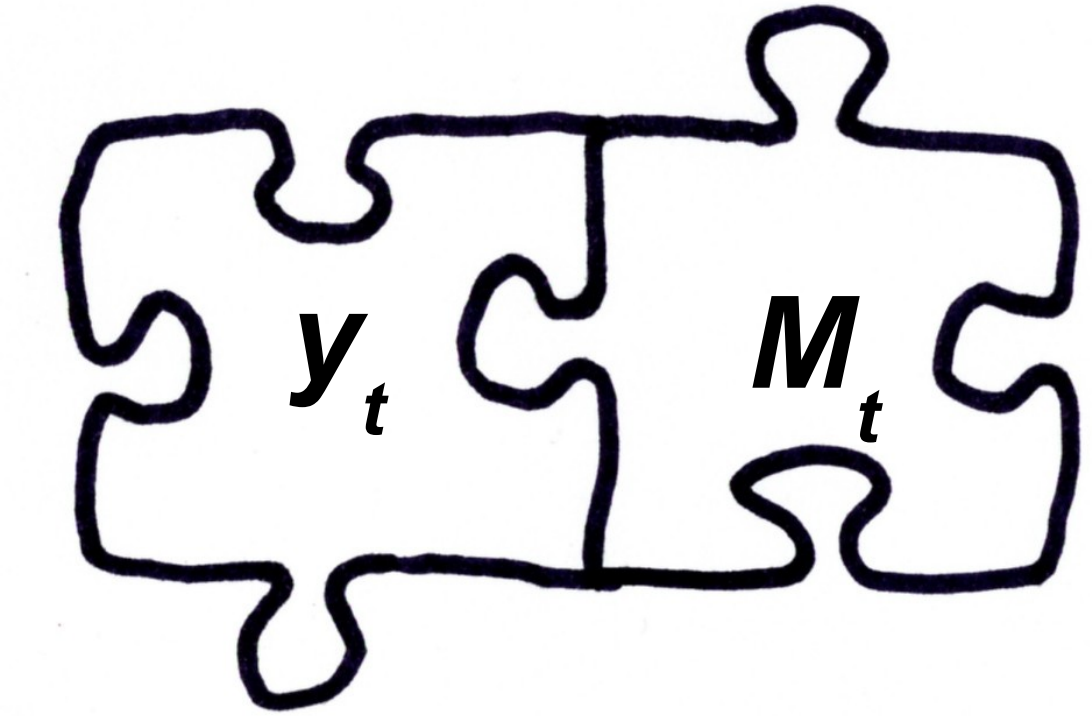
Who ordered that?

Investigations of the top-Higgs connection



Andrea Giammanco (CP3, UCLouvain)

Introduction



"Who ordered that?", I.Rabi

- 1936: discovery of the muon
  - Early consensus: Yukawa ordered that
- 1947: discovery of the pion
  - The muon has nothing to do with 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 $\nu_\mu \neq \nu_e$
  - 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
ν_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
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0	**c** charm	1.3	2/3
μ muon	0.106	−1	**s** strange	0.1	−1/3
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0	**t** top	173	2/3
τ 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, …

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
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μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
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s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

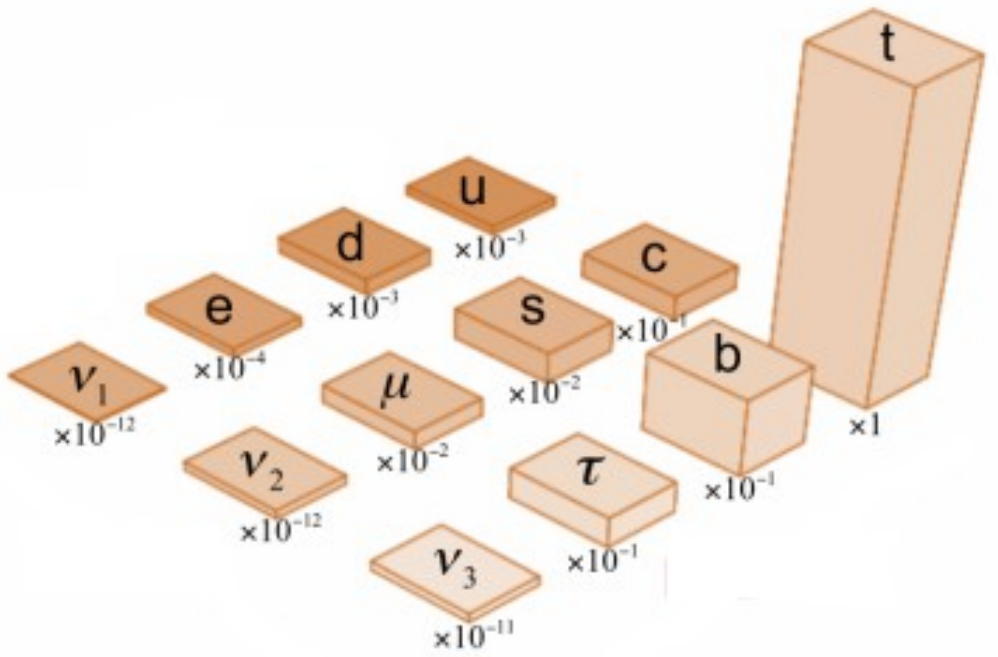
Image source: CPEP

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

a. & b. ⇒ I was led to the brink of madness!

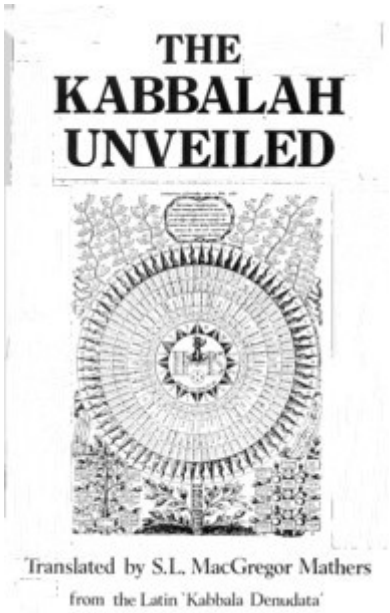
The Flavor Puzzle,

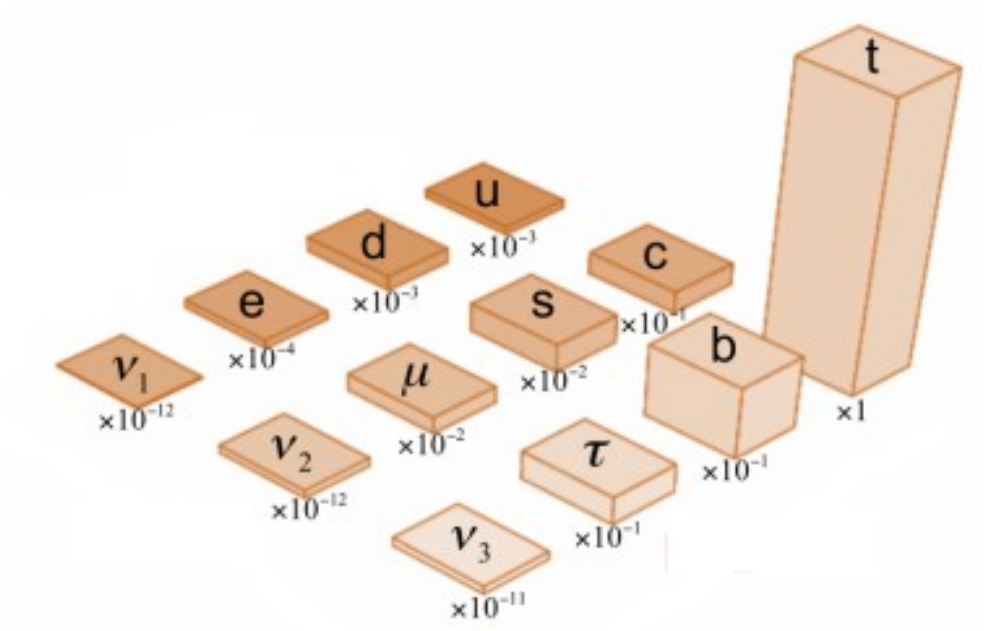
i.e., can we make sense of the fermion masses?



Picture stolen from here

Numerology





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
(and for neutrinos we don't know: J.-M.Gérard et al, Phys.Lett. B633 (2006) 563-566)

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

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):

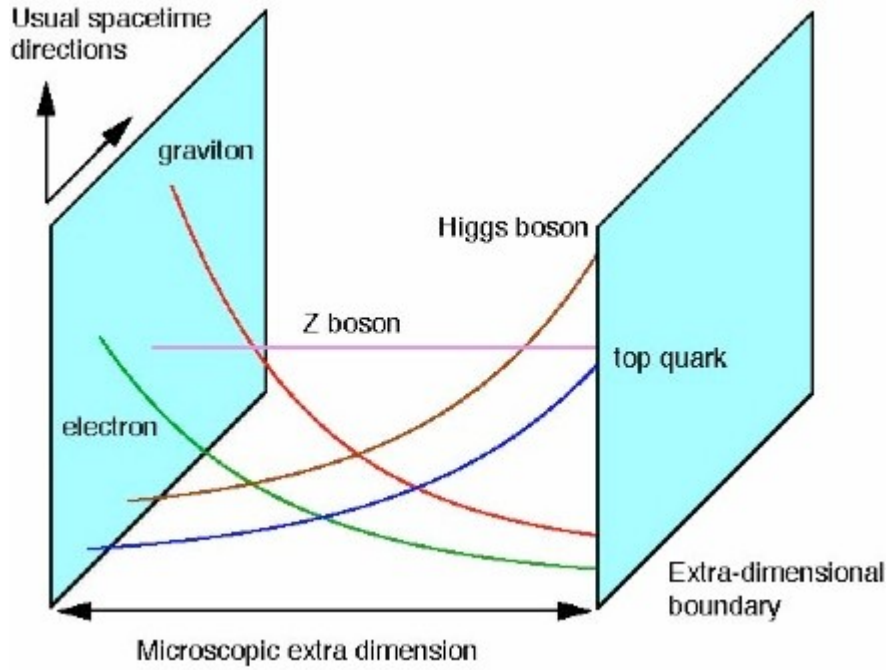


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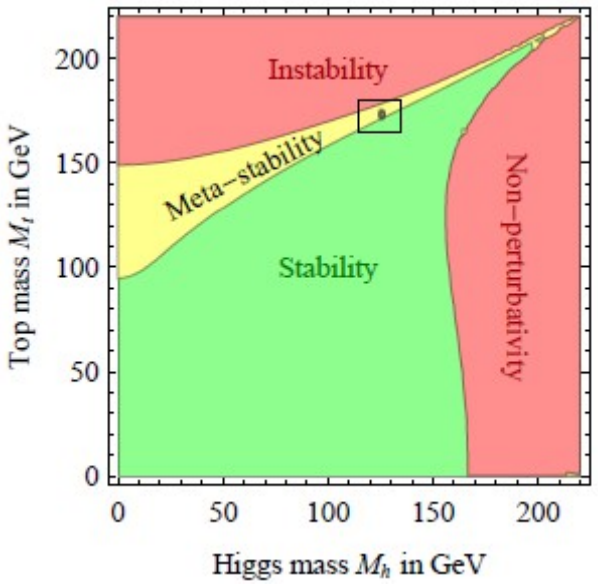
Coupling strengths come from the wavefunction shapes and their overlaps in the warped dimension.
Ok but who ordered … (multi-verse?)

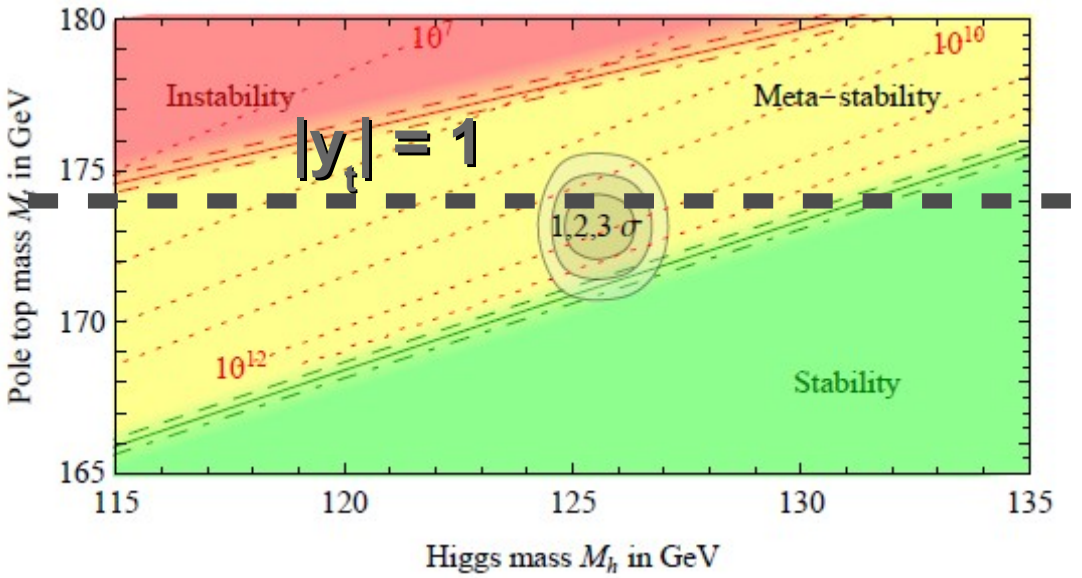
More numerology

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

- 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)
  - Closeness to 1 is interesting, for an adimensional parameter (Martinelli dixit: "In Physics there are only 0 and 1")
  - 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)

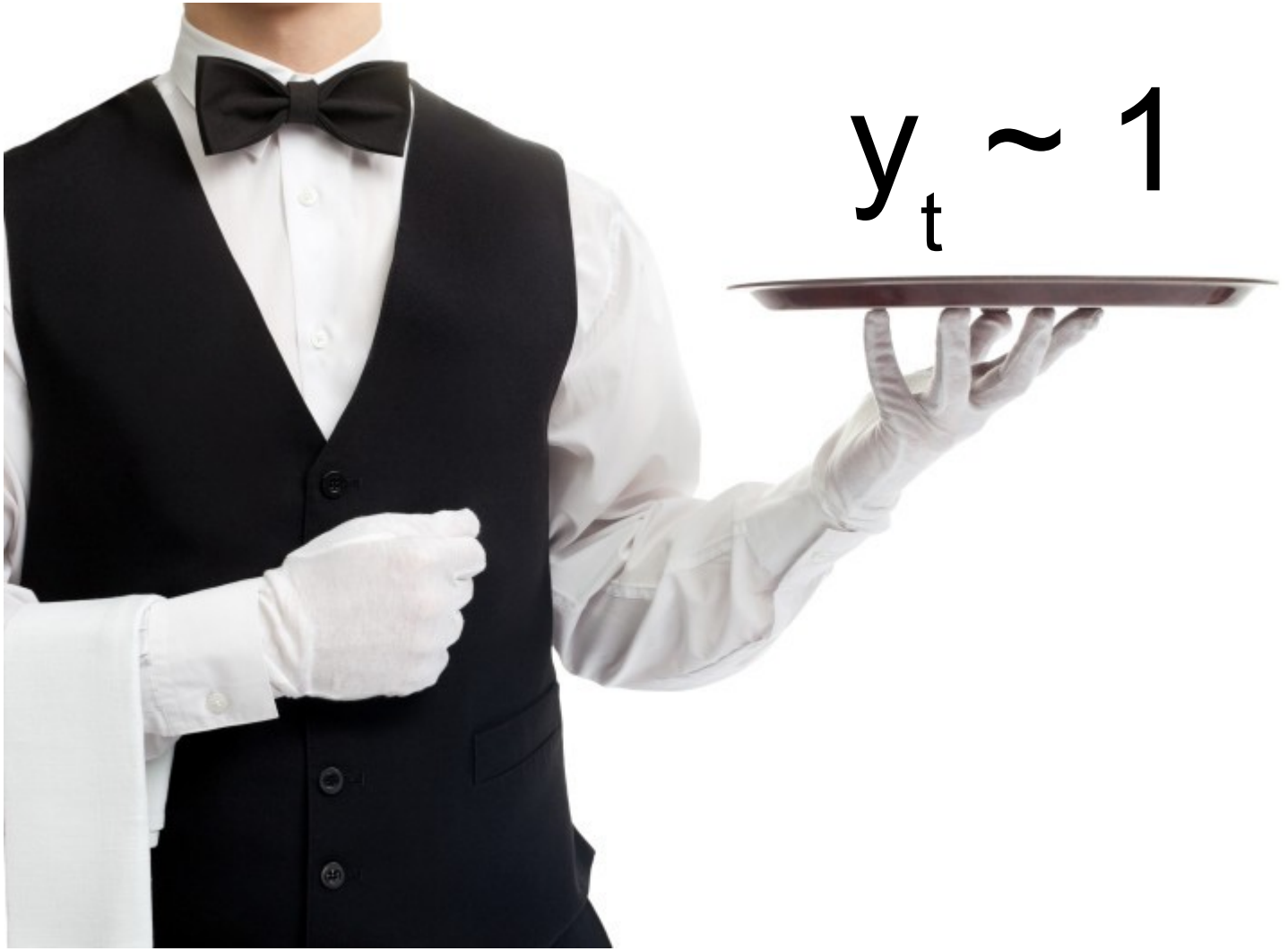
- This study assumes SM validity up to the Planck scale; and, in the SM, m_t and m_H are free parameters
- Under these assumptions, conspiracy of top and Higgs makes our Universe sit on the thin line between stability and instability
- Any deep reason for that? (Anthropic Principle at play?)

Is $y_t = 1$?

- It sounds short. But in practice this question is composed of a few blocks, each of them 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

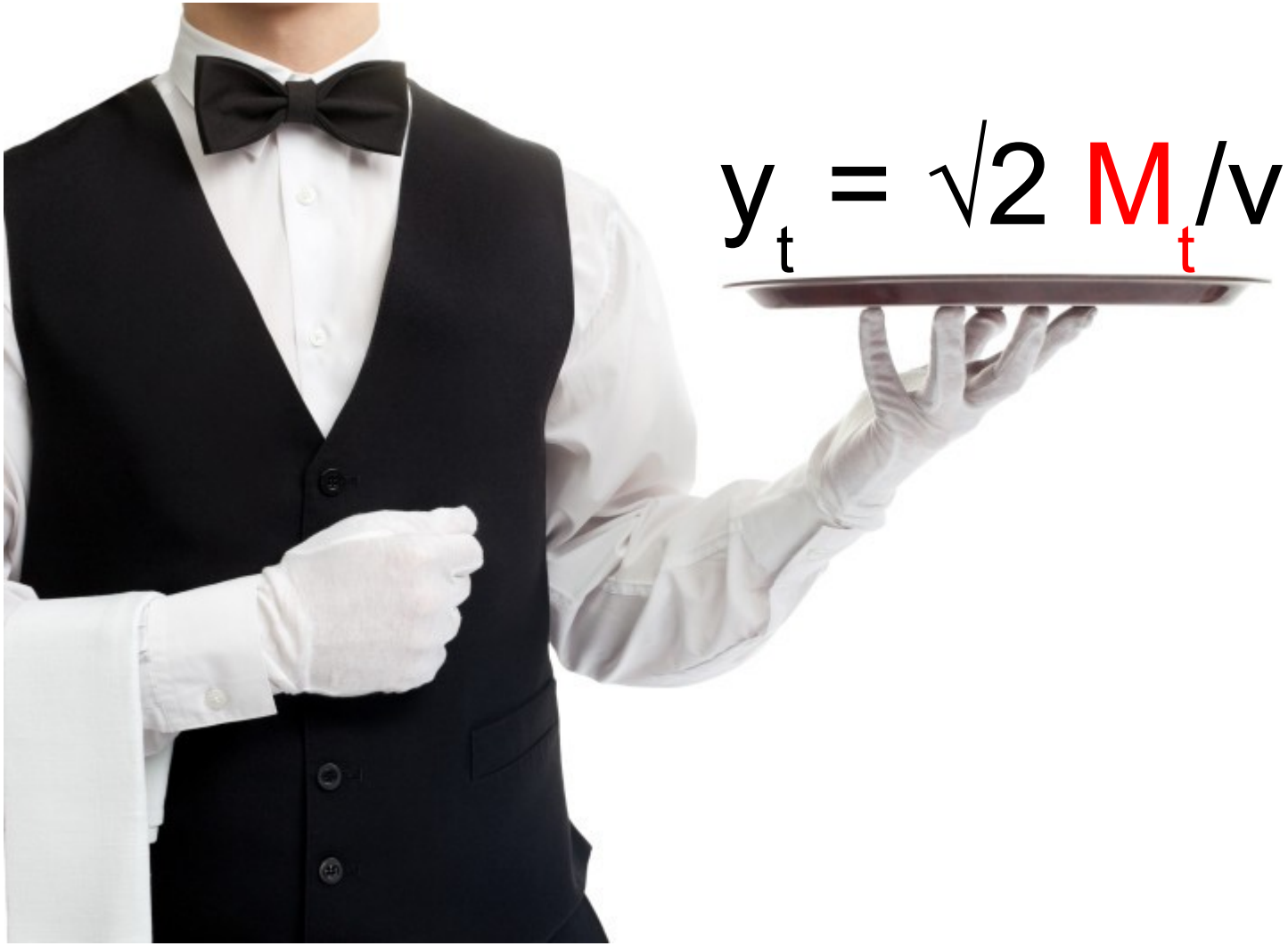
(*) HEP convention: *evidence* at 3σ, *observation* at 5σ

End of introduction



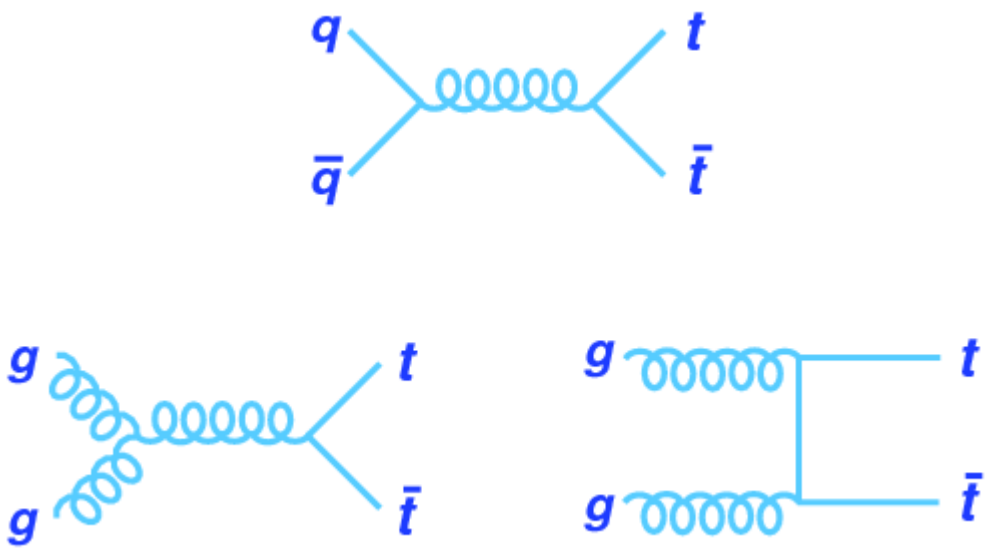
Rest of the talk: experimental work related to this question, involving scores of physicists in the ATLAS and CMS collaborations

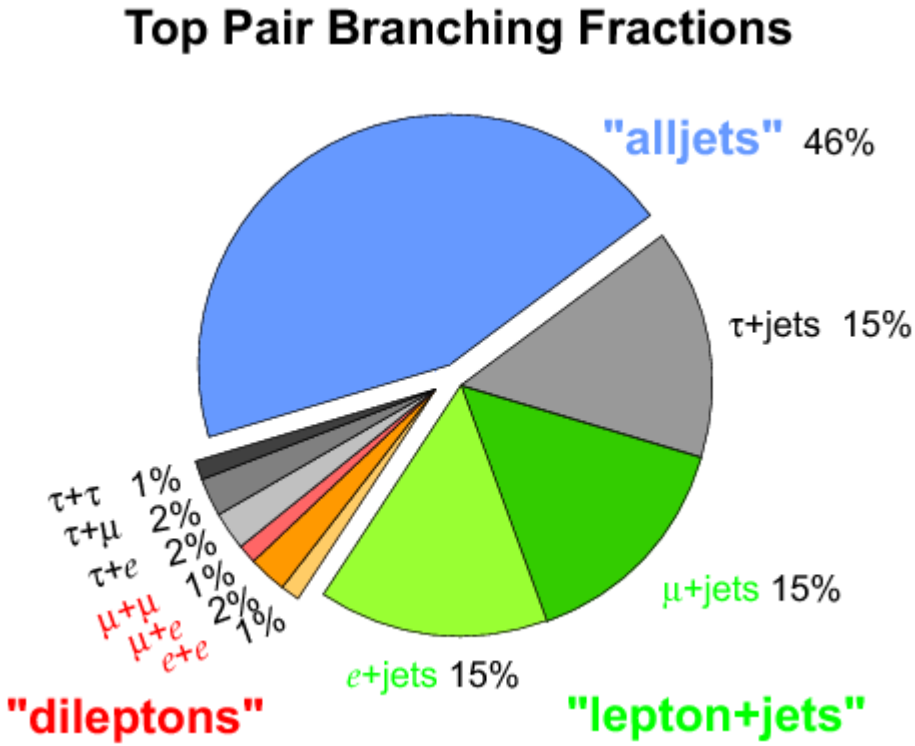
Top mass



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

Top-pair production and decays

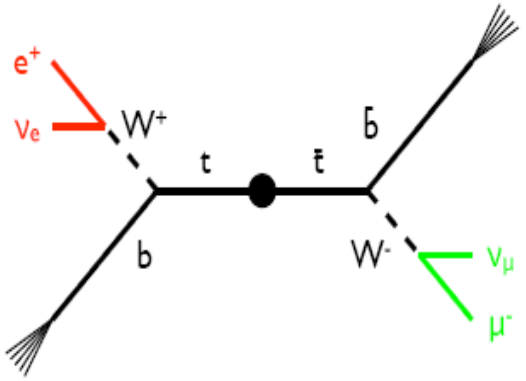


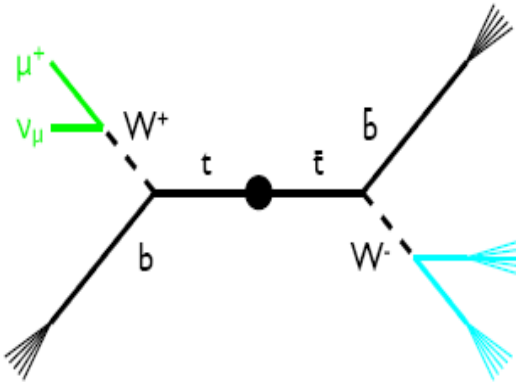


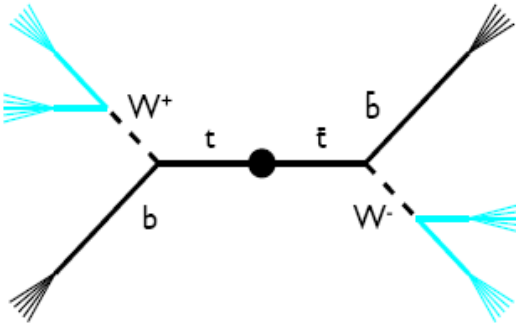
- The dominant production mechanism at LHC is $gg \rightarrow t\bar{t}$ (~85-90% of $t\bar{t}$ at 7-13 TeV)

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 $B(W \to l\nu)^2$;

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

Lepton (e,μ) + jets

Convenient trade-off btw purity and rate;

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

All-hadronic

Low purity;

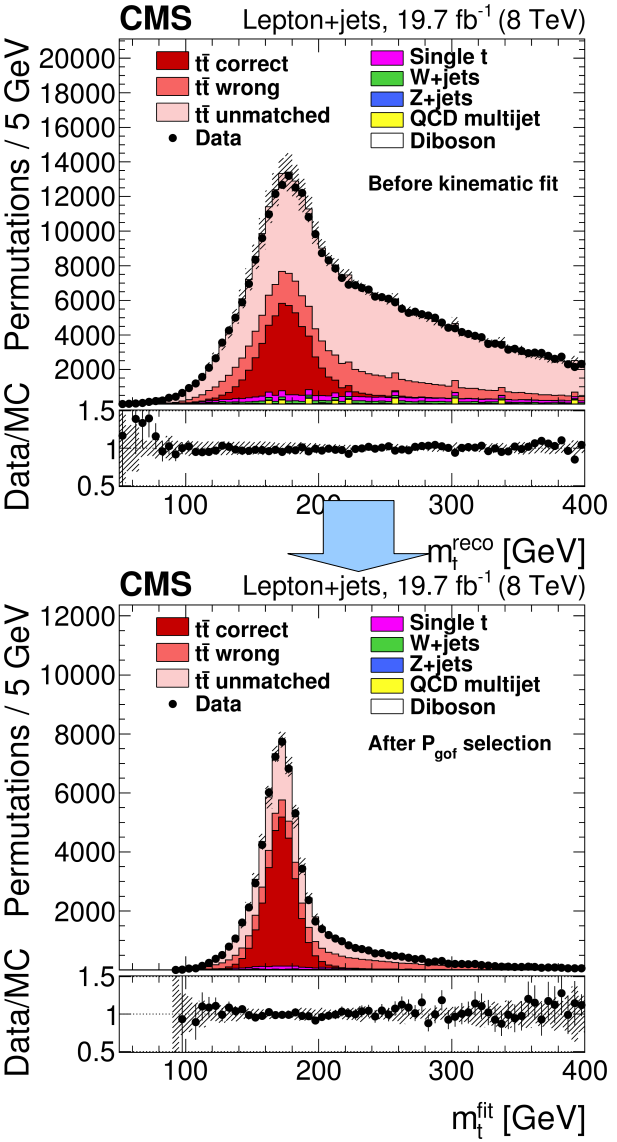
$W \to jj$ gives M_W as standard candle;

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(→jj) candidates, and of b jets to associate to them 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 (with very low resolution) is all that we can use to infer the neutrino momentum
  - Intrinsic quadratic ambiguity:

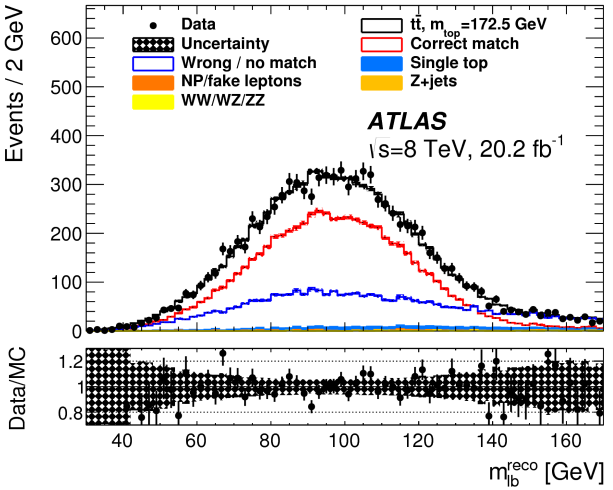
    $M_W^2=(E_l+E_\nu)^2-(\mathbf{P}_l+\mathbf{P}_\nu)^2$ has 2 solutions
- Full event interpretation by least squares method, aka kinematic fit, is often used



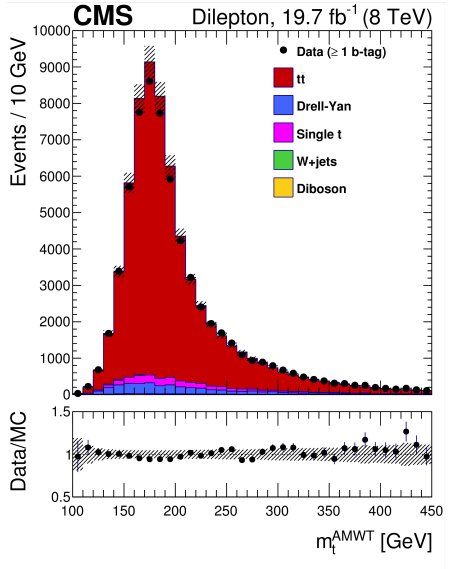
CMS coll., PRD 93 (2016) 072004

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 6th constraint
  - Solution is not unique: any mass constraint is a quadratic equation $\Rightarrow$ 4x2 = 8-fold ambiguity $\Rightarrow$ some criteria needed to pick the best

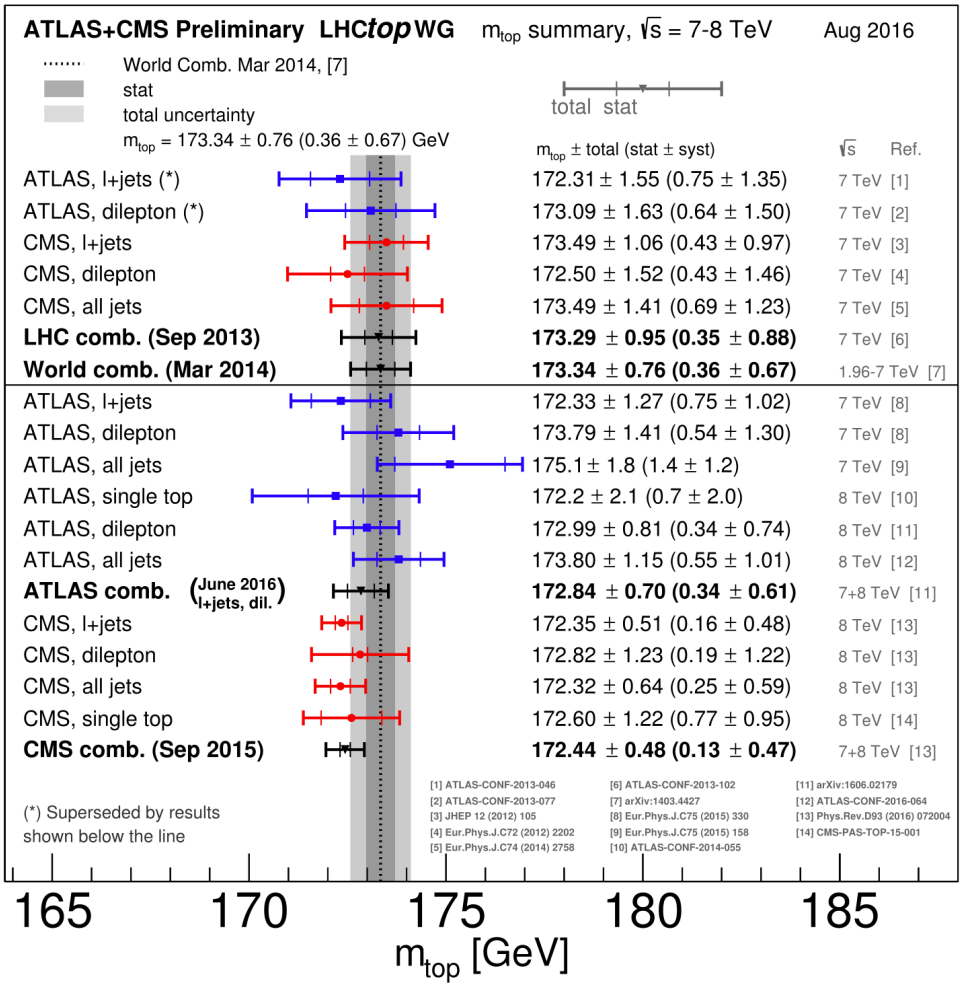


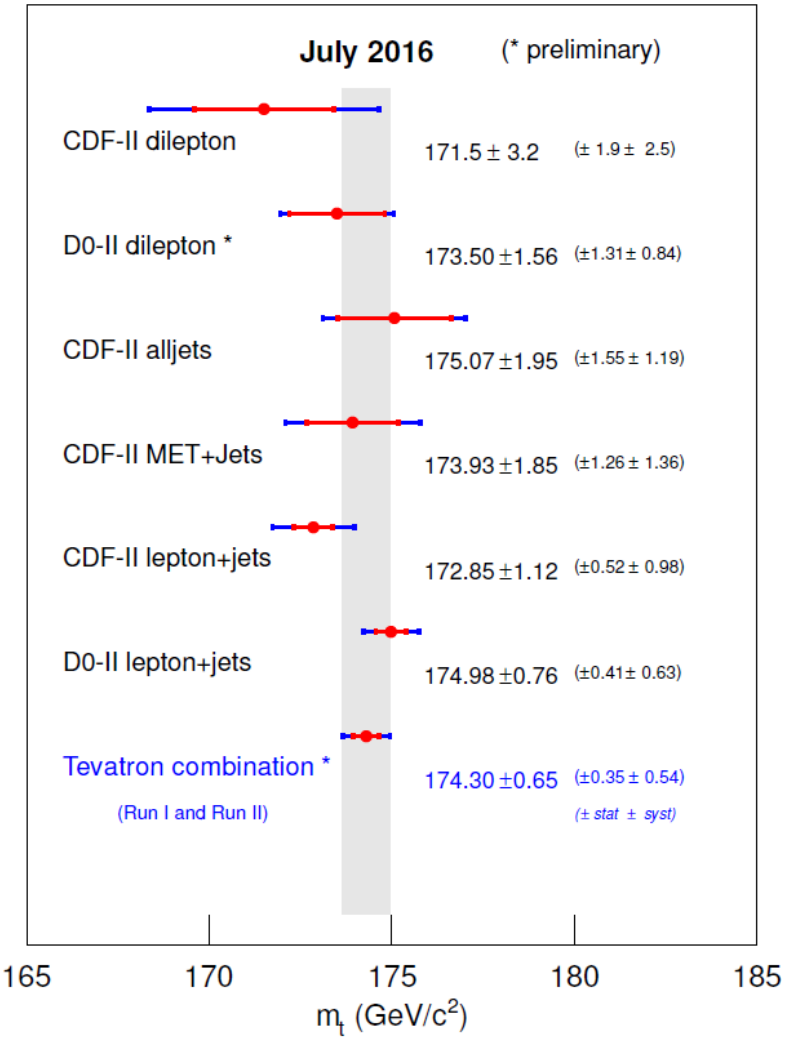
ATLAS coll., PLB 761 (2016) 350



CMS coll., PRD 93 (2016) 072004

Top mass: results





Precisions: ±0.3 (CMS), 0.4% (ATLAS, Tevatron)

What are we measuring exactly?

- These results are impressively *precise*
- Legitimate to ask: are they also *accurate*?

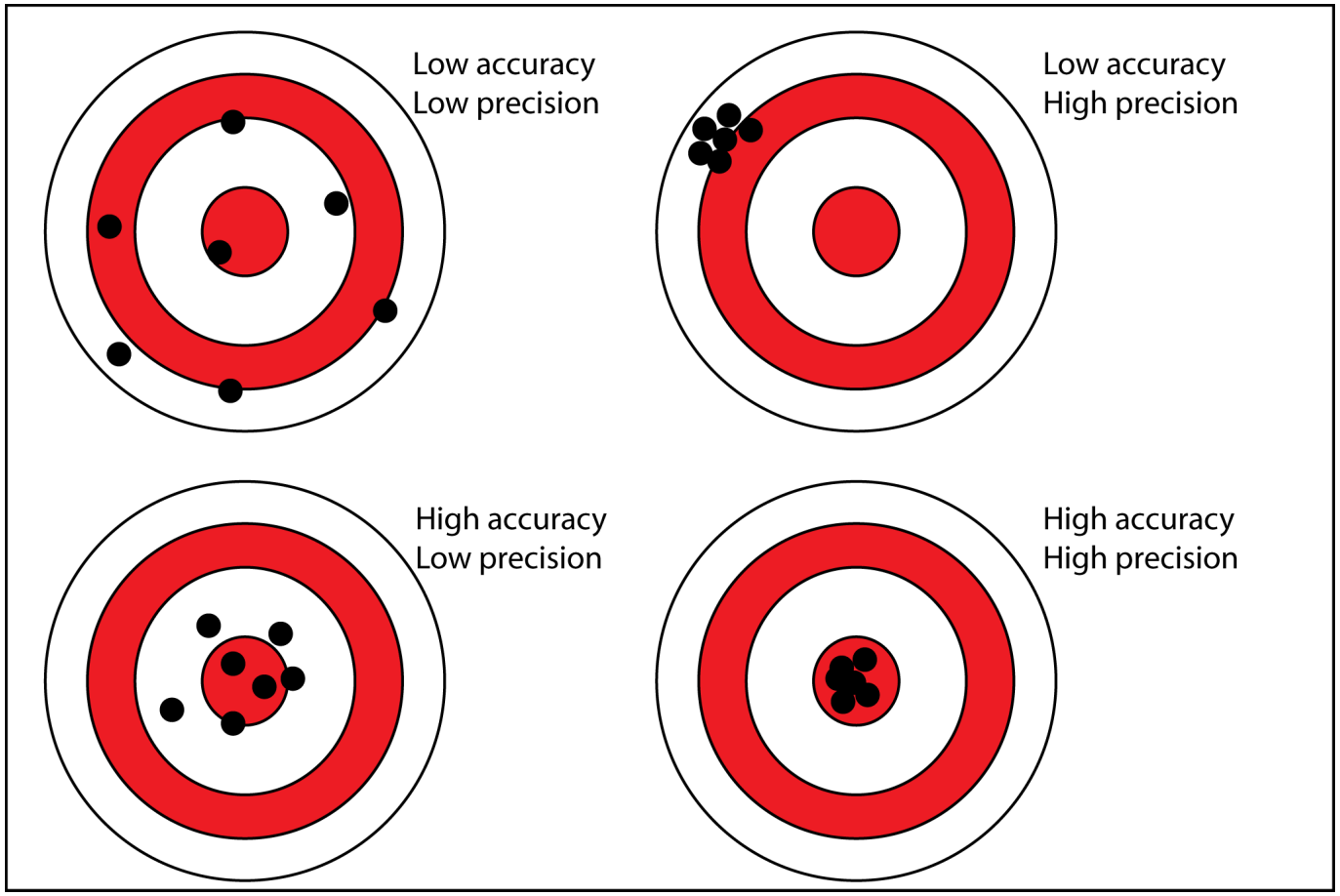
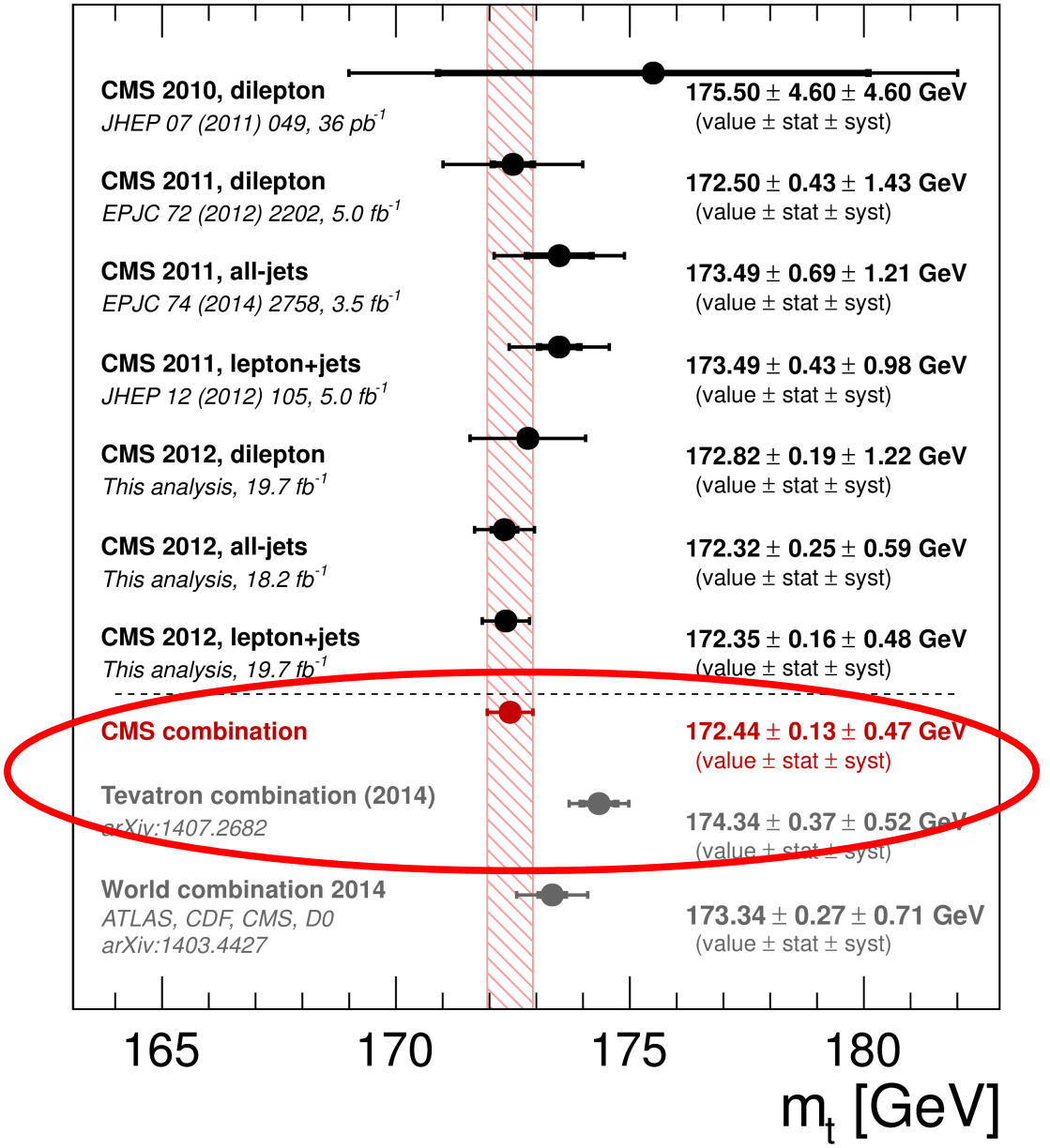


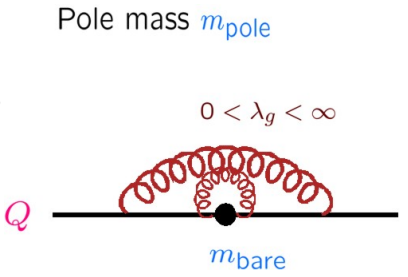
Image stolen from here

Hint of a problem?

