To spin, or not to spin, that is the question

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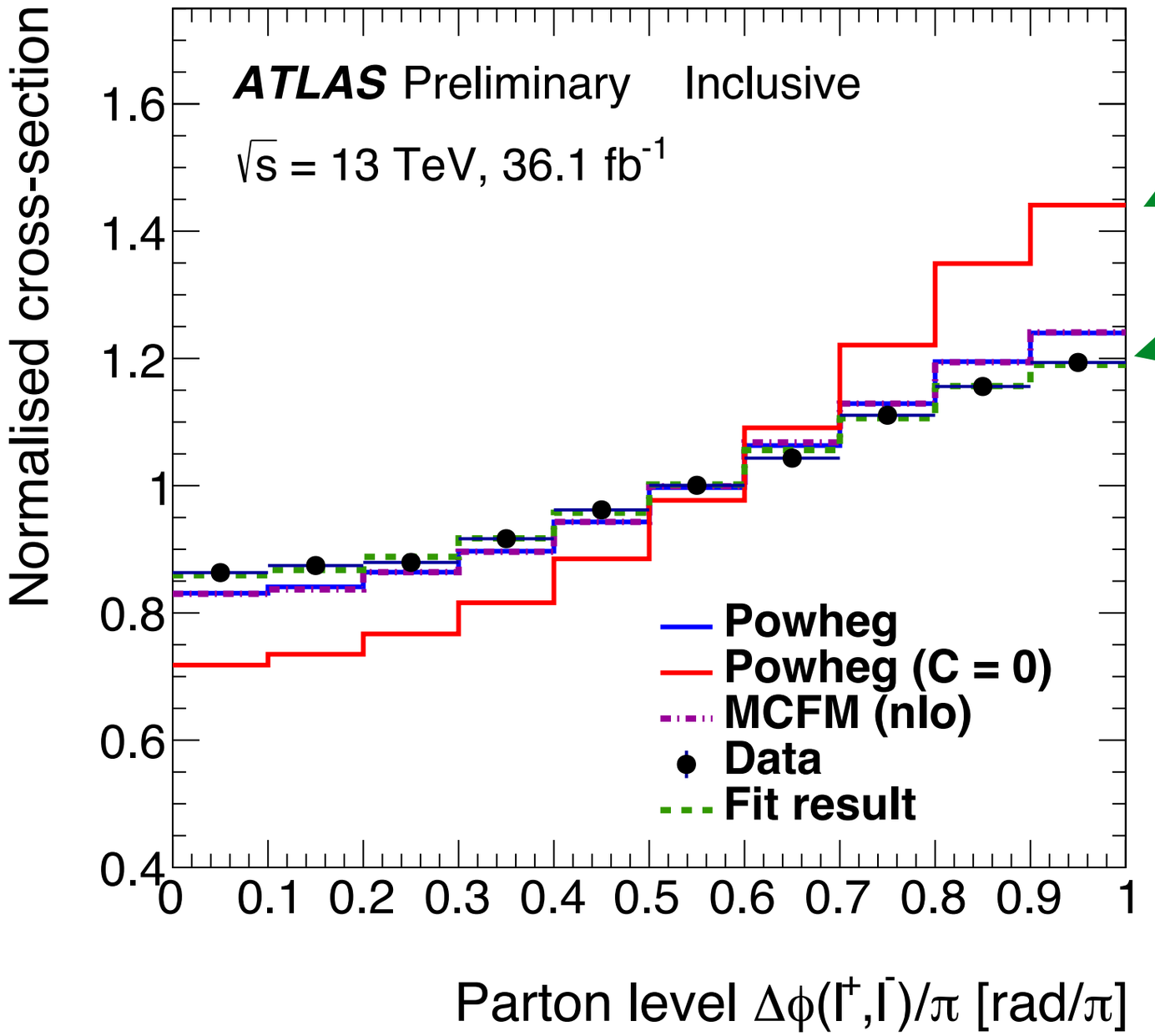
Based on 1806.07438 and further work with Michelangelo

In Run 2 data, ATLAS observed a 3.2σ / 3.7σ deviation from the NLO predictions for the dilepton azimuthal correlation $\phi = |\phi_{\ell+} - \phi_{\ell-}|$ in $t\bar{t} \rightarrow W^+b\,W^-b \rightarrow l^+\nu b\; l^-\nu b$



ignore this line

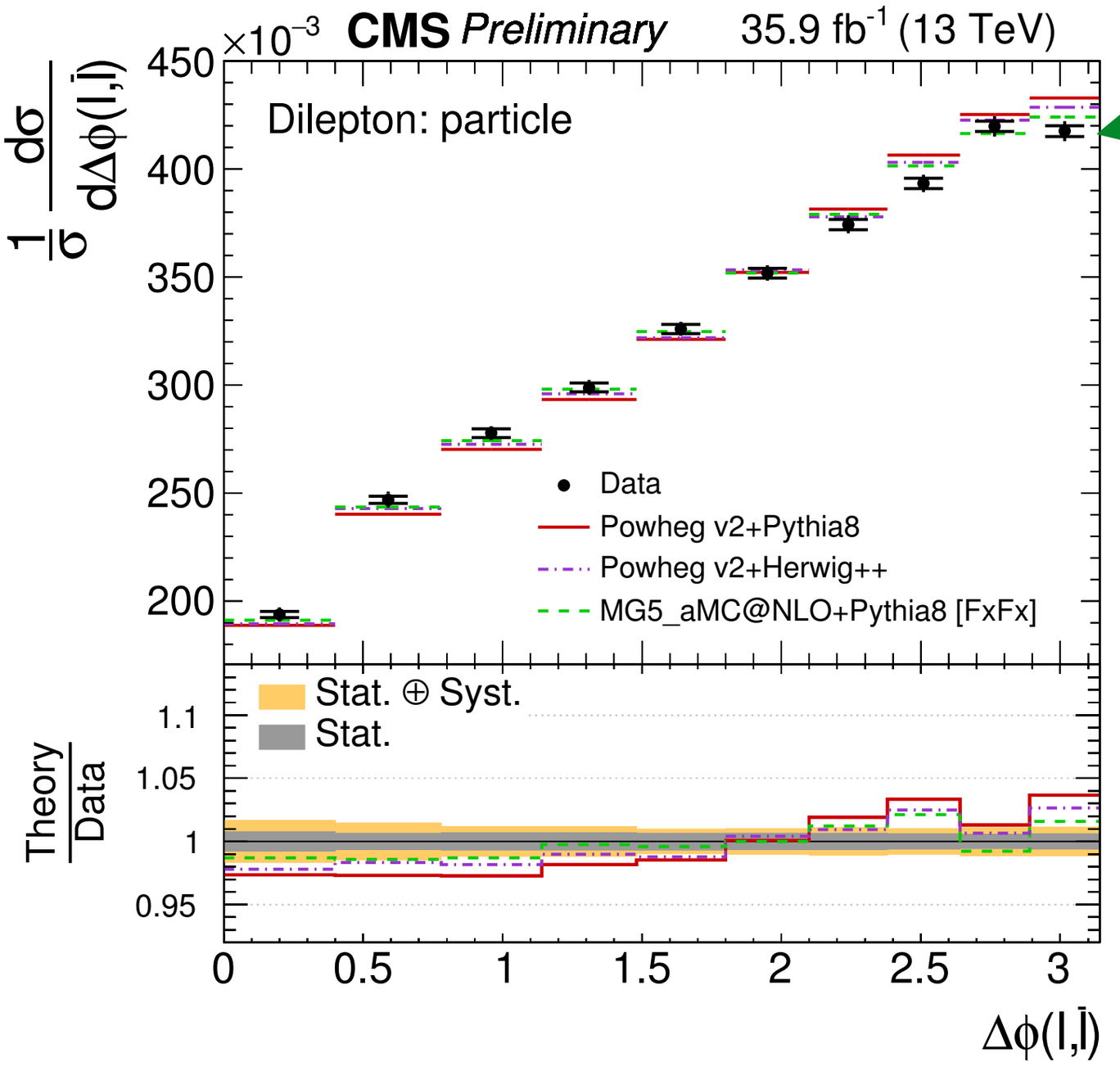
deviation

This distribution is sensitive to tt spin correlations.

As well as to kinematics.

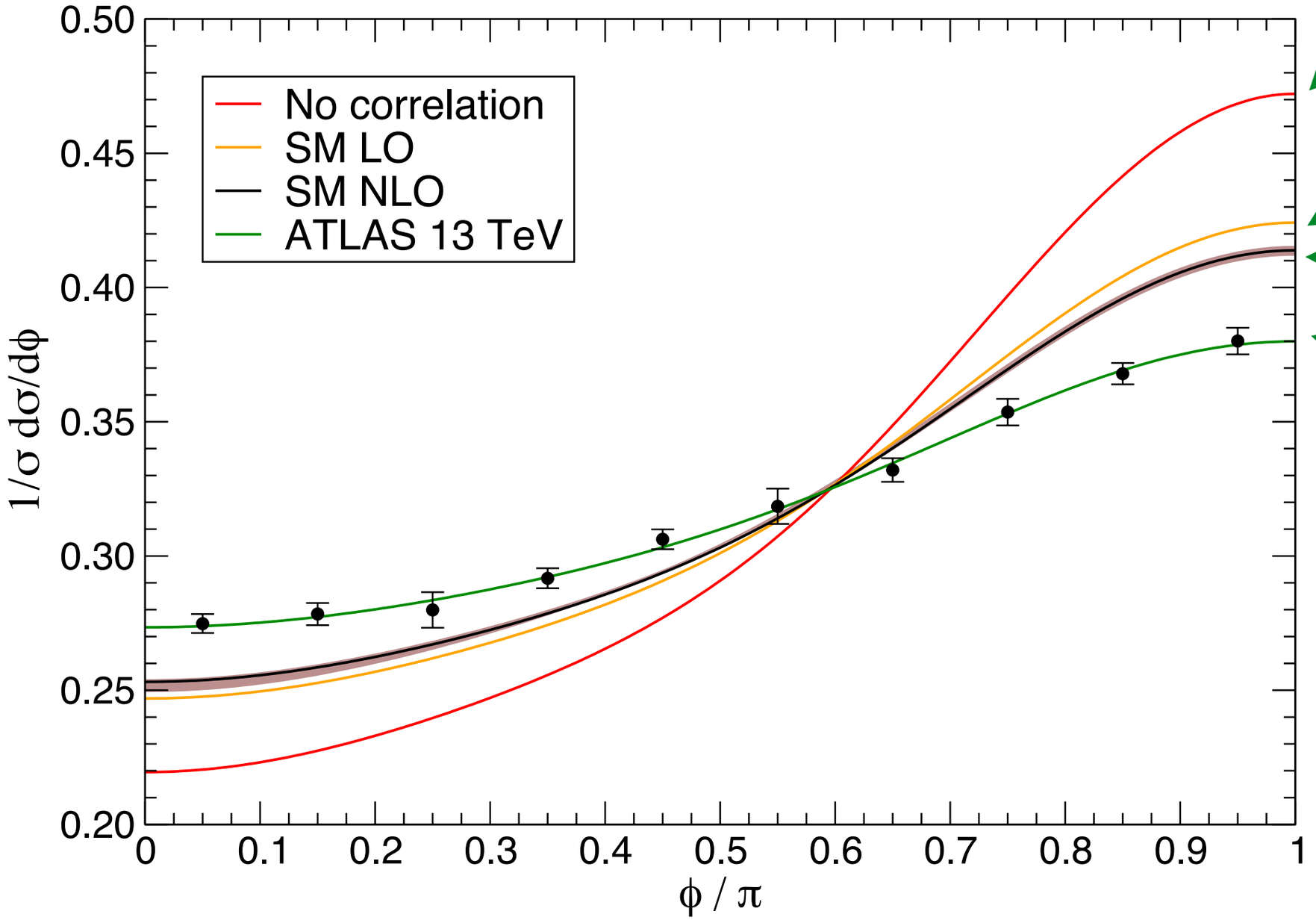
The same trend is seen in CMS Run 2 data, and was also seen in Run 1 at 7 and 8 TeV

Particle level: no parton level plots available.



deviation

Given the difference between LO and NLO predictions, and scale uncertainties, it would be quite surprising that the deviation from the ATLAS measurement arises from higher-order SM effects only.



ignore this line

LO

NLO with uncertainty*

ATLAS

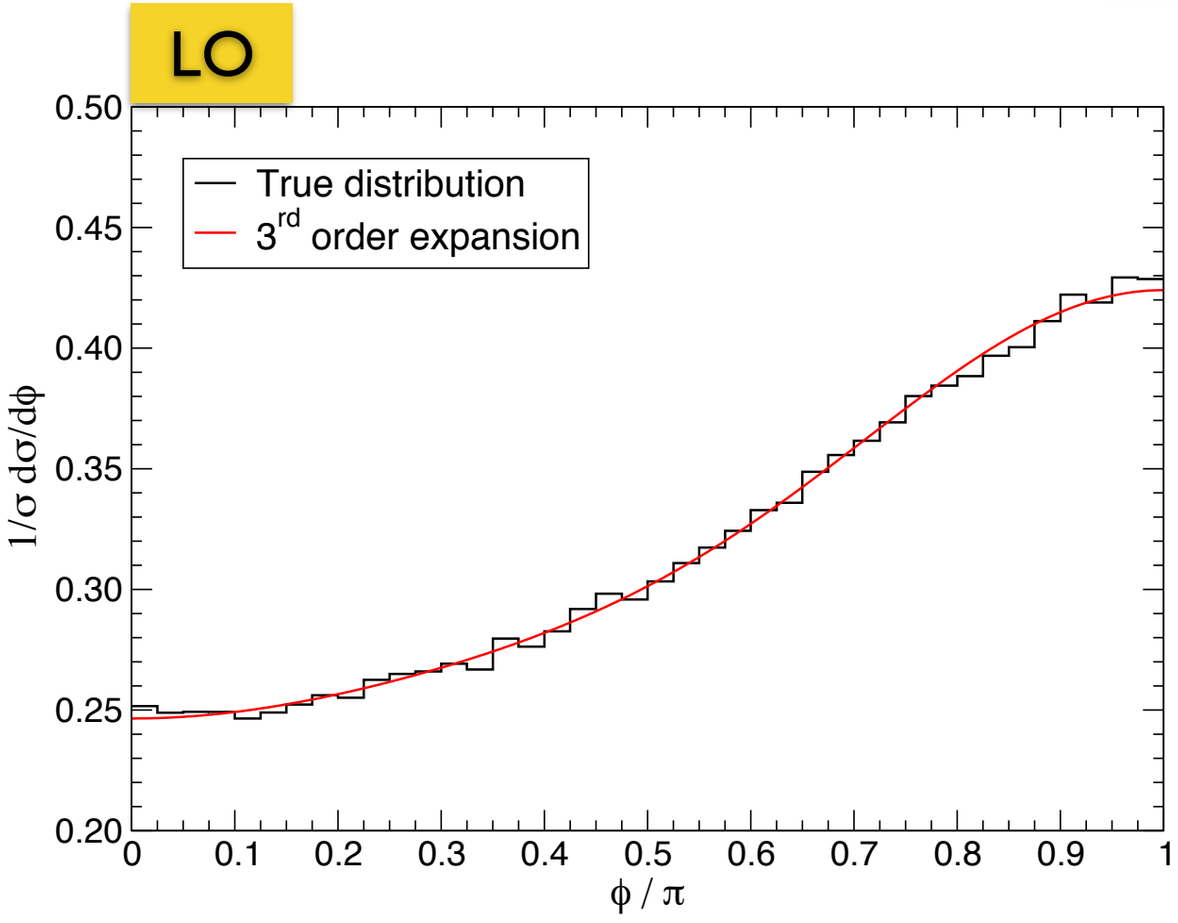
* Black: $Q = \Sigma m_T$
Gray: $Q/2$, $Q \times 2$

Framework

We will use a Fourier analysis of the distribution, first suggested by Fourier in 19th century and used at many places.

$$\frac{1}{\sigma}\frac{d\sigma}{d\phi} = a_0 + \sum_{n=1}^{\infty} a_n \cos n\phi$$

