today's top news
- recent top physics results from the LHC experiments and an outlook to future colliders

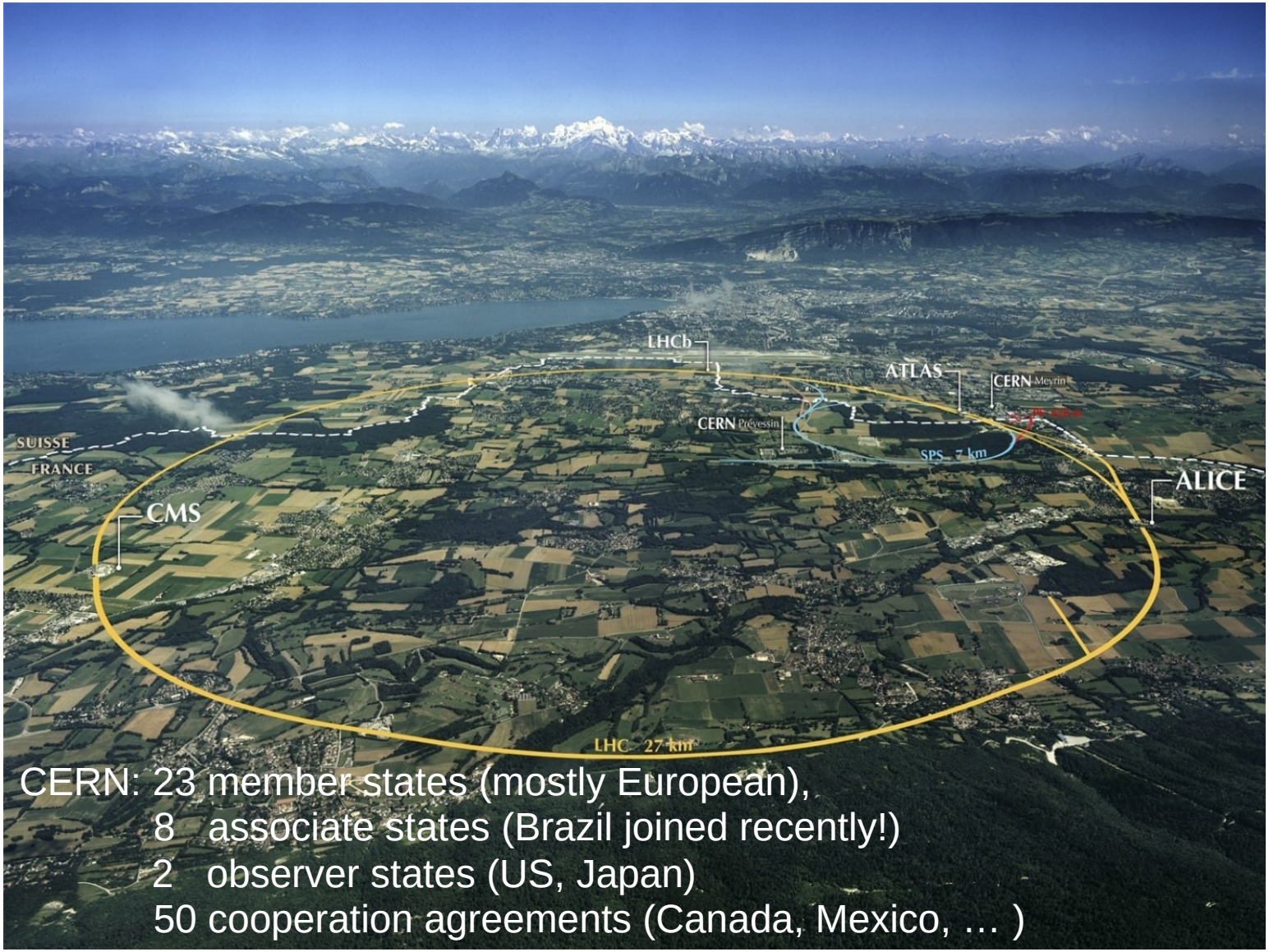
Marcel Vos,

IFIC, CSIC/UV, Valencia, Spain

Brown University, Providence (RI), June 2024

marcel.vos@ific.uv.es

The CERN Large Hadron Collider

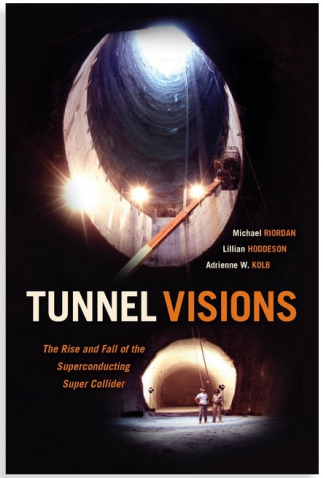


CERN: 23 member states (mostly European),
8 associate states (Brazil joined recently!)
2 observer states (US, Japan)
50 cooperation agreements (Canada, Mexico, …)

Should I go to Europe for cutting-edge science?

Yes, for the study of elementary particles at an “energy frontier” collider, you must come to Europe, now and in the immediate future

A highly recommended book on how the US lost its lead in particle physics



Tunnel Visions

The Rise and Fall of the Superconducting Super Collider

Michael Riordan, Lillian Hoddeson, and Adrienne W. Kolb

Starting in the 1950s, US physicists dominated the search for elementary particles; aided by the association of this research with national security, they held this position for decades. In an effort to maintain their hegemony and track down the elusive Higgs boson, they convinced President Reagan and Congress to support construction of the multibillion-dollar Superconducting Super Collider project in Texas—the largest basic-science project ever attempted. But after the Cold War ended and the estimated SSC cost surpassed ten billion dollars, Congress terminated the project in October 1993.

