

Group Meeting

Three Particle Correlation

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October 25, 2017

Introduction

$$C_{m,n,m+n} = \langle \cos(m\phi_1 + n\phi_2 - (m+n)\phi_3) \rangle$$

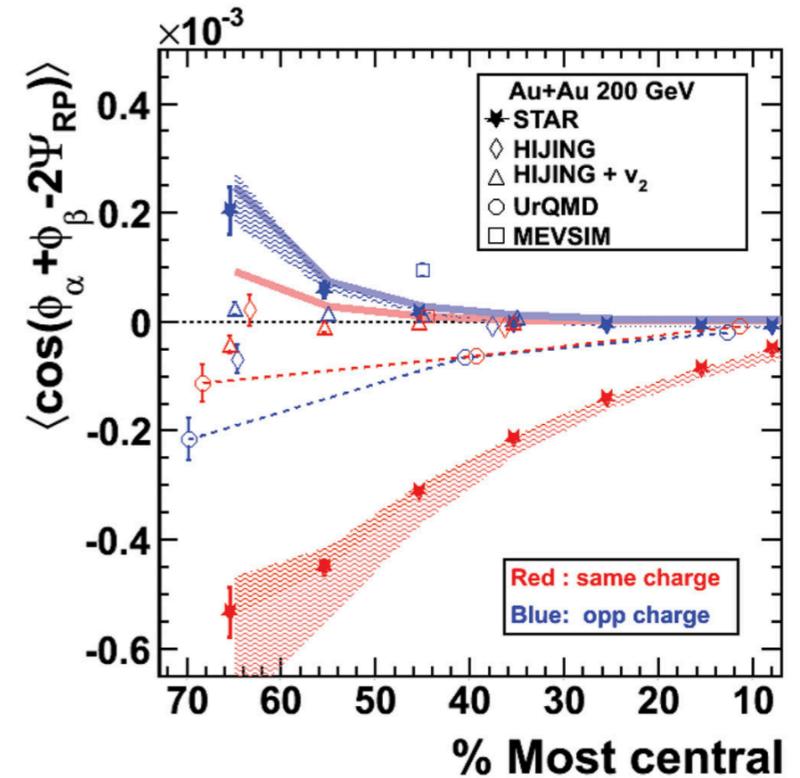
- Can be used for the search for evidence of CME - C_{112}
- 3PC is useful to study correlation among different vn harmonics - C_{123}
- Objective - Study 2-PC and 3-PC
- Study effect of GMC
- Disentangle GMC and Flow signal

CME Results

PRL 103, 251601 (2009)

- Charge separation observed in AuAu at STAR
- Theoretical models (no CME) can't explain data

Signal can be from CME!



CME Results

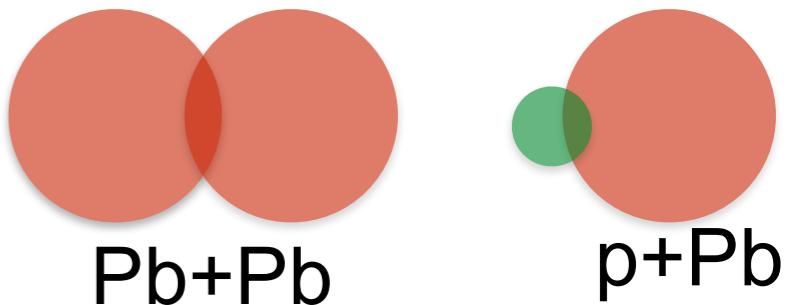
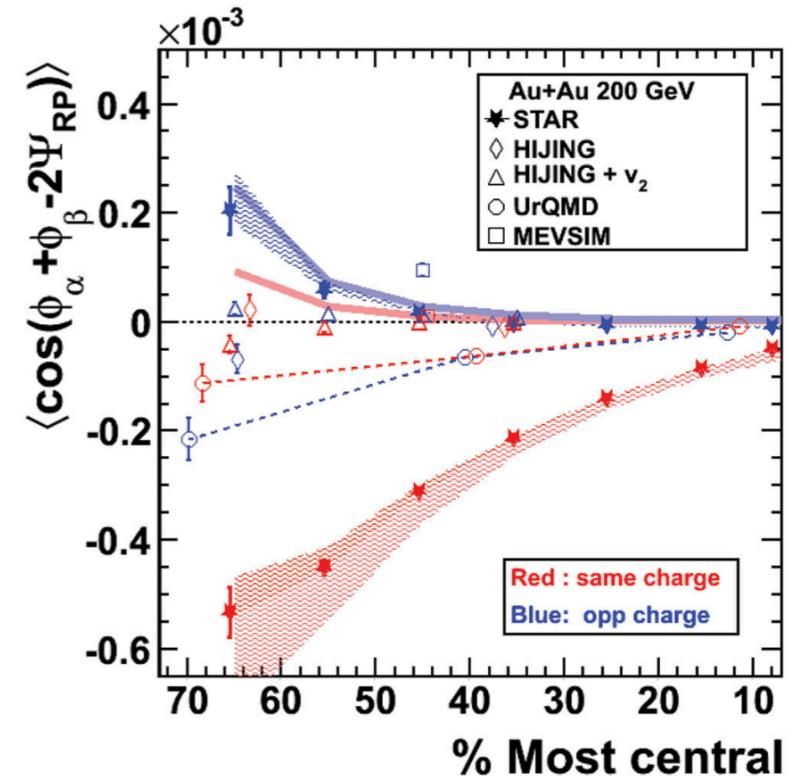
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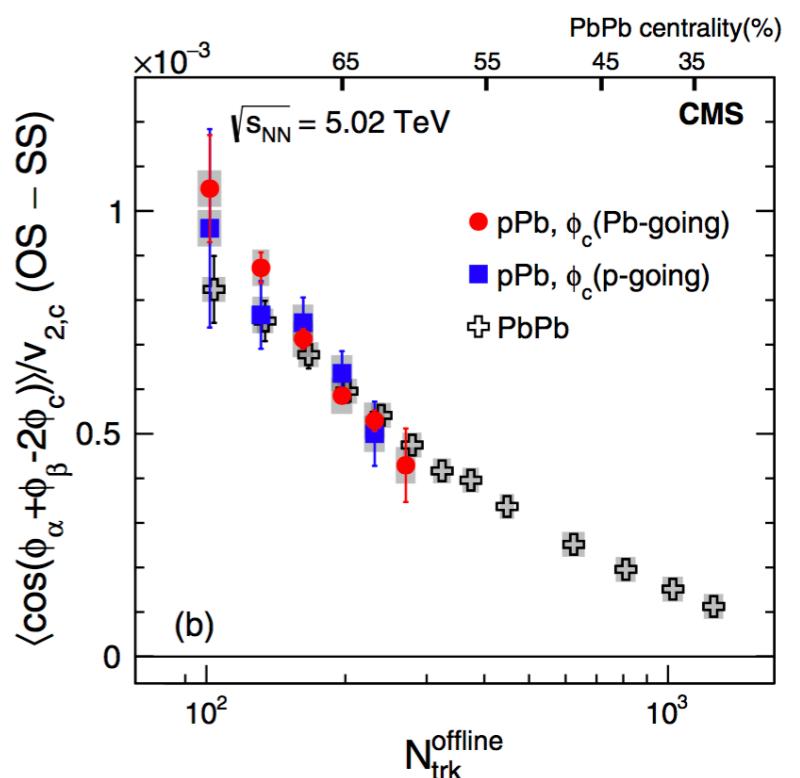
Signal can be from CME!

- CMS compared C112 in large and small systems
- Expectation - Lower CME in p+Pb than Pb+Pb due to reduced field strength and random field orientation
- Observed comparable signal

p+Pb signal not CME???



PRL 118, 122301 (2017)



CME Results

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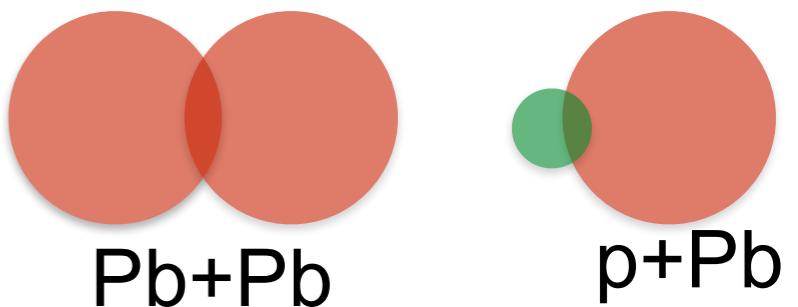
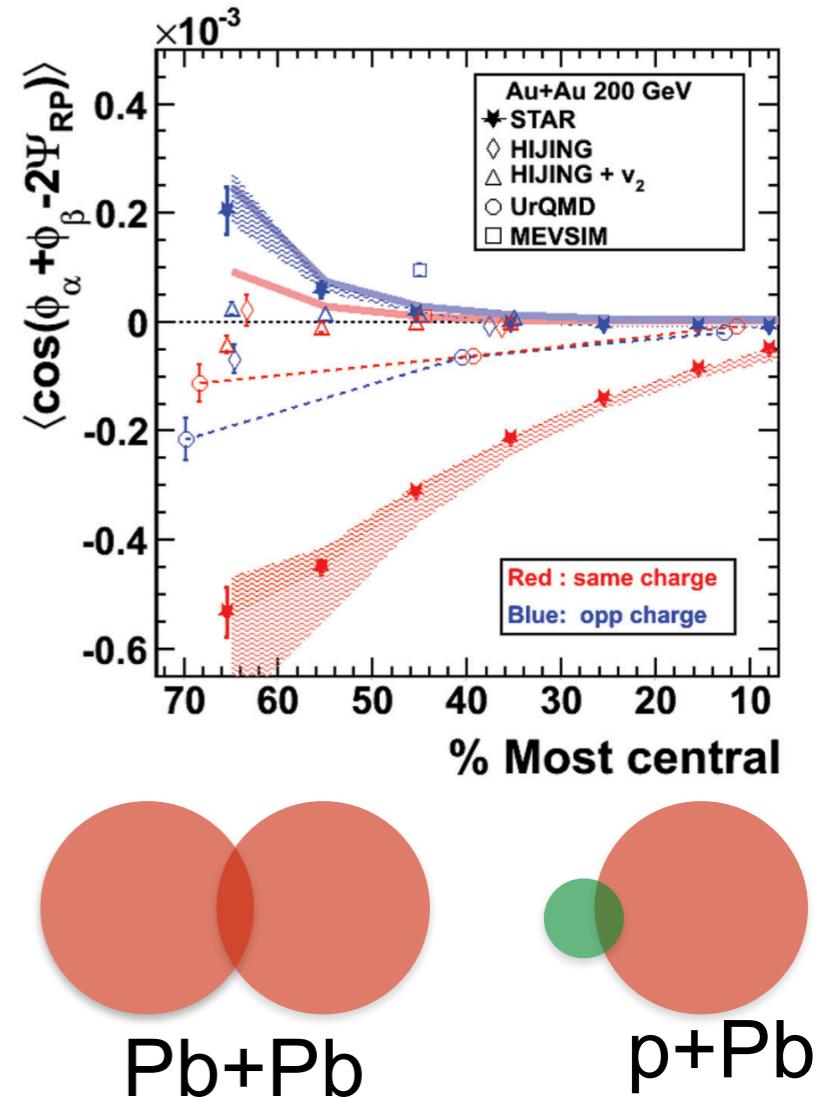
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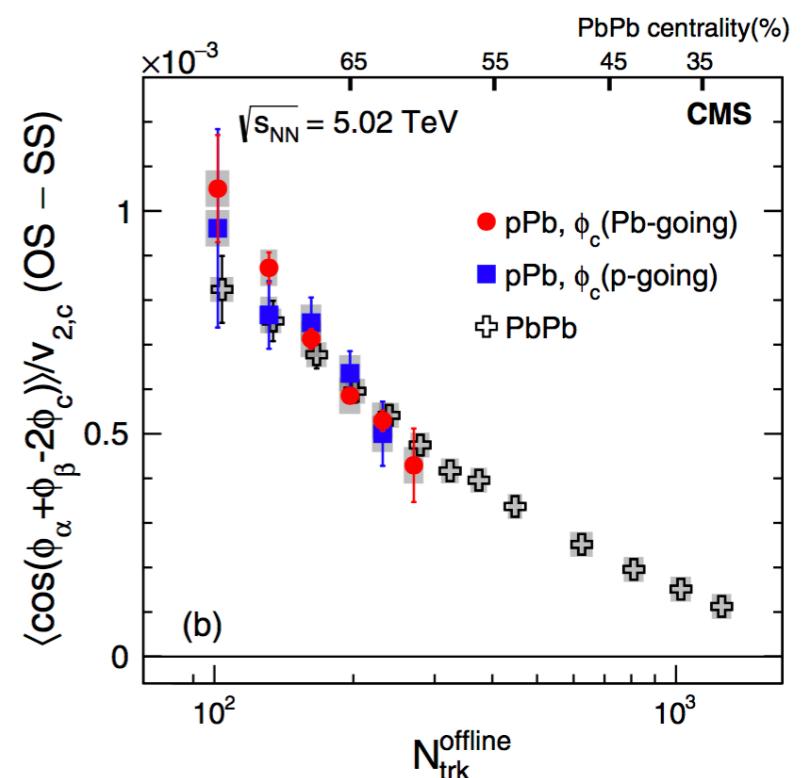
p+Pb signal not CME???

