Top invariant mass measurement as a window on BSM

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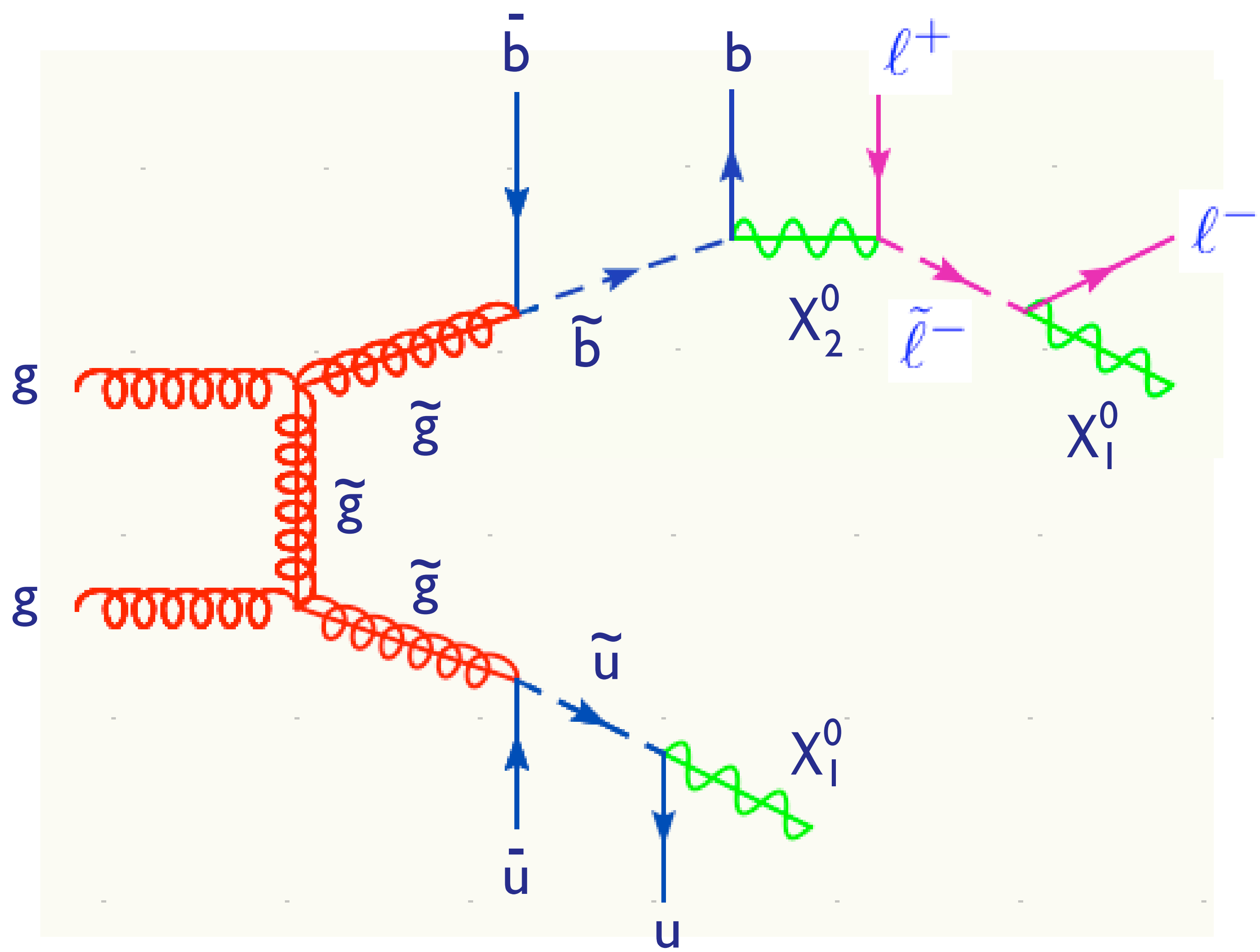
based on
R. Frederix, F.M. , arXiv:0712.2355

Outline

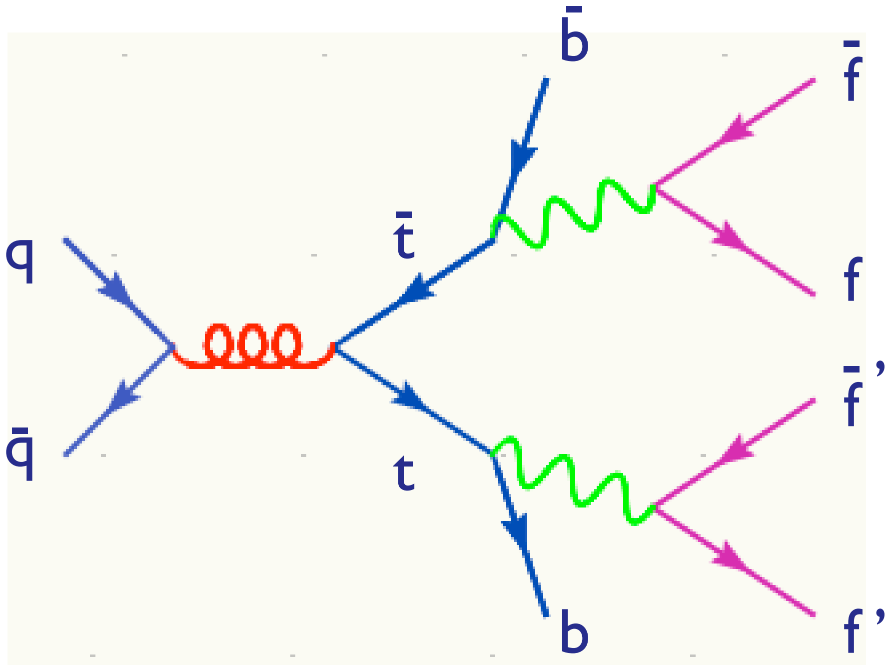
- Strategies for BSM at the LHC
- Top BSM potential
- Focus on m_{tt}
  - SM predictions
  - $pp \to X \to tt$: three step analysis
- Perspectives

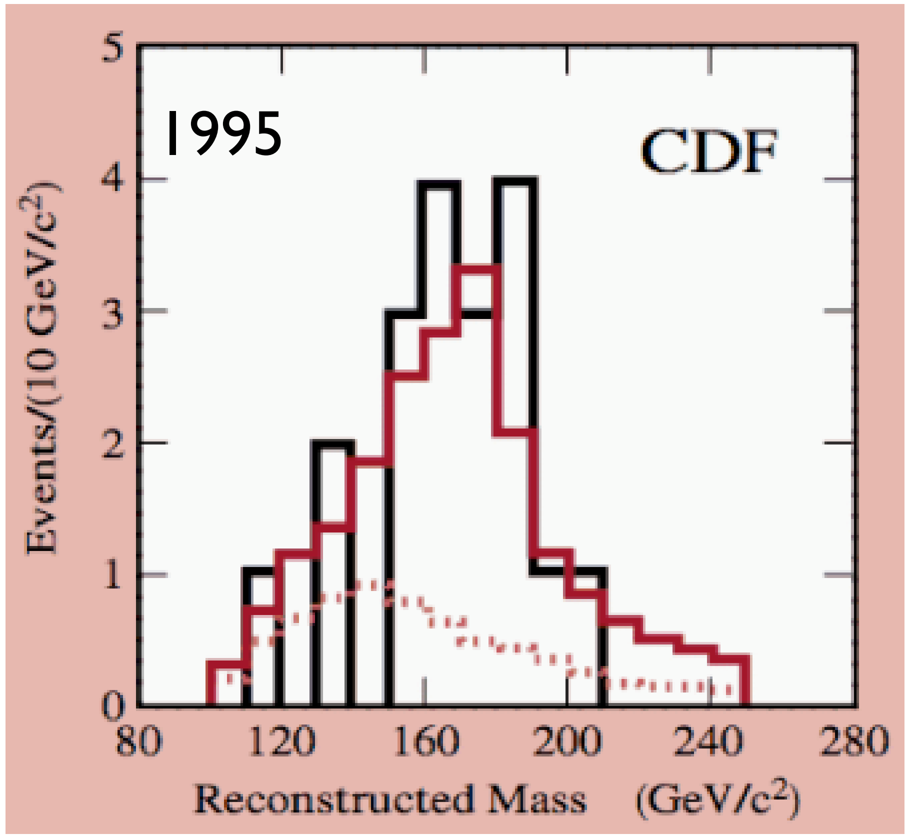
How are we going to discover BSM at the LHC?



Heavy states decaying in jets and leptons and $\not{E}_T$.

A lesson from the top





How did it go?

0. The only unknown was the top mass!

1. The experimentally easiest channel for triggering/ reconstruction/background-control was chosen.

2. Mass reconstruction employed

3. Backgrounds estimated via control samples with heavy flavors and also via MC ratio's.

4. Number of events consistent with the cross section expectation from QCD

Handful of events was enough!

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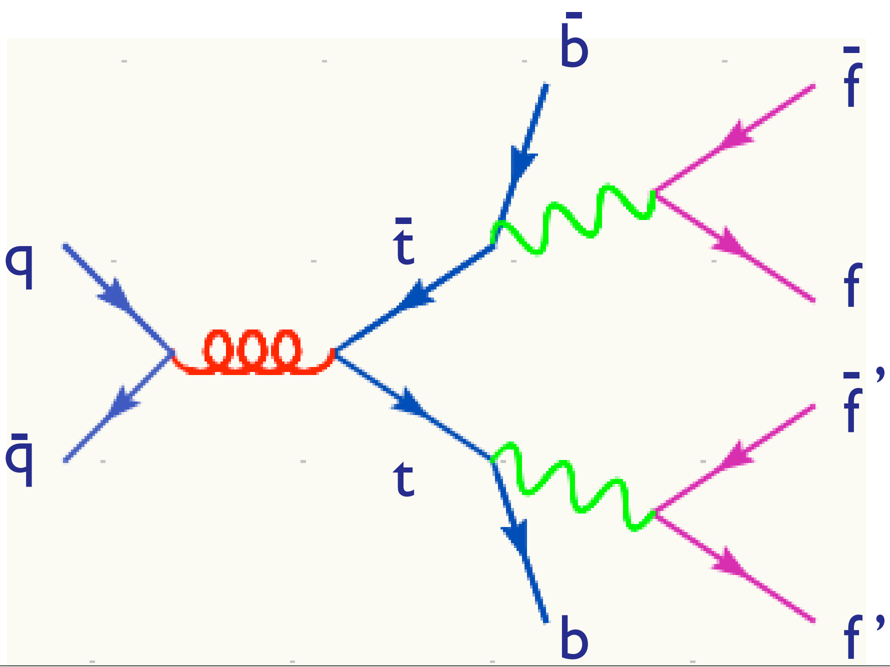
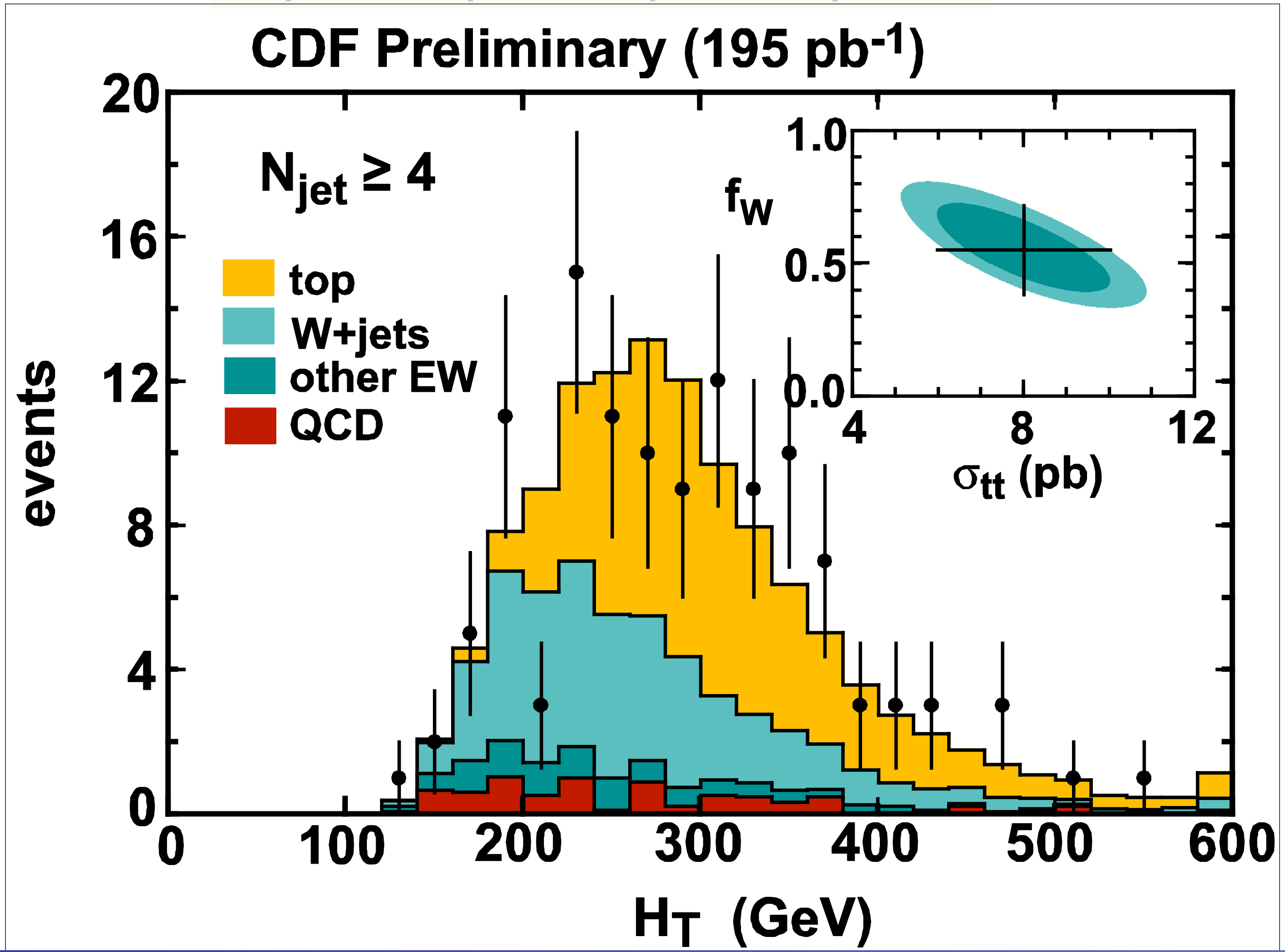




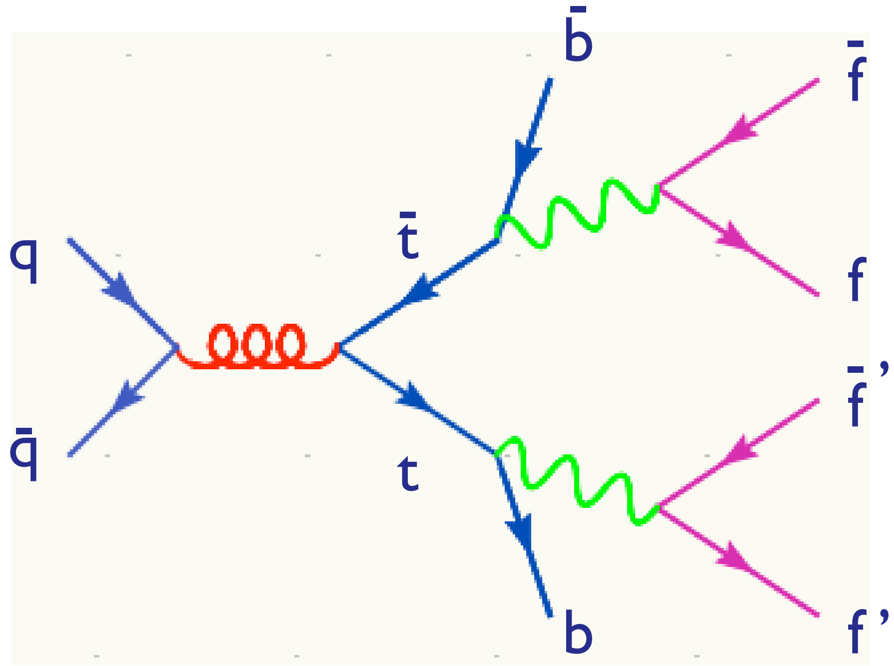
Immediately confirmed in Run II, also by the most inclusive measurements, H_T.

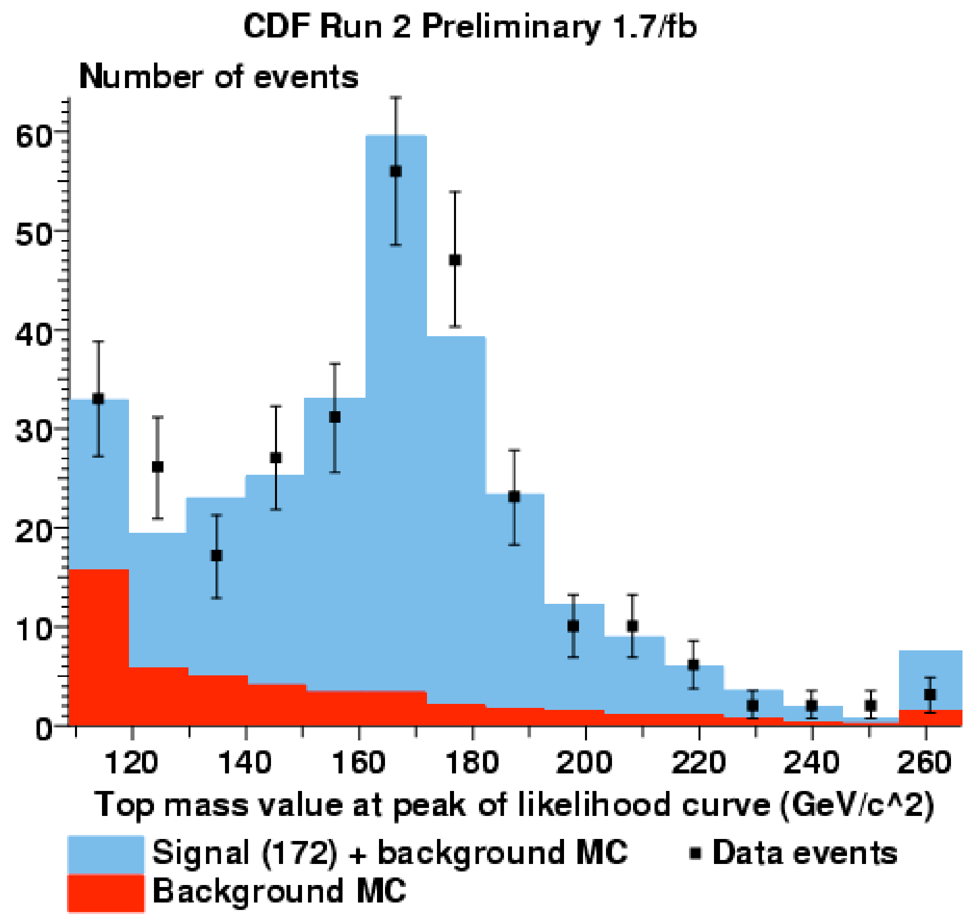
Other channels start to be considered as the statistics increases to have a consistent picture.

Cleaner and cleaner samples more exclusive studies:

1. W Polarization
2. BR's ratio's
3. Top Quark charge
4. Differential m_{tt} distribution
5. Search for new physics!!

A lesson from the top





Summary:

1. More than15-year long story

2. At all stages MC's played a role.

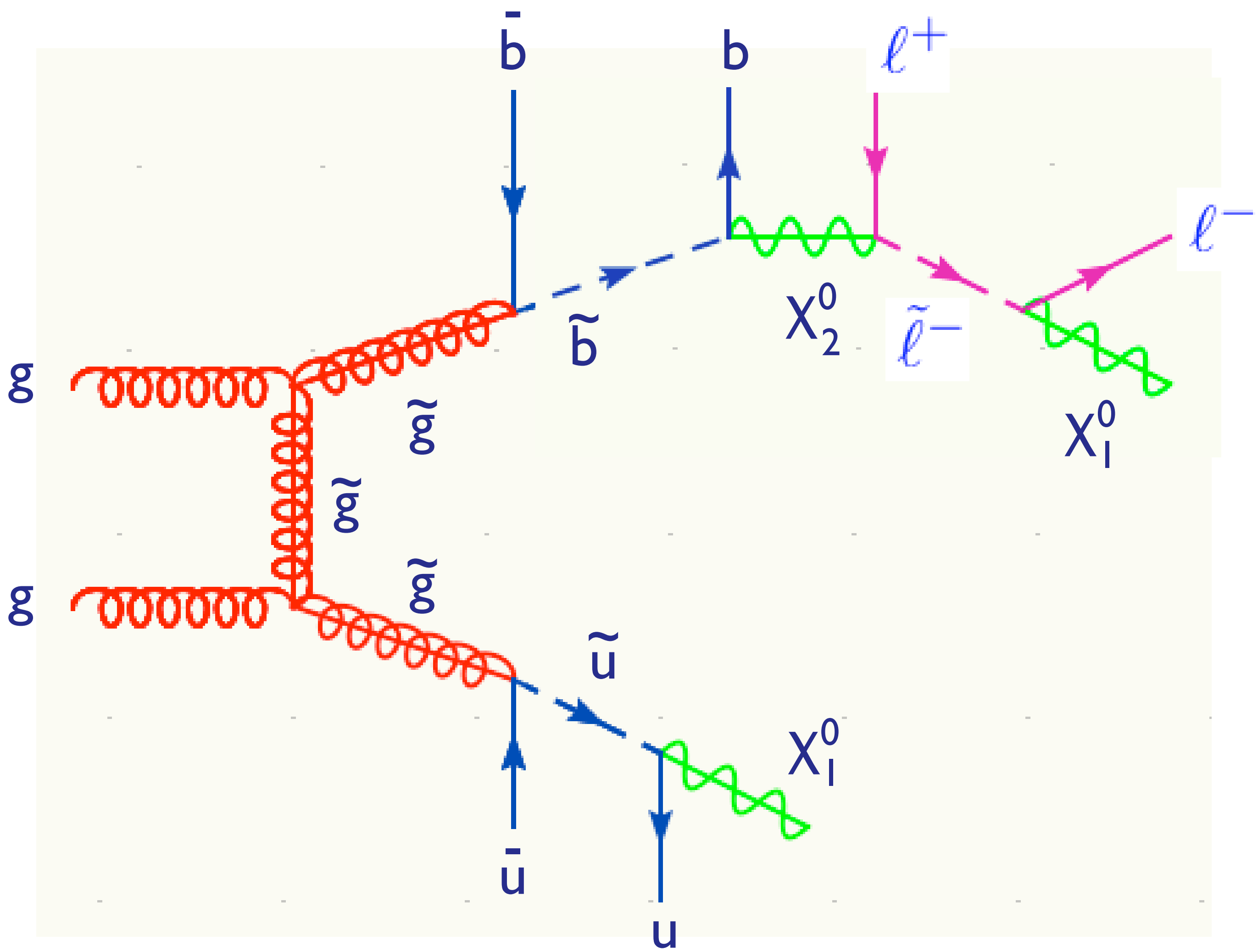
3. Now all studies, including the mass measurements, are strongly based on our simulation tools, i.e., matrix element methods.

More sophisticated analysis need more sophisticated MC's...

Is this strategy directly applicable to new heavy state searches?

A lesson from the top

Susy inclusive searches are similar but more complicated final states.



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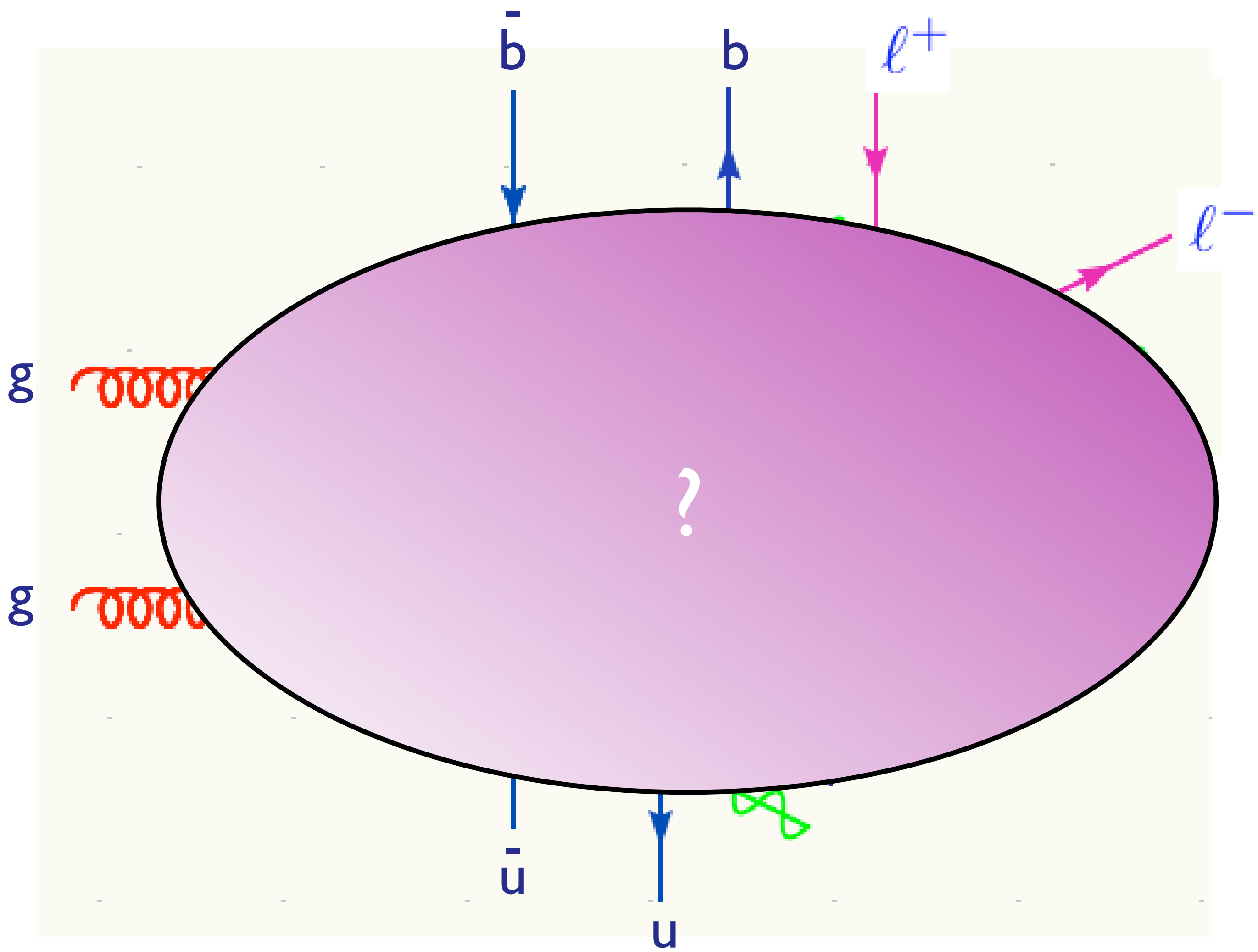


The main difference is that we don't know what to expect!!

Two approaches

- For new physics associated, two approaches are possible:
  - top-down (e.g. , model parameter scanning)
  - bottom-up (e.g., inverse problem, OSET)
- Different EXP strategies and different TH and MC tools:
  - Well defined models vs coarse structure
  - Extremely optimized (-> non portable) analyses vs general searches
  - Dedicated MC tools vs multipurpose MC's

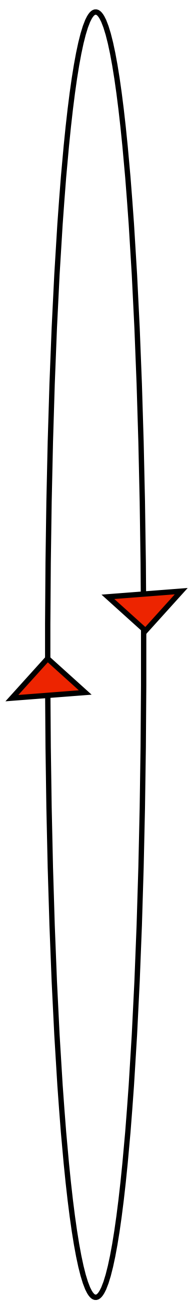
The ambitious plan

1. Find excess(es) over SM backgrounds

Fully exclusive description for rich and energetic final states (multi-jets + EW and QCD particles (W,Z, photon,b,t).

Flexible MC to be validated and tuned to control samples.

Accurate predictions (NLO,NNLO) for standard candles SM cross sections (with final state acceptance)



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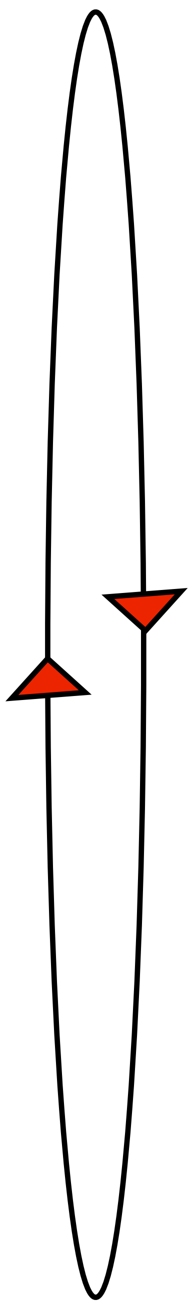

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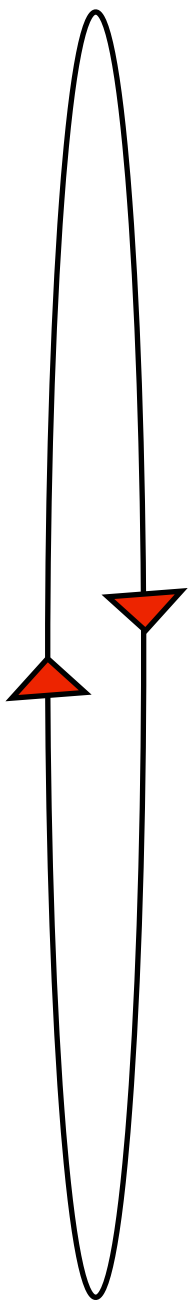

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Simulation of any BSM signature: from models to events in an easy and fast way.

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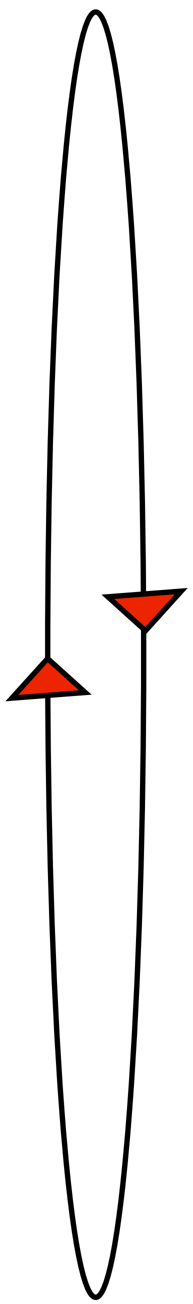

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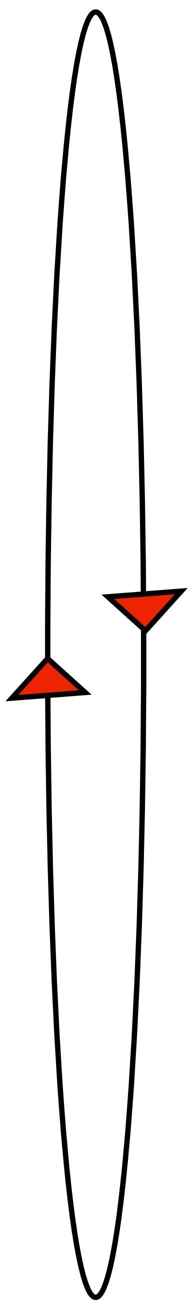

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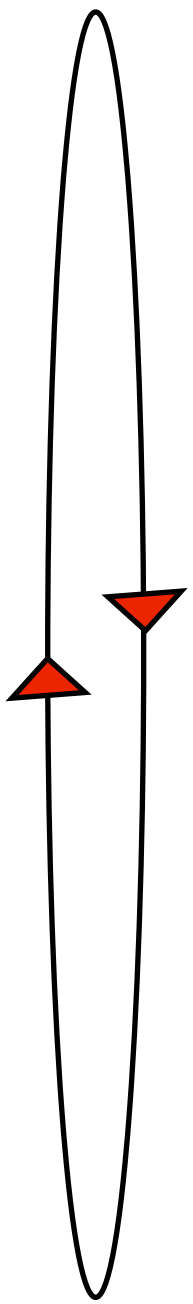

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6. Refine

Off-shell effects, Matrix Element methods, Global fits (Ex: Sfitter)

A more modest bottom-up strategy

1. Focus on a specific SM observable that is

   a. naturally sensitive to BSM
   b. is well-predicted & possibly "background free"

2. Search for a simple signature, eg "a peak" in a "model independent" way.

3. Information vs luminosity plan.

Tools:

* MC@NLO for the signal
* Multipurpose tree-level MC (MadGraph)

Resonances in m_{tt}!!

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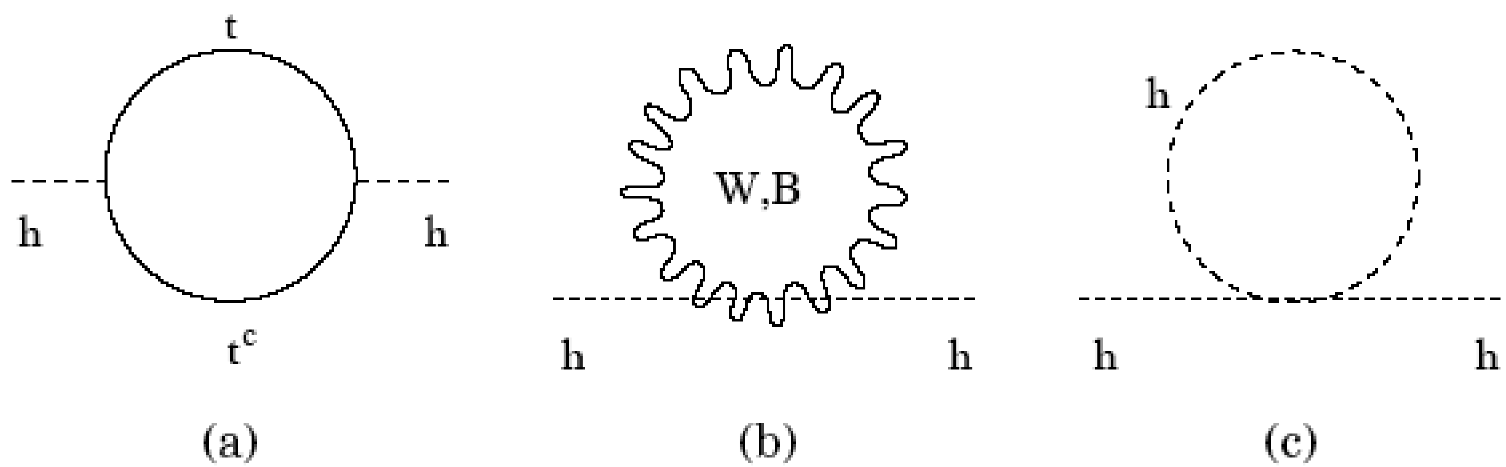
Hierarchy problem

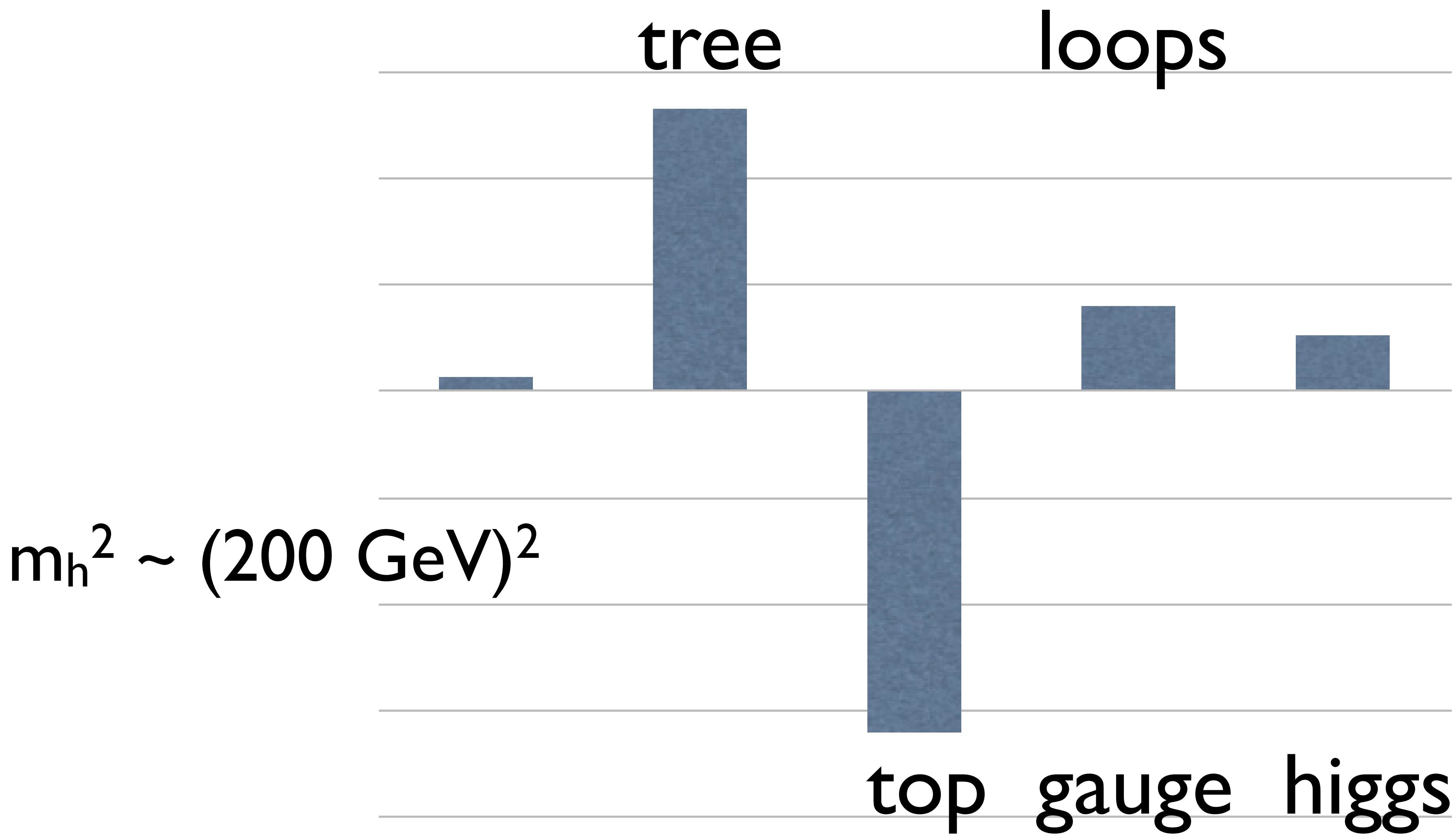
The top quark dramatically affects the stability of the Higgs mass:



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

$$(200\ \text{GeV})^2 = m_{H0}^2 + \left[-(2\ \text{TeV})^2 + (700\ \text{GeV})^2 + (500\ \text{GeV})^2\right] \left(\frac{\Lambda}{10\ \text{TeV}}\right)^2$$

Hierarchy problem



$$(200\ \mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\ \mathrm{TeV})^2 + (700\ \mathrm{GeV})^2 + (500\ \mathrm{GeV})^2\right]\left(\frac{\Lambda_{t,W,H}}{10\ \mathrm{TeV}}\right)^2$$

Definition of naturalness: less than 90% cancellation:

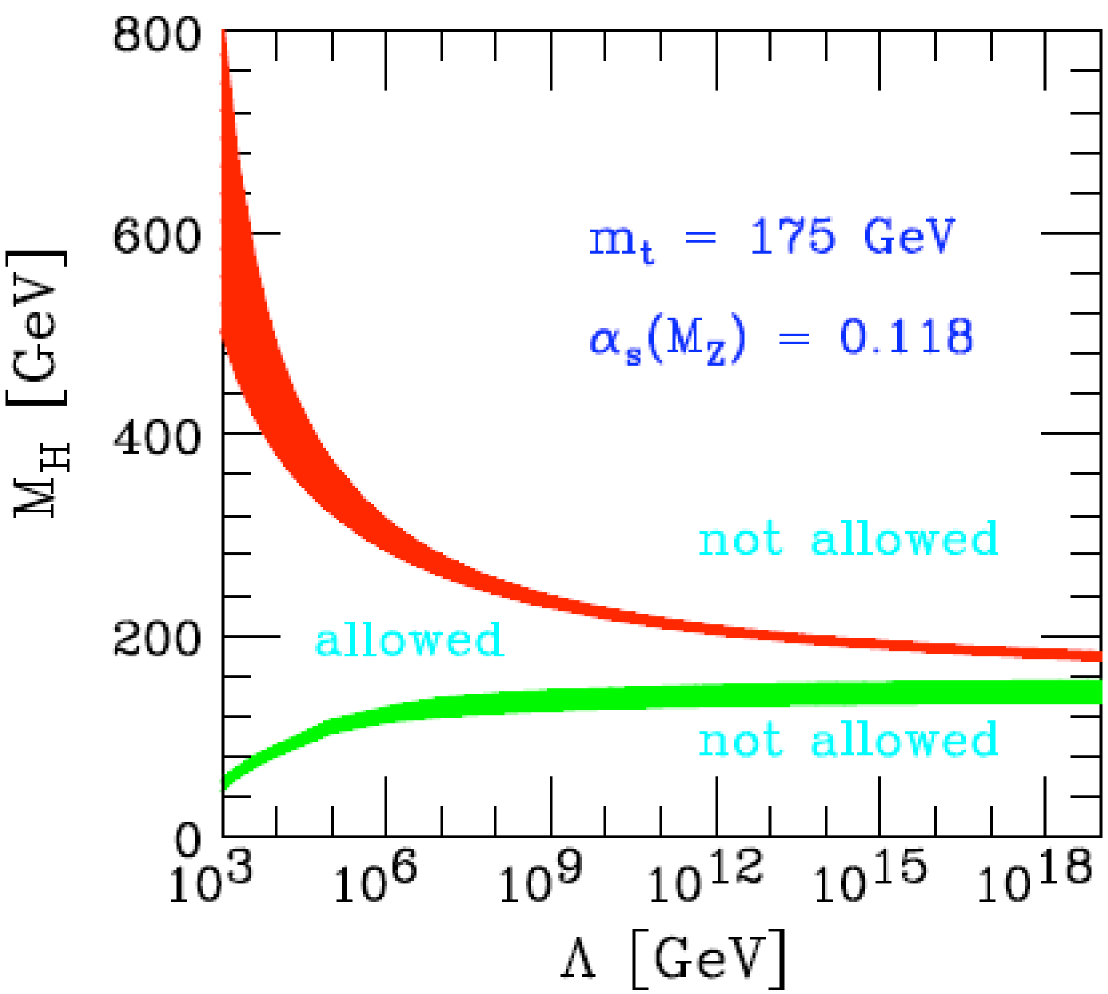
$$\Lambda_t \lesssim 3\ \mathrm{TeV} \quad \Lambda_W \lesssim 9\ \mathrm{TeV} \quad \Lambda_H \lesssim 12\ \mathrm{TeV}$$

* One can actually prove that this case in model independent way, i.e. that the scale associated with top mass generation is the same as that of EWSB.

Available solutions

There have been many different suggestions! Fortunately, we can say that they group in 1+3 large classes:

1. Denial: There is no problem. The SM is valid up to very high scale if the Higgs is either not too light or too heavy. Naturalness is our problem not Nature's. Pro's: we'll find the Higgs. Cons: that's it.



Top: just the Higgs.

Available solutions

There have been many different suggestions! Fortunately, we can say that they group in 1+3 large classes:

2. Weakly coupled model at the TeV scale:
Introduce new particles to cancel SM "divergences".

- This requires new particles to be related to the SM ones by some symmetry ⇒ partners.
- If we require less than 10% fine tuning, typical scale for top partners <2 TeV.
- All other particles might be heavier ⇒ first TeV the scale of new physics typically associated with top.
- Examples: SUSY (renormalizable), Little Higgs (EFT).
- Pro's: many. Con's: almost excluded.

Top: top parters, new scalars/vectors possibly strongly coupled with top.

Available solutions

There have been many different suggestions! Fortunately, we can say that they group in 1+3 large classes:

3. Strongly coupled model at the TeV scale: New strong dynamics enters at ~1TeV.

- Introduction of new (techni-) particles charged under a non-abelian group (not QCD). Higgs is composite.
- Top often enters as a player.
- Examples: Technicolor, Topcolor, Top see-saw...
- Pro's: It has a strong physical motivation (QCD).
- Con's: not perturbative, difficult to make predictions. Strong constraints from EW precision fits and flavor physics.

Top: t-tbar bound states, colorons.

Available solutions

There have been many different suggestions! Fortunately, we can say that they group in 1+3 large classes:

4. New space-time structure: Introduce extra space dimensions to lower the Planck scale cutoff to 1 TeV.

- No fine tuning anymore.
- Examples: ADD,RS,UED...
- Pro's: very exciting and revolutionary.
- Con's: not very plausible.

Top: KK-excitations including gravitons.

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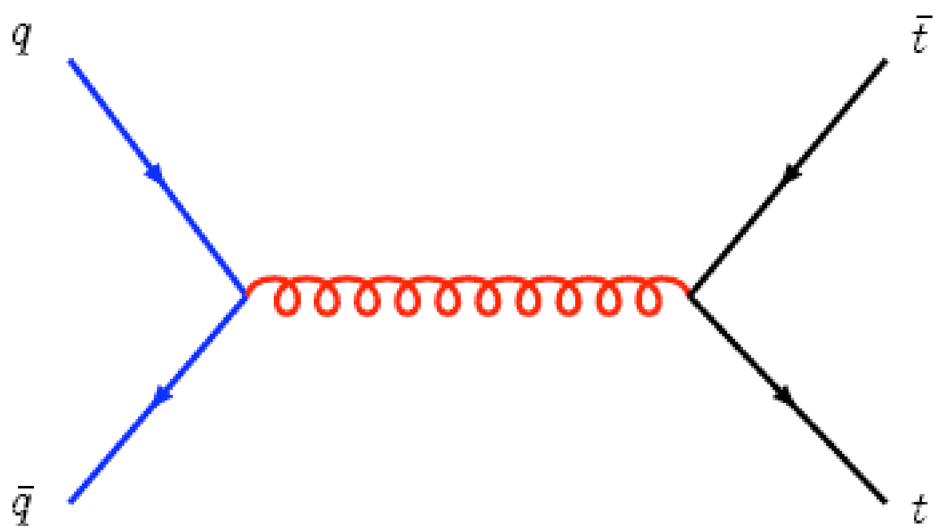
From Tevatron to LHC

Tevatron



85% of the total cross section

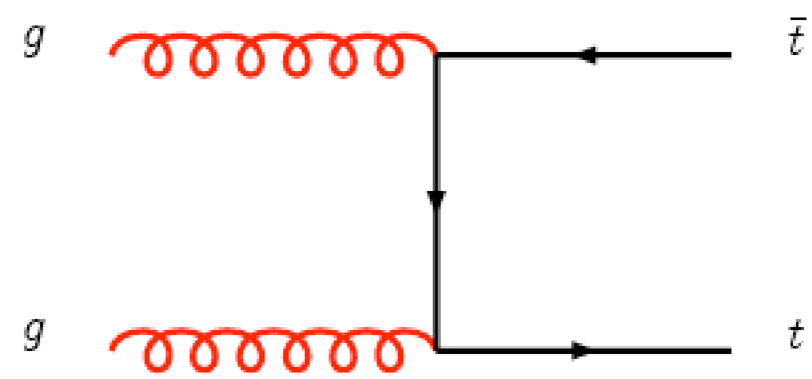
10 tt pairs per day

60% of the time there is extra radiation so that pt(tt)>15 GeV.

tt are produced closed to threshold, in a $^3S_1[8]$ state. Same spin directions. 100% correlated in the off-diagonal basis.

Worry because of the backgrounds: (W+jets, WQ+jets, WW+jets)

LHC



90% of the total cross section

1 tt pair per second

Almost 70% of the time there is extra radiation so that pt(tt)>30 GeV.

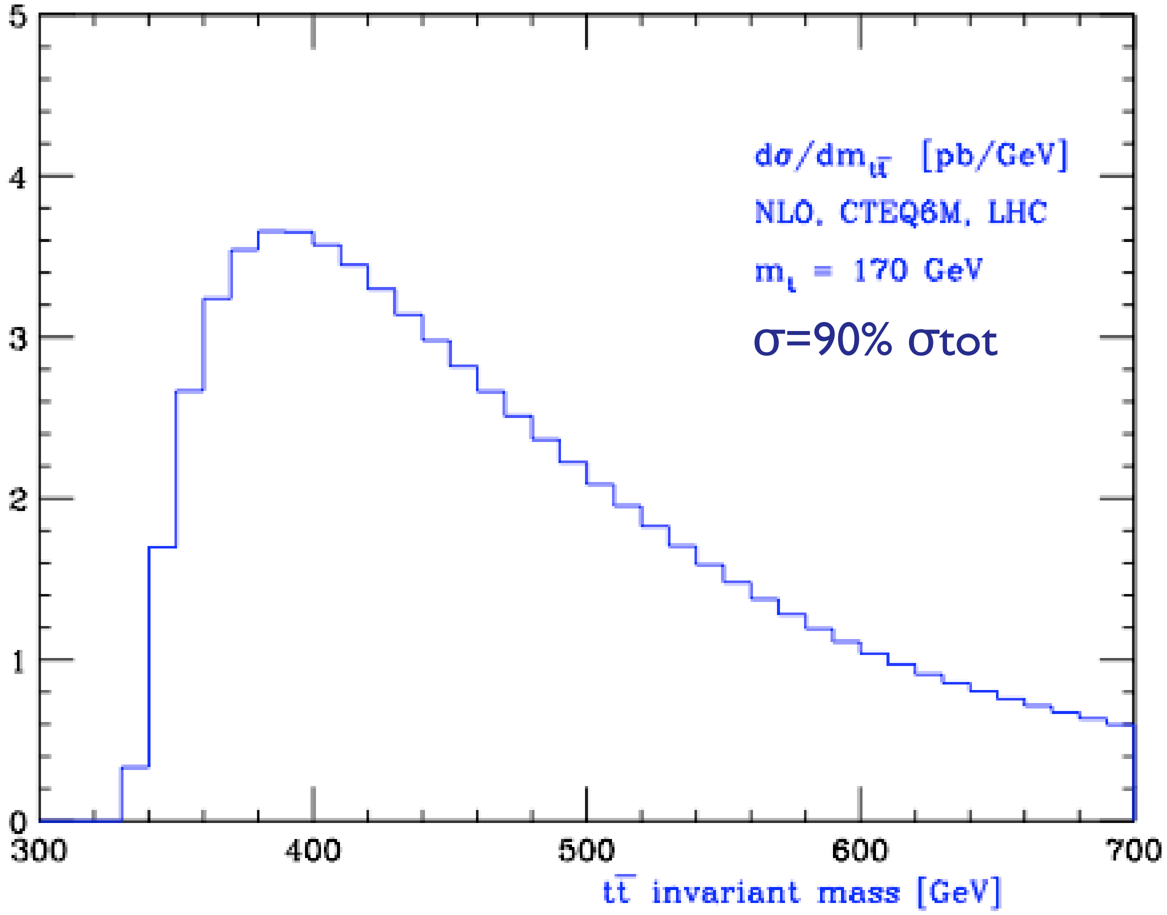
tt can be easily produced away from threshold. On threshold they are $^1S_0$ state, with opposite spin directions. No 100% correlation.

Background free*!

*Conditions apply. Consult with your local top expert before signing.

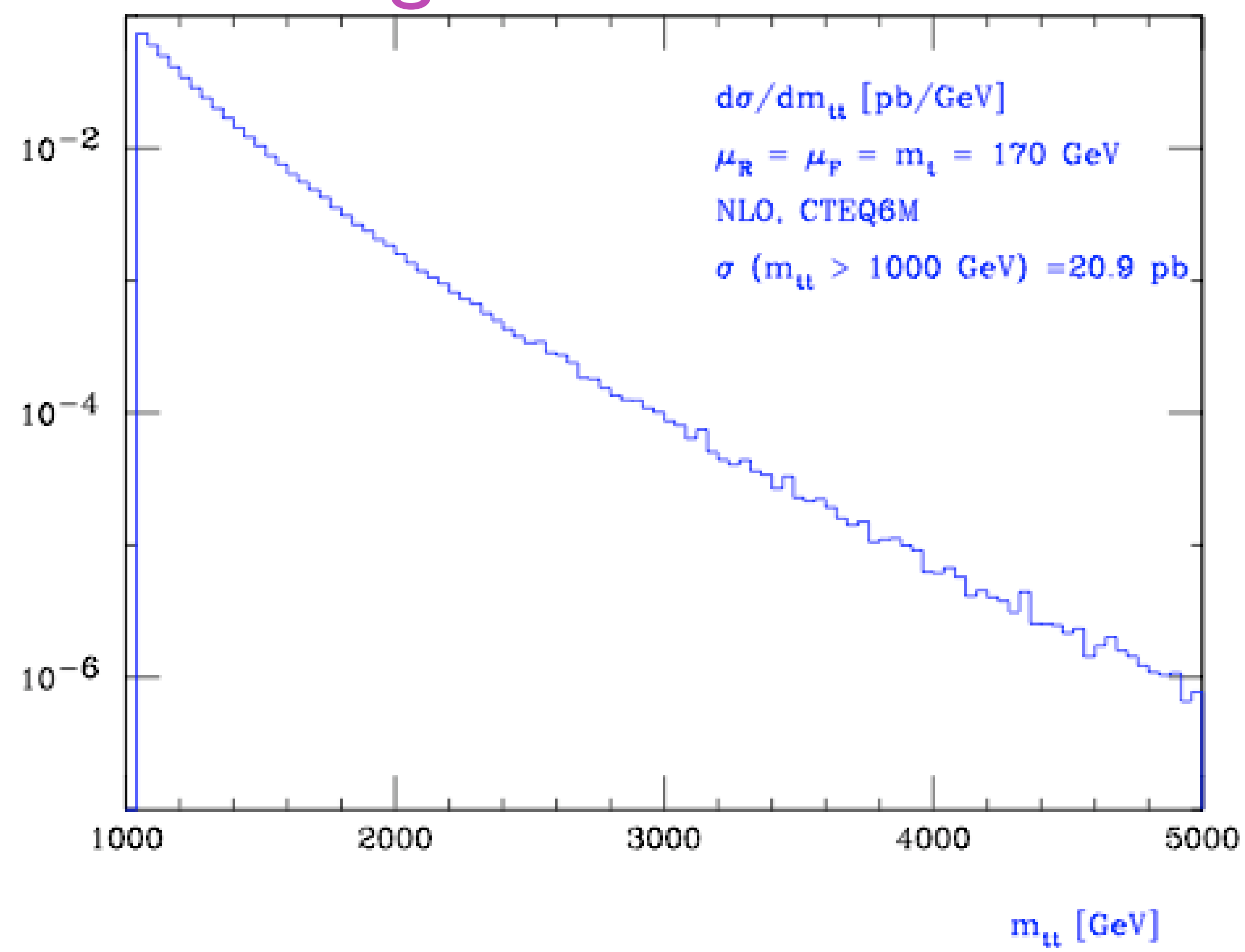
m_{tt} spectrum

low invariant mass



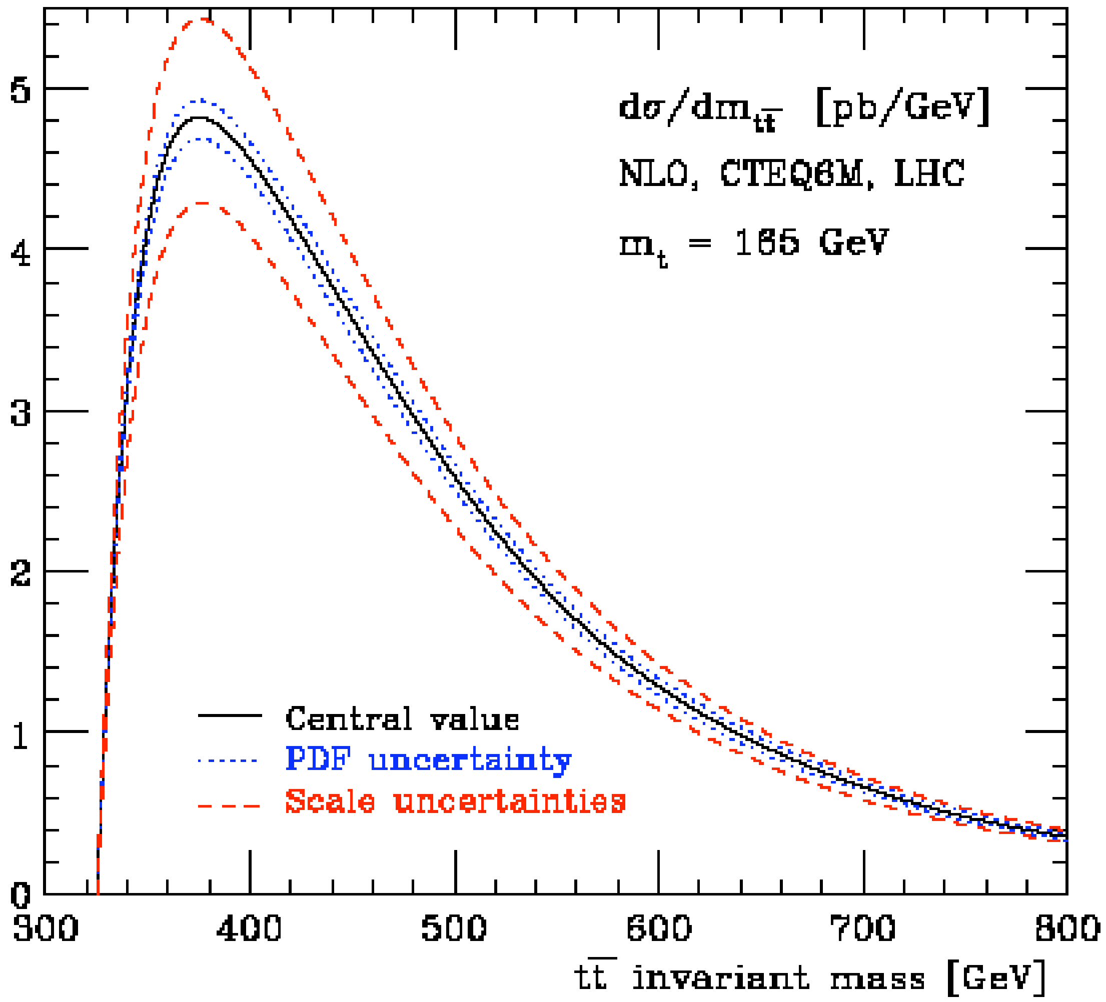
* ~90% of the total cross section
* ttbar at threshold in a 1S0[tt] state
* High-statistics sample⇒
  - early SM physics
  - CP-violation
  - top rare decays
  - low mass new resonances

high invariant mass



* m_{tt} >1 TeV ⇒ ~2% of the total cross section
* Events are more 2jet like ⇒ different selection
* EW effects (e.g. P-violation) start to be important
* Relevance of qq+qg increases
* TeV Resonances searches
* Top partners searches

m_{tt} spectrum: low mass



NLO corrections for total cross section are known since a long time (1989).

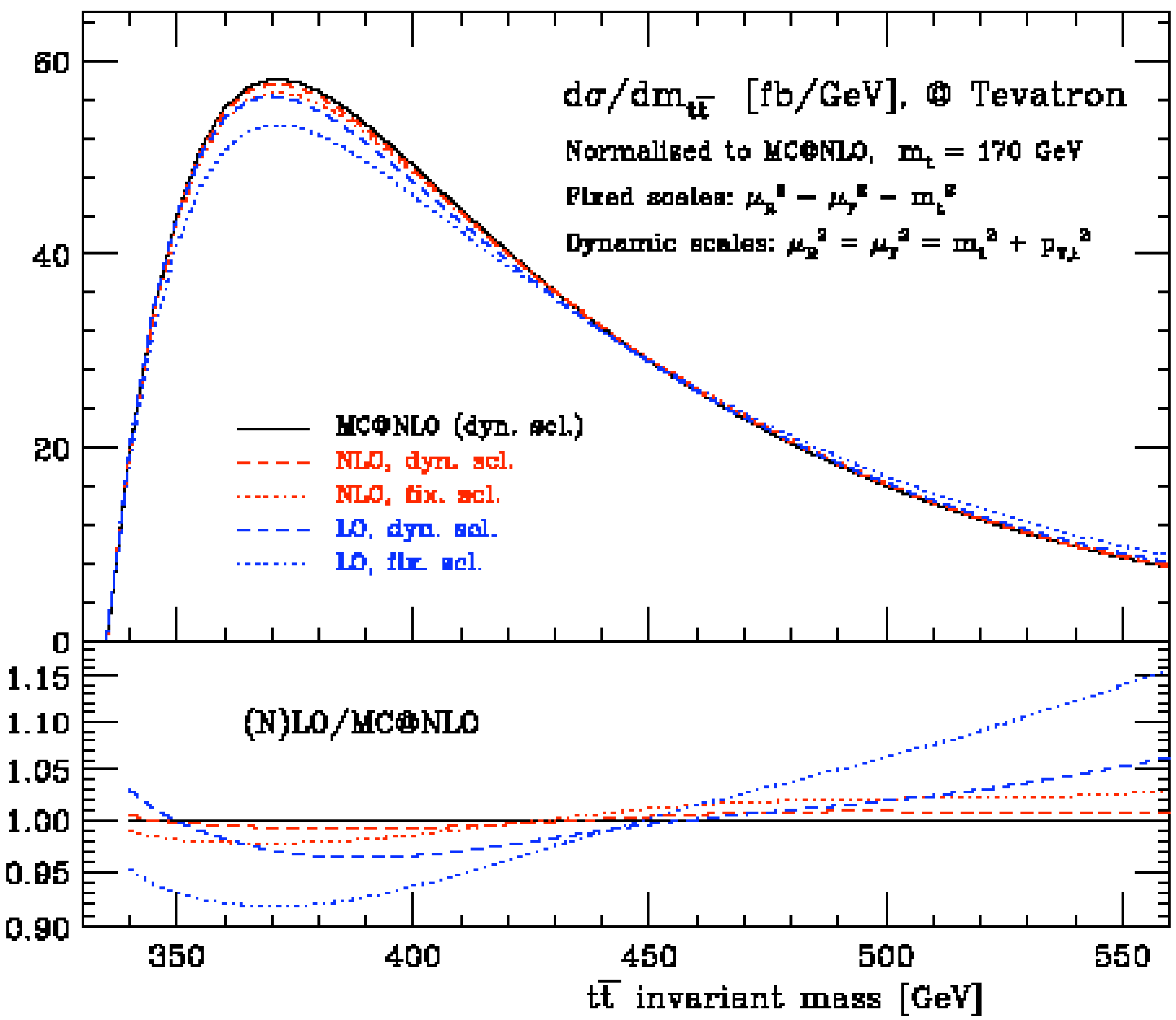
Improvements on resummation of threshold logs recently leading to a (partial) reduction of scale uncertaintes

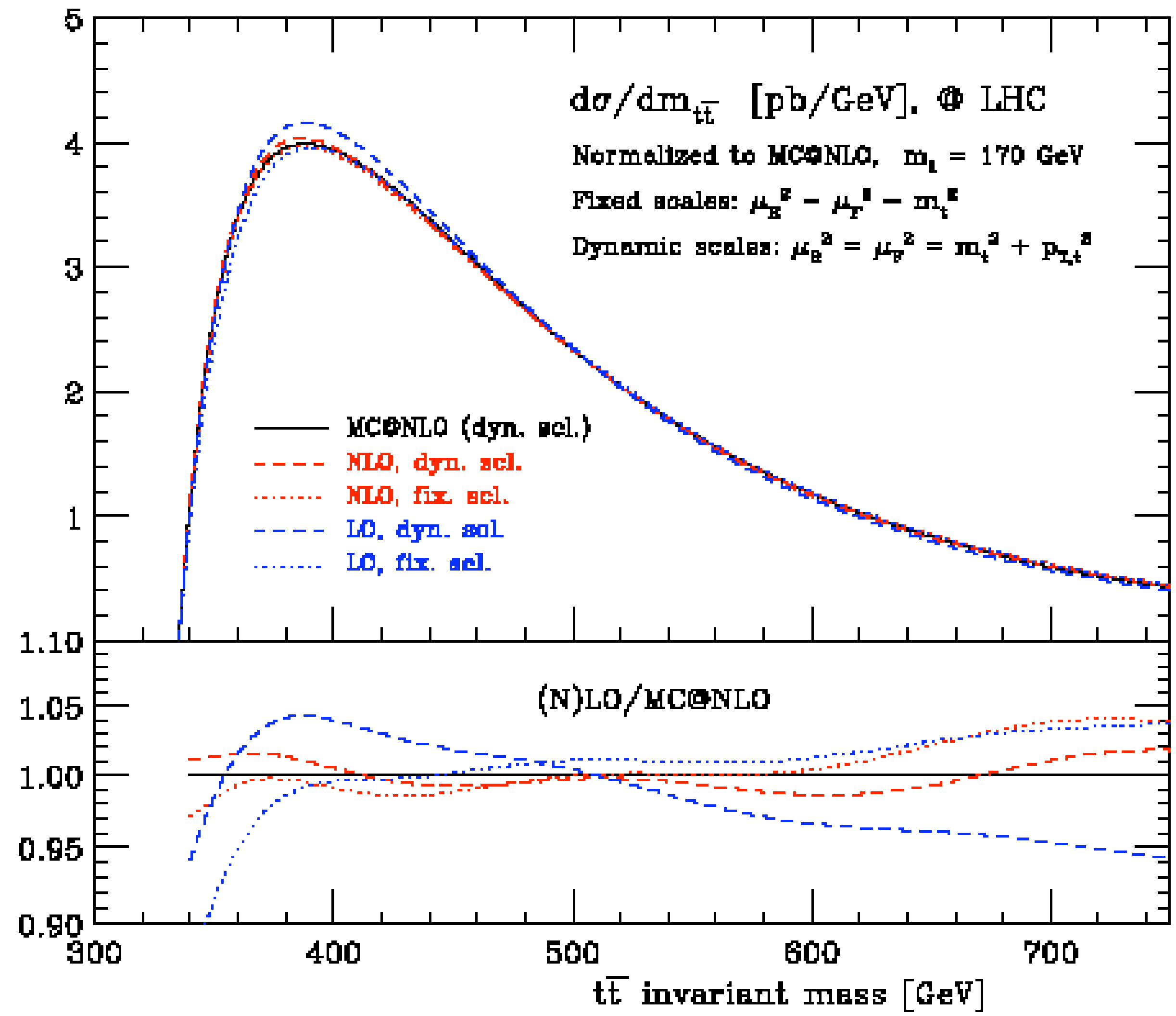
Spin correlations are basically unffected by NLO corrections.

Strong mass dependence.

NLO: Mangano, Nason & Ridolfi 1992
Incl. spin corr.: Bernreuther, Brandenburg, Si & Uwer 2001
NLL: Bonciani, Catani, Mangano & Nason 1998
MC@NLO: Frixione, Nason, Webber 2003

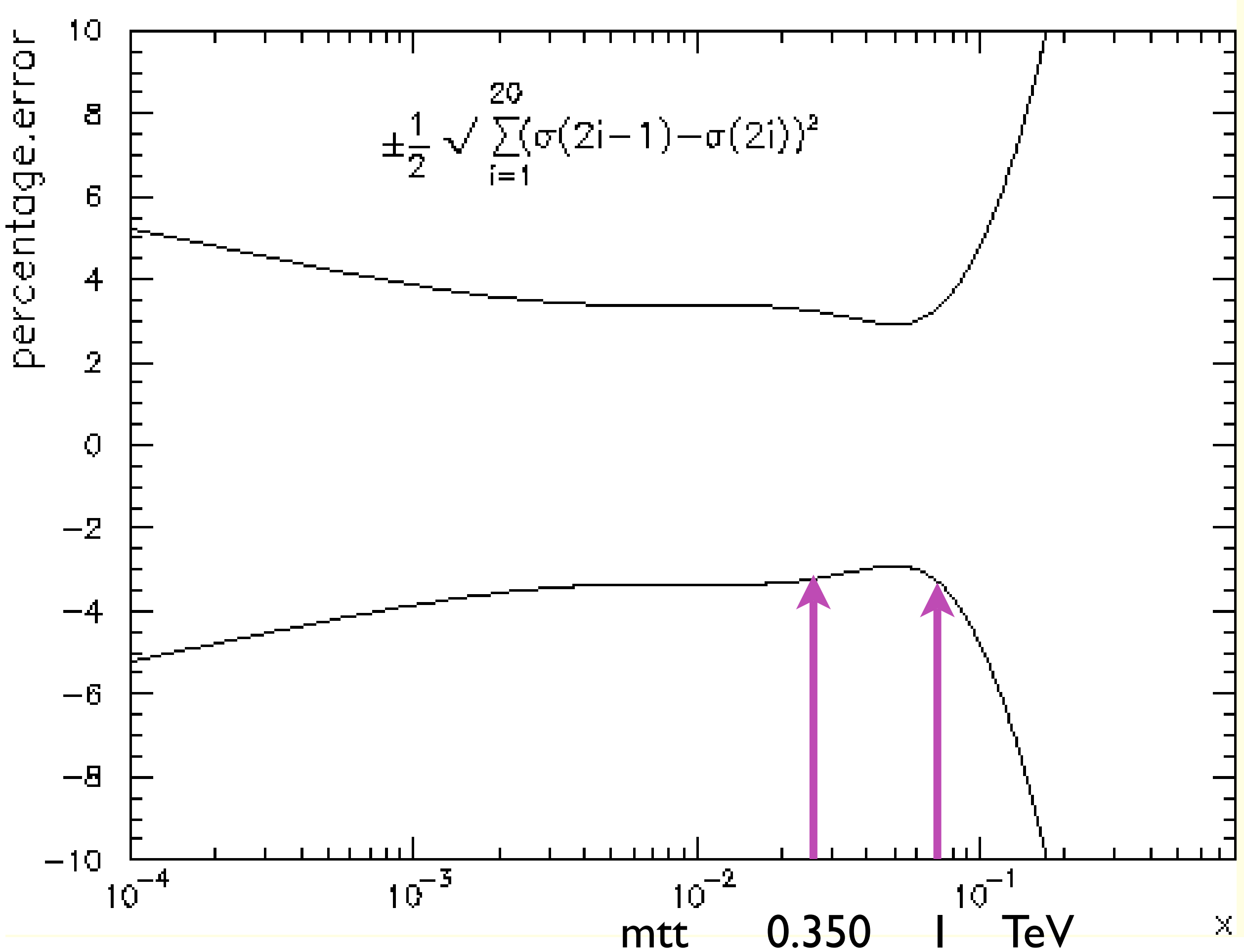
m_{tt} spectrum: low mass

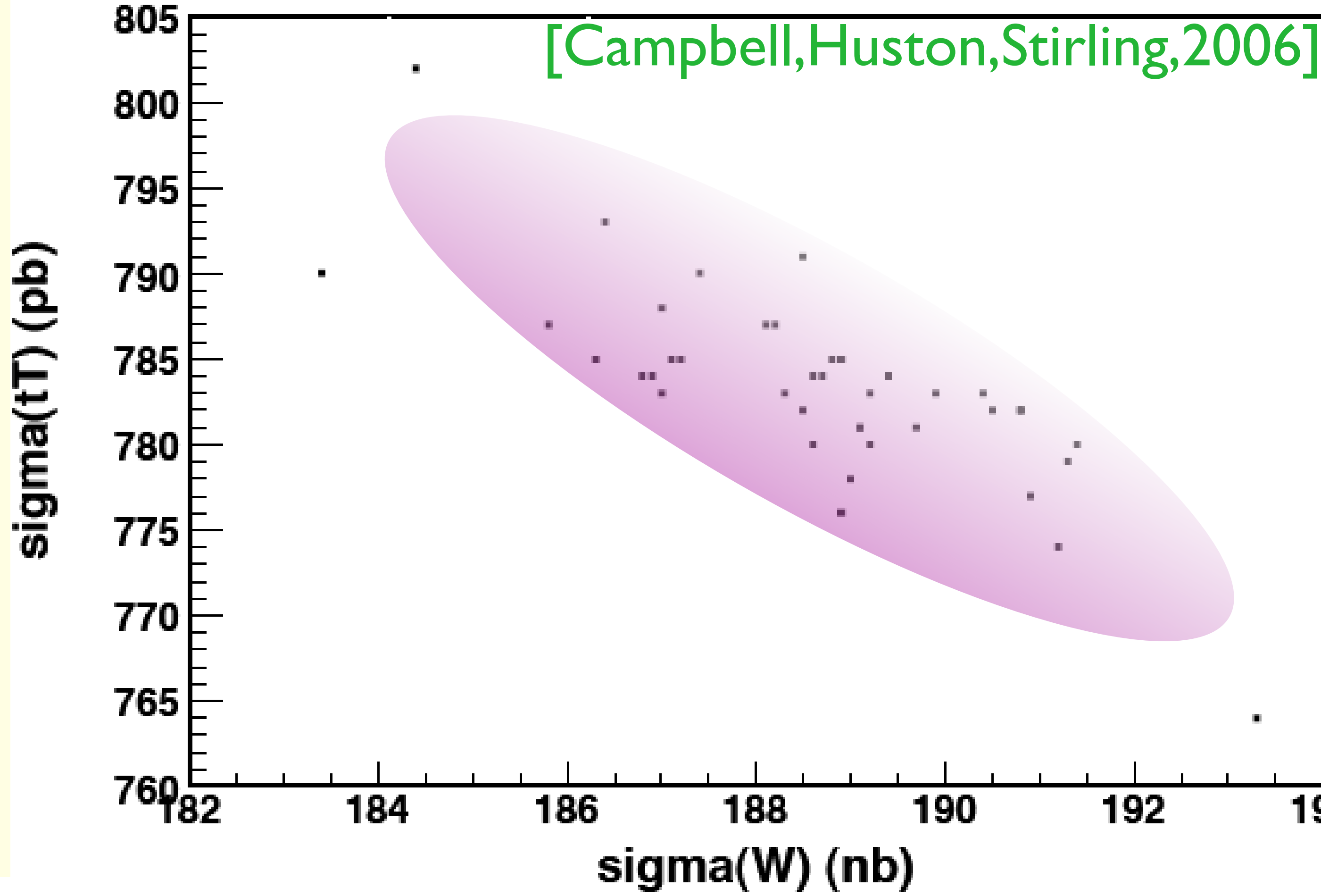




* Tree-level production with a dynamical scale reproduces the shape MC@NLO result extremely well. Very stable observable.

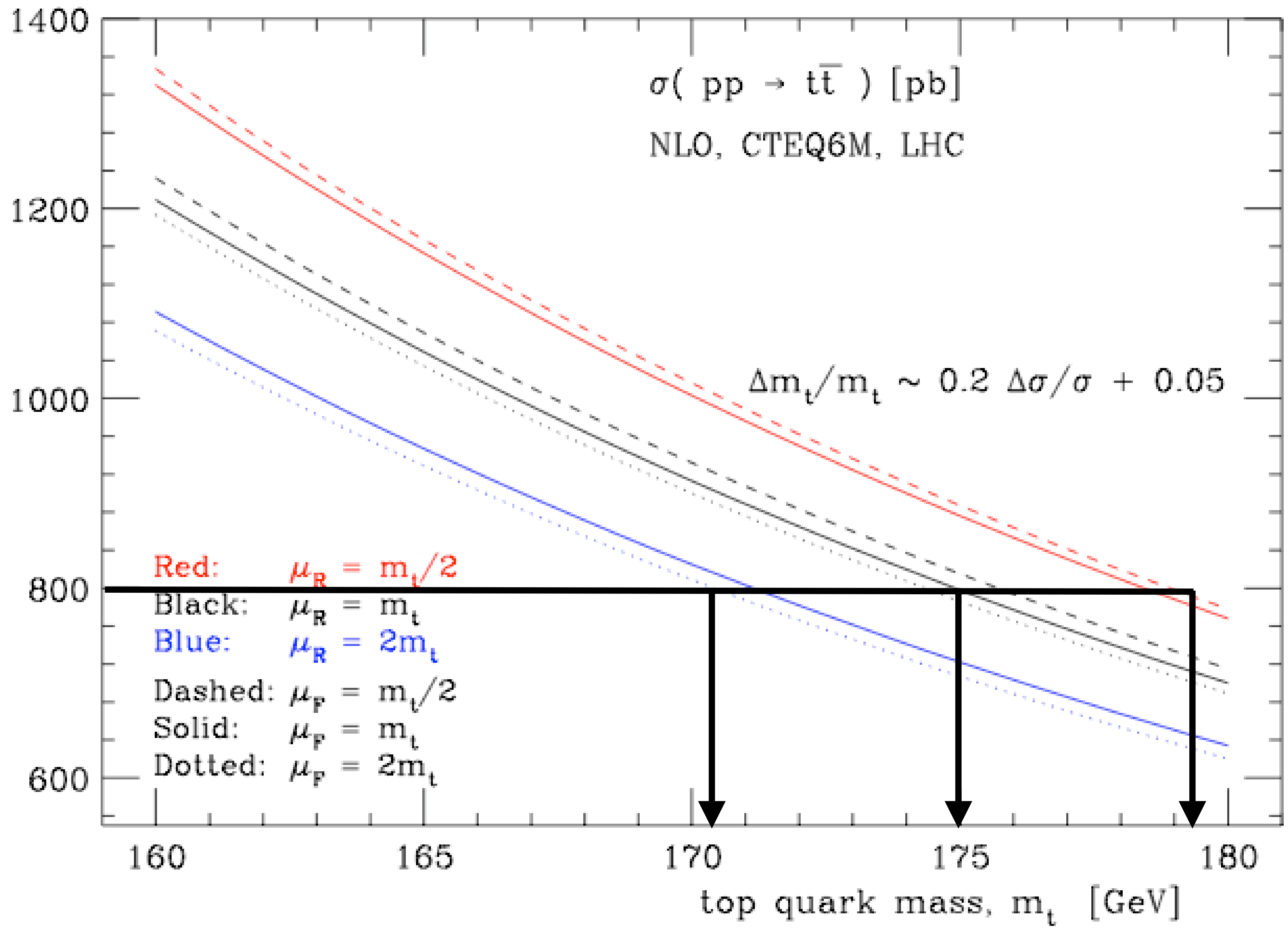
σ_{tt}: PDF errors





- * ttbar production sits exactly on the minimum uncertainty x for the gluon pdf.
- * Unticorrelated with the W cross section.
- * PDF error is very small compared to the scale uncertainties for low ttbar invariant masses.
- * higher invariant masses start to probe x areas characterized by larger uncertainties.

σ_{tt} vs m_t



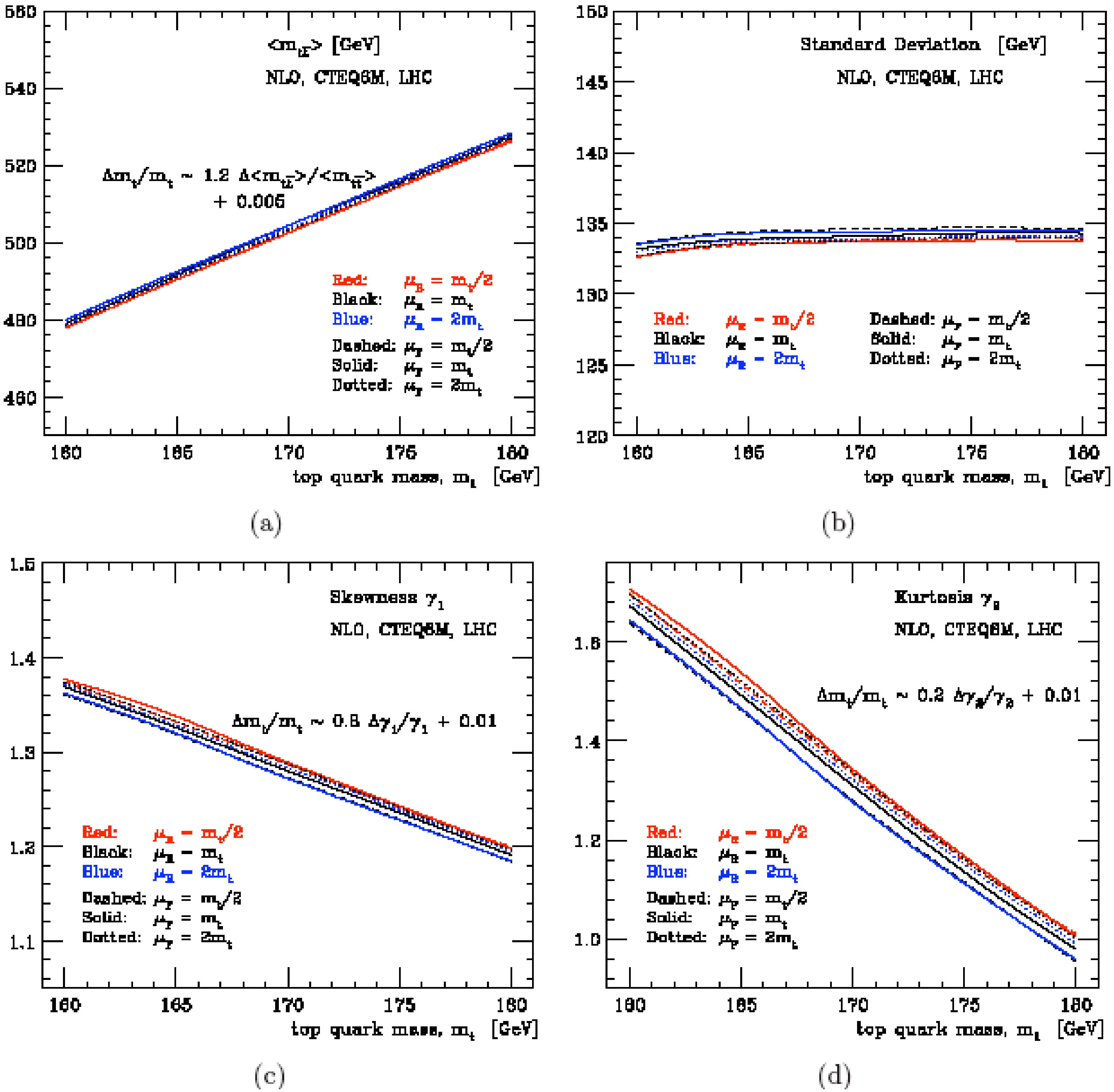
The total cross section depends strongly on the top mass.

