Elliptic flow (v2) measurements in heavy ion collisions at CMS

10th Dec. 2011

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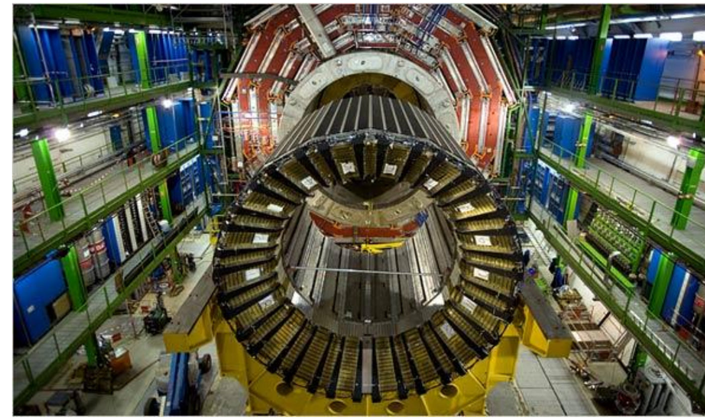
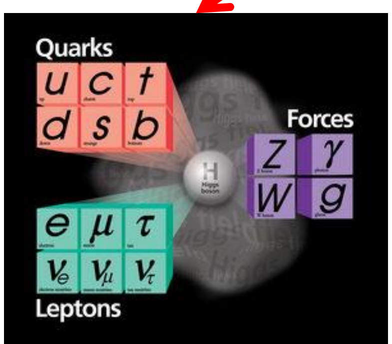
CERN / LHC : Physics goals

20 members
40 countries
Budget: ~$1B
~10,000 users
(50% HEPs)

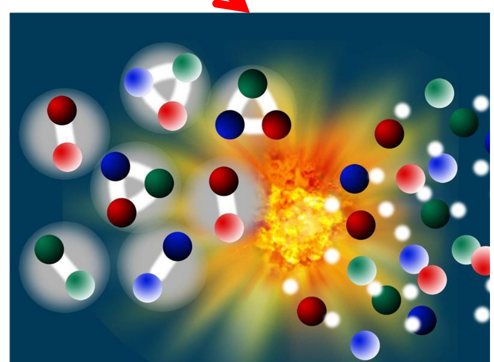
$\sqrt{s}$ =7TeV p-p
$\sqrt{s_{NN}}$ =2.76 Pb-Pb
LHC produces
Higgs, QGP



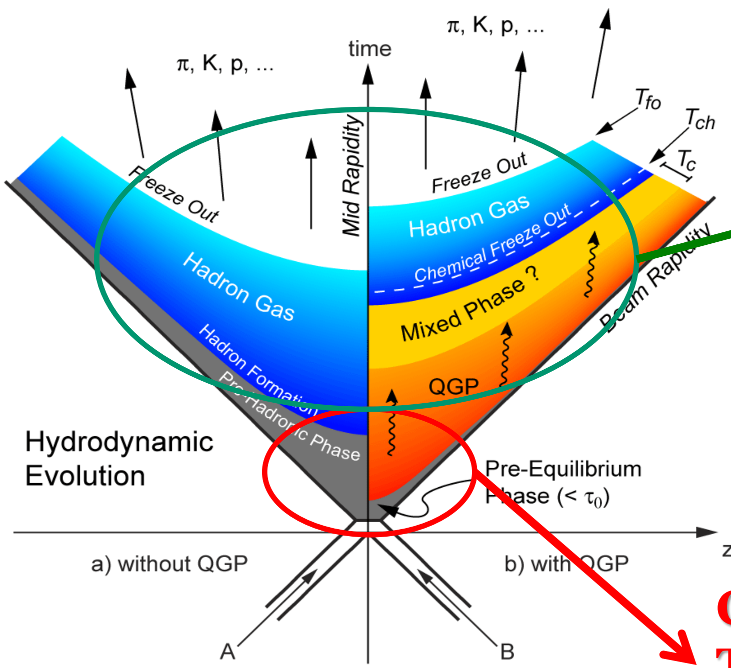
~40 countries
~200 institutions
~3600 scientists
15x15x20m
Compact Muon Solenoid



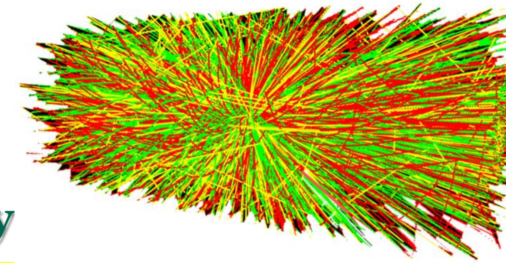
+



Goal of HI program



Hydrodynamics
Medium viscosity
QCD EoS



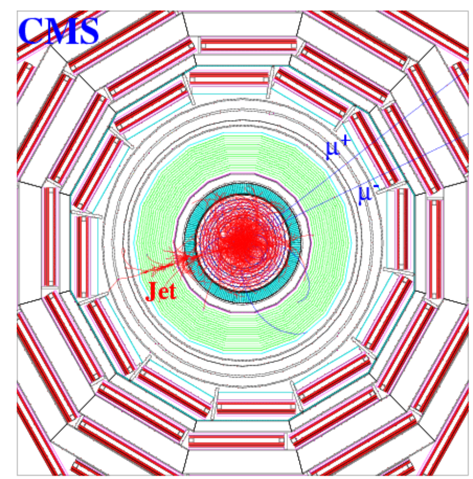
SOFT observables

- $dN_{ch}/d\eta$
- Low p_T spectra
- Elliptic flow
- Thermal photons
- ...

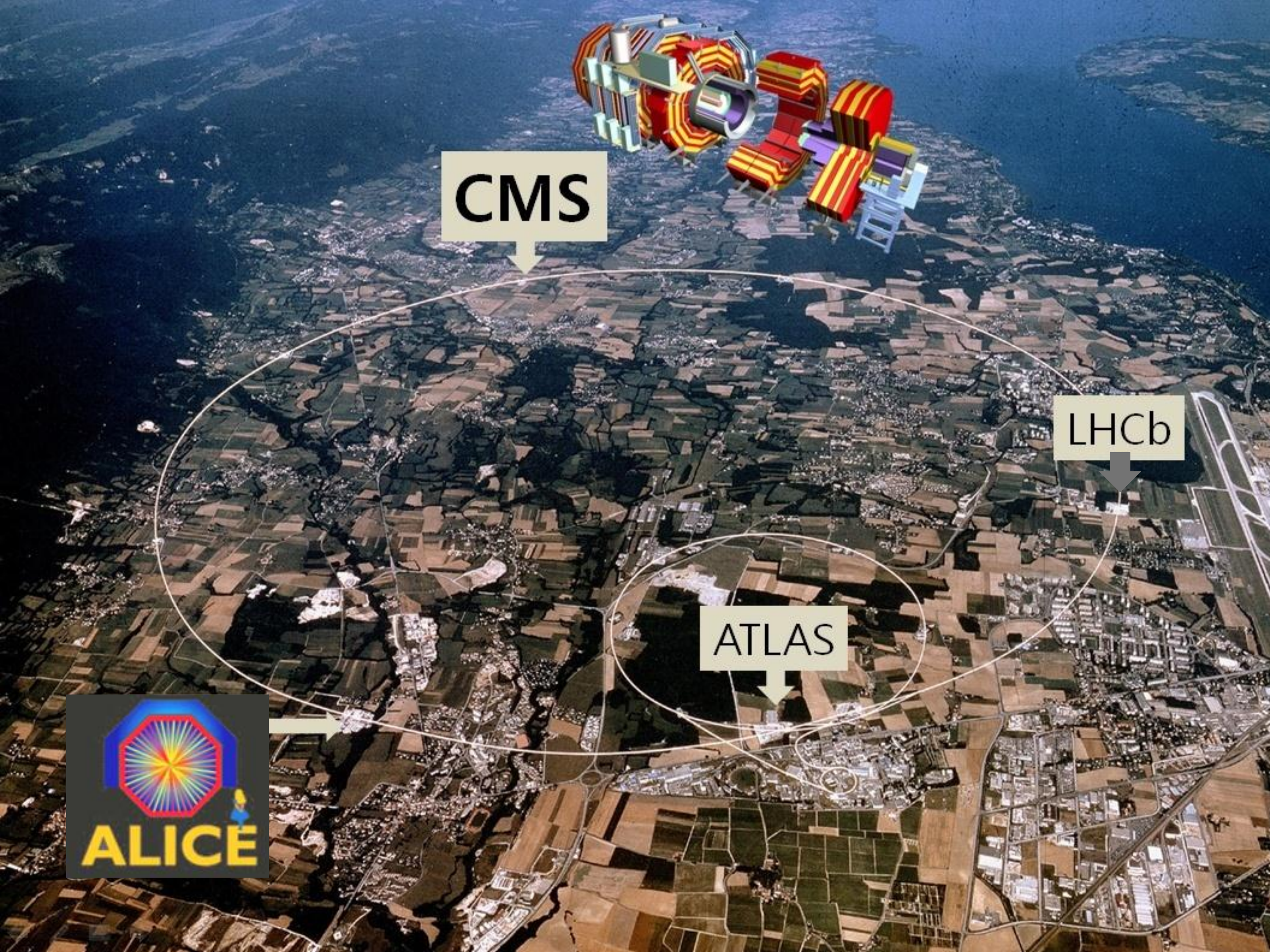
Color charge density,
Transport coefficient,
QCD ε_c & T_c

Hard observables

- High p_T spectra
- Jets
- g (g^*, Z^o)-jet correlation
- Quarkonia
- ...

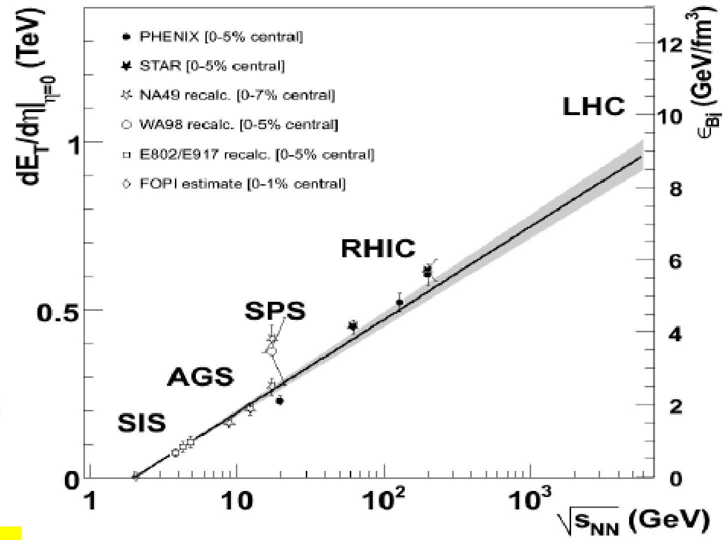


LHC / LHiC
as a new tool for HI Physics

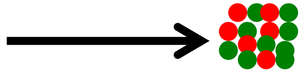

CMS
LHCb
ATLAS
ALICE

LHC as a new tool for HIP

- A big energy jump!
  - Extended kinematic reach for pp, pA, AA
  - New properties of the initial state
  - possible gluon saturation
  - A hotter and longer lived partonic phase
  - Increased cross sections, new hard probes



3.5TeV+3.5TeV
→ E=7TeV



1.38ATeV+1.38ATeV
→ E=2.76ATeV

$${}^{208}_{82}\text{Pb}$$

$$3.5\times\frac{82}{208}=1.38$$

$$\varepsilon_{Bjorken}\cong\frac{1}{\tau_0(\pi R^2)}\frac{dE_T}{d\eta}\geq 10\ \text{GeV/fm}^3$$

$$(\tau_0 \leq 1\,\text{fm/c})$$

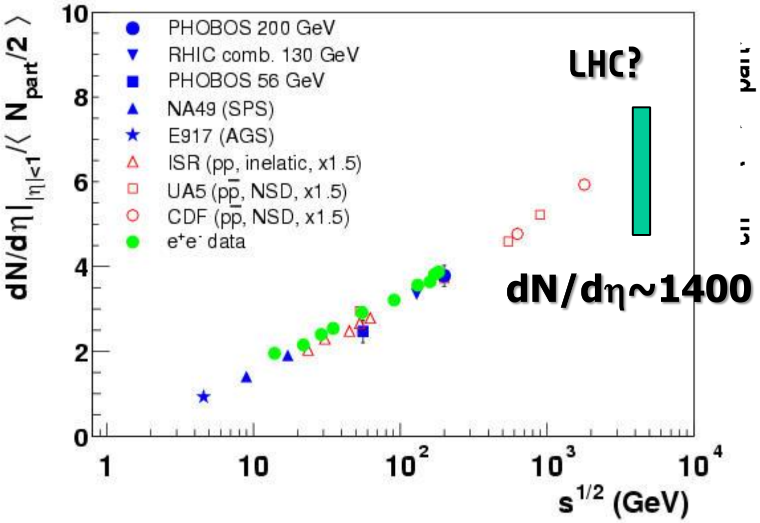
	AGS	SPS	RHIC	LHC (2010)	LHC
s_{NN}	5 GeV	20 GeV	200 GeV	2.76 TeV	5.5 TeV
E increase		x 4	x 10	x 14	x 2

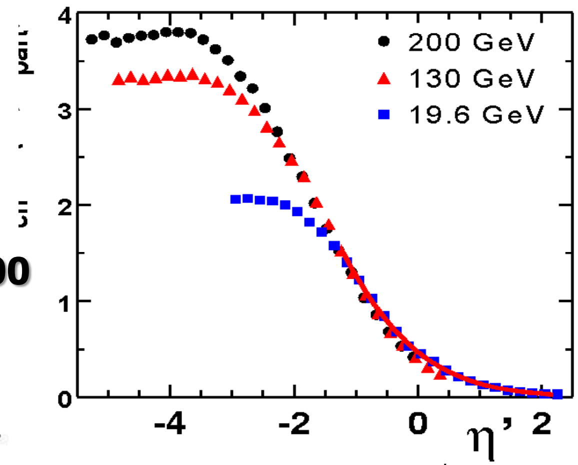
LHC HI : motivation

- **SPS & RHIC:**
  - show new and unexpected properties of hot nuclear matter
    - Jet quenching+high Elliptic Flow → strongly interacting color liquid
- **LHC:**
  - significant increases of energy density
    - new properties of the QGP are guaranteed
- **Observables:**
  - Soft probe observables
    - Multiplicity, Elliptic flow, Femto-scopy
      - Need small statistics, day 1 / week 1 measurement
  - Hard probe observables
    - Jet, Jet-quenching, Quarkonia production, High p_T spectra
      - Need large statistics, full statistic measurement

Soft observables: RHIC → LHC

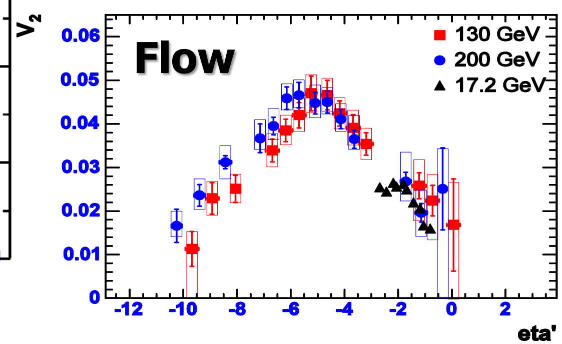
- RHIC shows a simple energy dependence. How about at the LHC ?





