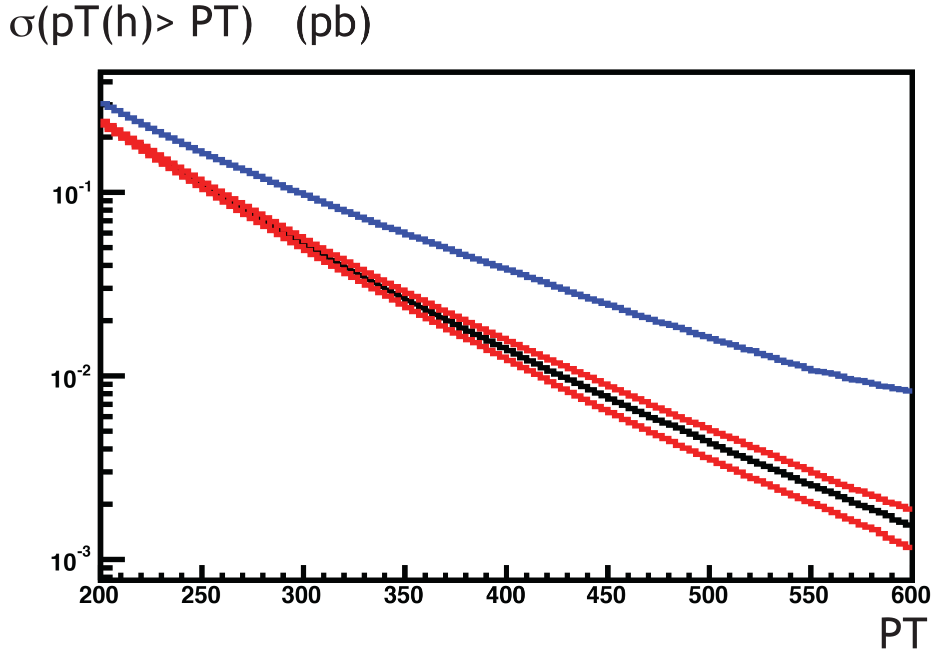
Precision Higgs Physics and the High-Luminosity LHC



M. E. Peskin
HL-LHC Workshop
May 2015

The main goal of the LHC remains the discovery of new physics beyond the Standard Model.

In run 2, the primary avenue for this will be the search for new particles. But, in the longer term, precision Higgs measurements are an essential part of this story:

Higgs is the least explored particle in the SM

Precision Higgs measurements give sensitivity in directions orthogonal to direct searches.

The HL-LHC will produce an enormous number of Higgs bosons

$$3000 \text{ fb}^{-1} \times 50 \text{ pb} = 150 \text{ M Higgs/expt.}$$

but, these appear in a setting in which it is very challenging to study them

$$\frac{\sigma(pp \to h)}{\sigma(pp)} \sim 10^{-9} \qquad \frac{\sigma(pp \to h)}{\sigma(pp \to Z)} \sim 10^{-3}$$

The essential barrier will not be statistics but rather systematic errors.

Are there strategies that mitigate these and get us closer to the statistics limits?

general principles for the study of Higgs boson couplings:

Higgs should couple to any particle that gets any fraction of its mass from SU(2)xU(1) breaking.

Through the "Higgs portal", the dimension 2 operator $\varphi^\dagger \varphi$, Higgs can couple to particles outside the SM.

Particles of both types, even if very heavy, can generate radiative corrections to Higgs vertices.

These principles also generate expectations for Higgs decay to exotic modes. I will not discuss this subject, but it will be a main focus of this afternoon's discussion. I will also defer discussion of the hhh coupling.

Unfortunately, there is a general expectation that the corrections to the SM predictions for the Higgs couplings cannot be large:

the "Decoupling Theorem" of Howard Haber

If the Higgs sector contains one light boson of mass

$$m_h = 125 \text{ GeV}$$

and many heavy particles with minimum mass M ,

the light boson has properties that agree with the SM predictions up to corrections of order

$$m_h^2 \,/\, M^2$$

Proof:

Integrate out the heavy fields. The result is the SM, plus a set of operators of minimum dimension 6.

Implication:

In most models of an extended Higgs sector or other new particles, the corrections to the Higgs couplings are at the few-% level. Precision measurement is needed to see these corrections.

The situation here is analogous to that of the cosmic microwave background. A high level of precision is necessary to observe deviations from the simplest picture. However, when that level is reached there is a wealth of information to be gathered.

The pattern of corrections is different in different schemes for new physics models. There is much to learn if we can see this pattern.

Given the mass of the Higgs boson, the Standard Model makes a precise set of predictions for the couplings. These should be considered as reference values for precision measurements.

For a Higgs boson of mass 125 GeV, the prediction for the total width is $\Gamma_h = 4.1 \text{ MeV}$.

The branching fractions are predicted to be

$b\bar{b}$	58%	$\tau^+\tau^-$	6.3%	$\gamma\gamma$	0.23%
WW^*	21%	$c\bar{c}$	2.9%	γZ	0.15%
gg	8.6%	ZZ^*	2.6%	$\mu^+\mu^-$	0.02%

Many decay modes of the Higgs will eventually be visible, and measurable. F. Gianotti: "Thank you, Nature."

footnote:

Can theory give us these SM reference values to the 0.1% level ?

A dedicated program in precision QFT computation and lattice QCD is needed, but

Yes!   see   arXiv:1404.0319

The study of the deviations from these predictions is guided by the idea that each Higgs coupling has its own personality and is guided by different types of new physics. This is something of a caricature, but, still, a useful one.

fermion couplings - multiple Higgs doublets

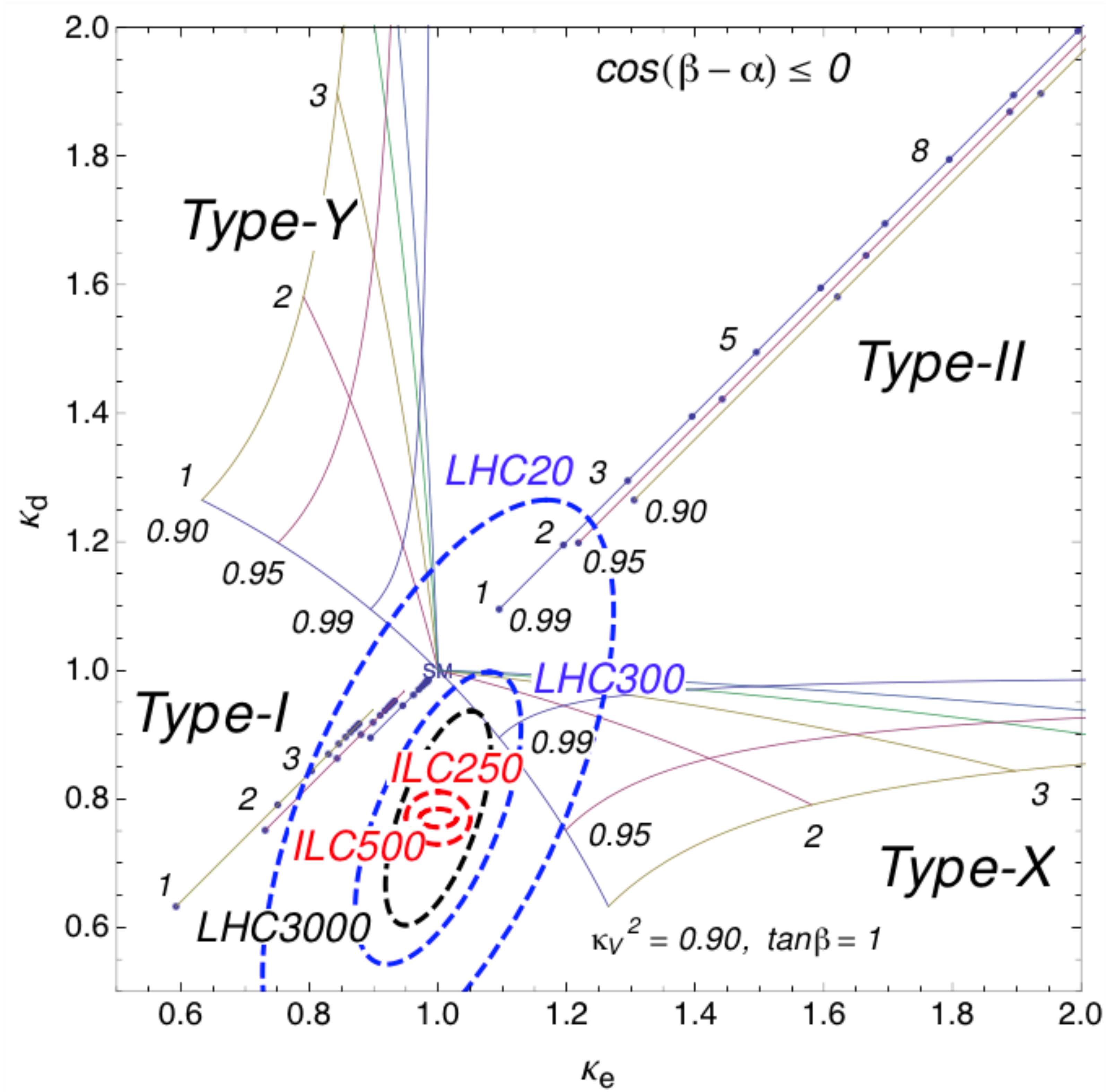
gauge boson couplings - Higgs singlets, composite Higgs