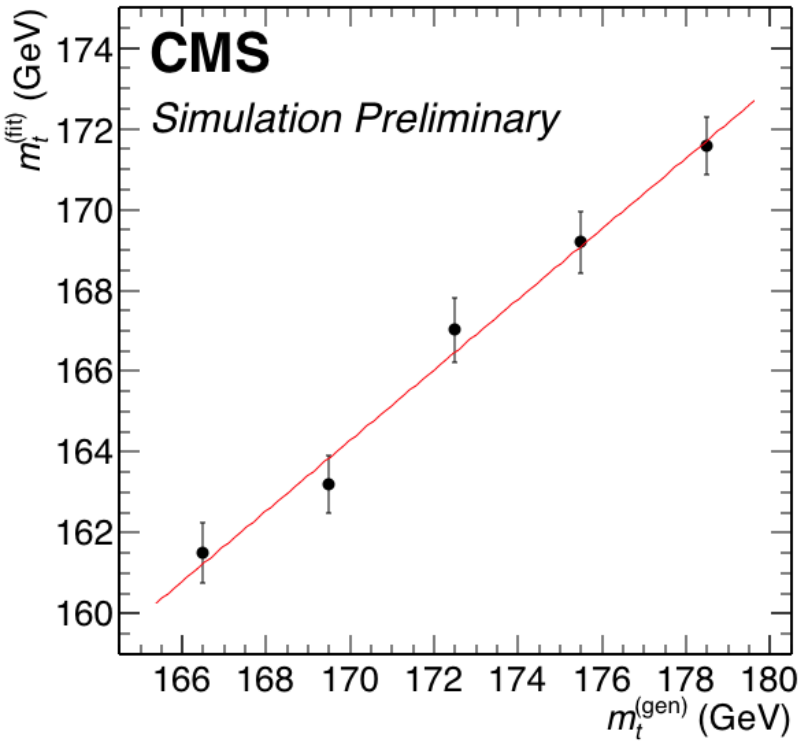


No big change from new Tevatron combination (FERMILAB-CONF-16-298-E): 174.30±0.35±0.54 GeV

What are we measuring?

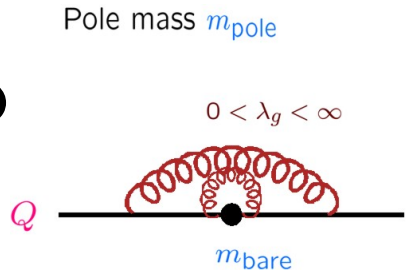


- Normally when we say "mass" we imply the "pole mass"
- But because of confinement, a quark is never observed isolated, hence its pole mass is unphysical: not an "observable"
- Top mass analyses are generally calibrated on MC simulation

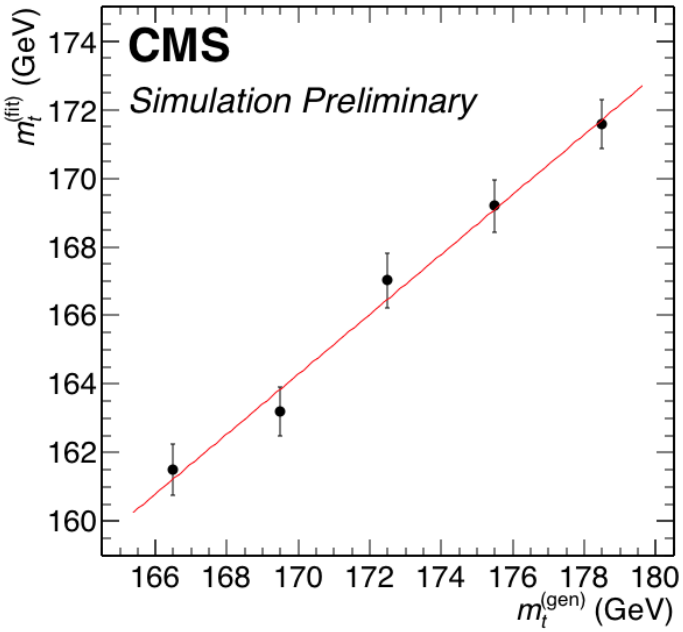


For illustration, plot from CMS-TOP-15-001

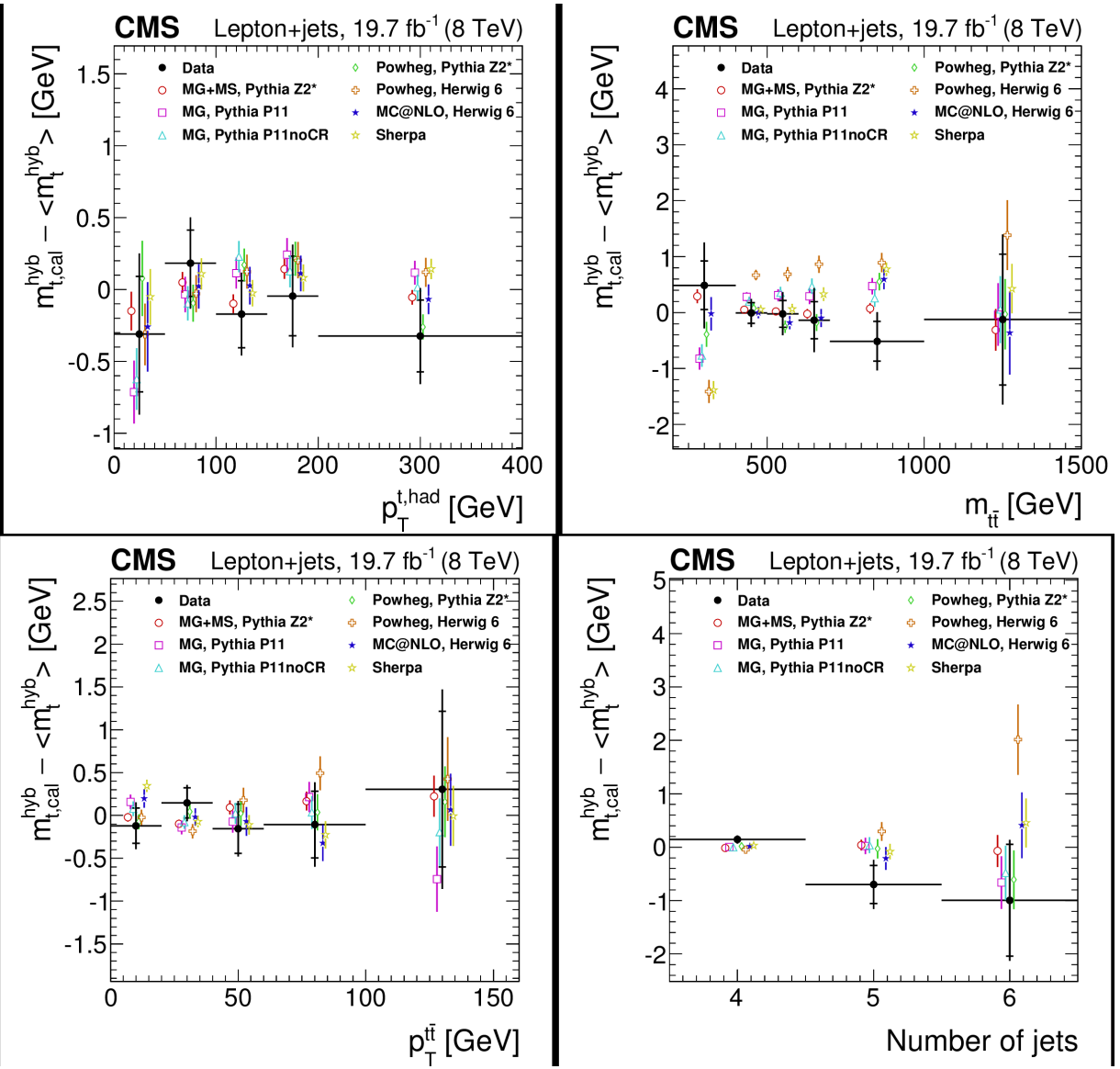
What are we measuring?



- 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
  - Standard wisdom: theory uncertainty must be of order Λ_{QCD}; but this view is not unanimous
- Just an academic problem? Practical impact when using this mass elsewhere?
- Underestimated model dependence of the measurement itself? And what if the CMS-Tevatron discrepancy...



Some test



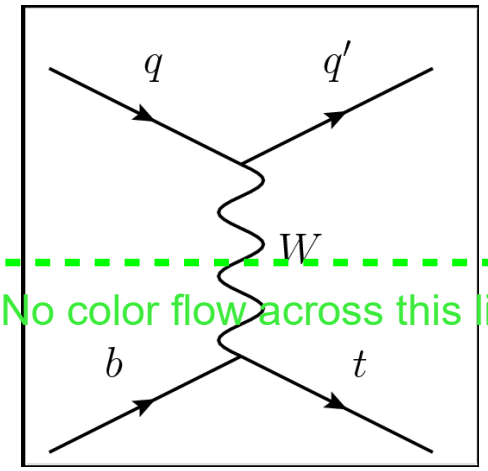
- *Uncalibrated* mass as function of several variables, chosen among the most sensitive to ISR/FSR, color reconnection, etc.

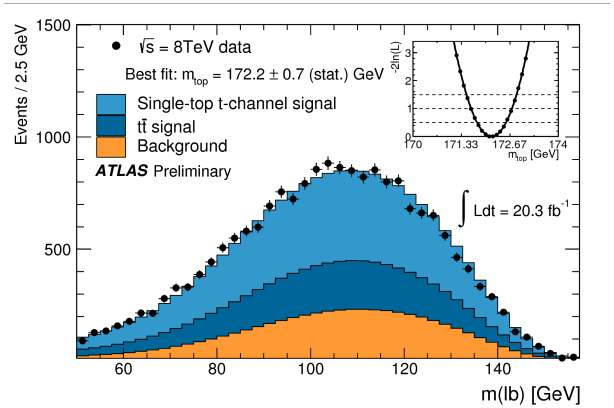
  (more plots are in the paper)

- 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





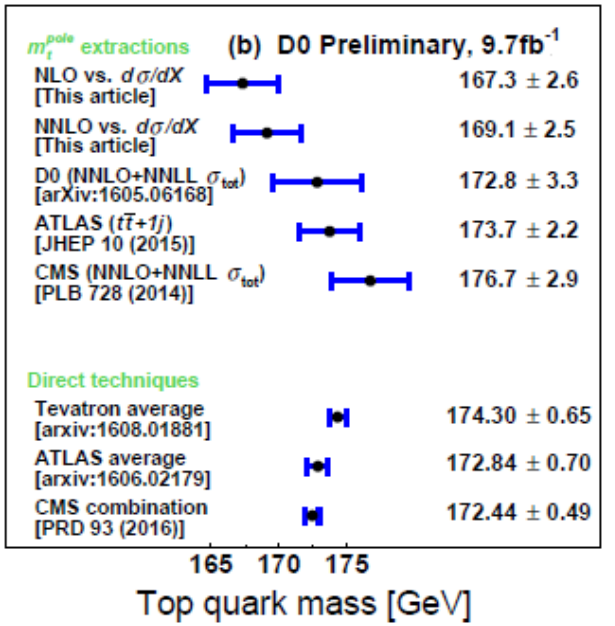
172.2±0.7(stat)±2.2(syst) GeV
ATLAS-CONF-2014-055

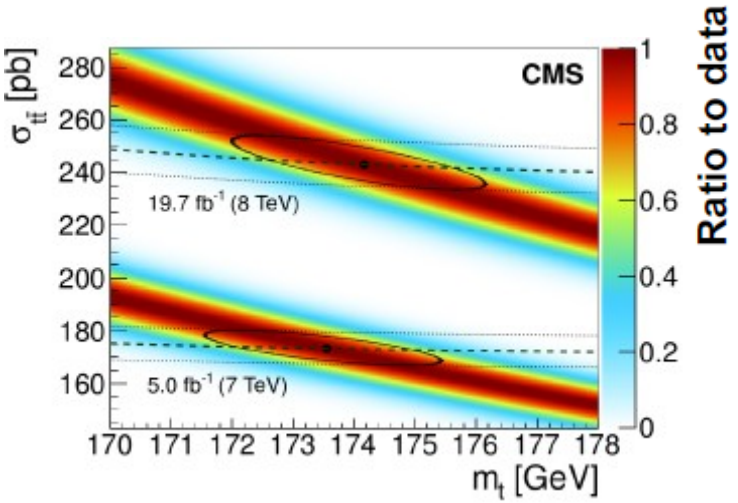
172.6±0.7(stat)±1.0(syst) GeV
CMS-PAS-TOP-15-001

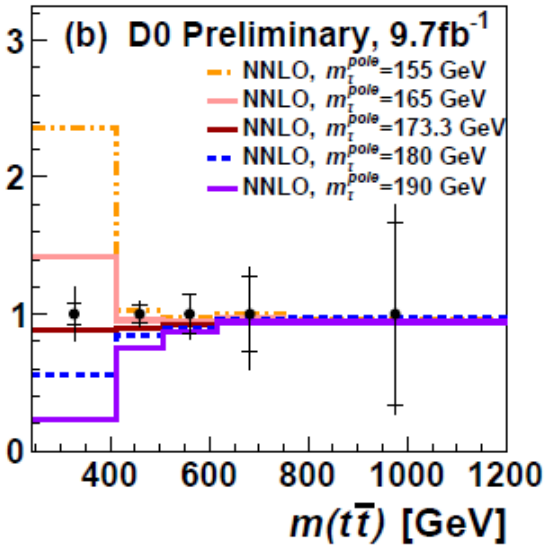
- Single top production in t-channel mode is not a rare process: ~1/3 of $t\bar{t}$
- Top candidate can be reconstructed, and used to extract a mass measurement
- Not included in combinations, because of much poorer precision with respect to $t\bar{t}$
  - Worse statistics
  - Larger background
  - Larger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

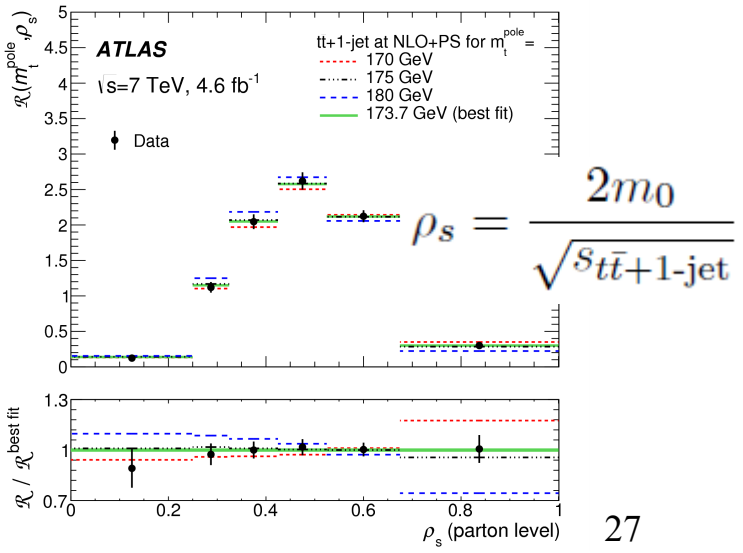
Measuring the pole mass?

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







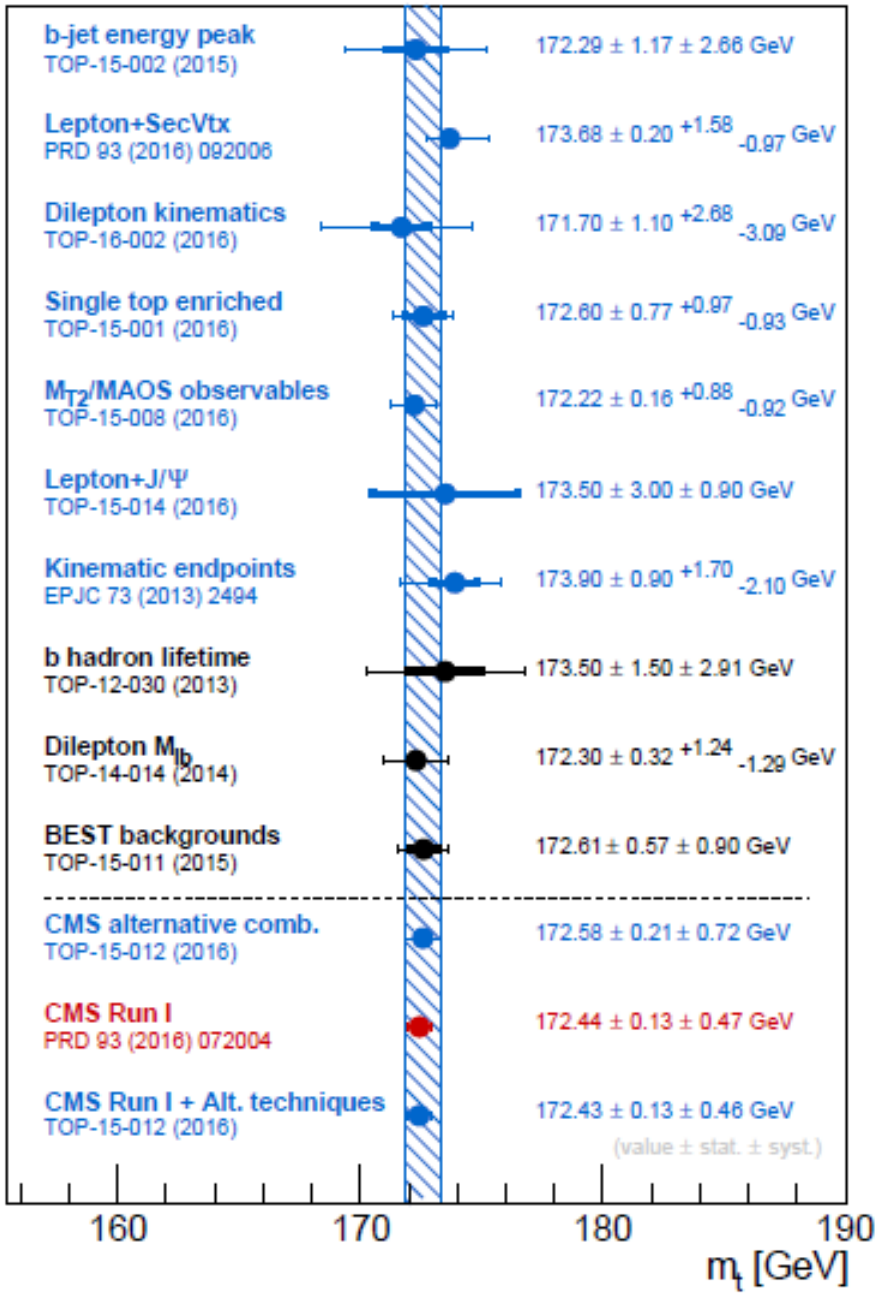


CMS coll., JHEP 08 (2016) 029

D0 coll., Note 6473-CONF

ATLAS coll., JHEP 10 (2015) 121

More tests



CMS-PAS-TOP-15-012

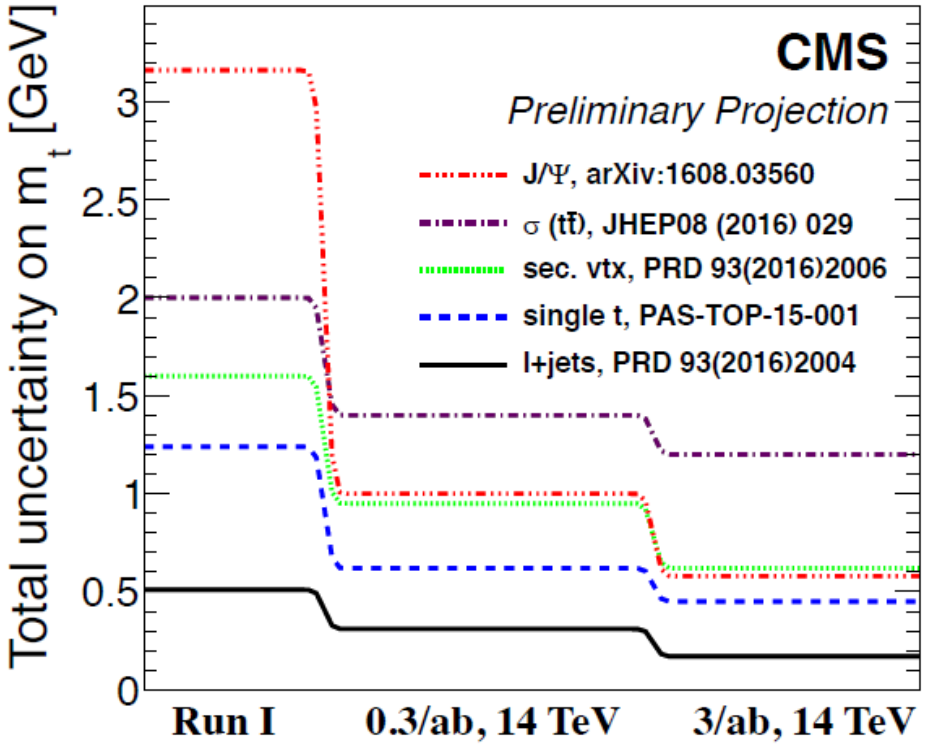


- Plethora of "alternative mass" measurements performed
- Typically designed to have very different dominant uncertainties with respect to standard methods
  - (e.g., lepton + secondary vertex and lepton + J/ψ have negligible dependence on Jet Energy Scale)
- Taken one by one, not very insightful as cross-checks: poor precision
- Interesting exercise: what happens if you combine them all?
- Result: you get ±0.4% precision!
  - And the global χ^2 looks ok

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



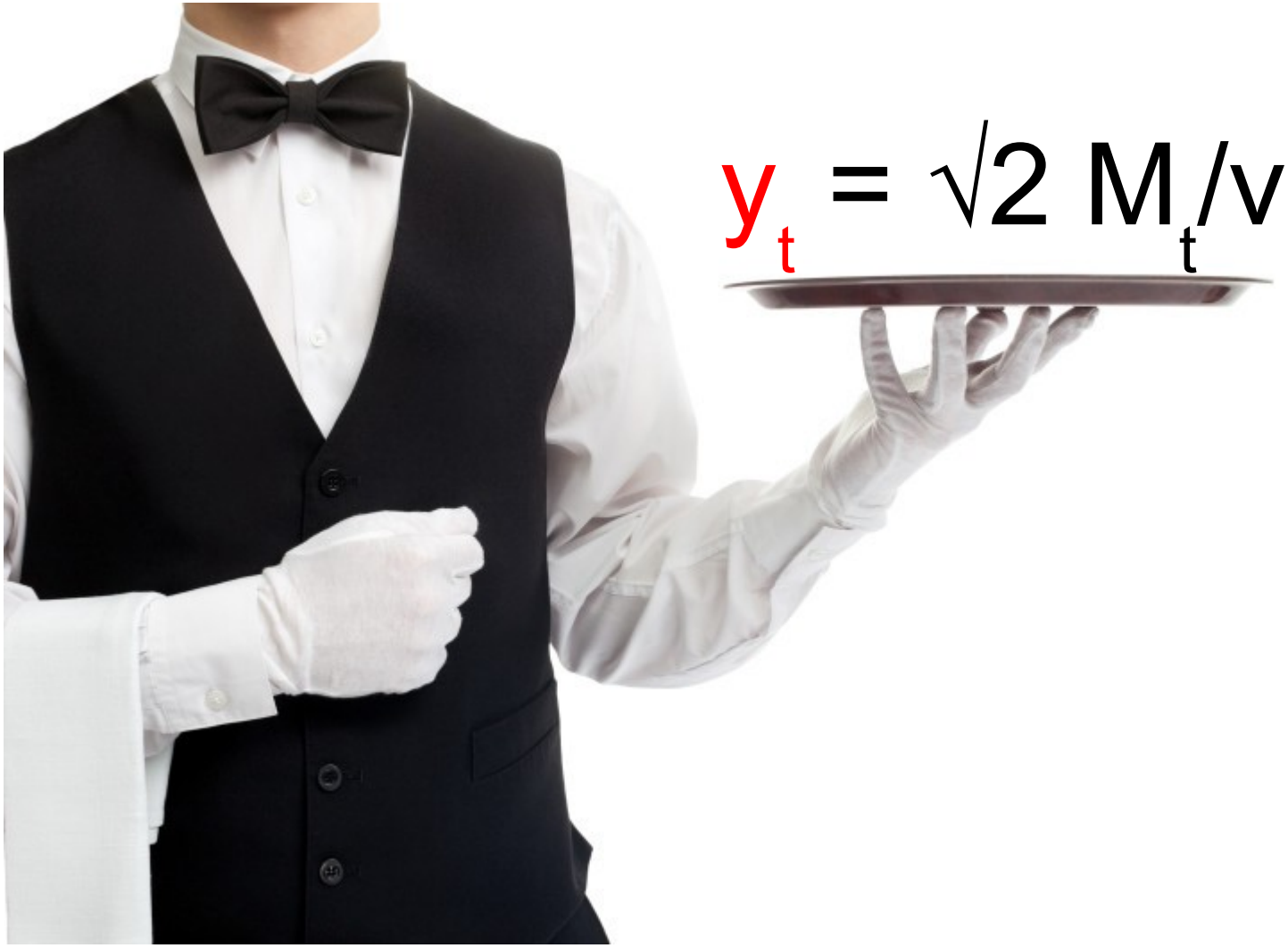
<0.1%

Plot from CMS-DP-2016-064

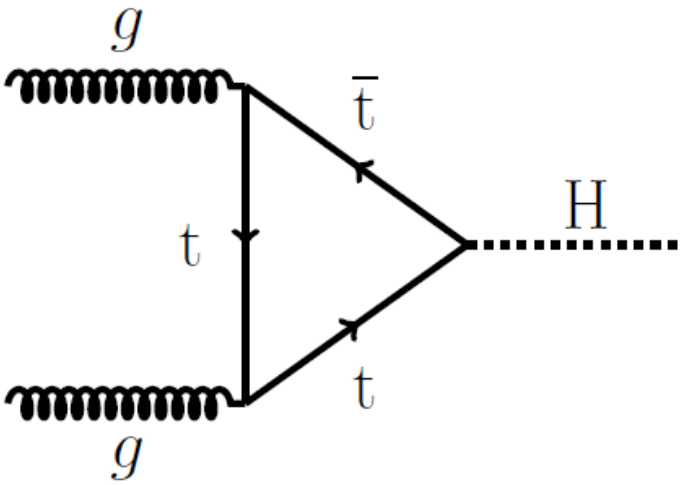
Assumptions: detector performance stays the same (i.e., harsher collision environment is perfectly compensated by detector upgrades), trigger efficiency is reduced to 1/3, and theory systematics are better constrained.

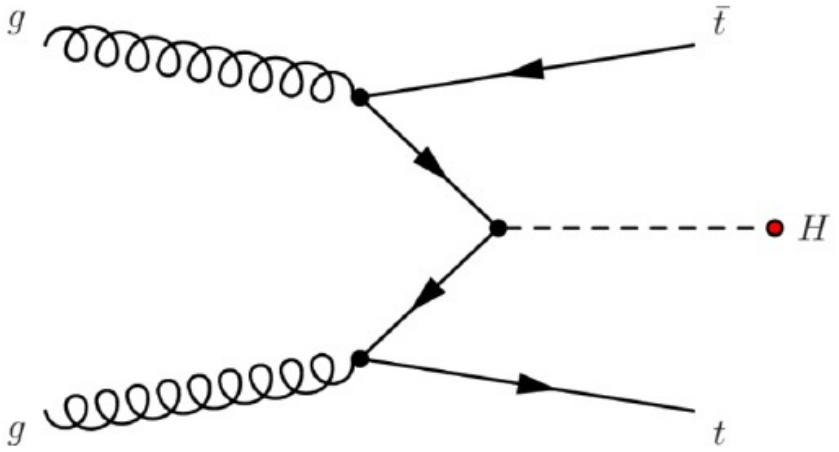
With 3/ab, all analyses expected to be systematics-limited.