$\eta' \equiv \eta - y_{beam}$

Charged particle multiplicity, limited fragmentation



- RHIC prefers Hydrodynamic limit. How about at the LHC?

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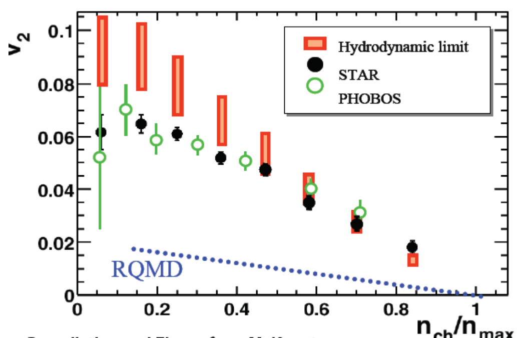
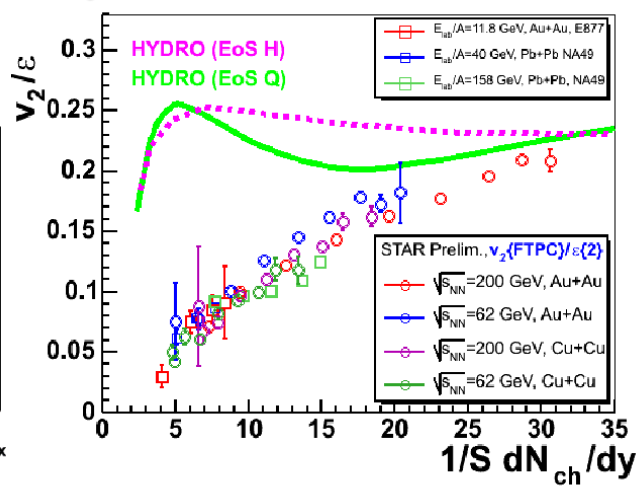
STAR: Phys. Rev. Lett. **86**, 402 (2001)

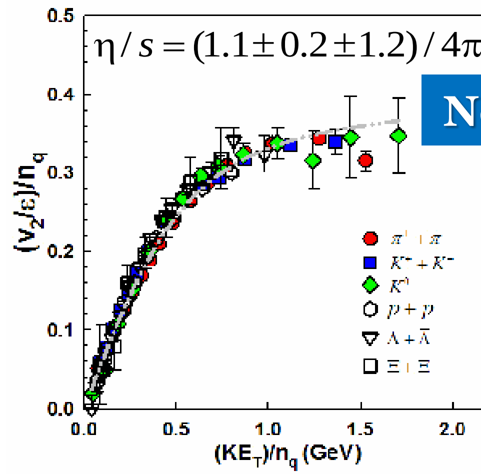


Compilation and Figure from M. Kaneta



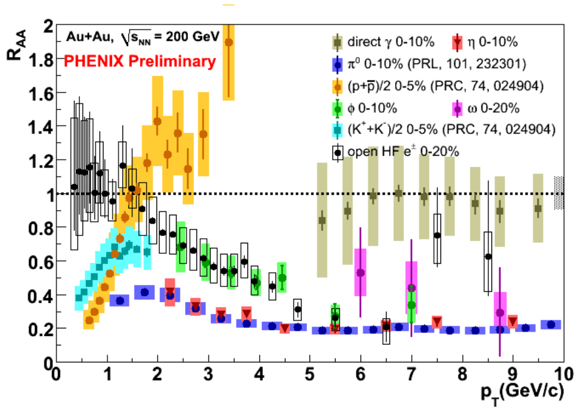
$\eta / s = (1.1 \pm 0.2 \pm 1.2)/4\pi$

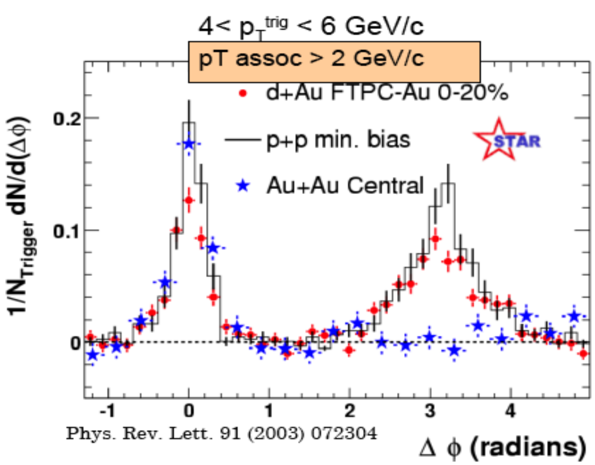
Nq scaling



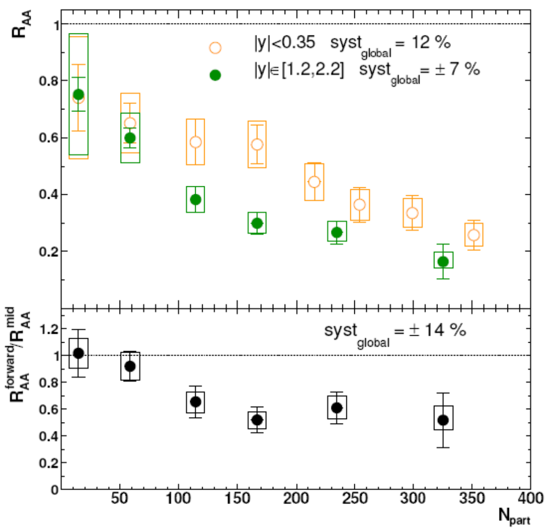
Hard observables: RHIC → LHC

Jet quenching: strong interaction of high-p_T hadrons with dense medium



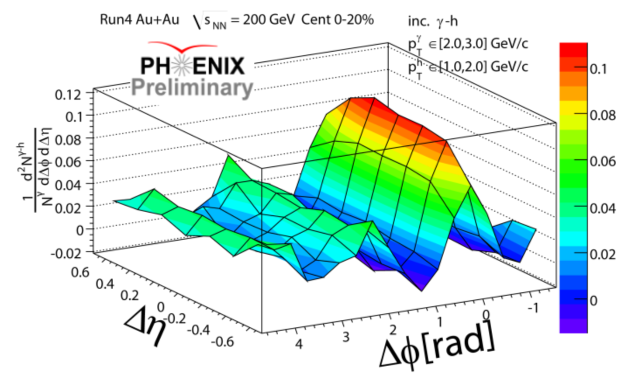


J/ψ suppression: SPS≈RHIC, larger at forward (CGC?)



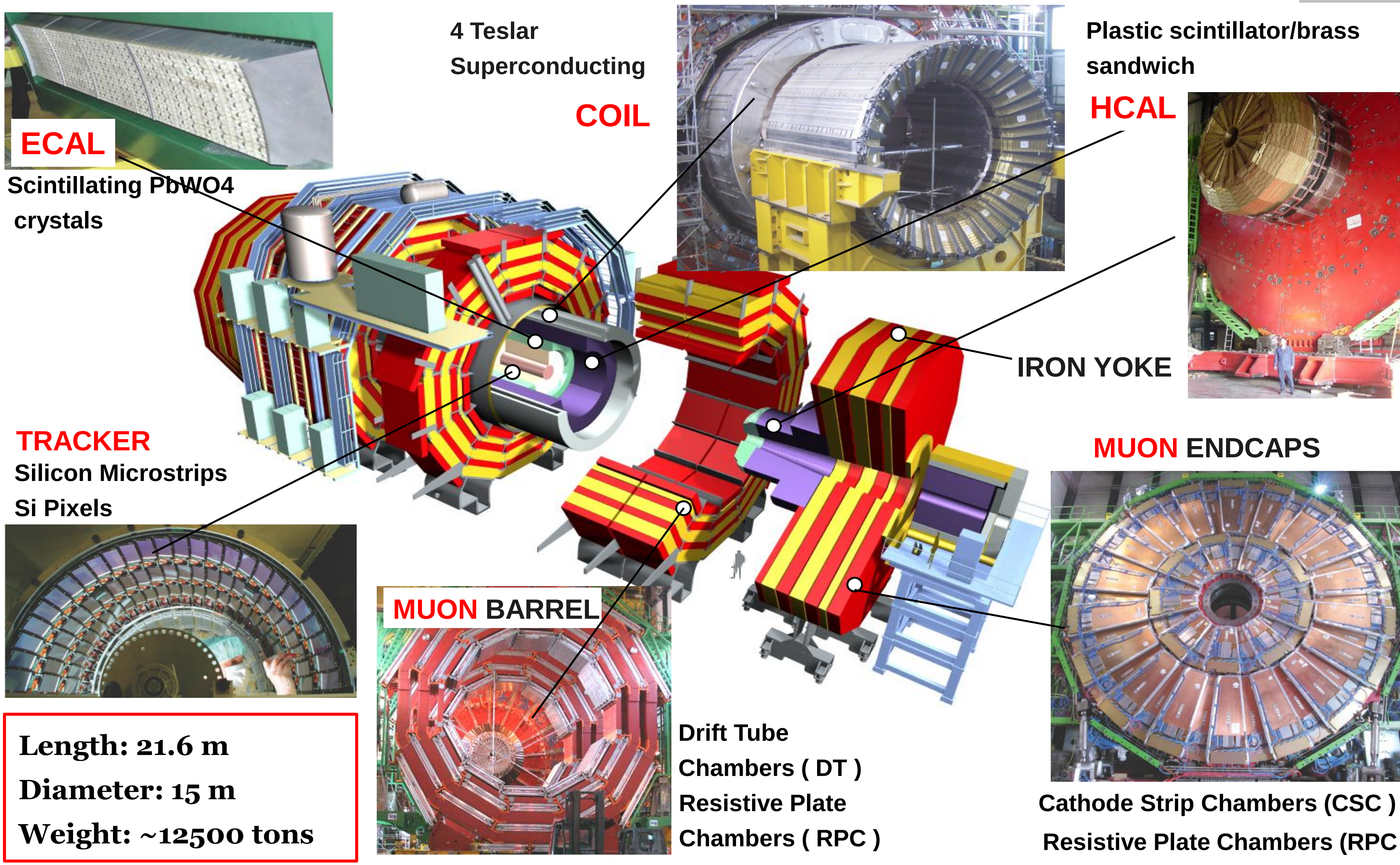
Strongly coupled hot & dense matter

Jets are modified in medium.



