Theoretical Perspective on the Top Quark

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Top 2015
Sept. 2015

“You’re the top...
You're the Tower of Pisa,
You're the smile
on the Mona Lisa

I'm a worthless check, a total wreck, a flop,
But, baby, if I'm the bottom, you're the top!”

- Cole Porter

The top quark is unique among Standard Model particles in many respects. Of course it is the heaviest particle in the model. But also:

The top quark is a bare quark. It decays before hadronization, preserving all spin information.

The top quark couplings to other generations are very small. Flavor is not an important consideration in top quark physics (note: the converse is not correct).

The top quark Yukawa coupling is the largest SM coupling at very high energies:

$$\alpha_t = y_t^2/4\pi = 1/12$$

outline of the talk:

top in the Standard Model

precision top and QCD
calibration of top as a tool

top in BSM

passive top - weak coupling
active top - strong coupling/extra dimensions
t, T, and Higgs - 3 ways
t composite structure - 3 ways

“I don’t get no respect.”

To the extent that the top quark behaves just as predicted by the SM, it allows very precise calculations of its properties.

Here are landmarks that have been achieved since Top2014:

NNLO calculation of FB asymmetry in $p\bar{p} \to t\bar{t}$

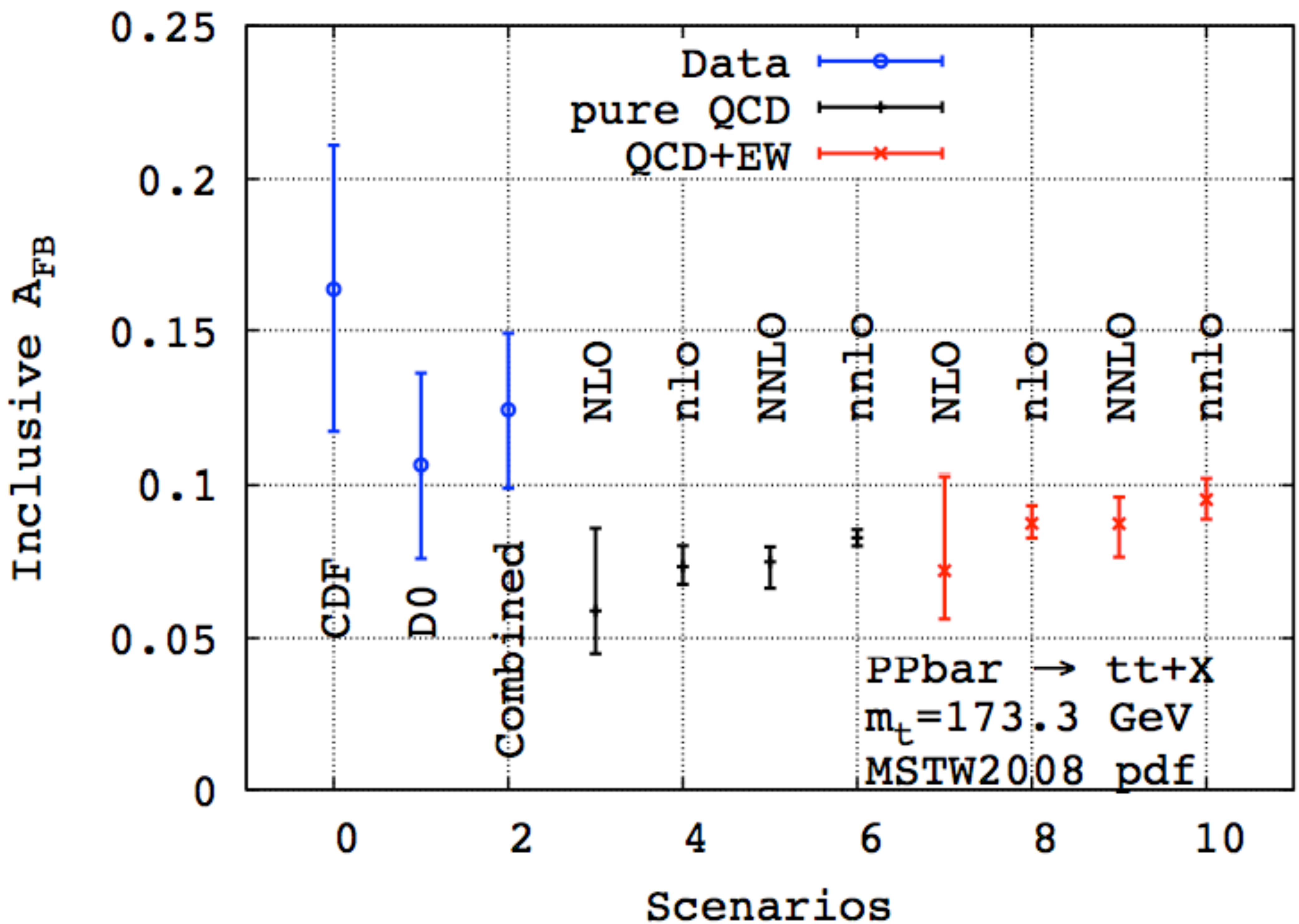
NNLO calculation of $e^+e^- \to t\bar{t}$

