Peering through the haze:
Experimentally Reconstructing the QGP

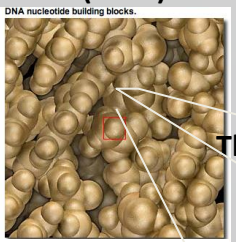
Mike Lisa
Ohio State University

- Accelerators
  - how to make the QGP
- The need for ions; hadronization
  - why physics makes the QGP hard to see
  - why we do it anyway
- Detectors, reconstruction, analysis
  - how we peer through the haze

ACCELERATORS – RHIC & LHC

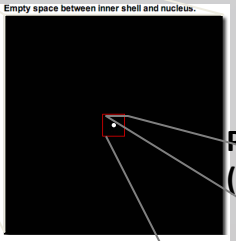
Particle Physics: Ever smaller, Ever higher energy

Atoms (1800)



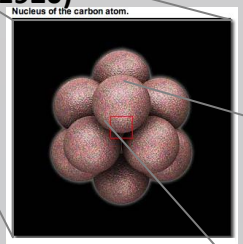
10^{-9} meters

The Nucleus (1910)



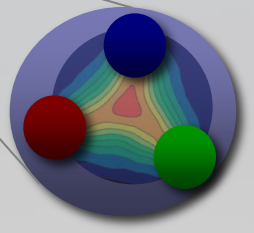
10^{-12} meters

Protons & Neutrons (1920)



10^{-14} meters

Quarks & Gluons (1970)



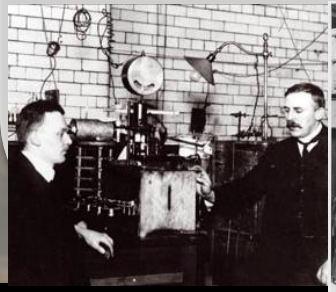
Exploring smaller scales has always required more energetic probes:

New physics has consistently been revealed at new energy frontiers accessed by ever more powerful accelerators

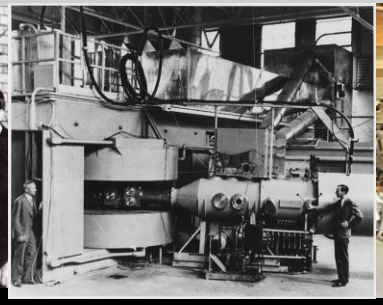
The Strong Force

- least well-understood, due to its "special" property...
- which is also what makes it of fundamental importance...

7.7 MeV



100 MeV



3 GeV

400 GeV

TeV

Quantum Chromodynamics' special feature

Heavy Ion Physics

Low Q: **Confinement**

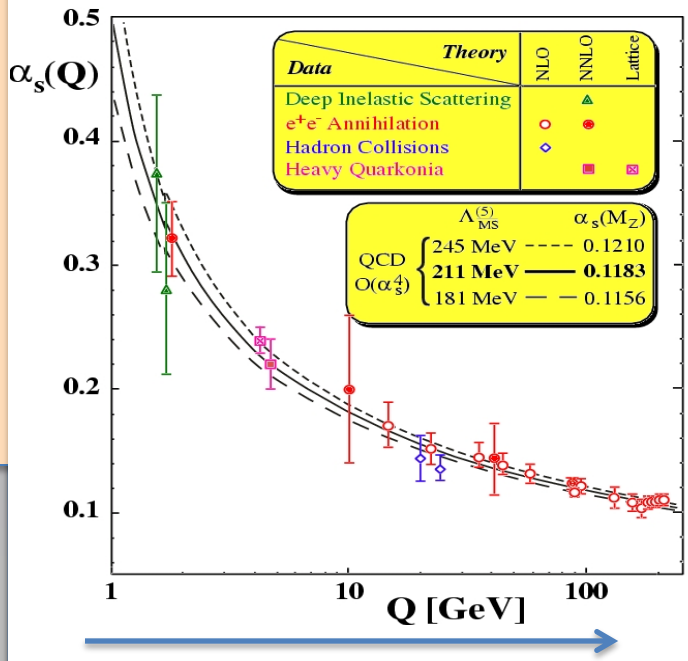
- **the** unique feature of QCD
- dominates almost all baryonic mass in universe
- theoretical insight limited

intrinsic scales of QCD→

✓ bigger is better (>> 1 fm)

✓ optimum energy range

focus on fundamental interaction

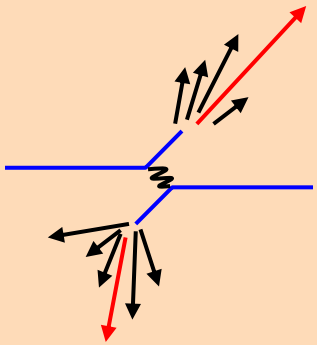


focus on fundamental particles

Particle Physics

Large Q : **Asymptotic Freedom**

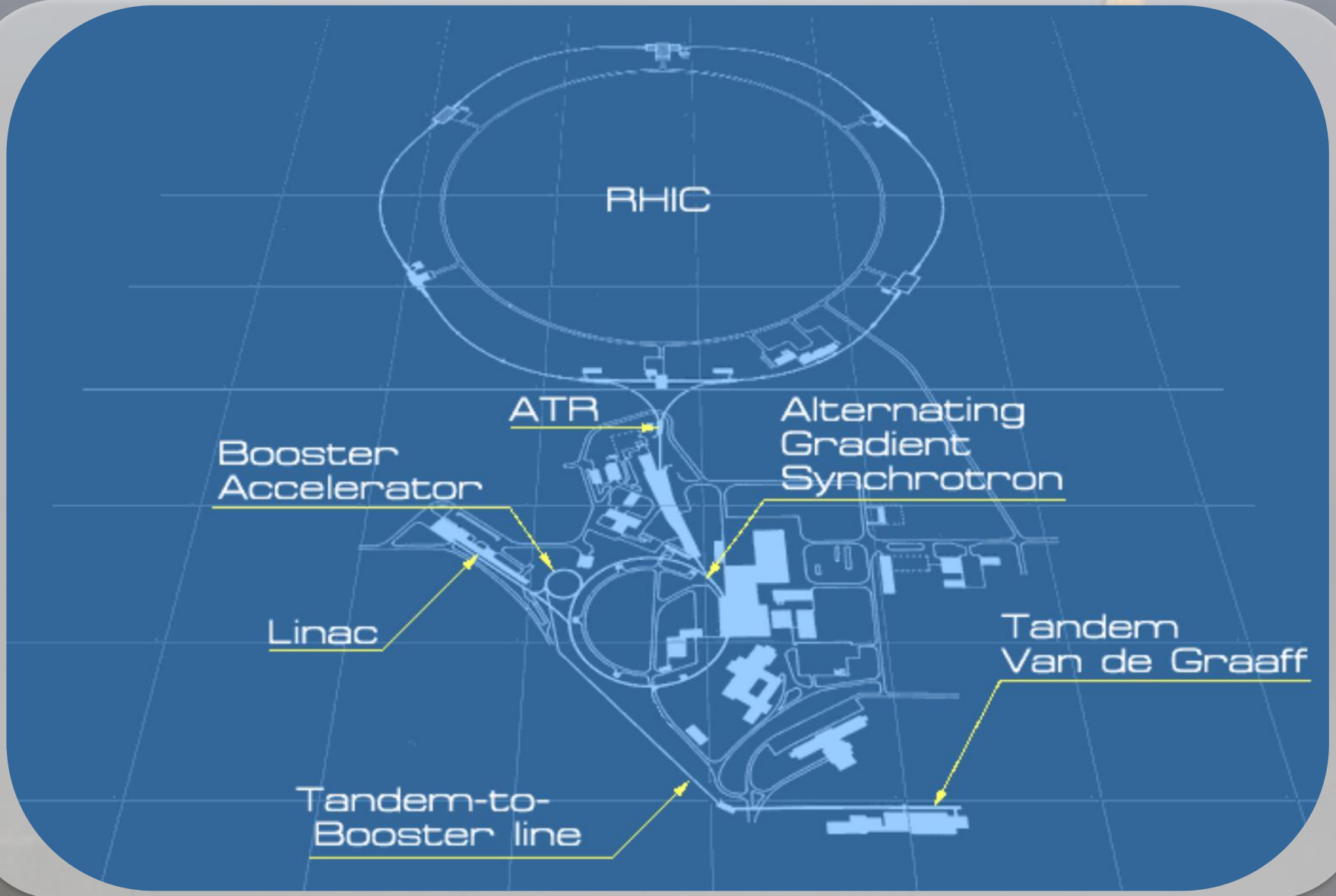
- α->0 @ r->0 (anti-screening)
- perturbative calculations
- reduce "messy" QCD effects



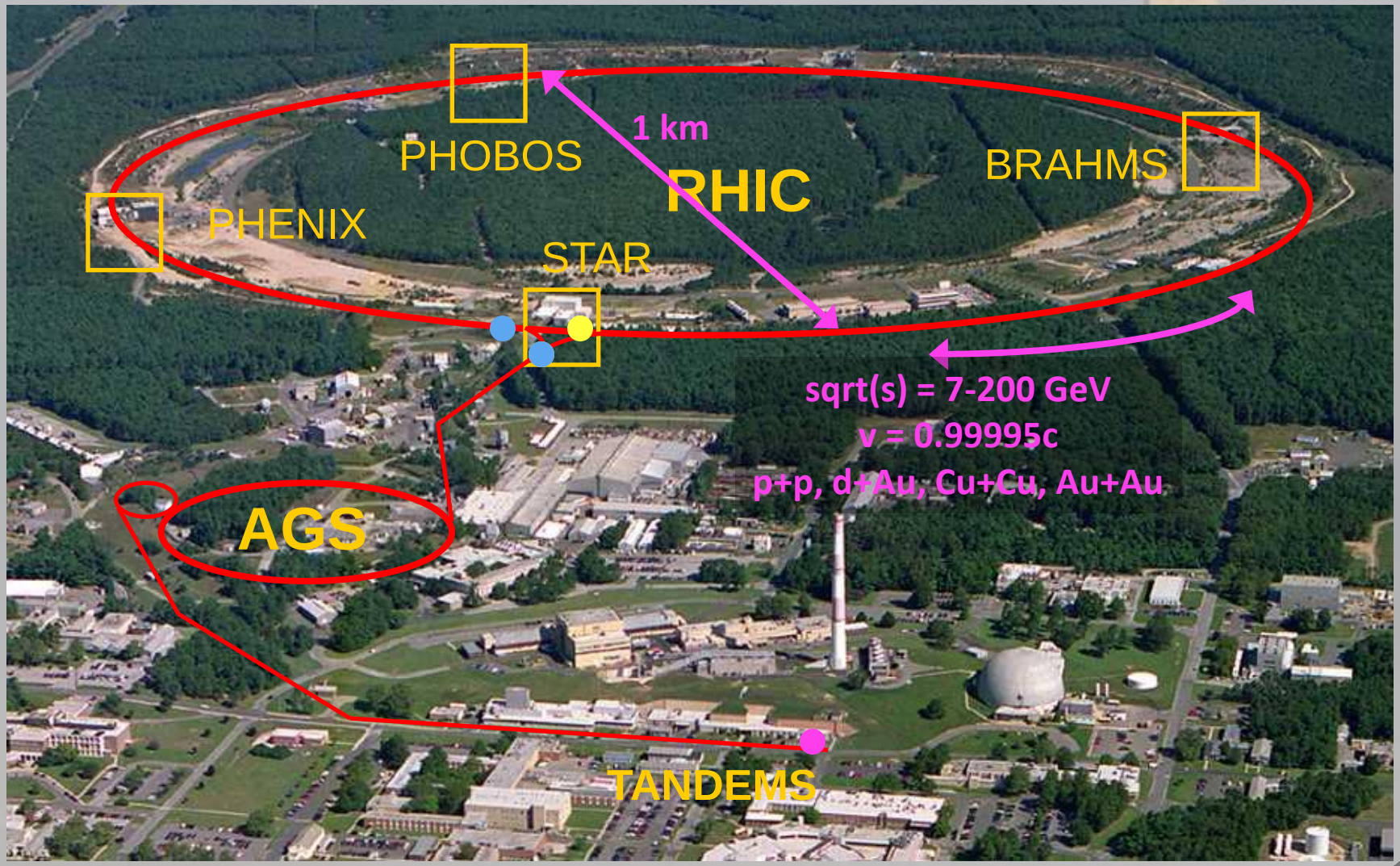
✓ Smaller/simpler is better (e+e, p+p)

✓ More energy is better (Minv)

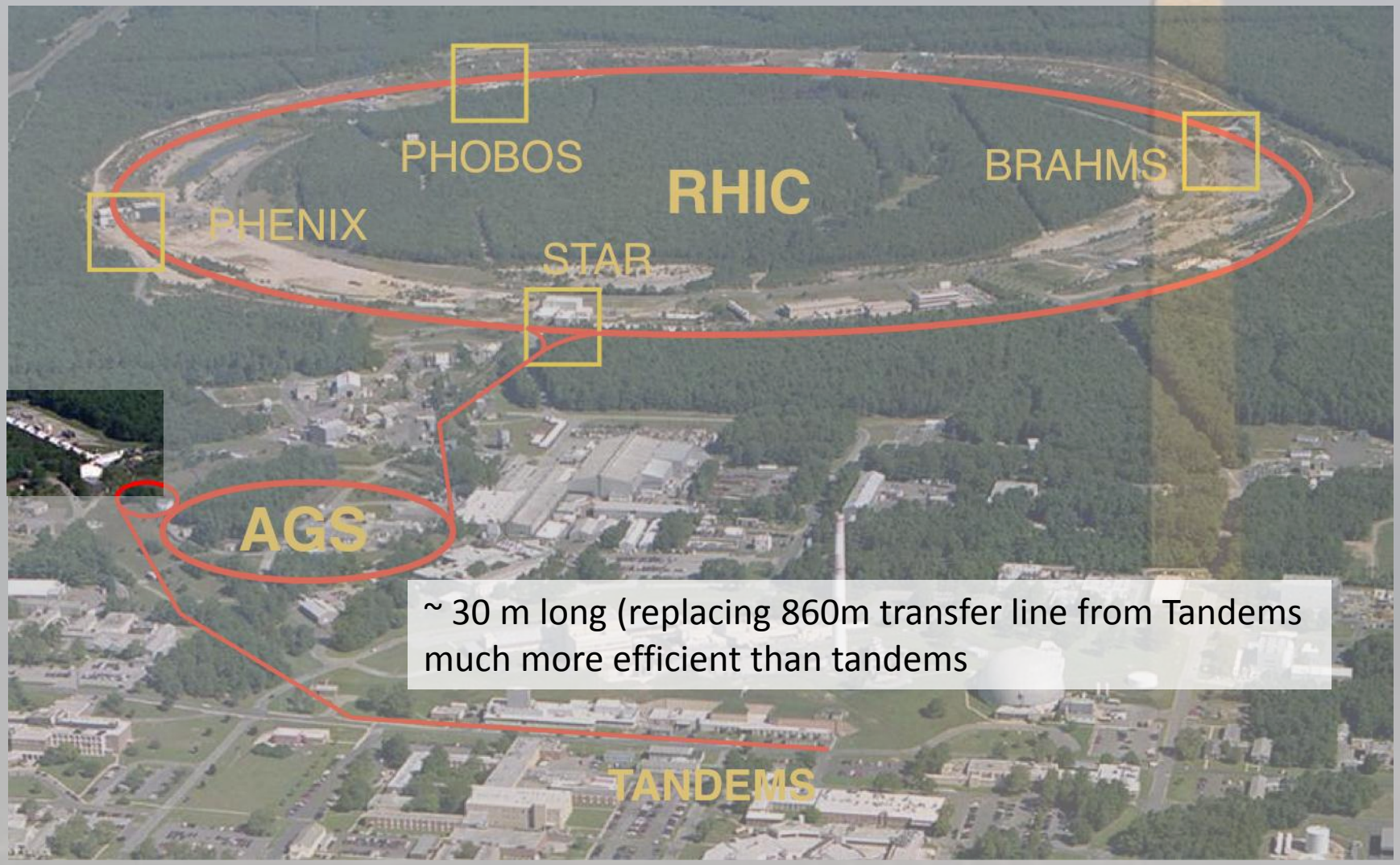
The RHIC complex – Brookhaven National Lab (NY)



Relativistic Heavy Ion Collider (RHIC)



Step 1: Electron Beam Ion Source (EBIS): from v=0 to 5%c (replaces Van de Graaff tandems)



~ 30 m long (replacing 860m transfer line from Tandems
much more efficient than tandems

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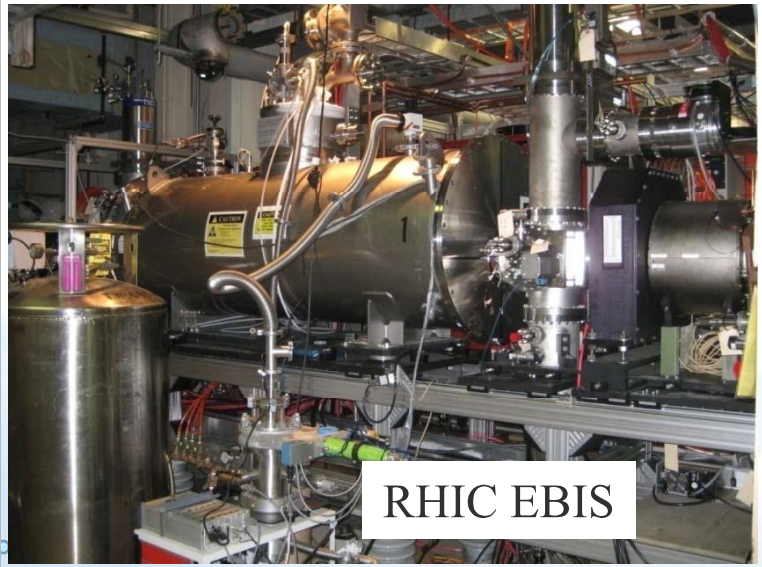
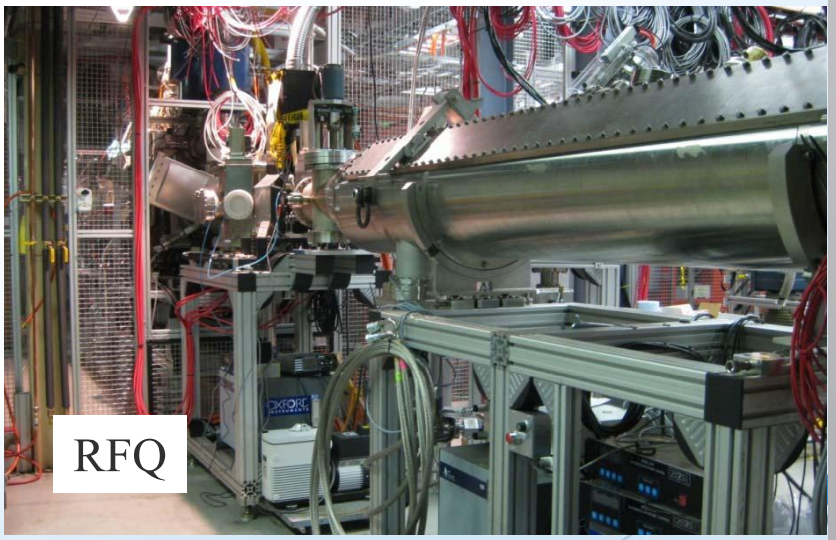
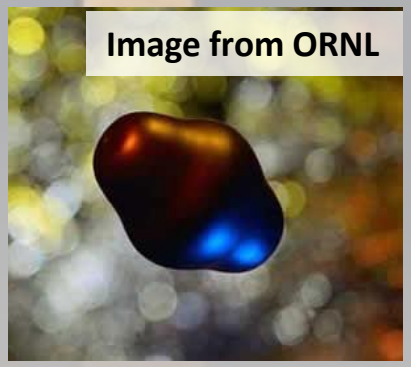




much wider range of isotopes than previously possible

- including, now, Uranium!
  - in a year, **less uranium accelerated than in one handful of soil**

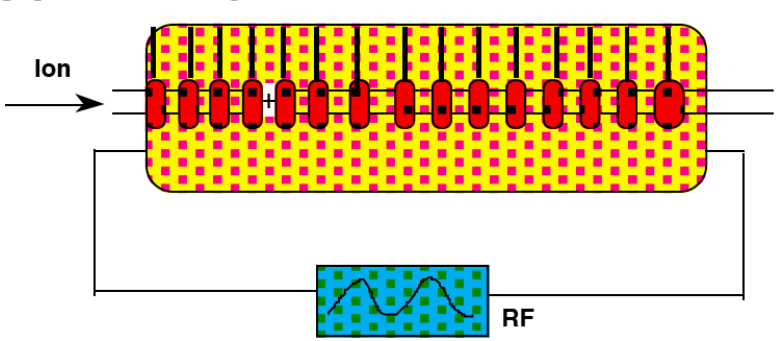


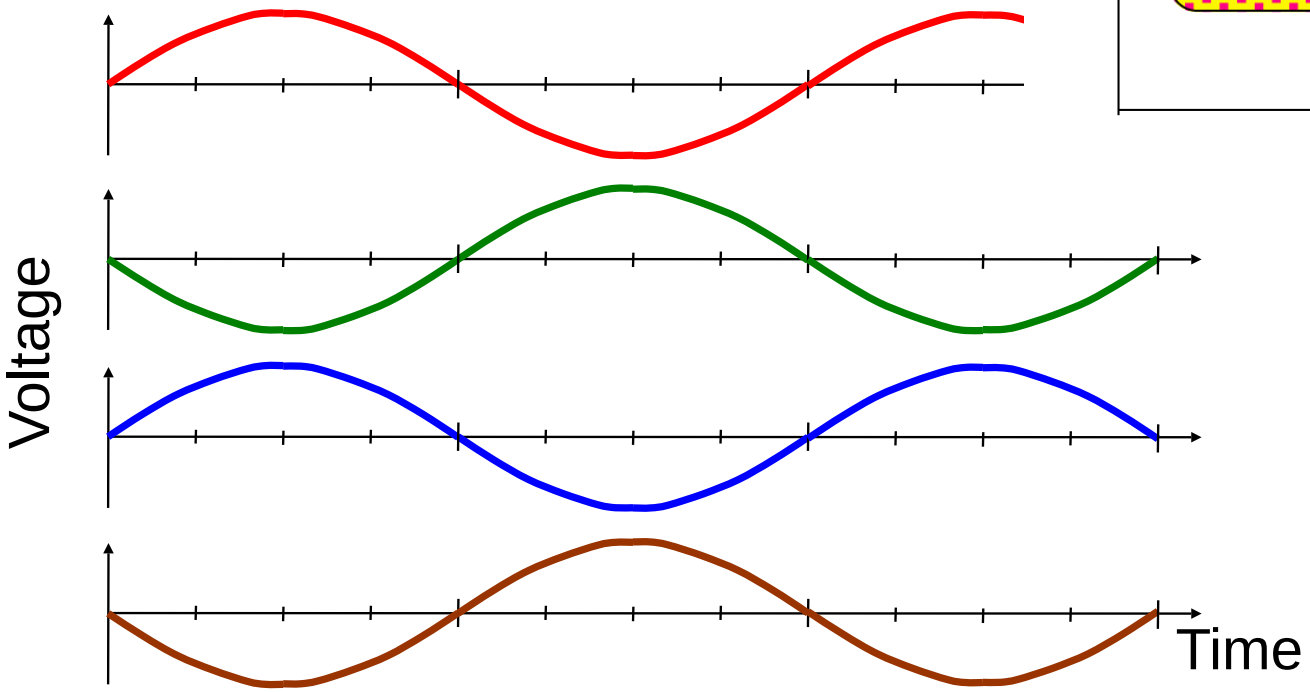
delivers 10^9 Au(+32) ions in each bunch, lasting ~50 microsec

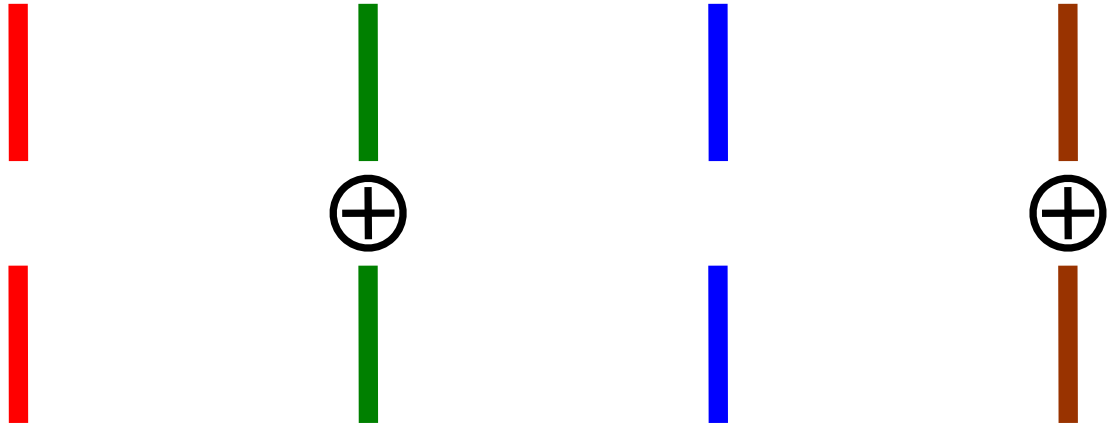
Followed by RFQ accelerator and linac to get them up to a few MeV/A

- gamma ~ 939/938 = 1.001 → beta ~0.05 (v=5%c)

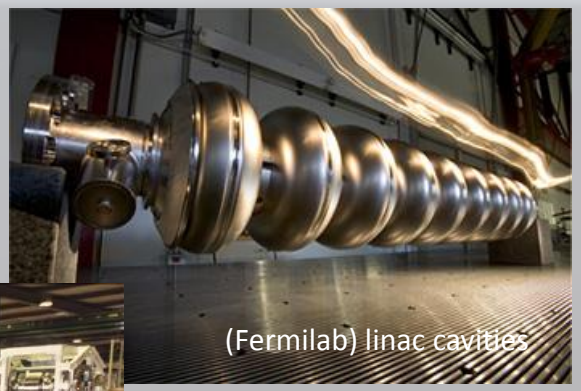
Basic operation of RF accelerators

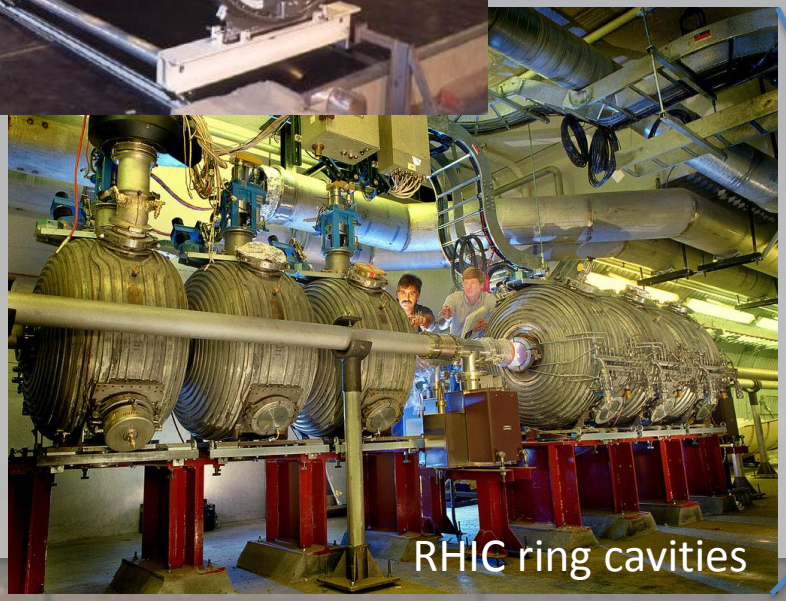






Acceleration with RF





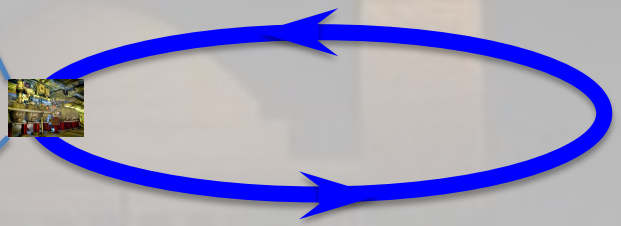
One pass thru an RF cavity is usually not sufficient

can build a long line of many RF cavities...

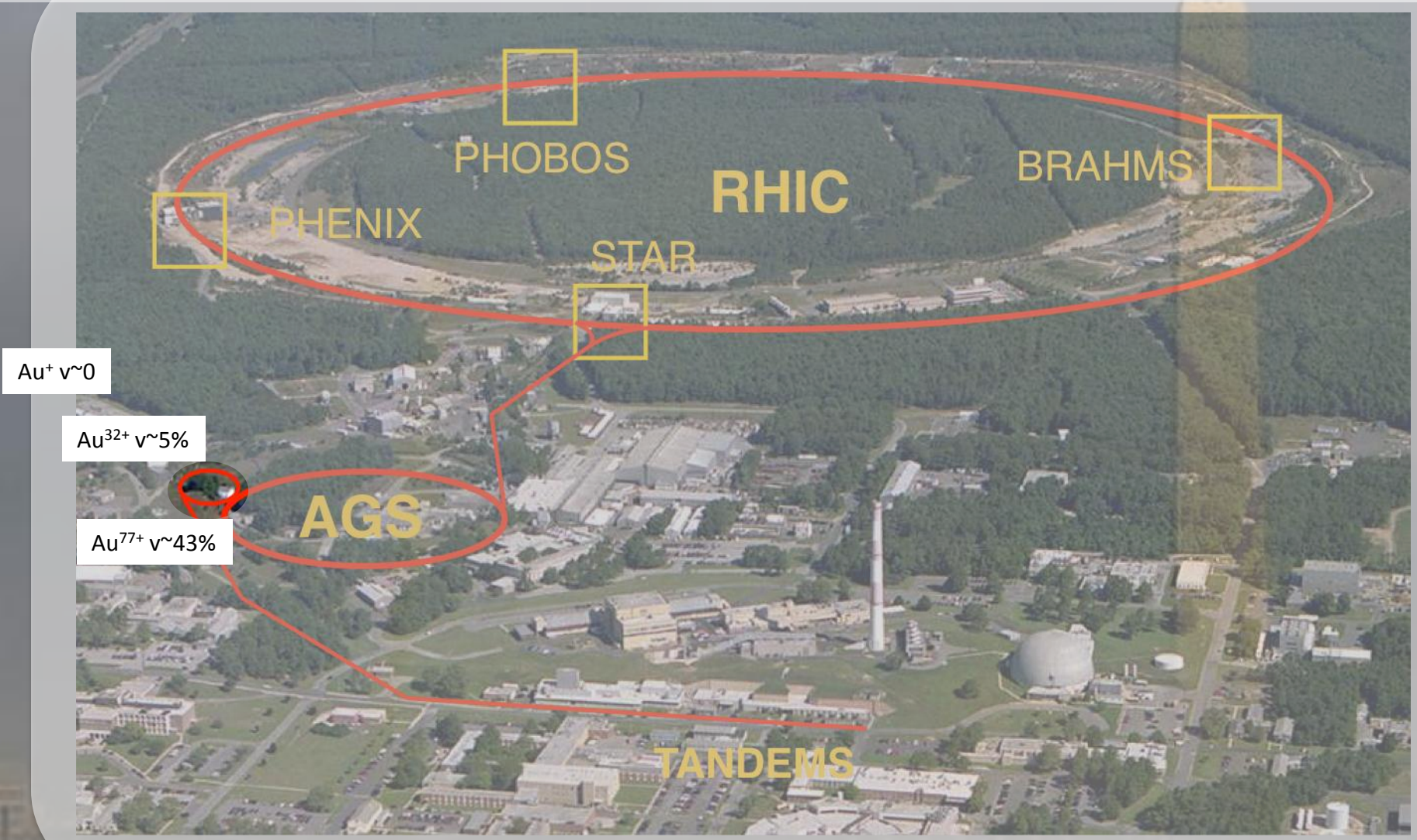
- linear accelerator like SLAC, small one like pre-injector

or... build only a few, but kick the beam each time it comes around.

