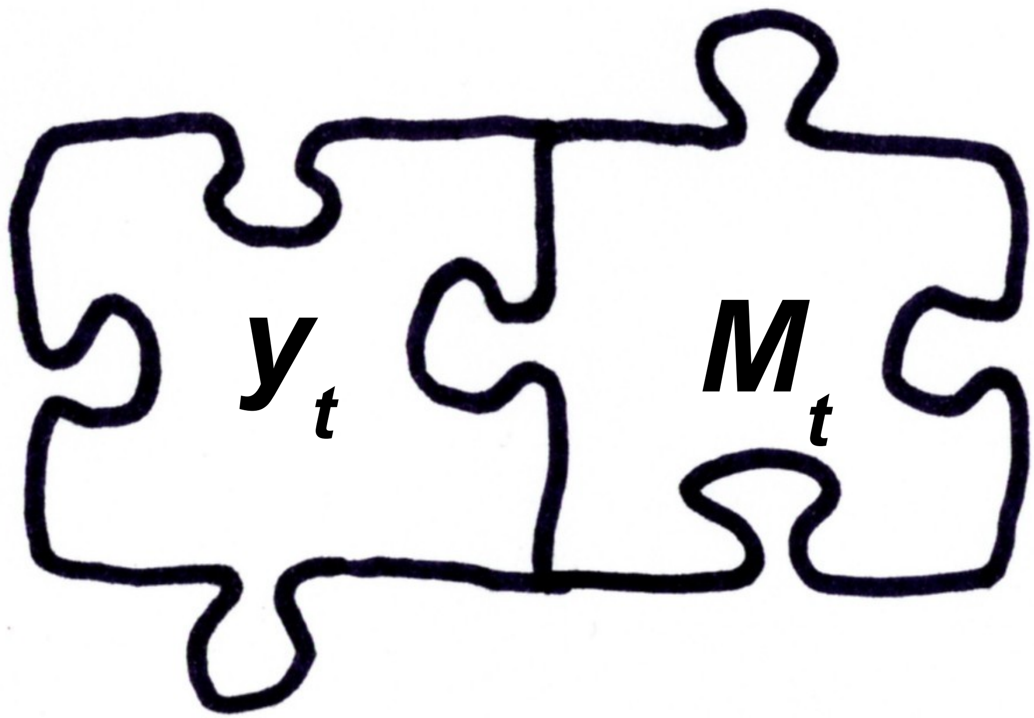
# Who ordered that?

## Investigations of the top-Higgs connection




Andrea Giammanco (CP3, UCLouvain)

# Introduction

# "Who ordered that?", I.Rabi

- 1936: discovery of the muon
- 1947: discovery of the pion, hence discovery that the muon has nothing to do with the Yukawa theory of the strong nuclear force
  - No physicist had any use for a *heavy replica of the electron*; it was considered a mystery, as expressed in Rabi's famous quip
- Pondering on this mystery led to the question whether there is only one neutrino type, or two
  - 1962: discovery that $\nu_m \neq \nu_e$
  - Birth of the concept of "generations"

# Who ordered *those*?

**FERMIONS** matter constituents spin = 1/2, 3/2, 5/2, ...

| Leptons spin =1/2 | | | Quarks spin =1/2 | | |
|---|---|---|---|---|---|
| Flavor | Mass GeV/$c^2$ | Electric charge | Flavor | Approx. Mass GeV/$c^2$ | Electric charge |
| $\nu_L$ lightest neutrino* | $(0-2)\times10^{-9}$ | 0 | **u** up | 0.002 | 2/3 |
| **e** electron | 0.000511 | –1 | **d** down | 0.005 | –1/3 |
| $\nu_M$ middle neutrino* | $(0.009-2)\times10^{-9}$ | 0 | **c** charm | 1.3 | 2/3 |
| $\mu$ muon | 0.106 | –1 | **s** strange | 0.1 | –1/3 |
| $\nu_H$ heaviest neutrino* | $(0.05-2)\times10^{-9}$ | 0 | **t** top | 173 | 2/3 |
| $\tau$ tau | 1.777 | –1 | **b** bottom | 4.2 | –1/3 |

?

?

Image source: CPEP

Nicely arranged in three generations.
Who ordered the second and the third?

# A personal note

**FERMIONS** matter constituents
spin = 1/2, 3/2, 5/2, ...

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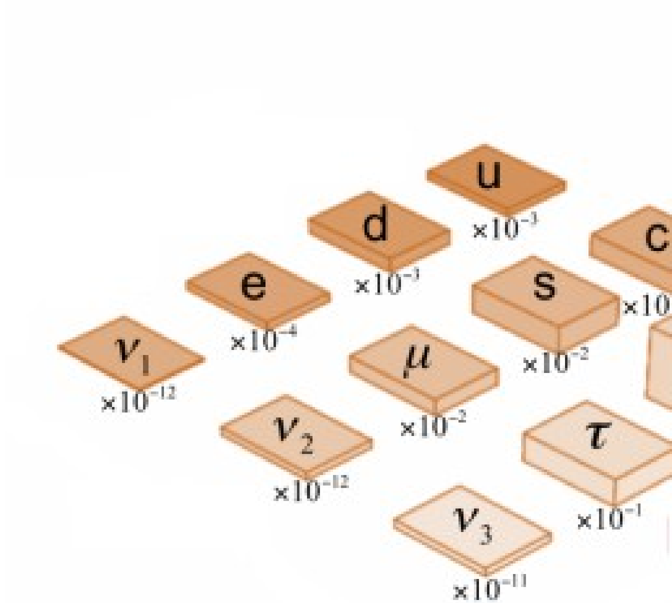
Image source: CPEP

a. As a teenager, I loved *complete the sequence* riddles.
b. 1995, top quark discovery, this table was everywhere.

a. & b. $\Rightarrow$ I was driven mad!

# The Flavor Puzzle,

## i.e., can we make sense of the fermion masses?




Picture stolen from here

Some authors tried *numerology* as a first step towards a model; the most (in)famous example is probably **Koide's formula** (*):

$$m_e + m_\mu + m_\tau = \frac{2}{3}(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2$$

Shockingly accurate (~$10^{-5}$ level) for charged leptons; a bit off for down-type quarks; and completely off for up-type quarks



(*) Y.Koide, Lett.Nuovo Cim. 34 (1982) 201; Y.Koide, Mod.Phys.Lett. A5 (1990) 2319-2324

# Where is the mass coming from?

- Back to the basics: the equation of motion for a massive fermion (aka Dirac's Equation) contains a term $m\psi$
- The corresponding term in the Lagrangian density is $m\bar{\psi}\psi$
- Any $\bar{\psi}\psi$ term breaks chiral symmetry and this makes the theory non-renormalizable
- It takes *Spontaneous Symmetry Breaking* to work around this: in the SM the mass term is not explicit in the true Lagrangian but emerges spontaneously below the breaking scale

# Where is the mass coming from?

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\Psi} \not{D} \psi + h.c.$$

$$+ \bar{\Psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

# Where is the mass coming from?

$$\phi = v + h \qquad L \supset \frac{y_t}{\sqrt{2}} \left( v \bar{\psi}_t \psi_t + \bar{\psi}_t \psi_t h \right)$$

In the SM, all fermion mass terms (here top as illustration) come from the Electro-Weak Symmetry Breaking.

The Vacuum Expectation Value, v, is a function of the fundamental parameters of the SM.

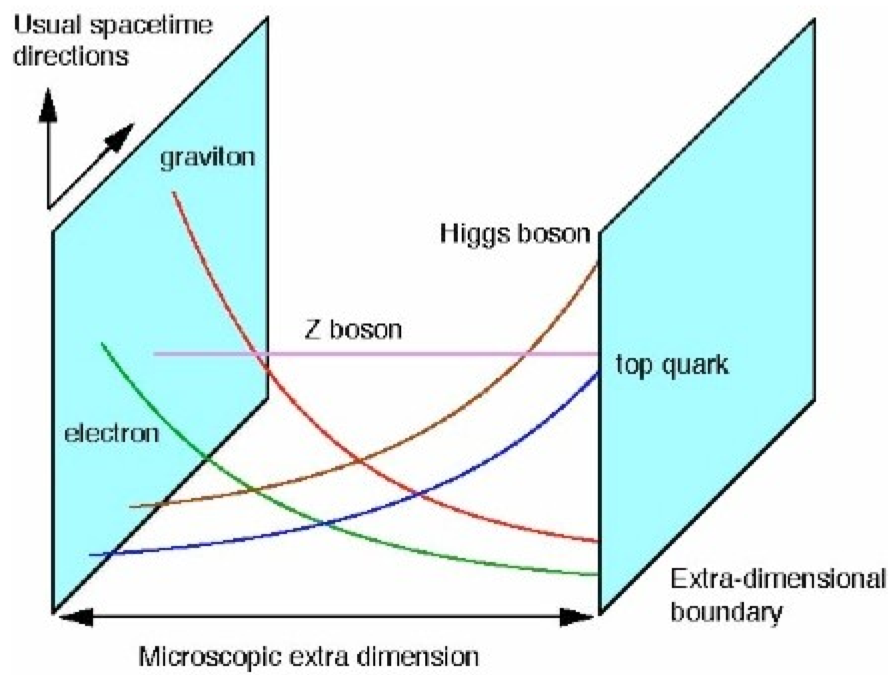
We have made some progress: we now know that the fermion mass hierarchy is a mere reflection of the hierarchy in Yukawa coupling strengths.



**But who ordered that pattern of Yukawa couplings?**

# An example of a deeper explanation

- Randall-Sundrum mechanism (string-inspired):

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Coupling strengths come from the wavefunction shapes and their overlaps in the warped dimension.
Ok but who ordered … (multi-verse?)

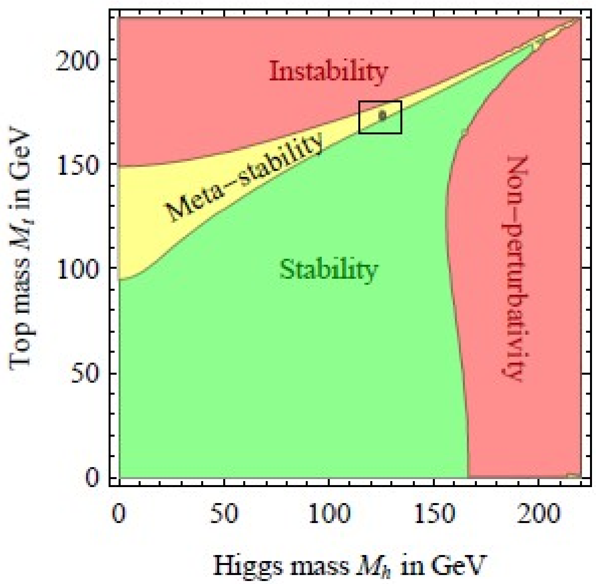
# The strange case of the fermion with a *natural* coupling to the Higgs

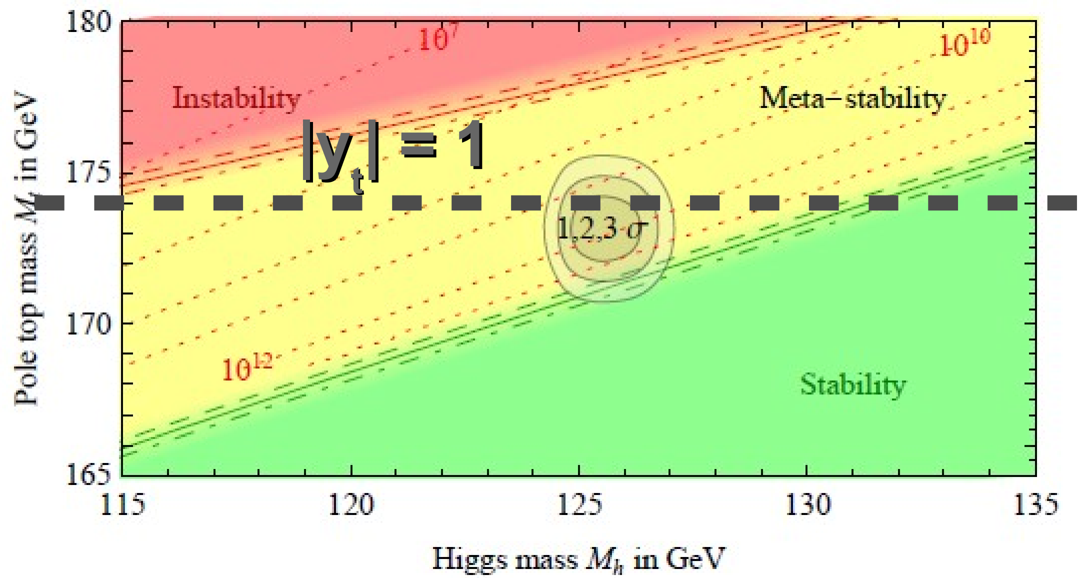
(Martinelli dixit: "In Physics there are only 0 and 1")

$$L \supset \frac{y_t v}{\sqrt{2}} \bar{\psi}_t \psi_t \equiv M_t \bar{\psi}_t \psi_t$$

- Fill actual numbers in:
  - $v = (\sqrt{2} G_F)^{-1/2} = 246.2196(1)$ GeV ($G_F = 1.166\,378\,7(6) \times 10^{-5}$ GeV$^{-2}$)
  - $M_t^{CMS} = 172.44 \pm 0.49$ GeV (CMS coll., Phys. Rev. D 93 (2016) 072004)
  - $M_t^{Tevatron} = 174.30 \pm 0.65$ GeV (CDF&D0 coll., FERMILAB-CONF-16-298-E)
- We get $y_t^{CMS} = 0.990 \pm 0.003$, $y_t^{Tev} = 1.001 \pm 0.004$
  - (I will comment on the CMS/Tevatron tension later)
  - 1 is an interesting value, for an adimensional parameter
  - Pure chance (numerology), or does it reflect something deep?
  - The SM offers no explanation (apart from pure chance)

# How $y_t$ once saved the Universe




Degrassi et al., JHEP 08 (2012) 098 (stimulated a prolific literature: link)

- This study assumes SM validity up to the Planck scale; and, in the SM, $m_t$ and $m_H$ are free parameters
- Under these assumptions, conspiracy of top and Higgs makes our Universe sit on the thin line between stability and instability
- Any deep reason for that? (Anthropic Principle at play?)

# A well-defined experimental question

- I am an experimentalist; my job is not to develop possible explanations, but to answer questions by testing hypotheses
- So I need a question that is well defined
- For example: **is $y_t = 1$?**

# Is $y_t = 1$?

- It sounds short. But in practice it is composed of a few blocks, each of them amounting to a major research program of its own:
  - Measure the mass of the top quark precisely
    - And also care about the exact relationship between what you are measuring in practice and the mass that enters the $y_t/m_t$ relationship
  - Measure the Yukawa coupling through observables independent from the top mass
    - The most direct is the $t\bar{t}H$ cross section
    - Note: $t\bar{t}H$ has not even been observed (*) yet