NNNNLO calculation of top quark mass relations

NNNLO calculation of the threshold shape in

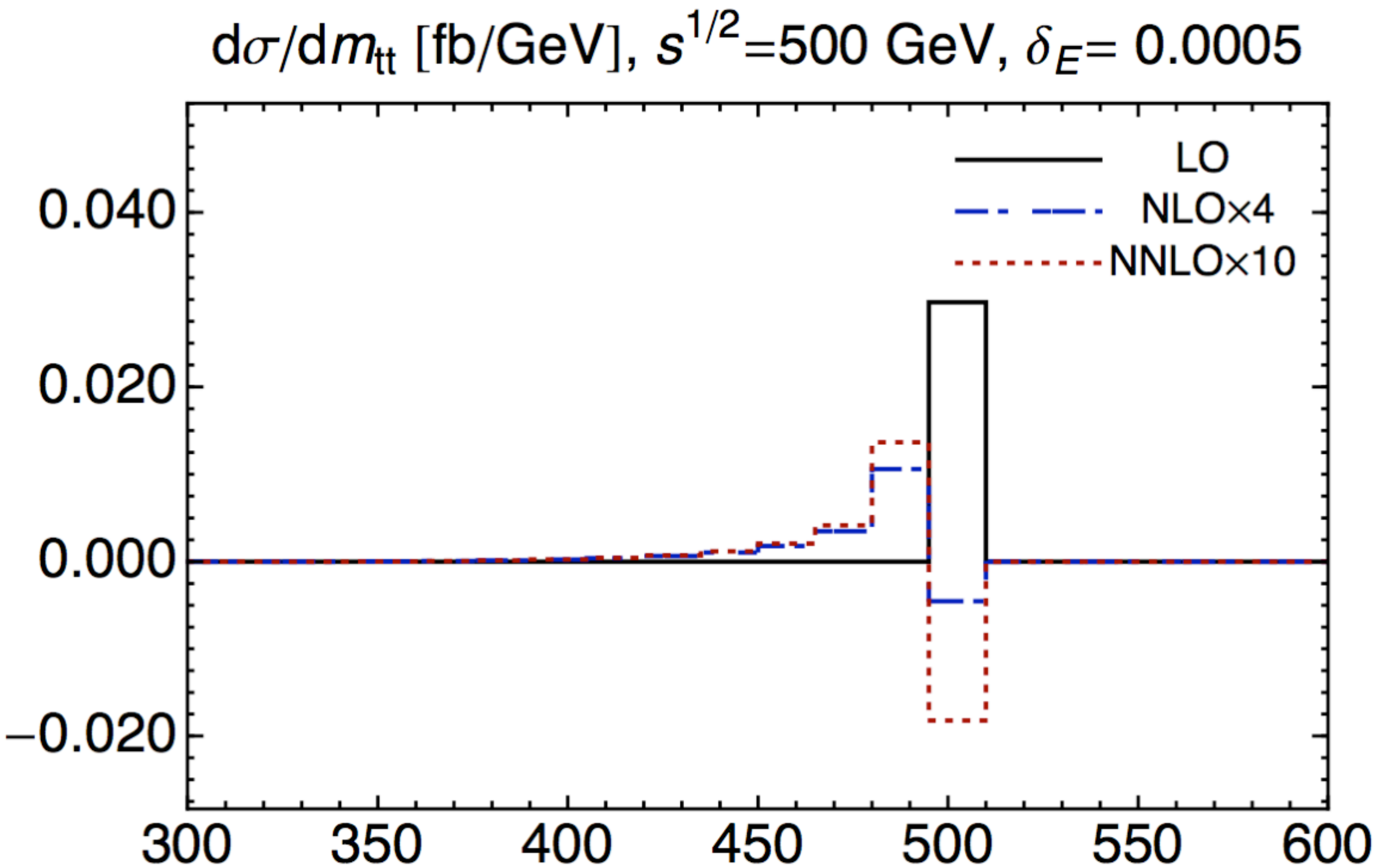
$$e^+e^- \to t\bar{t}$$

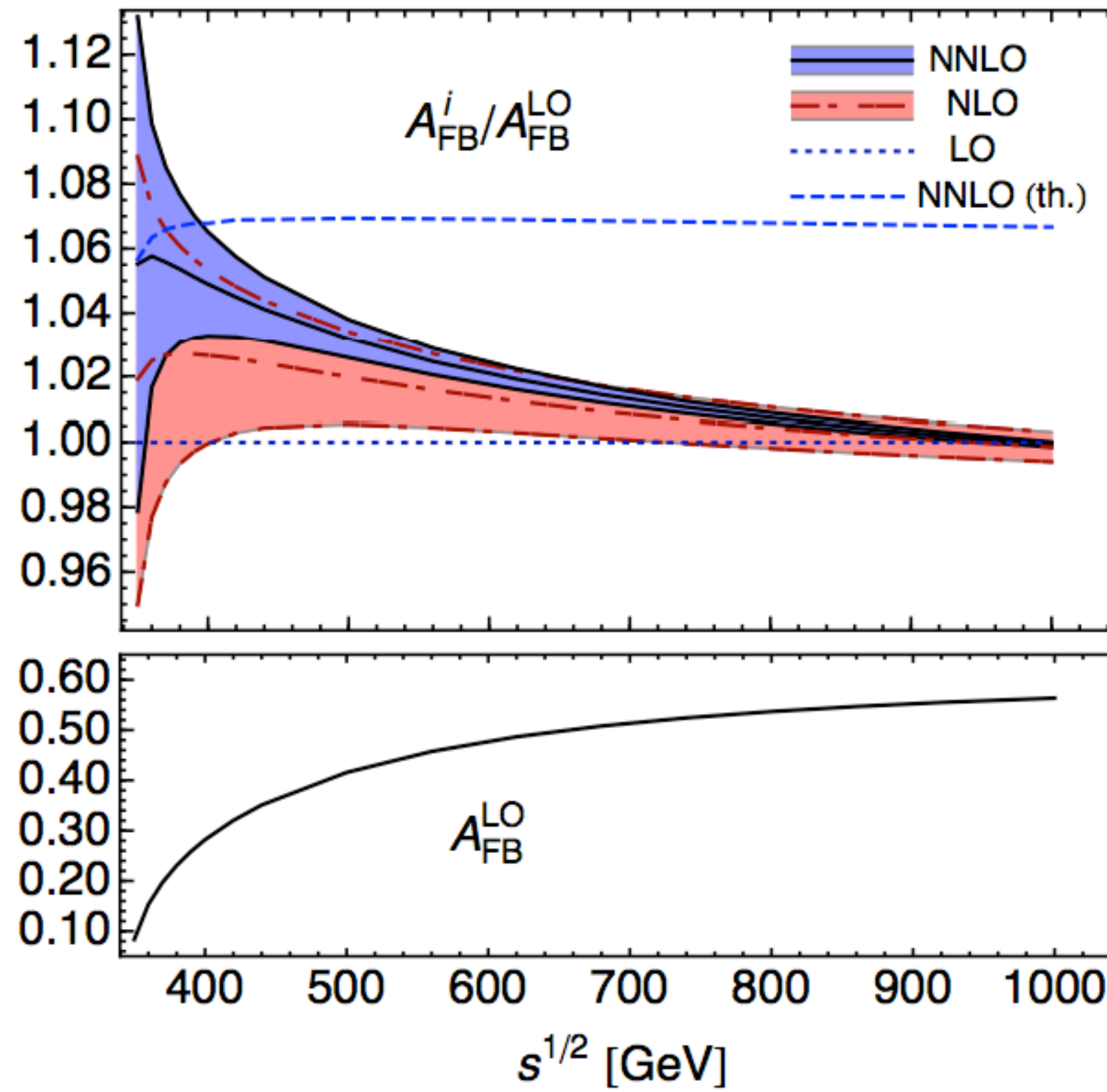
AFB in $p\bar{p} \to t\bar{t}$



Czakon, Fiedler, Mitov 2015

$e^+e^- \to t\bar{t}$





The calculation uses an innovative method in which virtual effects are cancelled only in the extreme soft limit, which the authors understand fully analytically.

Gao, Zhu 2014

Relation of the top quark pole mass (on-shell mass) and MS mass at 4 loops

$$M_t = m_t(1 + 0.4244\alpha_s + 0.8345\alpha_s^2 + 2.375\alpha_s^3 + (8.49 \pm 0.25)\alpha_s^4)$$

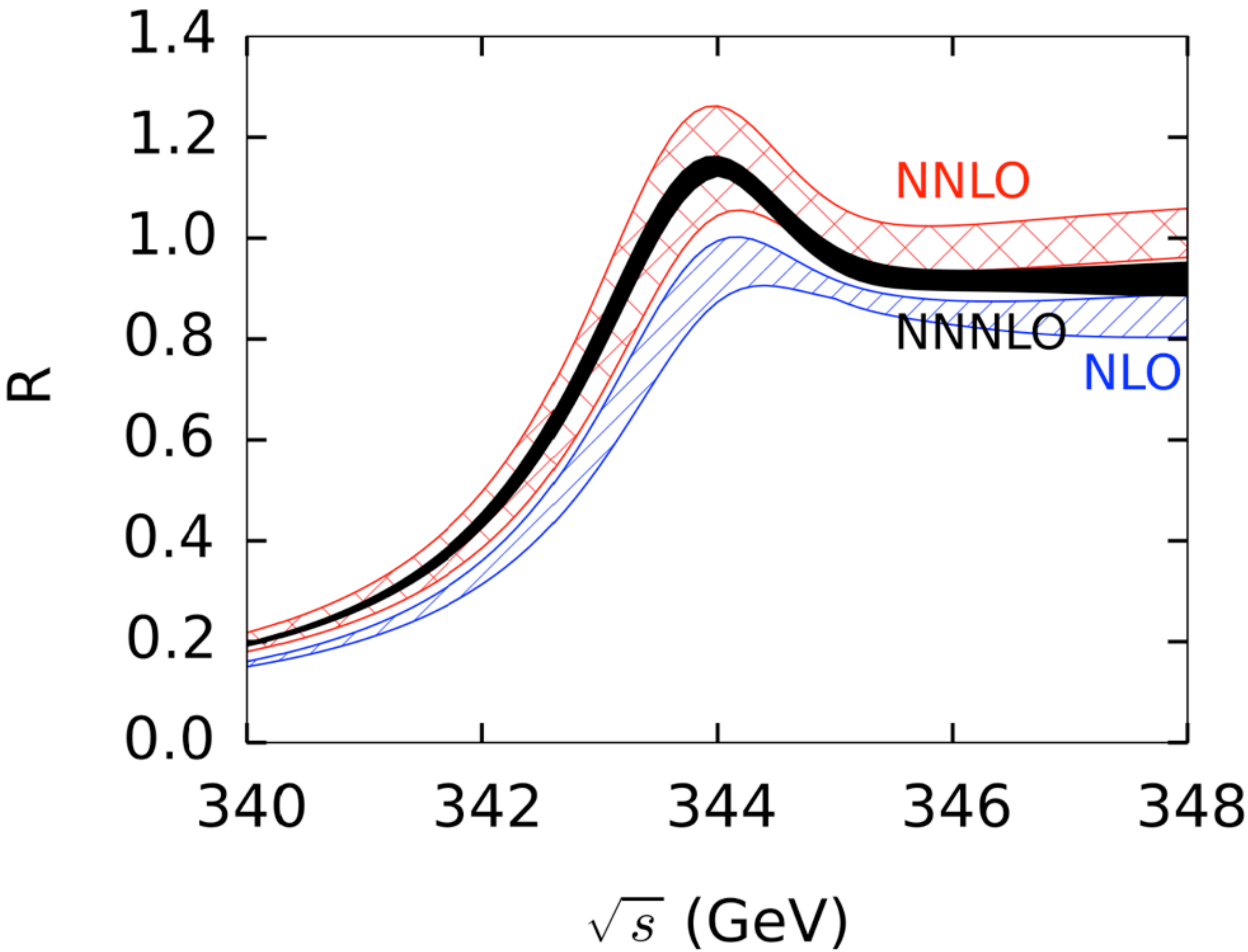
$$= 163.643 + 7.557 + 1.617 + 0.501 + 0.195 \pm 0.005$$