- accelerator rings like RHIC

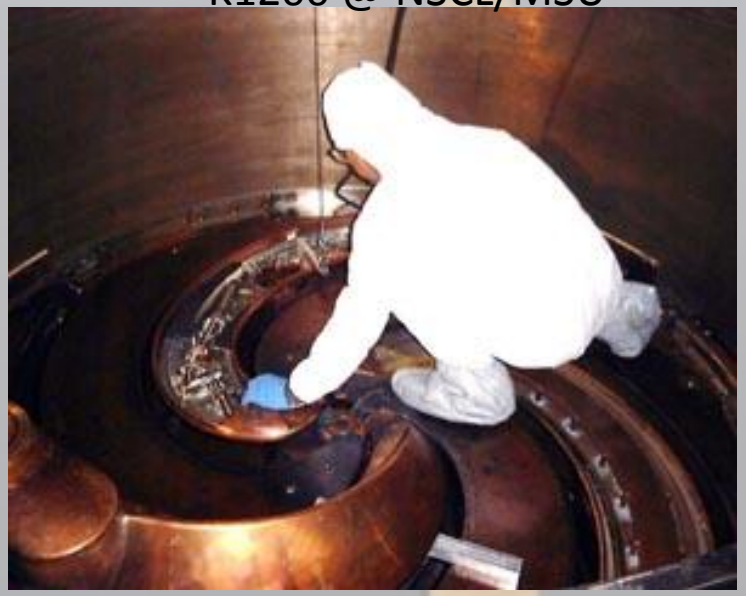


Step 2: Booster-accelerator:
1 AMeV to about 100 AMeV (5% to 43% c)



Synchrotron – a necessary step beyond a cyclotron

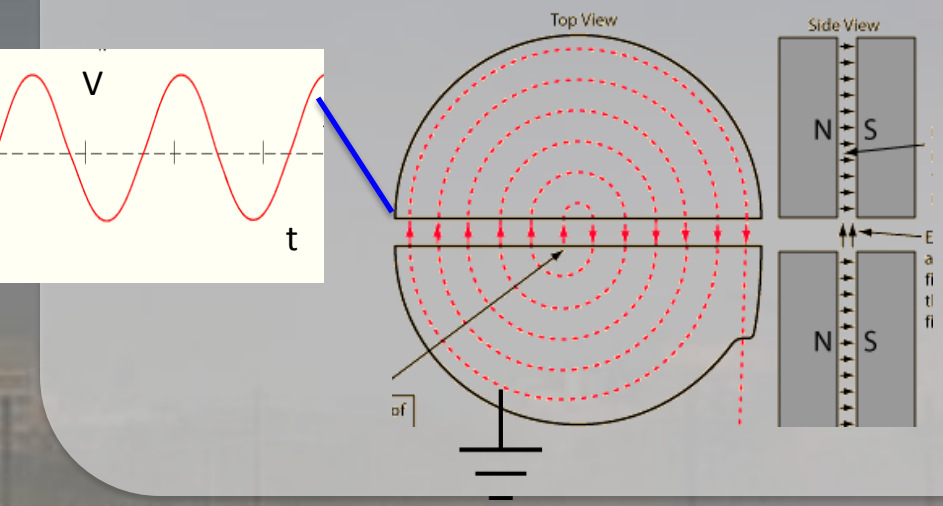
K1200 @ NSCL/MSU

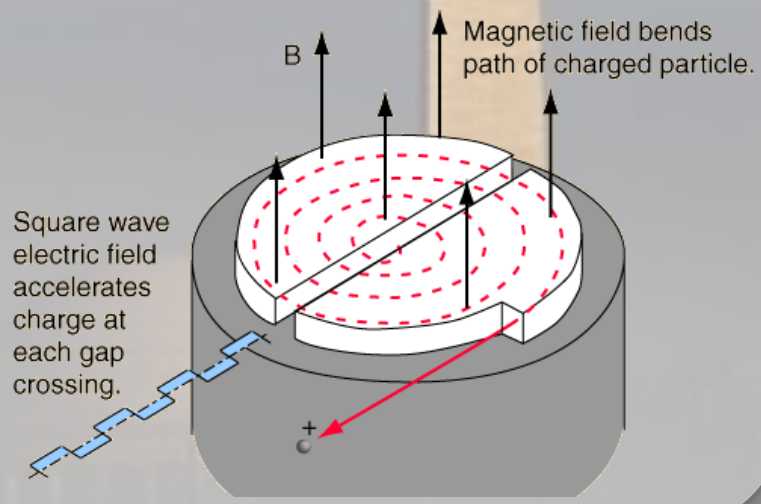


Cyclotron

- charged particles injected in the center
- forced to circular motion by constant B-field
- accelerate every time they cross a gap (V alternated)
- escape when orbital radius exceeds D region

- simple design & operation
- limited to about 10 AMeV (0.00001 ATeV)



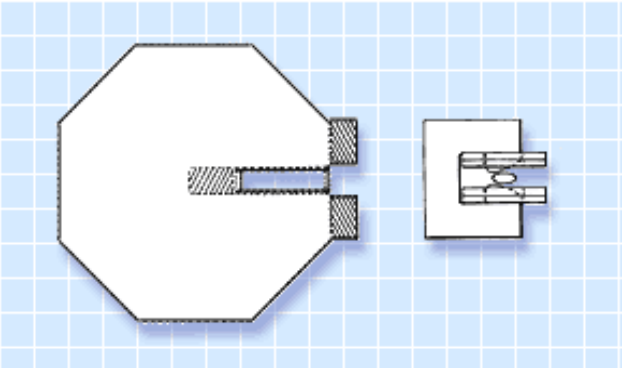


Synchrotron – a necessary step beyond a cyclotron

Way out: Synchrotron

Narrow beam pipe surrounded by smaller and more tightly focused magnets

Magnetic field and the electric field (to accelerate the particles) are carefully synchronized with the traveling particle beam.



Foil @ exit charges beam to +77 [only K-shell e^- remain]

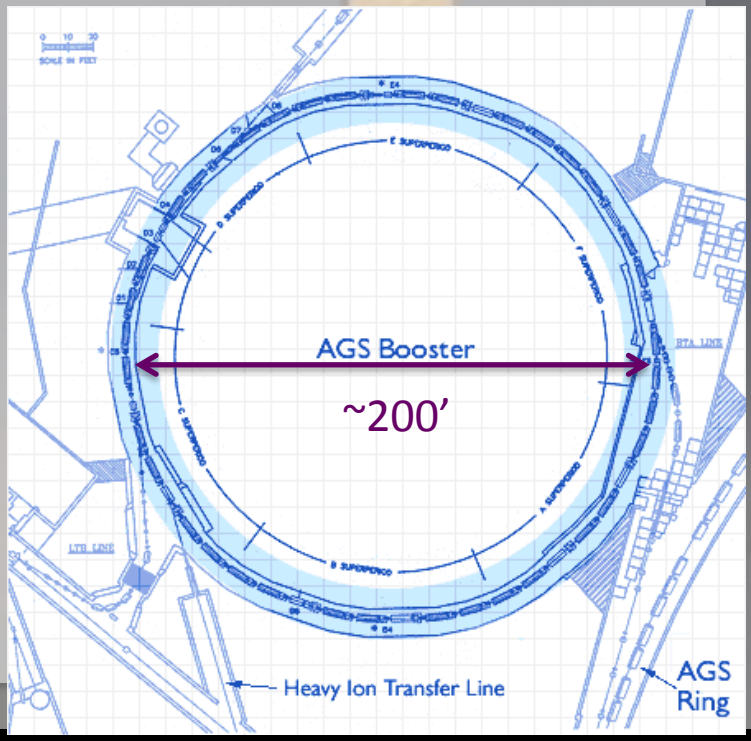
Exit with K.E. ~ 100 AMeV

E = (938+100) AMeV

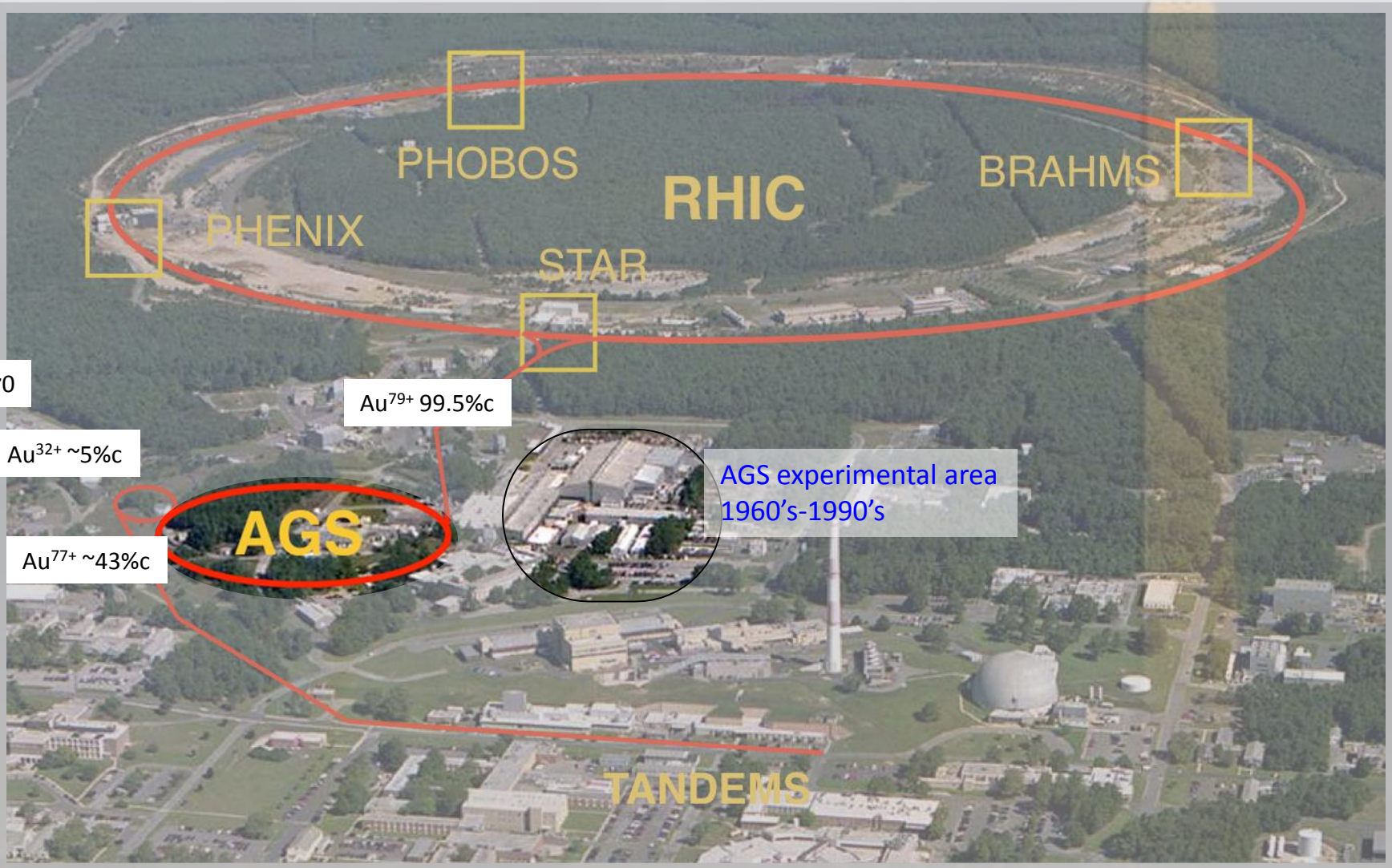
γ = (938+100)/938 = 1.107

β = 0.43

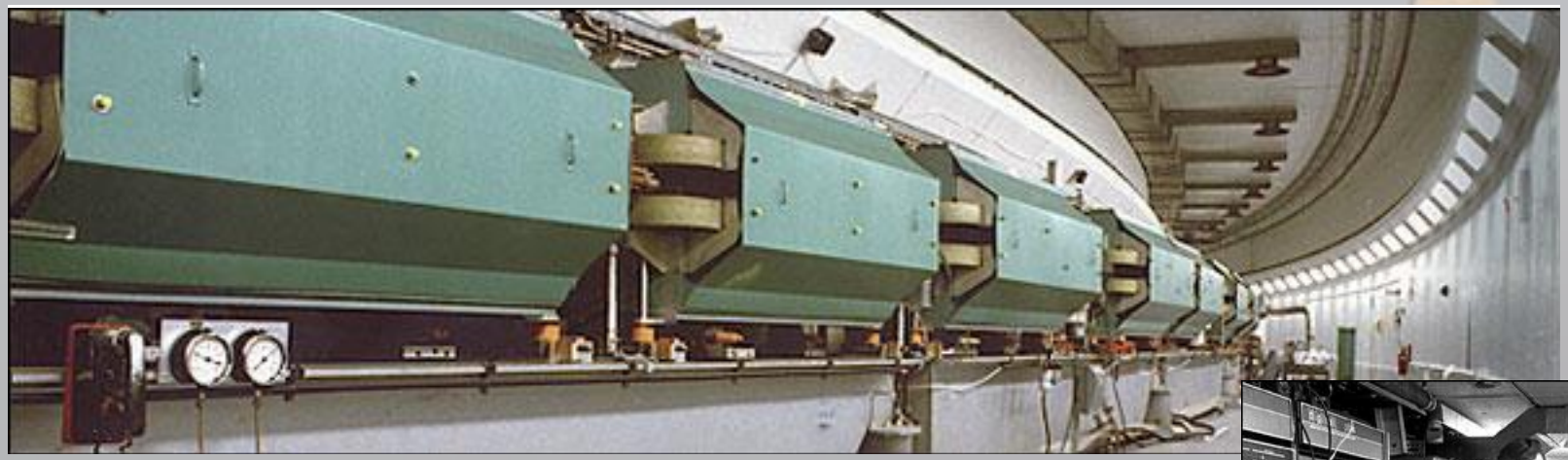
Usually less than x2 loss factor from EBIS thru Booster

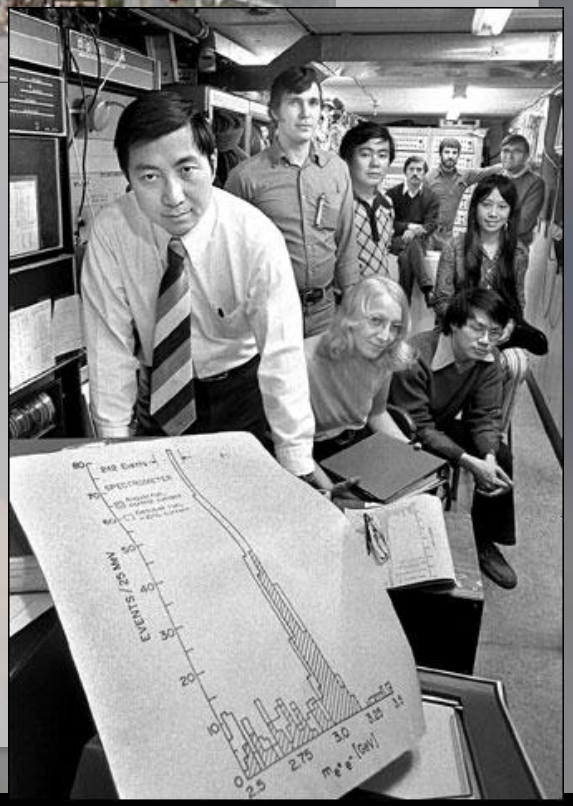


Step 3: AGS (once the world's highest energy machine. today a booster)
Fully strip the ion and boost to truly relativistic energy (~9 GeV)



Alternating Gradient Synchrotron (AGS)



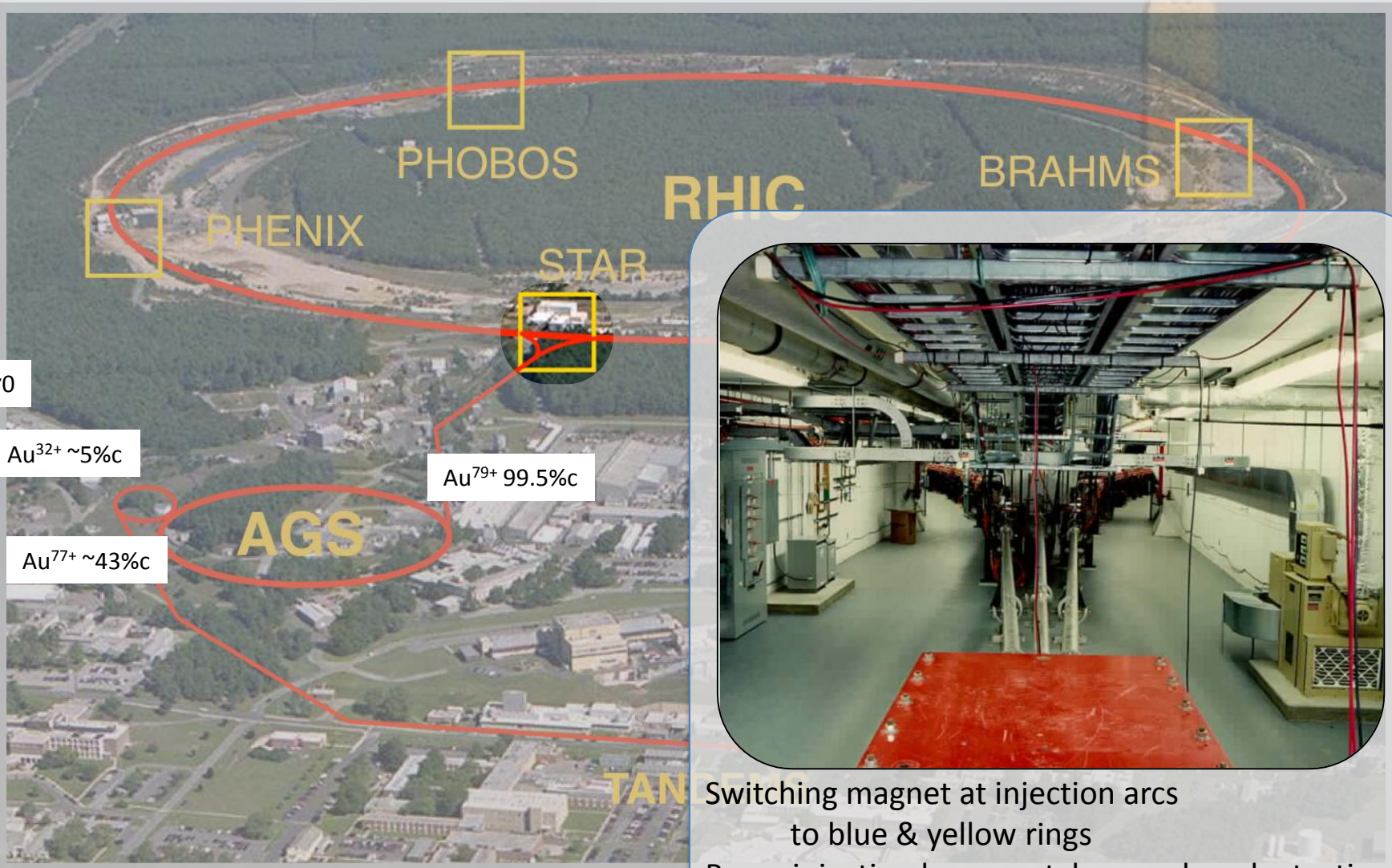


Larger version of booster, accelerating to 8.9 AGeV →
γ=10.5, β=0.995

Beam fully stripped at exit of AGS (before AtR beamline)

Produced 3 Nobel Prizes: J/ψ, CP violation with K, ν_μ

Step 4: AGS to RHIC (AtR) transfer line.



Switching magnet at injection arcs
to blue & yellow rings
Beam injection box-car style –one bunch at a time
Fill RF buckets (360 typical)

Welcome to the machine

From Injection Energy (10 AGeV) to full (100 AGeV)

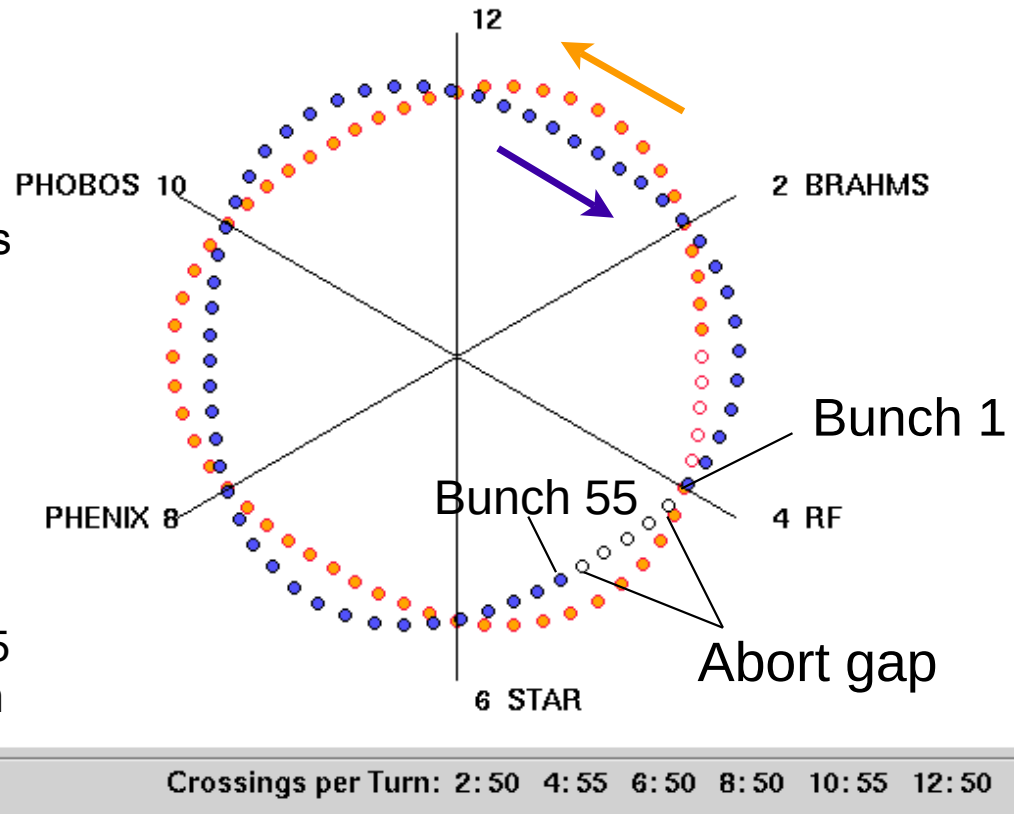
Beam is accelerated by Radio Frequency (RF) cavities:
28 MHz for acceleration
200 MHz for storage to reduce bunch length

28 MHz defines the number of "buckets" = 360, length is 35 ns each (or ~10.7 m)

Note: a continuous beam (no bunch structure), cannot be accelerated

Bunched (or captured) beam: every 6th (3rd) bucket, i.e. 55+5 (110+10) bunches per ring with 10^9 ions

Example: total of 55 bunches per ring



circumference: 3833 m (2.4 miles)

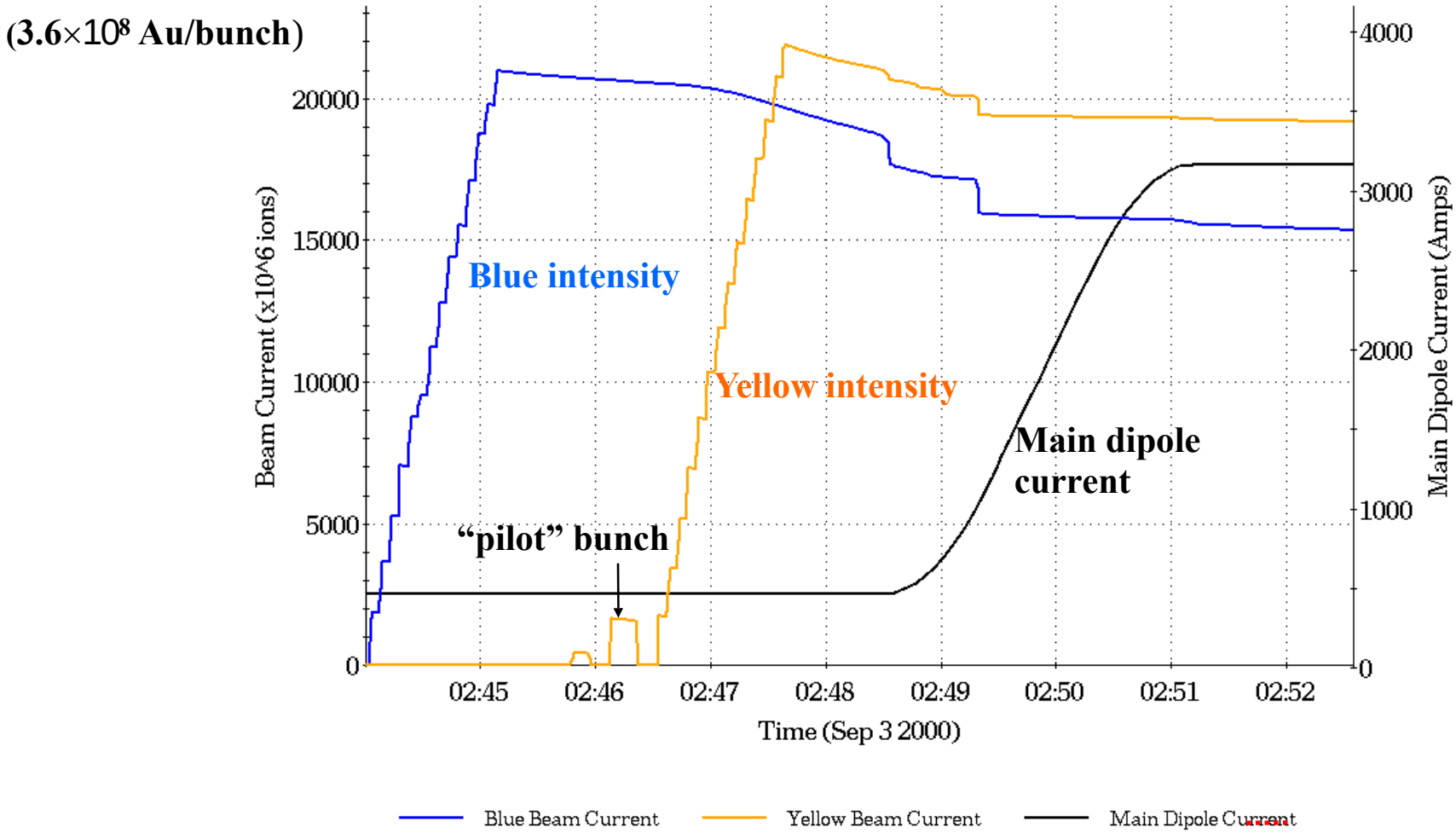
Transit time T = (3833 m)/(2.99E8 m/s) = 12.8 microsec

f = 1/T = 78 kHz (→ ion completes a rotation 78 thousand times/sec)

360 buckets → each bucket (3833 m)/360 ~ 10.7 m (or 35 ns)

frequency of RF cavities = 360*(78 kHz) = 28 MHz (also = (2.99E9 m/s)/(10.7 m))

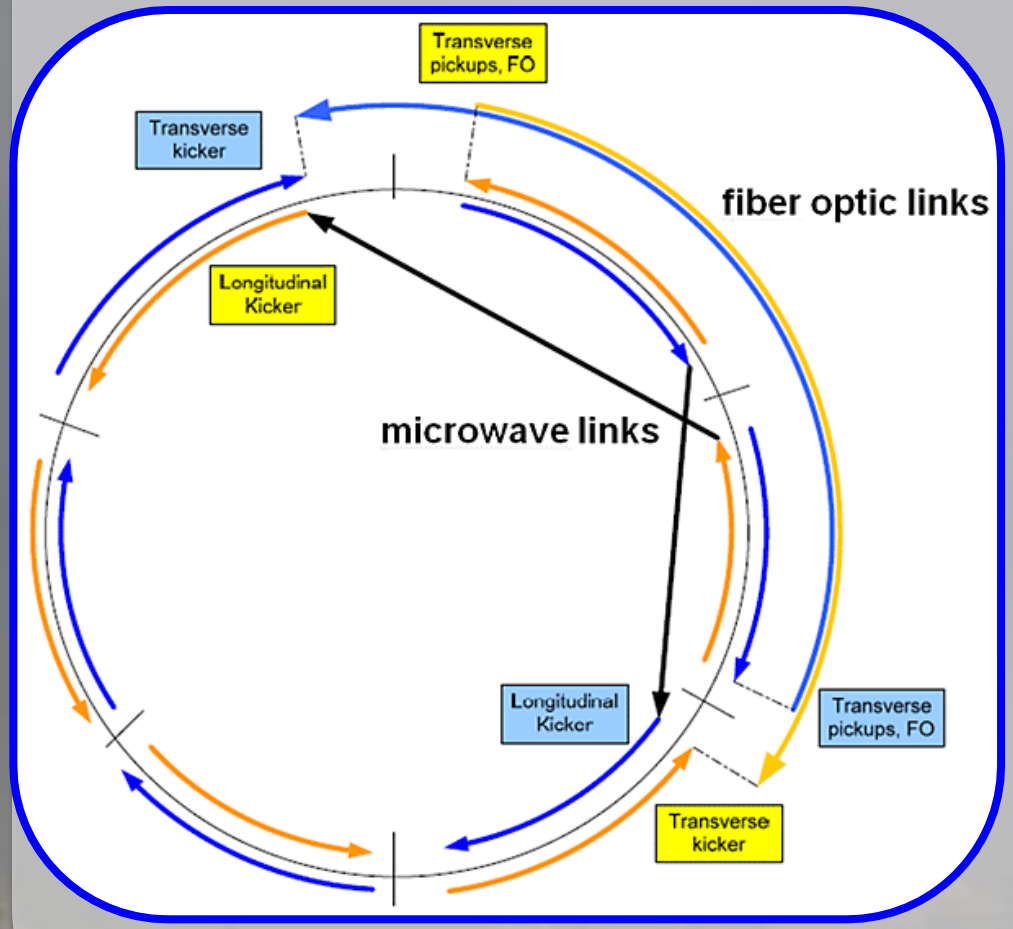
Injection and acceleration – what the experiment sees

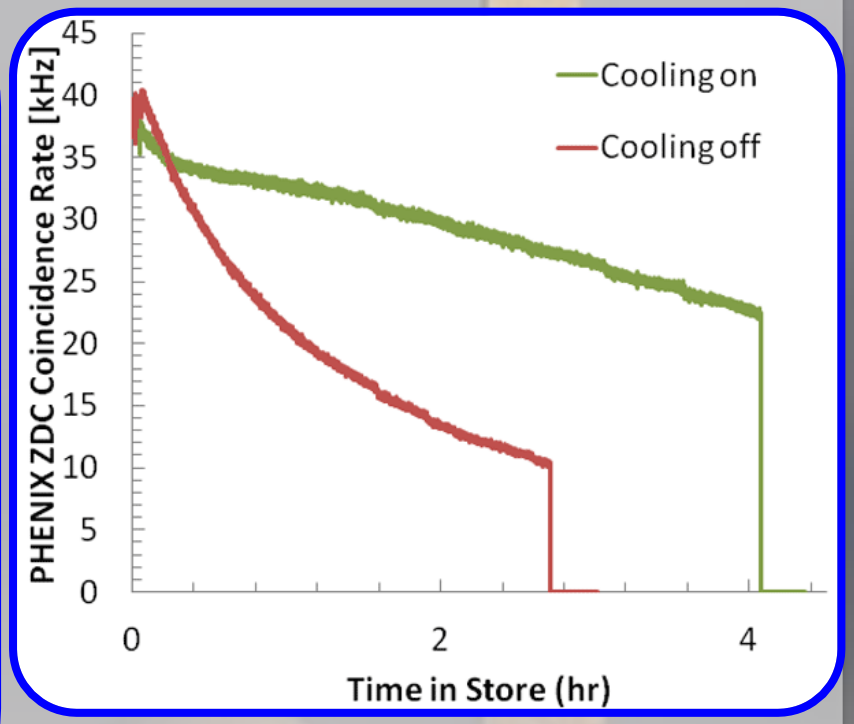


The beam is accelerated from Injection Energy (10 GeV) to Storage Energy (100 GeV). The acceleration process is called "ramp".

