Top pair invariant mass

Rikkert Frederix
Center for Particle Physics and Phenomenology (CP3)
Université catholique de Louvain
and CERN-TH

In collaboration with: Fabio Maltoni
JHEP **01** (2008) 47, [arXiv:0712.2355 [hep-ph]]

Outline

- Strategies for BSM at the LHC
- Focus on m_{tt}
  - SM predictions
  - pp → X → tt : three step analysis
- Conclusions

Bottom-up vs. Top-down

- 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:

Bottom-up vs. Top-down

- 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:

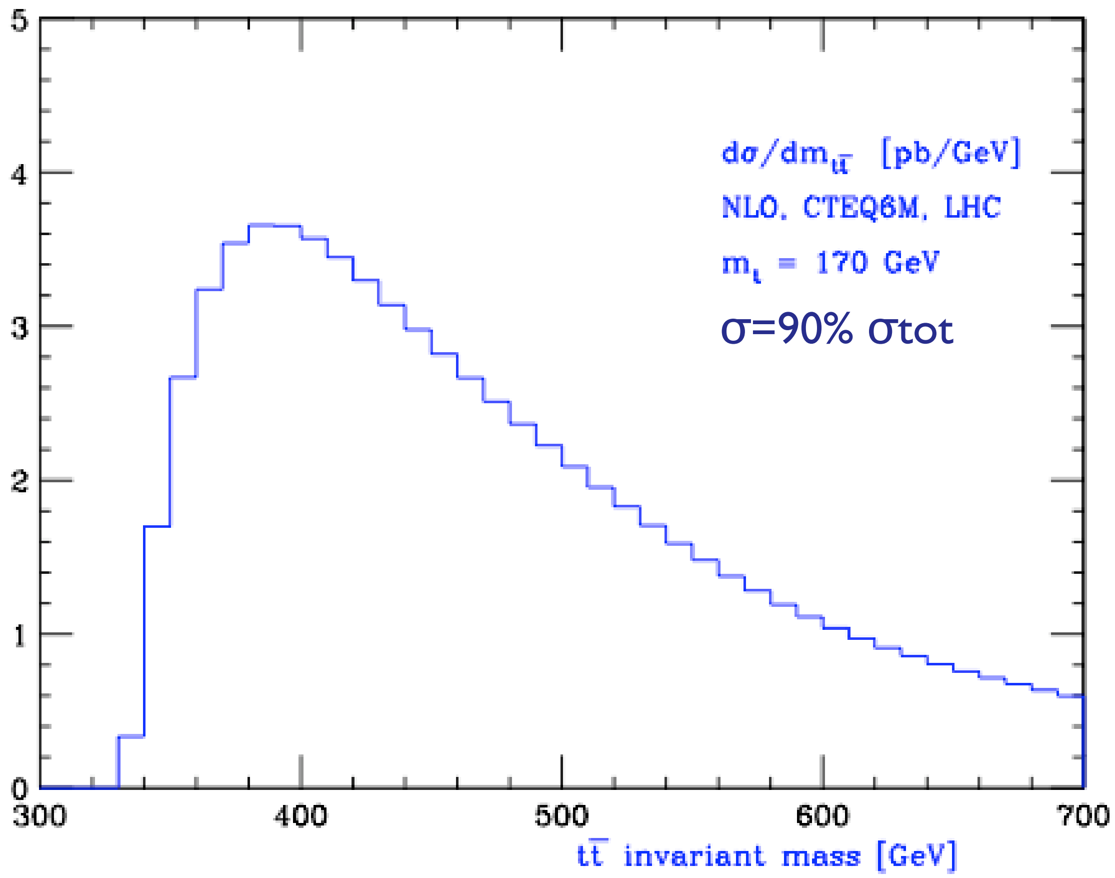
Well-defined models	Coarse structure
Extremely optimized (→non-portable) analysis	General searches
Dedicated MC tools	multi-purpose MC's

Bottom-up or ‘model-independent’ approach to BSM searches

- ‘Choose’ variable that could be sensitive to new physics.
- Use the best known approximations to study this variable.
- Study the possible effects from New Physics.
- Compare all results with data.
- If discrepancy is found, use other observables to determine properties of the new physics
- Try to develop a model that explains all discrepancies

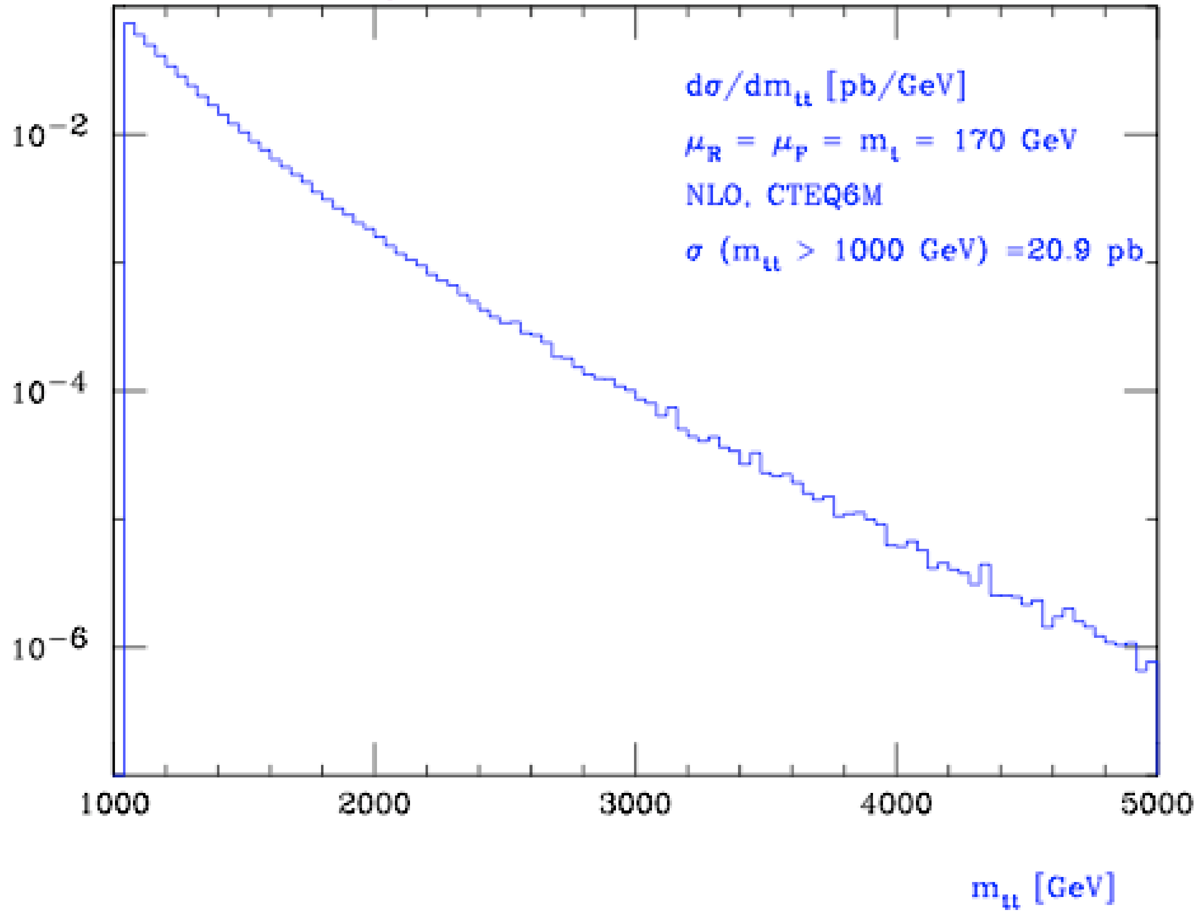
Top pair invariant mass

low invariant mass



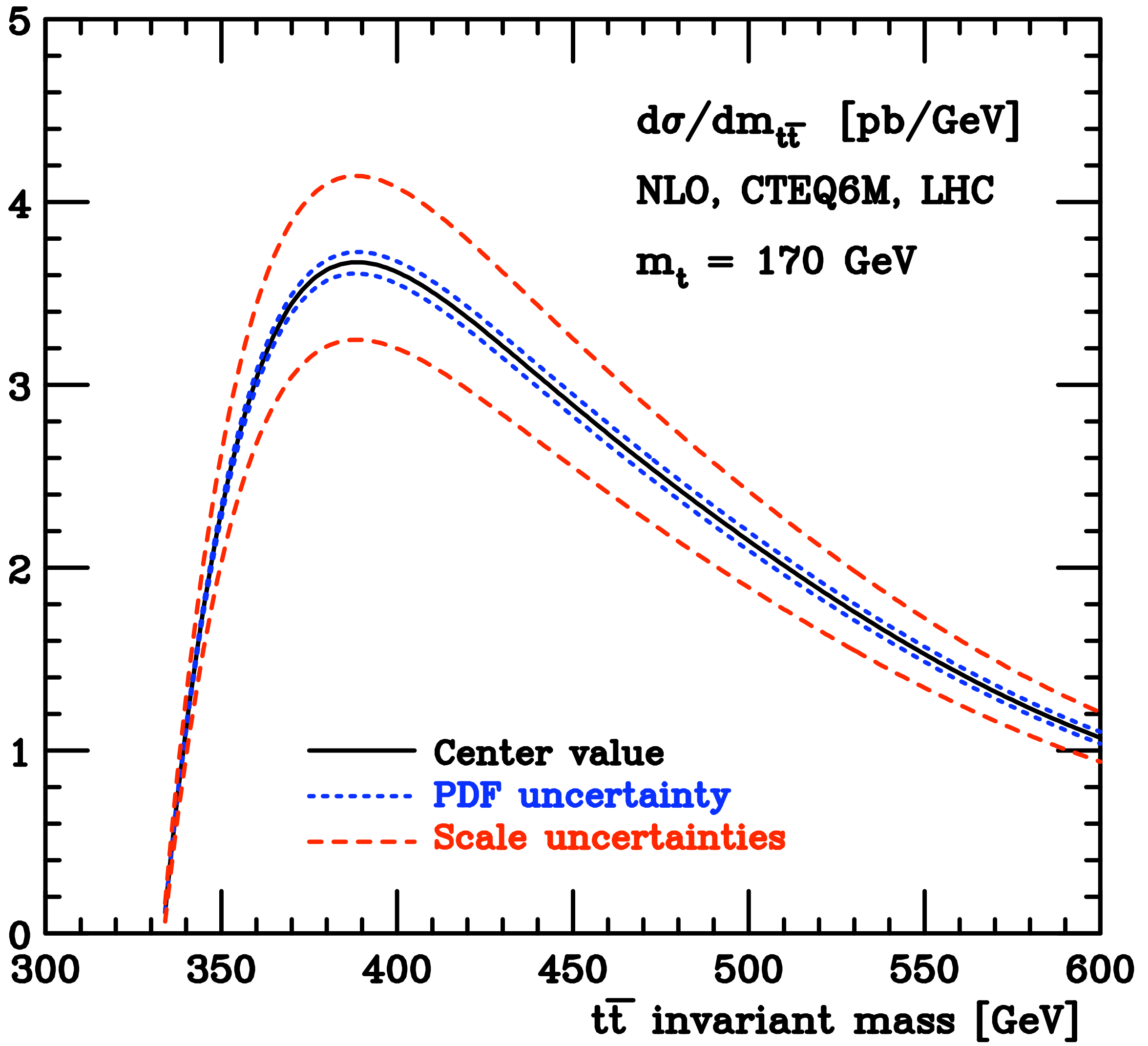
* ~90% of the total cross section
* ttbar at threshold in a 1S0[tt] state
* High-statistics sample⇒
    - early SM physics
    - CP-violation
    - top rare decays
    - low mass new resonances

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

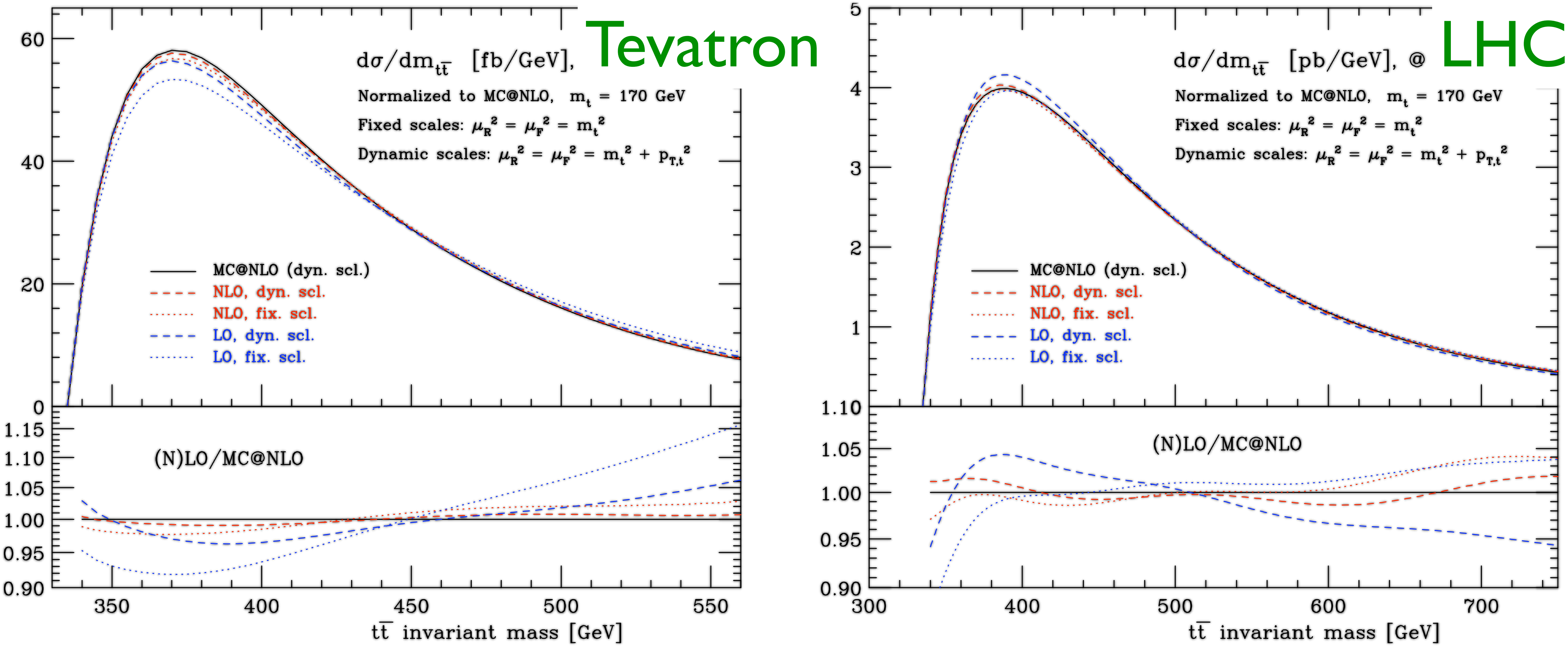
m_{tt} spectrum: low mass



- NLO corrections for total cross section are known since a long time (1989)
- Resummation of threshold log's leads to a (partial) reduction of in the scales.
- Spin correlations are unaffected by NLO corrections
- Strong mass dependence

