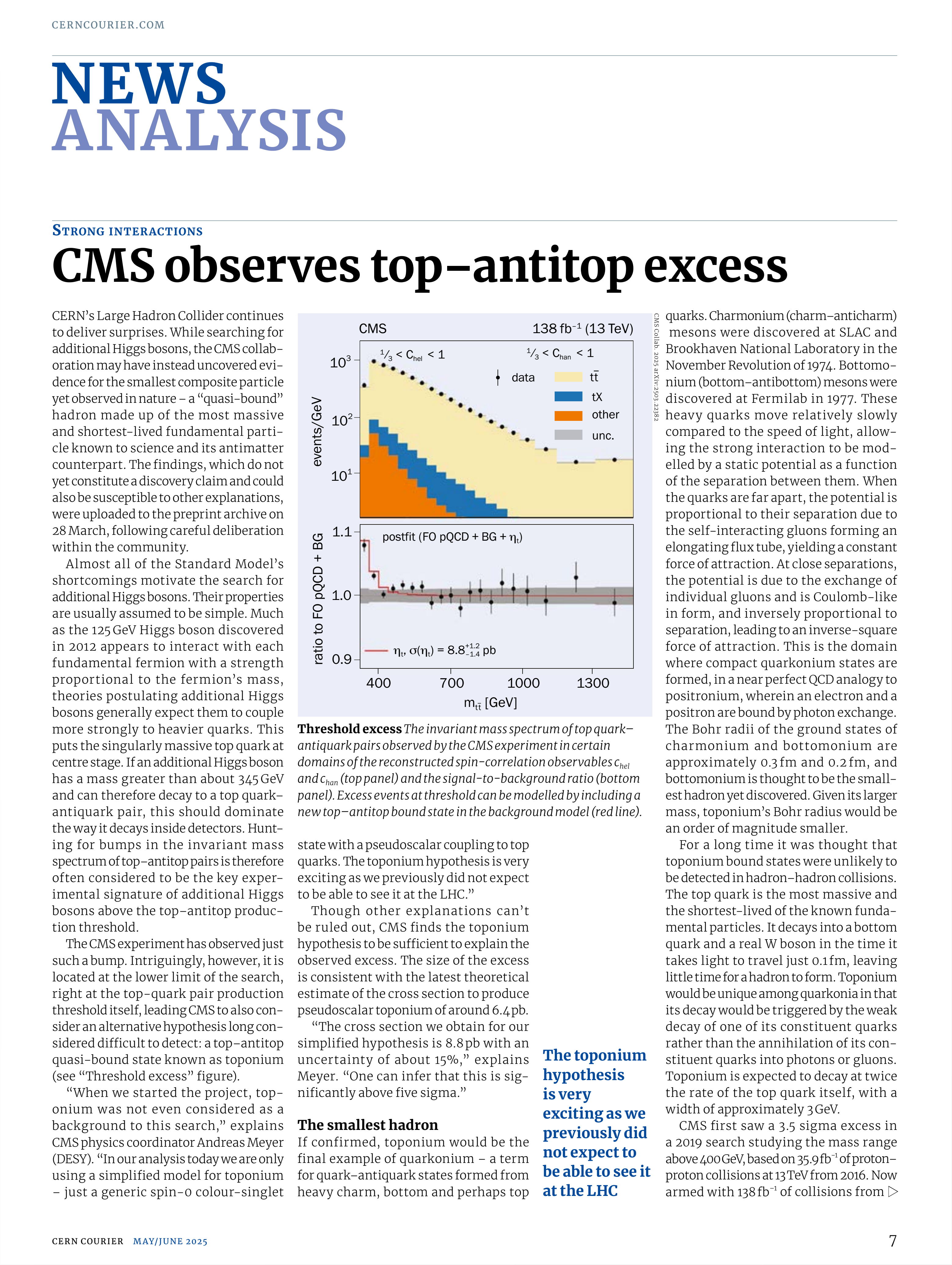
Top pair production near threshold at the LHC

Luca Rottoli

Largely based on 2505.00096 in collaboration with P. Nason and E. Re



NEWS ANALYSIS

Strong interactions

CMS observes top–antitop excess

CERN’s Large Hadron Collider continues to deliver surprises. While searching for additional Higgs bosons, the CMS collaboration may have instead uncovered evidence for the smallest composite particle yet observed in nature – a “quasi-bound” hadron made up of the most massive and shortest-lived fundamental particle known to science and its antimatter counterpart. The findings, which do not yet constitute a discovery claim and could also be susceptible to other explanations, were uploaded to the preprint archive on 28 March, following careful deliberation within the community.

Almost all of the Standard Model’s shortcomings motivate the search for additional Higgs bosons. Their properties are usually assumed to be simple. Much as the 125 GeV Higgs boson discovered in 2012 appears to interact with each fundamental fermion with a strength proportional to the fermion’s mass, theories postulating additional Higgs bosons generally expect them to couple more strongly to heavier quarks. This puts the singularly massive top quark at centre stage. If an additional Higgs boson has a mass greater than about 345 GeV and can therefore decay to a top quark–antiquark pair, this should dominate the way it decays inside detectors. Hunting for bumps in the invariant mass spectrum of top–antitop pairs is therefore often considered to be the key experimental signature of additional Higgs bosons above the top–antitop production threshold.

The CMS experiment has observed just such a bump. Intriguingly, however, it is located at the lower limit of the search, right at the top-quark pair production threshold itself, leading CMS to also consider an alternative hypothesis long considered difficult to detect: a top–antitop quasi-bound state known as toponium (see “Threshold excess” figure).

“When we started the project, toponium was not even considered as a background to this search,” explains CMS physics coordinator Andreas Meyer (DESY). “In our analysis today we are only using a simplified model for toponium – just a generic spin-0 colour-singlet state with a pseudoscalar coupling to top quarks. The toponium hypothesis is very exciting as we previously did not expect to be able to see it at the LHC.”

Though other explanations can’t be ruled out, CMS finds the toponium hypothesis to be sufficient to explain the observed excess. The size of the excess is consistent with the latest theoretical estimate of the cross section to produce pseudoscalar toponium of around 6.4 pb.

“The cross section we obtain for our simplified hypothesis is 8.8 pb with an uncertainty of about 15%,” explains Meyer. “One can infer that this is significantly above five sigma.”

Threshold excess *The invariant mass spectrum of top quark–antiquark pairs observed by the CMS experiment in certain domains of the reconstructed spin-correlation observables c_{hel} and c_{han} (top panel) and the signal-to-background ratio (bottom panel). Excess events at threshold can be modelled by including a new top–antitop bound state in the background model (red line).*

CMS Collab. 2025 arXiv:2503.22382

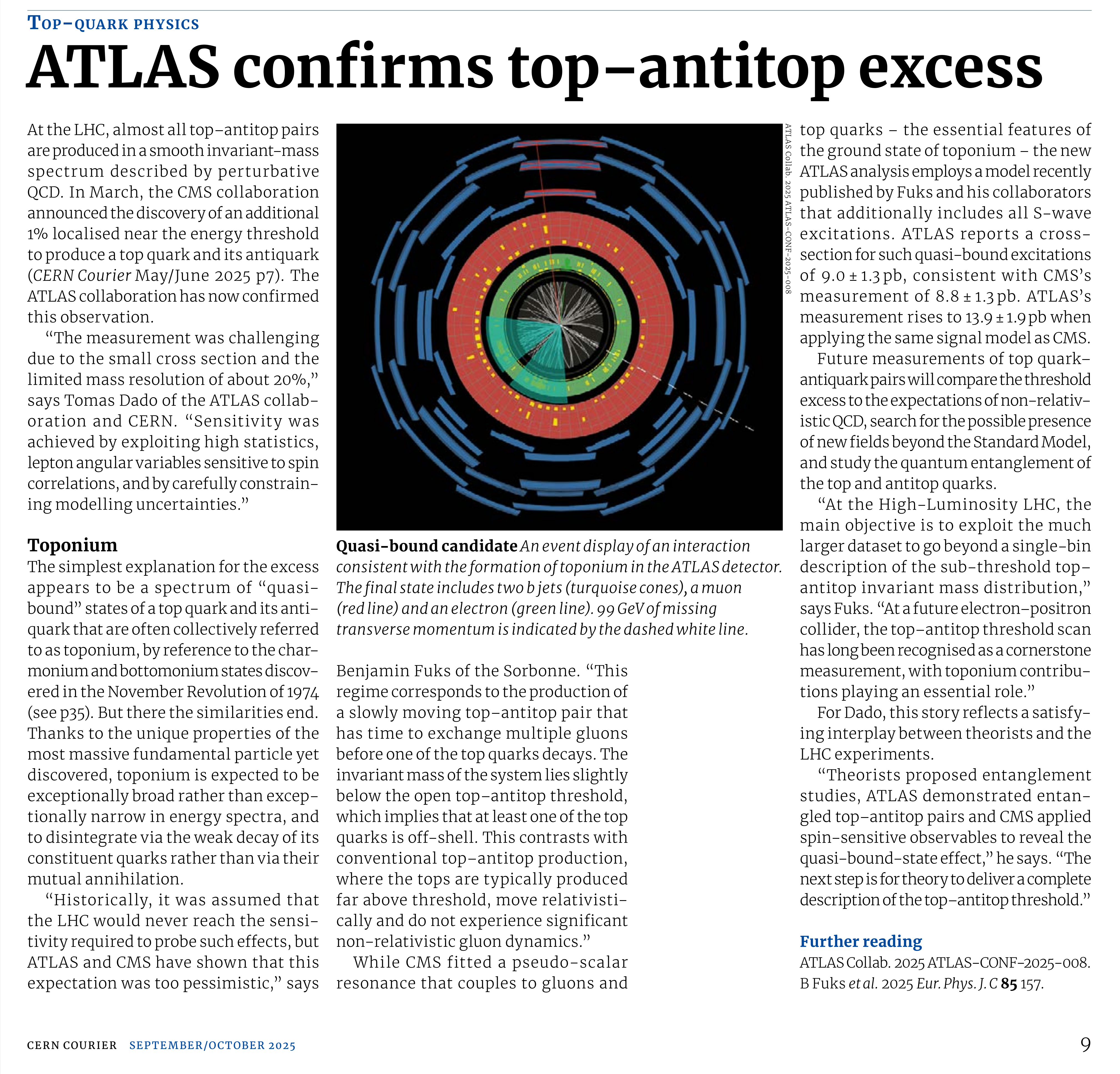
The toponium hypothesis is very exciting as we previously did not expect to be able to see it at the LHC

The smallest hadron

If confirmed, toponium would be the final example of quarkonium – a term for quark–antiquark states formed from heavy charm, bottom and perhaps top quarks. Charmonium (charm–anticharm) mesons were discovered at SLAC and Brookhaven National Laboratory in the November Revolution of 1974. Bottomonium (bottom–antibottom) mesons were discovered at Fermilab in 1977. These heavy quarks move relatively slowly compared to the speed of light, allowing the strong interaction to be modelled by a static potential as a function of the separation between them. When the quarks are far apart, the potential is proportional to their separation due to the self-interacting gluons forming an elongating flux tube, yielding a constant force of attraction. At close separations, the potential is due to the exchange of individual gluons and is Coulomb-like in form, and inversely proportional to separation, leading to an inverse-square force of attraction. This is the domain where compact quarkonium states are formed, in a near perfect QCD analogy to positronium, wherein an electron and a positron are bound by photon exchange. The Bohr radii of the ground states of charmonium and bottomonium are approximately 0.3 fm and 0.2 fm, and bottomonium is thought to be the smallest hadron yet discovered. Given its larger mass, toponium’s Bohr radius would be an order of magnitude smaller.