READ MORE +

480 pages | 47 halftones | 6 x 9 | © 2015

History: AMERICAN HISTORY, HISTORY OF TECHNOLOGY

HISTORY OF SCIENCE

There is an encouraging renaissance of faith in a new collider on American soil (see P5 report https://www.usparticlephysics.org/2023-p5-report/)

Geneva is not Providence, but…

Summer routine: Lake Geneva



Winter routine: weekends in Chamonix

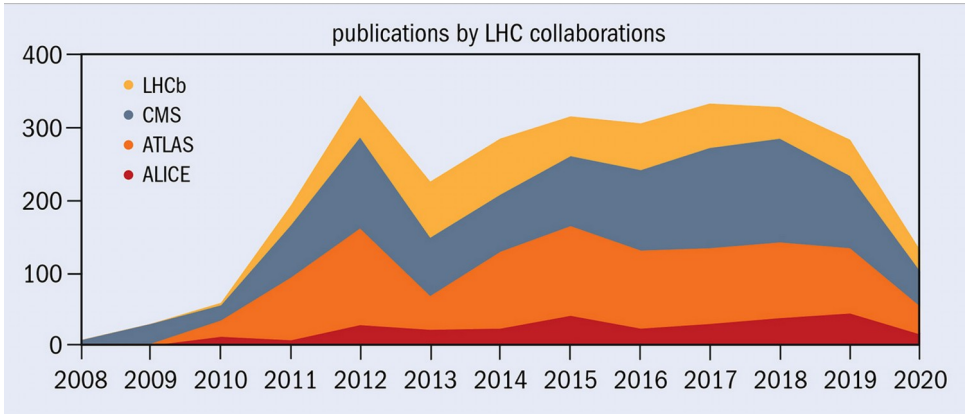


The Large Hadron Collider



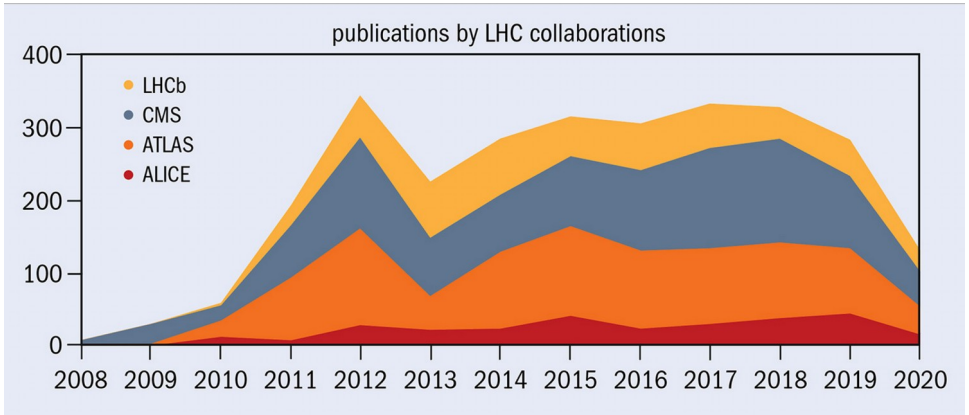
What do you really know about the Large Hadron Collider?

It’s large…



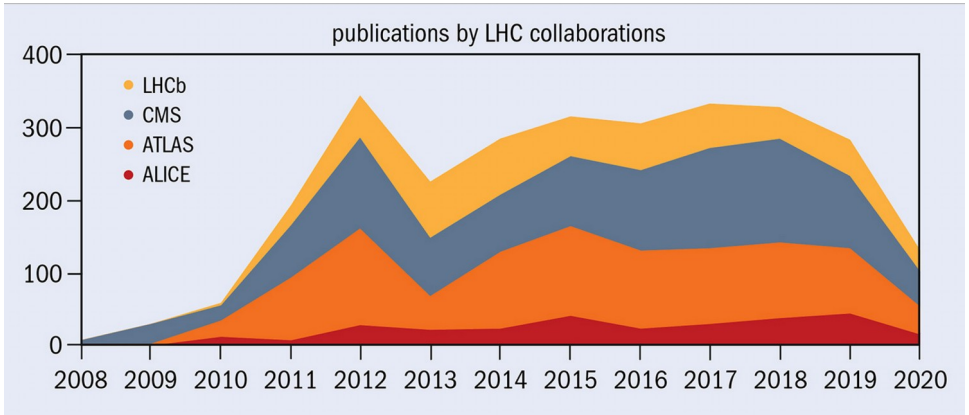
What do you really know about the Large Hadron Collider?

It's large…
It collides hadrons… [protons, heavy ions]



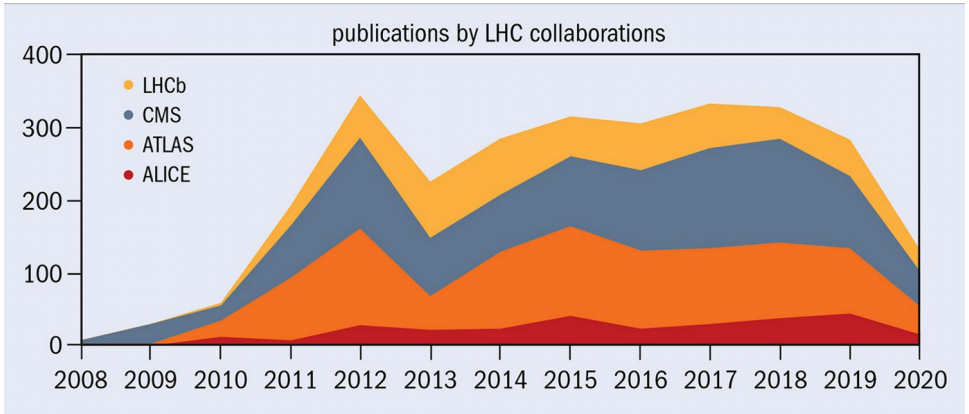
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It's large…
It collides hadrons… [protons, heavy ions]
It discovered the Higgs boson… [Englert&Higgs, 2013]



What do you really know about the Large Hadron Collider?

It's large…
It collides hadrons… [protons, heavy ions]
It discovered the Higgs boson… [Englert&Higgs, 2013]
It failed to find SuperSymmetry… [no comment]



What do you really know about the Large Hadron Collider?