“Stochastic cooling” has greatly increased beam brightness, liftetime

If there is a perturbation in the orbit, a signal is sent via straight-line “short-cut” to produce a corrective “kick”





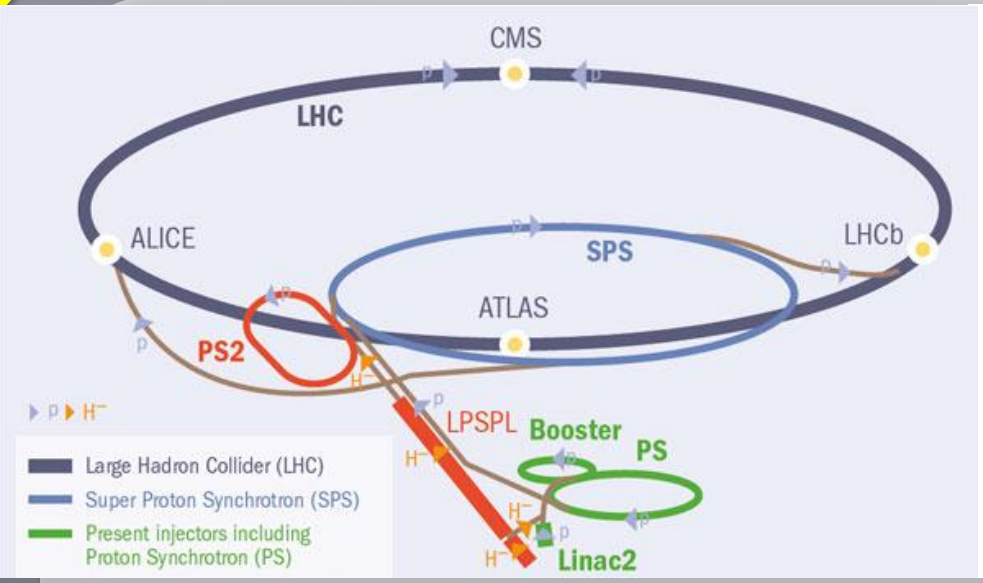
RHIC is big

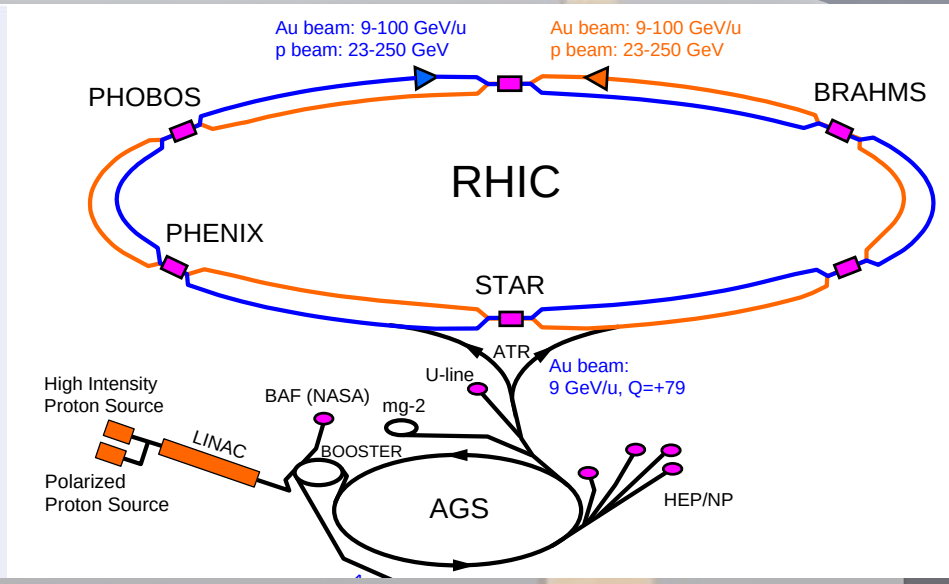
RHIC is big... but the LHC is bigger

HEAVY ION PHYSICS – CHARACTERISTICS & SPECIAL NEEDS

C

RHIC and LHC





C = Collider. RHIC and LHC are the only nuclear colliders in the world

Remarkably similar accelerator complexes:

- Electron-current-based source & linac – ions partially stripped & accelerated to ~2 AMeV
- Followed by synchrotrons (LEIR, PS & SPS for LHC, Booster & AGS for RHIC)
- Finally transferred to two counter-rotating rings in the collider with **4 major expts**

But very different size:

- RHIC: circumference = 3.8 km sqrt(s)=200 GeV
- LHC circumference = 26.7 km sqrt(s) = 5500 GeV

The reason is in the "**H**"

H

RHIC and LHC

Relativistic **Heavy** Ion Collider

- energy tuned to probe QCD @ interesting scale
- parasitic p+p program – spin [very successful]

Large **Hadron** (proton) Collider

- energy tuned to produce heaviest particles
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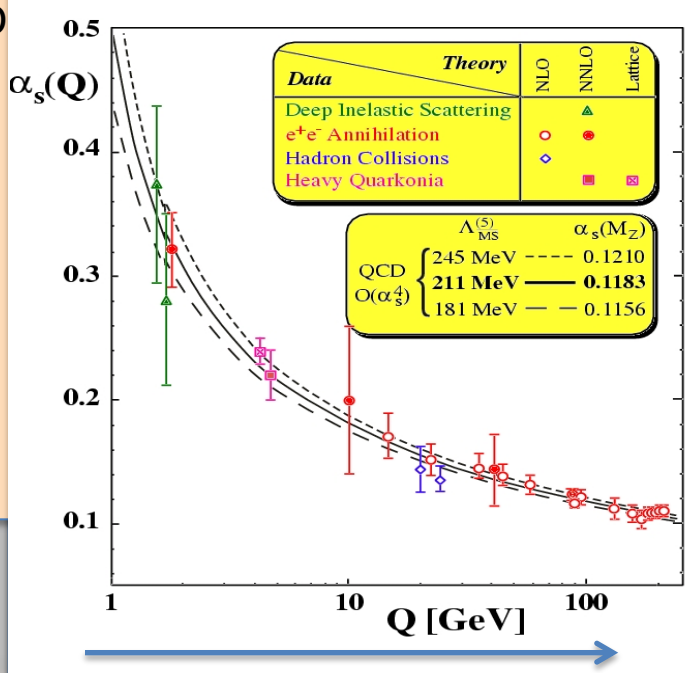

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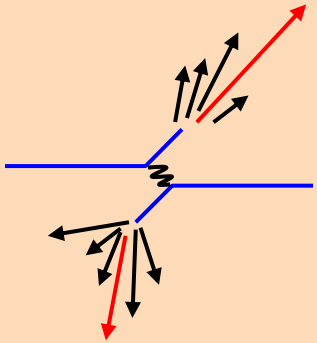

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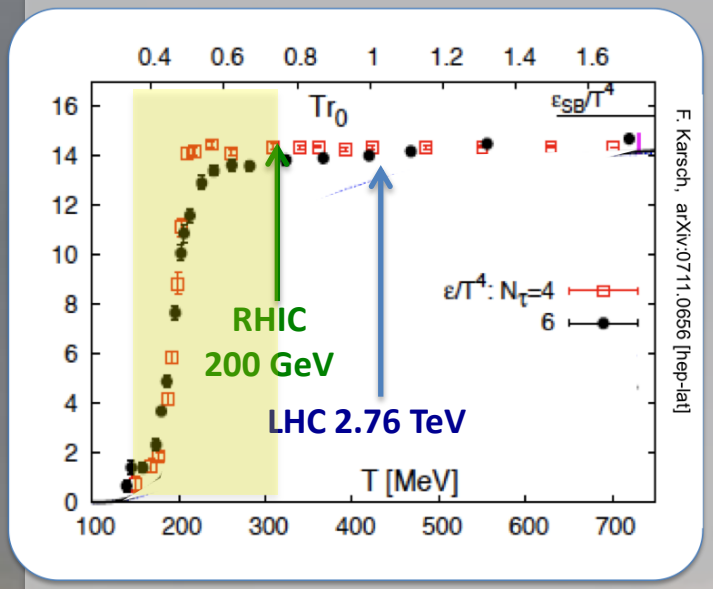
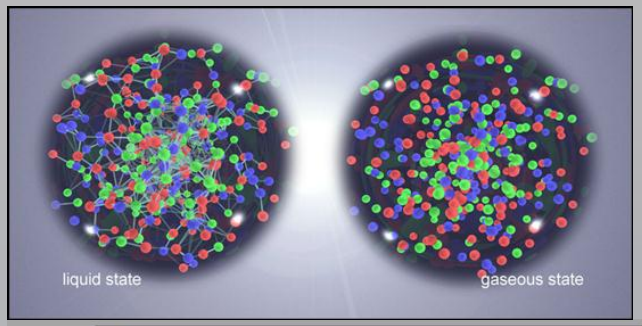
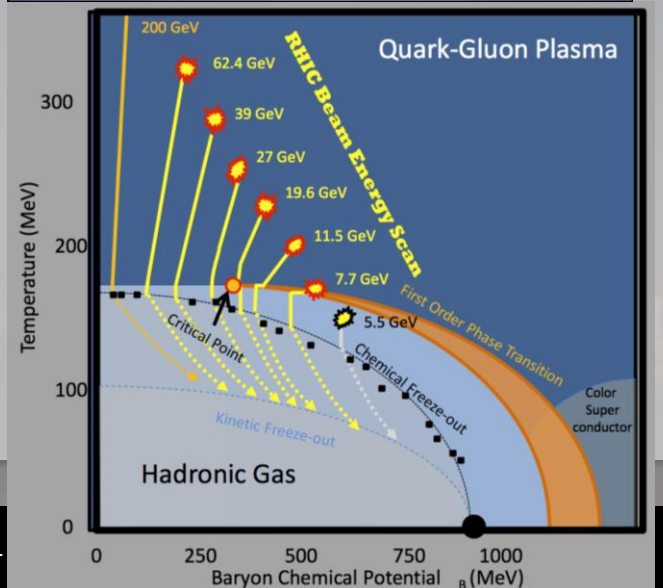
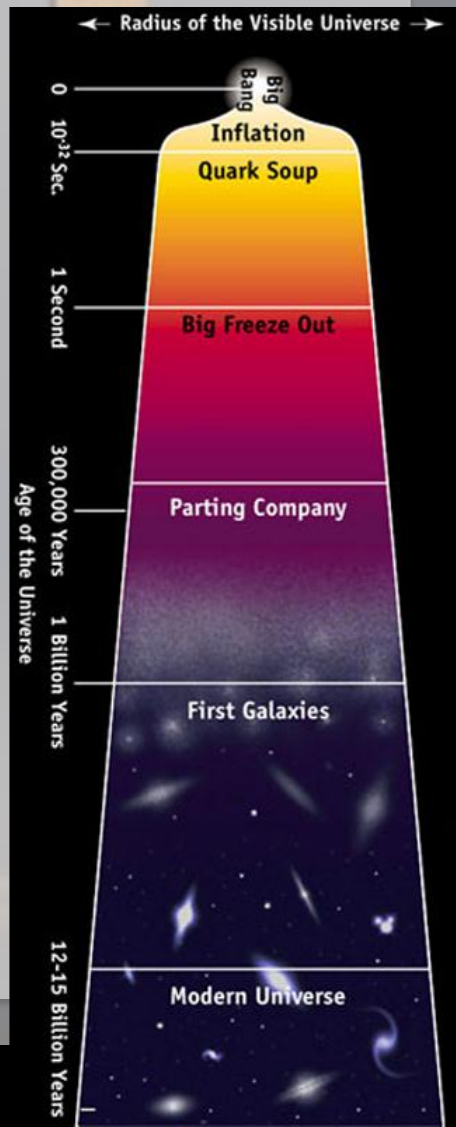
Heavy Ion physics looks like particle physics, but the focus is very different
- understand the special nature of a theory (**QCD**) that *has a scale*
- study phase structure → bulk (multiparticle/low momentum)









H

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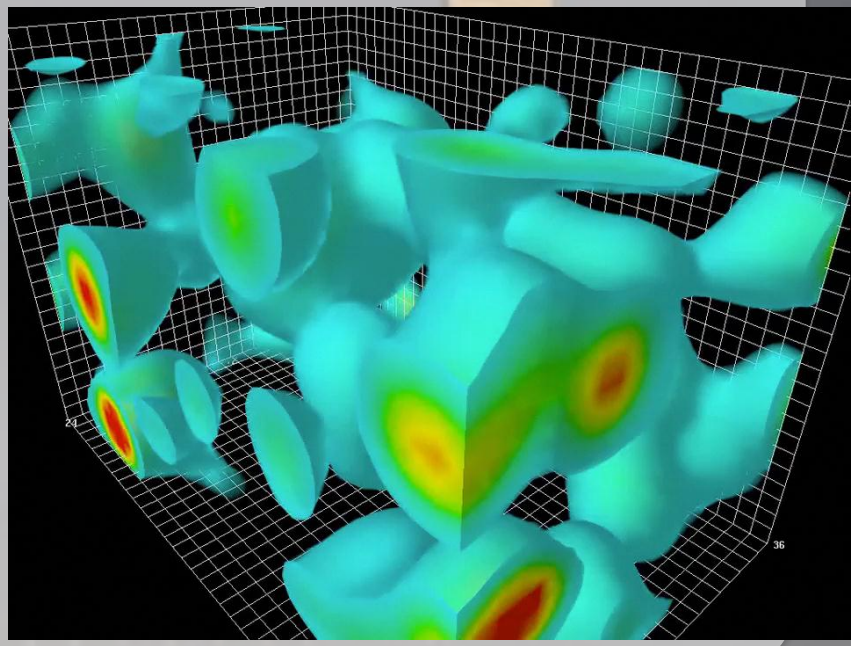
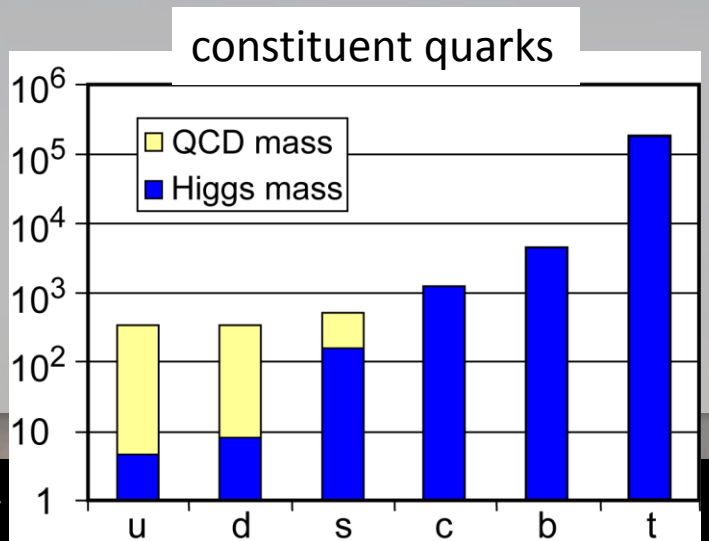
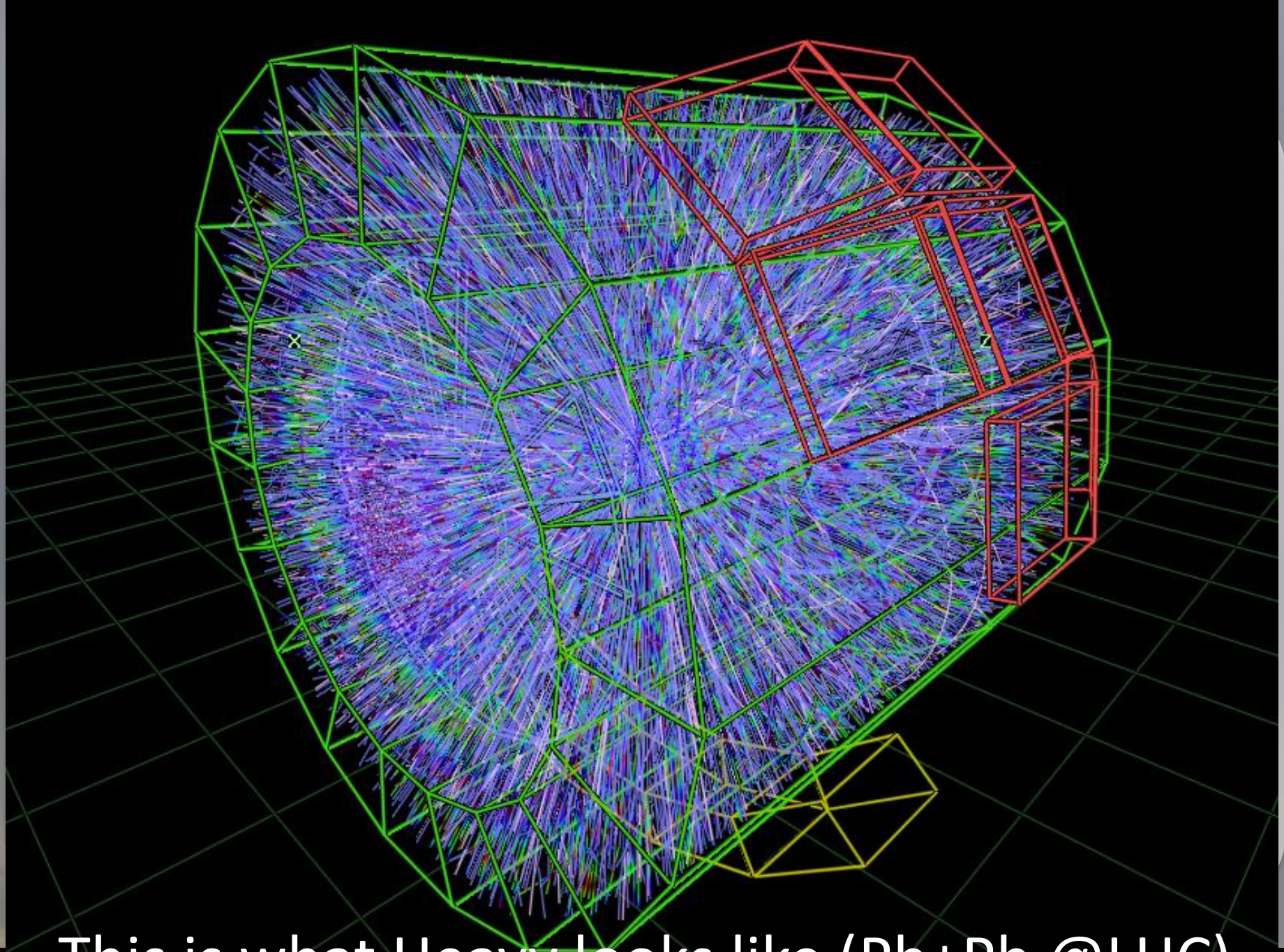
The other **H**: **Higgs**:
- it's what's responsible for mass, right?
- um, not really
- >99% of your mass comes from energy associated with dynamical quarks & gluons in nucleons: **QCD**







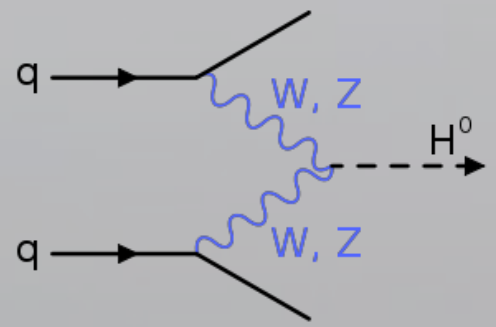
This is what Heavy looks like (Pb+Pb @LHC)

"If you still don't understand p+p, why study 180p+180p?"

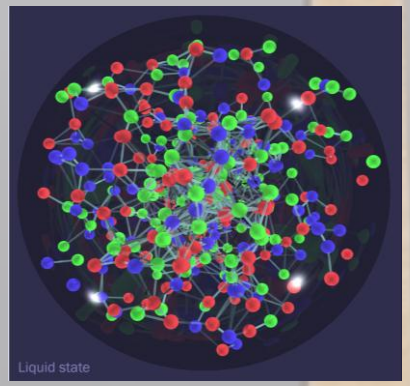
Similar to "If we are still studying atomic physics, why study condensed matter physics?"

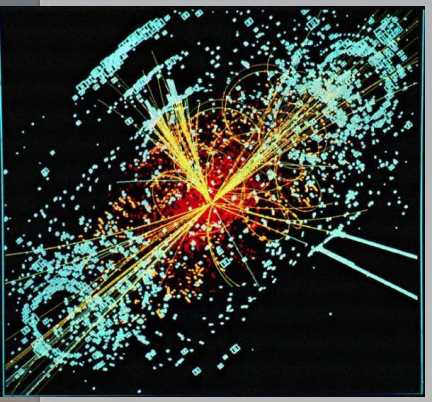
Because we are interested in phases of matter

A *process*

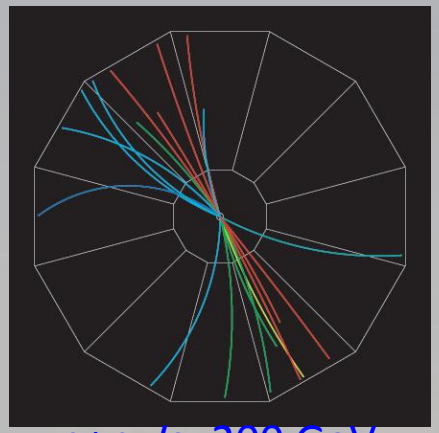


A *system* "Condensed matter QCD"

