Top Quark and Hunting for New physics

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TERAWORLD
UED
HIGGS
VTC
SUSY
LH

Outline

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

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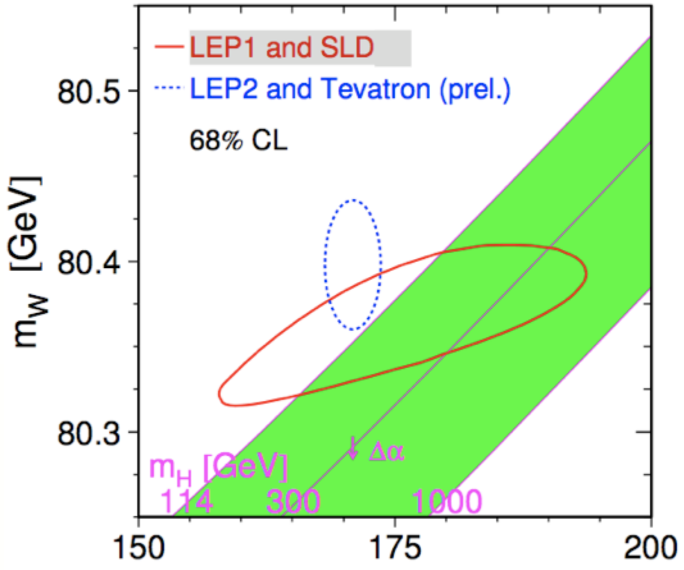
Top Physics aims

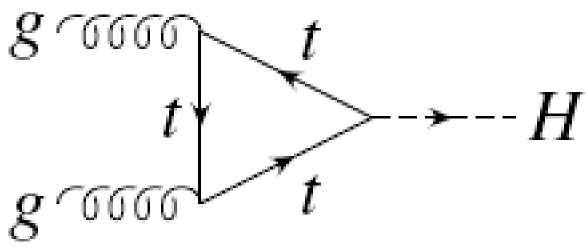
I. Measure all properties (mass, couplings, spin) to establish indirect evidence for SM and BSM physics.

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

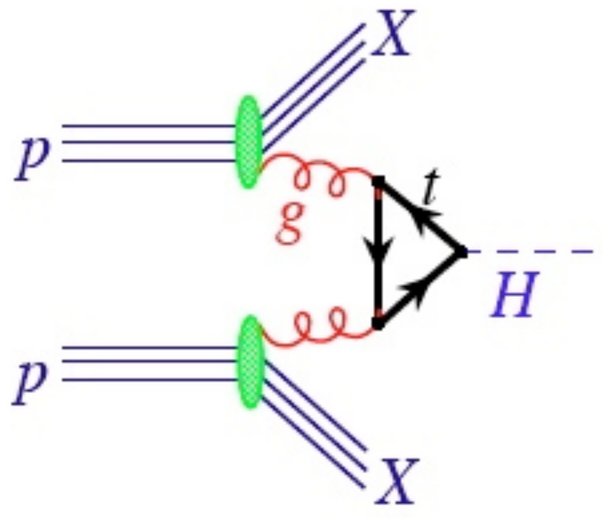


II. Use top as direct probe of the EWSB sector and BSM physics

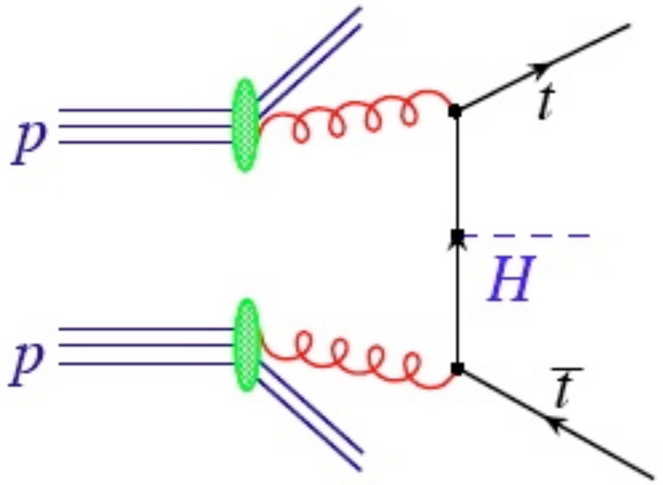
SM : ttH; tH
BSM: Z’ and W’ resonances;
SUSY: tH$^+$ and t→bH$^+$ or
stop →t X.

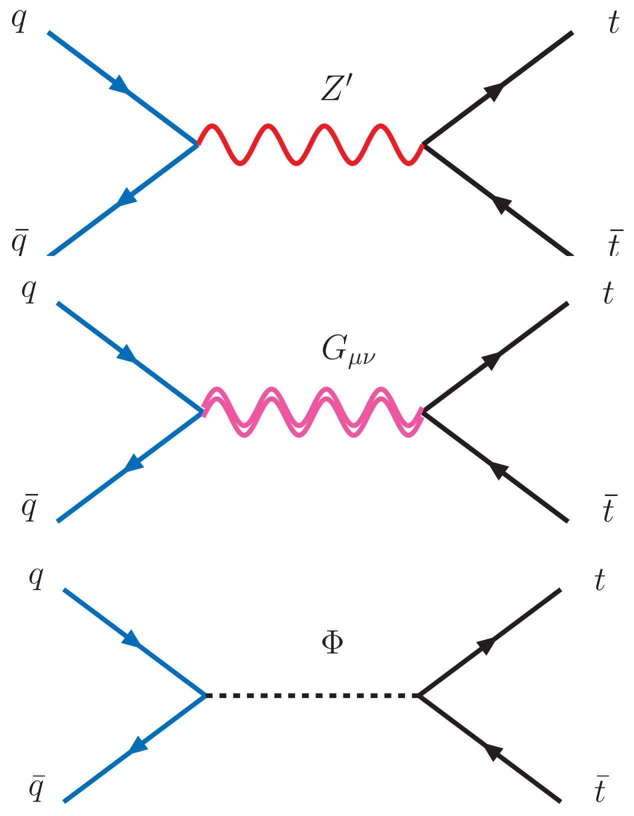


Top Physics aims II : direct probe

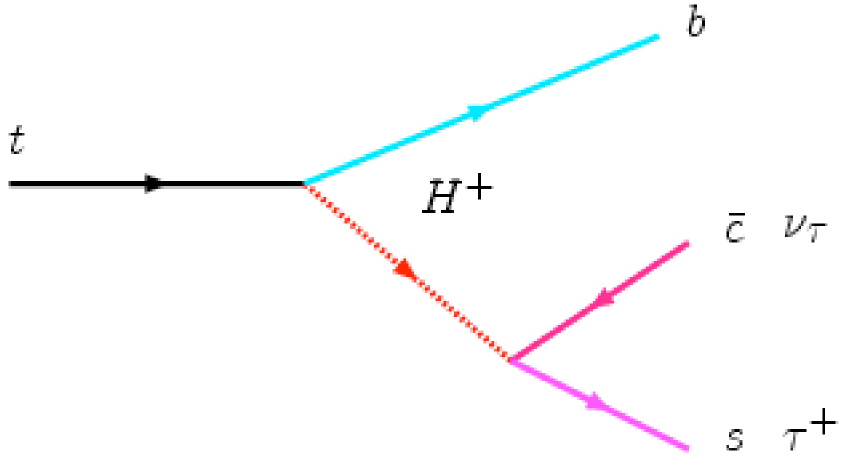


Exciting the Higgs



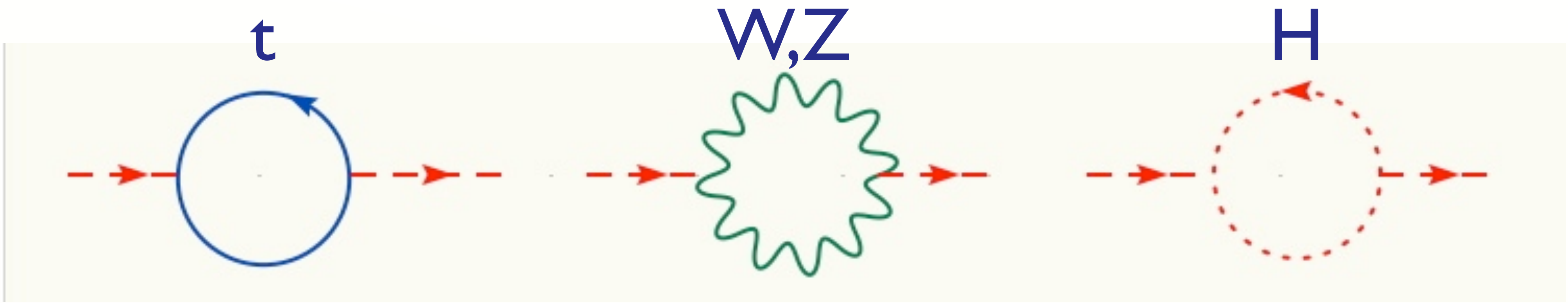


Exciting new degrees
of freedom



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 Λ:



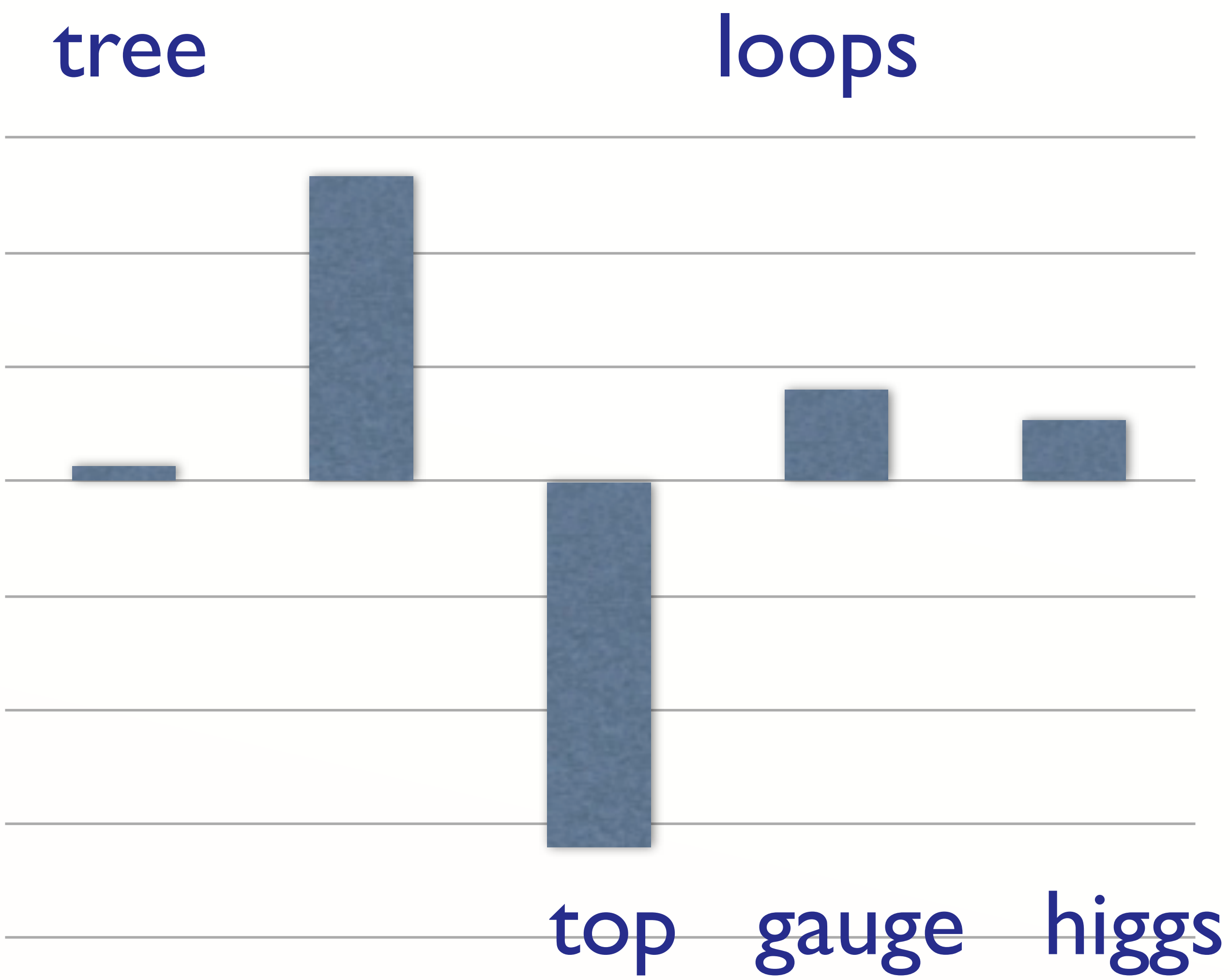
$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

Putting numbers, I have:

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

Top as a link to BSM

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



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

Definition of naturalness: less than 90% cancellation:

$$\Lambda_t < 3\,\mathrm{TeV} \qquad \Lambda_t < 9\,\mathrm{TeV} \qquad \Lambda_t < 12\,\mathrm{TeV}$$

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

Top is the only natural quark

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

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

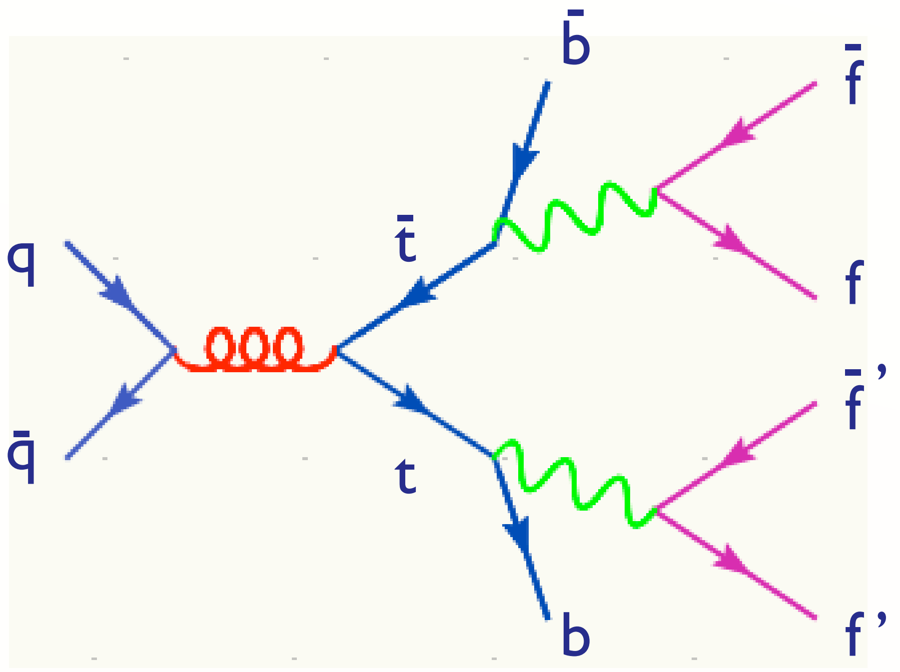
3. Strongly coupled model at the TeV scale: New strong dynamics enters at ~1TeV.

Top: t-tbar bound states, colorons. Top is not elementary

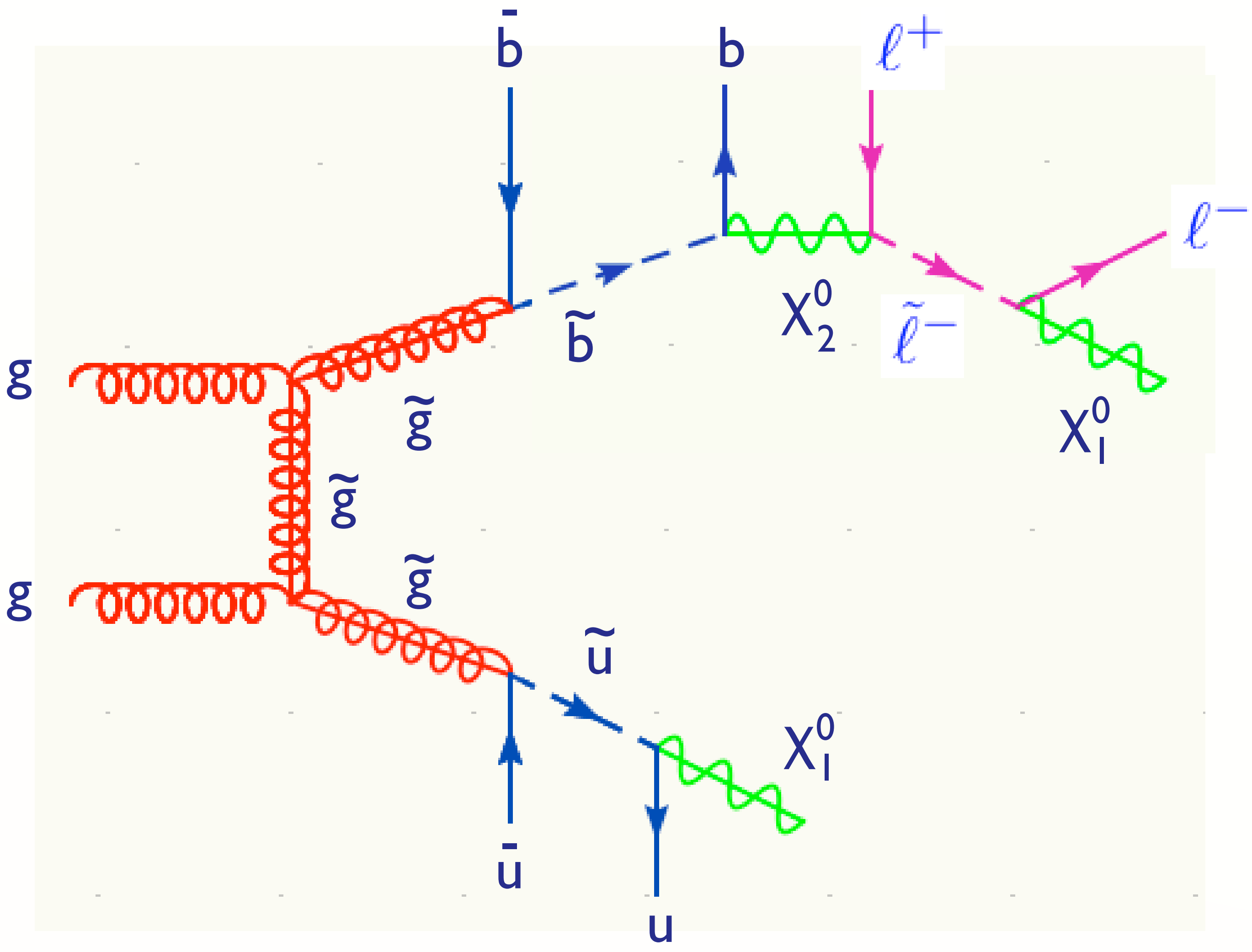
4. New space-time structure: Introduce extra space dimensions to lower the Planck scale cutoff to 1 TeV.

KK-excitations

Top as a template

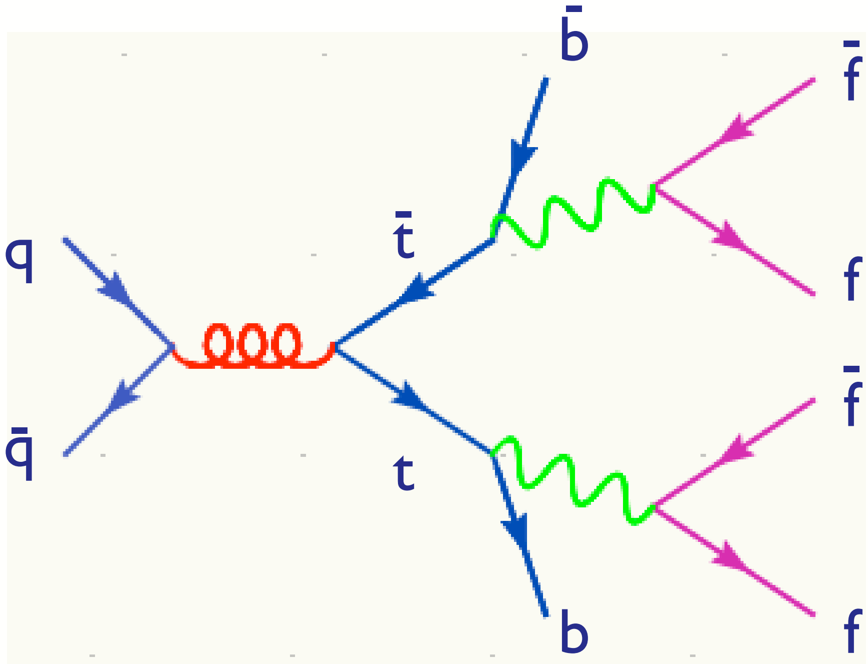


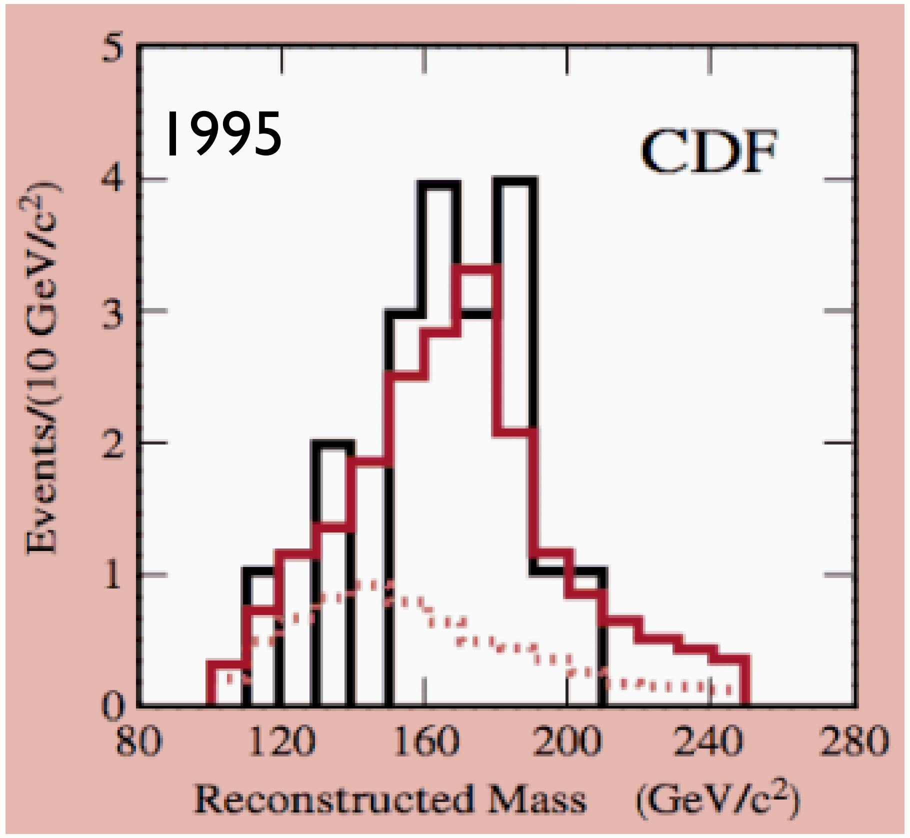
VS



Both involve production of heavy colored states decaying through a chain into jets, leptons and $\not{E}_T$.

A lesson from the top





How did it go?

0. The only unknown was the top mass!

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

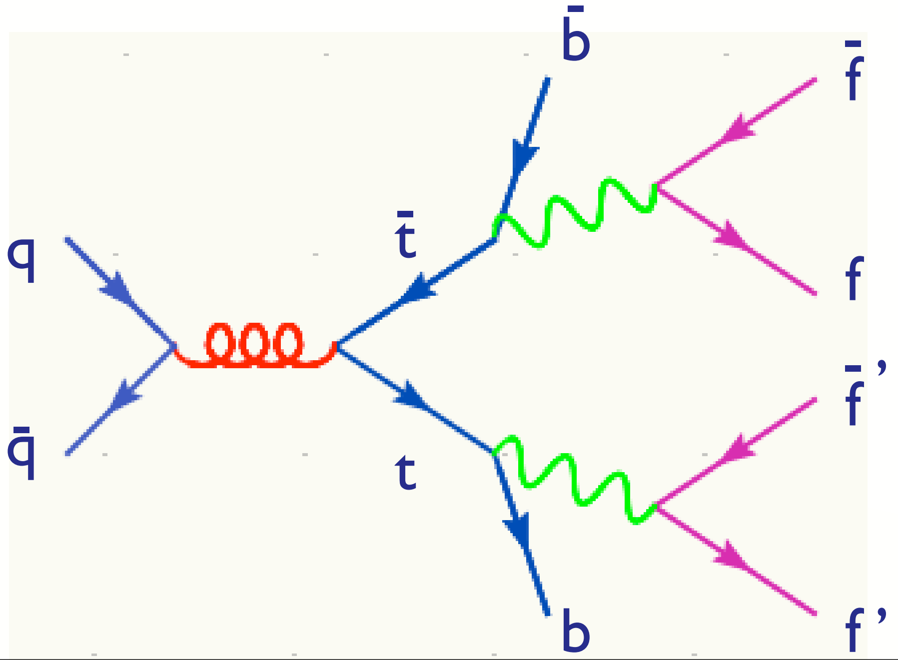
2. Mass reconstruction employed

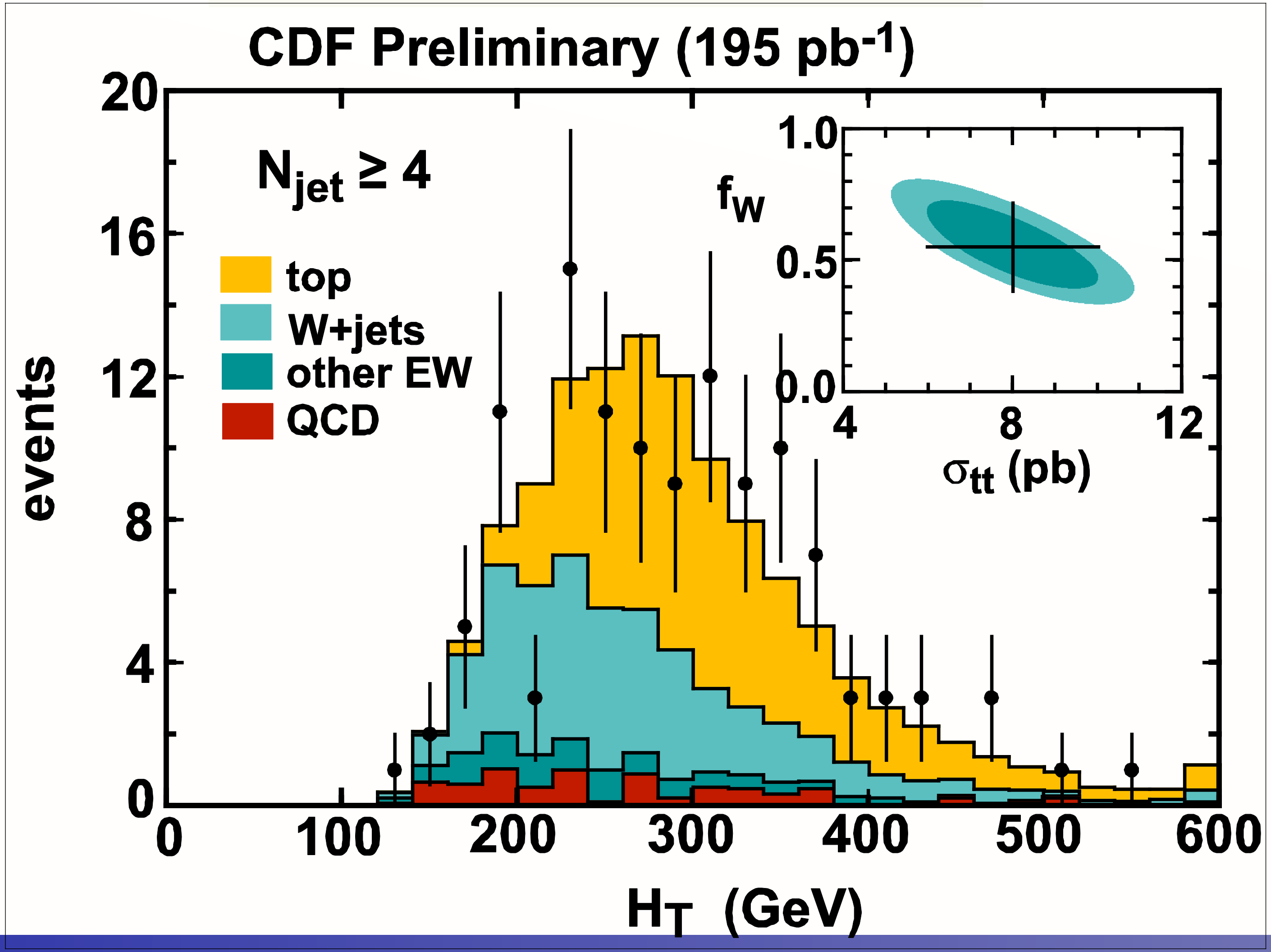
3. Backgrounds estimated via control samples with heavy flavors and also via MC ratio's.

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

Handful of events was enough!

A lesson from the top





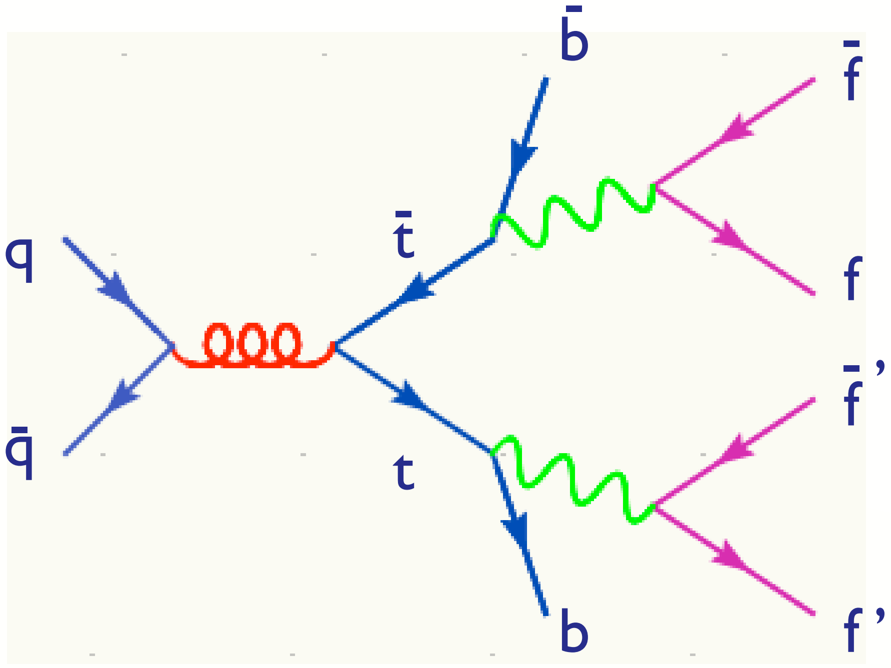
Immediately confirmed in Run II, also by the most inclusive measurements, H_T.

