One of the main purposes of heavy-ion physics is to study the Quark-Gluon Plasma (QGP).

**Properties**

- Hydrodynamic behavior
- Jet quenching
- Quarkonia suppression
- Opaque to colored partons
- Transparent to EM and weakly interacting particles
The CMS Detector

Hadronic Calorimeter
EM Calorimeter
Tracker
Muon Chambers

EM and Hadronic calorimeters
Photons, Jets

HF (Forward Calorimeter)
MinBias Trigger
Centrality

Muon detectors

Inner tracker:
Charged particles

Muon Chambers
Hadronic Calorimeter
EM Calorimeter
Tracker

BSC
(Beam Scintillation Counter)
MinBias Trigger

| η | < 2.4
| η | < 5.2
| η | < 3.0
| η | < 2.5
The azimuthal dependence of the particle yield with respect to the reaction plane can be expanded in a Fourier series:

\[ E \frac{d^3N}{d^3p} = \frac{1}{2\pi p_{t}dp_{t}dy} \left( 1 + \sum_{n=1}^{\infty} 2v_{n} \cos[n(\varphi - \Psi_{R})] \right) \]

- \( \Psi_{R} \) is the reaction plane angle
- \( v_{2} \) is known as elliptic flow

**Importance of Flow Measurements**

- Hydrodynamic properties of the QGP
- Effects of fluctuations in initial conditions
- Quantitative estimate of path length dependence of energy loss in QGP medium
The Event Plane Method

**Event Plane**
Experimentally observable, used to estimate the reaction plane.

\[ \Psi'_n = \frac{1}{n} \tan^{-1} \left( \frac{\sum w_i \sin (n \varphi_i)}{\sum w_i \cos (n \varphi_i)} \right) \]

**Elliptic Flow Coefficient**
Resolution Correction:
Accounts for the experimental uncertainty in estimating the reaction plane.

\[ v_2^{obs} \{EP\} = \langle \cos 2(\varphi - \Psi'_2) \rangle = \frac{1}{N_{ev}} \sum_j \left[ \frac{1}{M_j} \sum_i \cos 2(\varphi_i - \Psi'_2) \right] \]

\[ v_n \{EP\} = \frac{v_n^{obs} \{EP\}}{R} = \frac{\langle \cos n(\varphi - \Psi_n) \rangle}{\langle \cos n(\Psi_n - \Psi'_R) \rangle} \]

**Reaction Plane Angle**
Not experimentally observable

Rylan Conway
Moriond/QCD, La Thuile, March 10 - 17, 2012
**Event Plane Results**

- **CMS Preliminary Stat. Uncertainties Mid-Central**
  - $0 < p_T < 3 \text{ GeV/c}$

- **PHENIX Stat. Uncertainties**
  - $|\eta| < 0.35$

- **Significant increase in integrated $v_2$ from top RHIC energies due to rise in mean $p_T$**

- **Small increase in differential $v_2$ at low $p_T$ despite large increase in $\sqrt{s_{NN}}$ possibly because of saturation due to ideal hydrodynamic behavior**

---

**CMS PbPb $\sqrt{s_{NN}}=2.76$TeV**

**PHENIX AuAu $\sqrt{s_{NN}}=200$GeV**

**CMS Preliminary Stat. Uncertainties**

- CMS
- ALICE
- STAR
- PHENIX
- PHOBOS
- CERES
- NA49 std
- NA49 cumul
- AGS (E877)


**PRC68, 034903 (2003)**

**CMS-HIN-10-002**
Di-hadron Correlations

Signal distribution:

\[ S(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{same}}}{d\Delta \eta d\Delta \phi} \]

Particle 1: trigger
Particle 2: associated

Event 1

Event 2

Background distribution:

\[ B(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{mix}}}{d\Delta \eta d\Delta \phi} \]

Mixed events must be similar, i.e.
- similar collision centrality
- similar vertex position
Di-hadron Correlations

Signal pair distribution:

\[ S(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{same}}}{d \Delta \eta d \Delta \phi} \]

Background pair distribution:

\[ B(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{mix}}}{d \Delta \eta d \Delta \phi} \]

Associated yield per trigger particle:

\[ \Delta \eta = \eta^{\text{assoc}} - \eta^{\text{trig}} \]
\[ \Delta \phi = \phi^{\text{assoc}} - \phi^{\text{trig}} \]

\[ \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d \Delta \eta d \Delta \phi} = B(0,0) \times \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)} \]
Di-hadron Correlation Results

**0-5% central**

![Graph showing di-hadron correlation results for 0-5% central collisions.]