$\gamma\gamma$, gg couplings - heavy vectorlike particles

tt coupling - top compositeness

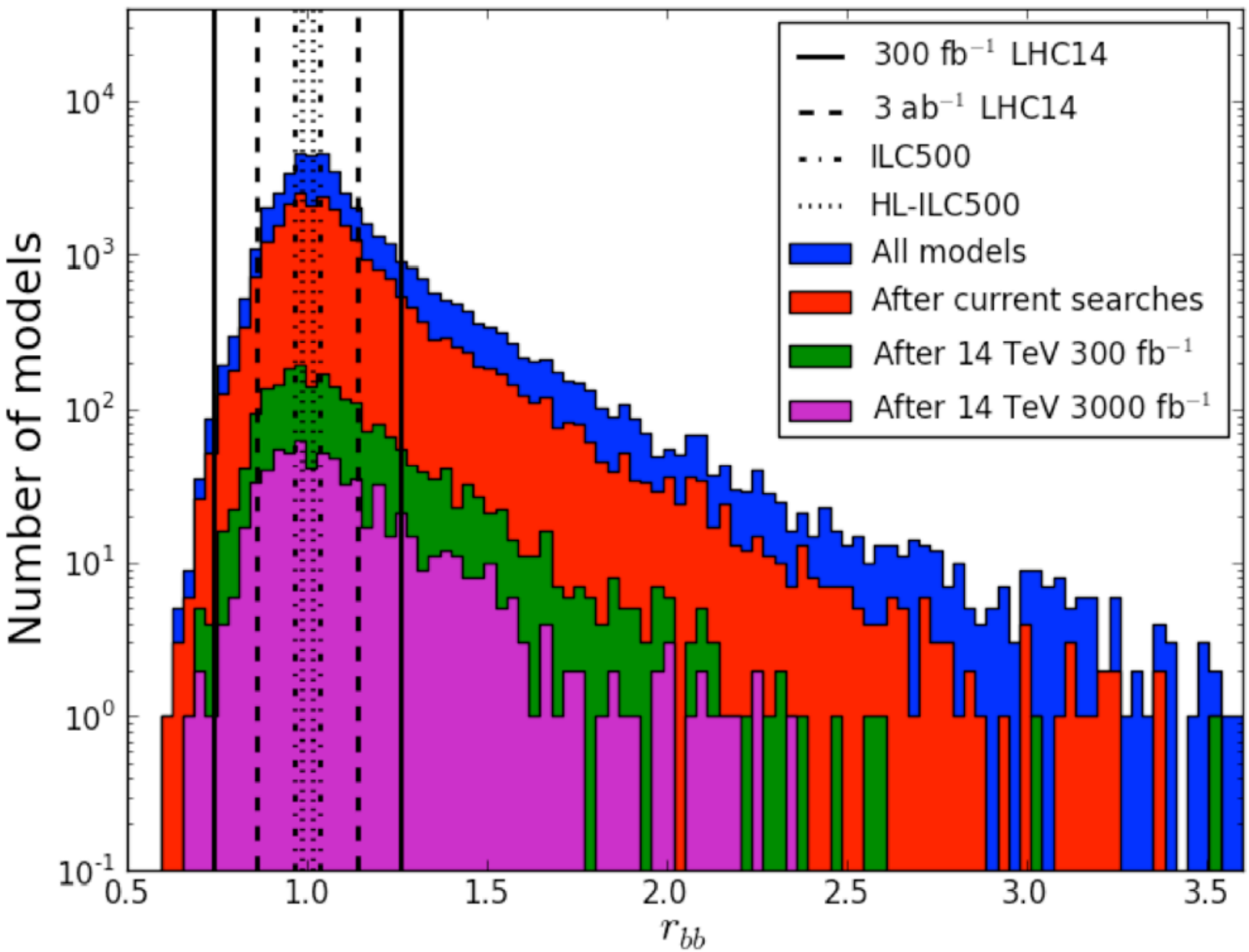
hhh coupling (large deviations) - baryogenesis