	Uncorrelated	SM LO	SM NLO	ATLAS
a_1	-0.1188	-0.0842	-0.0764	-0.0512
a_2	0.0275	0.0172	0.0151	0.0084
a_3	-0.0075	-0.0044	-0.0040	-0.0021



a_0 = 1/π for the normalised distribution

a_1 roughly gives the `slope´

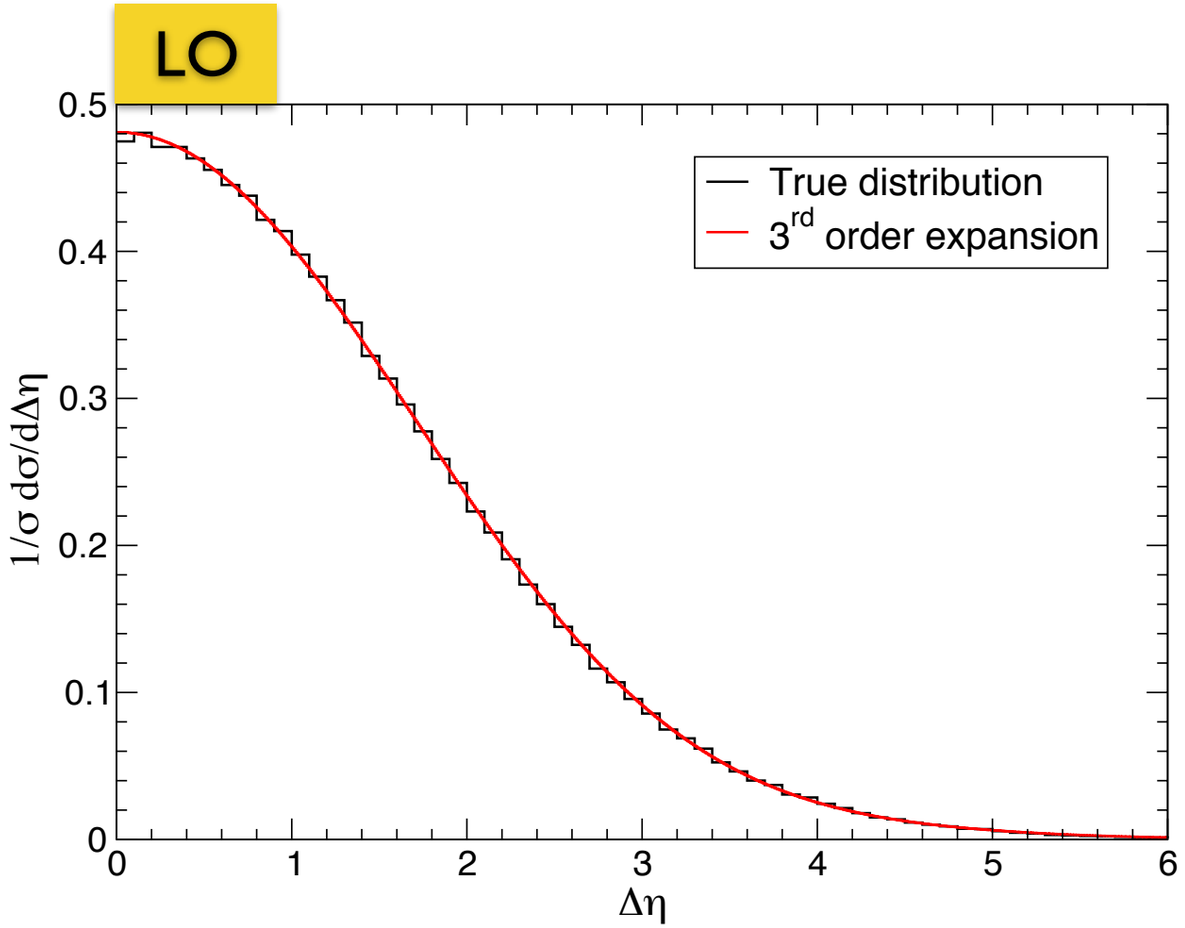
a_2 is small, reflects some features in distribution

a_3, … irrelevant

The rapidity correlation $\Delta\eta = |\eta_{\ell+} - \eta_{\ell-}|$ can also be written in terms of a Fourier series [here using period of 4π]

$$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\eta} = a_0 + \sum_{n=1}^{\infty} a_n \cos n\frac{\Delta\eta}{2}$$

	SM LO	SM NLO	ATLAS
a_1	0.226	0.225	TOP SECRET
a_2	0.0819	0.0801	TOP SECRET
a_3	0.0140	0.0122	TOP SECRET



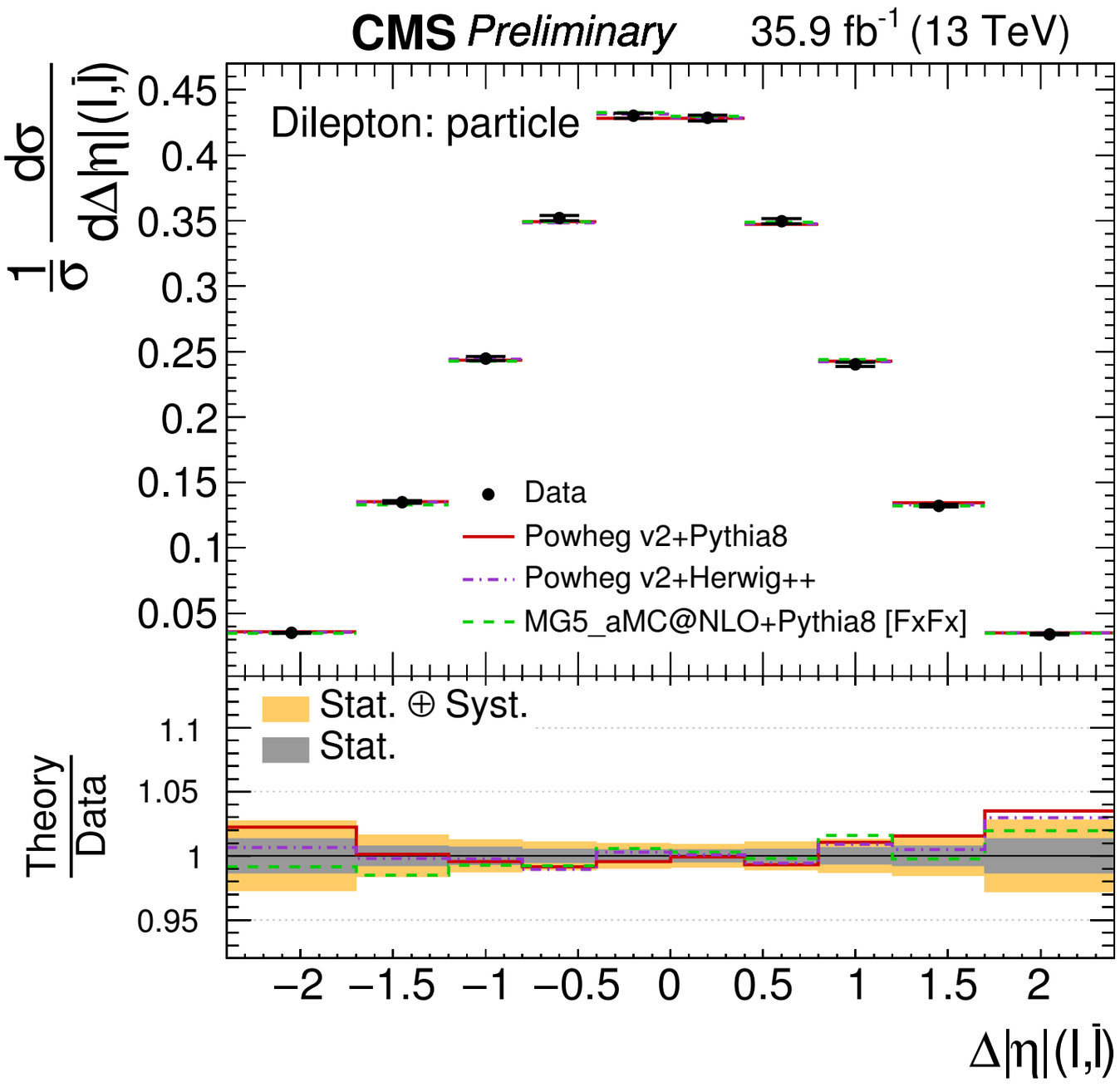
a_0 = 1/2π for the normalised distribution

a_1, a_2 give the shape

a_3 modifies minor details

ATLAS measurements not yet available, let us assume data agrees with the SM

CMS measures a similar distribution but using $\Delta|\eta|$. No deviations are seen, supporting our working hypothesis that $\Delta\eta$ agrees with SM predictions.



Key features of the analysis.

- LO is mostly used here for speed and simplicity.

  Justified as first approximation because the difference from LO to NLO is much smaller than from NLO to ATLAS data. [NLO used in 1806.07438]

- Fourier coefficients parameterised as a function of new physics coupling.

  By generating samples for several new physics scenarios one can fit the functional dependence.

- Main focus on leading first-order coefficient a_1.

  As we know, trigonometric functions are a basis, so in order to reproduce a distribution we have to reproduce all the coefficients.

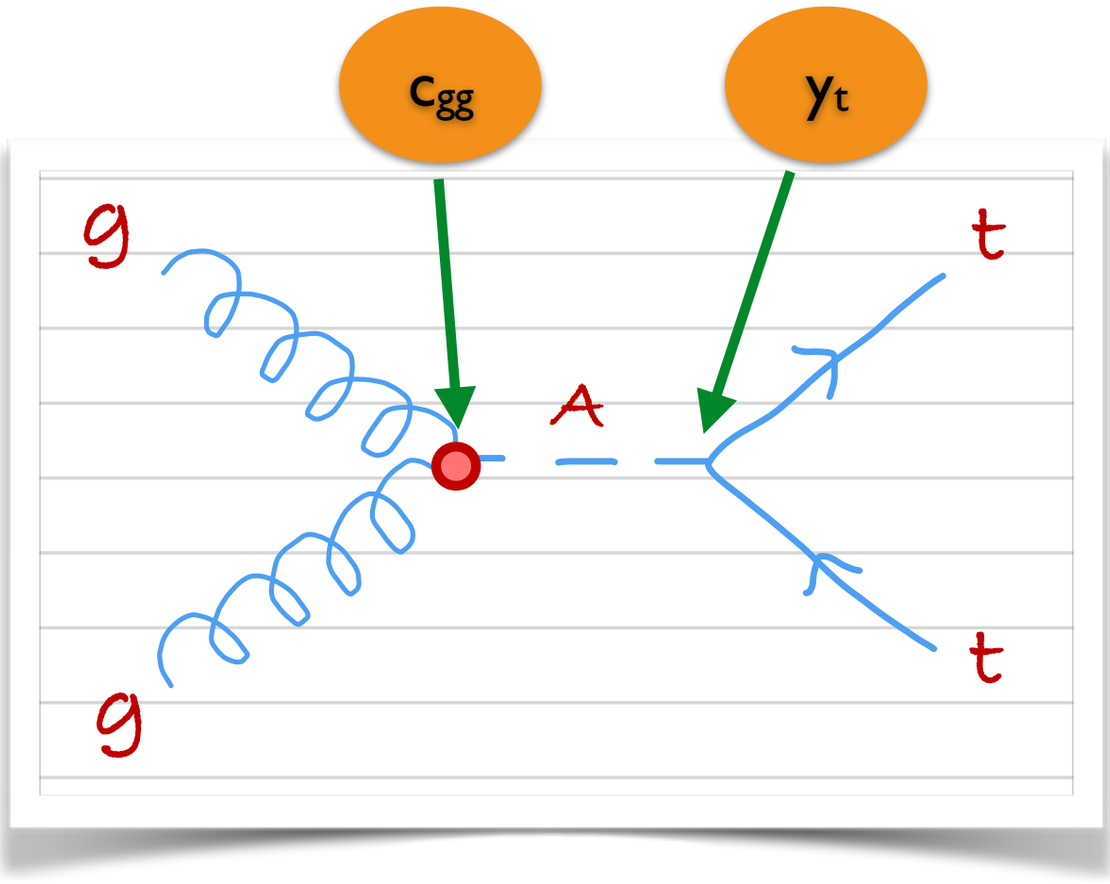
  A deviation in a_1 cannot be compensated by higher-order harmonics.

To spin

Pseudo-scalar in s channel

I will assume gg → A → tt is below threshold, because:

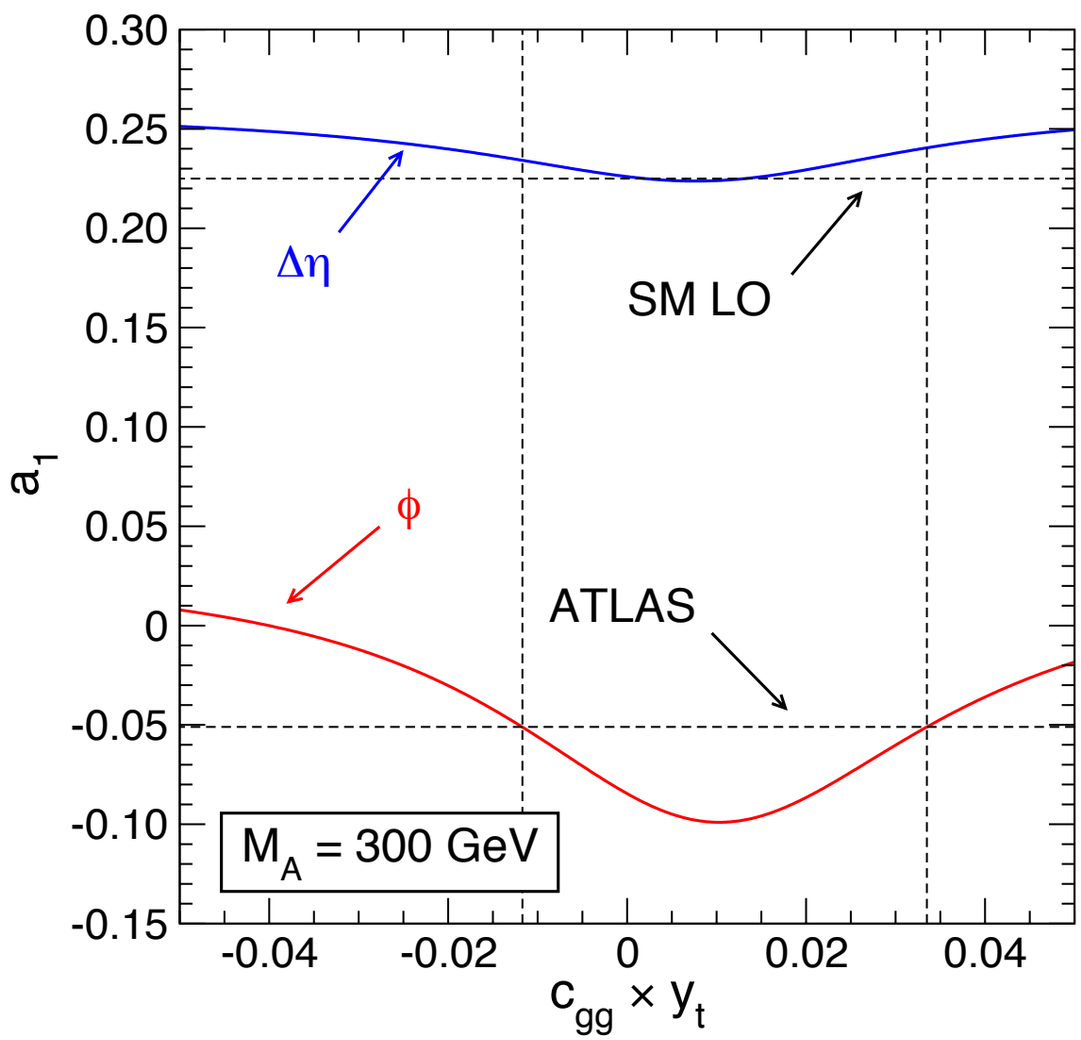
- noticeable bumps in distributions would appear if it is above
- the deviation in the distribution appears across the whole m_{tt} range