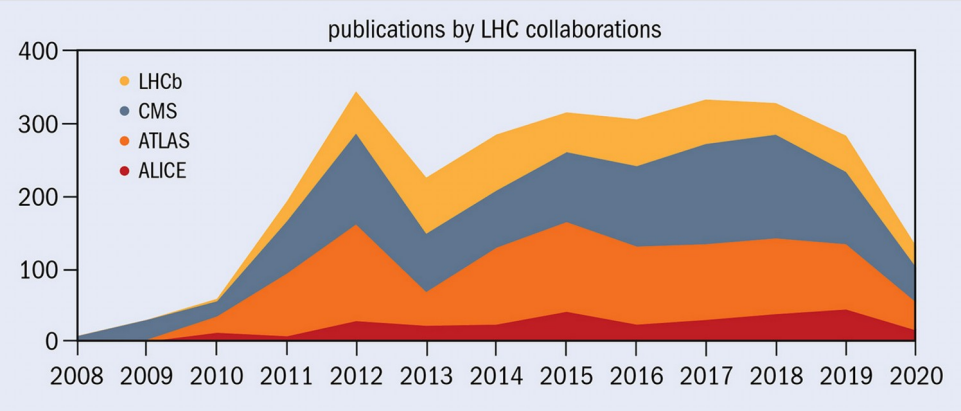
It's large… [protons, heavy ions]

It collides hadrons… [Englert&Higgs, 2013]

It discovered the Higgs boson… [no comment]

It failed to find SuperSymmetry… [today: a lot of top quark physics, some Higgs and some QCD]

It does some other stuff…



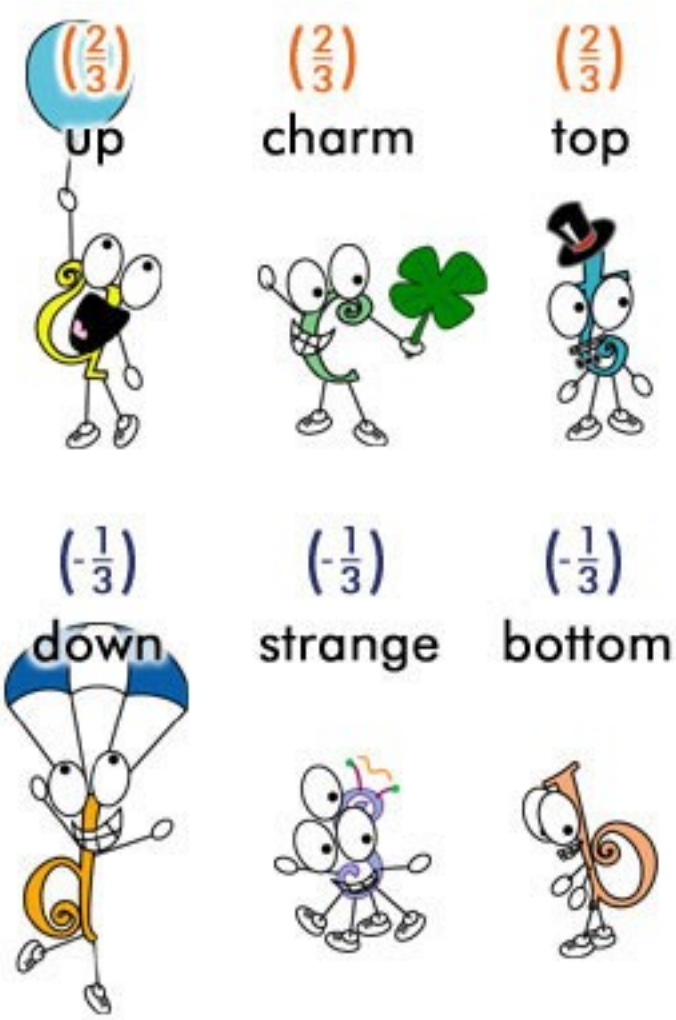
A tour of recent highlights among LHC results, guided by my own preference

The third-generation quarks...

My favourite quarks
Tightly coupled to Higgs boson, important in SM and BSM

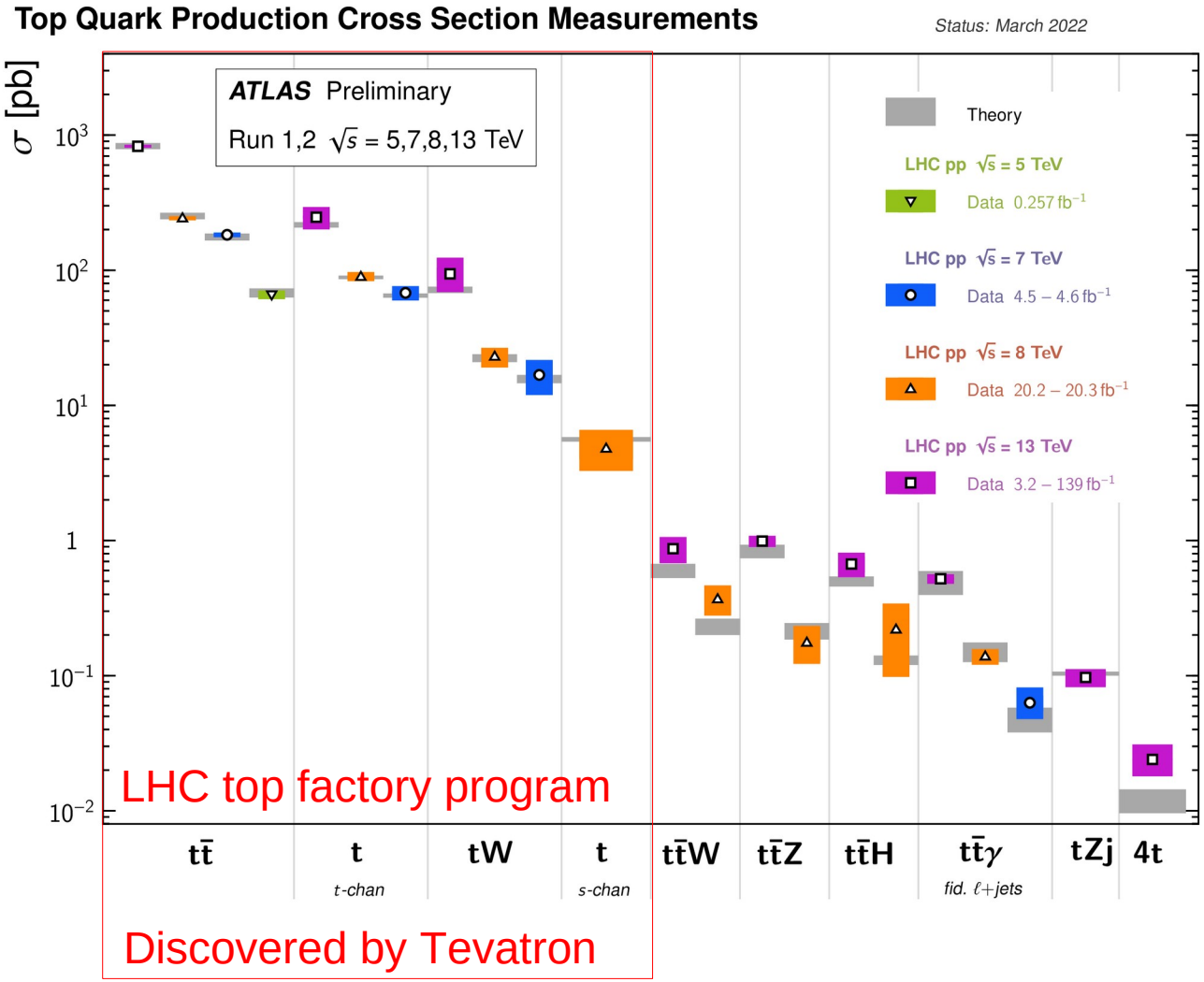
Part of the flavour mystery
Nobody understands the SM flavour structure