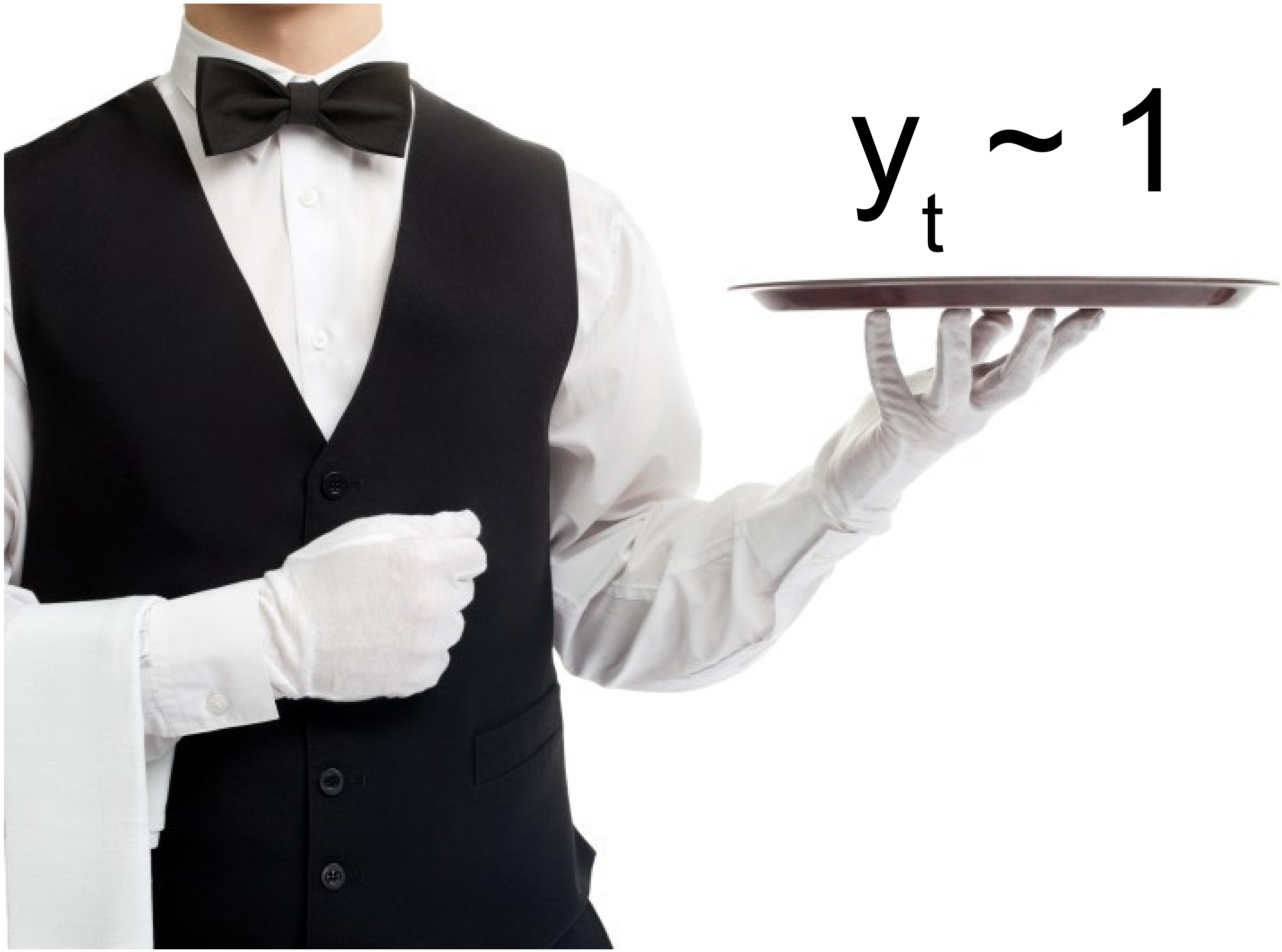


(*) HEP convention: *evidence* at $3\sigma$, *observation* at $5\sigma$

# Is $y_t = |y_t|$?

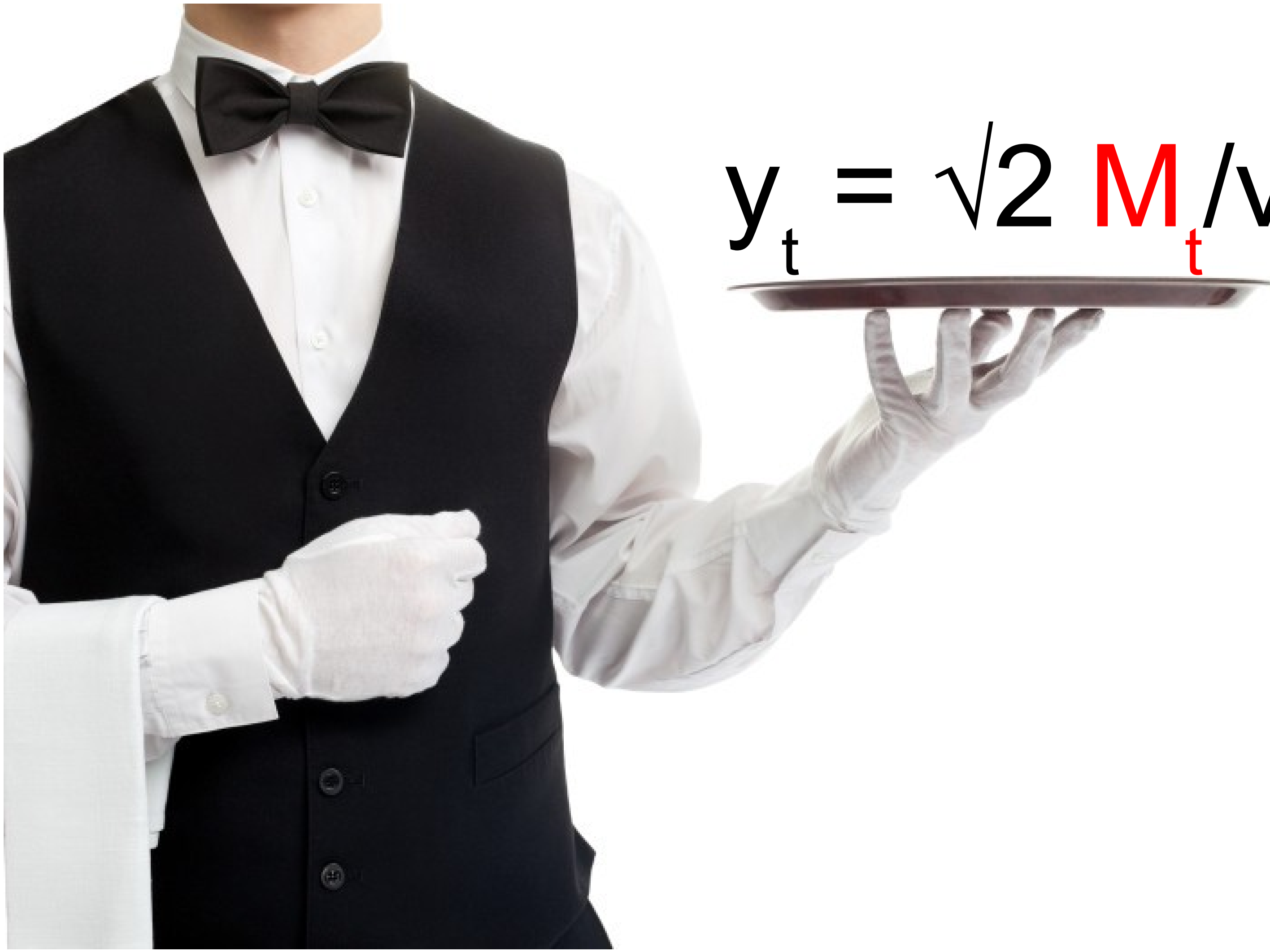
- The cross section of $t\bar{t}H$ is only sensitive to $|y_t|$
- If the phase of $y_t$ in the complex plane is the same as that of the Higgs coupling to gauge bosons ($g_{W,Z}$), it has no effect on any observable
- In the SM, these phases are aligned and so we don't care; we write $y_t$ as short-hand for $|y_t|$
- But here the entire premise is that we need to test the validity of the SM; in this mindset, we strive to avoid as many SM assumptions as possible
- In this talk I will also say how to measure the sign (if real; or the complex phase) of $y_t$ relative to $g_{W,Z}$

# End of introduction



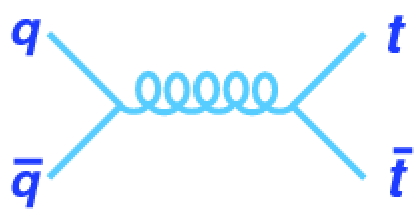

**Rest of the talk: experimental work related to this question, involving scores of physicists in the ATLAS and CMS collaborations**

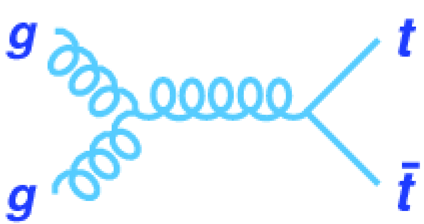
# Top mass

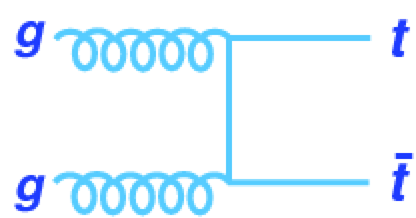


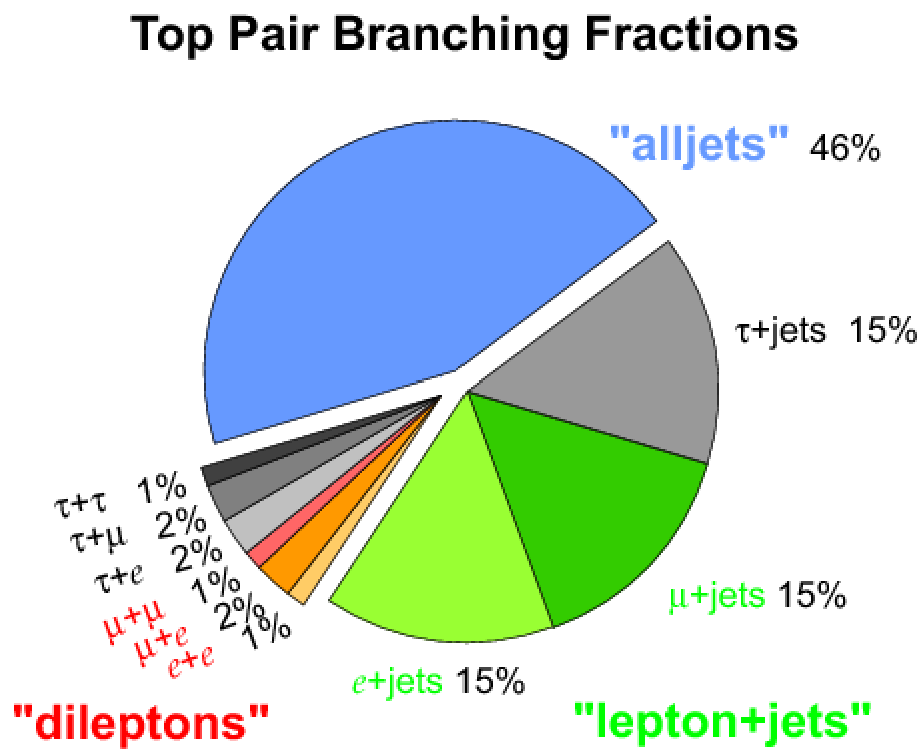
$$y_t = \sqrt{2}\, M_t / v$$

# Top-pair production and decays

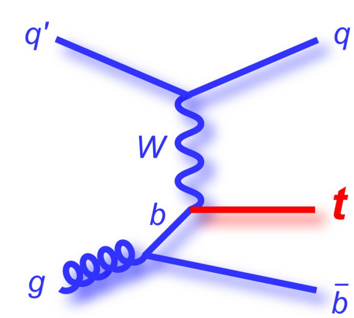


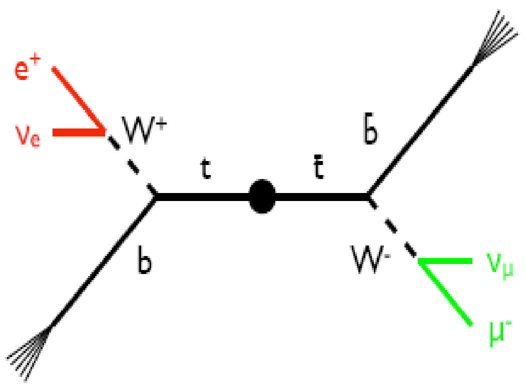



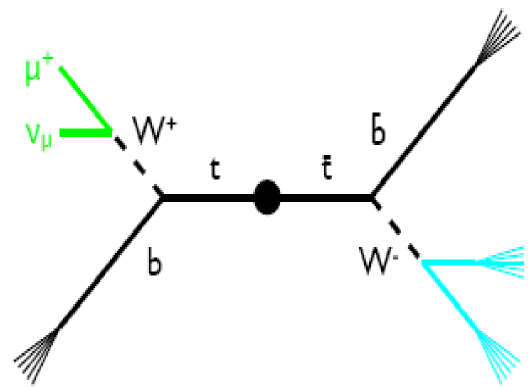

- The dominant production mechanism at LHC is $gg \rightarrow t\bar{t}$ (~85-90% of $t\bar{t}$ at 7-13 TeV)
- Another production mechanism is single top (mediated by the weak force), ~30% w.r.t. $t\bar{t}$

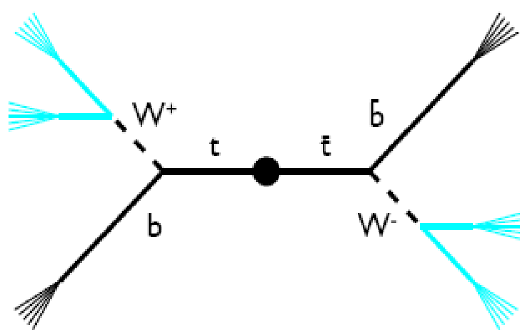


# Measuring the mass: top quark selections

- Typical final states exploited in $t\bar{t}$ production, with complementary pro's and con's:




**Dileptonic (ee, μμ, eμ)**

Very high purity;

Rate limited by $B(W\rightarrow l\nu)^2$;

Reconstructing the top and the antitop is non-trivial because of two neutrinos.

**Lepton (e,μ) + jets**

Convenient trade-off btw purity and rate;

$W\rightarrow jj$ gives $M_W$ as standard candle ⇒ self-calibration of jet energy scale.

**All-hadronic**

Low purity;

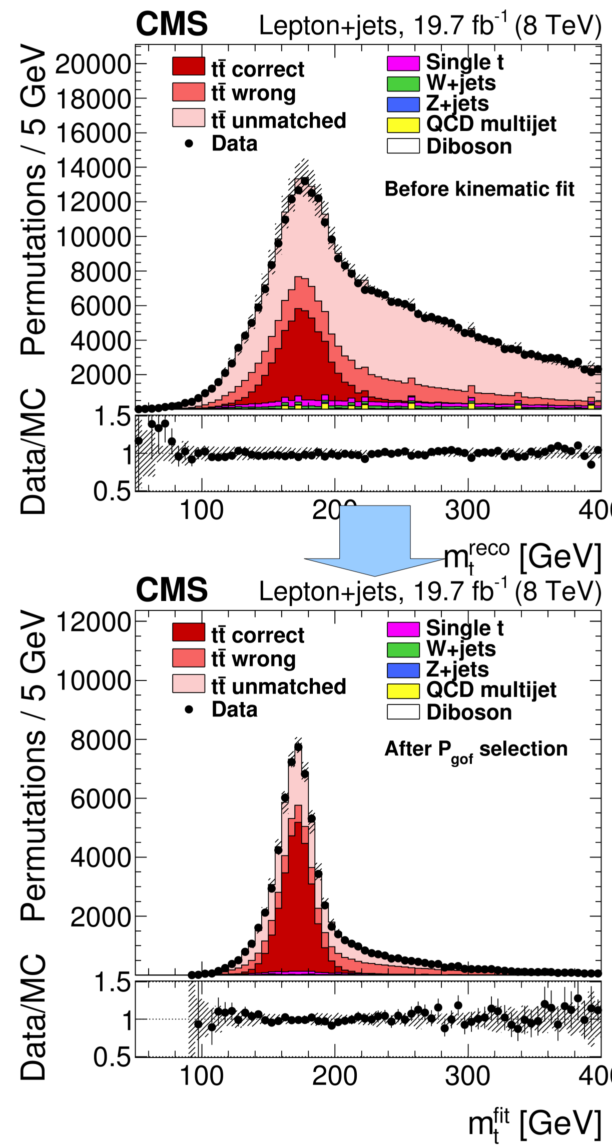
$W\rightarrow jj$ gives $M_W$ as standard candle;

Large combinatorics.

# Measuring the mass: sensitive observables

- In l+jets and all-hadronic, the most obvious proxy of the top mass is M(bjj)
- The name of the game is the choice of light jets to form W's, and of b jets to associate to those W's to form top quark candidates
  - Combinatorics is a major problem in all-hadronic
- The leptonic side of l+jets also brings information, but weighs less because missing energy is all that we can use to infer the neutrino momentum
  - Intrinsic quadratic ambiguity:

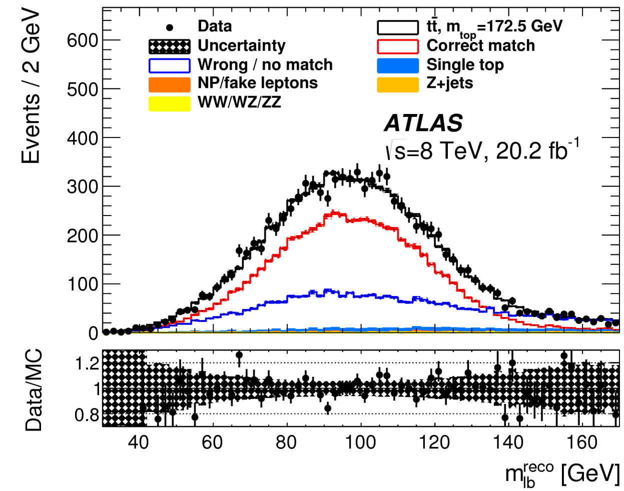
    $M_W^2=(E_l+E_\nu)^2-(\mathbf{P}_l+\mathbf{P}_\nu)^2$ has 2 solutions
- Full event interpretation by least squares method, aka kinematic fit, is often used



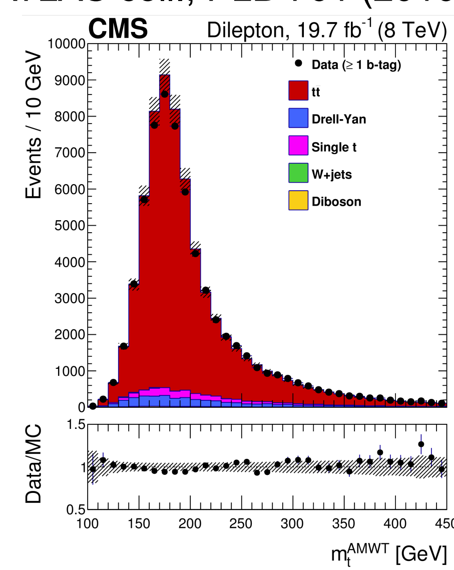

CMS coll., PRD 93 (2016) 072004

# Measuring the mass: sensitive observables

- In di-leptonic, things are not so simple
  - Two neutrinos
- One can still use observables highly correlated with the top mass, like M(lb)
- Or attempt full event reconstruction by solving for 6 unknowns (3-momenta of 2 neutrinos) with 5 constraints (2 components of $E_t^{miss}$, twice $M_W$, and $M_t = M_{\bar{t}}$), and scanning for several $M_t$ hypotheses used as 6$^{th}$ constraint
  - Solution is not unique: any mass constraint is a quadratic equation ⇒ 4x2 = 8-fold ambiguity ⇒ some criteria needed to pick the best



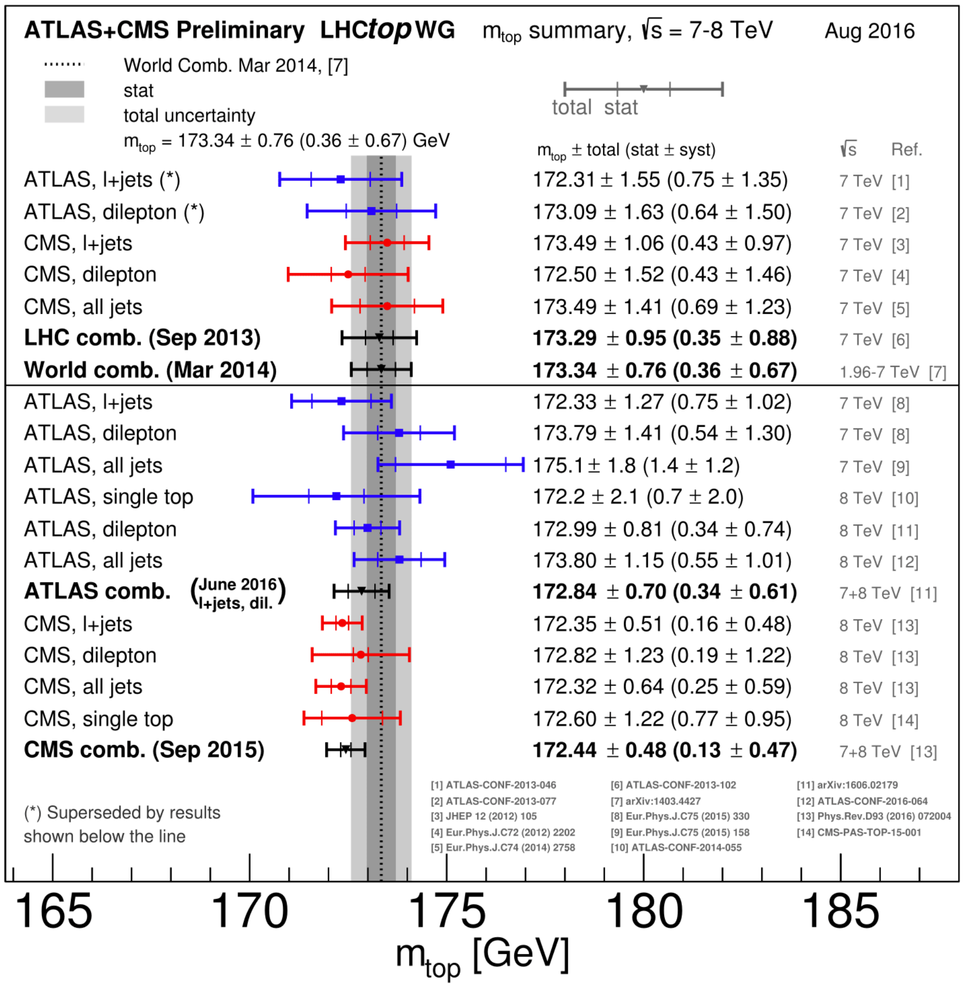

ATLAS coll., PLB 761 (2016) 350

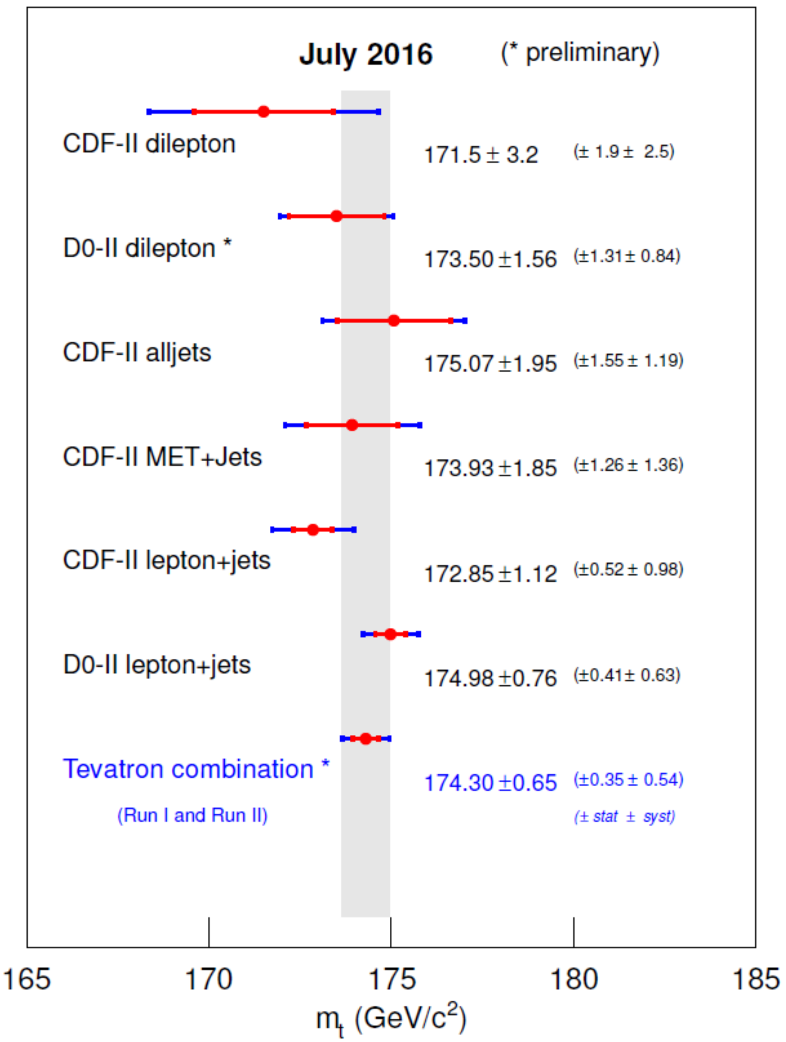





CMS coll., PRD 93 (2016) 072004

# Top mass: results



# What are we measuring exactly?

- These results are impressively *precise* (±0.3/0.4%)
- So, now time to ask: are they also *accurate*?