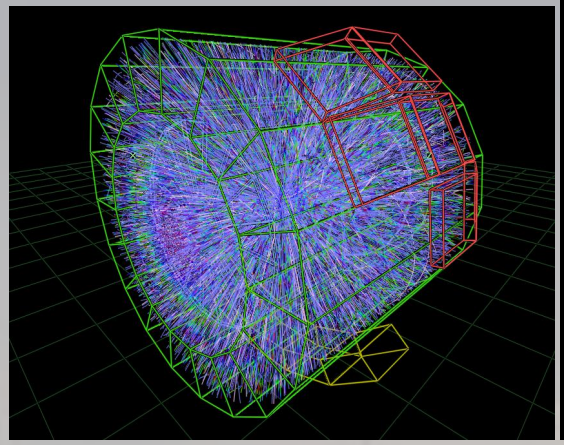




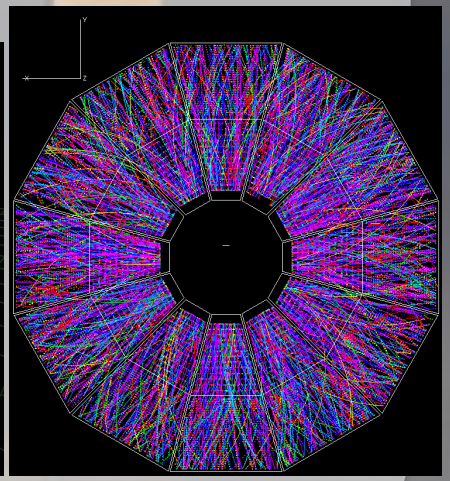
p+p √s=14 TeV



p+p √s=200 GeV

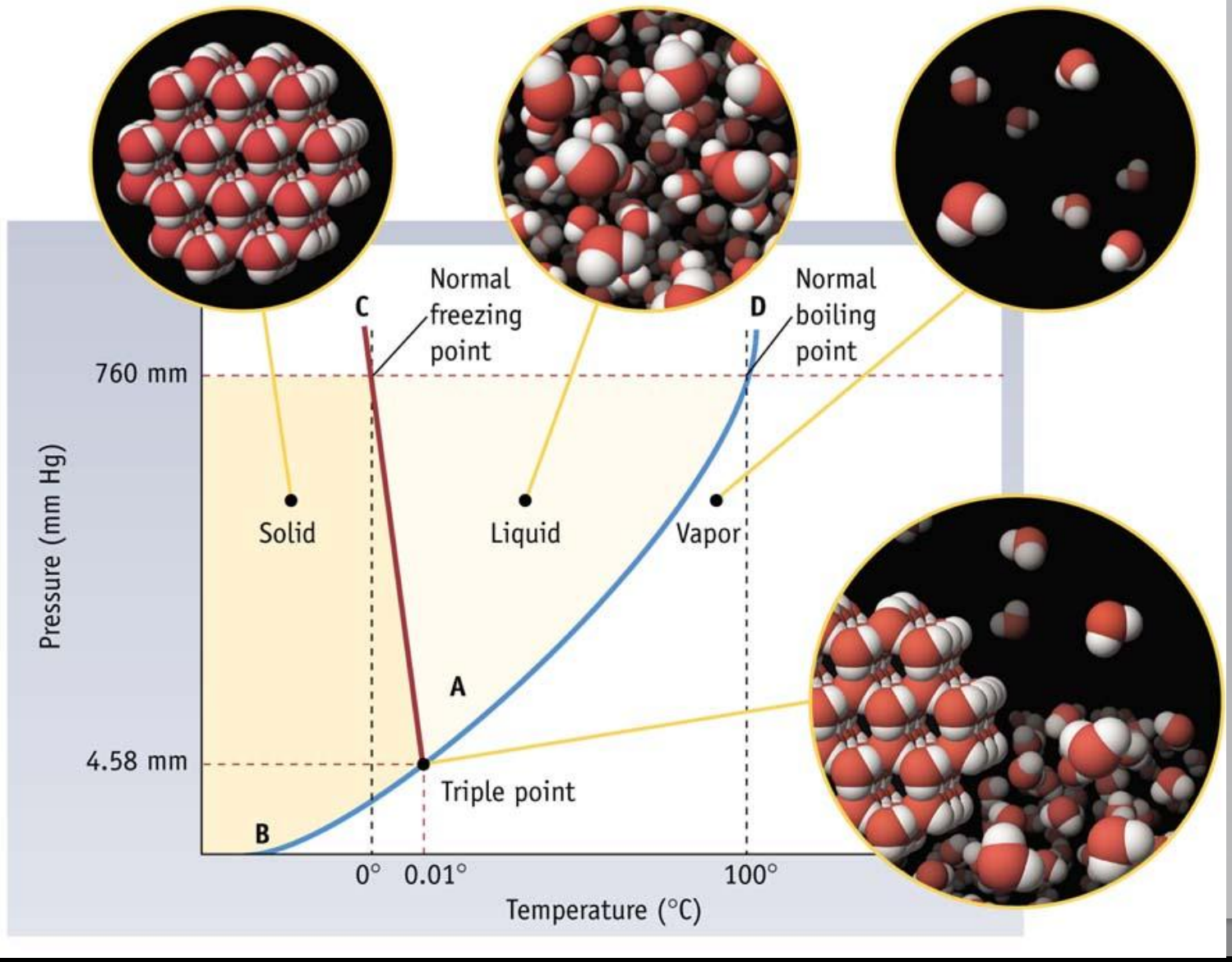


Pb+Pb $\sqrt{s_{NN}}$=5.5 TeV

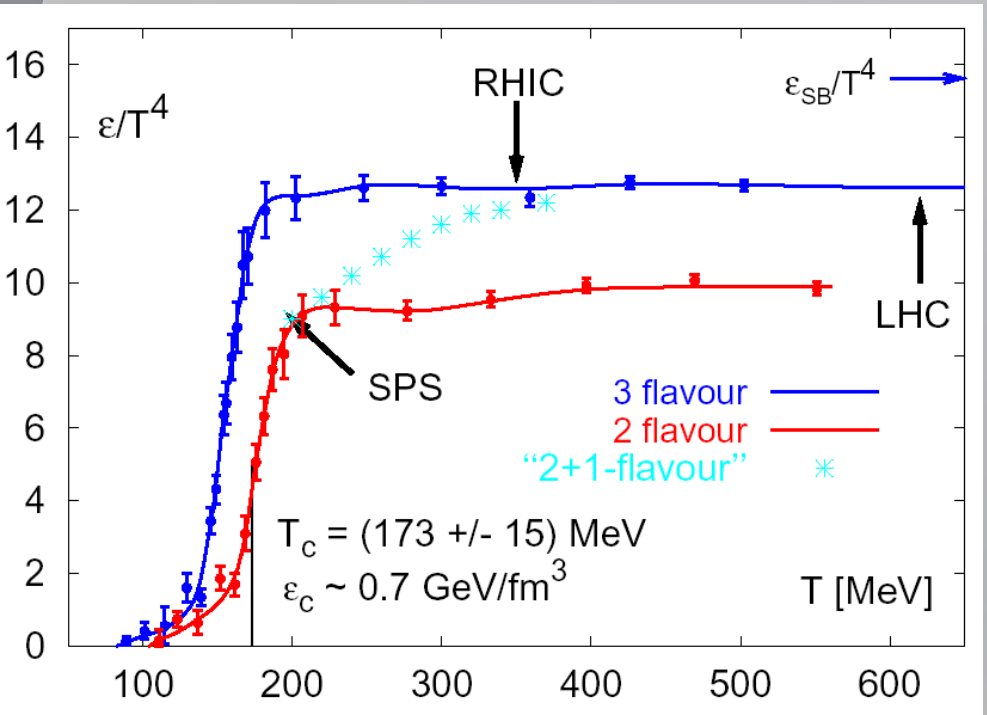


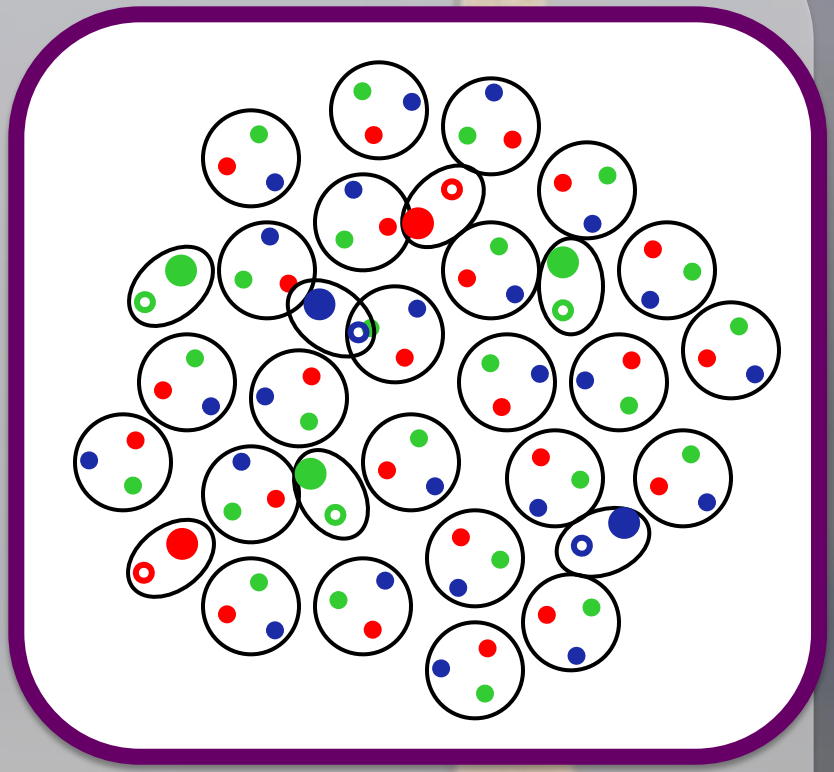
Au+Au $\sqrt{s_{NN}}$= 200 GeV

You can't freeze one molecule of water

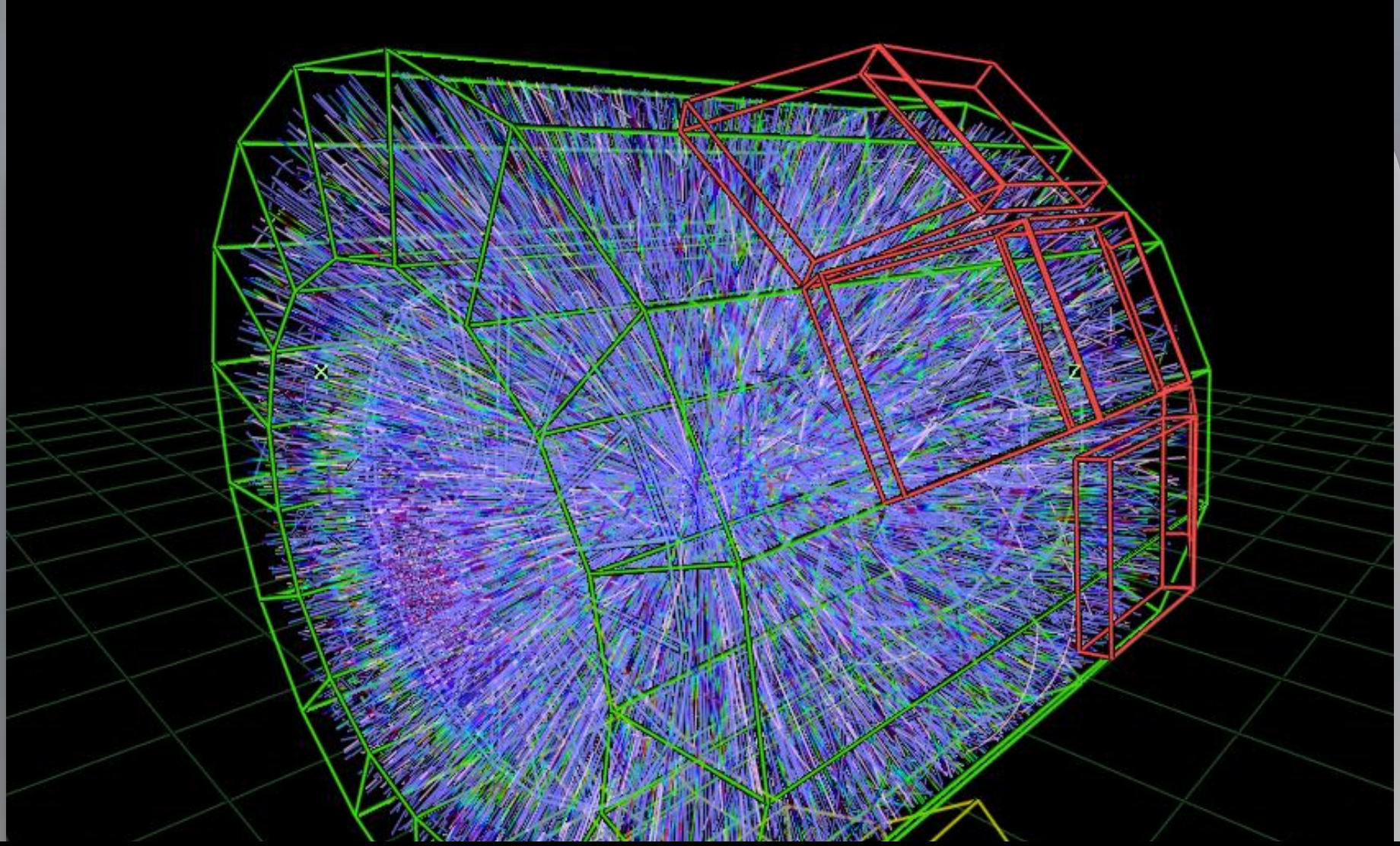


Confinement itself makes it even harder





Free quarks cannot be measured. Our job: identify patterns in the hadronic debris.

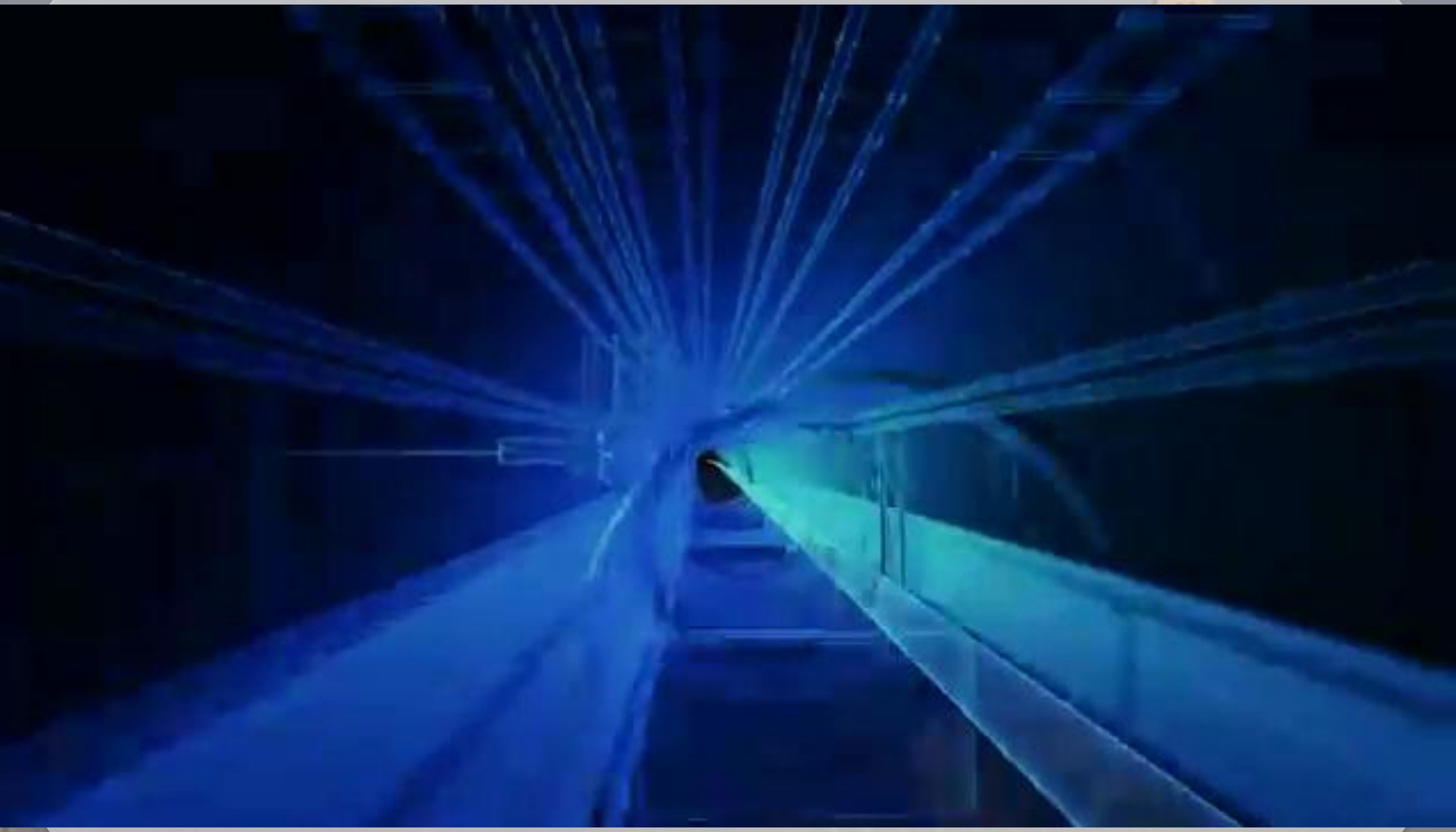


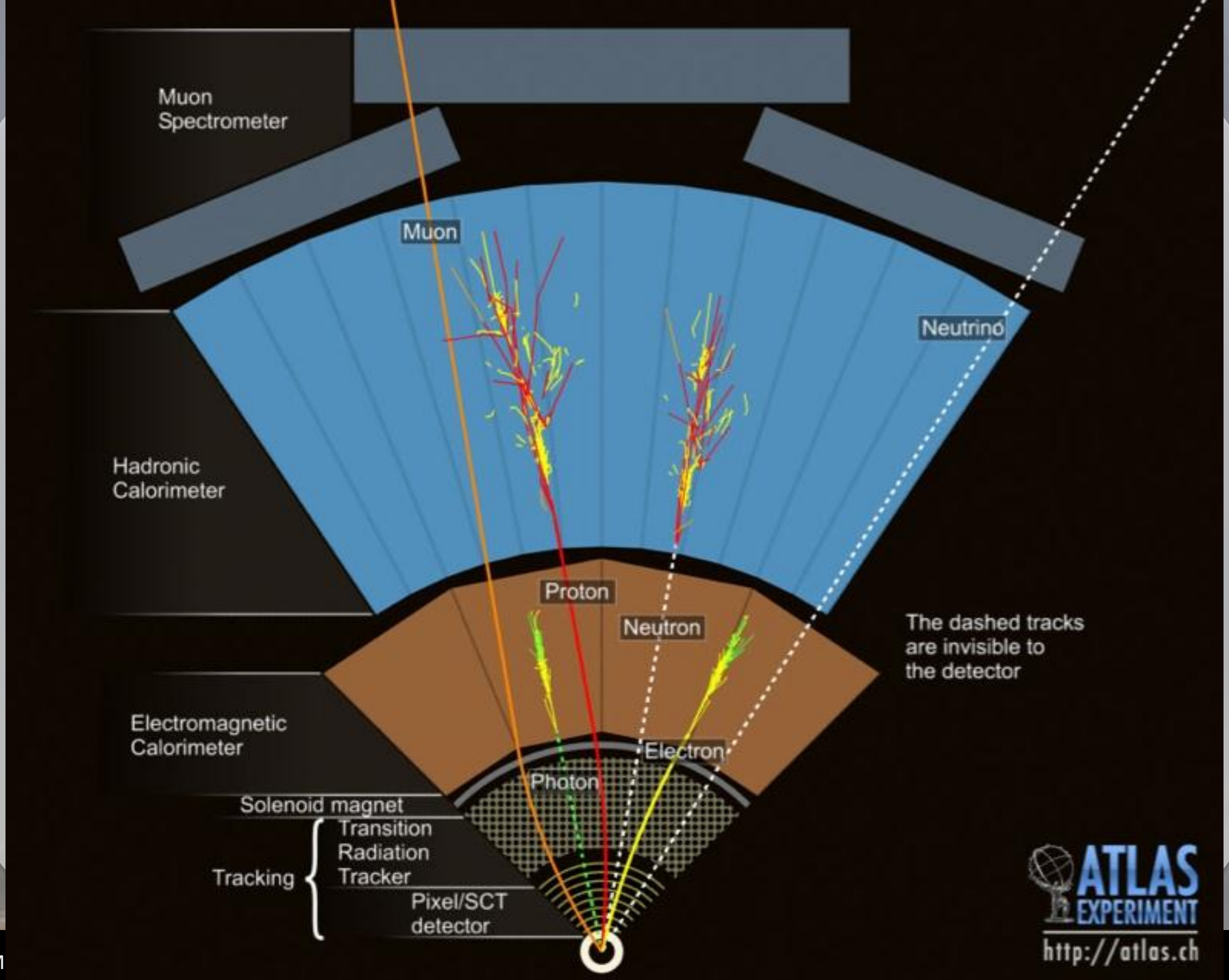
Did this hadronic debris come from a QG plasma?
How could we tell?
&... how can we measure this mess in the first place?!

