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

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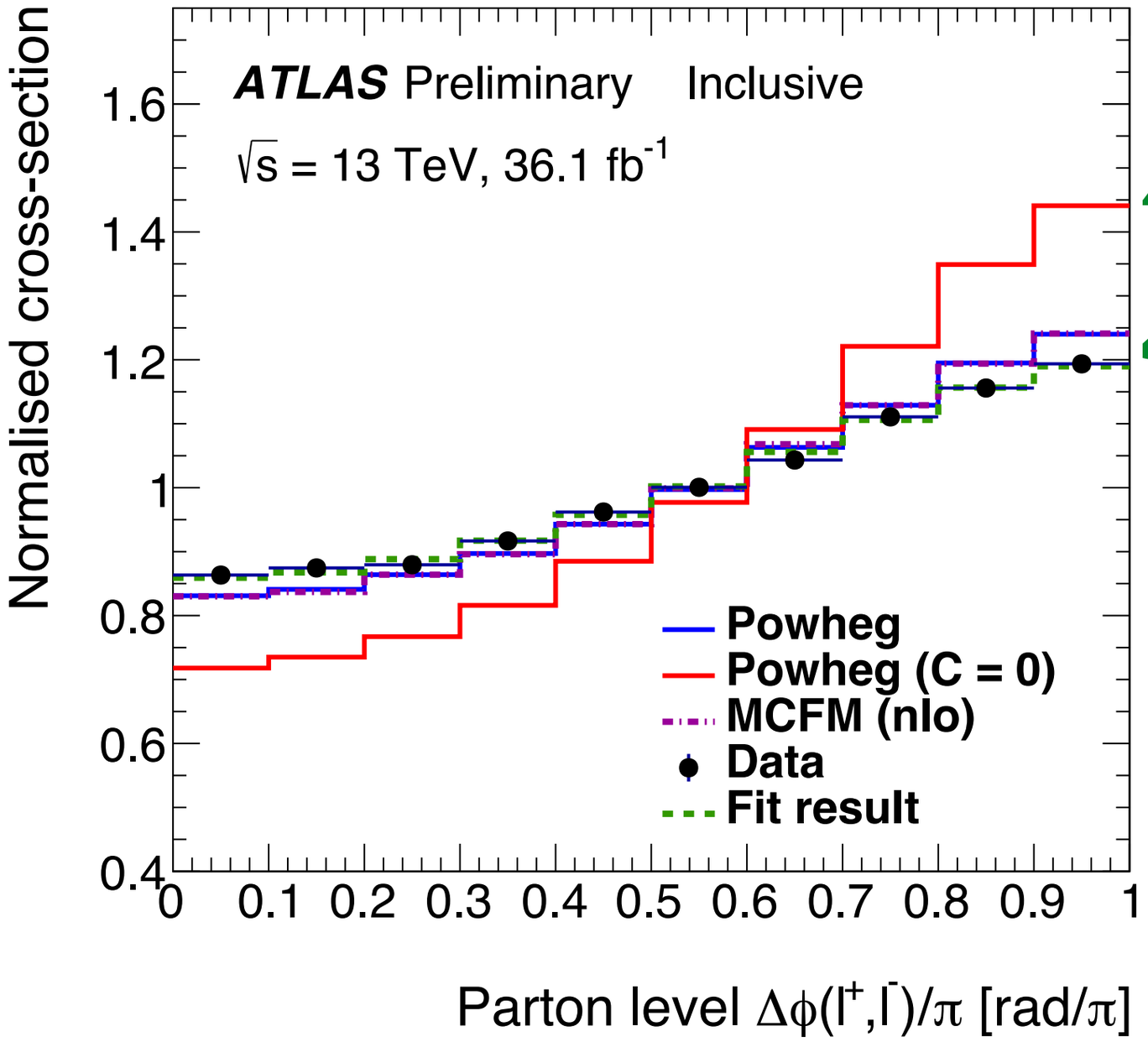
Based on 1806.07438 and further work with Michelangelo

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

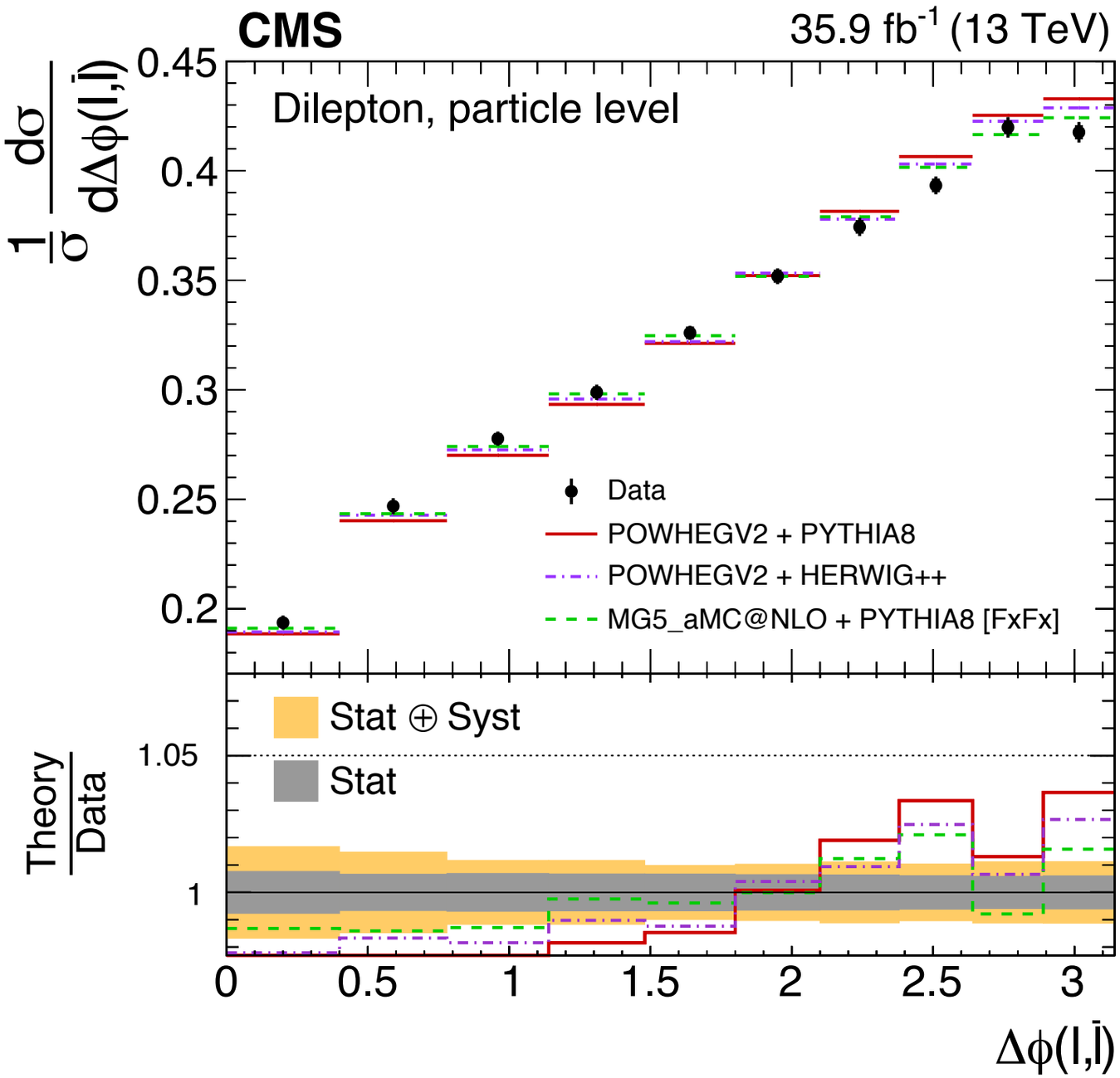
deviation

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

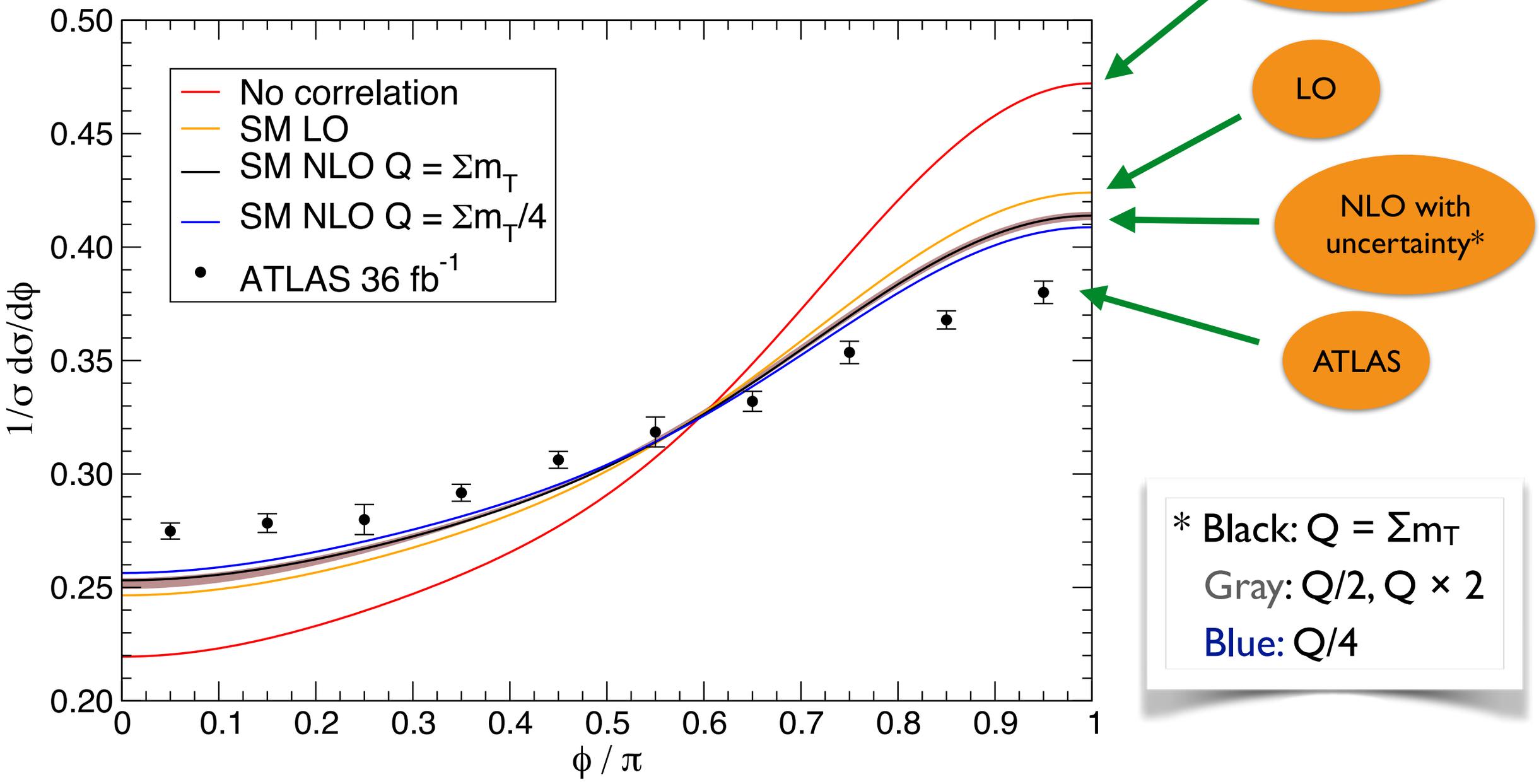
Particle level: no parton level plots available [or easy to find].



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.

Apparently, NNLO still does not reproduce data.

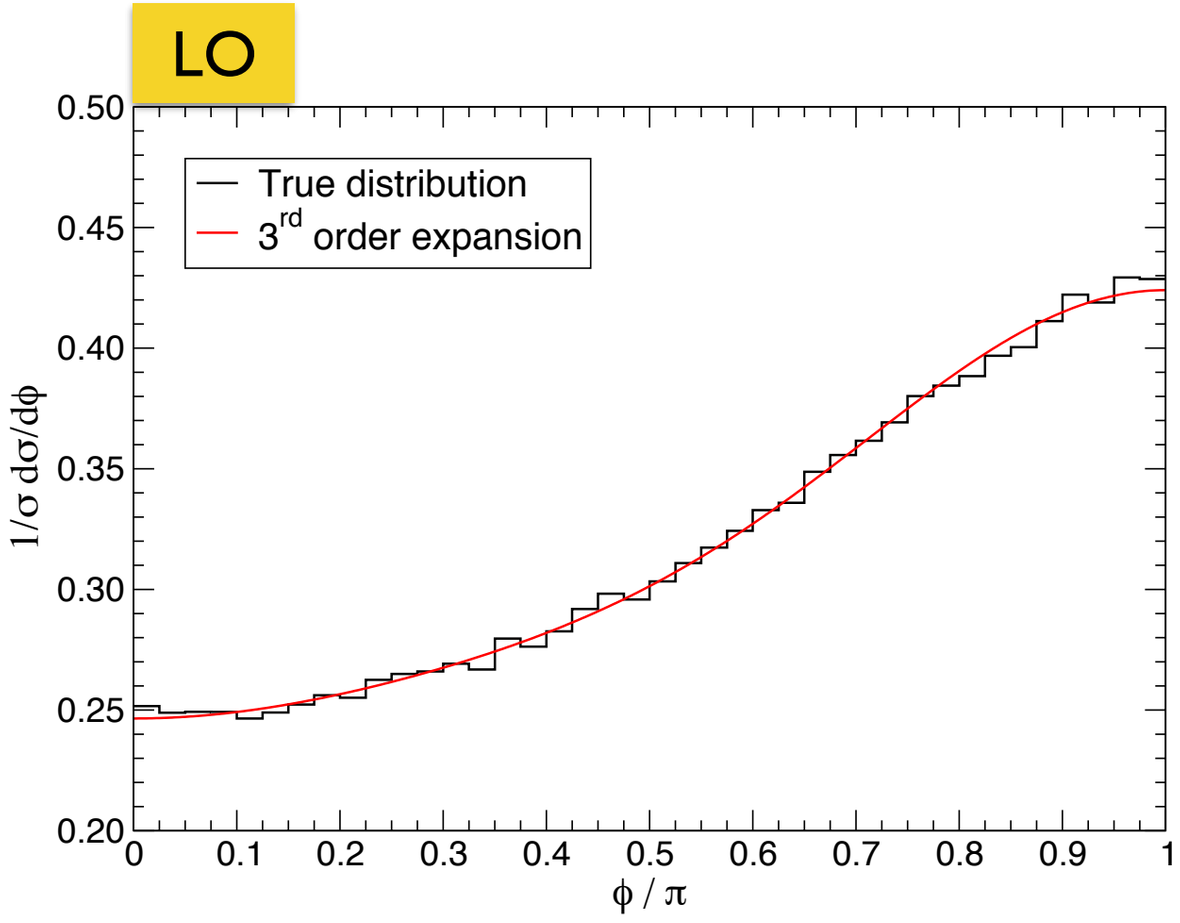


Framework for quick & accurate study

We will use a Fourier analysis of the distribution.

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

	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´

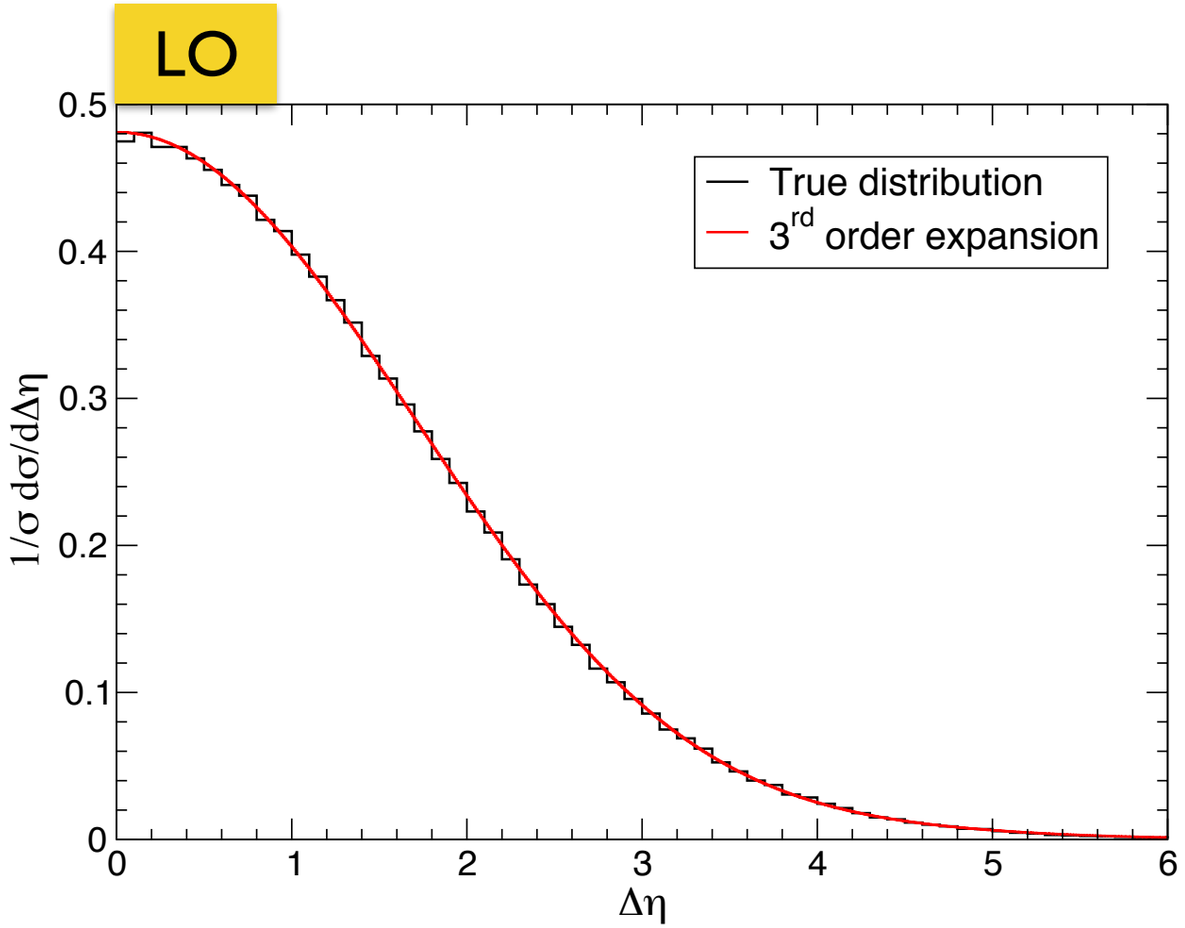
a_2 is small, reflects some features in distribution

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	0.222
a_2	0.0819	0.0801	0.0734
a_3	0.0140	0.0122	0.0116



a_0 = 1/2π for the normalised distribution

a_1, a_2 give the shape

a_3 modifies minor details

ATLAS measurements mostly agree with SM

Outline 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.

- First 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.

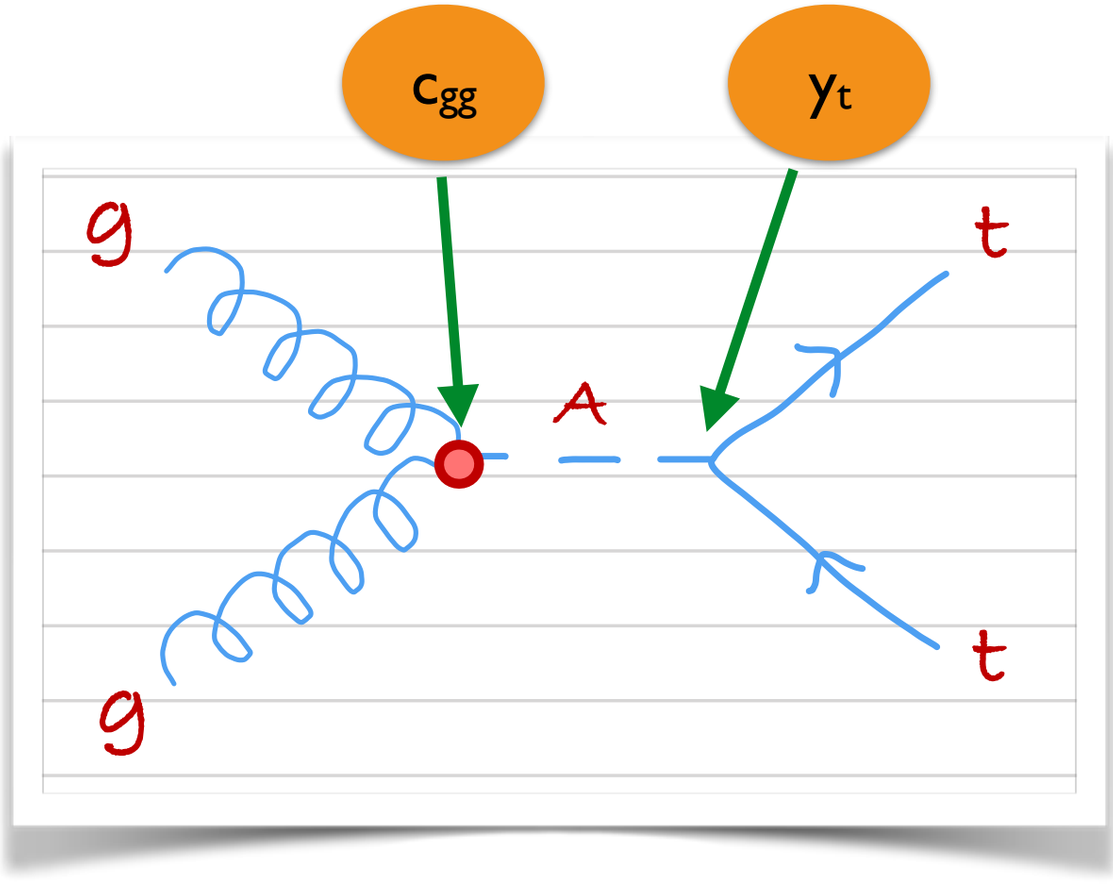
  A deviation in a_1 cannot be compensated by higher-order harmonics.

- Subsequent analysis of other distributions

New physics toy model: pseudo-scalar *A* in s channel

I will assume $gg \to A \to tt$ 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

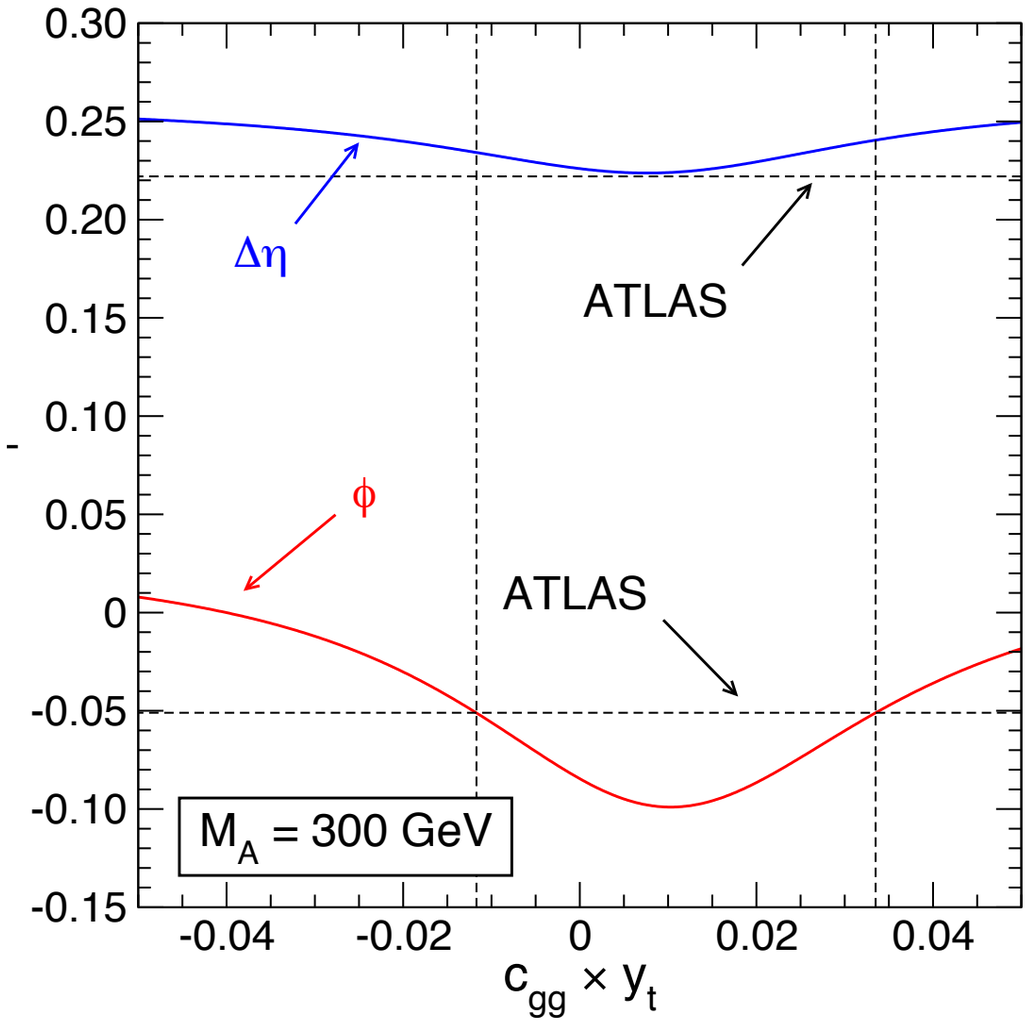


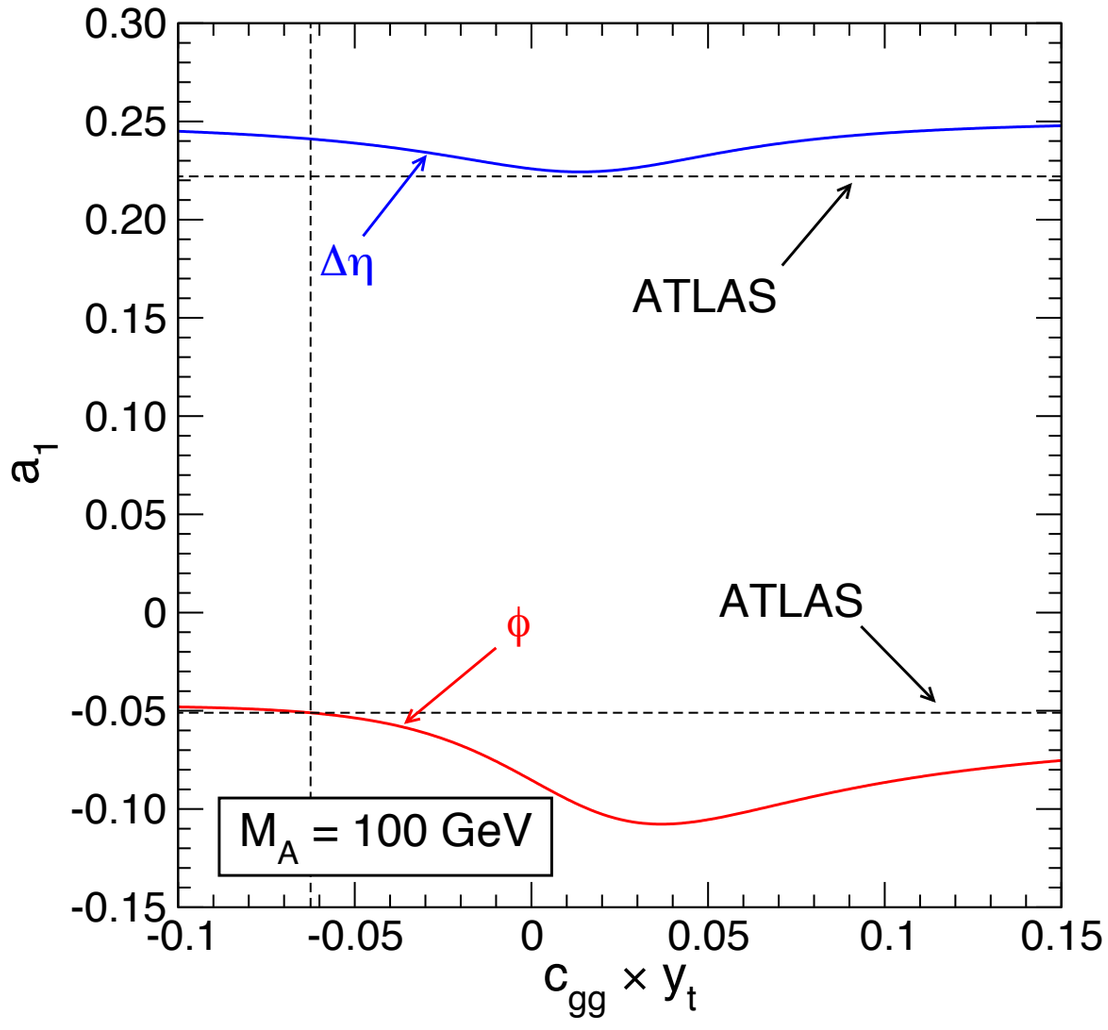
$$\mathcal{L} = \frac{g_s^2}{M_W} c_{gg}\, G^a_{\mu\nu} \tilde{G}^{\mu\nu a} A$$
$$- i \frac{m_t}{v} y_t\, \bar{t} \gamma_5 t\, A$$

