The Study Of Direct Photon Azimuthal Anisotropy At RHIC-PHENIX Experiment
**What is Azimuthal Anisotropy?**

Azimuthal anisotropy is relative deviation of the number of emitted particle between in and out of plane.

It is strongly related to **initial geometry** and $\eta/s$ of QGP. Expansion makes anisotropy in momentum space.

Mathematically:

$$
E \frac{d^3N}{dp^3} \propto [1 + 2 \sum_{n=1}^{\infty} \nu_n \cos\{n(\phi - \Phi_n)\}] 
$$

$$
\nu_n = \langle \cos\{n(\phi - \Phi_n)\} \rangle
$$

**Event Plane ($\Phi_n$):**
The base direction for expansion

$\nu_n$ : strength of anisotropy
Higher Order Anisotropy

Event Plane ($\Phi_n$) :
The base direction for expansion

$\nu_n = \langle \cos\{n(\phi - \Phi_n)\} \rangle$

$E \frac{d^3N}{dp^3} \propto [1 + 2 \sum_{n=1}^{\infty} \nu_n \cos\{n(\phi - \Phi_n)\}]$

Initial geometry is deformed because of statistics fluctuation. It makes higher order azimuthal anisotropy.

It is important to constrain initial geometry calculating model and $\eta/s$ of QGP.
What is Direct Photon?

Direct photon is all photons except ones from hadron decay.
- Penetrating QGP without scattering
- Created from various sources

Direct photon
- prompt photon
- thermal photon
- parton energy loss
- photon from hadron decay

Jet fragmentation

Inclusive photon
It is expected that the photon sources are identified by azimuthal anisotropy measurement (initial geometry dependence).

- prompt: $v_2 \sim 0$
- Jet fragmentation: $v_2 > 0$
- parton energy loss: $v_2 < 0$
- thermal QGP: $v_2 \geq 0$
- thermal HG: $v_2 > 0$

Superposition is measured.

$\gamma^{\text{dir.}}$. $v_2$ has been measured at PHENIX and ALICE.
$\gamma_{\text{dir.}} v_2$ is close to 0 in high $p_T$, which is consistent with expectation. It has strong $v_2$ as one of hadron in low $p_T$.

ALICE also measure $\gamma_{\text{dir.}} v_2$ and it is found that it has similar trend.
Deviation of Temperature

$T_\gamma = 233\pm14\pm19$ MeV is observed by direct photon spectrum. It is much higher than $T_{\text{had}} = 100-120$ MeV which is freeze-out temperature.

$T_\gamma \gg T_{\text{had}}$

Azimuthal anisotropy is created from initial geometry deformation. It is needed the enough expansion time to have large $v_2$.

$T_\gamma \sim T_{\text{had}}$
Underestimation for $\gamma_{\text{dir.}} v_2$

Model calculation is underestimated for $v_2$ while spectra is well described.

Additional component is needed to describe experiment results.

- Strong magnetic field
- Blue shift
What makes large $v_2$?

Magnetic Field effect
2nd of Event Plane is strongly correlated with Reaction Plane while 3rd is not.

- $v_2$ is strong : $v_3$ is weak

Blue shift effect
Observed temperature is affected by flow and it is overestimated.

- $v_2$ and $v_3$ are strong

$v_3$ measurement helps to understand.

\[
T_{obs} \sim T_{real} \sqrt{\frac{1+<\beta>}{1-<\beta>}}
\]

$<\beta>$ : average expansion velocity
Analysis flow

✓ $\pi^0$ and $\gamma^{inc.}$ $v_n$ measurement

✓ $\gamma^{dec.}$ $v_n$ simulation

It is simulated from $\pi^0$ $v_n$.

✓ $\gamma^{dir.}$ $v_n$ calculation

$$v_n^{dir.} = \frac{R_\gamma v_n^{inc.} - v_n^{dec.}}{R_\gamma - 1}$$

$$R_\gamma = \frac{N^{inc.}}{N^{dec.}}$$
Summary

Direct photon is powerful tools to study QGP. Azimuthal anisotropy is related with initial geometry. Higher order is thought to be more important.

Direct photon $v_2$ has been measured at PHENIX and ALICE. It is found that it has as strong $v_2$ as hadron, but it is not yet understood. Model calculation is underestimated.

Direct photon $v_3$ is expected to help understanding. Measurement is ongoing.
BACK UP
It is known that they have weak correlation.