This could be used to measure the top mass from a cross section measurement.

However, the error on the total cross section is theory dominated!

What about the shape of m_{tt}?

σ_{tt} vs m_t : the moments approach



$$\langle m_{t\bar{t}} \rangle = \int dm_{t\bar{t}}\, m_{t\bar{t}} \frac{\partial \sigma}{\partial m_{t\bar{t}}}\Big|_{\text{norm.}}$$

$$s = \sqrt{\mu_2},$$

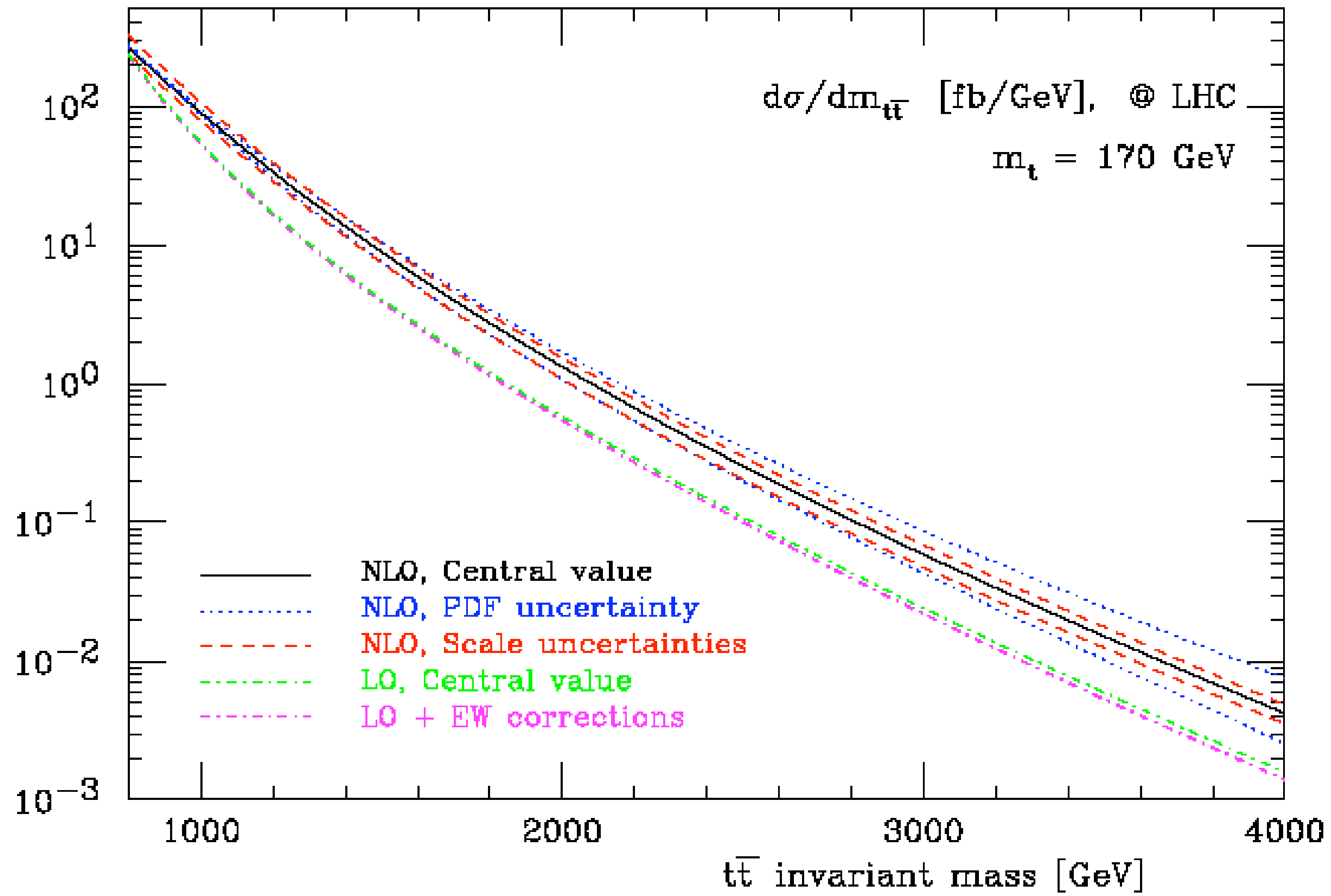
$$\gamma_1 = \frac{\mu_3}{\mu_2^{3/2}}$$

$$\gamma_2 = \frac{\mu_4}{\mu_2^2} - 3,$$

$$\mu_n = \int dm_{t\bar{t}} \left(m_{t\bar{t}} - \langle m_{t\bar{t}} \rangle\right)^n \frac{\partial \sigma}{\partial m_{t\bar{t}}}\Big|_{\text{norm.}}$$

Very promising!! Further EXP studies to study the systematics more than welcome!

m_{tt} spectrum: high mass



* Up to few percents the LO and NLO shape are the same.

* Quark initiated process start to be relevant only at high m_{tt}>3000 GeV

* Several groups have by now calculated the contribution from the virtual exchange of electro-weak bosons (W,Z,H,γ)

*The effect on the total cross section is small but it is enhaced at large m_{tt}, up to -10/-15%.

*SUSY could also lead to virtual corrections of similar size, relevant only for high-m_{tt} physics.

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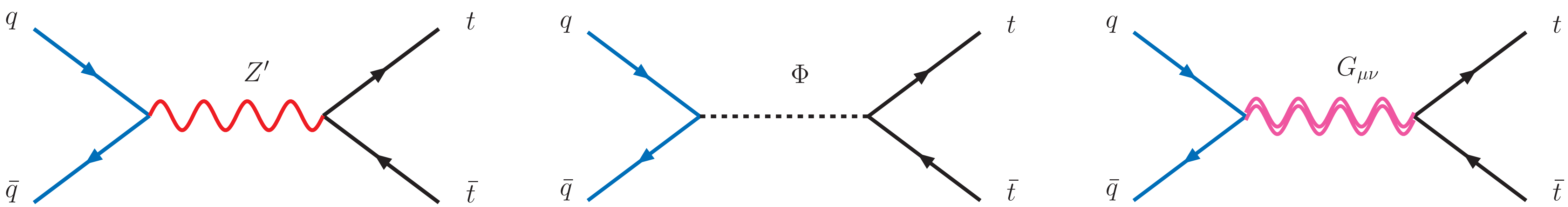
New resonances

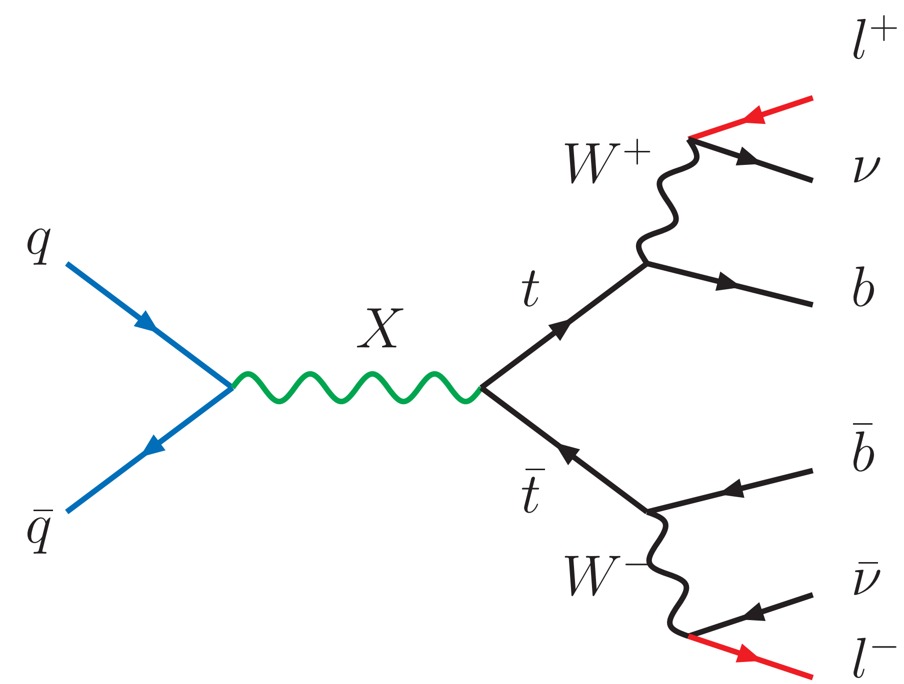
In many scenarios for EWSB new resonances show up, some of which preferably couple to 3rd generation quarks.



Given the large number of models, in this case is more efficient to adopt a “model independent” search and try to get as much information as possible on the quantum numbers and coupling of the resonance.

To access the spin of the intermediate resonance spin correlations should be measured.

It therefore mandatory for such cases to have MC samples where spin correlations are kept and the full matrix element pp>X>tt>6f is used.

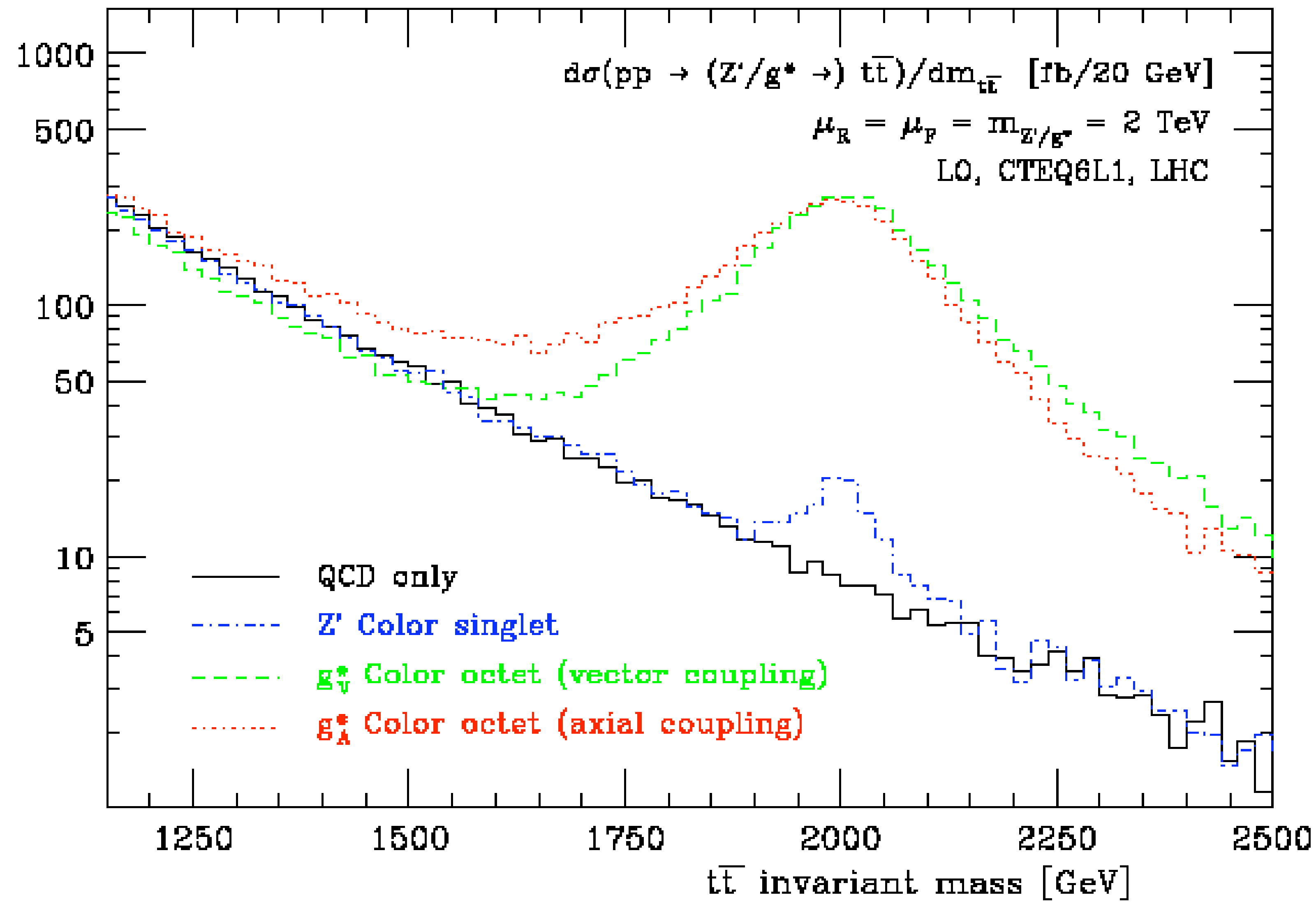


Zoology of new resonances

Spin	Color	$(1,\gamma_5)$ [L,R]	SM-interf	Example
0	0	(1,0)	no	Scalar
	0	(0,1)	no	PseudoScalar
	0	(0,1)	yes	Boso-phobic
	8	(0,1),(1,0)	no	Techni-pi0[8]
1	0	[sm,sm]	yes/no	Z'
	0	(1,0),(0,1)(1,1),(1,-1)	yes	vector
	8	(1,0)	yes	coloron/kk-gluon
	8	(0,1)	"yes"	axigluon
2	0	--	yes	kk-graviton

http://madgraph.phys.ucl.ac.be/

Phase 1: discovery



* Vector resonance, in a color singlet or octet states.
* Widths and rates very different
* Interference effects with SM ttbar production not always negligible
* Direct information on σ•Br and Γ.

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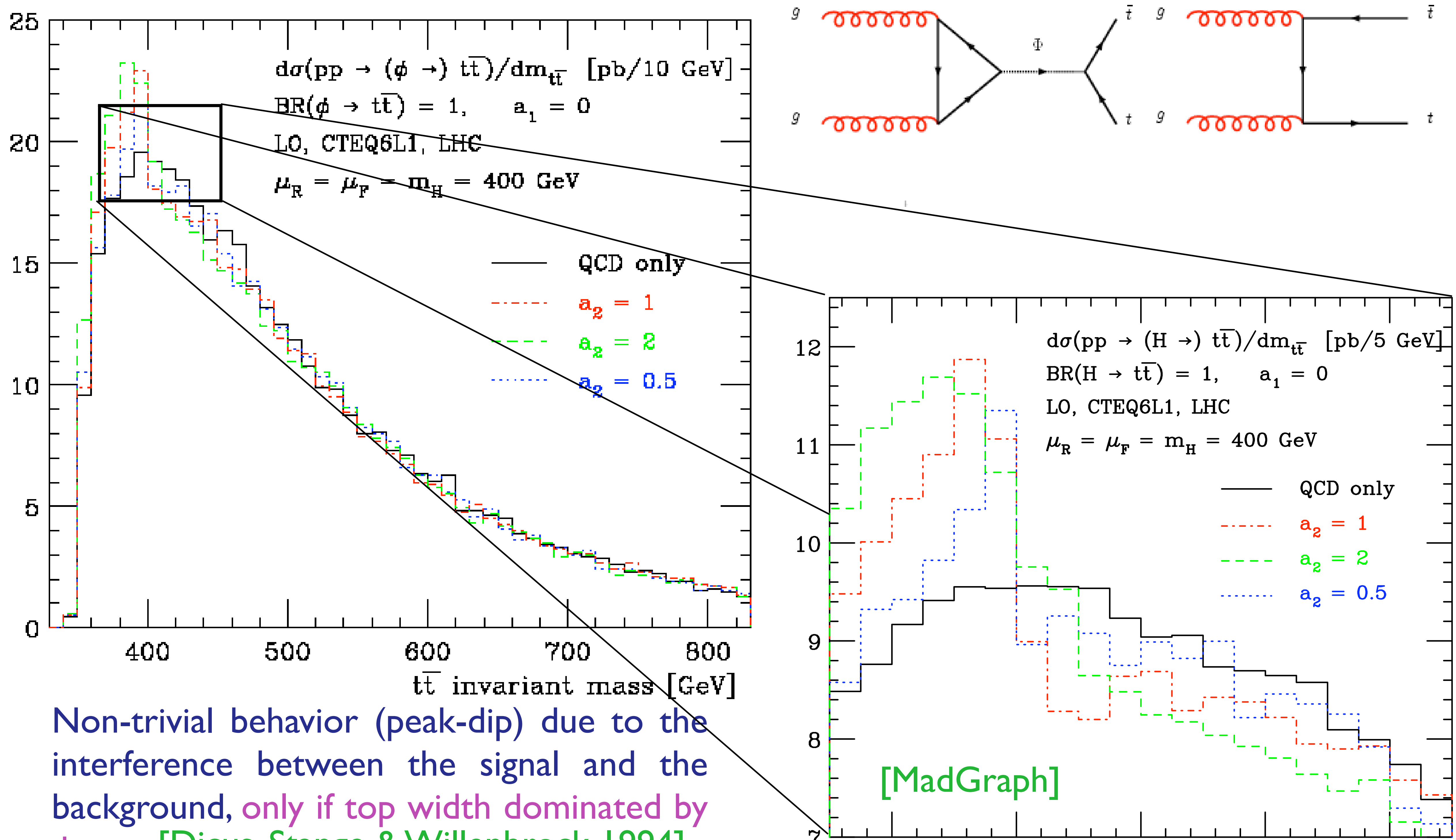

Non-trivial behavior (peak-dip) due to the interference between the signal and the background, only if top width dominated by $\Phi \to tt$. [Dicus, Stange & Willenbrock 1994]

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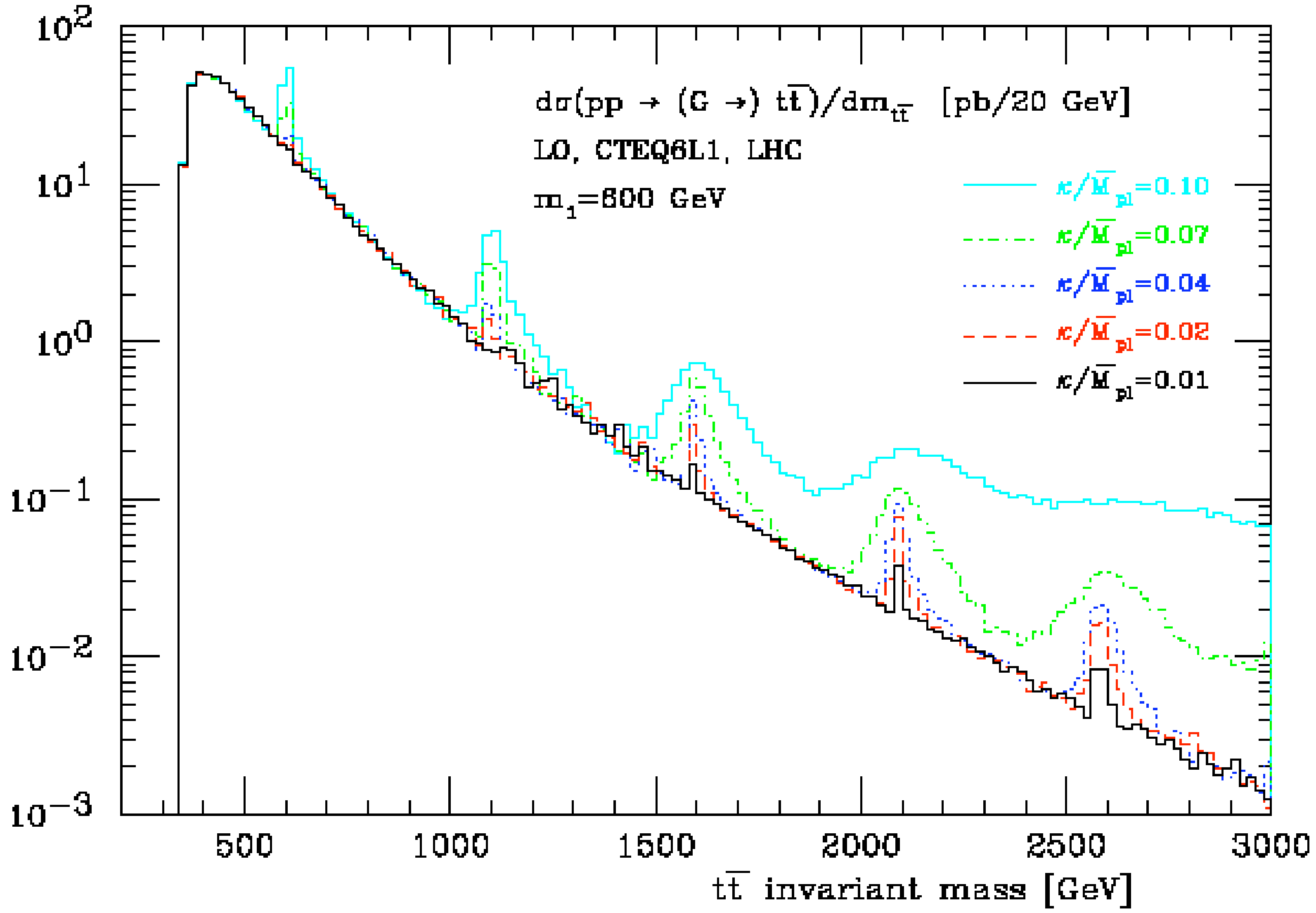
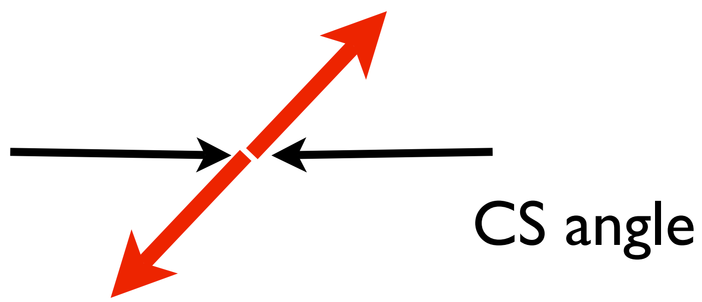
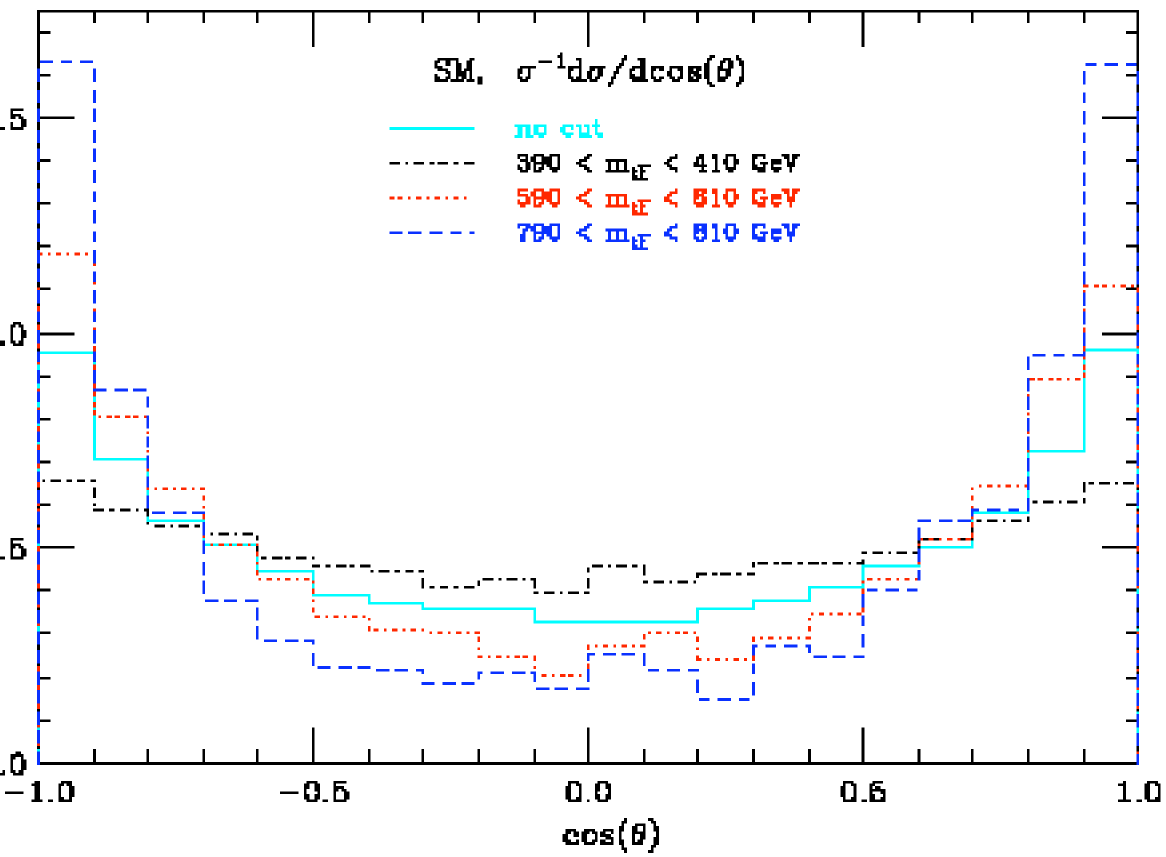


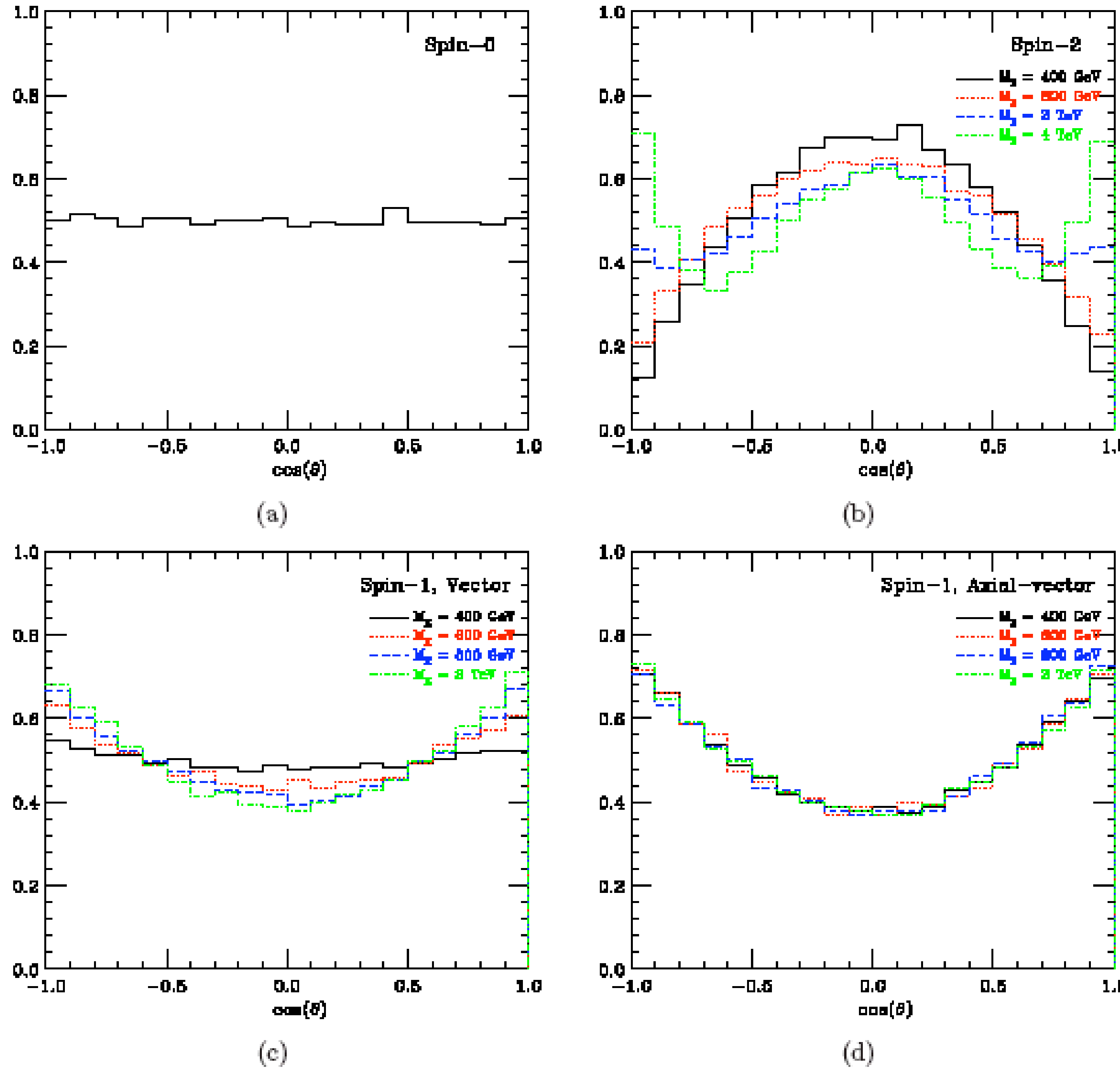
* Spectacular signature!

*RS Model with first KK=600 GeV

Phase 2: ttbar angular distributions

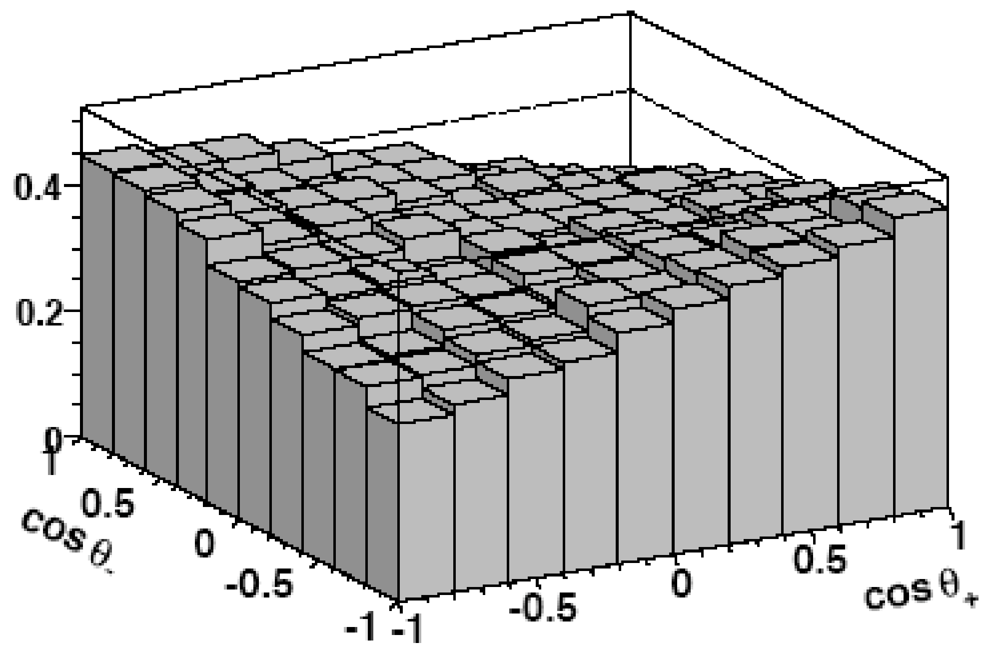






Robust reconstruction needed, but much easier than spin correlations...

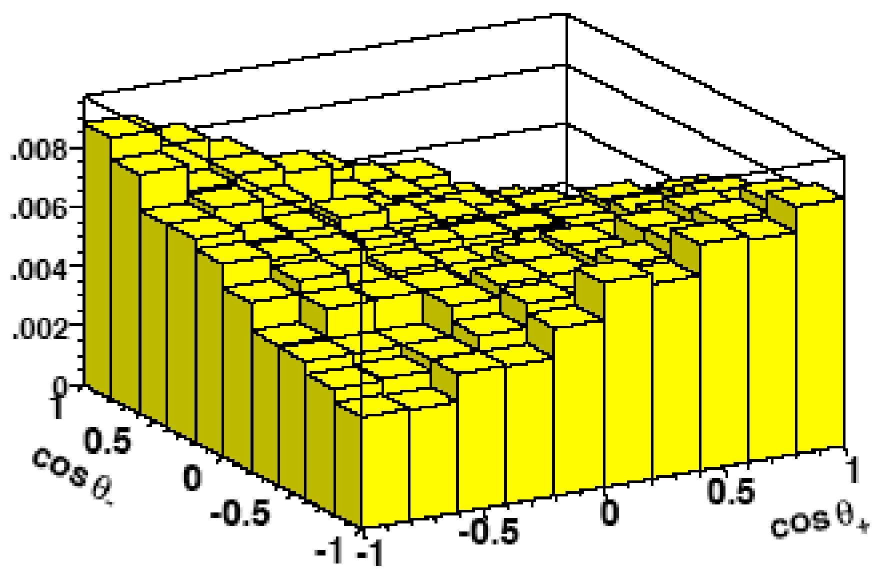
Phase 3: Spin correlations



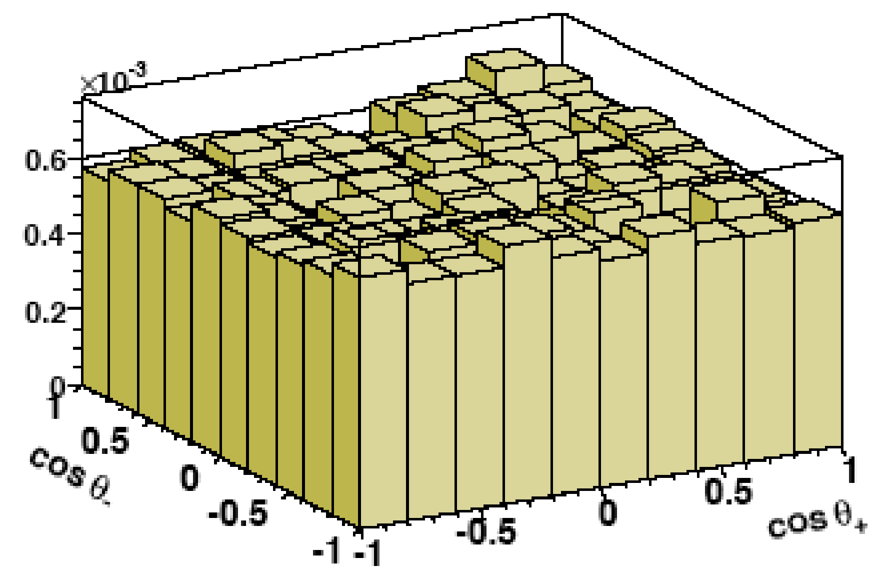
(a)

no cuts

low m_{tt}



(b)

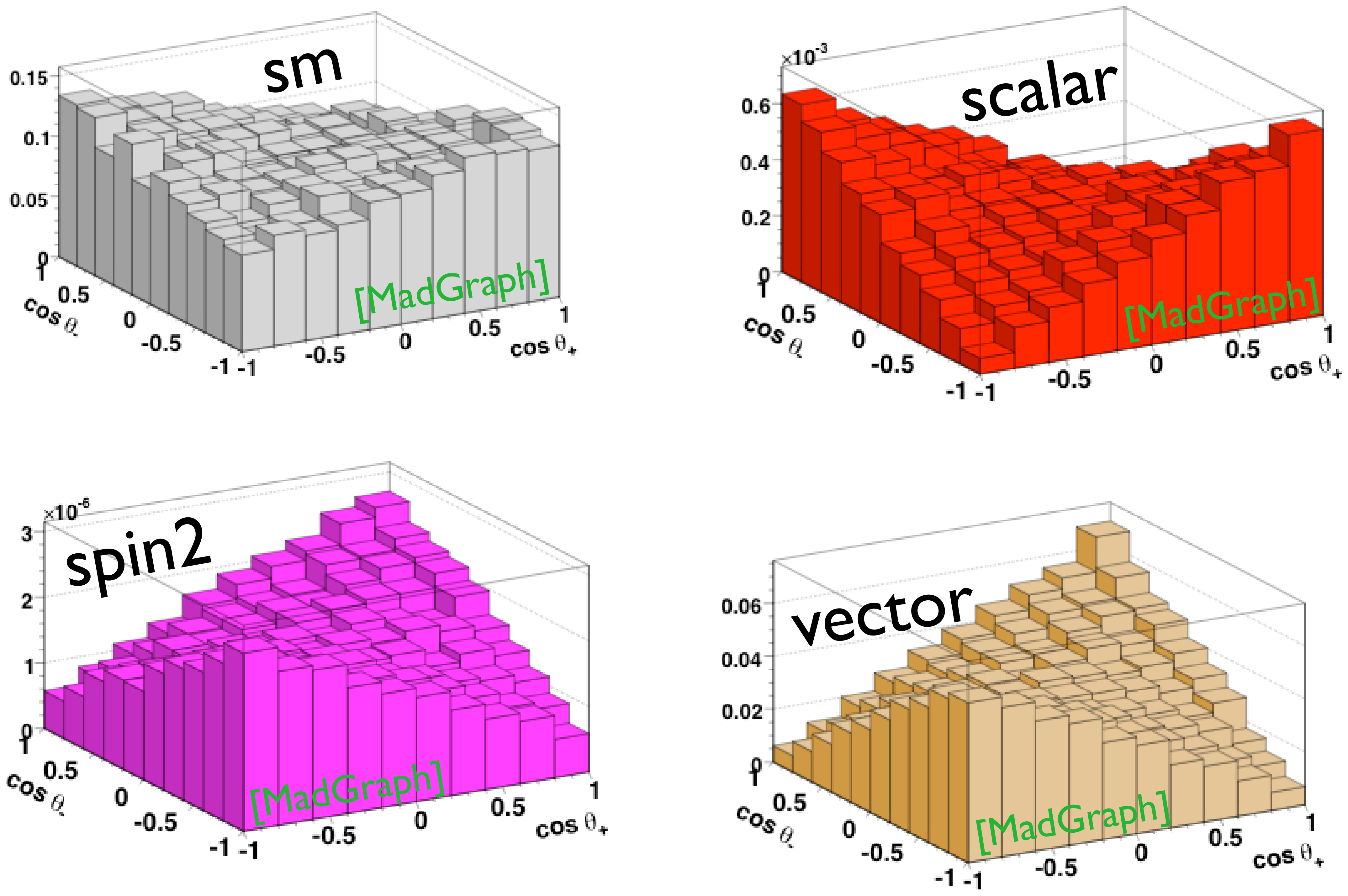


(c)

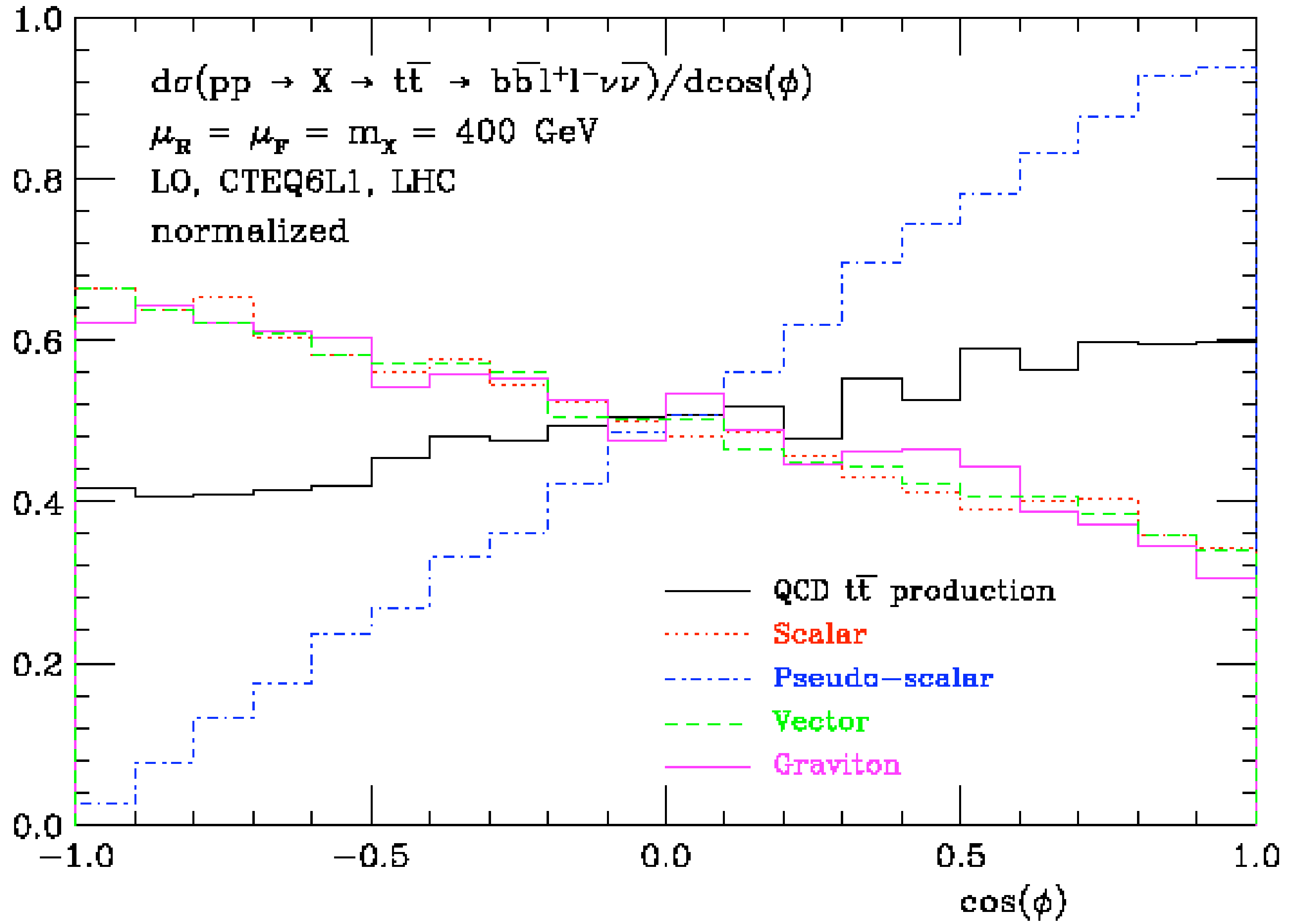
high m_{tt}

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1+\kappa_t\kappa_{\bar{t}}D\cos\theta_-\cos\theta_+\right)$$

Phase 3: Spin correlations



Phase 3: Spin correlations



Vector and Spin 2 are not distinguishable

Reconstruction issues

- Three possible different signatures (0,1,2, leptons in the final state) entail different event reconstruction strategies.
- Also the three different phases ask for (increasingly) sophisticated approaches
- To fix the final state (modulo combinatorics) we need 18 measurements.

<table>
<tr><th></th><th>0 lept</th><th>1 lepts</th><th>2 lepts</th></tr>
<tr><td># measured</td><td>6x3</td><td>5x3+ $\not{E}_T$ +m_W</td><td>4x3+$\not{E}_T$+(2m_W,2m_t)</td></tr>
<tr><td>m(tt)</td><td>no reco needed</td><td rowspan="2">reco
(no comb w/ constr)</td><td rowspan="3">full reco w/ comb

no spin comb</td></tr>
<tr><td>cos θ</td><td>reco
(no comb w/ constr)</td></tr>
<tr><td>spin corr.</td><td>full reco
+ 4-fold spin comb</td><td>full reco
+ 2-fold spin comb</td></tr>
</table>

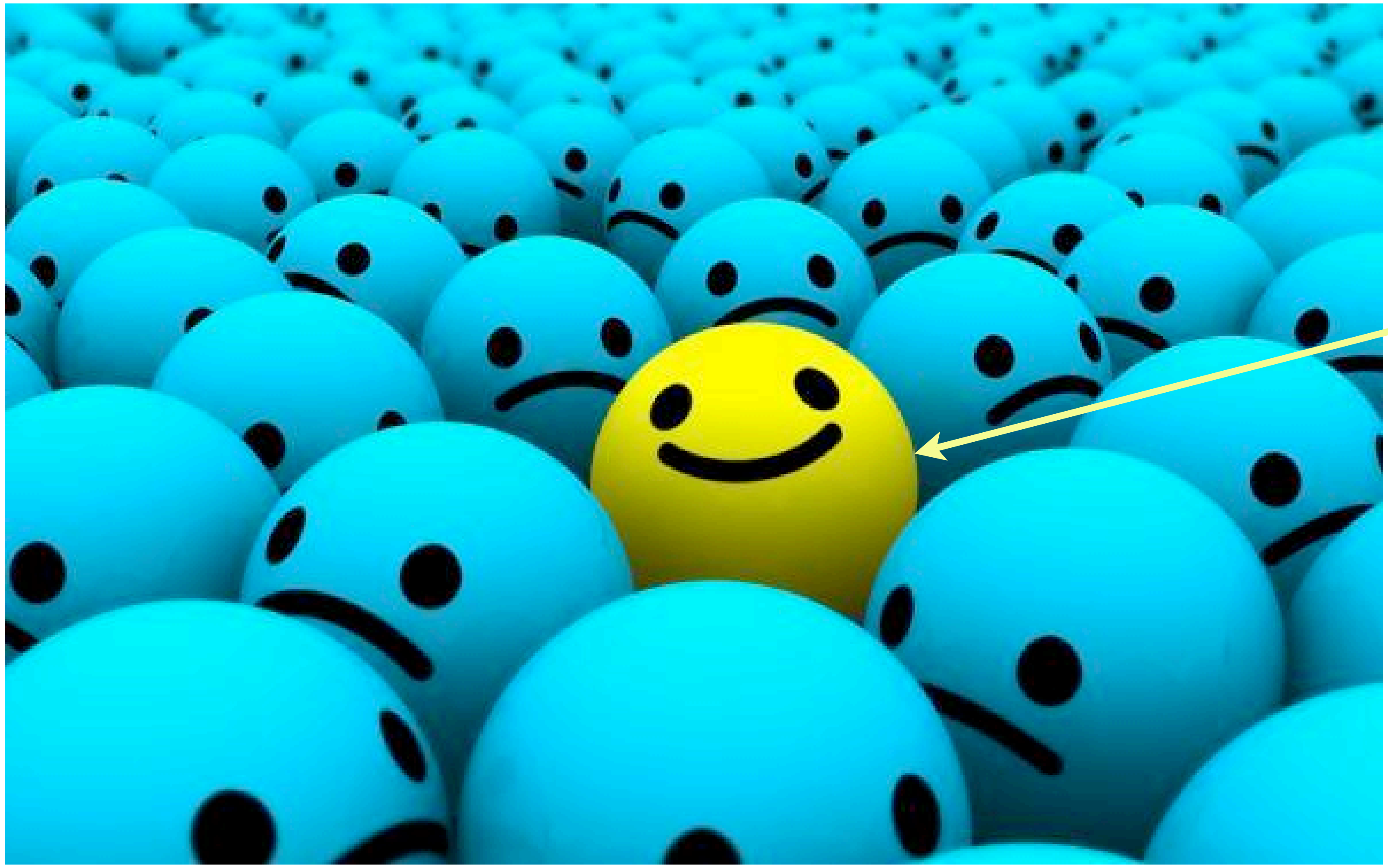
Plans and future directions

- Enlarge TopBSM to include non standard couplings and BSM effects relevant to single-top.
- Collaboration with experimental group(s) on efficient reconstruction techniques.
- Application of a new matrix element technique code (MadWeight) to possibly improve measurements.
- Any further idea/suggestion/request?

Conclusions

- Making discoveries at the LHC (most probably) won't be easy.
- A lot of activity in the last years in trying to identify general strategies to attack the problem with a bottom-up strategy. New tools being developed : TH, MC, statistical...
- We have studied m_{tt} as an example of the simplest possible bottom-up / model-independent strategy to try to discover and measure the properties of resonances.
- TopBSM is publicly available as a MadGraph model and work in progress on extensions/improvements.

We are so eagerly waiting for data...



HEP physicist after a black hole produced at the LHC