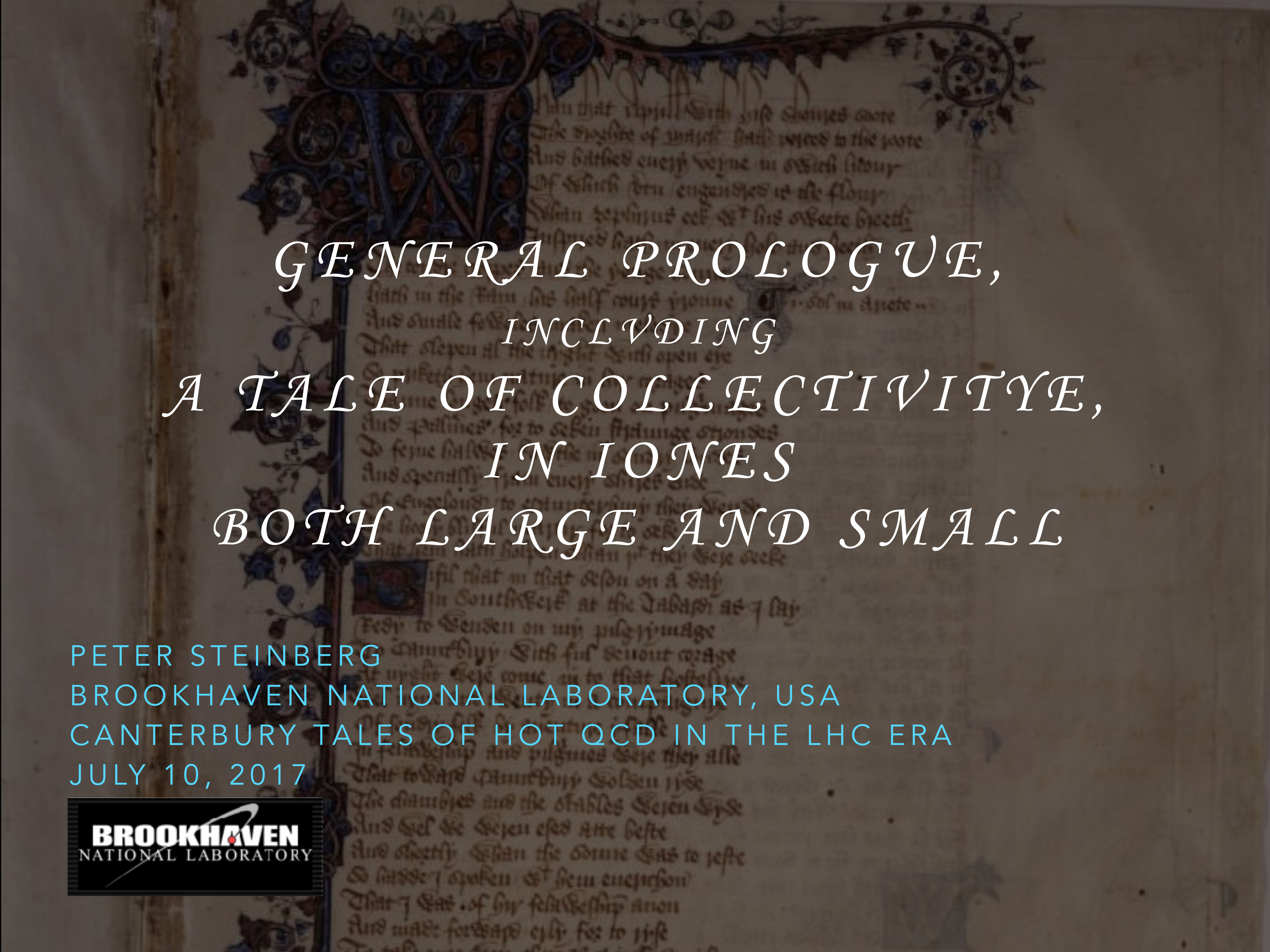
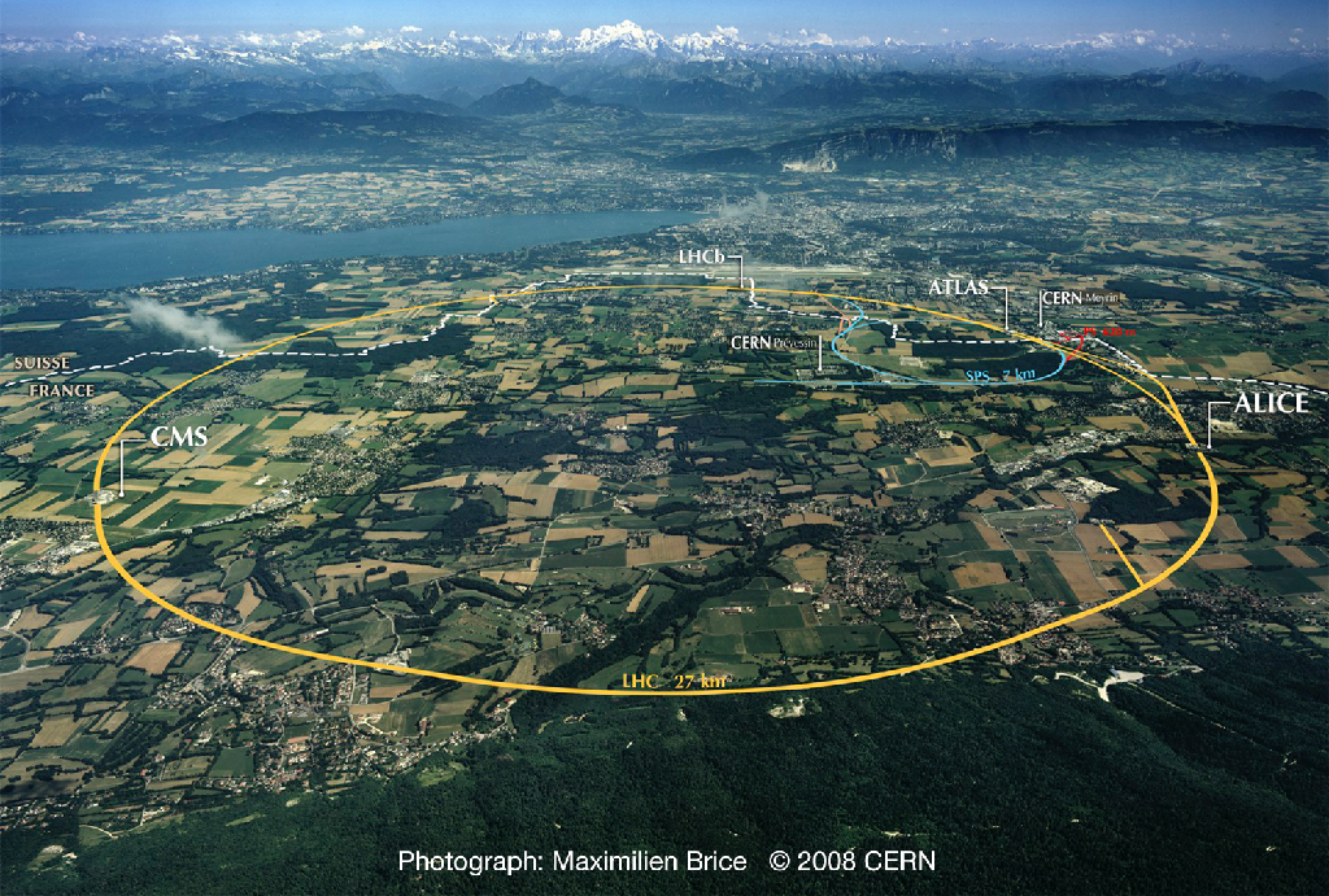


GENERAL PROLOGUE,
INCLVDING
A TALE OF COLLECTIVITYE, IN IONES BOTH LARGE AND SMALL

PETER STEINBERG
BROOKHAVEN NATIONAL LABORATORY, USA
CANTERBURY TALES OF HOT QCD IN THE LHC ERA
JULY 10, 2017

FRAGMENT I: PROTONS @ THE LHC



Photograph: Maximilien Brice © 2008 CERN

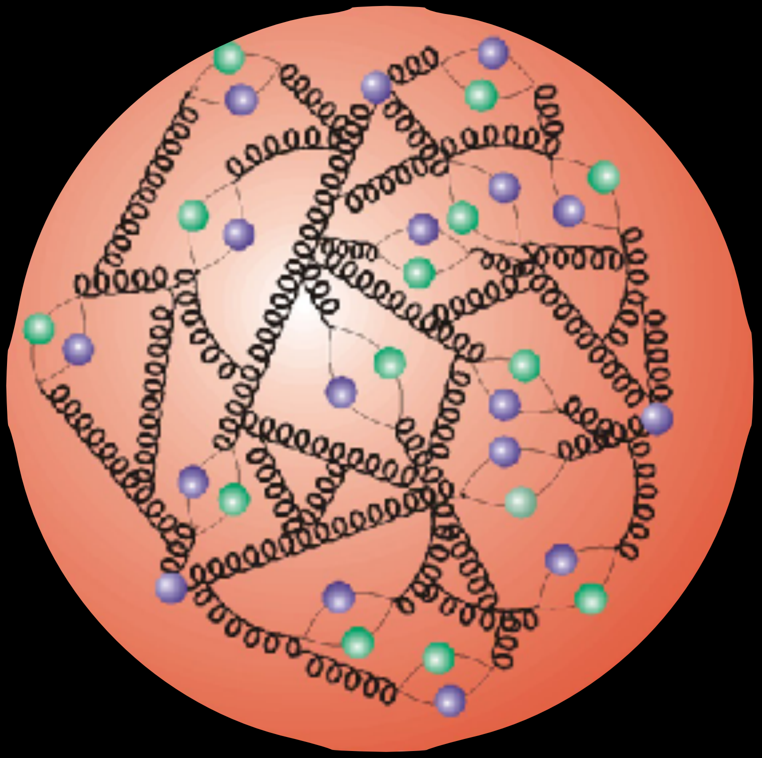
FRAGMENT I: PROTONS @ THE LHC

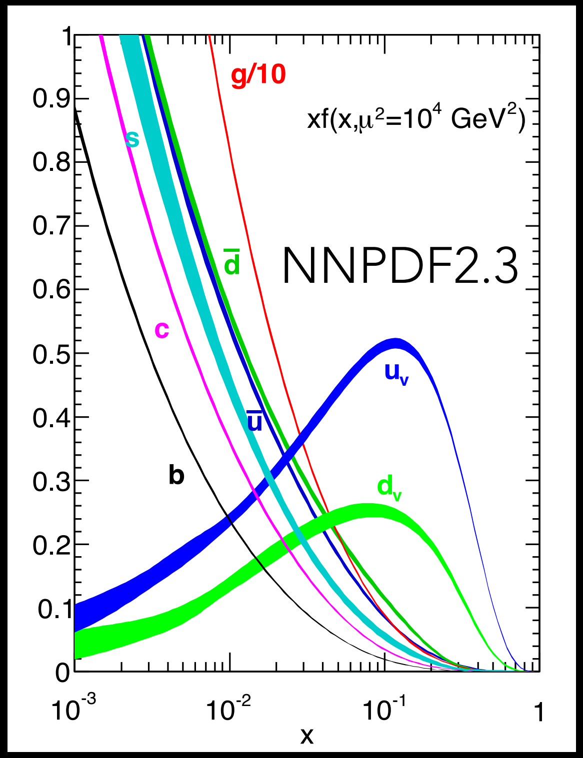
- **To discover new particles**
  - Large masses, so only rarely produced

- **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

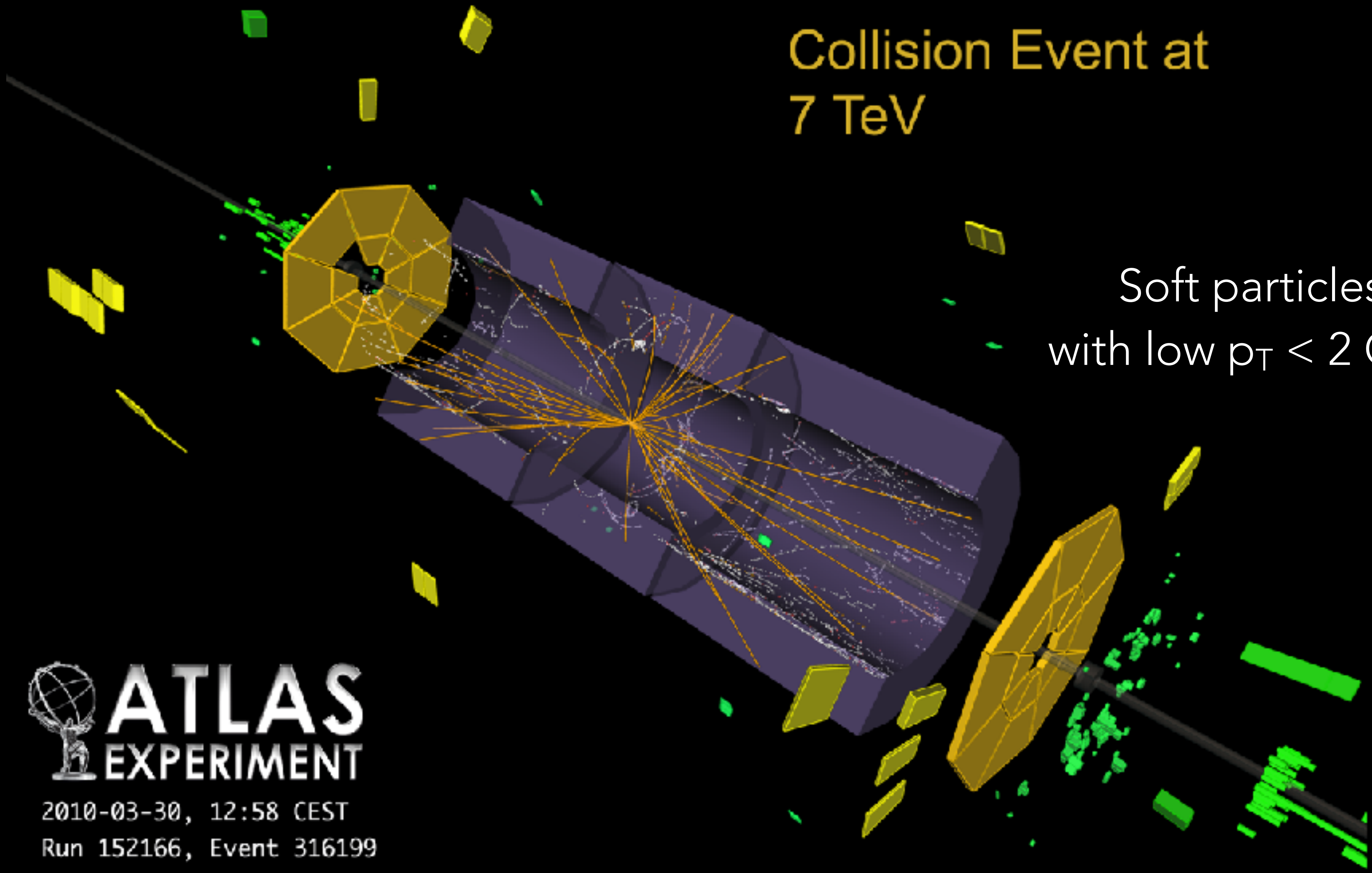
g





"x" is fraction of proton momentum, as probed at scale 1/μ: most partons take a very small fraction!

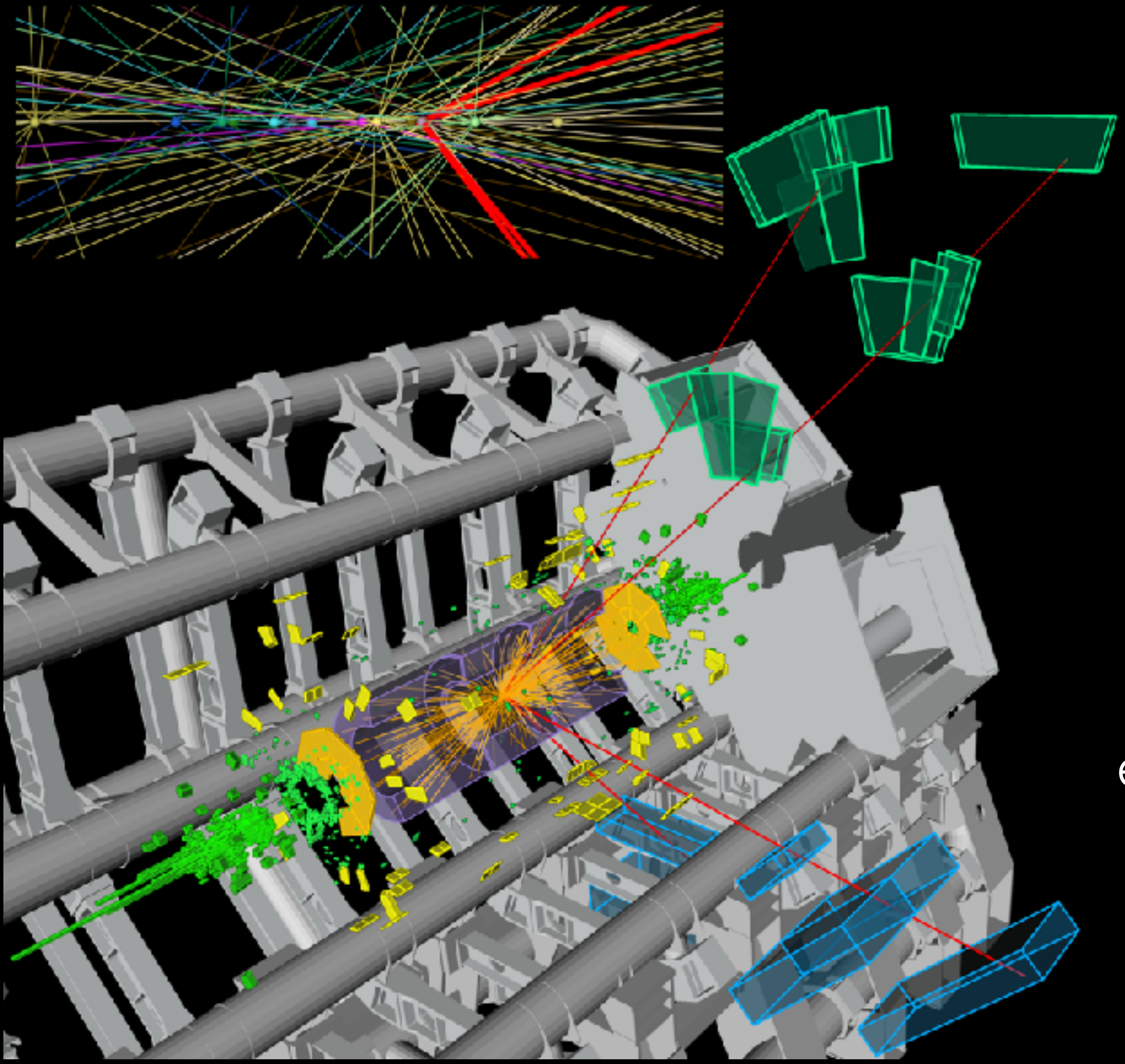
PROTON-PROTON COLLISIONS AT THE LHC: A TYPICAL EVENT

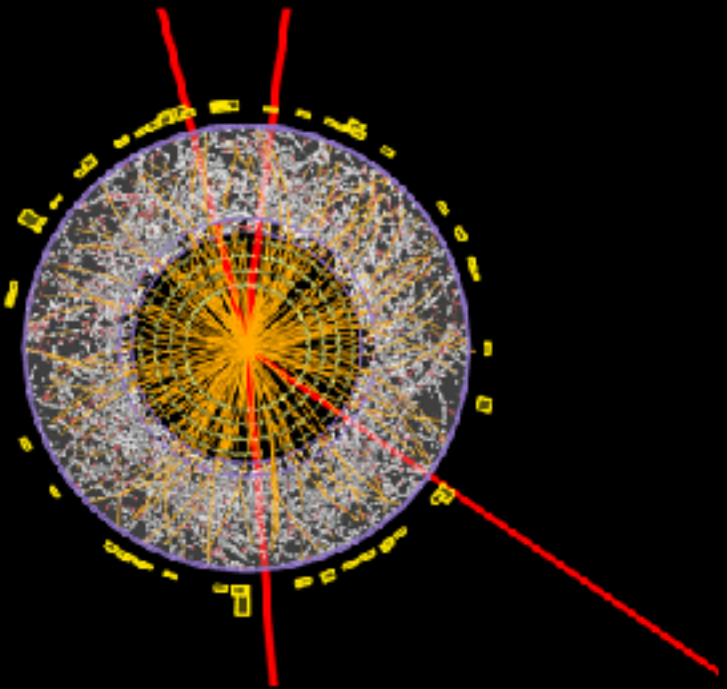


http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Soft particles with low $p_T < 2$ GeV

PROTON-PROTON COLLISIONS AT THE LHC: A RARE EVENT

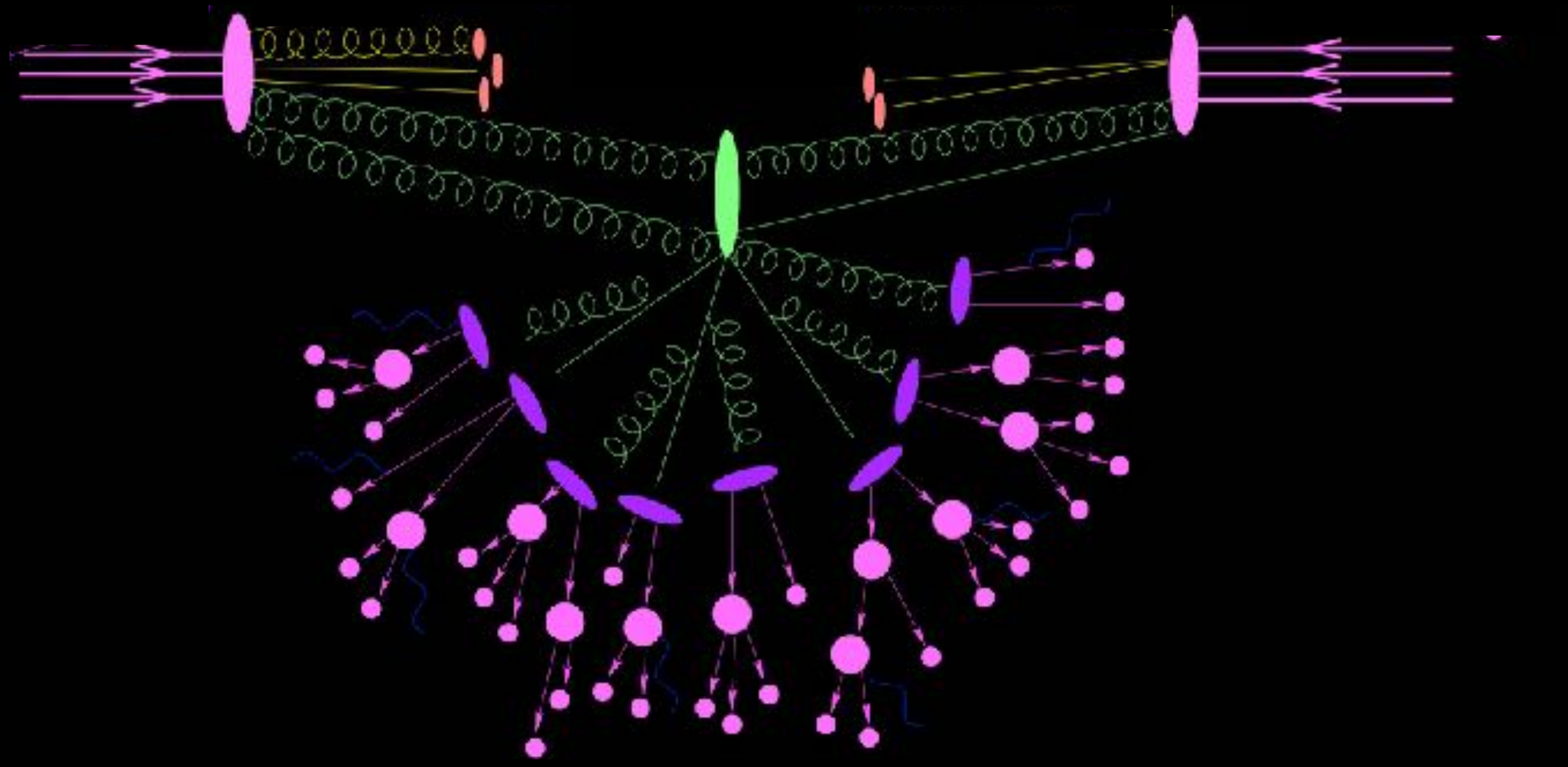




e.g. a Higgs boson candidate

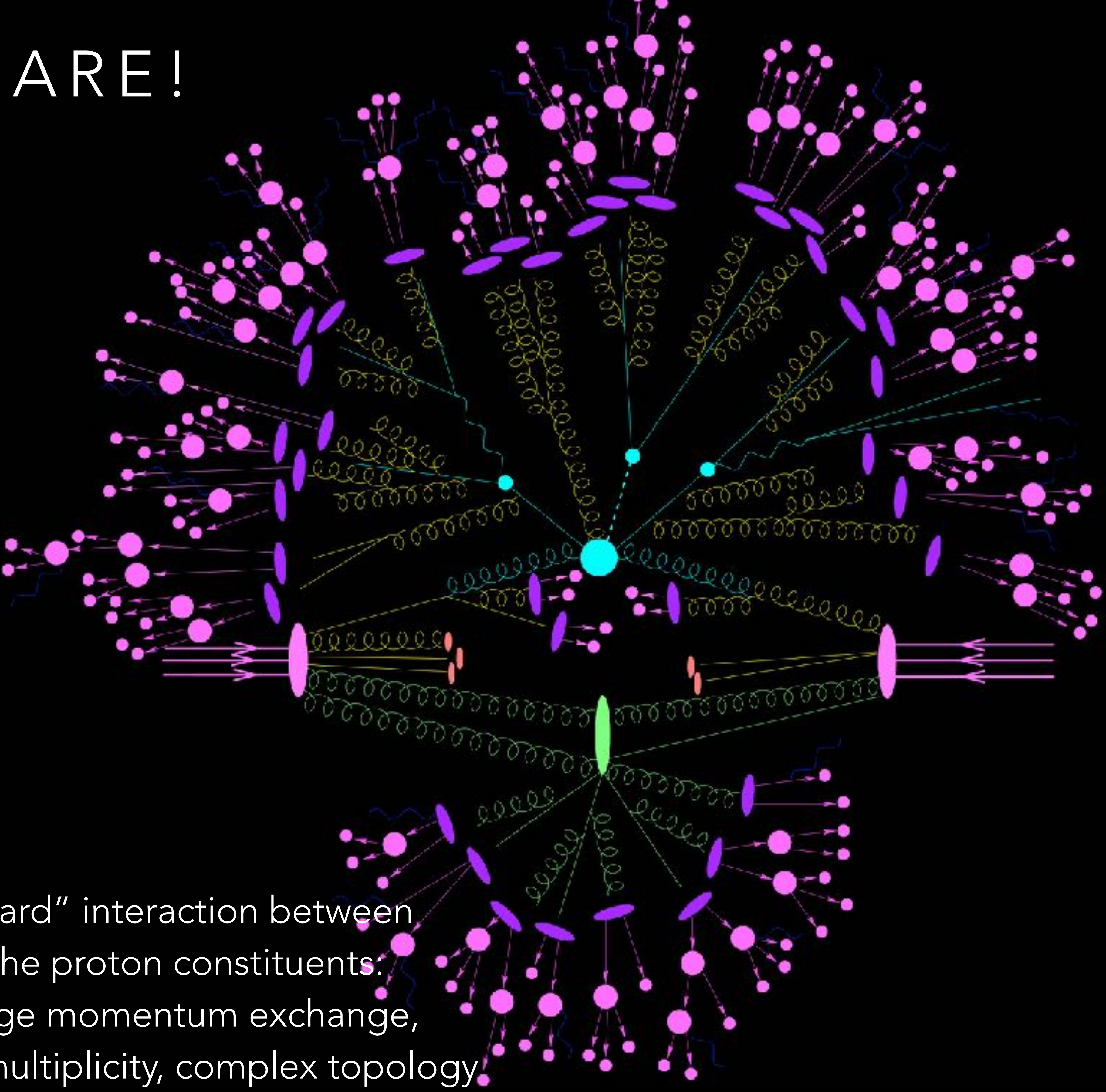
A TYPICAL EVENT

diagrammatic view of a
“soft” interaction between
the proton constituents



SHERPA

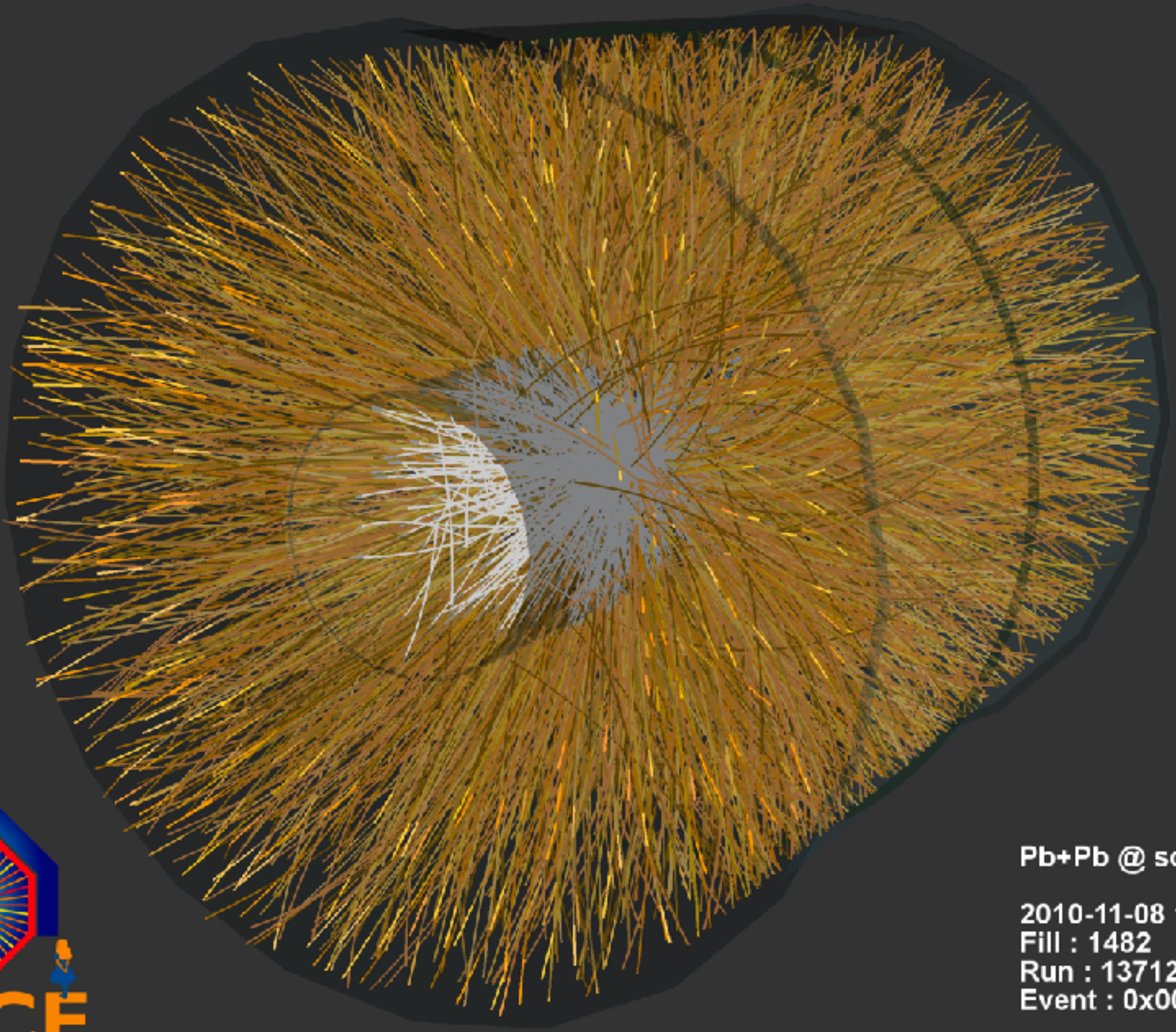
RARE!



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

SHERPA

A single heavy ion collision event from **ALICE**



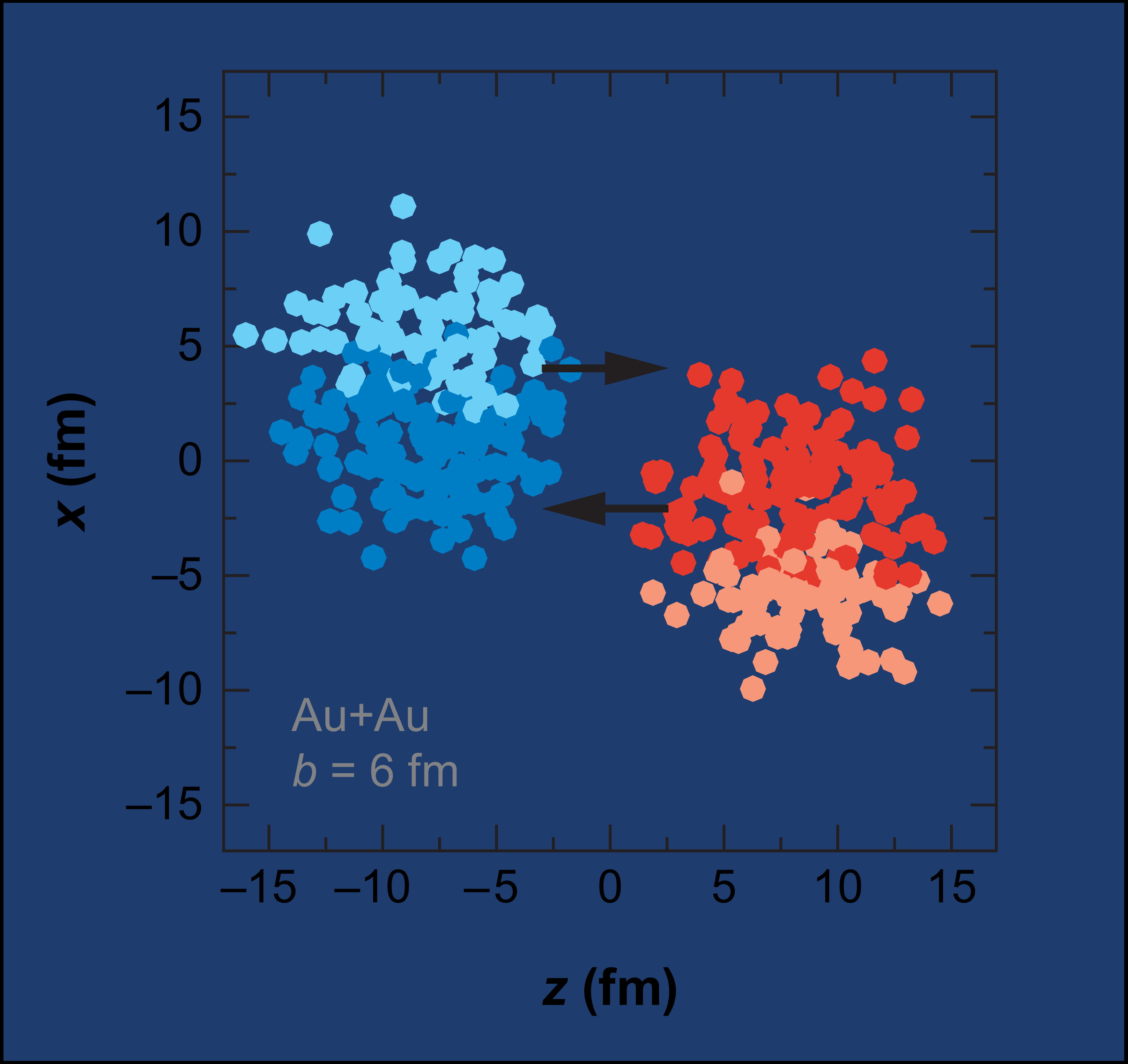
Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

ALICE

FRAGMENT 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"

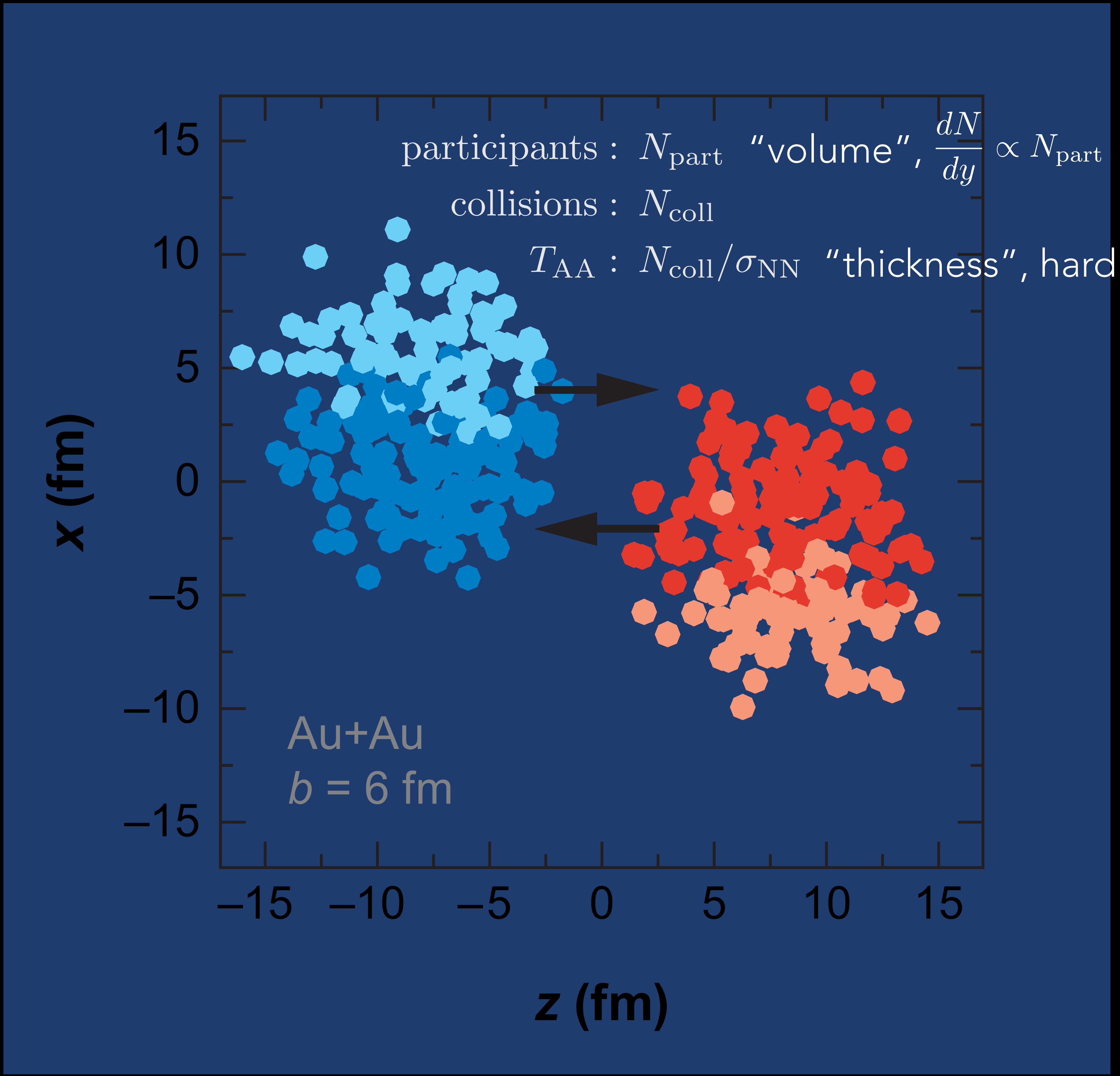
1. Generate two colliding nuclei with 3D nucleon positions chosen from **measured** density distributions (e$^-$ scattering)

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

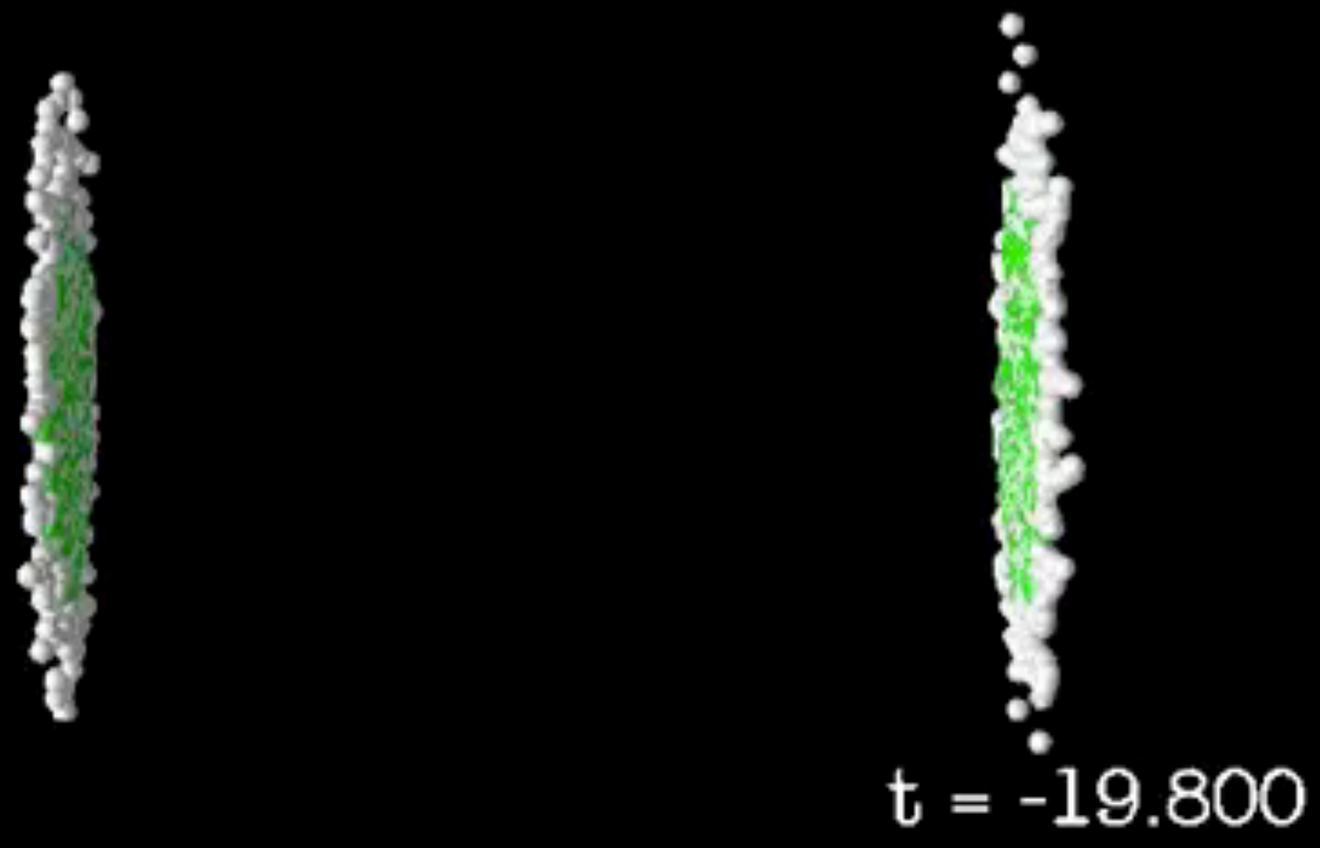
2. Nucleons interact when transverse distance satisfies

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

typically using the inelastic pp cross section for NN



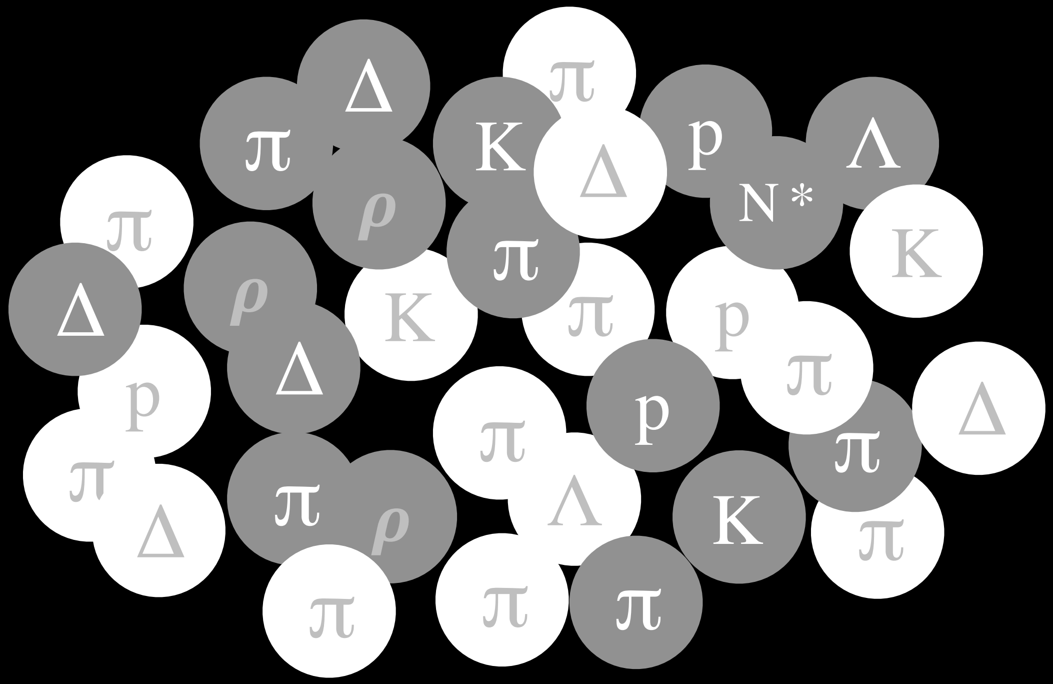
A+A IN ACTION



Simulation of two gold-nuclei colliding (at RHIC):

1. first collisions of **initial nuclei** deposit energy (particles)
2. **reinteractions** among constituents (dynamical evolution)
3. freeze out to **final-state hadrons**

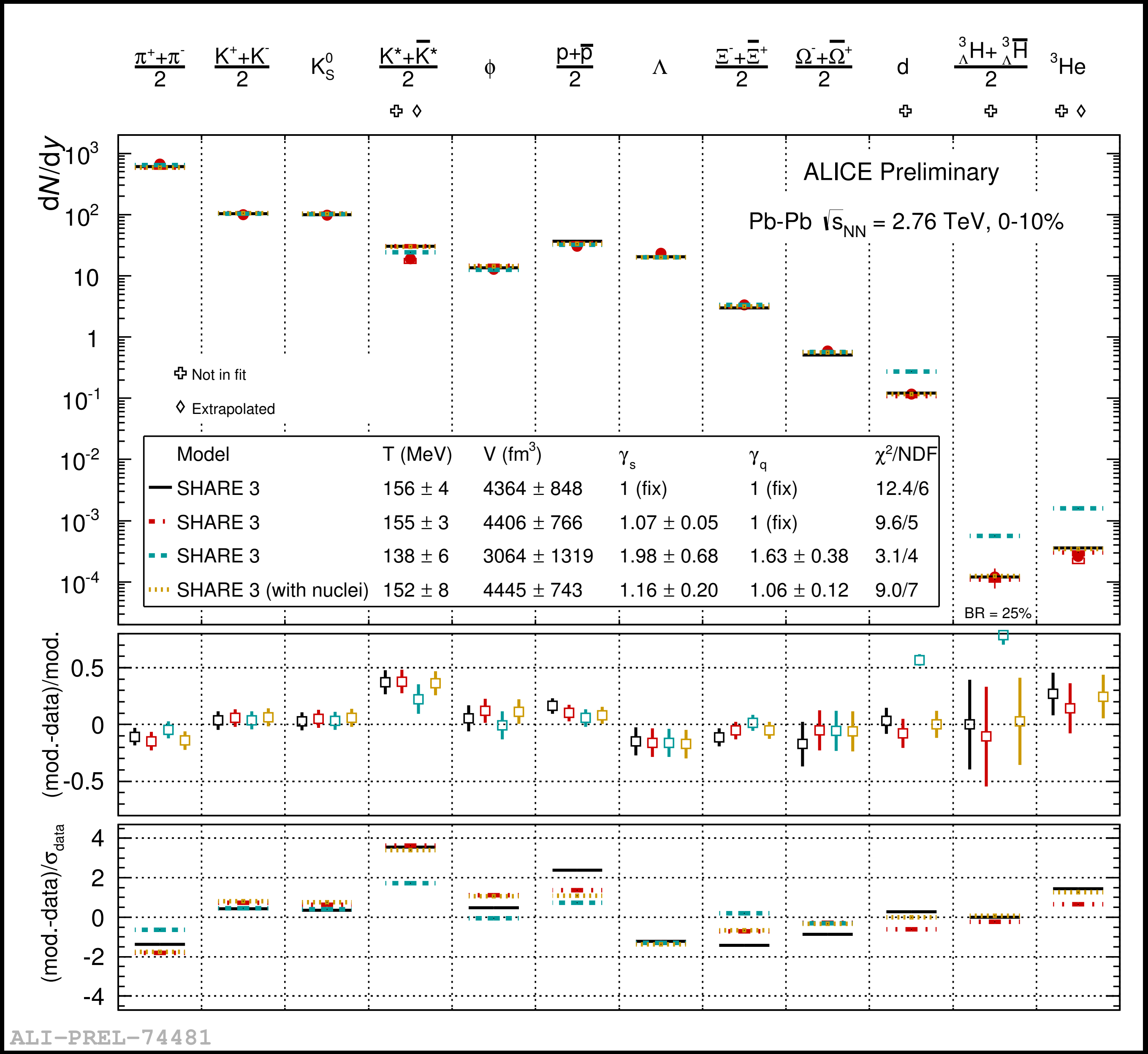
‘THERMAL’ PARTICLE YIELDS



100’s of particle states
listed in the Particle Data Book
→ equilibrated “hadron gas”: **T,μ_B**

Describes yields in many systems:
pp, e^+e^-, A+A →T ~ 160 MeV

T_{ch} = 2×10^{12} K (100k🌞)

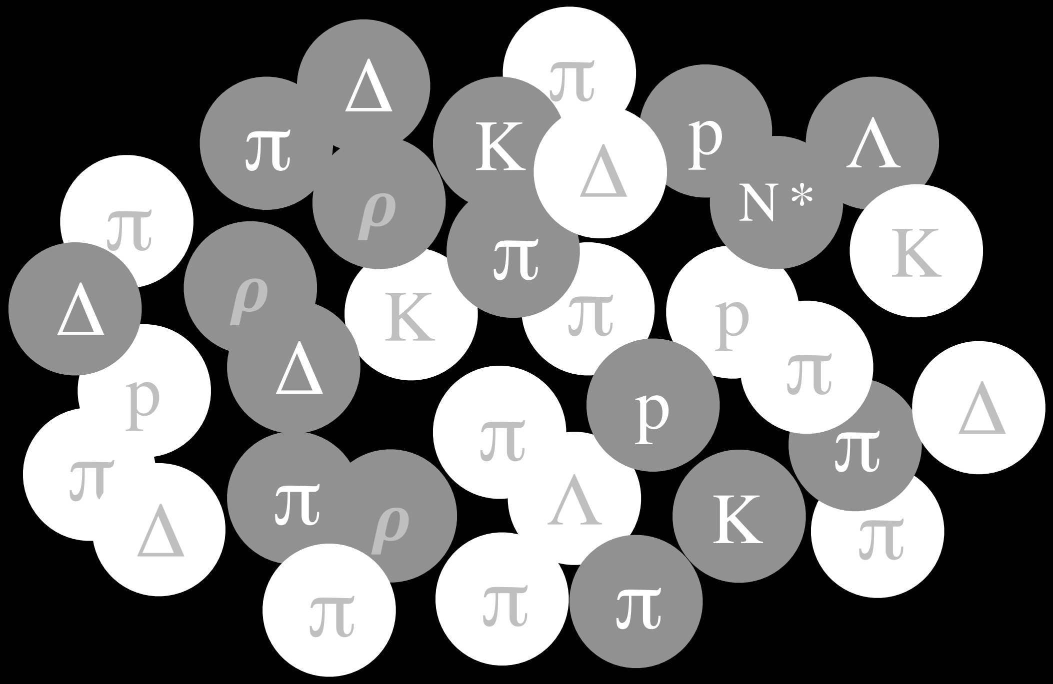


Model	T (MeV)	V (fm^3)	γ_s	γ_q	χ^2/NDF
— SHARE 3	156 ± 4	4364 ± 848	1 (fix)	1 (fix)	12.4/6
⋅-⋅ SHARE 3	155 ± 3	4406 ± 766	1.07 ± 0.05	1 (fix)	9.6/5
- - SHARE 3	138 ± 6	3064 ± 1319	1.98 ± 0.68	1.63 ± 0.38	3.1/4
⋯ SHARE 3 (with nuclei)	152 ± 8	4445 ± 743	1.16 ± 0.20	1.06 ± 0.12	9.0/7

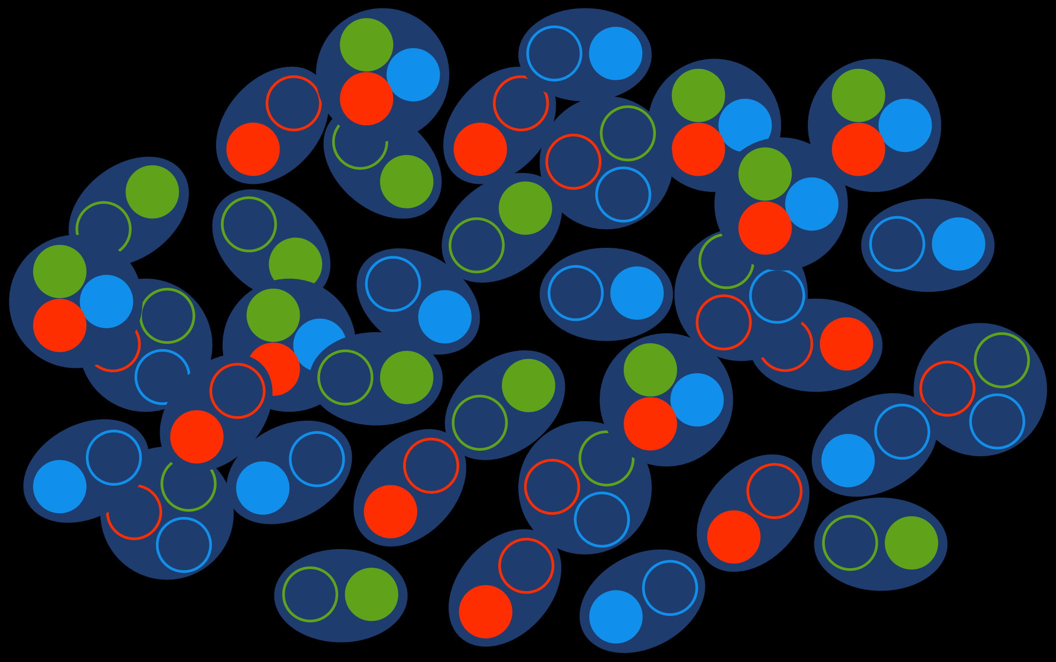
ALI-PREL-74481

Hagedorn’s pre-QCD “bootstrap”
argued for maximum T~T_H ~ 160 MeV
Higher T excites higher mass states!