⇧ last term is 200 MeV

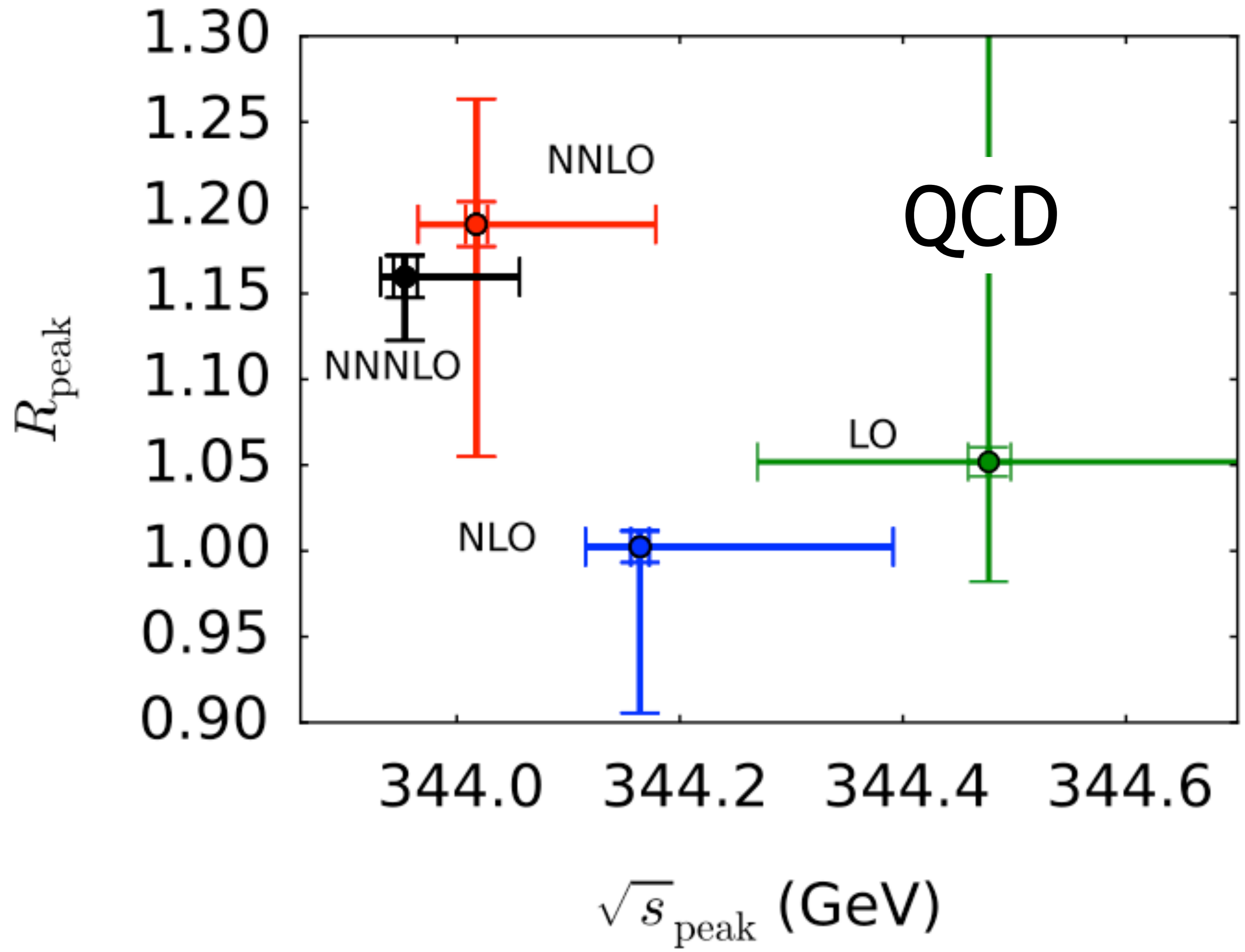
from input: 173.34 GeV

from the 1S mass - assuming this could be measured - the error in obtaining the MSbar mass is 7 MeV.

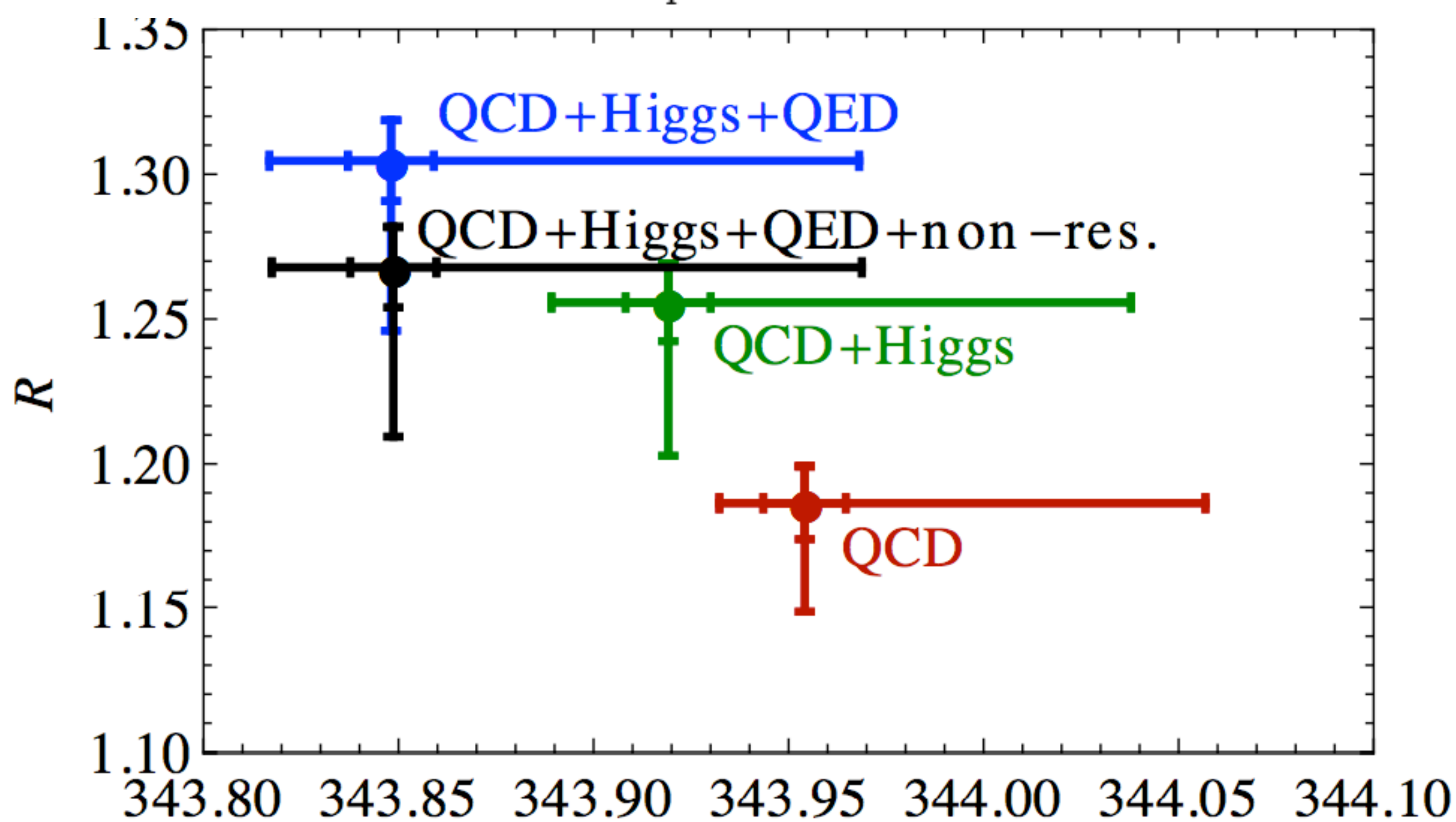
Marquard, Smirnov, Smirnov, Steinhauser 2015



Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser
2015



Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser



Beneke, Maier, Piclum, Rauh

2015

Because top decays before hadronization to a simple, structured W+b parton final state, and because top has a large (nb) cross section at the LHC, top is an important proving ground for jet taggers and analyzers:

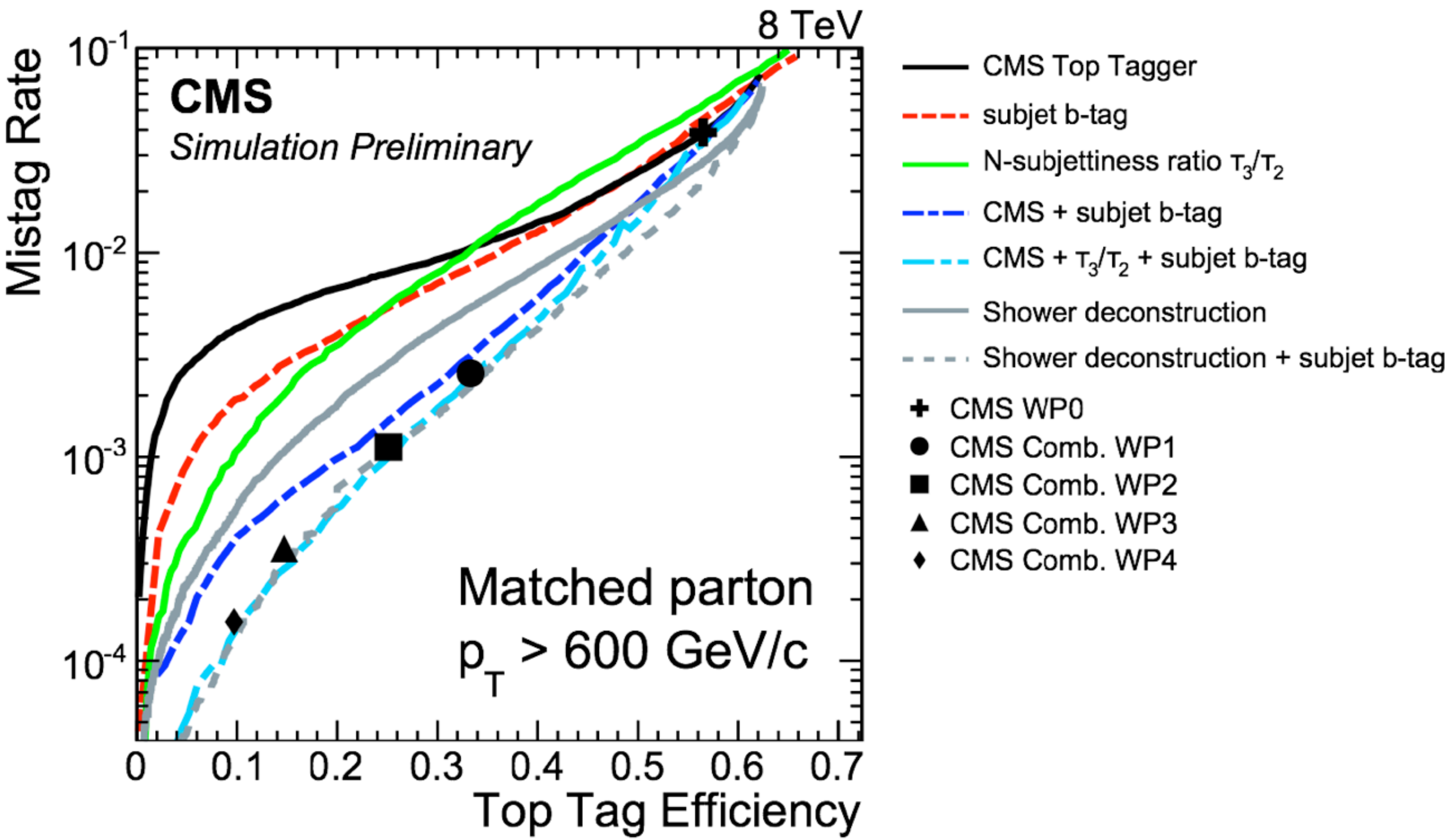
boosted tagging:

Kaplan, Rehermann, Schwartz, Tweedie (2008)
Ellis, Vermillion, Walsh
Plehn, Salam, Spannowsky, Takeuchi, Zerwas

polarization tagging:

Galante, Giammanco, Grossman, Kats,
Stamou, Zupan (2015)

current state of the art in CMS:



All production of b quarks by BSM physics is expected to varying strongly with b polarization. How can we measure this ?

Suggestion: hadronization $b \to \Lambda_b$ strongly retains the polarization (Mannel and Schuler, 1992). But, to what fraction ?

LEP experiments, using expected 94% b polarization in $Z \to b\bar{b}$: $\mathcal{P}(\Lambda_b) = 40 \pm 15\%$

Can we do better ?

with 10^8 top quarks, BR($t \to \Lambda_b$) $\sim 10\%$
b polarization > 99 % -- certainly!

Now turn to the role of top in BSM.

Crucial questions for BSM:

Why is electroweak symmetry spontaneously broken ?

What is the origin of dark matter ?

What is the origin of baryogenesis ?

What is the origin of flavor hierarchies and mixing ?

Yes, top is heavy, and yes, top is the particle most strongly coupled to the SM Higgs, but can it answer these questions ?

Example of SUSY:

EWSB: y_t is the largest SM coupling affecting the Higgs, so top partners can generate the negative Higgs μ^2 . Top is weakly coupled and structureless, so this effect is essentially passive.

Dark matter: special case "stop coannihilation"

Baryogenesis: strongly constrained; the phase must come from an extended Higgs sector or from the ν_R mass matrix.

Flavor: ask a GUT theorist, or, maybe, a string theorist

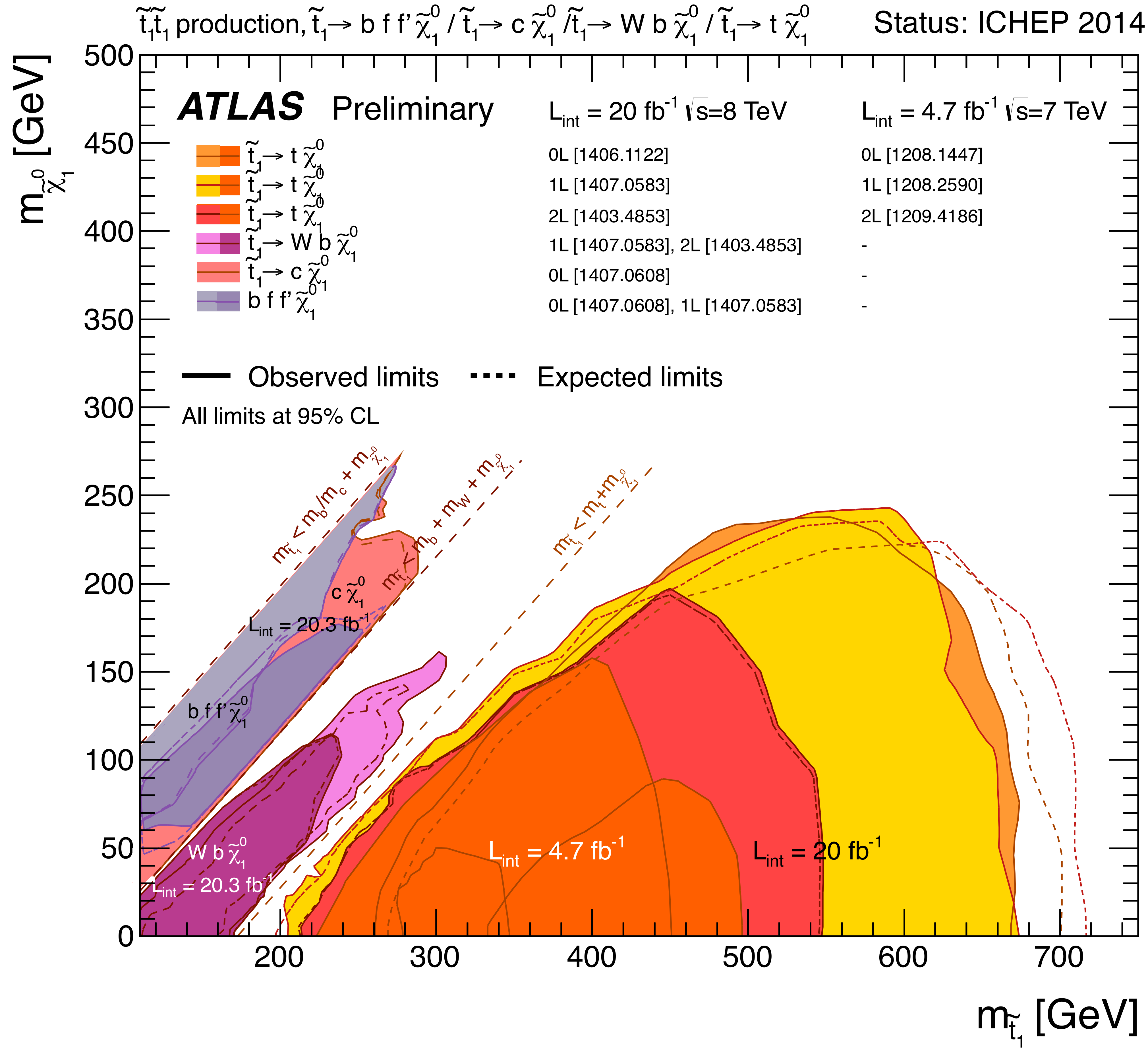
Nevertheless, the passive induction of a negative μ^2 is a crucial aspect of SUSY.