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

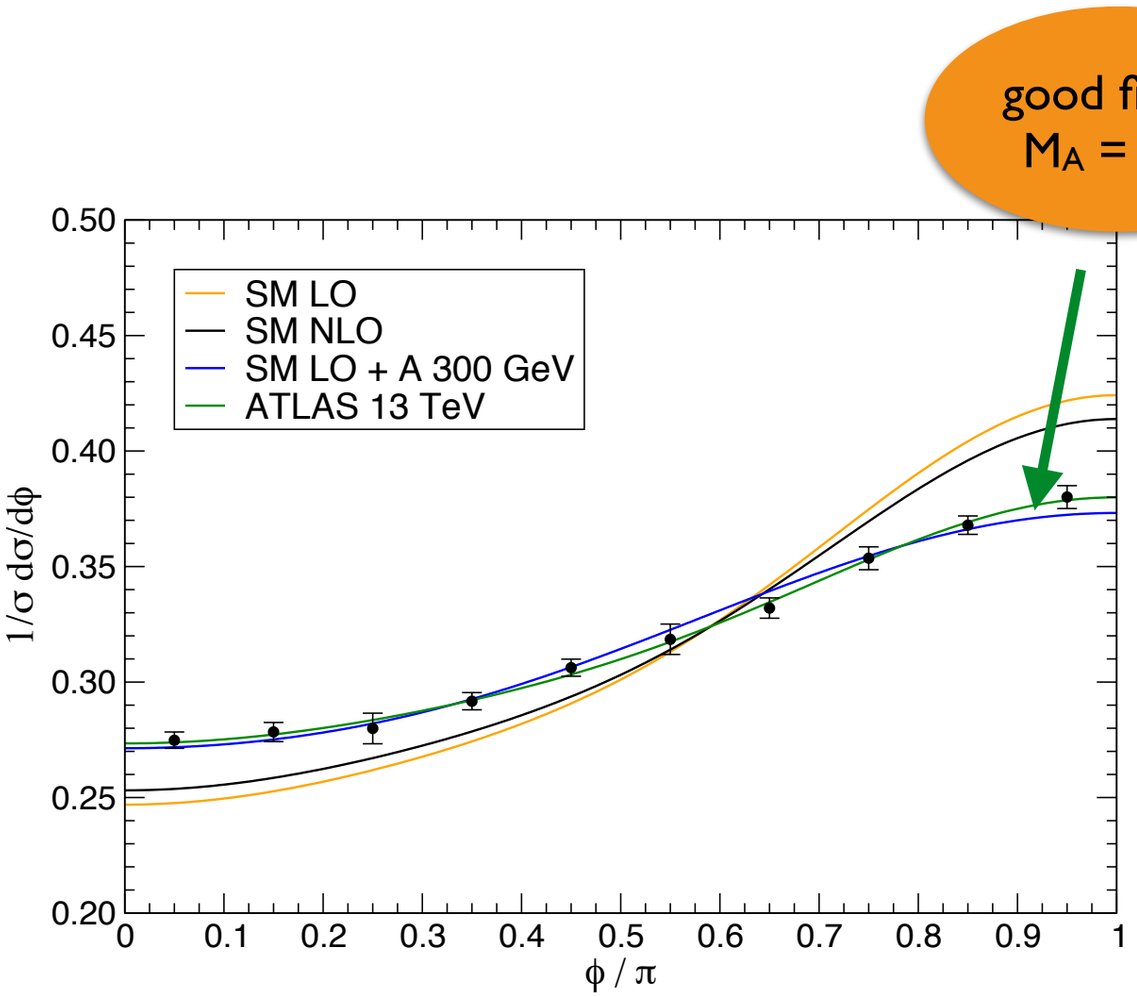
Reproducing $a_1 = -0.051$ for the azimuthal correlation ϕ unavoidably leads to deviations from the SM prediction for $\Delta\eta$.

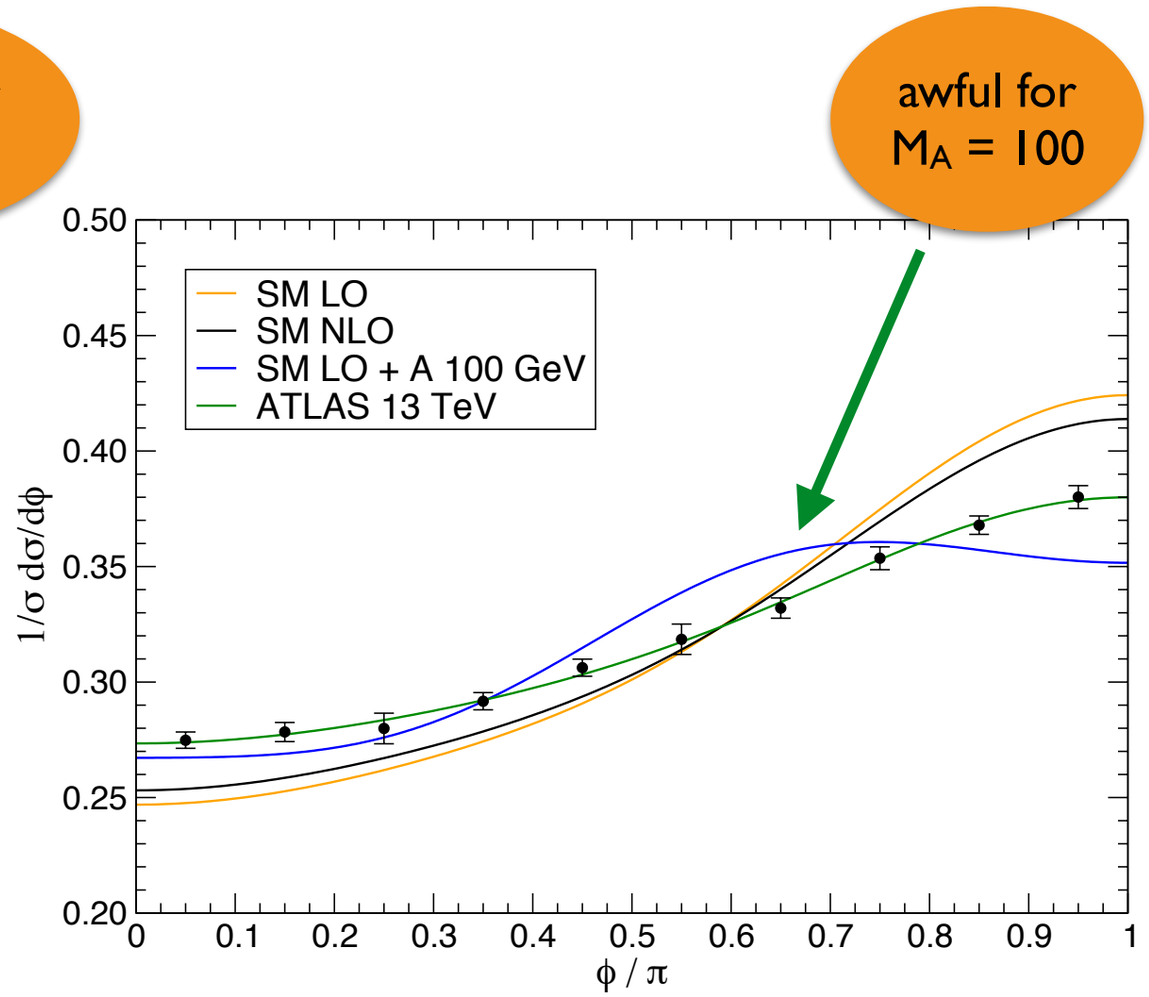
Interference can work in the `correct´ direction, and so does quadratic contribution.





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

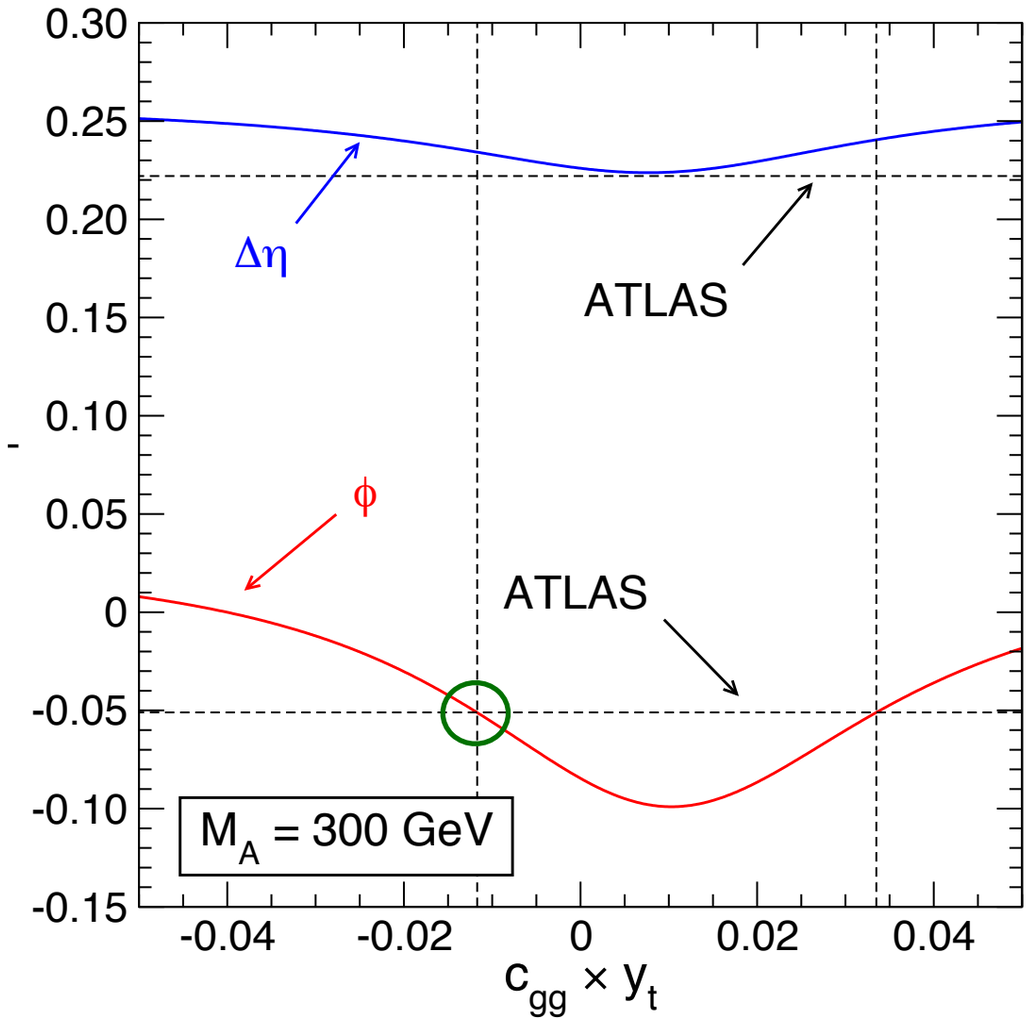




Moral: it is nontrivial to reproduce the distribution.

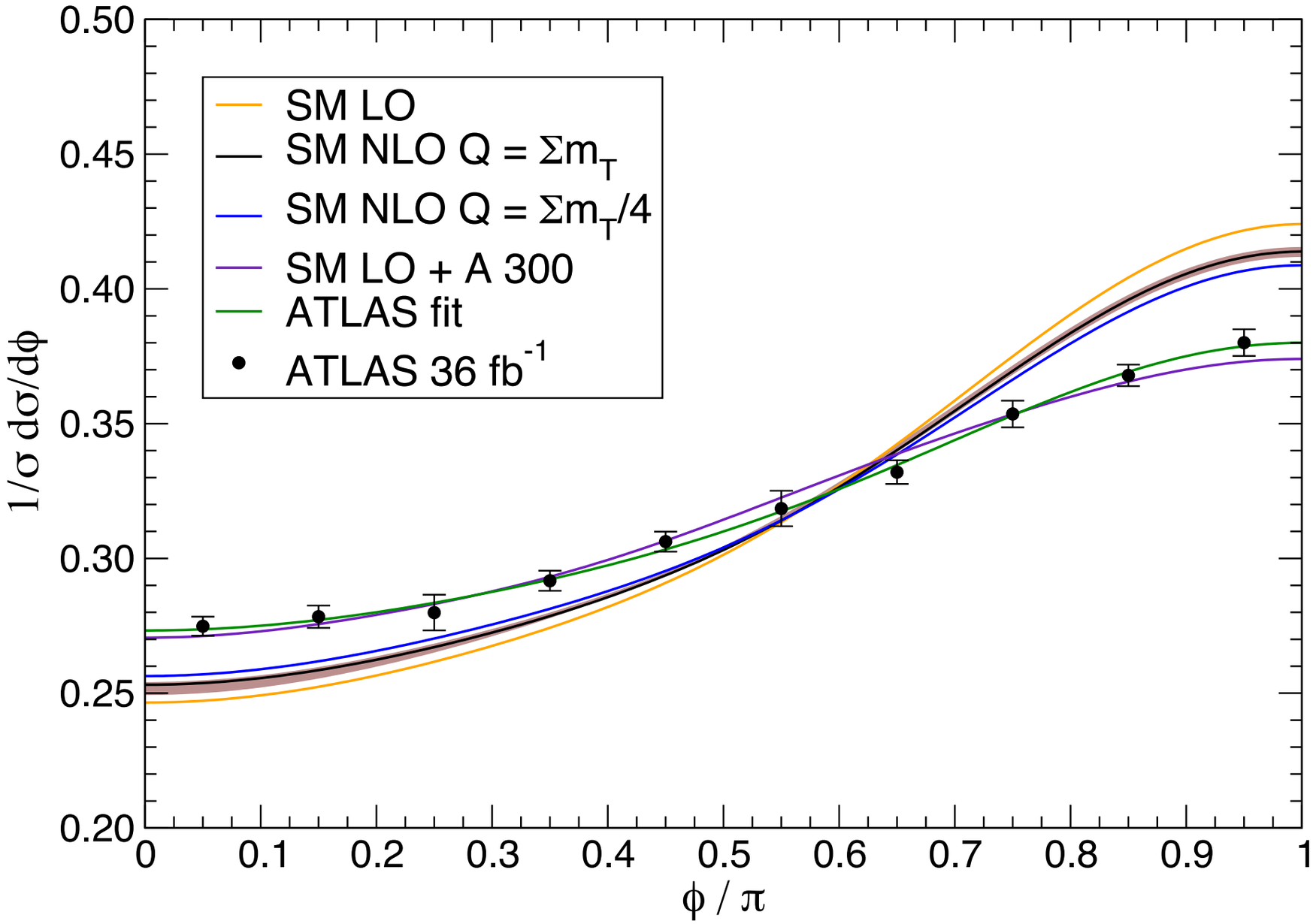
Surprise #1

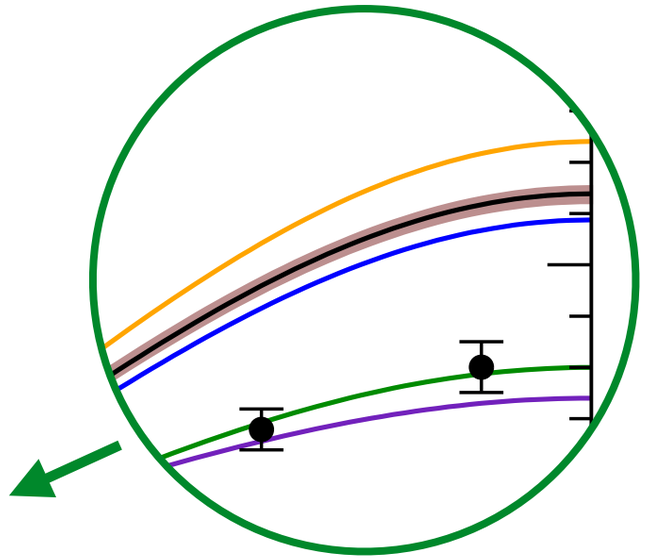
Consider this benchmark point with negative $c_{gg} \times y_t$ that reproduces the ϕ distribution for M = 300 GeV



Cross section: σ = 1.4 σ(LO)

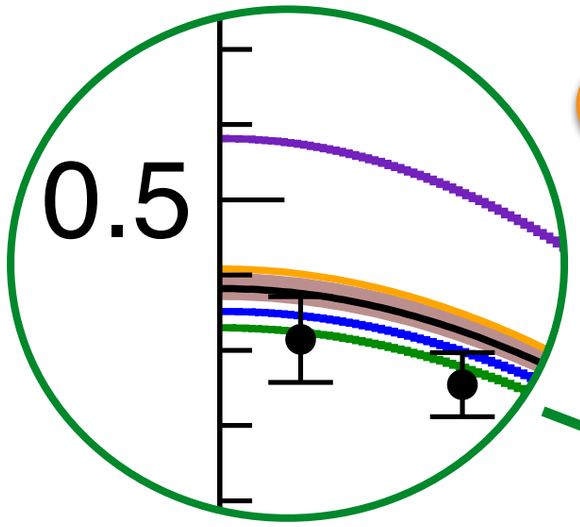
Closer look at ϕ



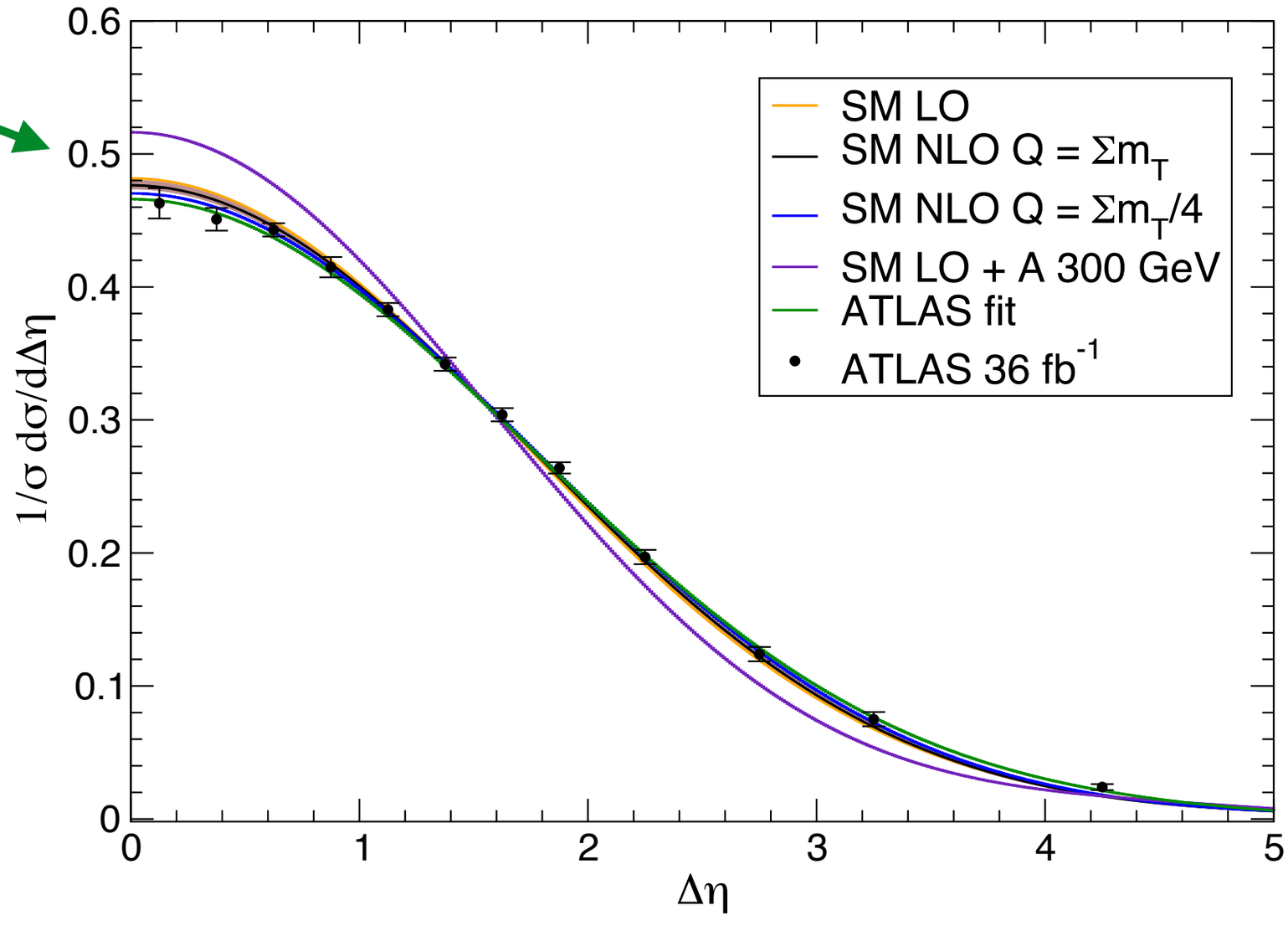


Changing scale to $\Sigma m_T/4$ at NLO helps a little but not much.

Closer look at Δη



7%
relative shift



A deviation of this size is unacceptable at face value...

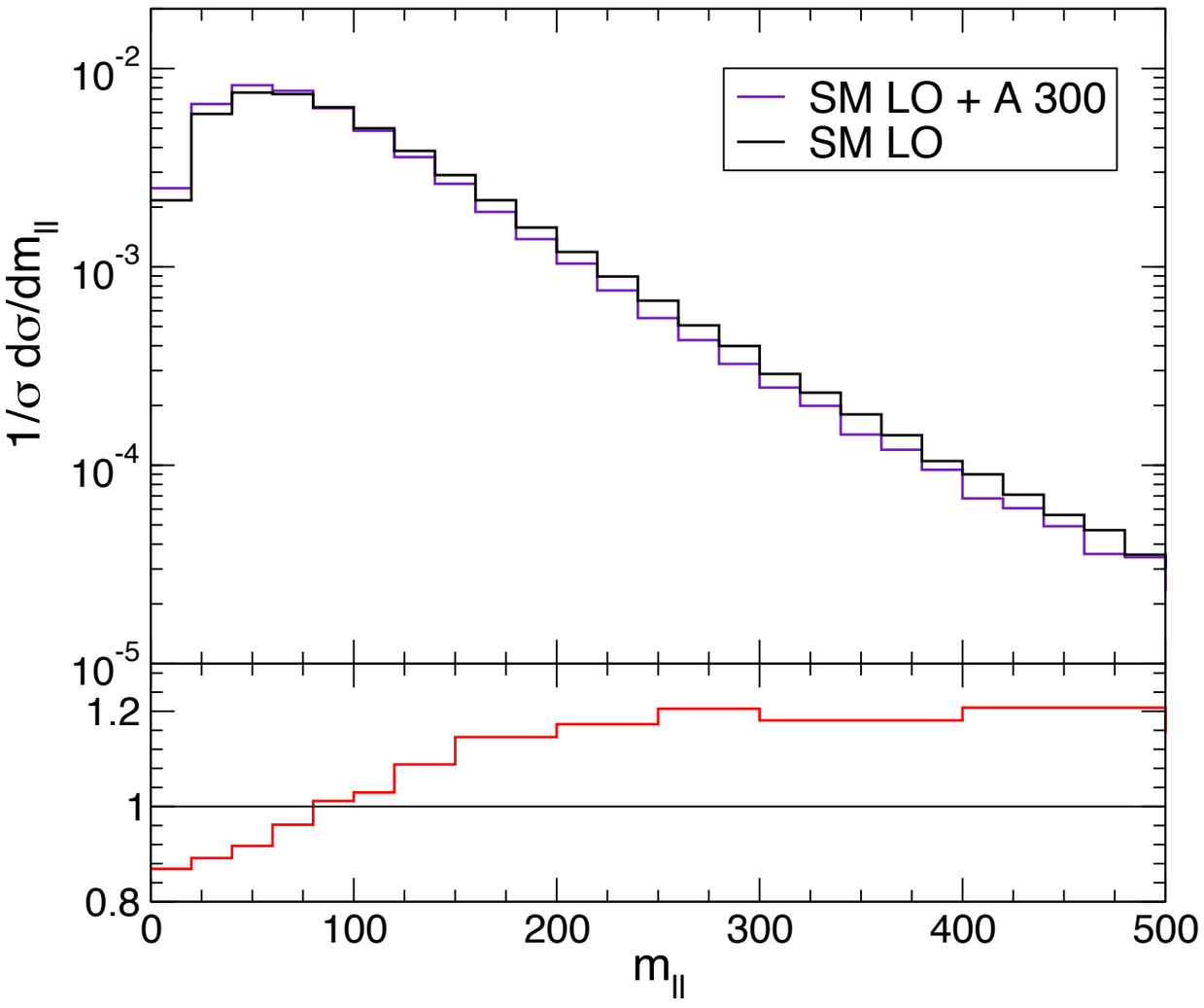
What else?