It is considered that 3rd order of Event Plane is defined as a deformation of initial geometry.
\[ \nu_n = \langle \cos\{n(\phi - \Phi_n)\} \rangle \]

The angles of particle emission and Event Plane are measured by different detectors in order to auto-correlation (e.g. Jet). Event Plane is determined as a strong direction of flow.

\[ Q_x = \langle w_i \cos(n\phi_i) \rangle \]
\[ Q_y = \langle w_i \sin(n\phi_i) \rangle \]
\[ \Phi_n = \text{atan2}(Q_y, Q_x) / n \]

\( i \) : direction of detector
\( w_i \) : weight
Direct photon at low $p_T$ provides temperature of QGP.

$T_{\text{eff}} = 233 \pm 14 \pm 19$ MeV (Min. Bias.)

$T_{\text{ini}} = 300\sim600$ MeV

$T_{\text{eff}}(\text{LHC}) = 304\pm51$ MeV (2.76TeV,0-40%)

$T = 170$MeV (Lattice QCD)

$T = 100$-120MeV (hadron freeze-out)

The photon from hot matter is observed.
\[ R_{AA} = \frac{\left(1/N_{AA}^{\text{evt}}\right) d^2 N_{AA}/dp_T dy}{<N_{\text{coll}}>/\sigma_{pp}^{\text{inel}} \times d^2 \sigma_{pp}/dp_T dy} \]

\begin{align*}
\text{Hadron is} & \quad \text{suppressed.} \\
\end{align*}

\( R_{AA} \) of direct photon is consistent with unity in high \( p_T \). This is consistent with the expectation that \( \gamma^{\text{dir.}} \) coming from initial scattering is dominant.
$v_3$ and $v_4$ have weak centrality dependence while $v_2$ has strong. It indicates $v_3$ and $v_4$ are created by the initial geometry deformation.
$v_n$ has mass and meson/baryon dependence. Higher harmonics are created from initial geometry deformation, they are affected by the effect of QGP expansion.
KE\_T scaling for PID v_n

Meson is scaled well, while proton isn’t scaled.
Similar trend with RHIC-PHENIX is observed by LHC-ALICE.
Strong magnetic field is thought to affect photon emit angle. It is created in perpendicular direction to Reaction Plane.
Quark annihilation effect

If \( n_{q,\gamma} = 2 \)

Late state photon production with q-q annihilation effect seems to work well.

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Measured temperature is shifted from real temperature due to flow effect.
Thermal photon $v_2$

Much smaller than PHENIX direct photon $v_2$. 

$Au + Au @ \sqrt{s_{NN}} = 200 \text{ GeV}$
PHENIX detector

EMCal is used to detect photon. PC3 is used to remove charged particle.

Event Plane is measured by RxN detector.

CNT coverage $|\eta| < 0.35$

$\phi : 180$

- Tracking detector DC, PC1, PC2, PC3
- particle identification RICH, TOF, AGEL, EMCal
Check to be consistent with $\pi^{\pm} v_3$

$\pi^0 v_3$ is measured up to 4.0 GeV/c with several centralities. It is confirmed to be consistent with $\pi^{\pm} v_3$.

Decay photon $v_n$ is simulated from $\pi^0$ and the other meson $v_3$. 
Event are classified by these detectors.
Event Plane are measured by these detectors.

- BBC (3.1 < |\(\eta\)| < 3.8)
- MPC (3.1 < |\(\eta\)| < 3.8)
- RxN (1.0 < |\(\eta\)| < 2.8)
Event Plane calculation

Event Plane is calculated by three steps.
1. gain correction
2. re-centering
3. flattening

\[ \nu_{n,\text{real}} = \nu_{n,\text{obs}} / \text{Res} \{ \Psi_n \} \]

- **2nd Event Plane correlation**
  - RxN(In)S&N
  - RxN(Out)S&N
  - RxN(In+Out)S&N

- **2nd Event Plane resolution**
  - RxN(In)S+N
  - RxN(Out)S+N
  - RxN(In+Out)S+N

Reaction Plane detector (RxN)
- Inner: \( 1.5 < |\eta| < 2.8 \)
- Outer: \( 1.0 < |\eta| < 1.5 \)
\[ T_f \]

\[ \rho_n \] behavior is similar to centrality dependence of charged particle \( v_n \).

\( s_3 \) and \( s_4 \) are smaller than \( s_2 \) but not zero in non-central.
It is estimated about $10^{17}$[Gauss].

It related to photon production angle??