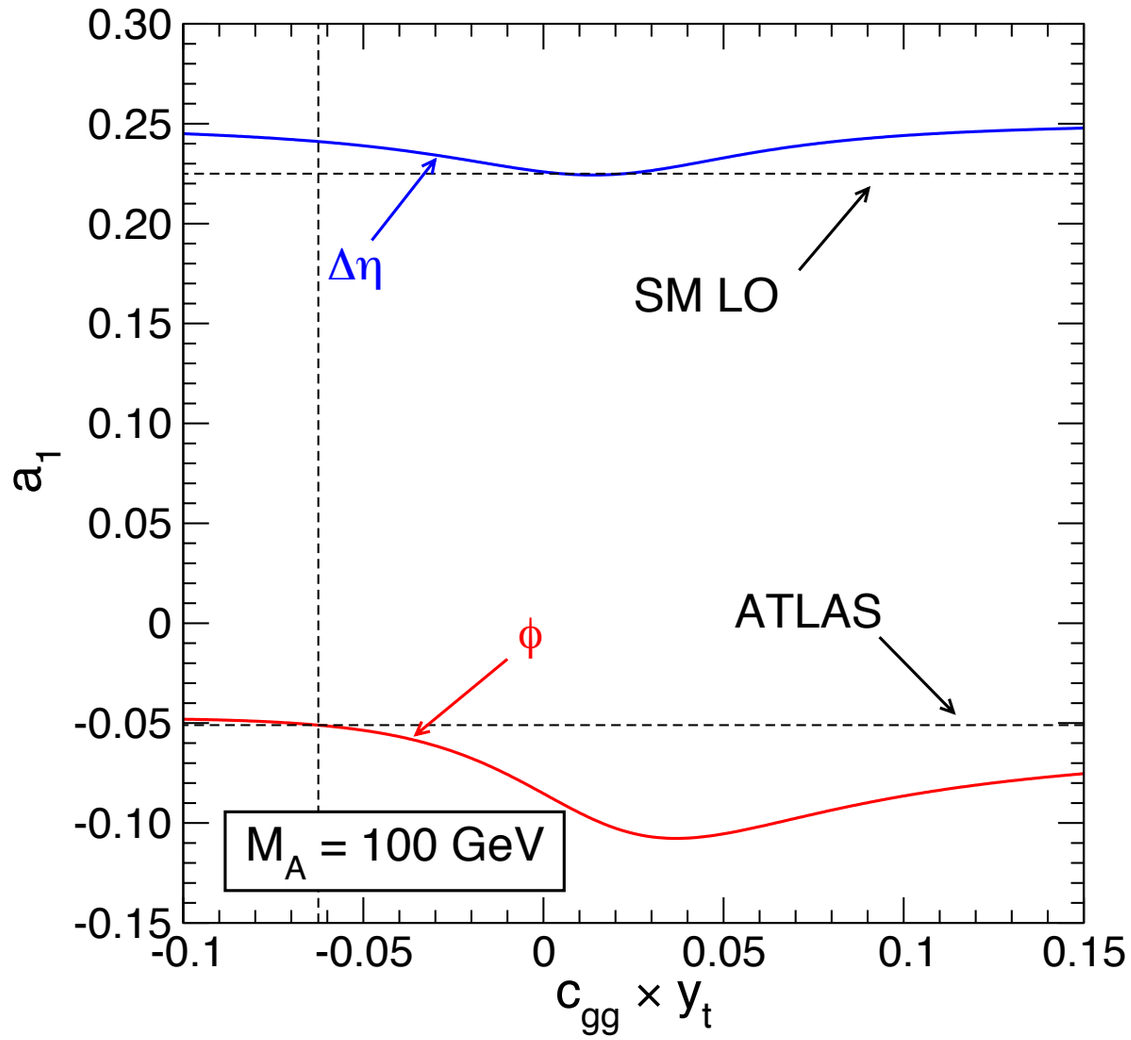


Amplitude proportional to $c_{gg} \times y_t$

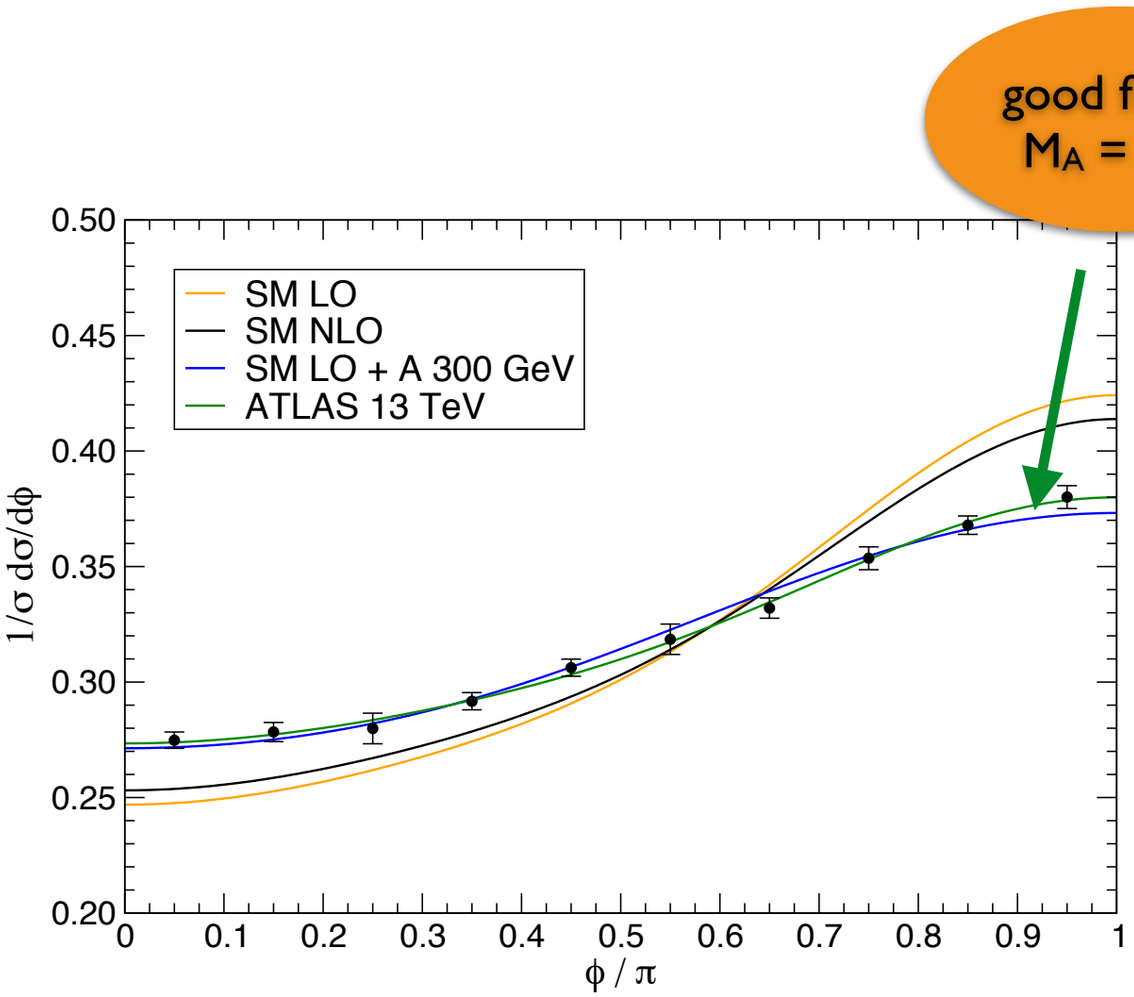
Reproducing $a_1 = -0.051$ for the azimuthal correlation ϕ unavoidably leads to deviations from the SM prediction for $\Delta\eta$

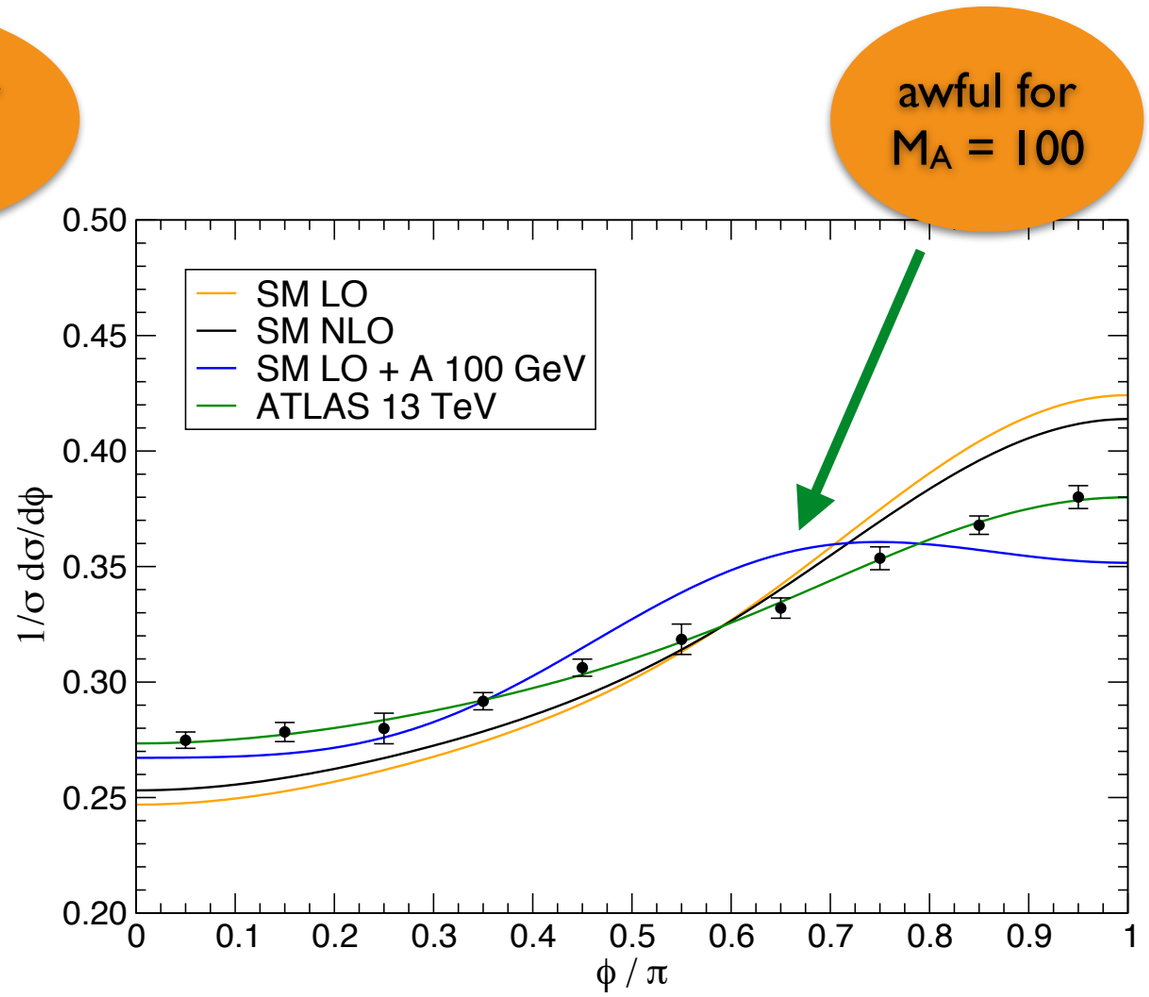
Interference can work in the `correct´ direction, and so does quadratic contribution.





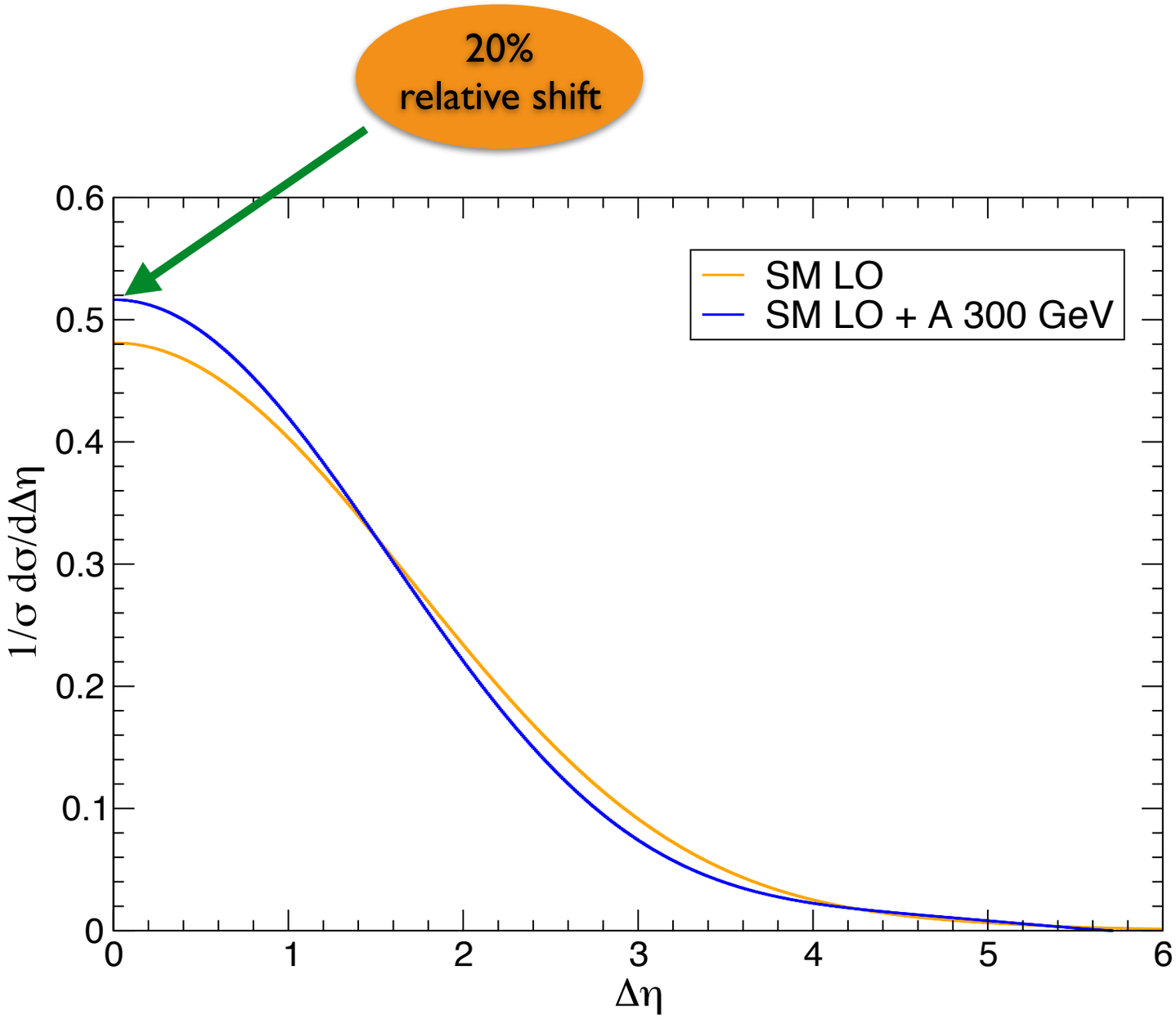
And fitting a_1 does not ensure that the measured distribution is well described, because one needs to reproduce a_2, …





