



# Top Quark Physics

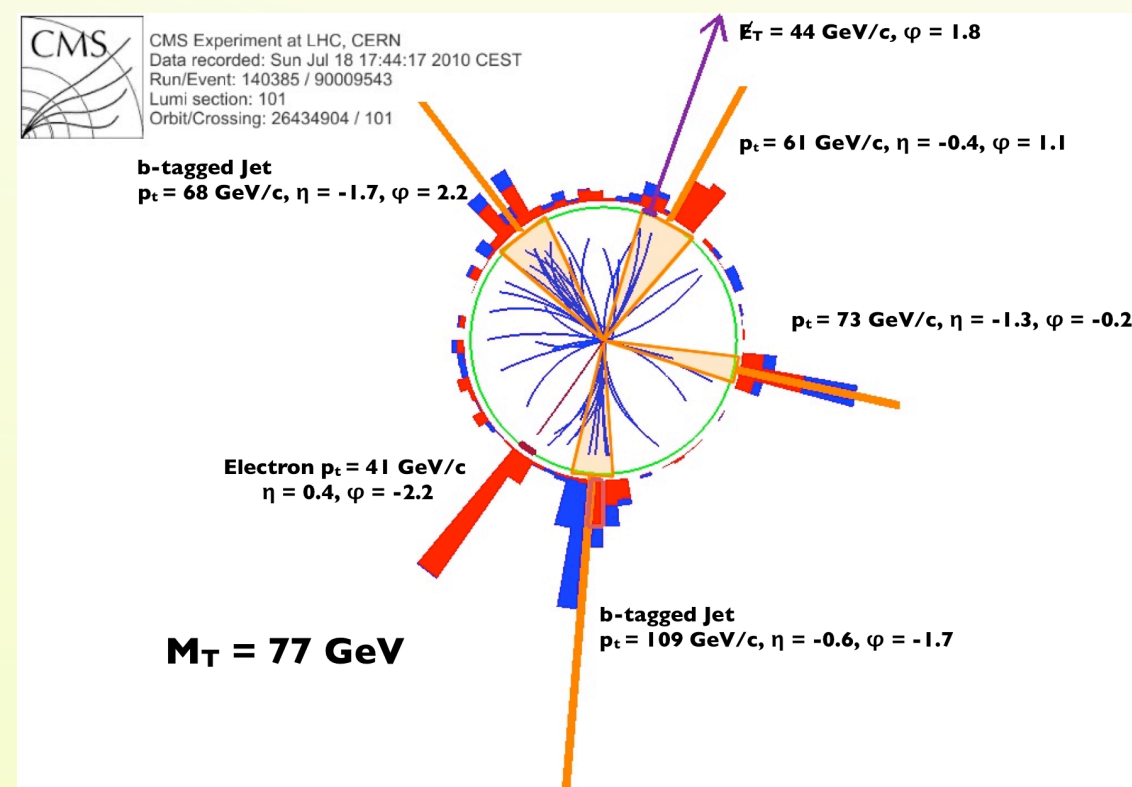
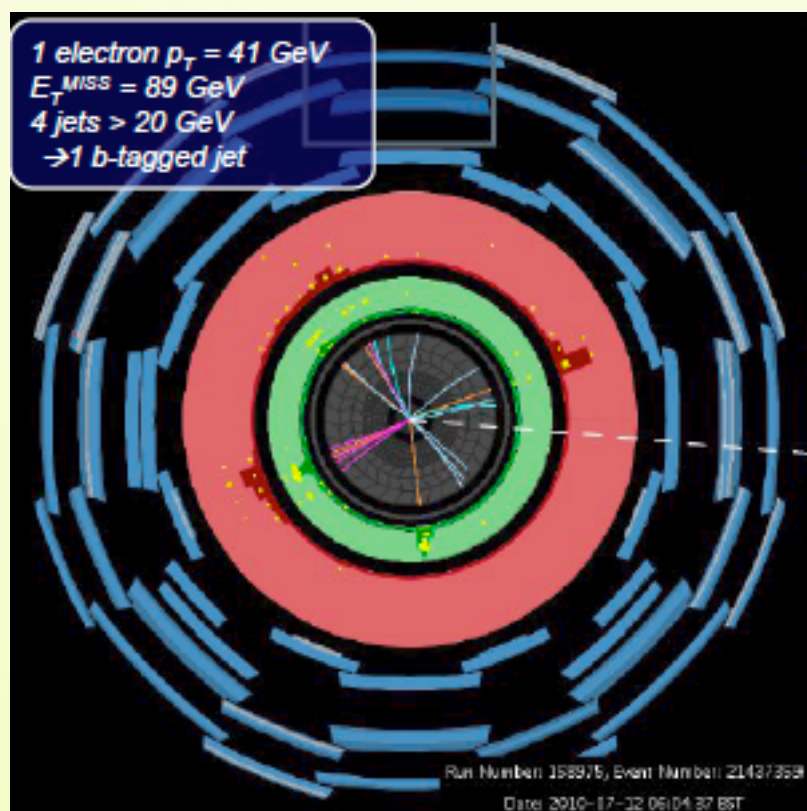
a brief introduction

Fabio Maltoni

Center for Cosmology, Particle Physics and Phenomenology (CP3)  
Université catholique de Louvain, Belgium



# Breaking news #1



Top quark seen in Europe!!



# Breaking news #2



## Breaking news #2





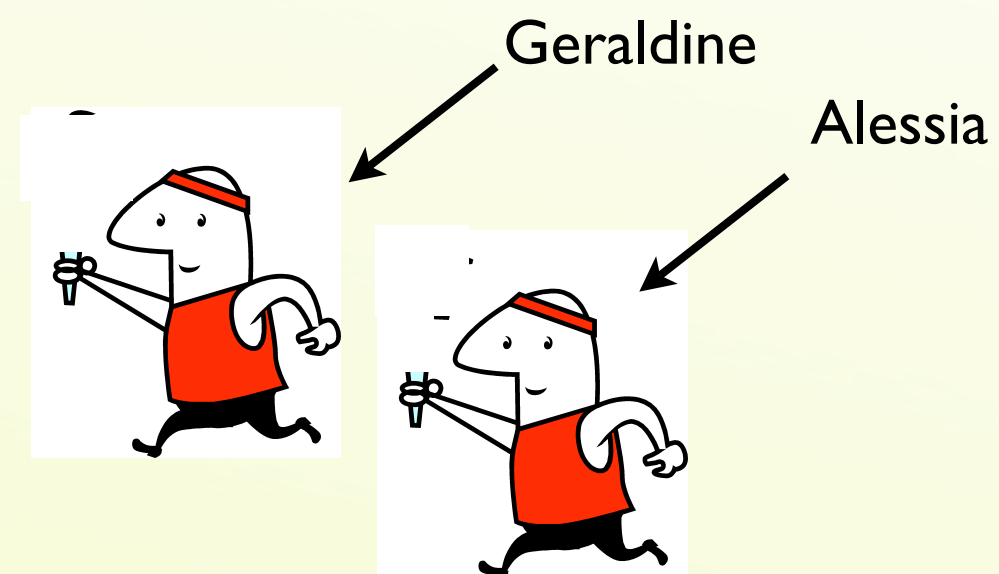


## Breaking news #2



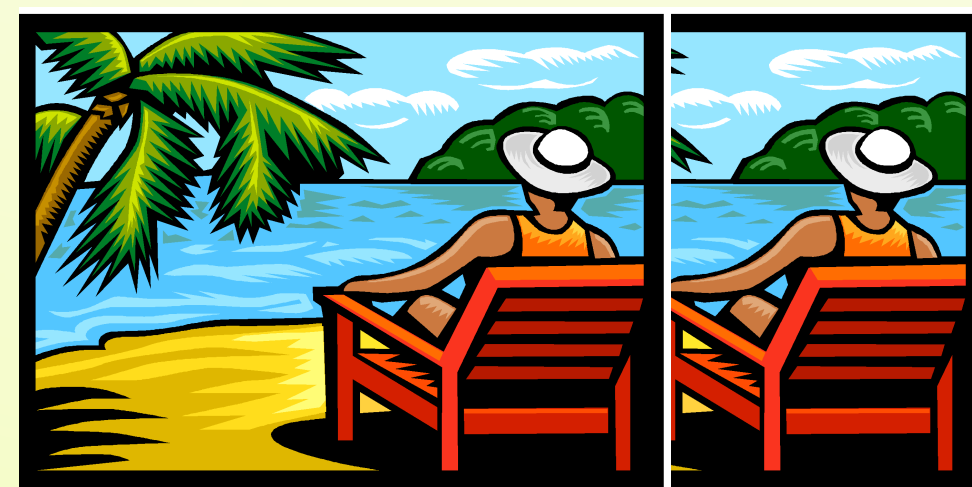
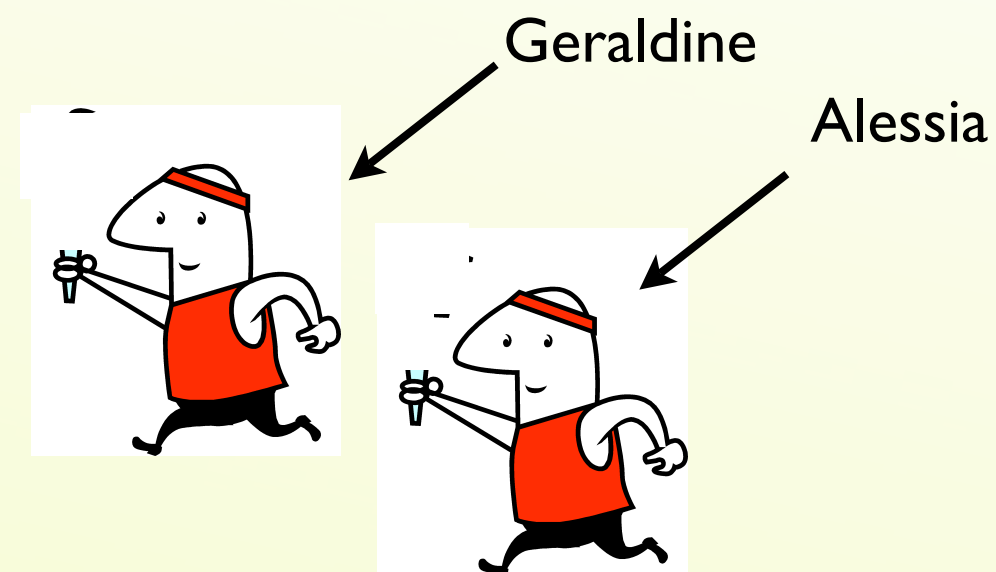


## Breaking news #2





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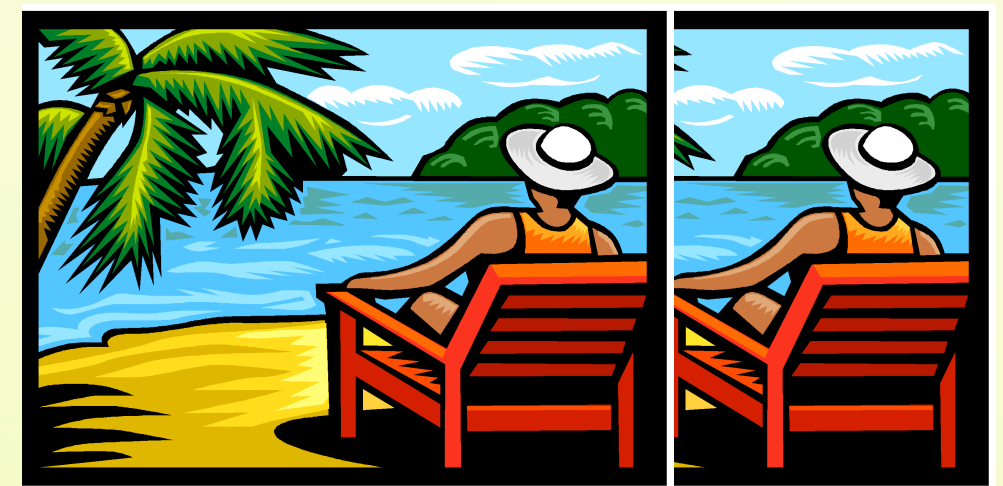
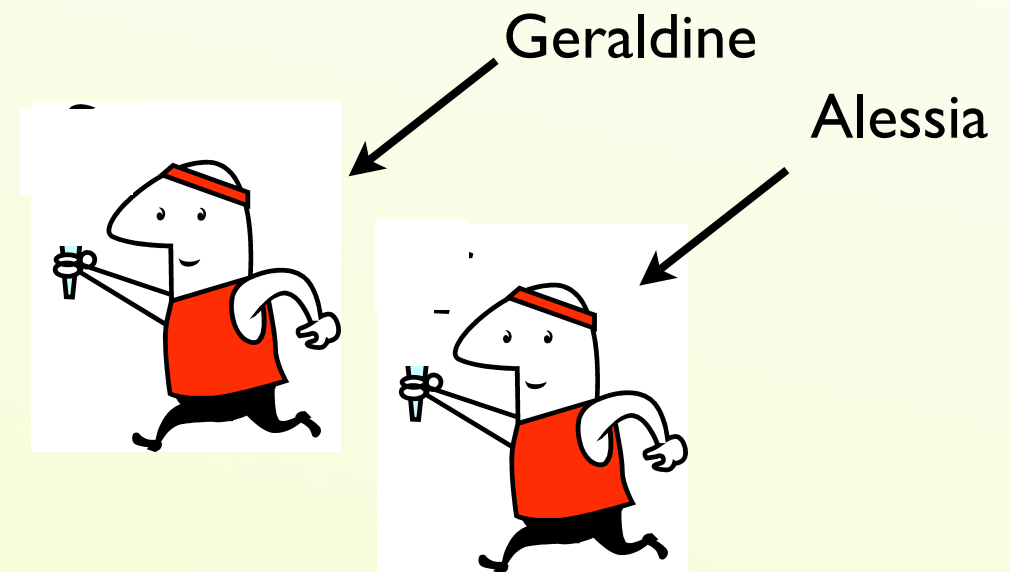


↑ Fabio      ↑ Christophe





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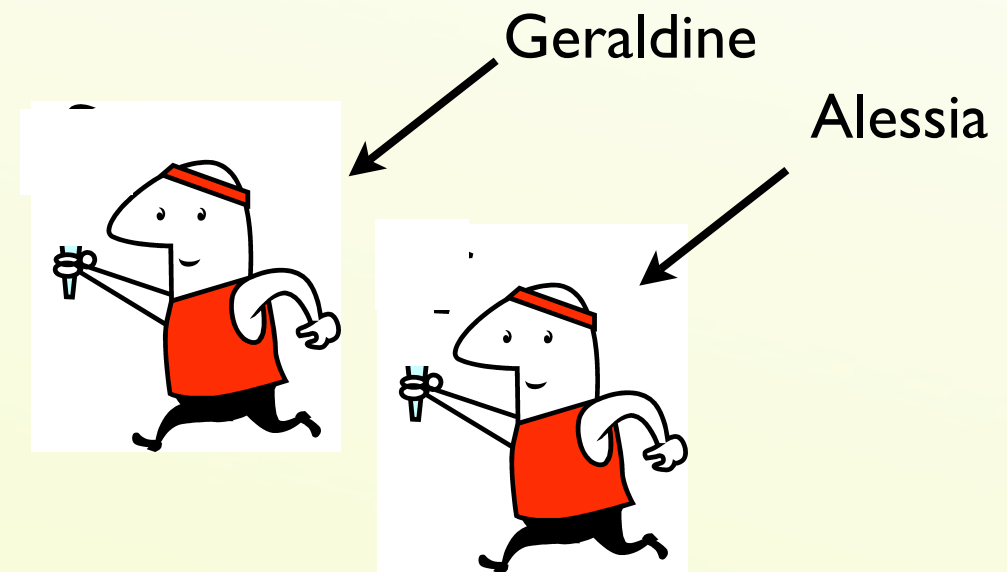


Fabio

Christophe



# Breaking news #2



Fabio  
Christophe

Baywatch seen in Peru Beach!







# Outline

- The importance of being Top
- Truth and myths about Top
- Top in the making
- Hot Topics



## Top Quark Physics at the LHC

### Authors

- Fabio Maltoni (lecturer)

### Lectures

Find the pdf of the 2 x 1h lectures:

- [Lecture 1](#) : Introduction to the top quark
- [Lecture 2](#) : Producing top at hadron colliders

### References

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- [Top mass definition](#), by M. Smith and S. Willenbrock. This is an easy and very clear discussion that it will make you appreciate the subtleties associated to a meaningful definition of a mass of a quark.

### Exercises

#### Decay

- [Top width](#): Calculate the width of the top quark.
- [Radiation from heavy quarks](#): the dead cone in  $e^+e^- \rightarrow Q\bar{Q}g$ .
- [W+ polarization in top decays](#).

#### Production

- [top production](#) :  $t\bar{t}$  production and single top at Tevatron vs LHC.
- [scalar vs fermion top cross sections at hadron colliders](#) : Compare the production of scalar and fermion heavy color triplets in hadron collisions.
- [Spin Correlations in top production?](#)

### Light material on the heaviest quark

- Movies
  - [Interactive Flash version](#) Note you may want to zoom in!
  - [Fast movie \(.avi\) of collision](#)
  - [Guided movie \(.mov\) of collision](#)
- Review
  - [Secrets of a heavyweight](#), by Kurt Riesselmann.



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# Outline

- The importance of being Top
- Truth and myths about Top
- Top in the making
- Hot Topics



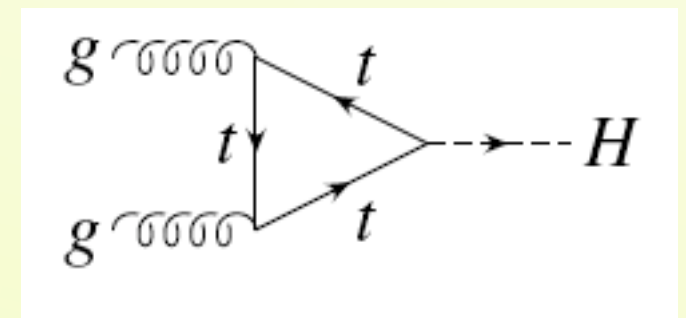
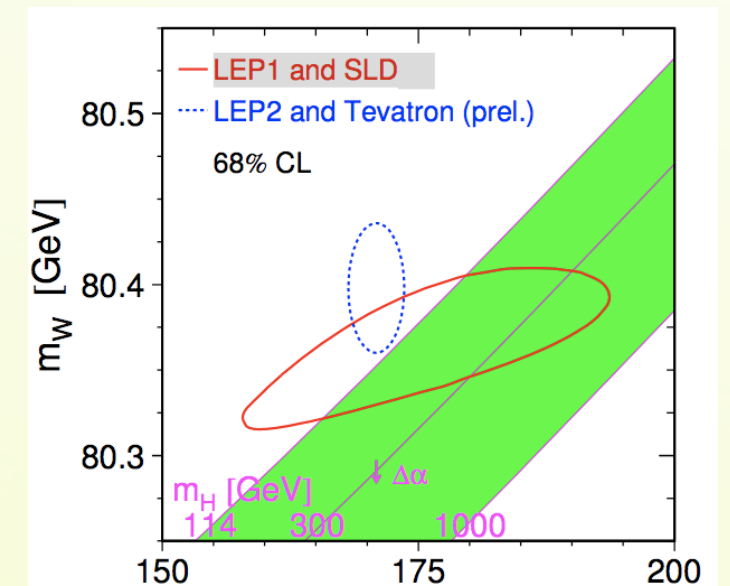
# Top Physics aims

I. Measure all properties (mass, couplings, spin) to establish **indirect** evidence for SM and BSM physics.

Precision EW and QCD;  
Rare decays and anomalous couplings. Flavor Physics.  
CP violation.

II. Use top as **direct** probe of the EWSB sector and BSM physics

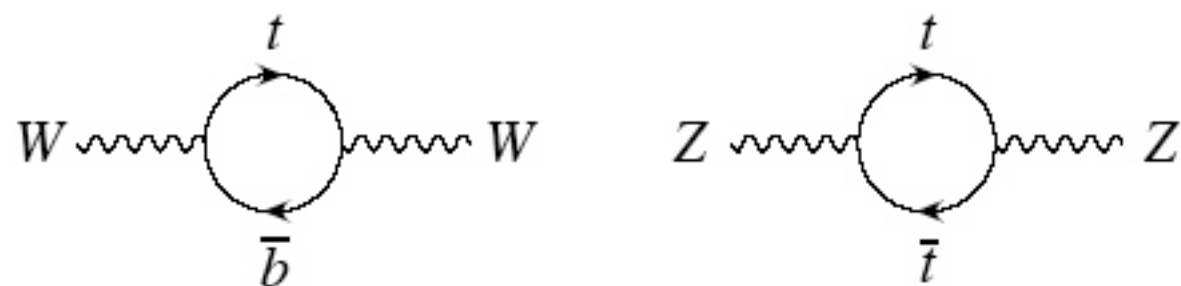
SM :  $t\bar{t}H$ ;  $tH$   
BSM:  $Z'$  and  $W'$  resonances;  
SUSY:  $tH^+$  and  $t \rightarrow bH^+$  or  
stop  $\rightarrow t X$ .



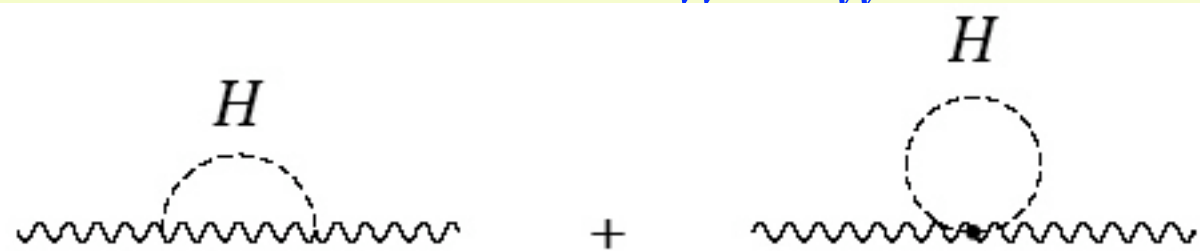
# Top Physics aims I : precision EW

Indirect evidence for the existence of particles not yet detected can be inferred from quantum corrections. At tree level  $m_W = m_Z \cos \theta_W$ . At one loop:

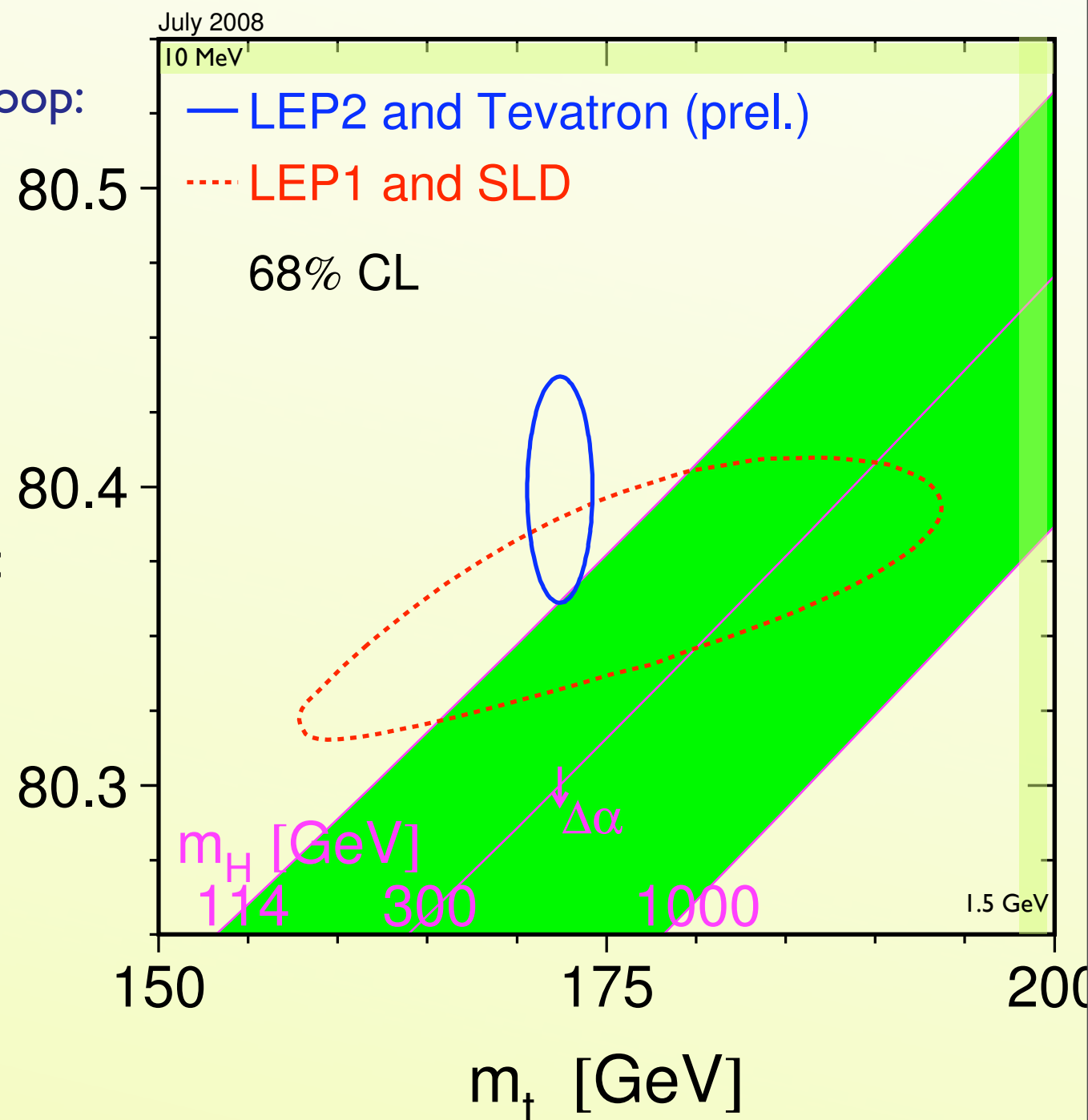
$$m_W^2 \left( 1 - \frac{m_W^2}{m_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_F} (1 + \Delta r)$$



$$\Delta r_{\text{top}} = - \frac{3\alpha}{16\pi} \frac{\cos^2 \theta_W}{\sin^4 \theta_W} \frac{m_t^2}{m_W^2}$$



$$\Delta r_{\text{Higgs}} = + \frac{11\alpha}{48\pi \sin^2 \theta_W} \log \frac{m_H^2}{m_W^2}$$

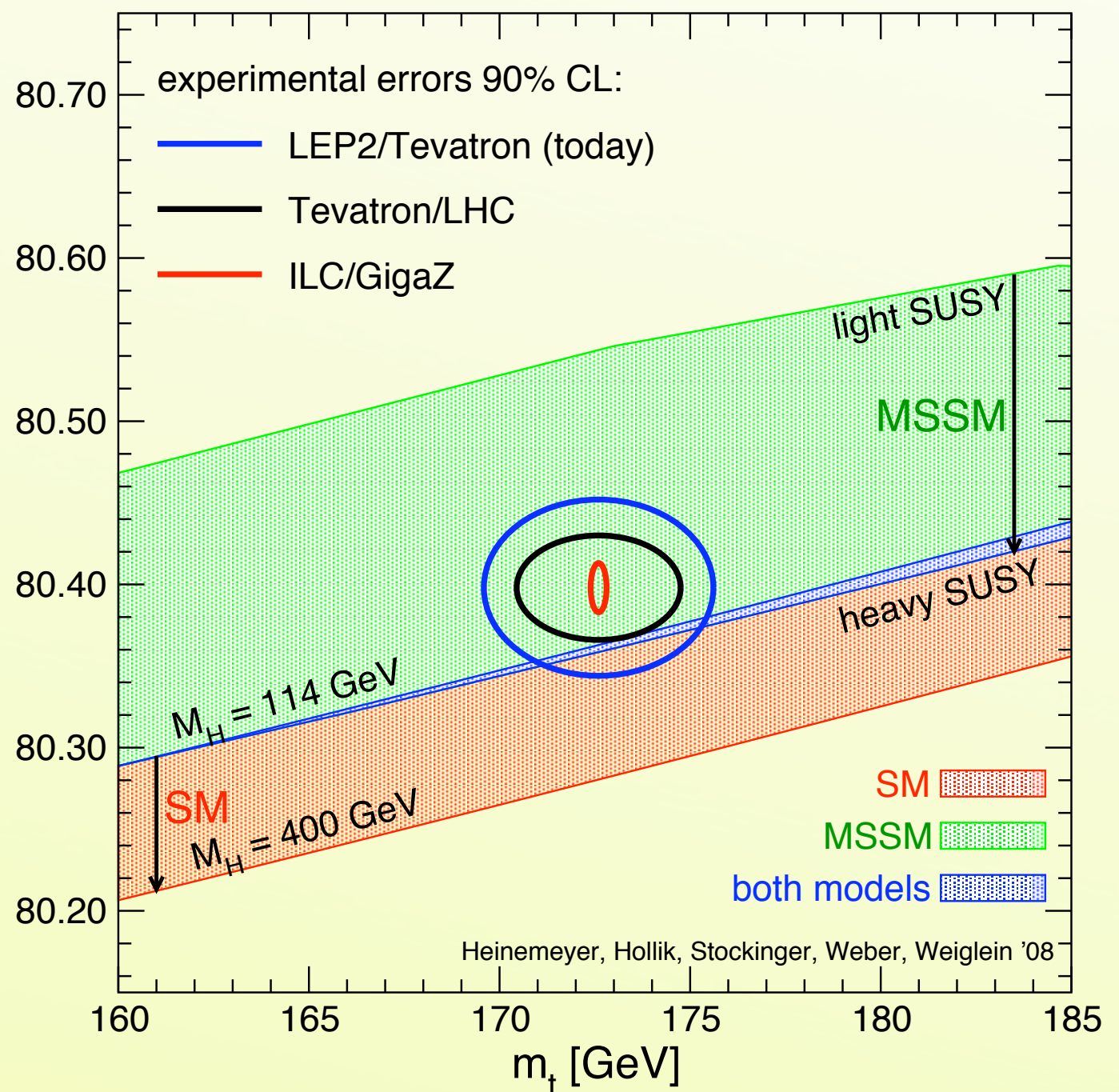


# Top Physics aims I : precision EW and SUSY

Beyond the SM precision measurements can be also very useful. For instance in SUSY, the corrections to the Higgs mass are given by:

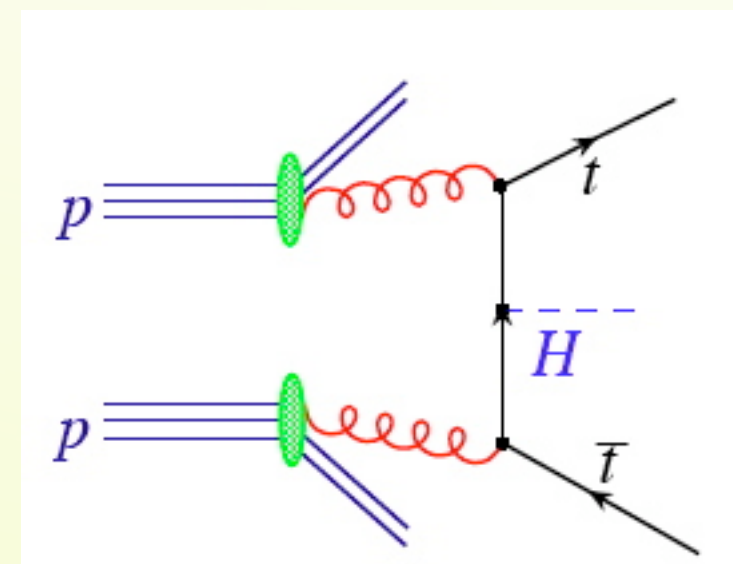
$$\Delta M^2 \simeq G_F m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} M_W [\text{GeV}]$$

In fact top effects can be really important in theories like SUSY: Large and negative 1-loop corrections can turn the Higgs mass parameters negative and even trigger ESWB.

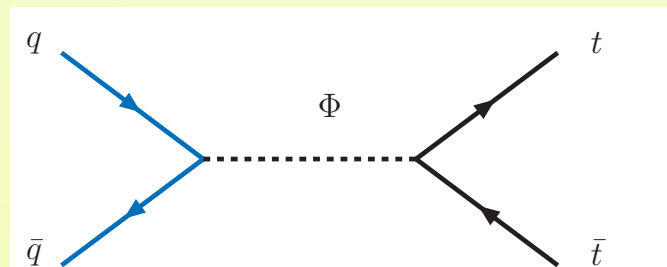
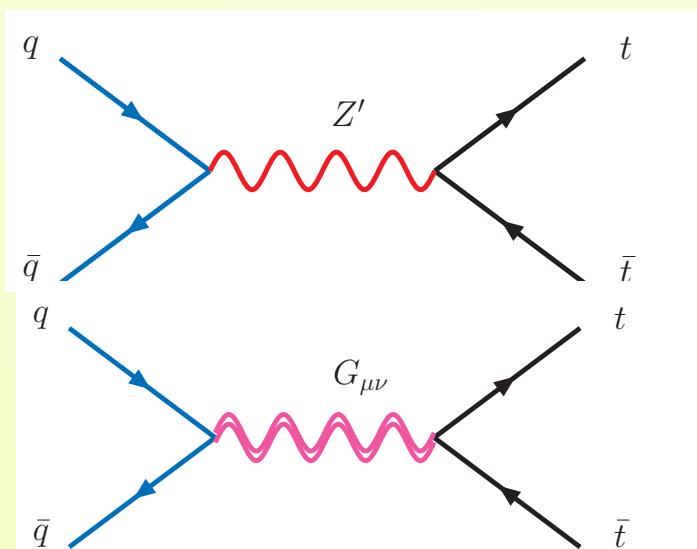
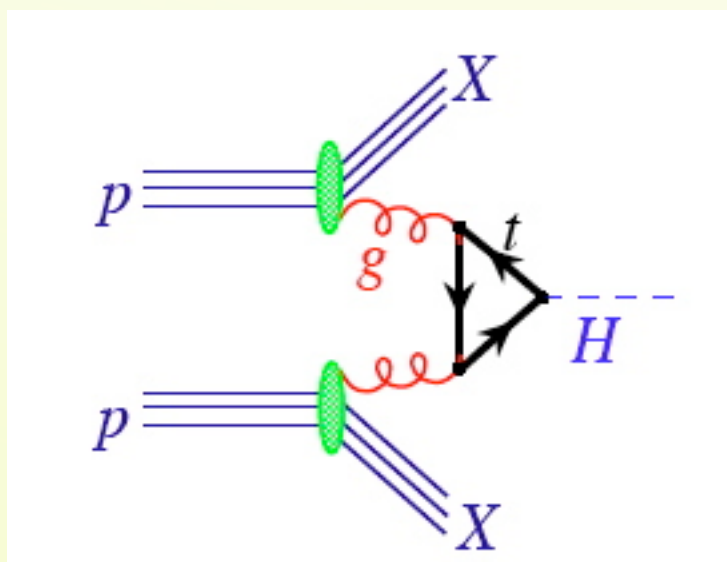
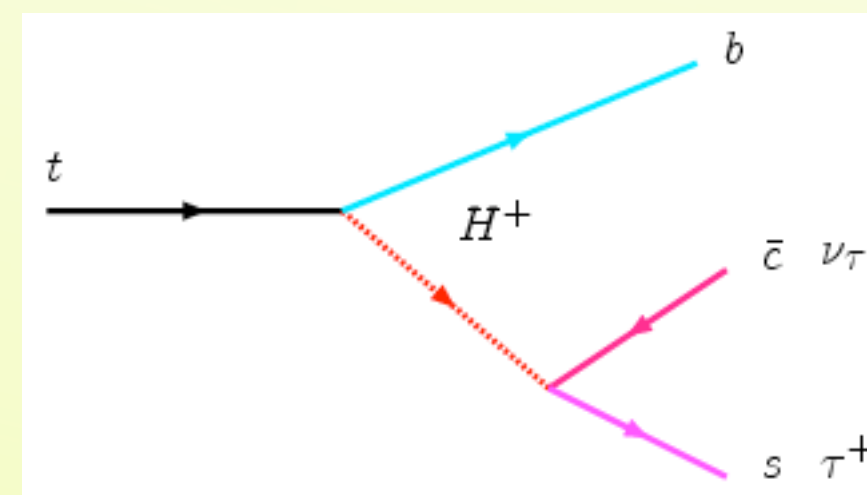


# Top Physics aims II : direct probe

Exciting the Higgs

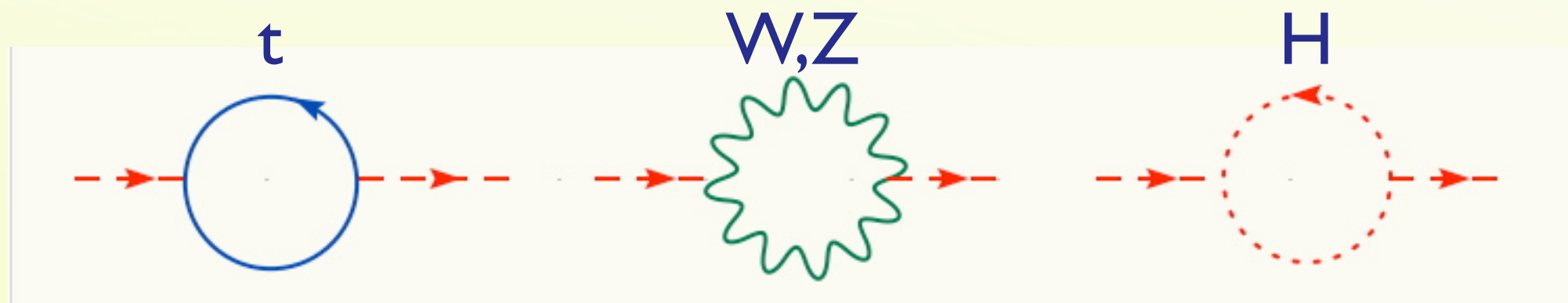


Exciting new degrees of freedom



# Top as a link to BSM

The top quark dramatically affects the stability of the Higgs mass.  
Consider the SM as an effective field theory valid up to scale  $\Lambda$ :



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

Putting numbers, I have:

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

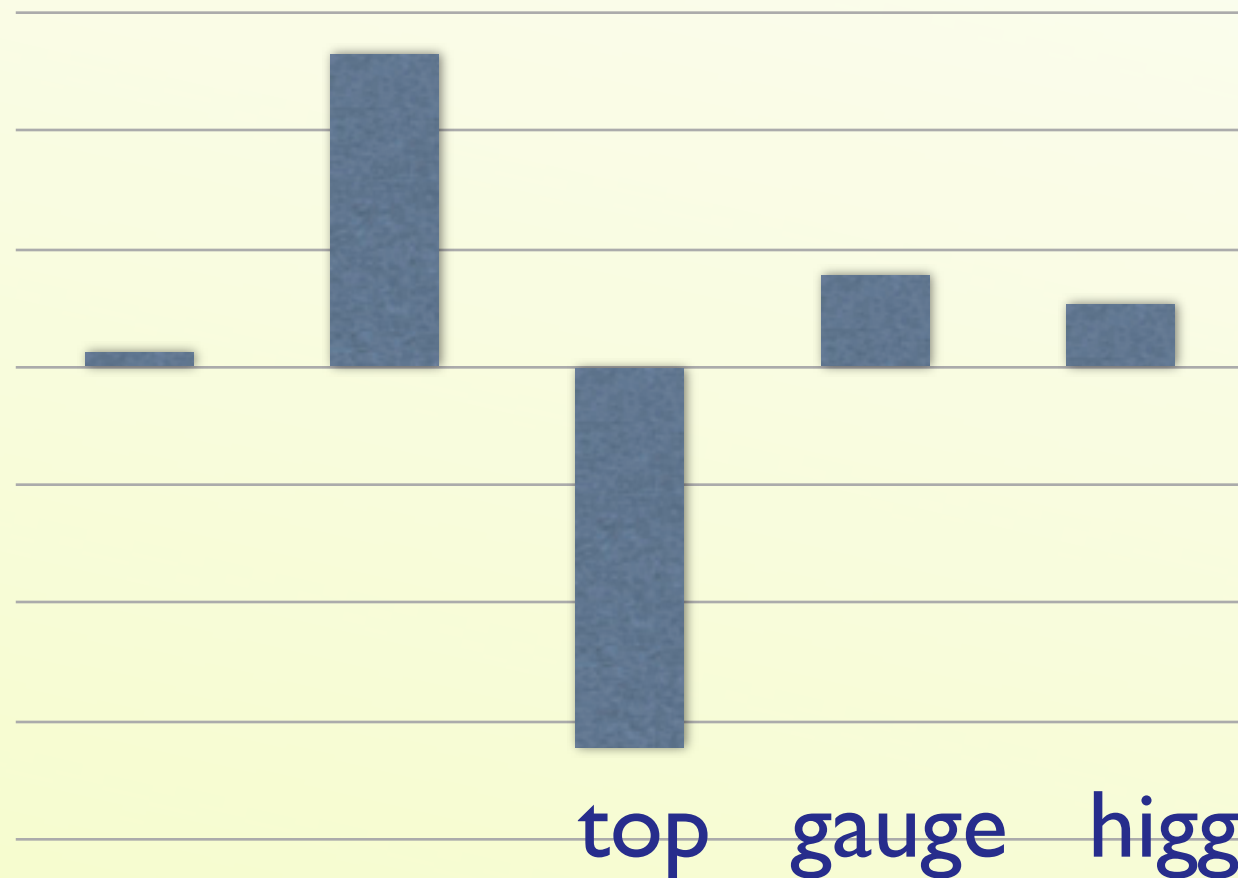




# Top as a link to BSM

tree

loops



$$m_h^2 \sim (200 \text{ GeV})^2$$

$$(200 \text{ GeV})^2 = m_{H_0}^2 + [-(2 \text{ TeV})^2 + (700 \text{ GeV})^2 + (500 \text{ GeV})^2] \left( \frac{\Lambda}{10 \text{ TeV}} \right)^2$$

Definition of naturalness: less than 90% cancellation:

$$\Lambda_t < 3 \text{ TeV} \quad \Lambda_t < 9 \text{ TeV} \quad \Lambda_t < 12 \text{ TeV}$$

One can actually prove that this case in model independent way, i.e. that the scale associated with top mass generation is very close to 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. Naturalness is our problem not Nature's. Pro's: we'll find the Higgs. Cons: that's it.
2. **Weakly coupled model at the TeV scale:**  
Introduce new particles to cancel SM "divergences".
3. **Strongly coupled model at the TeV scale:**  
New strong dynamics enters at  $\sim 1$  TeV.
4. **New space-time structure:**  
Introduce extra space dimensions to lower the Planck scale cutoff to 1 TeV.

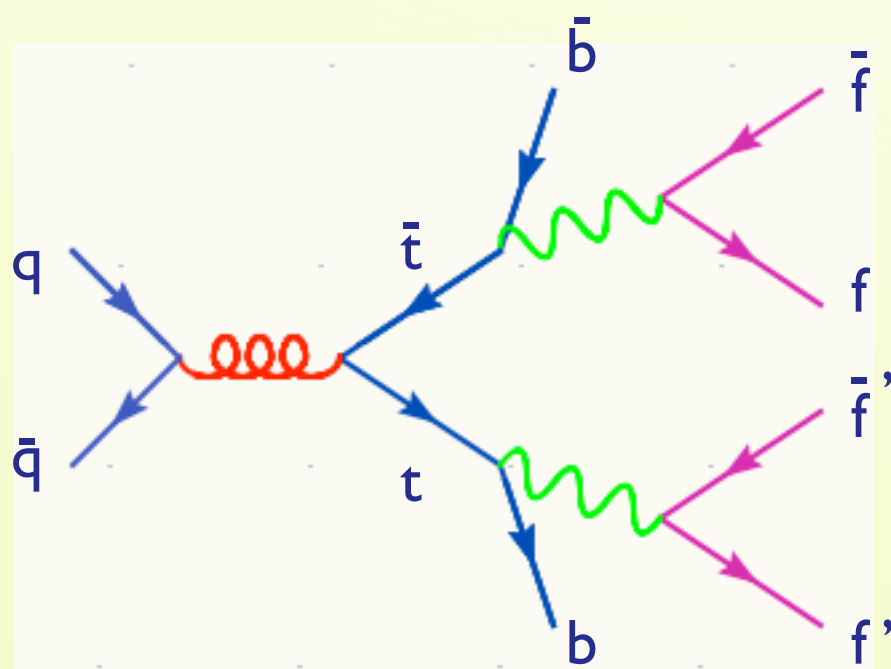
Top is the only natural quark

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

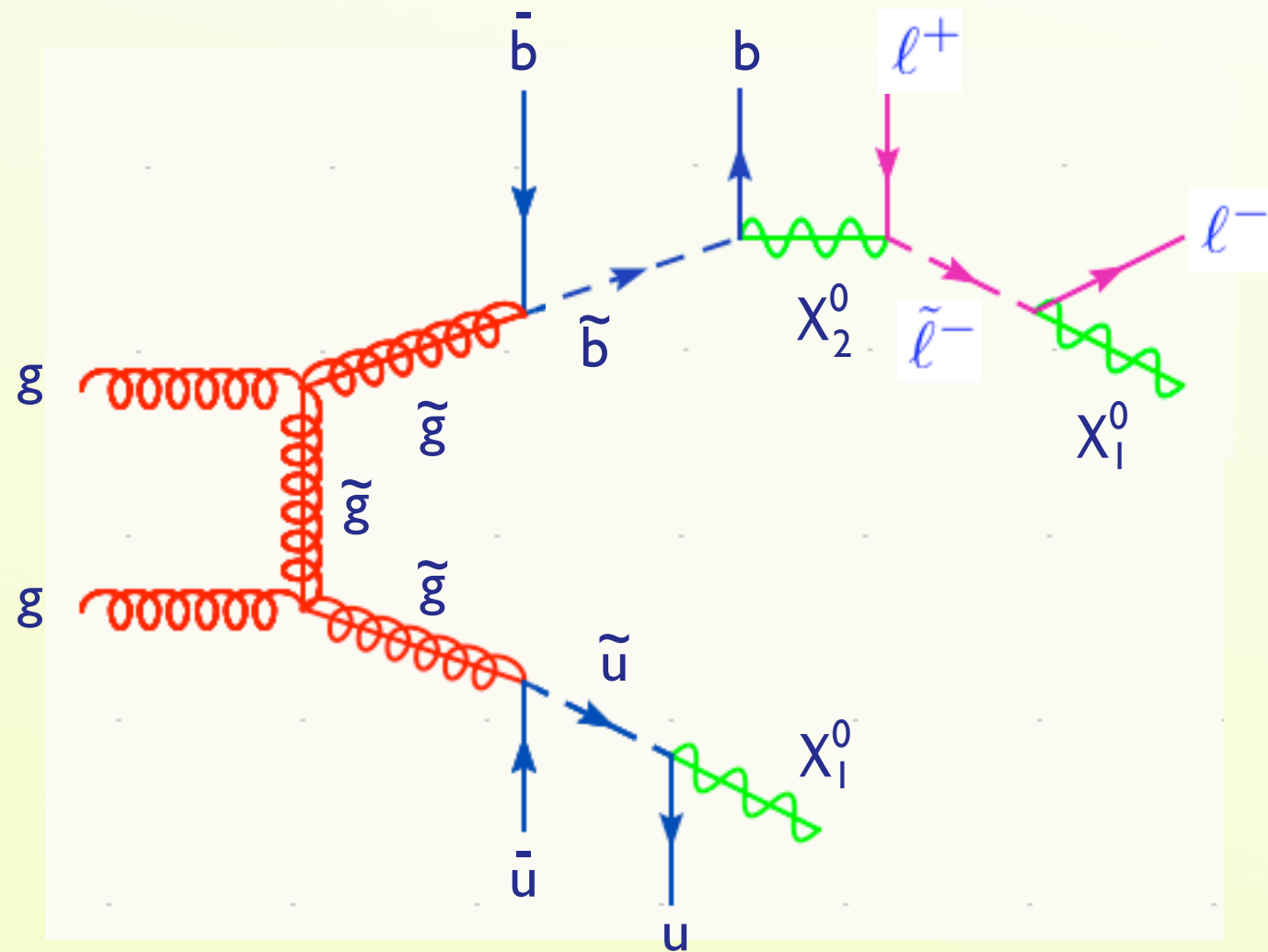
Top:  $t$ - $\bar{t}$  bound states, colorons.  
Top is not elementary

KK-excitations

# Top as a template

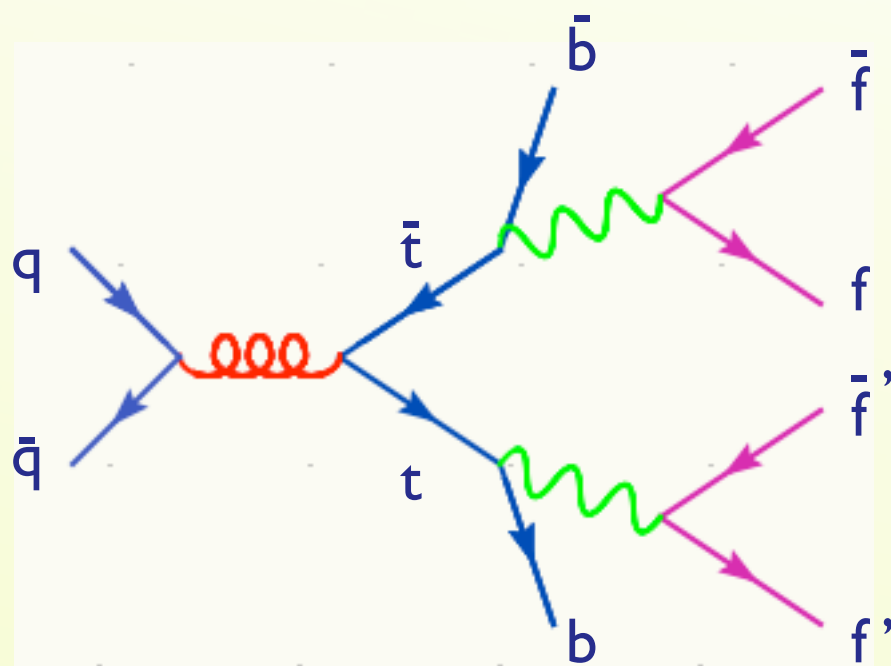


VS



Both involve production of heavy colored states decaying through a chain into jets, leptons and  $\cancel{E}_T$ .

# A lesson from the top



How did it go?

0. The only unknown was the top mass!

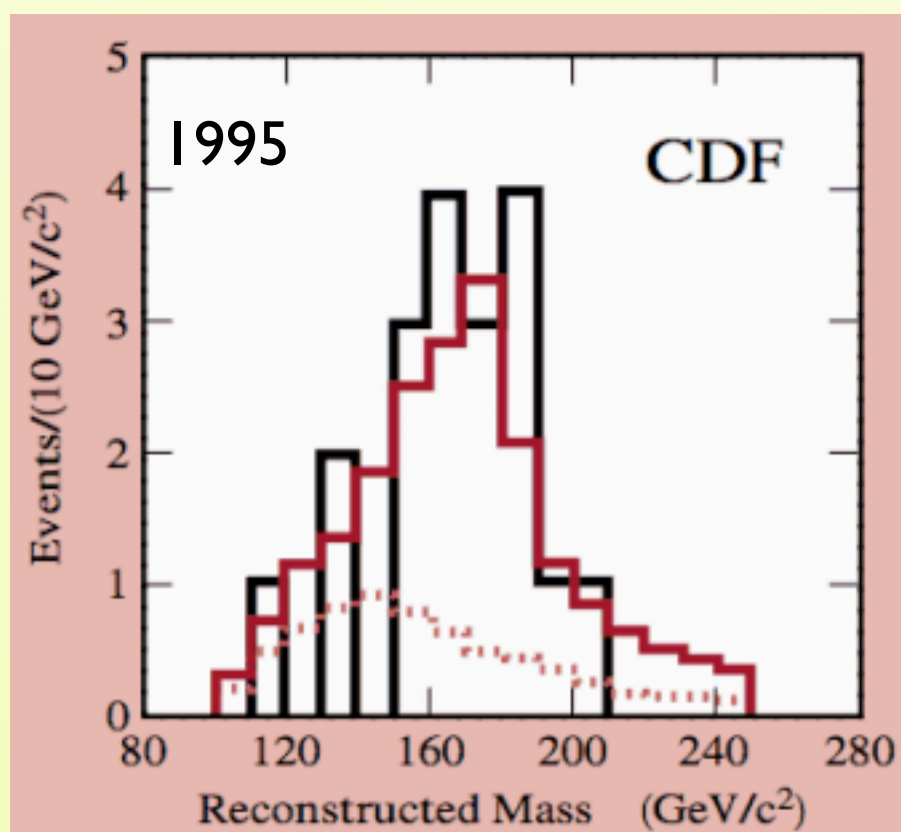
1. The experimentally easiest channel for triggering/reconstruction/background-control was chosen.

2. Mass reconstruction employed

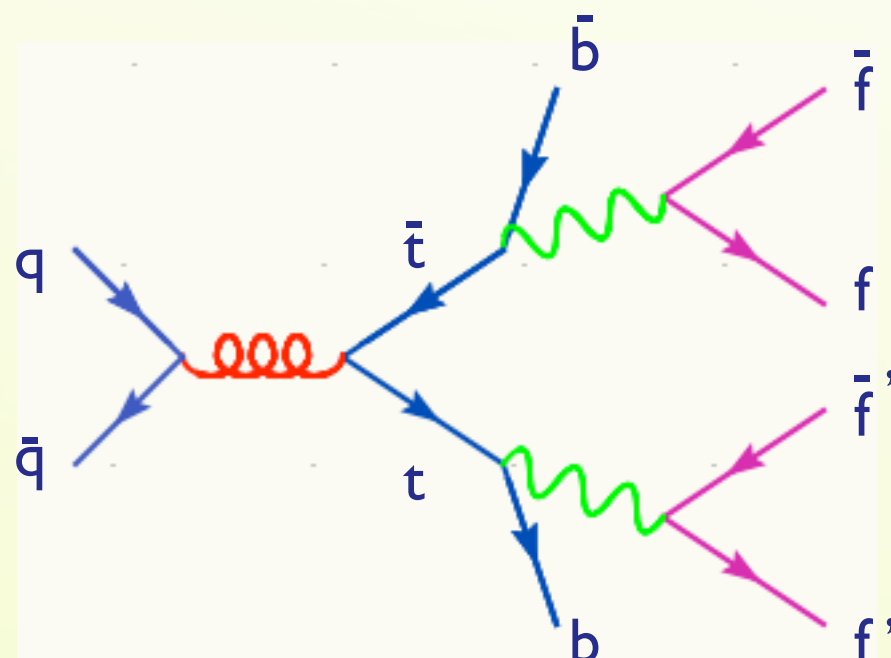
3. Backgrounds estimated via control samples with heavy flavors and also via MC ratio's.

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

Handful of events was enough!



# A lesson from the top

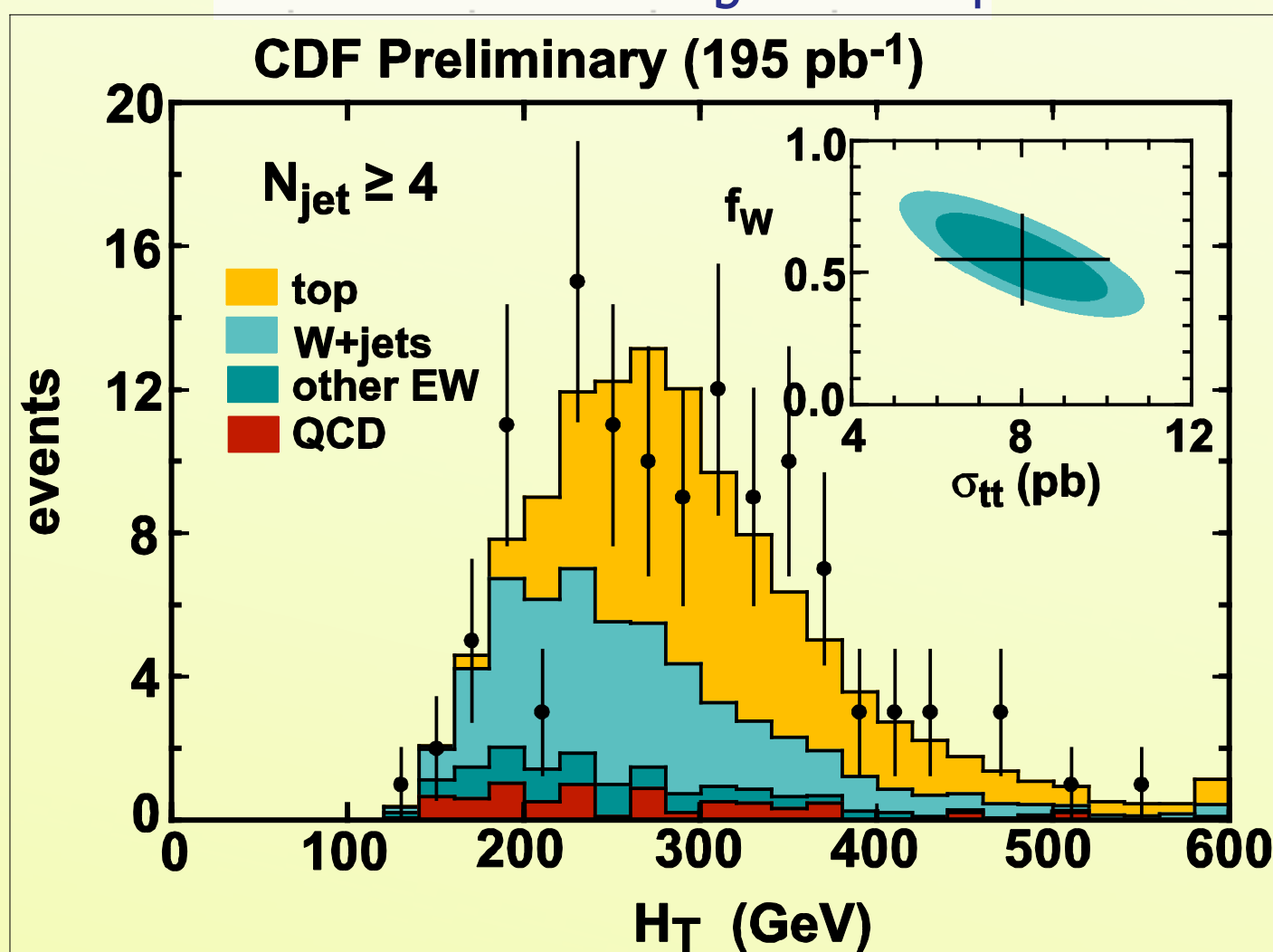


Immediately confirmed in Run II, also by the most inclusive measurements,  $H_T$ .