For a long time it was thought that toponium bound states were unlikely to be detected in hadron–hadron collisions. The top quark is the most massive and the shortest-lived of the known fundamental particles. It decays into a bottom quark and a real W boson in the time it takes light to travel just 0.1 fm, leaving little time for a hadron to form. Toponium would be unique among quarkonia in that its decay would be triggered by the weak decay of one of its constituent quarks rather than the annihilation of its constituent quarks into photons or gluons. Toponium is expected to decay at twice the rate of the top quark itself, with a width of approximately 3 GeV.

CMS first saw a 3.5 sigma excess in a 2019 search studying the mass range above 400 GeV, based on 35.9 fb^{-1} of proton–proton collisions at 13 TeV from 2016. Now armed with 138 fb^{-1} of collisions from ▷



Top-quark physics

ATLAS confirms top–antitop excess

At the LHC, almost all top–antitop pairs are produced in a smooth invariant-mass spectrum described by perturbative QCD. In March, the CMS collaboration announced the discovery of an additional 1% localised near the energy threshold to produce a top quark and its antiquark (*CERN Courier* May/June 2025 p7). The ATLAS collaboration has now confirmed this observation.

“The measurement was challenging due to the small cross section and the limited mass resolution of about 20%,” says Tomas Dado of the ATLAS collaboration and CERN. “Sensitivity was achieved by exploiting high statistics, lepton angular variables sensitive to spin correlations, and by carefully constraining modelling uncertainties.”

Toponium

The simplest explanation for the excess appears to be a spectrum of “quasi-bound” states of a top quark and its antiquark that are often collectively referred to as toponium, by reference to the charmonium and bottomonium states discovered in the November Revolution of 1974 (see p35). But there the similarities end. Thanks to the unique properties of the most massive fundamental particle yet discovered, toponium is expected to be exceptionally broad rather than exceptionally narrow in energy spectra, and to disintegrate via the weak decay of its constituent quarks rather than via their mutual annihilation.

“Historically, it was assumed that the LHC would never reach the sensitivity required to probe such effects, but ATLAS and CMS have shown that this expectation was too pessimistic,” says Benjamin Fuks of the Sorbonne. “This regime corresponds to the production of a slowly moving top–antitop pair that has time to exchange multiple gluons before one of the top quarks decays. The invariant mass of the system lies slightly below the open top–antitop threshold, which implies that at least one of the top quarks is off-shell. This contrasts with conventional top–antitop production, where the tops are typically produced far above threshold, move relativistically and do not experience significant non-relativistic gluon dynamics.”

While CMS fitted a pseudo-scalar resonance that couples to gluons and top quarks – the essential features of the ground state of toponium – the new ATLAS analysis employs a model recently published by Fuks and his collaborators that additionally includes all S-wave excitations. ATLAS reports a cross-section for such quasi-bound excitations of 9.0 ± 1.3 pb, consistent with CMS’s measurement of 8.8 ± 1.3 pb. ATLAS’s measurement rises to 13.9 ± 1.9 pb when applying the same signal model as CMS.

Future measurements of top quark–antiquark pairs will compare the threshold excess to the expectations of non-relativistic QCD, search for the possible presence of new fields beyond the Standard Model, and study the quantum entanglement of the top and antitop quarks.

“At the High-Luminosity LHC, the main objective is to exploit the much larger dataset to go beyond a single-bin description of the sub-threshold top–antitop invariant mass distribution,” says Fuks. “At a future electron–positron collider, the top–antitop threshold scan has long been recognised as a cornerstone measurement, with toponium contributions playing an essential role.”

For Dado, this story reflects a satisfying interplay between theorists and the LHC experiments.

“Theorists proposed entanglement studies, ATLAS demonstrated entangled top–antitop pairs and CMS applied spin-sensitive observables to reveal the quasi-bound-state effect,” he says. “The next step is for theory to deliver a complete description of the top–antitop threshold.”

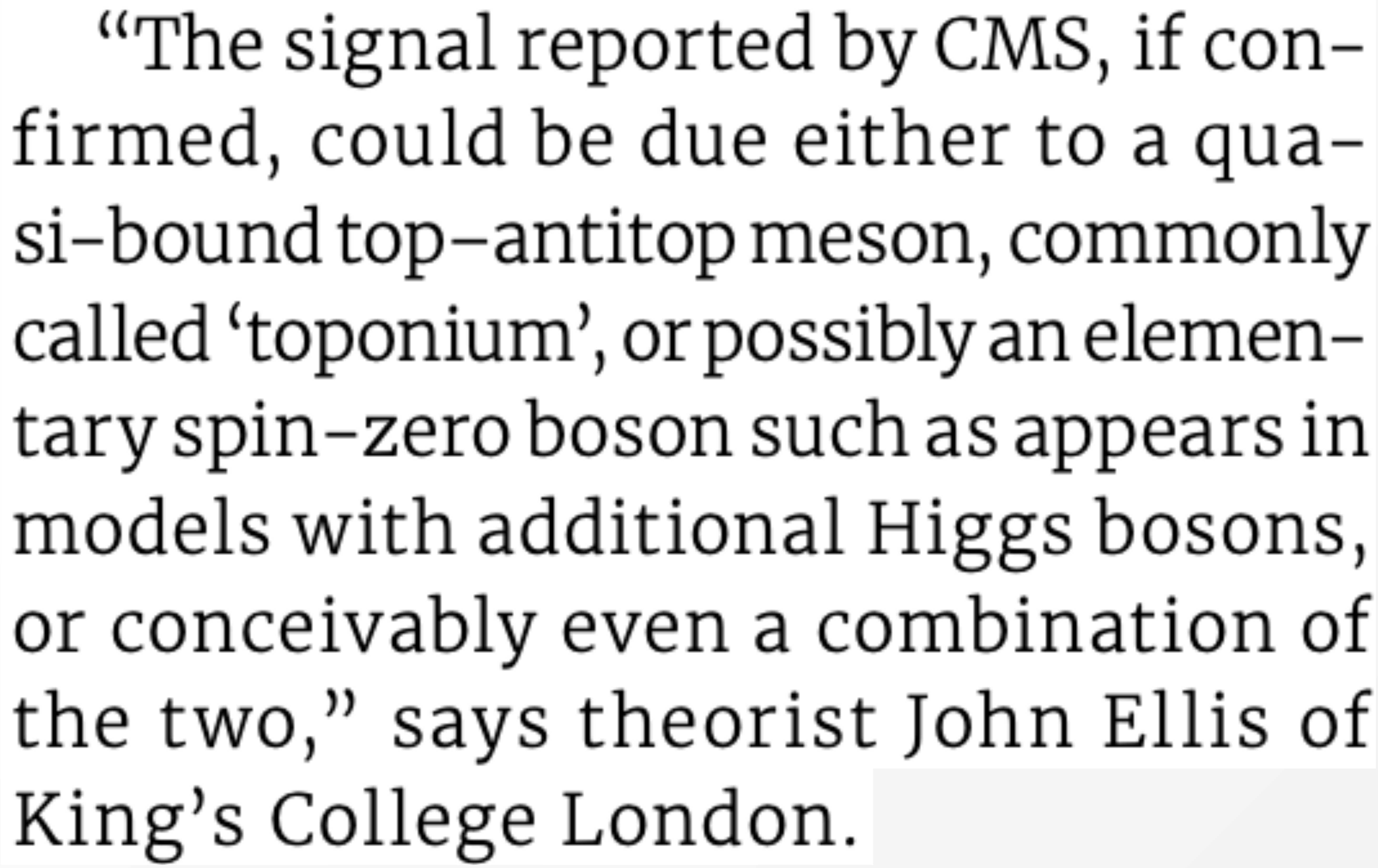
Quasi-bound candidate *An event display of an interaction consistent with the formation of toponium in the ATLAS detector. The final state includes two b jets (turquoise cones), a muon (red line) and an electron (green line). 99 GeV of missing transverse momentum is indicated by the dashed white line.*

ATLAS Collab. 2025 ATLAS-CONF-2025-008

Further reading

ATLAS Collab. 2025 ATLAS-CONF-2025-008.
B Fuks *et al.* 2025 *Eur. Phys. J. C* **85** 157.

CMS (2503.22382) and ATLAS (2601.11780) reported an excess in the $t\bar{t}$ production cross section in the pseudoscalar channel



“The signal reported by CMS, if confirmed, could be due either to a quasi-bound top–antitop meson, commonly called ‘toponium’, or possibly an elementary spin-zero boson such as appears in models with additional Higgs bosons, or conceivably even a combination of the two,” says theorist John Ellis of King’s College London.

The toponium hypothesis is very exciting as we previously did not expect to be able to see it at the LHC

[CERN COURIER, May-June issue 2026]

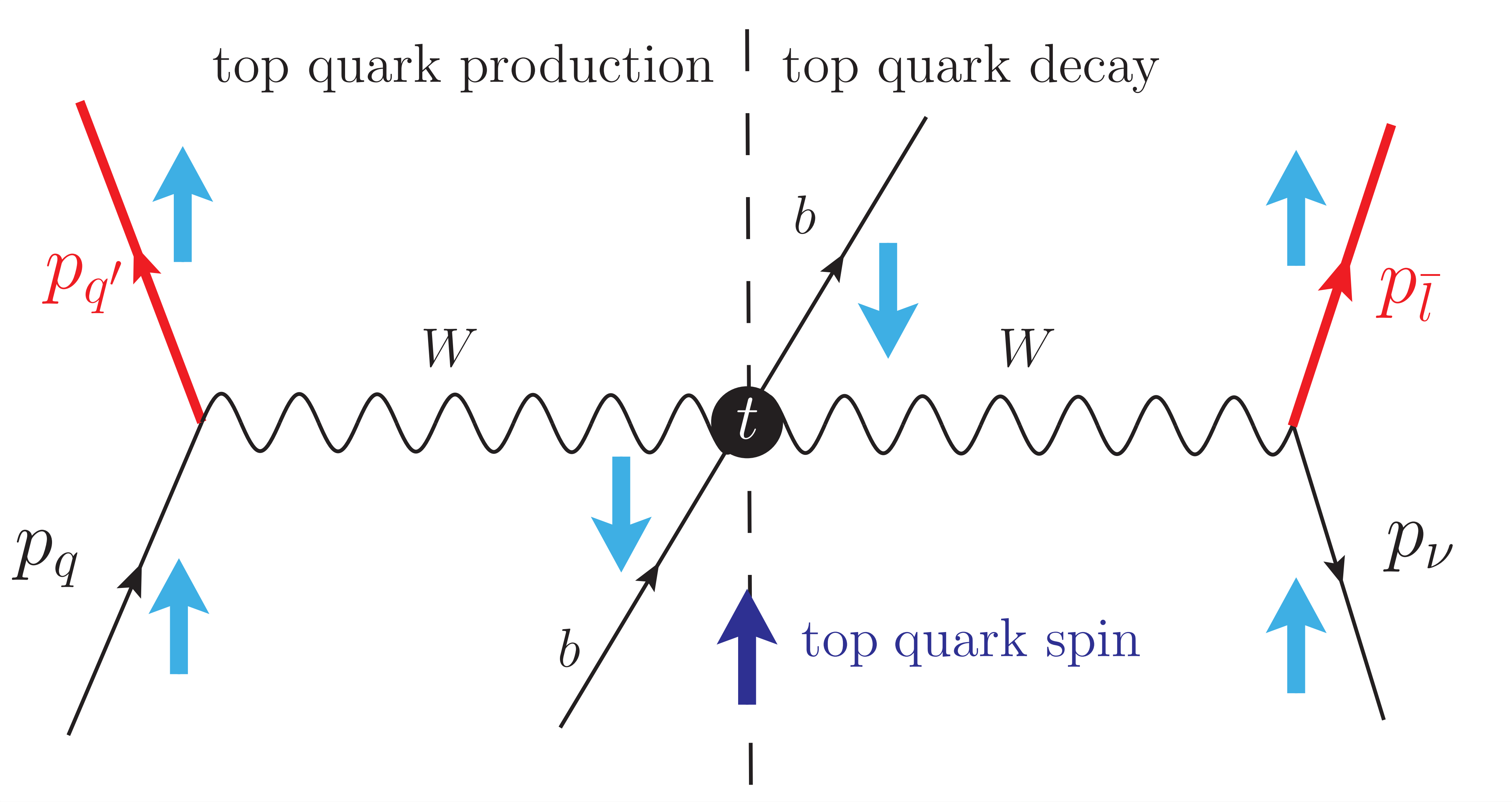
Toponium and where to find it

[Minni e il naufragio spaziale (Russo/Mottura), Minni & company 22, 1995]