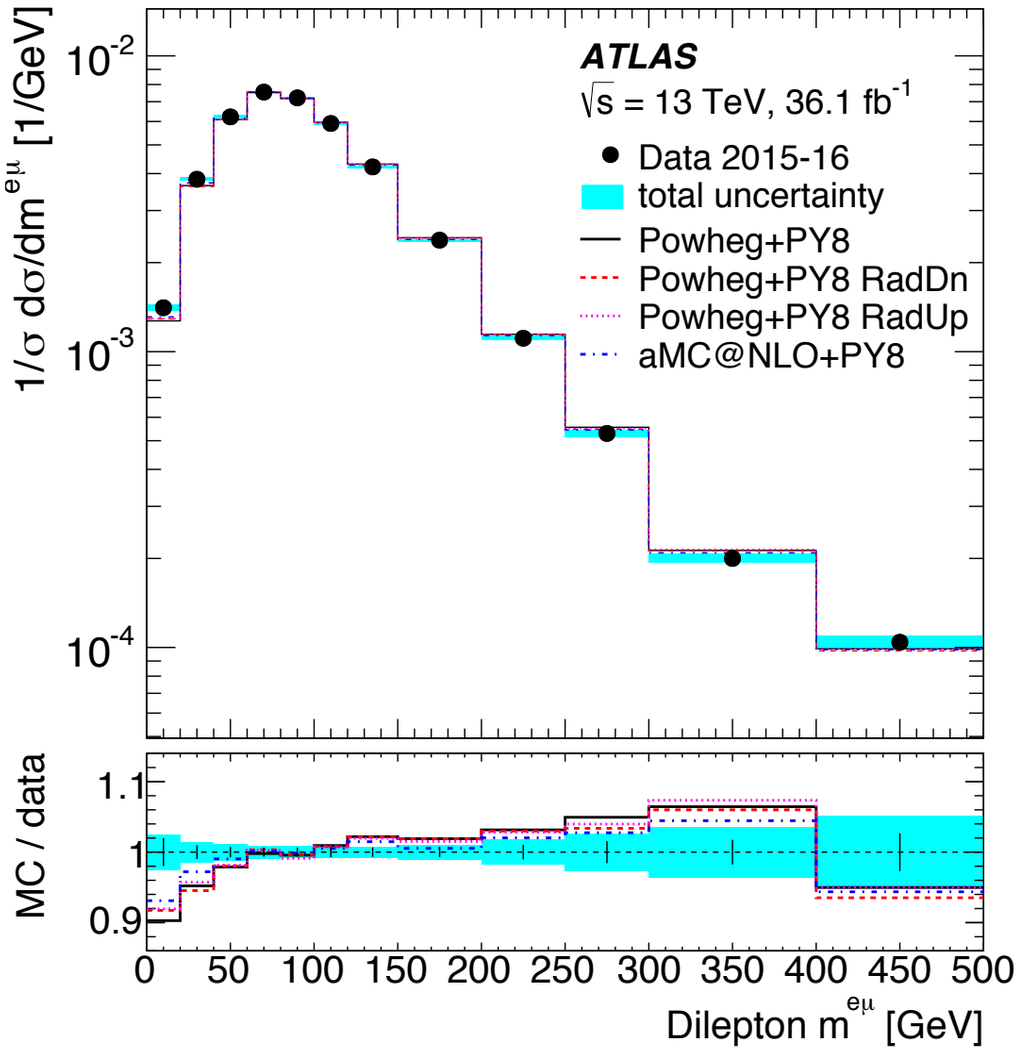
For the moment we are even: fix one distribution,

and spoil another.

Let us look at more distributions!

Closer look at m_{ll}



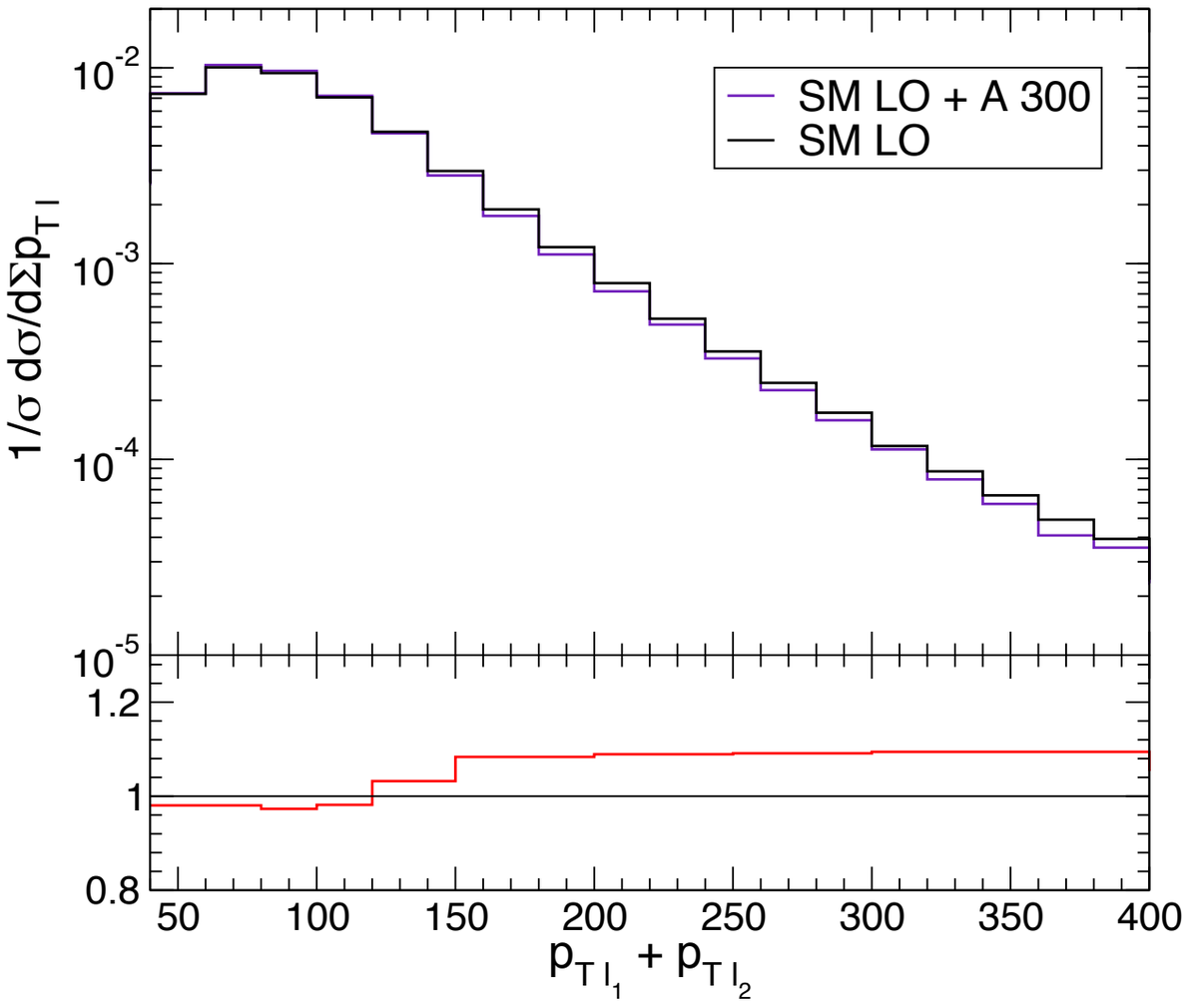


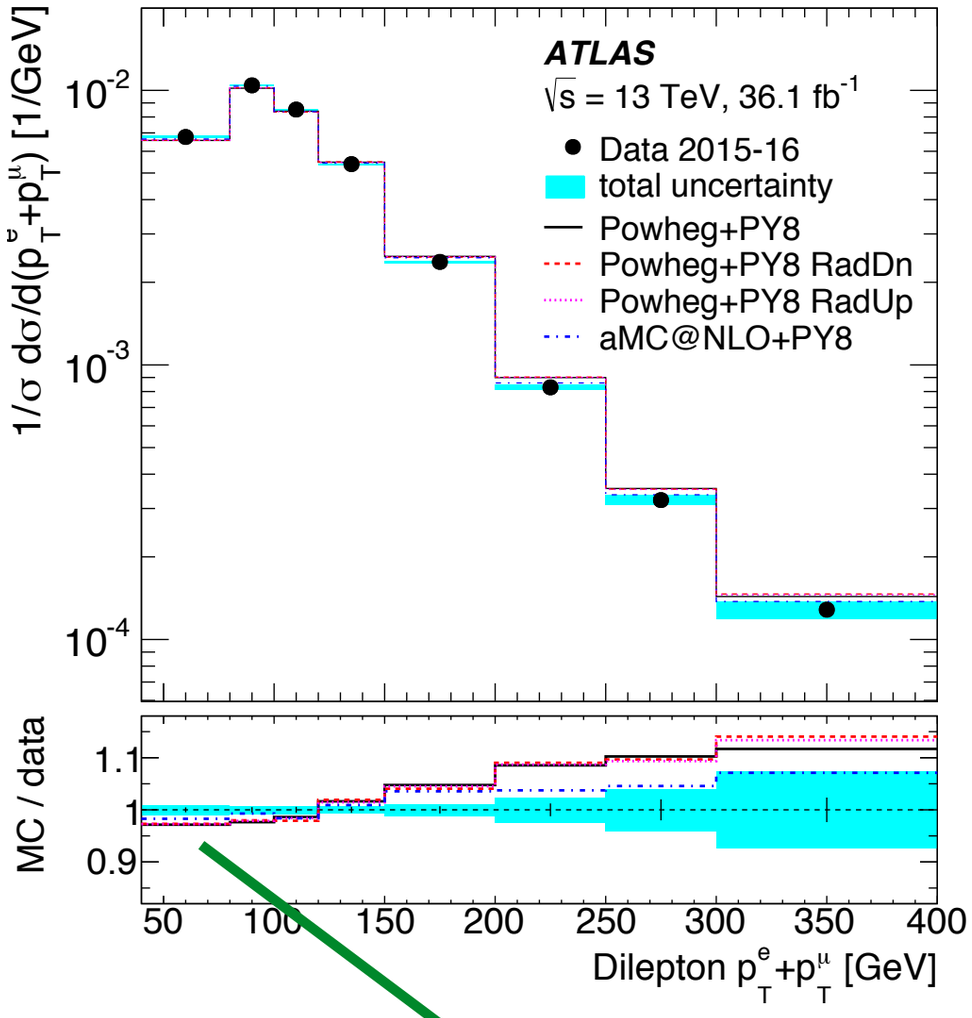
It is clear that ϕ and m_{ll} are related... but did we expect such a good match?

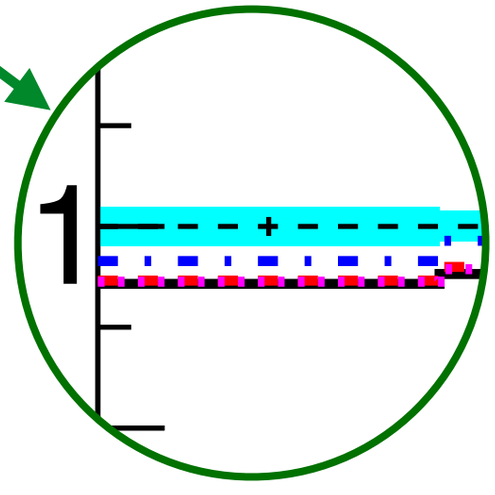
[ignore tails: calculation is LO]

Surprise #2

Closer look at $\Sigma p_{T\,l}$





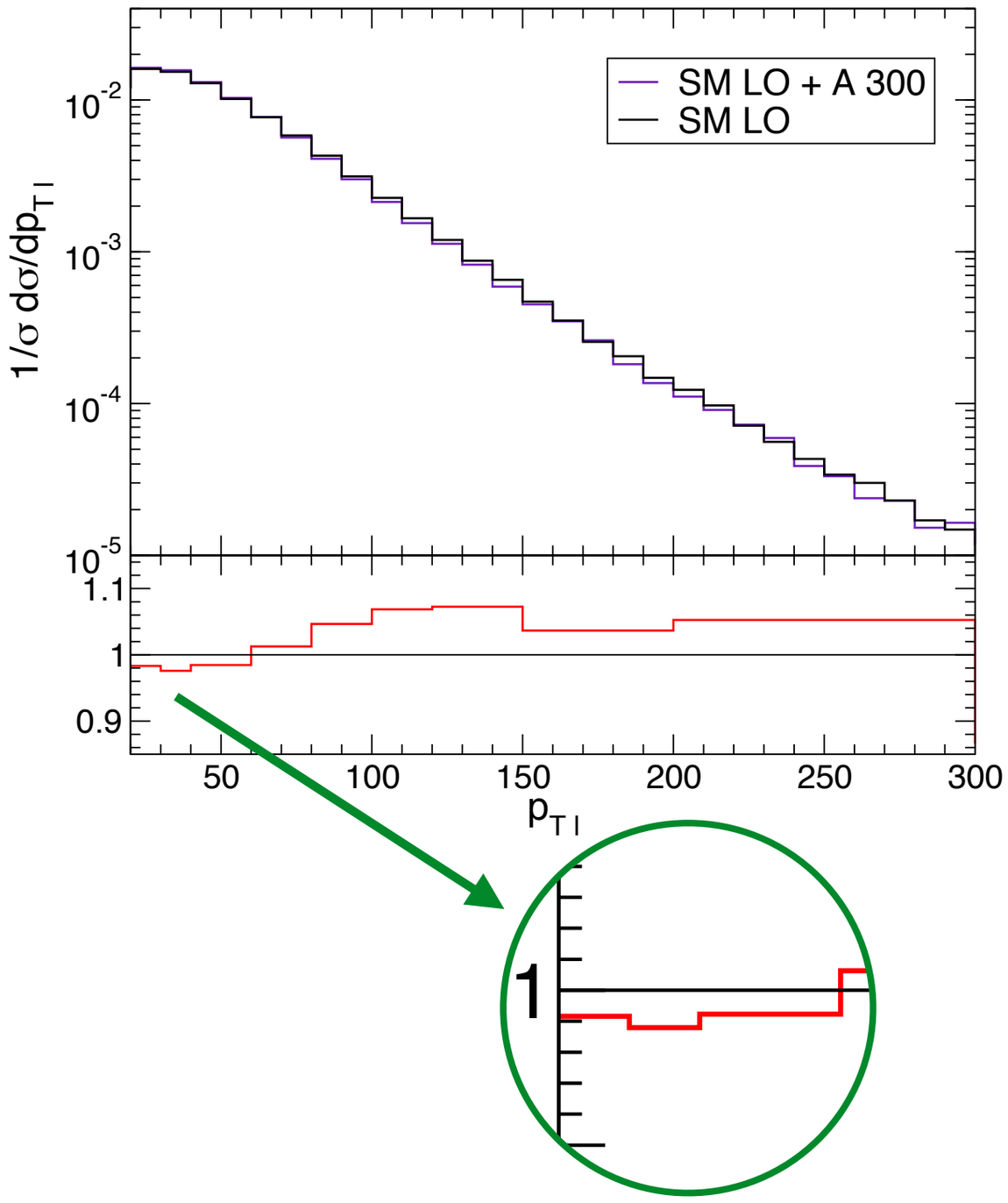


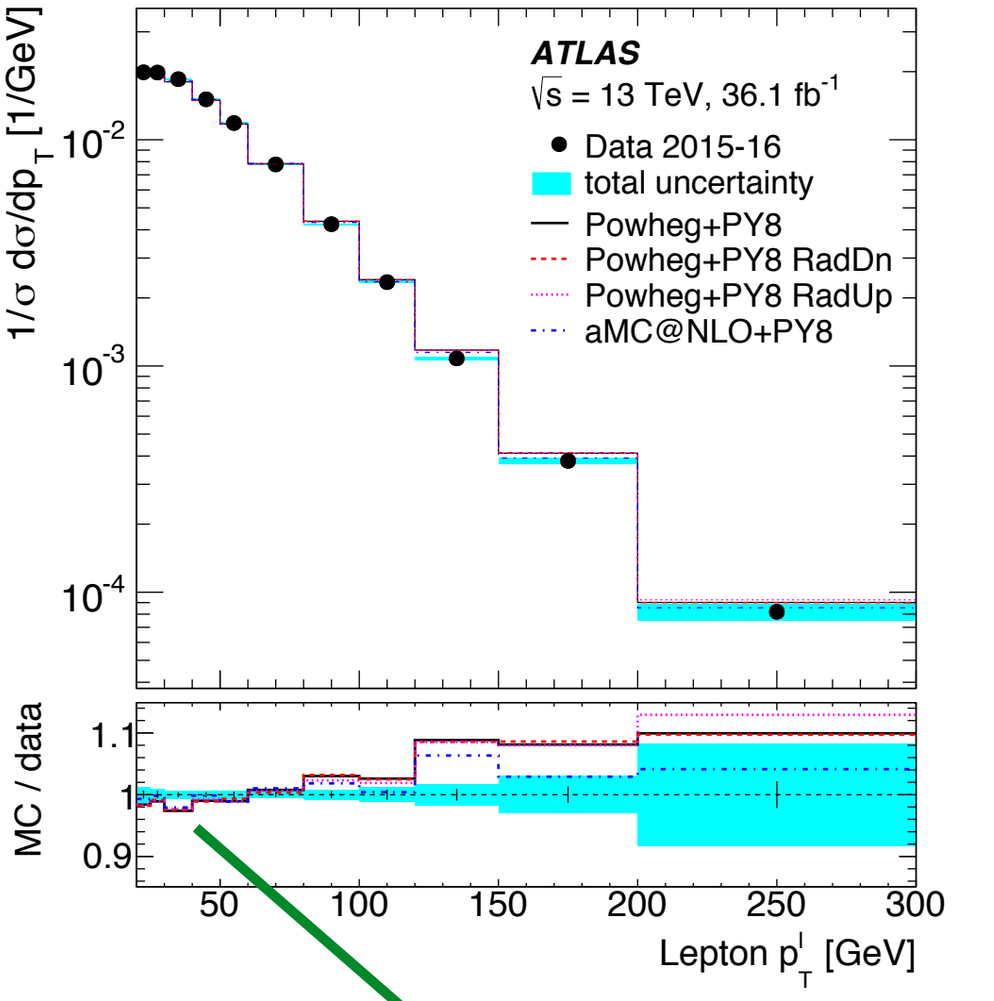
Deviations are small and hard to see with naked eye...

but again a good match! [ignore tails: calculation is LO]

Surprise #3

Closer look at $p_{T\,l}$





again a good match! [...]

Surprise #4

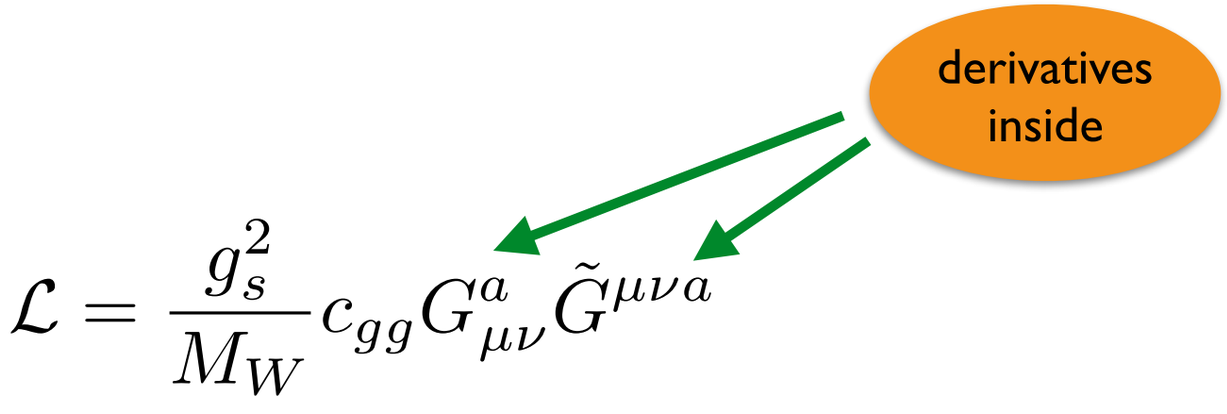
Is this something?

I think this coincidence is telling us something.

~~Naysayers~~ SM fans will claim all this is related and there is no coincidence.

Let us think about it.

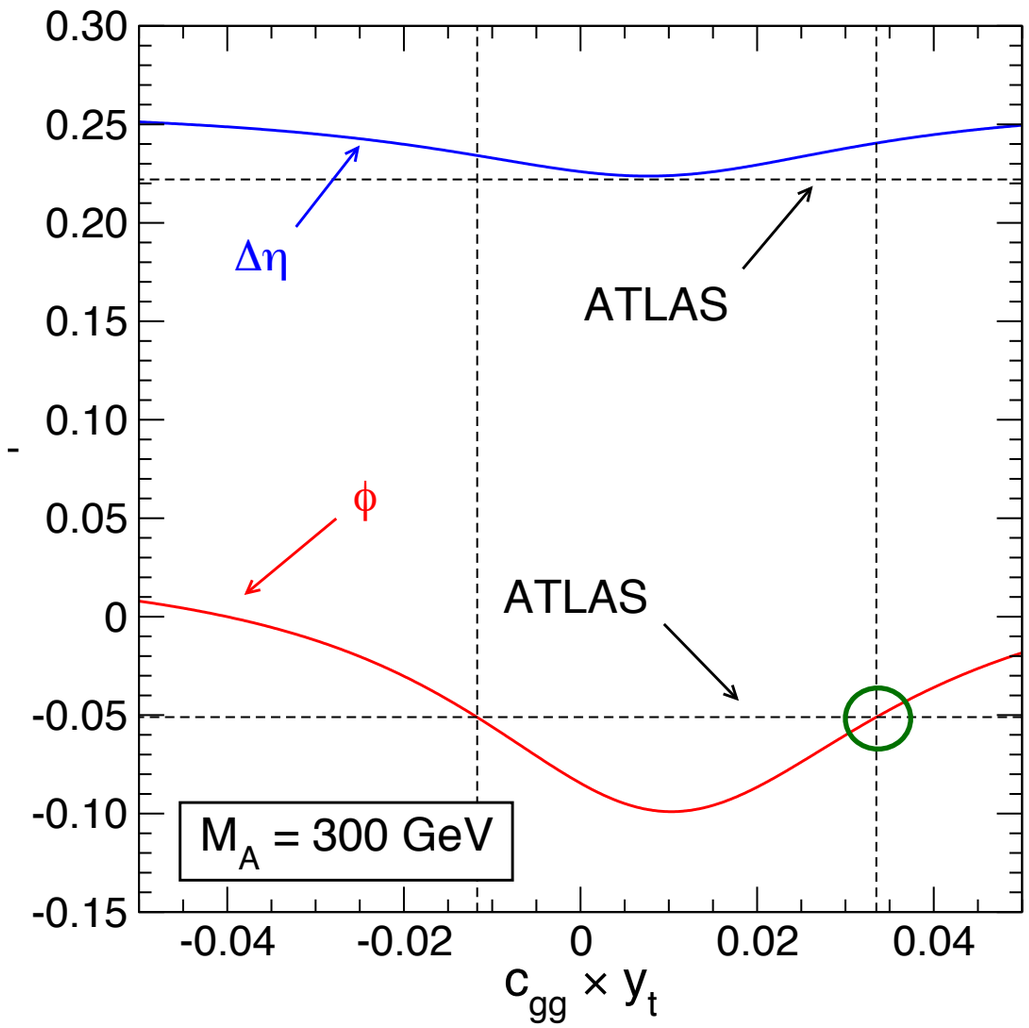
Is the drop at high p_T expected?



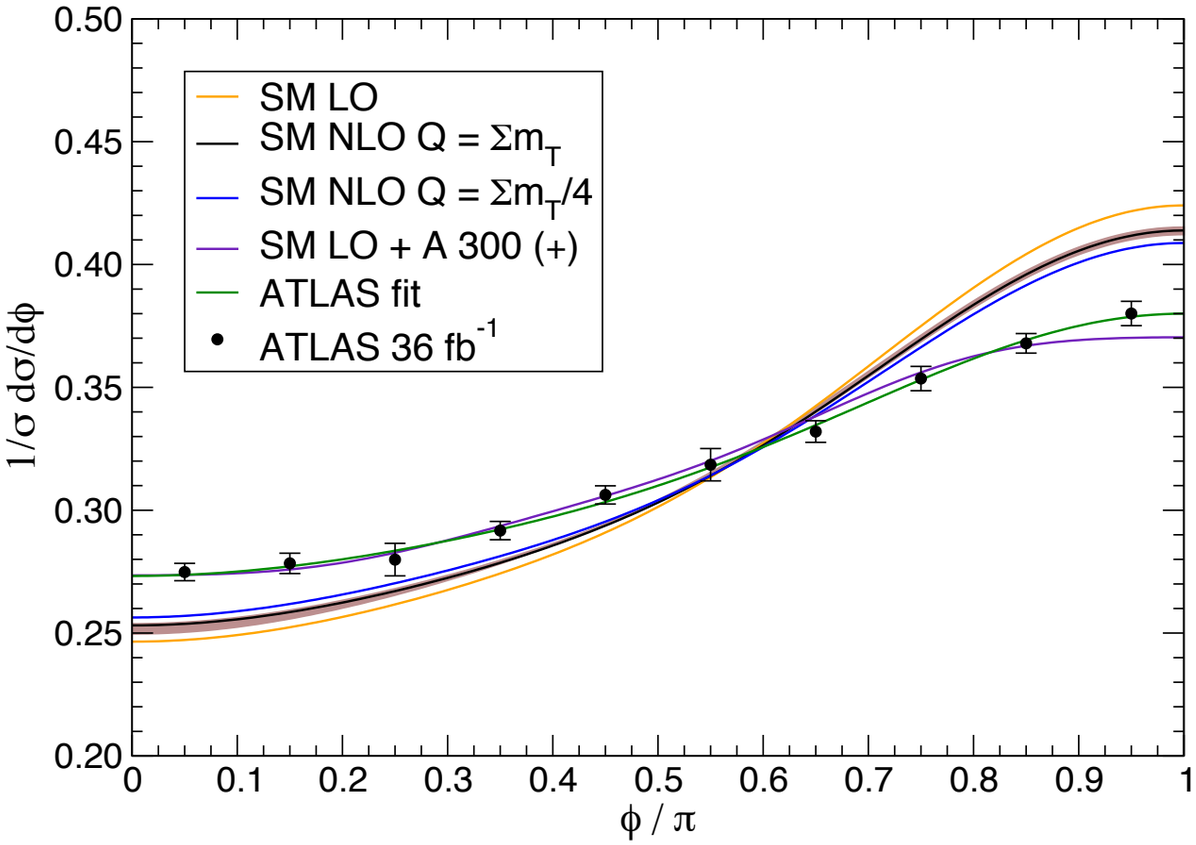
$$\mathcal{L} = \frac{g_s^2}{M_W} c_{gg} G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$$

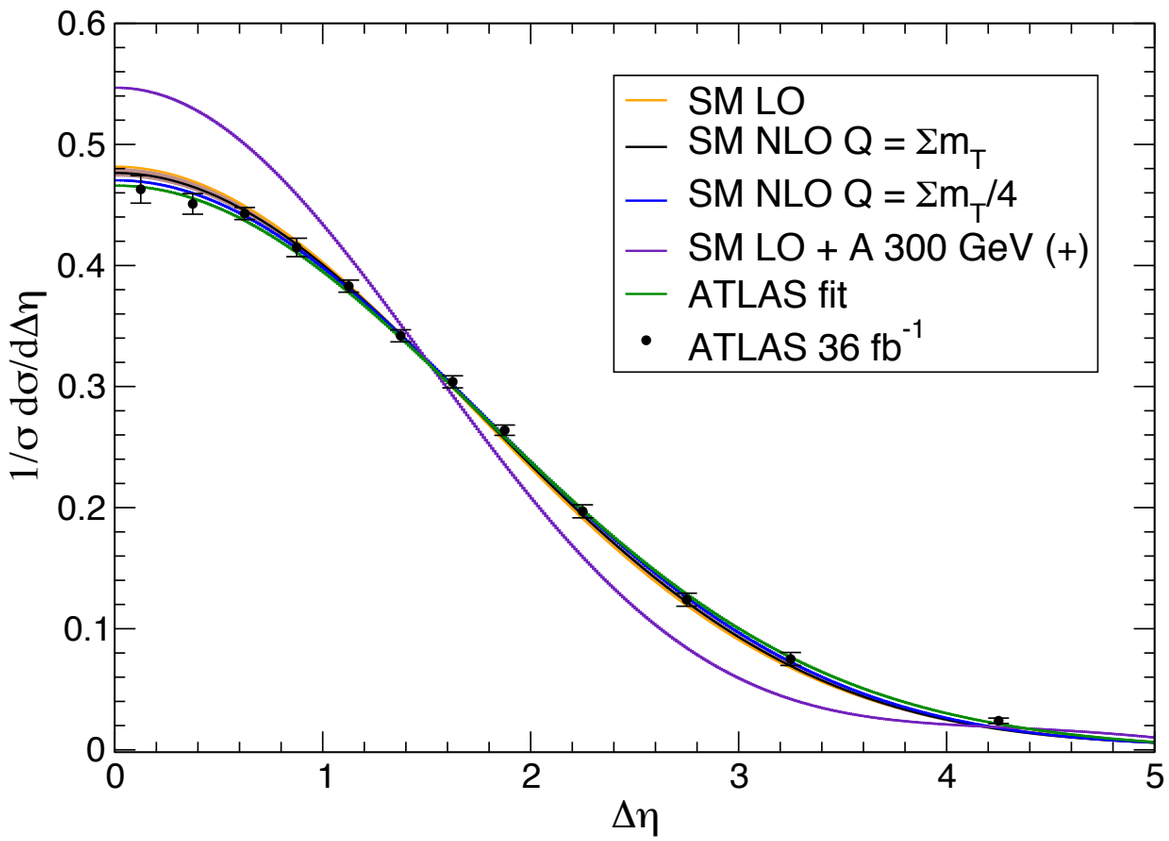
- The contribution of the pseudo-scalar is enhanced at high Q.
- If the interference with SM amplitude is negative, and quadratic NP contribution is comparable, the tail is moderate.
- If the interference is positive, the tail is pronounced.
- When considering normalised distributions there is a delicate imbalance between contributions close to threshold and at the tail.