Indeed, it is proposed that the top squarks are the only light SUSY partners

“Natural Supersymmetry”   Papucci, Ruderman, Weiler

This hypothesis makes top squarks searches the most important SUSY searches.   These searches are the most highly develped at the LHC, making use of boosted taggers, quark polarization observables, precision QCD computations of background.

An alternative approach searches for small deviations from precision top QCD predictions.



$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$
Status: ICHEP 2014
ATLAS Preliminary
L_{int} = 20 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ 0L [1406.1122] 0L [1208.1447]
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ 1L [1407.0583] 1L [1208.2590]
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ 2L [1403.4853] 2L [1209.4186]
$\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ 1L [1407.0583], 2L [1403.4853] -
$\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$ 0L [1407.0608] -
$b f f' \tilde{\chi}_1^0$ 0L [1407.0608], 1L [1407.0583] -
Observed limits
Expected limits
All limits at 95% CL
$m_{\tilde{t}_1} < m_b/m_c + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
$c \tilde{\chi}_1^0$
L_{int} = 20.3 fb^{-1}
$b f f' \tilde{\chi}_1^0$
$W b \tilde{\chi}_1^0$
L_{int} = 20.3 fb^{-1}
L_{int} = 4.7 fb^{-1}
L_{int} = 20 fb^{-1}
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
50
100
150
200
250
300
350
400
450
500
200
300
400
500
600
700

However, I would like to remind you that SUSY is not the only approach to BSM.   Far from it.

Indeed:

SUSY is over-rated.

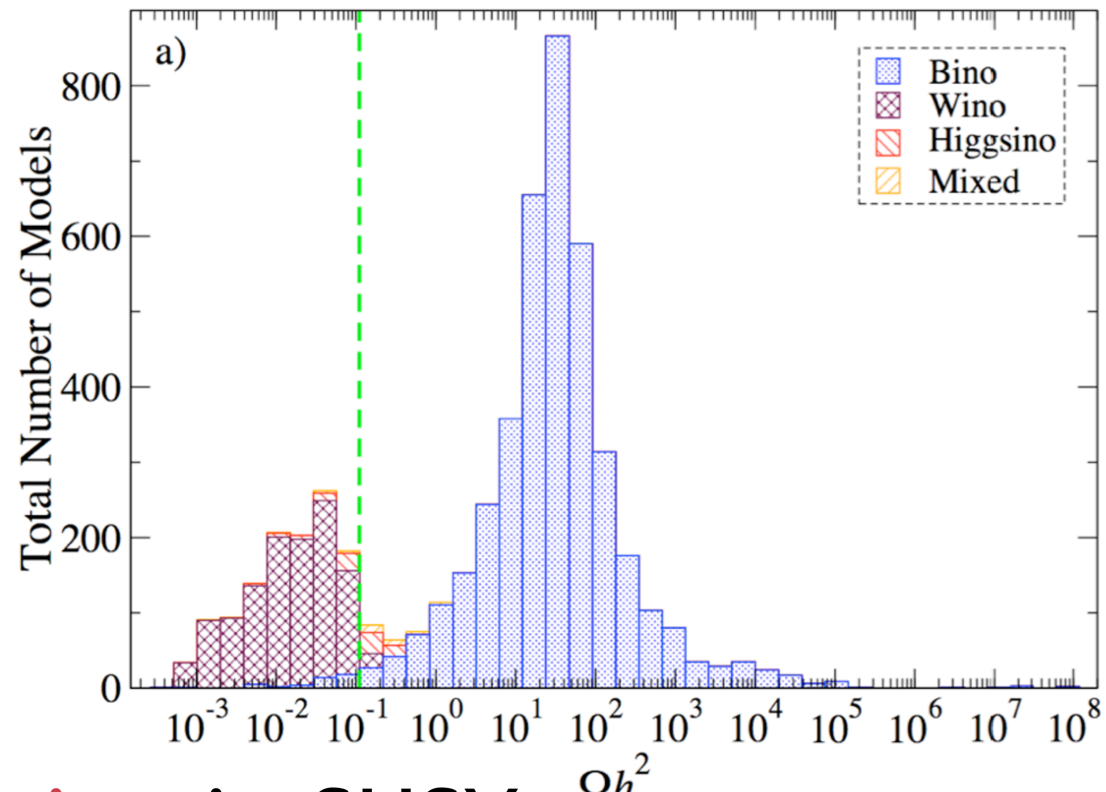
SUSY is over-rated:

1. For SUSY to be at the TeV scale, 3 unrelated parameters must have approximately equal values:

$$m_{\tilde{g}}\ , \quad \mu\ , \quad \text{zero of } M_{Hu}(Q)$$

Nelson

2. Value of the dark matter density in a scan of SUSY models:



Baer, Box, Summy

3. Grand unification in SUSY:

LO: perfect! NNLO: not so much ...

If we cannot believe in the Standard Model

(too ad hoc, the end of physics)

and we cannot believe in SUSY

(see above)

then maybe we are forced to accept that the Higgs is a composite state. This is associated to two deep theoretical ideas:

- Higgs as a Goldstone boson ("Little Higgs")
- Gauge-Higgs unification in 5-dimensions

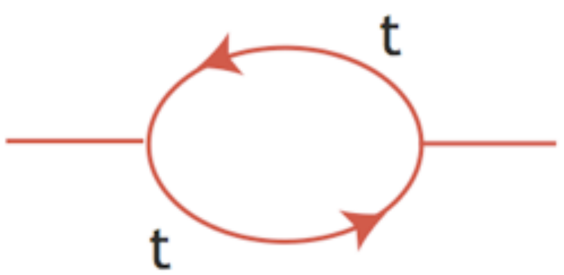
which might be dual descriptions of a new interaction.

Each of these theories has an extensive theoretical infrastructure that I will not try to describe here.

The simplest point is:

In the SM, the top quark corrects the Higgs mass parameter by an amount that is quadratically divergent.

$$\mu^2 = \mu^2_{\text{bare}} - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \cdots$$



In a model in which we can compute the Higgs potential, this divergence must be cancelled. In the models I am now discussing, the cancellation is by contributions from massive fermions. These must be vectorlike fermions, that is, fermions that get mass without the influence of the Higgs field vacuum value.

In “Little Higgs”models, these new fermions are put in by hand. But, they must appear so that the interaction that gives the top quark mass is invariant under the full symmetry of the model.

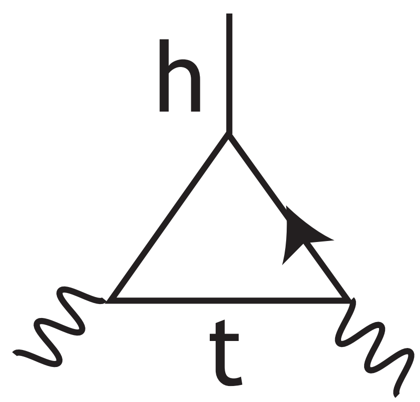
In 5-d models, the new fermions are the Kaluza-Klein excitations of the top quark. The descent from 5-d naturally leads to a tower of massive, vectorlike quarks.

In either case, summation over loops containing the new fermions cancels the divergence of the top quark loop. It looks like magic, but it is guided by the underlying symmetry.

