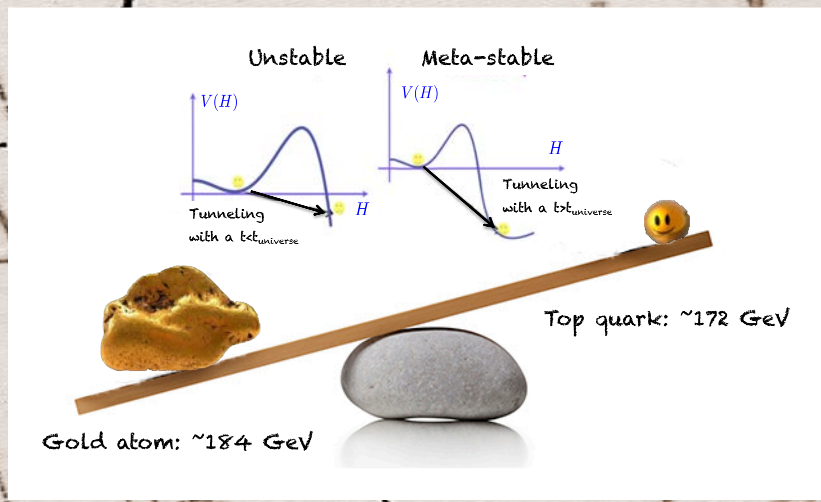
The top quark is *beautiful*, pretty *charming* and still very *strange*

(the *ups* and *downs* of the top mass)

Juan A. Fuster Verdú – IFIC, València

DESY-Zeuthen Colloquium

Zeuthen, July 10th 2019



Thanks and acknowledgements

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Sven-Olaf Moch (Hamburg), Peter Uwer (Berlin), Norbert Wermes (Bonn)

Warning

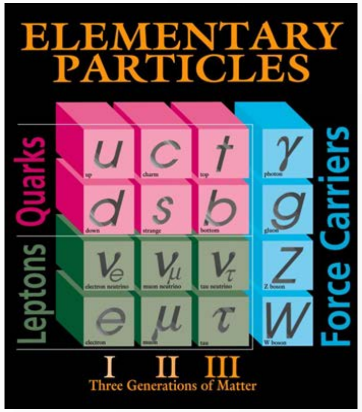
"Never underestimate the pleasure people get when they listen to something they already know", (E. Fermi).

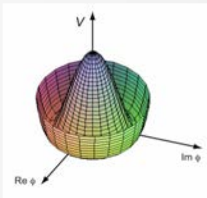
Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

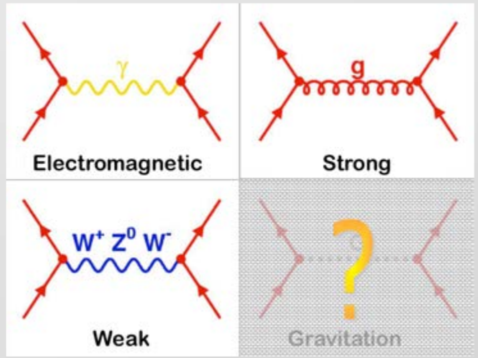
Symmetry

(~1980)





Higgs: EWSB



Particles

Interactions/Forces

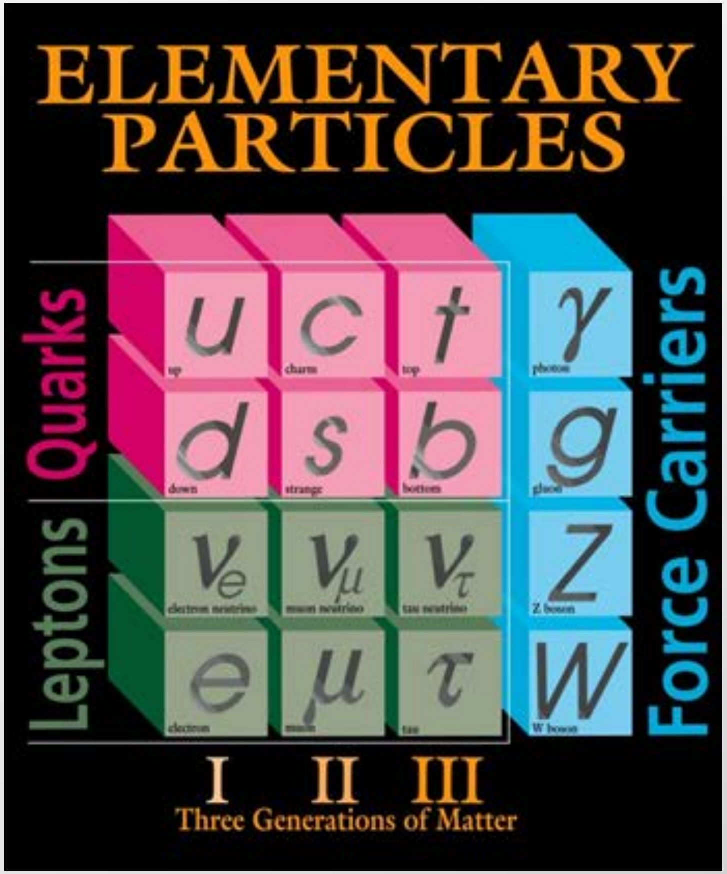
Why the Standard Model is as it is ?

- First and last column are necessary but what about the others !
- Averroes (Córdoba XII a.C.) says:

  "Nothing in nature is superfluous"
- We want to understand the reasons behind this structure,

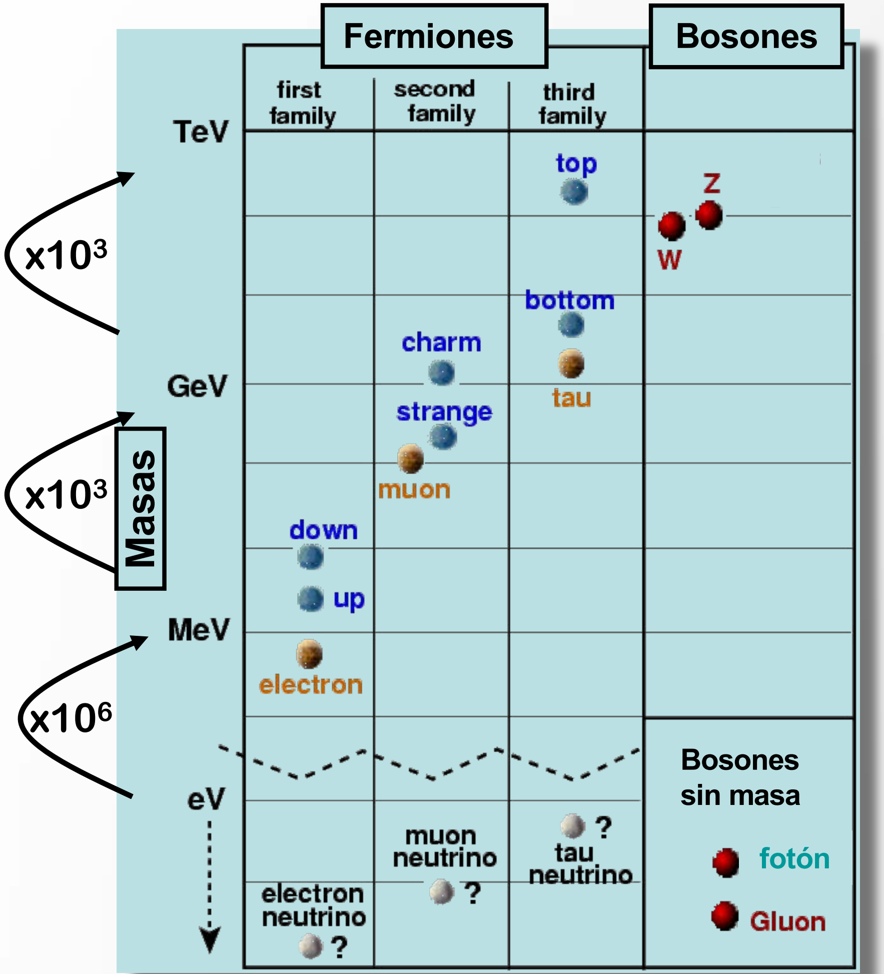
  Why ?

  Why the families are duplicated but with different mas ?



The masses of the elementary particles

- Large spectrum of masses



$$m_\gamma = 0 \quad i.e. \quad < 6 \bullet 10^{-26} \ \text{GeV}$$

$$m_{W^\pm} = 80.425 \pm 0.038 \ \text{GeV}$$

$$m_{Z^0} = 91.1876 \pm 0.0021 \ \text{GeV}$$

$$m_g = 0$$

Averroes: why ?

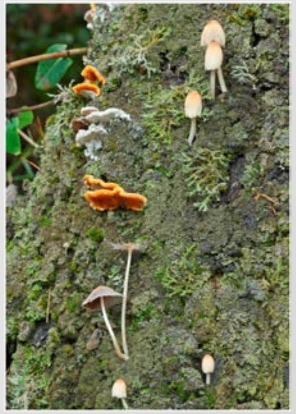
The masses of the elementary particles

- Masses cover at least ~12 orders of magnitude
- What does it mean ?
- Similar differences in scale imply very complex objects but we call all them "elementary"

- **Averroes:** are they really elementary ?

- **Earth = 12,74 x 10^{+6} m**

- **Vegetal cells ~1 x $10^{-[4,5]}$ m**



The masses of the elementary particles

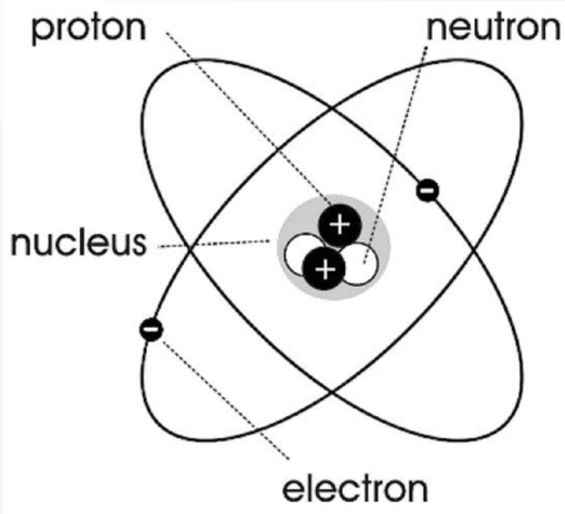
- Is it by chance or is it a necessity ? In other words can we change them without any consequence in the Universe ?

- There are cases in which such changes imply dramatic consequences

- Let's modify "slightly" the mases of the 1st family

  u d e

The masses of the elementary particles



- For instance a neutrón udd could be lighter tan a proton uud. But then Hydrogen would not be stable.
- $M_{electron} \neq 0$. If the mas of the electron would be zero the nucleus could NOT capture electrons. No atoms.

- **Averroes:** why?

The different faces of the mass

- **1687 Newton**: inertial mass, resistance to movement, laws of gravitation



$$\vec{F} = m\vec{a}$$

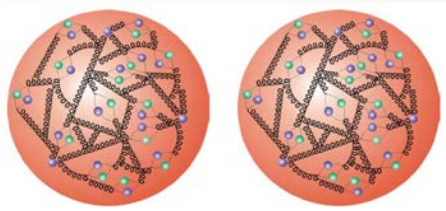
The different faces of the mass

- **1687 Newton**: inertial mass, resistance to movement, laws of gravitation



$$\vec{F} = m\vec{a}$$

- **1905 Einstein**: equivalence between mas-energy, proton mass is condensed energy of quarks-gluons



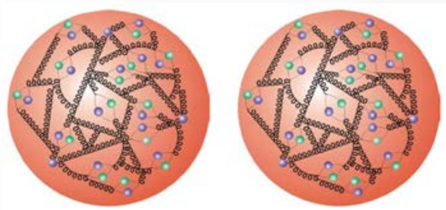
$$E = mc^2$$

The different faces of the mass

- **1687 Newton**: inertial mass, resistance to movement, laws of gravitation

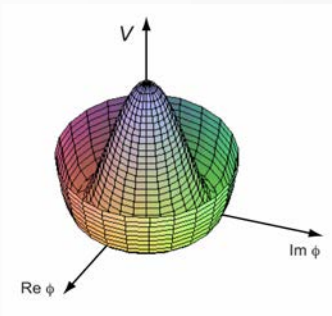
$$\vec{F} = m\vec{a}$$

- **1905 Einstein**: equivalence between mas-energy, proton mass is condensed energy of quarks-gluons



$$E = mc^2$$

- **1964 Brout-Englert-Higgs**: connects mass and the vacuum. The vacuum is not the “absence of things” but the “level of minimum energy”



$$|\phi| = a = \left(\frac{-\mu^2}{2\lambda}\right)^{1/2}$$

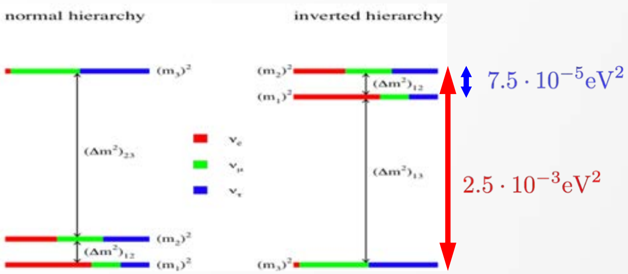
$$\phi(x) = a + \frac{\phi_1(x) + i\phi_2(x)}{\sqrt{2}}$$

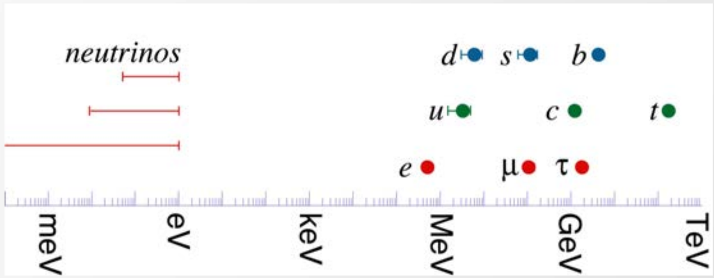
Averroes: why ?

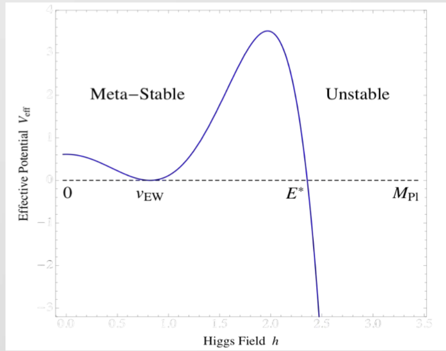
The masses of the elementary particles

The Standard Model boundaries:
massive ν

The Standard Model boundaries:
Connection: top-quark mass, Higgs mass and α_S







$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{12} \sim 34^\circ$

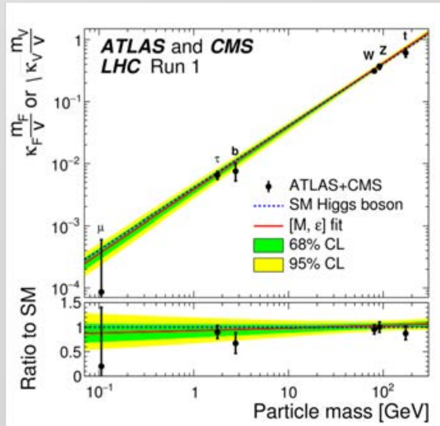
$\theta_{23} \sim 42^\circ$ o 48°

$\theta_{13} \sim 8.5^\circ$

$\delta \sim\ ?$

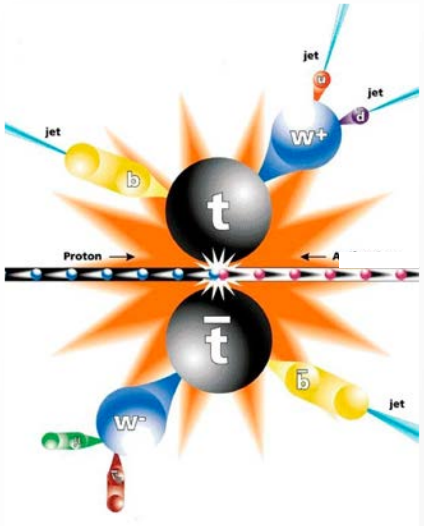
The borders of the mass spectrum region represent a golden place to test the validity of Standard Model therefore to look for its consistency and/or new physics.