Moral: it is nontrivial to reproduce the distribution

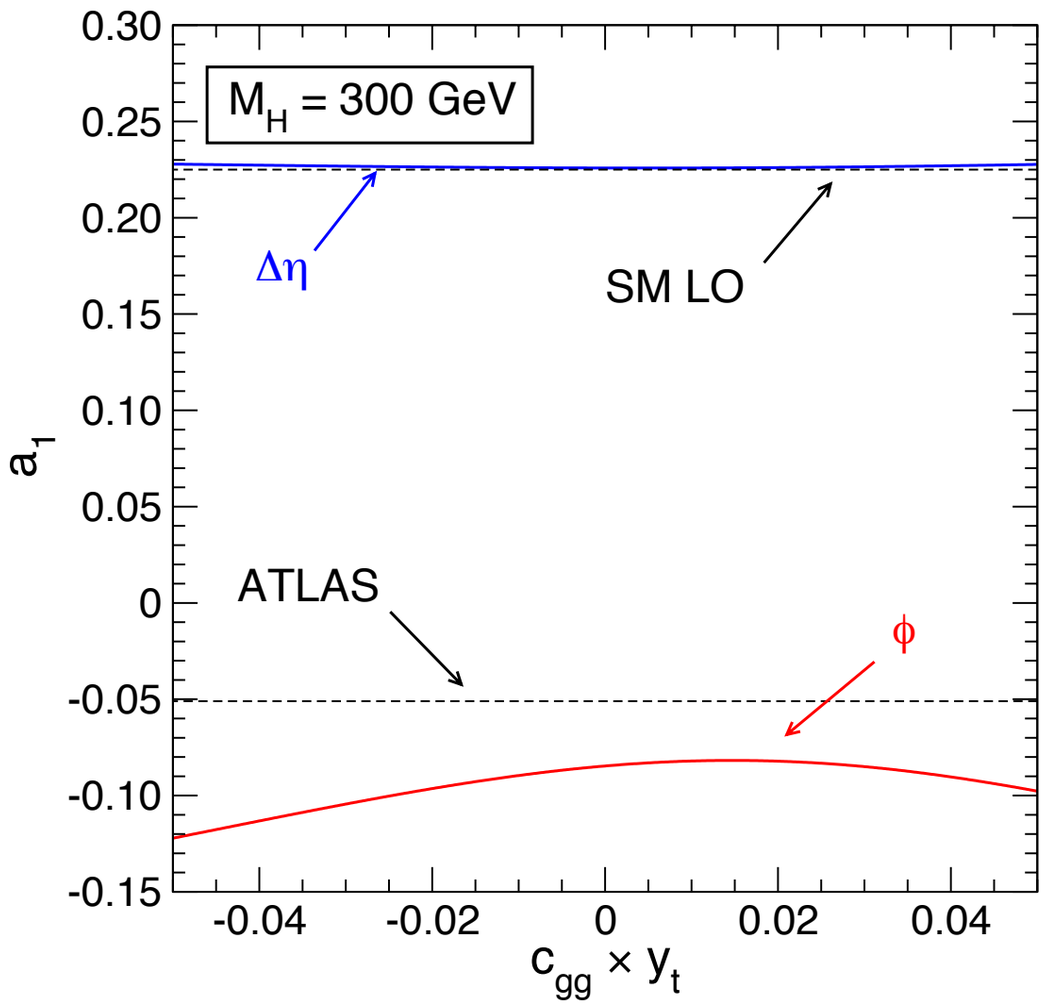
… moreover, one has to consider the effect in $\Delta\eta$

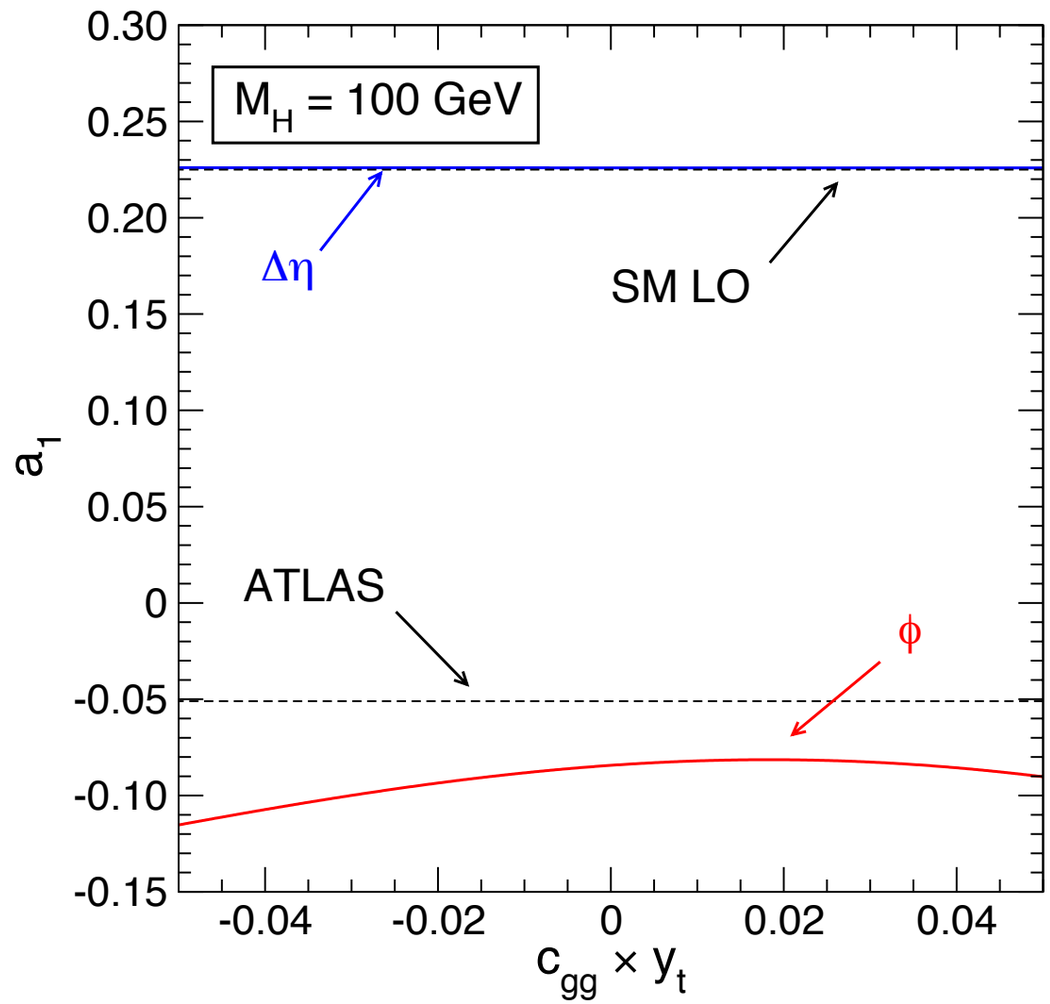


A deviation of this size is most likely unacceptable

Scalar in s channel

The effect in ϕ is basically in the opposite direction as desired, despite the fact that a scalar produces top pairs with opposite helicities…





Conjecture: the azimuthal correlation is most related to C_{nn} spin correlation coefficient [n: axis orthogonal to production plane]

seems not related to C_{rr}

	SM LO	M_H = 300 GeV, $c_{gg} \times y_t$ = -0.046	M_H = 300 GeV, $c_{gg} \times y_t$ = -0.066	Uncorrelated spins
C_{kk}	0.33	0.52	0.61	
C_{rr}	0.012	-0.22	-0.34	
C_{nn}	0.34	0.003	-0.16	
D	-0.23	-0.077	0.0008	
a_1	-0.0842	-0.118	-0.136	-0.119

Conjecture: the azimuthal correlation is most related to C_{nn} spin correlation coefficient [n: axis orthogonal to production plane]

definitely not related to C_{rr}

not related to C_{kk} either

seems related to C_{nn} rather than D

	SM LO	M_H = 300 GeV, $c_{gg} \times y_t$ = -0.046	M_H = 300 GeV, $c_{gg} \times y_t$ = -0.066	Uncorrelated spins
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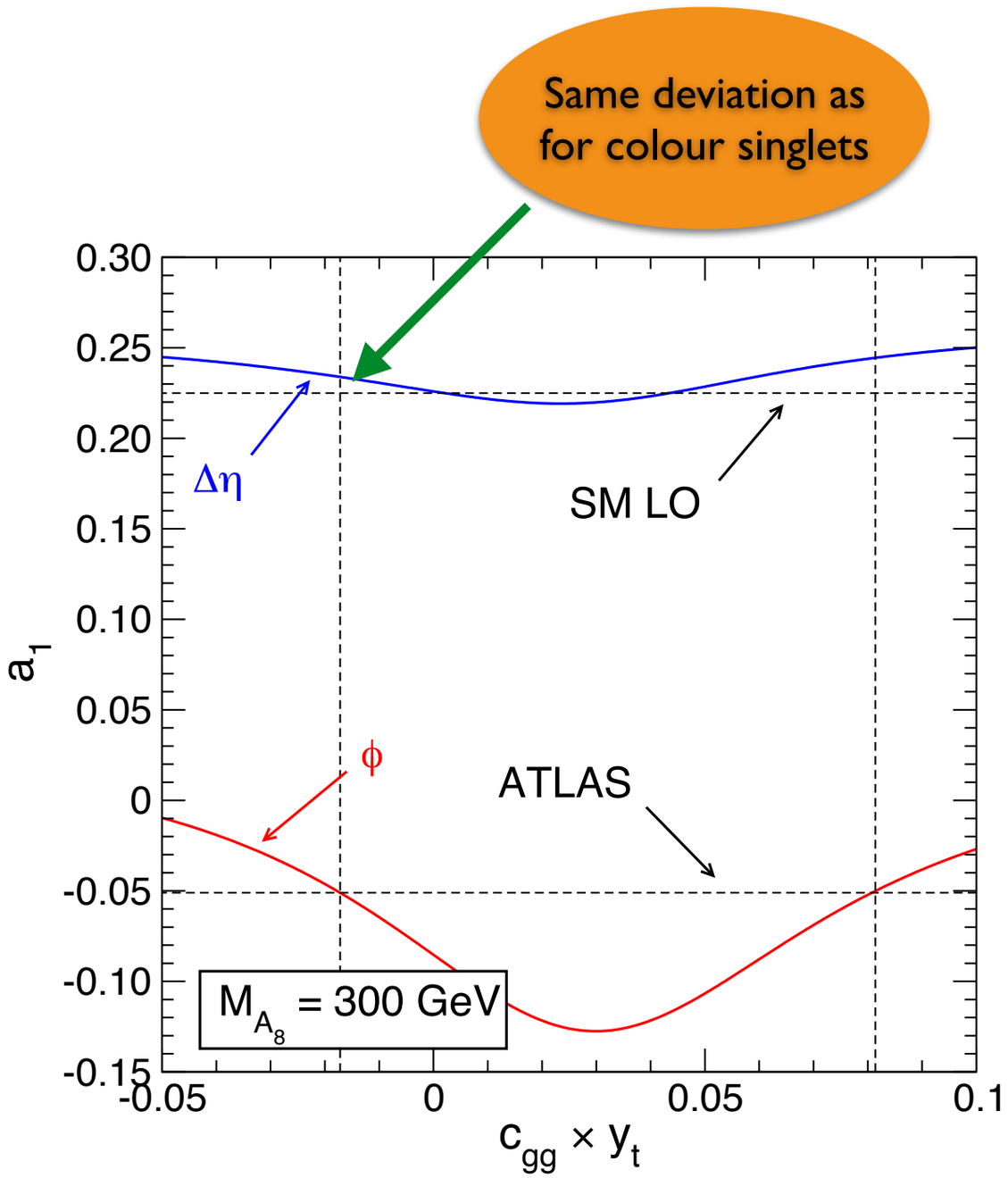
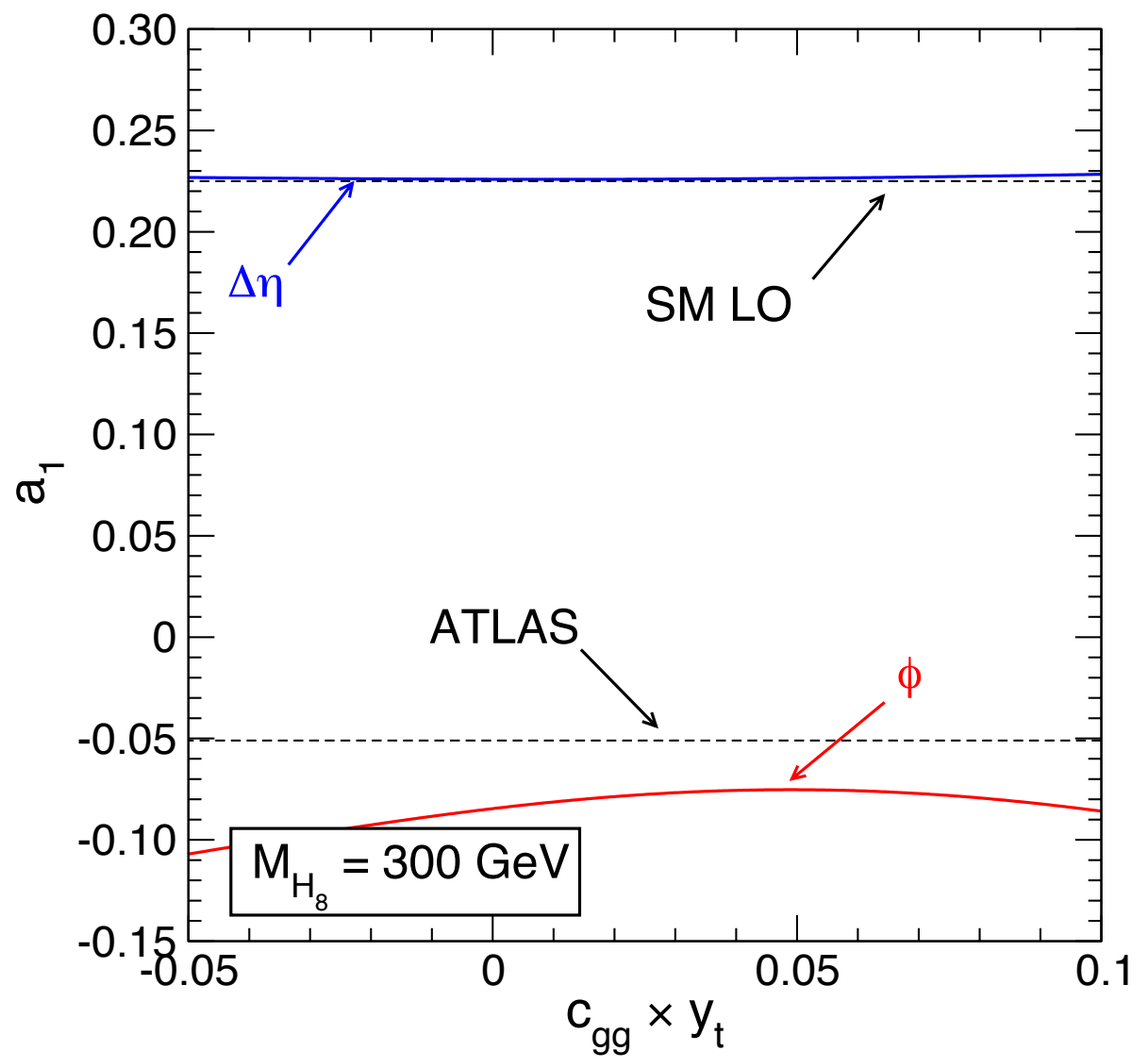
Going coloured

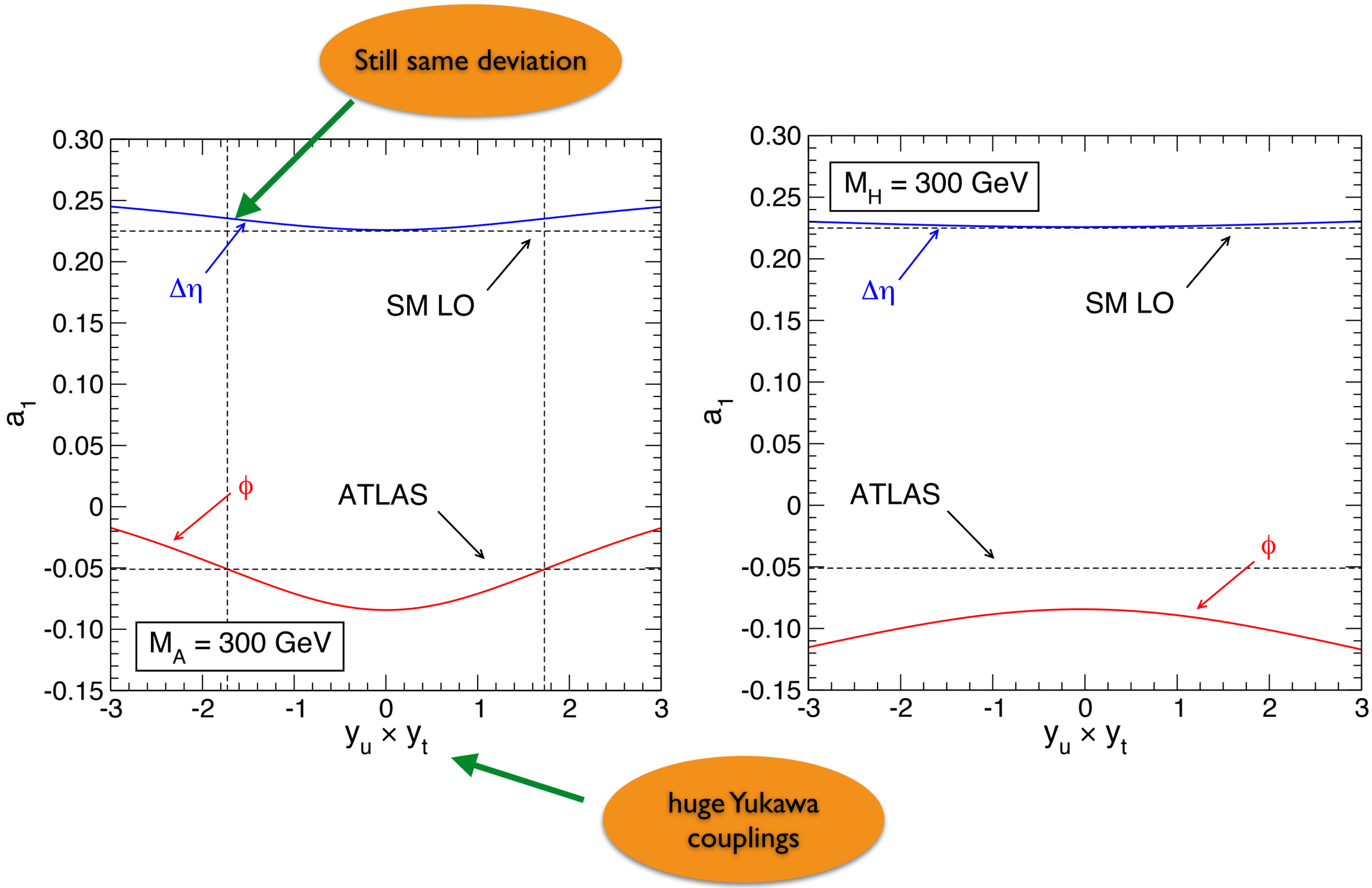
For colour octet (pseudo-)scalars the behaviour is the same.





