Measurement of long-range correlations in Z-boson tagged pp collisions

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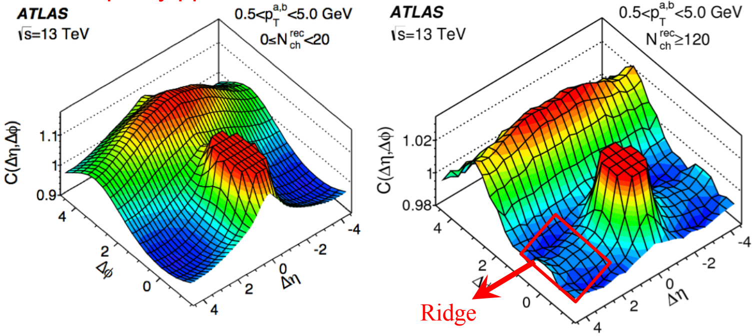
Ridge in *pp* collisions

Low multiplicity pp events

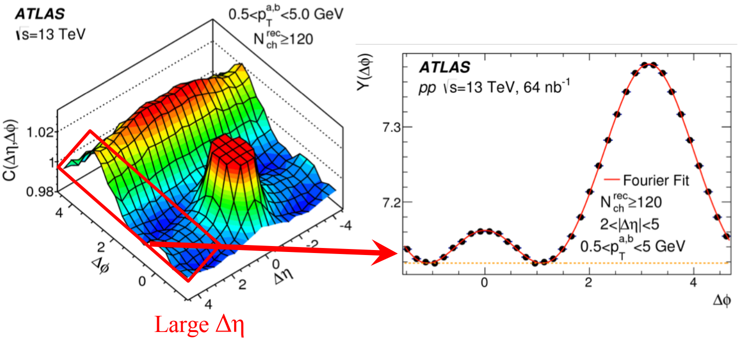
High multiplicity pp events



- Ridge "appears" at high multiplicity.
- Ridge signal much smaller compared to other features of correlation.

Phys. Rev. C 96 (2017) 024908

Analysis of 2PCs in pp collisions



- First step: look at long-range correlation component $|\Delta\eta|>2$
  - Removes near-side jet peak: same as what is done in A+A collisions
- Still dominated by away-side jet.
- Need new method to extract ridge signal.

Analysis technique: Template Fitting Procedure

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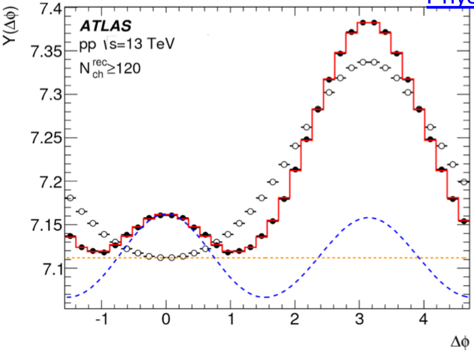
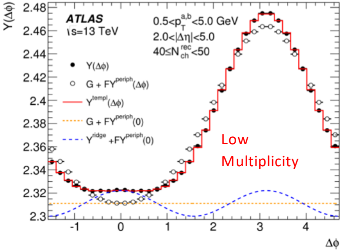
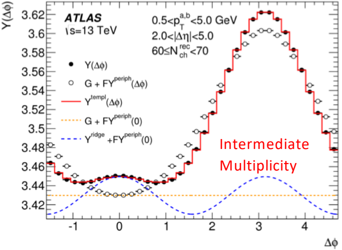


- A template fitting procedure used to extract long-range correlation.

- Fit correlation in high multiplicity events with two component Template :
  - C^{periph}: Correlation in peripheral events (N_{ch}<20) : Jet background
  - C^{ridge} : Pedestal*$(1 + 2v_n^2\cos(n\Delta\varphi))$: True signal

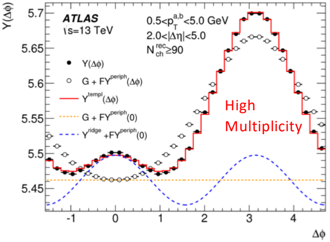
Template Fitting : Multiplicity dependence





Considerable long-range correlation even in low & intermediate multiplicity events.