2 Higgs doublet models



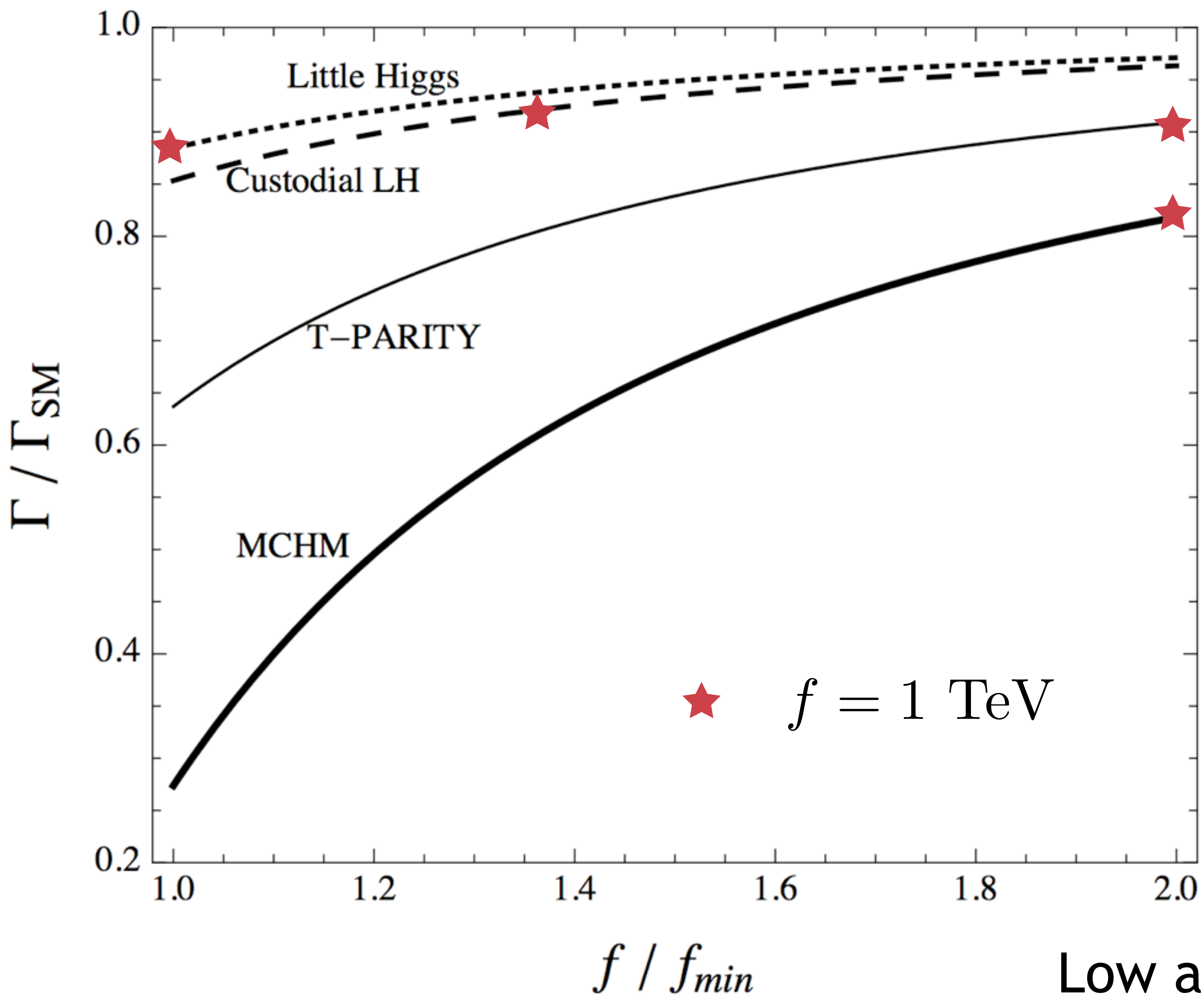
Kanemura, Tsumura, Yagyu, Yokoya

$\Gamma(h \to b\bar{b})$ in a large collection of SUSY models

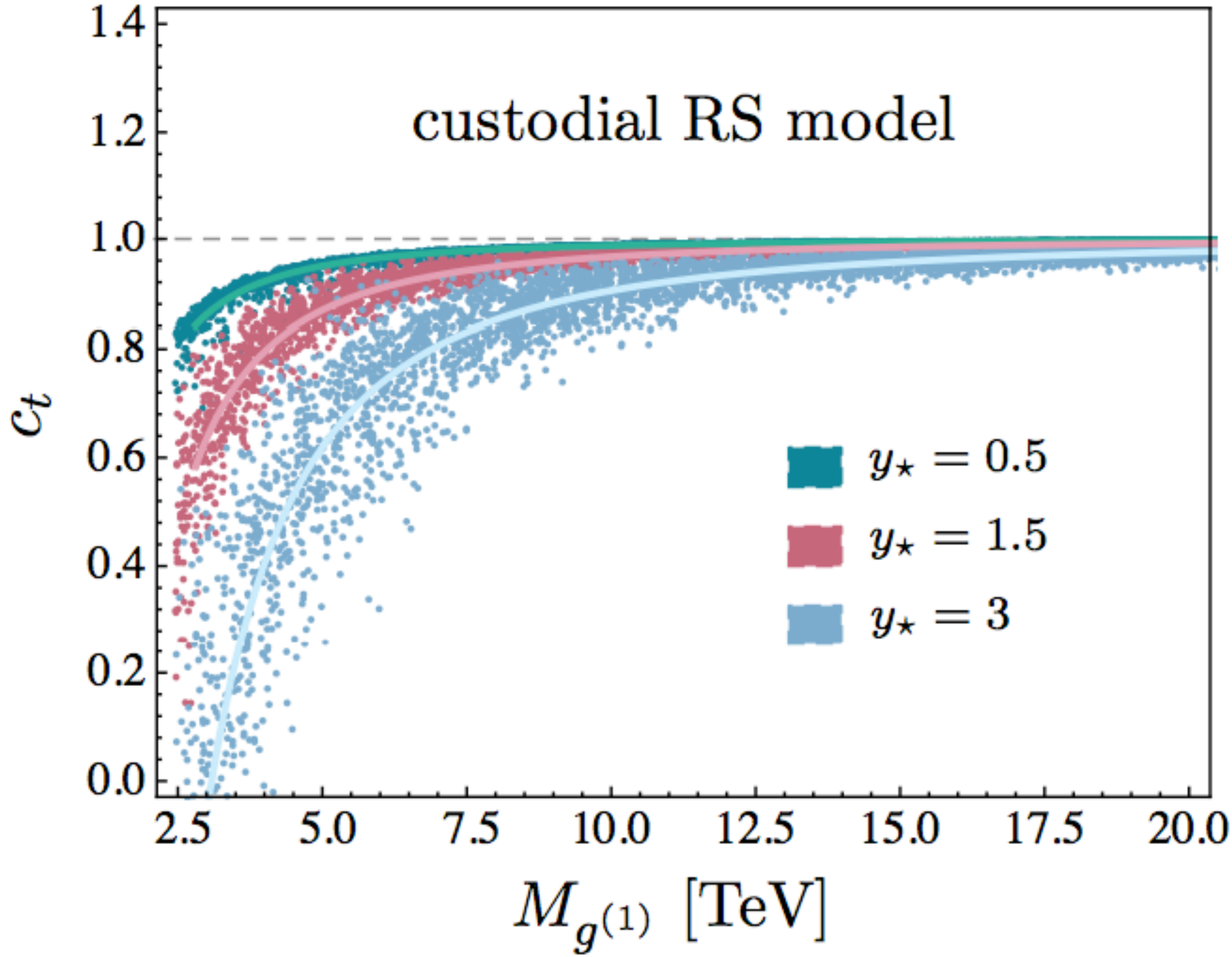


Cahill-Rowley, Hewett, Ismail, Rizzo

$\Gamma(h \to gg)$



Low and Vichi

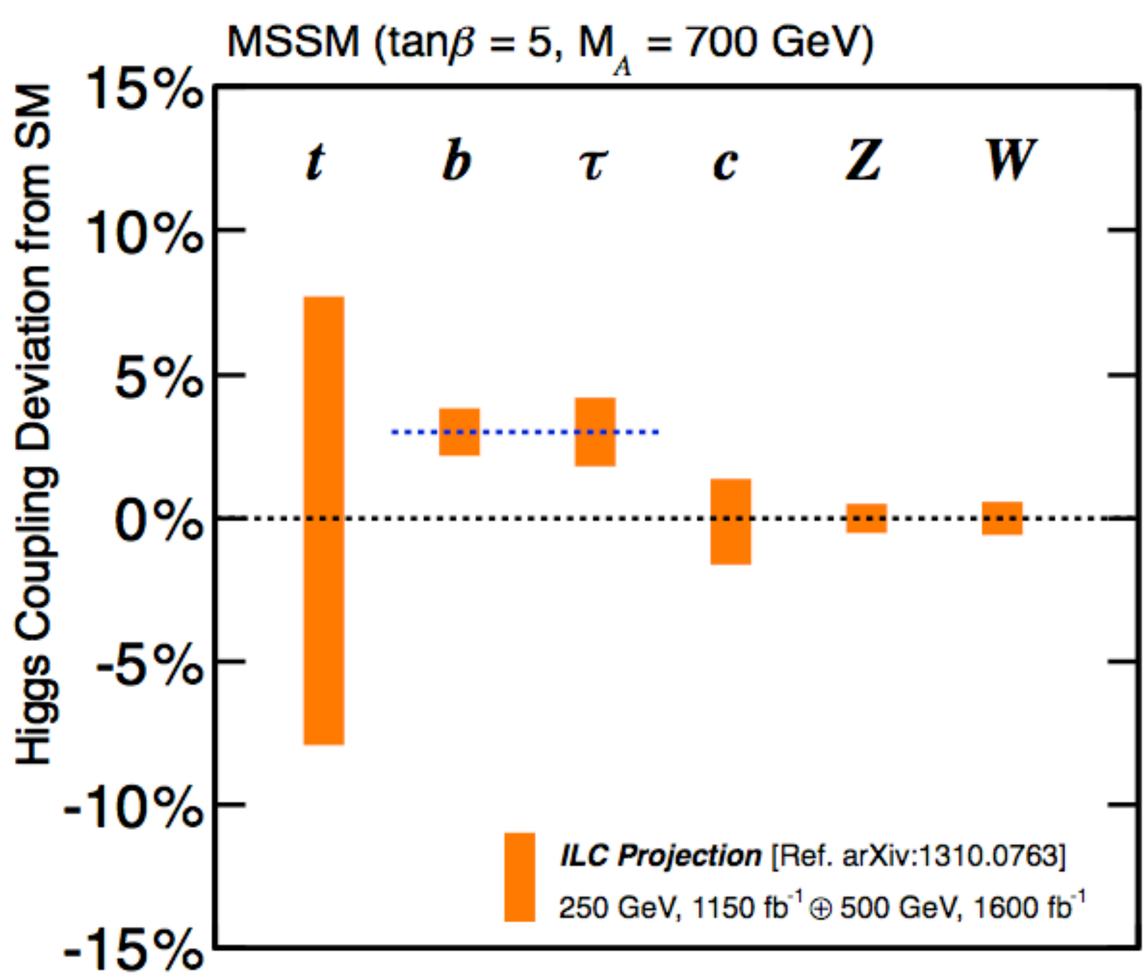


Malm, Neubert, Schmell

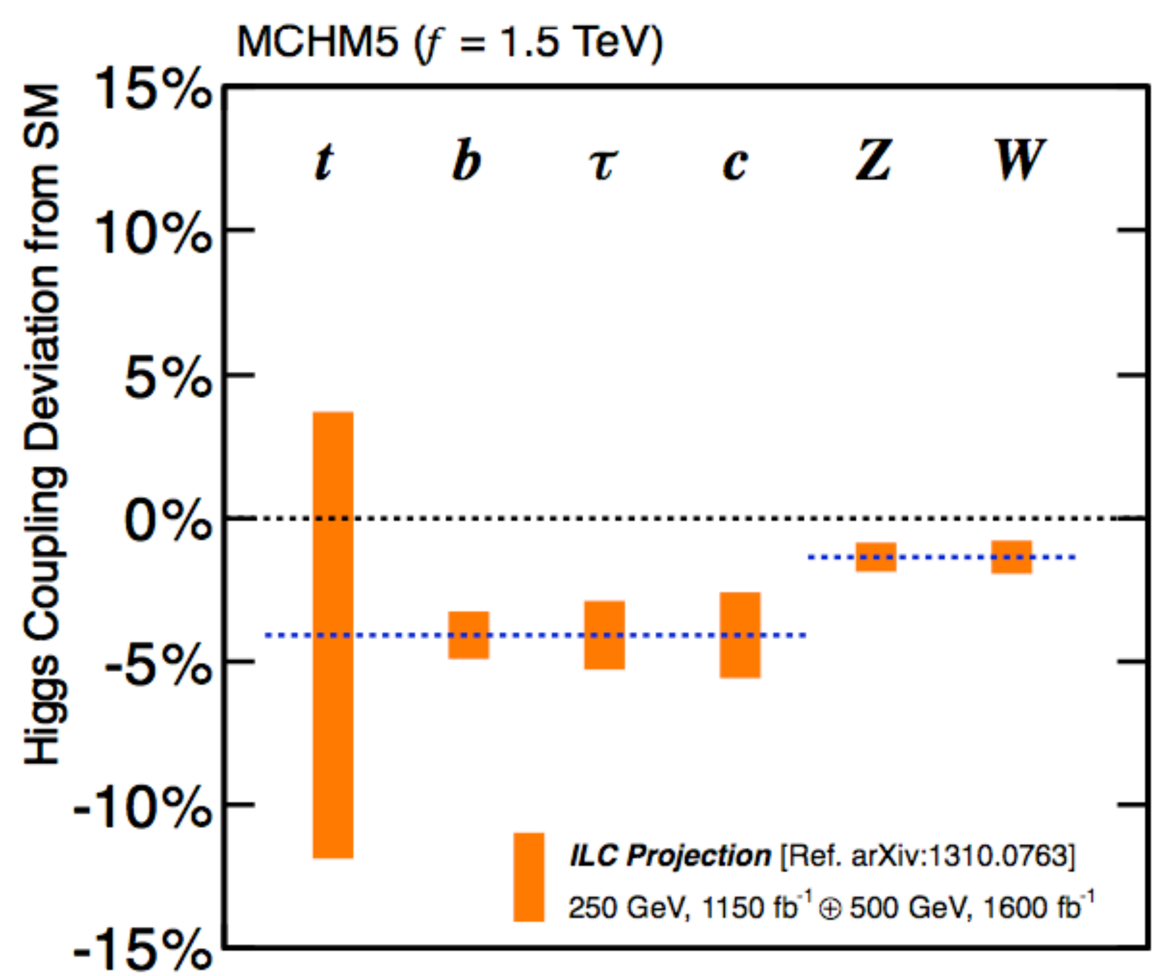
Putting all of these effects together, we find patterns of deviations from the SM predictions that are different for different schemes of new physics.

For example:

SUSY



Composite Higgs



Kanemura, Tsumura, Yagyu, Yokoya

1. Measure this pattern as completely and accurately as possible.

CMS projections for European Strategy and Snowmass

coupling accuracies in %,
with aggressive and conservative assumptions:

L (fb^{-1})	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to bb$	$H \to \tau\tau$	$H \to Z\gamma$	$H \to inv.$
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[6, 17]

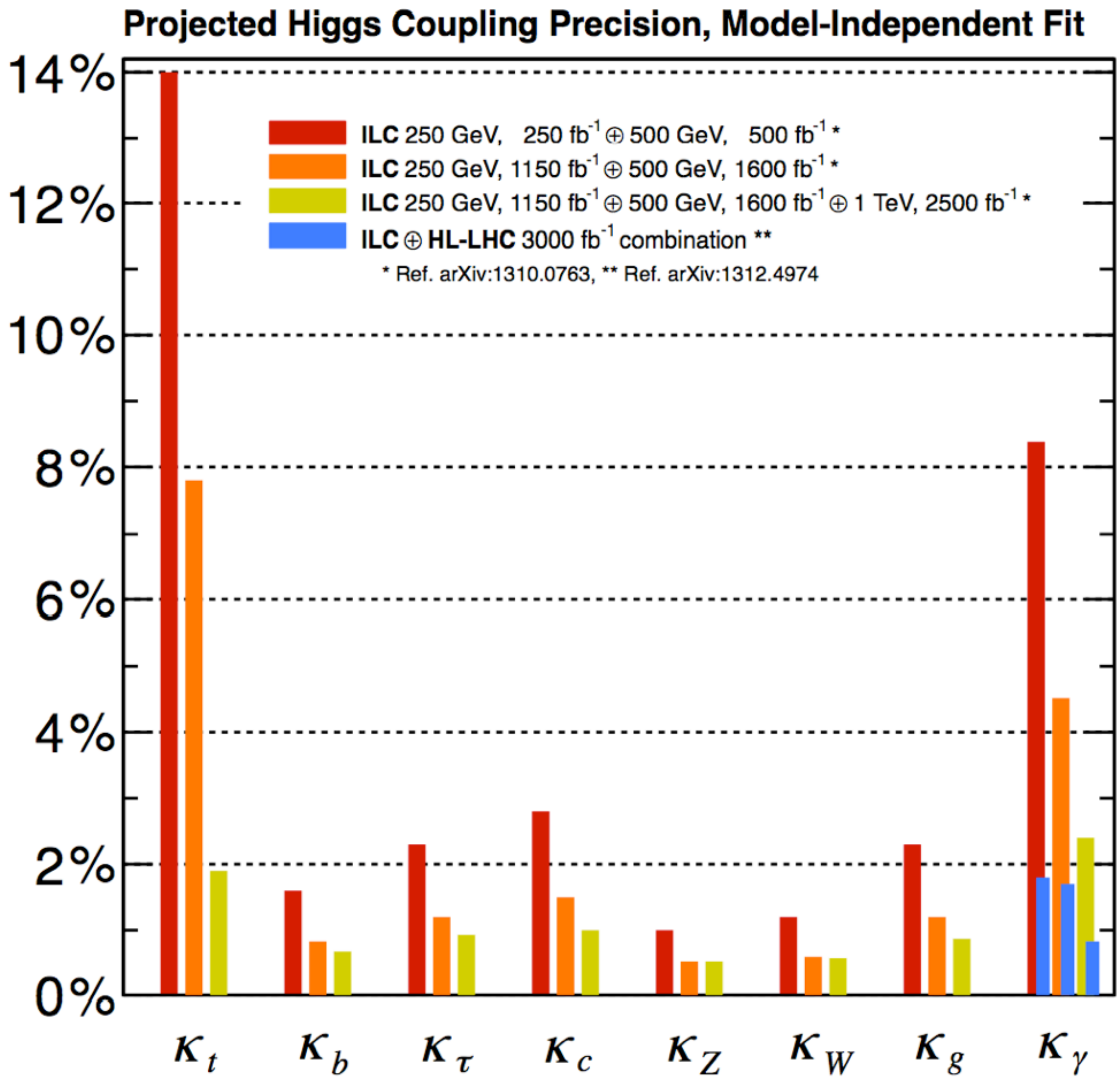
If we are lucky -- in particular, if there exist light new particles with electroweak couplings, not yet discovered -- we can see a break in the SM pattern at these levels.

2. Provide unique measurements of very high precision that might challenge the SM, and that can be combined into an eventual global fit to Higgs couplings

In the 2030's, we will hopefully see measurements of Higgs properties at e+e- colliders
-- in particular, ILC in Japan --
with very small systematic errors.

However, the HL-LHC statistics will always be higher.

There is an opportunity for complementarity; how can we use it ?