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

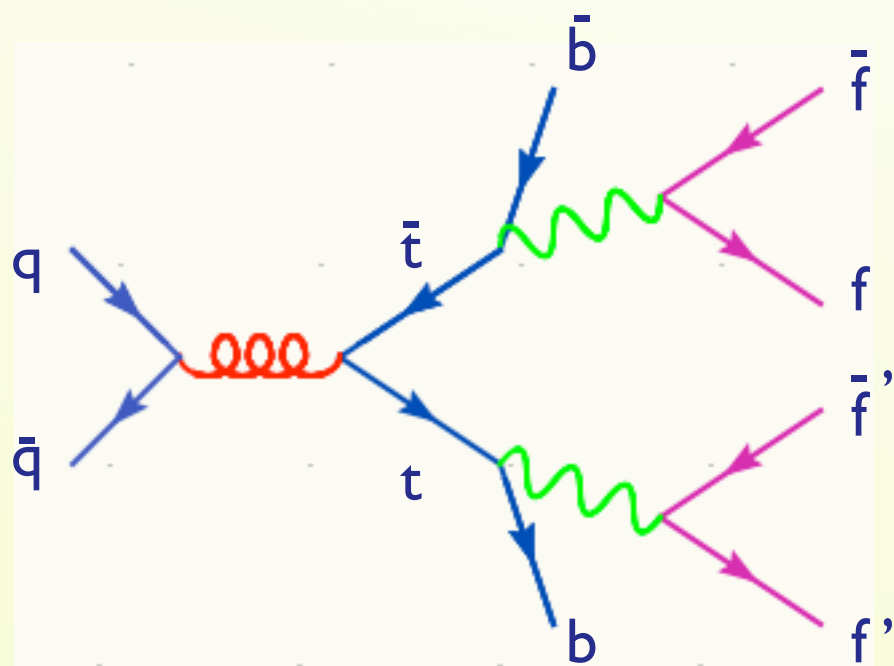
Cleaner and cleaner samples more exclusive studies:

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

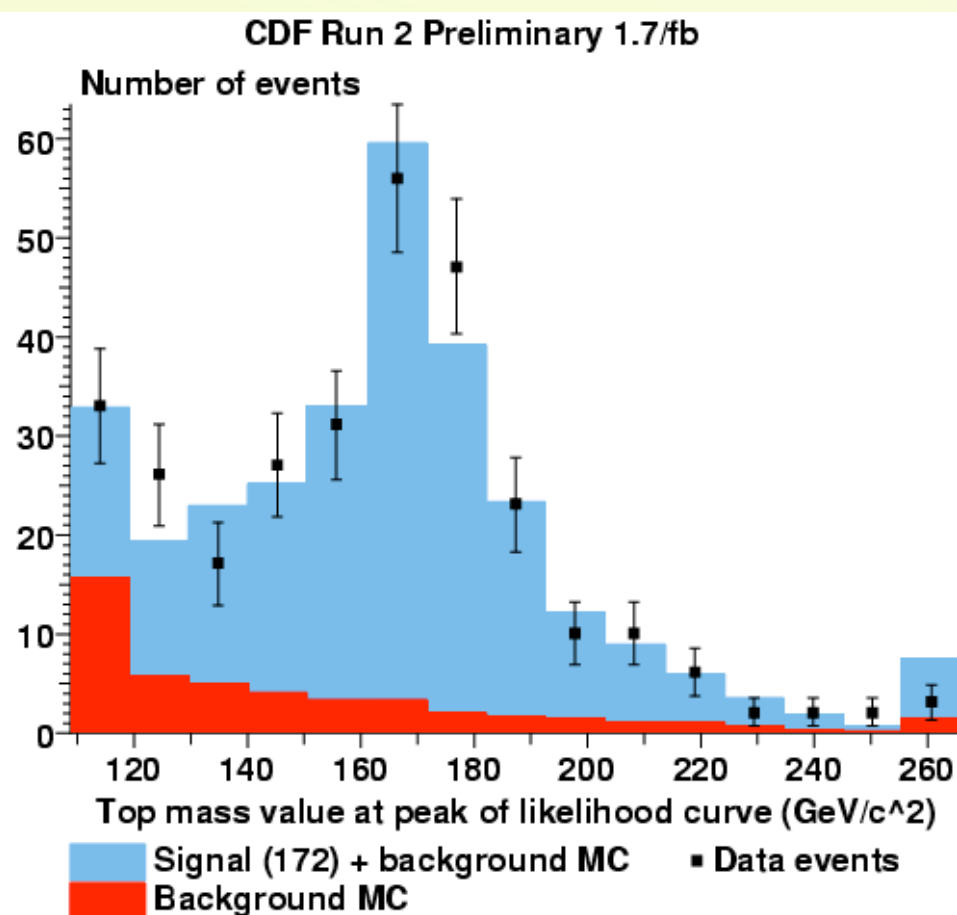


Summary:

1. More than 15-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.

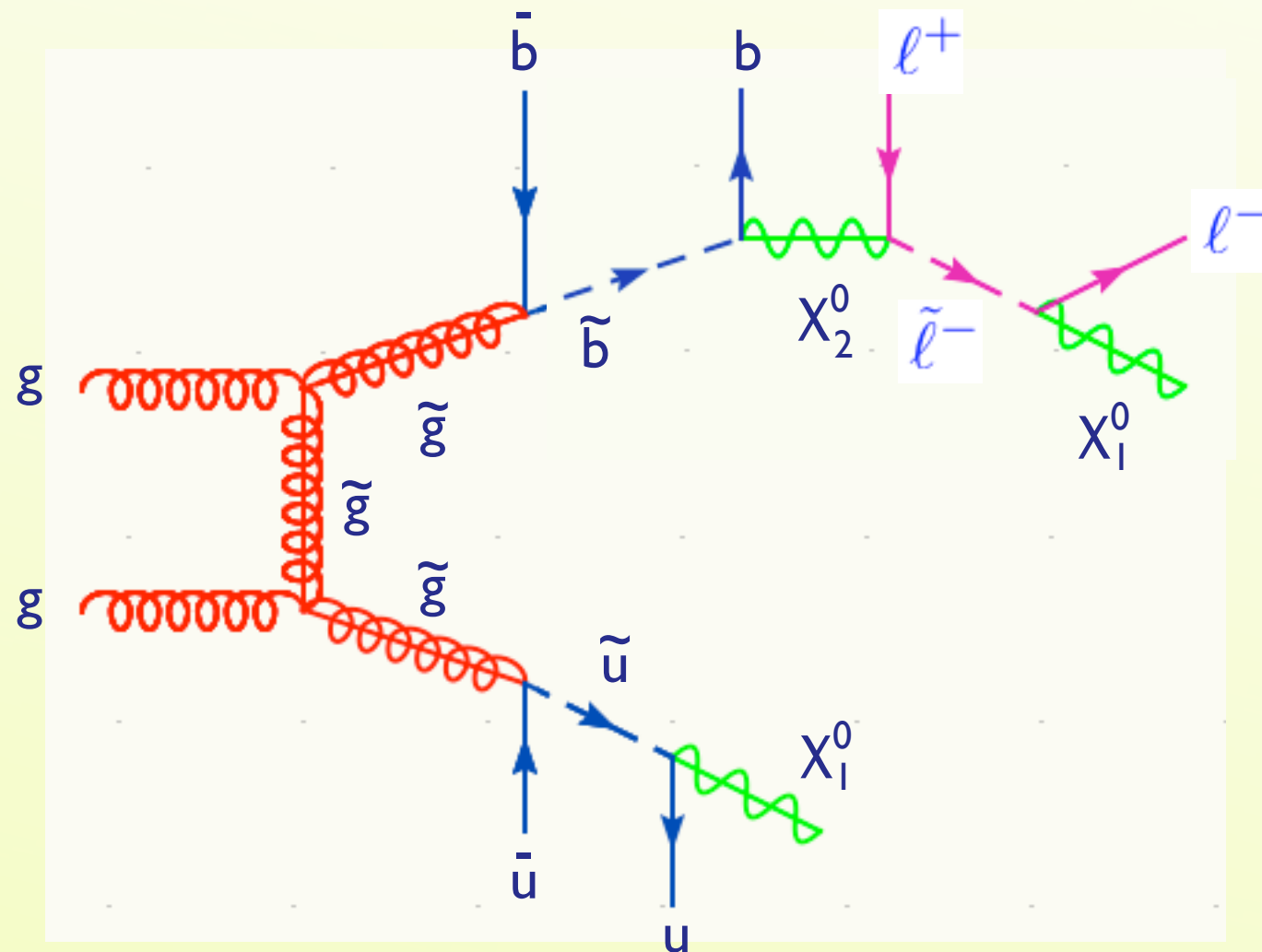
More sophisticated analysis need more sophisticated MC's...

Is this strategy directly applicable to new heavy state searches?



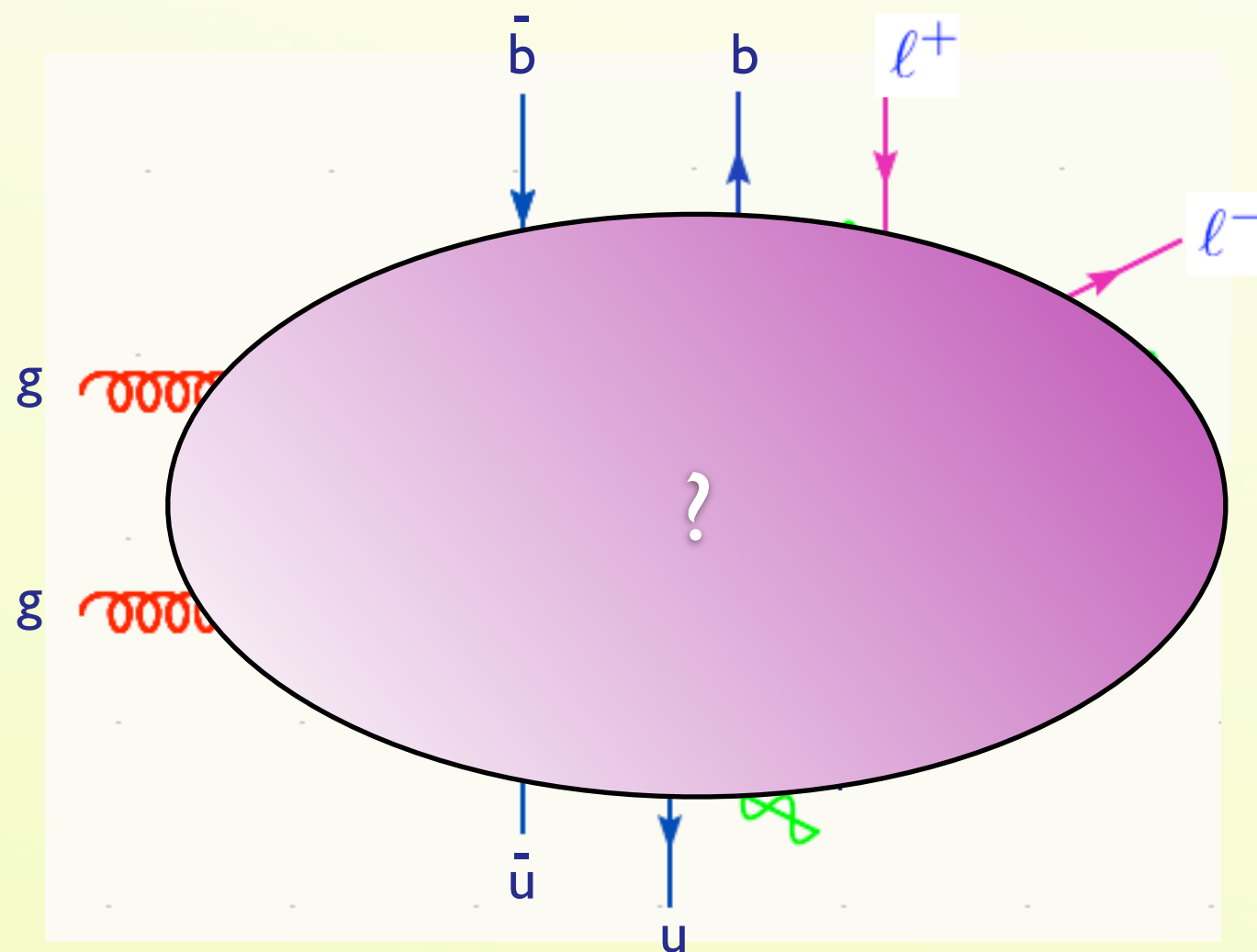
# A lesson from the top

Susy inclusive searches are similar but more complicated final states.



# A lesson from the top

Susy inclusive searches are similar but more complicated final states.



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



# Top as background

At the LHC, many measurements will need a good understanding and control of  $t\bar{t}$  and single top events.

A few examples:

- $gg \rightarrow H$  and  $qq \rightarrow Hqq$  with  $H \rightarrow WW$
- $t\bar{t}$  in single top measurements
- $t\bar{t}$ +jets and  $t\bar{t}b\bar{b}$  in  $t\bar{t}H$
- $t\bar{t}$ +jets in SUSY/UED searches (gluino pairs, stop pairs,  $tH^+$ ....)
- .....





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- Truth and myths about Top
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Charmonium is there, Bottomonium is there, what about Toponium?

Unfortunately, top decays too fast for bound states to form...

Radiation in top events? Everybody knows that top does not like to radiate a lot...

Measuring the top spin effects will prove that hadronization does not take place!

Have you heard of the latest top mass measurement?..

Which mass?

$V_{tb}$ ? I just measure it in top decays!





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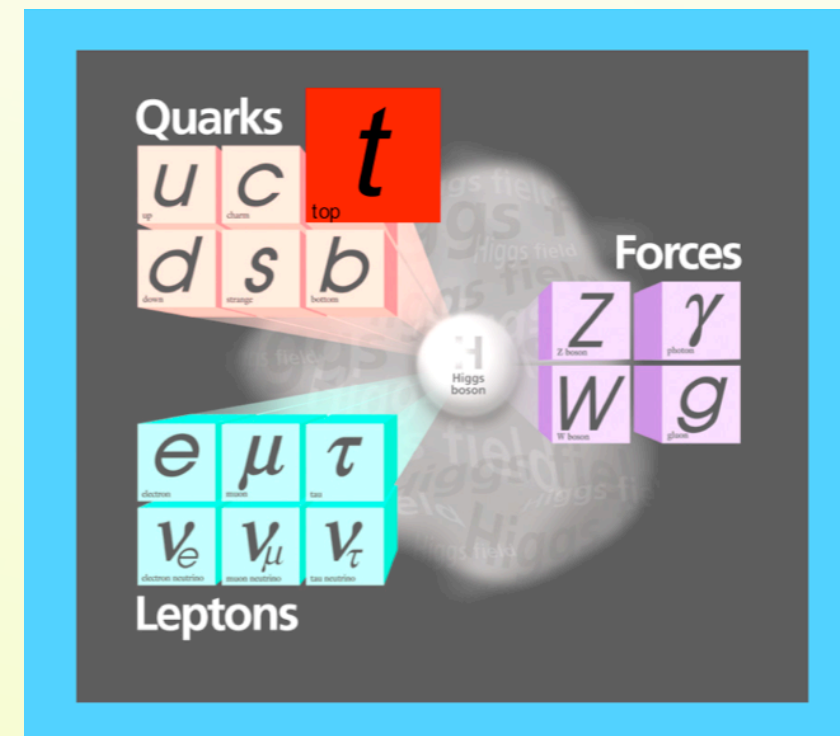
Vtb? I just measure it in top decays!

I don't understand why everybody gets so excited about Top: is just a quark like the others!



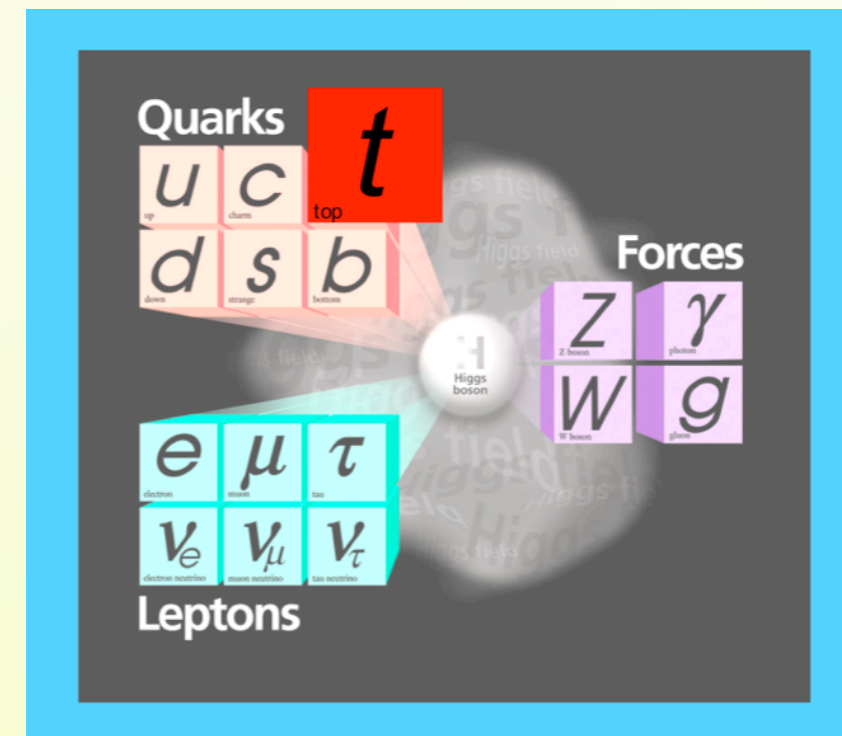
# Basic facts about top

- It is the  $SU(2)_L$  partner of the bottom.
- $t_L \Rightarrow T^3 = +1/2$ ,  $t_R$  singlet.
- Its mass is obtained in the EWSB.
- $Q_t = +2/3$  and is a color triplet.
- All couplings are fixed by the gauge structure.



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It is just as all other (up) quarks: what's so special about it?





# Truth or Myth #1 : “Top is special”

In the SM, it is the ONLY quark



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In the SM, it is the ONLY quark

1. with a “natural mass”:

$$m_{\text{top}} = y_t v / \sqrt{2} \approx 174 \text{ GeV} \Rightarrow y_t \approx 1$$

It “strongly” interacts with the Higgs sector. This also suggests that top might have special role in the mechanism of EWSB and/or fermion mass generation.

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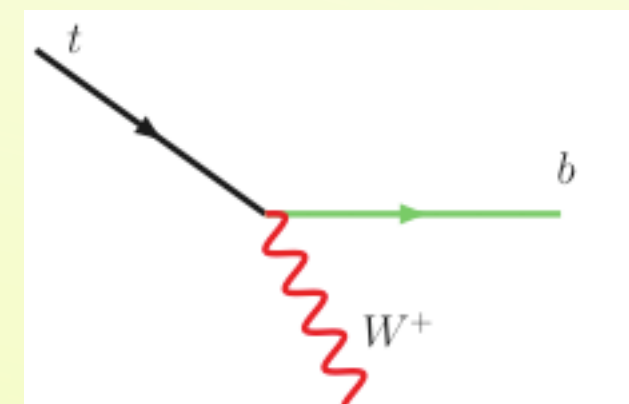
2. that decays before hadronizing

$$\tau_{\text{had}} \approx h / \Lambda_{\text{QCD}} \approx 2 \cdot 10^{-24} \text{ s}$$

$$\tau_{\text{top}} \approx h / \Gamma_{\text{top}} = 1 / (G_F m_t^3 |V_{tb}|^2 / 8\pi \sqrt{2}) \approx 5 \cdot 10^{-25} \text{ s}$$

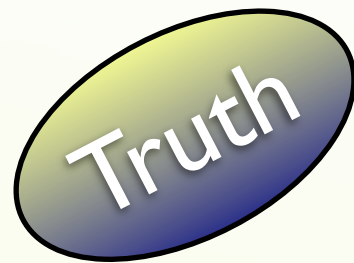
(with  $h = 6.6 \cdot 10^{-25} \text{ GeV s}$ )

(Compare with  $\tau_b \approx (G_F^2 m_b^5 |V_{bc}|^2 k)^{-1} \approx 10^{-12} \text{ s}$ )





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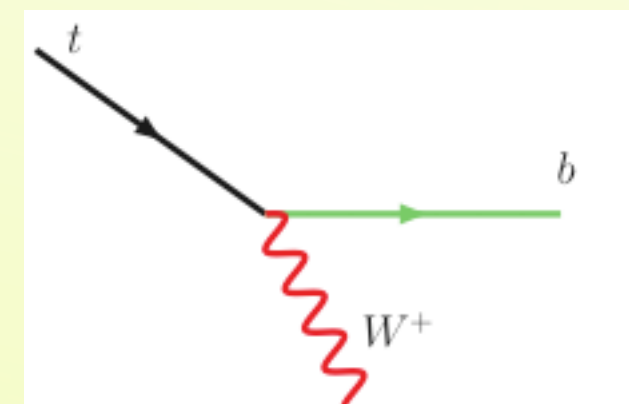
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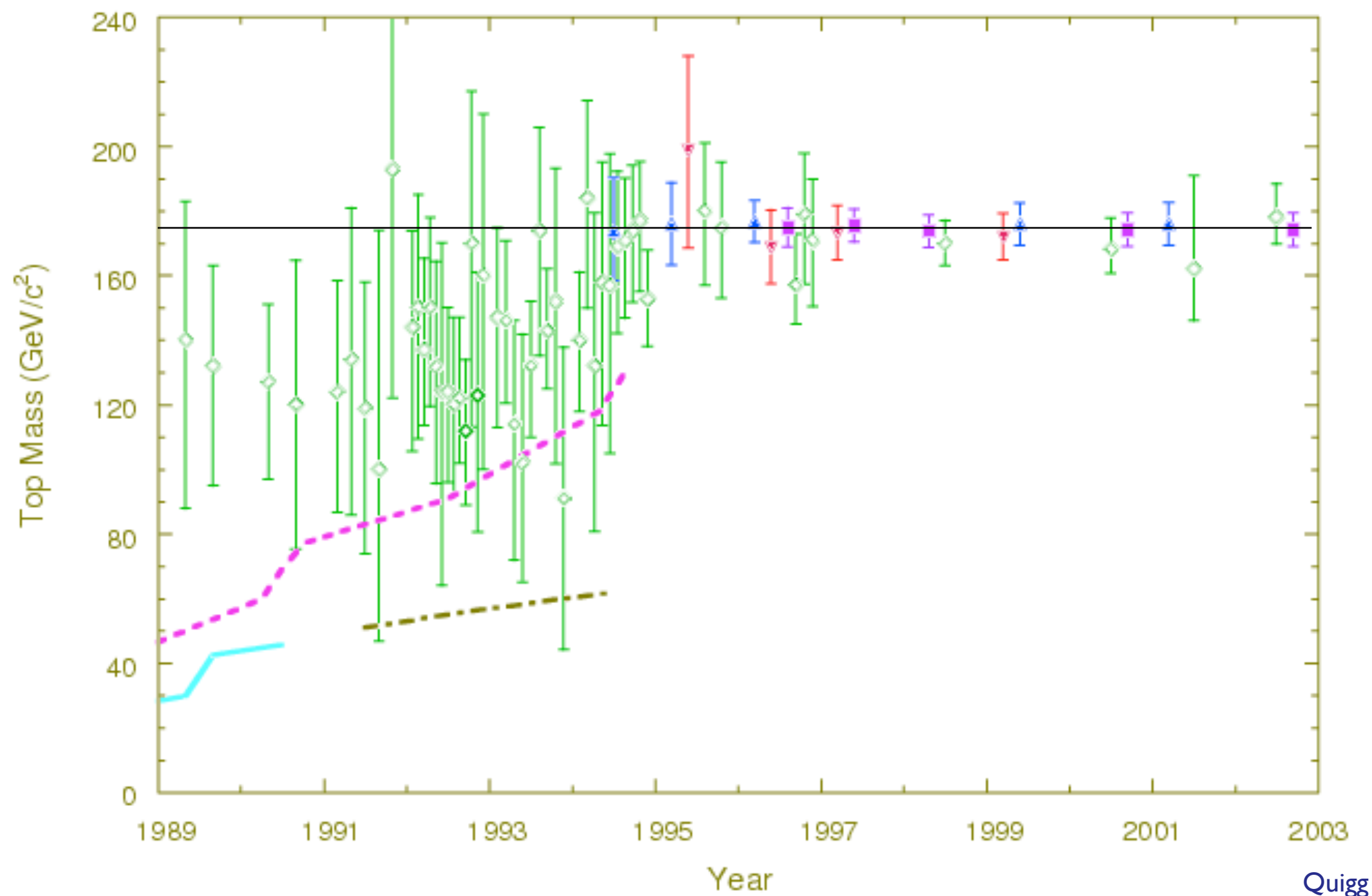
# What do we really know about top?

Quantity	Uncertainty	Measurement	Useful for...
Mass	$<1\%$	invariant mass	EW fits (Higgs and BSM)
Spin	consistent	decay products	BSM?
charge	$-4/3$ excluded	decay products	BSM?
R	10%	event counting	BSM?
$Wtb$ vtx	20%	W polarization	BSM
$\sigma(t\bar{t})$	10%	event counting	QCD, mass
$\sigma(\text{singletop})$	30%	event counting*	$V_{tb}$ , 4th gen, BSM
Width	$<12.7$ GeV	direct	$V_{tb}$ , 4th gen, QCD

<http://www-cdf.fnal.gov/physics/new/top/top.html>

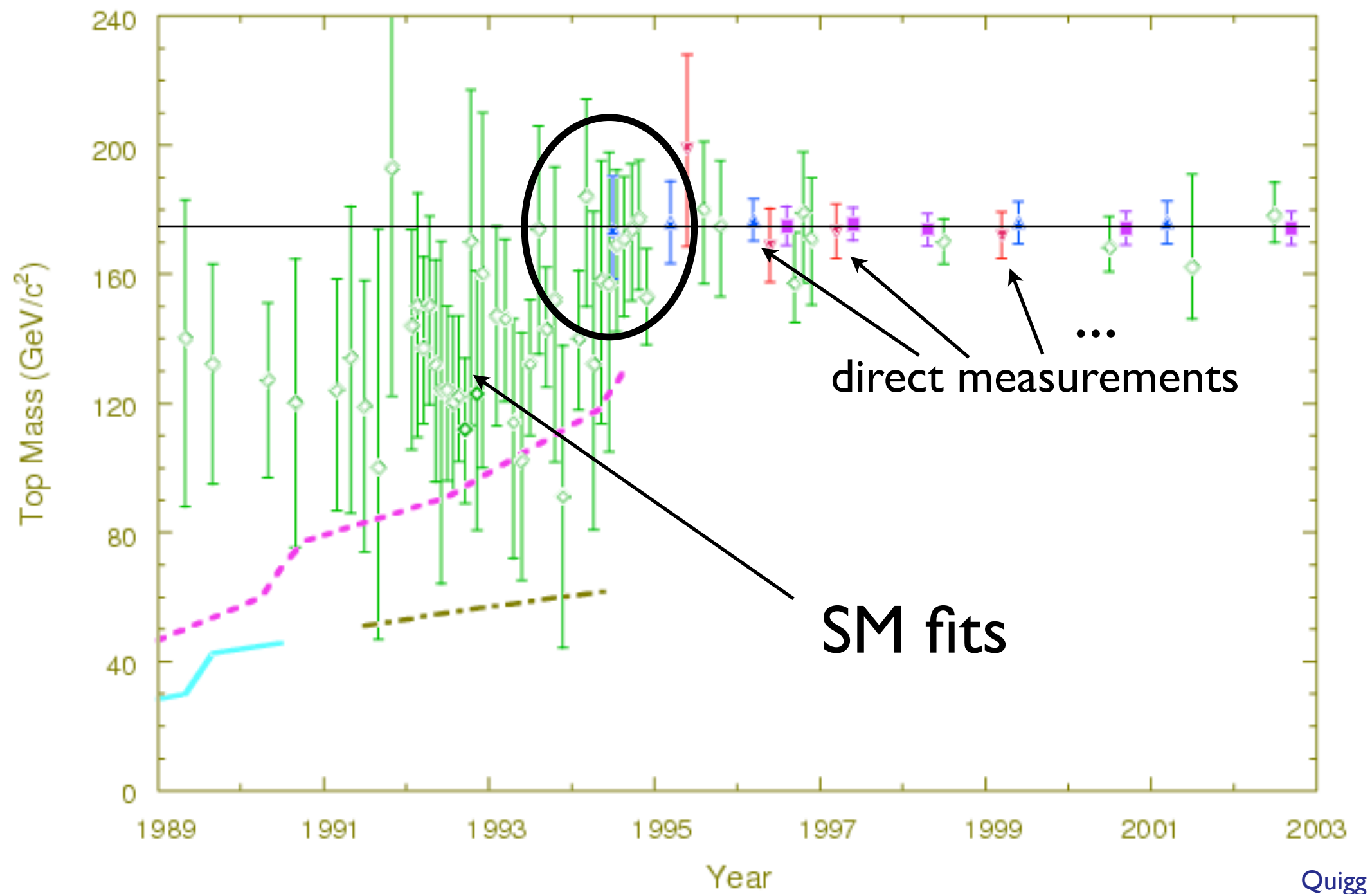
[http://www-d0.fnal.gov/Run2Physics/top/top\\_public\\_web\\_pages/top\\_public.html](http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html)

# Top mass history



Such a heavy top was a surprise. However, the lower limit had been increasing and there had been hints from analysis of electroweak data, where the top mass enters via loop corrections.

# Top mass history

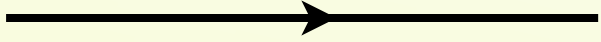


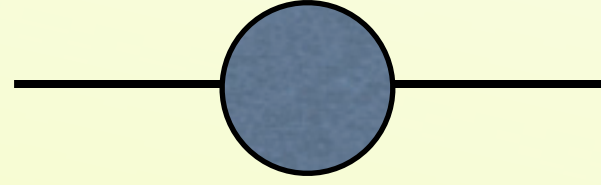
Such a heavy top was a surprise. However, the lower limit had been increasing and there had been hints from analysis of electroweak data, where the top mass enters via loop corrections.



# Mass definition

The **top mass** is so precisely measured ( $m_t = 173.1 \pm 1.0$  GeV) that we have to worry about its definition.

Leading order:   $\frac{1}{\not{p} - m}$  (pole) mass =  $m$

Higher orders:   $\frac{1}{\not{p} - m_R - \Sigma(\not{p})}$   $m_R$  = renor. mass

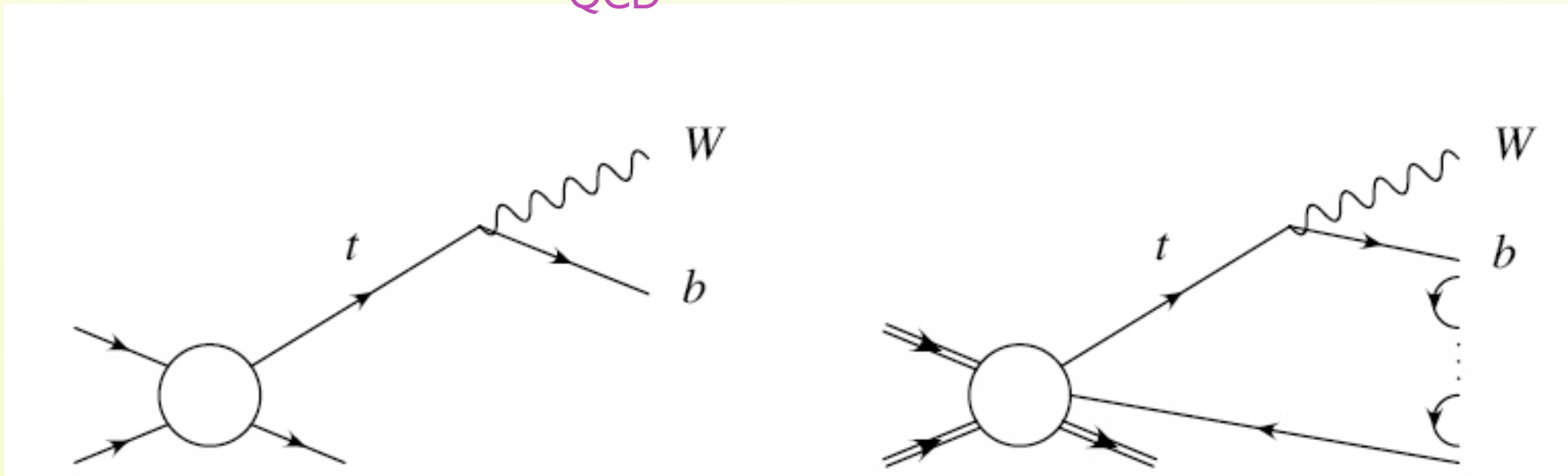
(At least) two possible renormalisation schemes:  **$\overline{\text{MS}}$**  and **on-shell**, leading to different mass definitions.

The  **$\overline{\text{MS}}$  mass** is a fully perturbative object, not sensitive to long-distance dynamics. It can be determined as precisely as the perturbative calculation allows. The mass is thought as any other parameter in the Lagrangian. It is the same as the Yukawa coupling. For example, it could be extracted from a cross section measurement (see later).



# Mass definition

The **pole mass** would be more physical (pole = propagation of particle, though a quark doesn't usually really propagate -- hadronisation!) but is affected by long-distance effects: **it can never be determined with accuracy better than  $\Lambda_{\text{QCD}}$** .



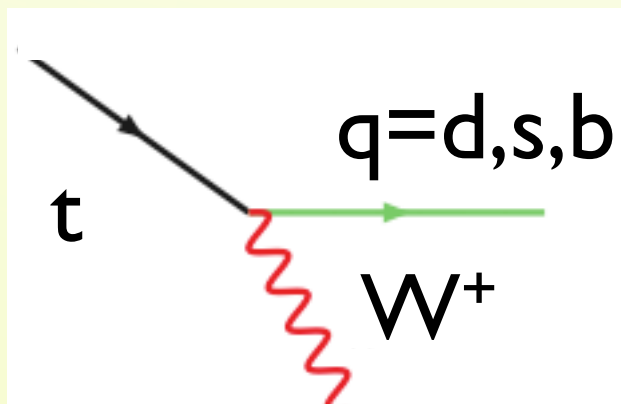
The **pole mass** is closer to what we measure at colliders through invariant mass of the top decay products. The ambiguities in that case are explicitly seen in the modeling of extra radiation, the color connect effects and hadronization.

The two masses can be related perturbatively (modulo non-perturbative corrections!!):

$$m_{\text{pole}} = \overline{m}(\overline{m}) \left( 1 + \frac{4}{3} \frac{\overline{\alpha}_s(\overline{m})}{\pi} + 8.28 \left( \frac{\overline{\alpha}_s(\overline{m})}{\pi} \right)^2 + \dots \right) + O(\Lambda_{\text{QCD}})$$

# Truth or Myth #2 :

## “ $V_{tb}$ can be measured from top decay rates”



The argument goes as follows.

The number of events where the top decays into b jets is given by

$$N_{\text{events}} = (\mathcal{L} \cdot \epsilon) \sigma(tt) \cdot \frac{\Gamma(t \rightarrow Wb)}{\sum_q \Gamma(t \rightarrow Wq)} = (\mathcal{L} \cdot \epsilon) \sigma(tt) \cdot |V_{tb}|^2$$

where we have used unitarity of the CKM:

$$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$$

The top cross section depends only on QCD and top mass and can be given by theory.  
Lumi and efficiencies are exp. determined.

Do you agree?



# Vtb intermezzo

Let's remind ourselves what the CKM matrix actually is

$$J_{\mu}^{+} = \bar{u}_L \gamma_{\mu} d_L \quad \text{mass eigenstates} \Rightarrow J_{\mu}^{+} = \bar{U}_L \gamma_{\mu} V_{\text{CKM}} D_L$$

By fitting all the information we have available mostly from  $K^0$ - $\bar{K}^0$  mixing, B-physics:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9739 - 0.9751 & 0.221 - 0.227 & 0.0029 - 0.0045 \\ 0.221 - 0.227 & 0.9730 - 0.9744 & 0.039 - 0.044 \\ \textcolor{red}{0.0048} - \textcolor{red}{0.014} & \textcolor{red}{0.037} - \textcolor{red}{0.043} & \textcolor{blue}{0.9990} - \textcolor{blue}{0.9992} \end{pmatrix}$$



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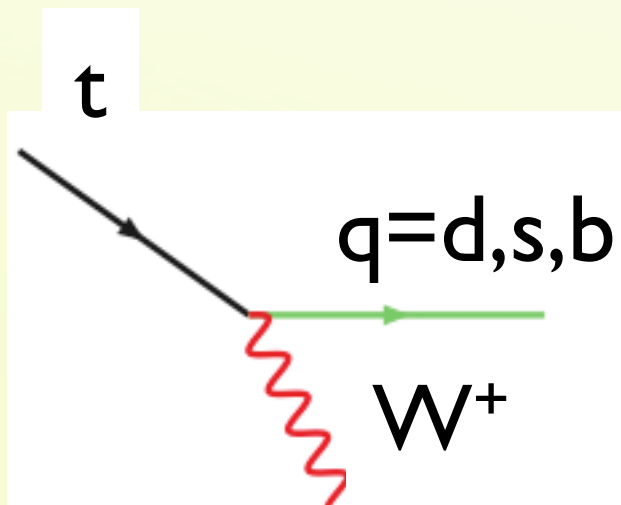
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However most of such information, does not tell us anything directly on the last row. It is the hypothesis of unitarity of the CKM which constraints the  $V_{ti}$  matrix elements. For example the last measurements from CDF on  $B_s$  -  $B_s$  mixing gives

$$0.20 < |V_{td}/V_{ts}| < 0.22$$

# Truth or Myth #2 : “ $V_{tb}$ can be measured from top decay rates”



Counter arguments:

1. Assuming 3 generation unitarity leaves OUT the interesting BSM physics that this measurement explores (4th generation)  
In addition within 3 generation,  $V_{tb} = 0.999...!!!$

2. Number of events is proportional to the Branching ratio,

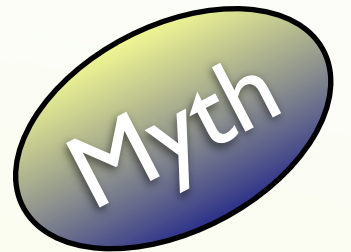
$$R = \frac{\Gamma(t \rightarrow Wb)}{\sum_{light} \Gamma(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

where we already know that  $V_{td}, V_{ts} \ll V_{tb}$ , so  $R \sim 1$   
independently of the overall scale of  $V_{td}, V_{ts}, V_{tb}$  and basically independent of  $V_{tb}$ .

Conclusion:  $V_{tb}$  cannot be measured from the decay of the top. From where then? You need quantities (almost) proportional to  $|V_{tb}|^2$  only. Two possibilities:

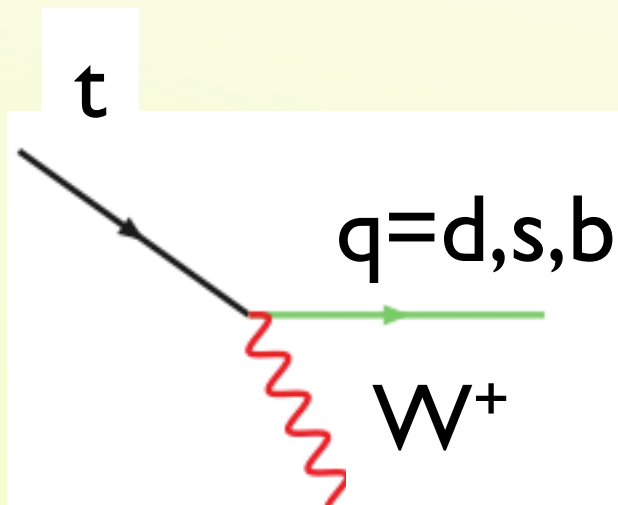
1. The width of the top
2. Single top cross section





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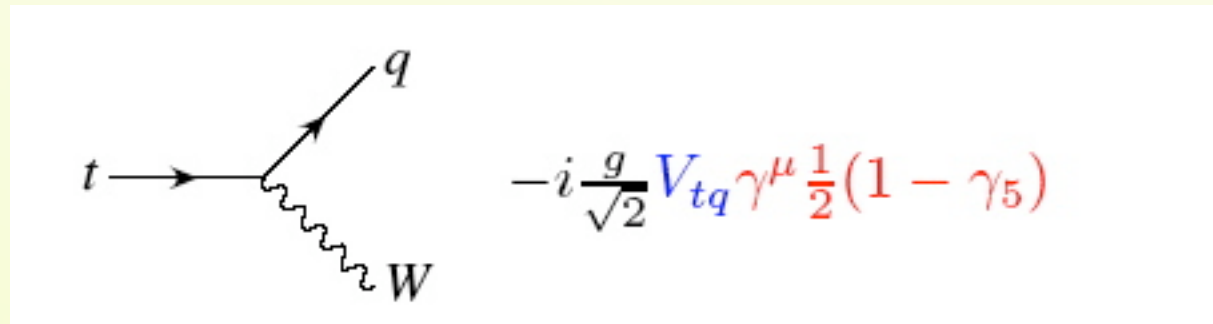
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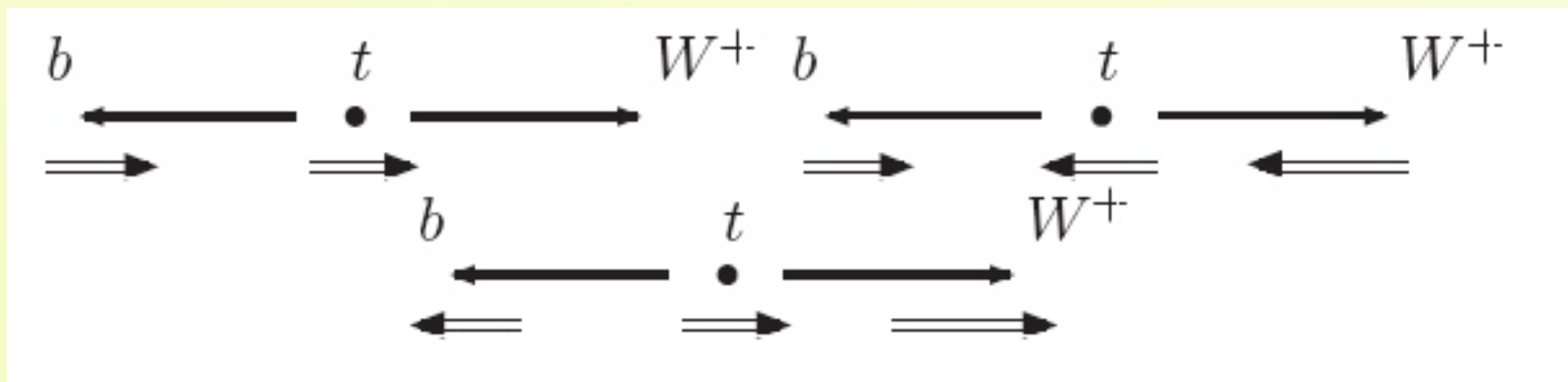
# W polarization



The SM vertex of the top decay implies that it's only the  $t_L$  that takes part to the interaction.

This has straightforward consequences on the possible helicity states of the on-shell W produced in the decay.

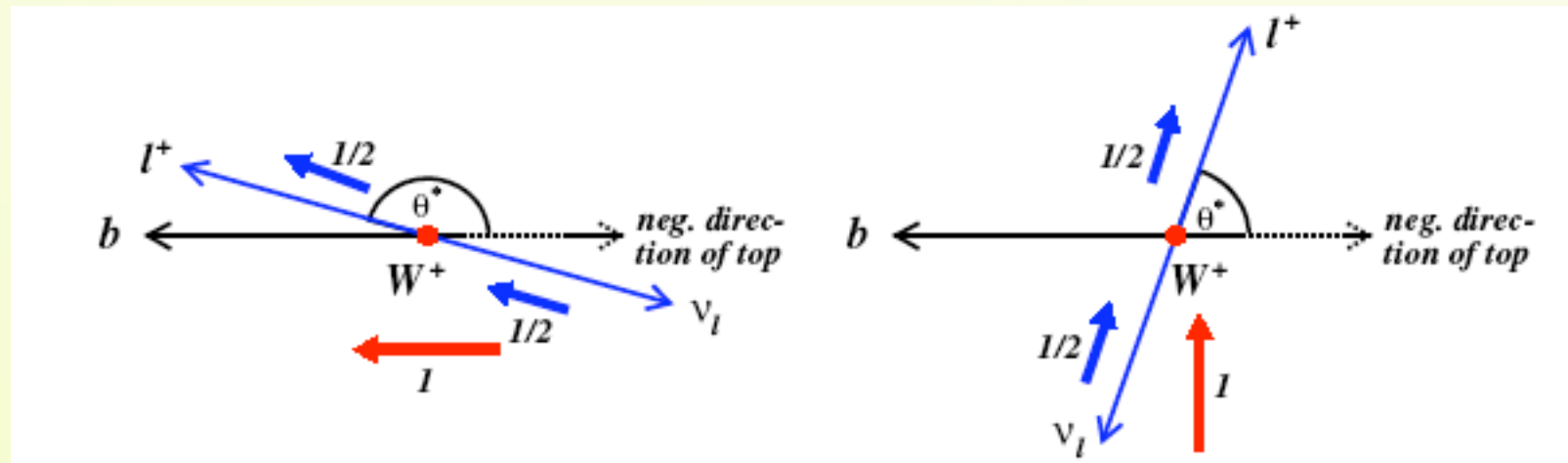
Neglecting  $m_b$ , this implies that the W can be only either longitudinally polarized or with negative helicity. In general:



How do we measure it?? The W polarization is inherited by its decay products, which “remember it” in their angular distributions.

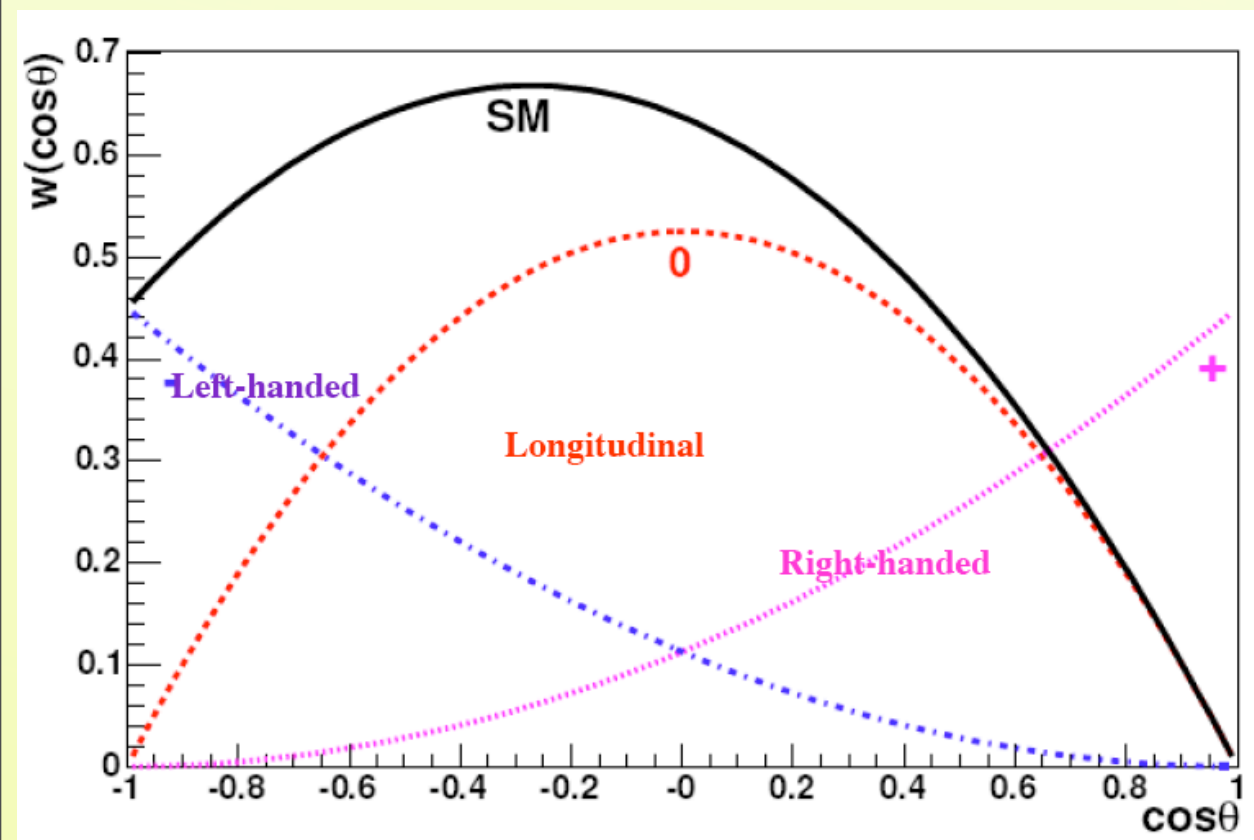
# W polarization

$$\frac{1}{N} \frac{dN(W \rightarrow l\nu)}{d\cos\theta} = K [f_0 \sin^2 \theta + f_L (1 - \cos \theta)^2 + f_R (1 + \cos \theta)^2]$$



$$f_0 = \frac{m_t^2}{2m_W^2 + m_t^2} = 70\%$$

Fraction of longitudinal W's  
(basically the only ones we see in a pp collider!)



\* The formula above is already not trivial since it says that W polarizations don't interfere! (This is true only for 1 dim distributions!)

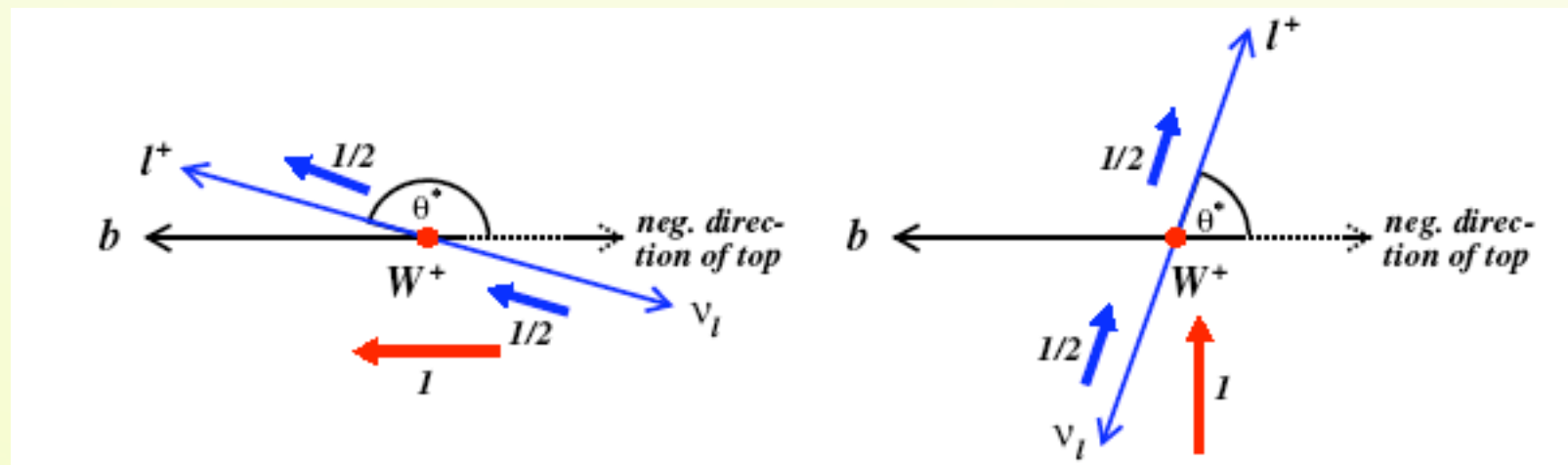
\* Longitudinal polarization come from the Higgs doublet (charged component).

\*  $\cos(\theta)$ , which is defined in a specific frame, can be related to  $m(\text{lepton, bottom})$  or  $p_t(\text{lepton})$ , ergo **no top momentum reconstruction necessary!**

\* Rather "easy measurement".

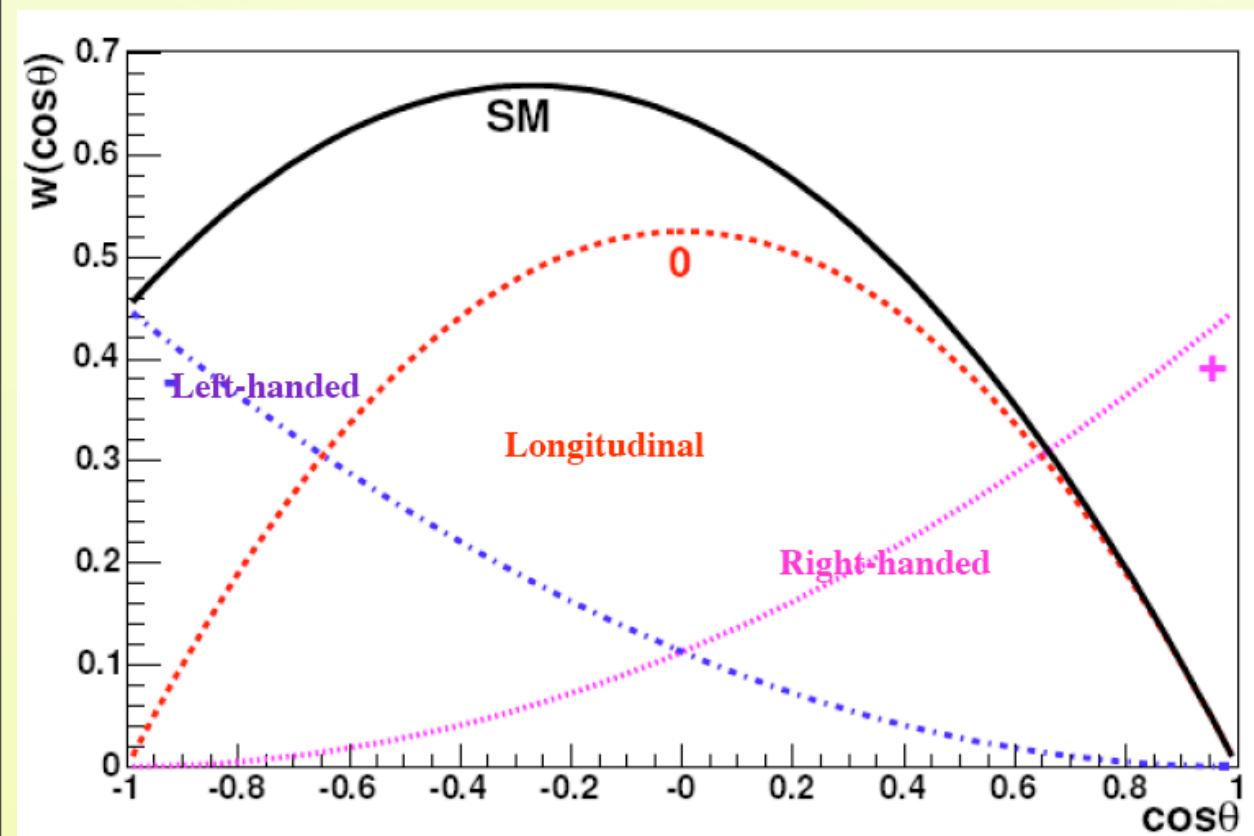
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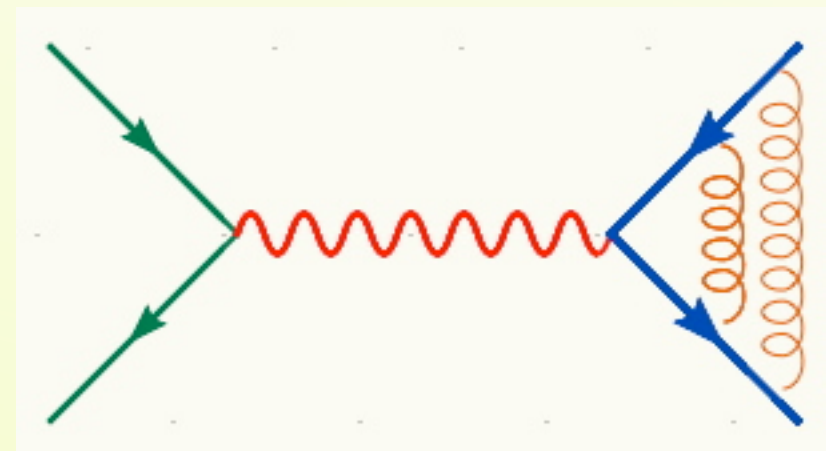
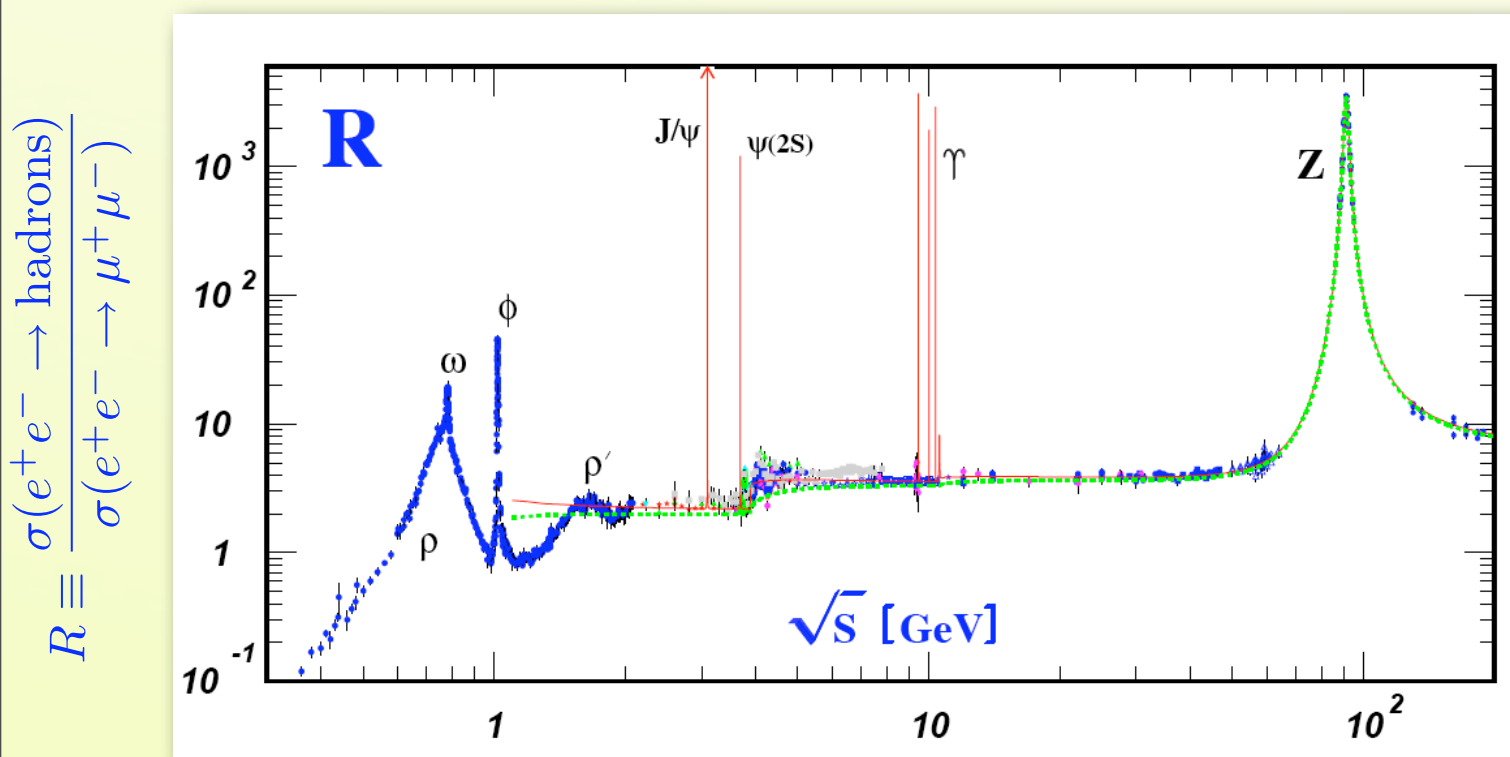
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# Truth or Myth #3 :

“no hadronization  $\Rightarrow$  no resonance physics”

Consider how the charm and the bottom quarks were discovered:



$$2S+1 L_J^{[C]} = 3 S_1^{[1]}$$

Very sharp peaks  $\Rightarrow$  small widths ( $\sim 100$  KeV) compared to hadronic resonances (100 MeV)  $\Rightarrow$  very long lived states. QCD is “weak” at scales  $\gg \Lambda_{\text{QCD}}$  (asymptotic freedom), non-relativistic bound states are formed like positronium!

The QCD-Coulomb potential is like  $V(r) \simeq -C_F \frac{\alpha_S(1/r)}{r}$   $C_F = 4/3$





# Truth or Myth #3 : “no hadronization $\Rightarrow$ no resonance physics”

Let analyse the scales which characterise the bound state. The scales can be found using the the enegy of the ground state and the virial theorem:

$$E_0 = -\frac{1}{2} \frac{m_t}{2} (C_F \alpha_S)^2 \quad \text{with} \quad \langle T \rangle = -\frac{1}{2} \langle V \rangle \quad \text{gives} \quad v \simeq C_F \alpha_S (m v)$$

$$R_0 = 1 / (C_F \alpha_S m_t / 2)$$

Scale	Quantity	e+e-	toponium
m	annihilation time	0.5 MeV	172 GeV
mv	size $p \sim 1/R$	3.7 KeV	15 GeV
mv <sup>2</sup>	Formation time	25 eV	2 GeV

This equation can be solved iteratively and gives scales that are all perturbative and well separated.

“Unfortunately” the formation time for the bound state is

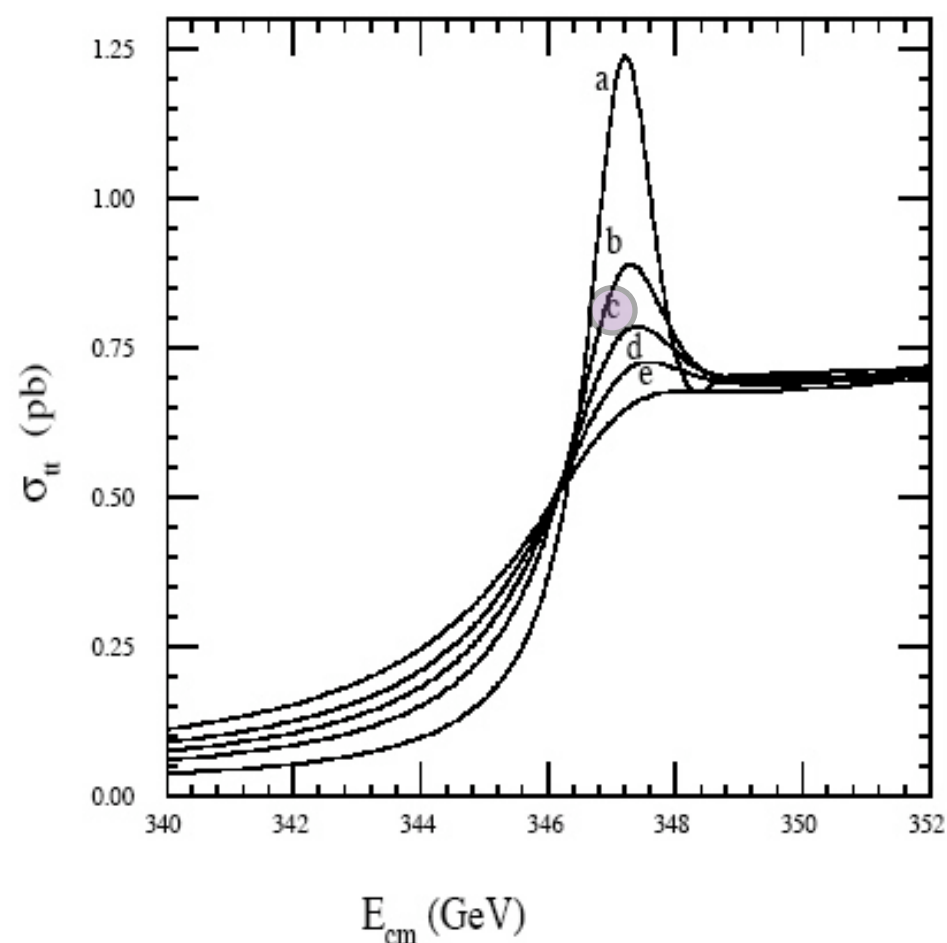
$$\tau_{\text{form}} \approx \text{size}/v \approx mv^2 \approx 1/(2 \text{ GeV})$$

$$\tau_{\text{weakdecay}} \approx \tau_{\text{top}}/2 \approx 1/(3 \text{ GeV}) < \tau_{\text{form}}$$

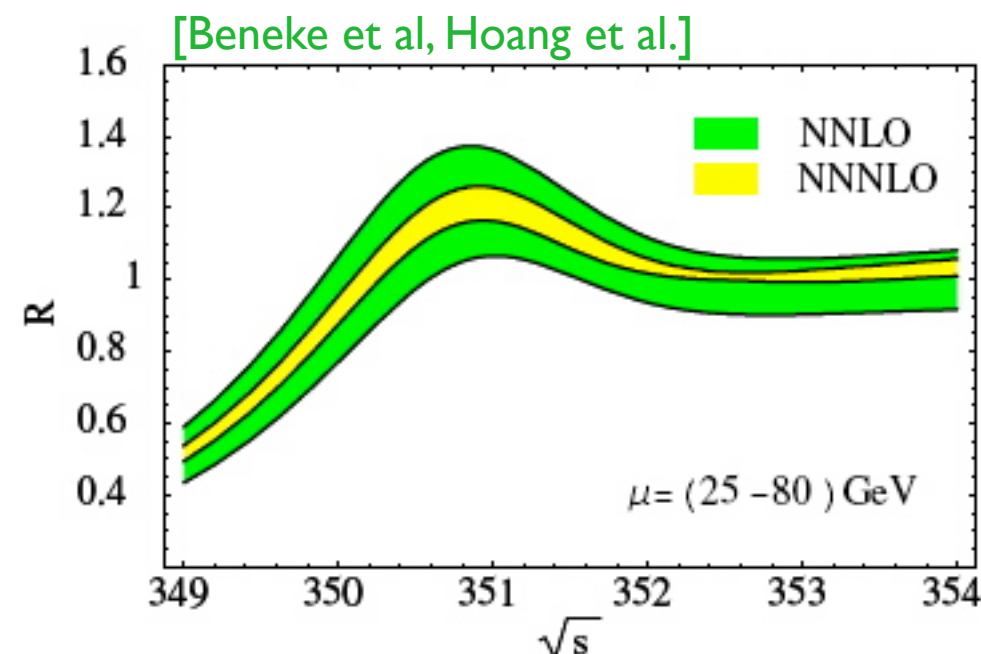
So..... no resonance physis???

## Truth or Myth #3 :

“no hadronization  $\Rightarrow$  no resonance physics”



The time scales, formation and decay, are not so widely different (by chance!). Therefore if we perform a threshold scan in  $e^+e^-$  we should be able to see an enhancement of the cross section, due to Coulomb rescattering. The width of the peak is proportional to the width (direct measurement) and the position of the peak would allow a very precise mass measurement. A serious calculation gives:

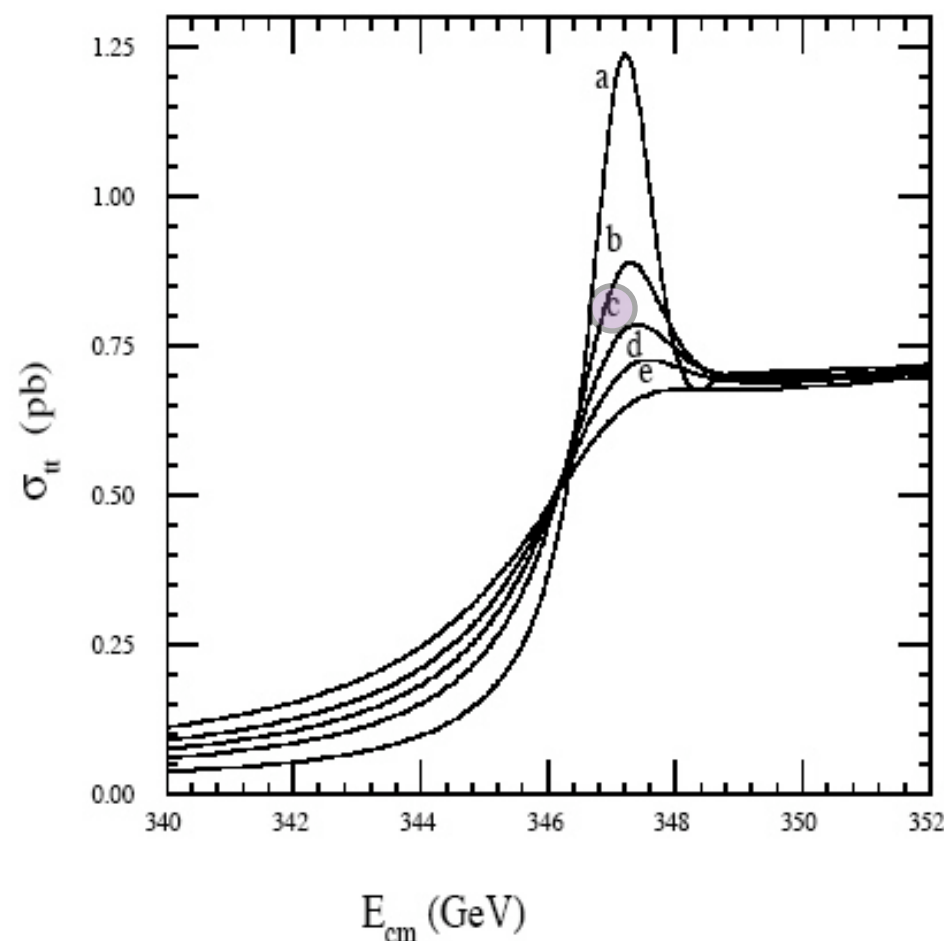


Can something similar happen in pp collisions? It's a good question!

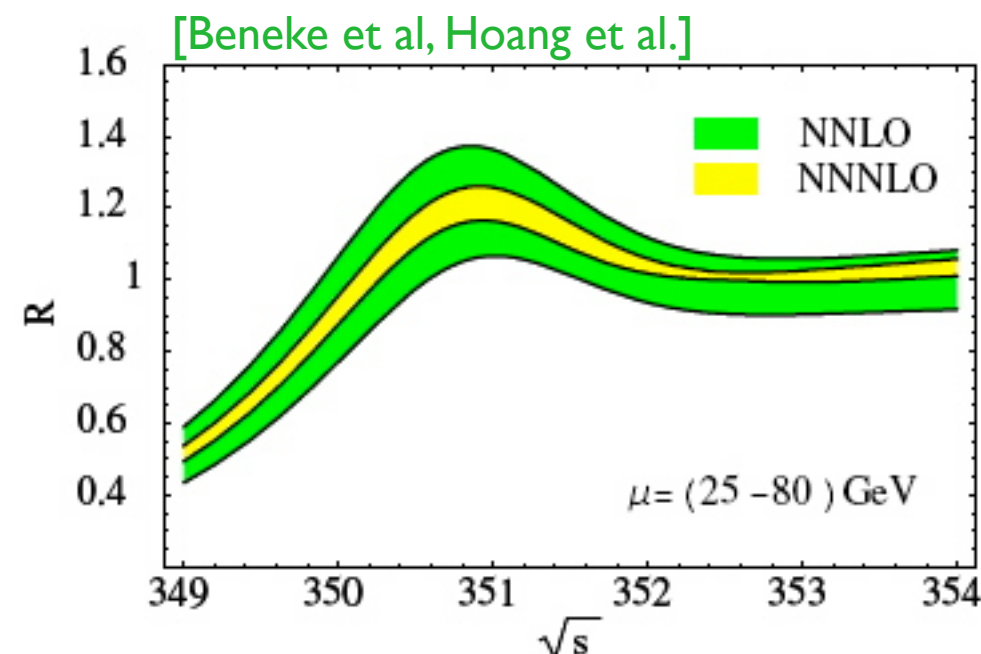
Myth

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# Truth or Myth #3b:

## “Resonance physics only accessible at the ILC”

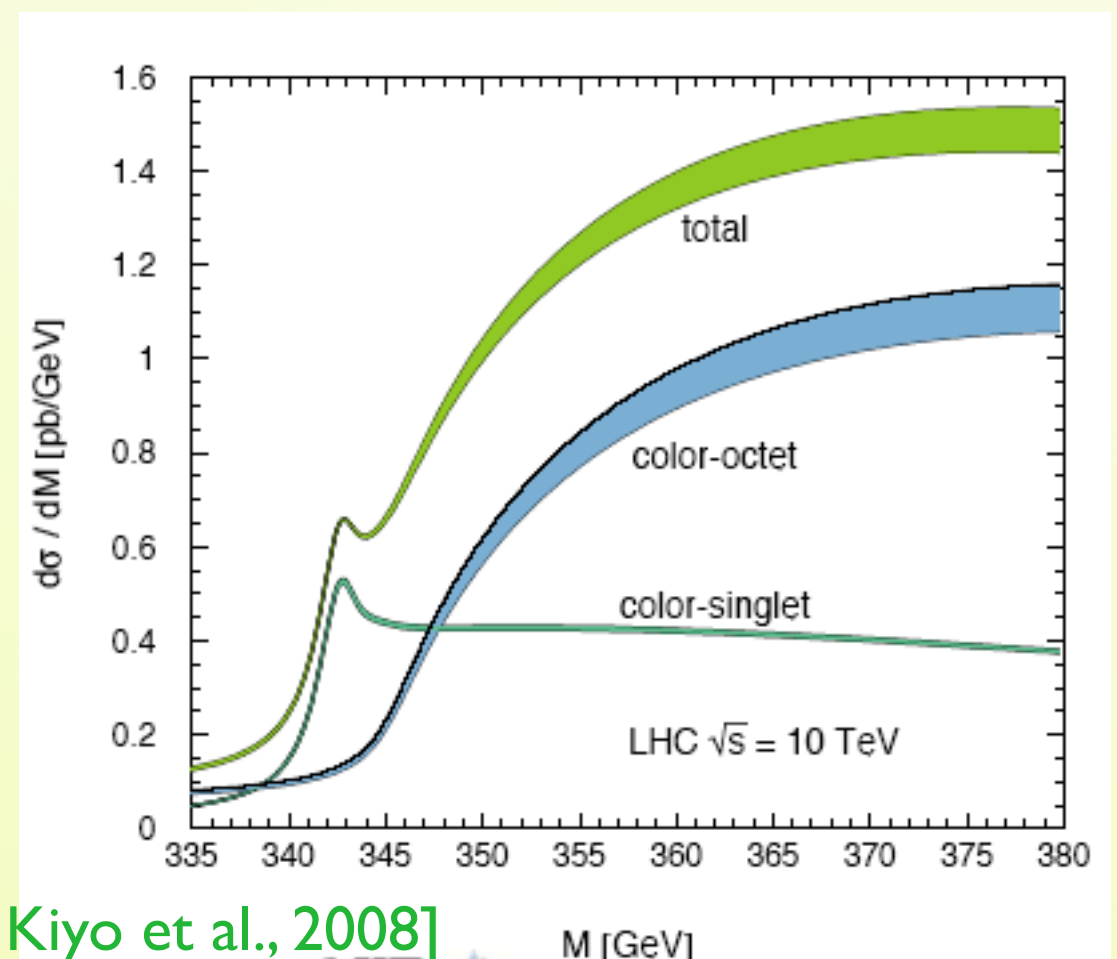
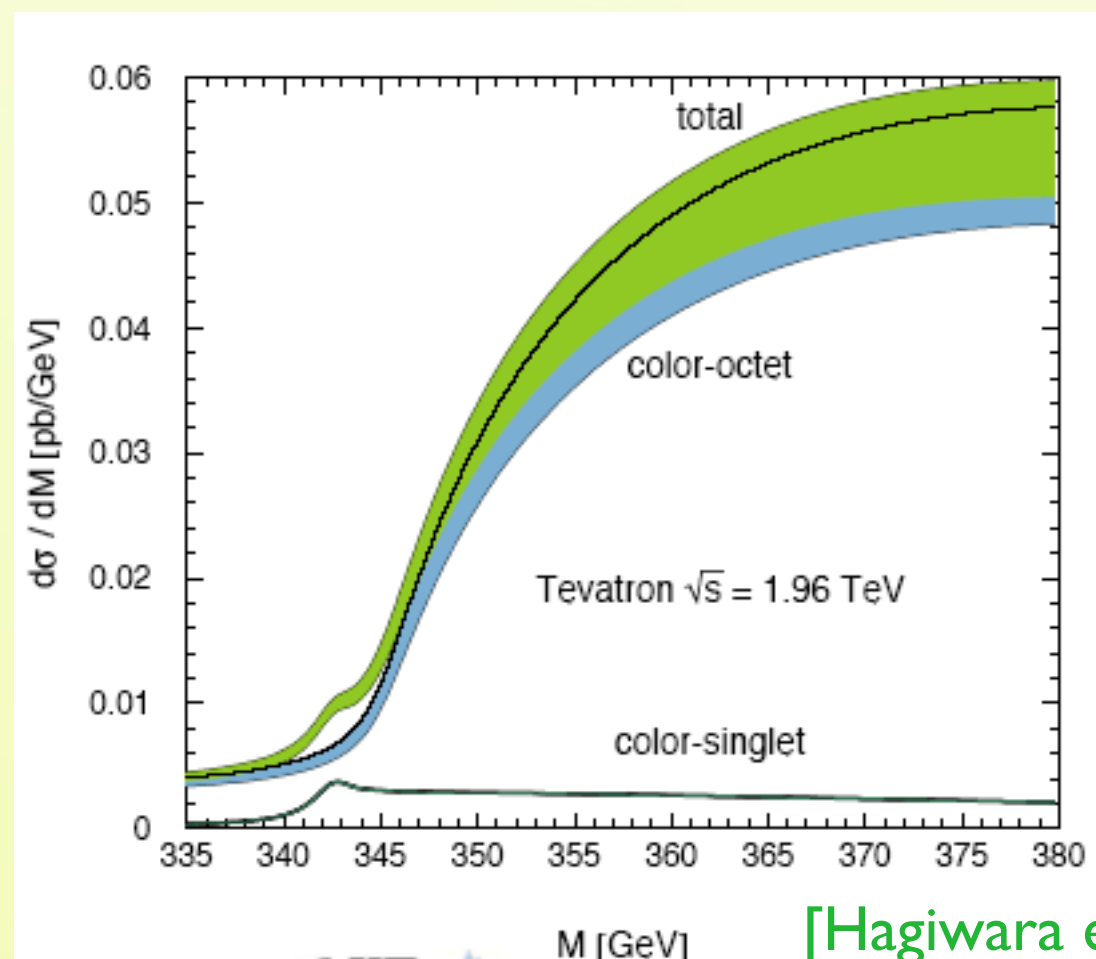
In hadronic collision, the interactions at threshold can be either attractive or repulsive! Octet larger cross section, but “bound state” effects are dominant in the singlet. Effects compete. Until last spring, the common lore was that PDF effects would smear any peak!

Precise mass measurement? Width measurement?

$$V(r) \simeq -C_{[1,8]} \frac{\alpha_S(1/r)}{r}$$

$$C^{[1]} = C_F = 4/3$$

$$C^{[8]} = C_F - C_A/2 = -1/6$$



[Hagiwara et al 2008; Kiyo et al., 2008]



# Truth or Myth #3b: “Resonance physics only accessible at the ILC”

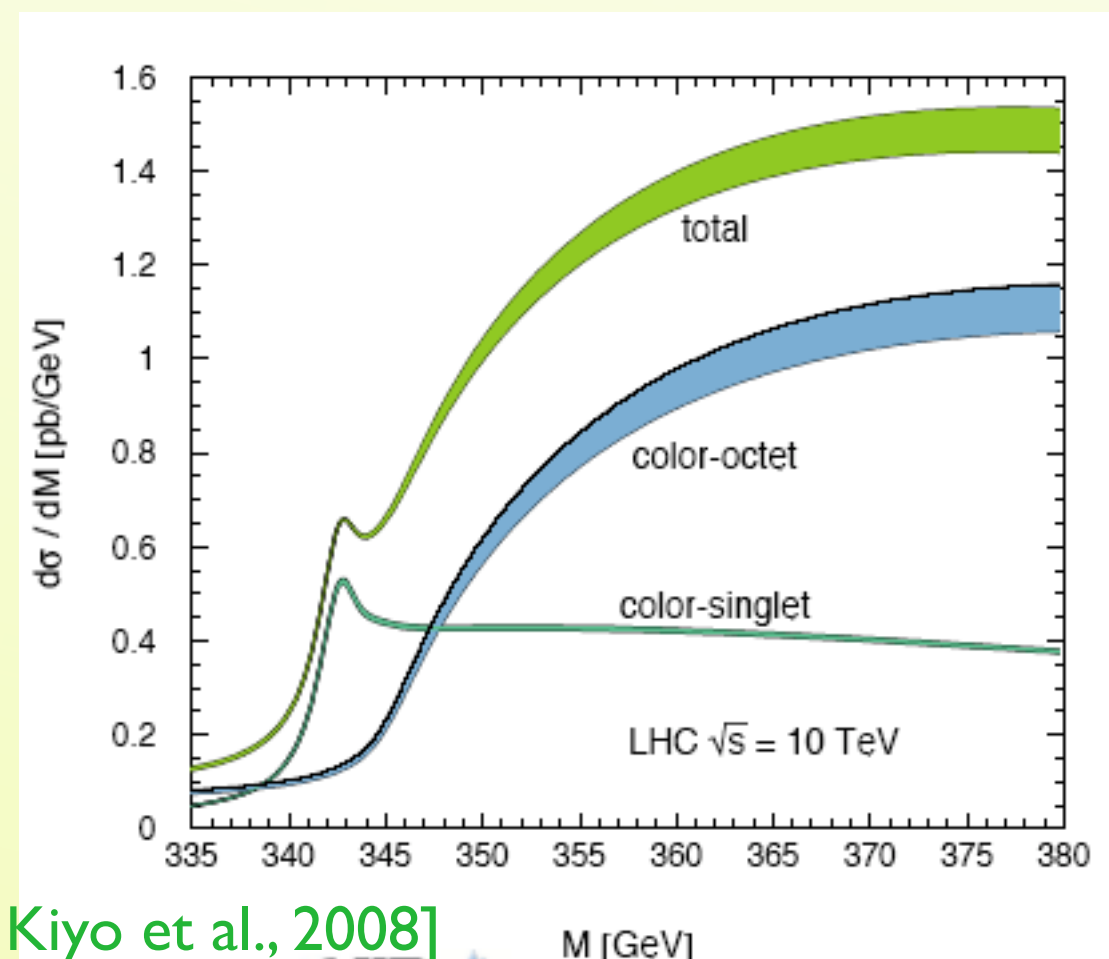
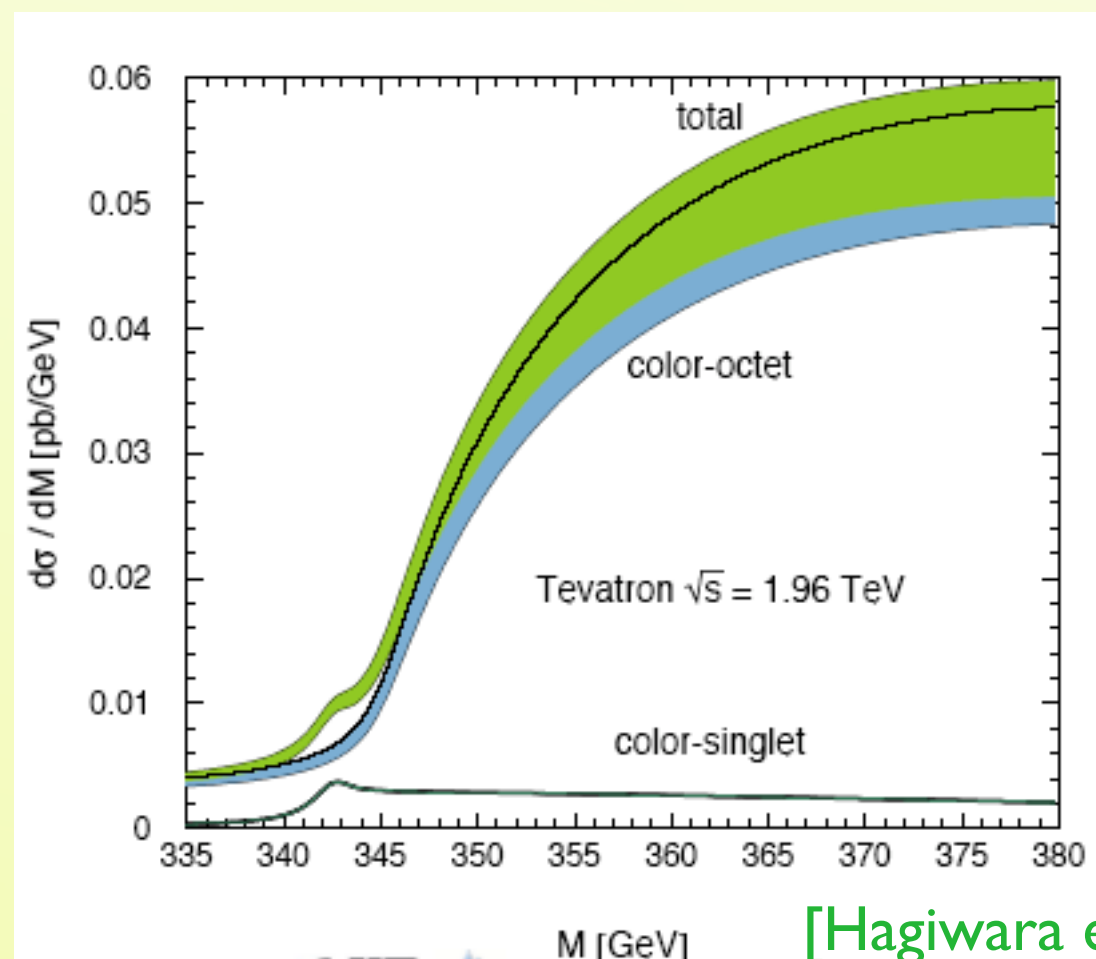
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## Truth or Myth #4 : “No hadronization $\Leftrightarrow$ Top spin effects”

We have now very clear that most probably (if  $V_{tb}$  is indeed 1) top decays before hadronizing,

$$\tau_{\text{had}} \approx h/\Lambda_{\text{QCD}} \approx 2 \cdot 10^{-24} \text{ s} > \tau_{\text{top dec}} \approx h/\Gamma_{\text{top}} 5 \cdot 10^{-25} \text{ s}$$

Therefore non-perturbative effects (soft-gluons) don't have the time to change the spin of the top which is then passed from the production to the decay. As a result the spin becomes a typical quantum mechanical quantity and correlation measurements can be performed (see tomorrow).

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HOWEVER, one can also ask : Is the opposite true? if we see spin correlation effects do we automatically put an upper bound on the width and hadronization? NO!

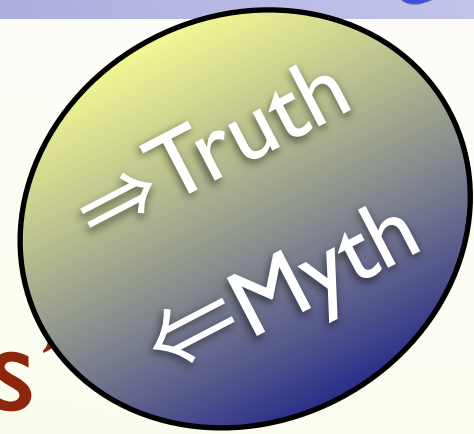
Spin-flips are due to CHROMOMAGNETIC interactions, which are mediated by dimension 5 operators:

$$\mathcal{L}_{\text{mag}} = \frac{C_m}{4m_t} \bar{Q}_v G_{\mu\nu} \sigma^{\mu\nu} Q_v \Rightarrow \tau_{\text{flip}} \simeq h \left( \frac{\Lambda_{\text{QCD}}^2}{m_t} \right)^{-1} \gg \tau_{\text{had}}$$

If, for instance,  $V_{tb} \sim 0.3$ , then top would start hadronizing into mesons and still conserve its spin!

[Falk and Peskin, 1994]

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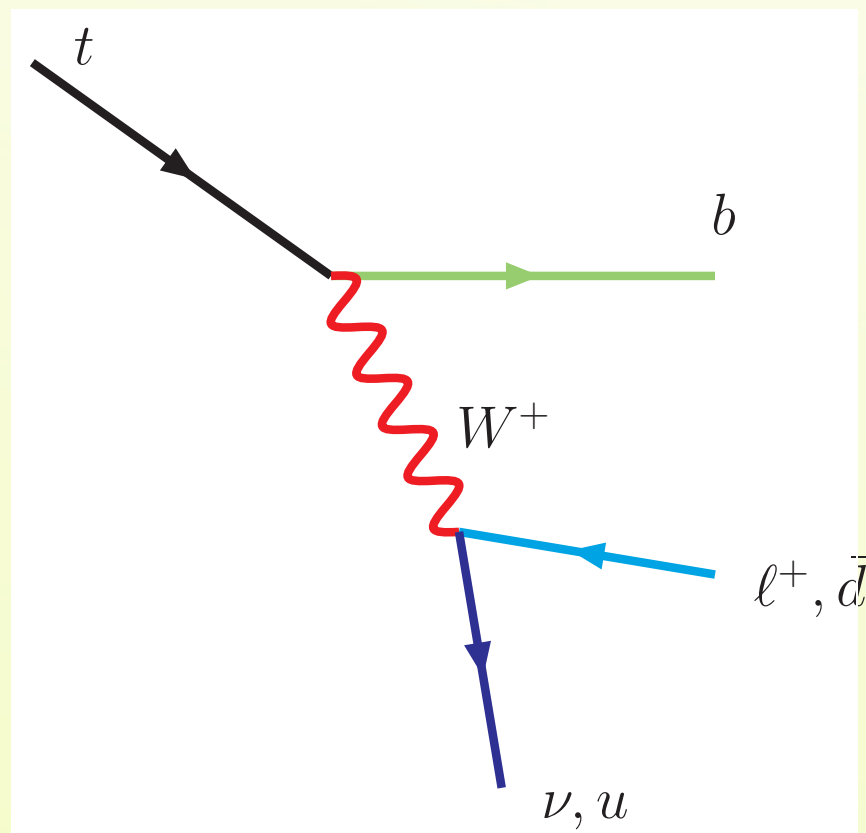
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[Falk and Peskin, 1994]

# How to measure top spin



In particular one can easily show that for the top, the lepton<sup>+</sup> (or the d), in the top rest frame, tends to be emitted in the same direction of the top spin.

Note that this has nothing to do with W polarization! In particular one studies spin correlations between the top and anti-top in ttbar production and the spin of the top in single top.

Results depend on the degree of polarization (p) of the tops themselves and from the choice of the “spin-analyzer”  $k_i$ .

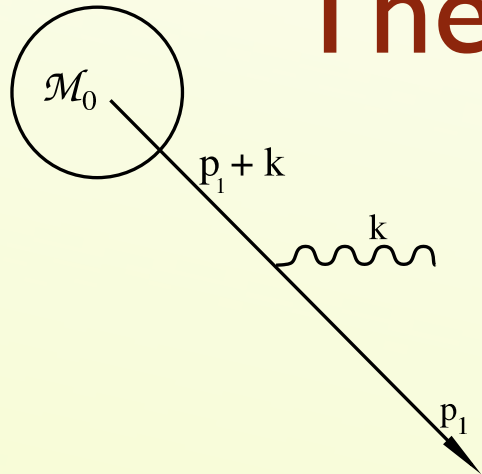
	$\ell^+$	$\bar{d}$	$u$	$b$	$j_<$	$\mathbf{T}$	$j_>$
LO:	1	1	-0.32	-0.39	0.51	-0.32	0.2
NLO:	0.999	0.97	-0.31	-0.37	0.47	-0.31	

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta} = \frac{1 + p k_i \cos \theta}{2}$$



# Truth or Myth #5 :

## “The top does not like to radiate much”



Consider gluon emission off a heavy quark using perturbation theory:

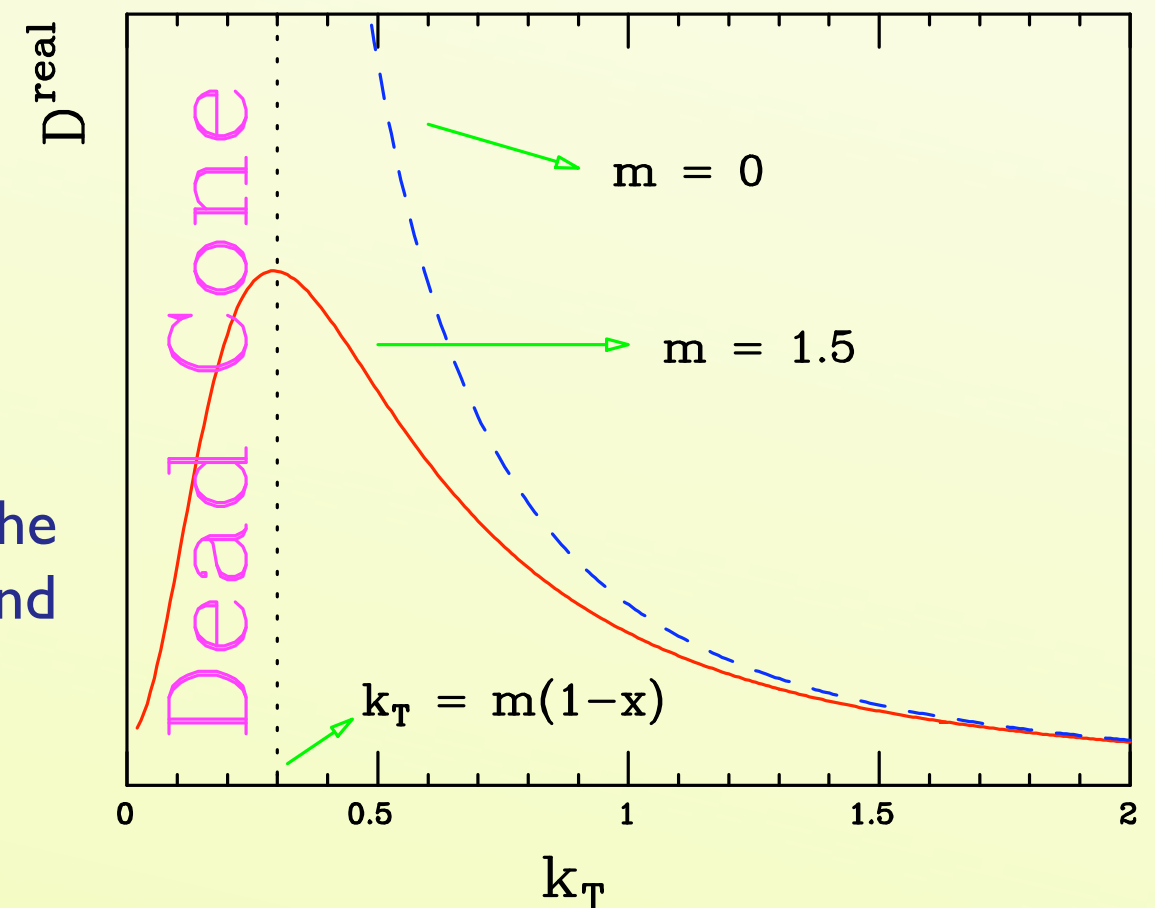
$$D^{\text{real}}(x, k_{\perp}^2, m^2) = \frac{C_F \alpha_S}{2\pi} \left[ \frac{1+x^2}{1-x} \frac{1}{k_{\perp}^2 + (1-x)^2 m^2} - x(1-x) \frac{2m^2}{(k_{\perp}^2 + (1-x)^2 m^2)^2} \right]$$

In the massless case ( $m=0$ ) we have a non-integrable collinear singularity:

$$\int_0^1 D(x, k_{\perp}^2) dk_{\perp}^2 = \frac{1+x^2}{1-x} \int_0^1 \frac{dk_{\perp}^2}{k_{\perp}^2} = \infty$$

The presence of the heavy quark mass suppresses the collinear radiation at small transverse momenta and allows the integration down to zero.

Be careful because it's a frame dependent statement!



# Truth or Myth #5 :

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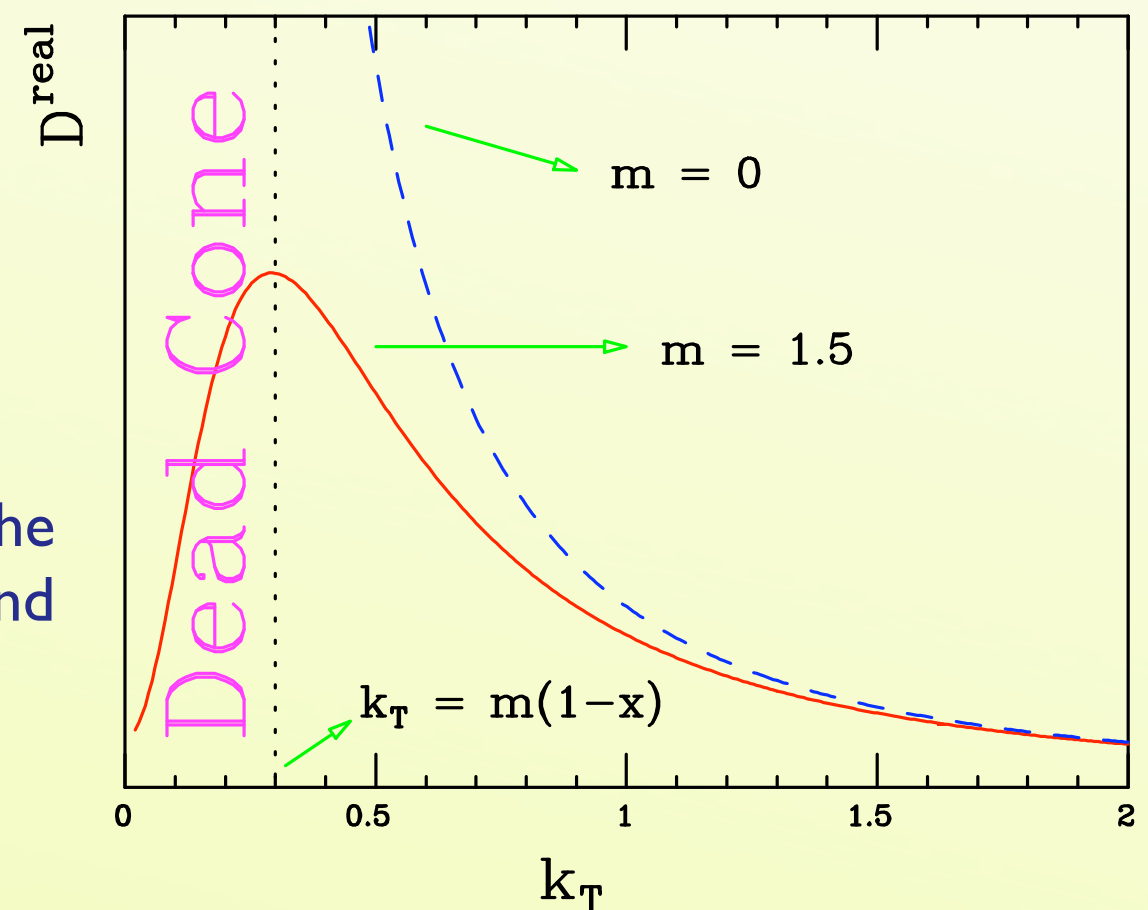
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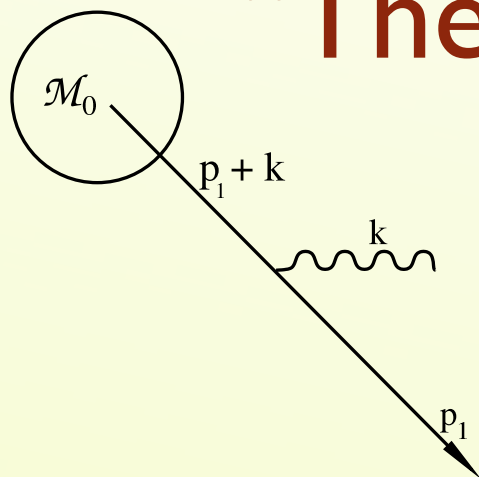




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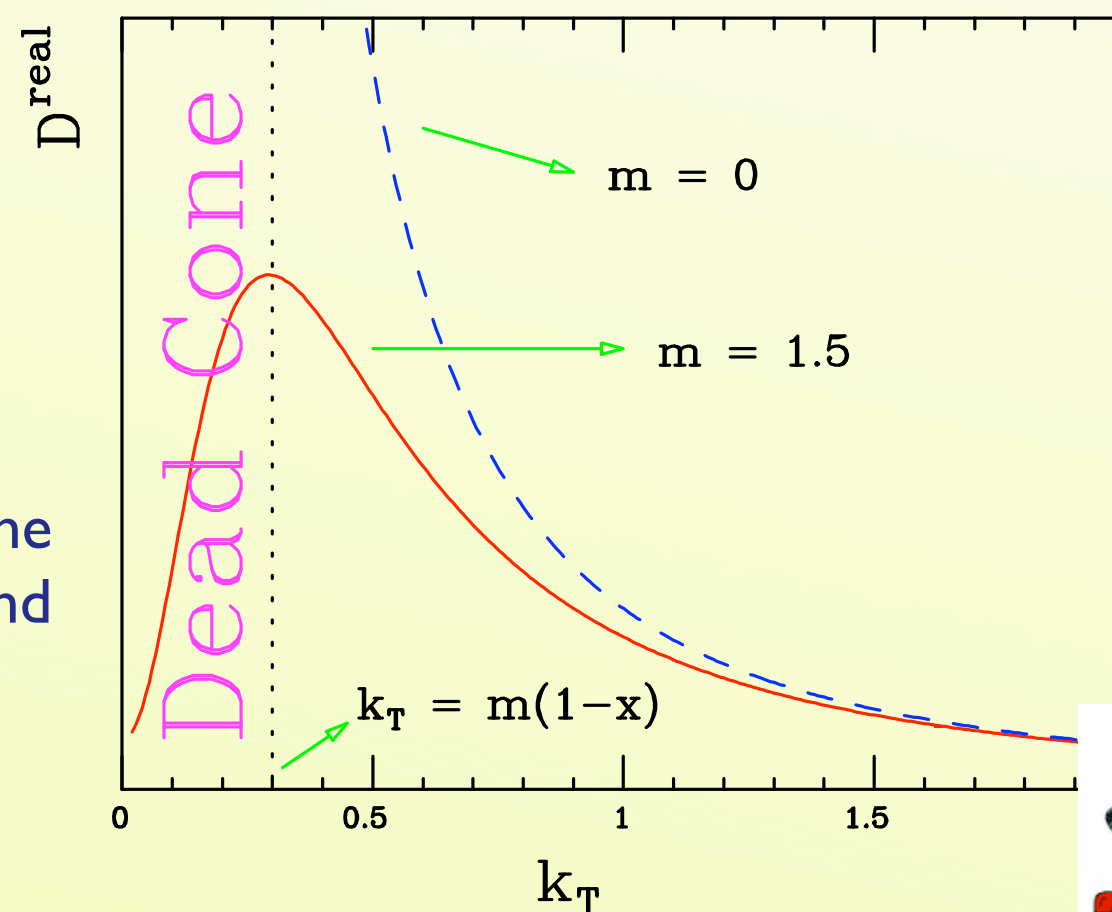
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$$\int_0 D(x, k_{\perp}^2) dk_{\perp}^2 = \frac{1+x^2}{1-x} \int_0 \frac{dk_{\perp}^2}{k_{\perp}^2} = \infty$$

The presence of the heavy quark mass suppresses the collinear radiation at small transverse momenta and allows the integration down to zero.

Be careful because it's a frame dependent statement!



# Summary

- Top is by all means special!
- The CKM elements  $V_{td}$ ,  $V_{ts}$ ,  $V_{tb}$  are not very well constrained (if unitarity is relaxed). Top decays do not help much. Need for width or single-top measurements
- Top anti-top pairs close to threshold can display a “bound state” behaviour even in pp collisions
- Top spin is a good and interesting observable
- Top mass screens collinear radiation



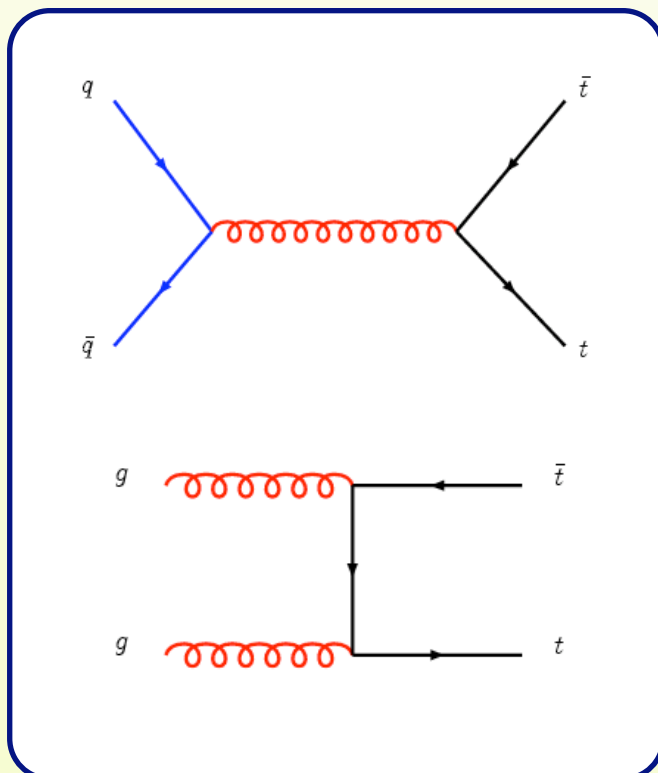


# Outline

- The importance of being Top
- Truth and myths about Top
- Top in the making
- Hot Topics

# Producing Top

Strong



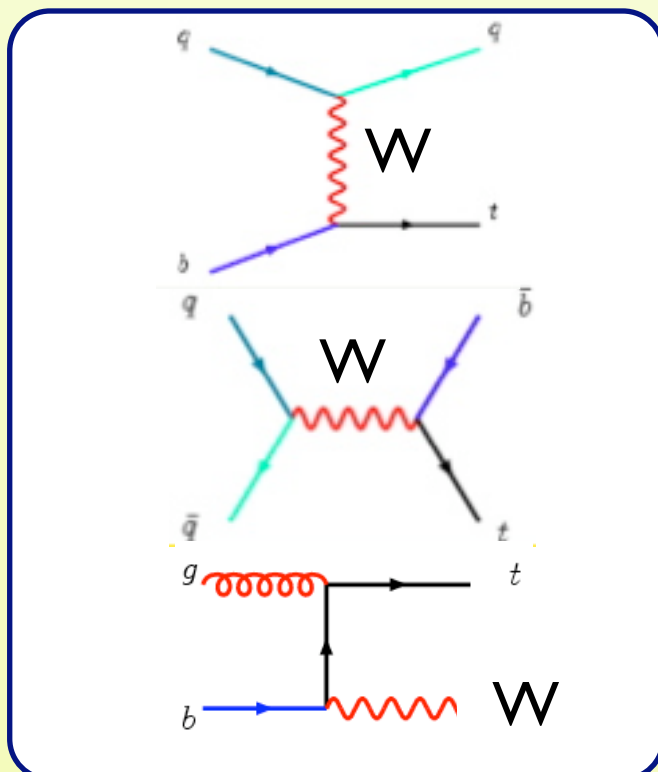
Largest cross section (LO at  $\alpha_s^2$ ):

$\sim 10$  pb at Tevatron

$\sim 1$  nb at the LHC14 (150pb at LHC7)

Top discovery mode.

Weak



Weak process : same diagrams as the top decay!

Cross sections smaller than QCD but enhanced by a lower energy cost:

$\sim 3$  pb at Tevatron

$\sim 300$  pb at the LHC14 (60pb at LHC7)

Three independent channels.

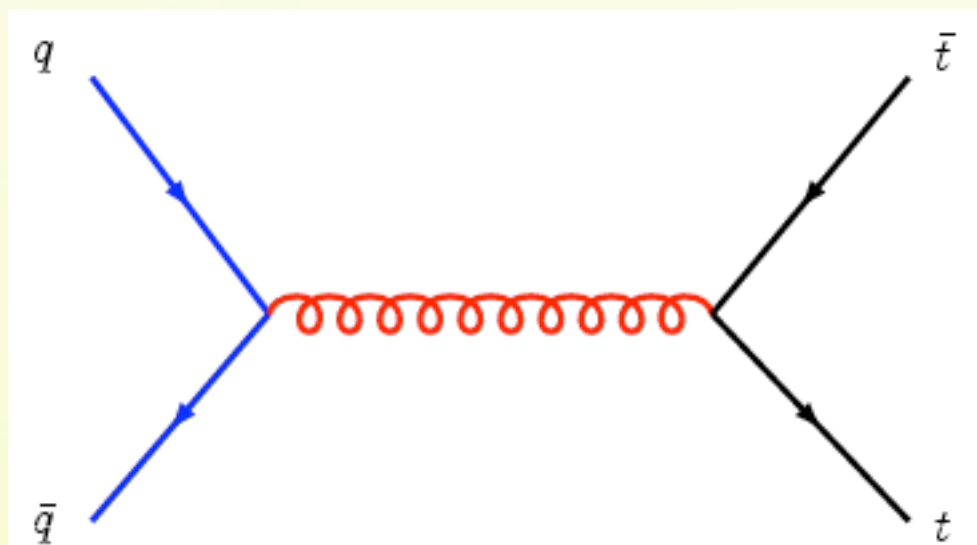
At the Tevatron  $\sigma(t) = \sigma(t\bar{b})$ . At

the LHC  $\sigma(t) > \sigma(t\bar{b})$  (for s- and t-)

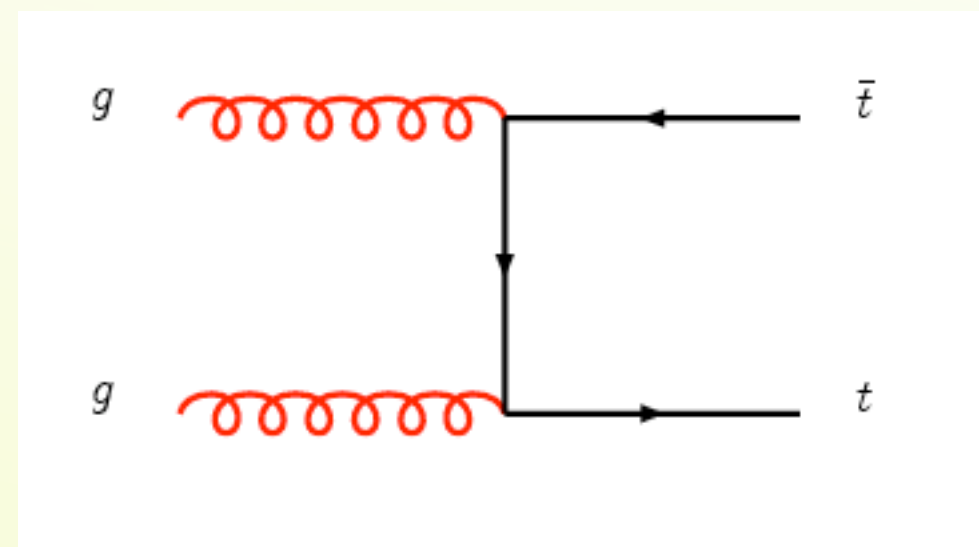


# From Tevatron to LHC

Tevatron

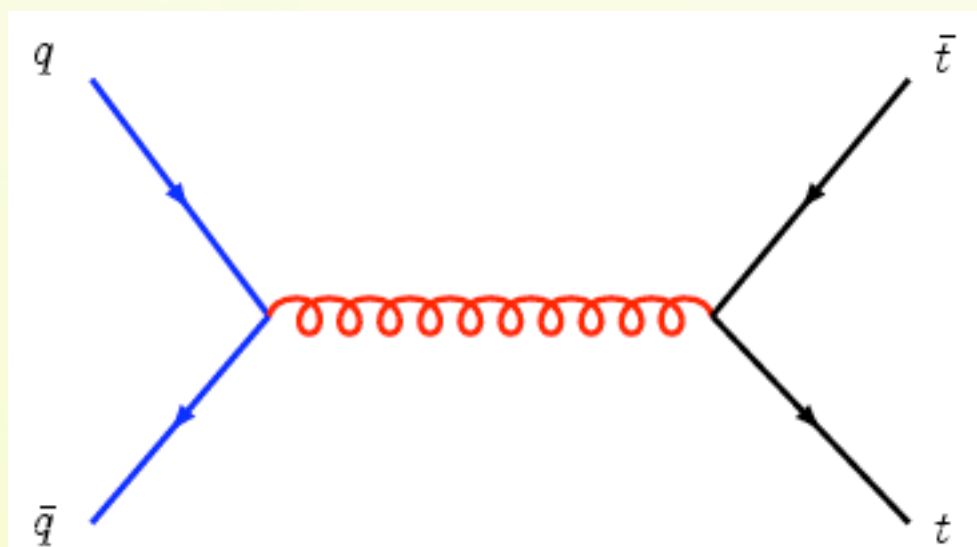


LHC

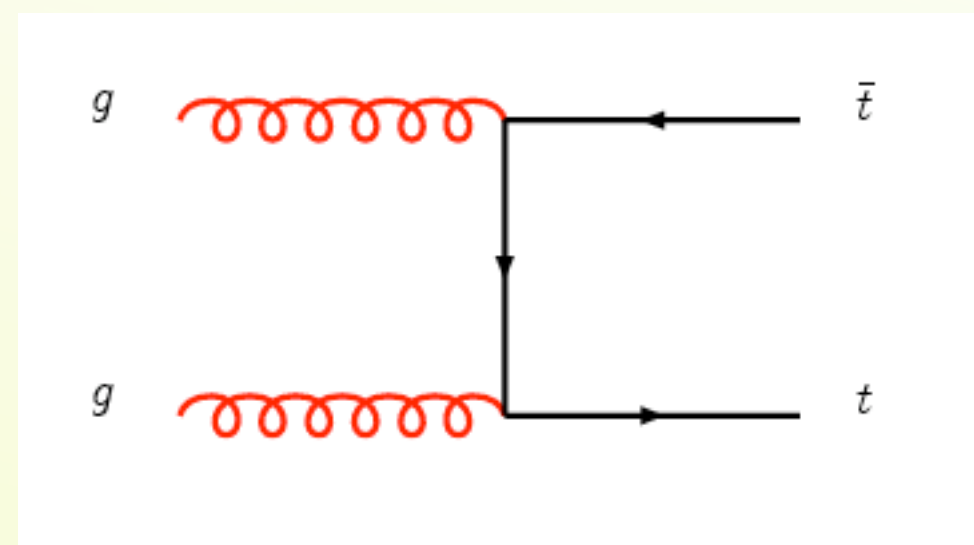


# From Tevatron to LHC

Tevatron



LHC



85% of the total cross section

10 tt pairs per day

60% of the time there is extra radiation  
so that  $p_t(tt) > 15 \text{ GeV}$ .

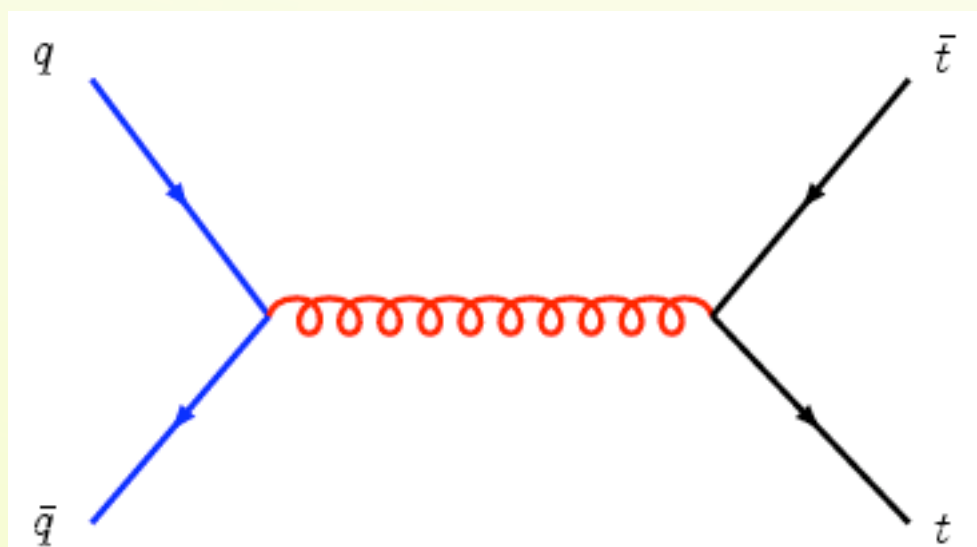
tt are produced closed to threshold, in a  $^3S_1^{[8]}$  state. Same spin directions. 100% correlated in the off-diagonal basis.

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



# From Tevatron to LHC

Tevatron



85% of the total cross section

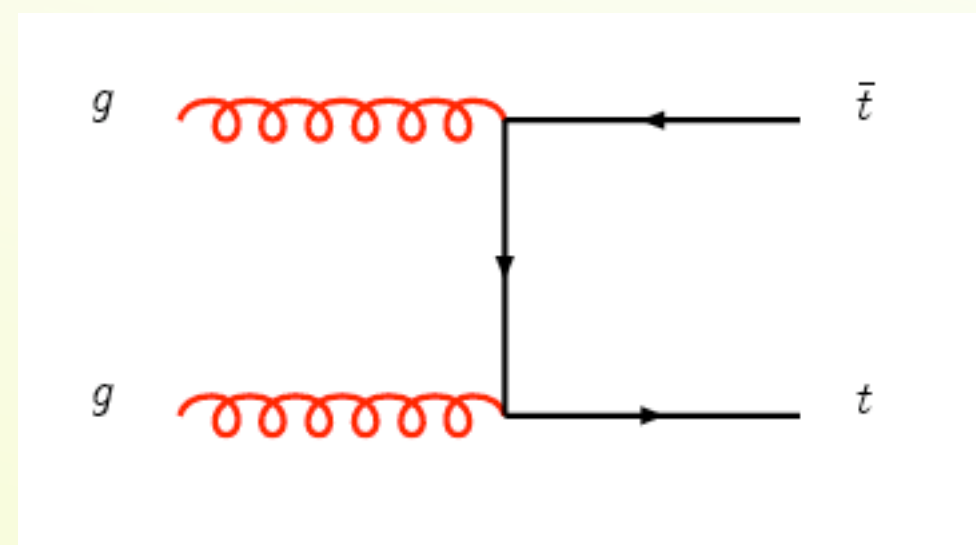
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LHC



90% of the total cross section

1 tt pair per second

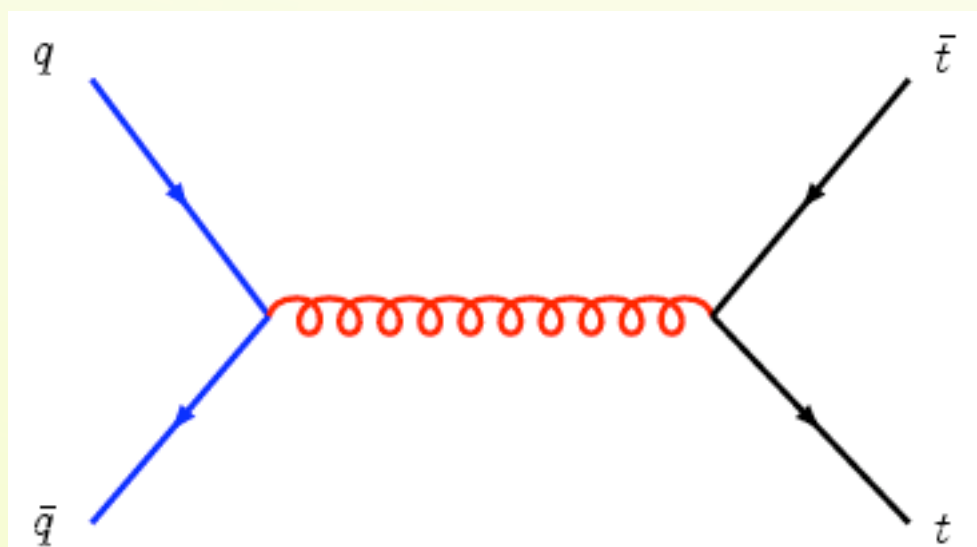
Almost 70% of the time there is extra radiation so that  $p_t(tt) > 30$  GeV.

tt can be easily produced away from threshold. On threshold they are  $^1S_0^{[1,8]}$  state with opposite spin directions. No 100% correlation.

Background free\*!

# From Tevatron to LHC

Tevatron



85% of the total cross section

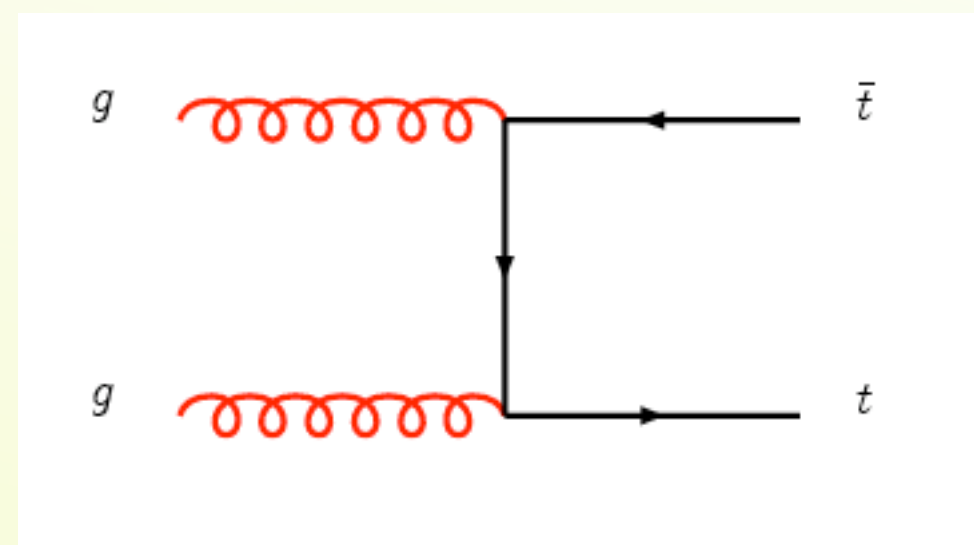
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Background free\*!

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

# Master QCD formula

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \rightarrow X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

Two ingredients necessary:

1. Parton Distribution functions (from exp, but evolution from th).
2. Short distance coefficients as an expansion in  $\alpha_S$  (from th).

$$\hat{\sigma}_{ab \rightarrow X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

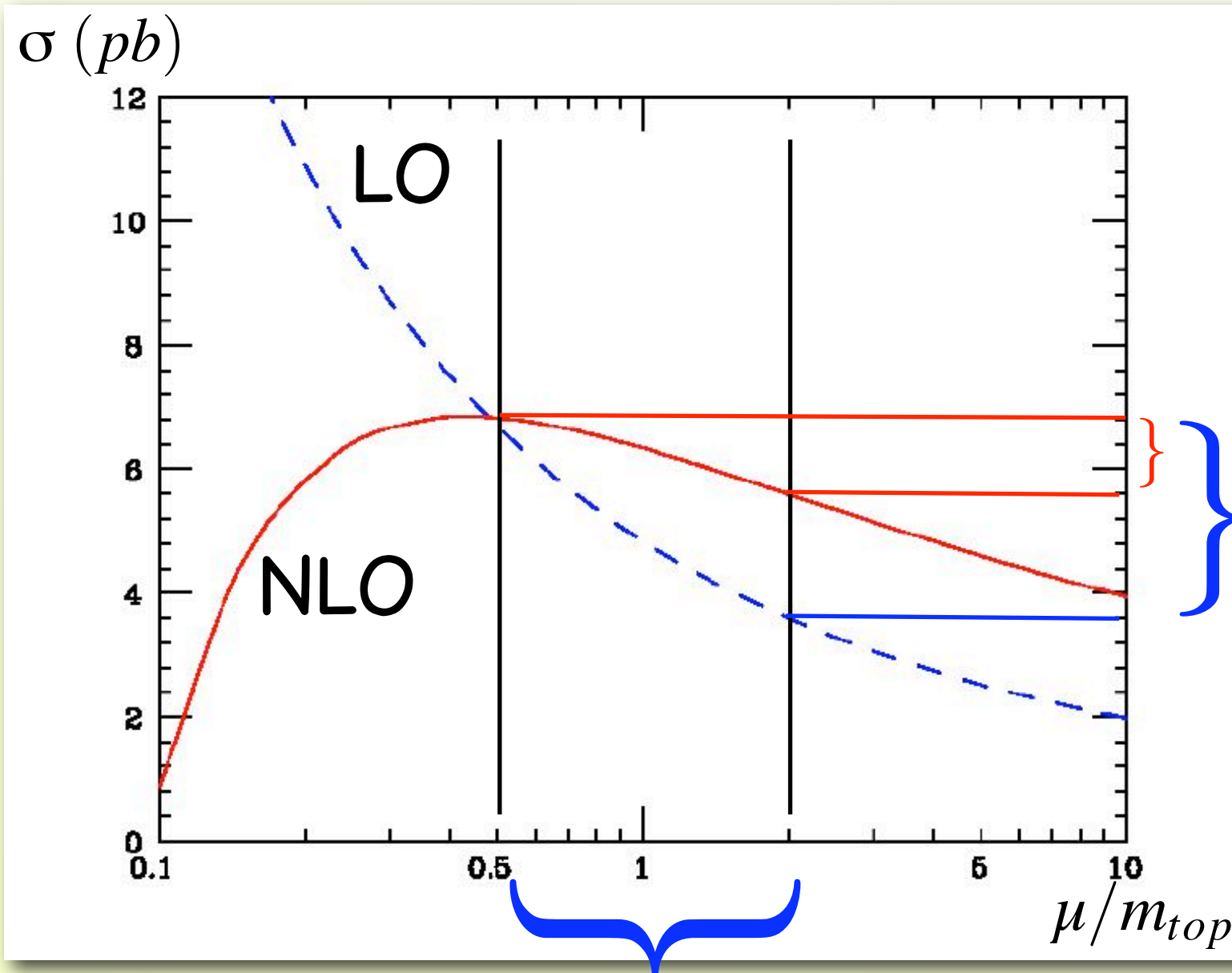
Leading order

Next-to-leading order

Next-to-next-to-leading order

# Estimating TH uncertainties

“Typical”  
behaviour of a  
cross-section  
w.r.t. scale  
variations

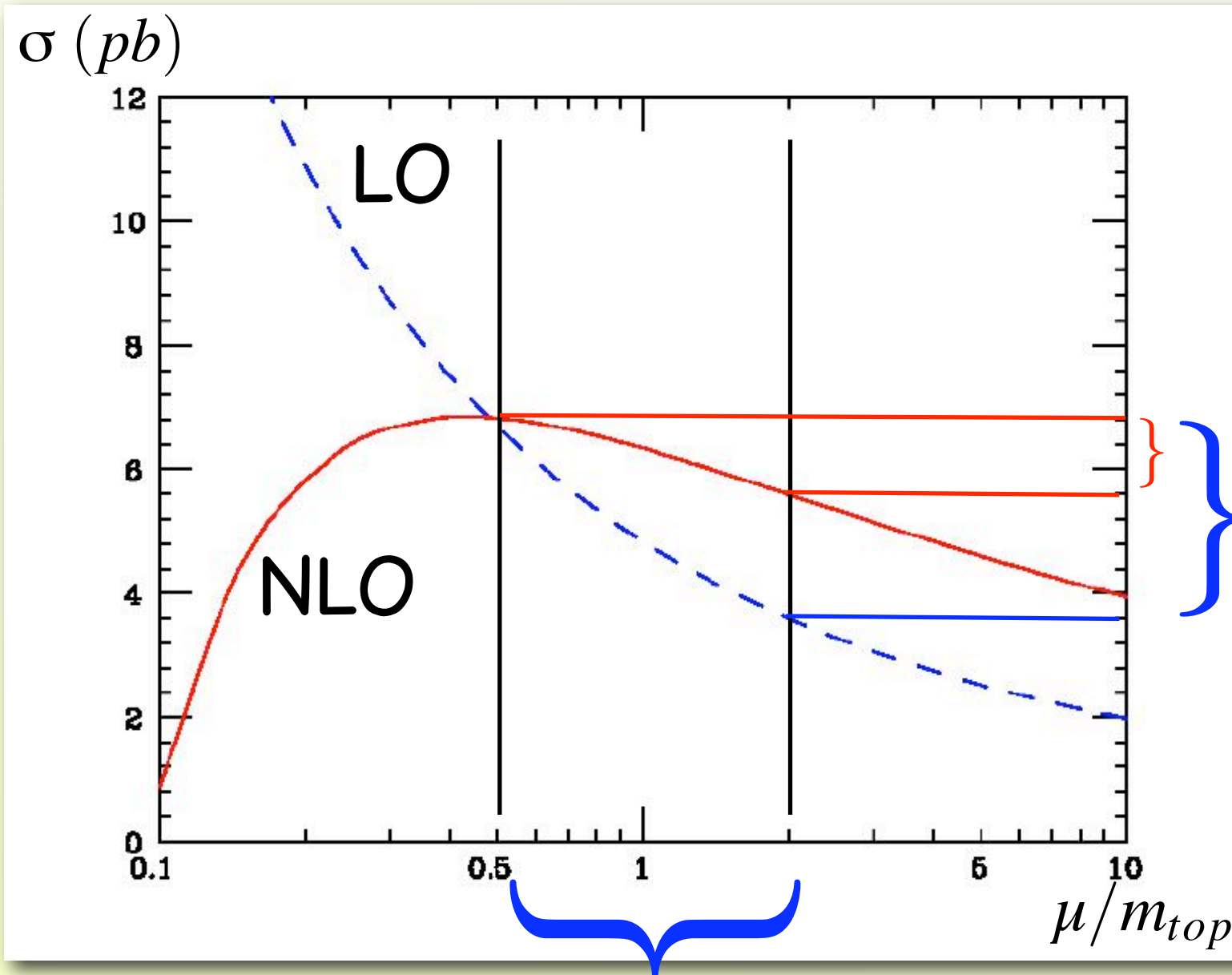


“Reasonable” scale variation



# Estimating TH uncertainties

“Typical”  
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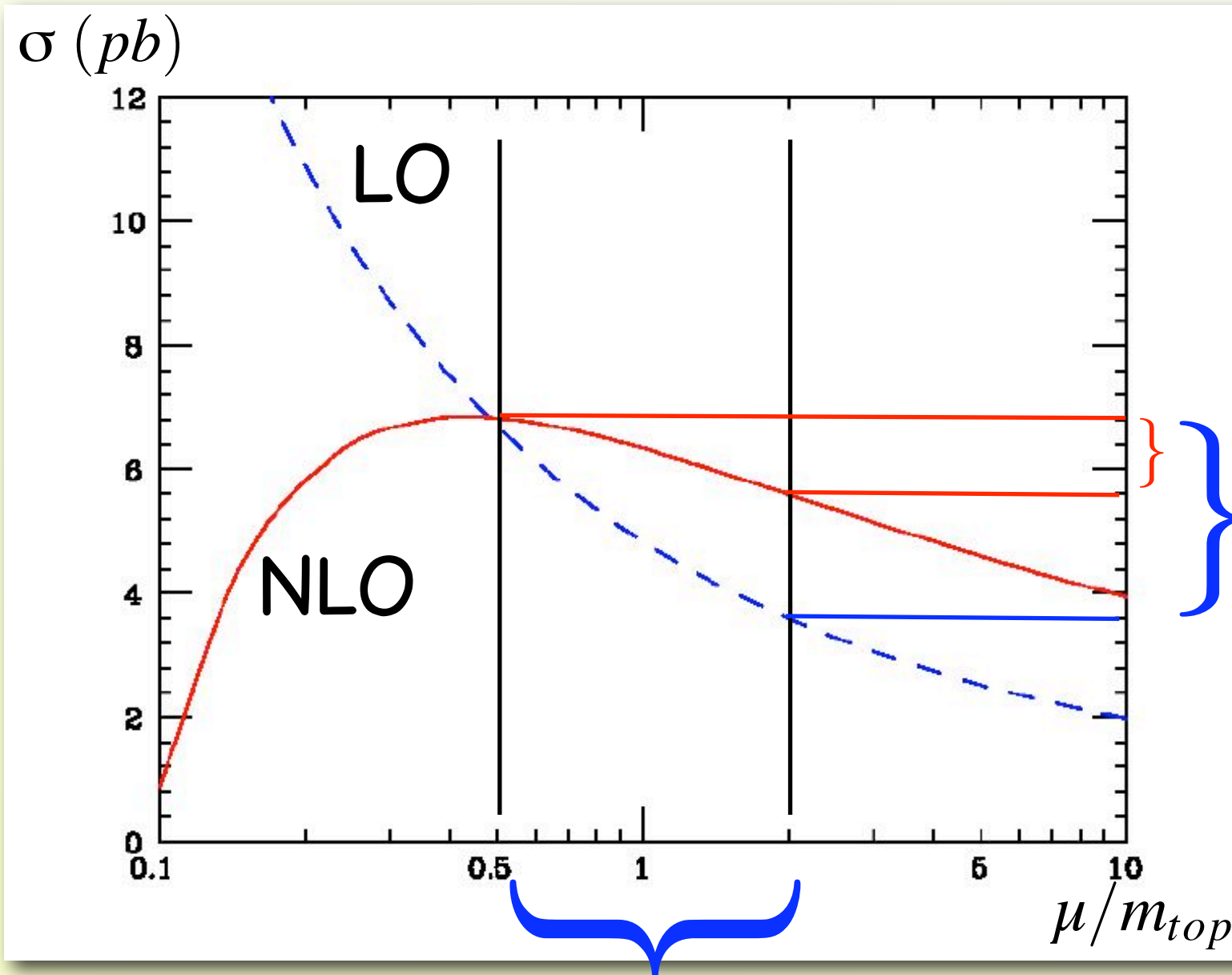


“Reasonable” scale variation

- A **LO** calculation gives you a rough estimate of the cross section

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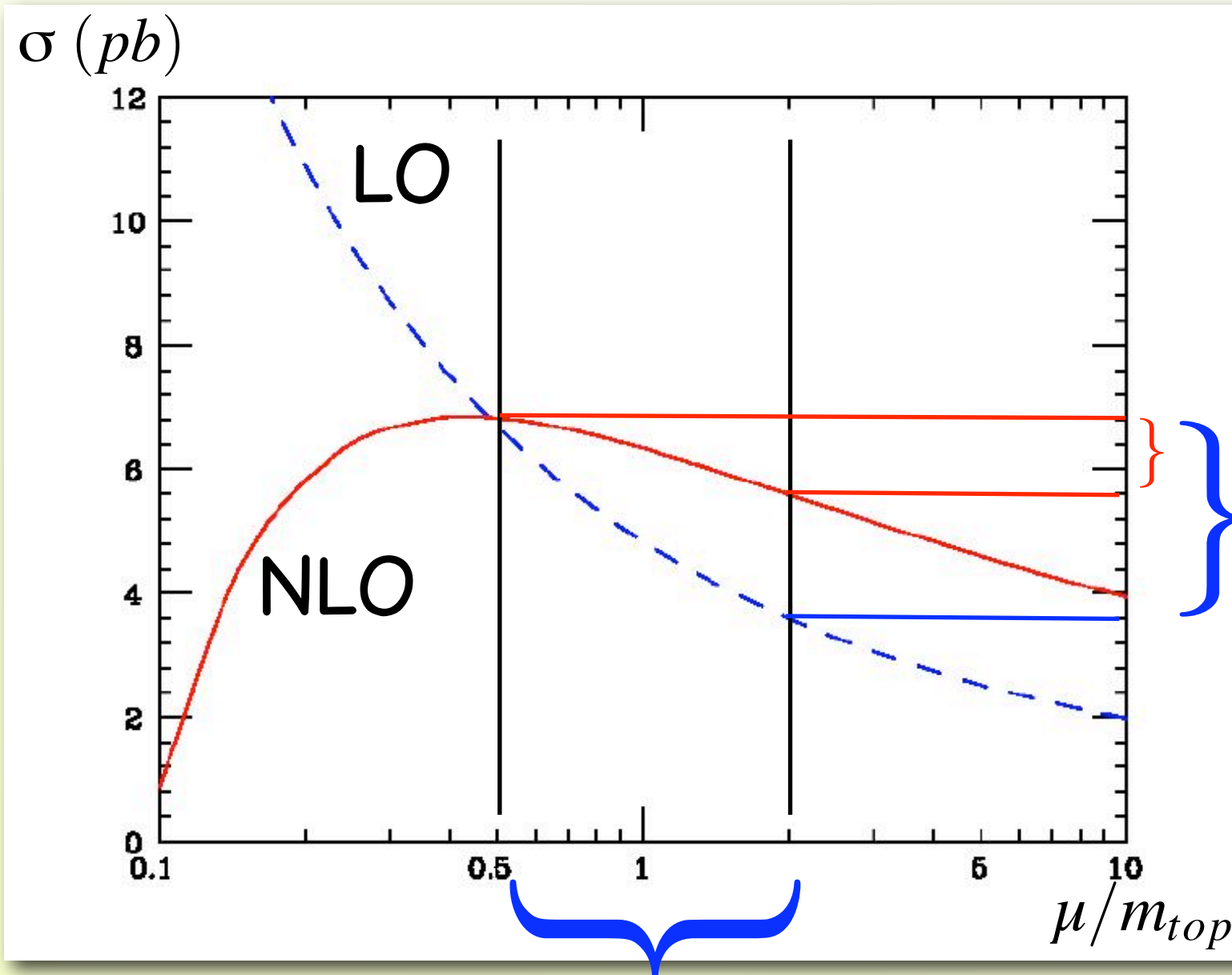


“Reasonable” scale variation

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- A **NLO** calculation gives you a **good estimate** of the cross section and a **rough estimate** of the uncertainty

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“Reasonable” scale variation

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- A **NLO** calculation gives you a **good estimate** of the cross section and a **rough estimate** of the uncertainty
- A **NNLO** calculation gives you a **good estimate** of the uncertainty



# Something to remember well

Calling a code “a NLO code” is an abuse of language and can be confusing.

A NLO calculation always refers to **an IR-safe observable**.

An NLO code will, in general, be able to produce results for several quantities and distributions, only some of which will be at NLO accuracy.



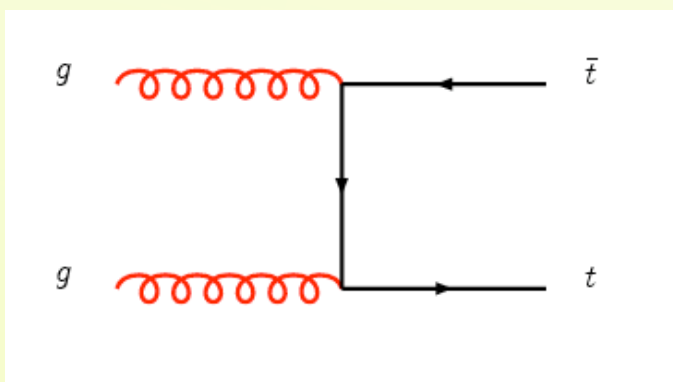
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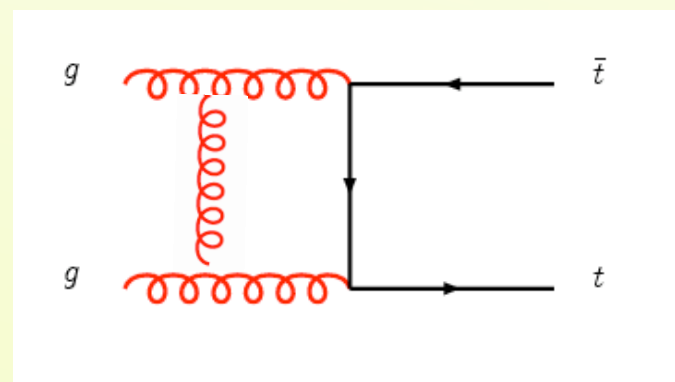
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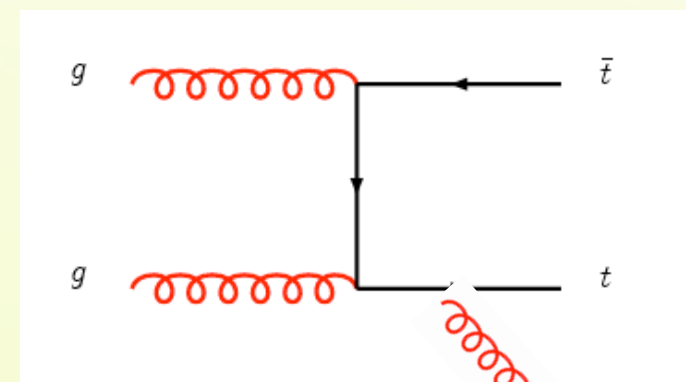
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LO



Virt



Real

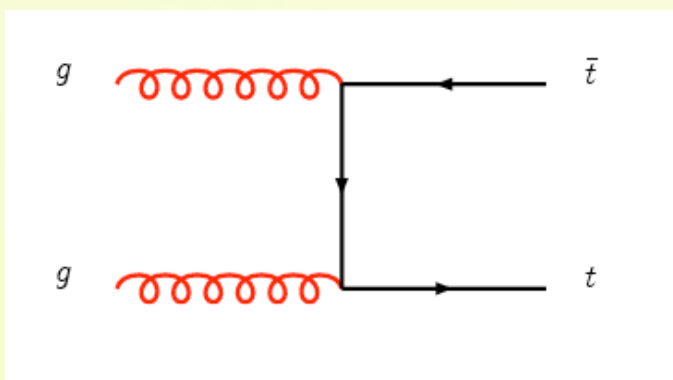
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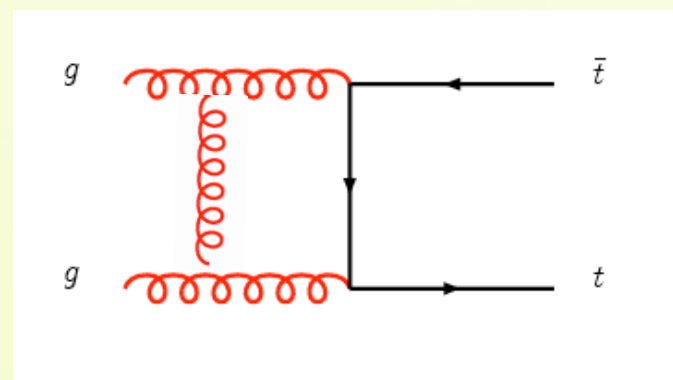
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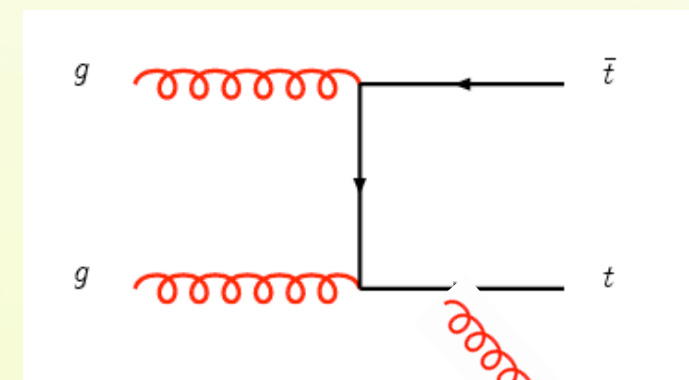
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- ☞  $P_T$  of the jet
- ☞  $t\bar{t}$  invariant mass,  $m(t\bar{t})$
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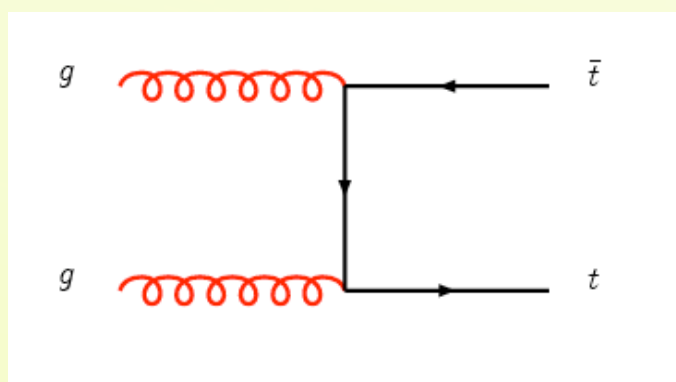
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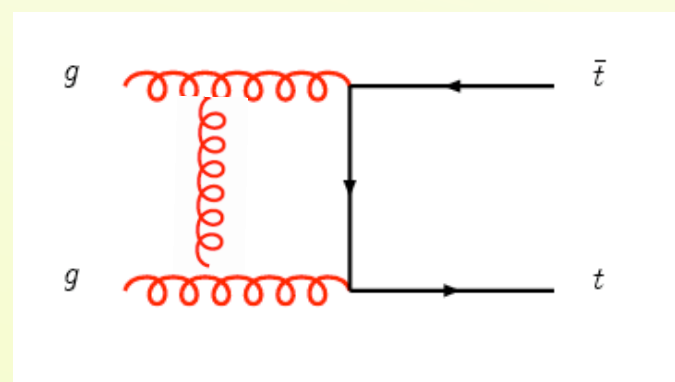
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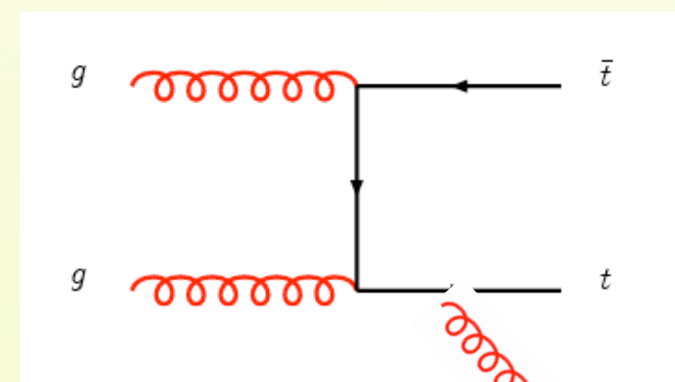
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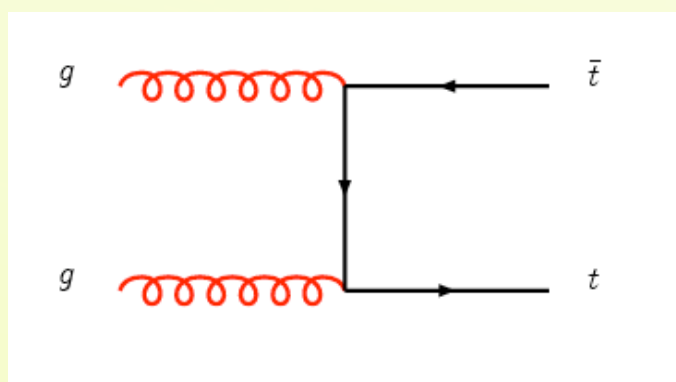
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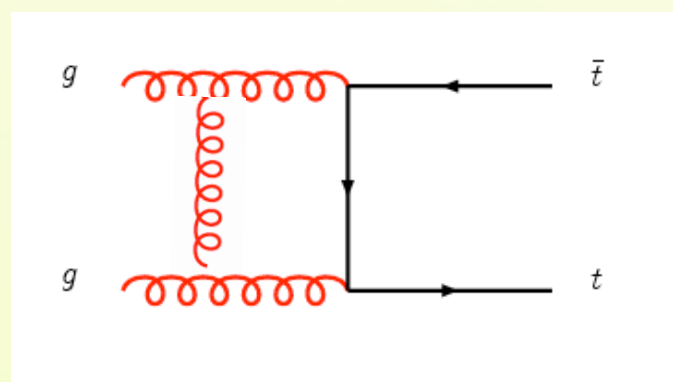
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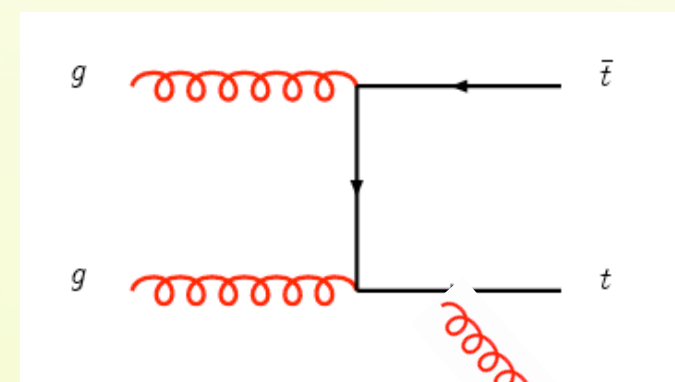
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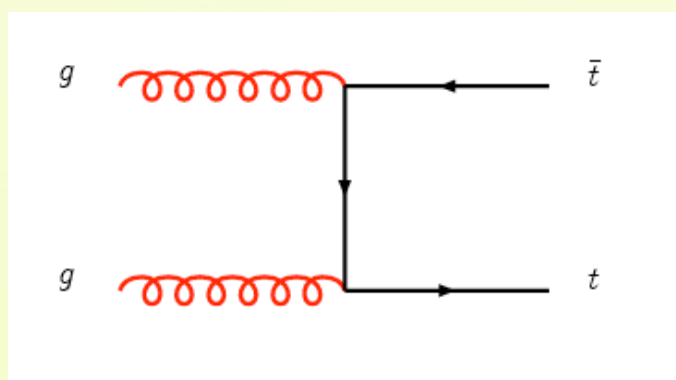
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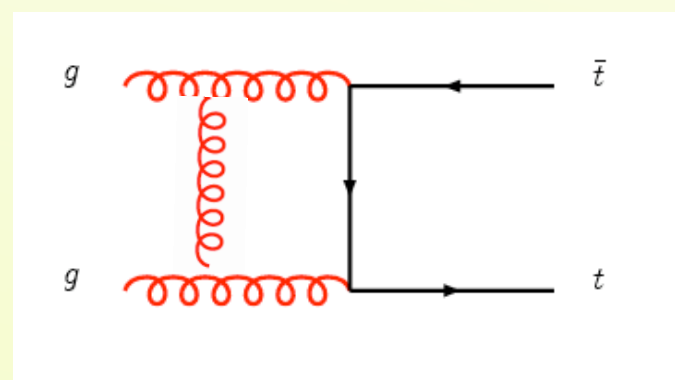
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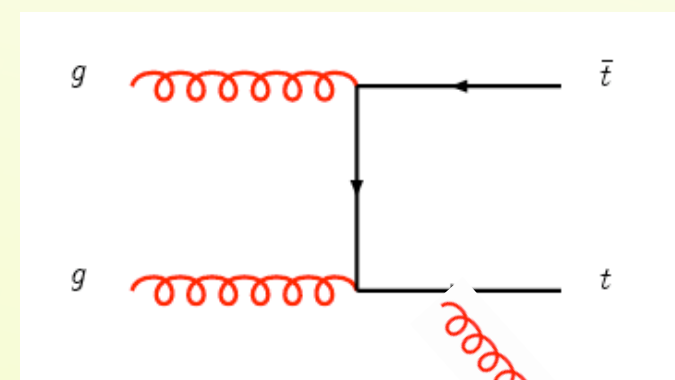
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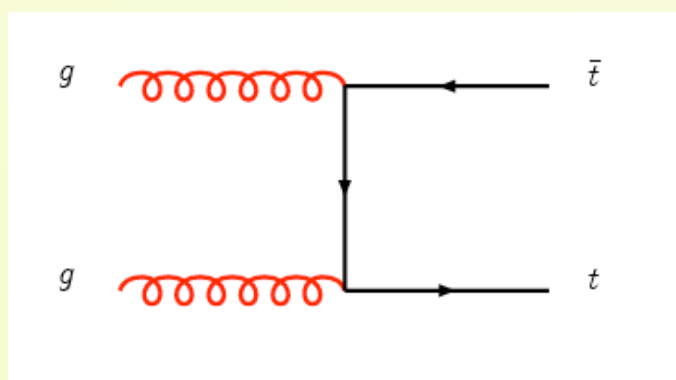
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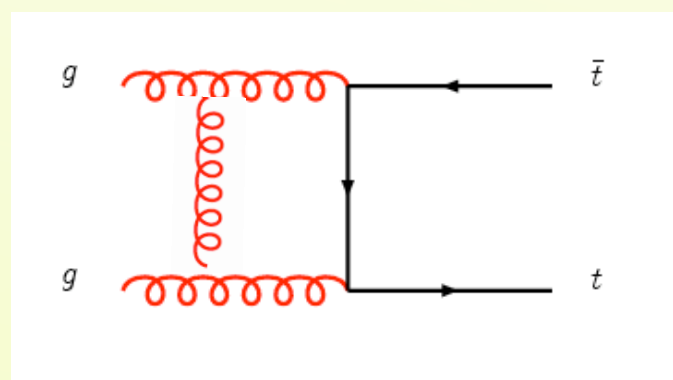
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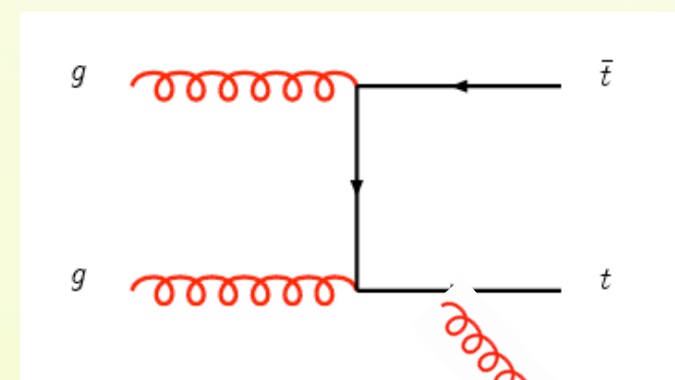
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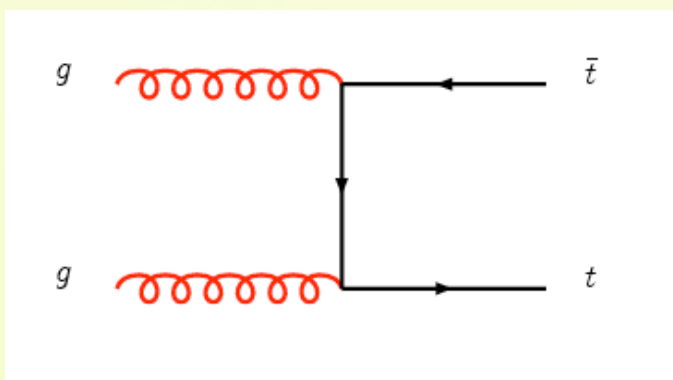
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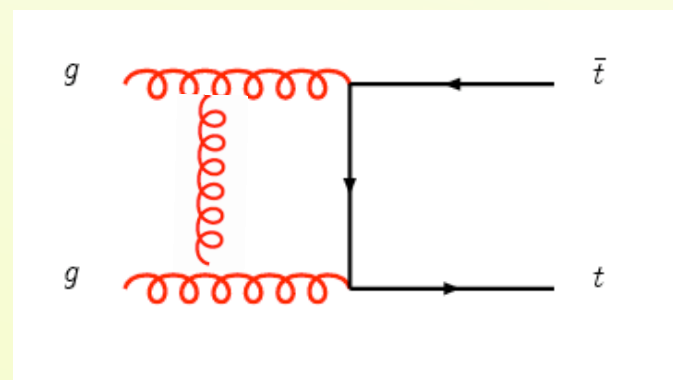
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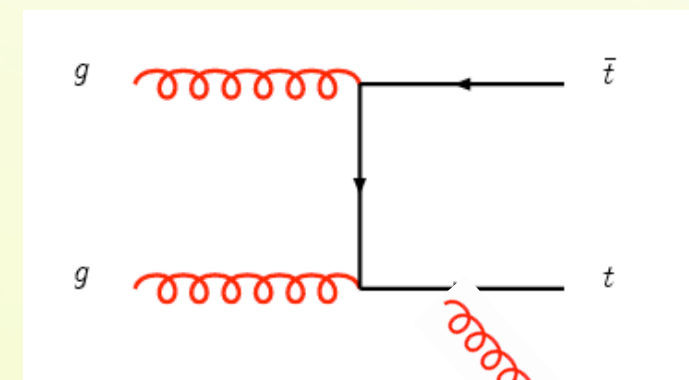
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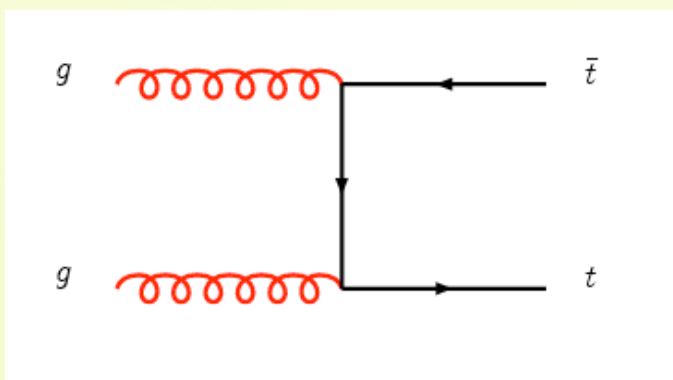
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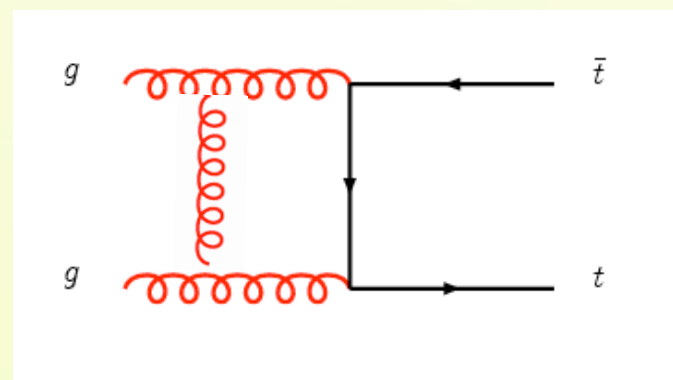
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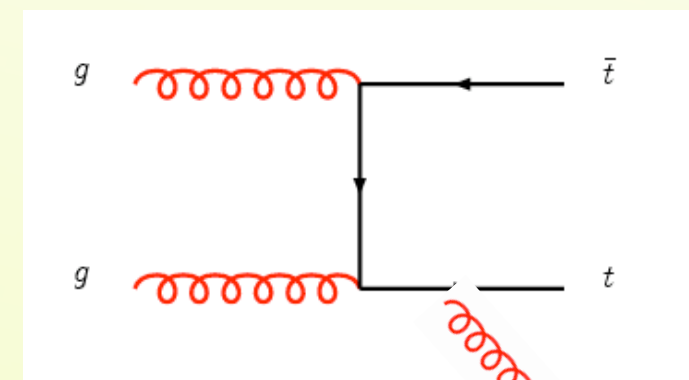
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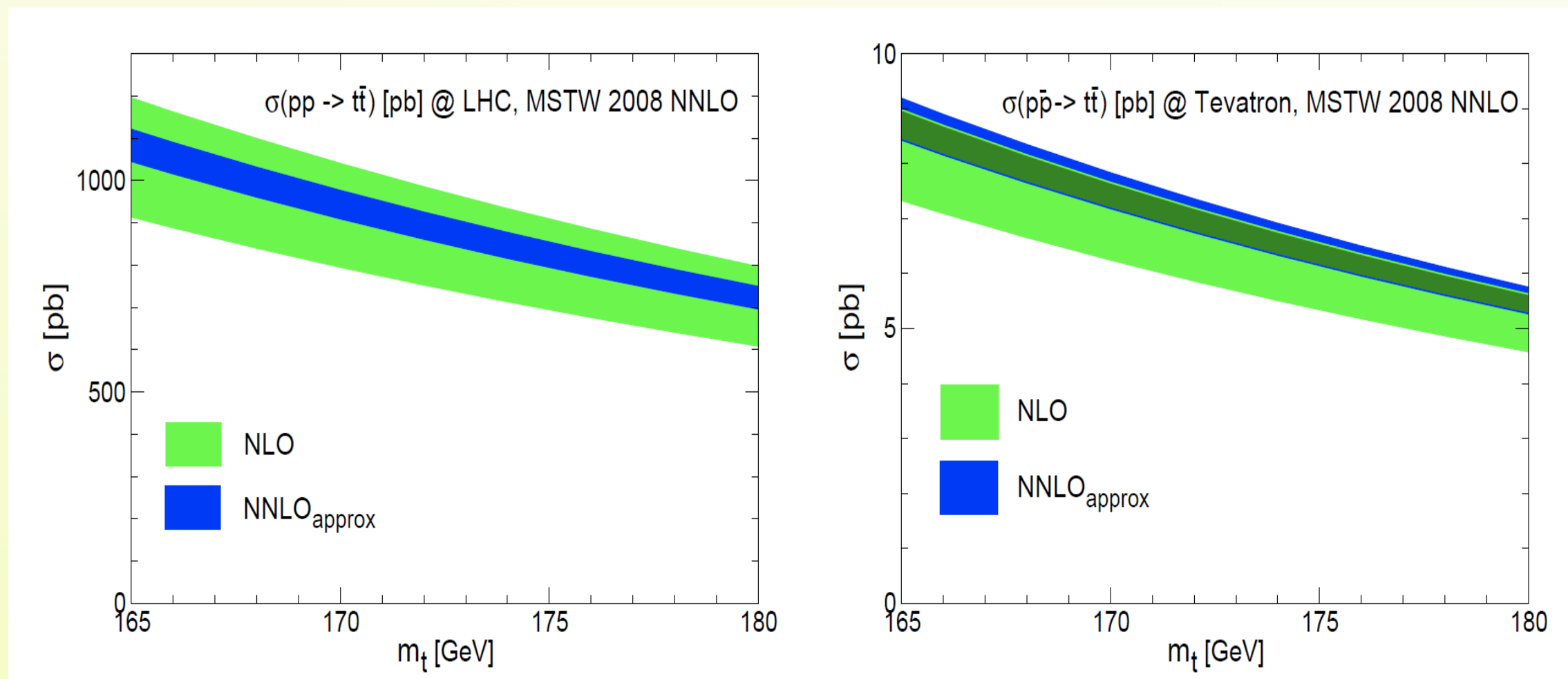


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# Top @ LHC vs Tevatron



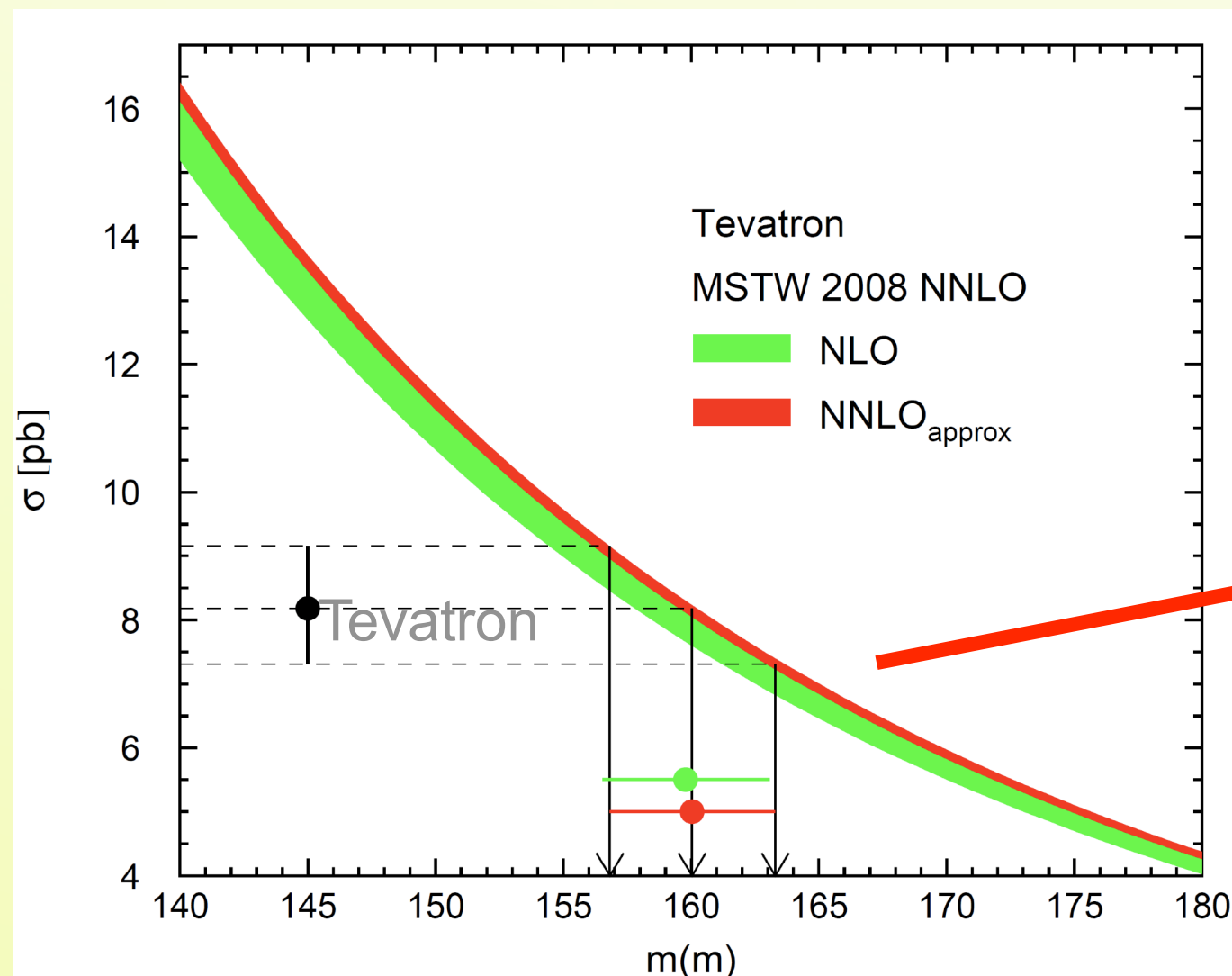
[Moch,Langenfeld,Uwer '08,'09]

The inclusion of leading terms that appear at NNLO seem to sizeably reduce the errors!

# Measuring $m_t$ (MSBar) from $\sigma_{t\bar{t}}$

[Langenfeld, Moch, Uwer 09]

In fact one can do better by reexpressing the cross section in terms of a short-distance well defined mass.



	$\bar{m}$ [GeV]	$m_t$ [GeV]
LO	$159.2^{+3.5}_{-3.4}$	$159.2^{+3.5}_{-3.4}$
NLO	$159.8^{+3.3}_{-3.3}$	$165.8^{+3.5}_{-3.5}$
NNLO	$160.0^{+3.3}_{-3.2}$	$168.2^{+3.6}_{-3.5}$

$$m_t = 168.9^{+3.5}_{-3.4}$$



# New Physics in $t\bar{t}b\bar{b}$



# Model independent direct search for NP in the $t\bar{t}$ invariant mass

Model independent (bottom-up) strategy for New Physics :

1. Focus on a specific SM observable that is
  - a. naturally sensitive to BSM
  - b. is well-predicted & possibly “background free”
2. Look for deviations.



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2. Look for deviations.

Is this going to work?

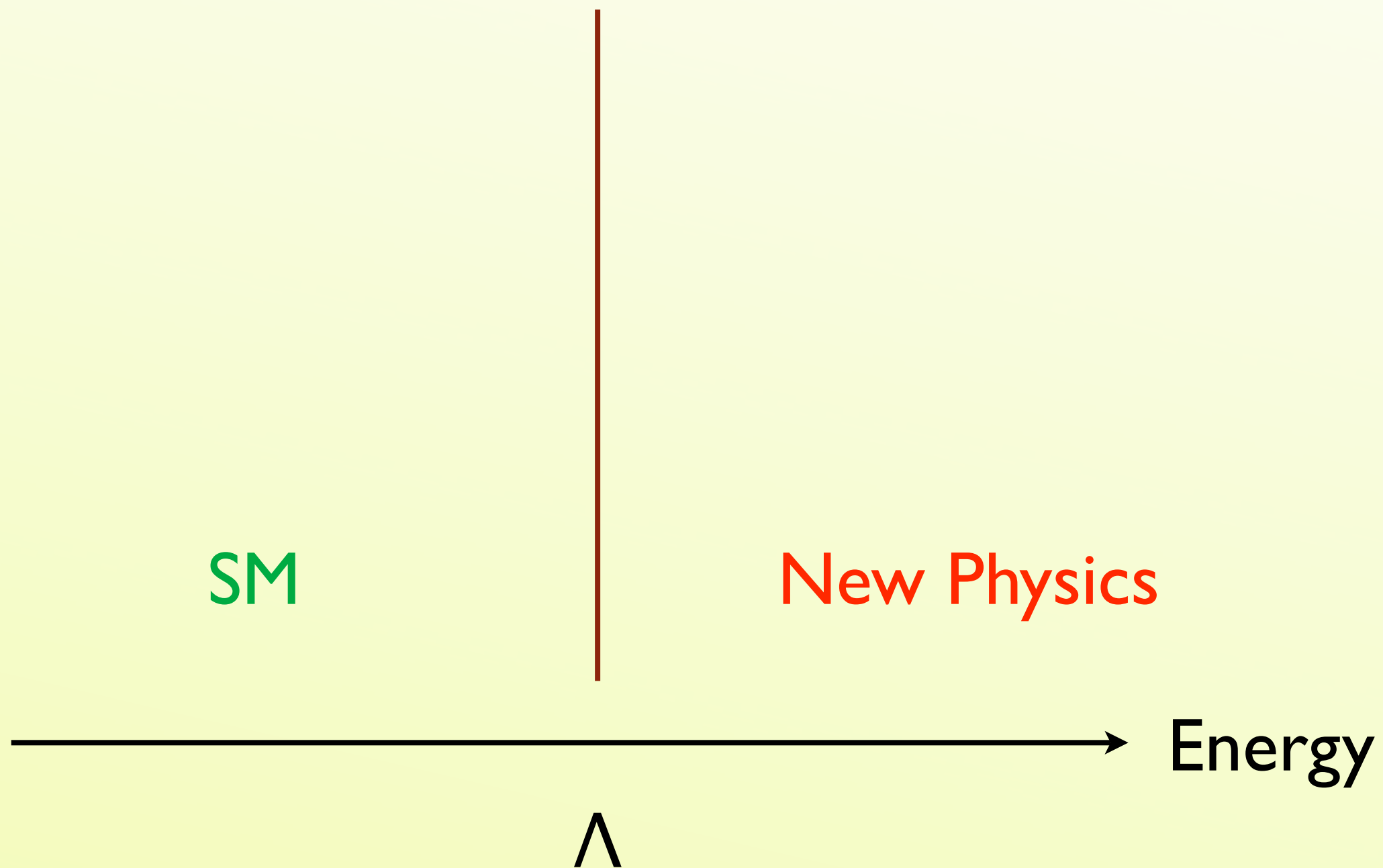
How can we do it?

And, even if we find “deviations”, how do we characterize  
New Physics in a model independent way?





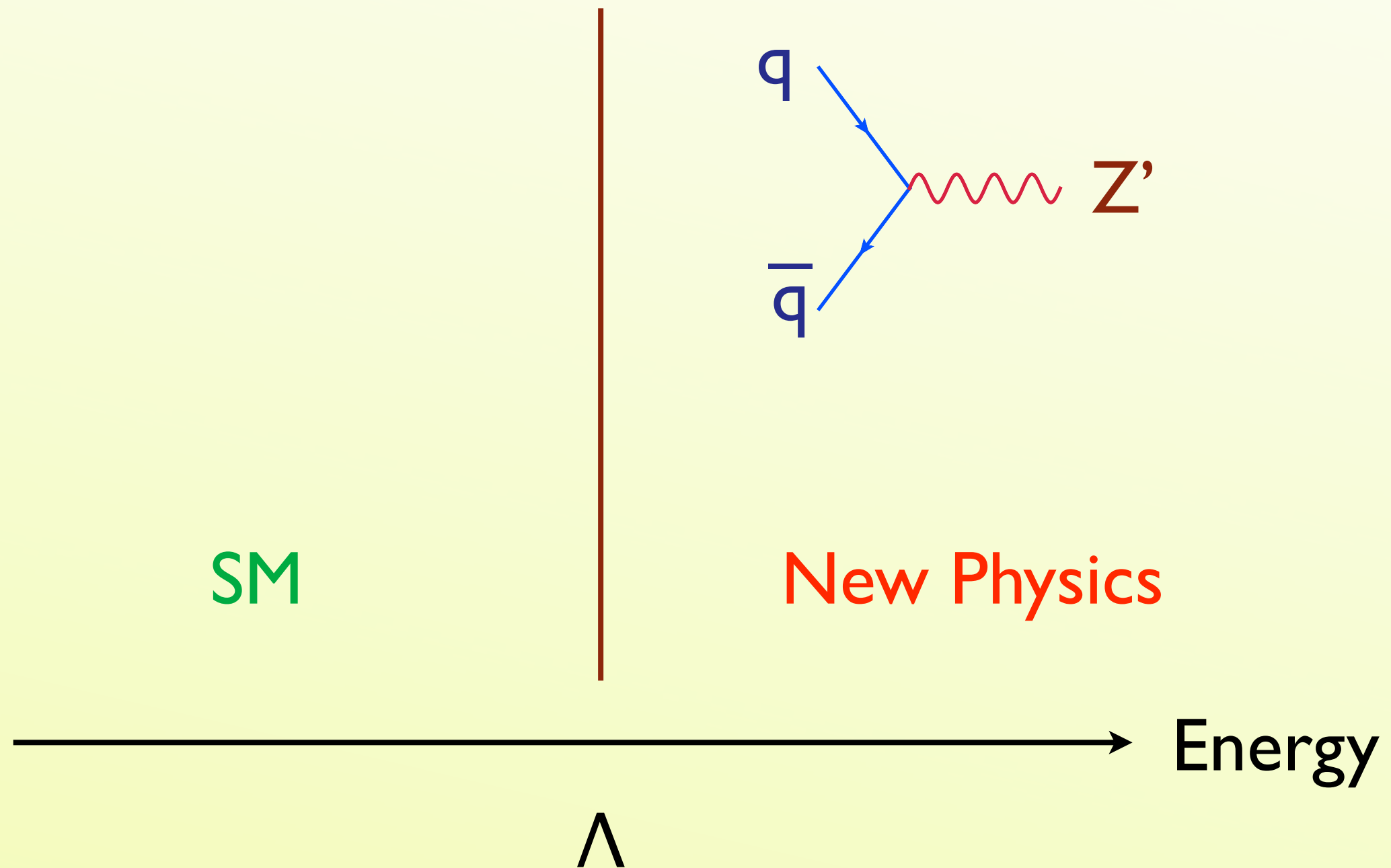
# Two possibilities



[see Willenbrock's talk at top2010]

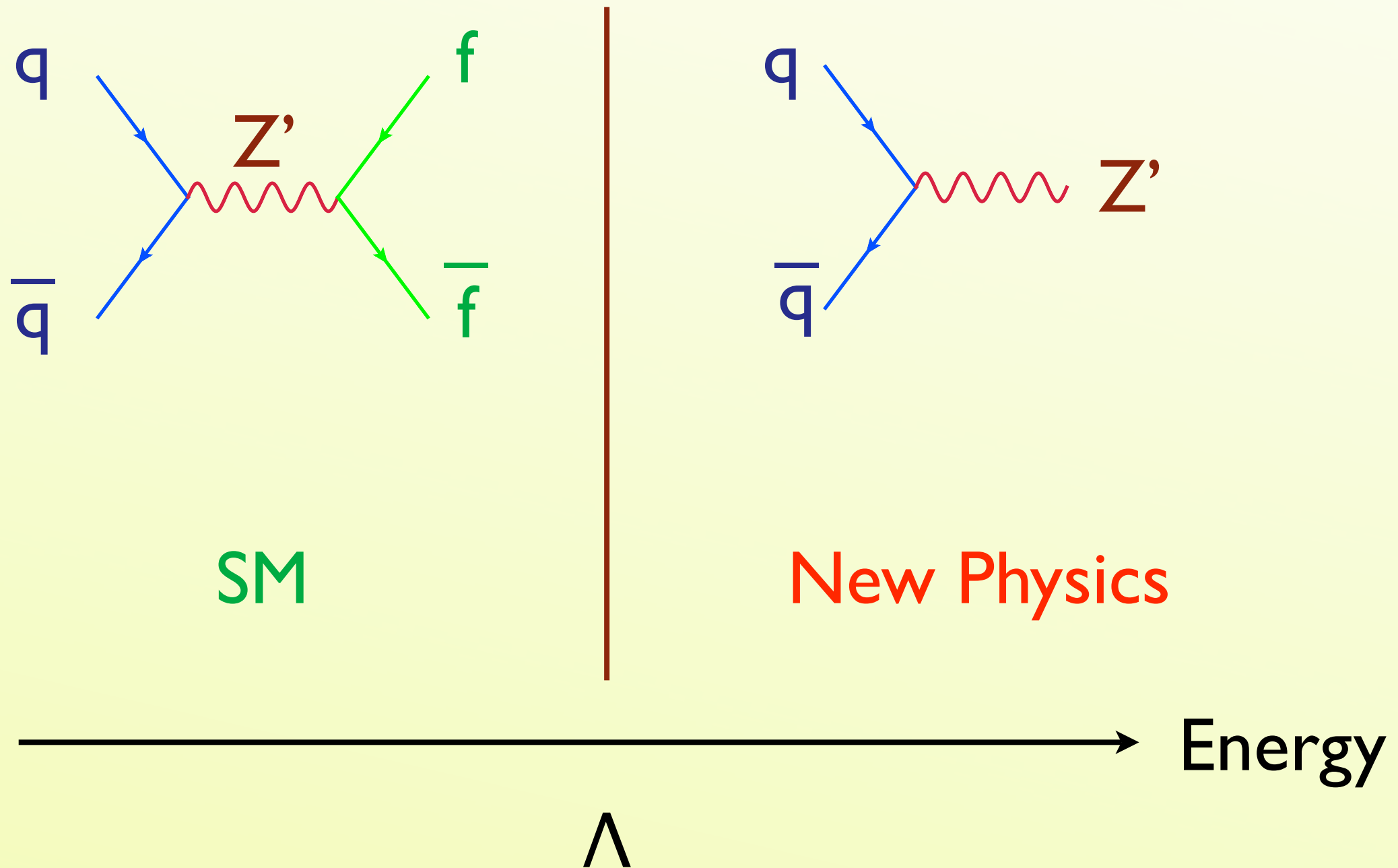


## Example : $Z'$



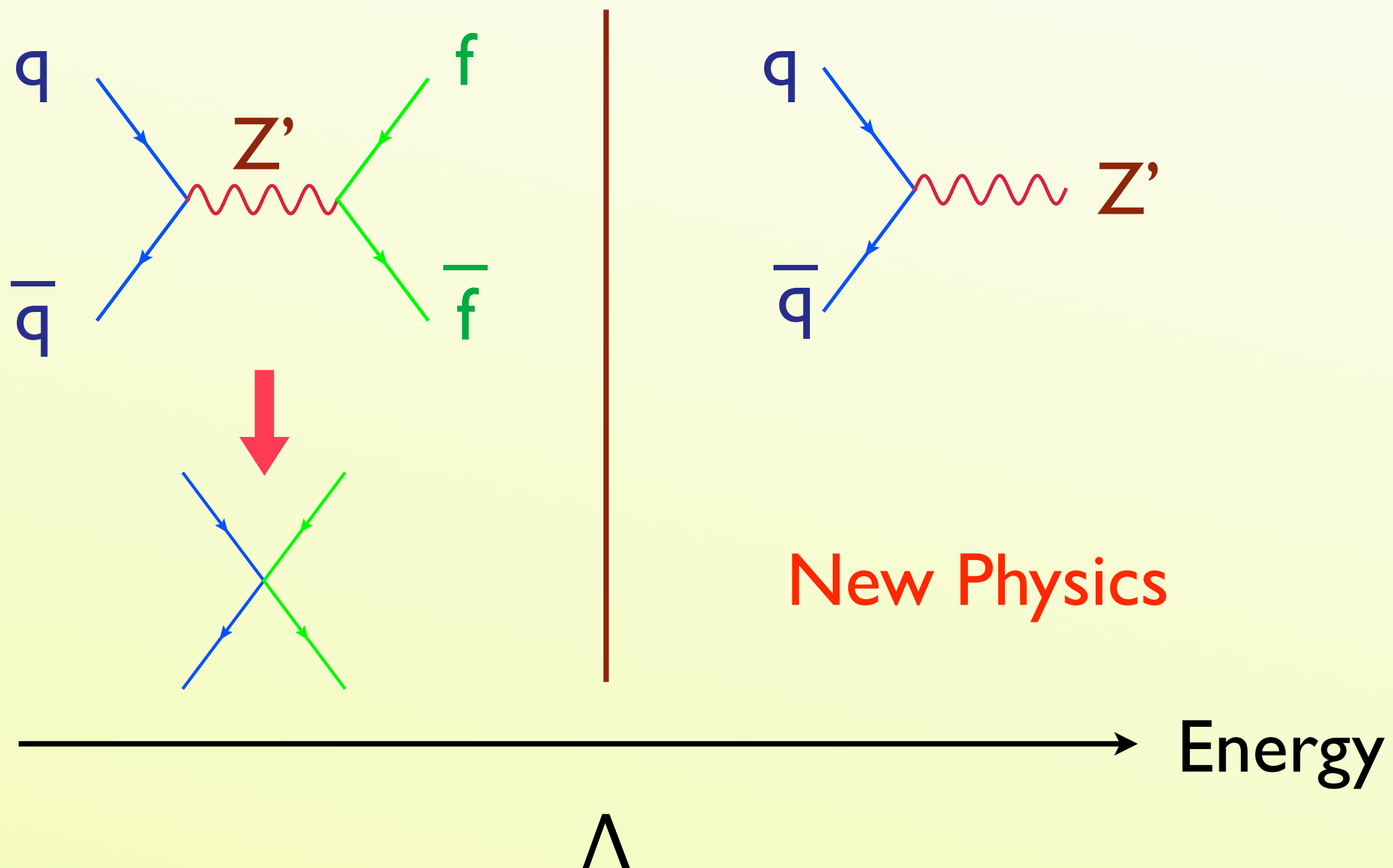


## Example : $Z'$



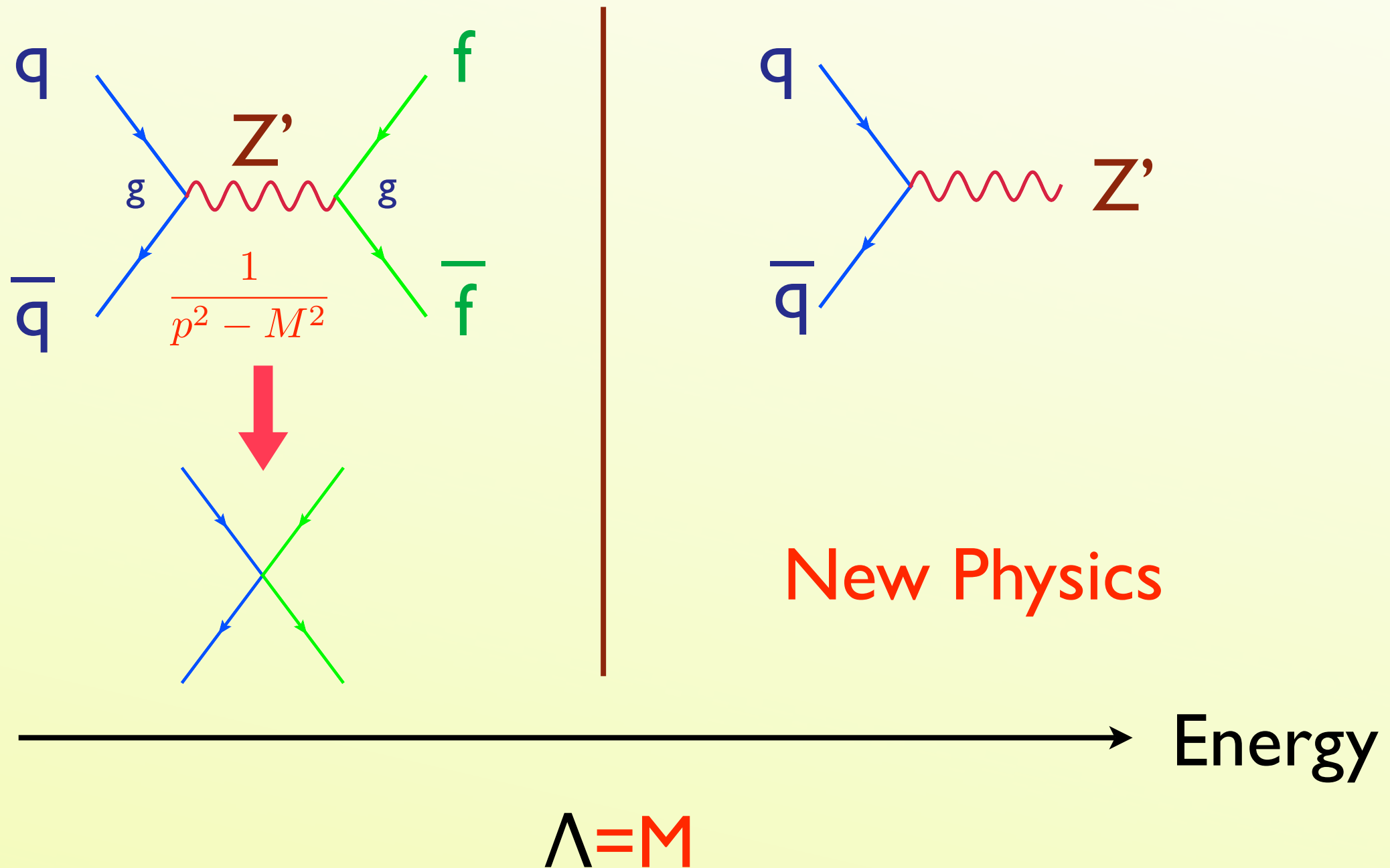


## Example : $Z'$





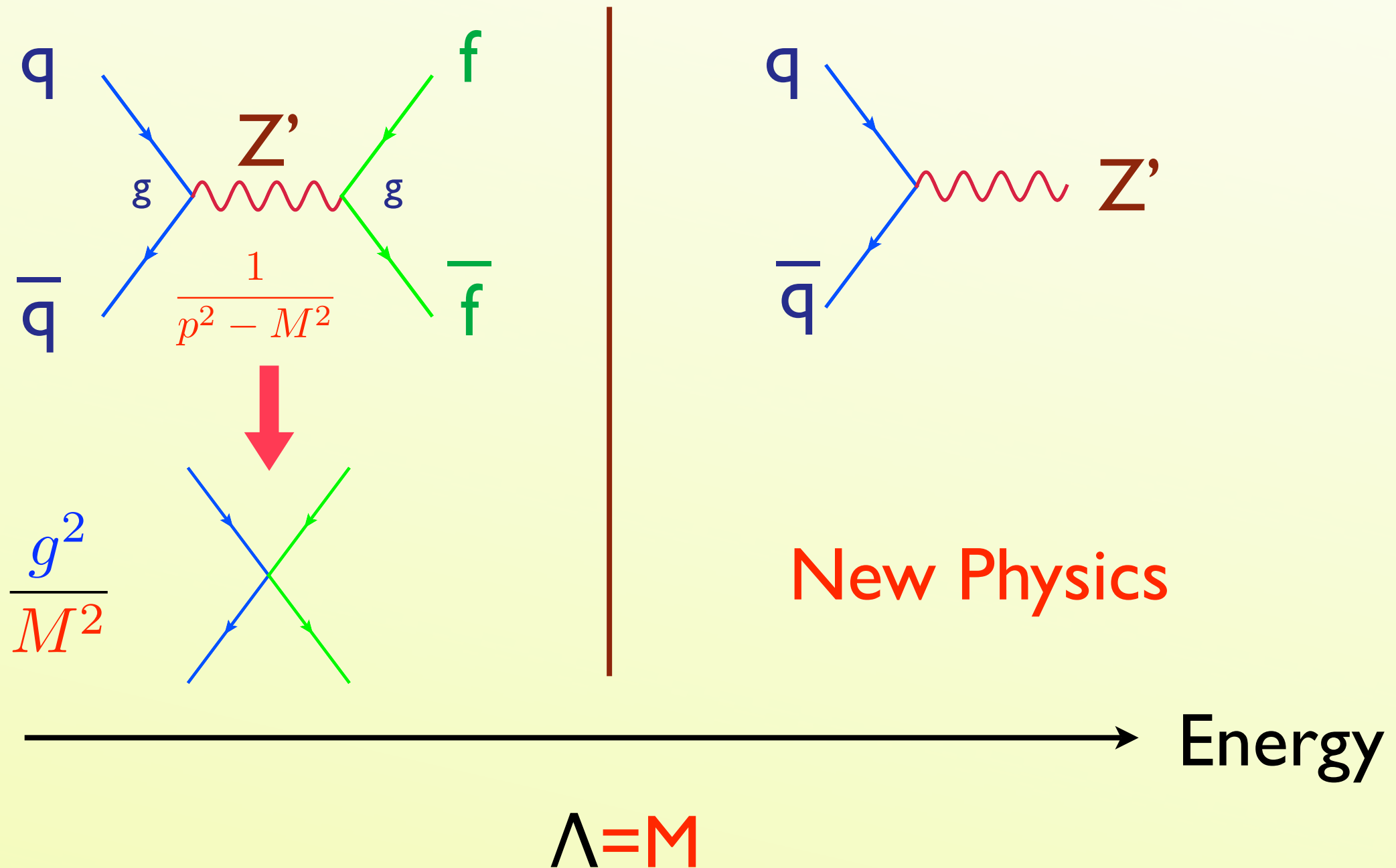
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## Example : $Z'$



## Example : $Z'$

$$\frac{g^2}{M^2} \begin{array}{c} \text{---} \text{blue} \text{---} \\ \text{---} \text{green} \text{---} \\ \text{---} \text{blue} \text{---} \\ \text{---} \text{green} \text{---} \end{array}$$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{g^2}{M^2} \bar{\psi} \psi \bar{\psi} \psi$$



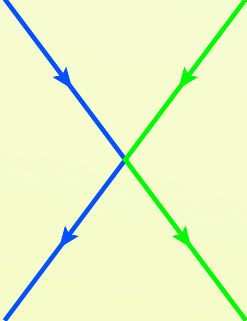
# Dimensional analysis

$$\hbar = c = 1$$

$$\dim A^\mu = 1$$

$$\dim \phi = 1$$

$$\dim \psi = 3/2$$

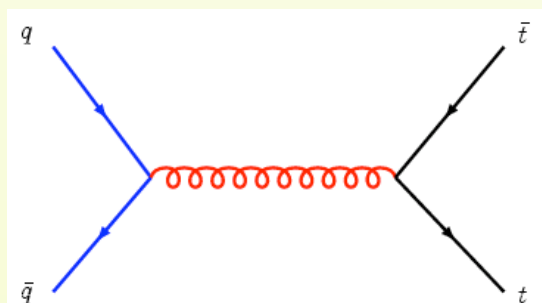
$$\frac{g^2}{M^2}$$


$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{\dim=6}$$

**Bad News:**  $> 60$  operators [Buchmuller, Wyler, 1986]

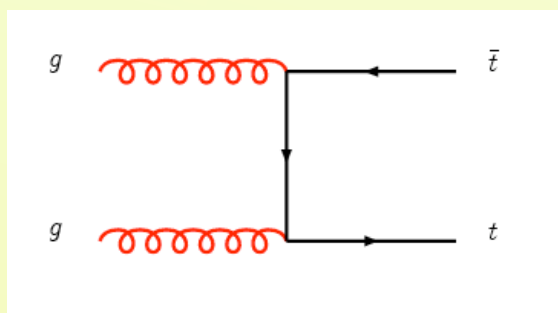
**Good News :** an handful are unconstrained and can significantly contribute to top physics!

# Is there anything to learn from a $\sigma_{t\bar{t}}$ measurement at the LHC?

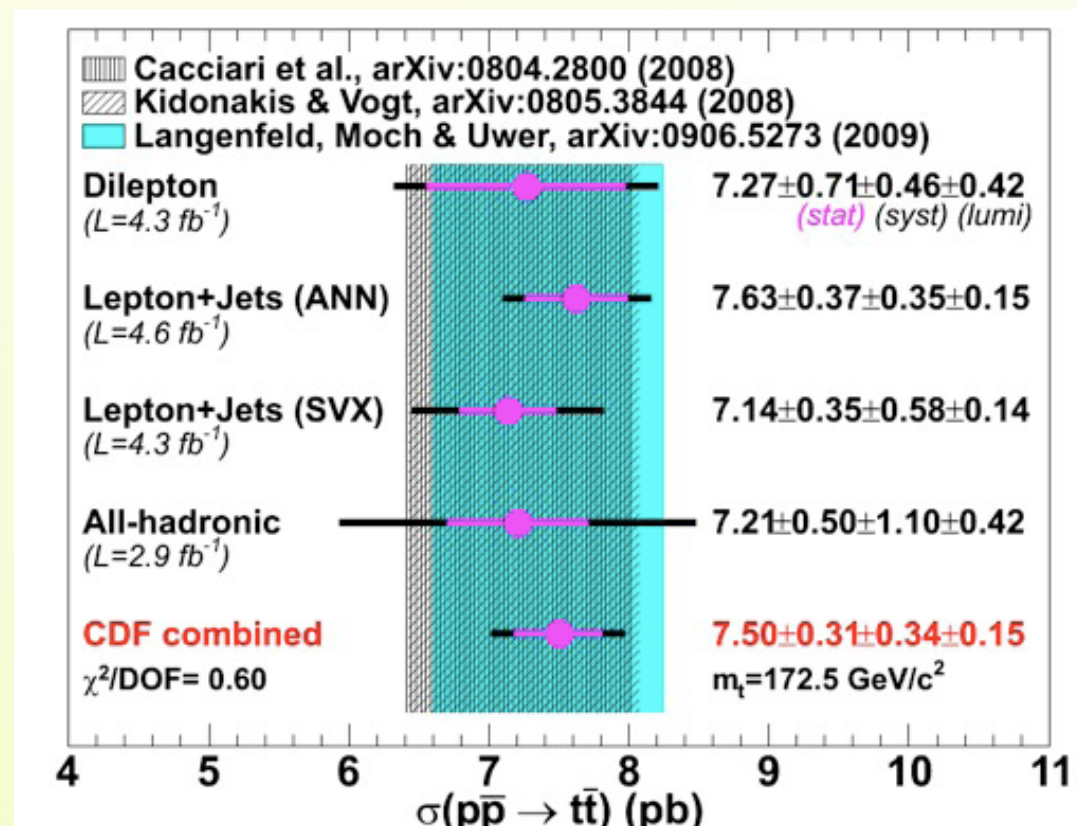


85% at TeV

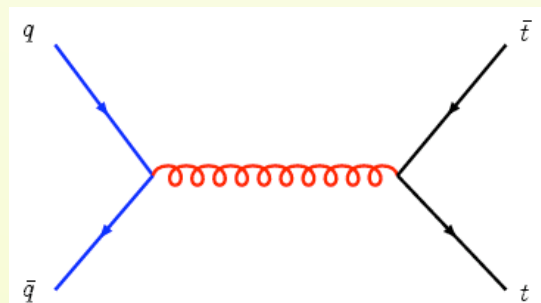
VS



90% at LHC

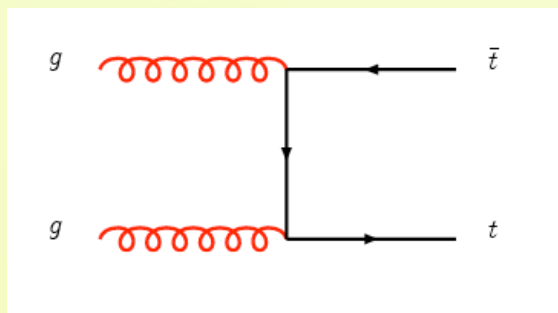


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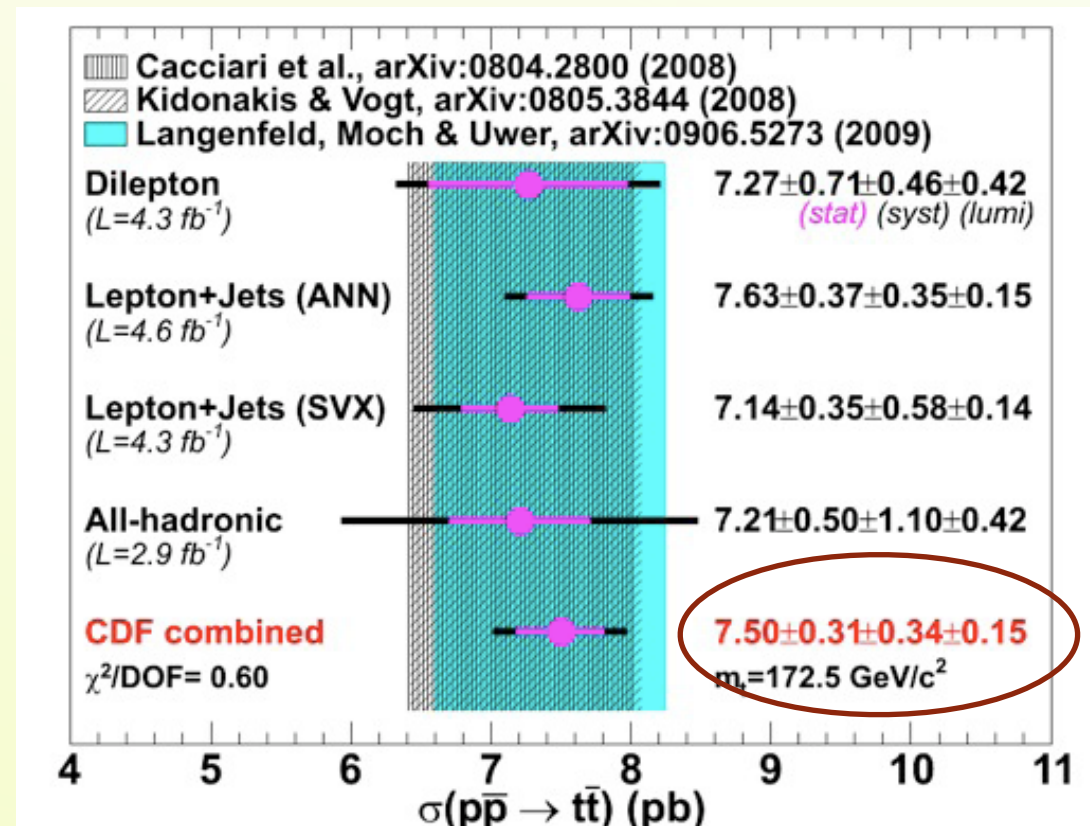


85% at TeV

VS



90% at LHC



The gg channel is only very roughly constrained!!!  
We might have missed some big and important NP effect connected with an gg initial state (such a scalar...).

How can we study such effects in a model independent way?





# Simple model independent analysis of NP in $\sigma_{t\bar{t}}$

[Willenbrock et al., wip, Degrande et al, wip]

Use an effective Lagrangian approach:

- Write down all the dominant (dim=6) operators involving a  $t$  and  $t\bar{t}$ .
- Use symmetries (like custodial symmetry) or well known constraints (such those on FCNC  $\Rightarrow$  MFV) to reduce the number of possibly important operators.
- Use, if you want, inspirations or scalings suggested by some physics models that you like (top compositeness).

You can show that you end up with five main operators,

$$\mathcal{L}_{t\bar{t}} = \mathcal{L}_{t\bar{t}}^{SM} + \frac{1}{\Lambda^2} \left[ g_h \mathcal{O}_{hg} + c_R \mathcal{O}_{Rg} + a_R \mathcal{O}_{Ra}^8 + (R \leftrightarrow L) \right]$$

and in case one is interested only in total rates (and spin independent / FB symmetries)  
only three parameters are left :  $g_h$  ,  $c_V = c_R + c_L$  and  $a_A = a_R - a_L$

# Simple model independent analysis of NP in $\sigma_{t\bar{t}}$

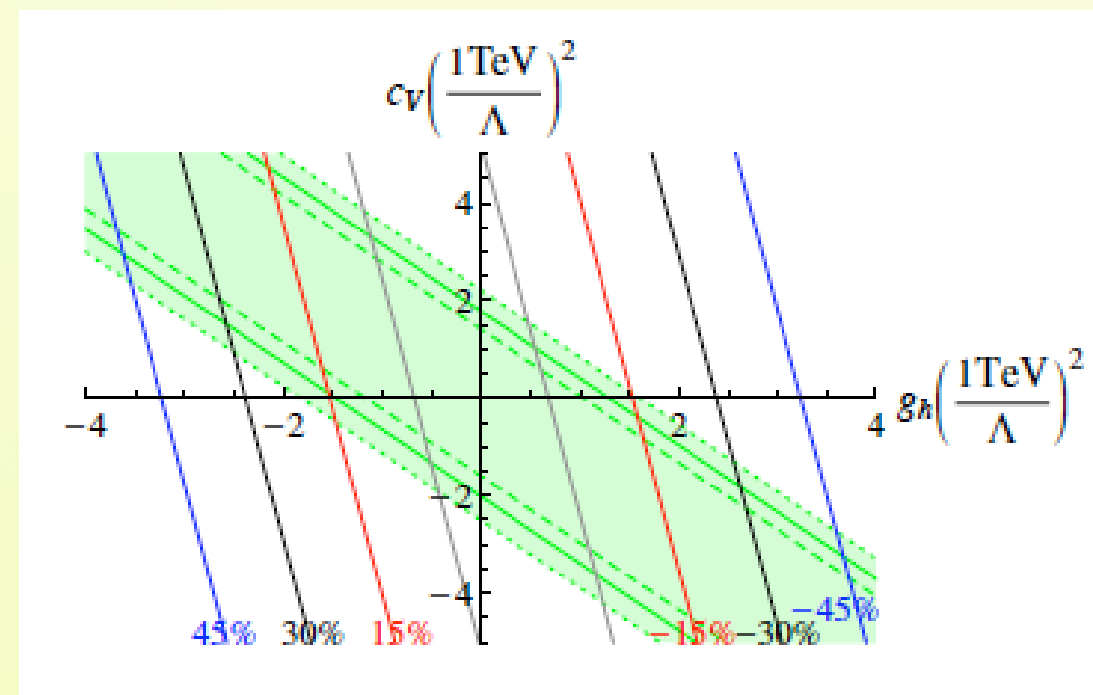
$$|M|^2 = |M_{SM}|^2 + 2\Re(M_{SM}M_{NP}^*) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

$$\frac{d\sigma}{dt}(q\bar{q} \rightarrow t\bar{t}) = \frac{d\sigma_{SM}}{dt} \left(1 - \frac{\Re c_V}{g_s} \frac{s}{\Lambda^2}\right) + \frac{1}{\Lambda^2} \frac{\alpha_s}{9s^2} \left(a_A(s + 2t - 2m_t^2) - 4g_s \Re g_h \sqrt{2}vm_t\right)$$

$$\frac{d\sigma}{dt}(gg \rightarrow t\bar{t}) = \frac{d\sigma_{SM}}{dt} + \frac{vm_t\alpha_s g_s}{12\sqrt{2}\Lambda^2} \Re g_h \frac{(4s^2 + 9m_t^4 + 9t^2 + 9st - 18m_t^2t - 9m_t^2s)}{s^2(m_t^2 - t)(m_t^2 - s - t)}$$

The effects on the differential cross section at the Tevatron and the LHC are different and dependent on different operators.

Already a pretty rough cross section measurement at the LHC will give important constraints on  $g_h$  !!!

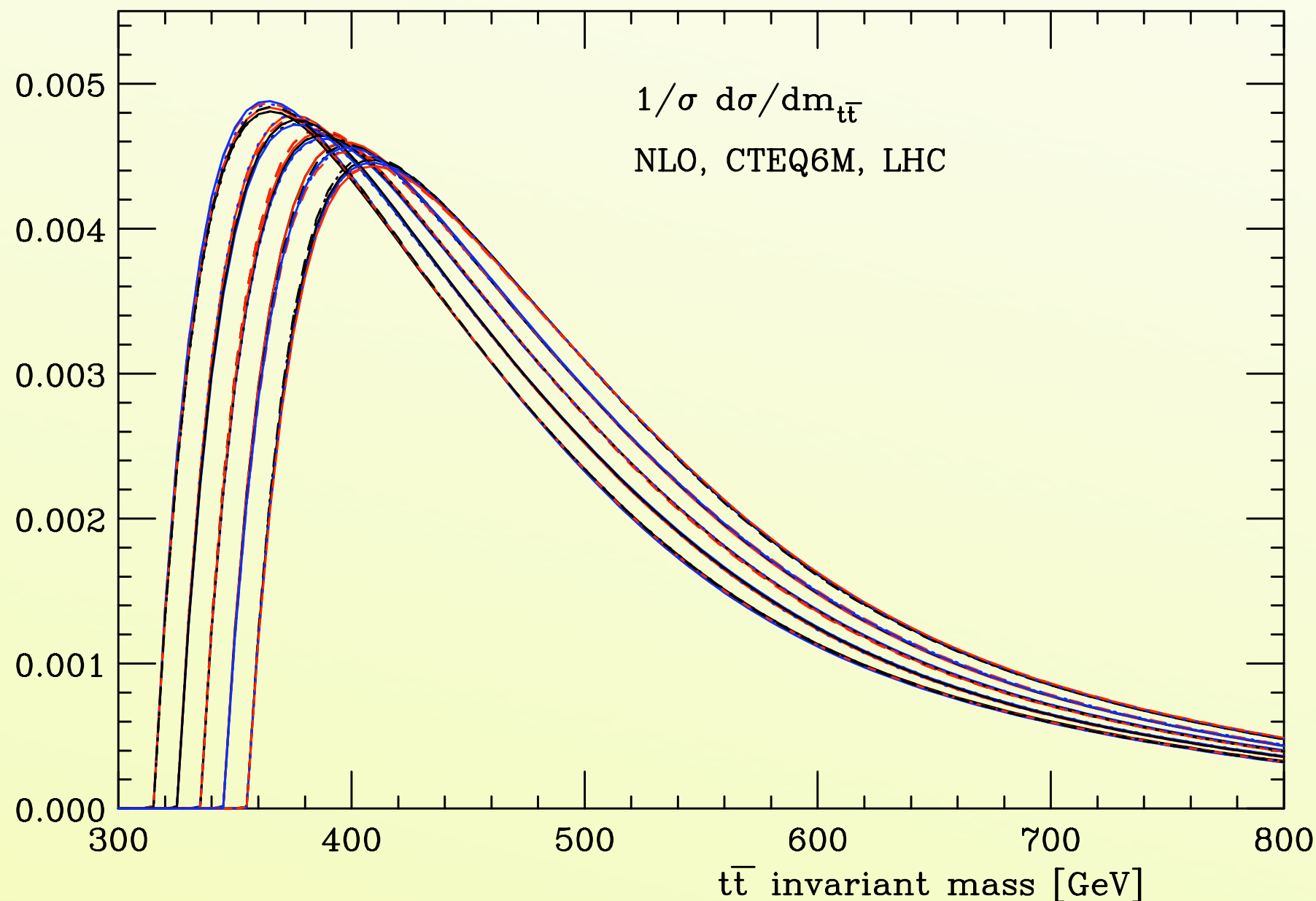




Are there other  
(more exclusive and yet quite accurately predicted)  
observables?



# $d\sigma/dm_{t\bar{t}}$ : shape differences



Interesting observable.

Shape very well predicted.

This could be also used to measure the top mass!

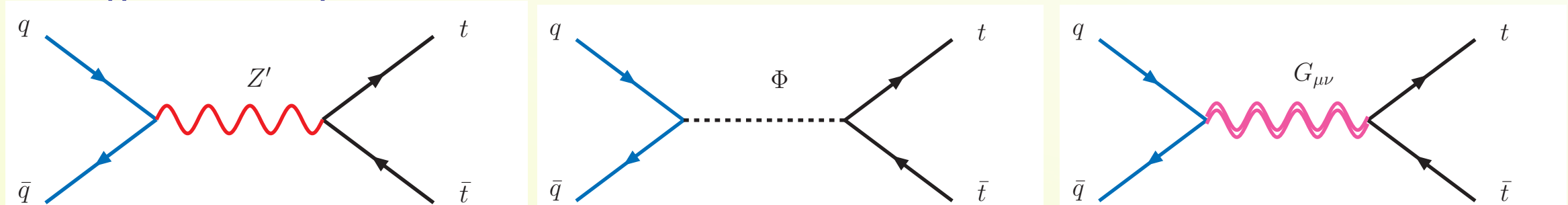
Reconstruction systematics is different from the usual top mass invariant mass reconstruction.

Any BSM effect would distort this shape =>

Model independent search for new Physics!

# New resonances

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

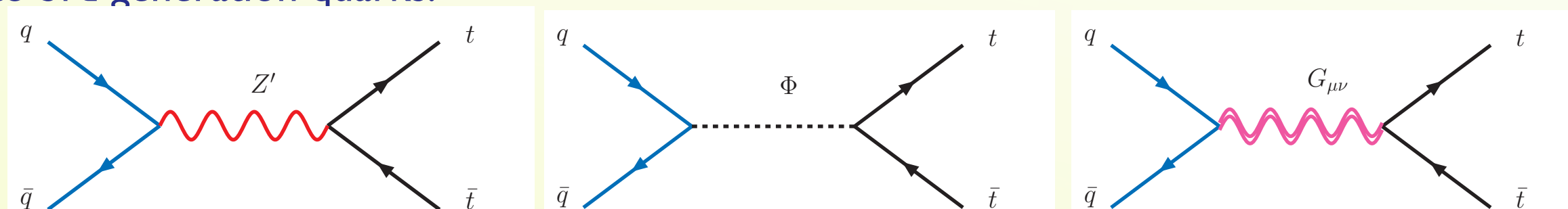


Given the large number of models, in this case is more efficient to adopt a “model independent” search and try to get as much information as possible on the quantum numbers and coupling of the resonance.



# New resonances

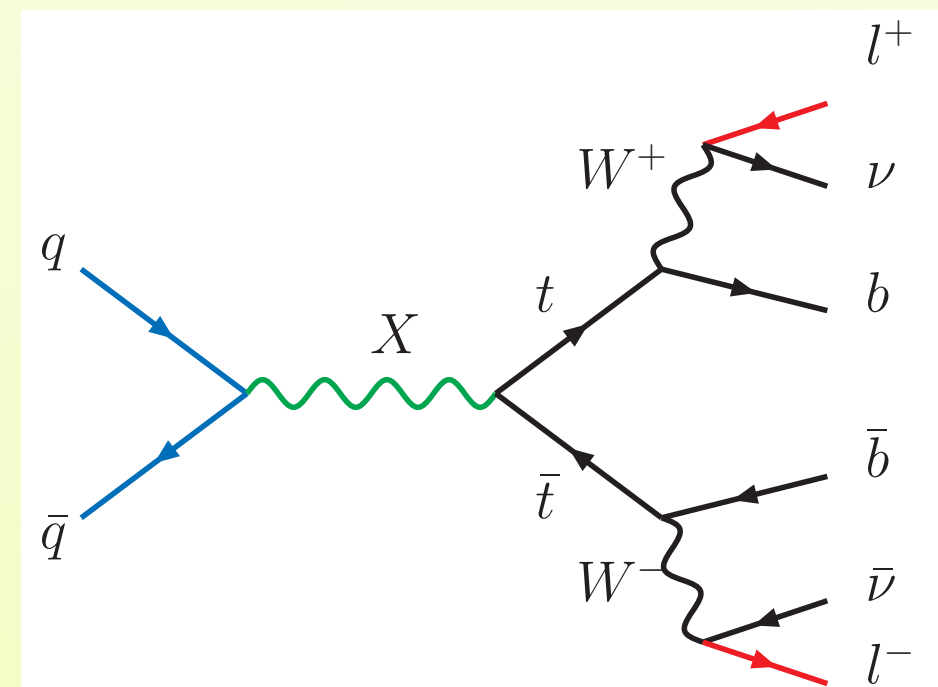
In many scenarios for EWSB new resonances show up, some of which preferably couple to 3rd generation quarks.



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  $pp \rightarrow X \rightarrow t\bar{t} \rightarrow 6f$  is used.

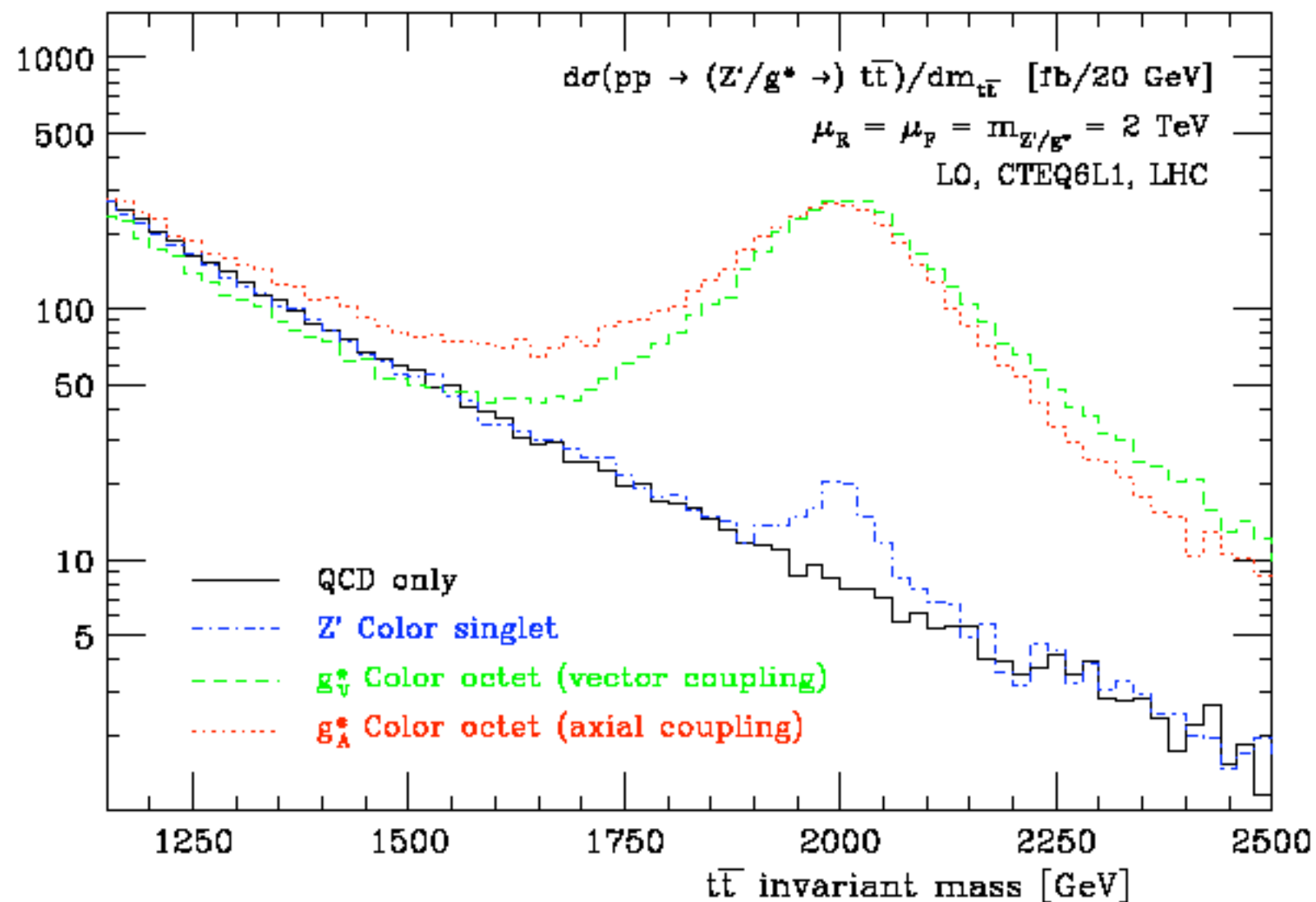




# Zoology of new resonances

Spin	Color	$(I, Y_5)$ [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

# Phase I: discovery



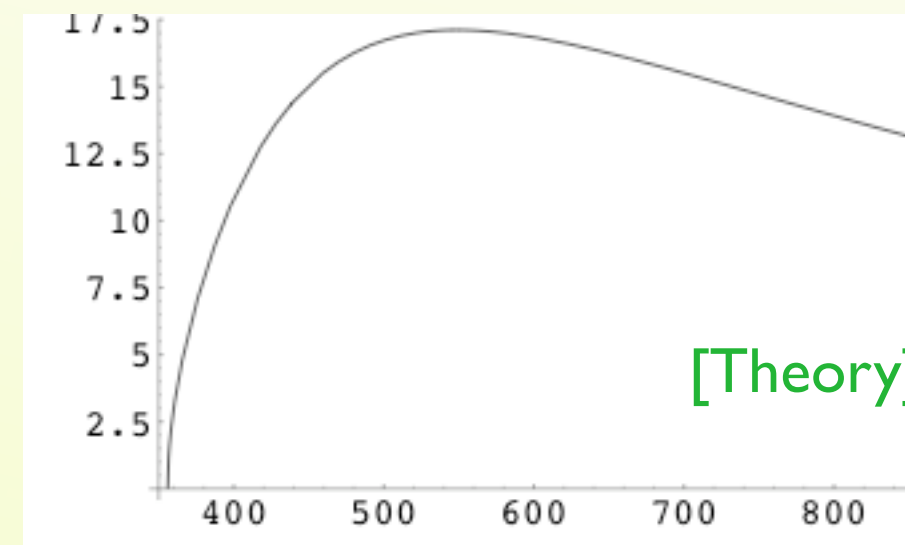
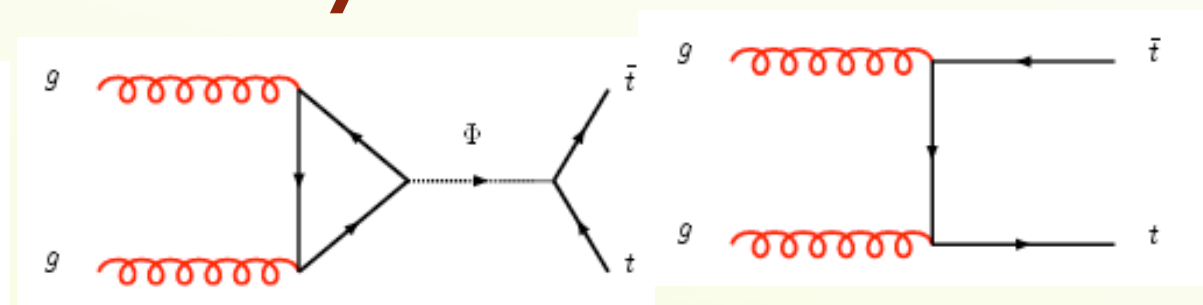
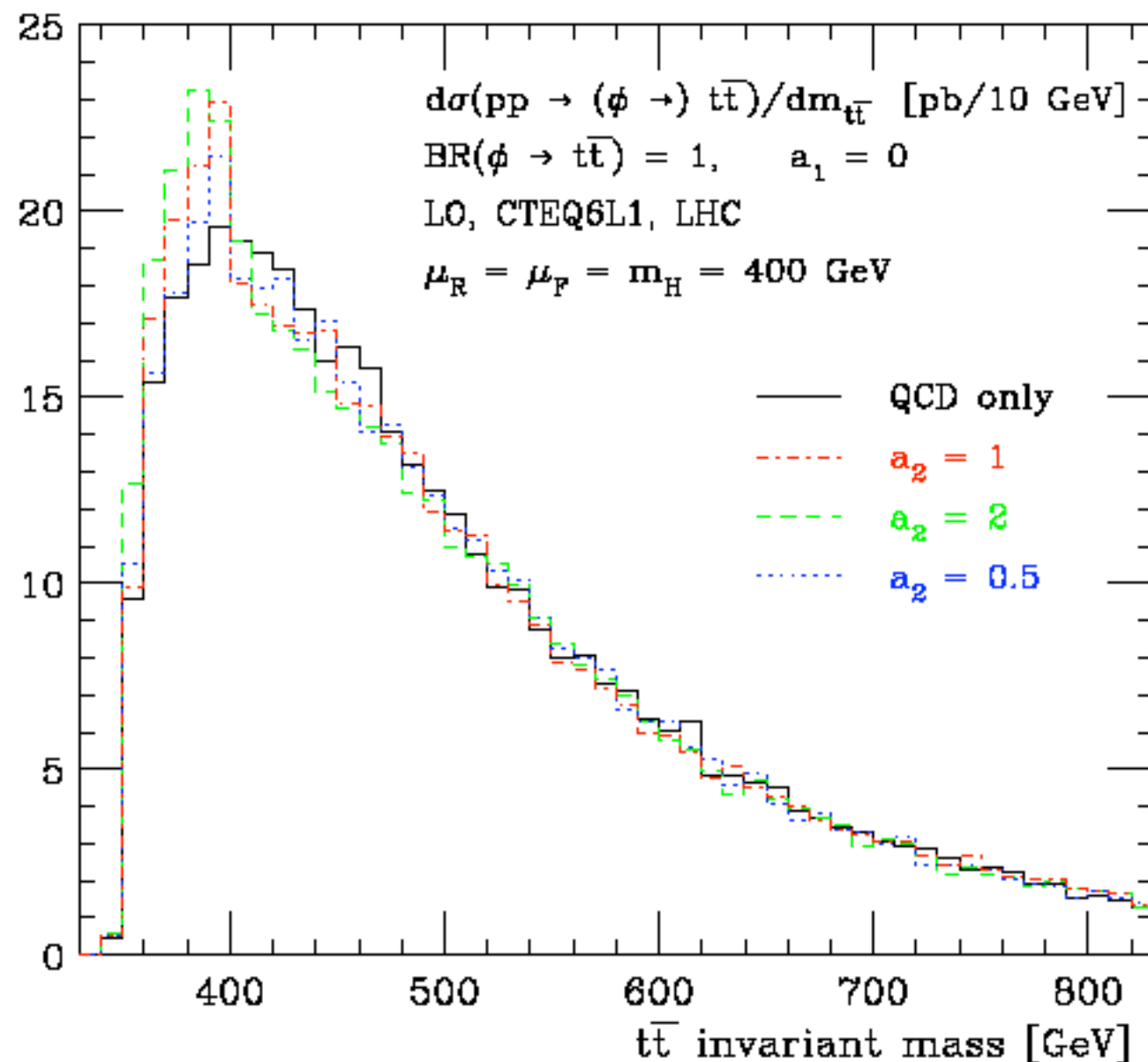
\* Vector resonance, in a color singlet or octet states.

\* Widths and rates very different

\* Interference effects with SM  $t\bar{t}$  production not always negligible

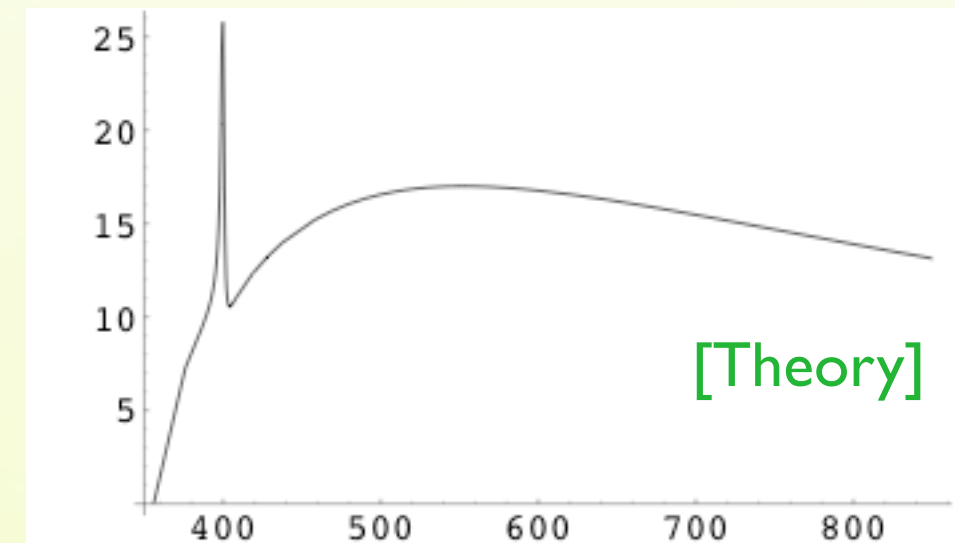
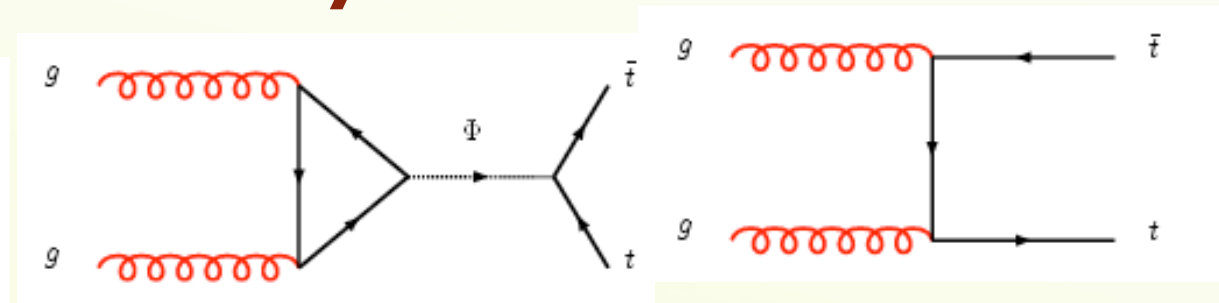
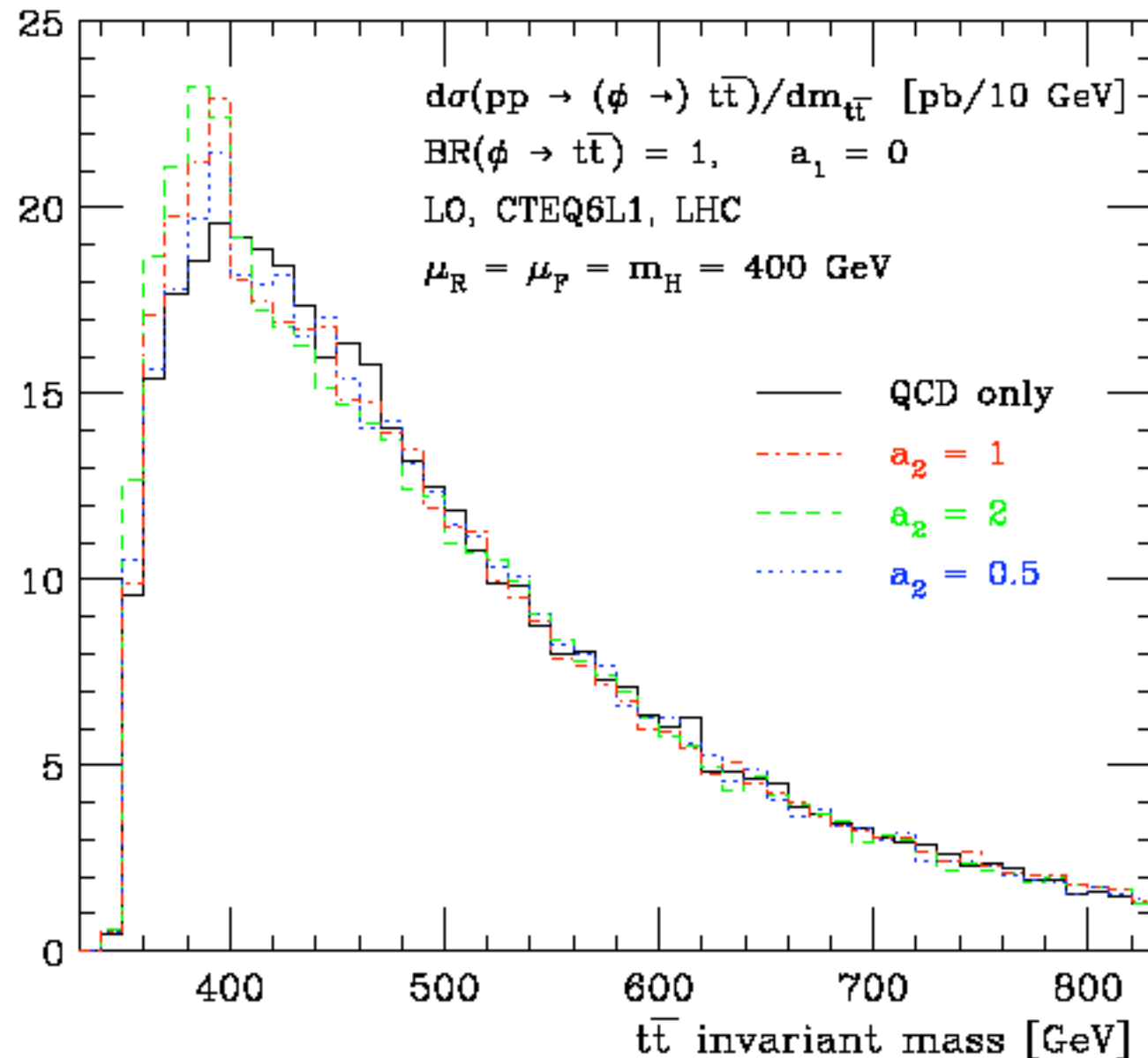
\* Direct information on  $\sigma \cdot \text{Br}$  and  $\Gamma$ .