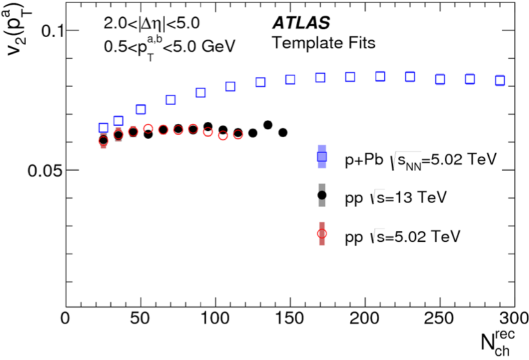
Broadening of away-side and emergence of peak on near-side well described.



Comparison of systems & energies : pp and p+Pb

Consistent values for v_2 between 5.02 TeV and 13 TeV pp collisions. No dependence of v_2 on collision energy.

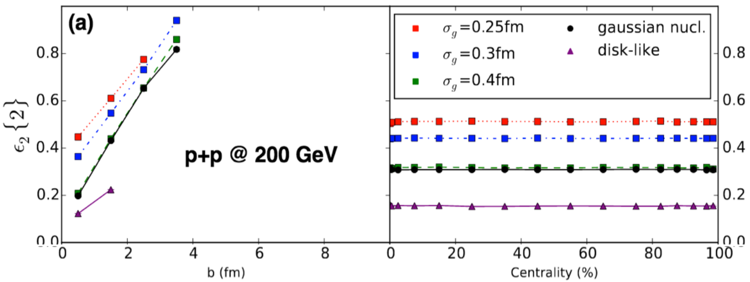
p+Pb v_2 is larger than pp v_2.



For p+Pb clear multiplicity dependence is seen for v_2.

No dependence on multiplicity seen for pp v_2.

Why is there no multiplicity dependence to *pp* v_n



- One answer comes from U. Heinz and collaborators.
- No correlation between multiplicity and eccentricity in pp collisions
- But correlation present between eccentricity and impact parameter
- Need to bin pp events not by multiplicity but by impact parameter!

[Phys. Rev. C. 94.024919]

How to select low-impact parameter pp events?

- Require process with large momentum transfer (large q^2)

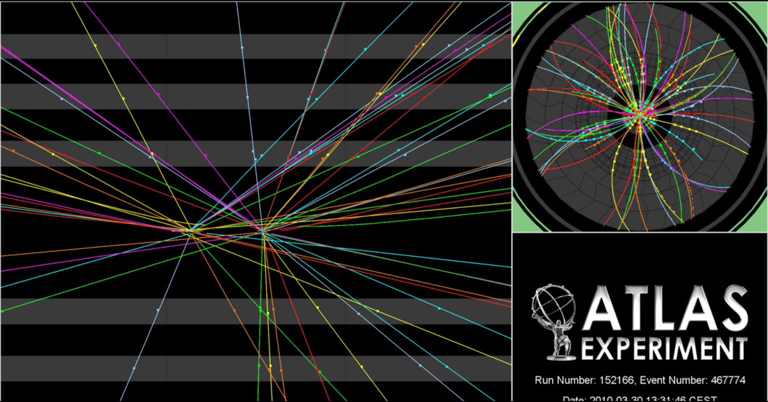
- Large $q^2 \Rightarrow$ small time-scale/short range $\Rightarrow$ smaller impact parameter

- Can impose large q^2 requirement by requiring a Z-boson in the event : $|q^2| \sim (90\ \text{GeV})^2$

- Z-boson requirement is easy to impose: require two muons with invariant mass in the region 80-100 GeV

- But this introduces a different complication

Collision Event at 7 TeV with 2 Pile Up Vertices



Correlation analyses only use low-luminosity pp data.

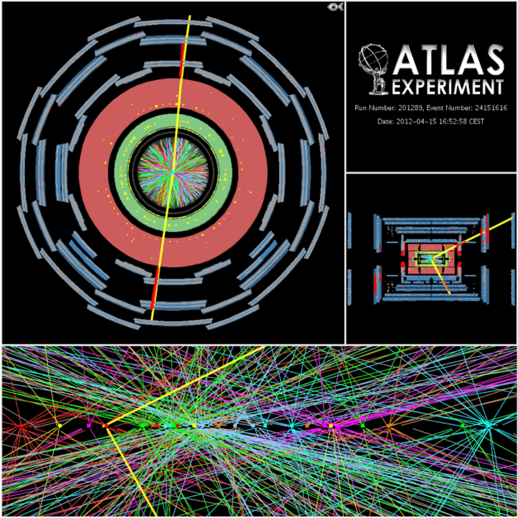
Typically only one interaction per event.
Two or more interactions very rare.

