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Signaling the Arrival of the LHC Era

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Top Quark Physics at the LHC

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Outline

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

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

- QCD and Collider Physics by Keith Ellis, James Stirling, Bryan Webber (Cambridge Monographs, 1996). General introduction QCD. The section on top is an easy and efficient reading to learn the basics.
- Top physics at the LHC, by Beneke et al. : A complete document, though a bit outdated, that covers many of the interestings studies that will be performed at the LHC. A very useful reference.
- Top Physics at the LHC, by Werner Bernreuther : A nice and up-to-date overview on top physics at the LHC. It has also a complete reference list that can be used for further studies.
- 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 $e^+e^- \to Q\bar{Q}g$.
- 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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- The importance of being Top
- Truth and myths about Top
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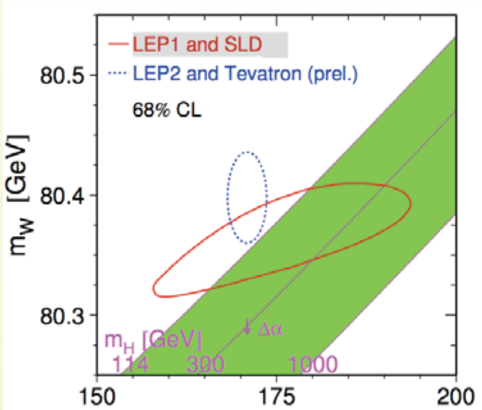
Top Physics aims

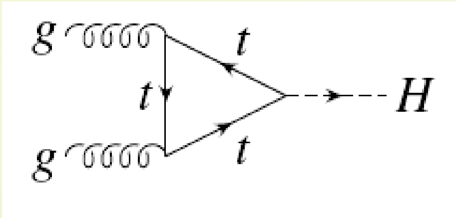
I. Measure all properties (mass, couplings, spin) to establish indirect evidence for SM and BSM physics.

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

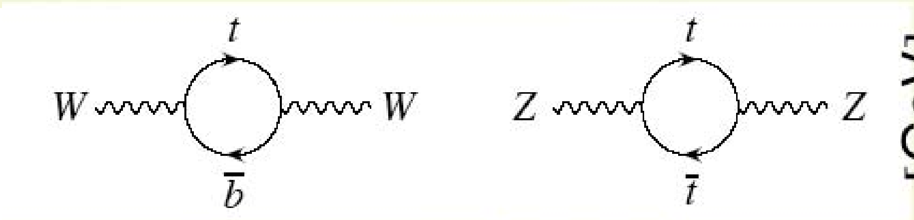
SM : ttH; tH
BSM: Z' and W' resonances;
SUSY: tH^+ and $t \to bH^+$ or stop $\to$ t X.



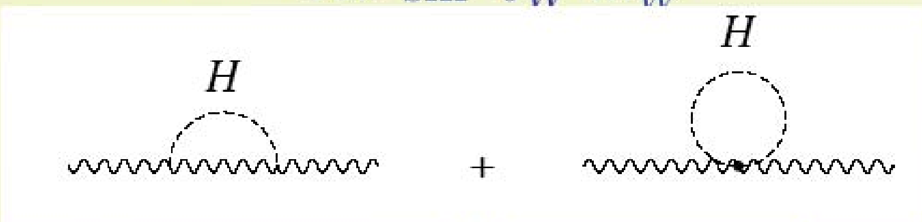
Top Physics aims I : precision EW

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:

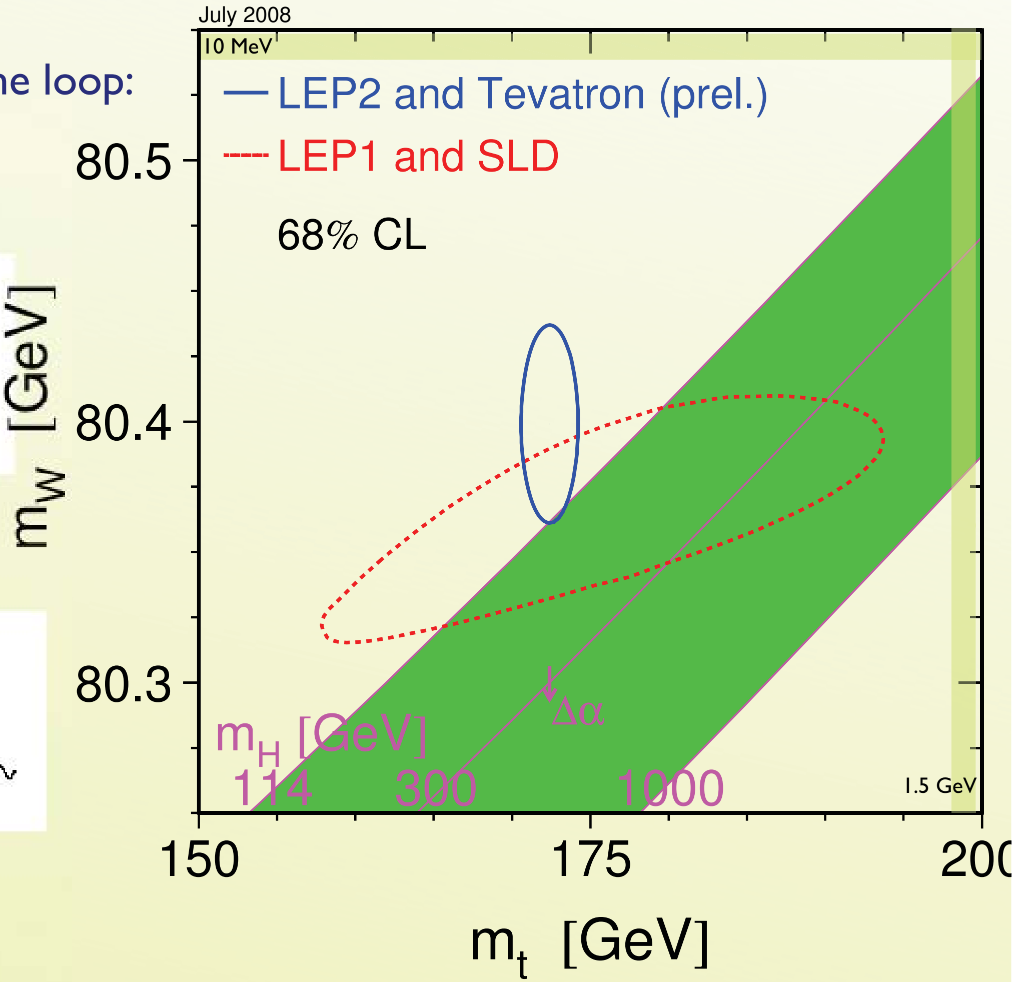
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



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



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

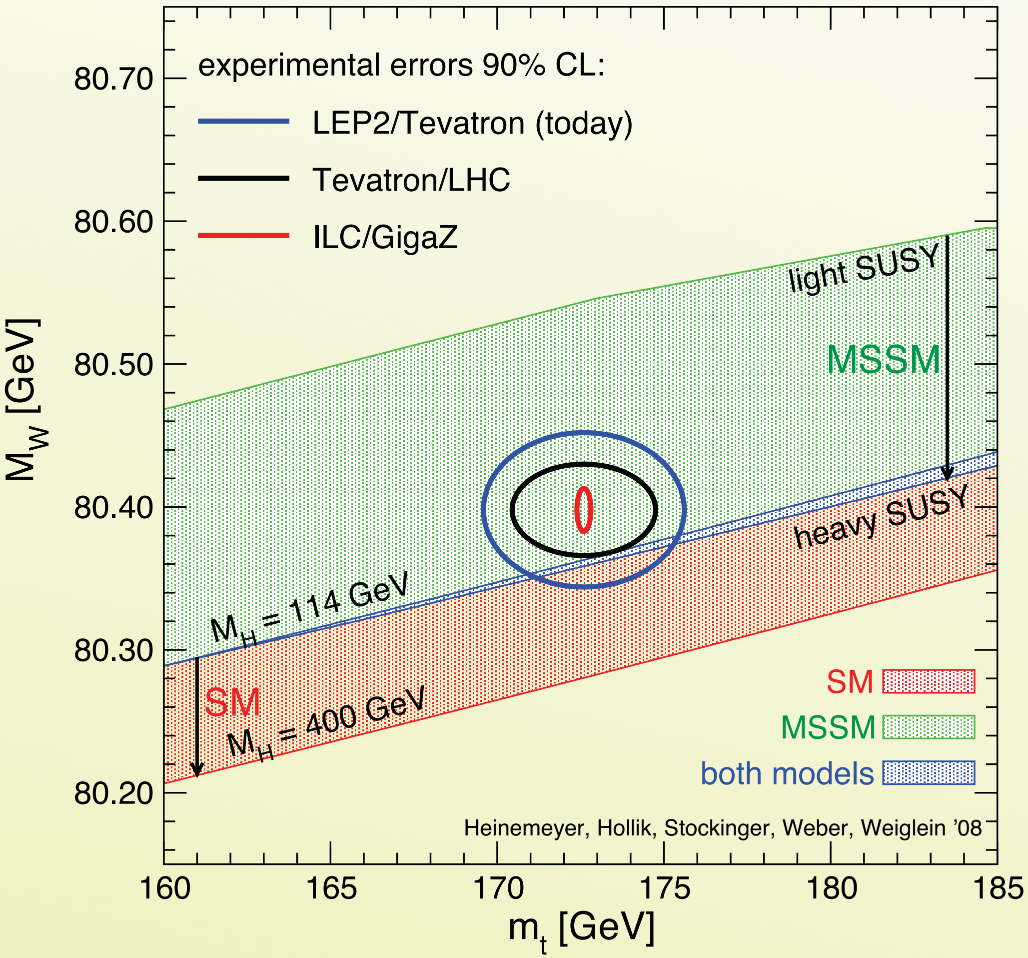


Top Physics aims I : precision EW

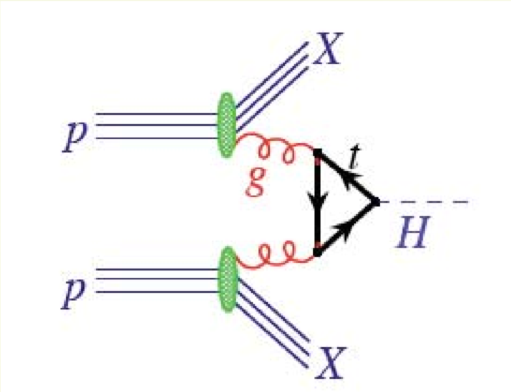
Beyond the SM precision measurements can be also very useful. For instance in SUSY, the corrections to the Higgs mass are given by:

$$\Delta M^2 \simeq G_F m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$

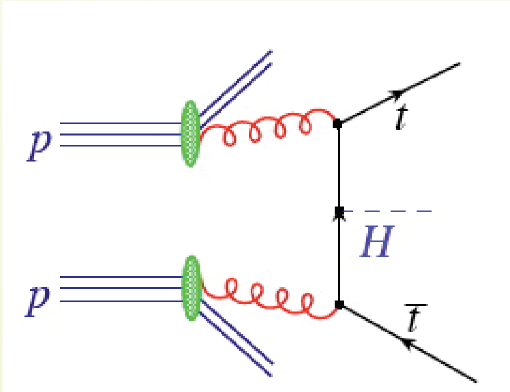
In fact top effects can be really important in theories like SUSY: Large and negative 1-loop corrections can turn the Higgs mass parameters negative and even trigger ESWB.

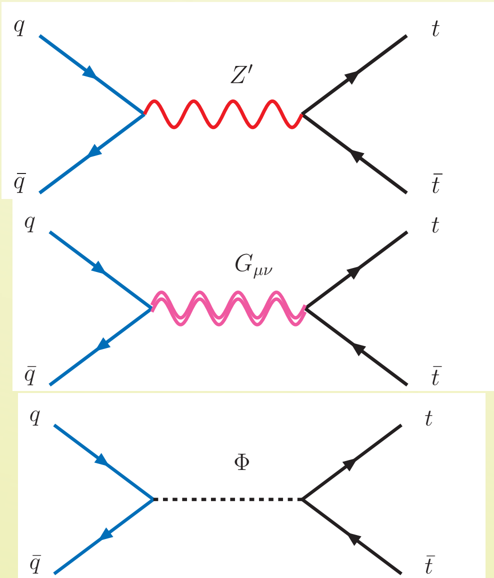


Top Physics aims II : direct probe

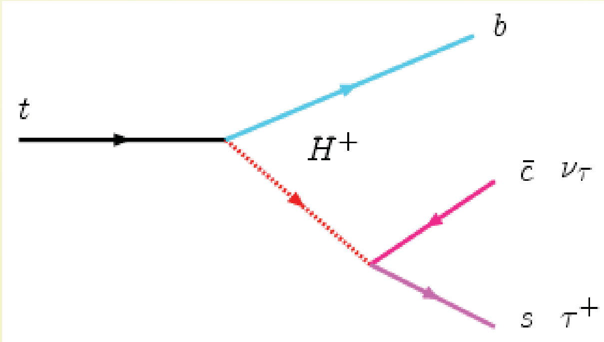


Exciting the Higgs



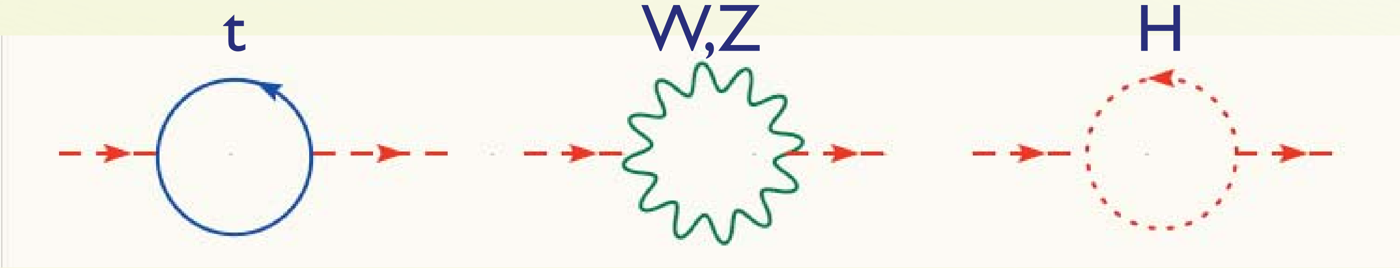


Exciting new degrees of freedom



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 Λ:



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

Putting numbers, I have:

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

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 =>

First new physics could be associated with top!!

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.

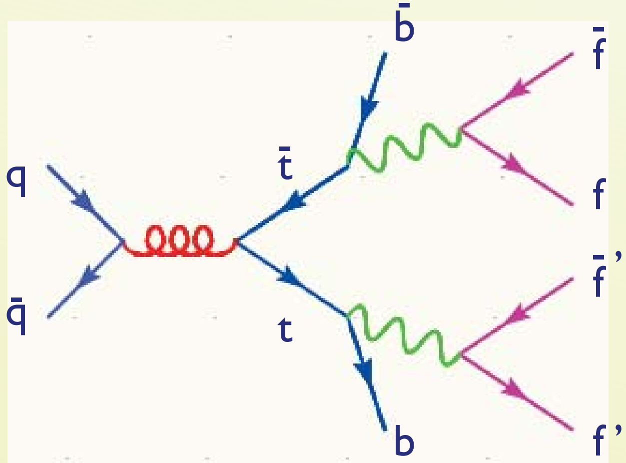
3. Strongly coupled model at the TeV scale:
   New strong dynamics enters at ~1TeV.

   Top: t-tbar bound states, colorons.

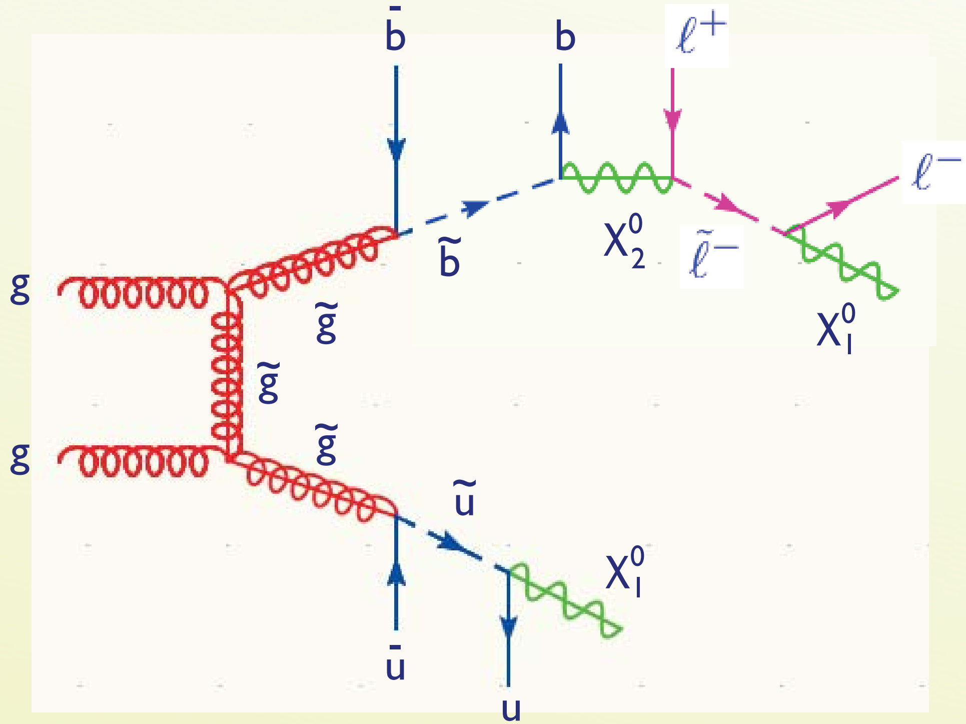
4. New space-time structure:
   Introduce extra space dimensions to lower the Planck scale cutoff to 1 TeV.