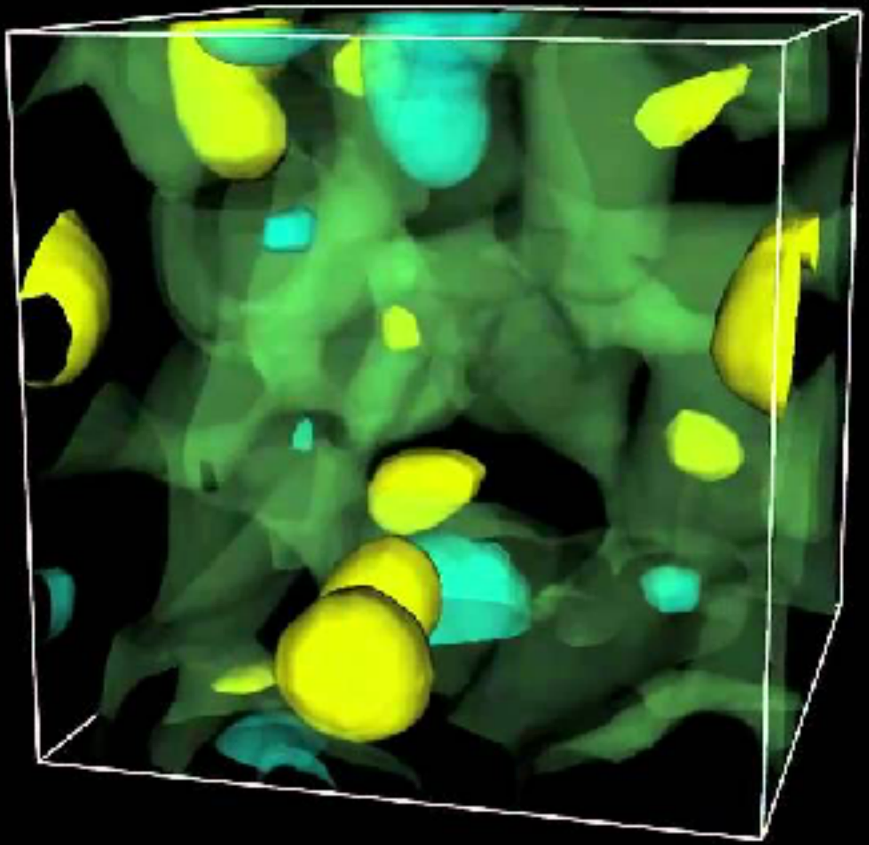
T < T_H HADRON GAS



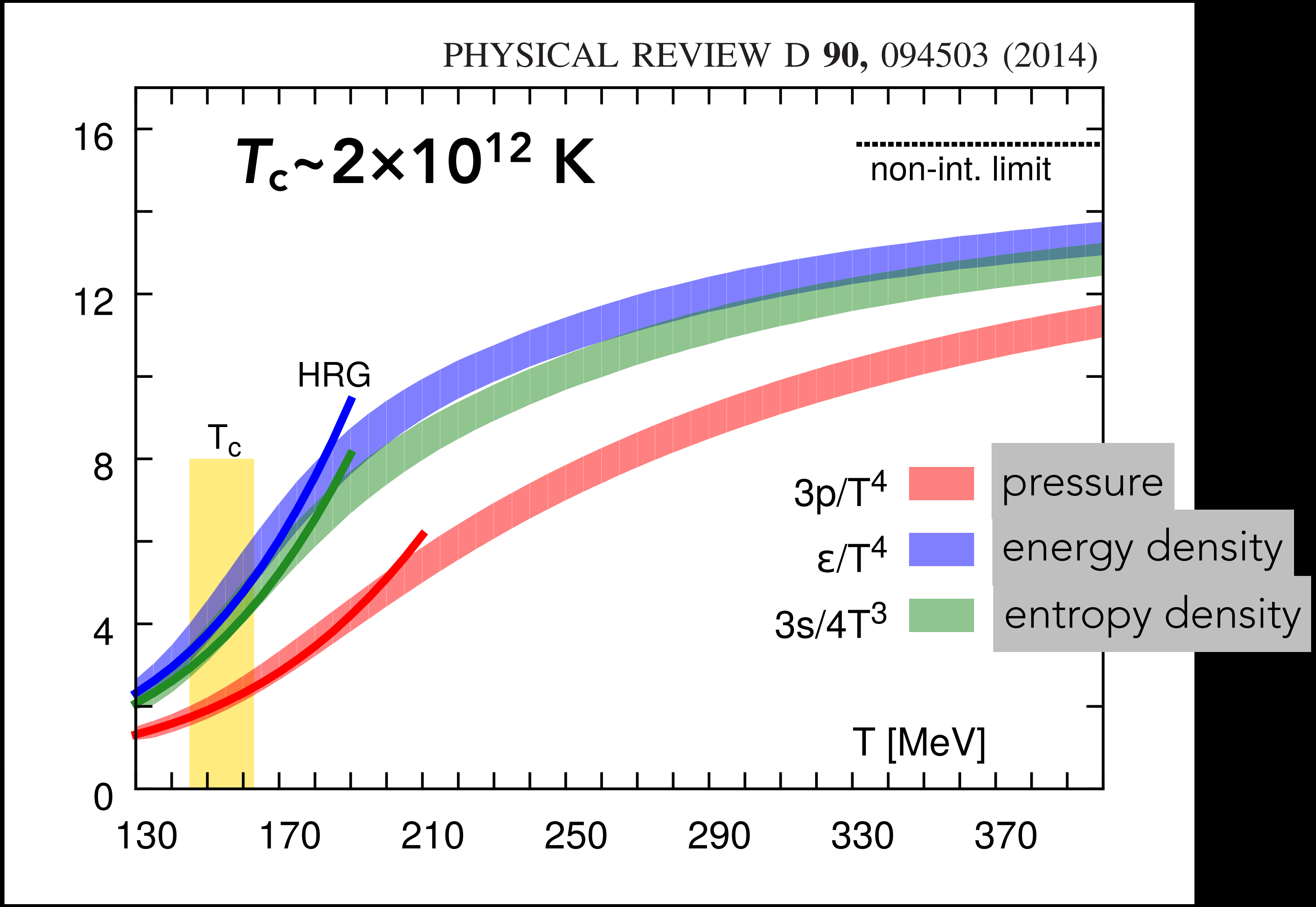
$T > T_H$ QUARKS & GLUONS



THE QUARK-GLUON PLASMA



quark & gluon
fields on a spacetime lattice



PHYSICAL REVIEW D **90,** 094503 (2014)

$T_c \sim 2\times10^{12}$ K

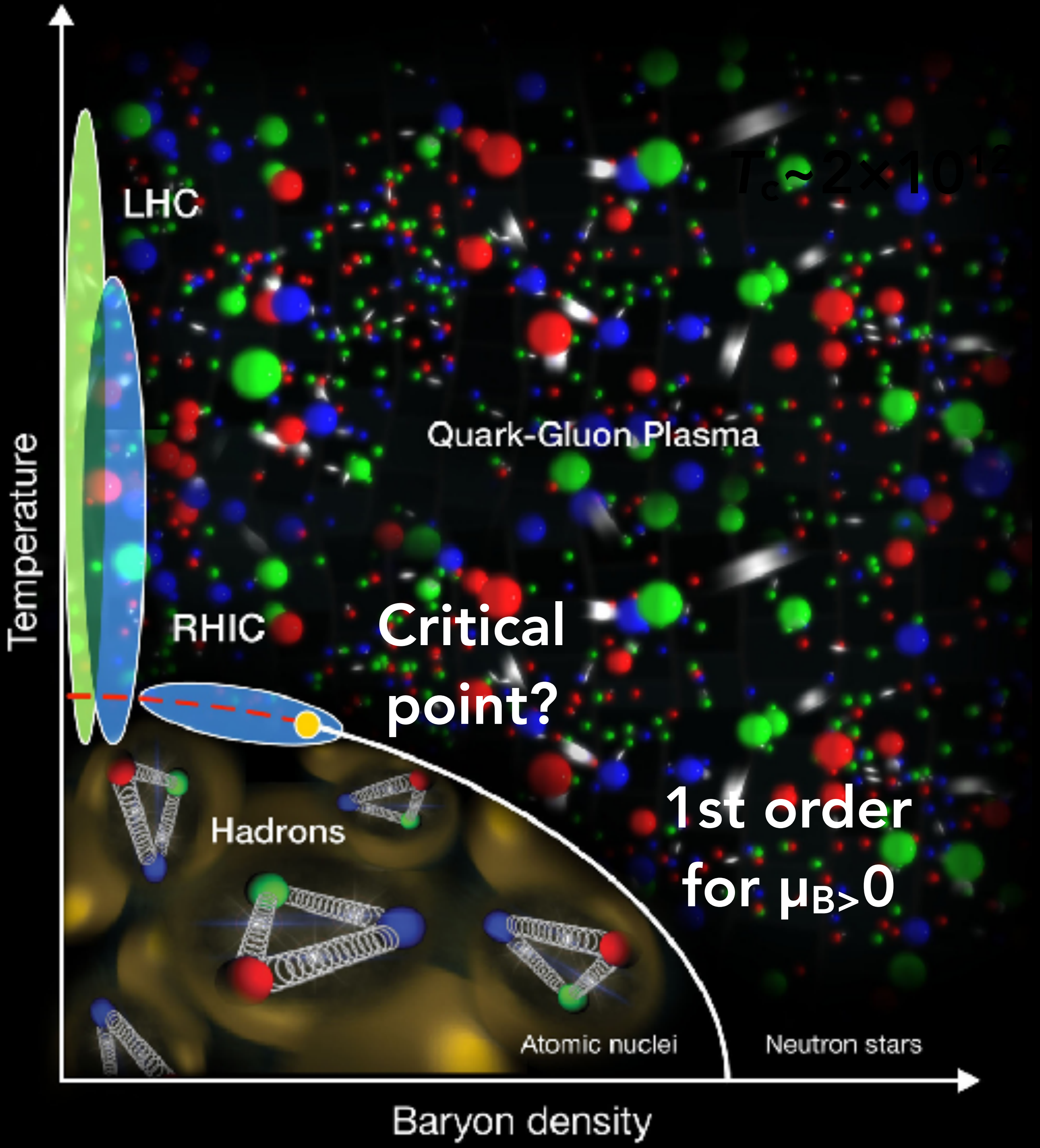
Equation of state from HotQCD lattice QCD calculations (Basazov et al) for μ_B=0

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

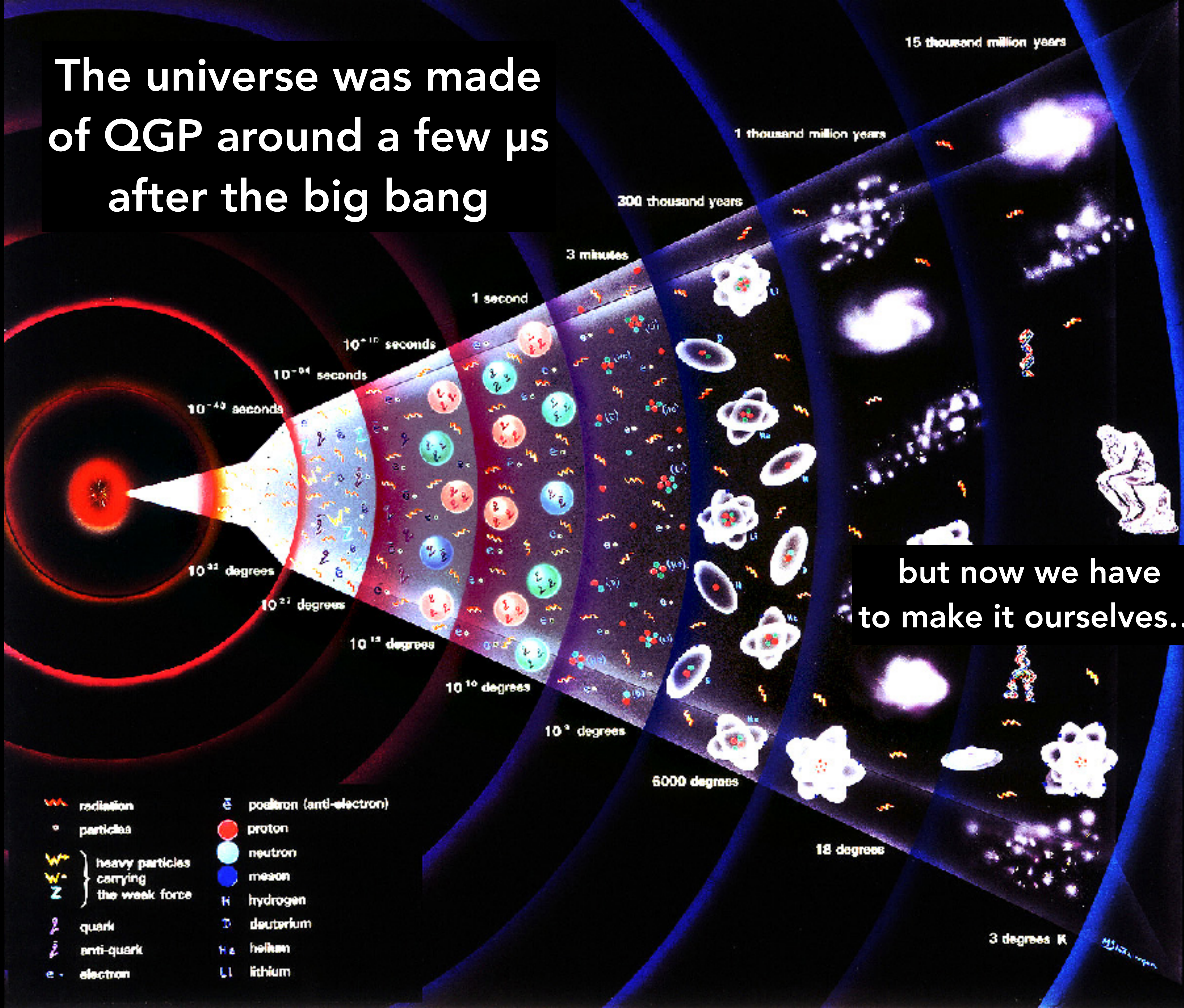
Crossover
for $\mu_B=0$



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

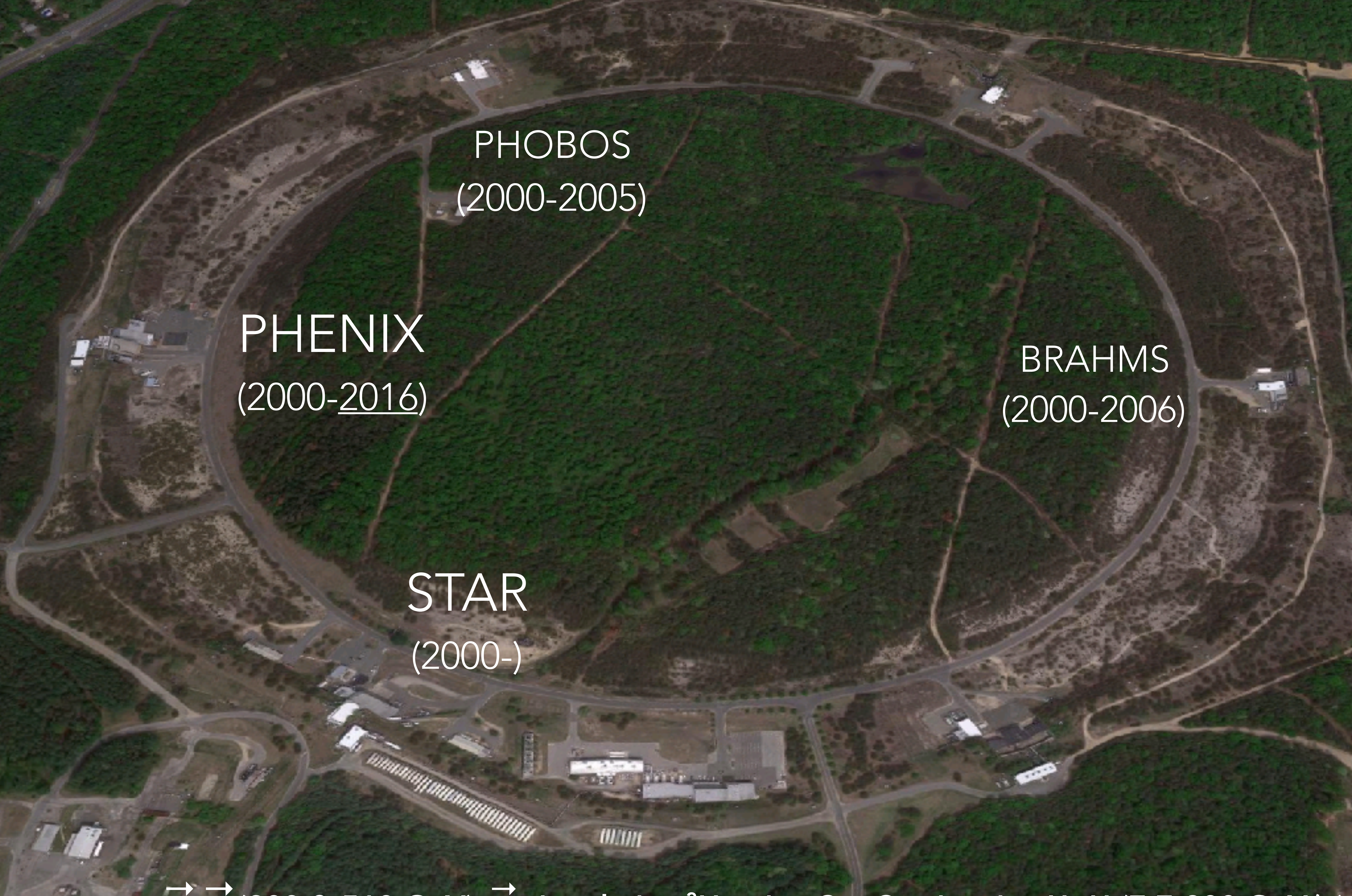
What do we know experimentally about hot QCD?

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, ^{3}He+Au, Cu+Cu, Au+Au, U+U (7.7-200 GeV/u)

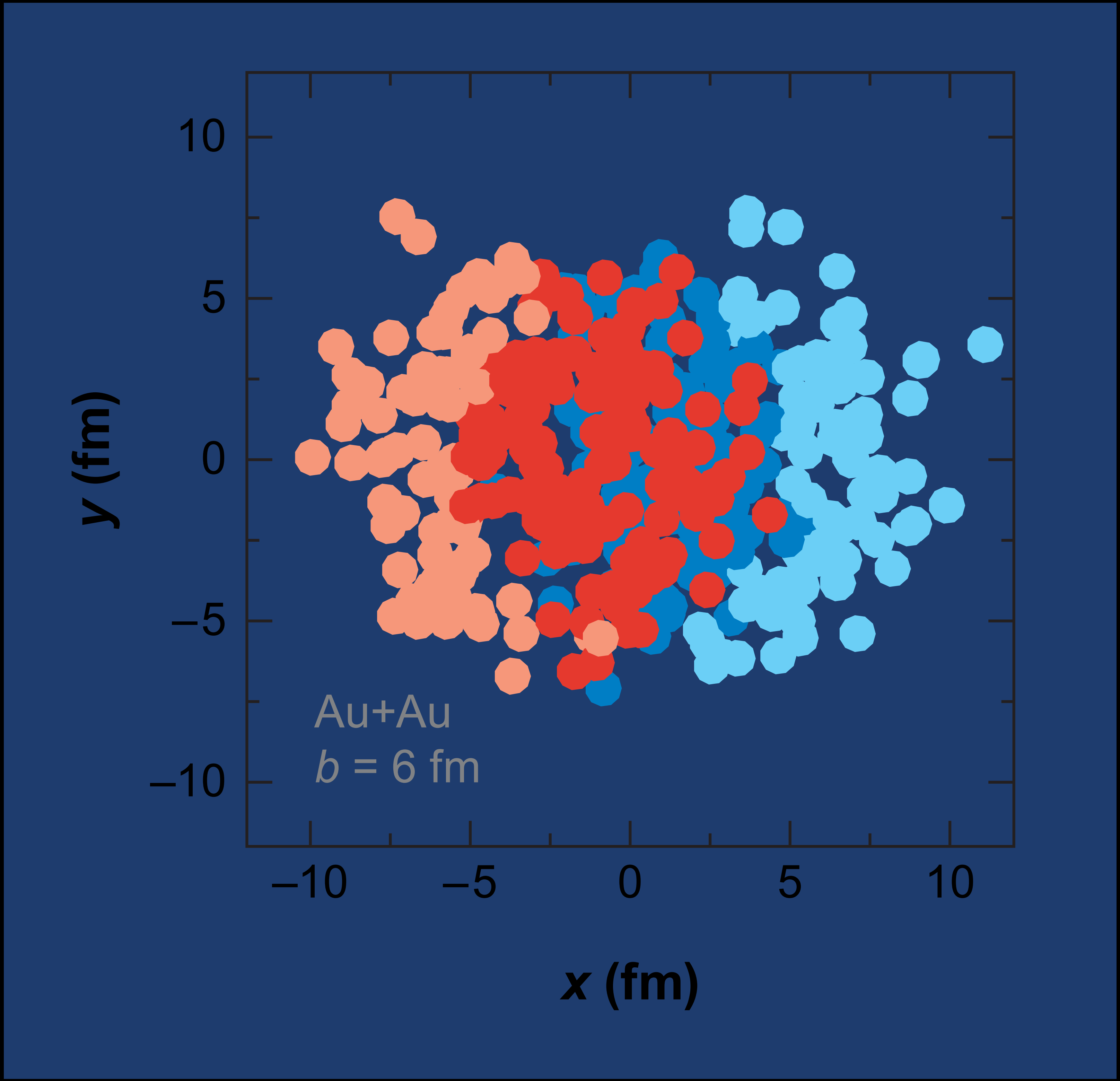
TWO MAIN DISCOVERIES @ RHIC

COLLECTIVE FLOW
(PERFECT FLUID)

JET QUENCHING

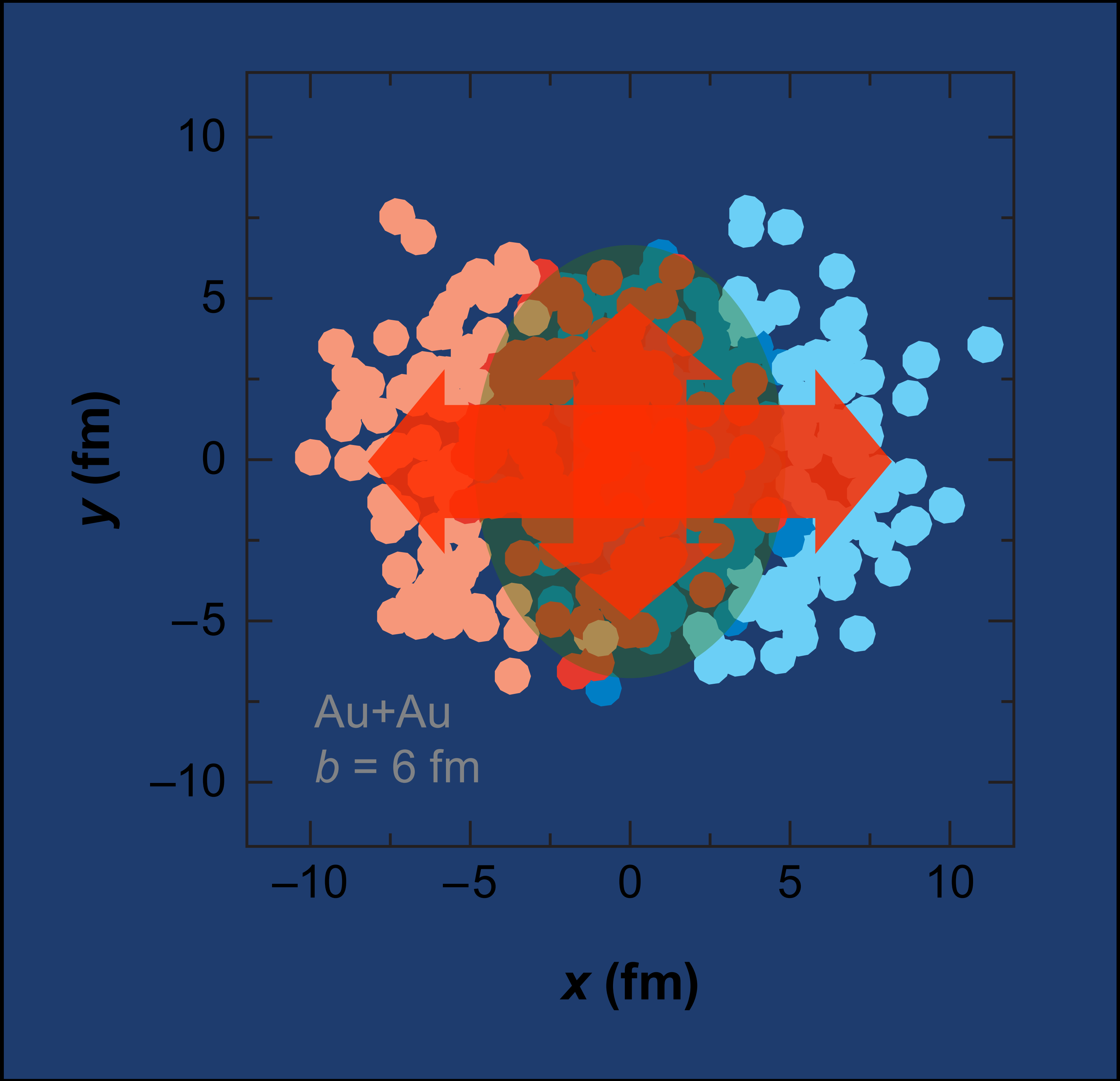
Explaining these two will make the LHC results much easier to understand

COLLECTIVE FLOW



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

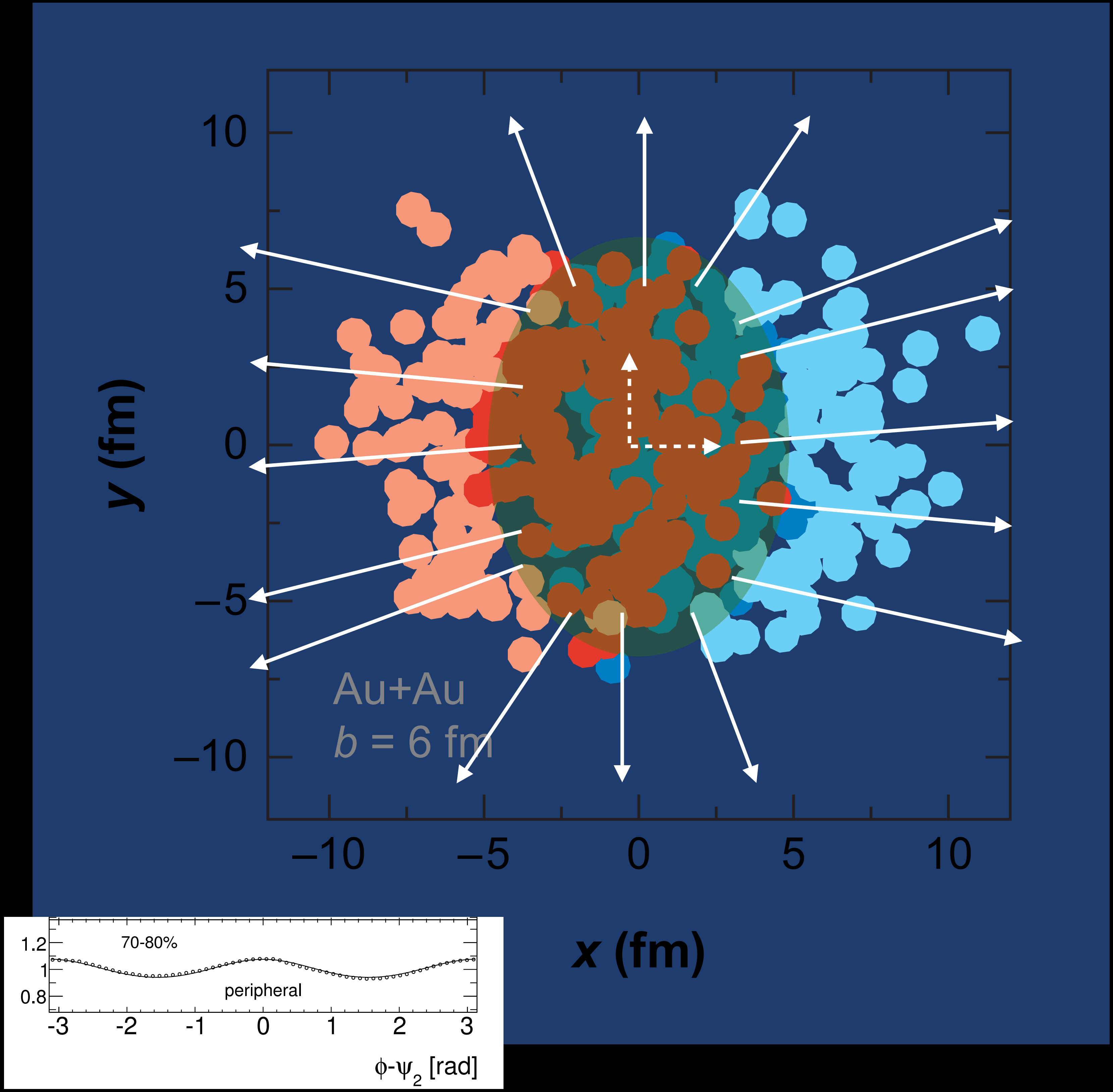
COLLECTIVE FLOW



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

If system <u>thermalizes</u> rapidly, then pressure gradients are larger along one direction

COLLECTIVE FLOW

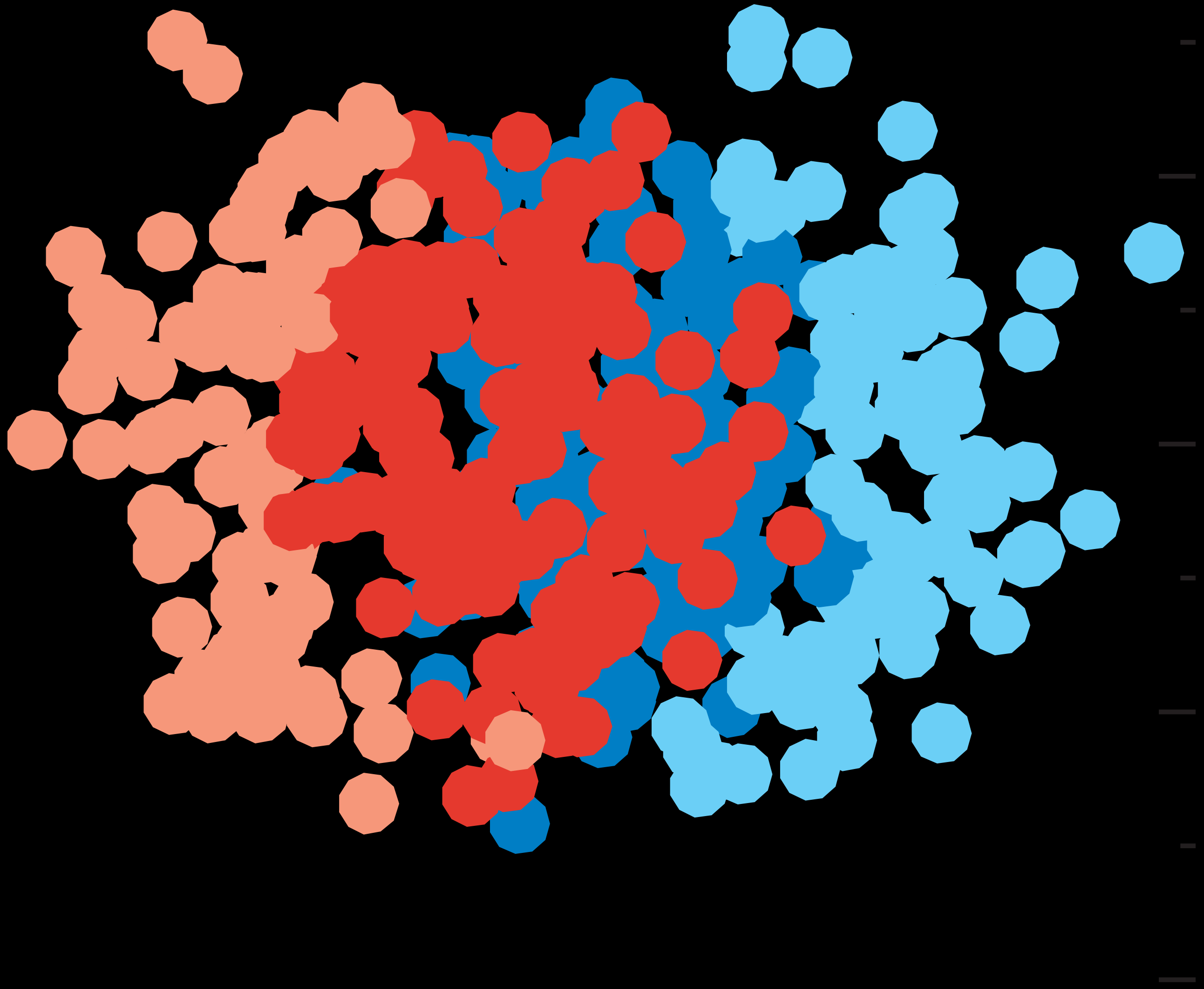


In a peripheral nuclear collision, overlap region is ellipse-shaped

If system <u>thermalizes</u> rapidly, then pressure gradients are larger along one direction

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

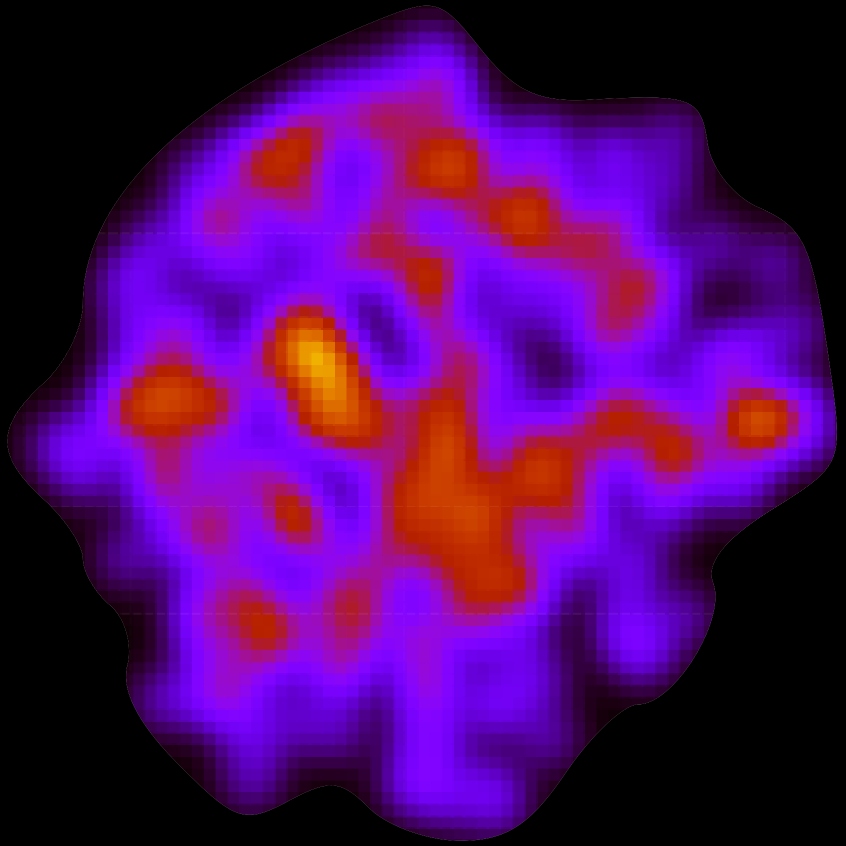
HYDRODYNAMICS FOR HI COLLISIONS



Collision of two nuclei (transverse plane)

HYDRODYNAMICS FOR HI COLLISIONS

B. Schenke, et al



"Initial stage", typically $\boldsymbol{\tau}_0<1$ fm/c

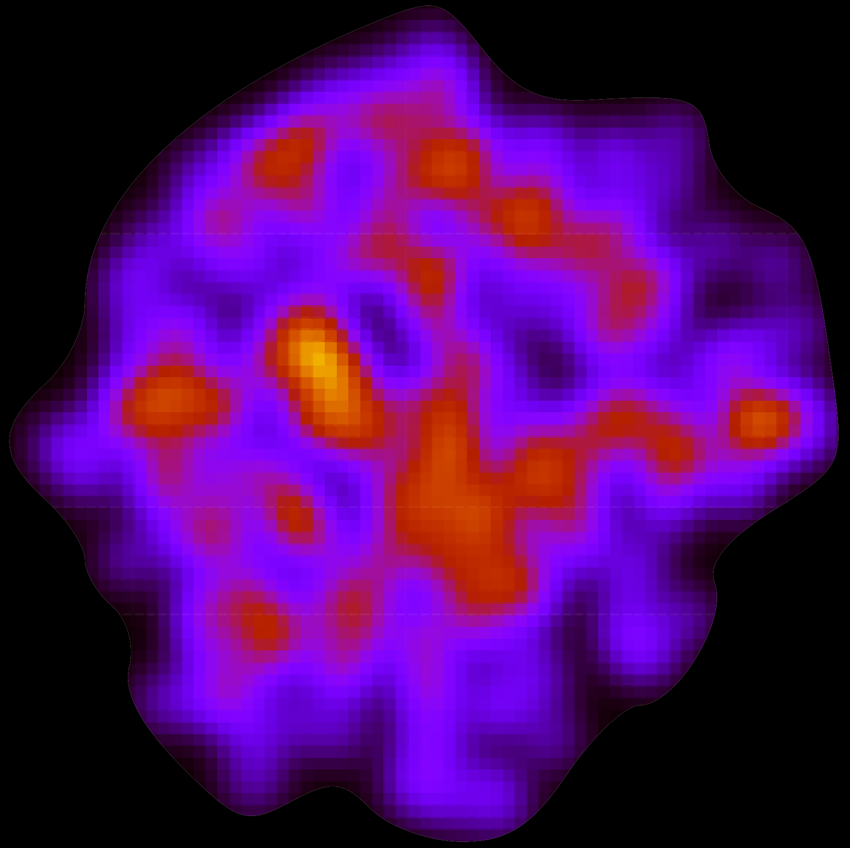
conversion of nucleon density to energy density

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

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

HYDRODYNAMICS FOR HI COLLISIONS

B. Schenke, et al



$t=t_0$

"thermalization time"

Hydrodynamic evolution:

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

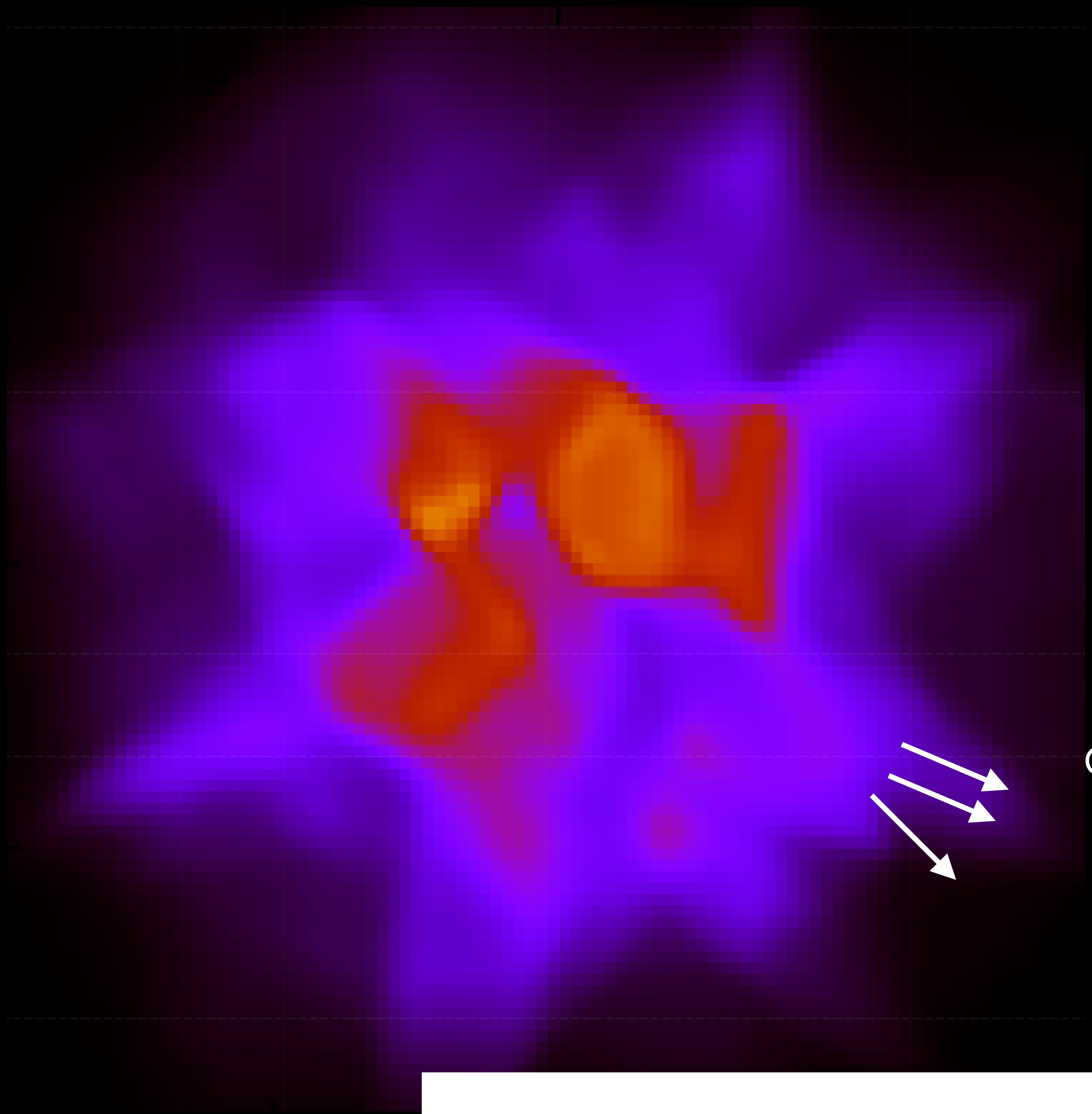
ideal hydro

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

& equation of state from lattice

HYDRODYNAMICS FOR HI COLLISIONS

B. Schenke, et al



t~6 fm/c

convert fluid cell to
hadron gas @
$T_f(x,y,z)$=120 MeV

Hydrodynamic
evolution:

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

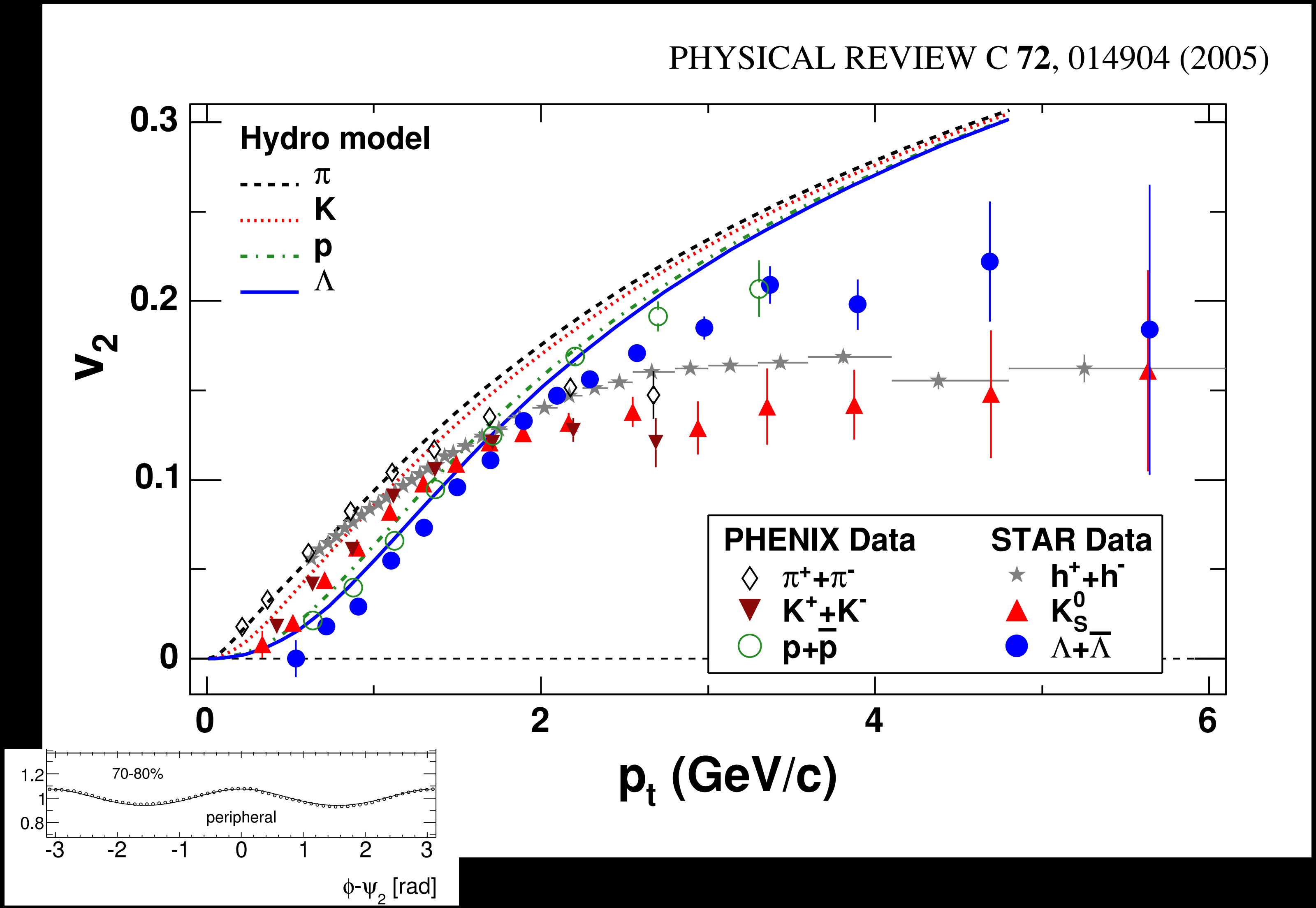
ideal
hydro

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

& equation of state from lattice

EXPERIMENTAL SIGNATURES OF COLLECTIVE FLOW

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


PHYSICAL REVIEW C **72**, 014904 (2005)