- CME Correlator C112 - possible large background
- Background - Momentum Conservation and Local Charge Conservation

Objective - To check impact of GMC in the 3P correlators and try to disentangle it from flow signal - Might give better and reliable results for CME!!!



PRL 118, 122301 (2017)

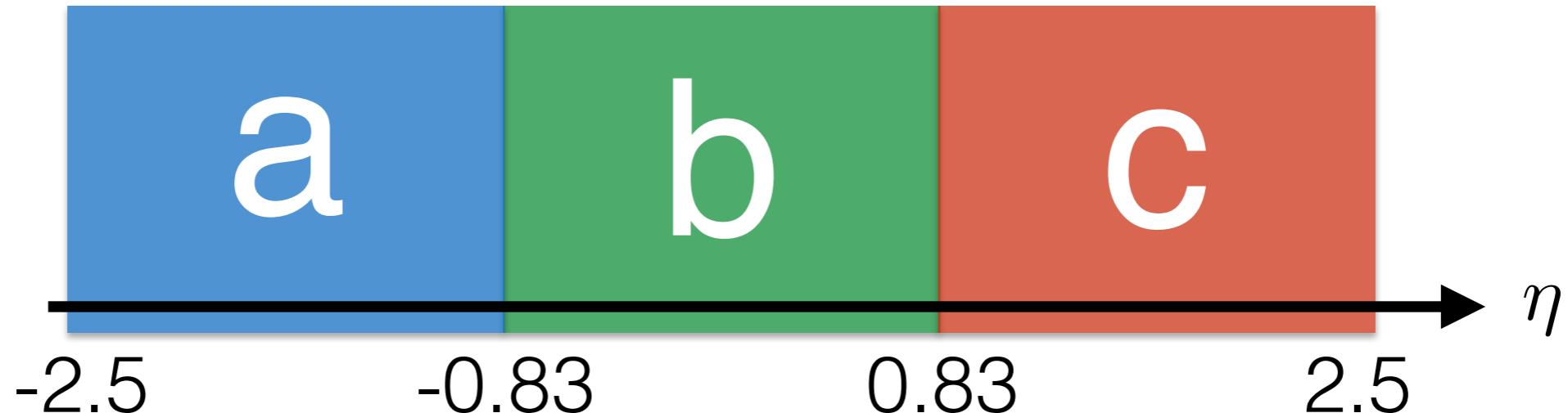


Calculation - 2PC and 3PC

- Flow Vector

$$\vec{q}_n = \left(\frac{\sum_i w_i \cos(n\phi_i)}{\sum_i w_i}, \frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i} \right)$$

- Subevents

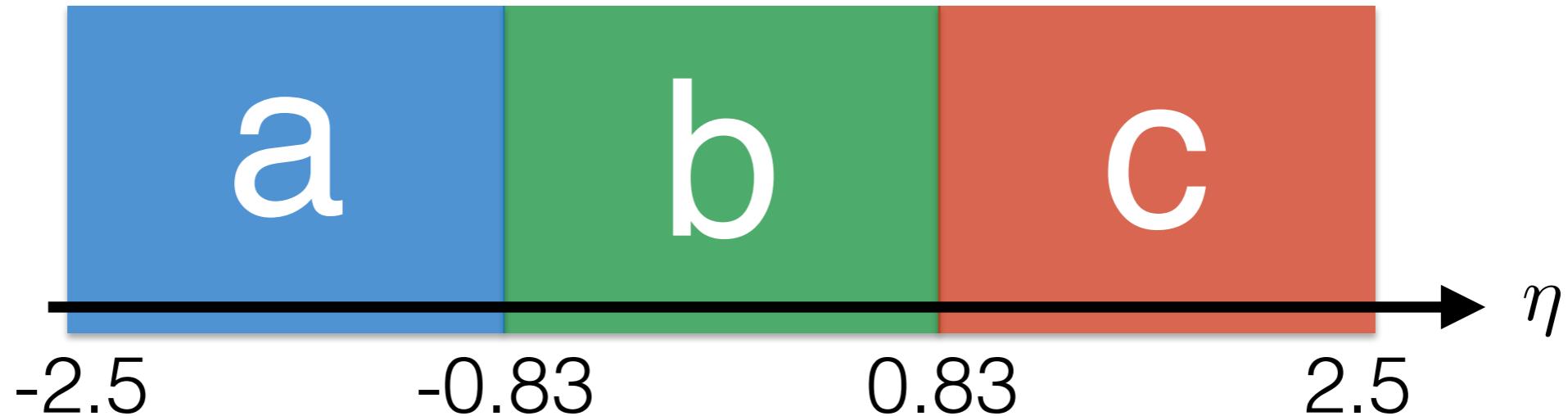


Calculation - 2PC and 3PC

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$$\vec{q}_n = \left(\frac{\sum_i w_i \cos(n\phi_i)}{\sum_i w_i}, \frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i} \right)$$

- Subevents



- 2PC in terms of q-vectors

$$C_{nn} = \langle \langle \cos n(\phi_1 - \phi_2) \rangle \rangle = \langle \mathbf{q}_n^a \mathbf{q}_n^{c*} \rangle$$

- 3PC in terms of q-vectors

$$C_{112} = \langle \langle \cos(\phi_1 + \phi_2 - 2\phi_3) \rangle \rangle = \langle \mathbf{q}_1^a \mathbf{q}_1^c \mathbf{q}_2^{b*} \rangle$$

$$C_{123} = \langle \langle \cos(\phi_1 + 2\phi_2 - 3\phi_3) \rangle \rangle = \langle \mathbf{q}_1^a \mathbf{q}_2^b \mathbf{q}_3^{c*} \rangle$$

Momentum Conservation

- Azimuthal distributions for a pair of particles $\frac{dN_{pairs}}{d\Delta\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_{nn}(p_{T_1}, p_{T_2}) \cos(n\Delta\phi)$
- Factorisation for $n > 1$: $v_{nn}(p_{T_1}, p_{T_2}) = v_n(p_{T_1})v_n(p_{T_2})$

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- Factorisation for $n > 1$: $v_{nn}(p_{T_1}, p_{T_2}) = v_n(p_{T_1})v_n(p_{T_2})$
- The factorization breaks for $n = 1$: $v_{11}(p_{T_1}, p_{T_2}) \approx v_1(p_{T_1})v_1(p_{T_2}) - \frac{p_{T_1}p_{T_2}}{M\langle p_T^2 \rangle}$
- Correction due to global momentum conservation :

$$\frac{dN_{ij}}{d^3\mathbf{p}_1 d^3\mathbf{p}_2} = \frac{dN_{ij}}{d^3\mathbf{p}_1} \frac{dN_{ij}}{d^3\mathbf{p}_2} [1 + C_{ij}(\mathbf{p}_1 \mathbf{p}_2)]$$

Momentum Conservation

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- For 2PC and 3PC, the momentum conservation correction is :

$$C_{ij}^{2PC}(\mathbf{p}_1, \mathbf{p}_2) = -\frac{2\mathbf{p}_1 \cdot \mathbf{p}_2}{M\langle p_T^2 \rangle}$$

PHYSICAL REVIEW C, VOLUME 62, 034902

$$C_{ij}^{3PC}(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) = -\frac{2(\mathbf{p}_1 \cdot \mathbf{p}_2 + \mathbf{p}_2 \cdot \mathbf{p}_3 + \mathbf{p}_3 \cdot \mathbf{p}_1)}{M\langle p_T^2 \rangle}$$

Momentum Conservation

- 2 and 3PC MC :
$$C_{11}^{MC} = C \int p_{T_1} p_{T_2} \cos(\phi_1 - \phi_2) \cos(\phi_1 - \phi_2) d\phi_1 d\phi_2$$
$$C_{112}^{MC} = C \int [p_{T_1} p_{T_2} \cos(\phi_1 - \phi_2) + p_{T_2} p_{T_3} \cos(\phi_2 - \phi_3) + p_{T_1} p_{T_3} \cos(\phi_1 - \phi_3)]$$
$$\cos(\phi_1 + \phi_2 - 2\phi_3) d\phi_1 d\phi_2 d\phi_3$$
$$C_{123}^{MC} = C \int [p_{T_1} p_{T_2} \cos(\phi_1 - \phi_2) + p_{T_2} p_{T_3} \cos(\phi_2 - \phi_3) + p_{T_1} p_{T_3} \cos(\phi_1 - \phi_3)]$$
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Momentum Conservation

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$$\cos(\phi_1 + 2\phi_2 - 3\phi_3) d\phi_1 d\phi_2 d\phi_3$$
- Azimuthal distribution

$$\frac{dN}{d\phi} = \frac{1}{2\pi} \left[1 + \sum_n 2v_n(p_T) \cos n(\phi - \Psi_{RP}) \right]$$

$$\begin{aligned}\mathbf{v}_n &= v_n \exp(in\Psi_n) \\ &= \{v_n \cos(n\Psi_n), v_n \sin(n\Psi_n)\}\end{aligned}$$

Momentum Conservation

- 2 and 3PC MC :
$$C_{11}^{MC} = C \int p_{T_1} p_{T_2} \cos(\phi_1 - \phi_2) \cos(\phi_1 - \phi_2) d\phi_1 d\phi_2$$
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- Azimuthal distribution

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$$\mathbf{v}_n = v_n \exp(-n\Psi_n)$$
$$= \{v_n \cos(n\Psi_n), v_n \sin(n\Psi_n)\}$$

- Normalised MC :

$$C_{mnp}^{MC} = \frac{\frac{C}{2} \int [\dots] \frac{dN}{d\phi_i} \frac{dN}{d\phi_j} \frac{dN}{d\phi_k} d\phi_i d\phi_j d\phi_k}{\int \frac{dN}{d\phi_i} \frac{dN}{d\phi_j} \frac{dN}{d\phi_k} d\phi_i d\phi_j d\phi_k}$$

Momentum Conservation

- 2 and 3PC MC : $C_{11}^{MC} = C \int p_{T_1} p_{T_2} \cos(\phi_1 - \phi_2) \cos(\phi_1 - \phi_2) d\phi_1 d\phi_2$

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$$\cos(\phi_1 + \phi_2 - 2\phi_3) d\phi_1 d\phi_2 d\phi_3$$

$$\cos(\phi_1 + 2\phi_2 - 3\phi_3) d\phi_1 d\phi_2 d\phi_3$$

- Azimuthal distribution

$$C_{11}^{MC} = C \frac{p_{T_1} p_{T_2}}{2} [1 + \mathbf{v}_2(p_{T_1}) \mathbf{v}_2^*(p_{T_2})]$$

$$\frac{dN}{d\phi} = \frac{1}{2\pi} \left[1 + \sum_n 2v_n(p_T) \cos(n(\phi - \Psi_{RP})) \right]$$

$$\mathbf{v}_n = v_n \exp(-n\Psi_n)$$

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$$C_{112}^{MC} = \frac{C}{2} p_{T_1} p_{T_2} [\mathbf{v}_2(p_{T_1}) \mathbf{v}_2^*(p_{T_3}) + \mathbf{v}_2(p_{T_2}) \mathbf{v}_2^*(p_{T_3})]$$

$$+ \frac{C}{2} p_{T_2} p_{T_3} [\mathbf{v}_1(p_{T_1}) \mathbf{v}_2(p_{T_2}) \mathbf{v}_3^*(p_{T_3}) + \mathbf{v}_1(p_{T_1}) \mathbf{v}_1^*(p_{T_3})]$$