Averroes: Neutrinos and top-quark

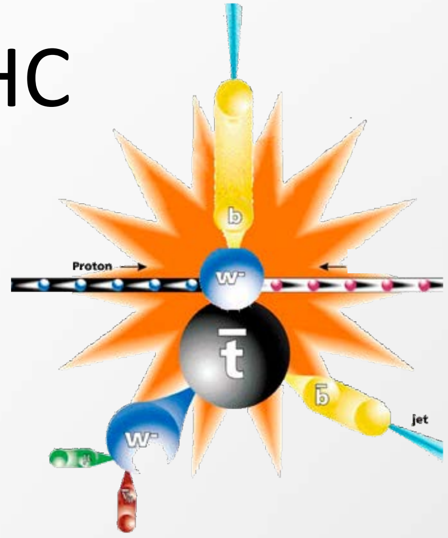


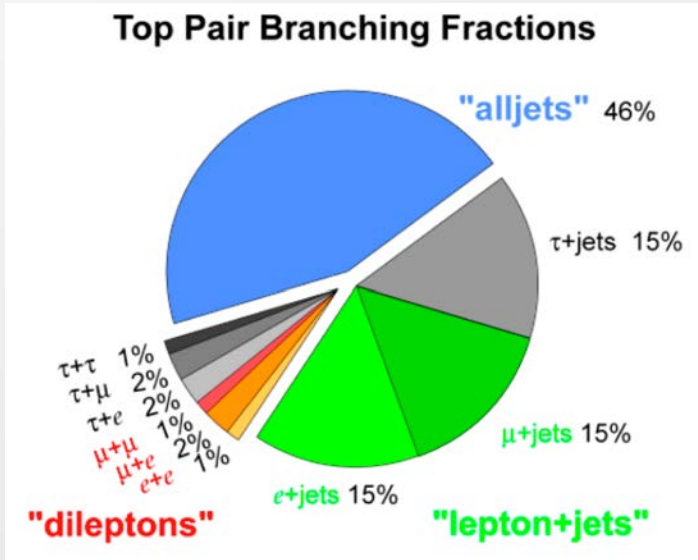
J. Fuster

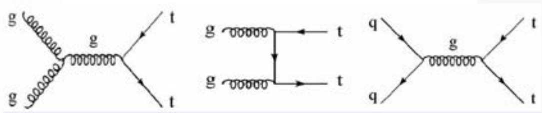
The top quark is *beautiful and charming*

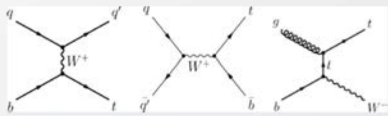


@LHC









- The heaviest known elementary particle
- Yukawa coupling to Higgs boson $y_t = \mathcal{O}(1)$: privilege position to test EWSB
- Special role in many BSM: a window to new physics that couples preferentially to top quarks
- Decays before hadronizing: the only "naked" quark

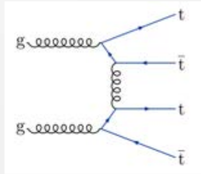
$$\tau_{\mathrm{had}} \approx h/\Lambda_{\mathrm{QCD}} = 2 \cdot 10^{-24}\mathrm{s}$$

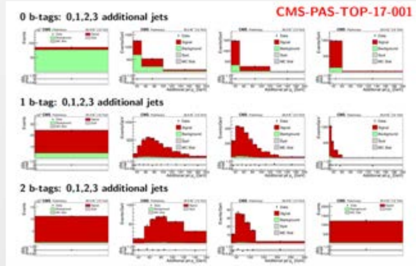
$$\tau_{\mathrm{top}} \approx h/\Gamma_{\mathrm{top}} = 1/(G_F m_t^3 |V_{tb}|^2 / 8\pi\sqrt{2}) = 5 \cdot 10^{-25}\mathrm{s}$$

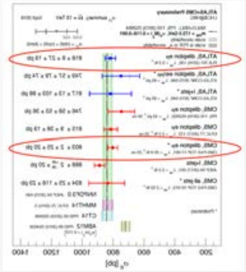
$$\tau_{\mathrm{bottom}} \approx 10^{-12}\mathrm{s}$$

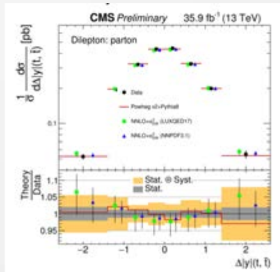
The top quark is *beautiful and charming*: rich physics programme

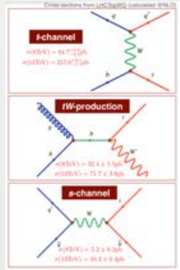
- Top properties:
  - Cross/differential sections (tt+0jets,+1jets,+2jets,+3jets)
  - Spin correlations
  - Charge asymmetries
  - Top Yukawa
  - Colour flow

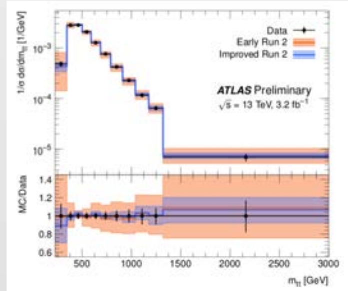




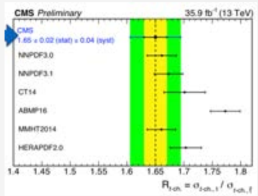


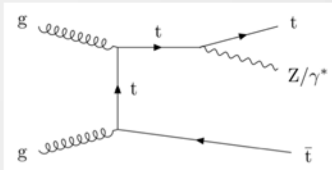


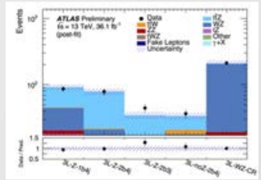




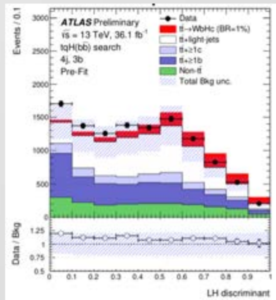
- Single top production

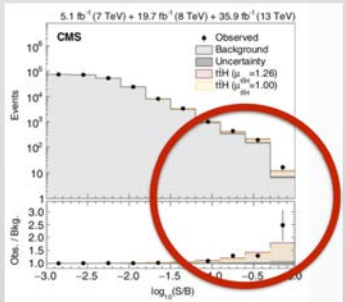


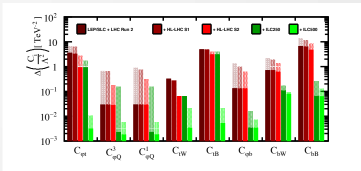




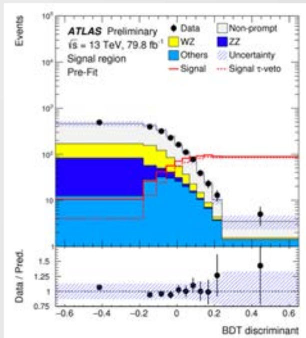
- New Physics
  - Anomalous couplings
  - Flavour Changing neutral Currents (tqZ,tqH)
  - ttγ

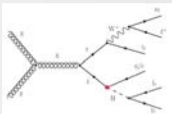


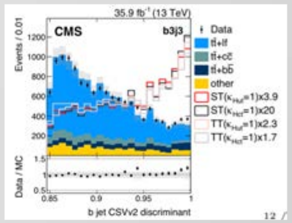


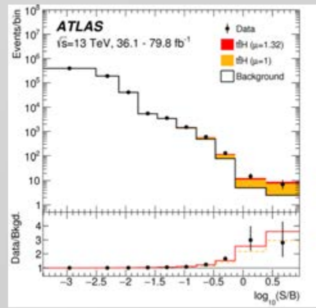


- Top mass
  - “Direct” measurements
  - “Alternative” measurements





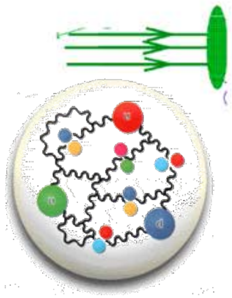


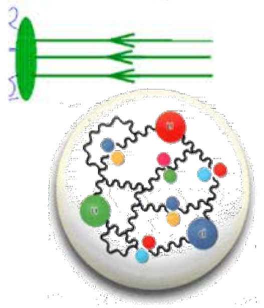


Disclaimer: This talk only covers part of the “top mass” topic

The top quark is *beautiful and charming* but LHC is challenging

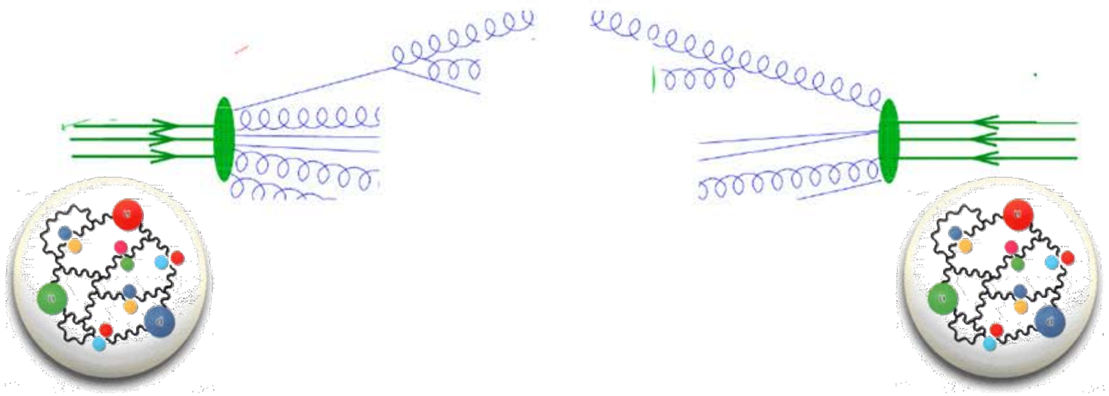
- Parton Distribution Functions (PDFs)





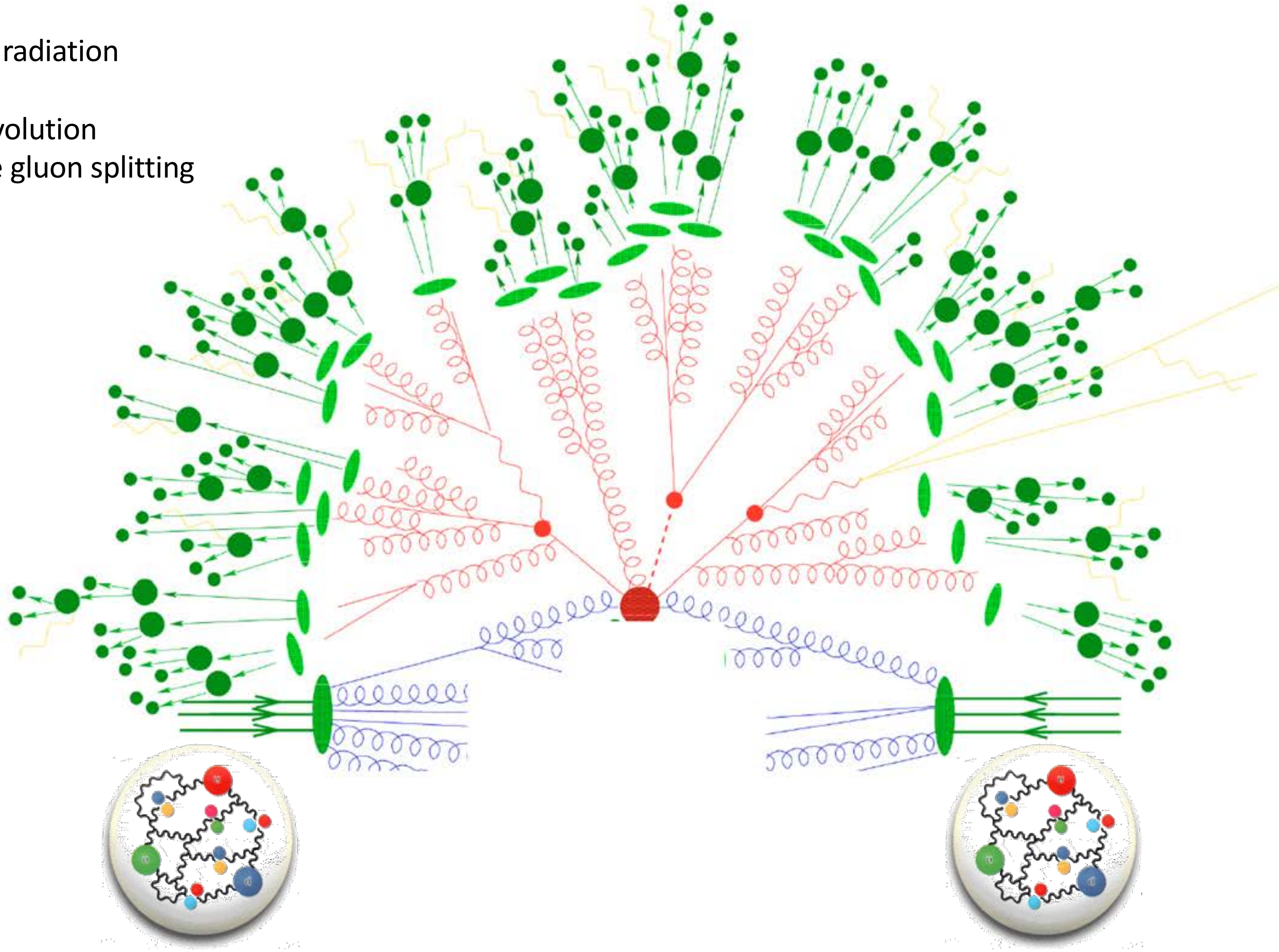
The top quark is *beautiful and charming* but LHC is challenging

- Parton Distribution Functions (PDFs)
- Hard process
- Initial/Final state radiation



The top quark is *beautiful and charming* but LHC is challenging

- Parton Distribution Functions (PDFs)
- Hard process
- Initial/Final state radiation
- Partonic decays
- Parton shower evolution
- Non-perturbative gluon splitting
- Colour singlets



- Colourless clusters
- Clusters into hadrons
- Hadronic decays

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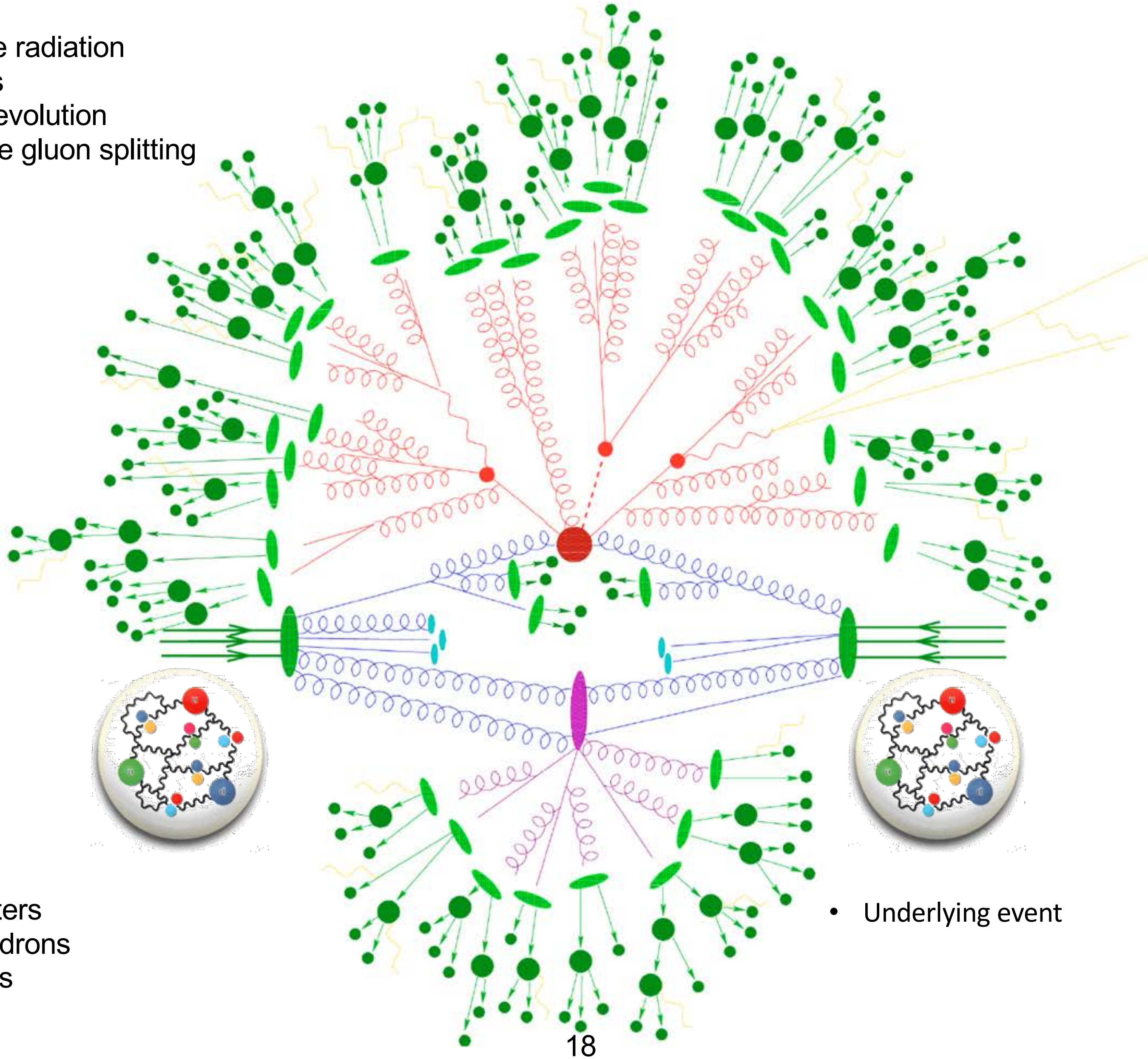

- Colourless clusters
- Clusters into hadrons
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- Underlying event

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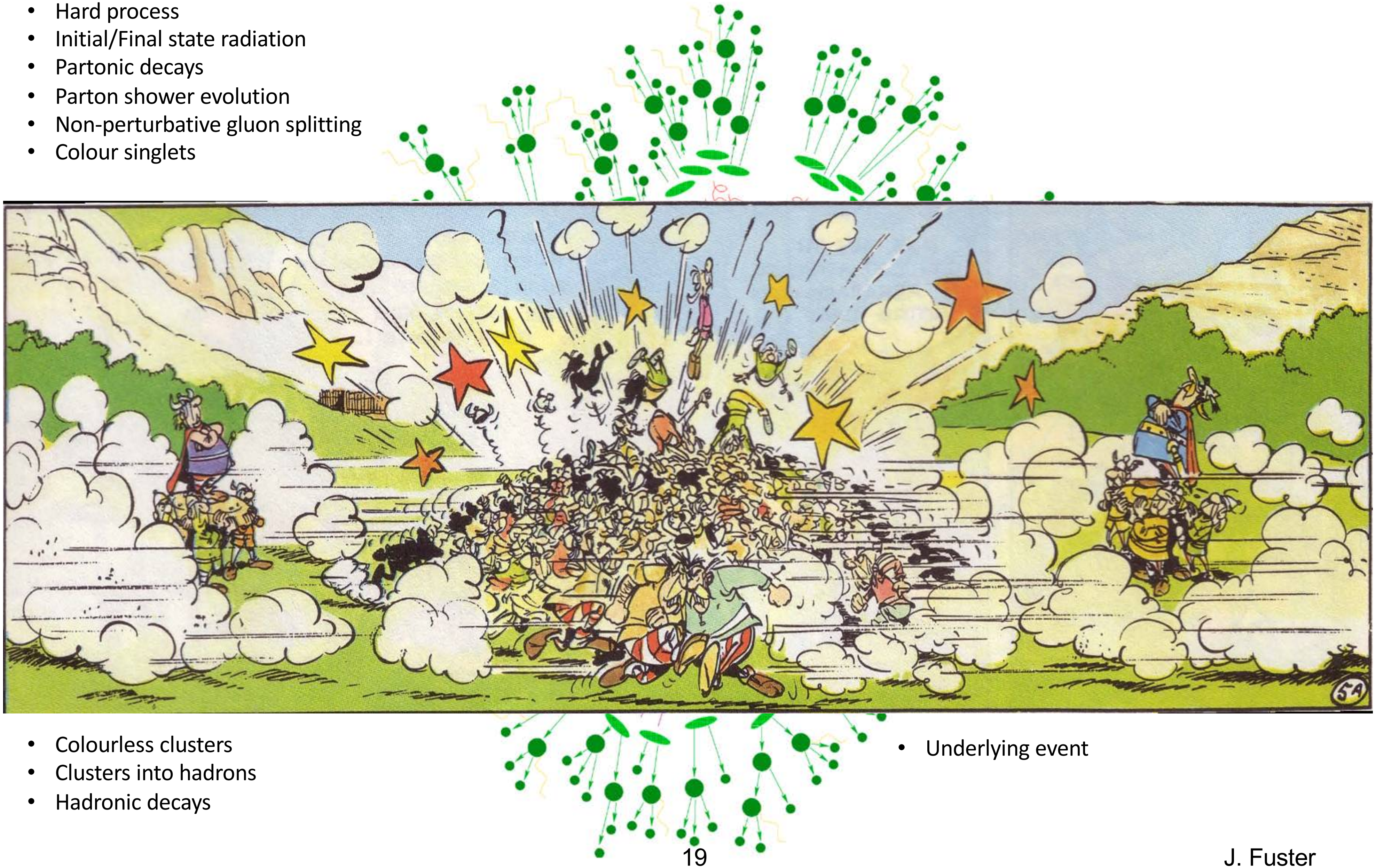

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The top quark is still *strange*: the consistency of the Standard Model

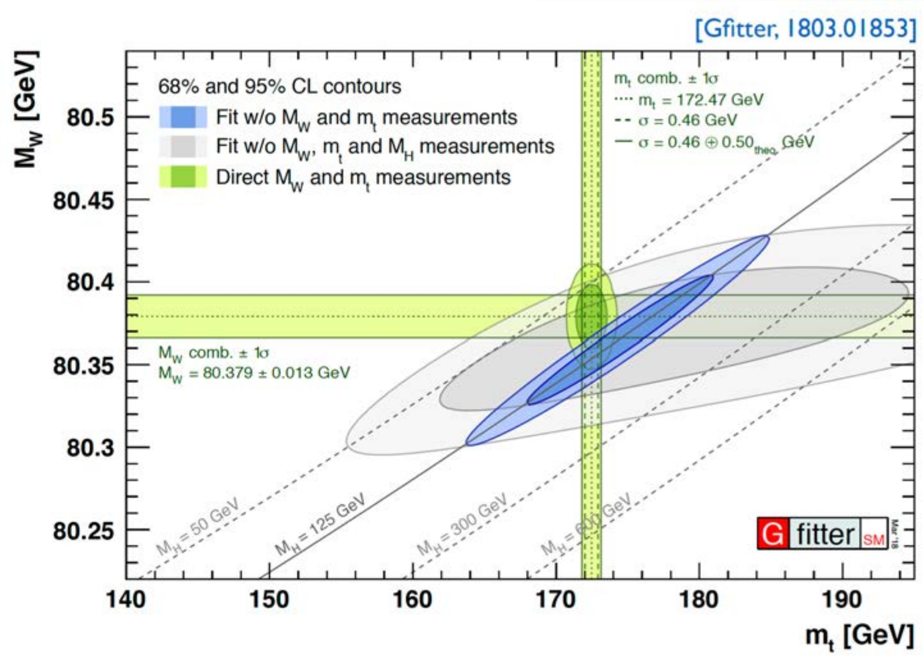
EW consistency between: M_W ⌘ M_H ⌘ M_t

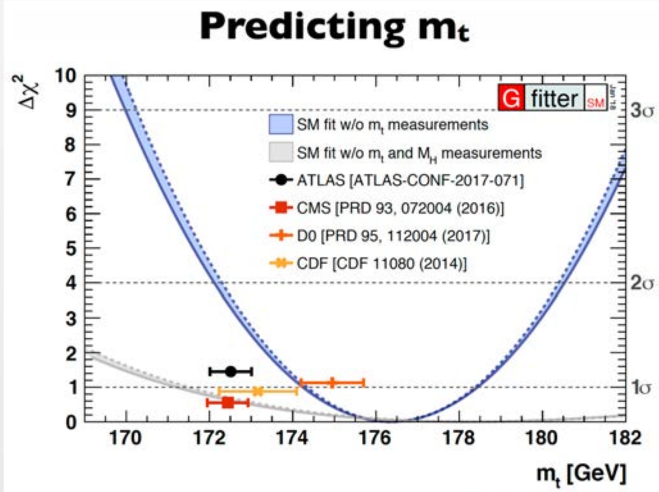
Roman Kogler Madrid 2019,

arXiv: 1509.00672;1708.06355;1803.01853

Gfitter group

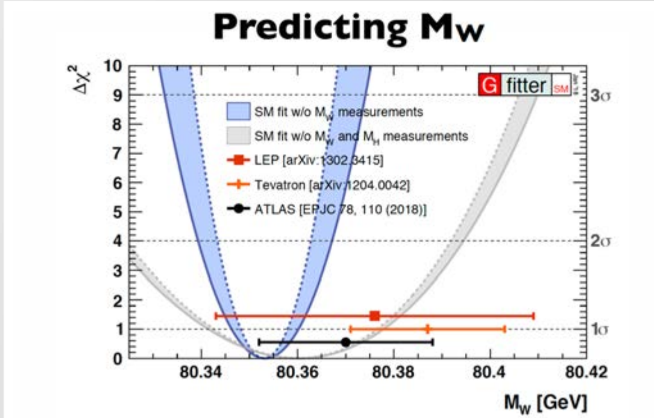
http://project-gfitter.web.cern.ch/project-gfitter/Standard_Model/





$m_t = 176.4 \pm 2.1\,\mathrm{GeV}$ (exp: ± 0.46 GeV)

(perfect knowledge of Mw: ± 0.9 GeV)



$$M_W = 80.3535 \pm 0.0027_{m_t} \pm 0.0030_{\delta_{\mathrm{theo}} m_t} \pm 0.0026_{M_Z} \pm 0.0026_{\alpha_S} \pm 0.0024_{\Delta\alpha_{\mathrm{had}}} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\mathrm{theo}} M_W}\ \mathrm{GeV},$$
$$= 80.354 \pm 0.007_{\mathrm{tot}}\ \mathrm{GeV}$$ (exp: ± 0.013 GeV)

δM_W (indirect) = 7 MeV

$$M_W = M_W^{LO} + \Delta r_{top} + \Delta r_H$$

Large contributions to δM_W from top and unknown higher-order EW corrections.

δM_W (direct) = 13 MeV

The top quark is still *strange*: the consistency of the Standard Model

EW consistency between: M_W ⌘ M_H ⌘ M_t

Roman Kogler Madrid 2019,

arXiv: 1509.00672;1708.06355;1803.01853

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http://project-gfitter.web.cern.ch/project-gfitter/Standard_Model/

Experimental Input

Fit is overconstrained

- All free parameters measured ($\alpha_s(M_Z)$) unconstrained in fit)
  - Most input from e^+e^- colliders
    - M_Z : $2\cdot10^{-5}$
  - Crucial input from Tevatron and LHC:
    - m_t : $4\cdot10^{-3}$
    - M_H : $2\cdot10^{-3}$
    - M_W : $2\cdot10^{-4}$
  - Remarkable precision, O(0.1%)
- Require precision calculations (NNLO corrections available)

M_H [GeV]	125.1 ± 0.2	LHC
M_W [GeV]	80.379 ± 0.013	Tev.+LHC
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLD
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	
$\sin^2\theta^\ell_{\rm eff}(\rm TEV)$	0.23148 ± 0.00033	Tev. (+LHC?)
A_c	0.670 ± 0.027	SLD
A_b	0.923 ± 0.020	
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	
R^0_c	0.1721 ± 0.0030	
R^0_b	0.21629 ± 0.00066	
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	2760 ± 9	low E
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]$^{(\nabla)}$	172.47 ± 0.68	Tev.+LHC

The top quark is still *strange*: the consistency of the Standard Model

EW consistency between: M_W ⌘ M_H ⌘ M_t

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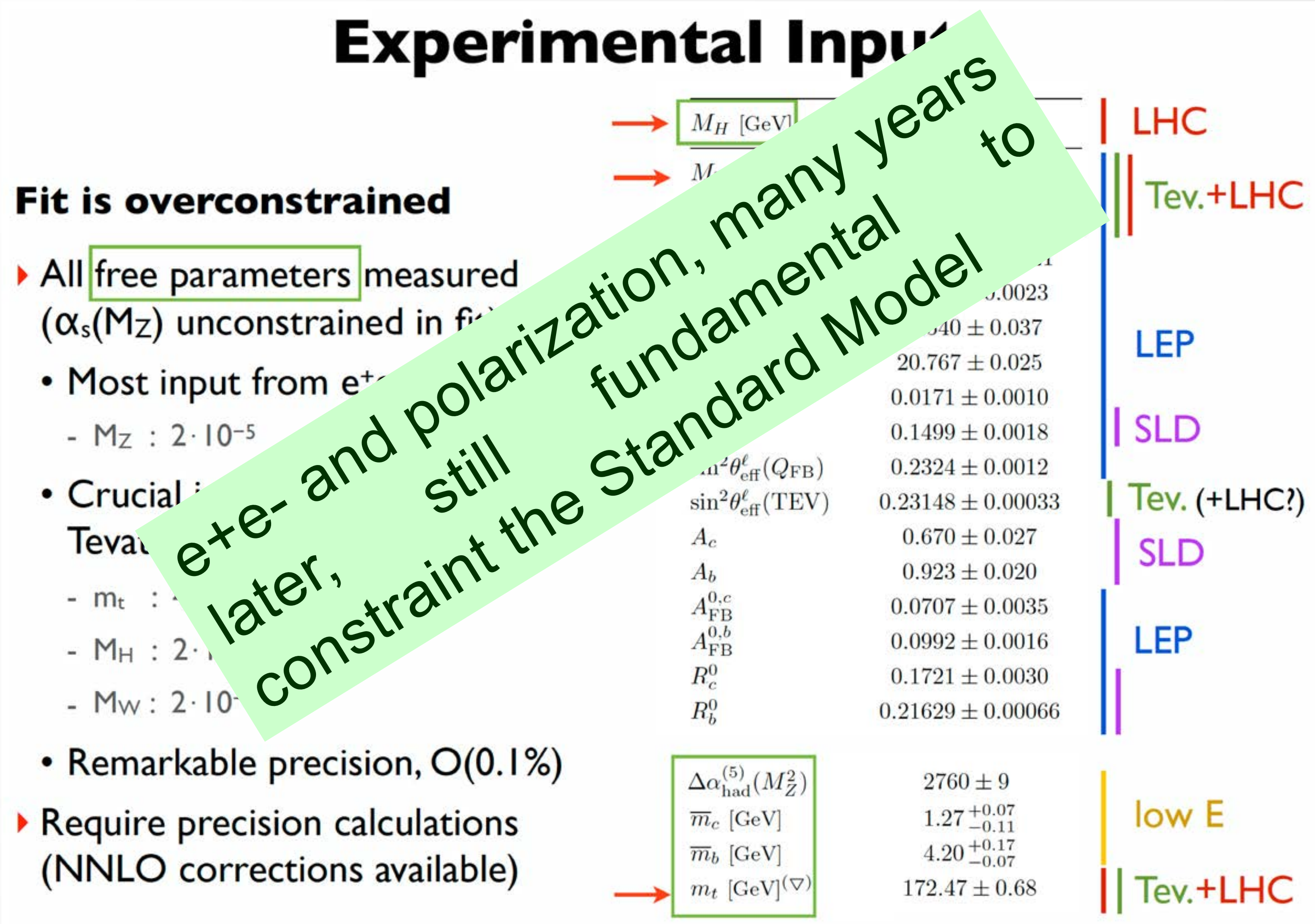
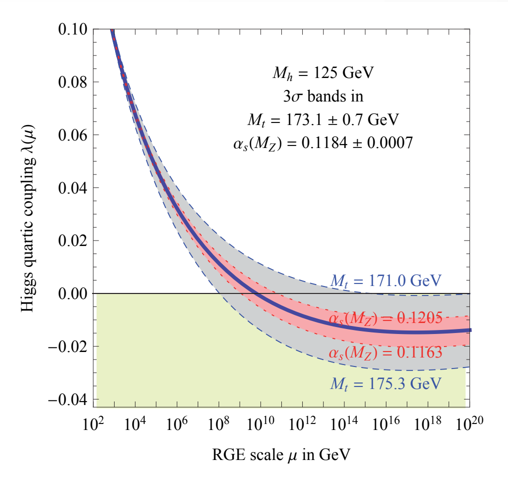


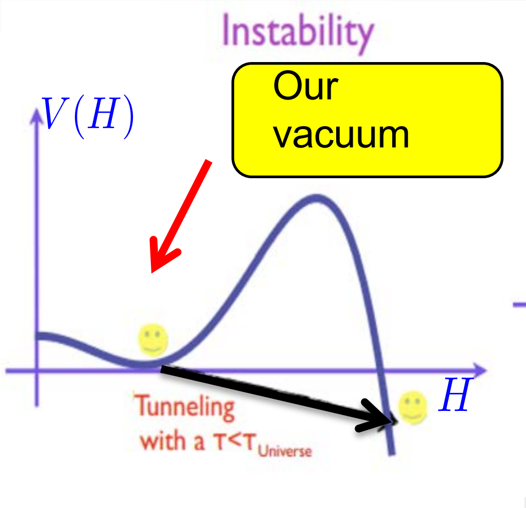
The top quark is still *strange*: the vacuum stability

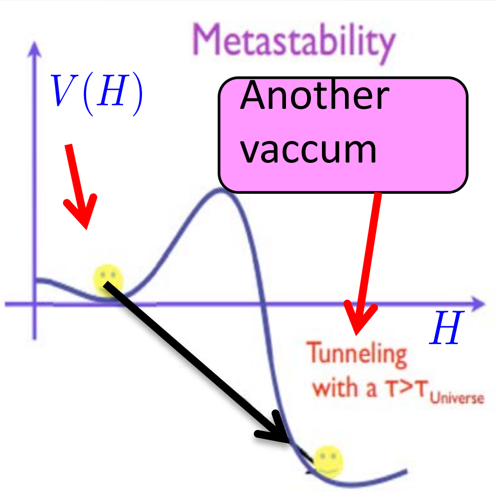
Vacuum Stability ($\lambda(\Lambda) \geq 0$)

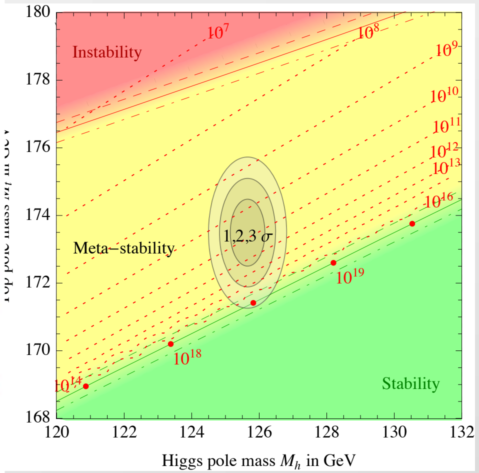
$\lambda(\Lambda)$ the $\overline{\text{MS}}$ quartic Higgs Coupling

Degrassi et al, **JHEP 1208 (2012) 098**
Butazzo et al, **1307.3536 (2013)**

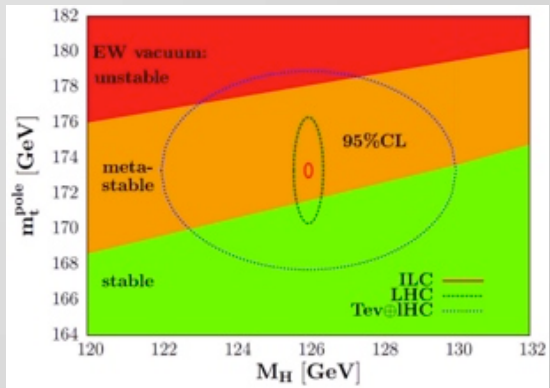








Alekhin et al, **Phys.Lett. B716 (2012) 214**



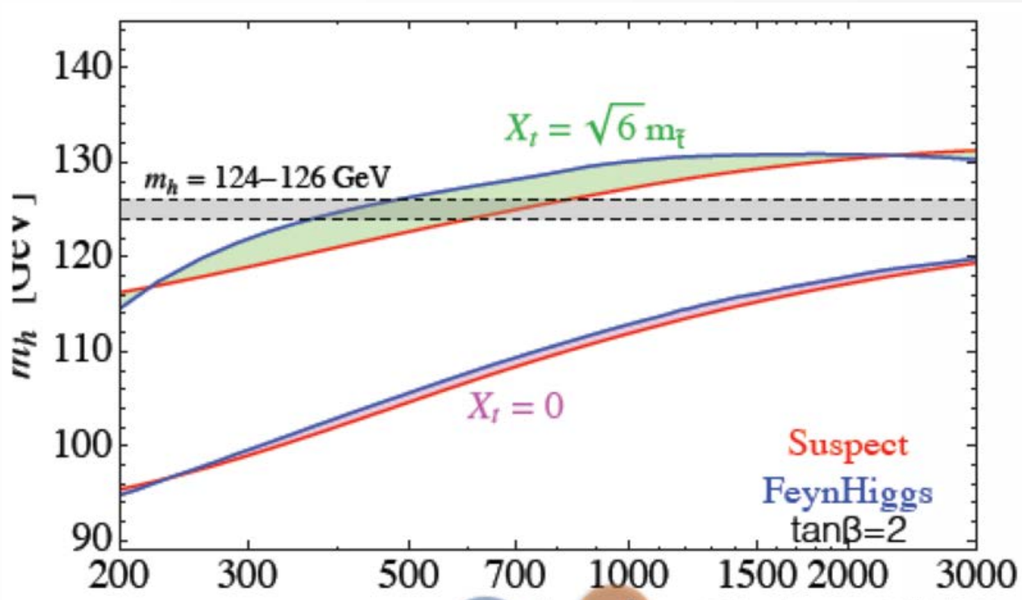
Need to measure m_t with very high accuracy:

Δm_t < 100-150 MeV

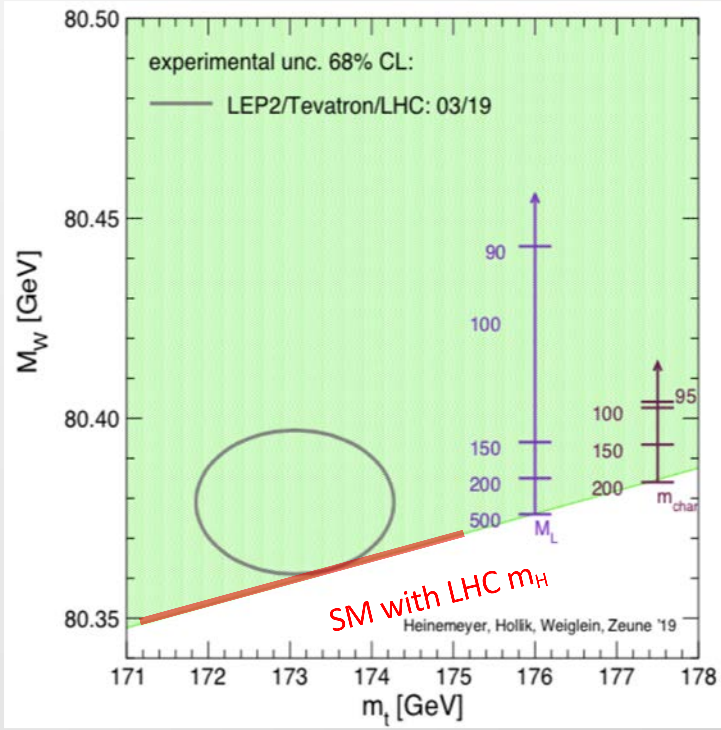
(The existence of New Physics would change the scenario)

The top quark is still strange: sensitive to New Physics

New Physics, general arguments:



$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$



Roberto Franceschini (IFIC seminar, Valencia)

[www.ifca.unican.es/users/heinemey/uni/plots]

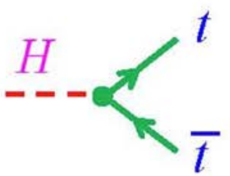
Large mass $\Leftrightarrow$ Sizeable effects

The *ups and downs* of the top-quark mass: the mass in the Lagrangian

$$\mathcal{L}_{QCD} = -\frac{1}{4}(\partial^\mu G^\nu_a - \partial^\nu G^\mu_a)(\partial_\mu G^a_\nu - \partial_\nu G^a_\mu) + \sum_f \bar{q}^\alpha_f \,(i\gamma^\mu \partial_\mu - m_f)\, q^\alpha_f$$
$$- g_s G^\mu_a \sum_f \bar{q}^\alpha_f \gamma_\mu \left(\frac{\lambda^a}{2}\right)_{\alpha\beta} q^\beta_f - \frac{g_s}{2} f^{abc}(\partial^\mu G^\nu_a - \partial^\nu G^\mu_a) G^b_\mu G^c_\nu - \frac{g_s{}^2}{4} f^{abc} f_{ade} G^\mu_b G^\nu_c G^d_\mu G^e_\nu$$

$\alpha_s = g_s^2/4\pi$ and quark masses are not predicted by the SM

m_t
- Fundamental parameter of the SM interesting "per se"
- Important for precise tests of the Standard Model, Yukawa coupling ~ 1
- Test of New Physics scenarios i.e. GUT scenarios, vacuum stability



$$y_t = \frac{\sqrt{2}}{v} m_t = 2^{3/4} G_F^{1/2} m_t = 1 \qquad (0.995)$$

The *ups and downs* of the top-quark mass: mass of quarks

- Free quarks are not observed in nature as they are confined into colourless hadrons, so there is no pole in the S-matrix

  ✓ quark-masses, in particular the top-quark mass, are not "observables" and they are parameters of the underlying theory

  ➔ fit $O^{exp}(x)$ with $O^{th}(m_t,\alpha_s;x)$ and extract m_t ➔

  ✓ precise value depends on the definition of the renormalization scheme selected (pole mass, $\overline{\text{MS}}$, MSR, etc..)

  ✓ to fix the renormalization scheme at least a NLO calculation is required

  ✓ In a way, "quark masses" are kind of "effective coupling constants"

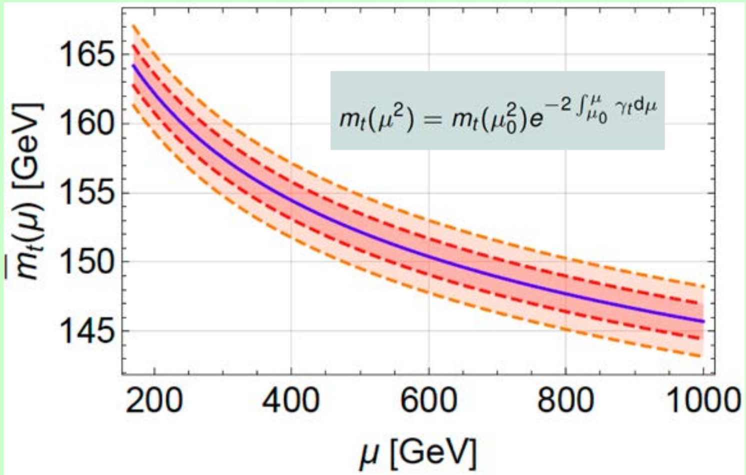
Corollary: the mass of quarks cannot be measured as the π^0 mass

The ups and downs of the top-quark mass: mass definitions

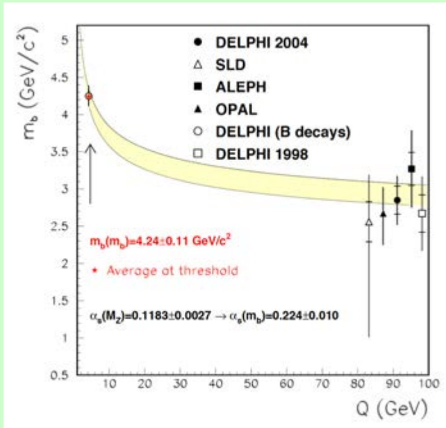
Most common definitions:

$m_t(\mu)$: the SM m_t renormalised in the $\overline{\text{MS}}$ / MS scheme,

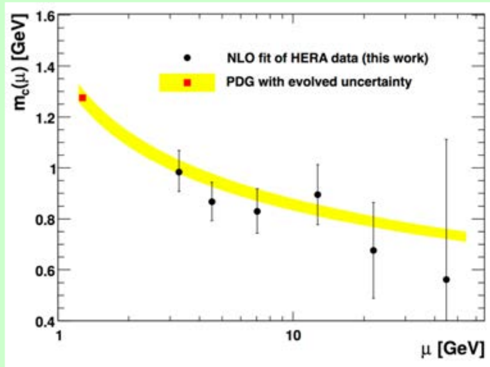
- Well defined order-by-order in pQCD
- It is function of an energy scale parameter
  (but a scale-independent number can be associated to it: $m_t(m_t)$)
- Good description of physics far from top-quark production thresholds
- Mass running typically of the form



RunDec: Chetyrkin, Kuehn & Steinhauser, arXiv:hep-ph/0004189



A. Gizhko et al., **Phys.Lett. B775 (2017) 233-238**



Quark masses run !!

The ups and downs of the top-quark mass: mass definitions

Most common definitions:

$m_t(\mu)$: the SM m_t renormalised in the $\overline{MS}$ / MS scheme,

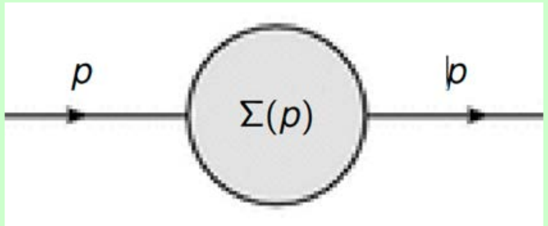
m_t^{pole}: the mass renormalised in the pole-mass scheme,

- Defined as the pole of the top-quark propagator
- Intrinsic uncertainty in definition (200 MeV renormalon problem)
- Good description of physics near top-quark production thresholds.
- If the top-quark mass would be a stable particle, m_t^{pole} would be its physical mass

$$\Pi(p^2) \propto \frac{1}{p^2 - m^2 + \Sigma(p^2) + i0}$$

renormalisation conditions:

$$\Sigma(p^2 = m^2) = 0\,, \quad \left[\frac{d\Sigma}{dp^2}\right]_{p^2=m^2} = 0.$$



- $m_t(\mu)$ and m_t^{pole} can be related using pQCD

Pole mass vs running mass

$$m_t = \overline{m}(\mu)\left(1 + \frac{\alpha_s(\mu)}{\pi}\left[\frac{4}{3} + \ln\left(\frac{\mu^2}{\overline{m}(\mu)^2}\right)\right] + O(\alpha_s^2)\right)$$

P. Marquard et al, Quark Mass Relations to Four-Loop Order in Perturbative QCD, **Phys. Rev. Lett. 114 (2015) 142002**

The ups and downs of the top-quark mass: mass definitions

Most common definitions:

$m_t(\mu)$: the SM m_t renormalised in the $\overline{\text{MS}}$ / MS scheme,

m_t^{pole}: the mass renormalised in the pole-mass scheme,

$m_t^{MSR}(R)$: short-distance mass that smoothly interpolates all R scales

- Renormalon free
- Precision in relation to any other short-distance mass: $\lesssim$ 20 MeV @ $O(\alpha_S^4)$

MSR Mass Definition

Jain, Lepenik, Mateu, Preisser, Scimemi, Stewart, AHH arXiv:1704.01580

MS Scheme: $(\mu > \overline{m}(\overline{m}))$

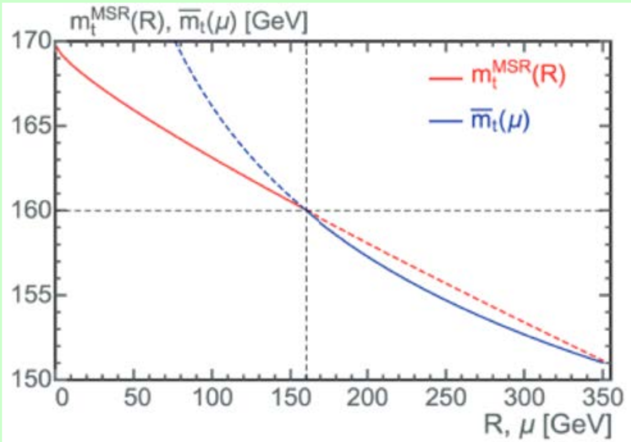
$$\overline{m}(\overline{m}) - m^{\text{pole}} = -\overline{m}(\overline{m})\,[0.42441\,\alpha_s(\overline{m}) + 0.8345\,\alpha_s^2(\overline{m}) + 2.368\,\alpha_s^3(\overline{m}) + \ldots]$$

$\Downarrow$

MSR Scheme: $(R < \overline{m}(\overline{m}))$

$$m_{\text{MSR}}(R) - m^{\text{pole}} = -R\,[0.42441\,\alpha_s(R) + 0.8345\,\alpha_s^2(R) + 2.368\,\alpha_s^3(R) + \ldots]$$

$$m_{\text{MSR}}(m_{\text{MSR}}) = \overline{m}(\overline{m})$$



A. Hoang et al., The MSR and the $O(\Lambda_{QCD})$ renormalon sum rule, **JHEP 1804 (2018) 003**

The ups and downs of the top-quark mass: mass definitions

Most common definitions:

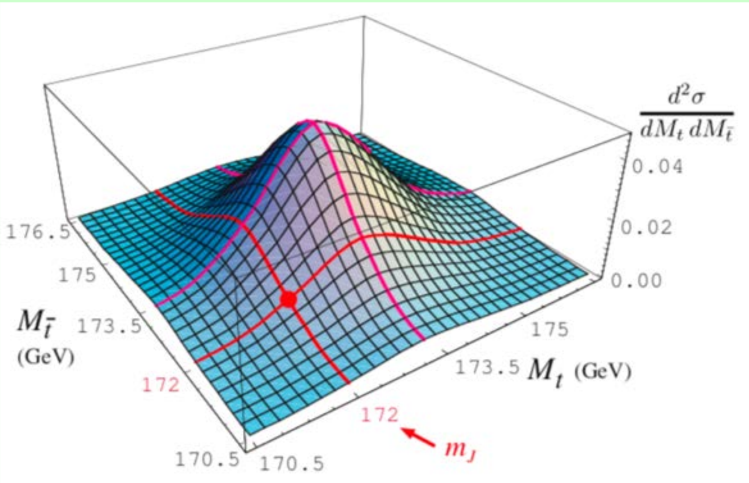
$m_t(\mu)$: the SM m_t renormalized in the $\overline{MS}$ / MS scheme,

m_t^{pole}: the mass renormalized in the pole-mass scheme,

$m_t^{MSR}(R)$: short-distance mass that smoothly interpolates all R scales

m_t^{MC}: top mass value as implemented in the Monte Carlo generators

- As an effective parameter used in hard process+parton shower+hadronization
- Not related with any top mass definition of the SM Lagrangian (EW fits, etc..)



Example from Phys. Rev. D77 (2008) 074010

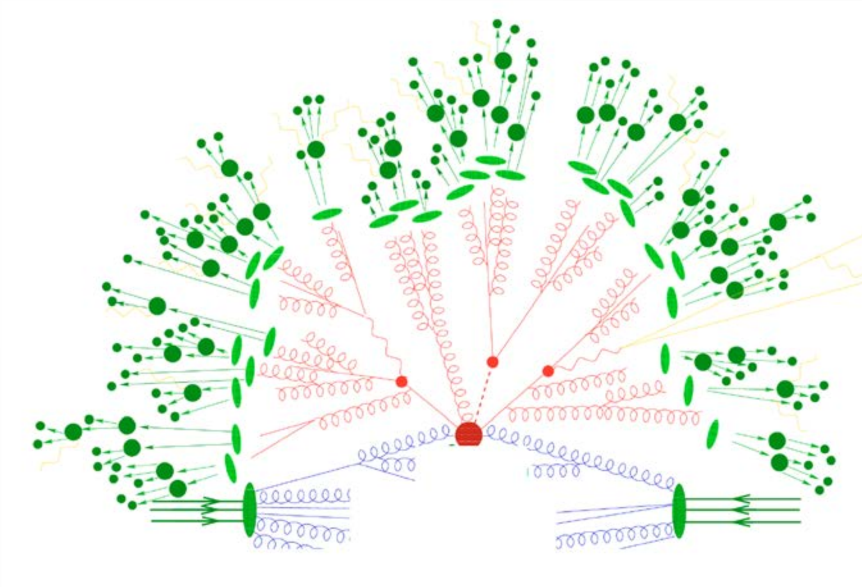
pQCD calculation generated with

$m_j = 172$ GeV

extracted value after shower/hadronization

$M_t = 173.5$ GeV

The ups and downs of the top-quark mass: Monte Carlo event generators



Monte Carlo event generators are used to describe these processes:

- Matrix elements (LO/NLO)
- Parton shower (LL)
- Hadronization model

- Experimental observables fully simulated
- QCD-inspired: partly first principles QCD and partly modelled (getting very sophisticated though)
- Modelling parameters are tuned to data getting better accuracy than intrinsic theory
- Top quark in parton shower is treated like a real particle ($m_t^{MC} \approx m_t^{pole}$ +?)
- Top quark in matrix elements: $m_t^{MC} = m_t^{pole}$

BUT:

- parton showers sum (real & virtual !) perturbative corrections only above the shower cut and not pickup any corrections from below.
- what is the meaning of MC parameters ? (calibration & theory)

A. Hoang at 2017 LC top workshop, M. Butenschoen et al., **Phys.Rev.Lett. 117 (2016) no.23, 232001**

The ups and downs of the top-quark mass: Monte Carlo event generators

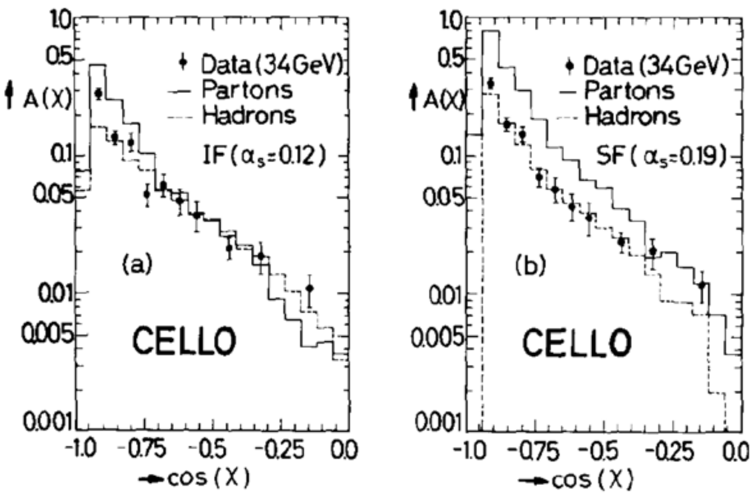


Fig. 1. (a) Corrected asymmetry data compared with the asymmetry of the partons and the generated final state hadrons in the independent fragmentation model (IF). (b) As (a), but now for the string model.

Already an old story 1984

method	SF	IF0	IF	IF1	SF/IF
asymmetry	0.19	0.12	0.12	0.15	1.58
cluster thrust	0.18	0.13	0.12	0.13	1.50

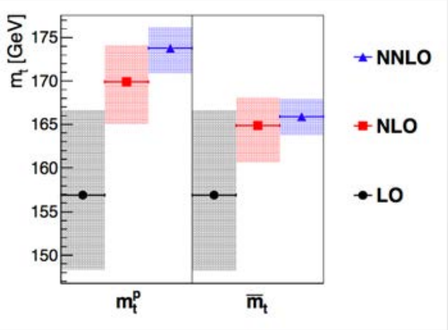
On the model dependence of the determination of the strong coupling constant in second order QCD from e+e --annihilation into hadrons
CELLO Collab., H-J Behrend et al.
Phys. Lett. 138B (1984) 311-316

The value of α_S was shown to have 50% uncertainty due "MC model dependence". At this time this was Independent Fragmentation vs String fragmentation.

A huge progress since then in theory and experiment but still modelling in MC is harming !!!

The ups and downs of the top-quark mass: Mass definition

- Studies to calibrate/relate m_t^{MC}:



- J. Kieseler et al., Phys, Lett, 116 (2016) 162001

$$\Delta_m = m_t - m_t^{MC} \sim 2\,\mathrm{GeV}$$

This study uses tt cross-sections

- M. Butenschoen et al., Phys.Rev.Lett. 117 (2016) no.23, 232001.

$$m_t^{MC} = m_t^{MSR}(1\,\mathrm{GeV}) + (0.18 \pm 0.22)\ \mathrm{GeV} \qquad m_t^{MC} = m_t^{pole} + (0.57 \pm 0.28)\ \mathrm{GeV}$$

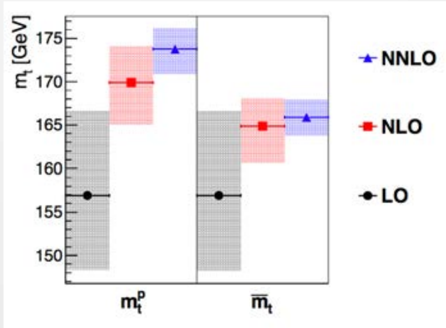
This study uses 2-jettines distribution in e+e- interactions.
Expanding the result to pp interactions and different observables remains to be proven

- Other estimates in literature Δ_m ~ O(0.5-1.0) GeV

- A lot of discussion/controversy on how to interpret these results/differences:
  - S. Moch et al., arXiv:1405.4781,
  - A. H. Hoang and I. W. Stewart, 500 Nouvo Cimento B123 (2008) 1092–1100,
  - A. Buckley et al., arXiv:1101.2599,
  - A. H. Hoang, arXiv:1412.3649,
  - A. Hoang et al., JHEP 1810 (2018) 200,
  - A. Hoang et al, JHEP 1804 (2018) 003,
  - M. Dasgupta et al., JHEP 09 (2013) 029,
  - A. J. Larkoski et al., JHEP 05 (2014) 146,
  - P. Nason, arXiv:1712.02796, arXiv:1901.04737,
  - G. Corcella, arXiv:1903.06574,
  - S. Ferrairo et al., arXiv:1906.09166,
  - S. Ferrairo et al., JHEP 1901 (2019) 203

The ups and downs of the top-quark mass: Mass definition

- Studies to calibrate/relate m_t^{MC}:



- J. Kieseler et al., Phys, Lett, 116 (2016) 162001

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This study uses 2-jettines distribution in e+e- interactions. Expanding the result to pp interactions and different observables remains to be proven

O(0.5-1.0) GeV represent 0.3%-0.6% relative effect to the top mass

Very small but significant given present accuracy

The prize of being so precise !!!!

- A. Buckley et al., arXiv:1101.2599,
- A. H. Hoang, arXiv:1412.3649,
- A. Hoang et al., JHEP 1810 (2018) 200,
- A. Hoang et al, JHEP 1804 (2018) 003,
- M. Dasgupta et al., JHEP 09 (2013) 029,
- A. J. Larkoski et al., JHEP 05 (2014) 146,
- P. Nason, arXiv:1712.02796, arXiv:1901.04737,
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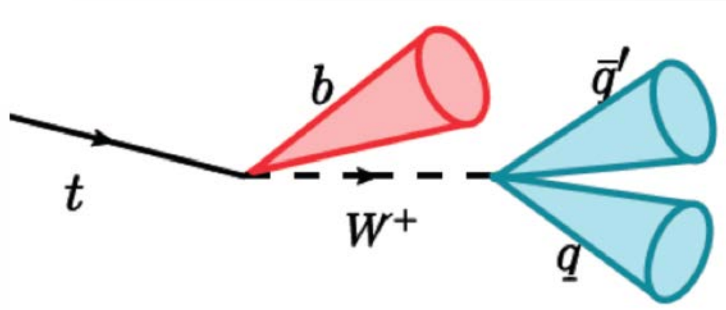
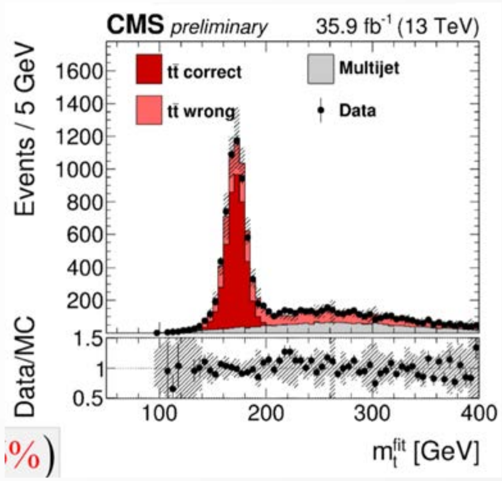
- S. Ferrairo et al., arXiv:1906.09166,
- S. Ferrairo et al., JHEP 1901 (2019) 203

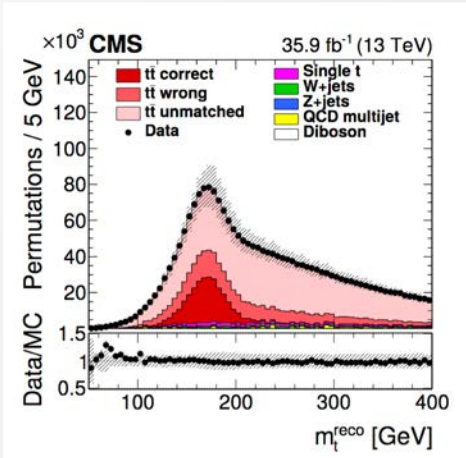
The ups and downs of the top-quark mass: experimental determinations

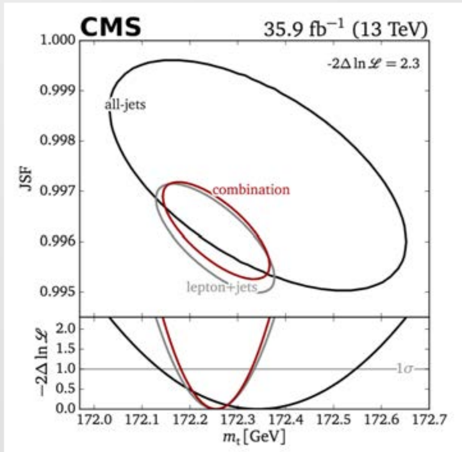


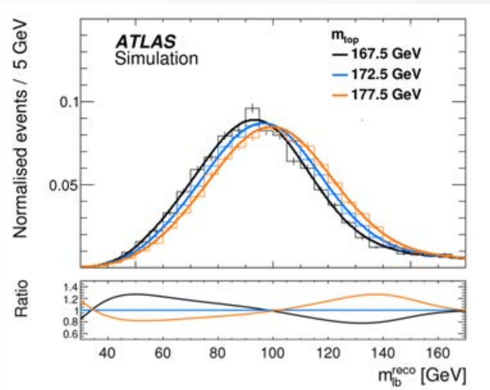
“Direct” mass measurements

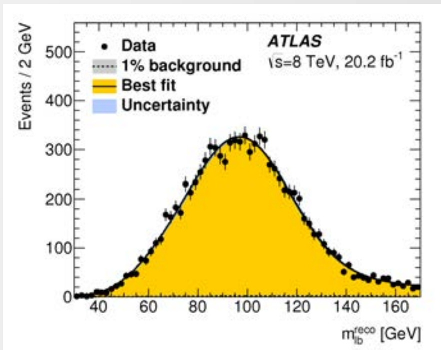
- Reconstruction of top-decay products
- High top mass sensitivity
- Template, matrix-element and ideogram methods
- Determine m_t^{MC}

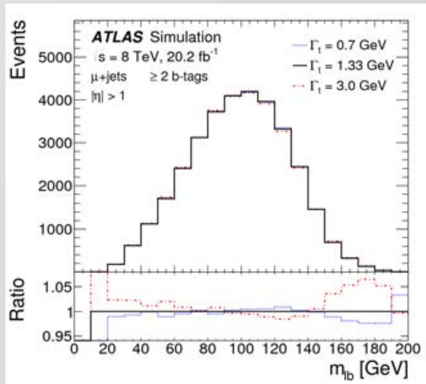




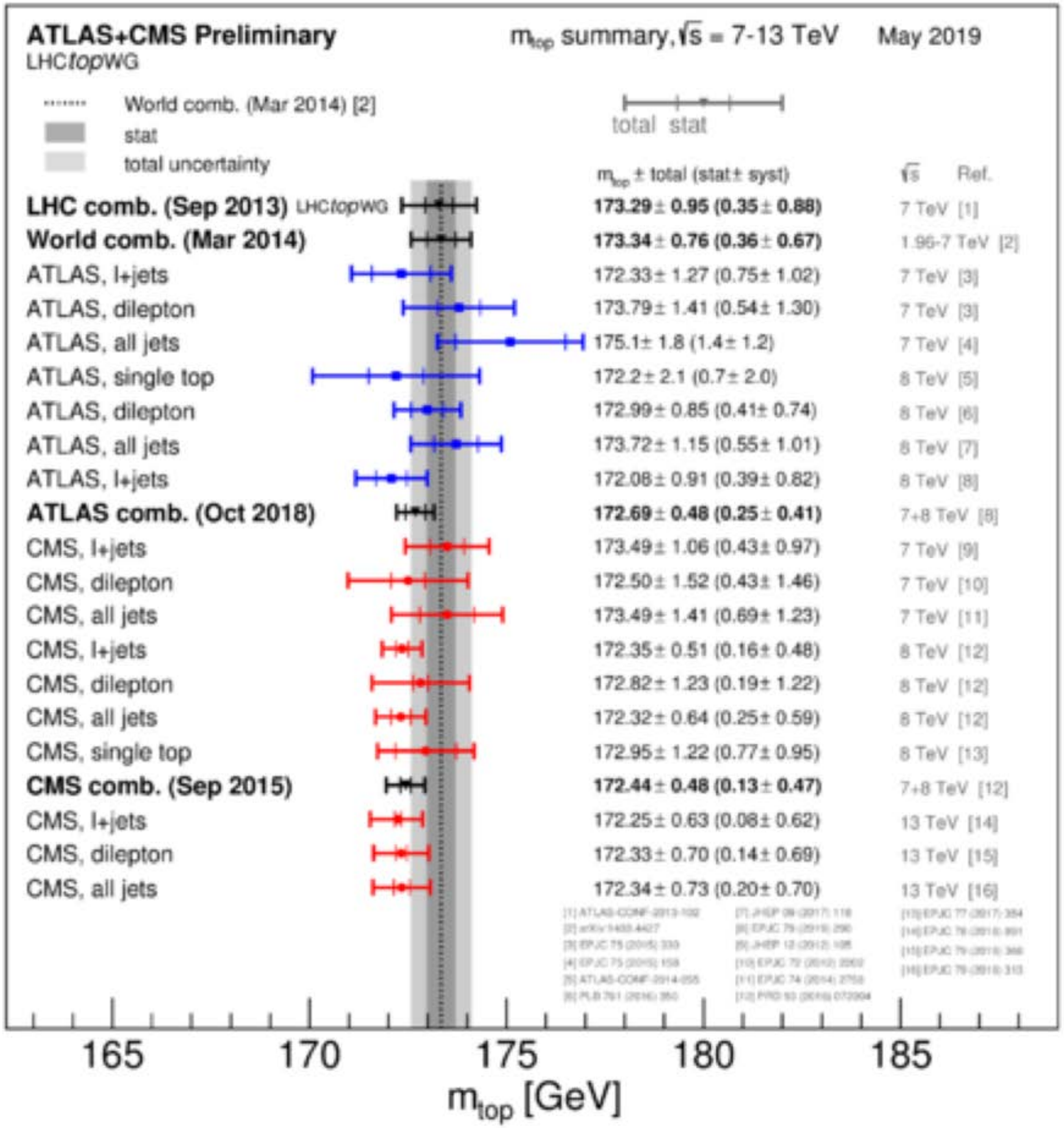








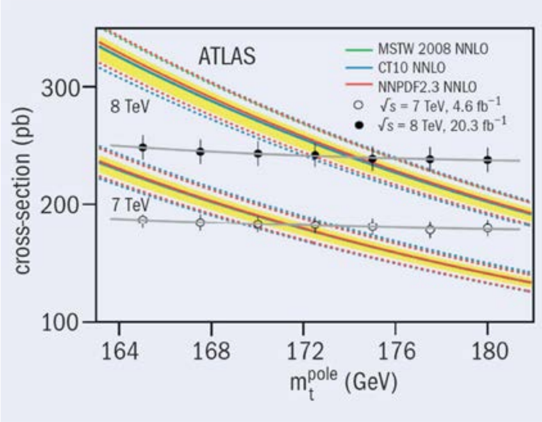
The ups and downs of the top-quark mass: experimental determinations



LHC Summary

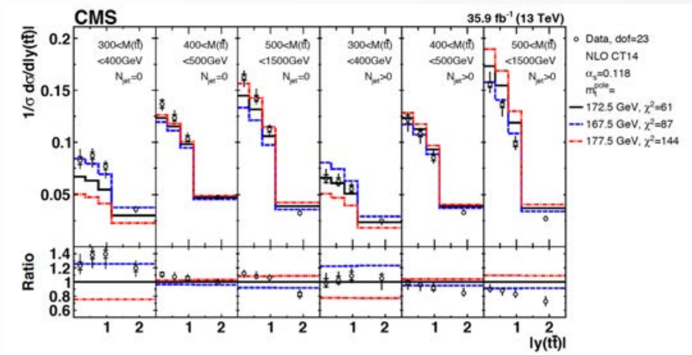
"Direct" measurements

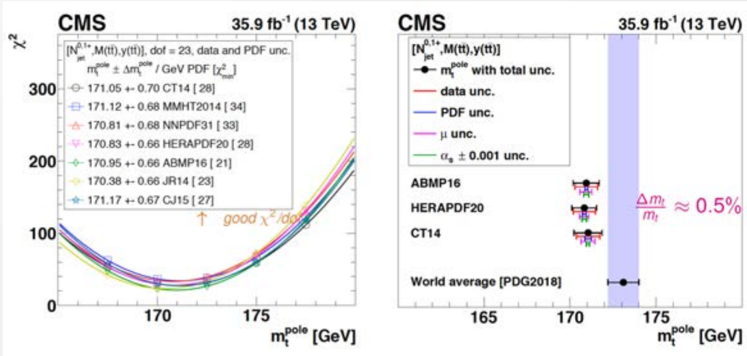
The ups and downs of the top-quark mass: experimental determinations

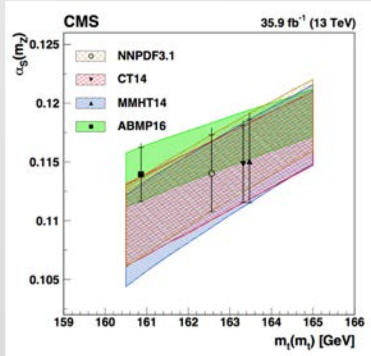


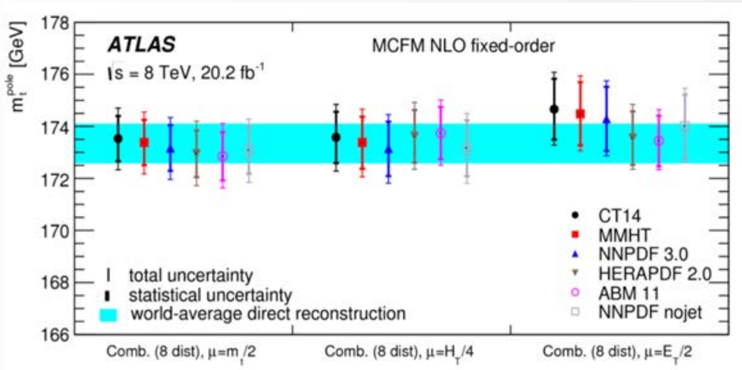
“Alternative” mass measurements

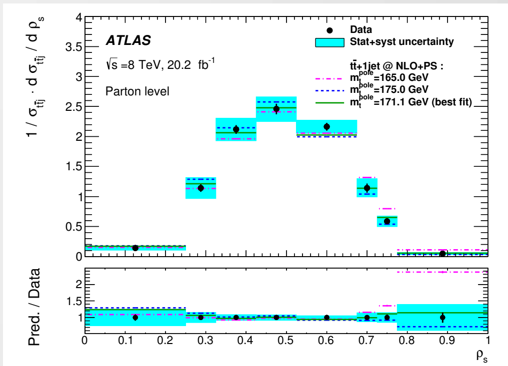
- Use total or differential cross-sections
- Compare corrected data to pQCD prediction (NLO/NNLO)
- Determine m_t^{pole} and $m_t(\mu)$
- Usually less sensitivity than “direct” measurements
- But.., entering to the sub-GeV accuracy

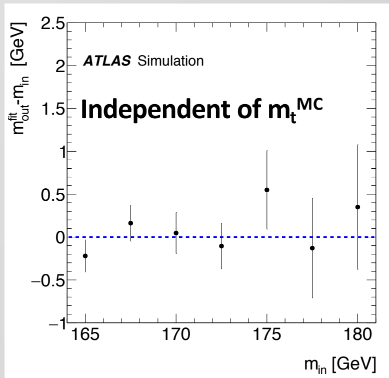




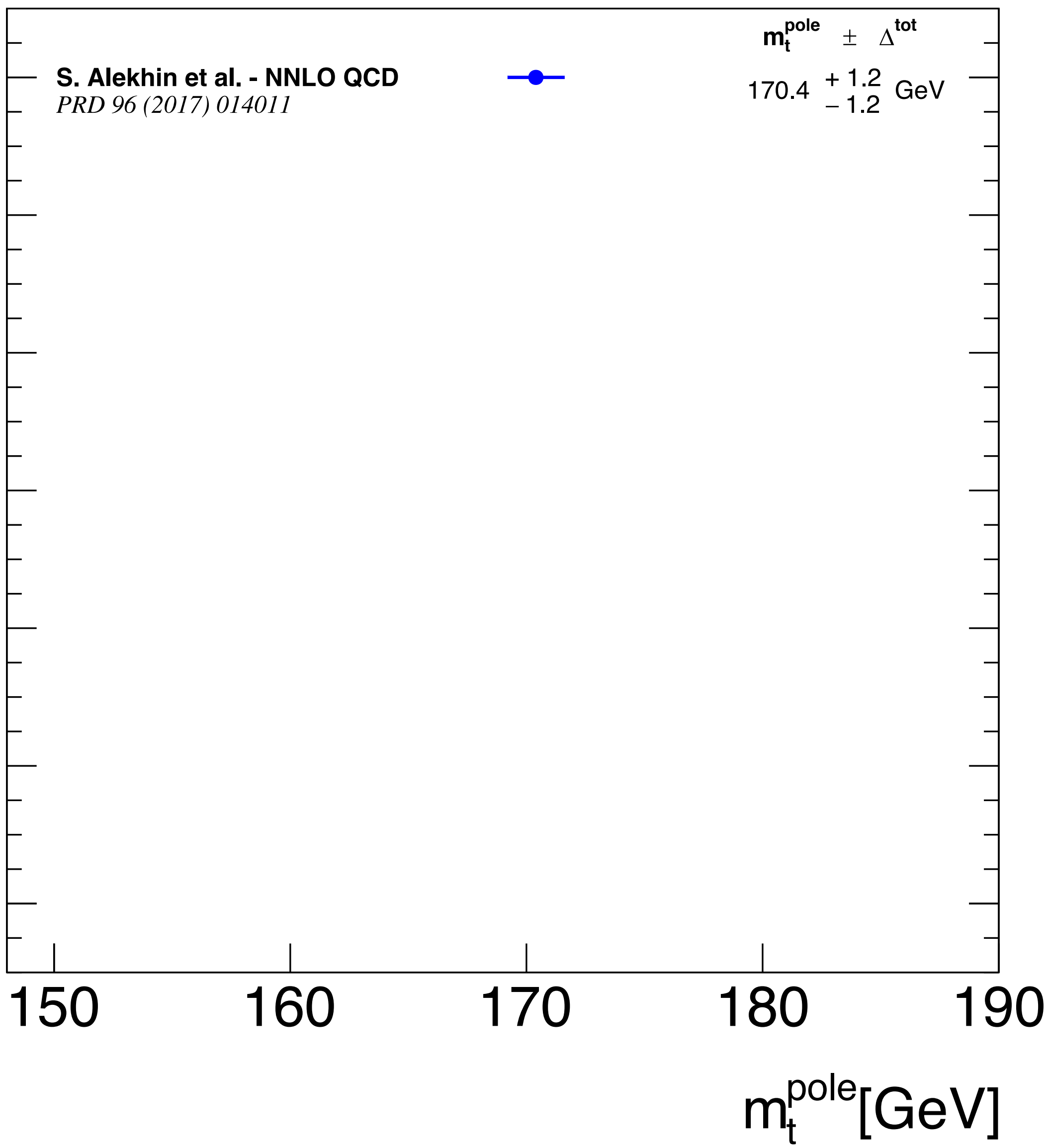








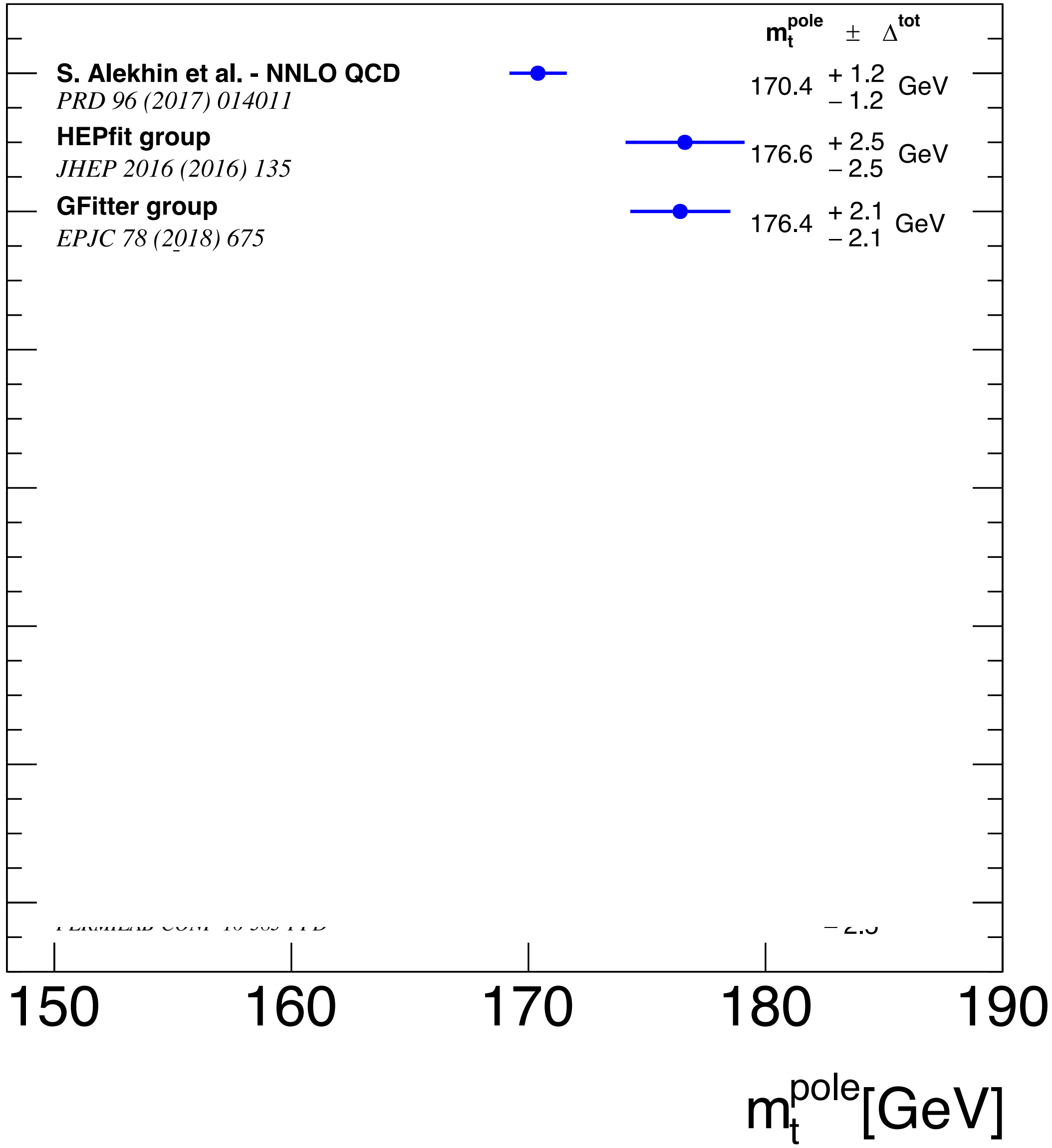
J. Fuster



Pole mass summary

Global Fit – NNLO QCD

The ups and downs of the top-quark mass: experimental determinations



Pole mass summary

Global Fit – NNLO QCD

EW- Fits: HEPfit. & GFitter

J. Fuster

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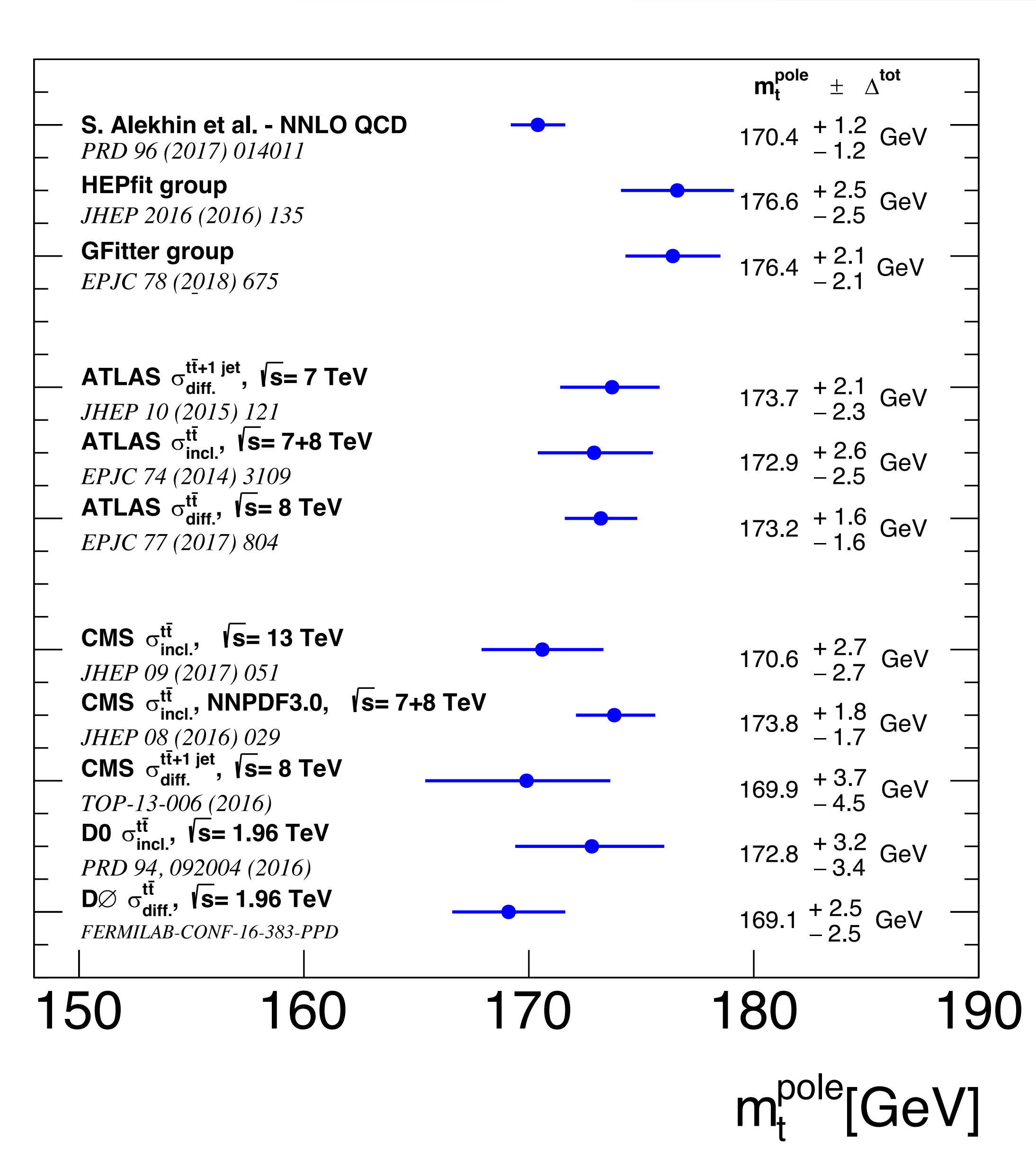

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Global Fit – NNLO QCD

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LHC & Tevatron:

- Cross-section & differential

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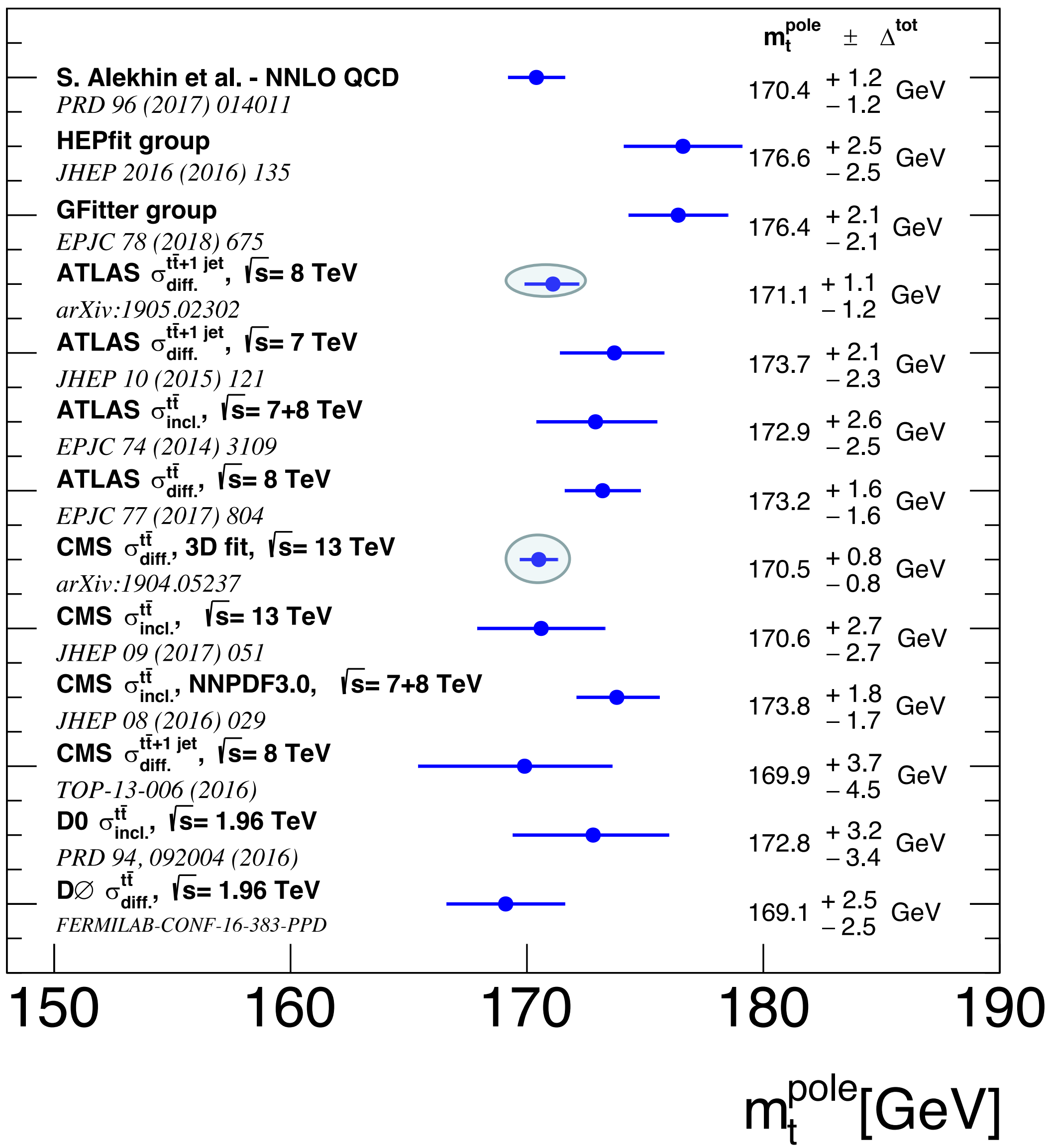

Pole mass summary

Global Fit – NNLO QCD

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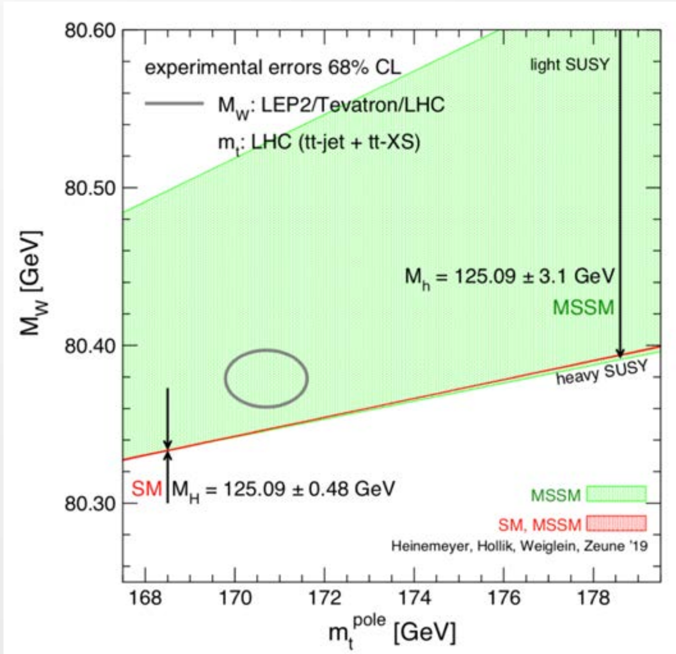
LHC & Tevatron:

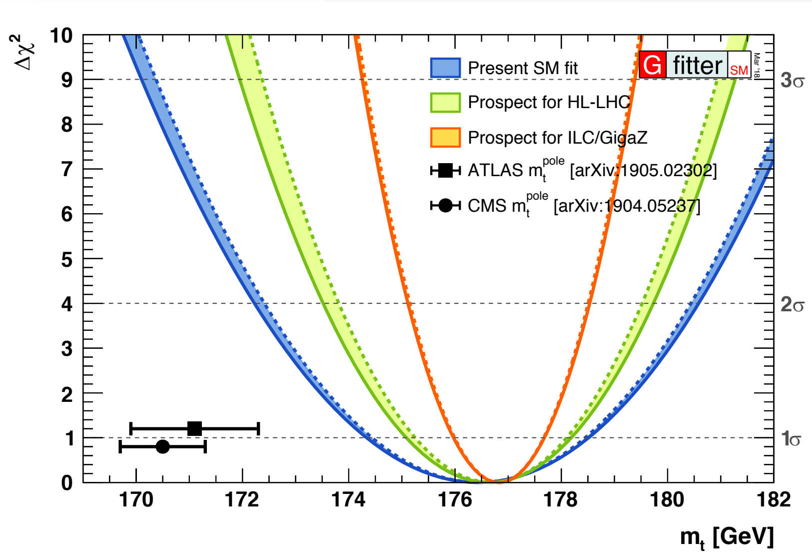
- Cross-section & differential

LHC latest results sub-GeV !!!