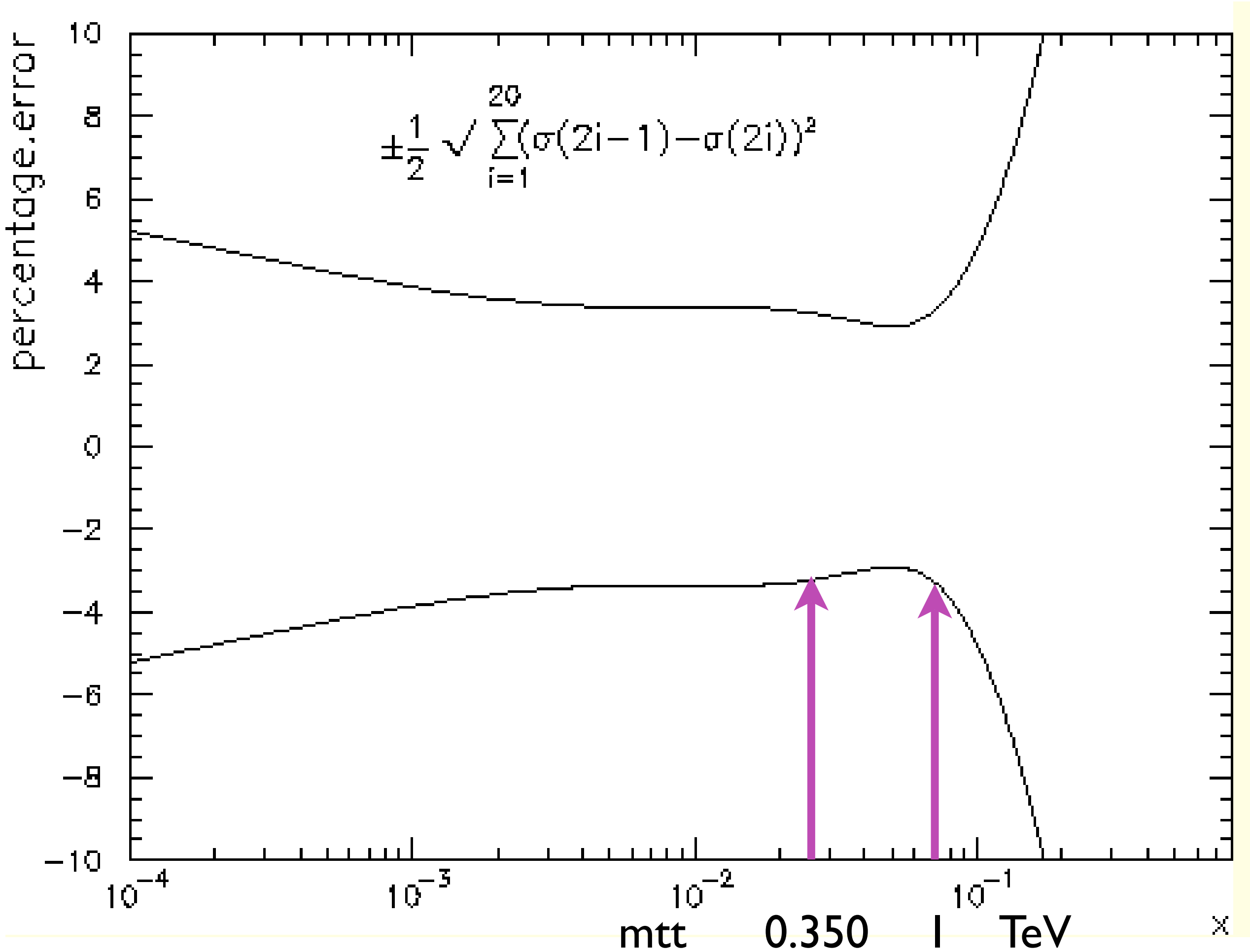
NLO: Mangano, Nason & Ridolfi 1992
Incl. spin corr.: Bernreuther, Brandenburg, Si & Uwer 2001
NLL: Bonciani, Catani, Mangano & Nason 1998
MC@NLO: Frixione, Nason, Webber 2003

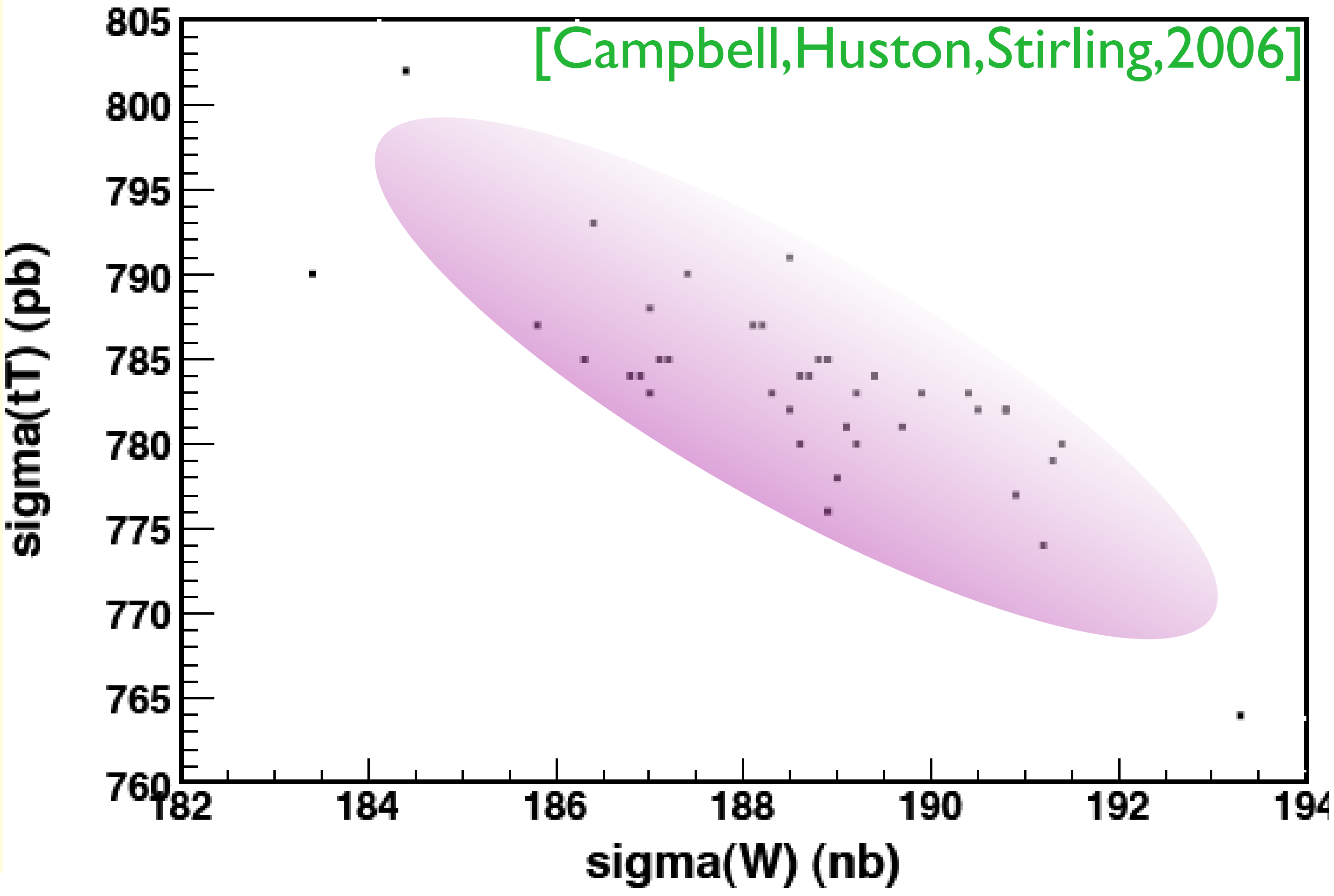
m_{tt} spectrum: low mass



Tree-level results with dynamical scales reproduces MC@NLO results well: a stable observable

PDF uncertainties in top pair production

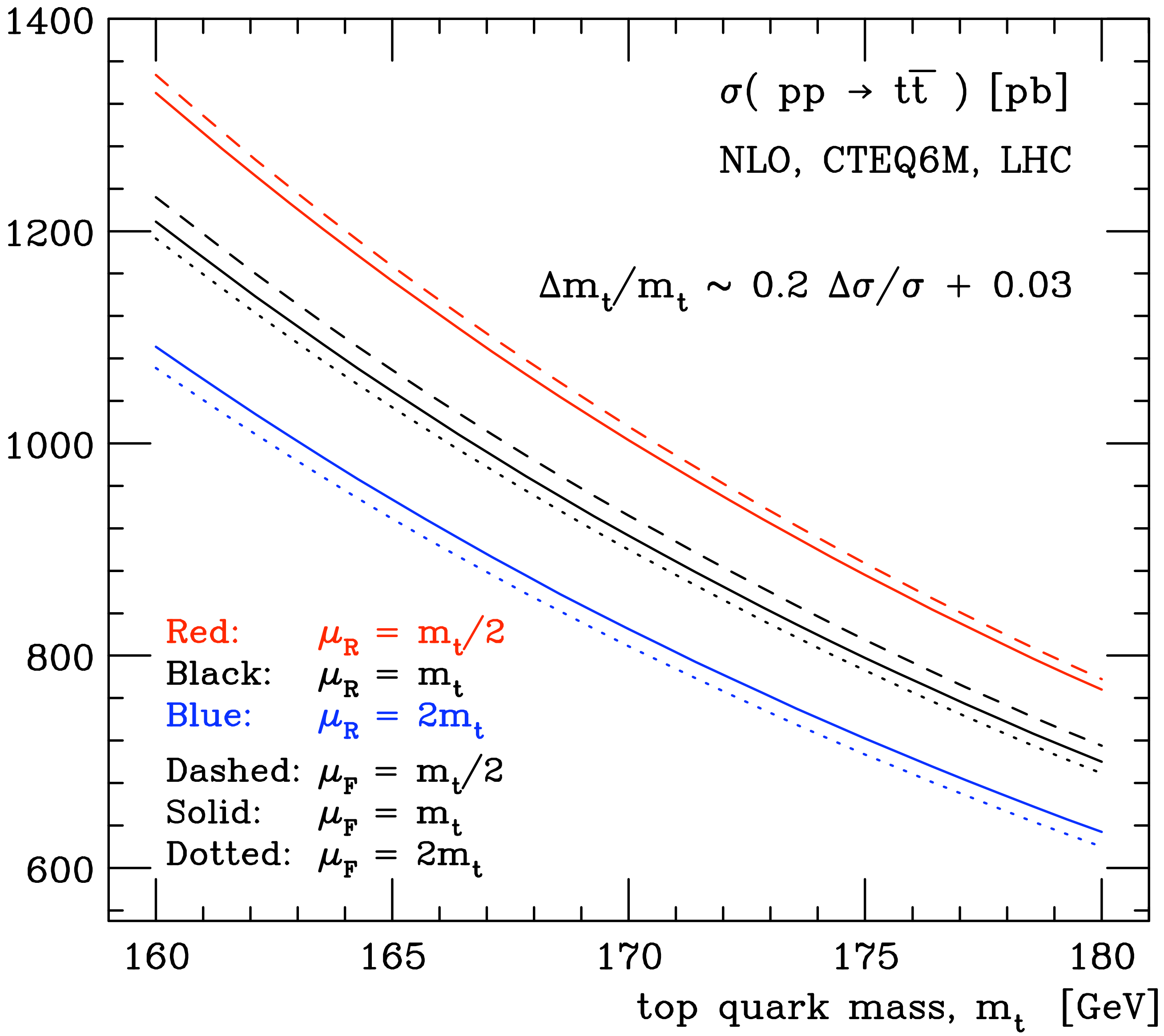




[Campbell,Huston,Stirling,2006]

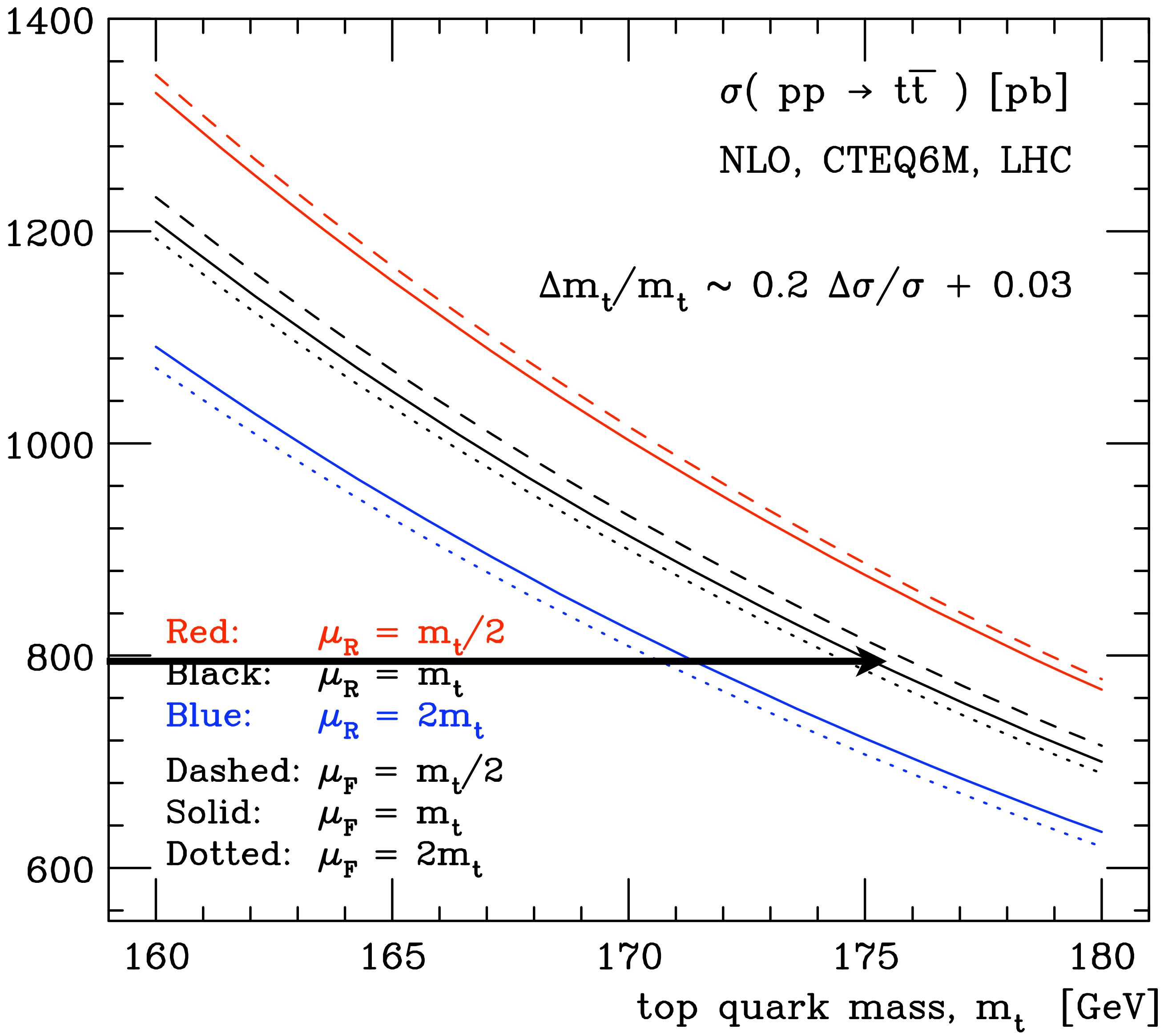
* ttbar production sits exactly on the minimum uncertainty x for the gluon pdf.
* Unticorrelated with the W cross section.
* PDF error is very small compared to the scale uncertainties for low ttbar invariant masses.
* higher invariant masses start to probe x areas characterized by larger uncertainties.