CMS
as detectors
for HI Physics

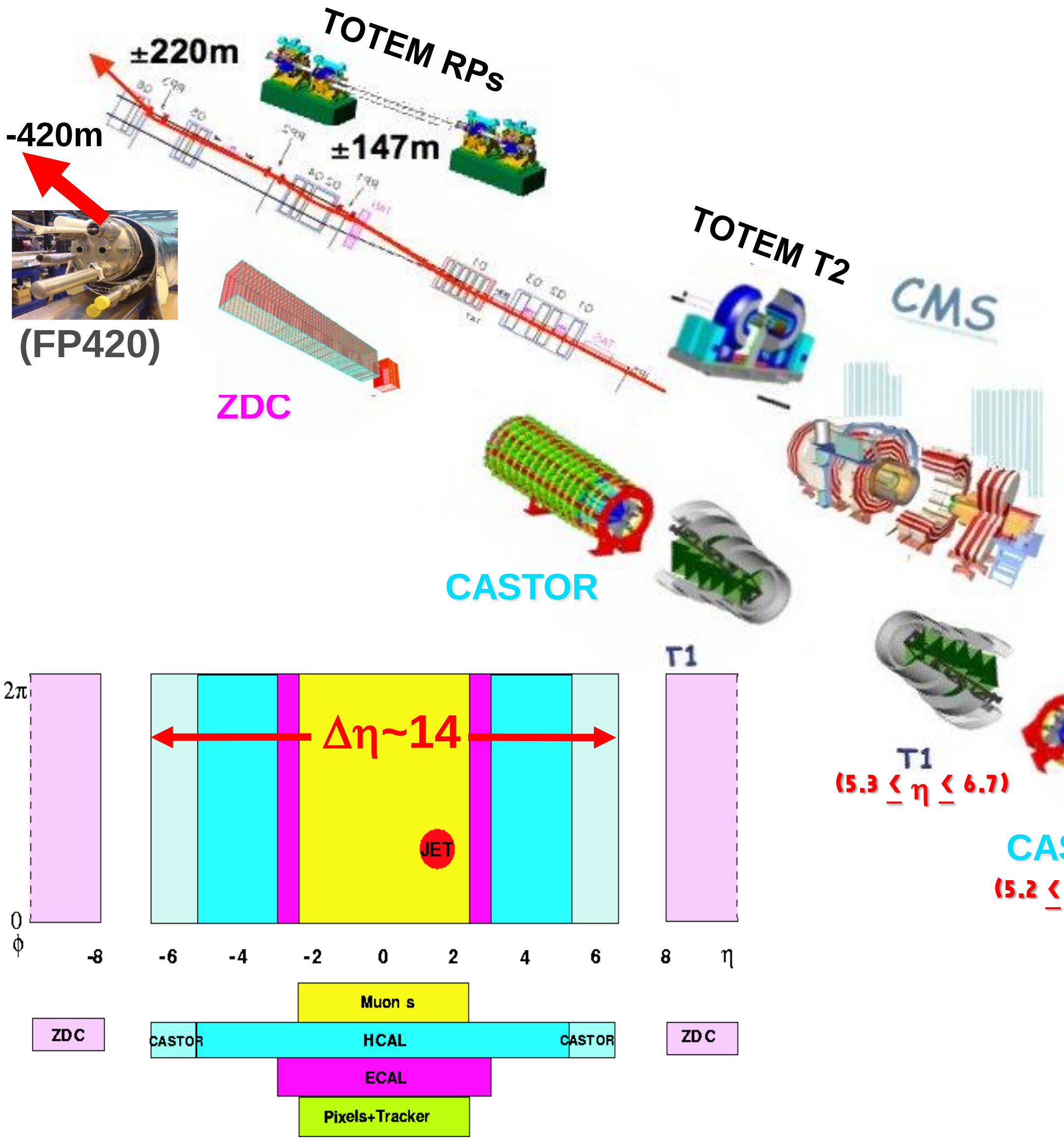
CMS Detector

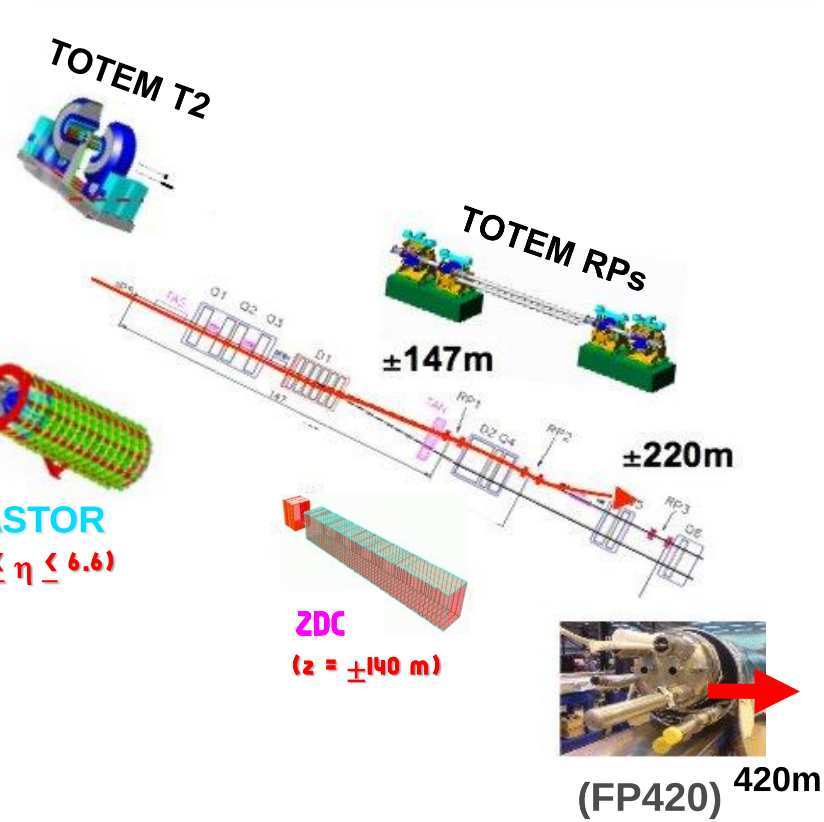


Length: 21.6 m
Diameter: 15 m
Weight: ~12500 tons

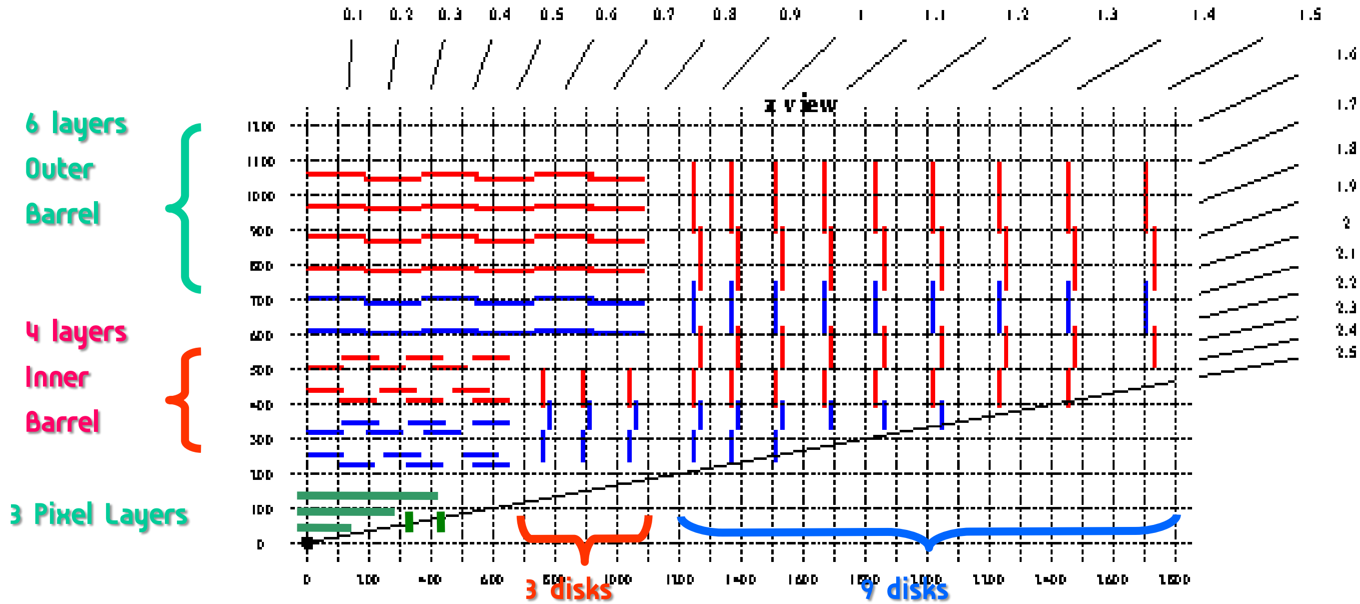
CMS add-ons

Silicon & μ Tracker	$\lvert\eta\rvert \le 2.4$
ECAL	$\lvert\eta\rvert \le 3.0$
HCAL	$\lvert\eta\rvert \le 5.2$
CASTOR	$5.2 \le \lvert\eta\rvert \le 6.6$
ZDC	$\lvert\eta\rvert \ge 8.3$ for neutrals

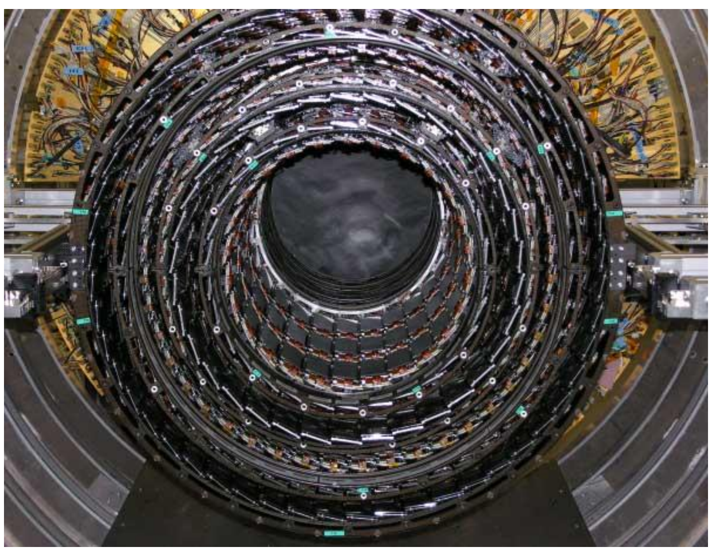


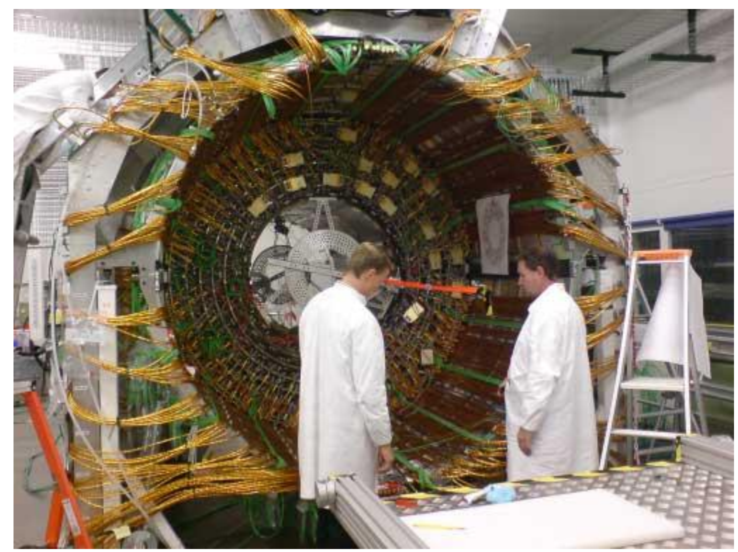


Trackers



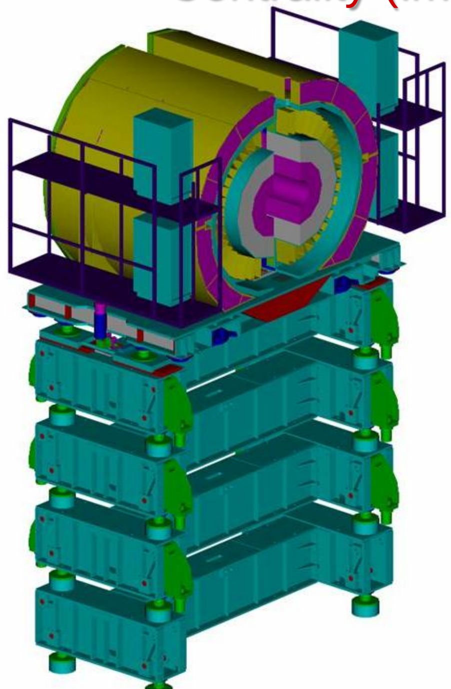
Total 66M Si Pixels Occupancy<2% at $dN_{ch}/d\eta \approx 3500$



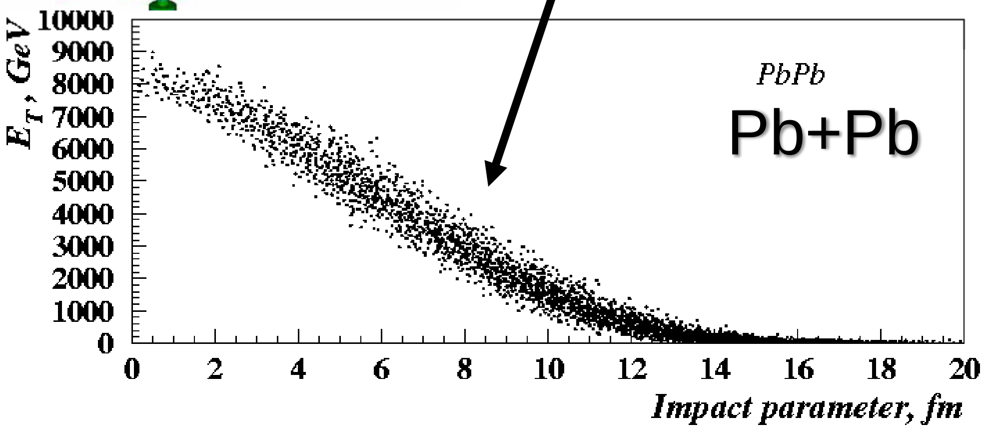


Centrality, forward detectors

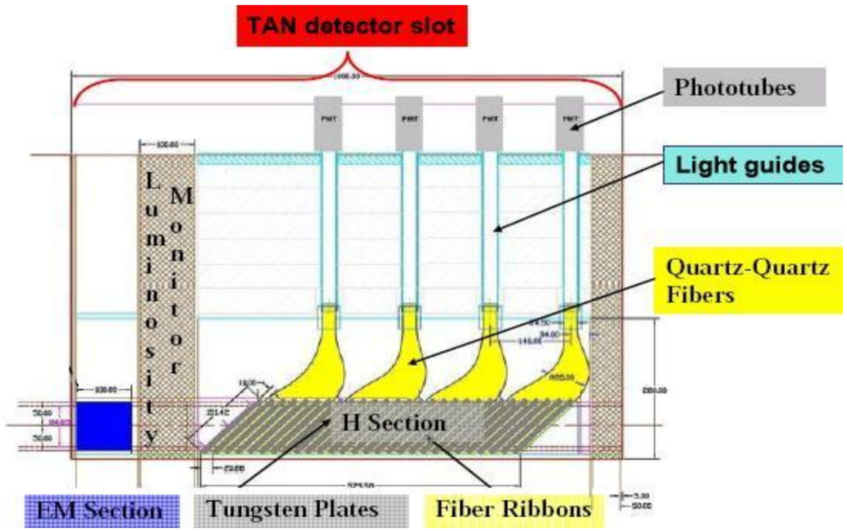
Centrality (impact parameter) determination is needed for physics analysis



Energy in the forward hadronic calorimeter



Zero Degree Calorimeter



- Tungsten-quartz fibre structure
- electromagnetic section: $19X_0$
- hadronic section $5.6\lambda_0$
- Rad. hard to ≈20 Grad (AA, pp low lum.)
- Energy resolution: ≈10% at 2.75 TeV
- Position resolution: ≈2 mm (EM sect.)