   KK-excitations

Top as a template



VS



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

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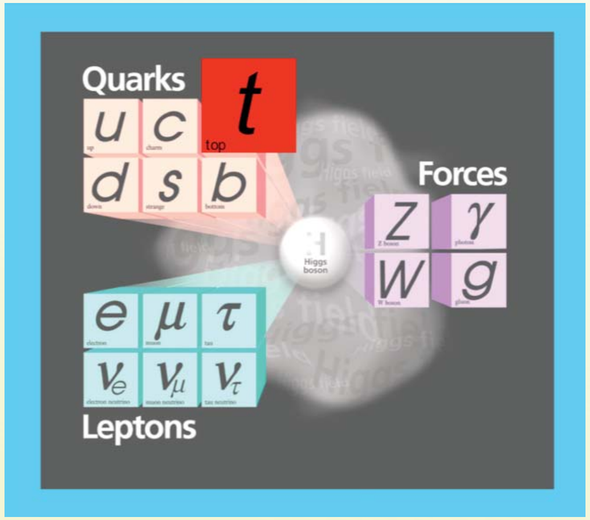
Charmonium is there, Bottomonium is there, what about Toponium?
Unfortunately, top decays too fast for bound states to form...
Radiation in top events? Everybody knows that top does not like to radiate a lot...
Measuring the top spin effects will prove that hadronization does not place!
Have you heard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

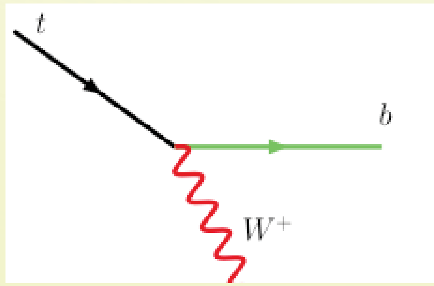
2. that decays before hadronizing

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



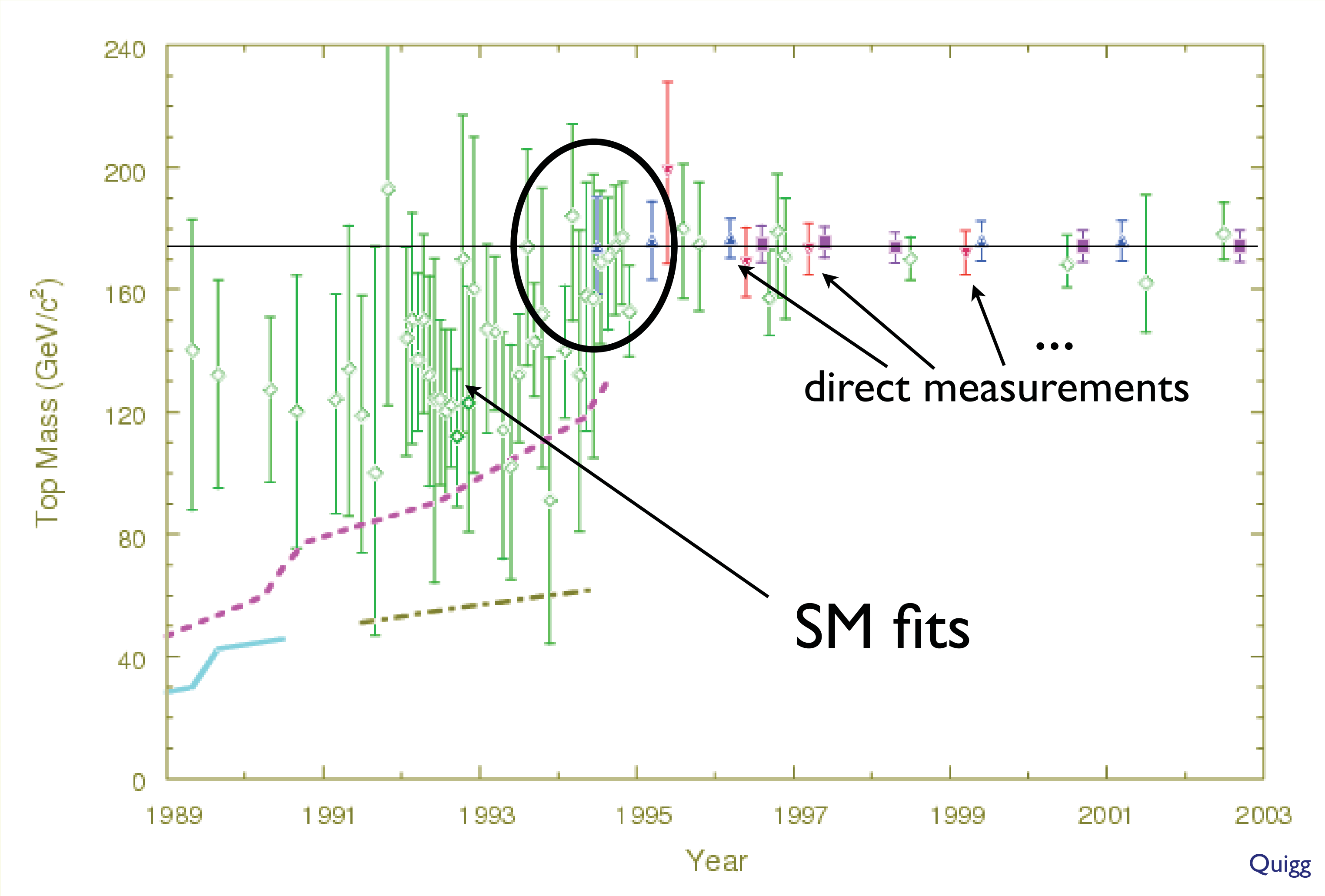
What do we really know about top?

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	30%	event counting	BSM?
Wtb vtx	15%	W polarization	BSM
sigma(ttbar)	10%	event counting	QCD, mass
sigma(singletop)	30%	event couting*	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

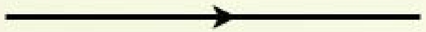
Top mass history

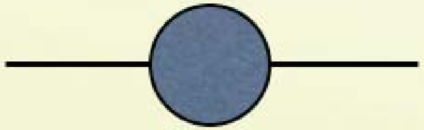


Such a heavy top was a surprise. However, the lower limit had been increasing and there had been hints from analysis of electroweak data, where the top mass enters via loop corrections.

Mass definition

The **top mass** is so precisely measured (m_t=171.2 ± 1.5 GeV) that we have to worry about its definition.

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

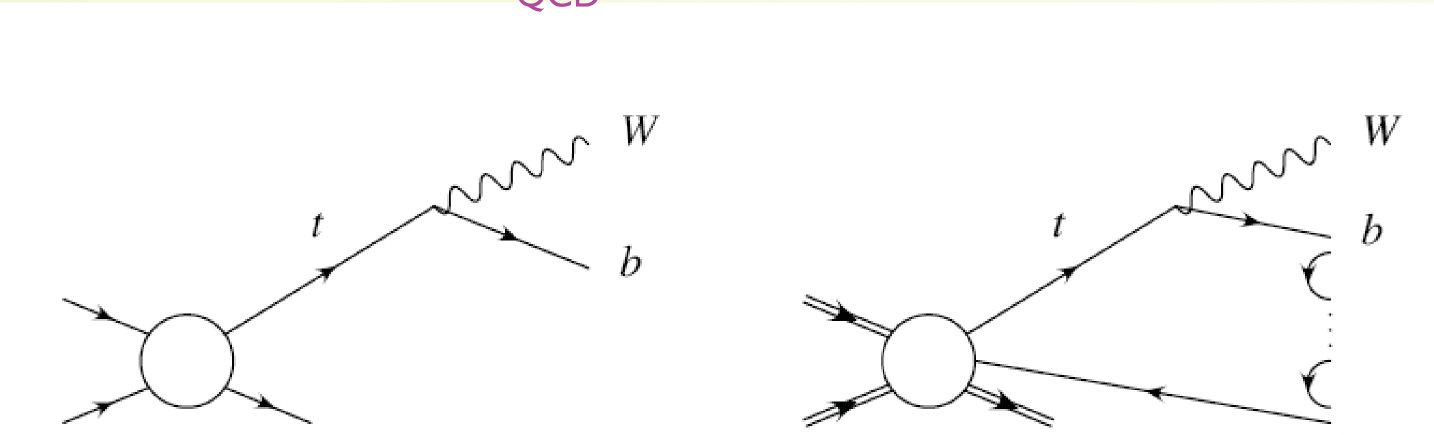
Higher orders:  $\frac{1}{\not{p} - m_R - \Sigma(\not{p})}$ m_R = renor. mass

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

The **$\overline{\text{M}}$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.

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}.

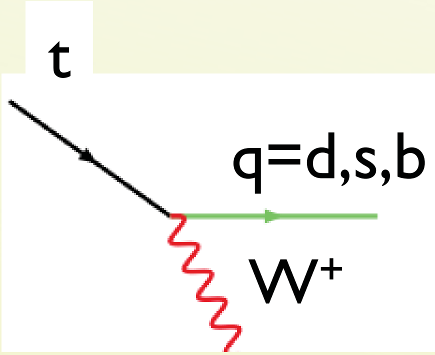


The **pole mass** is closer to what we measure at colliders through invariant mass of the top decay products. The ambiguities in that case are explicitly seen in the modeling of extra radiation, the color connect effects and hadronization.

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

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

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

$$J^+_\mu = \bar{u}_L \gamma_\mu d_L \quad \stackrel{\text{mass eigenstates}}{\Longrightarrow} \quad J^+_\mu = \bar{U}_L \gamma_\mu V_{\rm CKM} D_L$$

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

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

Vtb intermezzo

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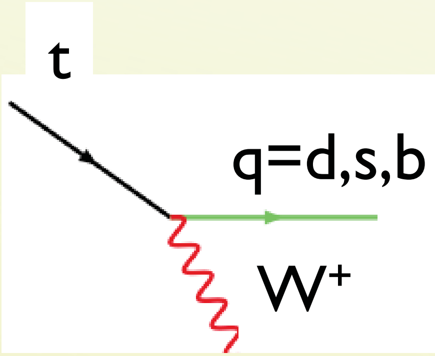
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \Rightarrow \begin{pmatrix} 0.9730 - 0.9746 & 0.2174 - 0.2241 & 0.0030 - 0.0044 \ldots \\ 0.213 \quad - 0.226 & 0.968 \quad - 0.975 & 0.039 \quad - 0.044 \quad \ldots \\ 0 \qquad - 0.08 &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

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

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

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,

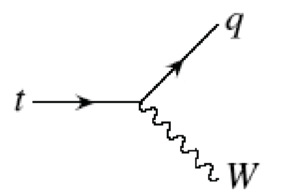
$$R = \frac{\Gamma(t \to Wb)}{\sum_{light} \Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

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

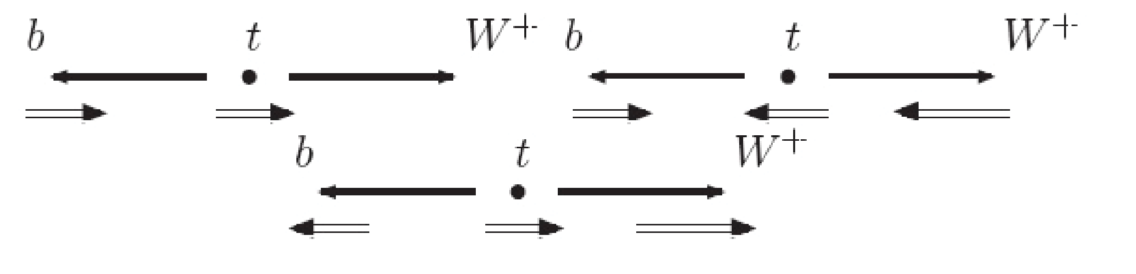


$$-i\frac{g}{\sqrt{2}}V_{tq}\gamma^\mu\frac{1}{2}(1-\gamma_5)$$

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.

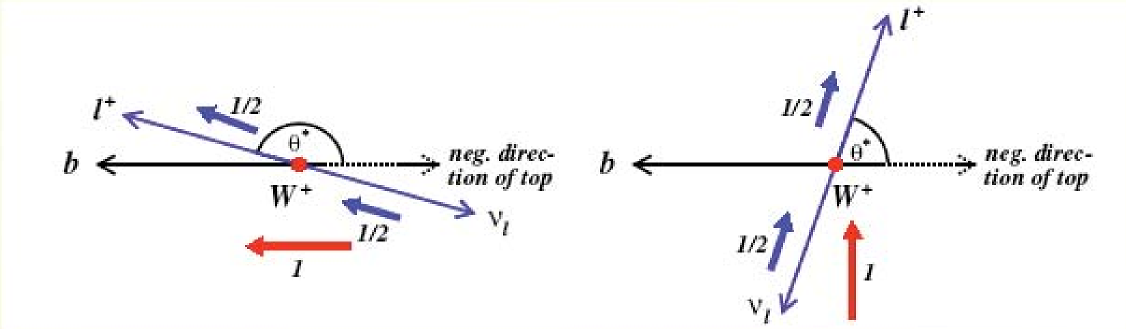
Neglecting m_b, this imples that the W can be only either longitudinally polarized or with negative helicity



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

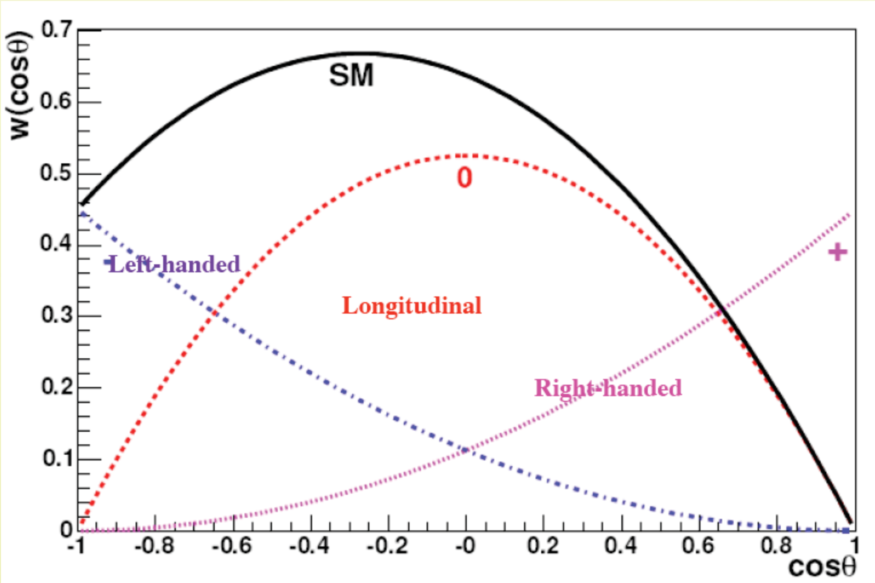
W polarization

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



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

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).

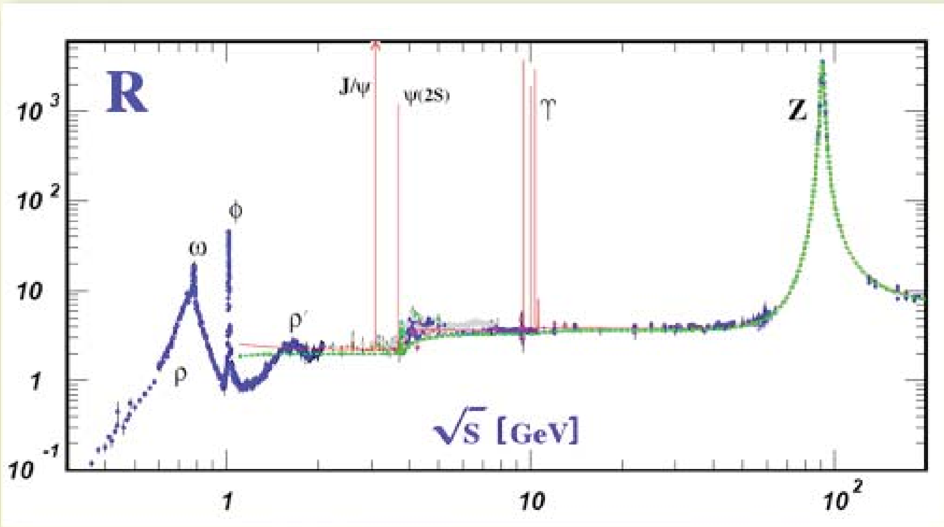
* cos(θ), which is defined in a specific frame, can be related to m(lepton,bottom) or pt(lepton) , ergo no top momentum reconstruction necessary!

