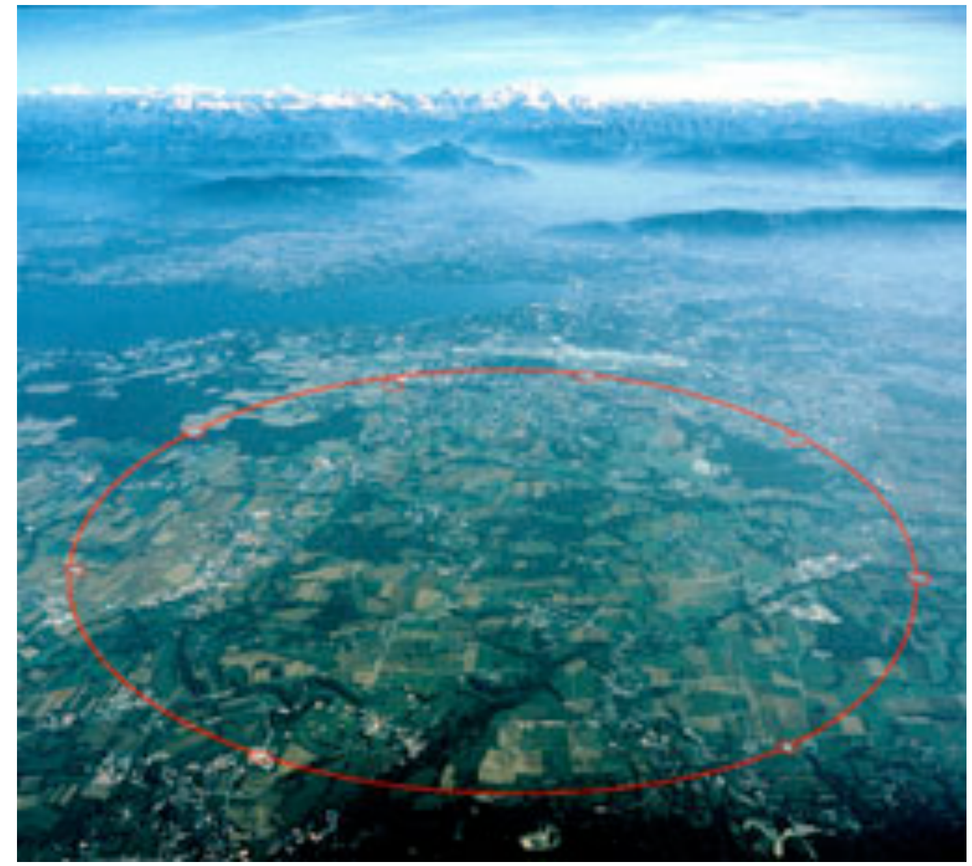
particle accelerators at BNL and CERN

RHIC (New York)