Analyze high-pileup *pp* events

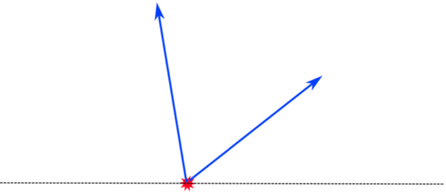
Need to go to nominal LHC luminosities, to get sufficient “Z”-tagged events

bunch crossings can have up to 40 simultaneous pp interactions

Pileup makes 2PC study difficult!



Estimating pileup in Z-tagged *pp* events



Event with Z-boson identified by presence of two high-p_T muons with invariant mass between 80-100 GeV

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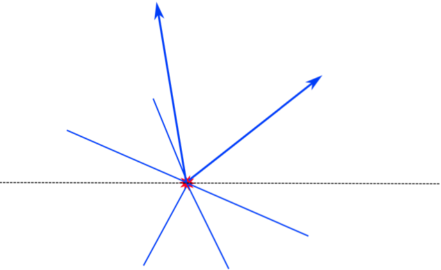

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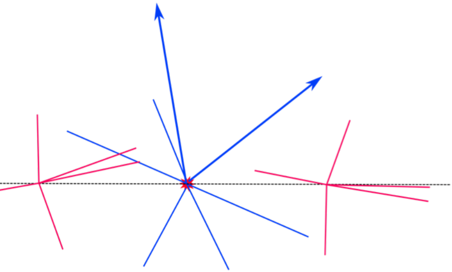
We are interested in correlations between the "other" particles in the event

Estimating pileup in Z-tagged *pp* events



Event with Z-boson identified by presence of two high-p_T muons with invariant mass between 80-100GeV

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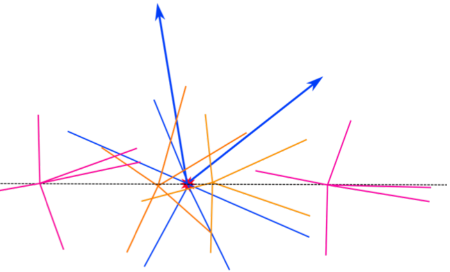
Have many pileup collisions. Tracks from pileup collisions well separated from Z-event can be easily removed

Estimating pileup in Z-tagged *pp* events



Event with Z-boson identified by presence of two high-p_T muons with invariant mass between 80-100GeV

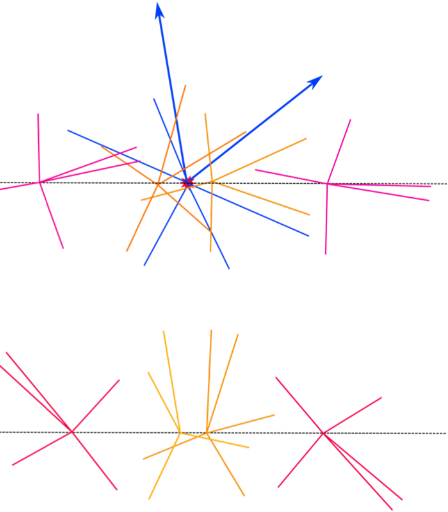
We are interested in correlations between the “other” particles in the event

Problem arises when pileup vertices are very close to the Z-event vertex.

It becomes difficult to distinguish such pileup tracks from the “signal” tracks.

Have many pileup collisions. Tracks from pileup collisions well separated from Z-event can be easily removed

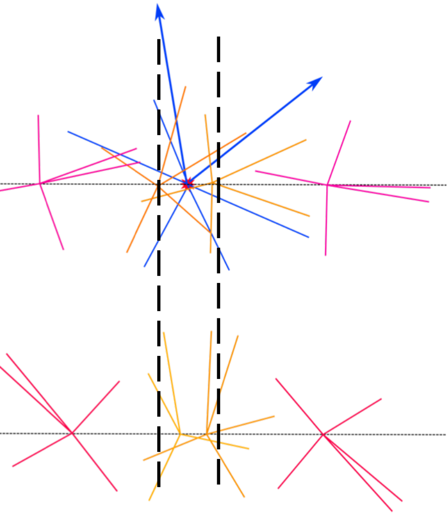
Estimating pileup in Z-tagged *pp* events



Pick a second "unbiased" event recorded under identical luminosity conditions as the first event.