Test: consider the other benchmark point with positive $c_{gg} \times y_t$ that reproduces the ϕ distribution for M = 300 GeV



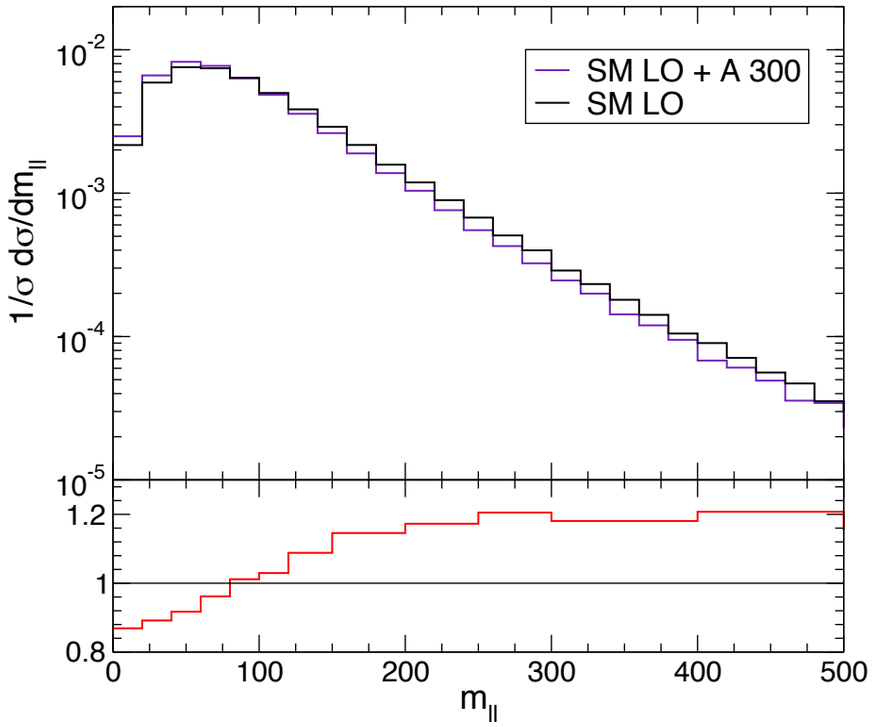
ϕ and $\Delta\eta$ distributions for the alternative benchmark

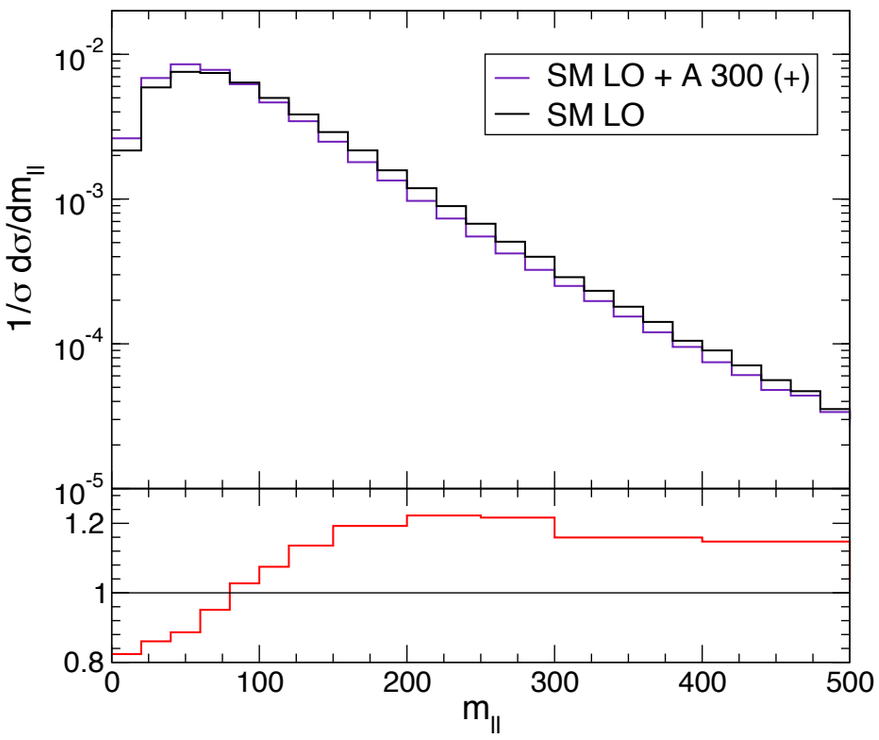


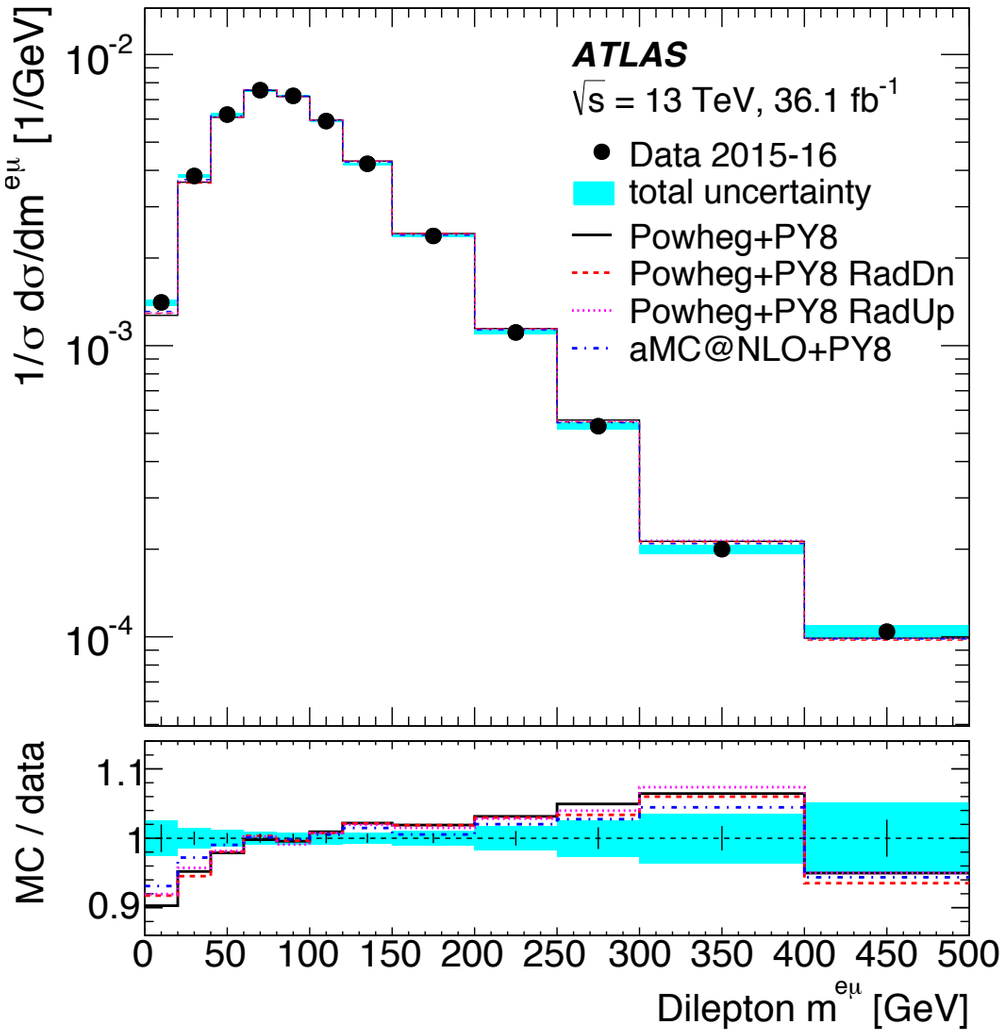


The ϕ distribution is overall well reproduced, the deviation in $\Delta\eta$ is larger.

Closer look at m_{ll}

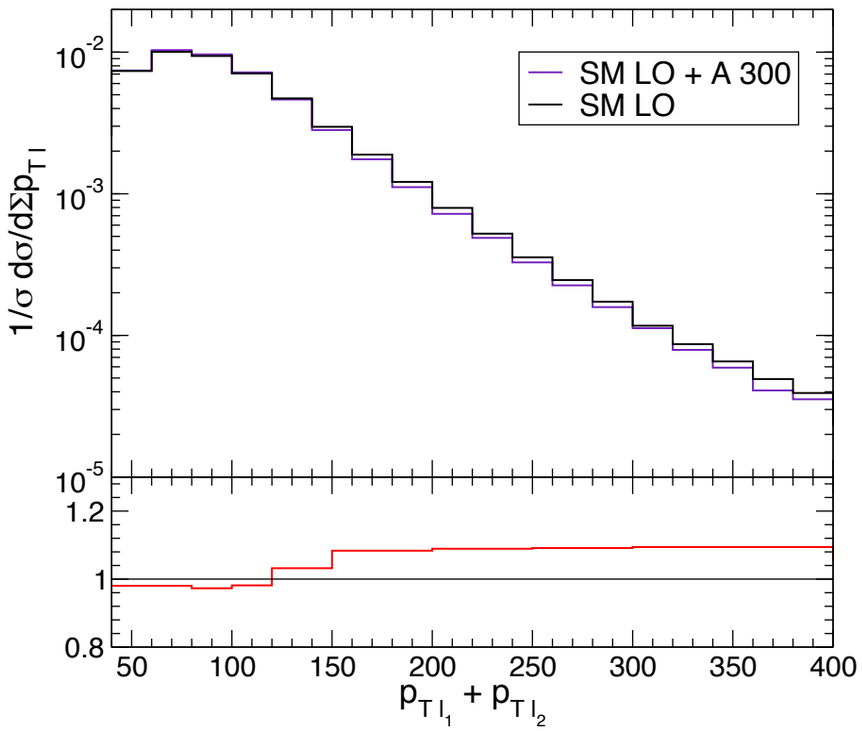


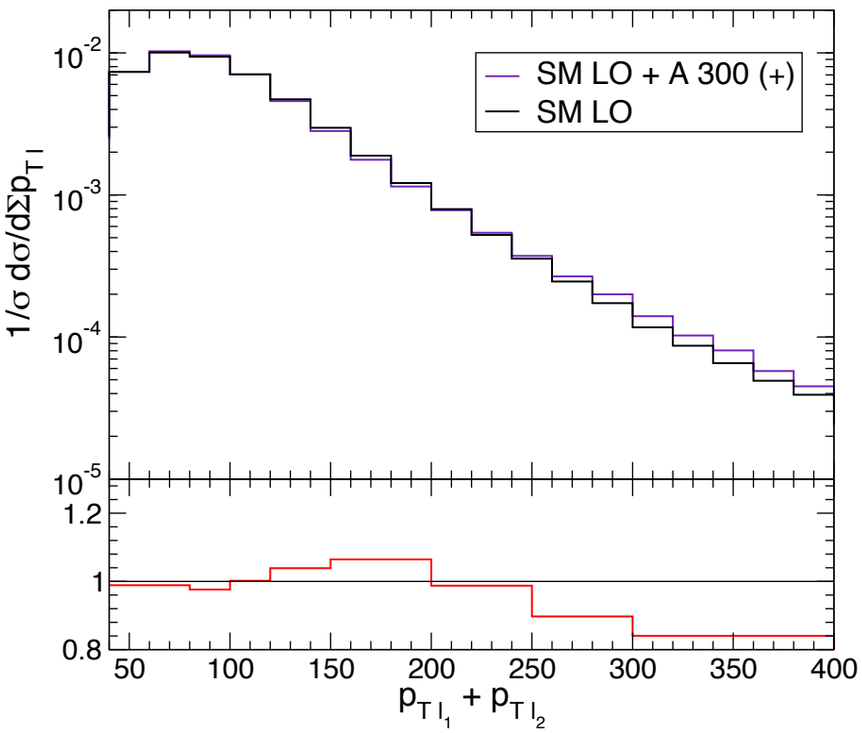


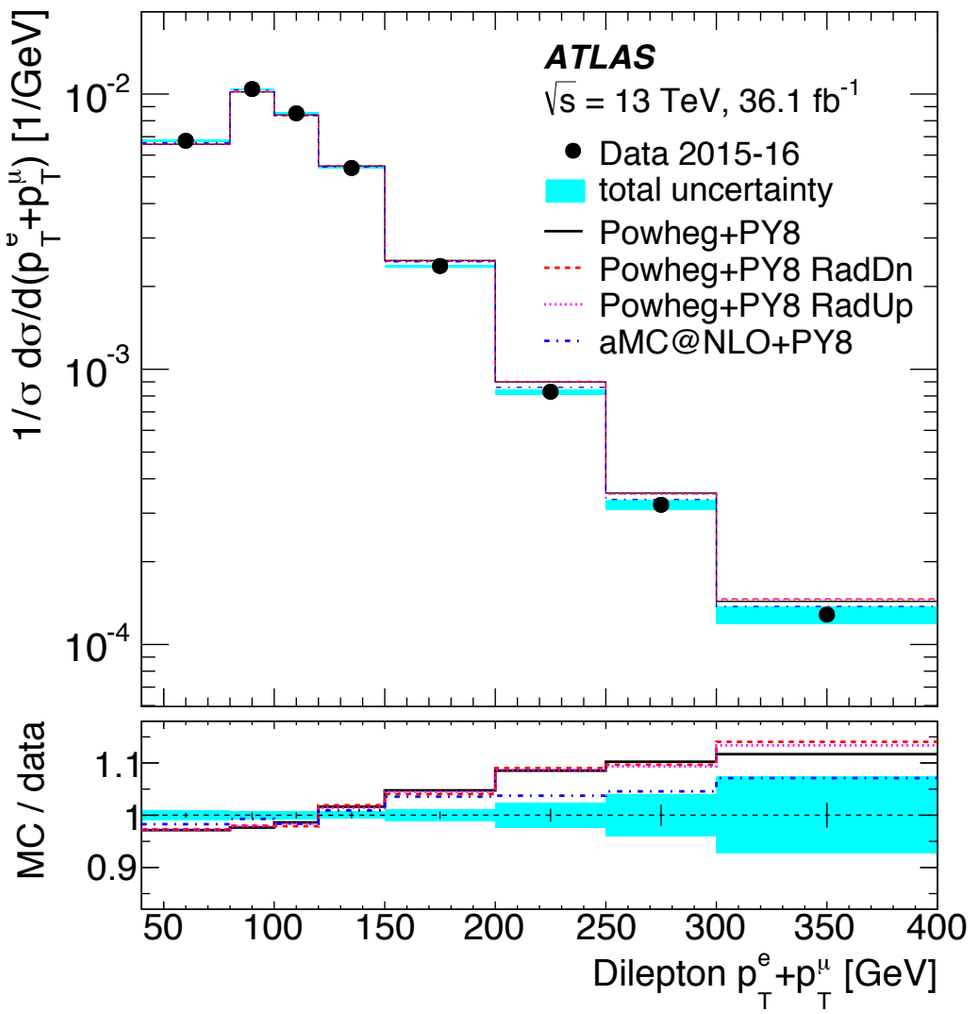


The agreement in the alternative benchmark is worse

Closer look at Σp_{Tl}

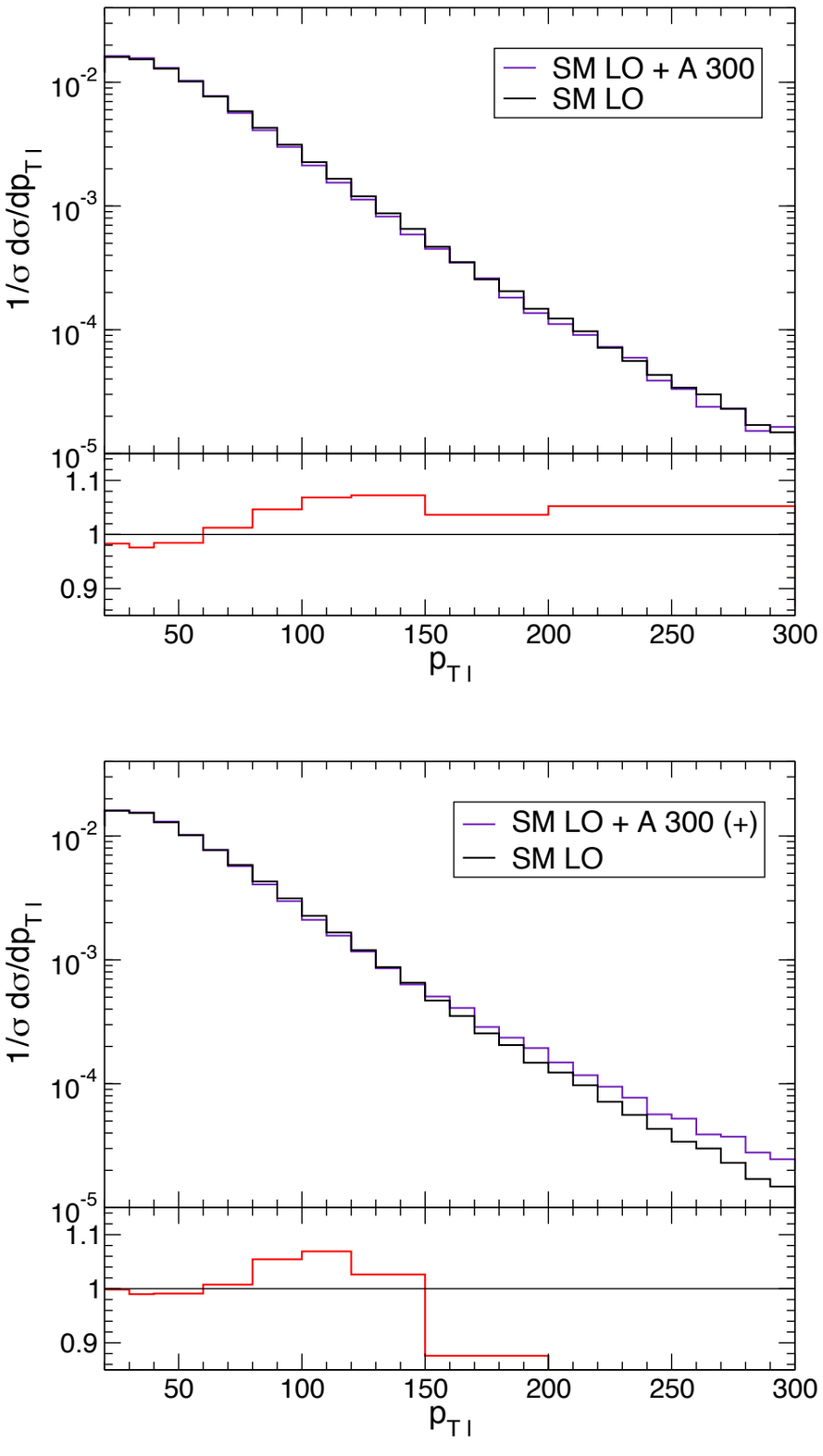


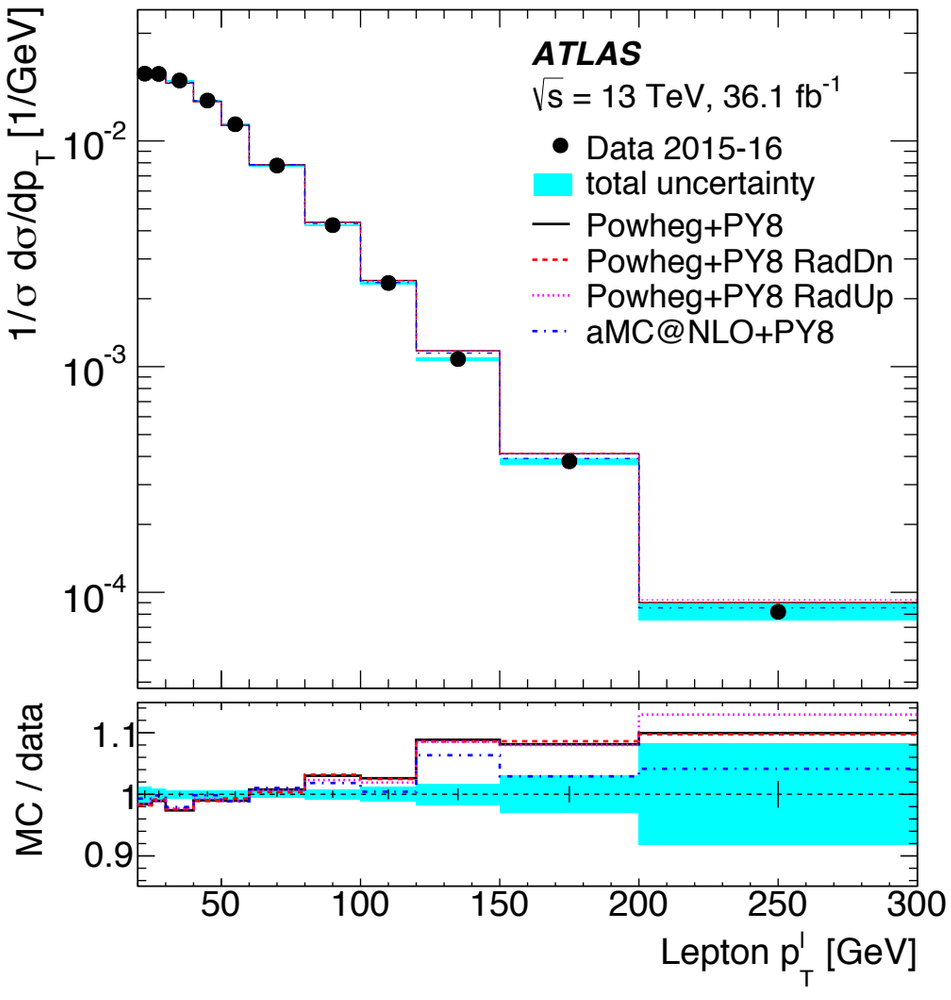




The agreement in the alternative benchmark is very bad

Closer look at $p_{T\,l}$





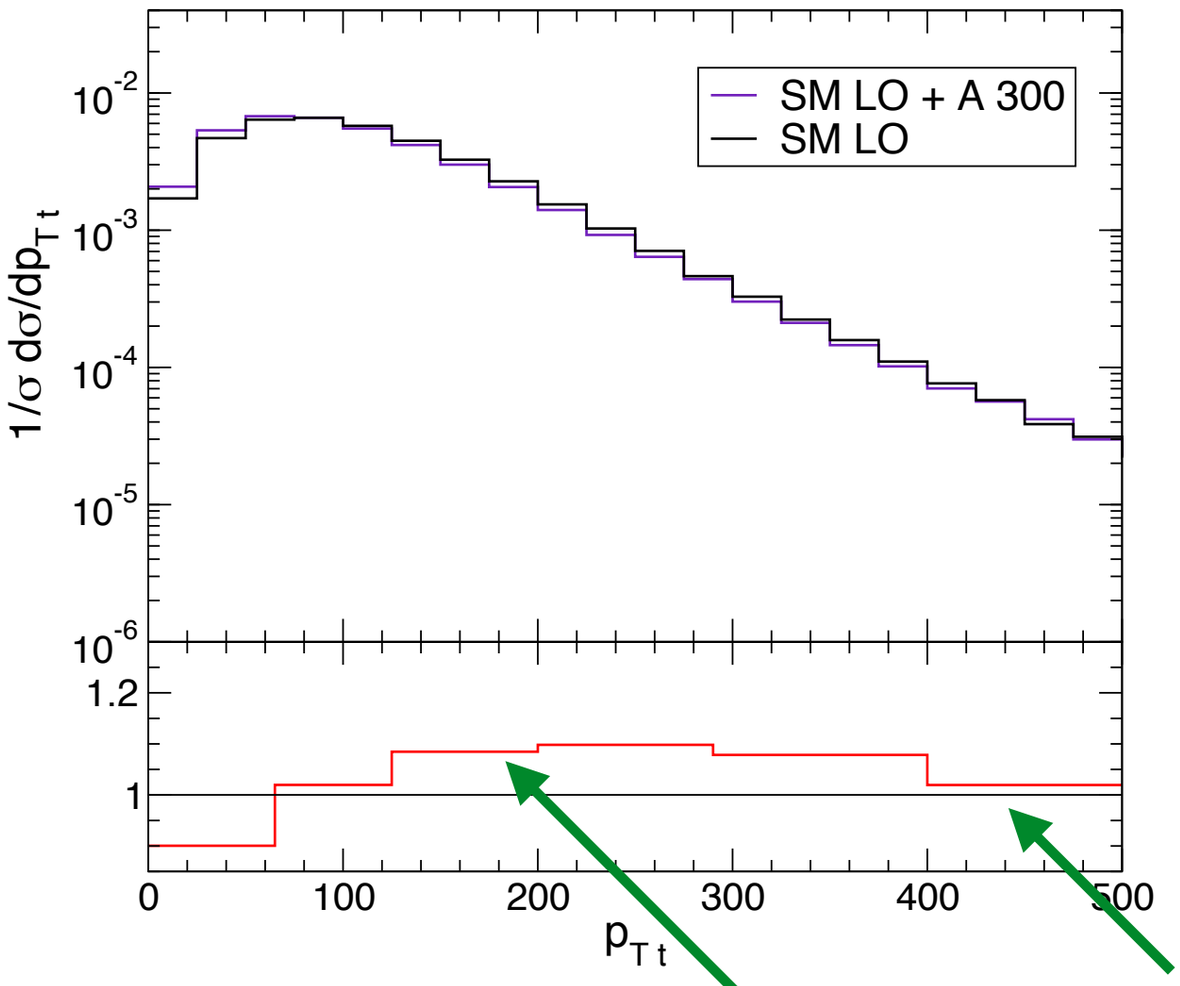
The agreement in the alternative benchmark is really bad