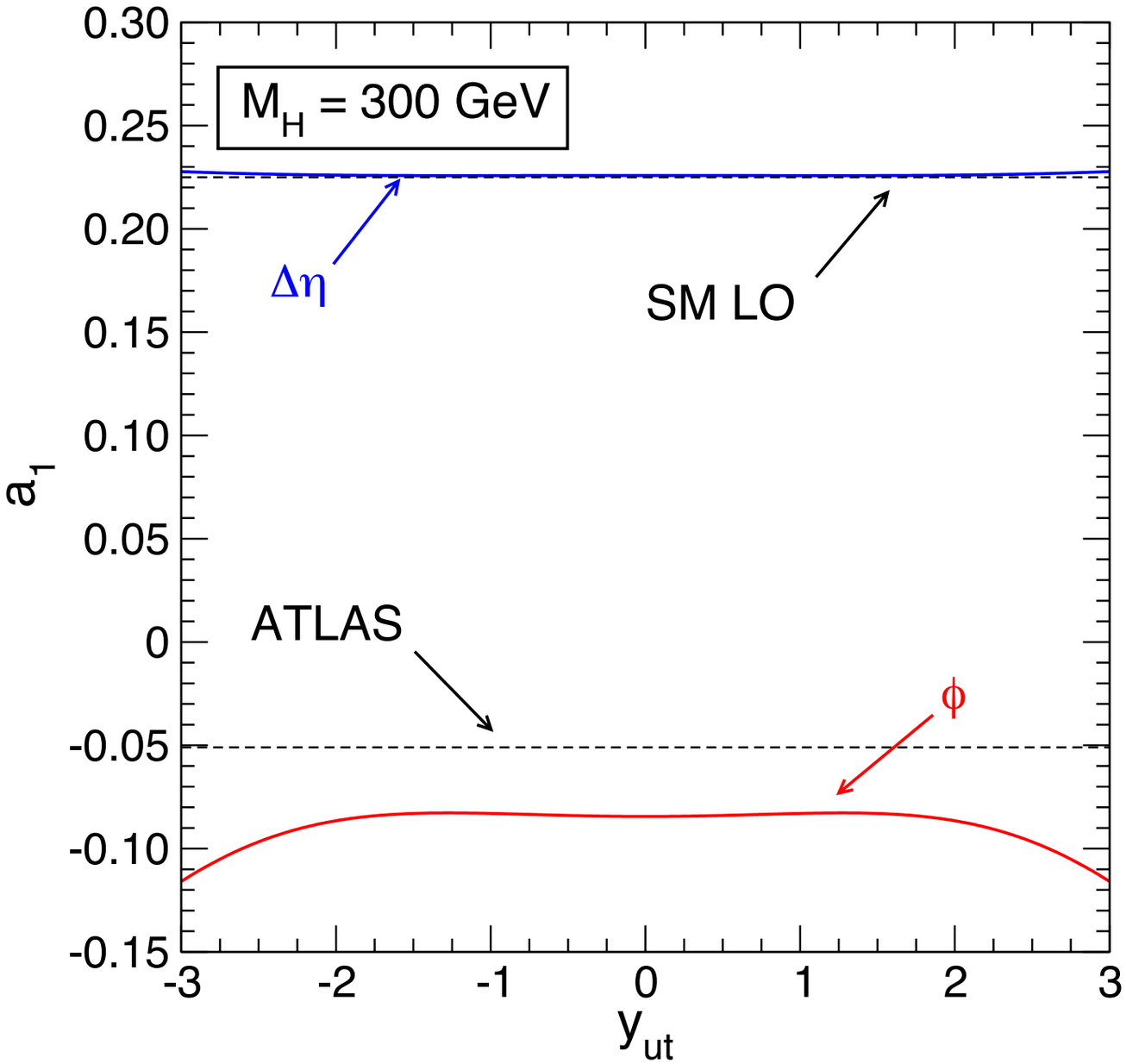
(Pseudo-)scalars in uu → tt

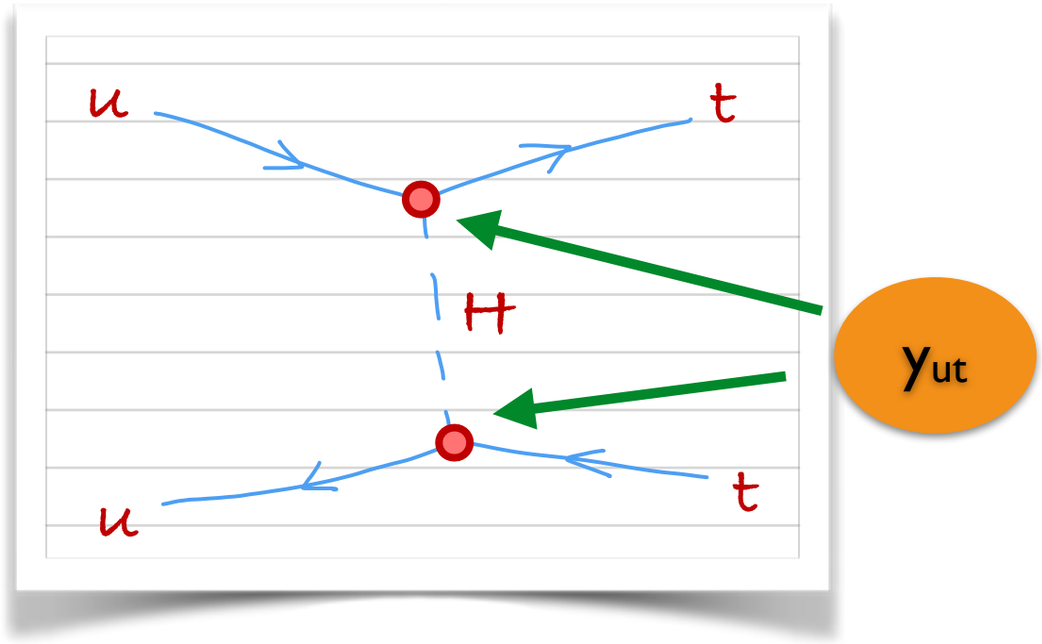
For this improbable possibility the behaviour is still the same



Flavour-changing scalars

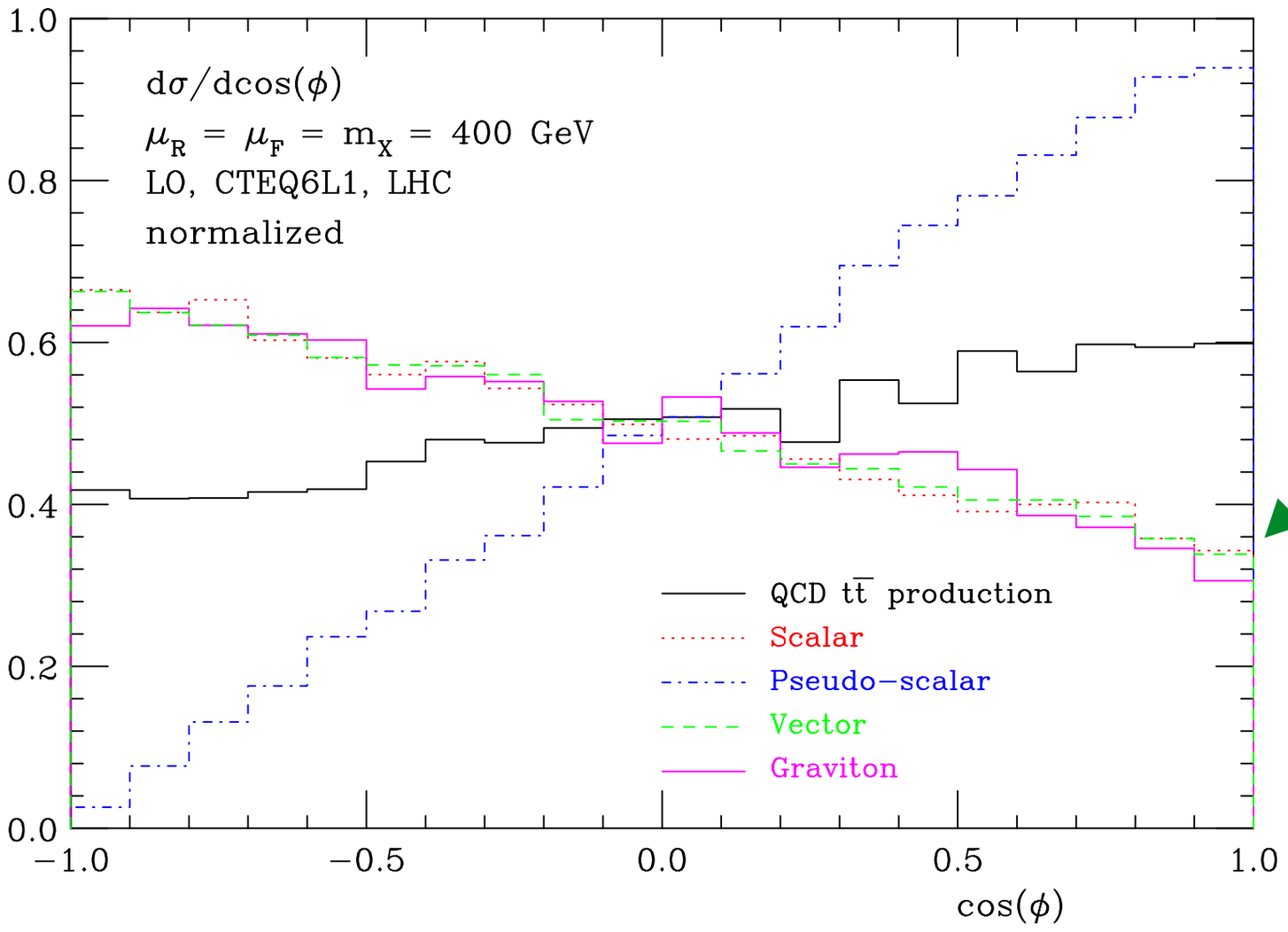
This even more improbable possibility would not work either…





Ignoring further resonant possibilities…

For vector resonances & gravitons I refer to Frederix, Maltoni 0712.2355

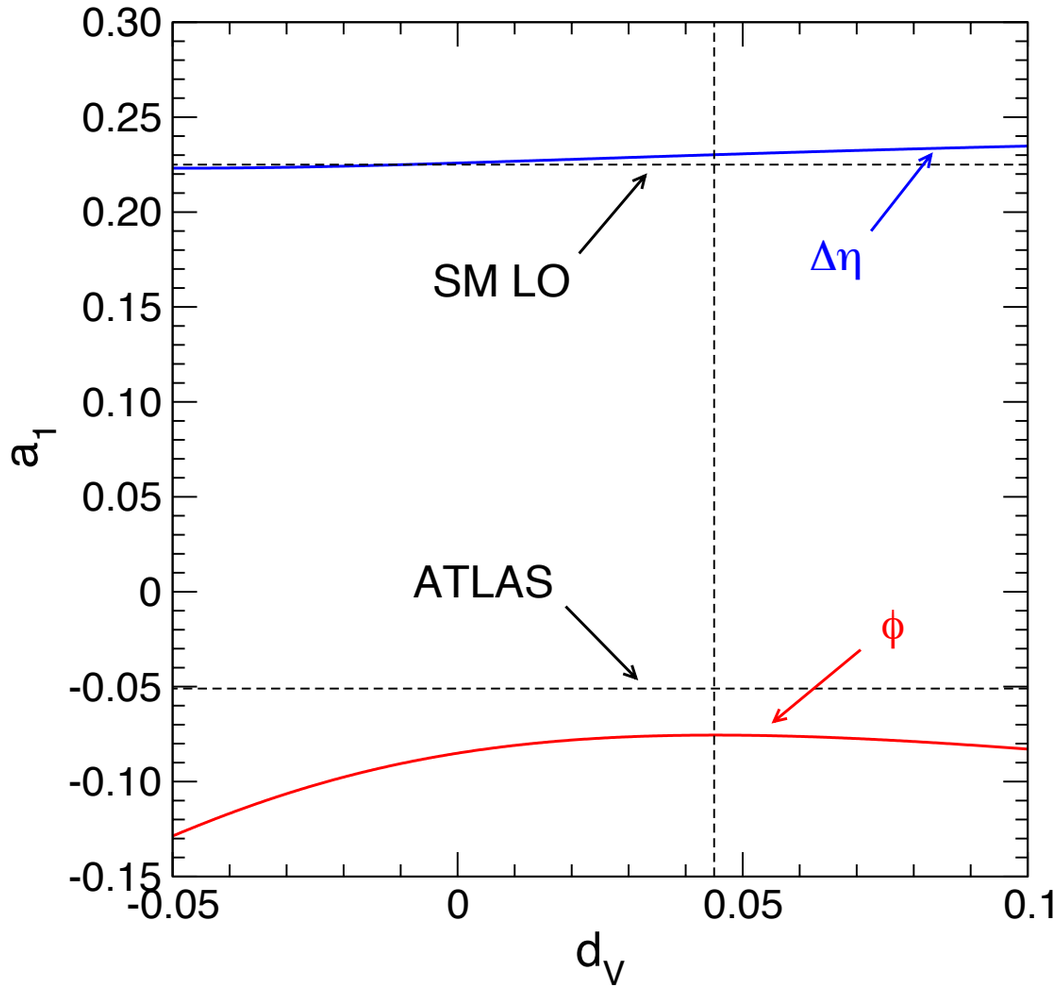


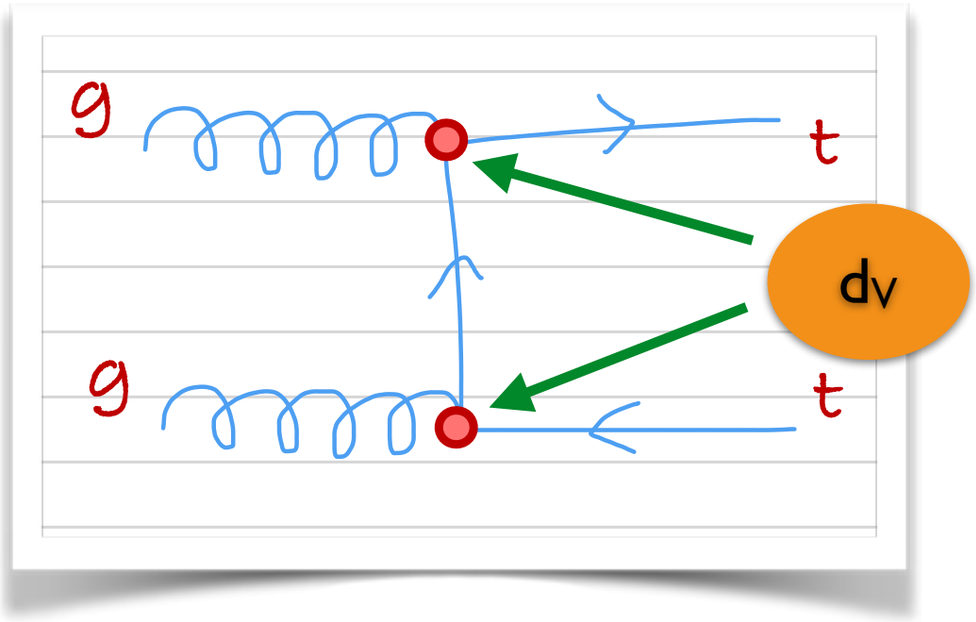
they give a shift in the opposite direction

Top chromomagnetic moment

It cannot fully explain the deviation, as the positive shift in a_1 from the interference is quickly overcome by the quadratic term.

