Initial-state angular asymmetries in pA collisions

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based on work done with Adrian Dumitru
arXiv:1406.5781
(Nuclear Physics A 933 (2015) 212–228)

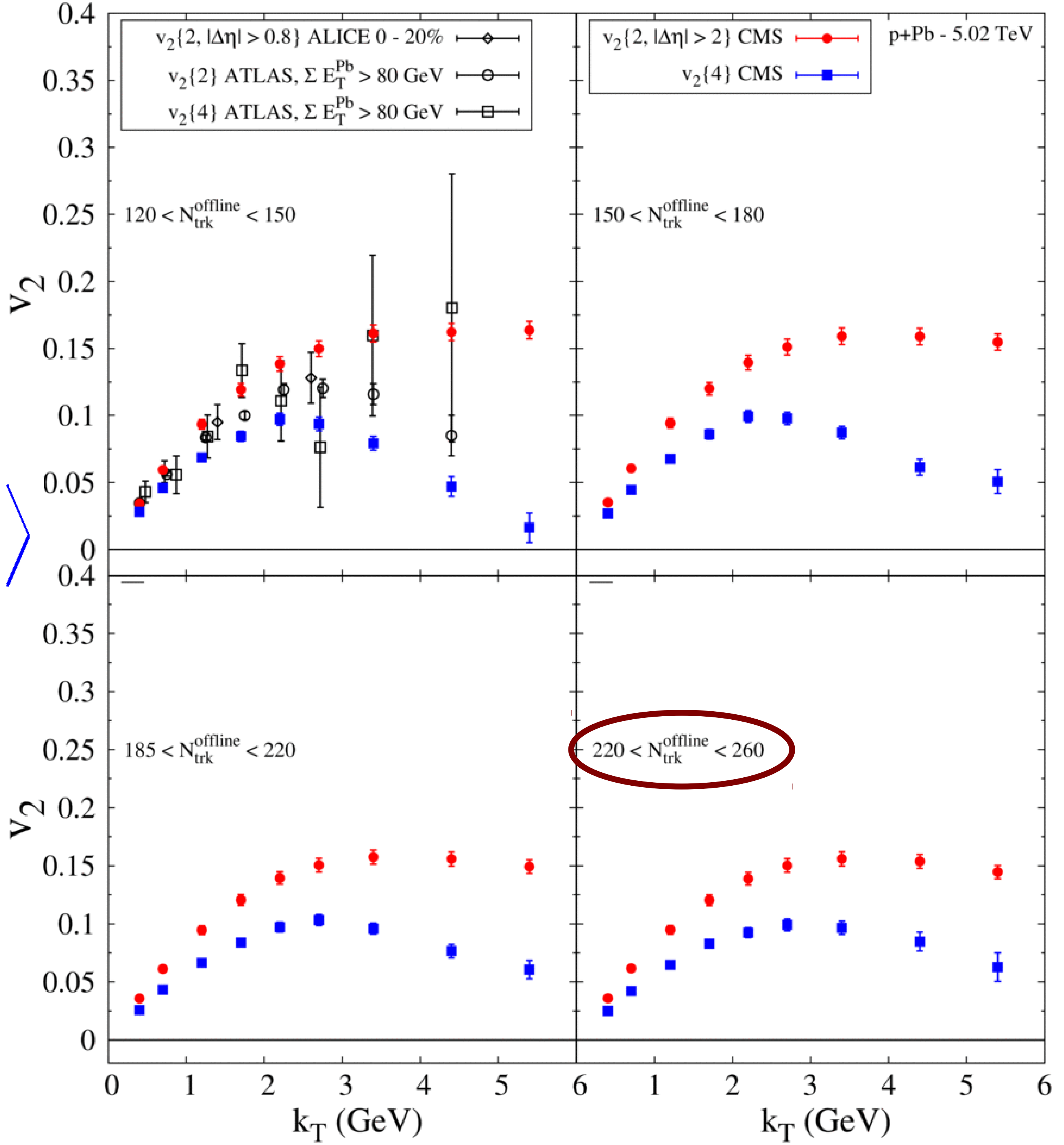
IS2014, Dec., 3rd – 7th, 2014, Napa, CA

Outline:

- Rotational symmetry breaking and initial-state v_n generated by $\vec{E}$ field "domains"
- Single domain case
- Domain model
- Genuine m-particle correlation
- Summary

ATLAS, ALICE & CMS data for $v_2(p_T)$ in high mult. p+Pb @ 5TeV

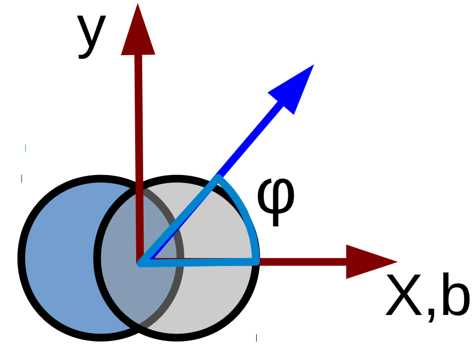
$$v_n\{2\}^2 = \left\langle e^{in(\phi_1-\phi_2)} \right\rangle$$



Angular asymmetries v_n

$$v_n = \langle \cos n\phi \rangle$$

avg on 1-particle distribution with $\phi \to -\phi$ symmetry



classical impact parameter picture

2D rotational symmetry spontaneously broken:

Non-central collisions → emergence of an event plane given by $\vec{b} - z$

- for even n = 2m: $\langle \cos n\phi \rangle = +\langle \cos n(\phi + \pi) \rangle$ P = +
- for odd n = 2m+1: $\langle \cos n\phi \rangle = -\langle \cos n(\phi + \pi) \rangle$ P = –

Spontaneous breaking of rotational symmetry : $\vec{E}$ field "domains"

Emergence of an event plane given by $\vec{E} - z$

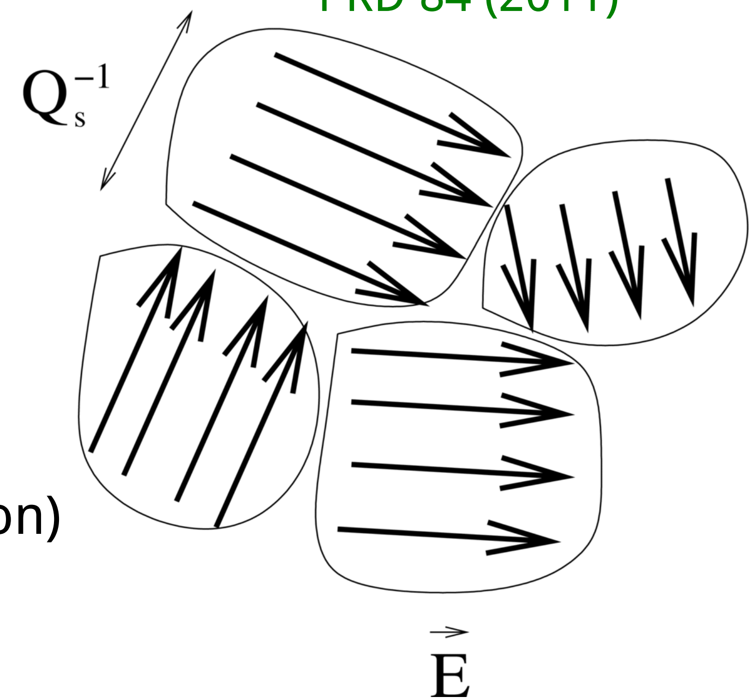
Kovner & Lublinsky: PRD 84 (2011)

- $\vec{E}$ field "domains": generates even v_n

$$D(\vec{r}) = \left\langle e^{-\frac{1}{2N_c}\mathrm{Tr}(g\,\vec{r}\cdot\vec{E})^2} \right\rangle$$

$$g^2\, r^i r^j \left\langle \mathrm{tr}\, E^i E^j \right\rangle \sim r^2\, Q_s^2 \left[1 + \mathcal{A}(\cos^2\phi_r - \frac{1}{2})\right]$$

(avg. over all configurations but for a fixed $\vec{E}$ orientation)



- coherent fluctuation in Q_s : generates odd v_n → odderon (not this talk)

- **Angular dependence of *single-particle* distribution, *any* particle correlated with "event plane"**

Single-inclusive distribution in q+A elastic scattering:

$$\frac{dN}{d^2k} = \int d^2r \, e^{-i\vec{k}\cdot\vec{r}} \, D(\vec{r})$$

dipole S-matrix (real part)

Qualitative work: no final state effects and no proton PDF convolution

MV model dipole:

polarization amplitude

$$D(\vec{r}) = \exp\left[-\frac{1}{4}r^2Q_s^2(1-\mathcal{A}+2\mathcal{A}\cos^2\phi_r)\log\frac{1}{r\Lambda}\right]$$

Fourier transform at $k_T \gg Q_s$:

$$\frac{dN}{k_T dk_T\, d\phi_k} = \frac{1}{2\pi}\frac{Q_s^2}{k_T^4}\ \left[1 - 2\mathcal{A} + 4\mathcal{A}\cos^2\phi_k\right]$$

Azimuthal harmonics :

- $v_2(k_T) = \mathcal{A}\left(1 + \frac{\#}{k_T^2}\right)$

- $v_4(k_T) \sim 1/k_T^2$

*** no v_{2n} without polarization! ***

Fourier transform at $k_T < Q_s$:

$$\frac{dN}{k_T dk_T\, d\phi_k} \sim \exp\left[-\frac{k_T^2}{Q_s^2 \log Q_s/\Lambda}\left(\frac{\cos^2\phi_k}{1+\mathcal{A}} + \frac{\sin^2\phi_k}{1-\mathcal{A}}\right)\right]$$