The ups and downs of the top-quark mass: Look into the new results



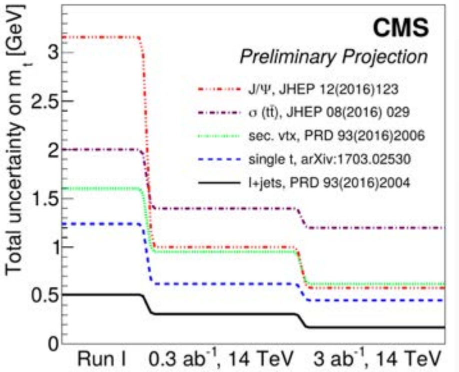
Courtesy of Sven Heinnemeyer
(Using latest ATLAS+CMS results)
(naïve combination)



Courtesy of Roman Kogler - Gfitter
(Using latest ATLAS+CMS results)
(including HL-LHC and ILC projections)

Nothing to claim but getting interesting

The ups and downs of the top-quark mass: looking into the future



Method	Statistical	Systematic	Total (GeV)
$t\bar{t}$ lepton+jets	0.17	0.02	0.17
single-t t-channel	0.45	0.06	0.45
m_{svl}	0.62	0.02	0.62
J/ψ	0.24	0.53	0.58
$\sigma_{t\bar{t}}$	0.4% (exp)	0.4% (theory)	1.2

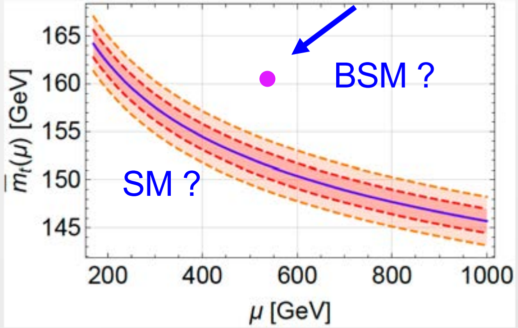
Standard Model Physics at the HL-LHC and HE-LHC, **arXiv:1902.04070**

HL-LHC (higher statistics):

- Possibility to use rare decays (J/Ψ)
- Restrict phase space regions
- Better control of systematics/modelling

- Expected accuracy: 200-300 MeV

Z.Z. Xing et al. et al, **Phys.Rev. D72 (2008) 113016**



- Need to develop further present theory calculations/predictions
- New observables or/and use of different mass definitions. To be explored

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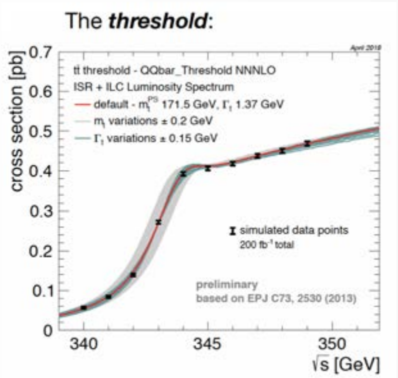
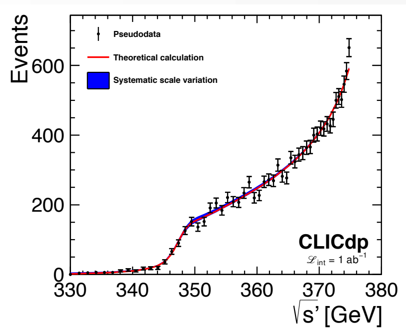


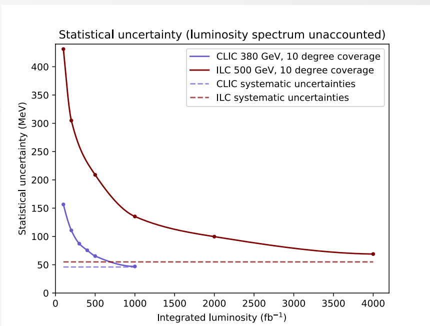
Collider e+e- (at top threshold): H. Abramowicz et al., CLICdp Collab., **arXiv:1807.02441**

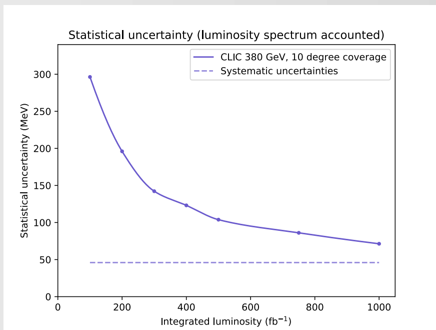
- Well-defined mass scheme
- Access to top-width and Yukawa coupling
- Expected accuracy: m_t~ 40-75 MeV; Γ_t~100 MeV; y_t~15%

Collider e+e- (at continuum above top threshold):

- Well-defined mass scheme
- After 1-2 years data taking better accuracy than LHC/HL-LHC complete programme
- Expected accuracy: m_t~ 100-150 MeV





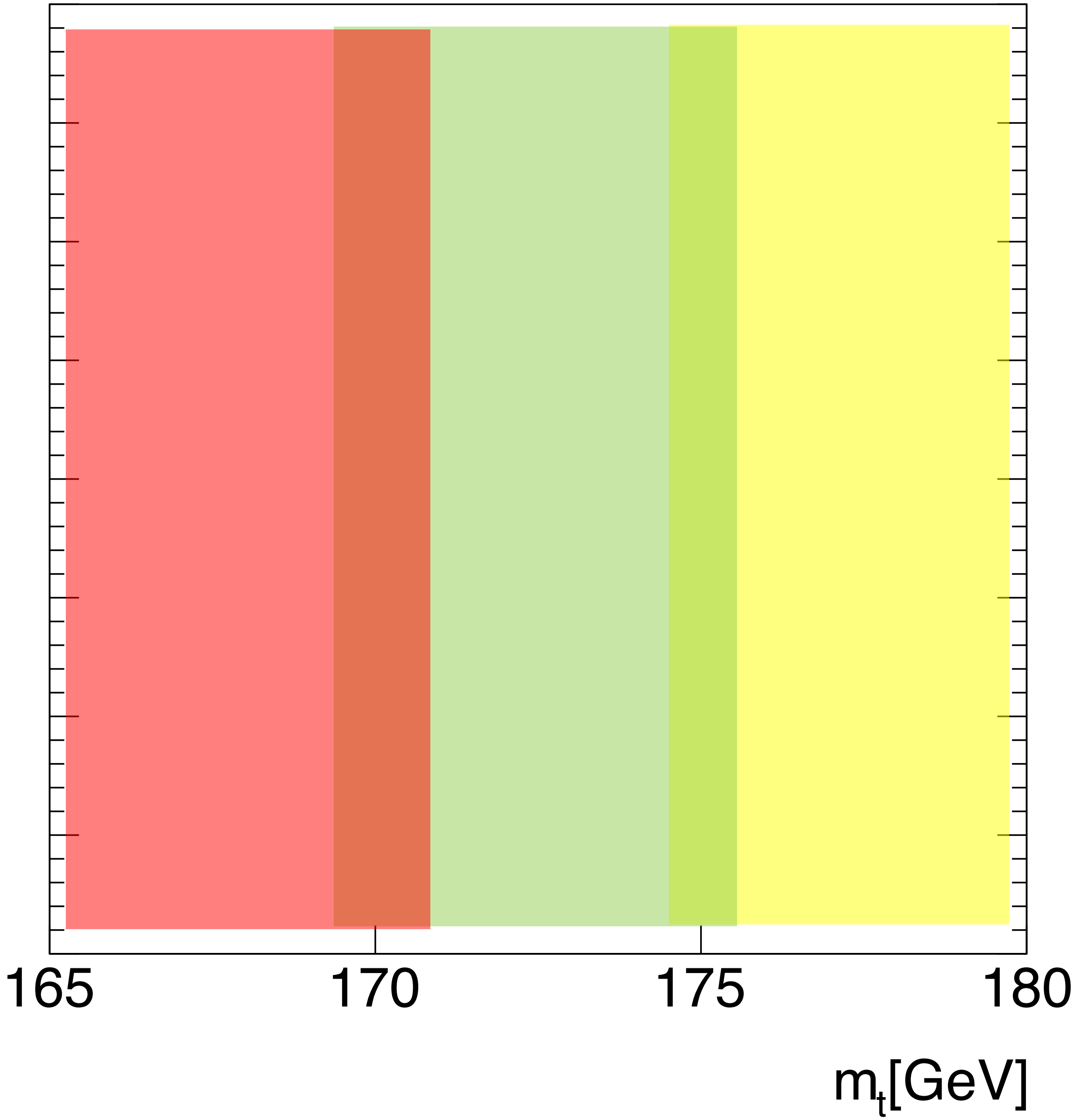


$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

J. Fuster

The ups and downs of the top-quark mass: discussion (qualitative)

Keeping present values/uncertainties of m_h and m_W



New Physics at Low EW Energy Scales (Heinemmeyer et al.)

Need for New Physics @ Large Energy Scales
Vacuum Stability: Meta-stable Universe

Need for New Physics @ Large Energy Scales
Vacuum Stability: Unstable Universe

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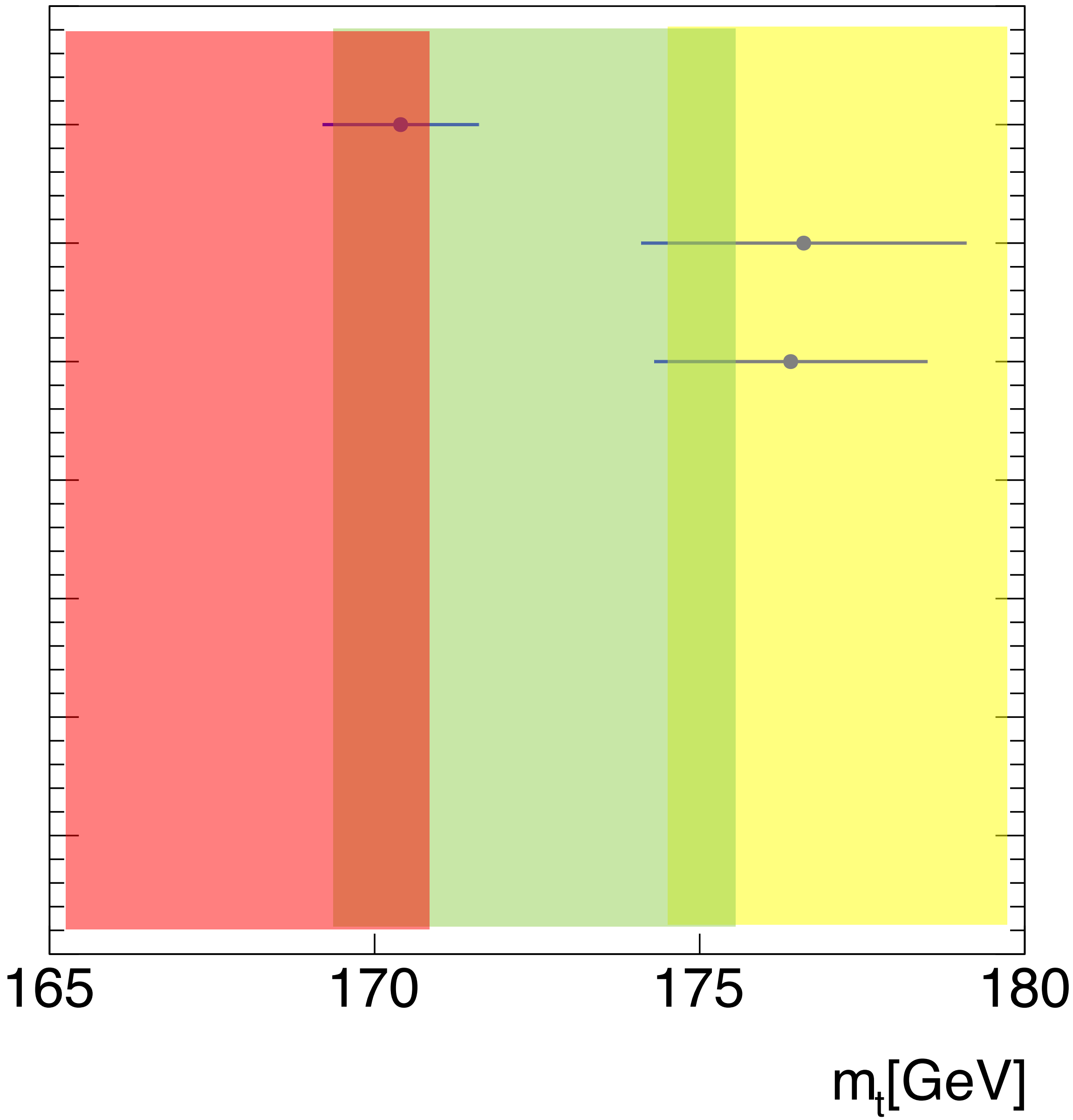

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Global Fit – NNLO QCD

EW- Fits: HEPfit. & Gfitter

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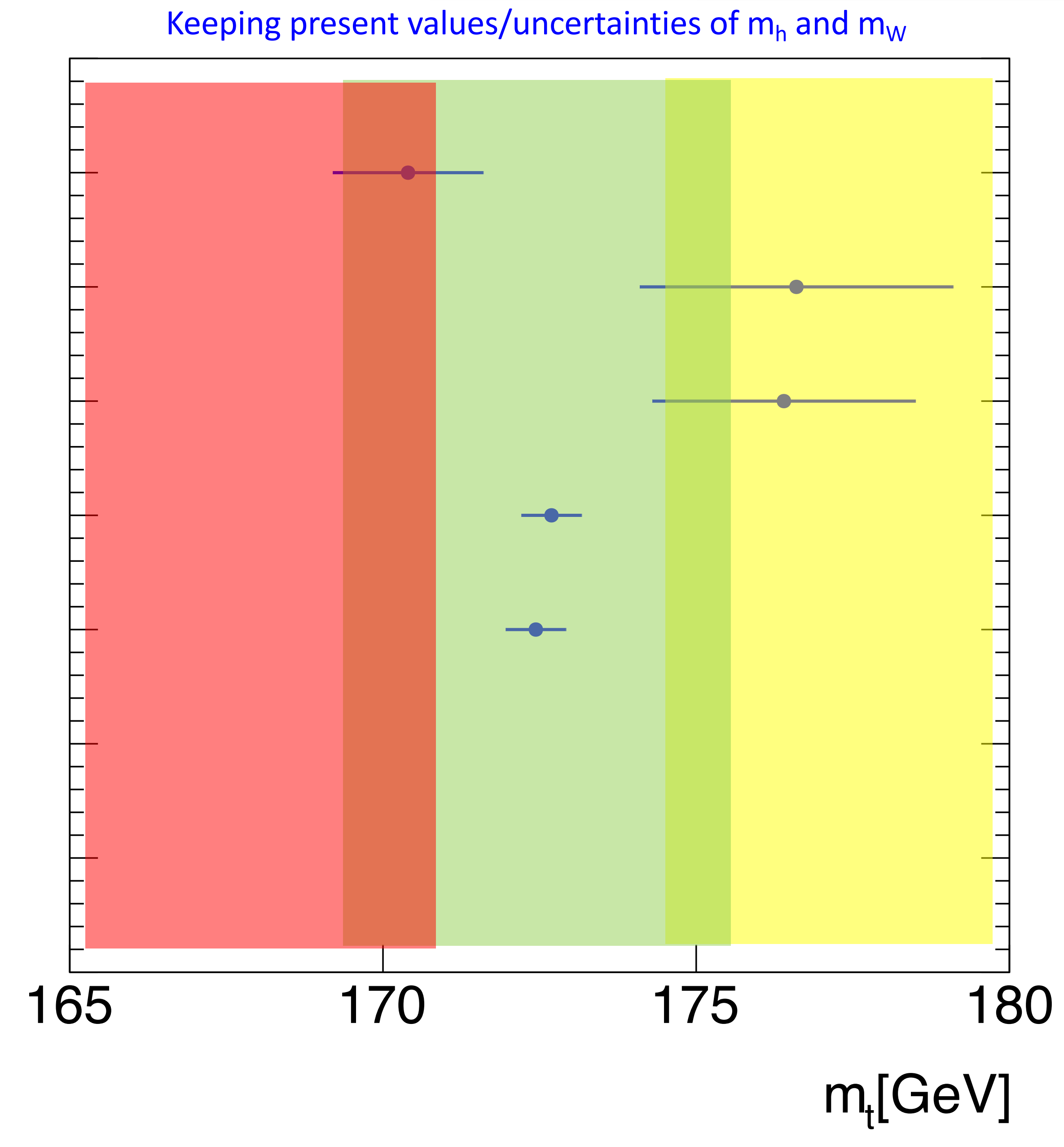

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ATLAS & CMS

Combinations of "Direct Measurements"