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

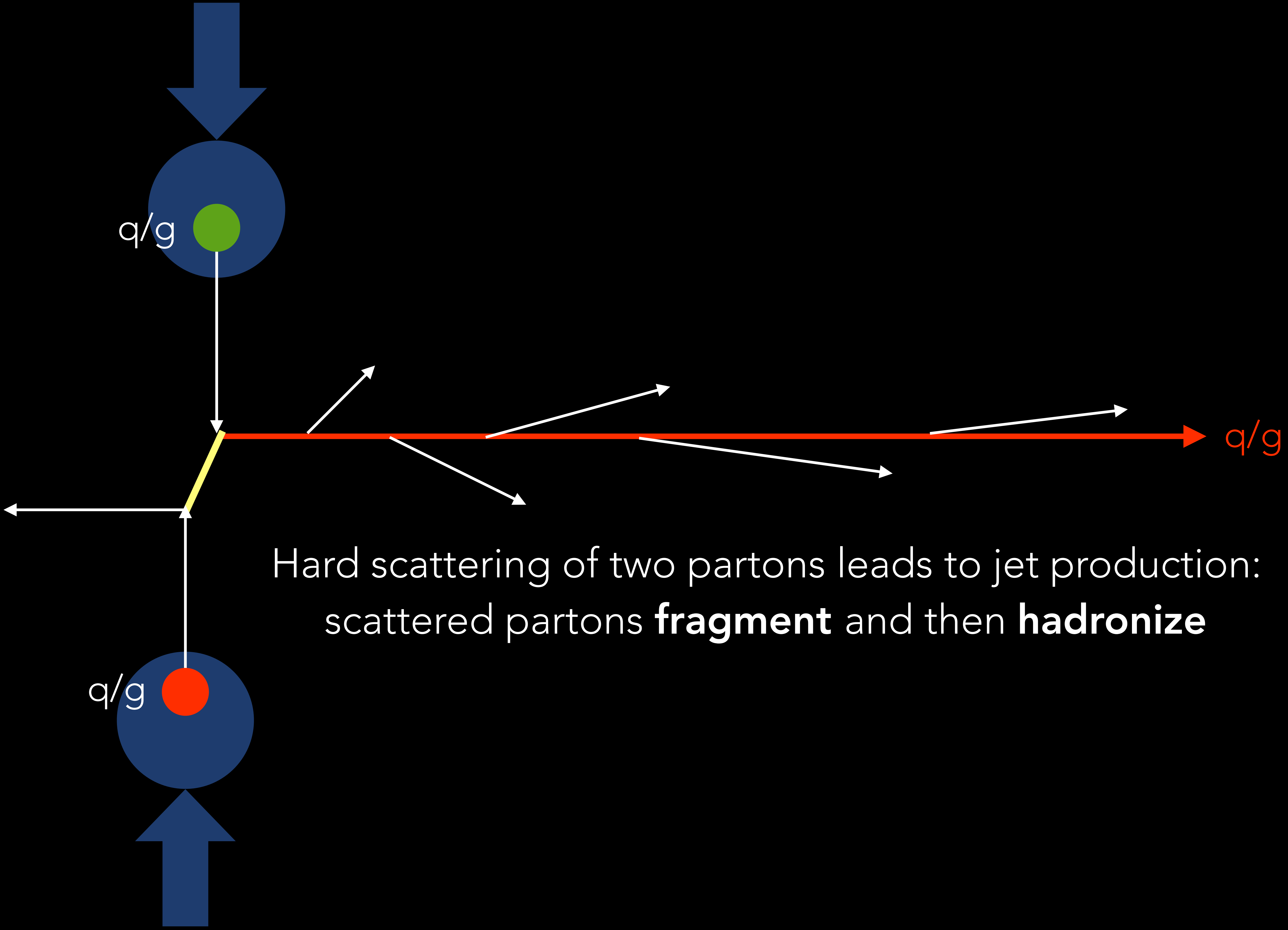
$$v_2 = \left\langle \cos\left(2\left[\phi - \Psi_2\right]\right)\right\rangle$$

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

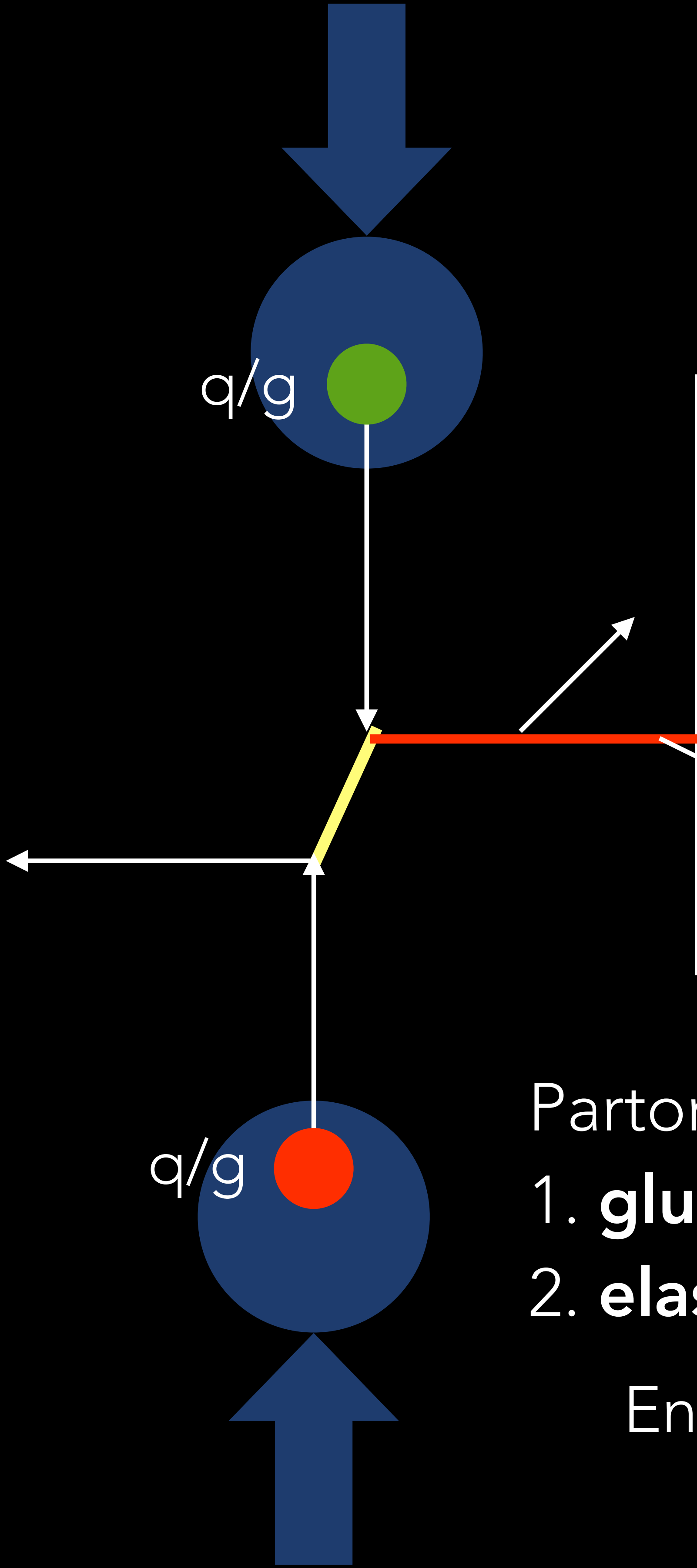


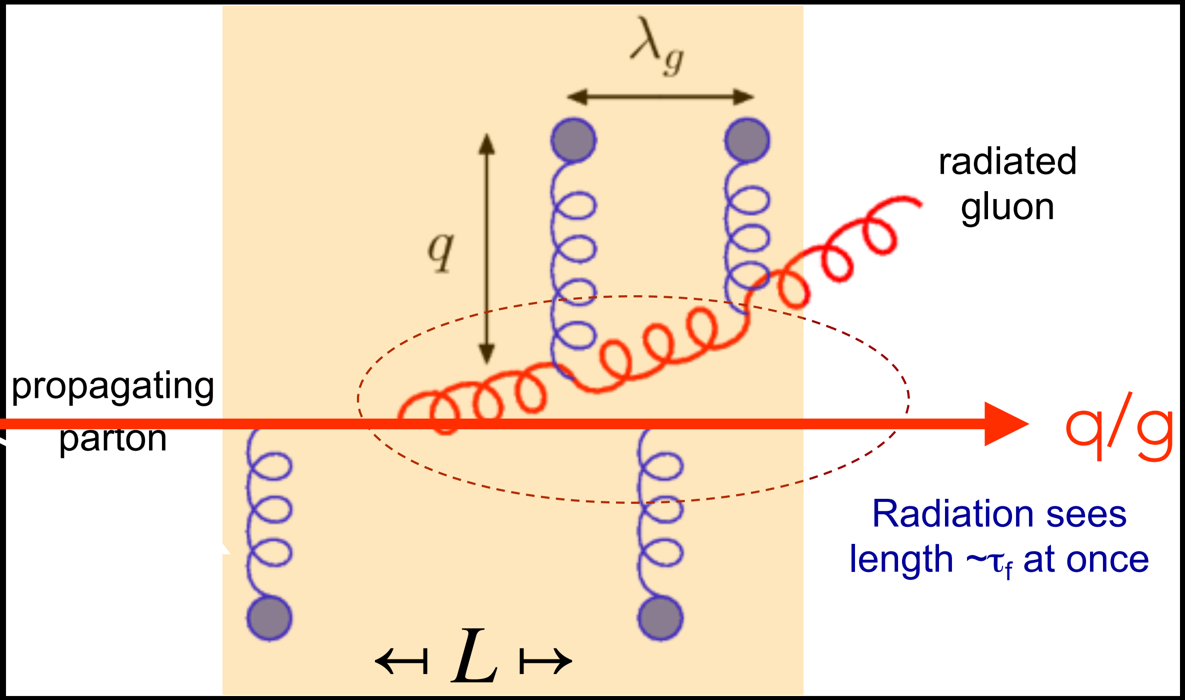
Hard scattering of two partons leads to jet production: scattered partons **fragment** and then **hadronize**

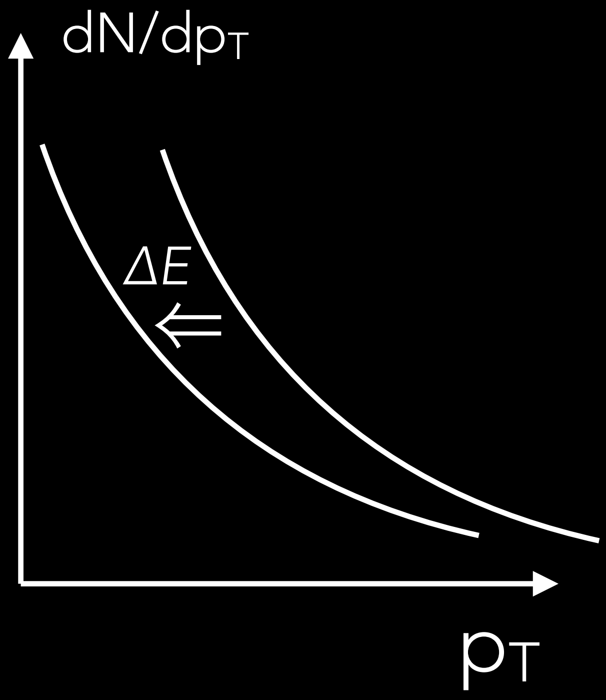
JET QUENCHING IN QCD

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

$$= \mathcal{L}_{AA} \times \sigma_X^{pp} \times \boxed{\langle N_{coll} \rangle \times \frac{\sigma_{AA}^{tot}}{\sigma_{tot}^{pp}}}$$

40,000!

"partonic luminosity"

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

minimum-bias rate

"mean nuclear thickness"

INTERMEZZO:
THE "MASTER EQUATION" FOR AA

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

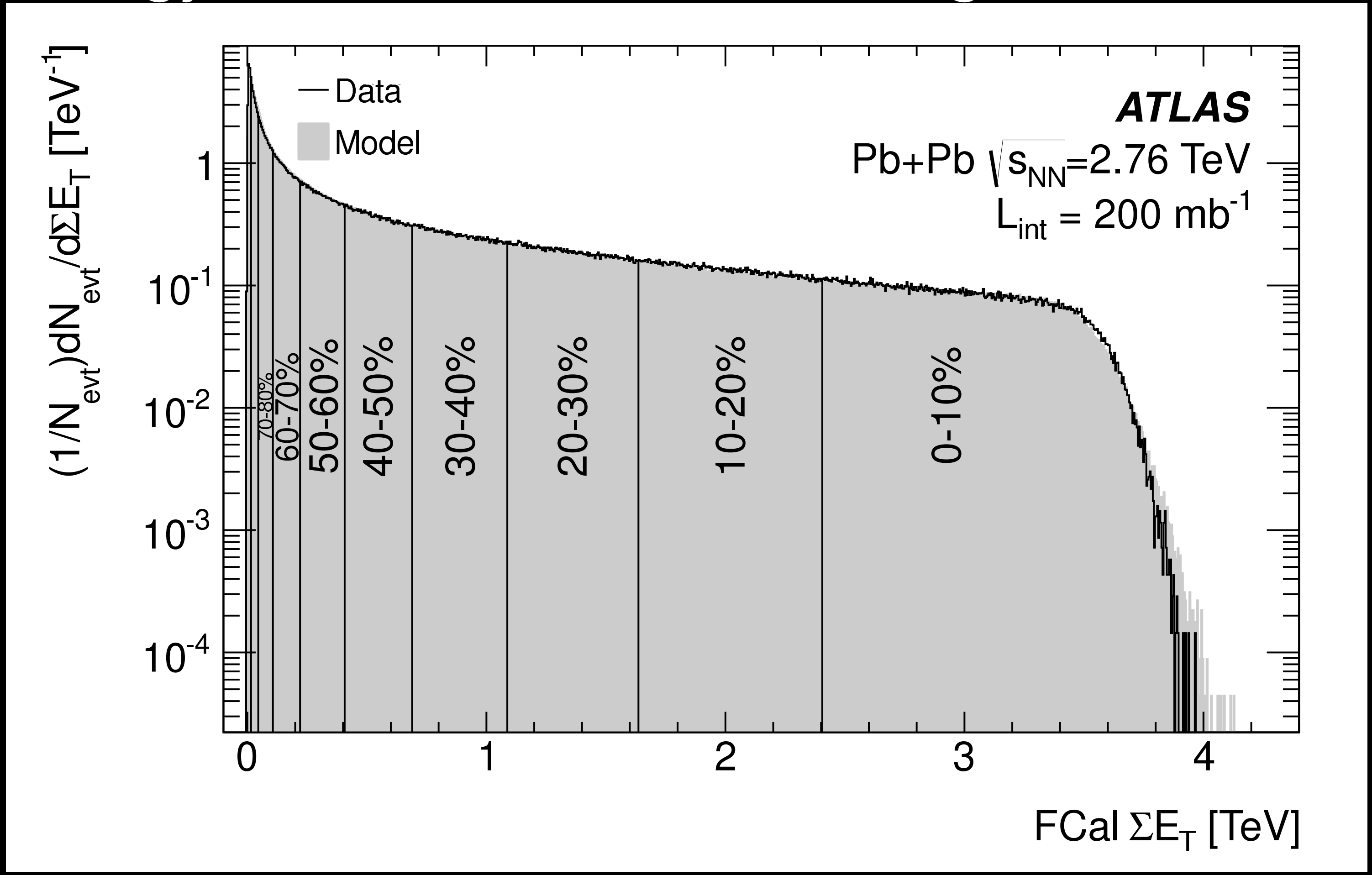
which defines "nuclear modification factor"

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

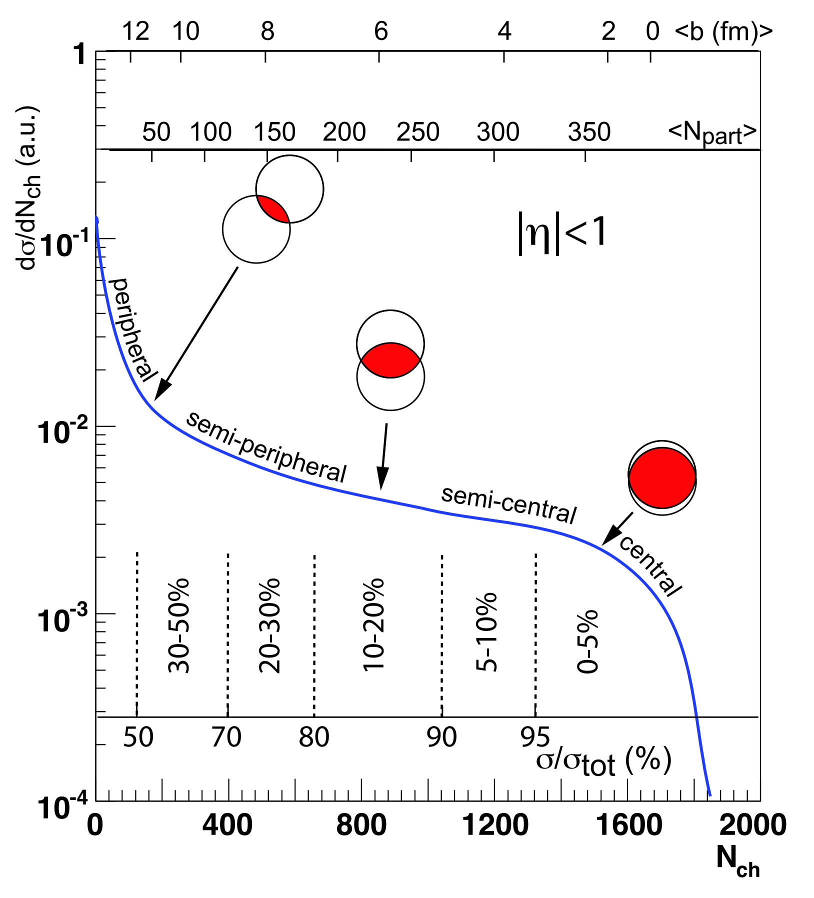
Cross sections in pp, yields in AA, and thickness from calculations

“CENTRALITY”

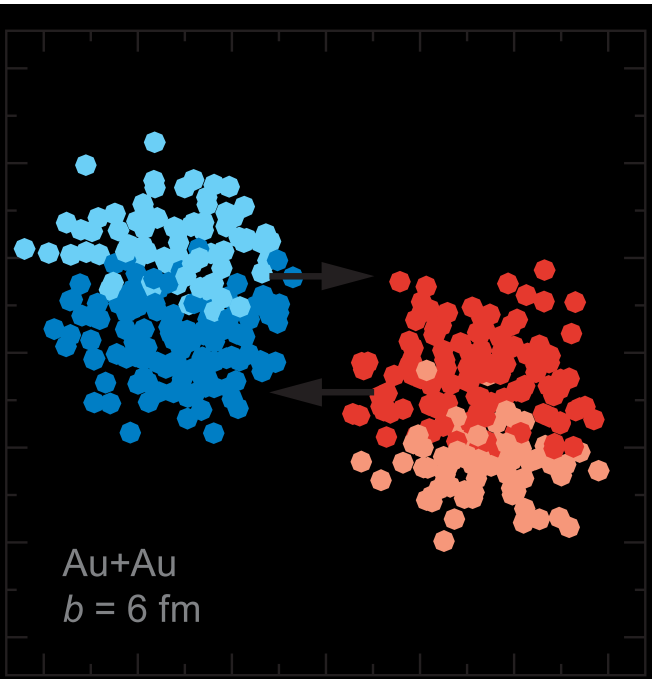
Energy measured at forward angles



Miller et al, 2007

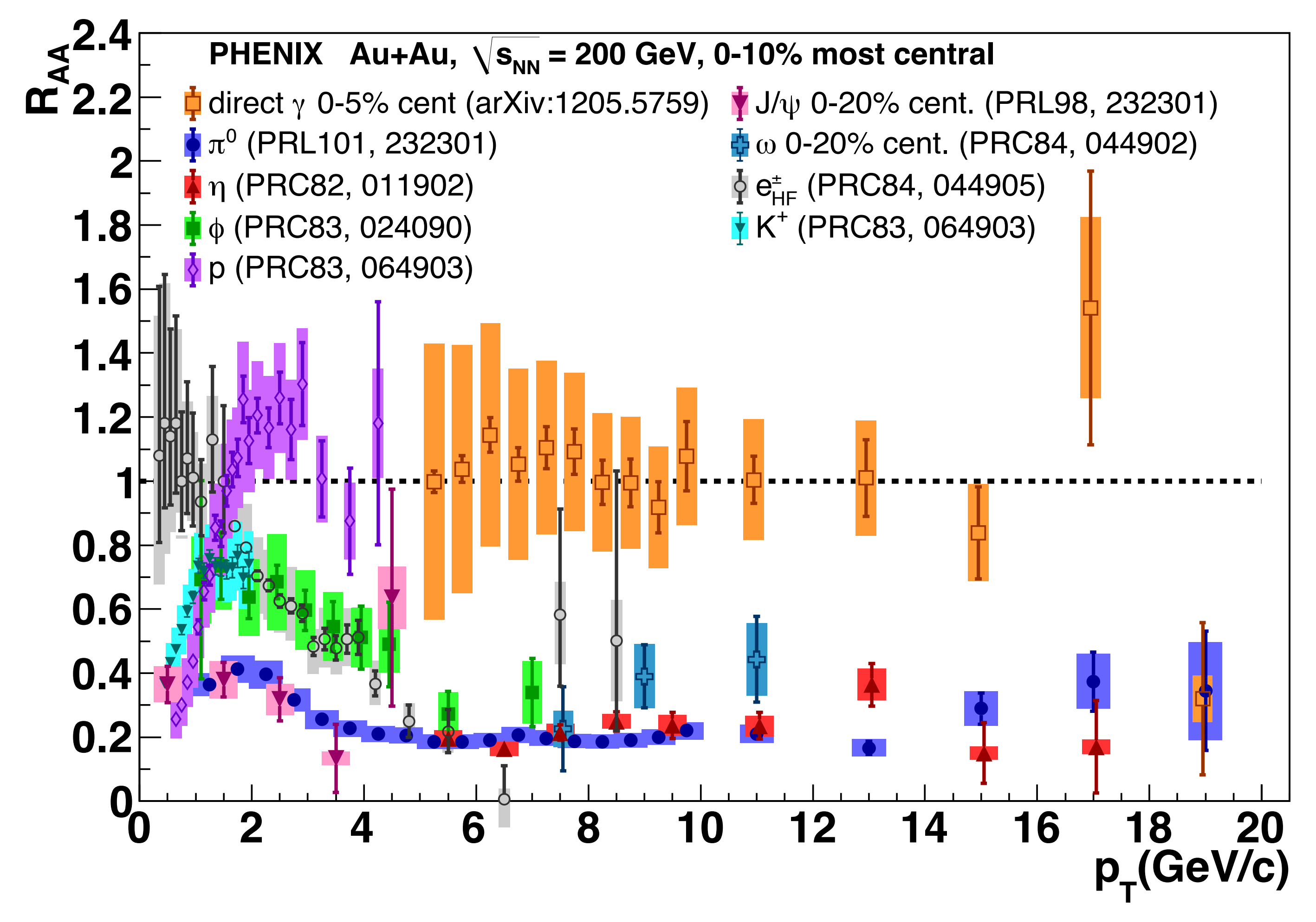


Convolve Glauber calculations with simple particle production models to estimate fraction of total AA cross section observed by each experiment



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

EXPERIMENTAL SIGNATURES OF JET QUENCHING (PHENIX @ RHIC)



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

← photons

← heavy flavor

← hadrons

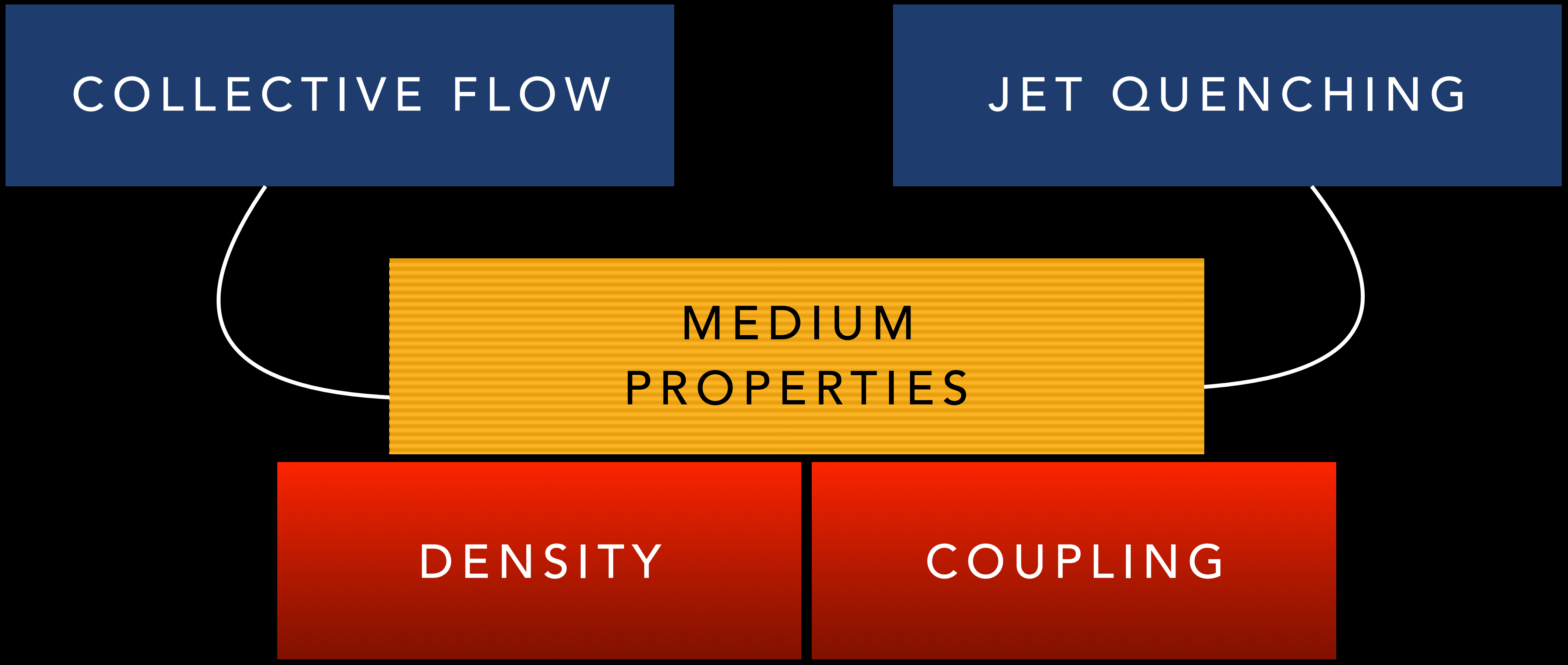
- **Initial state - fewer incoming partons? (nPDF)**

  ➔ *No similar deficit of direct (prompt) photons* $\boldsymbol{R_{AA}}$ *~ 1*

- **Final state - energy loss in final state?**

  ➔ *For* p_T*>6 GeV, all hadrons have* $\boldsymbol{R_{AA}}$ ***~ 0.2-0.4***

STRONG VS. WEAK COUPLING



COLLECTIVE FLOW

JET QUENCHING

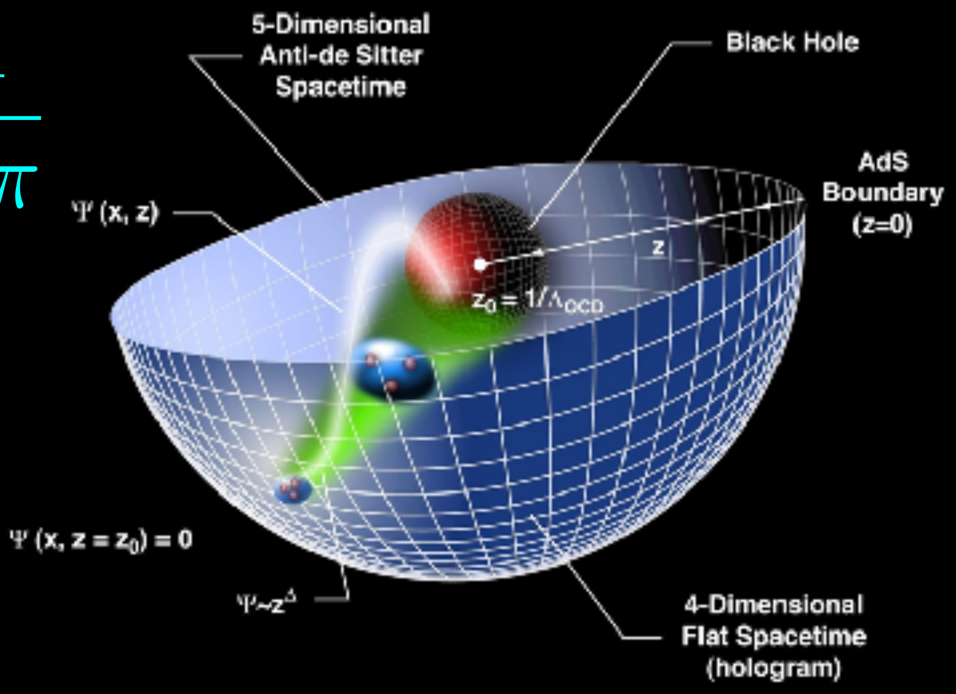
MEDIUM PROPERTIES

DENSITY

COUPLING

VISCOSITY/ ENTROPY

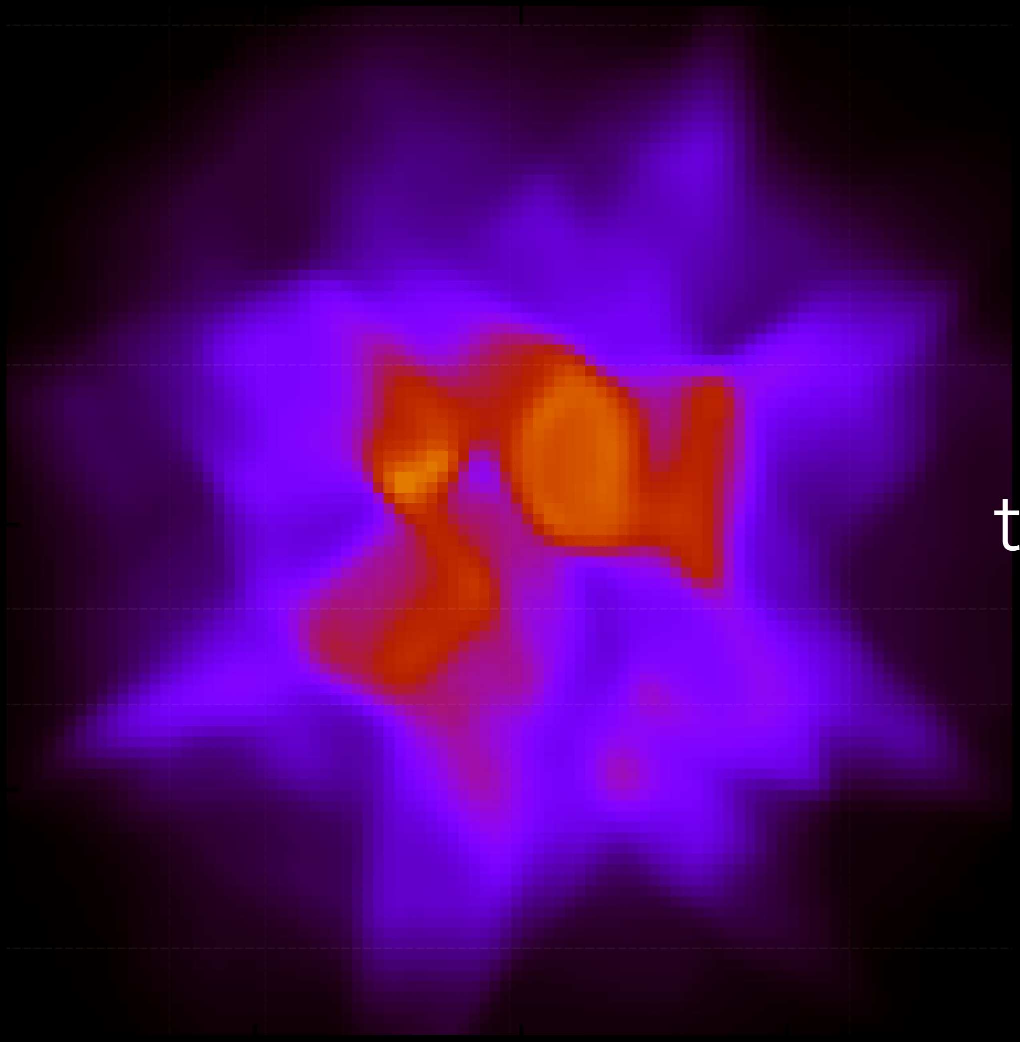
$$\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}} \Rightarrow \frac{\eta}{s} \geq \frac{1}{4\pi}$$



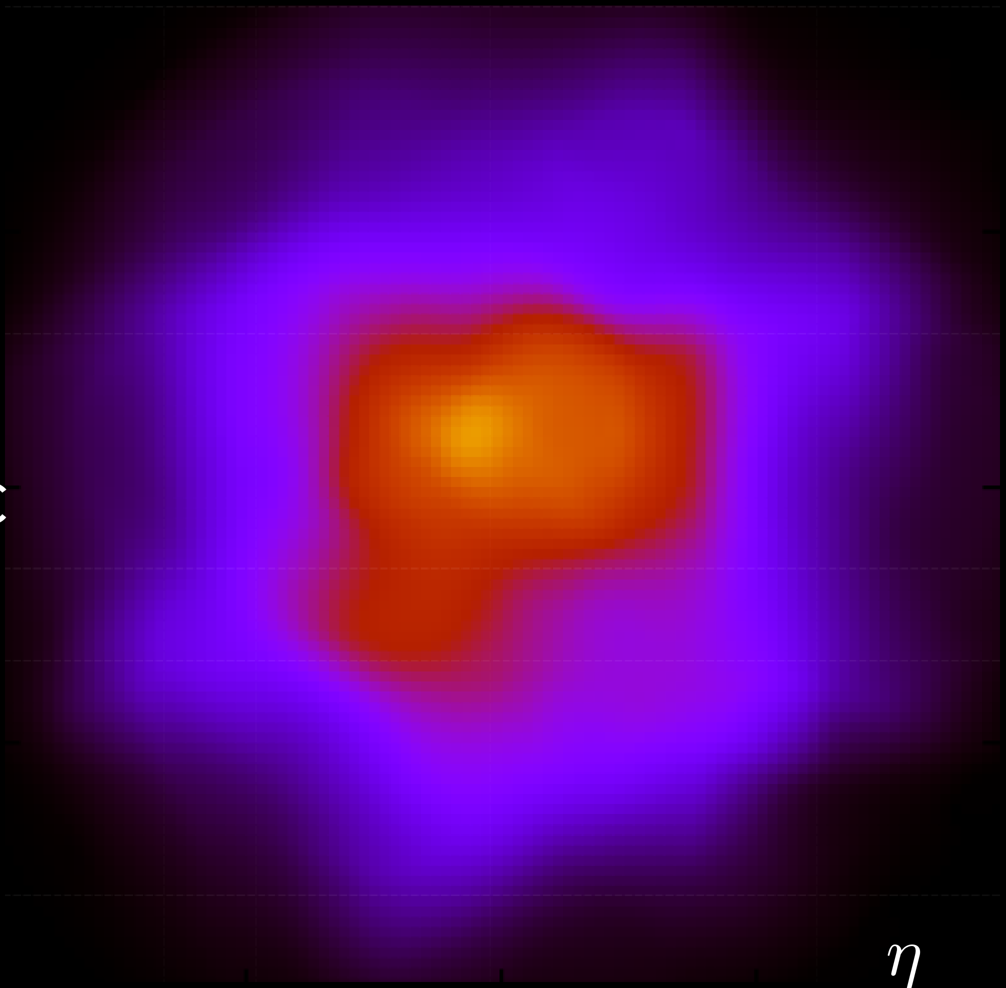
Determining QGP transport properties
is one of the only known ways to
test bound predicted using AdS/CFT (Son et al)

VISCOUS HYDRODYNAMICS

B. Schenke, et al



t=6 fm/c



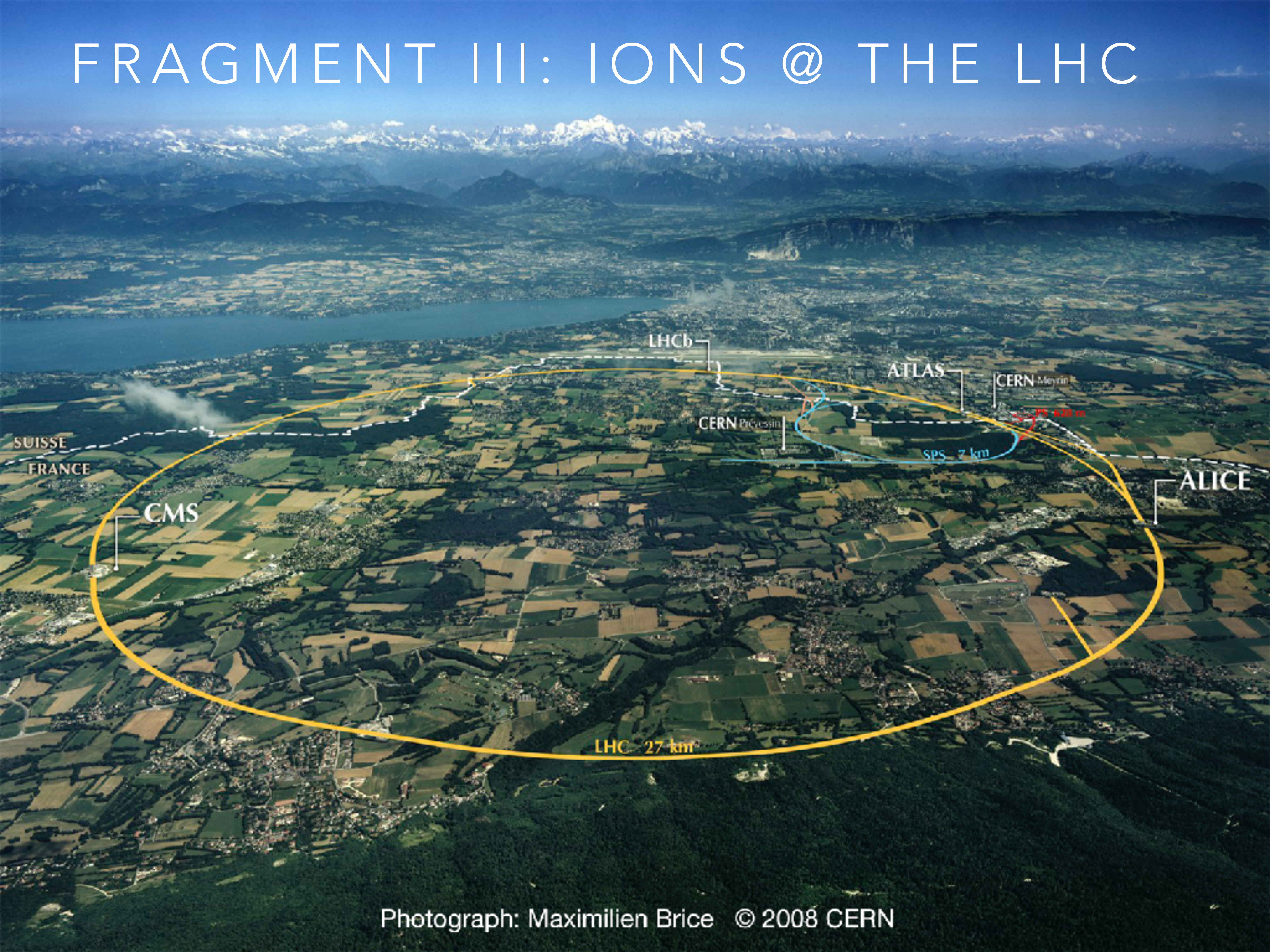
$$\frac{\eta}{s} = 0.16$$

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

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

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

FRAGMENT III: IONS @ THE LHC



Photograph: Maximilien Brice © 2008 CERN

FRAGMENT III: IONS @ THE LHC

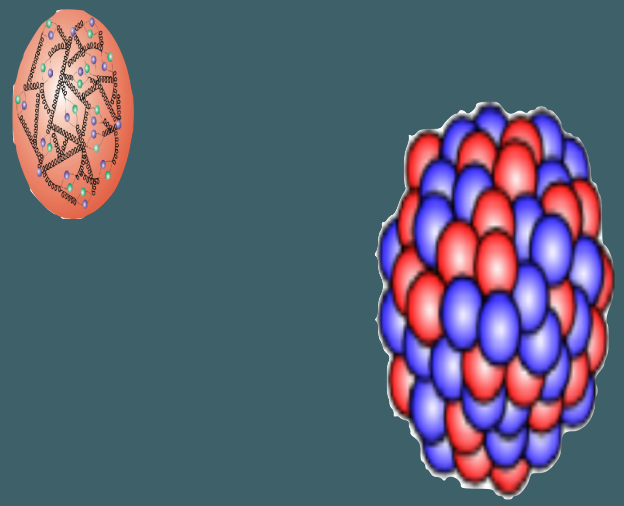
- **Heavy ion collisions at the LHC are**
  - Denser: ×2 in $dN/d\eta$ / $(N_{part}/2)$
  - Hotter
  - Longer-lived
  - with dramatic increases in hard process rates: probe medium

- **The LHC is a versatile machine**
  - lead-lead collisions
  - proton-proton collisions for “reference” data & an active “high multiplicity program”
  - proton-lead to study impact of nPDFs
  - New ions, e.g. possible Xe+Xe this fall?

COLLISIONS IN RUNS 1 & 2

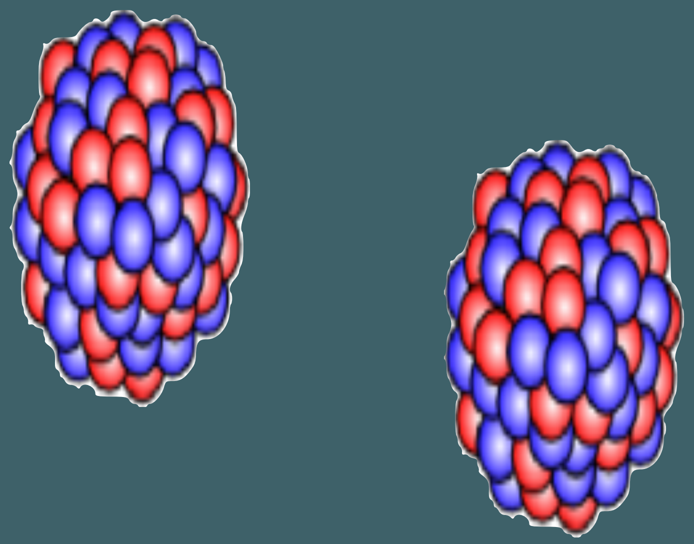
p+p

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)

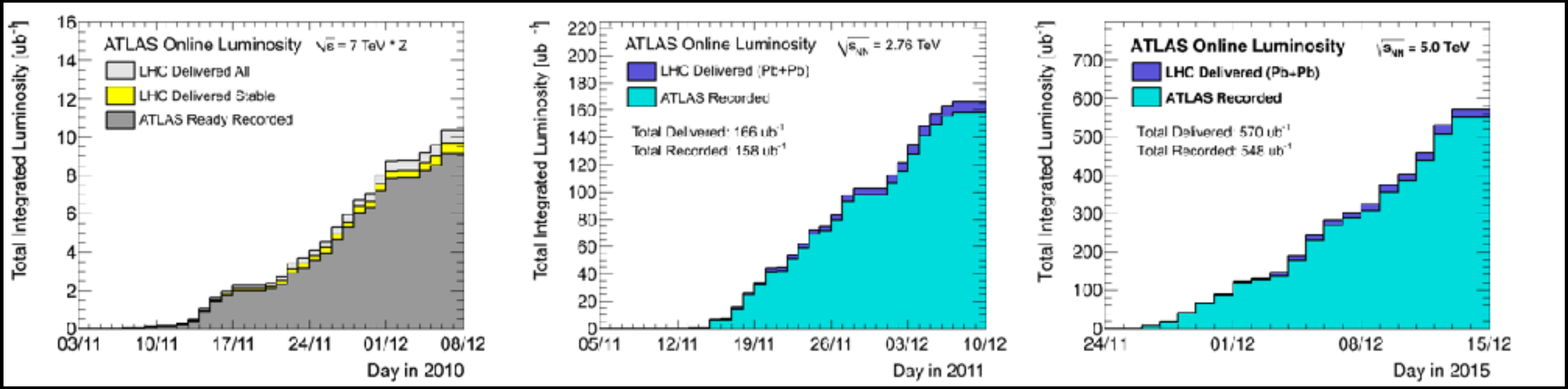


Pb+Pb

2.76 TeV (2010-11)
5.02 TeV (2015/18)

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

LHC AS A HEAVY ION COLLIDER



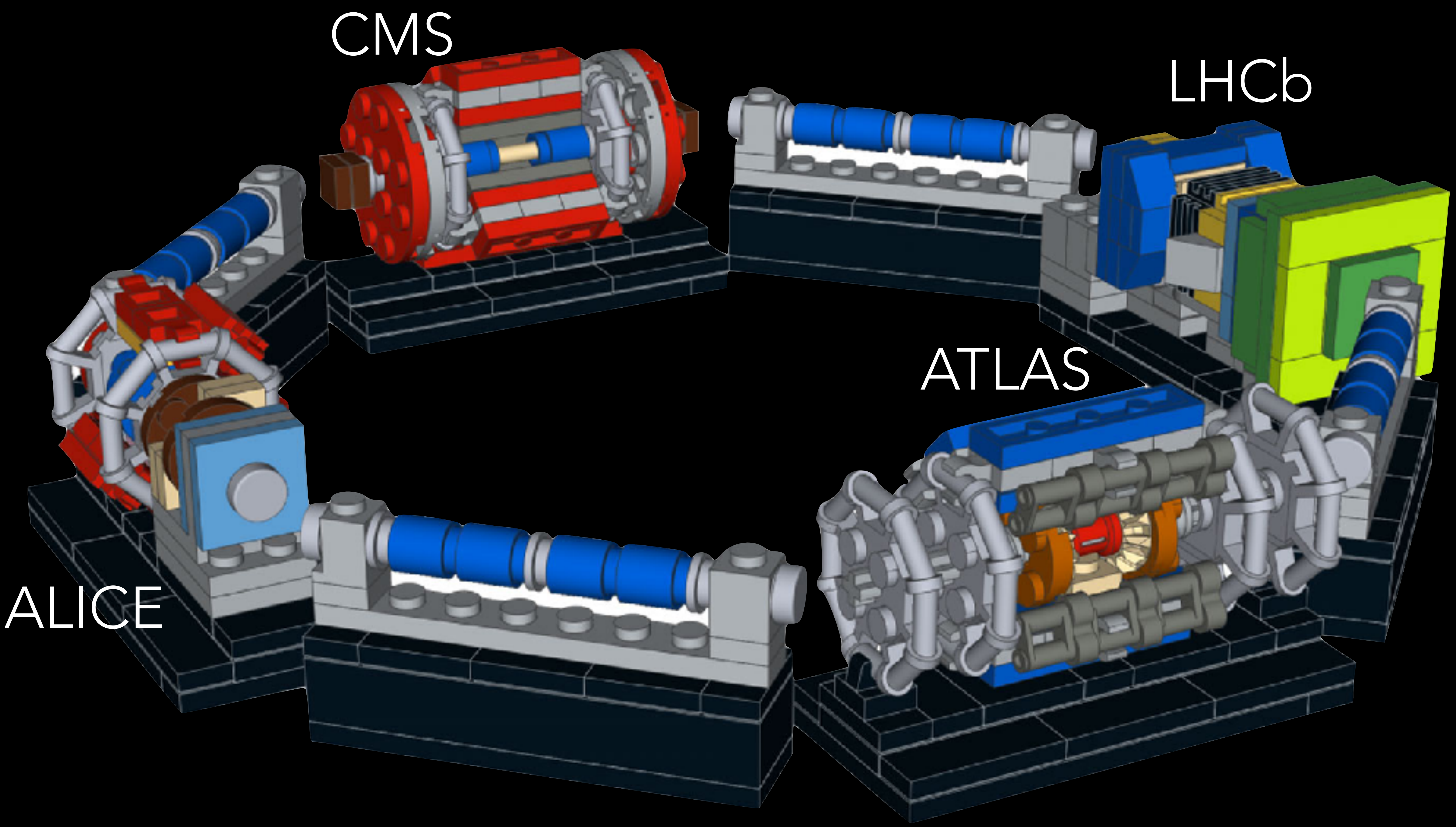
~0.3 μb^{-1}/day ~6 μb^{-1}/day ~30 μb^{-1}/day!