m_t from cross section



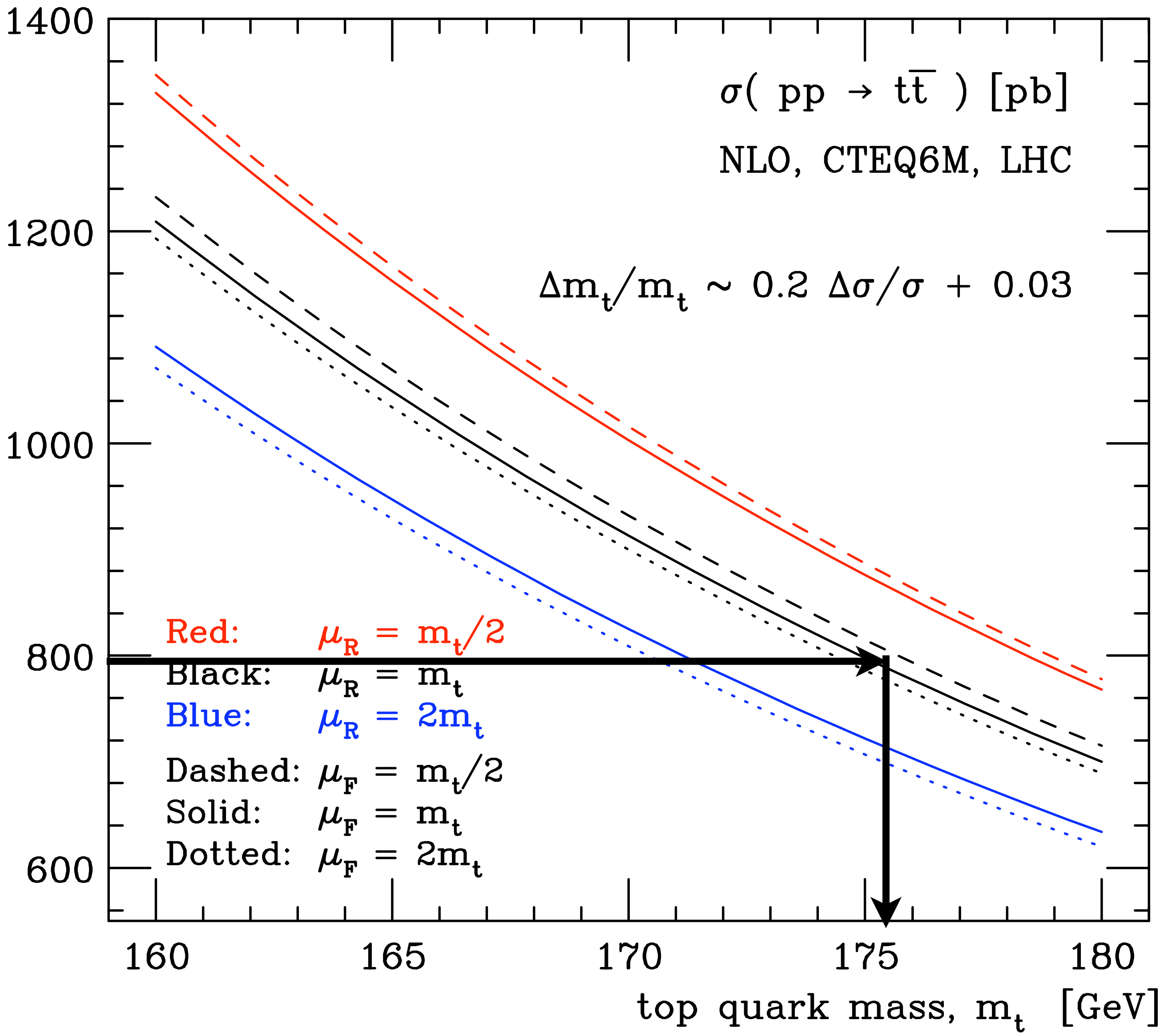
- Total cross section depends strongly on the top mass

m_t from cross section



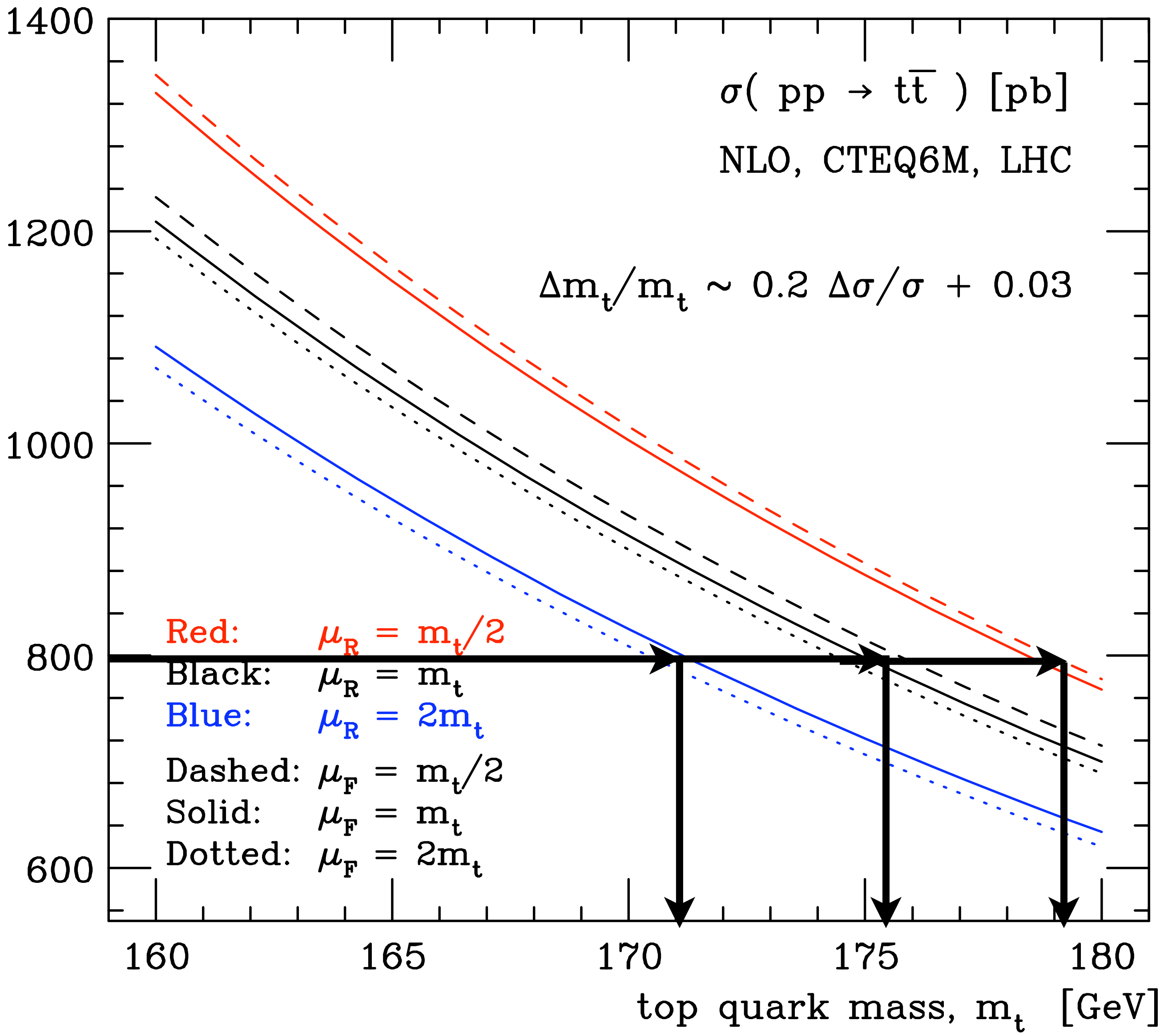
- Total cross section depends strongly on the top mass
- This could be used to measure the top mass from the total cross section

m_t from cross section



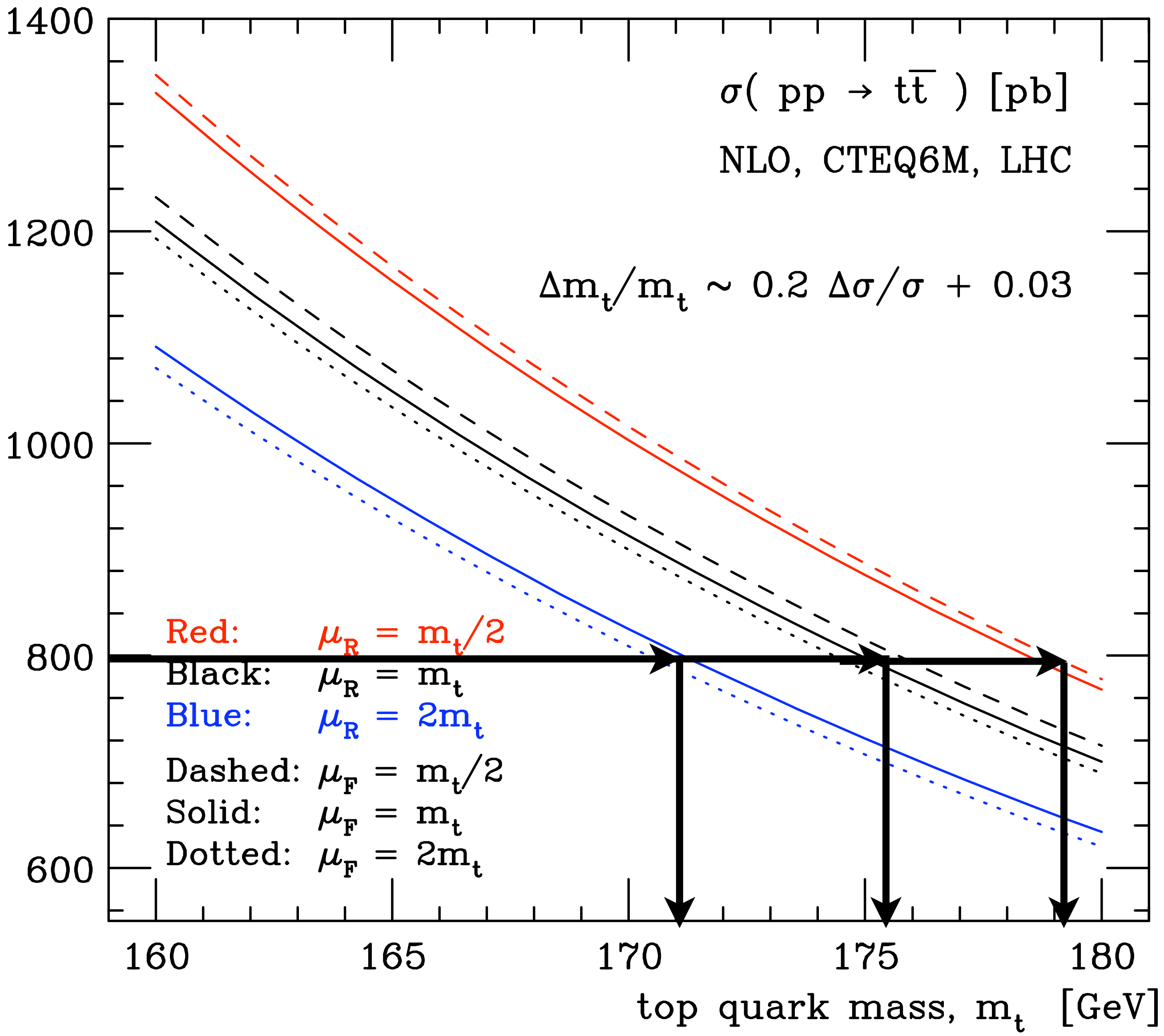
- Total cross section depends strongly on the top mass
- This could be used to measure the top mass from the total cross section

m_t from cross section



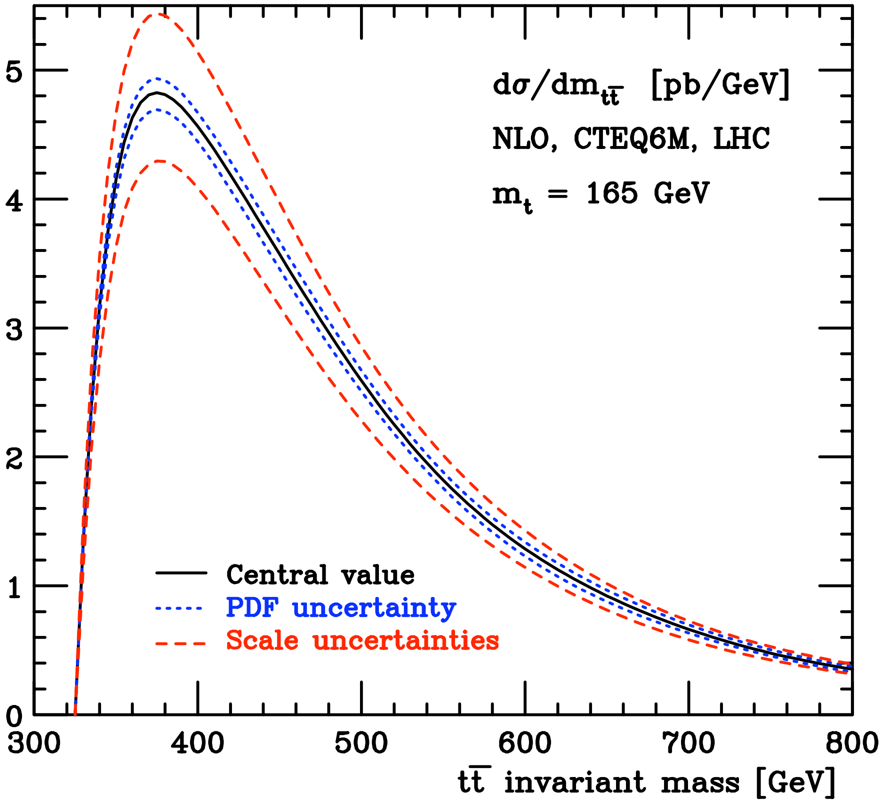
- Total cross section depends strongly on the top mass
- This could be used to measure the top mass from the total cross section
- However, the error on the total cross section is theory dominated!

m_t from cross section

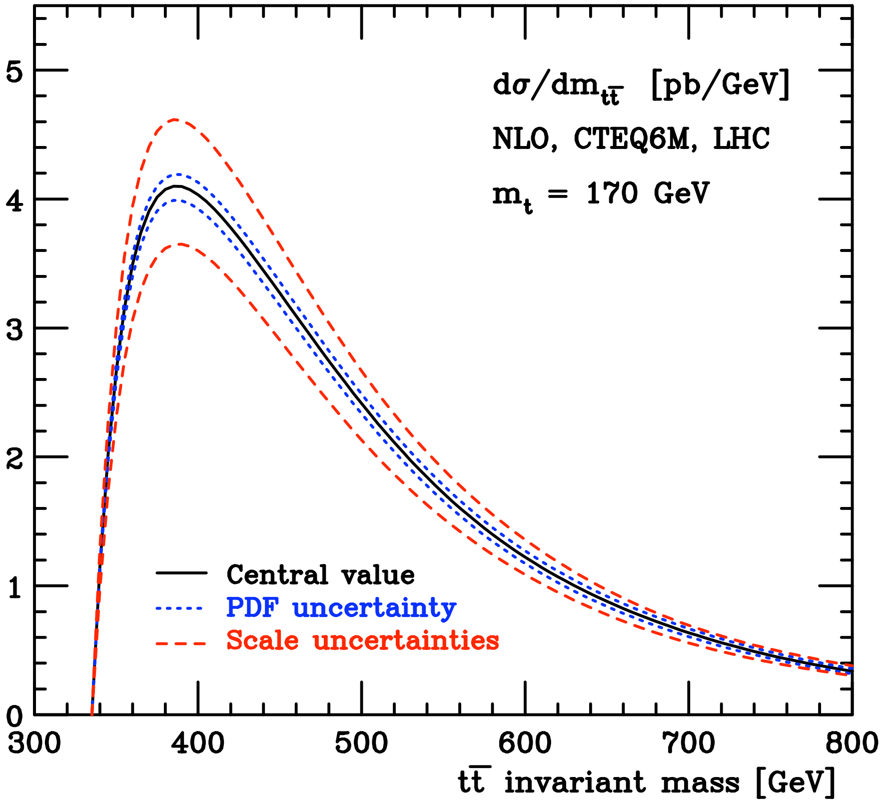


- Total cross section depends strongly on the top mass
- This could be used to measure the top mass from the total cross section
- However, the error on the total cross section is theory dominated!
- What about the shape of m_{tt}?