But (if we are lucky) the negative sign of the diagram remains.

Before going more deeply into the physics of t and its heavy vectorlike partners T, consider the interplay of t, T and Higgs.

The Higgs production rate comes mainly from $gg \to h$ through



$$\sim y_t/m_t \sim 1/v$$

T can also contribute is this loop. But, T does not get its full mass from the Higgs vev; in fact, it gets only a small part: $\Delta M_T = -c\, m_t^2/M_T$

Then the T diagram has the size

$$\sim -(c/v)(m_t^2/M_T^2)$$

To disentangle possible modifications of the tth coupling from the influence of the T quarks, it is important to make three orthogonal measurements with high precision:

$$g(tth) \quad \text{in} \quad pp\ , \quad e^+e^- \to t\bar{t}h$$

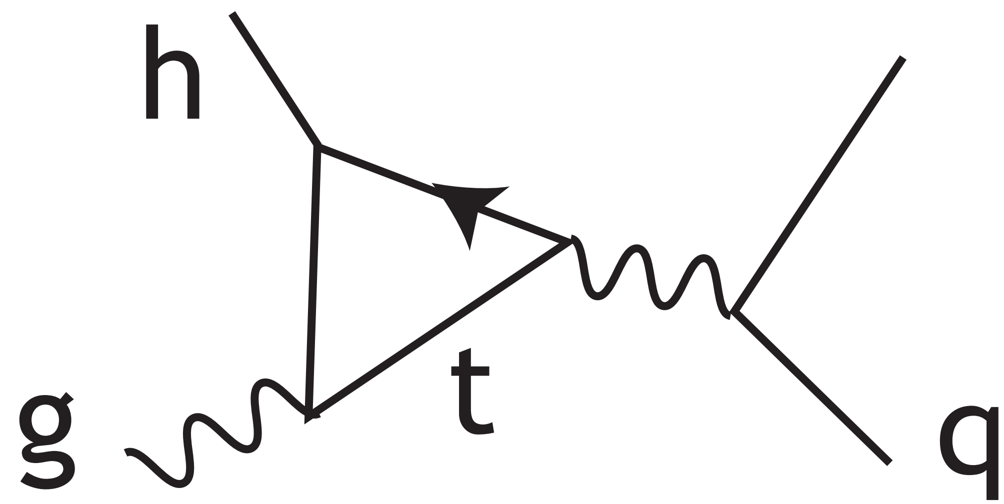
$$g(hgg) \quad \text{in} \ \ \sigma(pp \to g) \ \ \text{or} \ \ BR(h \to gg)$$

$$pp \to h + g \text{ or } q \text{ at high } p_T$$

The last of these deserves special comment.

Grojean, Salvioni, Schlaffer, Weiler:

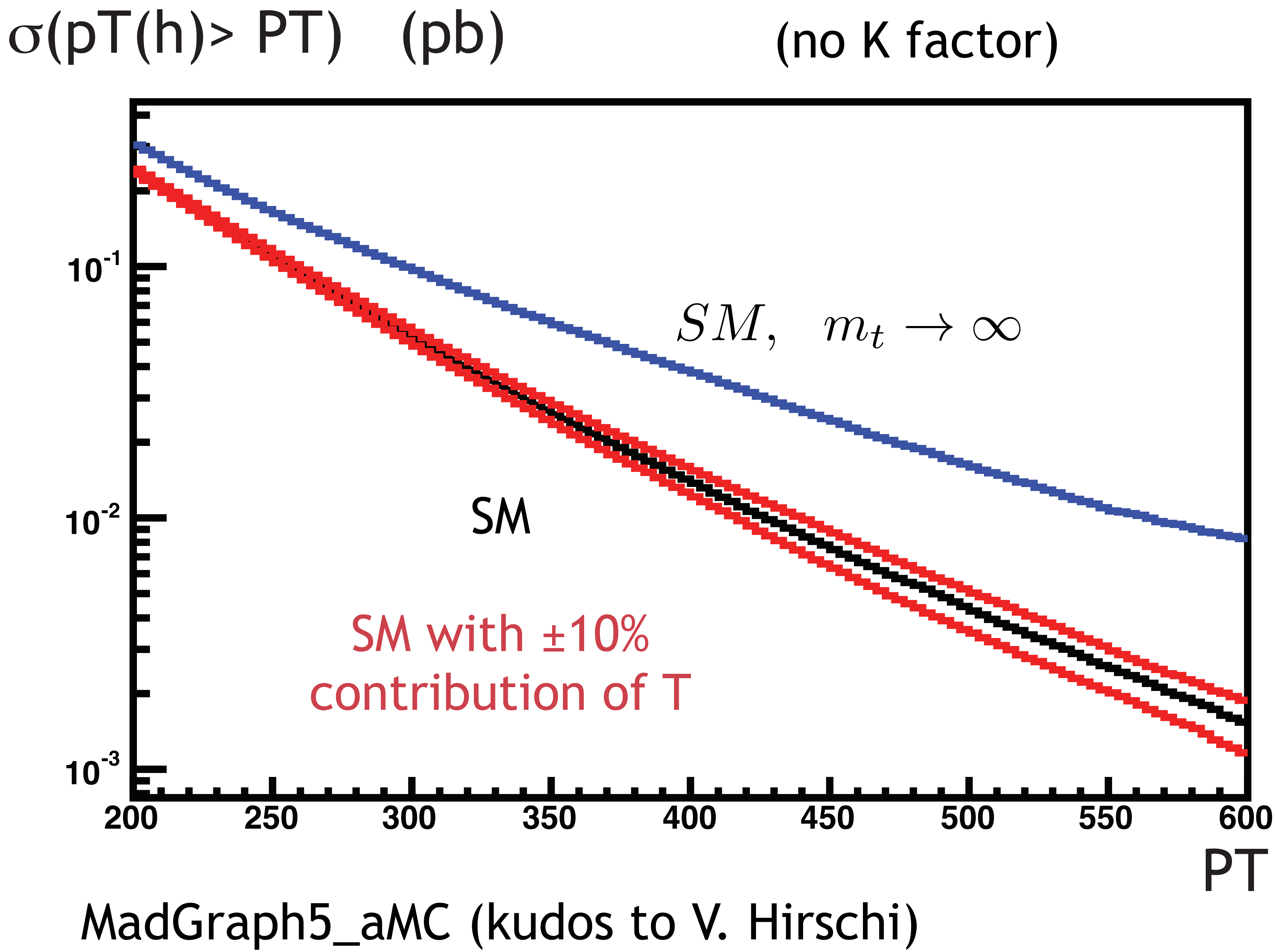
A typical diagram for $pp \to h \text{ at high } p_T$ is



The loop carries the momentum transferred to the Higgs and behaves as

$$m_t/(m_t^2 + p_T^2)^{1/2}$$

The top quark loop is then suppressed when $p_T > m_t$. Note that the Higgs is still on shell. At high pT, the T contribution can be left over.


σ(pT(h)> PT) (pb)
(no K factor)
10^-1
10^-2
10^-3
SM, m_t → ∞
SM
SM with ±10%
contribution of T
200
250
300
350
400
450
500
550
600
PT
MadGraph5_aMC (kudos to V. Hirschi)

So far, I have discussed only elementary t and elementary T. However, in Little Higgs and 5-d models, the Higgs field is composite. In many models, this means that t must also be composite. If new strong interactions are necessary to bind h, then also t must mix with composite states of the strong interactions to generate a sufficiently large value of y_t.