L_{int} = 2x10^{25}/cm^{2}s L_{int} = 5x10^{26}/cm^{2}s L_{int} = 3x10^{27}/cm^{2}s

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

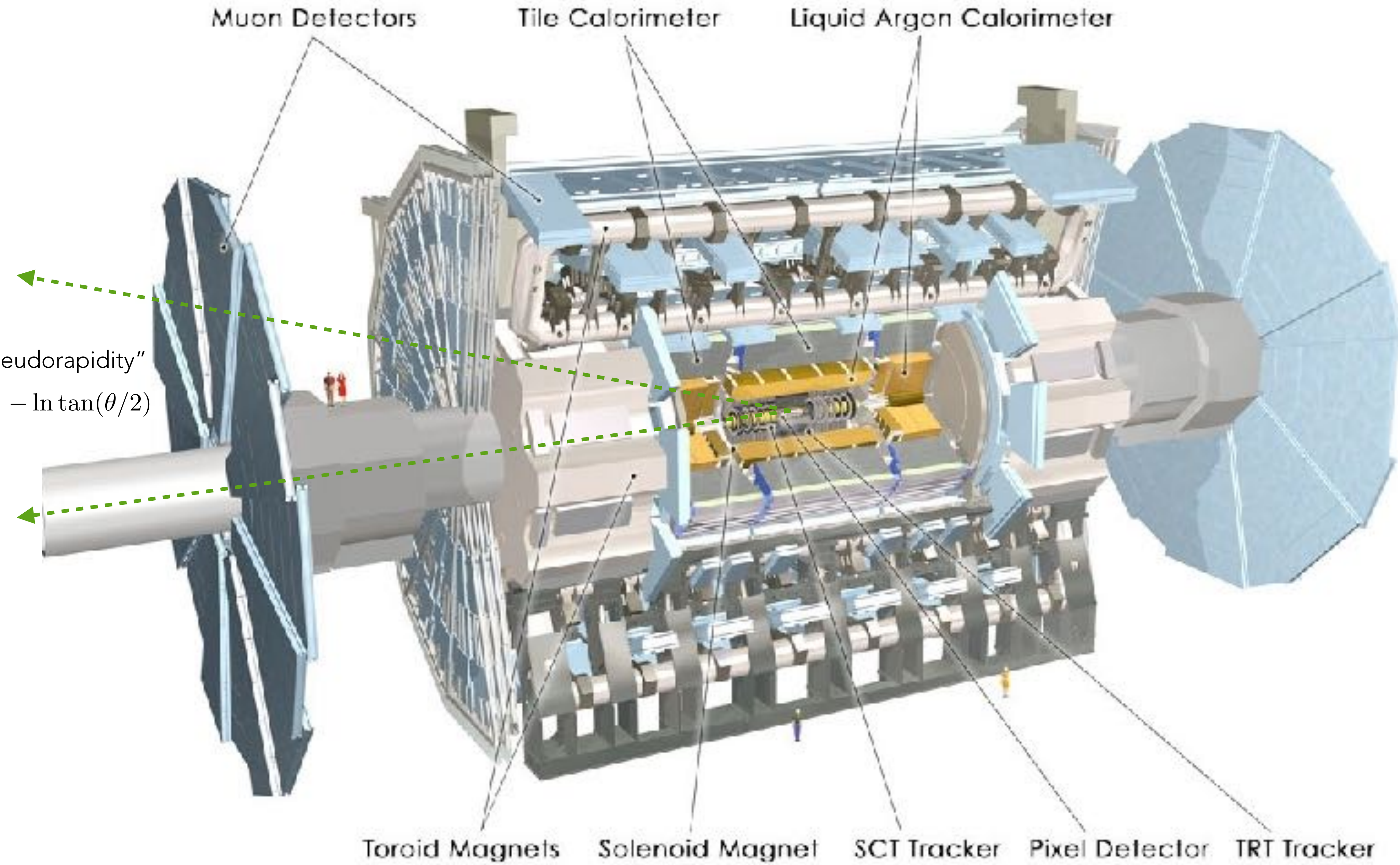
RUN 1 (2010-11)	RUN 2 (2015-2018)	RUN 3 (2021-2023)	RUN 4 (2026-2029)
0.15 nb^{-1}	1 nb^{-1}	10 nb^{-1}	?

THE LHC HEAVY ION PROGRAM



All experiments participating, including LHCb in Run 2

FRAGMENT IV: HI DETECTORS @ THE LHC



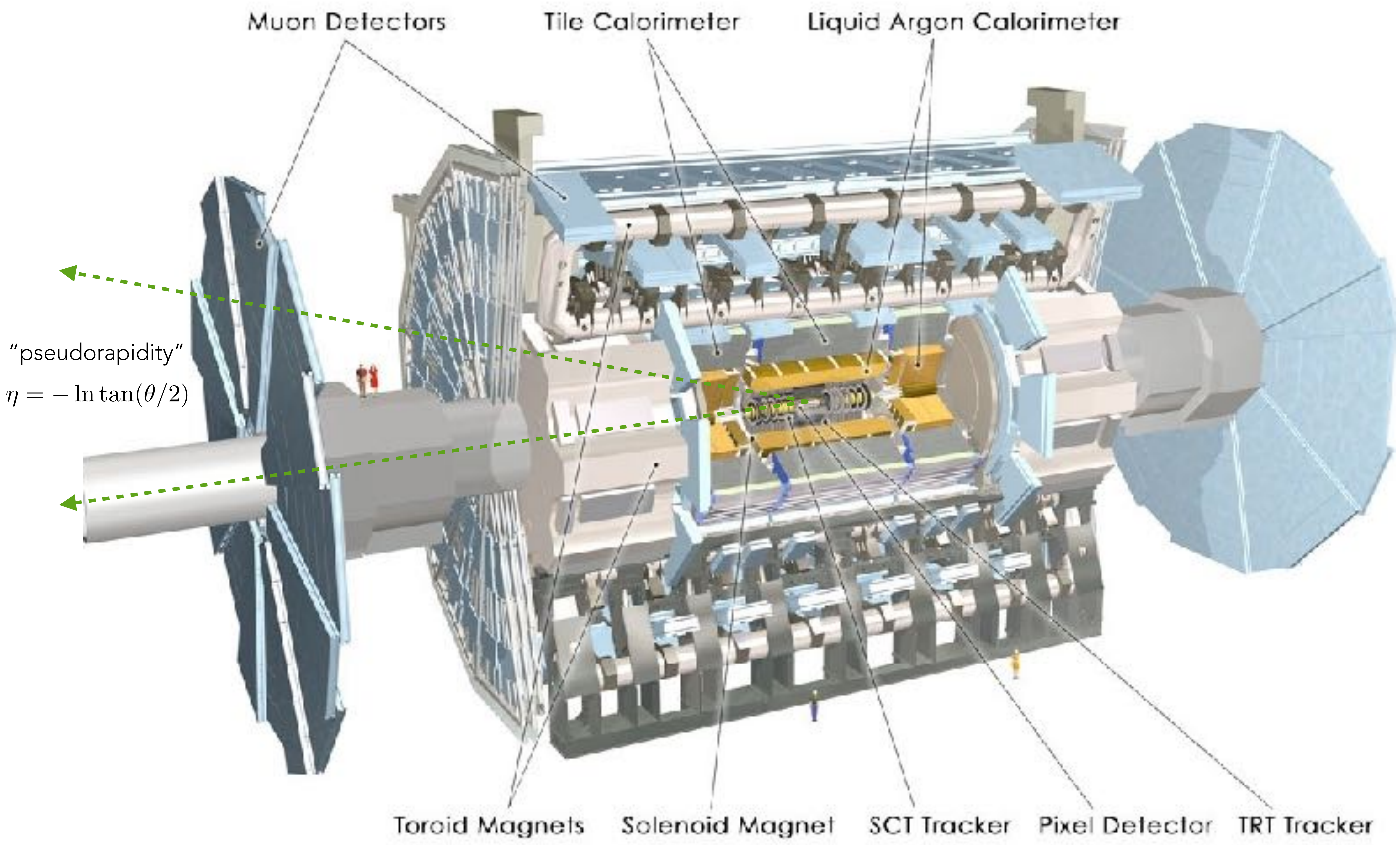
"pseudorapidity"

$\eta = -\ln\tan(\theta/2)$

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

FRAGMENT IV: HI DETECTORS @ THE LHC

2. Hadronic & EM calorimetry in $|\eta|<4.9$

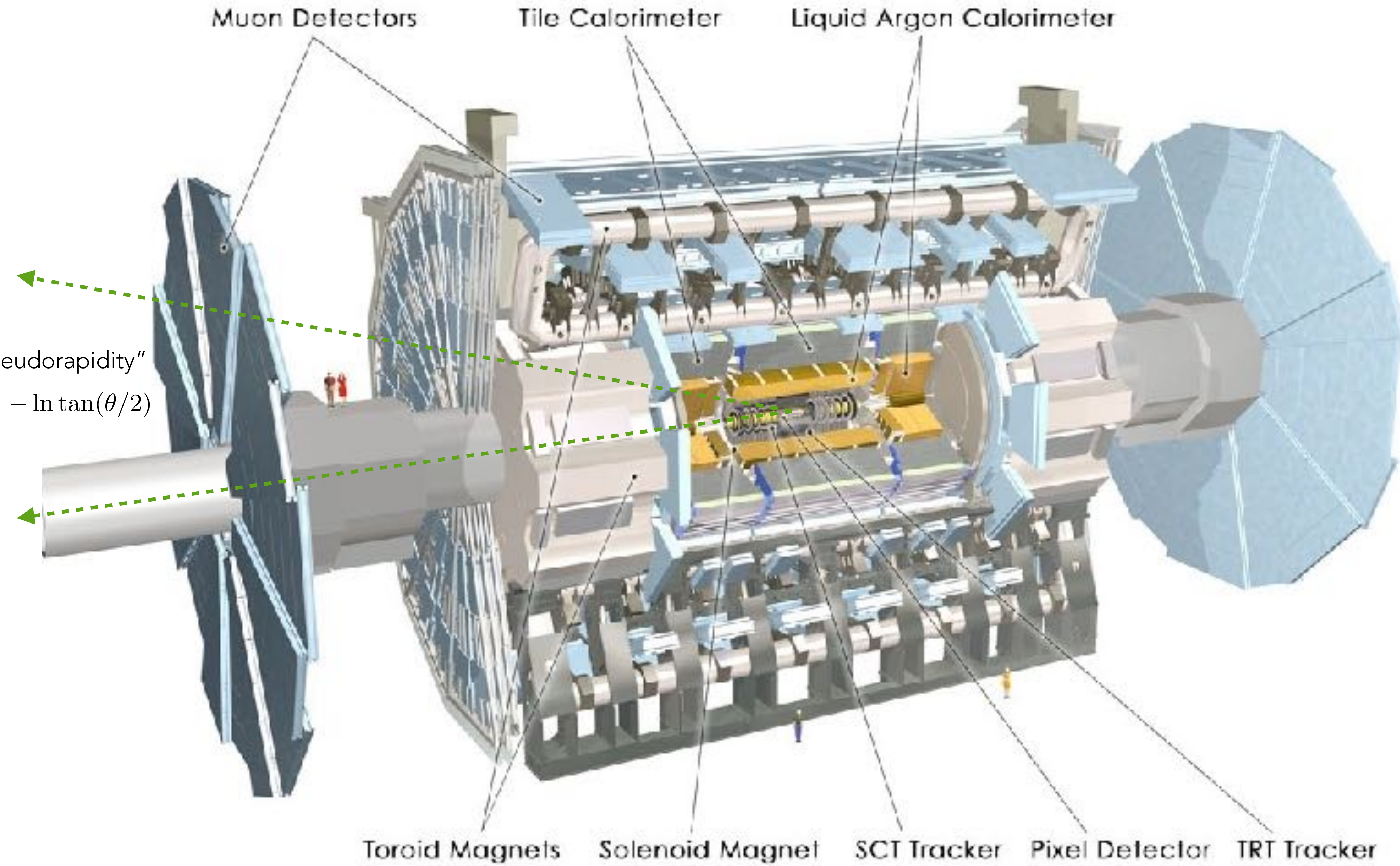


1. Precise charged-particle tracking in $|\eta|<2.5$

FRAGMENT IV: HI DETECTORS @ THE LHC

3. Precise μ tracking in |η|<2.7

2. Hadronic & EM calorimetry in |η|<4.9

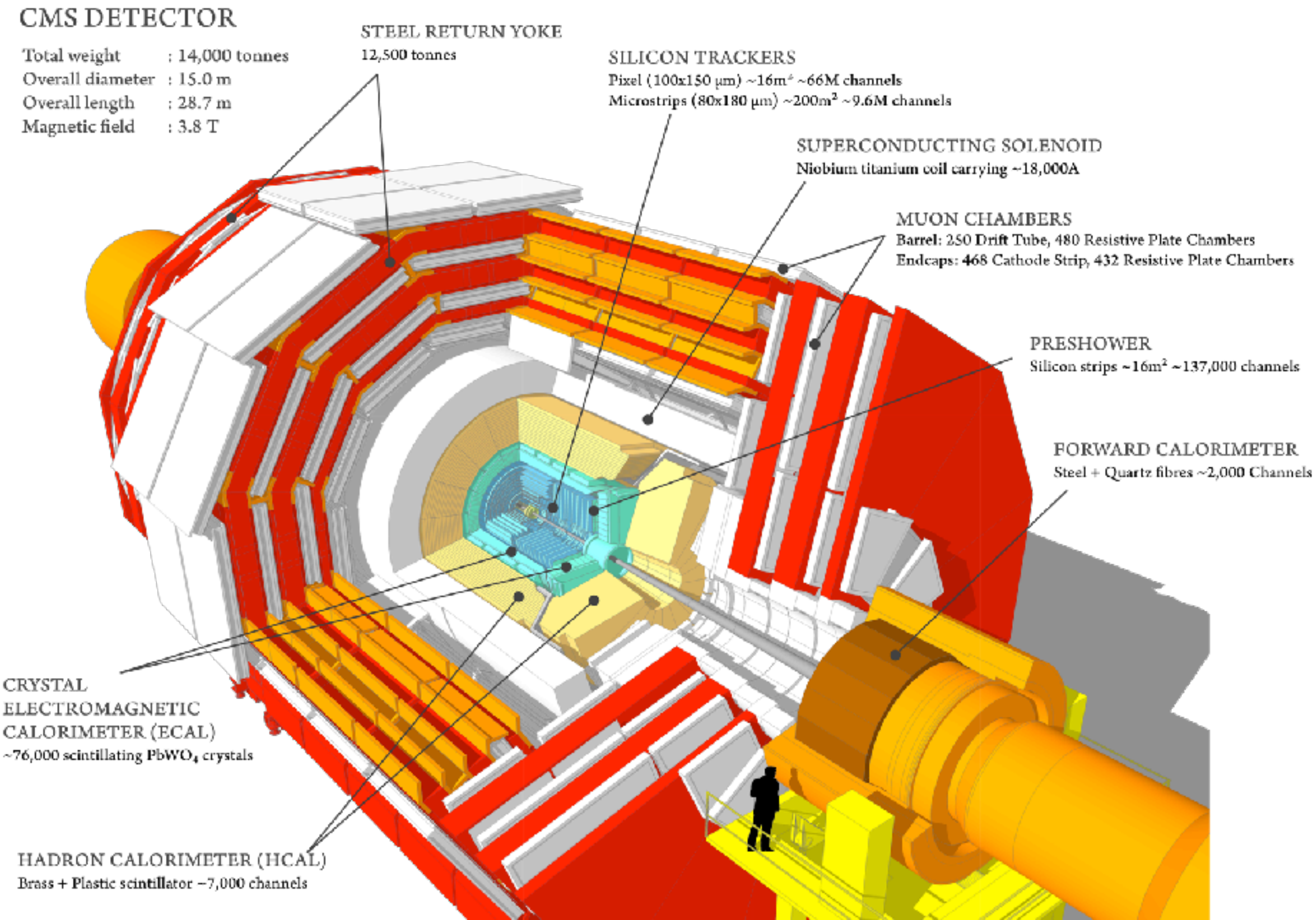


"pseudorapidity"

$\eta = -\ln \tan(\theta/2)$

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

ACT IV: HI DETECTORS @ THE LHC



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m^2 ~66M channels
Microstrips (80x180 μm) ~200m^2 ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

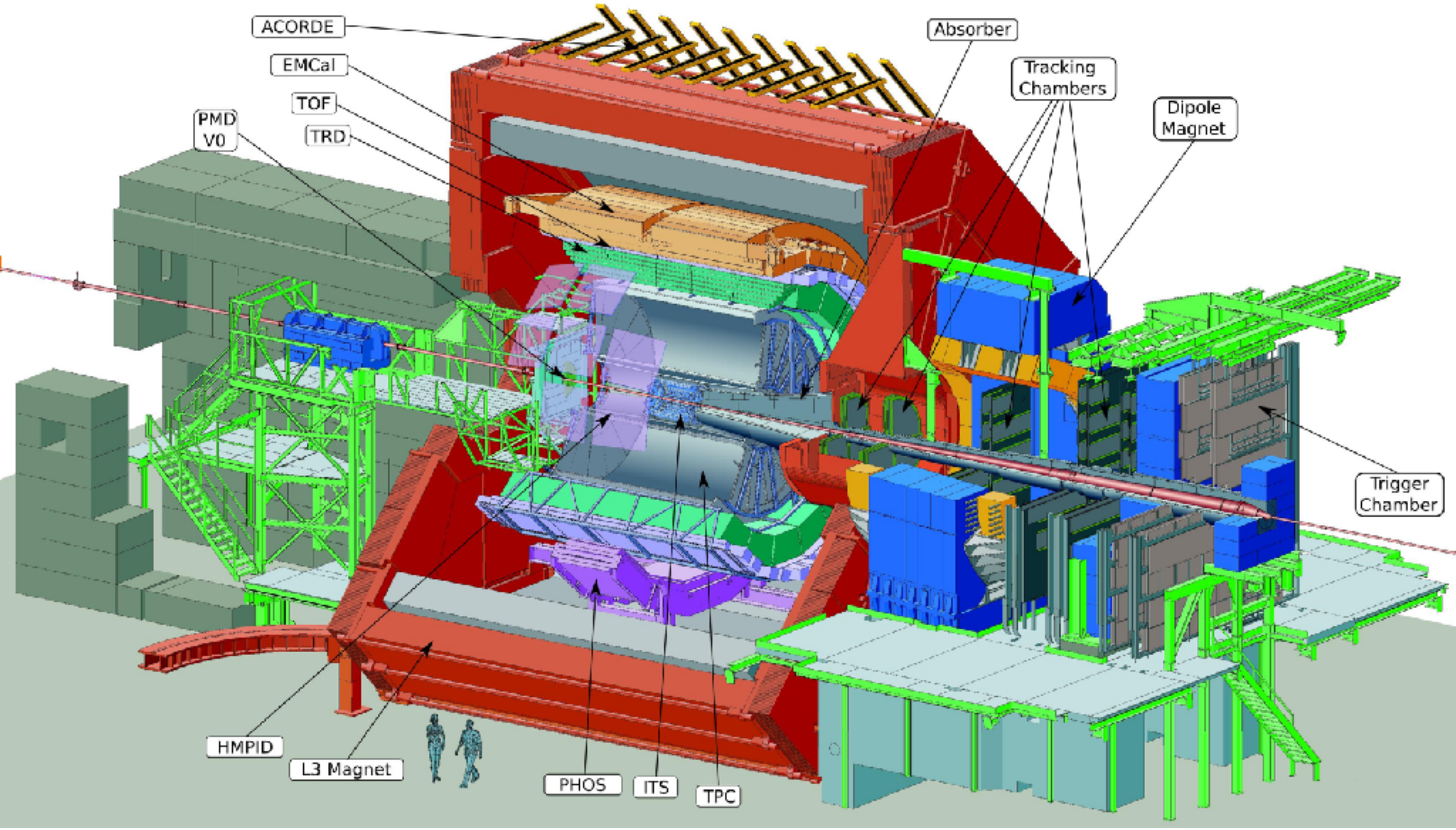
PRESHOWER
Silicon strips ~16m^2 ~137,000 channels

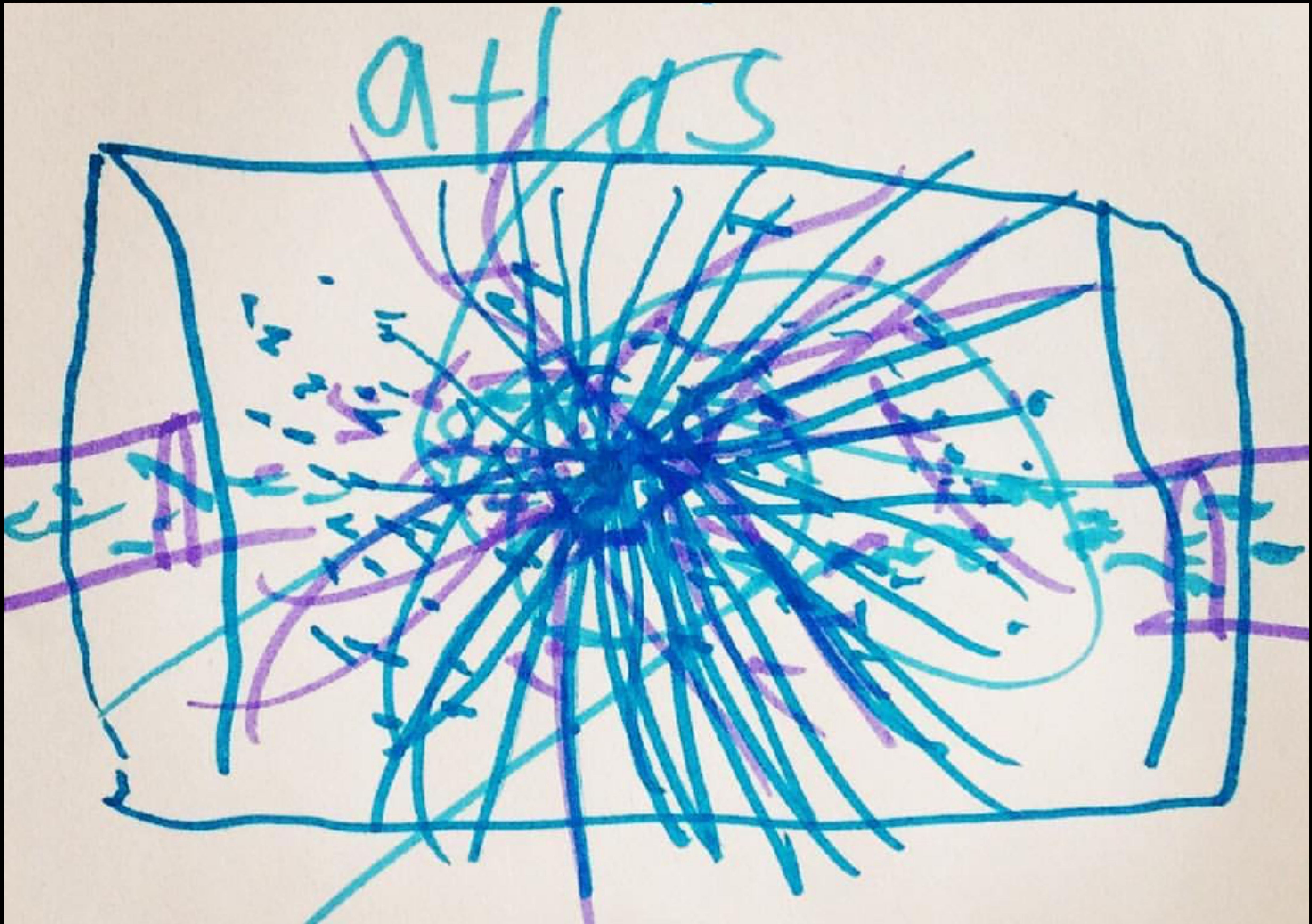
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

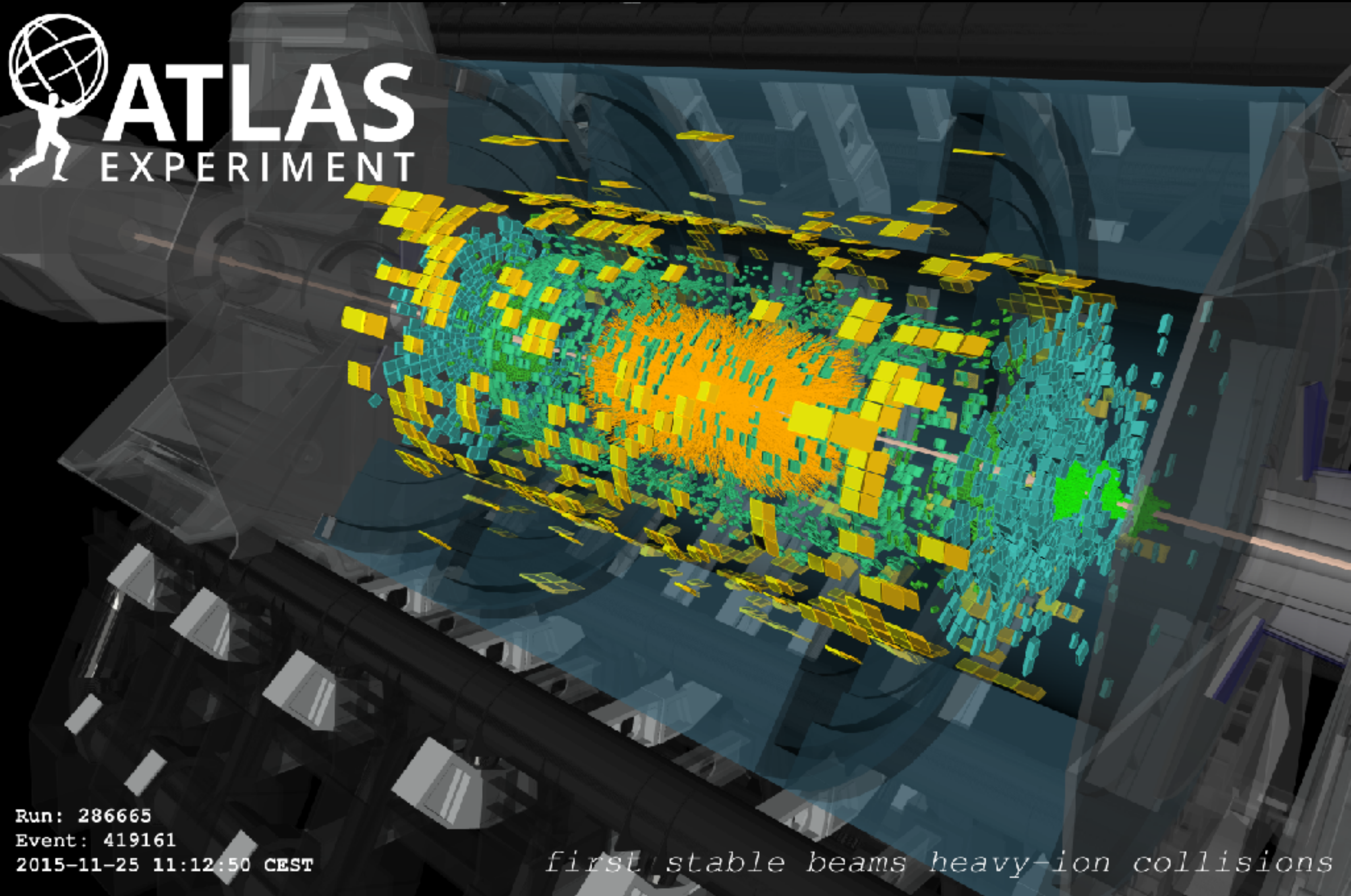
ACT IV: HI DETECTORS @ THE LHC





by Clea, 6

A RUN 2 PB+PB EVENT



FRAGMENT IV: HI DETECTORS @ THE LHC

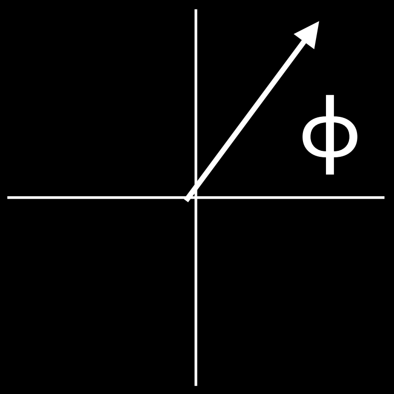
- **Sophisticated detectors**
  - Occupancies in silicon, calorimeter, and muon spectrometers are no problem in central Pb+Pb
  - ALICE TPC can fully track entire HI events down to low p_T

- **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

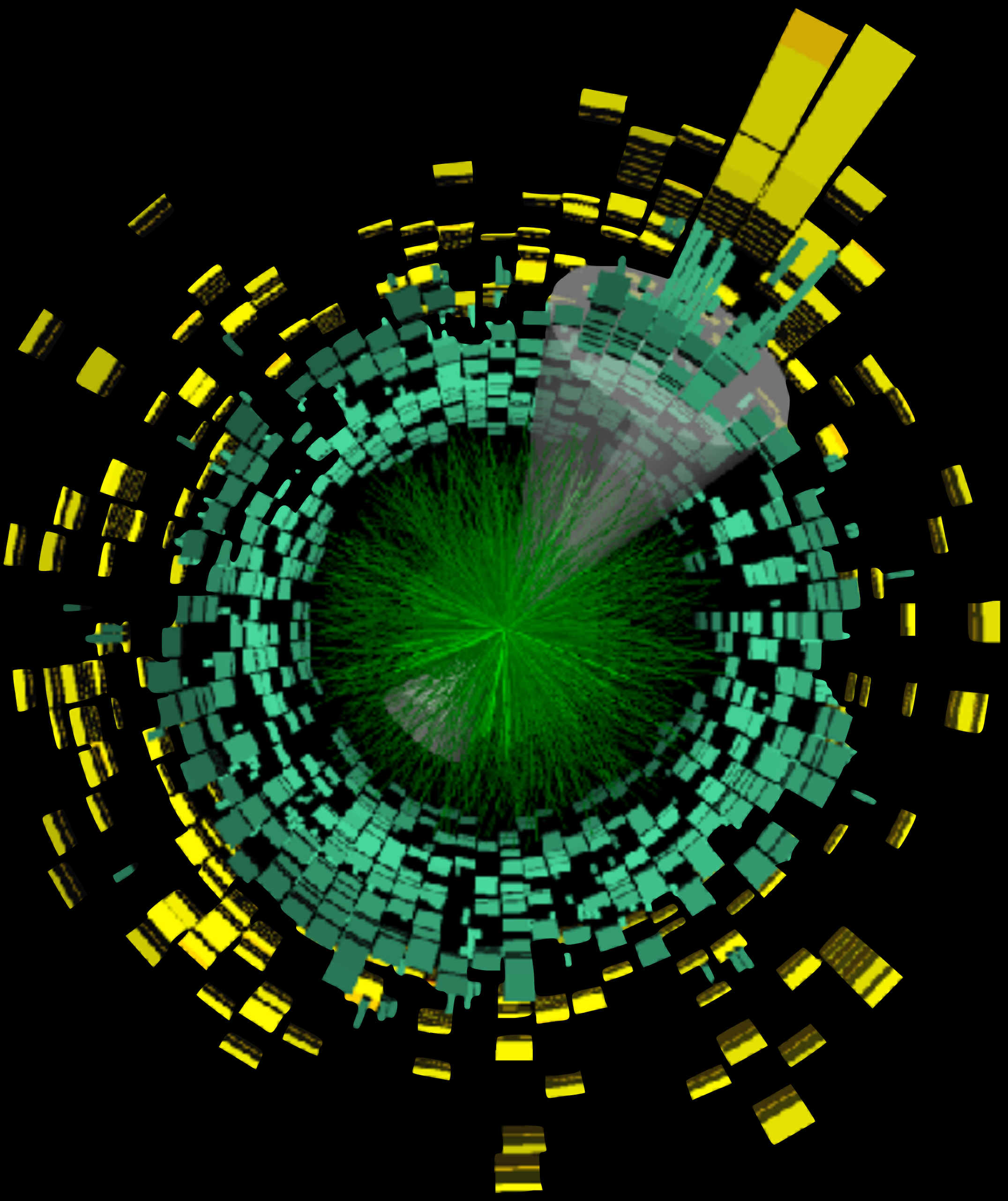
EARLY RESULTS FROM RUN 1 PB+PB

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

RHIC provided context of where to look first

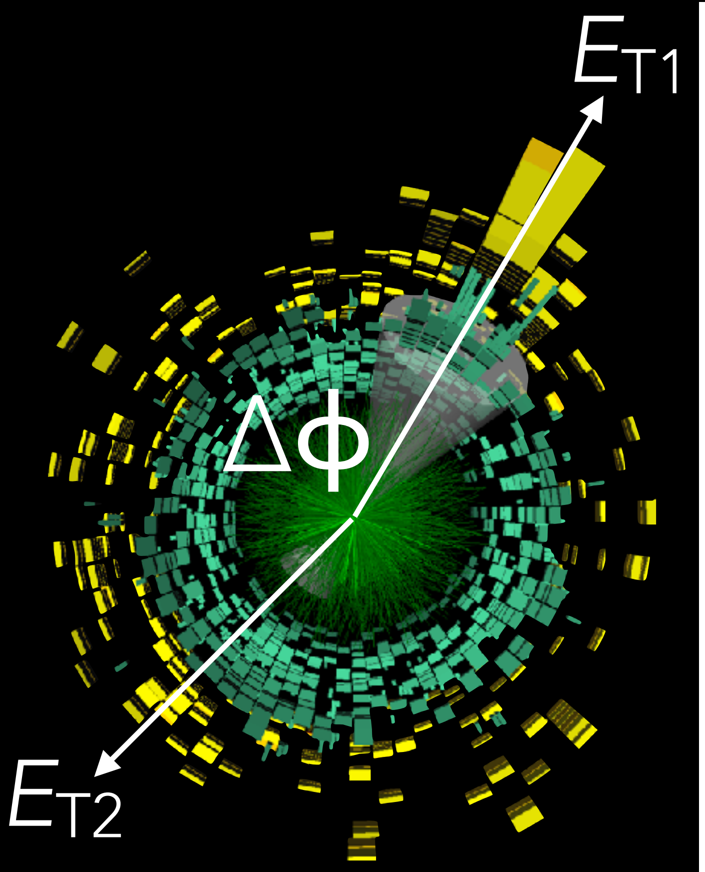


looking
along z direction

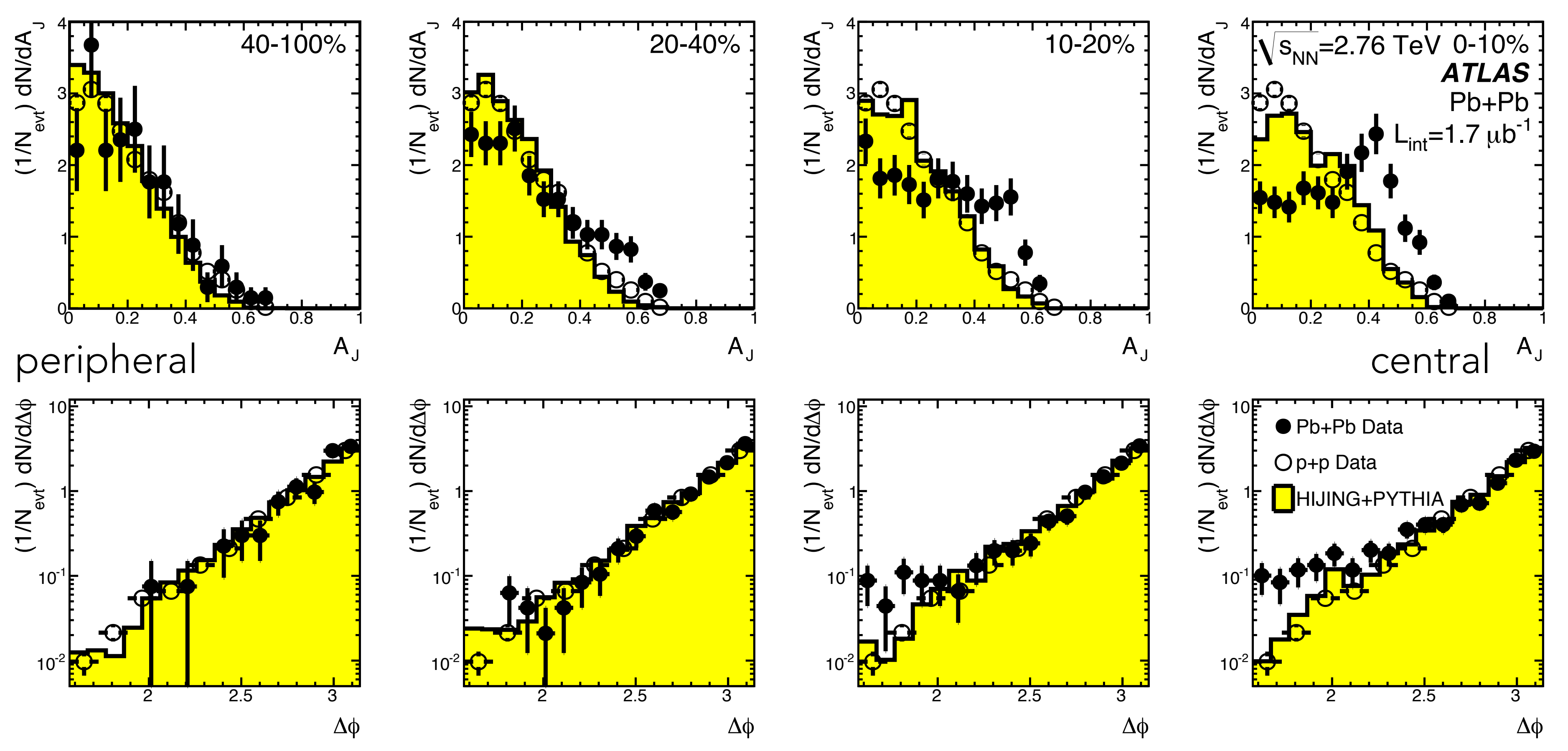


Almost immediately we observed individual collisions in ATLAS with one high p_T jet in the calorimeter, without a clear partner

FIRST DIRECT OBSERVATION OF JET QUENCHING AT THE LHC



PRL 105 (2010) 252303



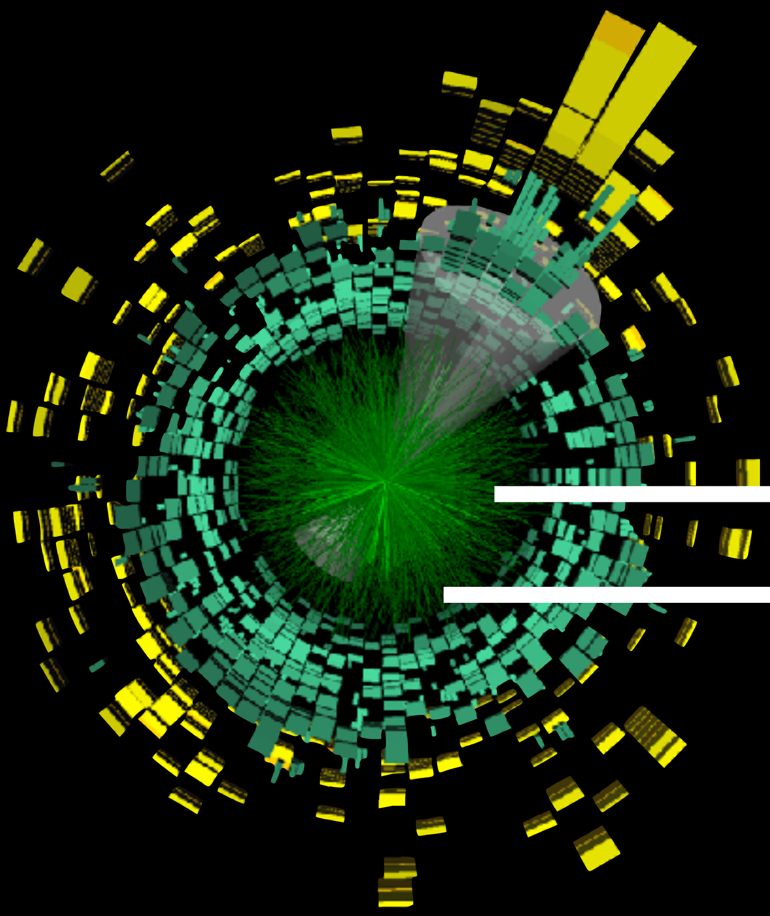
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

“Dijet asymmetry”

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

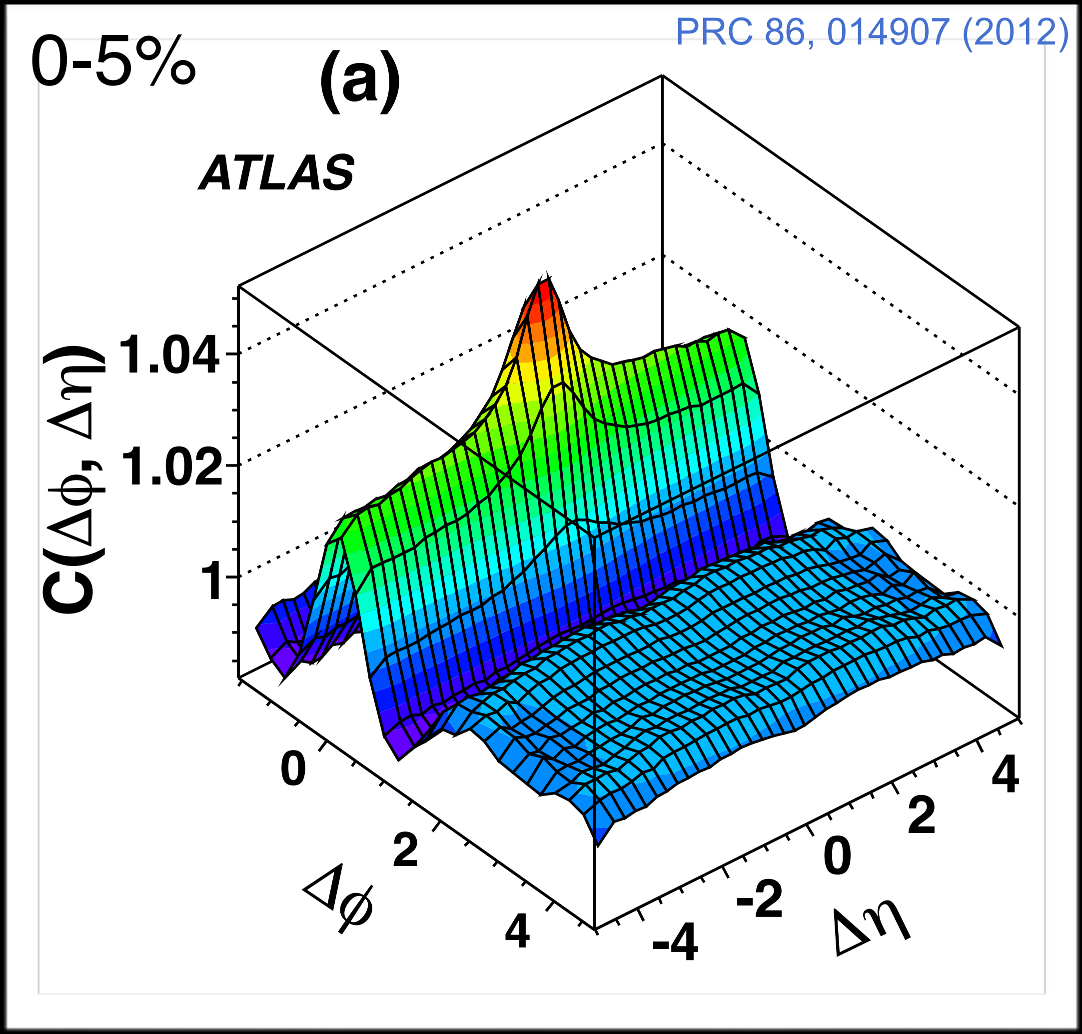
Interestingly, the jets remain back-to-back

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**)



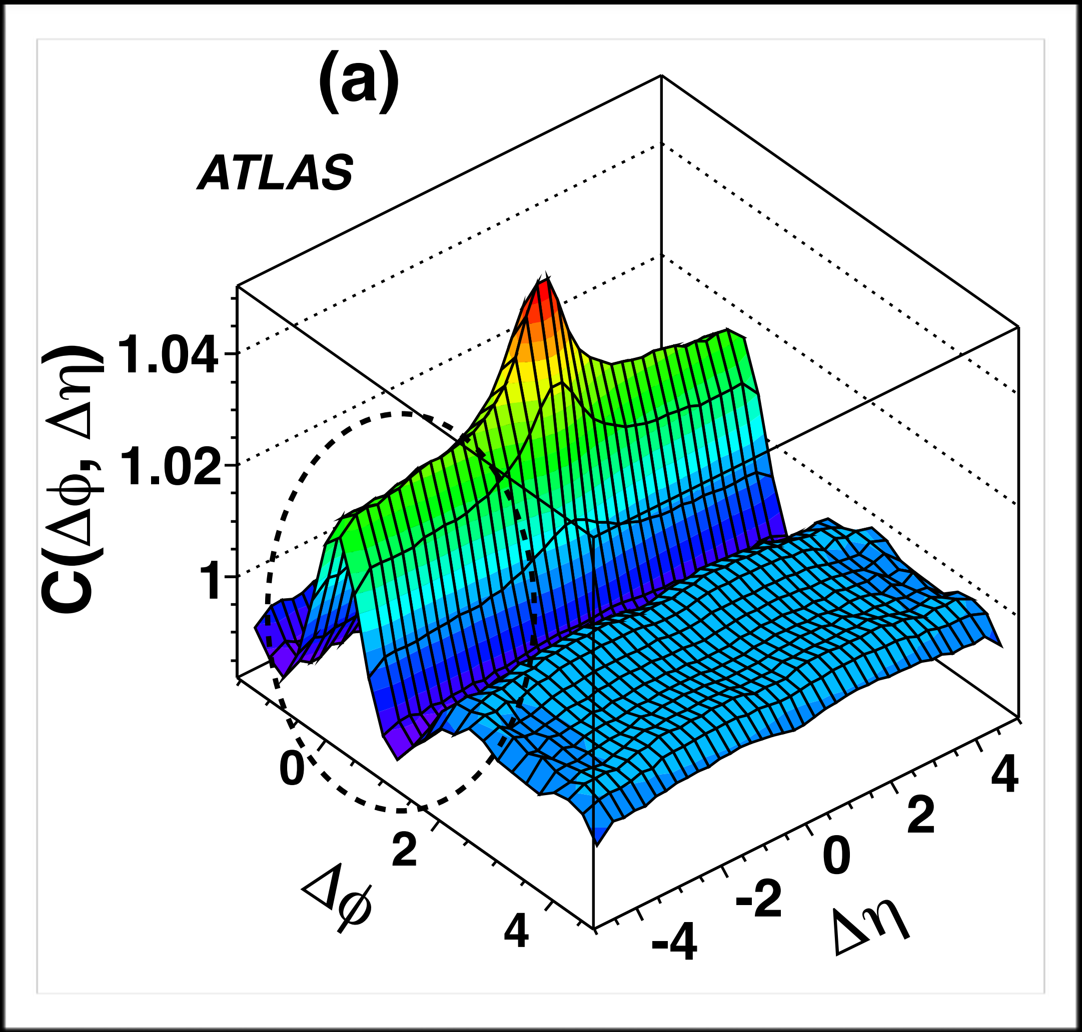
PRC 86, 014907 (2012)

“two-particle correlation function”

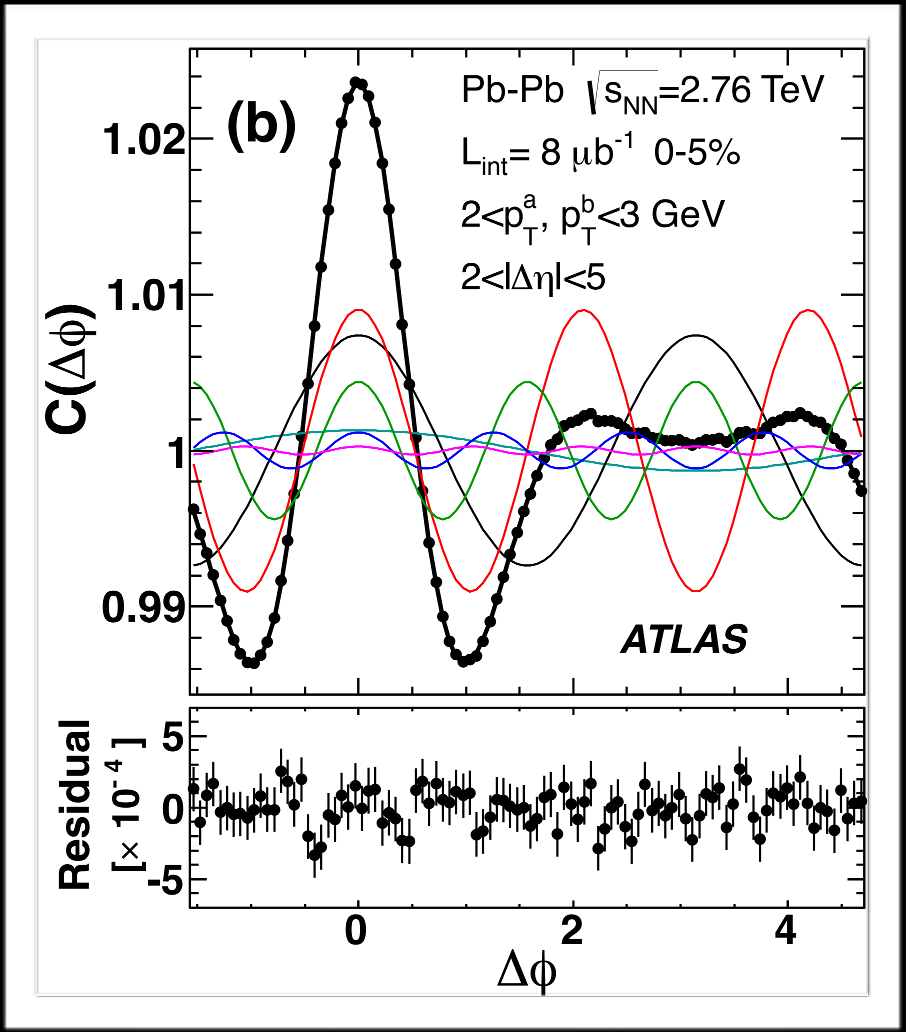
$$C(\Delta\eta,\Delta\phi)=\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

A huge “ridge” structure at Δ**ϕ**~0
(familiar to pp community from 2010 CMS pp measurement)