# Phase I: discovery



Non-trivial behavior (peak-dip) due to the interference between the signal and the background, **only if top width dominated by  $\phi \rightarrow t\bar{t}$** . [Dicus, Stange & Willenbrock 1994]

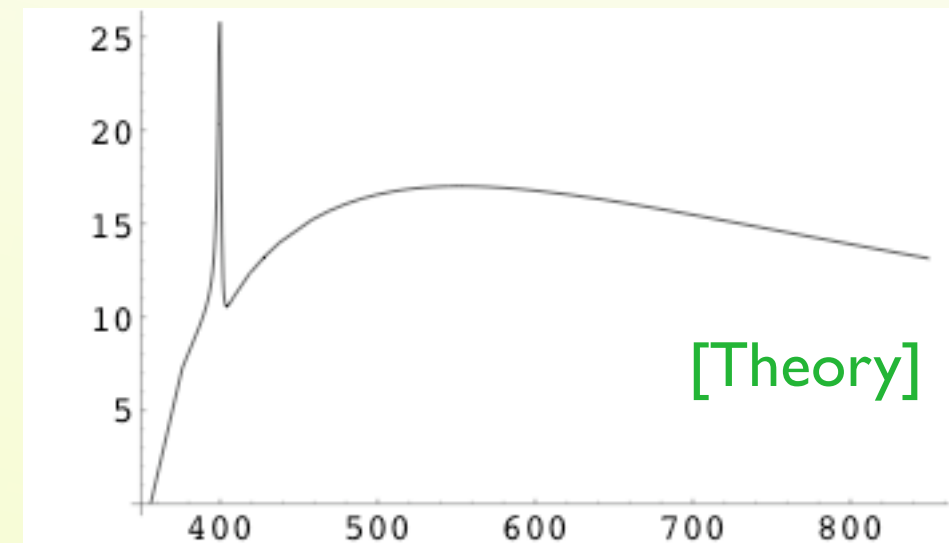
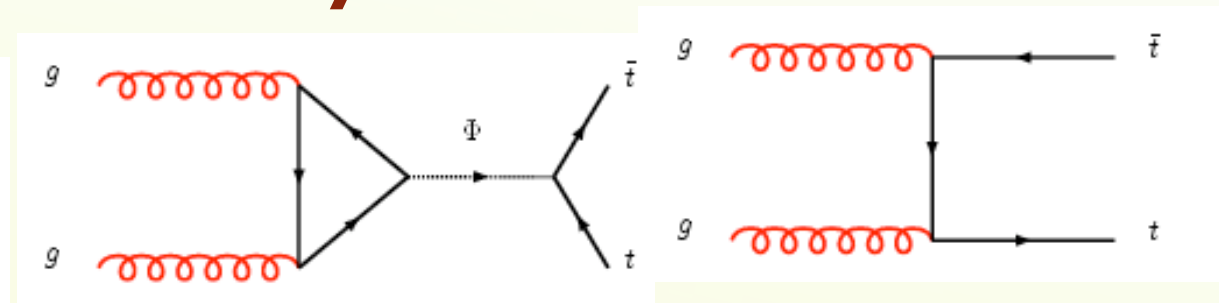
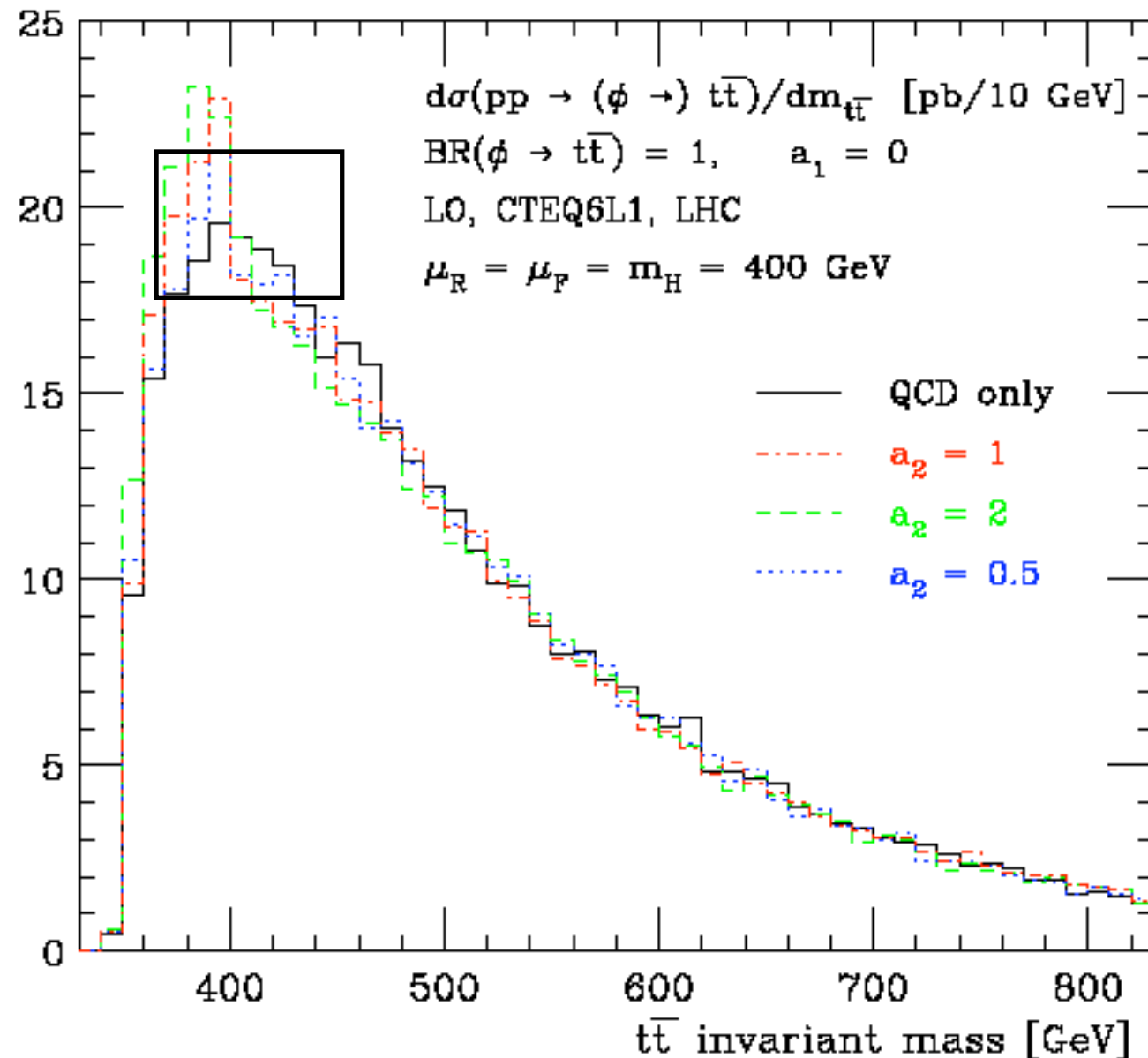
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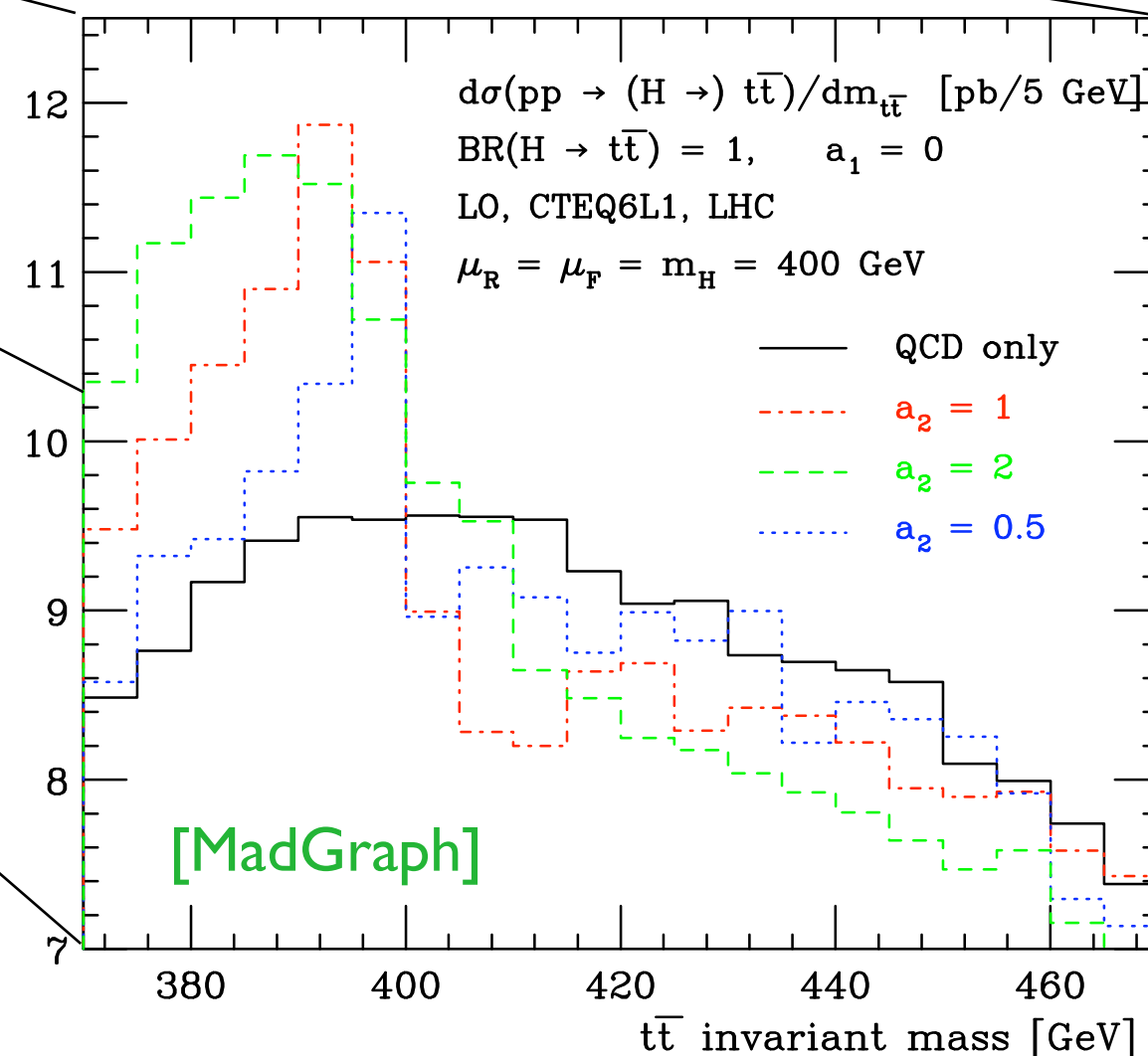
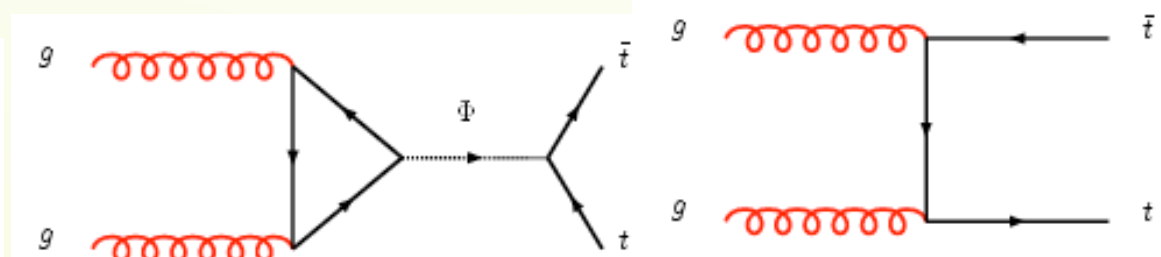
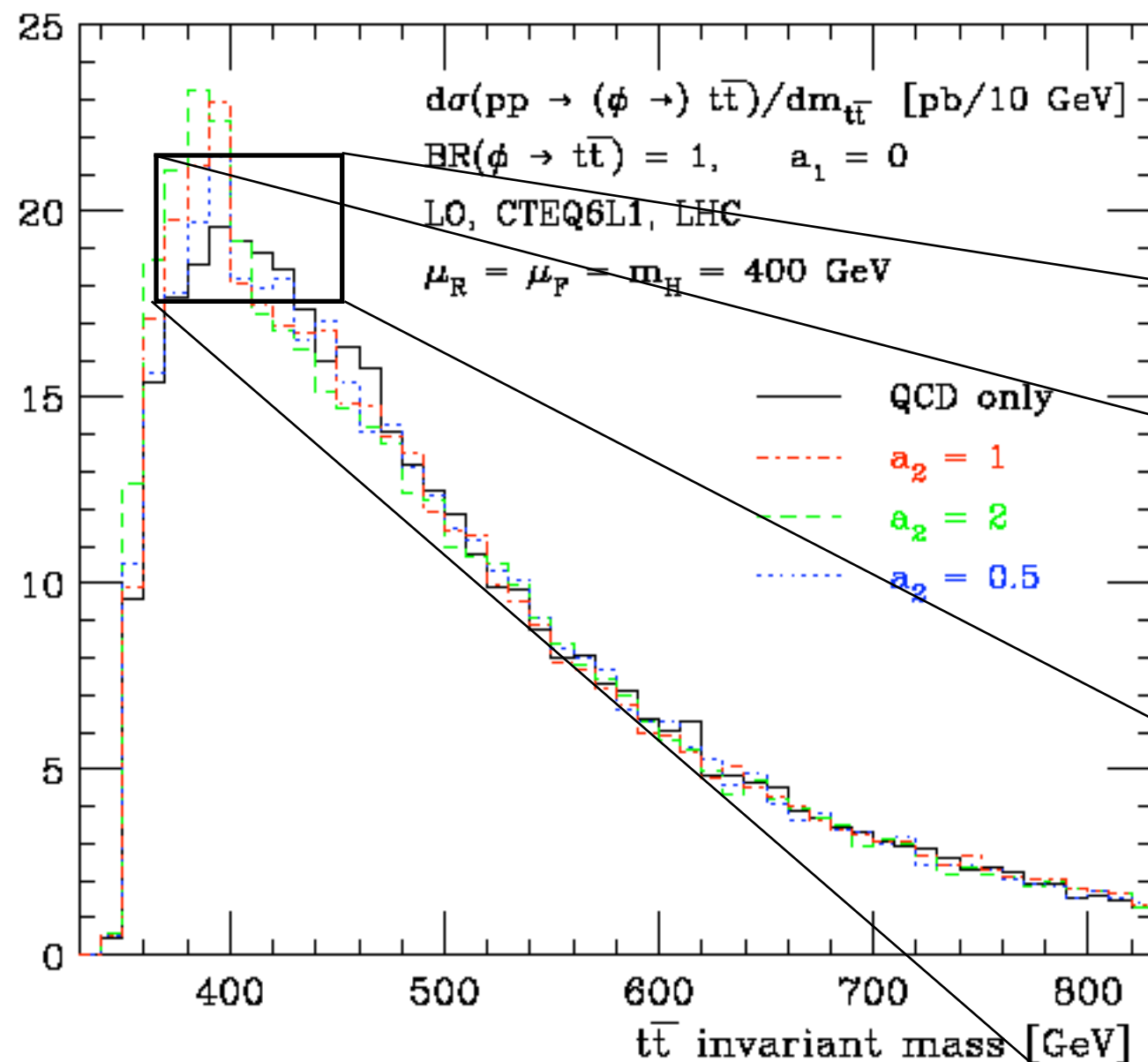


# Phase I: discovery



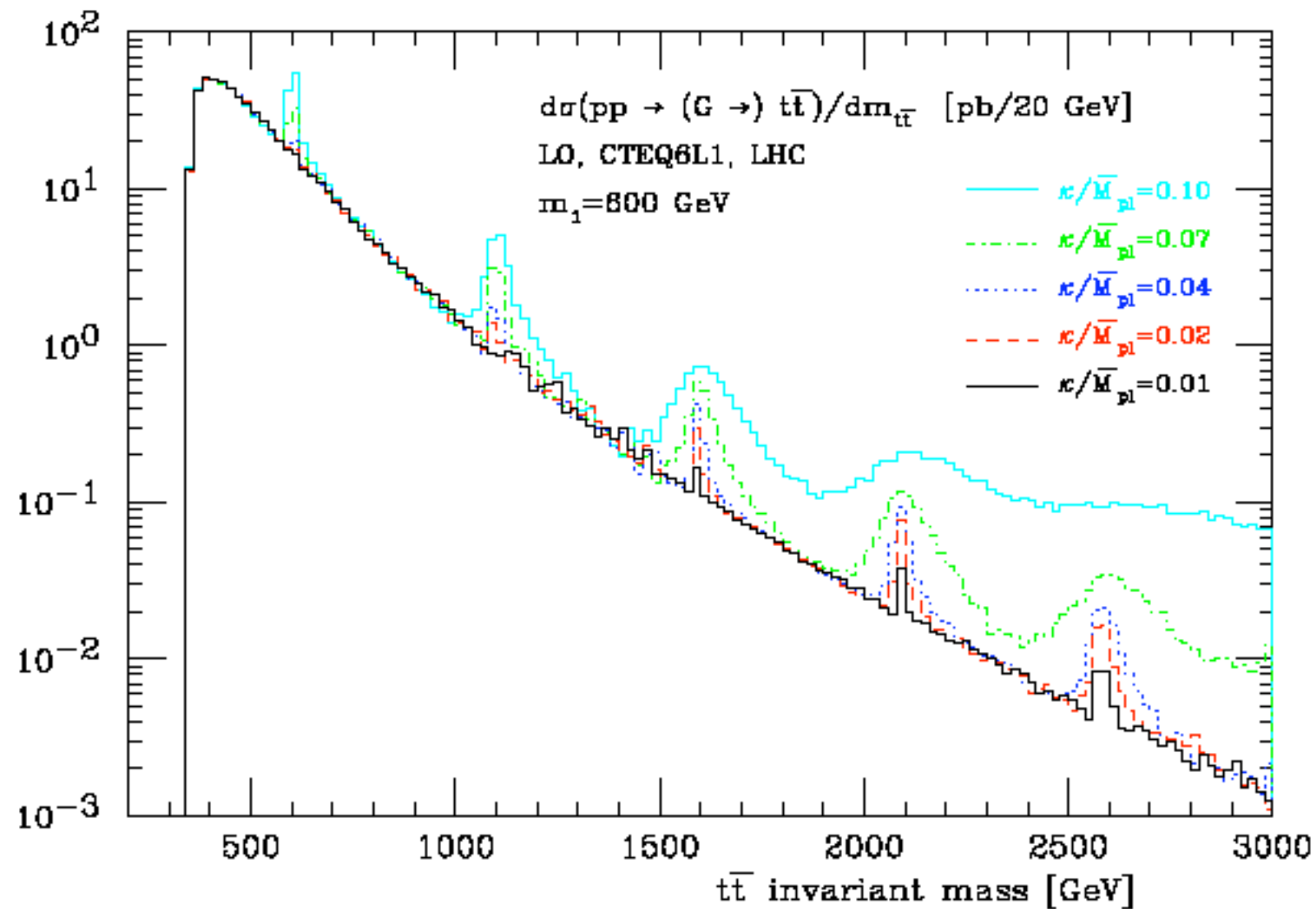
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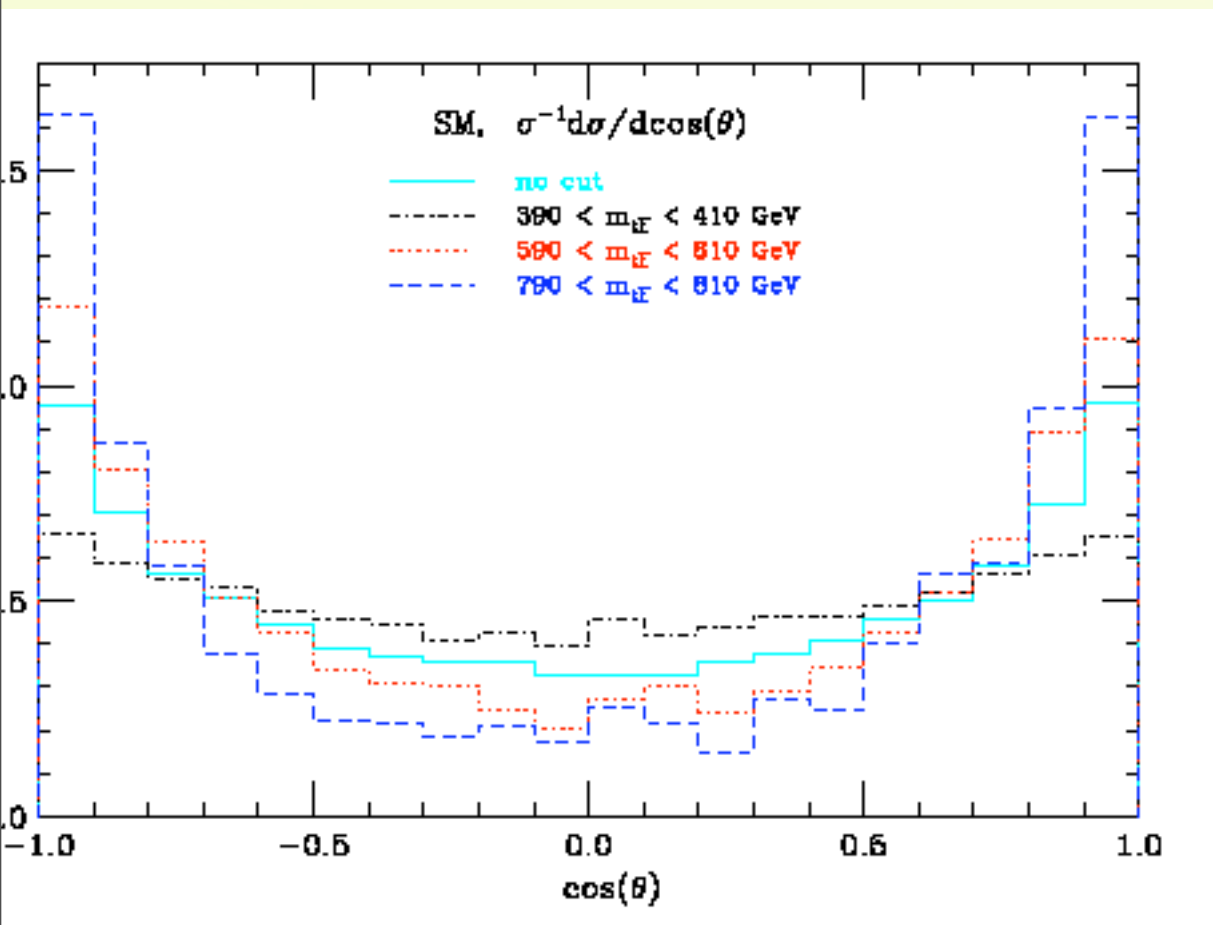
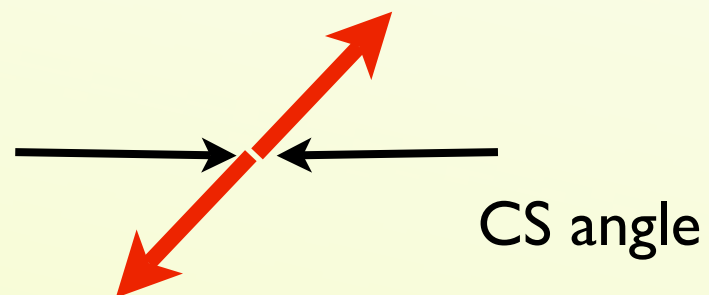
# Phase I: discovery



\* Spectacular signature!

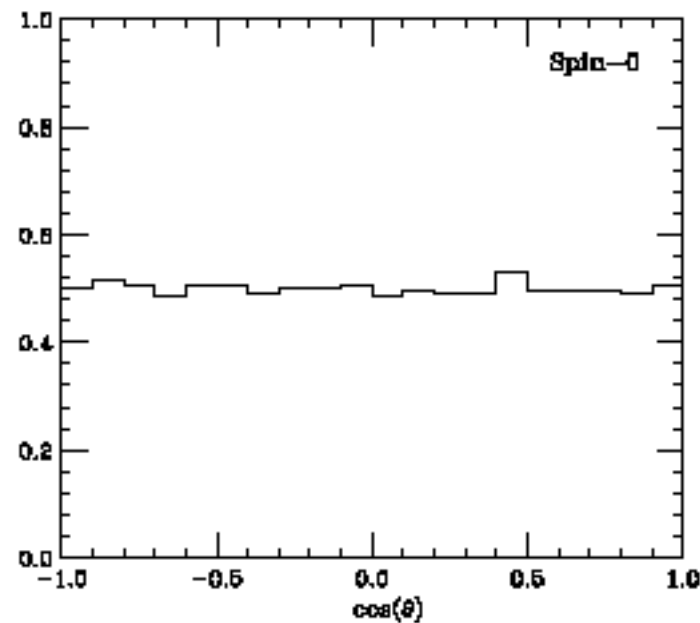
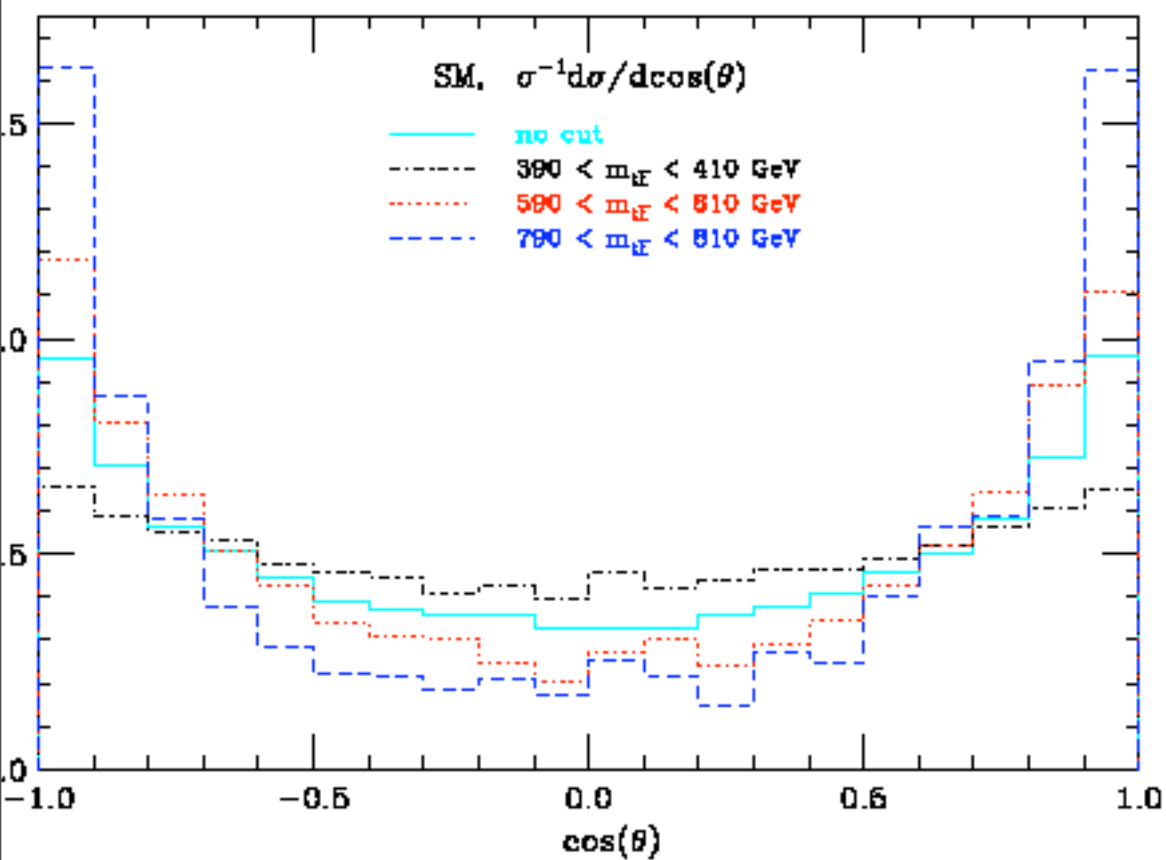
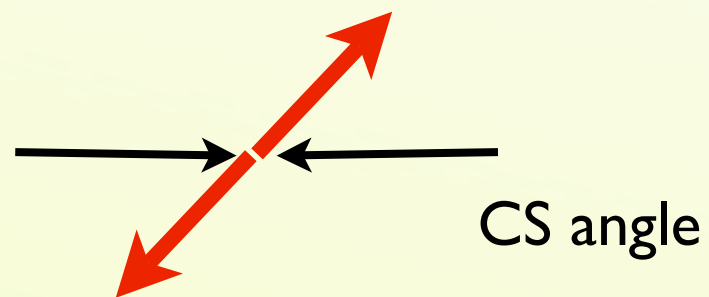
\*RS Model with first KK=600 GeV

# Phase 2: $t\bar{t}$ angular distributions

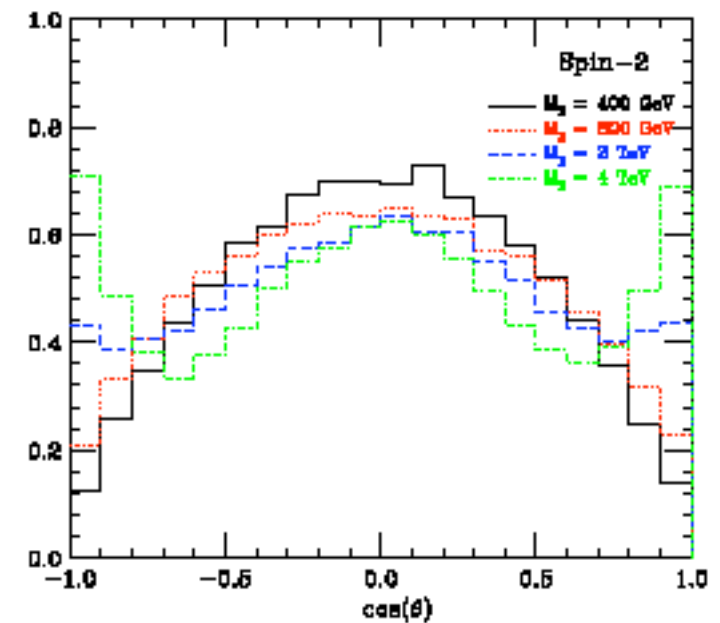


Robust reconstruction needed, but much easier than spin correlations...

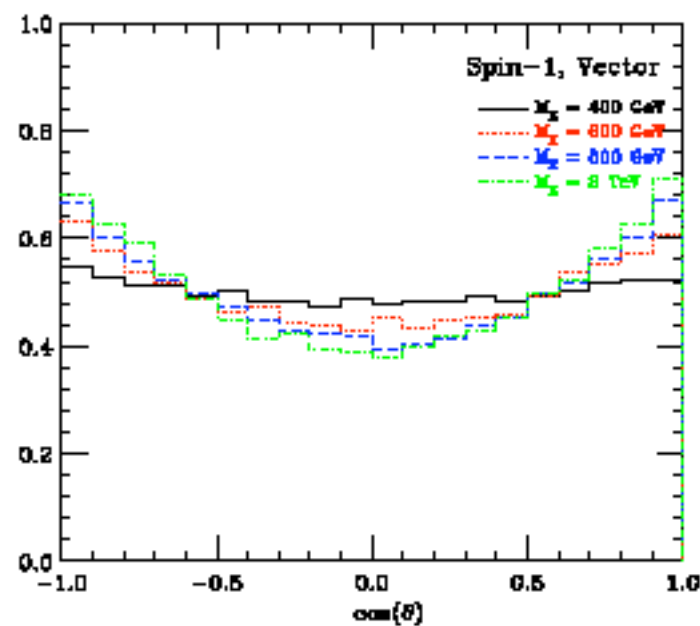
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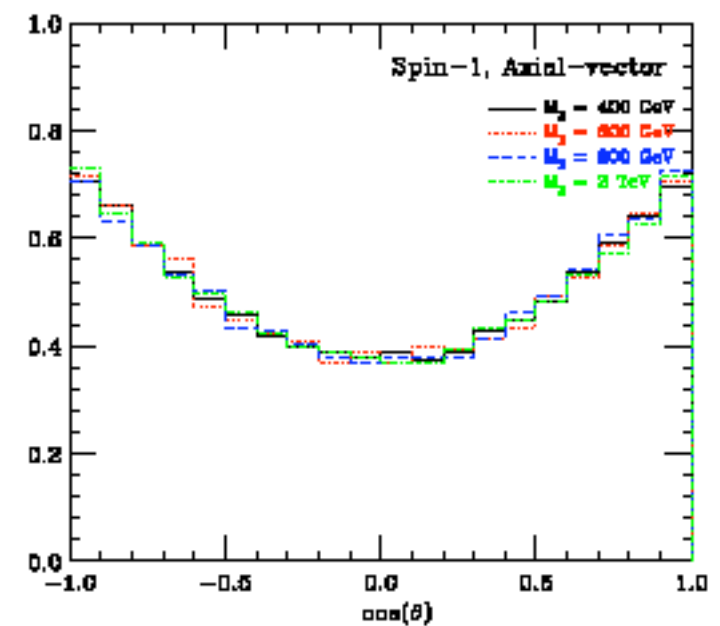
(a)



(b)



(c)

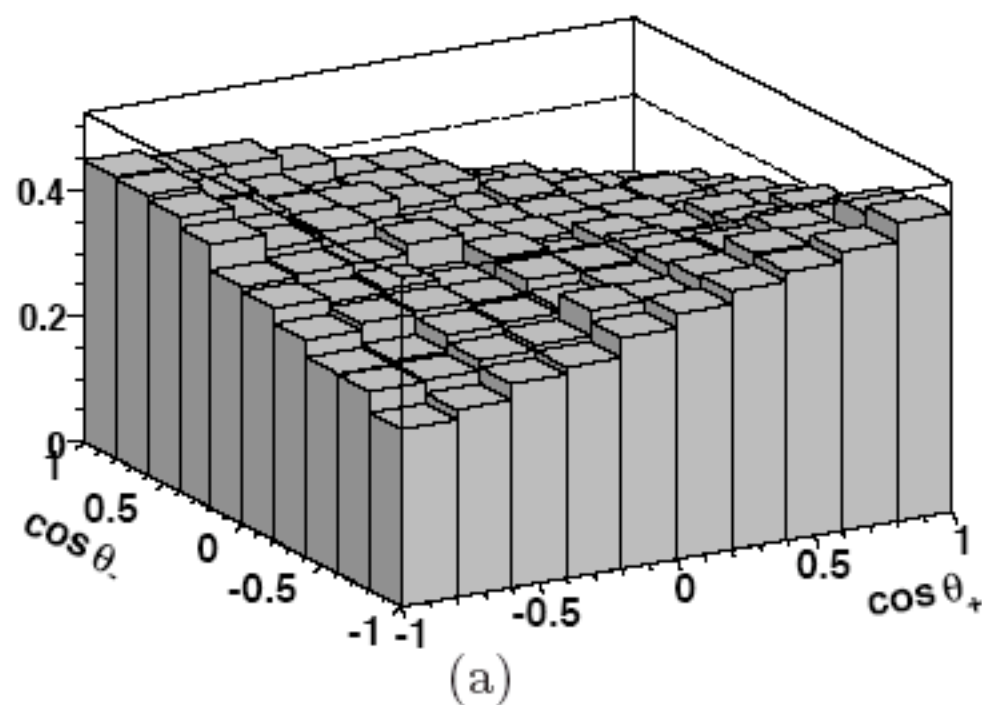


(d)

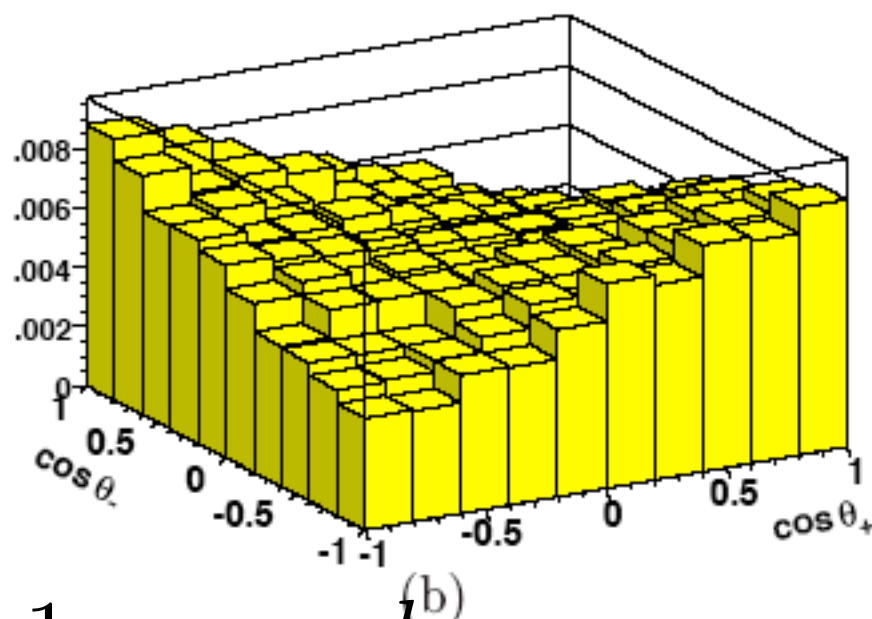
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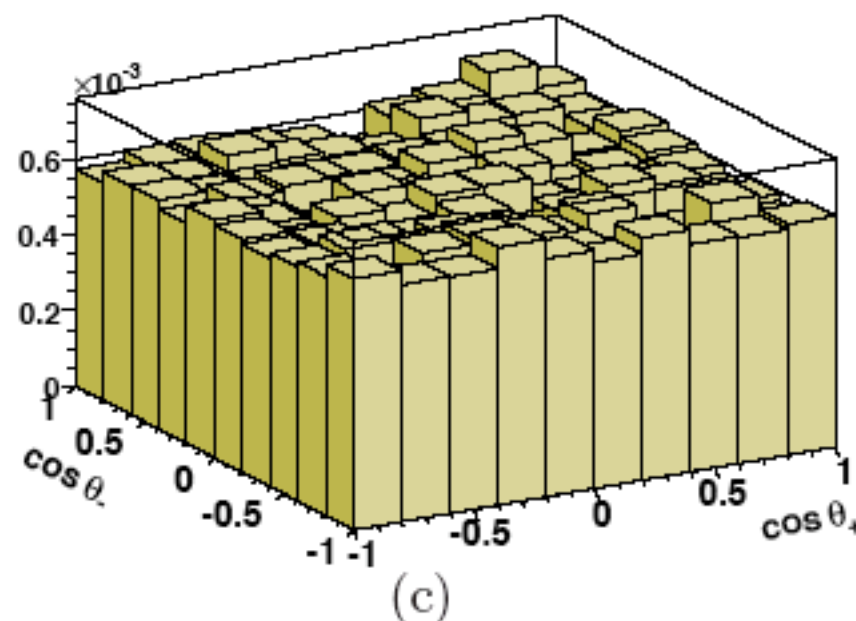
# Phase 3: Spin correlations



no cuts



low  $m_{tt}$



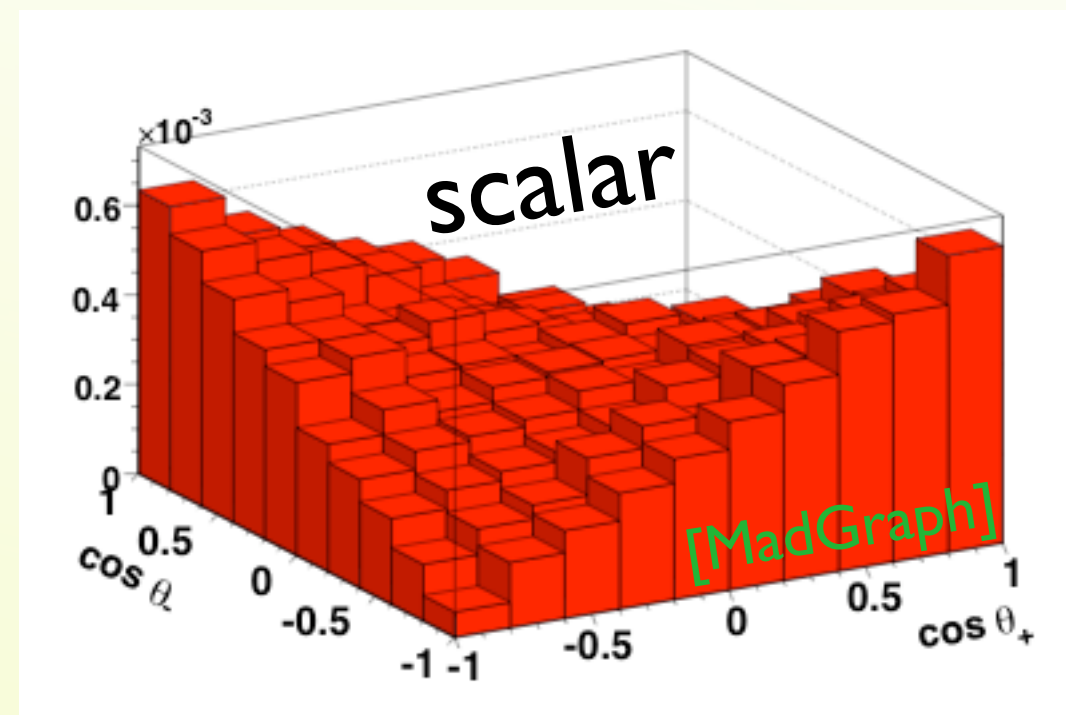
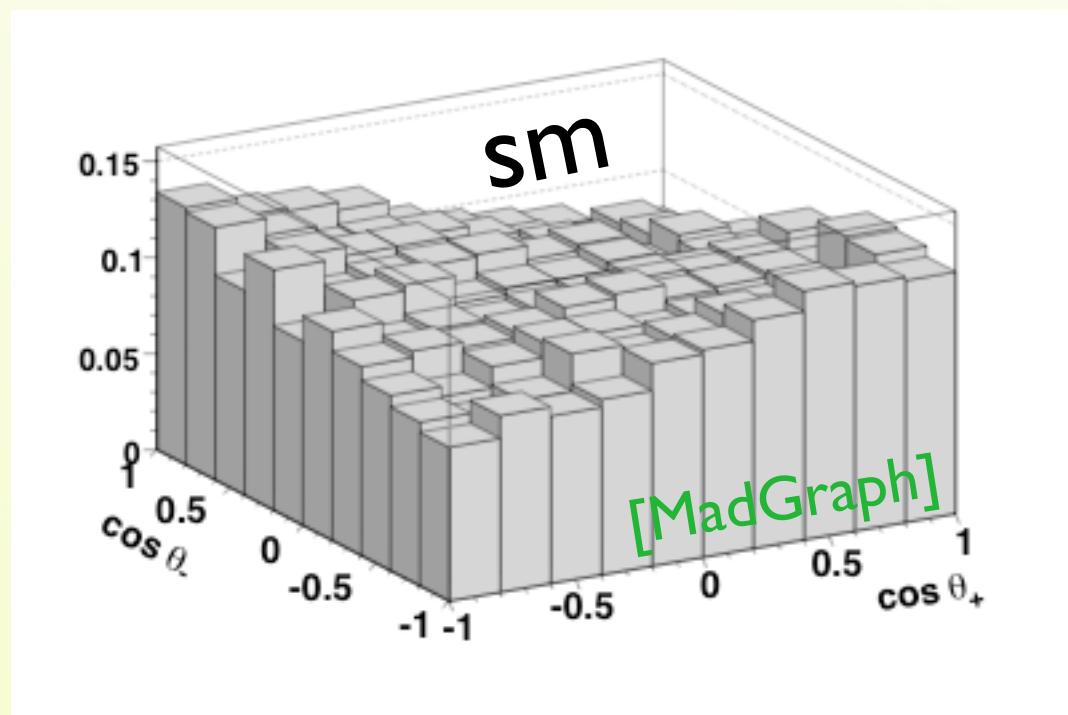
high  $m_{tt}$

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

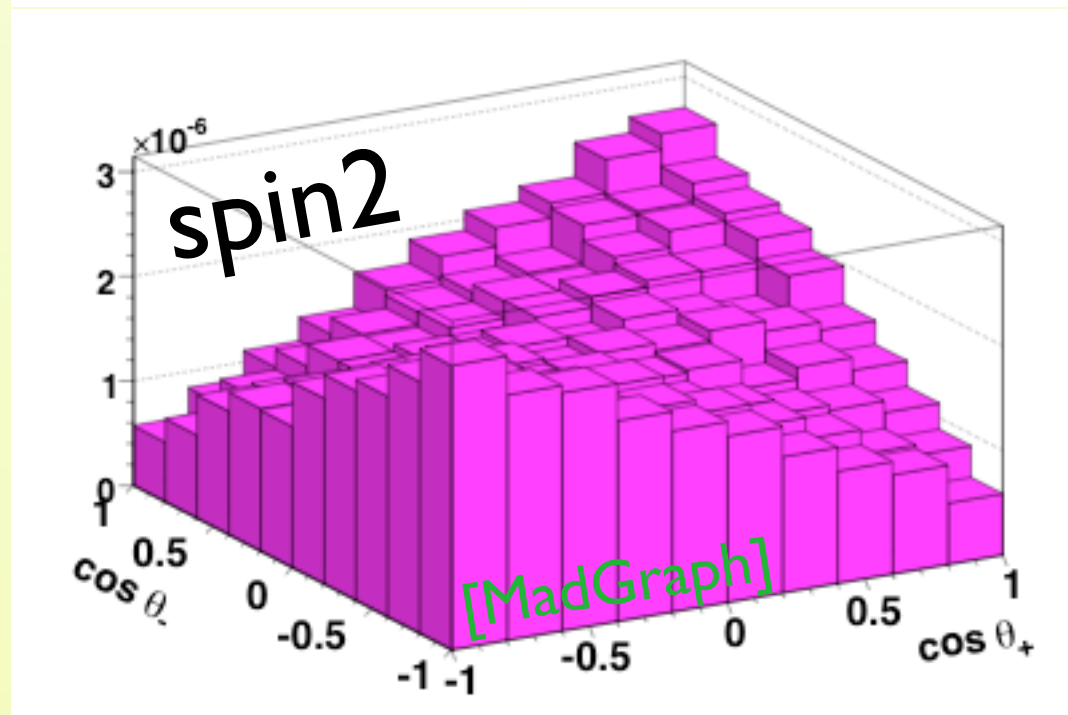
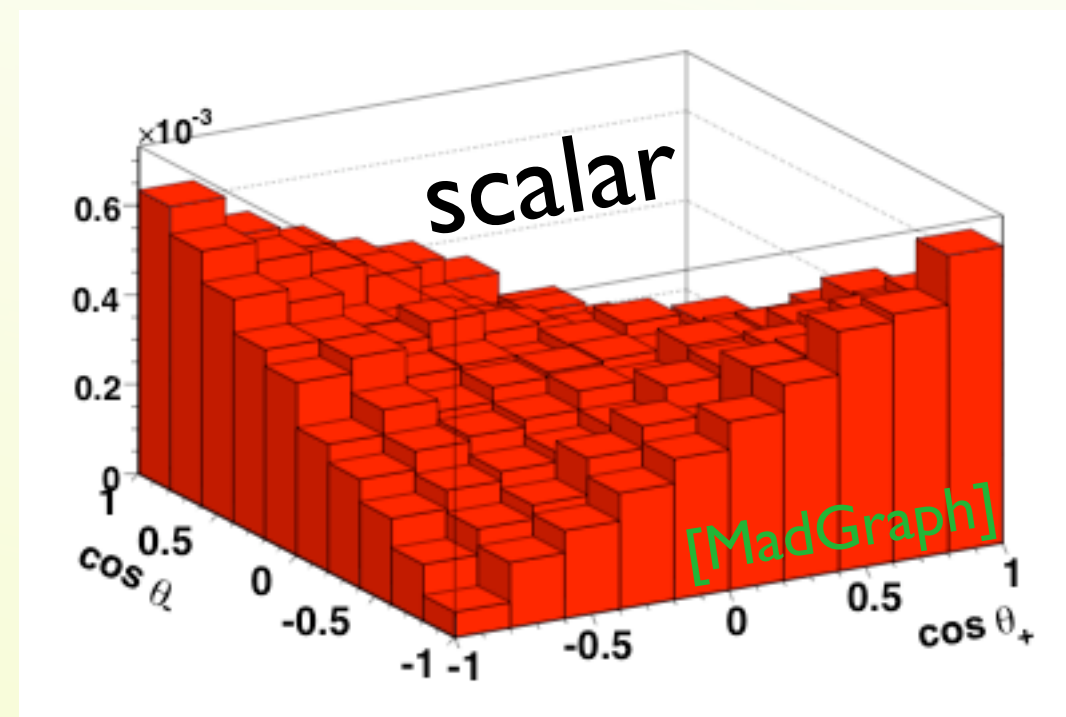
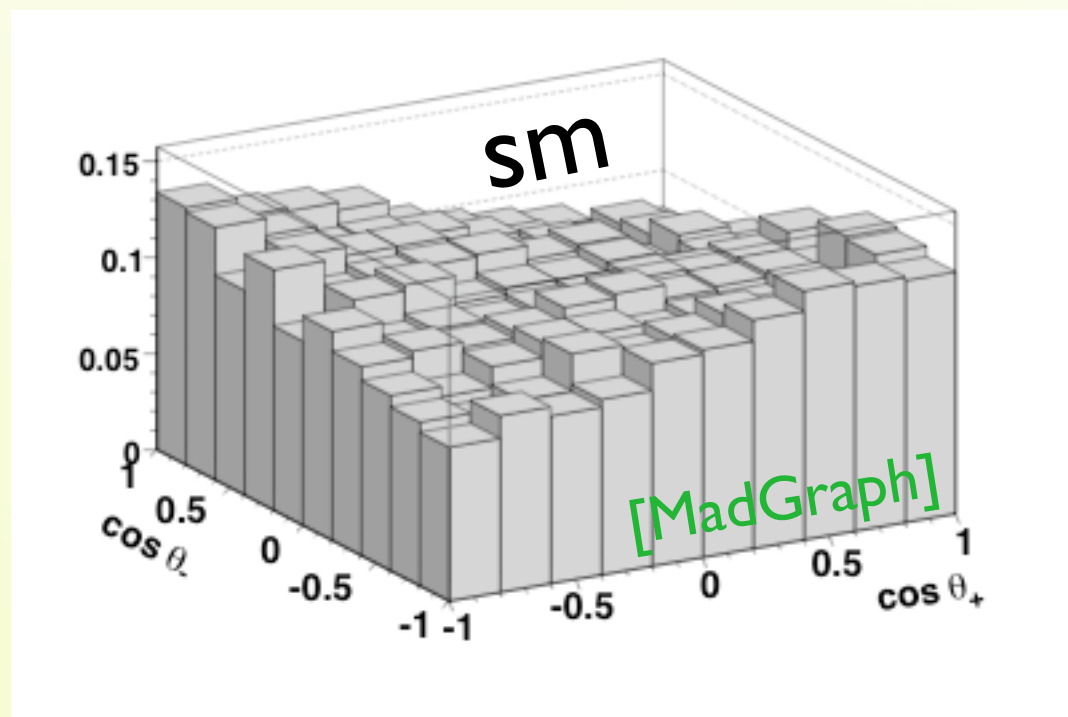


# Phase 3: Spin correlations

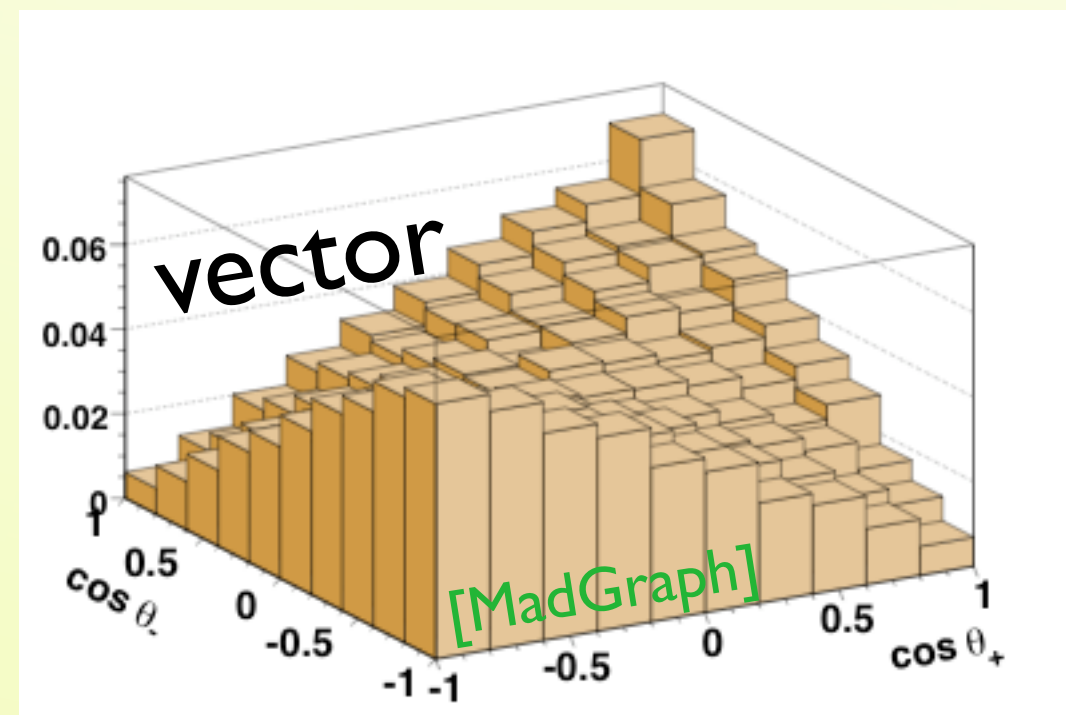
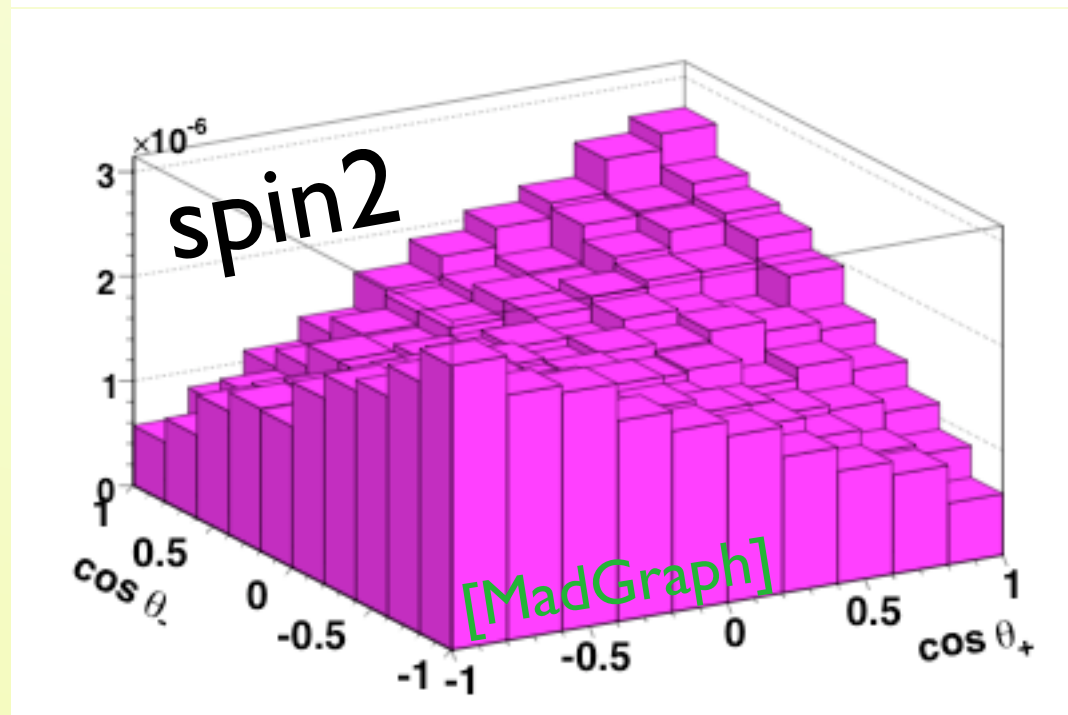
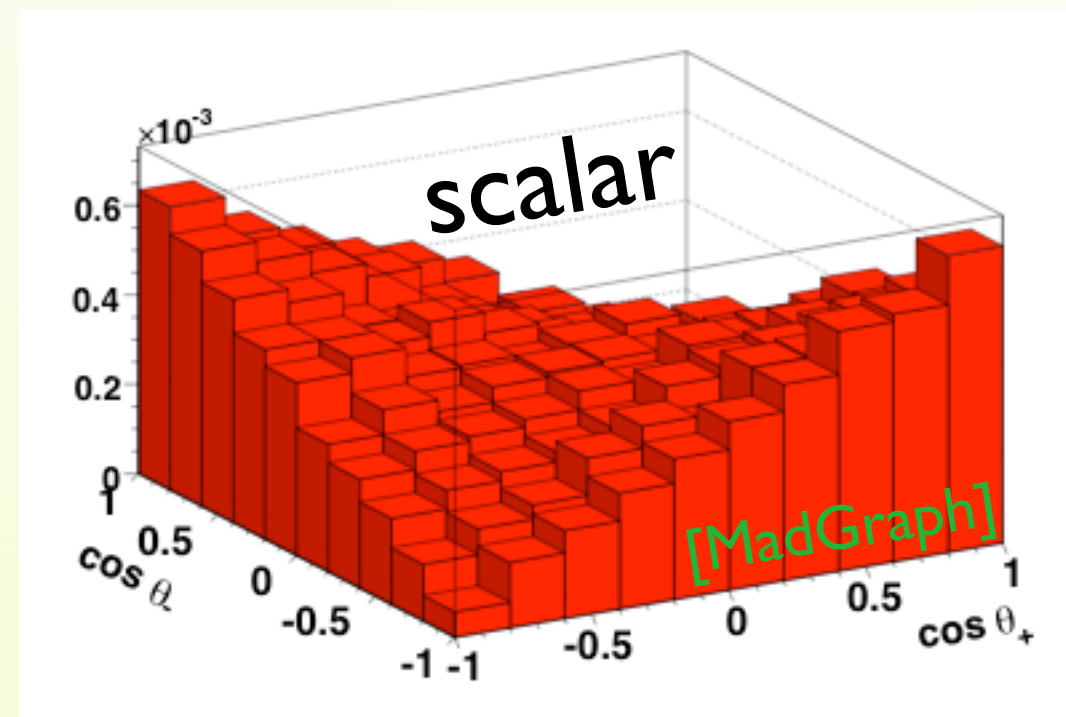
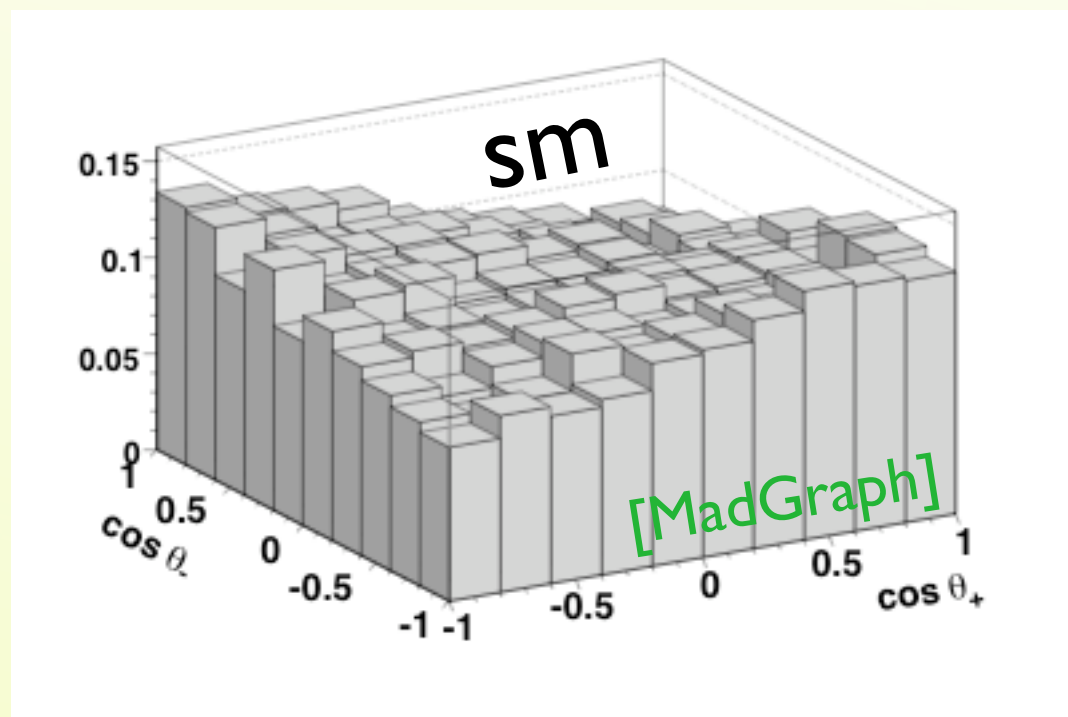
# Phase 3: Spin correlations



# Phase 3: Spin correlations



# Phase 3: Spin correlations







# 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.

	0 lept	1 lepts	2 lepts
# measured	6x3	5x3+ $E_T + m_W$	4x3+ $E_T + (2m_W, 2m_t)$
m(tt)	no reco needed	reco (no comb w/ constr)	full reco w/ comb  no spin comb
cos $\theta$	reco (no comb w/ constr)		
spin corr.	full reco + 4-fold spin comb	full reco + 2-fold spin comb	



## $t \bar{t}$ : Summary

- Large rates : plenty of top pairs at the LHC
- Discovery potential is huge and well motivated
- Simple strategy :  
observable  $\Leftrightarrow$  accurate SM predictions
- Both direct and indirect (through  $L_{\text{eff}}$ ) searches/constraints.

# Single-top

(Dated: March 4, 2009)

We report the first observation of single top quark production using  $3.2 \text{ fb}^{-1}$  of  $p\bar{p}$  collision data with  $\sqrt{s} = 1.96 \text{ TeV}$  collected by the Collider Detector at Fermilab. The significance of the observed data is 5.0 standard deviations, and the expected sensitivity for standard model production and decay is in excess of 5.9 standard deviations. Assuming  $m_t = 175 \text{ GeV}/c^2$ , we measure a cross section of  $2.3_{-0.5}^{+0.6}(\text{stat} + \text{syst}) \text{ pb}$ , extract the CKM matrix element value  $|V_{tb}| = 0.91 \pm 0.11(\text{stat} + \text{syst}) \pm 0.07(\text{theory})$ , and set the limit  $|V_{tb}| > 0.71$  at the 95% C.L.

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Why single top is cooler than  $t\bar{t}$ bar?



Why single top is cooler than  $t\bar{t}$ bar?

At least three reasons...





# Reason #1 : Teenager vs Newborn

## single-top



- Just a one year old!
- Good : a whole new world to explore
- Bad : sleep deprivation...

# Reason #1 : Teenager vs Newborn

t tbar



single-top

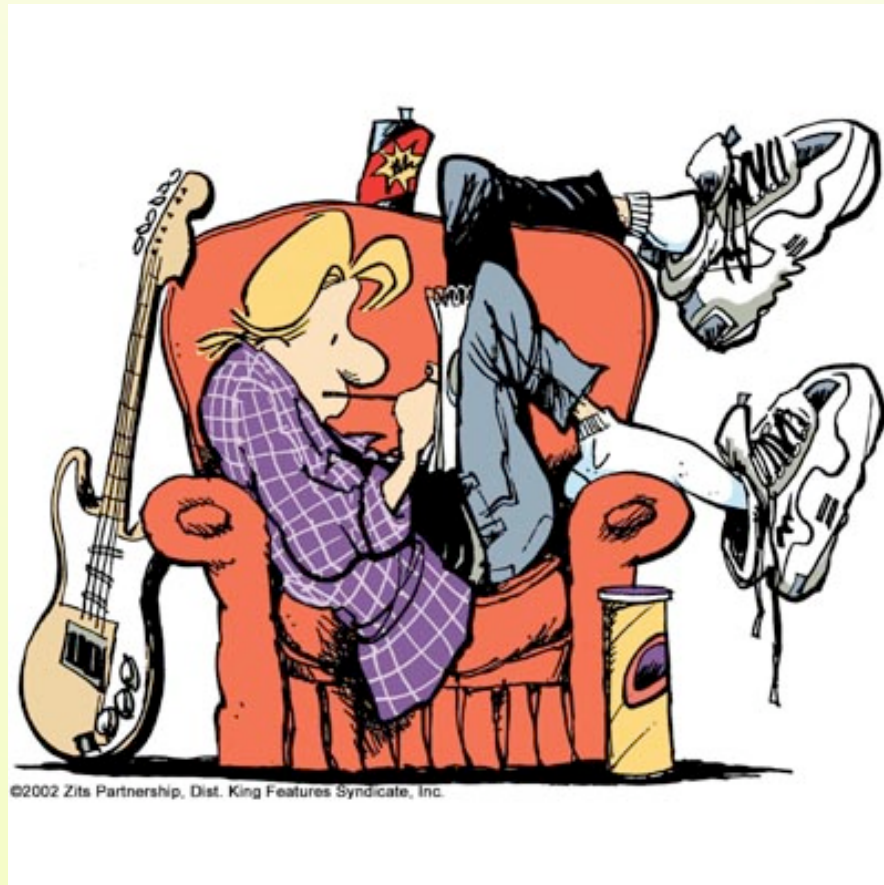


- Just a one year old!
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# Reason #1 : Teenager vs Newborn

t tbar



- Born in 1995
- Good : We already know him well
- Bad : We ask him a lot!