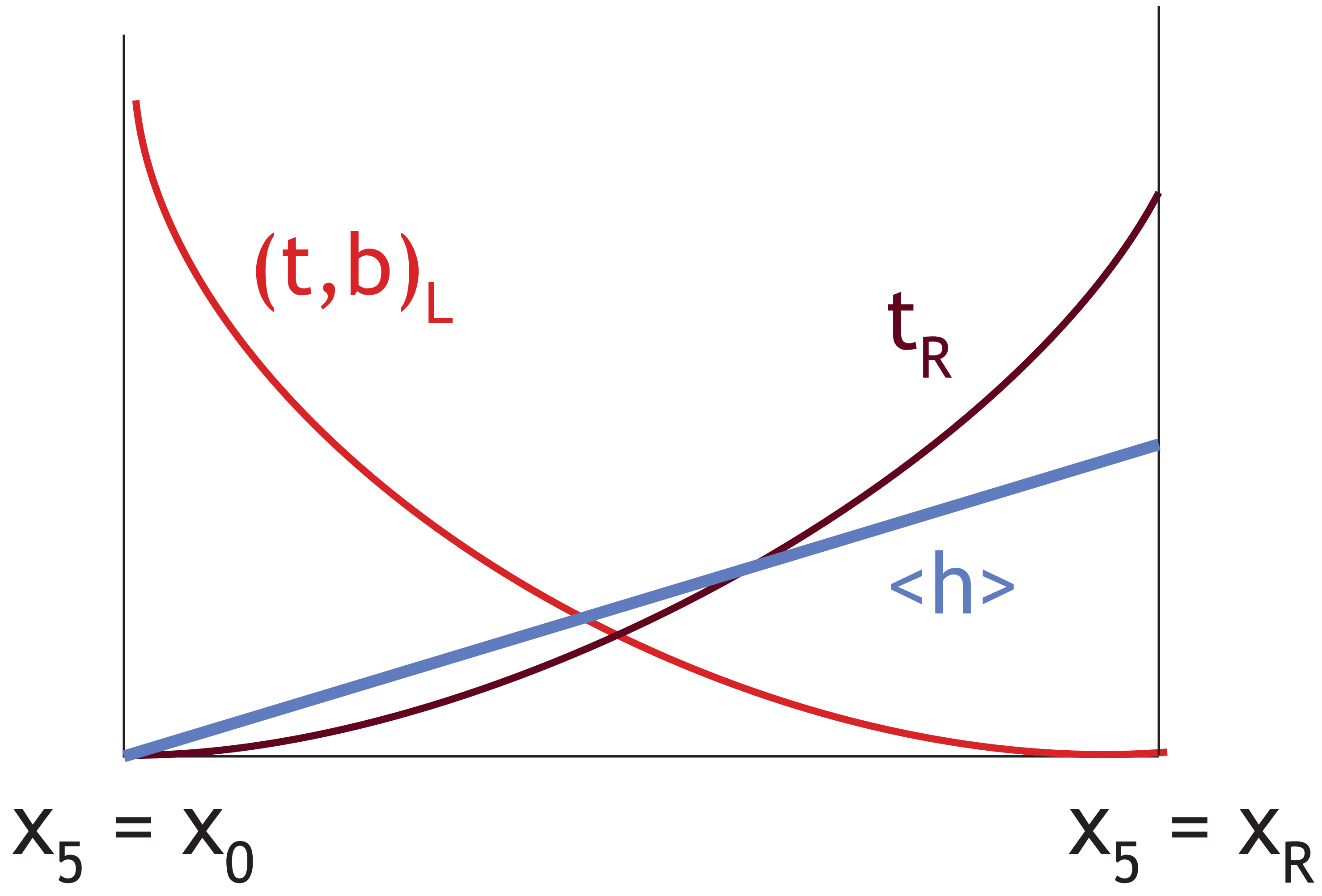
Randall-Sundrum picture:

curved (AdS) 5th dimension with

UV physics near $x^5 = x_0 = x_R \exp[-k\pi R]$
IR physics near $x^5 = x_R$
and Higgs localized near $x^5 = x_R$

The $(t,b)_L$ doublet must be very elementary, to satisfy precision electroweak constraints.

Then t_R must be highly composite, to provide good overlap with the Higgs vev in the 5th dimension



Form factors for gauge field couplings of the top quark:

gluon, photon: $F(q^2) = 1 + q^2/M_R^2 + \cdots$

where M_R is the mass of a resonance (KK excitation) decaying to $t\bar{t}$ and $T\overline{T}$ with sizable BRs.

For M_R = 3 TeV, this is a few-% effect.

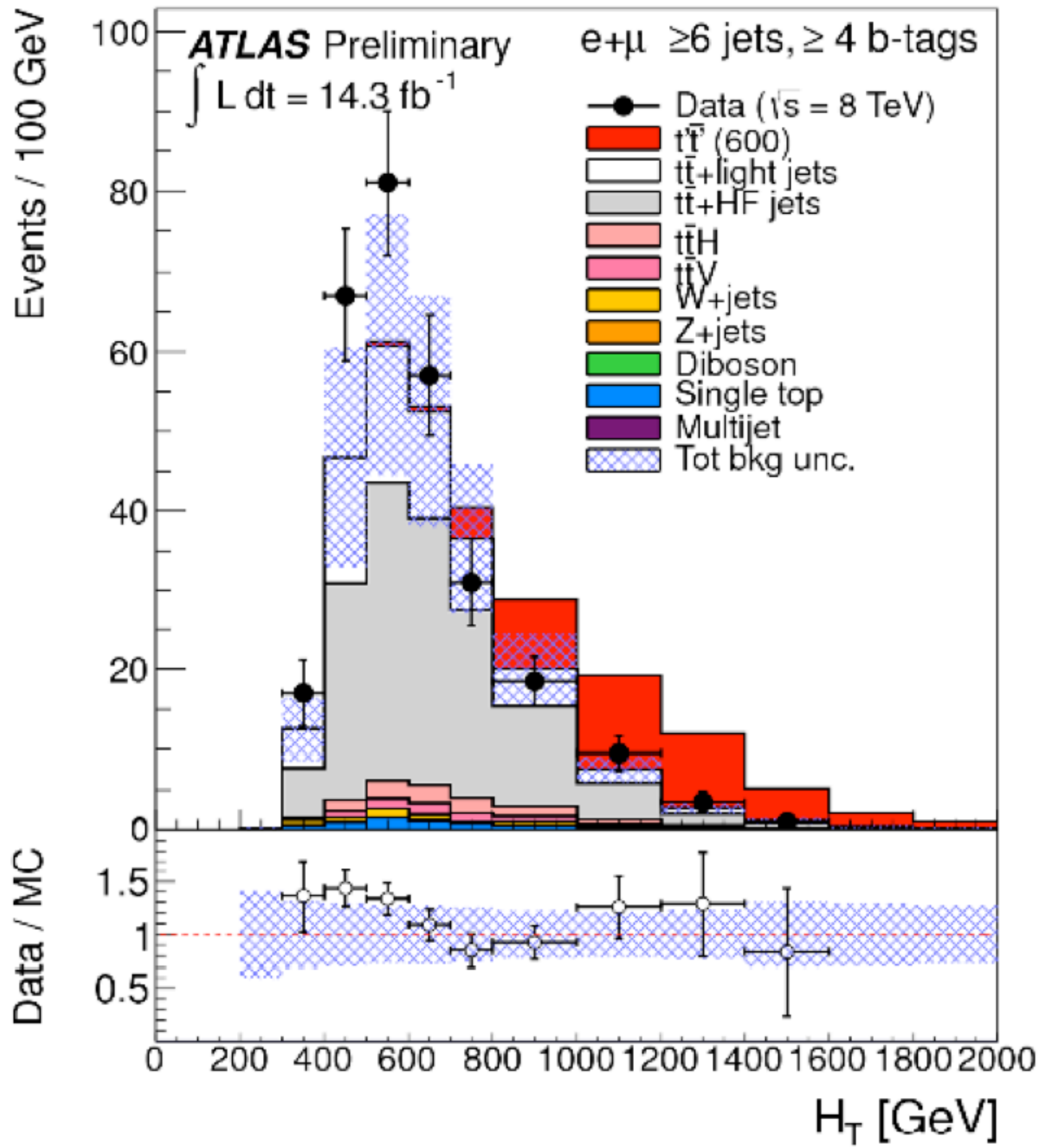
W, Z: the value at $q^2 = 0$ is not constrained by a Ward identity, so the modification can be larger.