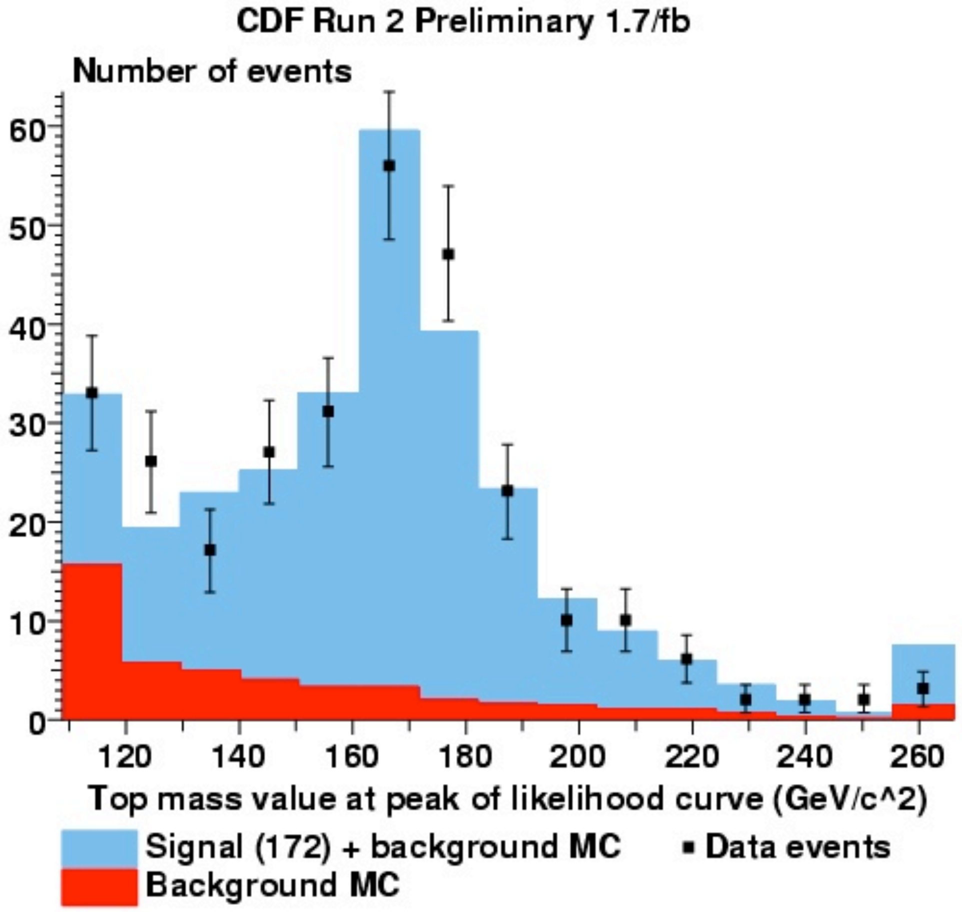
Other channels start to be considered as the statistics increases to have a consistent picture.

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 than15-year long story

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

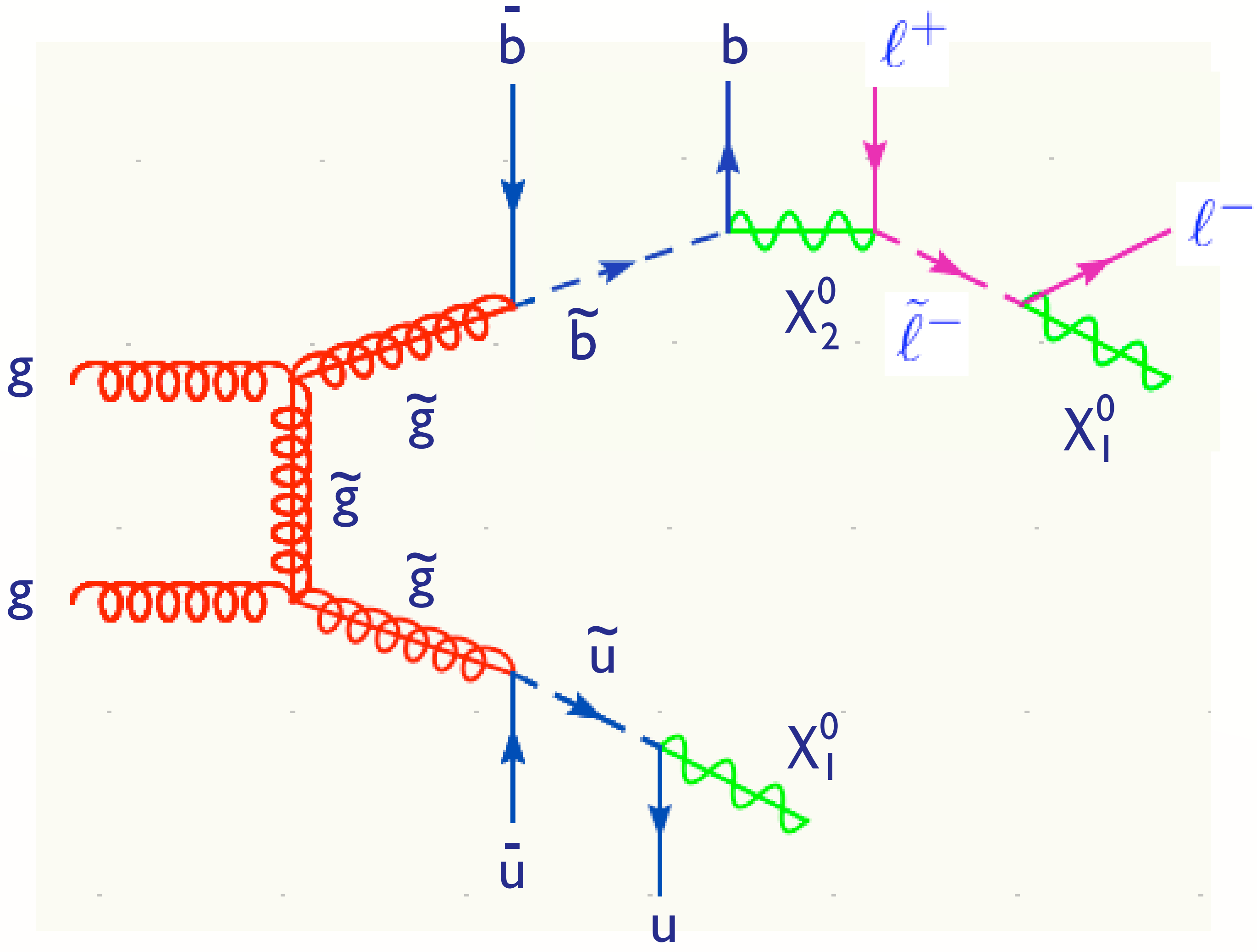
3. Now all studies, including the mass measurements, are strongly based on our simulation tools, i.e., matrix element methods.

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

Is this strategy directly applicable to new heavy state searches?

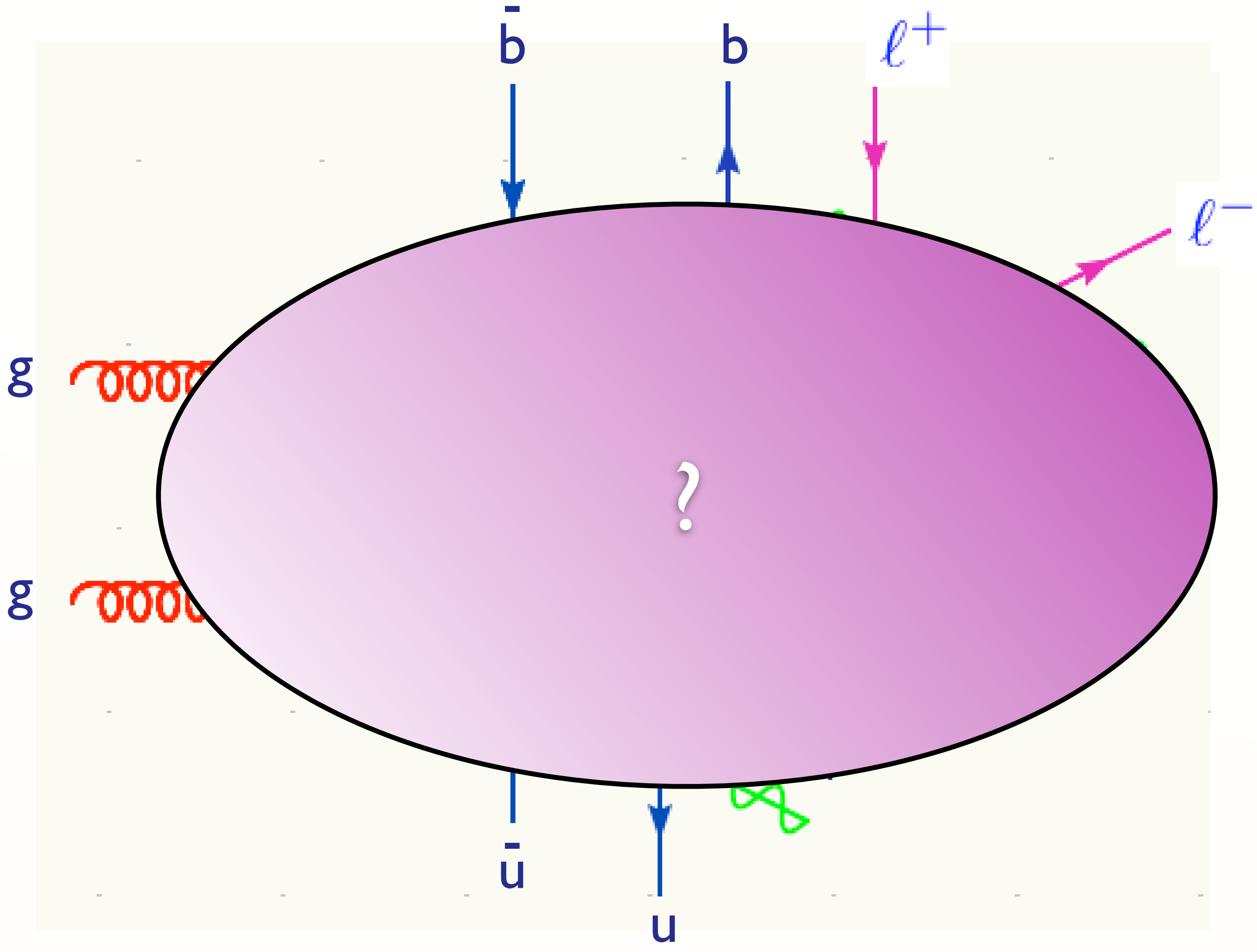
A lesson from the top

Susy inclusive searches are similar but more complicated final states.



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 tt and single top events.
A few examples:

- gg→H and qq→Hqq with H→WW
- tt in single top measurements
- tt+jets and ttbb in ttH
- tt+jets in SUSY/UED searches (gluino pairs, stop pairs, tH^{+}....)
- .....

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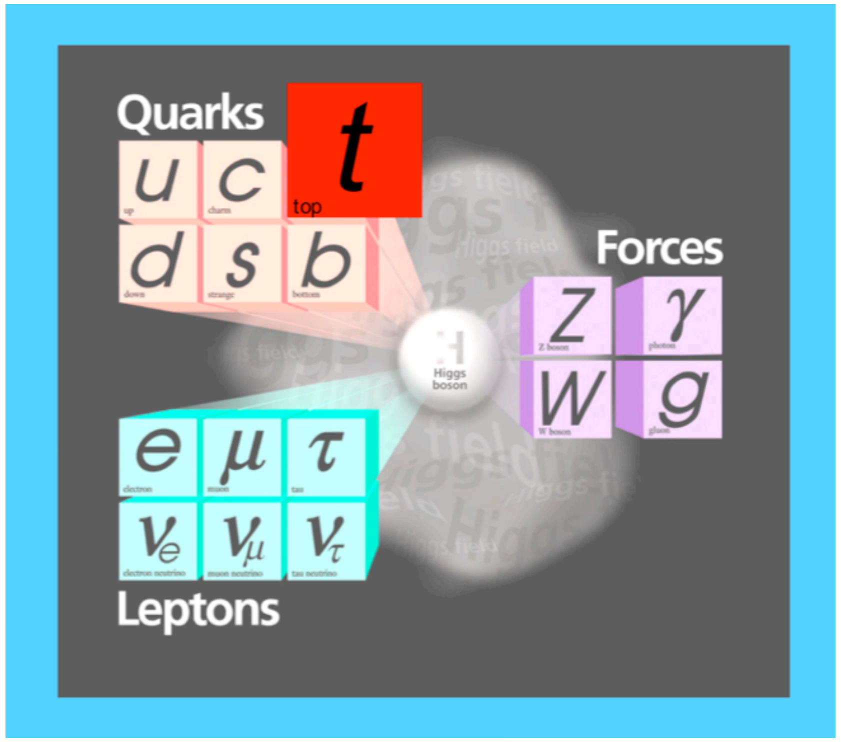
Charmonium is there, Bottomonium is there, what about Toponium?
Unfortunately, top decays too fast for bound states to form...
Radiation in top events? Everybody knows that top does not like to radiate a lot...
Measuring the top spin effects will prove that hadronization does not take place!
Have you heard of the latest top mass measurement?..
Which mass?
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.



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

Truth or Myth #1 : "Top is special"

Truth

In the SM, it is the ONLY quark

1. with a "natural mass":

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

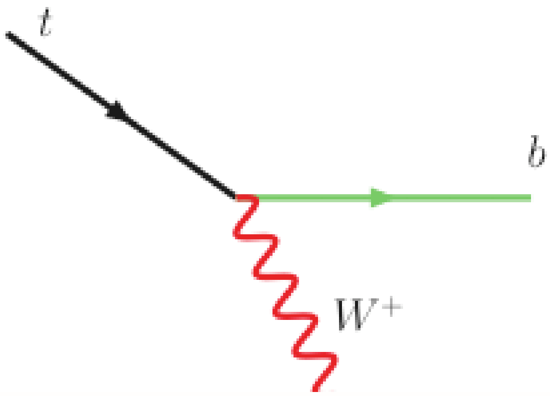
It "strongly" interacts with the Higgs sector. This also suggests that top might have special role in the mechanism of EWSB and/or fermion mass generation.

2. that decays before hadronizing

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

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

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



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

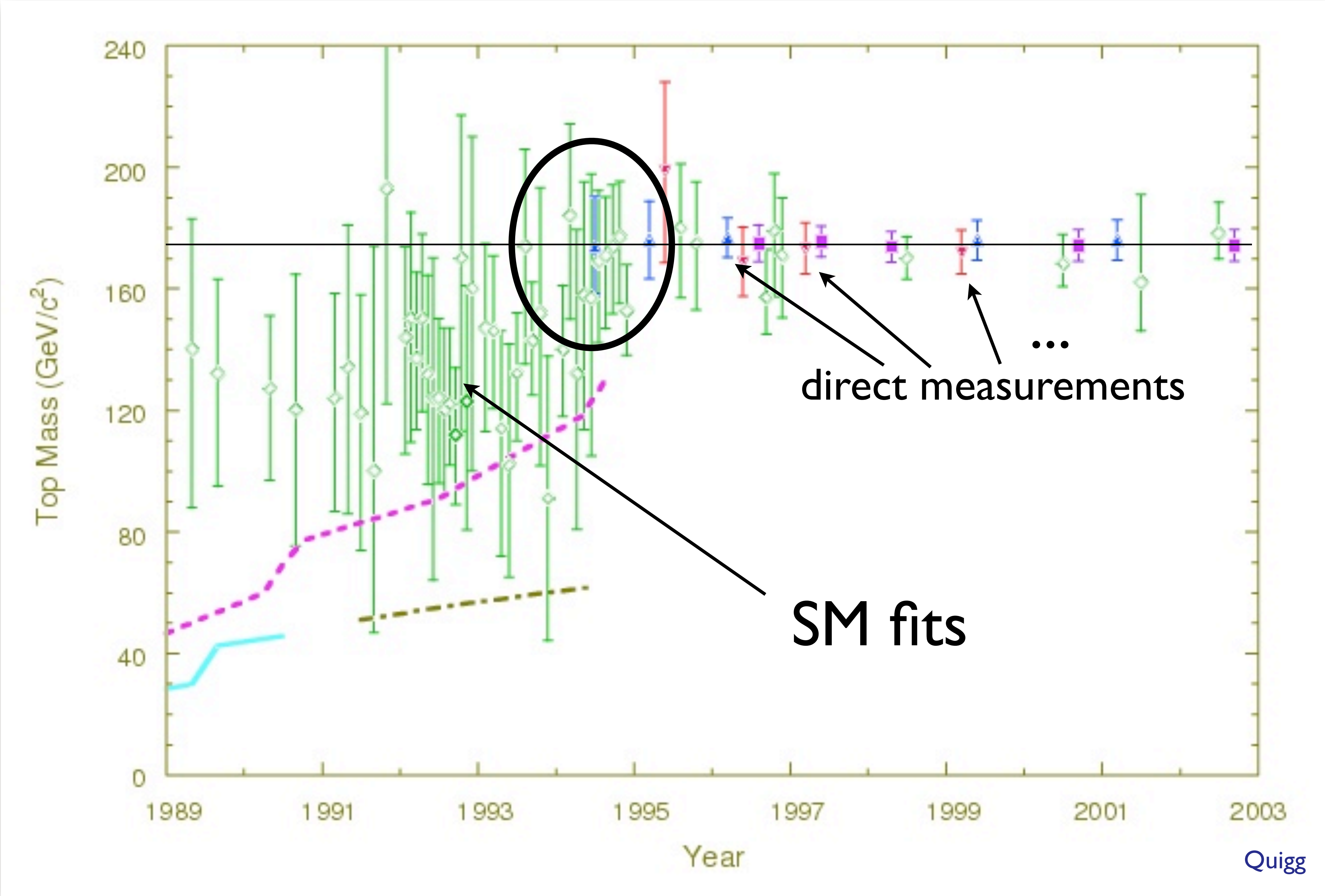
What do we really know about top?

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(ttbar)	10%	event counting	QCD, mass
sigma(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

Top mass history



...

direct measurements

SM fits

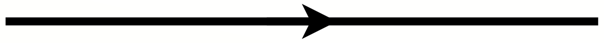
Quigg

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 ± 1.0 GeV) that we have to worry about its definition.

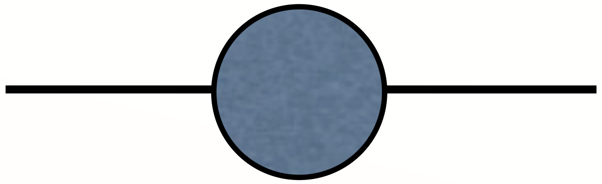
Leading order:



$$\frac{1}{\not{p} - m}$$

(pole) mass = *m*

Higher orders:



$$\frac{1}{\not{p} - m_R - \Sigma(\not{p})}$$

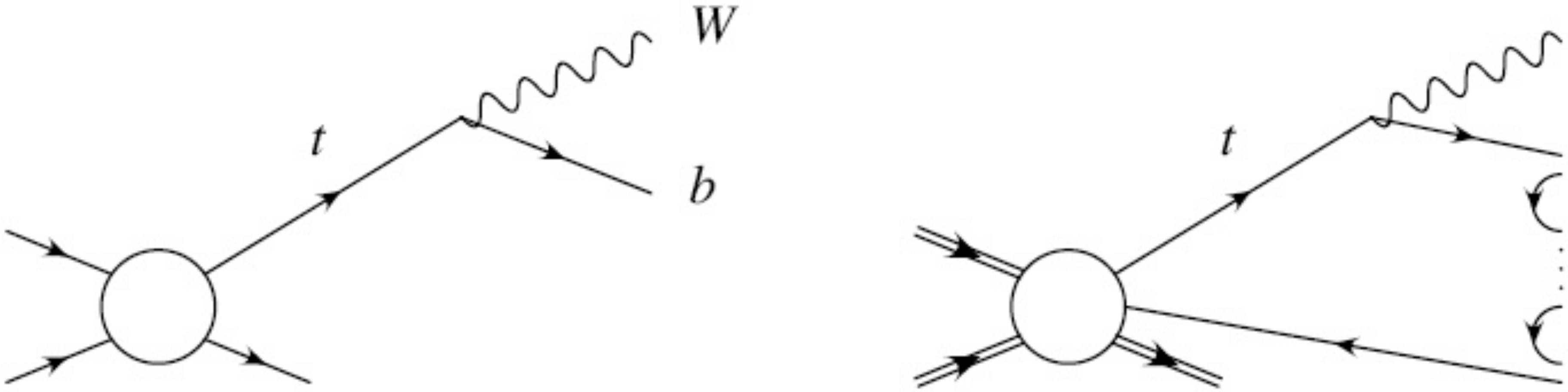
m_R = renor. mass

(At least) two possible renormalisation schemes: **MSbar** and **on-shell,** leading to to different mass definitions.

The **$\overline{\mathrm{M}}$Sbar 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 Λ_{QCD}.

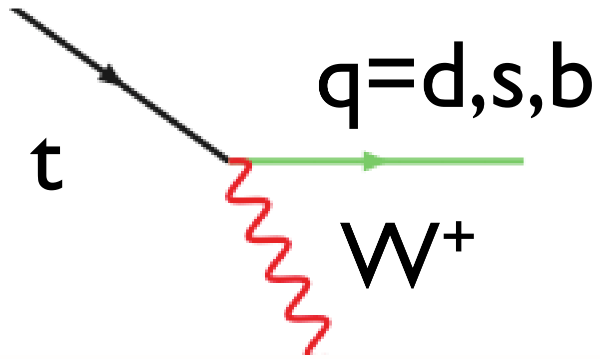


The **pole mass** is closer to what we measure at colliders through invariant mass of the top decay products. The ambiguities in that case are explicitly seen in the modeling of extra radiation, the color connect effects and hadronization.

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

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

Truth or Myth #2 :
“Vtb 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

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

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

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

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

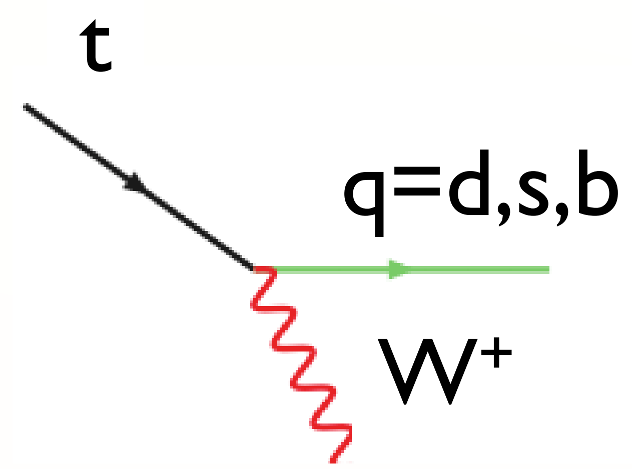
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \Rightarrow \begin{pmatrix} 0.9730-0.9746 & 0.2174-0.2241 & 0.0030-0.0044 \ldots \\ 0.213 \quad -0.226 & 0.968 \quad -0.975 & 0.039 \quad -0.044 \quad \ldots \\ 0 \quad\quad -0.08 & 0 \quad\quad -0.11 & 0.07 \quad -0.9993 \ldots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

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 contraints the V_{ti} matrix elements.
For example the last measurements from CDF on B_s - B_s mixing gives

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

Myth

Truth or Myth #2 :
“Vtb 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,

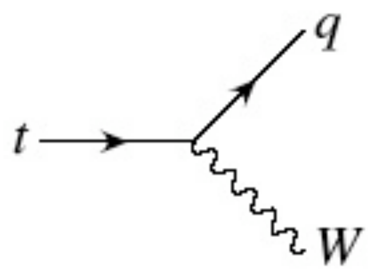
$$R = \frac{\Gamma(t \to Wb)}{\sum_{light} \Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

where we already know that $V_{td}, V_{ts} << V_{tb}$, so R~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

W polarization

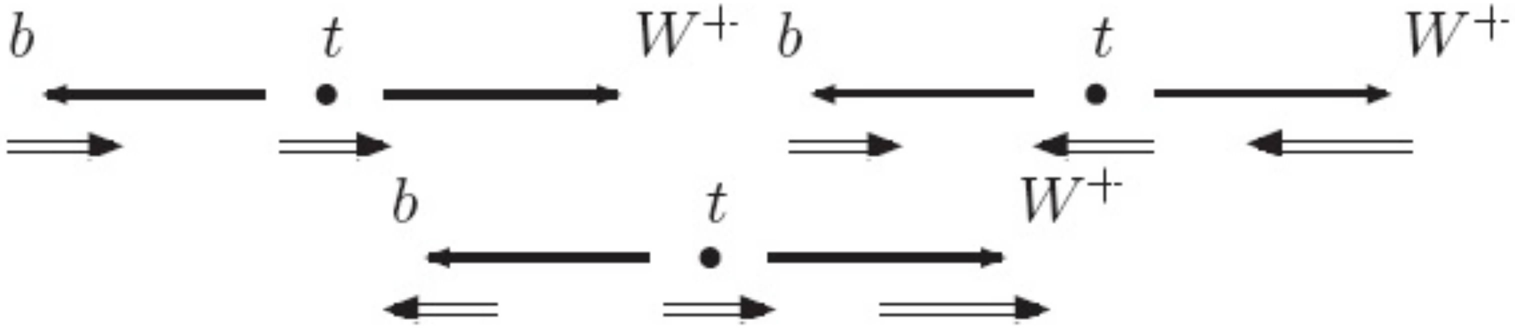


$$-i\frac{g}{\sqrt{2}}V_{tq}\gamma^\mu\frac{1}{2}(1-\gamma_5)$$

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.

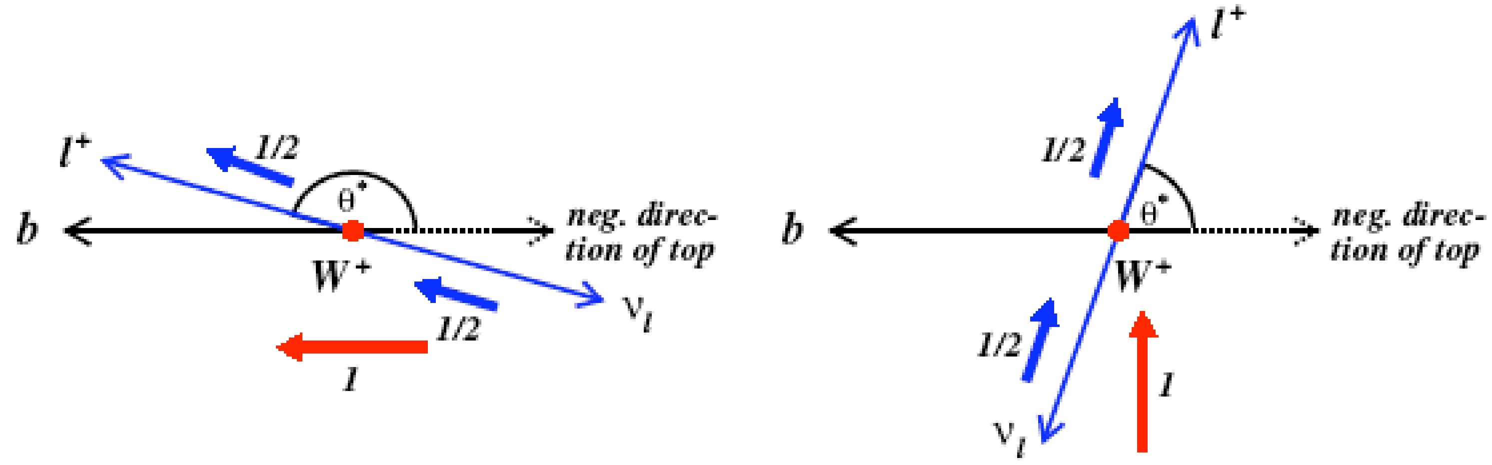
Neglecting m_b, this imples that the W can be only either longitudinally polarized or with negative helicity. In general:



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

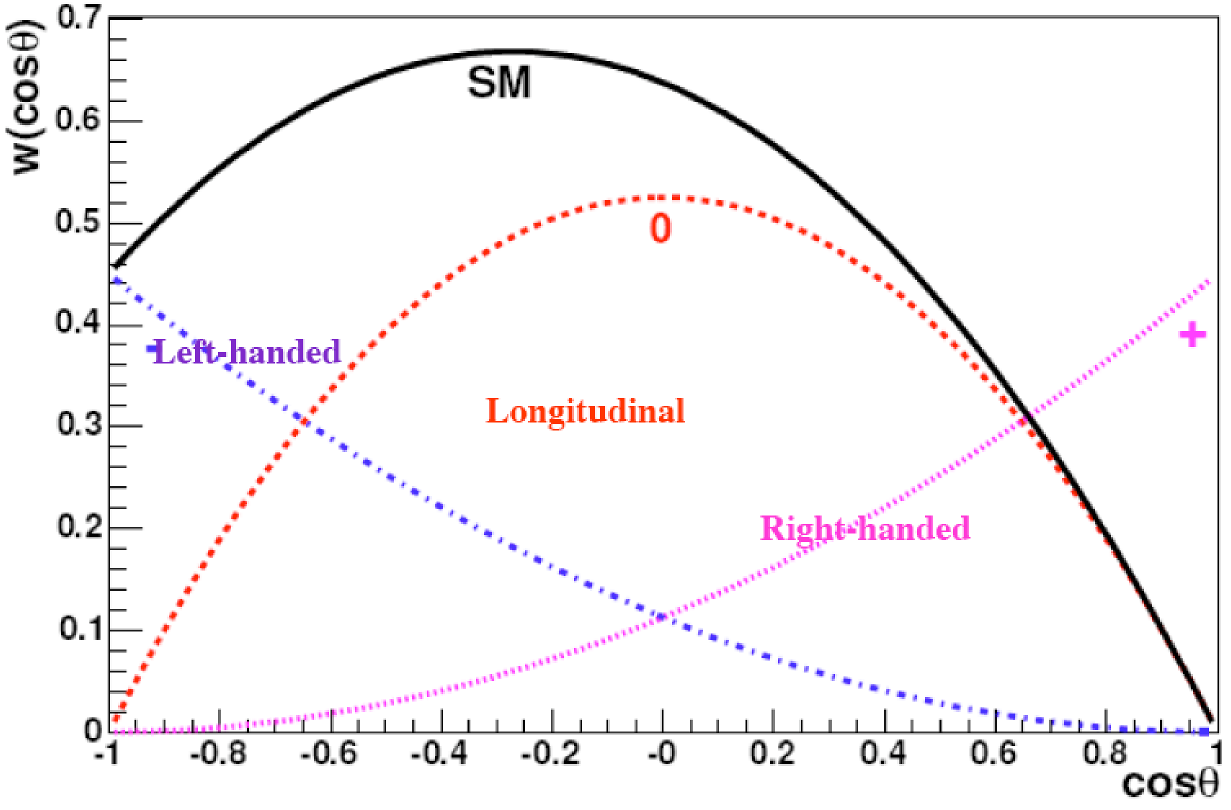
W polarization

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



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

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 1dim distributions!)

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

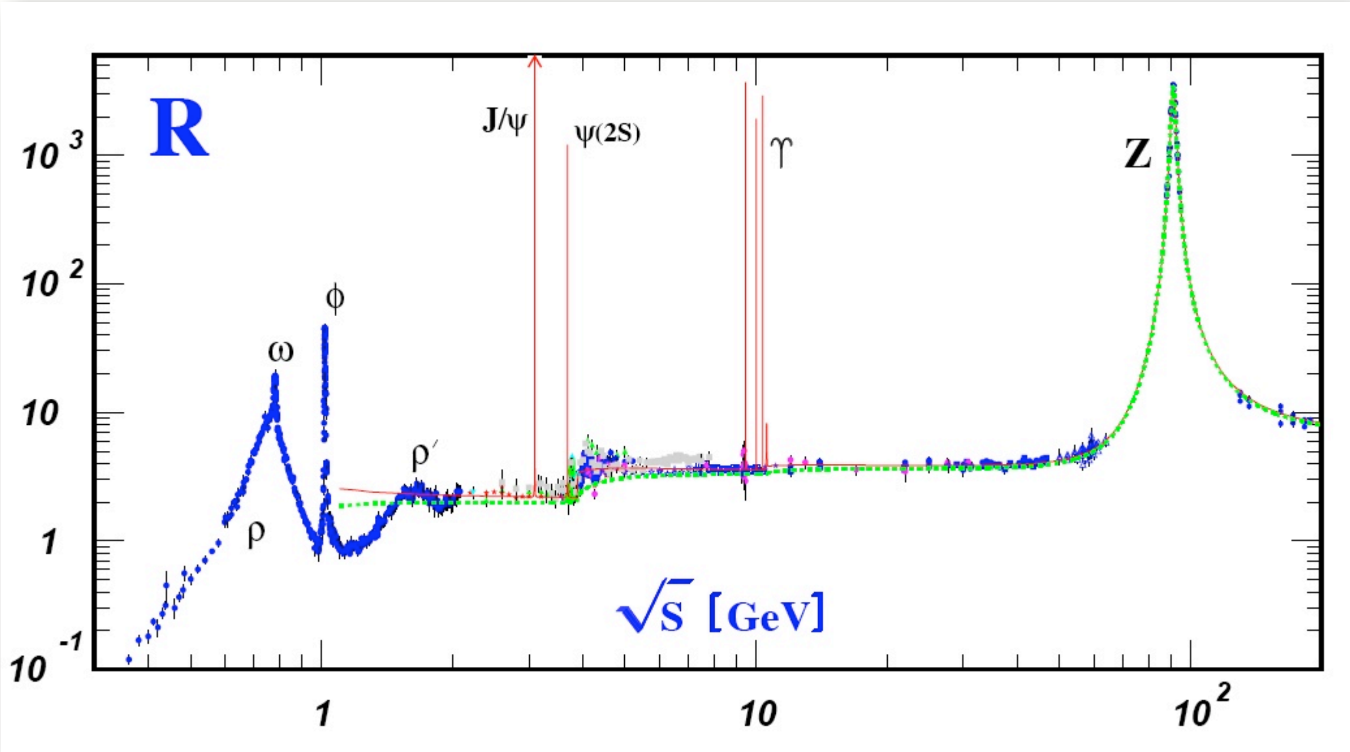
* cos(θ), which is defined in a specific frame, can be related to m(lepton,bottom) or pt(lepton) , ergo no top momentum reconstruction necessary!

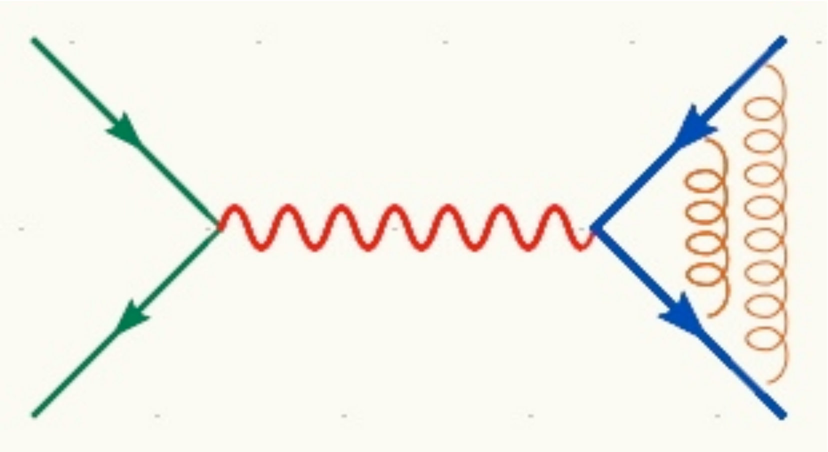
* Rather "easy measurement" .

Truth or Myth #3 :
“no hadronization ⇒ no resonance physics”

Consider how the charm and the bottom quarks were discovered:

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$





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

Very sharp peaks => small widths (~ 100 KeV) compared to hadronic resonances (100 MeV) => very long lived states. QCD is “weak” at scales >> Λ_{QCD} (asymptotic freedom), non-relativistic bound states are formed like positronium!

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

Truth or Myth #3 :
“no hadronization ⇒ 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:

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

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

Scale	Quantity	e+e-	toponium
m	annhilation time	0.5 MeV	172 GeV
mv	size p~1/R	3.7 KeV	15 GeV
mv^2	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

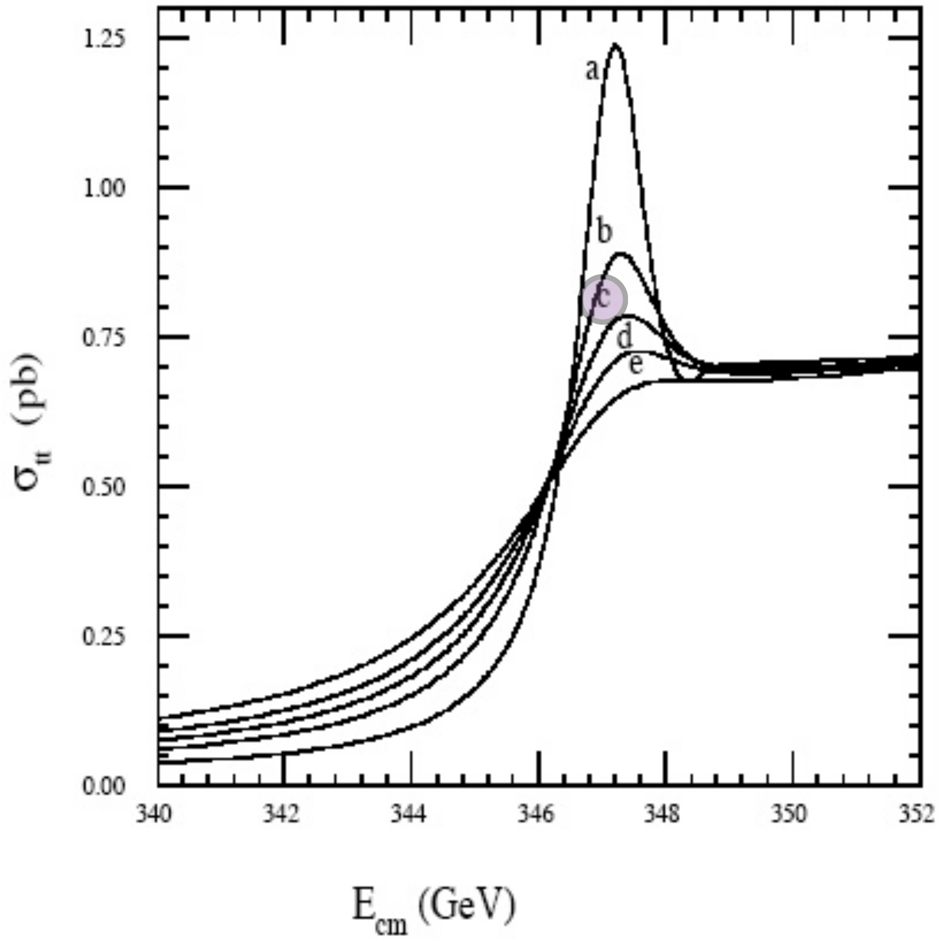
$\tau_{form} \approx$ size/v $\approx mv^2 \approx 1/(2$ GeV)

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

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

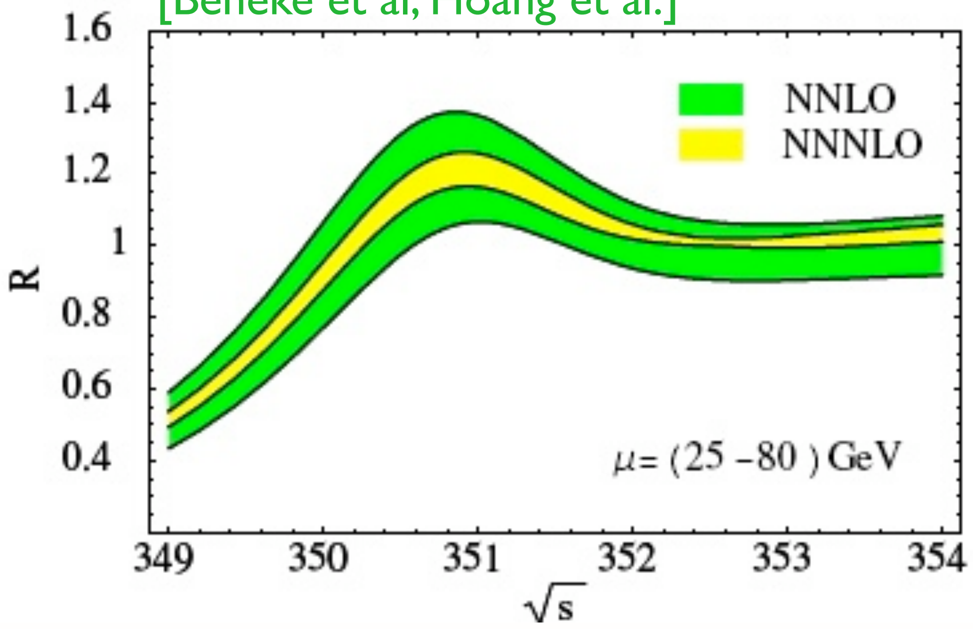
Myth

Truth or Myth #3 :
“no hadronization ⇒ 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 enhacement 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:

[Beneke et al, Hoang et al.]



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

TH Myth

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

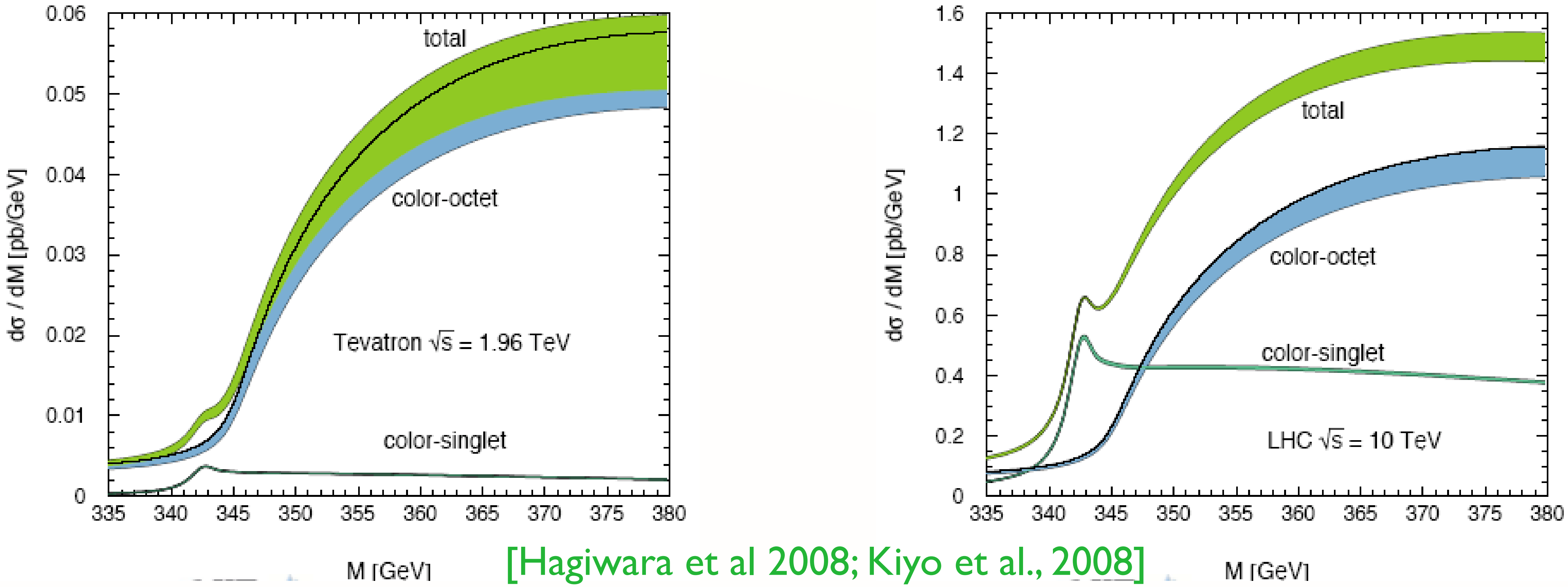
In hadronic collision, the interactions at threshold can be either attractive or repulsive! Octet larger cross section, but "bound state" effects are dominant in the singlet. Effects compete. Until last spring, the common lore was that PDF effects would smear any peak!

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

⇐Myth

Truth or Myth #4 :
“No hadronization ⇔ Top spin effects”

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

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

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).

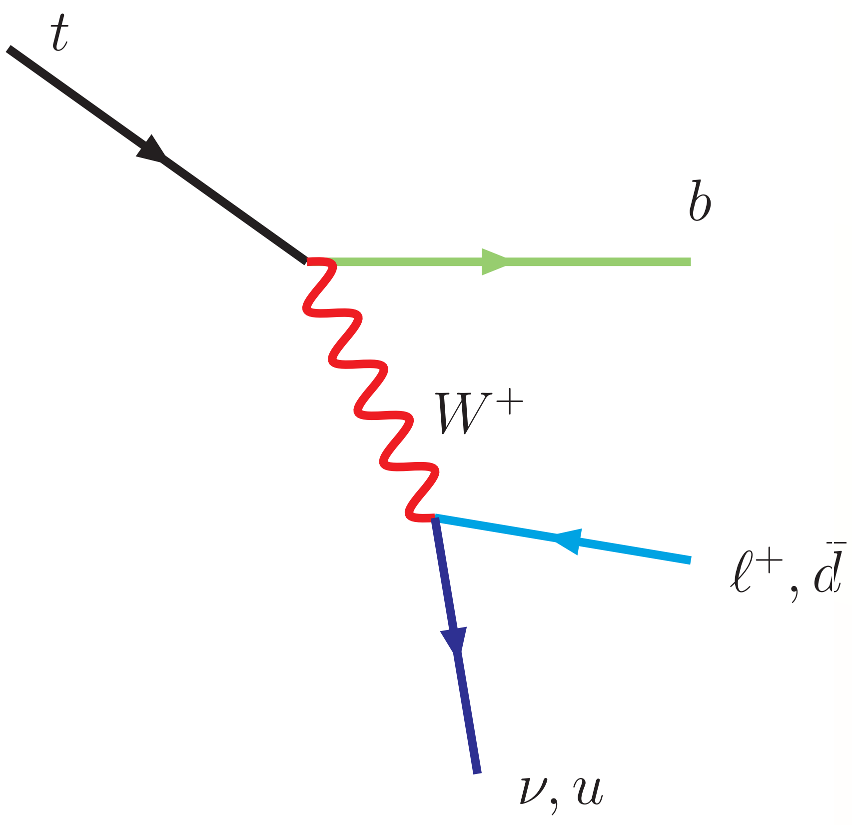
HOWEVER, one can also ask : Is the opposite true? if we see spin correlation effects do we automatically put an upper bound on the width and hadronization? NO!
Spin-flips are due to CHROMOMAGNETIC interactions, which are mediated by dimension 5 operators:

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

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

[Falk and Peskin, 1994]

How to measure top spin



In particular one can easily show that for the top, the lepton$^+$ (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.

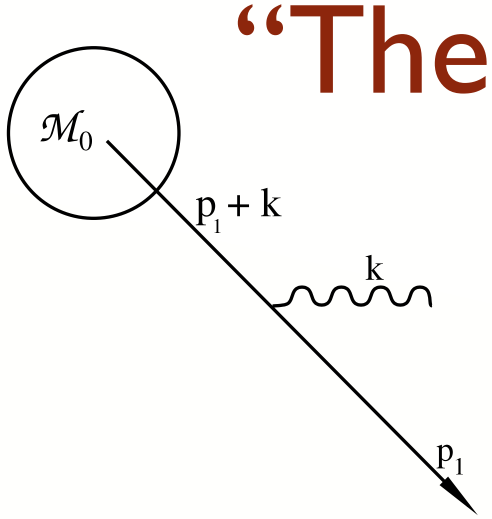
Results depend on the degree of polarization (p) of the tops themselves and from the choice of the “spin-analyzer” k_i.

	ℓ^+	$\bar{d}$	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”

True



Consider gluon emission off a heavy quark using perturbation theory:

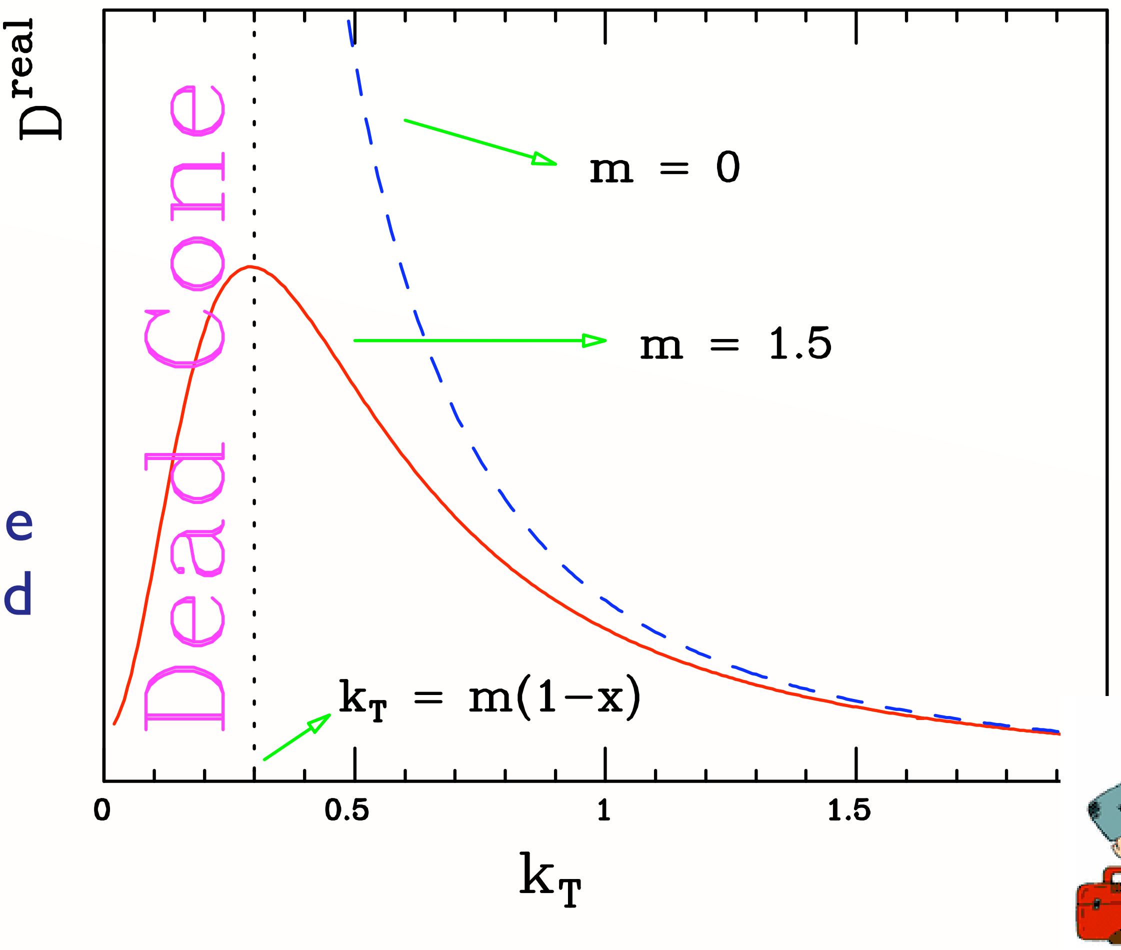
$$D^{\rm real}(x,k_\perp^2,m^2) = \frac{C_F\alpha_S}{2\pi}\left[\frac{1+x^2}{1-x}\,\frac{1}{k_\perp^2+(1-x)^2m^2} - x(1-x)\,\frac{2m^2}{(k_\perp^2+(1-x)^2m^2)^2}\right]$$

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

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

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

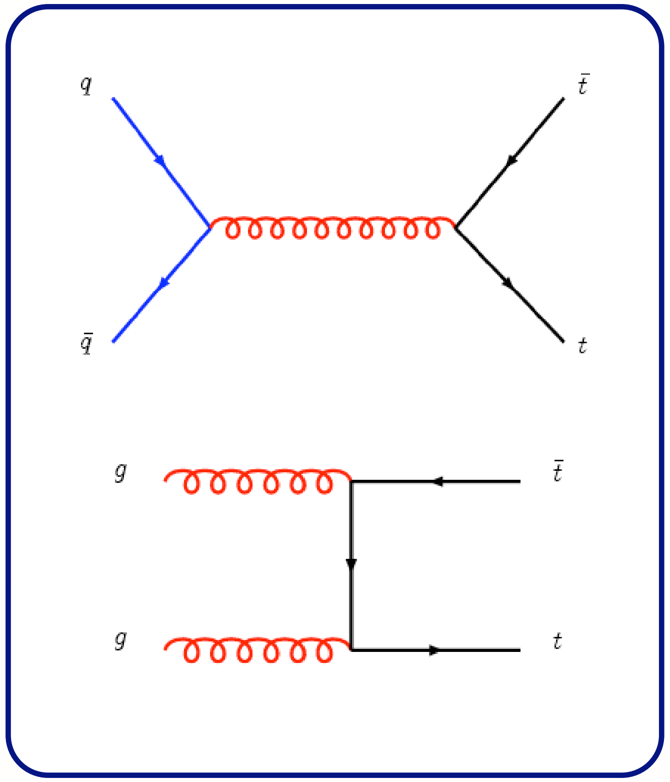
- Top is by all means special!
- The CKM elements V_{td} ,V_{ts} , V_{tb} are not very well constrained (if unitarity is relaxed).Top decays do not help much. Need for width or single-top measurements
- Top anti-top pairs close to threshold can display a "bound state" behaviour even in pp collisions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

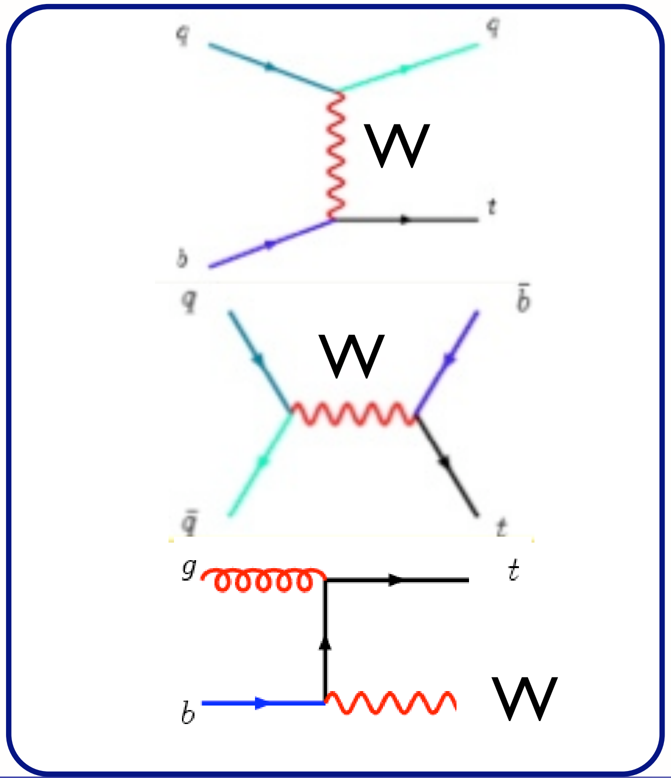


Largest cross section (LO at α_S^2):

~ 10 pb at Tevatron
~ 1 nb at the LHC14 (150pb at LHC7)

Top discovery mode.

Weak



Weak process : same diagrams as the top decay!

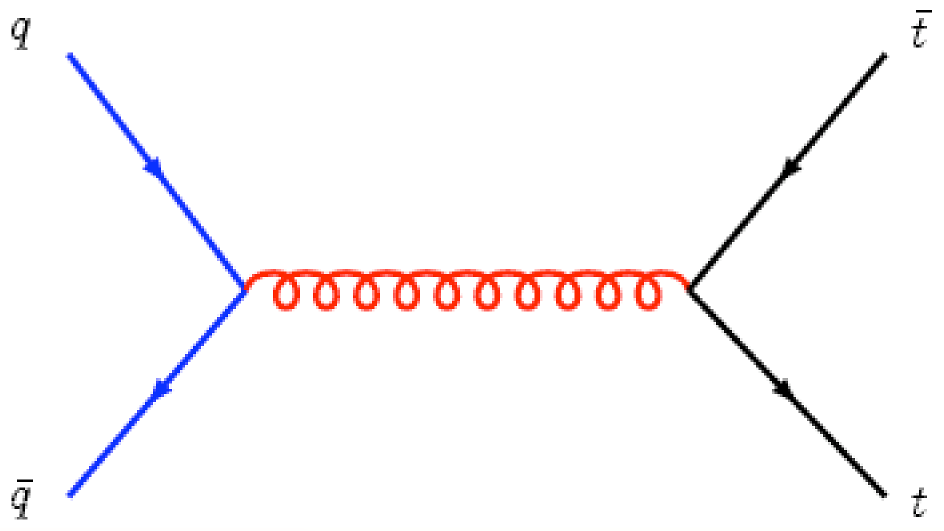
Cross sections smaller than QCD but enhanced by a lower energy cost:

~ 3 pb at Tevatron
~ 300 pb at the LHC14 (60pb at LHC7)

Three independent channels.
At the Tevatron sigma(t)=sigma(tbar). At
the LHC sigma(t)>sigma(tbar) (for s- and t-)

From Tevatron to LHC

Tevatron



85% of the total cross section

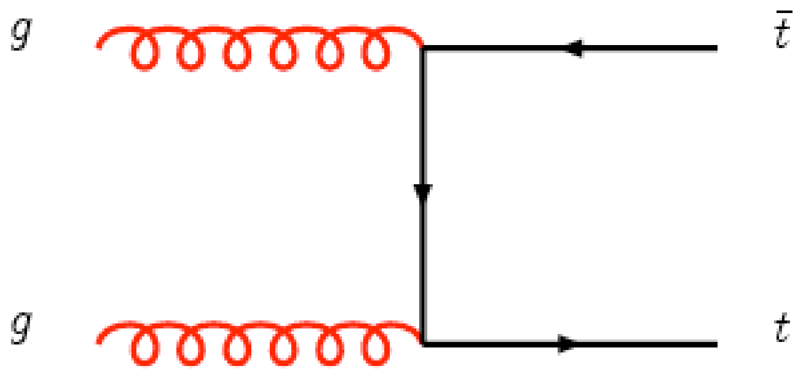
10 tt pairs per day

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

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

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

LHC



90% of the total cross section

1 tt pair per second

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

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

Background free*!

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

Master QCD formula

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

Two ingredients necessary:

1. Parton Distribution functions (from exp, but evolution from th).

2. Short distance coefficients as an expansion in α_S (from th).

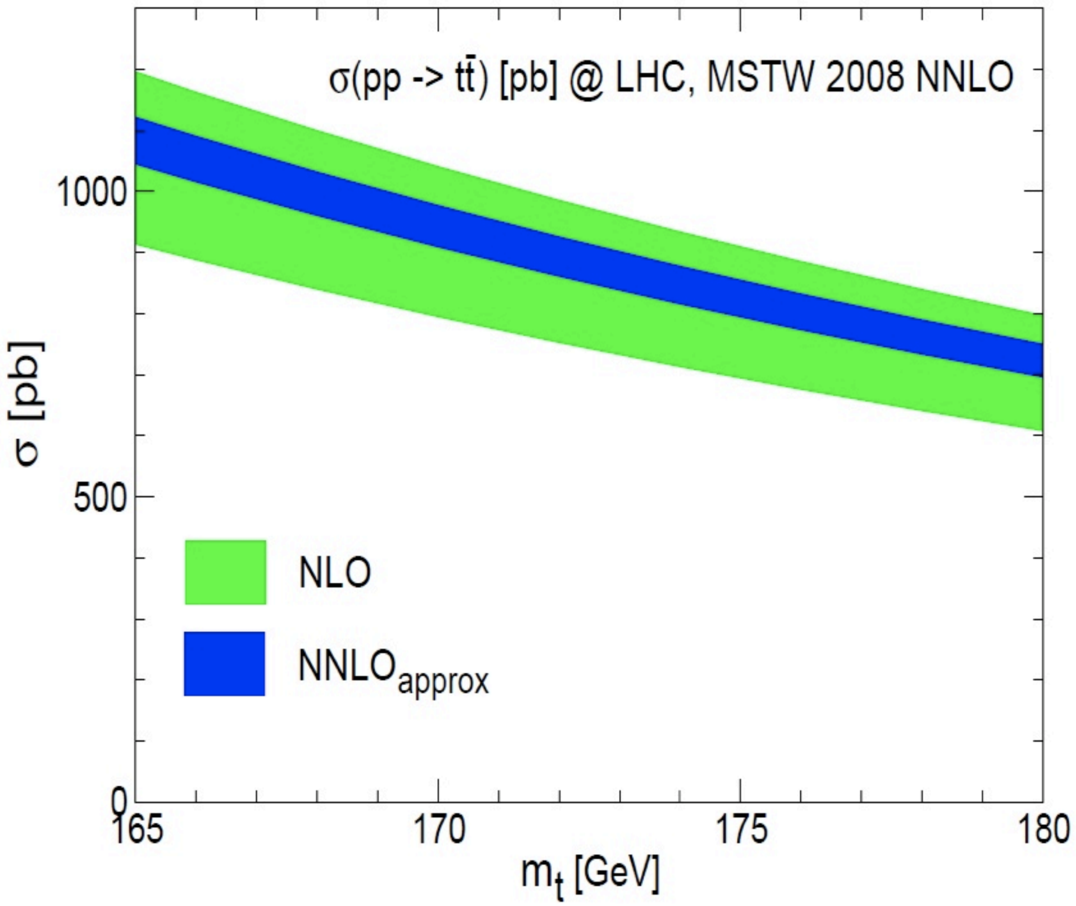
$$\hat\sigma_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

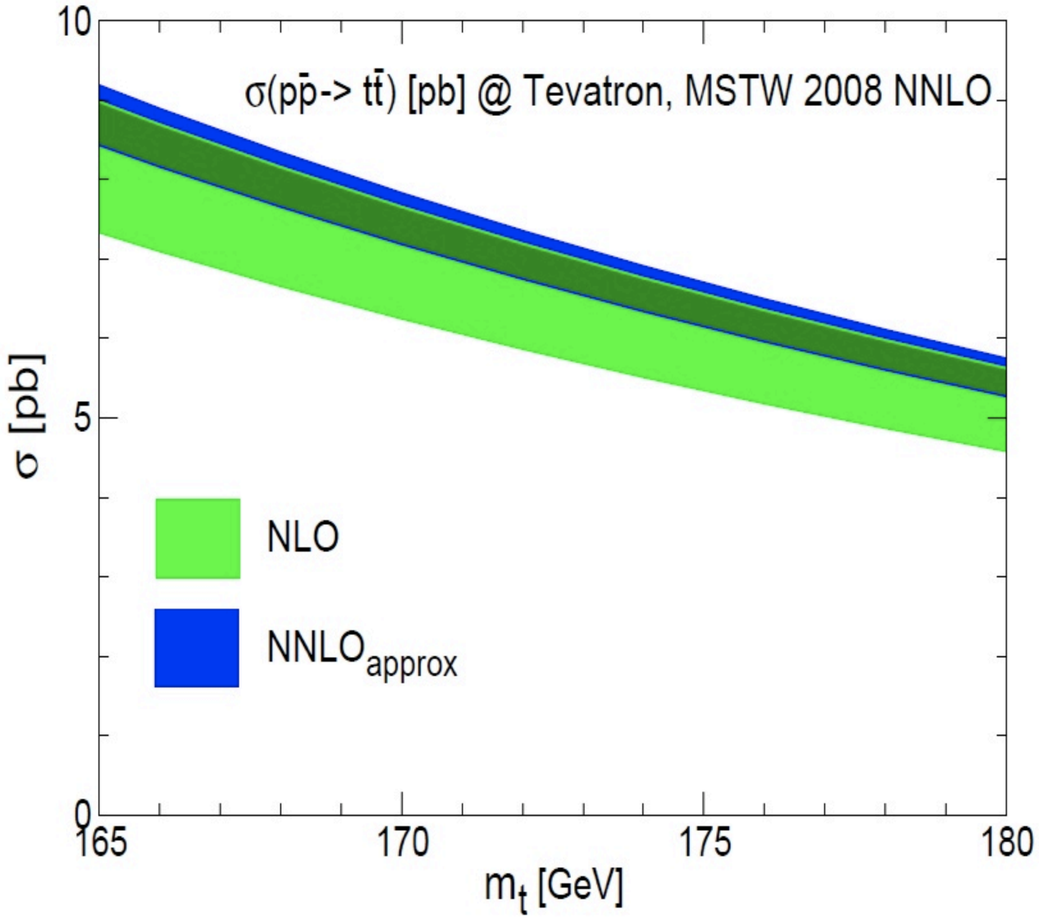
Leading order

Next-to-leading order

Next-to-next-to-leading order

Top @ LHC vs Tevatron





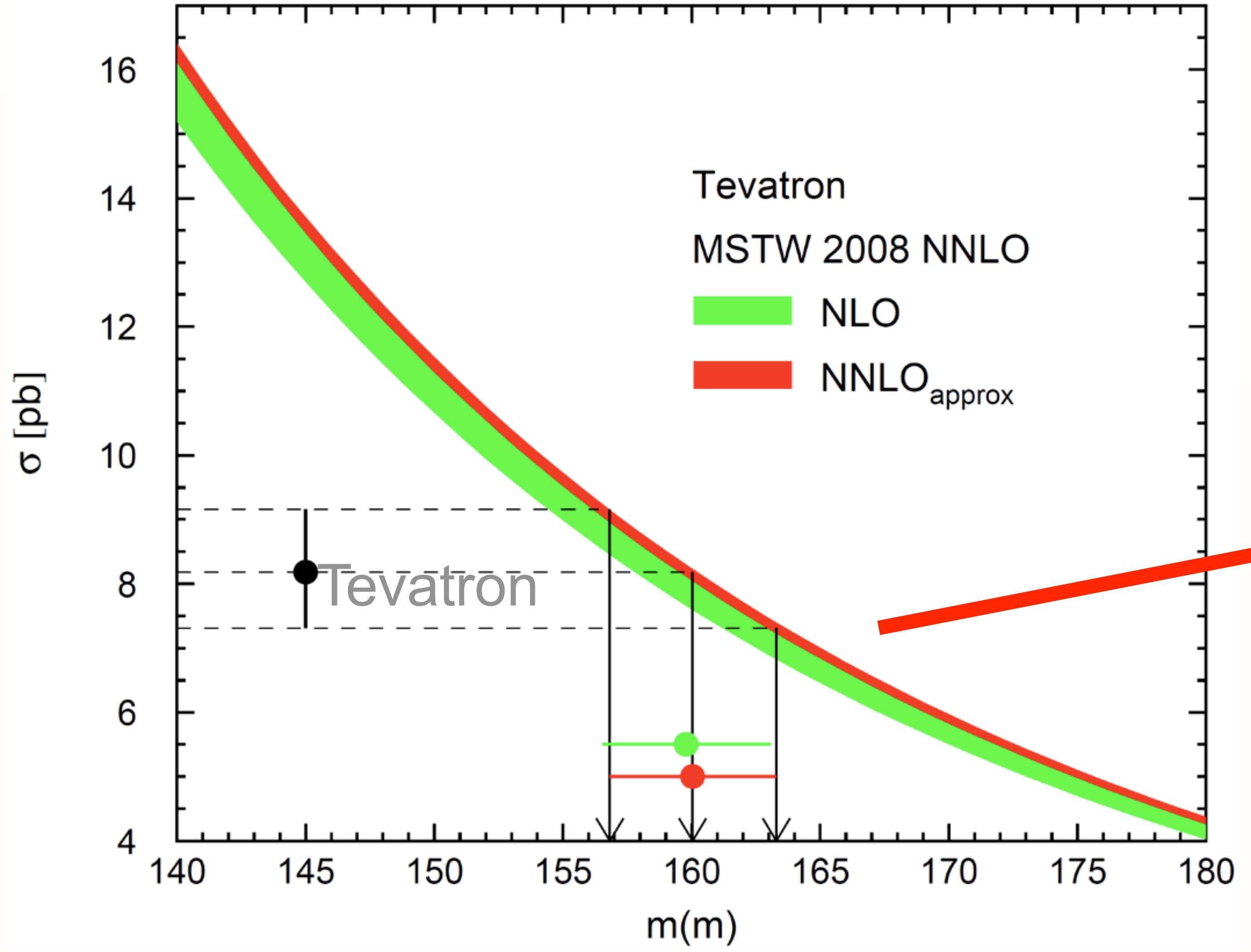
[Moch,Langenfeld,Uwer ’08,’09]

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

Measuring m_t (MSBar) from σ_{tt}

[Langenfeld, Moch, Uwer 09]

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



	$\overline{m}$ [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 ttbar

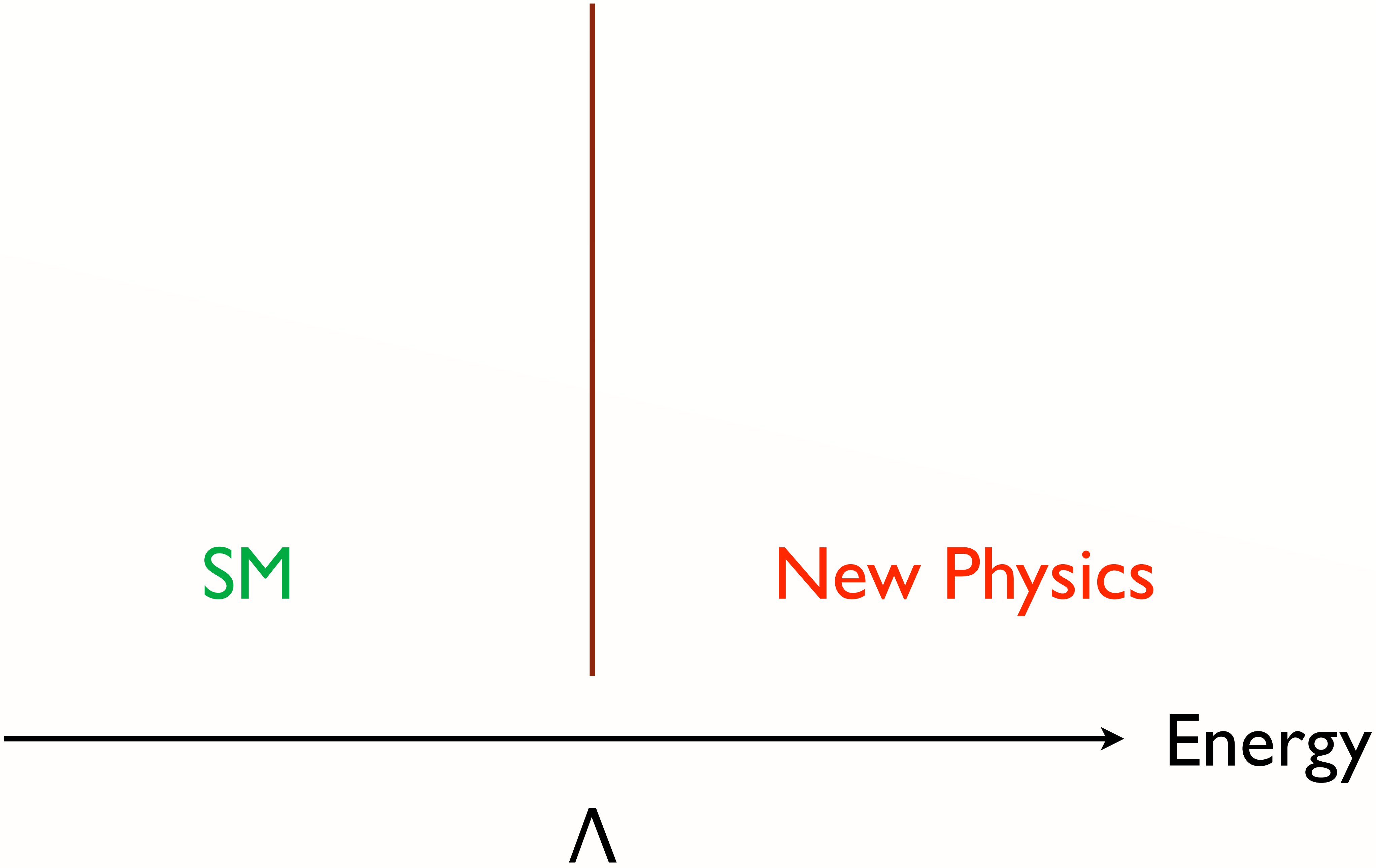
Model independent direct search for NP in the ttbar invariant mass

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.

Is this going to work?
How can we do it?
And, even if we find "deviations", how do we characterize New Physis in a model independent way?

Two possibilities



SM

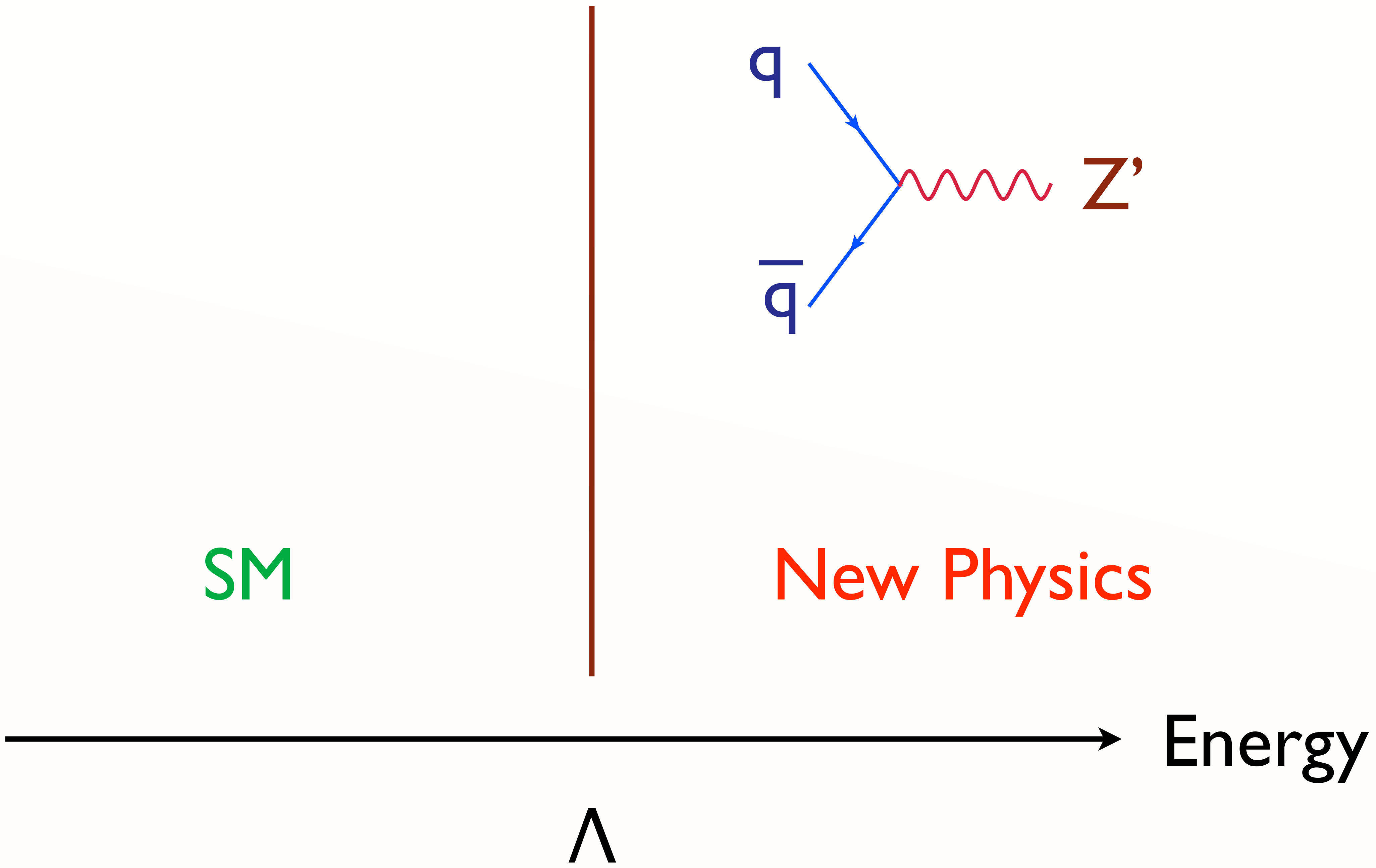
New Physics

Energy

Λ

[see Willenbrock's talk at top2010]

Example : Z'



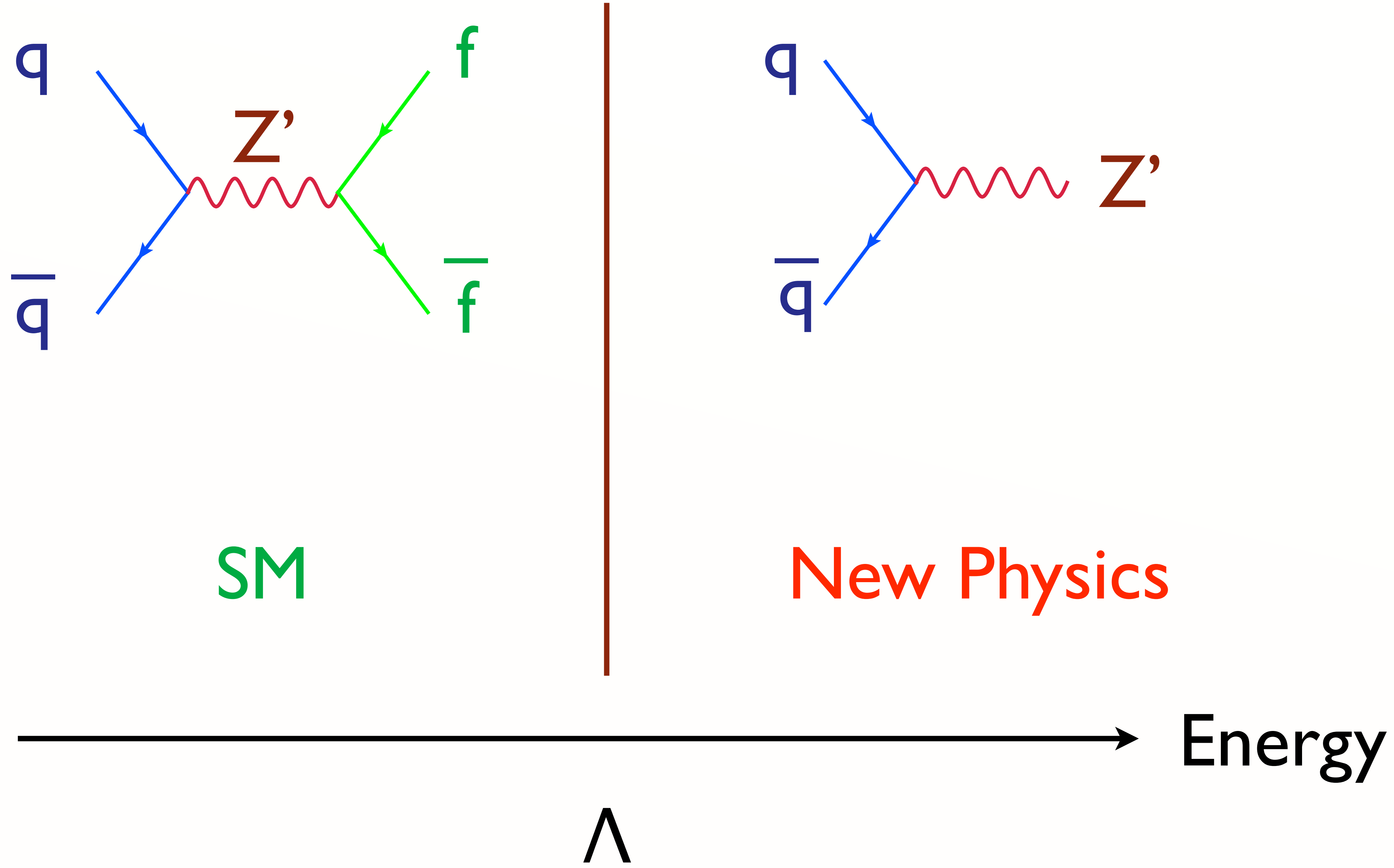
SM

New Physics

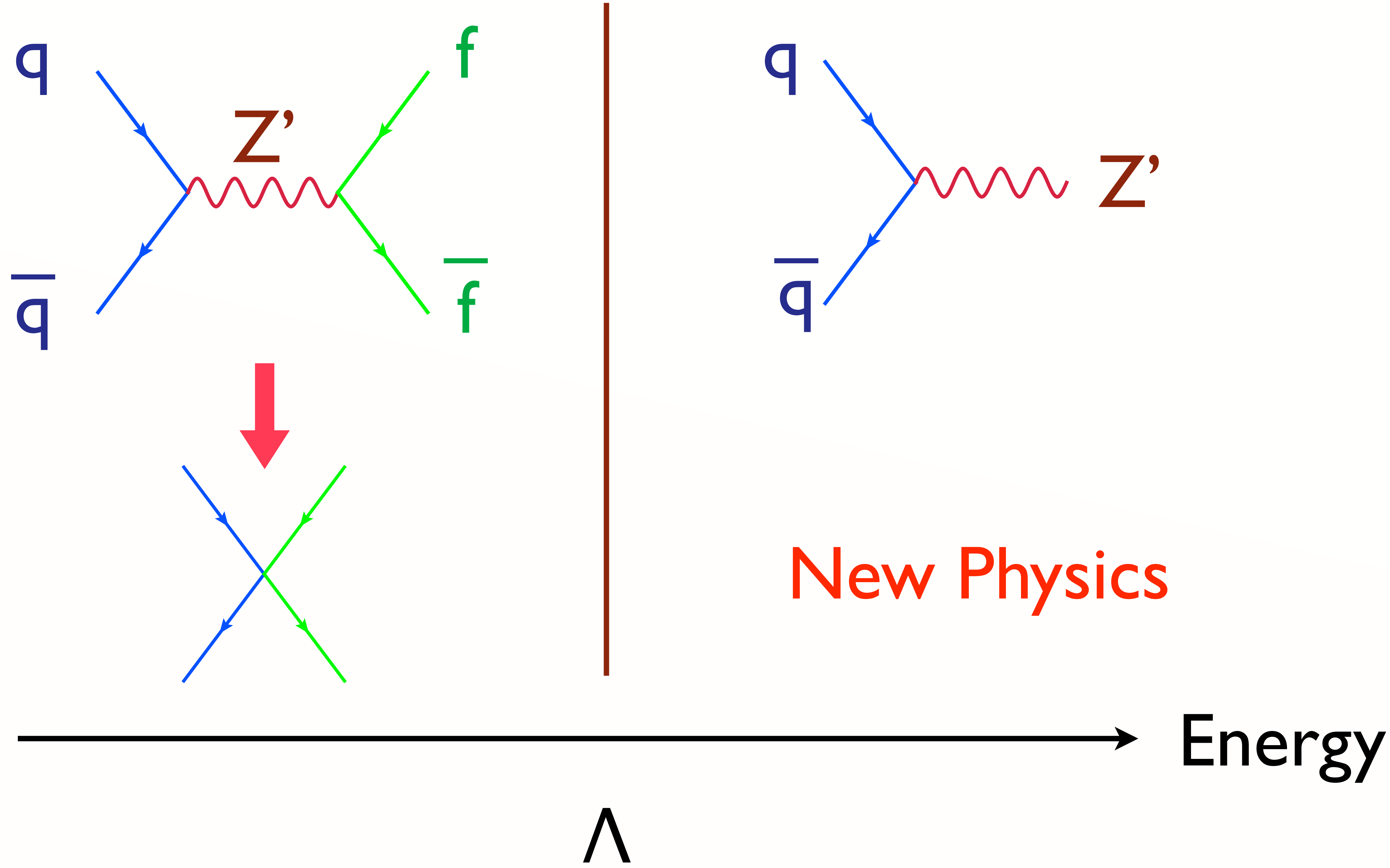
Energy

Λ

Example : Z’

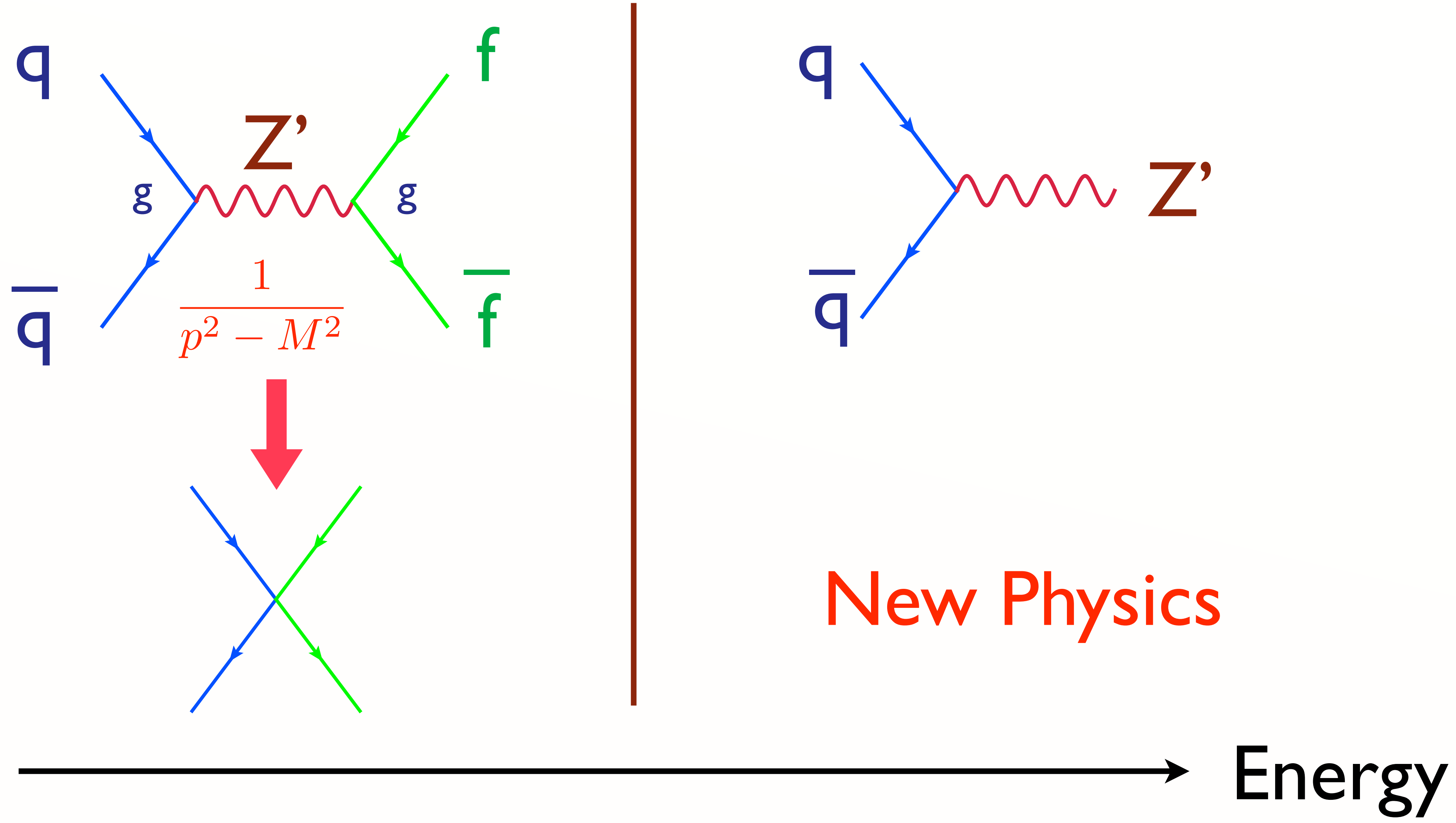


Example : Z'



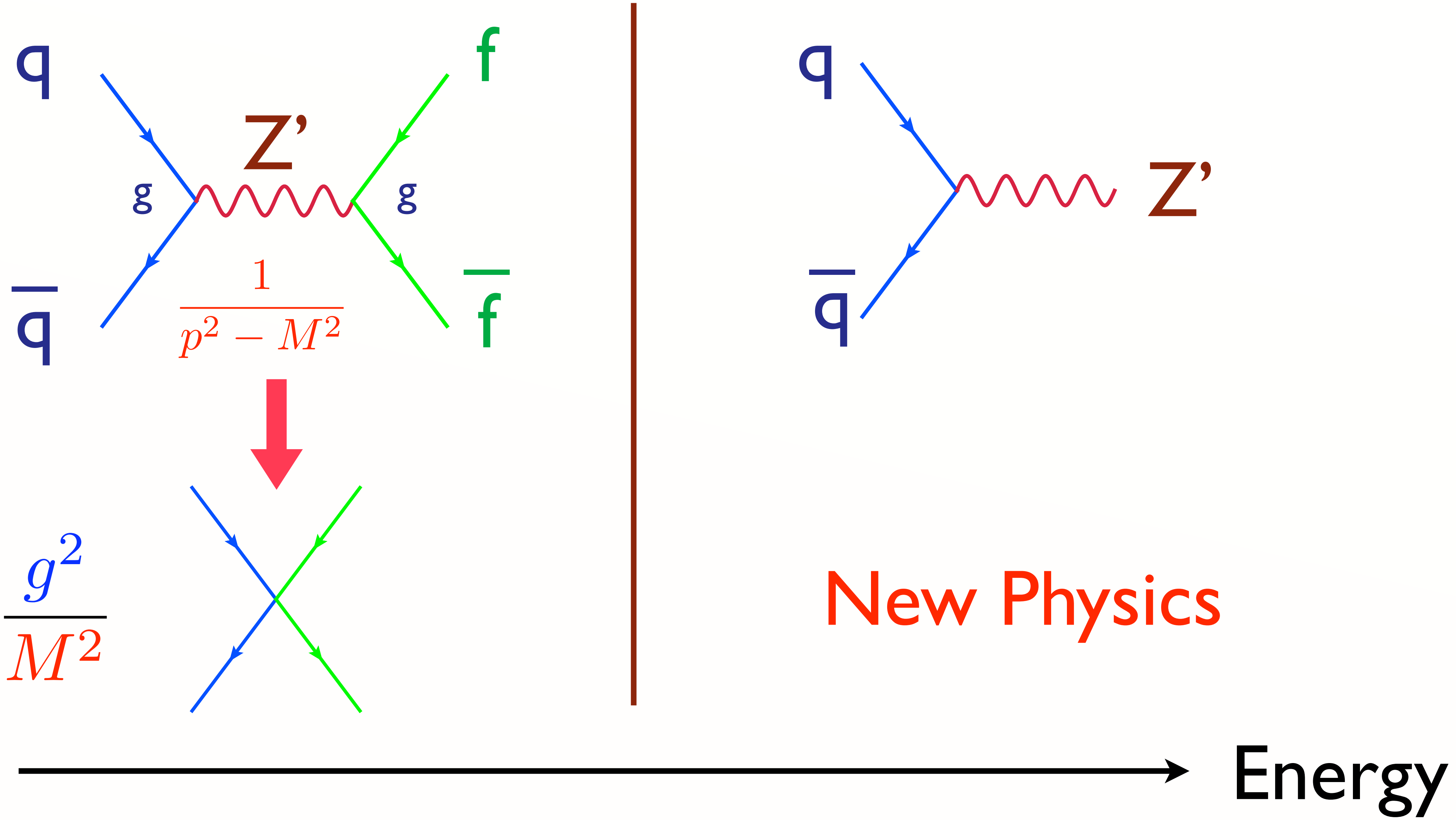
New Physics

Example : Z'



Λ=M

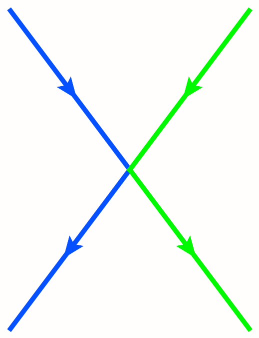
Example : Z'


q
$\bar{q}$
g
Z'
g
f
$\bar{f}$
$\frac{1}{p^2 - M^2}$
$\frac{g^2}{M^2}$
q
$\bar{q}$
Z'
New Physics
Energy

Λ=M

Example : Z’

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



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

Dimensional analysis

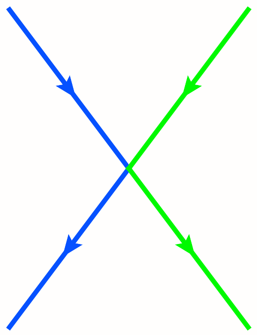
$$\hbar = c = 1$$

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

$$\dim \phi = 1$$

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

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

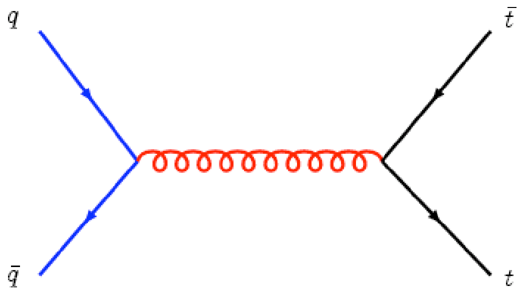


$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{\rm dim=6}$$

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

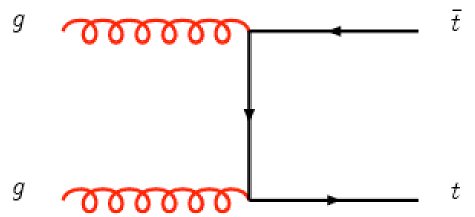
Good News : an handful are unconstrained and can signifcantly contribute to top physics!

Is there anything to learn from a σ_{tt} measurement at the LHC?

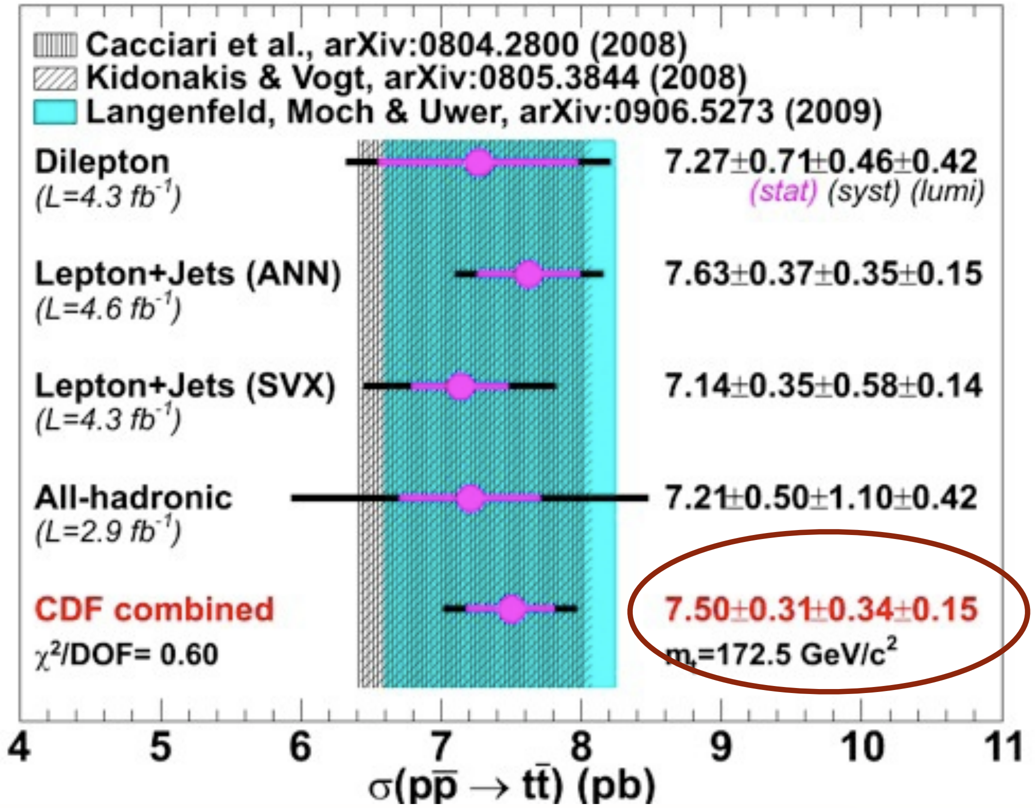


85% at TeV

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 σ_{tt}

[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 tbar.

•Use symmetries (like custodial symmetry) or well known contraints (such those on FCNC => 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 threeo parameters are left : g_h , $c_V=c_R+c_L$ and $a_A = a_R - a_R$

Simple model independent analysis of NP in σ_{tt}

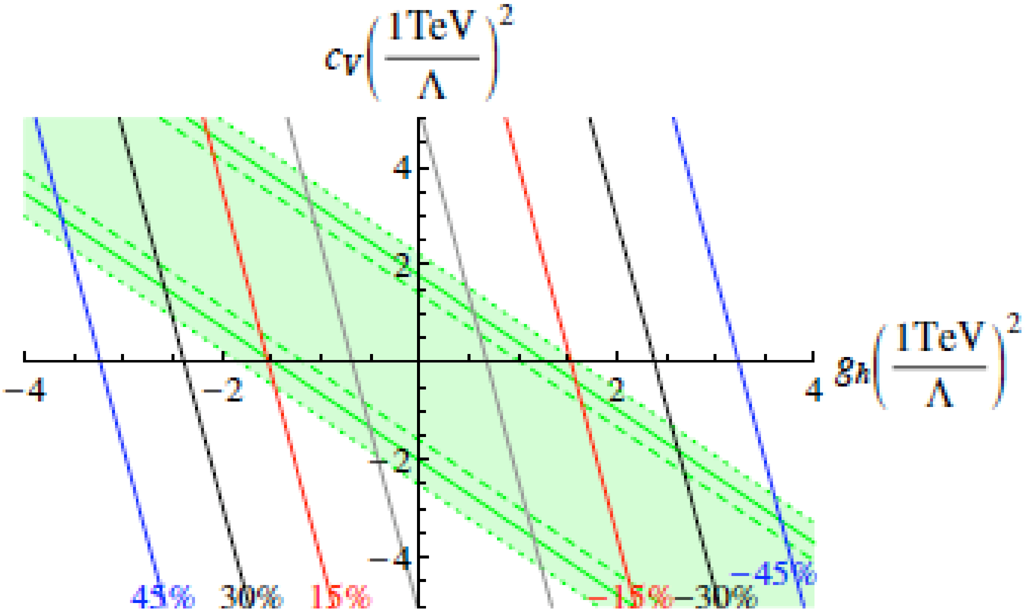
$$|M|^2 = |M_{SM}|^2 + 2\Re(M_{SM} M^*_{NP}) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

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

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

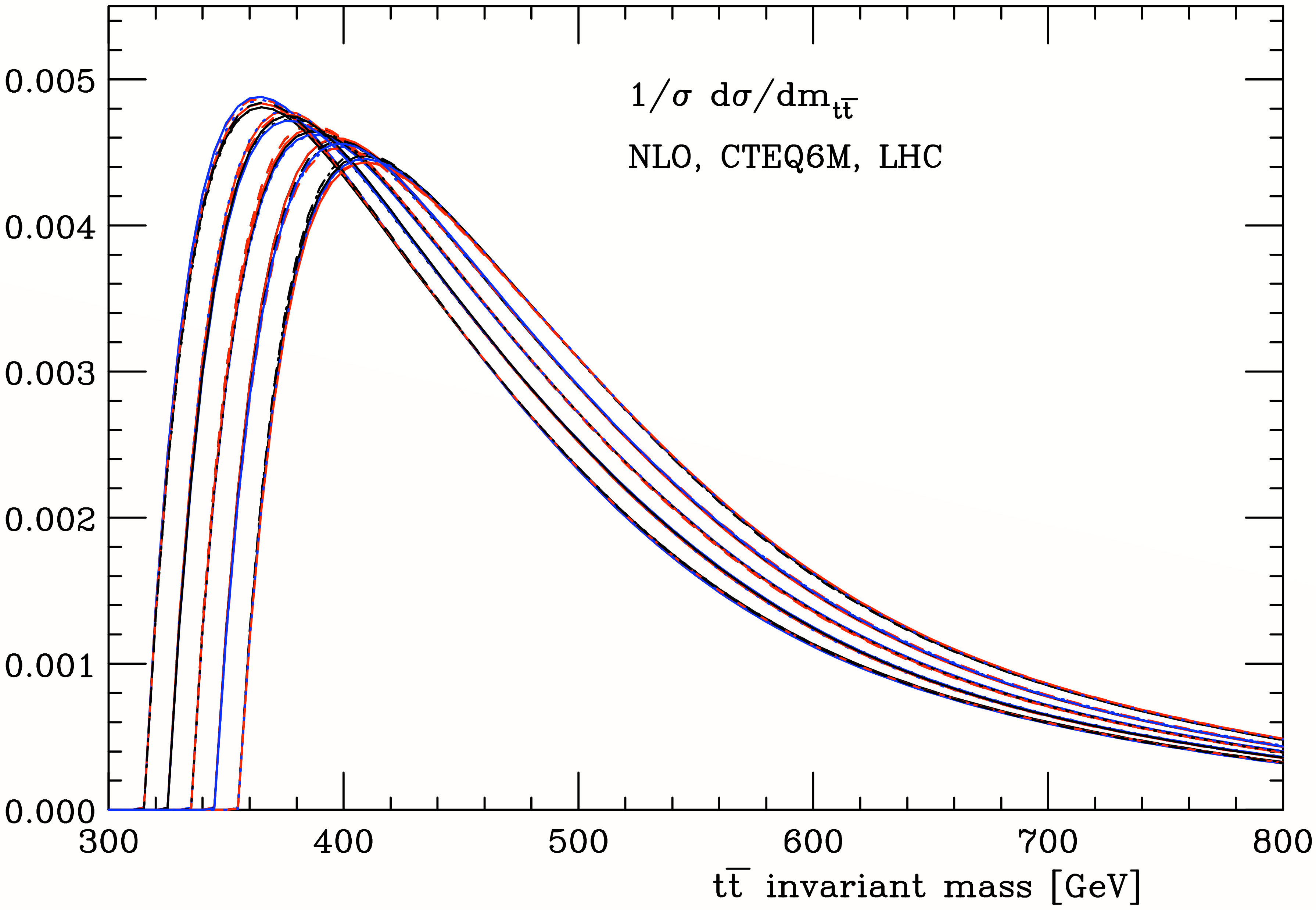
The effects on the differential cross section at the Tevatron and the LHC are different and dependent on different operators.

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?

$d\sigma/dm_{tt}$: shape differences



Interesting observable.

Shape very well predicted.

This could be also used to measure the top mass!

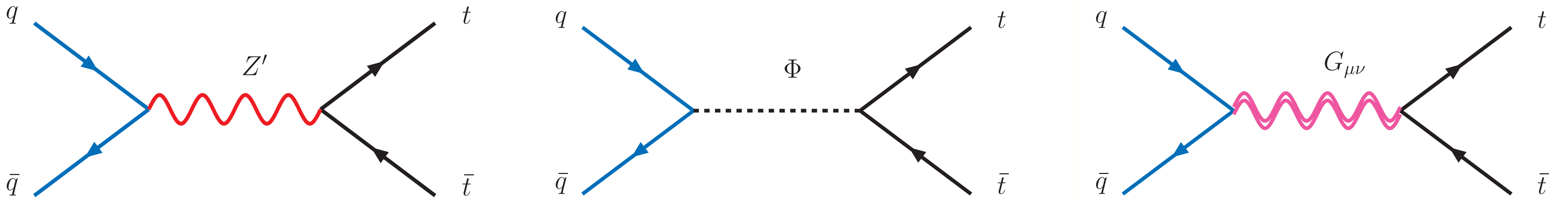
Reconstruction systematics is different from the usual top mass invariant mass reconstruction.

Any BSM effect would distort this shape =>

Model independent search for new Physics!

New resonances

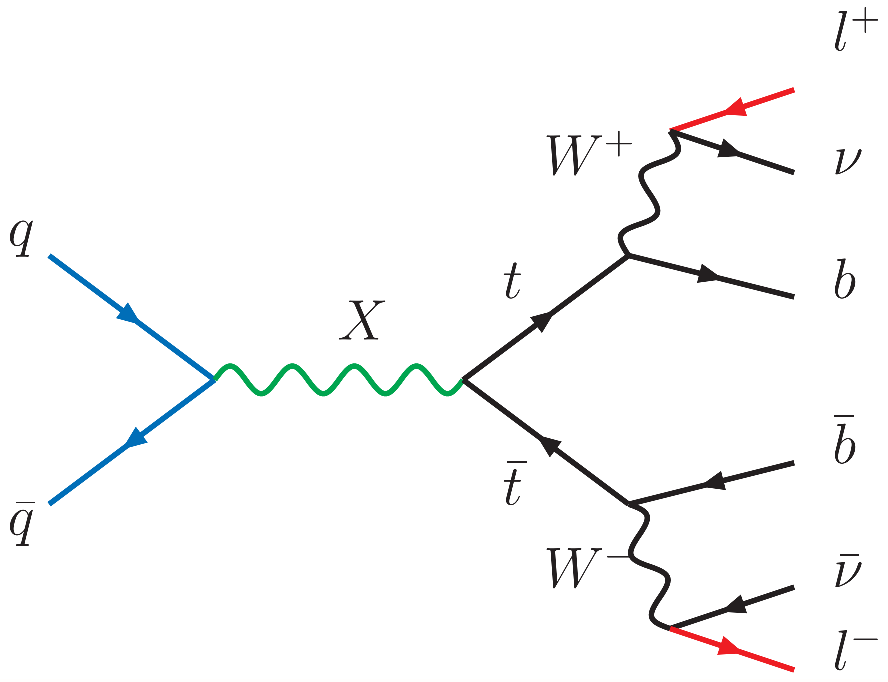
In many scenarios for EWSB new resonances show up, some of which preferably couple to 3rd generation quarks.



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.

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

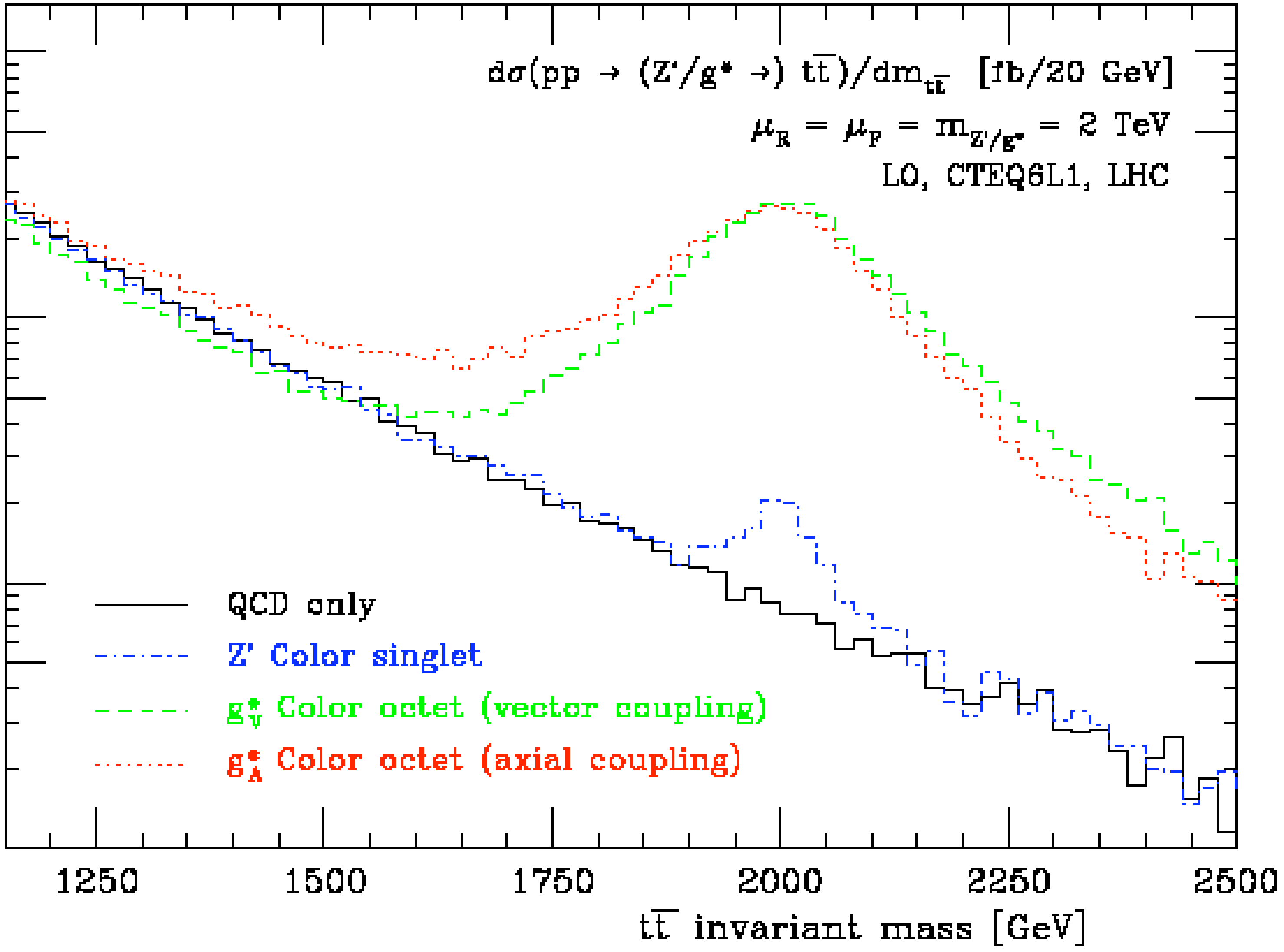
It therefore mandatory for such cases to have MC samples where spin correlations are kept and the full matrix element pp>X>tt>6f is used.



Zoology of new resonances

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

Phase I: discovery



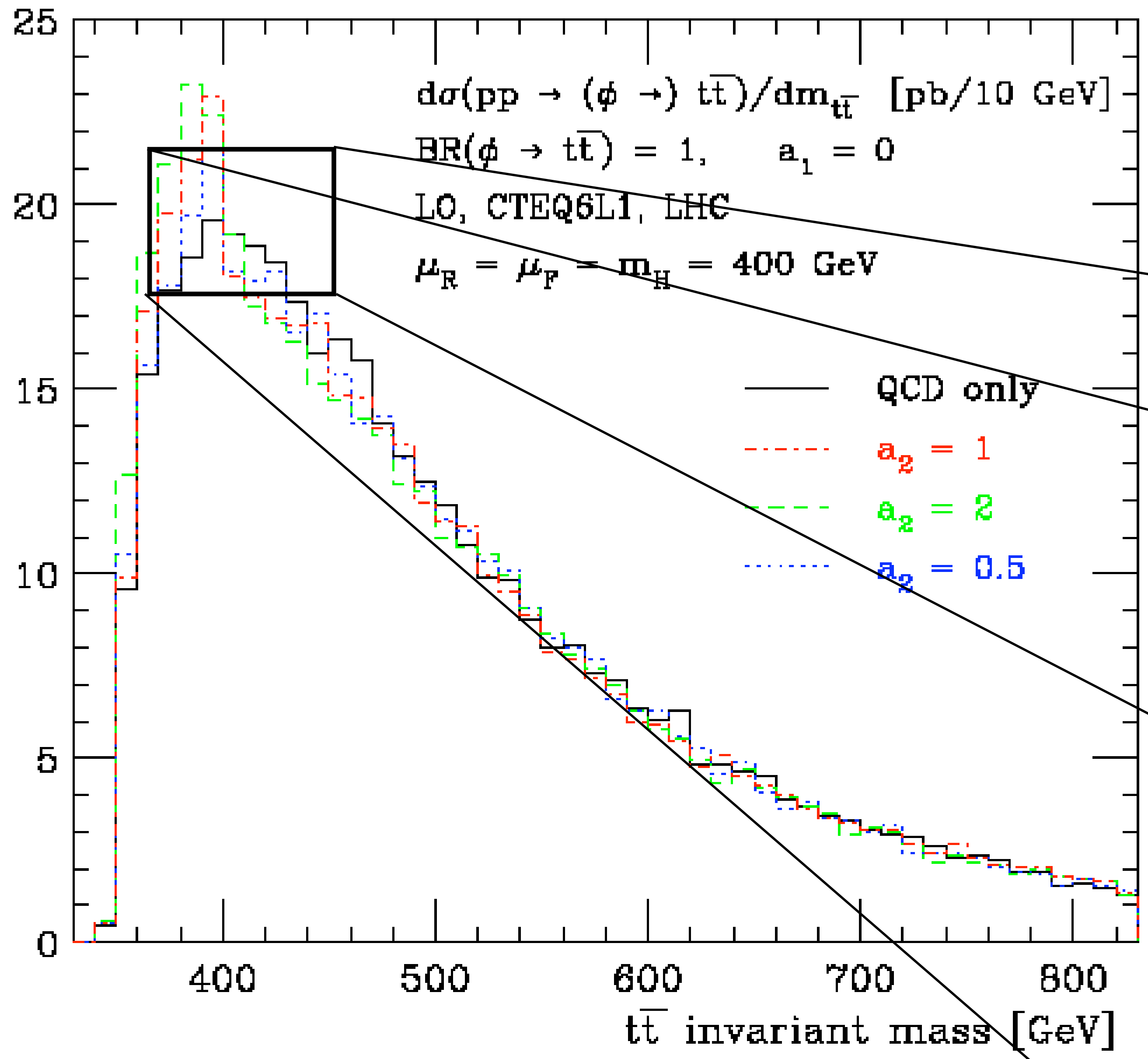
*Vector resonance, in a color singlet or octet states.

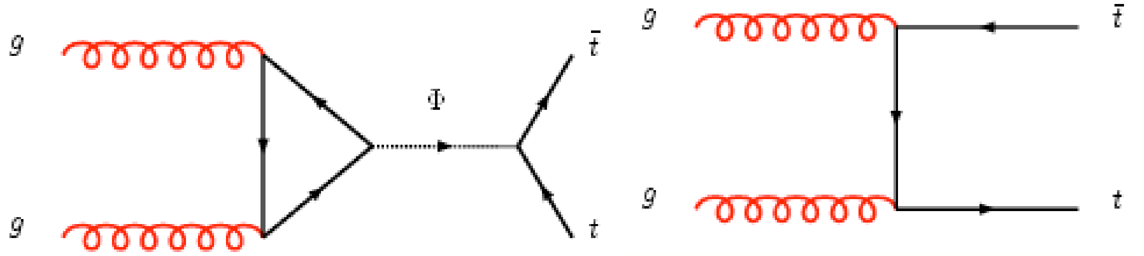
*Widths and rates very different

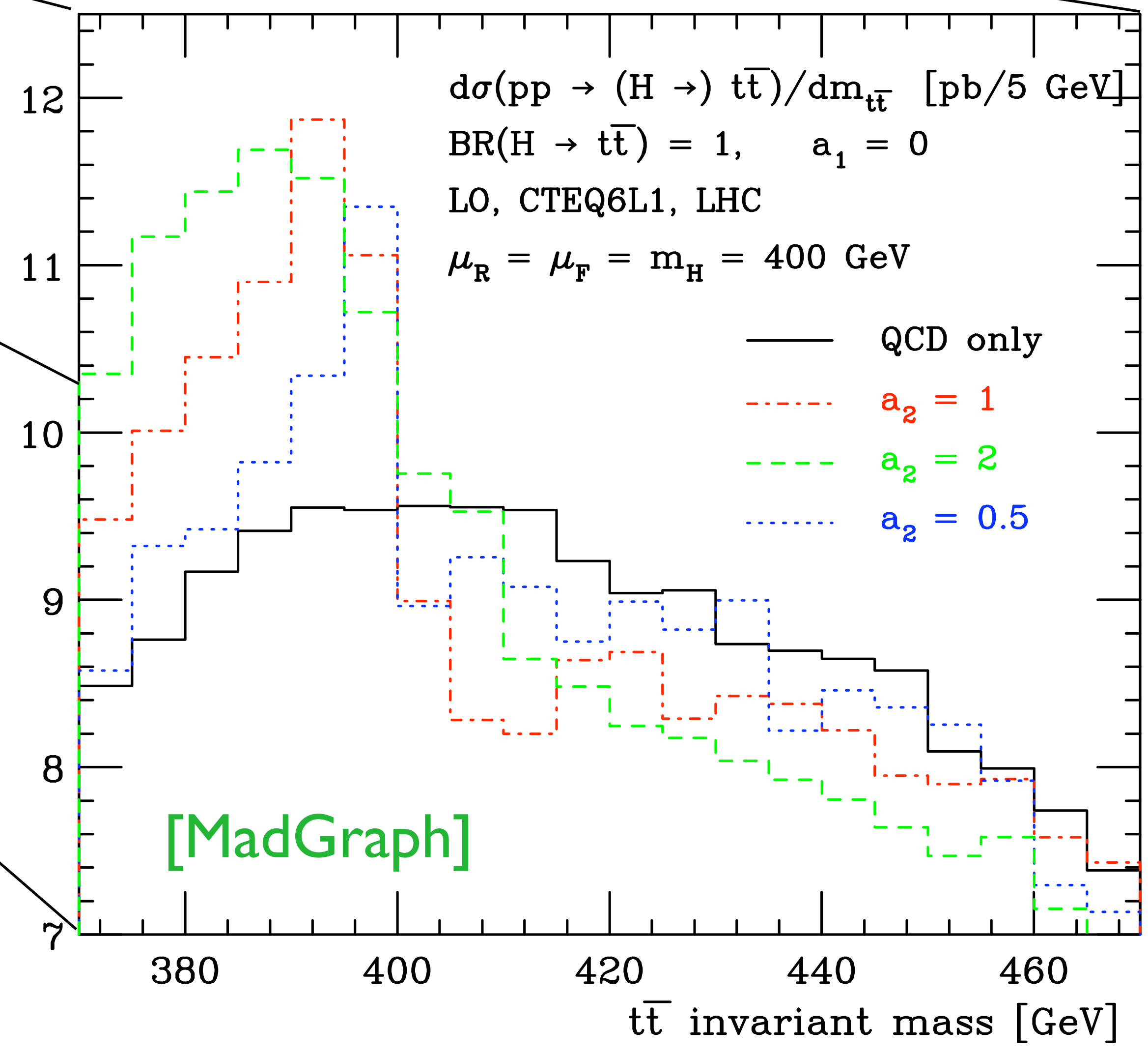
* Interference effects with SM ttbar production not always negligible

* Direct information on σ•Br and Γ.

Phase I: discovery

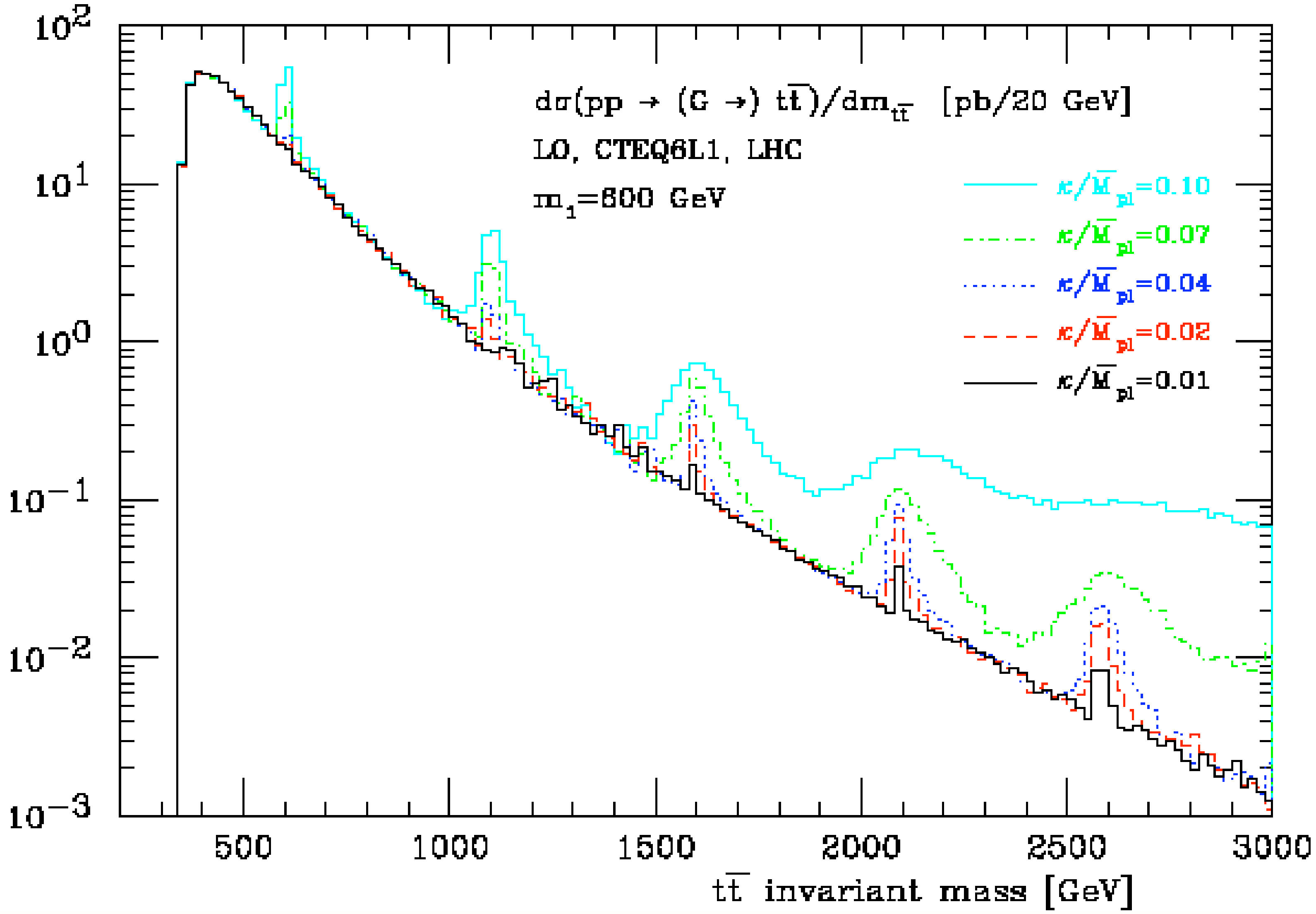






Non-trivial behavior (peak-dip) due to the interference between the signal and the background, only if top width dominated by $\Phi \to tt$. [Dicus, Stange & Willenbrock 1994]

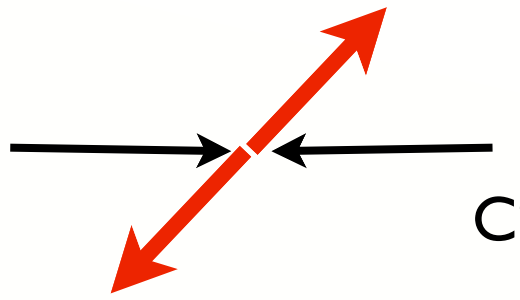
Phase 1: discovery



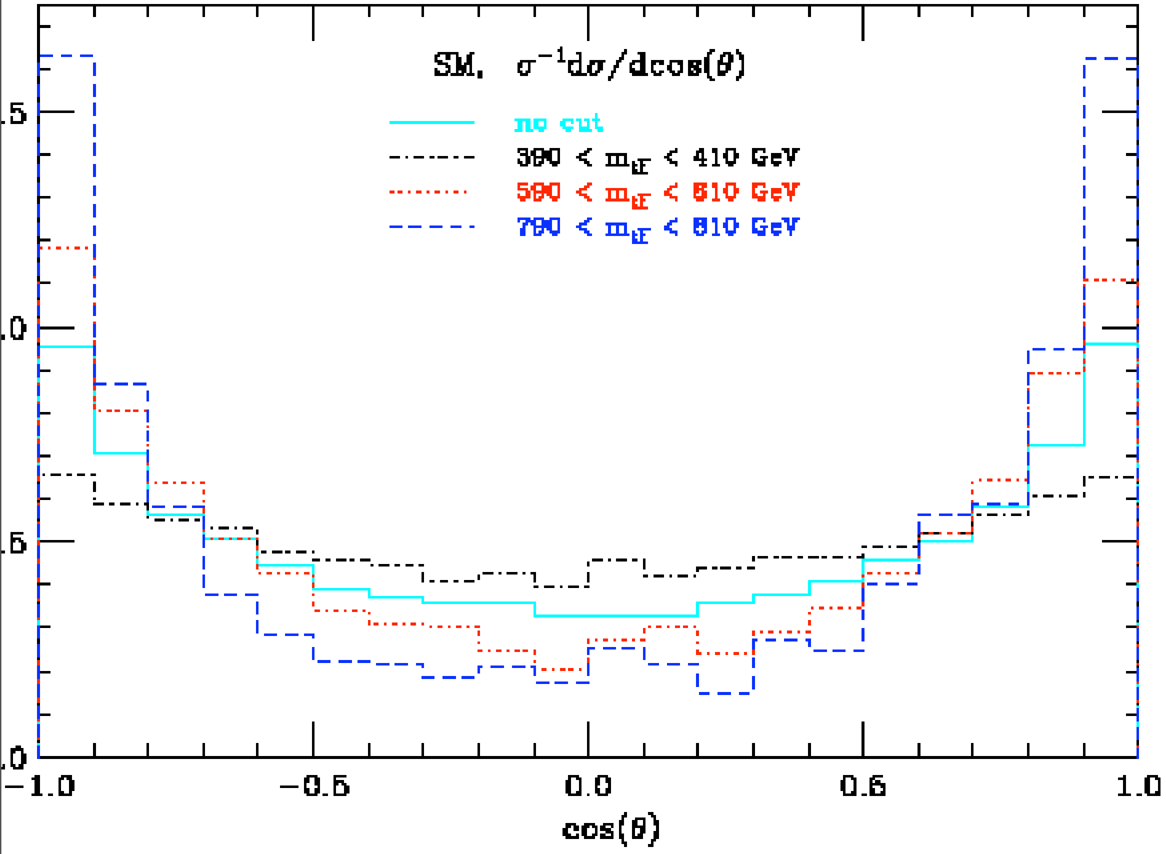
* Spectacular signature!

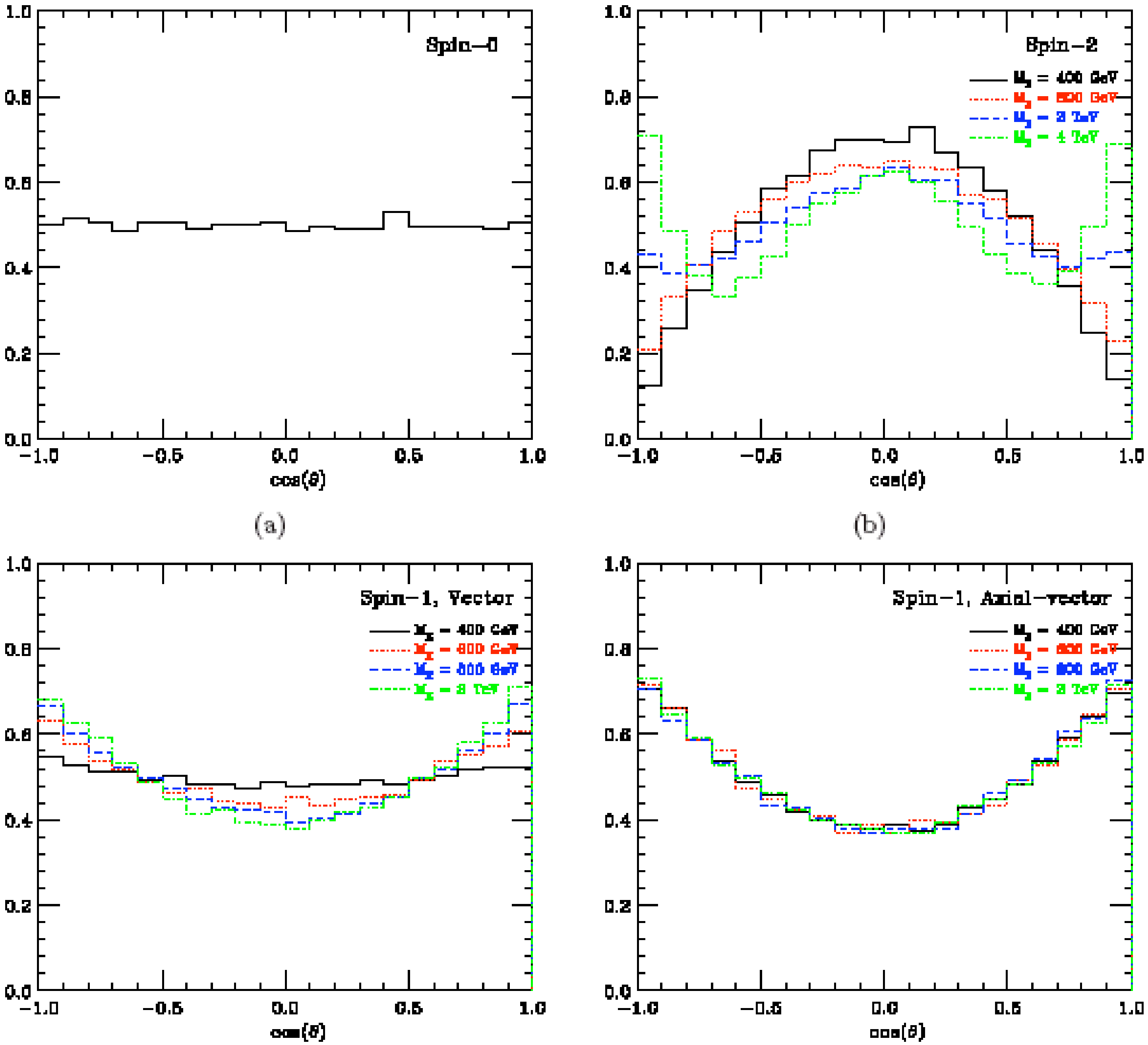
*RS Model with first KK=600 GeV

Phase 2: ttbar angular distributions



CS angle



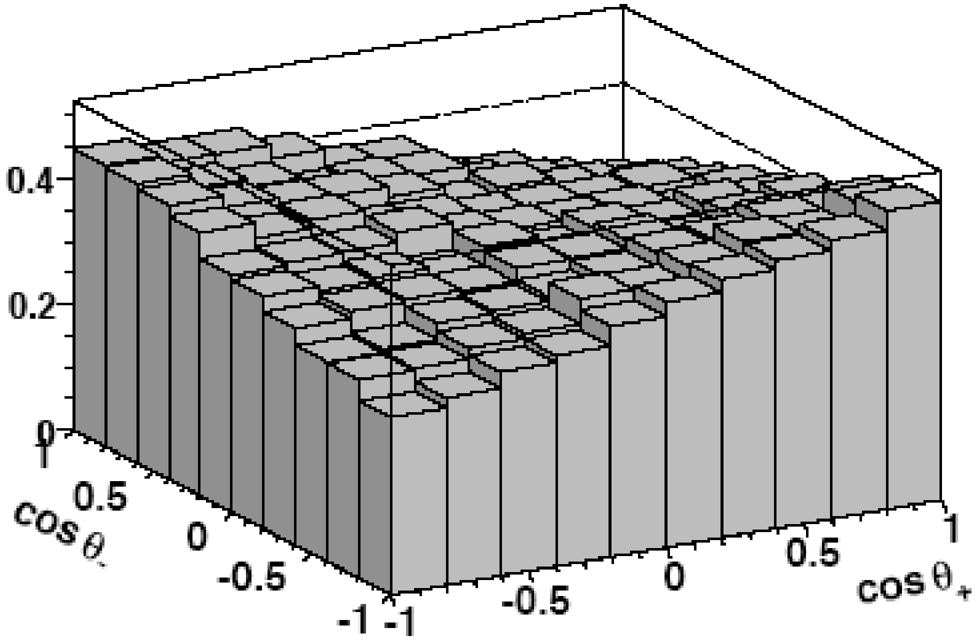


(a) (b)

(c) (d)

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

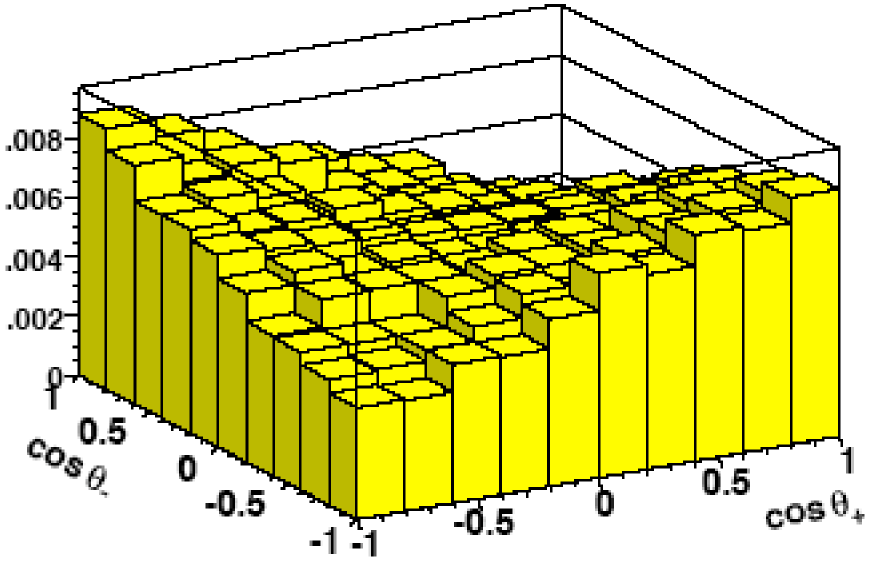
Phase 3: Spin correlations



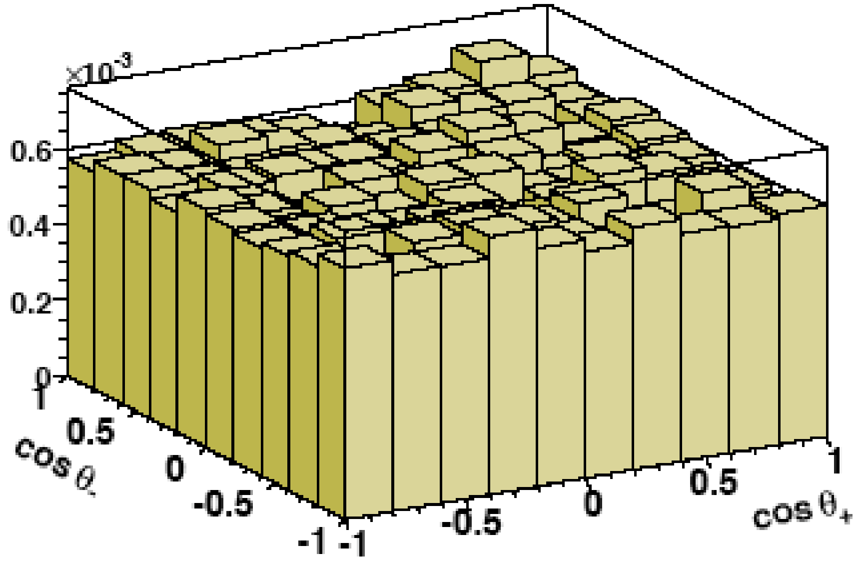
(a)

no cuts

low m_{tt}



(b)

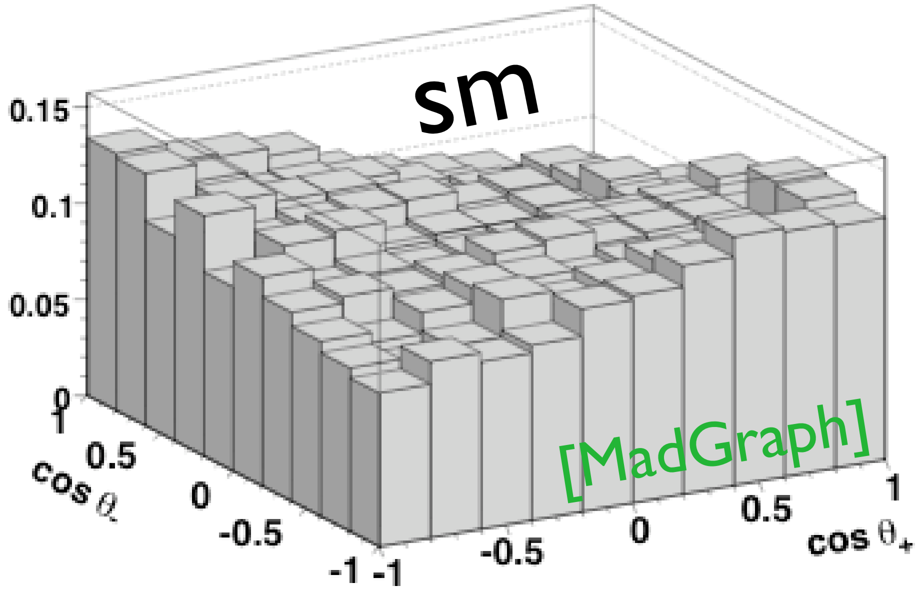


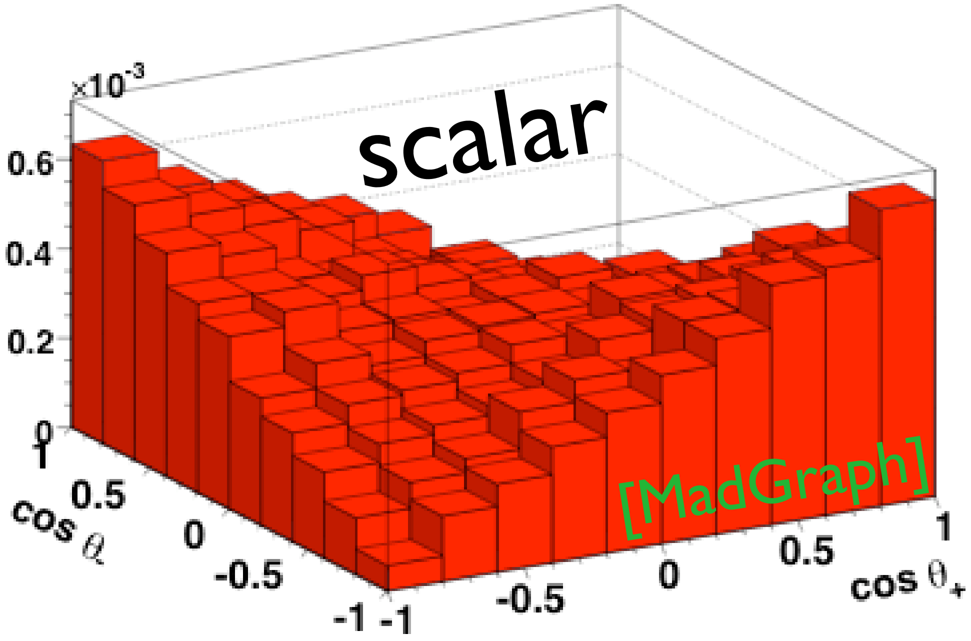
(c)

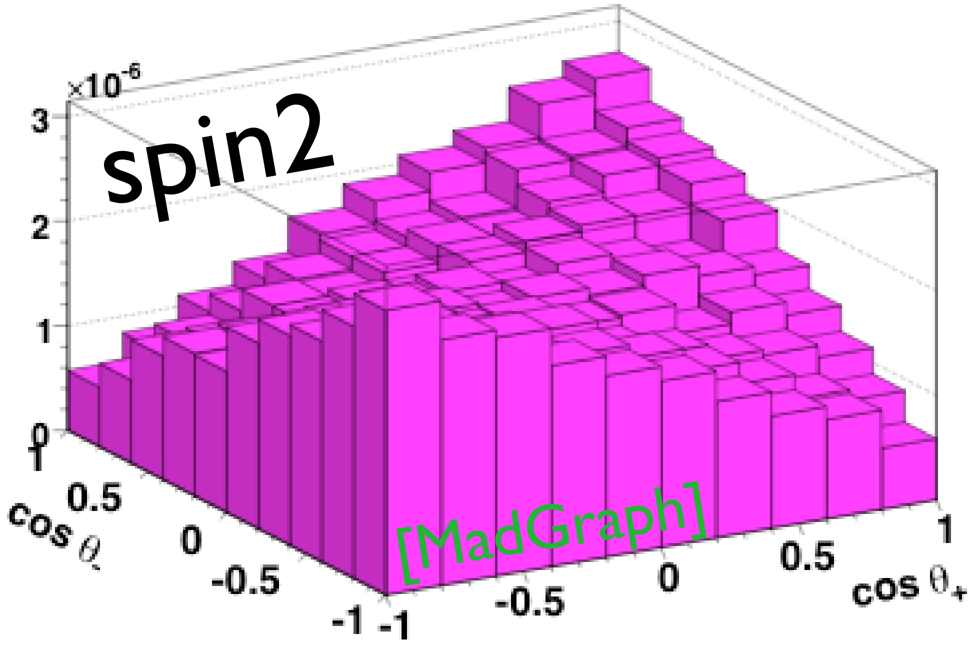
high m_{tt}

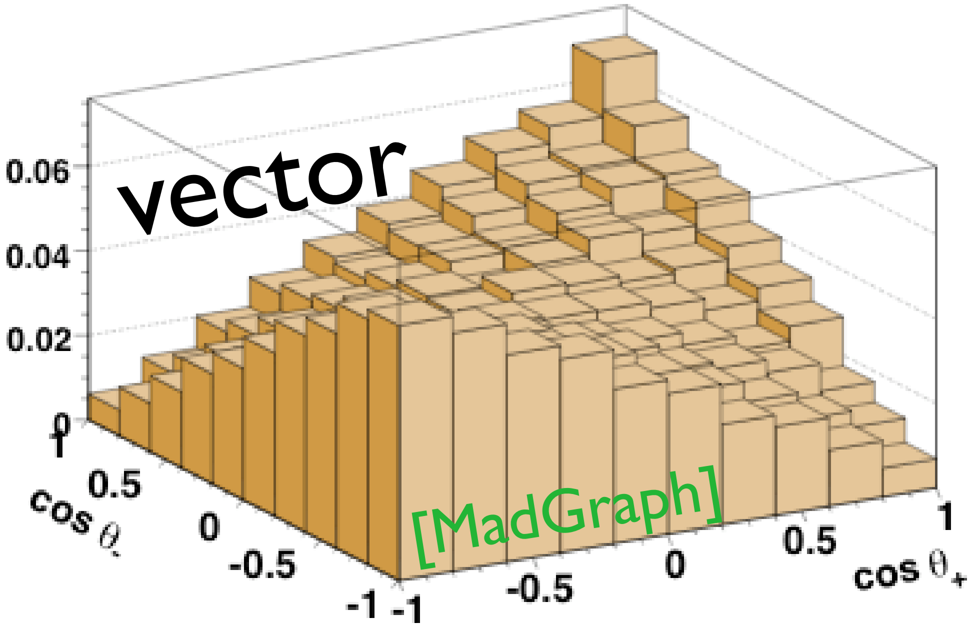
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}(1+\kappa_t\kappa_{\bar{t}} D\cos\theta_-\cos\theta_+)$$

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 θ	reco (no comb w/ constr)		
spin corr.	full reco + 4-fold spin comb	full reco + 2-fold spin comb	

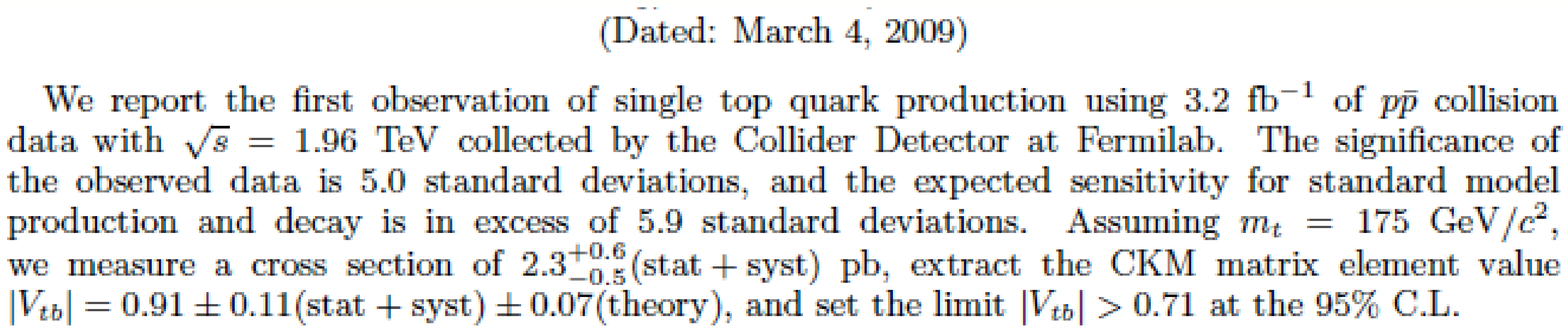
t tbar : Summary

- Large rates : plenty of top pairs at the LHC
- Discovery potential is huge and well motivated
- Simple strategy :

  observable ⇔ accurate SM predicitons

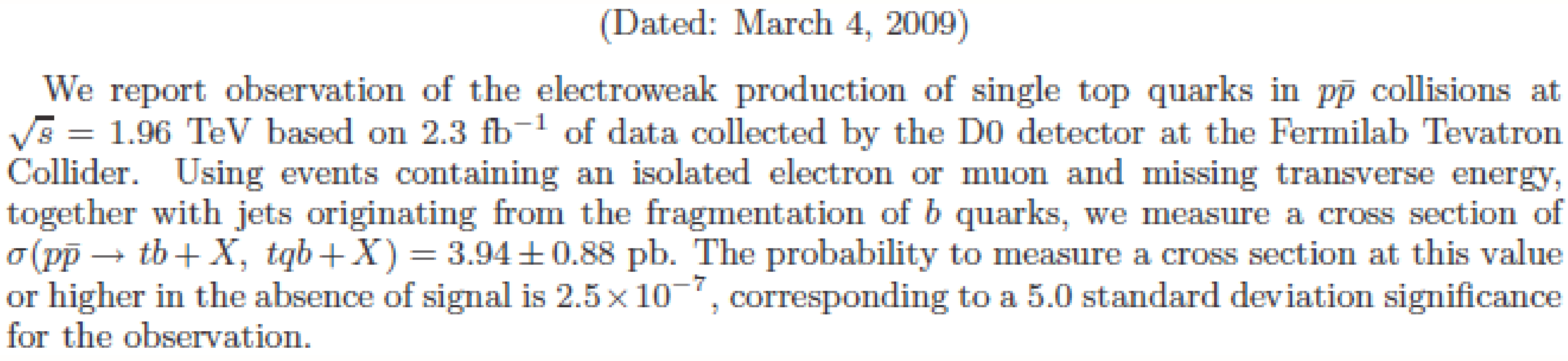
- Both direct and indirect (through L_{eff}) searches/constraints.

Single-top



(Dated: March 4, 2009)

We report the first observation of single top quark production using 3.2 fb^{-1} of $p\bar{p}$ collision data with $\sqrt{s} = 1.96$ 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 $m_t = 175$ GeV/c^2, we measure a cross section of $2.3^{+0.6}_{-0.5}(\text{stat} + \text{syst})$ 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.



(Dated: March 4, 2009)

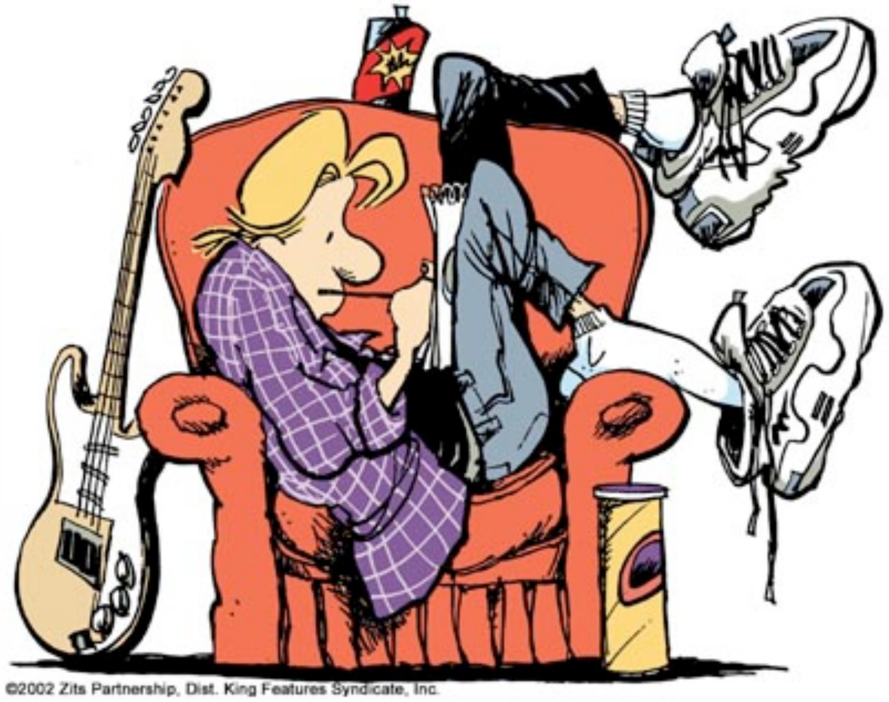
We report observation of the electroweak production of single top quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV based on 2.3 fb^{-1} of data collected by the D0 detector at the Fermilab Tevatron Collider. Using events containing an isolated electron or muon and missing transverse energy, together with jets originating from the fragmentation of b quarks, we measure a cross section of $\sigma(p\bar{p} \to tb + X,\ tqb + X) = 3.94 \pm 0.88$ pb. The probability to measure a cross section at this value or higher in the absence of signal is 2.5×10^{-7}, corresponding to a 5.0 standard deviation significance for the observation.

Why single top is cooler than ttbar?

At least three reasons...

Reason #1 : Teenager vs Newborn

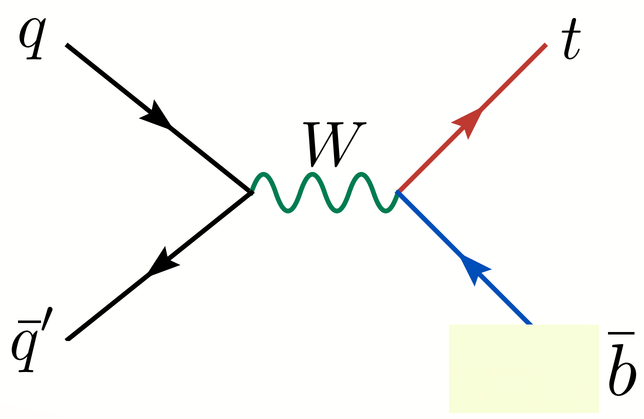
t tbar	single-top


©2002 Zits Partnership, Dist. King Features Syndicate, Inc.

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

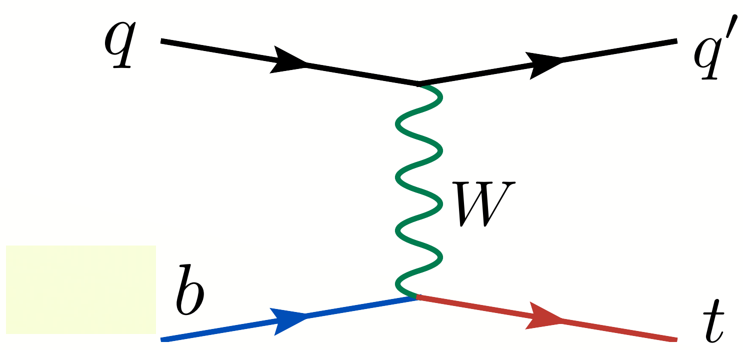
- Just a one year old!
- Good : a whole new world to explore
- Bad : sleep deprivation...

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



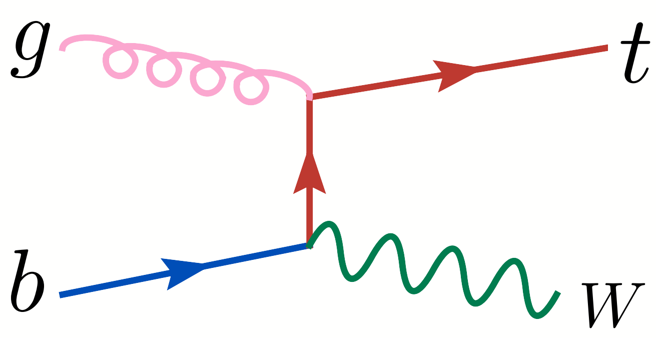
- * “Drell-Yan” production mode.
- * Tevatron is sizable (~1pb), quite small at the LHC14 (~10 pb).
- * Fully inclusive x-sec known at NNLO (leading Nc).
- * Channel to search for new charged resonances (H^+ or W’). Four-fermion interactions.
- * Final State: 2 b’s + W

“No brainer”



- * “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

“Interesting!”



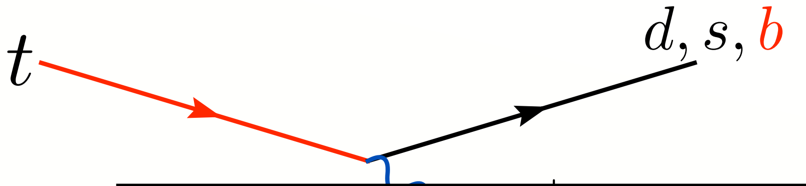
- * Associated production
- * Sizable cross section (60 pb) at LHC14, but difficult.
- * Template for tH^+ production.
- * b initiated
- *Interferes with ttbar at NLO : subtle definition.
- * Final State: 1b, 2W and jet veto

“Challenging!!” *

*Theorist’s comments

Example: Direct constraints on the 3rd row of CKM

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



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

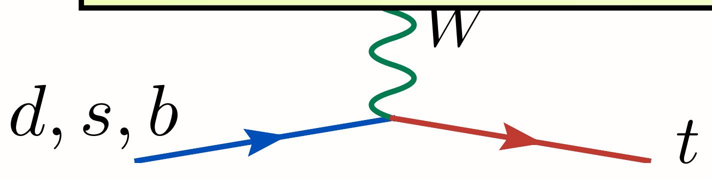
On t

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

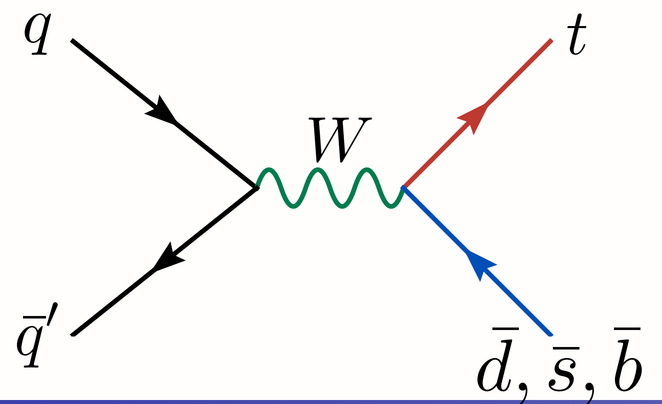
$$\sigma_{2b\text{-tag}} = R\,|V_{tb}|^2\,\sigma^{\text{s-ch}}$$

n.b. : naive estimate

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



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



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

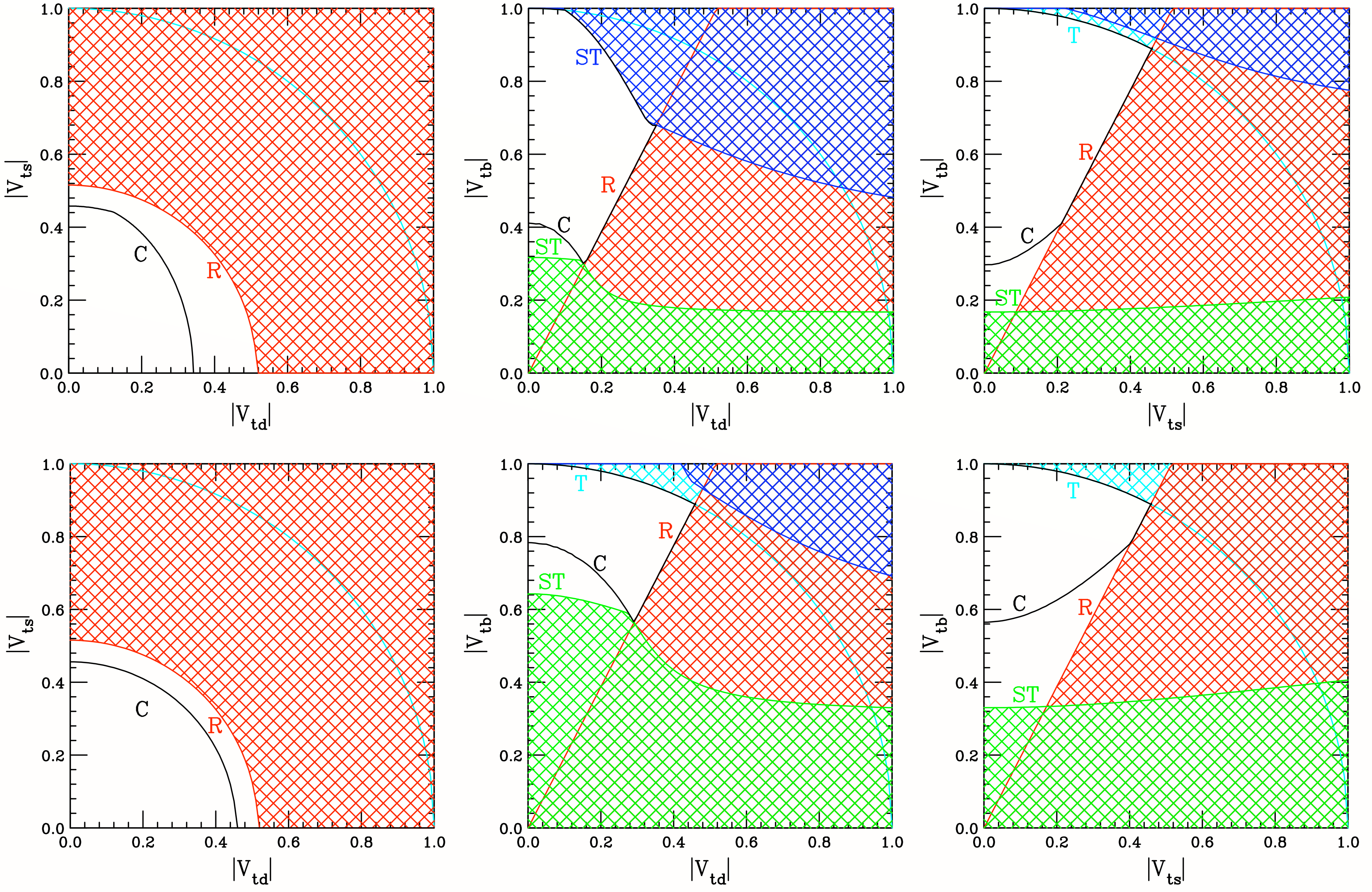
Signal becomes similar to t-channel (only 1 *b*-jet)

Example: Direct constraints on the 3rd row of CKM

$|V_{td}|$ vs $|V_{ts}|$ $\quad$ $|V_{td}|$ vs $|V_{tb}|$ $\quad$ $|V_{ts}|$ vs $|V_{tb}|$

CDF

DØ



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

Reason #3 : More work for theorists

- Current observation relies quite strongly on our confidence that signal is well described by theory and MC's.

- Uncertainty on the Vtb extraction obviously depends on precision of theory predictions. Source of errors : PDF (beware the bottom quark!), scales, α_s, m_b, m_t.

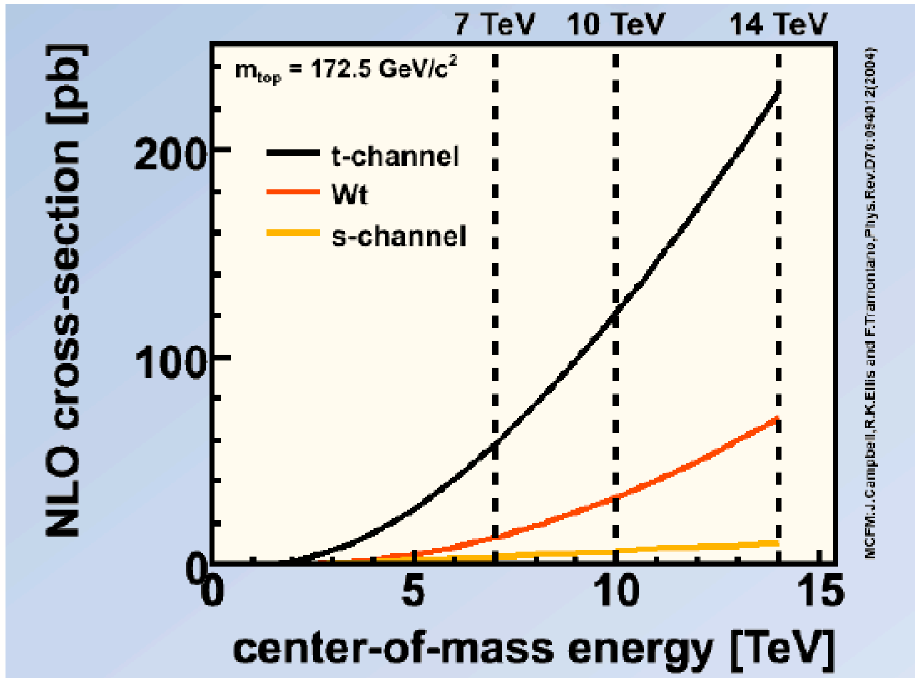
- Still work to do to match the accuracy of the older brother :

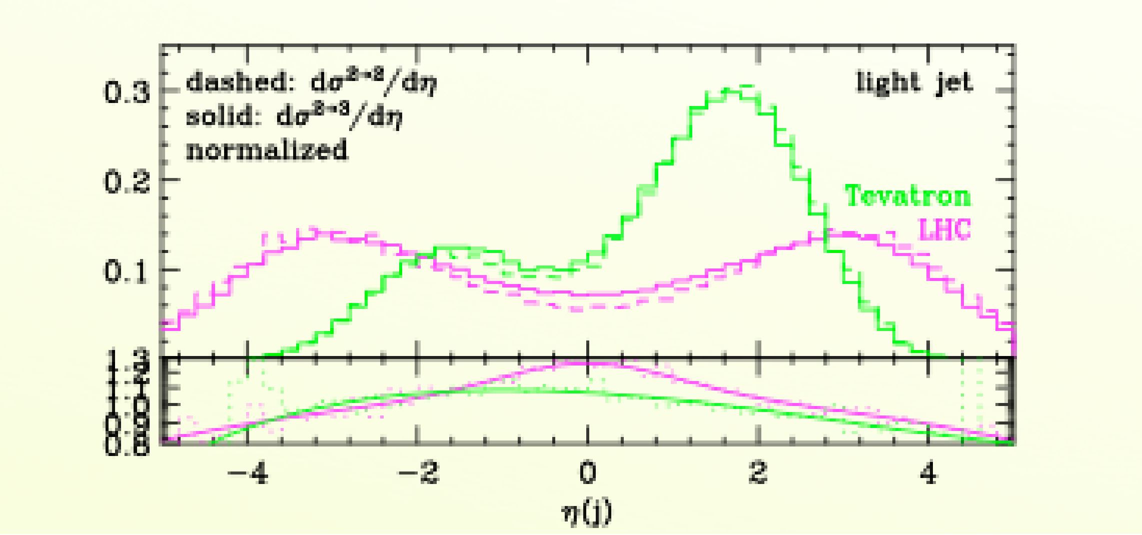
Calculation	t tbar	t-channel		s-channel	tW
		(2→2)	(2→3)		
NLO QCD	yes	yes	yes	yes	yes
NLOwPS QCD	yes	yes	no	yes	yes
Resummed NLO	yes	yes	no	yes	no
X+1 jet at NLO	yes	no	no	no	no
NNLO	work in progress	no	no	yes	no
NLO EW	yes	yes	no	yes	yes

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

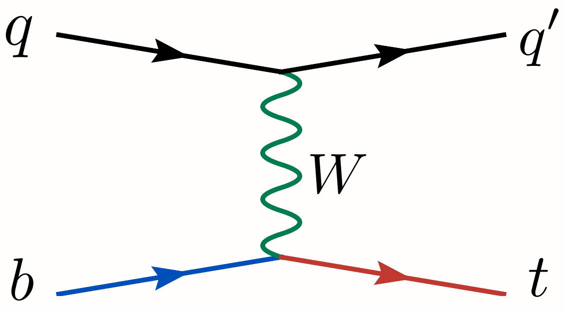
☹ All MC implementations currently available for single top processes neglect m_b.

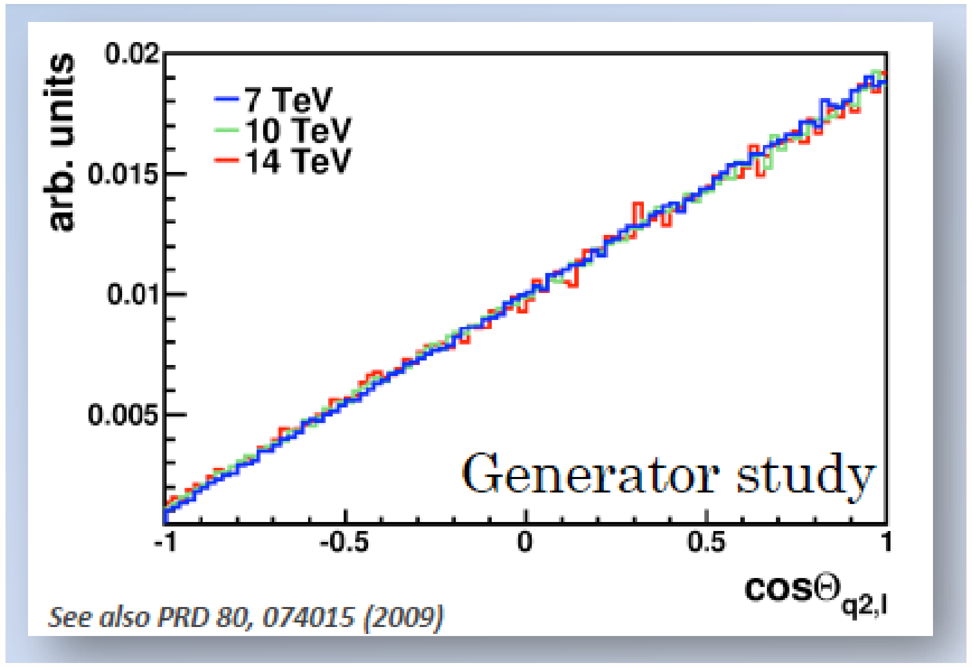
Single top at the LHC





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

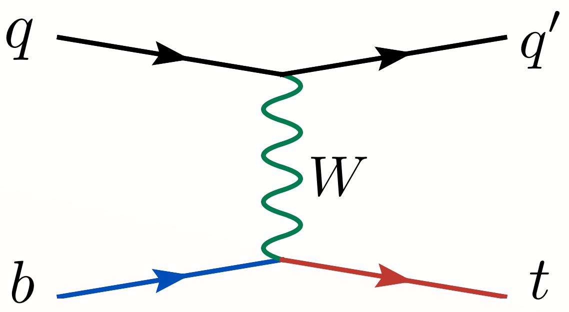


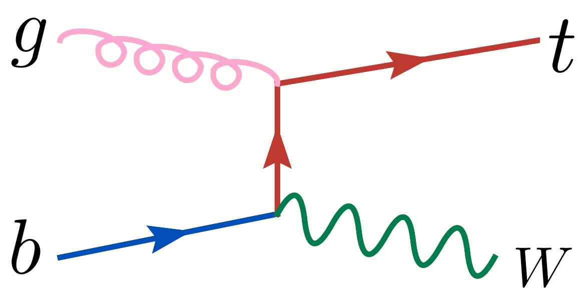


See also PRD 80, 074015 (2009)

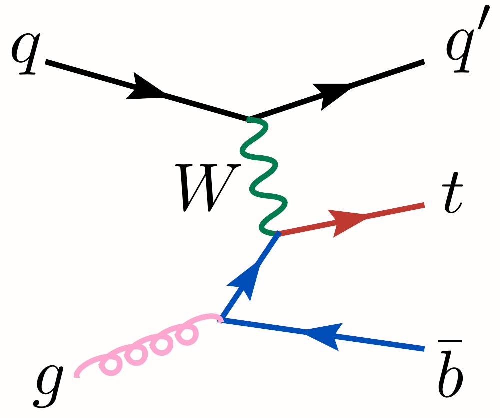
Deeper into t-channel...

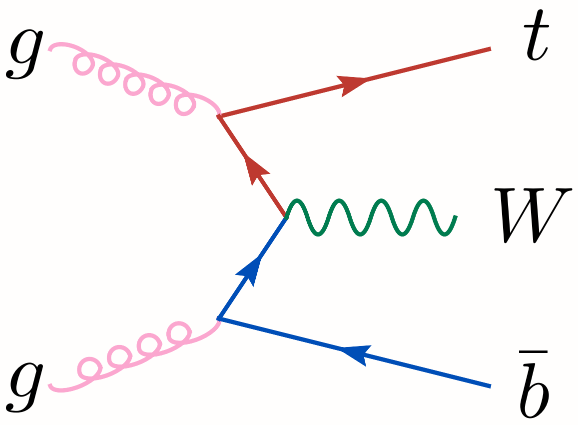
- Both the t-channel as well as the Wt associated production have a (heavy) b quark in the initial state





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

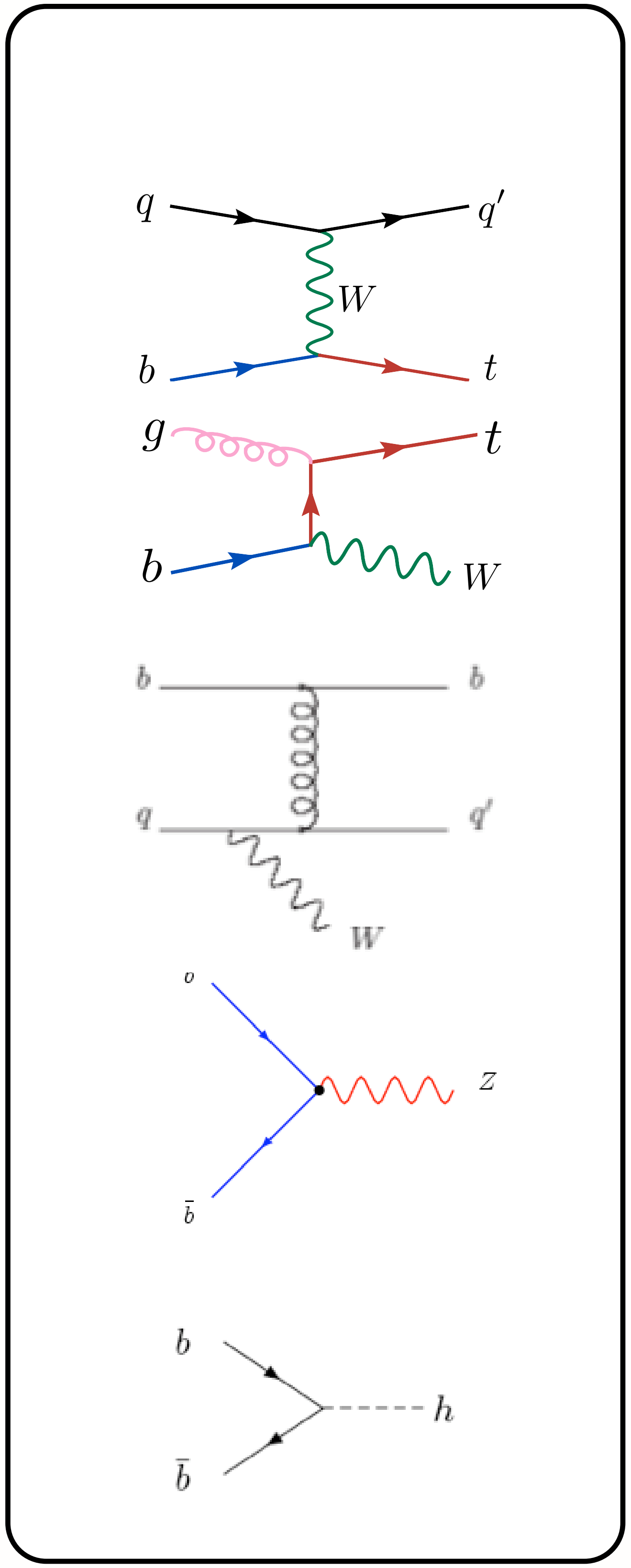




* At all orders. At fixed order differences arise...

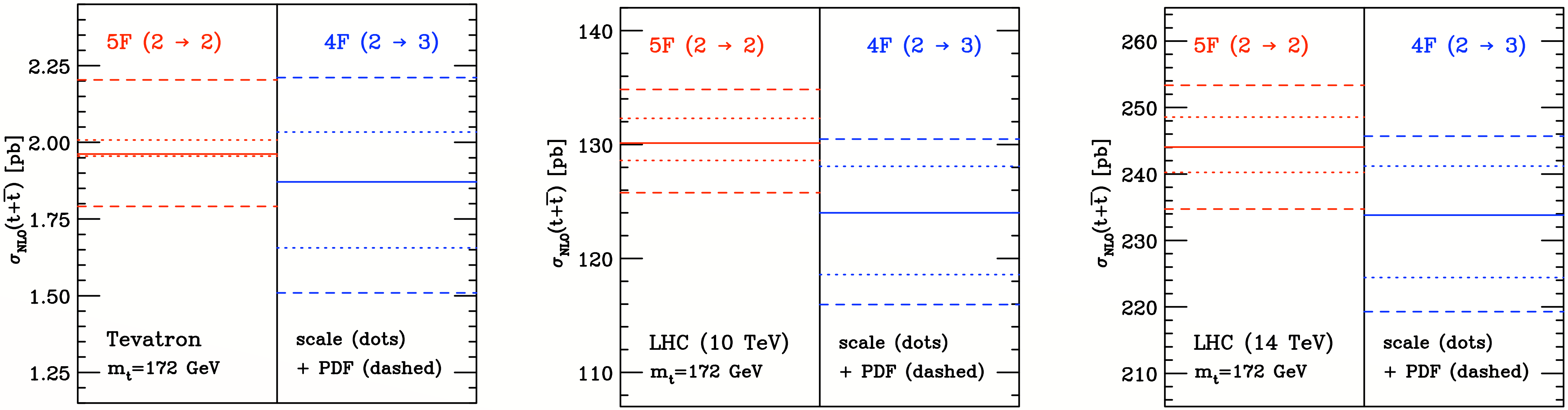
b-initiated processes

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



t-channel best cross sections : 2→2 vs 2→3

[Campbell, Frederix, FM, Tramontano, 0907.3933]

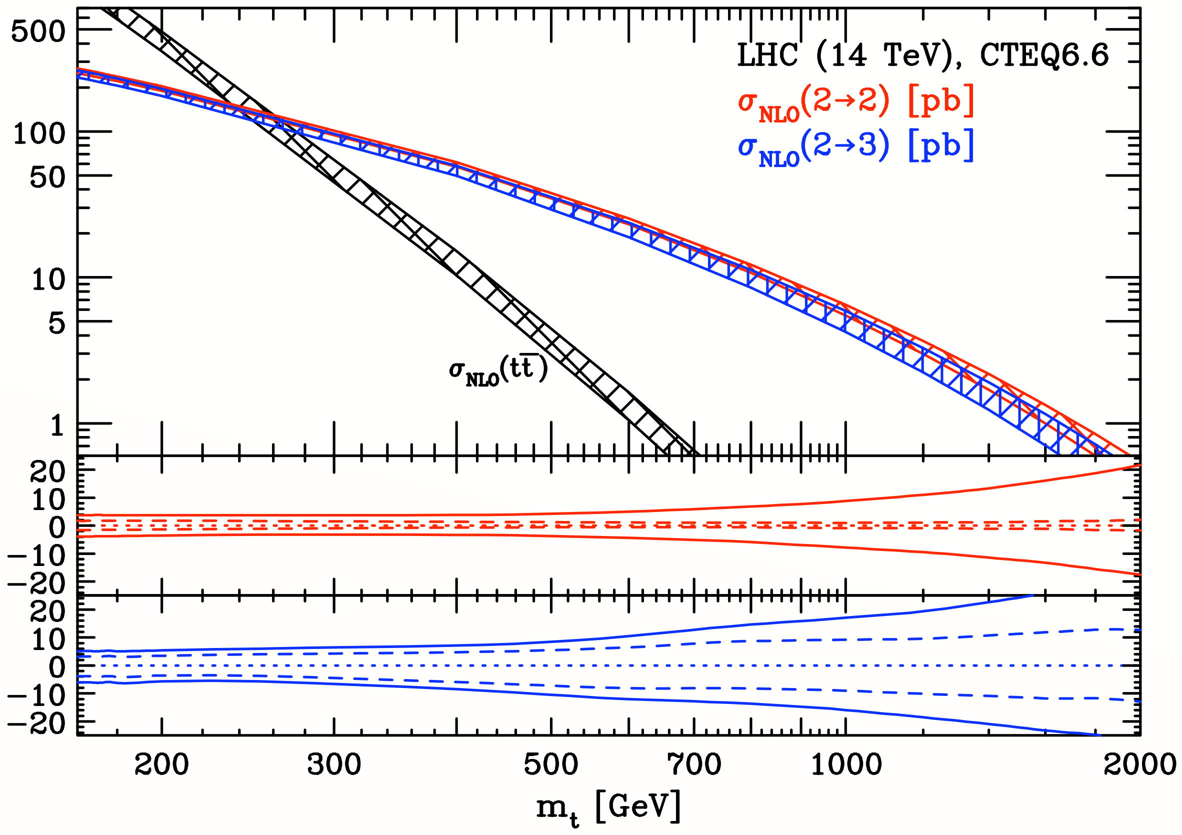


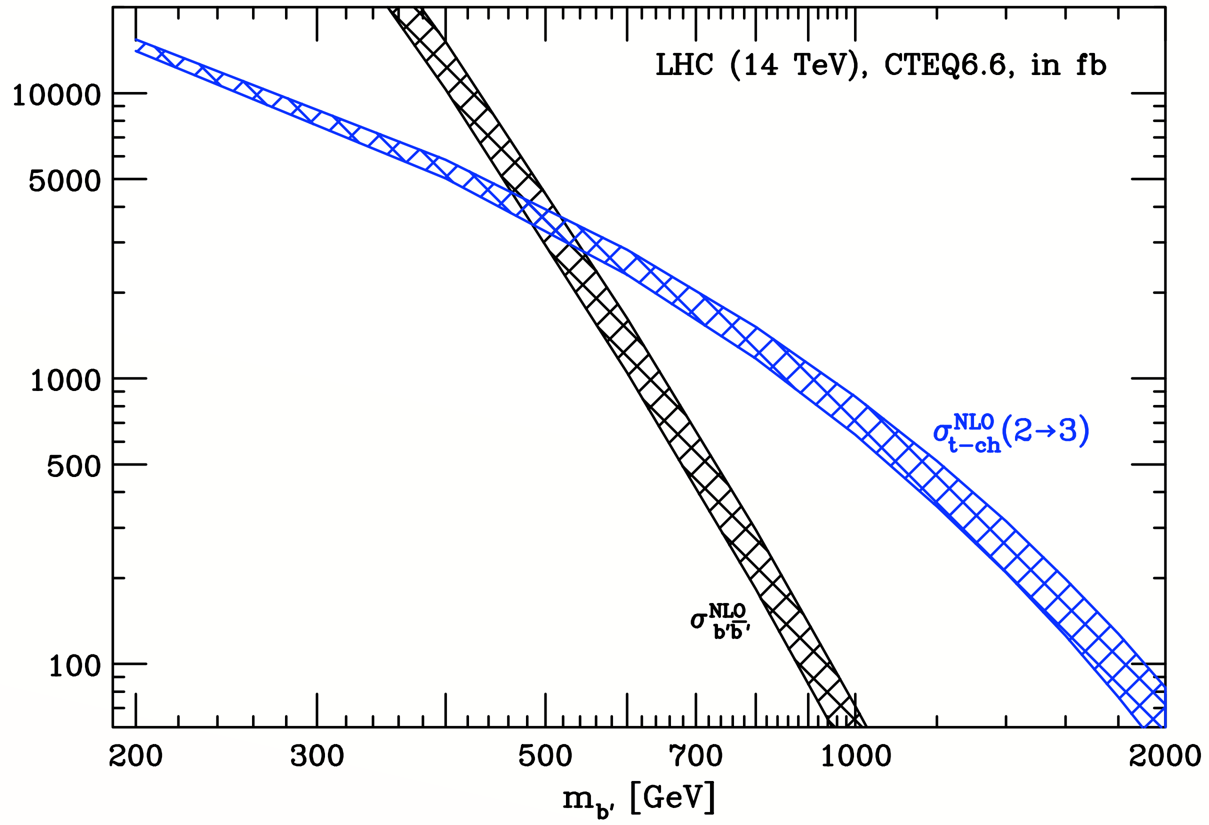
$\sigma^{\rm NLO}_{\rm t-ch}(t+\bar{t})$	$2 \to 2$ (pb)					$2 \to 3$ (pb)				
Tevatron Run II	1.96	$^{+0.05}_{-0.01}$	$^{+0.20}_{-0.16}$	$^{+0.06}_{-0.06}$	$^{+0.05}_{-0.05}$	1.87	$^{+0.16}_{-0.21}$	$^{+0.18}_{-0.15}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$
LHC (10 TeV)	130	$^{+2}_{-2}$	$^{+3}_{-3}$	$^{+2}_{-2}$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

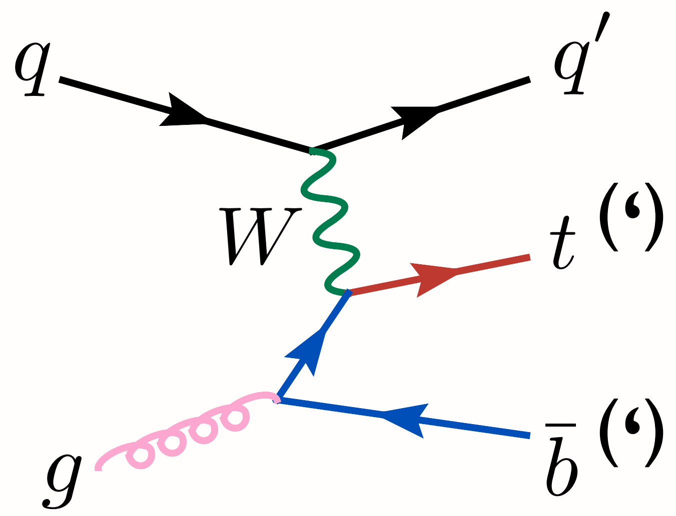
Uncertainties: scales, PDF, m_t (1%), m_b(4%)

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

Addendum: Fourth generation







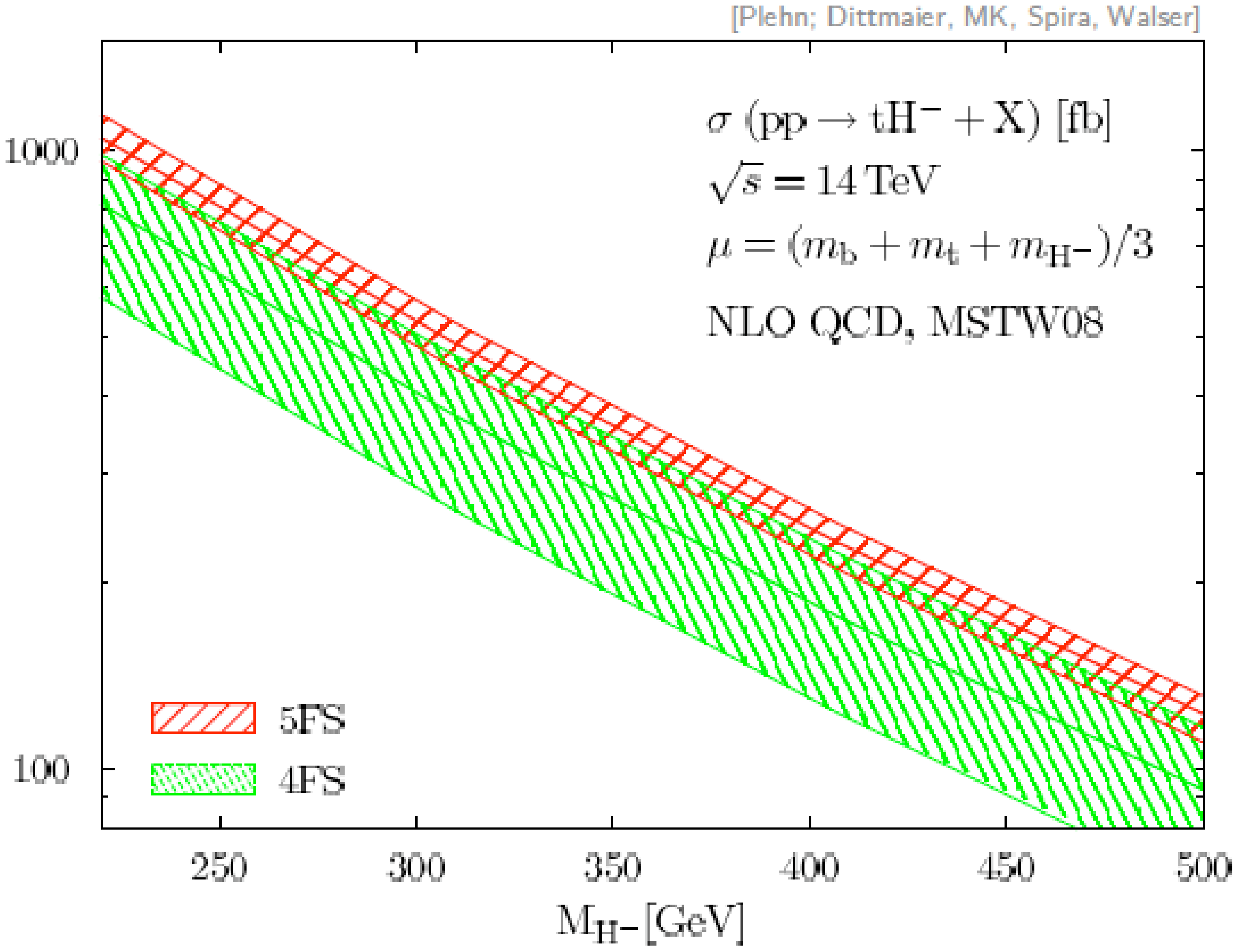
The NLO 2→3 massive calculation can be also used to make reliable predictions for t'b, b't and b't' cross sections.