HARMONIC FLOW IN PB+PB



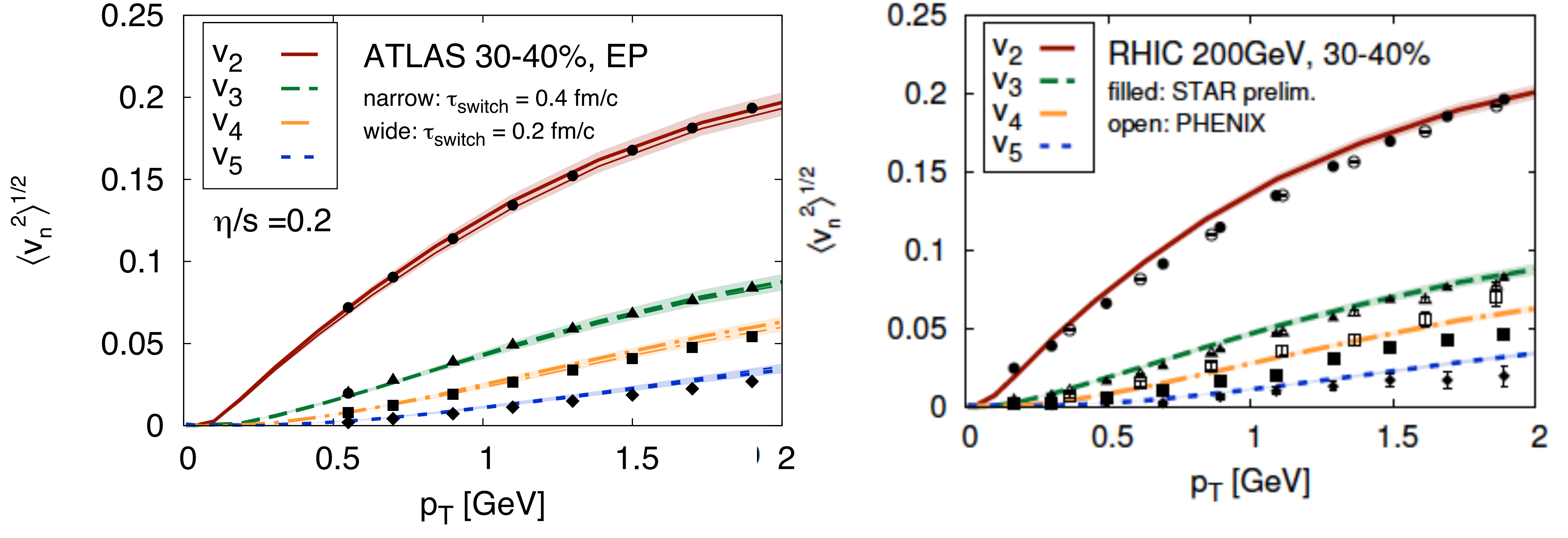
Requiring |η|>2 removes jets



$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos(n[\phi - \Psi_n]) \quad \Rightarrow \quad C(\Delta\phi, |\Delta\eta| > 2) = 1 + 2\sum_n v_n^2 \cos(n\Delta\phi)$$

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

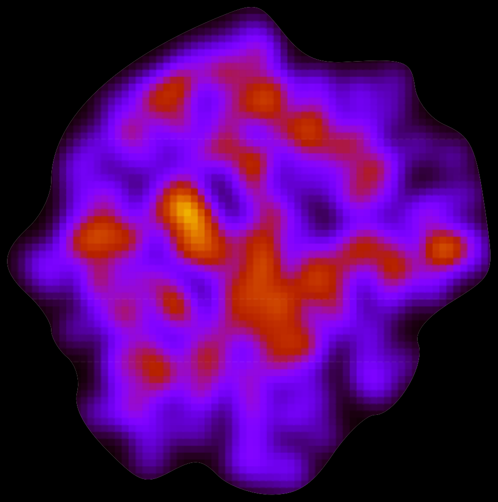
ESTIMATING VISCOSITY/ENTROPY

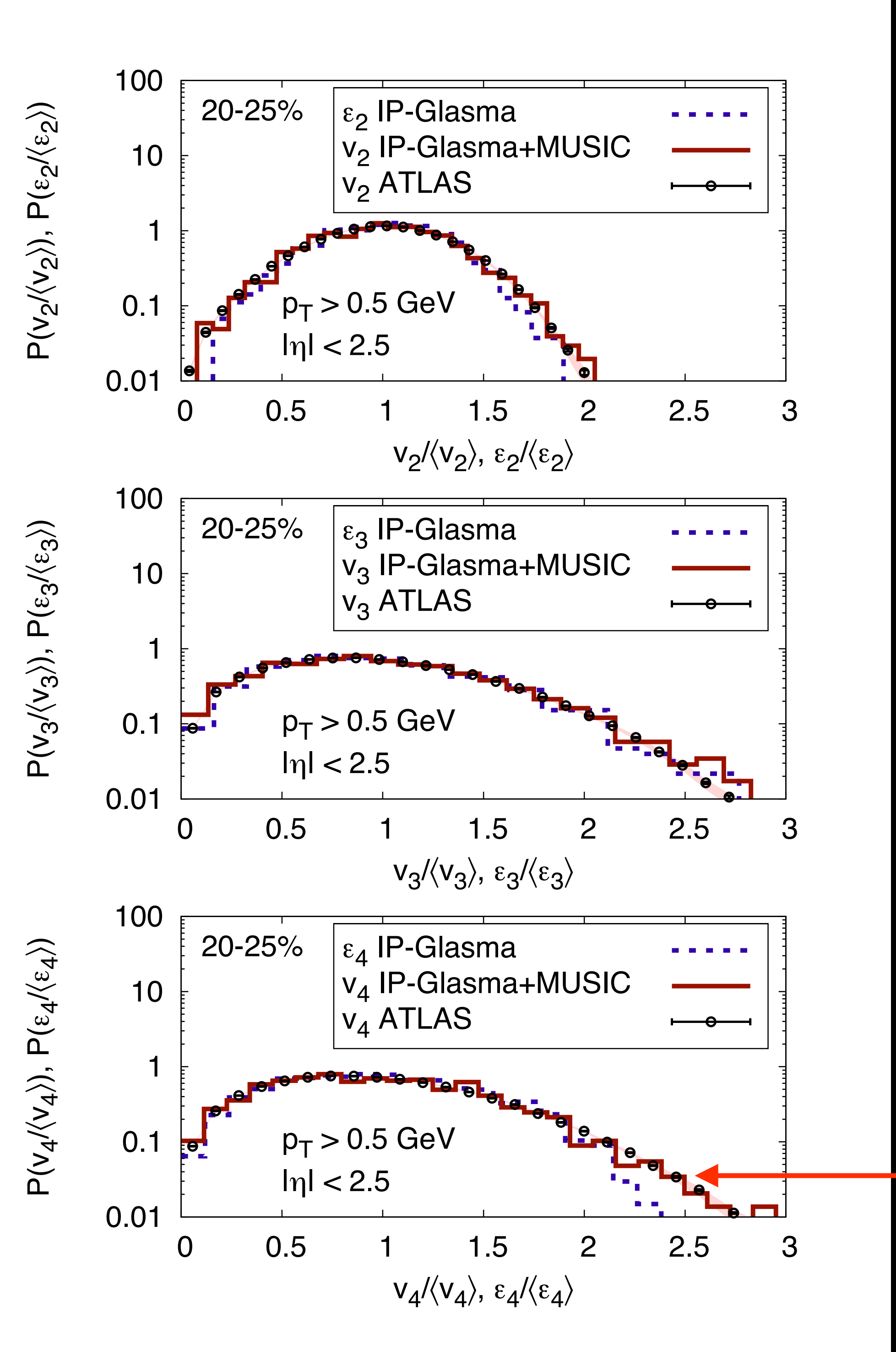


Gale et al, PRL 110 (2012) 012032

Viscous hydro agrees well with LHC experimental data: compared with RHIC (η/s~0.12) suggests rises slowly with √s.
√s dependence is major focus for
STAR beam energy scan (2018-2019), sPHENIX @ RHIC (2022-)

FLOW FLUCTUATIONS





$p(v_4)$ tails need hydro

In principle, initial state fluctuates into a different shape in each event: expect **flow fluctuations:** i.e. "v2" is really just a particular moment of *$p(v_2)$*

Measured directly by ATLAS, and indirectly using cumulant expansion

Also described in event-by-event hydro calculations of Gale, et al, using IP-Glasma initial state

WITH ONLY ~7 μb^{-1}

Established the presence of jet quenching

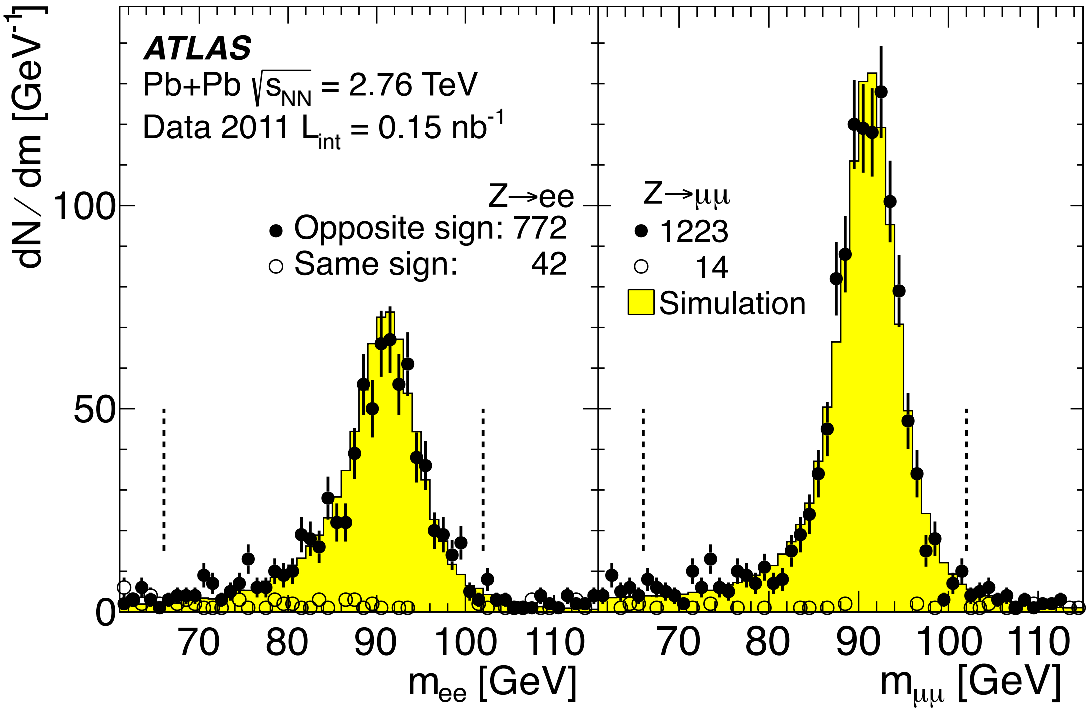
Provided data on collective expansion to constrain the initial conditions and transport properties

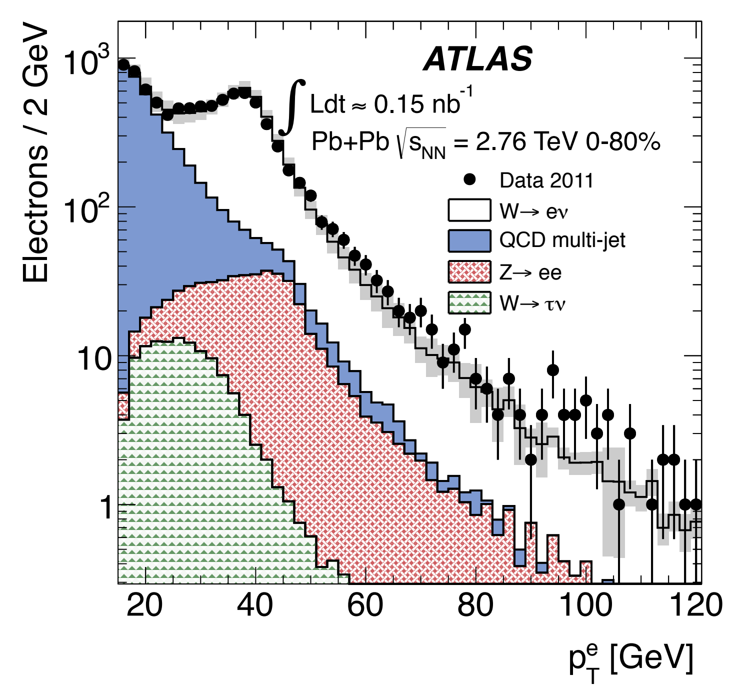
Almost all new heavy ion data
(whether energy, system, or new detectors)
provides striking new insights!

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

Z

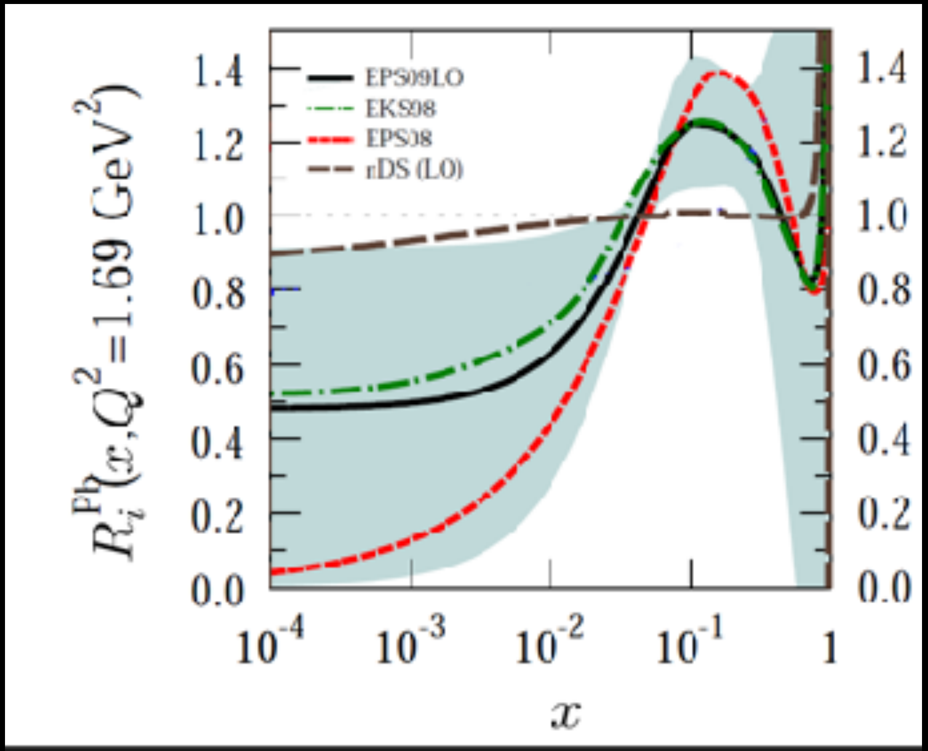
W





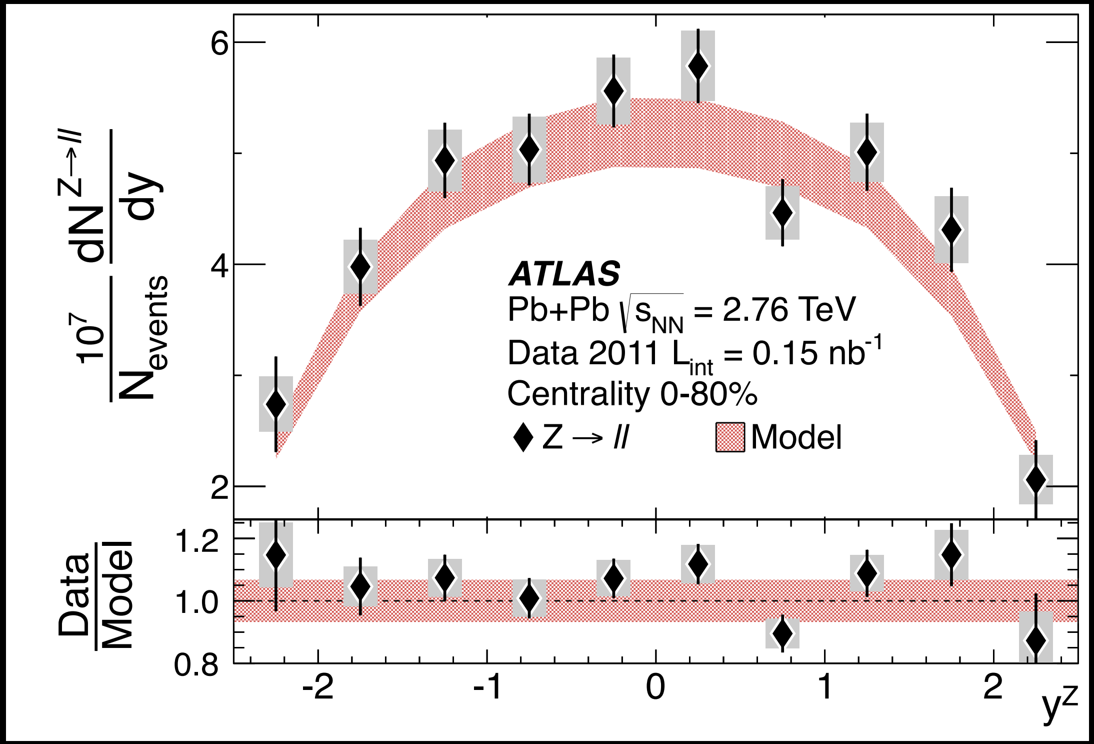
W and Z bosons, measured with leptonic decay modes

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



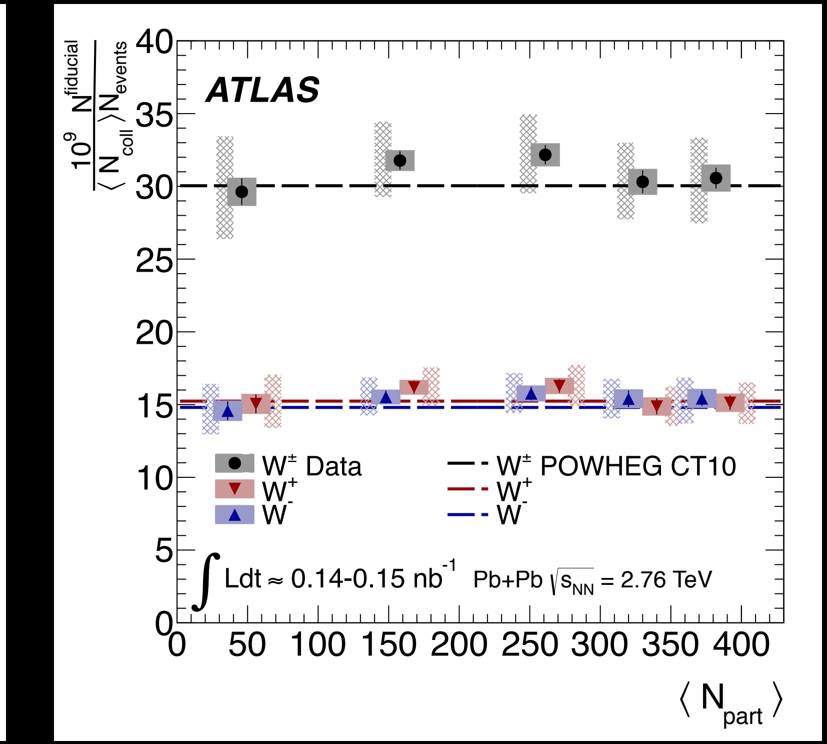
NUCLEAR THICKNESS WITH EW PROBES

Z



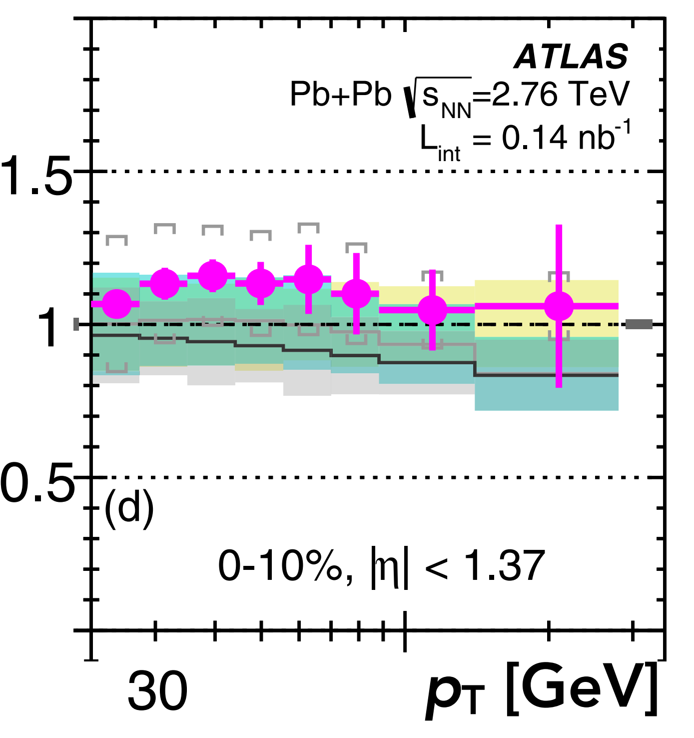
PYTHIA 6.425 rapidity shape scaled up by $\sigma_Z^{NNLO}\langle T_{AA}\rangle$

W



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

γ



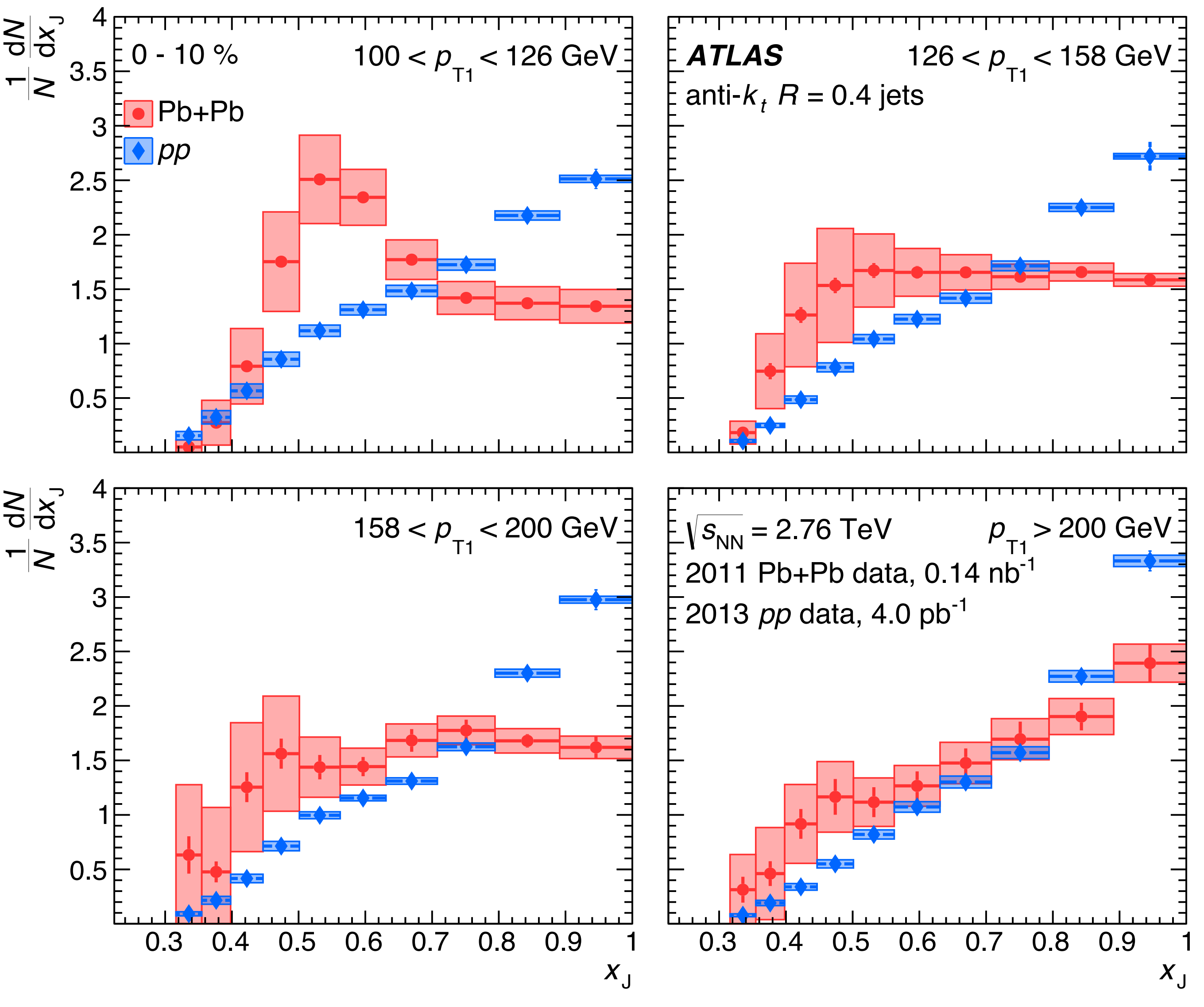
Photon yields, scaled by $\langle T_{AA}\rangle$, compared to pQCD

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

UPDATED DIJET ASYMMETRY

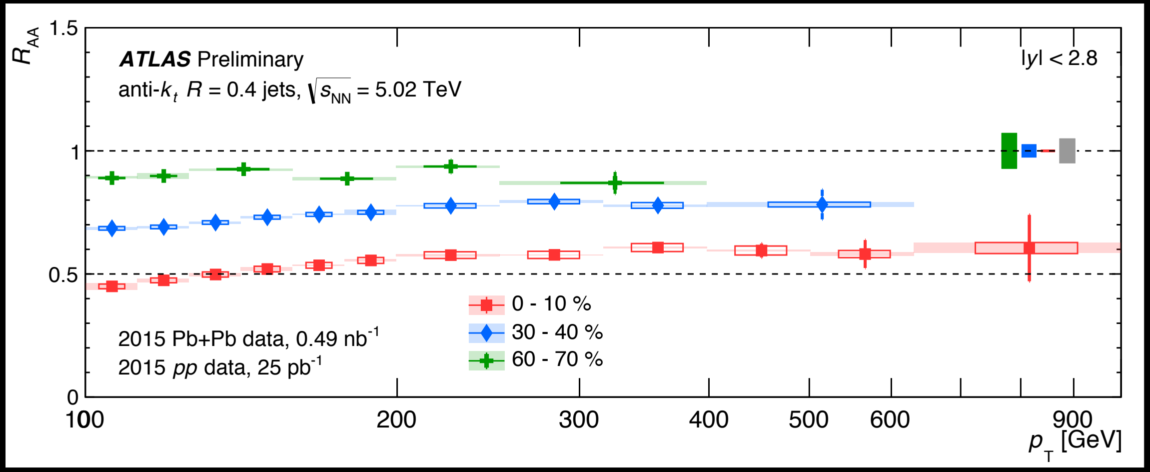
arXiv:1706.09363



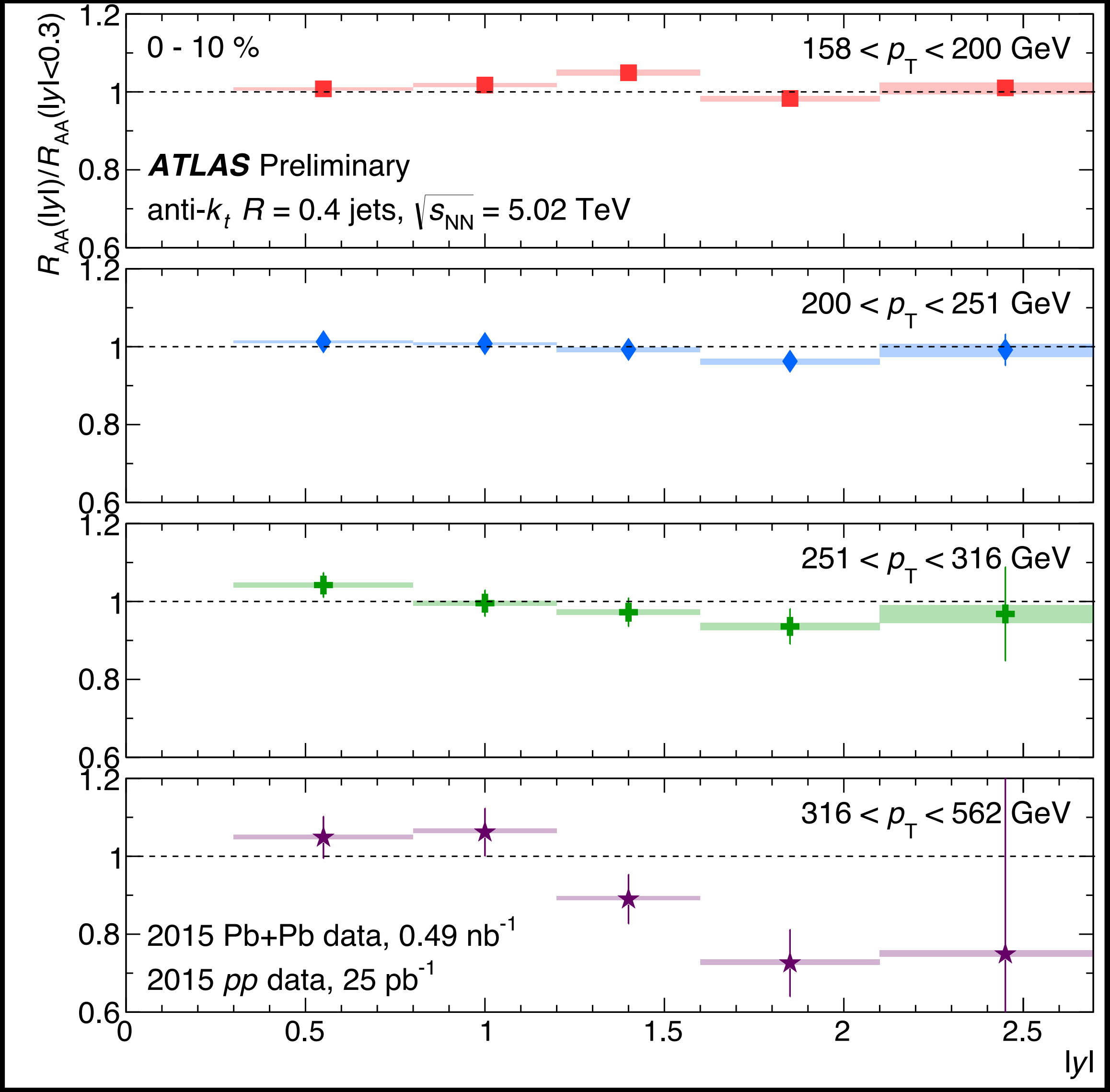
Dijet asymmetry updated (more sophisticated analysis procedure!) as measurement of $x_J = p_{T2}/p_{T1}$

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

NEW JET PHYSICS IN RUN 2

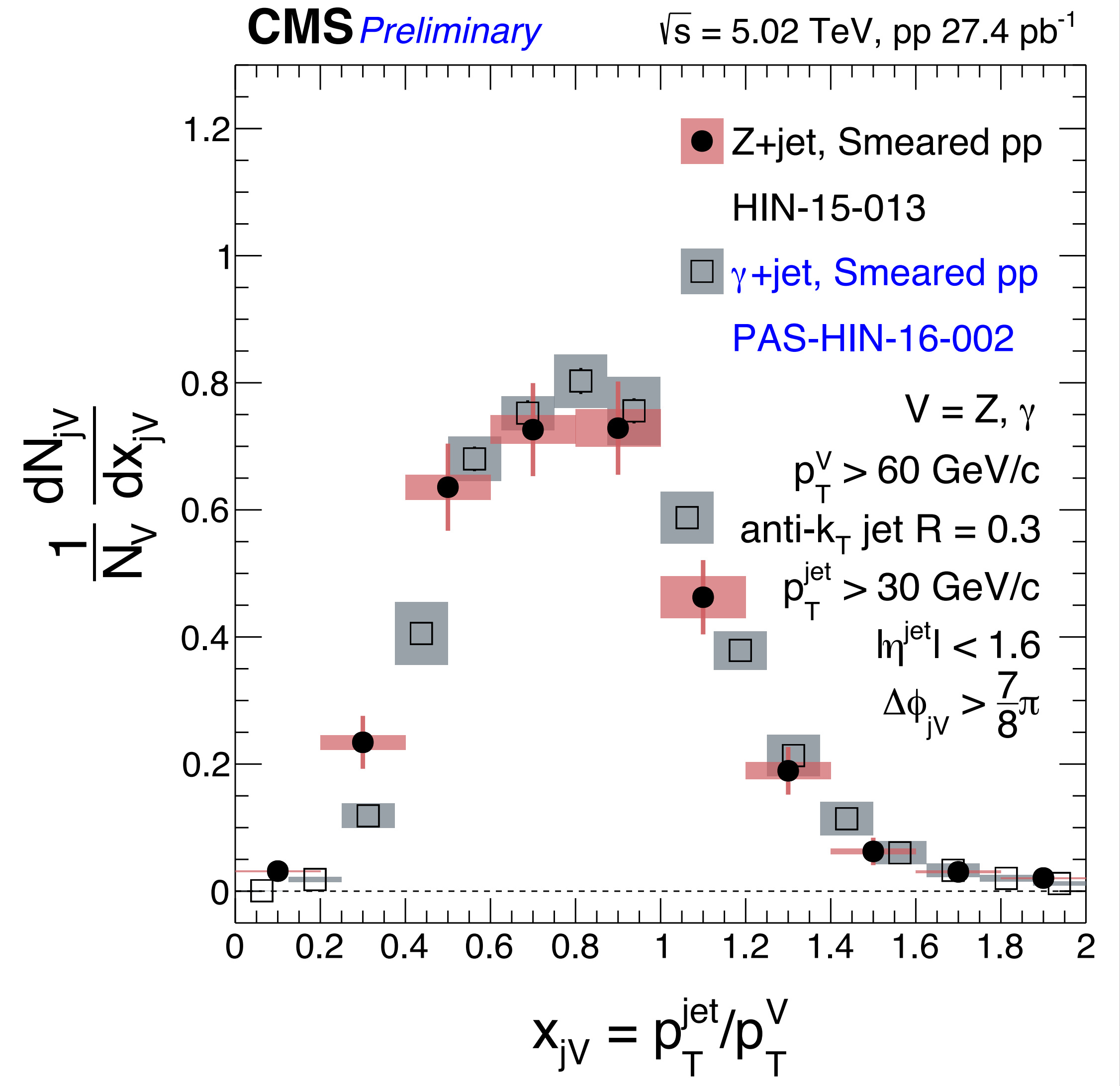


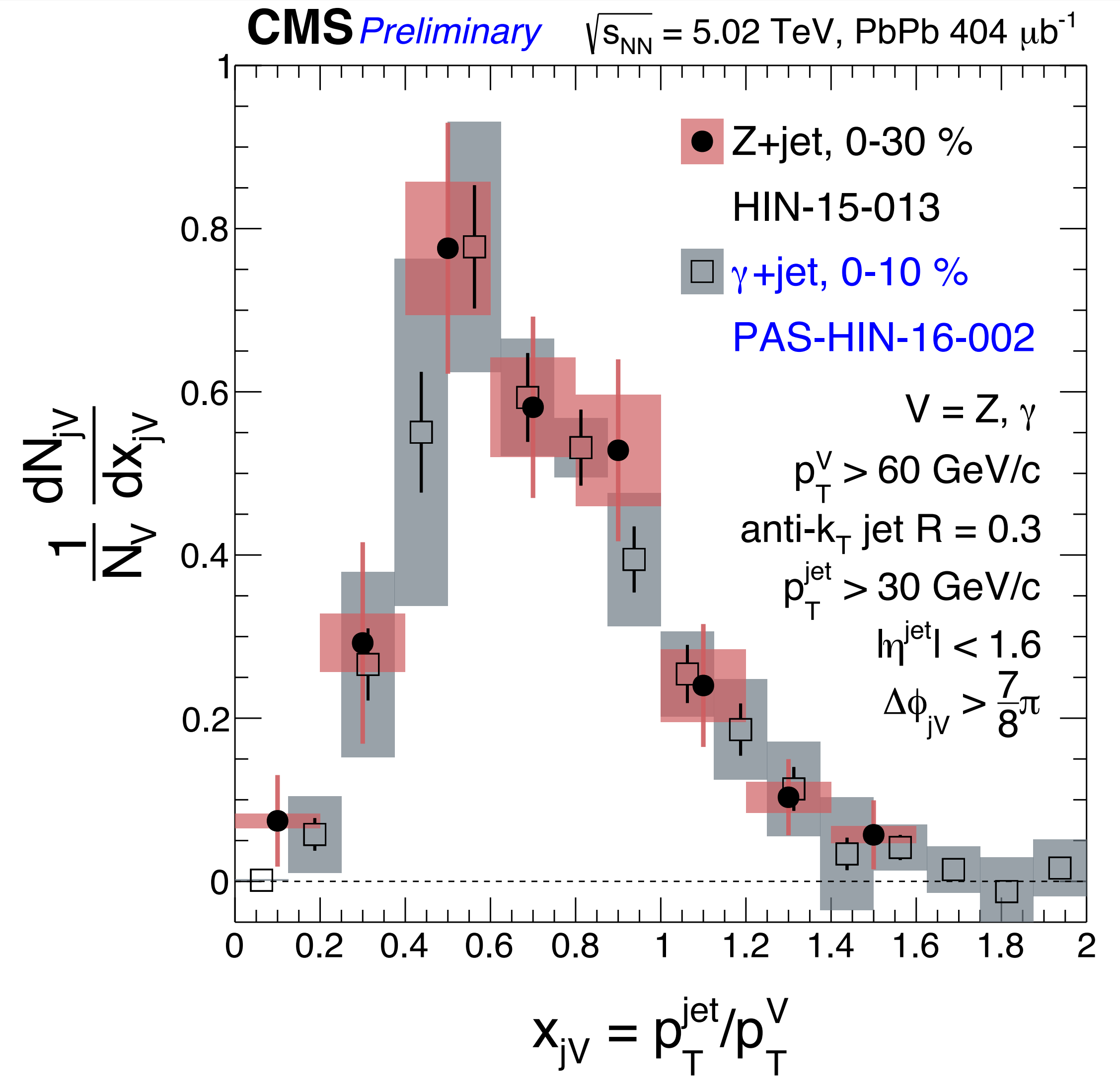
Jet suppression remains nearly constant out to ~1 TeV, but observed rise required the new Run 2 data



Jet suppression has a weak rapidity dependence except for the highest pT's available from the Run 2 data!

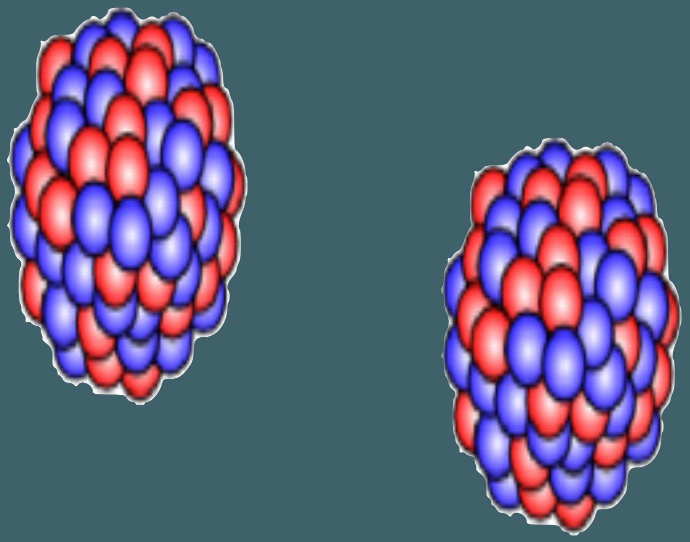
BOSON-JET PHYSICS IN RUN 2





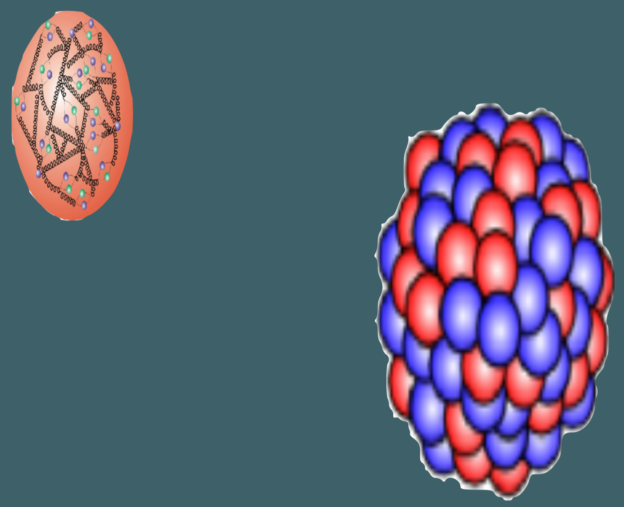
"Golden channel" for jet quenching, where the boson tags the primary scattering, and only the jet is modified. CMS results incorporate detector effects, but results unfolding these to particle level on the way!

FINALE: A TALE OF THREE SYSTEMS

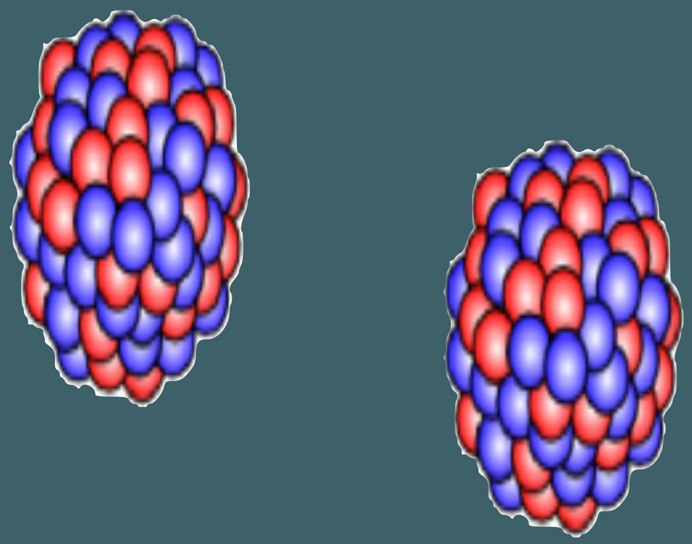


Pb+Pb

FINALE: A TALE OF THREE SYSTEMS



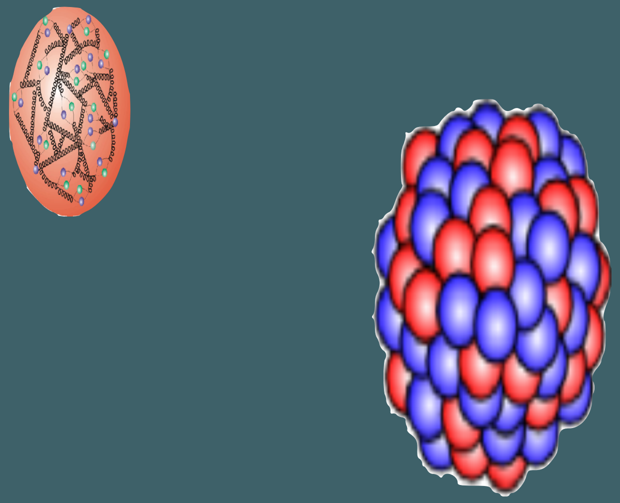
p+Pb



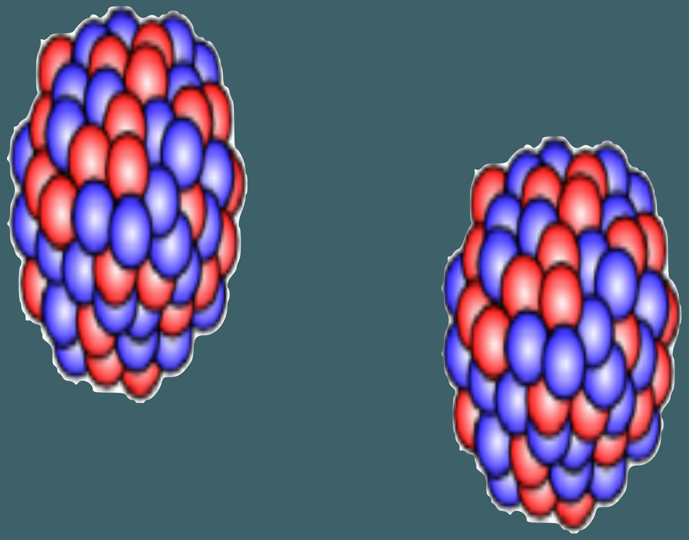
Pb+Pb

FINALE: A TALE OF THREE SYSTEMS

p+p



p+Pb

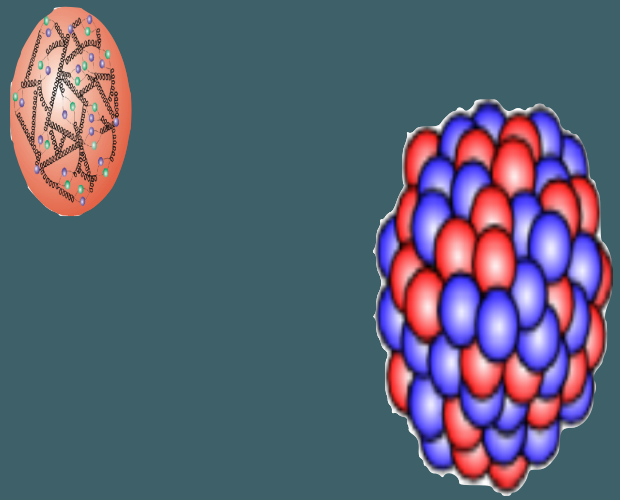


Pb+Pb

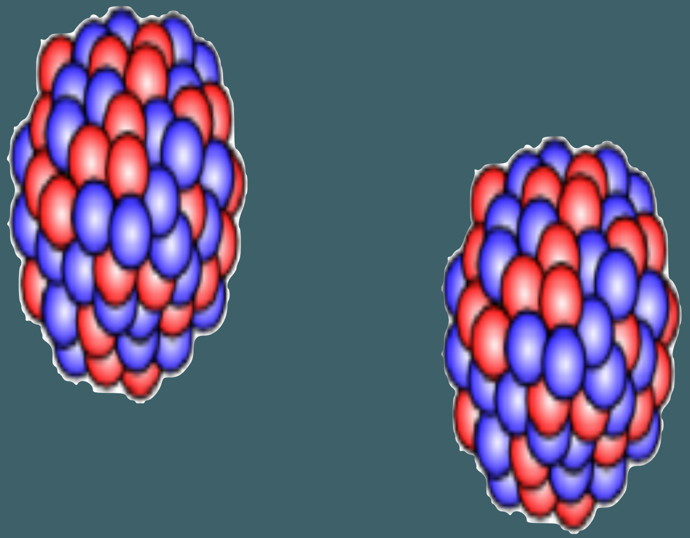
FINALE: A TALE OF THREE SYSTEMS

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

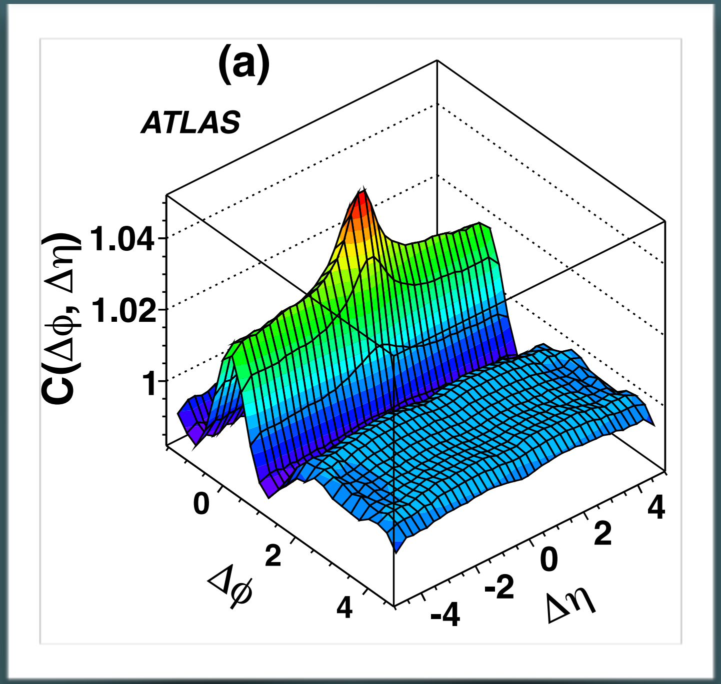
p+p



p+Pb



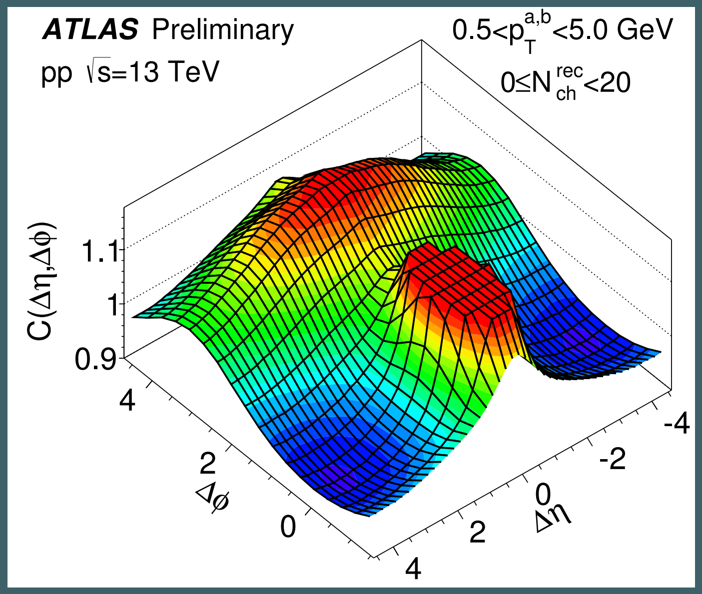
Pb+Pb

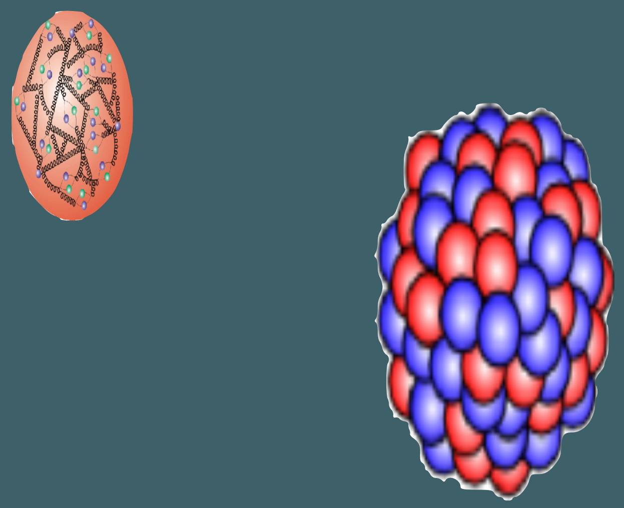


FINALE: A TALE OF THREE SYSTEMS

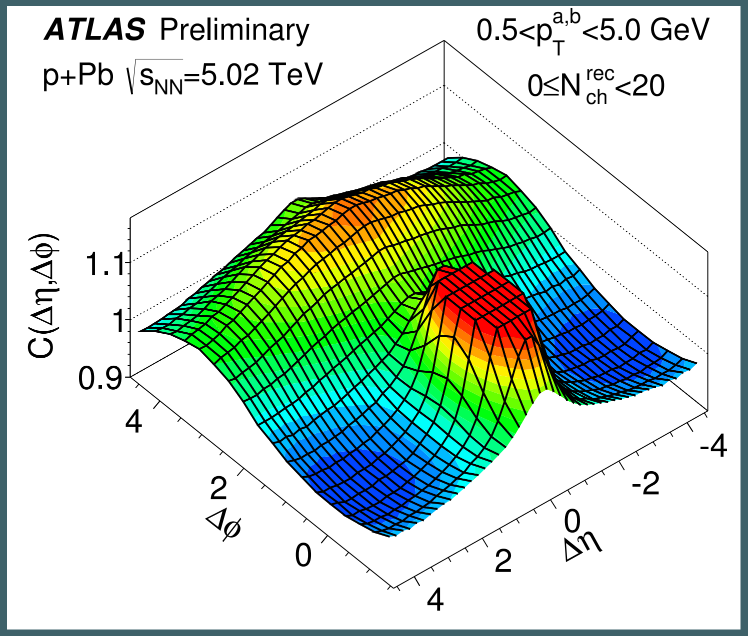
We have established collective behavior in Pb+Pb,
what about smaller systems?