0.200 TeV collision energy

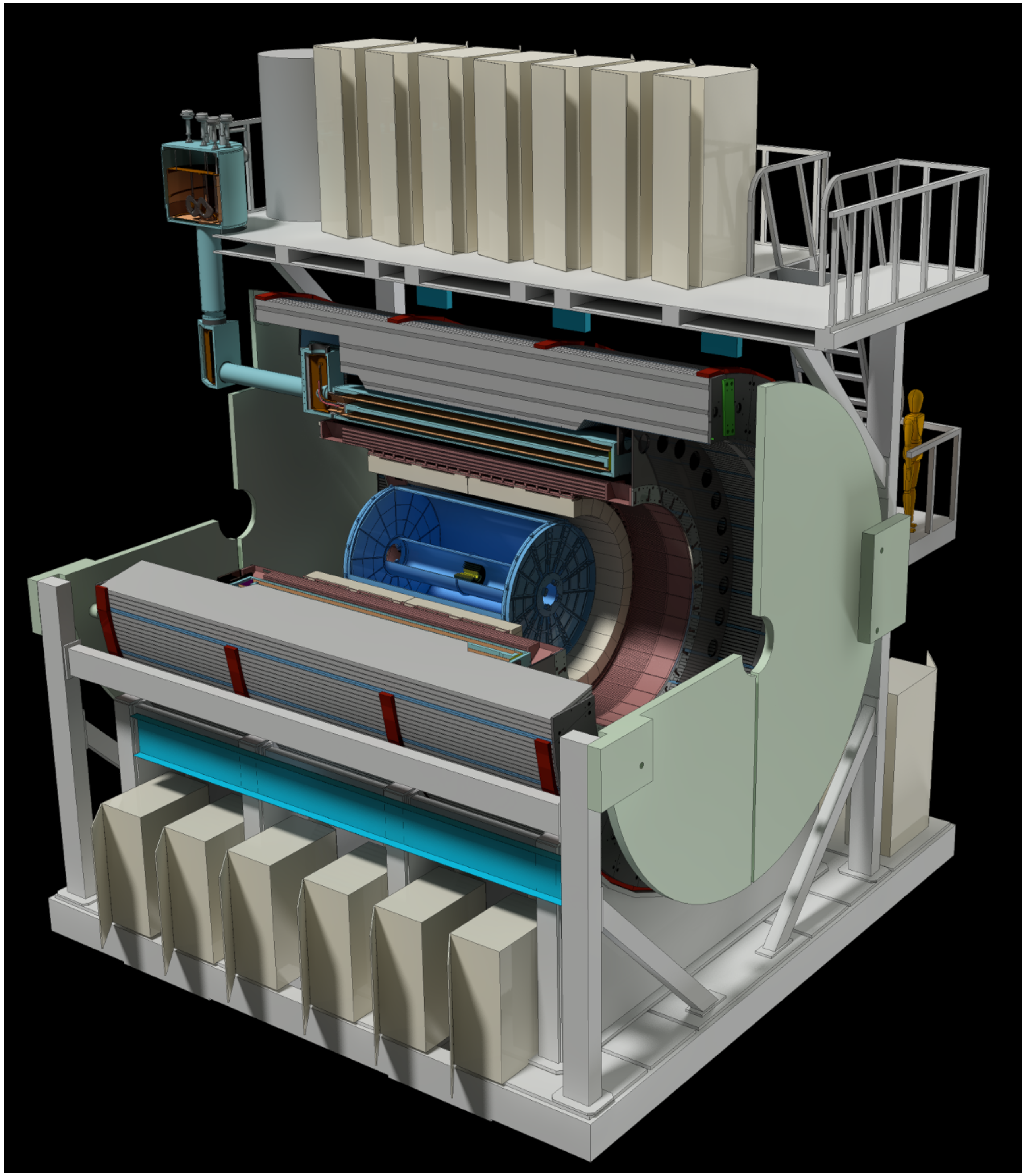
LHC (Switzerland)



5.02 TeV collision energy

energy of the collision sets the quark-gluon plasma temperature

sPHENIX



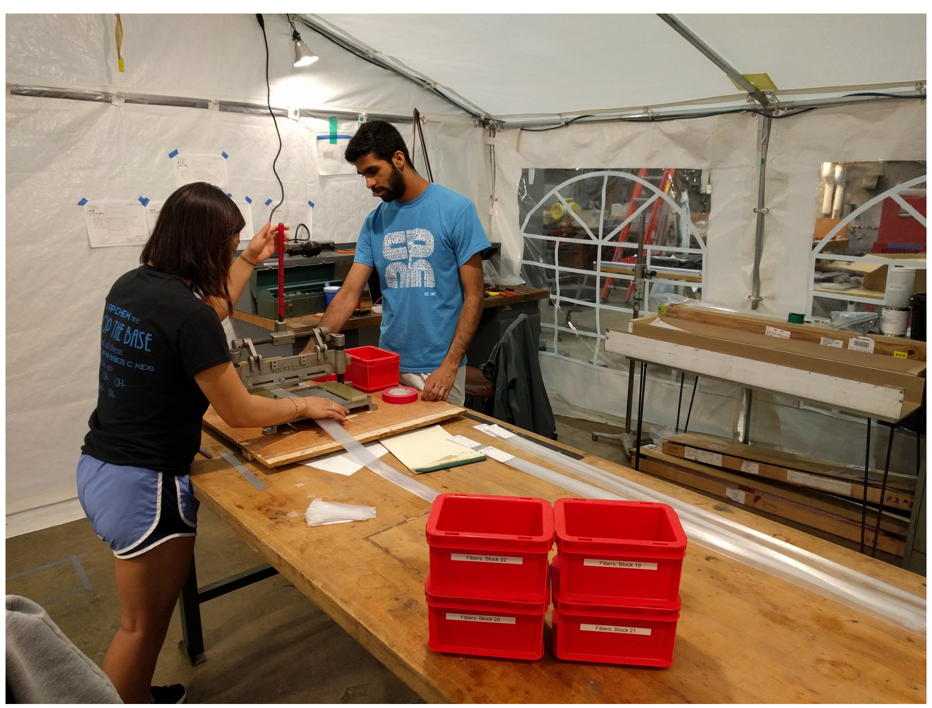
sPHENIX currently under construction as a new detector for RHIC optimized for jet measurements!