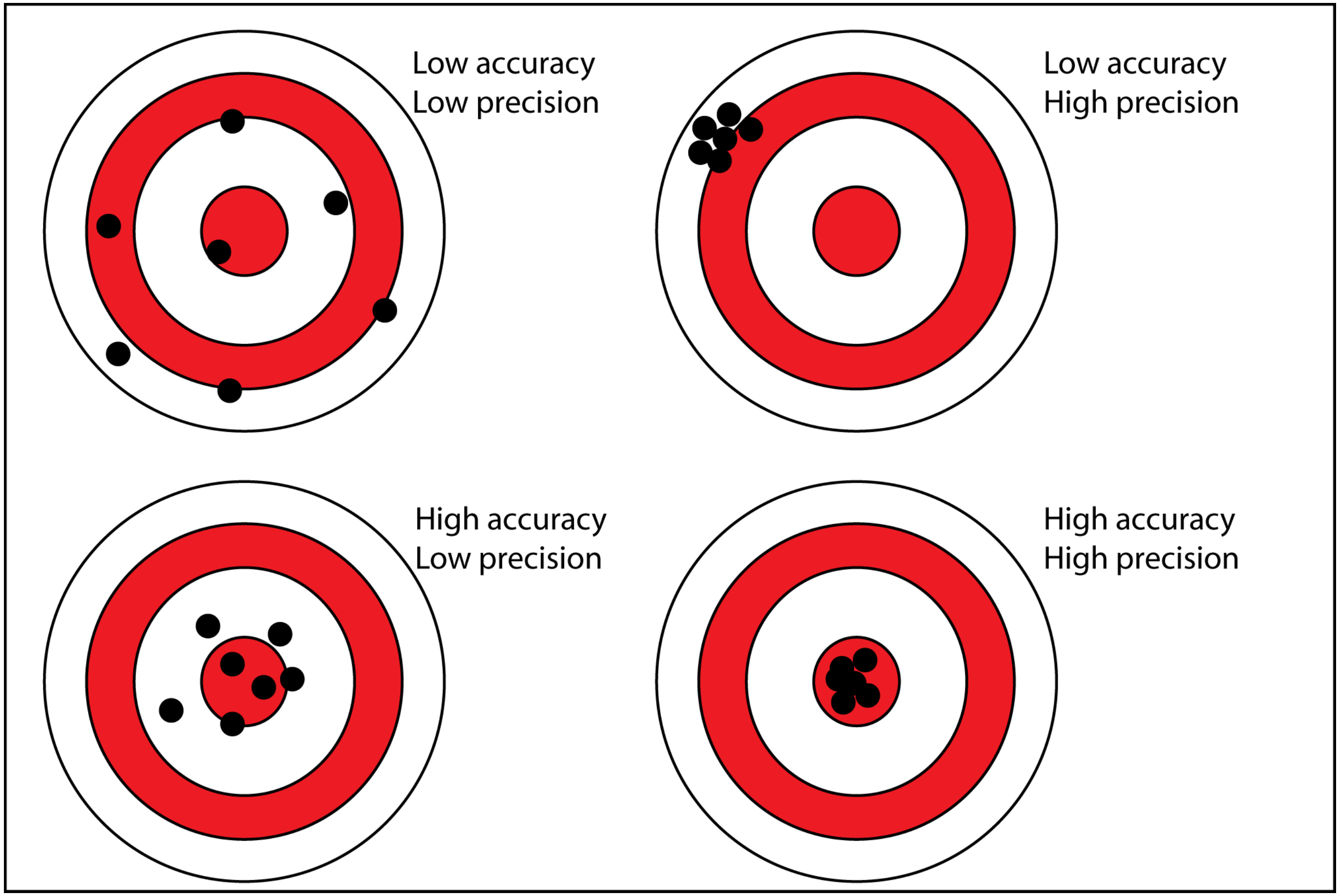
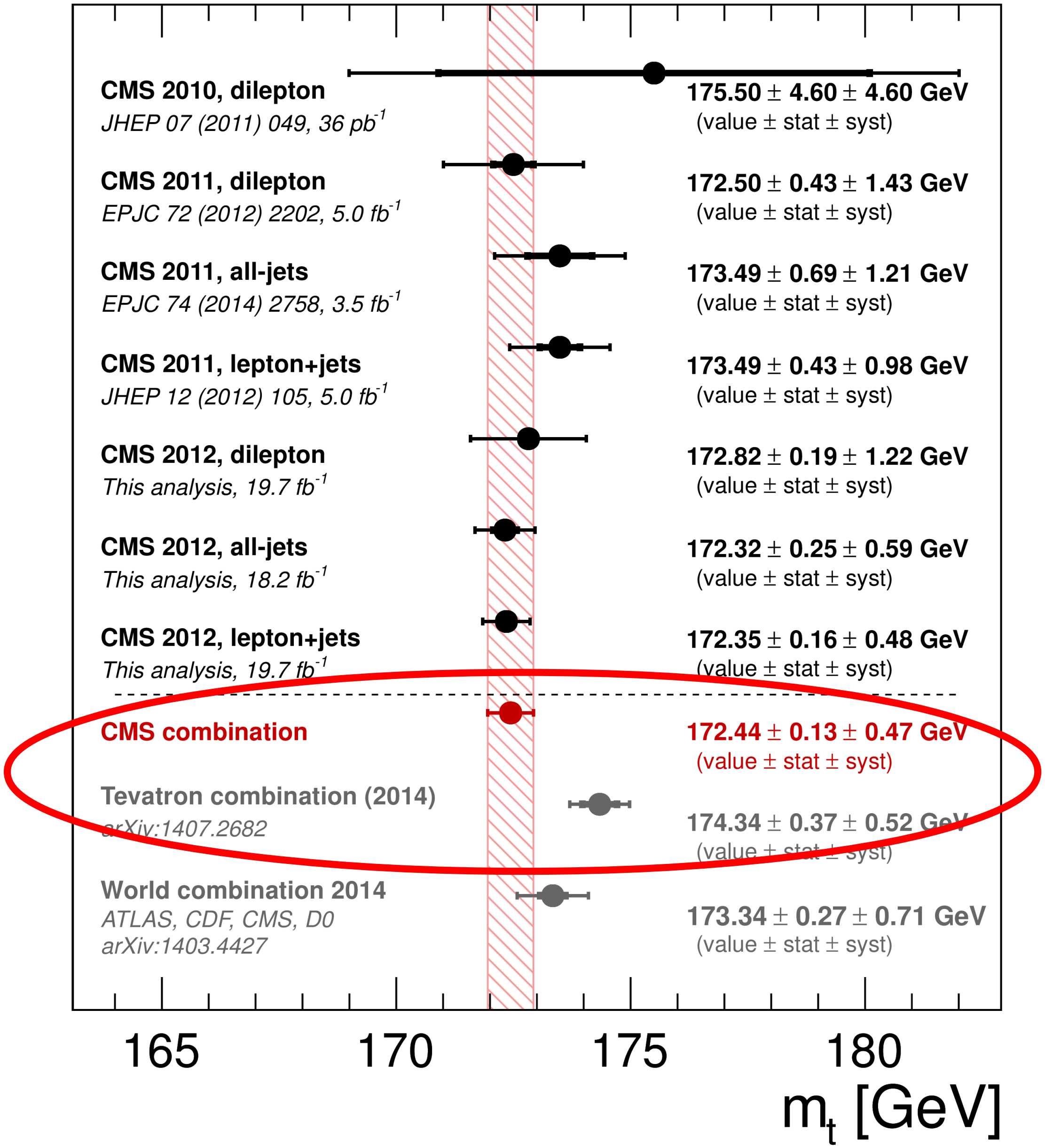


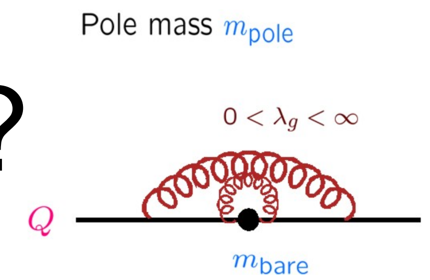

Image stolen from here

# Hint of a problem?



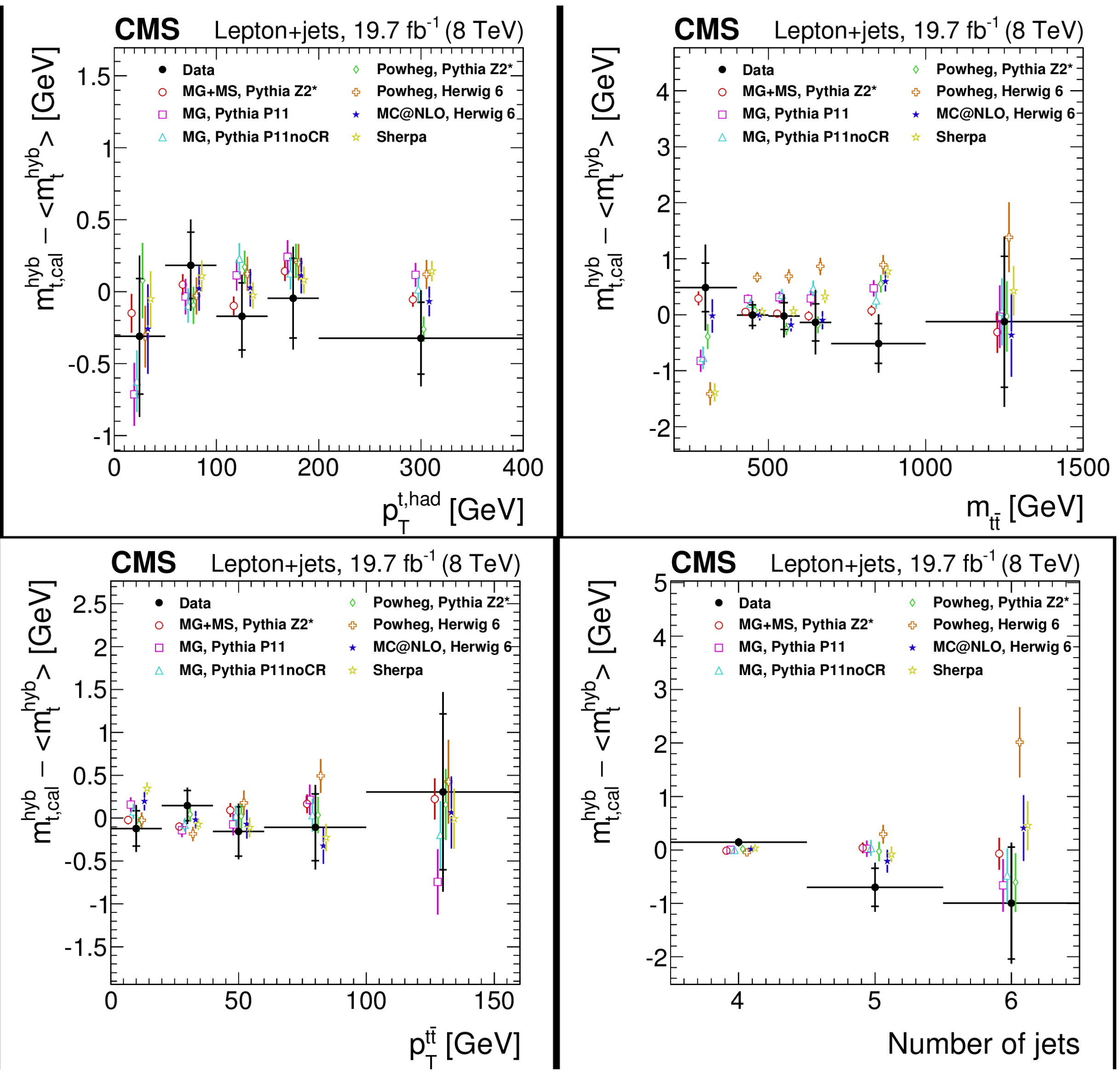

No big change from new Tevatron combination (FERMILAB-CONF-16-298-E): 174.30±0.35±0.54 GeV

# What are we measuring?




- Normally when we say "mass" we imply the "pole mass"
- But because of confinement, a quark is never observed isolated, hence its pole mass is unphysical: not an "observable"
- Top mass analyses are generally calibrated on MC simulation
- Are we just measuring a parameter called “top mass” in MC?
  - "MC mass" can be related to the pole mass, but with ambiguities from soft QCD, dependence on renormalization scheme, ...
- Very lively debate among QCD theorists about all that
  - Standard wisdom: theory uncertainty of order $\Lambda_{\text{QCD}}$; no unanimity
- But apart from the exact relationship with pole mass, one may wonder: maybe we underestimate model systematics?

# Some test



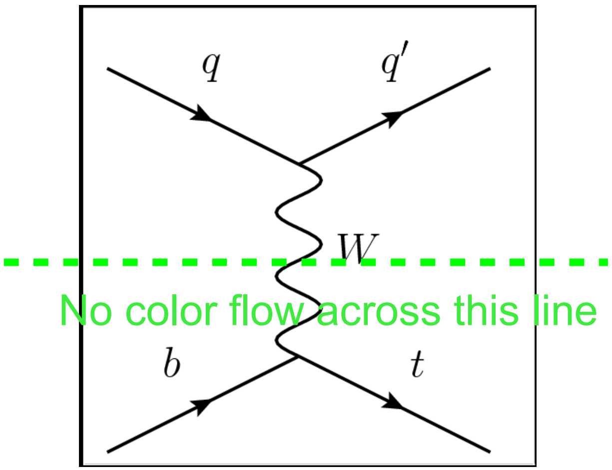

- *Uncalibrated* mass as function of several variables, chosen among the most sensitive to ISR/FSR, color reconnection, etc.

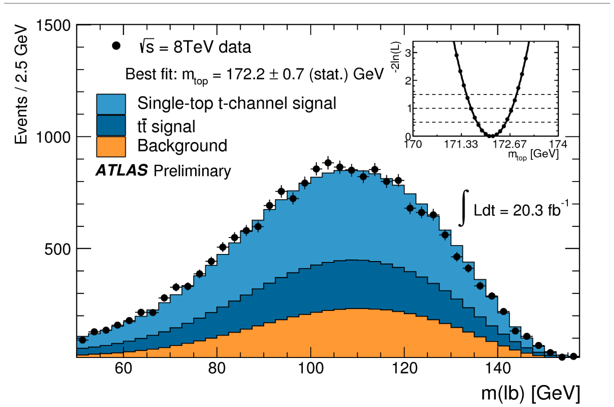
  (more plots are in the paper)

- Conclusion: data and MC agree within the precision, for a variety of MC models

CMS coll., PRD 93 (2016) 072004

# Another test: single-top-enriched samples



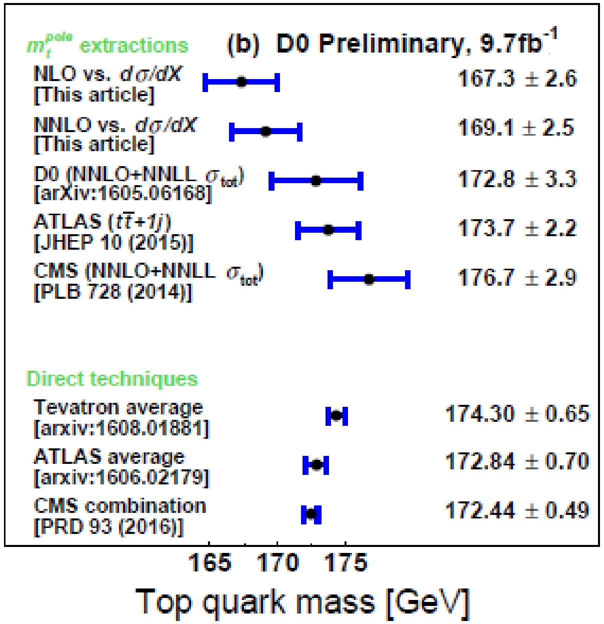

172.2±0.7(stat)±2.2(syst) GeV
ATLAS-CONF-2014-055

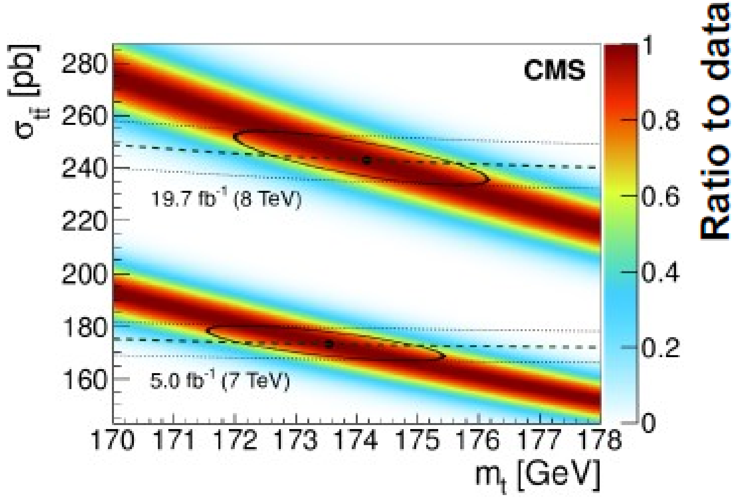
172.6±0.7(stat)±1.0(syst) GeV
CMS-PAS-TOP-15-001

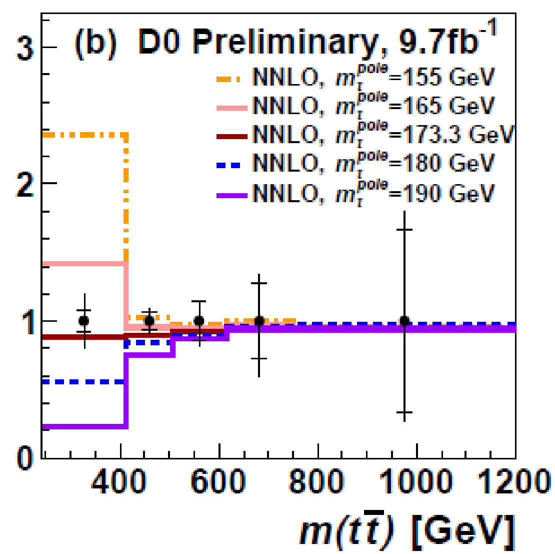
- Single top production in t-channel mode is not a rare process: ~1/3 of $t\bar{t}$
- Top candidate can be reconstructed, and used to extract a mass measurement
- Not included in combinations, because of much poorer precision with respect to $t\bar{t}$
  - Worse statistics
  - Larger background
  - Larger exp and modeling systematics
- But it is precious as a cross-check:
  - No color flow between the quark streams!
  - Conclusion: so far so good

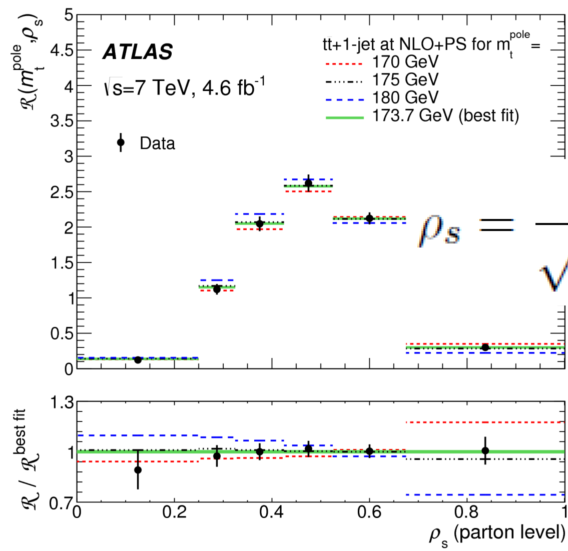
# Measuring the pole mass?