Projected Higgs Coupling Precision, Model-Independent Fit
14%
12%
10%
8%
6%
4%
2%
0%
ILC 250 GeV, 250 fb⁻¹ ⊕ 500 GeV, 500 fb⁻¹ *
ILC 250 GeV, 1150 fb⁻¹ ⊕ 500 GeV, 1600 fb⁻¹ *
ILC 250 GeV, 1150 fb⁻¹ ⊕ 500 GeV, 1600 fb⁻¹ ⊕ 1 TeV, 2500 fb⁻¹ *
ILC ⊕ HL-LHC 3000 fb⁻¹ combination **
* Ref. arXiv:1310.0763, ** Ref. arXiv:1312.4974
κ_t
κ_b
κ_τ
κ_c
κ_Z
κ_W
κ_g
κ_γ

What are the barriers to high-precision Higgs measurements at the LHC ?

LHC experiments measure $\sigma \cdot BR$, so theoretical errors in σ limit individual measurements.

Current errors (in %) from the LHC Higgs XSWG (14 TeV):

process	QCD	pdf, α_s	in quad.
$gg \to h$	7.8	6.6	10.2
$VV \to h$	0.4	1.7	1.7
Wh	0.5	3.8	3.8
Zh	2.3	3.7	4.4

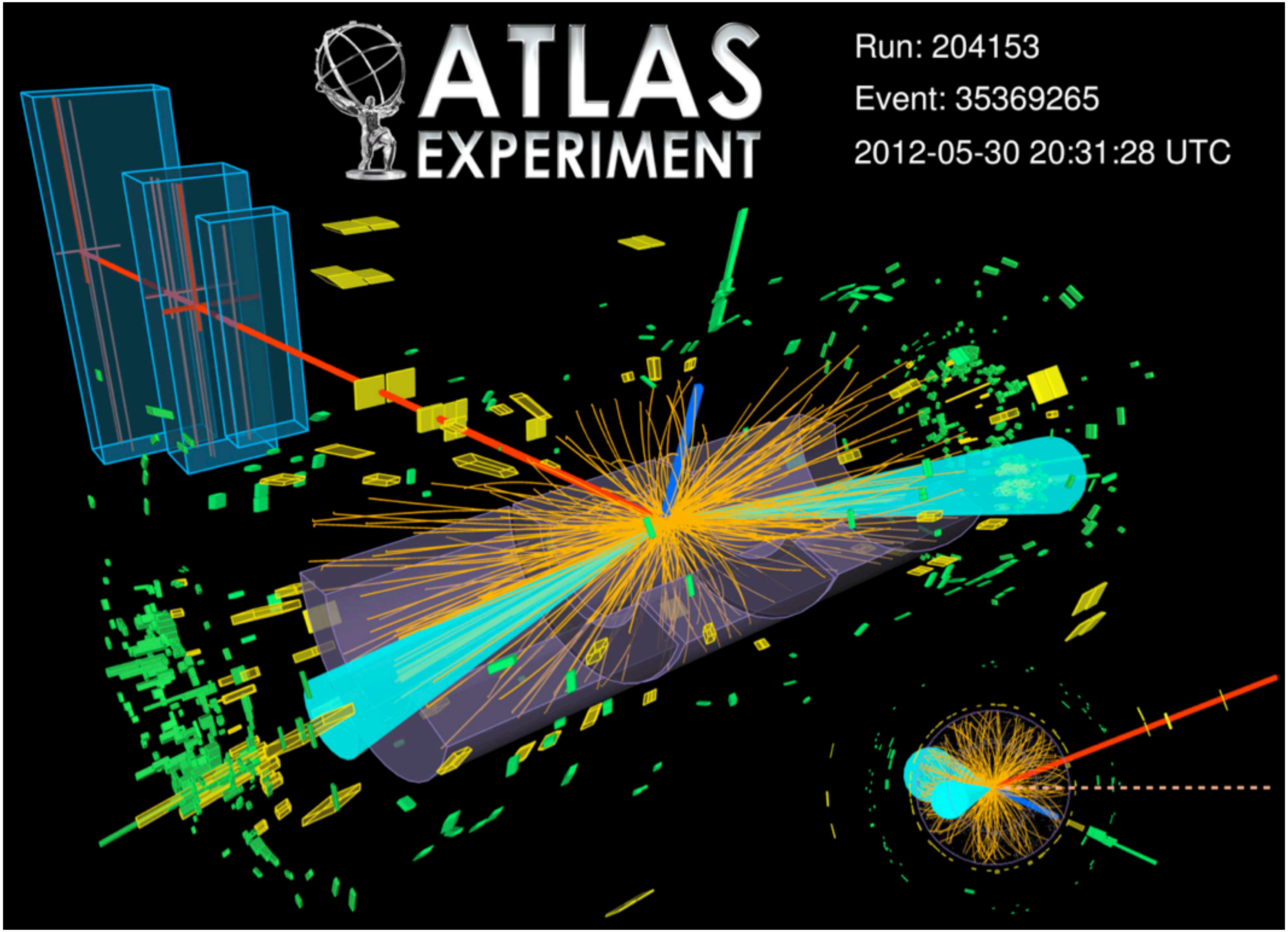
e.g. in the CMS analysis above, the improvement from 300/fb to 3000/fb comes entirely from gathering sufficient statistics in $VV \to h$.

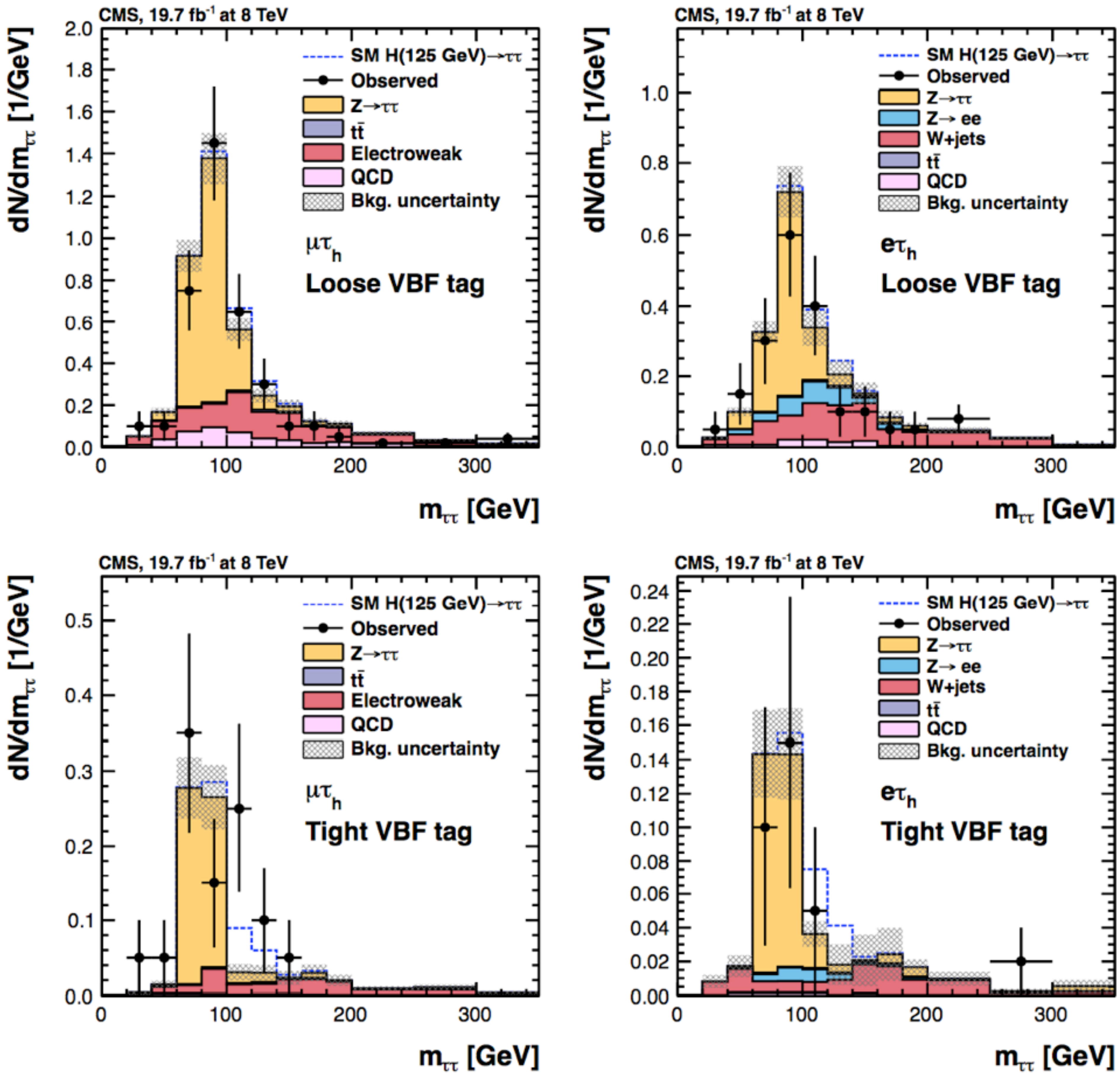
However, a greater limitation may come from Higgs selection systematics. In current analyses (except for $h \to \gamma\gamma, 4\ell$), Higgs is seen as a small excess in the final signal regions.

If the signal regions are 10% Higgs, a 5% measurement requires knowledge of the background rate to 0.5%.