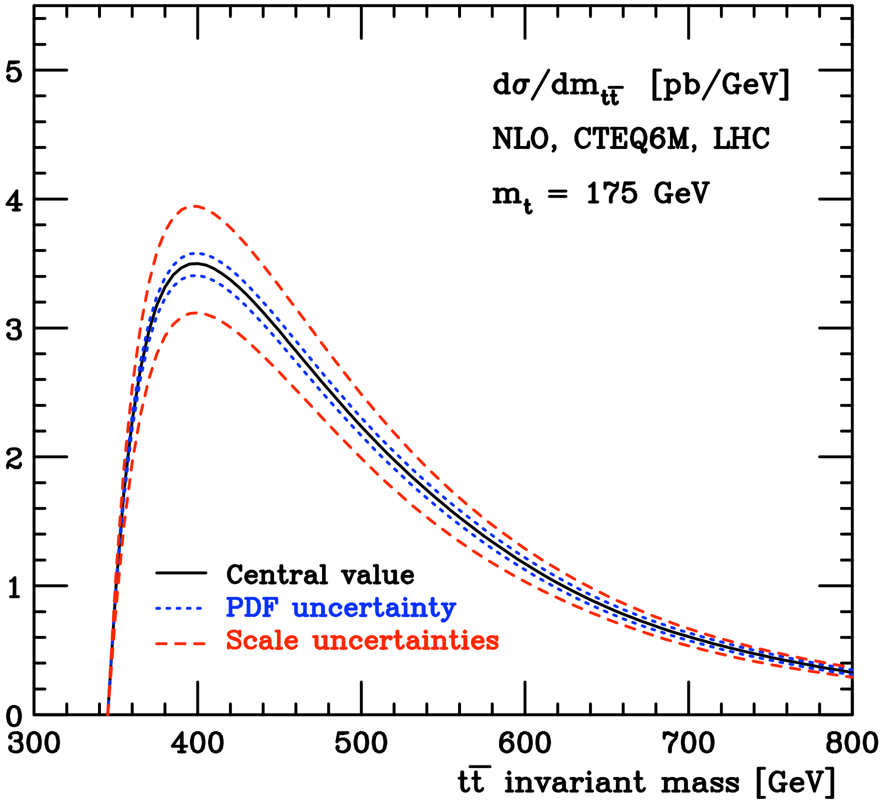
Theoretical uncertainties in top pair invariant mass



$m_t = 165\ \mathrm{GeV}$

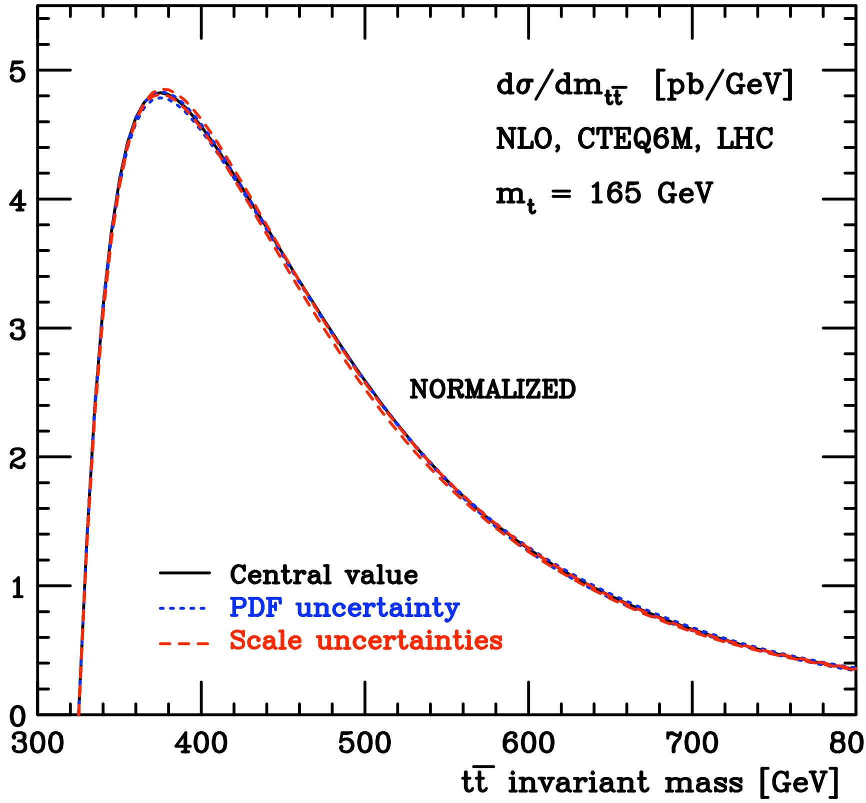


$m_t = 170\ \mathrm{GeV}$

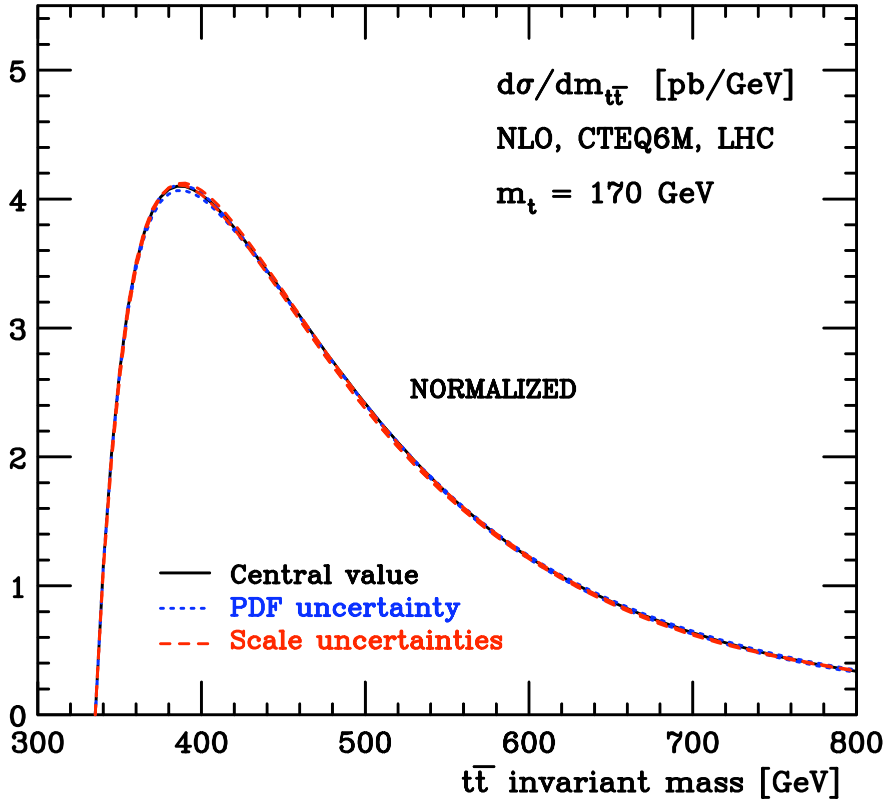


$m_t = 175\ \mathrm{GeV}$

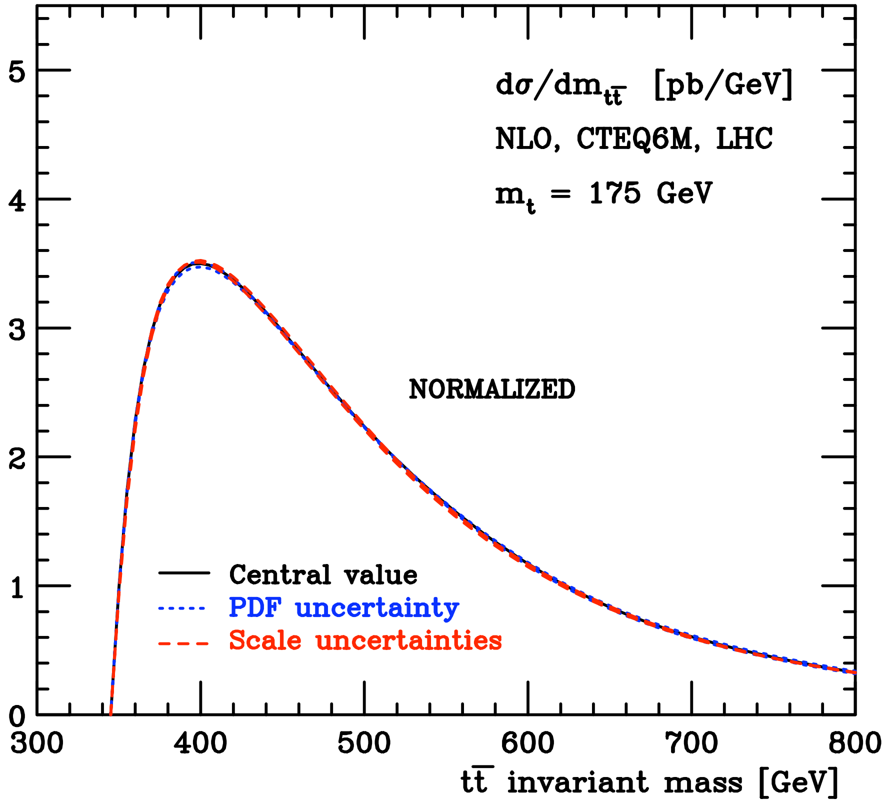
Theoretical uncertainties in top pair invariant mass



$m_t = 165$ GeV



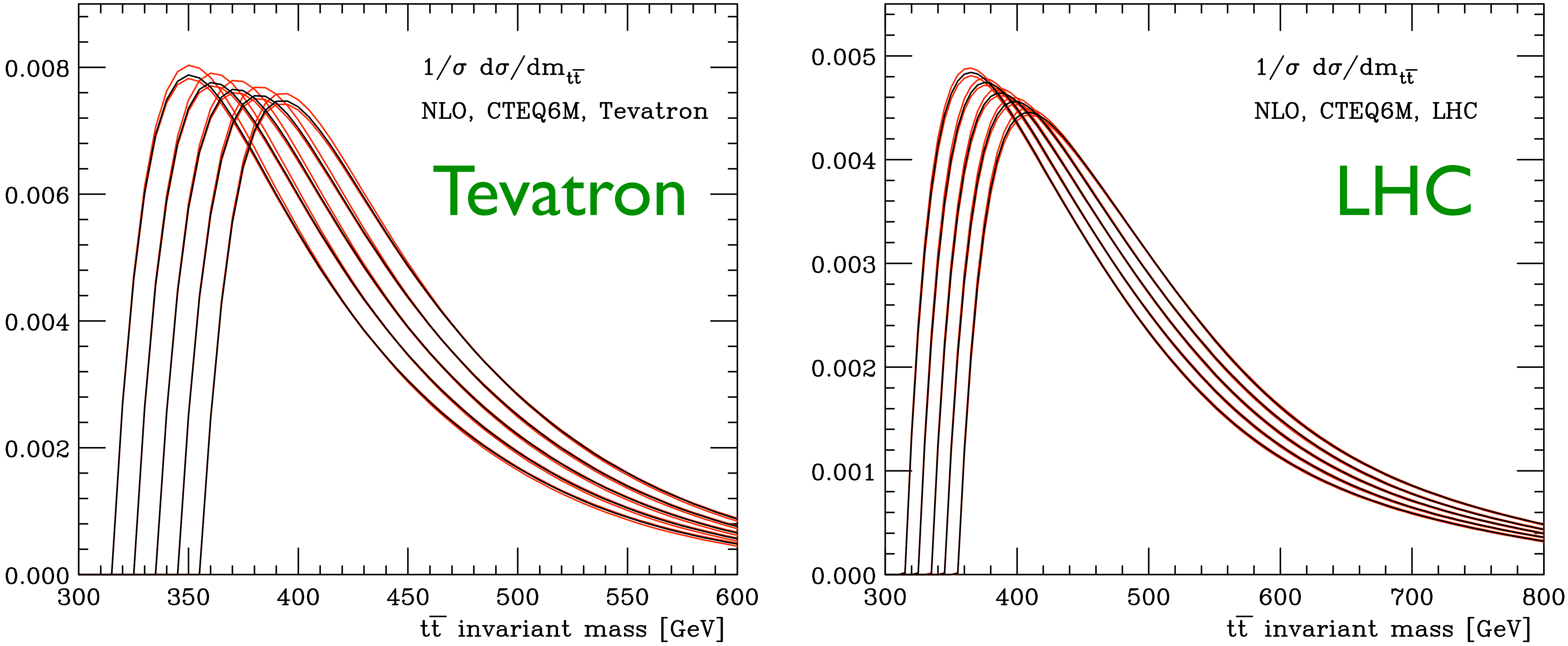
$m_t = 170$ GeV



$m_t = 175$ GeV

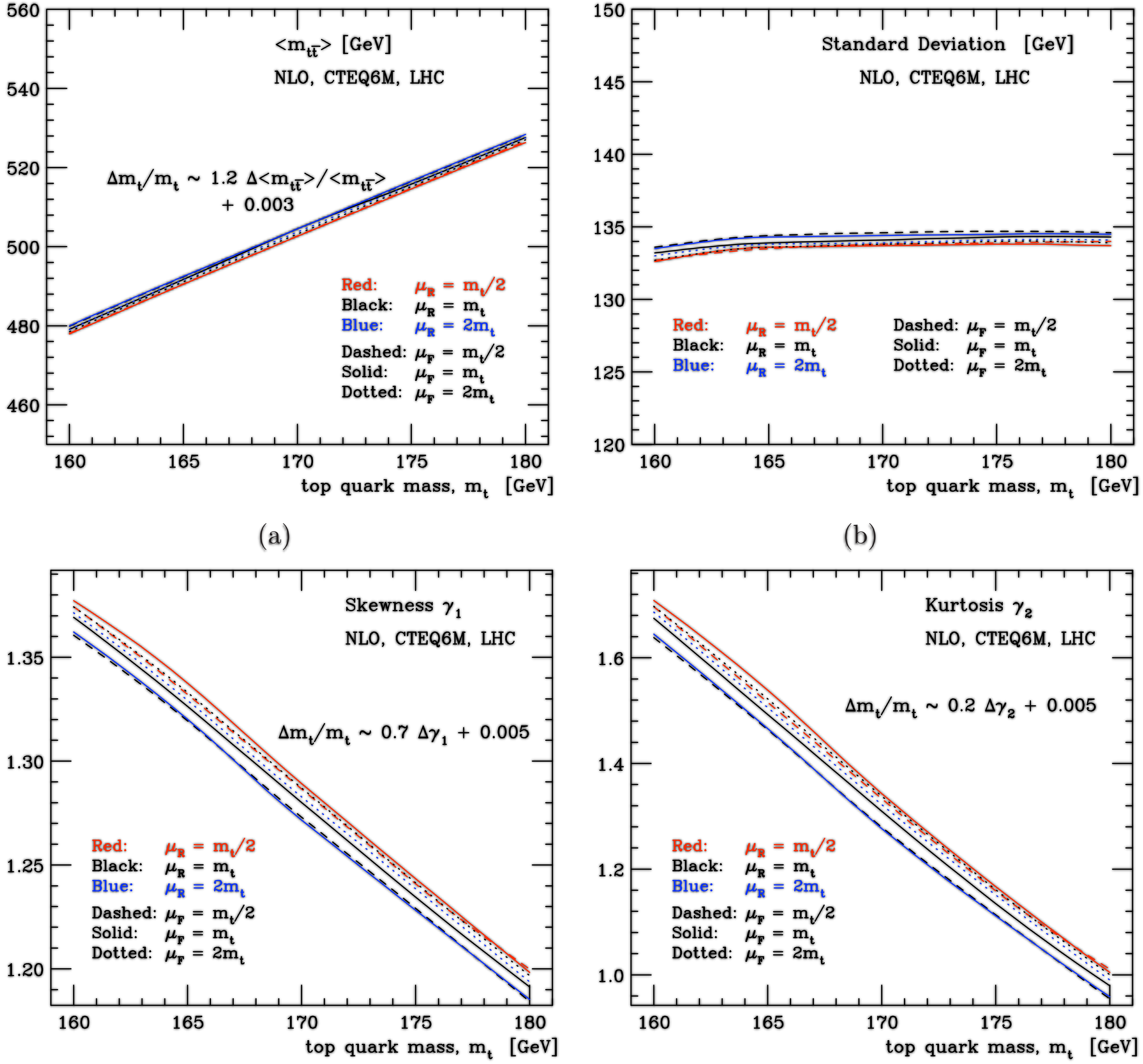
Theoretical uncertainties in top pair invariant mass

Normalized m_{tt} distributions for mt=160,...,180 GeV



Shape is under good control, normalization uncertainty is large.
Study moments to compare distributions!

m_t from m_{tt}: moments approach



(a)

(b)

$$\langle m_{t\bar{t}}\rangle = \int \mathrm{d}m_{t\bar{t}}\; m_{t\bar{t}} \frac{\partial\sigma}{\partial m_{t\bar{t}}}\Big|_{\mathrm{norm.}}$$

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

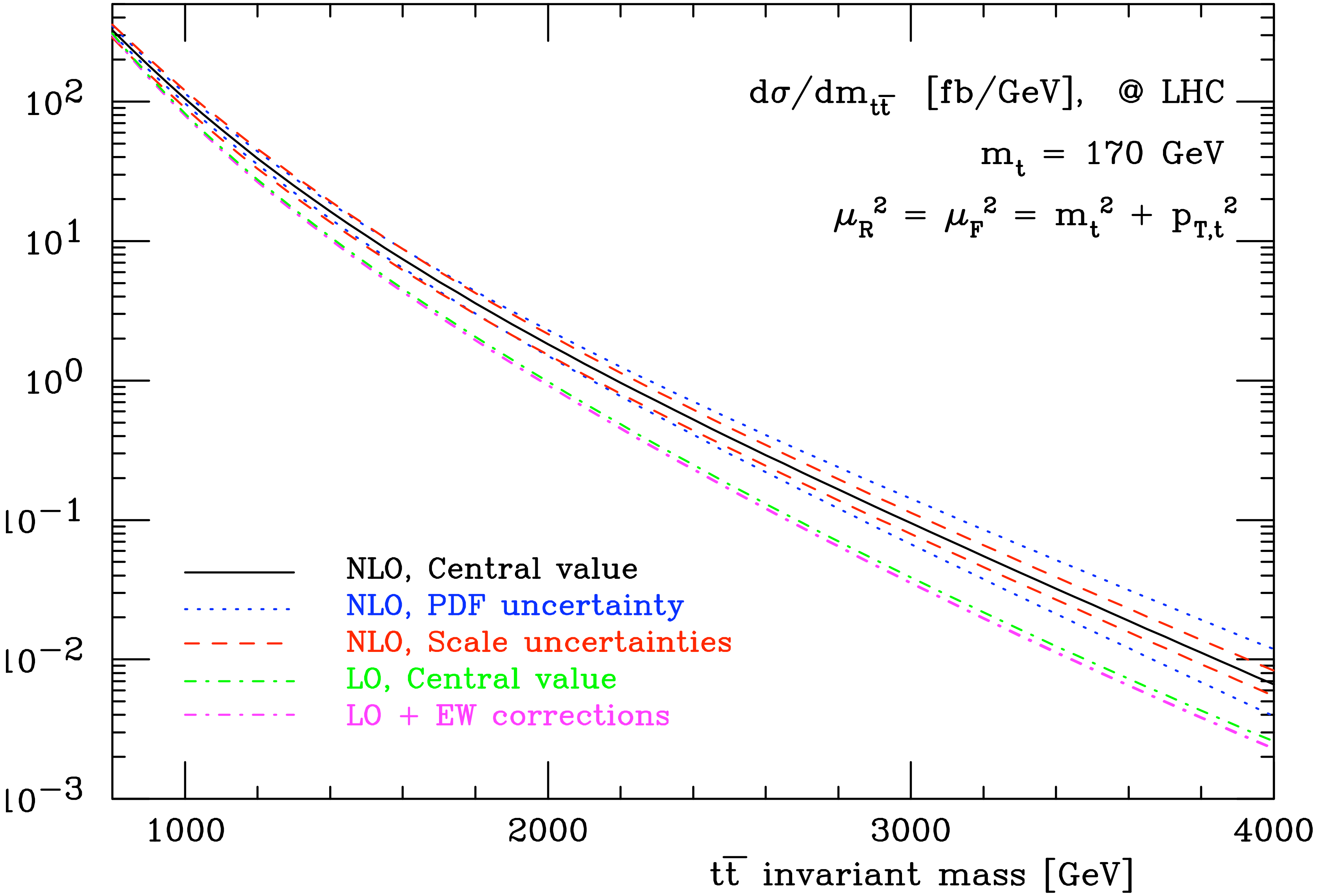
$$\gamma_1 = \frac{\mu_3}{\mu_2^{3/2}}$$

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

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

- Very promising: further exp. sudies for systematics needed!

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%.

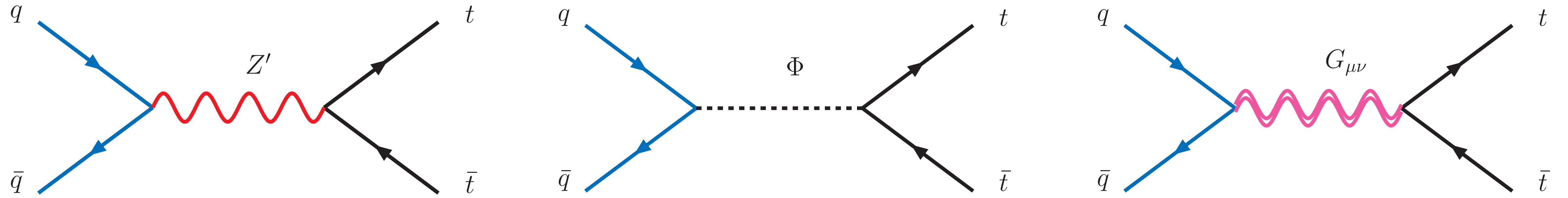
*SUSY could also lead to virtual corrections of similar size, relevant only for high-m_{tt} physics.

Outline

- Strategies for BSM at the LHC
- Focus on m_{tt}
  - SM predictions
  - pp → X → tt : three step analysis
- Perspectives

New resonances

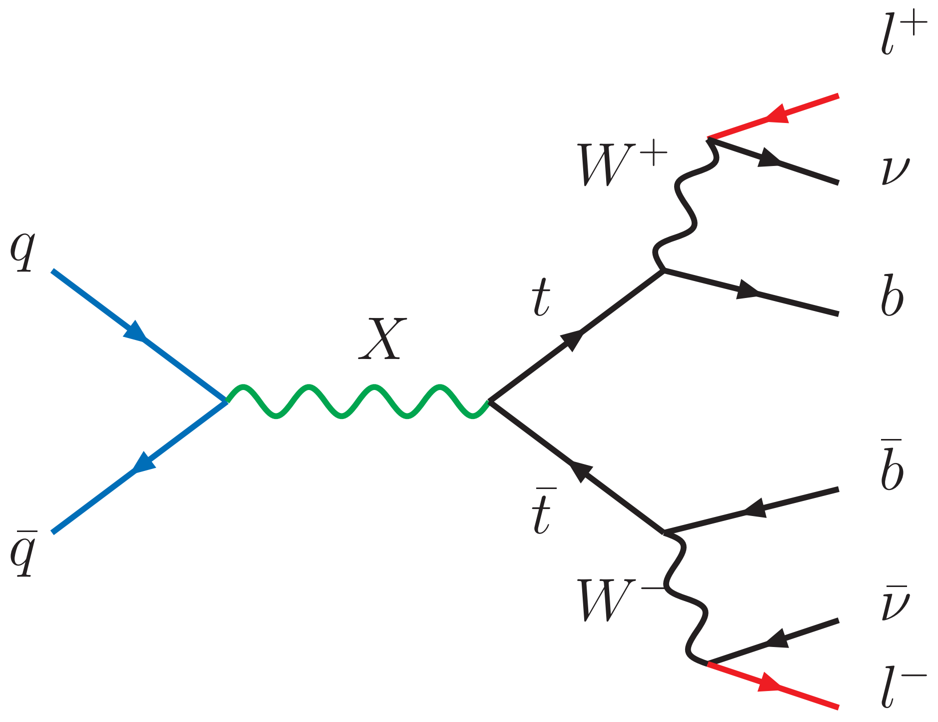
In many scenarios for EWSB new resonances show up, some of which preferably couple to 3rd generation quarks.



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,γ_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/

Three-phase analysis

phase I

Find an excess of events in a relatively simple observable, in our case: top pair invariant mass

↓

phase II

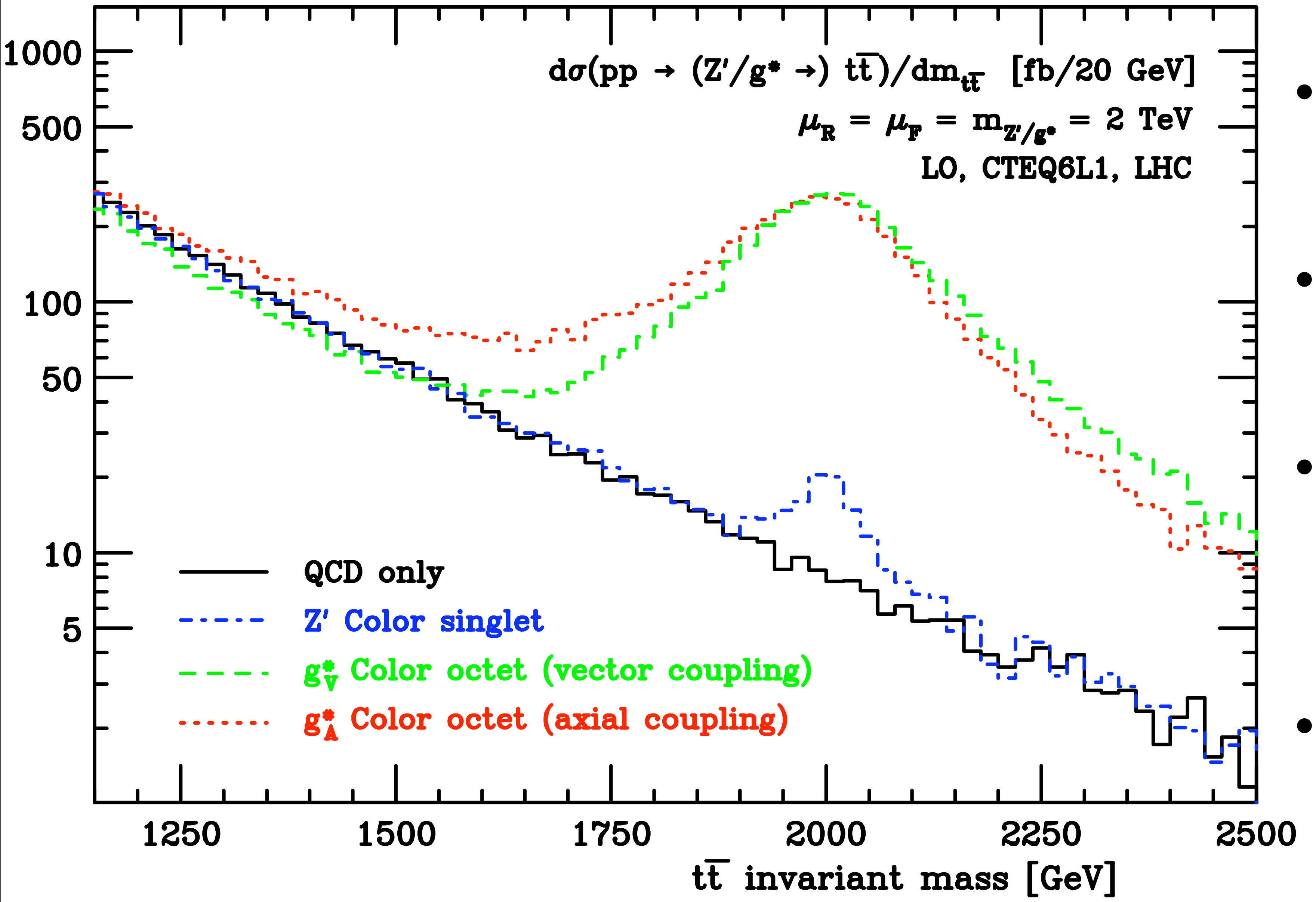
Use a more involved observable to determine the spin of the resonance, e.g. the Collins-Soper angle