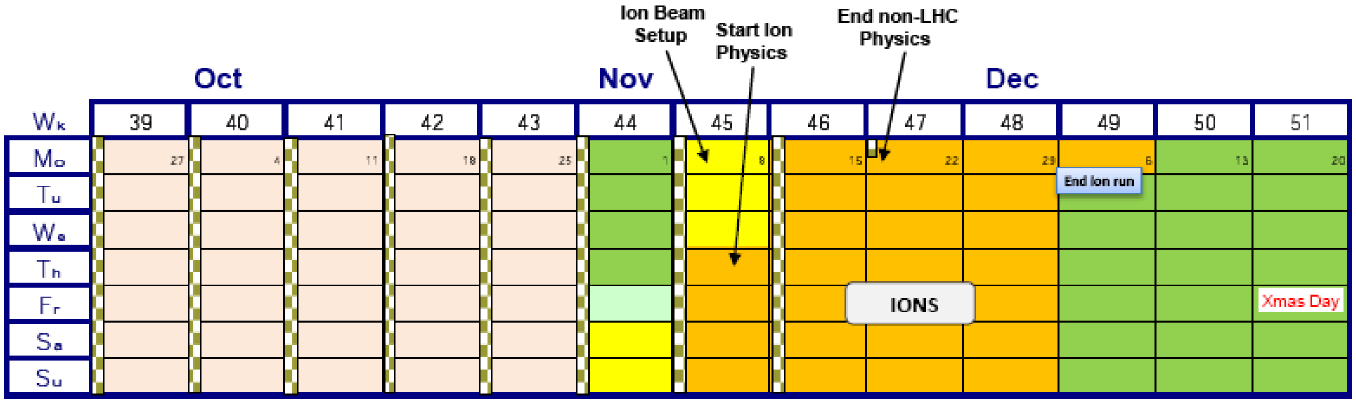
CMS HI team

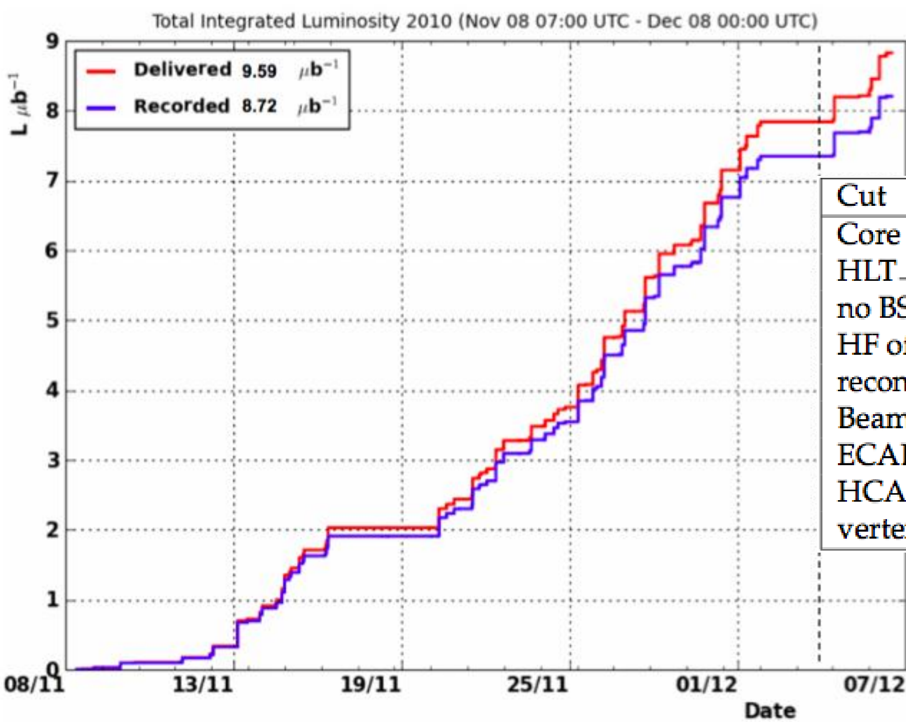
CMS Heavy Ion institutions:

- 13 countries, 25 institutions, > 100 participants, ~6 Koreans
  - CERN, Croatia (Zagreb), Greece(Athens, Ioannina), France (Lyon, Paris), Hungary (Budapest), India (Mumbai), Korea (Seoul, Korea Univ.), Lithuania (Vilnius), New Zealand (Auckland), Portugal (Lisbon),Russia (Moscow), Turkey (Cukurova), USA (Colorado, Iowa, Kansas, Los Alamos, Maryland, Minnesota, MIT, Vanderbilt, UC Davis, UI Chicago)

2010 Heavy Ion Run

- 2010 Mar-Nov
  - pp ~ 40 pb-1
- 2010 Nov-Dec
  - Pb-Pb ~9μb-1

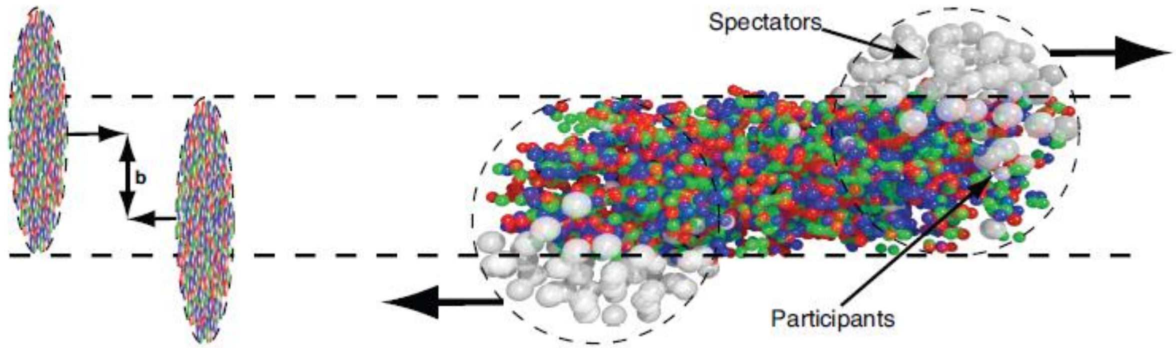


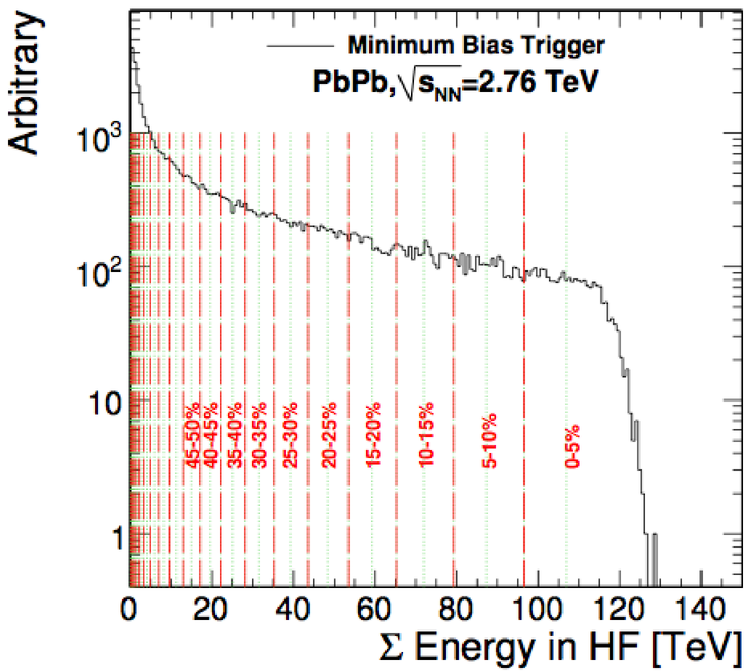


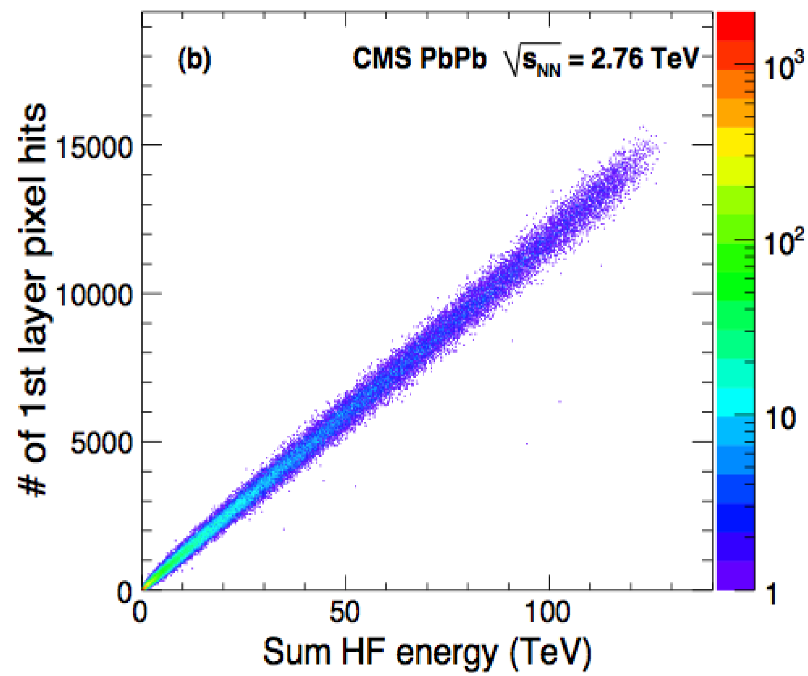
Cut	events remaining
Core Physics events	4604505
HLT_HIMinBiasHfOrBSC_Core trigger	2889239
no BSC halo	2857150
HF offline coincidence	2762005
reconstructed vertex	2686247
Beam-gas removal	2682361
ECAL cleaning	2673123
HCAL cleaning	2672977
vertex position	2316724

Centrality

– b → centrality ∝ Npart ∝ Forward calorimeter energy





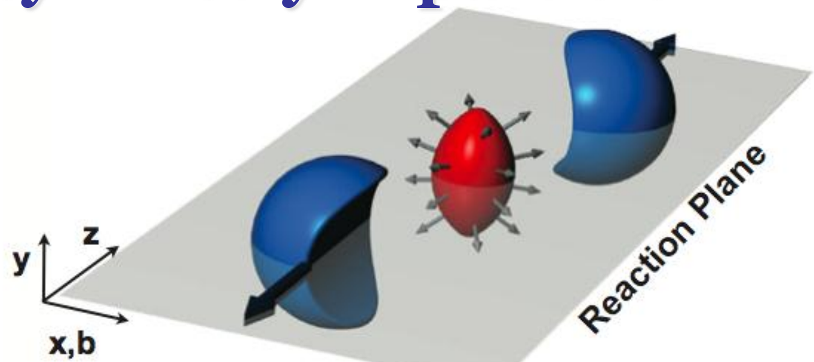


Elliptic Flow
@ CMS

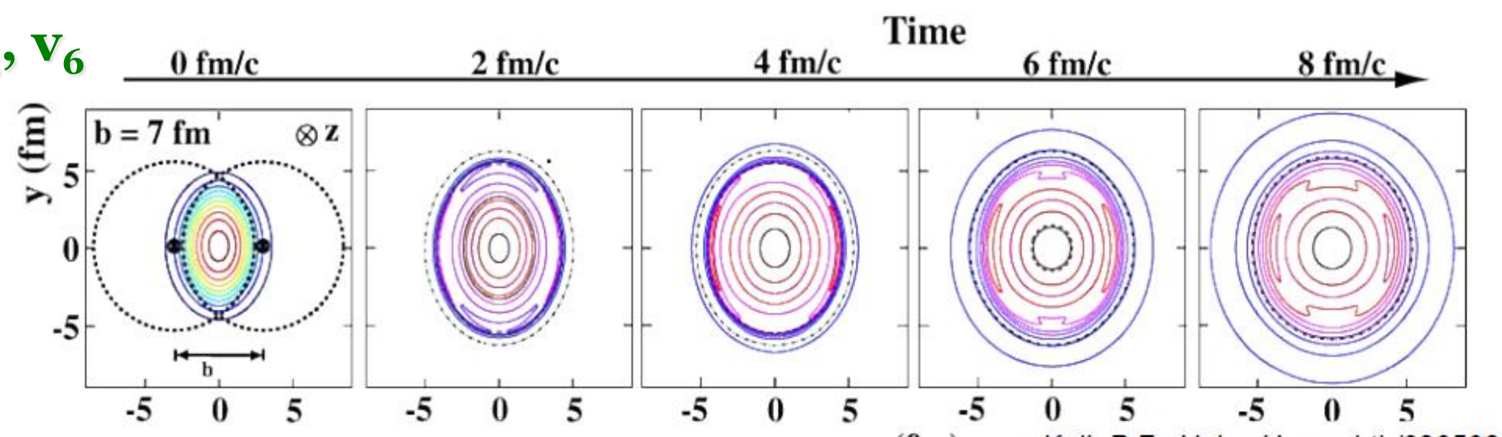
Elliptic flow Primer

Elliptic flow in HI collisions

- Measurement of azimuthal asymmetry in particle distribution in HI collisions
  - $\frac{dN}{d\varphi}(p_T, b, y)$