Top-Higgs coupling

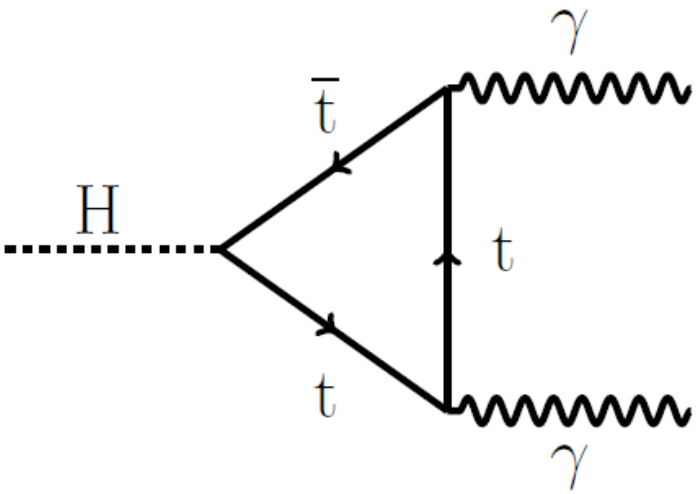


Measuring $|y_t|$





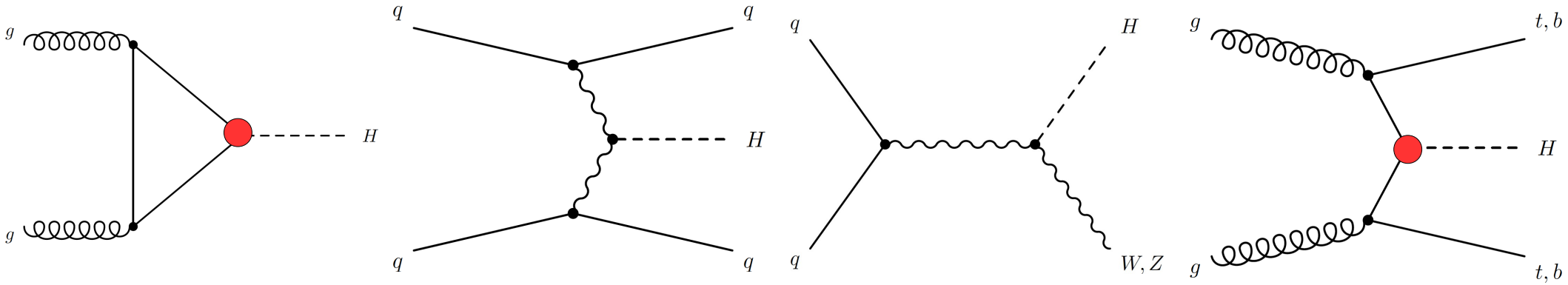
Direct: at tree level



Indirect: through loops

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)

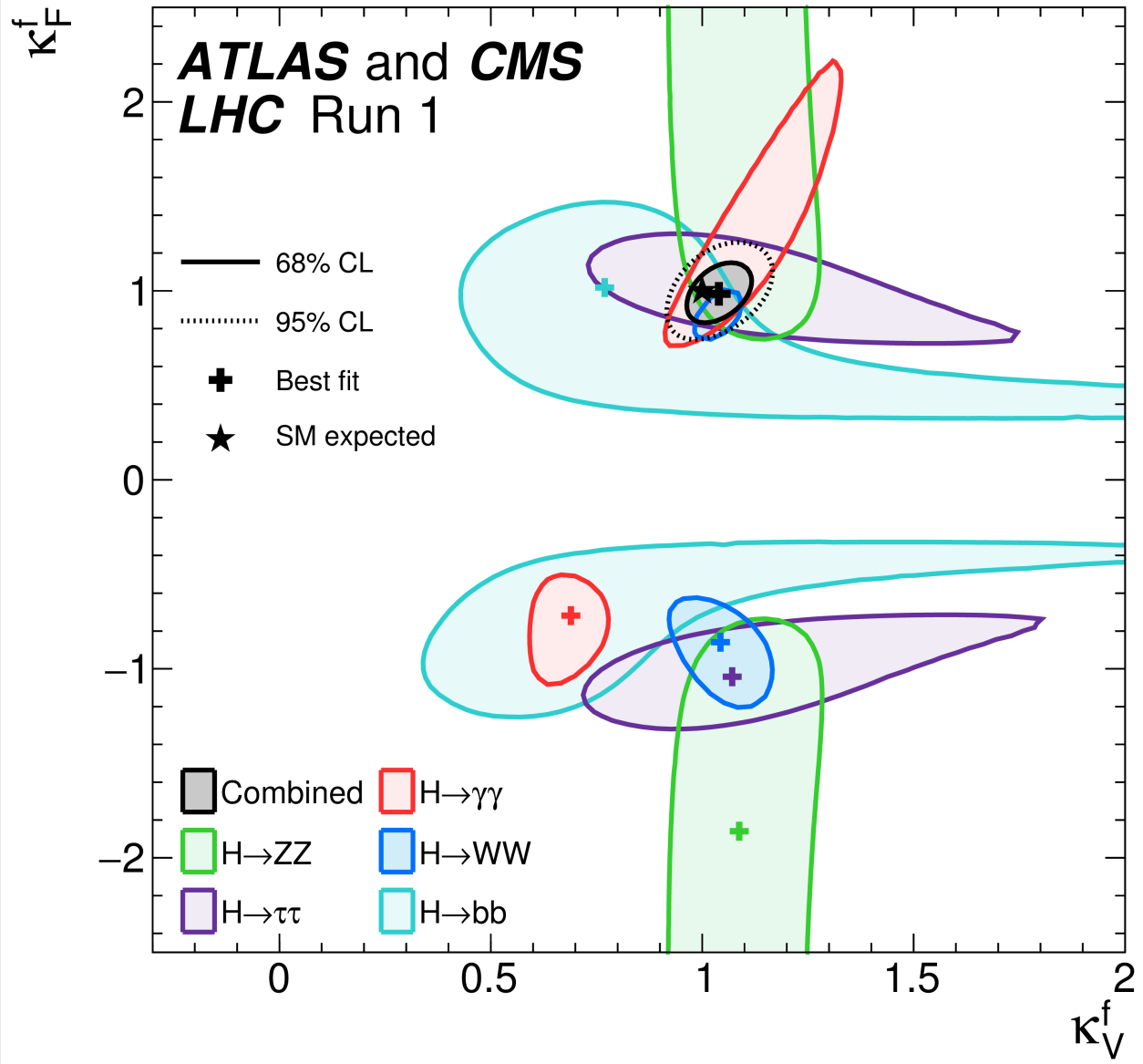
Measuring $|y_t|$: indirectly

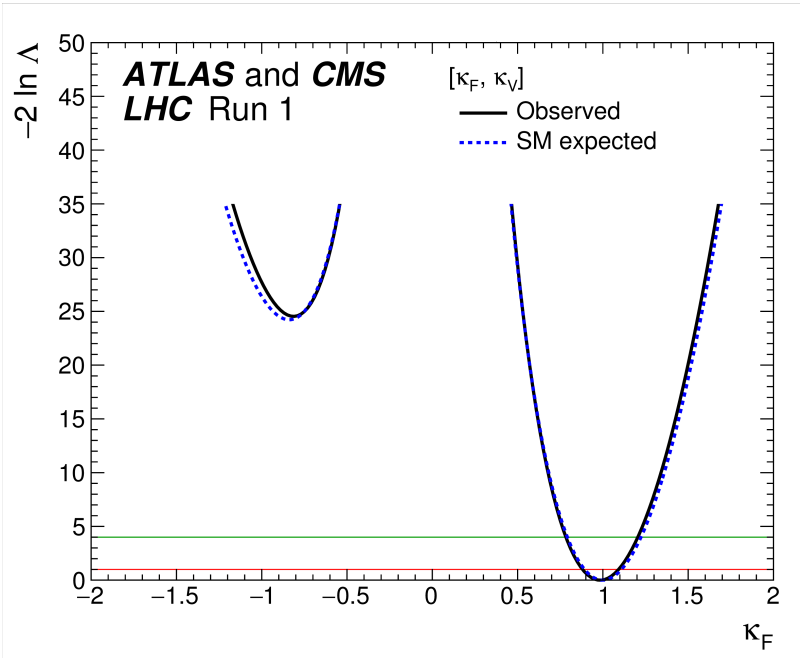


- Legacy ATLAS+CMS run-1 Higgs properties paper (*) combines many final states to extract constraints on several couplings, with several alternative parameterizations and assumptions
- Diagrams with indirect (loop) and direct (tree) sensitivity to the top-Higgs coupling are both considered but, at the 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; explicit $t\bar{t}H$ search presented later; role of tH explained in past seminars by A.Popov and F.Demartin)

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

Fermion (k_F) and boson (k_V) coupling multipliers

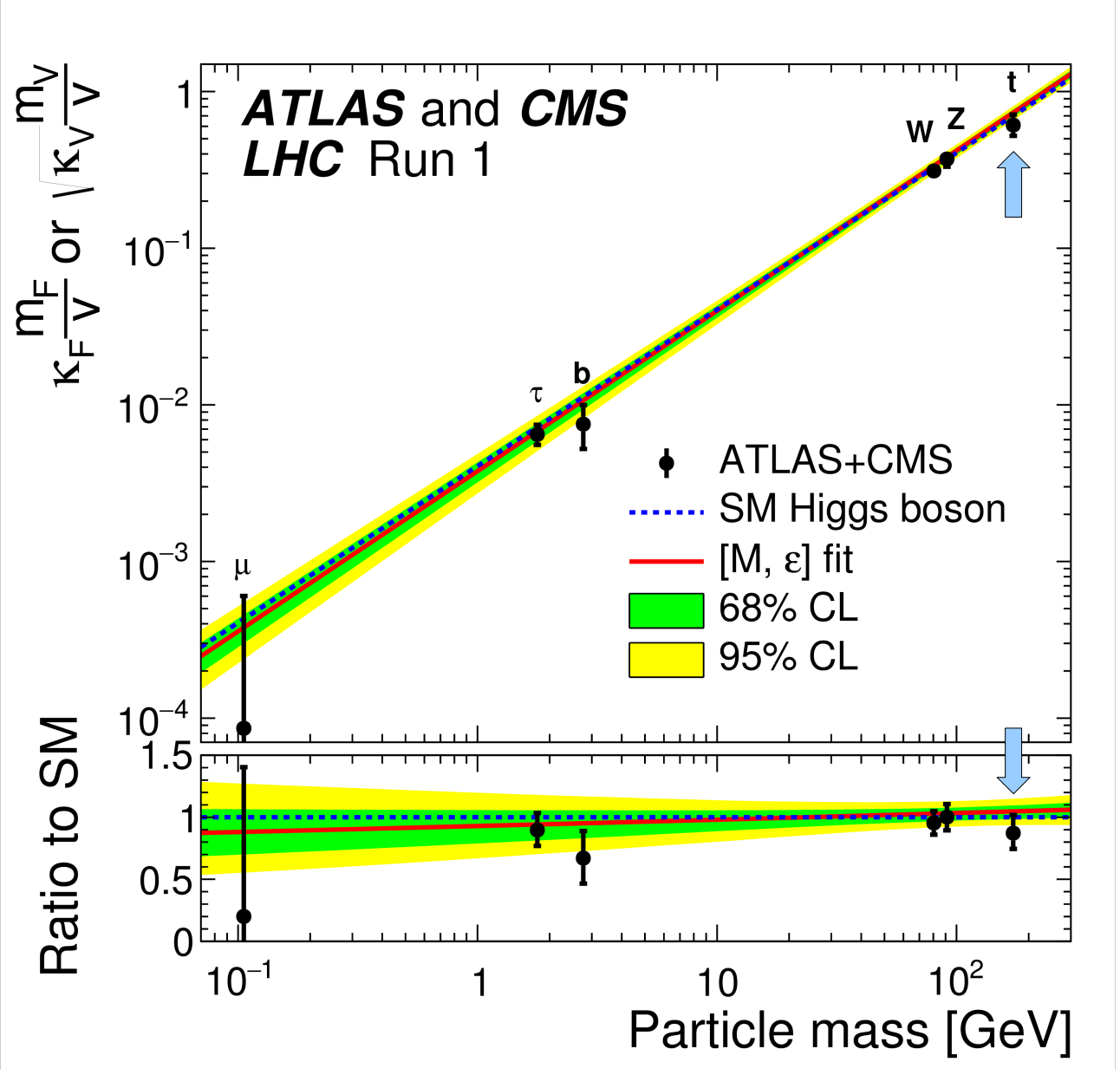




This parameterization considers a single multiplier for all fermions.
$k_F \sim 1 \Rightarrow y_t \sim 1$ (within ~25%)

Assumption: no BSM in loops

A test of the coupling-mass relationships

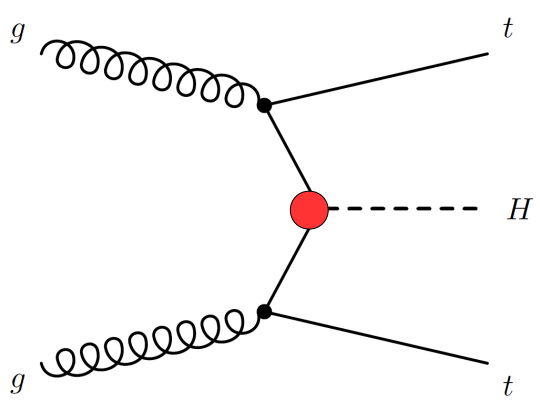


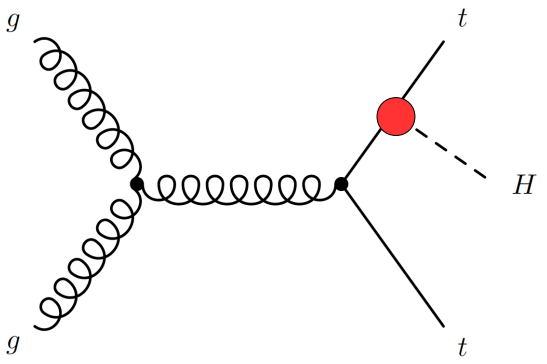
$\Rightarrow |y_t| \sim 1$

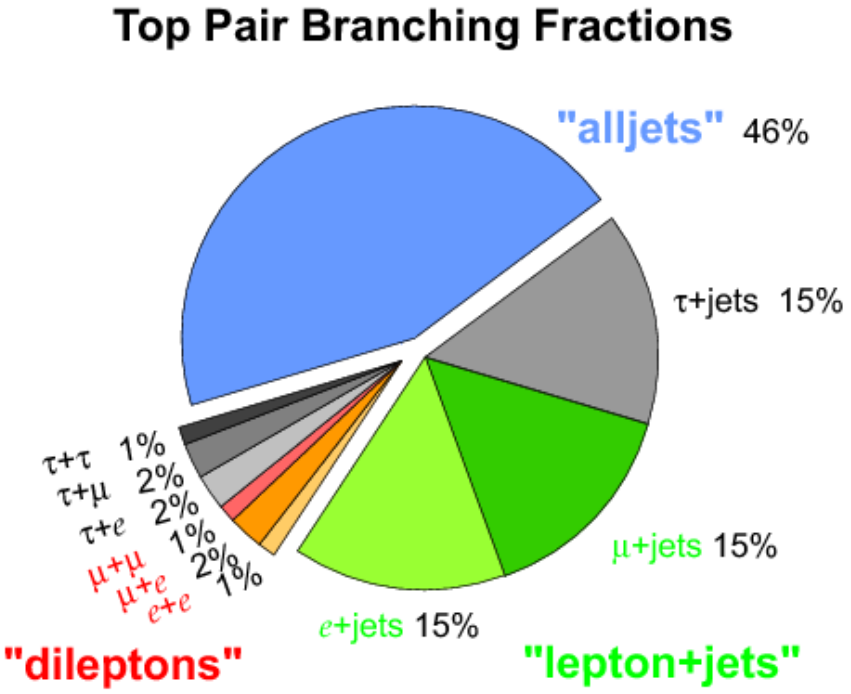
(within ~25%)