Experimentally accessible
Abundantly produced, easy to select, measurable



Standard THEORY* processes

** Paris Sphicas, ICHEP2020*



Precision measurement of top quark pair cross section

theory
5%

With current NNLO+NNLL calculations, the SM top quark pair production rate is known to 4-5% precision (Czakon et al., 2013)

Tevatron
5%

At the Tevatron, the $p\bar{p} \rightarrow t\bar{t}$ cross section was measured to 5% (CDF+D0, arXiv:1309.7570)

LHC 2022
3%

Until last year, state of the art inclusive $t\bar{t}$ cross section measurements had 3% uncertainty (ATLAS-CONF-2022-061)

LHC 2023
1.8%

ATLAS sub-% luminosity calibration (arXiv:2212.09379) improves cross section to <2% (arXiv:2303.15340)

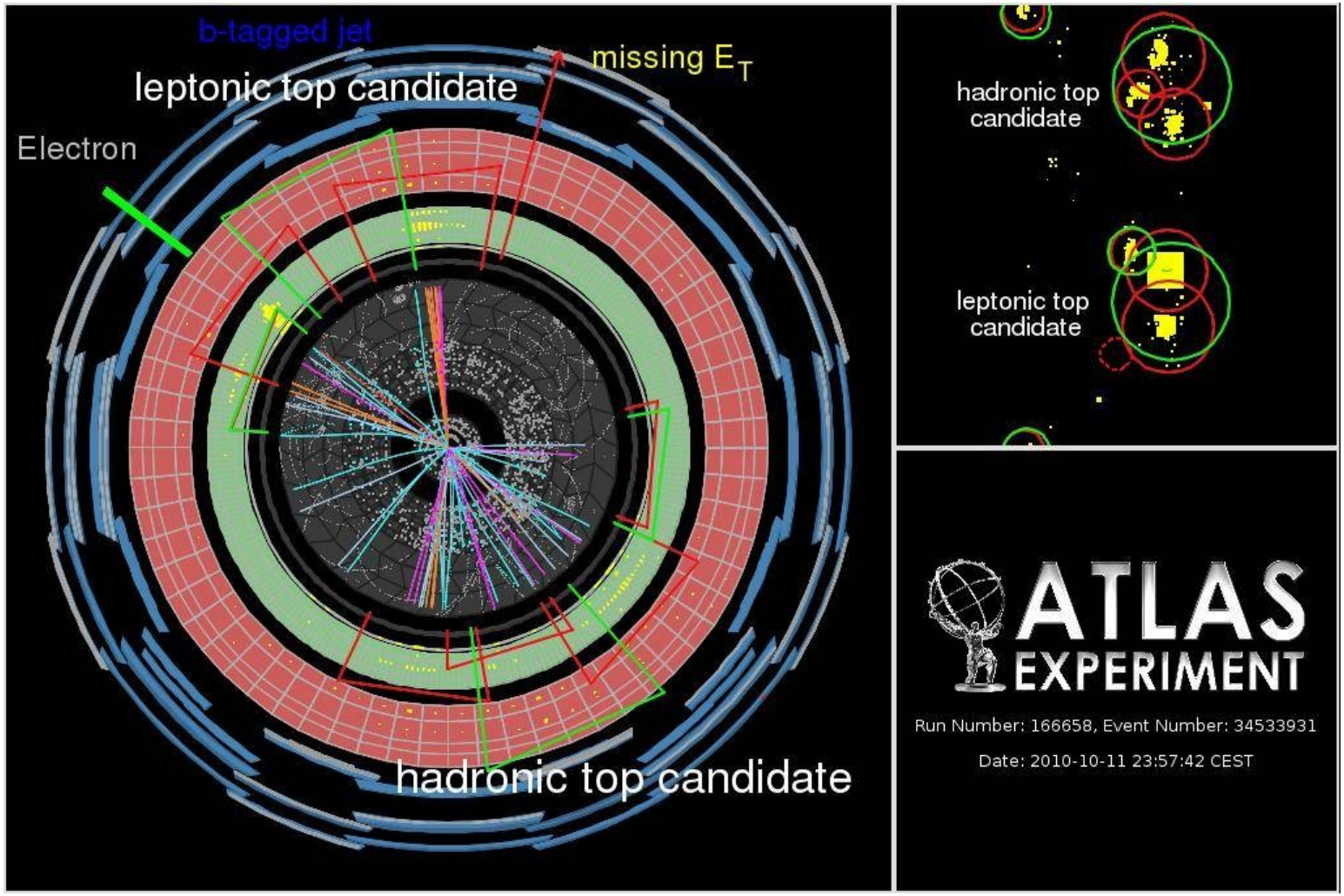
HL-LHC 2037
?%

New motivation to reduce luminosity and modelling uncertainties further

The ball is firmly in the field of theorists and PDF fitters

Boosted top quarks

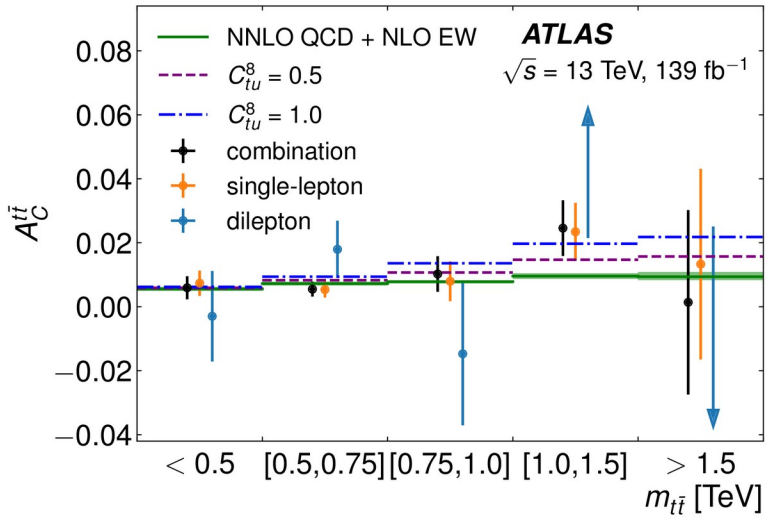
Boosted top quarks require special tools, developed since the 2010s. The top quark is too heavy for the Tevatron to boost it much, but the LHC has produced a large sample.