[could dim-8 contributions solve this?]



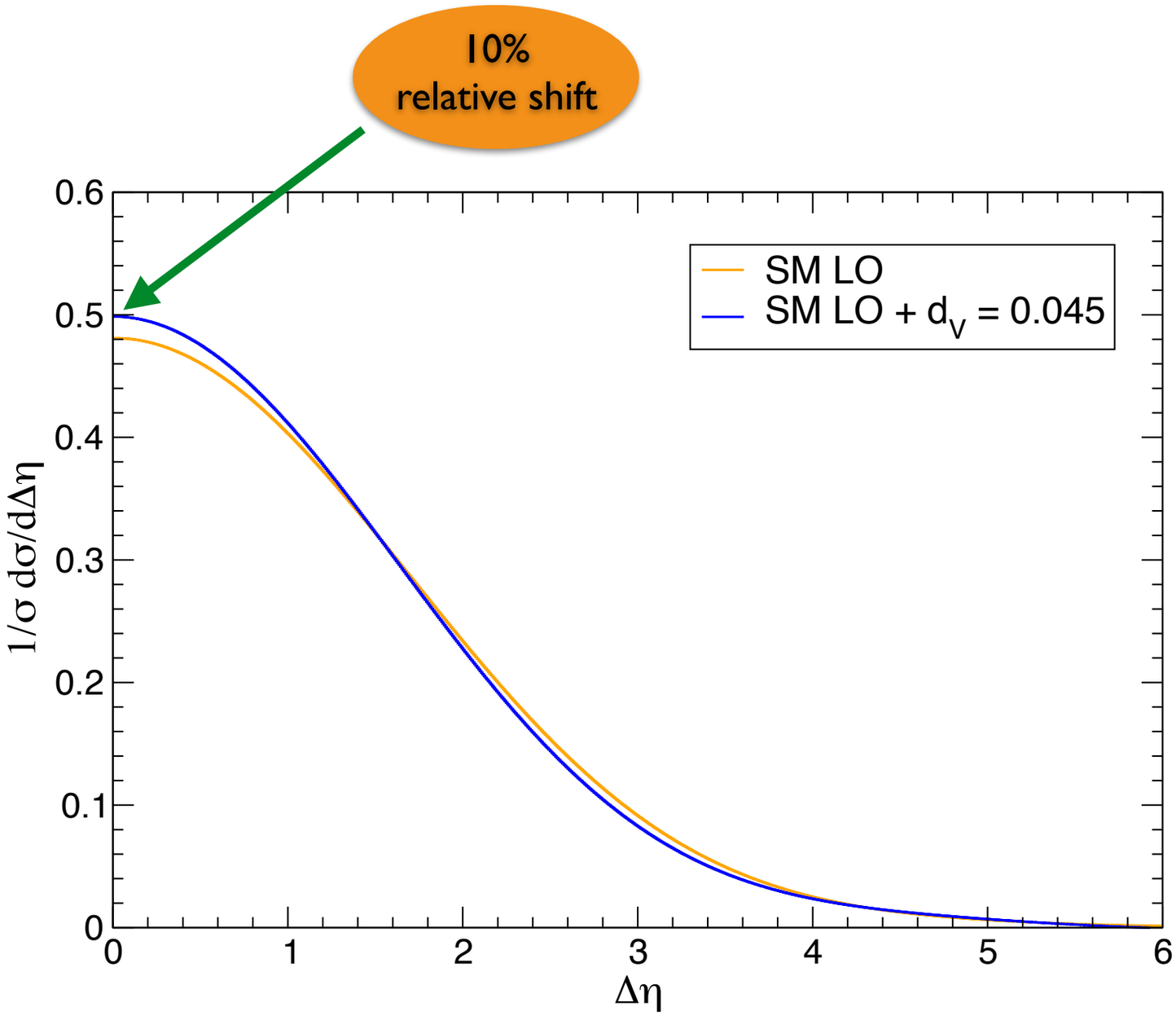


Amplitude contains terms up to d_V^2

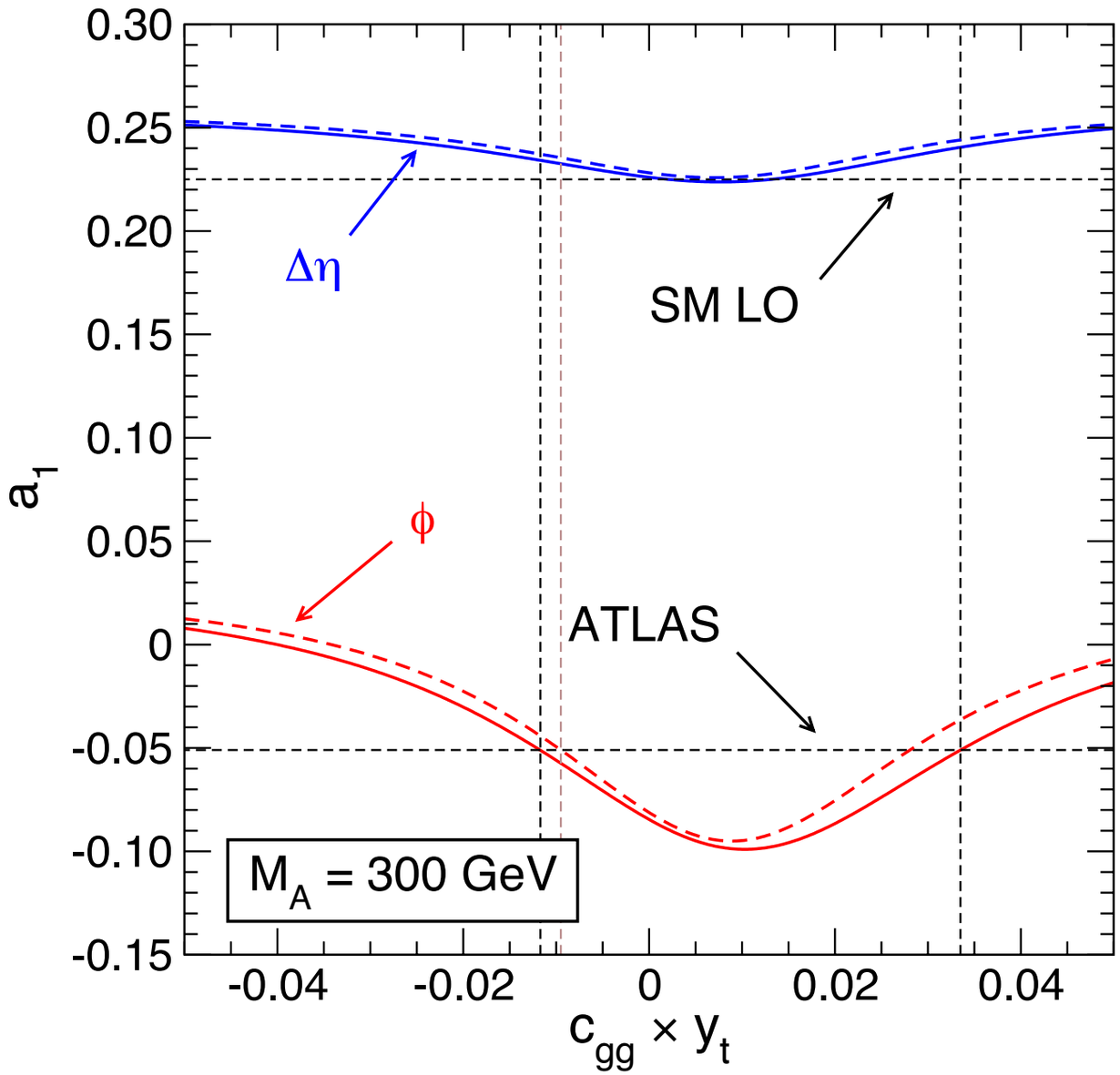
Even if the ϕ distribution is not reproduced

[a_1 = -0.051 required but only a_1 = -0.075 is reached]

the $\Delta\eta$ distribution is significantly modified.

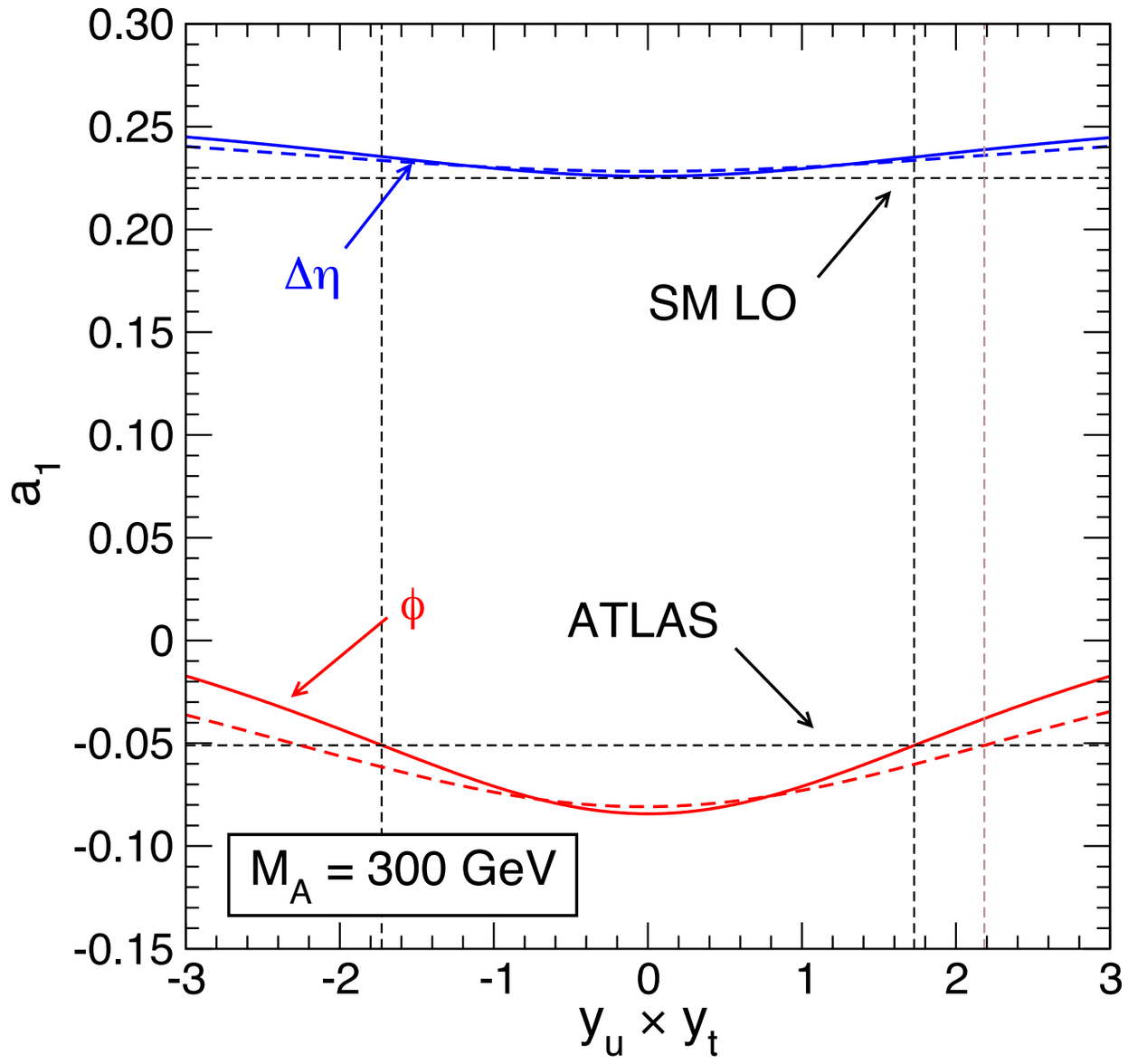


Pseudo-scalar contributions to tt + jet versus tt



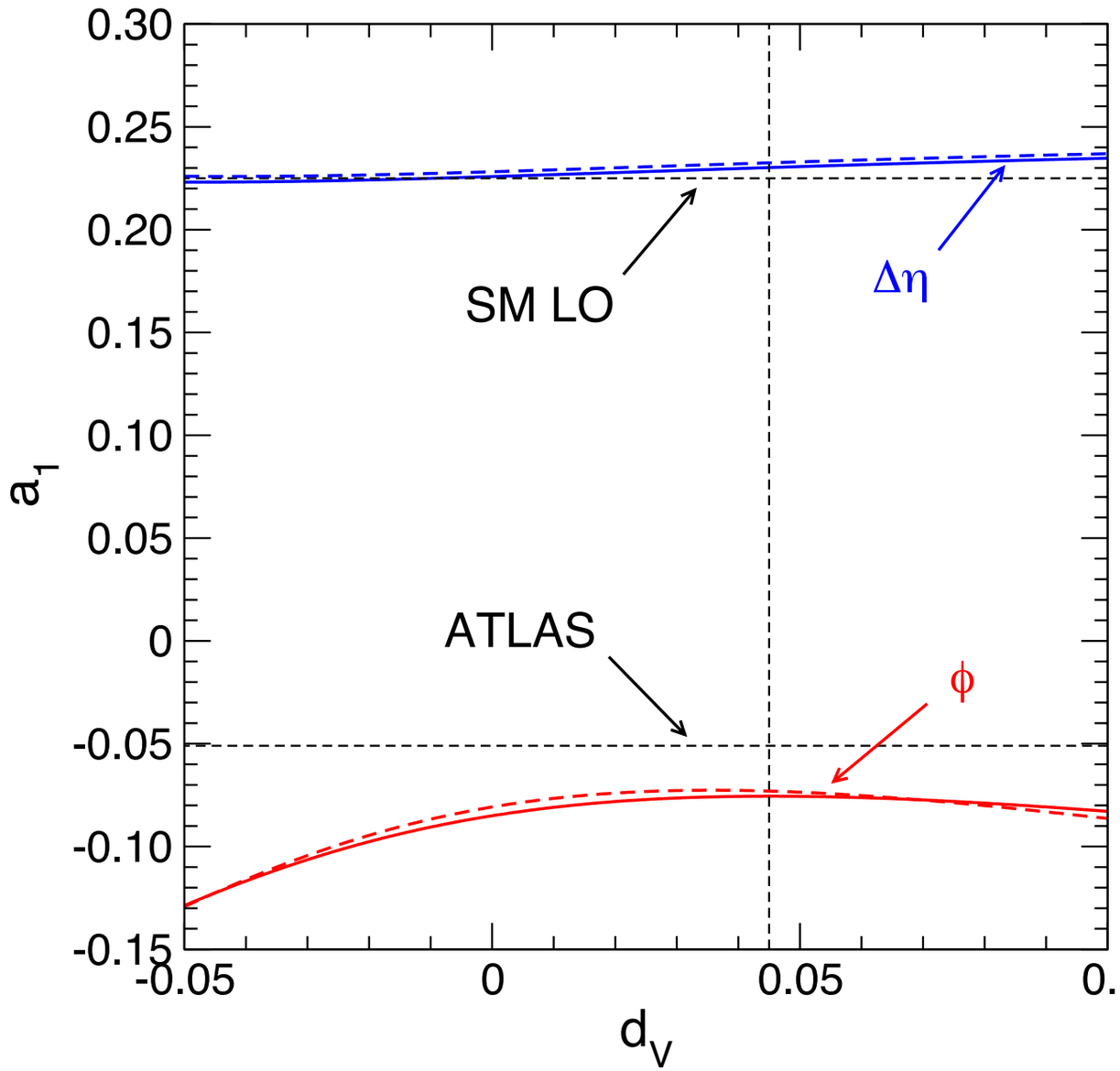
Deviation in a_1 of Δη of the same size

Pseudo-scalar [uu] contributions to tt + jet versus tt



Deviation in a_1 of Δη of the same size

Chromomagnetic moment contributions to tt + jet versus tt



Deviation in a_1 of Δη of the same size

Recap

- Spin correlation measurements in CM frame agree with the SM. But this is not conclusive, as:
  - the measurements rely on several assumptions for the extrapolation
  - the precision in the C_{nn} measurement is poor

- On the other hand, the $\Delta\eta$ distribution is as clean as ϕ and a deviation in $\Delta\eta$ is produced when enhancing a_1 to fit the ϕ distribution.