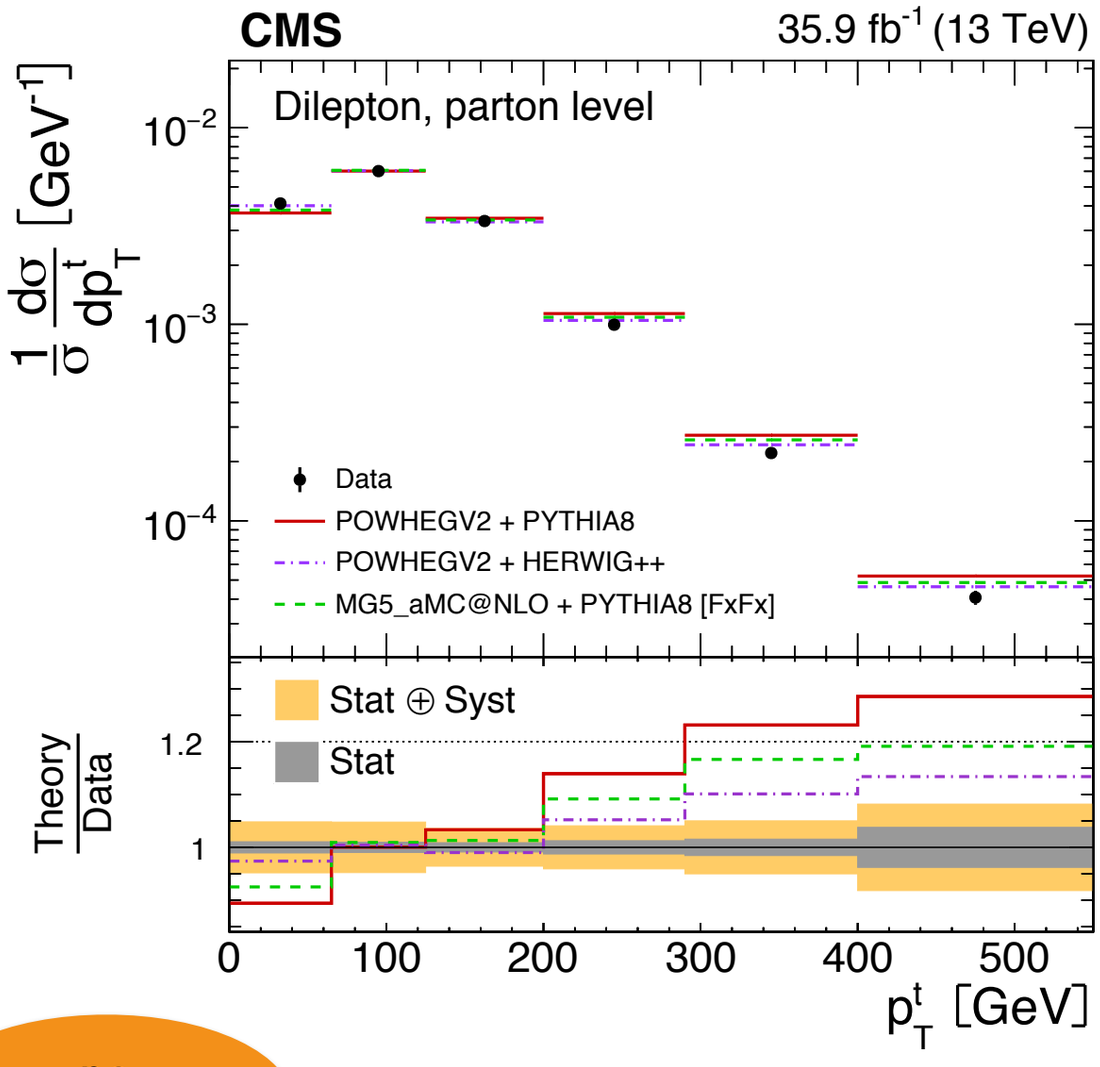
This is overall intriguing

Let us look at reconstructed quantities

(with a grain of salt!)

Closer look at p_{Tt}





relative decrease

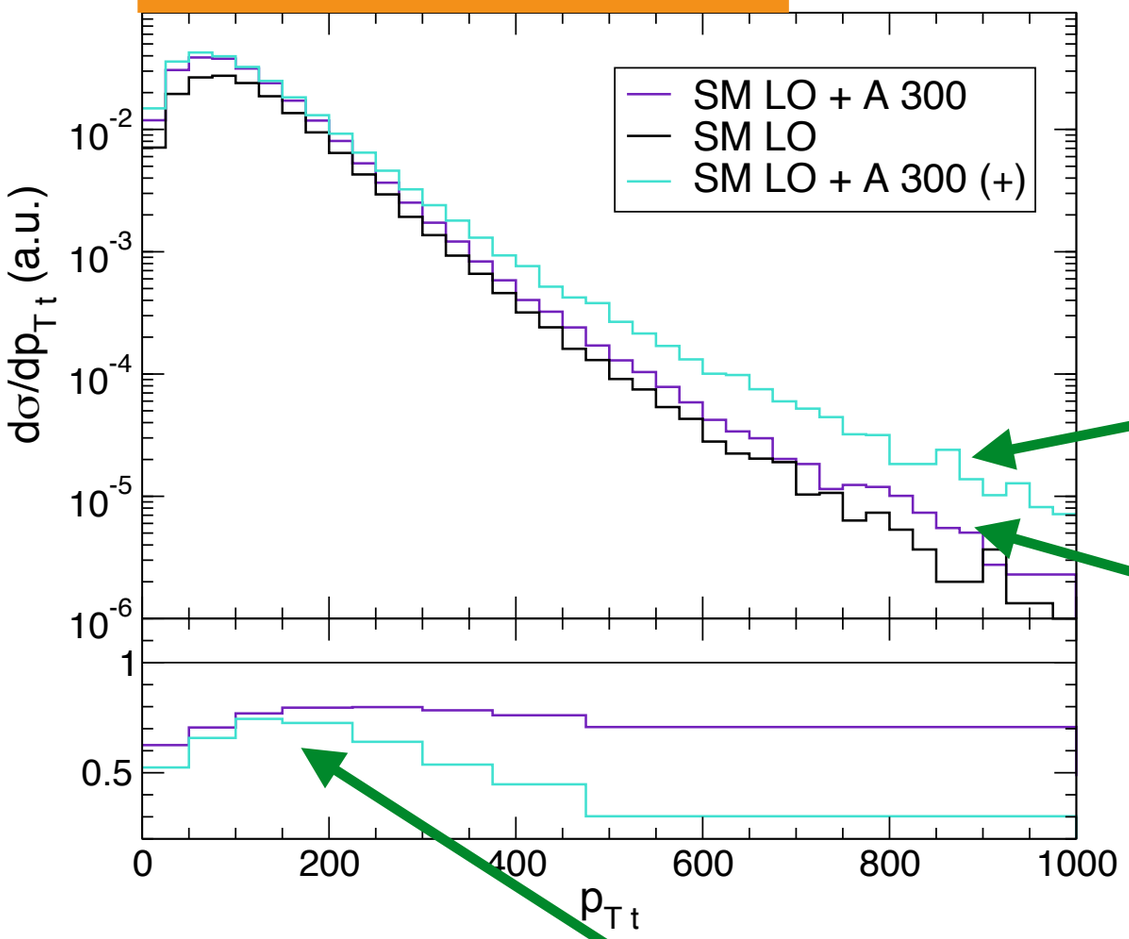
no decrease

Profile depends on normalisation and extrapolation

Similar agreement with ATLAS semileptonic [in backup]

Closer look at p_{Tt}

Absolute cross section

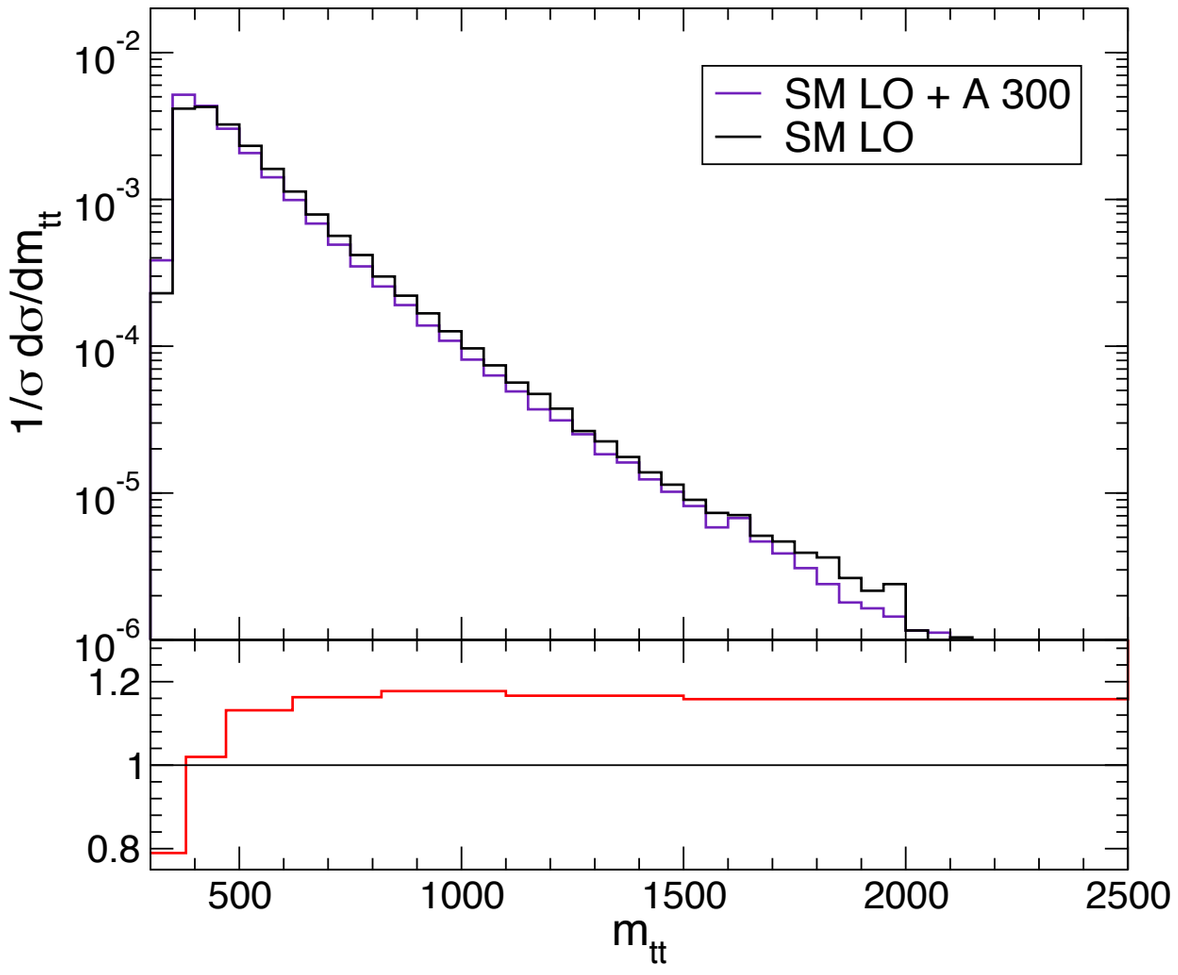


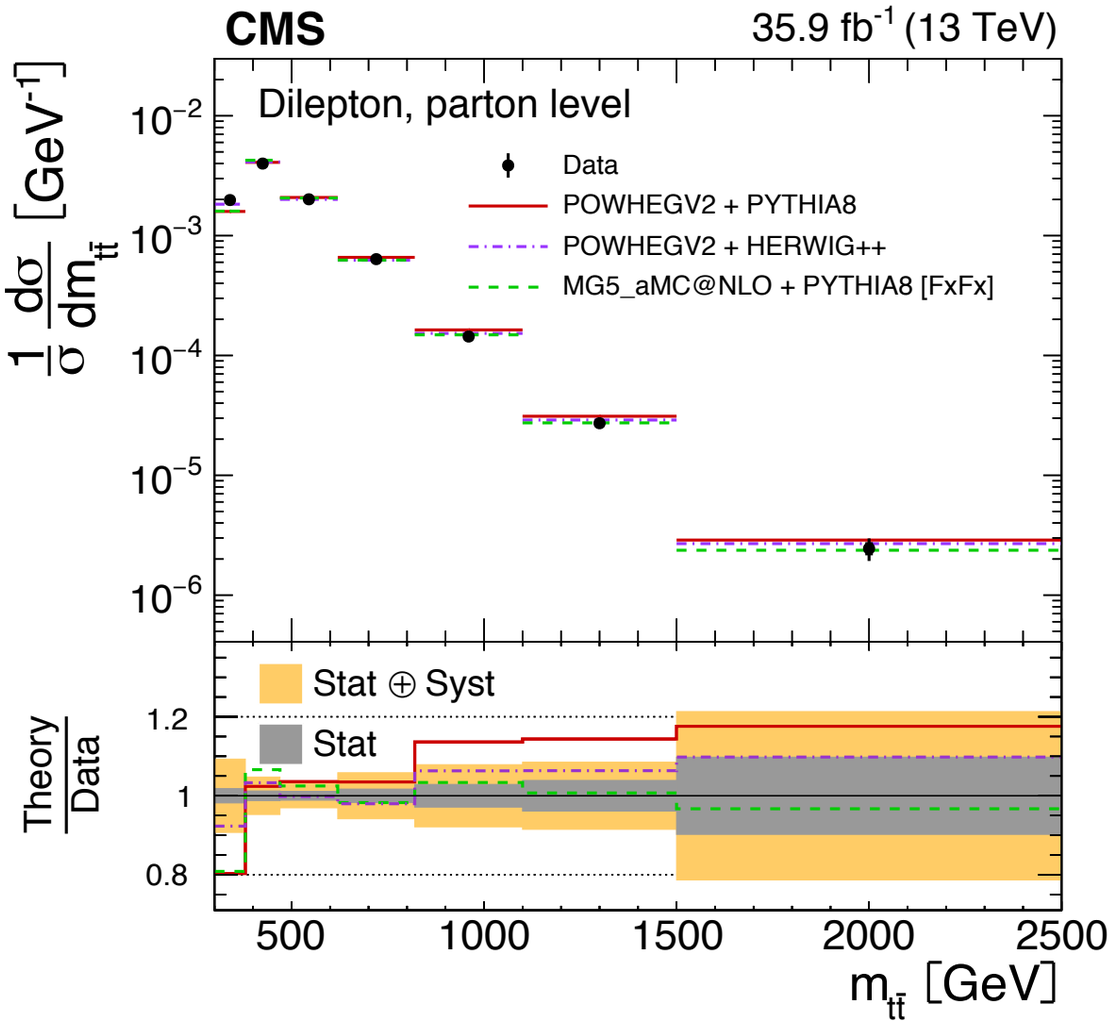
enhanced tail

moderate tail with interference

Interplay of s-channel suppression and Q depencence of coupling?

Closer look at m_{tt}



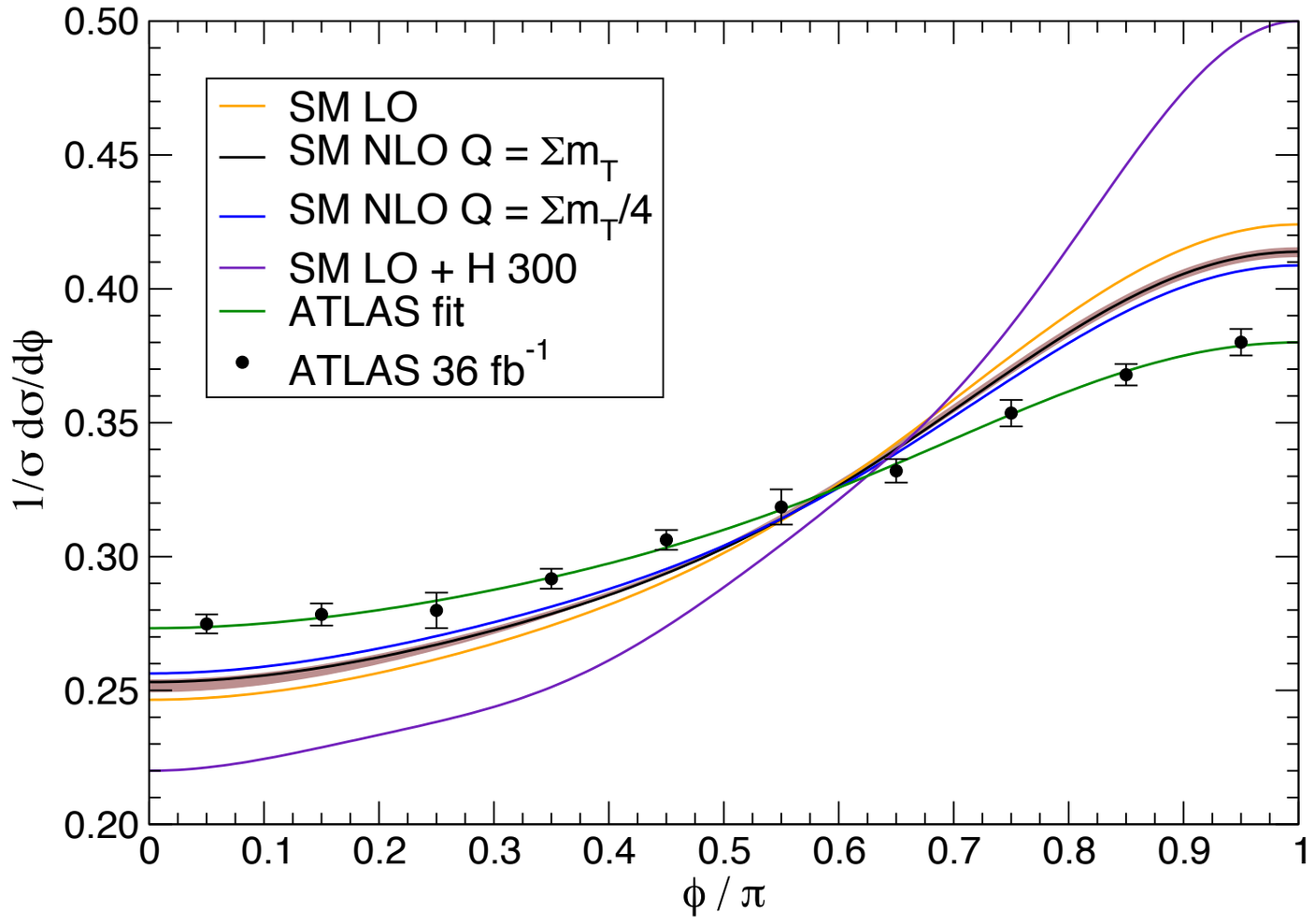


Profile depends on normalisation and extrapolation

Worse agreement with ATLAS semileptonic [in backup]

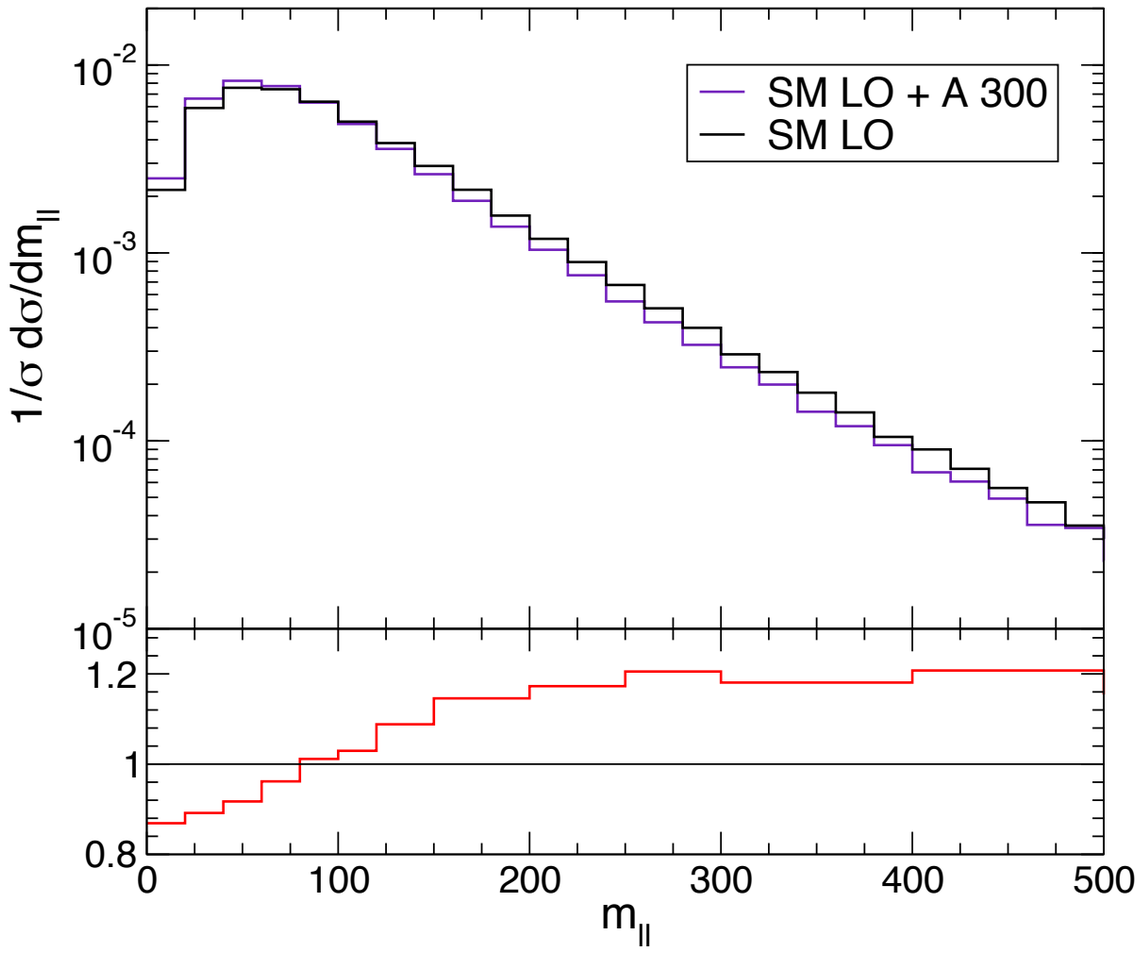
2nd test: scalar *H*

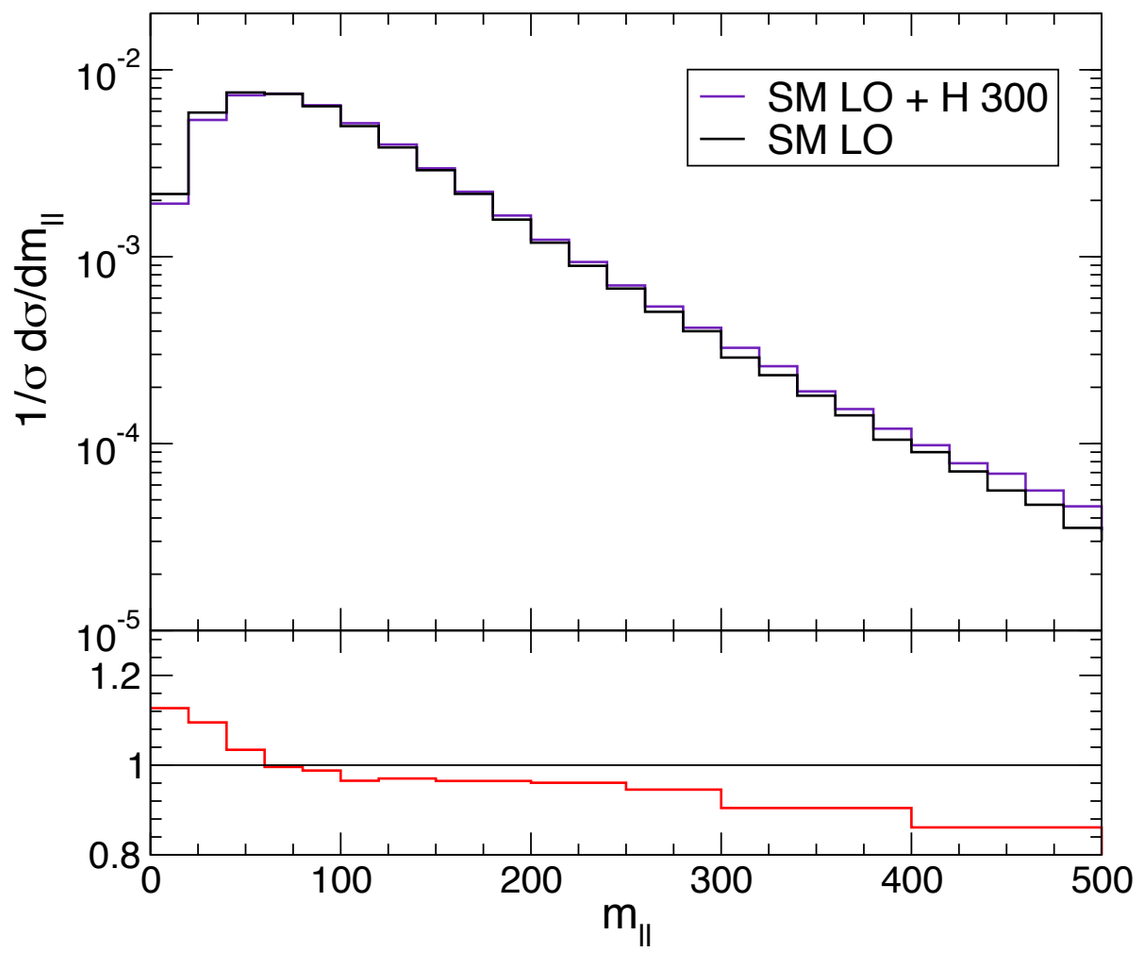
We already know a scalar does not tilt the distribution in the correct direction, but it is illuminating to see how it modifies the other distributions