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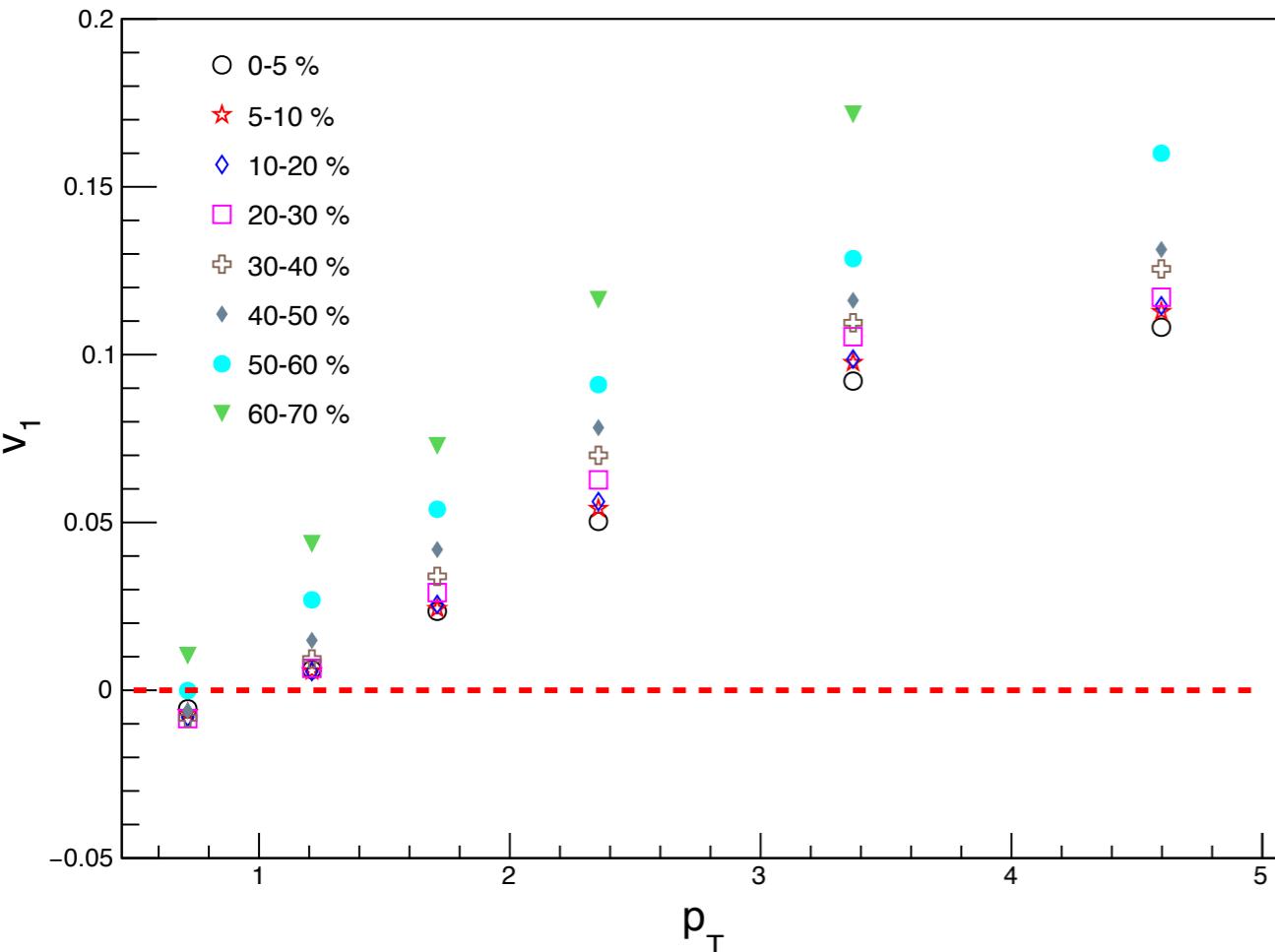
$$+ \frac{C}{2} p_{T_2} p_{T_3} [\mathbf{v}_1(p_{T_1}) \mathbf{v}_3(p_{T_2}) \mathbf{v}_4^*(p_{T_3}) + \mathbf{v}_1(p_{T_1}) \mathbf{v}_1(p_{T_2}) \mathbf{v}_2^*(p_{T_3})]$$

$$+ \frac{C}{2} p_{T_1} p_{T_3} [\mathbf{v}_2(p_{T_1}) \mathbf{v}_2(p_{T_2}) \mathbf{v}_4^*(p_{T_3}) + \mathbf{v}_2(p_{T_2}) \mathbf{v}_2^*(p_{T_3})]$$

Results

Results - C11 MC

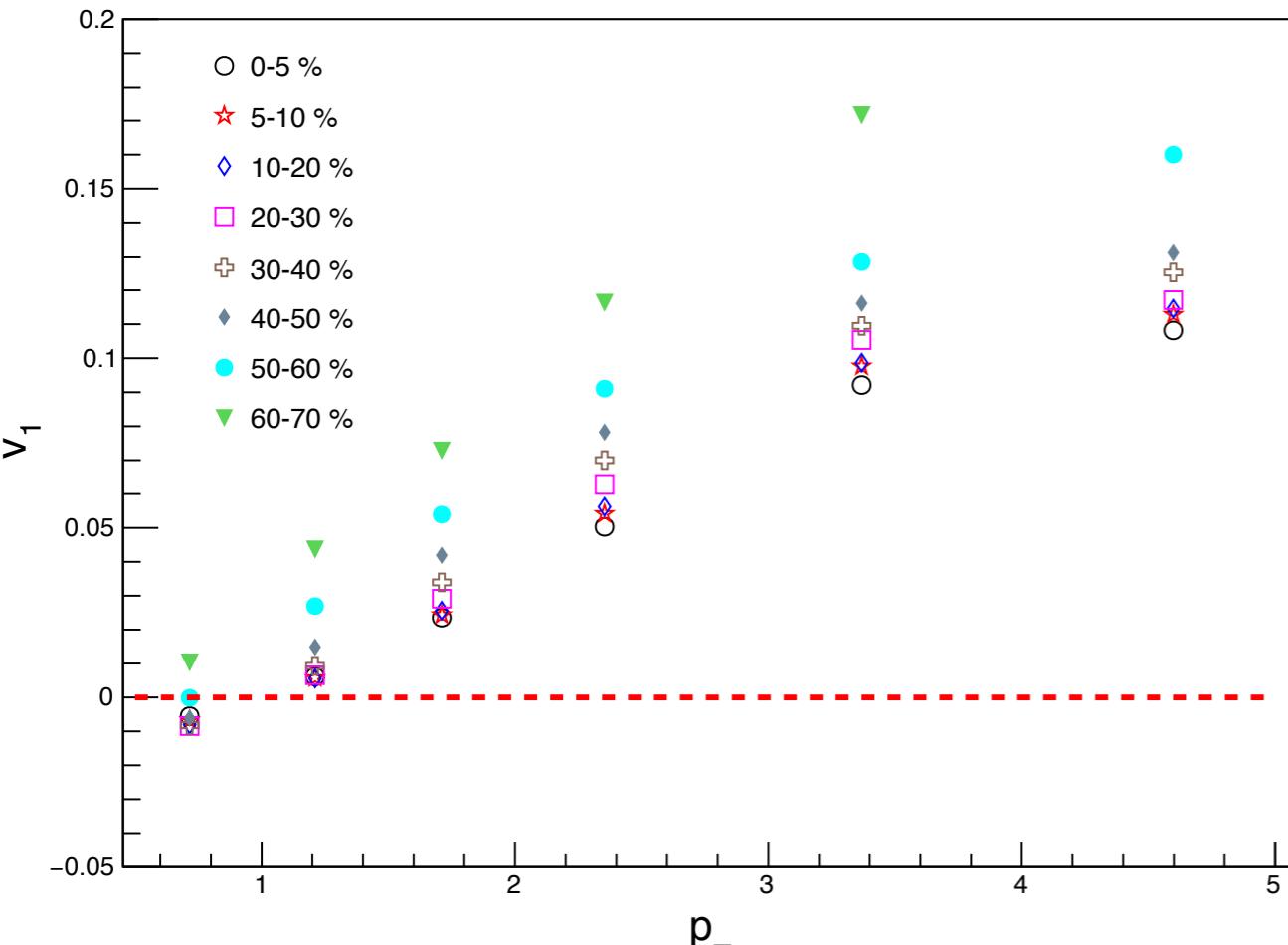
$$v_{11} = v_1(p_{T_1})v_1(p_{T_2}) + C \frac{p_{T_1}p_{T_2}}{2} [1 + \mathbf{v}_2(p_{T_1})\mathbf{v}_2^*(p_{T_2})]$$



- $v_1(p_T)$ obtained after fitting
- v_1 starts as -ve then changes sign and increases with p_T
- Similar trend for different centralities

Results - C11 MC

$$v_{11} = v_1(p_{T_1})v_1(p_{T_2}) + C \frac{p_{T_1}p_{T_2}}{2} [1 + \mathbf{v}_2(p_{T_1})\mathbf{v}_2^*(p_{T_2})]$$



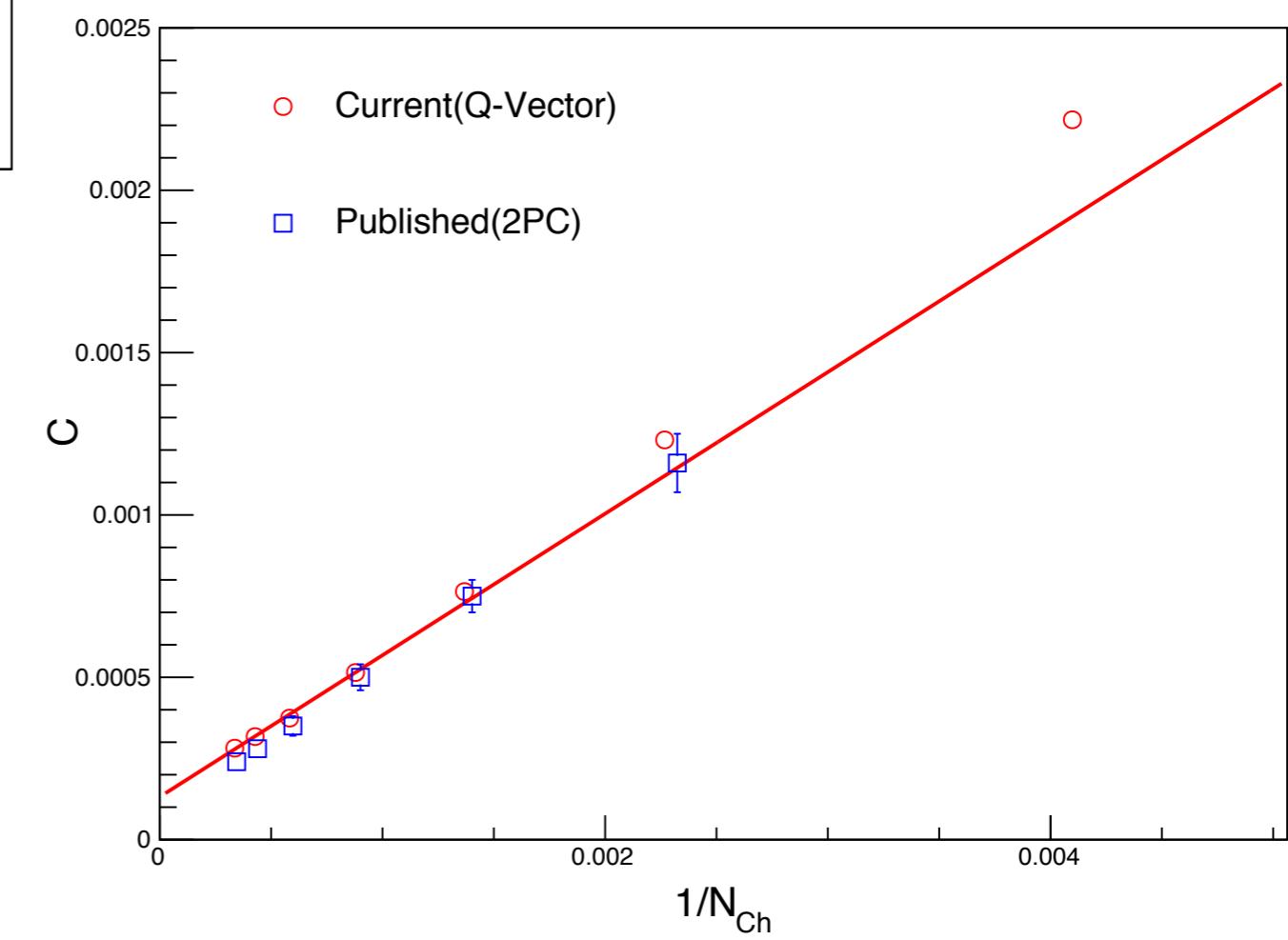
$$C = -\frac{2}{N \langle p_T^2 \rangle}$$

- C vs $1/N_{\text{ch}}$ is fitted with a straight line
- C values consistent with published results

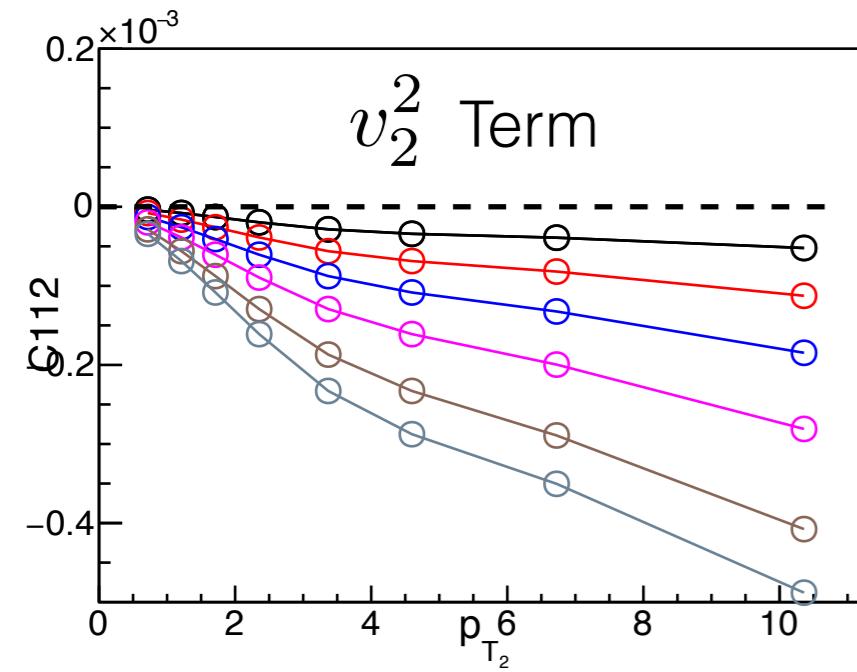
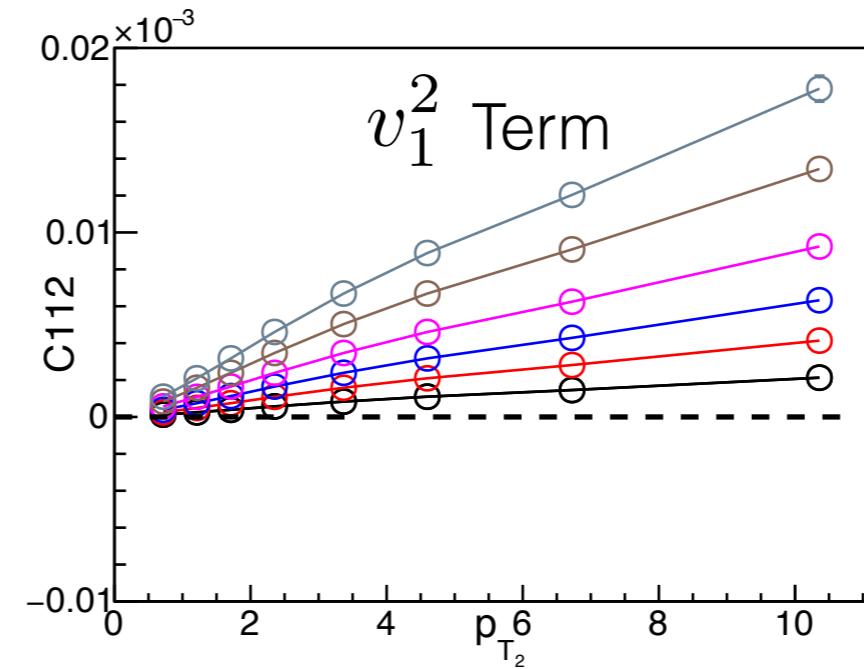
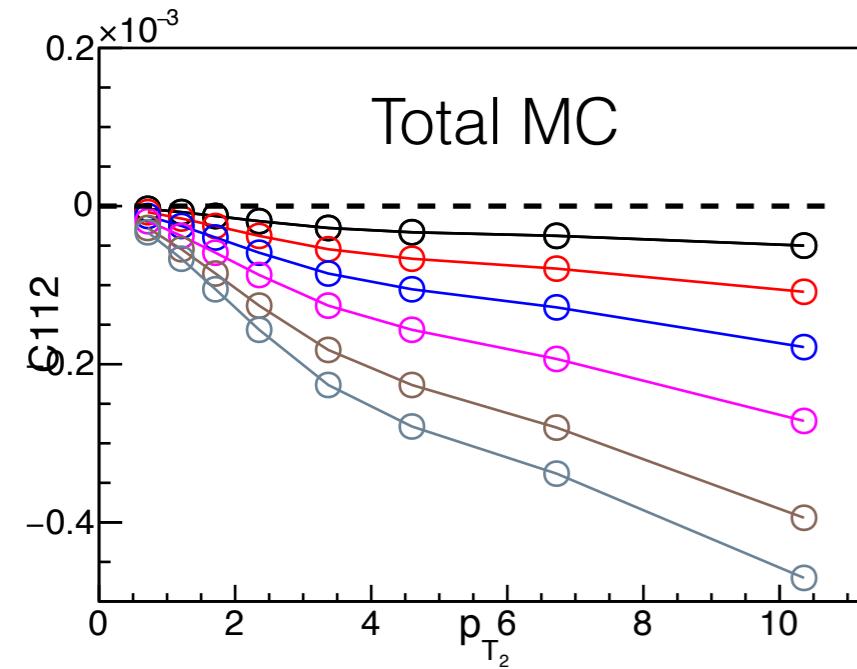
Slope = 0.44

Intercept = 1.3×10^{-4}

- $v_1(p_T)$ obtained after fitting
- v_1 starts as -ve then changes sign and increases with p_T
- Similar trend for different centralities



C112 - Individual MC terms



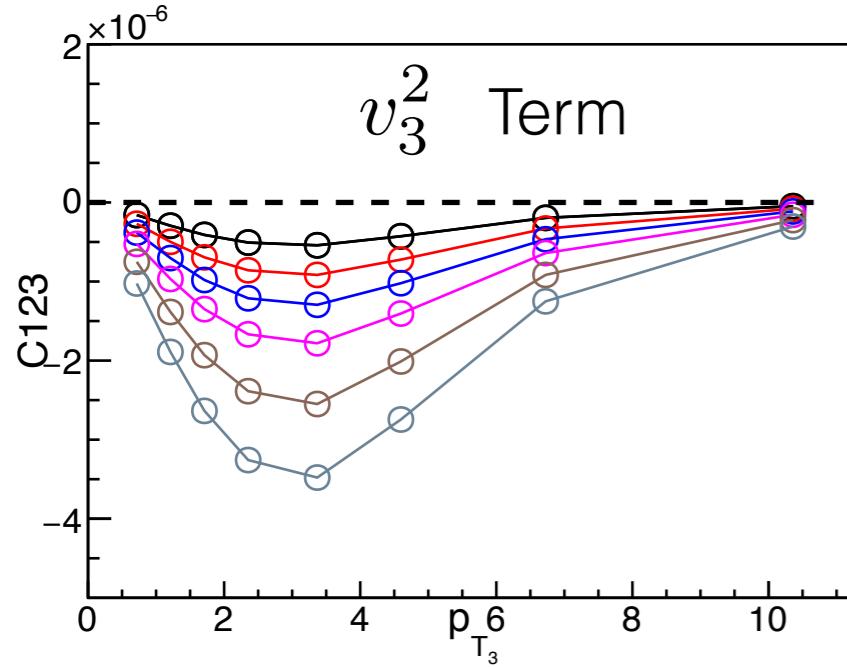
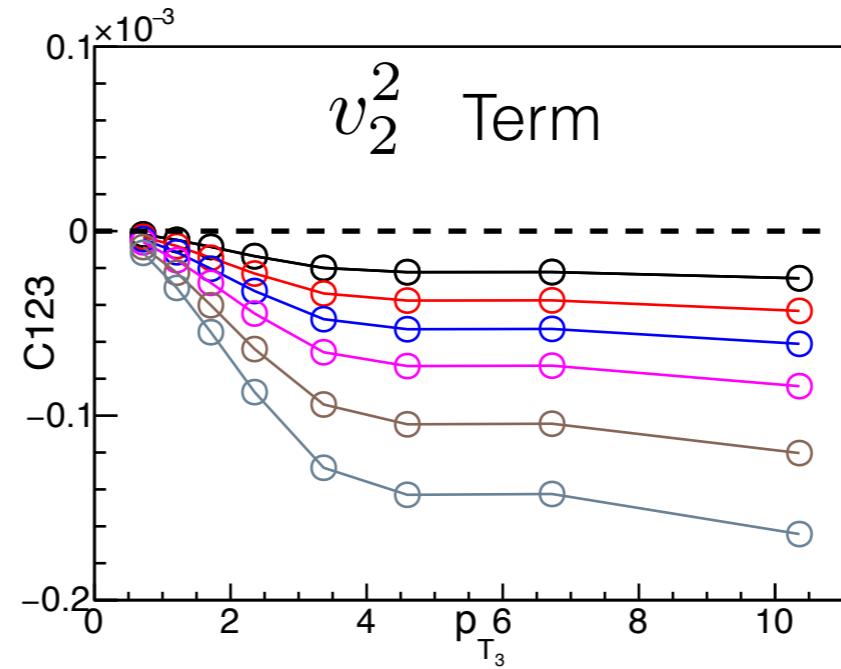
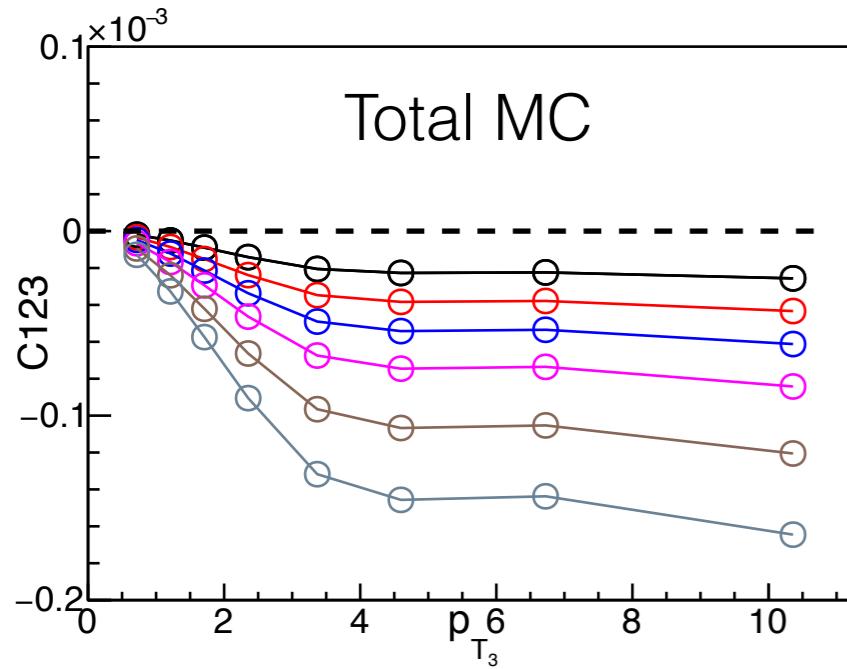
- $0.5 < p_{T_1}^6 < 1.0$
- $1.0 < p_{T_1}^6 < 1.5$
- $1.5 < p_{T_1}^6 < 2.0$
- $2.0 < p_{T_1}^6 < 3.0$
- $3.0 < p_{T_1}^6 < 4.0$
- $4.0 < p_{T_1}^6 < 6.0$

- For fixed $p_k = (0.5-1.0)$
- v_1^2 term is smaller by a factor of 10
- v_2^2 term is the main source of MC

$$\begin{aligned}
 C_{112}^{MC} = & \frac{C}{2} p_{T_1} p_{T_2} [\mathbf{v}_2(p_{T_1}) \mathbf{v}_2^*(p_{T_3}) + \mathbf{v}_2(p_{T_2}) \mathbf{v}_2^*(p_{T_3})] \\
 & + \frac{C}{2} p_{T_2} p_{T_3} [\mathbf{v}_1(p_{T_1}) \mathbf{v}_2(p_{T_2}) \mathbf{v}_3^*(p_{T_3}) + \mathbf{v}_1(p_{T_1}) \mathbf{v}_1^*(p_{T_3})] \\
 & + \frac{C}{2} p_{T_1} p_{T_3} [\mathbf{v}_1(p_{T_2}) \mathbf{v}_2(p_{T_1}) \mathbf{v}_3^*(p_{T_3}) + \mathbf{v}_1(p_{T_2}) \mathbf{v}_1^*(p_{T_3})]
 \end{aligned}$$

9

C123 - Individual MC terms



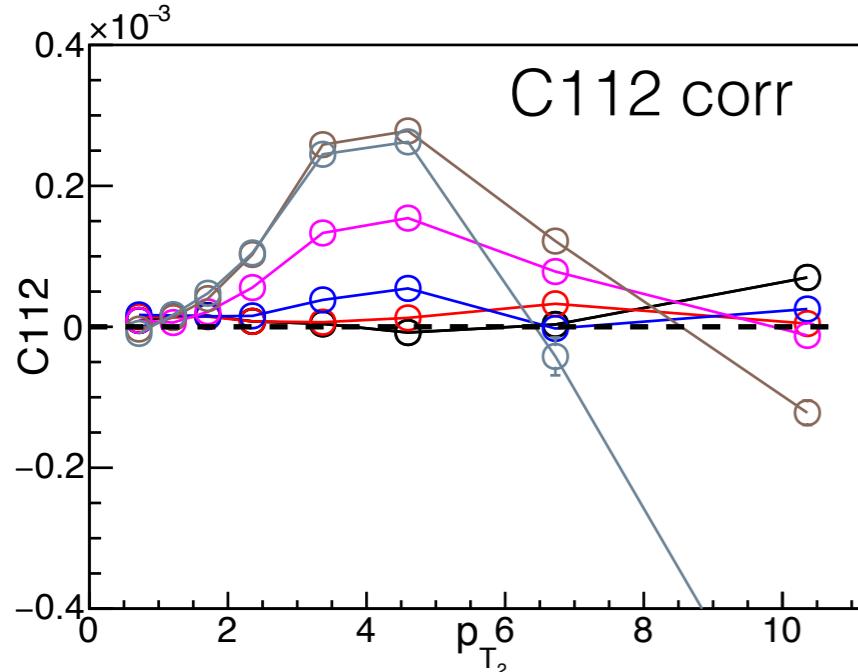
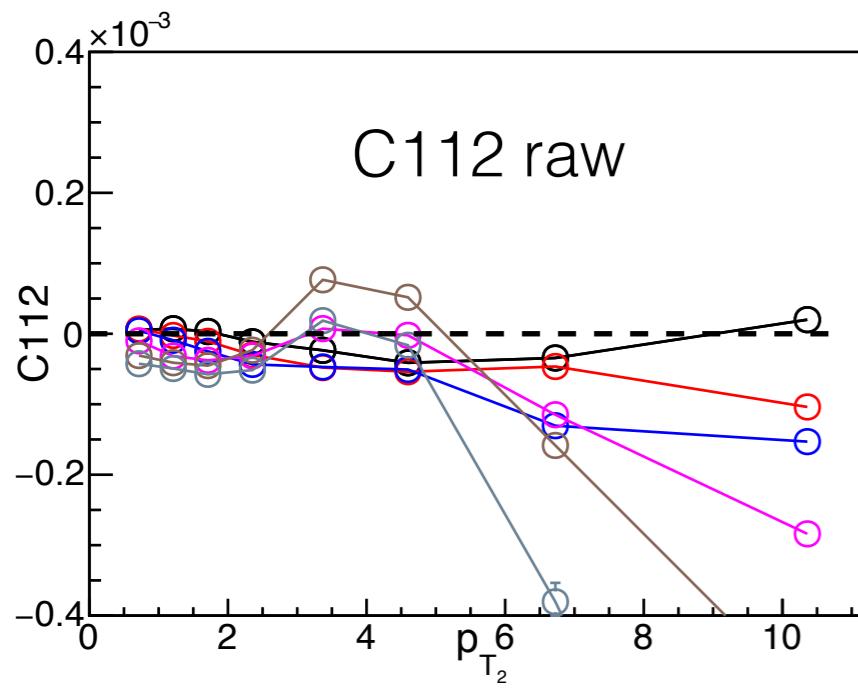
- $0.5 < p_{T_1} < 1.0$
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- $2.0 < p_{T_1} < 3.0$
- $3.0 < p_{T_1} < 4.0$
- $4.0 < p_{T_1} < 6.0$

- For fixed $-0.5 < p_{T_2} < 1.0$
- v_3^2 term is smaller by a factor of 100
- v_2^2 term is the main source of MC

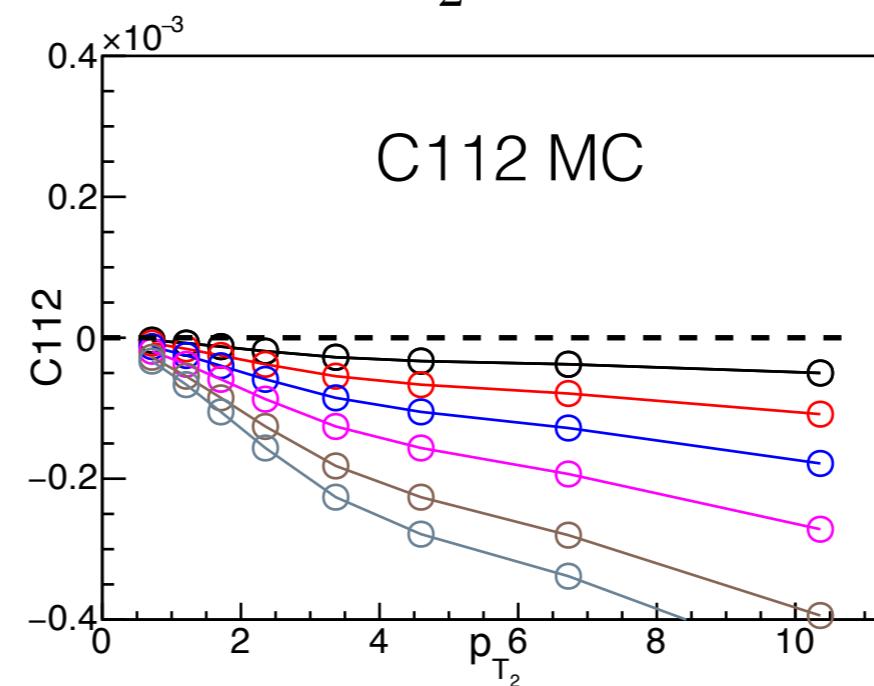
$$\begin{aligned}
 C_{123}^{MC} = & \frac{C}{2} p_{T_1} p_{T_2} [\mathbf{v}_1(p_{T_2}) \mathbf{v}_2(p_{T_1}) \mathbf{v}_3^*(p_{T_3}) + \mathbf{v}_3(p_{T_2}) \mathbf{v}_3^*(p_{T_3})] \\
 & + \frac{C}{2} p_{T_2} p_{T_3} [\mathbf{v}_1(p_{T_1}) \mathbf{v}_3(p_{T_2}) \mathbf{v}_4^*(p_{T_3}) + \mathbf{v}_1(p_{T_1}) \mathbf{v}_1(p_{T_2}) \mathbf{v}_2^*(p_{T_3})] \\
 & + \frac{C}{2} p_{T_1} p_{T_3} [\mathbf{v}_2(p_{T_1}) \mathbf{v}_2(p_{T_2}) \mathbf{v}_4^*(p_{T_3}) + \mathbf{v}_2(p_{T_2}) \mathbf{v}_2^*(p_{T_3})]
 \end{aligned}$$

Results - C112

20-30%



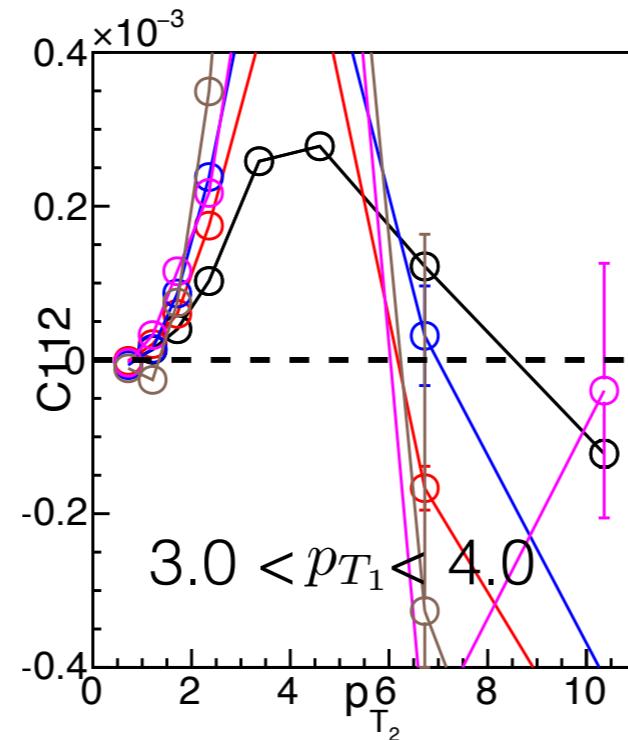
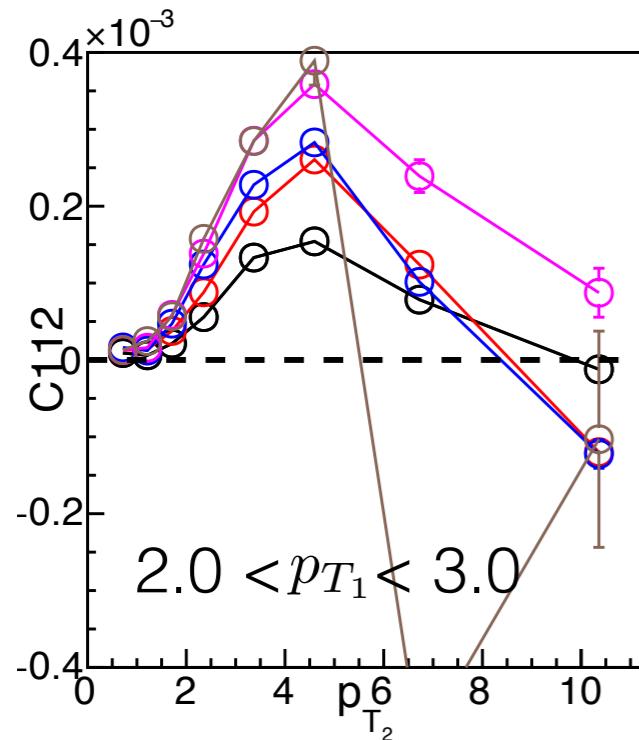
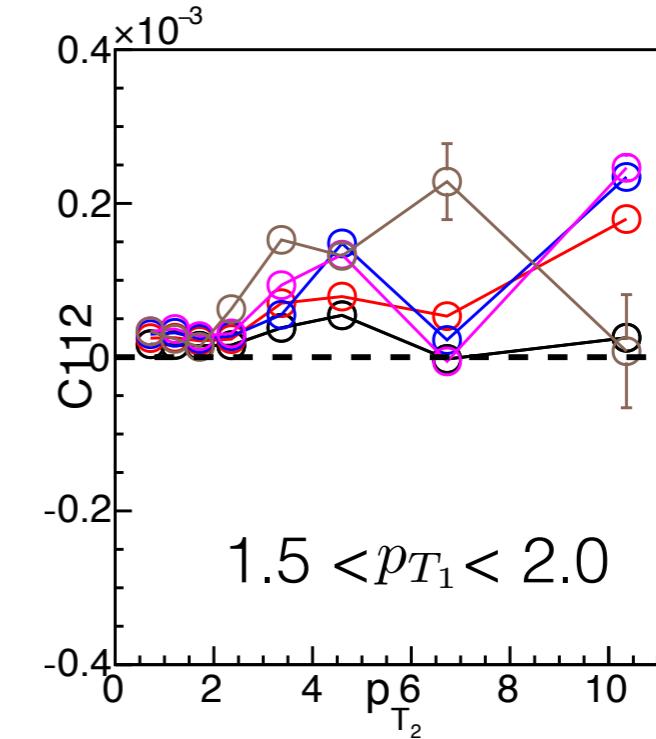
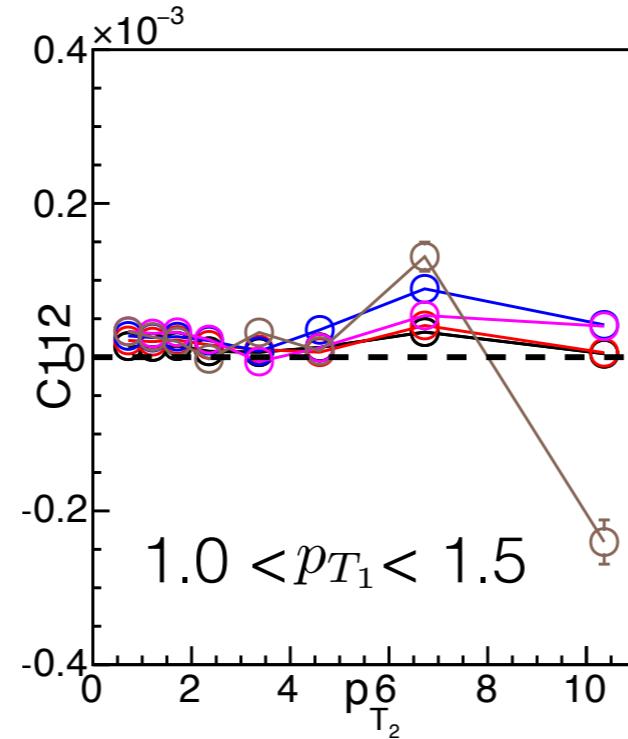
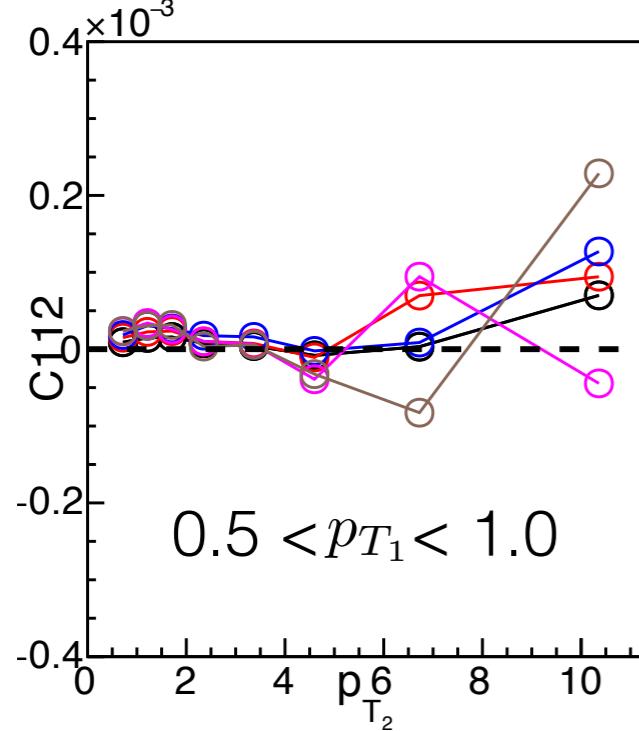
$$\begin{aligned}
 C_{112}^{raw} = & \mathbf{v}_1(p_{T_1}) * \mathbf{v}_1(p_{T_2}) * \mathbf{v}_2^*(p_{T_3}) \\
 & + \frac{C}{2} p_{T_1} p_{T_2} [\mathbf{v}_2(p_{T_1}) \mathbf{v}_2^*(p_{T_3}) + \mathbf{v}_2(p_{T_2}) \mathbf{v}_2^*(p_{T_3})] \\
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 & + \frac{C}{2} p_{T_1} p_{T_3} [\mathbf{v}_1(p_{T_2}) \mathbf{v}_2(p_{T_1}) \mathbf{v}_3^*(p_{T_3}) + \mathbf{v}_1(p_{T_2}) \mathbf{v}_1^*(p_{T_3})]
 \end{aligned}$$



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- $3.0 < p_{T_1} < 4.0$
- $4.0 < p_{T_1} < 6.0$

- C112 for different p_{T_1} and fixed $0.5 < p_{T_3} < 1.0$
- Significant MC contribution