- It is not "observable", but it has effects
- Top production cross sections (inclusive and differential) strongly depend on pole mass
- Use them as indirect measurements of the pole mass itself
  - Result is well defined if you specify the details of calculation: perturbative order and PDF set




$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

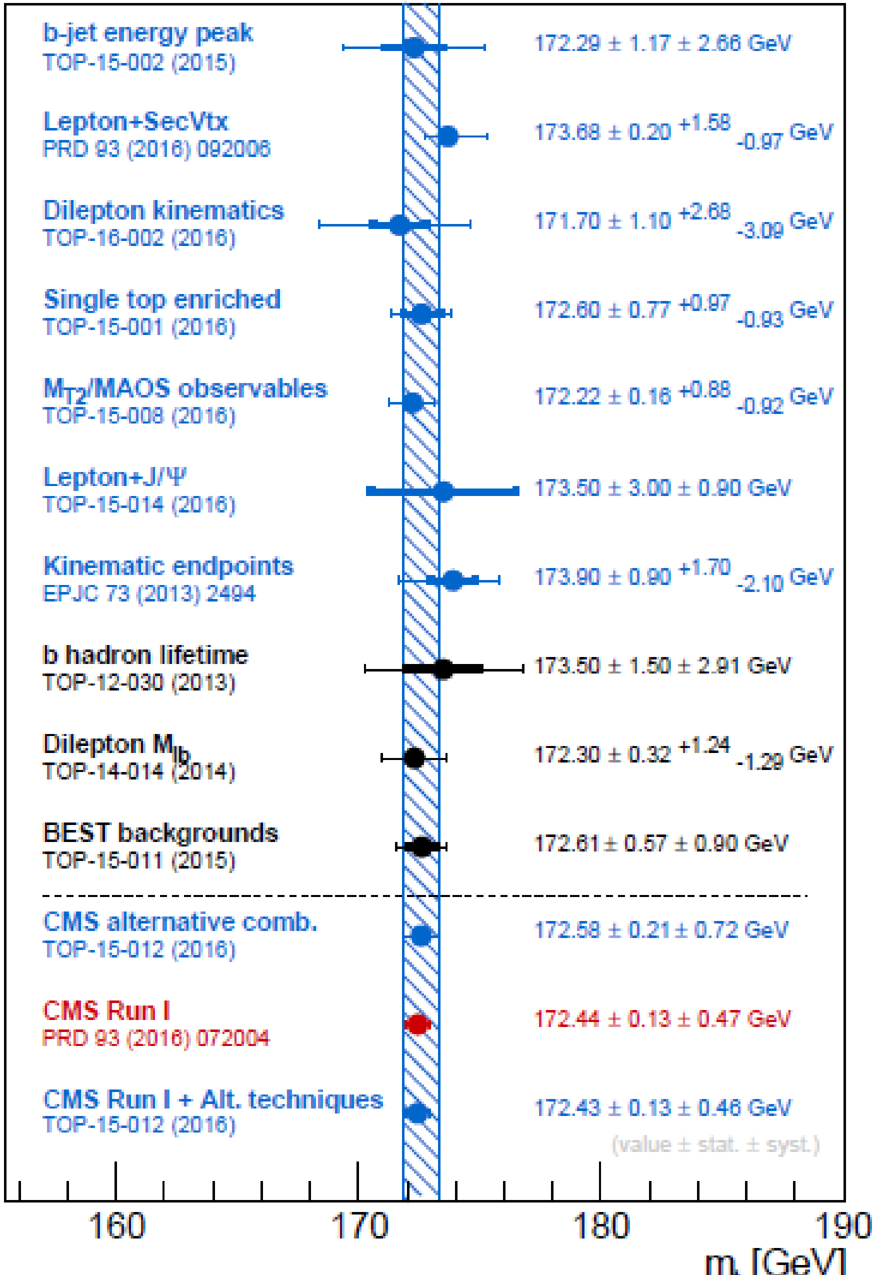


CMS coll., JHEP 08 (2016) 029

D0 coll., Note 6473-CONF

ATLAS coll., JHEP 10 (2015) 121

# More tests



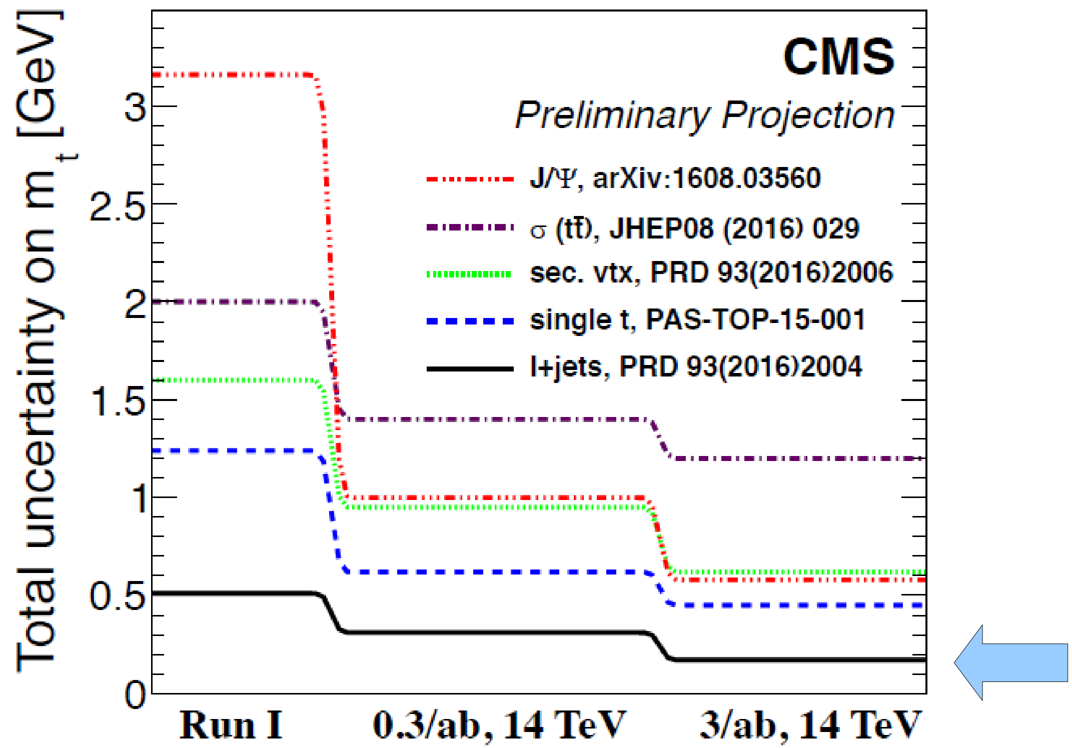

CMS-PAS-TOP-15-012

- Plethora of "alternative mass" measurements performed
- Typically designed to have very different dominant uncertainties with respect to standard methods
  - (e.g., lepton + secondary vertex and lepton + J/ψ have negligible dependence on JES)
- Taken one by one, not very insightful as cross-checks: poor precision
- Interesting exercise: what happens if you combine them all?
- Result: you get ±0.4% precision!
  - And so far so good

# LHC-Tevatron discrepancy: hinting at something wrong?

- Short answer: I don't know
- Tests are ongoing on both sides to check if there may be some unaccounted systematic
- Digression: human factors matter in science
  - Tevatron closed since years; hard to find personpower even for a high-profile analysis, even more difficult for a cross-check of an already published result
  - However, the fact that many D0/CDF members are now CMS/ATLAS members sort of helps: some key people have access to technical details on both sides! (Risk of bias: larger or smaller?)
  - ATLAS l+jets analysis @ 8 TeV eagerly awaited: expected to significantly improve ATLAS-only combination and perhaps settle the issue

# Future prospects for the top mass



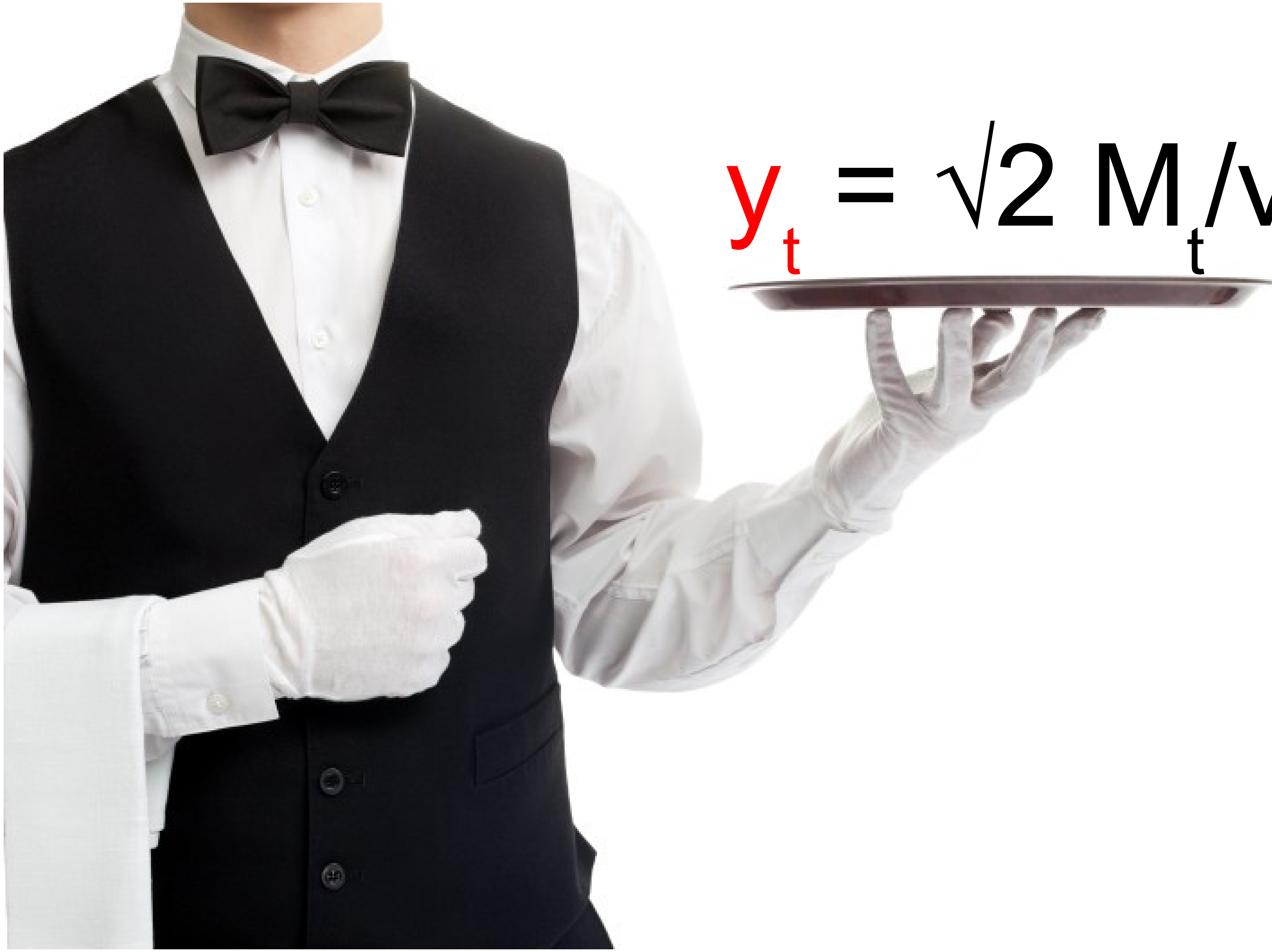

<0.1%

Plot from CMS-DP-2016-064

Assumptions: detector performance stays the same (i.e., harsher collision environment is perfectly compensated by detector upgrades), trigger efficiency is reduced to 1/3, and theory systematics are better constrained.

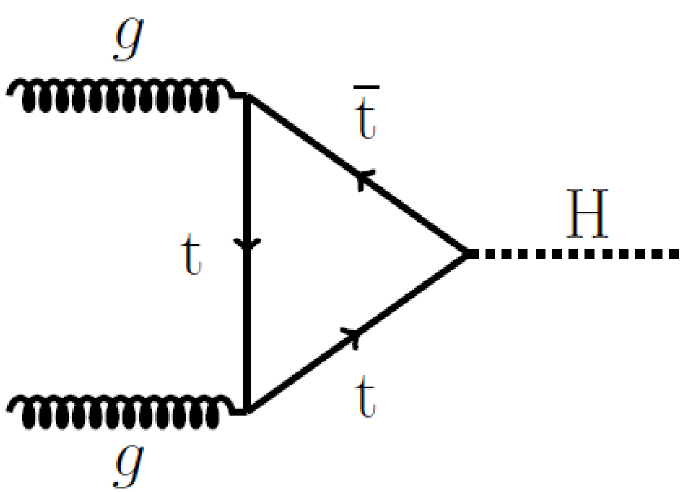
**With 3/ab, all analyses expected to be systematics-limited.**

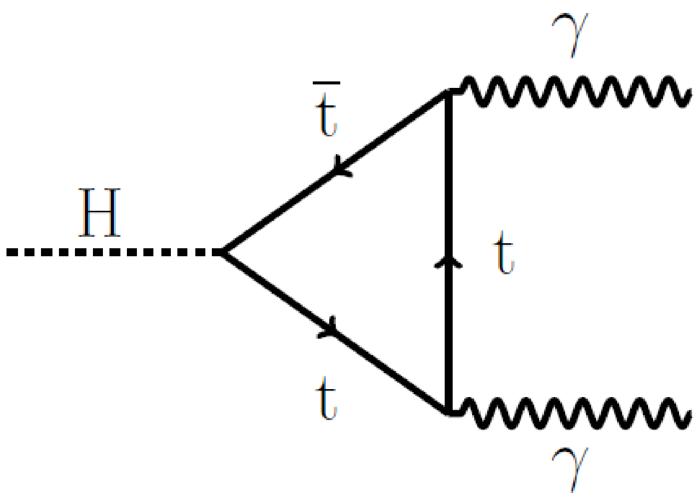
# Top-Higgs coupling



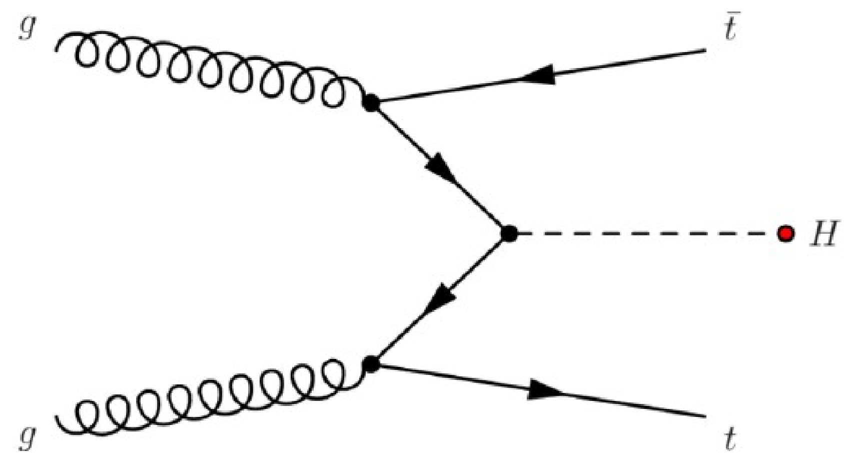
$$y_t = \sqrt{2}\, M_t / v$$

# Measuring $|y_t|$



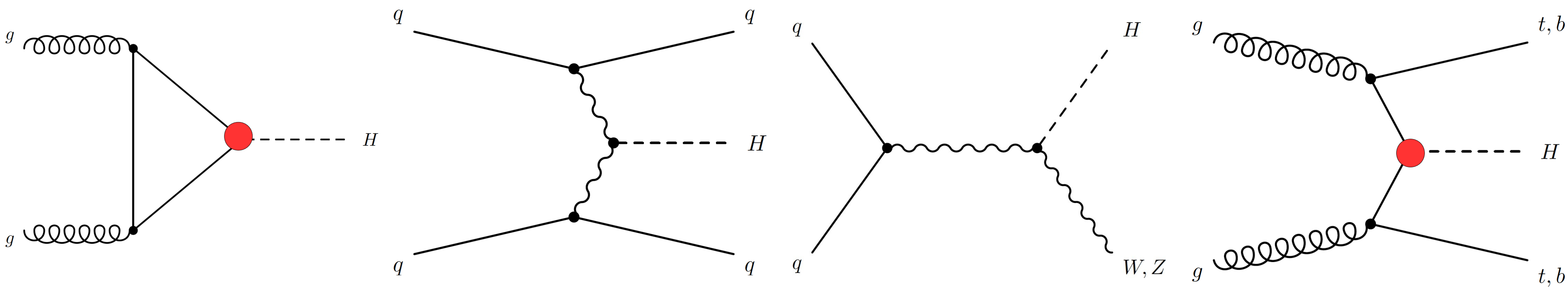

Indirect: through loops




Direct: at tree level

General consideration:
when sensitivity is induced by loops, one needs to rely more on some model assumptions (e.g., what particles run in the loop)