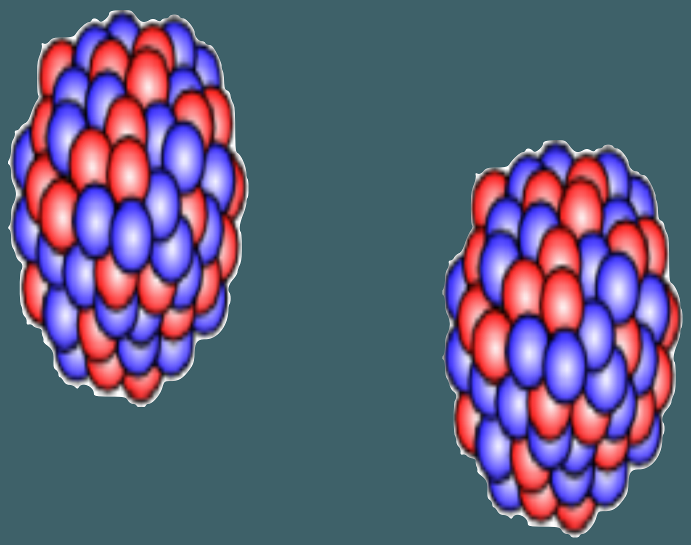
p+p



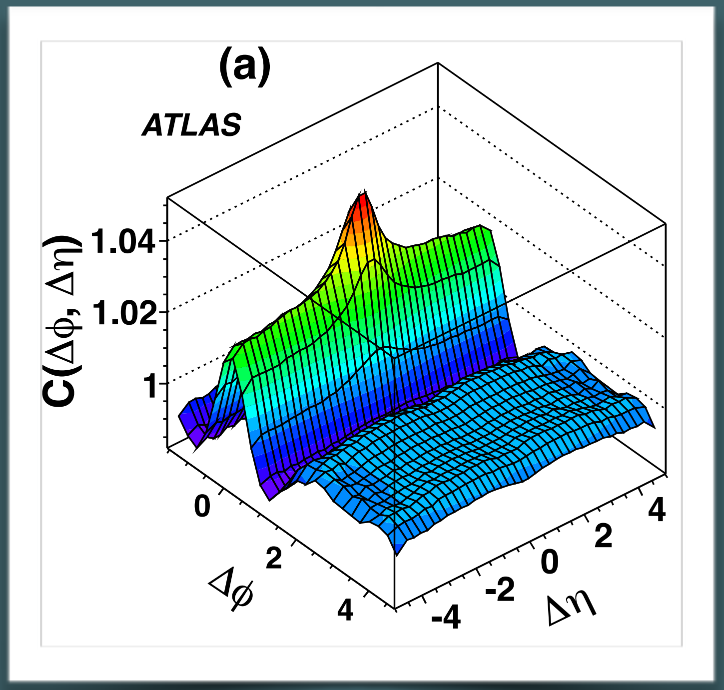


p+Pb





Pb+Pb

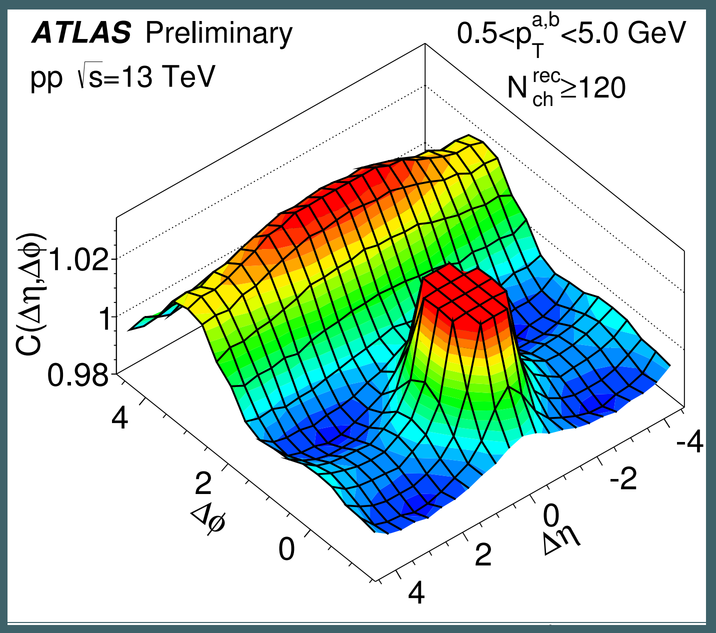


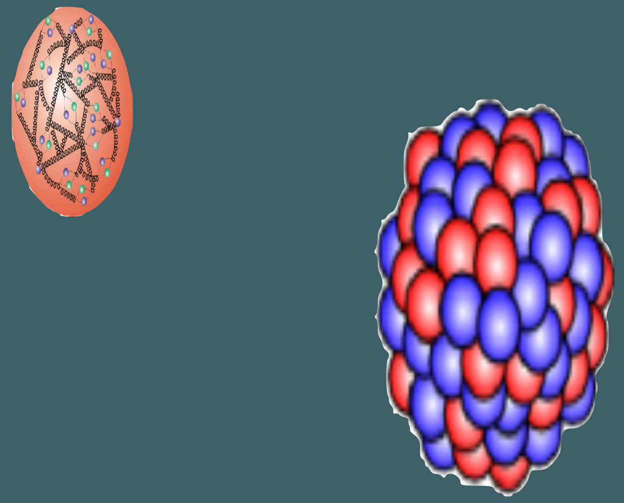
For “peripheral” p+p & p+Pb, no long range behavior at $\Delta\phi=0$

FINALE: A TALE OF THREE SYSTEMS

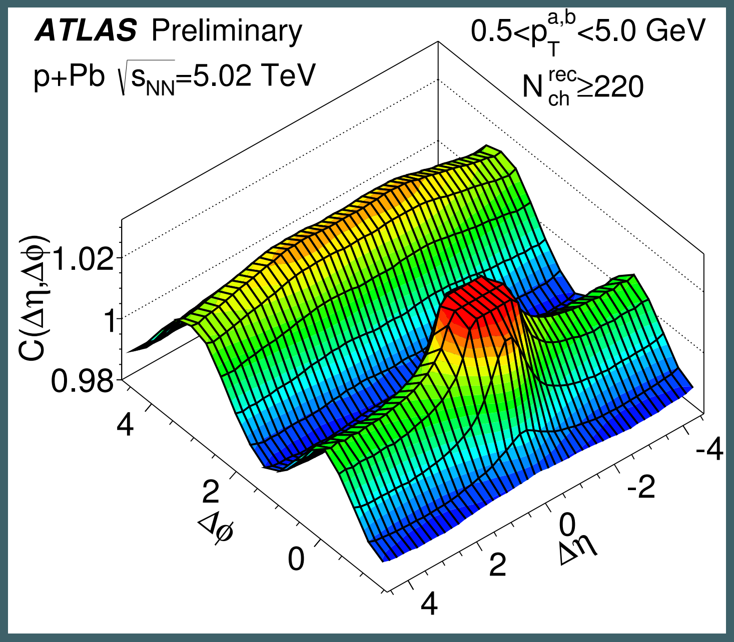
We have established collective behavior in Pb+Pb,
what about smaller systems?

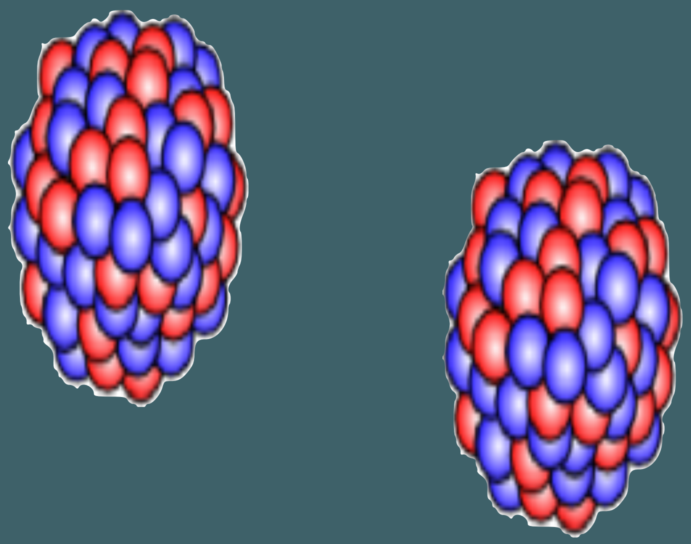
p+p



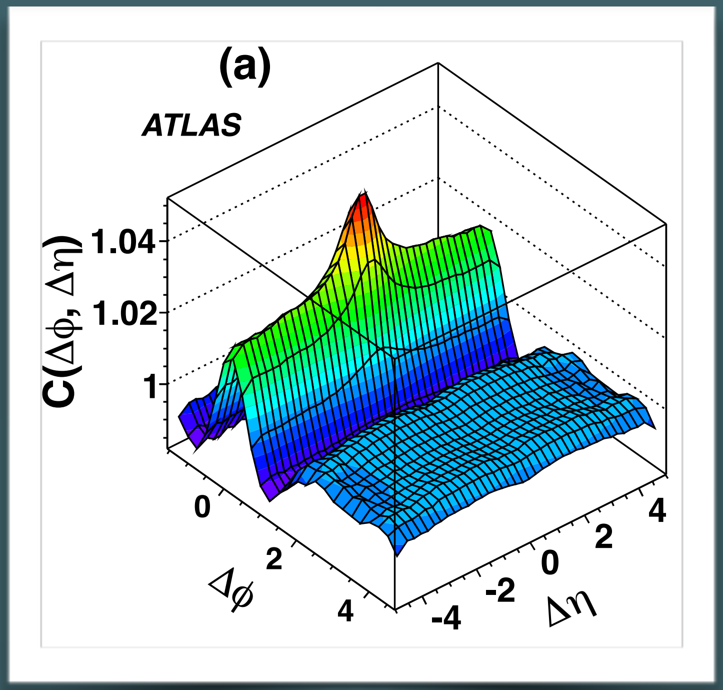


p+Pb





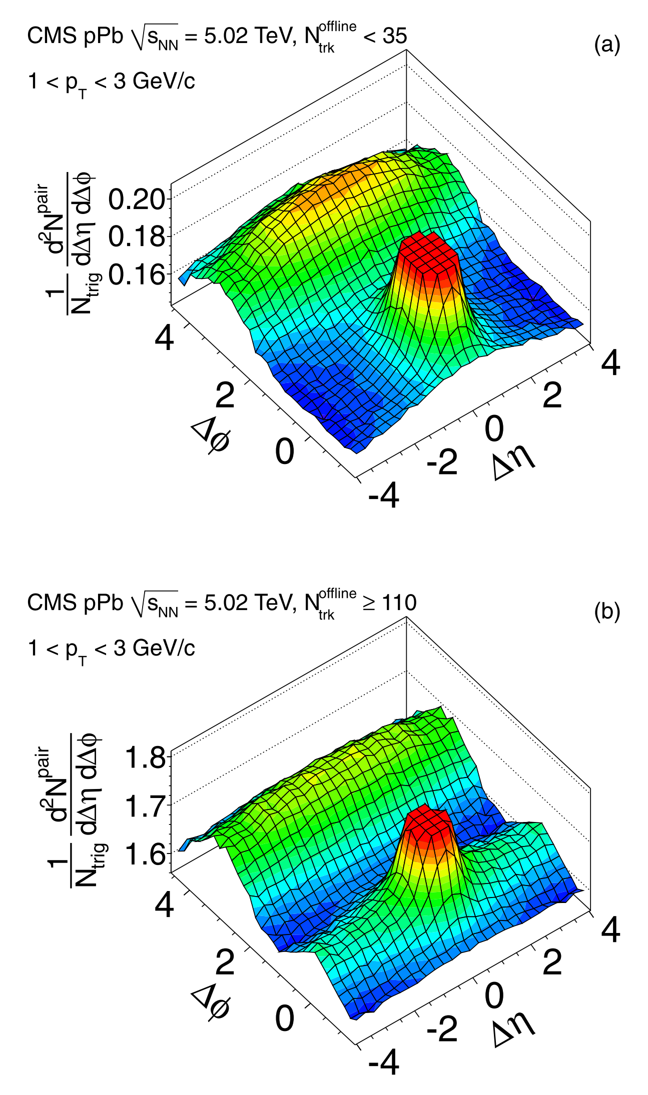
Pb+Pb

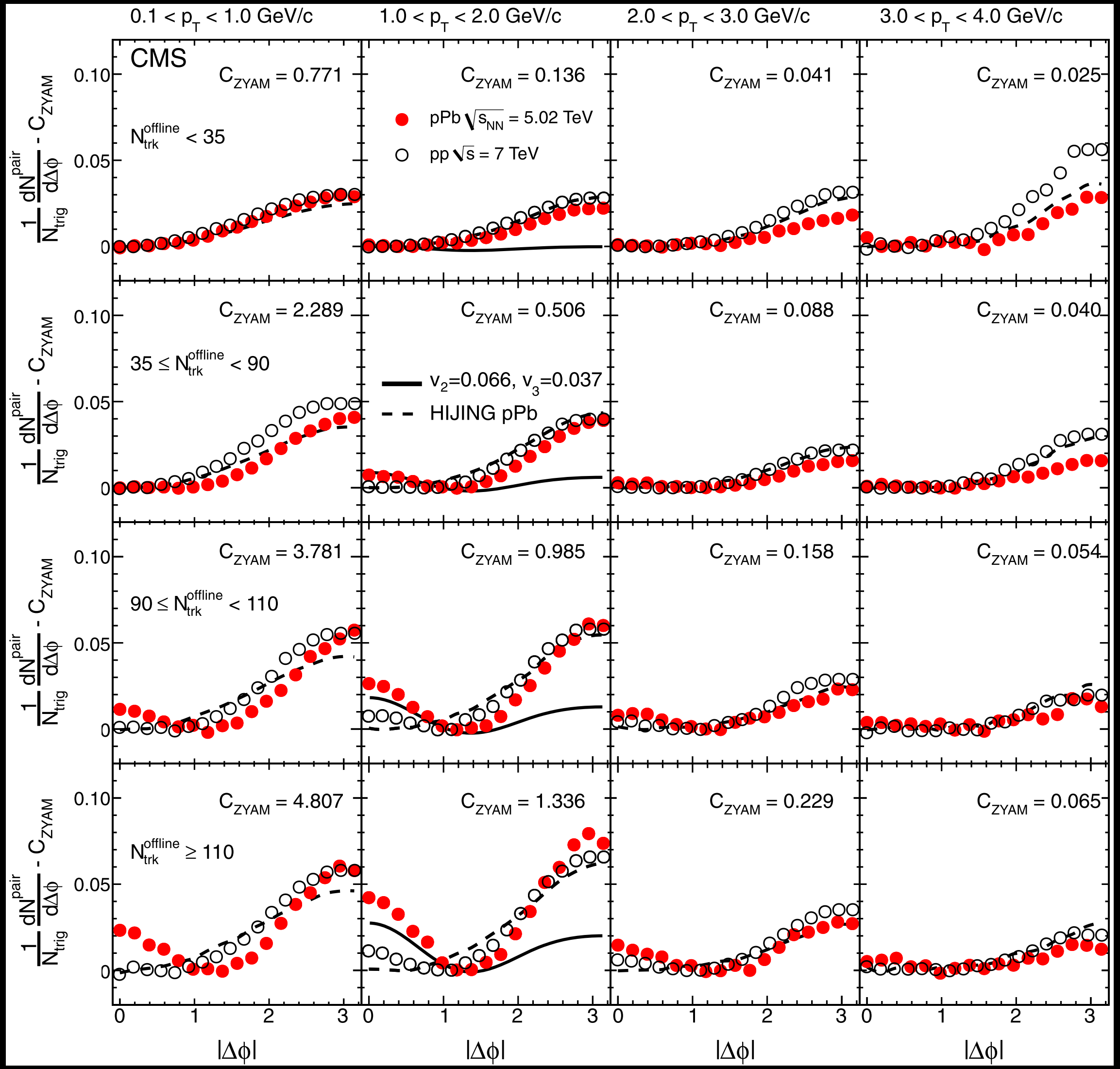


Increase the multiplicity, and a "ridge" appears!

FIRST RESULTS FROM THE P+PB "PILOT RUN"

- **A brief ~8 hour run in September 2012**

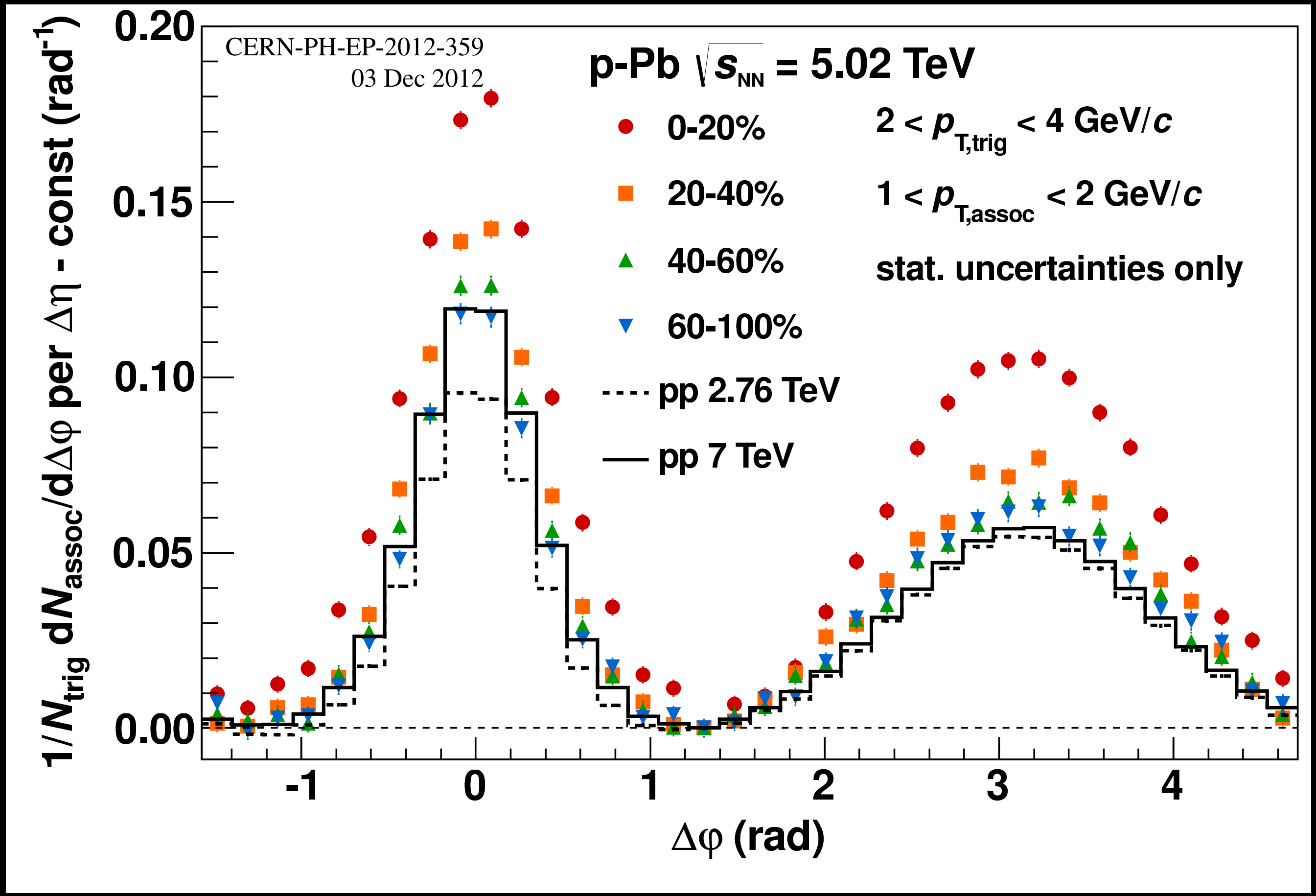


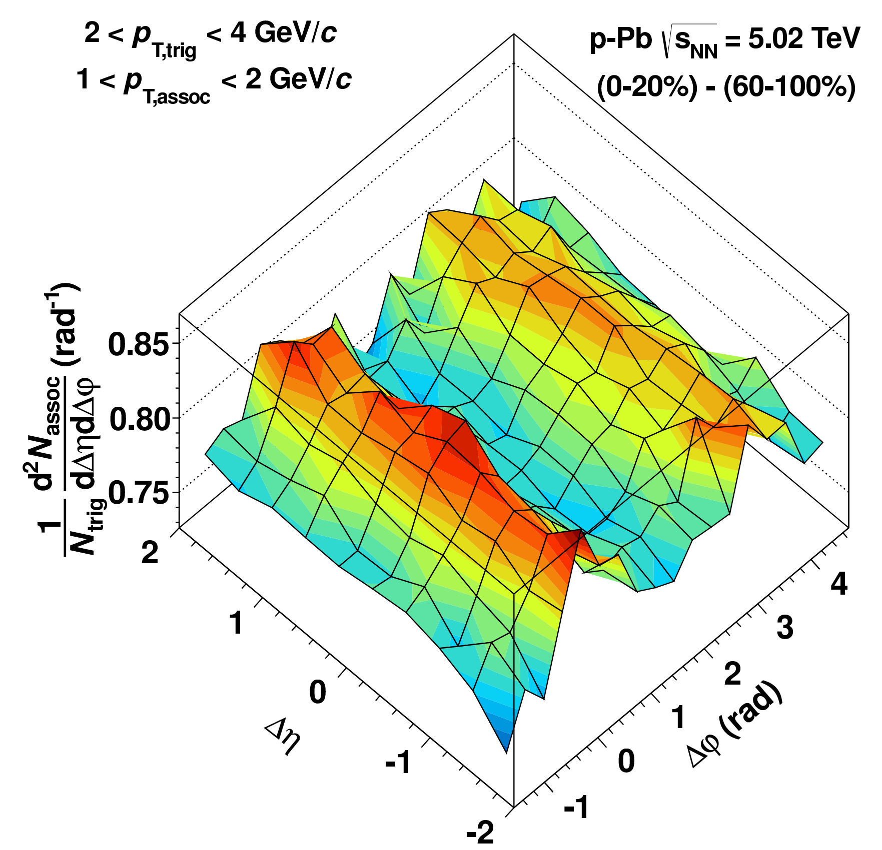


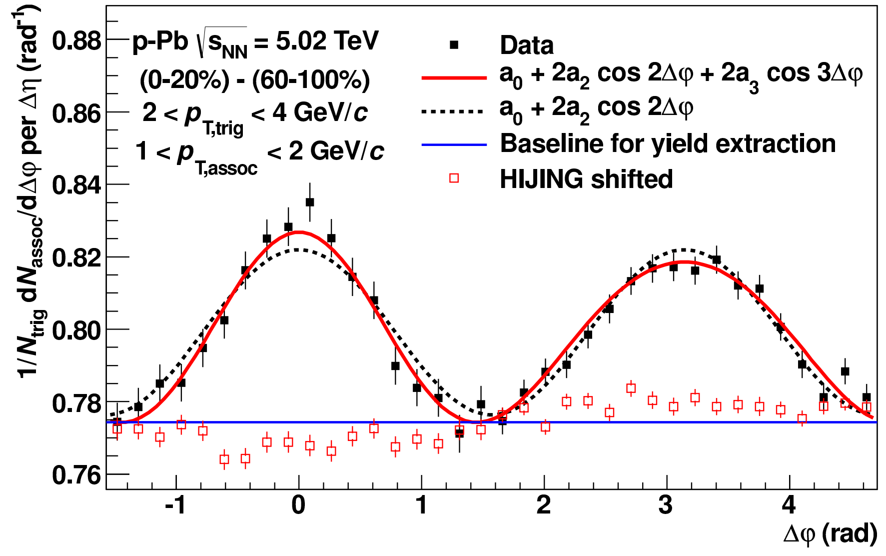
Ridge amplitude studied relative to "ZYAM",
<u>assume</u> zero yield at the minimum

THE DECEMBER SURPRISE

- **First reported by ALICE**
  - Subtracted 60-100% central from the other centralities, to observe "double ridge"

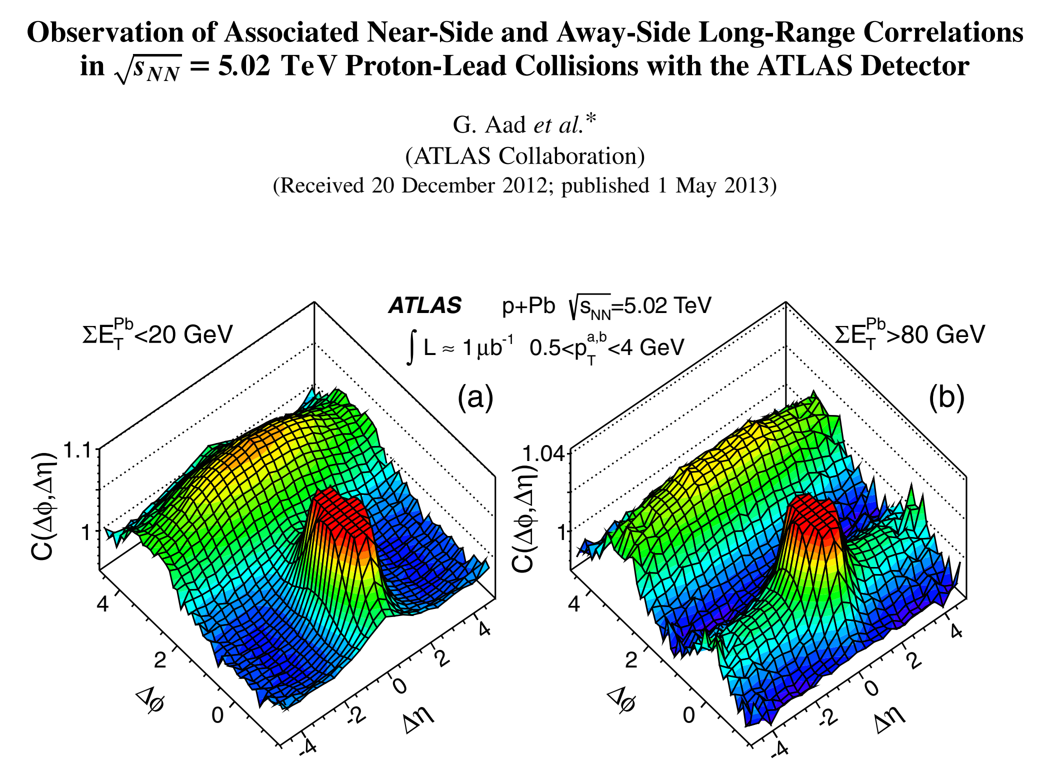






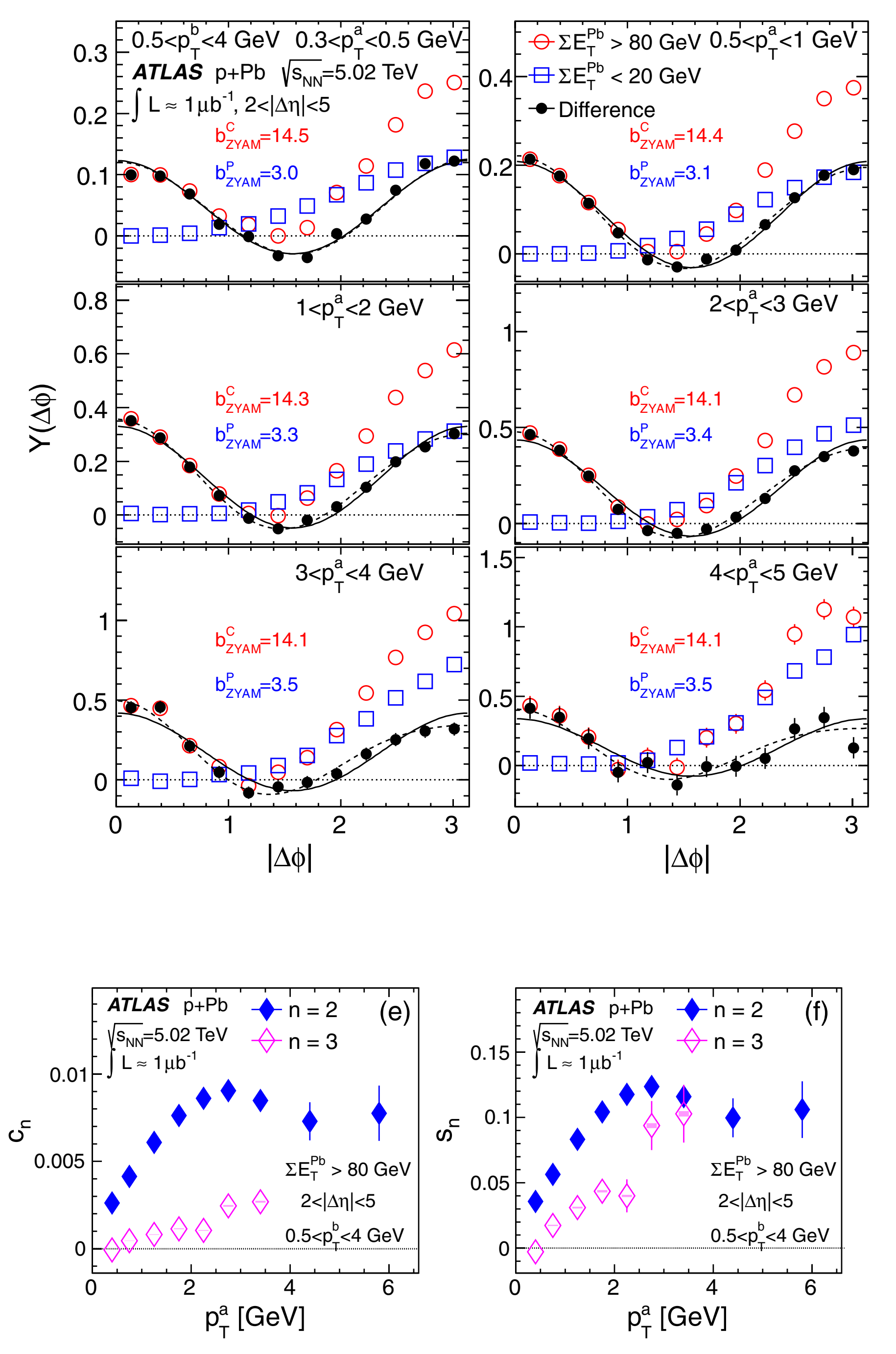
THE DECEMBER SURPRISE

- **Followed closely by ATLAS**
  - Same technique, using the backwards E_T to define quasi-centrality bins



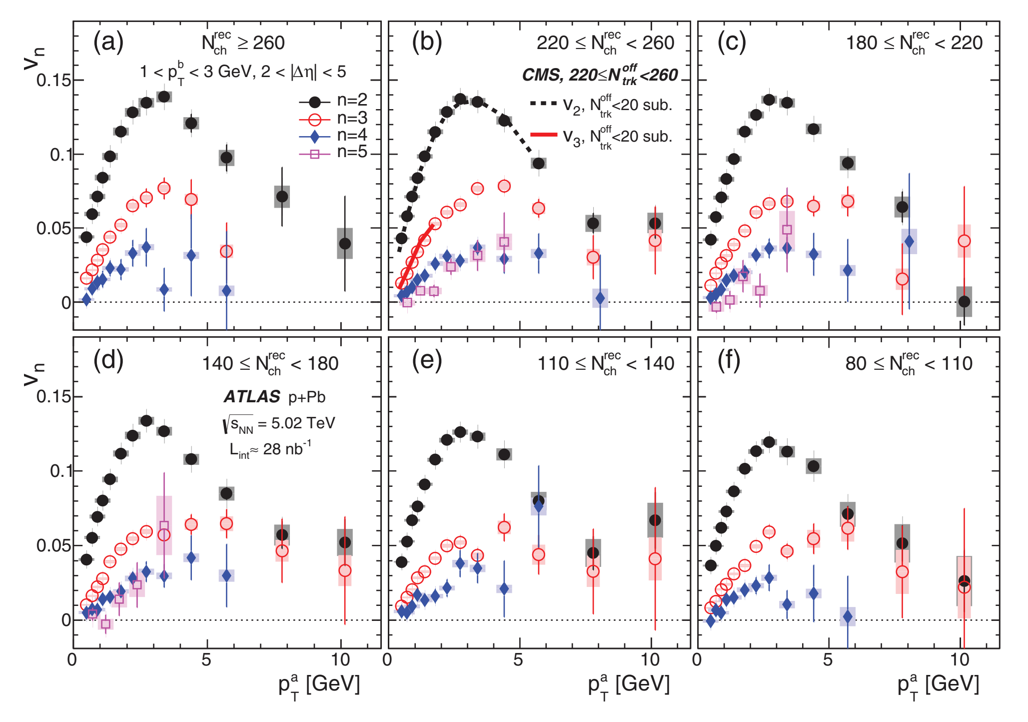
Observation of Associated Near-Side and Away-Side Long-Range Correlations in $\sqrt{s_{NN}}$ = 5.02 TeV Proton-Lead Collisions with the ATLAS Detector

G. Aad *et al.**
(ATLAS Collaboration)
(Received 20 December 2012; published 1 May 2013)

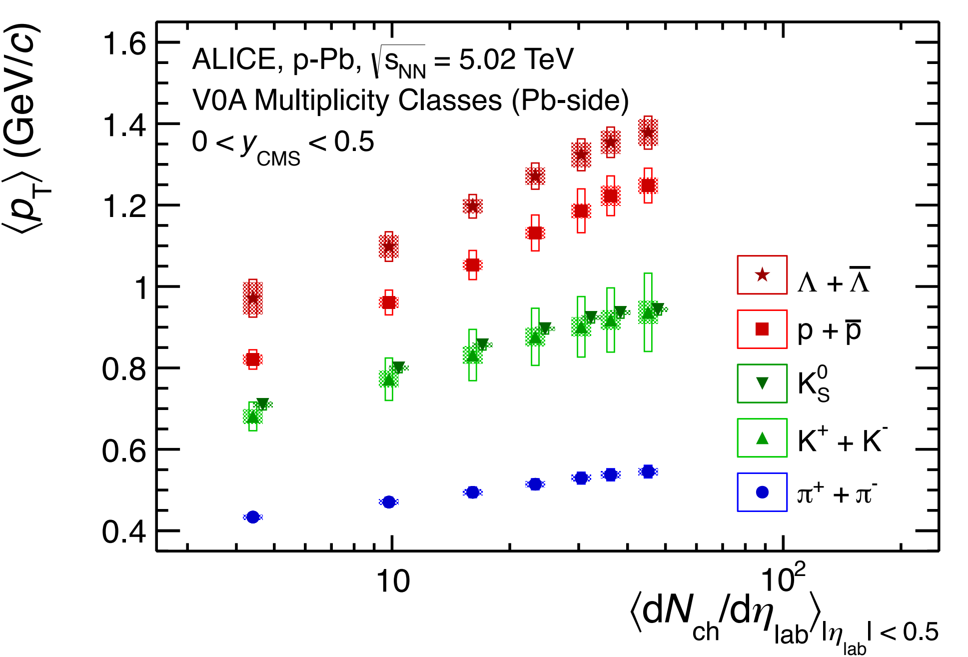


p_T dependence of v_2 & v_3 w/ familiar shape

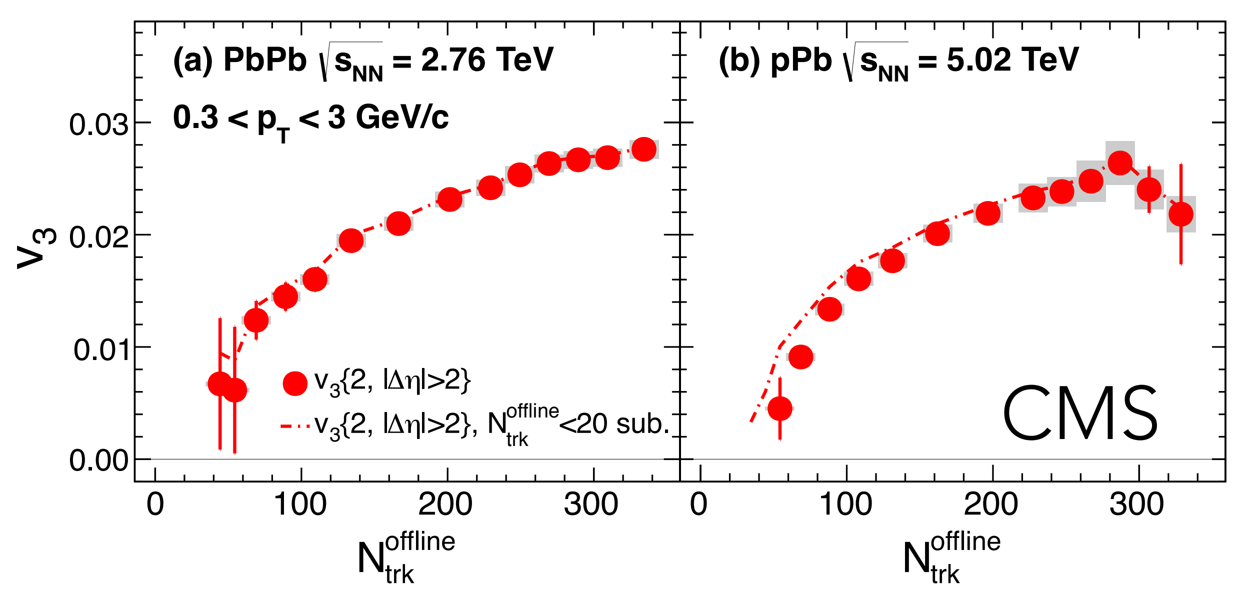
THE REALLY LITTLE BANG:
AN EXPLOSION OF ACTIVITY SINCE 2013



n=2-5,
5% at 10 GeV!

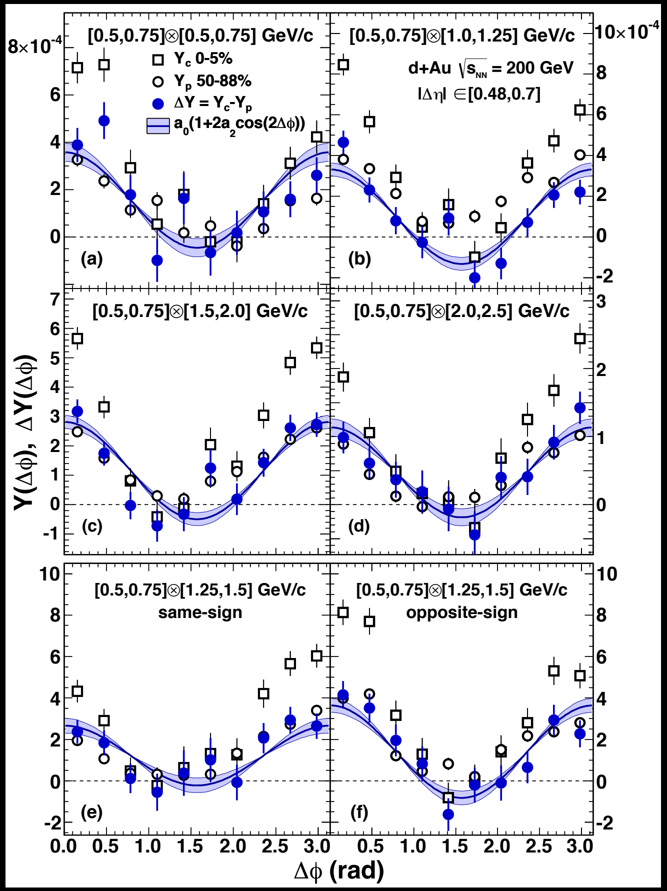


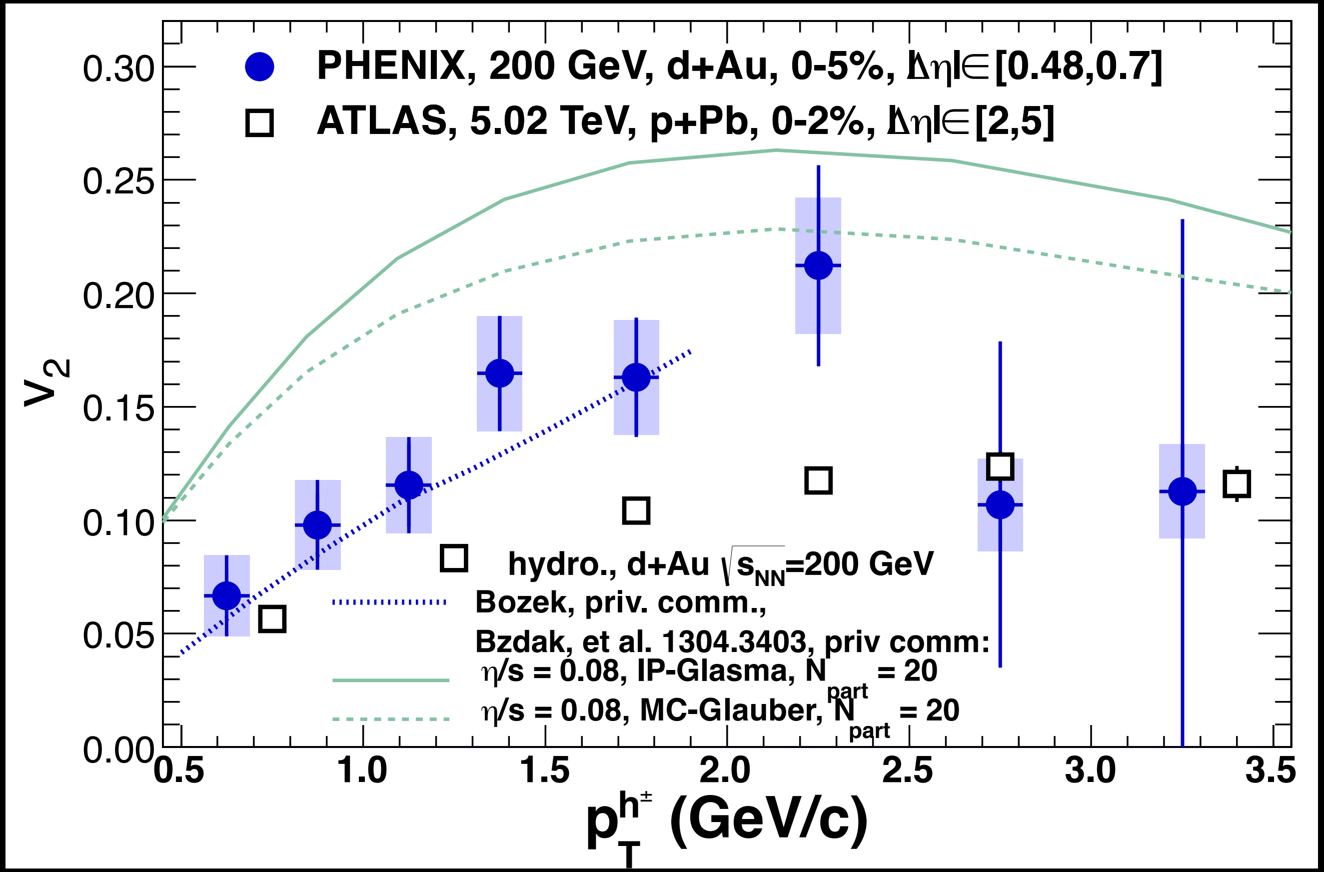
Radial flow



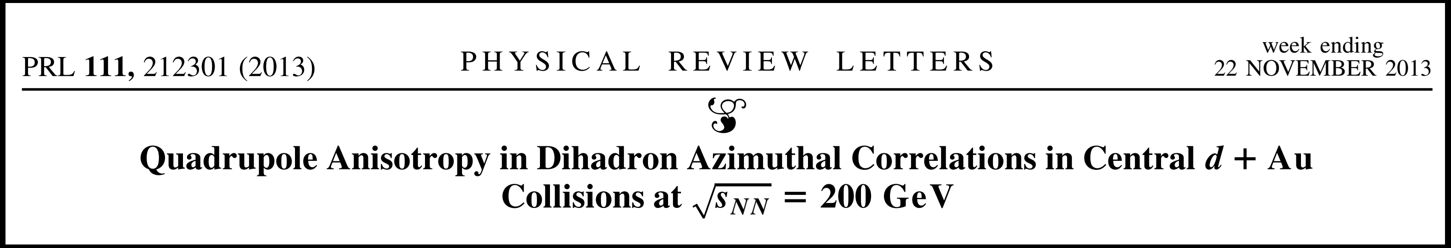
p+Pb~Pb+Pb at same N_{ch}

WHICH REVERBERATED BACK TO RHIC!





Submitted March '13

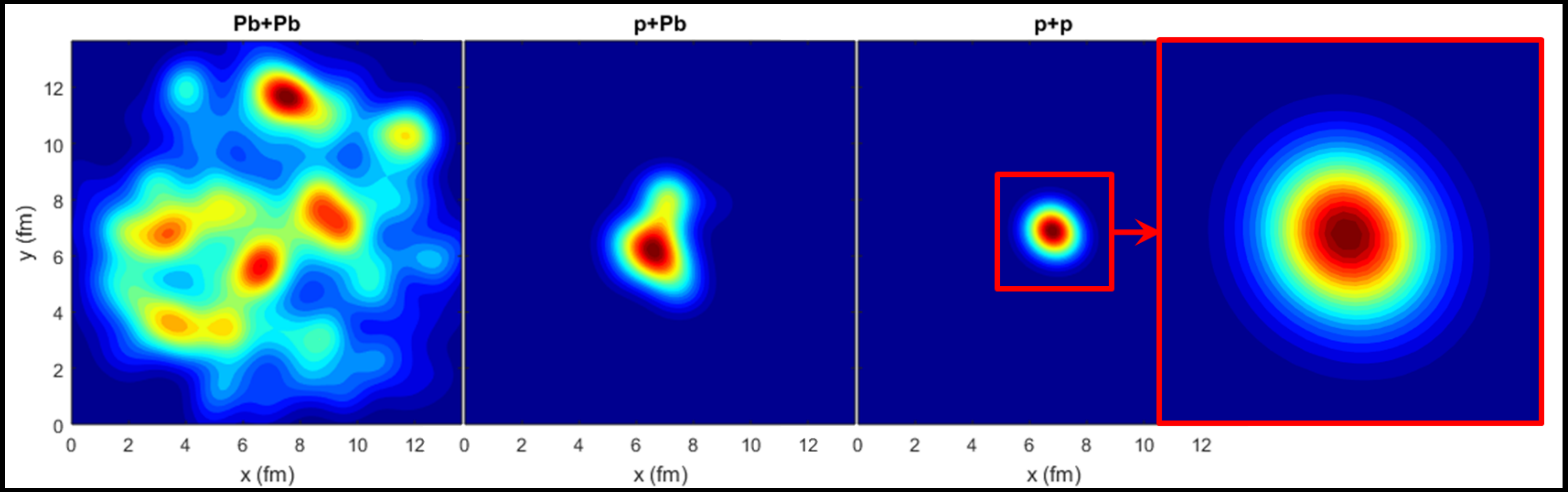


PRL **111,** 212301 (2013) PHYSICAL REVIEW LETTERS week ending 22 NOVEMBER 2013

Quadrupole Anisotropy in Dihadron Azimuthal Correlations in Central $d + \mathrm{Au}$ Collisions at $\sqrt{s_{NN}} = 200$ GeV

COLLECTIVITY IN SMALL SYSTEMS

Weller & Romatschke



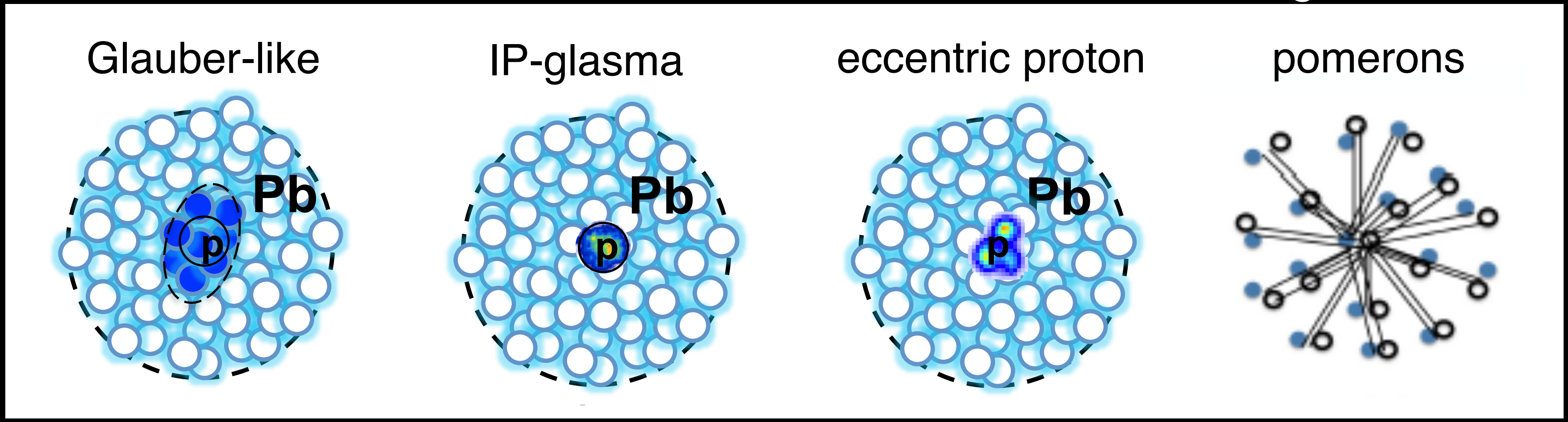
We have been comfortable with collective expansions from A+A, where the system is large, and fluctuations can be understood (at least) at the nucleon level

Possibly seeing flow in smaller systems has pushed us to consider the spatial structure fluctuations at sub-nucleon level, and how they imprint themselves on the final state flow

OUTSTANDING ISSUES

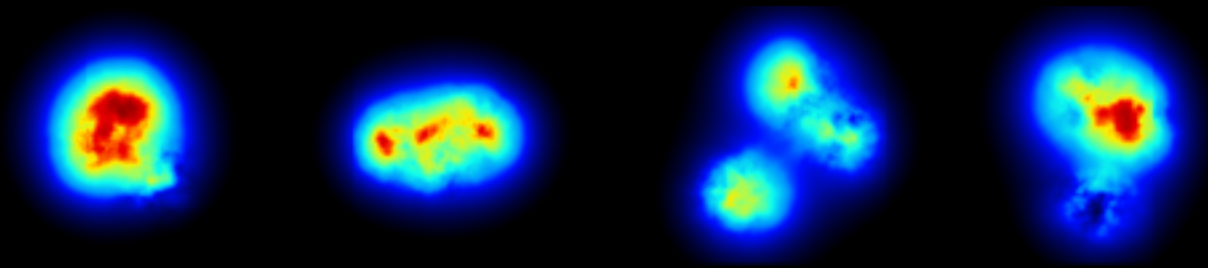
What are the relevant features of the initial state?