Azimuthal harmonics :

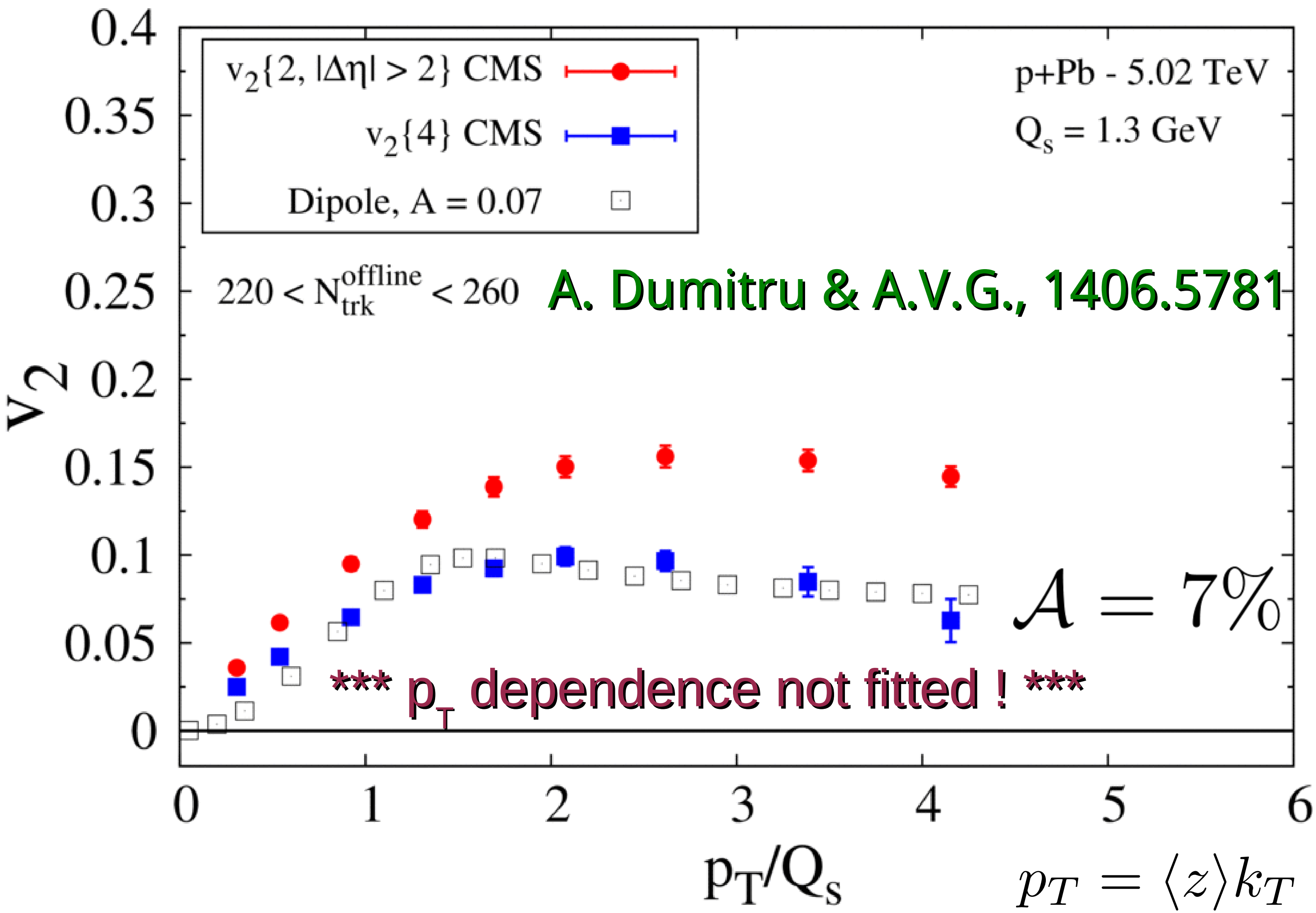
$$v_2(k_T) = \frac{I_1\left(\frac{\mathcal{A}}{1-\mathcal{A}^2}\frac{k_T^2}{Q_s^2 \log Q_s/\Lambda}\right)}{I_0\left(\frac{\mathcal{A}}{1-\mathcal{A}^2}\frac{k_T^2}{Q_s^2 \log Q_s/\Lambda}\right)} \simeq \frac{\mathcal{A}}{2}\,\frac{k_T^2}{Q_s^2 \log Q_s/\Lambda}$$

$$v_4(k_T) = \frac{I_2\left(\frac{\mathcal{A}}{1-\mathcal{A}^2}\frac{k_T^2}{Q_s^2 \log Q_s/\Lambda}\right)}{I_0\left(\frac{\mathcal{A}}{1-\mathcal{A}^2}\frac{k_T^2}{Q_s^2 \log Q_s/\Lambda}\right)} \simeq \frac{\mathcal{A}^2}{8}\left(\frac{k_T^2}{Q_s^2 \log Q_s/\Lambda}\right)^2$$

- $v_2 \sim \mathcal{A}\, k_T^2$
- $v_4 \sim (v_2)^2$ → suppressed

*** no v_{2n} without polarization! ***

Numerical Fourier transform: single domain case



$p_T = \langle z \rangle k_T = k_T/2$

- $\mathcal{A} \sim 7\%$
- $v_4 < 1\%$ –try domain model

Domain model :

$$v_n^2\{2\}\, e^{i\psi} \equiv \left\langle e^{in(\phi_1-\phi_2)} \right\rangle$$
$$= \frac{1}{N} \int \frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi} e^{in\phi_1} e^{-in\phi_2} \frac{dN}{k_T dk_T\, d\phi_1}\frac{dN}{k_T dk_T\, d\phi_2}$$

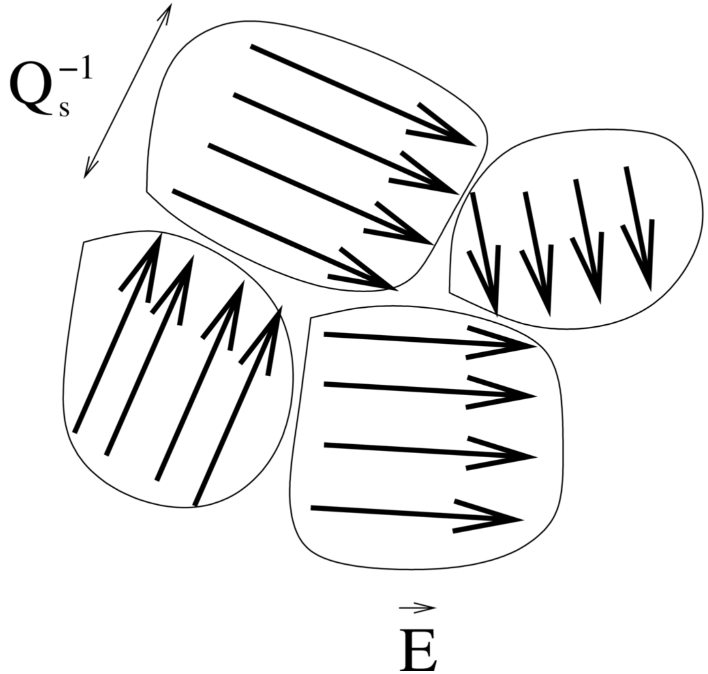
+ two-particle correl. → in a couple of slides

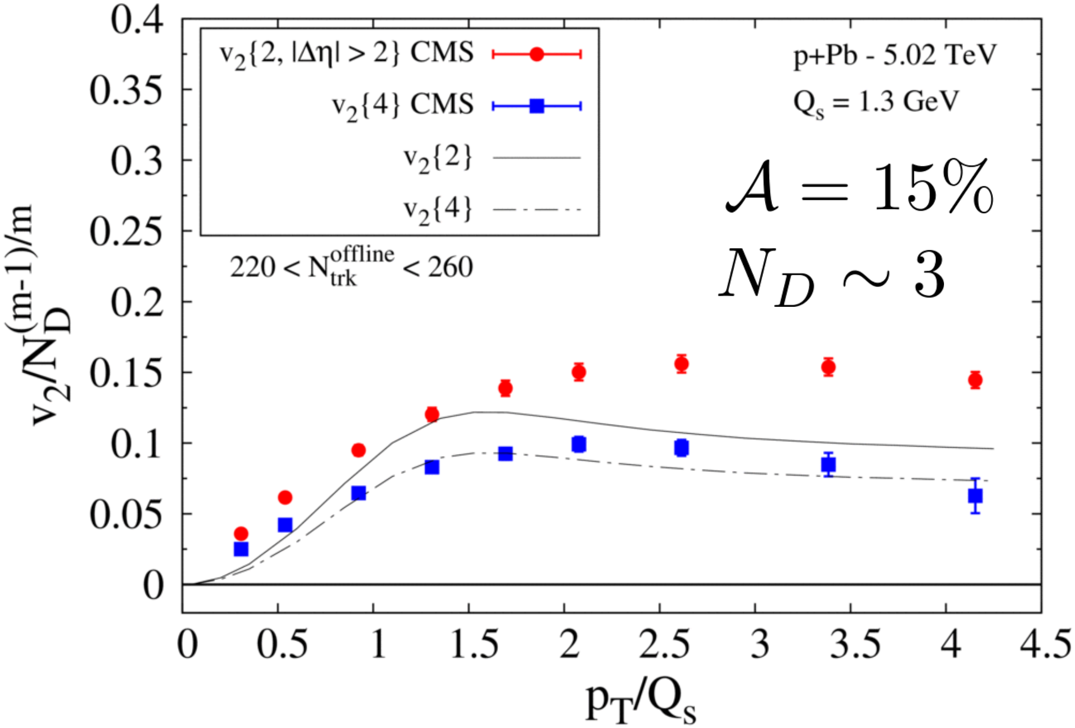
$$(v_n\{m\})^m = (v_n\{1\})^m$$ (all m particles in same domain)

