Acceptance corrections and first results of collectivity analysis in PHP

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Azimuthal correlations to probe collective behavior

Reminder of how 2- and 4-particle azimuthal correlations are defined.

2-particle azimuthal correlations

$$c_n\{2\} = \langle \cos\left(n(\varphi_1 - \varphi_2)\right)\rangle$$

harmonic

Azimuthal angle particle 1

Azimuthal angle particle 2

4-particle azimuthal correlations (more robust probe of collectivity)

Borghini, Dinh, Ollitrault PRC 64 054901

$$c_n\{4\} = \langle \cos\left(n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\right)\rangle - 2\,\langle \cos\left(n(\varphi_1 - \varphi_3)\right)\rangle\,\langle \cos\left(n(\varphi_2 - \varphi_4)\right)\rangle$$

Explicit removal of 2-body “non-collecitve” bkg correlations

- Studied only briefly in the DIS analysis.
- Requires more statistics at high multiplicity, which PHP should provide.

Expectations of 2-particle cumulants, $c_n\{2\}$, from heavy-ion collisions

The azimuthal component of particle production in “collective” heavy-ion collisions is typically parametrized with a Fourier decomposition:

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$$

<u>“Flow” coefficients</u>

$$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$$

<u>Parity-odd terms vanish</u>

$$\langle \sin n(\varphi - \Psi_n) \rangle = 0$$

Assuming that particles within any given pair are only correlated with each other through a common symmetry plane with angle Ψ_n, and also assuming no event-by-event fluctuations of v_n, we have:

$$\begin{aligned} c_n\{2\} &= \langle \cos n(\varphi_1 - \varphi_2) \rangle \\ &= \langle \cos n((\varphi_1 - \Psi_n) - (\varphi_2 - \Psi_n)) \rangle \\ &= \langle \cos n(\varphi_1 - \Psi_n) \rangle \langle \cos n(\varphi_2 - \Psi_n) \rangle \\ &= v_n^2 \end{aligned}$$

Expectations of 4-particle cumulants, $c_n\{4\}$, from heavy-ion collisions

Assuming again the same things from the previous slide we can rewrite $c_n\{4\}$ as follows:

$$\begin{aligned} c_n\{4\} &= \langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle - 2 \langle \cos n(\varphi_1 - \varphi_3) \rangle \langle \cos n(\varphi_2 - \varphi_4) \rangle \\ &= v_n^4 - 2 v_n^2 \, v_n^2 \\ &= -v_n^4 \end{aligned}$$

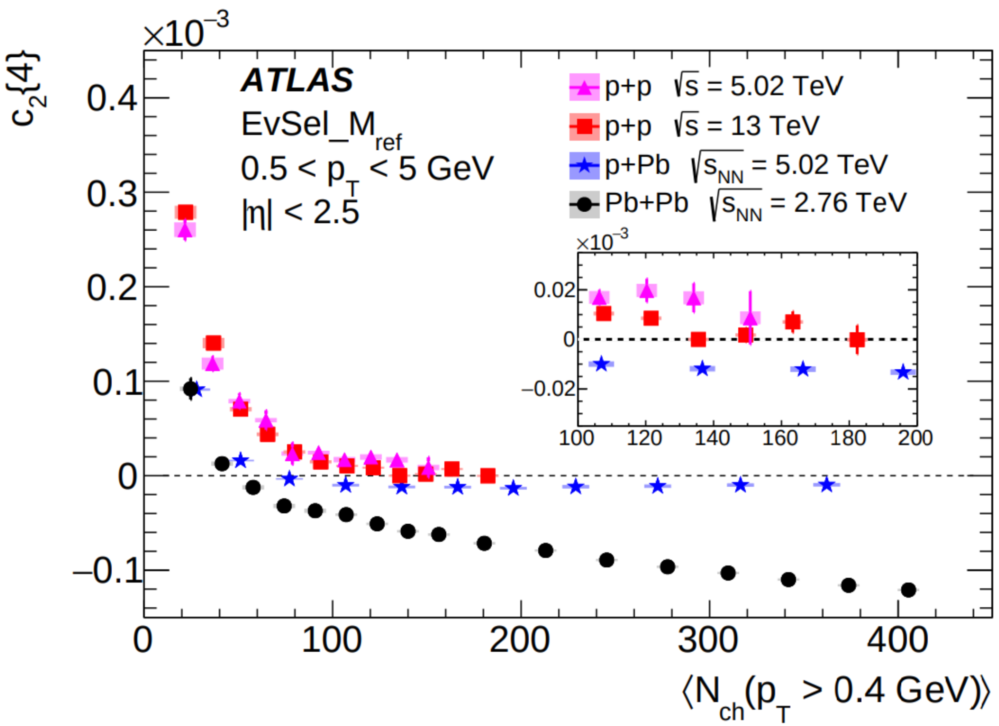
The 4-particle cumulant is thus **negative** when collective correlations dominate.

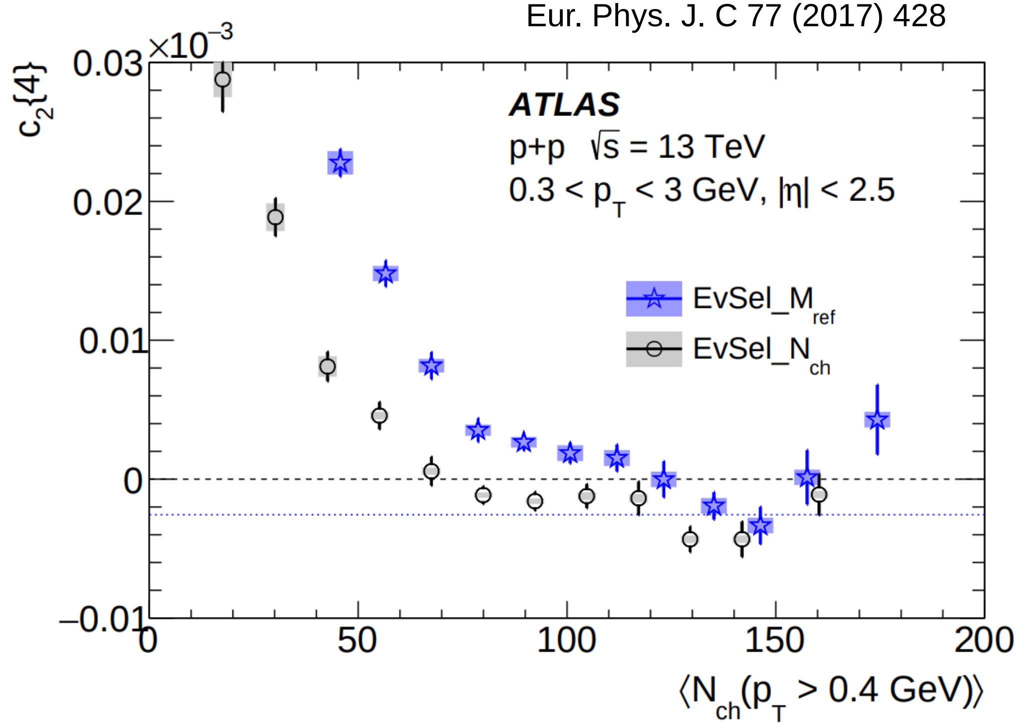
However, in small systems like e+p and p+p, event-by-event fluctuations of v_n may be substantial and distort this simple picture given above.
A theoretical calculation is needed to estimate such distortions.

Noncollective 2-particle contributions are explicitly subtracted off.
The cumulant is more robust against background contributions.

Expectations of 4-particle cumulants, $c_n\{4\}$, from heavy-ion collisions

Eur. Phys. J. C 77 (2017) 428





$c_2\{4\}$ in Pb+Pb and p+Pb are clearly negative for multiplicities larger than 50.

In p+p it is not so clearly negative but by selecting events with a minimum number of higher pT particles (“EvSel_N_{ch}”), $c_2\{4\}$ becomes negative at high multiplicity.

In small systems it may be that even-by-event fluctuations of v_n distort the simple picture we gave you on the previous slide.

$$c_n\{4\} \stackrel{?}{=} -v_n^4$$

Offline PHP event selection and multiplicity definitions

PHP offline event selection

- Primary Vertex QA (same as in DIS paper)
- Sinistra probability < 0.95
- Electron energy < 20 GeV
- E – Pz < 65 GeV

$\mathbf{N_{rec}}$

The number of reconstructed tracks passing the below criteria:

- ZTT track type
- >= 1 MVD hit
- DCAxy < 2 cm, DCAz < 2 cm
- 0.1 < pT < 5.0 GeV
- -1.5 < eta < 2

$\mathbf{N_{ch}^{gen}}$

The number of long-lived primary charged hadrons with mean proper lifetime tau > 1cm, which were produced directly or from the decay of a particle with tau < 1cm.

$$N_{ch}^{rec} = \sum_{i}^{N_{rec}} w_i$$

where w_i is the single-particle efficiency correction factor

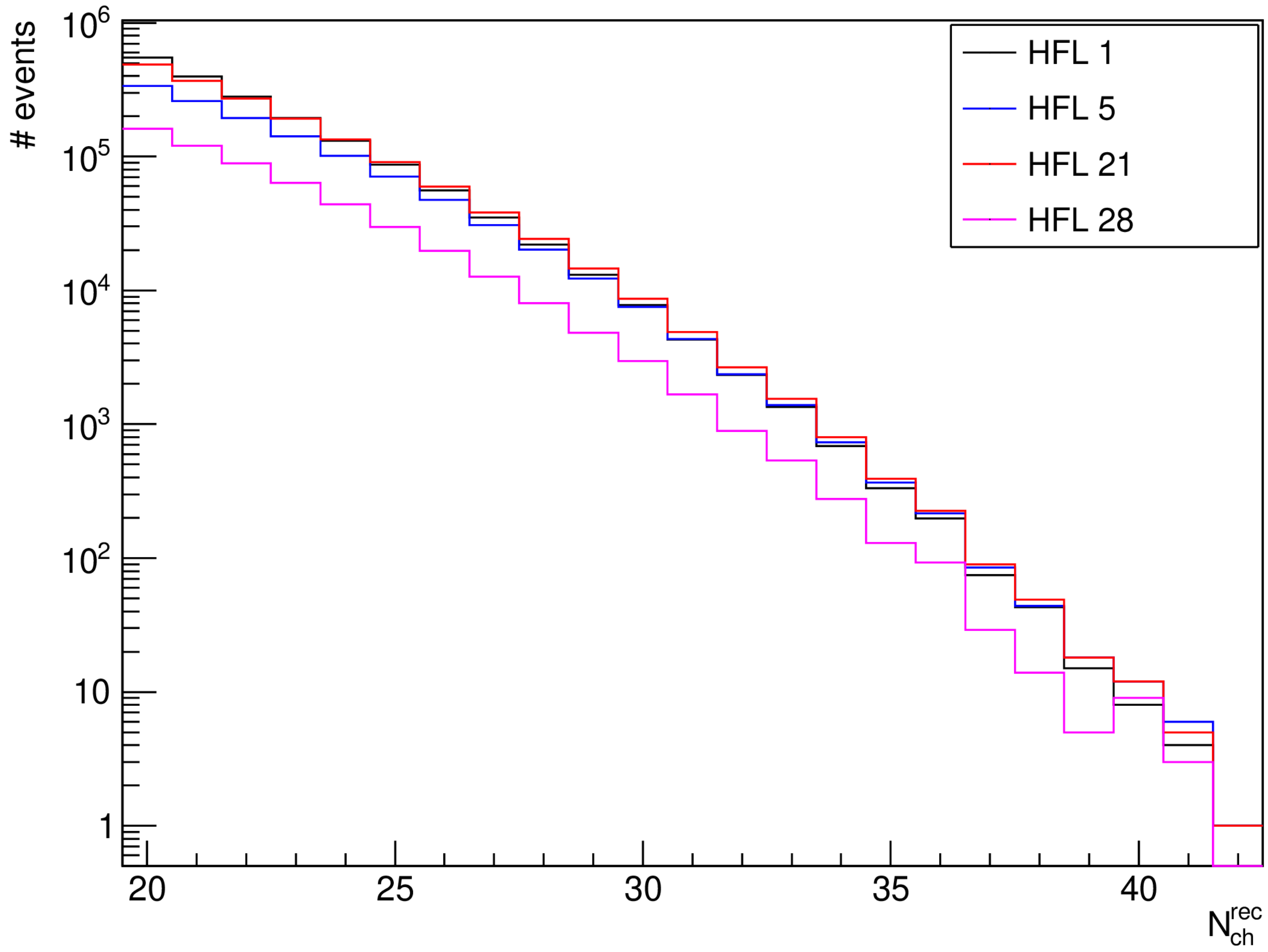
Reminder of HFL TLT descriptions

HFL TLT web page

TLT	Short description	Long description
HFL 1	Charmed hadrons in PHP	Or of all HFM triggers with hard cuts: pT thresholds and invariant mass thresholds of decay daughters.
HFL 2	Charmed hadrons in DIS	DIS electron Or of all HFM triggers with loose cuts:
HFL 5	inclusive dijets (similar to old HPP 14)	Two jets ET>4.5, eta<2.5 (EUCELL) Pz/E < 0.95 and E-Pz<100
HFL 6	jets in DIS	Two Jets ET>3.5, eta<2.5 (EUCELL) Pz/E < 1.0 and E-Pz<100
HFL 9	electron in PHP	Number of tracks > 2, Island Energy < 1000 Momentum track > 0 , pt of the track > 1.4 GeV , 0.6 < track theta < 2.55 , DCA < 30. EMC Island energy Fraction eEMCIsland/EIsland < 0.8
HFL 18	D* gold selection	See web pages for longer description.
HFL 19	D0/D0-bar mixing	See web pages for longer description.
HFL 21	MESON + jets	Two Jets ET>3.5, eta<2.5 (EUCELL) Pz/E < 1.0 and E-Pz<100 .or. of any of the 6 D meson low Pt cut channels
HFL 24	jet(s) + electron	See web pages for longer description
HFL 25	jet(s) + muon	See web pages for longer description
HFL 27	MVD inclusive trigger Only active since May 30th 2006 (~40% of HERA II integrated lumi)	All SLT PHP, DIS and MUON slots MVD vertex within -30 cm < z(vtx) < 30 cm at least 4 tracks fitted to the primary vertex Et > 8 GeV (excluding the 1st two inner rings around the beam pipe) At least three tracks with pt > 0.75, 0.6, 0.45 GeV Impact parameter significance cut for the 3rd highest significance track. The impact parameter significance is evaluated with respect to the primary event vertex.
HFL 28	MVD inclusive trigger using beam spot Only active since May 30th 2006	Same cuts as for HFL 27, but the impact parameter significance is evaluated with respect to the beam spot.