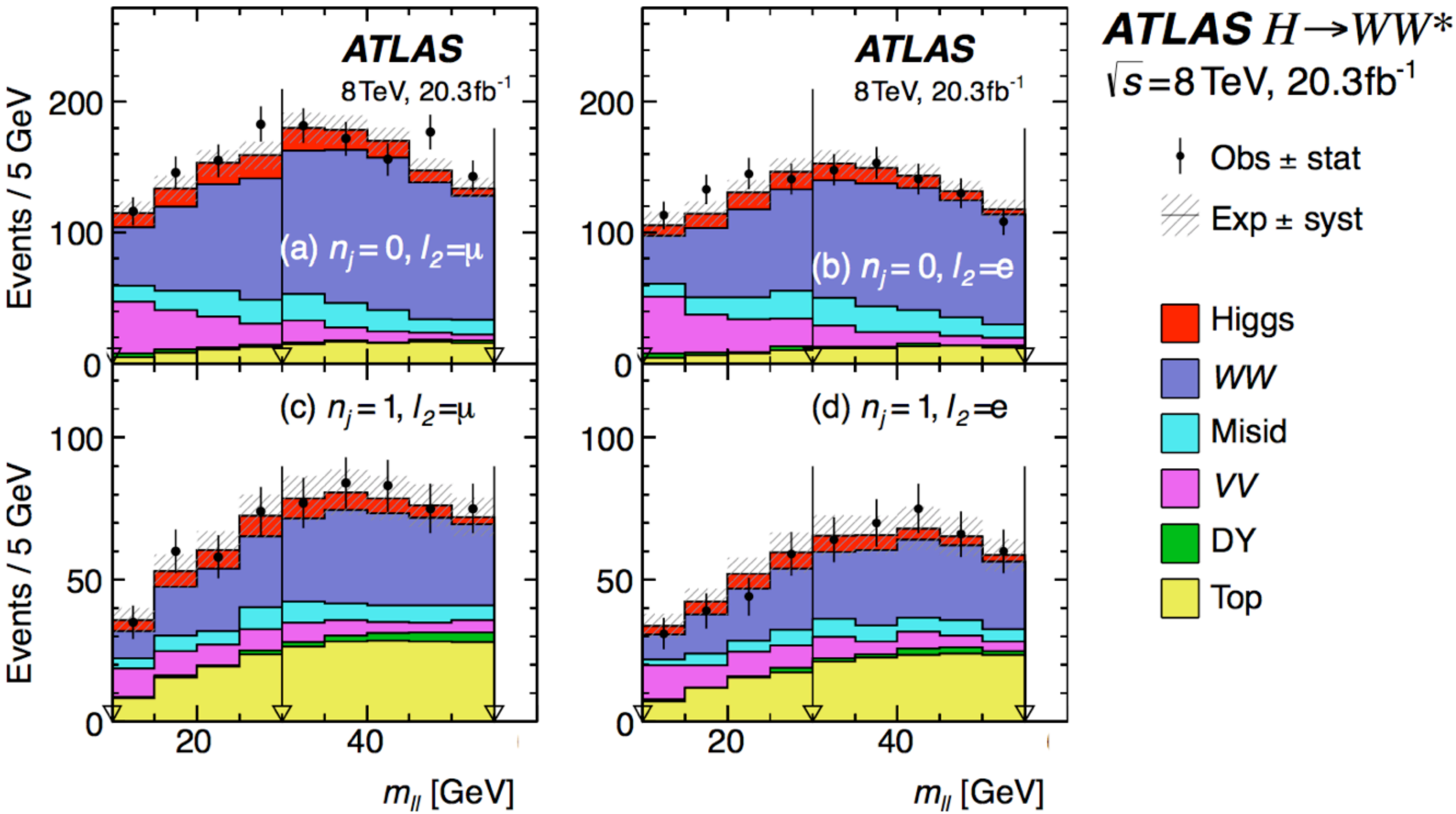
New theory uncertainties come in here, in prediction of event shape variables, jet veto probability. Most likely, to reach the needed accuracies, the background estimates must be data-driven.

It is feasible to reach high accuracy in the simplest cases (e.g. $Z \to \tau^+\tau^-$ modeled by $Z \to \mu^+\mu^-$). What about the background to VBF production of $h \to \tau^+\tau^-$ from $pp \to WW + \text{jets}$?

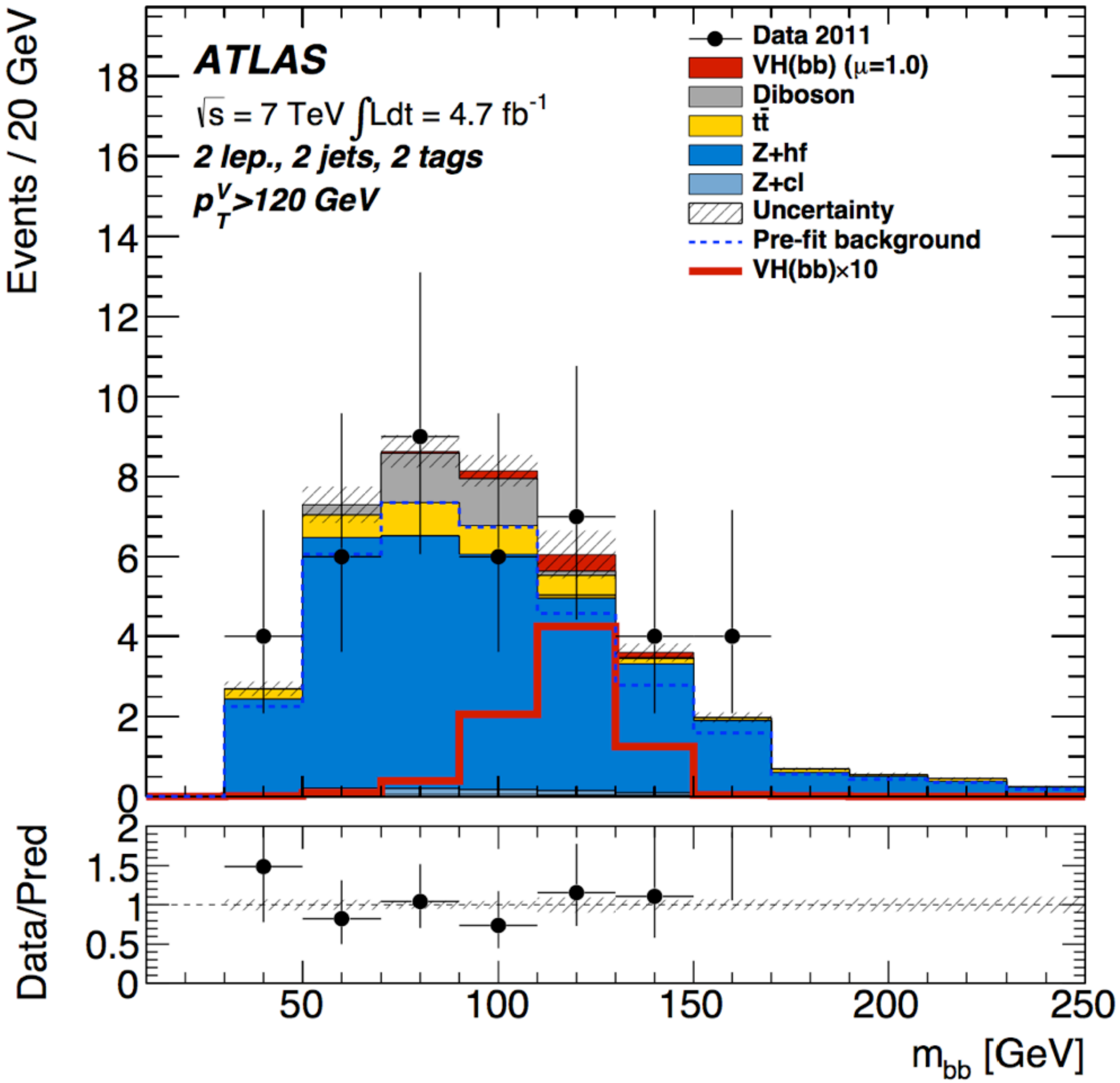

ATLAS
EXPERIMENT
Run: 204153
Event: 35369265
2012-05-30 20:31:28 UTC



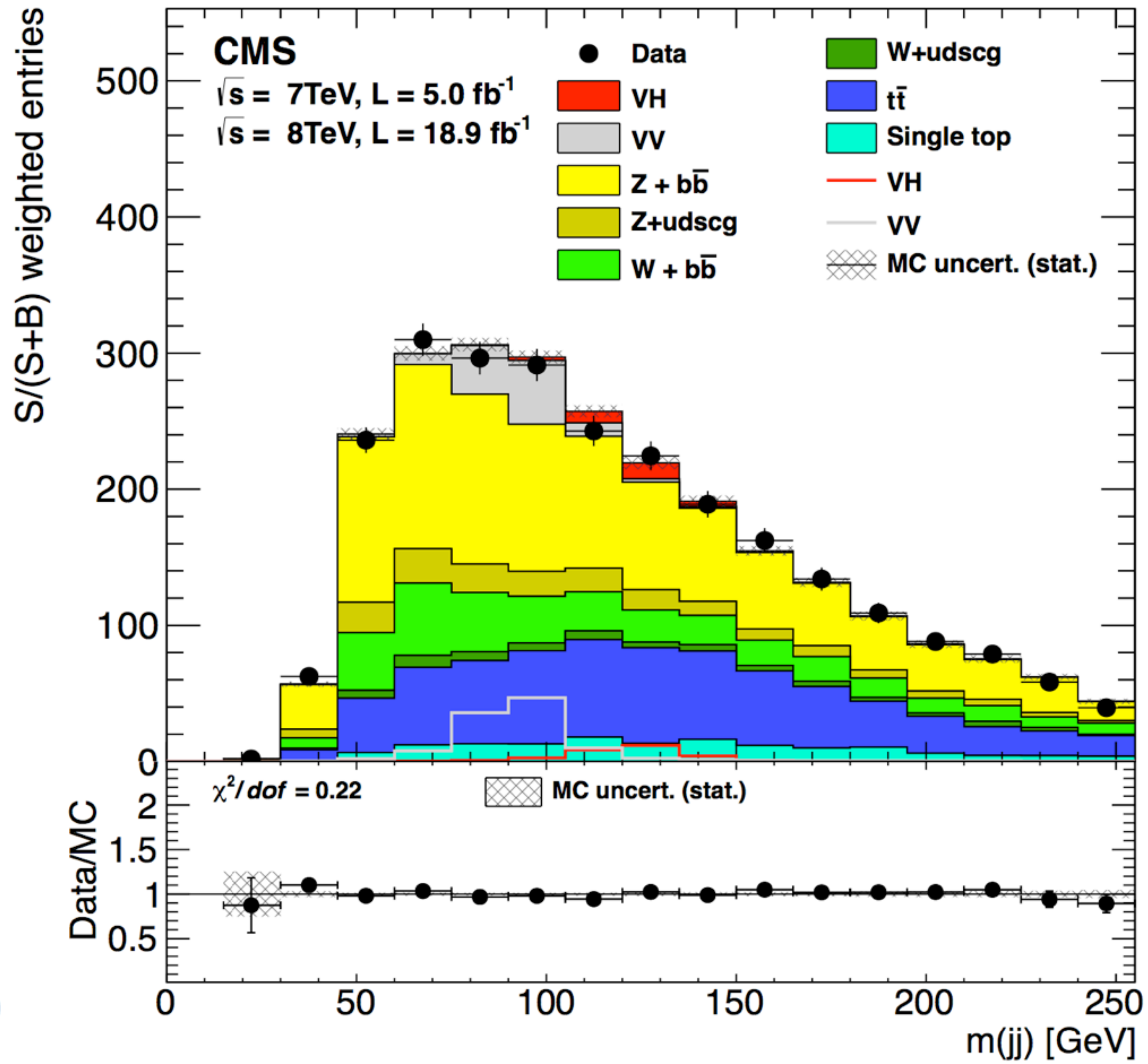
CMS, 19.7 fb-1 at 8 TeV
SM H(125 GeV)→ττ
Observed
Z→ττ
tt̄
Electroweak
QCD
Bkg. uncertainty
μτh
Loose VBF tag
dN/dmττ [1/GeV]
mττ [GeV]
CMS, 19.7 fb-1 at 8 TeV
SM H(125 GeV)→ττ
Observed
Z→ττ
Z→ ee
W+jets
tt̄
QCD
Bkg. uncertainty
eτh
Loose VBF tag
dN/dmττ [1/GeV]
mττ [GeV]
CMS, 19.7 fb-1 at 8 TeV
μτh
Tight VBF tag
dN/dmττ [1/GeV]
mττ [GeV]
CMS, 19.7 fb-1 at 8 TeV
eτh
Tight VBF tag
dN/dmττ [1/GeV]
mττ [GeV]



ATLAS
8 TeV, 20.3 fb-1
(a) nj = 0, l2 = μ
(b) nj = 0, l2 = e
(c) nj = 1, l2 = μ
(d) nj = 1, l2 = e
Events / 5 GeV
mll [GeV]
ATLAS H→WW*
√s = 8 TeV, 20.3 fb-1
Obs ± stat
Exp ± syst
Higgs
WW
Misid
VV
DY
Top



ATLAS
$\sqrt{s}$ = 7 TeV $\int$Ldt = 4.7 fb^{-1}
2 lep., 2 jets, 2 tags
p_T^V>120 GeV
Data 2011
VH(bb) (μ=1.0)
Diboson
tt̄
Z+hf
Z+cl
Uncertainty
Pre-fit background
VH(bb)×10
Events / 20 GeV
Data/Pred
m_{bb} [GeV]



CMS
$\sqrt{s}$ = 7TeV, L = 5.0 fb^{-1}
$\sqrt{s}$ = 8TeV, L = 18.9 fb^{-1}
Data
VH
VV
Z + bb̄
Z+udscg
W + bb̄
W+udscg
tt̄
Single top
VH
VV
MC uncert. (stat.)
S/(S+B) weighted entries
χ^2/dof = 0.22
MC uncert. (stat.)
Data/MC
m(jj) [GeV]

Can we devise analyses that measure ratios of BRs with cancelling systematics ?