- Significant difference in shape due to larger contribution of higher order harmonics from fluctuating initial conditions.

**35-40% peripheral**

![Graph showing di-hadron correlation results for 35-40% peripheral collisions.]

- \( p_T^{\text{trig}} \): 4 ~ 6 GeV/c
- \( p_T^{\text{assoc}} \): 2 ~ 4 GeV/c

- \( \cos(2\Delta\phi) \) behavior is visible outside of the jet region.

PbPb 2.76 TeV

- CMS PAS HIN-11-006
- JHEP 07 (2011) 076
- arXiv:1201.3158

---

Rylan Conway

Moriond/QCD, La Thuile, March 10 - 17, 2012
Higher Order Harmonics: $v_n$

$$\frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta \phi} = \frac{N_{\text{assoc}}}{2\pi} \left( 1 + 2 \sum_{n=1}^{\infty} V_n^f \cos(n\Delta \phi) \right)$$

**Fluctuating initial condition $\Rightarrow$ higher-order flow harmonics (e.g., “triangular flow”, $v_3$)**

**Participants**

PRC81, 054905 (2010)

$$V_n^f = v_n(p_T^{\text{trig}}) \times v_n(p_T^{\text{assoc}})$$

$\int L \, dt = 3.1 \mu b^{-1}$

PbPb $\sqrt{s_{NN}} = 2.76$ TeV

CMS PAS HIN-11-006

arXiv:1201.3158

10
**High-$p_T \, v_2$ Measurements**

$v_2$ can be used to quantitatively estimate what happens with di-jets in jet quenching scenarios with respect to the Event Plane.

Note: we are NOT measuring the effects of hydrodynamic flow at high $p_T$, we are investigating the path length dependence of energy loss in a QGP medium.
High-$p_T$ Data Selection

• Full 2011 HI Data set: $L_{int} = 150 \text{ mb}^{-1}$

• High $p_T$ Triggers
  - Single-Track High-$p_T$ Triggers (Total # of events: $\sim 1.55M$ with $p_T > 20 \text{ GeV}$)

All triggers are at least 95% efficient
Avoiding Di-Jet Correlations in EP Method

- This is done to minimize systematic effects arising from back-to-back di-jet correlations.

Particles from the positive $\eta$ region are correlated with the event plane calculated in the negative $\eta$ region.

to calculate $V_2$:
$V_2^+ \text{ with } EP^- \text{ and } V_2^- \text{ with } EP^+$

in this analysis we used:
EP+ (3<$\eta$<5)
EP- (-5<$\eta$<-3)

*Hadronic Forward Calorimeters used for determining the Event Plane.
High-$p_T$ $v_2$ Results

The first accurate measurements done at high $p_T$!
Gradual decrease of $v_2$ above $p_T \sim 10$ GeV/c
High-$p_T$ $v_2$ Results

- No significant $\eta$ dependence of $v_2$ observed
High-$p_T$ $v_2$ Results

- Strong correlation between $v_2$ and collision centrality
- Significant, non-zero, $v_2$ for $28.8 < p_T < 48$ GeV/c
- Above $p_T \sim 48$ GeV/c, $v_2$ is consistent with zero in mid-peripheral collisions

CMS Preliminary

$|\eta| < 1$

$1 < |\eta| < 2$

$L_{int} = 150 \mu b^{-1}$

$PbPb \sqrt{s_{NN}} = 2.76$ TeV
Summary

• Significant increase of integrated $v_2$ from RHIC to LHC energies due to increase in mean $p_T$

• Di-hadron correlations suggest large contributions from higher order harmonics due to fluctuations in the initial conditions

• First accurate $v_2$ measurements done at high $p_T$
  
  - Significant $v_2$ values observed up to $p_T \sim 40$ GeV/c
  
  - $v_2$ consistent with zero in mid-peripheral events for $50 < p_T < 60$ GeV/c

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN