DM: EFT validity and truncation

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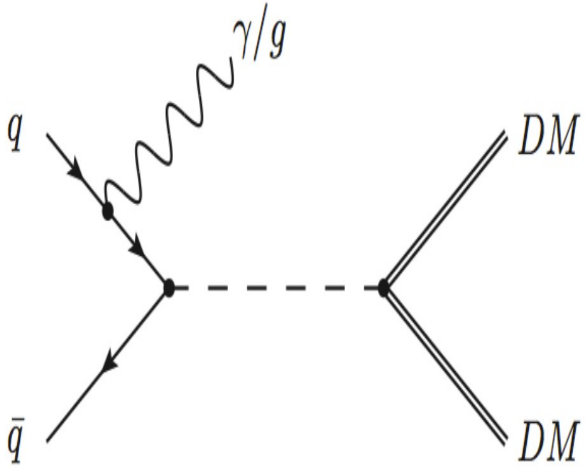
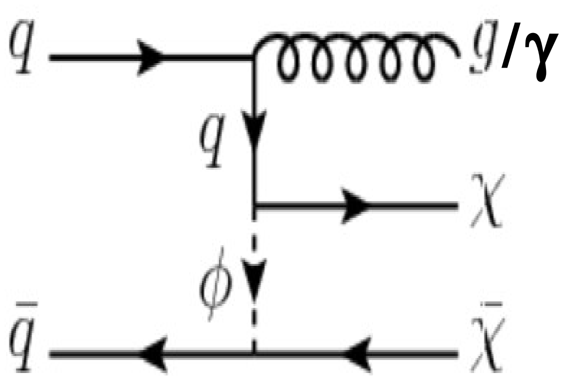
Introduction / disclaimer

- Disclaimer: this is NOT a talk comparing Simplified Models versus EFT approaches. Not even a talk to discuss whether EFT is a sensible way to search for dark matter at LHC or not.
- The objective of this talk is to discuss:
  1) How to deal with EFT in the region where it gives random answers and leads to optimistic limits. There was no specific CMS convention to deal with this until now.
  2) We are considering two approaches around: a) **QUANTIFICATION** of how wrong we could be if we do not correct anything; b) modifying the experimental search to be conservative (event **TRUNCATION**, discussion started on March 12th DM forum by ATLAS). Note that for cases where the quantification concludes "not OK", only truncation can give us any hope to get some sensible experimental information.

What is behind the EFT logic

True model

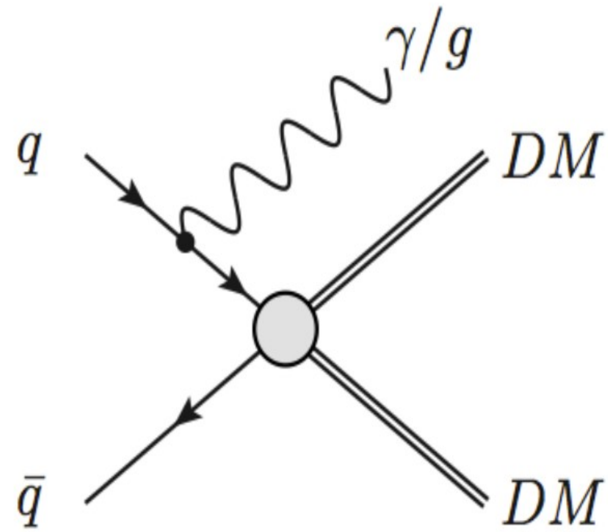




Mediators of mass ≈Λ, couplings of size ≈1

⇒

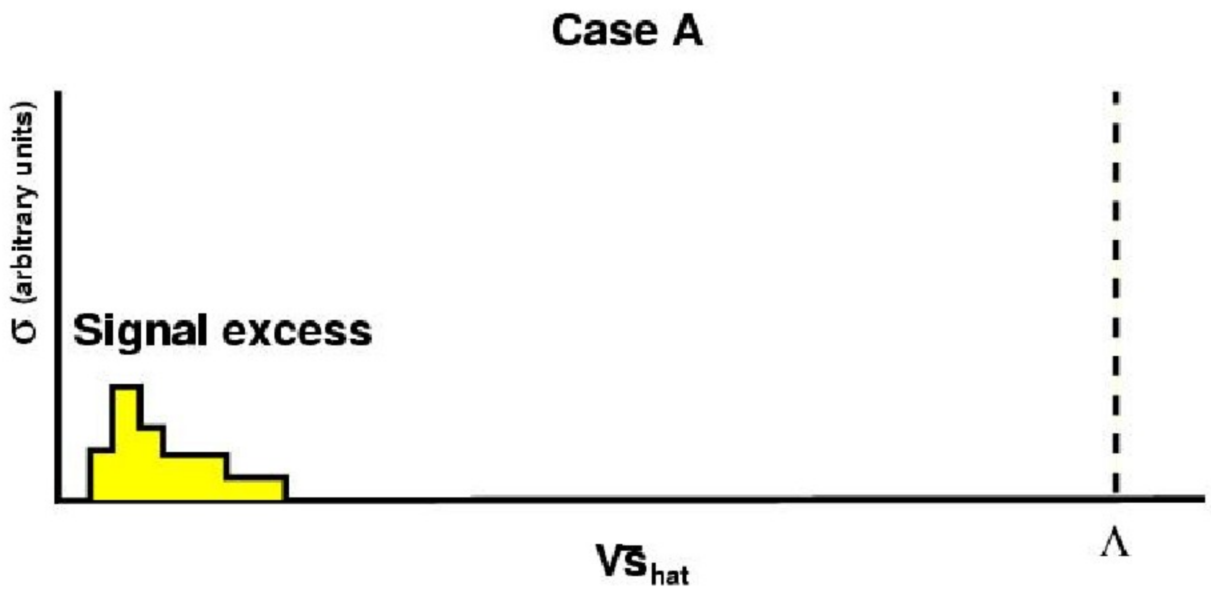
EFT



Λ much larger than the exchanged energies in the collision

Dimensional coupling at blob, only the leading terms in a $(1/\Lambda)^N$ expansion needed

EFT when Q ($\approx\sqrt{s}_{hat}$) $\ll\Lambda$

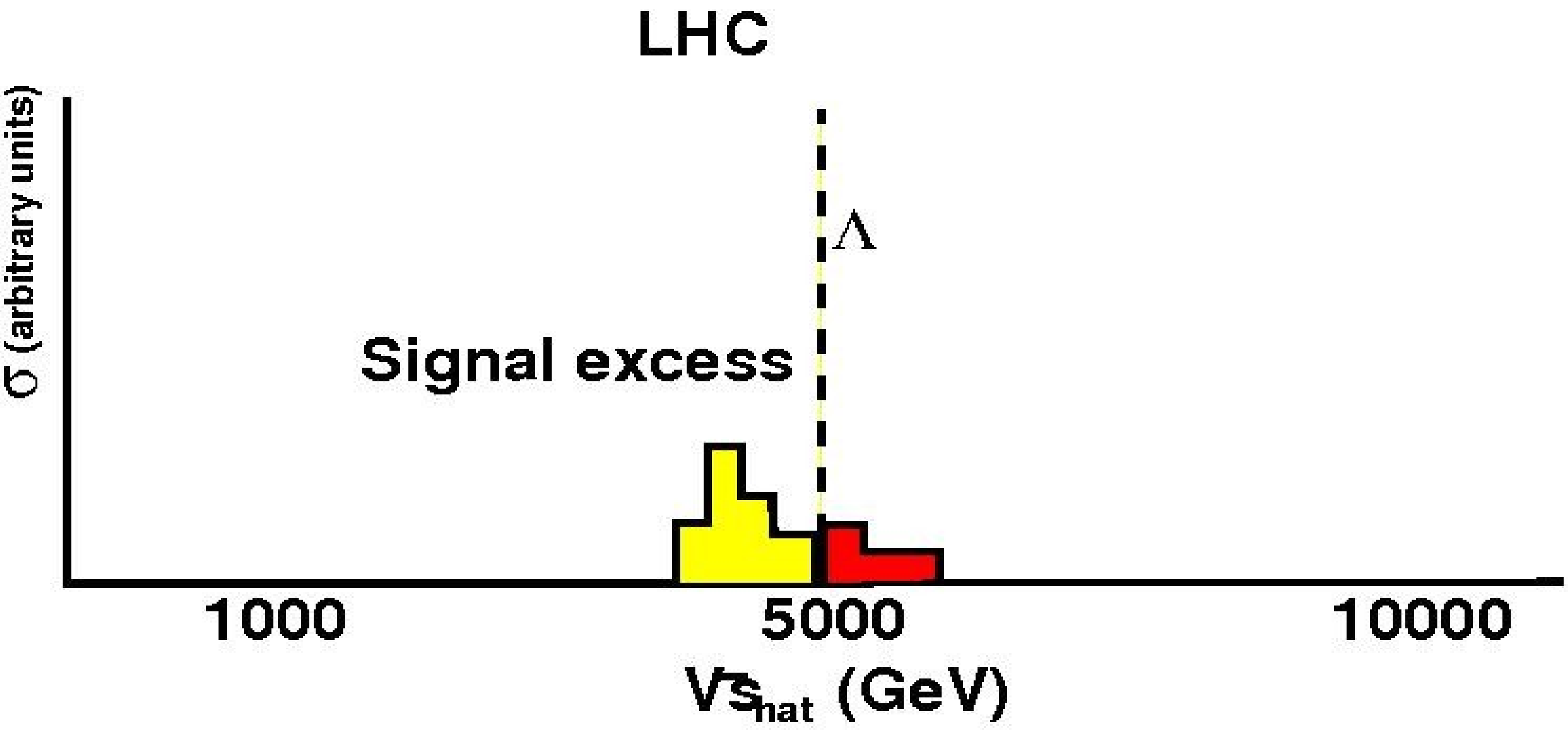


- If $\sqrt{s} \ll \Lambda$ no higher order terms must be considered:

$$\frac{\text{Anomalous coupling}}{\Lambda^n} \equiv \frac{f}{\Lambda^n}$$

which does not depend on $\sqrt{s}_{hat}$

NOT OK when Q ($\approx\sqrt{s}_{hat}$) $\gtrsim\Lambda$

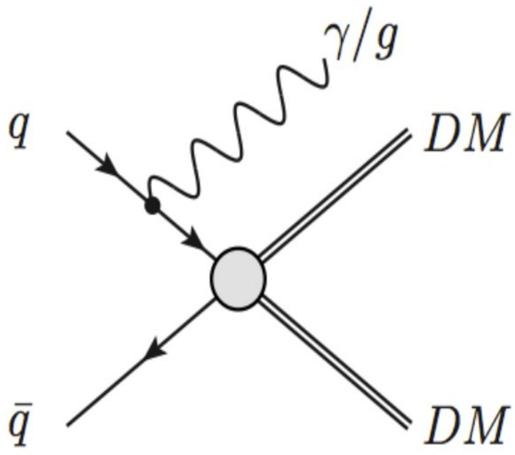


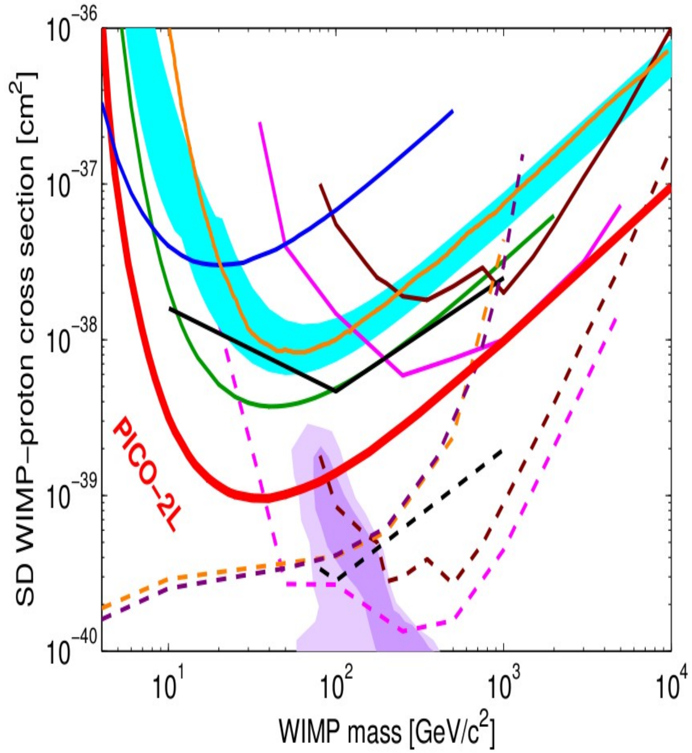
- In this case, there is no clear recipe. One needs to know exactly the "underlying" new physics theory near thershold (SUSY could be an example).

The issue is not new

- Intrinsically speaking this is not a new problem. It is a known concern for all searches using effective Lagrangians related with a scale of new physics Λ. When the energy transferred in the hard scattering process Q is such that $Q \gtrsim \Lambda$, then the approach is 'invalid' or at least 'incomplete'. For several reasons: a) unitarity violations, b) an expansion in powers of (Q/Λ) does not make much sense if we do not know the coefficients.

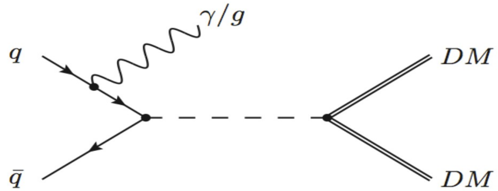
- At the end of the day the main driving argument in these DM discussions is the 'desire' to appear in the well known 'key' plot comparing our results with other Direct Detection searches.





First on unitarity issues

- The desire to appear in a plot of comparison with Direct Detection cross section limits has biased the discussion in the DM EFT business towards a slightly different place compared to other searches:
  - The typical issue in current DM discussions is about the EFT Lagrangian not being an accurate prediction for the model for Q≳Λ. Unitarity is only addressed in terms of order of magnitude of coupling (g<4π is used as a non-perturbative 'wall').



$$\frac{1}{Q_{\rm tr}^2 - M^2} = -\frac{1}{M^2}\left(1 + \frac{Q_{\rm tr}^2}{M^2} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{M^4}\right)\right)$$

  - In other searches we are happy with an approximate way to quantify deviations, even knowing than EFT is not an accurate description, and the main discussion is about whether or not the EFT Lagrangian violates unitarity “quantitatively” because of a huge cross section (→use of form factors for aTGCs, Q>Λ truncation, ...)
- Both views are obviously related, but let me note that the latter has been essentially ignored in the DM discussions until now.

Quantitative unitarity constraints

- I am talking about the usual unitarity conditions, connecting the differential inelastic cross section with the imaginary part of the elastic total cross section. I.e. the differential cross section derived from the DM Lagrangian can not be arbitrarily high.
- Most of the constraints for the usual DM Lagrangians have been collected for example in: http://arxiv.org/abs/1403.6610:
  - For vector-vector and axialVector-axialVector cases and mass(DM) << Q:

$$Q < 5.1\ \Lambda \qquad \Lambda_V \geq \left[\frac{\bar{s}(\bar{s}+2m_{\rm DM}^2)}{72\pi^2}\sqrt{1-\frac{4m_{\rm DM}^2}{\bar{s}}}\right]^{1/4}$$

  - To be compared with the usual recipe (Busoni et al.):

$$Q < M_{mediator} \equiv g\ \Lambda$$

- I.e. if the coupling "g" is larger than 5 (4 in the scalar case),the Q<M condition is even too loose. **Unavoidable unitarity constraints on the chosen Lagrangian terms seem to be more stringent than the qualitative condition g<4π.**

Quantifying before truncating

- I will only discuss operators via s-channel. This covers almost all operators we current use in the EFT approach. The logic to deal with t-channel operators is similar to the s-channel, but the details of the momentum transfer are more involved. Also LHC is less sensitive to this scenario if we need to 'truncate' (http://arxiv.org/abs/arXiv:1405.3101).
- The recipe from Busoni et al. (http://arxiv.org/abs/arXiv:1402.1275) quantifies what is the fraction of events used in the analysis that makes sense for EFT, i.e. the fraction satisfying Q<mass(mediator):

$$R_{M_{mediator}} = \frac{\text{fraction of used events with } Q_{tr} < M_{mediator}}{\text{total used events}}$$

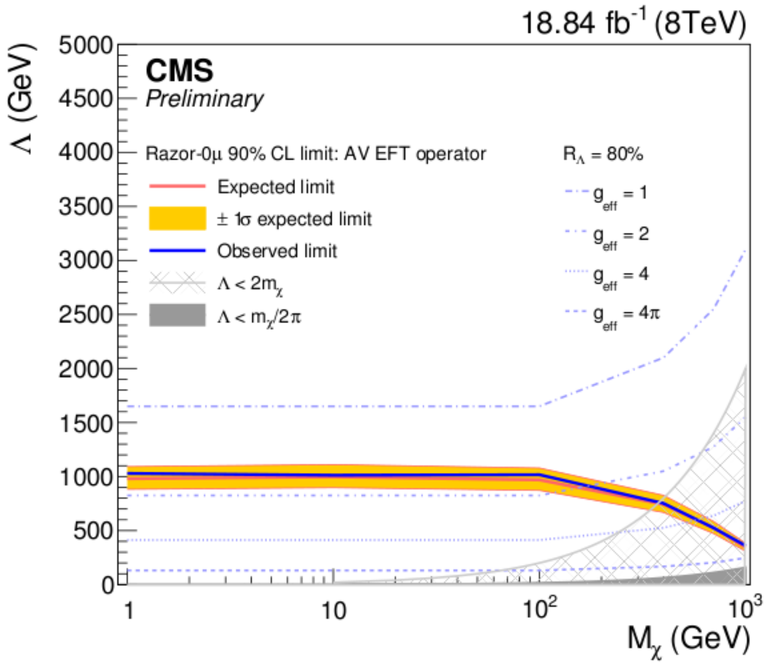
$$Q_{tr} = \text{mass of the system of the two DM particles}$$

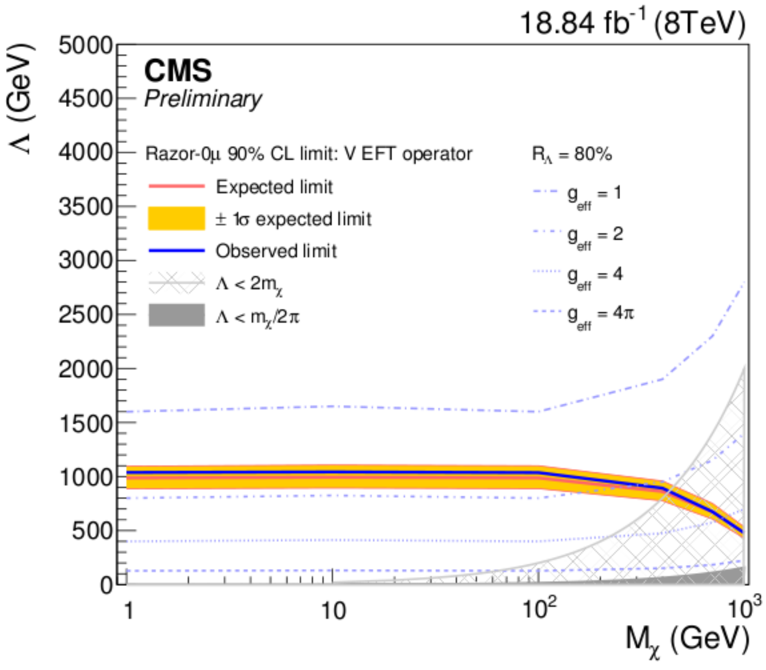
- The paper above focuses on Q_{tr}^2 as $(p_{parton1}+p_{parton2}-p_{jet})^2$. This is also the mass squared of the DM pair system. But note that for our estimates we just need to count events at the hard scattering generator level. So it is simpler than using jet momenta and initial state partons (it can be trivially extended to cases with more ISR jets !!).

Example of what we do (CMS-EXO-14-004)

$$R_{M_{mediator}} = \frac{\text{fraction of used events with } Q_{tr} < M_{mediator}}{\text{total used events}}$$

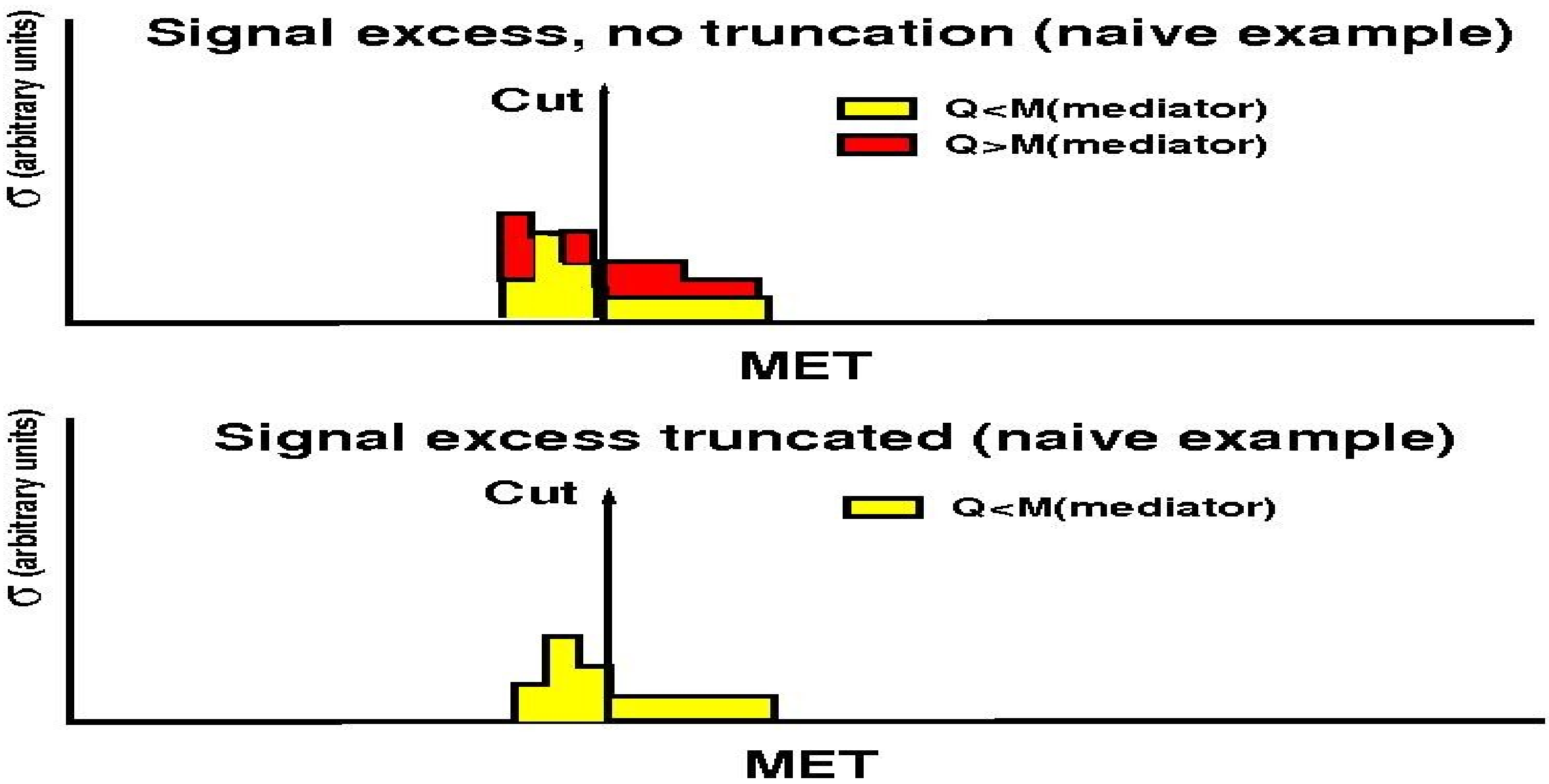
$$Q_{tr} = \text{mass of the system of the two DM particles}$$





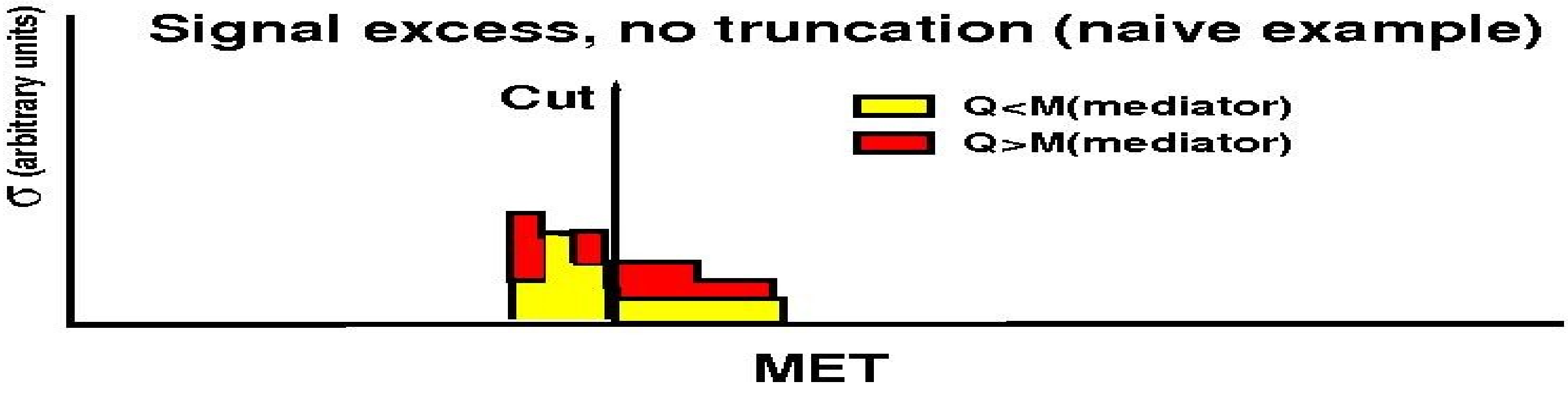
- Since M_mediator = g * Lambda and we have Lamdba in the plot, there are different curves for different “g”s.

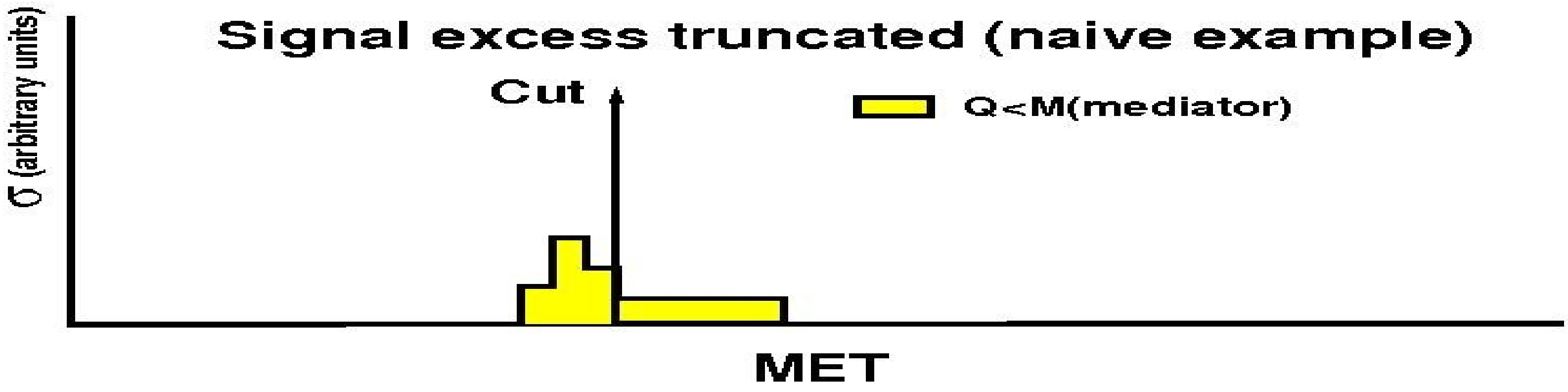
Truncation for Q>M



1) **Note that this is a conservative treatment.** For the yellow part our single term EFT hypothesis is basically OK (quantitatively it still depends on the exact details of the theory when Q~M, but it is even conservative in the s-channel due to resonant enhancement). In the red region we do not know the true UV completion, but it can not be worse than a “zero” cross section.

Truncation for Q>M

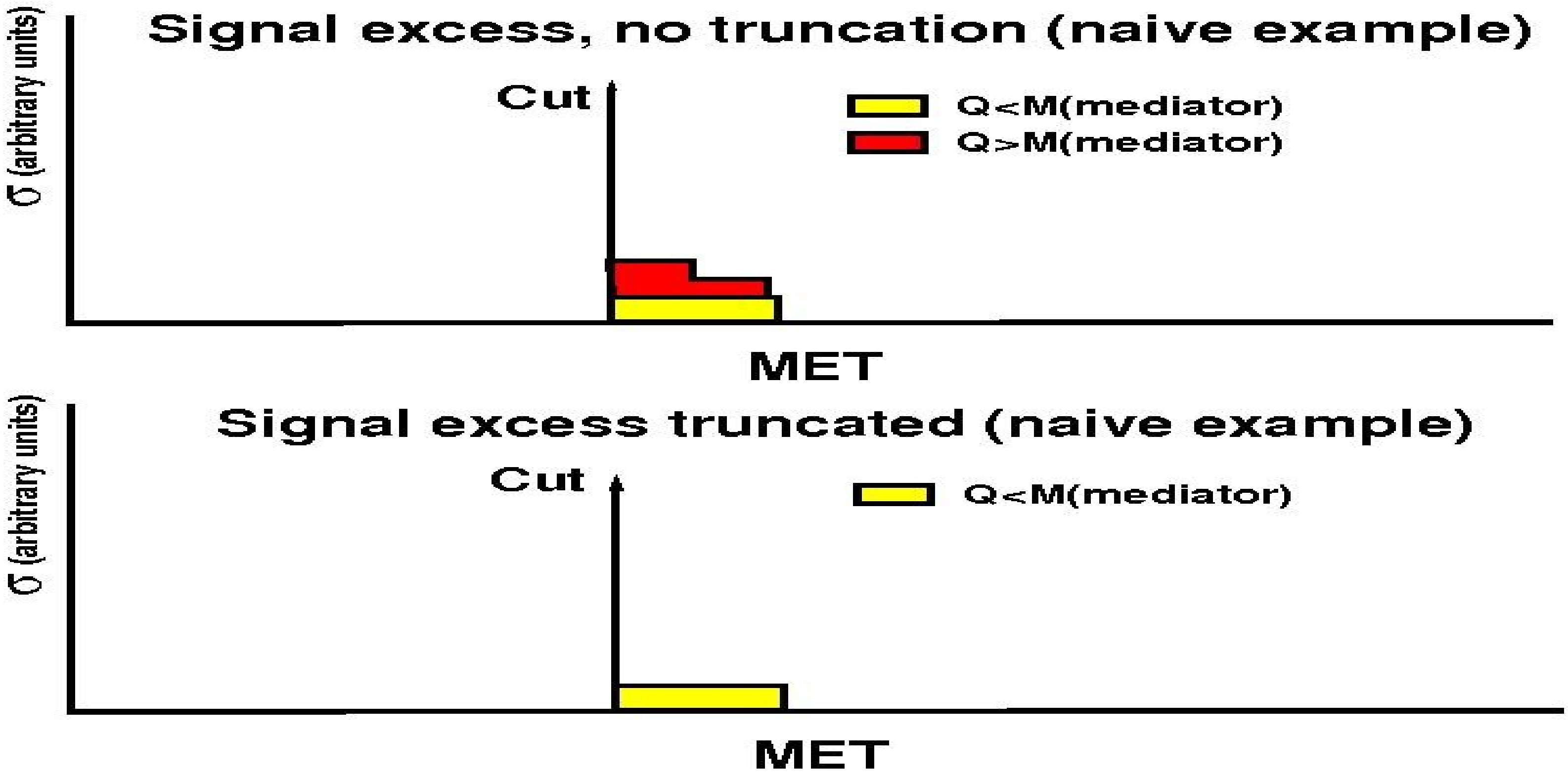




2) We are already using this truncation in other searches/analyses:

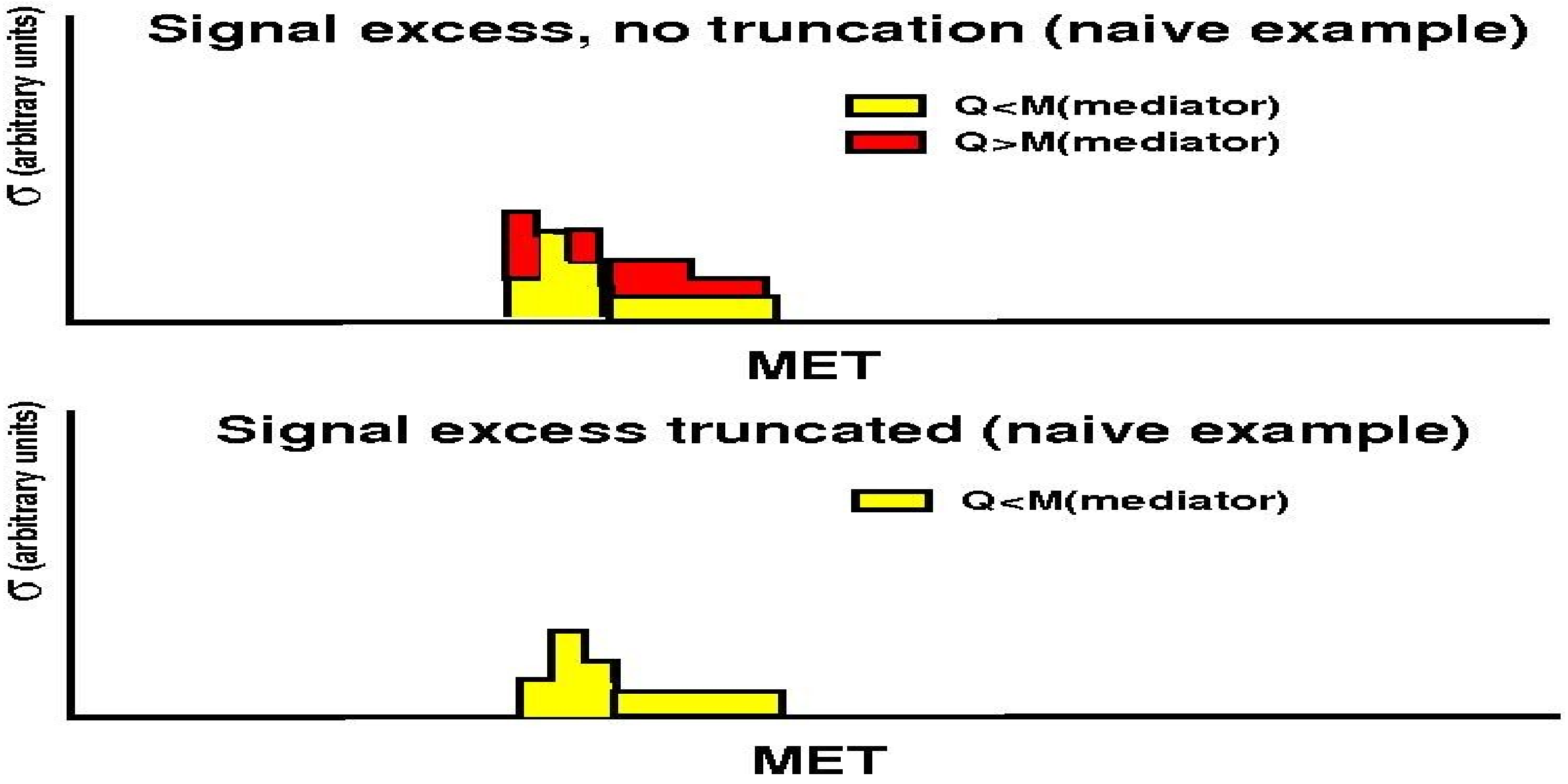
- ADD deviations in dilepton channels
- aTGC measurements too
- ...

Truncation: cut based (ATLAS recipe)



- Recipe: recalculate the expected selected cross section after truncation as a function of M. Then map the observed cross section limit into a limit on M.
  - It assumes no change in the analysis, just that the number of predicted signal events has to be re-scaled after truncation.
  - But it does not work for a more general shape-based analysis (see next slide).

Truncation: shape-based analysis (general)



- Recipe: redo the analysis dropping events with Q<M(mediator).
  - Logically simple.Technically as complicated as the cut-and-count case (it requires the same loop operation on the generator information for accepted events).
  - It leads to an M-dependent analysis. But most LHC searches are mass-dependent, there is nothing fundamentally complicated here.
  - Less pessimistic than it could seem at first sight (internally tested at CMS).

Summarizing

- The coupling "g" can not be larger than 4-5 in general (small M_{DM}) for $\sqrt{s} \gtrsim M(\text{mediator})$ due to unavoidable unitarity bounds for the Lagrangian terms.
- The removal of events with $\sqrt{s}>\Lambda$ is a simple way of obtaining conservative limits for an EFT (s-channel Lagrangian) analysis. This imposes that the cross section in the UV completion region goes very rapidly to zero for $\sqrt{s}$ above Λ.
- A reevaluation of the accepted cross section after truncation is only applicable to a pure cut&count analysis (with one bin). A direct event removal for $\sqrt{s}>M(\text{mediator})$ is conceptually simple as an algorithm and also valid for a general shape analysis.
- We propose a two-step logic:
  - Evaluate how much percentage of the initially accepted number of events survives after truncation (convention to use 80% as a reasonable estimate of what is reasonable to avoid truncation?).
  - Do event truncation if too many events get cut out: it leads to conservative limits for s-channel terms.

Some references

- R integral definition and Q upper edge discussion:
  - General: Busoni et al, http://arxiv.org/abs/arXiv:1307.2253
  - S-channel: Busoni et al, http://arxiv.org/abs/arXiv:1402.1275
  - T-channel: Busoni et al, http://arxiv.org/abs/arXiv:1405.3101
  - Ultra-safe approach (not used): Racco, Wulser, Zwirner, http://arxiv.org/abs/1502.04701

- ATLAS truncation method:
  - Main reference: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2014-007/
  - Presentation at DM forum by S. Schramm: https://indico.cern.ch/event/379191/session/1/contribution/6/material/slides/0.pdf

- General reviews on approaches for DM searches at LHC:
  - Oxford meeting: http://arxiv.org/abs/1409.4075
  - ATLAS side: http://arxiv.org/abs/1409.2893