Easiest case: $BR(h \to \gamma\gamma)/BR(h \to ZZ^*)$

Both final states are well visible above background in the dominant production mode $gg \to h$.

Introduce cuts to make the distributions as similar as possible: $|y(h)| < 2$, vetoing events with forward jets.

In the limit where all systematics cancel

$$150M\ h \times 2 \text{ expts.} \times [BR(h \to 4l) = 1 \times 10^{-4}]$$
$$\times [30\% \text{ eff.}] \quad \to \quad 1/\sqrt{N} = 1\%$$

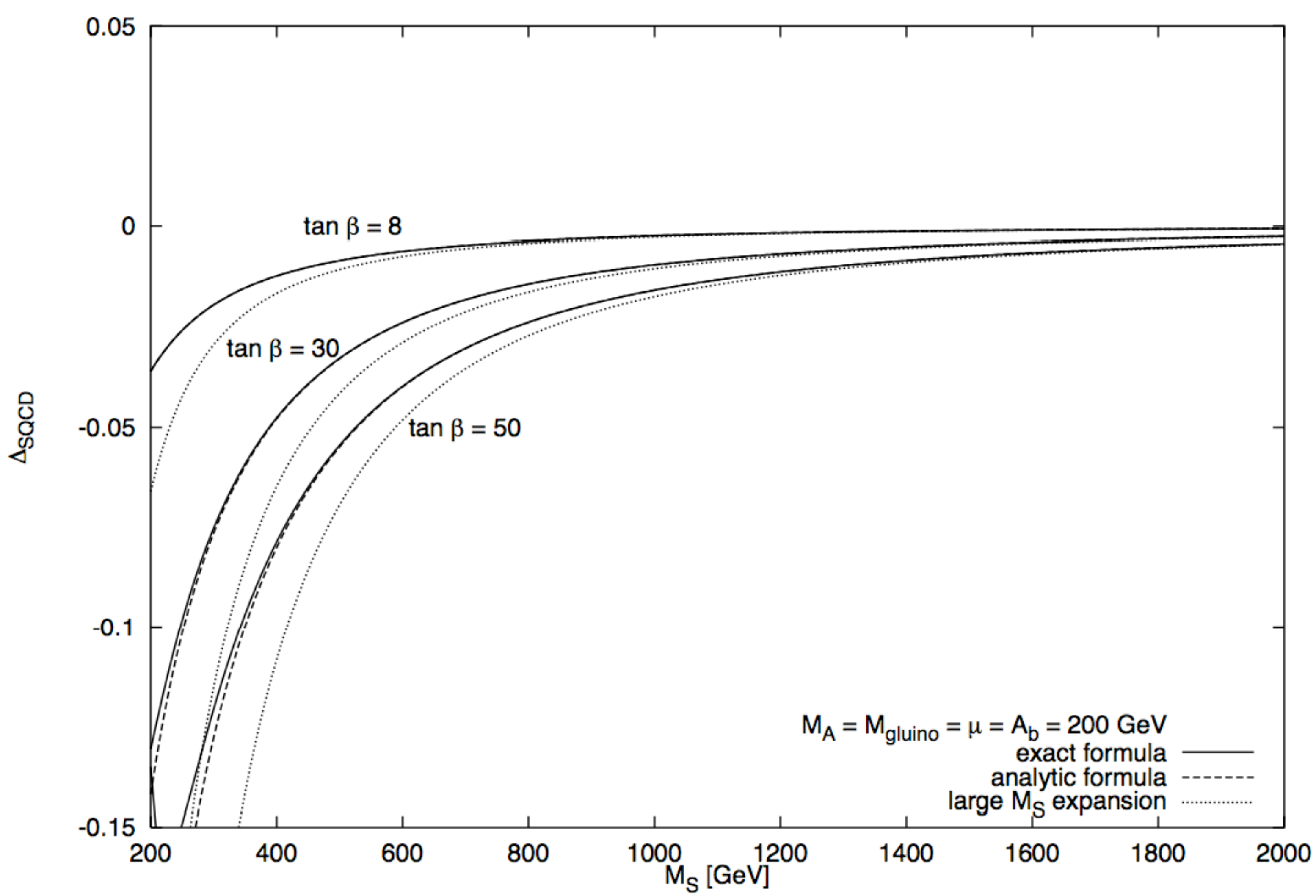
cf. ATLAS 2013 projection : 3.6% This already has important complementarity to ILC.

Another very important ratio of BRs is

$$BR(h \to \tau^+\tau^-)/BR(h \to b\bar{b})$$

In SUSY with large $\tan\beta$, both modes have tree-level shifts, but $h \to b\bar{b}$ is also shifted by radiative corrections from heavy squarks.

Haber, Herrero, Logan, Penaranda, Rigolin, Temes



Can we design an analysis with cancelling systematics ?

same production mode: $pp \to W, Z + h$ with boosted Higgs
similar acceptance taggers: e.g. ℓ-tagged b / $\tau \to \ell$
parallel estimation of the background from

$$pp \to W, Z + Z \to b\bar{b}, \tau^+\tau^-$$

The major problem is the background from

$$pp \to W, Z + g \to b\bar{b}$$

with no analogue on the $\tau^+\tau^-$ side. This would need a very well calibrated color 8 dijet tagger.
The statistics-limited uncertainty is

$$7.2M\ Vh \times 2 \text{ expts.} \times [BR(h \to \tau^+\tau^-) = 6\%] \times [1\% \text{ eff.}] \quad \to \quad 1/\sqrt{N} = 1\%$$

Aside from its intrinsic interest, this potentially improves e+e- determinations of the $h\tau\tau$ coupling.

Another possible strategy is to abandon b and compare the rather similar trilepton final states

$$pp \to Zh \to Z + \tau^+\tau^- \to (\ell^+\ell^-)\ e\mu + MET$$

$$pp \to Zh \to Z + WW^* \to (\ell^+\ell^-)\ e\mu + MET$$

to obtain $BR(\tau^+\tau^-)/BR(WW^*)$.

There will be ample statistics. The backgrounds, aside from hadrons faking leptons, come from higher order electroweak processes such as $pp \to ZWW$. Is the WW modes sufficiently characteristic to allow a 1% measurement?

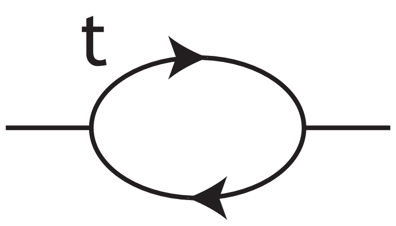
The LHC also provides processes that complement the direct measurement of Higgs BRs.

The most important of these is Higgs production at high pT, emphasized by

Grojean, Salvioni, Schlaffer, and Weiler
Azatov and Paul
Buschmann, Englert, Goncalves, Plehn, and Spannowsky

This complements the hgg and $ht\bar{t}$ coupling measurements. Most analyses use an effective Lagrangian approach. This is the best formalism to set a limit, but here I will use a simpler, more physical, model.

The hgg and $ht\bar{t}$ couplings are particularly interesting to explore for the presence of heavy vectorlike quarks, required in models of Higgs and top compositeness to cancel the quadratic divergence in



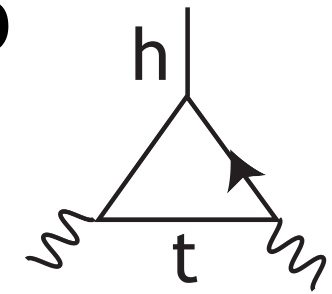
These quarks get most of their mass from SU(2)xU(1) invariant effects (e.g. Kaluza-Klein), but they must couple to the Higgs and so get a small mass shift proportional to the Higgs vev, typically of the form

$$\Delta M_T = -c\frac{m_t^2}{M_T}$$

The corresponding effect on the hgg coupling is

$$\frac{\Delta g_{hgg}}{g_{hgg}} = -c\frac{m_t^2}{M_T^2}$$

In the SM, the dominant contribution to the hgg vertex comes from the top quark loop



This diagram has the property that it does not decouple as the top quark becomes heavy. Instead, it is proportional to