- However, some difficulties
  - Non-flow correlations : jets, decays, detectors, etc.
- Several different techniques and higher orders
  - Event plane, cumulants, Lee-Yang zero
  - v_3, v_4, v_5, v_6



Kolb P.F., Heinz U., nucl-th/0305084

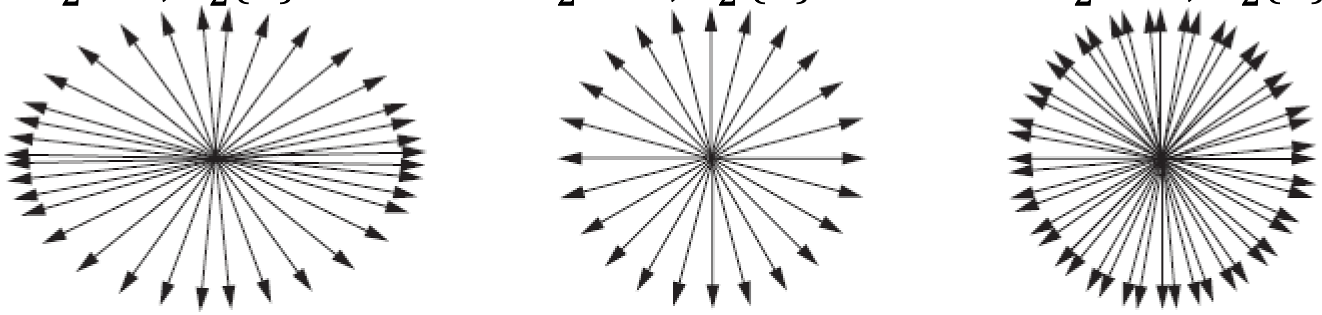
Some details

- **Fourier expansion of azimuthal particle distribution**

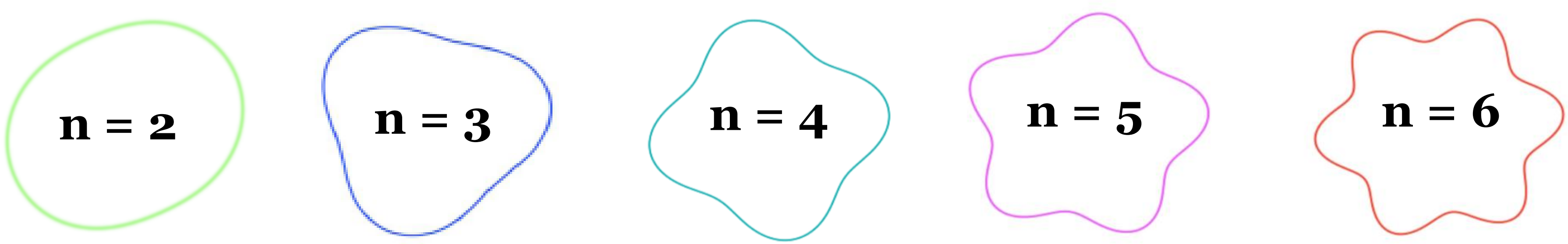
$$\frac{dN}{d\varphi} = N_0\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[\mathrm{n}(\varphi - \Psi_R)]\right) \qquad v_2 = \langle \cos[2(\varphi - \Psi_R)] \rangle$$

- **2-particle correlations**

$v_2 > 0, v_2\{2\} > 0$ $\qquad$ $v_2 = 0, v_2\{2\} = 0$ $\qquad$ $v_2 = 0, v_2\{2\} > 0$



- **Higher harmonics**



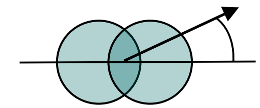
Some major points

- The $v_2(p_T)$ gives us important **information on viscosity of medium and jet-quenching**.
- The $v_2(\eta)$ provides constraints on the system evolution in the longitudinal direction (EoS).
- **Odd harmonic** v_3, v_5 are new challenges and tell us fluctuations of initial state of medium.
- Different analysis methods show us the different sensitivities to non-flow contribution and eccentricity fluctuations.

Measurement techniques

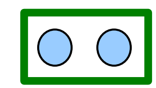
❑ Event Plane

- based on particle correlations with the event plane
- gives an estimate of the reaction plane
- requires corrections for the detector acceptance



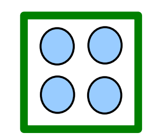
❑ 2nd Order Cumulant

- based on 2-particle correlations



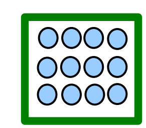
❑ 4th Order Cumulant

- based on 4-particle correlations
- removes lower order non-flow effects



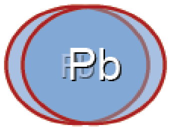
❑ Lee-Yang Zeros

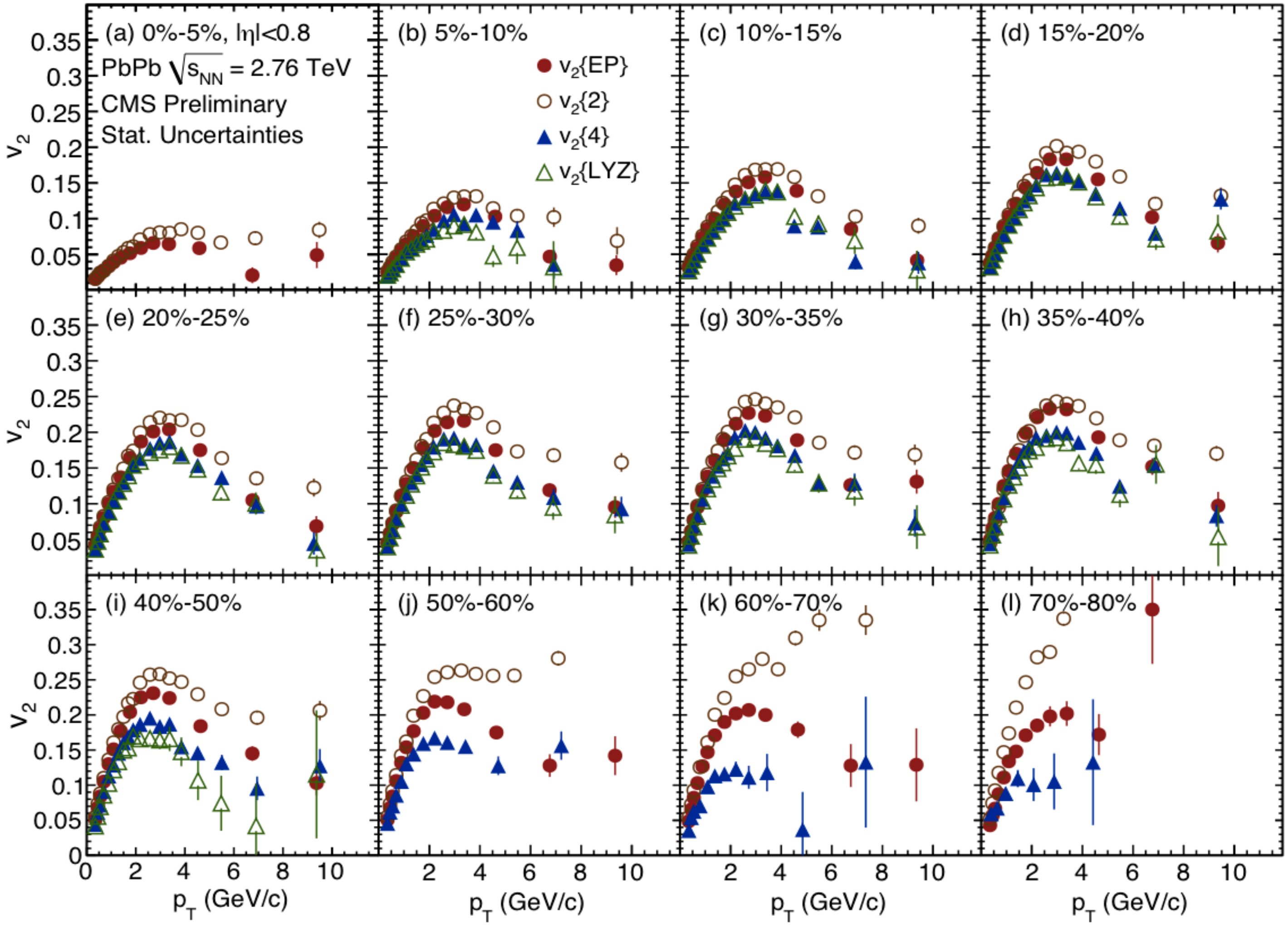
- based on all particle correlations in each event
- removes non-flow effects

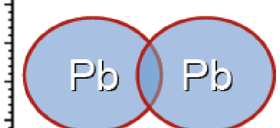


$v_2(p_T)$, $v_2(cen)$, $v_2(\eta)$

$v_2(p_T)$ at mid-η : |η|< 0.8



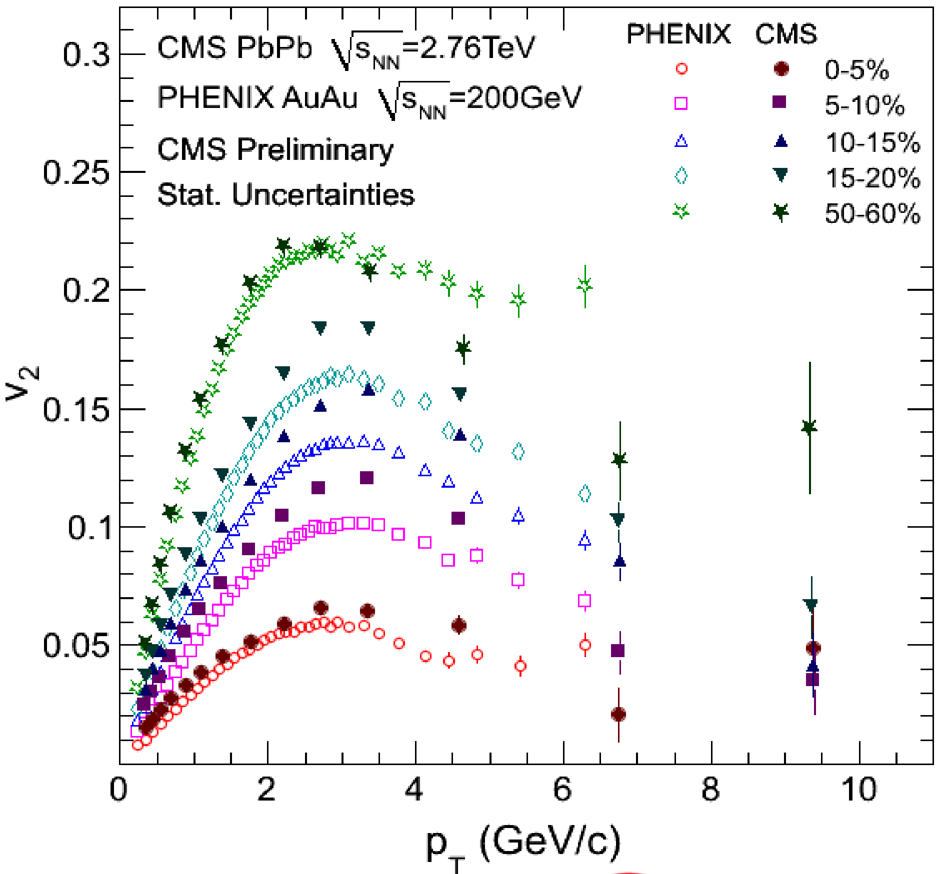


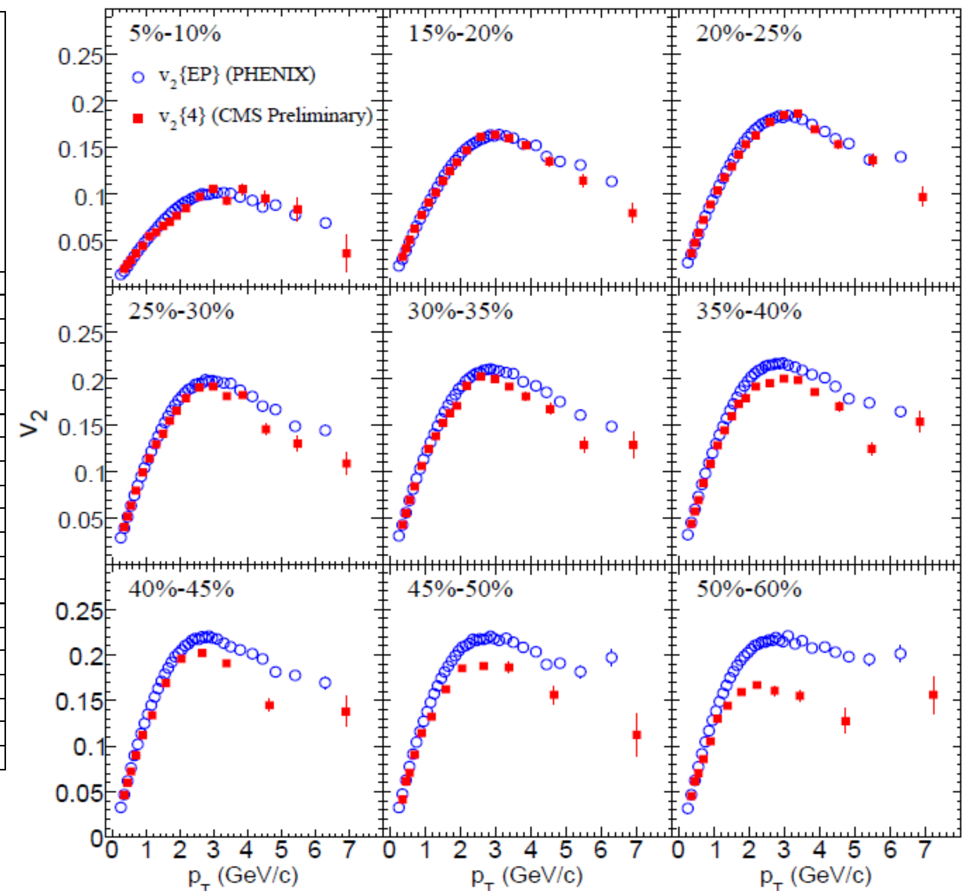


– **Peaked at ~ 3 GeV/c, finite at ~ 10 GeV/c , strongest in 40-50% cent.**

$v_2(p_T)$ at mid-η : LHC vs RHIC

- LHC: Pb-Pb 2.76TeV, RHIC: Au-Au 0.2 TeV
  - Low pT – within 15%, High pT – CMS < PHENIX for cent > 30%

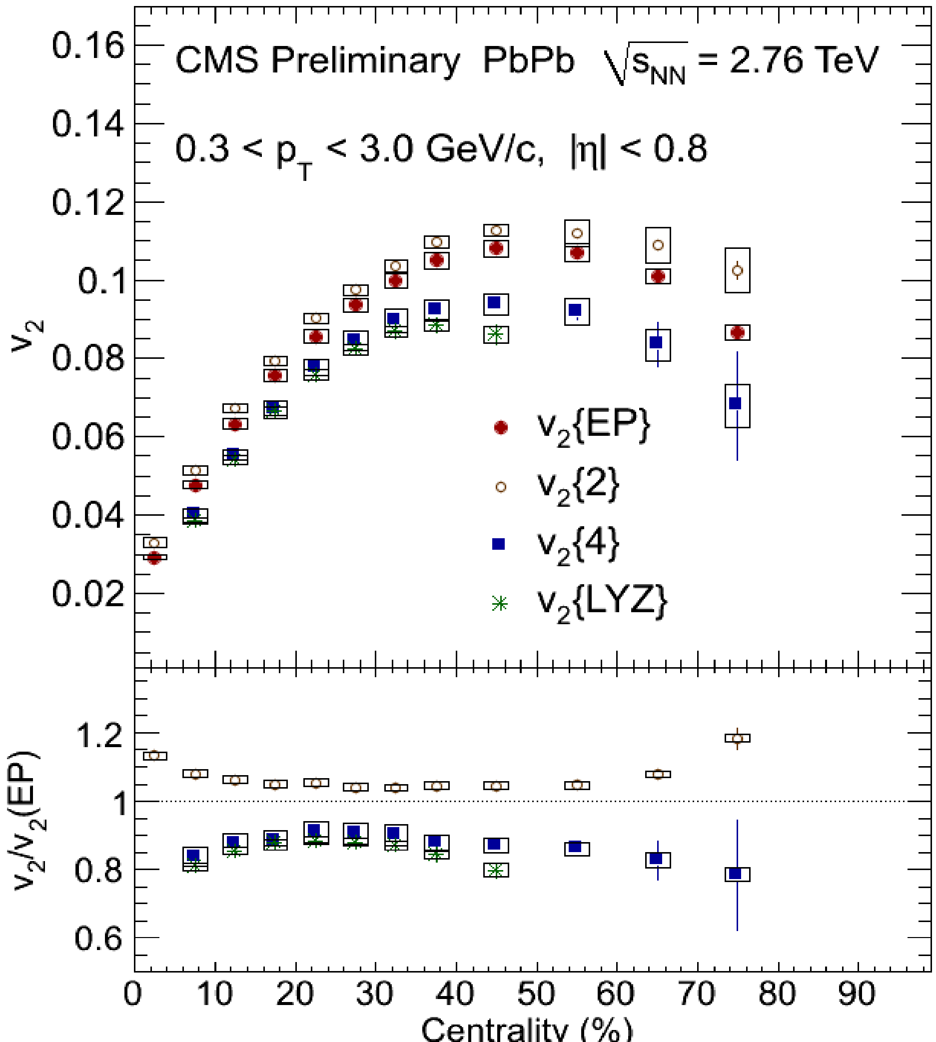


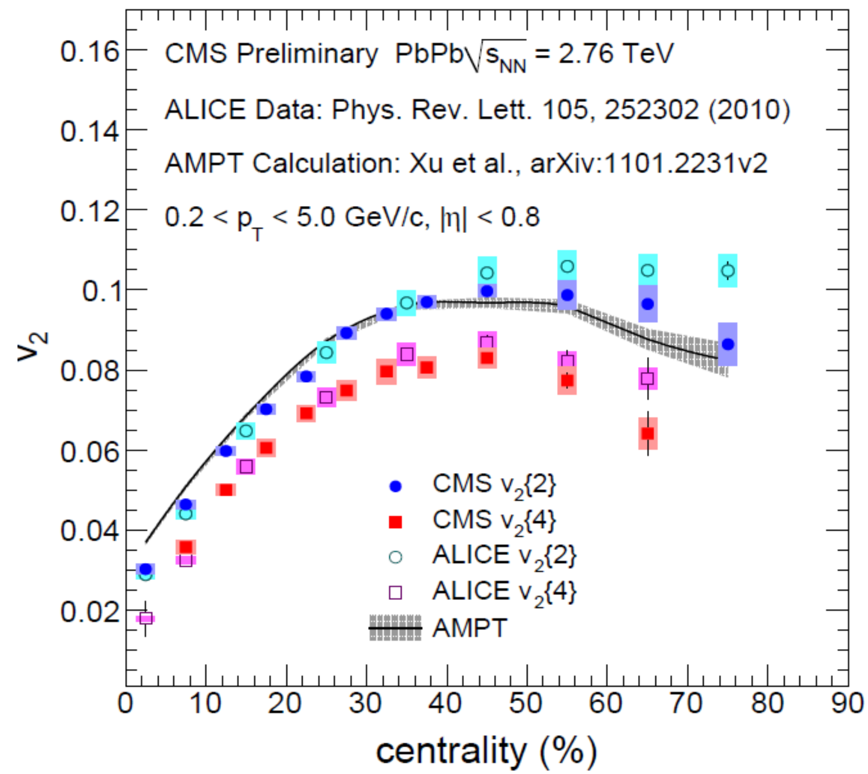


PHENIX Phys. Rev. Lett. 105, 062301 (2010)

v_2(centrality) at mid-η

❑ v2 rises up to 40-50% , then decreases

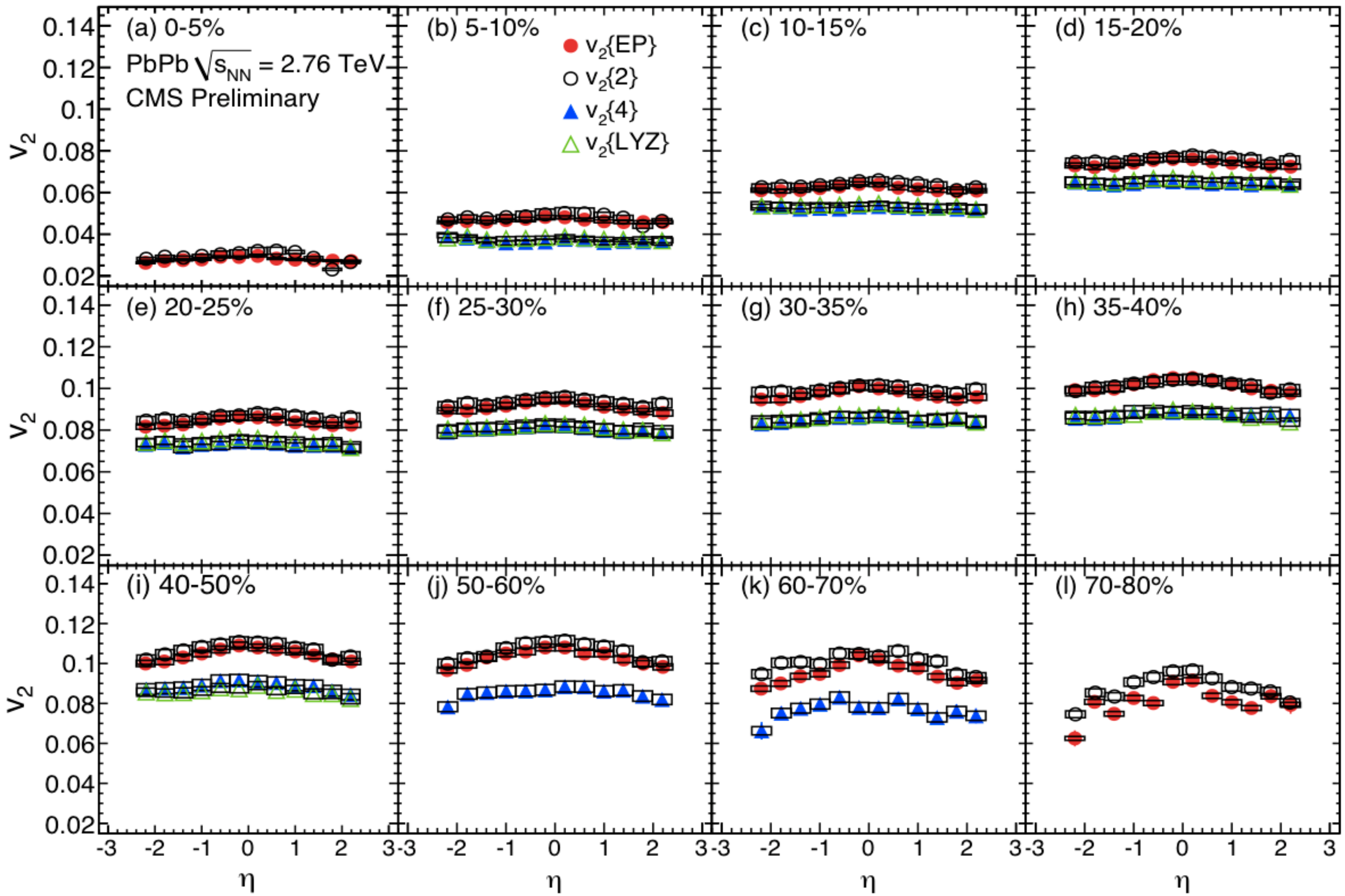




Good agreement with ALICE, except in most peripheral events
AMPT is consistent with v2{2}

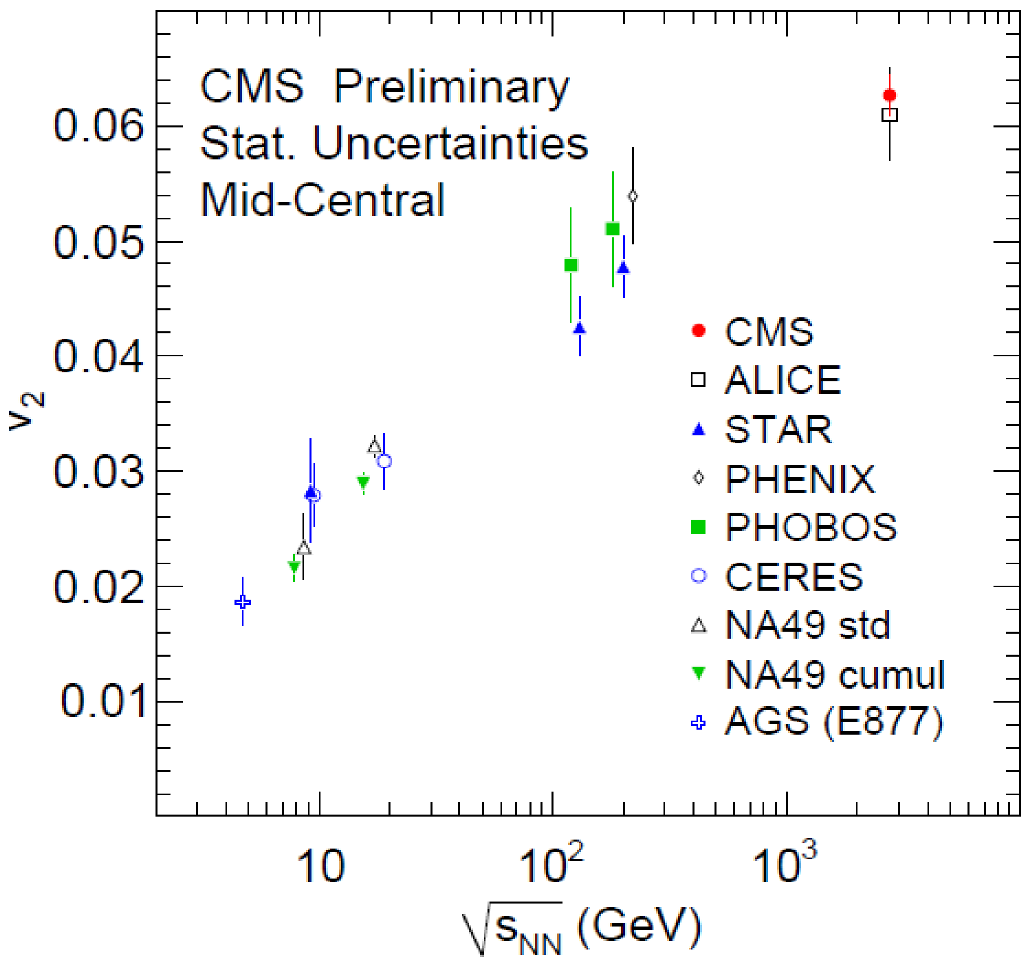
$v_2(\eta)$: centrality dependence

– Weak η-dependence, except for most peripheral (EP and v2{2})