C112_corr - Dependence on $p_{\{T\}}$

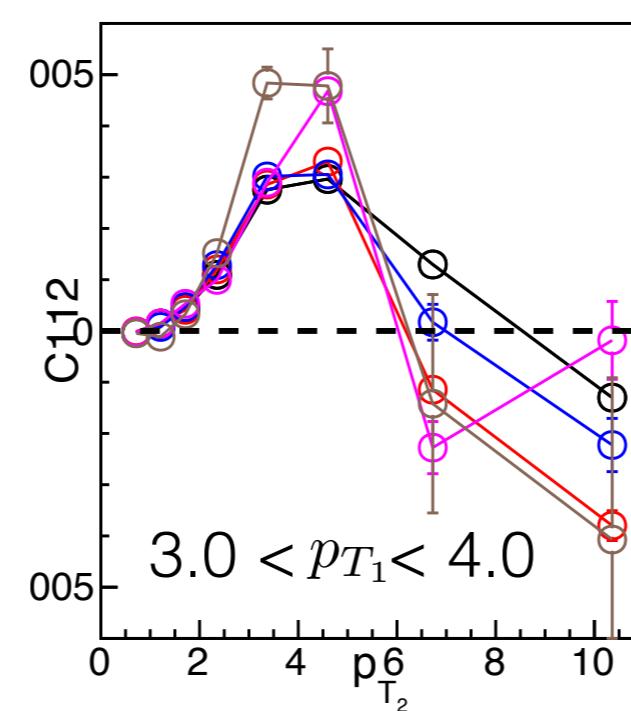
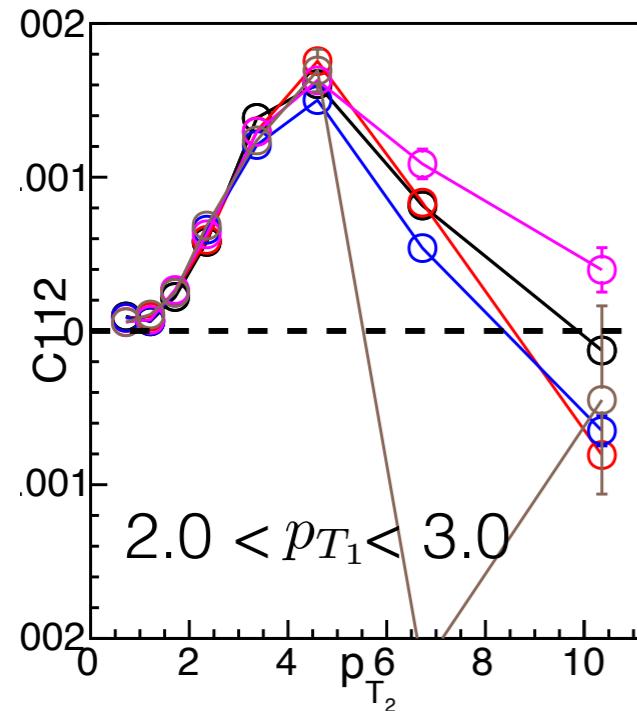
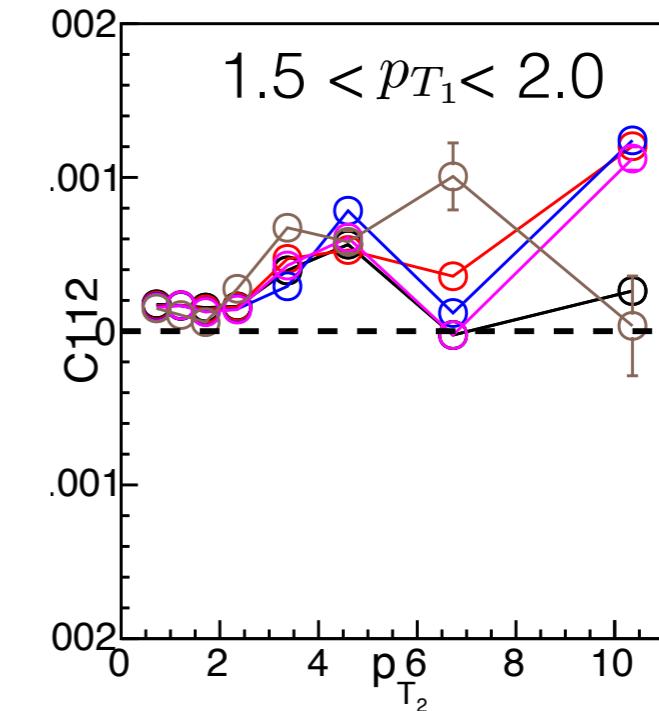
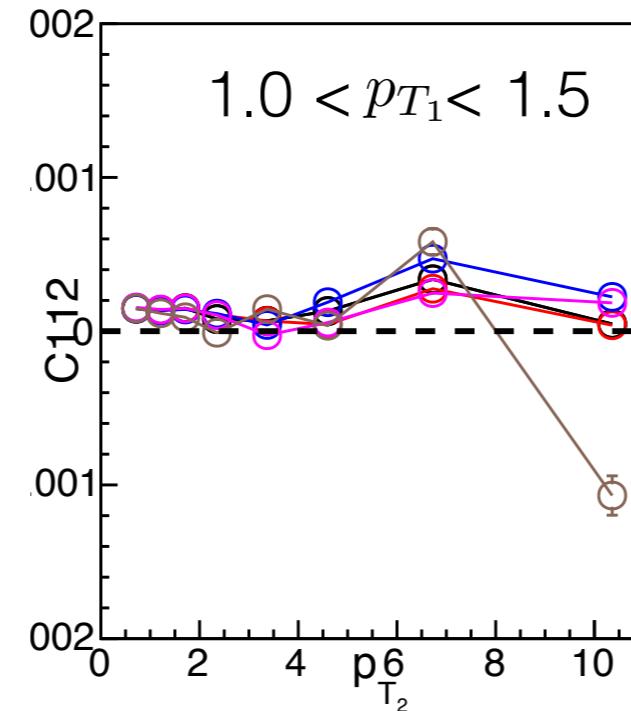
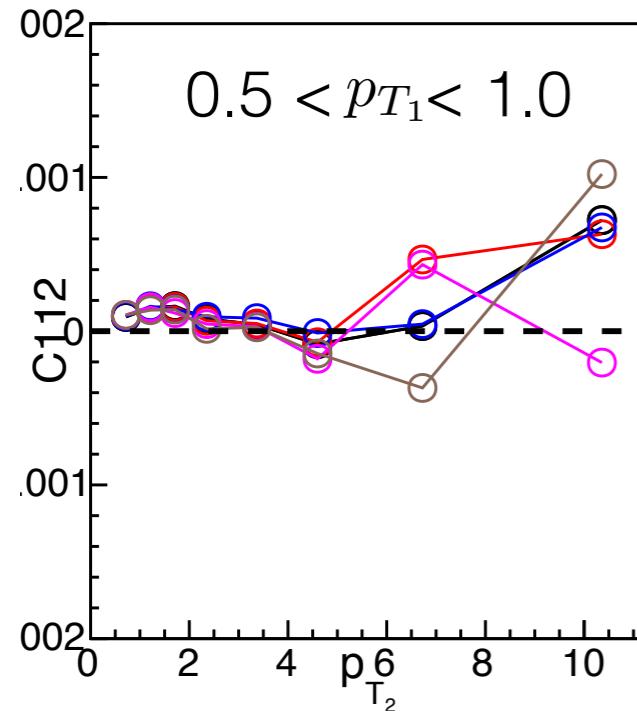


- $0.5 < p_{T_3} < 1.0$
- $1.0 < p_{T_3} < 1.5$
- $1.5 < p_{T_3} < 2.0$
- $2.0 < p_{T_3} < 3.0$
- $3.0 < p_{T_3} < 4.0$

- $C112(p_{\{T2\}})$ for different pk at fixed $p_{\{T1\}}$

- There seems little dependence on $p_{\{T3\}}$

C112/v2 - Dependence on p_{T3}



- $0.5 < p_{T_3} < 1.0$
- $1.0 < p_{T_3} < 1.5$
- $1.5 < p_{T_3} < 2.0$
- $2.0 < p_{T_3} < 3.0$
- $3.0 < p_{T_3} < 4.0$

- C112 after removal of MC
should be $\sim v1^*v1^*v2$

- C112/v2 - Dependence on p_{T3} is almost gone

Results - C123

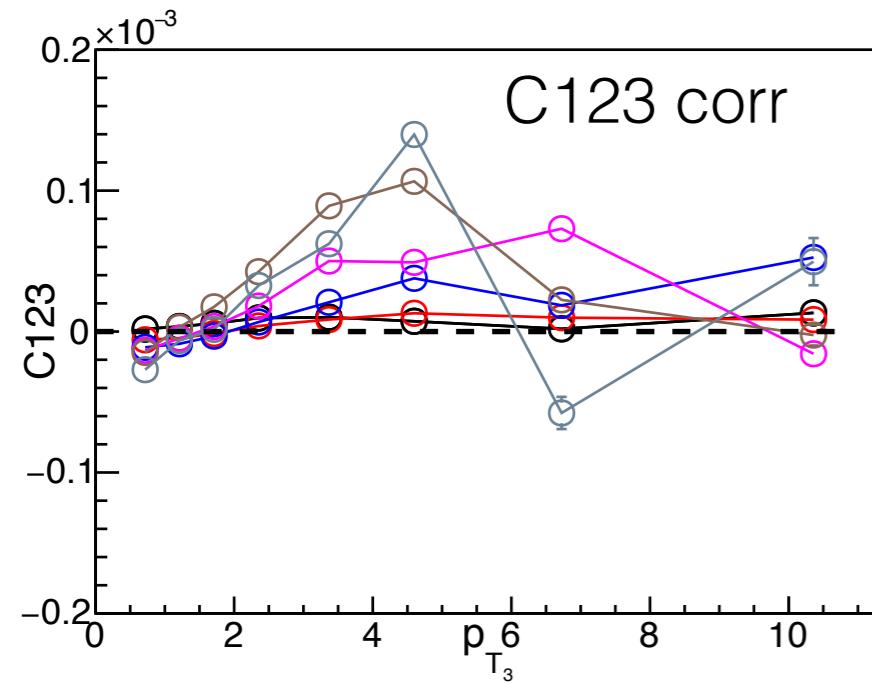
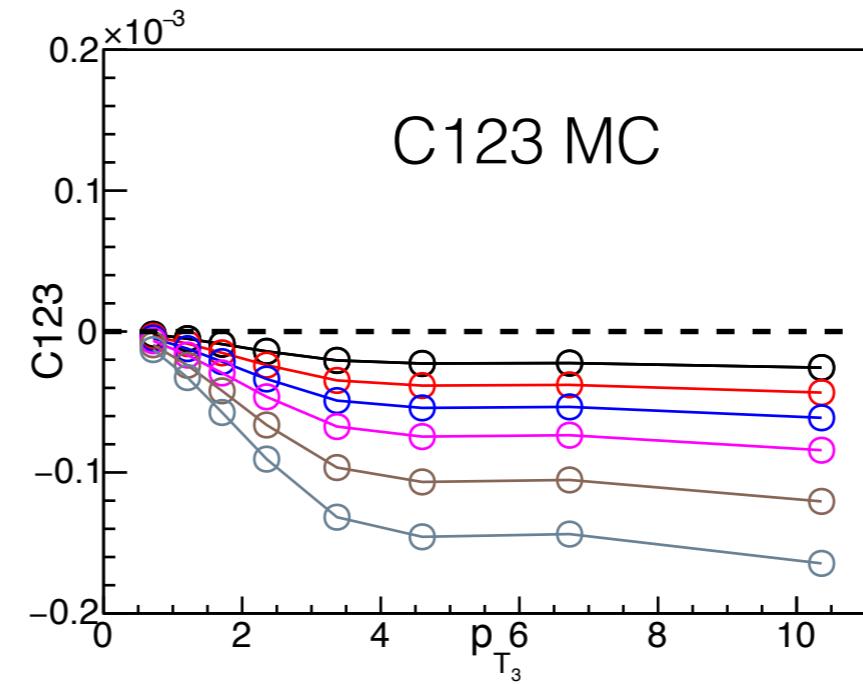
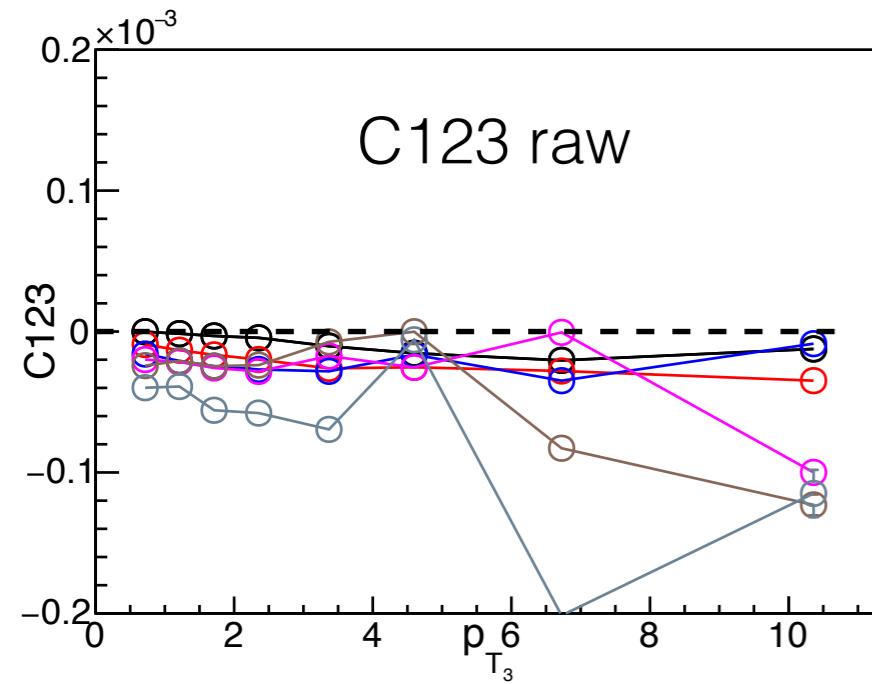
20-30%

$$C_{123}^{raw} = \mathbf{v}_1(p_{T_1}) * \mathbf{v}_2(p_{T_2}) * \mathbf{v}_3^*(p_{T_3})$$

$$+ \frac{C}{2} p_{T_1} p_{T_2} [\mathbf{v}_1(p_{T_2}) \mathbf{v}_2(p_{T_1}) \mathbf{v}_3^*(p_{T_3}) + \mathbf{v}_3(p_{T_2}) \mathbf{v}_3^*(p_{T_3})]$$

$$+ \frac{C}{2} p_{T_2} p_{T_3} [\mathbf{v}_1(p_{T_1}) \mathbf{v}_3(p_{T_2}) \mathbf{v}_4^*(p_{T_3}) + \mathbf{v}_1(p_{T_1}) \mathbf{v}_1(p_{T_2}) \mathbf{v}_2^*(p_{T_3})]$$