Thanks to Giovanni Pelliccioli and Ventenni Paperoni who helped me in the hunt for Toponio

Spin correlations in $t\bar{t}$ production at threshold

Due to its short lifetime, the top spin in top leptonic decays is **strongly correlated** with the direction of the outgoing antilepton: the positron direction coincides with the direction of the top spin



[Schwienhorst, Cao, C.-P. Yuan, Mueller 1012.5132]

Production near threshold implies that the zero orbital angular momentum prevails: ***S*-wave production**

Total final state angular momentum is determined solely by the spins of the top quarks: spin triplet ($q\bar{q}$ annihilation) or spin singlet (gg annihilation, as a consequence of Landau-Yang theorem)

At LHC and for threshold production the **singlet is dominant**

$$|\psi\rangle = \frac{1}{2}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

Maximally entangled state, parity-odd

Spin correlations in $t\bar{t}$ production at the LHC

Define the vectors $\hat{l}_1, \hat{l}_2$ as the direction of the leptons from top decay in the frame obtained by boosting the $t\bar{t}$ CM rest frame to the t ($\bar{t}$) rest frame and define

$$C_{\text{hel}} = \hat{l}_1 \cdot \hat{l}_2$$

For a non-relativistic $t\bar{t}$ pair in a singlet state

$$\frac{1}{\sigma}\frac{d\sigma}{dC_{\text{hel}}} = \frac{1 + C_{\text{hel}}}{2}$$

N.B. vanishes when the spins are aligned (incompatibile with singlet configuration)

Integrating we get immediately

$$\langle C_{\text{hel}} \rangle = \frac{1}{3}$$

We also introduce the quantity

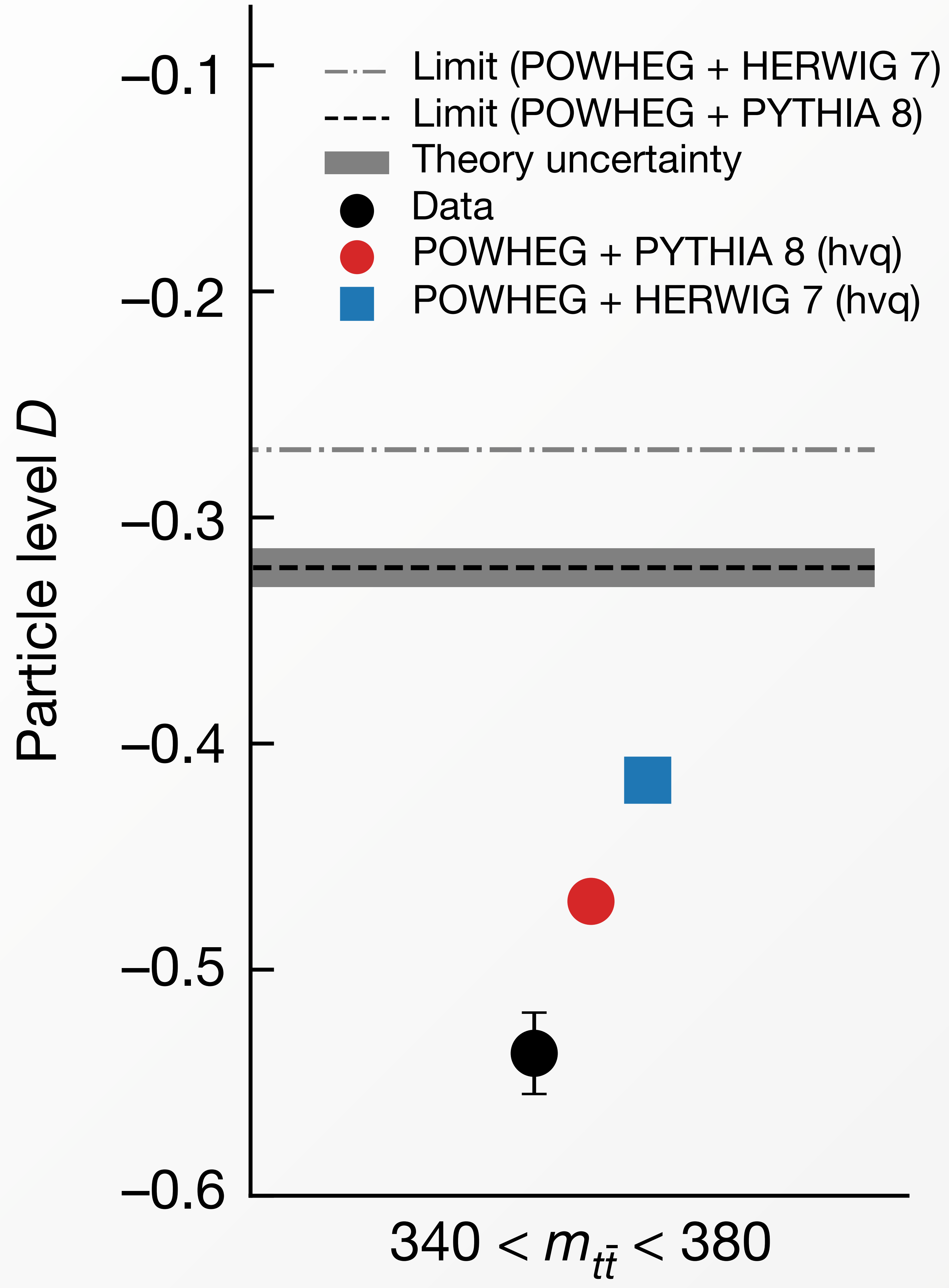
$$D = -3\langle C_{\text{hel}} \rangle$$

$D = -1$ for a pure singlet configuration

Entanglement condition

$$D < -1/3$$

Spin correlations in $t\bar{t}$ production at the LHC



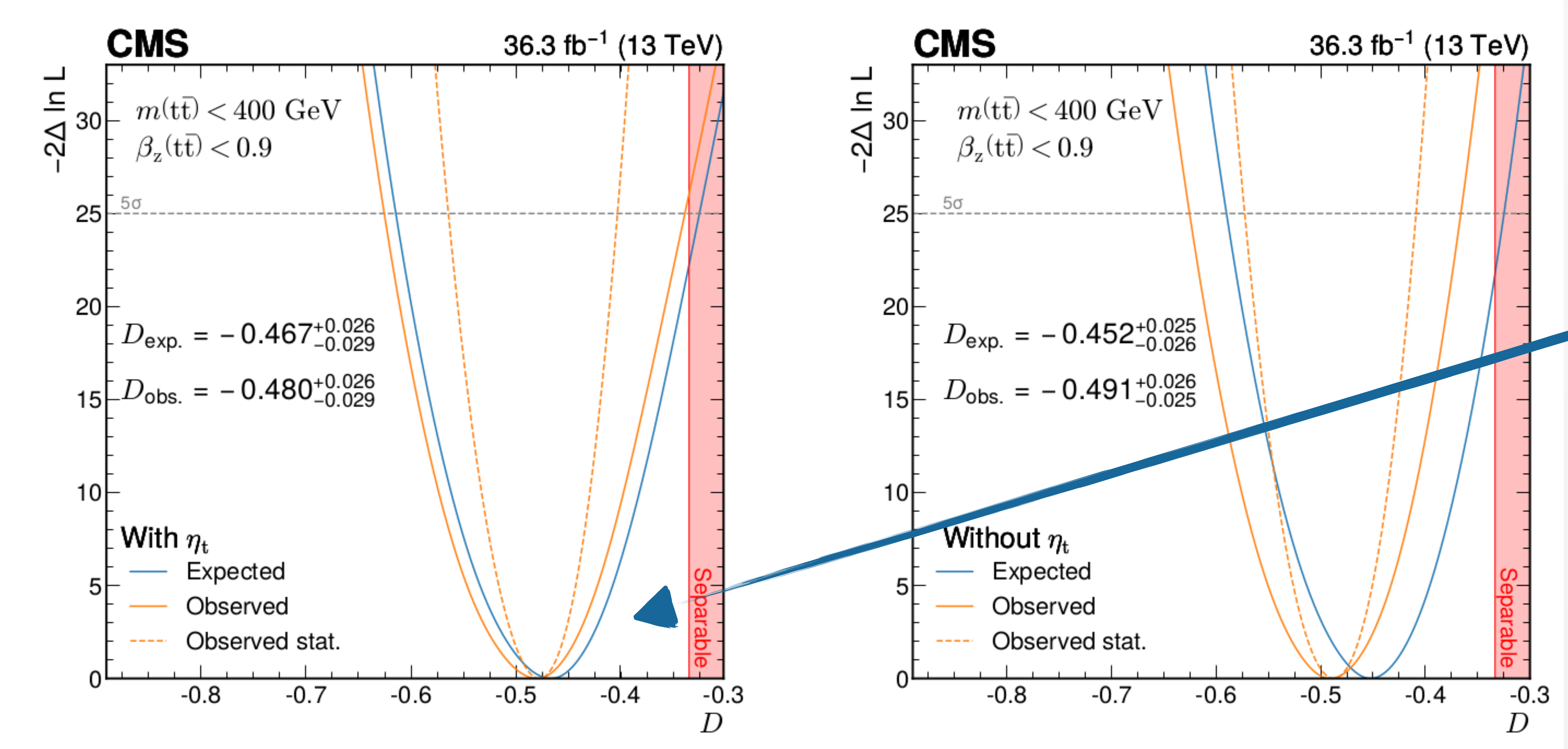
[ATLAS ’23]

$$D = -0.537 \pm 0.002\,(\text{stat.})$$
$$\pm 0.019\,(\text{syst.})\,(-0.470 \pm 0.002\,(\text{stat.}) \pm 0.017\,(\text{syst.}))$$

Expected value from various MC generators is a bit larger, $D \simeq -0.45$

Tension with theoretical predictions: more singlet needed?