J. Fuster

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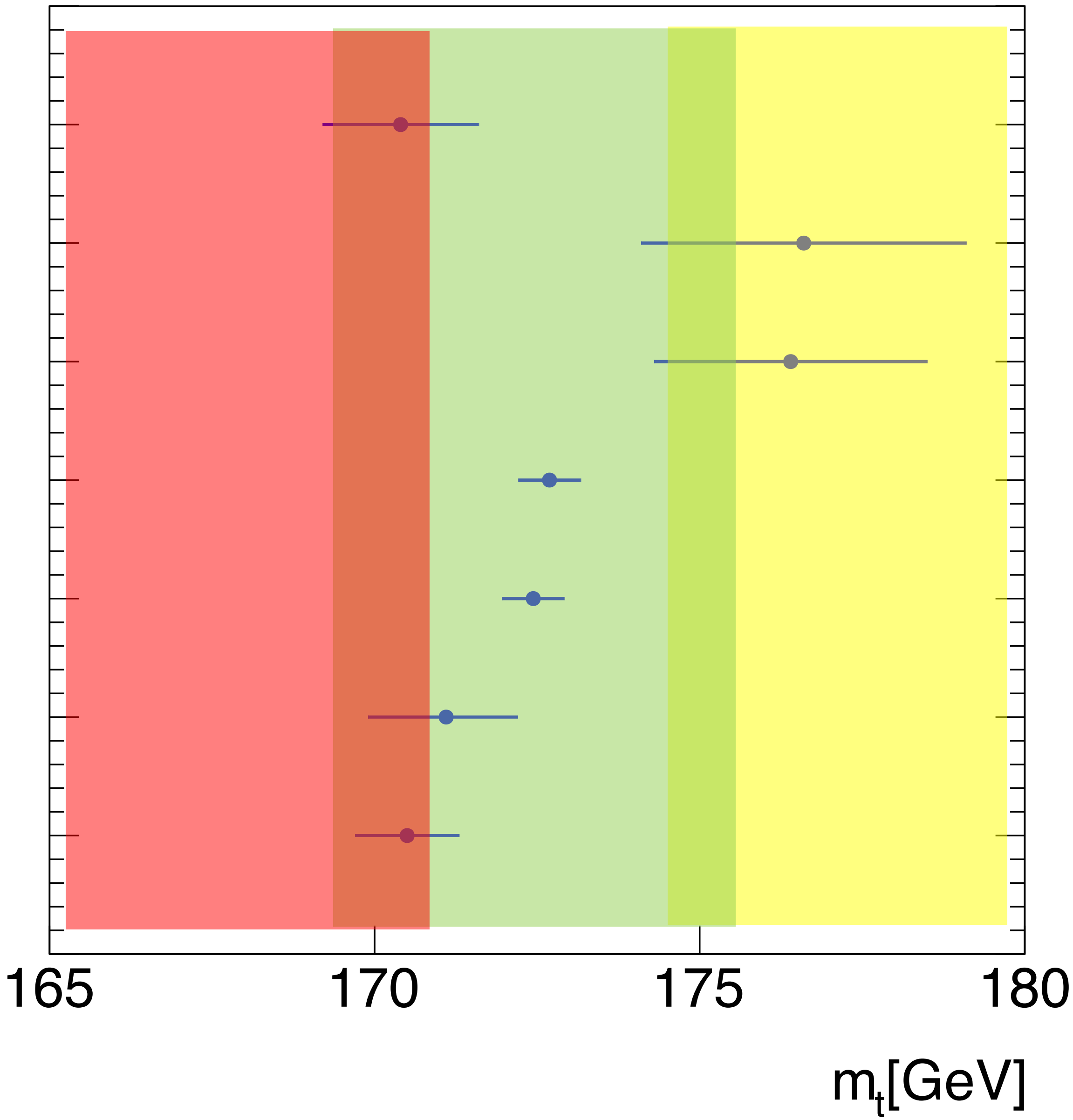

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3D and tt+1jet

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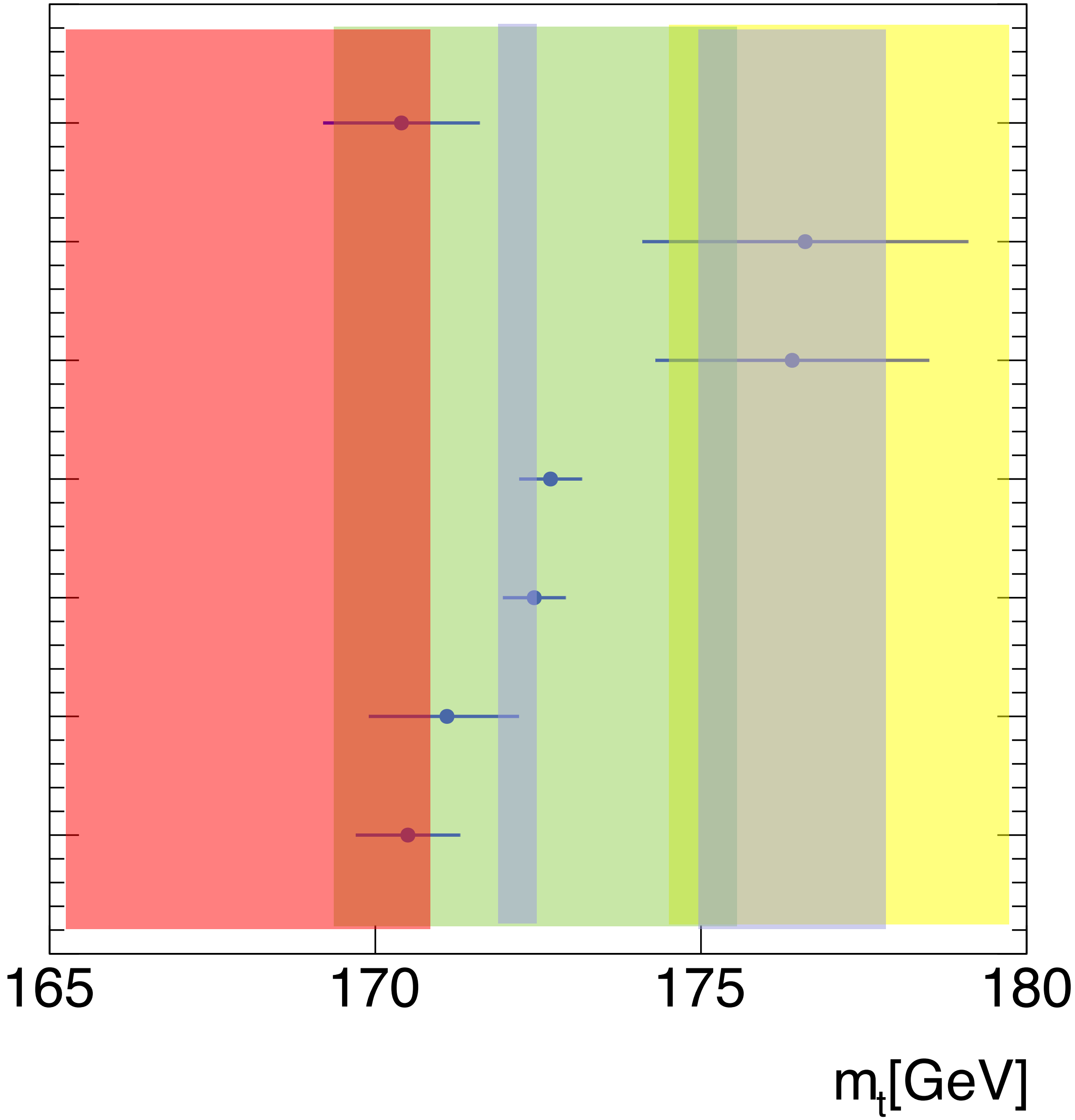

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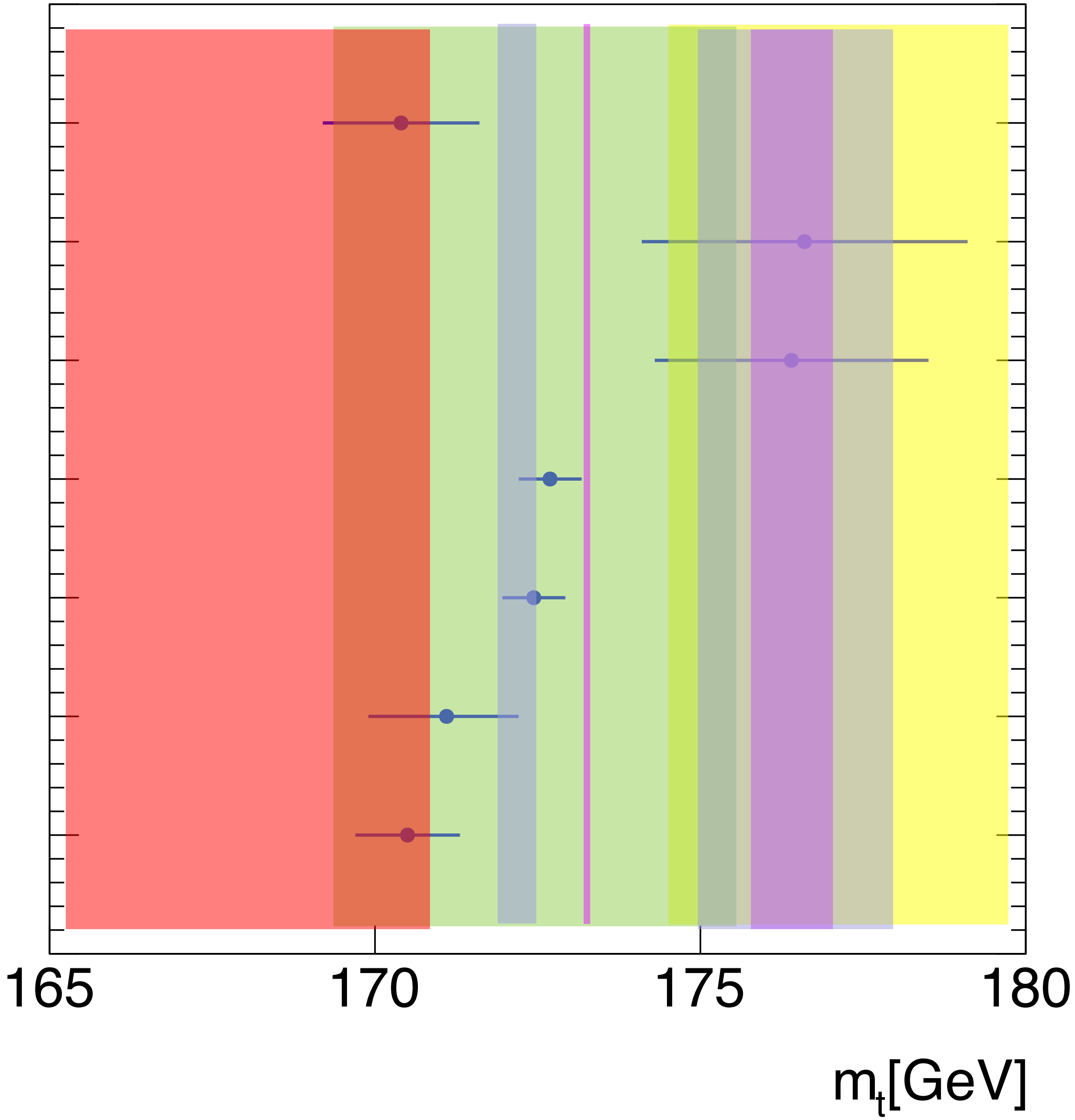

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Future e+e- Collider

J. Fuster

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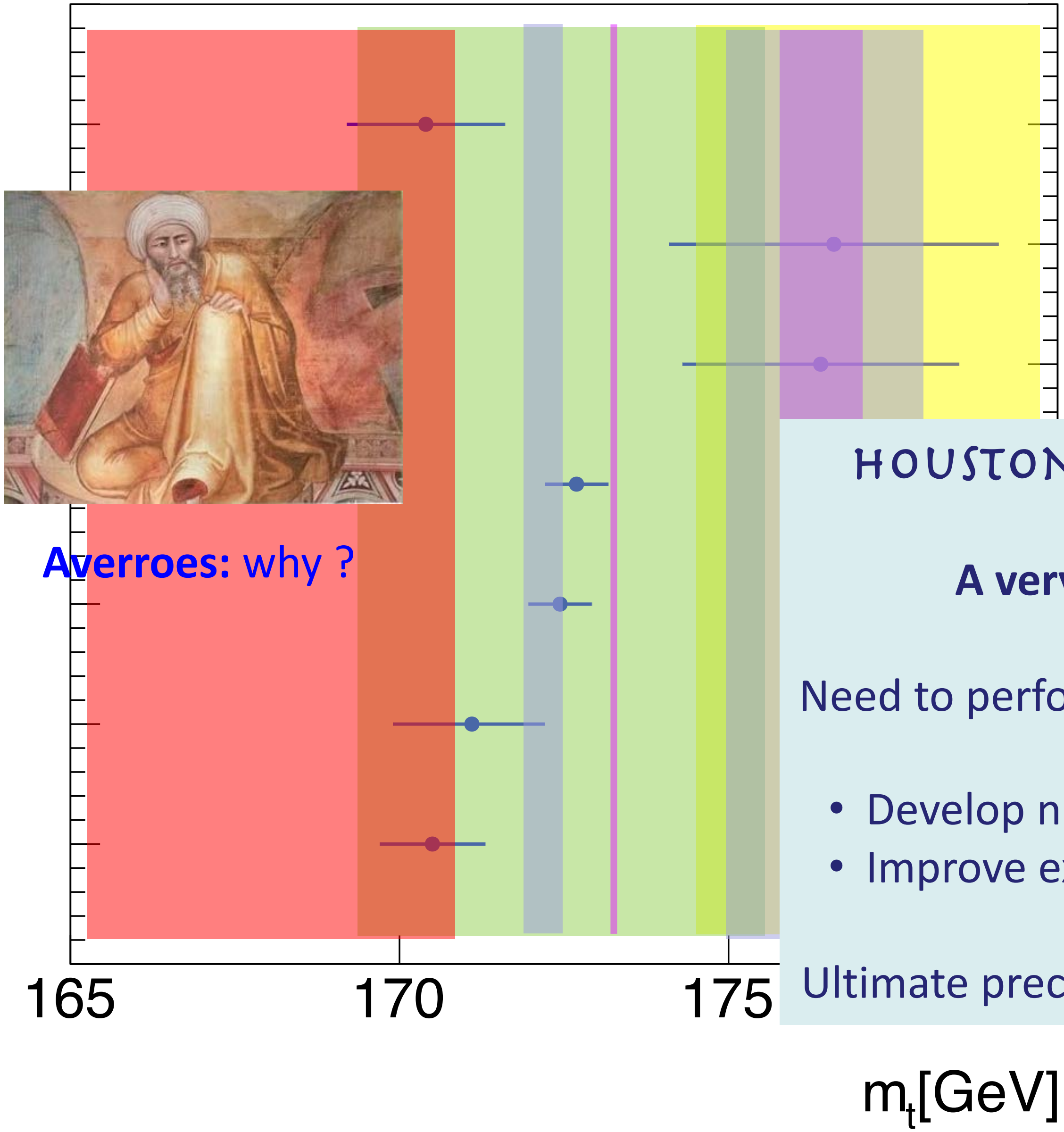

Averroes: why ?

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Vacuum Stability: Meta-stable

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HOUSTON WE HAVE A CHALLENGE !!!

A very interesting challenge in fact

Need to perform highly precise m_t measurements:

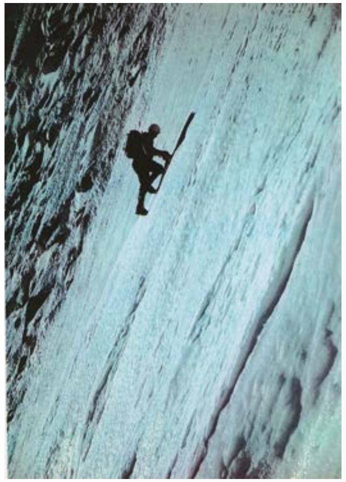
- Develop new calculations/observables
- Improve experimental methods

Ultimate precision at e+e- future colliders

Future e+e- Collider

J. Fuster

The top quark is *beautiful and charming and* *still very strange*



Long and successful scientific programme, many studies, resources, and investigations during years of research in theory and experiment (PETRA, PEP, Babar, Belle, HERA, SLD, LEP, Tevatron, LHC, etc..) have led to build up the Standard Model

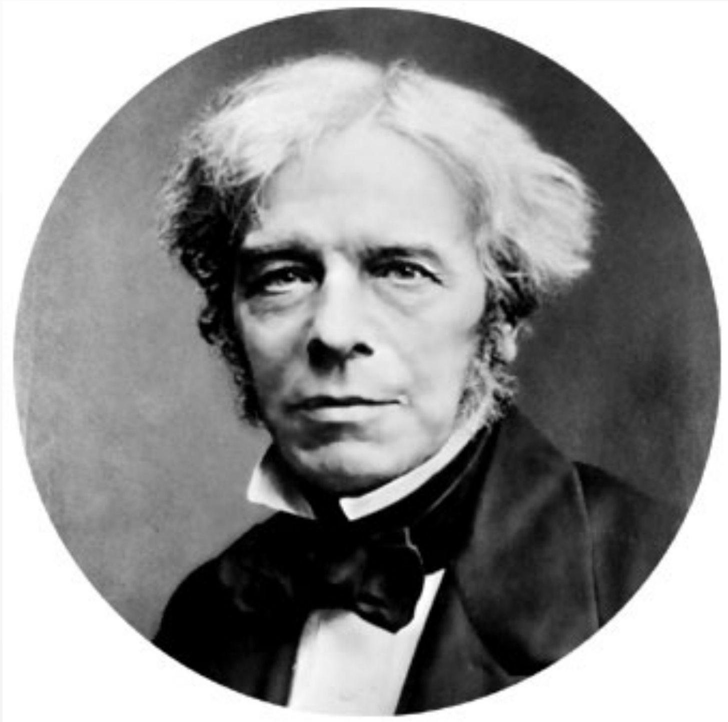
Reinhold Messner

Culminated with the discovery of H(125)

But.. this is just one more "step" which allows us to have a "better view" of what is coming next.

- One question answered, H(125)
- Still some old questions remain
- New questions open

In much nicer words and better English



"It is the great beauty of our science that advancement in it, whether in a degree great or small, instead of exhausting the subject of research, opens the doors to further and more abundant knowledge, overflowing with beauty and utility", (M. Faraday)