Benchmark point: *H* with 300 GeV, coupling $c_{gg} \times y_t$ giving the same deviation as *A* 300 GeV in the total cross section

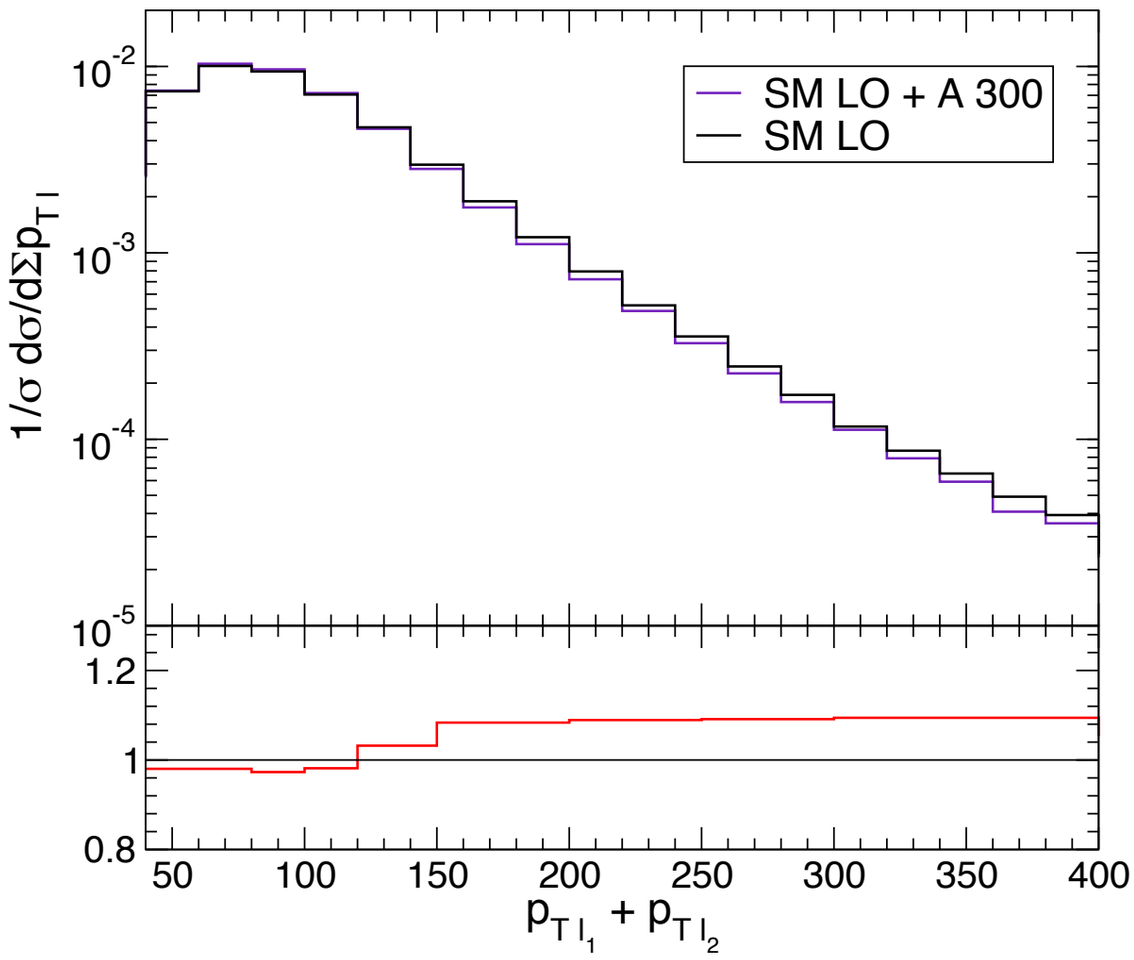
A vs *H*: m_{ll}

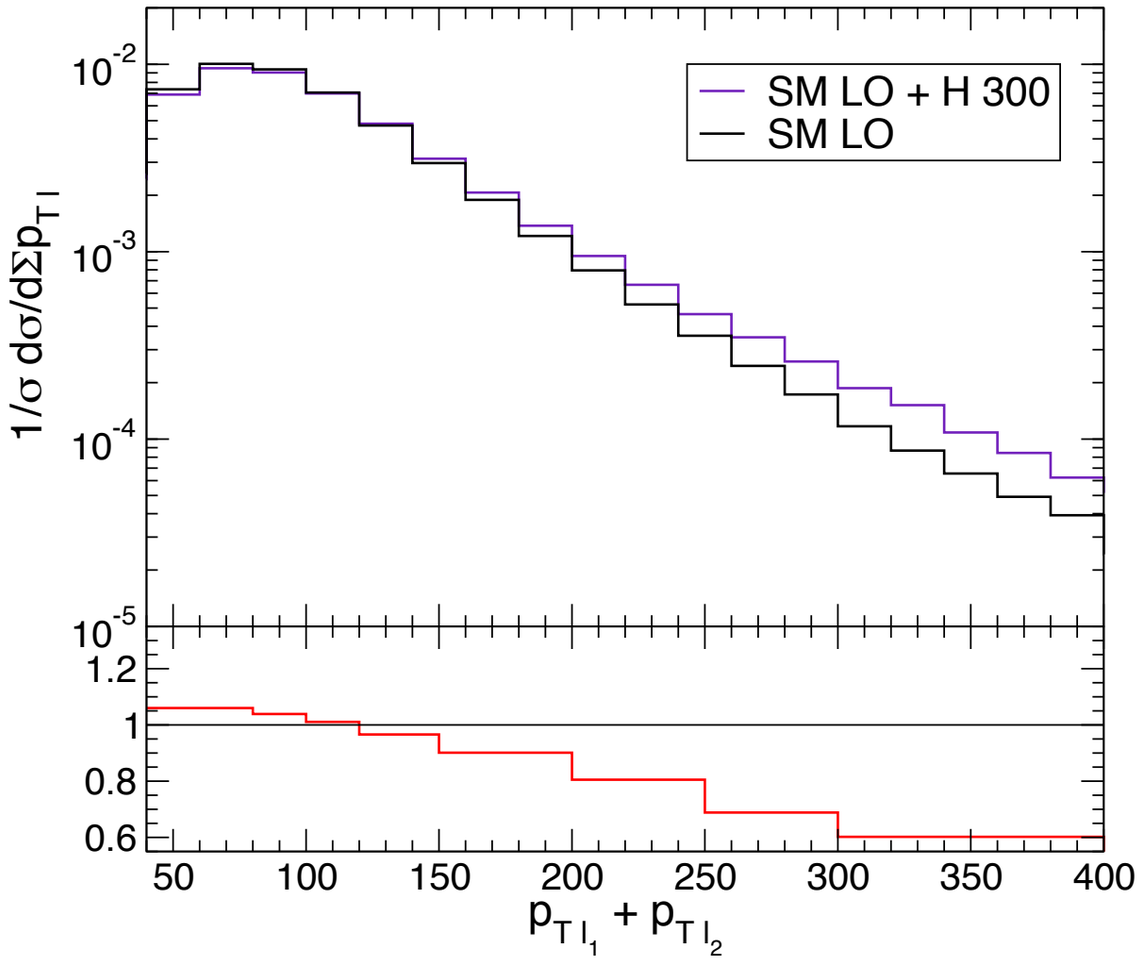




All in the opposite direction, as expected from relation with ϕ

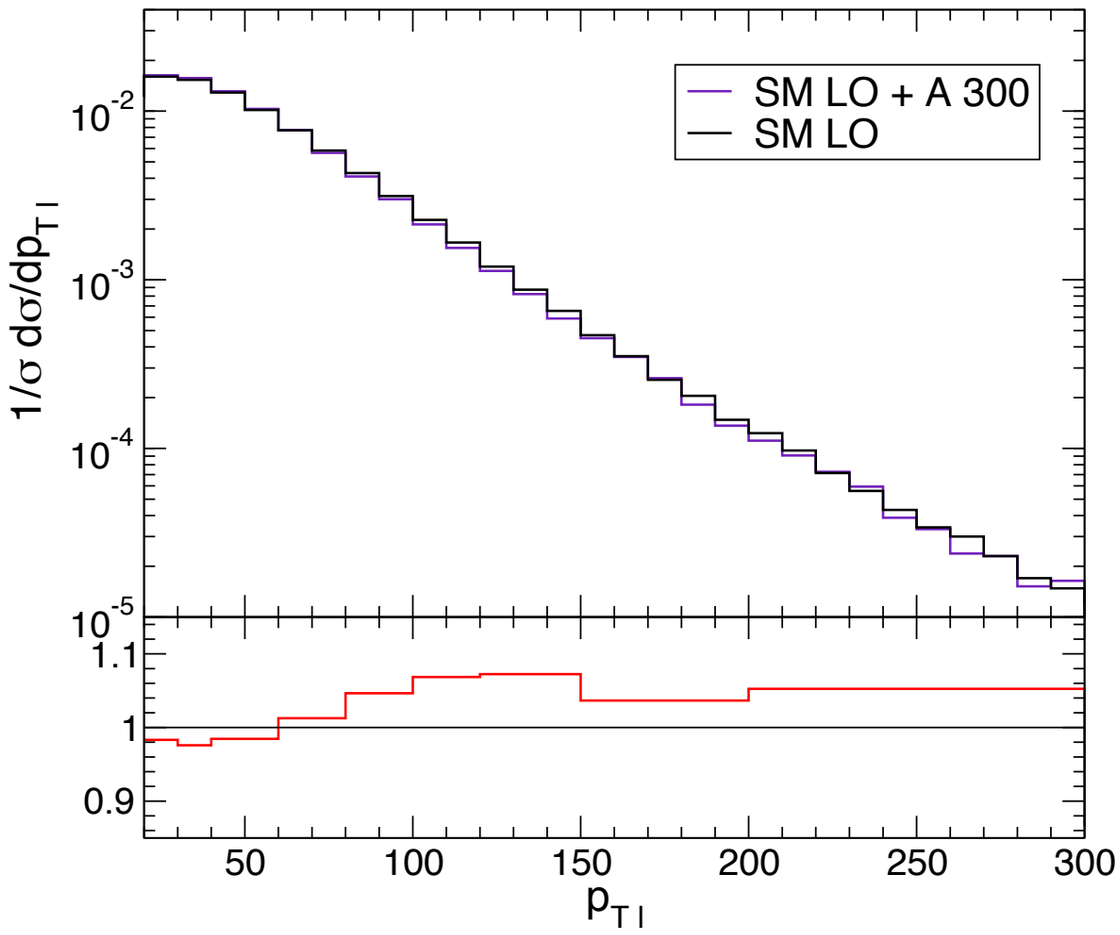
A vs *H*: $\Sigma p_{T\,l}$

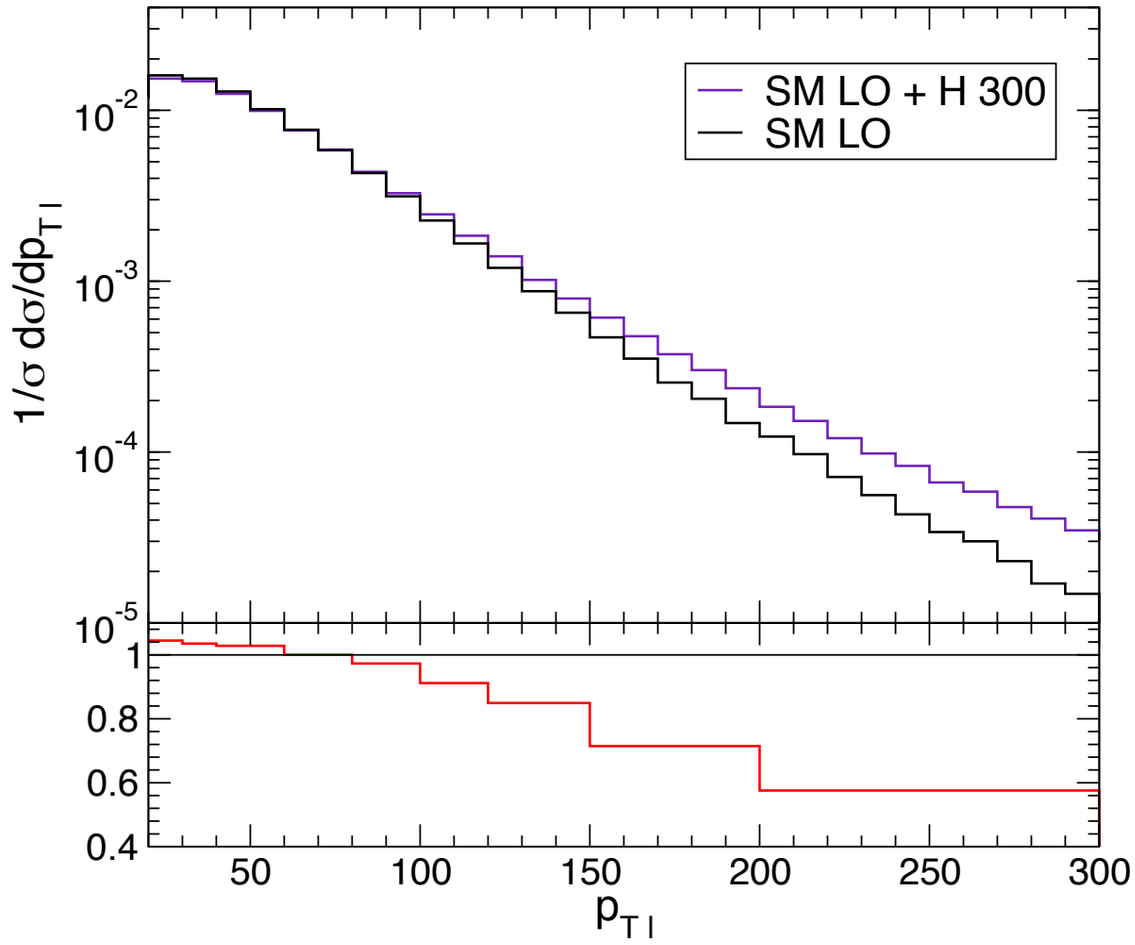




Expected from quadratic $\frac{g_s^2}{M_W} c_{gg} G^a_{\mu\nu} G^{\mu\nu a}$ contribution

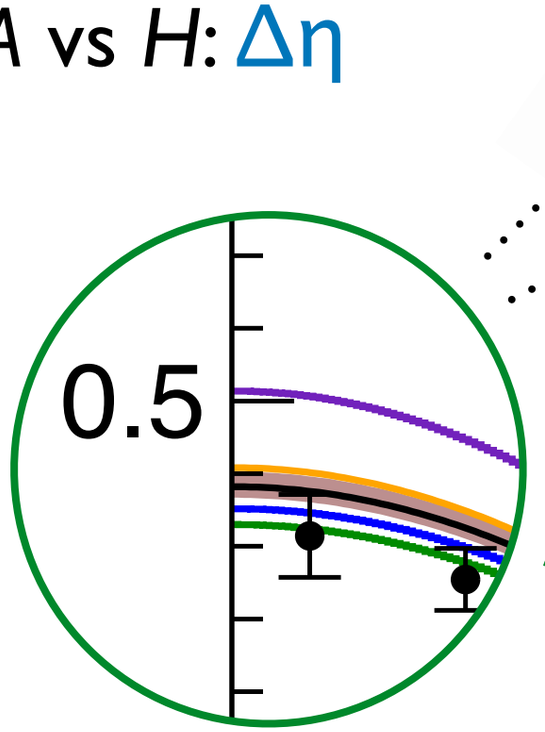
A vs *H*: p_{Tl}



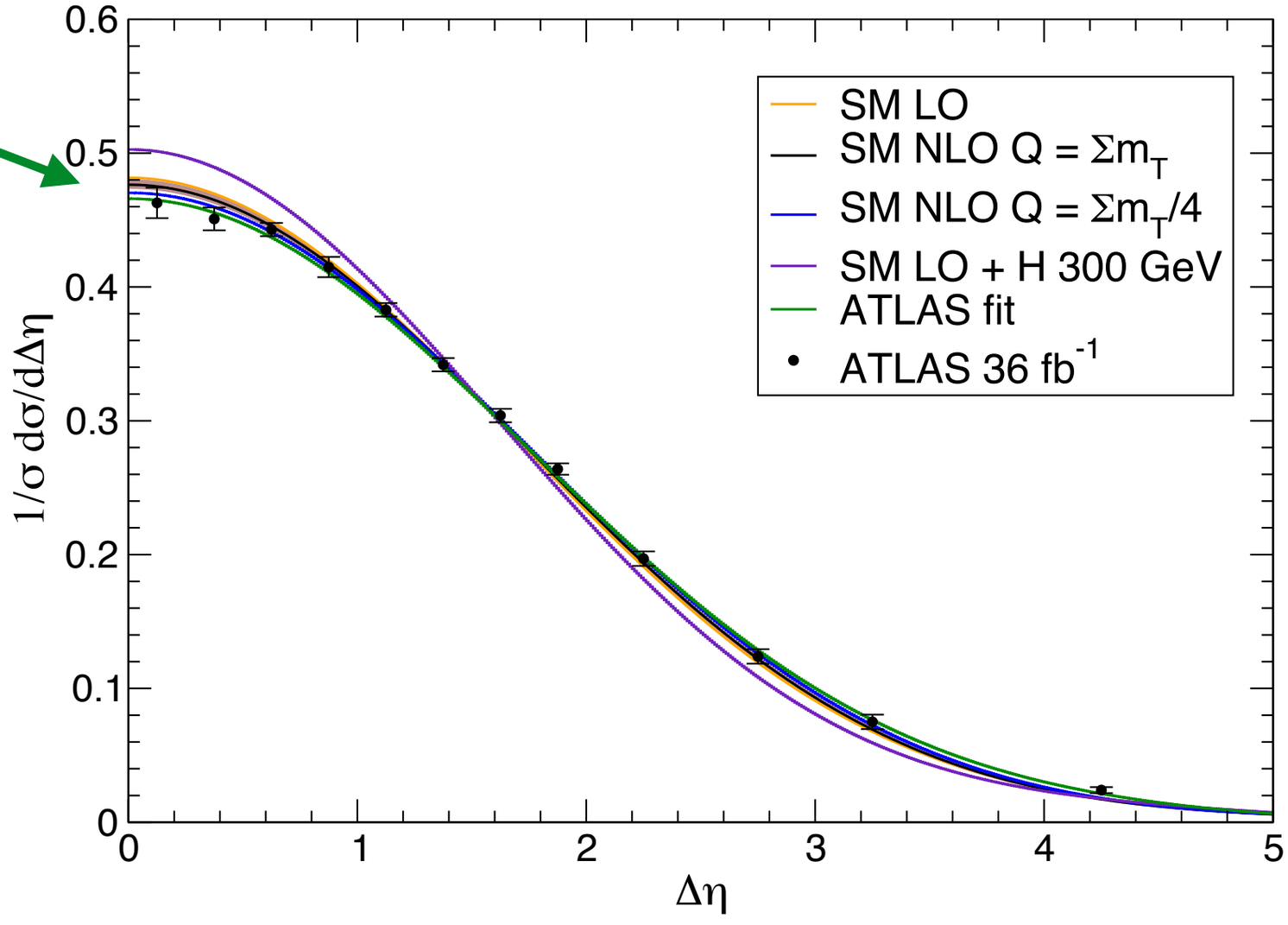


Expected from quadratic $\frac{g_s^2}{M_W} c_{gg} G^a_{\mu\nu} G^{\mu\nu a}$ contribution

A vs *H*: Δη



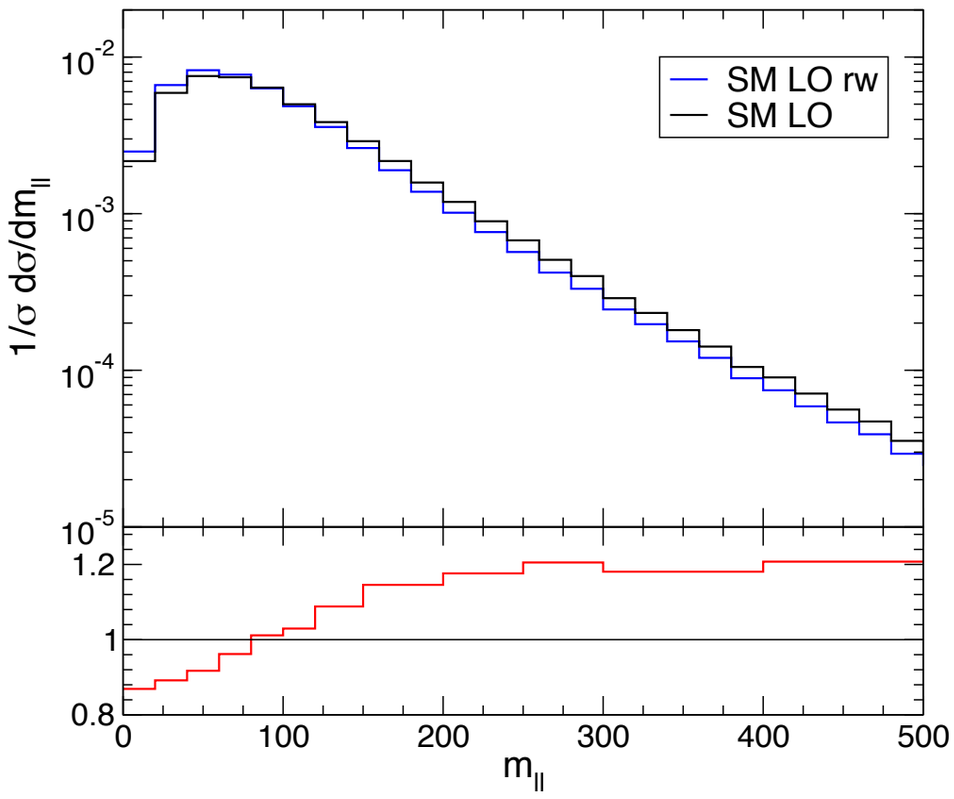
Still!!

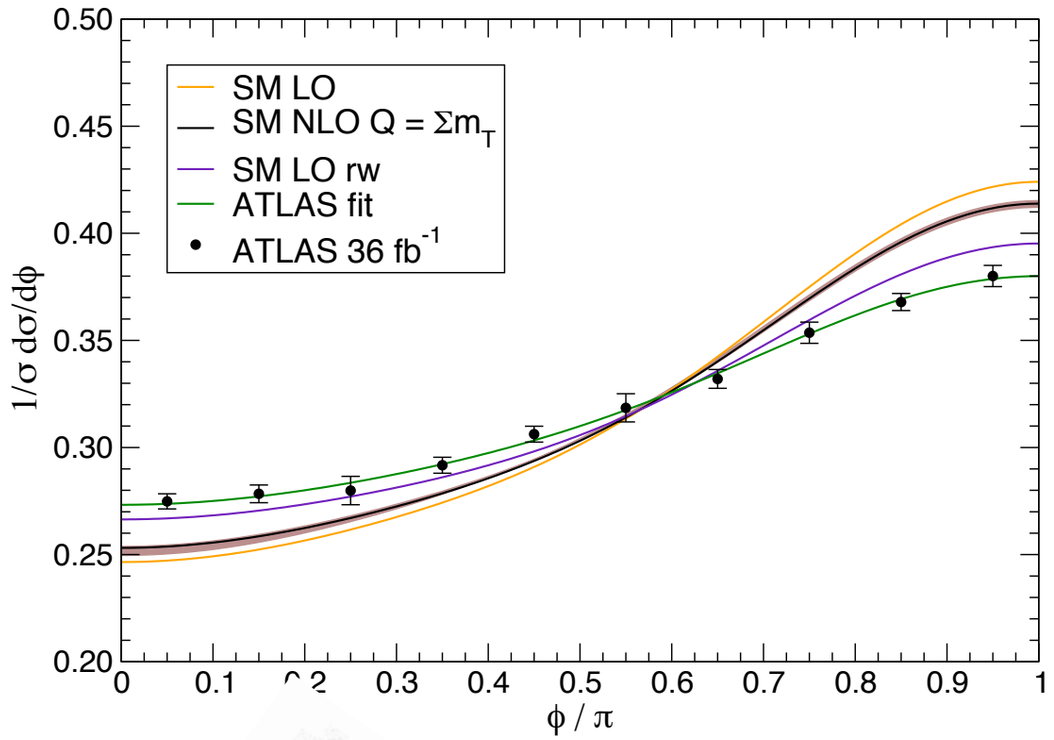


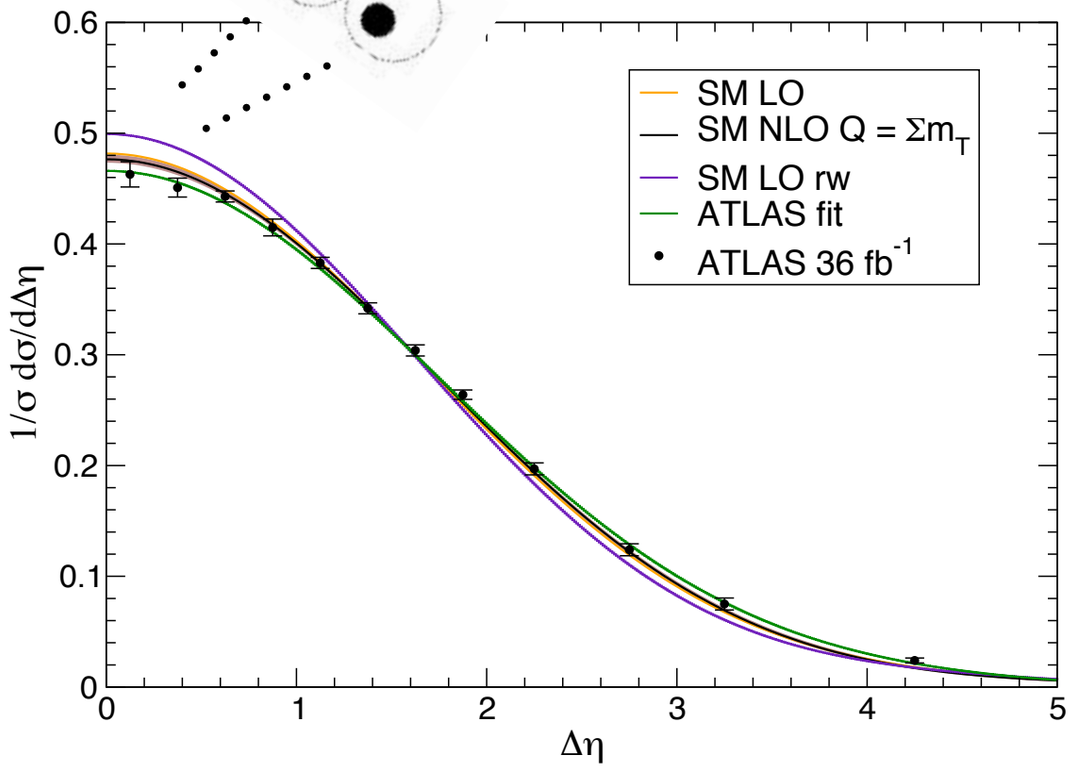
Final test: reweighting the m_{ll} distribution SM LO → A 300

ϕ not recovered

Δη exhibits upward deviation (!!!)