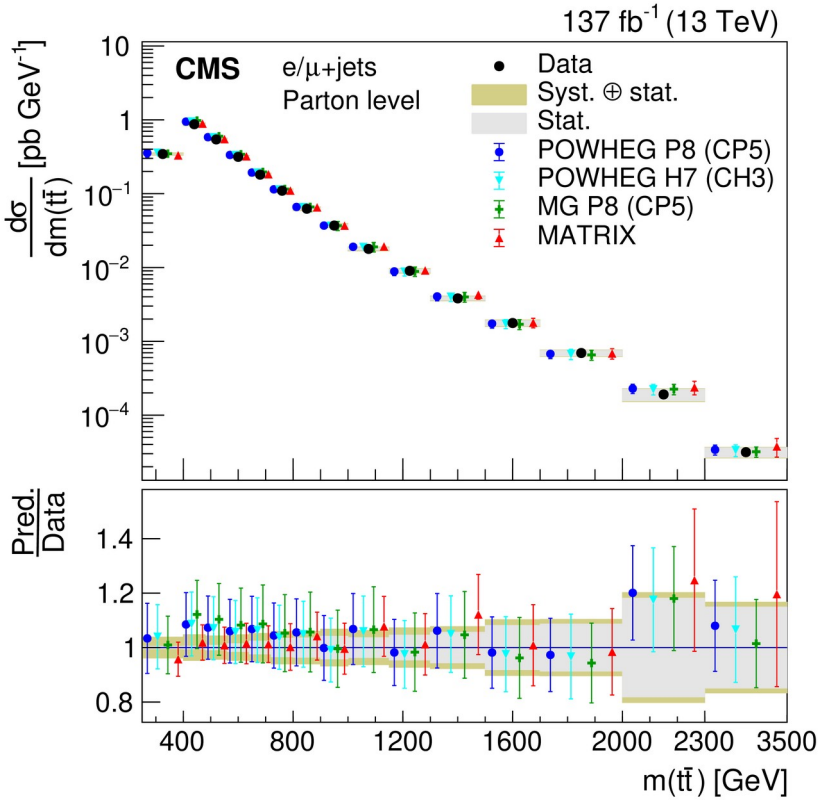


Boosted top quarks

CMS measurement of top quark pair production throughout the entire kinematic range. arXiv:2108.02803

Uncertainty 5-20%, similar to NNLO calculation

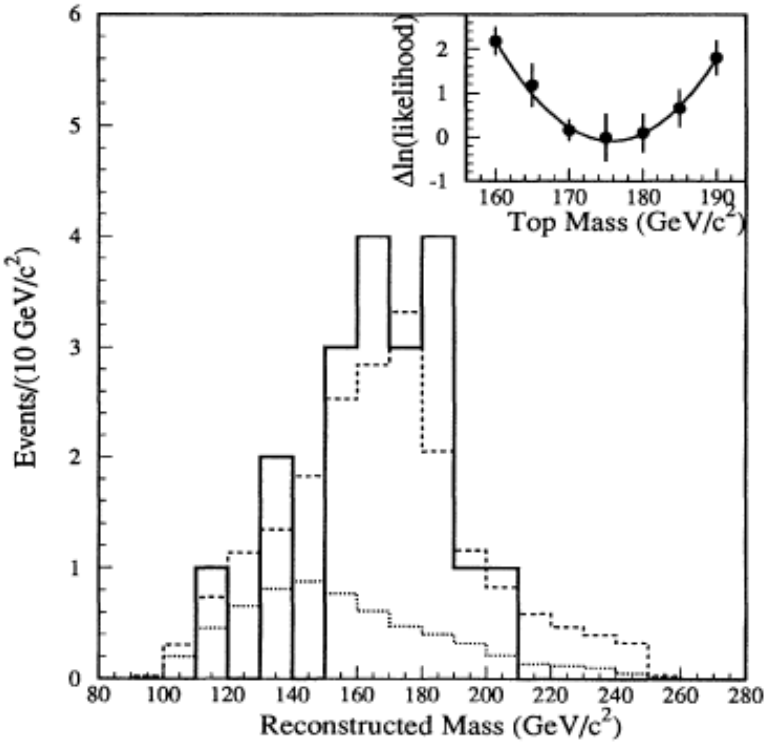




ATLAS measurement of top quark pair production asymmetry throughout the entire kinematic range. arXiv:2208.12095

Boosted top quark production: observed for the first time at the LHC and now characterized to 10-20% precision

The top quark mass



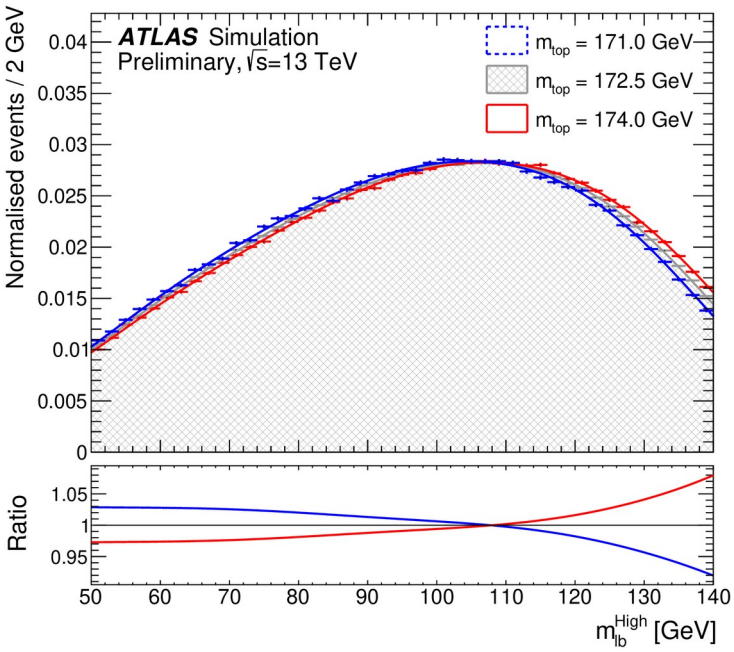
Top mass - approaches: 1 direct

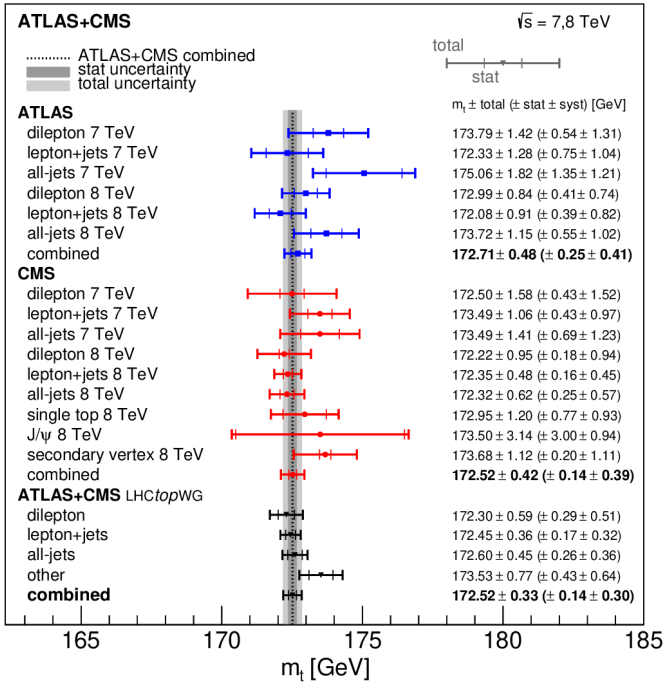
1. Reconstruct top decay products

2. Generate Monte Carlo templates

3. Fit for the best value of the MC mass parameter

ATLAS-CONF-2022-058



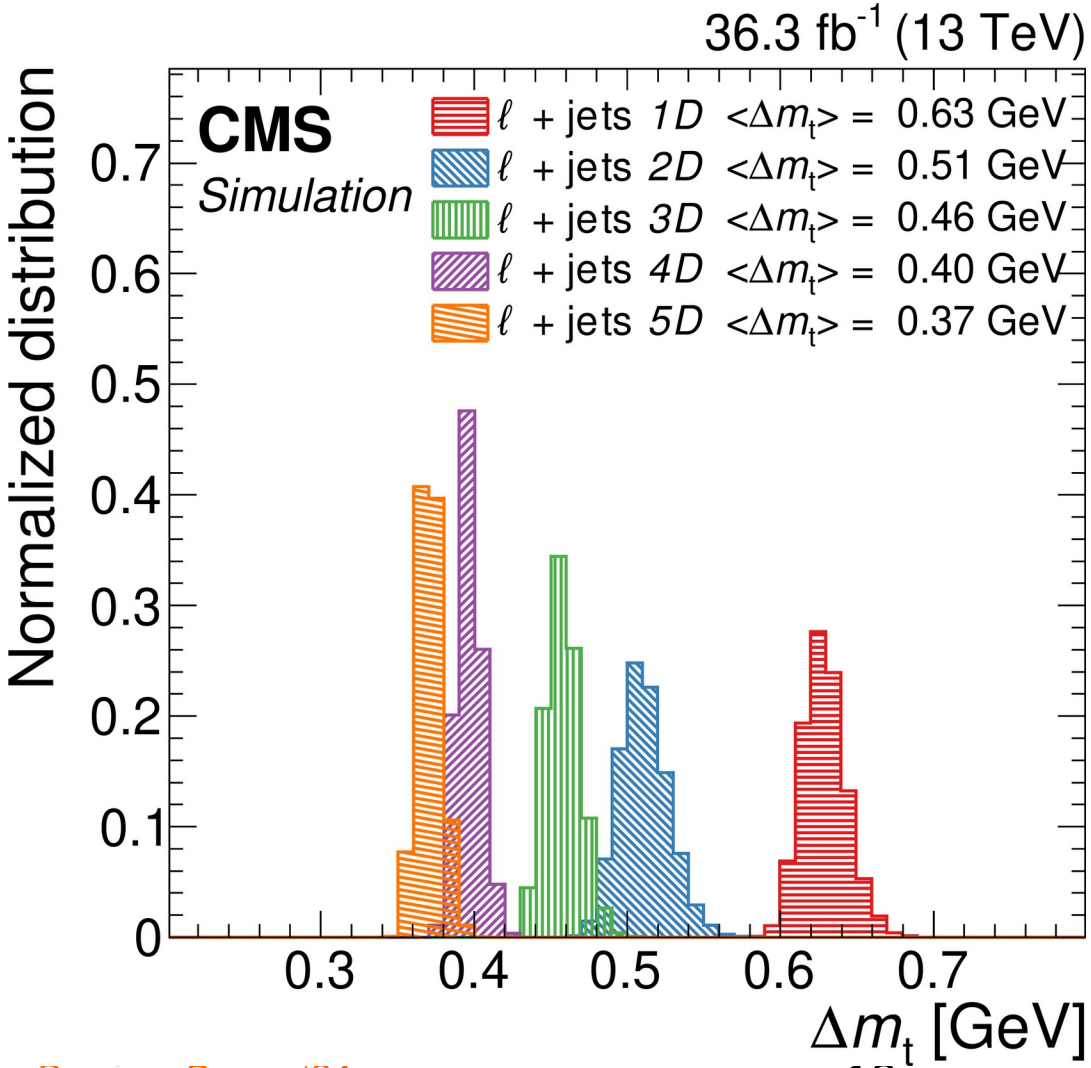


Experiment is extremely precise:
- 600 MeV for single measurements
- 300 MeV for LHC run 1 combination

arXiv:2402.08713 (PRL soon)

Top mass – approaches: 2 direct PL fit

CMS template top mass, l+jets, 36/fb: $m_t = 171.8 \pm 0.4$ (total), arXiv:2302.1967