N_{ch} distributions in ZEUS data for the HFL triggers of interest

ZEUS data
2003 to 2007



HFL 28 showed the least trigger bias for PHP at high multiplicity from MC studies.

It is ~3 times less populated mostly because it was only available since May 30th 2016.

MC closure studies

Compare generator-level MC correlations to the reconstructed ones.

Discrepancies between them were observed in the DIS analysis and were assigned a systematic uncertainty.

There are two sources of MC nonclosure.

<u>Source 1:</u>

Generated N_{ch} != reconstructed N_{ch}:
→ correlation gets assigned to a wrong N_{ch} bin (Unfolding problem).
To isolate this, we will plot gen correlations against N_{ch}^{rec} and N_{ch}^{gen}.

<u>Source 2:</u>

Reconstruction inefficiencies:
1-particle, 2-particle, …, n-particle inefficiencies
To isolate this, we will plot both gen and weighted correlations against N_{ch}^{rec}

In the DIS analysis, both were lumped together.

That is, (c_n^{gen} vs N_{ch}^{gen}) – (c_n^{rec} vs N_{ch}^{rec}) was the MC nonclosure systematic.

Here, we'll look into 1) and 2) separately.

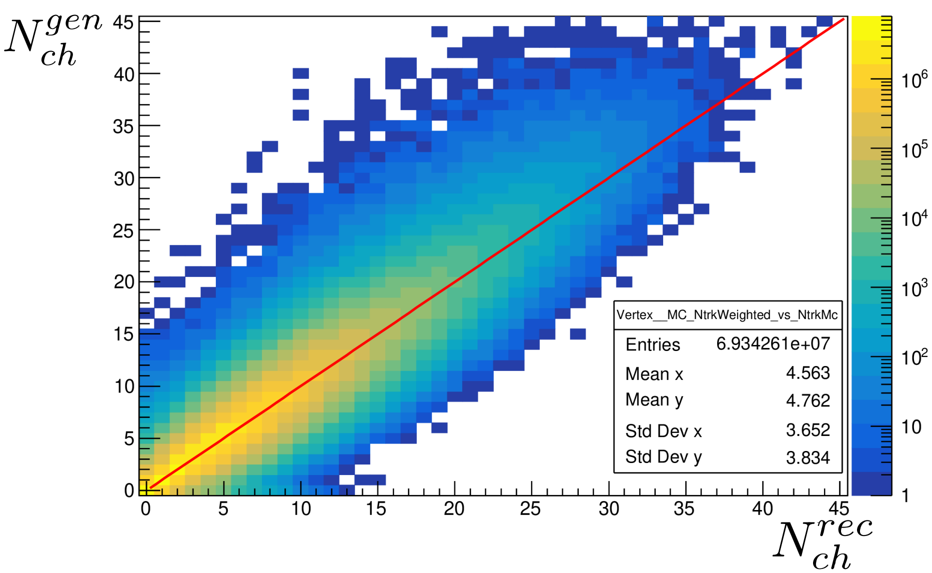
Source 1 MC closure source
Bin migration

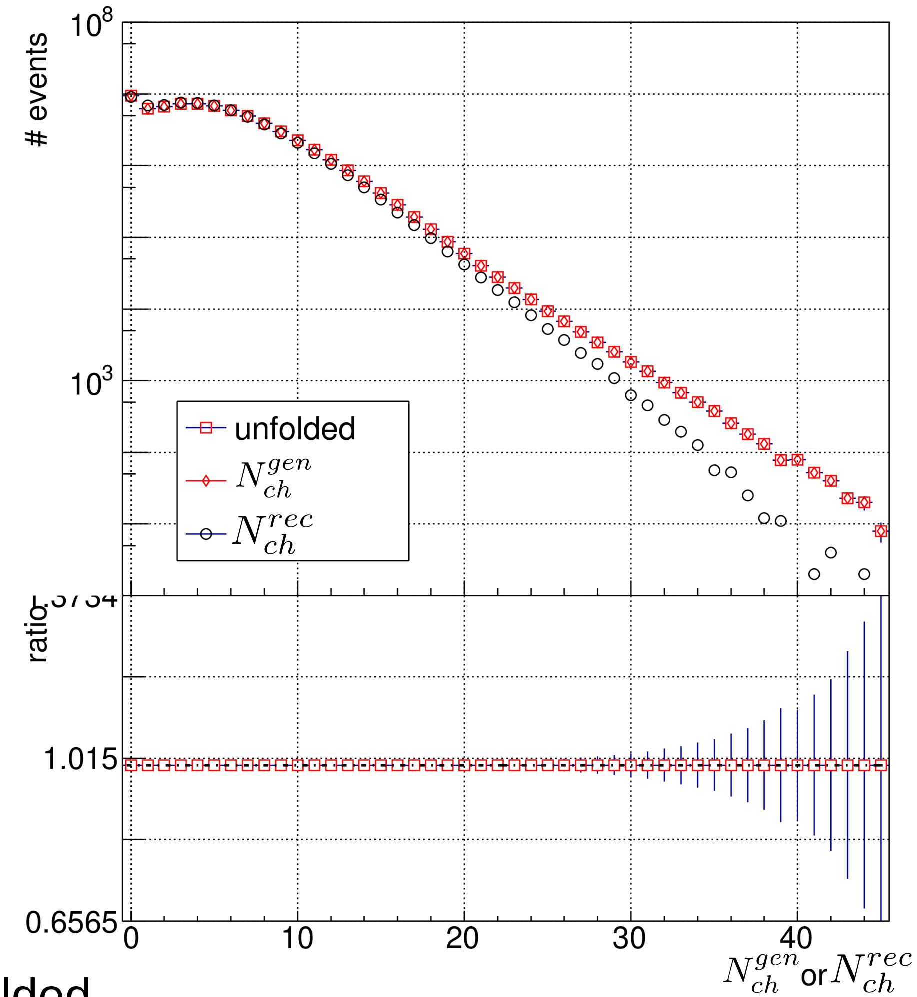
DIS Ariadne 0607p

We can use the RooUnfold package to treat bin migration.

Use the Bayesion method with the regularization parameter: “iterations” = 4.

Response matrix





The multiplicity distribution can be easily unfolded.

Source 1 MC closure
Bin migration

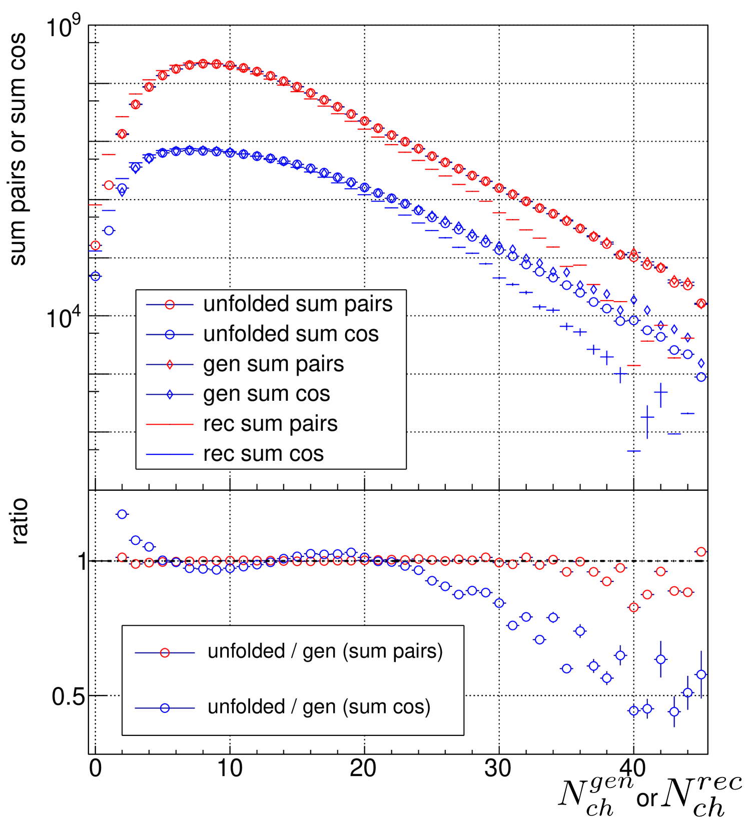
DIS Ariadne 0607p

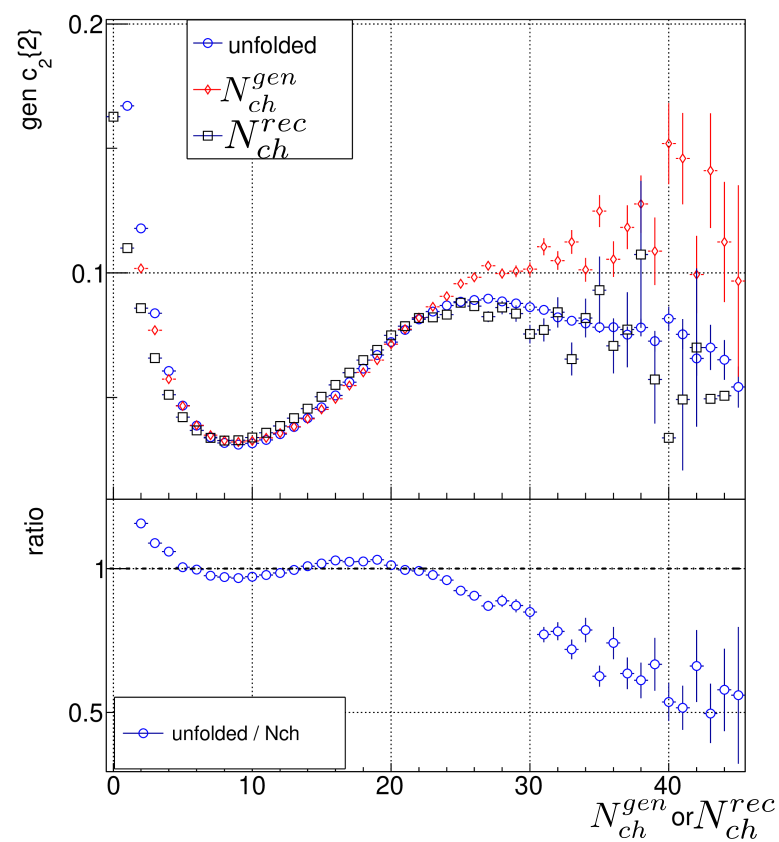
Attempt to unfold the **generated** correlation function $c_2\{2\}$.

We cannot directly unfold a correlation function like a multiplicity distribution.

Instead, try to unfold the numerator and denominator of c2{2} separately.

Numerator = Sum of cosines, Denominator = Sum of pairs





The pair distributions can be easily unfolded but not the sum cosines.
This is because events with different correlation strengths may migrate differently.
A multi-dimensional unfolding problem.

Source 2 MC closure
Reconstruction inefficiencies

As in the DIS analysis, we will apply pair-reconstruction efficiency corrections to 2-particle correlations.