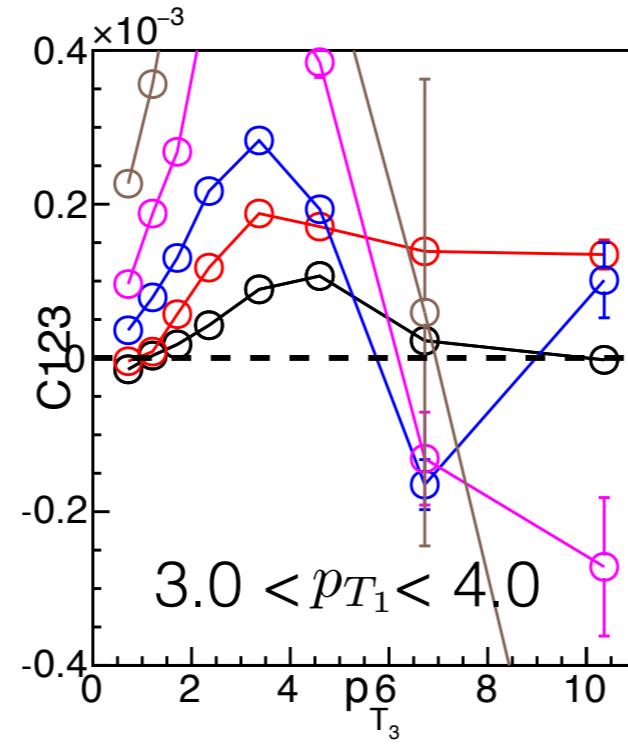
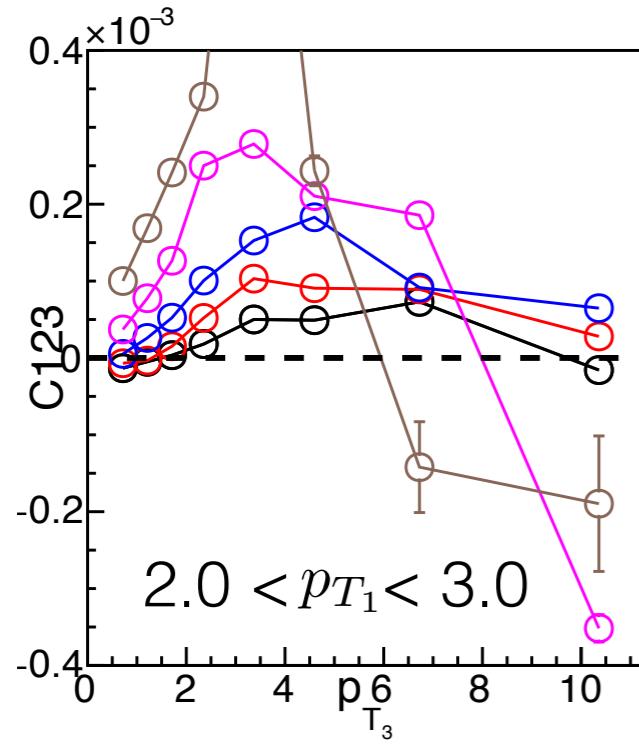
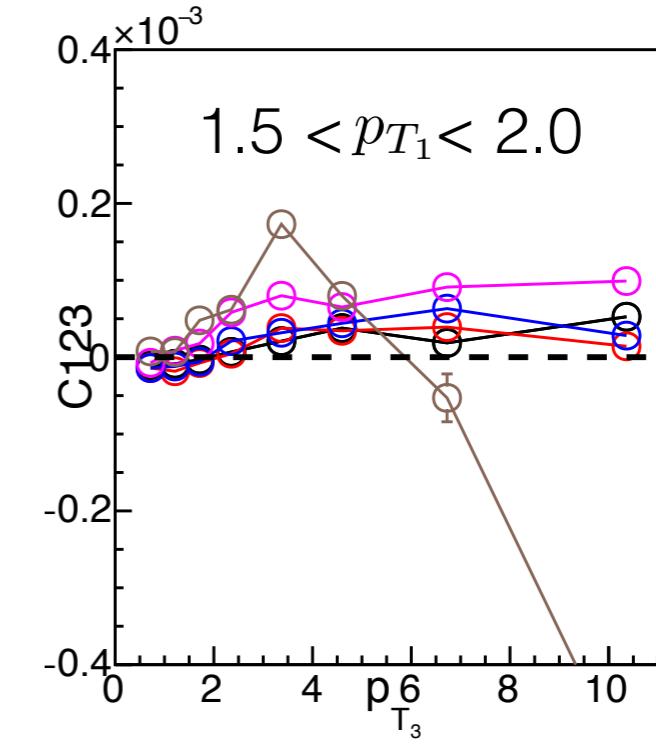
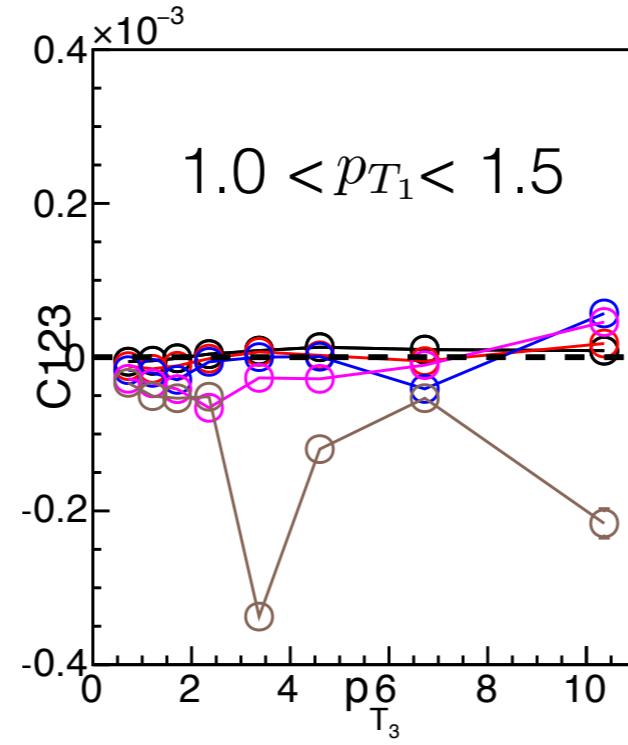
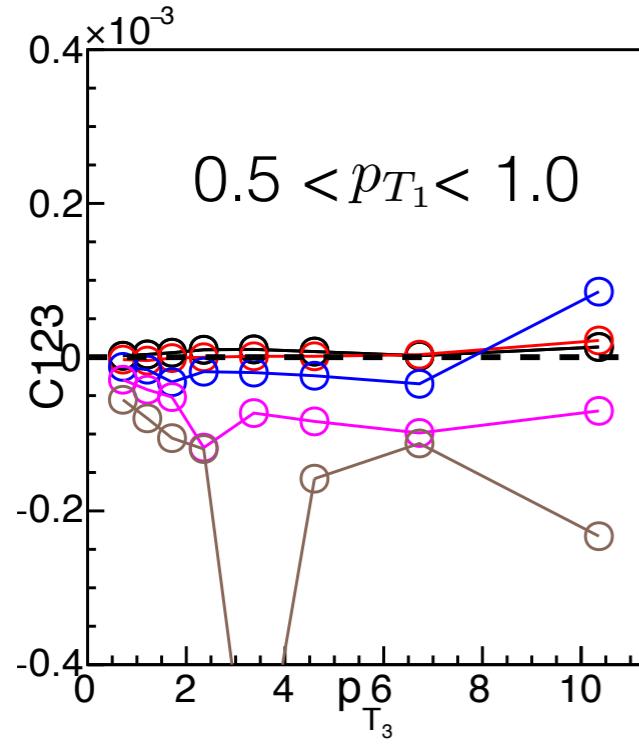
$$+ \frac{C}{2} p_{T_1} p_{T_3} [\mathbf{v}_2(p_{T_1}) \mathbf{v}_2(p_{T_2}) \mathbf{v}_4^*(p_{T_3}) + \mathbf{v}_2(p_{T_2}) \mathbf{v}_2^*(p_{T_3})]$$



- $0.5 < p_{T_1} < 1.0$
- $1.0 < p_{T_1} < 1.5$
- $1.5 < p_{T_1} < 2.0$
- $2.0 < p_{T_1} < 3.0$
- $3.0 < p_{T_1} < 4.0$
- $4.0 < p_{T_1} < 6.0$

- MC subtracted C123 for different p_{T_1} and fixed $0.5 < p_{T_3} < 1.0$
- Significant MC contribution