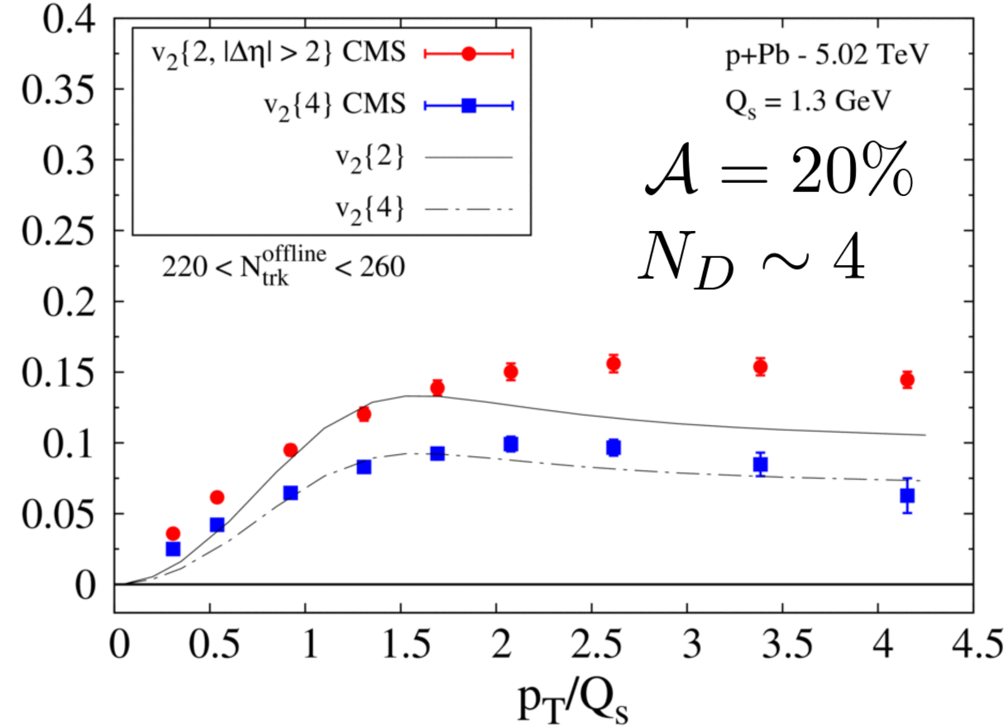
$$= 0$$ (≥1 particle in other domain)

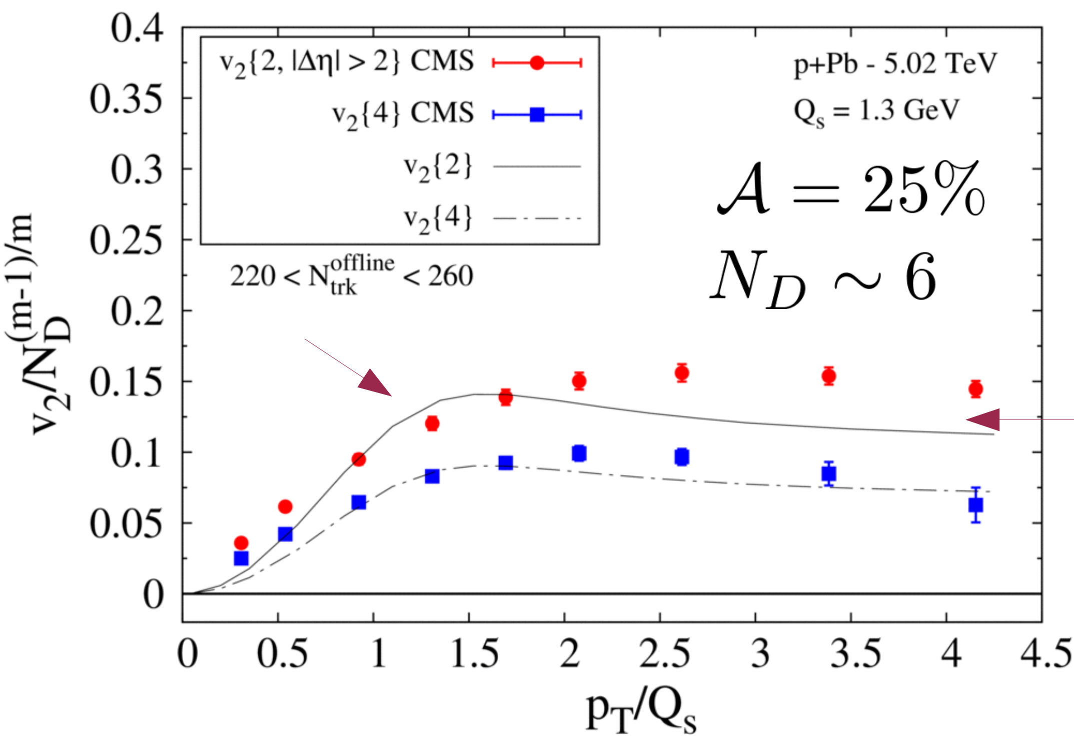
$$v_n\{m\} = \frac{v_n\{1\}}{N_D^{(m-1)/m}}$$

probability of having all m particles in same domain





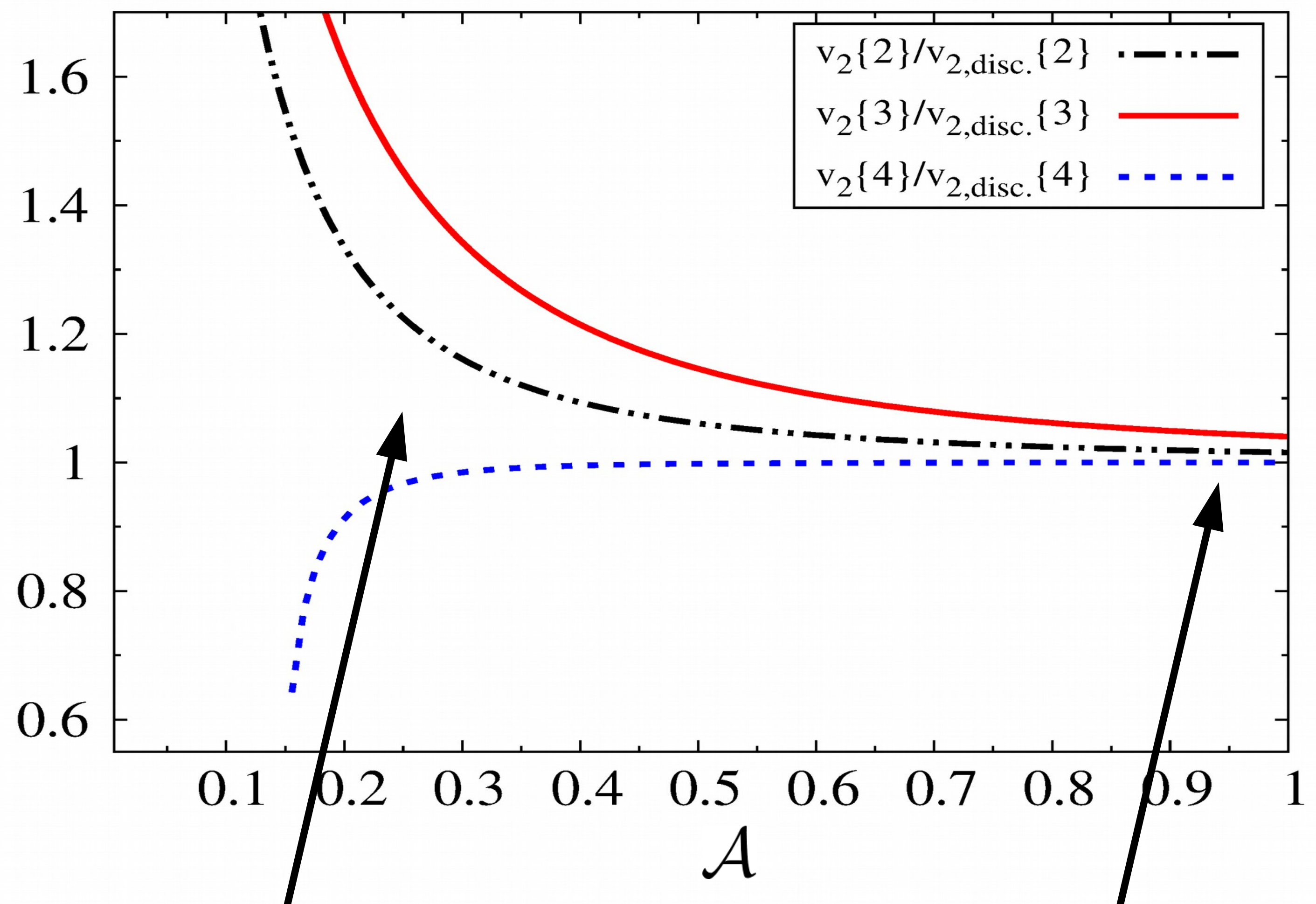




- $\mathcal{A} \sim 15\% - 25\%$
- $N_D \sim 3 - 6$

Undershoots v2{2}
–corrections

How about genuine multi-particle correlations?