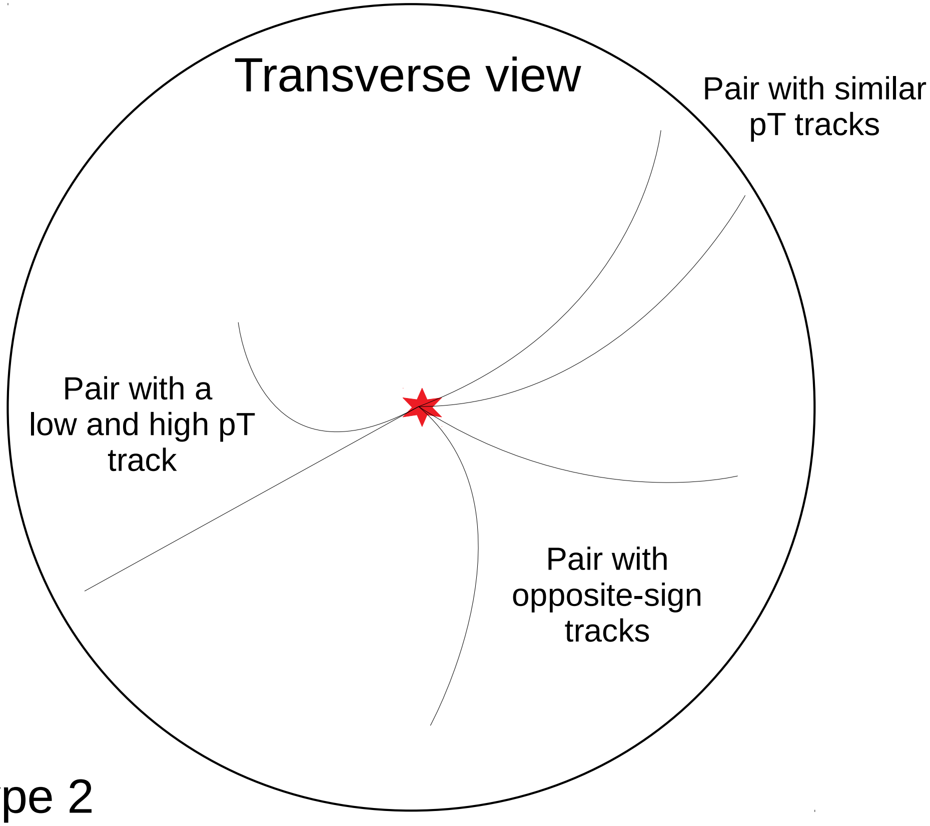
<u>Single-particle correction factor</u>

$$w_i = \frac{N_{gen}(p_T, \eta, \varphi, q)}{N_{rec}(p_T, \eta, \varphi, q)}$$

charge

<u>Pair correction factor</u>

$$w^{(2)} = \frac{N_{gen}^{pairs}(\vec{x})}{w_1\, w_2\, N_{rec}^{pairs}(\vec{x})}$$



Type 1 (from DIS analysis) was called $w_{\Delta\varphi}$

$$\begin{aligned} x_1 &= \Phi = \varphi_1 - \varphi_2 \\ x_2 &= |\Delta\eta| \\ x_3 &= |q_1 + q_2| \\ x_4 &= N_{ch}^{rec} \end{aligned}$$

Type 2

$$x_1 = \Phi = \varphi_1 - \varphi_2$$ φ angular proximity at PV

$$x_2 = \langle \hat{p}_i \cdot \langle \hat{p} \rangle \rangle$$ General angular proximity

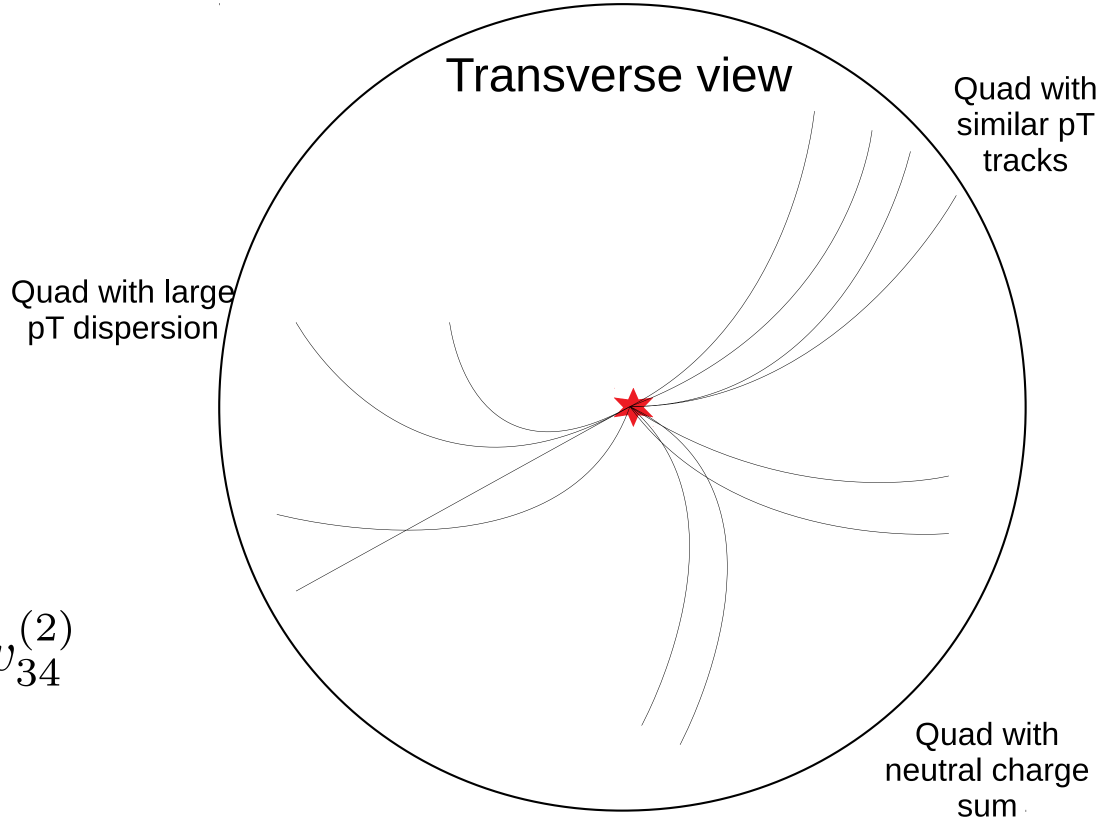
$$x_3 = \langle p_{T,i} - \langle p_T \rangle \rangle$$ p_T dispersion in pair (depicted above)

$$x_4 = |q_1 + q_2|$$ Charge combination: 0 or 1

$$x_5 = N_{ch}^{rec}$$ 3 bins: 0-10, 10-20, 20-50

Source 2 MC closure
Reconstruction inefficiencies

New 4-particle correction factor.



Quadruplet correction factors

Full calculation

$$w^{(4)} = \frac{N_{gen}^{quads}(\vec{x})}{w_1\, w_2\, w_3\, w_4\, N_{rec}^{quads}(\vec{x})}$$

Product of 6 pairs approximation

$$w^{(4)} = w_{12}^{(2)}\, w_{13}^{(2)}\, w_{14}^{(2)}\, w_{23}^{(2)}\, w_{24}^{(2)}\, w_{34}^{(2)}$$

$$x_1 = \Phi = \varphi_1 + \varphi_2 - \varphi_3 - \varphi_4$$ φ angular proximity at PV

$$x_2 = \langle \hat{p}_i \cdot \langle \hat{p} \rangle \rangle$$ General angular proximity

$$x_3 = \langle p_{T,i} - \langle p_T \rangle \rangle$$ p_T dispersion in quadruplet (depicted above)

$$x_4 = |q_1 + q_2 + q_3 + q_4|$$ Charge combination: 0, 1, or 2

$$x_5 = N_{ch}^{rec}$$ 3 bins: 0-10, 10-20, 20-50

Application of weights to correct for tracking inefficiencies

2 passes over the MC data are needed to calculate the efficiency corrections.
Pythia PHP light-flavour jet 06e used exclusively at the moment.

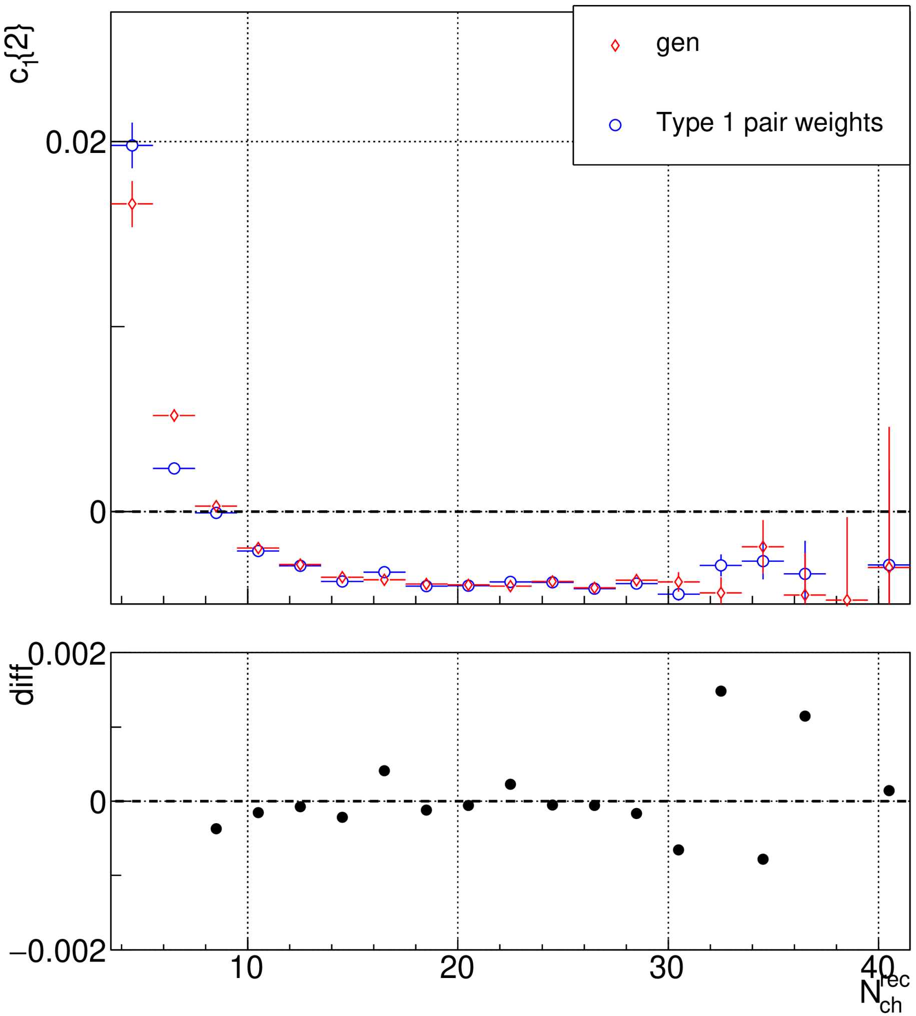
1^{st} pass: No weights applied.
Results used to calculate single-particle efficiency corrections, w_i

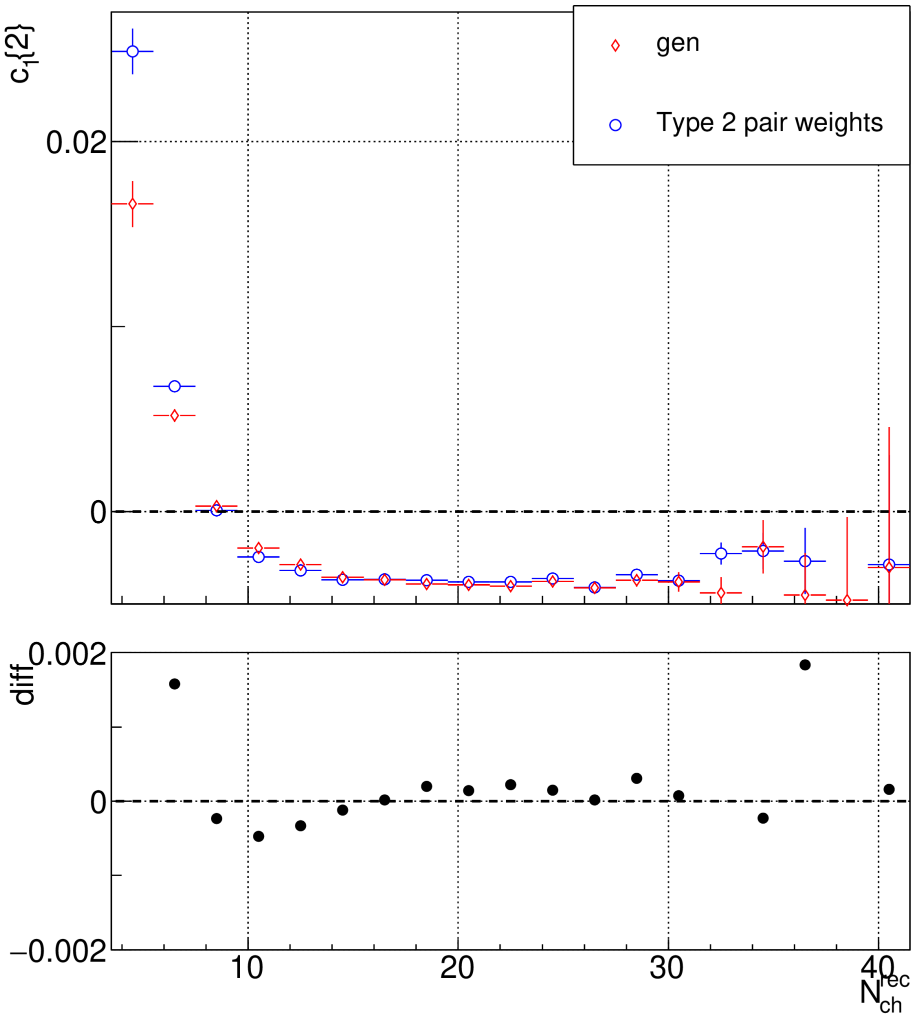
2^{nd} pass: w_i applied.
Results used to calculate pair and quadruplet efficiency corrections.