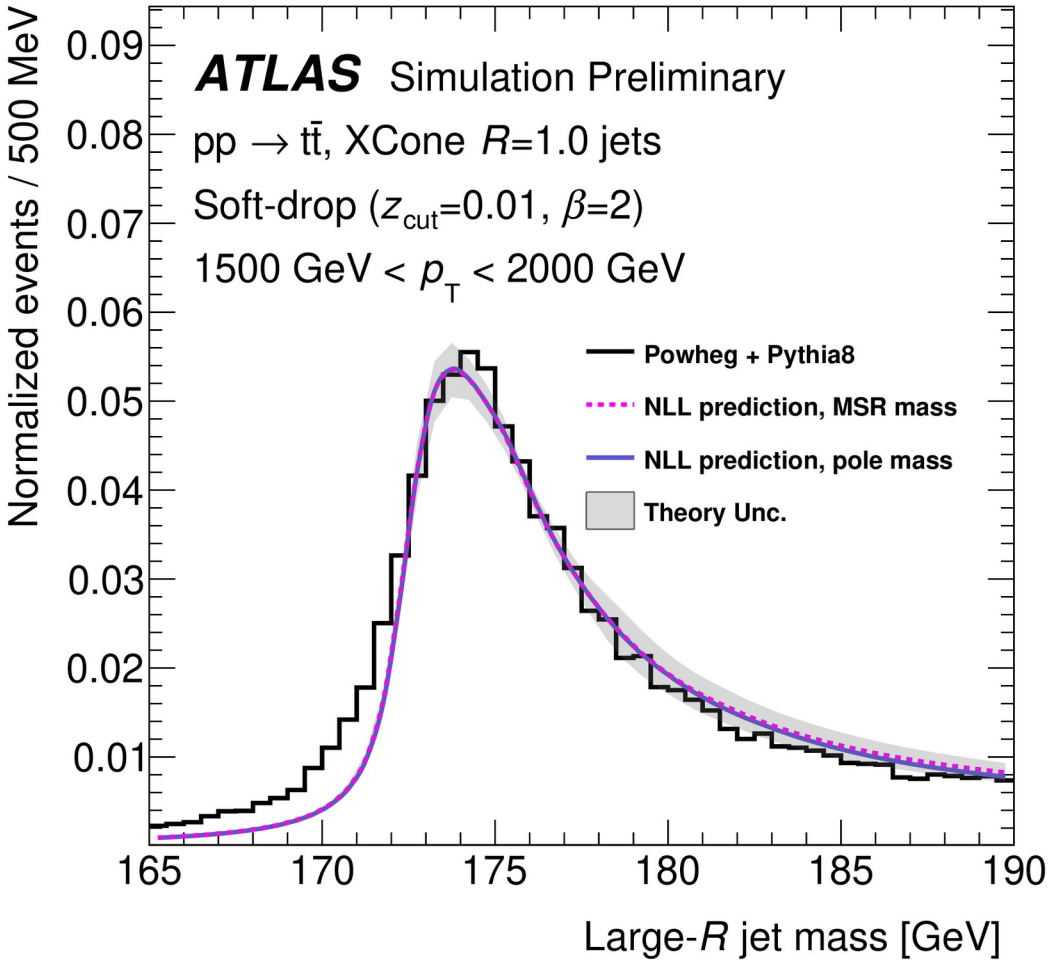


CMS demonstrates the power of profile-likelihood fits

With better MC and modelling uncertainties, the sky is the limit

More work is needed to bring interpretation to the same level
(Hoang, What is the top quark mass? Ann. Rev. Nucl. Part. Sci. 70 (2020)