"full v2{m}"
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factorized

Strong correlations

Factorization limit

Genuine mult-particle correlations cont'd

A.~Dumitru, L.~McLerran and V.~Skokov, arXiv:1410.4844 [hep-ph].

$$c_2\{2\} = \langle e^{2i(\phi_1-\phi_2)} \rangle$$

$$c_2\{4\} = \langle e^{2i(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle - 2\langle e^{2i(\phi_1-\phi_3)} \rangle \langle e^{2i(\phi_2-\phi_4)} \rangle$$

From MV model (high p_T):

2-part. corr. $\longrightarrow$ $\langle S \rangle \sim \left(\frac{(ig)^2}{2N_c} \right)^2 \left\langle \mathrm{tr}\,(\vec{r}_1 \cdot \vec{E}(\vec{b}_1))^2 \; \mathrm{tr}\,(\vec{r}_2 \cdot \vec{E}(\vec{b}_2))^2 \right\rangle$

$$(v_2\{2\})^2 = c_2\{2\} \equiv \frac{1}{N_D}\left((v_2\{1\})^2 + \frac{1}{4(N_c^2-1)} \right) = \frac{1}{N_D}\left(\mathcal{A}^2 + \frac{1}{4(N_c^2-1)} \right)$$

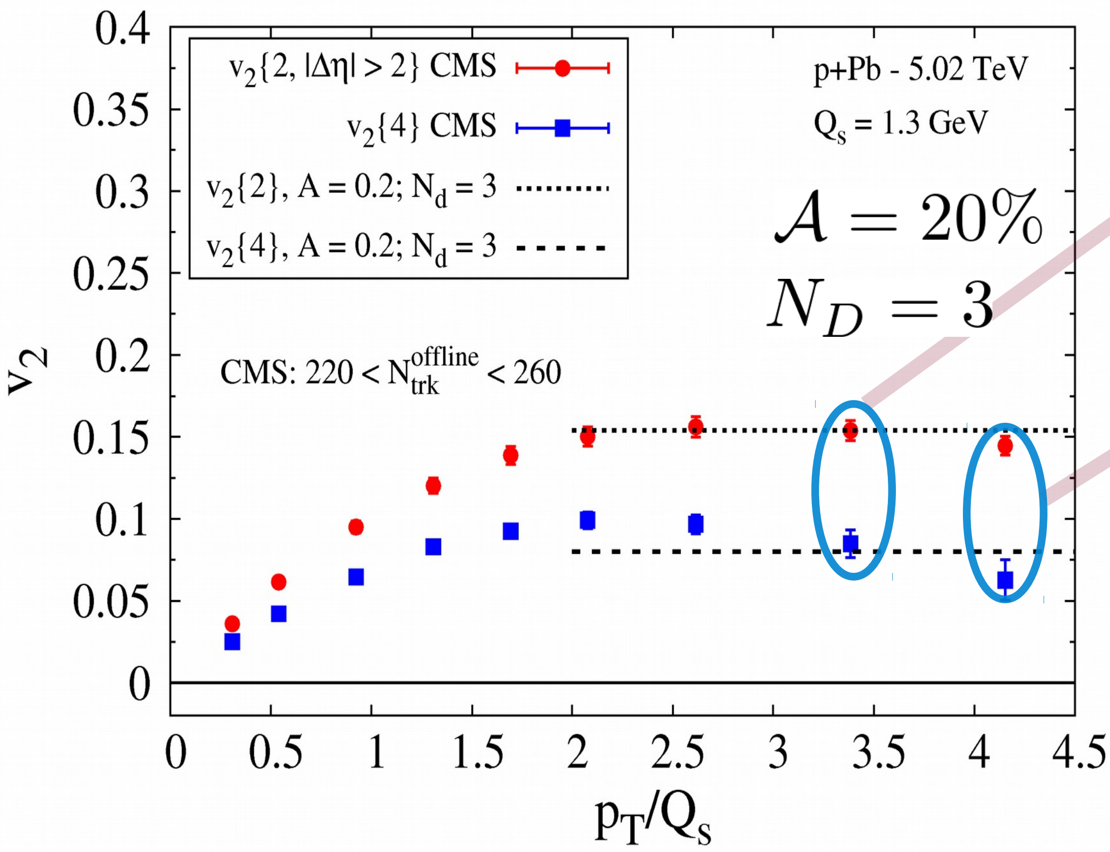
disconnected contribution (i.e. factorizable)

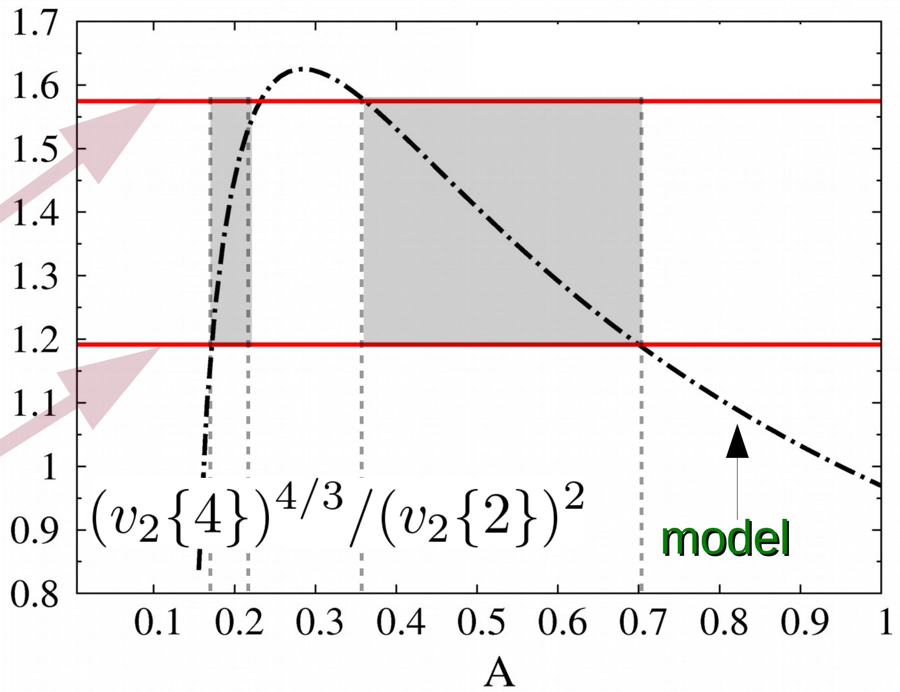
connected contribution

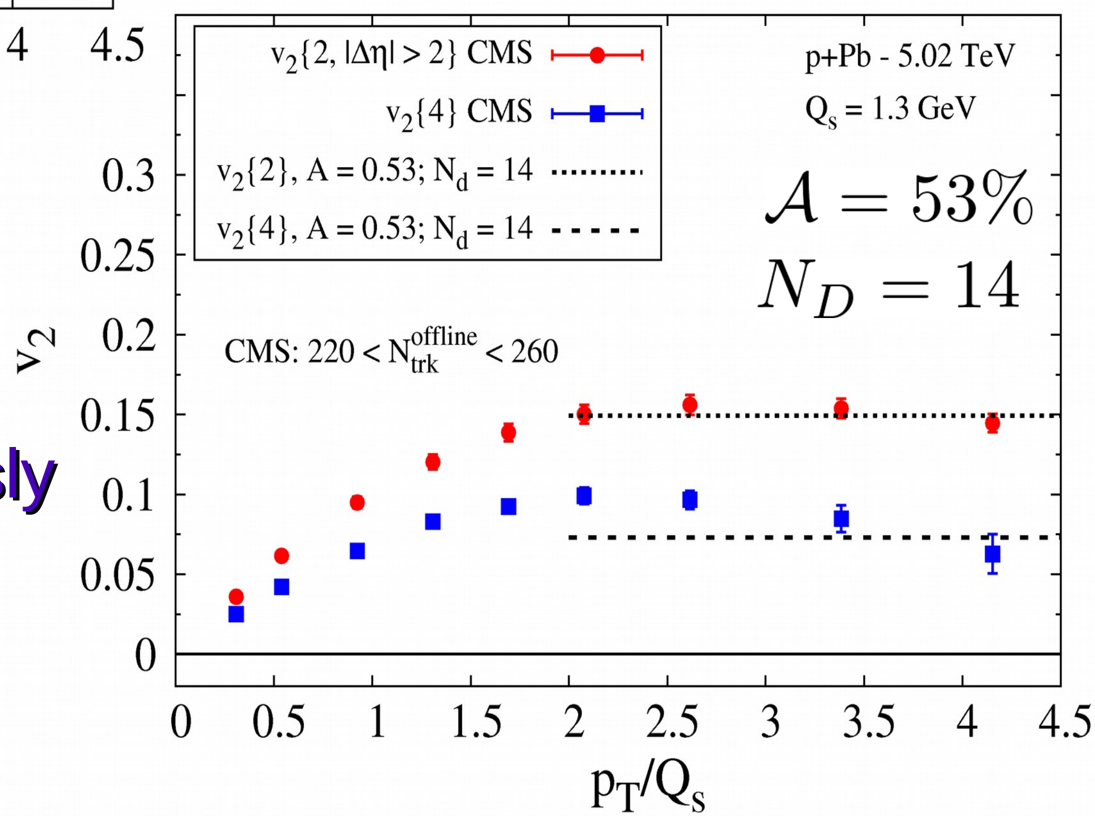
$$(v_2\{4\})^4 \equiv -c_2\{4\} = \frac{1}{N_D^3}\left((v_2\{1\})^4 - \frac{1}{4(N_c^2-1)^3} \right) = \frac{1}{N_D^3}\left(\mathcal{A}^4 - \frac{1}{4(N_c^2-1)^3} \right)$$