DETECTORS, COMPUTING & ANALYSIS

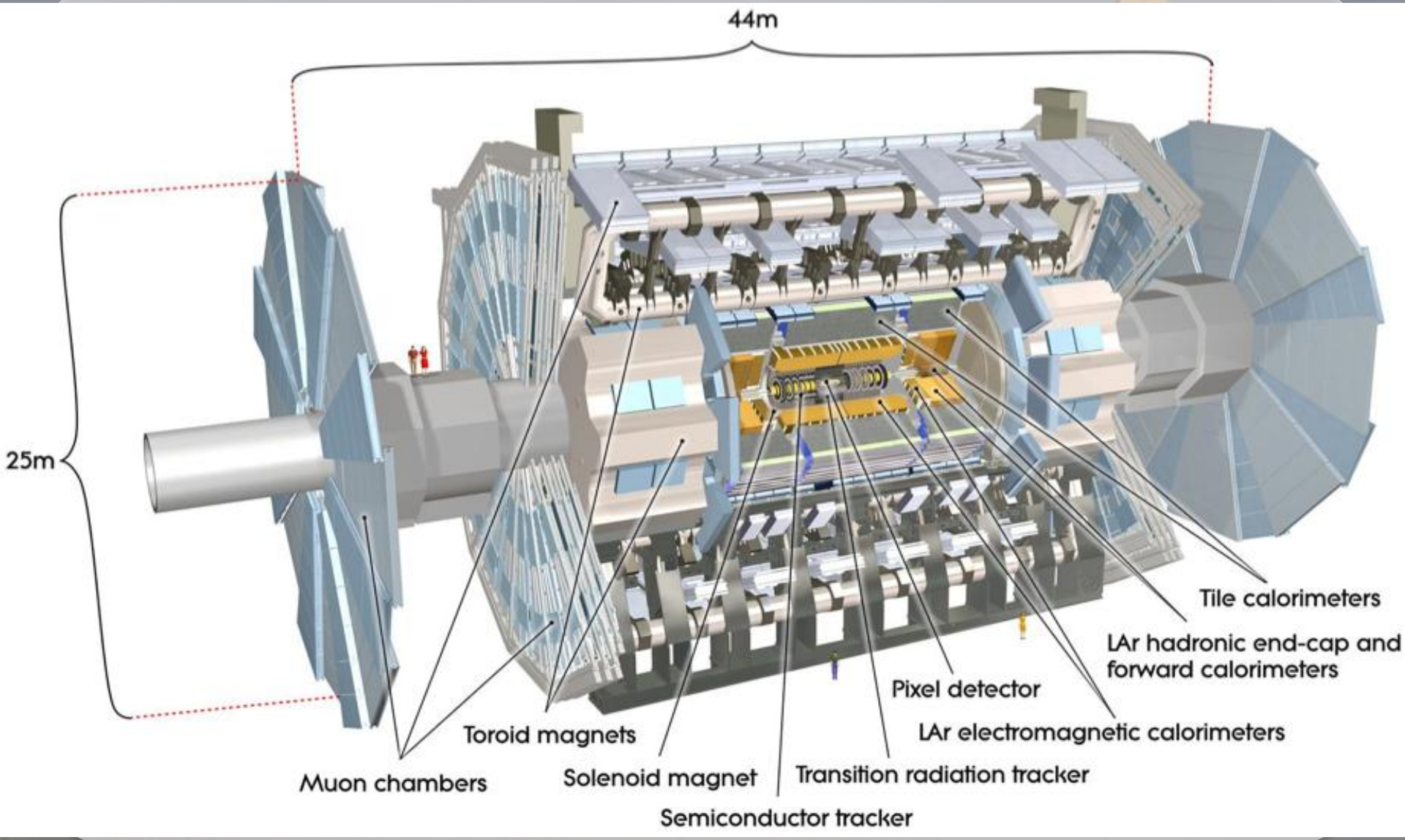
The Big Picture

Simulated collision in ATLAS @ LHC

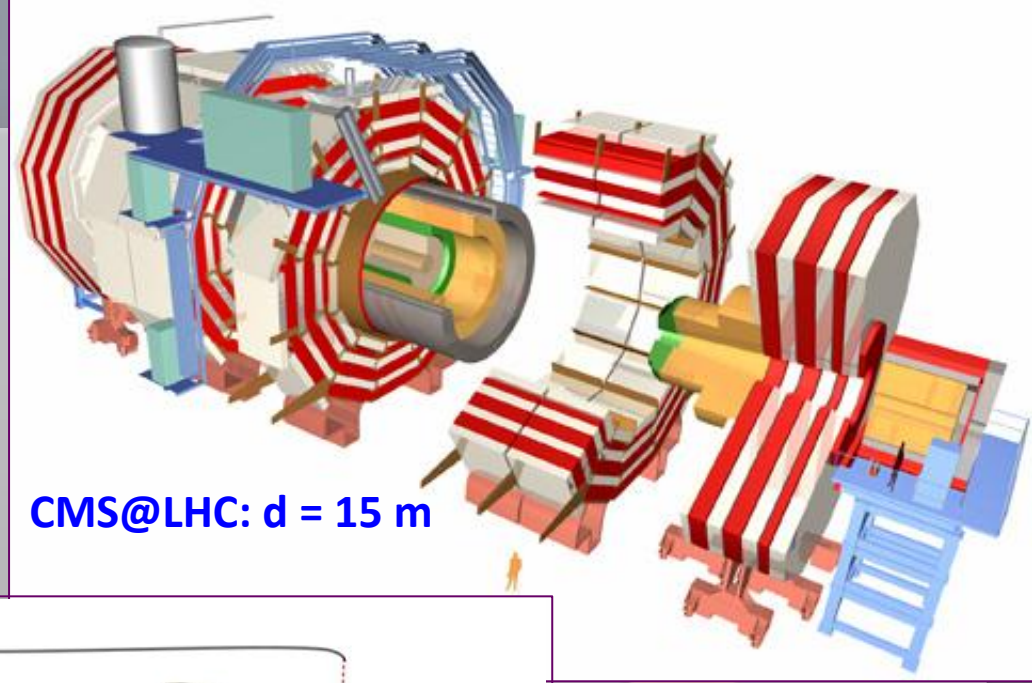


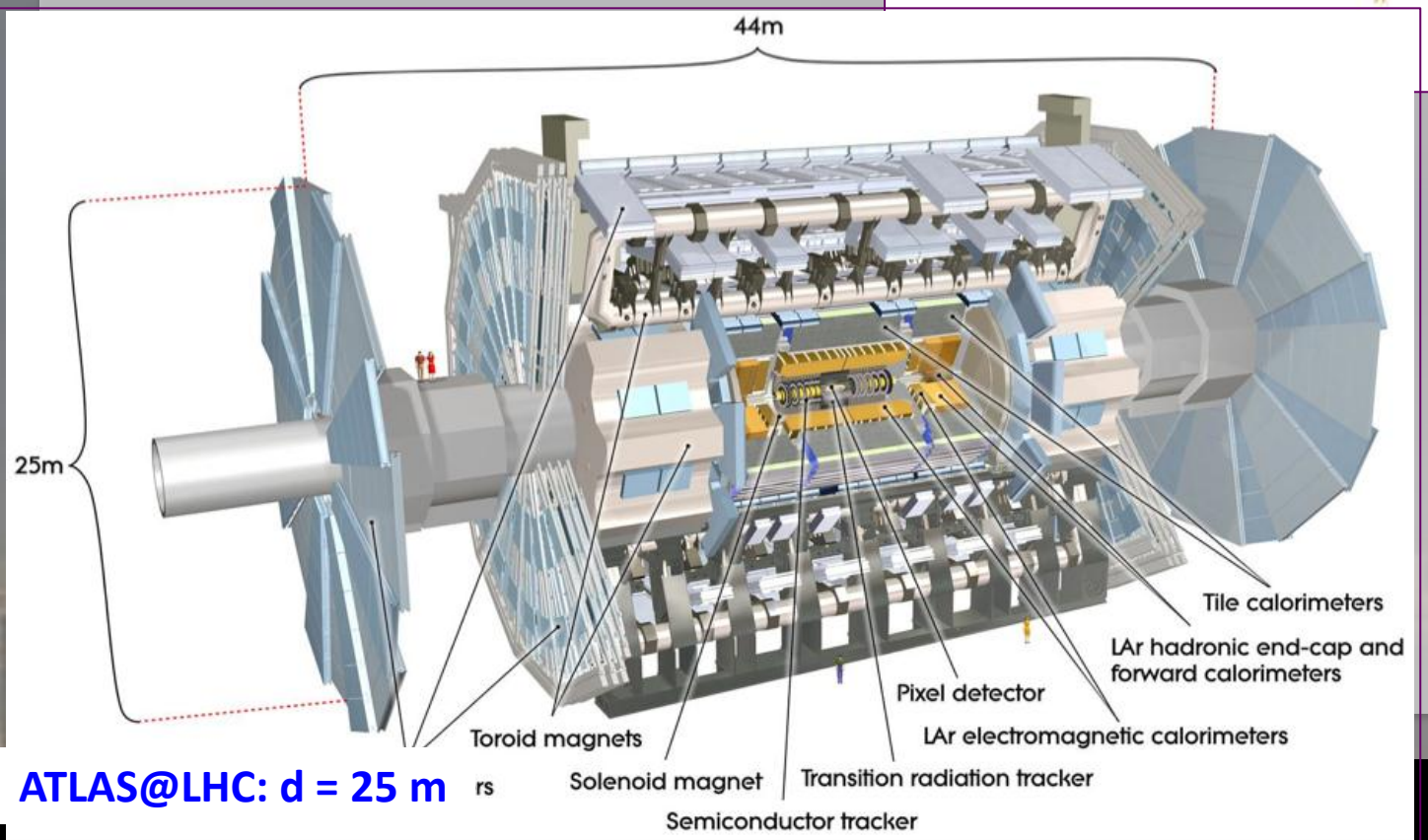

Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch

ATLAS @ LHC


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

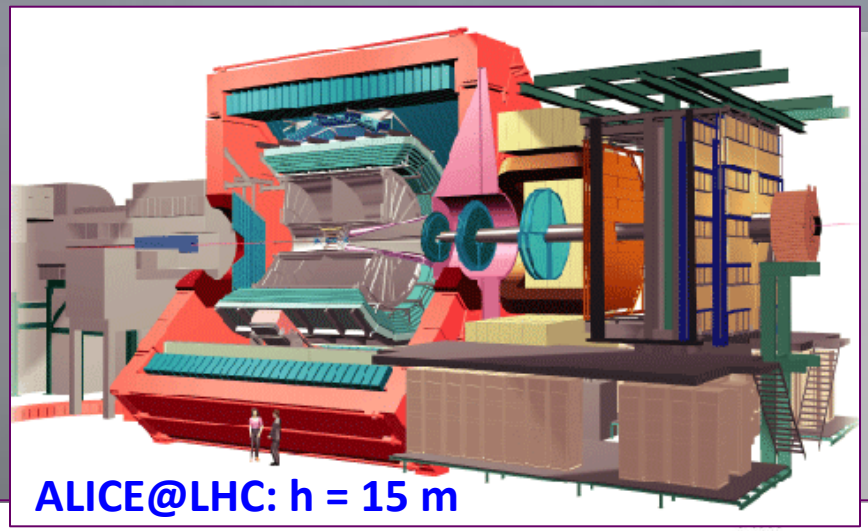
“Natural” geometry



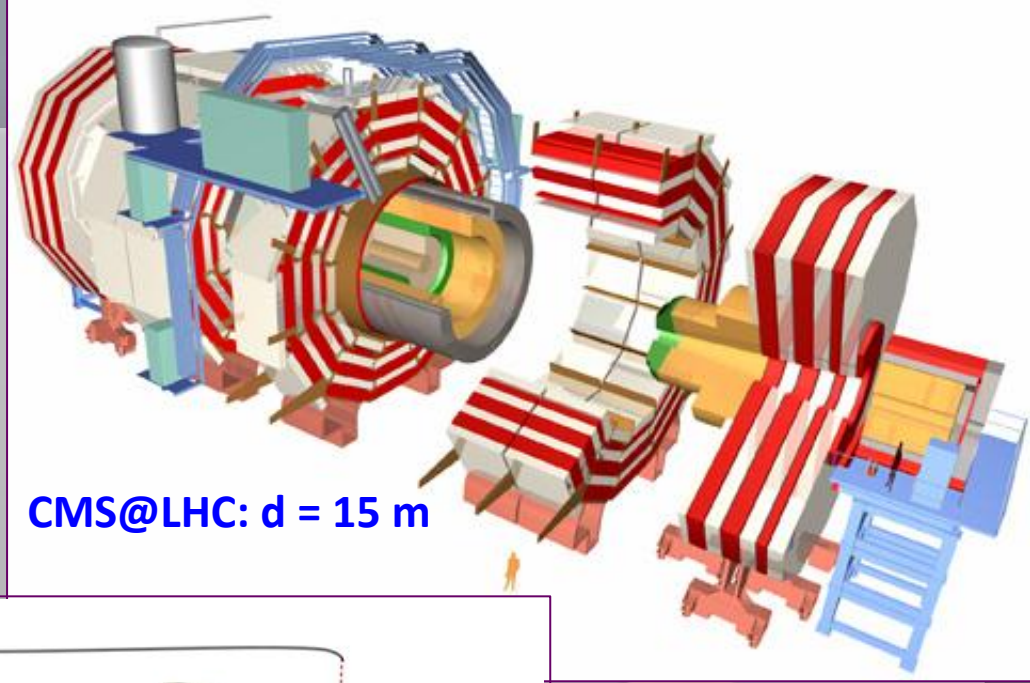


ATLAS@LHC: d = 25 m

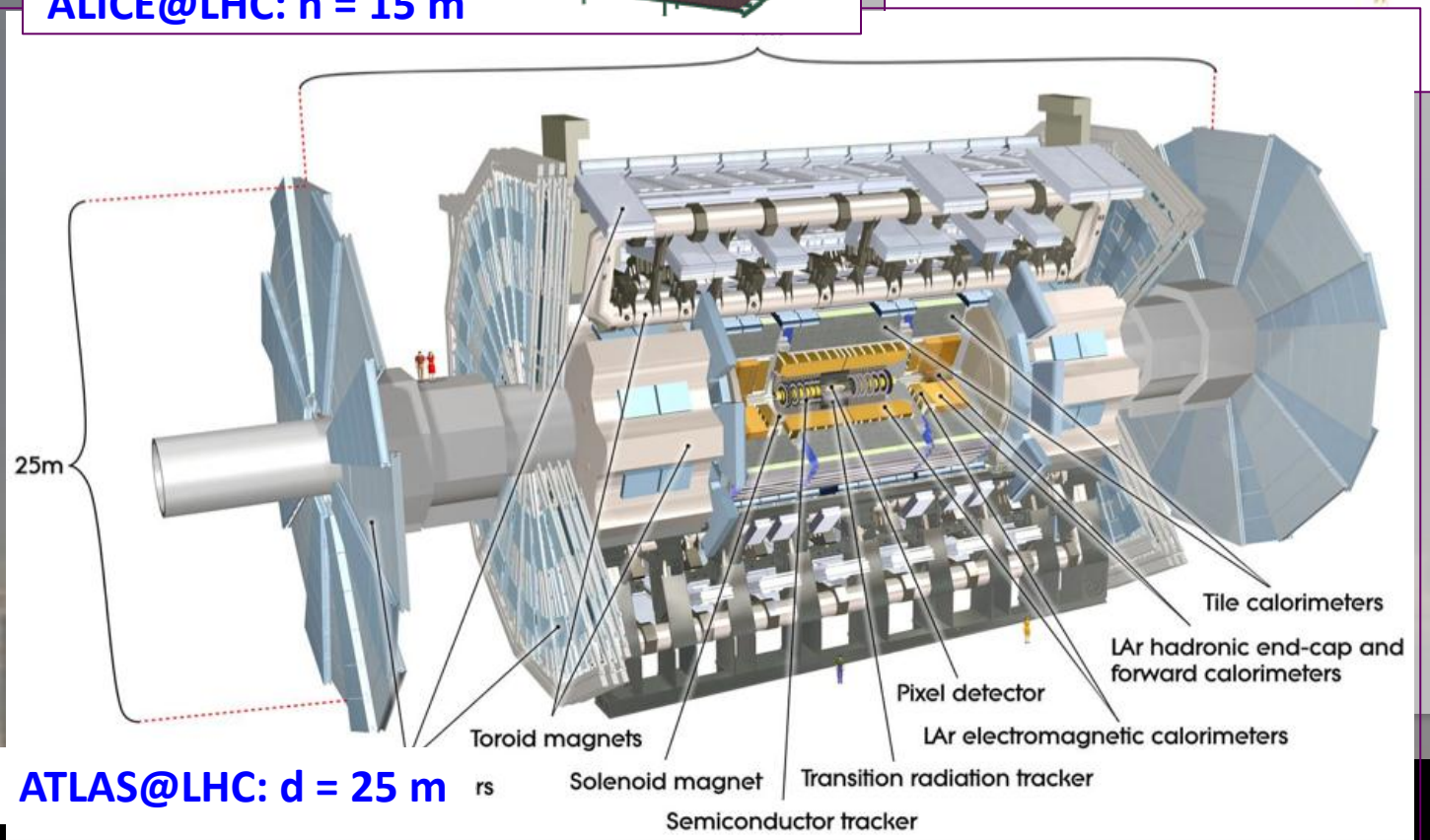
“Natural” geometry



ALICE@LHC: h = 15 m

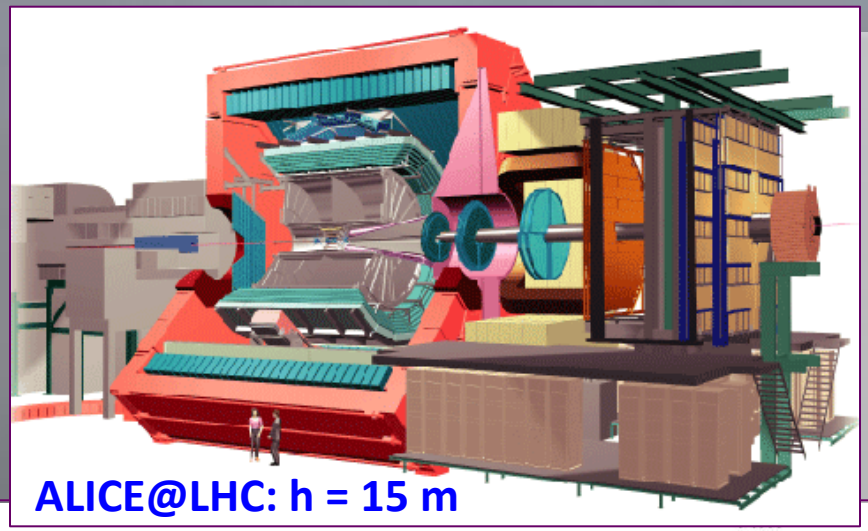


CMS@LHC: d = 15 m

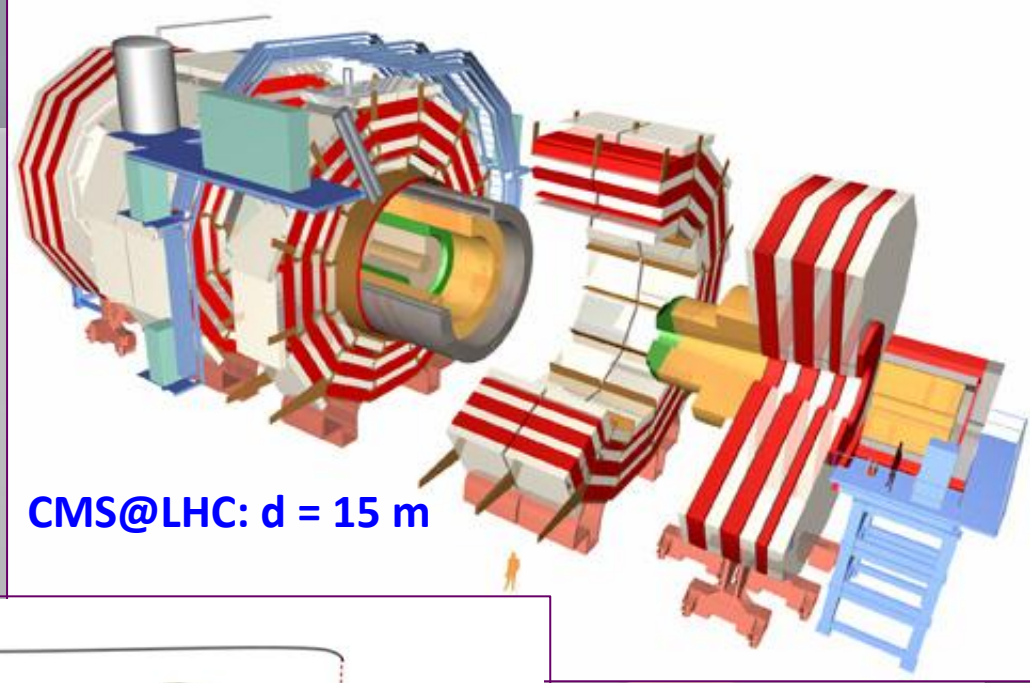


ATLAS@LHC: d = 25 m

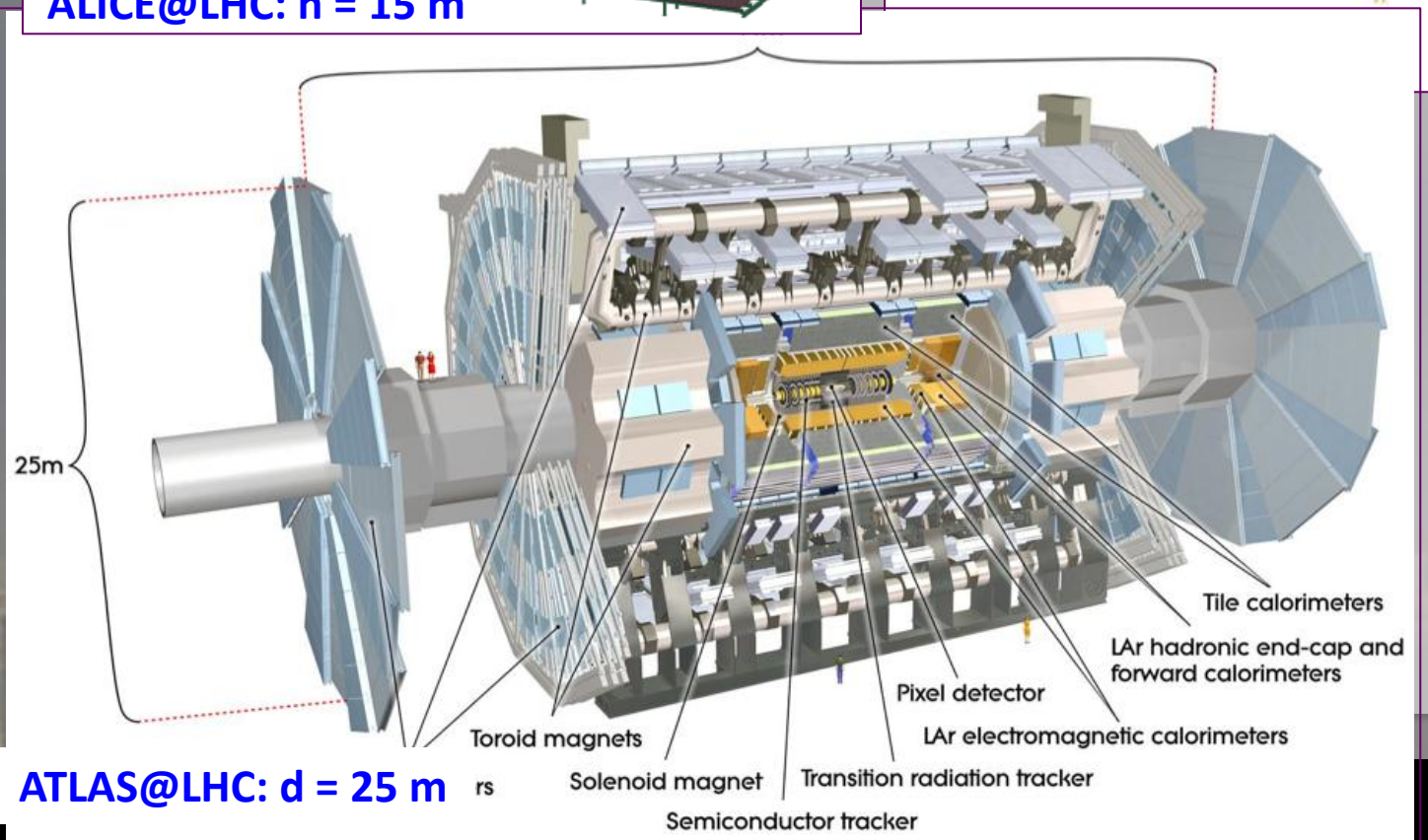
“Natural” geometry



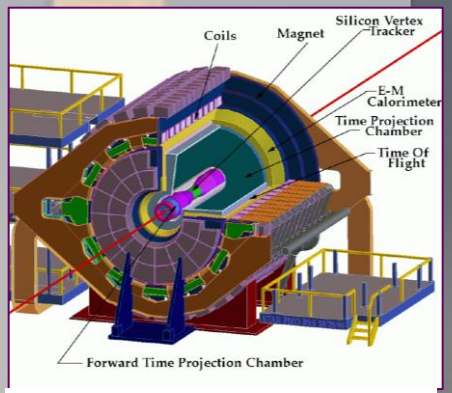
ALICE@LHC: h = 15 m



CMS@LHC: d = 15 m

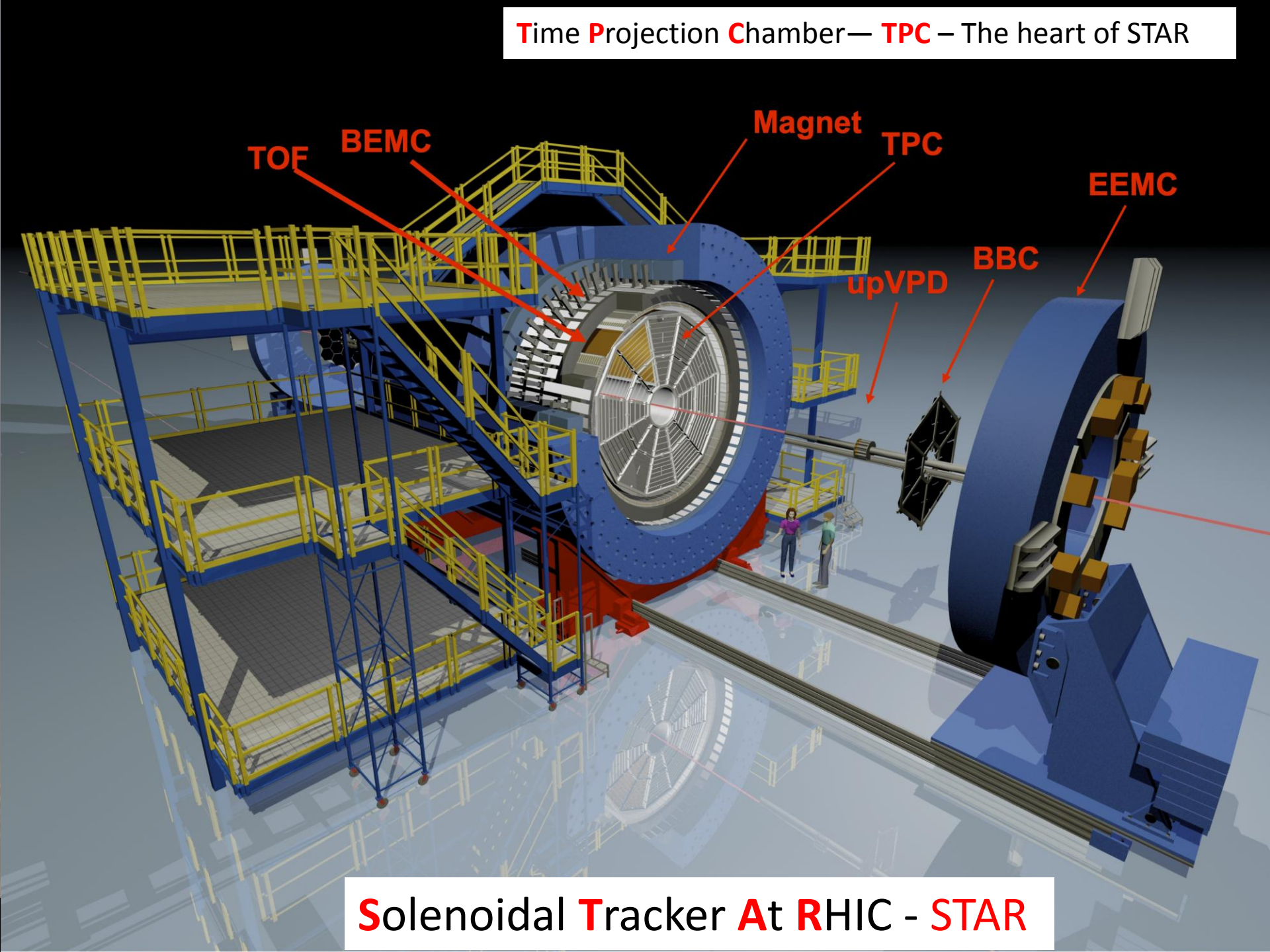


ATLAS@LHC: d = 25 m



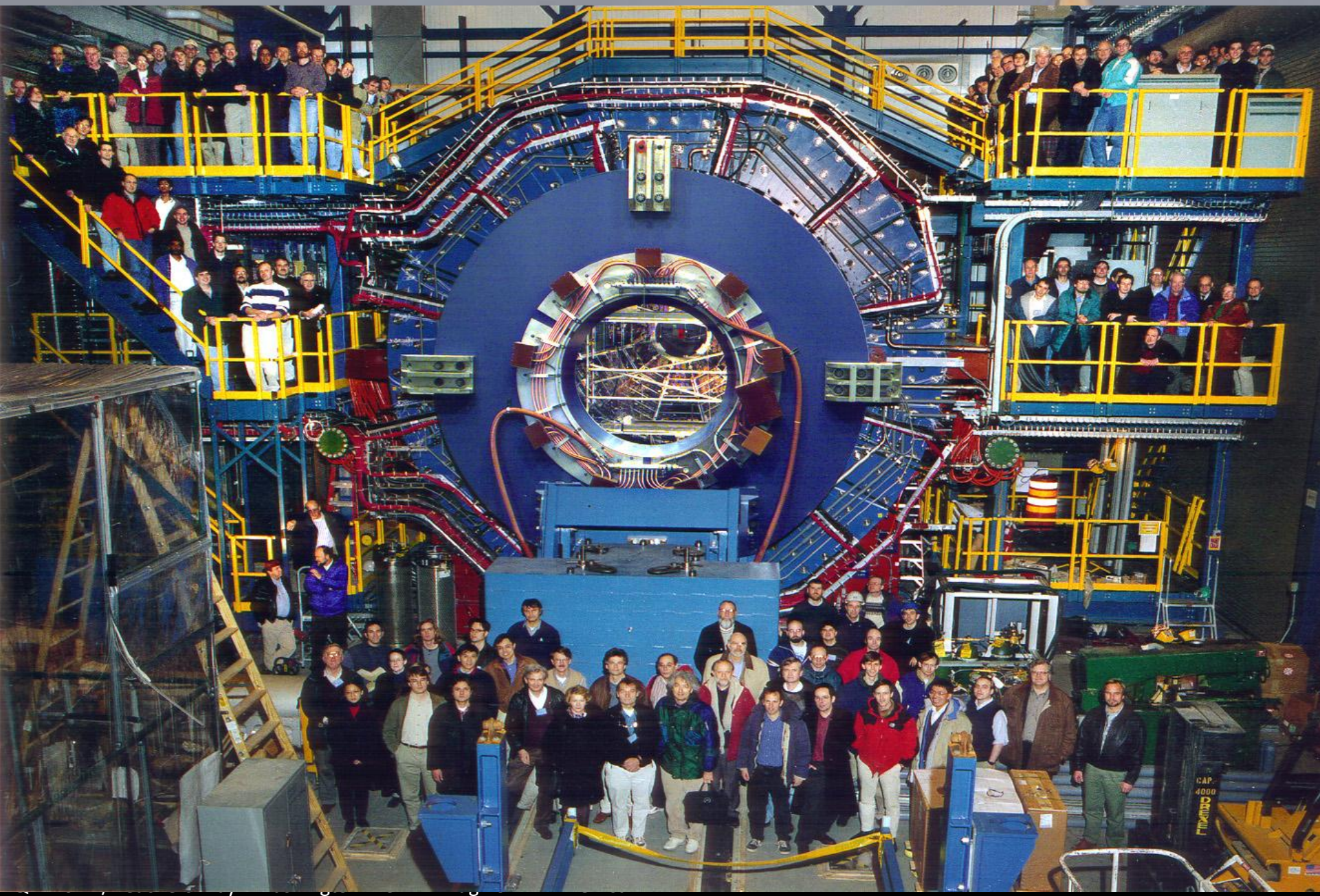
STAR@RHIC: d=7 m

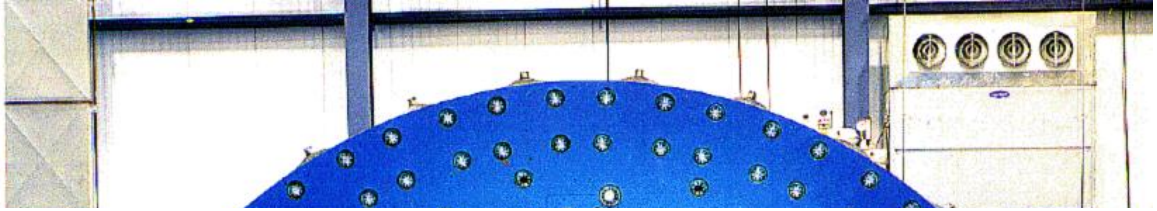
Time Projection Chamber— TPC – The heart of STAR



Solenoidal Tracker At RHIC - STAR

STAR @ RHIC

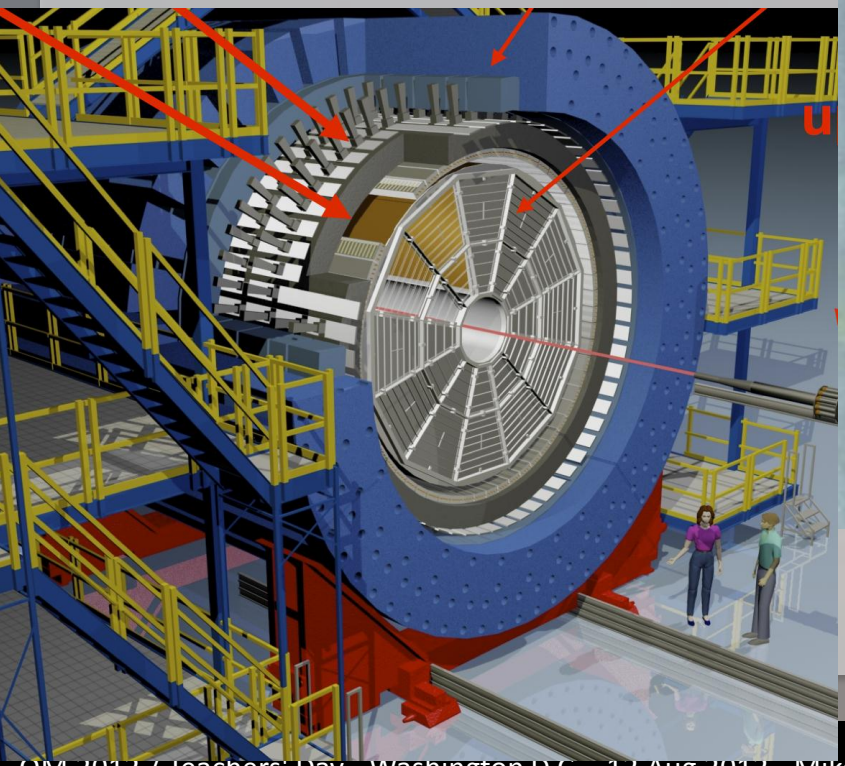


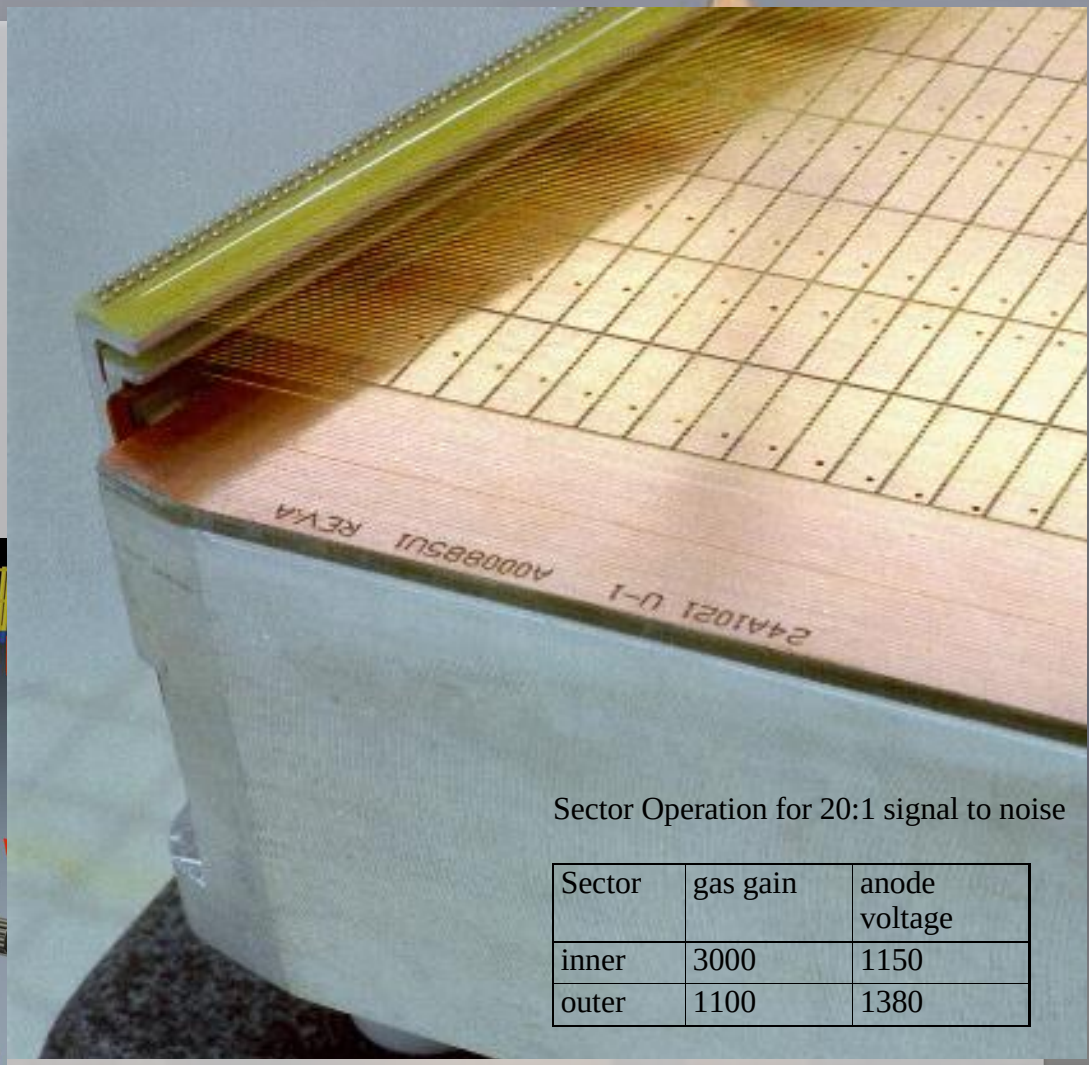


Solenoidal Tracker At RHIC

goal: track “all” charged hadrons (bags of quarks) emitted in each collision

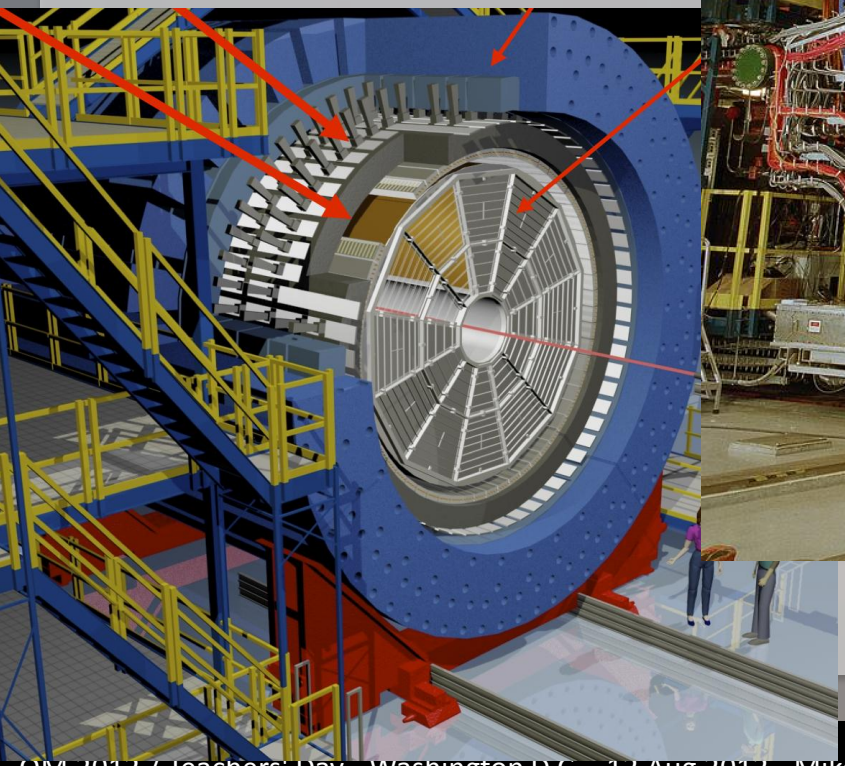
End-plane instrumentation – pads and wires

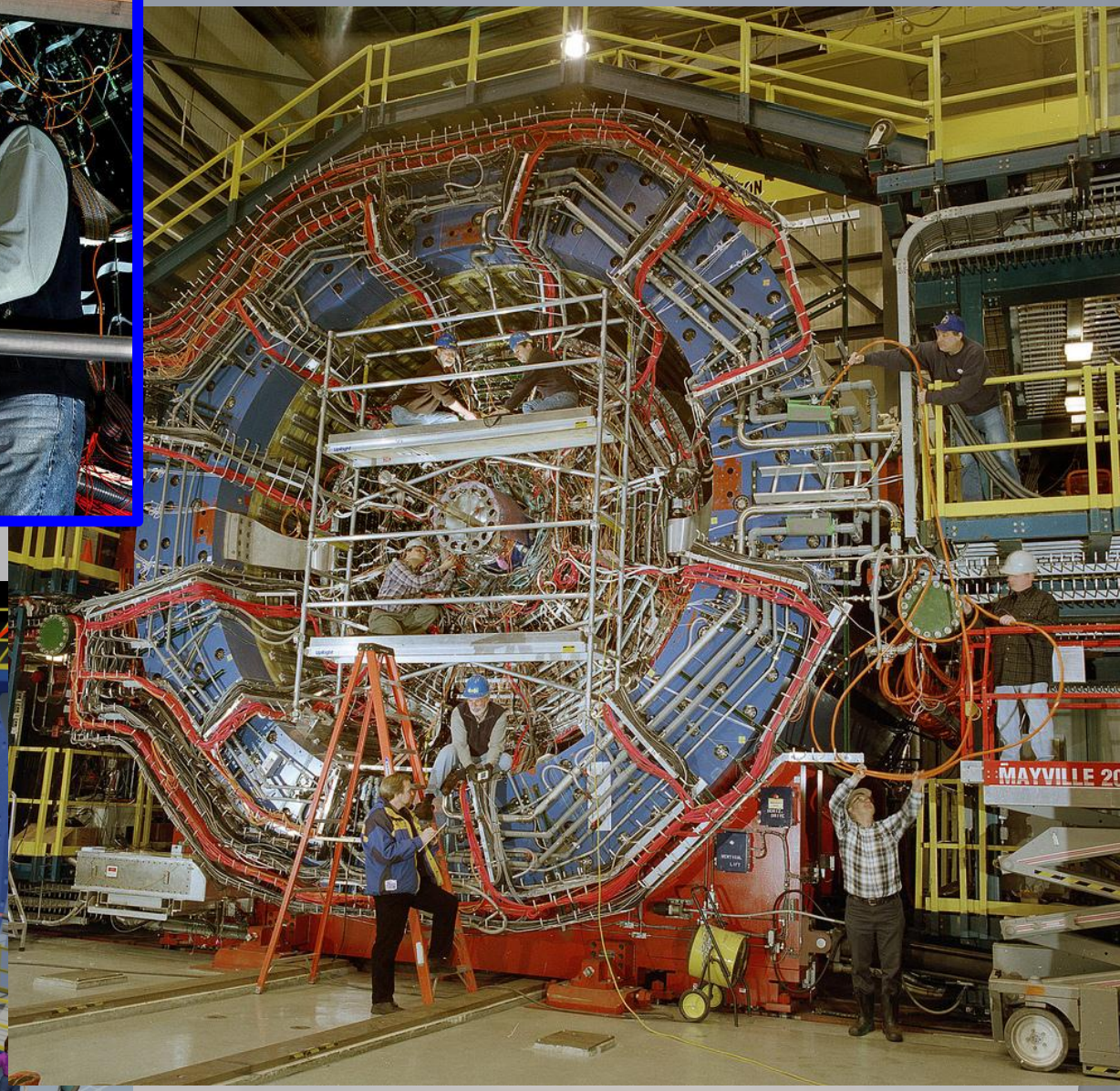




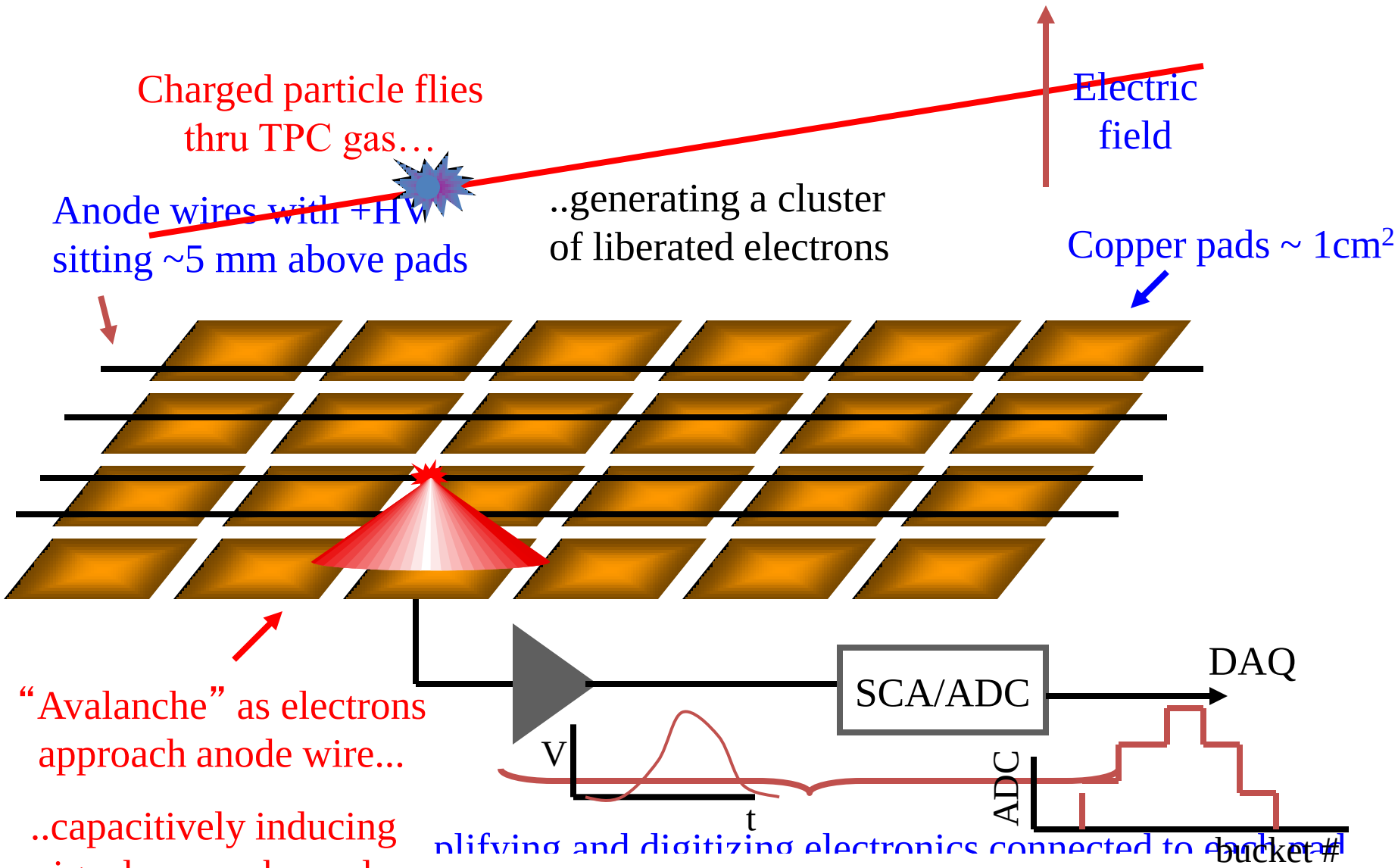
Sector Operation for 20:1 signal to noise