Spin correlations in $t\bar{t}$ production at the LHC



Contains an additional contribution from a pseudo scalar $t\bar{t}$ bound state η_t

To ease the tension, theoretical models obtained by adding an η_t bound state to the SM production mechanism have been proposed **[Maltoni,Severy,Vryonidou,2024]**

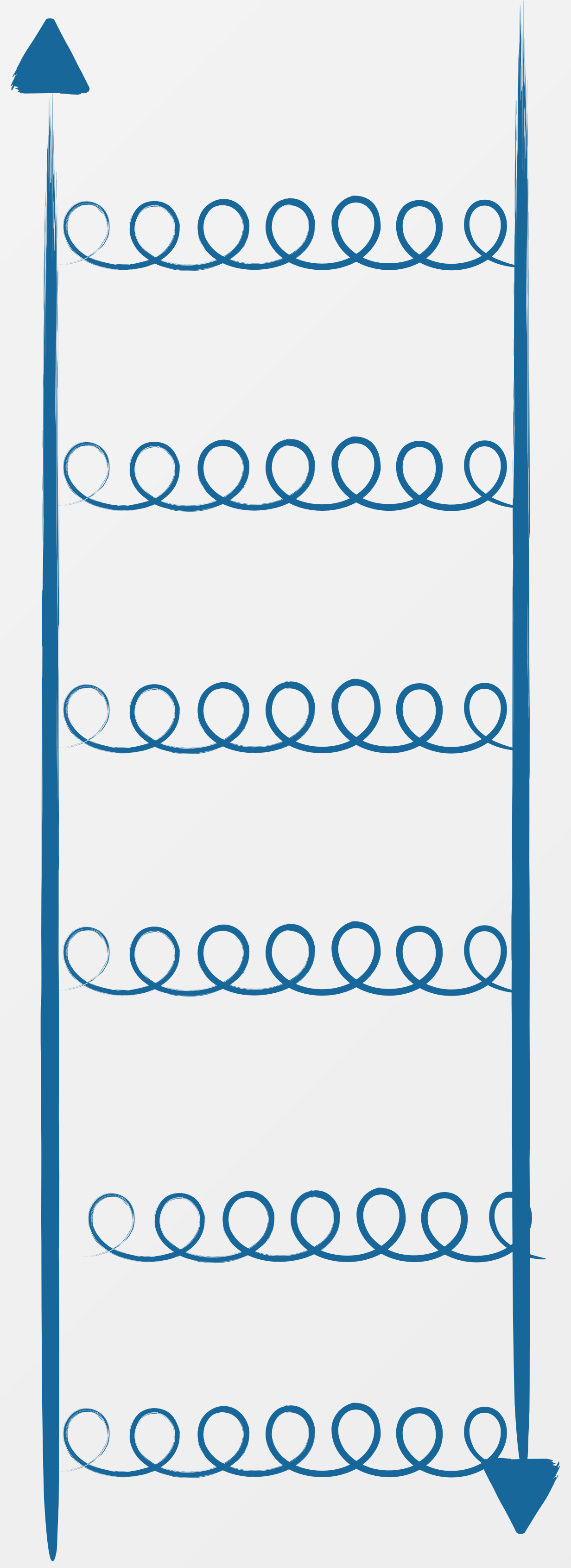
Other authors are improving MC generator by including full treatment of threshold-enhanced contributions to $t\bar{t}$ production in the non-relativistic approximation **[Fuks,Hagiwara,Ma,Zheng,2024]**

The CMS and ATLAS results on a pseudoscalar excess near threshold seem to support the need for an η_t contribution…

Threshold enhancement in bound Coulombic systems

Coulomb interactions dominate close to the production threshold and may lead to the formation of bound states

In terms of Feynman diagrams, the formation of a bound state is represented by a **ladder diagram**



Coulomb exchanges lead to perturbative corrections enhanced by $1/v$, where v is the velocity of the top in the $t\bar{t}$ rest frame. Each ladder contributes a factor a_s/v ($a_s = \alpha_s \times$ colour factor)

In a bound Coulombic system, potential energy is a_s/r, momentum is $p \approx 1/r$ (by the uncertainty principle); kinetic energy and momentum must be of the same order, $p^2/m \approx a_s/r$, leading to $v = p/m \approx a_s$

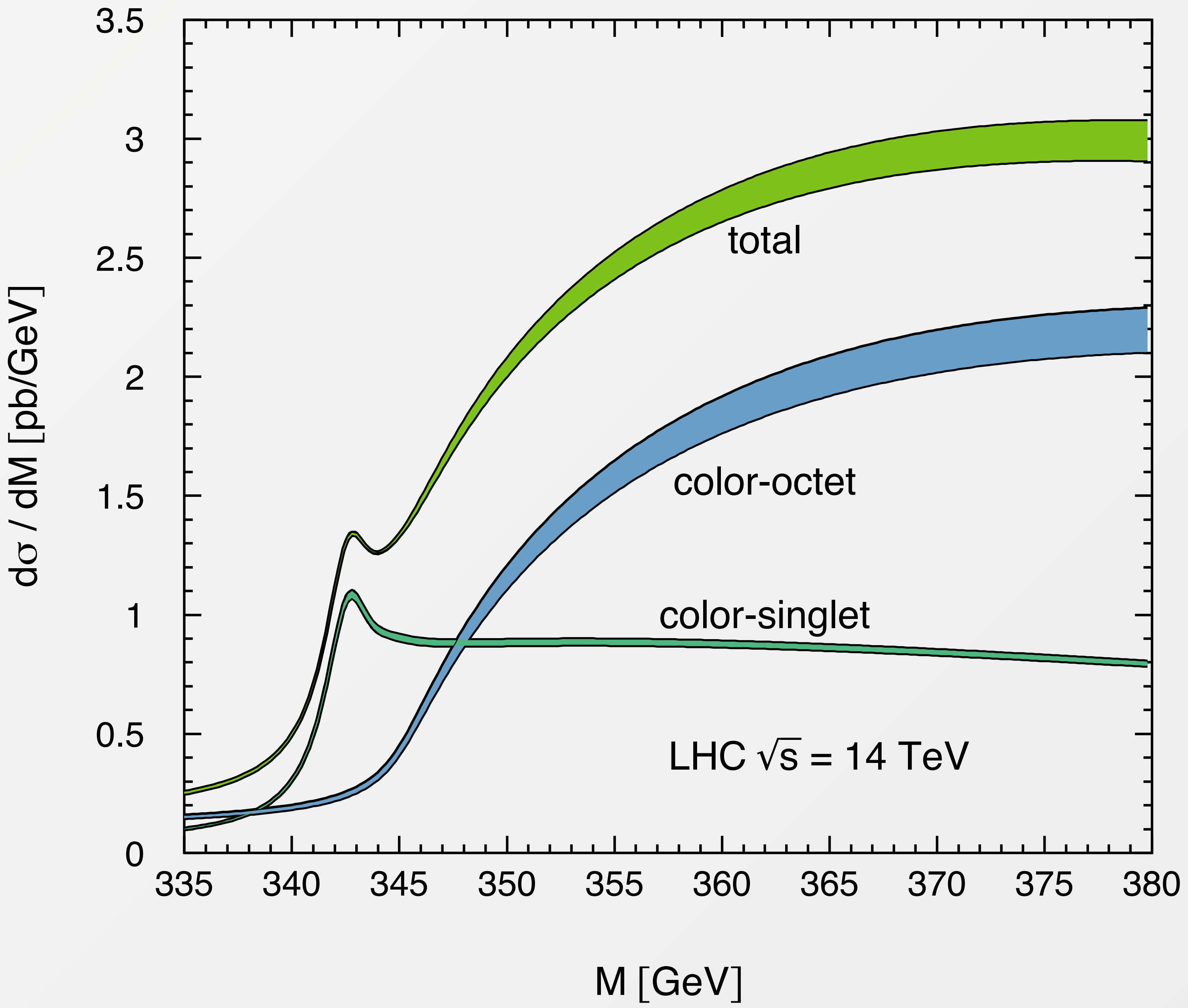
Near the bound state Coulomb exchanges leads to correction of order $\alpha_s/v \approx 1$ which must all be resummed to all orders

Threshold enhancement in bound Coulombic systems at the LHC

At Born level the $t\bar{t}$ pair can be produced in a colour singlet or colour octet state

$$\sigma_{gg}^{(1)} \approx 2\frac{\alpha_s^2}{m^2}\frac{\pi v}{192} \qquad \sigma_{gg}^{(8)} \approx 5\frac{\alpha_s^2}{m^2}\frac{\pi v}{192}$$

in the threshold limit



[Kiyo, Kühn, Moch, Steinhauser, Uwer 2009]

Coulomb exchange yields enhanced correction near threshold, proportional to the corresponding colour factor: C_F for singlet, $-1/(2N_C)$ for the octet: **the singlet prevails**

The a_s/v correction leads to an **enhancement** of the correlation

In perturbation theory, corrections for order $(a_s v)^n$ arise at all orders in perturbation theory; NLO accurate generators include a_s/v corrections; NNLO accurate generators include $(a_s/v)^2$ corrections, etc.

Bound states

A bound states contributes to the cross section as

hard production

$$\sigma(E) \approx \frac{1}{m^4}\delta(E-2m)\,|\psi(0)|^2\,\alpha_s^2$$

Estimating $|\psi(0)|^2 \approx 1/r_b^3 \approx (a_s m)^3$

$$\sigma(E) \approx \frac{1}{m}\delta(E-2m)\alpha_s^2 a_s^3$$

N³LO correction

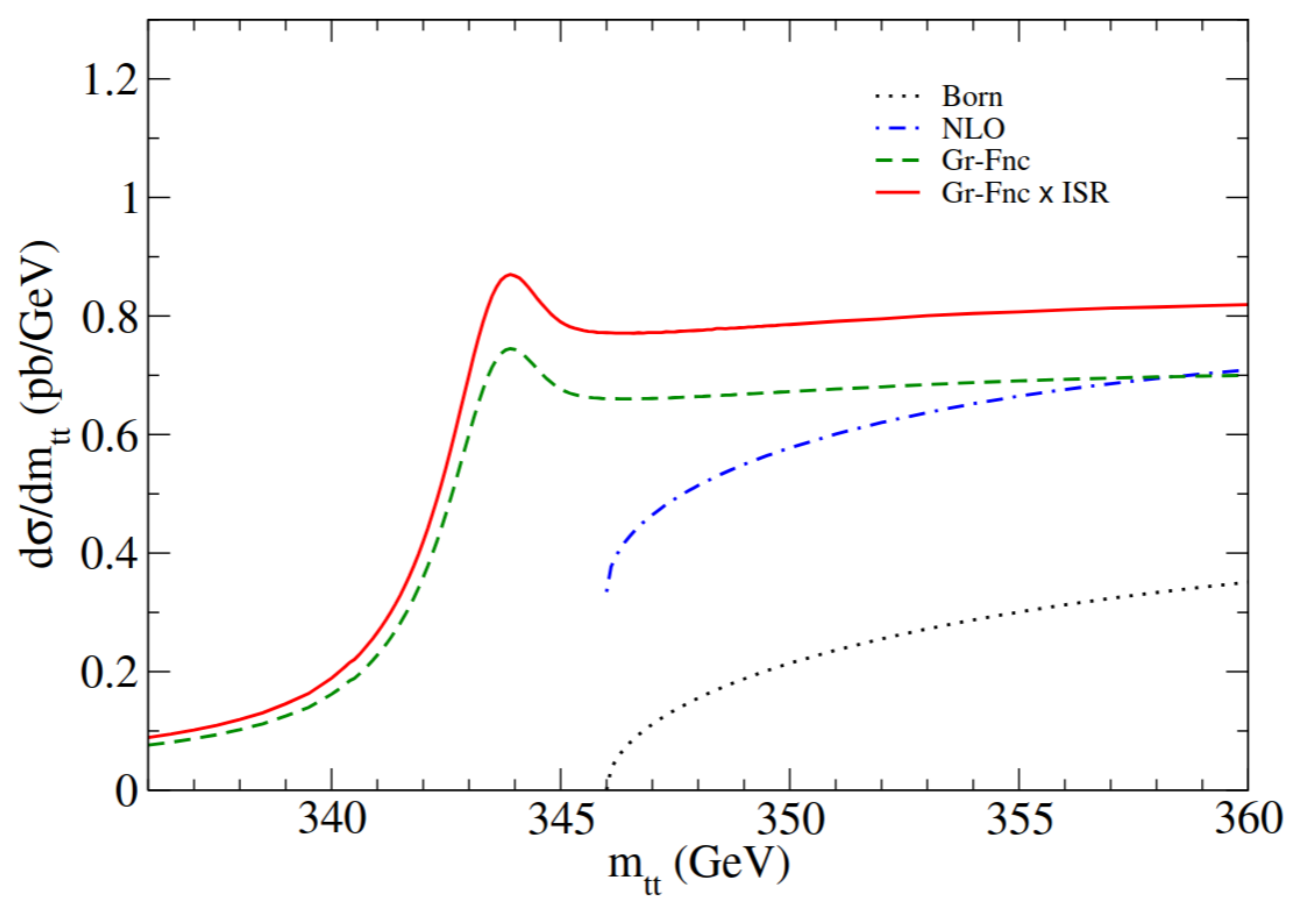
Note: this term **cannot arise in perturbation theory,** since it vanishes for negative values of the coupling: bound states exist only for positive values of a_s

Threshold enhancement and bound states

In a bound Coulombic system, in analogy with the Hydrogen atom, bound states are characterised by $v \approx a_s$, momenta of order ma_s, size of order $1/(ma_s)$ and energies of order ma_s^2