The deviation is [almost] always produced in the same direction, so cancellations are not envisaged.

This distribution is expected to depend on C_{kk}, C_{rr} and C_{rk} but a clear dependence is not seen.

Not to spin

ttj at LO

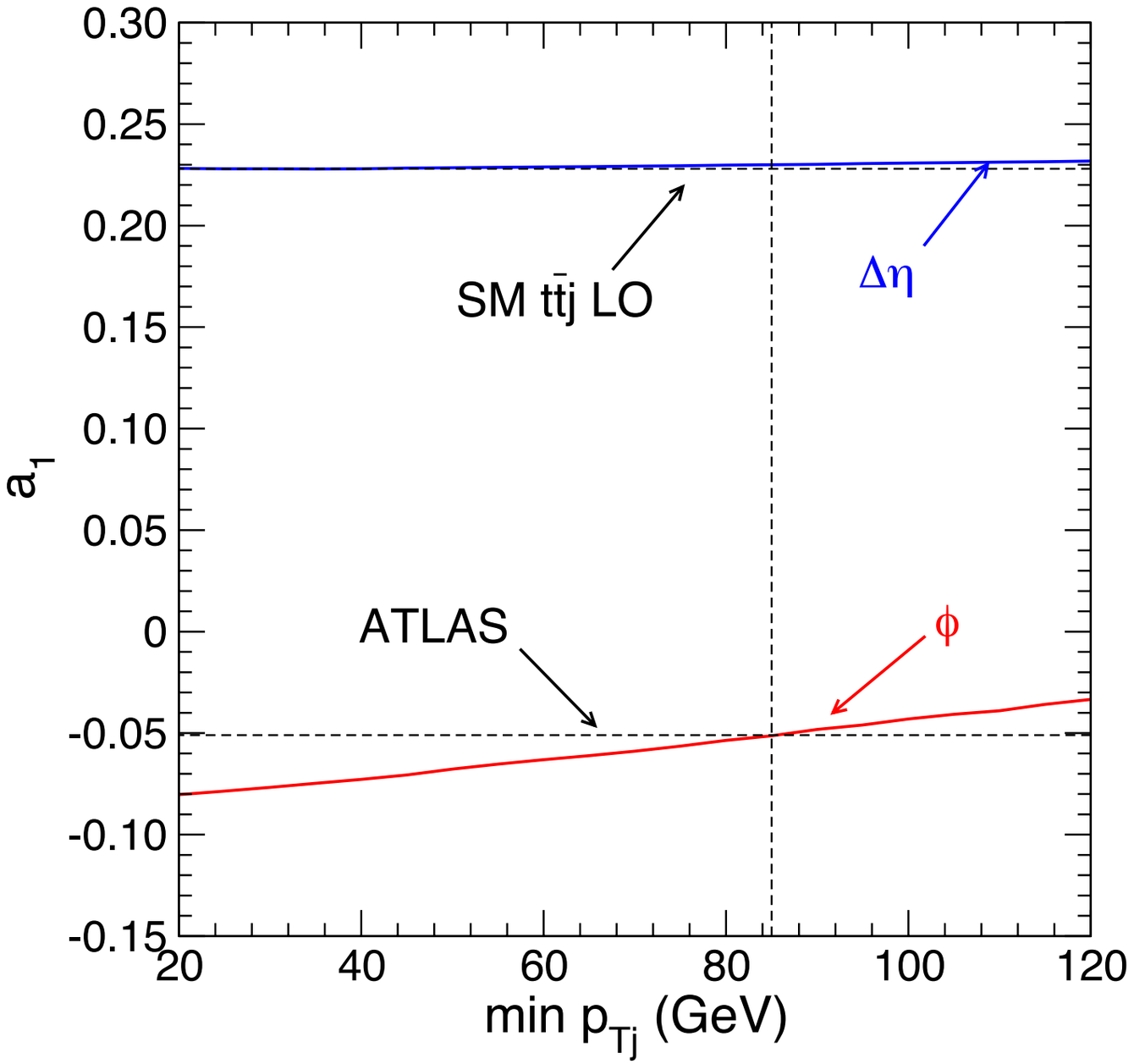
Use SM ttj production to investigate the effect of a transverse boost of the tt pair.

With $p_{Tj} \geq 20$ GeV, the ϕ and $\Delta\eta$ distributions are quite similar to tt

	ϕ tt LO	ϕ ttj LO	$\Delta\eta$ tt LO	$\Delta\eta$ ttj LO
a_1	-0.0842	-0.0803	0.226	0.228
a_2	0.0172	0.0166	0.0819	0.0856
a_3	-0.0044	-0.0048	0.0140	0.0164

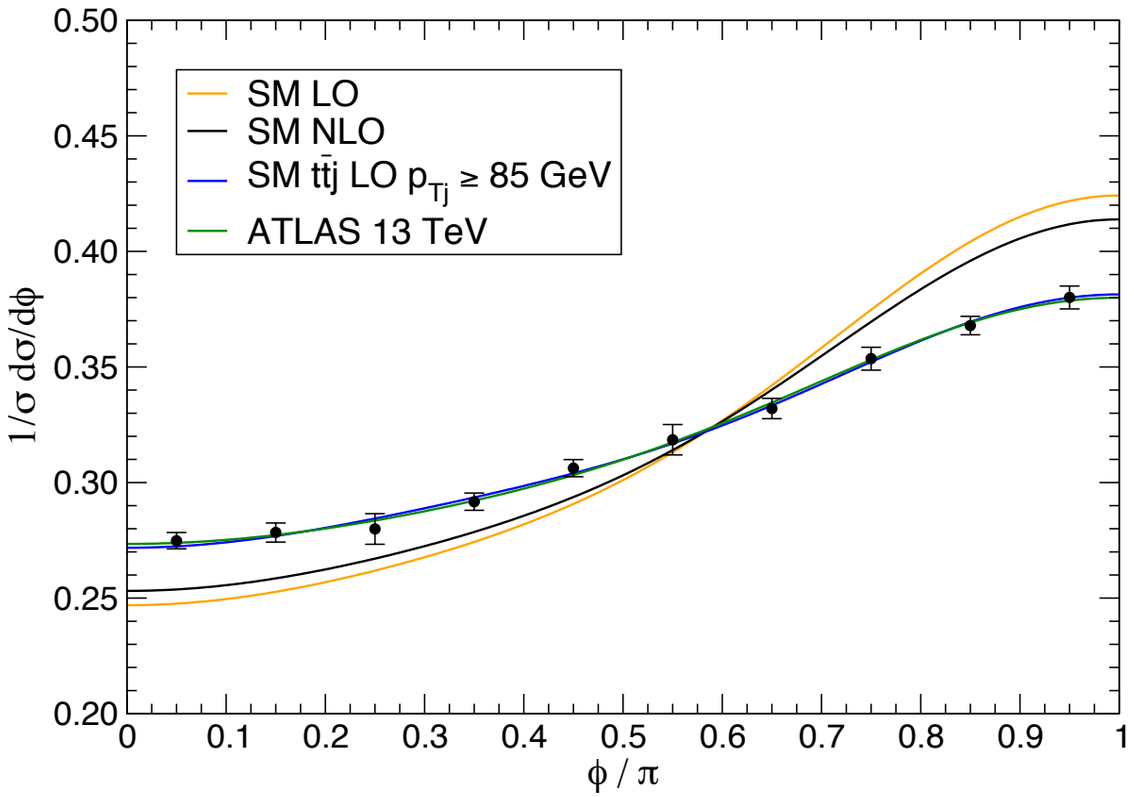
What happens for higher p_{Tj}?

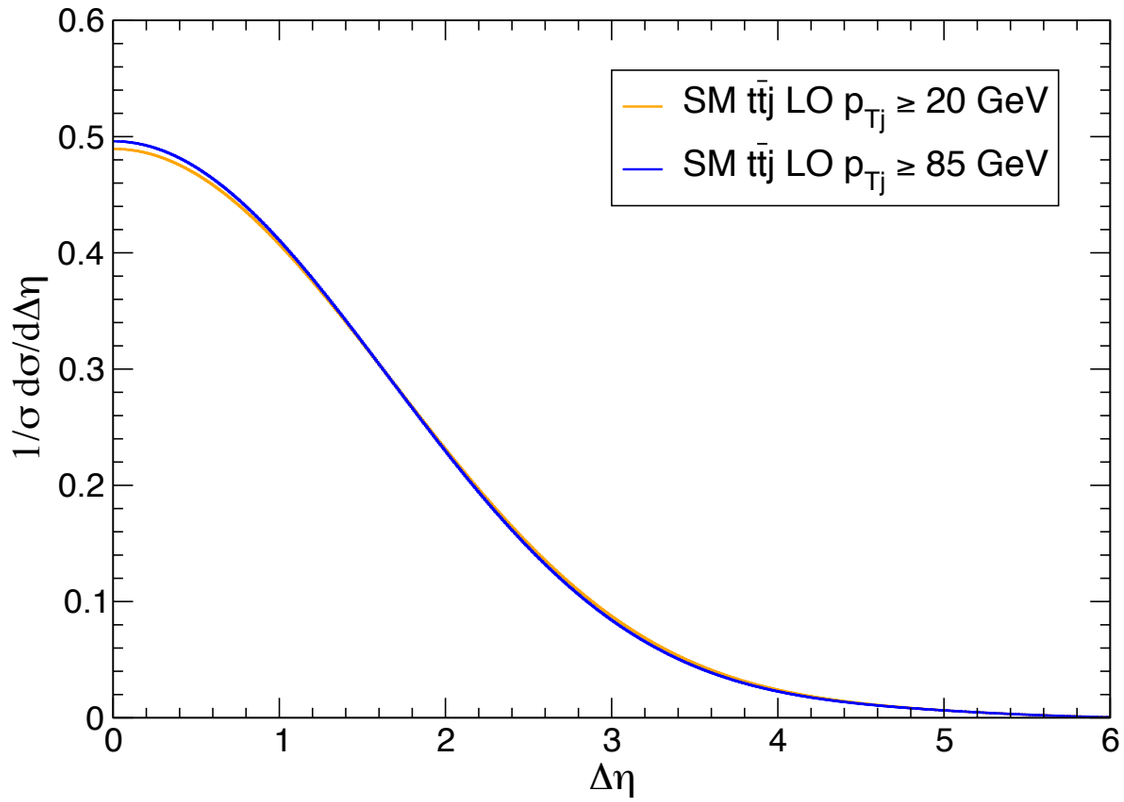
A transverse boost of the tt pair can modify a_1 of the azimuthal correlation without disturbing much the $\Delta\eta$ distribution



Do not jump yet to claim that the deviation is due to higher order SM corrections!

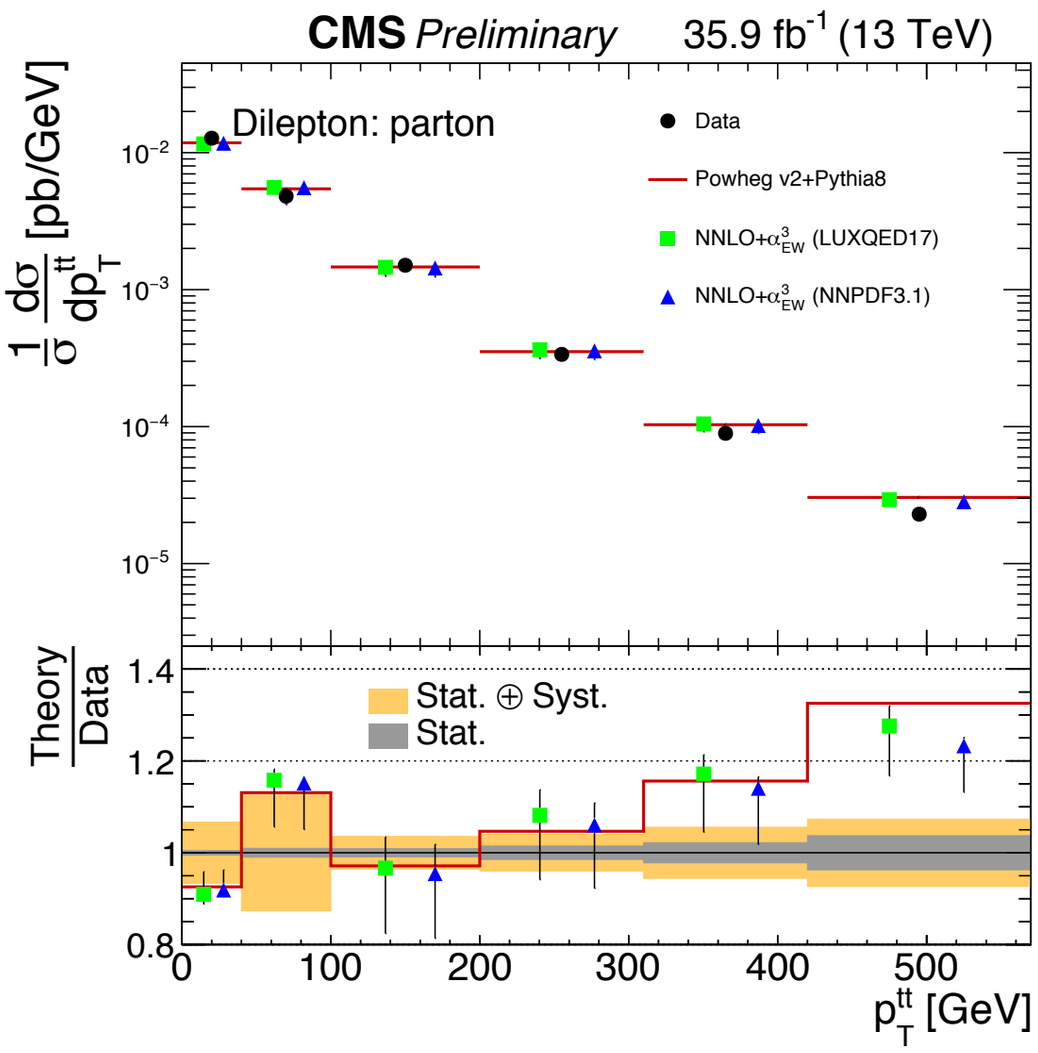
Amazingly, the agreement of the ϕ distribution is perfect for $p_{Tj} \geq 85$ GeV, with much smaller modifications in $\Delta\eta$