The weights are then applied to MC data to test their effectiveness (MC closure).

Type 1 vs Type 2 pair weights

PHP pythia lf jet 06e

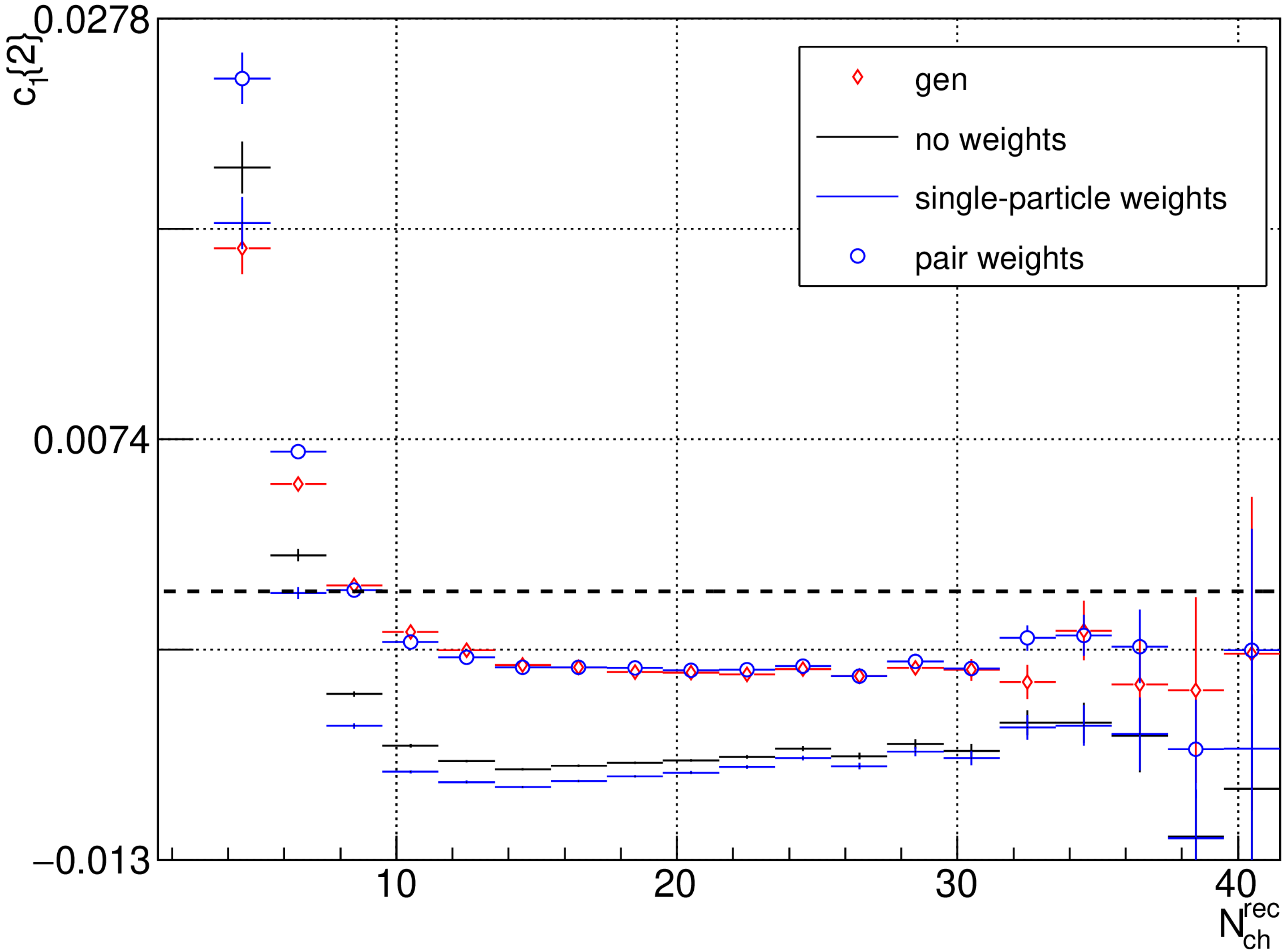




The effectiveness of both is comparable.

Type 2 weights are preferred since they have the same structure as that used for 4-particle correlations.

Source 2 MC closure: $c_1\{2\}$ correction sequence PHP pythia lf jet 06e

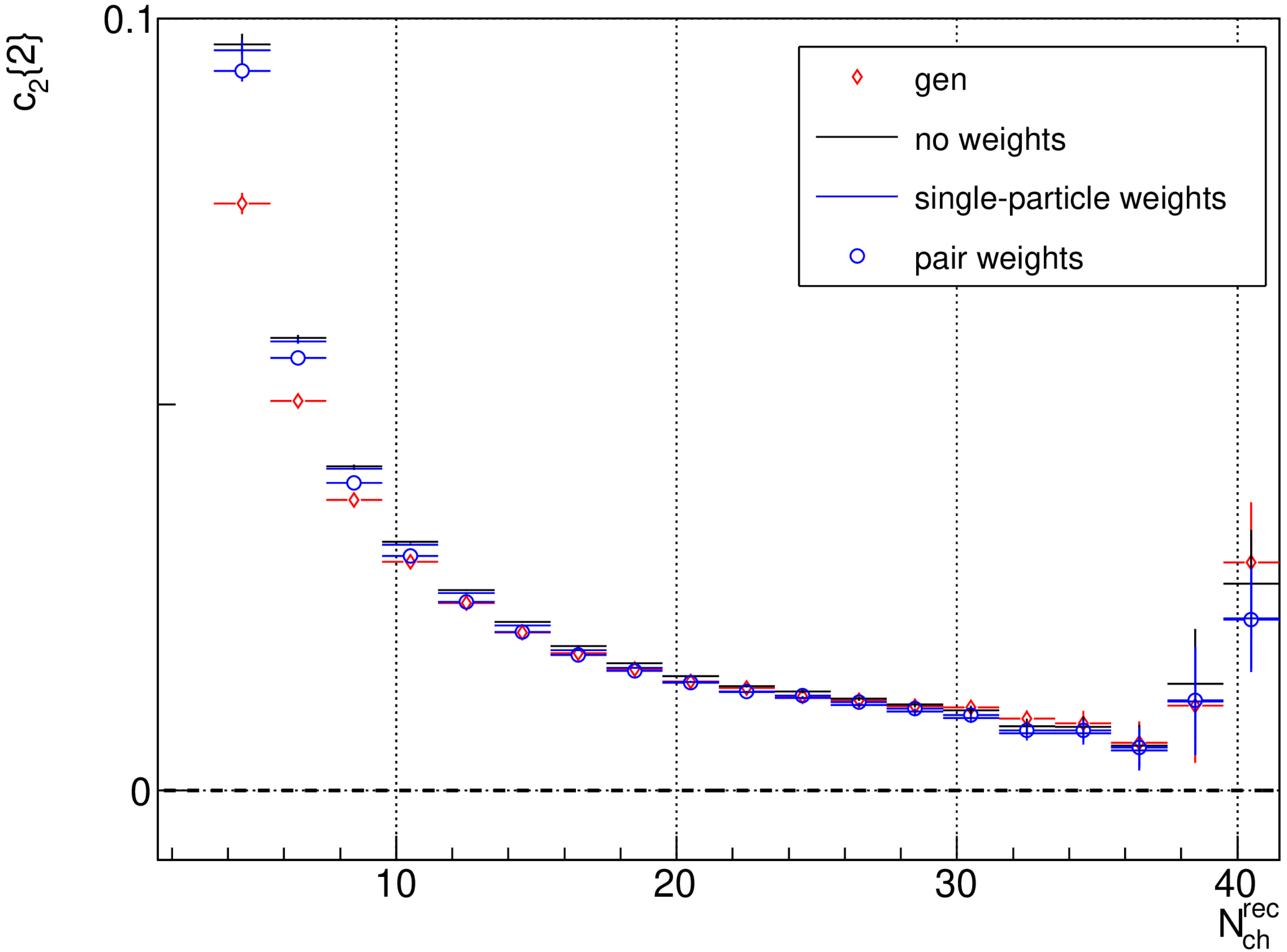


Single-particle weights are clearly not enough, as observed in the DIS analysis.

Pair weights work well except at low N_{ch}^{rec}.

Both rec and gen correlations are plotted versus N_{ch}^{rec}.

Source 2 MC closure: $c_2\{2\}$ correction sequence PHP pythia lf jet 06e

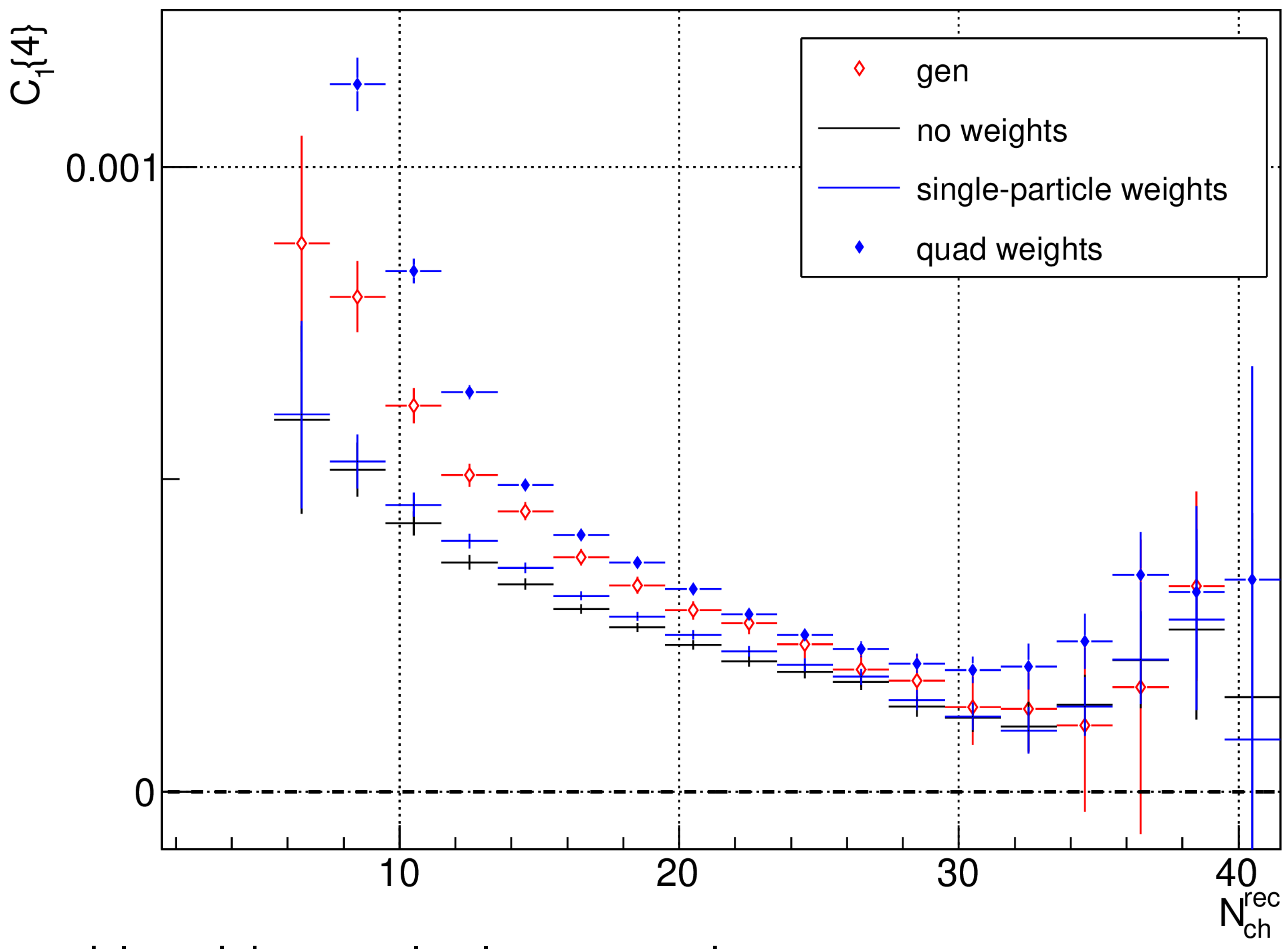


Single-particle weights are clearly not enough, as observed in the DIS analysis.