Time to sweep an orbit is approximately the inverse of the binding energy, $1/(ma_s^2) \sim (1\,\mathrm{GeV})^{-1}$, which is comparable to the top lifetime

Although no narrow bond state can be formed, top pairs which live much longer than the average lifetime could make a few orbits: **bump visible in the cross section**



[Hgiwara,Sumino,Yokoya, 2008]

Bound state formation and experimental resolution

Experiments do not measure exactly the distribution of $m_{t\bar{t}}$ but rather a **smeared distribution.** Experimental results are quoted for mass bins that go from threshold ($\approx 340\,\mathrm{GeV}$) up to $360, 380, 400\,\mathrm{GeV}$

Results should be sensitive to times of the order of the inverse bin size. Part of the cross section goes into bound state formation, part in operation production, but the experimental result **should be insensitive to the exact proportion of the two contribution**

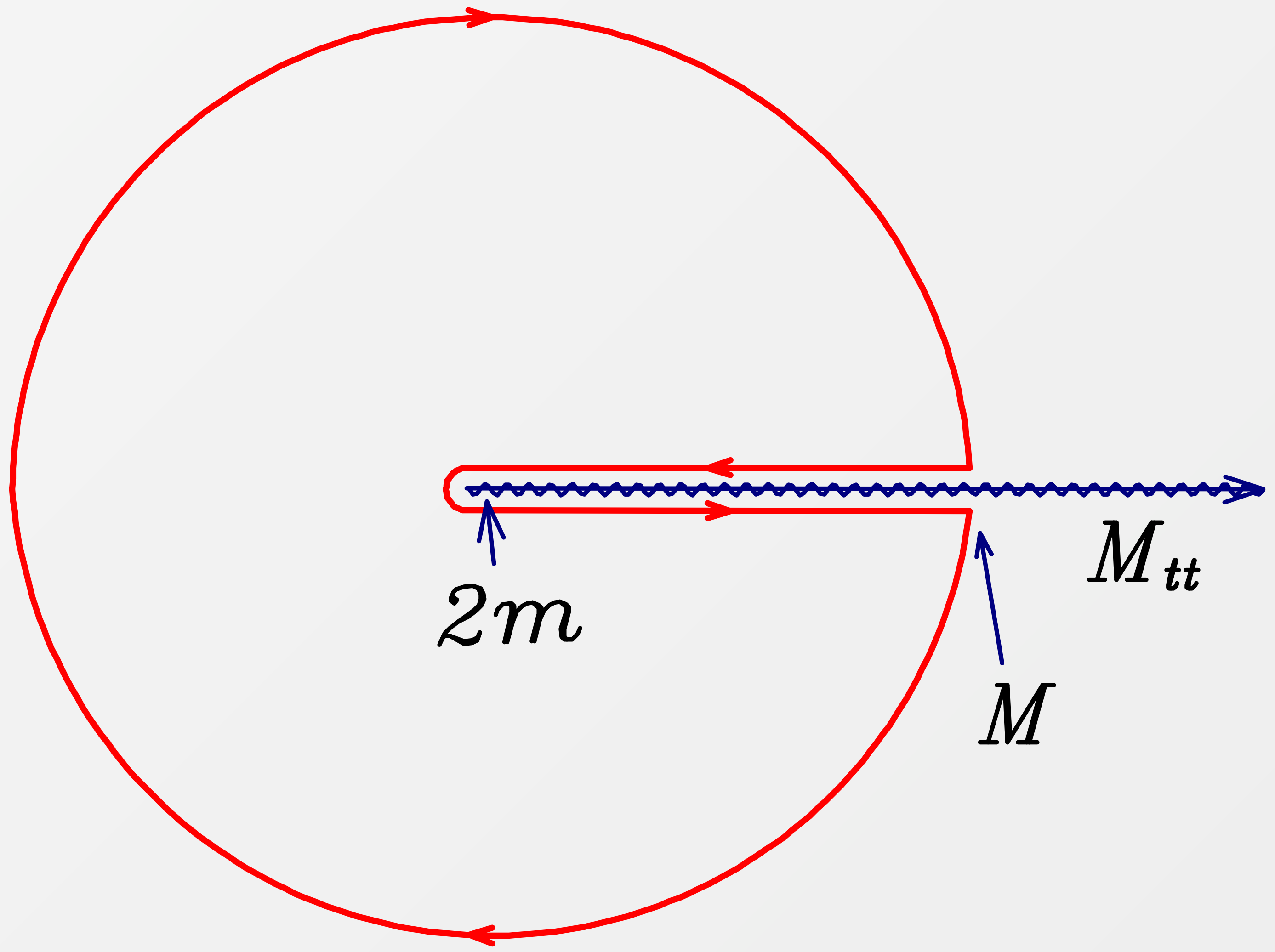
Enhanced contributions of order a_s/v should be sensitive to the velocities corresponding to the adopted mass cut M rather than $v \approx a_s$, and it should be possible to perform the calculation **using perturbation theory**

Bound states in (non-relativistic) quantum mechanics

Top production dynamics near threshold can be studied in terms of **non-relativistic quantum mechanics**

In this limit, we can only consider s_{s}-wave final states. The cross section is related to the density of states $\rho(E)$, which can be in turn related to the imaginary part of the **forward resolvent**

$$R(E) = \frac{1}{H - E}$$



By analicity, its integral up to a sufficiently large energy cut can be expressed as an integral of the forward resolvent along a circle in the complex energy plane that is far from the origin

Sufficiently away from threshold, there should be no sensitivity to bound state formation. It should be possible to compute it with a **convergent perturbative expansion theory**

The problem we are facing arises in quantum mechanics every time we deal with the formation of a bound state

In order to better understand what goes on we considered a **simple quantum mechanical example**: the single particle in a **delta-function potential in one dimension**

Spectral density for the delta-function potential

Schrödinger Equation

$$-\frac{1}{2m}\frac{d^2}{dx^2}\psi - \lambda\,\delta(x)\,\psi = E\psi$$

Bound state (n.b. no bound state if $\lambda < 0$!)

$$\psi_0(x) = \theta(\lambda)\sqrt{m\lambda}\left[e^{\lambda m x}\theta(-x) + e^{-\lambda m x}\theta(x)\right], \quad E_0 = -\frac{m\lambda^2}{2}$$

Only parity-even solutions are relevant:

$$\psi_k(x) = \sqrt{\frac{2}{L(1+\lambda^2/v_k^2)}}\left[\cos(kx) - \frac{x}{|x|}\frac{\lambda}{v_k}\sin(kx)\right], \quad v_k = \frac{k}{m}; E_k = \frac{k^2}{2m}$$

Density of states turns out to be

$$\rho(E) = \sum_k |\psi_k(0)|^2\,\delta(E - E_k) = \theta(\lambda)\lambda m\,\delta\left(E + \frac{1}{2}m\lambda^2\right) + \frac{1}{\pi}\frac{m}{k_E}\frac{1}{1+\lambda^2/v_E^2}$$

This expression does not seem to have a power expansion in λ; first term cannot appear in a perturbative calculation (due to the Heaviside theta function)

Spectral density for the delta-function potential

We can however compute the integral of the density of states from the threshold up to a given value

$$\int^{E'} dE\, \rho(E) = \frac{1}{\pi} k_{E'} + m \underbrace{\left[\lambda\theta(\lambda) - \frac{|\lambda|}{2} \right]}_{=\lambda/2} + \frac{m\lambda^2}{\pi} \frac{m}{k_{E'}} + \dots$$

The **non-analytic term** arising from the bound state combines with a **non-analytic term** arising from the continuum and form **an analytic term**

A perturbative expansion for $\rho(E)$ is possible as long as we interpret its coefficients as distribution

$$\rho(E) \Longrightarrow \frac{\lambda}{2} m\delta\left(E + \frac{1}{2} m\lambda^2\right) + \frac{1}{\pi} \frac{m}{k_E} \left(\frac{1}{1 + \lambda^2/v_E^2} \right)_+$$

Expanding at order λ one gets

$$\rho(E) = \theta(E) \frac{m}{\pi k_E} + \frac{\lambda m}{2} \delta(E)$$

This result can also be obtained in a **direct perturbative calculation**, without need to introduce bound states, nor being aware of the existence of effects arising from the resummation of the perturbative expansion near threshold

The $t\bar{t}$ case

The $t\bar{t}$ case is equivalent to the Hydrogen atom problem; following a similar reasoning to the simpler delta case, one can obtain from the energy density the first three perturbative orders obtaining

$$\rho_l(\mathscr{E}) \to \frac{(m)^2}{4\pi^2}\left(v + \frac{\pi a_l}{2} + \frac{\pi^2 a_l^2}{12v} + \frac{\pi\zeta(3)a_l^3}{4} m\delta(\mathscr{E})\right)$$

See also [Beneke, P. Ruiz-Femenia, 2016]

$$\mathscr{E} = E - 2m, \qquad l = 1(8), \qquad a_1 = C_F\alpha_s, \qquad a_8 = -\alpha_s/(2N_C)$$

Among state of the art calculations used for this process, some include the first correction (NLO calculations), some up to the second one (NNLO), none includes the third term (which is however very small)

N^3LO term includes effect of **bound-states** and **other perturbative N^3LO corrections**, which **cannot be disentangled** with the resolution currently available at the LHC

Funes el memorioso

Ut nihil non isdem verbis redderetur auditum
[So that nothing that had been heard failed to be rendered in the same words]
Pliny the Elder, Naturalis historia

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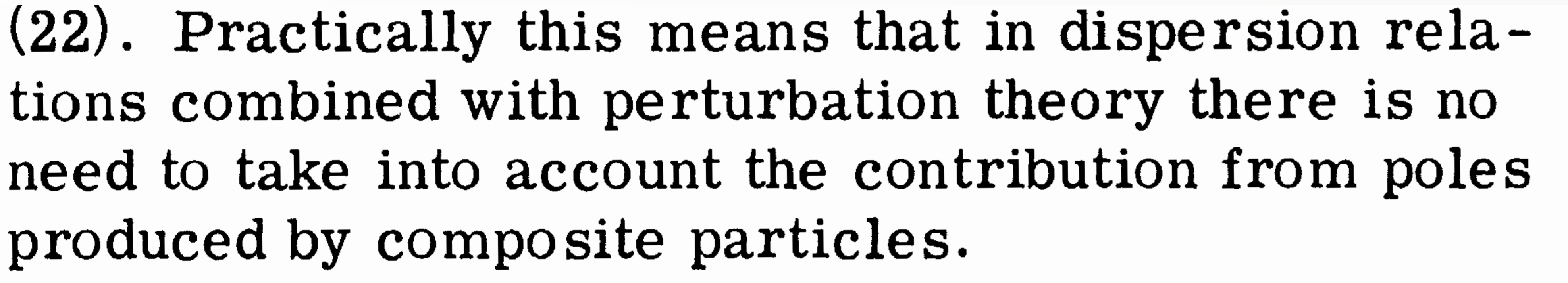
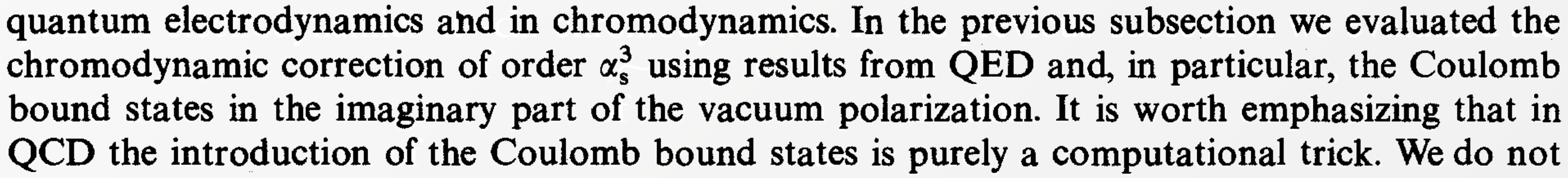

(22). Practically this means that in dispersion relations combined with perturbation theory there is no need to take into account the contribution from poles produced by composite particles.