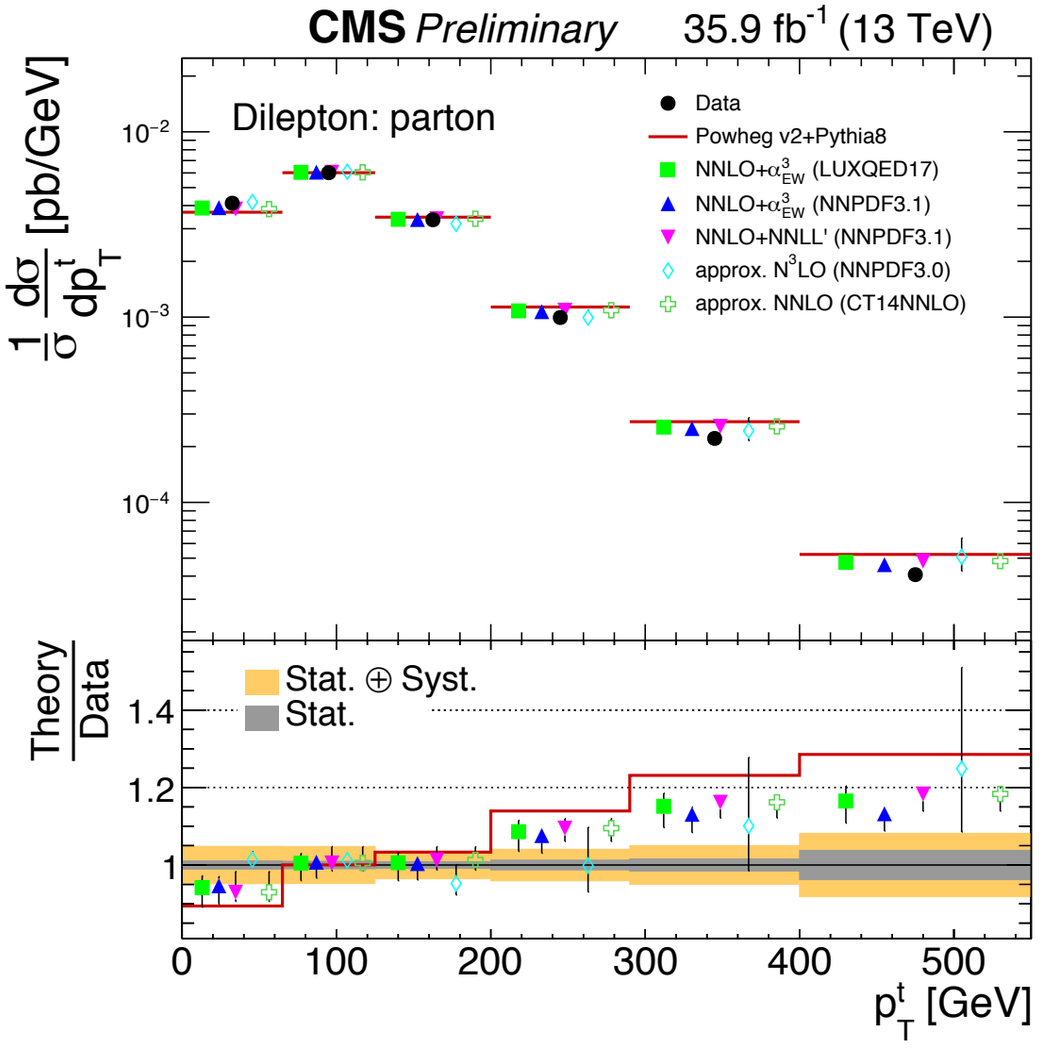




The question seems answered: the deviation is (mostly) due to kinematics. Really?

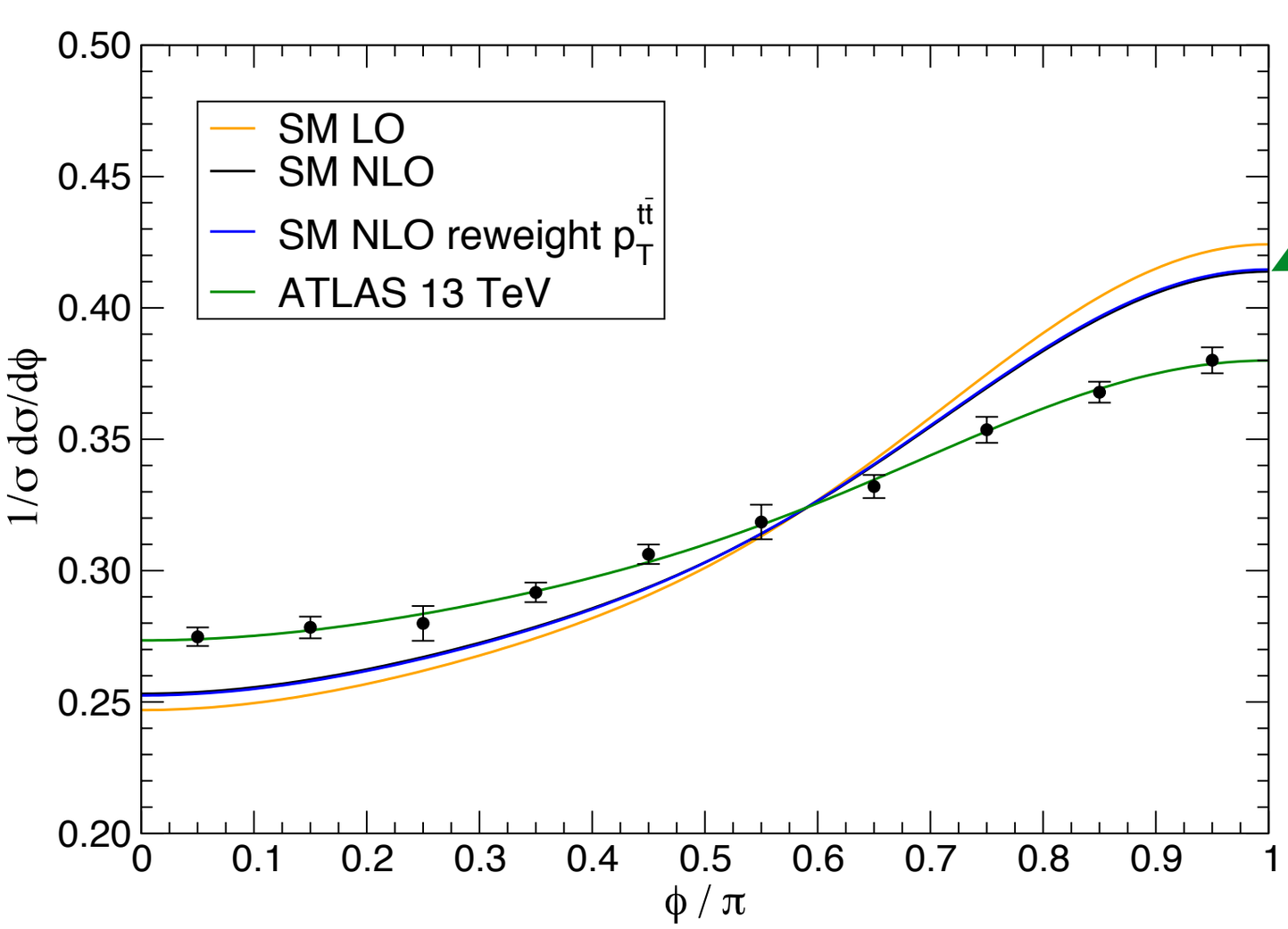
CMS finds features in p_T^{tt} and p_T^{t} distributions: the measured distributions are softer than the NLO and NNLO predictions.





Reweighting NLO by p_T^{tt} [Using POWHEG prediction in CMS plot]

The reweighting effect is tiny and goes in the opposite direction: softer p_T^{tt} spectrum means the leptons are more separated in LAB frame

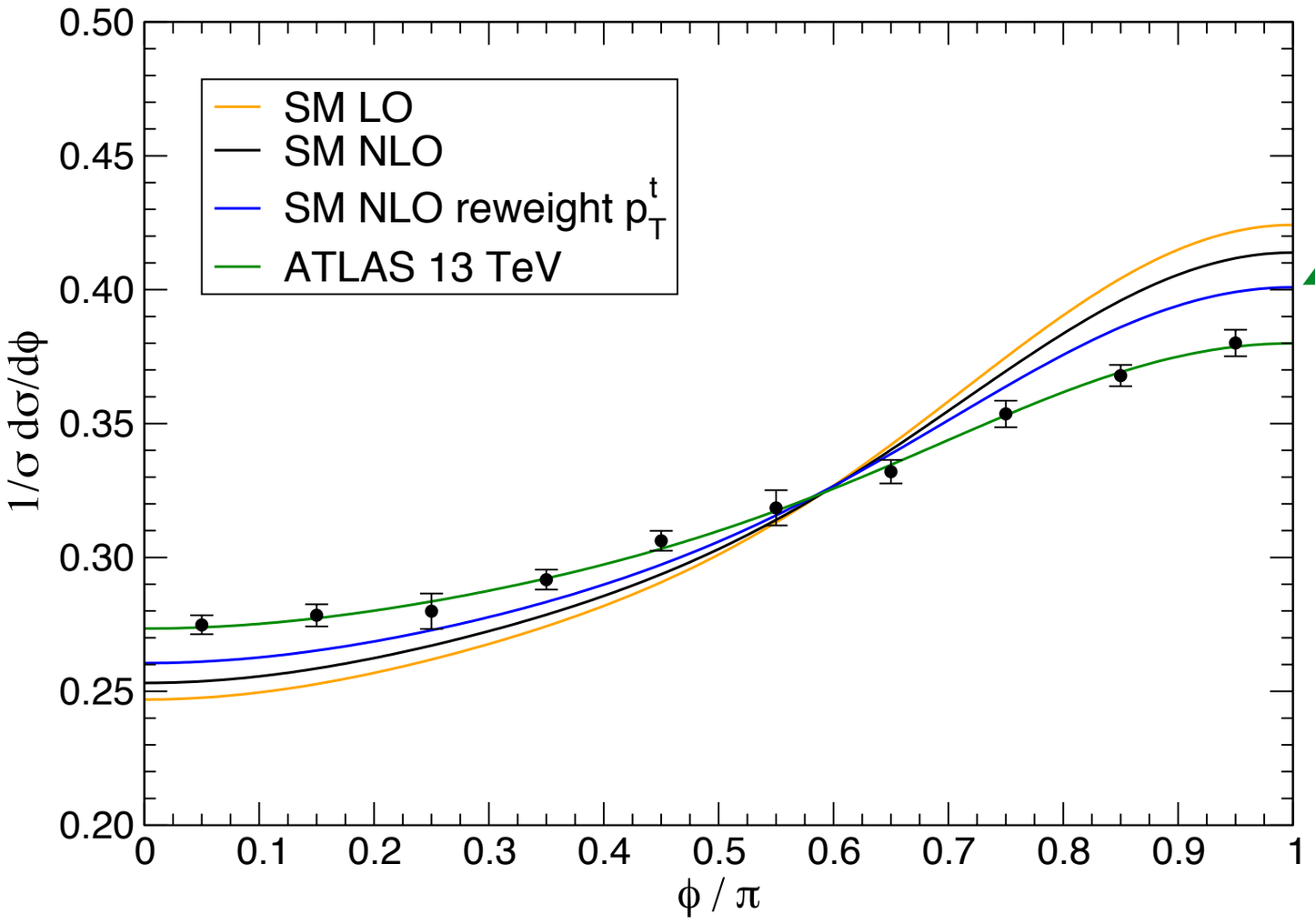


slightly closer to LO

	NLO	NLO rw	ATLAS
a_1	-0.0764	-0.0771	-0.0512
a_2	0.0151	0.0152	0.0084
a_3	-0.0040	-0.0039	-0.0021

Reweighting NLO by p_T^t [Using POWHEG prediction in CMS plot]

The reweighting effect goes in the right direction: softer p_T^t spectrum means the leptons follow less the top direction. But it is not enough.



still away from data

	NLO	NLO rw	ATLAS
a_1	-0.0764	-0.0672	-0.0512
a_2	0.0151	0.0124	0.0084
a_3	-0.0040	-0.0029	-0.0021

Recap

- The deviation in the ϕ distribution would be nicely explained by kinematics… but the modifications necessary do not seem to agree with data.

- The reweighting is an estimation, but since the effect of p_T^{tt} reweighting is tiny, I expect we are capturing the main effects by p_T^{t} reweighting.

- Kinematics does not seem to explain the deviation. These calculations agree with ATLAS findings.

That is the question

Much adoe about Nothing.

Actus Primus, Scæna Prima.

Enter Leonato Governour of Messina, Inogen his wife, Hero his daughter, and Beatrice his Neece, with a Messenger.

Leonato.

I Learne in this Letter, that *Don Peter* of *Arragon* comes this night to *Messina*.

Mess. He is very neere by this: he was not three Leagues off when I left him.

Leon. How many Gentlemen have you lost in this action?

Mess. But few of any sort, and none of name.

Leon. A victory is twice it selfe, when the atchiever brings home full numbers: I find heere, that *Don Peter* hath bestowed much honour on a yong *Florentine*, called *Claudio*.

Mess. Much deserv'd on his part, and equally remembred by Don *Pedro*, he hath borne himselfe beyond the promise of his age, doing in the figure of a Lambe, the feates of a Lyon, he hath indeed better bettred expectation, than you must expect of me to tell you how.

Leo. He hath an Vncle here in *Messina*, will be very much glad of it.

Mess. I have already delivered him Letters, and there appeares much joy in him, even so much that joy could not shew it selfe modest enough, without a badge of bitternesse.

Leo. Did he breake out into teares?

Mess. In great measure.

Leo. A kinde overflow of kindenesse: there are no face-strues, then those that are so wash'd, how much better is it to weepe at joy, then to joy at weeping?

Bea. I pray you, is Signior *Mountanto* return'd from the warres, or no?

Mess. I know none of that name, Lady, there was none such in the Army of any sort.

Leo. What is he that you aske for Neece?

Hero. My Cosin meanes Signior *Benedicke* of *Padua*.

Mess. O he's return'd, and as pleasant as ever he was.

Beat. He set up his bills heere in *Messina*, and challeng'd Cupid at the Flight: and my Vncles foole reading the Challenge, subscrib'd for Cupid, and Challeng'd him at the Burbolt. I pray you, how many hath hee kill'd and eaten in these warres? But how many hath he kill'd? for indeed, I promis'd to eate all of his killing.

Leon. 'Faith Neece, you taxe Signior *Benedicke* too much, but he'll be meet with you, I doubt it not.

Mess. He hath done good service Lady in these warres.

Mess. You had musty victuall, and he hath holpe to eate it: he's a very valiant Trencher-man, he hath an excellent stomacke.

Mess. And a good Souldier too Lady.

Beat. And a good Souldier to a Lady: But what is he to a Lord?

Mess. A Lord to a Lord, a Man to a Man, stuft with all honourable vertues.

Beat. It is so indeed, he is no lesse then a stuft man: but for the stuffing well, we are all mortall.

Leon. You must not (sir) mistake my Neece, there is a kinde of merry War betwixt Signior *Benedicke* and her: they never meet, but there's a skirmish of wit betweene them.

Bea. Alas, he gets nothing by that. In our last conflict, foure of his five wits went halting off, and now is the whole man govern'd with one: so that if hee have wit enough to keepe himselfe warme, let him beare it for a difference betweene himselfe and his horse: For it is all the wealth that he hath left, to be knowne a reasonable creature. Who is his Companion now? He hath every moneth a new sworne brother.

Mess. I'st possible?

Beat. Very easily possible: he weares his faith but as the fashion of his hat, it ever changes with the next blocke.

Mess. I see (Lady) the Gentleman is not in your bookes.

Beat. No, and he were, I would burne my study. But I pray you who is his companion? Is there no young squarer now, that will make a voyage with him to the Devill?

Mess. He is most in the company of the right noble *Claudio*.

Beat. O Lord, he will hang upon him like a disease: he is sooner caught then the Pestilence, and the taker runnes presently mad. God helpe the noble *Claudio*, if he have caught the *Benedicke*, it will cost him a thousand pound ere it be cur'd.

Mess. I will hold friends with you Lady.

Beat. Doe good friend.

Leo. You'll ne're run mad Neece.

Bea. No, not till a hot January.

Mess. Don Pedro is approach'd.

Enter Don Pedro, Claudio, Benedicke, Balthazar, and John the bastard.

Pedro. Good Signior *Leonato*, you are come to meete your trouble: the fashion of the world is to avoyde cost, and you encounter it.

Leon. Never came trouble to my house in the likenesse of your Grace: for trouble being gone, comfort should remaine: but when you depart from me, sorrow abides, and happinesse takes his leave.