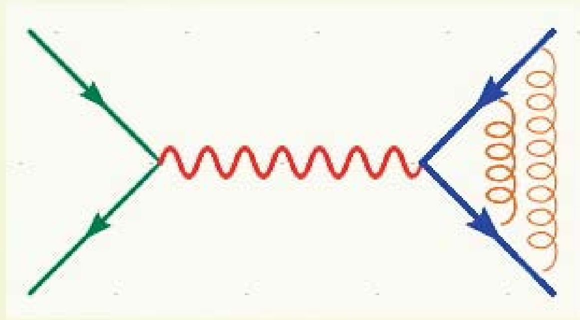
* Rather "easy measurement" .

Truth or Myth #3 :
“no hadronization $\Rightarrow$ 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 $V(r) \simeq -C_F \frac{\alpha_S(1/r)}{r}$ $\quad C_F = 4/3$

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:

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

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

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

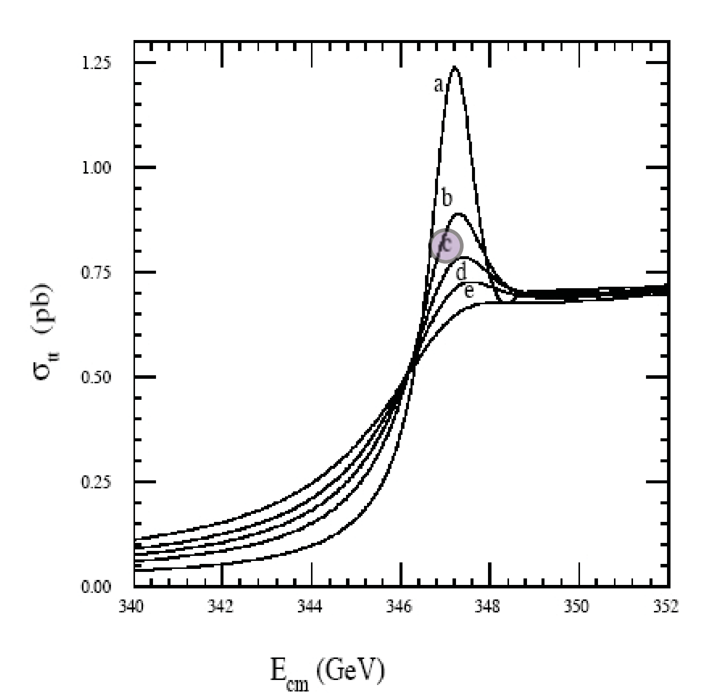
$\tau_{form} \approx$ size/v $\approx mv^2 \approx 1/(2\text{ GeV})$

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

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

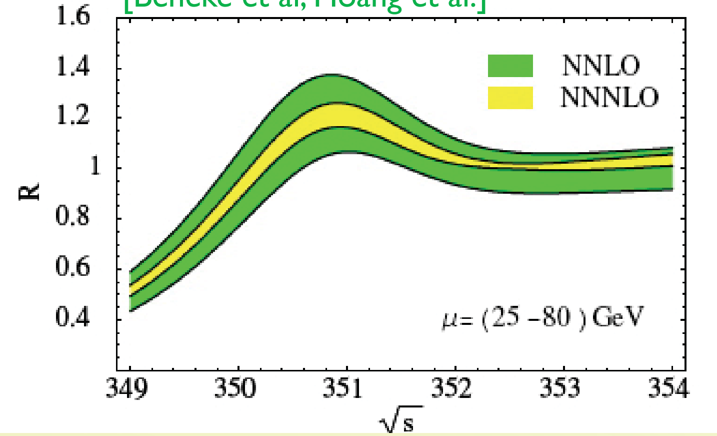
Truth or Myth #3 : “no hadronization ⇒ no resonance physics”

Myth



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!...Stay tuned!!

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

$\Rightarrow$ Truth
$\Leftarrow$ Myth

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

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

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).

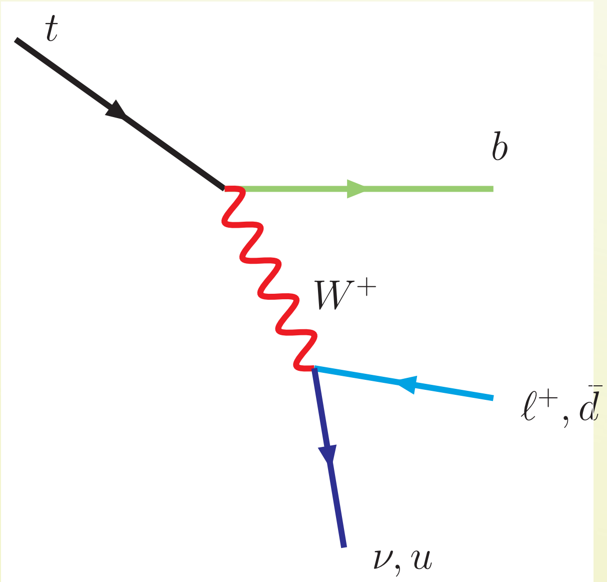
HOWEVER, one can also ask : Is the opposite true? if we see spin correlation effects do we automatically put an upper bound on the width and hadronization? NO!
Spin-flips are due to CHROMOMAGNETIC interactions, which are mediated by dimension 5 operators:

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

If, for instance, V_{tb} ~ 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.

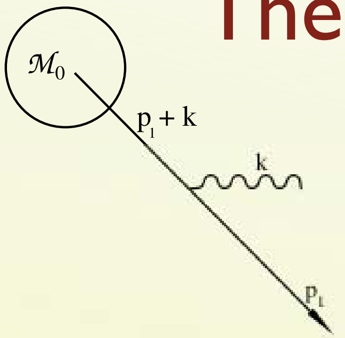
Results depend on the degree of polarization (p) of the tops themselves and from the choice of the "spin-analyzer" k_i.

	ℓ^+	$\bar{d}$	u	b	$j_<$	**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

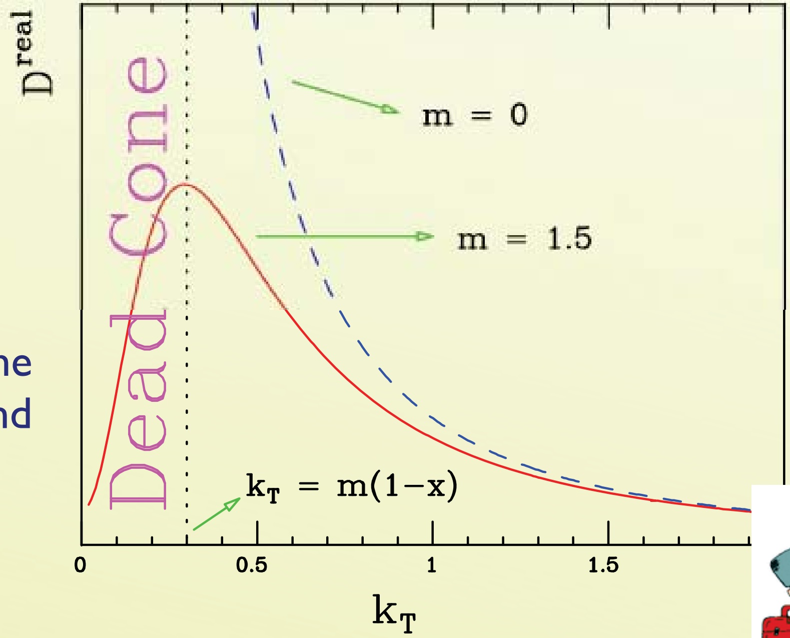


Consider gluon emission off a heavy quark using perturbation theory:

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

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

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



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

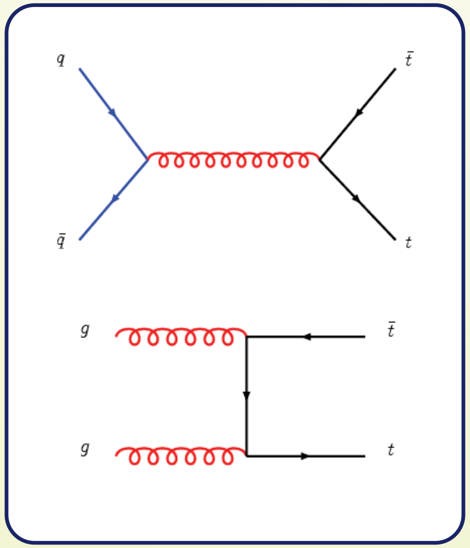
- Top is by all means special!
- The CKM elements V_{td} ,V_{ts} ,V_{tb} are not very well constrained (if unitarity is relaxed). Top decays do not help much. Need for width or single-top measurements
- Top anti-top pairs close to threshold can display a "bound state" behaviour.
- Top spin is a good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

Outline

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

Producing Top

Strong

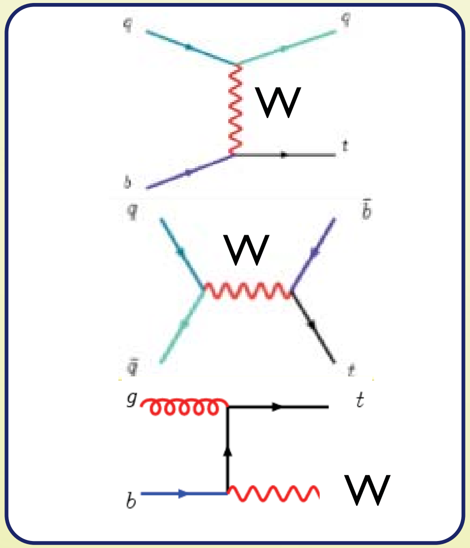


Largest cross section (LO at α_S^2):

~ 10 pb at Tevatron
~ 1 nb at the LHC

Top discovery mode.

Weak



Weak process : same diagrams as the top decay!

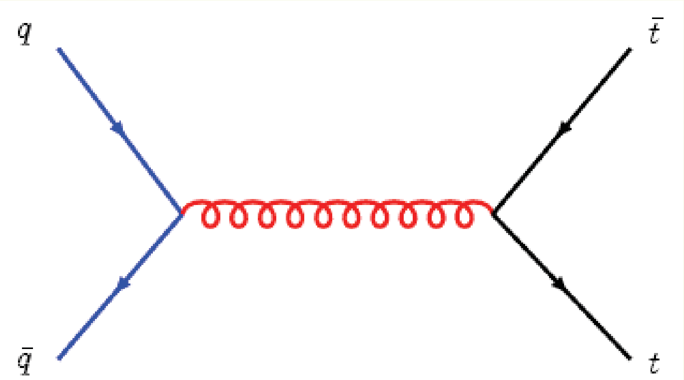
Cross sections smaller than QCD but enhanced by a lower energy cost:

~ 2 pb at Tevatron
~ 300 pb at the LHC

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

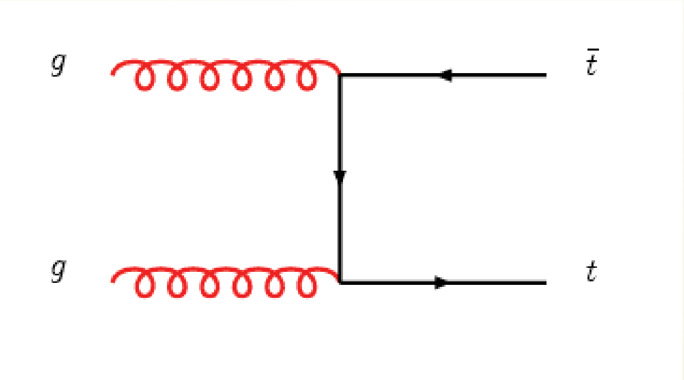
10 tt pairs per day

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*!

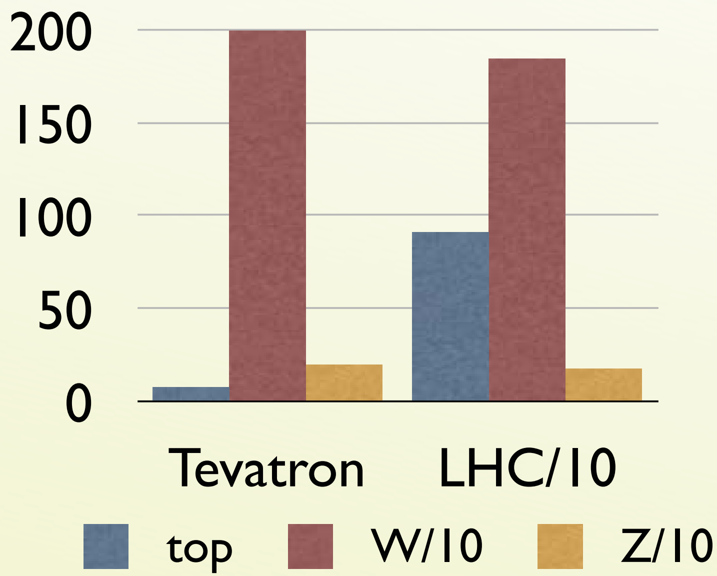
*Conditions apply. Consult with your local top expert before signing.

Cross sections : from Tevatron to the LHC

Total cross section for ttbar increases by a factor of 100, while Drell-Yan only by a factor of 10.

Top will be one of the major background to any new physics!

However, extra hard radiation is much easier at the LHC than at the Tevatron!



pb	tt	$W^{+-} \to e^{+-} \nu_e$ inclusive	$Z \to e^+ e^-$ inclusive	$W \to e^{+-} \nu_e$ + 4jets		$Z \to e^+ e^-$ + 4jets	
TeV	7.6	2000	200	0.98		0.096	
LHC	910	18500	1800	220	(20)	21	(2.1)
Gain	120	9	9	220	(21)	220	(22)

pt(j)>20 (50) GeV , |eta(j)|<3, DeltaR(jj)>0.7

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).

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

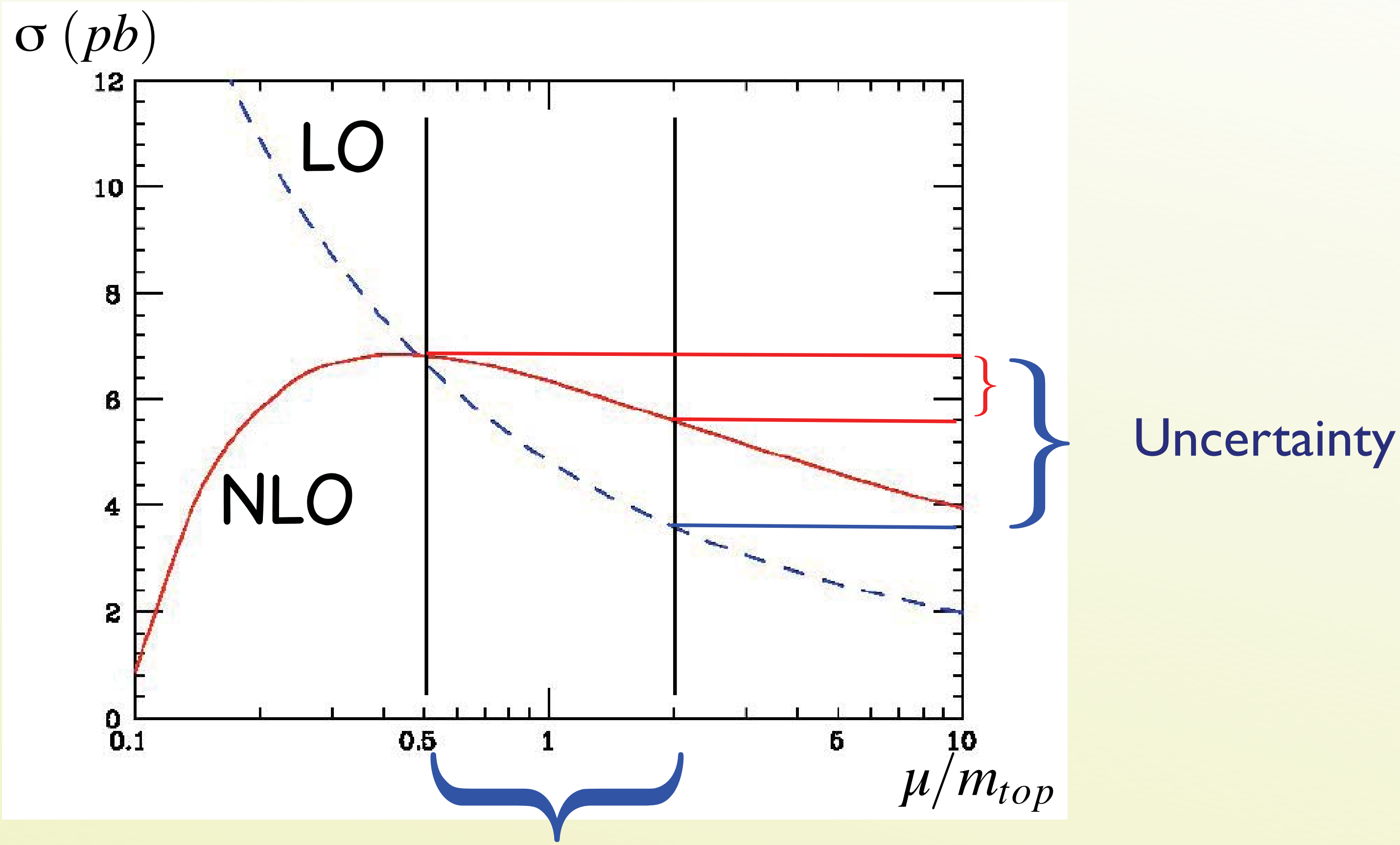
Leading order

Next-to-leading order

Next-to-next-to-leading order

Estimating TH uncertaintes

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



"Reasonable" scale variation

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

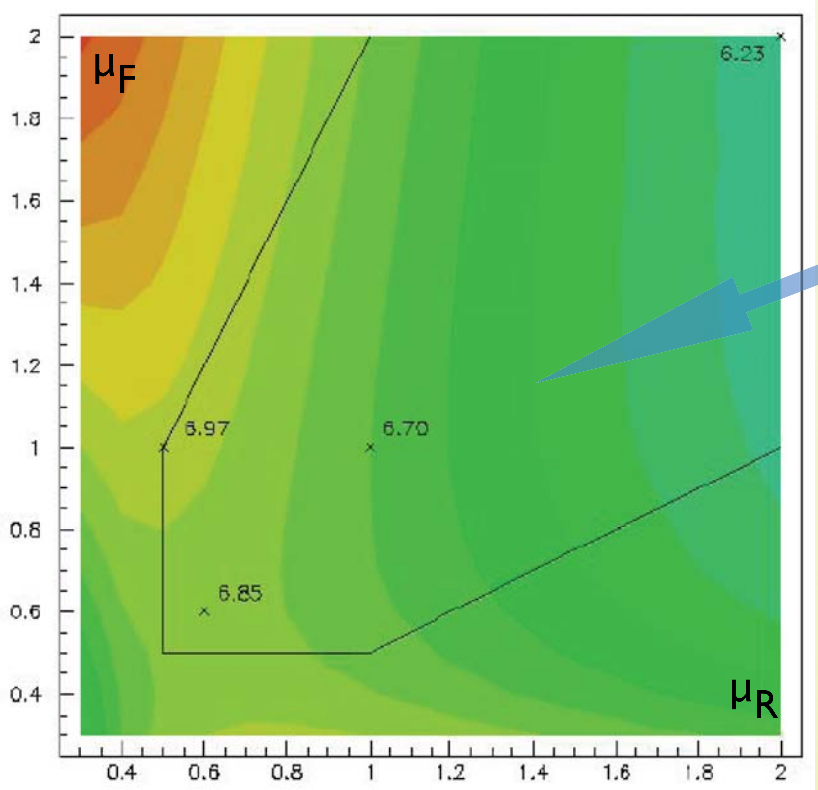
Top @ Tevatron

Standard procedure: vary renormalisation and factorisation scales.

(NLO+NLL, m=175 GeV) But, better do so independently

σ: 6.82 > 6.70 > 6.23 pb $\quad 0.5 < \mu_{R,F}/m < 2$

σ: 6.97 > 6.70 > 6.23 pb $\quad 0.5 < \mu_{R,F}/m < 2 \;\&\&\; 0.5 < \mu_R/\mu_F < 2$



"Fiducial" region

Order **±5%** uncertainty along the diagonal, a little more considering independent scale variations

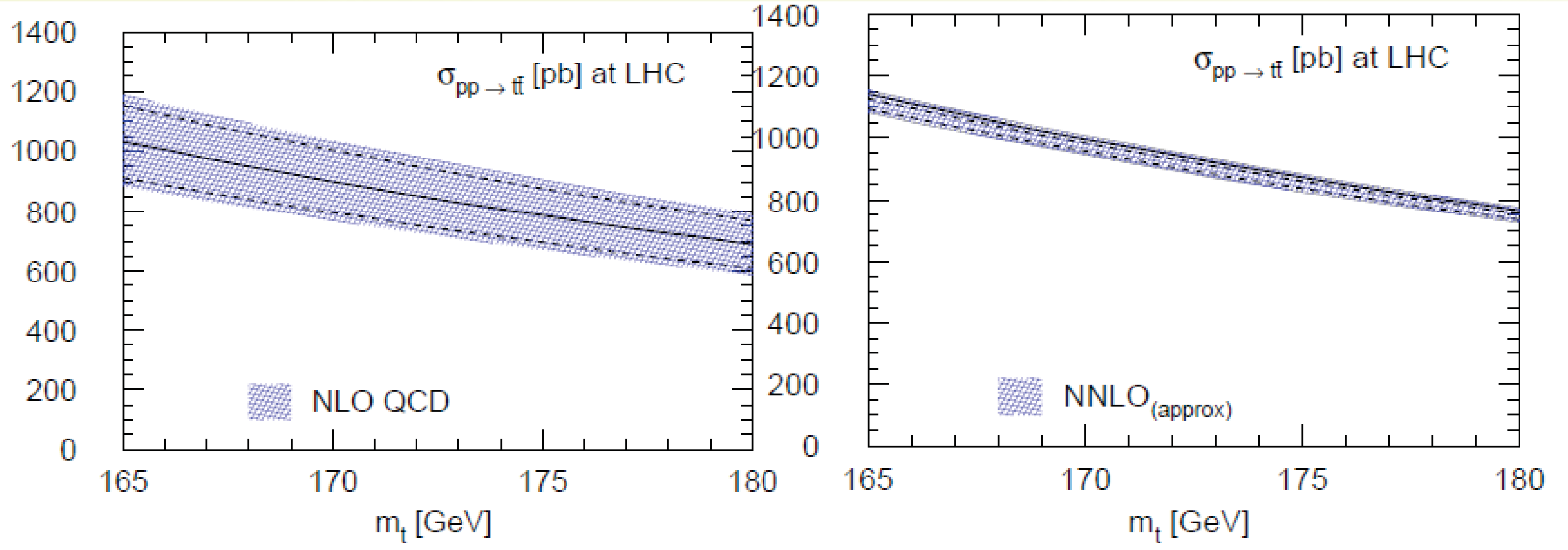
BTW, the PDF uncertainty (±10-15%) is probably the dominant one here

Top @ LHC

[Cacciari et al., 2008]

σ: 970 > 908 > 860 pb $\quad 0.5 < \mu_{R,F}/m < 2$

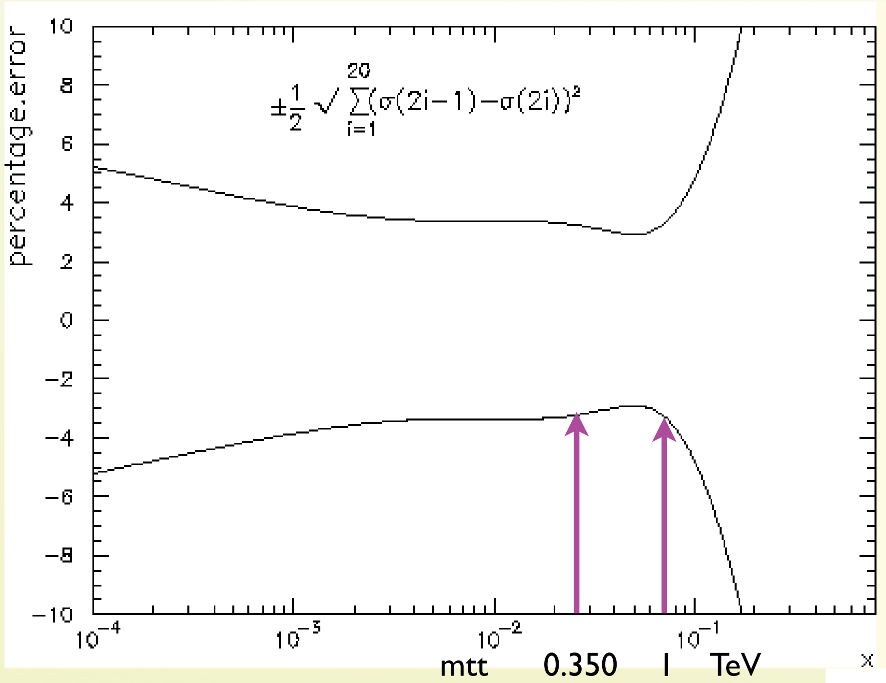
σ: 990 > 908 > 823 pb $\quad 0.5 < \mu_{R,F}/m < 2$ && $0.5 < \mu_R/\mu_F < 2$

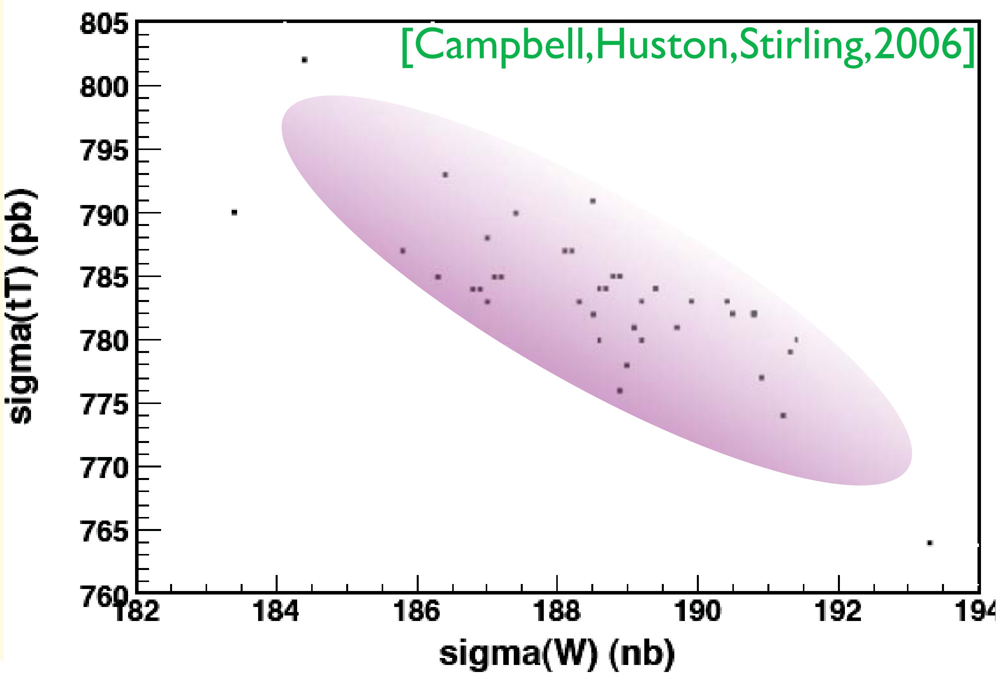


[Moch and Uwer, 2008]

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

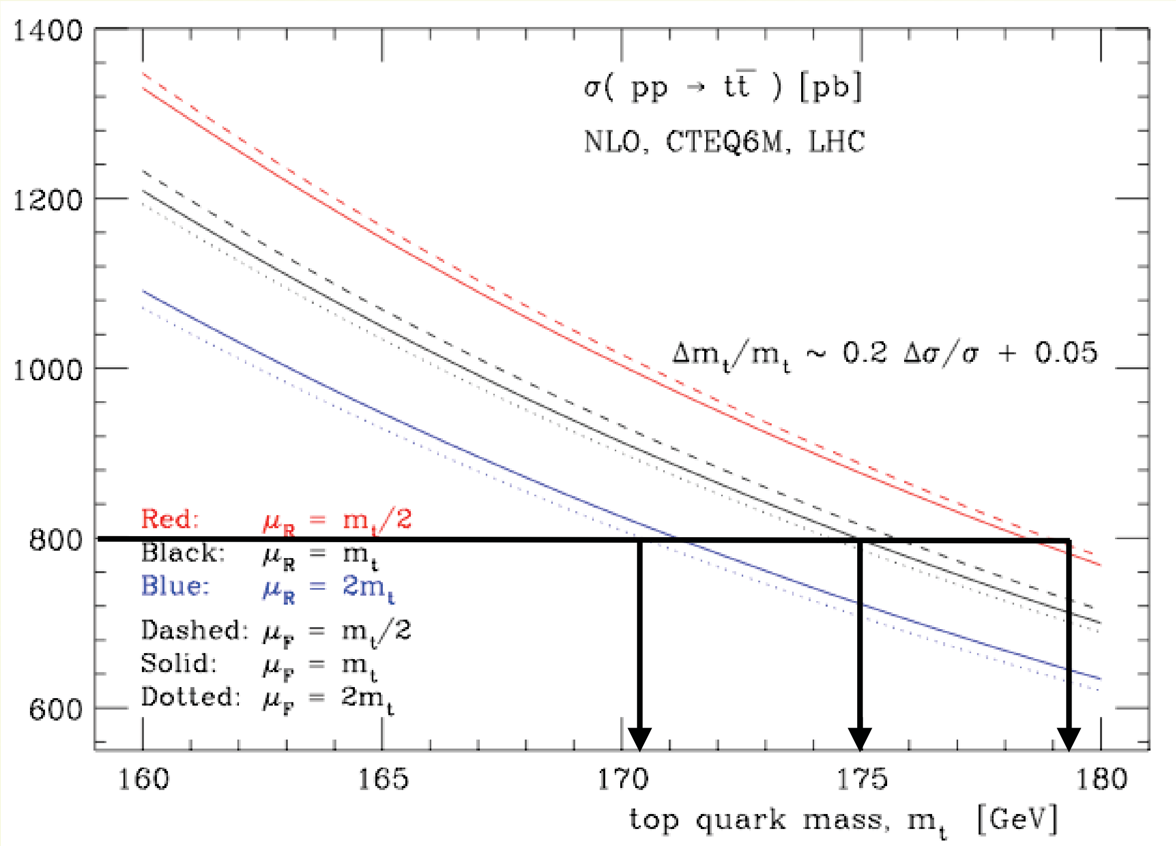
σ_{tt}: PDF errors at the LHC





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

measuring m_t from σ_{tt}



The total cross section depends strongly on the top mass.

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

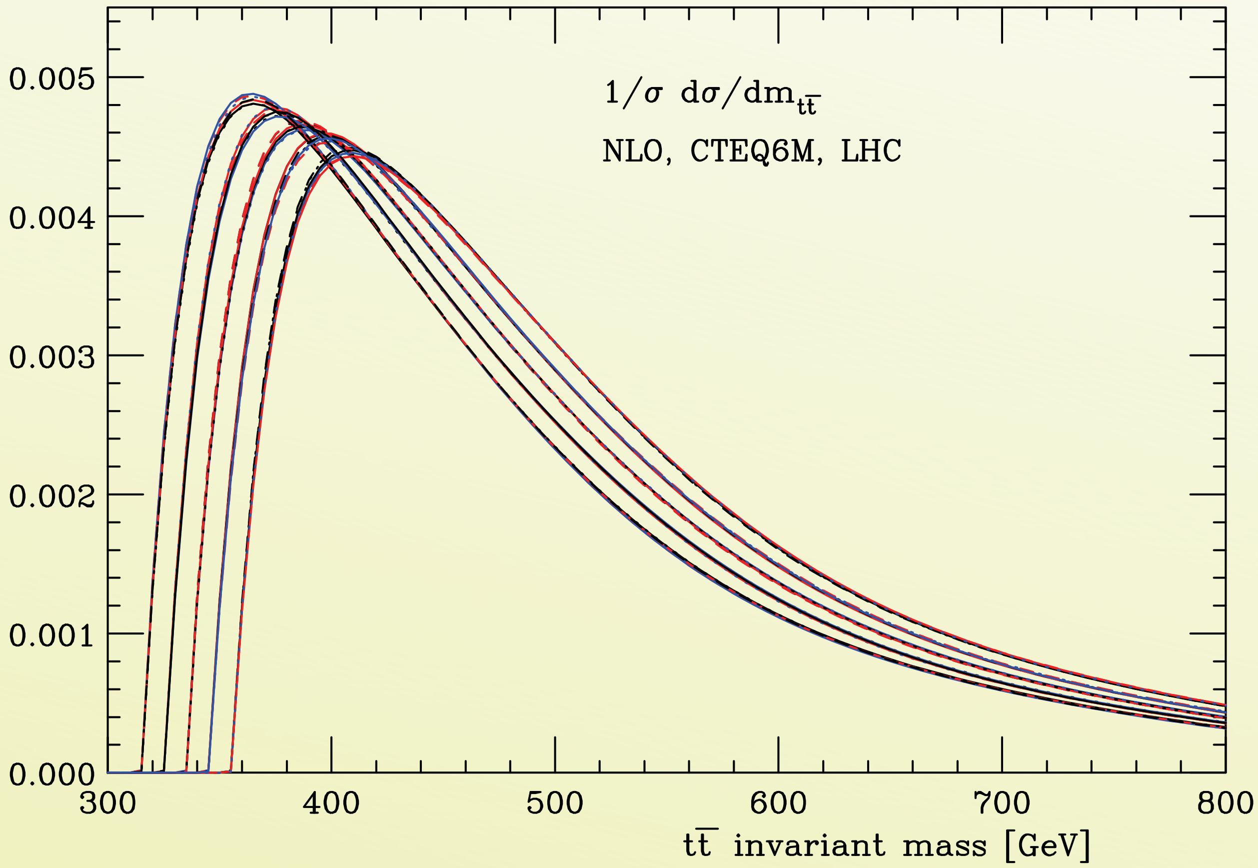
However, the error on the total cross section is theory dominated!