# Measuring $|y_t|$: indirectly

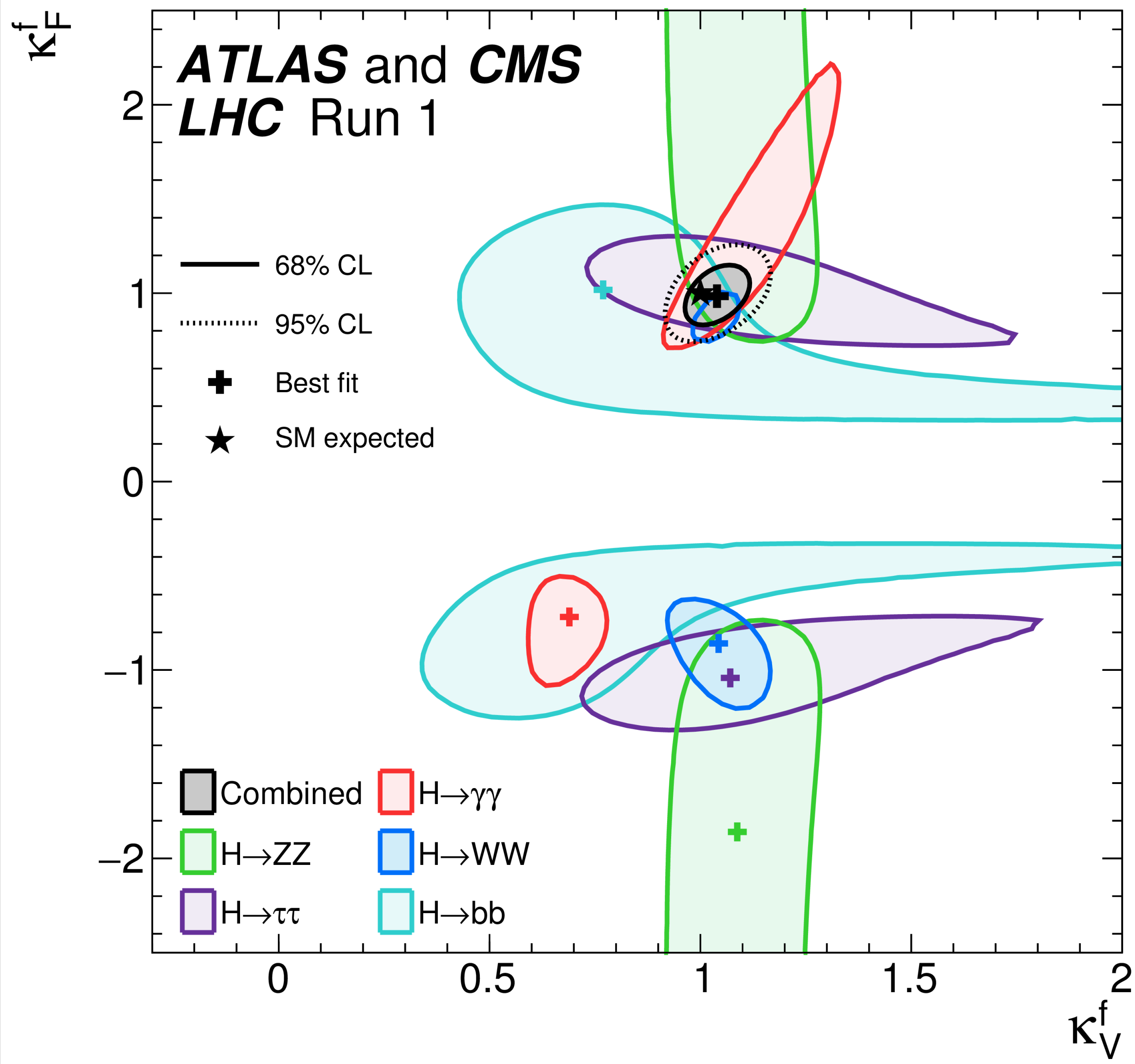


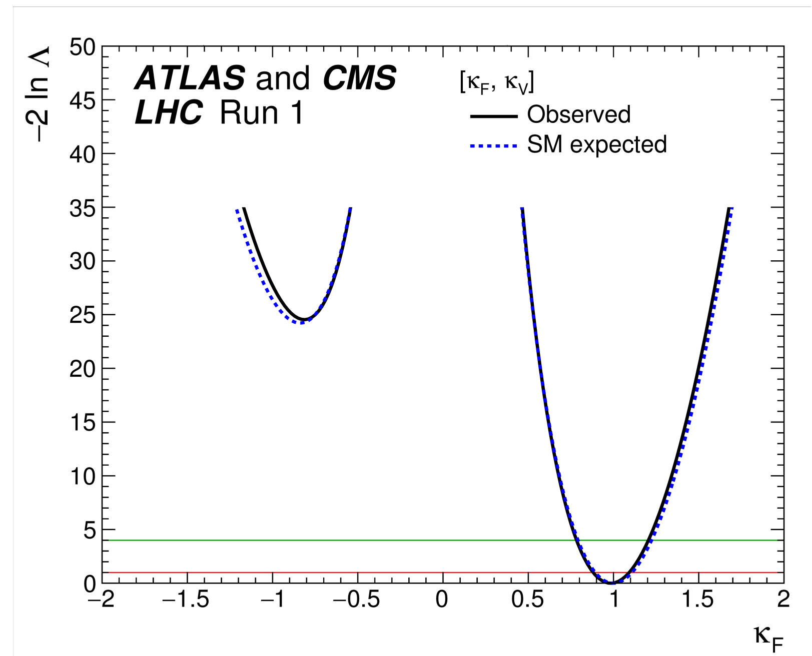

- Legacy ATLAS+CMS run-1 Higgs properties paper (*) combines many final states to extract constraints on several couplings, with several alternative parameterizations and assumptions
- Diagrams with indirect (loop) and direct (tree) sensitivity to the top-Higgs coupling are both considered but, at the current state, precision on this parameter is driven by the former
  - (For sake of clarity, I will not elaborate on the role of $t\bar{t}H$ and tH in this global combination; I present their explicit searches later)



(*) ATLAS & CMS, JHEP 08 (2016) 045

# Fermion ($k_F$) and boson ($k_V$) coupling multipliers

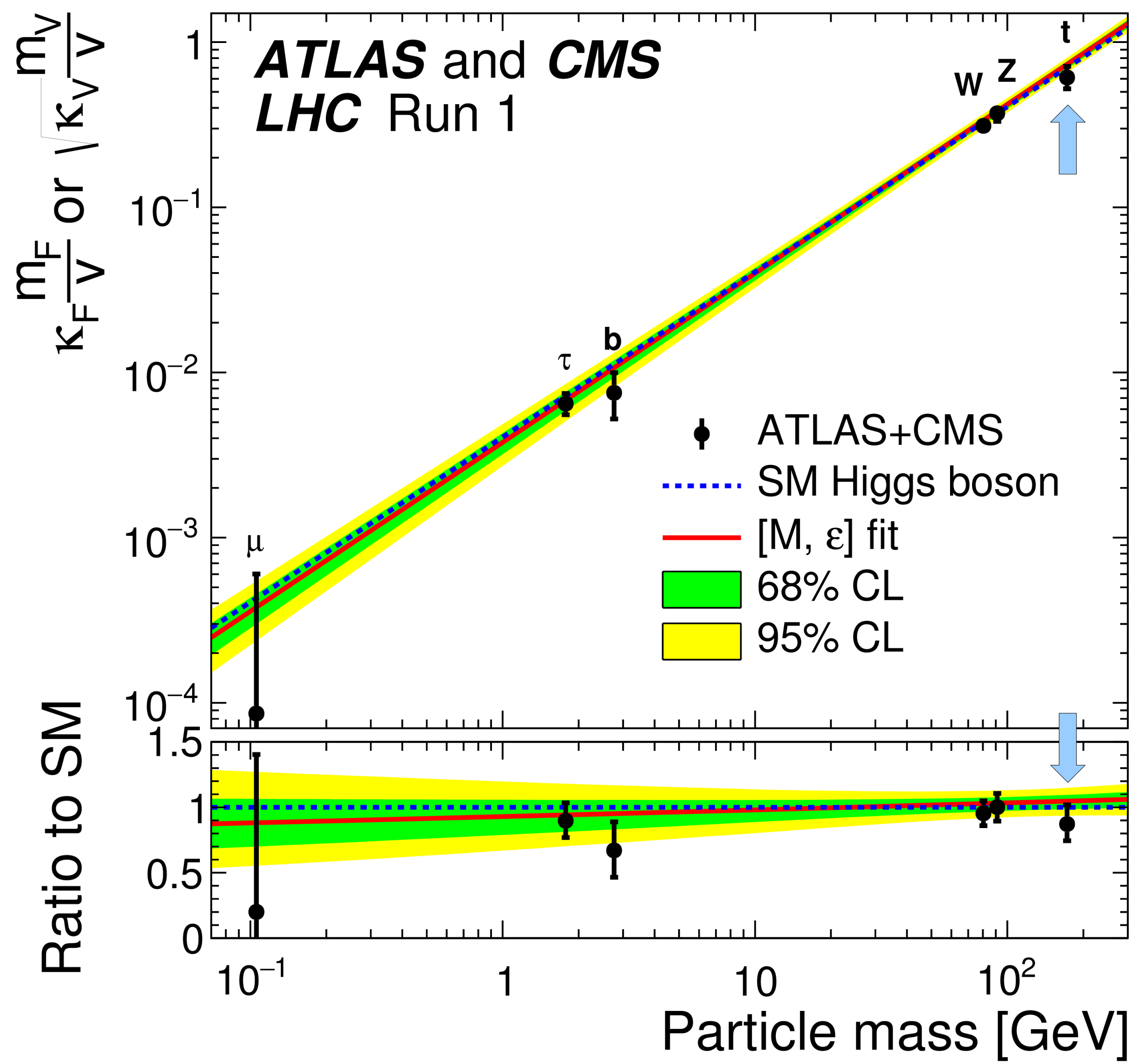



This parameterization considers a single multiplier for all fermions.
**$k_F$ ~ 1 ⇒ $y_t$ ~ 1** (within ~25%)

Assumption: no BSM in loops

# A test of the coupling-mass relationships

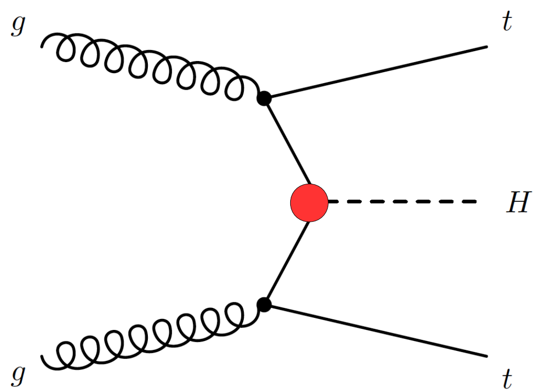


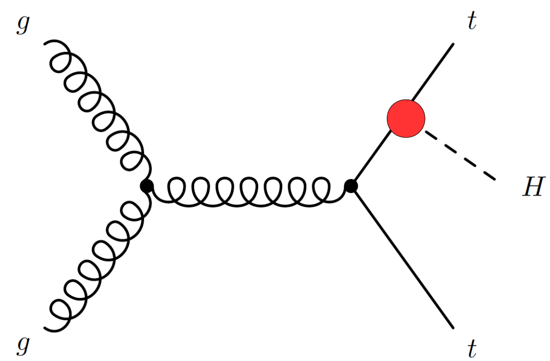

$\Rightarrow |y_t| \sim 1$

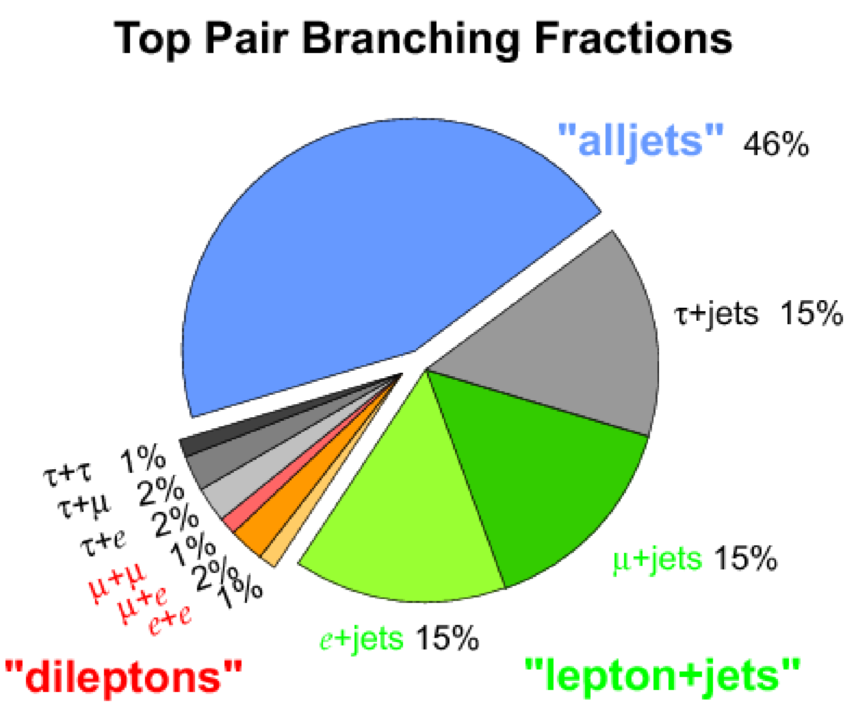
(within ~25%)

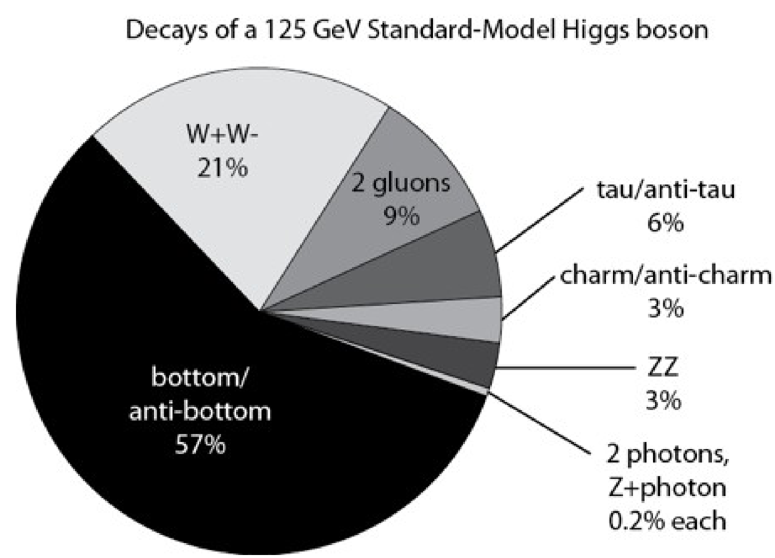
# Measuring $|y_t|$: directly

$$\sigma(t\bar{t}H) \propto \left| \text{[diagram 1]} + \text{[diagram 2]} + \ldots \right|^2 \propto |y_t|^2$$

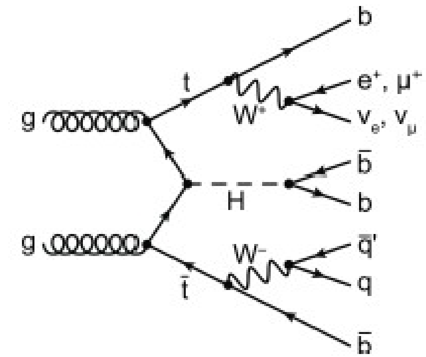


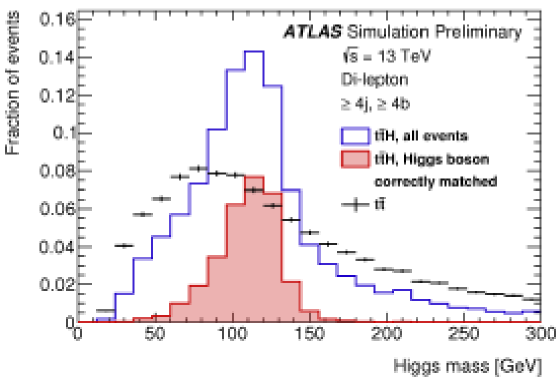



# Searches for $t\bar{t}H$: $b\bar{b}$ channel

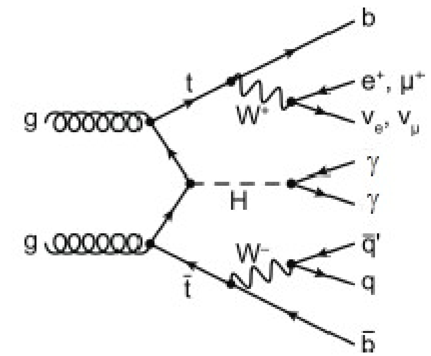



- Pros:
  - Largest BR (~60%)
  - Large multiplicity of jets and b-tags
- Cons:
  - Overwhelming $t\bar{t}$+jets background
  - Heavy flavour component of bkg is poorly constrained
  - Very large combinatorics of jet-parton associations
- Approaches:
  - Use several combinations of lepton / jet / b-tag multiplicities in simultaneous fit; it helps a lot in constraining bkg fractions
  - (MVA for jet-parton association, followed by) MVA for classification
  - Alternative: Matrix Element Method (more sensitive but more work)

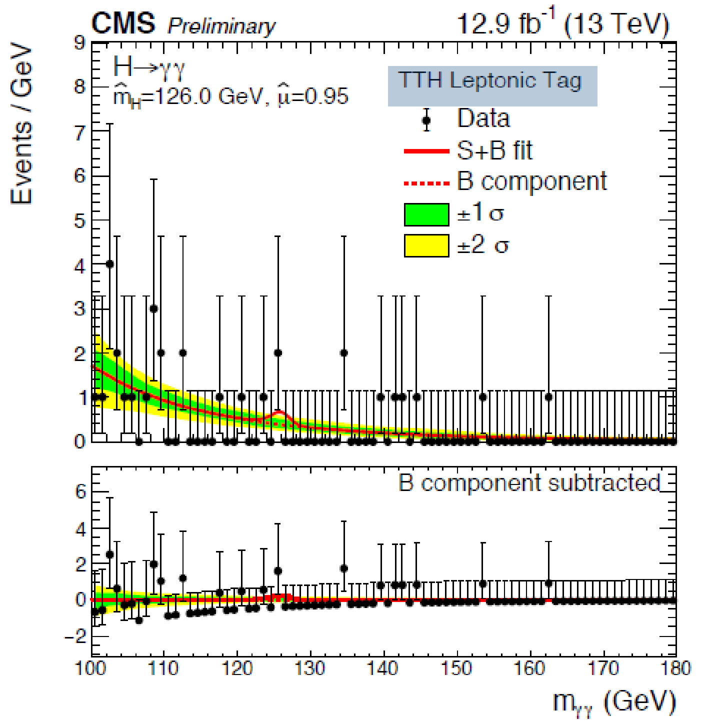



ATLAS-CONF-2016-080

# Searches for $t\bar{t}H$: $\gamma\gamma$ channel

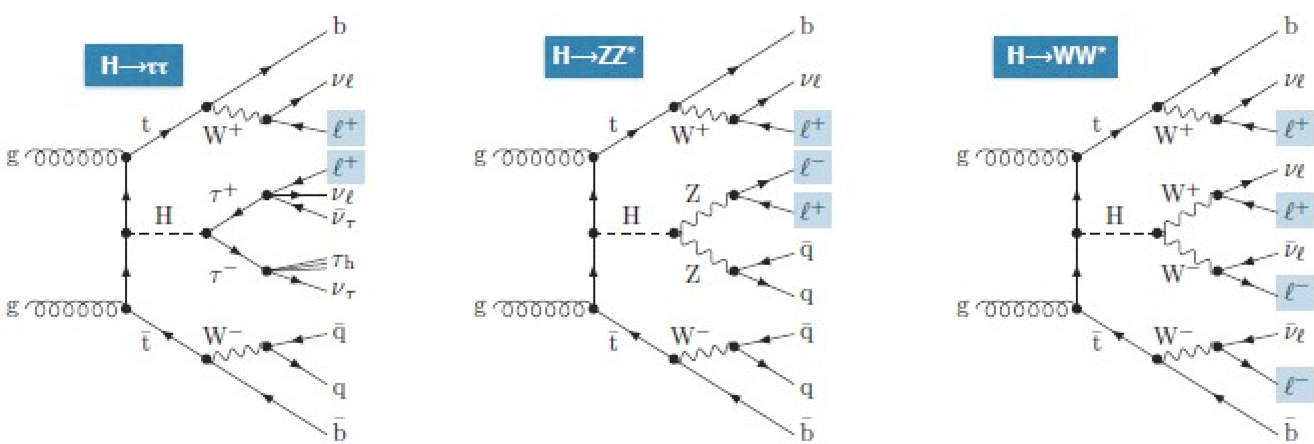


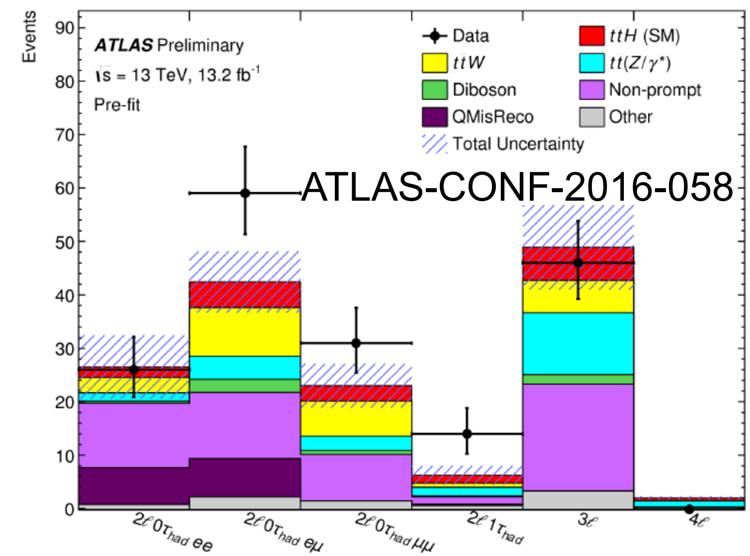

- Pros:
  - High-resolution mass peak
  - Background: smoothly falling mass spectrum
- Cons:
  - Small branching ratio (~0.2%)
- Approach:
  - Target events with 0 or 1 leptons from tops
  - Part of general $\gamma\gamma$ analysis where events are categorized by additional objects ("tags") to get discrimination power between production modes