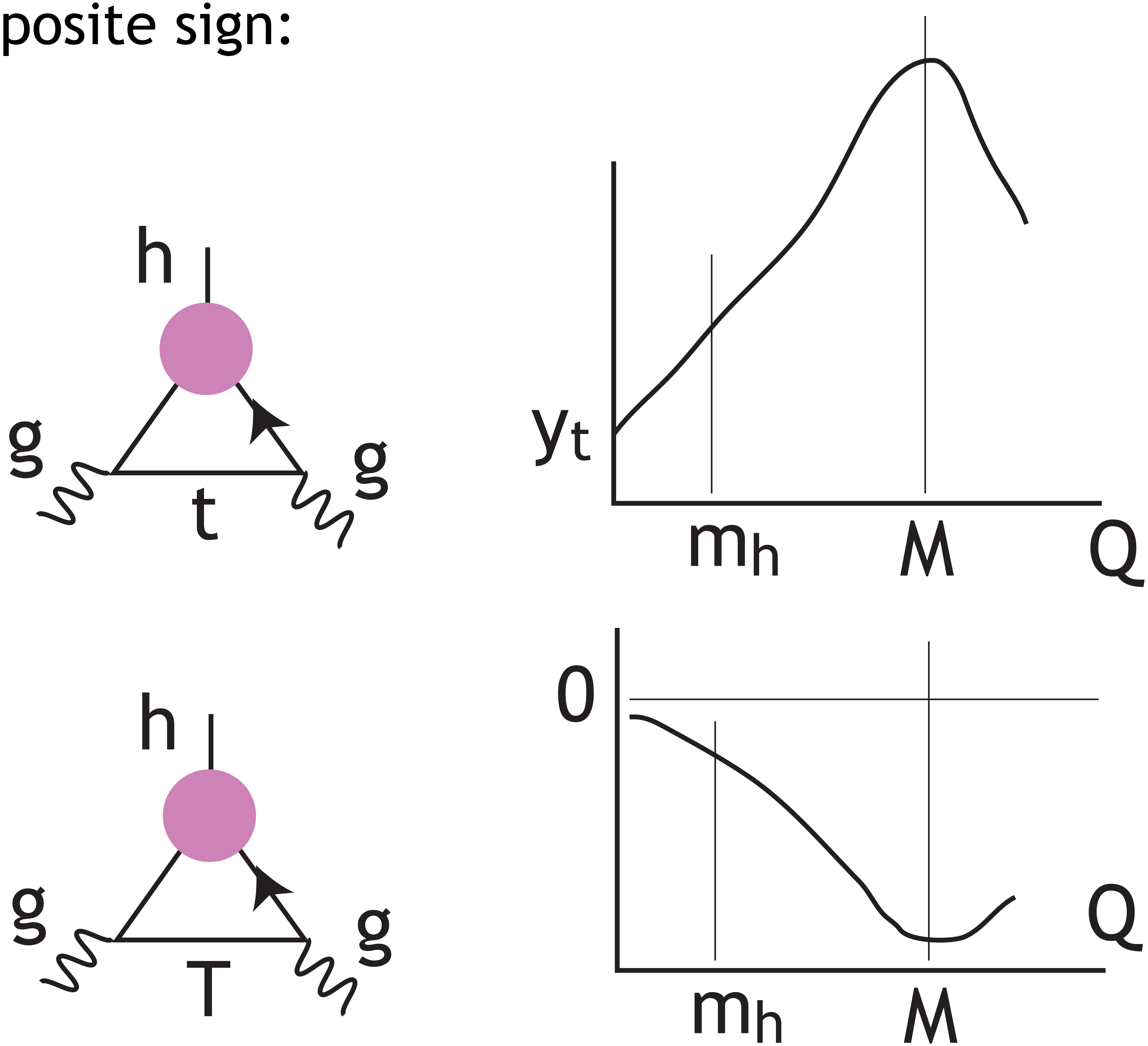
$$y_t/m_t$$

The denominator is m_t rather than m_h because $m_h < 2m_t$. For a lighter quark, eg. b, the comparable diagram has the size

$$y_b/m_h$$

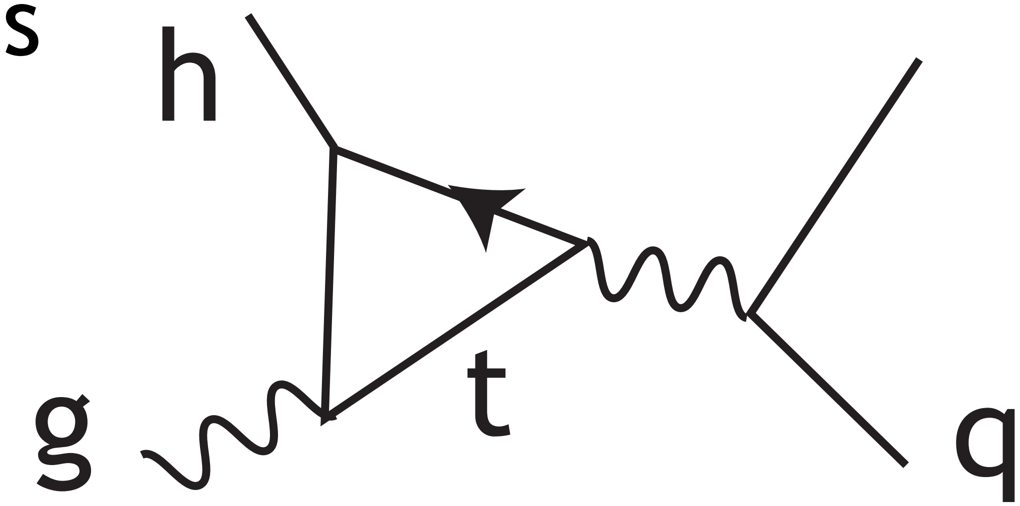
Contributions from heavy T quarks are decoupling because the T receives only a fraction of its mass from the Higgs vev; hence the estimate given above.

The hgg vertex is then a sum of contributions, typically of opposite sign:



One way to disentangle these contributions is to measure the hgg and $ht\bar{t}$ couplings separately.

Another way is to consider Higgs at high pT, for which a typical SM diagram is



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

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

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

Numerical exercise:

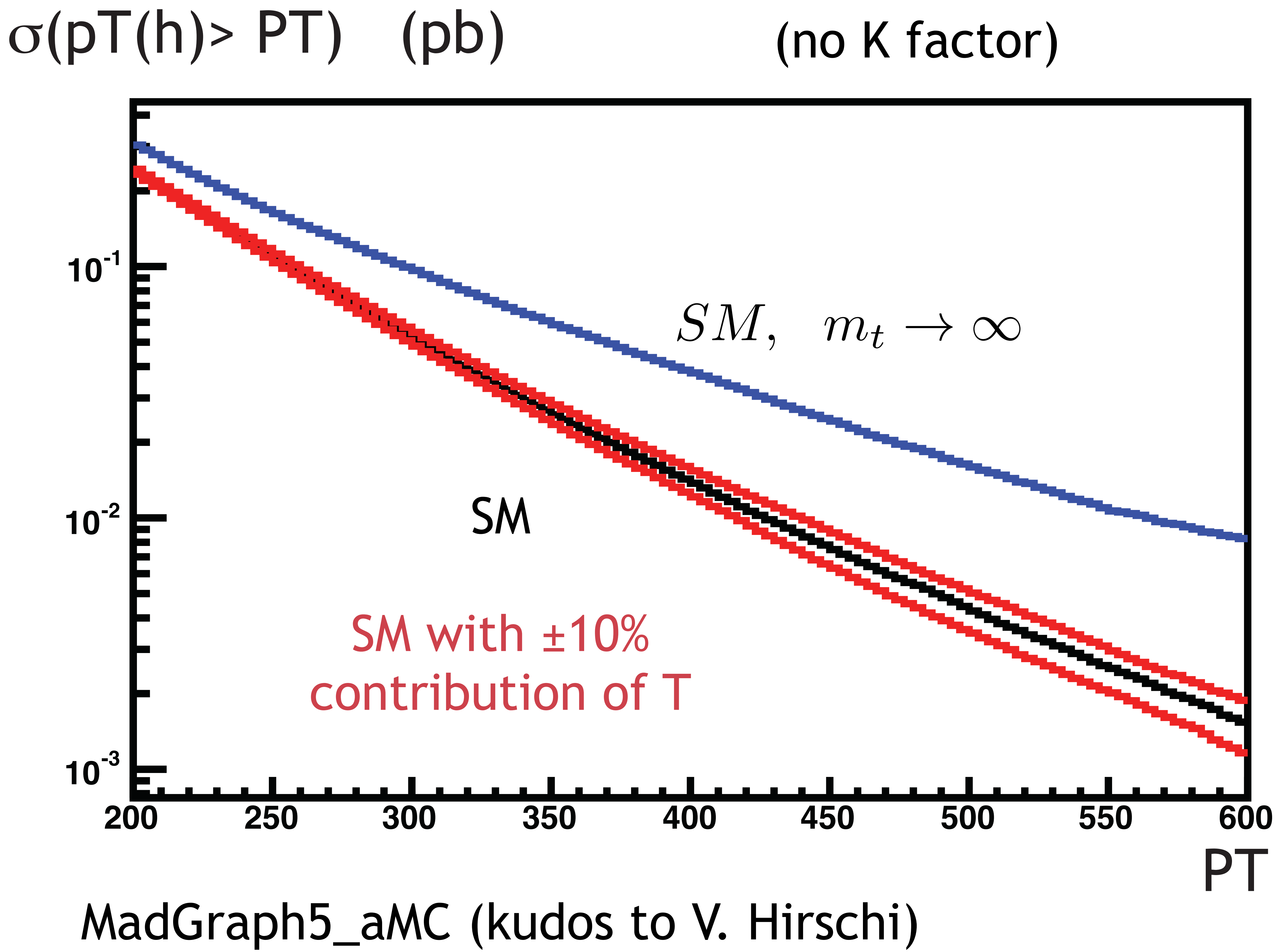
Add to the SM a T quark of 2 TeV with a coupling to h that is 10% of the t quark coupling, with exact compensation in the hgg coupling.

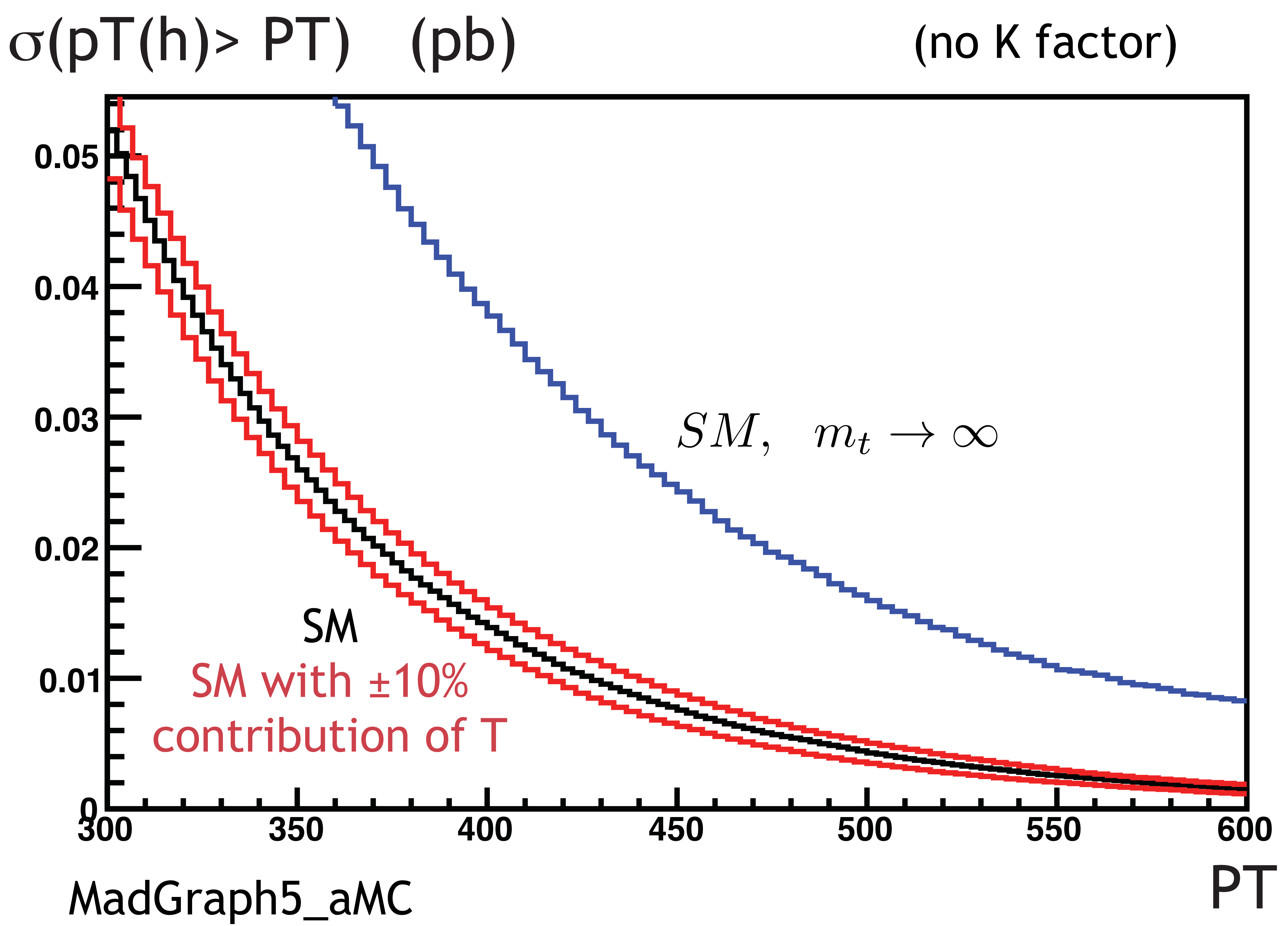
For these parameters, there is a 10% shift of the Higgs production cross section for $p_T(h) > 400 \text{ GeV}$. This would be normalized to a cross section at lower pT.

