COLLISIONS OF HEAVY IONS WITH ATLAS AT THE LHC

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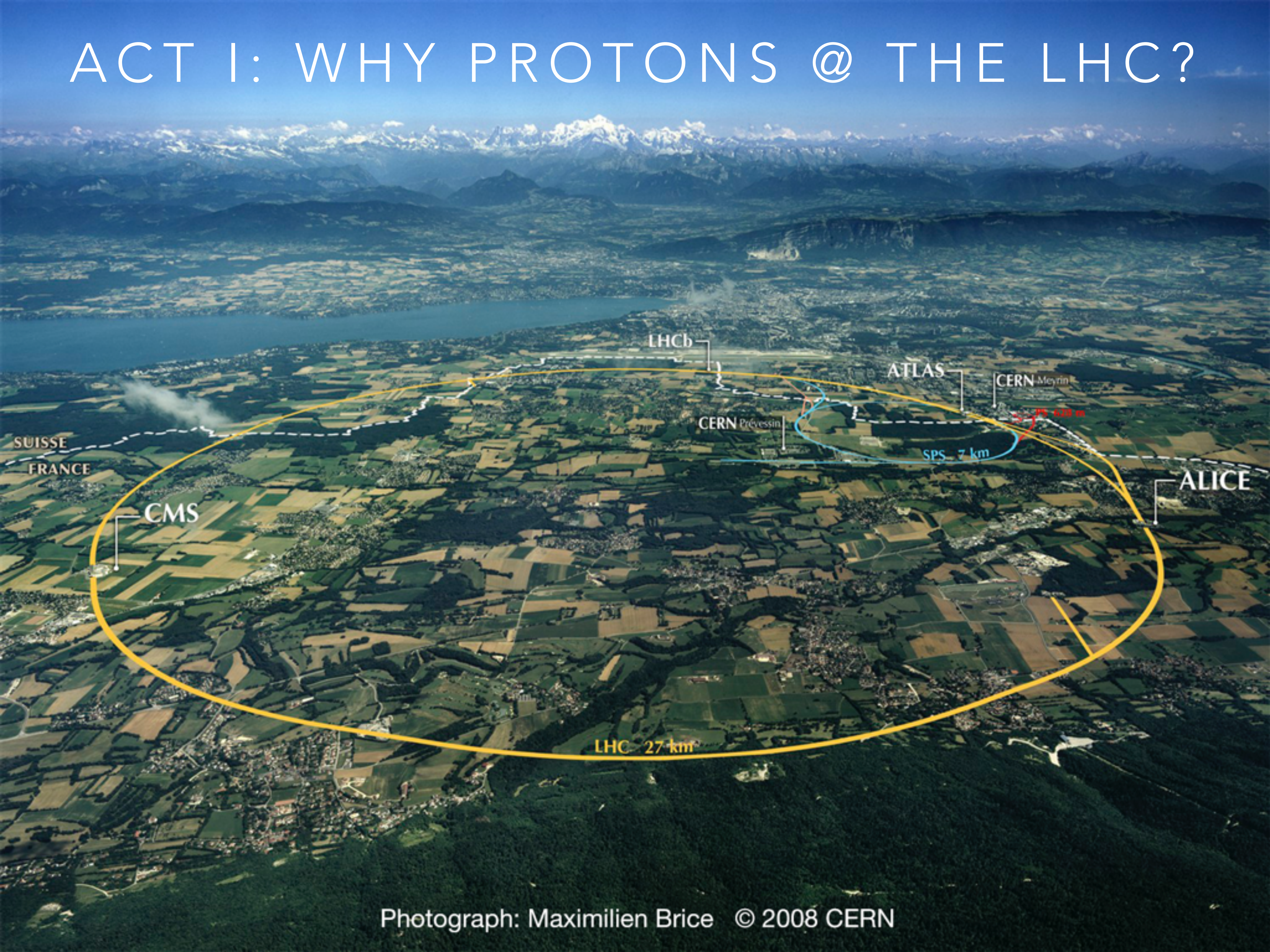
DESY COLLOQUIUM
JULY 12/13, 2016

ACT I: WHY PROTONS @ THE LHC?



Photograph: Maximilien Brice © 2008 CERN

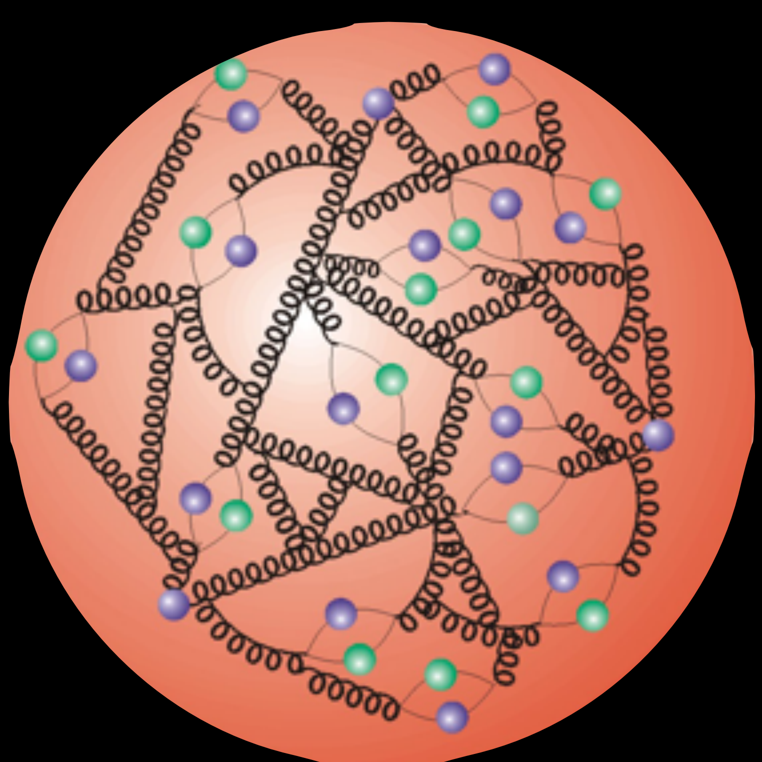
ACT I: WHY PROTONS @ THE LHC?

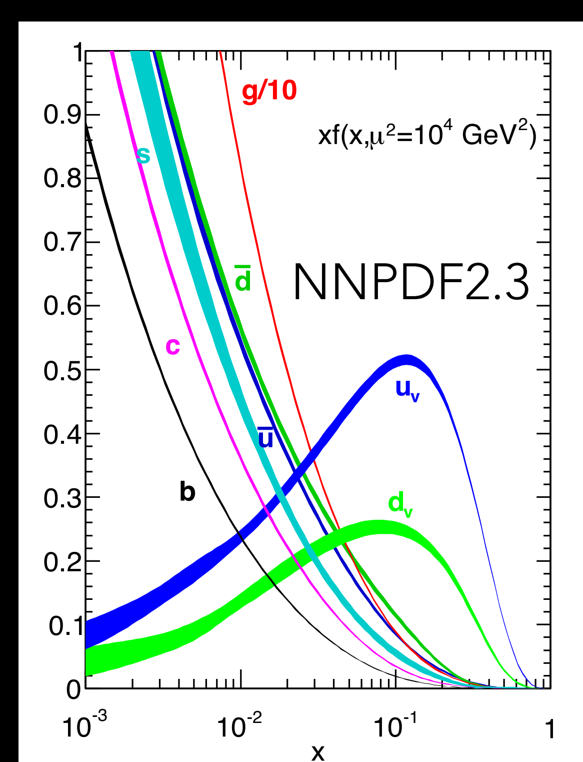
- **To discover new particles**
  - Large masses, so only rarely produced

- **At the LHC, proton is used as a source of “partons”**
  - generic term for “quark and gluon” constituents
  - Structure mapped out by HERA in exquisite detail

u	c	t
d	s	b

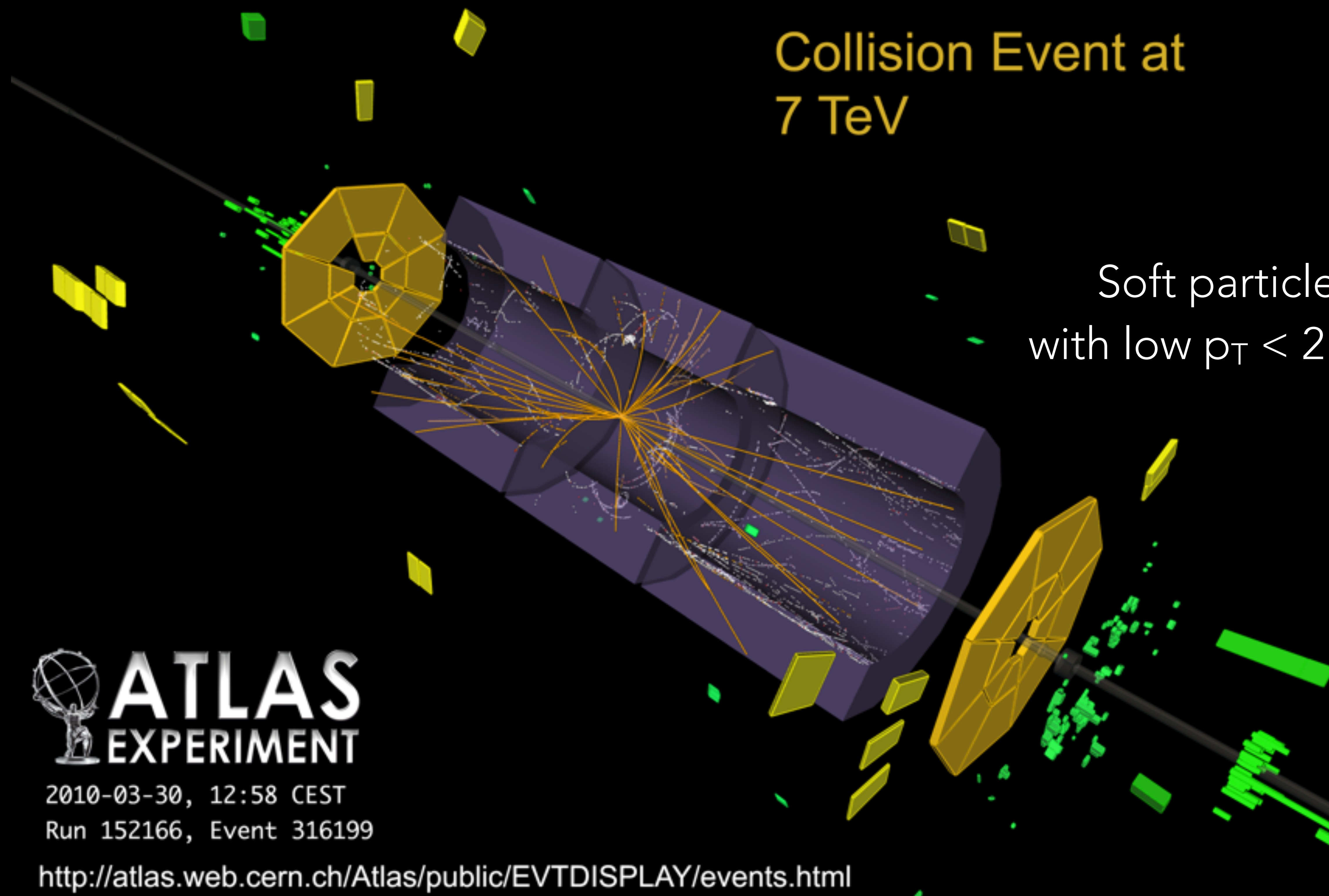
g





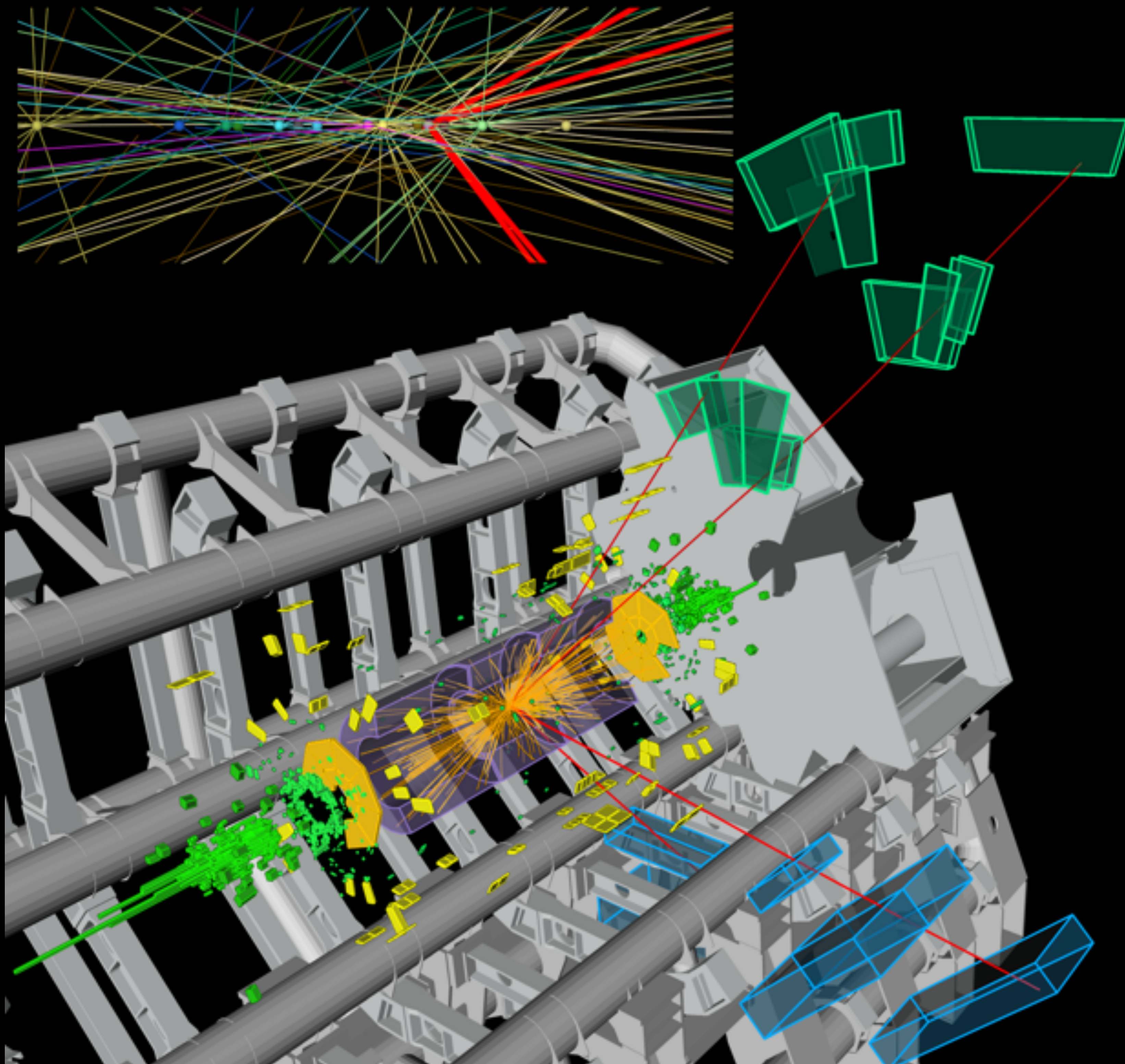
“x” is fraction of proton momentum, as probed at scale $1/\mu$: most partons take a very small fraction!

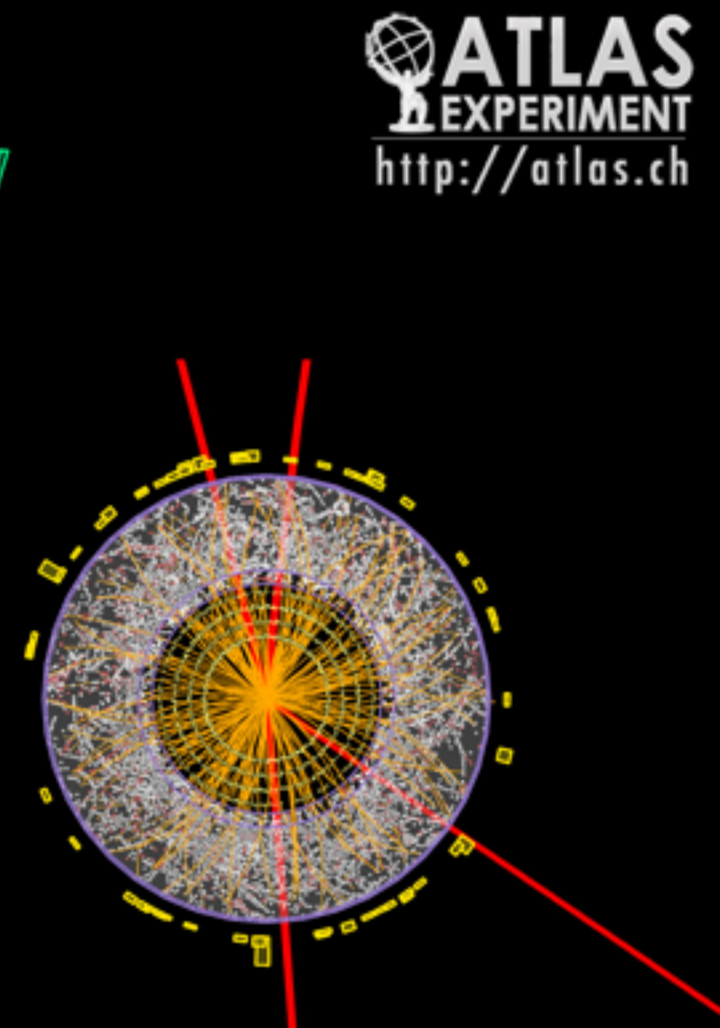
PROTON-PROTON COLLISIONS AT THE LHC: A TYPICAL EVENT



Soft particles with low $p_T < 2$ GeV

PROTON-PROTON COLLISIONS AT THE LHC: A RARE EVENT



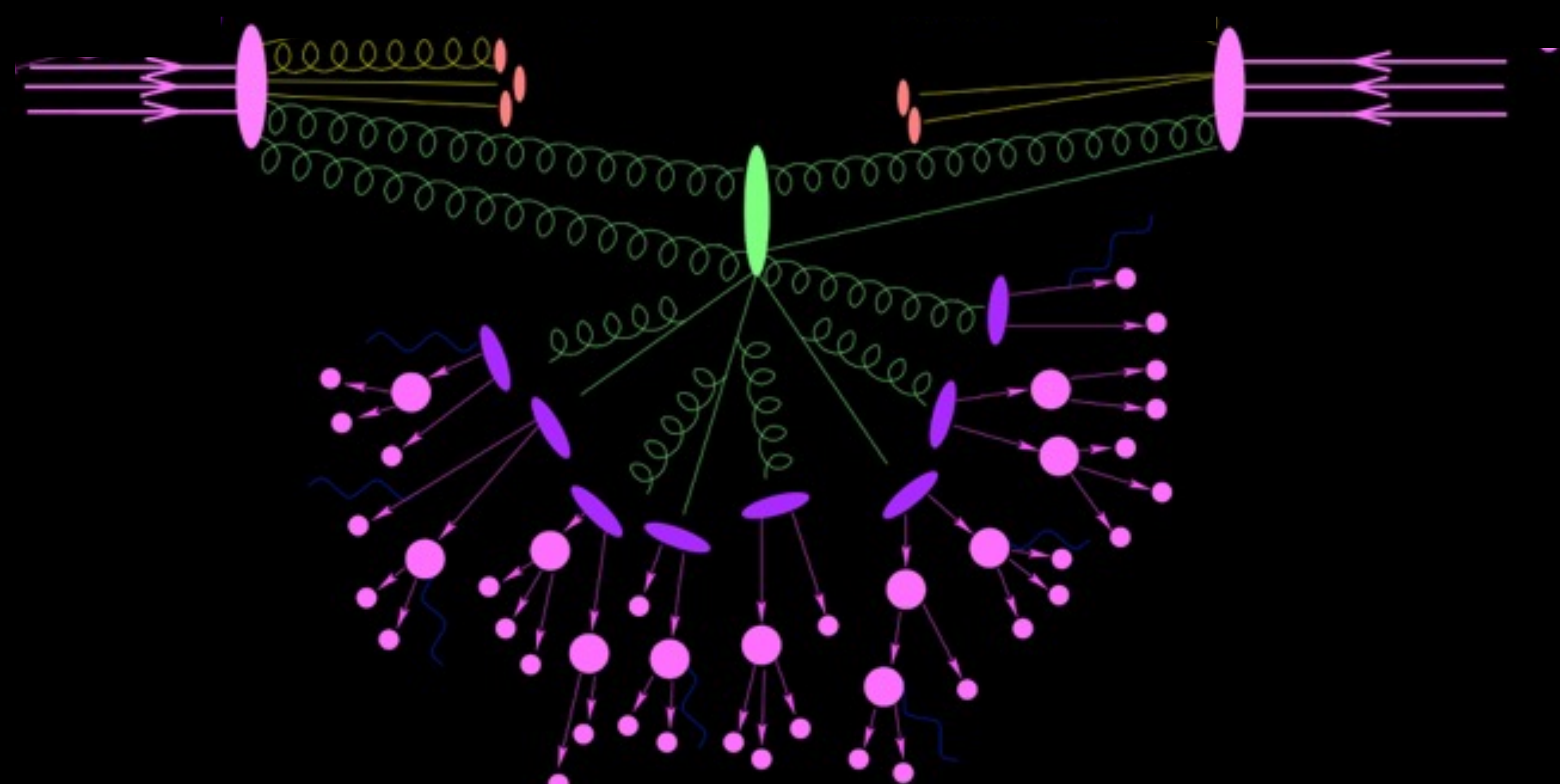


e.g. a Higgs boson candidate

Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

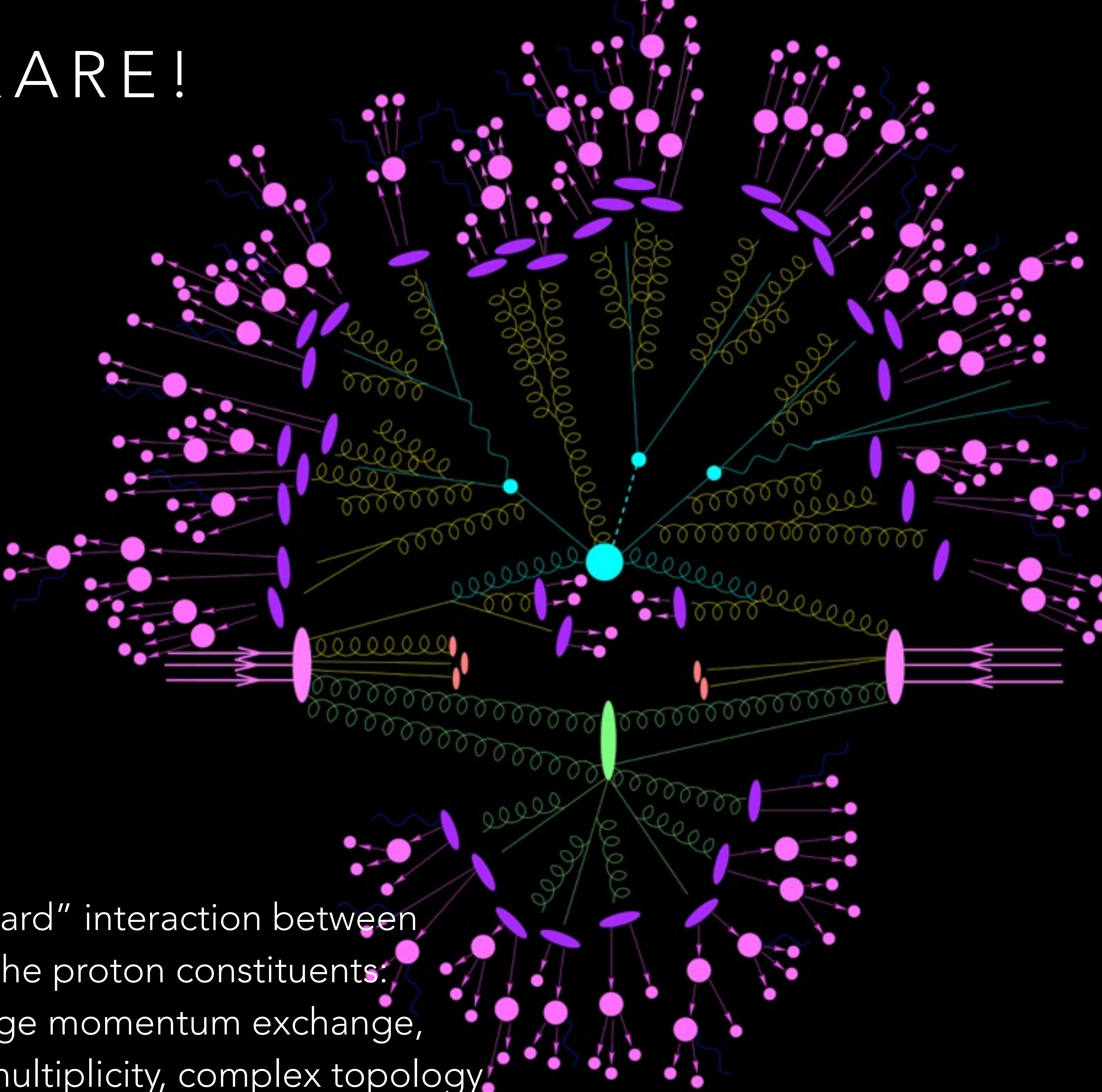
A TYPICAL EVENT

diagrammatic view of a
"soft" interaction between
the proton constituents



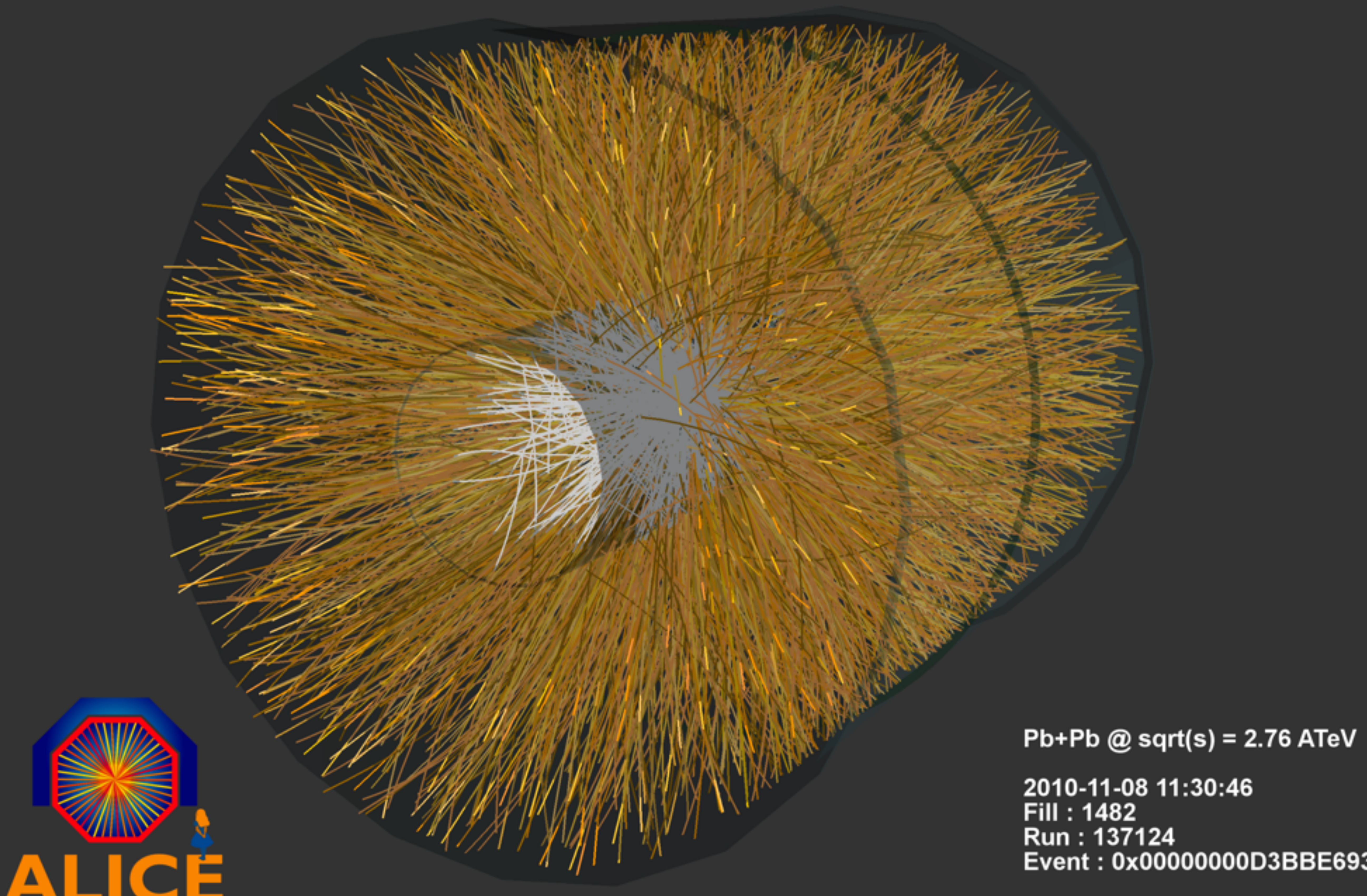
SHERPA

RARE!



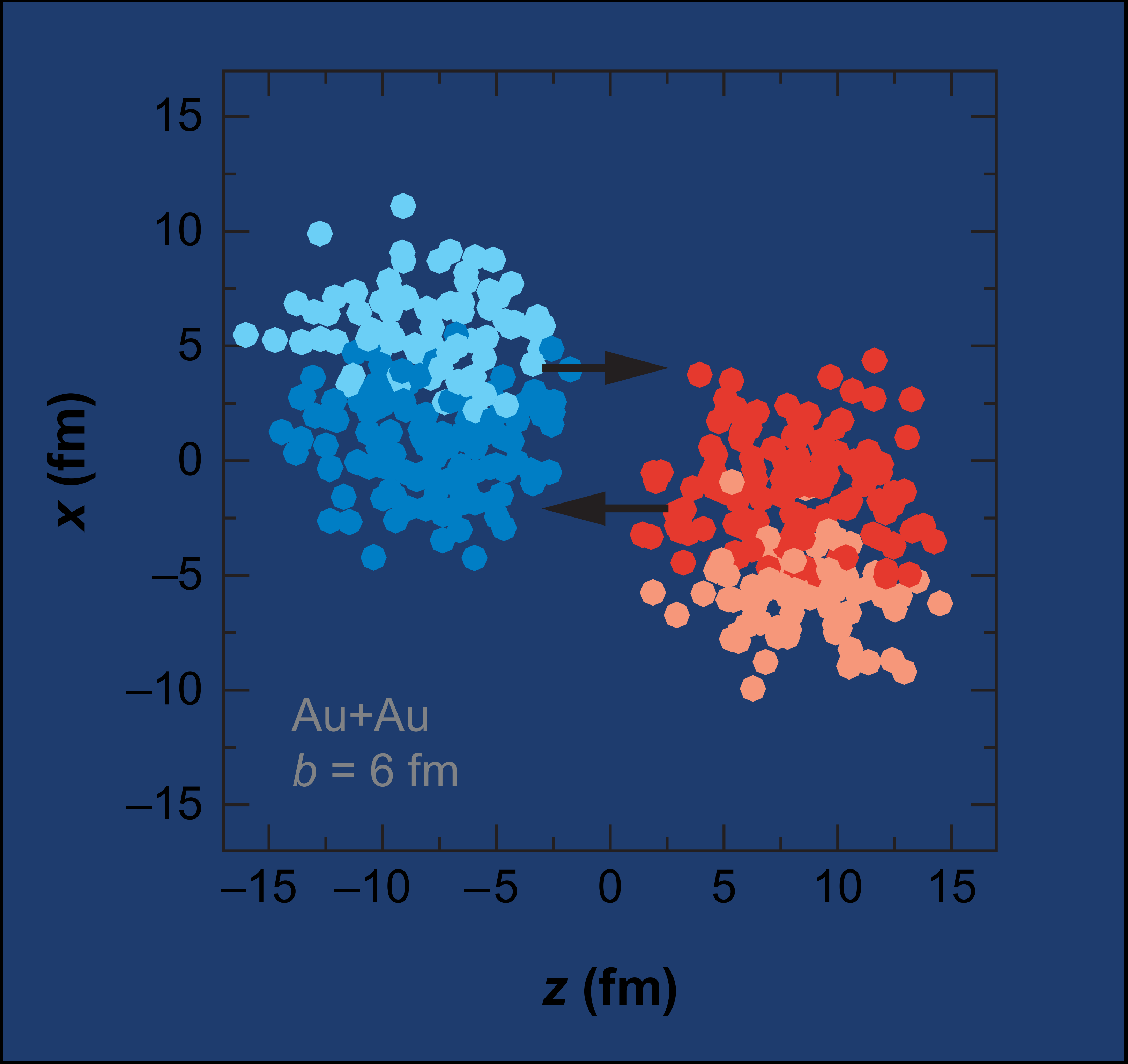
"hard" interaction between the proton constituents: large momentum exchange, high multiplicity, complex topology

SHERPA


Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
ALICE

ACT II: BUILDING A+A FROM P+P

To first order, A+A is just O(A) p+p collisions at the same time:
but huge variations event-to-event



BUILDING A+A FROM P+P

"Glauber model"

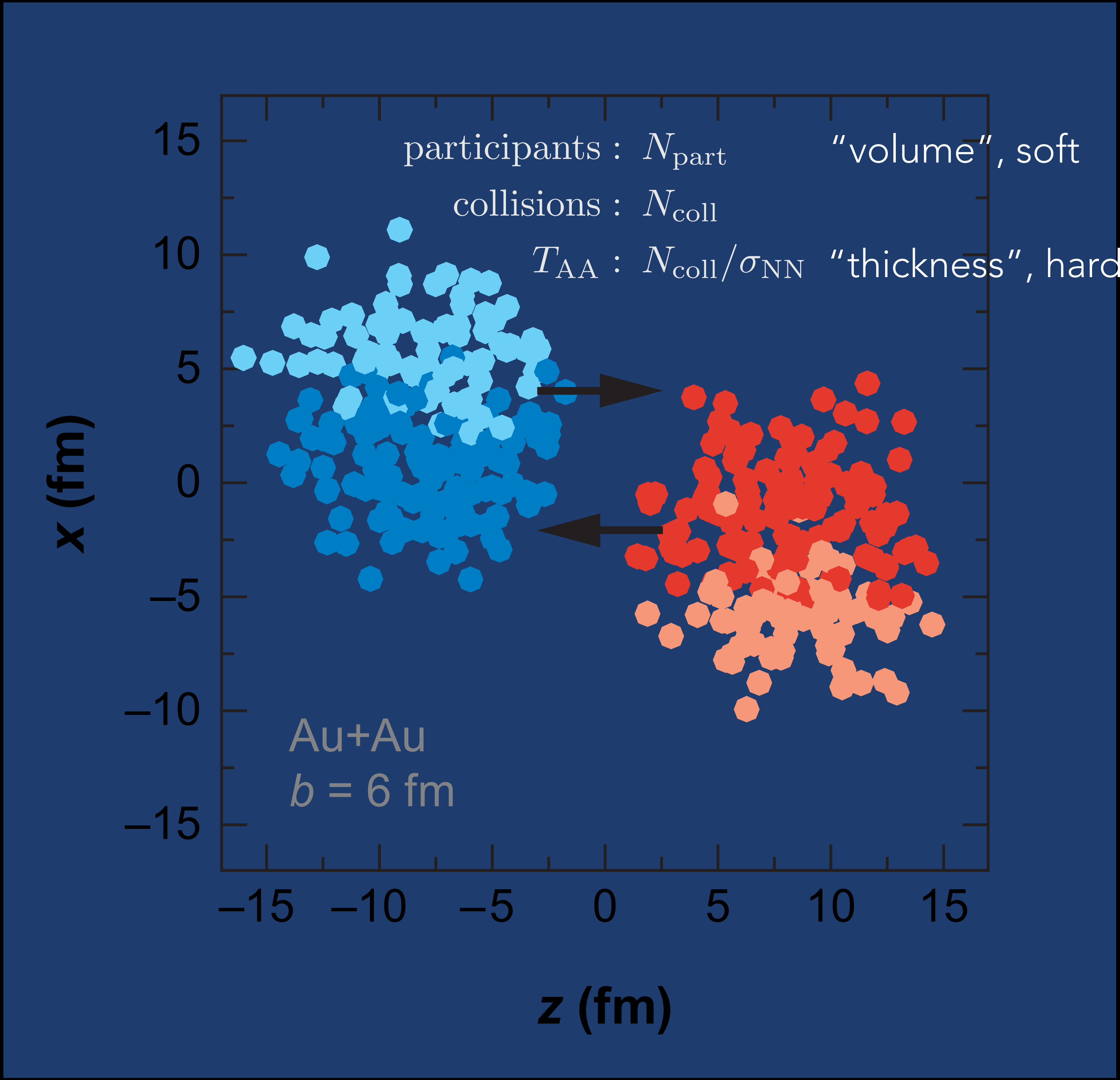
1. Generate two colliding nuclei with 3D nucleon positions chosen from **measured** density distributions (e scattering)