Tevatron has started doing this....

NNLO corrections and reduced TH errors could make a top mass extraction from the cross section possible!

What about differential distributions?

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



Interesting observable.

Shape very well predicted.

This could be also used to measure the top mass!

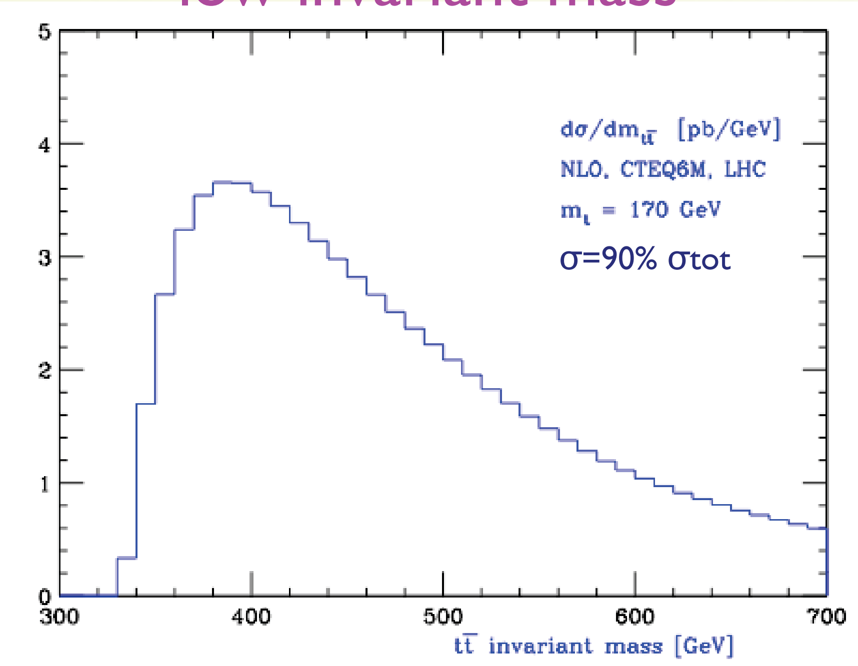
Reconstruction systematics is different from the usual top mass invariant mass reconstruction.

Any BSM effect would distort this shape =>

Model independent search for new Physics!

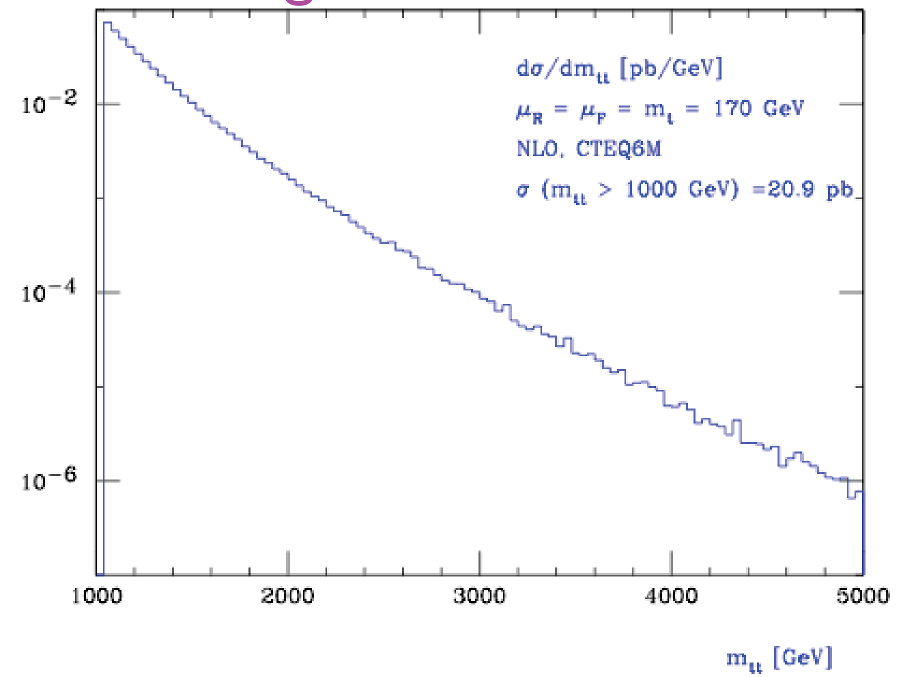
m_{tt} spectrum at the LHC

low invariant mass



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

high invariant mass



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

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

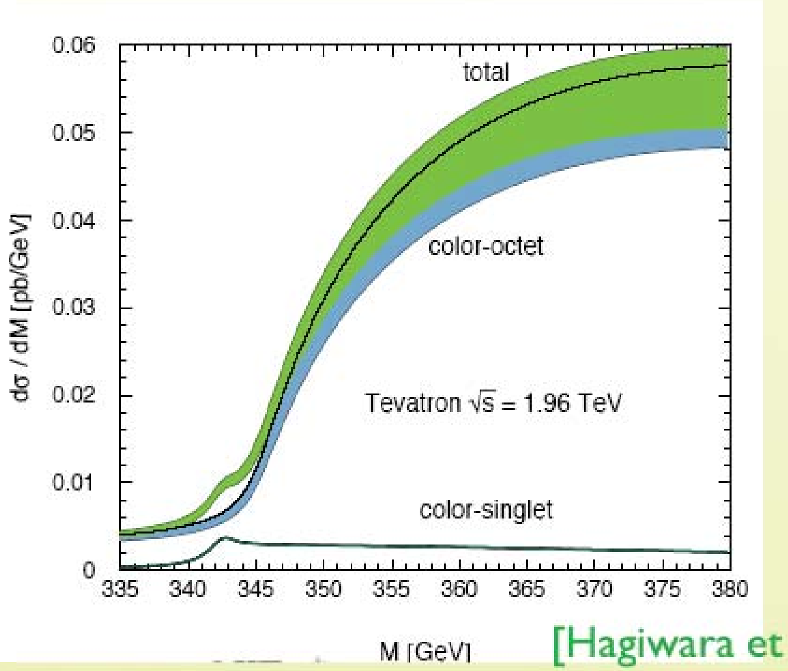
In hadronic collision, the interactions at threshold can be either attractive or repulsive! Octet larger cross section, but "bound state" effects are dominant in the singlet. Effects compete. Until last spring, the common lore was that PDF effects would smear any peak!

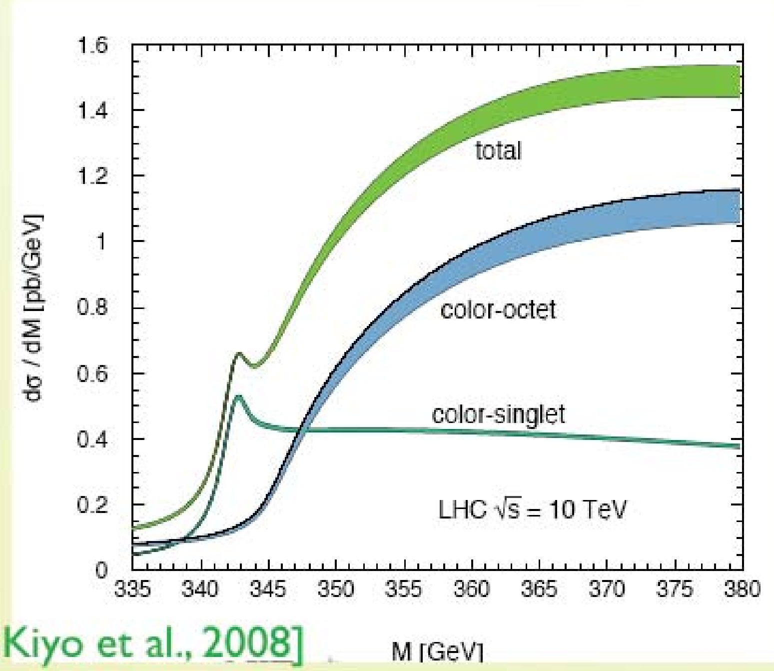
Precise mass measurement? Width measurement?

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

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

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





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

Example of a model independent search for New Physics in the ttbar invariant mass

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

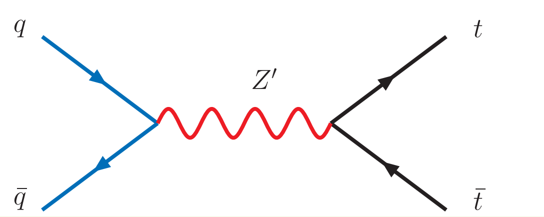
1. Focus on a specific SM observable that is

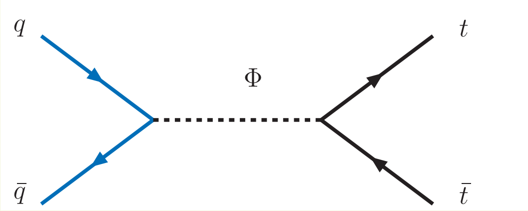
   a. naturally sensitive to BSM
   b. is well-predicted & possibly "background free"

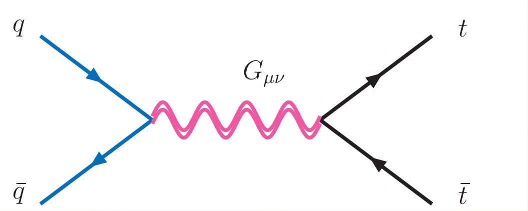
2. Search for a simple signature, eg "a peak" in a "model independent" way.

New resonances

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



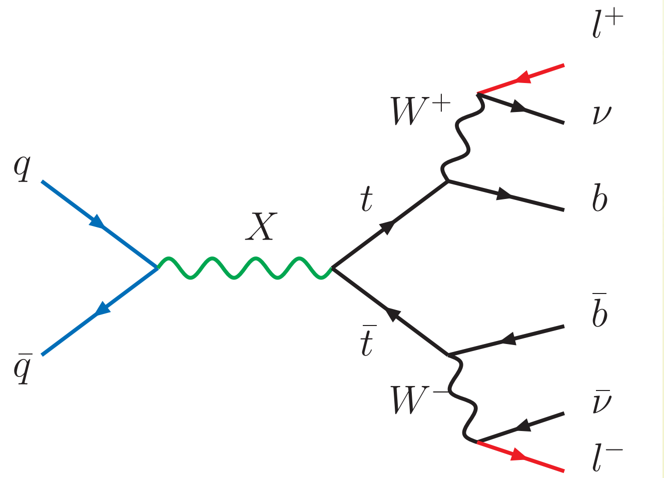




Given the large number of models, in this case is more efficient to adopt a "model independent" search and try to get as much information as possible on the quantum numbers and coupling of the resonance.

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

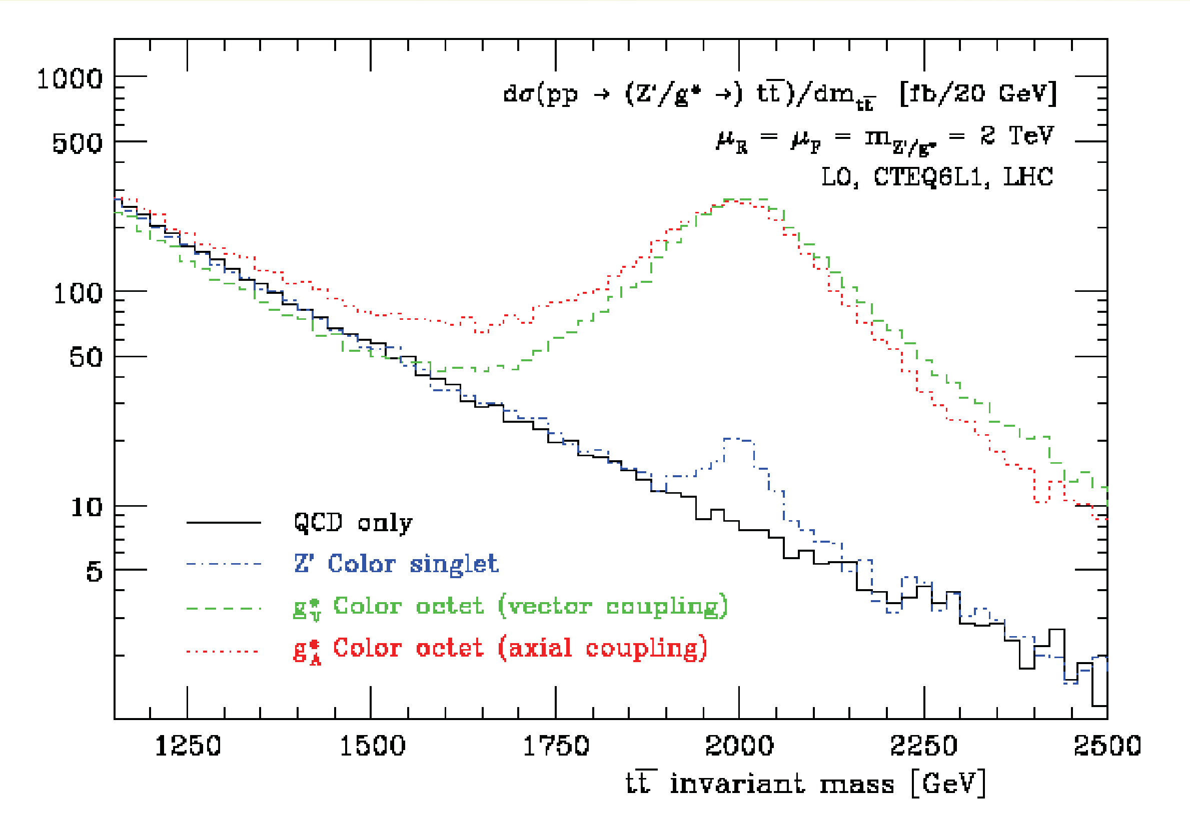
It therefore mandatory for such cases to have MC samples where spin correlations are kept and the full matrix element pp>X>tt>6f is used.



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 1: discovery



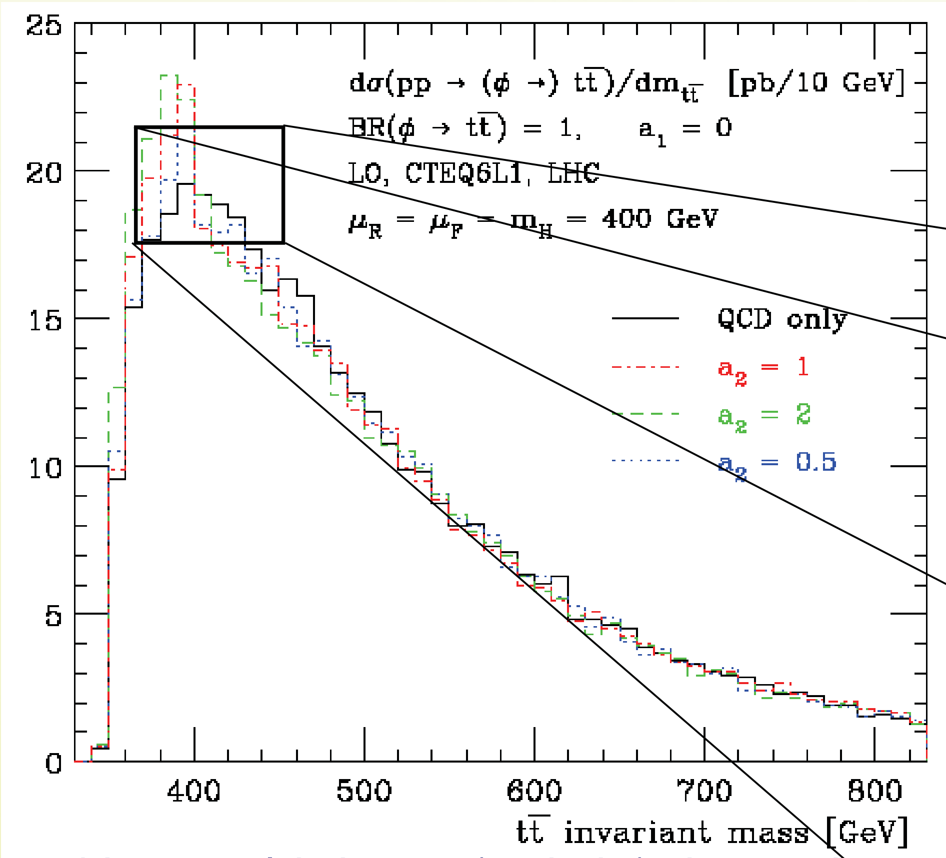
* Vector resonance, in a color singlet or octet states.