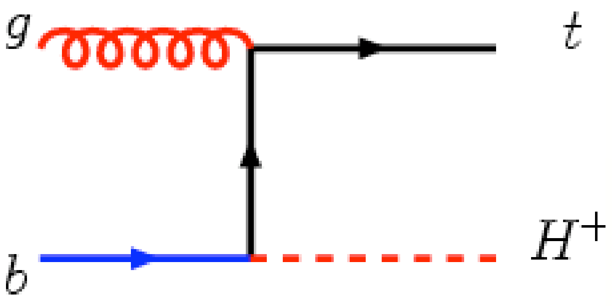
It is interesting to see where the cross over between the QCD and the EW productions are at the LHC.

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

tH$^+$ in the 4F

[Dittmaier, Kramer, Spira, Walser, 2009]



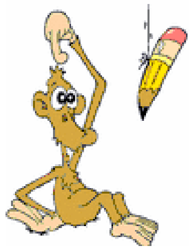


Upshot: Similar results also for other processes!

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

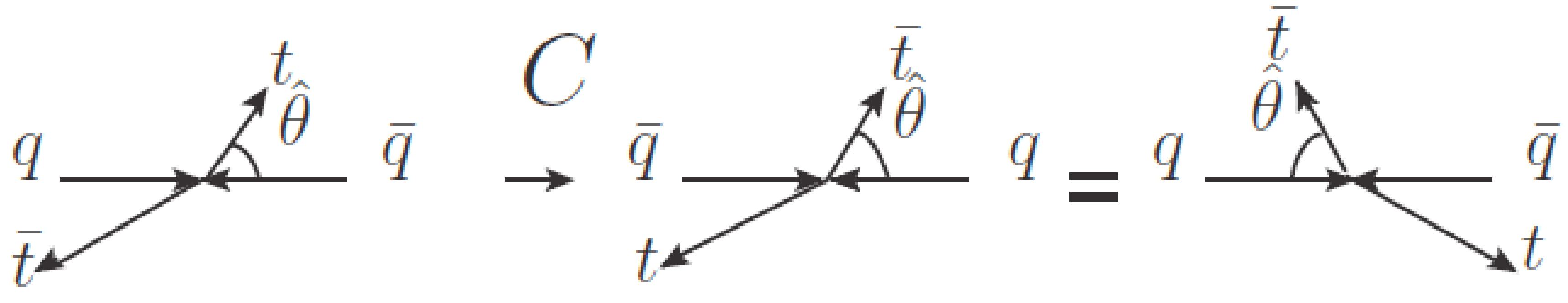
Hot TOPic #4 : ....

Hot TOPic #1 :

Forward-backward asymmetry

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

Charge asymmetry ⇔ FB asymmetry



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

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

ok. But where does it come from?

Charge asymmetry in QCD

[Kühn, Rodrigo, 1998]

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

A charge asymmetry arises at O(α_s^3)

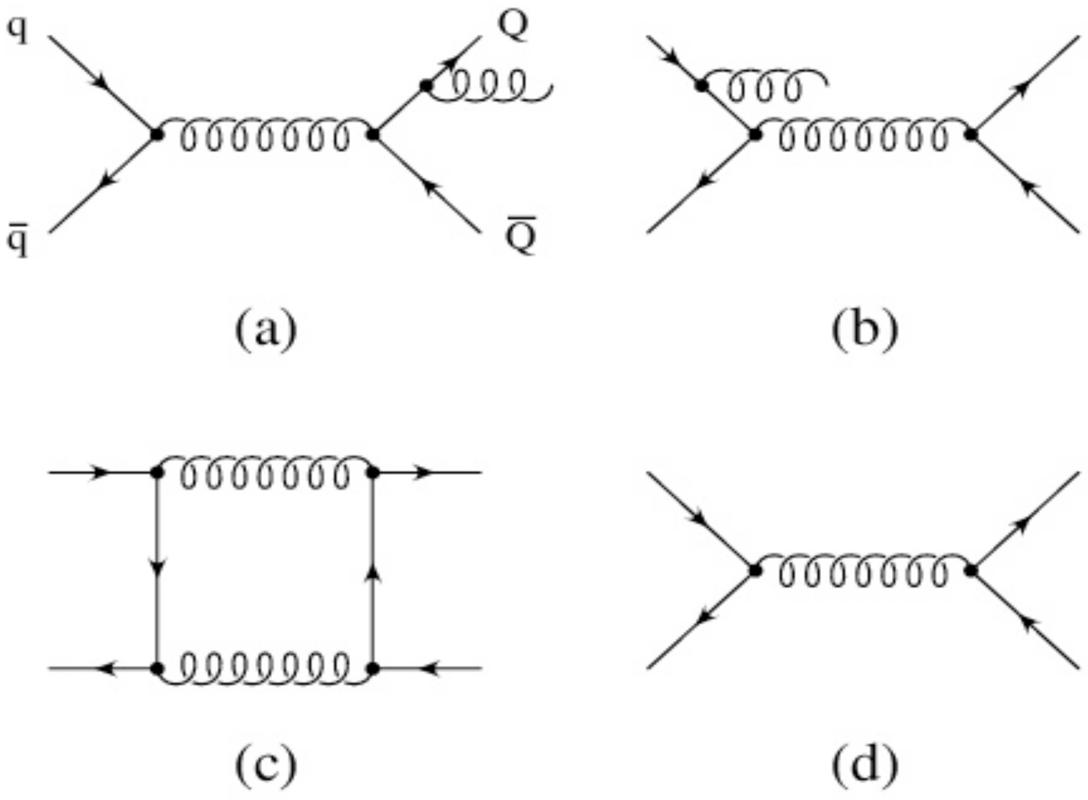
1. Interference of ISR with FSR LO for ttbar+jet **negative** contribution

2. Interference of box diagrams with Born **positive** contribution

?

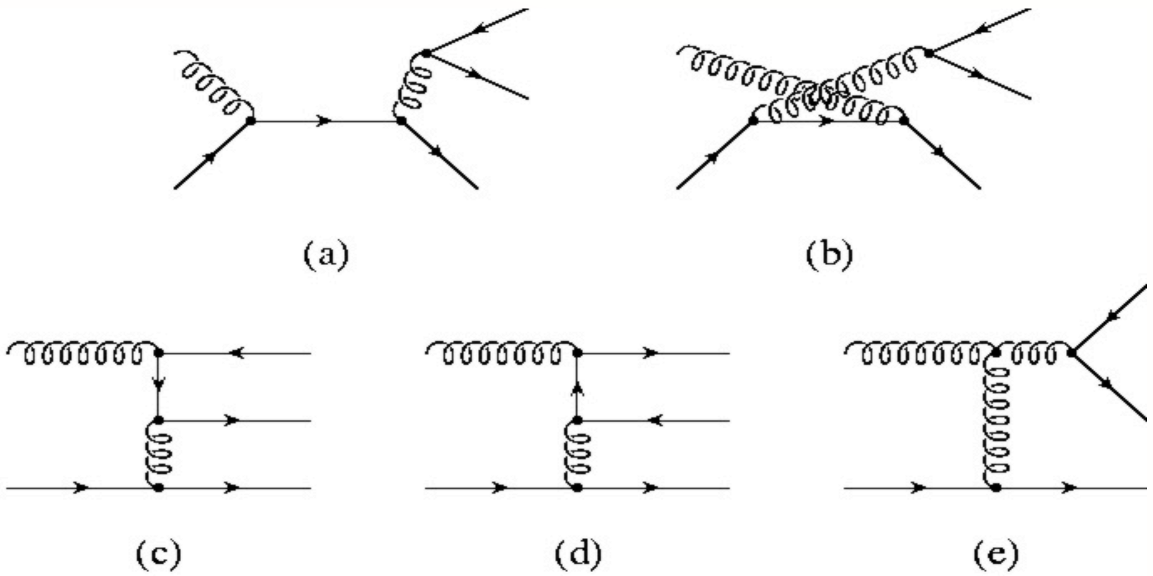
3. Flavor excitation (qg channel) much smaller

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



(a) (b)

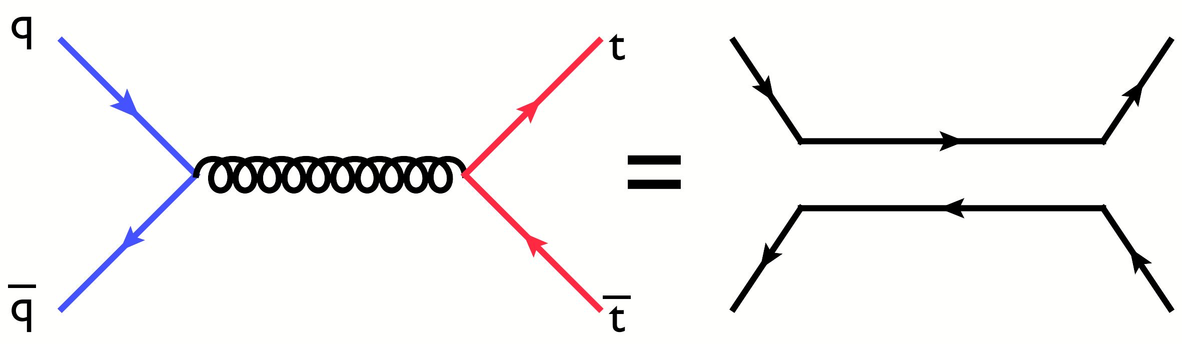
(c) (d)



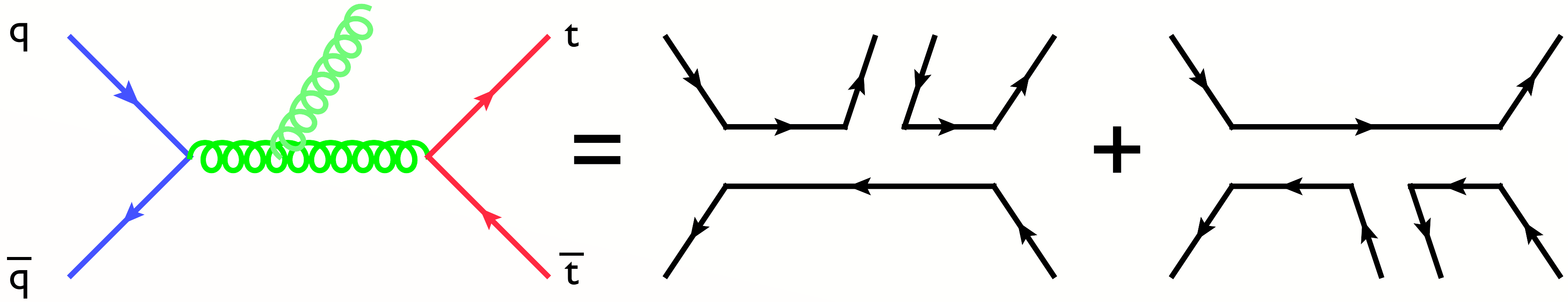
(a) (b)

(c) (d) (e)

An intuitive picture

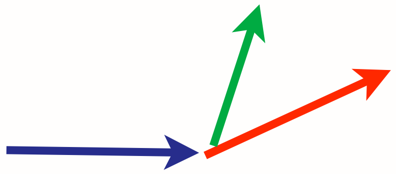
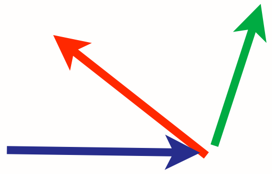


two color flows = two antennas



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() < P()

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

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

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

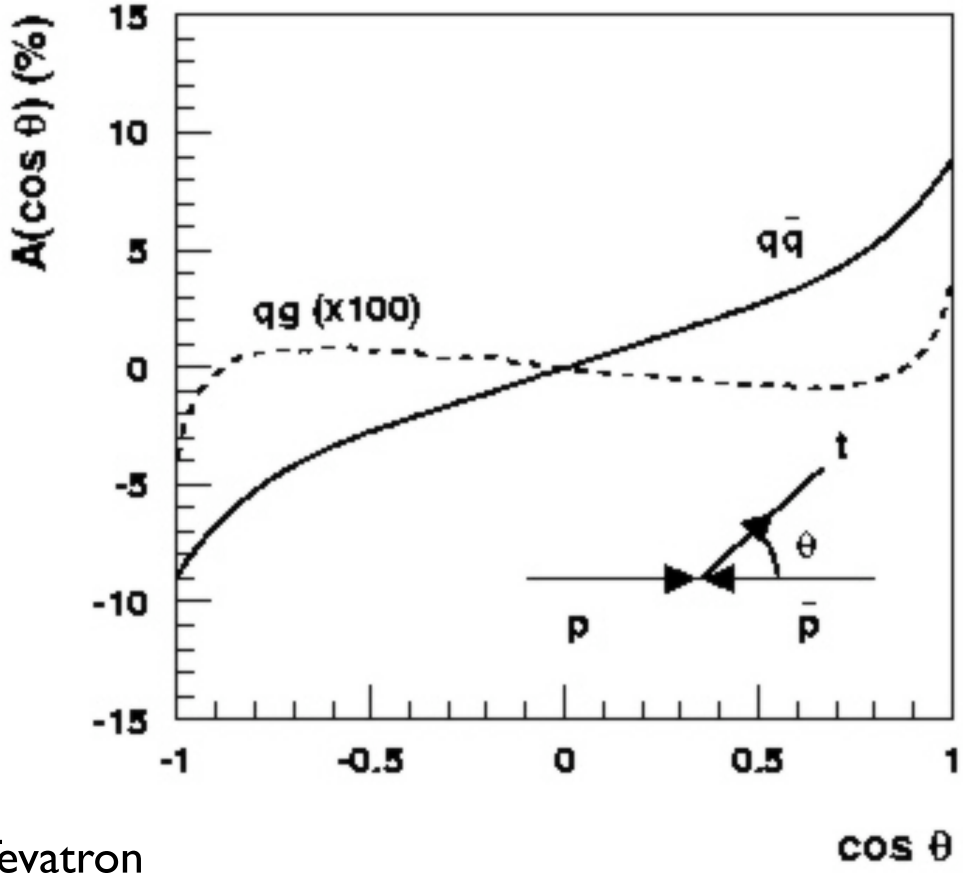
- mixed QCD-EW interference: factor 1.09 included
- stable to NLL threshold resummations (one per mille) [Almeida,Sterman,Vogelsang, 2008]
- NNLL threshold resummations [Ahrens, Ferroglia, Neubert, Pecjak, Yang, 2010]

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

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

[Kühn, Rodrigo,1998]

[Antuñano, Kühn, Rodrigo, 2008]



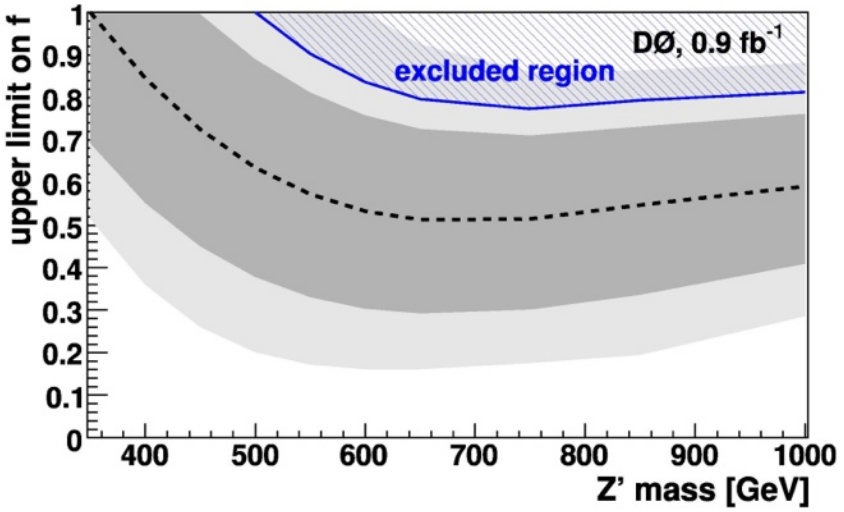
Tevatron

Asymmetry measurements at Tevatron

- **D0** [PRL101(2008)202001]

A_{FB}^{ppbar} = 0.12 ± 0.08 (stat) ± 0.01 (syst) 0.9 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 ± 0.065 (stat) ± 0.024 (syst) 3.2 fb^{-1}
A_{FB}^{ppbar} = 0.17 ± 0.07 (stat) ± 0.04 (syst) 1.9 fb^{-1}

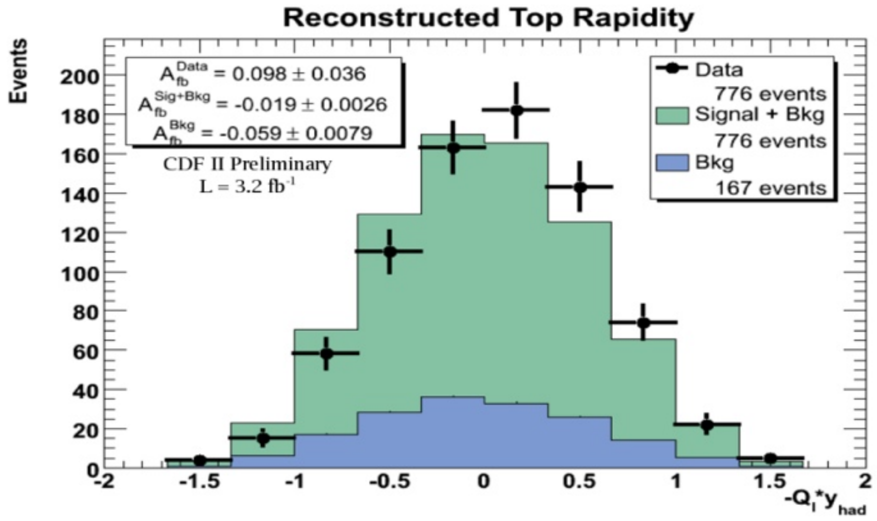
ttbar rest frame

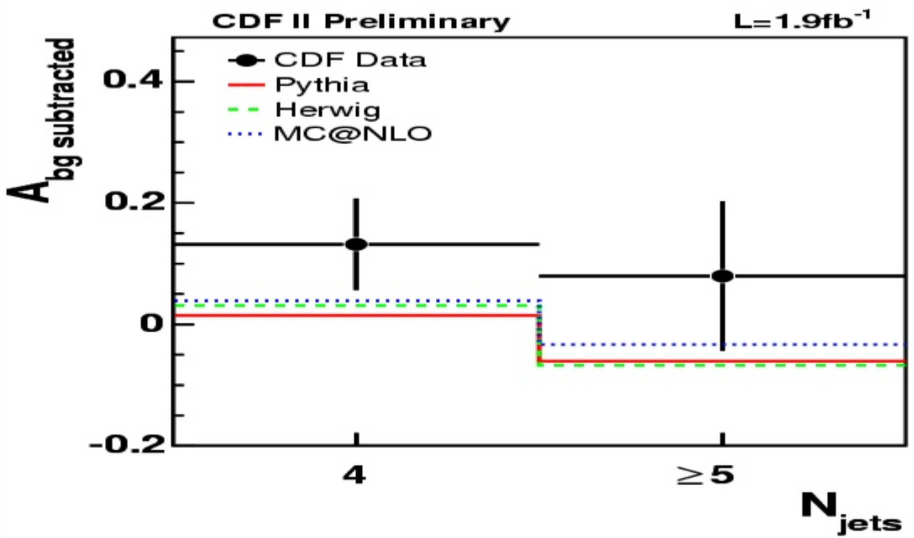
A_{FB}^{ttbar} = 0.24 ± 0.13 (stat) ± 0.04 (syst) 1.9 fb^{-1}

At least 4 jets: A_{FB}^{ttbar} = 0.119 ± 0.064 (stat)
Exact 4 jets: A_{FB}^{ttbar} = 0.132 ± 0.075 (stat)
At least 5 jets: A_{FB}^{ttbar} = 0.079 ± 0.123 (stat)

2.8σ from zero, $(A^{exp} – A^{SM})_{ppbar}$ =0.142 ± 0.069

room for BSM within 2σ





Massive gluon diff cross section

Resonances might produce charge asymmetry at LO

$$L = g_S T^a \overline{q_i} \gamma^\mu (g_V^{qi} + g_A^{qi}\gamma_5) G'_\mu q_i$$

- **Quark-antiquark annihilation**

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

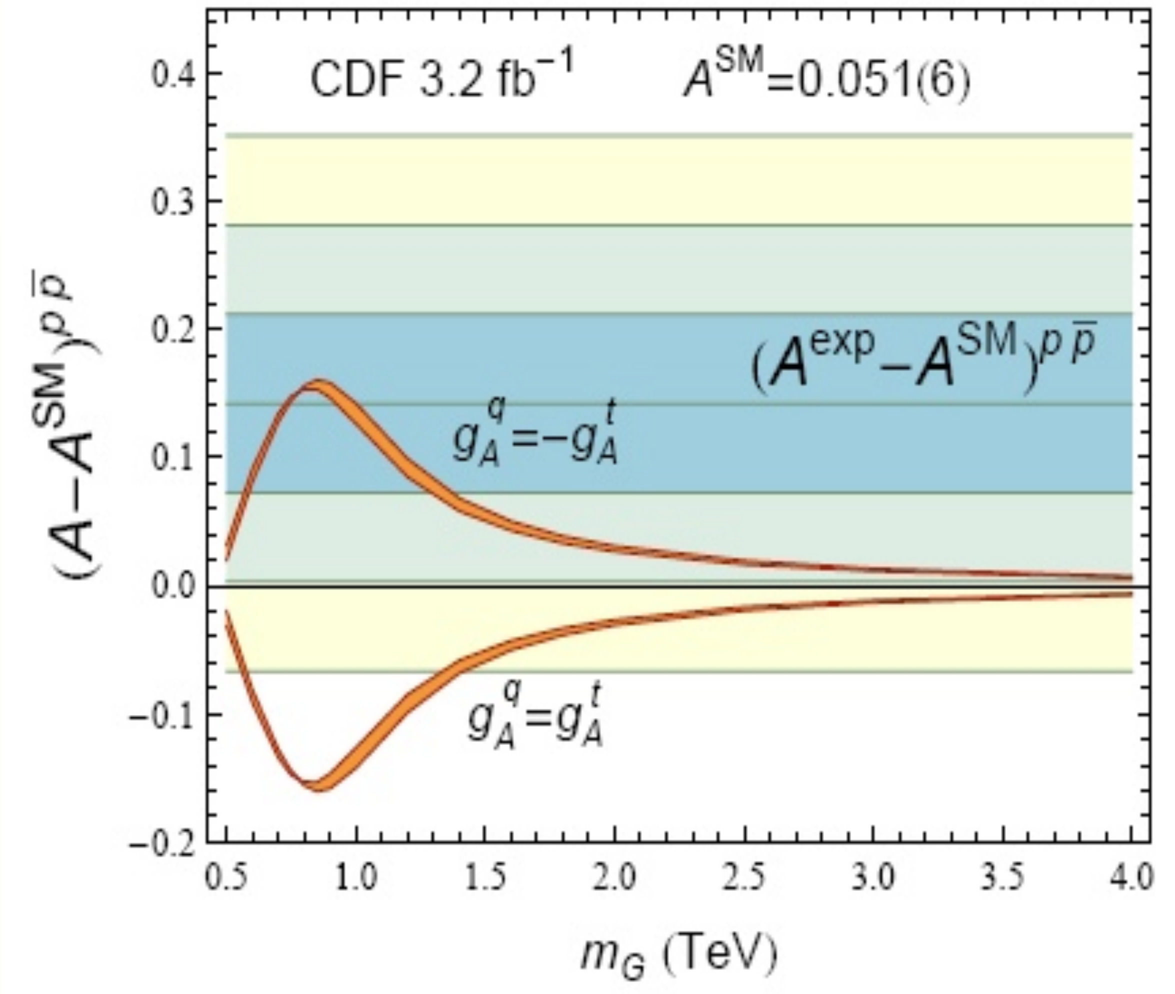
where

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

- **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 2σ vanishing or negative contributions (axigluons or colorons)

m_G > 1.6 TeV at 99%C.L. (g_V=0,g_A=1)

- Larger exclusion limit than dijet channel.

- It is still possible to generate a positive asymmetry

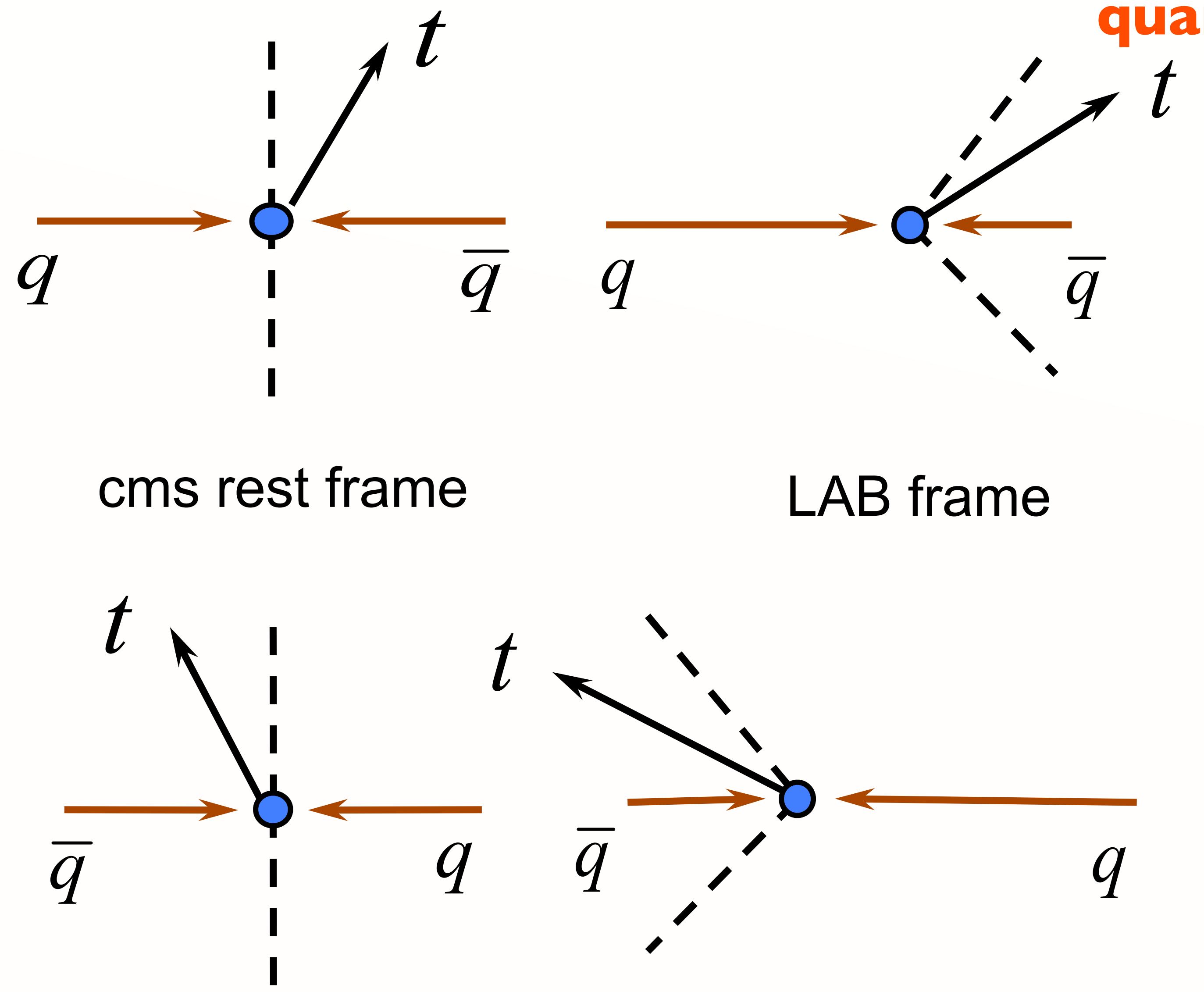
if sign(g_A^q)= -sign(g_A^t)

[Ferrario, Rodrigo, arXiv:0906.5541]
[Frampton,Shu,Wang, arXiv:0911.2955]

Charge asymmetry at LHC

LHC is symmetric ⇒ 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_G) and relative sign of couplings)



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LAB frame

quarks carry more momenta than antiquar

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

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

$$A_C(y_C >> 1) = 0$$

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

- Top physics is rich and exciting
- Top is the perfect lab where to test our understanding of EW and QCD.
- Top offers also one of the most promising windows on New Physics
- Room for new ideas both at the theoretical and experimental level and new collaborations!

and if you really become crazy about Top...

TOP QUARK

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