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

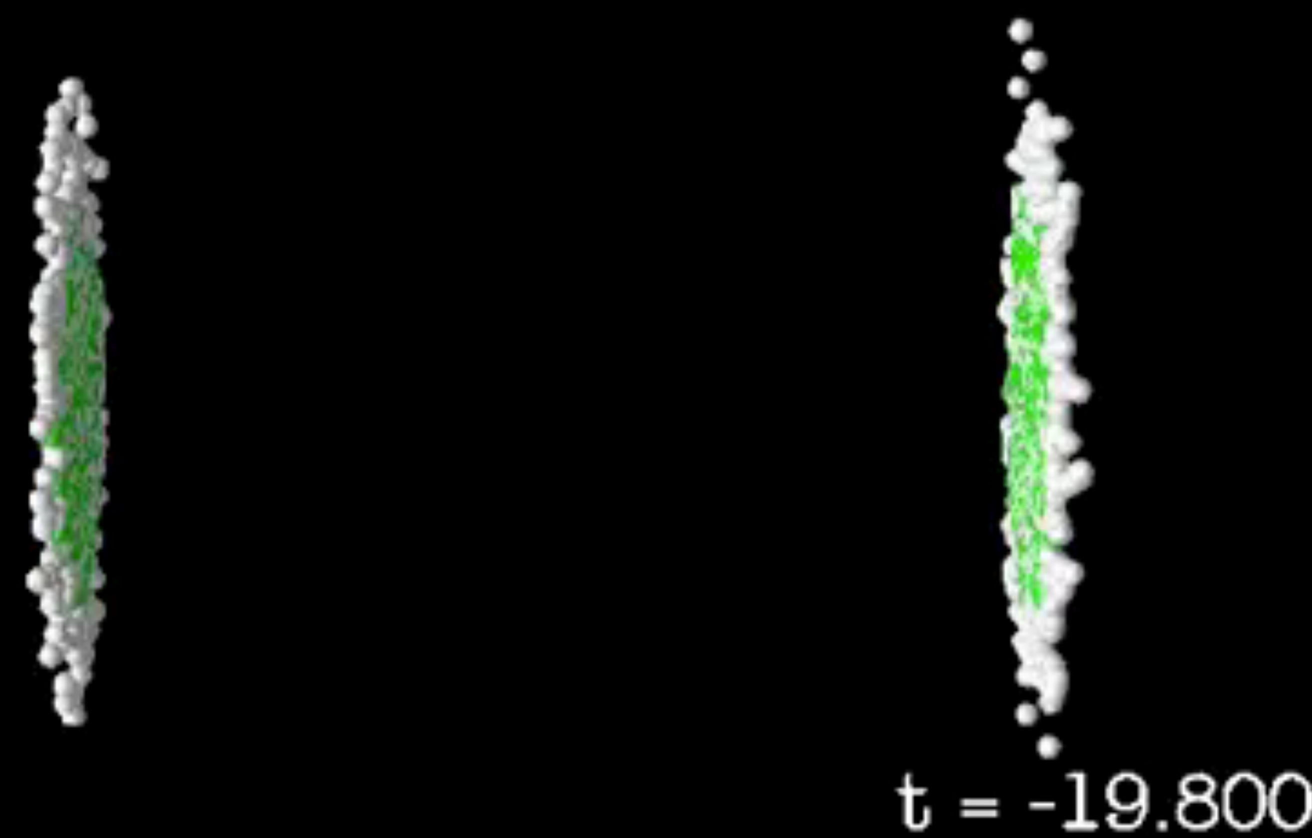
2. Nucleons interact when transverse distance satisfies

$$d < \sqrt{\sigma_{NN}/\pi}$$

typically using the inelastic pp cross section for NN



A+A IN ACTION



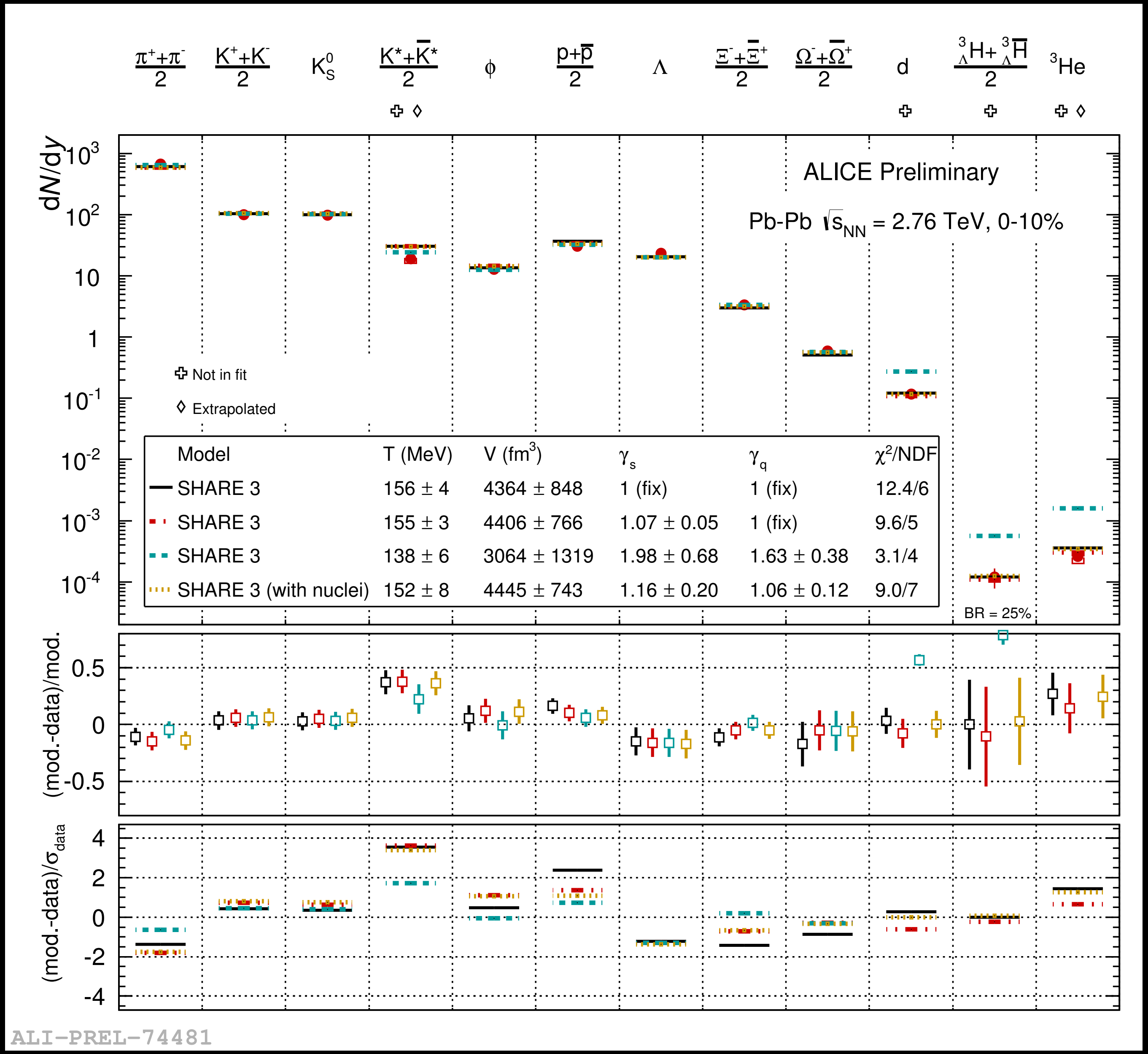
simulation of two gold-nuclei colliding at RHIC:
many collisions in **initial state** produce many partices,
with many **reinteractions** among them (dynamical evolution),
and then freeze out to **final-state hadrons**

THERMALIZED PARTICLE YIELDS

100's of particle states
listed in the Particle Data Book

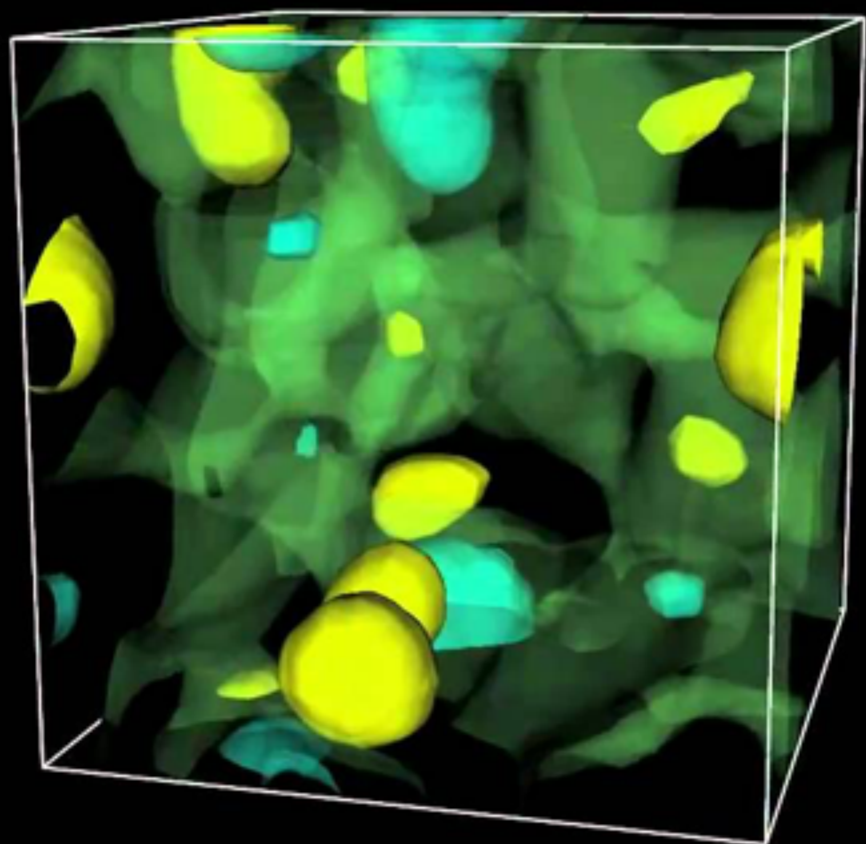
"hadron gas":
hadrons in thermal equilibrium
w/ temperature **T** and
chemical potential $\boldsymbol{\mu_B}$

Describes yields in many systems:
proton-proton, electron-positron,
heavy ion collisions…
all with a similar T ~ 160 MeV
~ 2 trillion K (100x core of sun!)

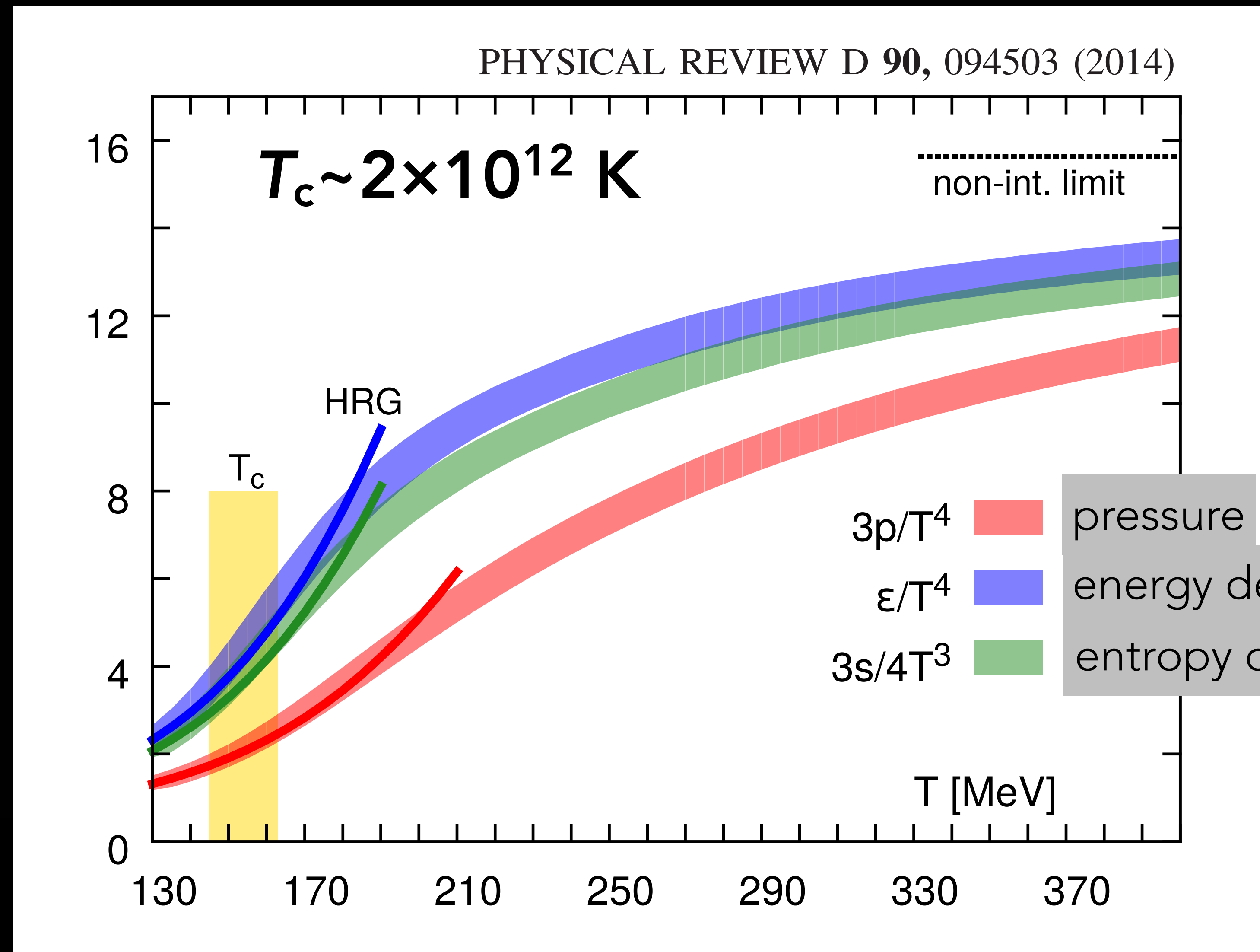


Bears out Hagedorn's pre-QCD "bootstrap" picture
of the 1960's: hadrons can only be heated up to $T \sim T_H$.
Hotter temperatures simply produce higher mass states!

THE QUARK-GLUON PLASMA



quark & gluon
fields on a spacetime lattice



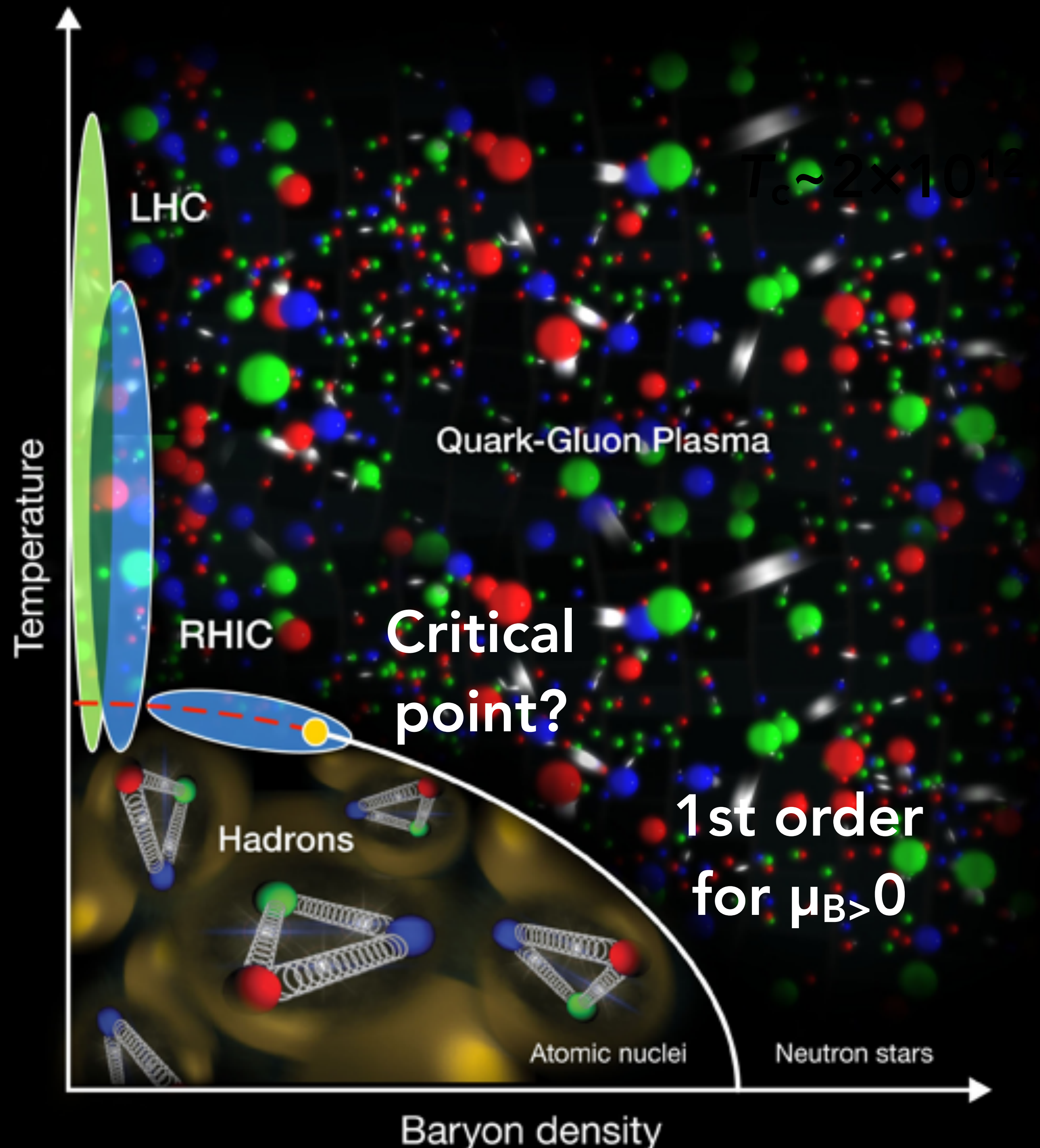
Equation of state from HotQCD lattice QCD calculations (Basazov et al) for μ_B=0

Similar features to hadron gas at low T, but breaks from it above $\boldsymbol{T_c}$ **= 154(9) MeV (!)**
with a smooth crossover transition

Deviations from the Stefan-Boltzmann limit attributed to **strong-coupling** (AdS/CFT)

THE QGP PHASE DIAGRAM

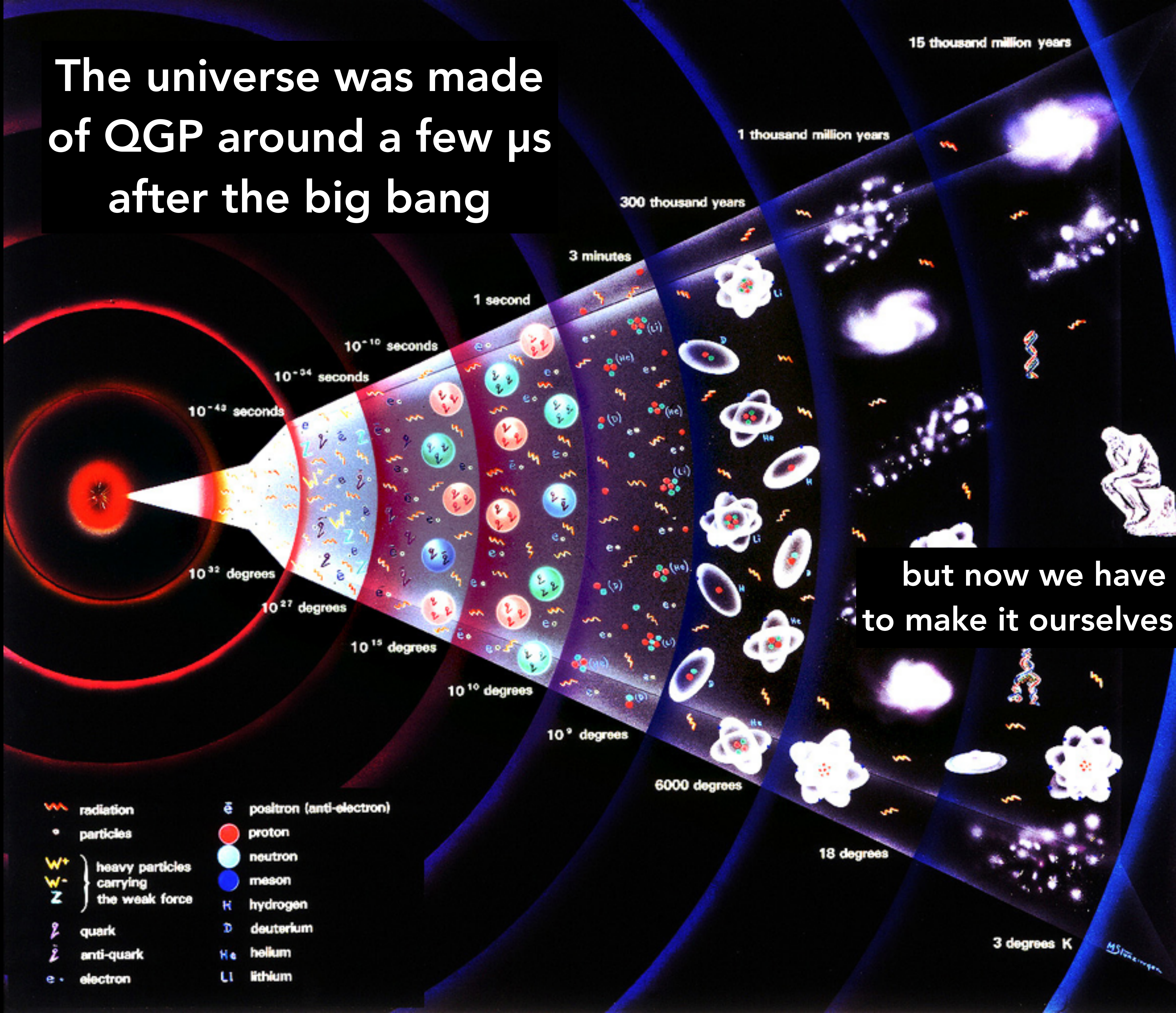
Crossover for $\mu_B=0$



search for critical point is a major focus of RHIC energy scan (2018-2019)

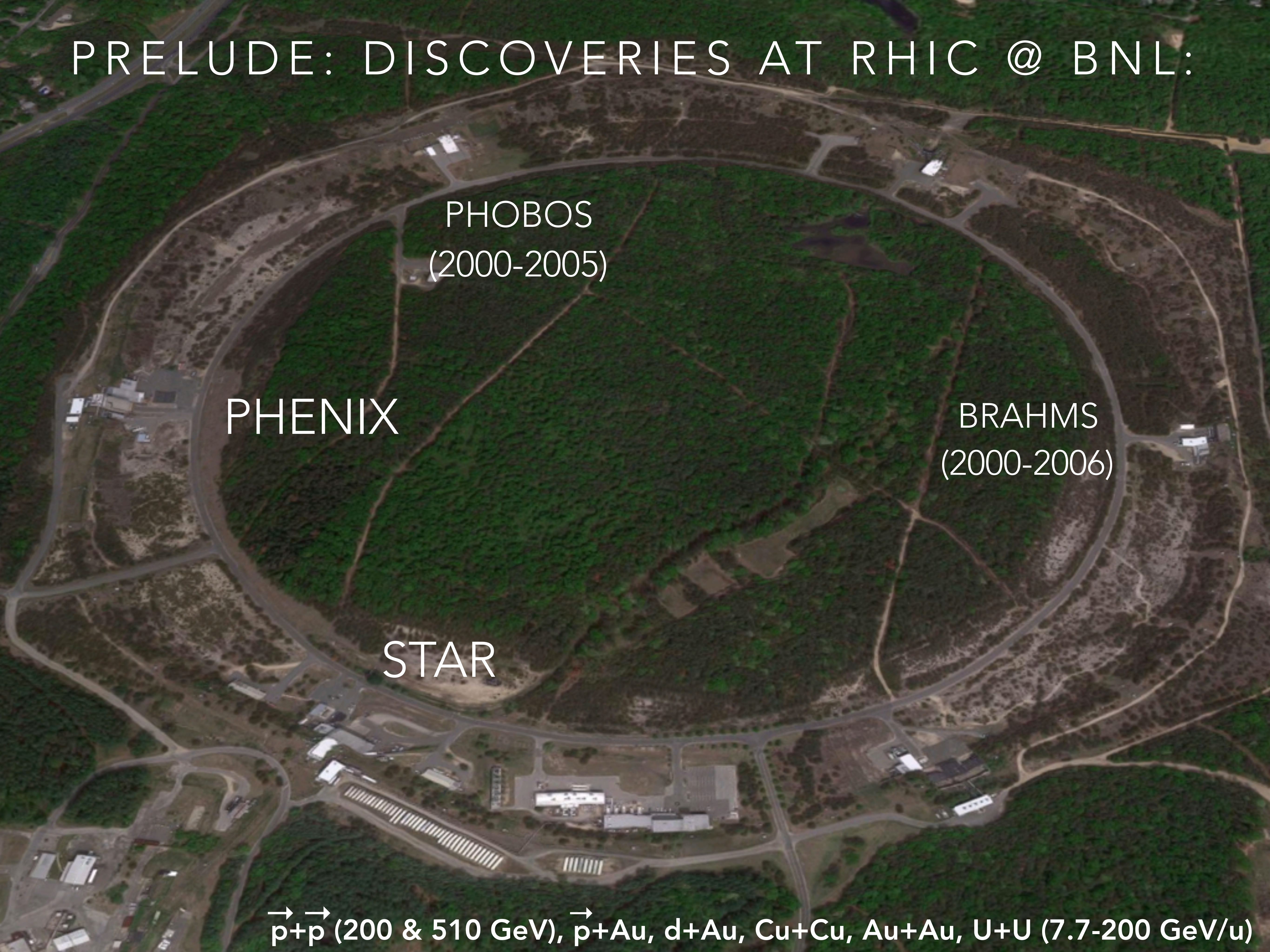
what do we know already about hot QCD?

The universe was made of QGP around a few μs after the big bang



but now we have to make it ourselves…

PRELUDE: DISCOVERIES AT RHIC @ BNL:



$\vec{p}+\vec{p}$ (200 & 510 GeV), $\vec{p}$+Au, d+Au, Cu+Cu, Au+Au, U+U (7.7-200 GeV/u)

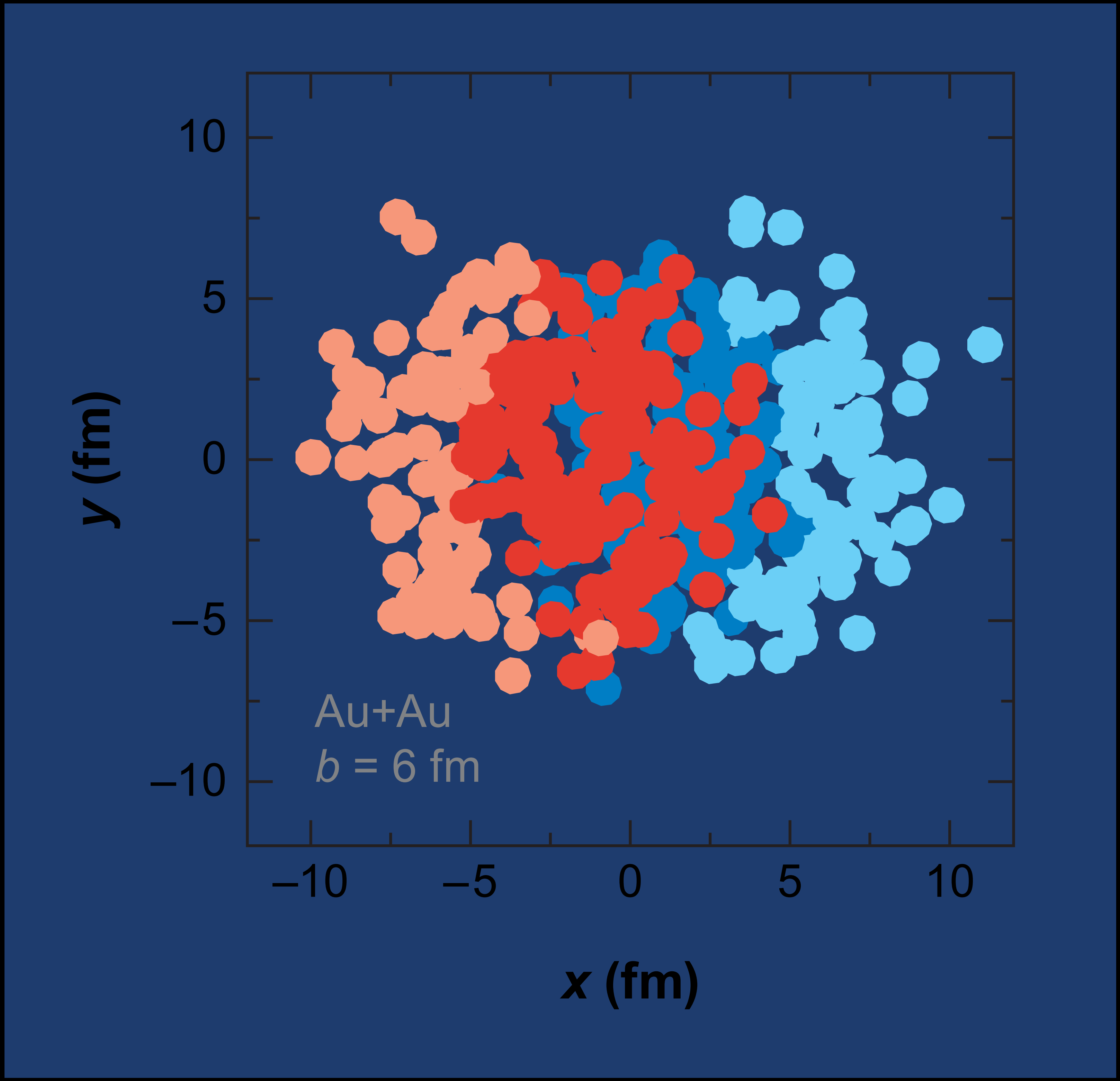
TWO MAIN DISCOVERIES @ RHIC

COLLECTIVE FLOW
(PERFECT FLUID)

JET QUENCHING

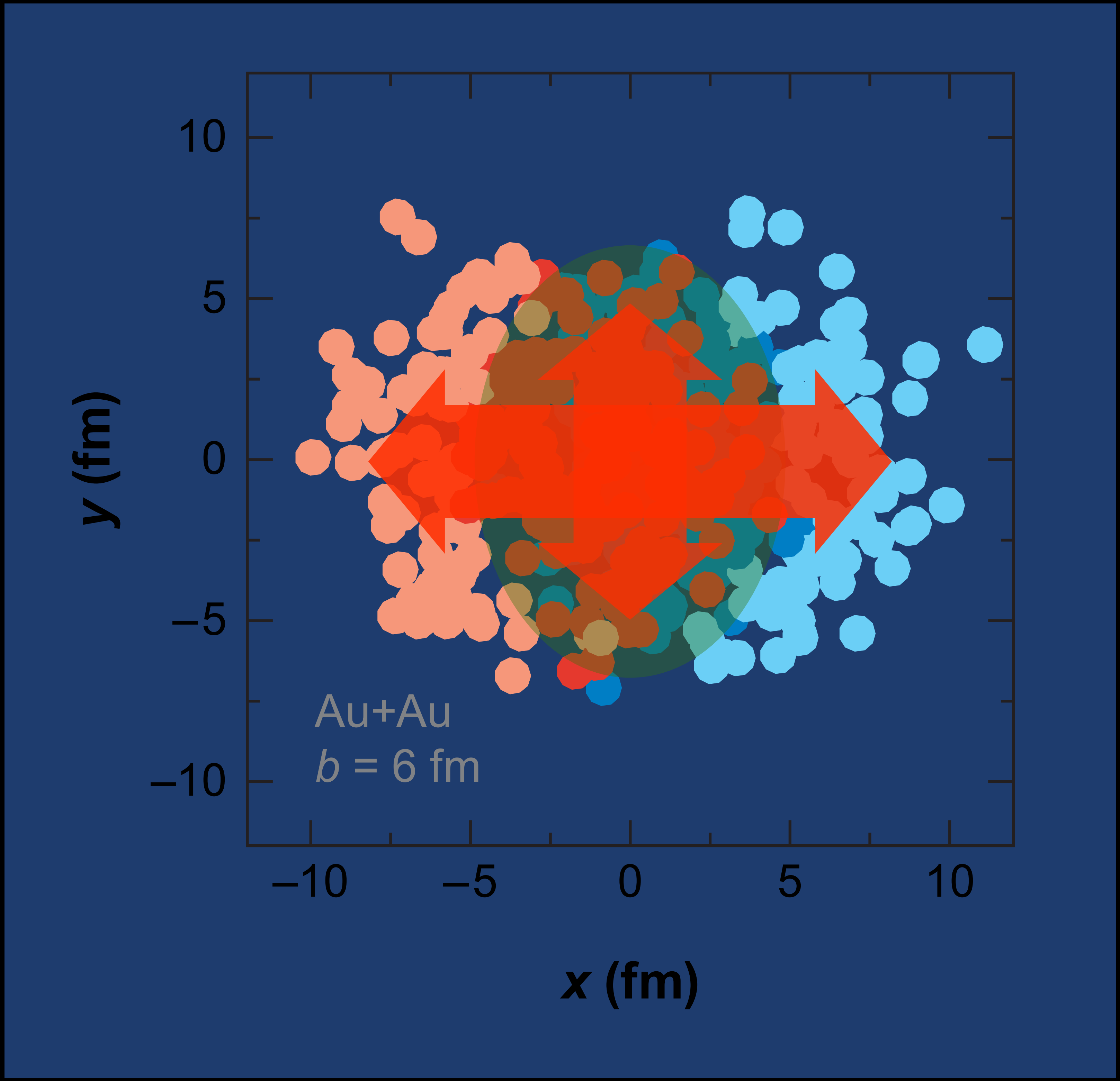
explaining these two will make the LHC results much easier to understand