C123_corr - Dependence on p_T

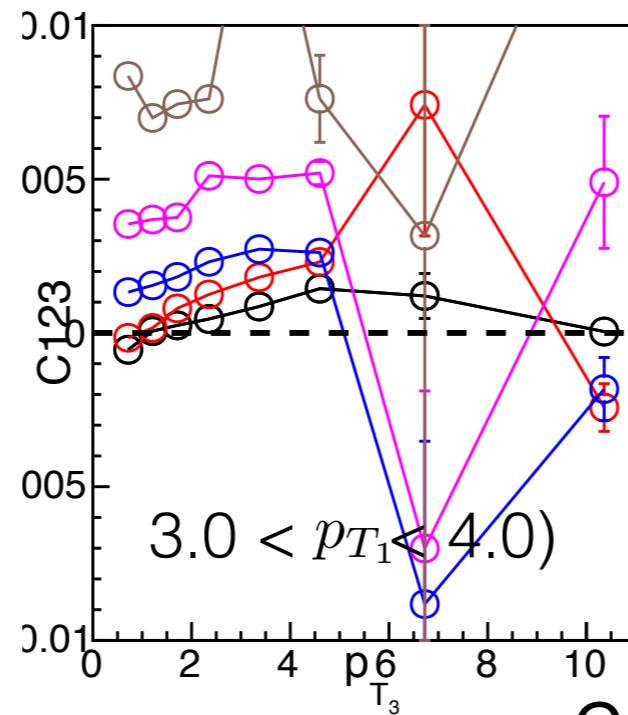
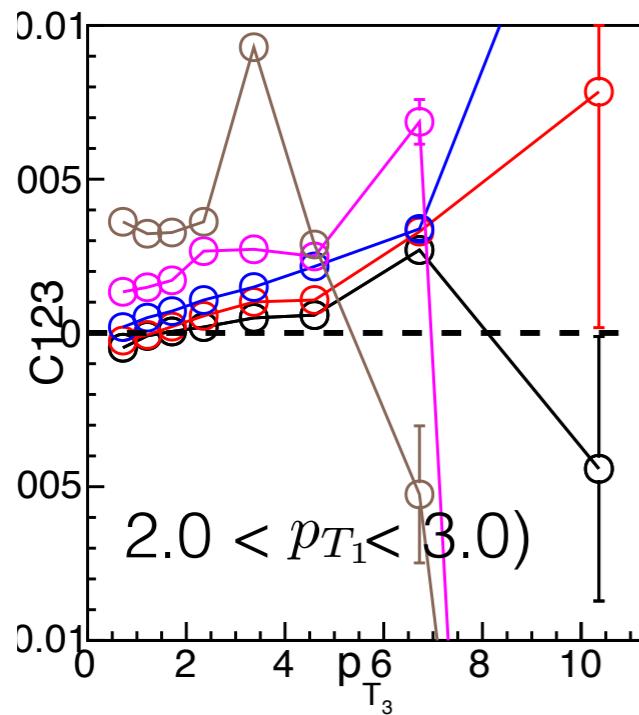
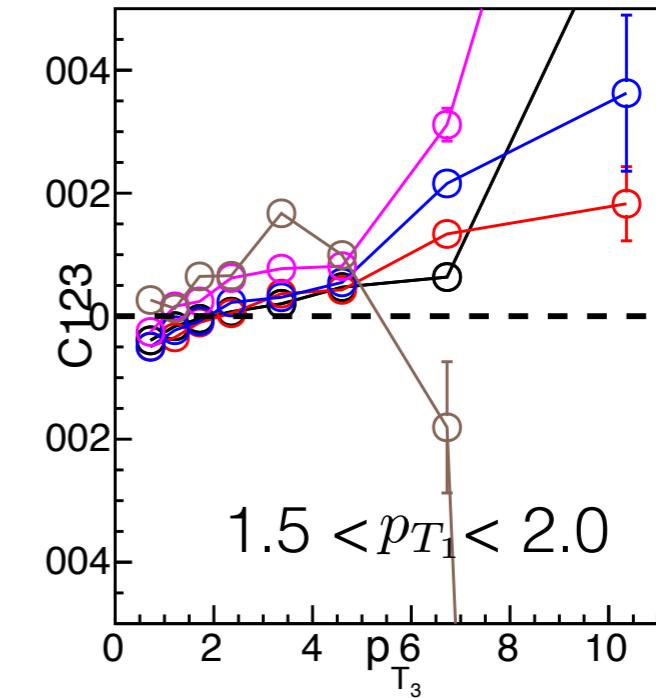
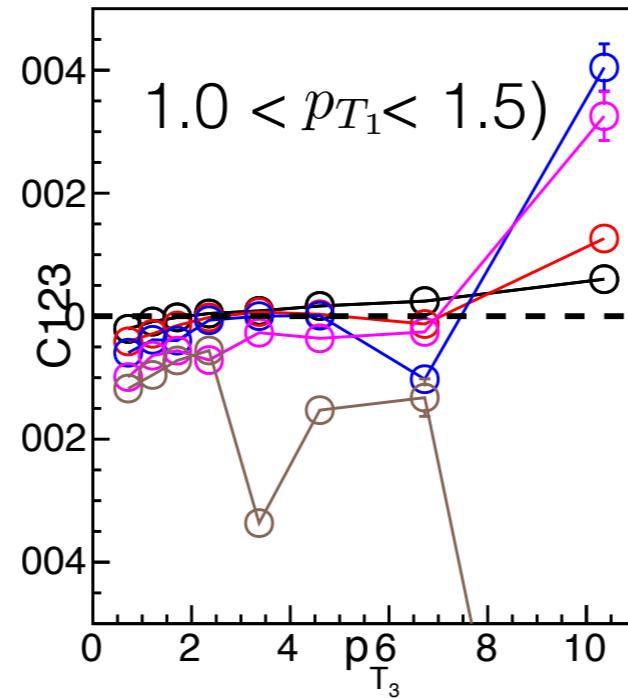
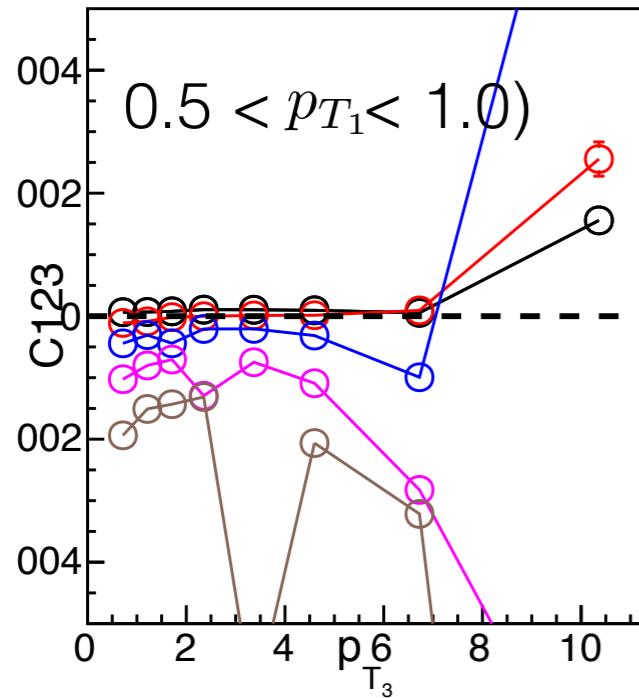


- $0.5 < p_{T_2} < 1.0$
- $1.0 < p_{T_2} < 1.5$
- $1.5 < p_{T_2} < 2.0$
- $2.0 < p_{T_2} < 3.0$
- $3.0 < p_{T_2} < 4.0$

- C123(pk) for different pj at fixed pi

- Increase in pk shows increase in magnitude of C123

C123/v3 - Dependence on p_{T3}

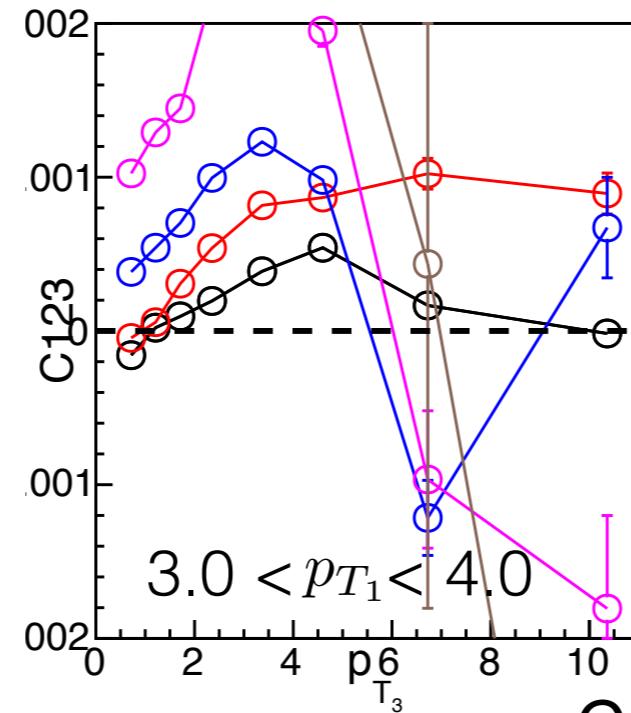
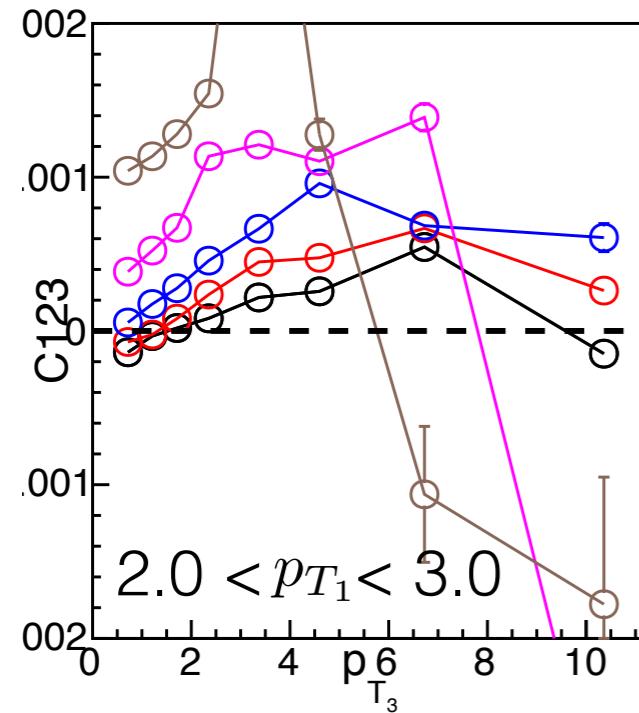
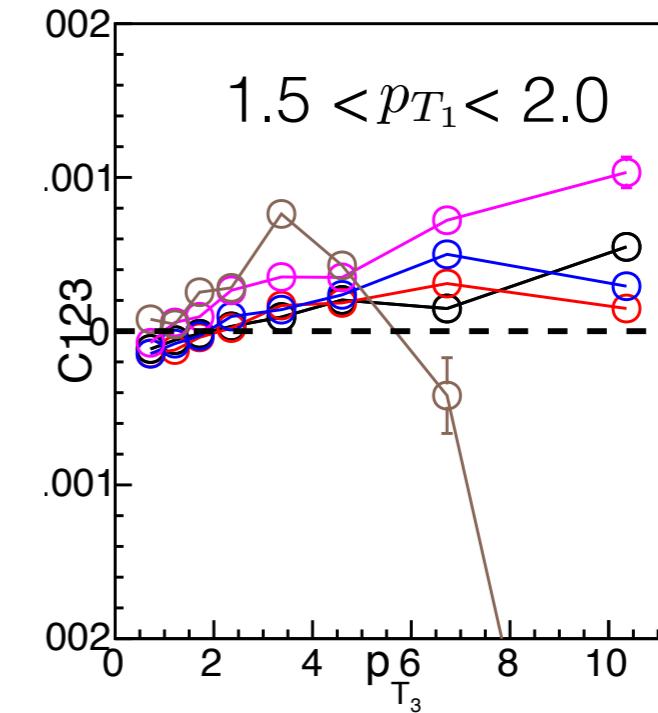
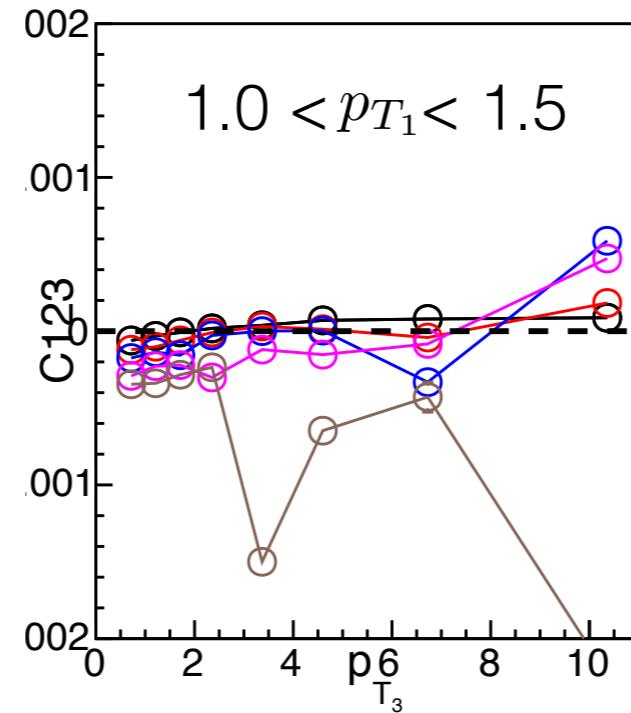
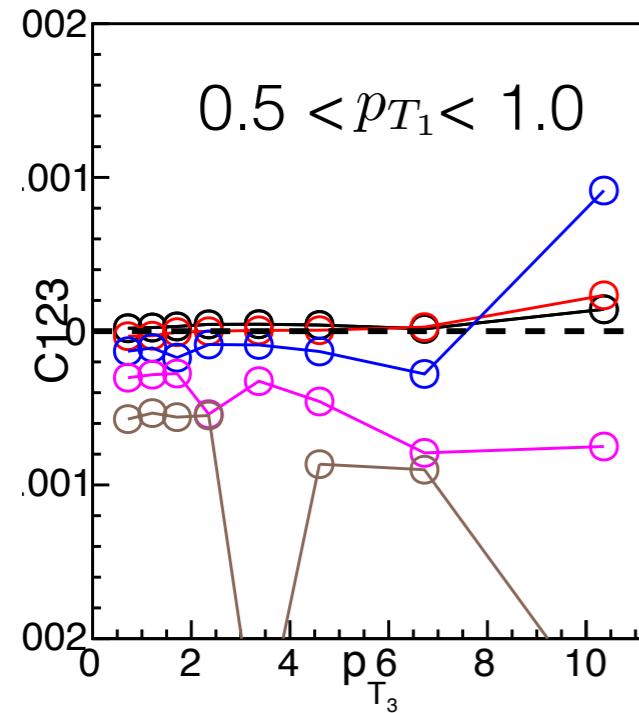


- $0.5 < p_{T_2} < 1.0$
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- $3.0 < p_{T_2} < 4.0$

- C123/v3(p_{T3}) for different p_{T2}
- C112/v3 removes some dependence on p_{T3}

- C123 after removal of MC should be $\sim v1^*v2^*v3$

C123/v2 - Dependence on p_{T2}



- $0.5 < p_{T_2} < 1.0$
- $1.0 < p_{T_2} < 1.5$
- $1.5 < p_{T_2} < 2.0$
- $2.0 < p_{T_2} < 3.0$
- $3.0 < p_{T_2} < 4.0$

- C123/v2(p_{T3}) for different p_{T2}
- C112/v2 scaling doesn't remove dependence on p_{T2}

- C123 after removal of MC should be $\sim v1^*v2^*v3$

Summary

- Did 2PC and 3PC in ATLAS 2.76TeV Pb+Pb
- 2PC results agree with published results
- Derived momentum conservation corrections in detail
- Simultaneous fitting of V11 to obtain $v_1(pT)$ and coefficient C
- Separated MC from flow signal in C112 and C123
- Observed significant MC in C112 and C123
- C112 could be broken down into $\sim v_1^*v_1^*v_2$
- C123 has some contamination other than $\sim v_1^*v_2^*v_3$

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- C112 could be broken down into $\sim v_1^*v_1^*v_2$
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Next Step

- Proper breakdown of C112 and C123
- Physical interpretation of 3PC
- Charge Dependence study
- Systematics