↓

phase III

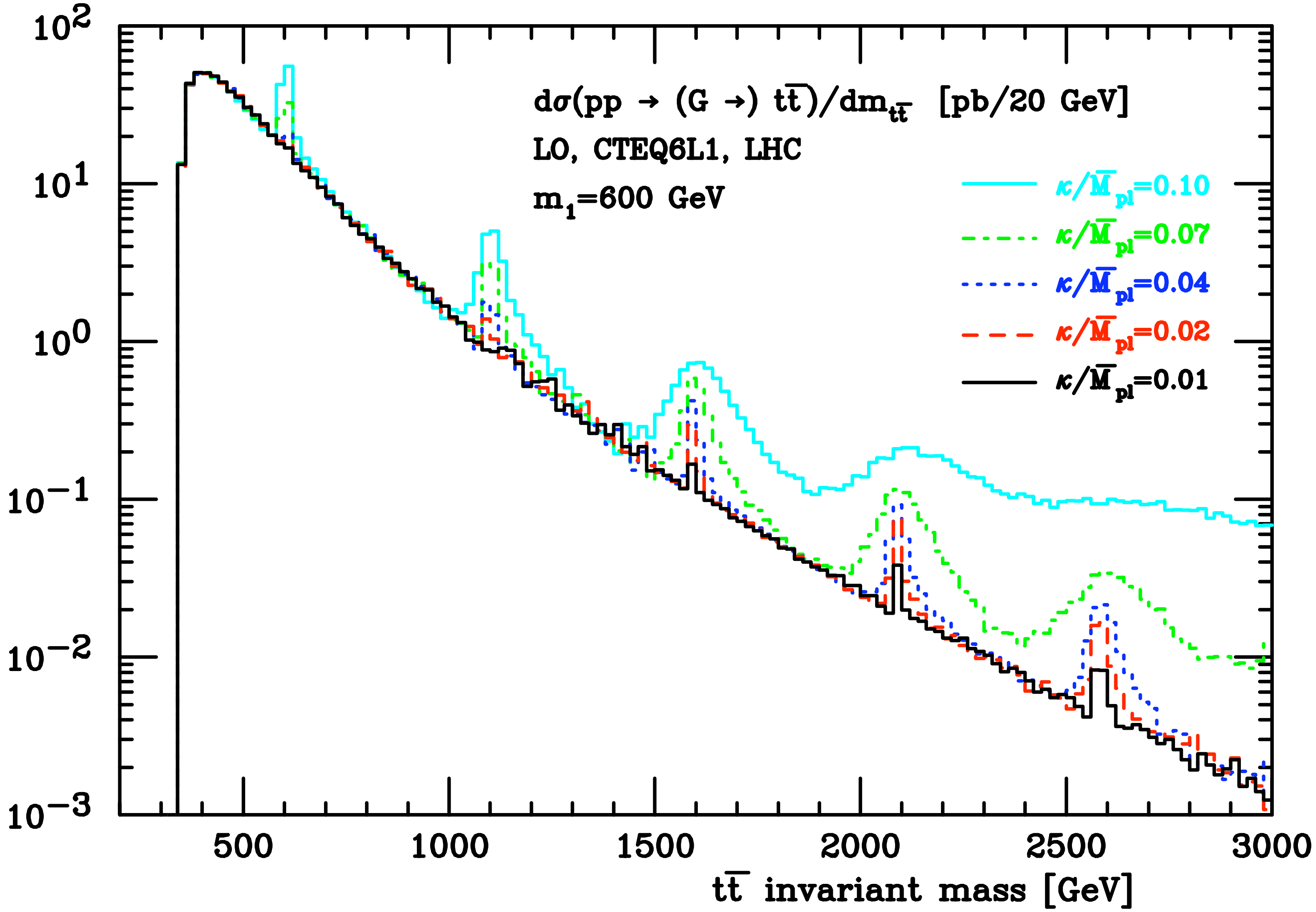
Use the full information in the event to determine the coupling-structure of the resonance

Phase I: Excess of events



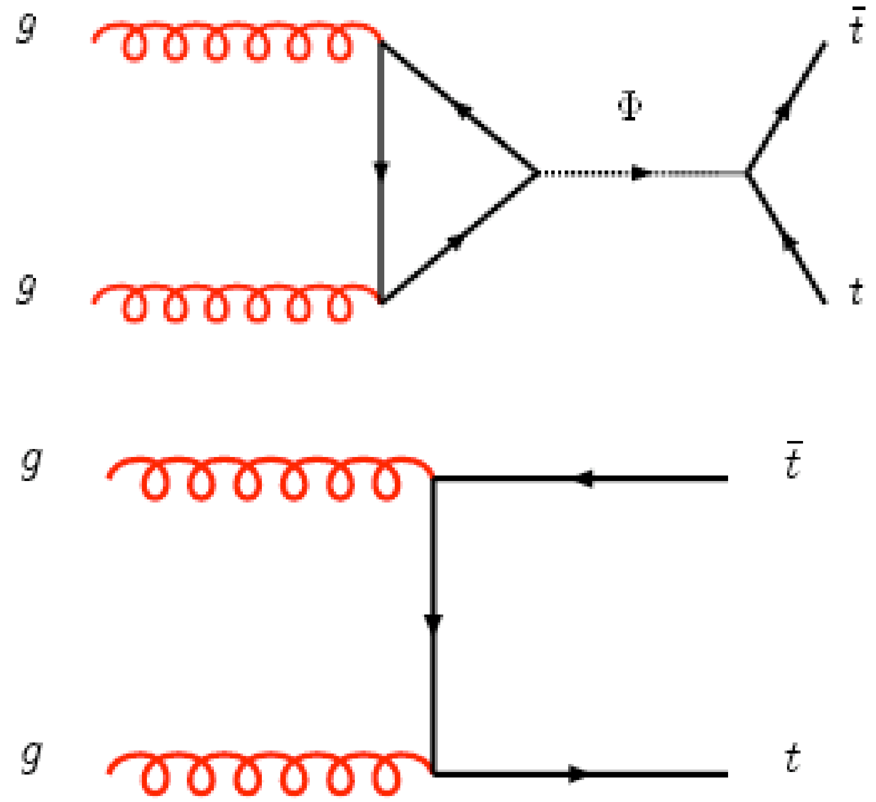
- Vector resonance in color singlet or octet state
- Widths and rates very different
- Interferences with ttbar backgr. not always negligible.
- Direct information of σ·BR and Γ_t

Phase I: Excess of events

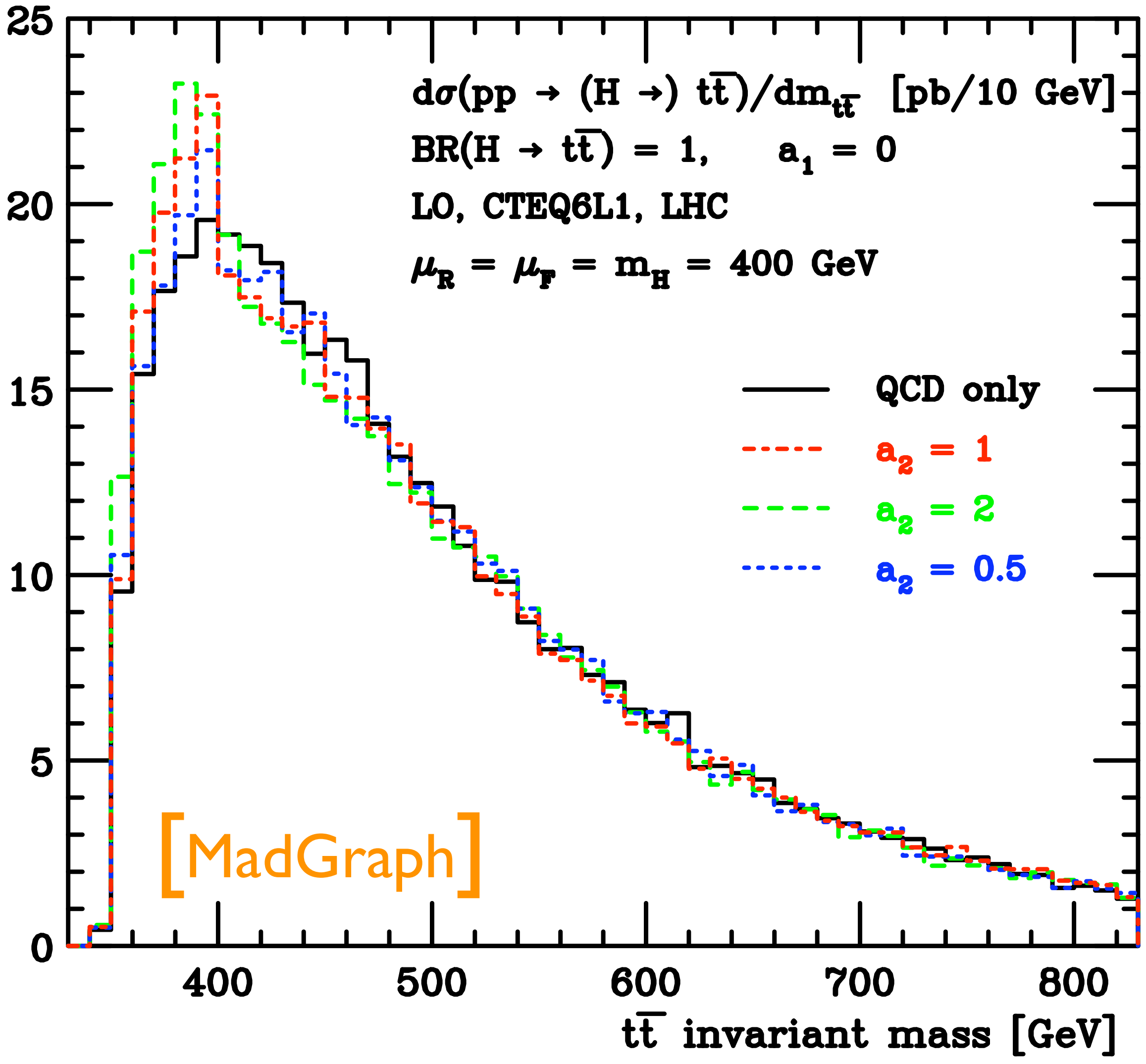


- RS model with first KK graviton resonance at 600 GeV
- Spectacular signature!