Final words... 1/2

- A light pseudo-scalar in $gg \rightarrow A \rightarrow tt$ that accomodates the ϕ distribution nicely fits several other leptonic distributions: m_{ll} , Σp_{Tl} , p_{Tl} and it's not trivial!

- But it has a problem with $\Delta\eta$.

- The pseudo-scalar agrees with top p_T in ATLAS but not CMS; agrees for m_{tt} in CMS, but not in ATLAS. Needs investigation.

- I have not found any NP that can tilt $\Delta\eta$ counterclockwise [see talk last year].

- Indeed, ϕ and $\Delta\eta$ cannot be reconciled. Fixing the first in any possible way spoils the second [still trying].

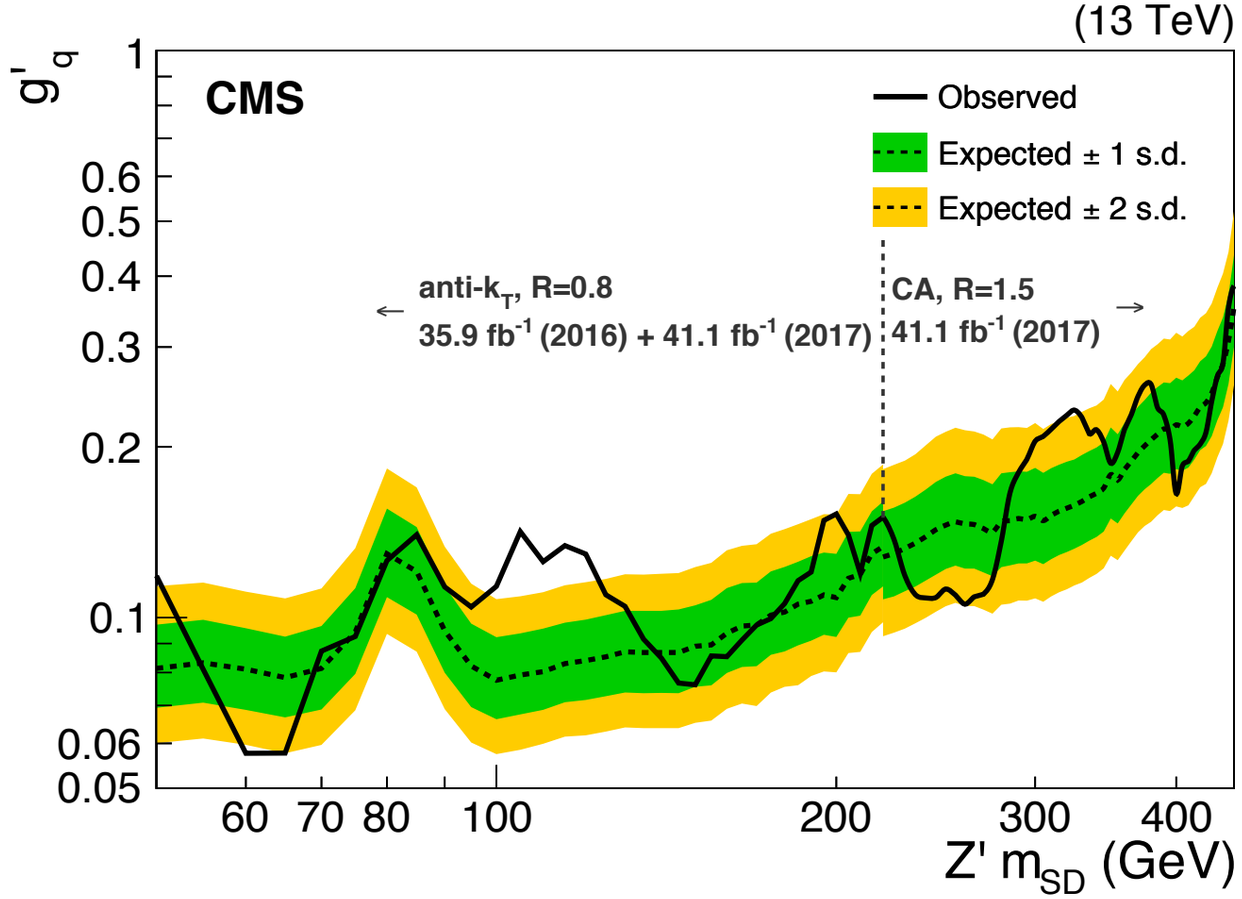
- By the way, it would have been nice to have $\Delta\eta$ from CMS. We are waiting... 🕛🕐🕑🕒🕓🕔🕕🕖🕗🕘🕙🕚🕛

Final words... 2/2

- Model? $c_{gg} \times y_t = -0.0117$ needed is not large; might be generated by extra VLQ.

  For $y_t = 1$, c_{gg} is about 2x the SM top contribution.

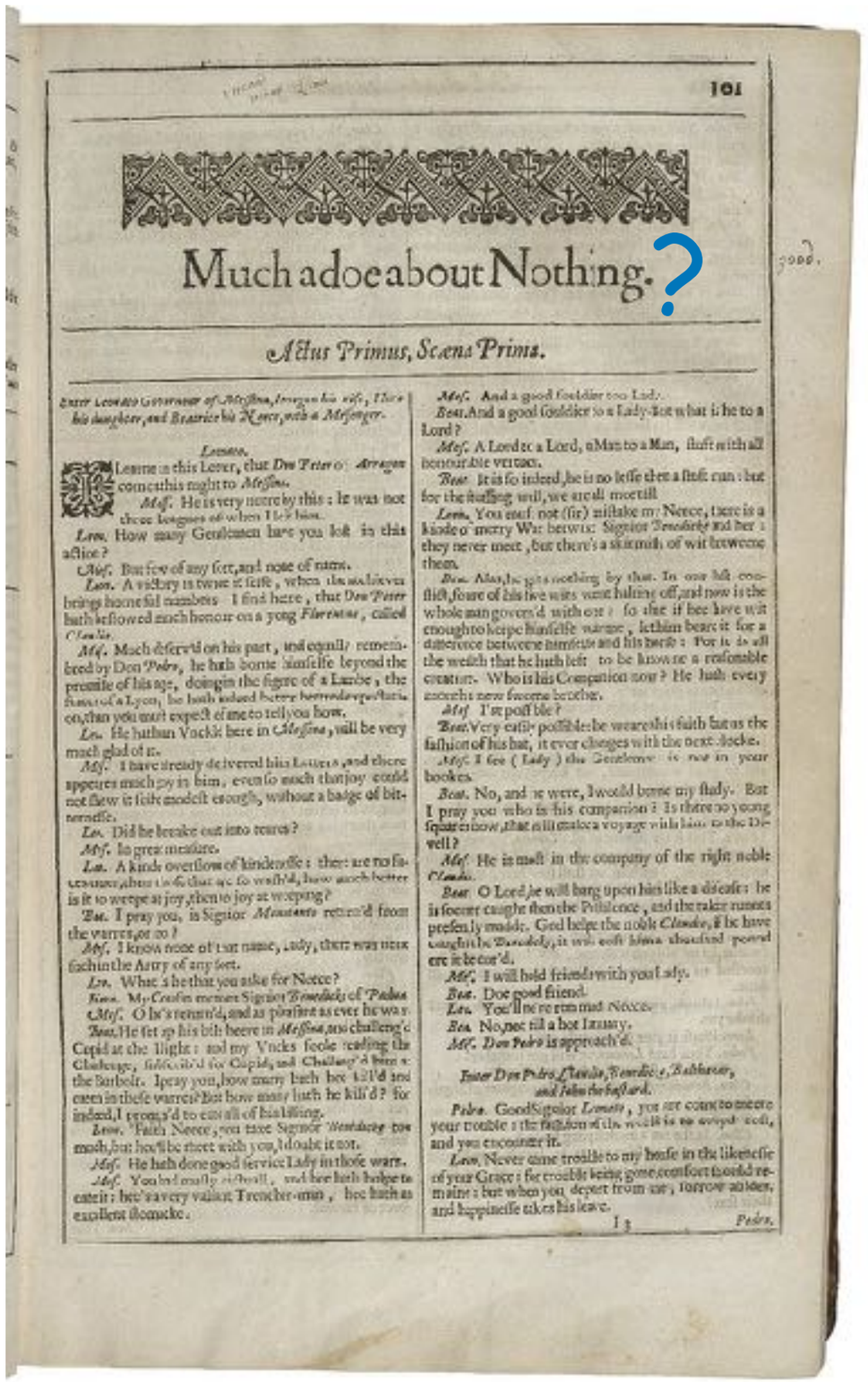
- A pseudo-scalar with this coupling can be probed in associated production with a jet.



Final words...3/2

- A light pseudo-scalar in $uu \to A \to tt$ may also fit ϕ (and spoil $\Delta\eta$) [see my talk last year]
- But the effect in leptonic distributions does not agree with data. No negative interference.
- Also, the model needs huge Yukawa couplings $y_u \times y_t = 1.7$ (!) which does not seem reasonable.

Conclusion



101

Much adoe about Nothing.?

Actus Primus, Scæna Prima.

Enter Leonato Governour of Messina, Innogen 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*.

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

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

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

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

Mes. 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 indued strange heartinesse: you must expect of me to tell you how.

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

Mes. 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?

Mes. In great measure.

Leo. A kinde overflow of kindnesse: there are no faces truer, than those that are so washt. How much better is it to weepe at joy, than to joy at weeping?

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

Mes. 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 means Signior *Benedick* of *Padua*.

Mes. O he's returned, and as pleasant as ever he was.

Bea. He set up his bils here in *Messina*, and challeng'd Cupid at the Flight: and my Vncles foole reading the Challenge, subscribed for Cupid, and Challeng'd him at the Burbolt. I pray you, how many hath he 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.

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

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

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

Mes. And a good Souldier too Lady.

Bea. And a good Souldier to a Lady: but what is he to a Lord?

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

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

Leo. You must not (sir) mistake my Neece, there is a kinde of merry War betwixt Signior *Benedick* and her: they never meet, but there's a skirmish of wit between 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 he 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 known a reasonable creature. Who is his Companion now? He hath every moneth a new sworne brother.

Mes. Is't possible?

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

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

Bea. No, and if 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?

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

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

Mes. I will hold friends with you Lady.

Bea. Do good friend.

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

Bea. No, not till a hot January.

Mes. Don Pedro is approach'd.

Enter Don Pedro, Claudio, Benedick, Balthasar, 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.

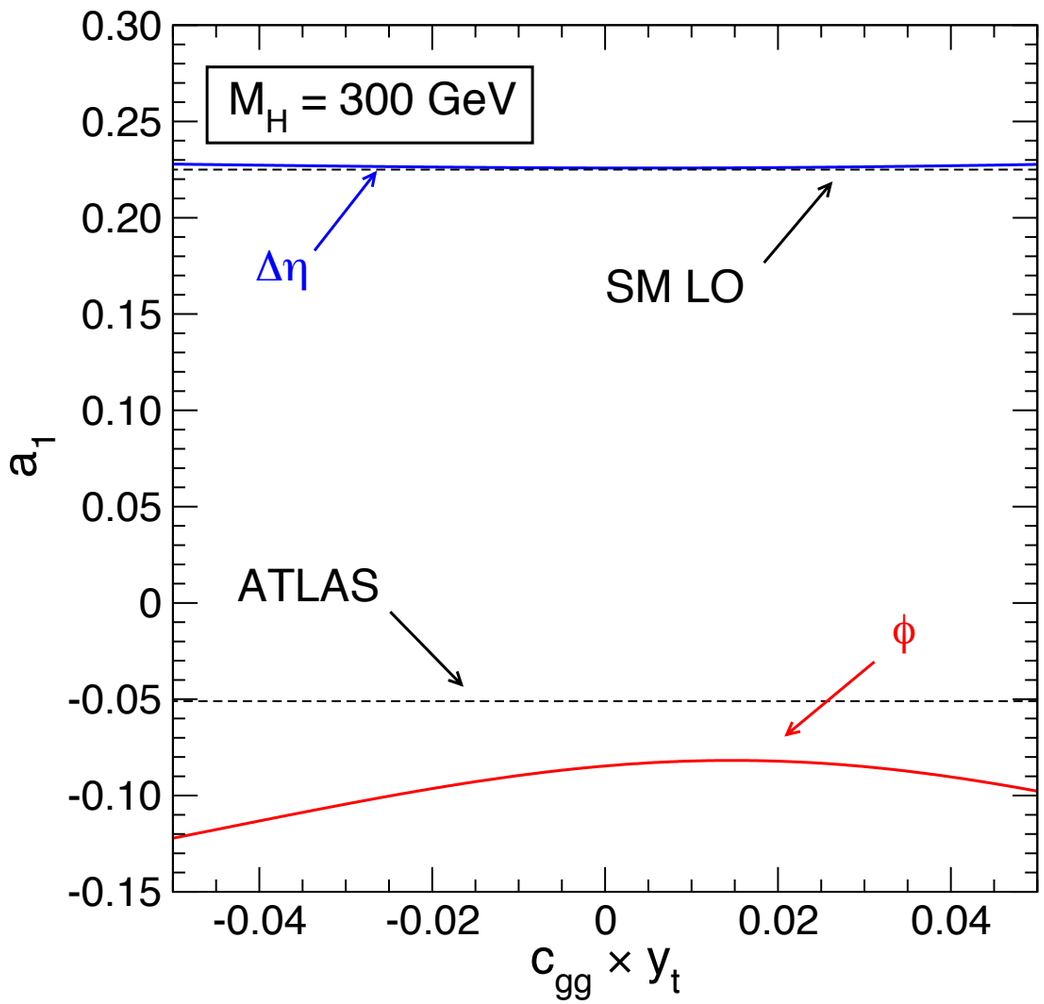
Leon. Never came trouble to my house in the likenesse of your Grace: for trouble being gone, comfort should remaine: but when you depart from me, sorrow abides, and happinesse takes his leave.

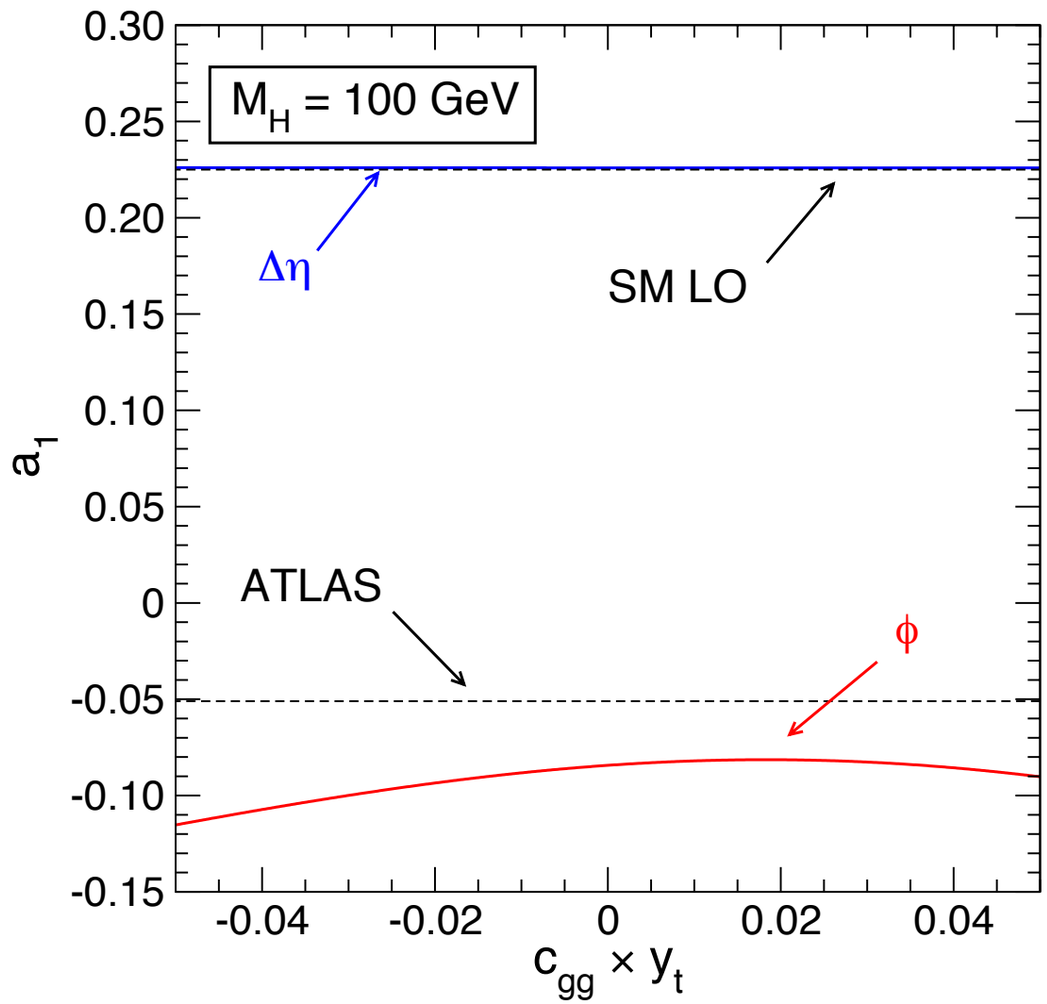
Maybe not!

Extra!

Scalar in s channel

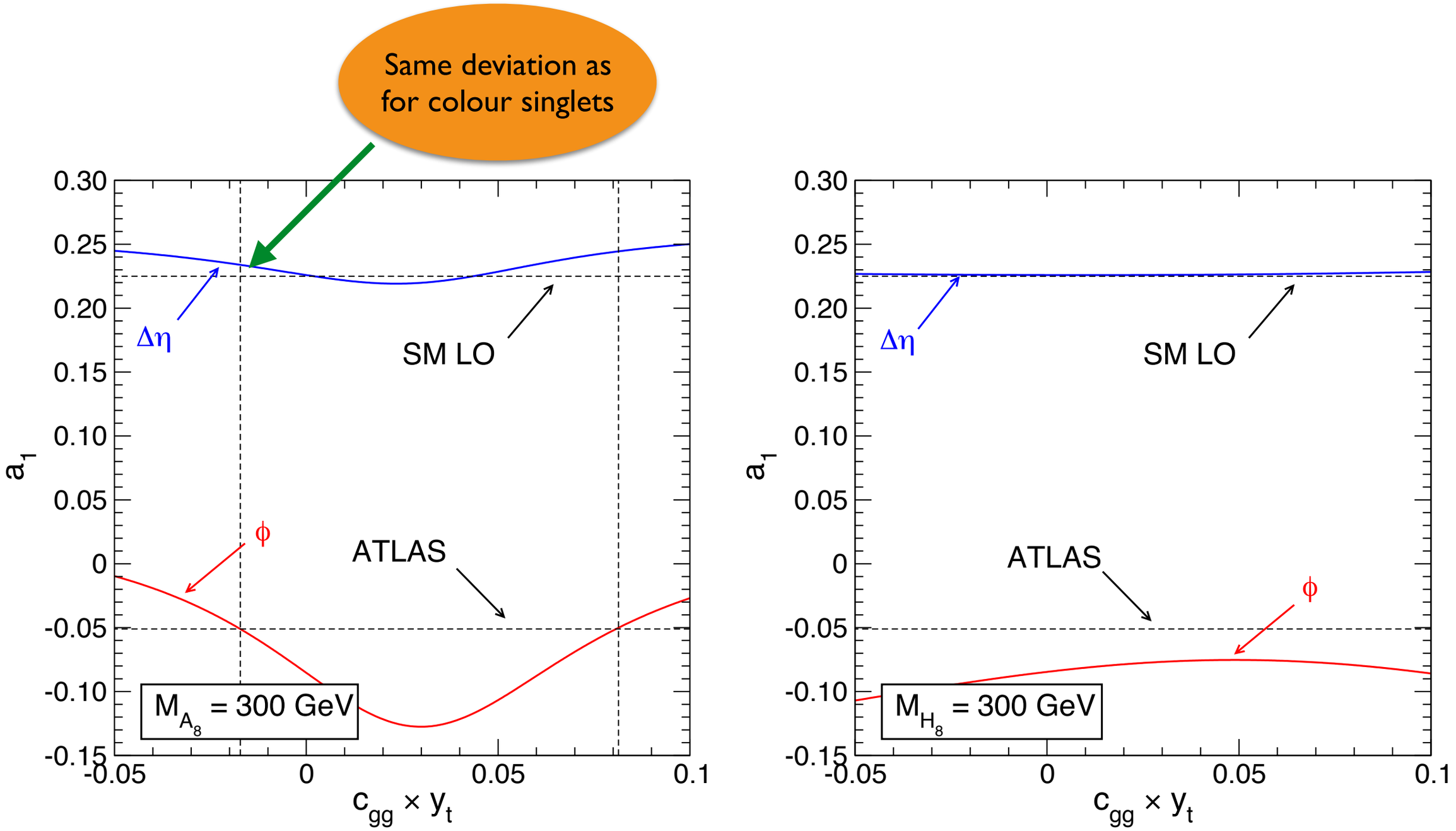
The effect in ϕ is basically in the opposite direction as desired, despite the fact that a scalar produces top pairs with opposite helicities…