Pair weights work well except at low N_{ch}^{rec}.

Both rec and gen correlations are plotted versus N_{ch}^{rec}.

Source 2 MC closure: $C_1\{4\}$ correction sequence PHP pythia lf jet 06e

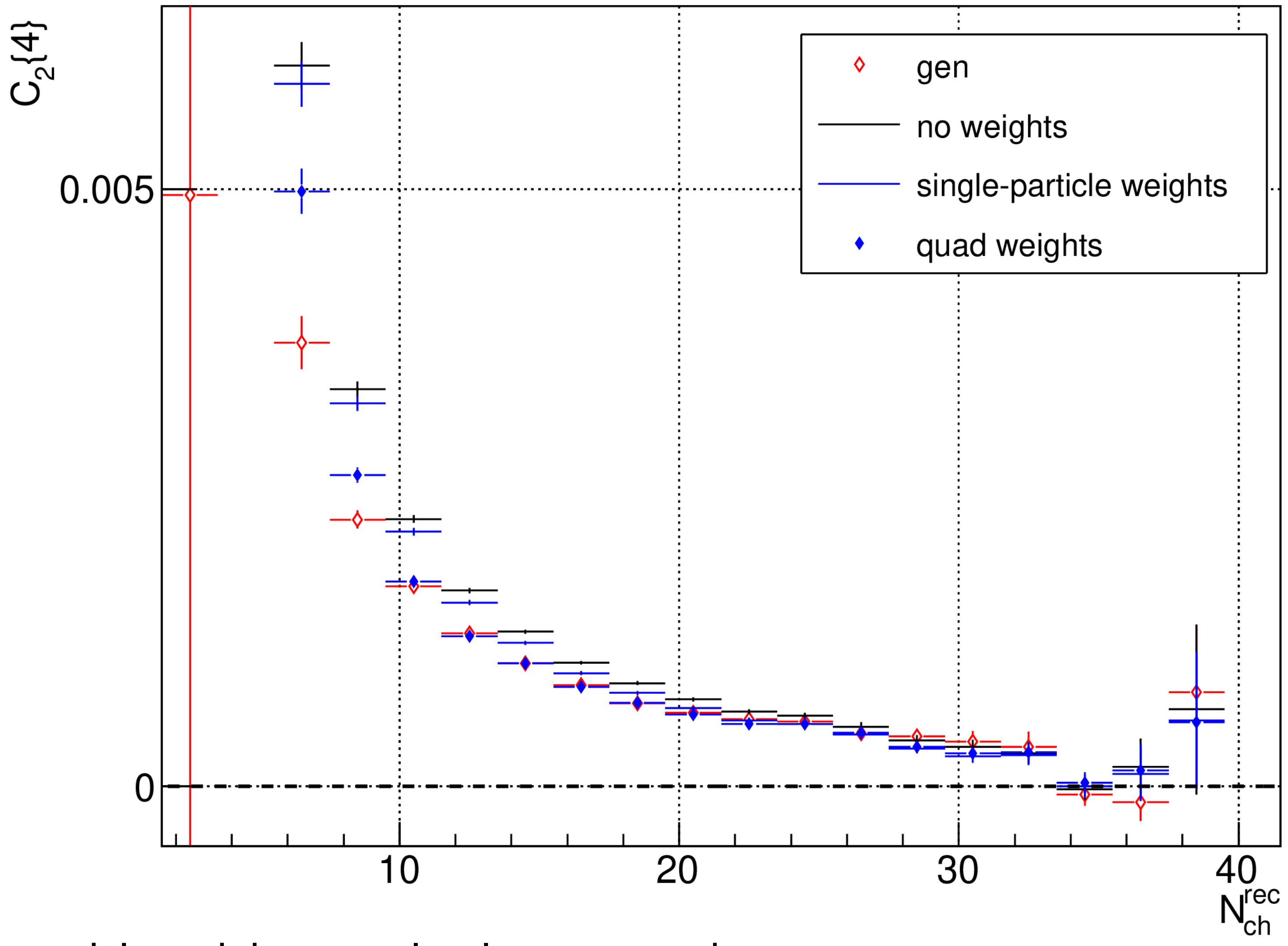


Single-particle weights are clearly not enough.

Quad weights work well except at low N_{ch}^{rec}.

Both rec and gen correlations are plotted versus N_{ch}^{rec}.

Source 2 MC closure: $C_2\{4\}$ correction sequence PHP pythia lf jet 06e



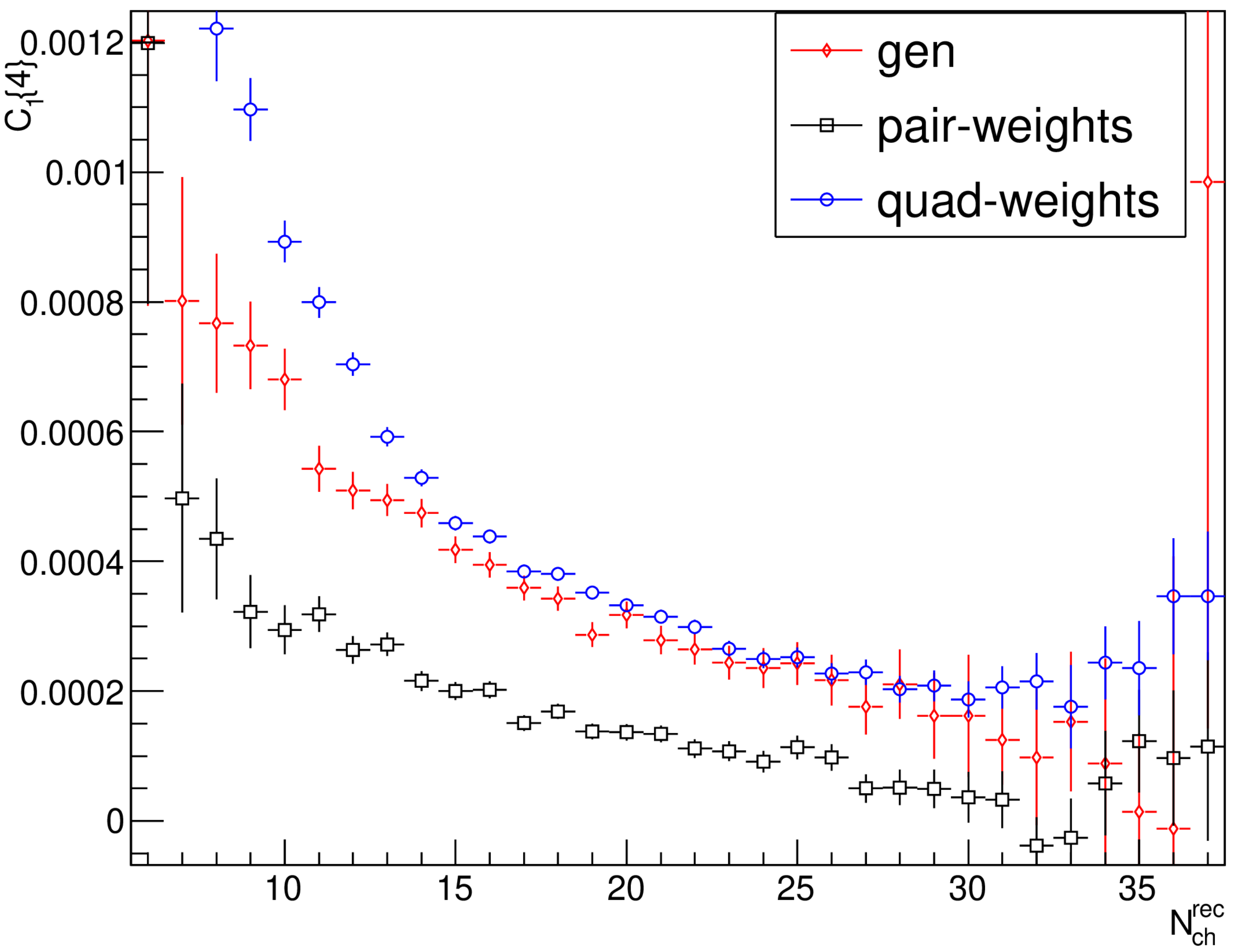
Single-particle weights are clearly not enough.

Quad weights work well except at low N_{ch}^{rec}.

Both rec and gen correlations are plotted versus N_{ch}^{rec}.

Pair-wise vs quad-wise correction scheme

PHP pythia lf jet 06e

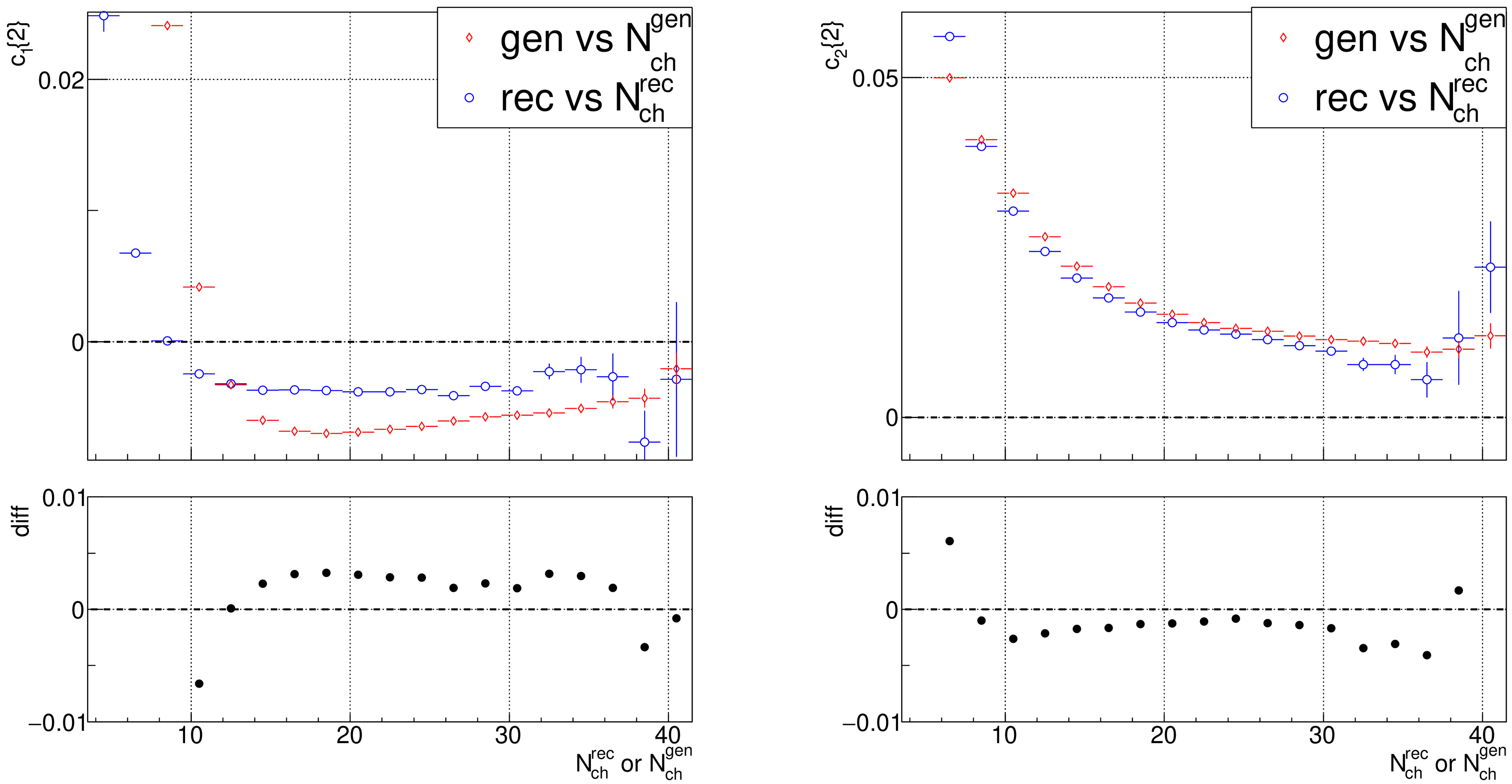


Product of 6 pair weights to correct 4-particle correlations does not work well.

Quad weights work well except at low N_{ch}^{rec}.