Dusling, Li, Schenke



nucleon sub-nucleon AdS/CFT

Can we understand the event-by-event shape of the proton?



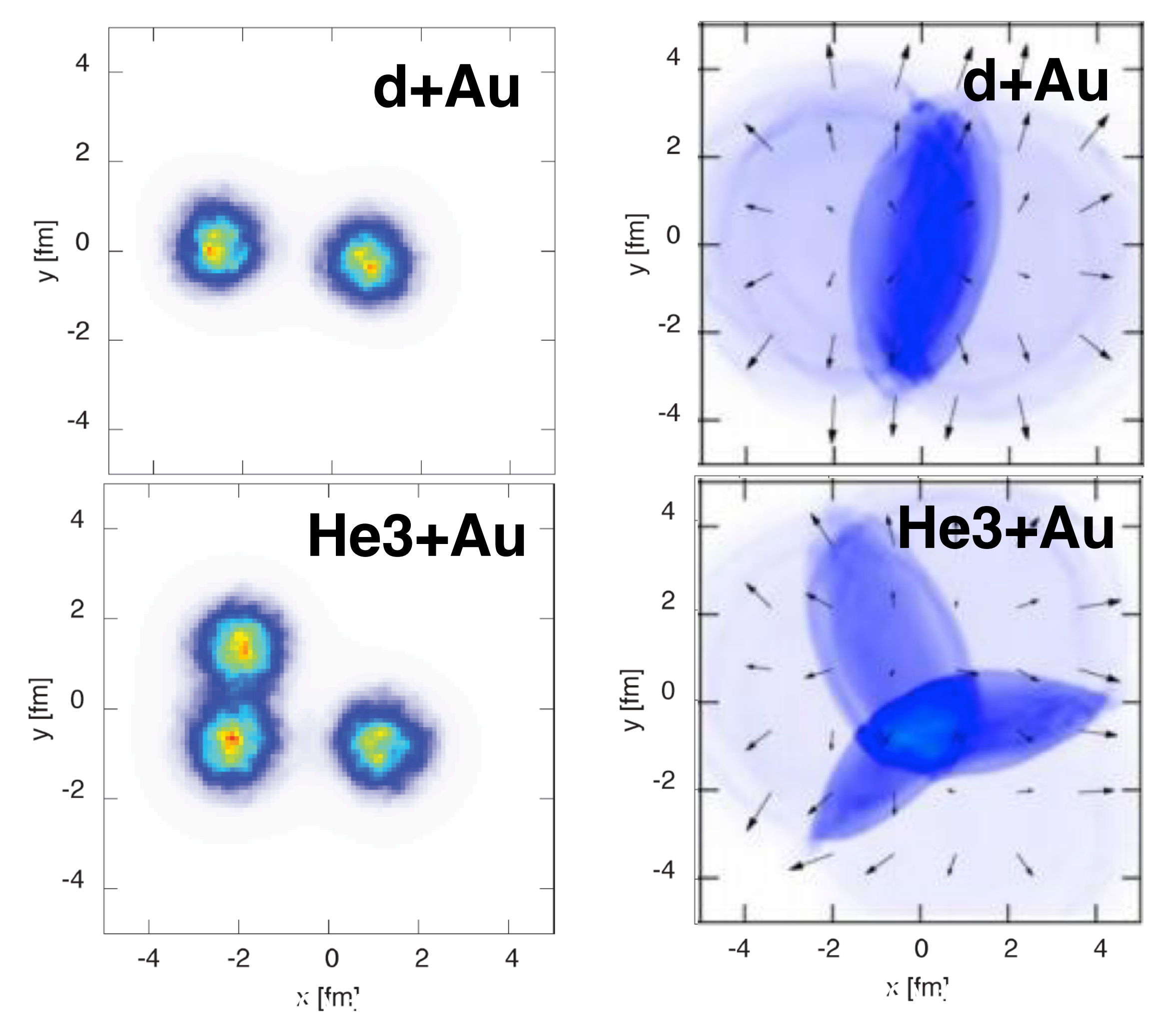
examples from Schenke, arXiv:1603.04349
Also see Welsh, Singer, Heinz, arXiv:1605.09418

Do we need flow before thermalization?, e.g. SONIC vs. superSONIC

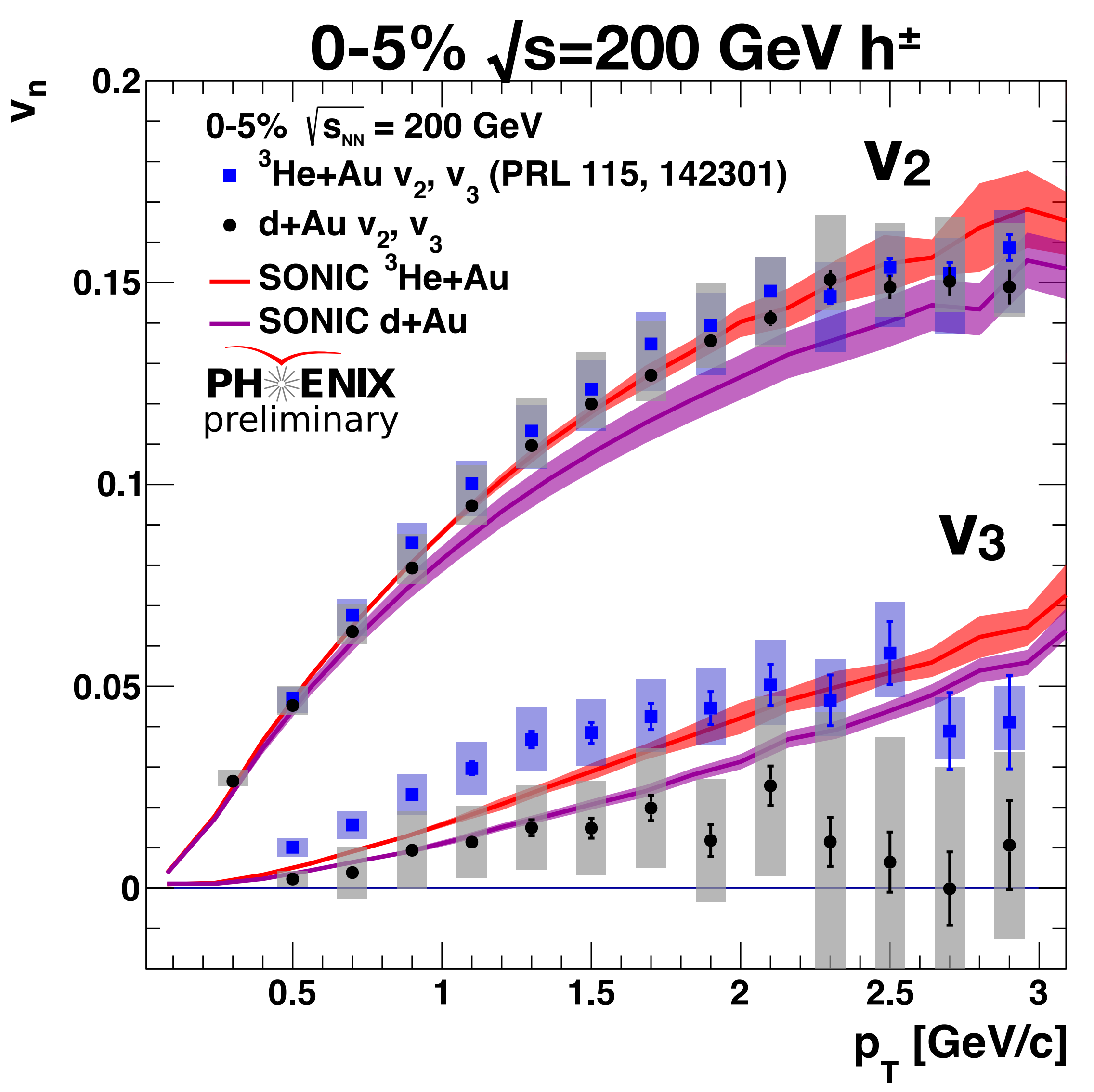
How important is hadronic rescattering?

LIGHT+HEAVY AT RHIC

W. Li, QM2017



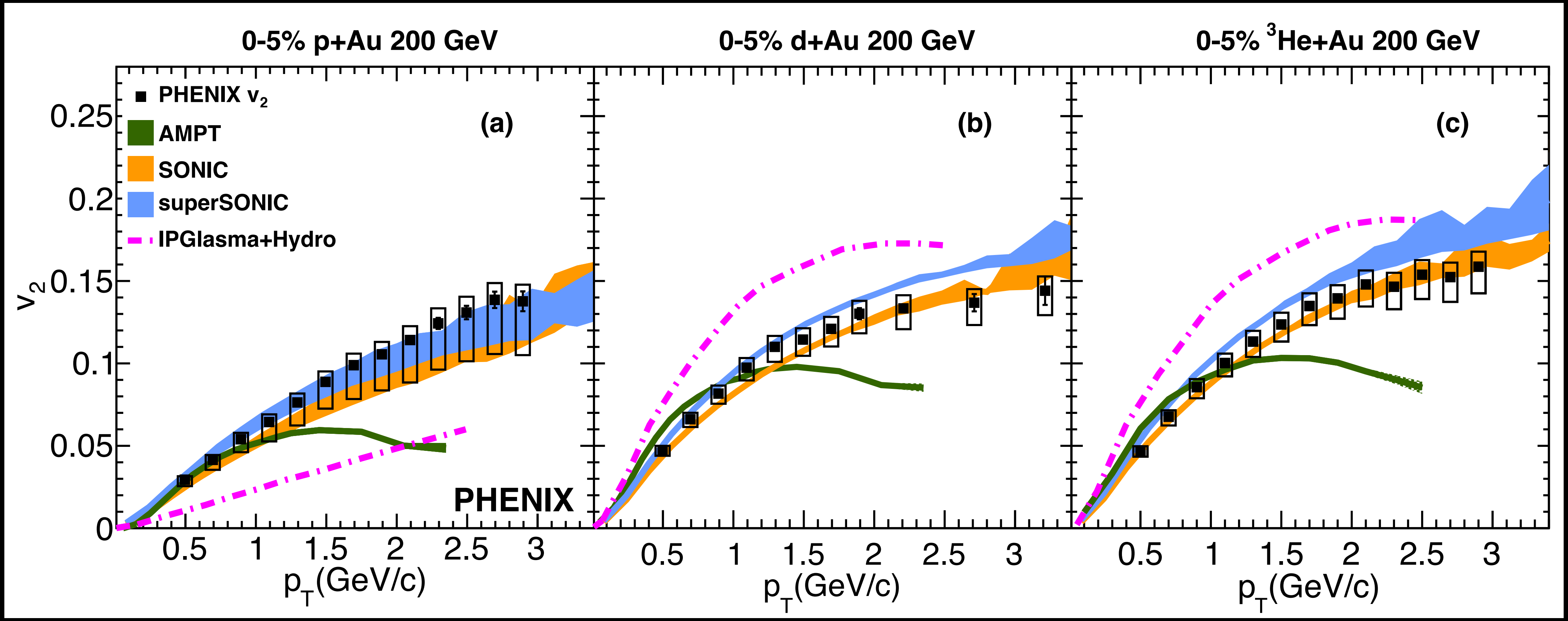
D. McGlinchey, QM2017



A nice set of PHENIX measurements using flexibility of RHIC to test impact of few-body geometry on v_2,v_3: hydro codes are in fact able to get some of the details

LIGHT+HEAVY AT RHIC

PHENIX, 1609.02894



Transport codes (AMPT) can capture the features at low p_T

Hydro seems to be necessary at higher p_T

IP-Glasma (successful in Pb+Pb) fails to get overall description

QUANTIFYING COLLECTIVITY IN SMALL SYSTEMS

- **The techniques to measure flow have been around for years now (late 90’s)**

- **Smaller systems have required a much more careful consideration of how to remove “non-flow”**
  - Energy/momentum conservation
  - Hadronic resonance decays
  - Intra-jet and inter-jet correlations

- **The main techniques used so far**
  - Multiparticle cumulants
  - Templates (“ridge excavation”)
  - New: "subevent" cumulants

MULTIPARTICLE CUMULANTS

$$\begin{aligned}
\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle &\equiv \langle\langle \mathrm{e}^{\mathrm{i}n(\phi_1-\phi_2)}\rangle\rangle,\\
\langle\langle \mathrm{corr}_n\{4\}\rangle\rangle &\equiv \langle\langle \mathrm{e}^{\mathrm{i}n(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle,\\
\langle\langle \mathrm{corr}_n\{6\}\rangle\rangle &\equiv \langle\langle \mathrm{e}^{\mathrm{i}n(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\rangle\rangle,\\
\langle\langle \mathrm{corr}_n\{8\}\rangle\rangle &\equiv \langle\langle \mathrm{e}^{\mathrm{i}n(\phi_1+\phi_2+\phi_3+\phi_4-\phi_5-\phi_6-\phi_7-\phi_8)}\rangle\rangle
\end{aligned}$$

n-particle
correlators

$$\begin{aligned}
c_n\{2\} &= \langle\langle \mathrm{corr}_n\{2\}\rangle\rangle,\\
c_n\{4\} &= \langle\langle \mathrm{corr}_n\{4\}\rangle\rangle - 2\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle^2,\\
c_n\{6\} &= \langle\langle \mathrm{corr}_n\{6\}\rangle\rangle - 9\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle\\
&\quad \times\langle\langle \mathrm{corr}_n\{4\}\rangle\rangle + 12\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle^3,\\
c_n\{8\} &= \langle\langle \mathrm{corr}_n\{8\}\rangle\rangle - 16\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle\\
&\quad \times\langle\langle \mathrm{corr}_n\{6\}\rangle\rangle - 18\langle\langle \mathrm{corr}_n\{4\}\rangle\rangle^2\\
&\quad +144\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle^2\langle\langle \mathrm{corr}_n\{4\}\rangle\rangle - 144\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle^4
\end{aligned}$$

n-particle cumulants,
derived from
a generating function

$$\ln\langle e^{z(\boldsymbol{v}_n+\boldsymbol{v}_n^\star)}\rangle = \sum_{k=1}^{\infty}\frac{z^{2k}}{k!^2}c_n\{2k\}$$

$$\begin{aligned}
\mathrm{v}_n\{2\} &= \sqrt{c_n\{2\}},\\
\mathrm{v}_n\{4\} &= \sqrt[4]{-c_n\{4\}},\\
\mathrm{v}_n\{6\} &= \sqrt[6]{c_n\{6\}/4},\\
\mathrm{v}_n\{8\} &= \sqrt[8]{-c_n\{8\}/33}
\end{aligned}$$

Flow coefficients,
assuming non-flow
is cancelled

IS NON-FLOW NEGLIGIBLE?

- **Nice derivation in recent paper by Jia, et al (arxiv:1701.03830)**

Single-event azimuthal distribution

$$P(\phi) = \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} \boldsymbol{v}_n e^{-in\phi}, \quad \boldsymbol{v}_n = v_n e^{in\Phi_n}$$

Single-event flow coefficients: Bessel-Gaussian

$$p(\boldsymbol{v}_n) = \frac{1}{2\pi\delta_n^2} e^{-|\boldsymbol{v}_n - v_n^0|^2 \big/ (2\delta_n^2)}, \; p(v_n) = \frac{v_n}{\delta_n^2} e^{-\frac{(v_n)^2 + (v_n^0)^2}{2\delta_n^2}} I_0\left(\frac{v_n^0 v_n}{\delta_n^2}\right)$$

We measure “q” vector

$$\boldsymbol{q}_n \equiv \frac{\sum_i e^{in\phi_i}}{M} = q_n e^{in\Psi_n}$$

Which is the sum of flow + nonflow

$$\boldsymbol{q}_n = \boldsymbol{v}_n + \boldsymbol{s}_\mathrm{n} + \boldsymbol{s}_\mathrm{n}^\mathrm{stat}$$

Which convolves non-flow with the underlying flow PDF

$$p(\boldsymbol{q}_n) = p(\boldsymbol{v}_n) \otimes p(\boldsymbol{s}_n) \otimes p(\boldsymbol{s}_\mathrm{n}^\mathrm{stat})$$

Generating function for flow coefficients is easily generalized to include non-flow

$$\ln \left\langle e^{z(\boldsymbol{v}_n + \boldsymbol{v}_n^*)} \right\rangle = \ln \left(\sum_{k=1}^{\infty} \frac{z^{2k}}{k!^2} \left\langle (\boldsymbol{v}_n \boldsymbol{v}_n^*)^k \right\rangle \right) = \ln \left(\sum_{k=1}^{\infty} \frac{z^{2k}}{k!^2} \langle\langle 2k \rangle\rangle \right) \equiv \sum_{k=1}^{\infty} \frac{z^{2k}}{k!^2} c_n\{2k\}$$

$$\ln \left\langle e^{z(\boldsymbol{q}_n + \boldsymbol{q}_n^*)} \right\rangle = \ln \left\langle e^{z(\boldsymbol{v}_n + \boldsymbol{v}_n^*)} \right\rangle + \ln \left\langle e^{z(\boldsymbol{s}_n + \boldsymbol{s}_n^*)} \right\rangle = \sum_{k=1}^{\infty} \frac{z^{2k}}{k!^2} \left(c_n\{2k, v\} + c_n\{2k, s\} \right)$$

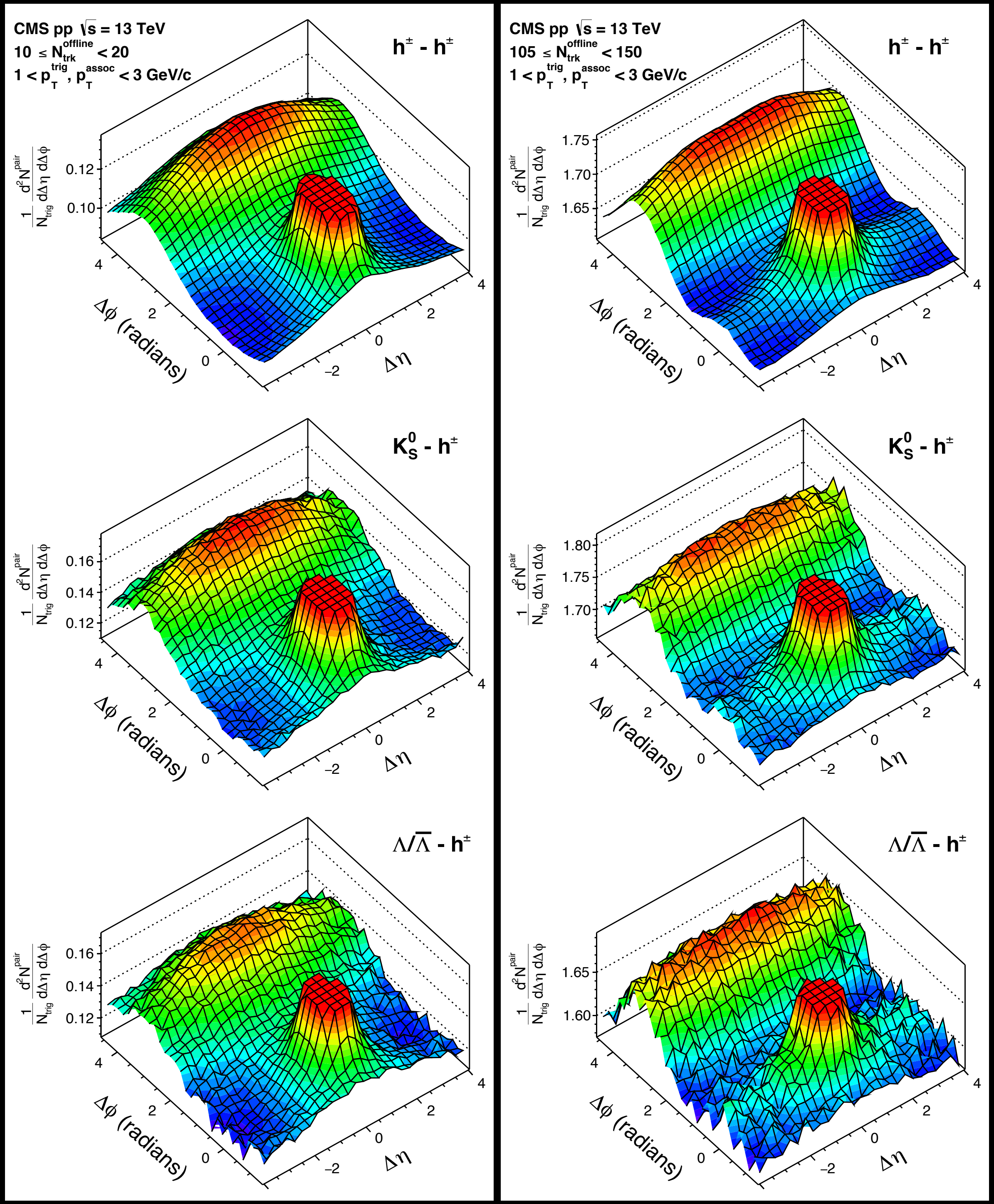
Cumulants carry contributions from non-flow as well as flow!

$$c_n\{2k\} = c_n\{2k, v\} + c_n\{2k, s\}$$

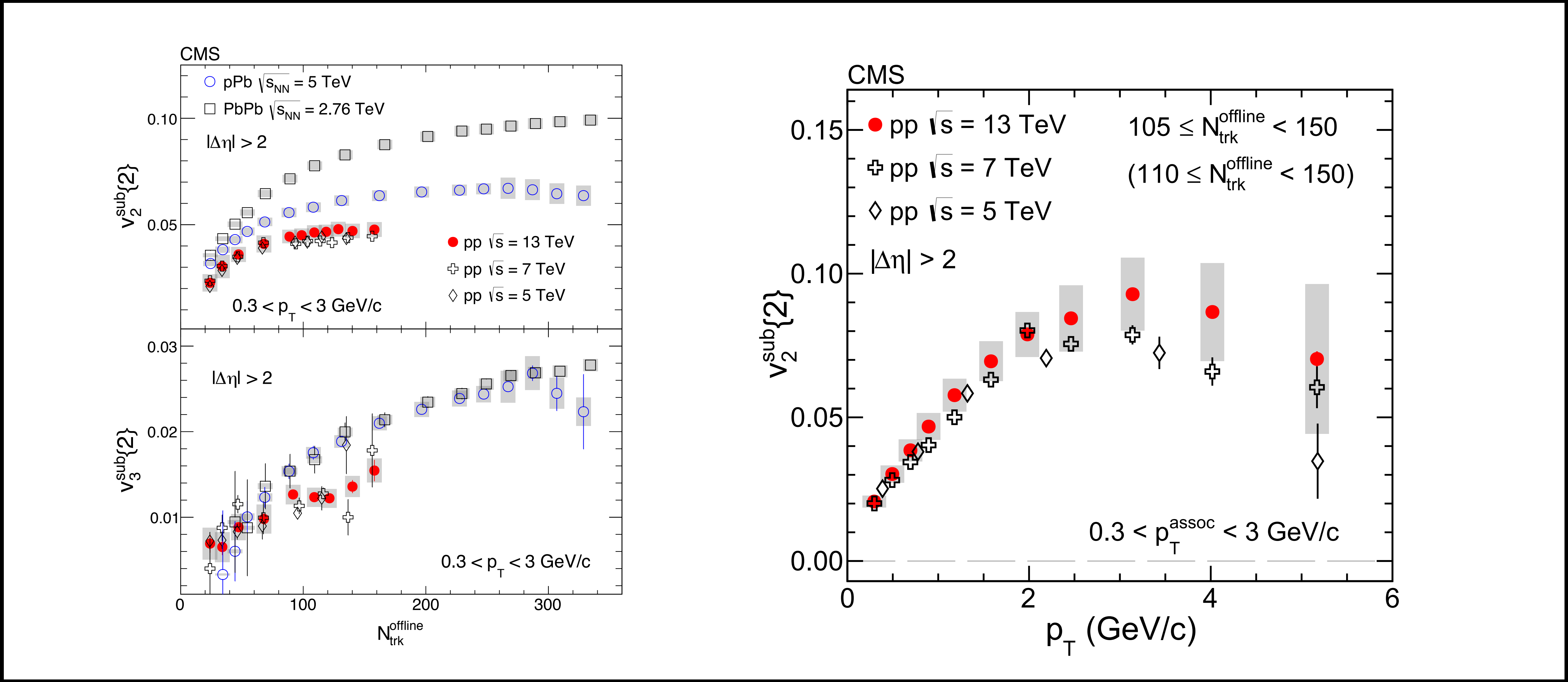
Correlators only trivially non-flow if the non-flow <u>fluctuations</u> are negligible

CMS COLLECTIVITY IN PP

- **CMS used two different approaches for inclusive and strange hadrons**
    - Two particle correlations with a peripheral subtraction
    - Multiparticle cumulants with no additional nonflow subtraction except |Δ|>2 for two particles

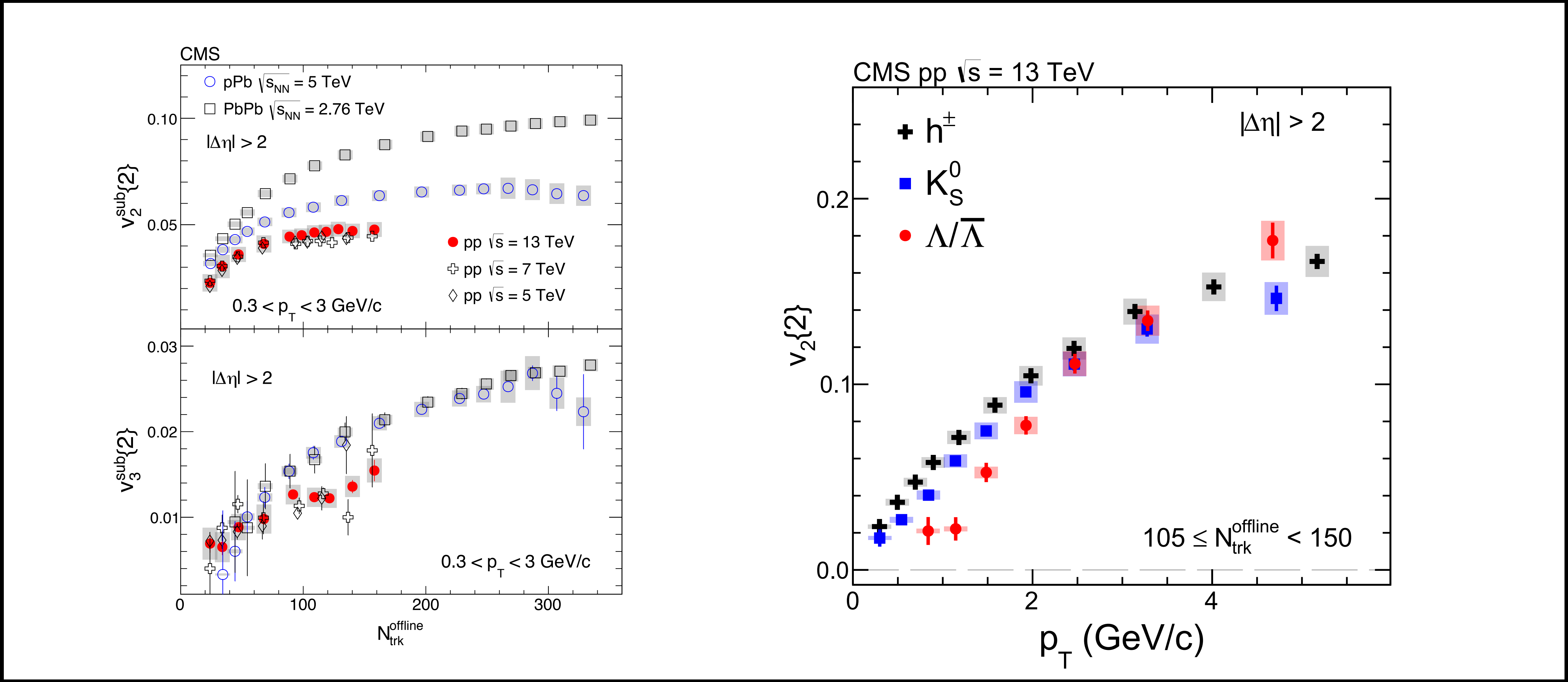


JET-SUBTRACTED V_2 & V_3 FROM 2-PARTICLE CORRELATIONS



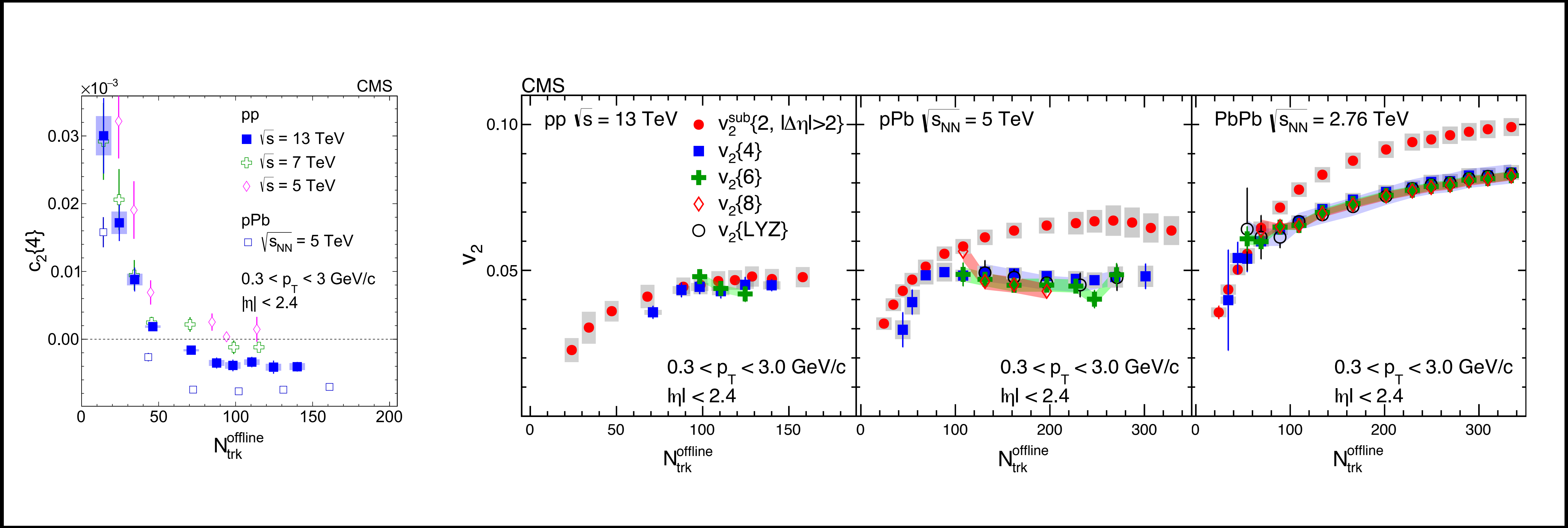
A familiar shape from p+Pb and Pb+Pb:
no variation with beam energy

JET-SUBTRACTED V_2 & V_3 FROM 2-PARTICLE CORRELATIONS



A familiar shape from p+Pb and Pb+Pb:
no variation with beam energy,
when including strange hadrons, a clear mass ordering

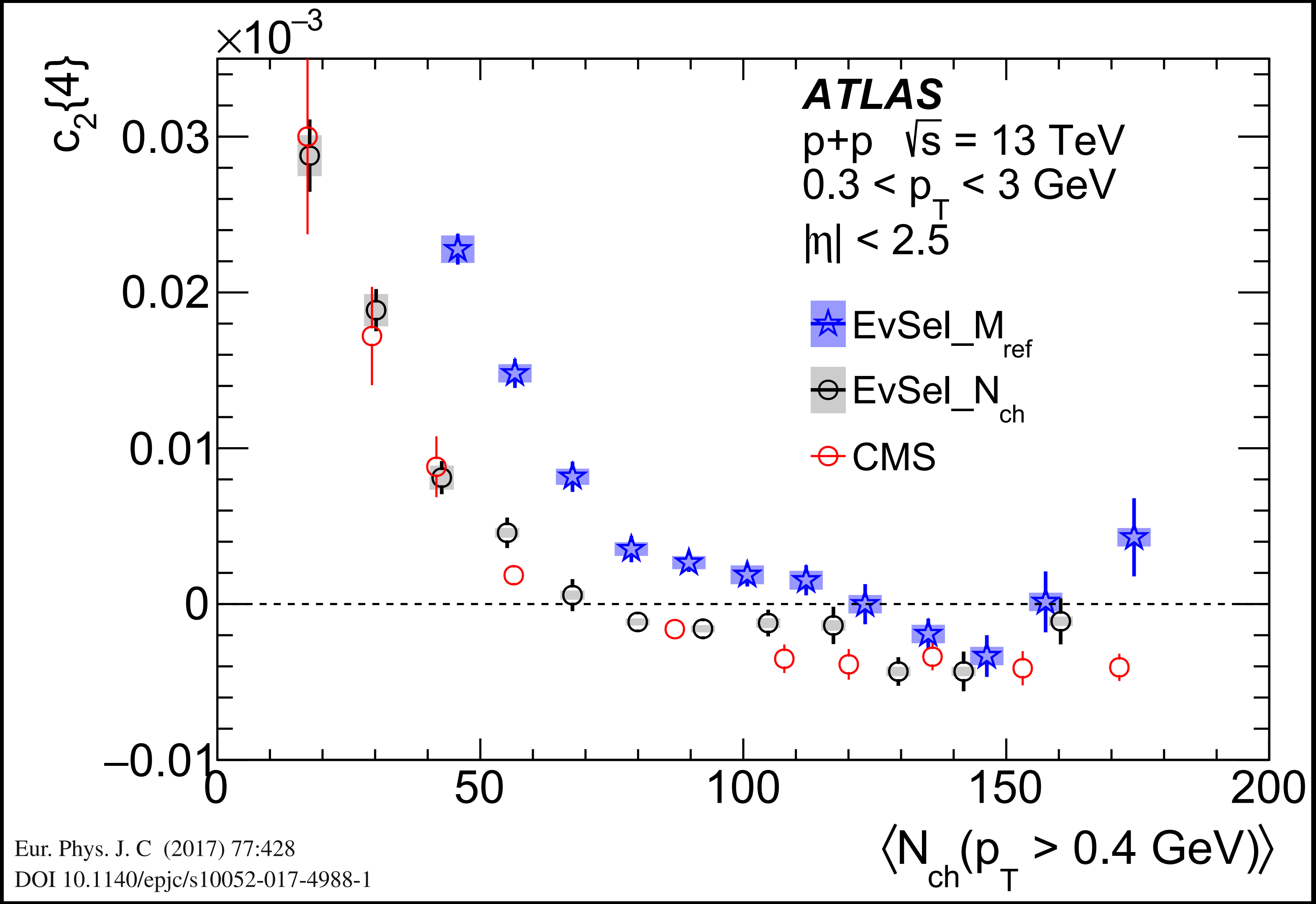
CMS MULTI PARTICLE CUMULANTS



4-particle flow only defined when cumulant is negative:
Only happens at higher multiplicities,
when non-flow is apparently less relevant ($N_{trk} > 50$)

But where defined, **higher order cumulants ~agree**.
In p+Pb and Pb+Pb, $v_2\{2\}>v_2\{4,6,8\}$ since **$v_2\{2\}$** more sensitive to v_2 fluctuations

COMPARISON WITH ATLAS: IMPORTANCE OF FLUCTUATIONS



Eur. Phys. J. C (2017) 77:428
DOI 10.1140/epjc/s10052-017-4988-1

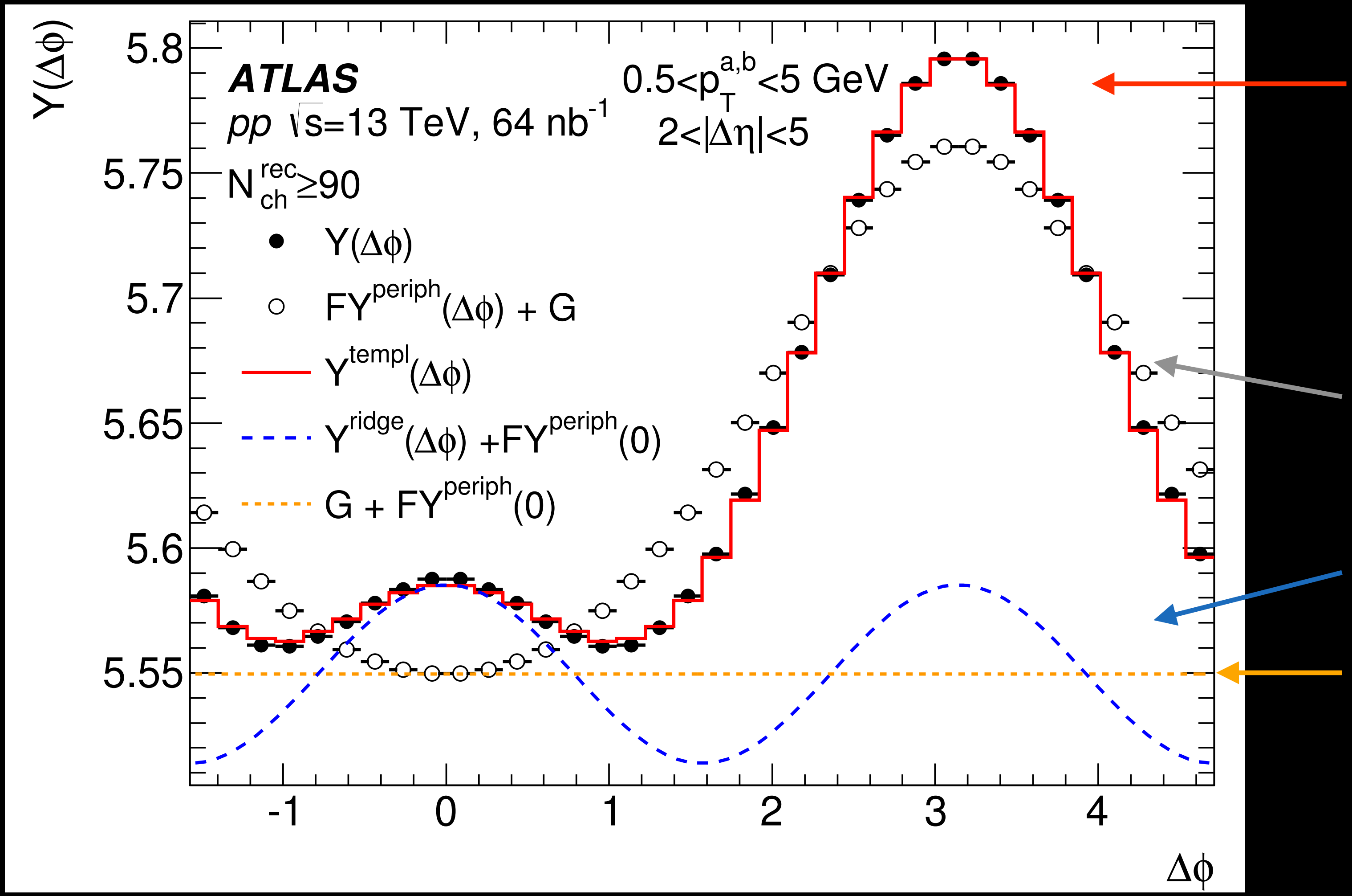
$c_2\{4\}$ sensitive to how the events are selected:
In ATLAS, combining events with fixed number of raw tracks gives a higher value to $c_2\{4\}$ — killing flow signal seen by CMS

RIDGE "EXCAVATION"

Does the ridge really disappear at low multiplicities,
or is it just overwhelmed by non-flow?

RIDGE "EXCAVATION"

PRL 116, 172301 (2016)
arXiv:1609.06213



total

peripheral pp

ridge $G\left[1+2\sum_{n=2}^{4}v_n^2\cos\left(n\Delta\phi\right)\right]$

combinatoric pairs

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

YIELD IN "PERIPHERAL" PP

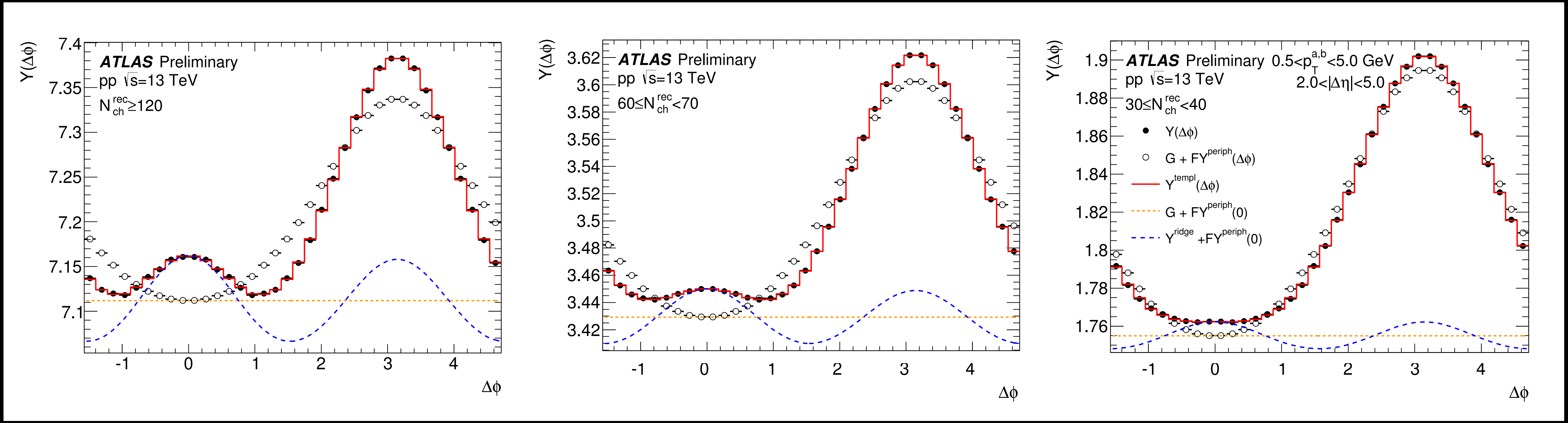
RIDGE (SINUSOIDAL)

COMBINATORIC

Unexpectedly provides explanation for narrowing around Δϕ~π

RIDGE "EXCAVATION"

PRL 116, 172301 (2016)
arXiv:1609.06213



High multiplicity

Medium multiplicity

Low multiplicity

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

YIELD IN "PERIPHERAL" PP

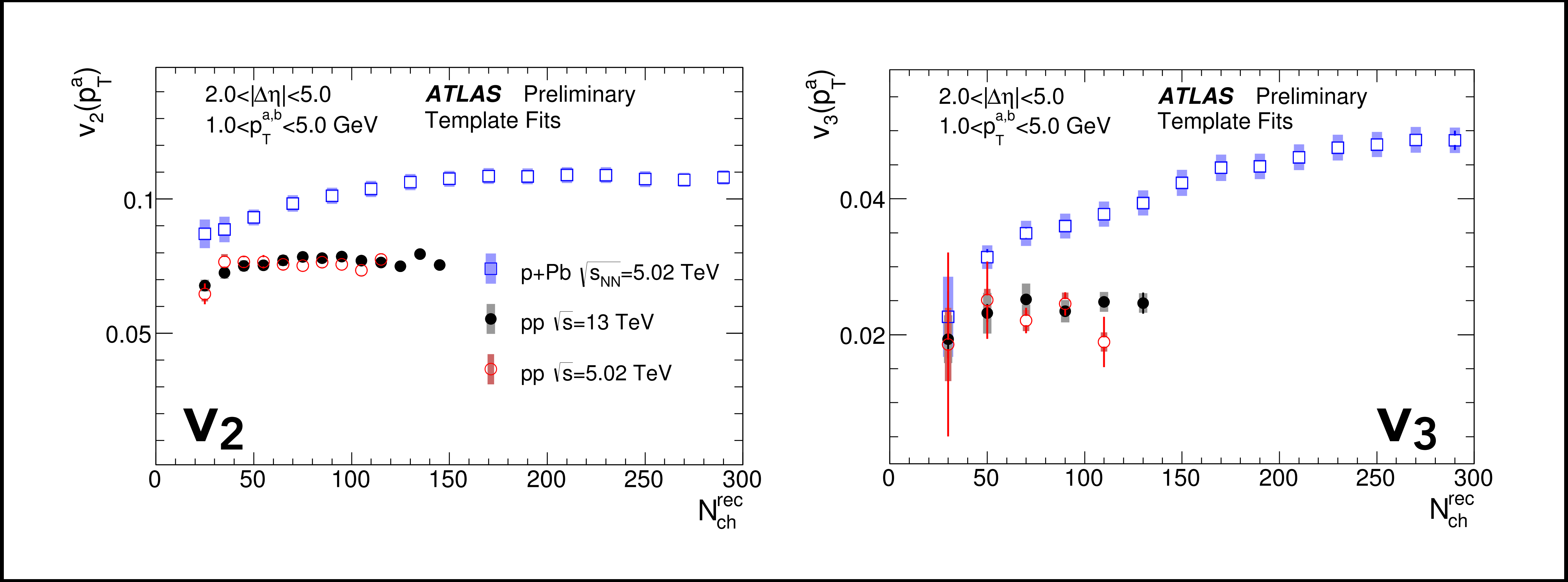
RIDGE (SINUSOIDAL)

COMBINATORIC

$$G\left[1+2\sum_{n=2}^{4} v_n^2\cos\left(n\Delta\phi\right)\right]$$

MULTIPLICITY DEPENDENCE

PRL 116, 172301 (2016)
arXiv:1609.06213

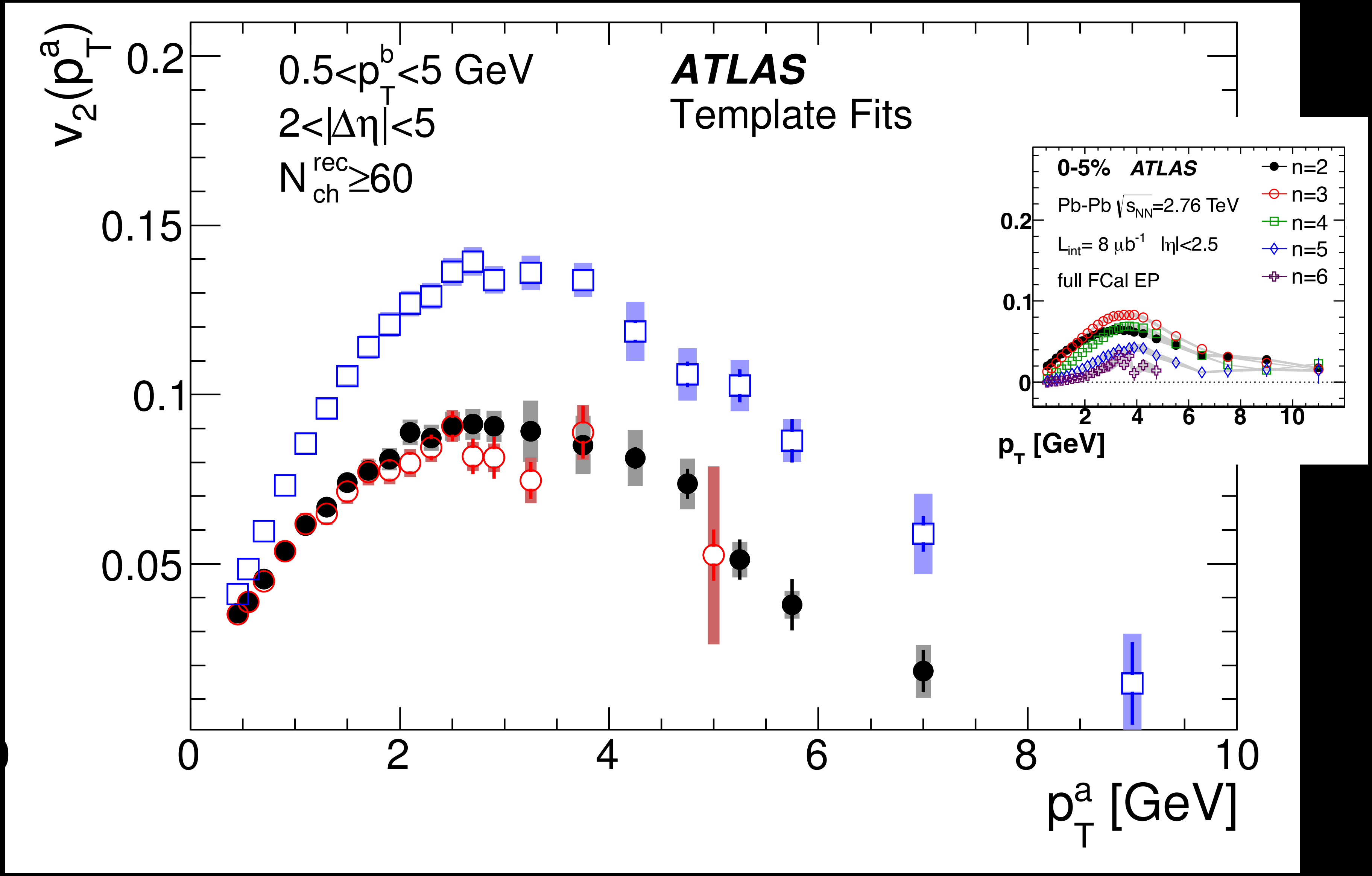


PRL 116, 172301 (2016)
ATLAS-CONF-2016-025

Sinusoidal terms in pp persist to lower multiplicities (N_{ch}~20-30), suggesting there is no need to only select high multiplicity events

TRANSVERSE MOMENTUM DEPENDENCE

PRL 116, 172301 (2016)
arXiv:1609.06213

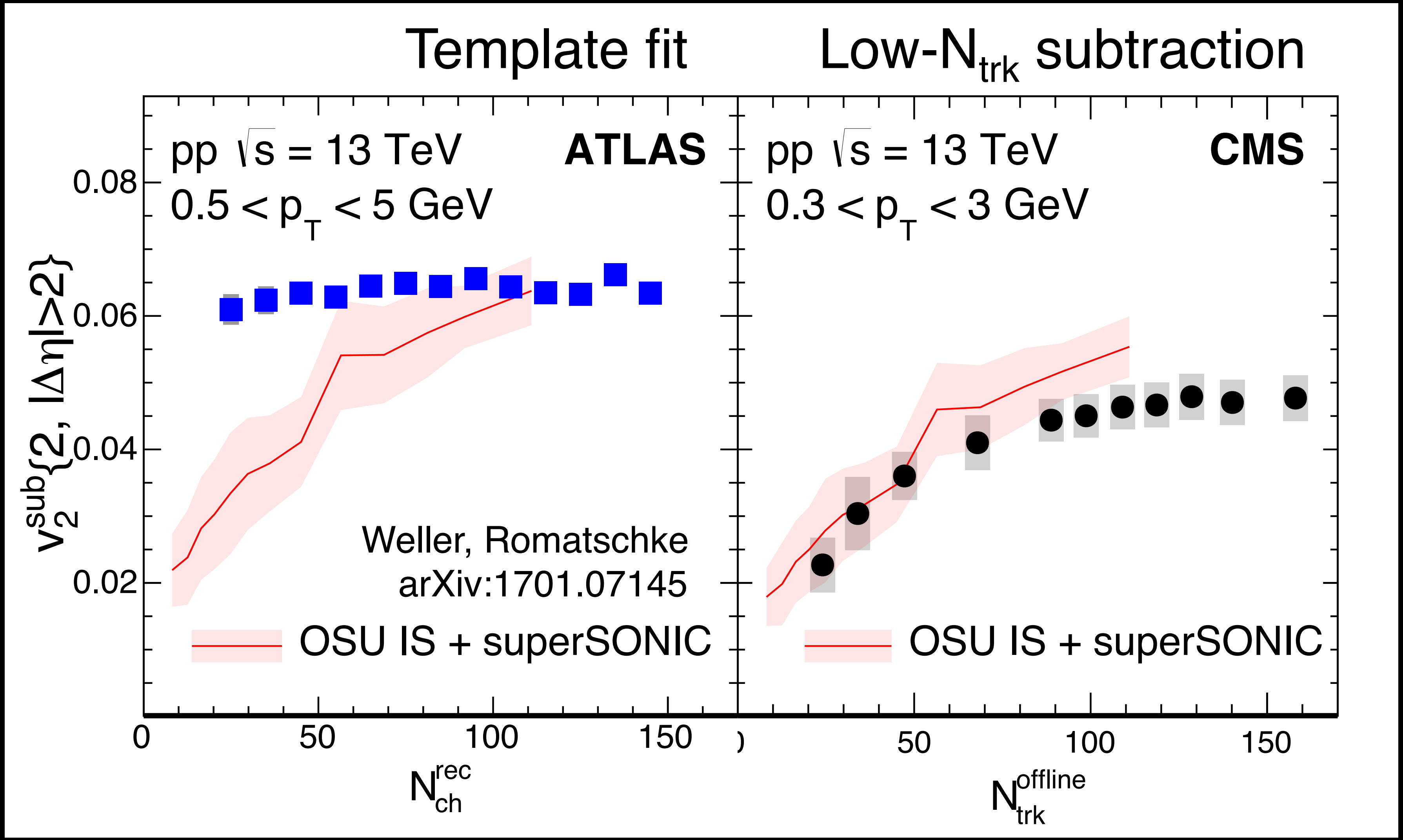


Shape familiar from Pb+Pb, attributed to flow below 4 GeV

Very high p_T behavior complicated by some multiplicity dependence in the template at high p_T

A STANDOFF?