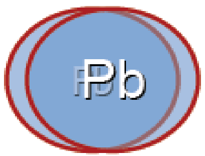
√s dependence

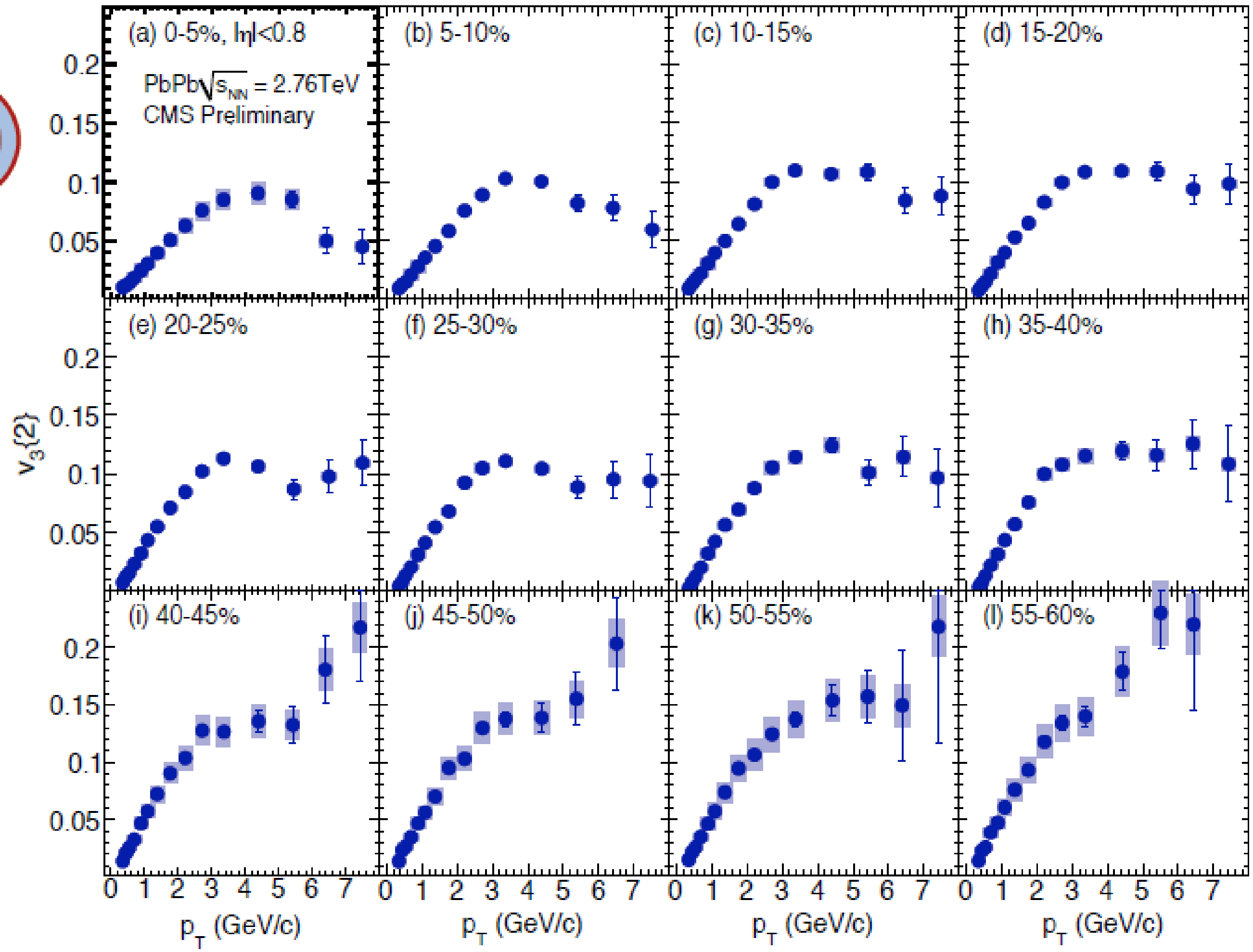
- 15-30% increase in integral v_2 from top RHIC energy to LHC

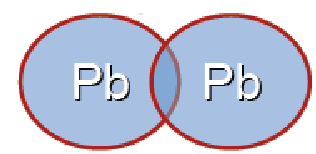


Higher harmonics

$v_3(p_T)$ at mid-η



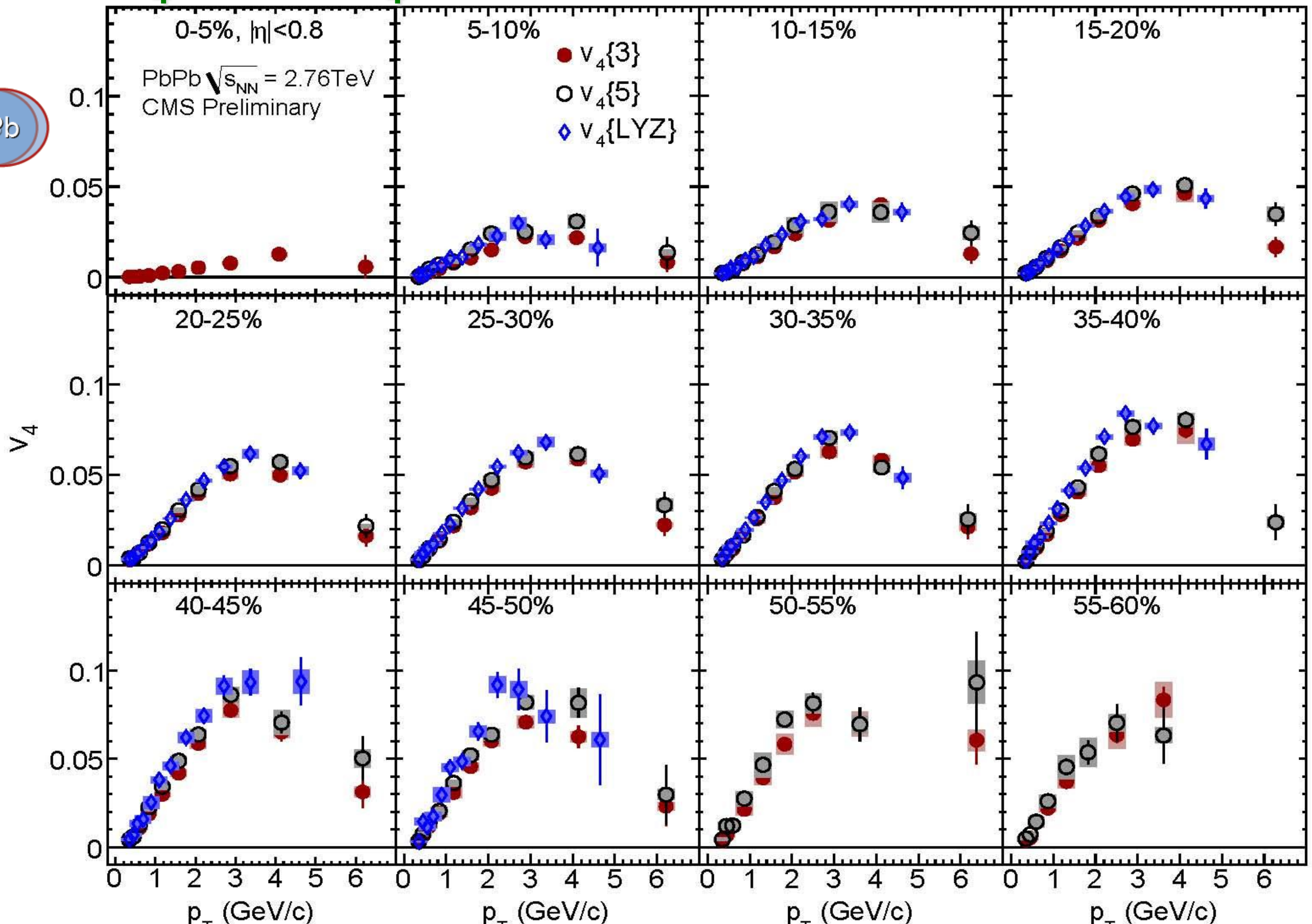


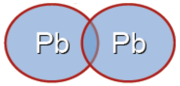


- Sizable signal; weak centrality dependence
  - v_3 at mid-rapidity driven by fluctuations

$v_4(p_T)$ at mid-η for 3 methods

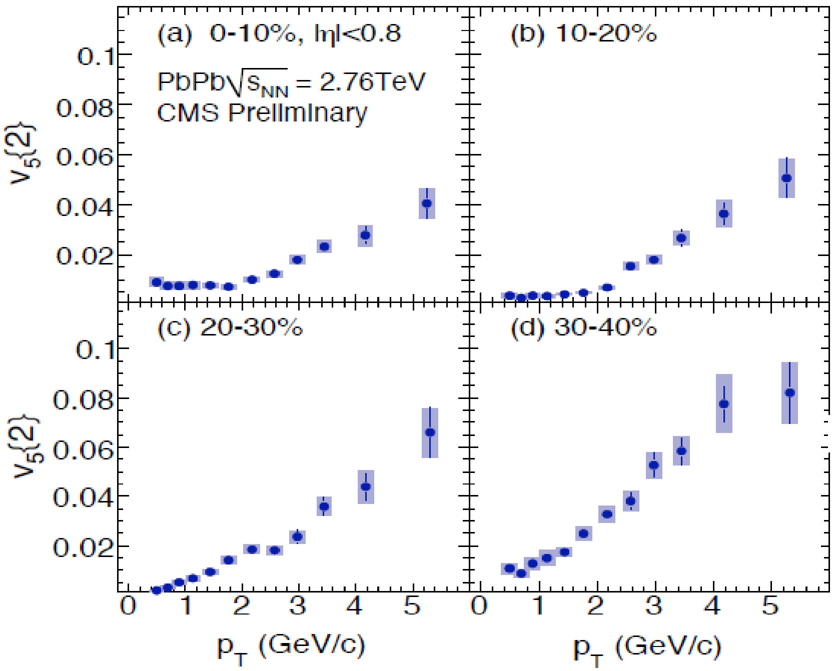
– LYZ , $v_4\{3\}$ and $v_4\{5\}$

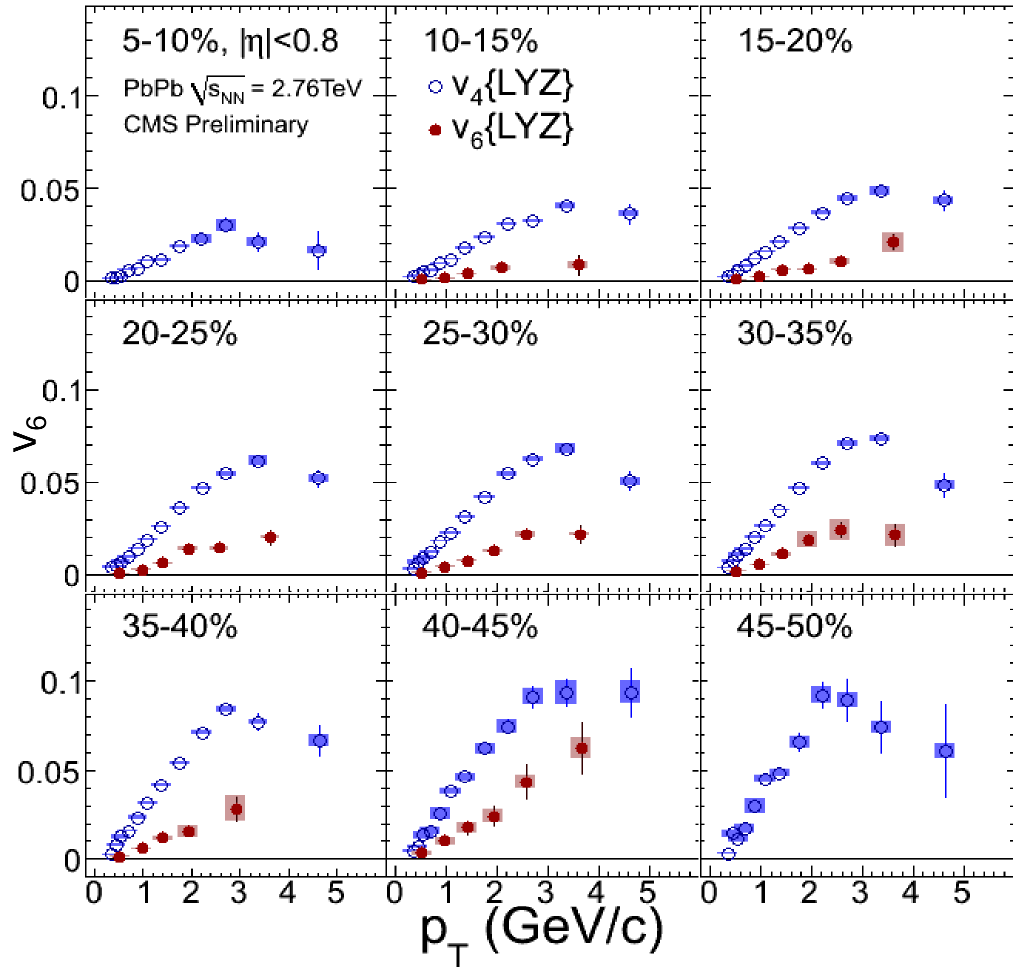




v_5 and v_6

- v_5 rises quadratically with p_T
- v_6 is small, reaches 2% in mid-central collisions