An estimate of the statistical error is

$$30 \text{ fb} \times 3000 \text{ fb}^{-1} \times 2 \text{ expts.}$$
$$\times[10\% \text{ eff.}] \quad \rightarrow \quad 1/\sqrt{N} = 1\%$$

This would be superior to projected LHC measurements of the hgg and $ht\bar{t}$ couplings, and comparable (and compelementary) to the ILC measurements


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

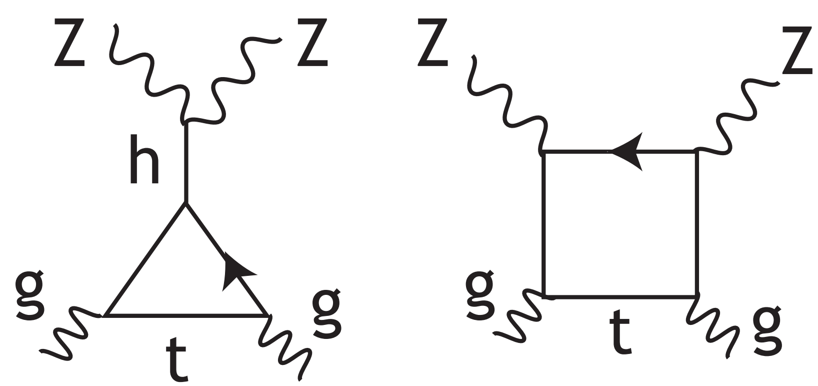


σ(pT(h)> PT) (pb)
(no K factor)
0.05
0.04
0.03
0.02
0.01
0
300
350
400
450
500
550
600
PT
$SM, \quad m_t \to \infty$
SM
SM with ±10%
contribution of T
MadGraph5_aMC

A related observable, but one more complex to analyze, is the off-shell Higgs contribution in the process

$$gg \to ZZ$$

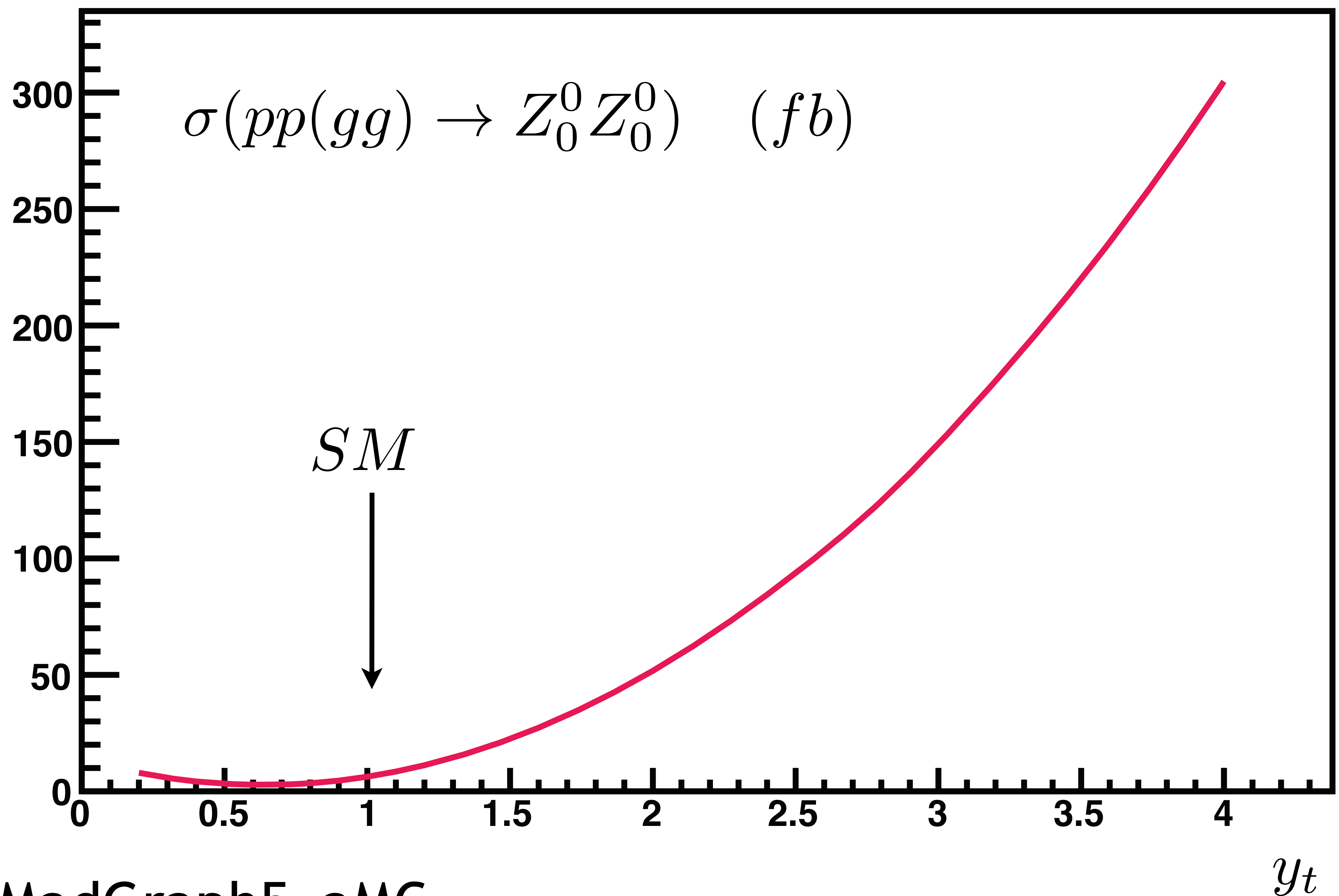
Englert and Spannowsky have pointed out that it is essential to consider the Higgs diagrams together with box diagrams without a Higgs.



For longitudinal Z bosons, the amplitude is required to agree with the result for production of a pair of Goldstone bosons: $$gg \to \pi^0 \pi^0$$

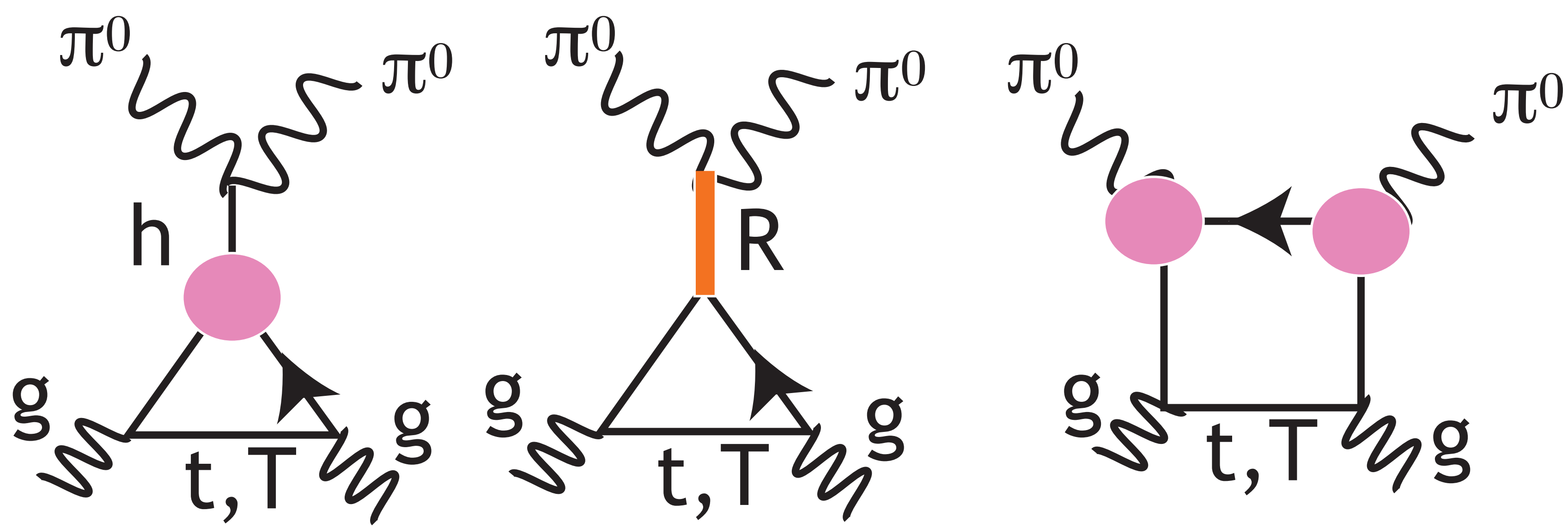
This requires cancellation of terms of relative order s/m_Z^2 in the separate amplitudes.

It is interesting to plot the cross section for longitudinal Zs only as a function of the amplification of the Higgs diagram:



MadGraph5_aMC

Now the Higgs is off-shell, so we are sensitive to form factor effect described above. A complete analysis within a composite Higgs model has a number of components



Resonances would also appear as ZZ resonances in vector boson scattering -- to be discussed this afternoon -- and so this observable needs to be considered as a part of that study.

I would like to raise one more question:

The current plan for HL-LHC is to run for 10 years at a constant luminosity of 0.5×10^{35}. The luminosity is limited by the physics requirements. Higgs is an important part of the argument: We must be able to trigger on general events from $gg \to h$ (125 GeV), and very high pileup makes this difficult.

On the other hand, highly boosted Higgs, from Wh, Zh, and hg, will be triggerable at high pileup. Higher luminosity will also benefit new particle searches and will be especially important for VV scattering.

So, the option to run the HL-LHC in its later years at 2×10^{35} or higher should be on the table.

The choice will depend on what are seen as a most important physics goals at that time (15 years in the future).

It is well appreciated that precision study of the Higgs boson will give us important new opportunities to search for physics beyond the SM.

It is well appreciated that the HL-LHC will greatly advance that study.

It is less clear today how we will reach the ultimate Higgs capabilities of the LHC. New tricks and specialized analysis need to be developed.

I hope that the material in this lecture will stimulate some thought in that direction.