"Unbiased" : no selection criteria, except requirement of identical luminosity condition as first event.

Estimating pileup in Z-tagged *pp* events



Pick a second "unbiased" event recorded under identical luminosity conditions as the first event.

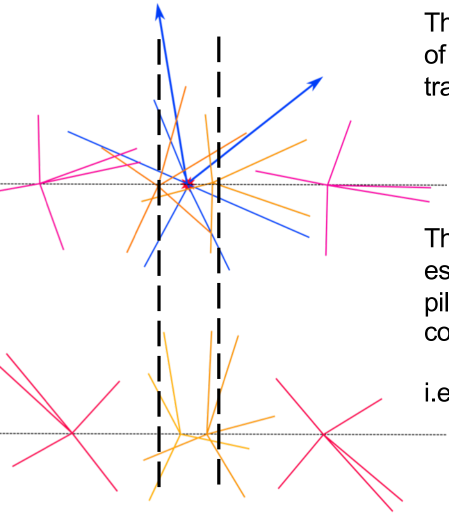
"Unbiased" : no selection criteria, except requirement of identical luminosity condition as first event.

Select tracks in second event, pretending there was a Z-tagged collision in it, in the same location as in the first event.

Call this combination "Mixed" event.

Mixed=> tracks from 2nd event, but vertex position from first.

Analyze high-pileup *pp* events



The "Direct Event" consists of "Signal" and "Pileup" tracks

The "Mixed" event gives an estimation of the number of pileup tracks as well as their correlation in **$\Delta\phi$**.

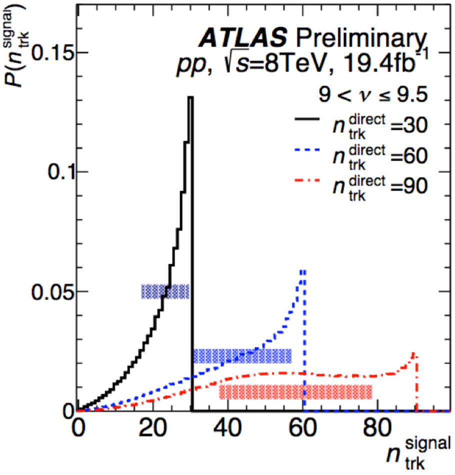
i.e. <Mixed>≡<Pileup>

Correcting multiplicities

Plot shows probability distribution for number of Signal tracks for events with different number of Direct tracks:

1. Black : 30 Direct tracks
2. Blue: 60 direct tracks
3. Red: 90 direct tracks

Bands indicate ±r.m.s. widths of the distributions centered around mean values



Correcting for Background pairs

- When considering the pair correlations we have:

$$\begin{aligned}\text{Direct}^a \times \text{Direct}^b = {} & \text{Signal}^a \times \text{Signal}^b \\ & + \text{Signal}^a \times \text{Pileup}^b + \text{Pileup}^a \times \text{Signal}^b \\ & + \text{Pileup}^a \times \text{Pileup}^b\end{aligned}$$

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\begin{aligned}
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\end{aligned}
$$

- Rearranging we get:

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\text{Signal}^a \text{x} \text{Signal}^b = {} & \text{Direct}^a \text{x} \text{Direct}^b - \text{Pileup}^a \text{x} \text{Pileup}^b \\
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- Unfortunately “Signal” appears on both LHS and RHS

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- Unfortunately "Signal" appears on both LHS and RHS

- (Very legitimate) Assumption : $\langle \mathrm{Signal}^a \mathrm{x} \mathrm{Pileup}^b \rangle = \langle \mathrm{Signal}^a \rangle \langle \mathrm{Pileup}^b \rangle$
  Where <...> indicates average over events

Correcting for Background pairs

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  Where <...> indicates average over events

- We get:

$$\langle \text{Signal}^a \times \text{Pileup}^b \rangle = \langle \text{Signal}^a + \text{Pileup}^a \rangle \langle \text{Pileup}^b \rangle - \langle \text{Pileup}^a \rangle \langle \text{Pileup}^b \rangle$$
$$= \langle \text{Direct}^a \rangle \langle \text{Pileup}^b \rangle - \langle \text{Pileup}^a \rangle \langle \text{Pileup}^b \rangle$$

Correcting for Background pairs

- So we get:

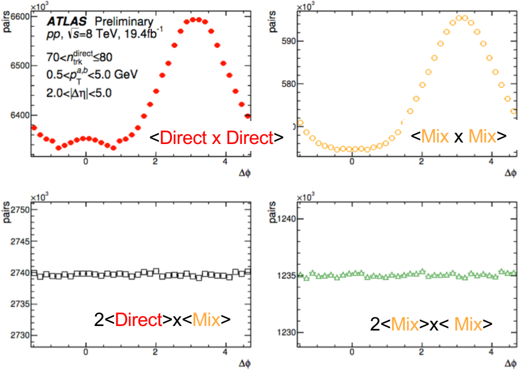
$$\langle \text{Signal}^a \times \text{Signal}^b \rangle = \langle \text{Direct}^a \times \text{Direct}^b \rangle - \langle \text{Pileup}^a \times \text{Pileup}^b \rangle - \langle \text{Direct}^a \rangle \langle \text{Pileup}^b \rangle - \langle \text{Pileup}^a \rangle \langle \text{Direct}^b \rangle + 2 \langle \text{Pileup}^a \rangle \langle \text{Pileup}^b \rangle$$

- This is the “Master formula” for correcting the 2PC with the substitution: Pileup $\rightarrow$ Mixed

$$\langle \text{Signal}^a \times \text{Signal}^b \rangle = \langle \text{Direct}^a \times \text{Direct}^b \rangle - \langle \text{Mixed}^a \times \text{Mixed}^b \rangle - \langle \text{Direct}^a \rangle \langle \text{Mixed}^b \rangle - \langle \text{Mixed}^a \rangle \langle \text{Direct}^b \rangle + 2 \langle \text{Mixed}^a \rangle \langle \text{Mixed}^b \rangle$$

- Where the items in the last two lines of the above equation are obtained from correlating tracks between different events

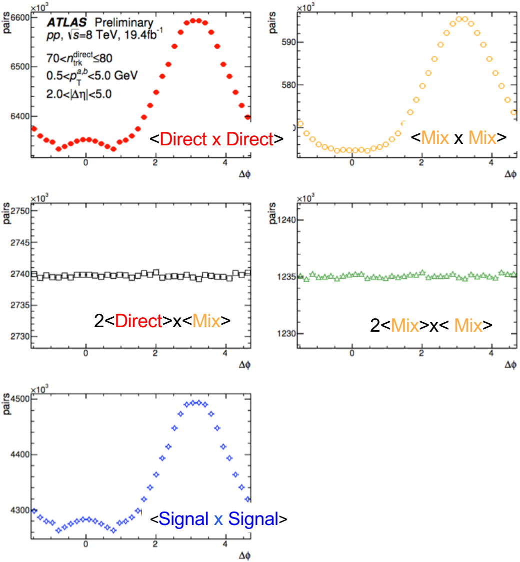
Example Correction Procedure



Example Correction Procedure

<SS>=
<DD>-<MM>
-2<DM>+2<M><M>

~30% change in number of pairs independent of **Δϕ**



Example Correction Procedure

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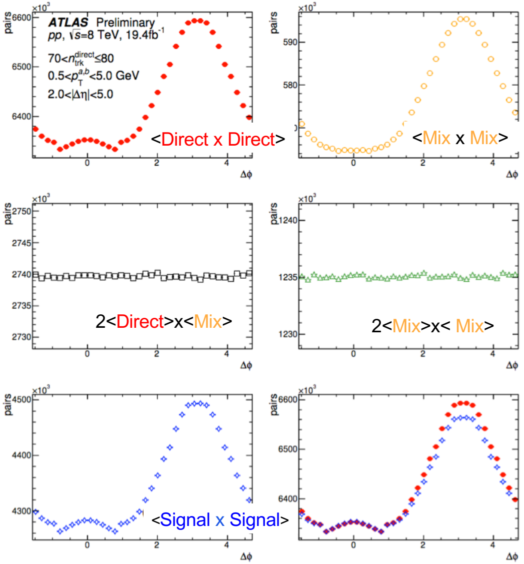
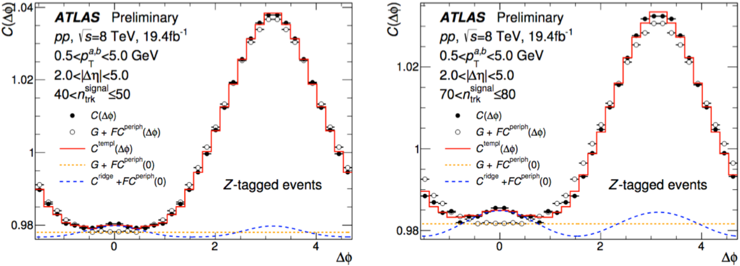
~30% change in number of pairs independent of **Δϕ**