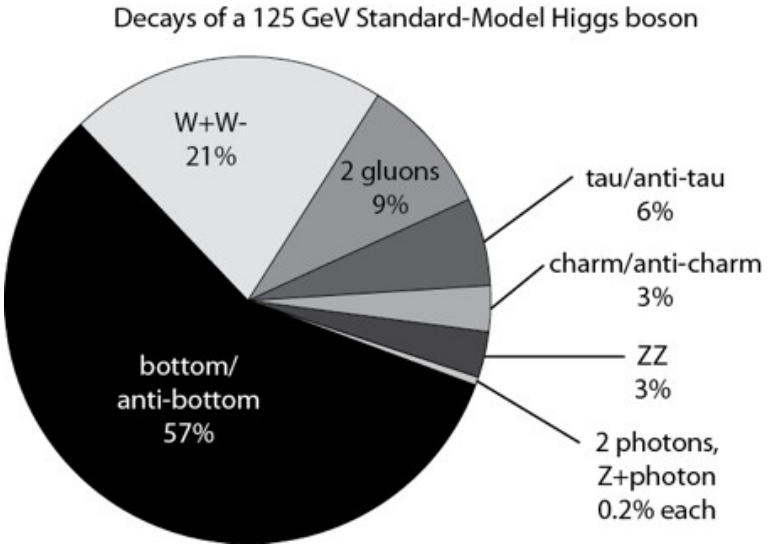
Measuring $|y_t|$: directly

$$\sigma(t\bar{t}H) \propto \left| \; + \; + \ldots \right|^2 \propto |y_t|^2$$

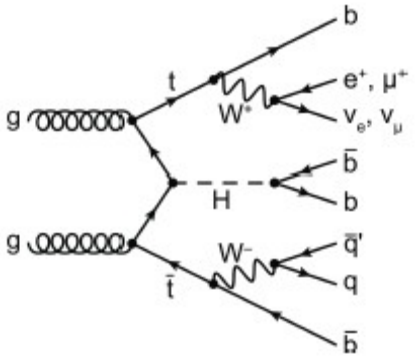




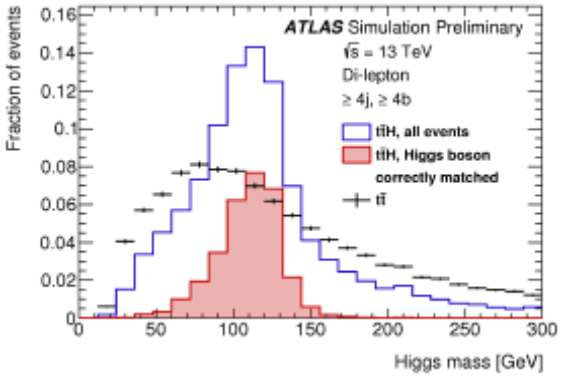




Searches for $t\bar{t}H$: $b\bar{b}$ channel

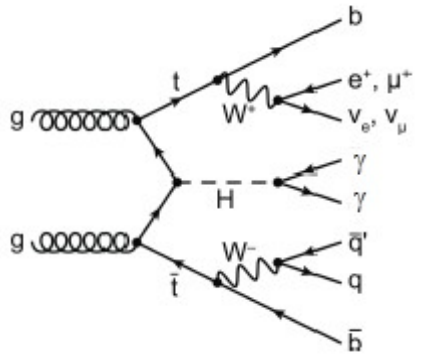


- Pros:
  - Largest BR (~60%)
  - Large multiplicity of jets and b-tags
- Cons:
  - Overwhelming $t\bar{t}$+jets background
  - Heavy flavour component of bkg is poorly constrained
  - Very large combinatorics of jet-parton associations
- Approaches:
  - Use several combinations of lepton / jet / b-tag 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)

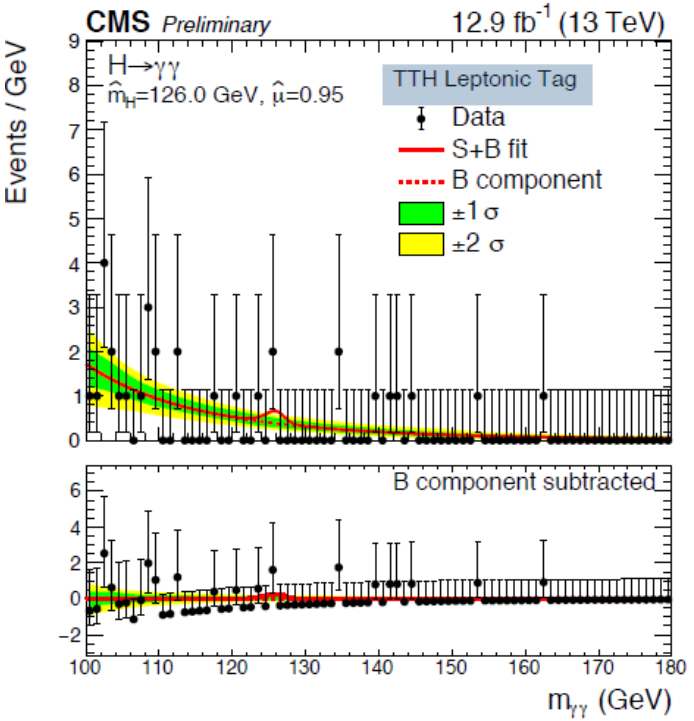


ATLAS-CONF-2016-080

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

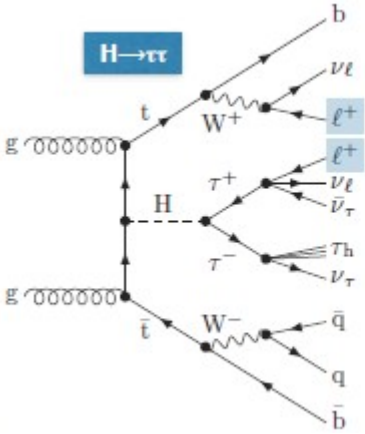


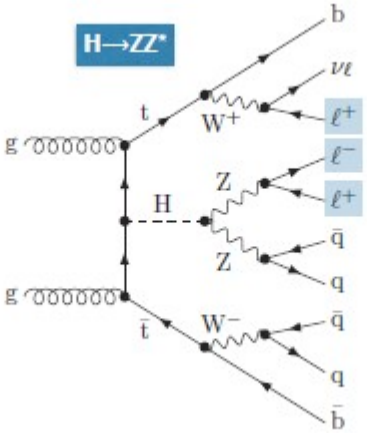
- Pros:
  - High-resolution mass peak
  - Background: smoothly falling mass spectrum
- Cons:
  - Small branching ratio (~0.2%)
- Approach:
  - Target events with 0 or 1 leptons from tops
  - Part of general $\gamma\gamma$ analysis where events are categorized by additional objects ("tags") to get discrimination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

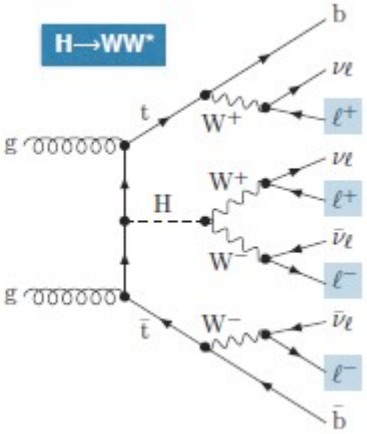


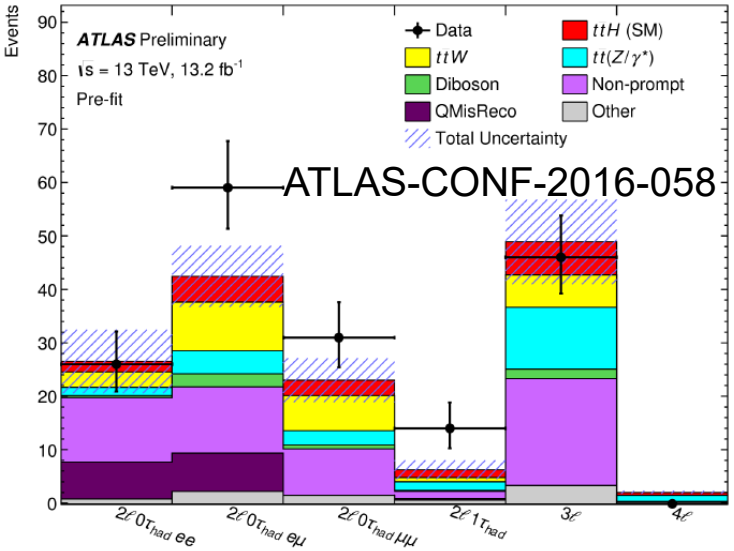
CMS-PAS-HIG-16-020

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



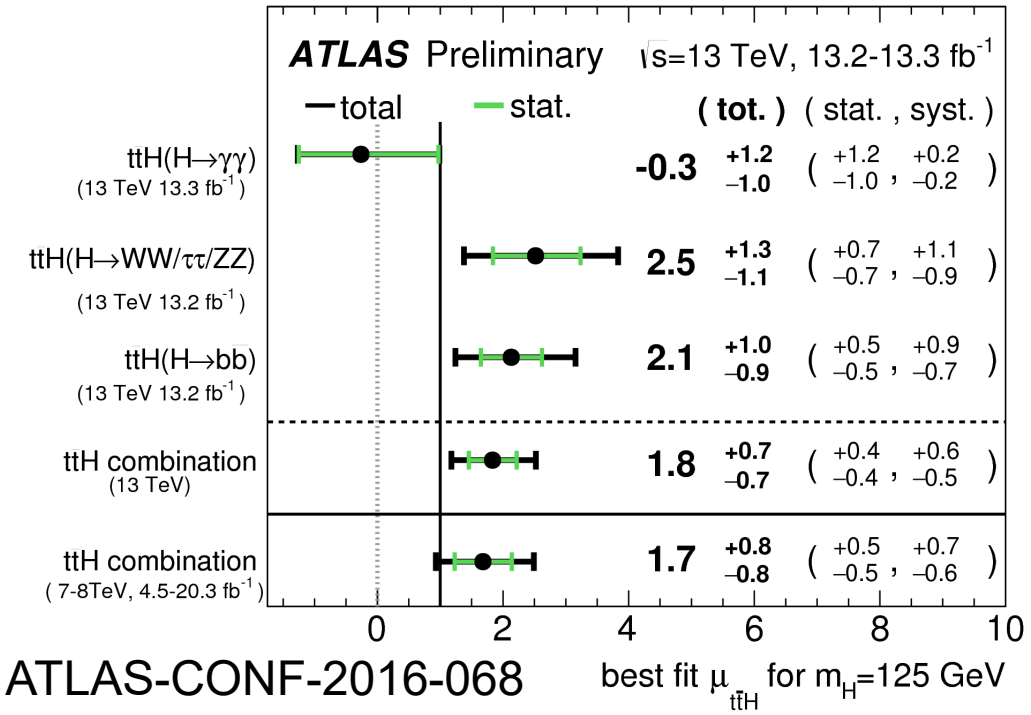






- Very clean selections: 2 same-sign leptons, or ≥3 leptons
  - Target final states with at least one leptonic top decay and more leptons from H→ττ (6.3%), H→ZZ (2.6%), H→WW (21.5%)
- Most challenging background is $t\bar{t}$ with non-prompt leptons (b/c→l, π/K→l, γ→e^+e^-) or lepton charge confusion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

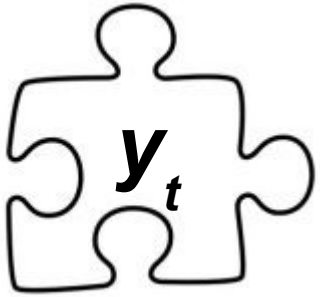
- $\mu = 2.3^{+0.7}_{-0.6}$

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

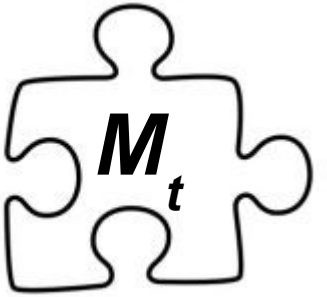
($\mu \equiv \sigma_{obs}/\sigma_{exp} \propto y_t^2 \Rightarrow \Delta\mu/\mu = 2\Delta y_t/y_t$)

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

(further progress only by reducing theory uncertainties)



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 the top mass entirely explained by the Higgs mechanism? In other words, is $y_t = \sqrt{2} M_t / v$?
- 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!

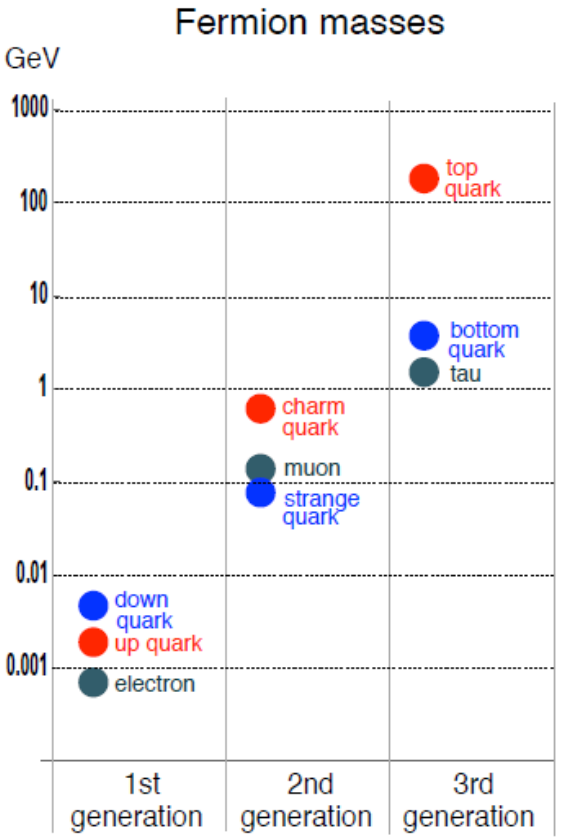
Thanks for your attention

And thanks to Martijn Mulders, André David, Matthias Komm, Georgios Krintiras, for their comments and suggestions during the preparation of this talk; and to the audience at "Selected puzzles in particle physics" for asking excellent questions when I presented this topic in Dec.2016

Where is the mass coming from?