$c_n\{2\}$ Total magnitude of MC nonclosure
Sources 1 and 2 combined

PHP pythia lf jet 06e



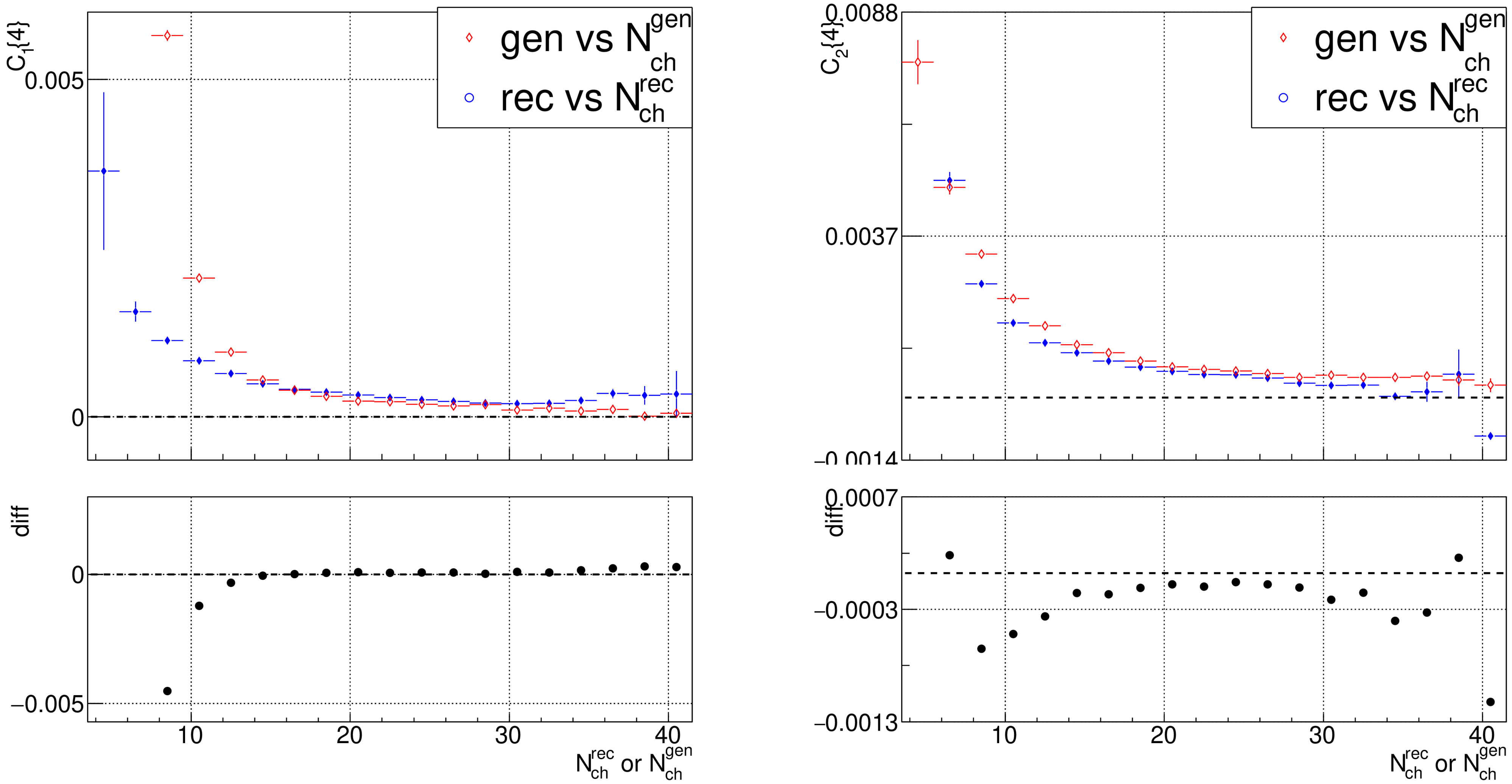
Total MC nonclosure is poor when correlation changes rapidly with Nch.

The scale here is much smaller than in DIS MC samples.

Note that the correction scheme explored here is different than that used in the DIS analysis. Main difference is x_4 on slide 12. In DIS analysis N_{ch}^{gen} was used. Here we used N_{ch}^{rec}

$C_n\{4\}$ Total magnitude of MC nonclosure
Sources 1 and 2 combined

PHP pythia lf jet 06e

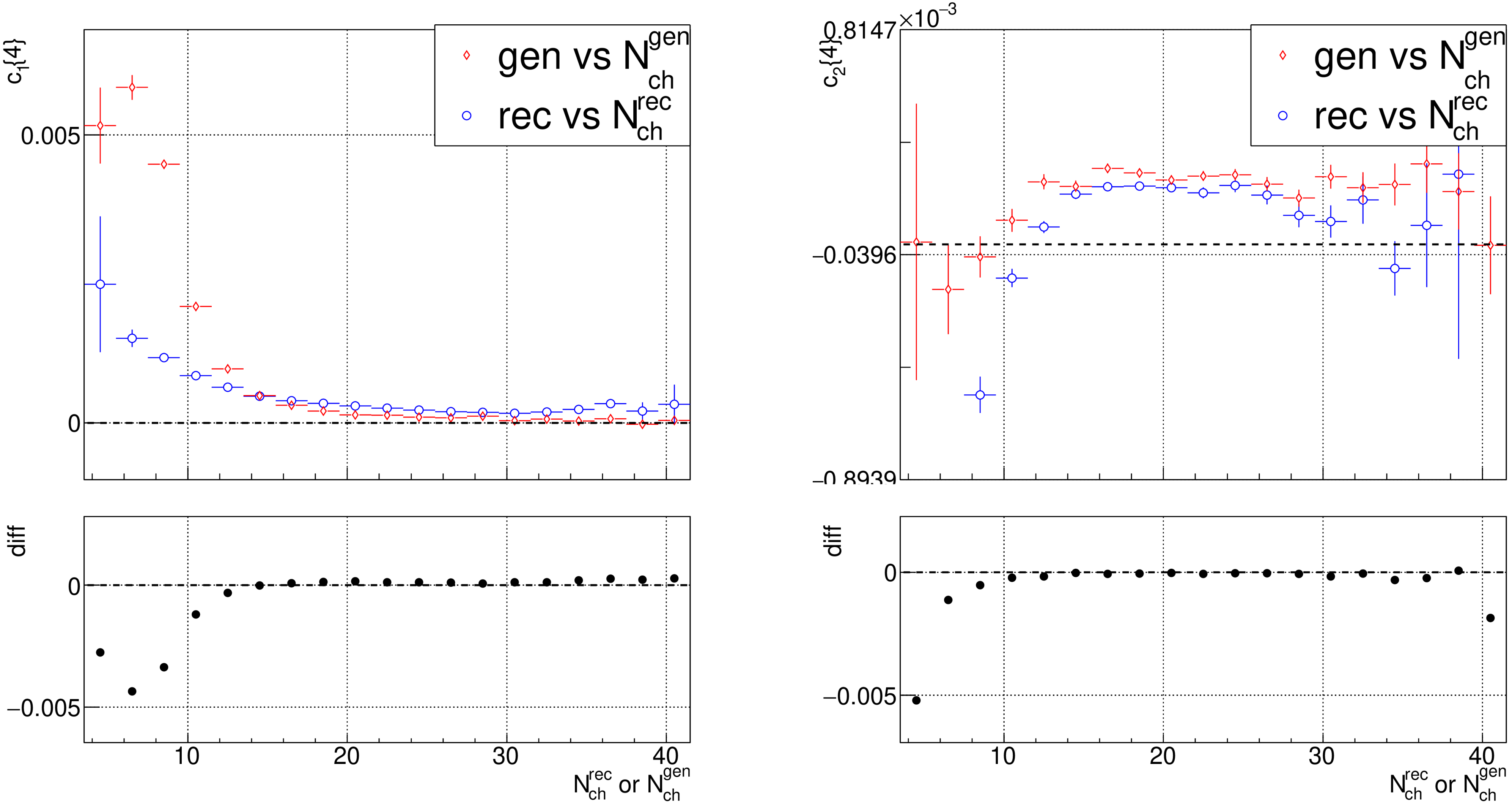


Total MC nonclosure is poor when correlation changes rapidly with N_{ch}.

Note that the scales are very small.

$c_n\{4\}$ Total magnitude of MC nonclosure
Sources 1 and 2 combined

PHP pythia lf jet 06e



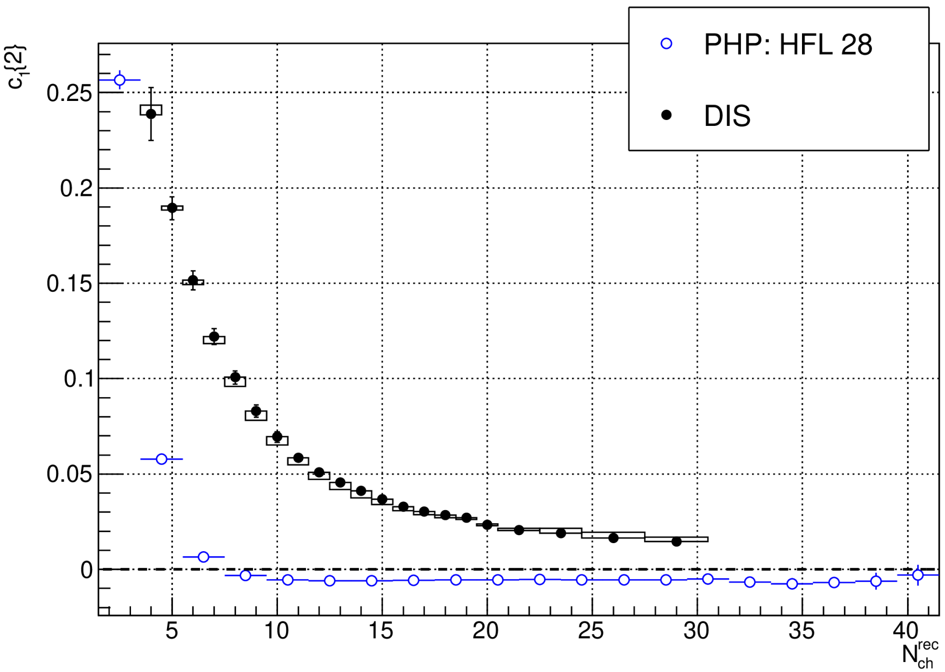
Total MC nonclosure is poor when correlation changes rapidly with N_{ch}.

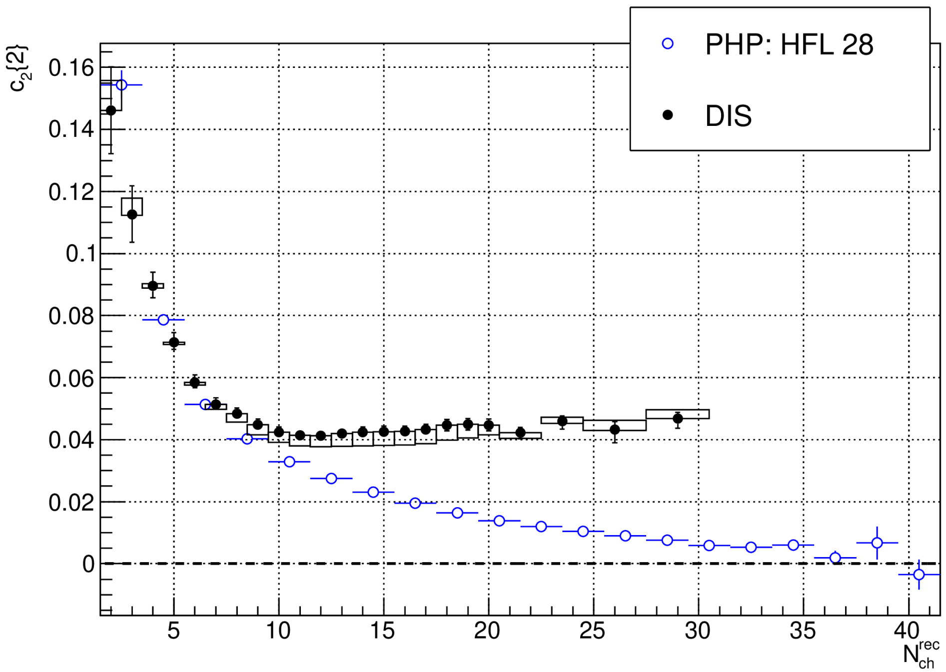
Note that the scales are very small.