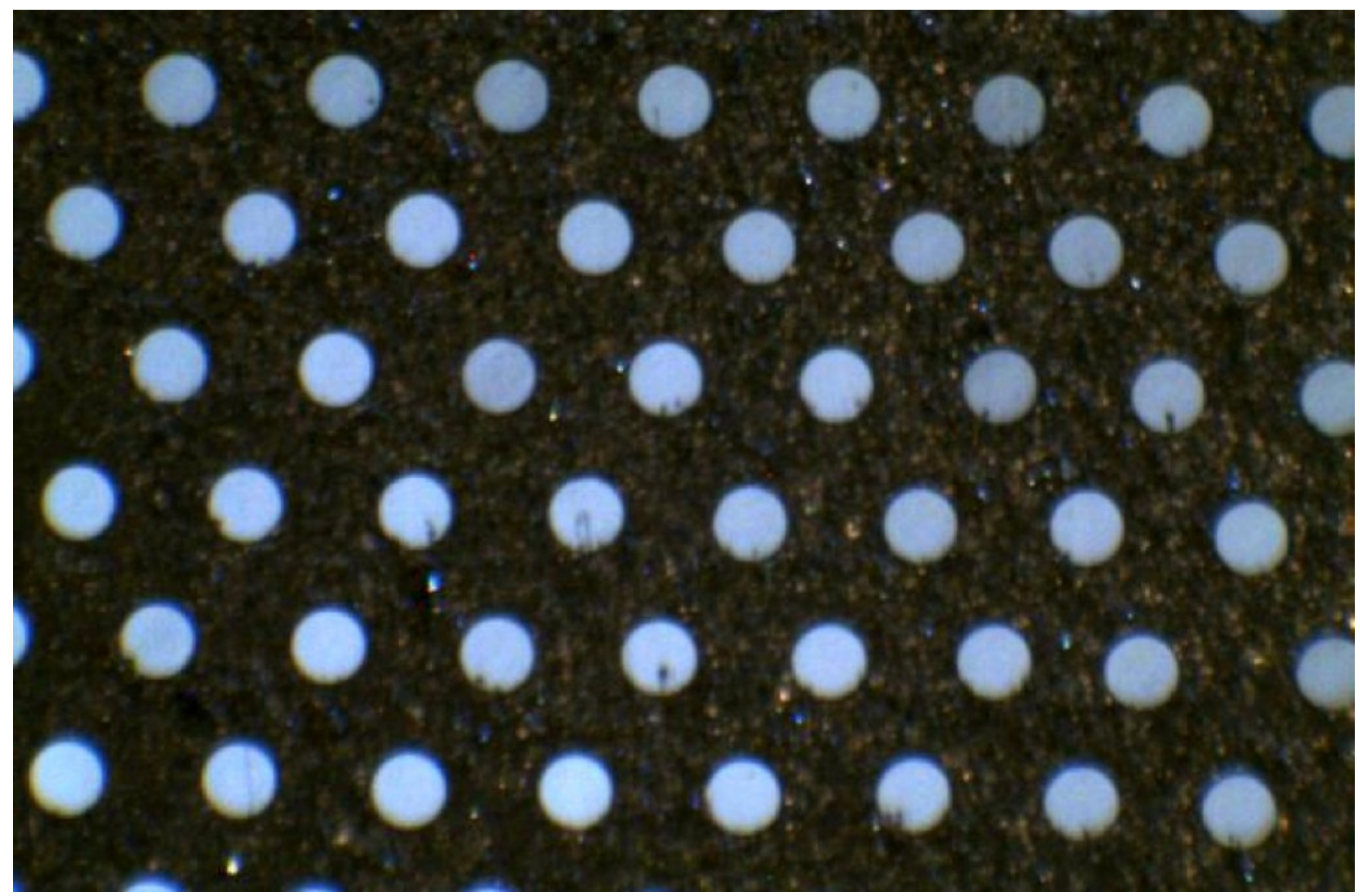
first data: 2023

made in Illinois: sPHENIX electromagnetic calorimeter

plan on making 6000 tungsten powder scintillating fiber blocks as an essential component of the jet measurement in sPHENIX