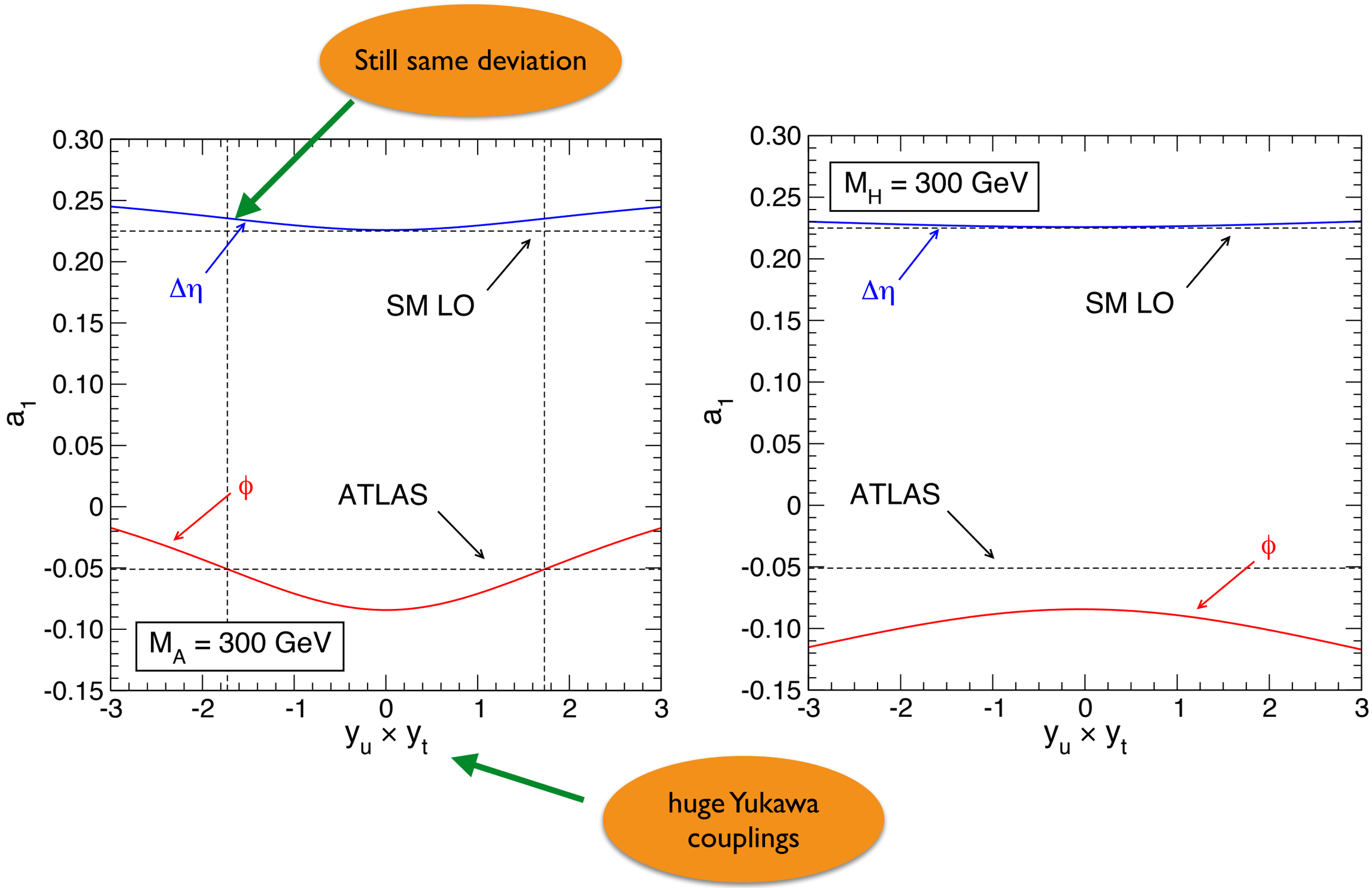
Going coloured

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



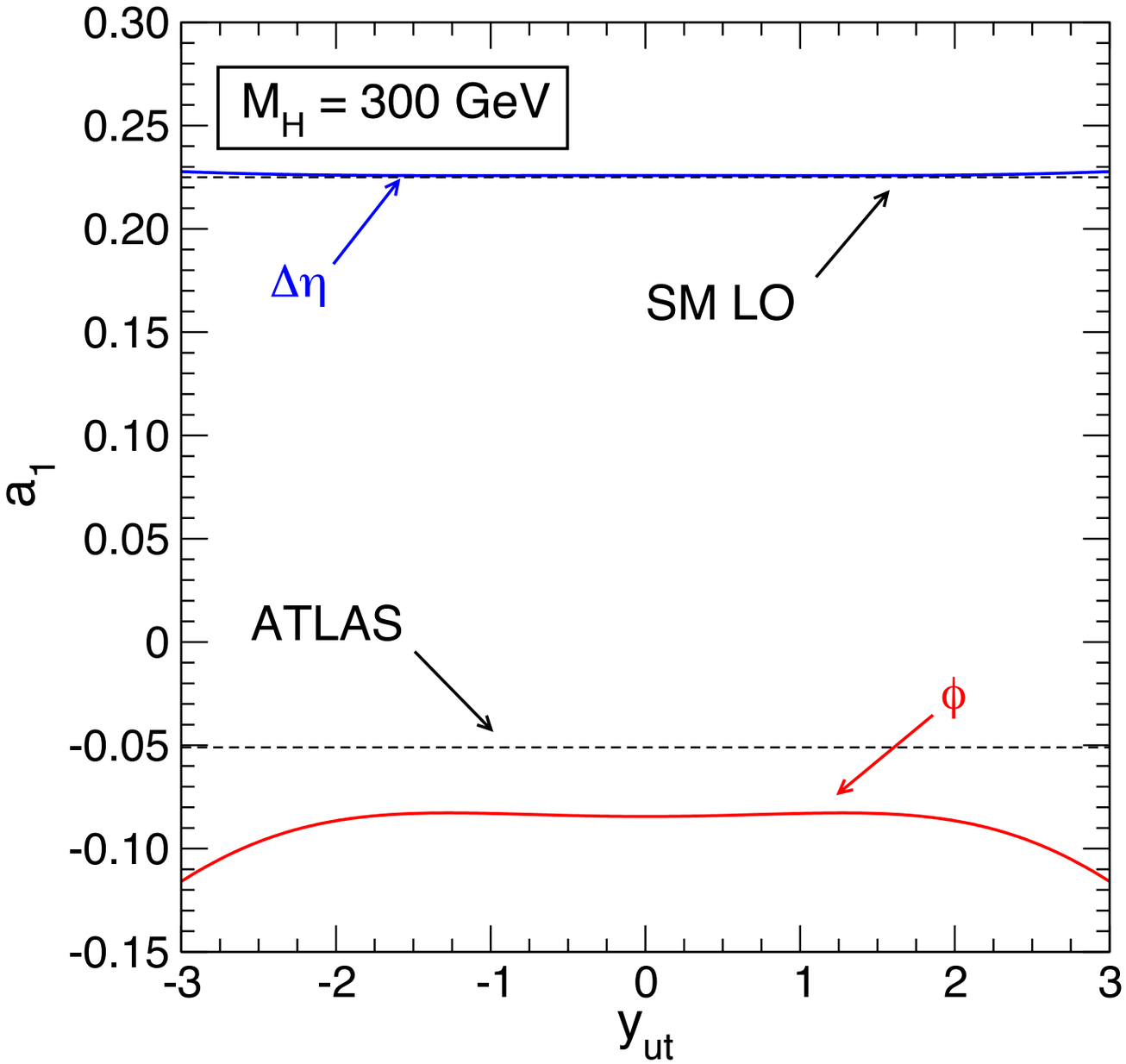
(Pseudo-)scalars in uu → tt

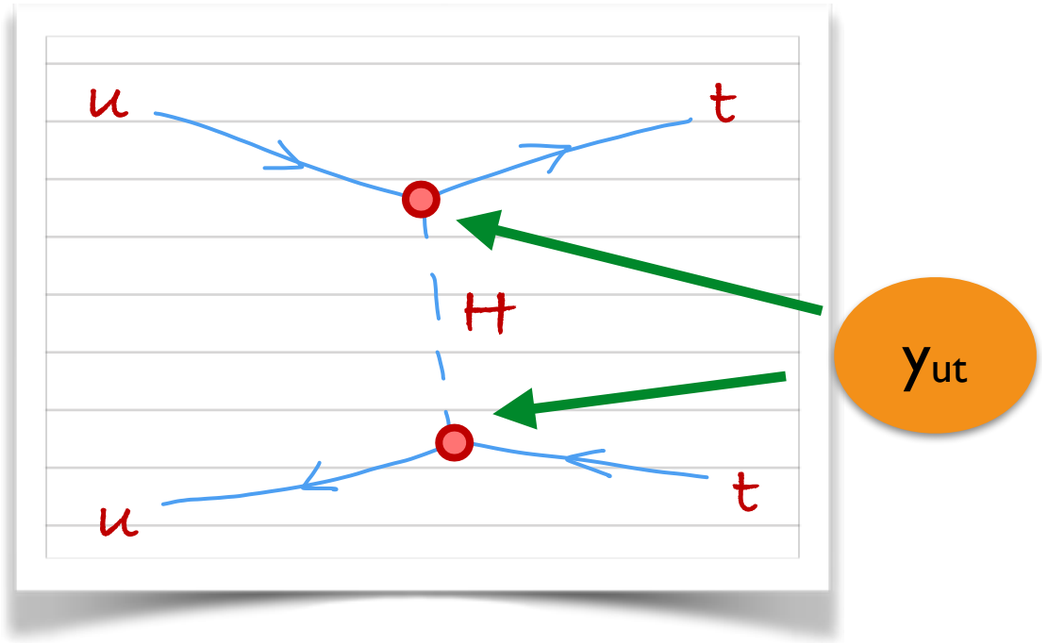
For this improbable possibility the behaviour is still the same



Flavour-changing scalars

This even more improbable possibility would not work either…

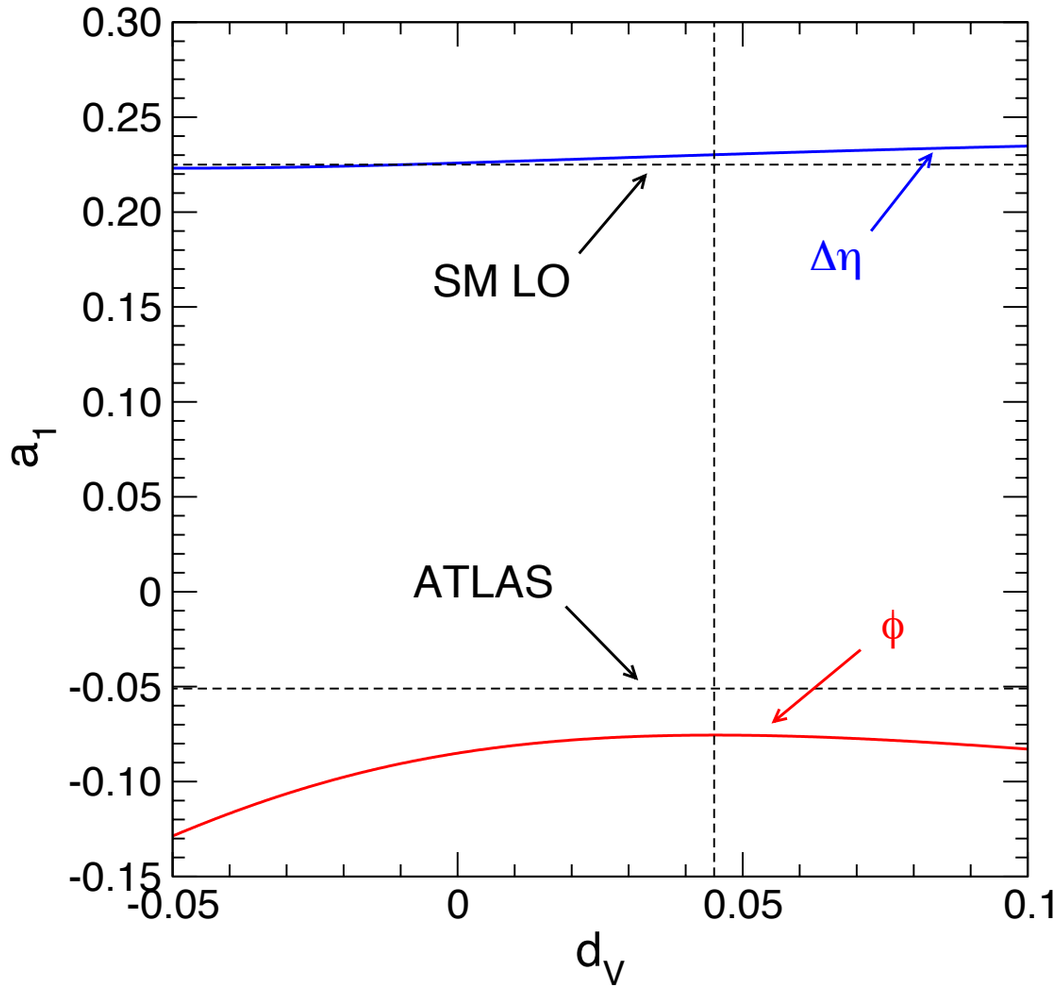


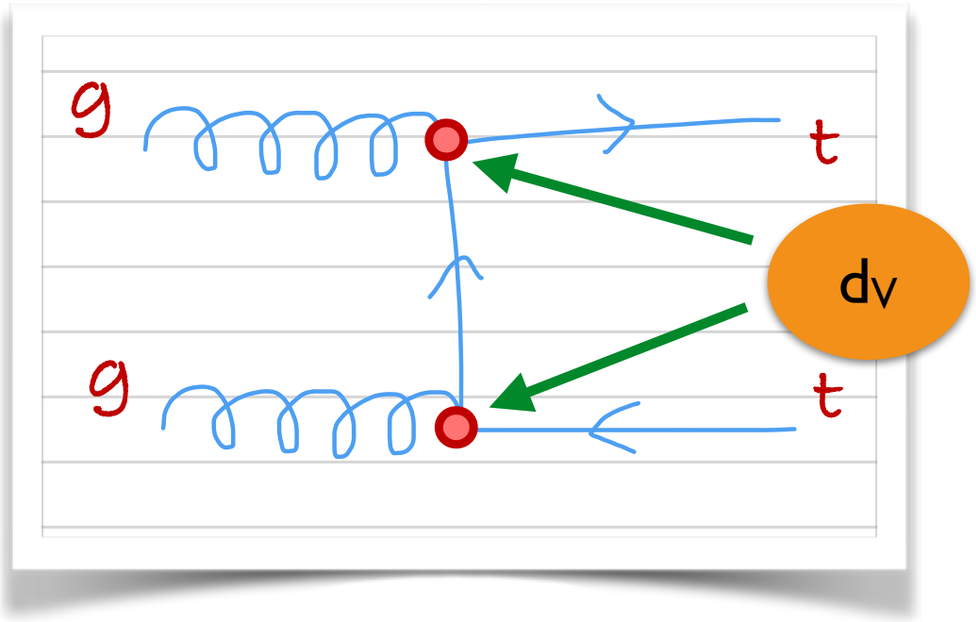


Top chromomagnetic moment

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?]



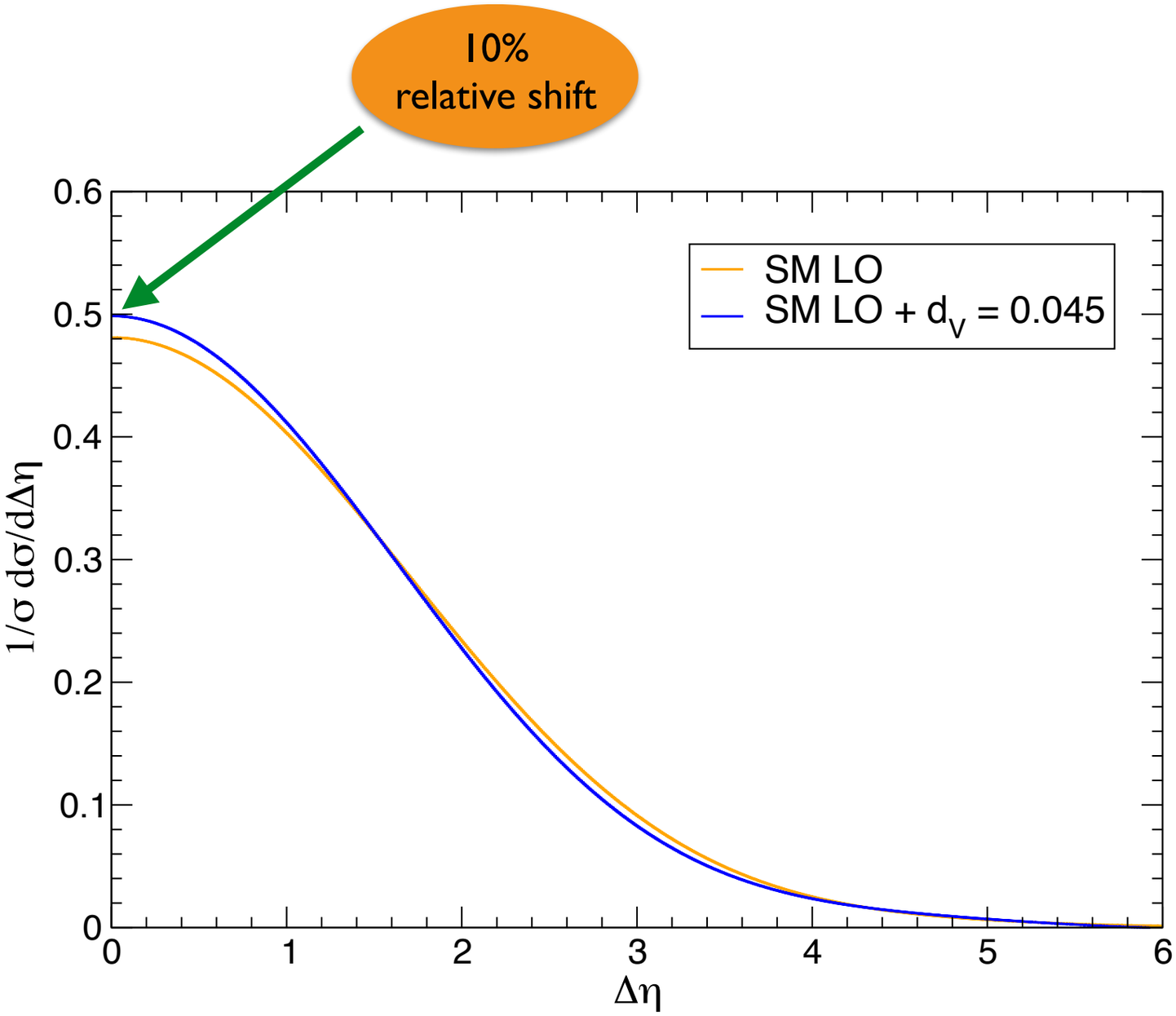


Amplitude contains terms up to d_V^2

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.



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
C_{kk}	0.33	0.52	0.61	
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definitely related to C_{nn}

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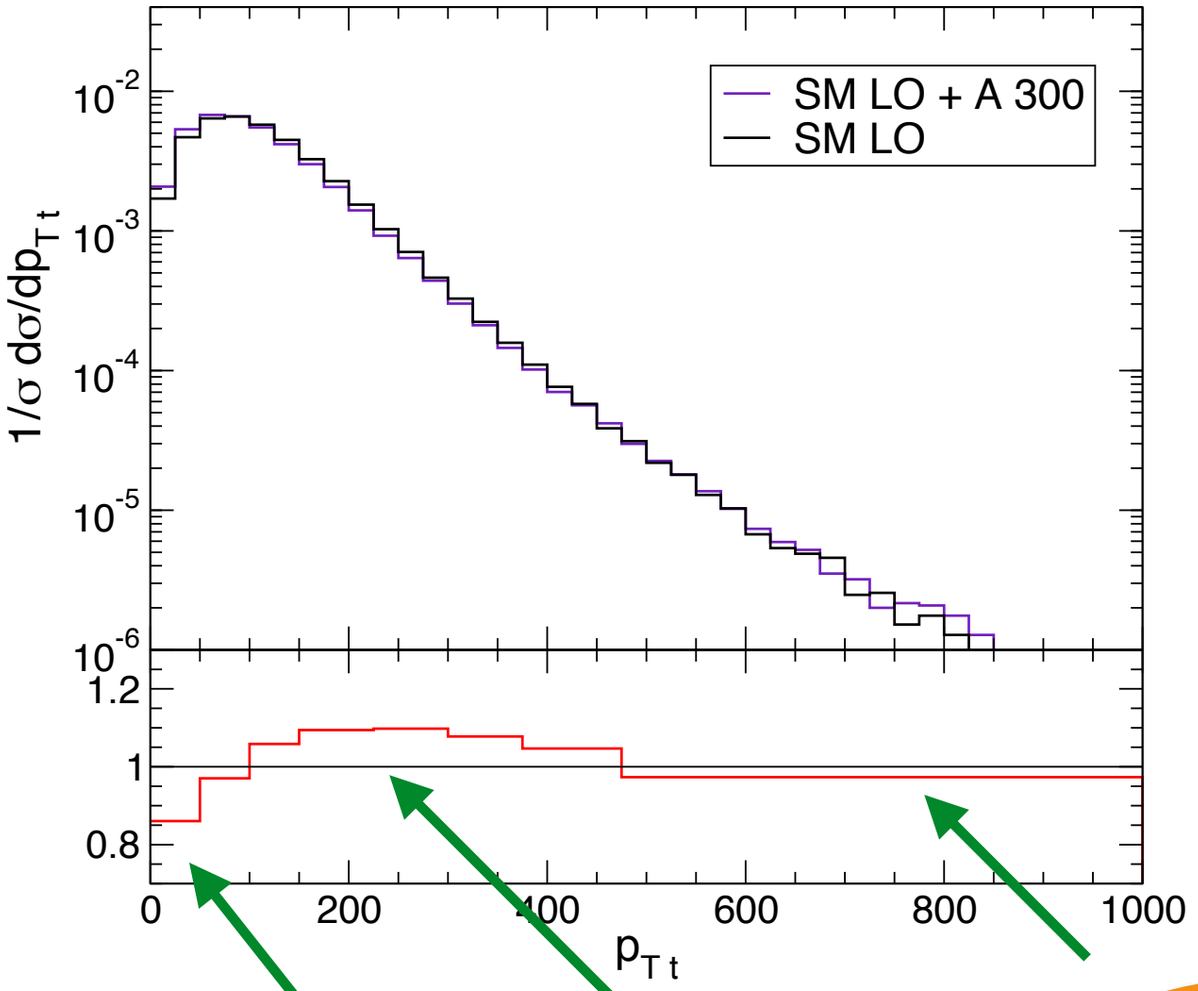
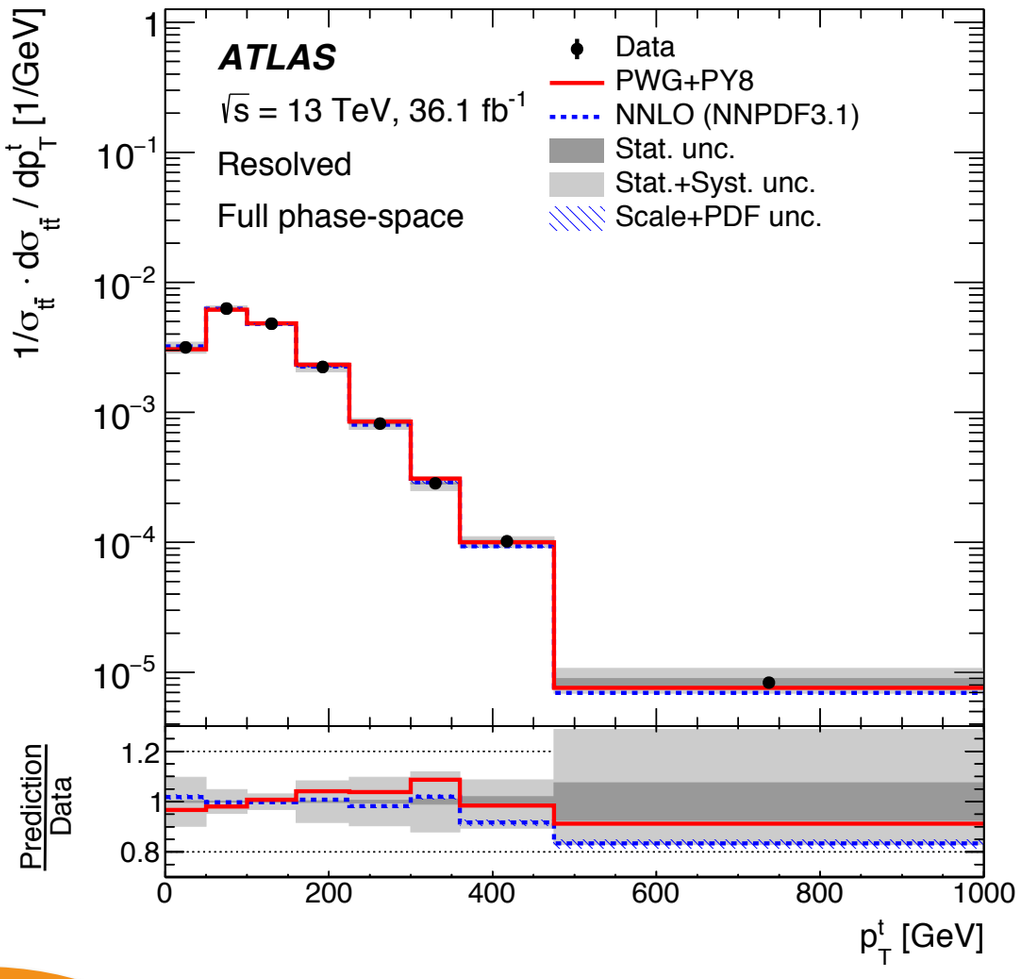
Closer look at p_{Tt}



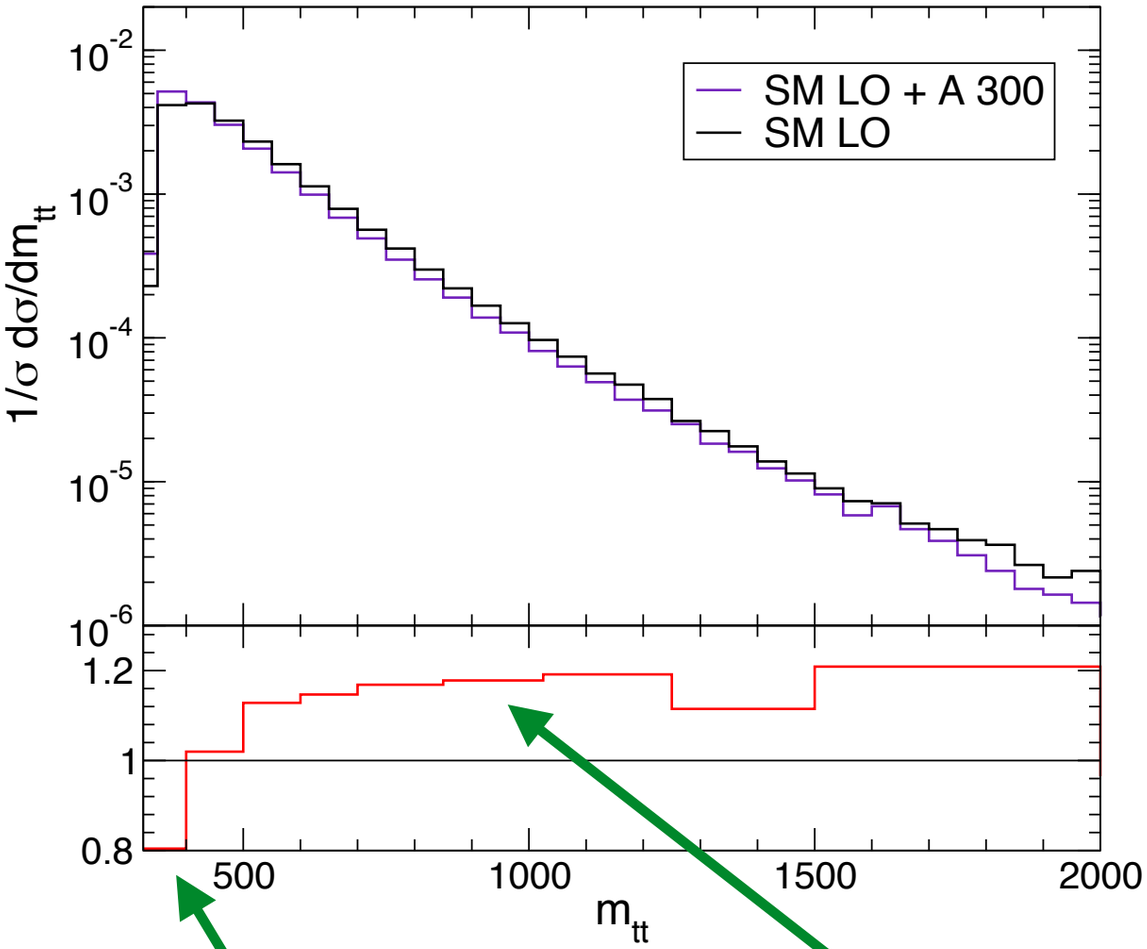


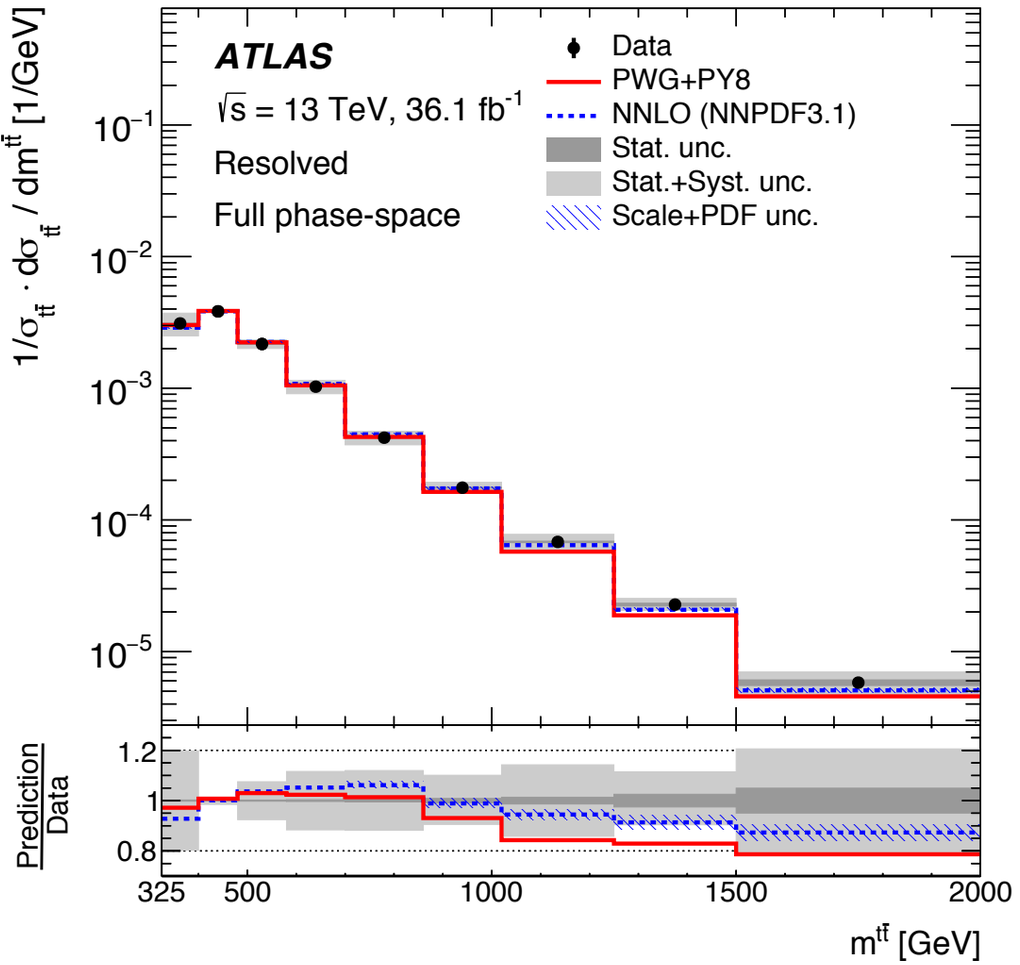
relative decrease

relative enhancement

This bin is too low, need to investigate acceptance / reconstruction issues

Closer look at m_{tt}





No turnover, maybe related to deviation in 1st bin and overall normalisation

This bin is too low, need to investigate acceptance / reconstruction issues