COLLECTIVE FLOW



In a peripheral nuclear collision, overlap region is ellipse-shaped

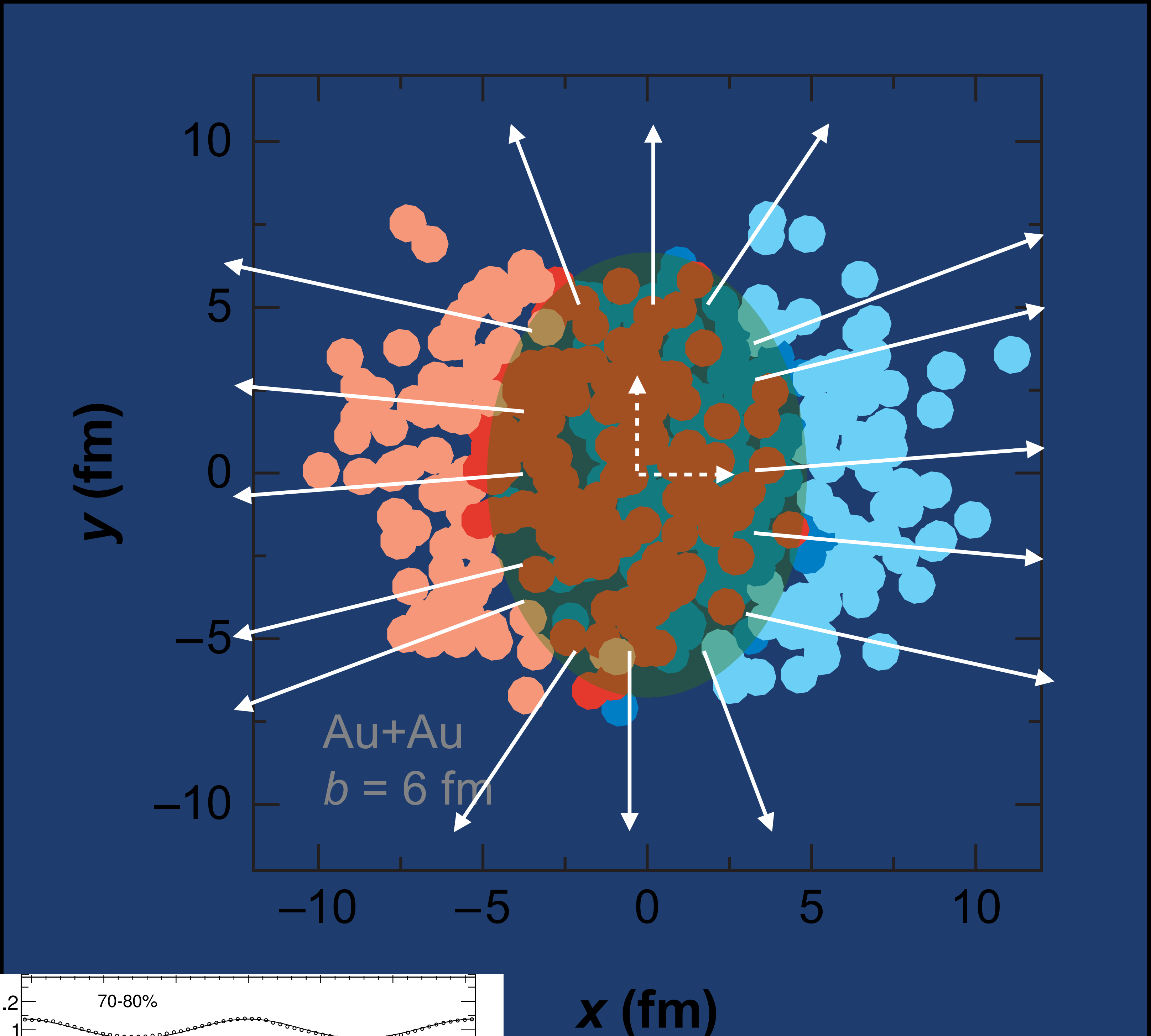
COLLECTIVE FLOW

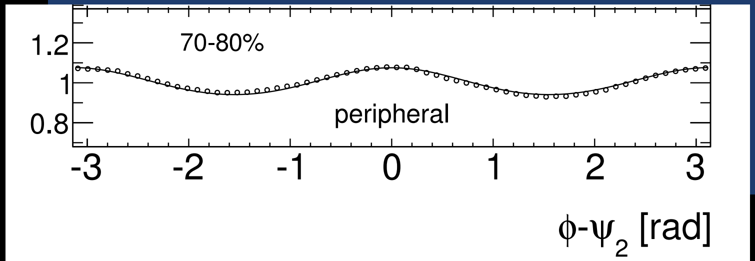


In a peripheral nuclear collision, overlap region is ellipse-shaped

If system thermalizes rapidly, then pressure gradients are larger along one direction

COLLECTIVE FLOW



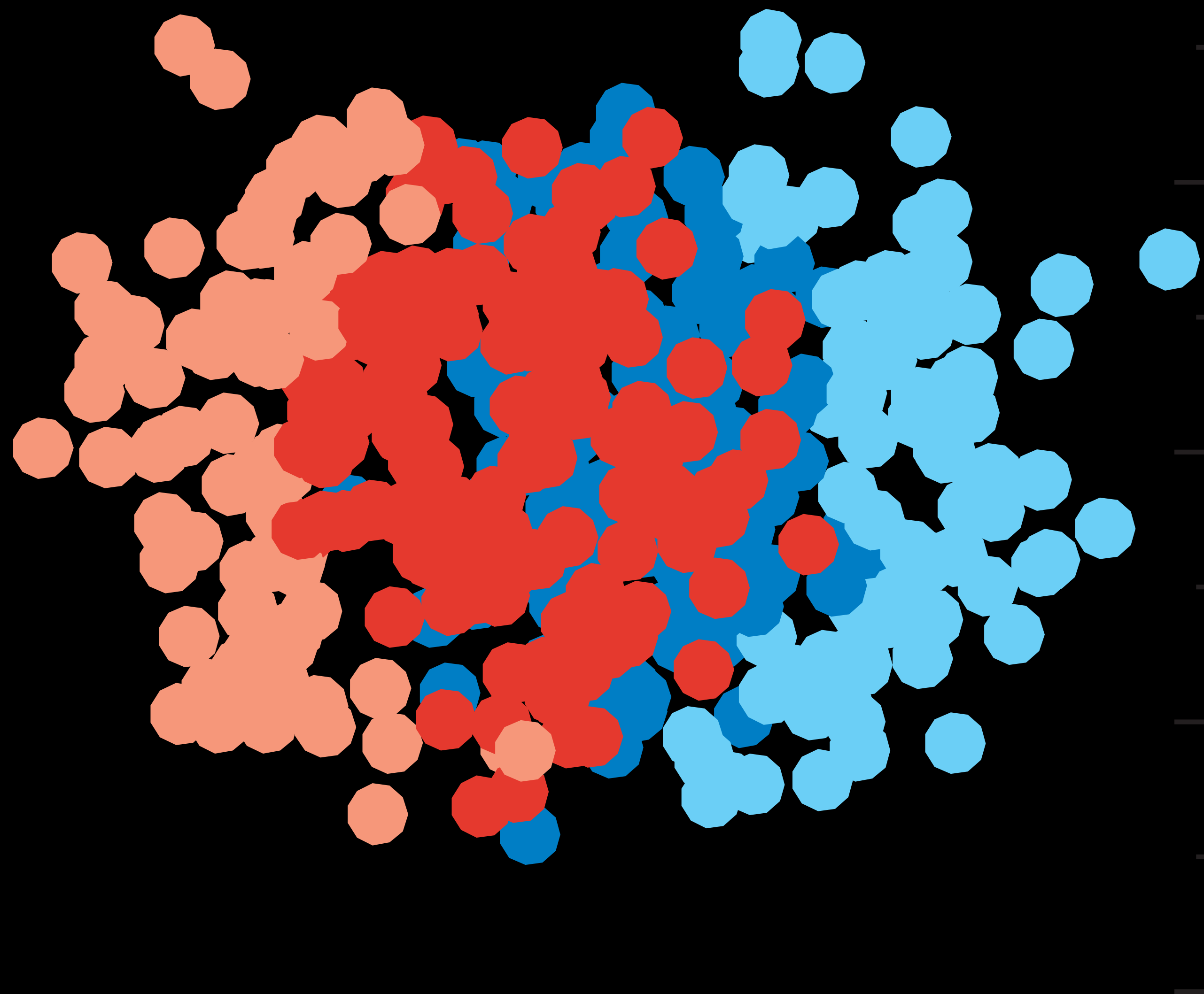


In a peripheral nuclear collision, overlap region is ellipse-shaped

If system thermalizes rapidly, then pressure gradients are larger along one direction

Events will show distinct modulation in azimuth (ϕ) about "event plane" (more particles "in plane"!)

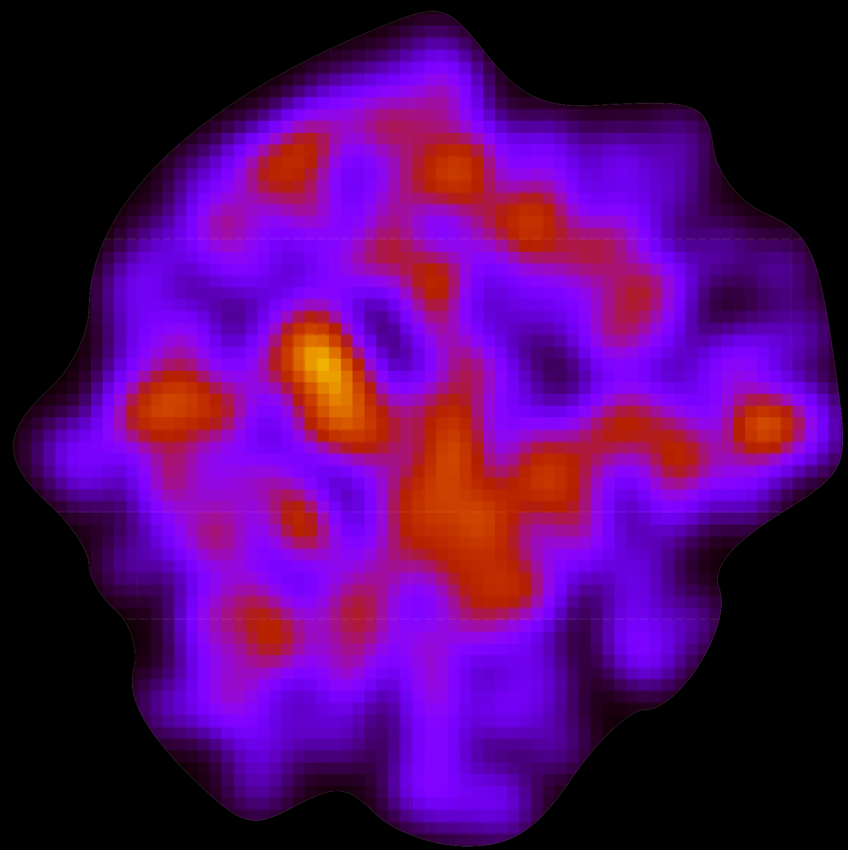
HYDRODYNAMICS FOR HI COLLISIONS



Collision of two nuclei (transverse plane)

HYDRODYNAMICS FOR HI COLLISIONS

B. Schenke, et al



"Initial stage"

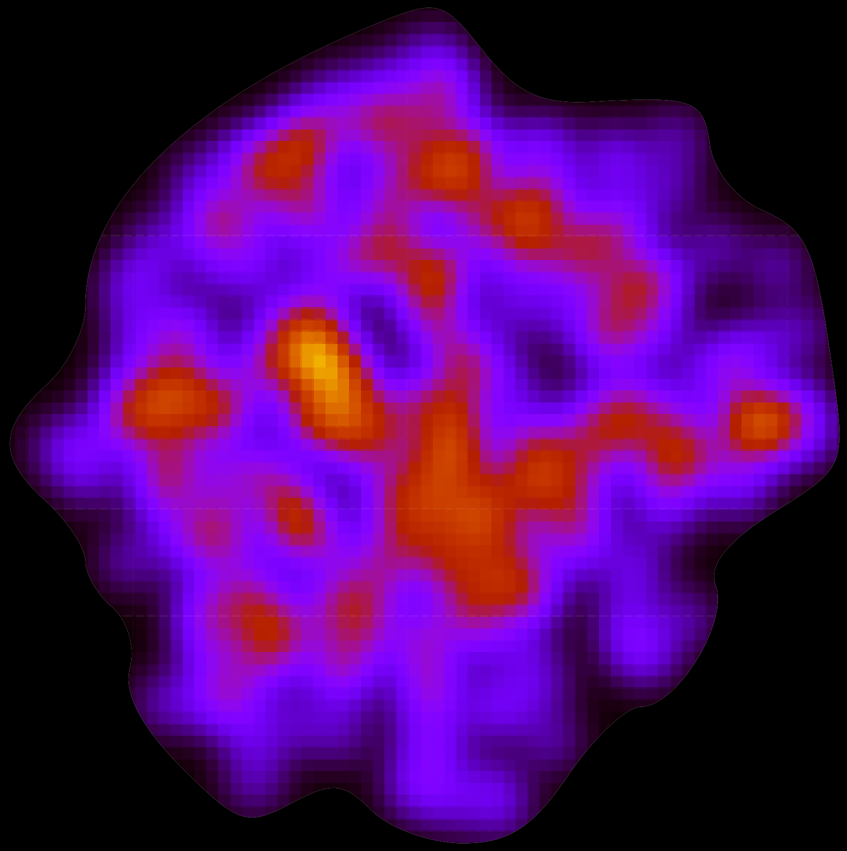
conversion of nucleon density to energy density

$$\epsilon(x,y) \propto \rho(x,y)$$

(some calculations use this to seed & evolve classical Yang-Mills)

HYDRODYNAMICS FOR HI COLLISIONS

B. Schenke, et al



t=0

Hydrodynamic evolution:

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

ideal hydro

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

& equation of state from lattice

HYDRODYNAMICS FOR HI COLLISIONS

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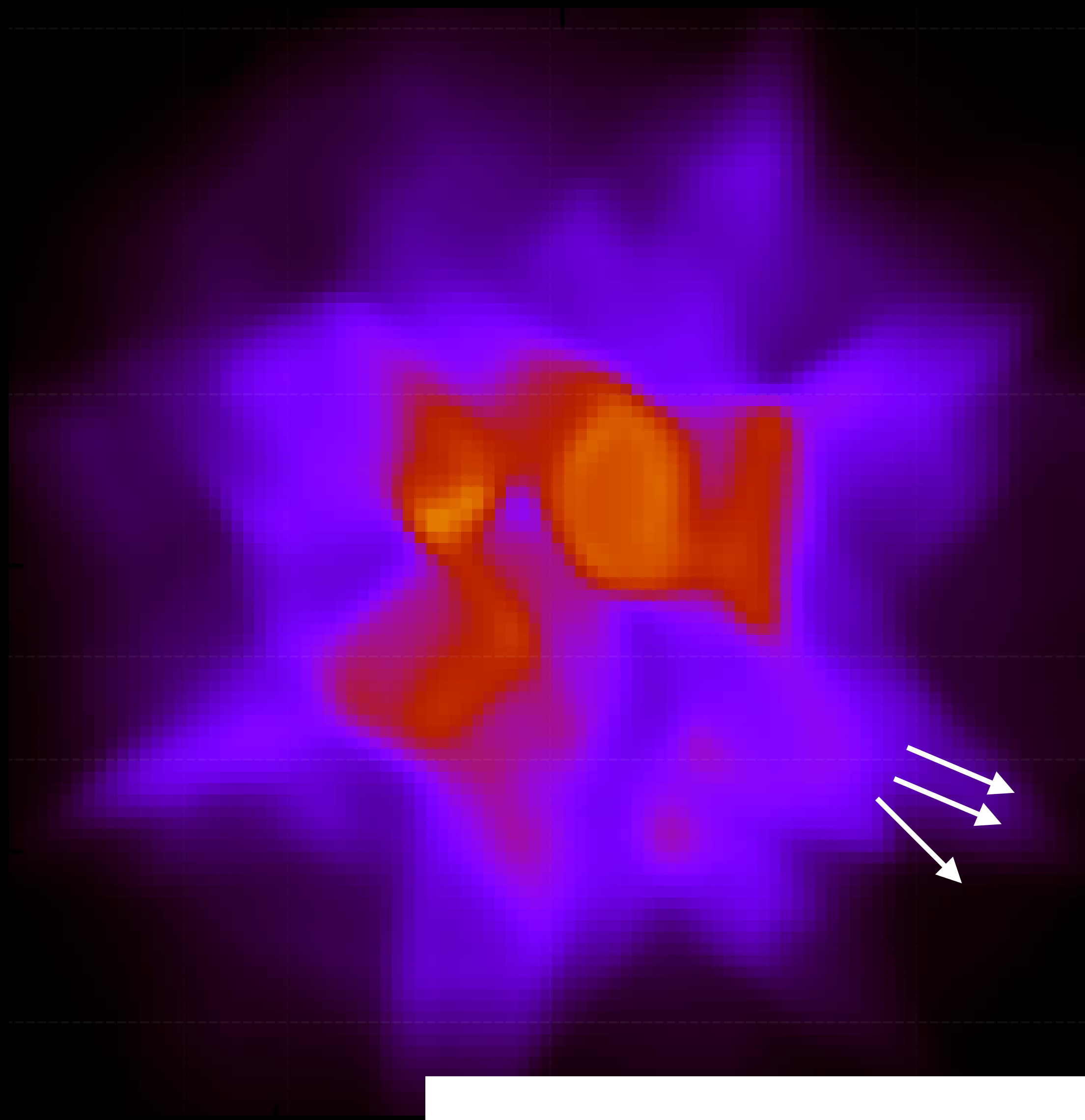


t=6 fm/c

convert to hadrons
$T_f(x,y,z)$=120 MeV

Hydrodynamic evolution:

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

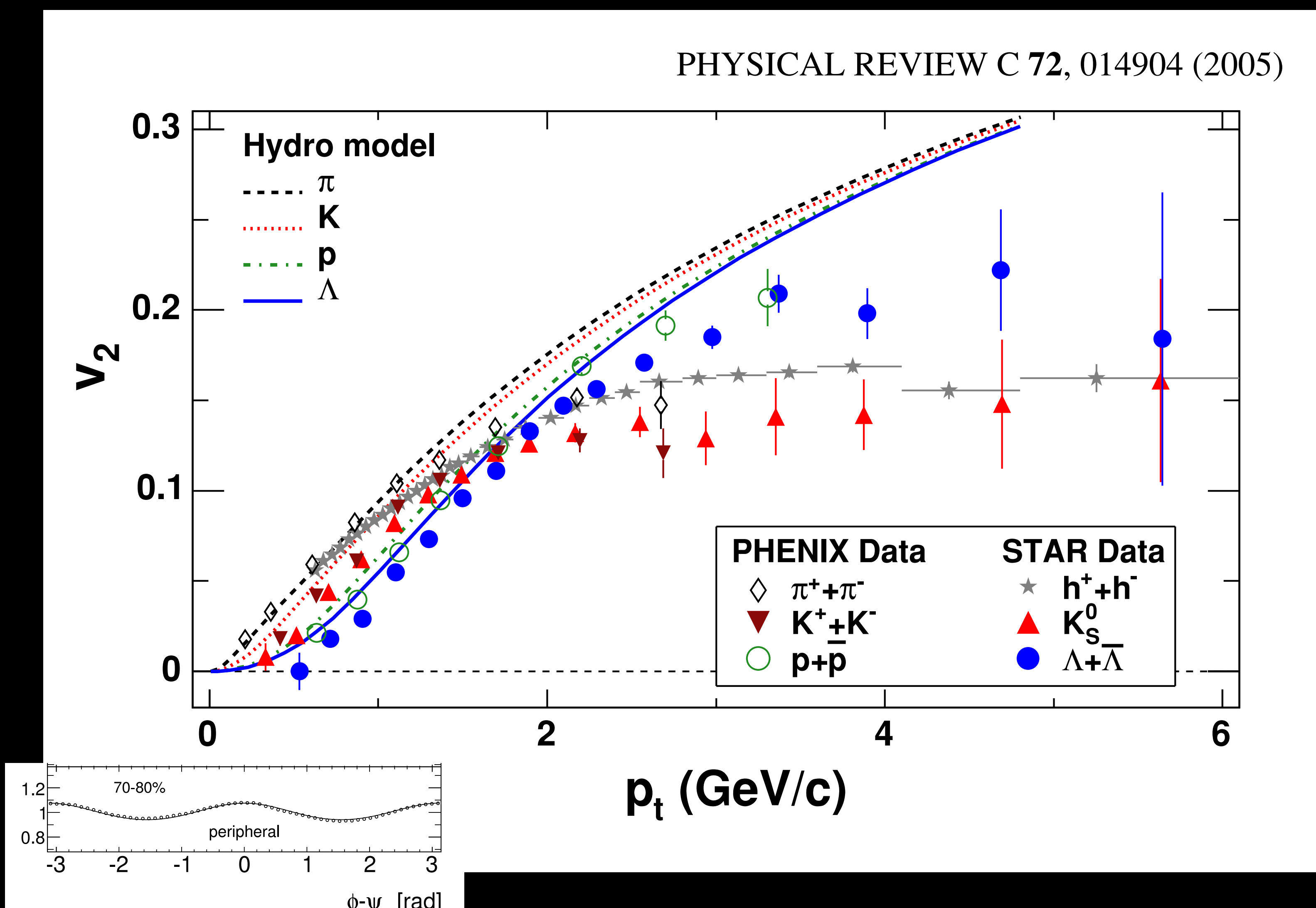
ideal hydro

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

& equation of state from lattice

EXPERIMENTAL SIGNATURES OF COLLECTIVE FLOW

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos\left(n\left[\phi - \Psi_n\right]\right)$$



Estimate Ψ_2 using forward measurements (particles or energy) and extract

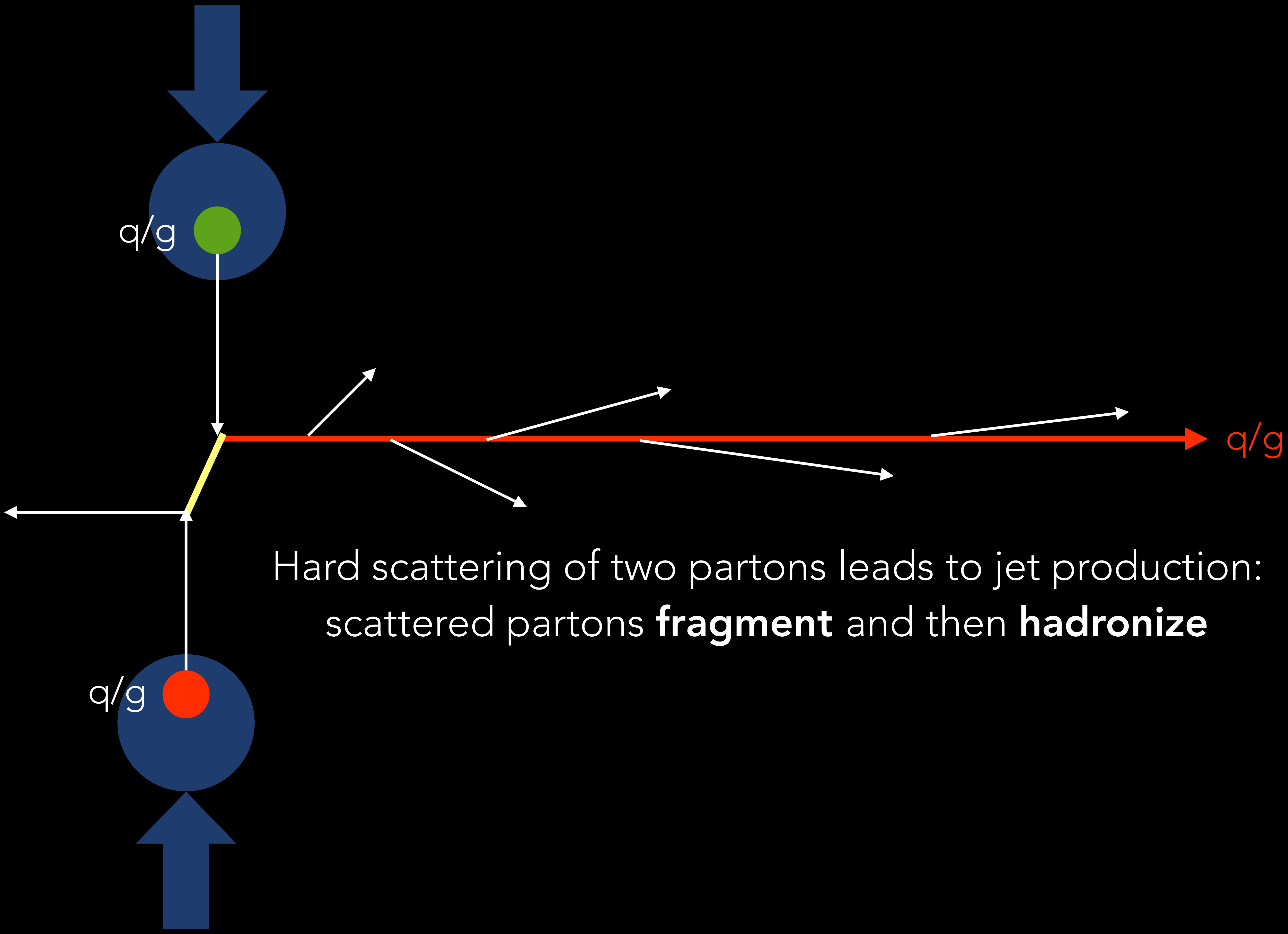
$$v_2 = \langle \cos\left(2\left[\phi - \Psi_2\right]\right)\rangle$$

for identified hadrons

Large amplitudes & "mass splitting" at low p_T and high p_T

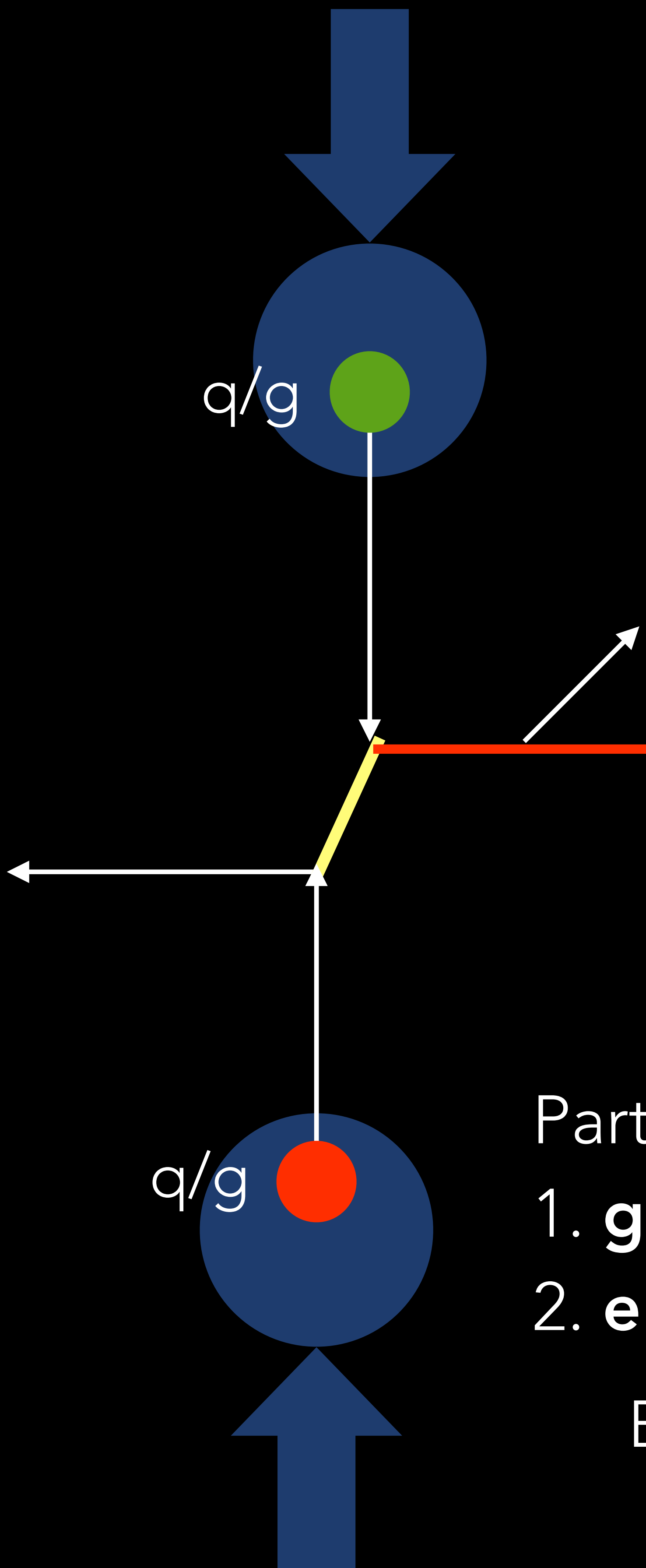
Bulk of particles behave like subatomic droplet of **relativistic fluid,** which thermalize in less than 1fm/c ~ 0.3×10^{-23} s!

JET QUENCHING IN QCD



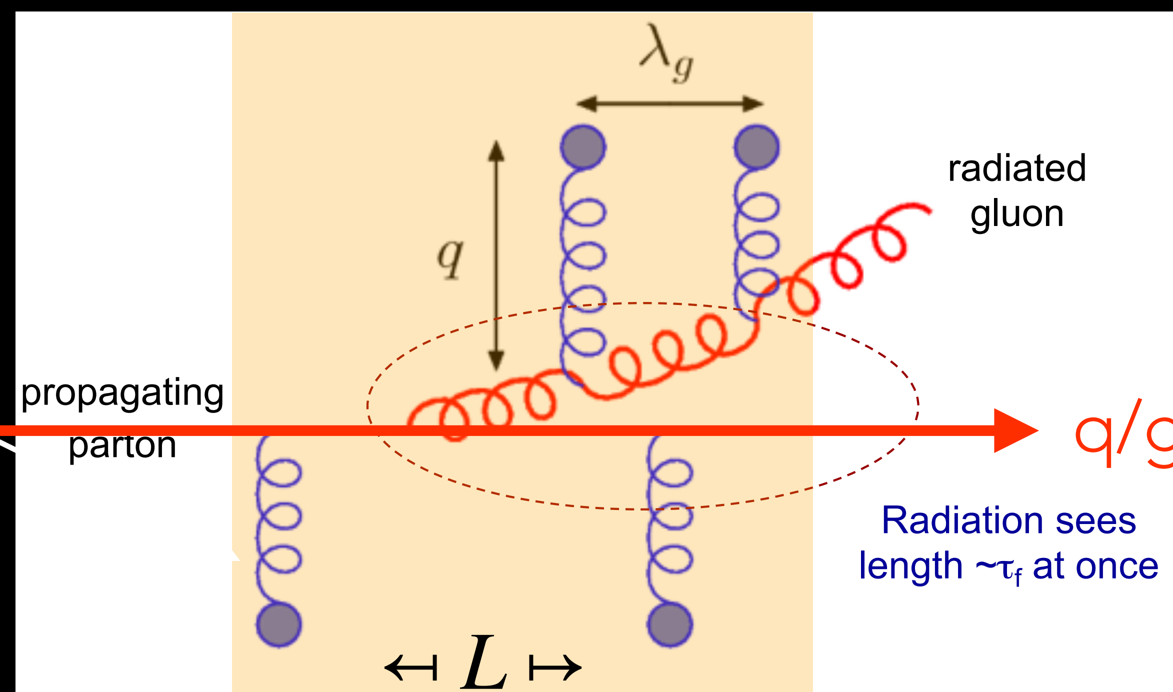
Hard scattering of two partons leads to jet production: scattered partons **fragment** and then **hadronize**

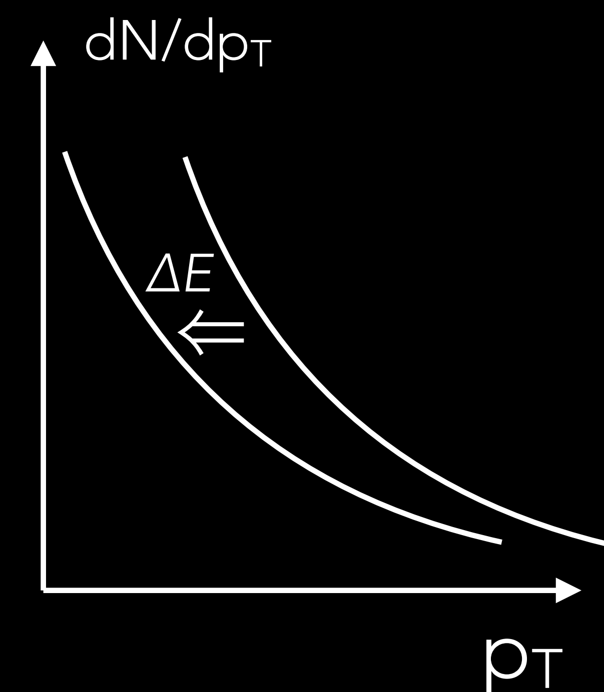
JET QUENCHING IN QCD



transport coefficient:

$$\hat{q}\left[\frac{\mathrm{GeV}^2}{\mathrm{fm}}\right] \propto \frac{\langle q_\perp^2 \rangle}{\lambda} \sim \text{density} \qquad \Delta E \propto \alpha_s \hat{q} L^2$$





Partons lose energy traversing medium, due to :

1. **gluon radiation** (coherently if t_{form}> m.f.p. ➔ L^2)
2. **elastic scattering** (transfer of energy to medium)

Energy loss sensitive to density & coupling,
⇒ reduction in rate at fixed p_T

INTERMEZZO:
HARD PROCESS RATES IN PP & AA

Rate of X in pp $R_X^{pp} = \mathcal{L}_{pp} \times \sigma_X^{pp}$

Rate of X in AA $R_X^{AA} = \mathcal{L}_{AA} \times \sigma_{tot}^{AA} \times \langle N_{coll} \rangle \times \frac{\sigma_X^{pp}}{\sigma_{tot}^{pp}}$

$= \mathcal{L}_{AA} \times \sigma_X^{pp} \times \langle N_{coll} \rangle \times \frac{\sigma_{AA}^{tot}}{\sigma_{tot}^{pp}}$ 40,000! "partonic luminosity"