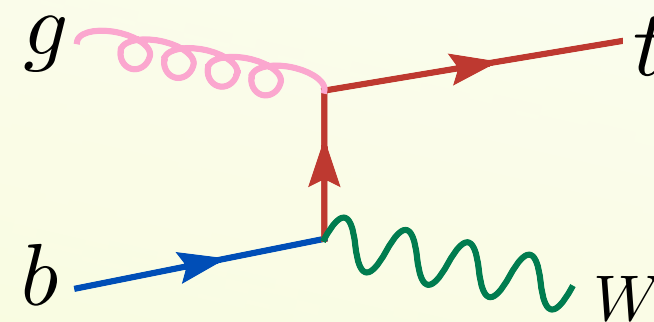
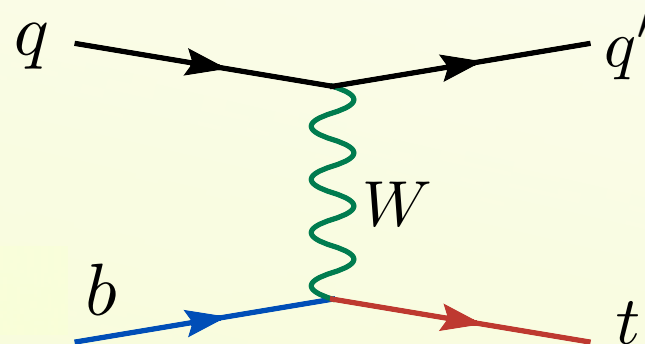
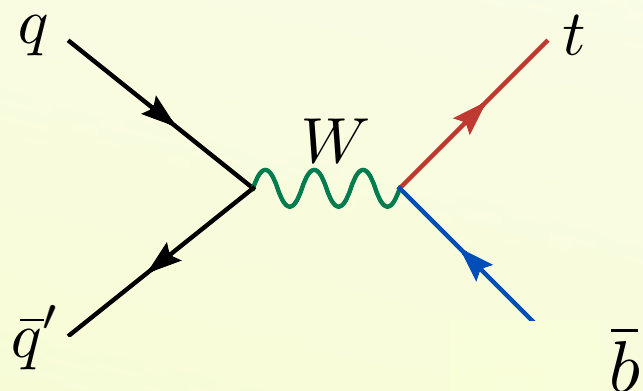
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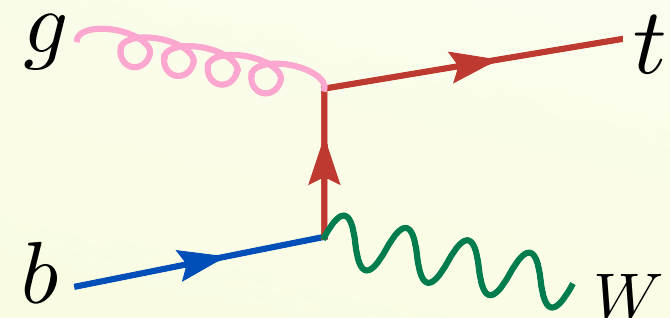
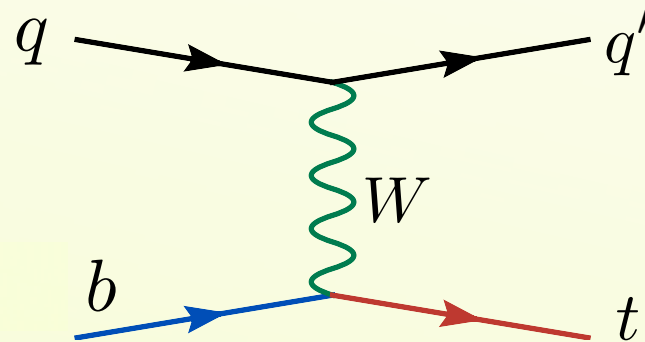
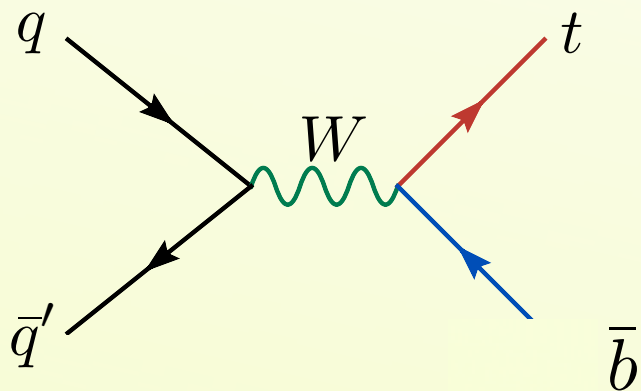
# Reason #2 : Single top comes in more shapes and forms!



\*

\*Theorist's comments

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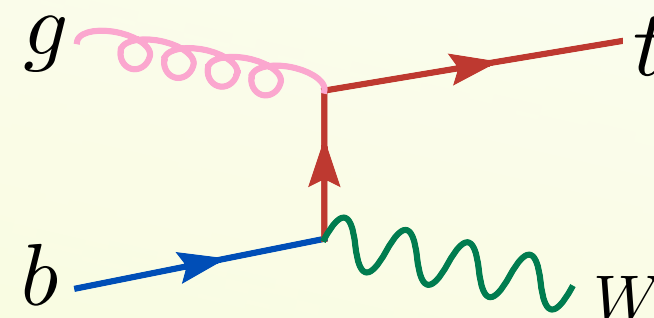
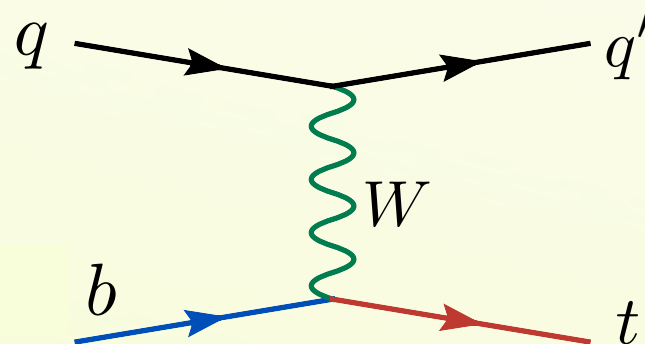
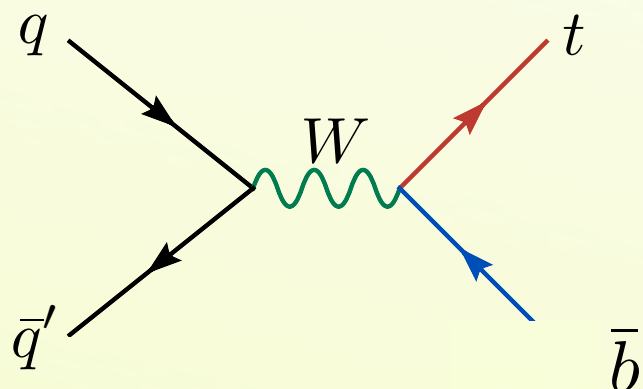
- \* “Drell-Yan” production mode.
- \* Tevatron is sizable ( $\sim 1$  pb), quite small at the LHC14 ( $\sim 10$  pb).
- \* Fully inclusive x-sec known at NNLO (leading  $N_c$ ).
- \* Channel to search for new charged resonances ( $H^+$  or  $W'$ ).
- Four-fermion interactions.
- \* Final State: 2 b's + W

\*

\*Theorist's comments



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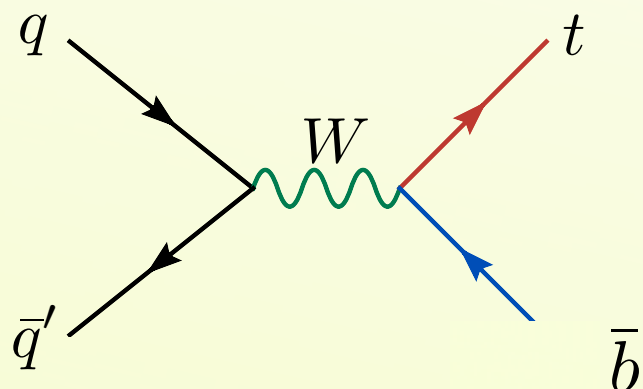
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- \* “DIS” production mode.
- \* Largest cross sections thanks to the t-channel W.
- \* Sensitive to FCNC involving top. Four-fermion interactions.
- \* **b initiated**
- \* Final State: 1 or 2 b's, W, forward jet

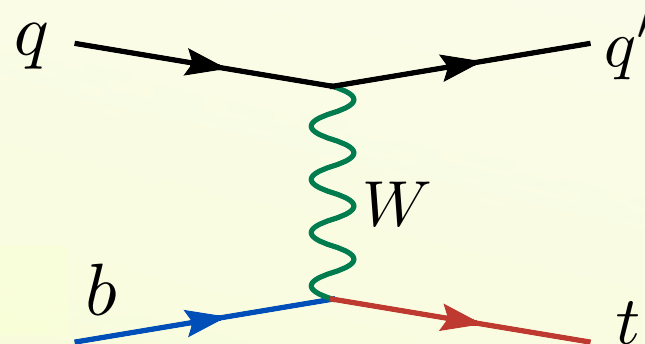
\*

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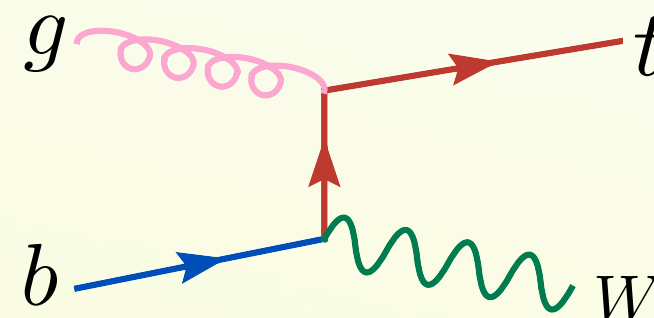
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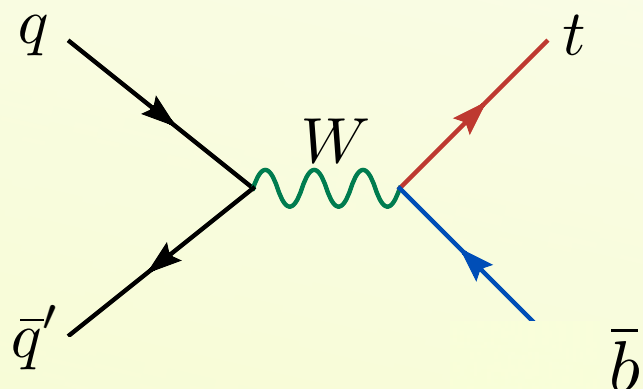


- \* Associated production
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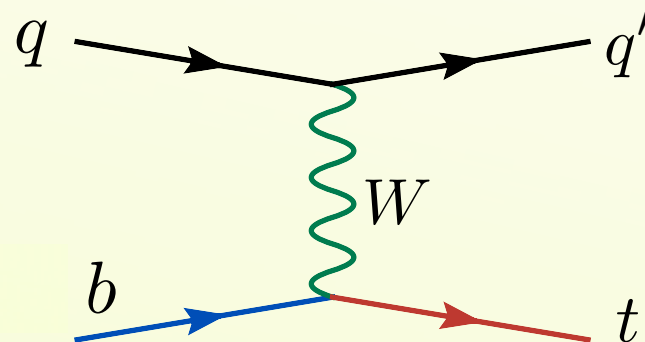
\*

\*Theorist's comments

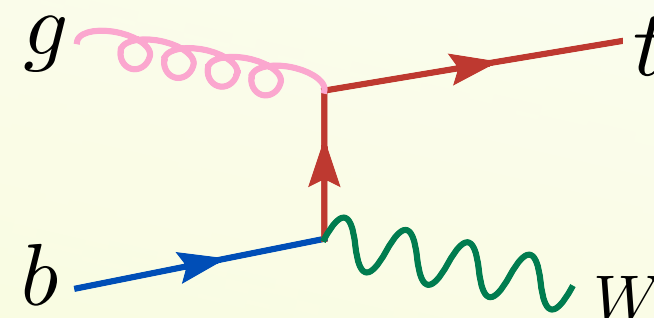
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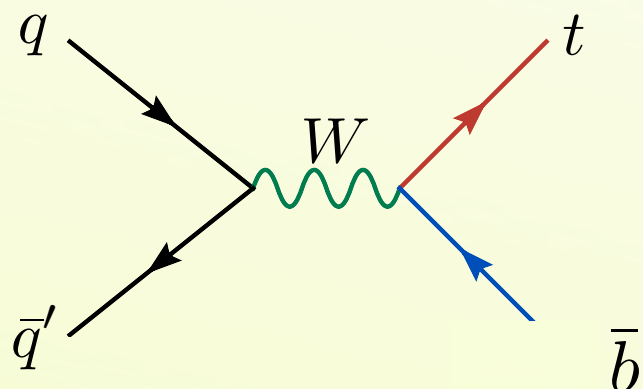
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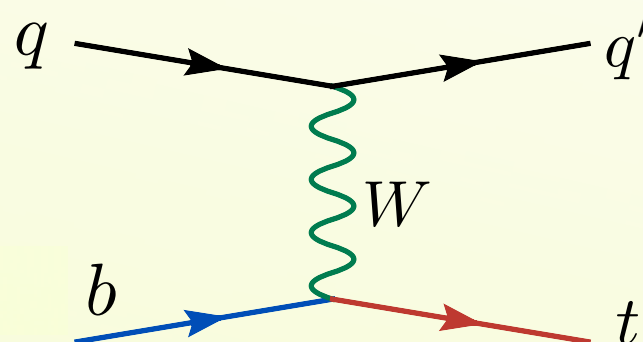
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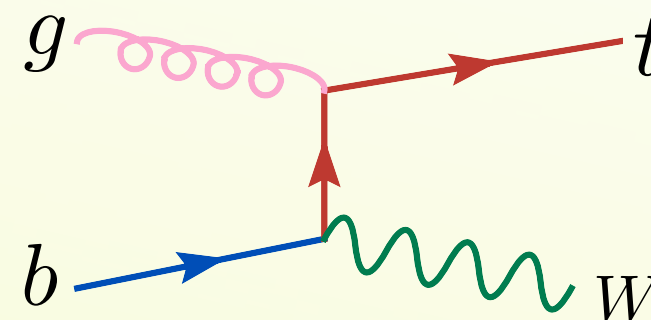
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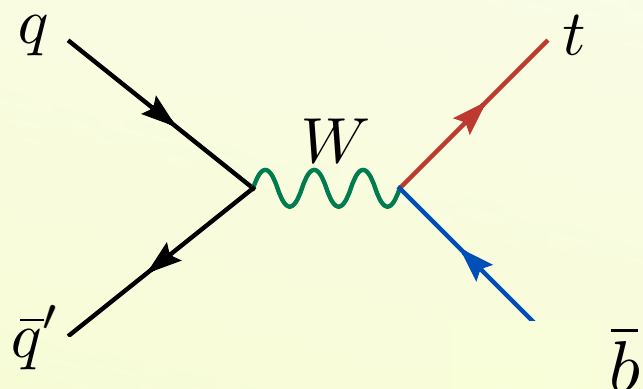


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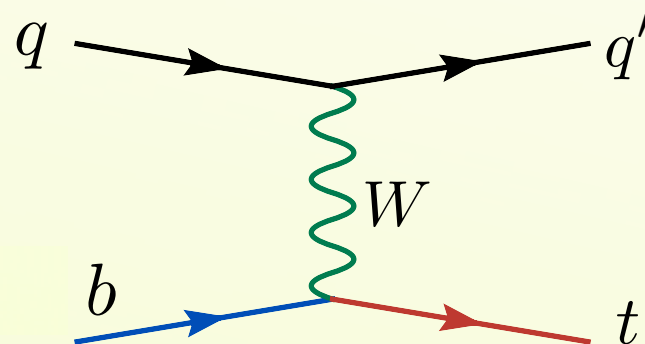
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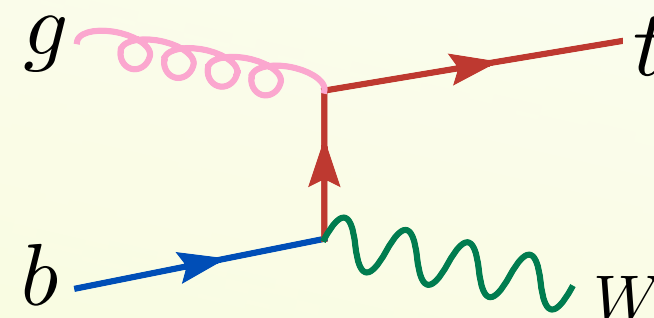
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“Challenging!!” \*

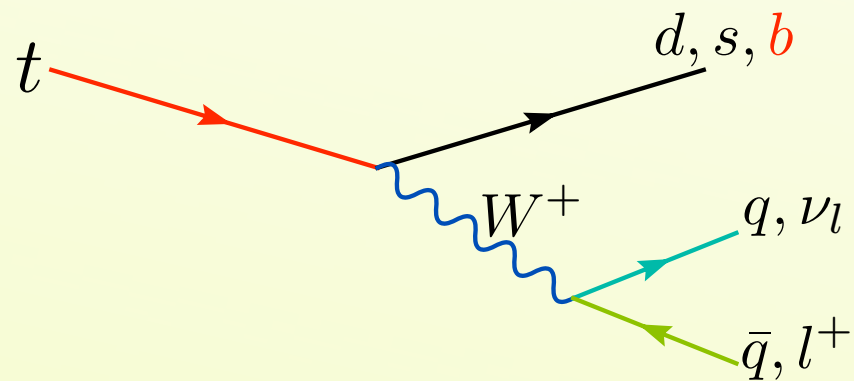
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# Example: Direct constraints on the 3rd row of CKM

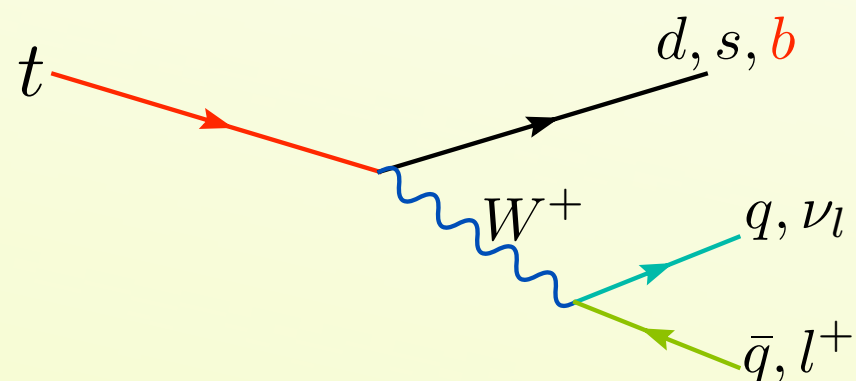
Remember that  $R$  is not so sensitive to  $V_{tb}$  as we already know that  $V_{tb} > V_{ts}, V_{td}$



$$R = \frac{\Gamma(t \rightarrow Wb)}{\Gamma(t \rightarrow Wq(=d, s, b))} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

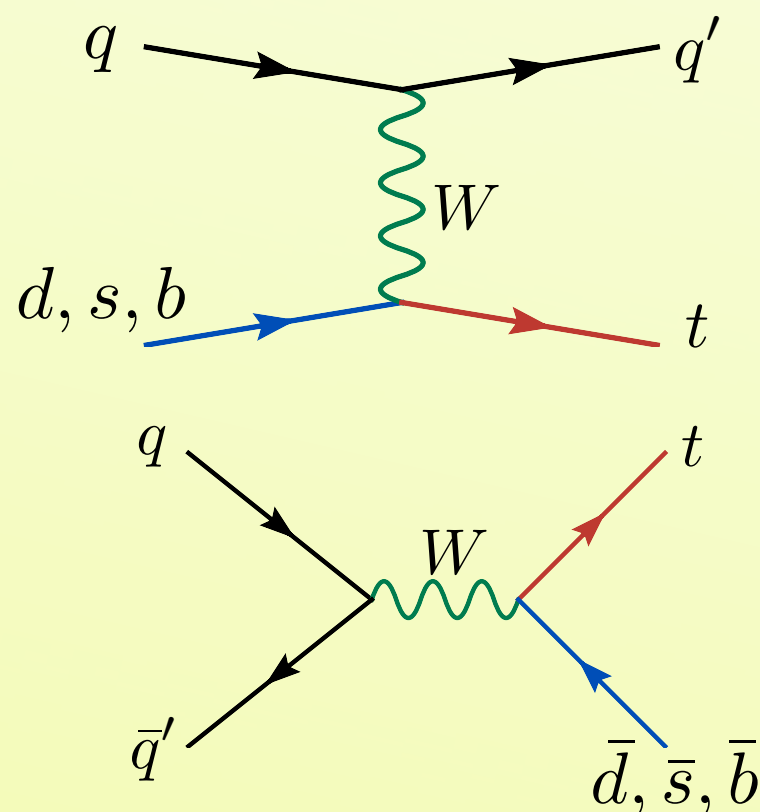
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On the other hand, single top is **DIRECTLY** sensitive to  $V_{tb}, V_{ts}, V_{td}$ :



$$\sim |V_{td}|^2 \sigma_d^{\text{t-ch}} + |V_{ts}|^2 \sigma_s^{\text{t-ch}} + |V_{tb}|^2 \sigma_b^{\text{t-ch}}$$

Enhancement due to large  $d$  and  $s$  densities

$$\sim (|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2) \sigma^{\text{s-ch}}$$

Signal becomes similar to t-channel (only 1  $b$ -jet)



# Example: Direct constraints on the 3rd row of CKM

Remember that  $R$  is not so sensitive to  $V_{tb}$  as we already know that  $V_{tb} > V_{ts}, V_{td}$

$t$   $d, s, b$

$$R = \frac{\Gamma(t \rightarrow W b)}{\Gamma(t \rightarrow W d) + \Gamma(t \rightarrow W s) + \Gamma(t \rightarrow W b)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

On t

$$\sigma_{1b\text{-tag}} = R \left\{ \sum_{i=b,s,d} |V_{ti}|^2 \sigma_i^{t\text{-ch}} + 2(|V_{td}|^2 + |V_{ts}|^2) \sigma^{s\text{-ch}} \right\}$$
$$\sigma_{2b\text{-tag}} = R |V_{tb}|^2 \sigma^{s\text{-ch}}$$

n.b. : naive estimate ch

$d, s, b$   $t$

$q$   $t$

$\bar{q}'$   $\bar{d}, \bar{s}, \bar{b}$

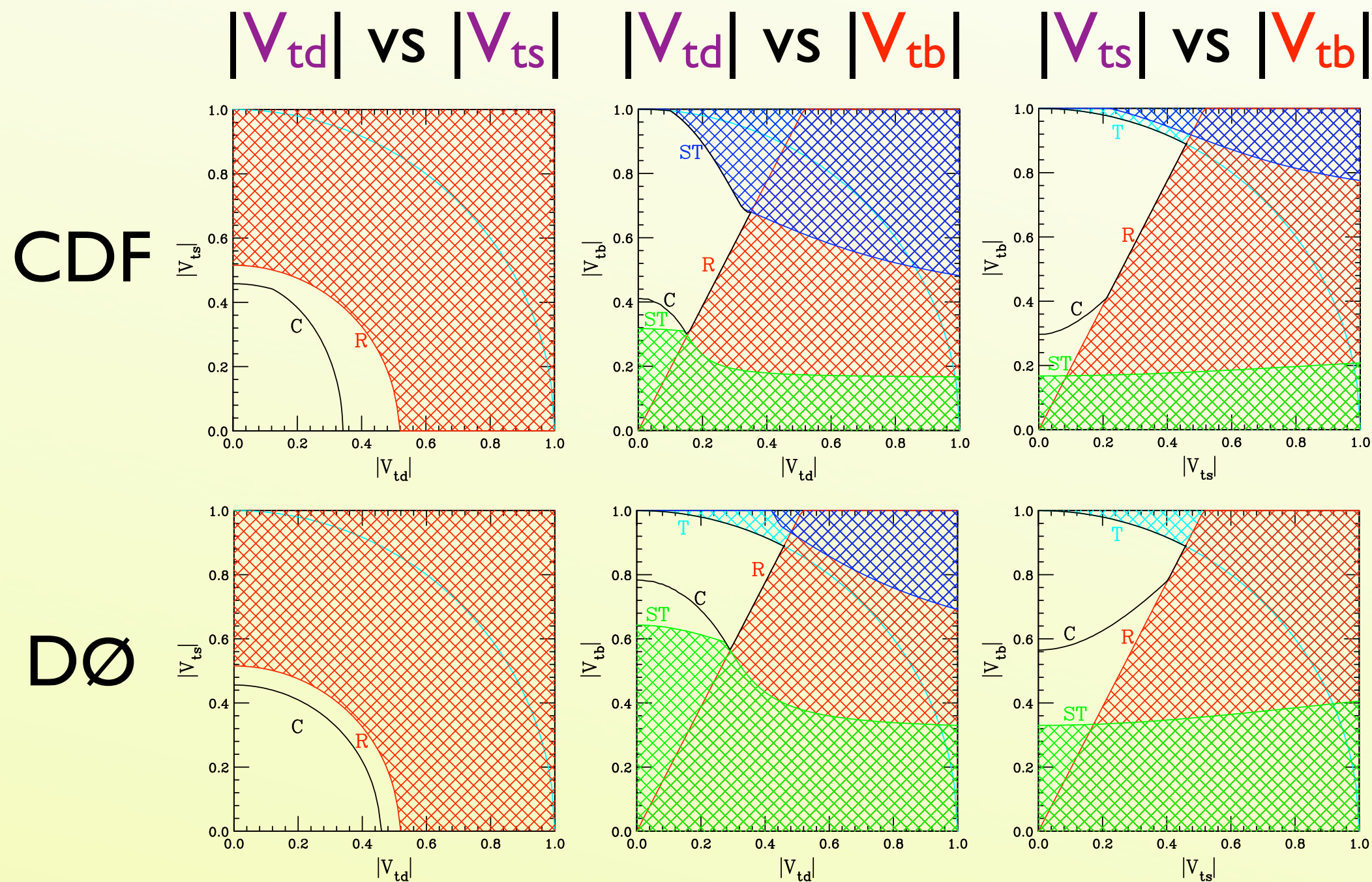
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Alwall et al., Eur. Phys. J. C49 791 (2007) + updates



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NLO <sub>w</sub> PS QCD	yes	yes	no	yes	yes
Resummed NLO	yes	yes	no	yes	no
X+1 jet at NLO	yes	no	no	no	no
NNLO	work in progress	no	no	yes	no
NLO EW	yes	yes	no	yes	yes



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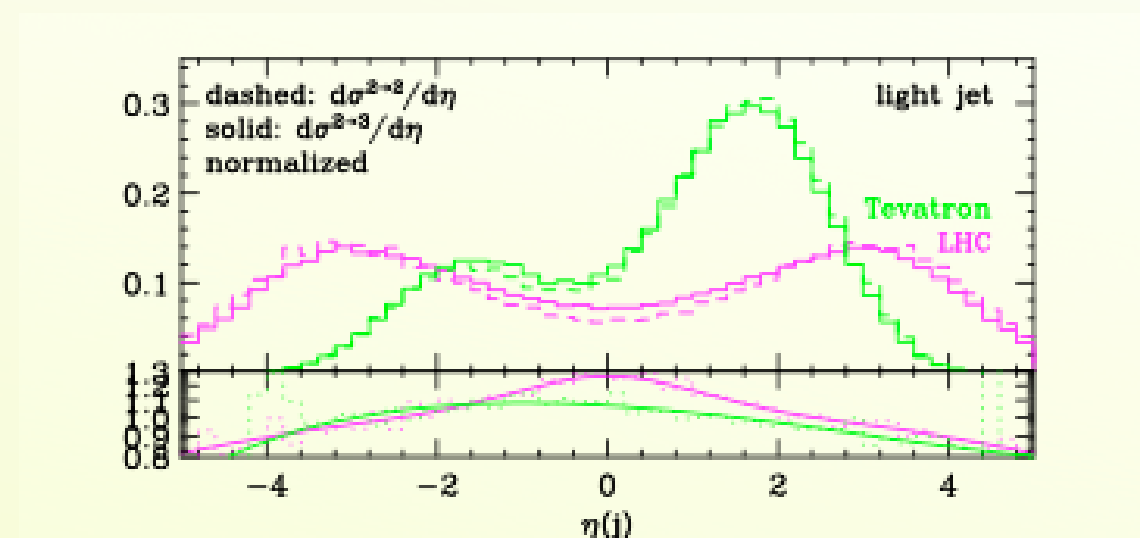
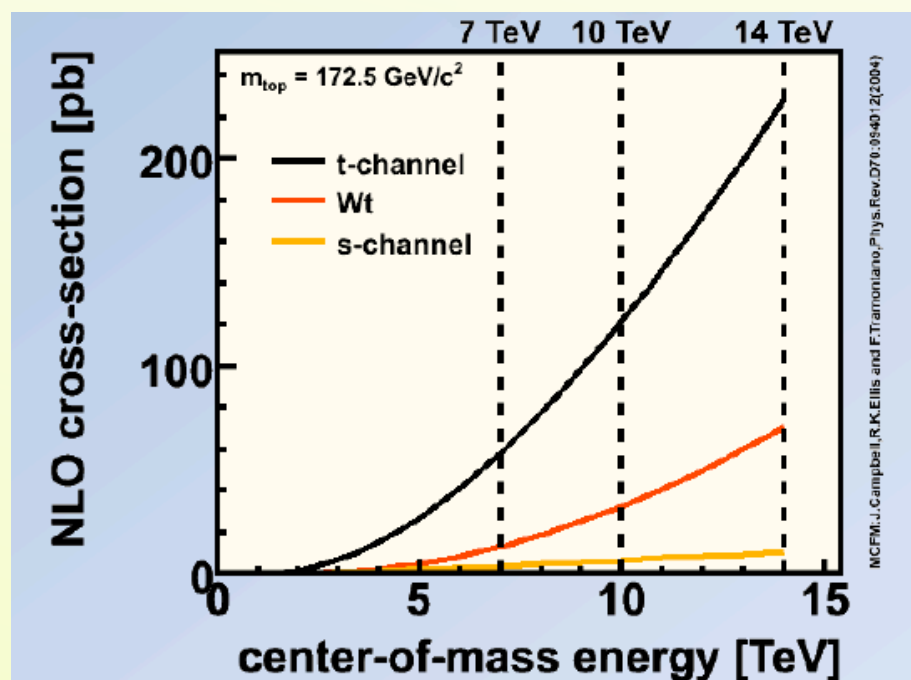
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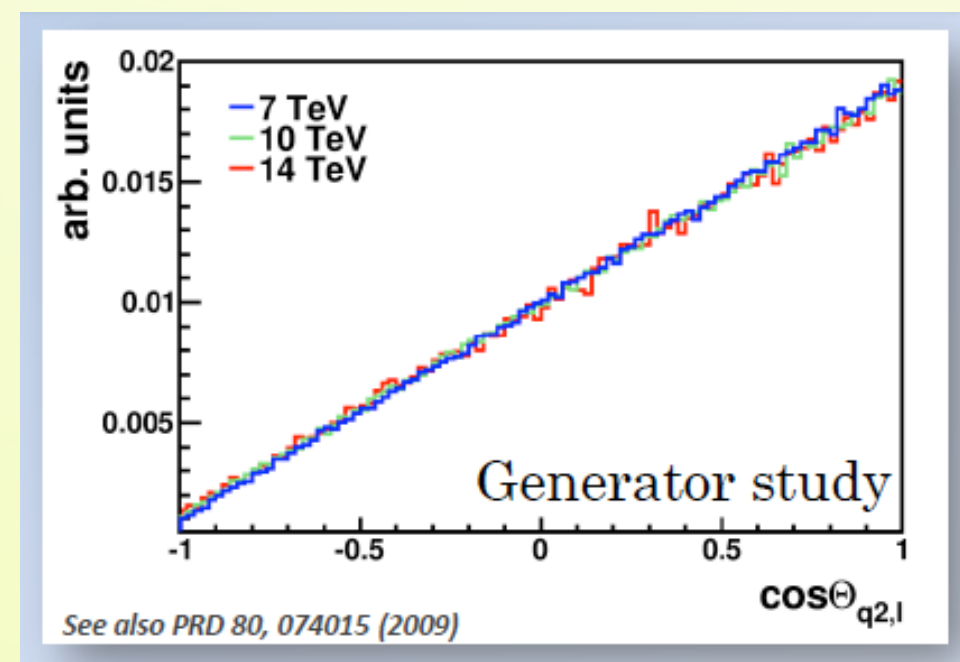
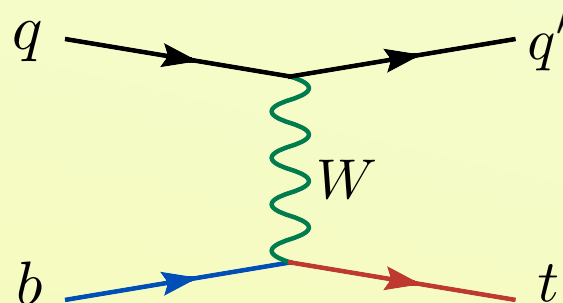
☺ All three 2→2 channels available in MC@NLO [**Frixione et al.**], w/ spin correlations!

☹ All MC implementations currently available for single top processes neglect  $m_b$ .

# Single top at the LHC

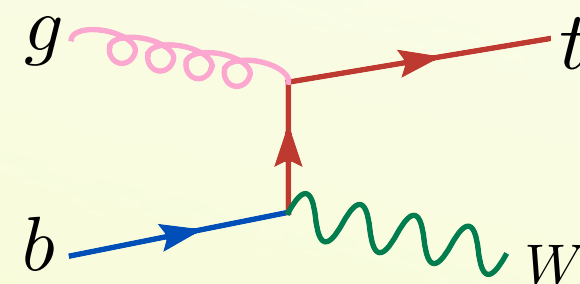
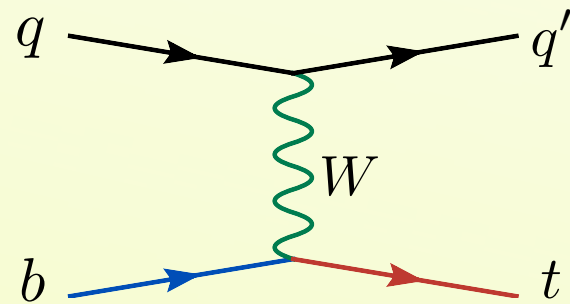


- \* t-channel has the largest cross sections
- \* forward jet + 1 lepton + 1 b + miss Et
- \* top spin inherited by the lepton!

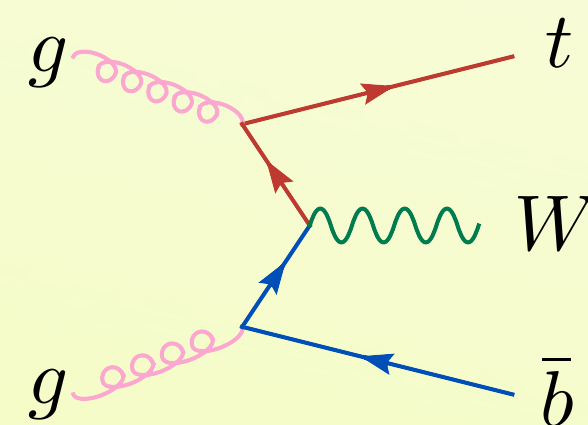
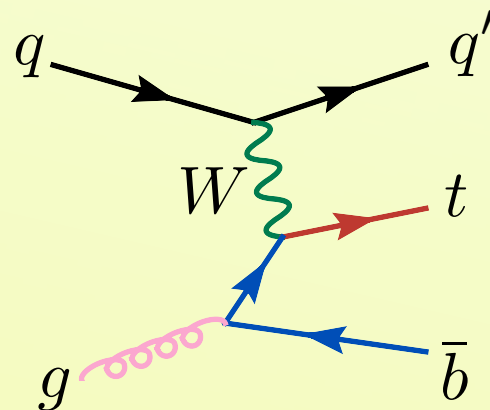


# Deeper into t-channel...

- Both the t-channel as well as the  $Wt$  associated production have a (heavy) b quark in the initial state



- There is an **equivalent**\* description with a gluon splitting to b quark pairs



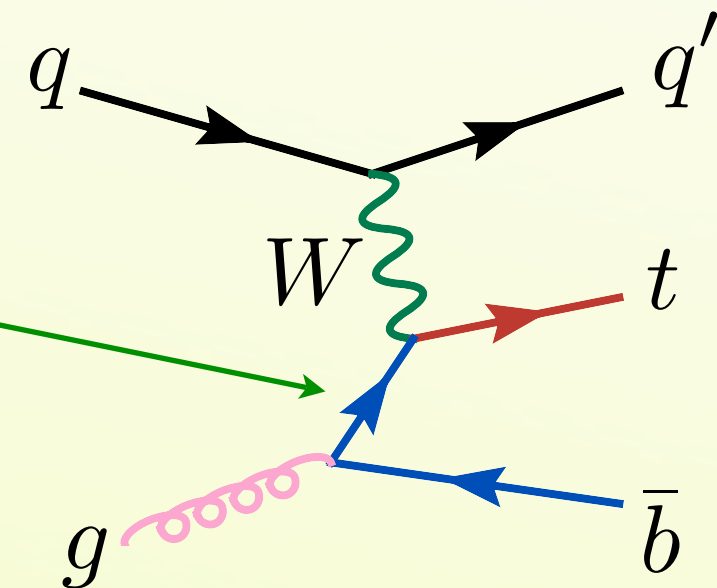
\* At all orders. At fixed order differences arise...

# Collinear logarithms

- Both t-channel and Wt production are enhanced by a collinear logarithm
- This results from integrating over a t-channel propagator

$$\frac{1}{t - m_b^2} \sim \frac{1}{p_T^2 + m_b^2}$$

$$t = (p_{\bar{b}} - p_g)^2, \quad p_T^2 = p_{T,\bar{b}}^2$$

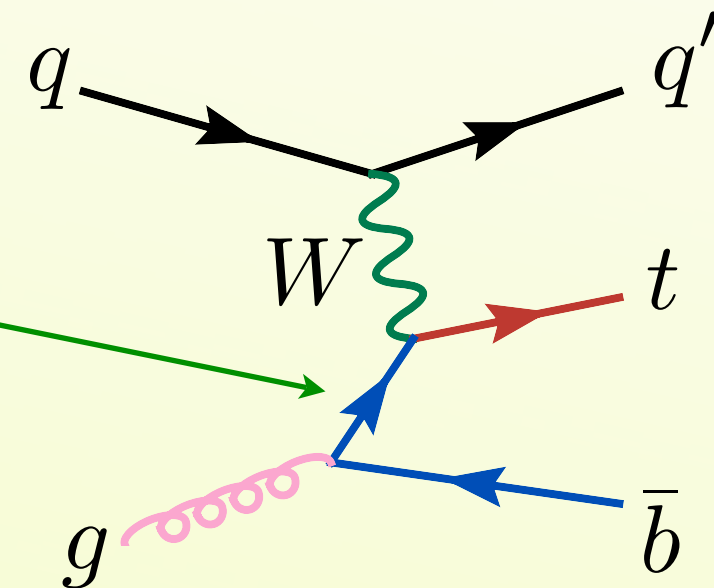


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- Coefficient of the logarithm is:

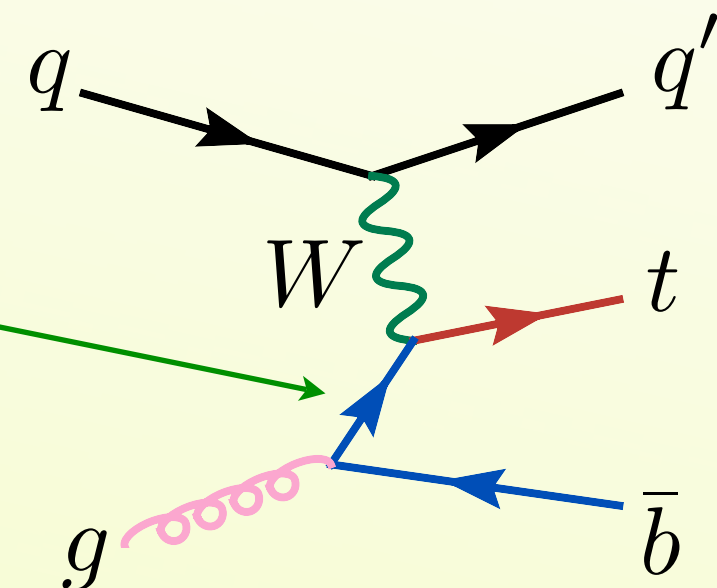


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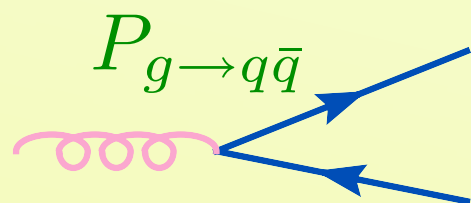
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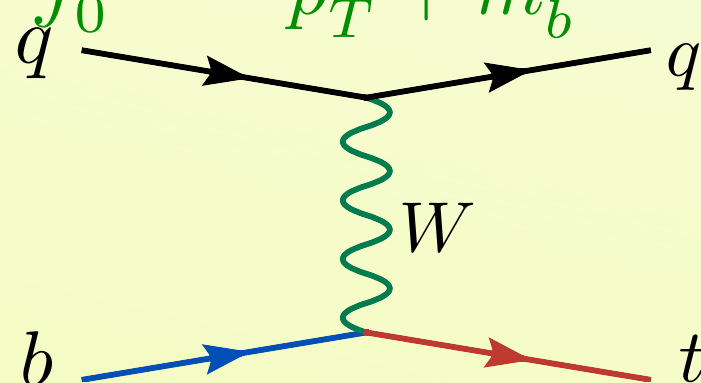


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AP splitting function



times



matrix elements with splitting removed

# Resummation into PDF

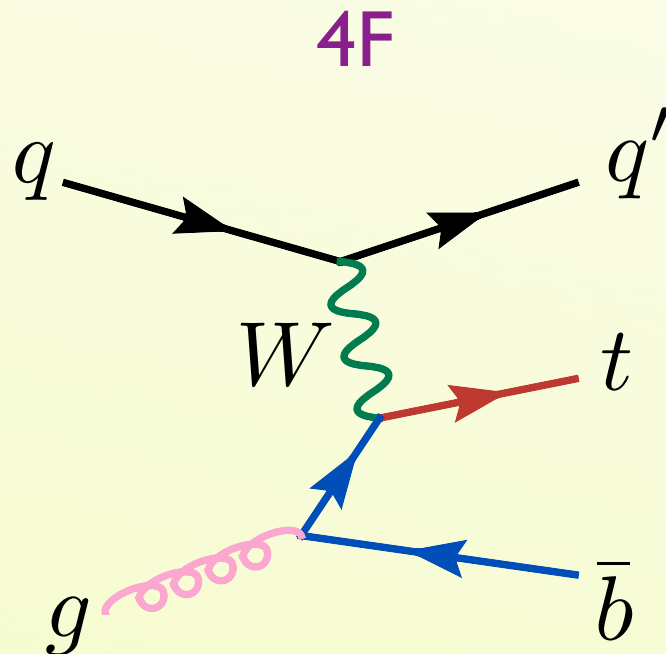
- Putting it together:  $\frac{d\sigma(qg \rightarrow q't\bar{b})}{d\log p_{T,\max}^2} \sim \left(\frac{\alpha_s}{2\pi}\right) \left[ \int \frac{dx}{x} P_{g \rightarrow q\bar{q}} f_g \right] \times \hat{\sigma}(qb \rightarrow q't)$
- But the first part resembles the evolution equation for a quark:

$$\frac{df_q}{d\log q^2} \sim \left(\frac{\alpha_s}{2\pi}\right) \int \frac{dx}{x} [P_{g \rightarrow q\bar{q}} f_g + P_{q \rightarrow qg} f_q]$$

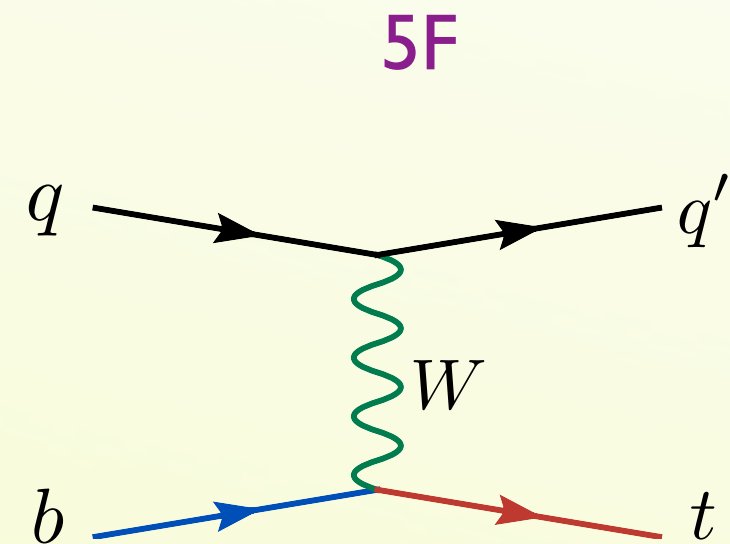
- So when the logarithms really dominate, we can replace this description by  $\sigma(qg \rightarrow q't\bar{b}) \approx \sigma(qb \rightarrow q't)$
- Scale of the bottom quark PDF should be related  $p_{T,\max}$
- At all orders both description should agree; otherwise, differ by:
  - evolution of logarithms in PDF: they are resummed
  - ranges of integration (obscured here)
  - approximation by large logarithm

# Schemes

Two different ways of computing the same quantities:



1. It does not resum (possibly) large logs ( $\Rightarrow$  norm. uncertainties)
2. Going NLO might be difficult.
3. Mass effects are there at any order in PT.
4. MC implementation with ME/PS merging a bit involved.



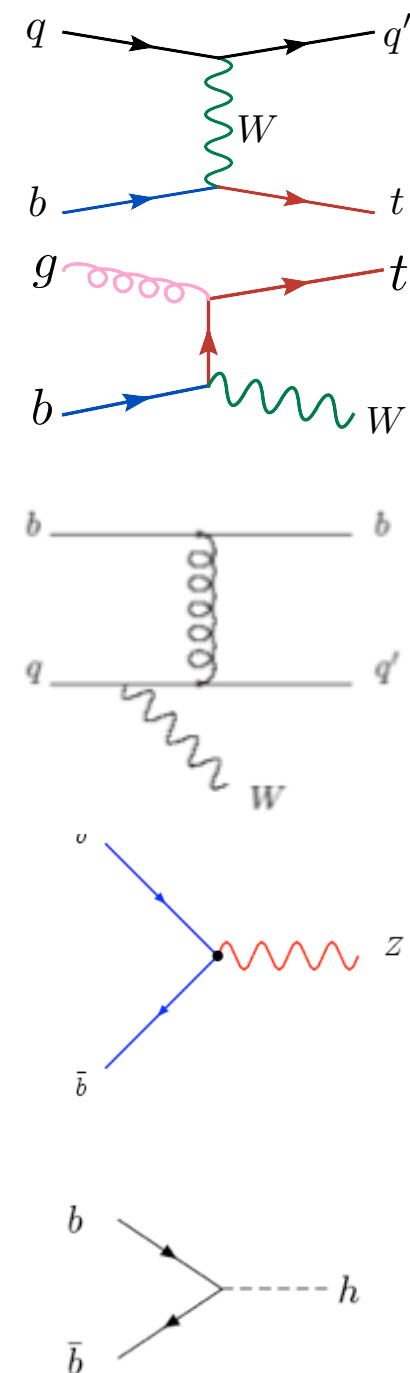
1. It resums initial state large logs in the b pdf, leading to more stable predictions
2. Going NLO (and NNLO) “easy”.
3. Mass effects are normally corrections and enter at higher orders.
4. Implementation in MC relies on mass effects given by the PS, which are presently not very accurate.

Are they really equivalent?

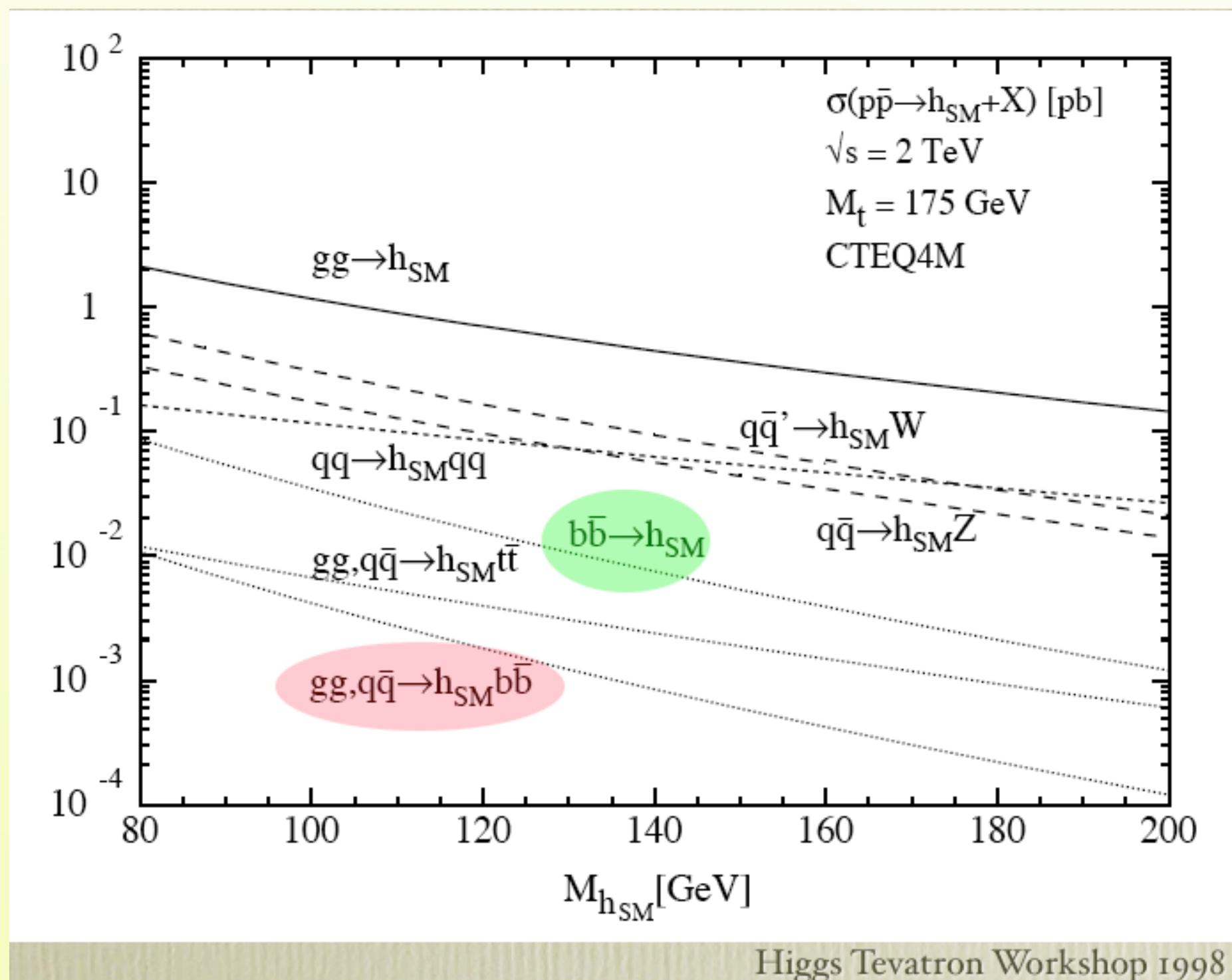


# b-initiated processes

Class	Process	Interest
Top	$qb \rightarrow tq$ (t-channel)	SM, top EW couplings and polarization, $V_{tb}$ . Anomalous couplings. $H^+$ : SUSY, 2HDM
	$gb \rightarrow t(W, H^+)$	
Vector Bosons	$pp \rightarrow Wb$ $pp \rightarrow Wbj$	SM, bkg to single top
	$bb \rightarrow Z$ $gb \rightarrow Zb$ $pp \rightarrow Zbj$	Standard candle: SM BSM bkg, b-pdf
	$gb \rightarrow \text{gamma} + b$	
Higgs	$bb \rightarrow (h, A)$ $gb \rightarrow (h, A) + b$	SUSY discovery/ measurements at large $\tan(\beta)$

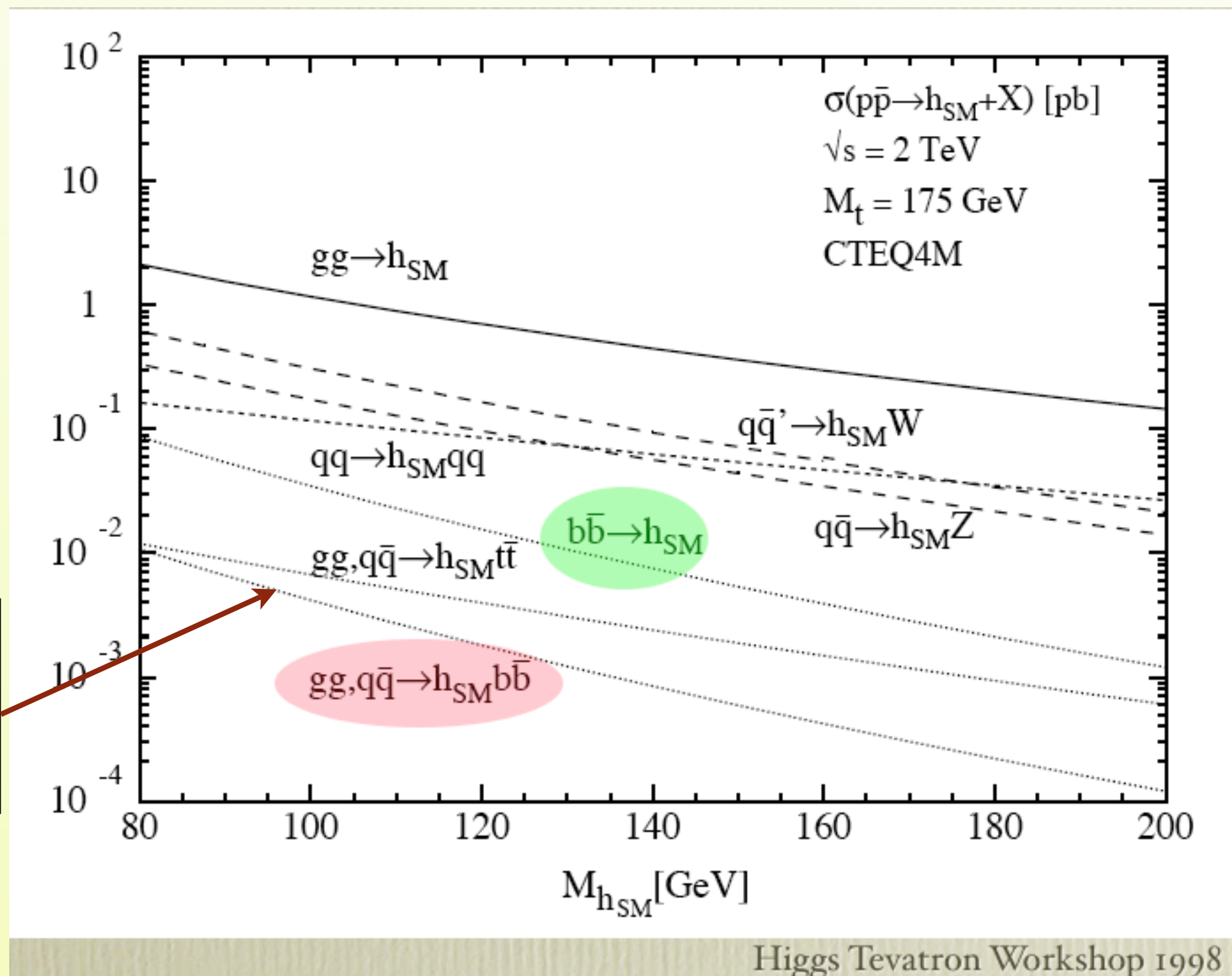


# Scheme choice in Higgs production

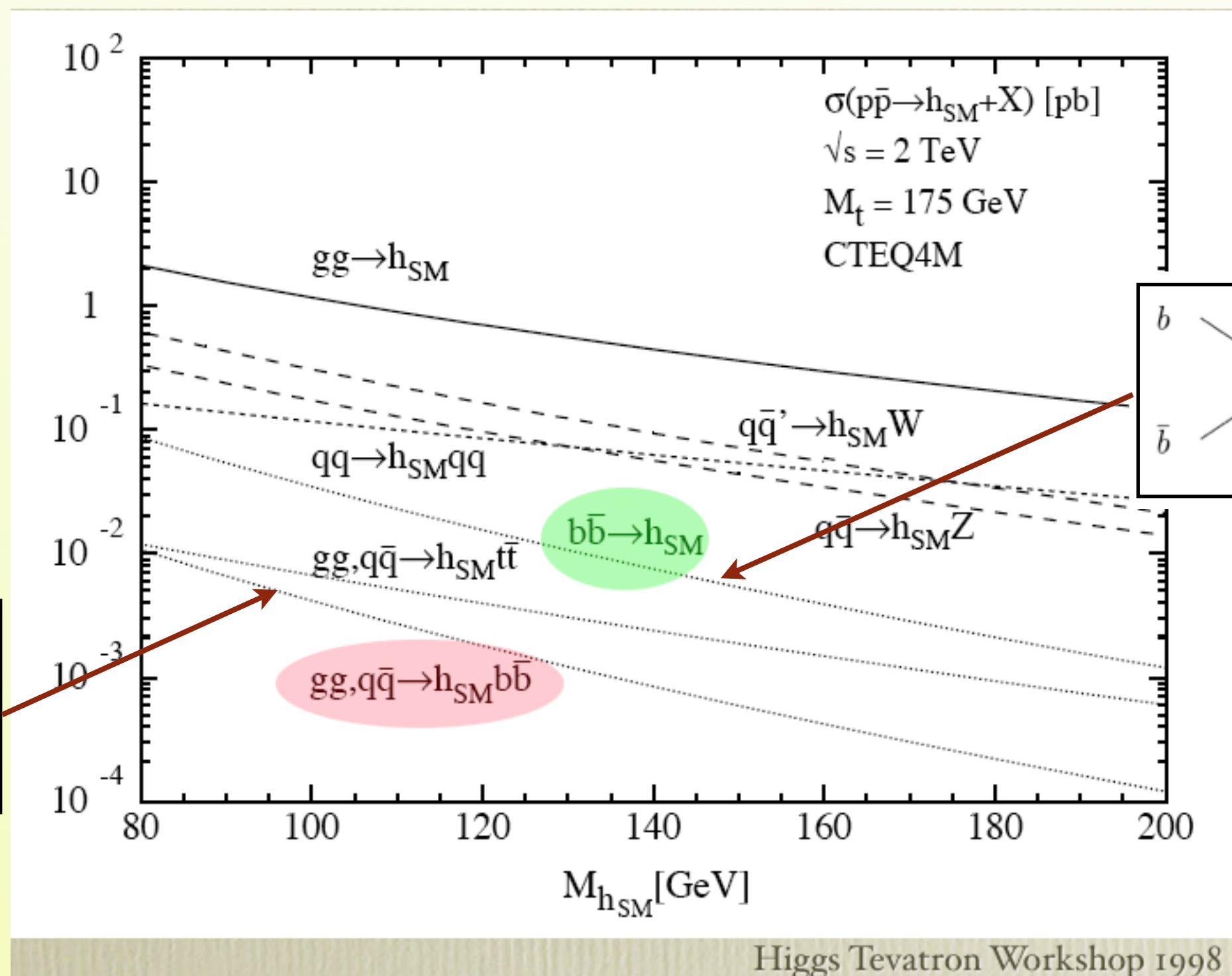




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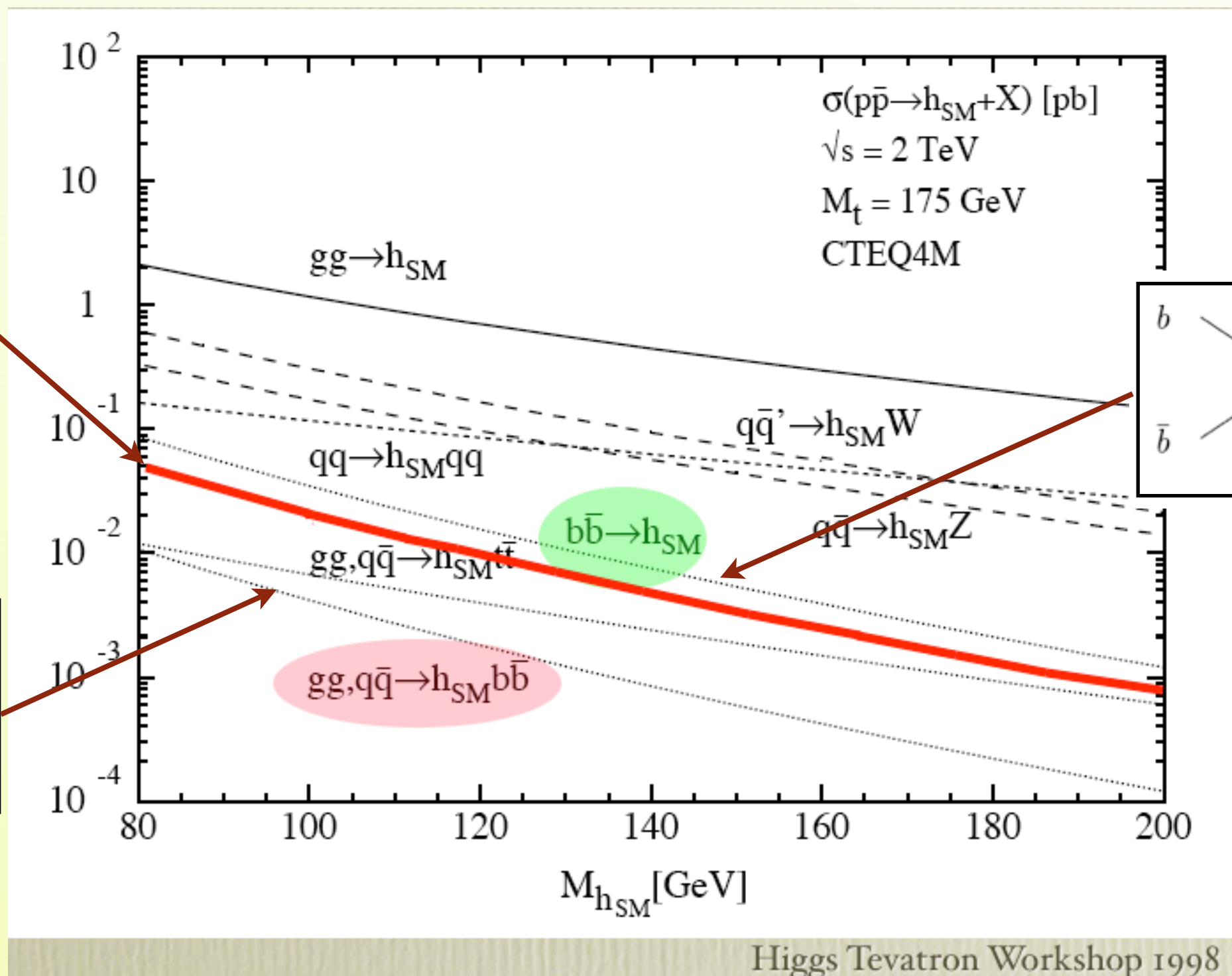


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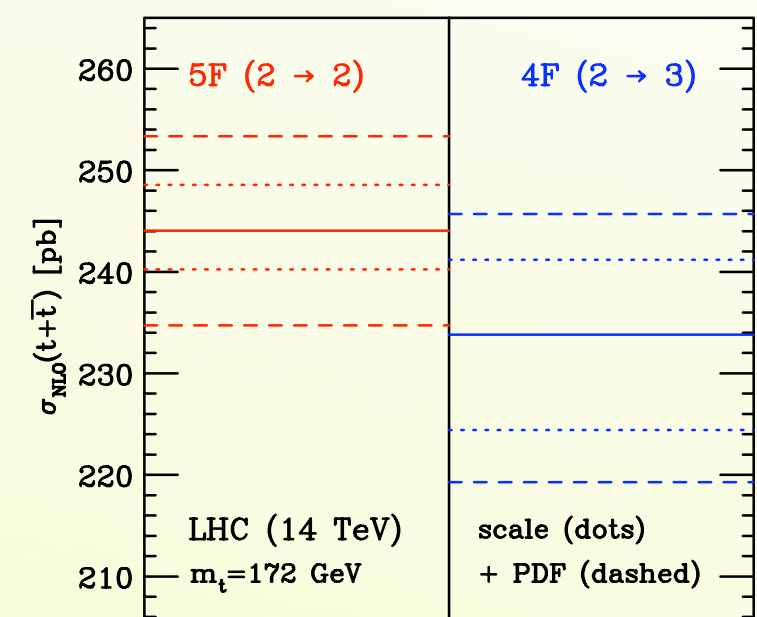
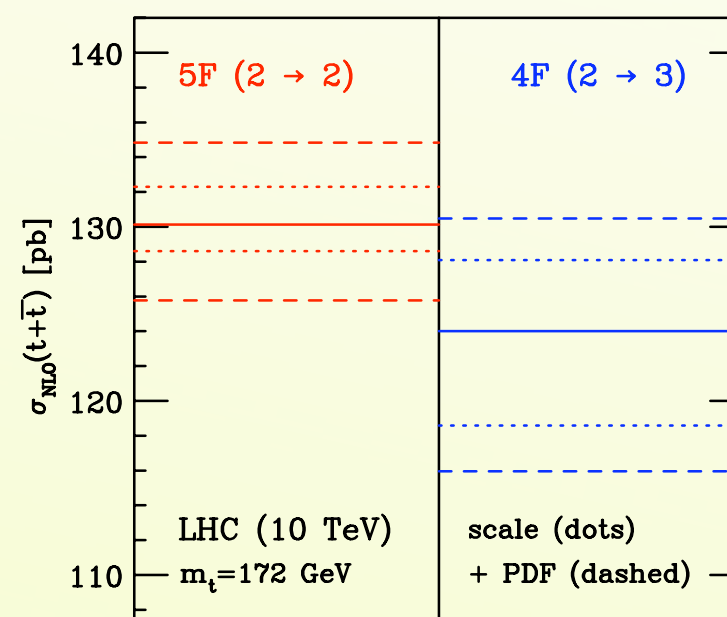
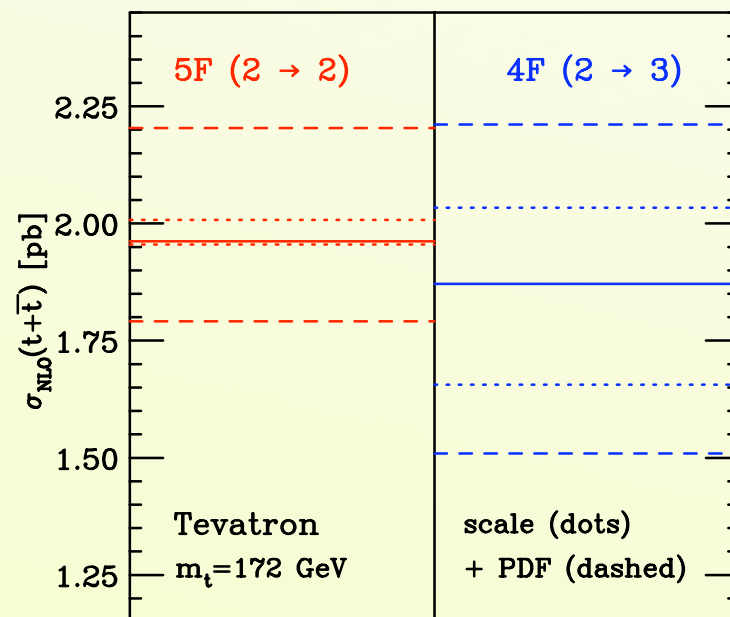
# Scheme choice in Higgs production

Les Houches 03  
HO corrections+  
Scale choice!