(around $c_2\{4\}$~0)

More details → Adrian's and Vladimir's talks







- Corrections improve the high-pt region
- $v_2\{2\}$ and $v_2\{4\}$ simultaneously
- Two solutions for $\mathcal{A}$

How about 3-particle correlations ? (again: high p_T)

$$c_2\{3\} = \left\langle e^{2i(\phi_1+\phi_2-2\phi_3)} \right\rangle$$

with Dumitru & Skokov

requires v4-like contribution from particle 3 → expand S-matrix to order r_1^2, r_2^2, r_3^4

$$\frac{1}{2}\left(\frac{(ig)^2}{2N_c}\right)^4 \left\langle \mathrm{tr}\,(\vec{r}_1\cdot\vec{E}(\vec{b}_1))^2\ \mathrm{tr}\,(\vec{r}_2\cdot\vec{E}(\vec{b}_2))^2\ \left[\mathrm{tr}\,(\vec{r}_3\cdot\vec{E}(\vec{b}_3))^2\right]^2 \right\rangle$$

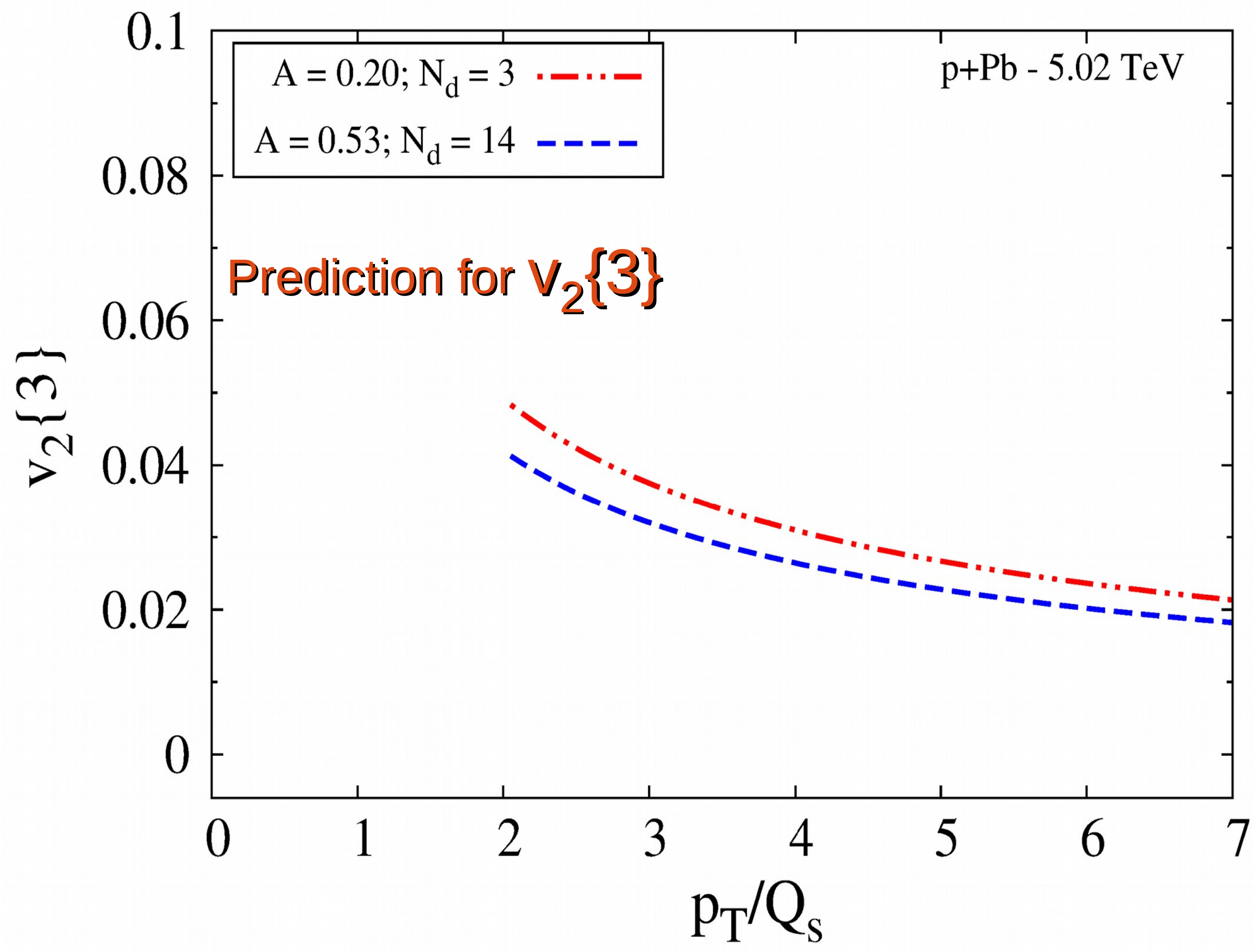
gives ($\mathcal{A} \sim 1/N_c$):

$$c_2\{3\} \sim \frac{Q_s^2}{k_{\perp 3}^2}\frac{1}{N_D^2}\left[\frac{1}{2}\mathcal{A}^4 + \frac{1}{2}\mathcal{A}^2\frac{1}{N_c^2-1} + \frac{1}{16}\left(\frac{1}{N_c^2-1}\right)^2\right]$$

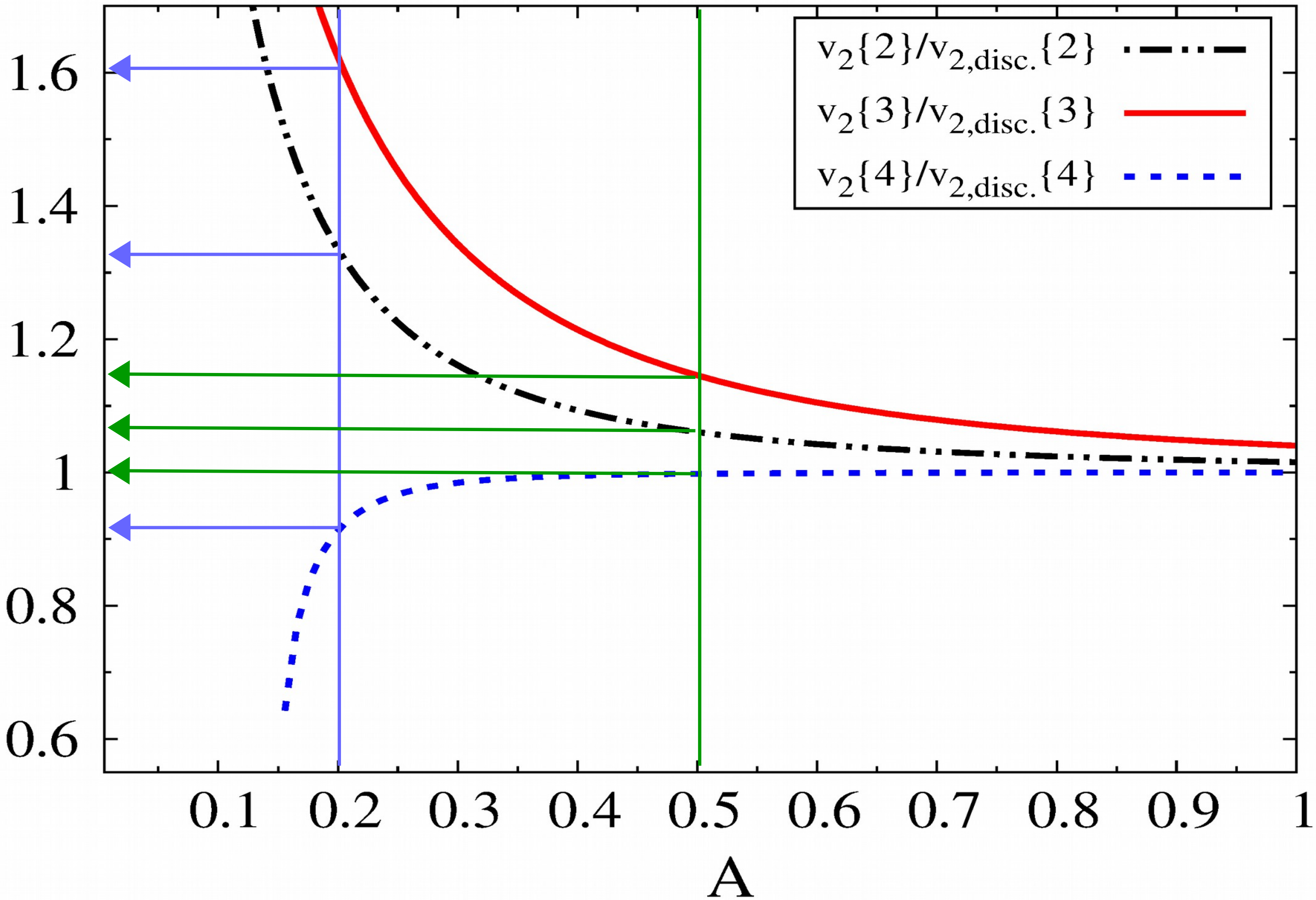
disconnected, 4 dipoles

3-particle connected, $dN_1 * dN_3$

2 2-particle connected, $dN_2 * dN_2$



Are the connected diagrams important?



"full v2{m}"
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factorized

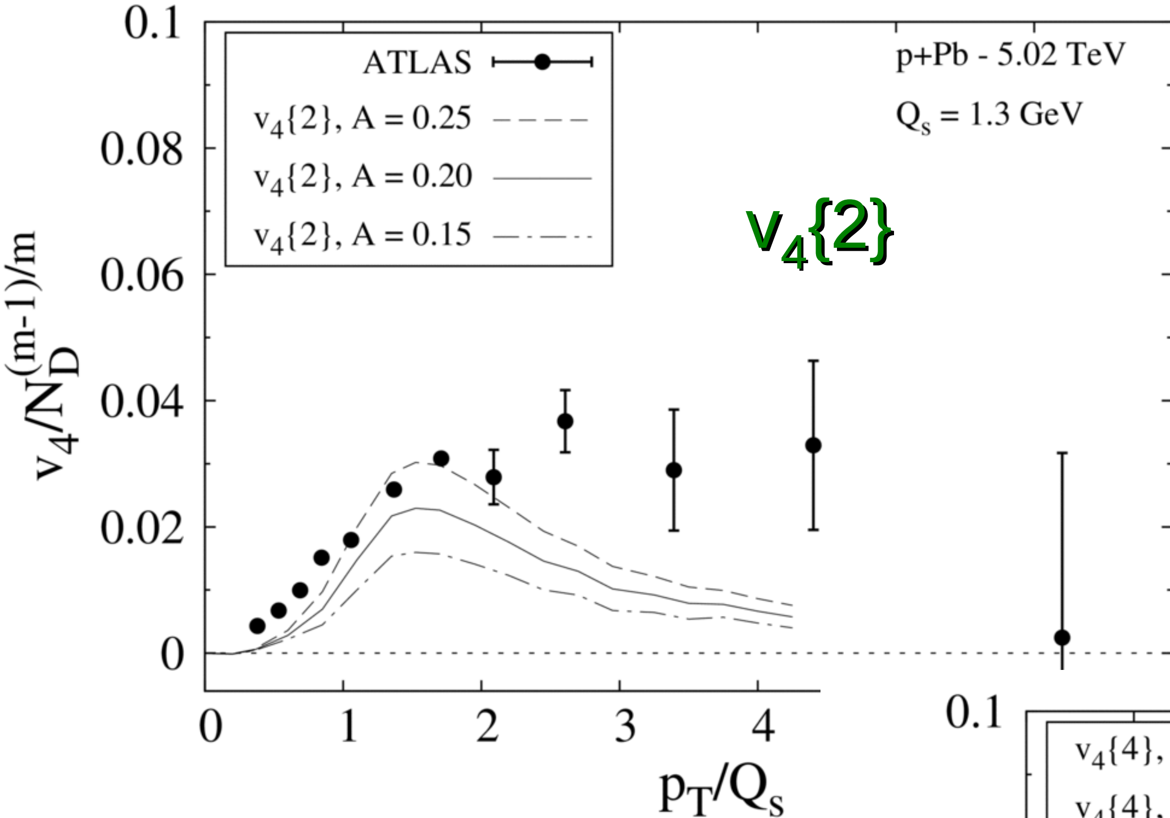
$\mathcal{A}$	$v_2\{2\}/v_{2,disc.}\{2\}$	$v_2\{3\}/v_{2,disc.}\{3\}$	$v_2\{4\}/v_{2,disc.}\{4\}$
0.2	1.3	1.6	0.9
0.5	1.05	1.15	1.0

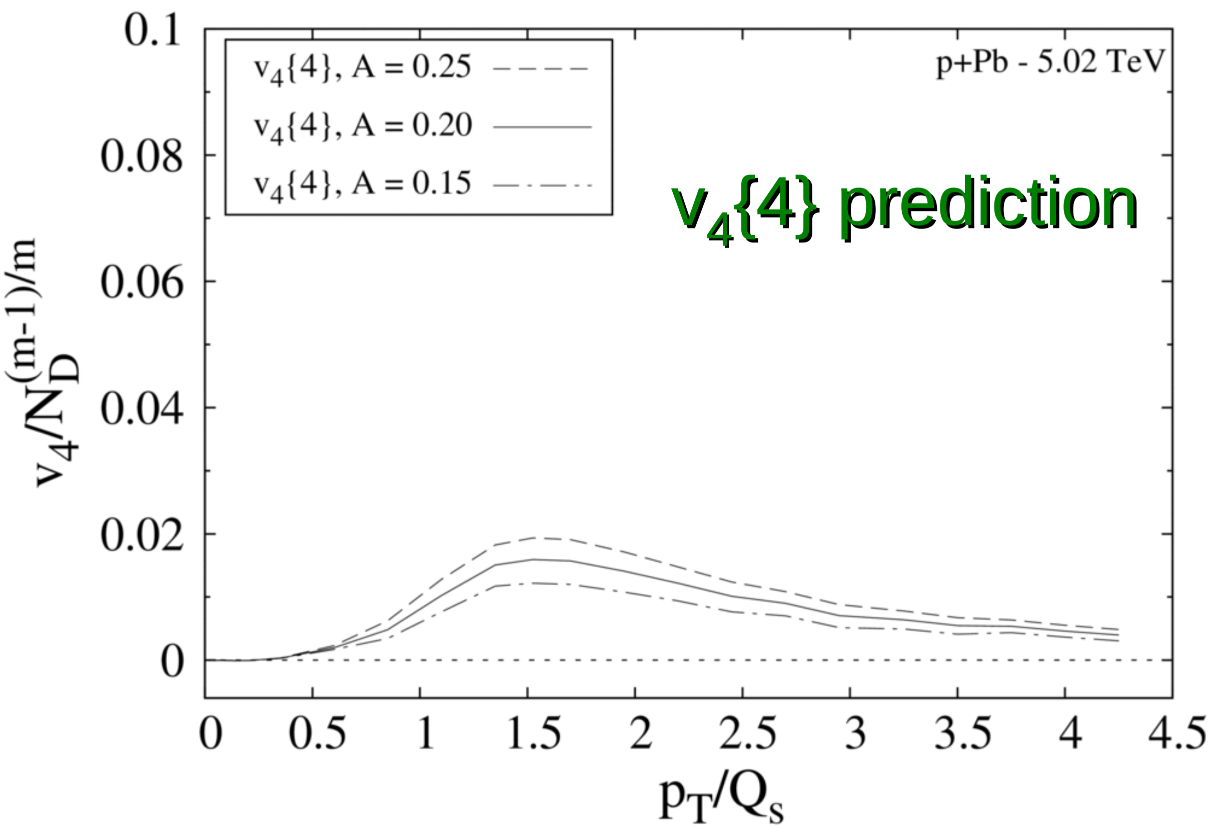
Summary / Outlook

- Initial-state v_n due to anisotropic target E field
- Connected diagrams improve the high-pt region description
- Allows fitting $v_2\{2\}$ and $v_2\{4\}$ simultaneously
- Can not uniquely fix $\mathcal{A}$ and N_D from high p_T alone
- $\mathcal{A} \gg 0.2$ results ruled out by $v_2\{4\}$ low pt data ?

If so: large connected contributions to m-particle correlation functions

Backup Slides





- model predicts $v_4\{4\} \ll v_2\{4\}$
- also, $v_4\{4\}$ drops with p_T

Now let's get even with the odderon:

$$iO(\vec{r}) = \frac{1}{2N_c} \mathrm{tr} \, \left\langle V_x V_y^\dagger - V_y V_x^\dagger \right\rangle$$

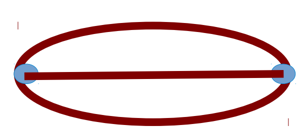
for C-even MV action, $S_{\rm MV} = \int d^2x \, \frac{\rho^a \rho^a}{2\mu^2}$ → O(r) = 0

however, adding cubic Casimir $-\frac{d^{abc}\rho^a\rho^b\rho^c}{\kappa_3}$ → O(r) ≠0

[Kovchegov, Szymanowski & Wallon: PLB 586 (2004);
Jeon & Venugopalan: PRD 71 (2005)]

Technical side remarks:

- Beyond perturbative treatment of ~ρ^3 operator one needs to add quartic Casimir ~ρ^4 too
- Even though κ_3 ~ $A^{2/3}$, at small r one has that O(r) ~ $A^{1/3}$, just as D(r)