$= \mathcal{L}_{AA} \times \sigma_{AA}^{tot} \times \sigma_X^{pp} \times \frac{\langle N_{coll} \rangle}{\sigma_{tot}^{pp}}$ $= \langle T_{AA} \rangle$ "mean nuclear thickness"

minimum-bias rate

INTERMEZZO:
THE "MASTER EQUATION" FOR AA

$$N_X = N_{AA} \times \sigma_X^{pp} \langle T_{AA} \rangle$$

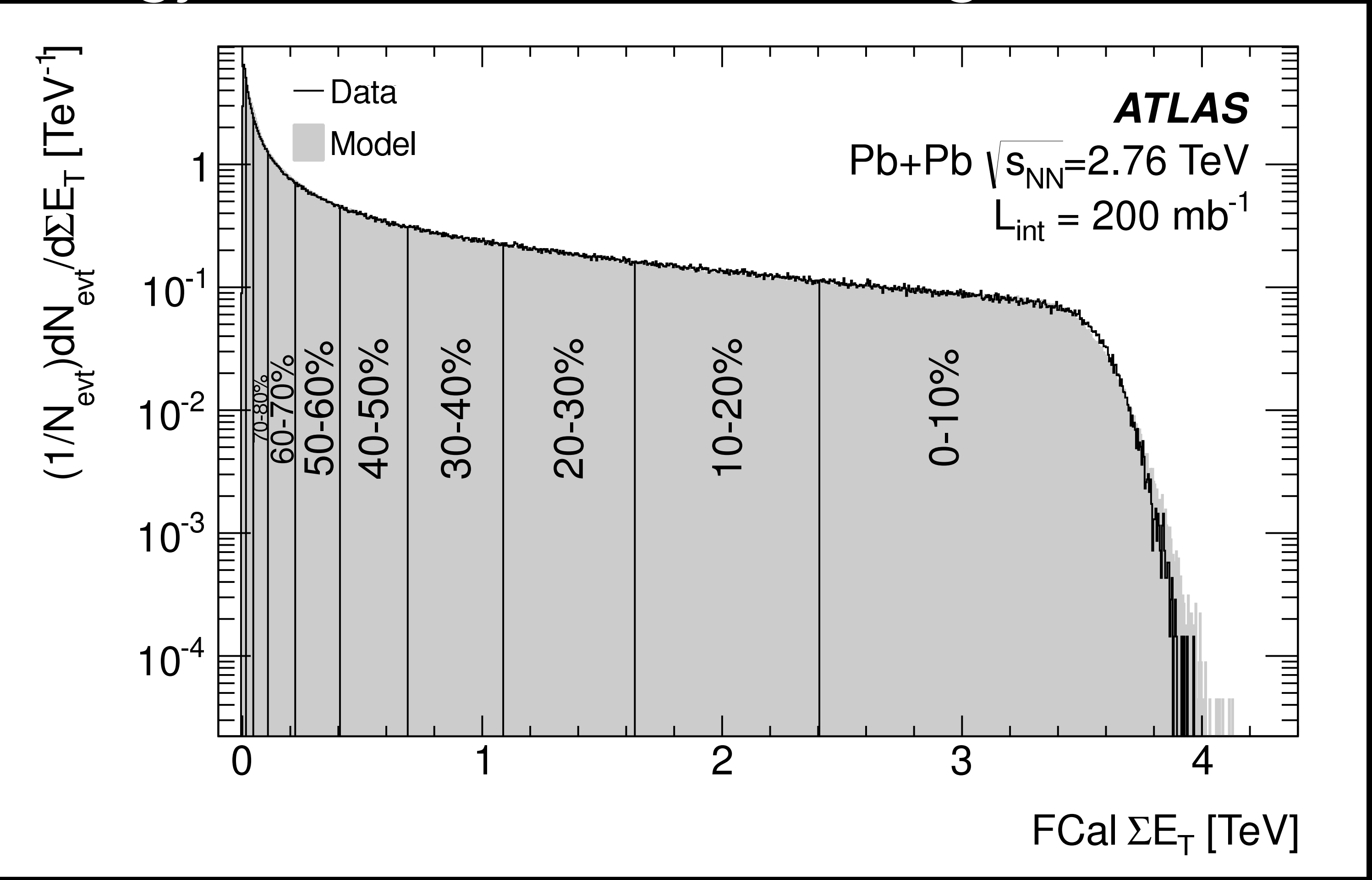
which defines "nuclear modification factor"

$$R_{AA}^X = \frac{N_X}{N_{AA} \sigma_X^{pp} \langle T_{AA} \rangle}$$

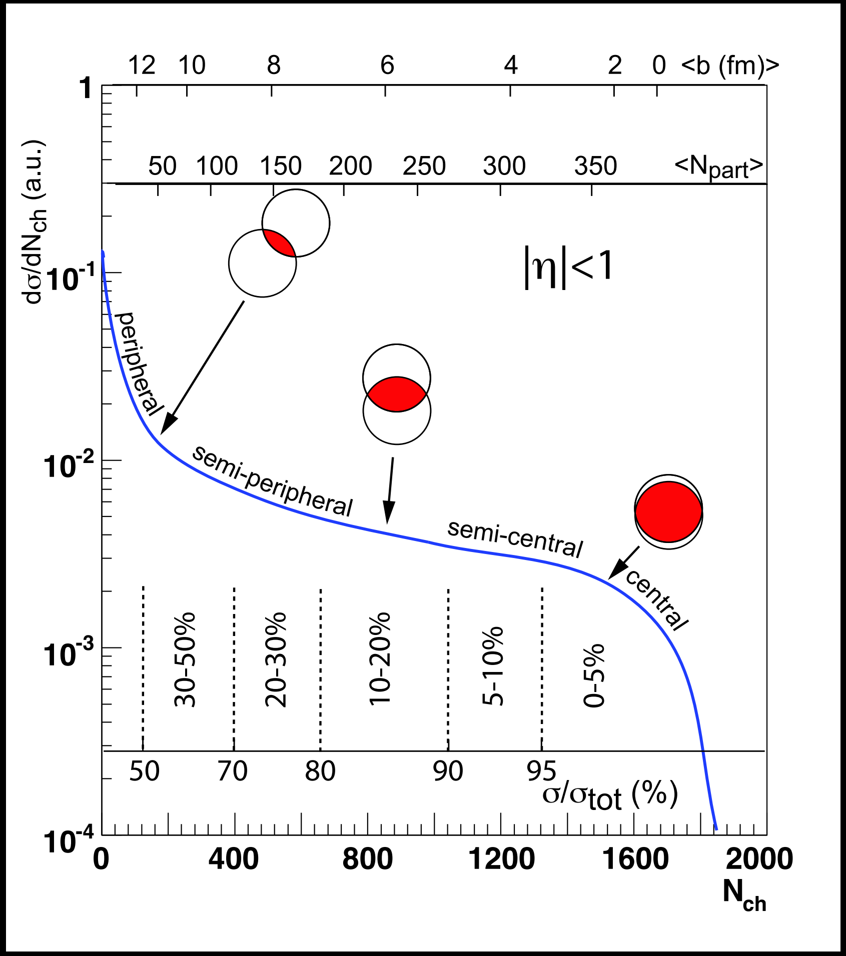
Cross sections in pp, yields in AA, and thickness from calculations

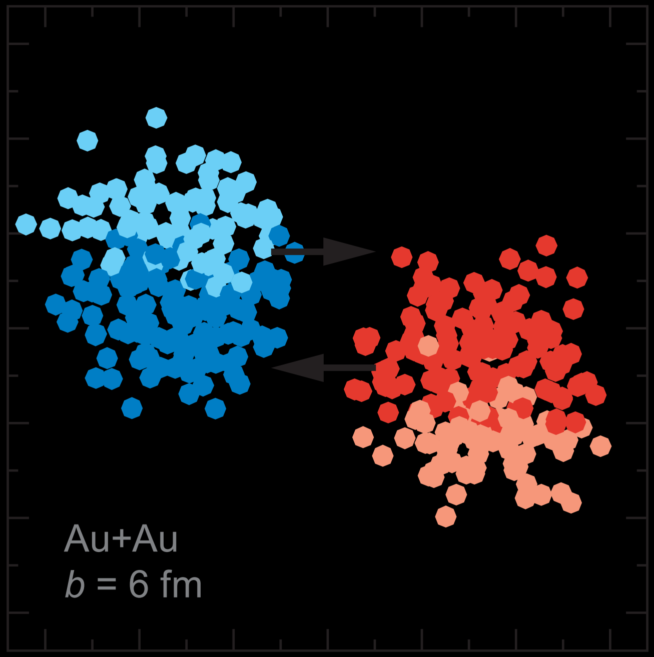
"CENTRALITY"

Energy measured at forward angles



Miller et al, 2007

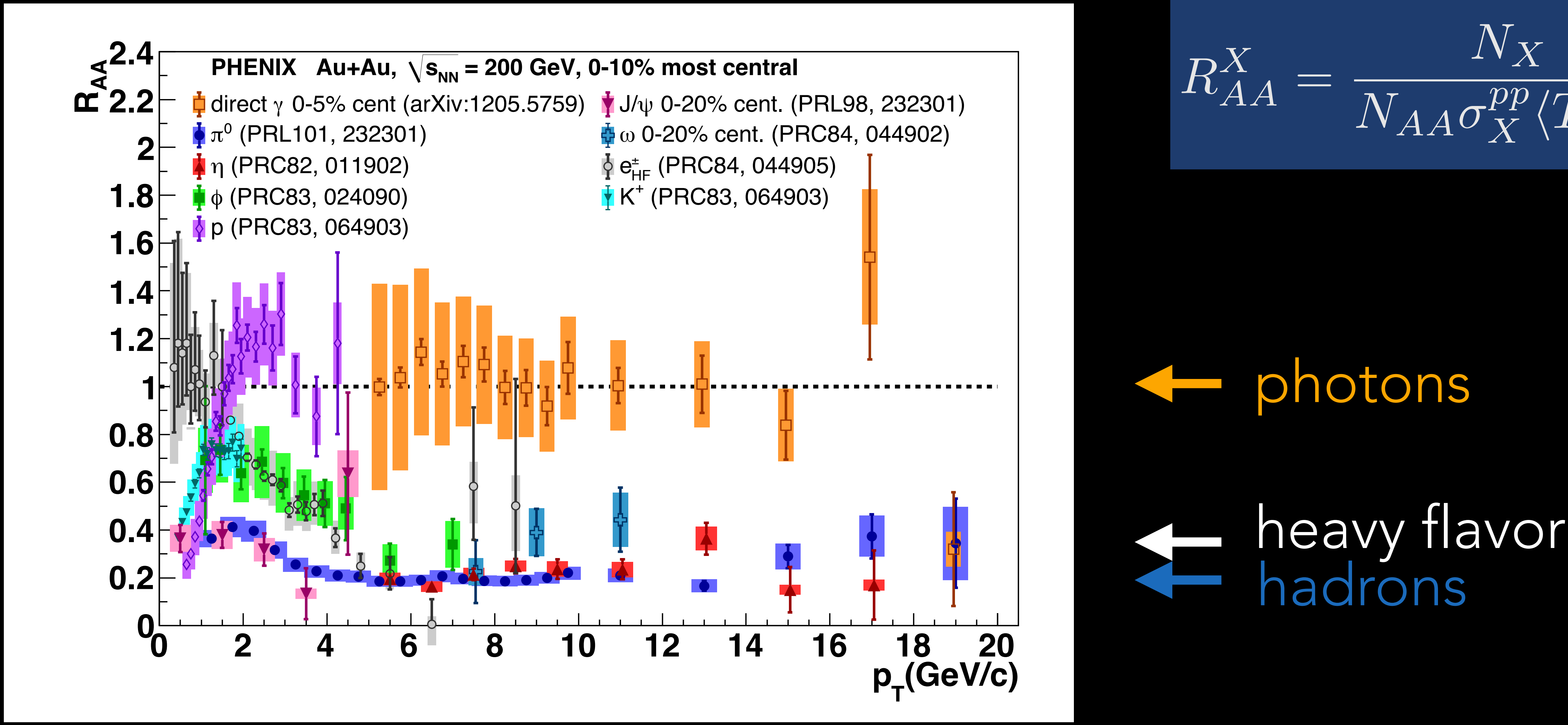




Convolve Glauber calculations with simple particle production models to estimate fraction of total AA cross section observed by each experiment

Data is then divided into percentile bins:
Using only monotonicity, model allows extraction of $\langle N_{part}\rangle$, $\langle N_{coll}\rangle$, $\langle T_{AA}\rangle$ for each bin!

EXPERIMENTAL SIGNATURES OF JET QUENCHING (PHENIX @ RHIC)



$$R^X_{AA} = \frac{N_X}{N_{AA}\sigma^{pp}_X \langle T_{AA} \rangle}$$

- **Initial state - fewer incoming partons? (nPDF)**
  - ➔ *No similar deficit of direct (prompt) photons* $\boldsymbol{R_{AA} \sim 1}$
- **Final state - energy loss in final state?**
  - ➔ *For* $p_T > 6$ *GeV, all hadrons have* $\boldsymbol{R_{AA} \sim 0.2\text{-}0.4}$

STRONG VS. WEAK COUPLING

COLLECTIVE FLOW

JET QUENCHING

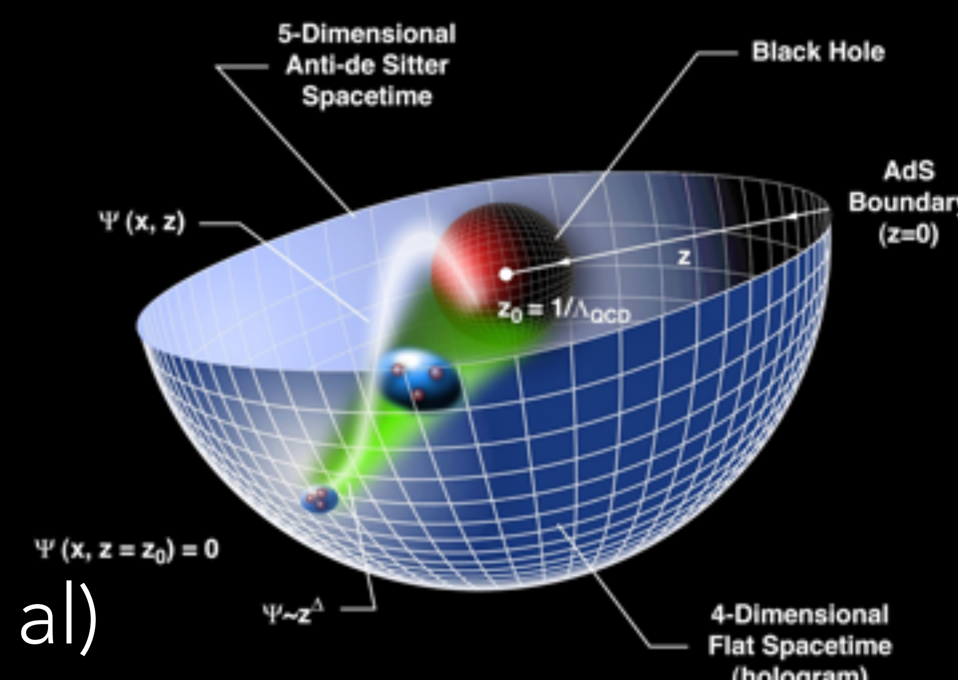
MEDIUM PROPERTIES

DENSITY

COUPLING

VISCOSITY/ ENTROPY

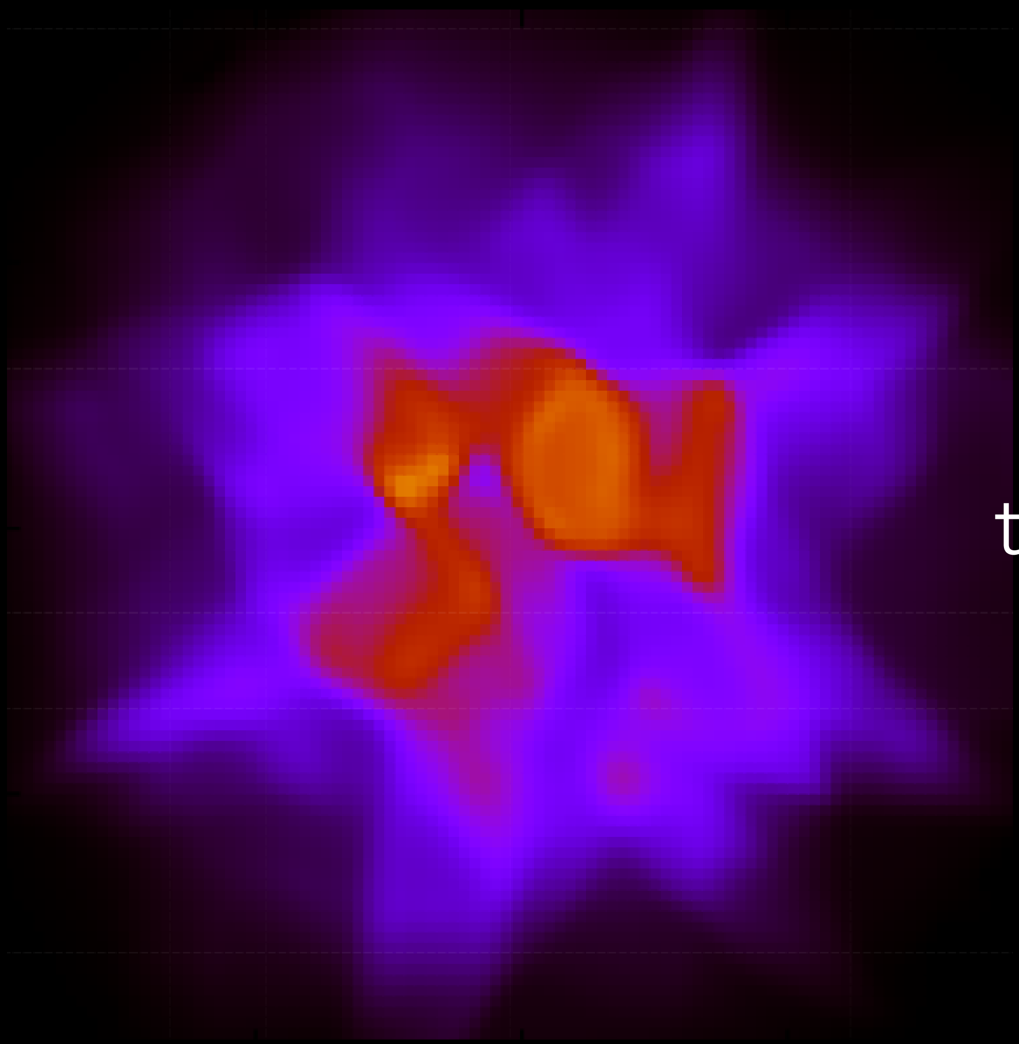
$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$



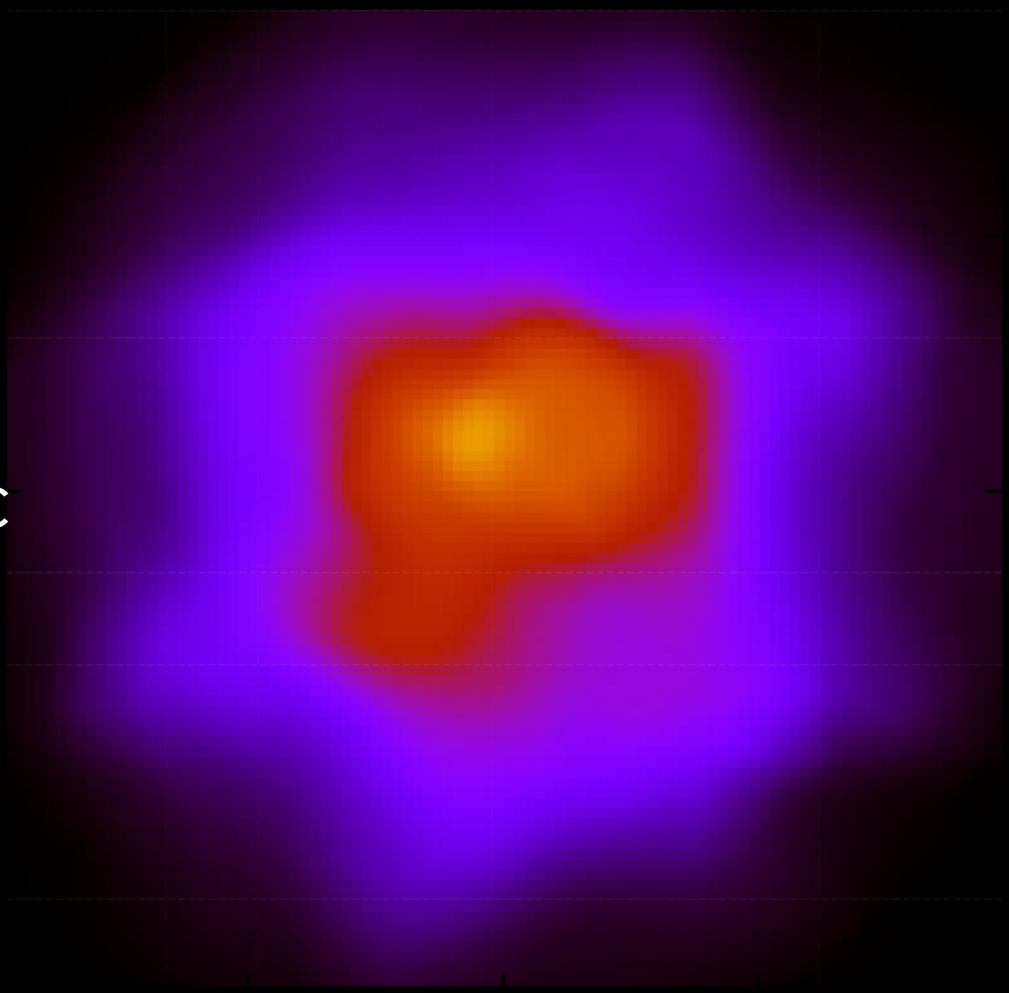
Determining QGP transport properties is one of the only known ways to test bound predicted using AdS/CFT (Son et al)

VISCOUS HYDRODYNAMICS

B. Schenke, et al



t=6 fm/c

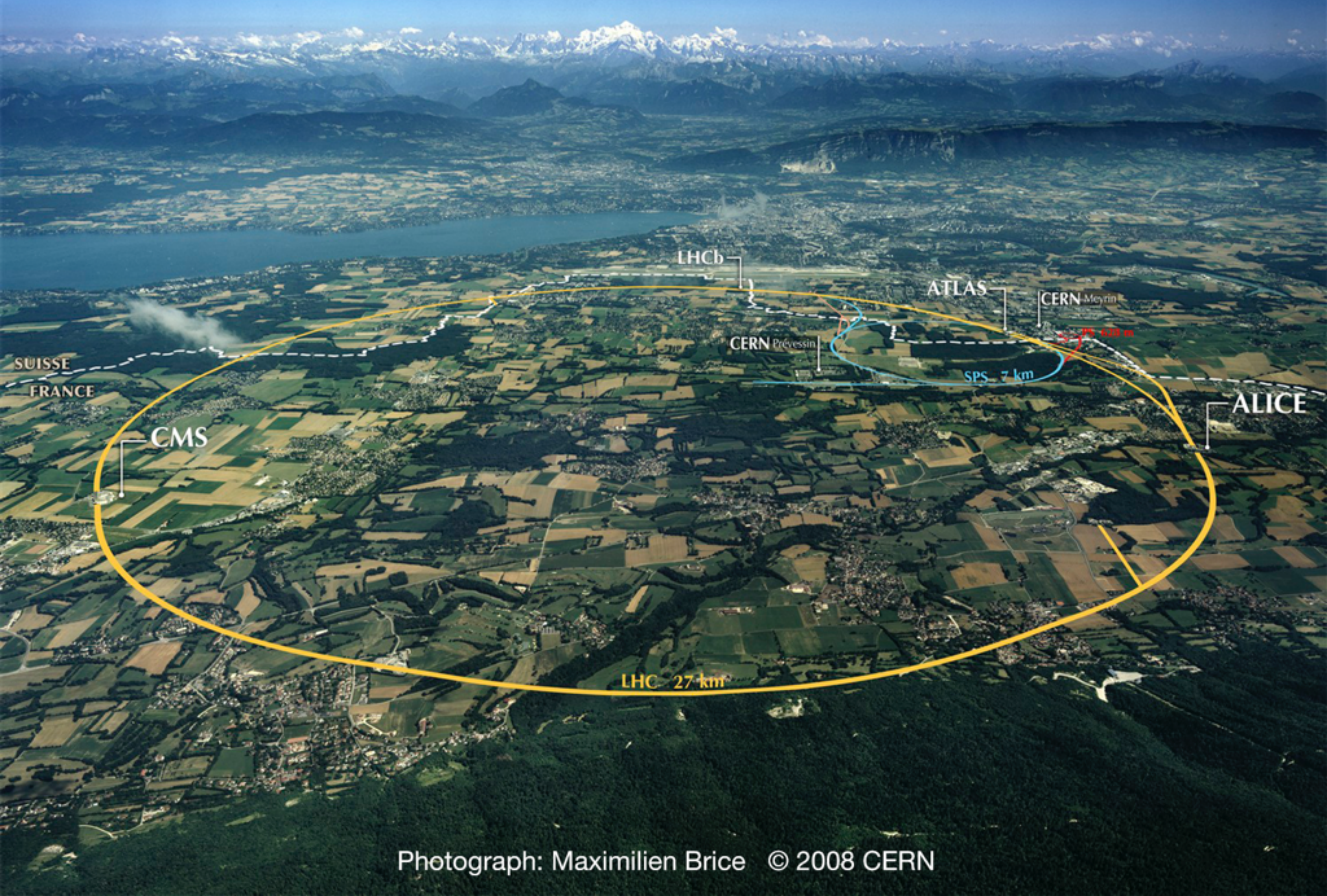


$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$

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

Viscosity is dissipative (think friction): reduces v_2, and blurs fine structure of hydrodynamic evolution

ACT III: IONS @ THE LHC



ACT III: IONS @ THE LHC

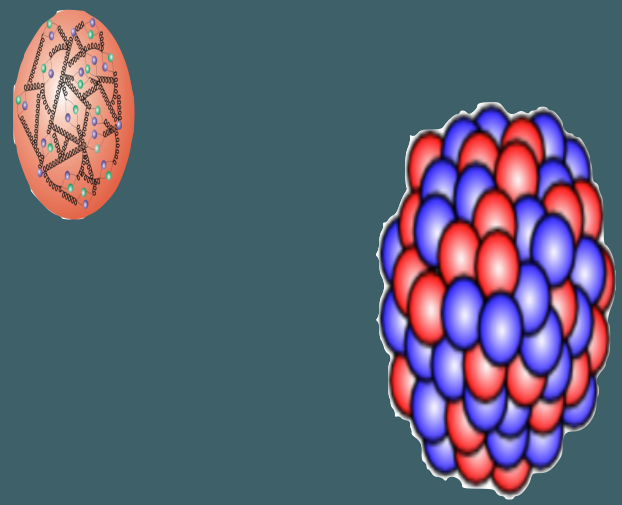
- **Collisions at the LHC are**
  - Denser: ×2 in $dN/d\eta$ / ($N_{part}/2$)
  - Hotter
  - Longer-lived
  - with dramatic increases in hard process rates: probe medium

- **The LHC is a versatile machine**
  - lead-lead collisions
  - proton-proton collisions for reference data
  - proton-lead to study impact of nPDFs

COLLISIONS IN RUNS 1 & 2

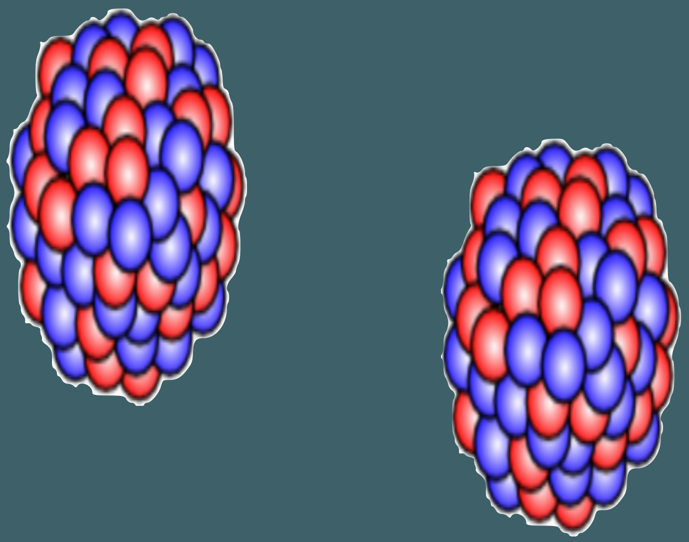
p+p

900 GeV (2009)
2.76 TeV (2013)
5.02 TeV (2015)
7 TeV (2010-11)
8 TeV (2012)
13 TeV (2015)



p+Pb

5.02 TeV (2012-13)
8.16 TeV (2016)

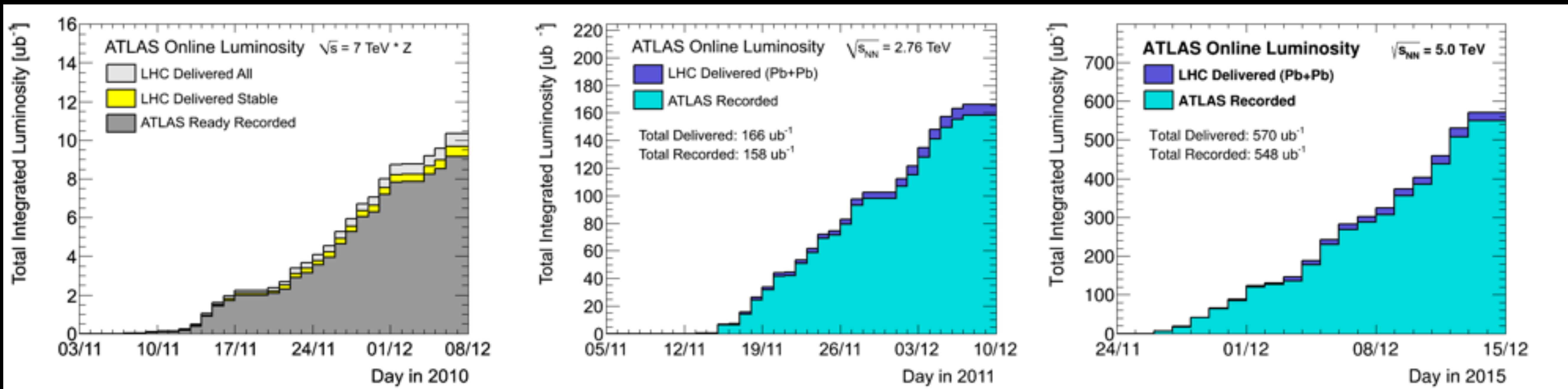


Pb+Pb

2.76 TeV (2010-11)
5.02 TeV (2015)

EVERY PB+PB & P+PB RUN HAS "REFERENCE" P+P RUN

LHC AS A HEAVY ION COLLIDER

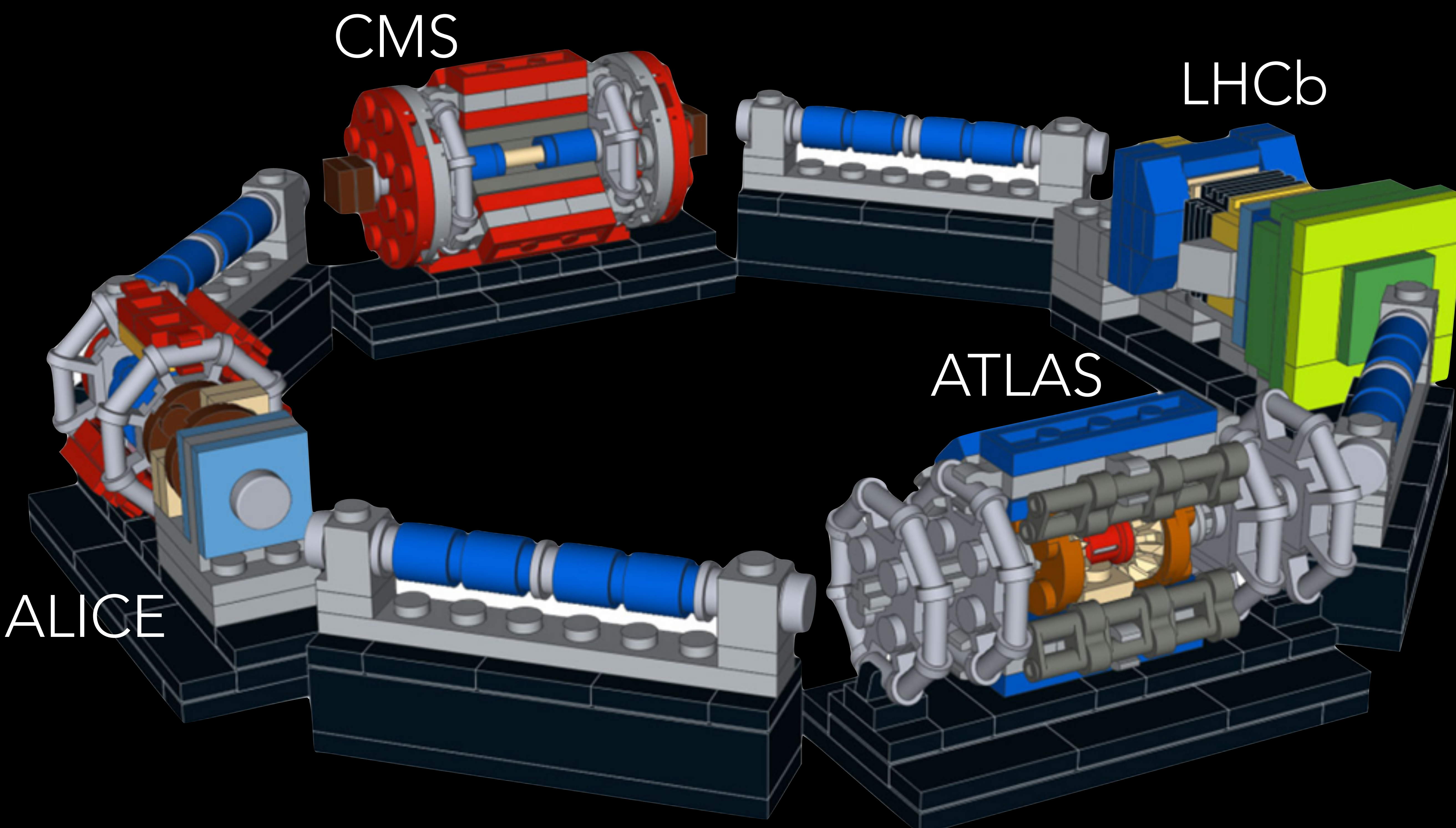


~0.3 μb^{-1}/day	~6 μb^{-1}/day	~30 μb^{-1}/day!
$L_{int} = 2x10^{25}/cm^2s$	$L_{int} = 5x10^{26}/cm^2s$	$L_{int} = 3x10^{27}/cm^2s$

Huge improvements year-to-year, with a key limitation for future runs being **burn-off** from electromagnetic interactions

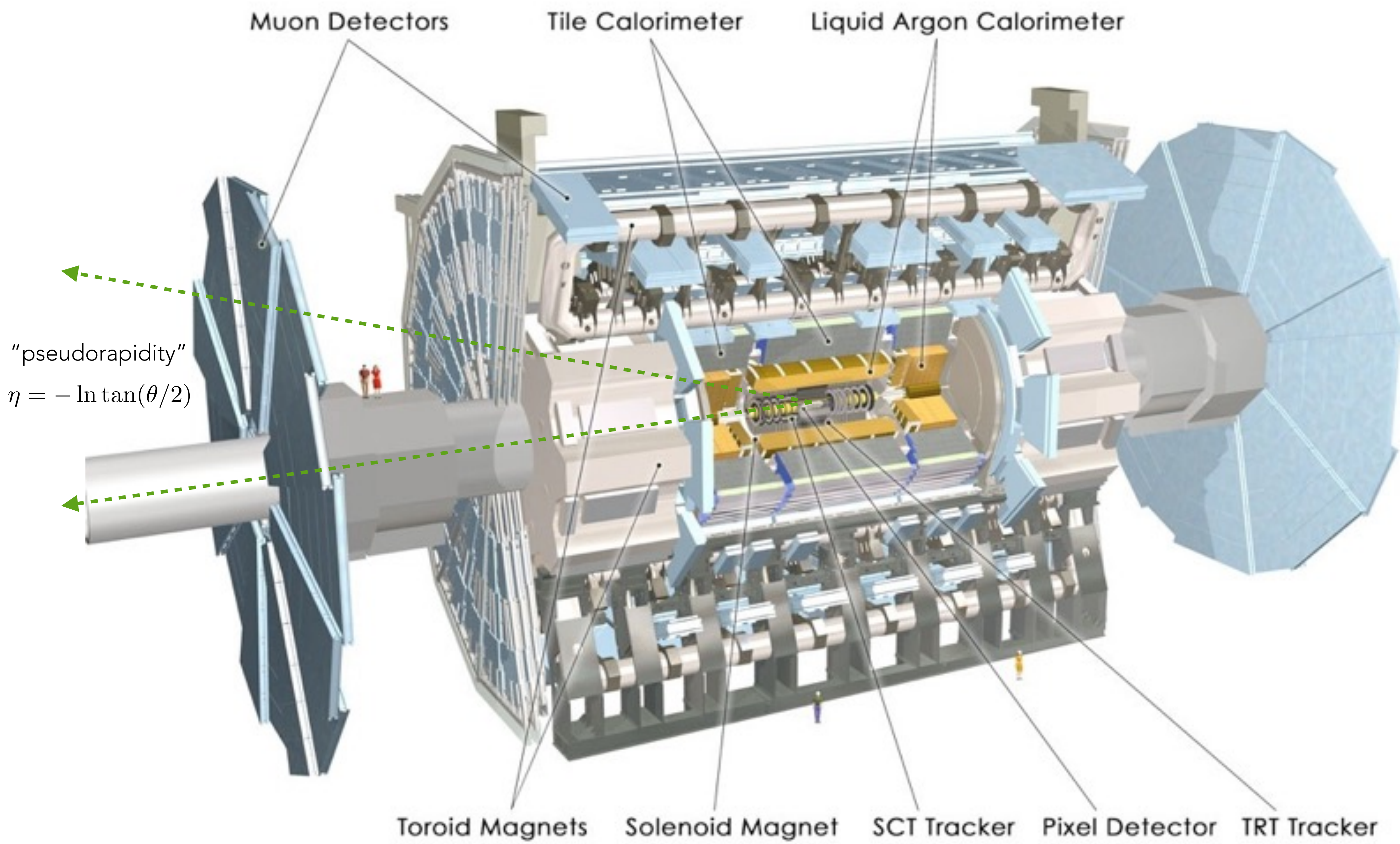
RUN 1 (2010-11)	RUN 2 (2015-2018)	RUN 3 (2021-2023)	RUN 4 (2026-2029)
0.15 nb^{-1}	1 nb^{-1}	10 nb^{-1}	?