Sector	gas gain	anode voltage
inner	3000	1150
outer	1100	1380

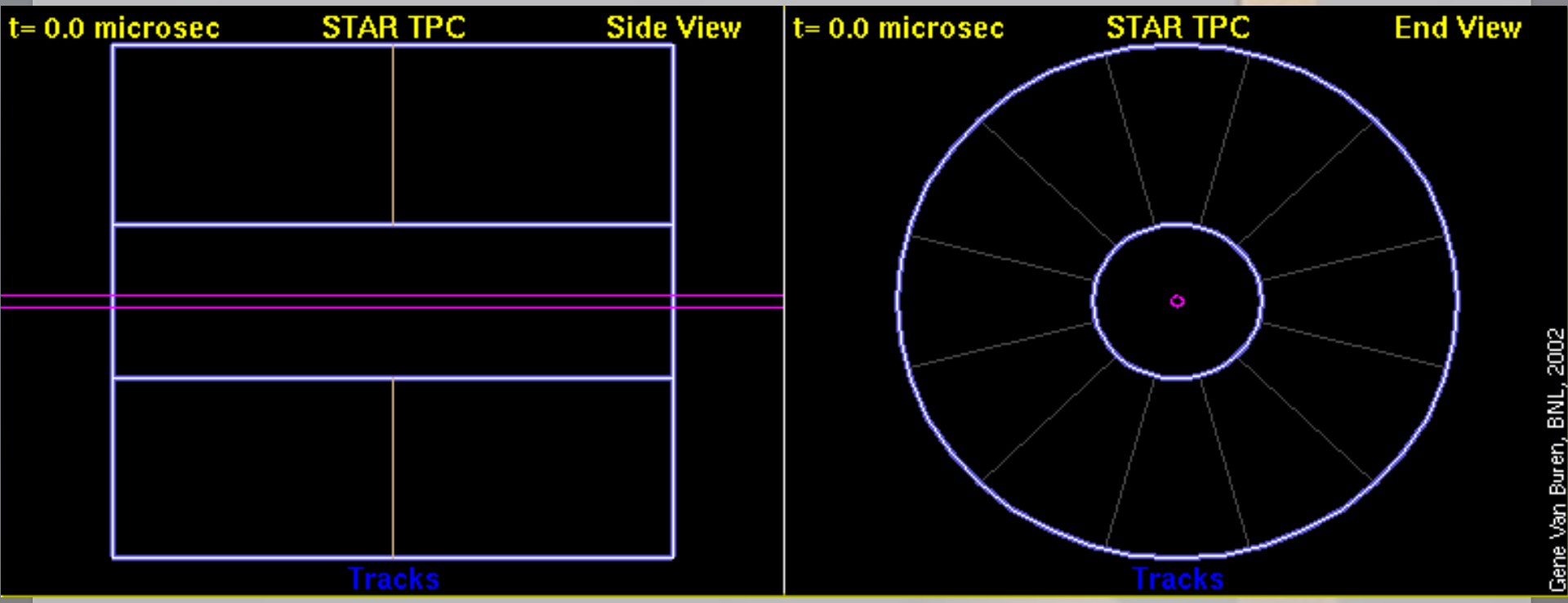



MAYVILLE 20

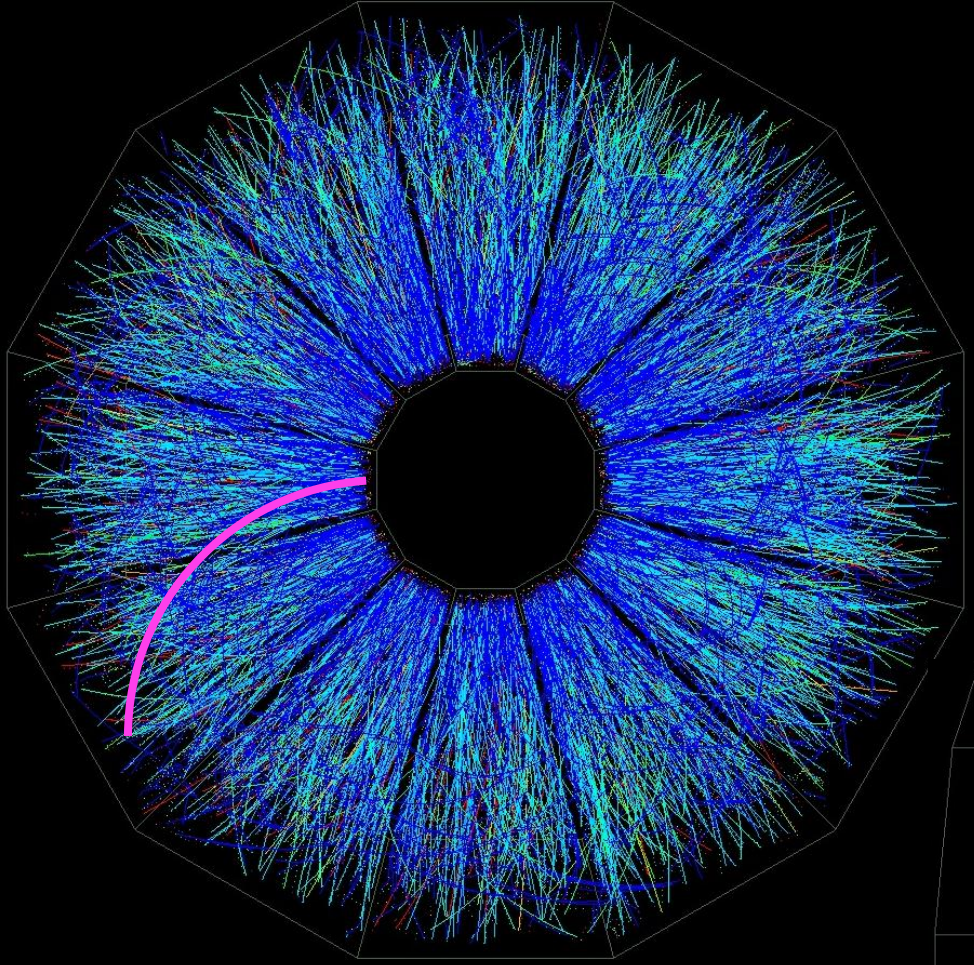
Operation of a Time Projection Chamber



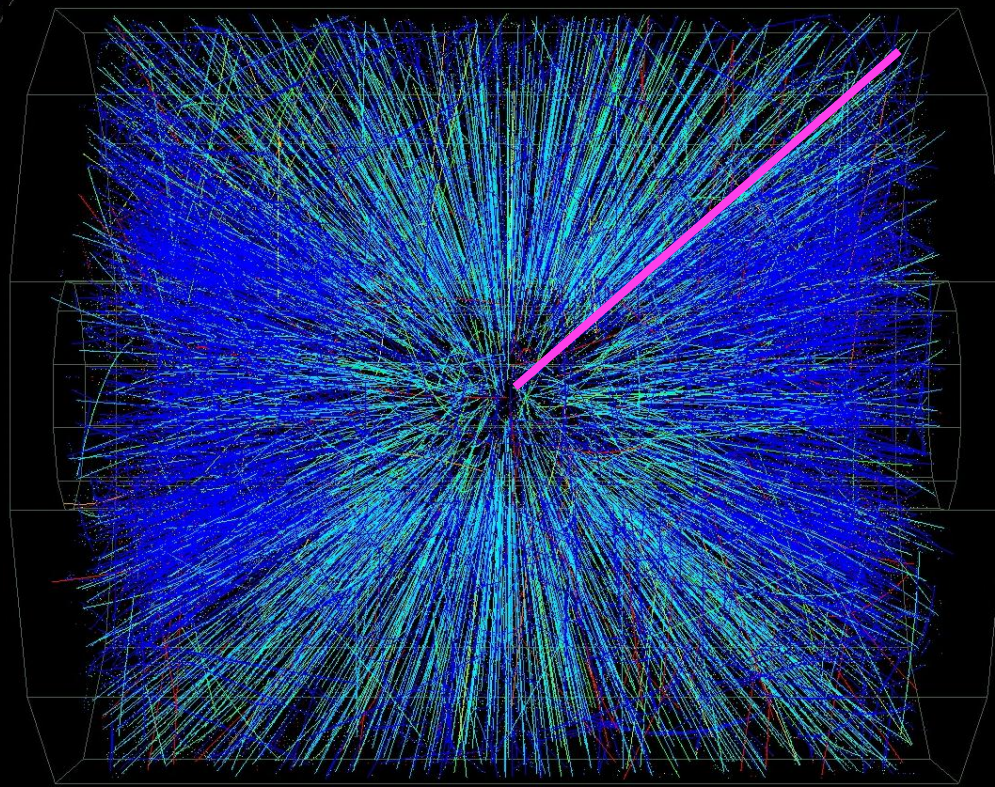
TPC Operation



One collision seen by STAR TPC

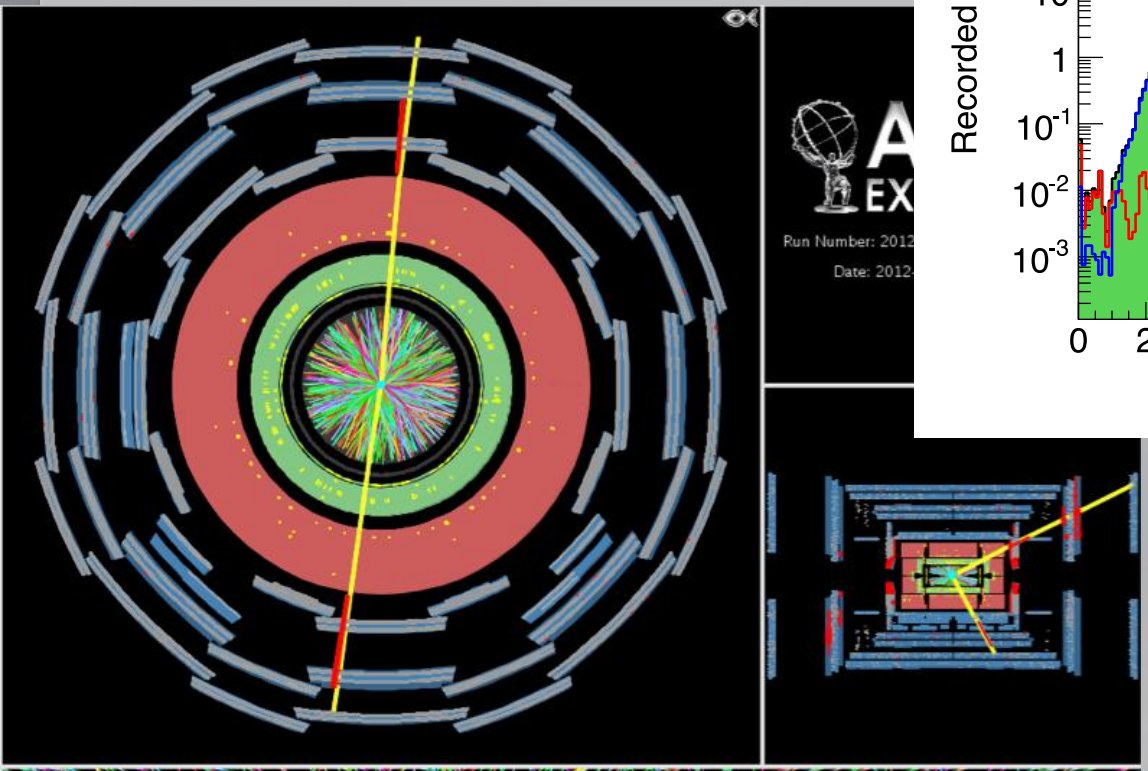


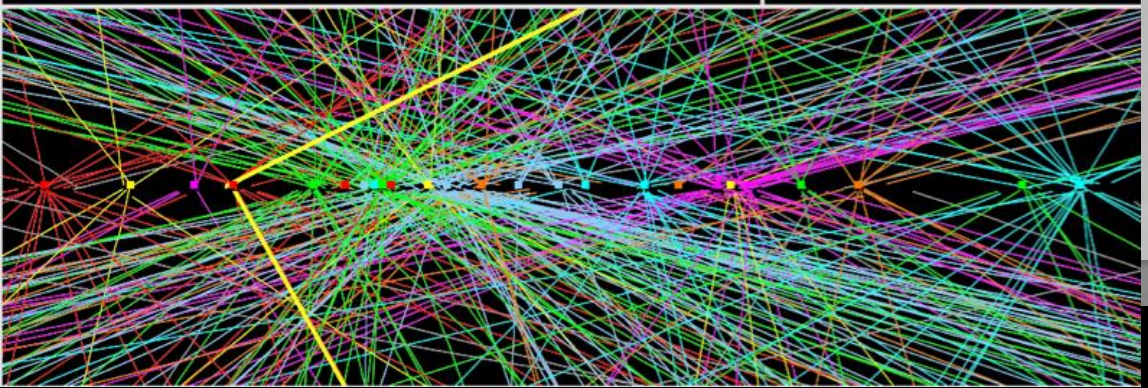
Momentum determined by track curvature in magnetic field…

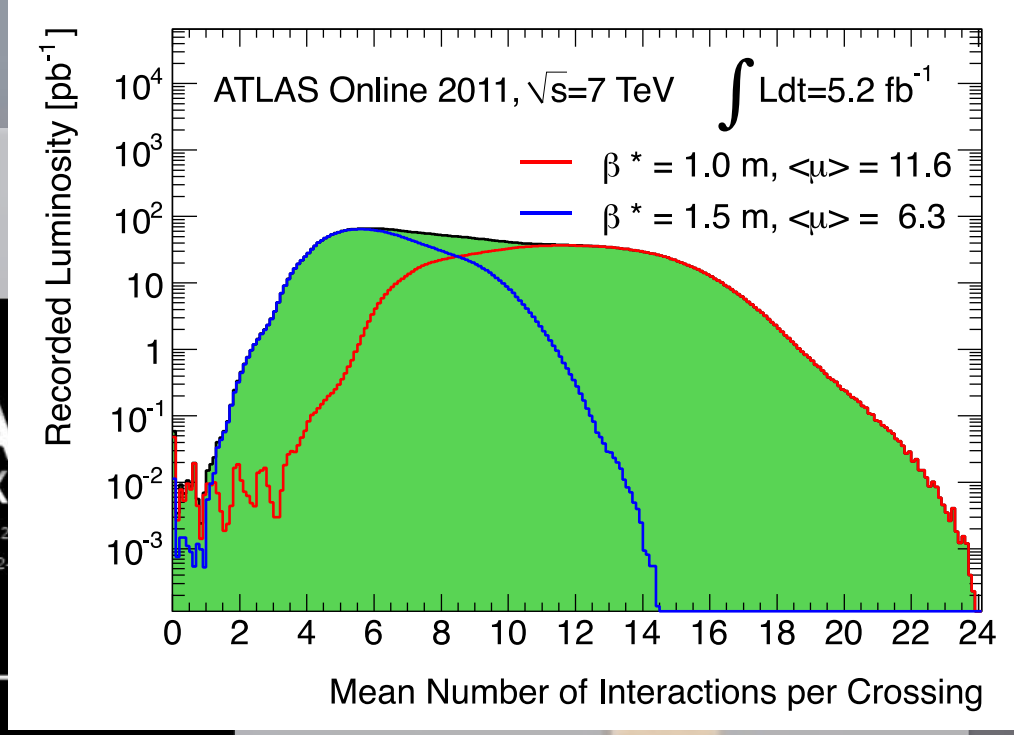


…and by direction relative to beam

Challenges – even for "just" p+p collisions







Z→μμ with 25 pile-up interactions in 2012

Data storage

RHIC experiments:
presently ~ 6-10 PB each of raw, “derived” data

LHC experiments:
~15 PB of new data each year.

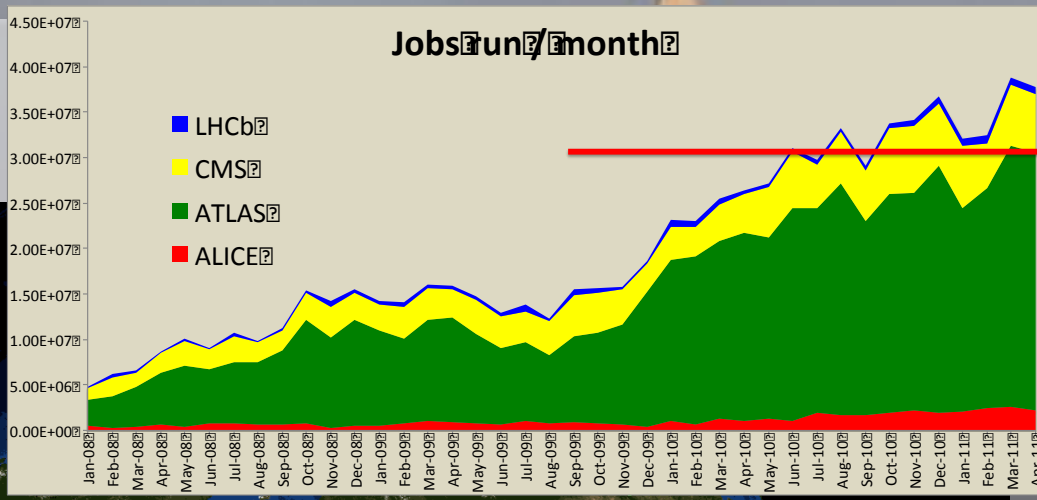
~1000x more data discarded pre-storage by filtering triggers

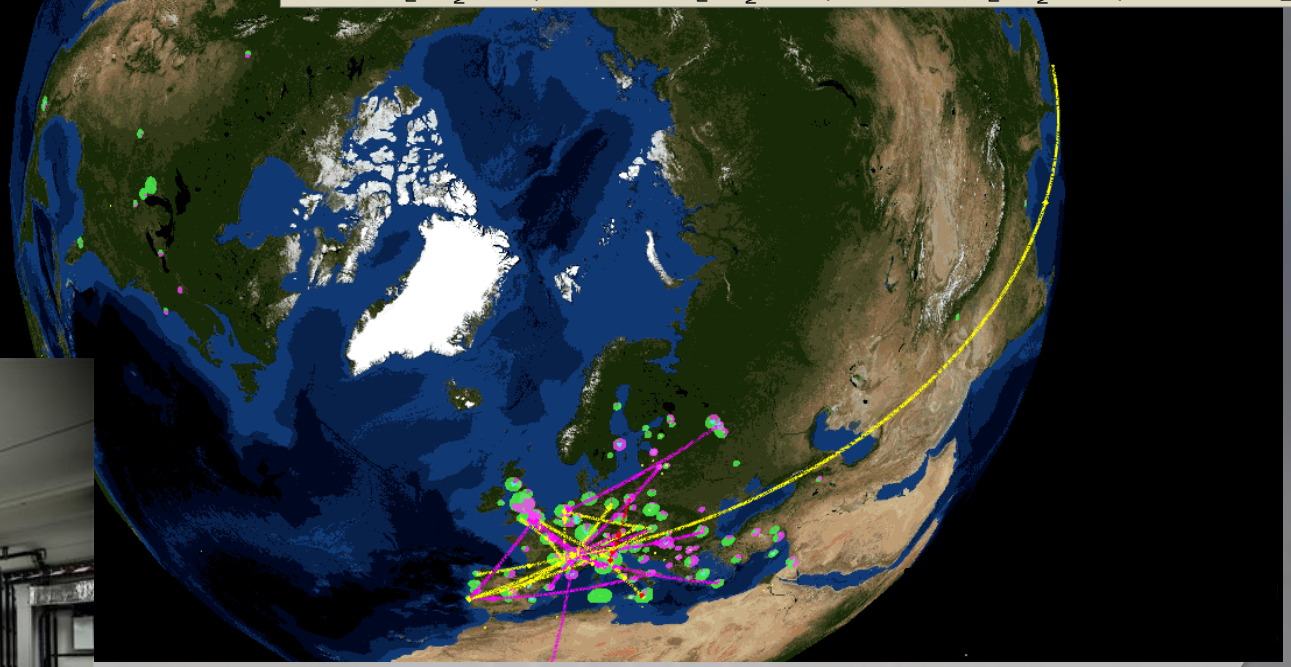
50 PB =

- entire written works of all mankind, from beginning of recorded history
- 660 years of HD-TV video
- 10 million DVDs

(source: Mozy.com)

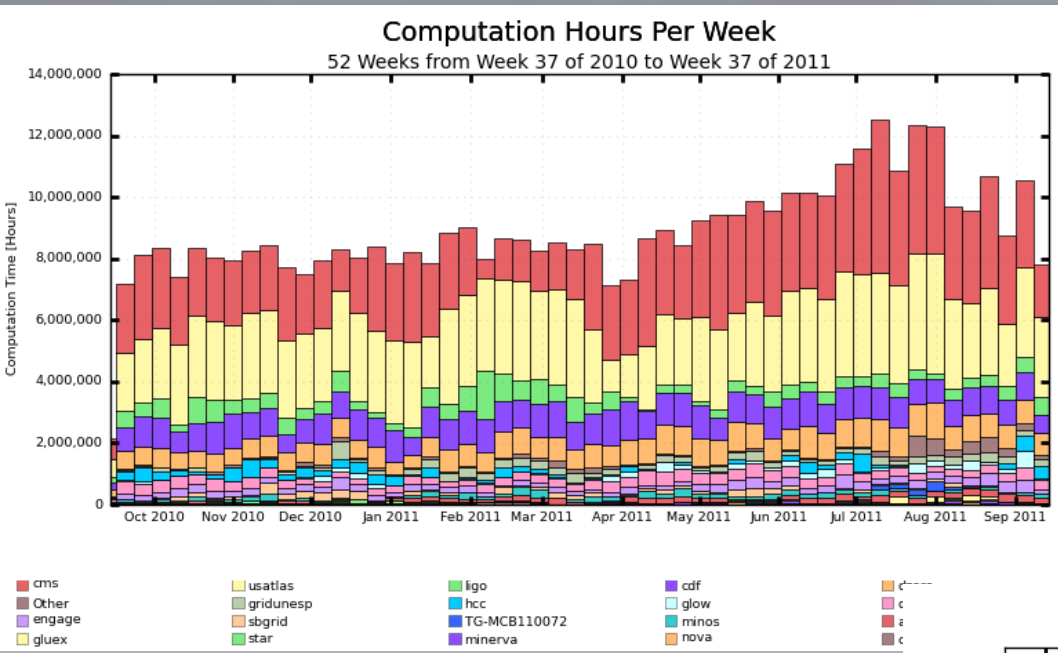
Grids – LCG, …



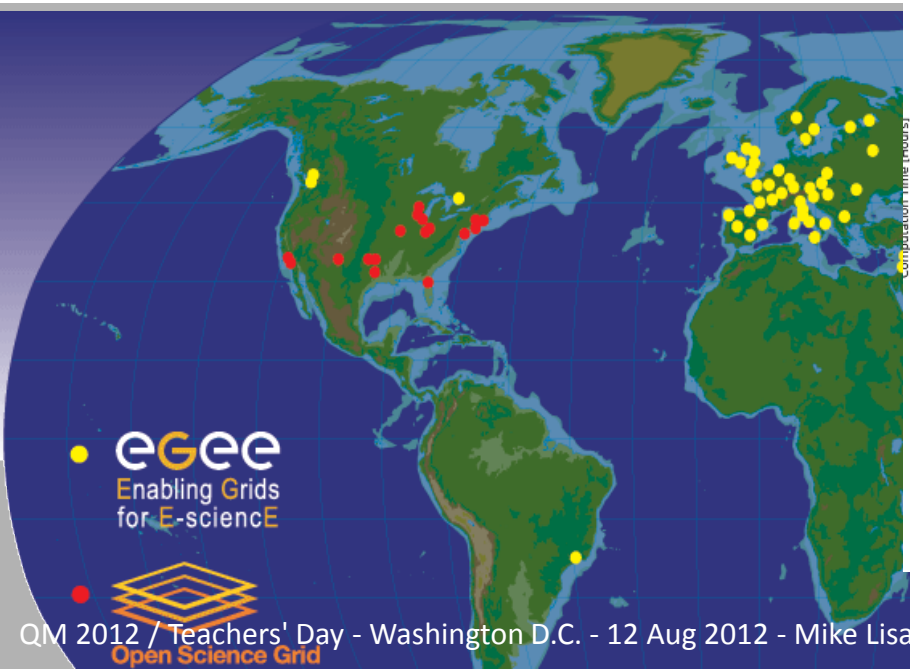


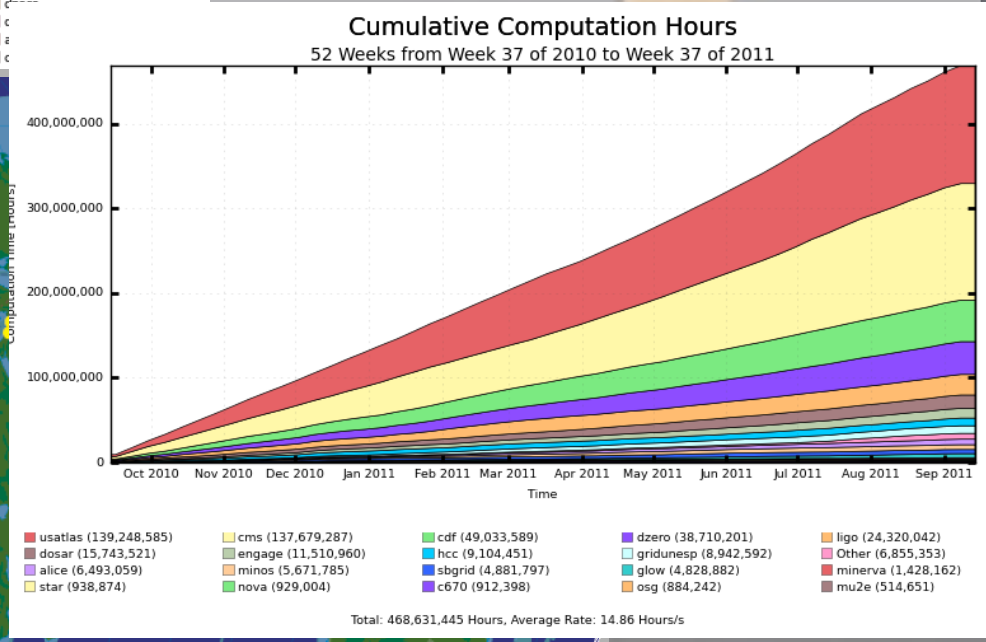
All collaborators have equal access to all data, thanks to grids