Results in ZEUS PHP data

2-particle correlations in PHP compared to DIS

ZEUS data





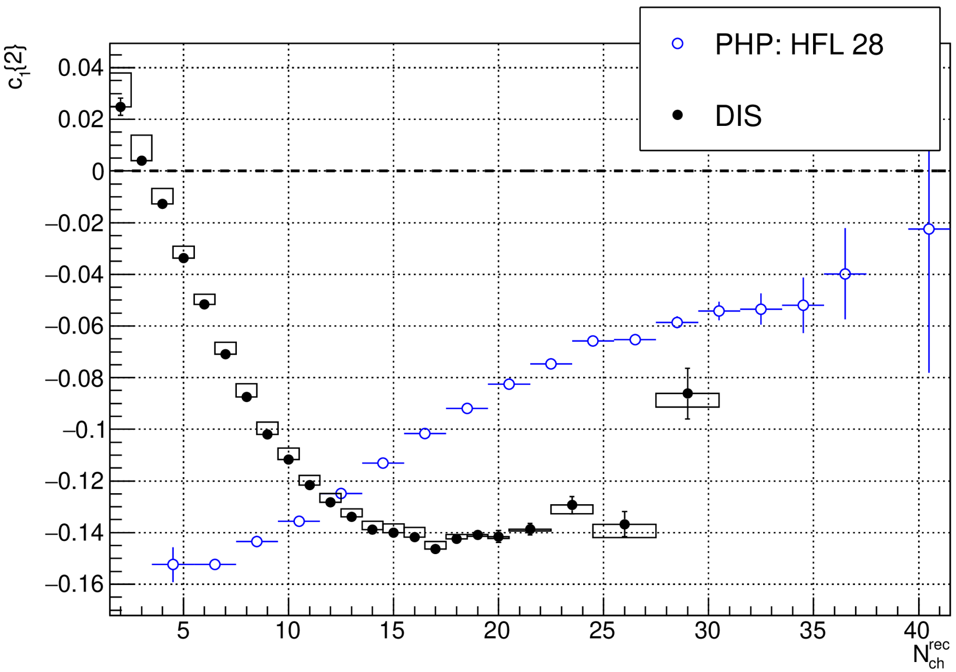
Error bars for PHP are statistical only.

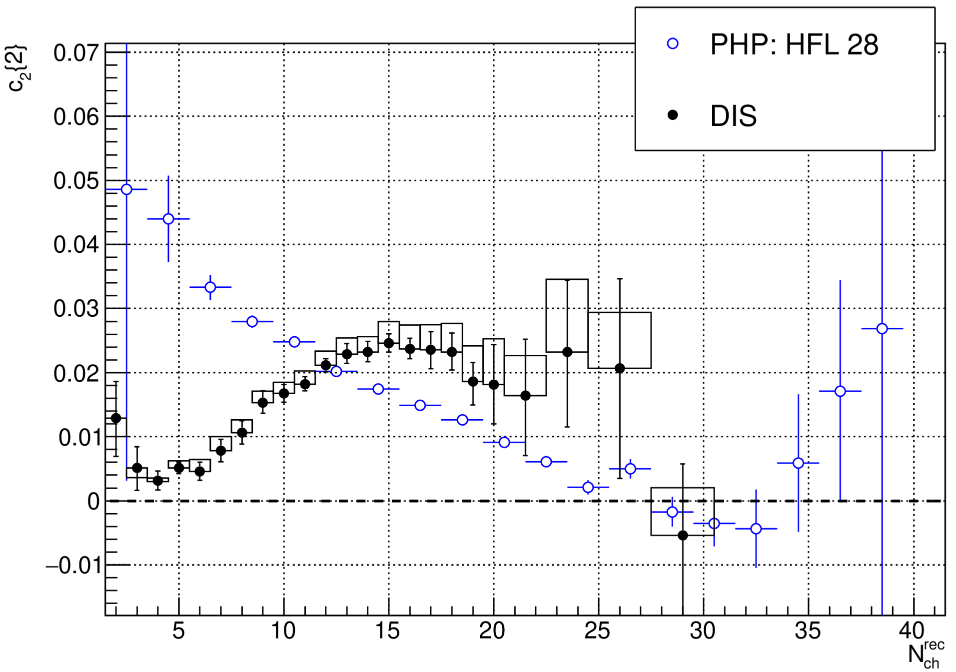
Keep in mind that HFL 28 has a substantial trigger bias for N_{ch} <~ 10.

2-particle correlations in PHP compared to DIS

ZEUS data

$p_T > 0.5$ GeV & $\Delta\eta > 2.0$



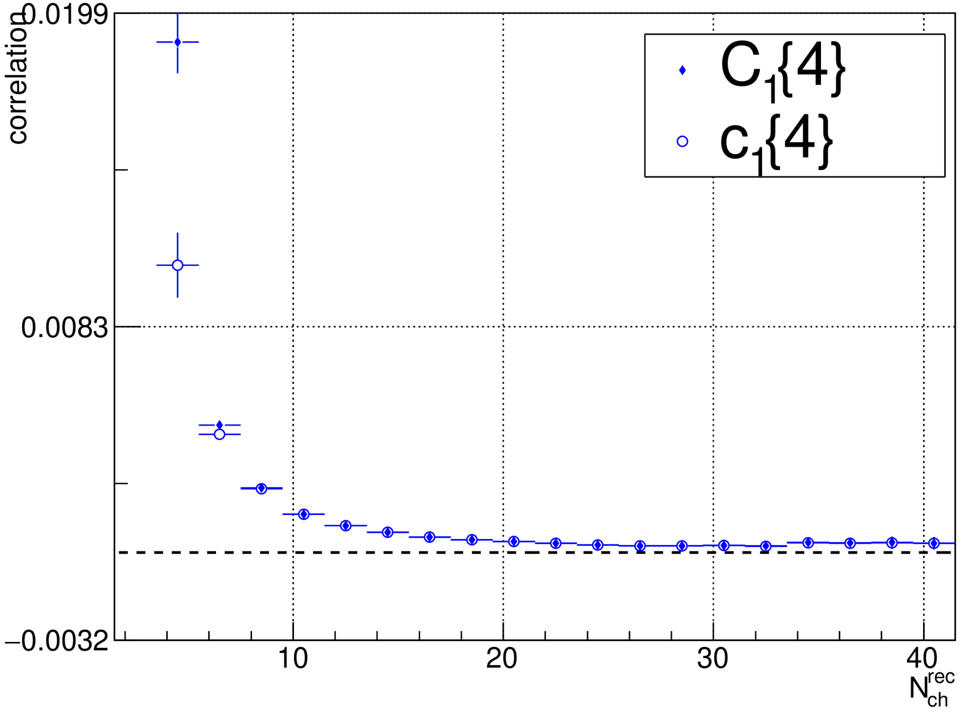


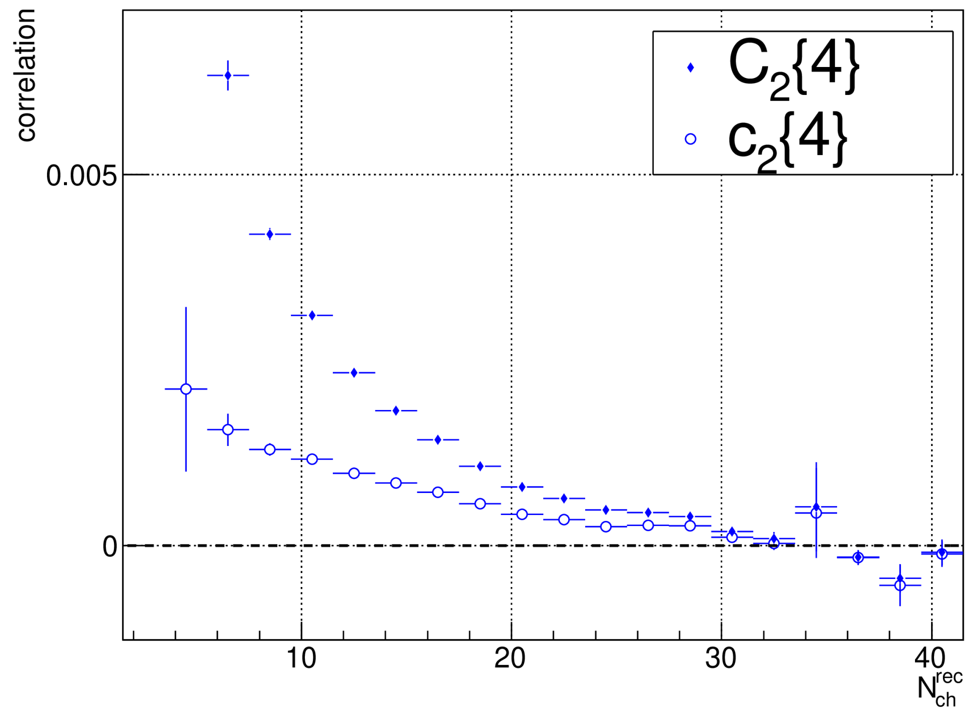
Error bars for PHP are statistical only.

Keep in mind that HFL 28 has a substantial trigger bias for N_{ch} <~ 10.

4-particle correlations in PHP

ZEUS data





The cumulant is positive within statistical uncertainties up to N_{ch}~30.

It is not significantly negative at very high N_{ch}.

Keep in mind that HFL 28 has a substantial trigger bias for N_{ch} <~ 10.

Summary

MC nonclosure

- 2 sources of nonclosure exist.
- 1st source arises from bin migration due to N_{ch}^{rec} distortions and is not easily unfolded in a 1D approach.
- 2nd source arises from distortions to the correlation function from tracking inefficiences.
- Pair and quadruplet weights have been calculated and applied as a correction.

Results in PHP

- Correlations are quite different than those in DIS.
- 4-particle cumulant is not significantly negative as seen in heavy-ion collisions. However, the expectation of negative values may not apply to such small systems.
- $c_2\{2\}$ and $c_2\{4\}$ both go to zero at high Nch.
- This observation seems to suggest that collective signatures are not observed in PHP.

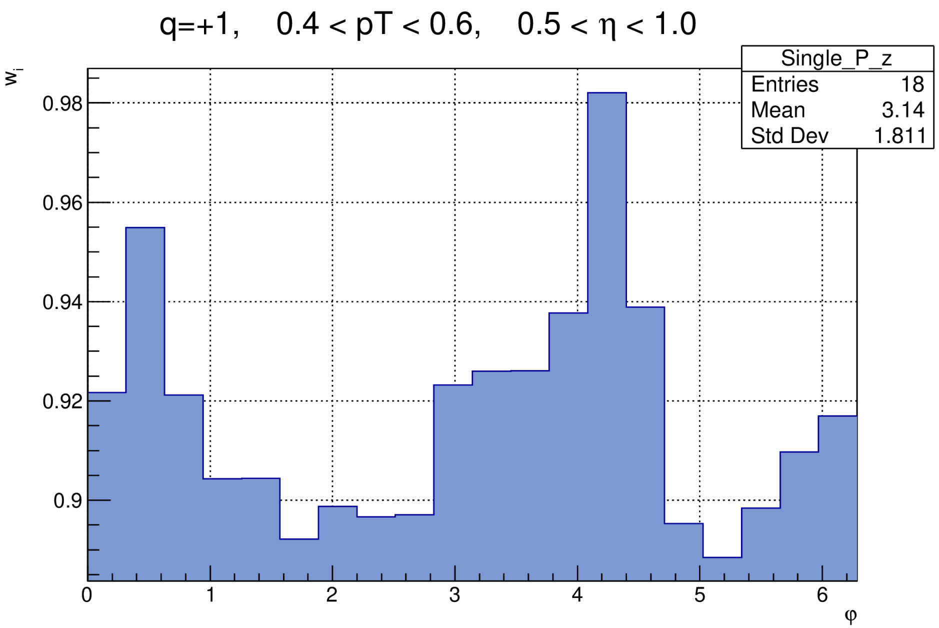
Next Steps

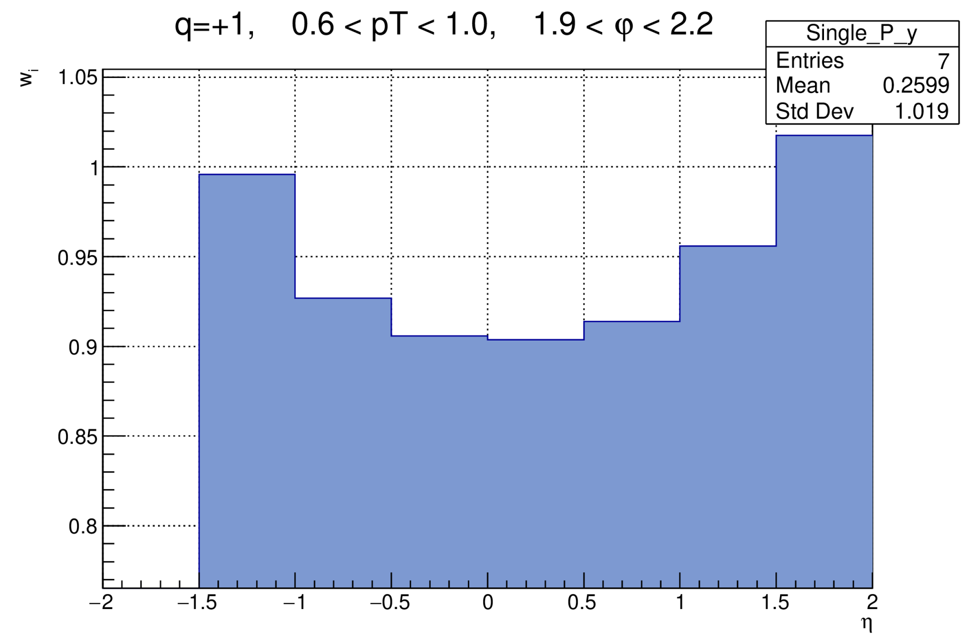
- Begin estimates of other systematic uncertainties and DIS contamination levels.
- Complete the analysis note.