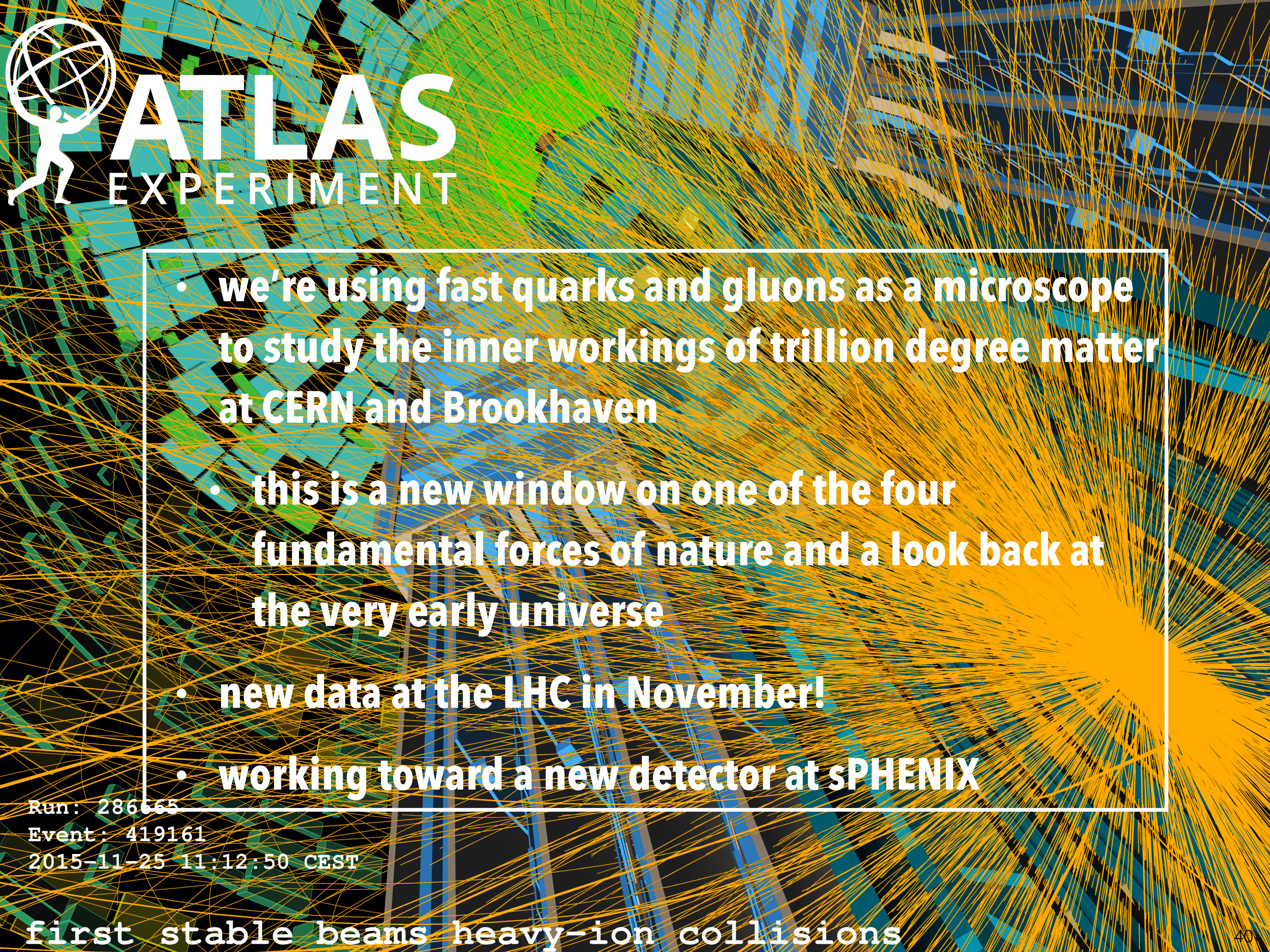
students in the lab





ATLAS EXPERIMENT

- we're using fast quarks and gluons as a microscope to study the inner workings of trillion degree matter at CERN and Brookhaven
  - this is a new window on one of the four fundamental forces of nature and a look back at the very early universe
- new data at the LHC in November!
- working toward a new detector at sPHENIX



first stable beams heavy-ion collisions

4 fundamental forces of nature

<table>
<tr><td>gravity</td><td>solar system, airplanes, you sitting in the seats, sports, black holes, …</td></tr>
<tr><td>electricity & magnetism</td><td>chemistry, biology, cell phones, solar power, superconductors, semiconductors</td></tr>
<tr><td>strong force</td><td rowspan="2">stars, atoms, neutron stars, nuclear power, nuclear bombs, PET scans…</td></tr>
<tr><td>weak force</td></tr>
</table>

these things can all be understood in terms of the forces that cause them, but it is not easy to predict all the important consequences from the force