CMS-PAS-HIG-16-020

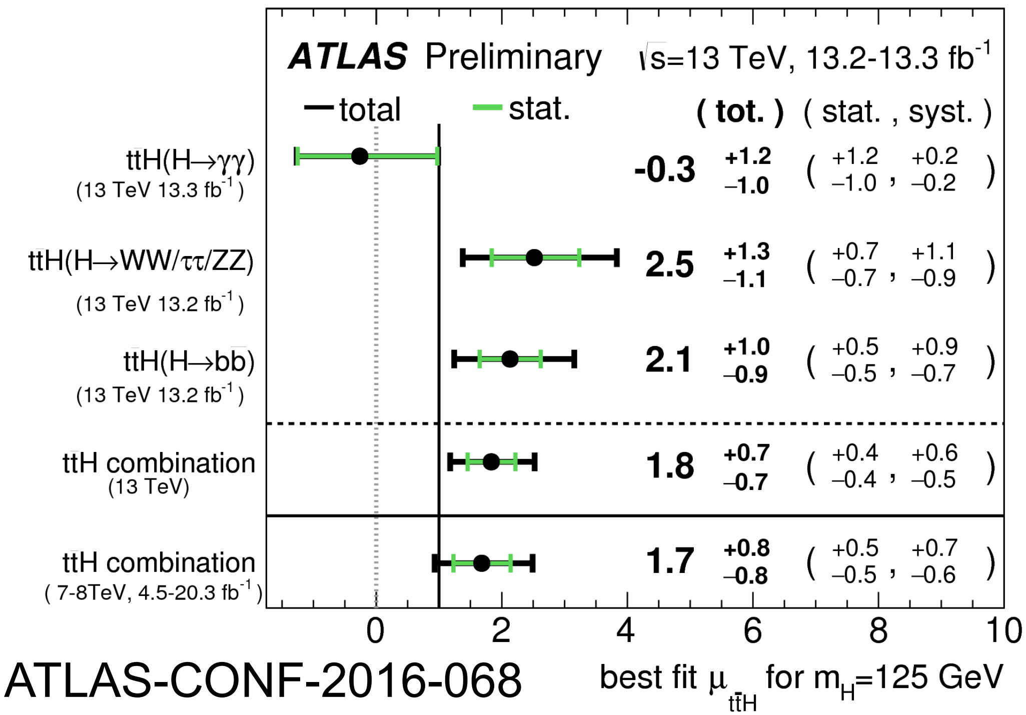
# Searches for $t\bar{t}H$: multi-lepton




- Very clean selections: 2 same-sign leptons, or ≥3 leptons
  - Target final states with at least one leptonic top decay and more leptons from H→ττ (6.3%), H→ZZ (2.6%), H→WW (21.5%)
- Most challenging background is $t\bar{t}$ with non-prompt leptons (b/c→l, π/K→l, $\gamma \to e^+e^-$) or lepton charge confusion
  - Specific lepton-ID optimized for this analysis
  - Control regions to estimate fake rate and charge confusion

# Searches for $t\bar{t}H$: latest results (Run-2)



ATLAS-CONF-2016-068

**CMS** (13-15/fb)**:**

- $H\to\gamma\gamma$: $\mu = 1.9^{+1.5}_{-1.2}$
  CMS-PAS-HIG-16-020
- Multilepton: $\mu = 2.0^{+0.8}_{-0.7}$
  CMS-PAS-HIG-16-022
- $H\to b\bar{b}$: $\mu = -0.2\pm0.8$
  CMS-PAS-HIG-16-038

**LHC Run-1 combination:**

- $\mu = 2.3^{+0.7}_{-0.6}$

~40% uncertainty on signal strength ($\mu$) $\Rightarrow$ ~20% on $y_t$

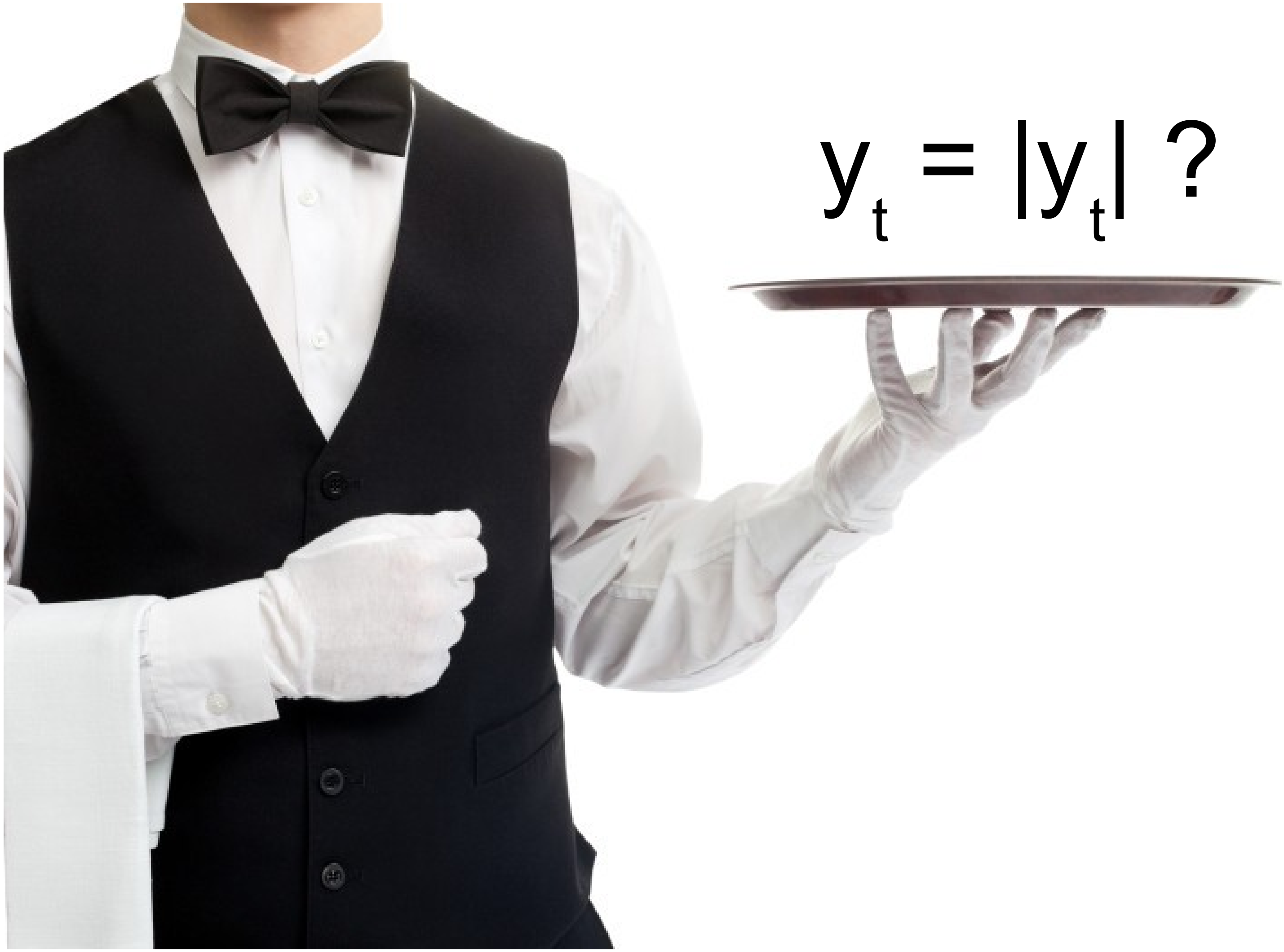
($\mu \equiv \sigma_{obs}/\sigma_{exp} \propto y_t^2 \Rightarrow \Delta\mu/\mu = 2\Delta y_t/y_t$)

Extrapolations to HL-LHC: reach $\Delta y_t/y_t$~10% asymptotically

(further progress only by reducing theory uncertainties)

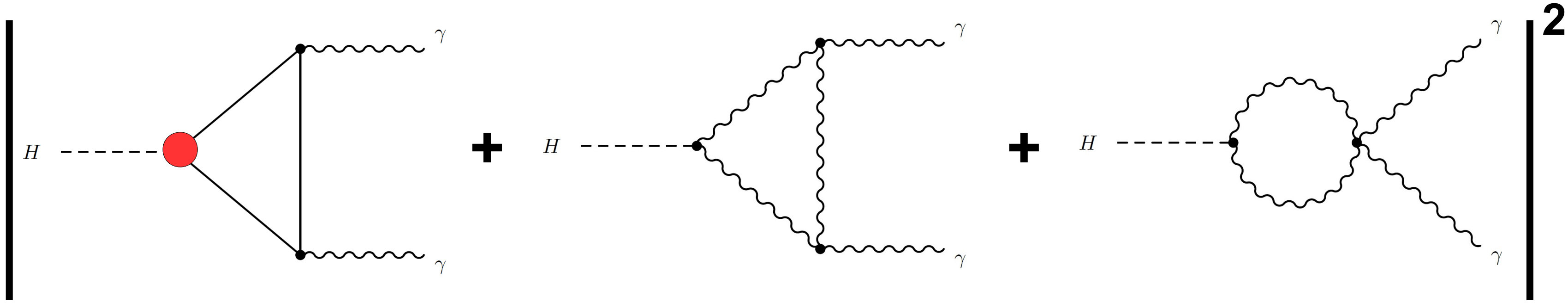
# Real and positive?

$y_t = |y_t|$ ?



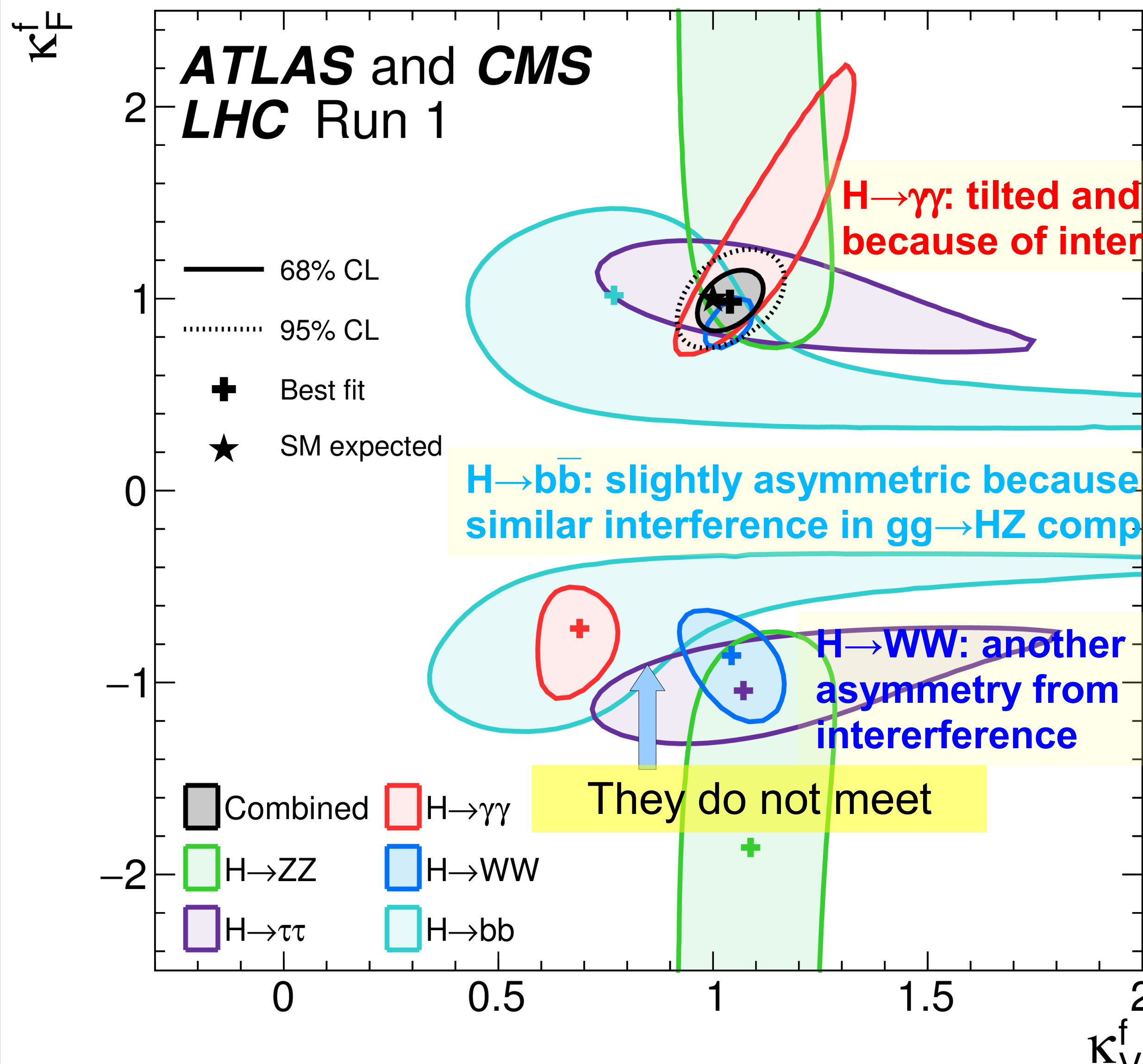
# Use interference

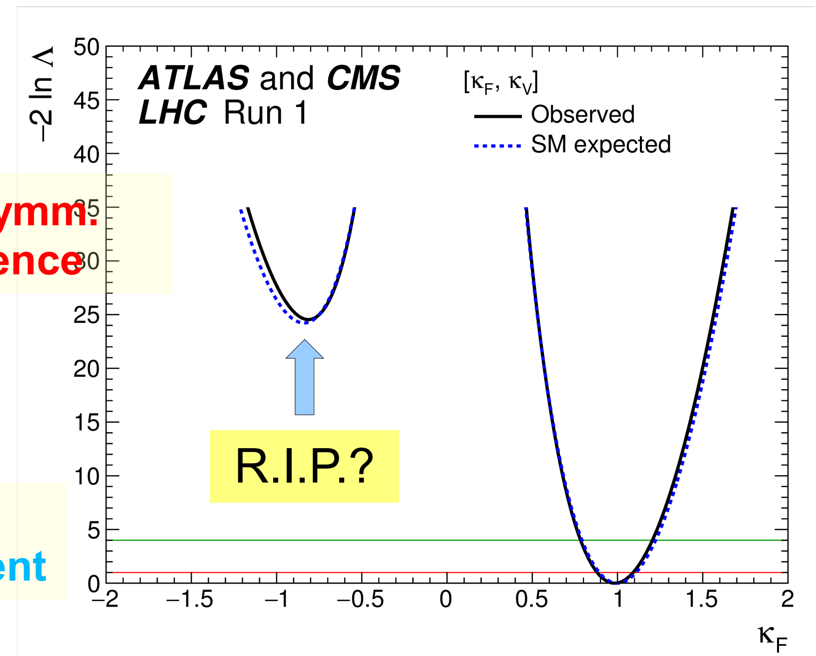
$B(H\to\gamma\gamma)\propto$




- This branching ratio has both a quadratic and a linear term in $y_t$, the latter coming from interference
- Fermion loops and boson loops have amplitudes of opposite sign → destructive interference in SM
- Swapping the sign of $y_t$ makes interference constructive, and BR enhanced by 2.4 times

# The case is closed?



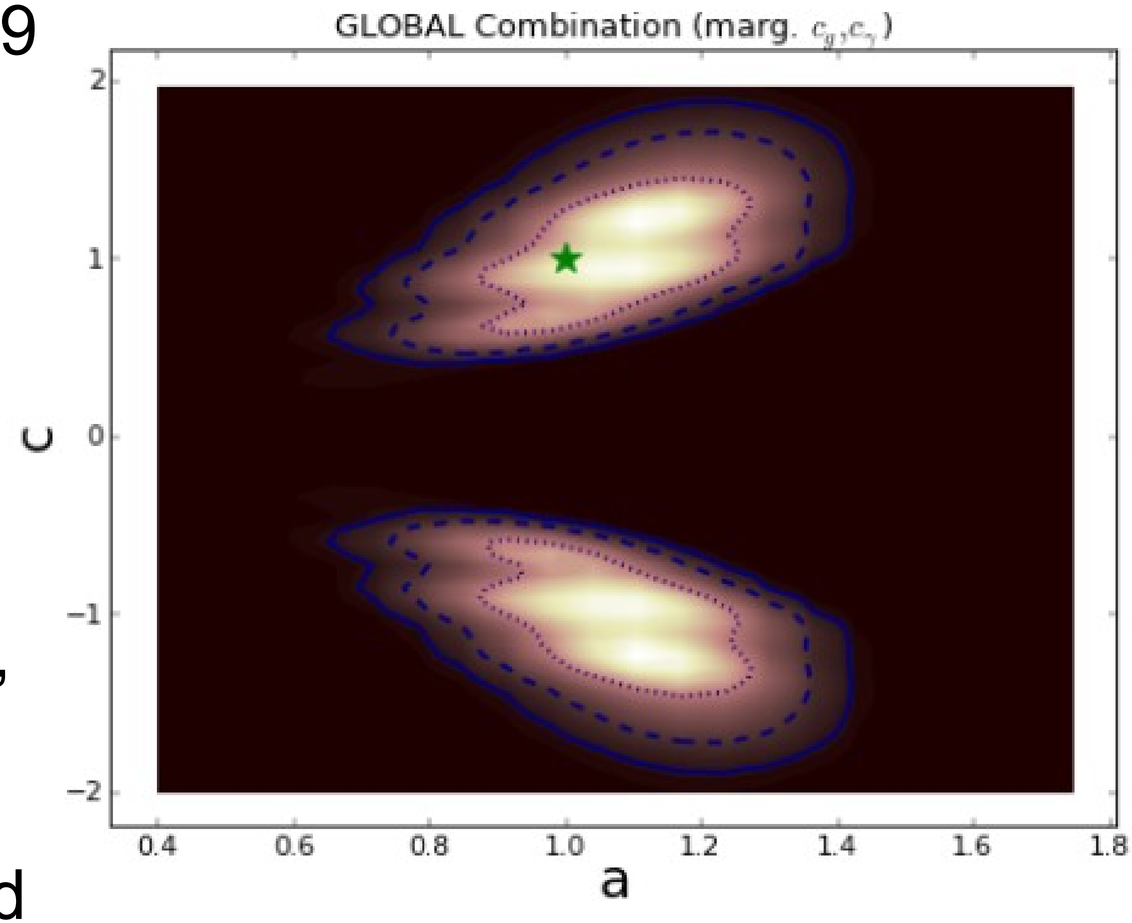




This parameterization considers a single multiplier for all fermions. Compatible with 1 ⇒ $y_t \sim 1$