THE LHC HEAVY ION PROGRAM



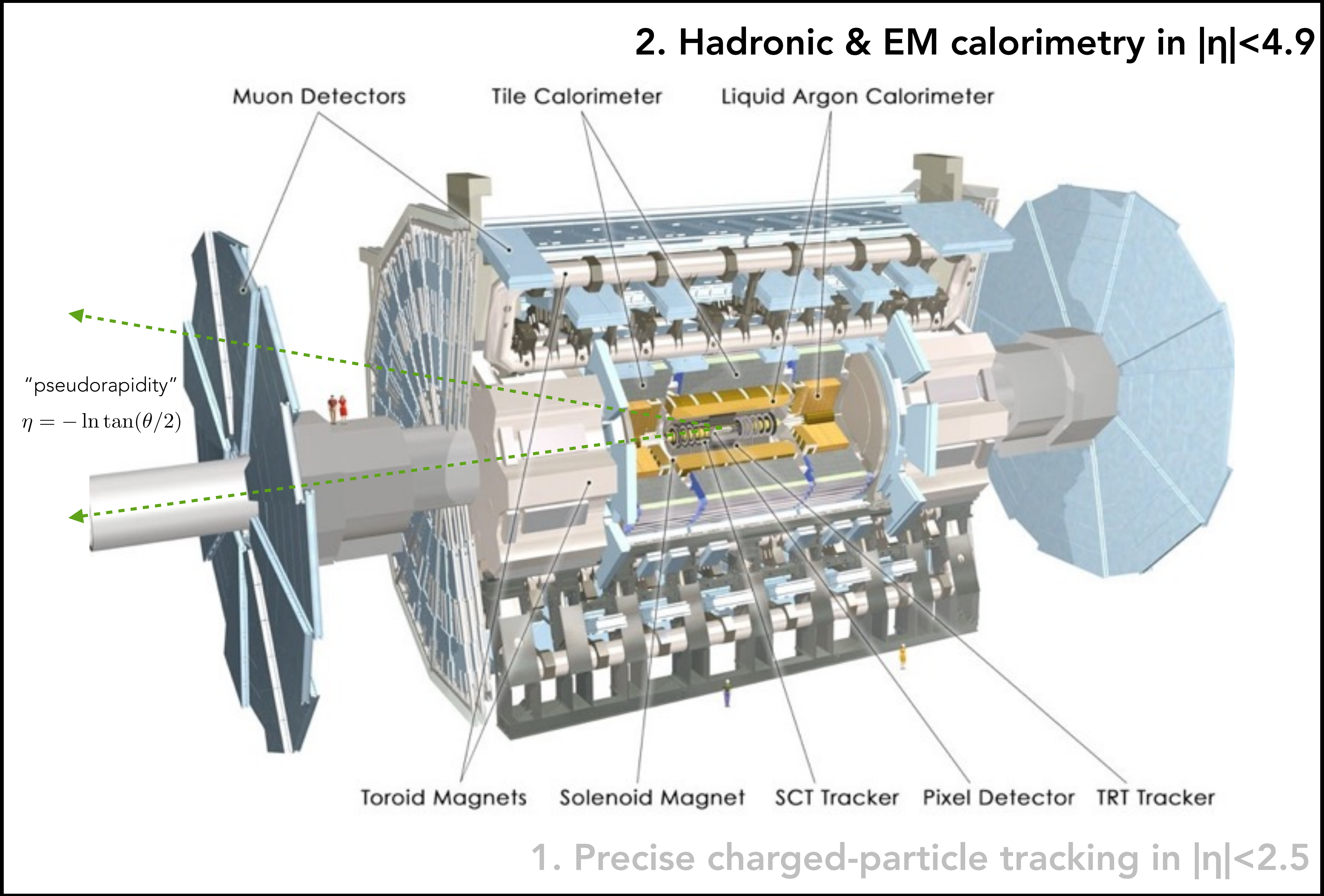
All experiments participating, including LHCb in Run 2

ACT IV: *ATLAS* HI @ THE LHC

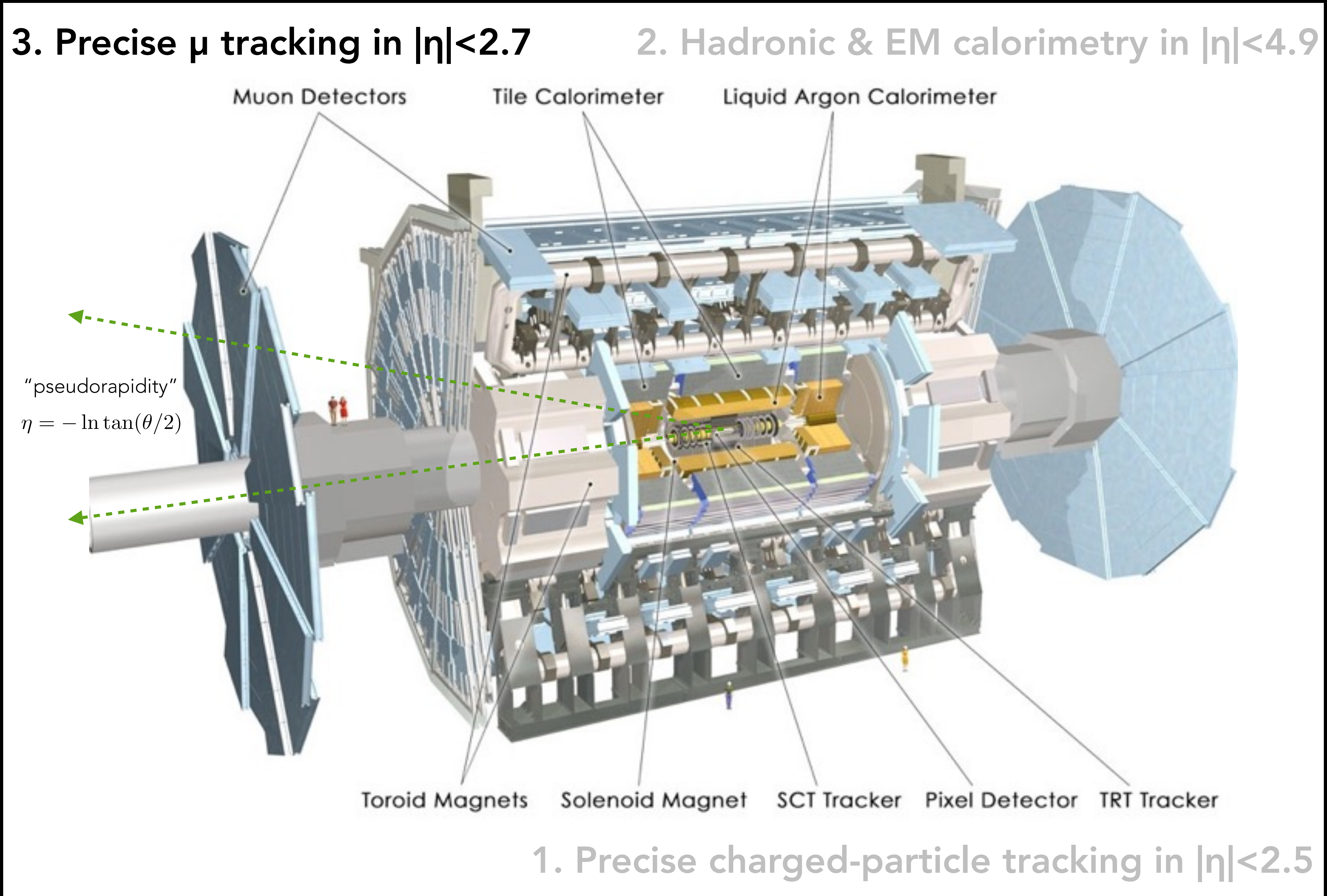


1. Precise charged-particle tracking in |η|<2.5

ACT IV: *ATLAS* HI @ THE LHC

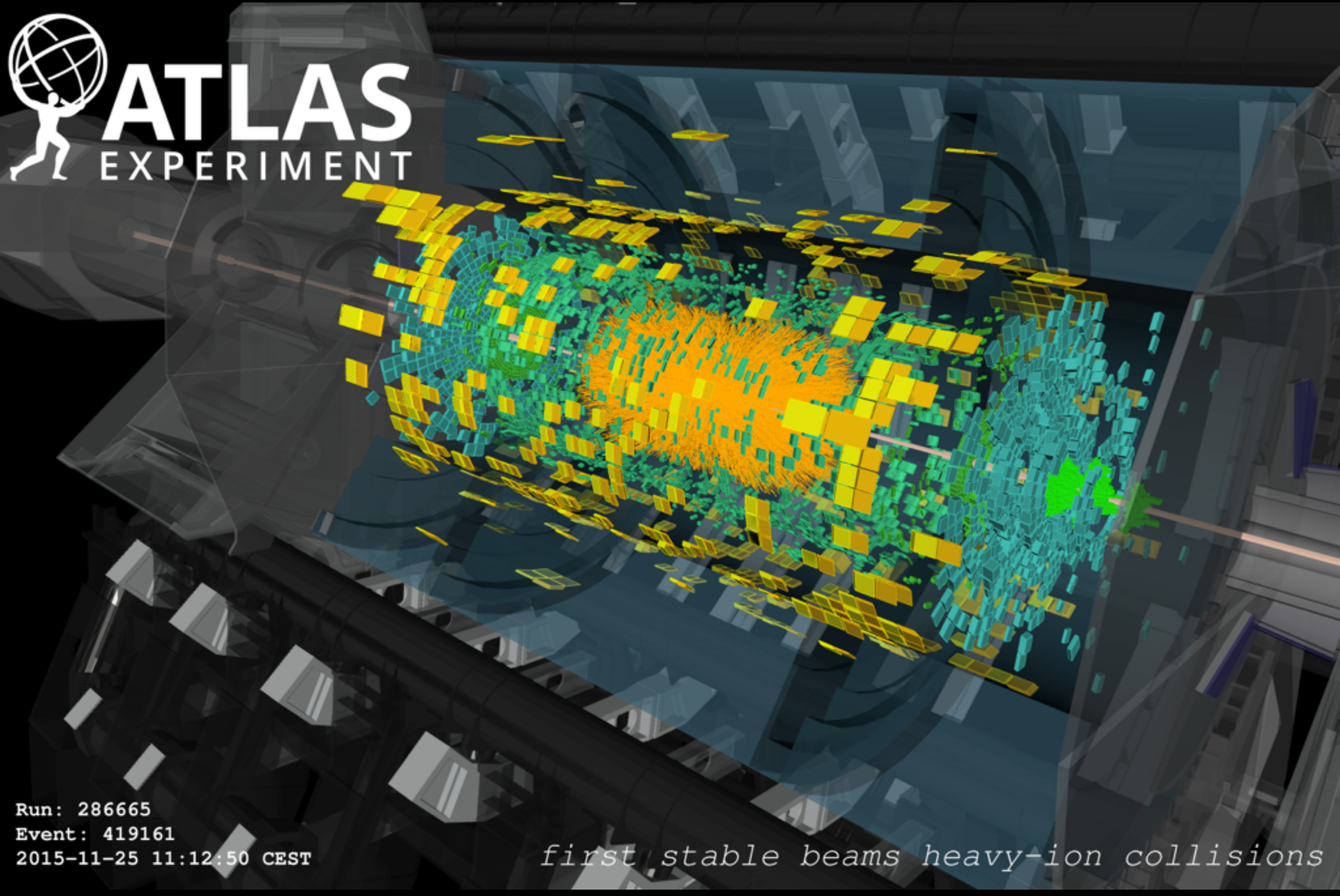


ACT IV: *ATLAS* HI @ THE LHC



by Clea, 6

A RUN 2 PB+PB EVENT



ACT IV: ***ATLAS*** HI @ THE LHC

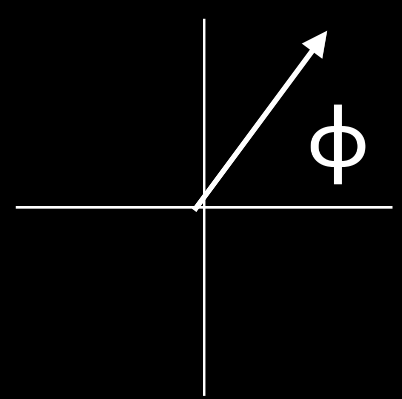
- **Sophisticated detector**
  - Occupancies in silicon, calorimeter, and muon spectrometers are no problem in central Pb+Pb
  - Only the TRT has typical occupancies (>80%) too high for use for most reconstructed tracks

- **Powerful multi-level trigger system**
  - Hardware (L1) triggers for typical collisions, muons, electrons, photons
  - Software-based (HLT) triggering, at nearly-full rate, for selecting events with jets, and even exclusive states
  - Allows utilization of full LHC delivered luminosity

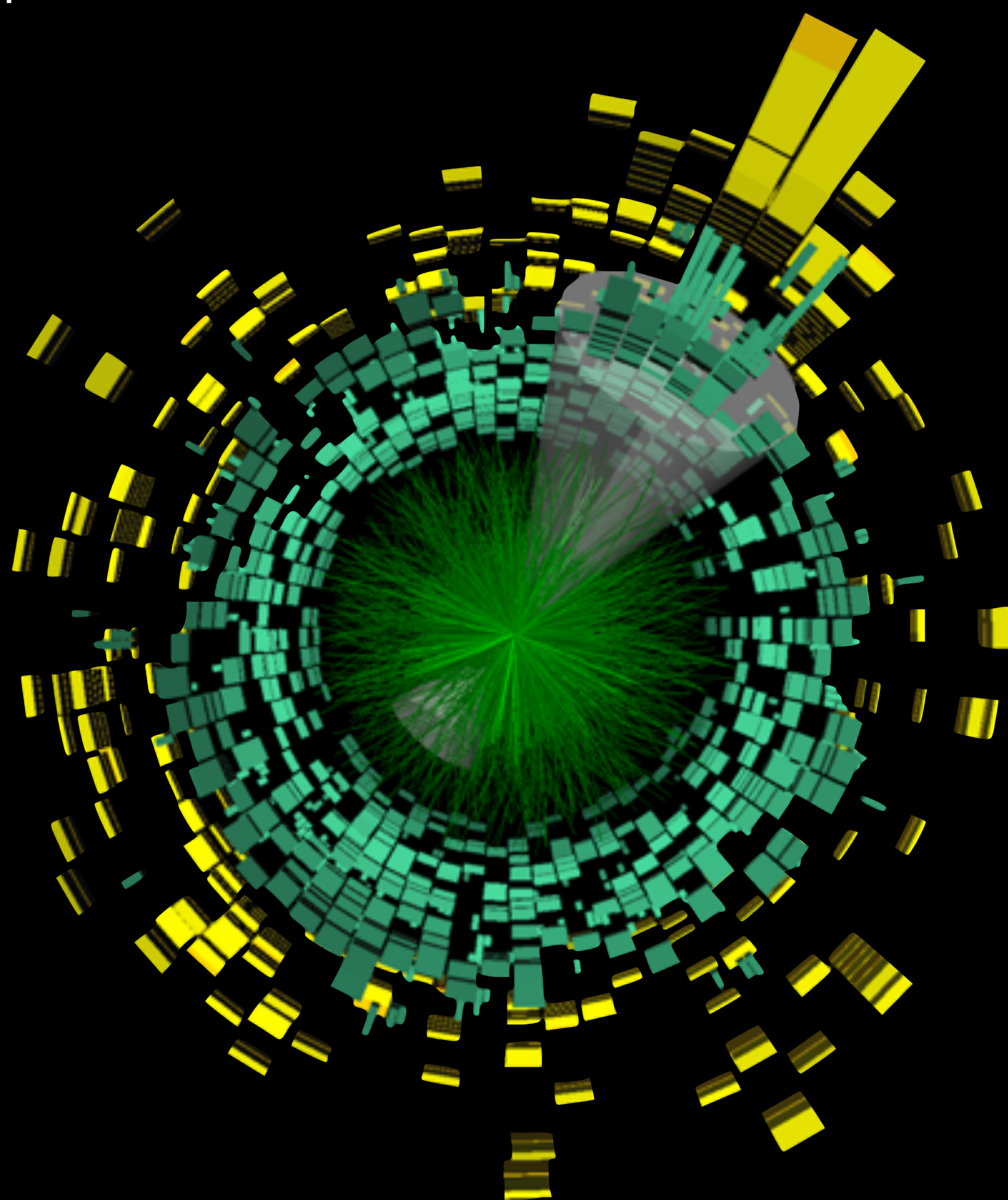
FIRST RESULTS FROM RUN 1 PB+PB

LHC provided first Pb+Pb collisions on Nov 7, 2010.

RHIC provided context of where to look first



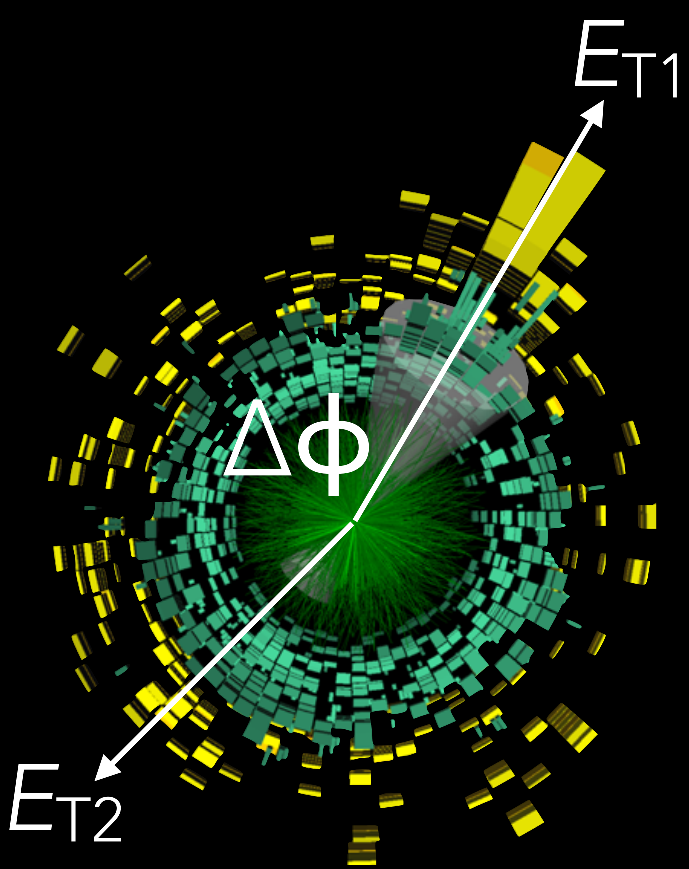
looking
along z direction

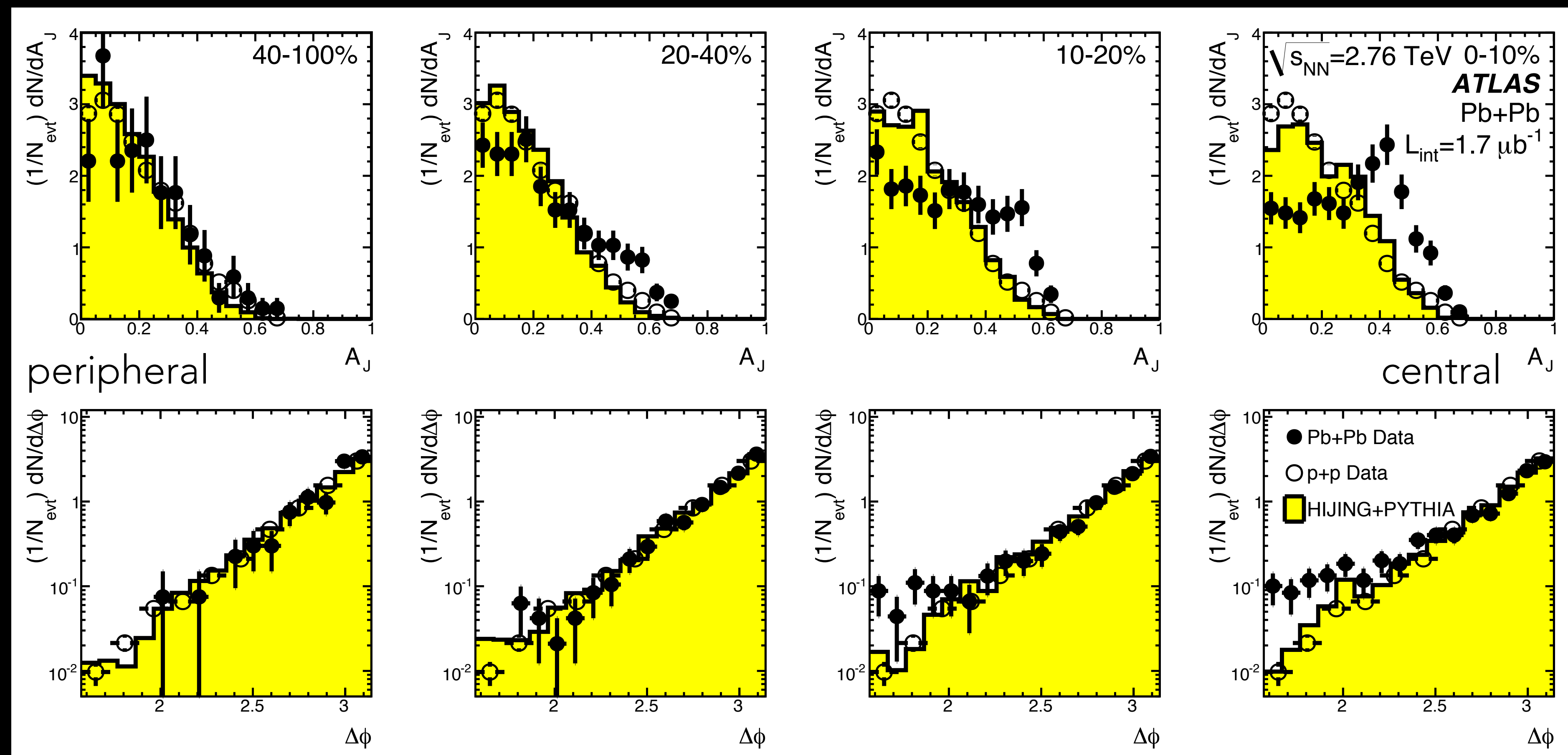


Almost immediately we observed individual collisions in ATLAS with one high p_T jet in the calorimeter, without a clear partner

FIRST DIRECT OBSERVATION OF JET QUENCHING AT THE LHC

PRL 105 (2010) 252303





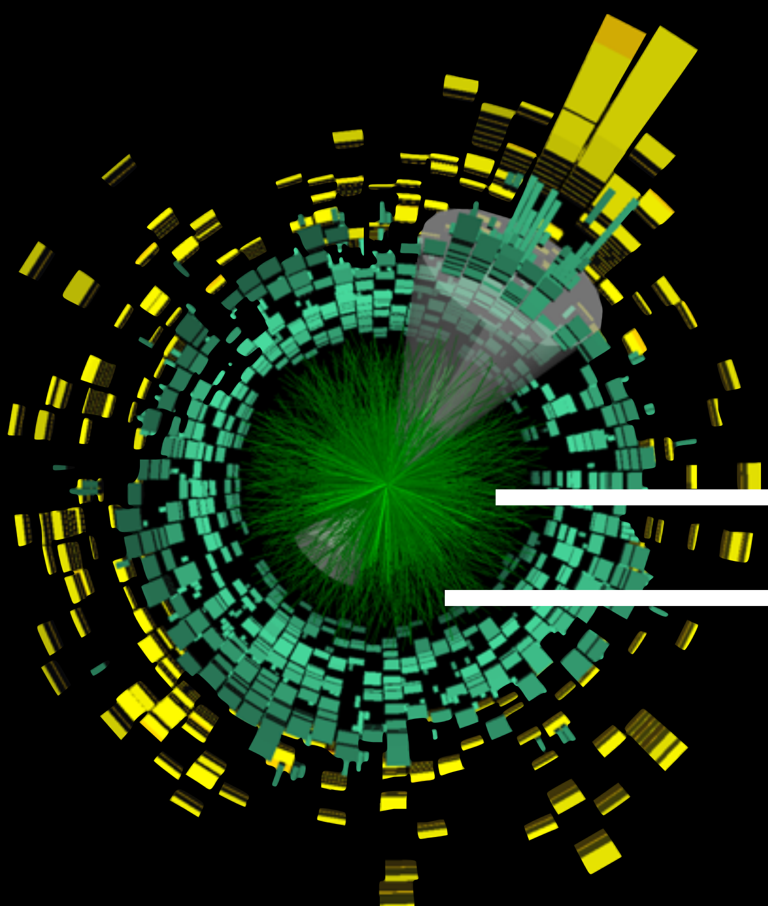
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

"Dijet asymmetry"

In more central collisions,
increasing probability of asymmetric dijet pairs,
relative to expectations from pp or simulated Pb+Pb.

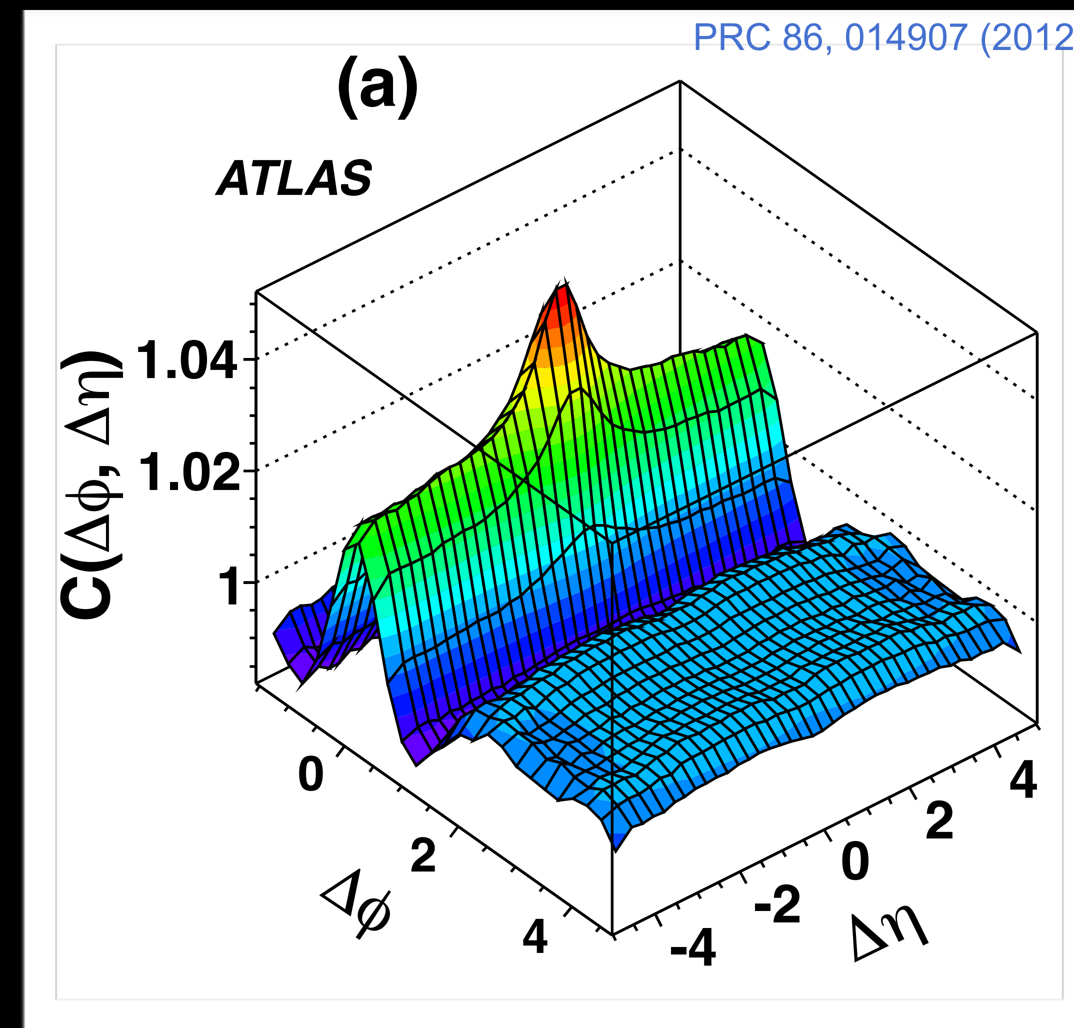
Interestingly, the jets remain back-to-back

COLLECTIVITY IN PB+PB



take **pairs** of charged tracks in ATLAS with e.g. $2 < p_T < 3$ GeV and plot difference (Δ) in η & ϕ

Normalize by choosing partner from a different event with similar features (**background**)



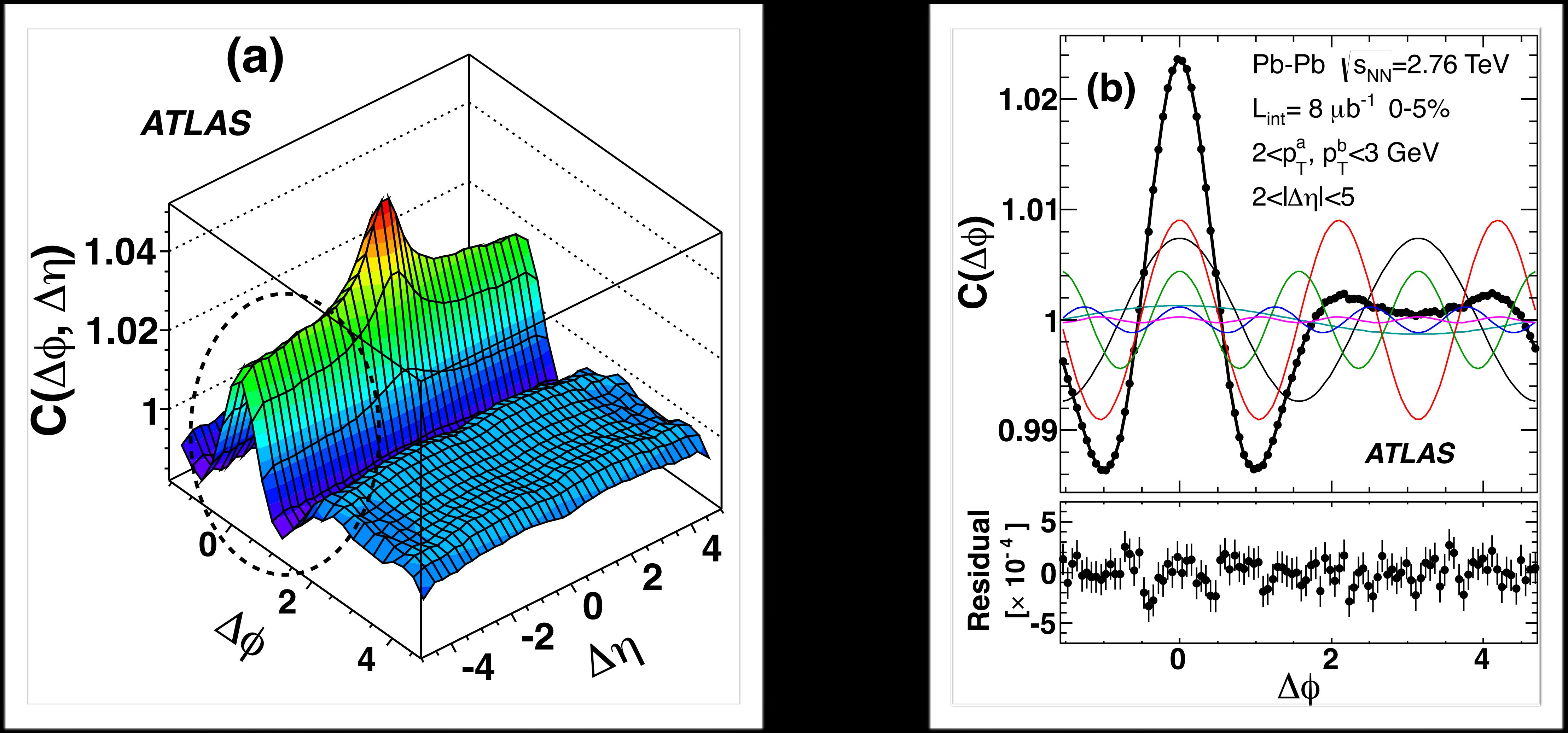
"two-particle correlation function"

$$C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

A huge "ridge" structure at $\Delta\phi$~0

(familiar to pp community from 2010 CMS measurement)