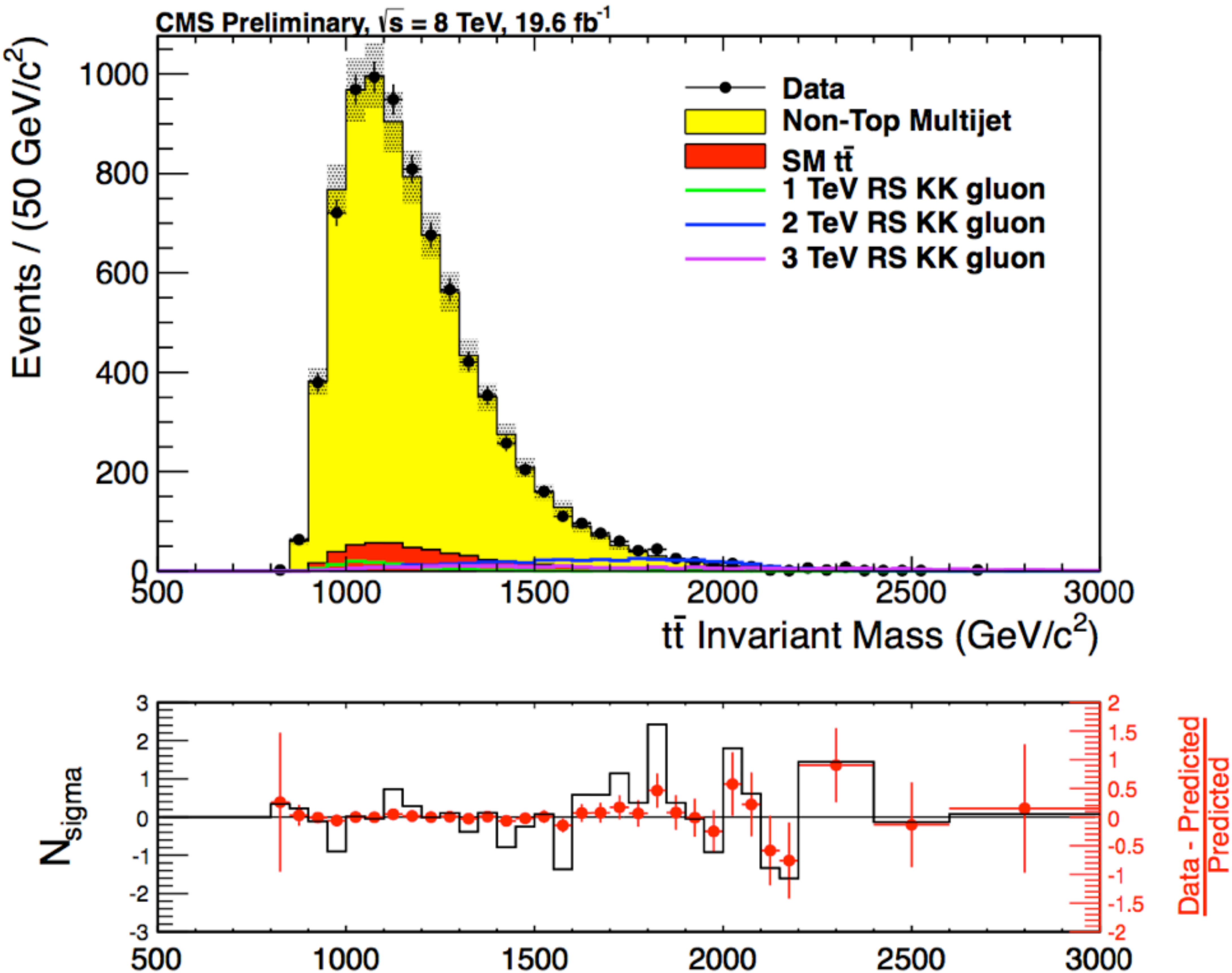
We need to go after these effects, also,
in 3 complementary ways:

direct search for T in $pp \to T\overline{T}$

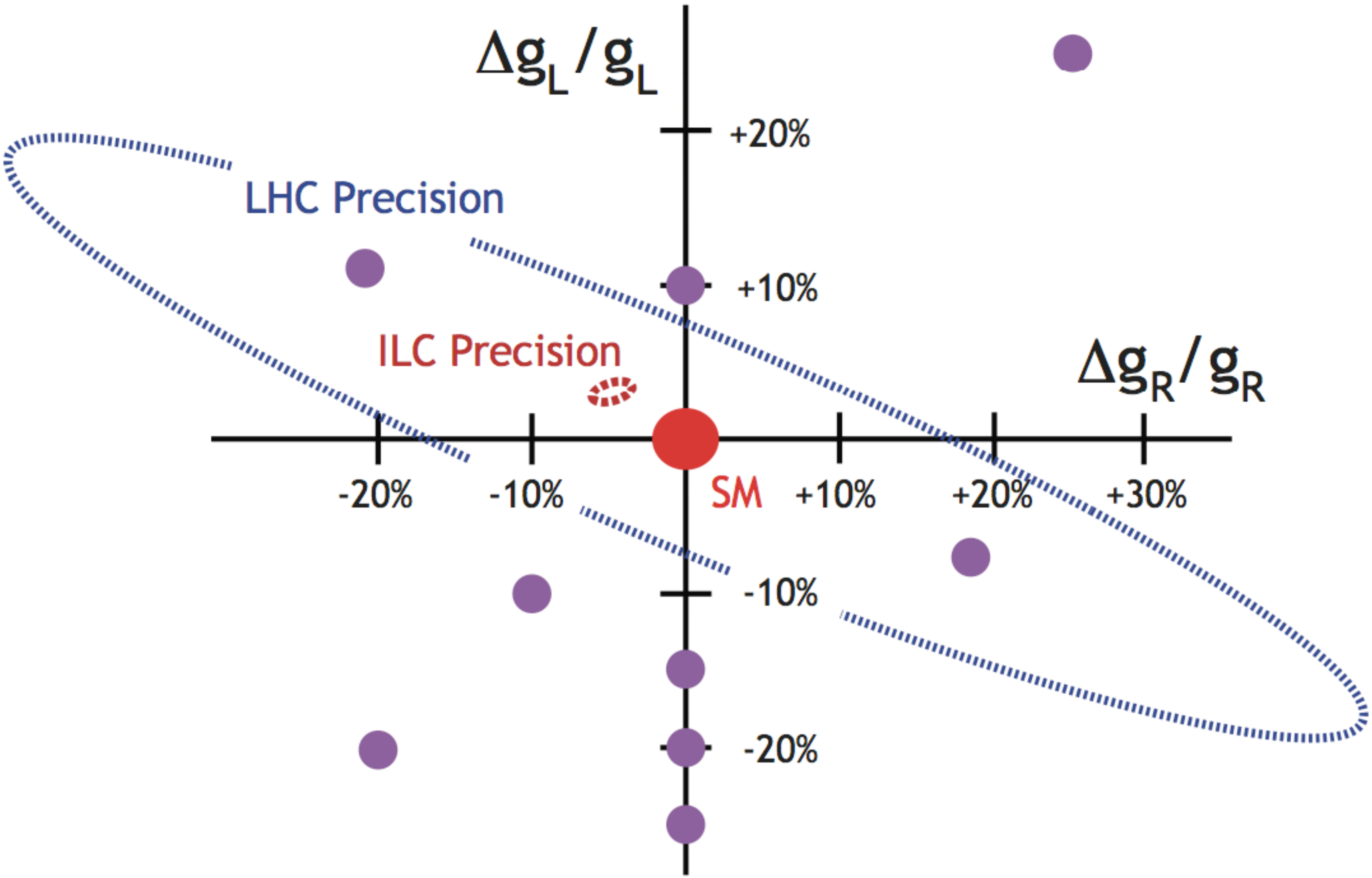
search for color 8 and 1 resonances in $pp \to t\bar{t}$

search for form factor effects through precision measurement of the t gauge couplings, especially for W and Z.


ATLAS Preliminary
∫ L dt = 14.3 fb⁻¹
e+μ ≥6 jets, ≥ 4 b-tags
Data (√s = 8 TeV)
t't̄' (600)
tt̄+light jets
tt̄+HF jets
tt̄H
tt̄V
W+jets
Z+jets
Diboson
Single top
Multijet
Tot bkg unc.
Events / 100 GeV
Data / MC
H_T [GeV]


CMS Preliminary, √s = 8 TeV, 19.6 fb-1
Events / (50 GeV/c2)
Data
Non-Top Multijet
SM tt̄
1 TeV RS KK gluon
2 TeV RS KK gluon
3 TeV RS KK gluon
tt̄ Invariant Mass (GeV/c2)
Nsigma
Data - Predicted / Predicted

LHC and ILC opportunities to measure the t_L and t_R form factors for coupling to the Z:



models collected by Richard and Wulzer

The theory of the top quark in the SM is now a high-precision theory.   It offers sharp goals for experimental measurements both at e+e- and pp colliders.

At the same time, models of new physics predict substantial deviations from those predictions, and new processes - production of top partners - that mimic SM top.

The top quark is important in models of SUSY, but much more important in models in which the Higgs field is composite.   In those models, the top quark can also be composite, and its precision study can reveal this.

Through these ideas, the top quark can be the most important route to the discovery of new fundamental interactions.