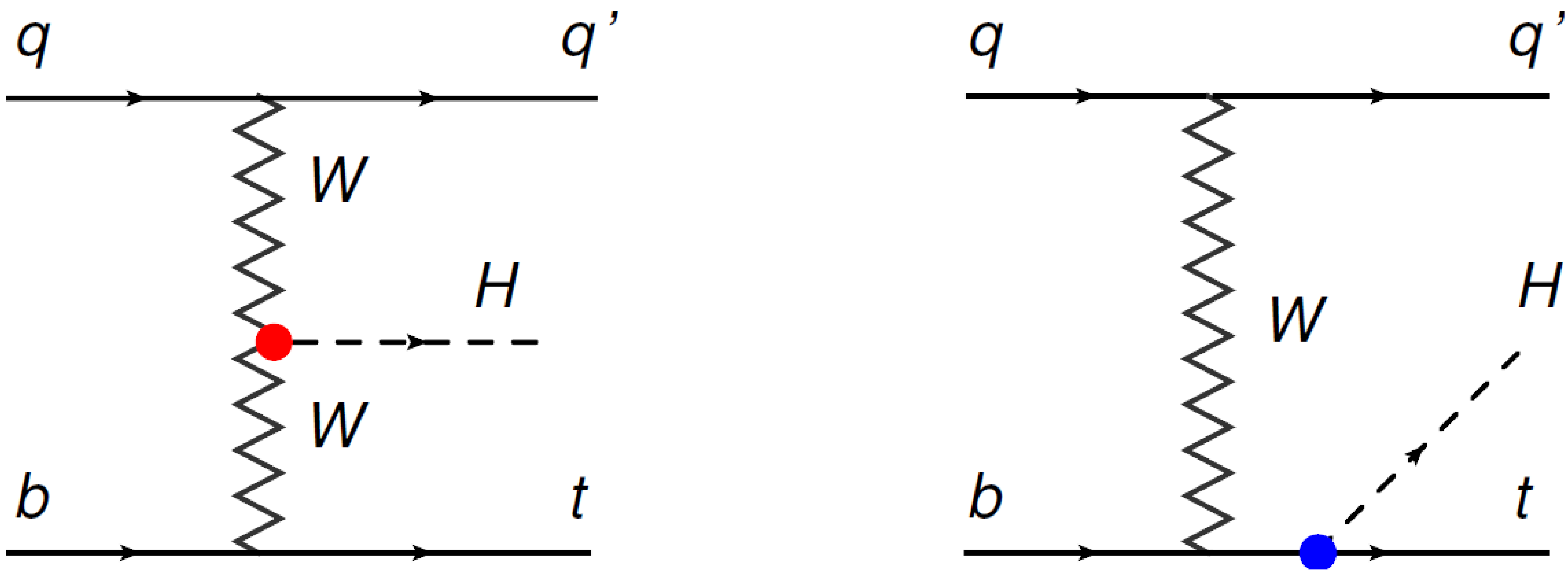
**Assumption: no BSM in loops**

# Remove that assumption and...

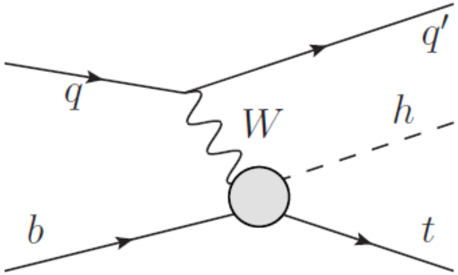
- J.Ellis, T.You, JHEP 06 (2013) 103, arXiv:1303.3879
  - Based on home-made combination of CMS, ATLAS, and Tevatron (not up to date, but here it doesn't matter)
- Here *a,c* have similar meaning as $k_V$, $k_F$
- In the plot reproduced here, BSM contributions are allowed in ggH and Hγγ loops and marginalised, and **the minima are degenerate**



# Looking for a better "interferometer"



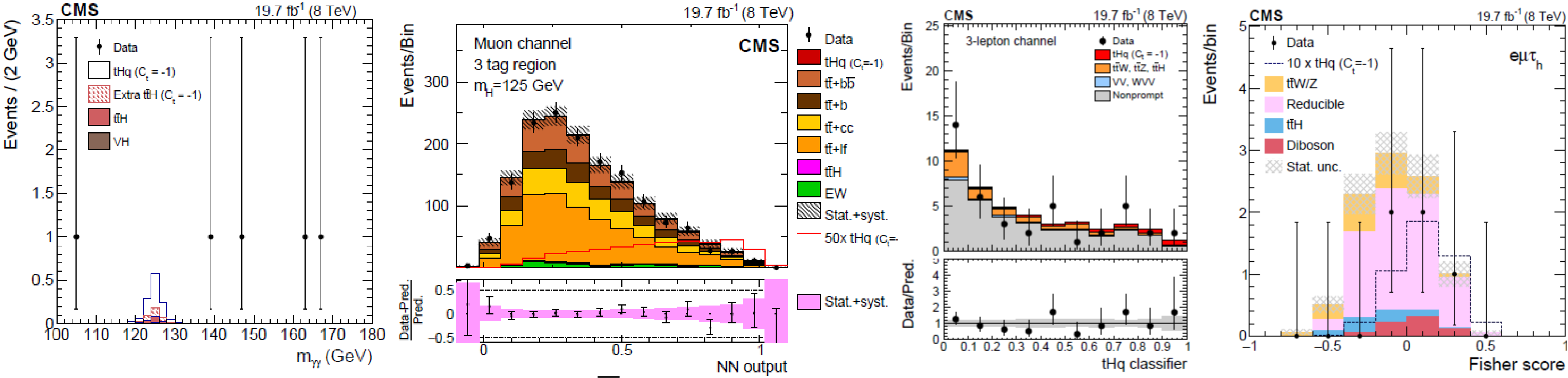

- In tHq production, accidentally (*) strong cancellation *at tree level* in the SM (only 18 fb @ 8 TeV)
  - (*) note: the same that plays a role in the „naturalness“ problem...
- Hence, strong enhancement (~13x) if the relative sign between HWW and Htt couplings turns out to be negative




# tH: Run-1 analyses

CMS coll., JHEP 06 (2016) 177

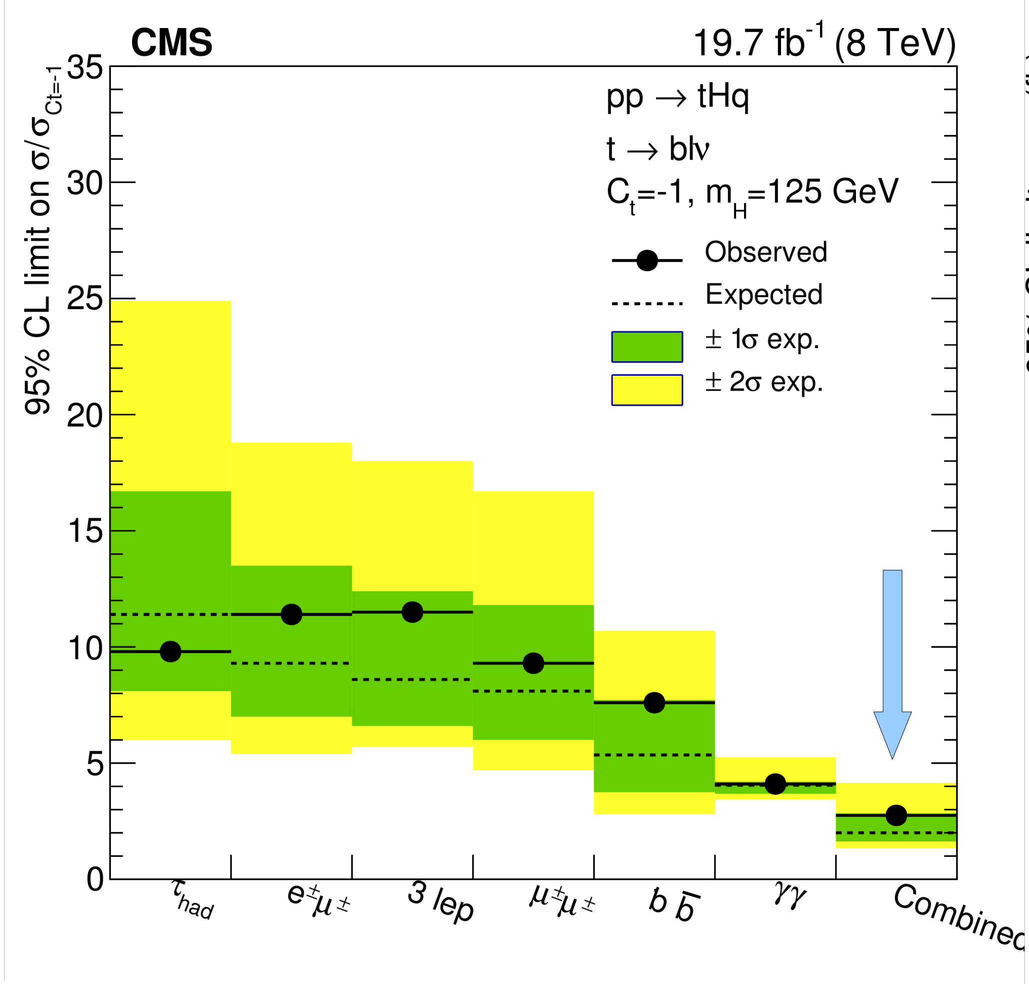
- Search was performed in γγ, $b\bar{b}$, multi-lepton, ττ decays
- Common features:
  - Top quark always assumed to decay leptonically
  - Pseudorapidity of "recoil quark" (q') is a good discriminant
  - Exploiting dominance of top over anti-top in signal
  - Analyses optimized for $y_t$=-1

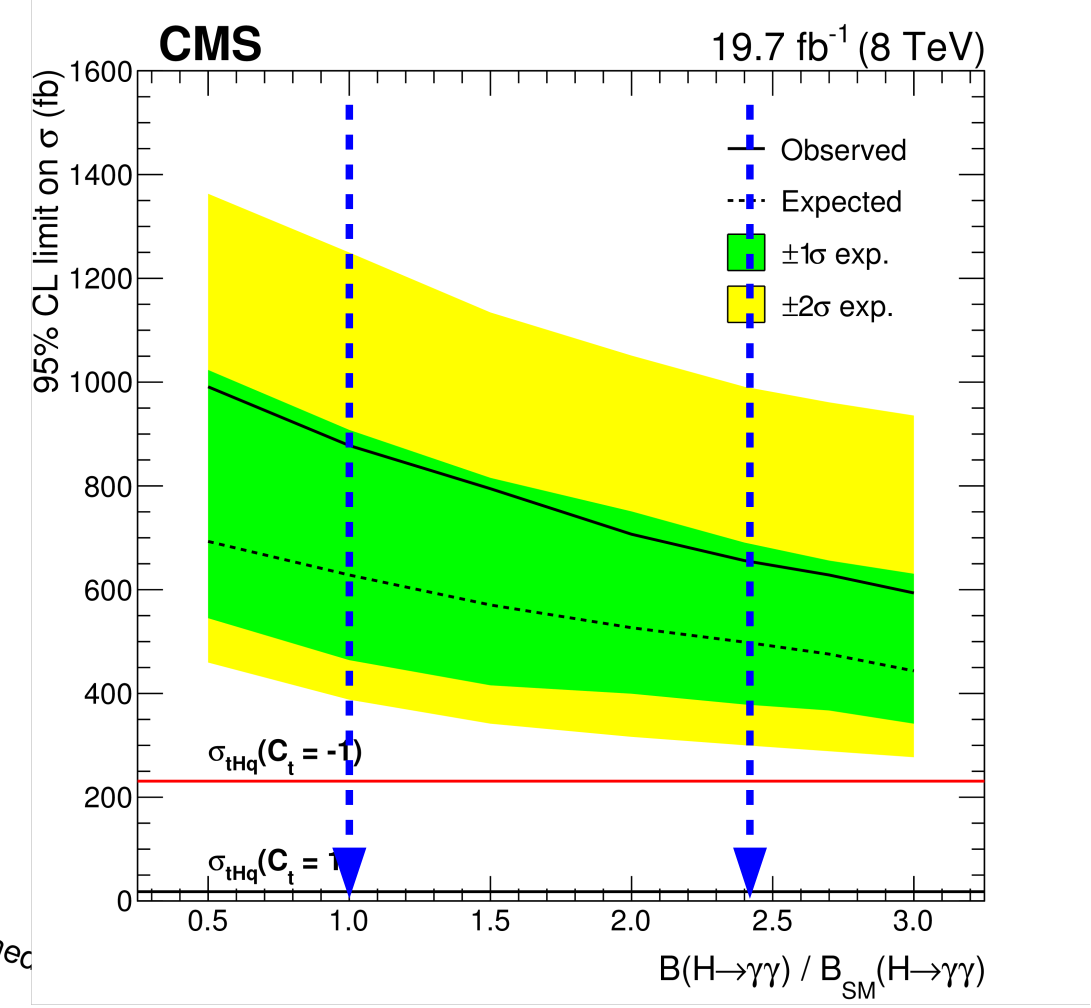



γγ    $b\bar{b}$    multi-lepton    ττ

# tH: Run-1 combination

CMS coll., JHEP 06 (2016) 177



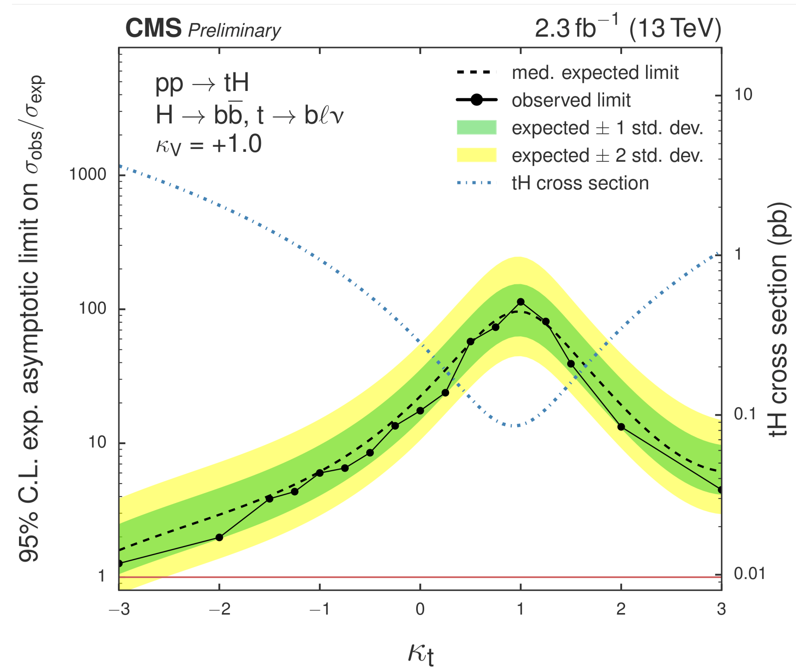

**Observed (expected) limit: 2.8 (2.0) times the expectation for $y_t$=-1**

This plot assumes B(H→γγ) = 2.4xSM

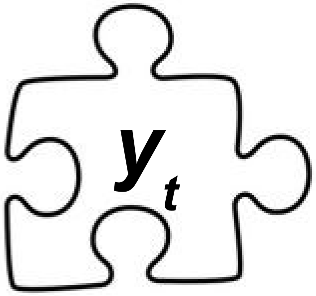
This plot is agnostic about B(H→γγ)

# tH: Run-2 status

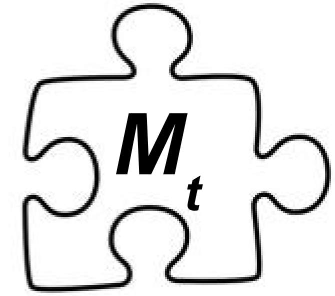
- Cross section: 4x from 8 to 13 TeV
- Preliminary result in $b\bar{b}$ channel with 2015 data (2.3/fb) is available
  - Similar analysis but multi-MVA optimized across the ($k_F$,$k_V$) plane
  - Not improving over Run-1 yet, but:
  - Inclusion of tHW as part of signal
  - More theory interpretations
- Other channels: work in progress
  - A priori, di-photon "golden channel" is expected to drive the sensitivity in the combination of 2016 data (as it did in Run-1)




CMS-PAS-HIG-16-019




# Summary

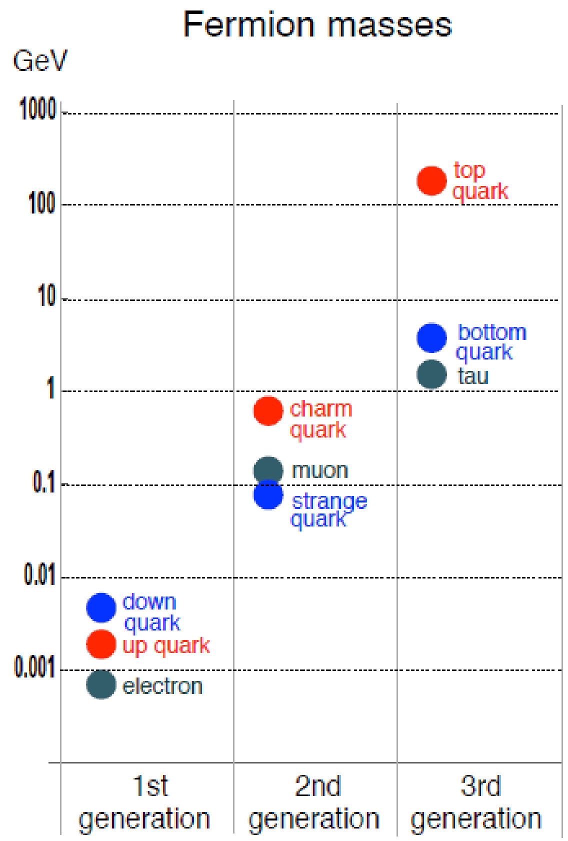



- The fermion mass pattern is a puzzle
- And the top-Higgs coupling is really close to 1; who ordered that? Does it *mean* something?
- Is it 1 or just very close? Real or complex?
- If we answer those questions, will we unlock the solution to the puzzle?
- We are attacking the problem from many experimental directions, all quite challenging
- Work in progress. Stay tuned!