[Braun 1967]


quantum electrodynamics and in chromodynamics. In the previous subsection we evaluated the chromodynamic correction of order α_s^3 using results from QED and, in particular, the Coulomb bound states in the imaginary part of the vacuum polarization. It is worth emphasizing that in QCD the introduction of the Coulomb bound states is purely a computational trick. We do not

[Novikov et al. 1977]

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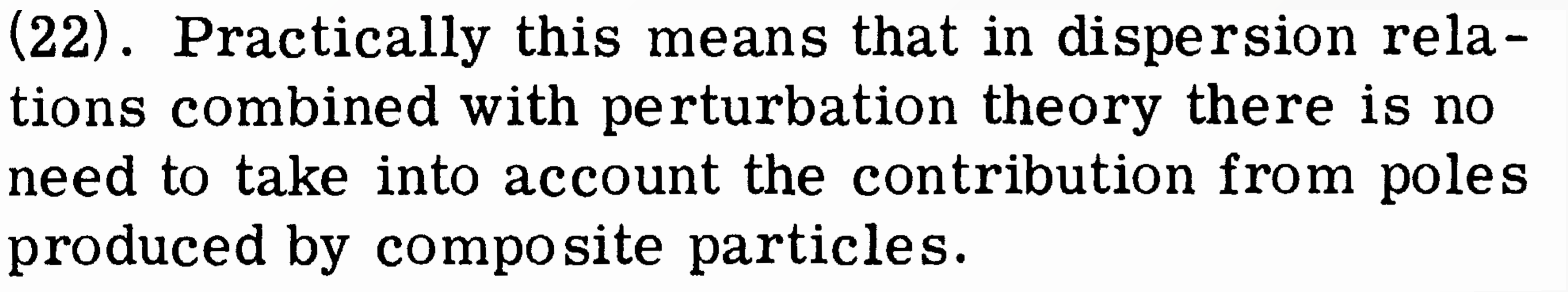
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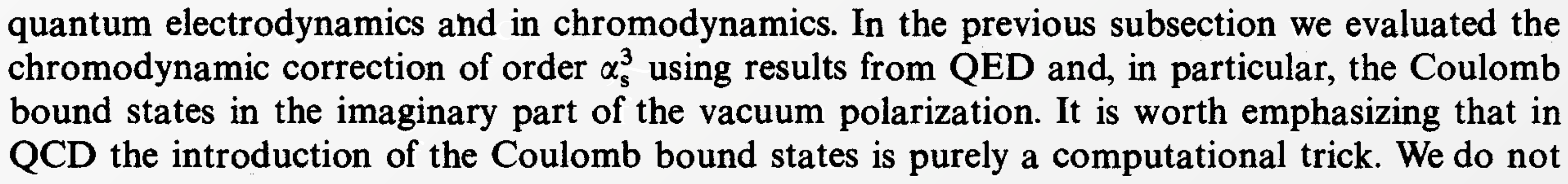
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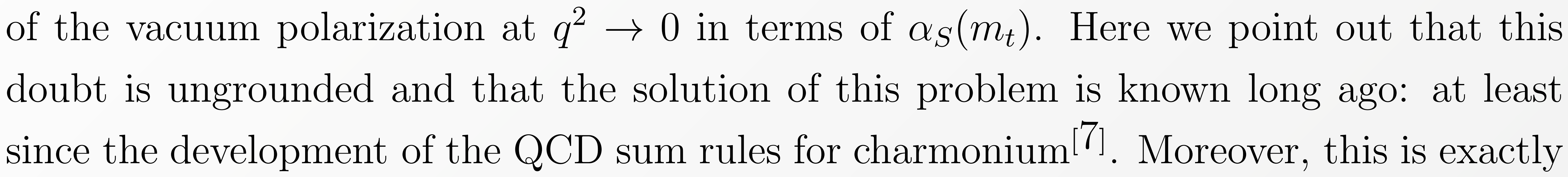
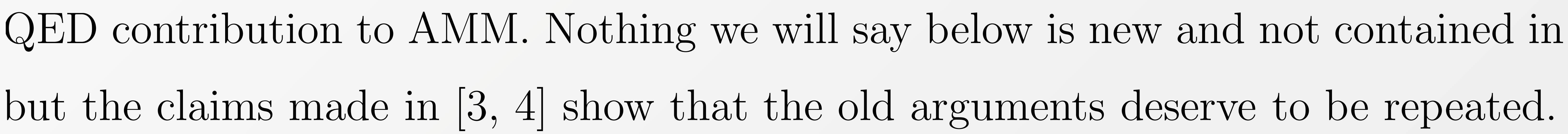
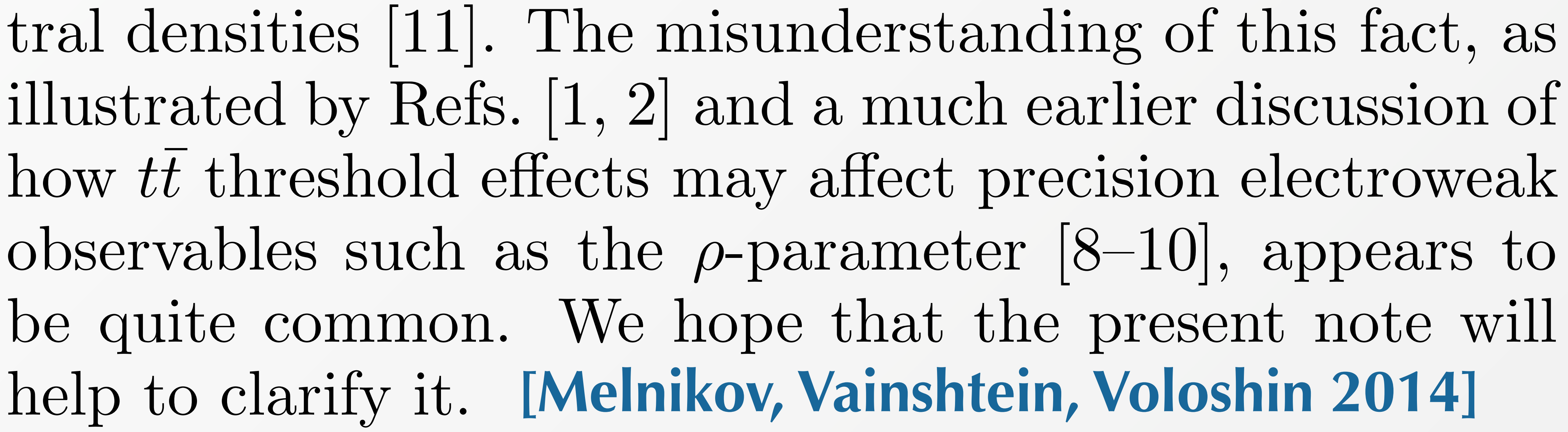

of the vacuum polarization at $q^2 \to 0$ in terms of $\alpha_S(m_t)$. Here we point out that this doubt is ungrounded and that the solution of this problem is known long ago: at least since the development of the QCD sum rules for charmonium[7]. Moreover, this is exactly

[Smith, Voloshin 1994]


QED contribution to AMM. Nothing we will say below is new and not contained in [15, 16], but the claims made in [3, 4] show that the old arguments deserve to be repeated.

[Eides 2014]


tral densities [11]. The misunderstanding of this fact, as illustrated by Refs. [1, 2] and a much earlier discussion of how $t\bar{t}$ threshold effects may affect precision electroweak observables such as the ρ-parameter [8–10], appears to be quite common. We hope that the present note will help to clarify it.

[Melnikov, Vainshtein, Voloshin 2014]

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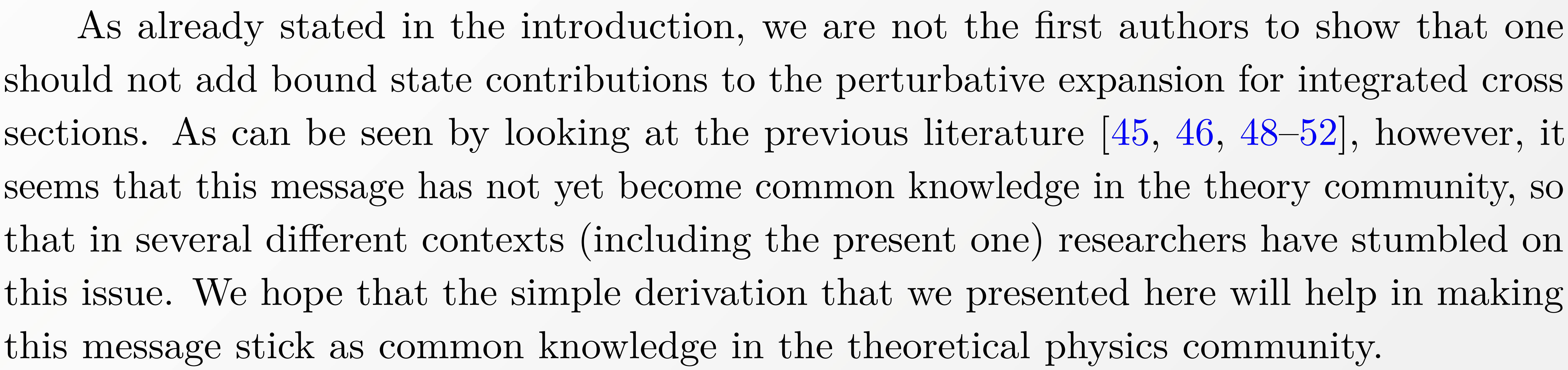

As already stated in the introduction, we are not the first authors to show that one should not add bound state contributions to the perturbative expansion for integrated cross sections. As can be seen by looking at the previous literature [45, 46, 48–52], however, it seems that this message has not yet become common knowledge in the theory community, so that in several different contexts (including the present one) researchers have stumbled on this issue. We hope that the simple derivation that we presented here will help in making this message stick as common knowledge in the theoretical physics community.

[Nason, Re, LR 2025]

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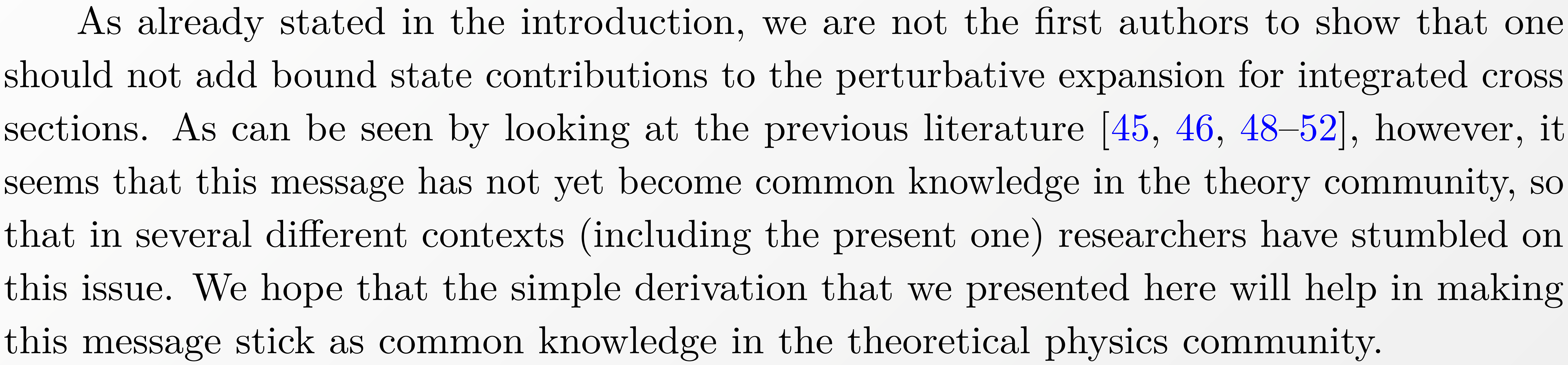
Pliny the Elder, Naturalis historia



As already stated in the introduction, we are not the first authors to show that one should not add bound state contributions to the perturbative expansion for integrated cross sections. As can be seen by looking at the previous literature [45, 46, 48–52], however, it seems that this message has not yet become common knowledge in the theory community, so that in several different contexts (including the present one) researchers have stumbled on this issue. We hope that the simple derivation that we presented here will help in making this message stick as common knowledge in the theoretical physics community.