Small change in modulation only on away-side

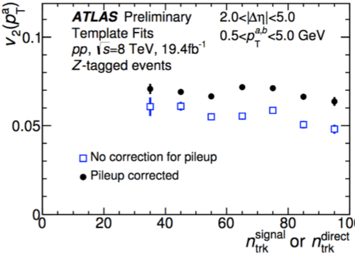


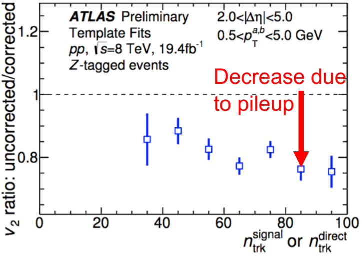
Template fits after pileup correction



- Once the correlations are corrected for Pileup, we can proceed with the template fitting analysis
- Plots Show example fits to extract the Fourier Coefficients
- Reminder:
  - Measured 2PC= (Scale1)*(Low multiplicity 2PC) + Scale2*(1+2$v_{n,n}$cos(nΔφ))
  - Parameters of Template fit are “Scale1” and the $v_{n,n}$(n=2-4)

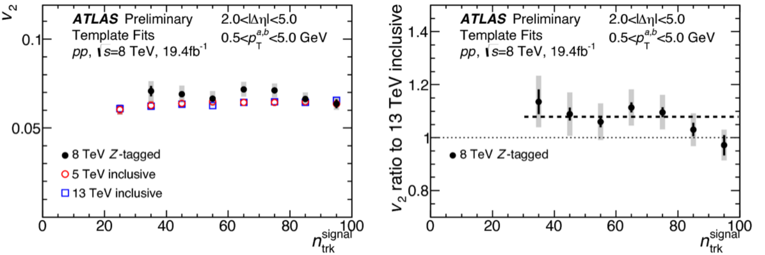
v_2 signal : before and after pileup correction





- v_2 before and after pileup correction : multiplicity dependence
- Left panel: 8 TeV Z-tagged v_2 : before and after correction
- Right Panel: Ratio of before/after correction

v_2 in Z-boson tagged pp events



- Left panel: v_2 in Z-tagged 8 TeV events
  - compared to v_2 in inclusive 5 TeV and 13 TeV pp collisions
  - Weak multiplicity dependence in Z-tagged v_2
- Right panel ratio to 13 TeV measurements

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The v_2 in Z-tagged events shows slight increase rather than a decrease!

Summary

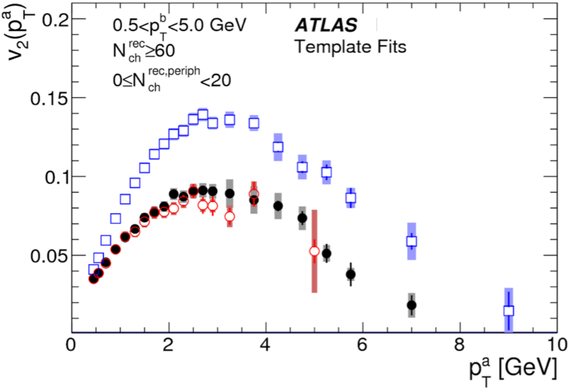
- Global azimuthal correlations present in inclusive pp collisions
- Very unexpected multiplicity dependence of v_2 in pp: no multiplicity dependence!

- Possible explanation: poor correlation between multiplicity and impact parameter
  - U. Heinz et.al. Phys. Rev. C. 94.024919

- Measure v_2 in events with small impact parameter:
  - selected by requiring a Z-boson
  - Considerable problems from pileup

- Developed a data-driven procedure to correct for pileup in multiplicity and 2PC distributions
- Measurement shows that v_2 in Z-tagged is not reduced compared to inclusive pp collisions!

Comparison of systems & energies : pp and p+Pb



Consistent values for v_2 between 5.02 TeV and 13 TeV pp collisions.
No dependence of v_2 on collision energy.

p_T dependence very similar between pp and p+Pb