HARMONIC FLOW IN PB+PB



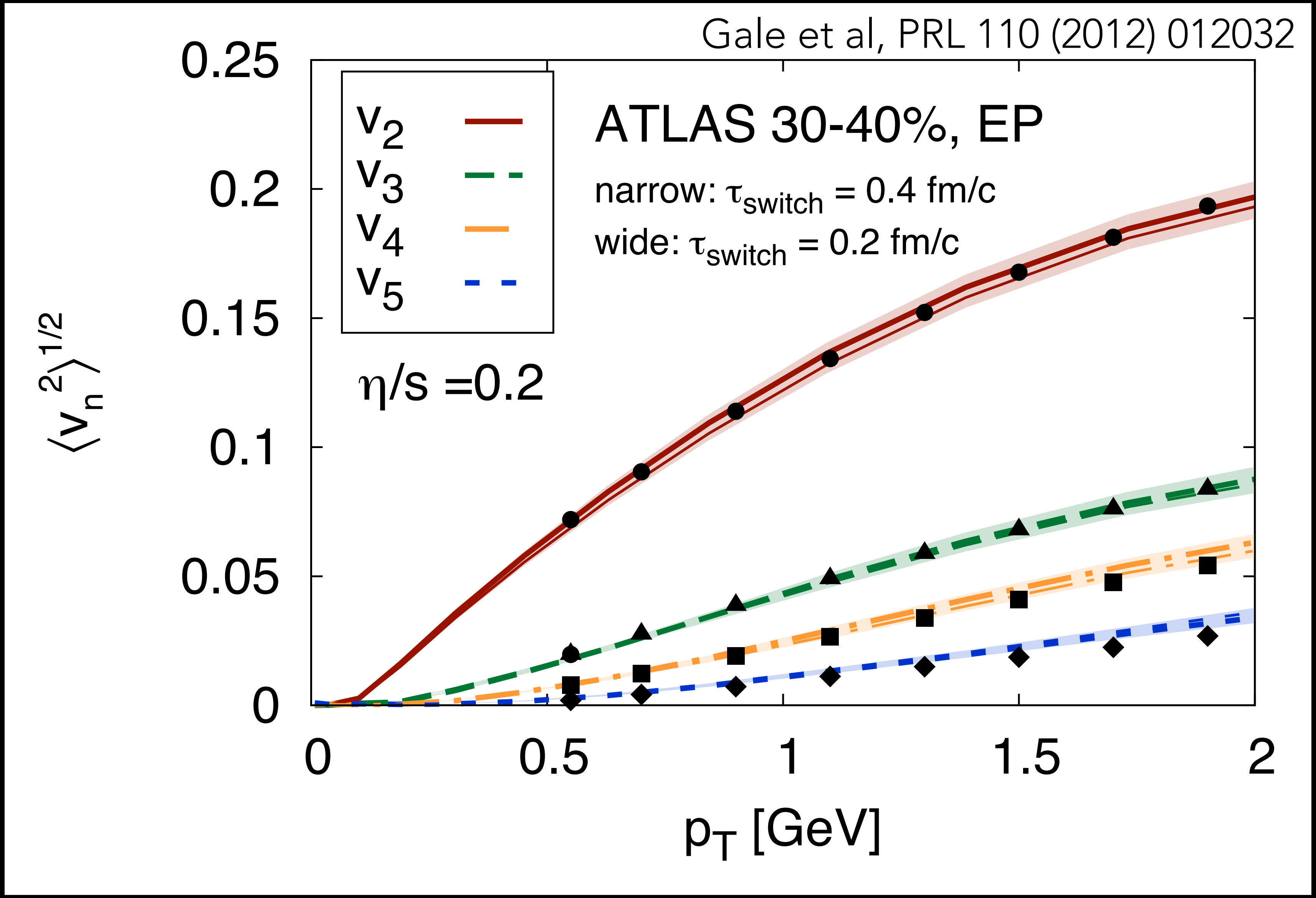
Requiring |η|>2 removes jets

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos(n[\phi - \Psi_n])$$

$$C(\Delta\phi, |\Delta\eta| > 2) = 1 + 2\sum_n v_n^2 \cos(n\Delta\phi)$$

These measurements (& other methods) give v_n out to **n=6**
(& all add coherently at Δ**ϕ**~0 to make the ridge huge)

ESTIMATING VISCOSITY/ENTROPY



Viscous hydro agrees well with LHC experimental data: compared with RHIC (η/s~0.12) suggests rises slowly with √s. Major focus for sPHENIX @ RHIC (2022-)

WITH ONLY ~7 μb^{-1}

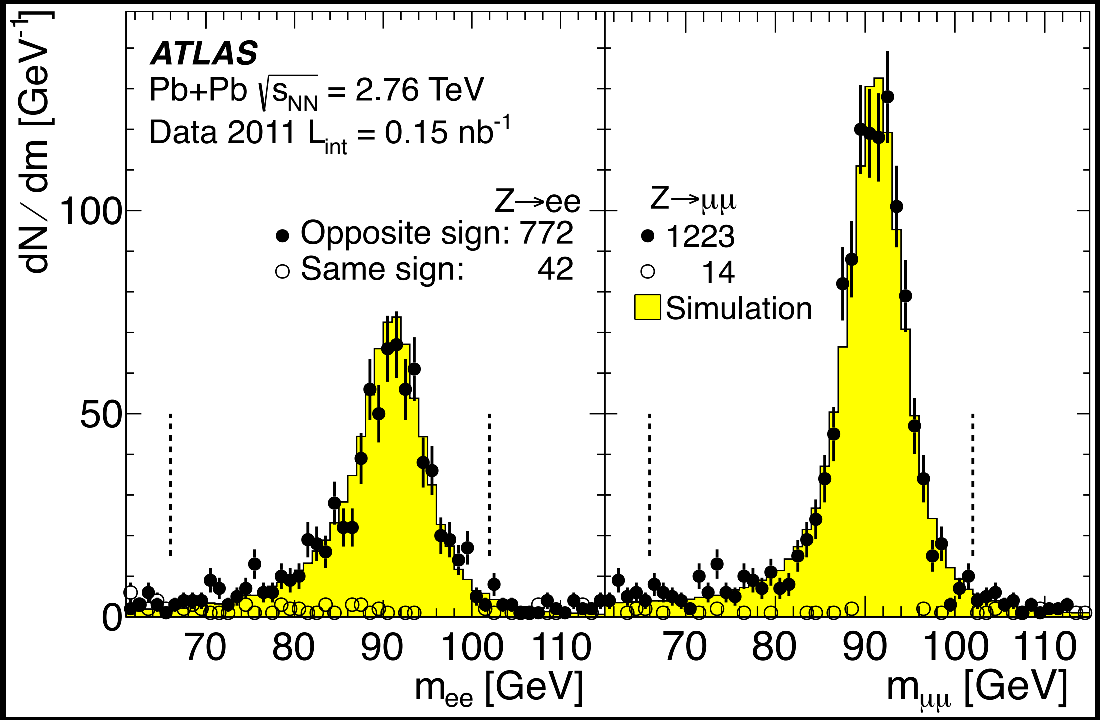
Established the presence of jet quenching

Provided data on collective expansion to constrain the initial conditions and transport properties

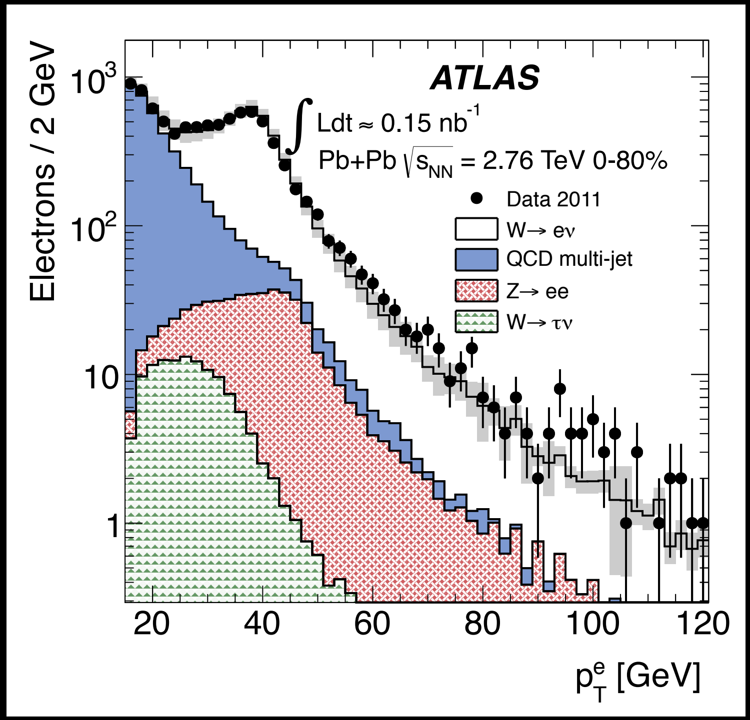
Almost all new heavy ion data
(whether energy, system, or new detectors)
provides striking new insights!

WITH ~150μb^{-1}: ELECTROWEAK PROBES IN RUN 2

Z

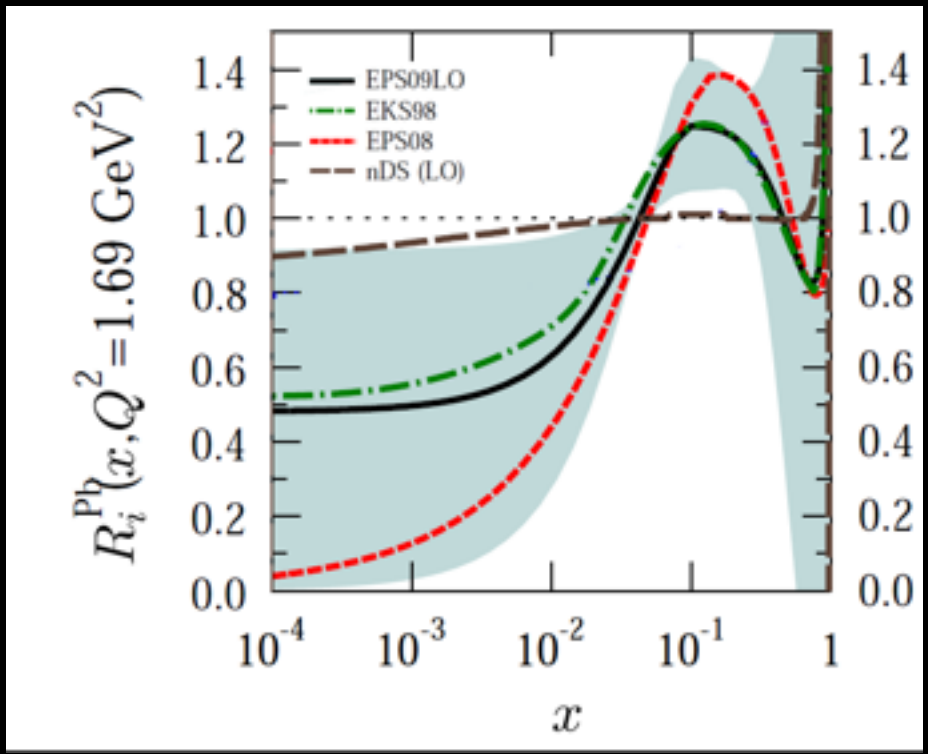


W



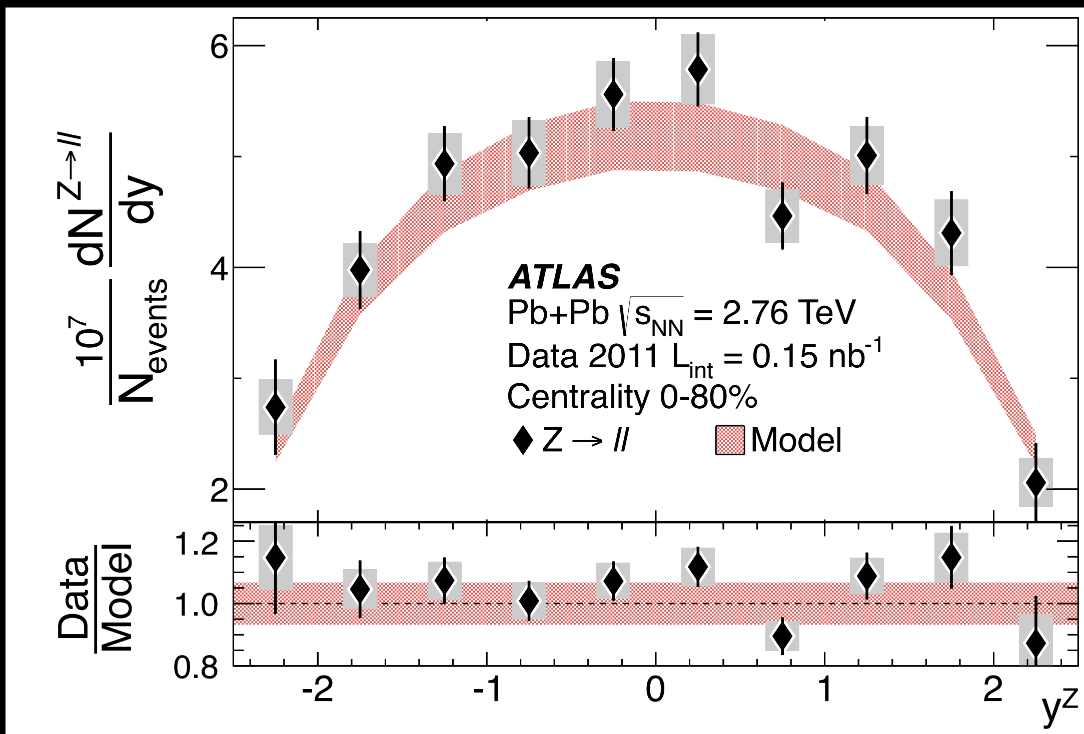
W and Z bosons, measured with leptonic decay modes

Electroweak probes do not couple to QGP: but might expect impact of **nuclear PDF modifications** (depending on initial kinematics)



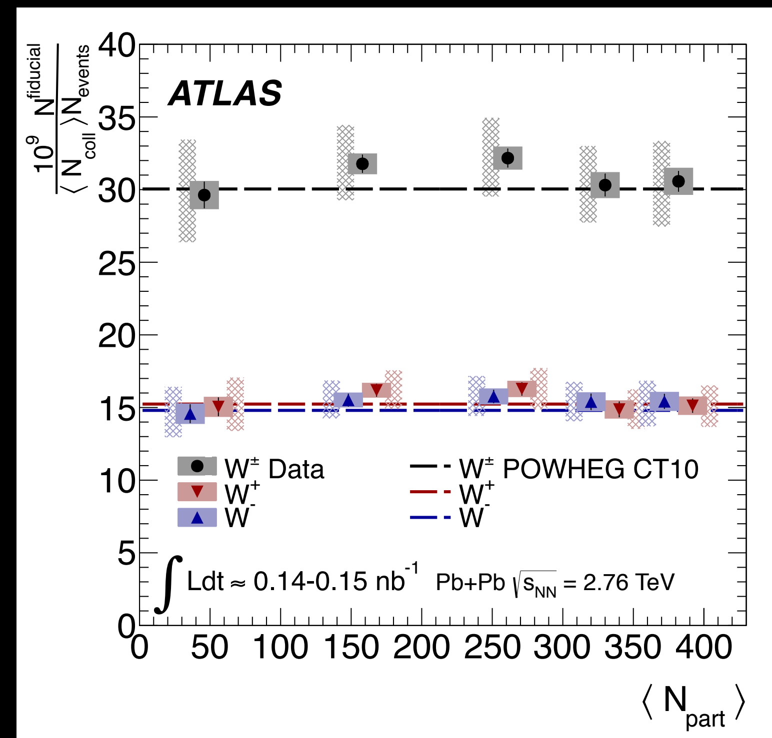
NUCLEAR THICKNESS WITH EW PROBES

Z



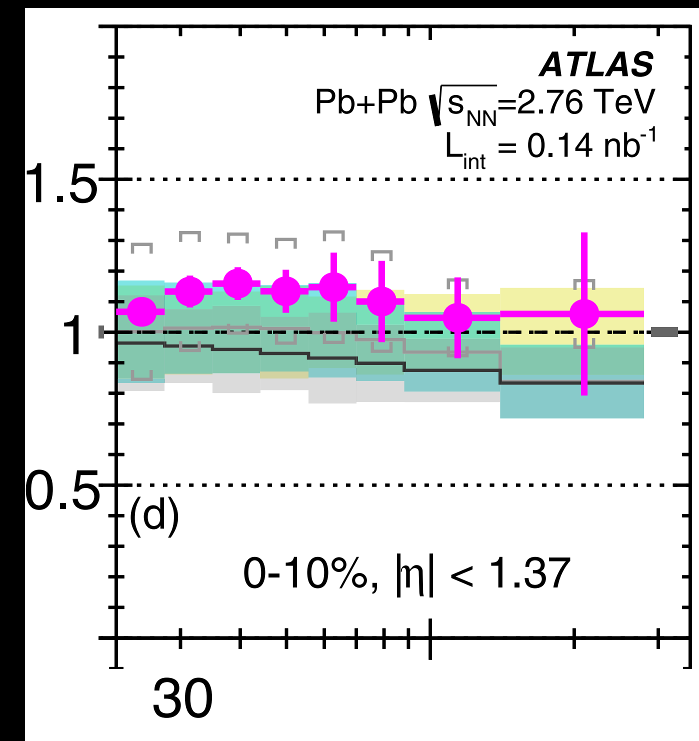
PYTHIA 6.425 rapidity shape scaled up by $\sigma_Z^{NNLO}\langle T_{AA}\rangle$

W



W yields corrected to fiducial region, scaled by N_{coll}

γ

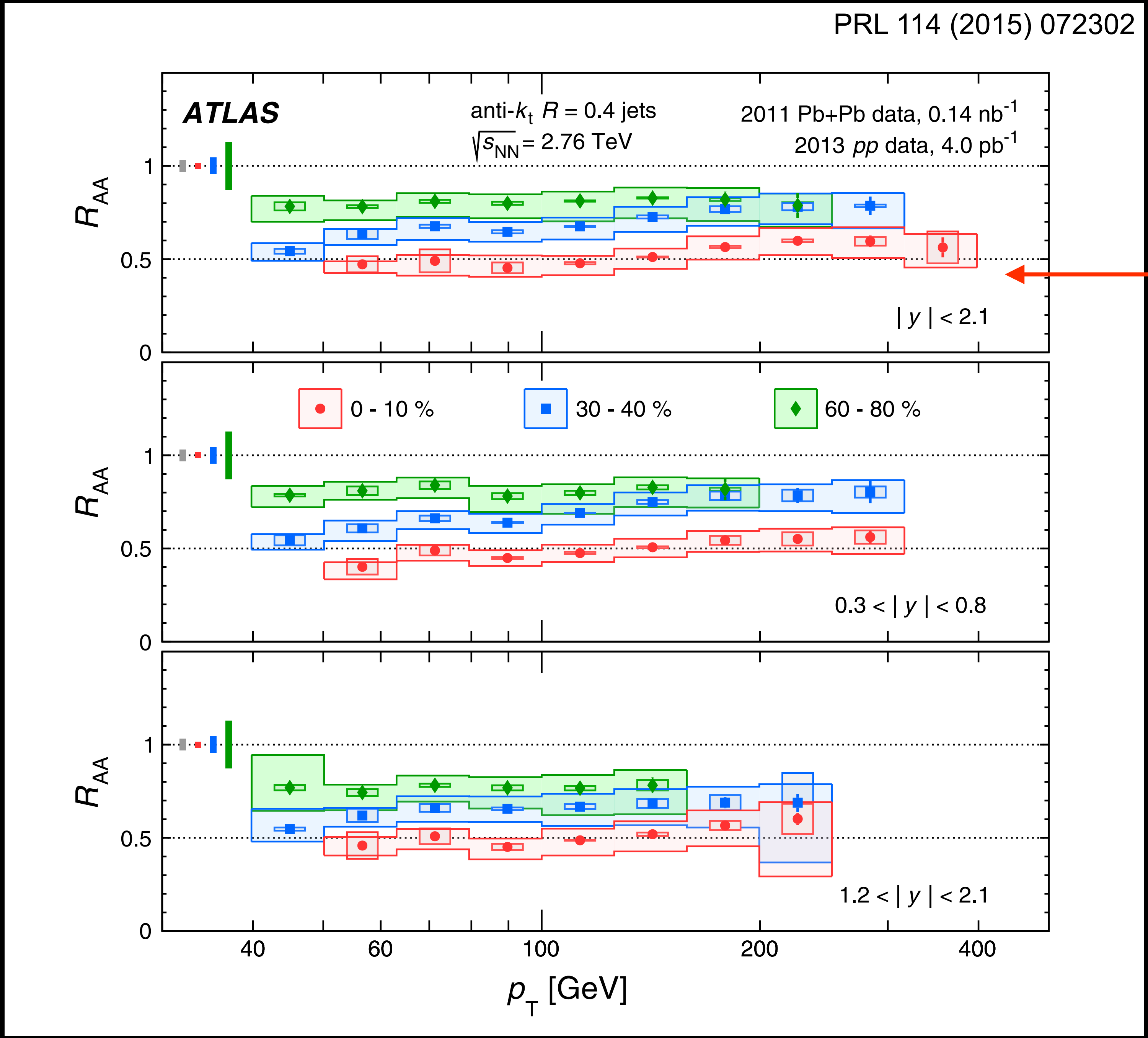


Photon yields, scaled by $\langle T_{AA}\rangle$, compared to pQCD

Geometry is under control, but no strong modifications observed: Standard Model works very well for HI.

With increased precision, look for small nPDF effects in Run 2

JET SUPPRESSION



x2 suppression

in more central events

Slow rise

with increasing jet p_T

Weak dependence

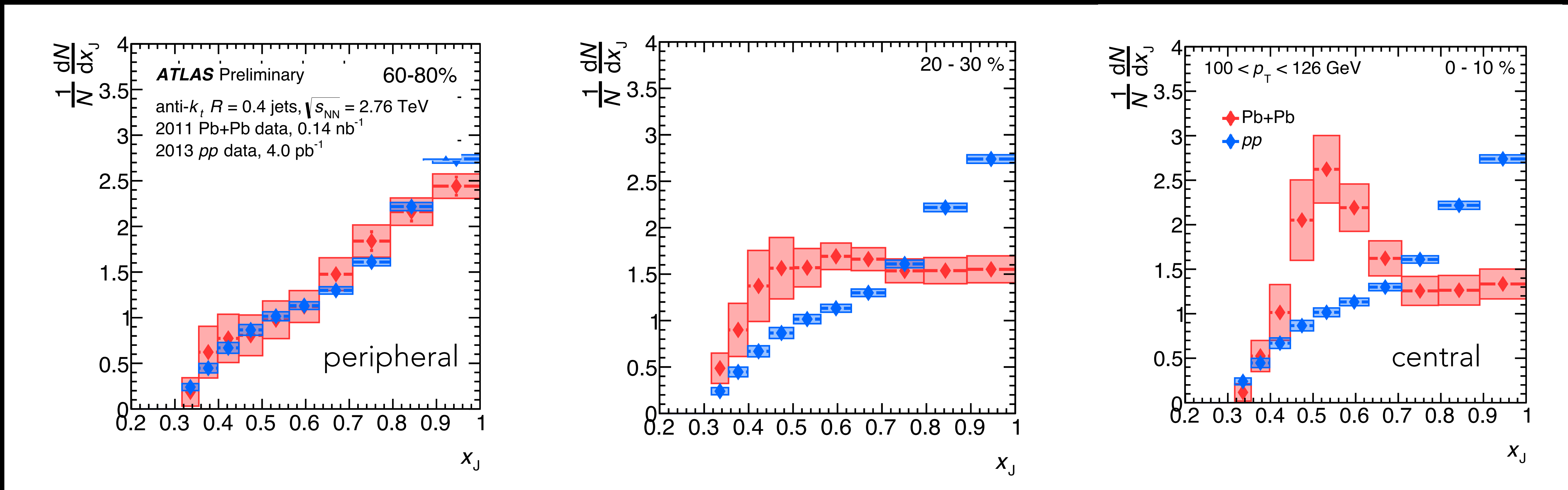
on jet rapidity

Surprisingly little variation with p_T or y:

Increased fraction of q jets compensate more-steeply falling spectrum?

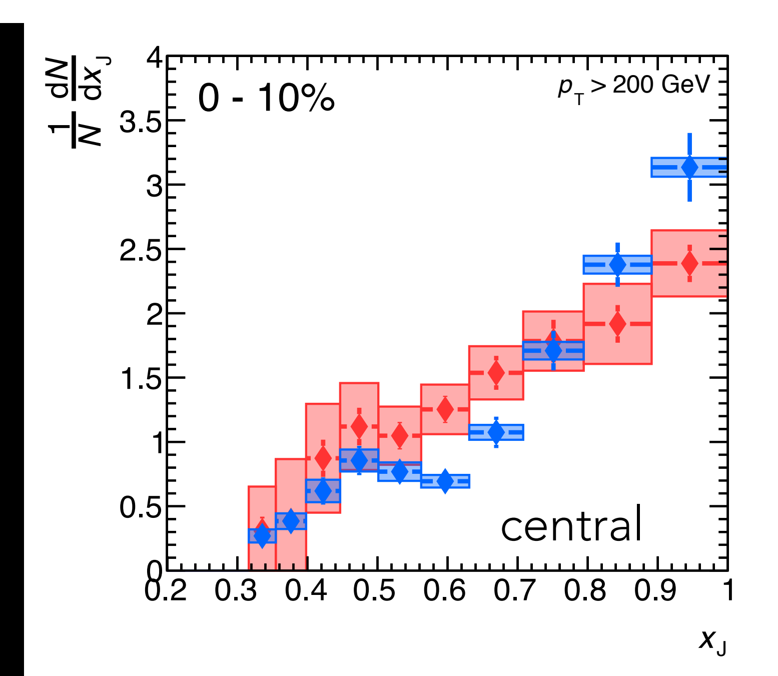
UPDATED DIJET ASYMMETRY

ATLAS-CONF-2015-052

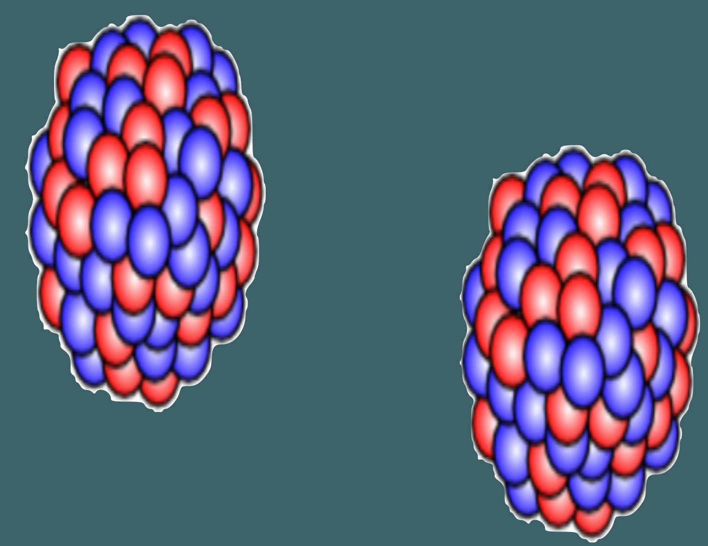


Dijet asymmetry updated (more sophisticated analysis procedure!) as measurement of $x_J = p_{T2}/p_{T1}$

Surprising **peak structure** at **x_J~0.5** in 0-10%, disappearing in peripheral events, and when p_{T1} > 200 GeV

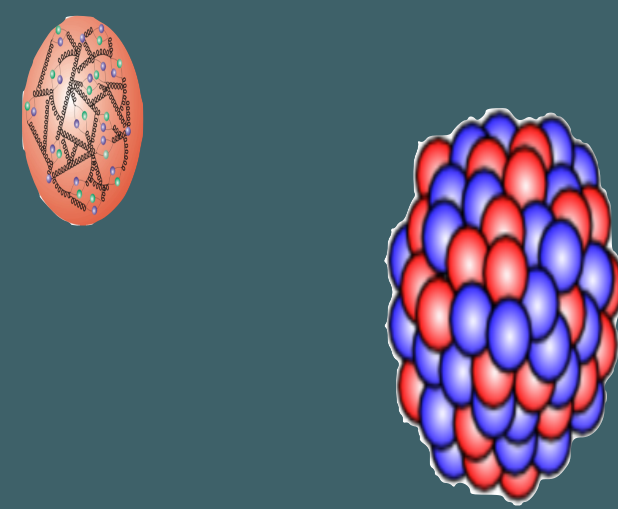


FINALE: A TALE OF THREE SYSTEMS

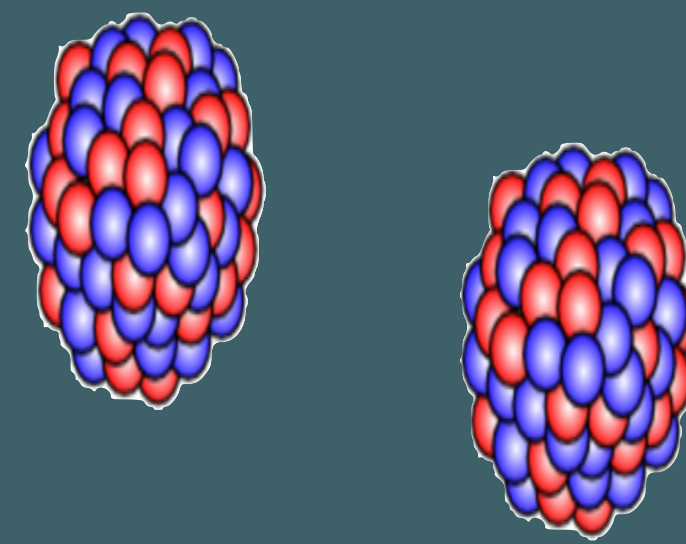


Pb+Pb

FINALE: A TALE OF THREE SYSTEMS



p+Pb



Pb+Pb

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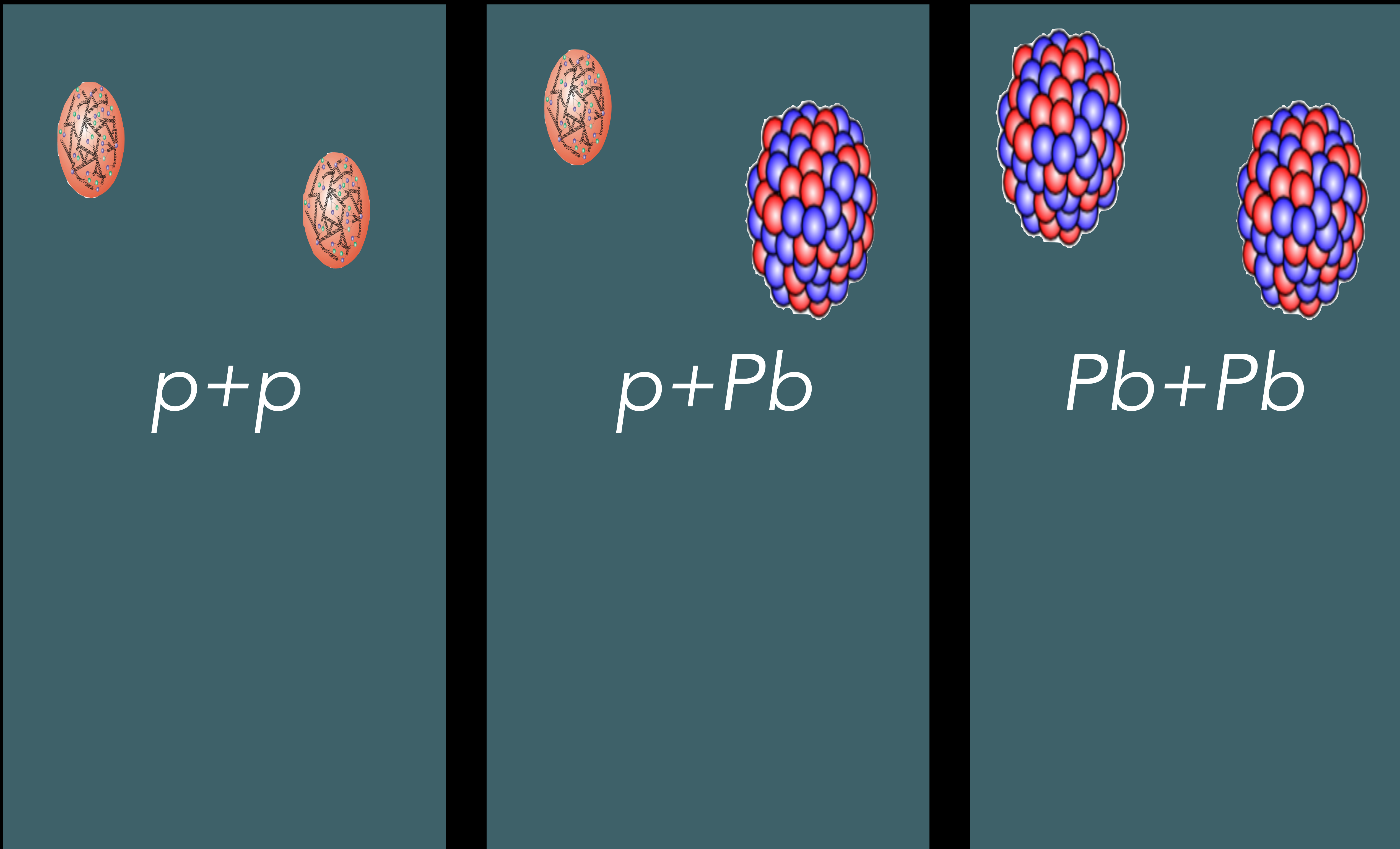
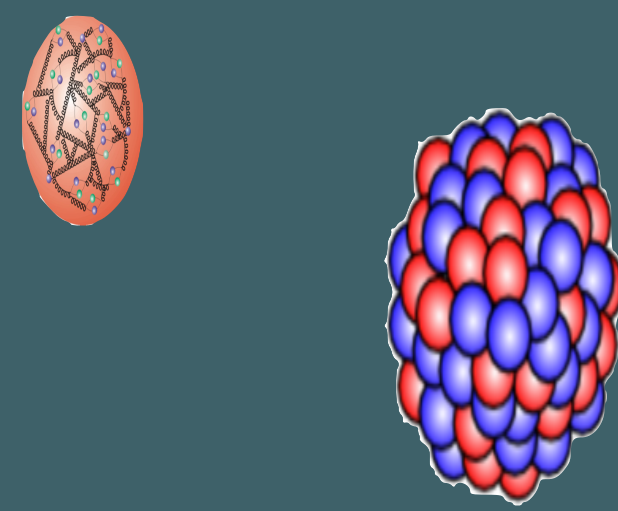


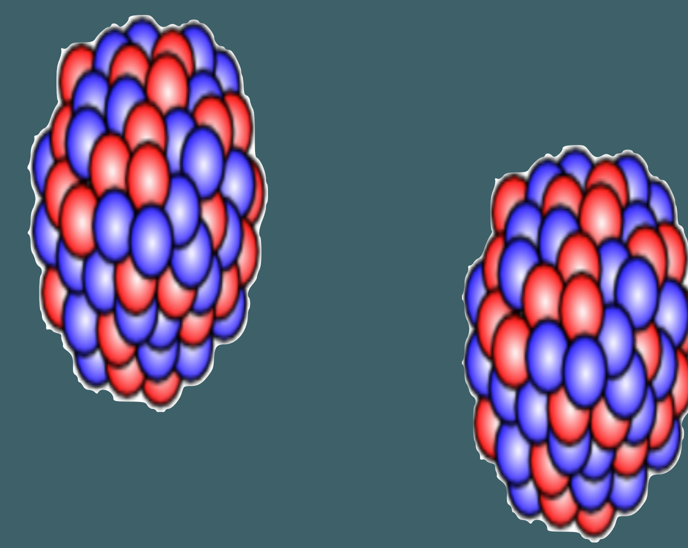
FINALE: A TALE OF THREE SYSTEMS

We have established collective behavior in Pb+Pb,
associated with the “ridge” structure near $\Delta\phi=0$:

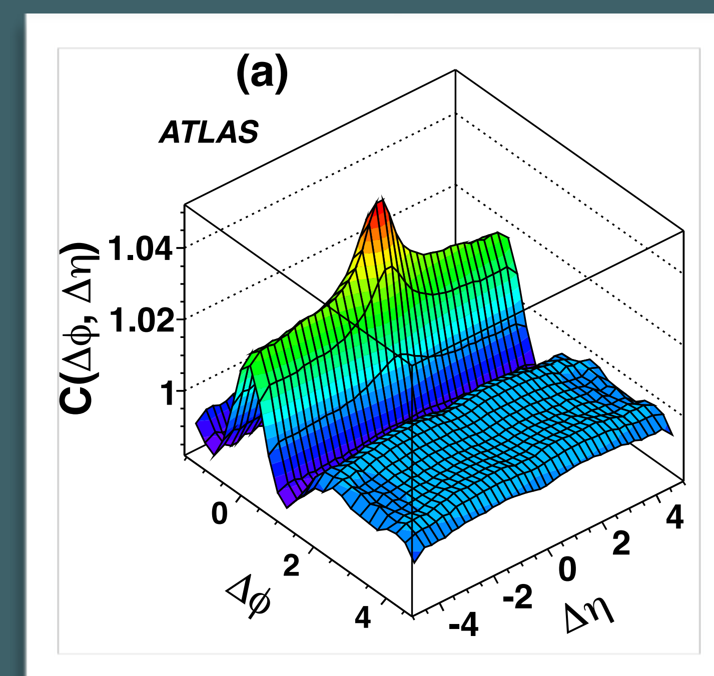
p+p



p+Pb



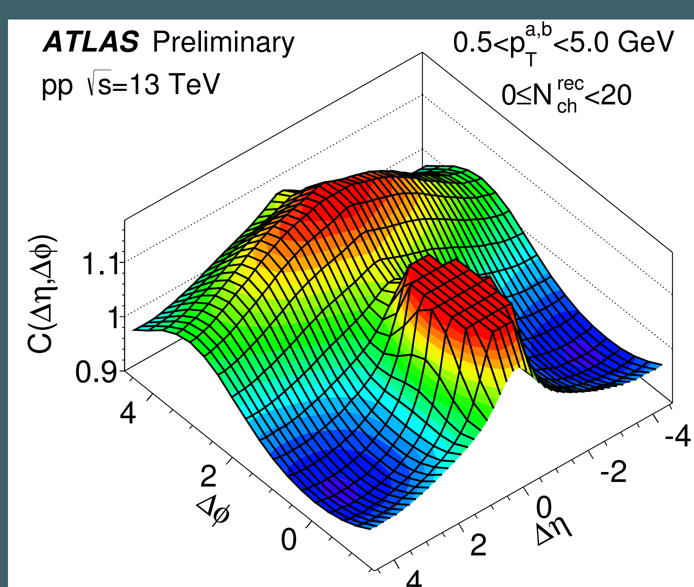
Pb+Pb

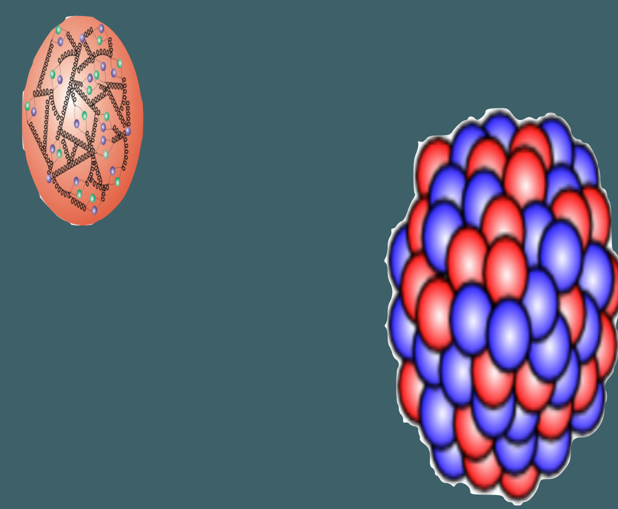


FINALE: A TALE OF THREE SYSTEMS

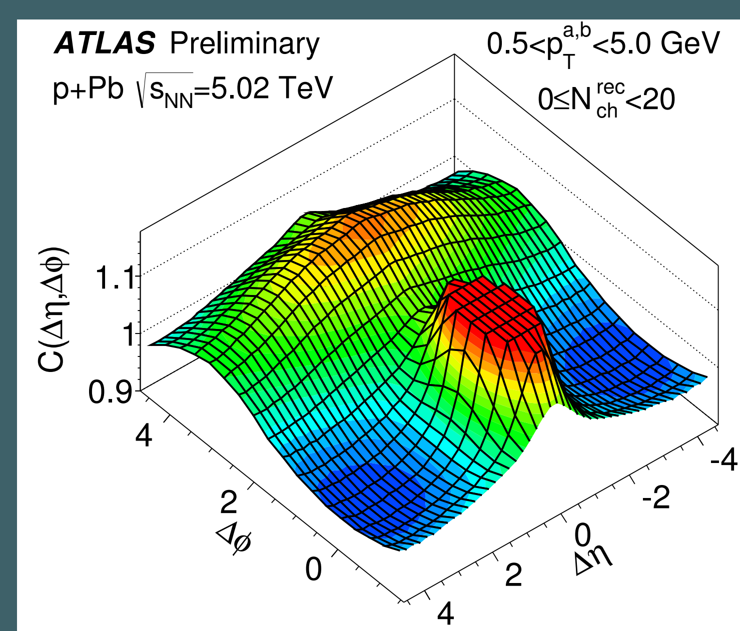
We have established collective behavior in Pb+Pb,
what about smaller systems?

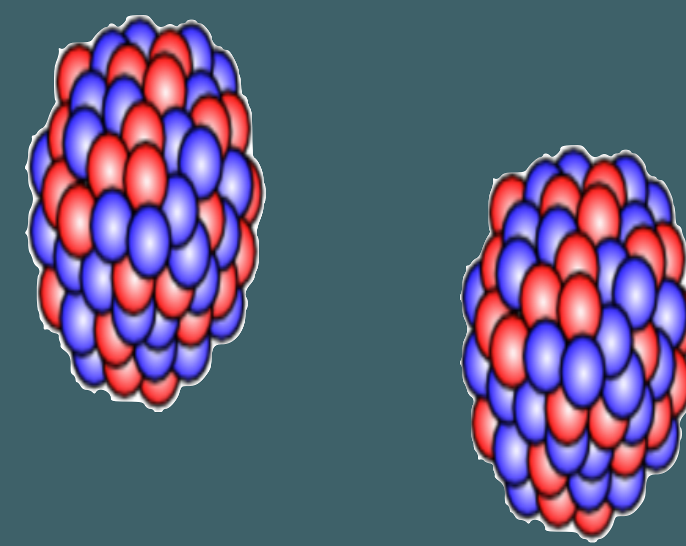
p+p



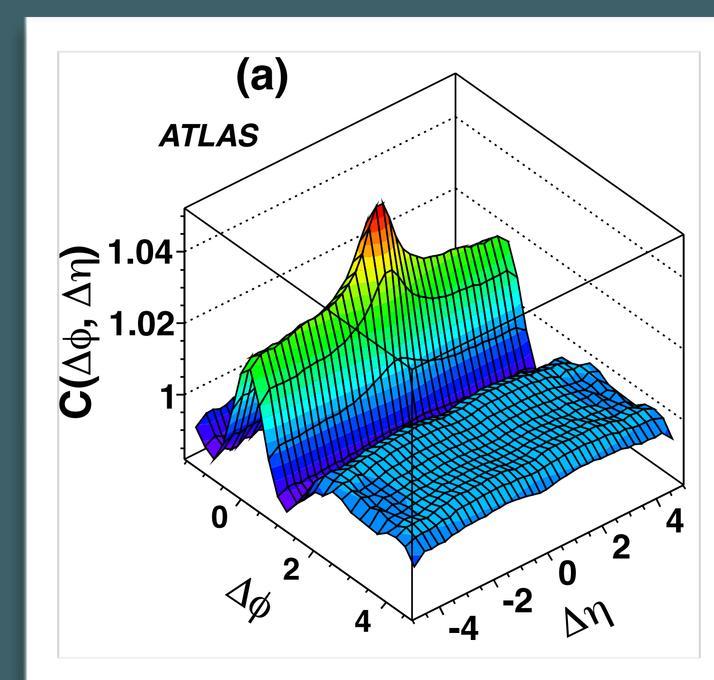


p+Pb





Pb+Pb

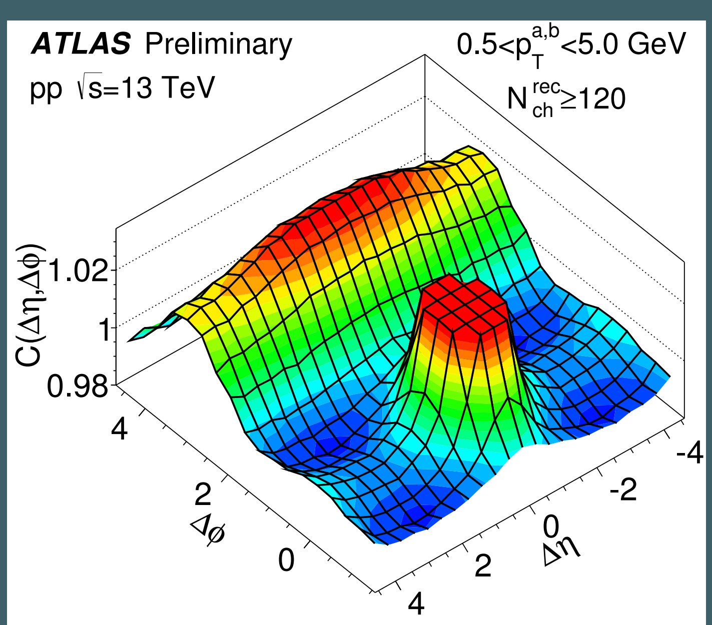


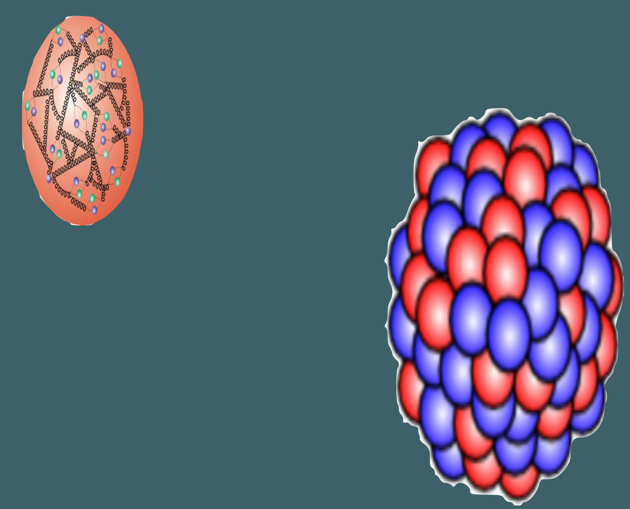
For "peripheral" p+p & p+Pb, no long range behavior at Δϕ=0

FINALE: A TALE OF THREE SYSTEMS

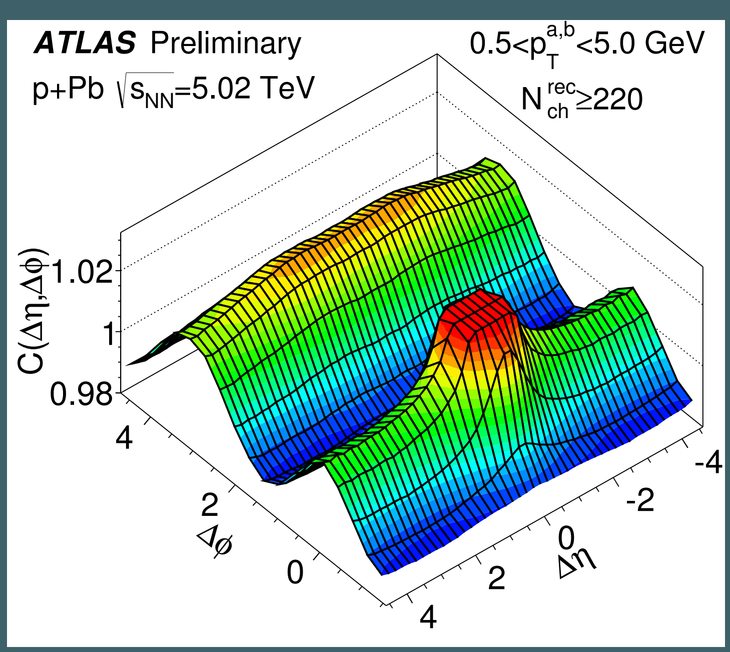
We have established collective behavior in Pb+Pb,
what about smaller systems?

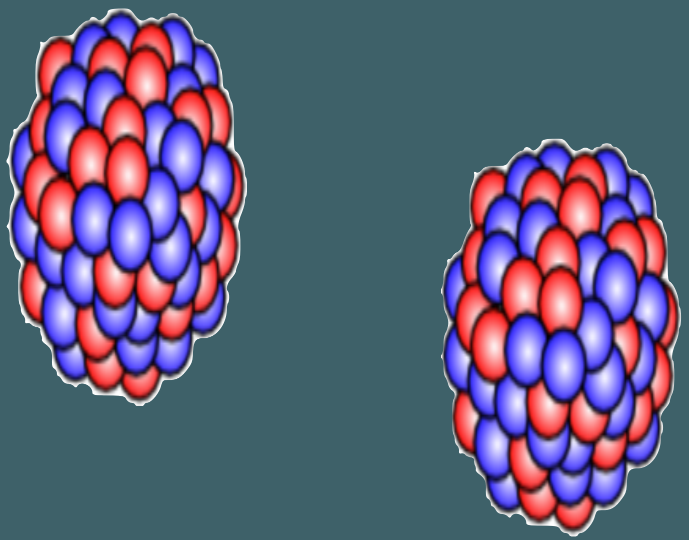
p+p



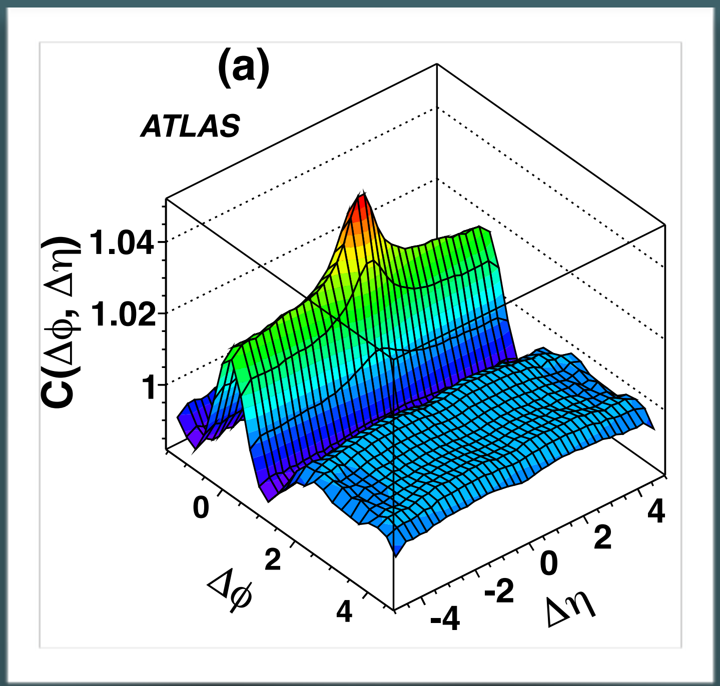


p+Pb





Pb+Pb



Increase the multiplicity, and a "ridge" appears!

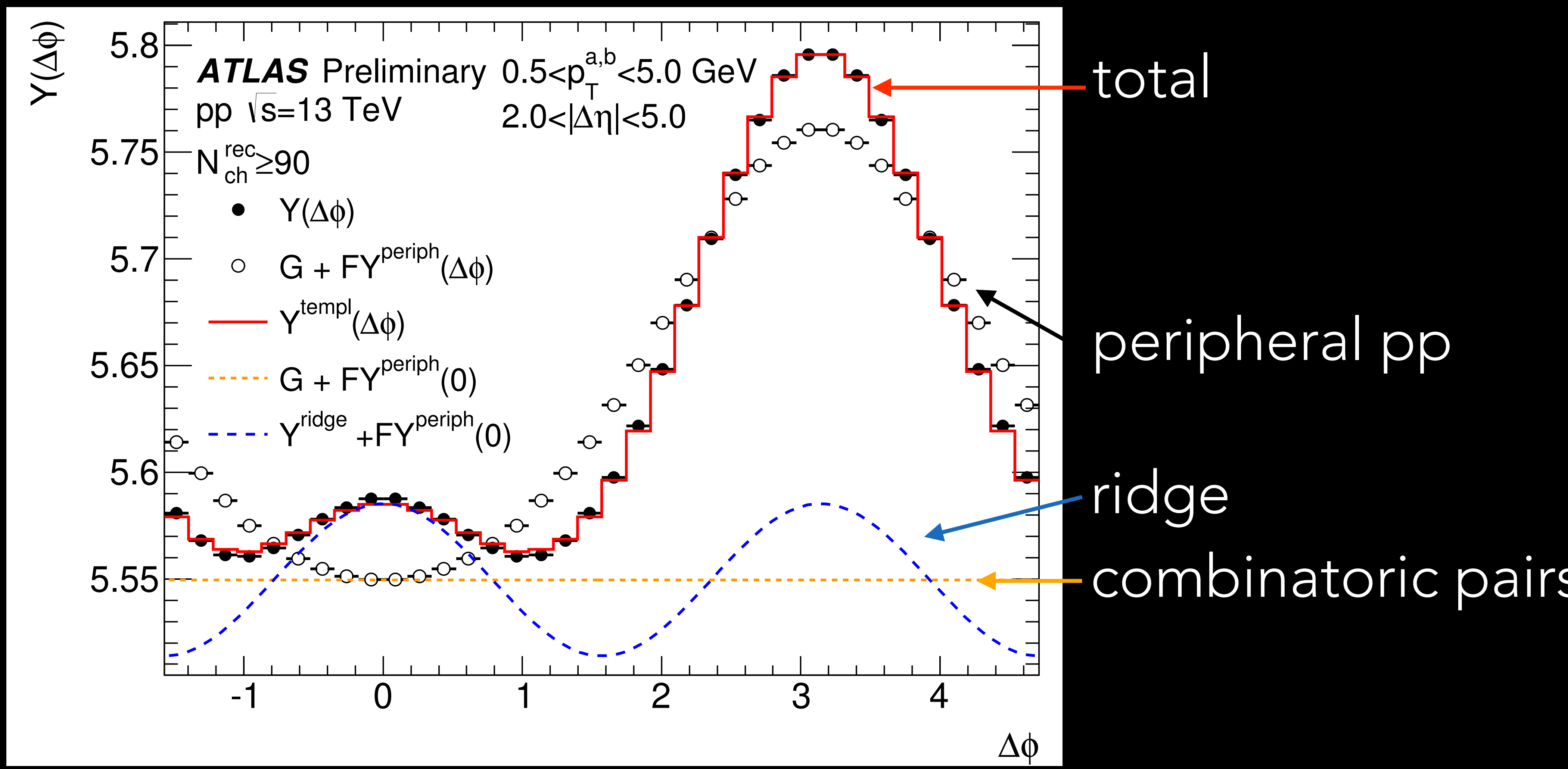
“EXCAVATING” THE RIDGE

PRL 116, 172301 (2016)
ATLAS-CONF-2016-025

Does the ridge really disappear at low multiplicities?
(as CMS reported in 2010)

RIDGE "EXCAVATION"

PRL 116, 172301 (2016)
ATLAS-CONF-2016-025



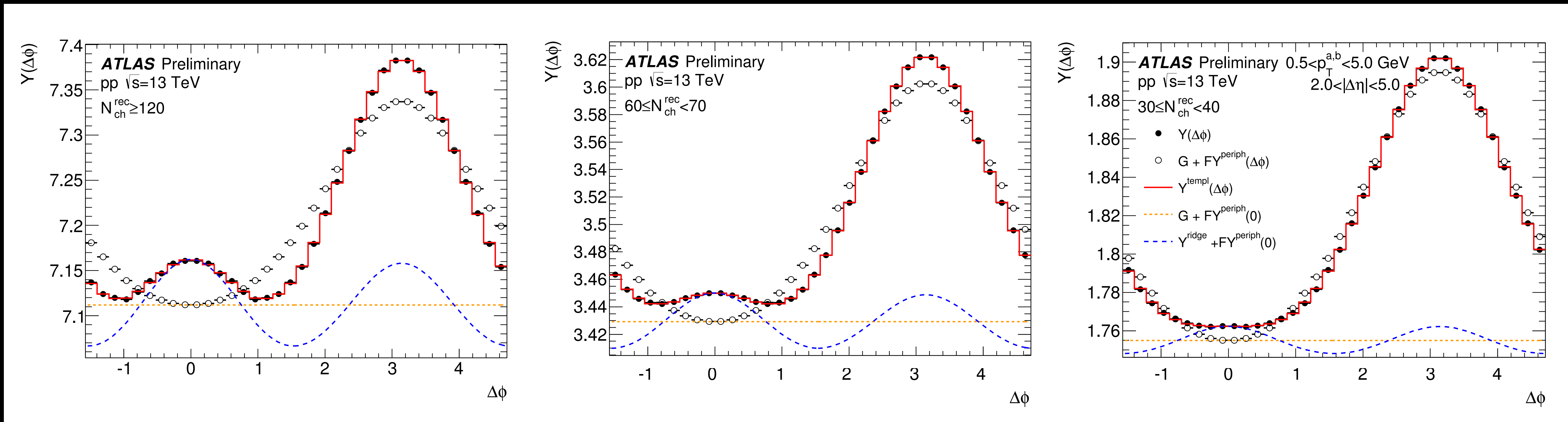
ATLAS fit procedure, decomposes per-trigger yield (~B×C)

YIELD IN "PERIPHERAL" PP	RIDGE (SINUSOIDAL)	COMBINATORIC

Unexpectedly provides explanation for narrowing around Δϕ~π

RIDGE "EXCAVATION"

PRL 116, 172301 (2016)
ATLAS-CONF-2016-025



High multiplicity | Medium multiplicity | Low multiplicity

Sinusoid term needed for **all** multiplicities, even when ridge **seems** to disappear for low N_{ch}

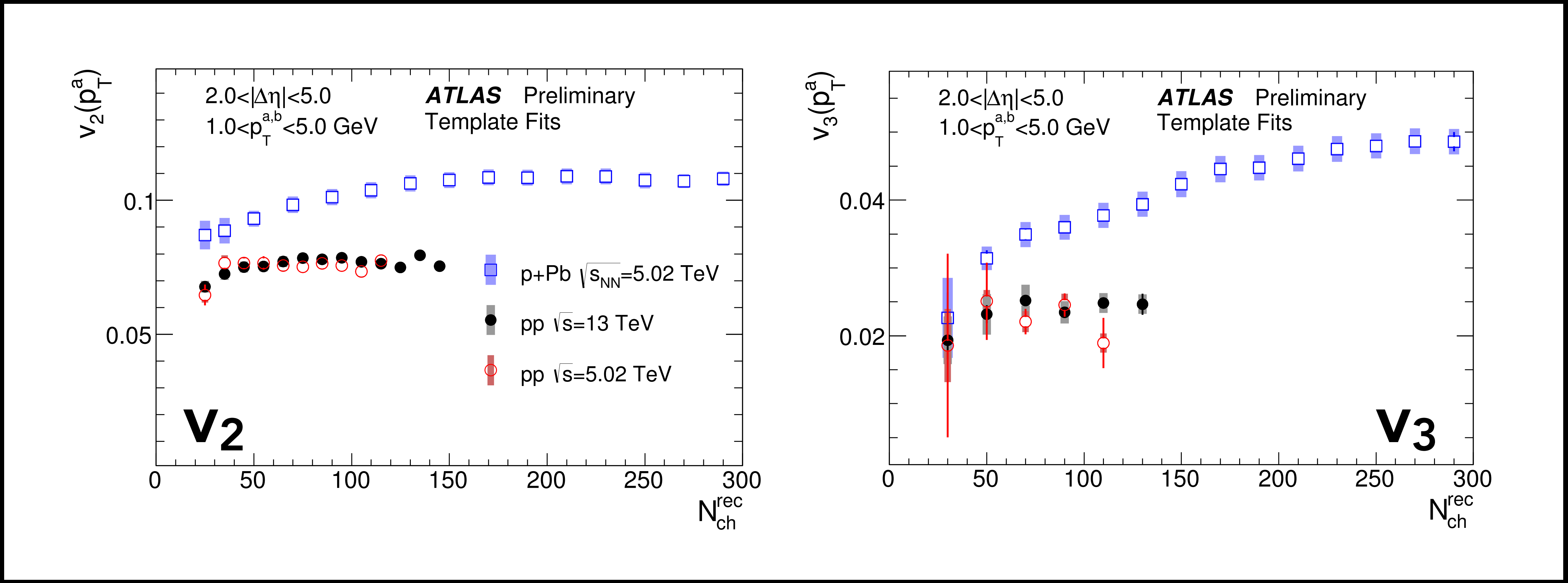
YIELD IN "PERIPHERAL" PP

RIDGE (SINUSOIDAL)

COMBINATORIC

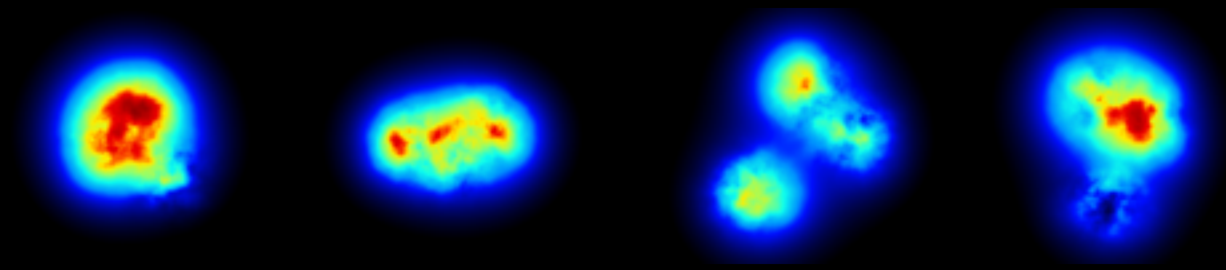
HARMONIC FLOW IN PP?

PRL 116, 172301 (2016)
ATLAS-CONF-2016-025



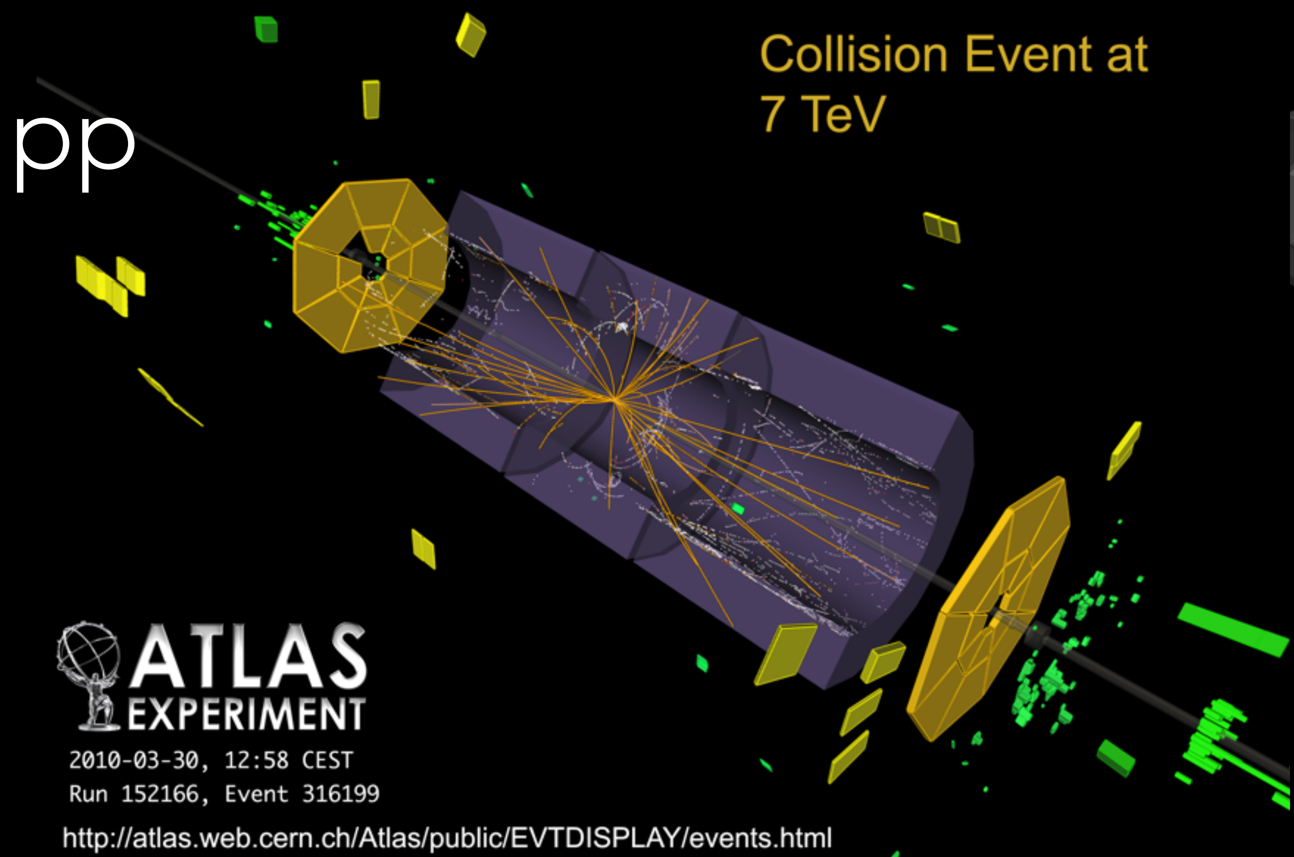
Sinusoid term in pp underlying event persists to lower multiplicities!
Are all pp collisions "collective" at some level?