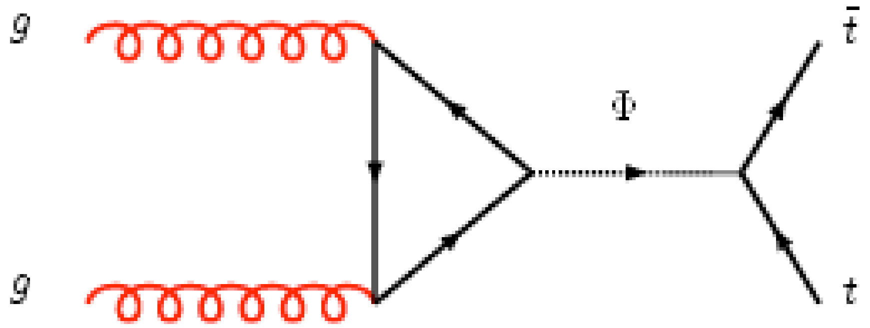
Phase I:
Also non-trivial interferences

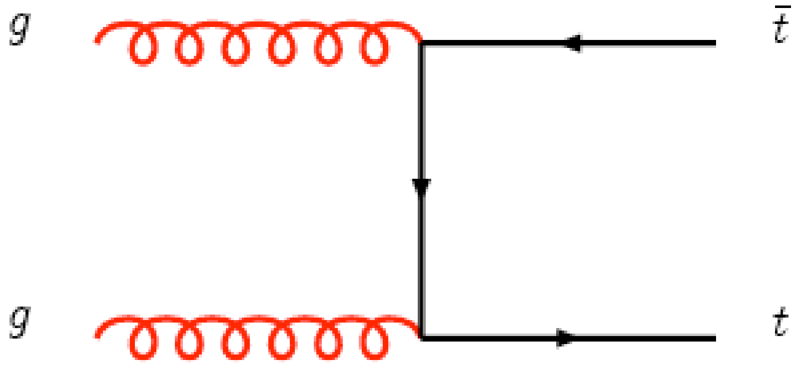


Dicus, Stange & Willenbrock 1994

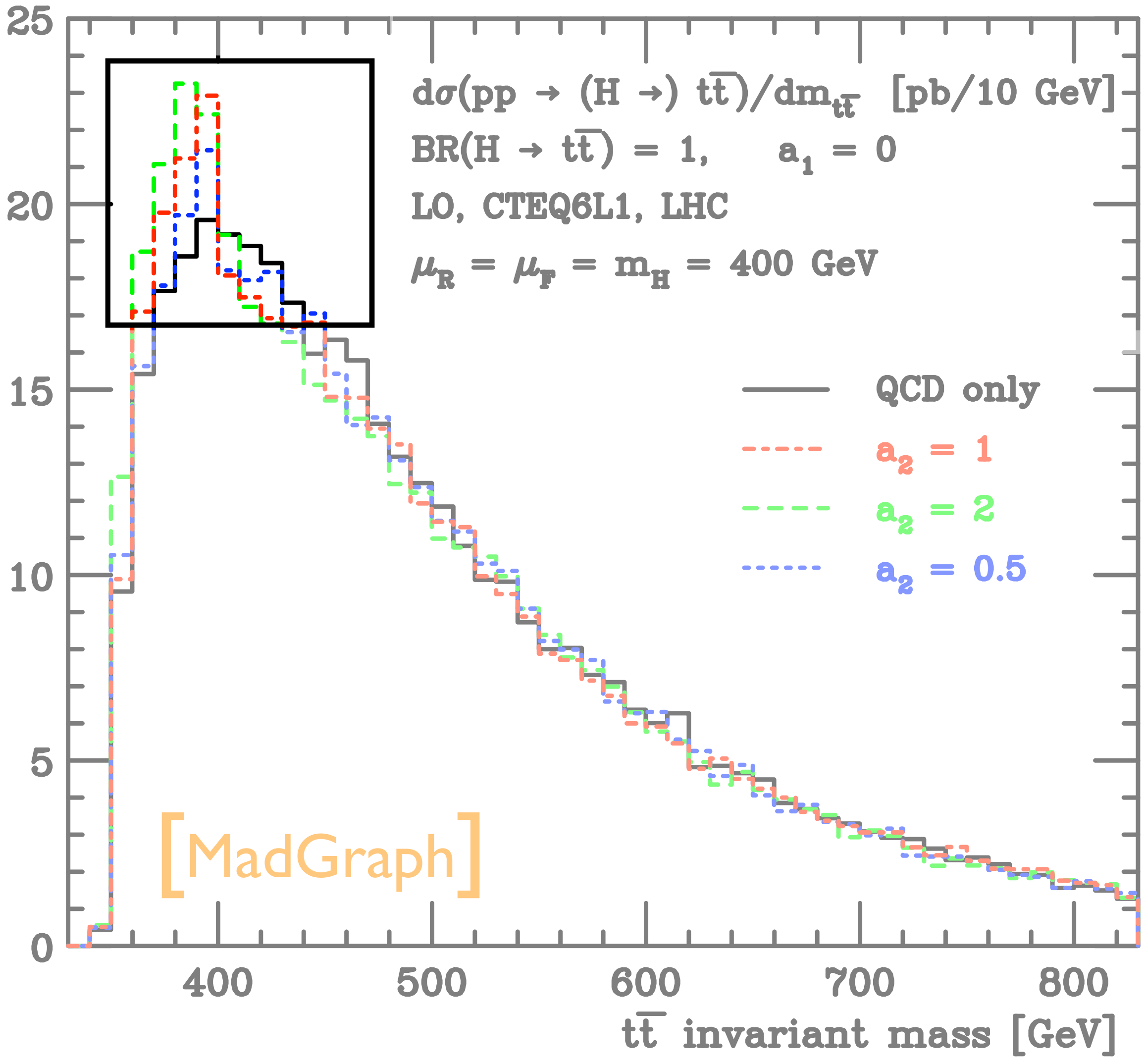


Phase I:
Also non-trivial interferences

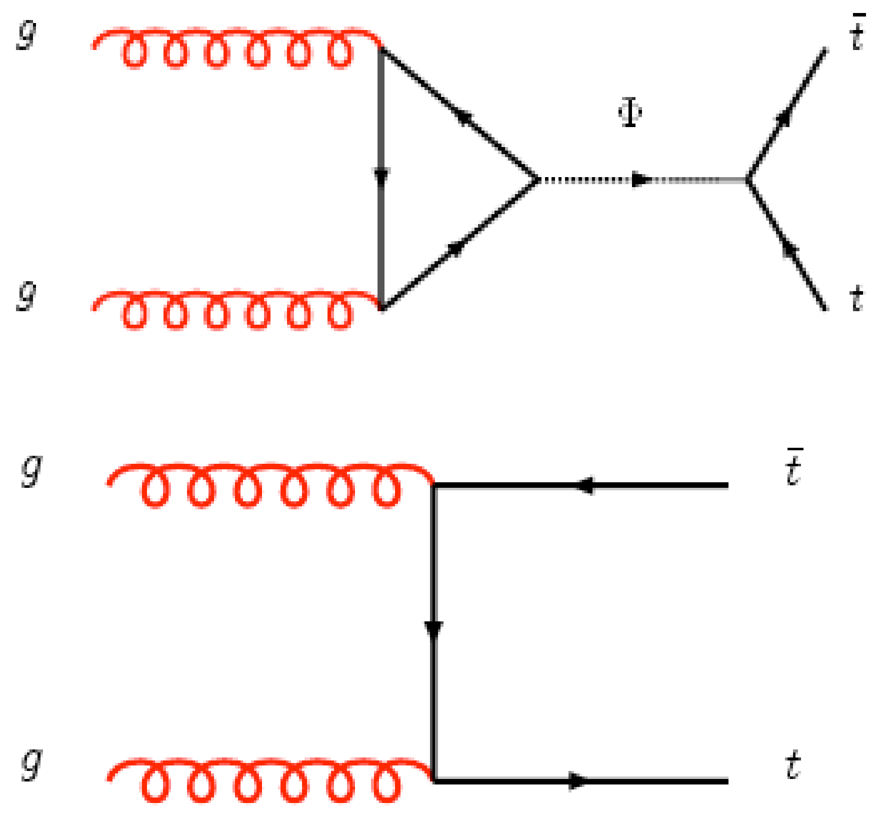




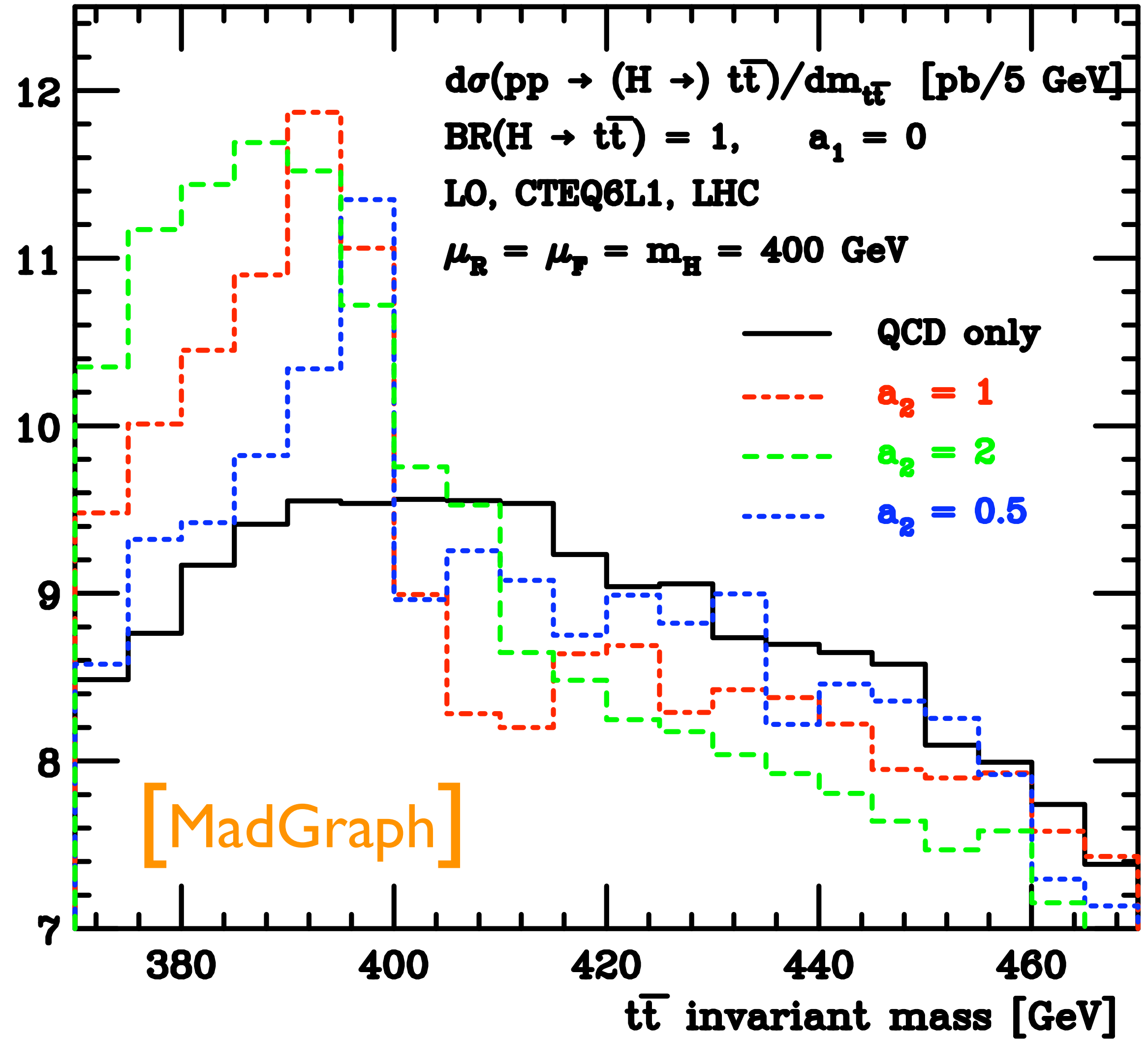
Dicus, Stange & Willenbrock 1994



Phase I: Also non-trivial interferences

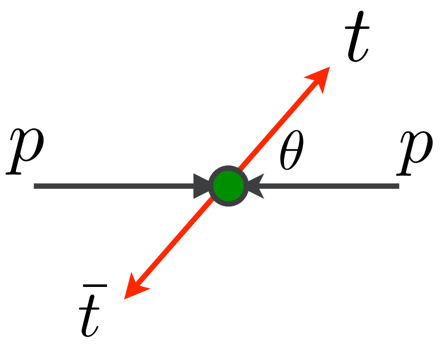


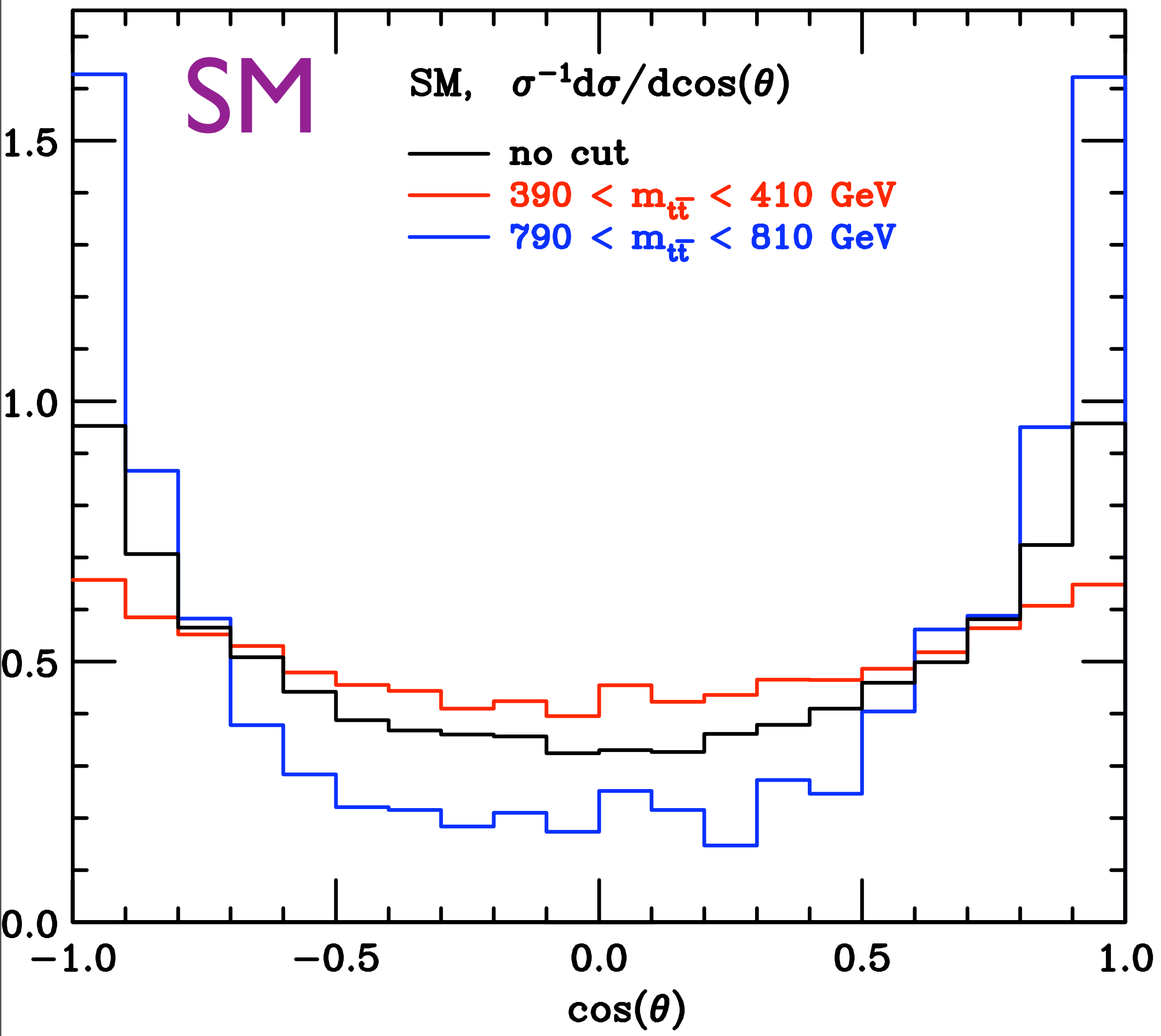
Dicus, Stange & Willenbrock 1994

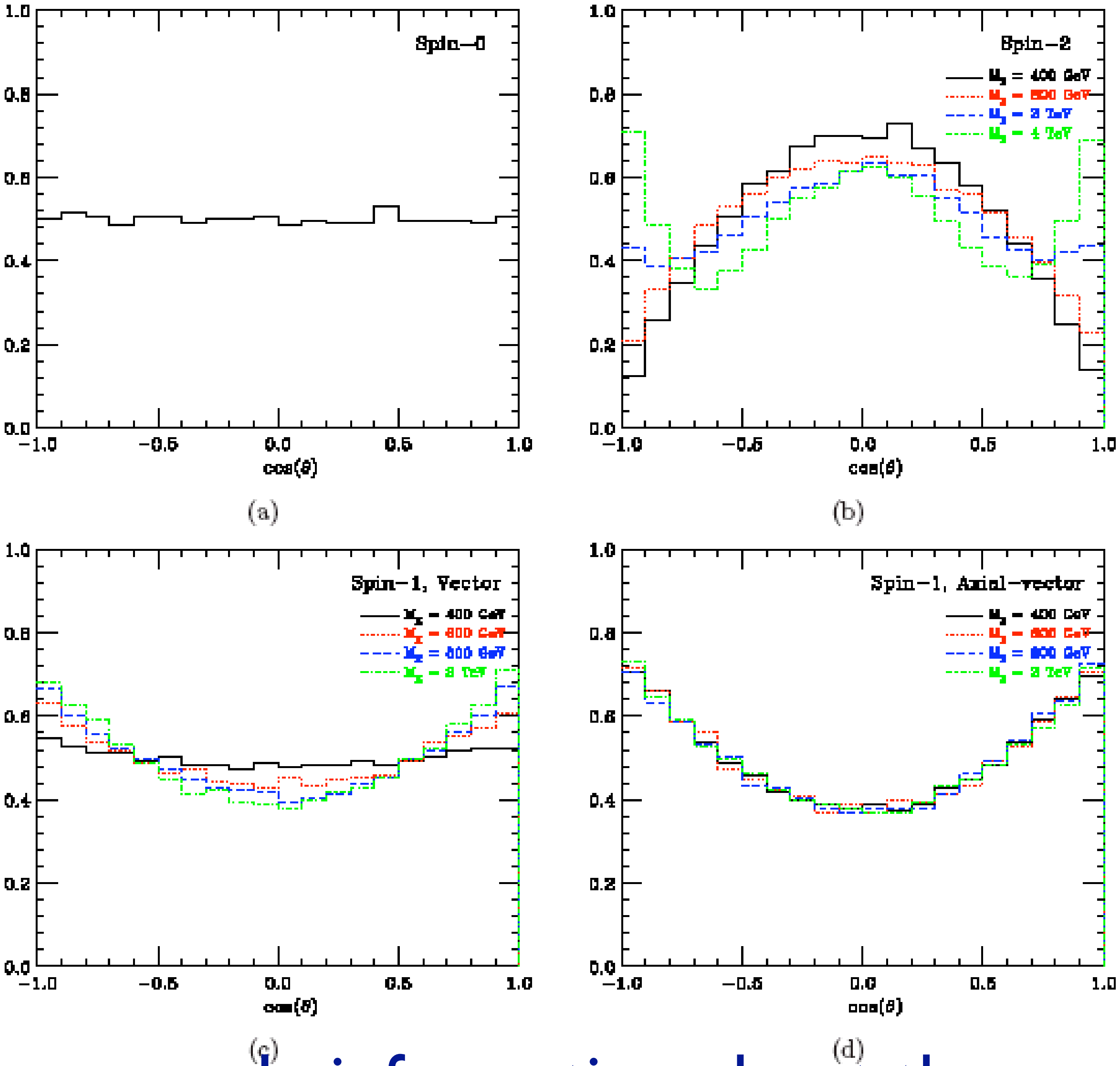


Interference effects between New Physics and SM background leads to 'peak-dip' structure. It is important to simulate signal and background consistently in one go!

Phase II: Determine Spin



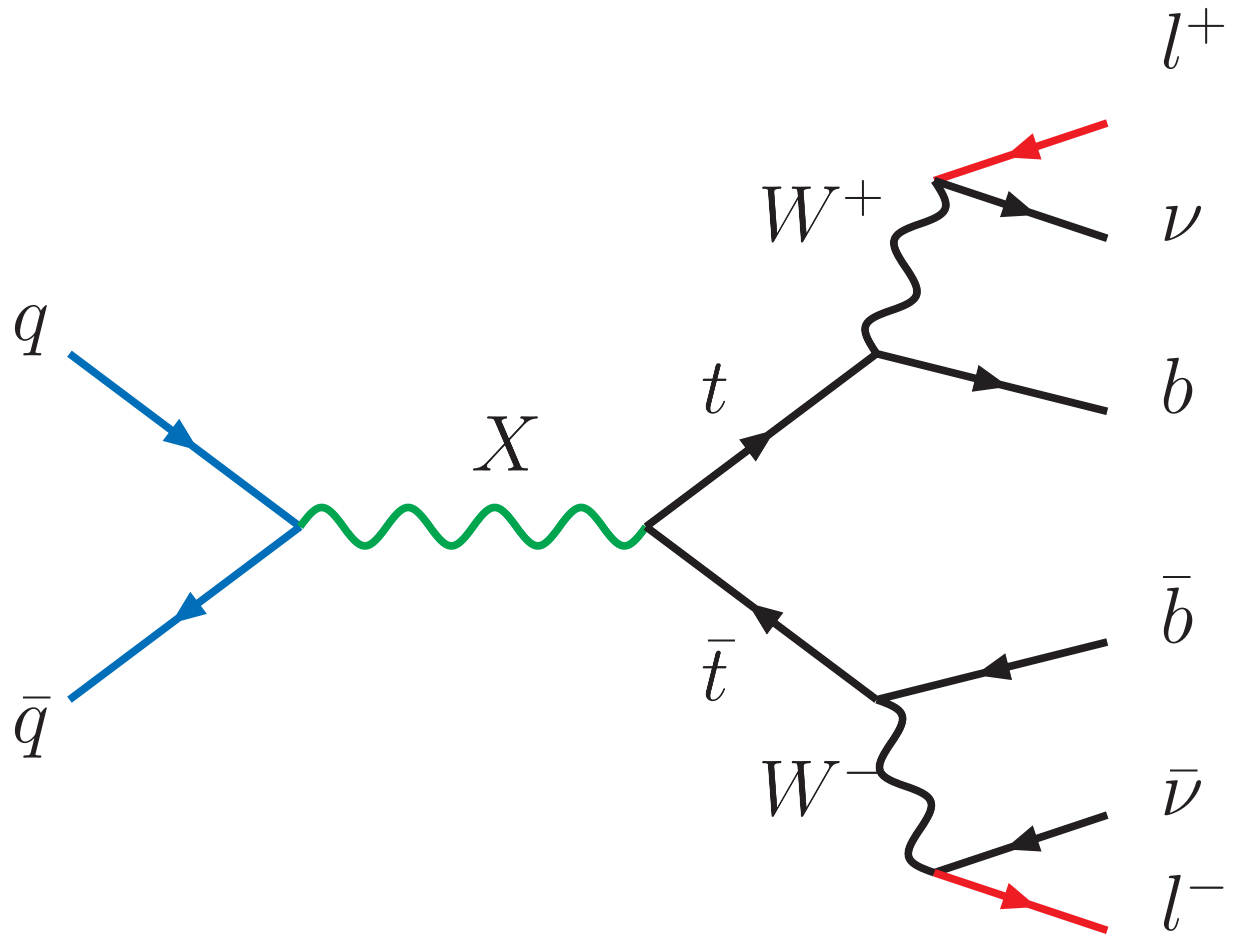




By measuring the Collins-Soper angle information about the spin structure of the resonance can be obtained