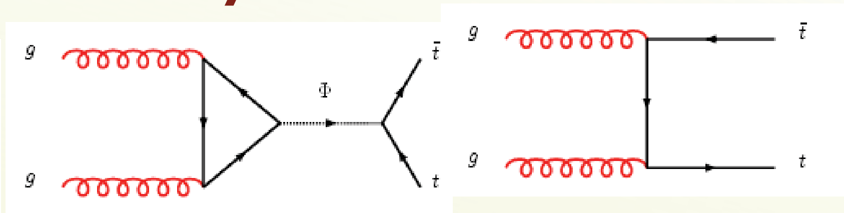
* Widths and rates very different

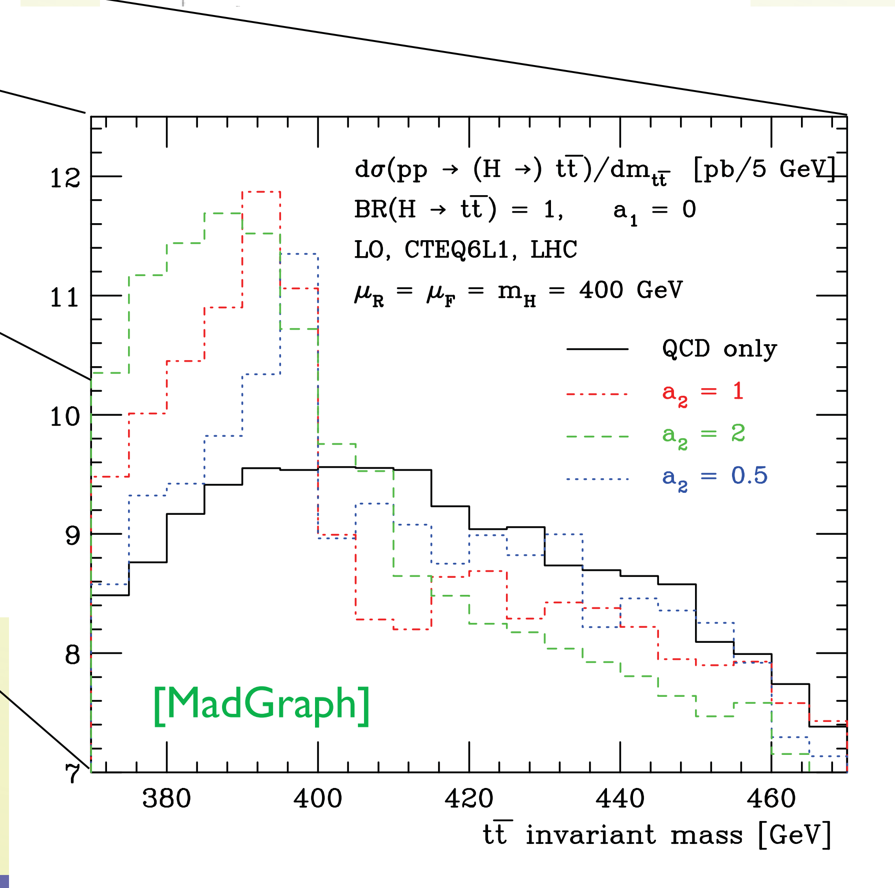
* Interference effects with SM ttbar production not always negligible

* Direct information on σ•Br and Γ.

Phase I: discovery

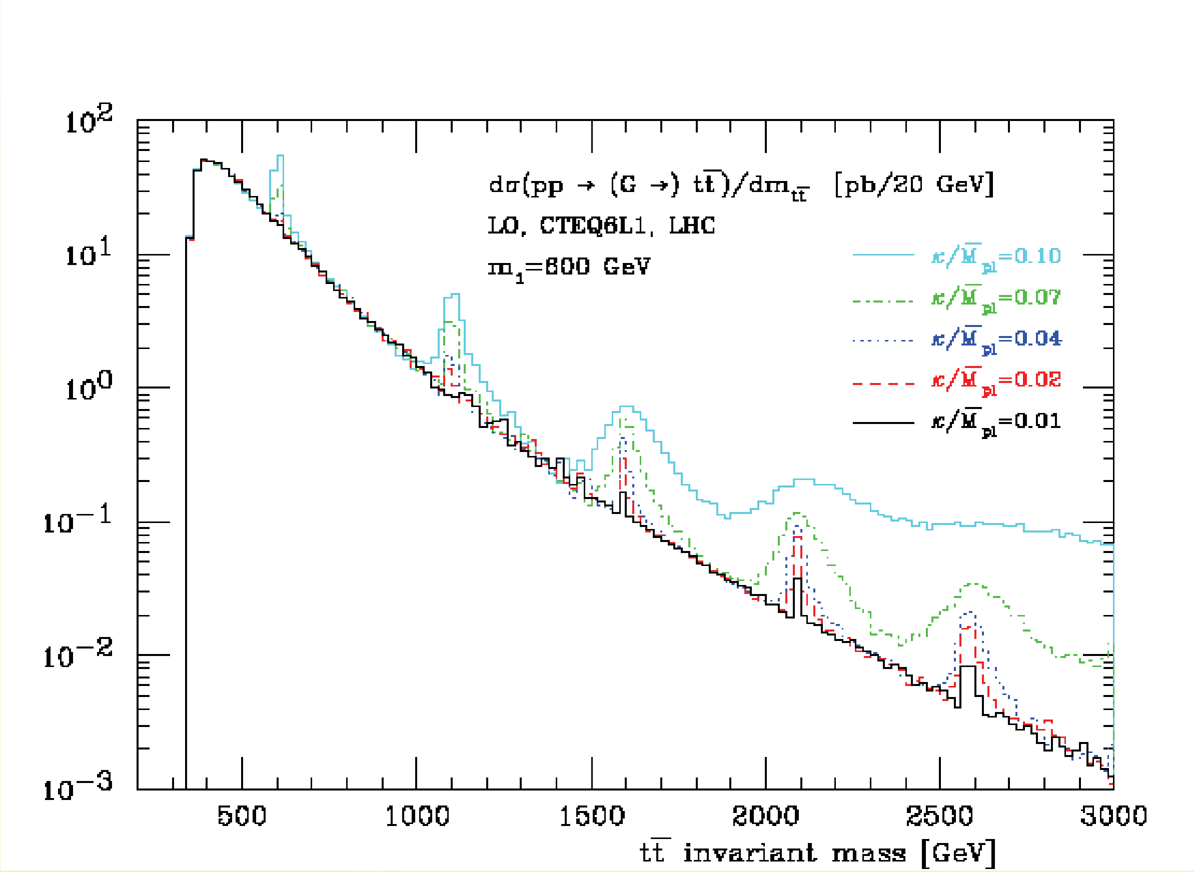






Non-trivial behavior (peak-dip) due to the interference between the signal and the background, only if top width dominated by $\Phi \to tt$. [Dicus, Stange & Willenbrock 1994]

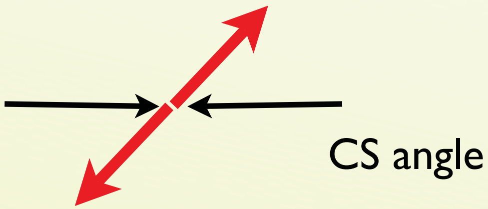
Phase 1: discovery

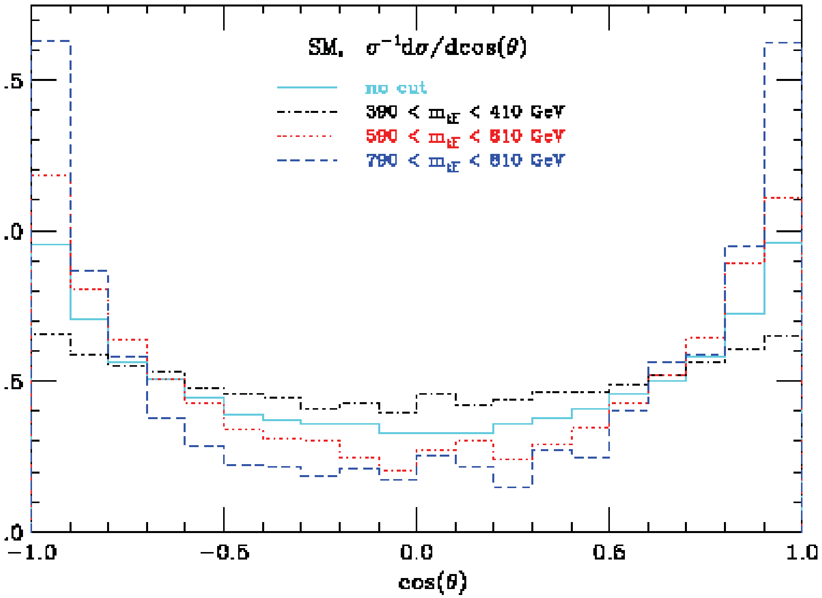


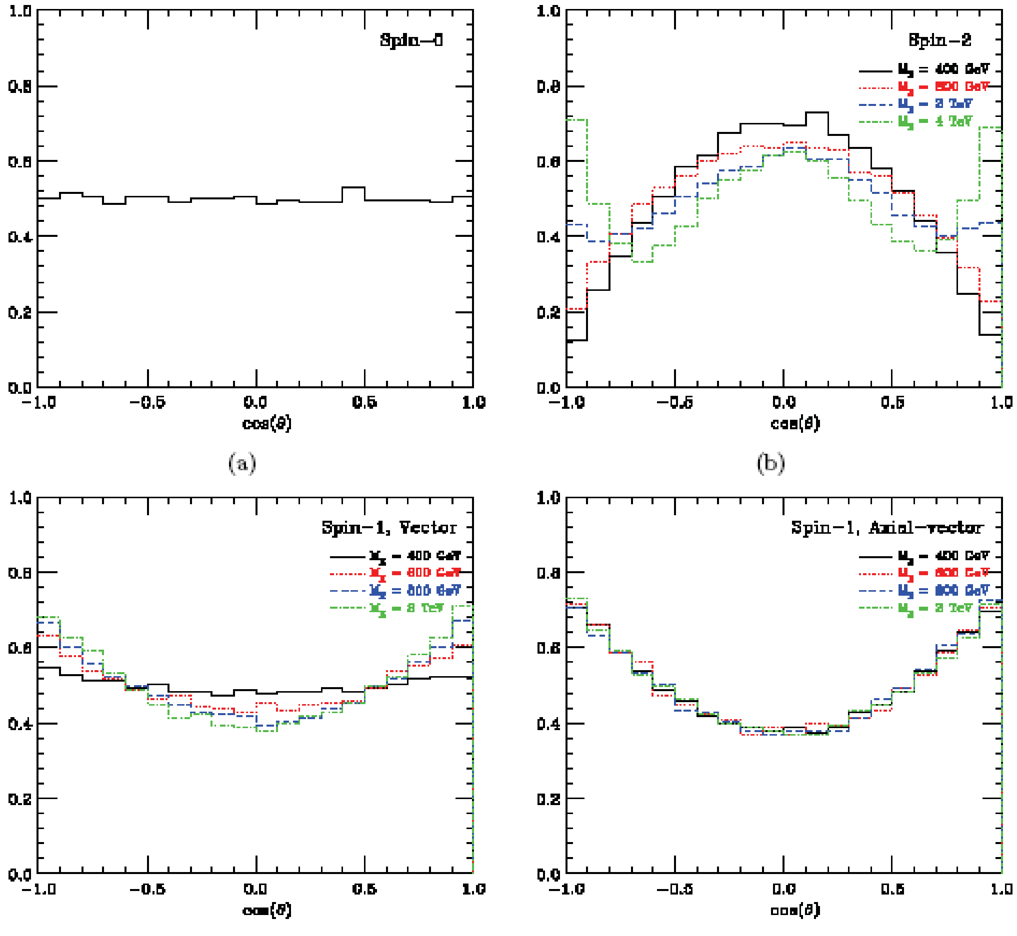
* Spectacular signature!

*RS Model with first KK=600 GeV

Phase 2: ttbar angular distributions



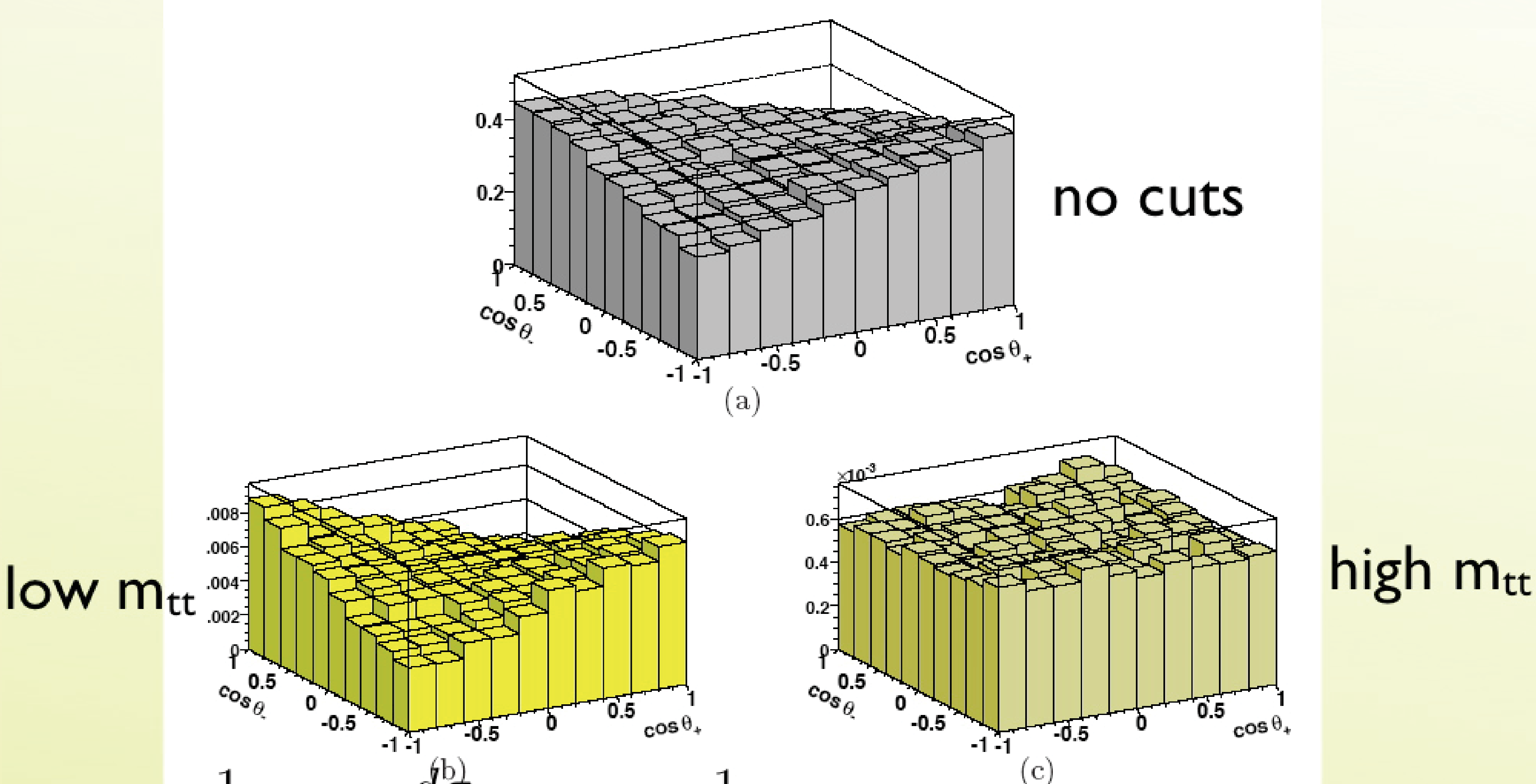




(a) (b) (c) (d)

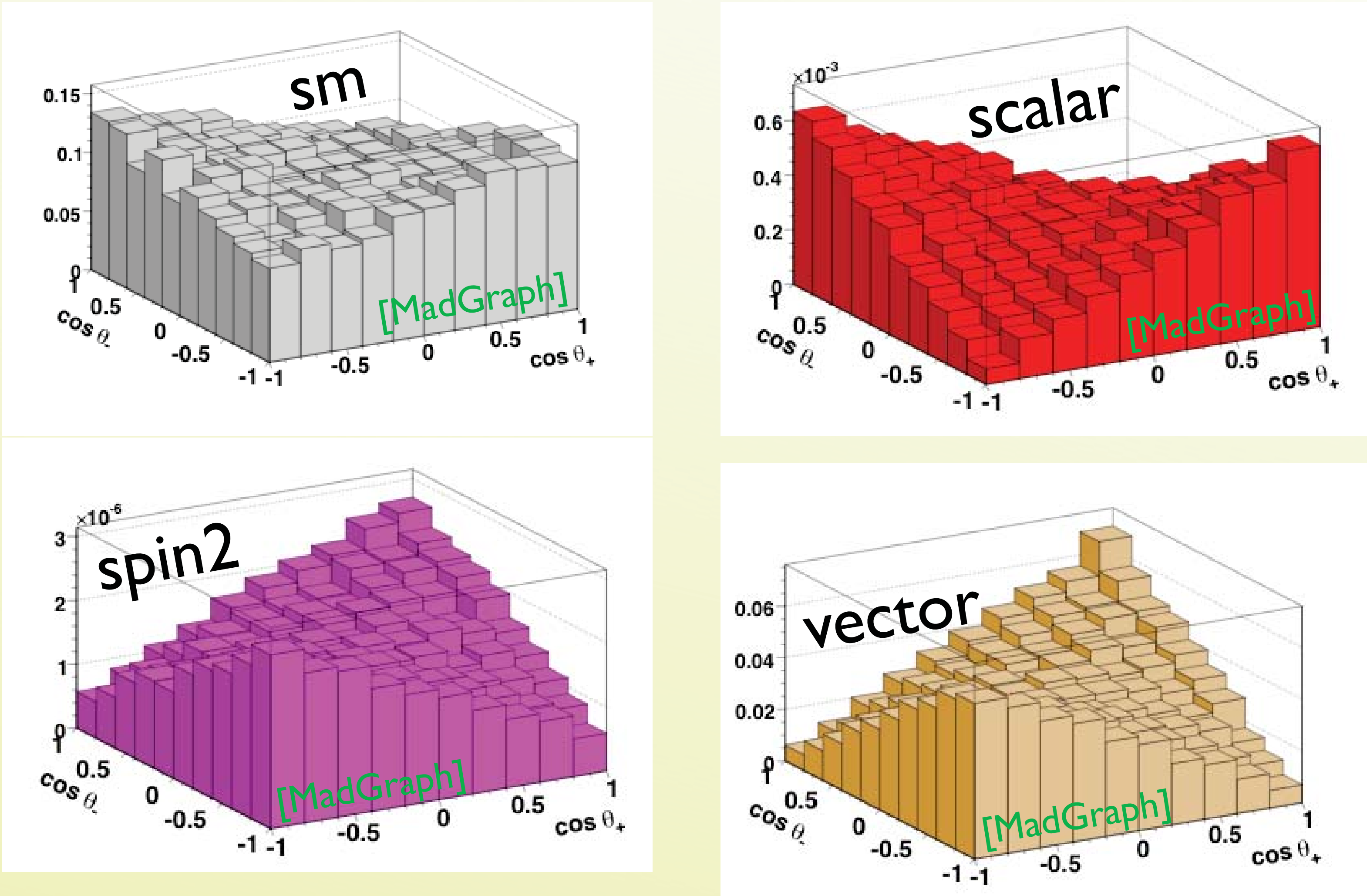
Robust reconstruction needed, but much easier than spin correlations...

Phase 3: Spin correlations



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

Phase 3: Spin correlations



Reconstruction issues

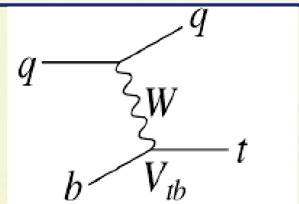
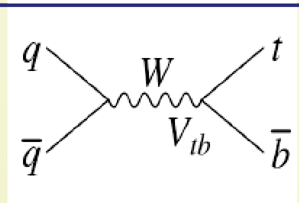
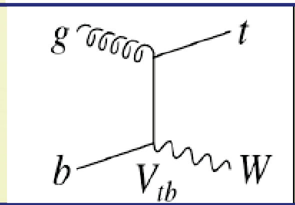
- Three possible different signatures (0,1,2, leptons in the final state) entail different event reconstruction strategies.
- Also the three different phases ask for (increasingly) sophisticated approaches
- To fix the final state (modulo combinatorics) we need 18 measurements.

<table>
<tr><th></th><th>0 lept</th><th>1 lepts</th><th>2 lepts</th></tr>
<tr><td># measured</td><td>6x3</td><td>5x3+ E_T +m_W</td><td>4x3+E_T+(2m_W,2m_t)</td></tr>
<tr><td>m(tt)</td><td>no reco needed</td><td rowspan="2">reco
(no comb w/ constr)</td><td rowspan="3">full reco w/ comb

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

Single-top

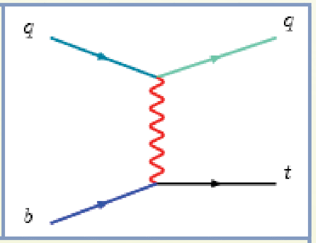
Single-top

Process	Diagram	Accuracy	CTEQ6M, mt=172 GeV,th err≅10% σ (pb)	
			TeV II	LHC
t-channel		NLO Stelzer, Sullivan, Willenbrock ‘97	1.98	247
s-channel		(N)NLO Smith, Willenbrock ‘96	0.88	10.7
tW		NLO Campbell, Tramontano ‘05	0.07	66

All signals available in MCFM [Campbell, et al.] and in MC@NLO [Frixione et al.]. Most of the backgrounds are also known at NLO. However, analysis still rely on LO calculations for the heavy-quark fractions in W+jets events (largest background)
⇒ room for improvement.

A closer look at single top

t channel



SM info

Largest rate, dominant at the LHC, where 62% top, 38% anti-top.

$\sigma \propto |Vtb|^2$.

Forward jet in final state, top central, sometimes one extra forward bottom. FB asymmetric at the Tevatron. Main background W+Q's+jet (and tt at the LHC).

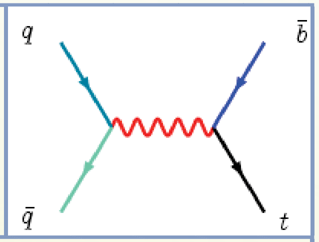
Top is polarized along spectator jet (most of the times) in the 2→2 configuration.

BSM window

Sensitive to new production modes, through FCNC (qc→qt).

Associated Higgs production in SUSY.

s channel



SM info

Smallest at the LHC, where 63% top, 37% anti-top.

$\sigma \propto |Vtb|^2$.

Very well known. DY might be used for normalization.

Central high-pt b-jet. Main backgrounds: tt, tj, and W+Q's+jets.

Top is polarized along beam axis at the Tevatron.

BSM window

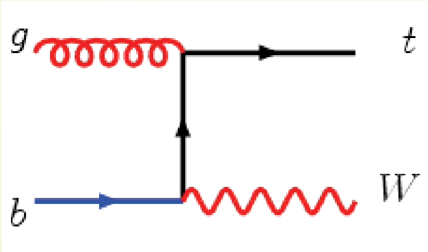
Sensitive to vector (extra W) and scalar (top pions) resonances.
Spin correlations to study the handness of the couplings.

Tait and Yuan, '00

tW and tH$^+$

Interest: V_{tb} measurement

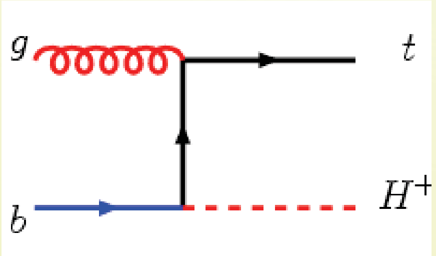
The Cinderella of the three channels. Not studied as much as s and t. Tiny at the Tevatron, sizeable at the LHC. It is similar to tt: it just has one b-jet less! Possible interesting signature: 2 leptons, missing Et, and exactly one b-jet. A b-jet veto is needed for a meaningful definition even at the TH level. Focus on Vtb.



Important background when tt + jet veto is large (Ex: gg→H→WW).

Interest: Charged Higgs discovery

When $m_{H^+} > m_t$, no overlap with tt production, no TH need for a b-jet veto.

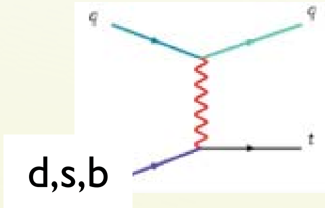


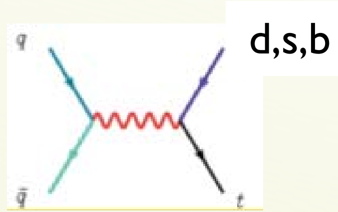
When $m_{H^+} < m_t$, tt production, with $t \to H^+ b$ dominates. Overlap with $gb \to tH^+$ does not create a problem for discovery.

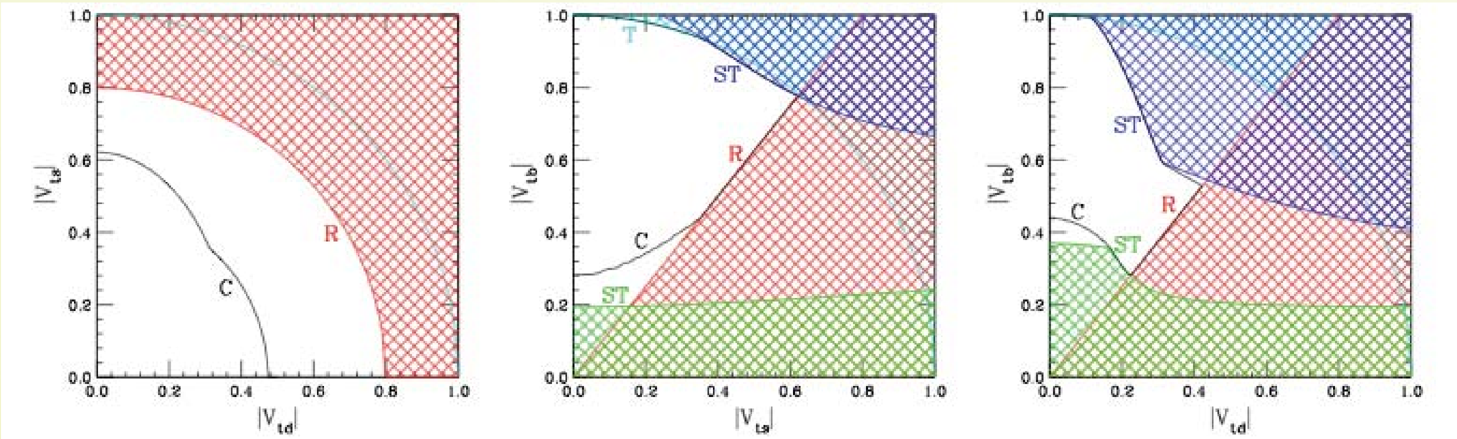
Need to be careful in the transition region $m_{H^+} \sim m_t$.

Example: Relaxing the unitarity constraint in single top analyses

Current analyses at Tevatron assume Standard Model. With more data independent direct limits on V_{td}, V_{ts}, V_{tb} are possible.







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

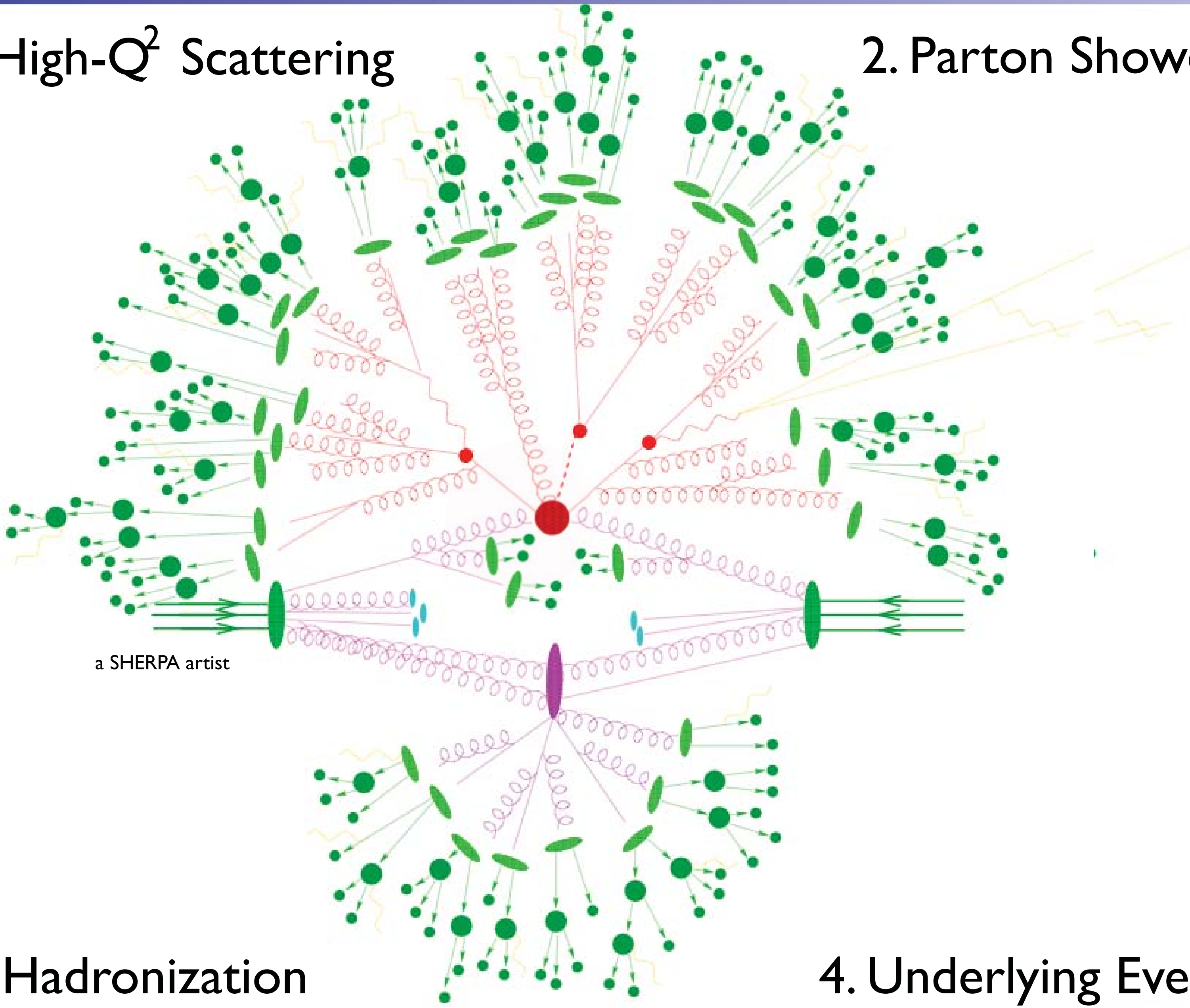
$$\sigma_{2b\text{-tag}} = R|V_{tb}|^2\sigma^{s\text{-ch}}.$$

Outline

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

1. High-Q^2 Scattering

2. Parton Shower

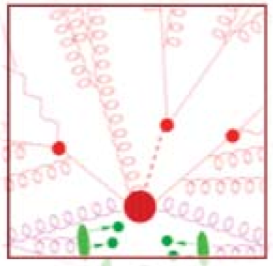


a SHERPA artist

3. Hadronization

4. Underlying Event

How theorists (used to) make predictions?



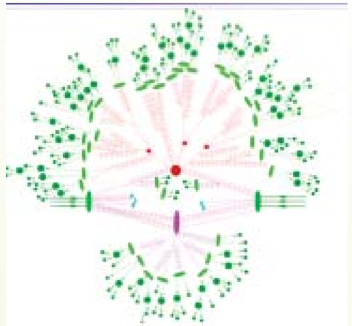
Evolution is unitary and universal: ignore it!
Focus on the high Q^2:

- For low parton multiplicity include higher order terms in our fixed-order calculations (LO→NLO→NNLO...)
  $\Rightarrow \hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \ldots$
- For high parton multiplicity use the tree-level results

Comments:

1. The theoretical errors systematically decrease
2. A lot of new techniques and universal algorithms are developed
3. Final description only in terms of partons and calculation of IR safe observables ⇒ cannot be directly employed in experimental studies

How experimentalists (used to) make predictions?



Fully exclusive final state description for detector simulations more important ⇒ give up on the high Q^2 complexity.

- Describe final states with high multiplicities starting from $2 \to 1$ or $2 \to 2$ procs, using a parton shower, and then an hadronization model

Comments:

1. Very flexible and tunable tools. Good description of the data possible
2. Catches the bulk (log-enhanced) part of the cross section
3. Predictive power for normalization and kinematic distributions for high-pt multi-parton final states very limited

most known and used: PYTHIA, HERWIG, SHERPA*

Improving our predictions

Common Principle:

Avoid the weakest link! Balance the accuracy over the steps in the simulation chain. Improve not only the single steps but also their merging.