# Thanks for your attention

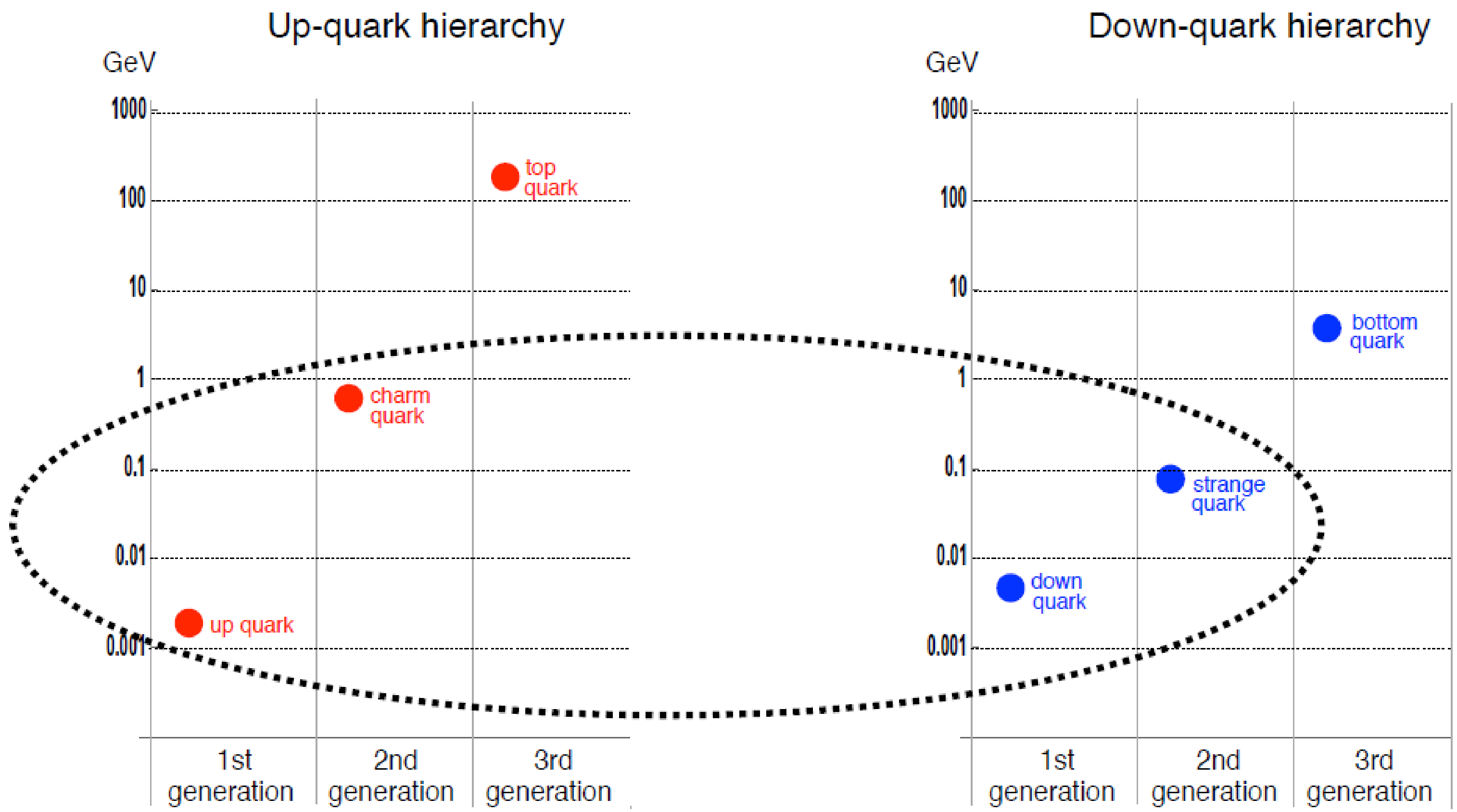
And thanks to Martijn Mulders, André David, Matthias Komm, Georgios Krintiras, for their comments and suggestions during the preparation of this talk

# A different look at it (1)




From Gilad Perez

# A different look at it (2)

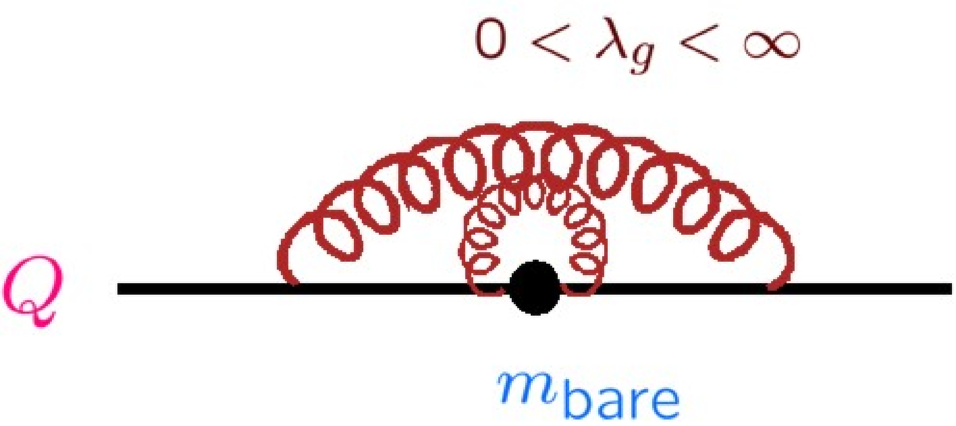


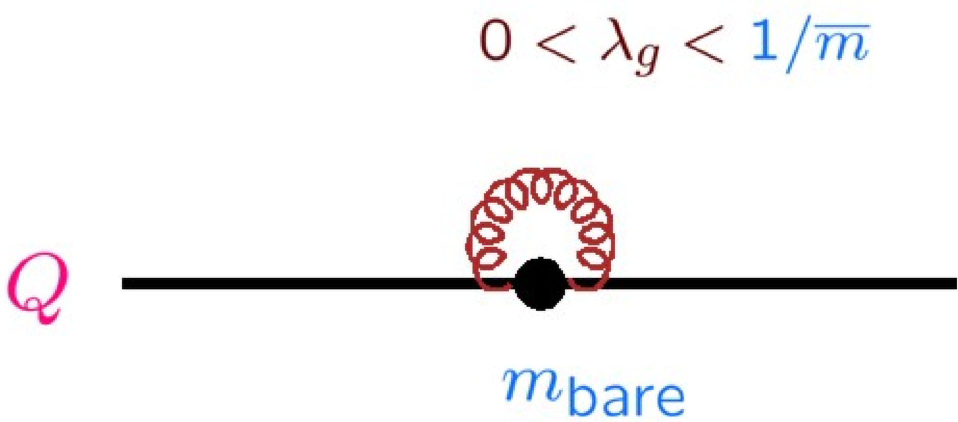

From Gilad Perez

# Masses

Pole mass $m_{\text{pole}}$

$\overline{\text{MS}}$ mass $\overline{m} \equiv m_{\overline{\text{MS}}}(m_{\overline{\text{MS}}})$

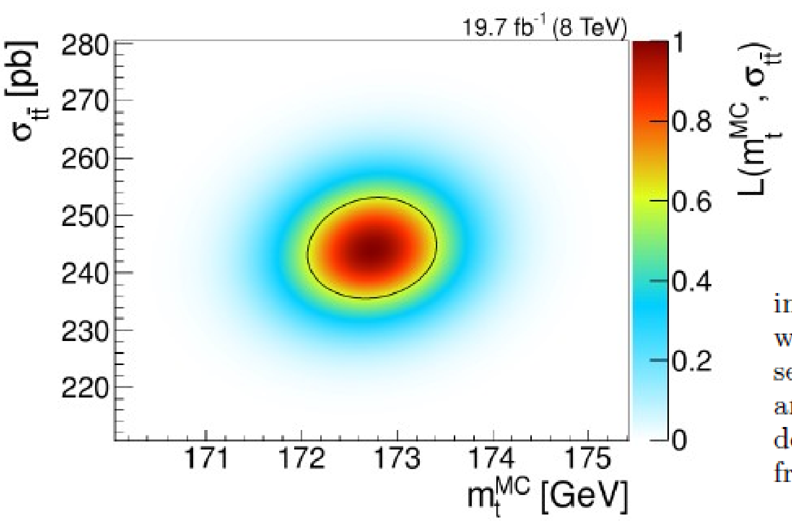



From arXiv:1407.5353 [hep-ph]

# Top mass meaurements: MC and pole?

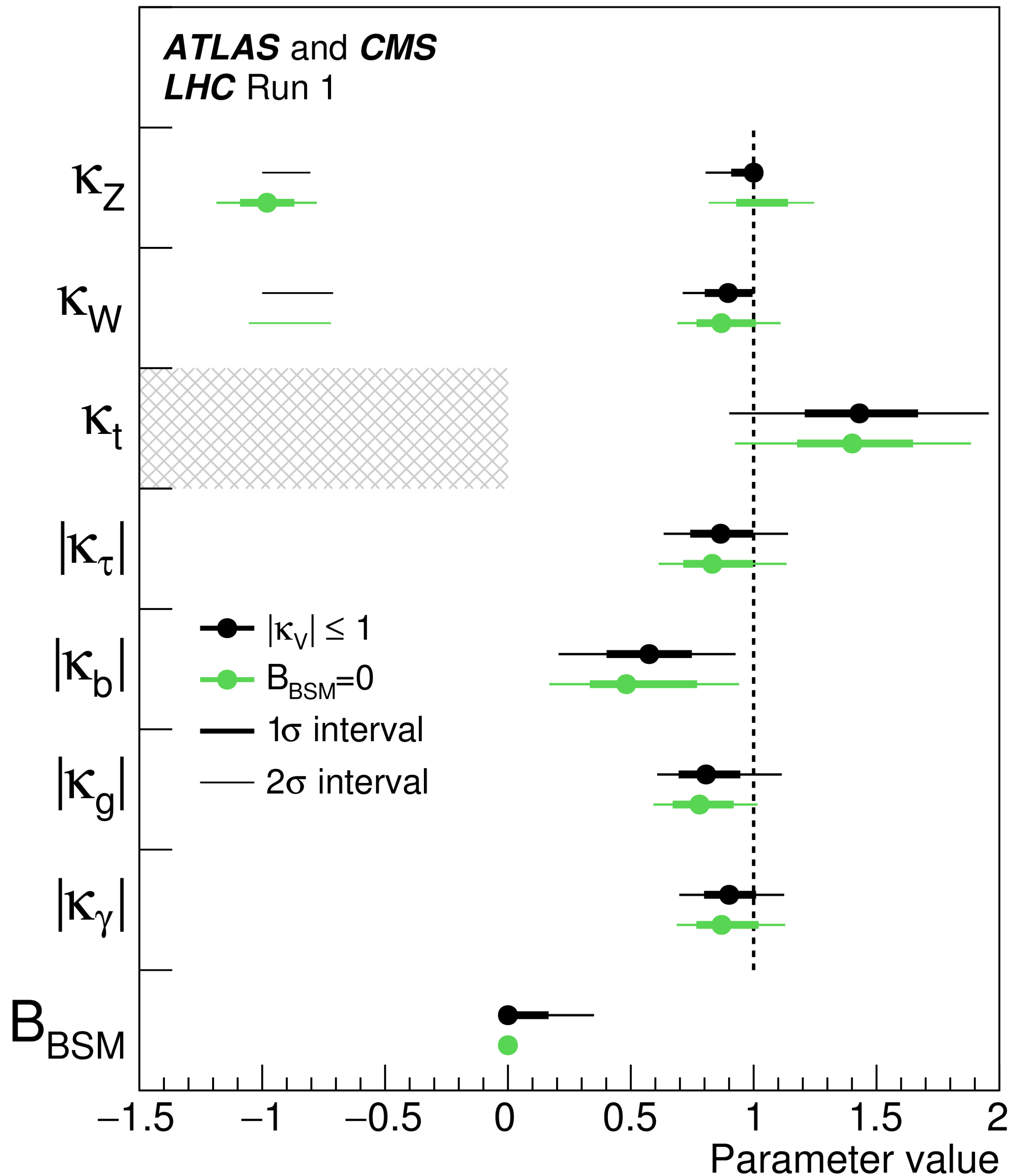
J.Kieseler, K.Lipka, O.Moch, „Calibration of the Top-Quark Monte Carlo Mass“, Phys.Rev.Lett. 116 (2016) 16, 162001, arXiv:1511.00841 [hep-ph]




We present a method to establish experimentally the relation between the top-quark mass $m_t^{\mathrm{MC}}$ as implemented in Monte-Carlo generators and the Lagrangian mass parameter $m_t$ in a theoretically well-defined renormalization scheme. We propose a simultaneous fit of $m_t^{\mathrm{MC}}$ and an observable sensitive to $m_t$, which does not rely on any prior assumptions about the relation between $m_t$ and $m_t^{\mathrm{MC}}$. The measured observable is independent of $m_t^{\mathrm{MC}}$ and can be used subsequently for a determination of $m_t$. The analysis strategy is illustrated with examples for the extraction of $m_t$ from inclusive and differential cross sections for hadro-production of top-quarks.

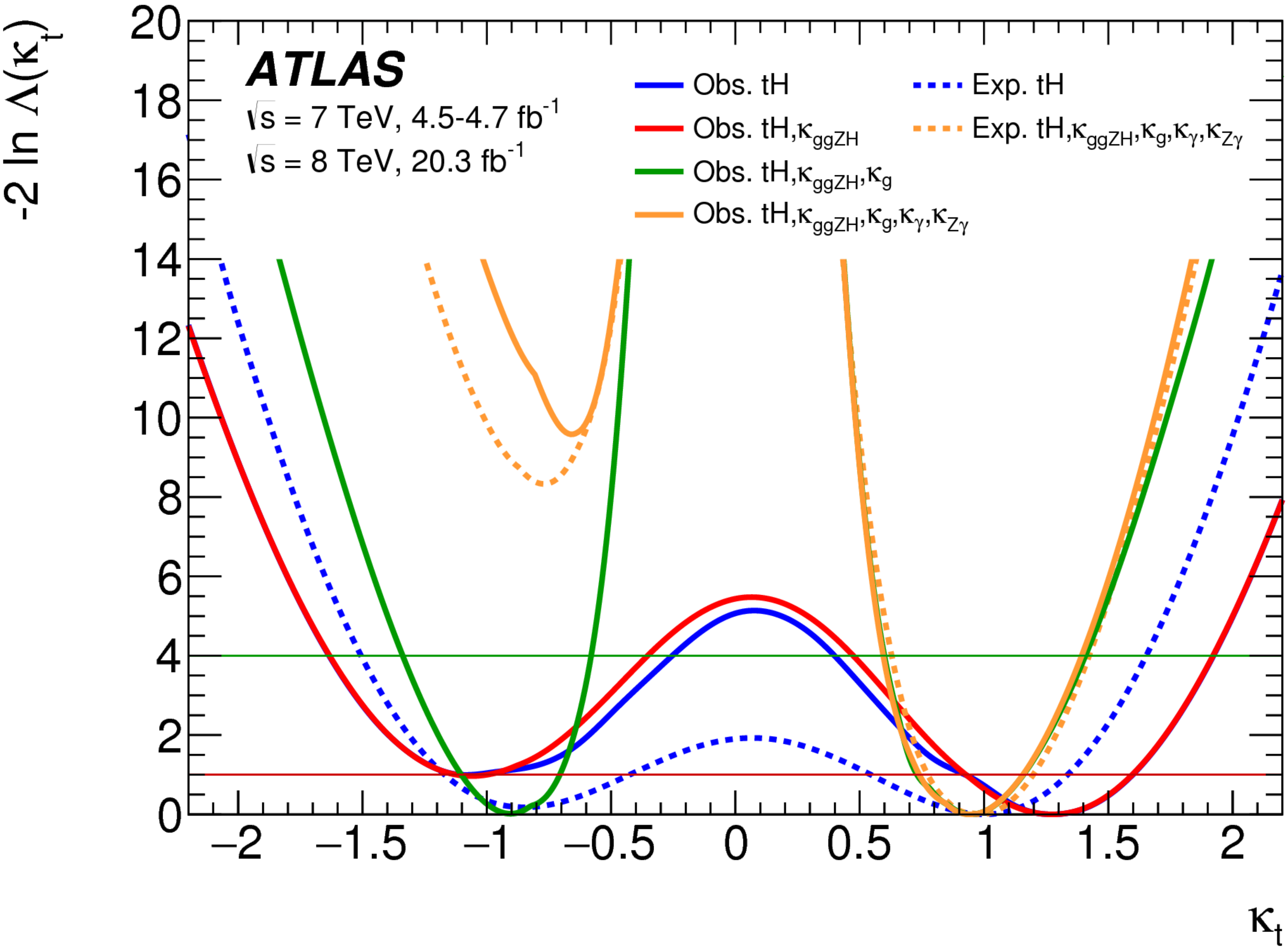
# Main top mass measurement techniques

- Template method:
  - Compare data with templates from simulation with different masses
- Ideogram method:
  - Signal event likelihood from Breit-Wigner convoluted with detector response
- Matrix Element method:
  - Event likelihood as a function of observed final state configuration, from the (LO) matrix element (which is a function of top mass in the signal case)



ATLAS and CMS
LHC Run 1
κZ
κW
κt
|κτ|
|κb|
|κg|
|κγ|
BBSM
|κV| ≤ 1
BBSM=0
1σ interval
2σ interval
−1.5
−1
−0.5
0
0.5
1
1.5
2
Parameter value

| Production | Loops | Interference | Expression in fundamental coupling-strength scale factors |
|---|---|---|---|
| $\sigma(\text{ggF})$ | ✓ | $b$–$t$ | $\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$ |
| $\sigma(\text{VBF})$ | - | - | $\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$ |
| $\sigma(WH)$ | - | - | $\sim \kappa_W^2$ |
| $\sigma(q\bar{q} \to ZH)$ | - | - | $\sim \kappa_Z^2$ |
| $\sigma(gg \to ZH)$ | ✓ | $Z$–$t$ | $\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$ |
| $\sigma(bbH)$ | - | - | $\sim \kappa_b^2$ |
| $\sigma(ttH)$ | - | - | $\sim \kappa_t^2$ |
| $\sigma(gb \to WtH)$ | - | $W$–$t$ | $\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$ |
| $\sigma(qb \to tHq')$ | - | $W$–$t$ | $\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$ |
| Partial decay width | | | |
| $\Gamma_{b\bar{b}}$ | - | - | $\sim \kappa_b^2$ |
| $\Gamma_{WW}$ | - | - | $\sim \kappa_W^2$ |
| $\Gamma_{ZZ}$ | - | - | $\sim \kappa_Z^2$ |
| $\Gamma_{\tau\tau}$ | - | - | $\sim \kappa_\tau^2$ |
| $\Gamma_{\mu\mu}$ | - | - | $\sim \kappa_\mu^2$ |
| $\Gamma_{\gamma\gamma}$ | ✓ | $W$–$t$ | $\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$ |
| $\Gamma_{Z\gamma}$ | ✓ | $W$–$t$ | $\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$ |
| Total decay width | | | |
| $\Gamma_H$ | ✓ | $W - t$<br>$b - t$ | $\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$ |



ATLAS
√s = 7 TeV, 4.5-4.7 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
Obs. tH
Obs. tH,κggZH
Obs. tH,κggZH,κg
Obs. tH,κggZH,κg,κγ,κZγ
Exp. tH
Exp. tH,κggZH,κg,κγ,κZγ
-2 ln Λ(κt)
κt