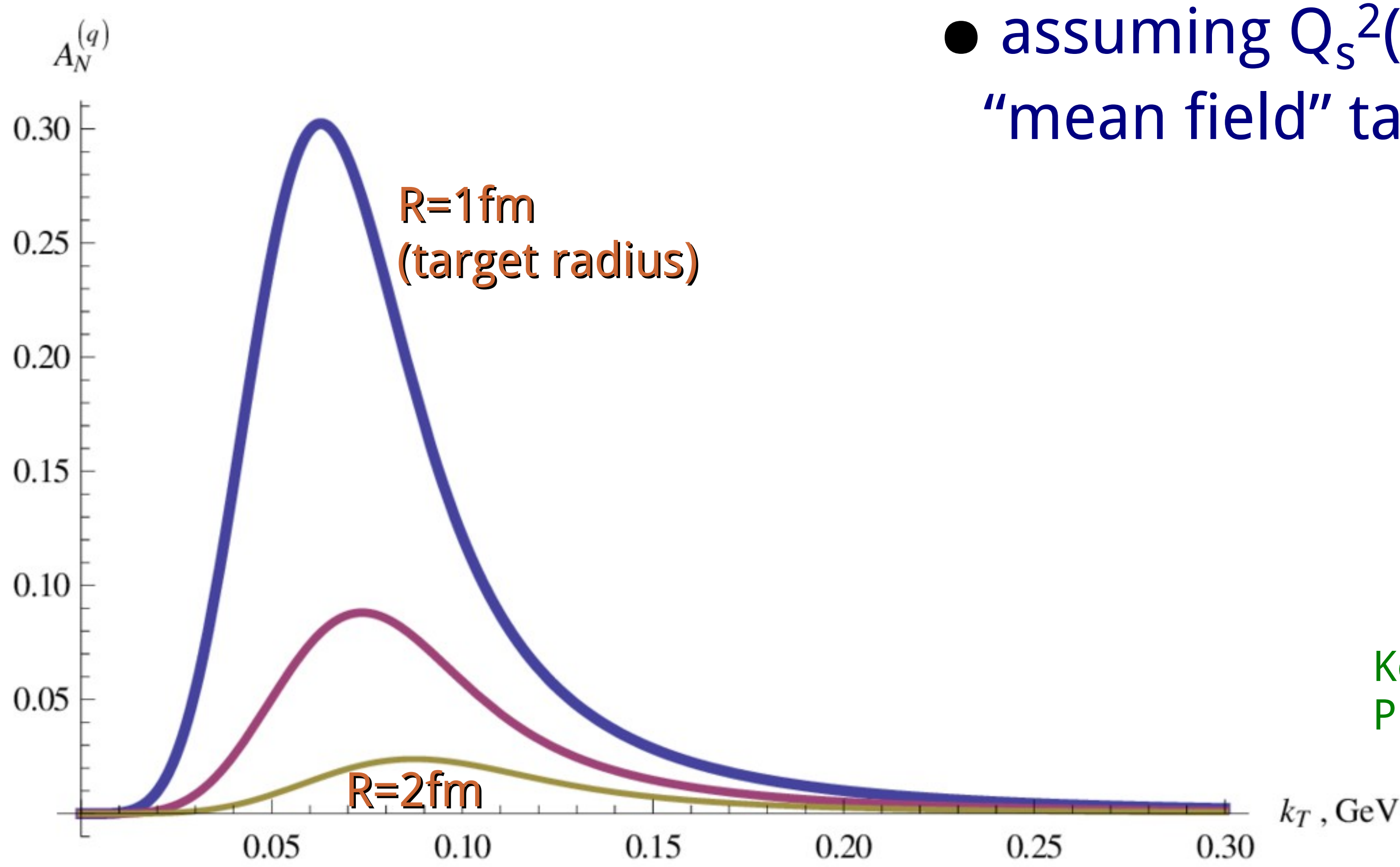
$$\sim \frac{1}{\kappa_3} A \sim A^{1/3}$$

Single transverse spin asymmetry in pA

In quasi-classical approximation:

$$iO(\vec{r},\vec{b}) \sim i\alpha_s \vec{r}\cdot\vec{\nabla}_b D(\vec{r},\vec{b})$$

$$D(\vec{r},\vec{b}) = e^{-\frac{1}{4}r^2 Q_s^2(b)\log\frac{1}{r\Lambda}}$$



- assuming $Q_s^2(b) \sim T(b)$, "mean field" target thickness

Kovchegov & Sievert: PRD 86 (2012)

semi-cl. odderon cont'd

Target fluctuations (single mode):

$$\frac{Q_s^2(\vec{s})}{Q_s^2} = 1 + \int \frac{d^2q}{(2\pi)^2}\, \delta f(\vec{q})\, e^{i\vec{q}\cdot\vec{s}}$$

$$\delta f(\vec{q}) = \frac{(2\pi)^2}{2}\mathcal{B}(q_0)\left[(1+i)\delta(\vec{q}-\vec{q}_0) + (1-i)\delta(\vec{q}+\vec{q}_0)\right]$$

→

$$iO(\vec{r}) \sim \frac{i}{2}\,\alpha_s\, r^2\, Q_s^2\, \mathcal{B}(q_0)\sin\left(\frac{1}{2}rq_0\cos\phi_r\right)\log\frac{1}{\Lambda r}\, e^{-\frac{1}{4}r^2 Q_s^2 \log\frac{1}{\Lambda r}}$$

high k_T / small r :

$$\frac{dN}{d^2k_T} \sim \mathcal{B}(q_0)\frac{q_0}{k_T}\frac{Q_s^2}{k_T^4}\cos(\phi_k)$$

- V_1 =/= 0
- $v_3 = 0$

semi-cl. odderon cont'd

for $v_3 \neq 0$ we need a "string" (analogous to AdS/CFT calculation):

$$iO(\vec{r}) \sim i\alpha_s \vec{r} \cdot \vec{\nabla}_b D(\vec{r}, \vec{b}) \to i\alpha_s \int_{\vec{y}}^{\vec{x}} d\vec{s} \cdot \vec{\nabla}_s D(\vec{r}, \vec{s})$$

$$r = x - y \quad , \quad \vec{b} = \frac{\vec{x} + \vec{y}}{2}$$

Target fluctuations (dq_0/q_0 spectrum with exp. cutoff):

$$\frac{Q_s^2(\vec{s})}{Q_s^2} = 1 + \int \frac{d^2q}{(2\pi)^2} \delta f(\vec{q})\, e^{i\vec{q}\cdot\vec{s}}$$

$$\delta f(\vec{q}) = \frac{(2\pi)^2}{2} \mathcal{B} \int \frac{dq_0^2}{q_0^2} e^{-q_0/Q_c} \left[(1+i)\delta(\vec{q} - \vec{q}_0) + (1-i)\delta(\vec{q} + \vec{q}_0)\right]$$

$$iO(\vec{r}) \sim i\, \alpha_s\, r^2\, Q_s^2\, \mathcal{B} \arctan\left(\frac{1}{2} r Q_c \cos\phi_r\right) D(\vec{r}) \,\log\frac{1}{r\Lambda}$$

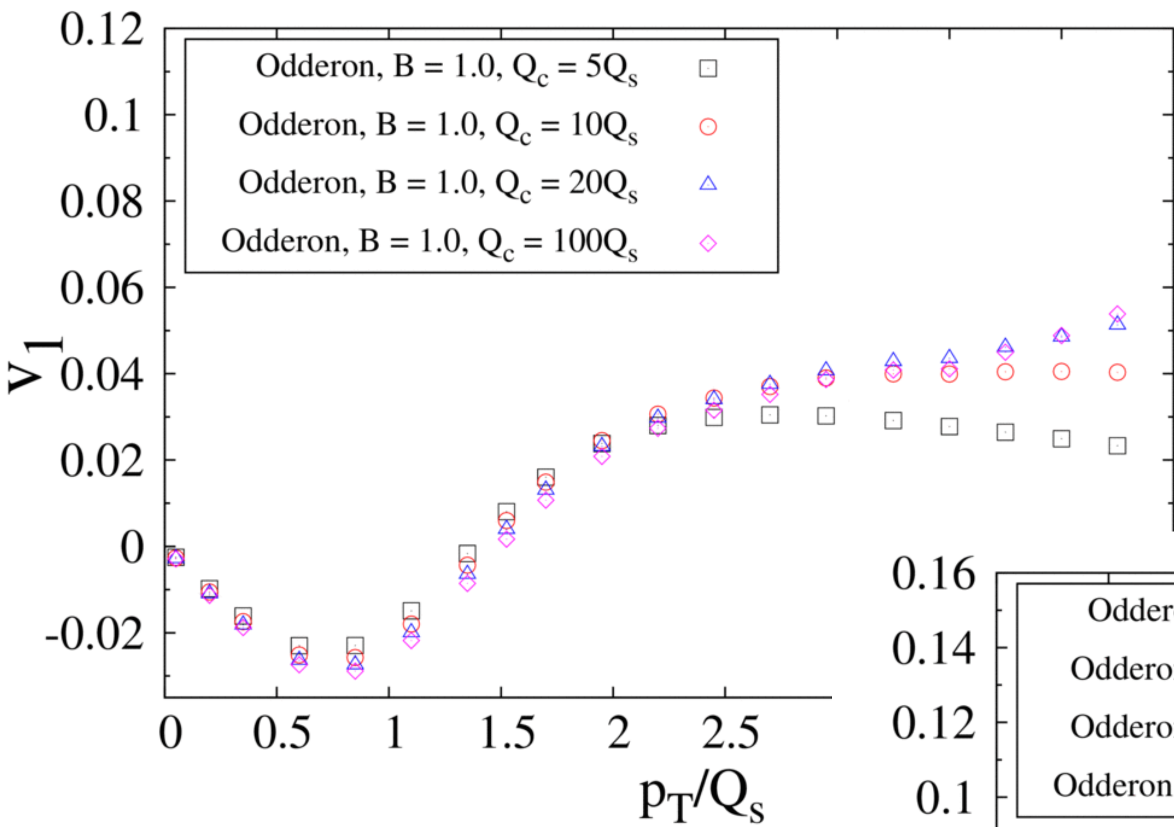
all v_{2n+1}, awesome...