# t-channel best cross sections : $2 \rightarrow 2$ vs $2 \rightarrow 3$

[Campbell, Frederix, FM, Tramontano, 0907.3933]

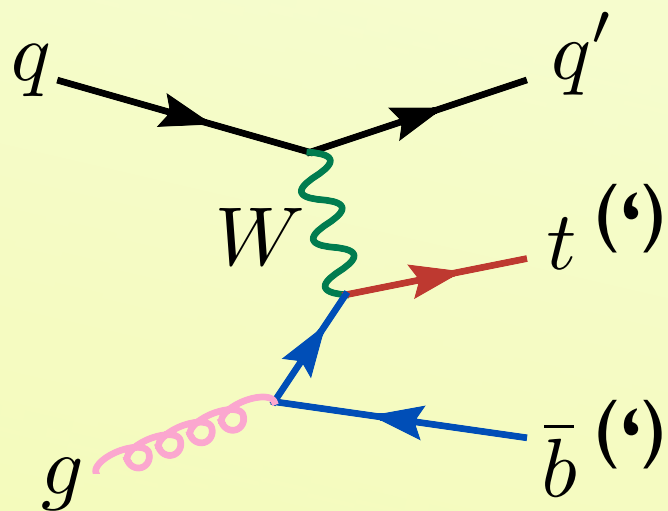
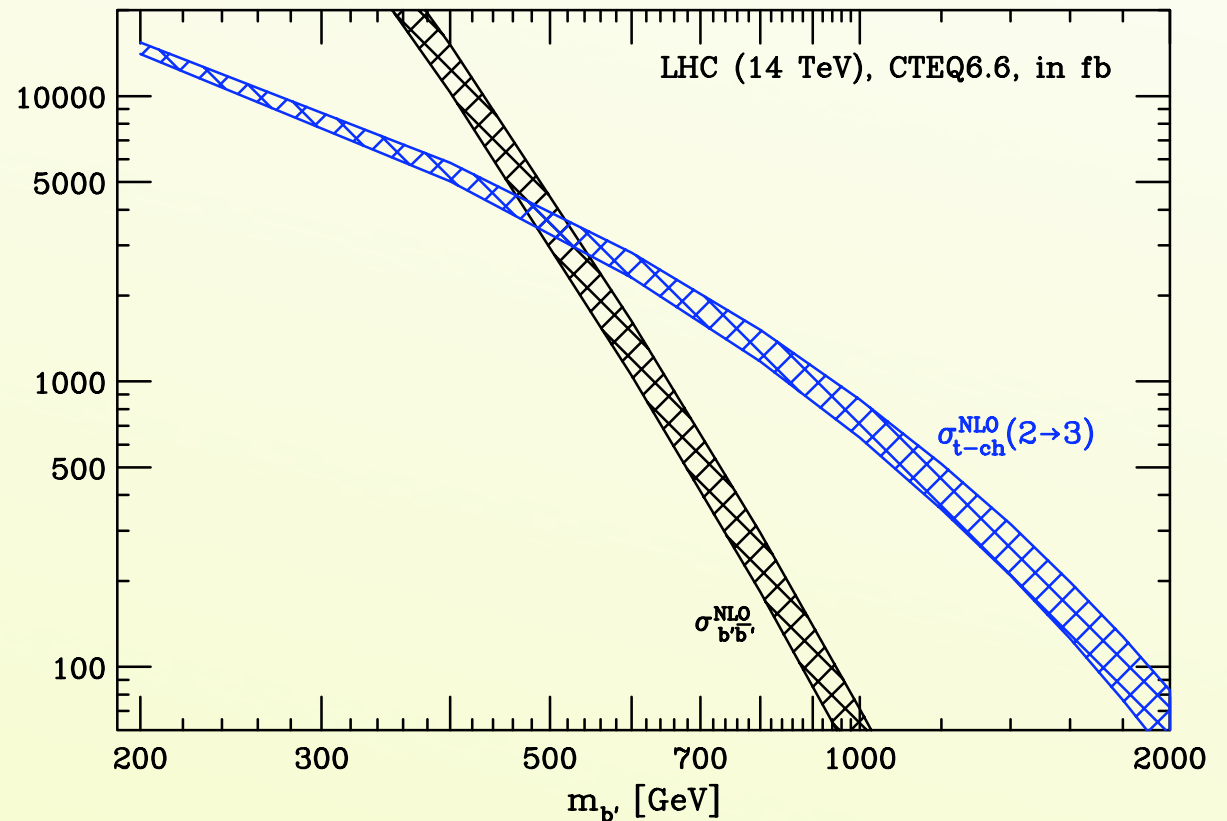
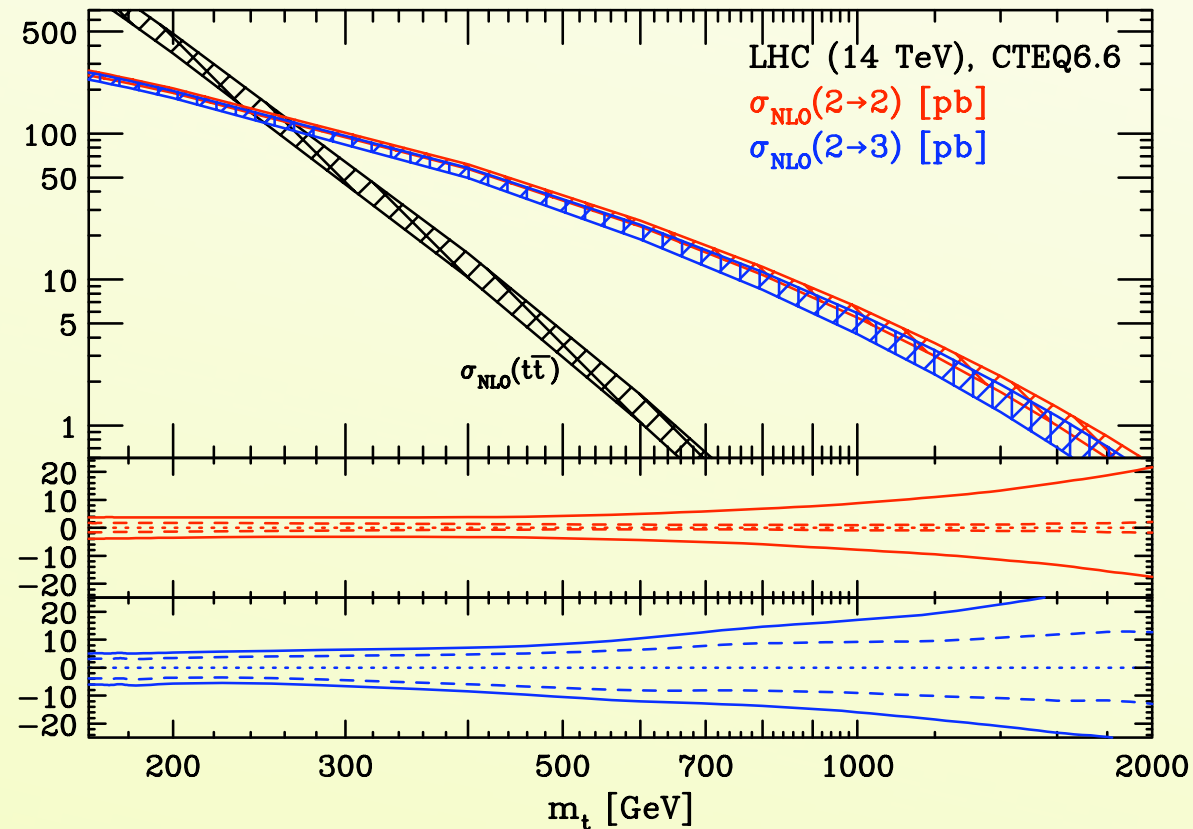


$\sigma_{t\text{-ch}}^{\text{NLO}}(t + \bar{t})$	$2 \rightarrow 2$ (pb)					$2 \rightarrow 3$ (pb)				
Tevatron Run II	1.96	$+0.05$ $-0.01$	$+0.20$ $-0.16$	$+0.06$ $-0.06$	$+0.05$ $-0.05$	1.87	$+0.16$ $-0.21$	$+0.18$ $-0.15$	$+0.06$ $-0.06$	$+0.04$ $-0.04$
LHC (10 TeV)	130	$+2$ $-2$	$+3$ $-3$	$+2$ $-2$	$+2$ $-2$	124	$+4$ $-5$	$+2$ $-3$	$+2$ $-2$	$+2$ $-2$
LHC (14 TeV)	244	$+5$ $-4$	$+5$ $-6$	$+3$ $-3$	$+4$ $-4$	234	$+7$ $-9$	$+5$ $-5$	$+3$ $-3$	$+4$ $-4$

Uncertainties: scales, PDF,  $m_t$  (1%),  $m_b$ (4%)

Upshot: two schemes agree within uncertainties. Choice on their respective use depends on the specific needs.

# Addendum: Fourth generation



The NLO  $2 \rightarrow 3$  massive calculation can be also used to make reliable predictions for  $t'b$ ,  $b't$  and  $b't'$  cross sections.

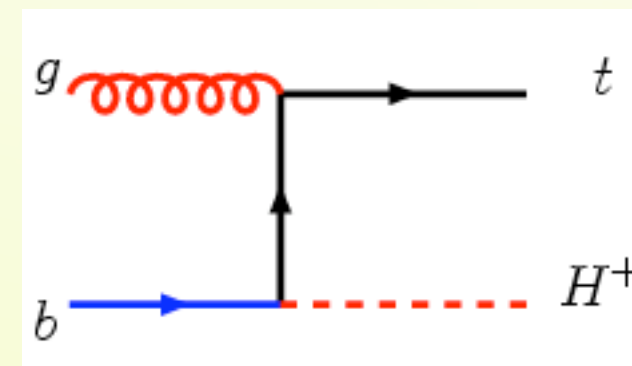
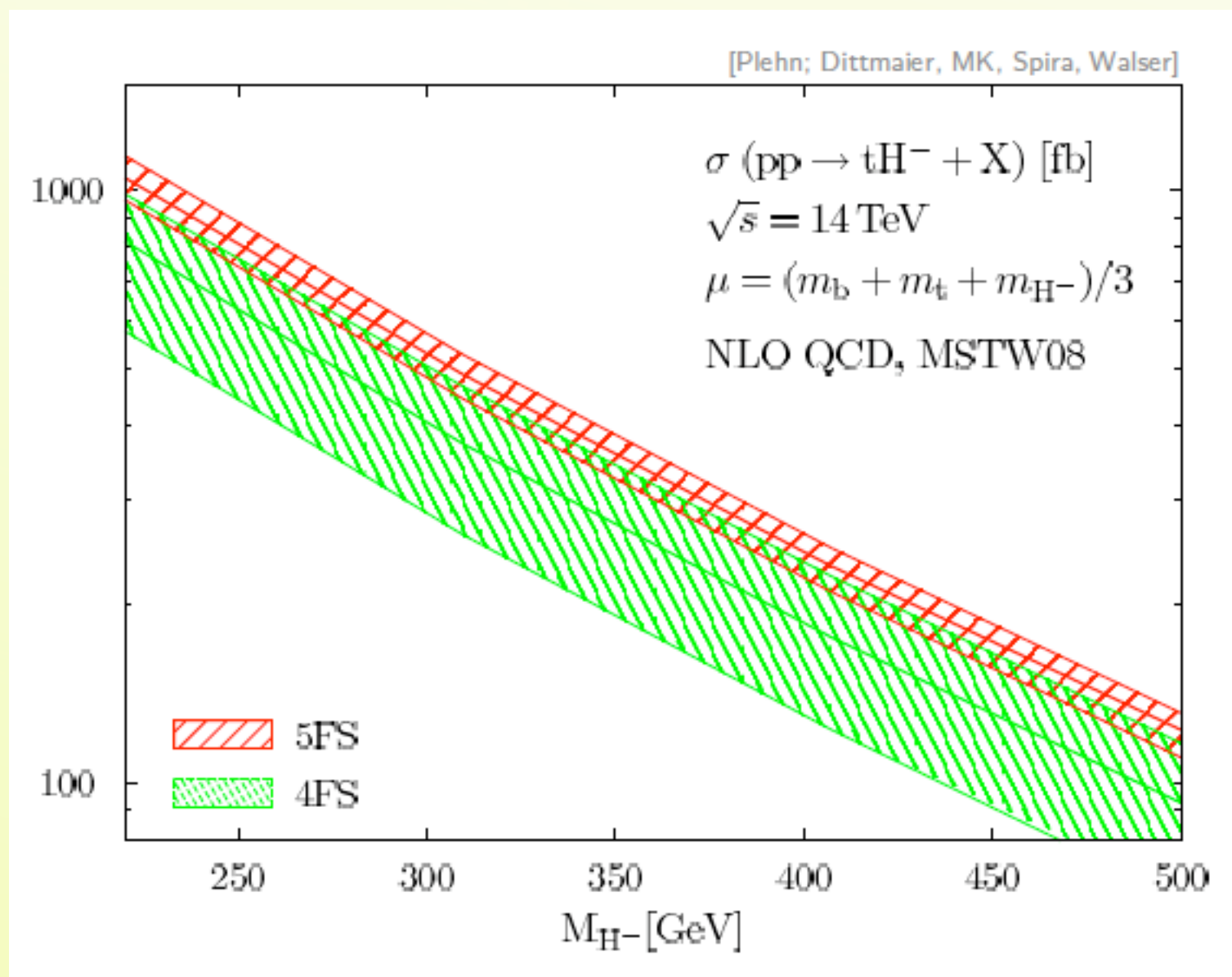
It is interesting to see where the cross over between the QCD and the EW productions are at the LHC.

In these plots all the relevant CKM elements are set to one.



# $tH^+$ in the 4F

[Dittmaier, Kramer, Spira, Walser, 2009]



Upshot: Similar results also for other processes!



# Outline

- The importance of being Top
- Truth and myths about Top
- Top in the making
- Hot Topics



# Hot TOPics

Hot TOPic #1 : Forward/Backward symmetry

Hot TOPic #2 : Boosted Tops

Hot TOPic #3 : Fourth generation

Hot TOPic #4 : ....



# Hot TOPics



Hot TOPic #1 : Forward/Backward symmetry

Hot TOPic #2 : Boosted Tops

Hot TOPic #3 : Fourth generation

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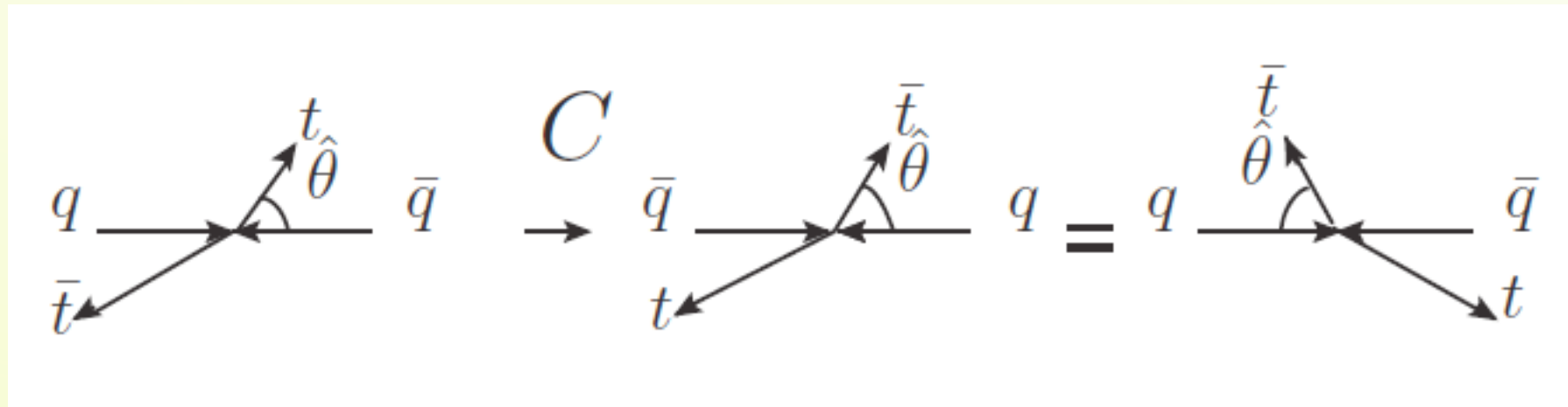


Hot TOPic #1 :

Forward-backward asymmetry

[From German, Rodrigo's review talk at top2010]

# Charge asymmetry $\Leftrightarrow$ FB asymmetry



$$\hat{A} = \frac{d\sigma_t(\cos \hat{\theta} \geq 0) - d\sigma_{\bar{t}}(\cos \hat{\theta} \geq 0)}{d\sigma_t(\cos \hat{\theta} \geq 0) + d\sigma_{\bar{t}}(\cos \hat{\theta} \geq 0)}$$

$$\hat{A}_{\text{FB}} = \frac{d\sigma_t(\cos \hat{\theta} \geq 0) - d\sigma_t(\cos \hat{\theta} \leq 0)}{d\sigma_t(\cos \hat{\theta} \geq 0) + d\sigma_t(\cos \hat{\theta} \leq 0)}$$

ok. But where does it come from?

# Charge asymmetry in QCD

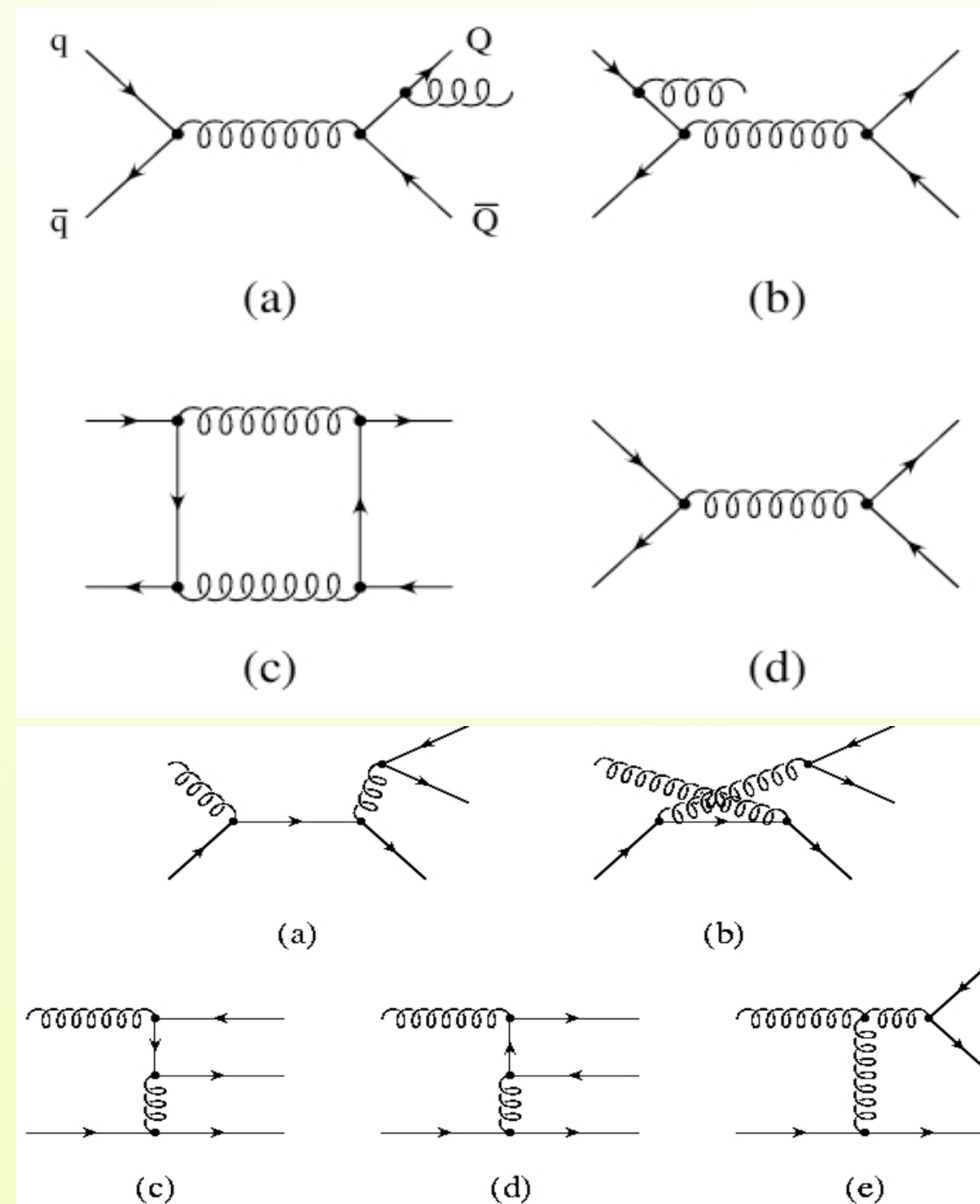
[Kühn, Rodrigo, 1998]

At  $O(\alpha_s^2)$ : top and antitop quarks have identical angular distributions.

A charge asymmetry arises at  $O(\alpha_s^3)$

1. Interference of ISR with FSR LO for  $t\bar{t}$  + jet **negative** contribution
2. Interference of box diagrams with Born **positive** contribution
3. Flavor excitation (qg channel) much smaller

Loop contribution larger than tree level: **top quarks are preferentially emitted in the direction of the incoming quark**



# Charge asymmetry in QCD

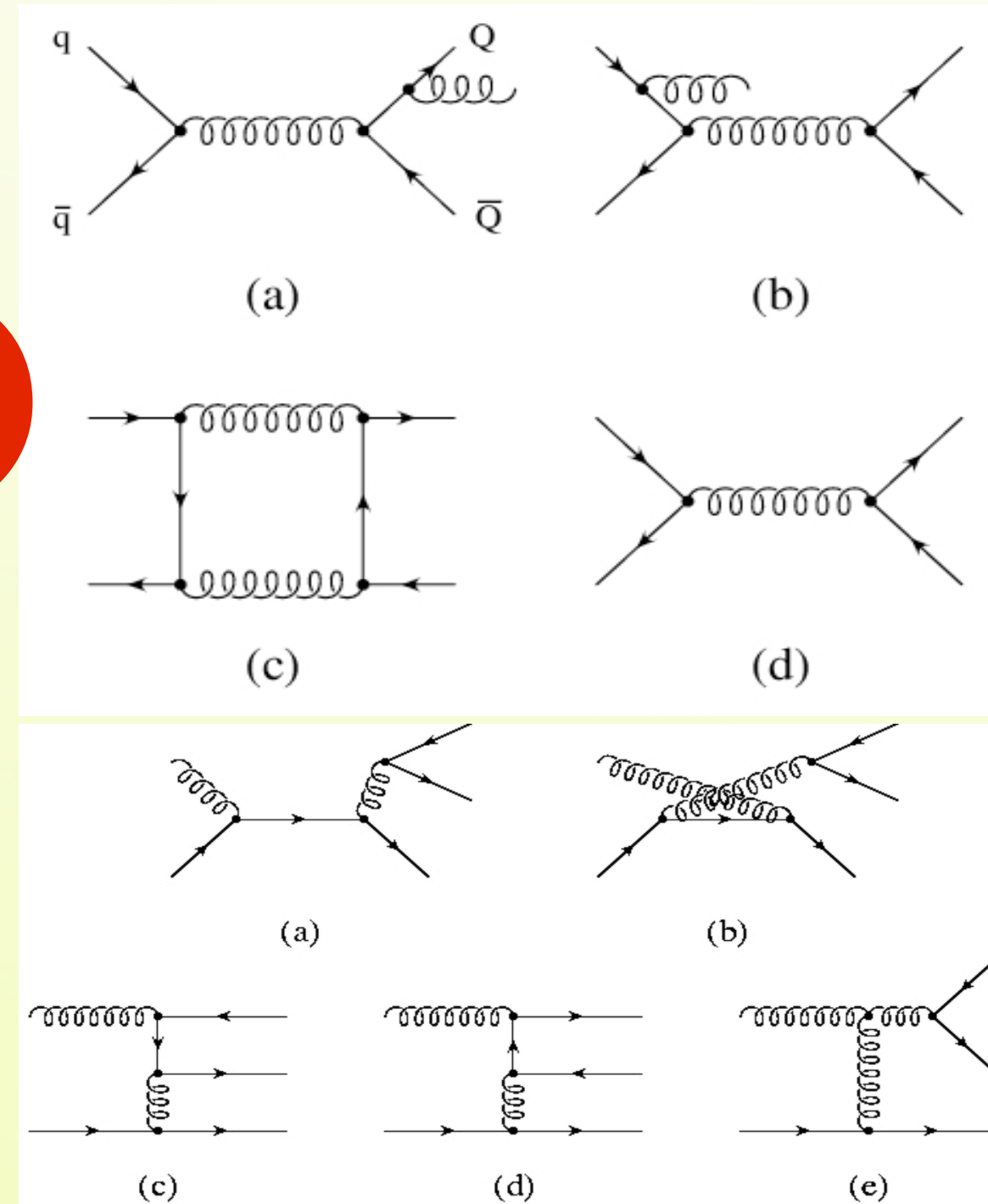
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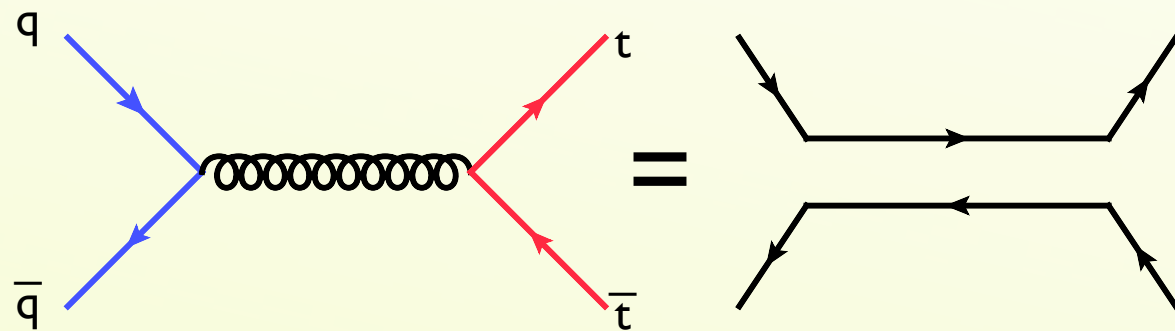
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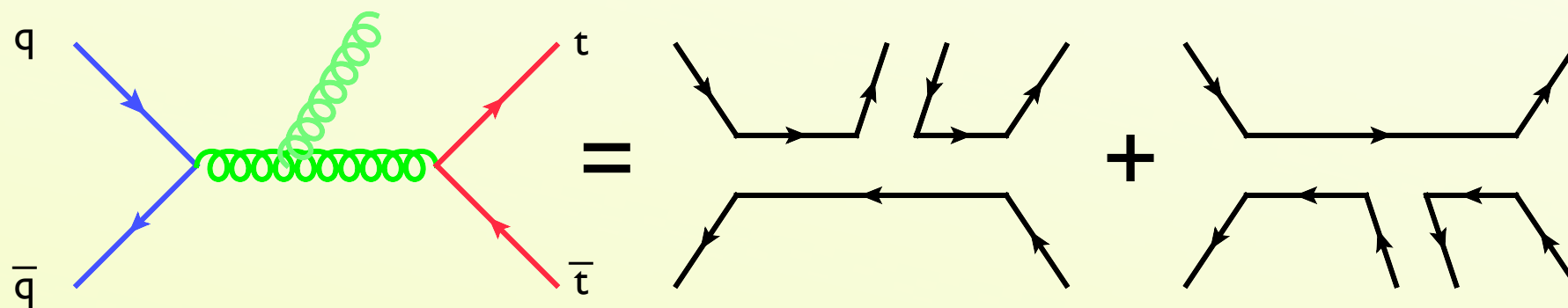
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# An intuitive picture



two color flows = two antennas



In the soft limit  $|A_{soft}|^2 \simeq |A_{born}|^2 \left( \frac{q \cdot t}{q \cdot k \ t \cdot k} + \frac{\bar{q} \cdot \bar{t}}{\bar{q} \cdot k \ \bar{t} \cdot k} \right)$   $q \cdot t = E_q E_t (1 - \cos \theta)$

The probability to emit a gluon is larger the more the top is accelerated (like in QED) and therefore going backwards, so the contribution to the  $A_{FB}$  asymmetry is negative

$$P(\text{blue arrow} \rightarrow \text{red arrow} \uparrow) < P(\text{blue arrow} \rightarrow \text{red arrow} \downarrow)$$

The virtuals have to cancel the soft divergences of the reals and therefore the contribution is of the opposite sign.



# Inclusive asymmetry at Tevatron

Charge conjugation symmetry

$$(N_{\bar{t}}(y) = N_t(-y))$$

**Forward-backward**

$$A^{p\bar{p}} = \frac{N_t(y > 0) - N_{\bar{t}}(y > 0)}{N_t(y > 0) + N_{\bar{t}}(y > 0)} = 0.051(6)$$

$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = 0.078(9) \quad \Delta y = y_t - y_{\bar{t}}$$

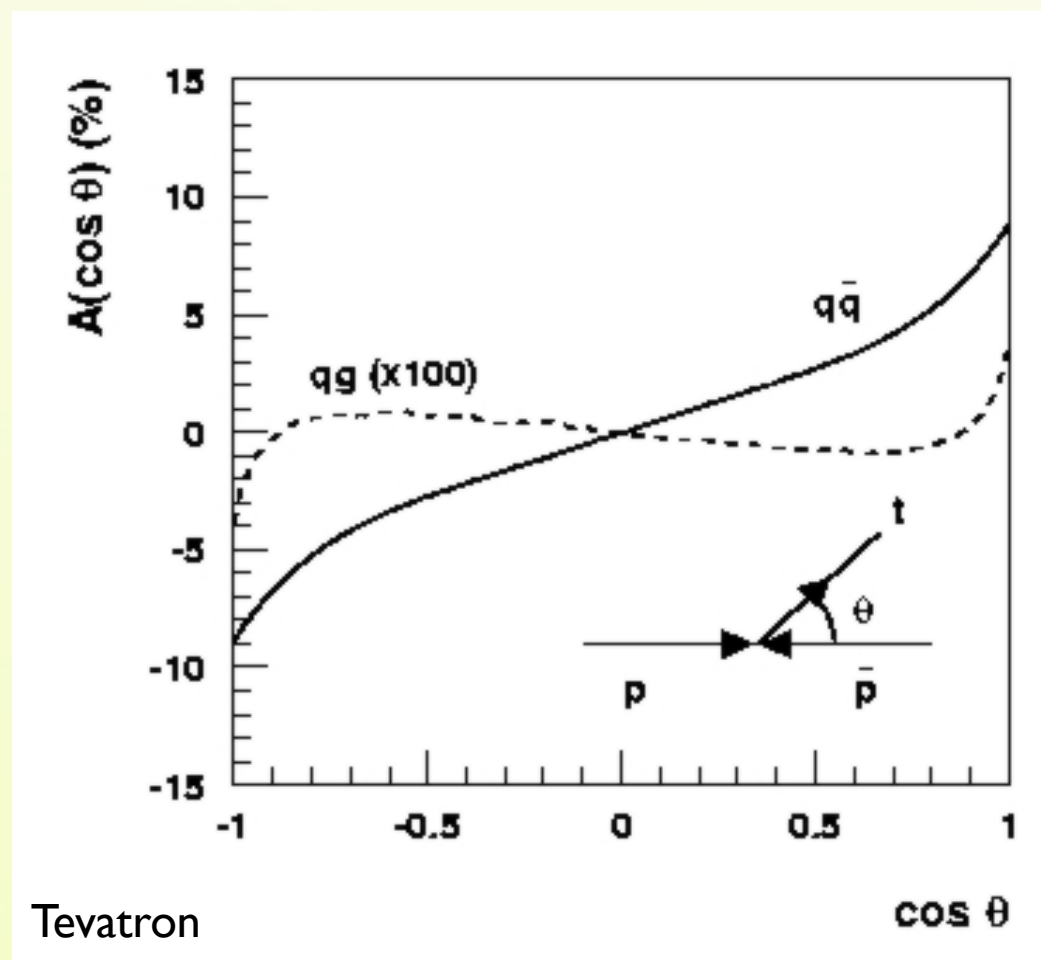
- mixed QCD-EW interference: factor 1.09 included
- stable to NLL threshold resummations (one per mille) [Almeida, Stermann, Vogelsang, 2008]
- NNLL threshold resummations [Ahrens, Ferroglia, Neubert, Pecjak, Yang, 2010]

Not expanding the asymmetry in  $\alpha_s$  : the asymmetry decreases by 20% at NLO (K factor), but only by 5% at NLO+NNLL

- In any case, remember that INFACCT this observable is known only at leading order!!!

[Kühn, Rodrigo, 1998]

[Antuñano, Kühn, Rodrigo, 2008]

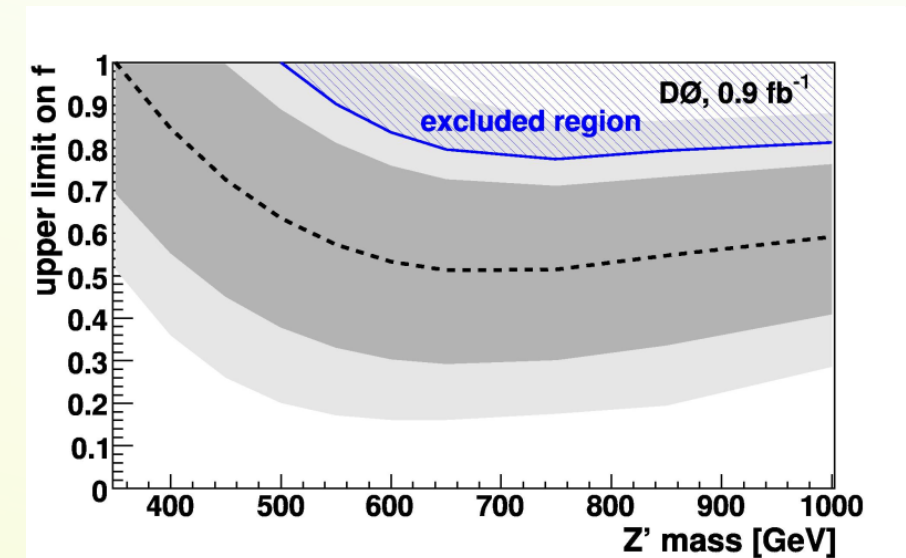


# Asymmetry measurements at Tevatron

- D0** [PRL101(2008)202001]

$$A_{FB}^{ppbar} = 0.12 \pm 0.08 \text{ (stat)} \pm 0.01 \text{ (syst)} \quad 0.9 \text{ fb}^{-1}$$

Limits as a function of the fraction (f) of ttbar events produced via a topcolor leptophobic Z' resonance



- CDF** [Conf. Note 9724, PRL101(2008)202001]

ppbar rest frame

$$A_{FB}^{ppbar} = 0.193 \pm 0.065 \text{ (stat)} \pm 0.024 \text{ (syst)} \quad 3.2 \text{ fb}^{-1}$$

$$A_{FB}^{ppbar} = 0.17 \pm 0.07 \text{ (stat)} \pm 0.04 \text{ (syst)} \quad 1.9 \text{ fb}^{-1}$$

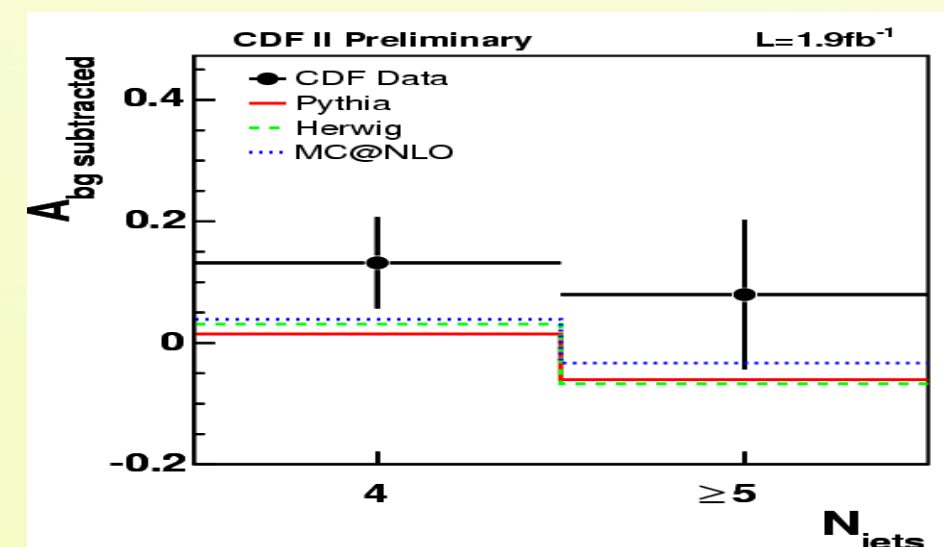
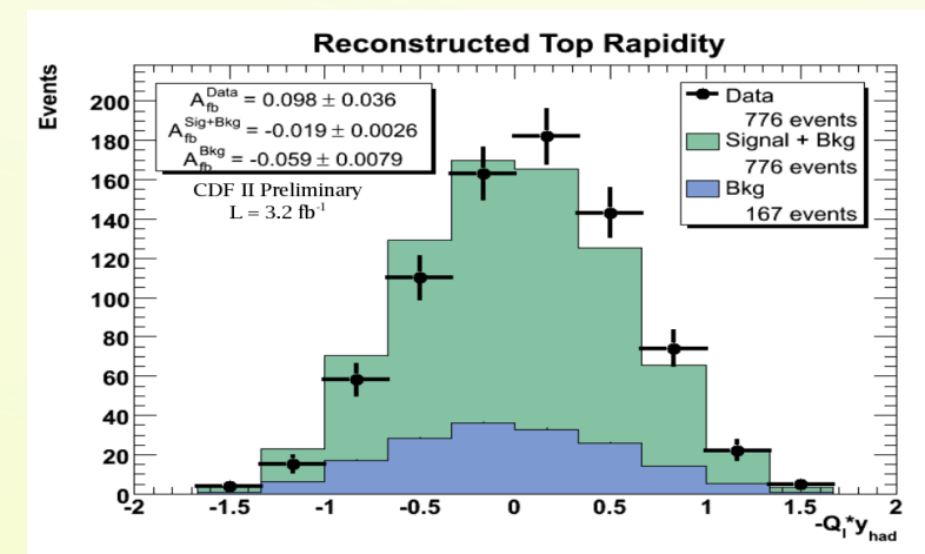
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At least 4 jets:  $A_{FB}^{ttbar} = 0.119 \pm 0.064 \text{ (stat)}$

Exact 4 jets:  $A_{FB}^{ttbar} = 0.132 \pm 0.075 \text{ (stat)}$

At least 5 jets:  $A_{FB}^{ttbar} = 0.079 \pm 0.123 \text{ (stat)}$

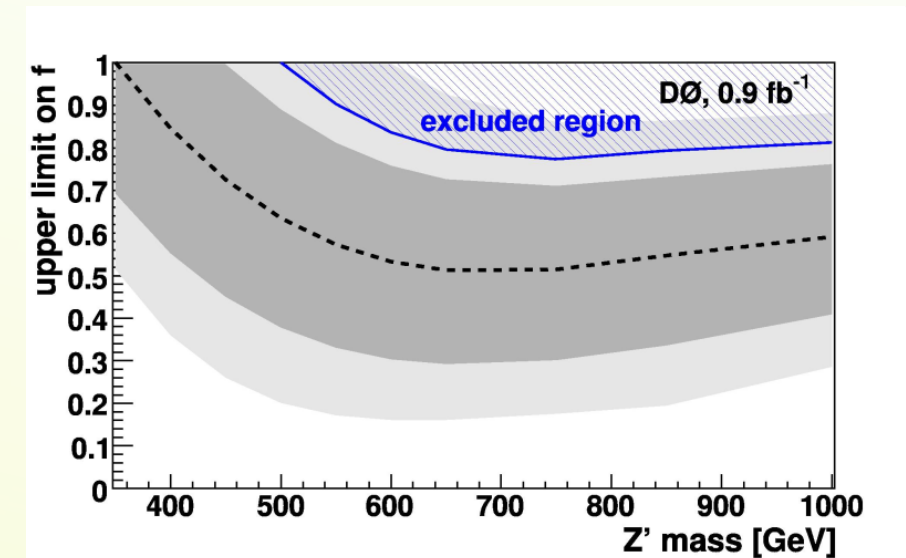


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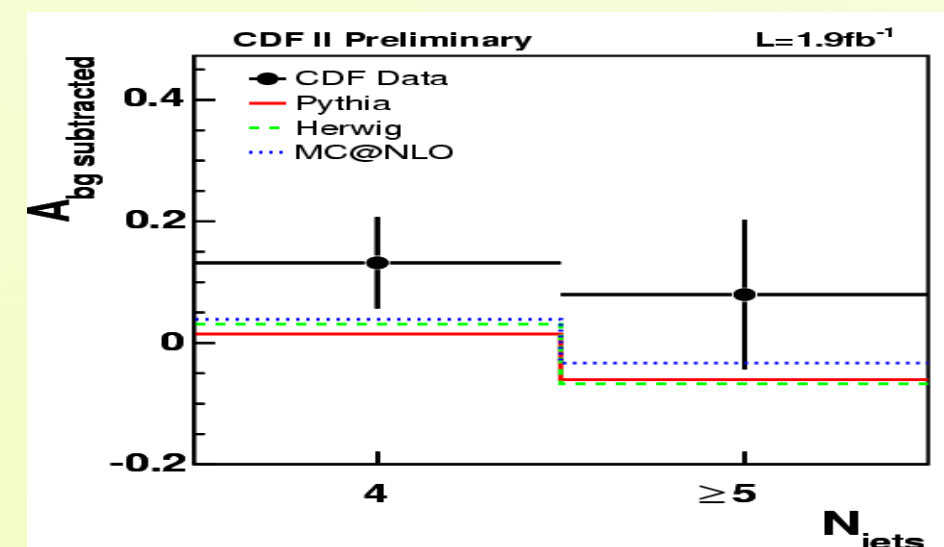
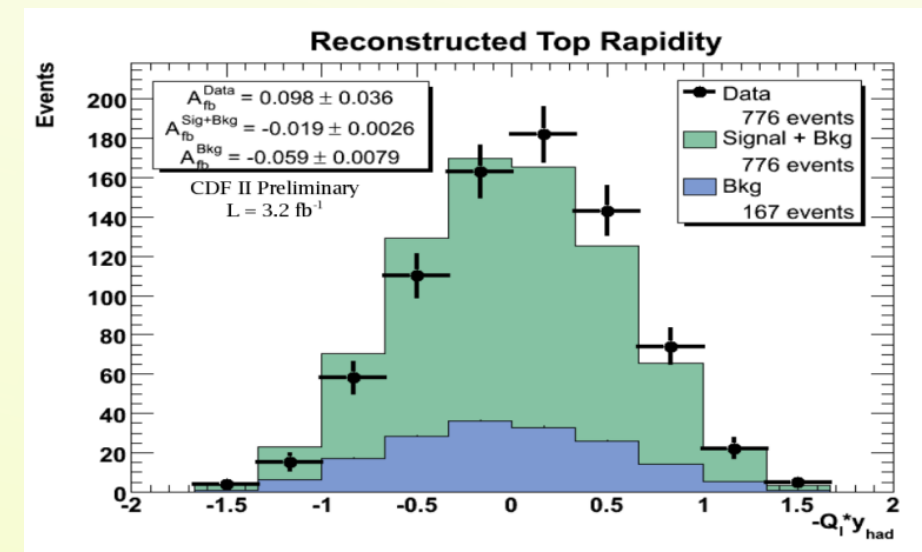
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$$2.8\sigma \text{ from zero, } (A^{\text{exp}} - A^{\text{SM}})_{\text{ppbar}} = 0.142 \pm 0.069$$

room for BSM within  $2\sigma$



# Massive gluon diff cross section

Resonances might produce charge asymmetry at LO

$$L = g_S T^a \bar{q}_i \gamma^\mu (g_V^{qi} + g_A^{qi} \gamma^5) G'_\mu q_i$$

- Quark-antiquark annihilation

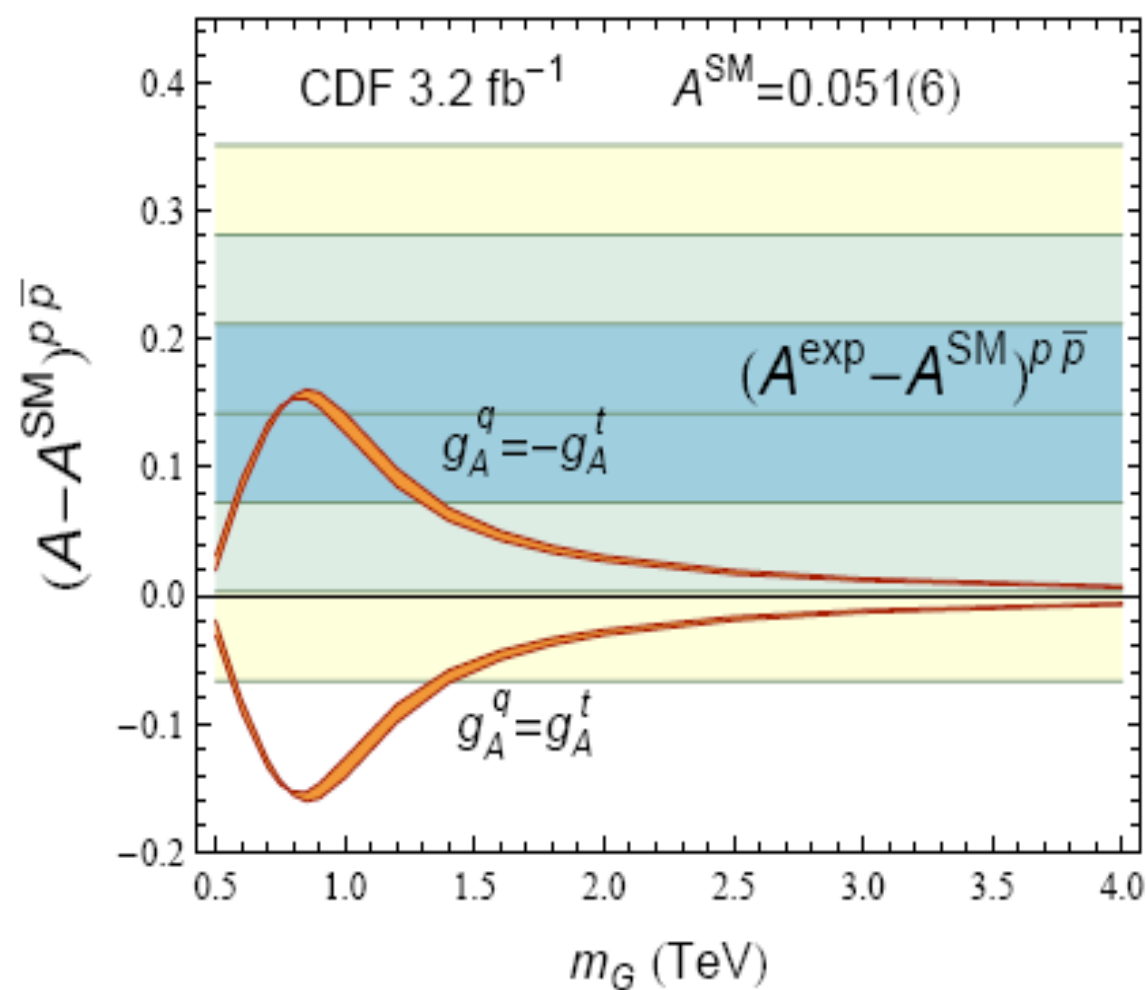
$$\begin{aligned} \frac{d\sigma^{q\bar{q} \rightarrow t\bar{t}}}{d\cos\theta} = & \alpha_s^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \left( 1 + c^2 + 4m^2 + \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \left[ g_V^q g_V^t (1 + c^2 + 4m^2) + g_A^q g_A^t (2c) \right] \right. \\ & + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \left[ \left( (g_V^q)^2 + (g_A^q)^2 \right) \left( (g_V^t)^2 (1 + c^2 + 4m^2) + (g_A^t)^2 (1 + c^2 - 4m^2) \right) \right. \\ & \left. \left. + g_V^q g_A^q g_V^t g_A^t (8c) \right] \right] \end{aligned}$$

where

$$m = \frac{m_t}{\sqrt{\hat{s}}} \quad c = \beta \cos\theta = \sqrt{1 - 4m^2} \cos\theta \quad \frac{\Gamma_G}{m_G} \approx \frac{\alpha_s}{6} \sum_{i=q,t} \left( (g_V^i)^2 + (g_A^i)^2 \right)$$

- gluon-gluon fusion at tree-level the same as in the SM  
(gauge invariance, parity, orthonormality of field profiles in extra dimensions)

# Axigluons?



- The FB asymmetry disfavour at  $2\sigma$  vanishing or negative contributions (axigluons or colorons)

$$m_G > 1.6 \text{ TeV at } 99\% \text{C.L.} \quad (g_V=0, g_A=1)$$

- Larger exclusion limit than dijet channel.

- It is still possible to generate a positive asymmetry

$$\text{if } \text{sign}(g_A^q) = -\text{sign}(g_A^t)$$

[Ferrario, Rodrigo, arXiv:0906.5541]

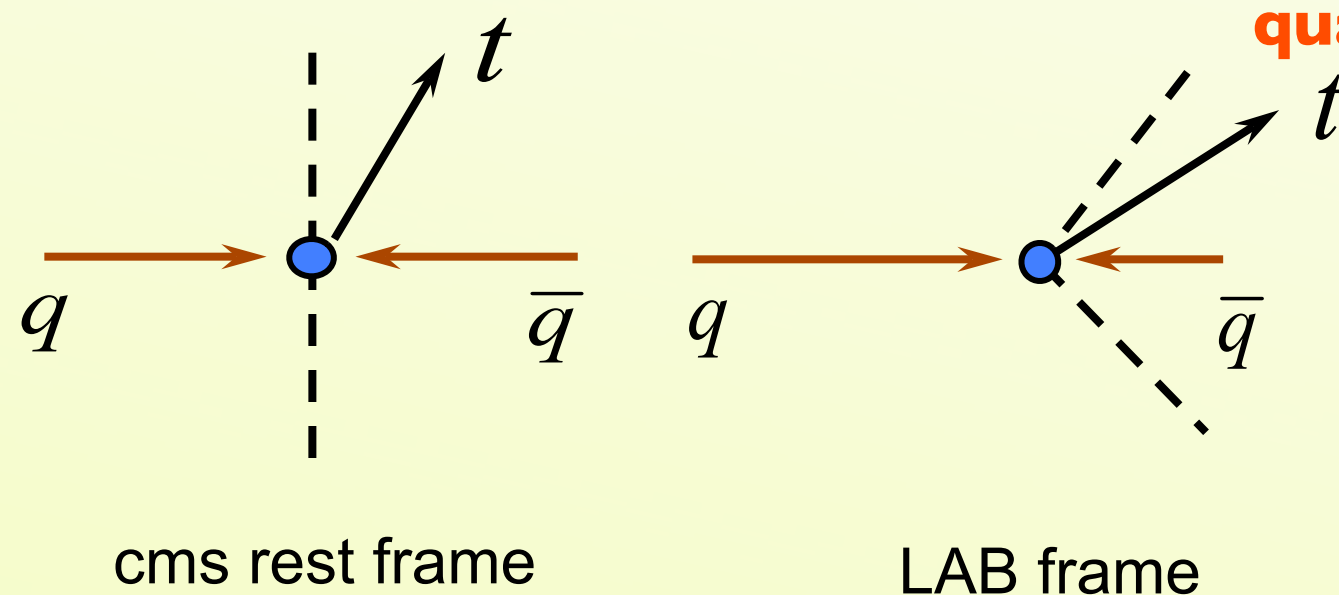
[Frampton, Shu, Wang, arXiv:0911.2955]



# Charge asymmetry at LHC

**LHC is symmetric  $\Rightarrow$  no forward-backward**

But suppose that there is a charge asymmetry at parton level (QCD predicts that tops are preferentially emitted in the direction of incoming quark, resonance asymmetry positive/negative on (s-m<sub>G</sub>) and relative sign of couplings)



**quarks carry more momenta than antiquarks**



- Excess of tops (or antitops) in the forward and backward regions

$$A_C(y_C) = \frac{N_t(|y| < y_C) - N_{\bar{t}}(|y| < y_C)}{N_t(|y| < y_C) + N_{\bar{t}}(|y| < y_C)}$$

$$A_C(y_C \gg 1) = 0$$

Opposite in sign to the parton asymmetry

- However, top cross section is gg dominated, which is symmetric; but gg can be suppressed by selecting pairs with large invariant mass



# Conclusions

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- Top is the perfect lab where to test our understanding of EW and QCD.
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and if you really become crazy about Top...

 $t$ 

*Acrylic felt with  
gravel fill for  
maximum mass.*

PLUS SHIPPING



HEAVY

# The PARTICLE ZOO

# Cargese 2010