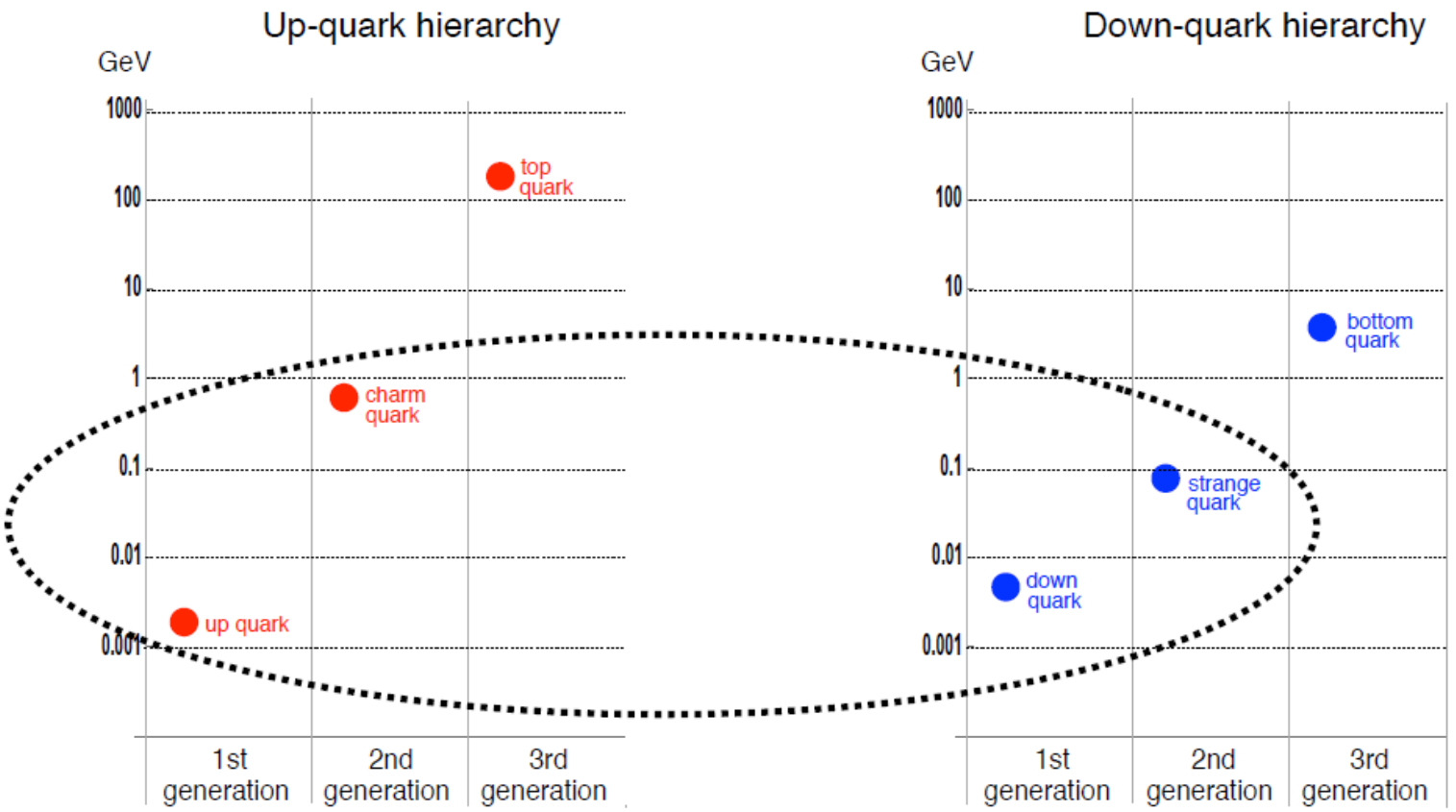
- Back to the basics: the equation of motion for a massive fermion (aka Dirac's Equation) contains a term $m\psi$
- The corresponding term in the Lagrangian density is $m\bar{\psi}\psi$
- Any $\bar{\psi}\psi$ term breaks chiral symmetry and this makes the theory non-renormalizable
- It takes *Spontaneous 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

A different look at it (1)



From Gilad Perez

A different look at it (2)

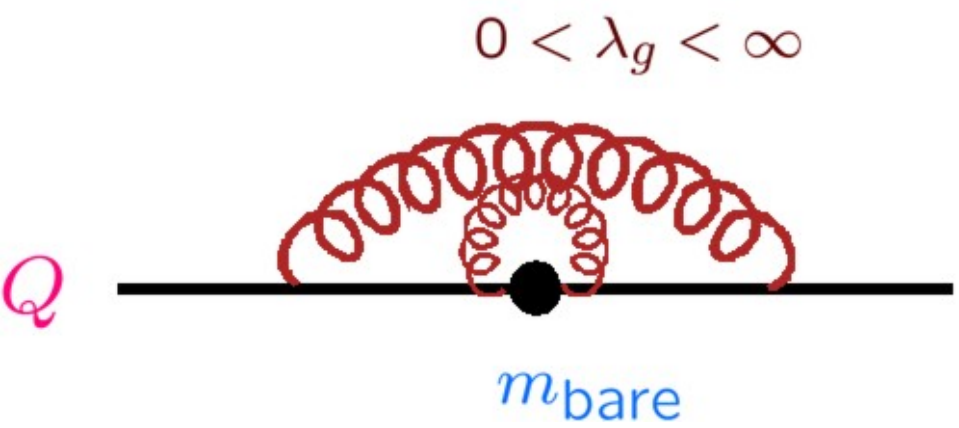


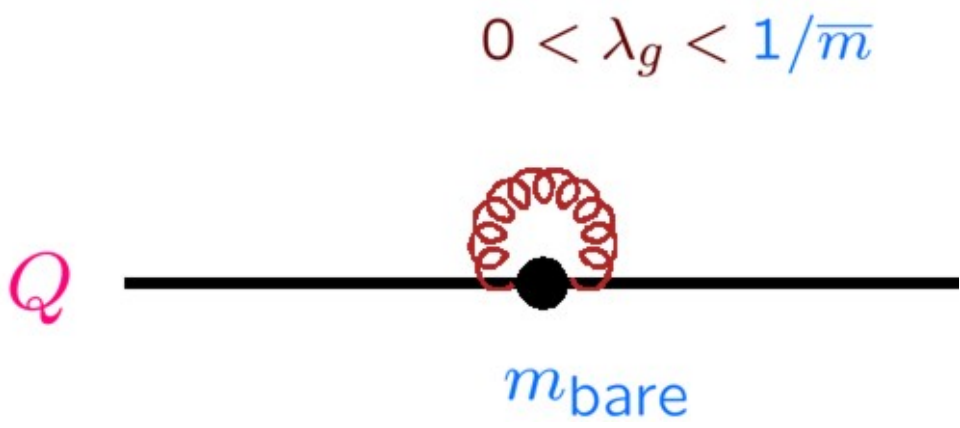
From Gilad Perez

Masses

Pole mass m_{pole}

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

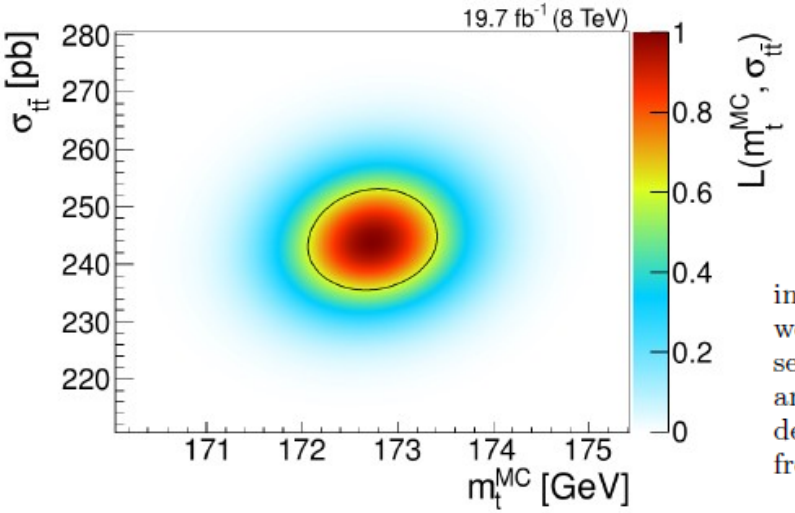




From arXiv:1407.5353 [hep-ph]

Top mass meaurements: MC and pole?

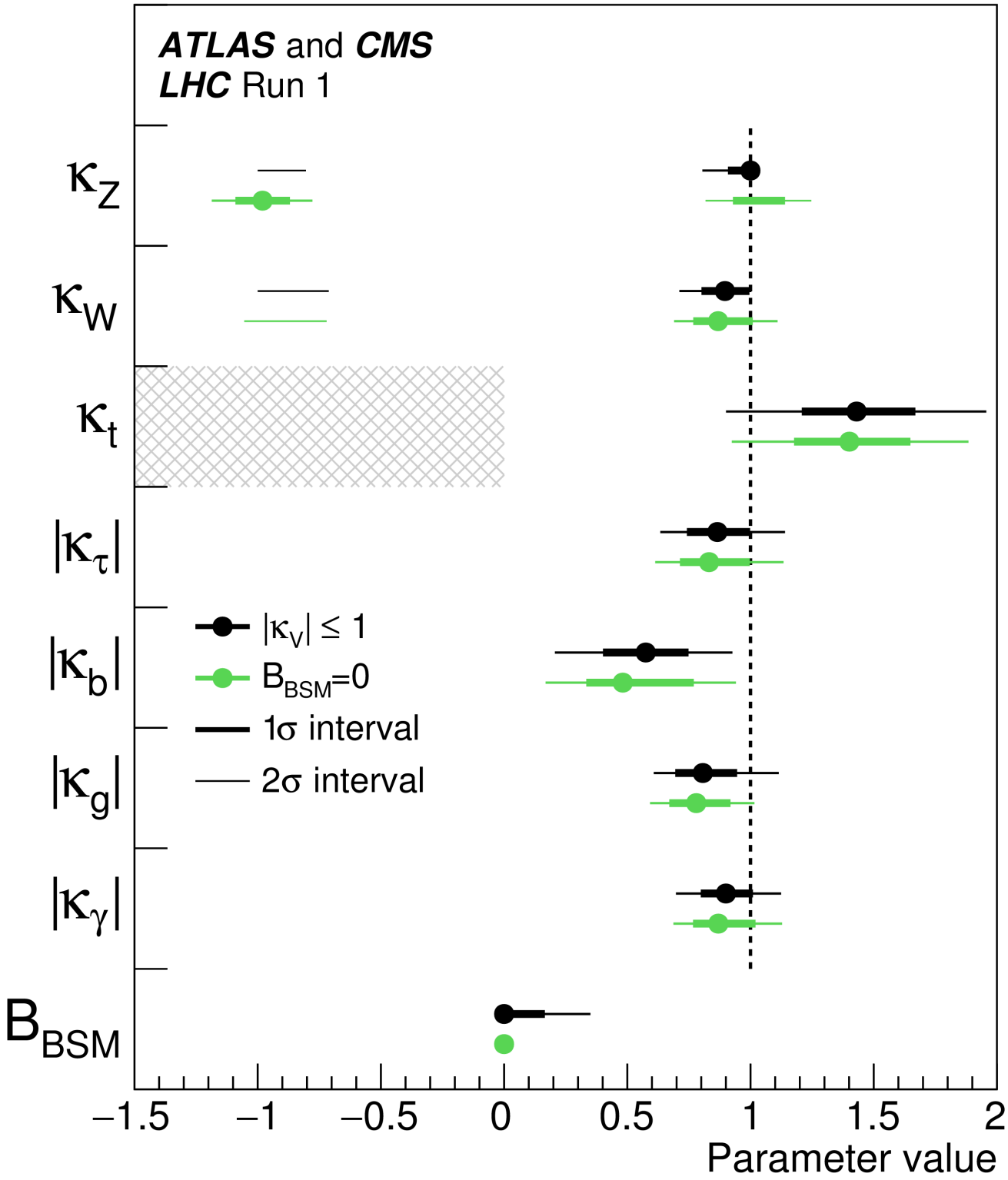
J.Kieseler, K.Lipka, O.Moch, „Calibration of the Top-Quark Monte Carlo Mass“, Phys.Rev.Lett. 116 (2016) 16, 162001, arXiv:1511.00841 [hep-ph]



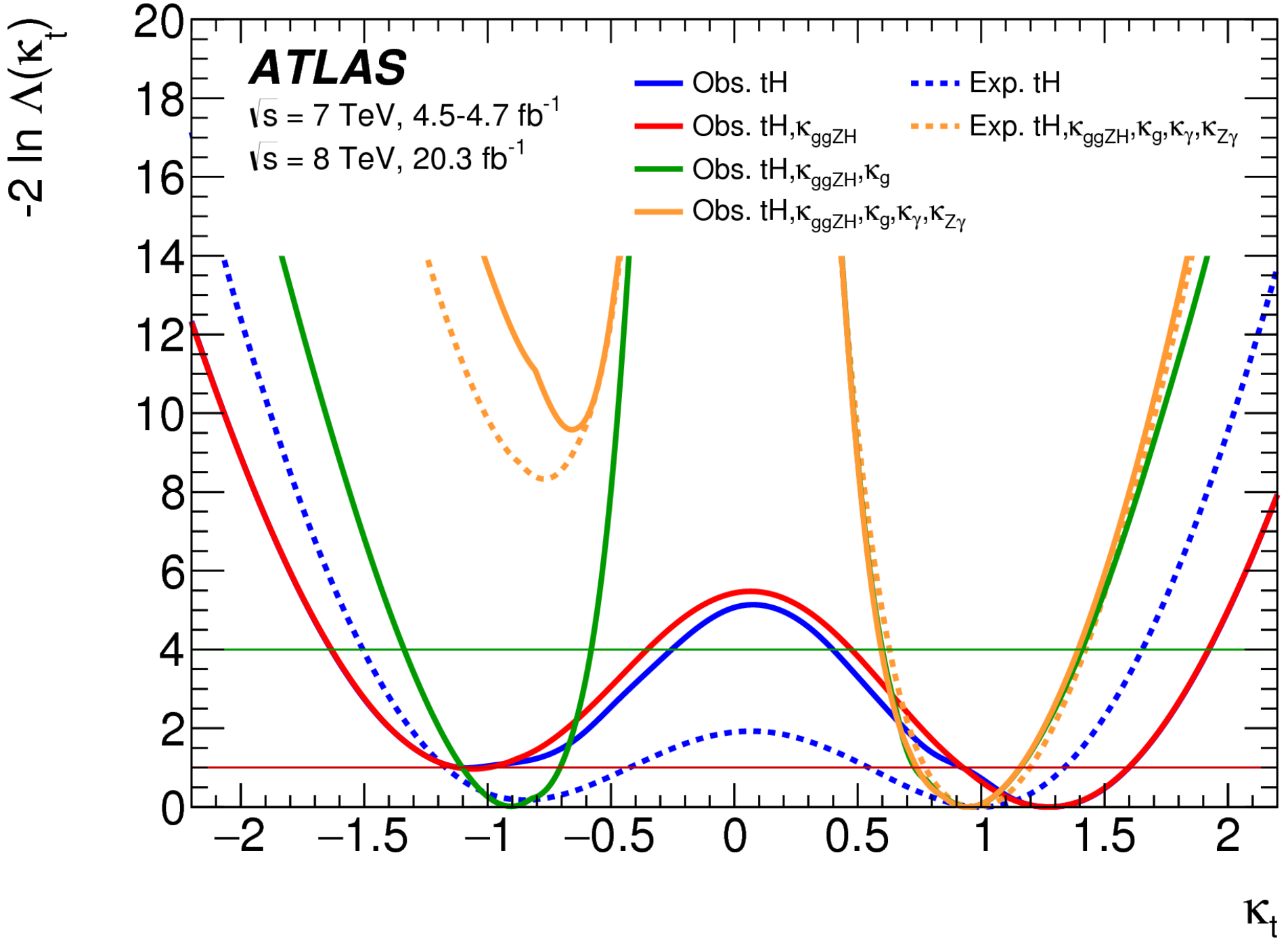
We present a method to establish experimentally the relation between the top-quark mass m_t^{MC} as implemented in Monte-Carlo generators and the Lagrangian mass parameter m_t in a theoretically well-defined renormalization scheme. We propose a simultaneous fit of m_t^{MC} and an observable sensitive to m_t, which does not rely on any prior assumptions about the relation between m_t and m_t^{MC}. The measured observable is independent of m_t^{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
κ_Z
κ_W
κ_t
$|\kappa_\tau|$
$|\kappa_b|$
$|\kappa_g|$
$|\kappa_\gamma|$
B_{BSM}
$|\kappa_V| \leq 1$
$B_{BSM}=0$
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	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	-	-	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim$	κ_W^2
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim$	κ_b^2
$\sigma(ttH)$	-	-	$\sim$	κ_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				
$\Gamma_{b\bar{b}}$	-	-	$\sim$	κ_b^2
Γ_{WW}	-	-	$\sim$	κ_W^2
Γ_{ZZ}	-	-	$\sim$	κ_Z^2
$\Gamma_{\tau\tau}$	-	-	$\sim$	κ_τ^2
$\Gamma_{\mu\mu}$	-	-	$\sim$	κ_μ^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				
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$


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
20
18
16
14
12
10
8
6
4
2
0
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2