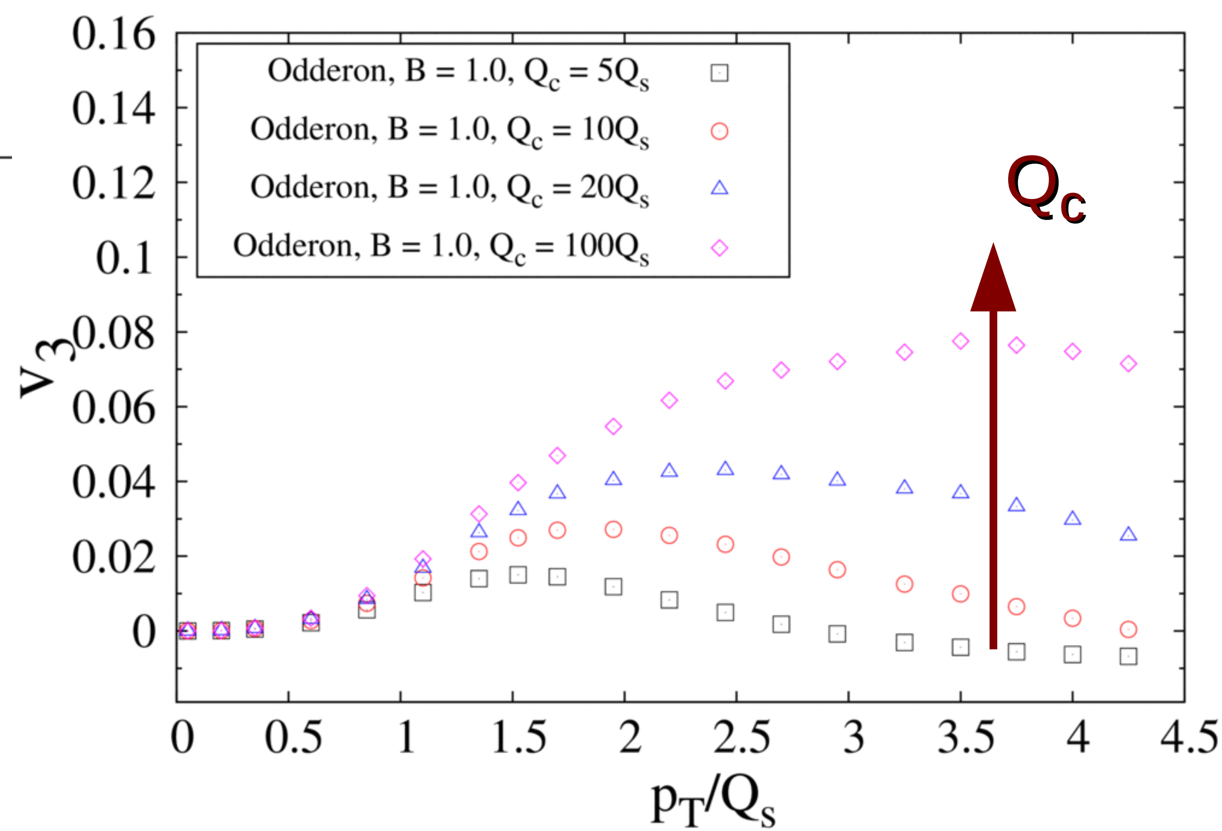
Expansion for 1/r » Q_s, Q_c :

$$iO(\vec{r}) \sim r^3 Q_c \cos\phi_r \left[1 - \frac{r^2}{4}\left(Q_s^2 \log\frac{1}{r} + \frac{1}{3} Q_c^2 \cos^2\phi_r\right)\right]$$

- isotr.: $\sim r^2 \rightarrow 1/k_T^4$
- v_1: $\sim r^3 \rightarrow 1/k_T^5$
- v_3: $\sim r^5 \rightarrow 1/k_T^7$

Numerical F.T. of O(r) : behavior of cutoff Q_c

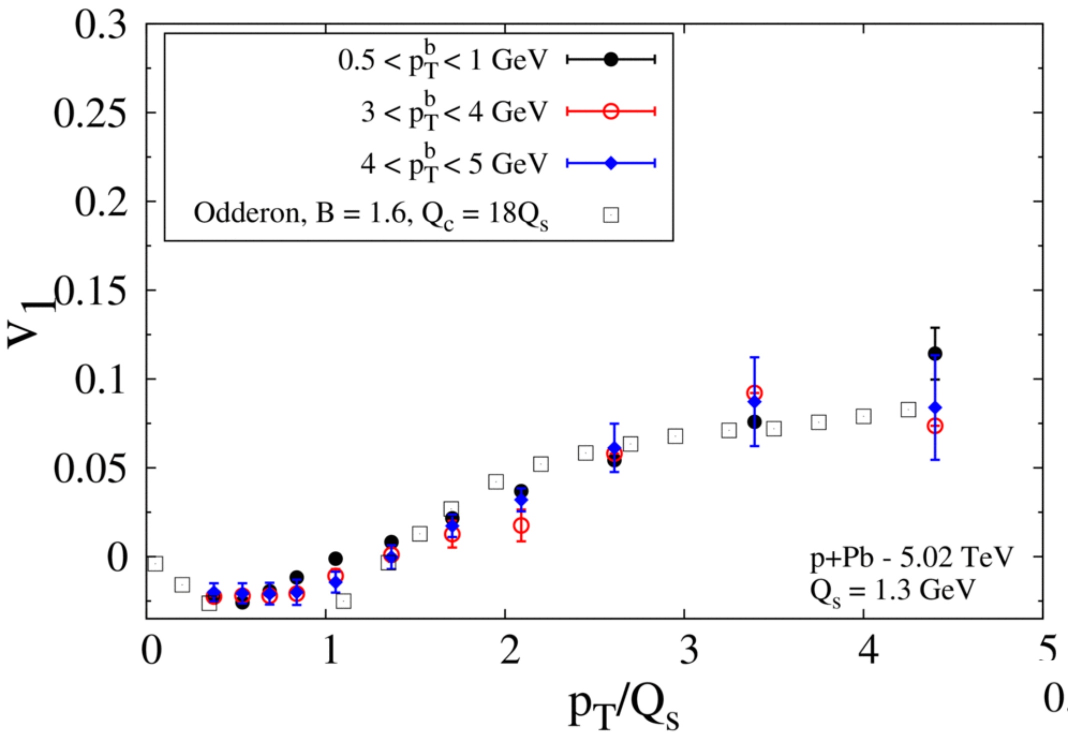


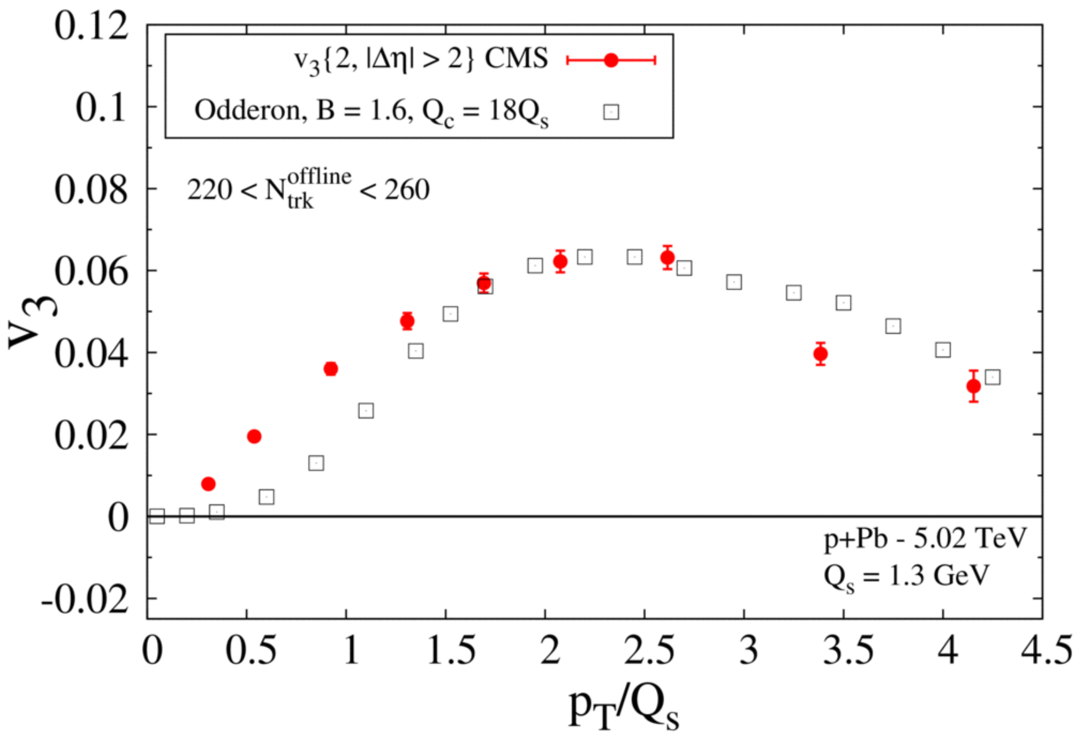


- v_1 affected only at high p_T
- low Q_c kills v_3:

$$\int d\vec{s} \cdot \vec{\nabla}_s \, Q_s^2 \to \vec{r} \cdot \vec{\nabla}_b \, Q_s^2$$

Numerical F.T. of O(r) : comparison to data; v_1 and v_3





- one fluctuation amplitude B=1.6 fits v_1 and v_3 simultaneously
- large $Q_c \sim 18\ Q_s$ gives decent p_T dependence for both v_1 and v_3