W. Li, QM2017

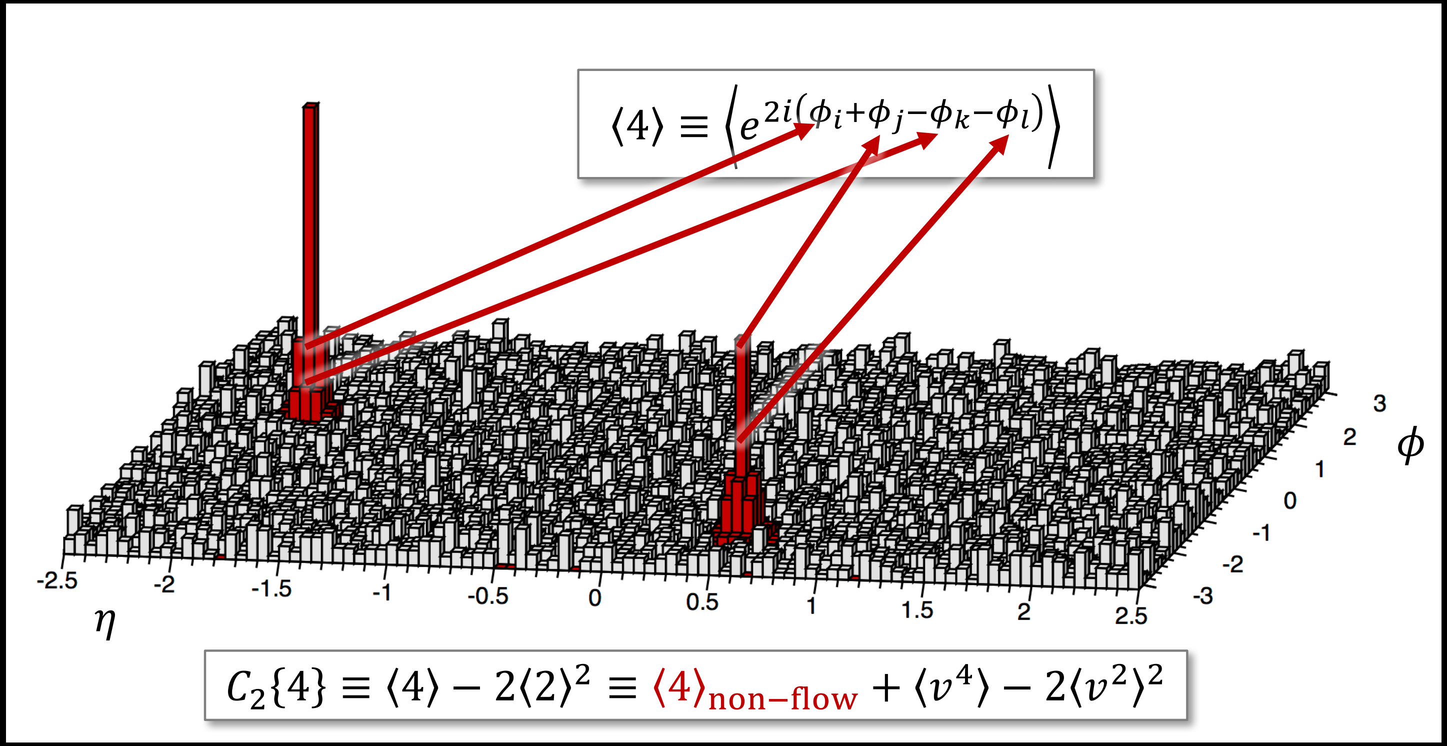


Comparisons of v_2 extracted from 2PC,
but with different methods to remove non-flow.

Difference in magnitude just reflects p_T selection.
Hydro calculations seem to prefer the CMS data (how much is this from IS?)
Is there another way to control non-flow?

SUBEVENT CUMULANTS

M. Zhou, QM2017

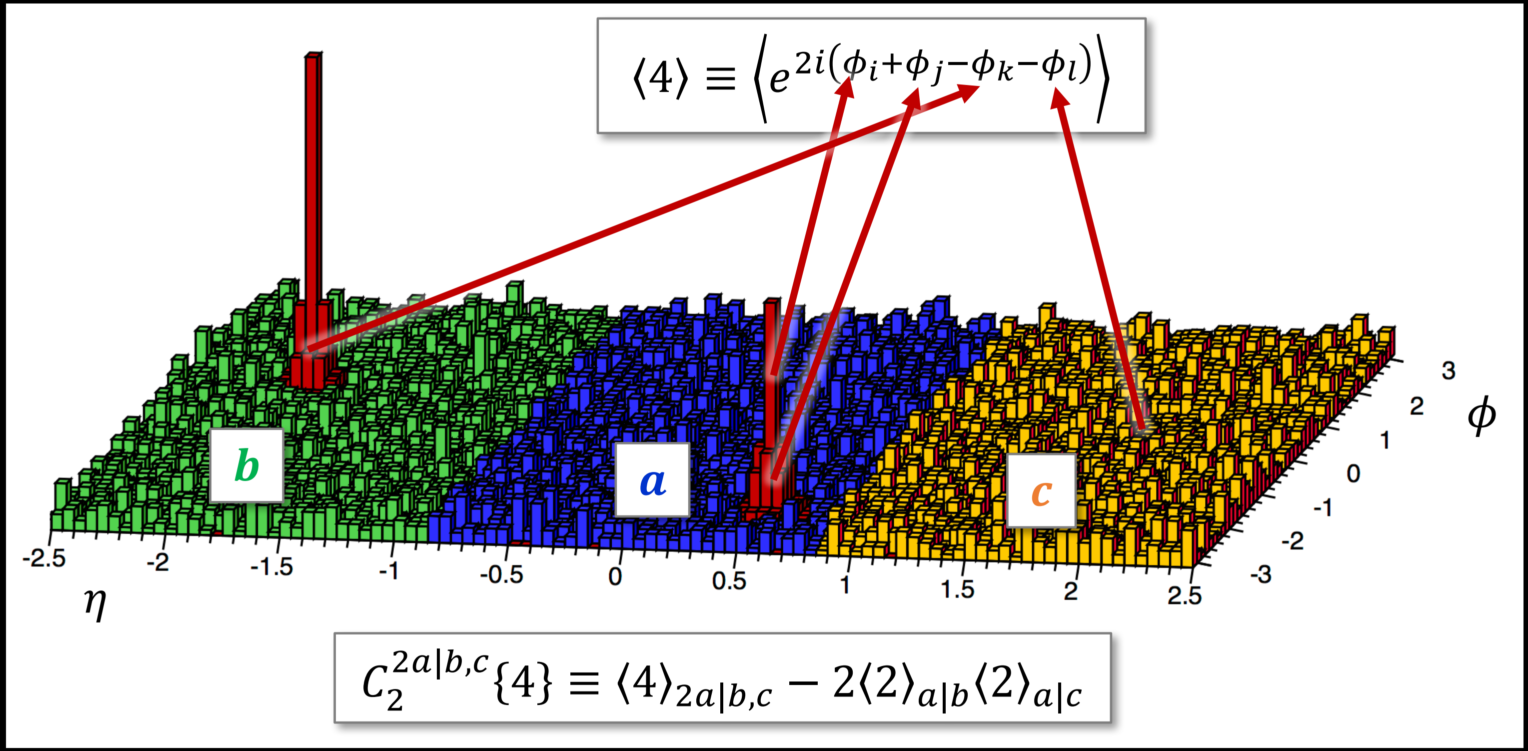


$$\langle 4\rangle \equiv \left\langle e^{2i(\phi_i+\phi_j-\phi_k-\phi_l)}\right\rangle$$

$$C_2\{4\} \equiv \langle 4\rangle - 2\langle 2\rangle^2 \equiv \langle 4\rangle_{\mathrm{non-flow}} + \langle v^4\rangle - 2\langle v^2\rangle^2$$

In "standard" cumulant method, jets can contribute to non-flow in a way that fluctuates event-by-event.

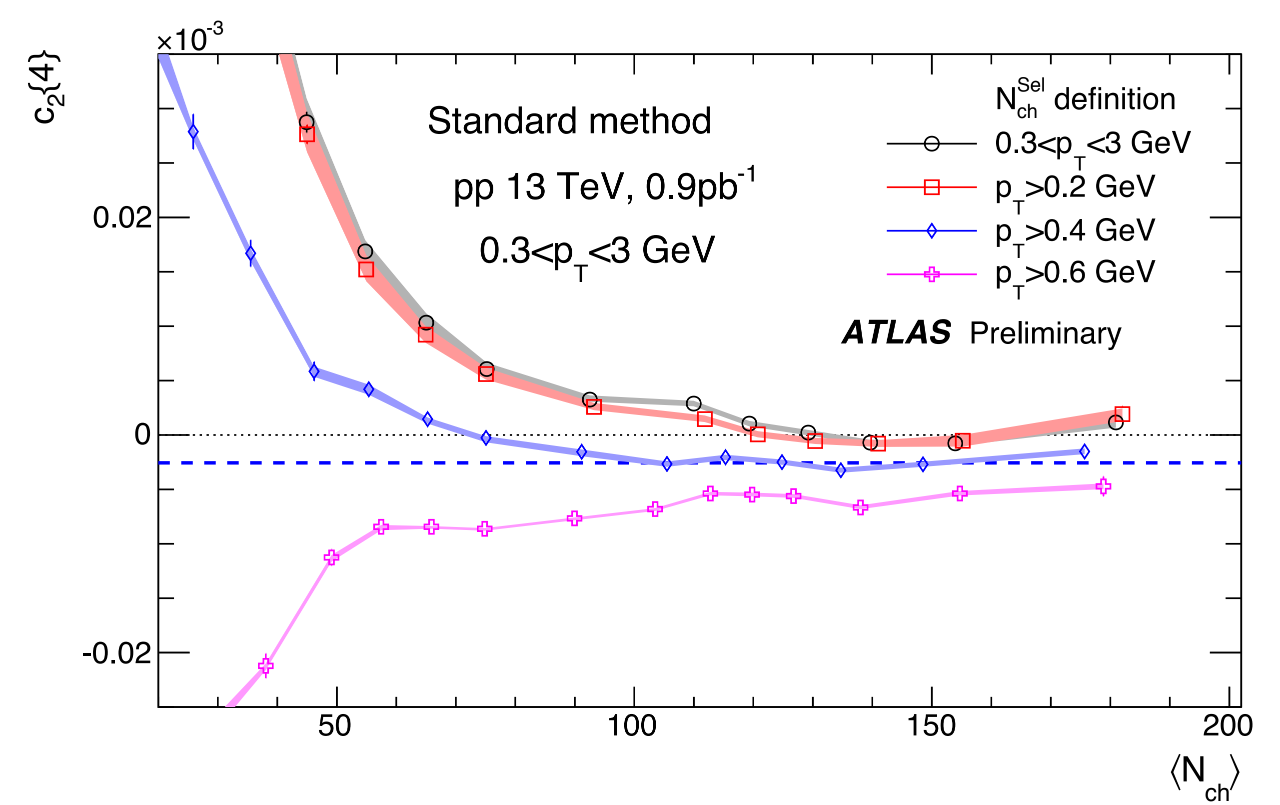
In "subevent" cumulant method, require that particles come from two or three different detector regions: break up sources of non-flow, to only look at long-range



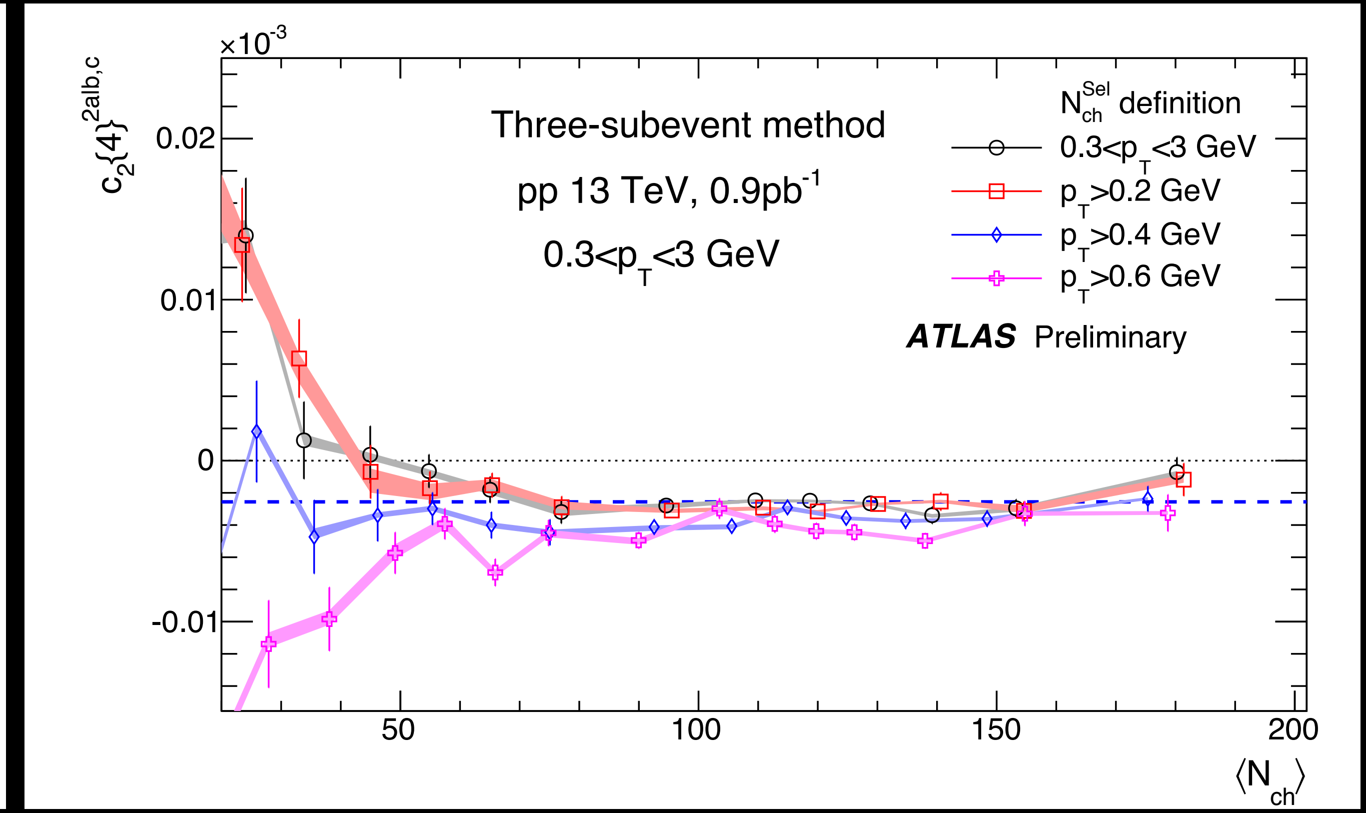
$$\langle 4\rangle \equiv \left\langle e^{2i(\phi_i+\phi_j-\phi_k-\phi_l)}\right\rangle$$

$$C_2^{2a|b,c}\{4\} \equiv \langle 4\rangle_{2a|b,c} - 2\langle 2\rangle_{a|b}\langle 2\rangle_{a|c}$$

STANDARD VS. SUBEVENT

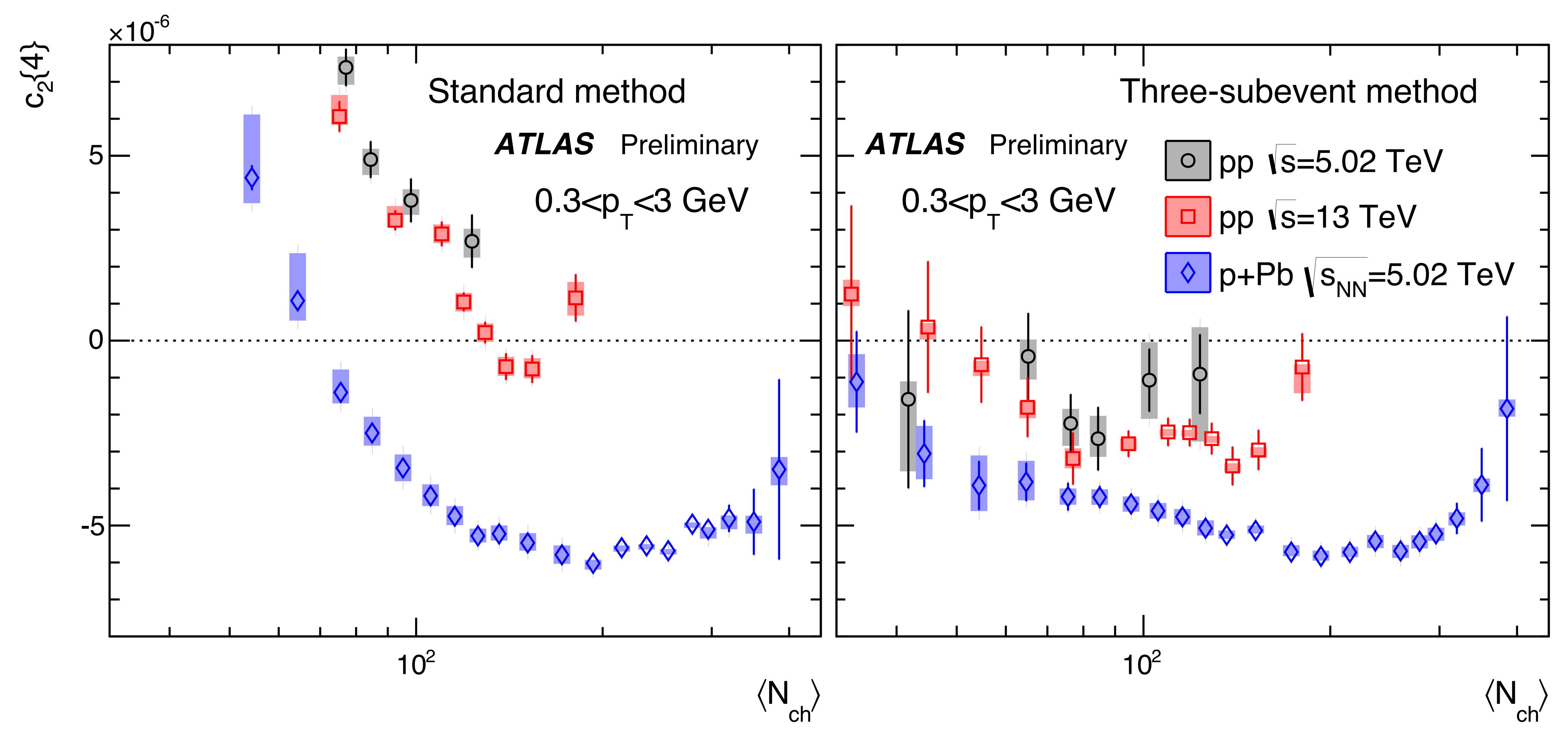


Strong dependence on how events are classified: non-flow fluctuations can apparently induce a flow signal



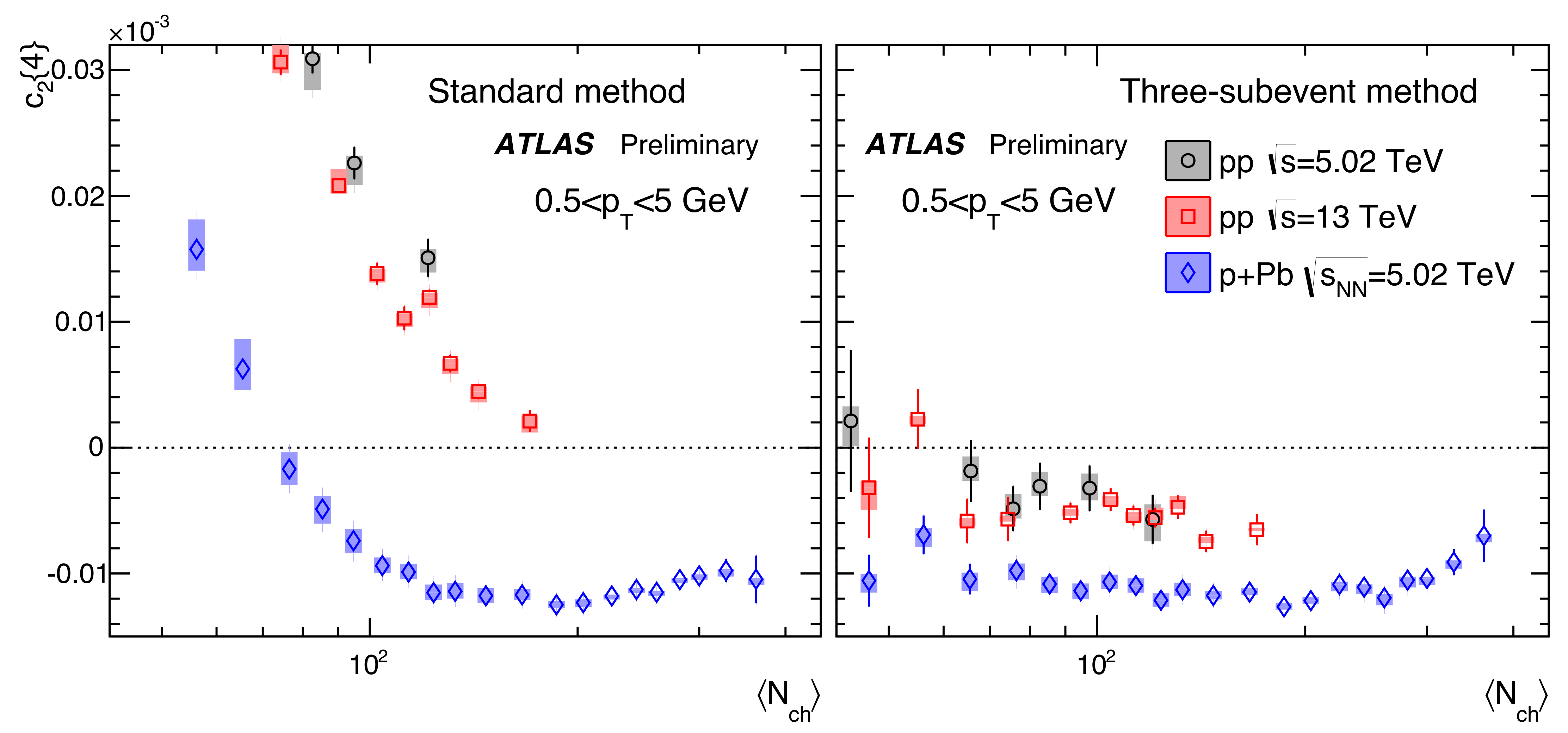
Non-flow fluctuations are tamed using subevents in the cumulants: negative $c_2\{4\}$ over a wide range in multiplicity, less sensitive to selection criteria

STANDARD VS. SUBEVENT



Suggests a wide range in which a true v_2 signal can be extracted from pp data

STANDARD VS. SUBEVENT

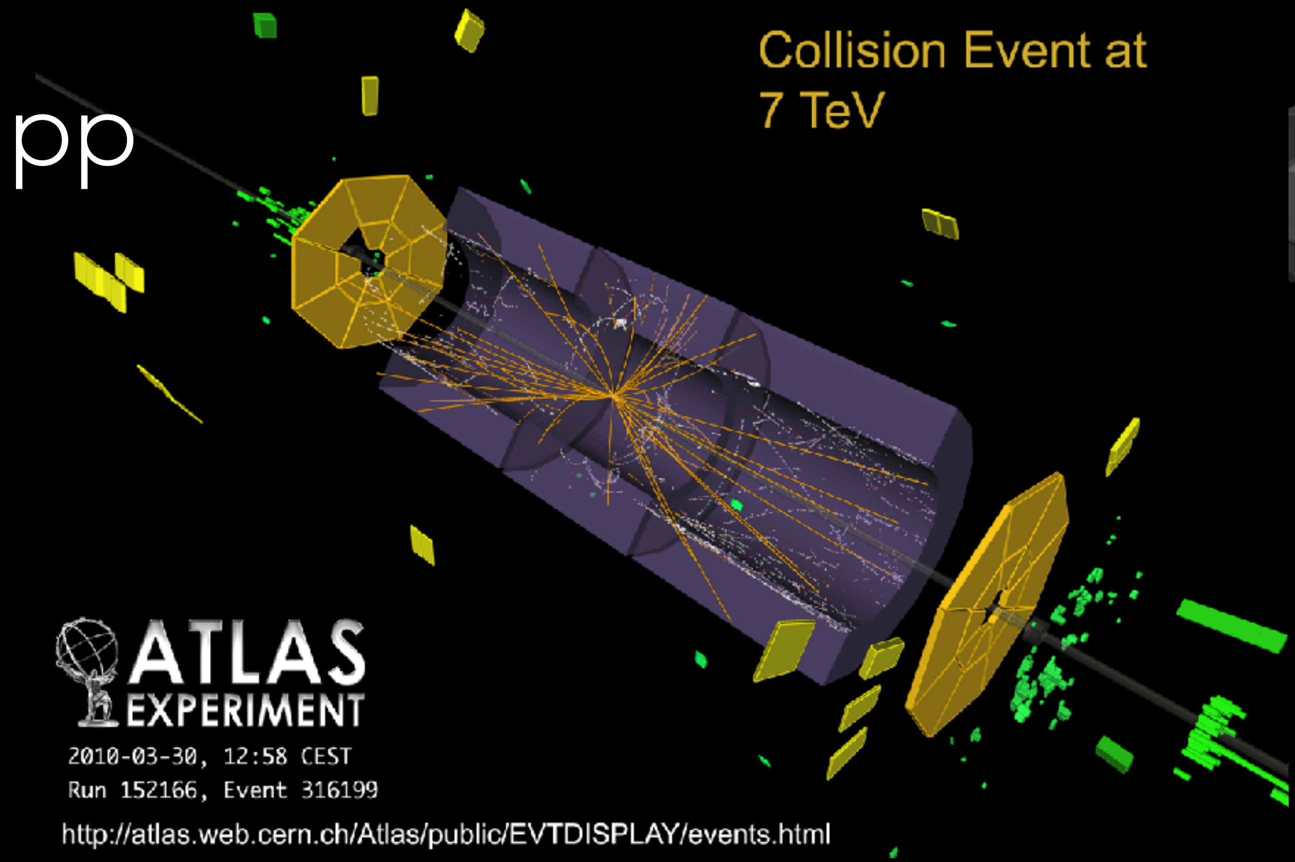


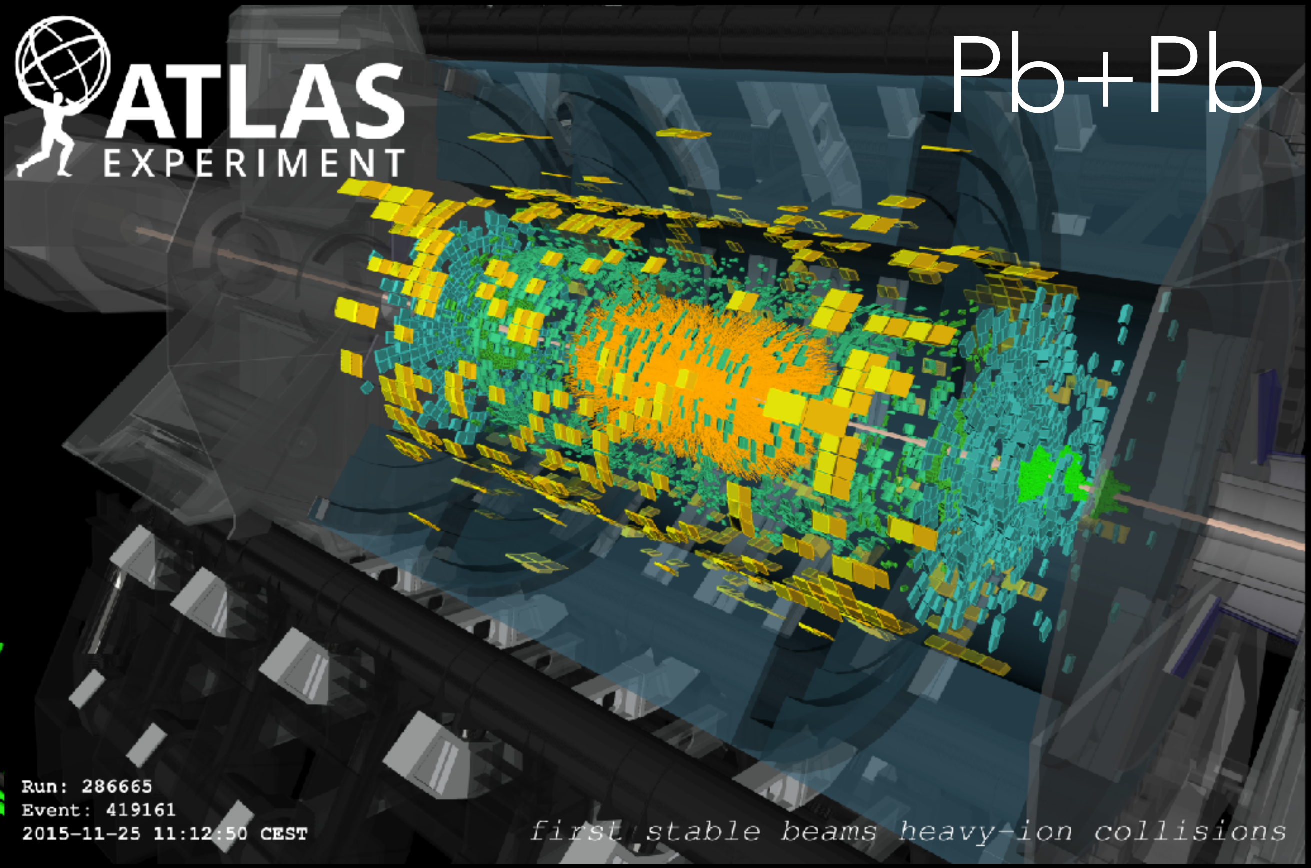
Increasing the minimum p_T from 0.3 to 0.5 GeV, increases the flow signal substantially

FLOW IN PP?

- **The evidence for “collectivity” in pp certainly looks compelling, as much as it does for A+A**
- **The source of the collectivity remains under debate**
  - Both hydro and CGC approaches are improving year-over-year (you will certainly hear more on this this week)
- **Clearly, we cannot decide this one way or another without a better, and shared, understanding of non-flow correlations in all of its manifestations**

FIN: BACK TO THE FUTURE

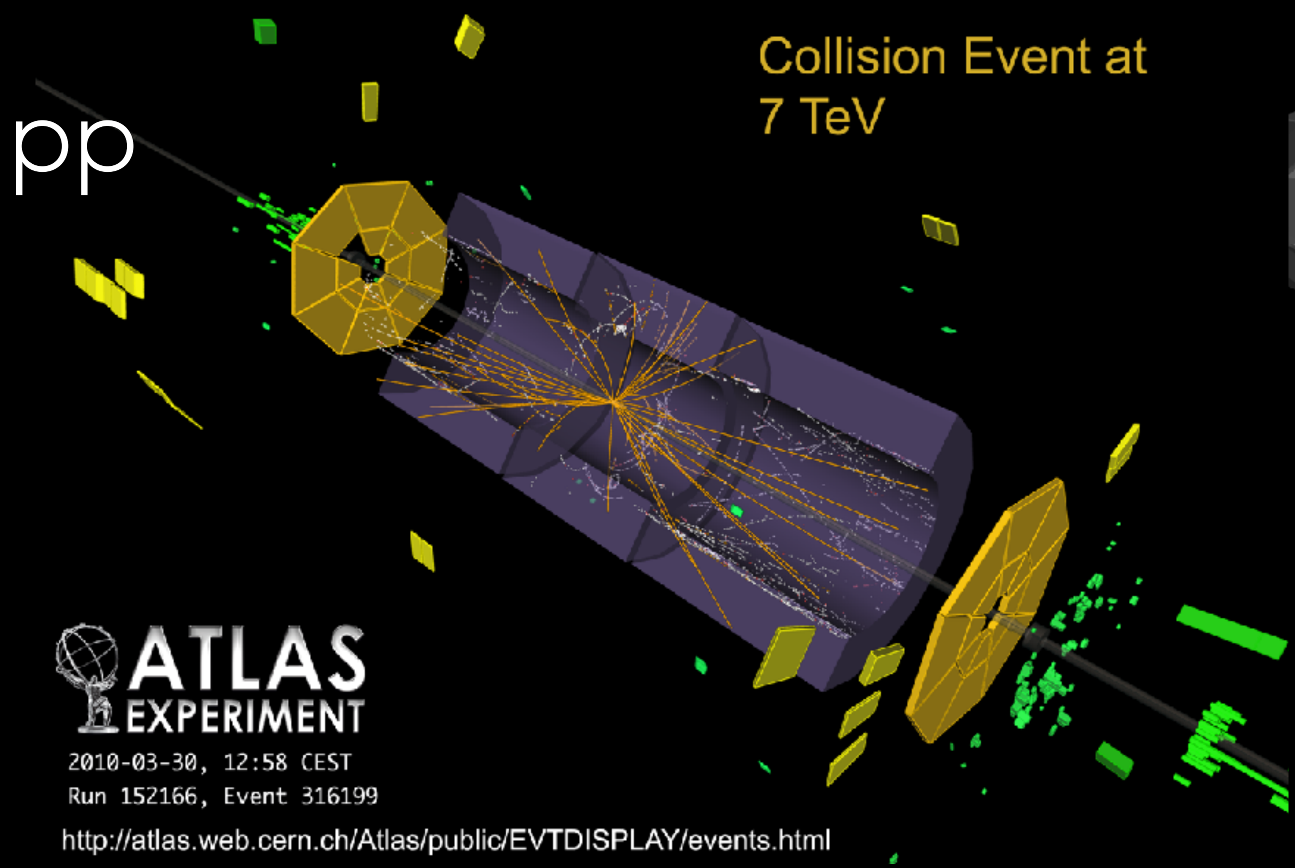


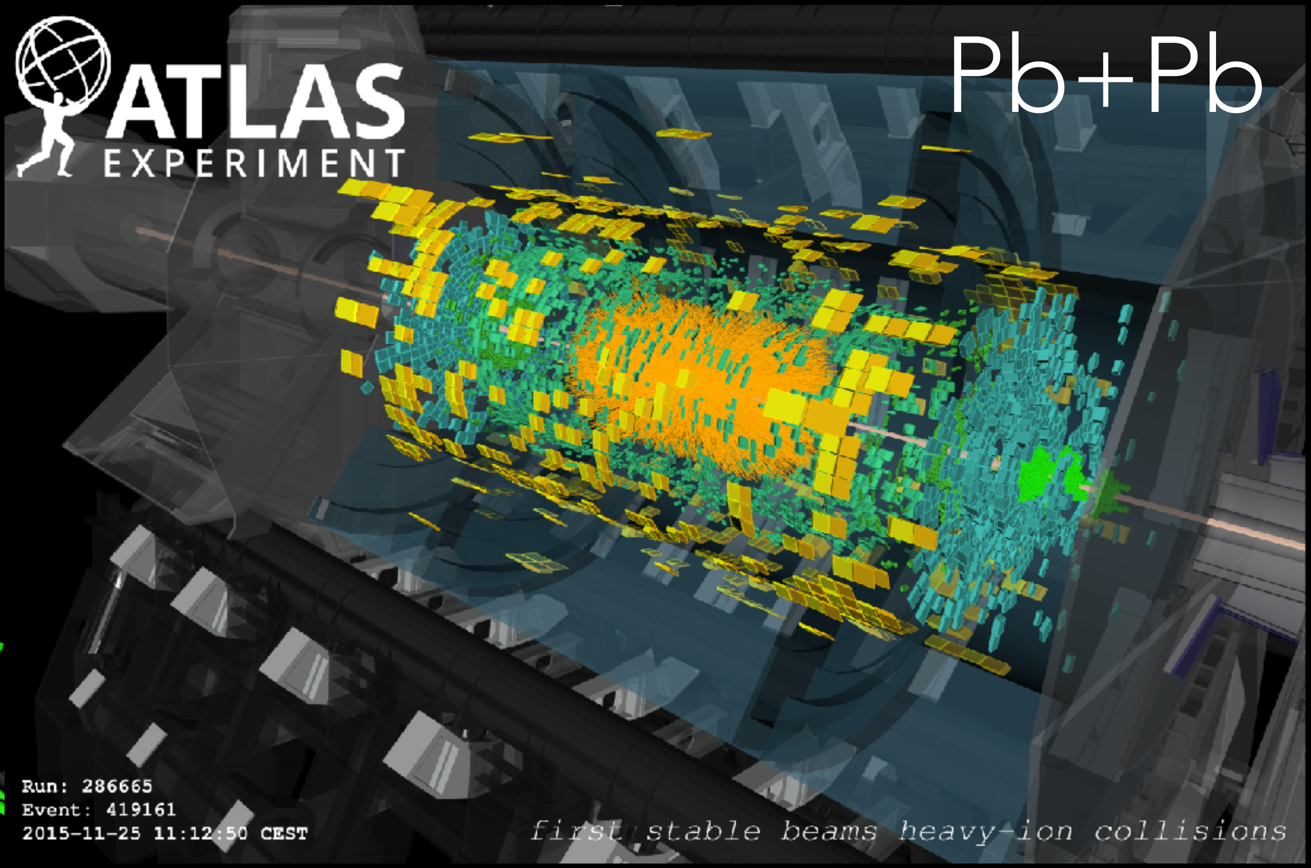


Intriguing prospect: Pb+Pb may provide a new (collective?) perspective on the pp underlying event.

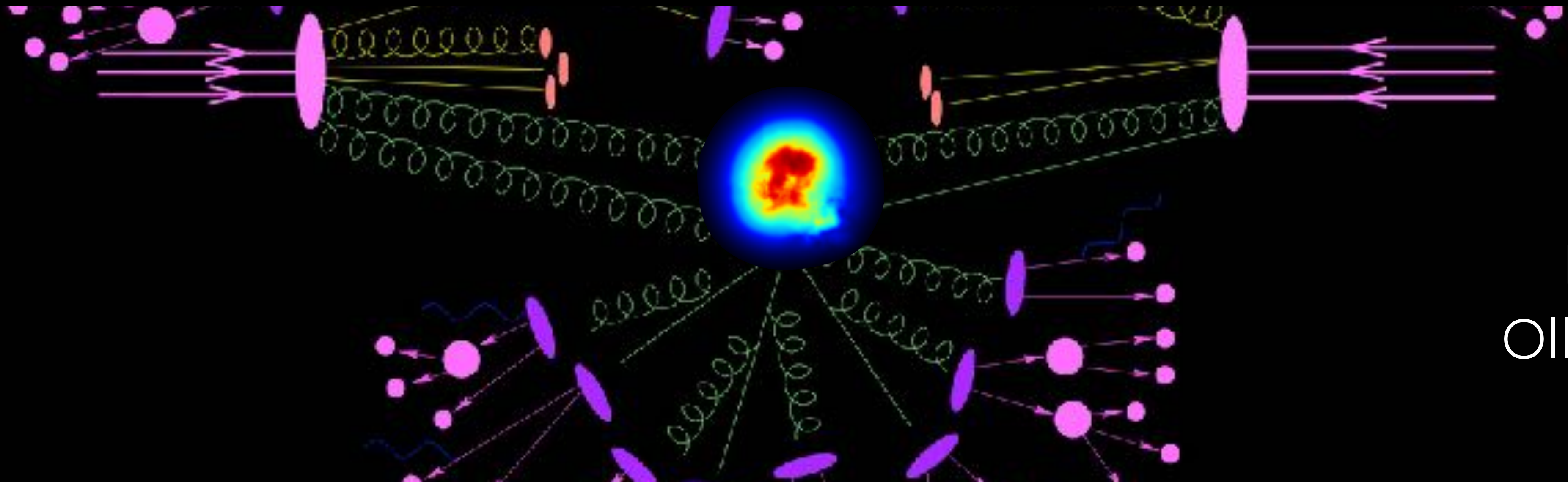
Hydro in pp:
Ollitrault, Werner,
Bzdak, etc.

FIN: BACK TO THE FUTURE


pp


Pb+Pb

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

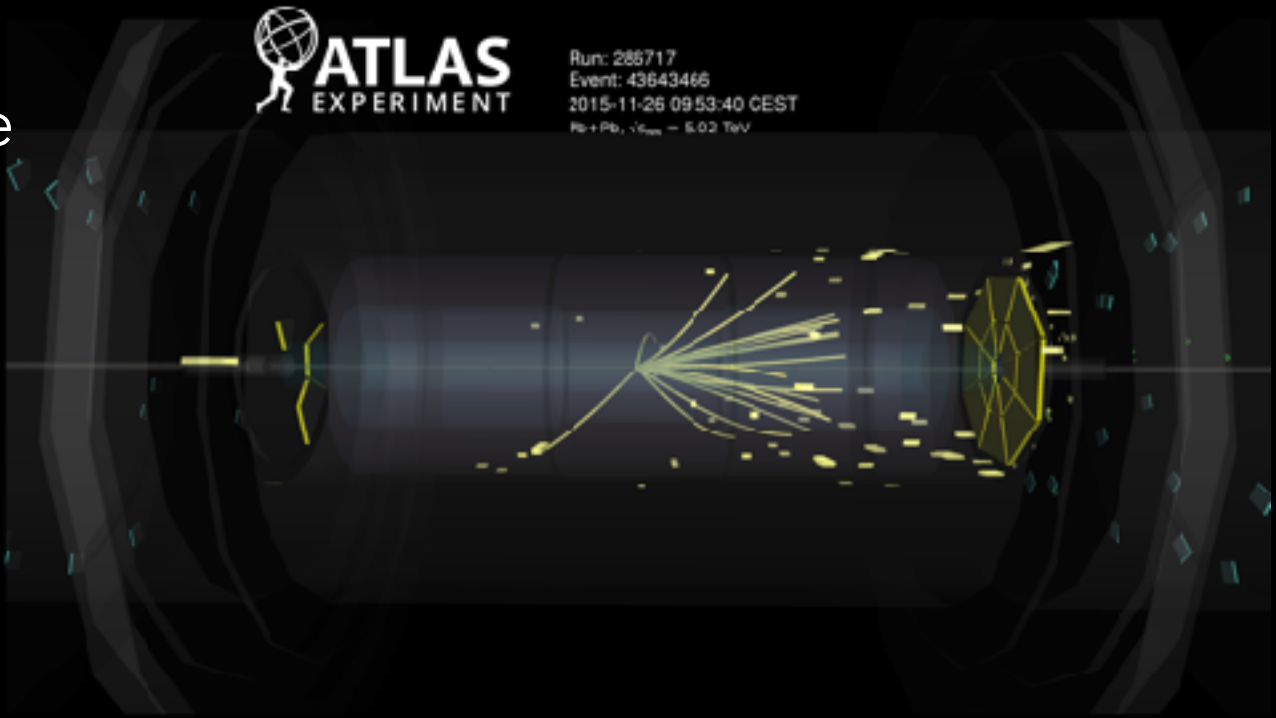


Hydro in pp:
Ollitrault, Werner,
Bzdak, etc.

OTHER SYSTEMS?

e^+e^- at Z pole produces
~20 charged particles/event,
more at LEP2 energies.
Does it have a ridge?
Complicated by correlations
between multiplicity & N_{jet}

Inclusive photoproduction (γ+A) has a large
cross section in A+A collisions,
easily tagged using ZDCs
Physics should be ~low-energy p+A:
Does it have a ridge?
Accessible at LHC and EIC (RHIC?)



CONCLUSIONS

- **A brief prologue on what is known about**
  - Pb+Pb, p+Pb and p+p at the LHC
  - Au+Au, p/d/^{3}He+Au at RHIC

- **Since the RHIC data, the LHC data have deepened our understanding of jet quenching and collective flow in Pb+Pb collisions**
  - But RHIC is pushing in new directions as well, with extensive energy and system scans

- **Systematic study of smaller systems showing evidence for collective behavior even at low multiplicities**
  - All experiments are reporting similar evidence
  - How will this affect our understanding of soft pp collisions, cf. PYTHIA8
  - How should it inform our plans for the study of QCD matter in the future?

- **Many interesting new directions just hinted at here**
  - I didn't even cover new measurements involving physics in the longitudinal direction!
  - Even smaller systems?
  - Using pp flow measurements to image the proton, complementary to previous studies with p+Pb (jets) and future studies at an EIC?

MULTIPARTICLE CUMULANTS: FORMALISM

$$\begin{aligned}
\langle\langle \mathrm{corr}_n\{2\}\rangle\rangle &\equiv \langle\langle \mathrm{e}^{\mathrm{i}n(\phi_1-\phi_2)}\rangle\rangle,\\
\langle\langle \mathrm{corr}_n\{4\}\rangle\rangle &\equiv \langle\langle \mathrm{e}^{\mathrm{i}n(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle,\\
\langle\langle \mathrm{corr}_n\{6\}\rangle\rangle &\equiv \langle\langle \mathrm{e}^{\mathrm{i}n(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\rangle\rangle,\\
\langle\langle \mathrm{corr}_n\{8\}\rangle\rangle &\equiv \langle\langle \mathrm{e}^{\mathrm{i}n(\phi_1+\phi_2+\phi_3+\phi_4-\phi_5-\phi_6-\phi_7-\phi_8)}\rangle\rangle
\end{aligned}$$

$$Q_{n,j} \equiv \sum_{i=1}^{M} w_i^j \, \mathrm{e}^{\mathrm{i}n\phi_i}$$

$$\langle 2\rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

$$\begin{aligned}
\langle 4\rangle = {} & \frac{|Q_n|^4 + |Q_{2n}|^2 - 2\cdot \mathfrak{Re}\left[Q_{2n}Q_n^*Q_n^*\right]}{M(M-1)(M-2)(M-3)}\\
& - 2\,\frac{2(M-2)\cdot|Q_n|^2 - M(M-3)}{M(M-1)(M-2)(M-3)}\,.
\end{aligned}$$

$$\begin{aligned}
\langle 6\rangle \equiv {} & \frac{1}{P_{M,6}} \sum_{i,j,k,l,m,n=1}^{M}{}' e^{in(\phi_i+\phi_j+\phi_k-\phi_l-\phi_m-\phi_n)}\\
= {} & \frac{|Q_n|^6 + 9\cdot|Q_{2n}|^2|Q_n|^2 - 6\cdot\mathfrak{Re}\left[Q_{2n}Q_nQ_n^*Q_n^*Q_n^*\right]}{M(M-1)(M-2)(M-3)(M-4)(M-5)}\\
& + 4\,\frac{\mathfrak{Re}\left[Q_{3n}Q_n^*Q_n^*Q_n^*\right] - 3\cdot\mathfrak{Re}\left[Q_{3n}Q_{2n}^*Q_n^*\right]}{M(M-1)(M-2)(M-3)(M-4)(M-5)}\\
& + 2\,\frac{9(M-4)\cdot\mathfrak{Re}\left[Q_{2n}Q_n^*Q_n^*\right] + 2\cdot|Q_{3n}|^2}{M(M-1)(M-2)(M-3)(M-4)(M-5)}\\
& - 9\,\frac{|Q_n|^4 + |Q_{2n}|^2}{M(M-1)(M-2)(M-3)(M-5)}\\
& + 18\,\frac{|Q_n|^2}{M(M-1)(M-3)(M-4)}\\
& - \frac{6}{(M-1)(M-2)(M-3)}\,. \qquad \text{(A10)}
\end{aligned}$$