Two directions:

1. Matrix Elements + Parton Showers
Get fully exclusive description of many parton events correct at LO (LL) in all the phase space — ME+PS

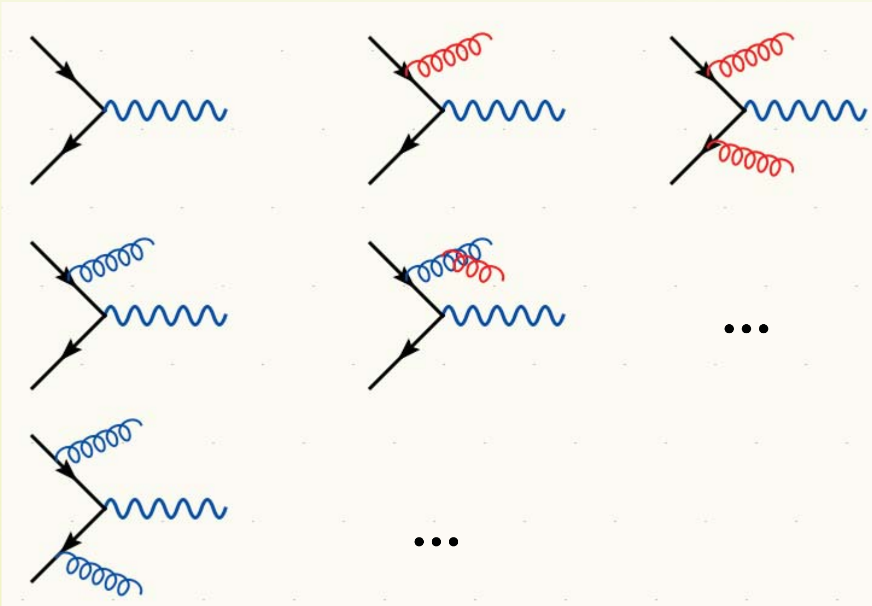
2. NLO with Parton Shower
Get fully exclusive description of events correct at NLO in the normalization and distributions. — NLOwPS

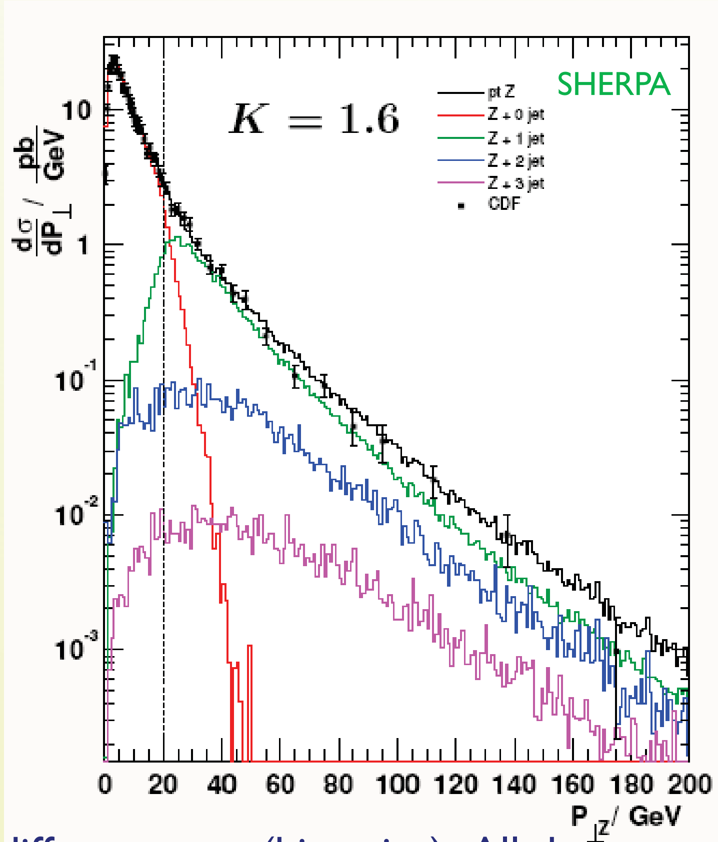
Merging fixed order with PS

[Mangano]
[Catani, Krauss, Kuhn, Webber]

PS →

ME ↓

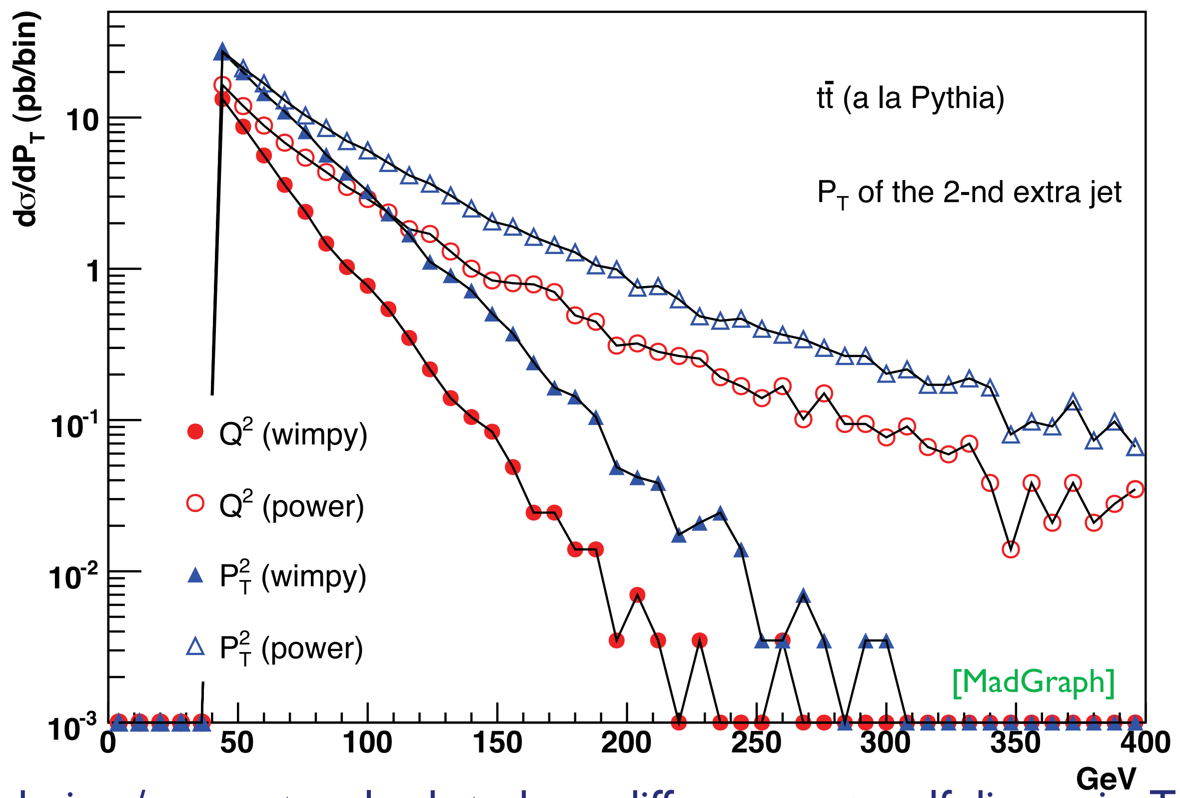




Double counting of configurations that can be obtained in different ways (histories). All the matching algorithms (CKKW, MLM,...) apply criteria to select only one possibility based on the hardness of the partons. As the result events are exclusive and can be added together into an inclusive sample. Distributions are accurate but overall normalization still "arbitrary".

PS alone vs matched samples

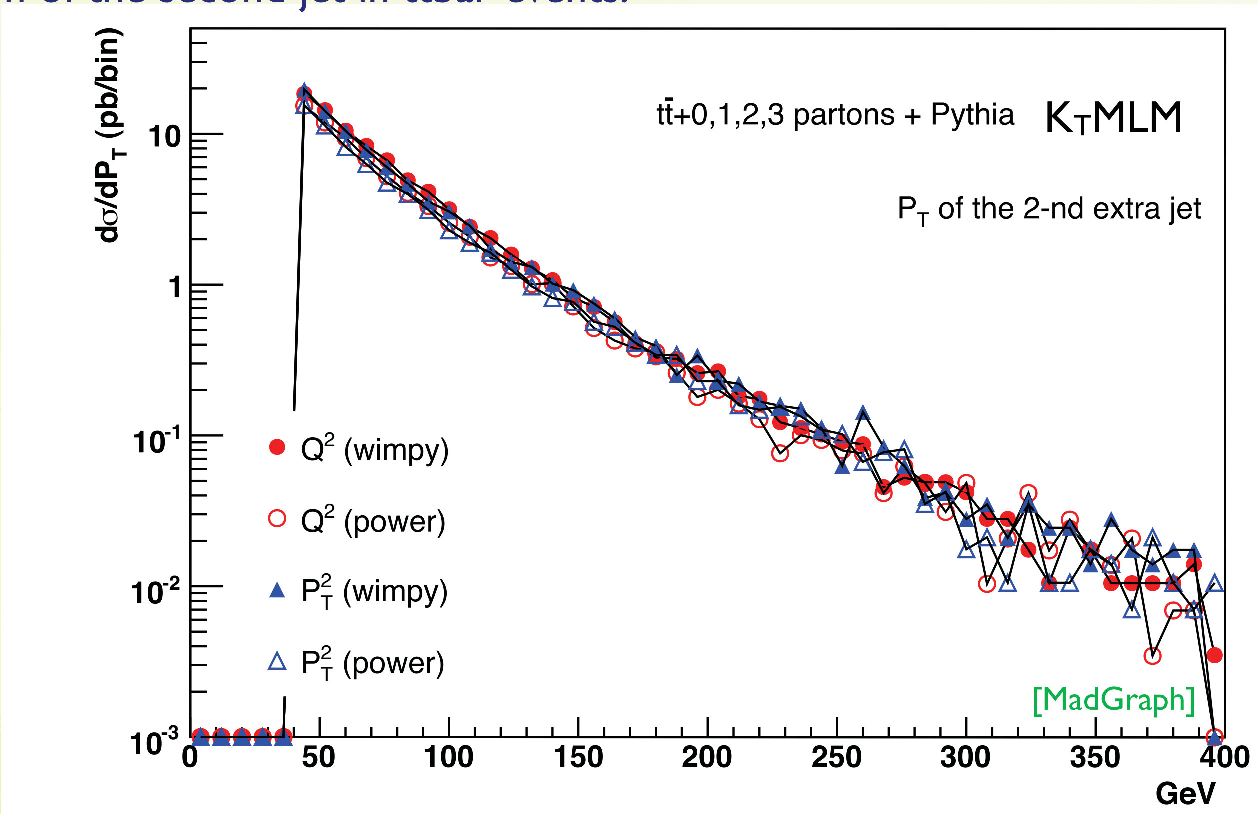
A MC shower produces inclusive samples covering all phase space. However, there are regions of the phase space (ex. high pt tails) which cannot be described well by the log enhanced (shower) terms in the QCD expansion and lead to ambiguities. Consider for instance the high-pt distribution of the second jet in ttbar events:



Changing some choices/parameters leads to huge differences ⇒ self diagnosis. Trying to tune the log terms to make up for it not a good idea ⇒ problems in other regions/shapes, proc dependence.

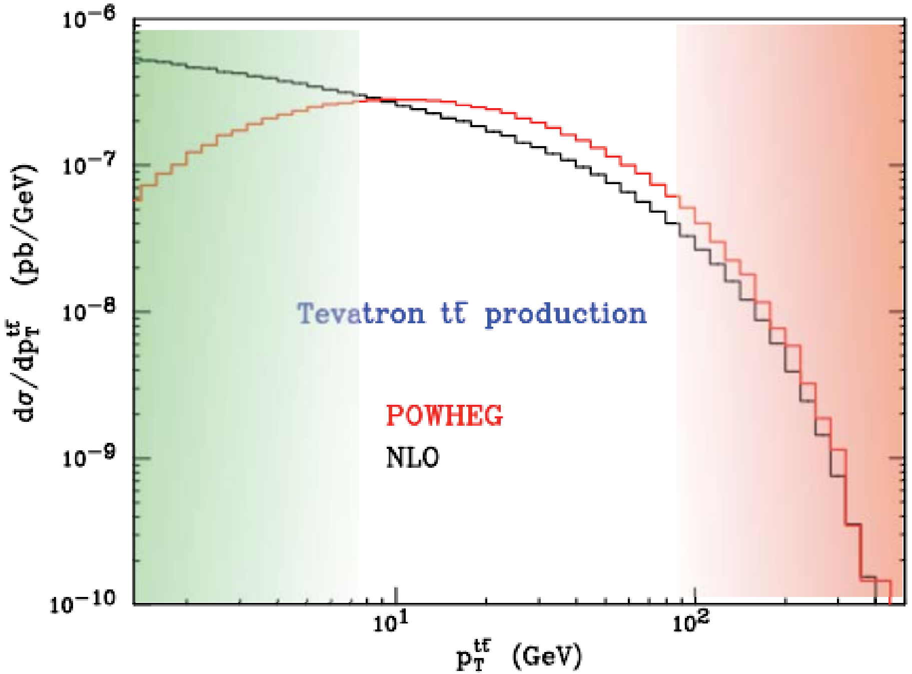
PS alone vs matched samples

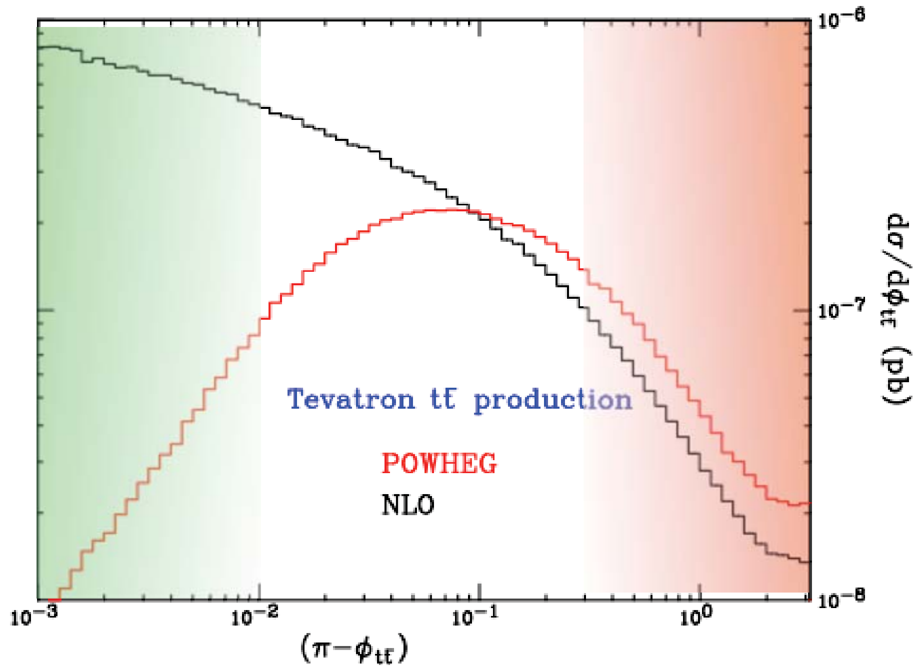
A MC shower produces inclusive samples covering all phase space. However, there are regions of the phase space (ex. high pt tails) which cannot be described well by the log enhanced (shower) terms in the QCD expansion and lead to ambiguities. Consider for instance the high-pt distribution of the second jet in ttbar events:



In a matched sample these differences are irrelevant since the behaviour at high pt is dominated by the matrix element. LO+LL is more reliable. (Matching uncertaintes not shown.)

Going beyond NLO : NLOwPS





* Soft/Collinear resummation of the $p_T(tt) \to 0$ region.
* At high $p_T(tt)$ it approaches the tt+parton (tree-level) result.
* When $\Phi(tt) \to 0$ ($\Phi(tt) \to \pi$) the emitted radiation is hard (soft).
* Normalization is FIXED and non trivial!!

MC tools for top physics

ME+PS

- Herwig
- Pythia
- SingleTop, TopRex
- Phantom
- AcerMC
- GRAPPA
- CompHEP

Always the FIRST tools. Main purpose is to provide an easily tunable description of the data. Complete exclusive description of the events: hard scattering, showering & hadronization, underlying event.

Optimized for a few or several processes. Based on a library of matrix elements (analytic or numeric). Limited in breath but easy to use, and optimal for specific studies.

ME+PS+merging

- Alpgen
- MadGraph
- Sherpa

Multipurpose Matrix Element creators and generators. Calculations are automatic at tree level. Matching is performed with the parton shower to produce inclusive multi-jet samples. Some codes (Alpgen) are optimized for multi-parton ME. Some codes are suitable for BSM physics.

NLO+PS

- MC@NLO
- POWHEG

Combine NLO accuracy in normalization and shapes of hard radiation with parton shower. "Best" tools when NLO calculation is available (i.e. low jet multiplicity). Current limitation is manual work ⇒ small libraries. Only SM

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...

...remember that you can always get one all for you!!