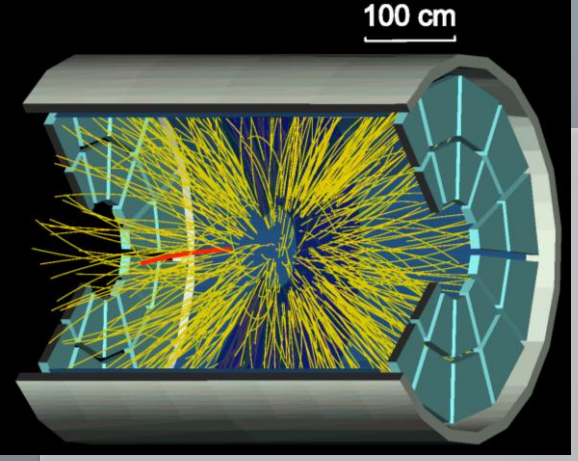
Grids – OSG, …



"Average: ~14 hr/sec"



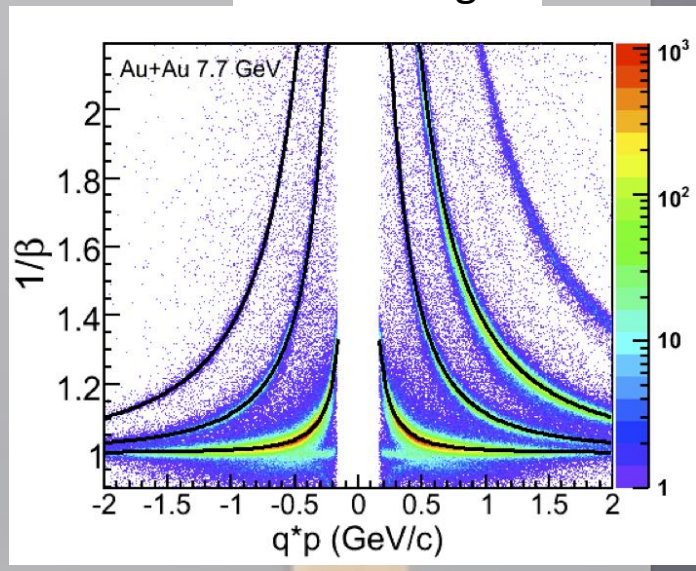




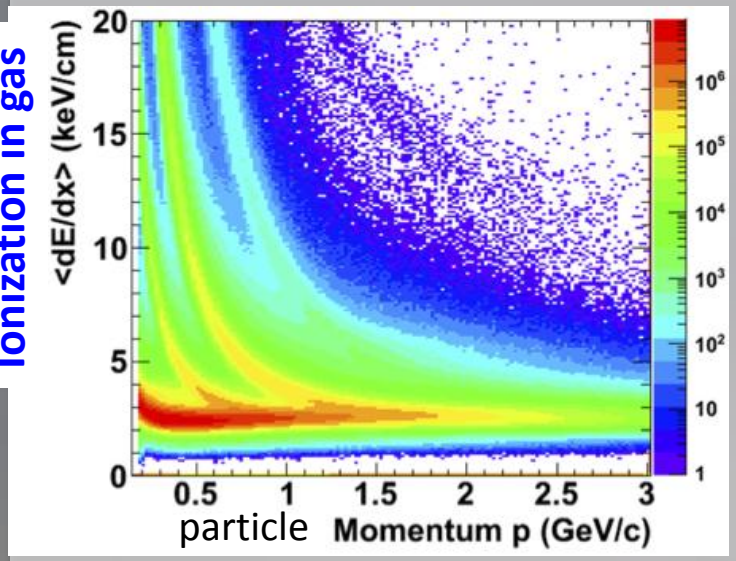
TOF and TPC

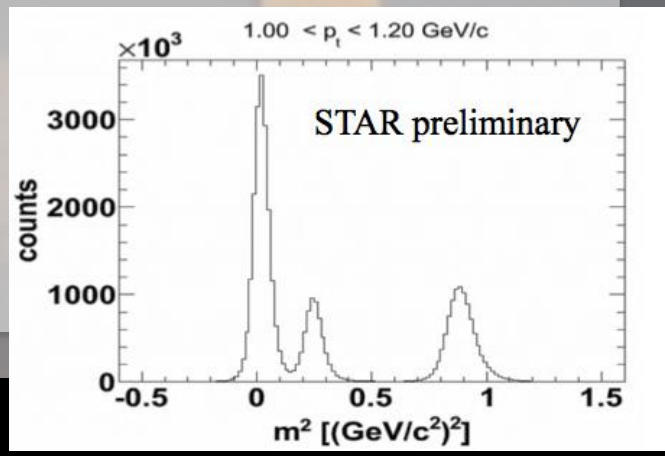
- clean separation of pi/K to pT~1.6 GeV
- full azimuthal coverage
- |η|<1

Time of Flight



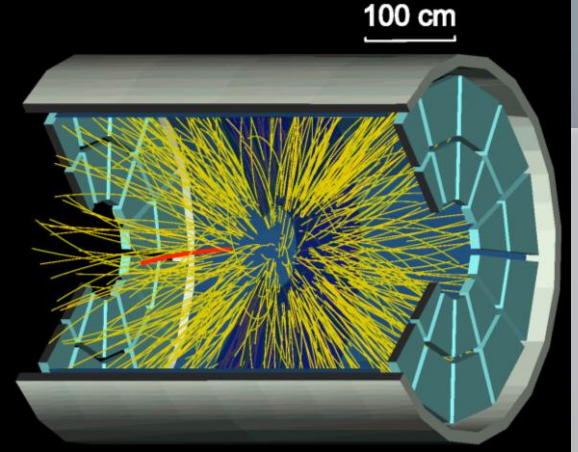
Ionization in gas

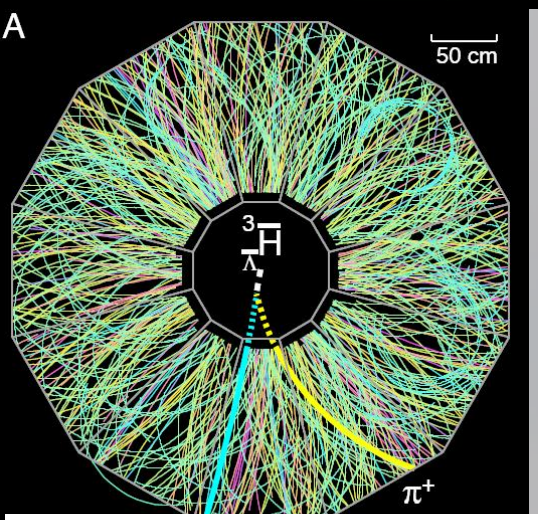


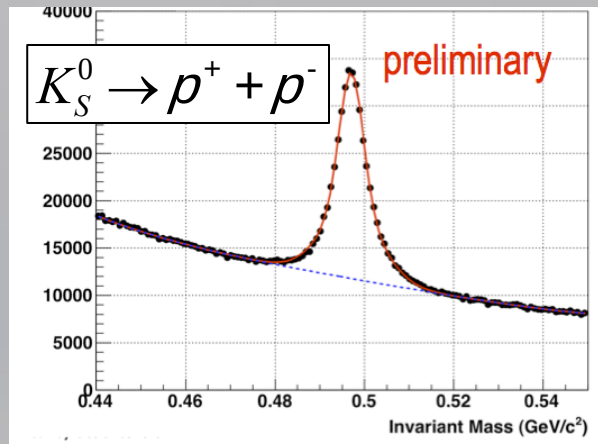


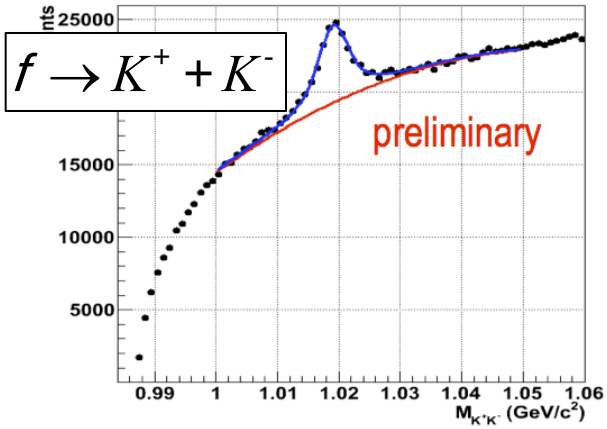
TOF and TPC

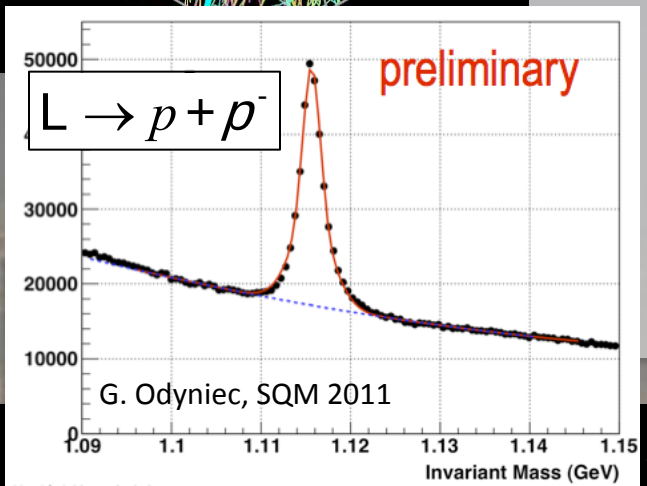
- clean separation of pi/K to pT~1.6 GeV
- full azimuthal coverage
- |η|<1
- **topological/combinatoric reconstruction of weak decays**

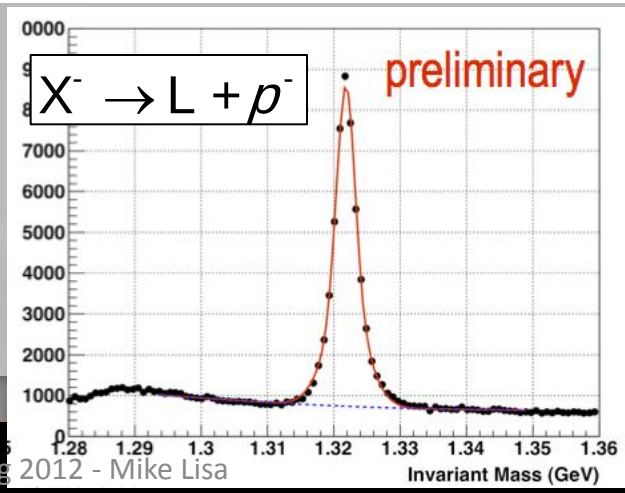


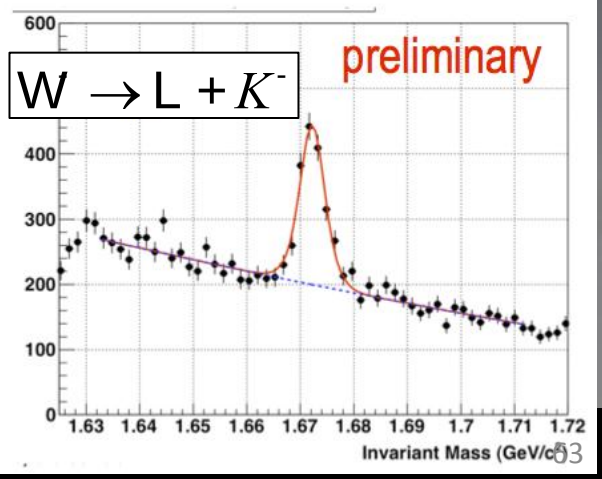










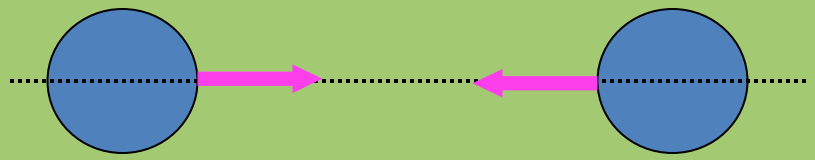


Impact parameter & Reaction plane

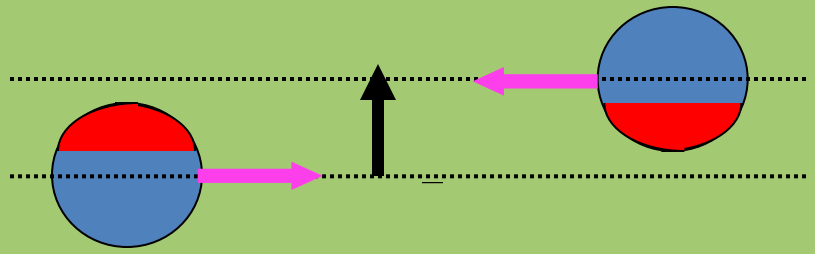
Impact parameter vector $\vec{b}$:

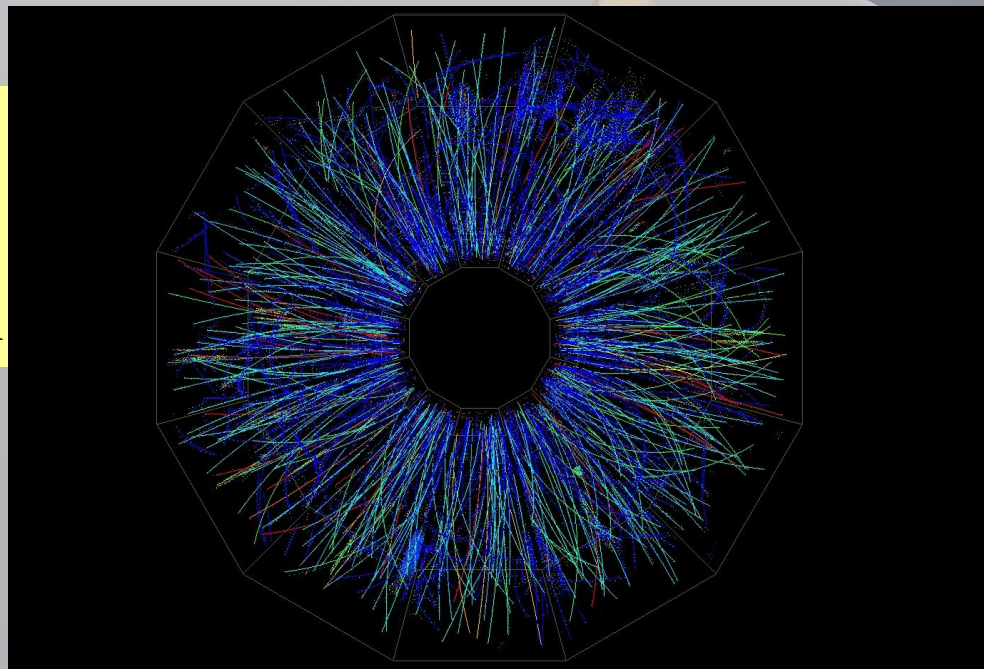
- ^ beam direction
- connects centers of colliding nuclei

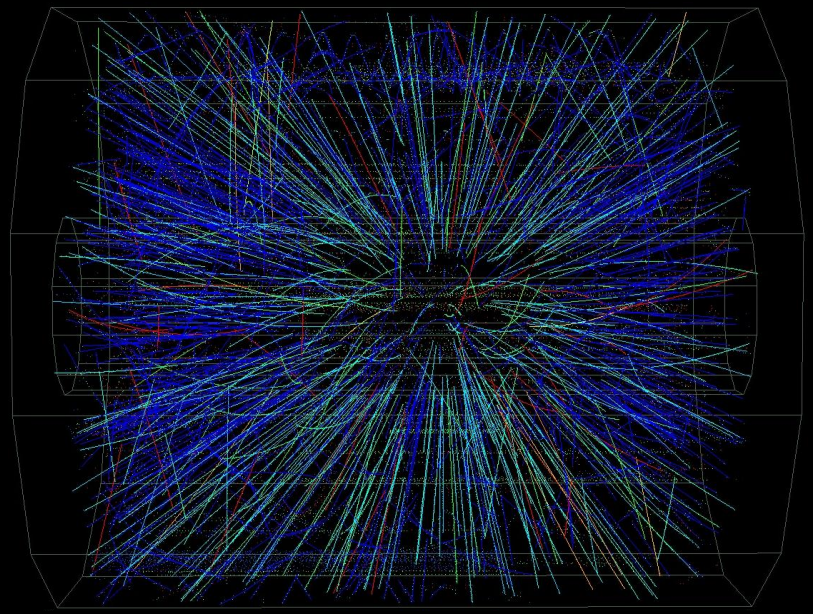
b = 0 → "central collision"
many particles produced



"peripheral collision"
fewer particles produced







Impact parameter & Reaction plane

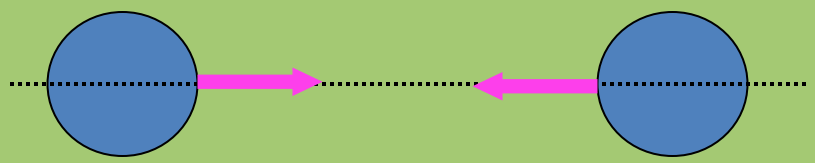
Impact parameter vector $\vec{b}$:

- ^ beam direction
- connects centers of colliding nuclei

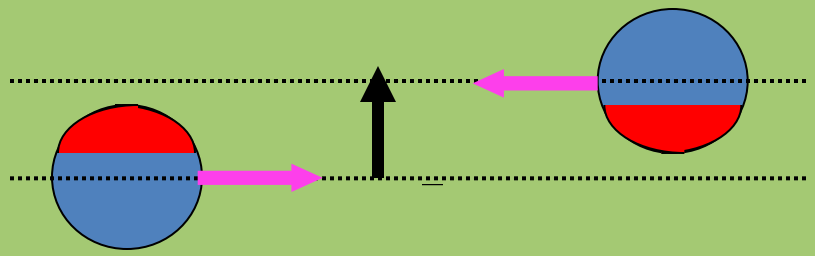
Reaction plane:

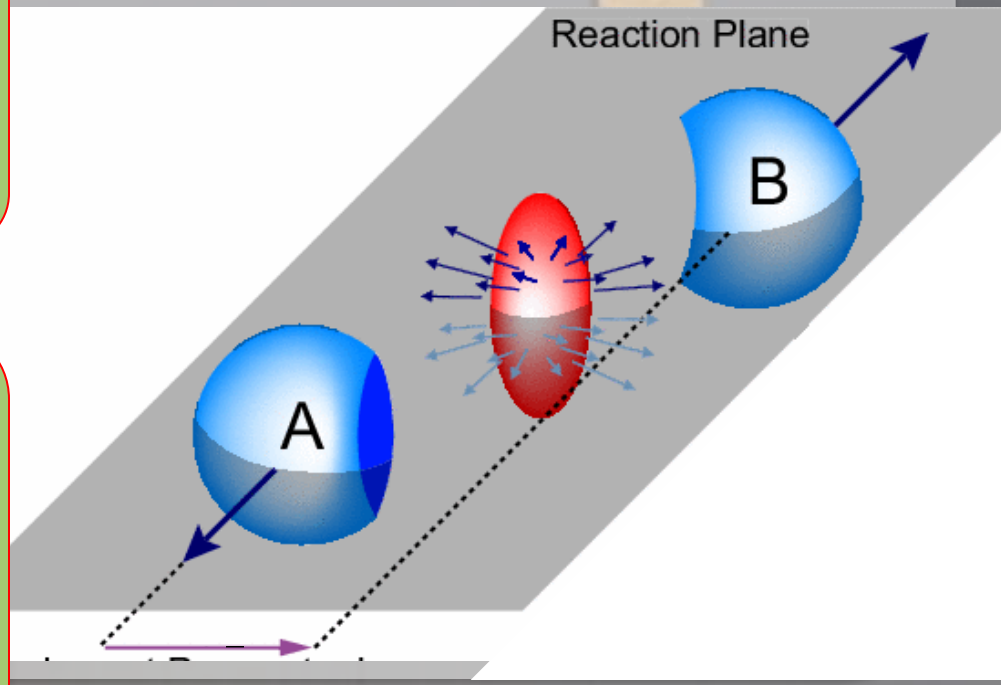
spanned by beam direction and $\vec{b}$

b = 0 → "central collision"
many particles produced



"peripheral collision"
fewer particles produced

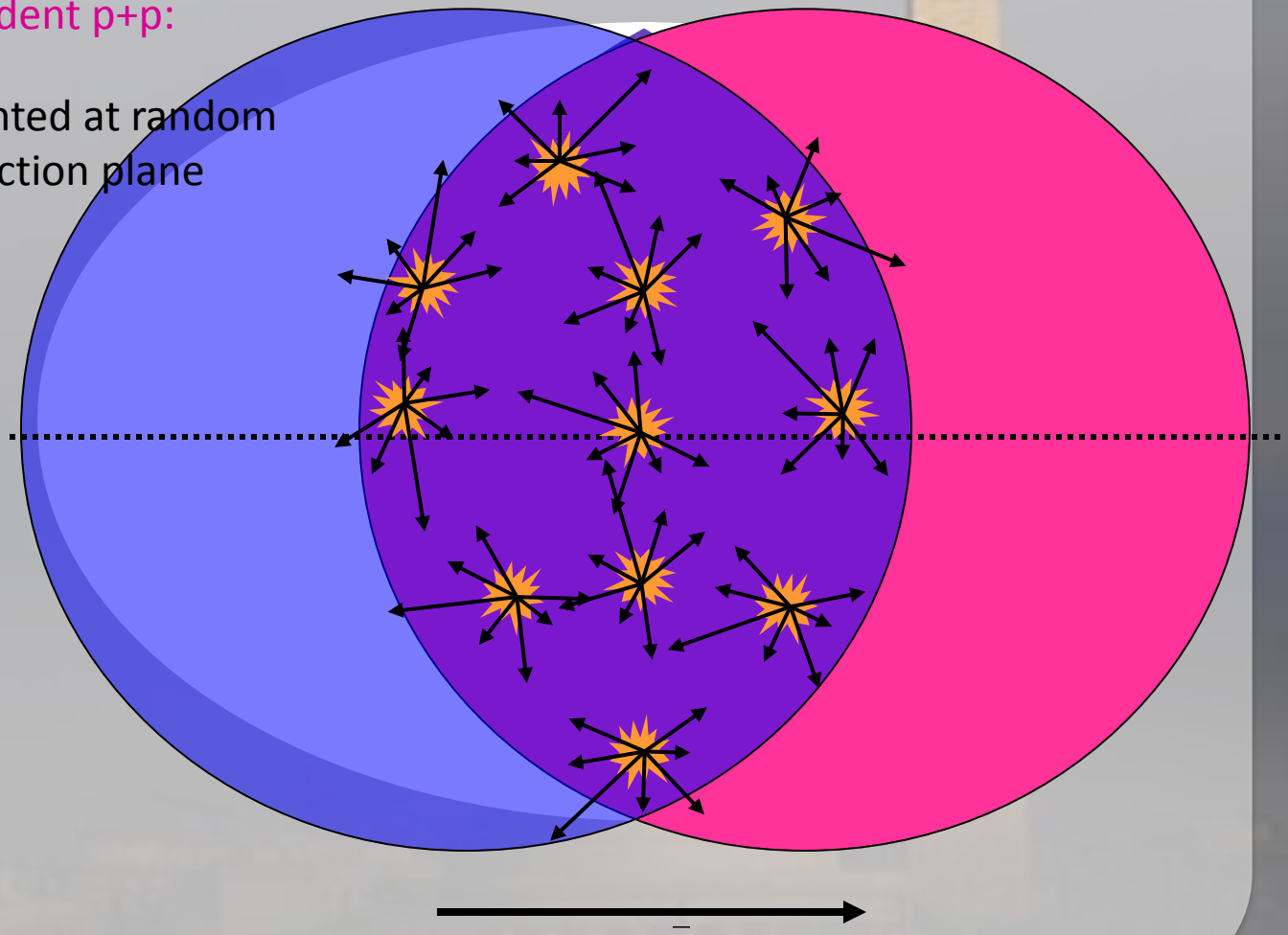




How do semi-central collisions evolve?

1) Superposition of independent p+p:

momenta pointed at random relative to reaction plane



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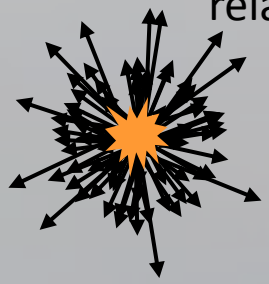
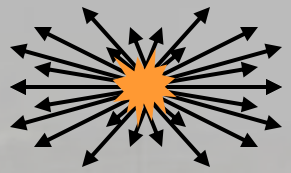
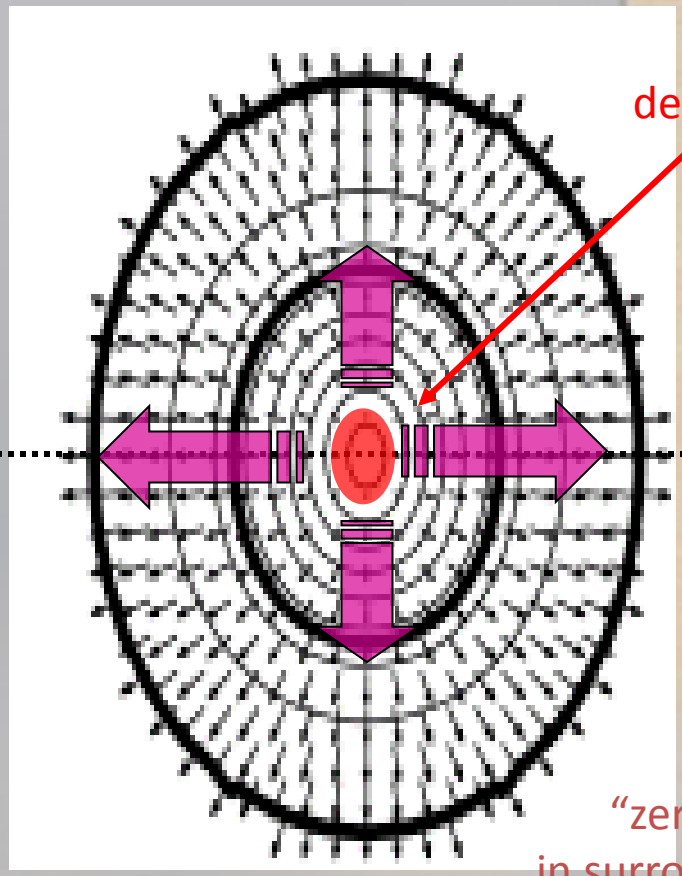


2) Evolution as a **bulk** **<u>system</u>**

Pressure gradients (larger in-plane) push bulk "out" → "flow"



more, faster particles seen in-plane



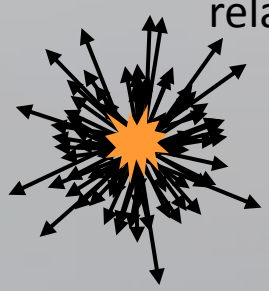
high density / pressure at center

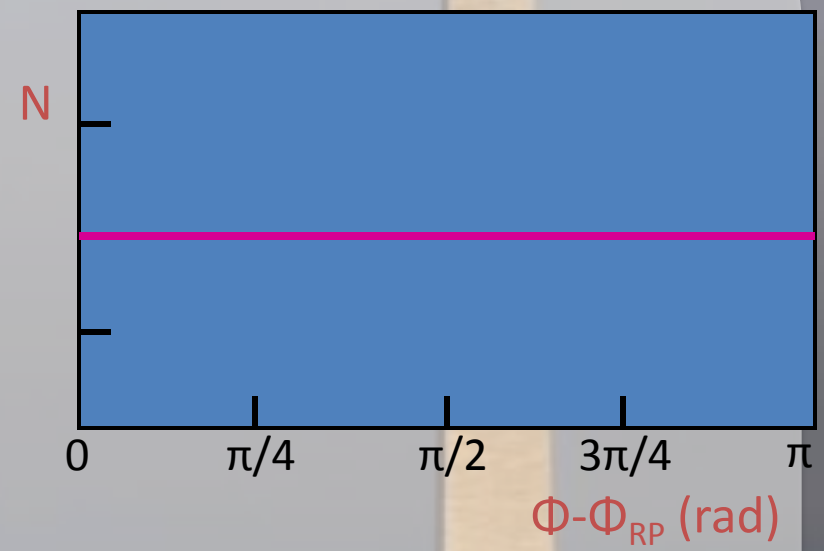
"zero" pressure in surrounding vacuum

How do semi-central collisions evolve?