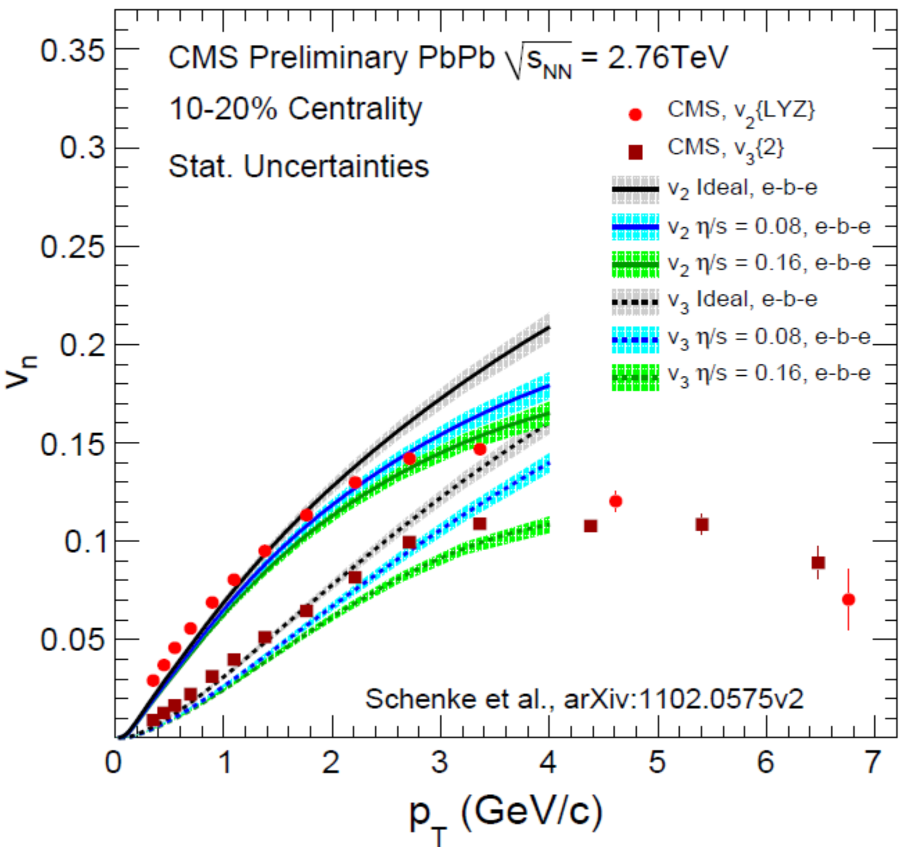


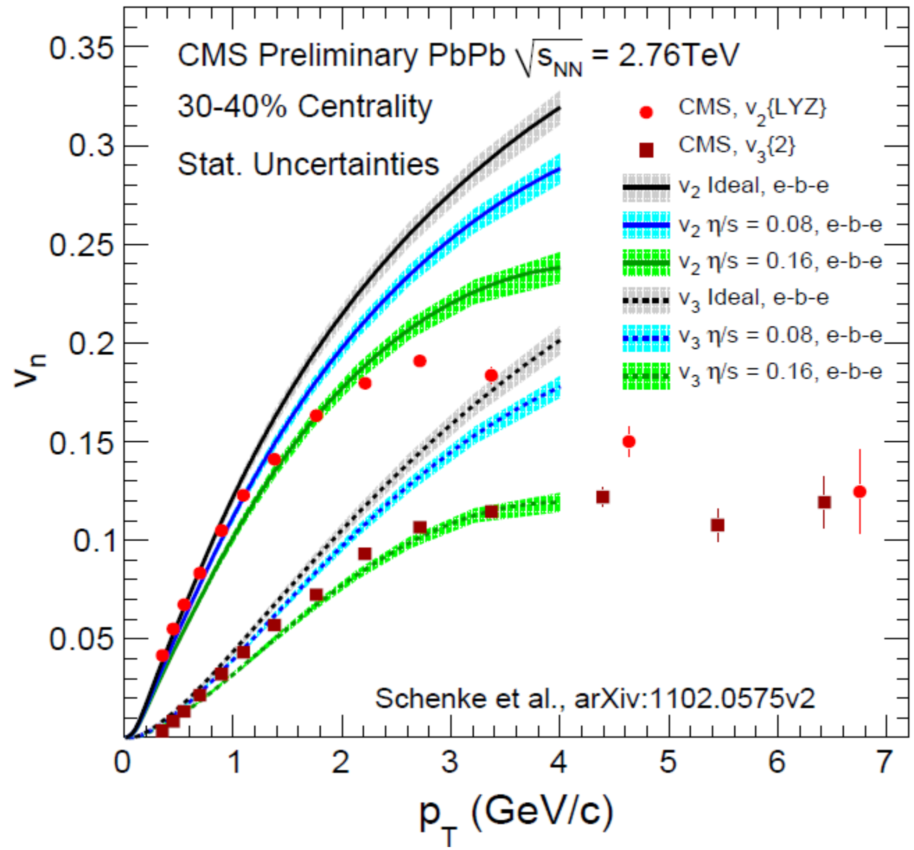
Inkyu Park

Comparison to Hydrodynamics

v_2 and v_3 : sensitivity to η/s

- v_2 and v_3 together have better sensitivity
  - The centrality dependence adds further constraints

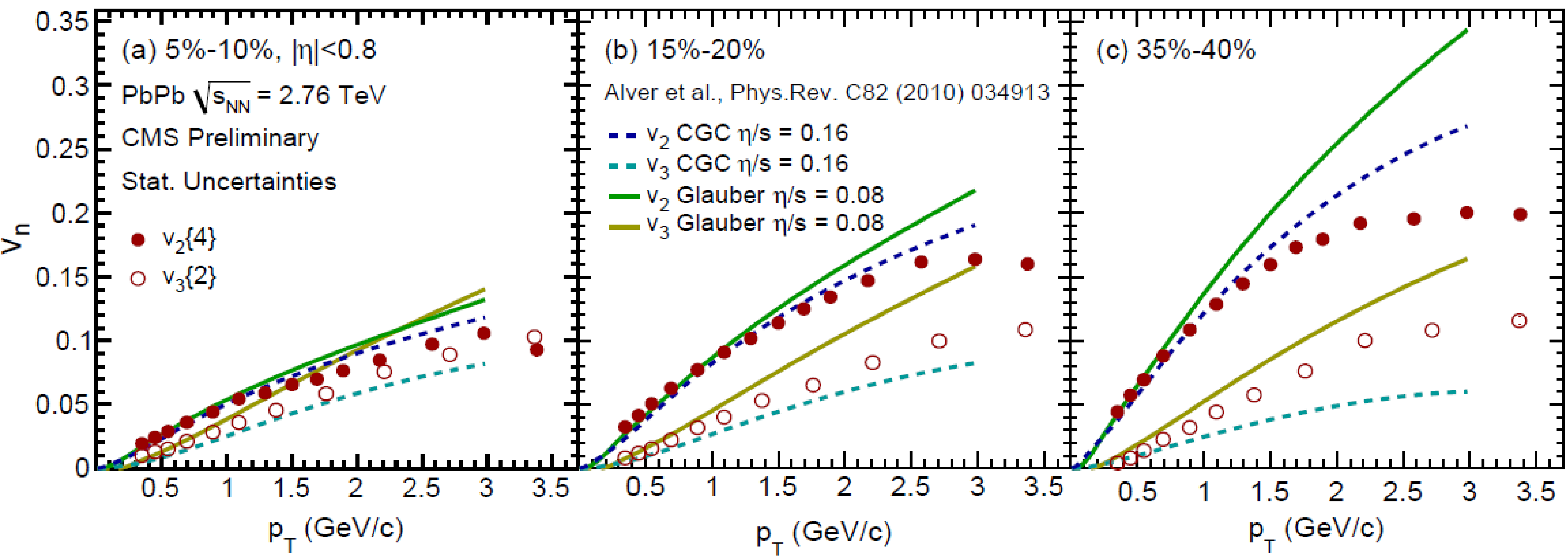




Glauber initial conditions

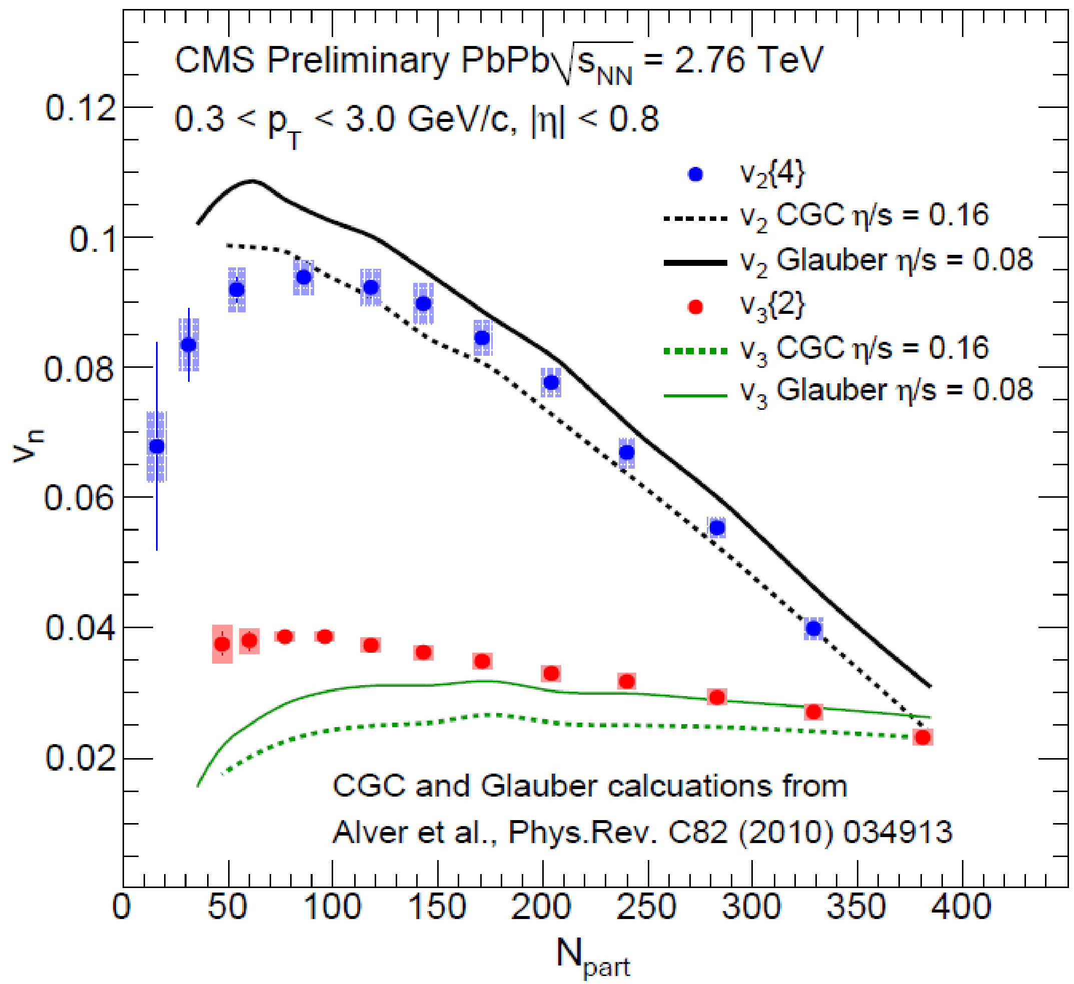
v_2 and v_3 : initial conditions

- **Different initial conditions**
  - CGC, Glauber initial condition



v_2 and v_3 vs N_{part} : Hydro

- Qualitative agreement with the data



Conclusion

Conclusions

- CMS has measured up to 6th order harmonic coefficients in a broad centrality, p_T and rapidity range using a variety of methods
- $v_2(p_T)$ is comparable to RHIC
  - Integral v_2 scaling with transverse density and $\sqrt{s_{NN}}$
- v_3 is sizable and almost independent of centrality
  - v_5, v_6 are small, finite
- Our results provide the basis for future detailed comparison to sQGP properties