[Nason, Re, LR 2025]

If you wish to forget anything on the spot, make a note that this thing is to be remembered
Edgar Allan Poe, Marginalia

Modelling spins correlations near threshold in Monte Carlo simulations

$$\rho_l(\mathscr{E}) \to \frac{(m)^2}{4\pi^2}\left(v + \frac{\pi a_l}{2} + \frac{\pi^2 a_l^2}{12v} + \frac{\pi\zeta(3)a_l^3}{4} m\delta(\mathscr{E}) \right)$$

The threshold corrections to use in practice are obtained by replacing v with **the round parenthesis above**

$$\sigma_{q\bar{q}}^{(8)} \approx \frac{\alpha_s^2}{m^2}\frac{\pi v}{9}, \quad \sigma_{q\bar{q}}^{(1)} = 0, \quad \sigma_{gg}^{(8)} \approx \frac{\alpha_s^2}{m^2}\frac{\pi v}{192} \times 5, \quad \sigma_{gg}^{(1)} \approx \frac{\alpha_s^2}{m^2}\frac{\pi v}{192} \times 2$$

Scale choice: The appropriate scale to use for threshold corrections is the typical momentum of the top quarks in the $t\bar{t}$ centre of mass, that is of the order of the momentum when the energy equals to $E_{\text{cut}} \ll m_t$

When adding our corrections to the results obtained with standard Monte Carlo generators, in order to avoid overcounting, we should **subtract the corrections** that are already included in the MC generators

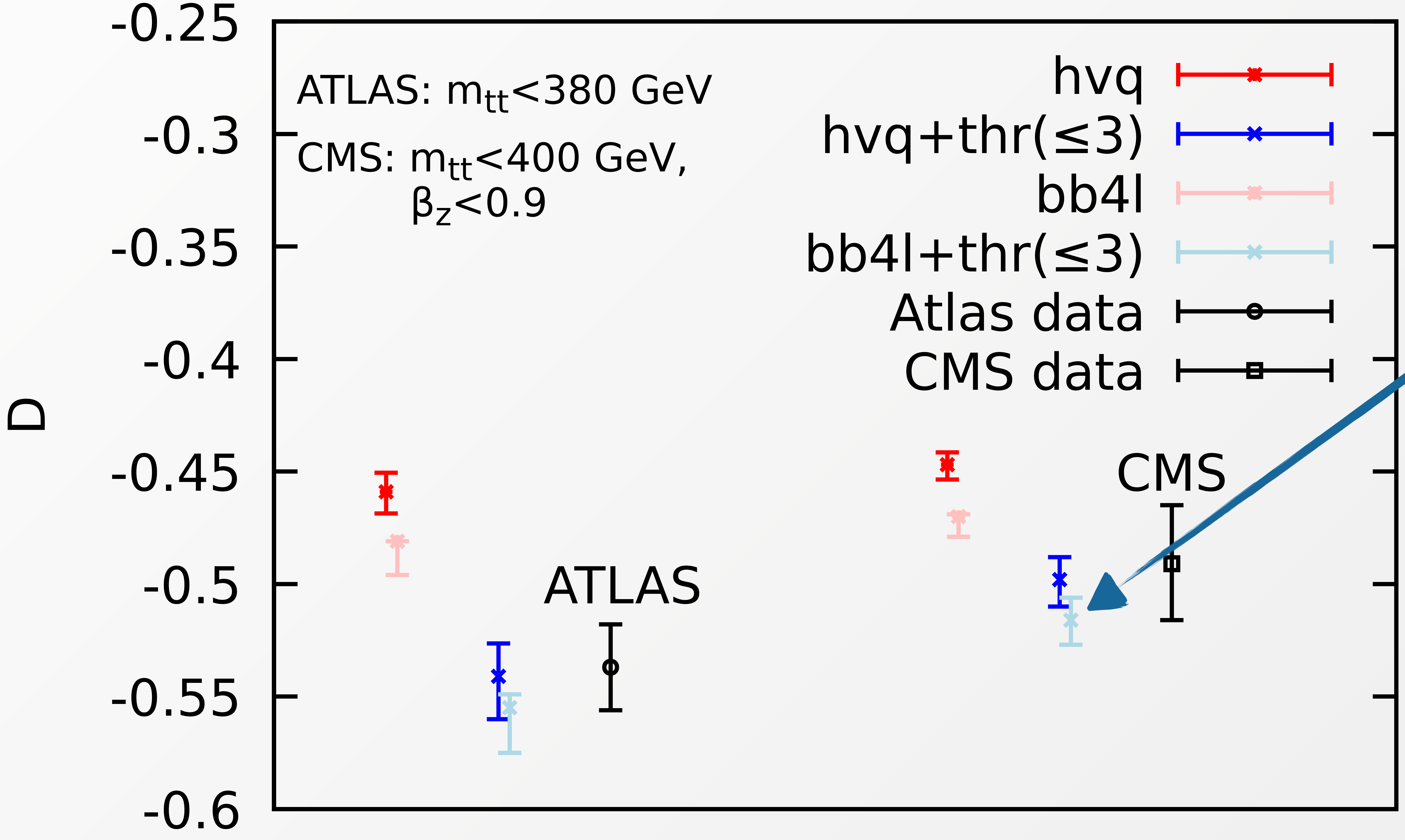
In NLO event generators, we subtract the a_l term **at the high scale**

In NNLO event generators, we subtract the a_l term **at the low scale** (since that contribution in the MC includes running effects) and the a_l^2 term **at the high scale**