Extra

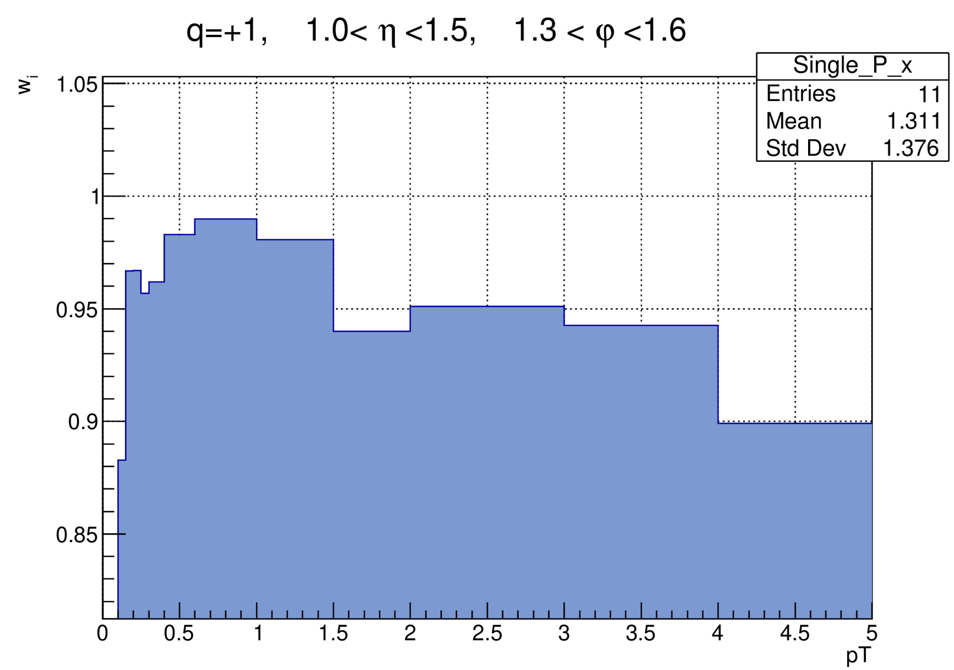
Single-particle correction factors

PHP pythia lf jet 06e



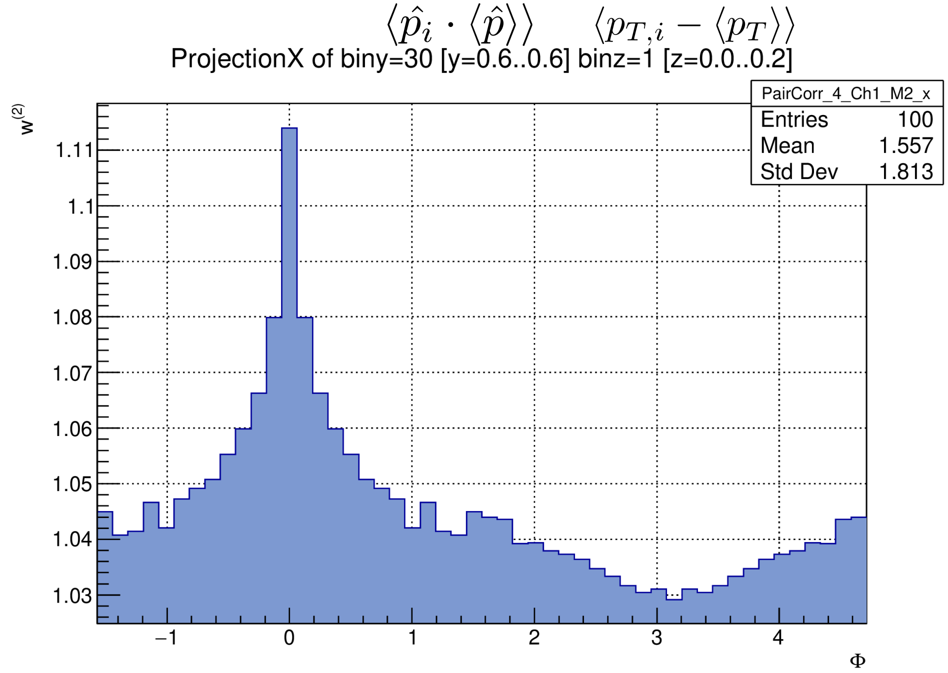


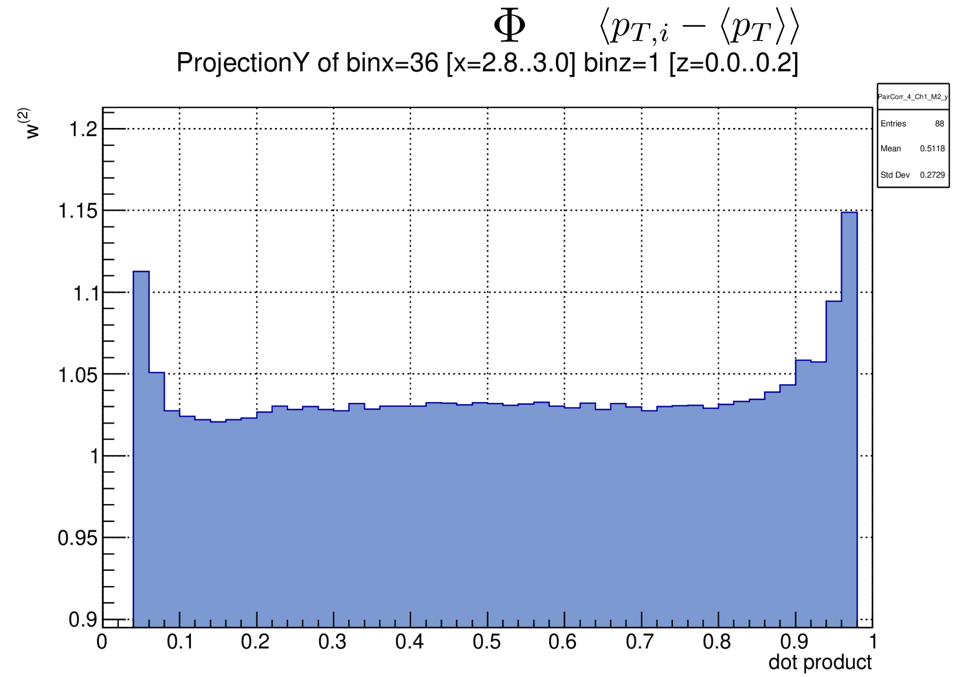
These are just sample projections of a multidimensional landscape



Type 2 Pair correction factors (10 < Nch < 20)

PHP pythia lf jet 06e





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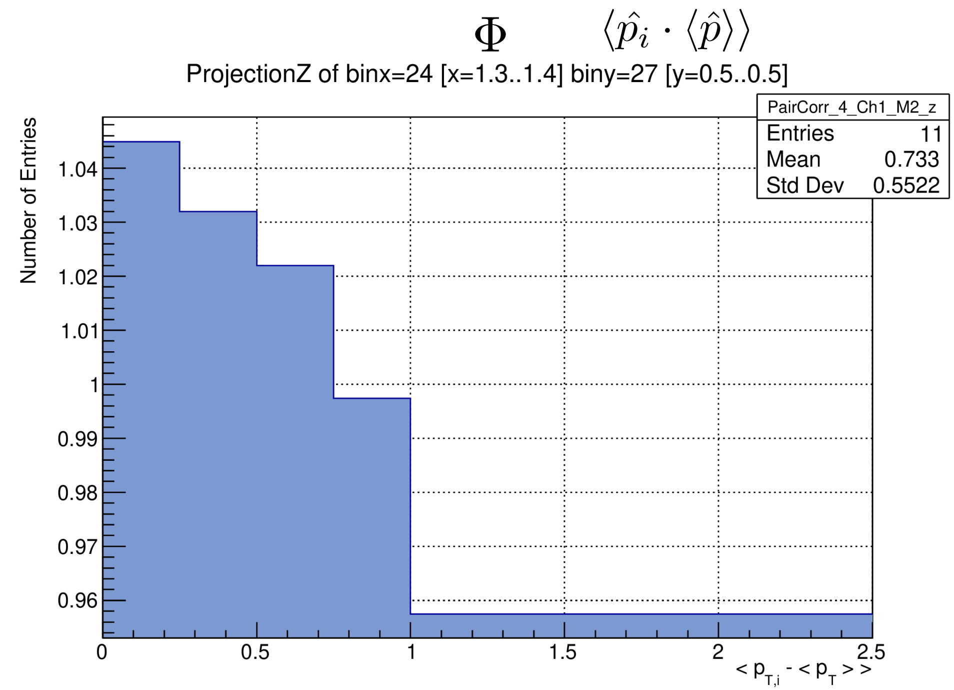
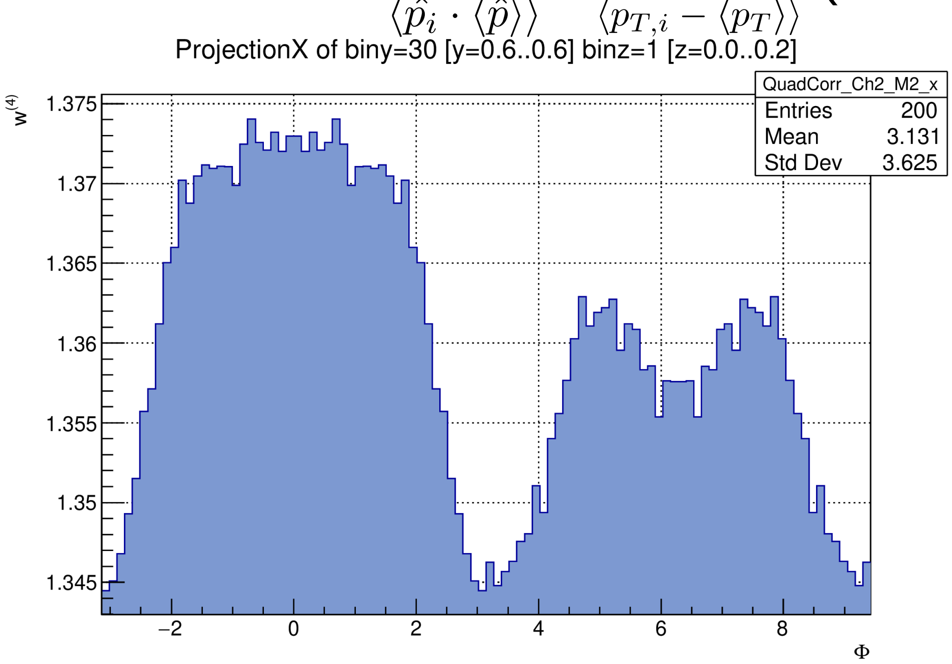
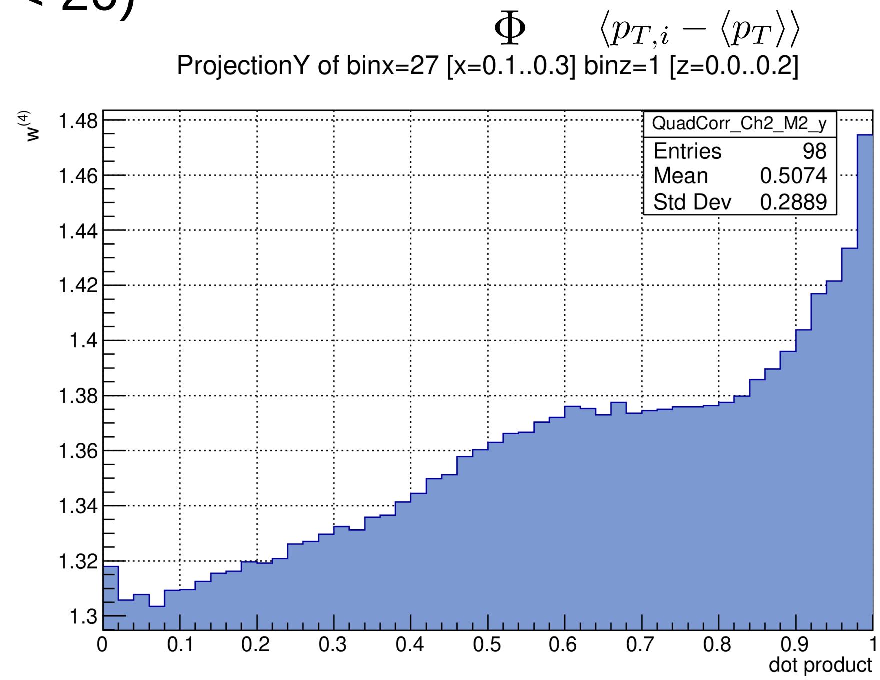


Quad same-charge correction factors
(10 < Nch < 20)

PHP pythia lf jet 06e





These are just sample projections of a multidimensional landscape