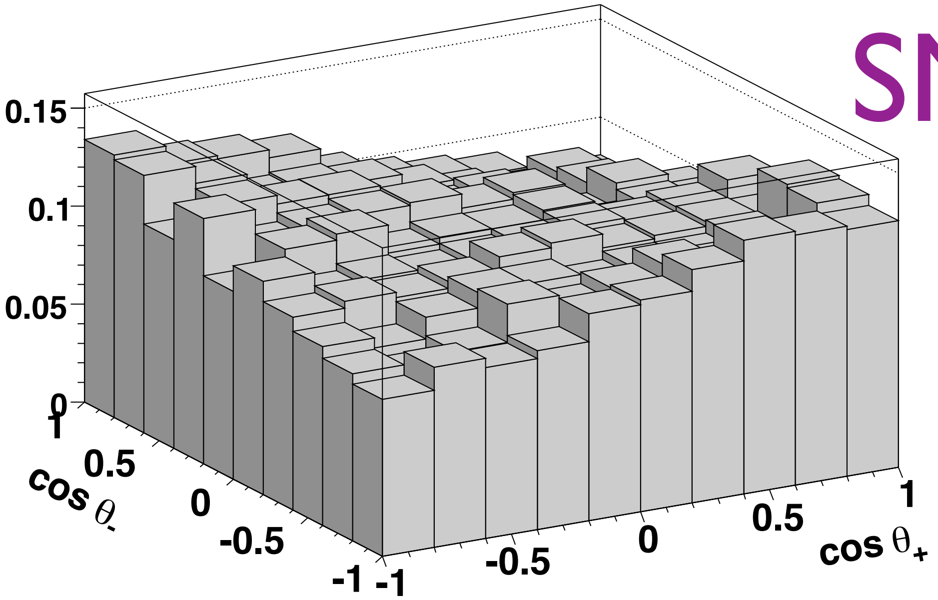
Phase III: Spin correlations

- Use the full information of the events to determine coupling-structure
- We also need matrix element simulation of the decay of the top quarks, i.e. the full 2→6 process
- In general each resonance is more sensitive to a different distribution



Phase III: Spin correlations

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 - A\cos\boxed{\theta_+}\cos\theta_- + b_+\cos\theta_+ + b_-\cos\boxed{\theta_-}\right)$$



SM

Angle between l^+ in top rest-frame and top in top pair rest-frame

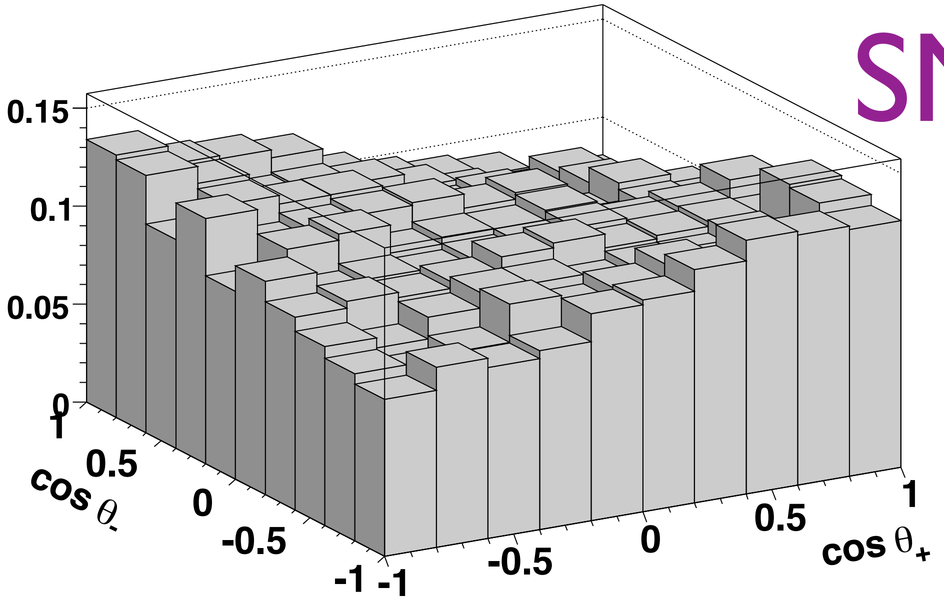
Angle between l^- in anti-top rest-frame and anti-top in top pair rest-frame

Example: Spin-1

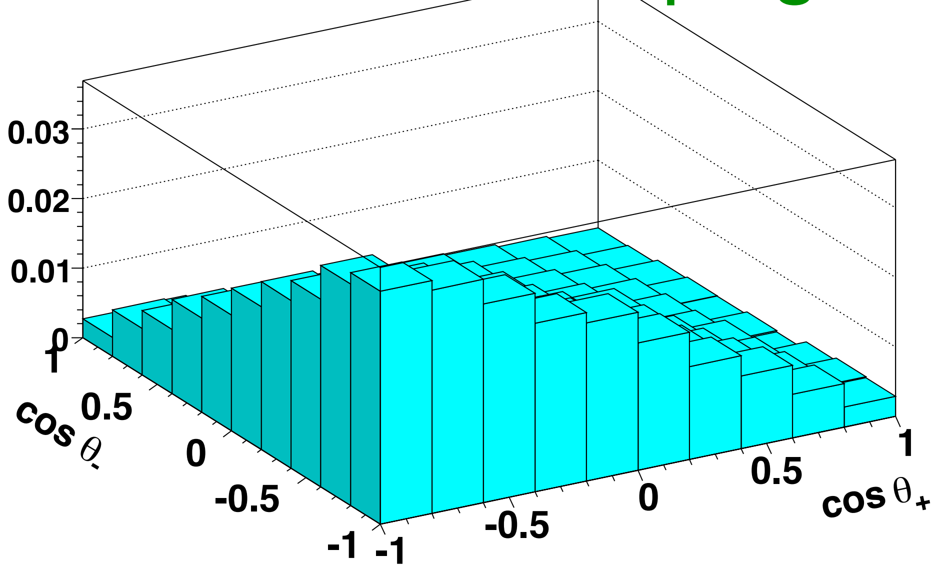
Phase III: Spin correlations

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 - A\cos\theta_+\cos\theta_- + b_+\cos\theta_+ + b_-\cos\theta_-\right)$$

SM

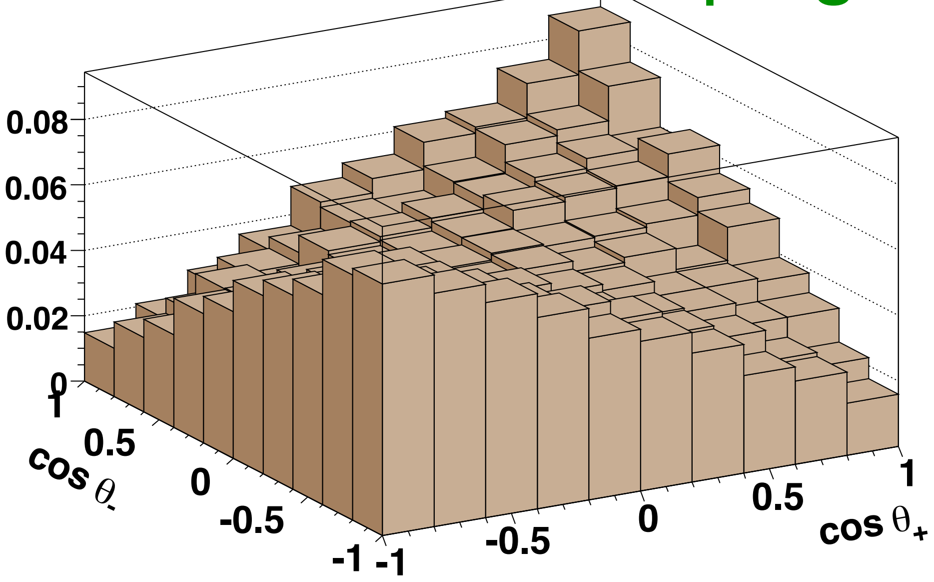


Left-handed coupling

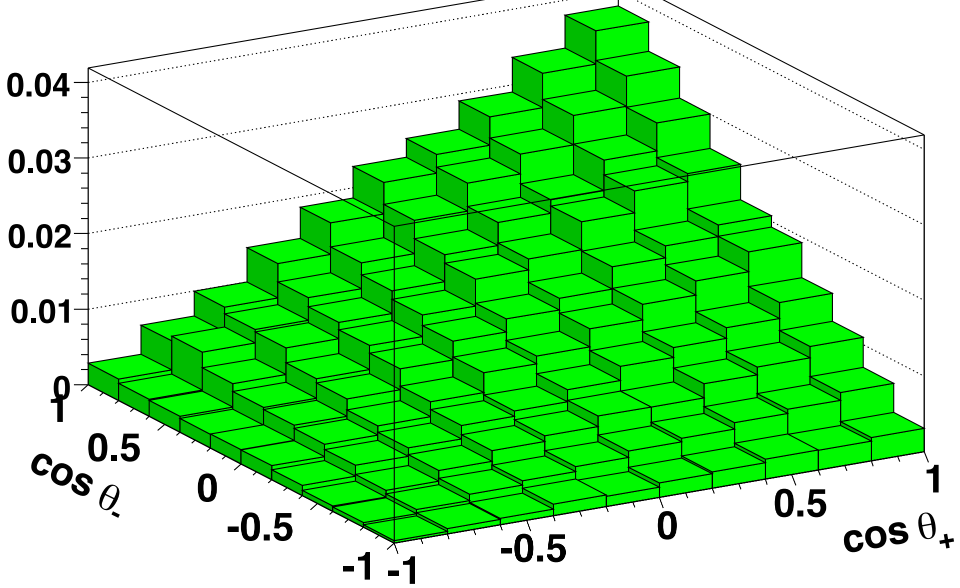


Spin-1

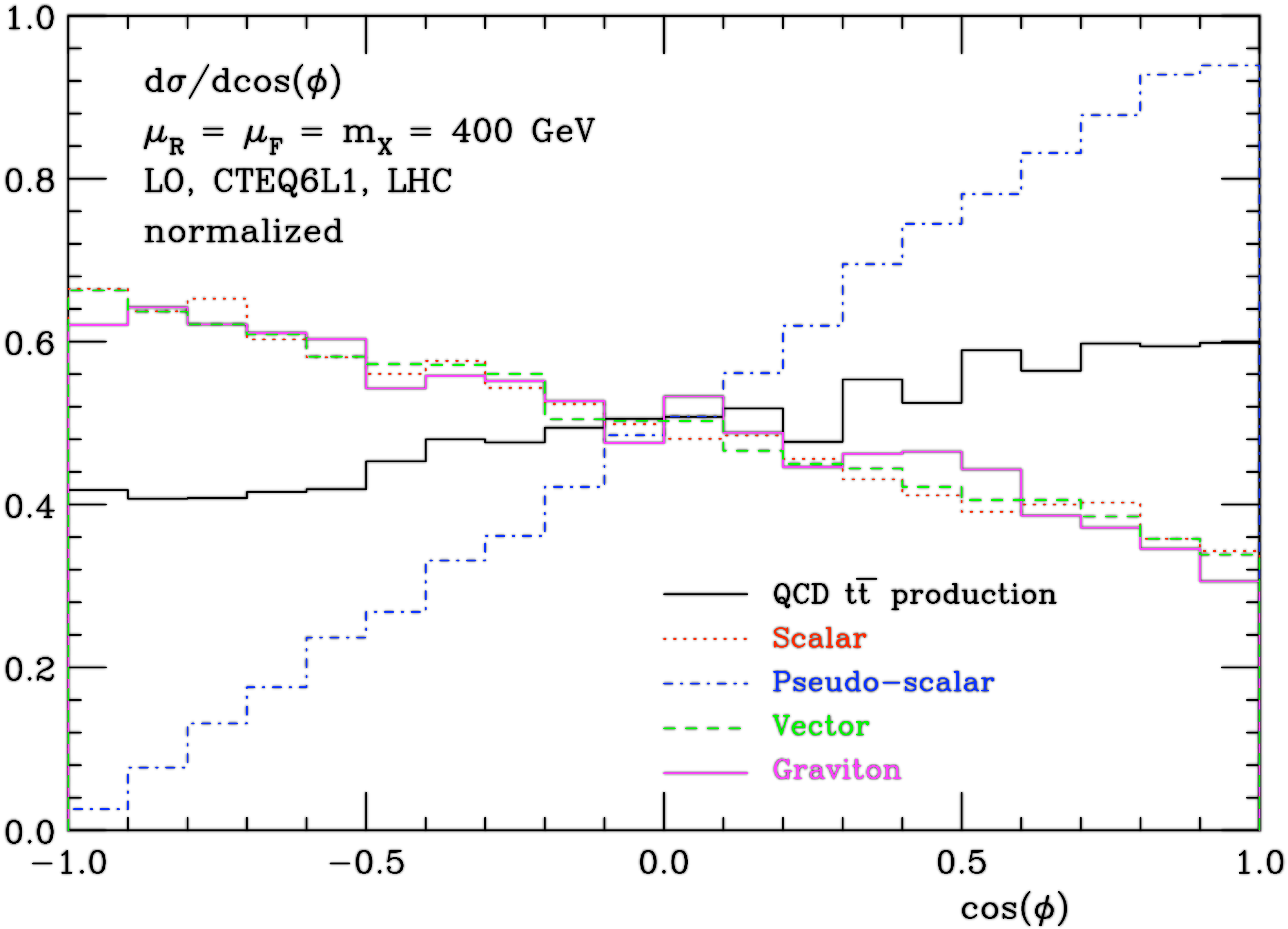
Vector-like coupling



Right-handed coupling



Phase III: Spin correlations



- Angle between lepton in top frame and anti-lepton in anti-top frame.

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.

Extra slides

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 approach
- To fix the final state (modulo combinatorics) we need 18 measurements.

	0 lept	1 lepts	2 lepts
# measured	6x3	5x3+ $\not{E}_T$ +m_W	4x3+$\not{E}_T$+(2m_W,2m_t)
m(tt)	no reco needed	reco (no comb w/ constr)	full reco w/ comb no spin comb
cos θ	reco (no comb w/ constr)		
spin corr.	full reco + 4-fold spin comb	full reco + 2-fold spin comb	