1) Superposition of independent p+p:

momenta pointed at random relative to reaction plane





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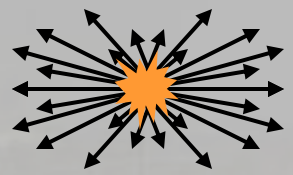

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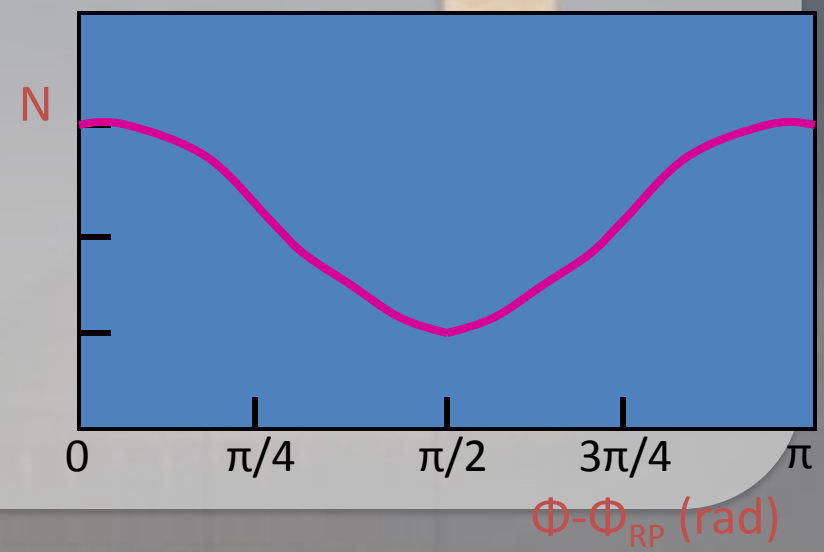
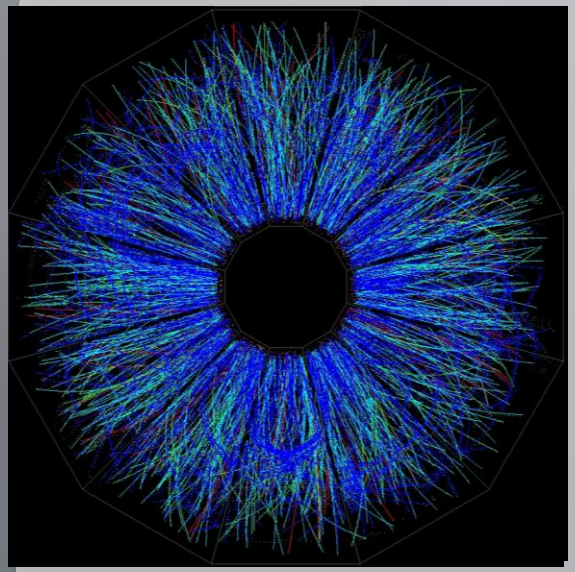
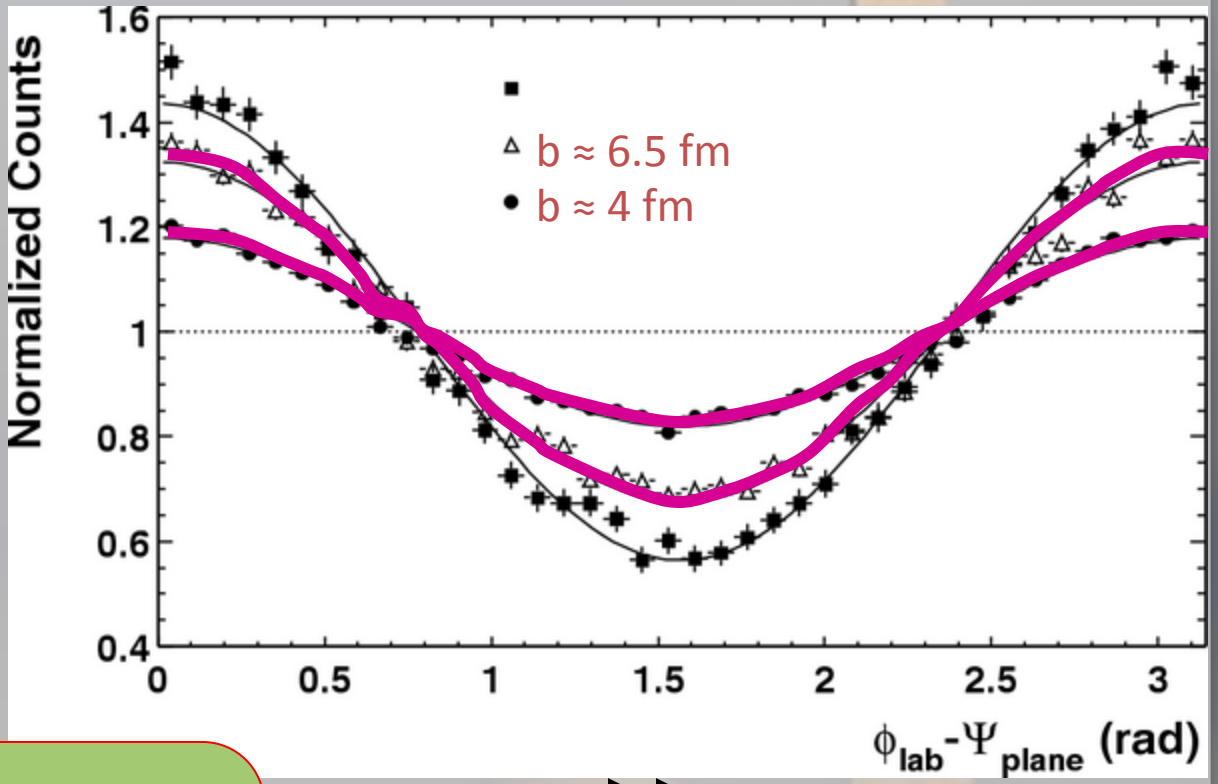


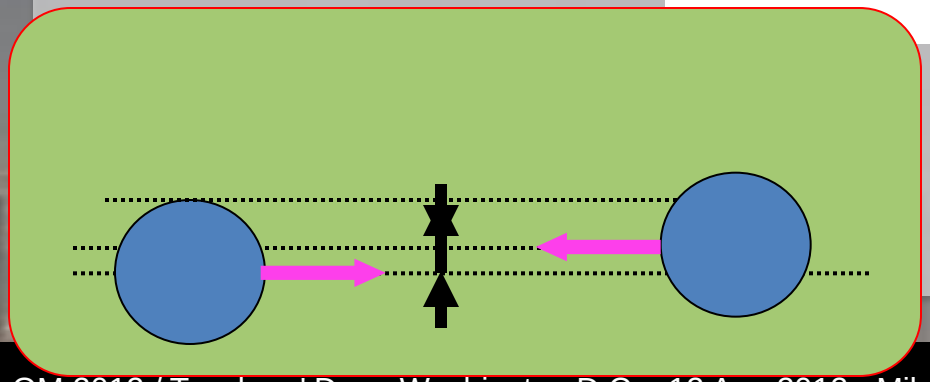
Azimuthal distributions at RHIC

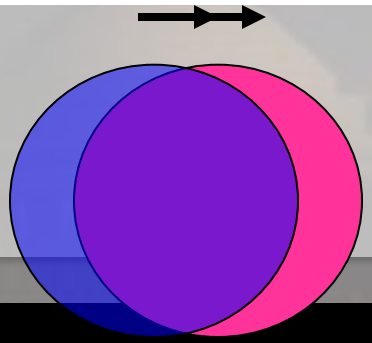


STAR, PRL**90** 032301 (2003)



mid-central collisions





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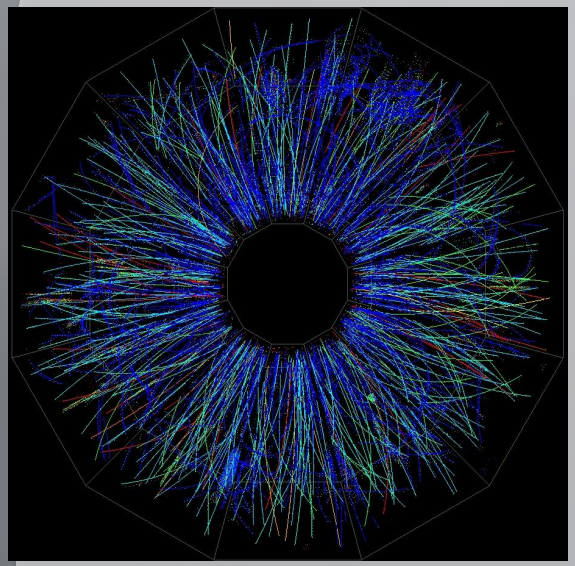

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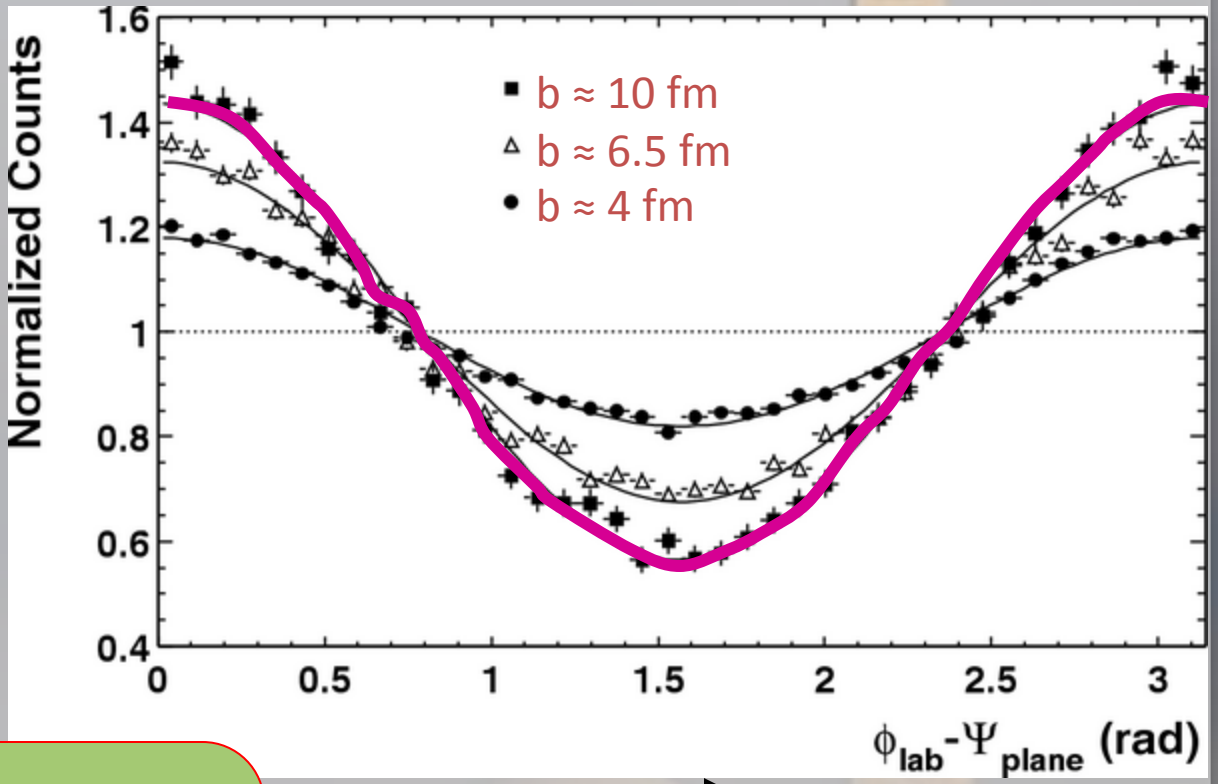
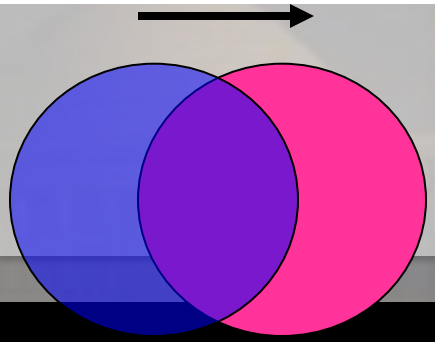
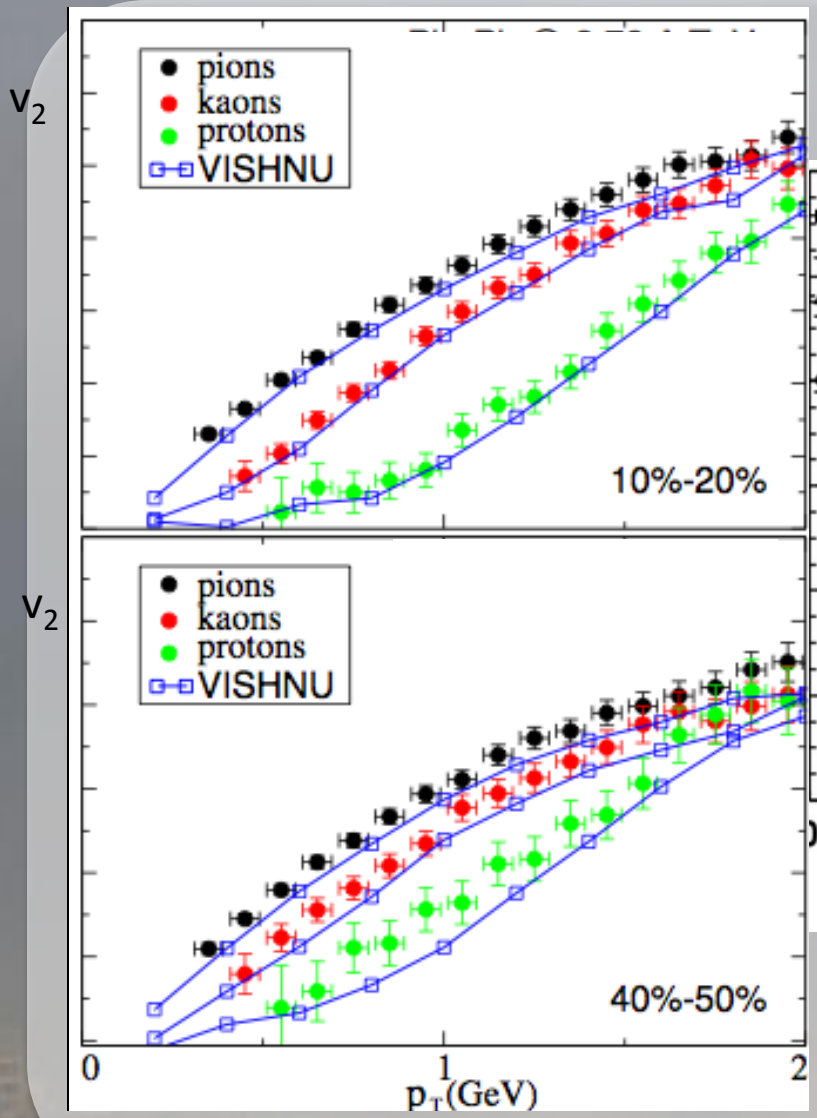


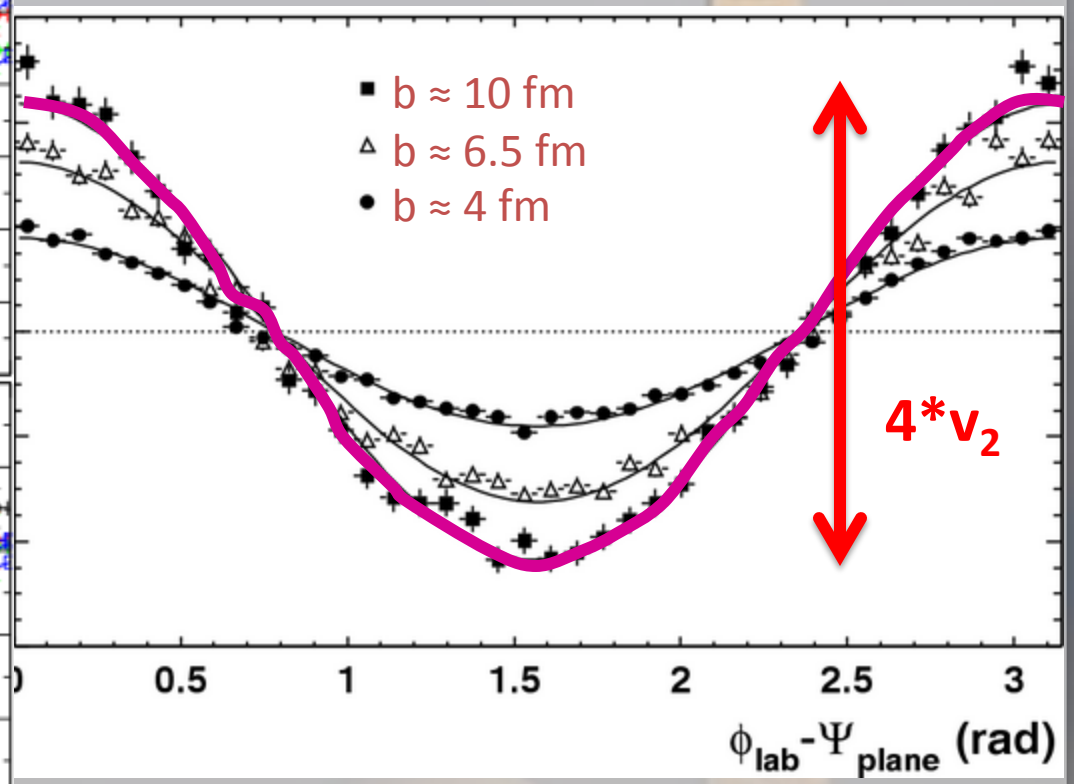
peripheral collisions



Keyword: Elliptic Flow



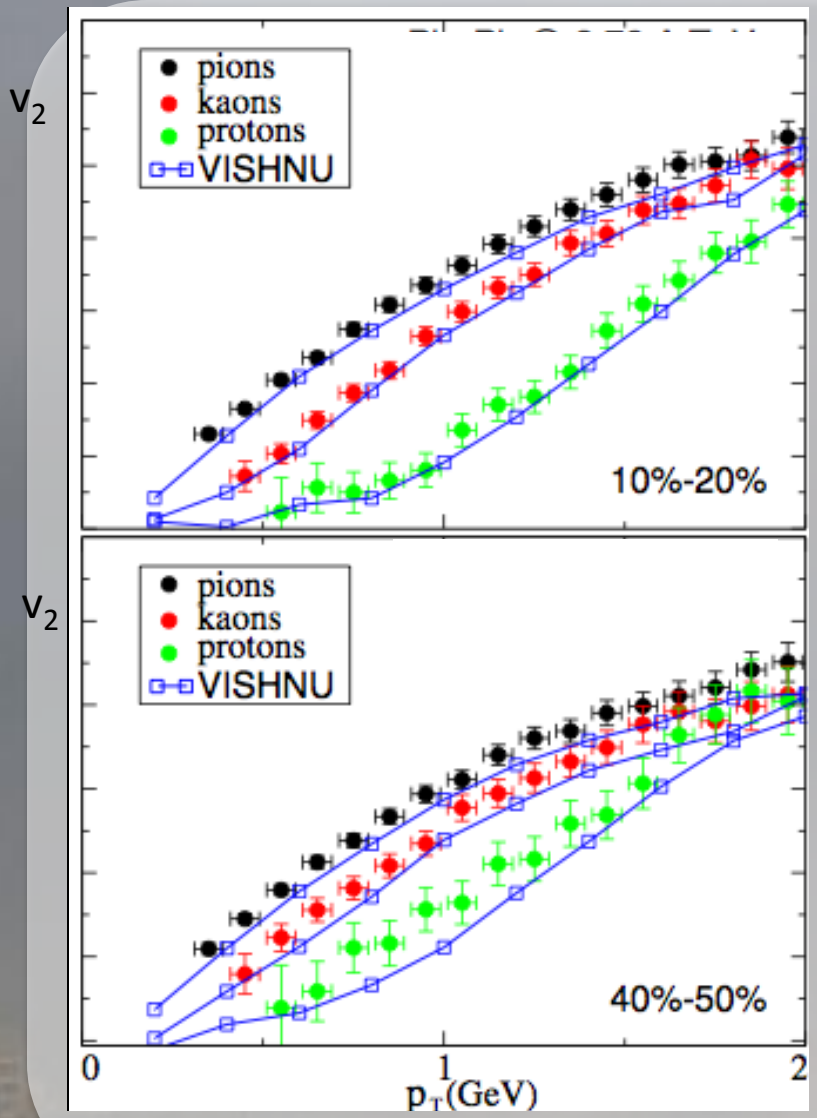
STAR, PRL**90** 032301 (2003)

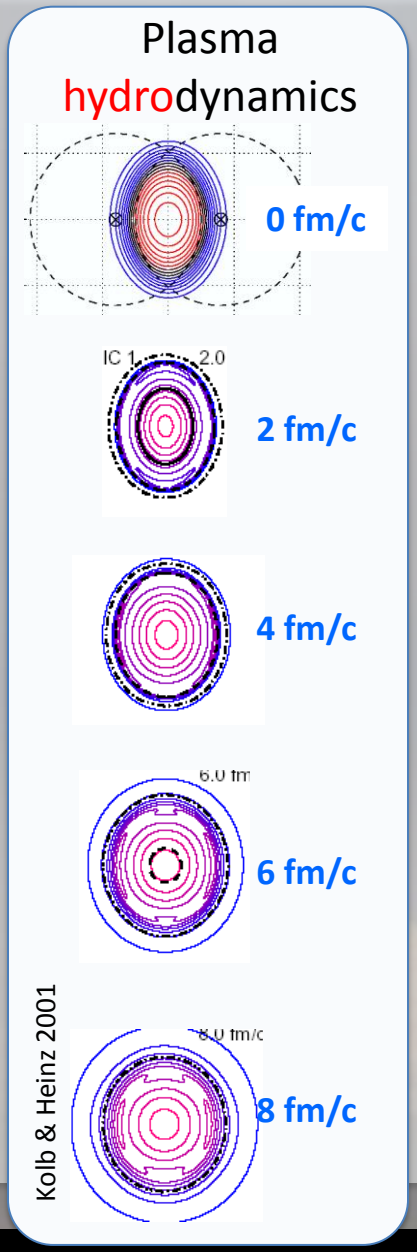


"elliptic flow"

$$N(f) \mu 1 + 2v_1 \cos(f) + 2v_2 \cos(2f) + 2v_3 \cos(3f) + \ldots$$

Keyword: Elliptic Flow





strongly self-interacting fluid (!!)

Hydrodynamics: conservation laws for long wavelength modes

$$\partial_\mu T^{\mu\nu} = 0$$

Generally:

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \pi^{\mu\nu}.$$

First order Navier Stokes theory:

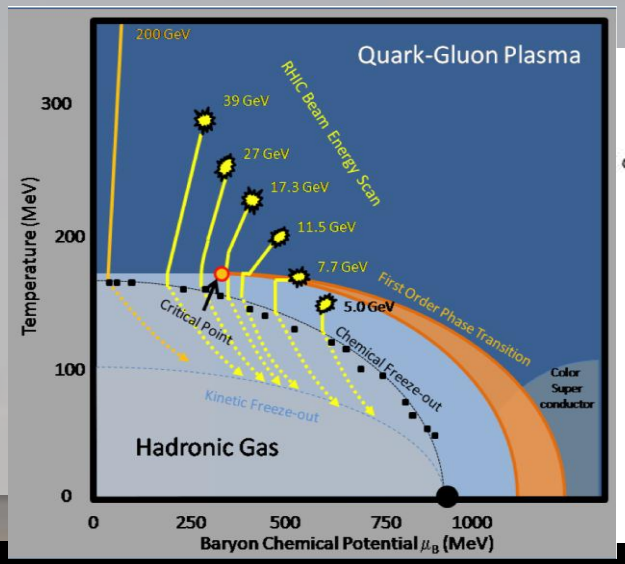
$$\pi^{\mu\nu} = \pi^{\mu\nu}_{(1)} = \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \tfrac{2}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha).$$

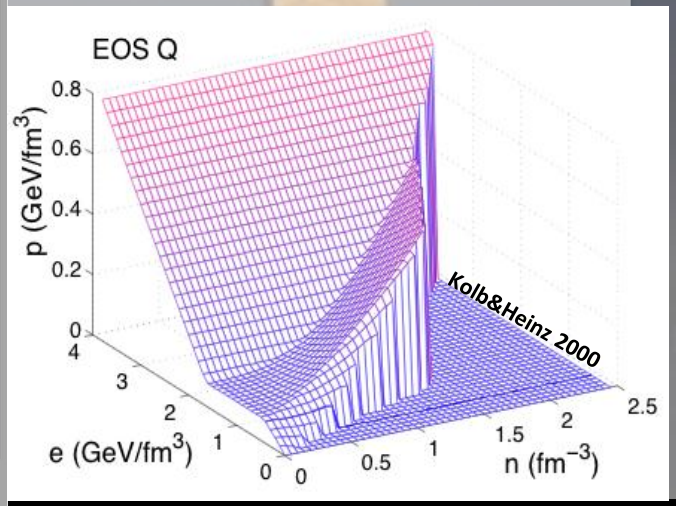
η: Shear viscosity

Large η = transport of momentum across fluid layers

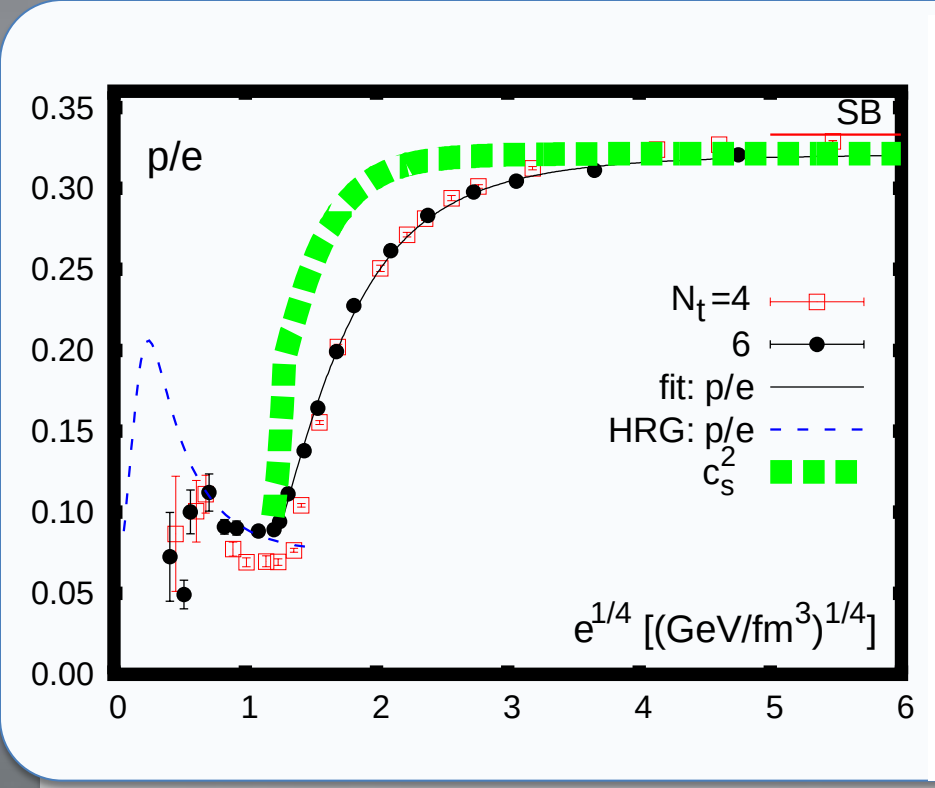
+ initial conditions (nontrivial!)

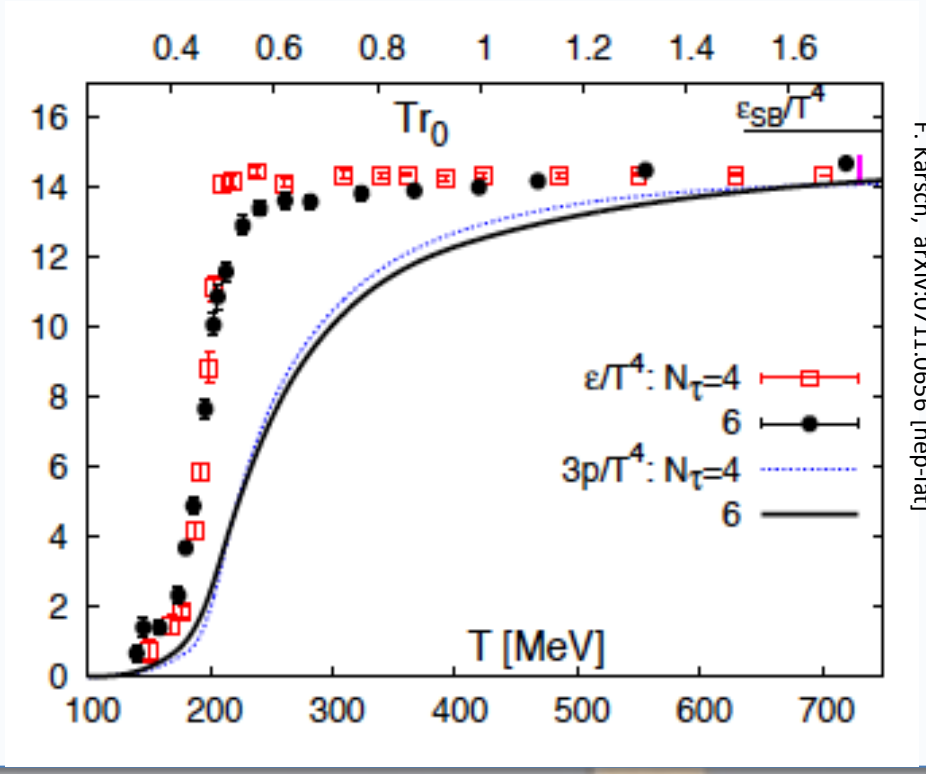
+ Equation of State (fundamental)





owalski, T. Lappi and R. Venugopalan, Phys.Rev.Lett. 100:022303





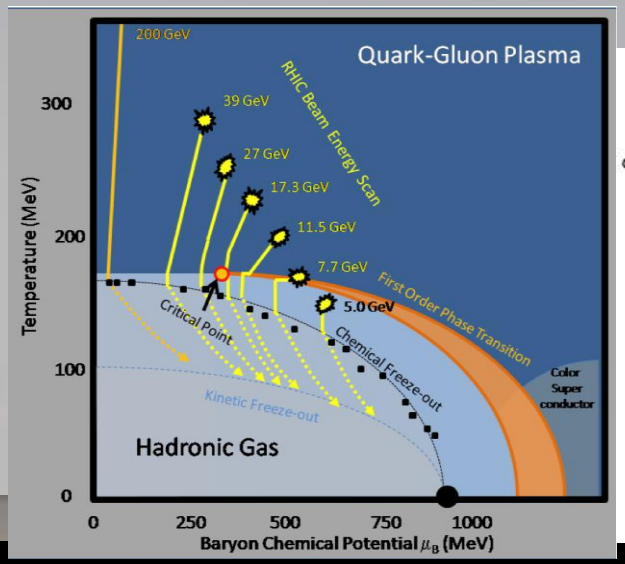
F. Karsch, arXiv:0711.0656 [hep-lat]

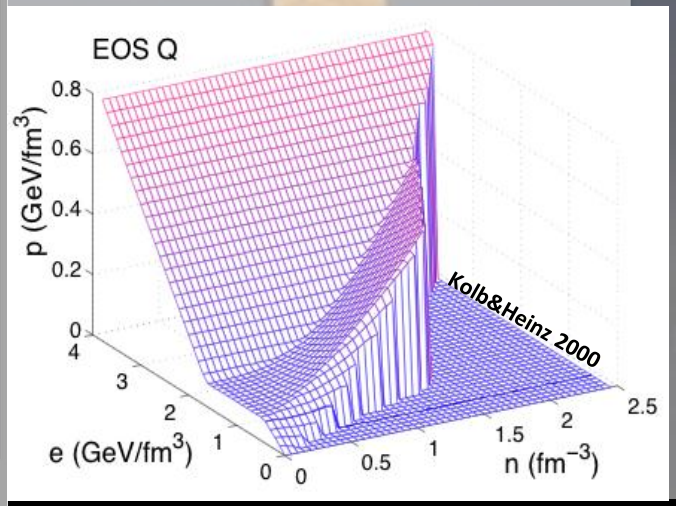
Data support
Lattice QCD EoS near zero net baryon density

- Cross-over transition.

Also: almost zero viscosity

- surprise!





Summary

- Relativistic Heavy Ion physics “resembles” High-Energy Particle physics...
  - ~1000-person collaborations, distributed worldwide
  - accelerators, computing & detectors at (& pushing) the limits of possibility
  - fully quantum, fully relativistic; fundamental forces, particles

- ...but is distinctly different
  - focus is on QCD confinement and phase structure
  - requires heaviest systems – special pressures on detectors/analysis

- peering through the QCD mist to short-lived (10E-23 sec) color-deconfined stage requires every effort of a ~10^4-person world-wide community
  - check out some of our most exciting findings this week