The N^{3}LO term is always evaluated **at the low scale**

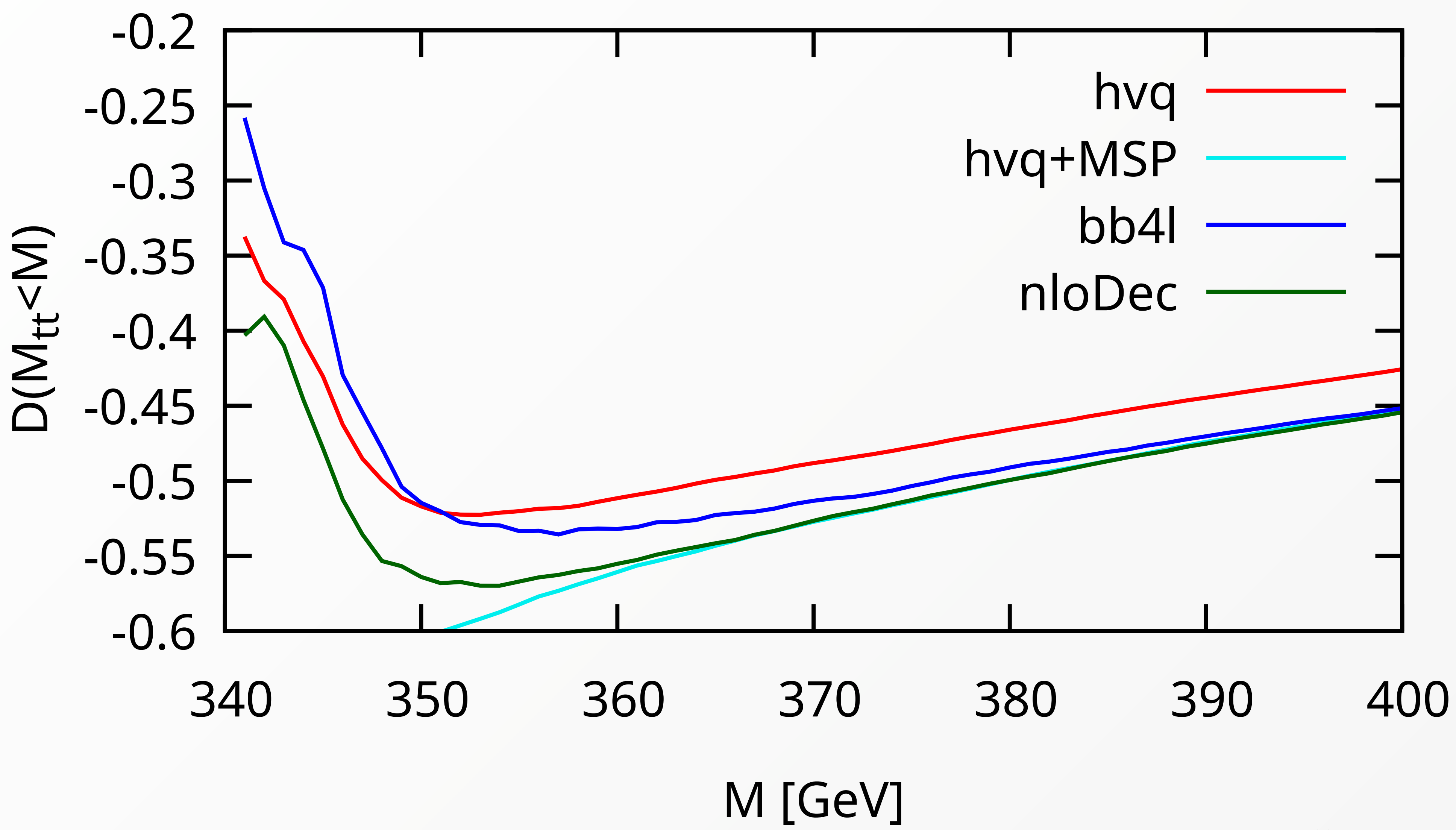
Comparison with data: NLO

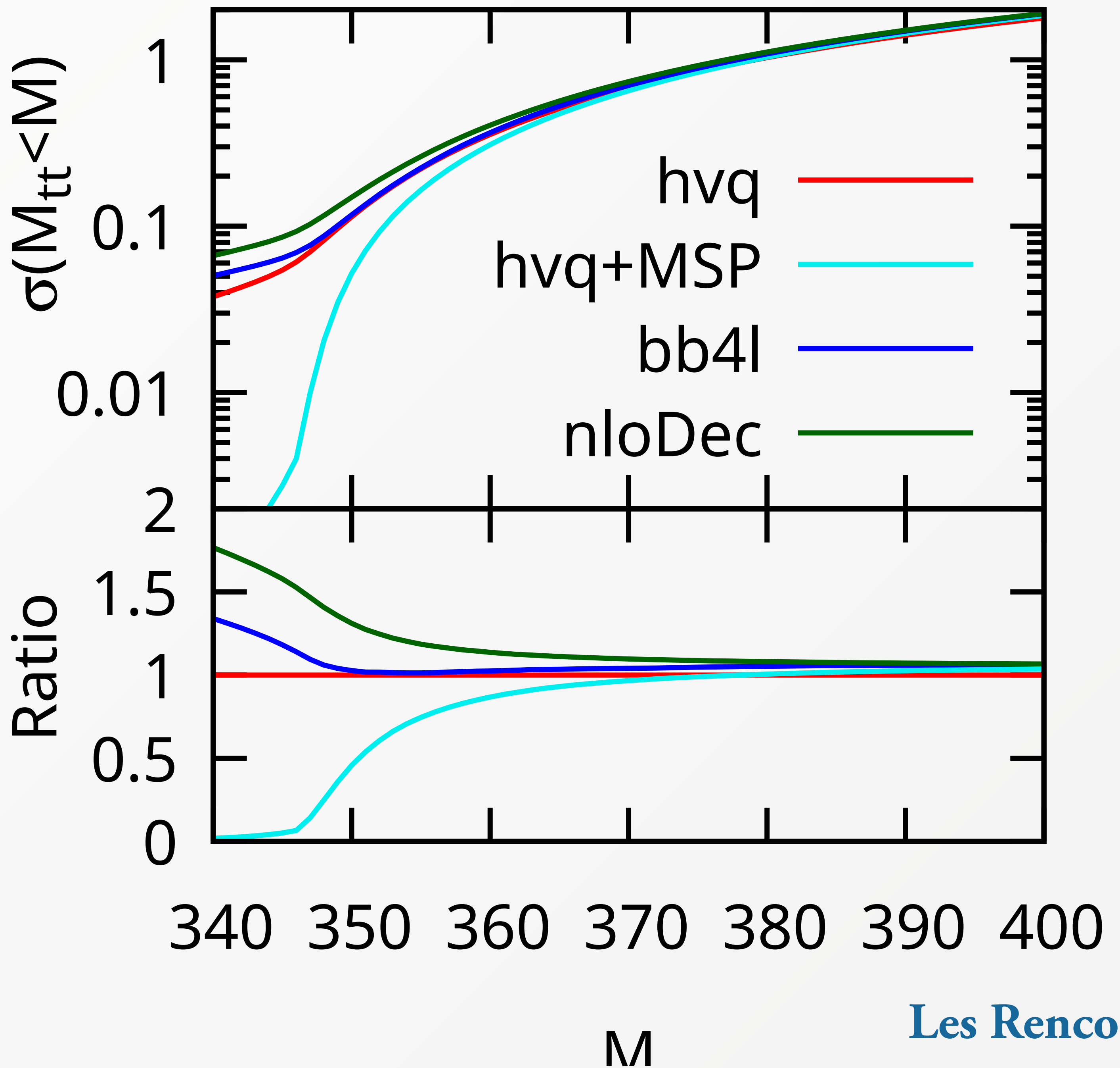
The tension with data disappears at NLO



Residual dependence on the generator used, to be investigated

Monte Carlo results at NLO





Four generators:

- `POWHEG-hvq` **[Frixione,Ridolfi,Nason,2007]**
- `hvq+MDS`: hvq with the MadSpin decays **[Artoisenet et. al 2013]**
- `POWHEG-ttb_NLO_dec`, **[Campbell,Ellis,Re,Nason]**
- `POWHEG-bbar_4l` **[Ježo,Lindert,Oleari,Pozzorini,Nason,2016]**

Important differences depending upon which generator is used

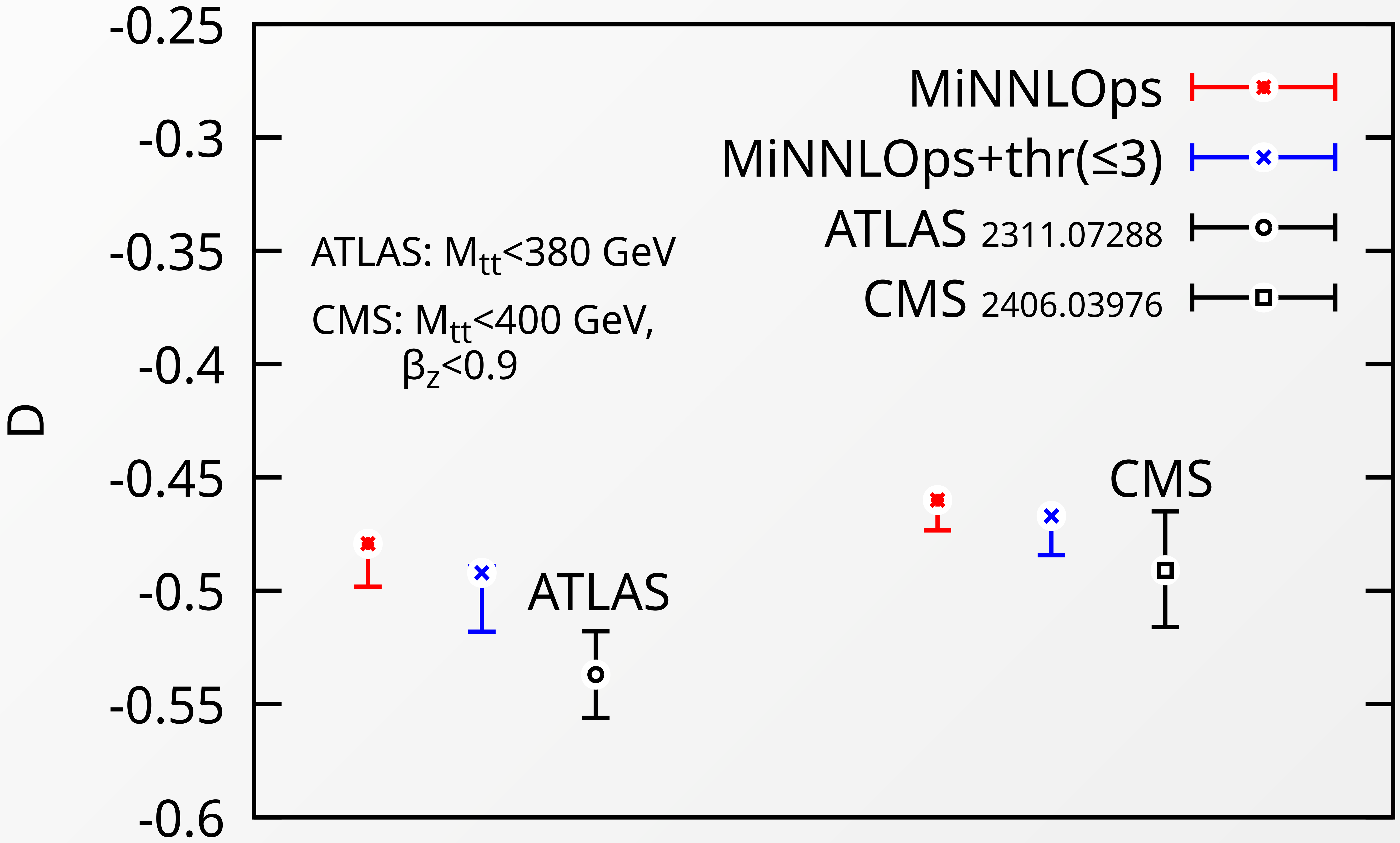
The generator differs in the way they implement spin correlation in decays, with `hvq` being the least accurate and `bb4l` the most accurate

`hvq` uses its own implementation of the algorithm of **[Frixione et al. 2007]** (also implemented in `MadSpin`)

Strong temptation to privilege the `bb4l` code, but since we have been unable to pinpoint the causes of the differences, **more studies are needed**

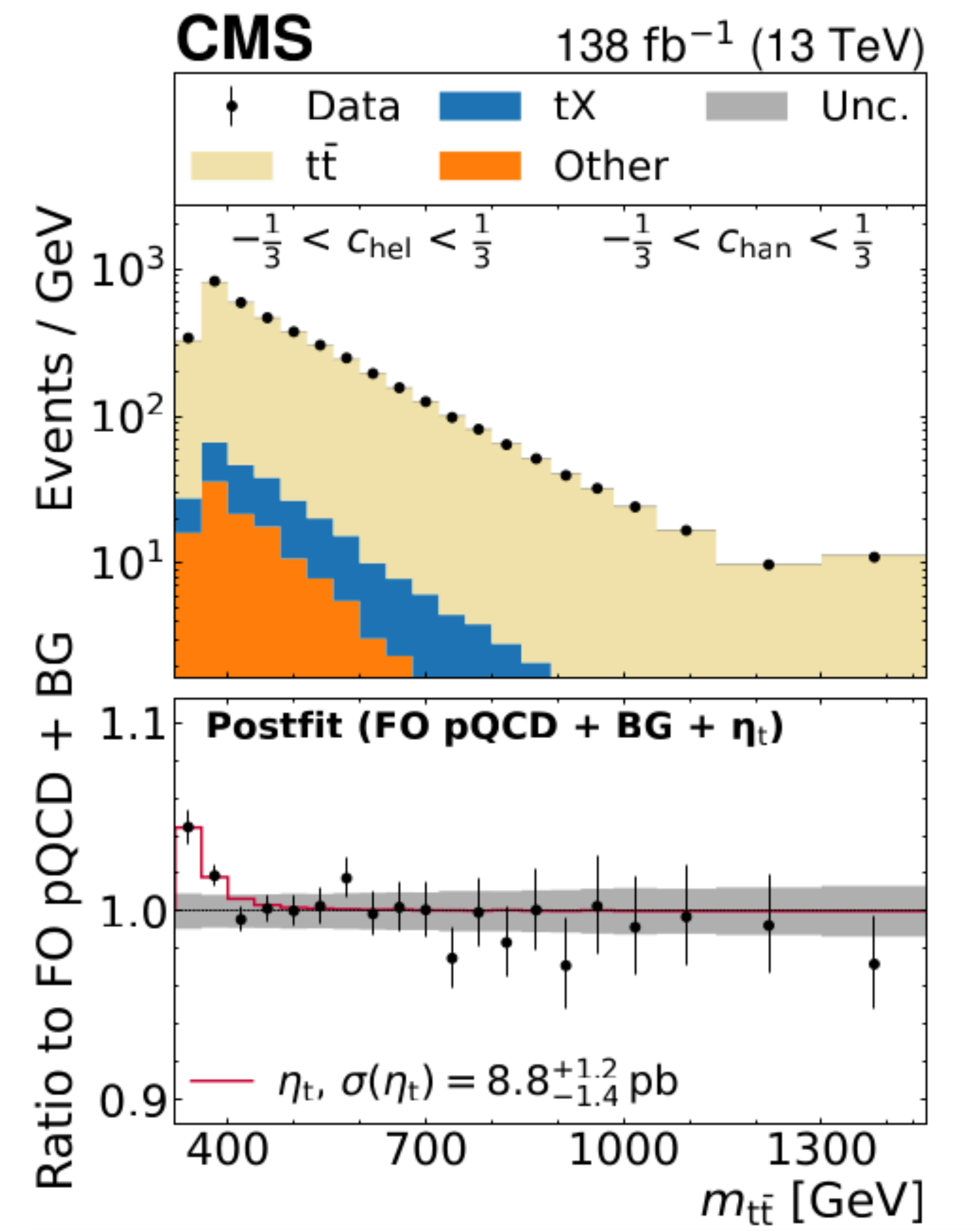
Comparison with data: NNLO

Using NNLO generators already decreases considerably the tension with data



Adding the a_s^3 correction leads to a small improvement

How about the pseudo scalar excess?



Excess estimated by

- Generating sample with `hvq`
- Reweighting performed such that normalisation of $m_{t\bar{t}}$ yields NNLO result as predicted by `MATRIX`
- Additional component fitted to the data, yielding 8.8 pb, argued to be consisted with estimates from the Green's function method

If we compute the threshold enhanced contributions to the cross section in the first bin $m_{t\bar{t}} < 360$ GeV we get

a_s/v	a_s^2/v^2	a_s^3/v^3	
3.36 pb	4.43 pb	1.56 pb	~ 9 pb

CMS, however, should include already a good portion of the a_s/v and a_s^2/v^2 term

Tension with CMS/ATLAS results remains

Conclusions and final remarks

- It is not necessary to fully solve the bound state problem in order to compute spin correlations effects in $t\bar{t}$ production and decay as long as the experimental resolution in the $M_{t\bar{t}}$ is large
- Event simulations must deliver reliable predictions near kinematic thresholds. While feasible in practice, ensuring that cross sections integrated over relatively broad threshold bins match perturbative results is nontrivial
- Comparison with data for the pseudoscalar excess needs to be understood. Unfolded cross sections from CMS and ATLAS are crucial to really understand if the excess is compatible with the Standard Model
- Other possible explanation of the discrepancy, such as limitations in current MC generators, need more studies. In particular, studies with the decay process treated at NNLO accuracy are badly needed