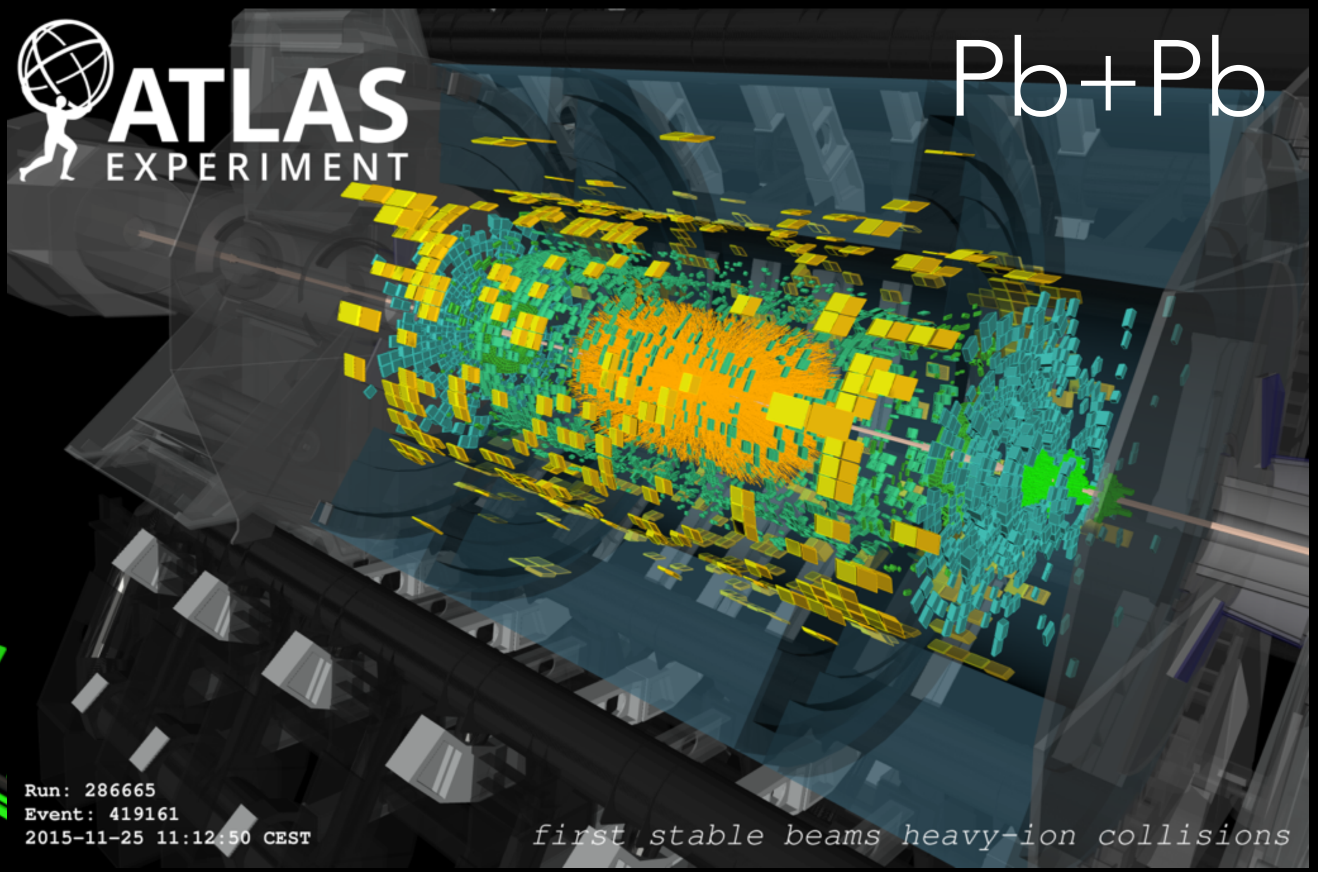
New questions: what is the "shape" of a proton?
Does it fluctuate event to event?



examples from Schenke, arXiv:1603.04349

FIN: BACK TO THE FUTURE

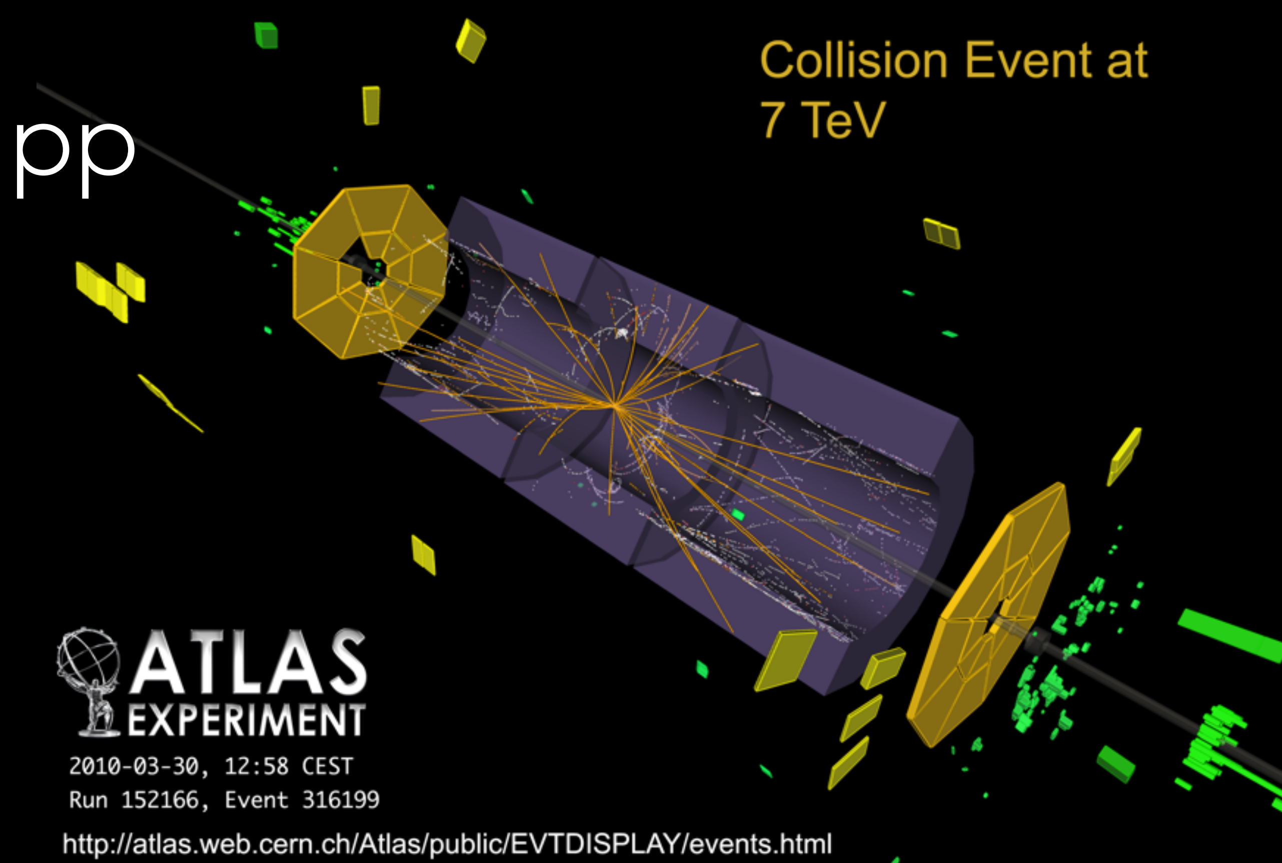


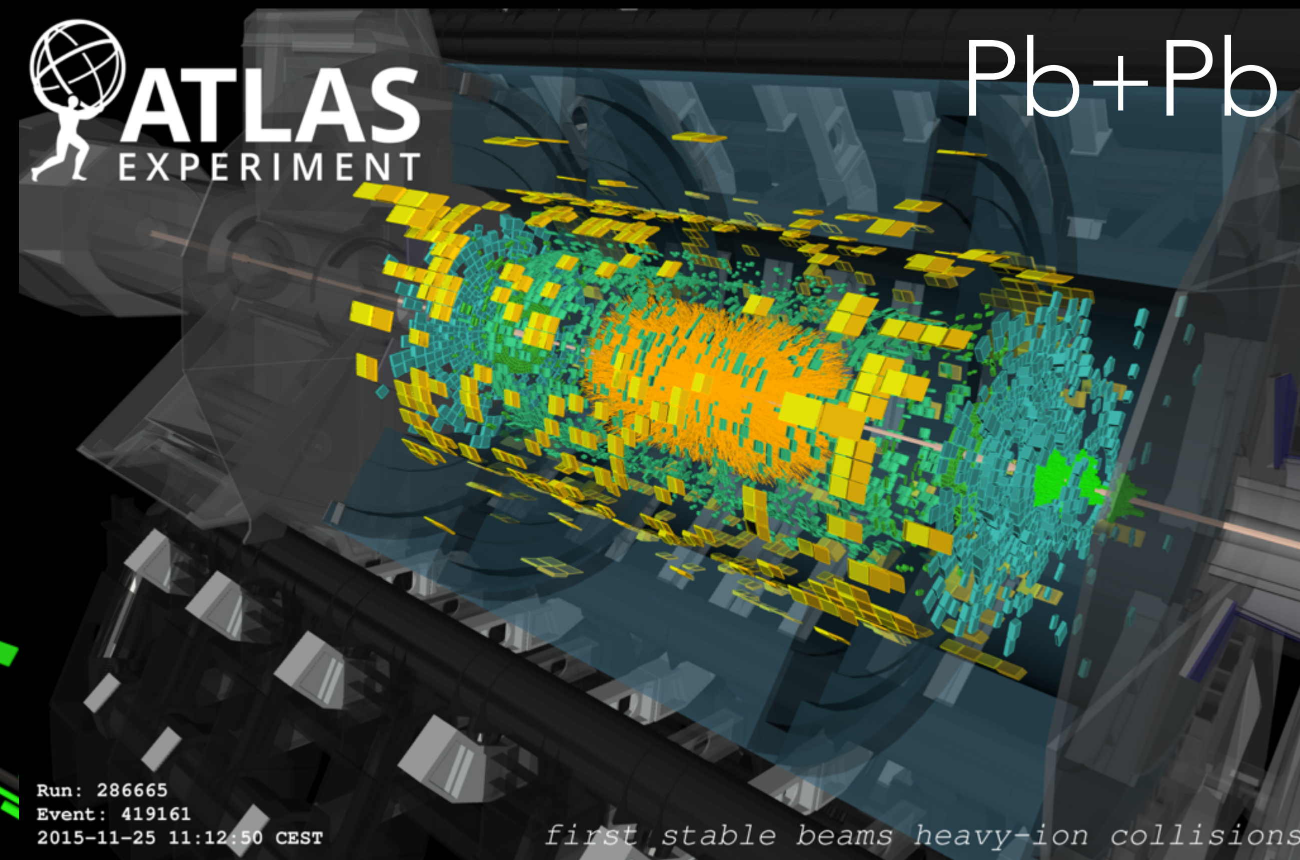


Intriguing prospect: Pb+Pb may provide
a new (collective?) perspective on the pp underlying event.

Hydro in pp:
Ollitrault, Werner,
Bzdak, etc.

FIN: BACK TO THE FUTURE





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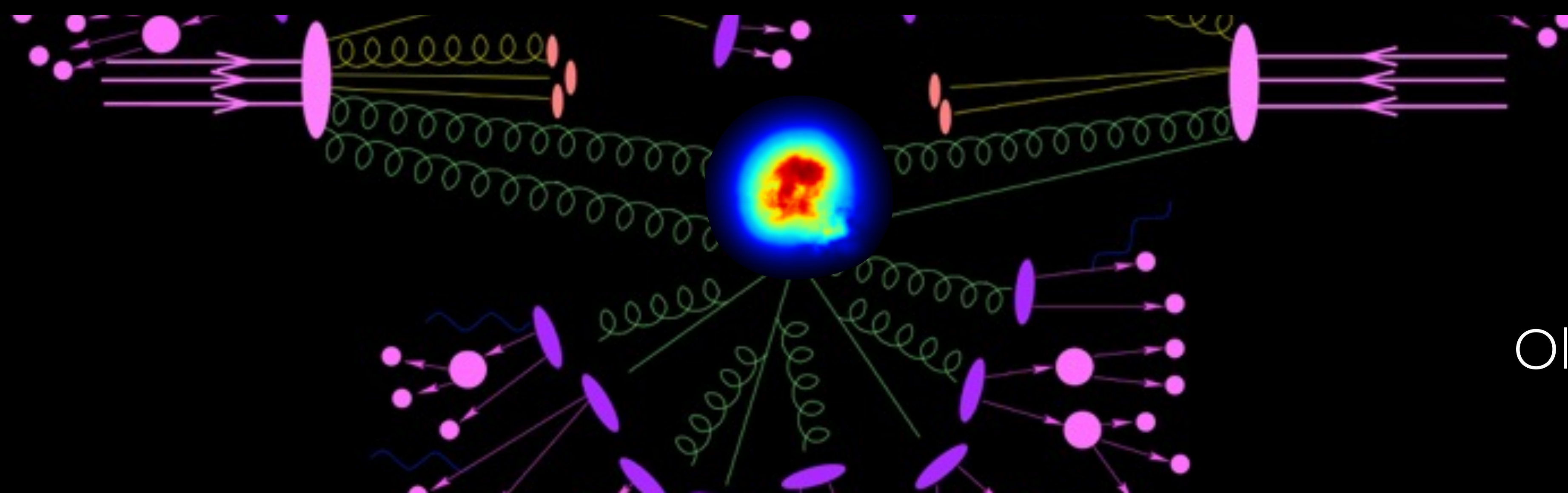

Hydro in pp:
Ollitrault, Werner,
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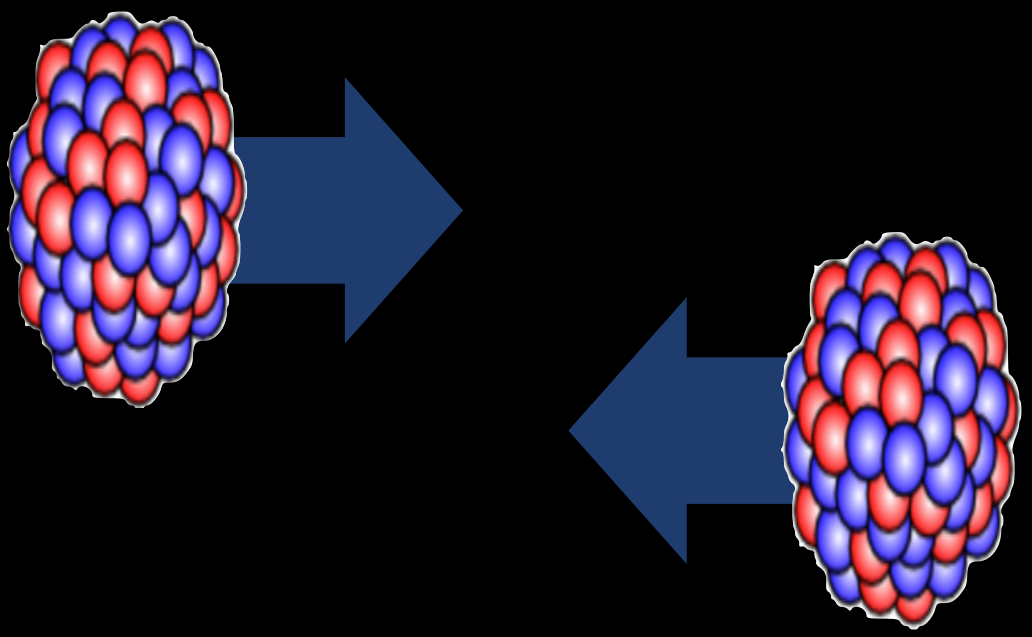
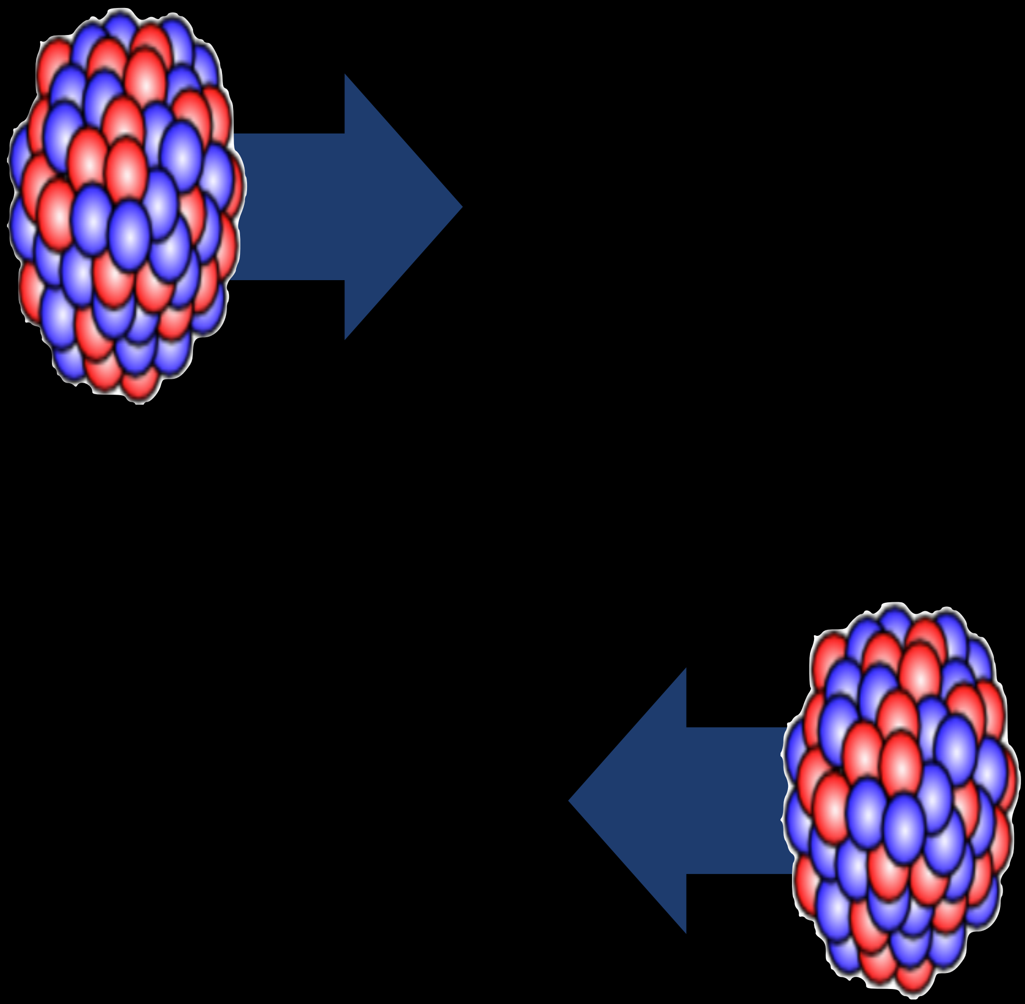
ENCORE: ULTRA-PERIPHERAL COLLISIONS



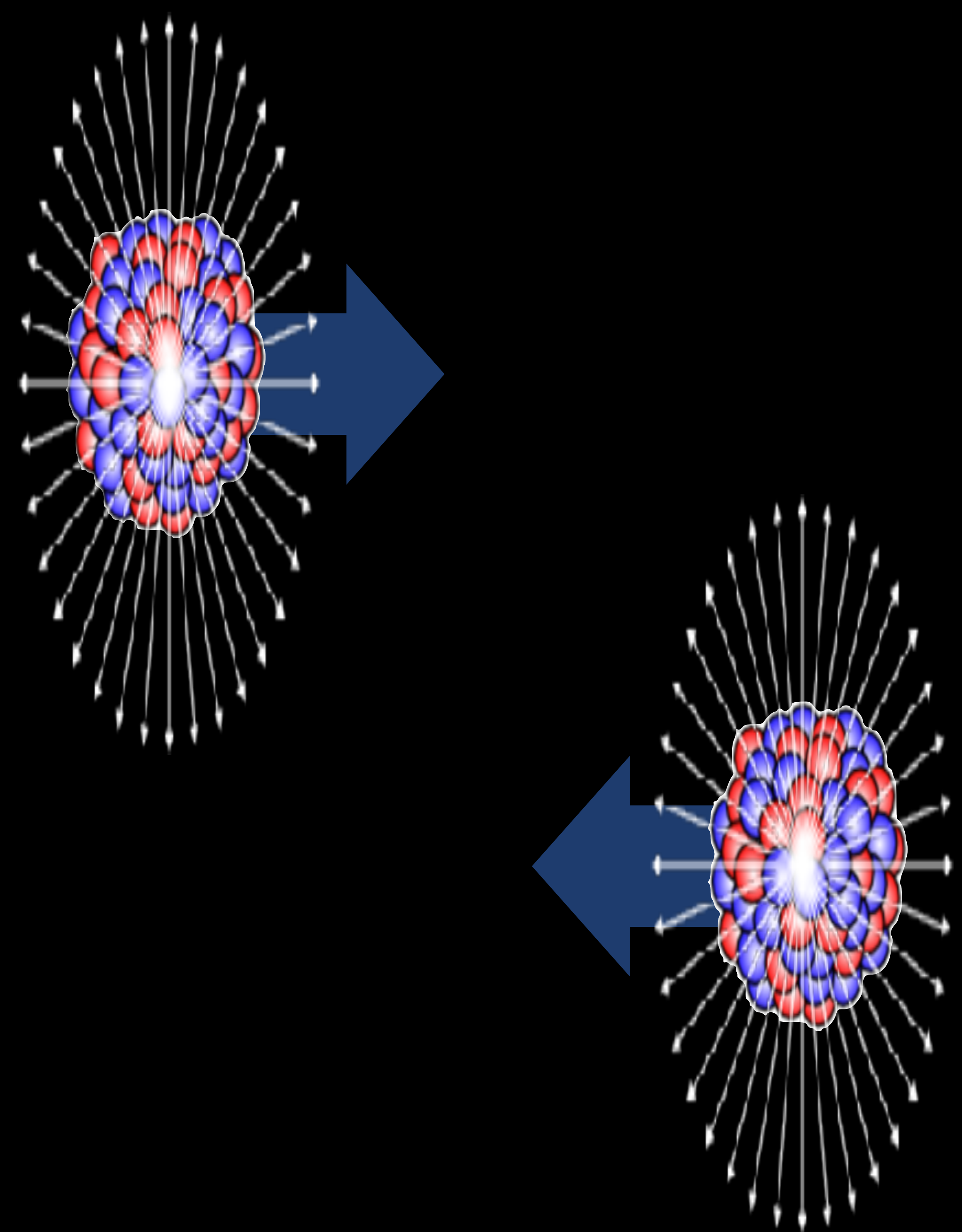
We have always assumed the two nuclei overlap

ENCORE: ULTRA-PERIPHERAL COLLISIONS



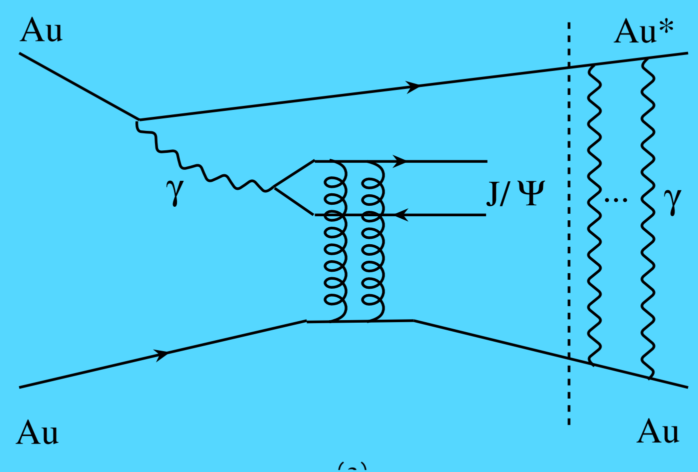
But what if they miss?

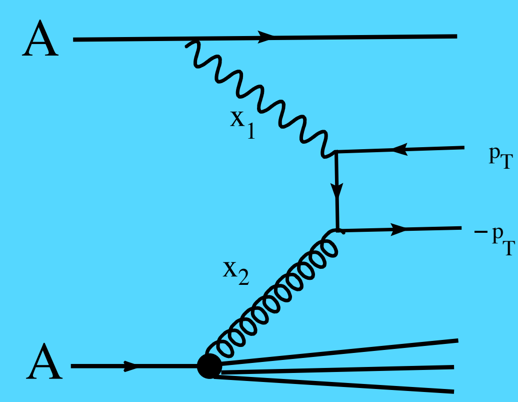
ENCORE: ULTRA-PERIPHERAL COLLISIONS

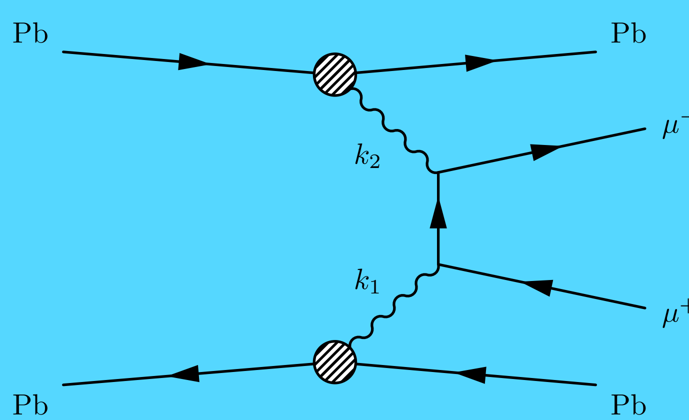


Strong EM fields, highly contracted: quasi-real photons

ULTRA-PERIPHERAL PHYSICS @ LHC







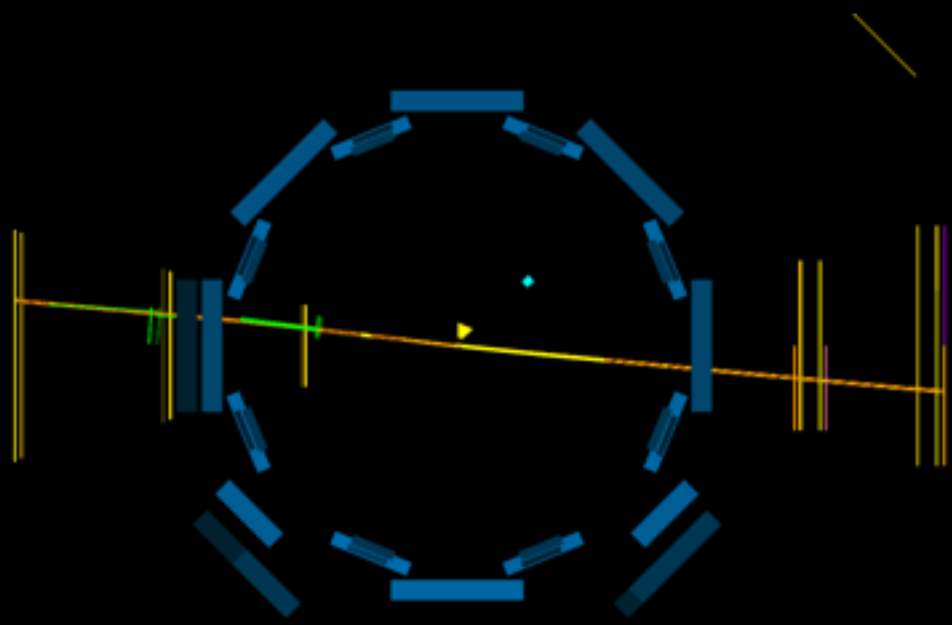
Photon-pomeron:
production of vector mesons
(sensitivity to nPDF)

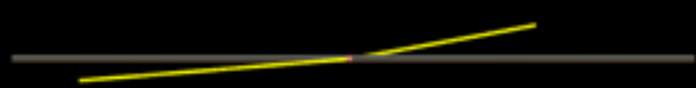
Photo-nuclear:
jet photoproduction
(probe nPDF directly)

Photon-photon:
dilepton production
(& other exclusive states)

First Run 2 result
from ATLAS

EXCLUSIVE DIMUON EVENT

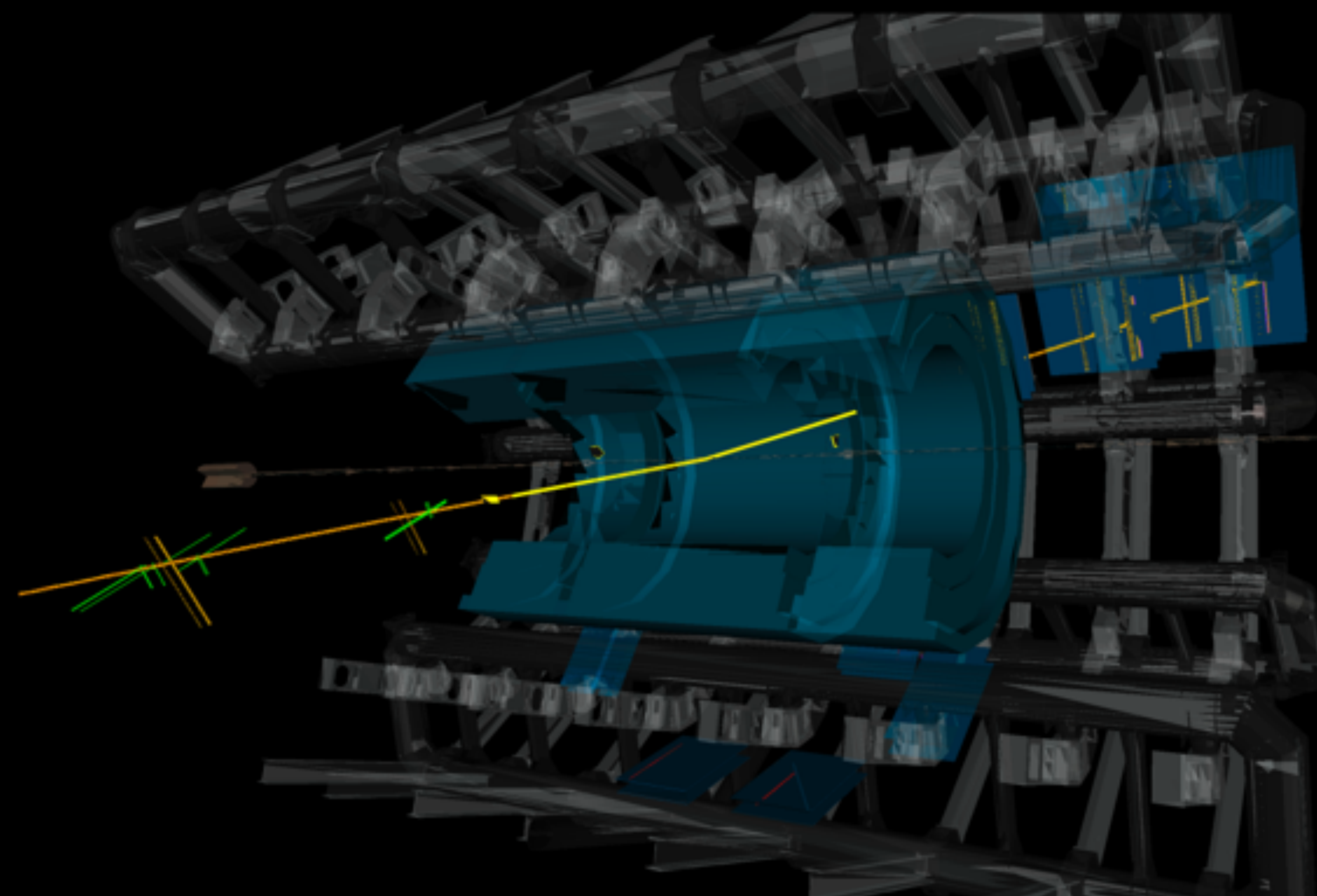




Run: 287038
Event: 71765109
2015-11-30 23:20:10 CEST

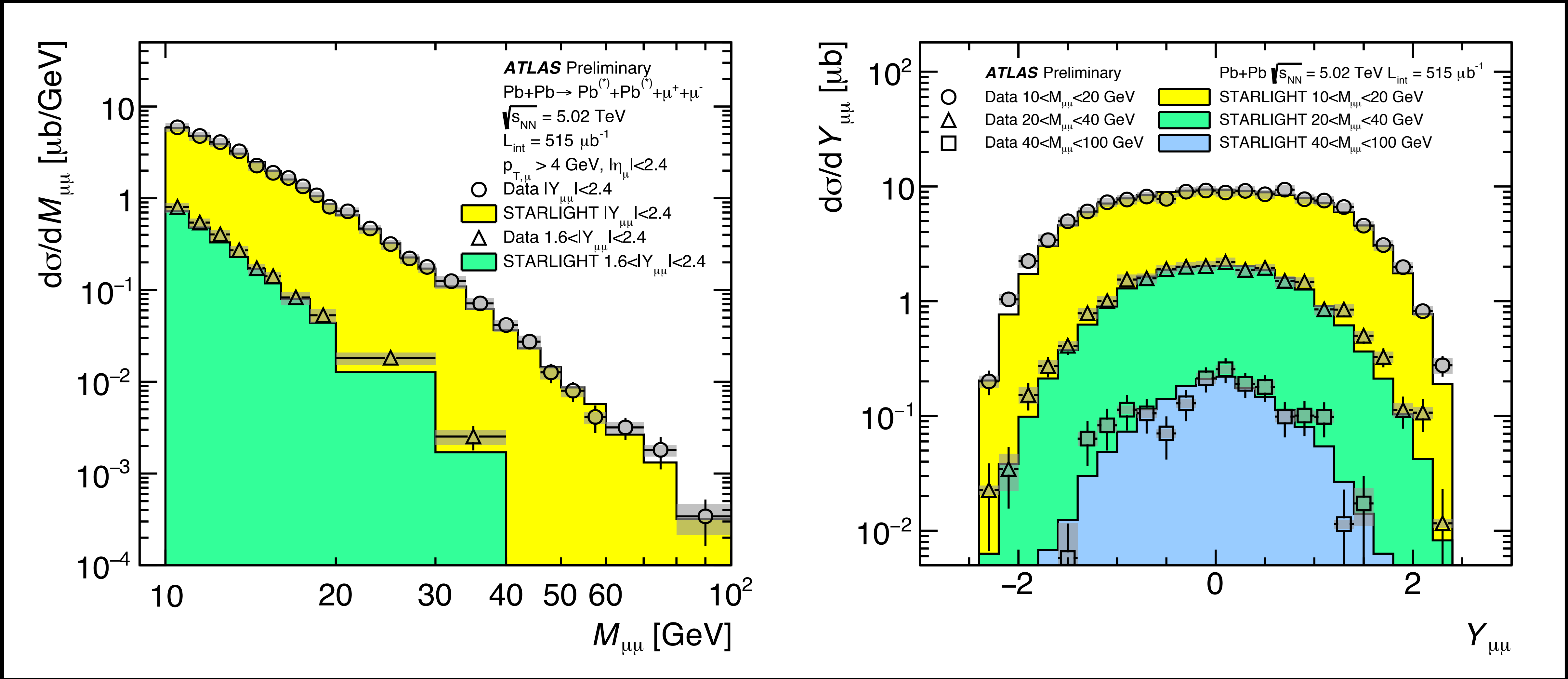
$M_{\mu\mu}$=173 GeV

Dimuons UPC Pb+Pb 5.02 TeV



SPECTRAL SHAPES IN DATA AND MC

ATLAS-CONF-2016-025

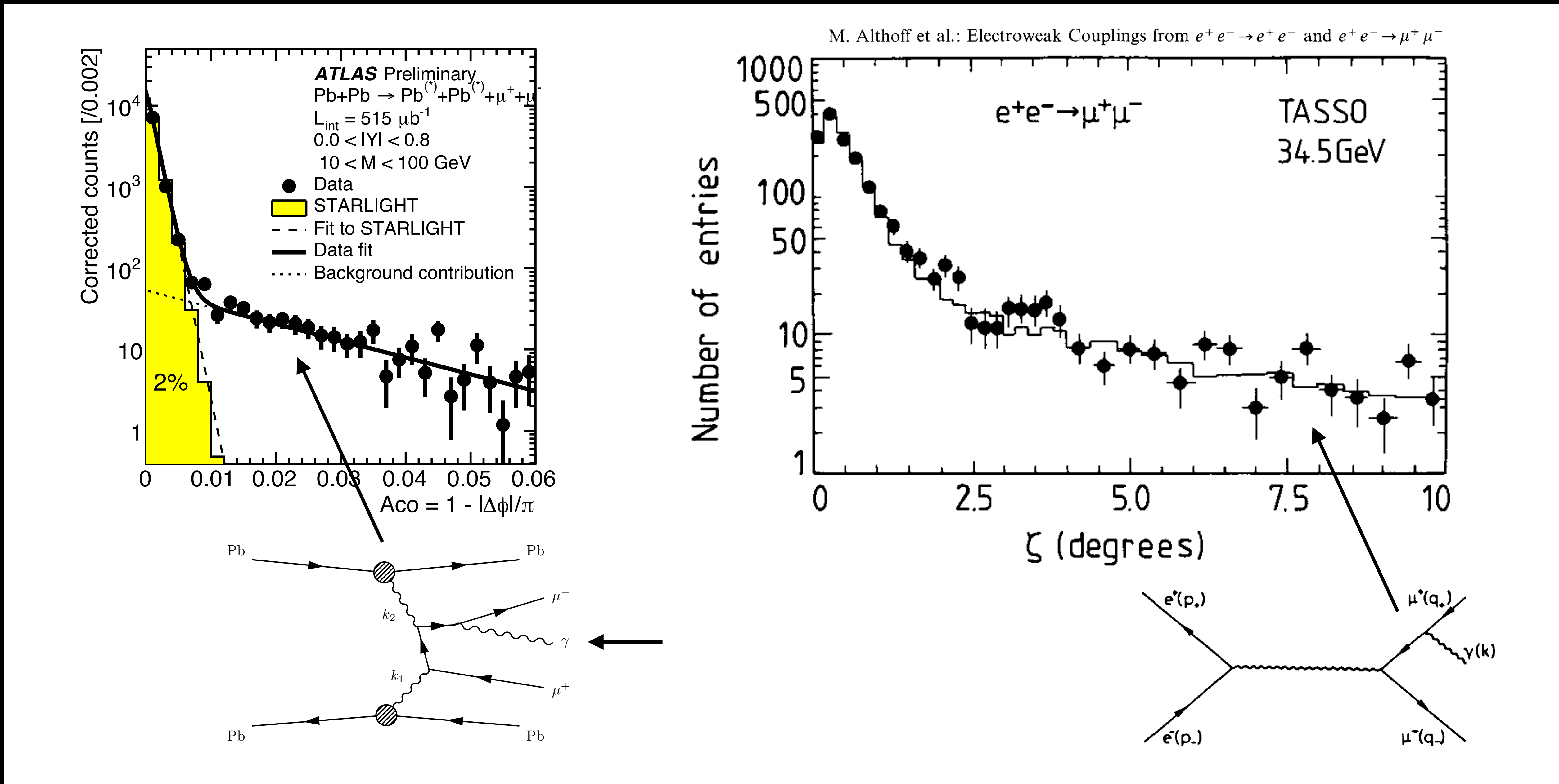


STARLIGHT MC implements collisions of Weisacker-Williams quasi-real photons + QED $\mu^{\pm}$ production: good agreement with new ATLAS data.

Will help calibrate incoming photon flux for γ+A measurements

QED ATTACKS

ATLAS-CONF-2016-025



STARLIGHT calculations only include pure $\mu^+\mu^-$, w/ no final state QED.

Clearly required in $e^+e^- \rightarrow \mu^+\mu^-$, e.g. from DESY.

Not easily available in existing MC codes: exploring several avenues

CONCLUSIONS

- **Overview of the ATLAS HI program: involving Pb+Pb, p+Pb and p+p**
- **ATLAS has deepened our understanding of jet quenching and collective flow in Pb+Pb collisions**
- **Systematic study of smaller systems showing evidence for collective behavior even at low multiplicities**
  - All LHC experiments are reporting similar evidence
  - Help our understanding of soft pp collisions?
- **Ions are an excellent source of hight energy photons**
  - Exclusive production processes, with low backgrounds (modulo QED!)
  - Looking forward to photo-production measurements to probe parton structure of nuclei