Mass interpretation

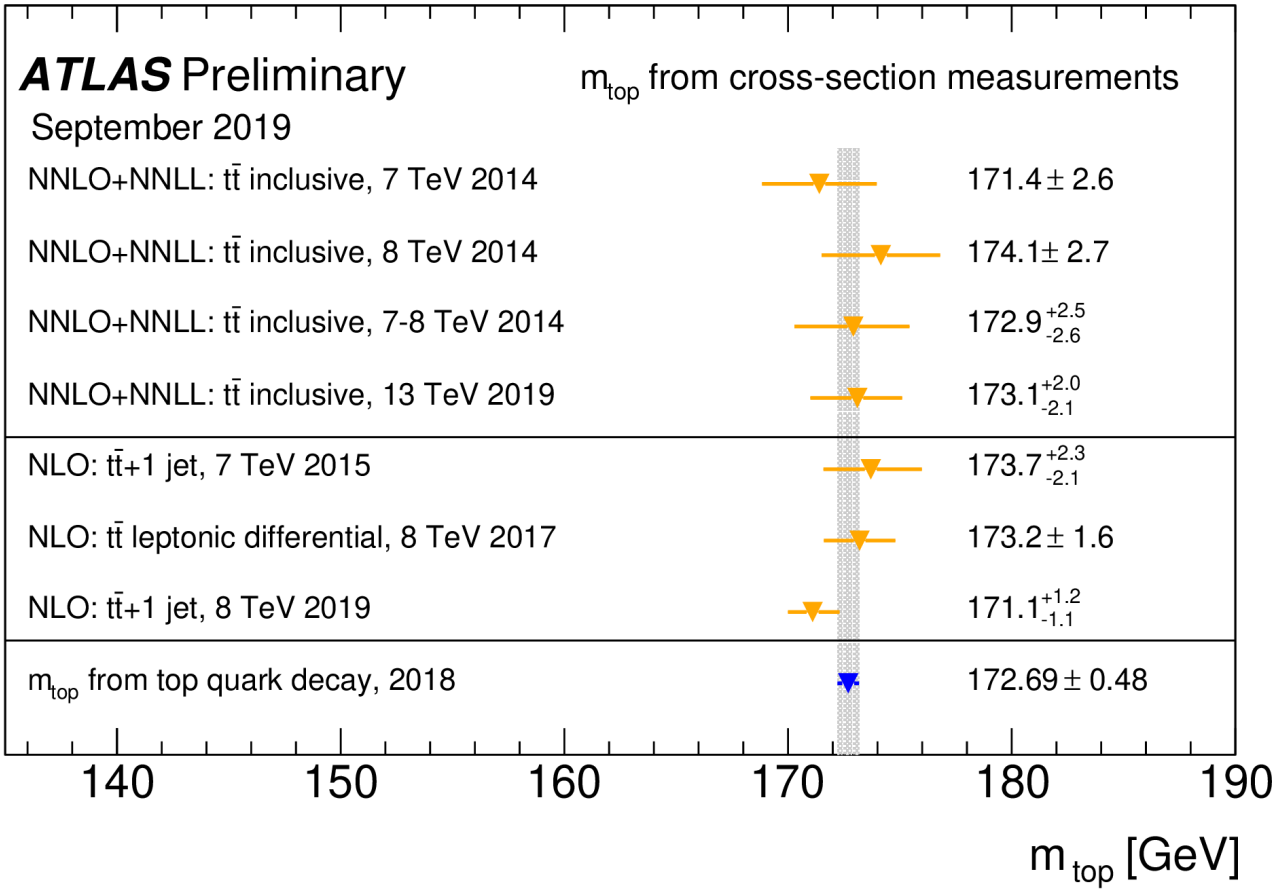


Fit first-principle calculations to Monte Carlo generator predictions *(Butenschoen et al., PRL 117 (2016), Hoang et al. PRD100 (2019))*

MC mass parameter is indeed within ~500 MeV of the pole mass, more precise identification possible with MSR mass

ATL-PHYS-PUB-2021-034

Top mass – approaches: 3 cross section



Inclusive cross section: 2 GeV/measurement → 1 GeV possible
Differential tt+jet: ~1 GeV/measurement → 0.5 GeV possible

A combination of such measurements is a powerful validation

Top quark mass: precision

theory
500 MeV — Identification of MC mass parameter with pole mass scheme (Hoang, 2022)

Tevatron
640 MeV — CDF and D0 combination (arXiv:1407.2682)

LHC run 1
300 MeV — LHC run 1 combination

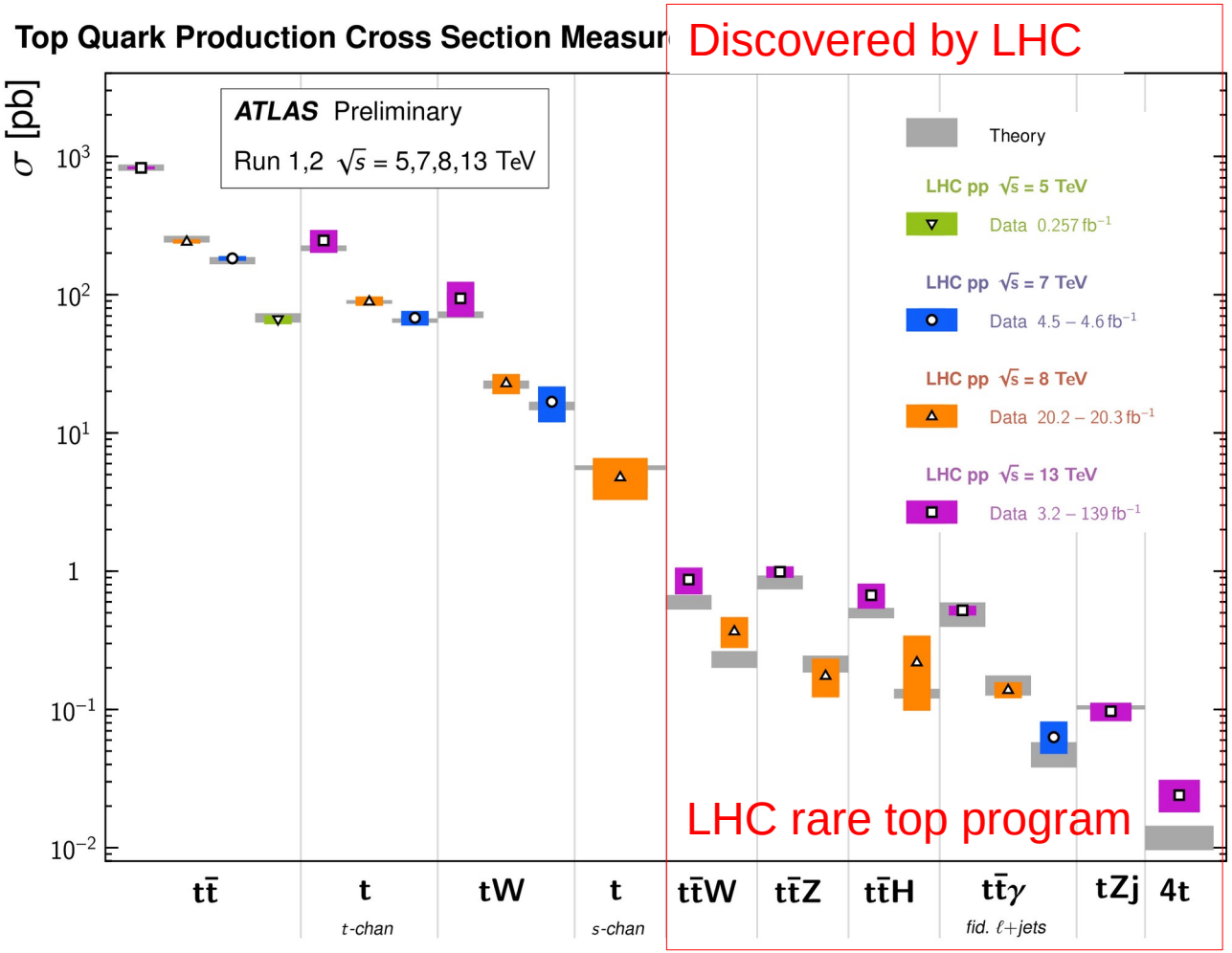
Cross section-based
<1 GeV — Differential cross sections

HL-LHC 2037
200 MeV? — An experimental combination of this precision is certainly feasible; the challenge is to improve understanding and modelling uncertainties

Experimental precision to be matched by improved understanding

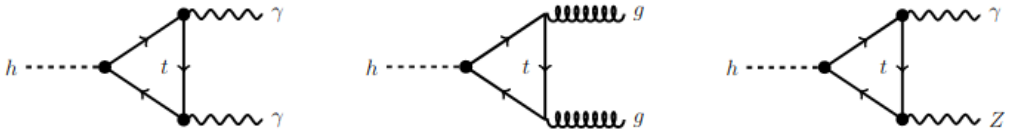
More Standard THEORY* processes

** Paris Sphicas, ICHEP2020*



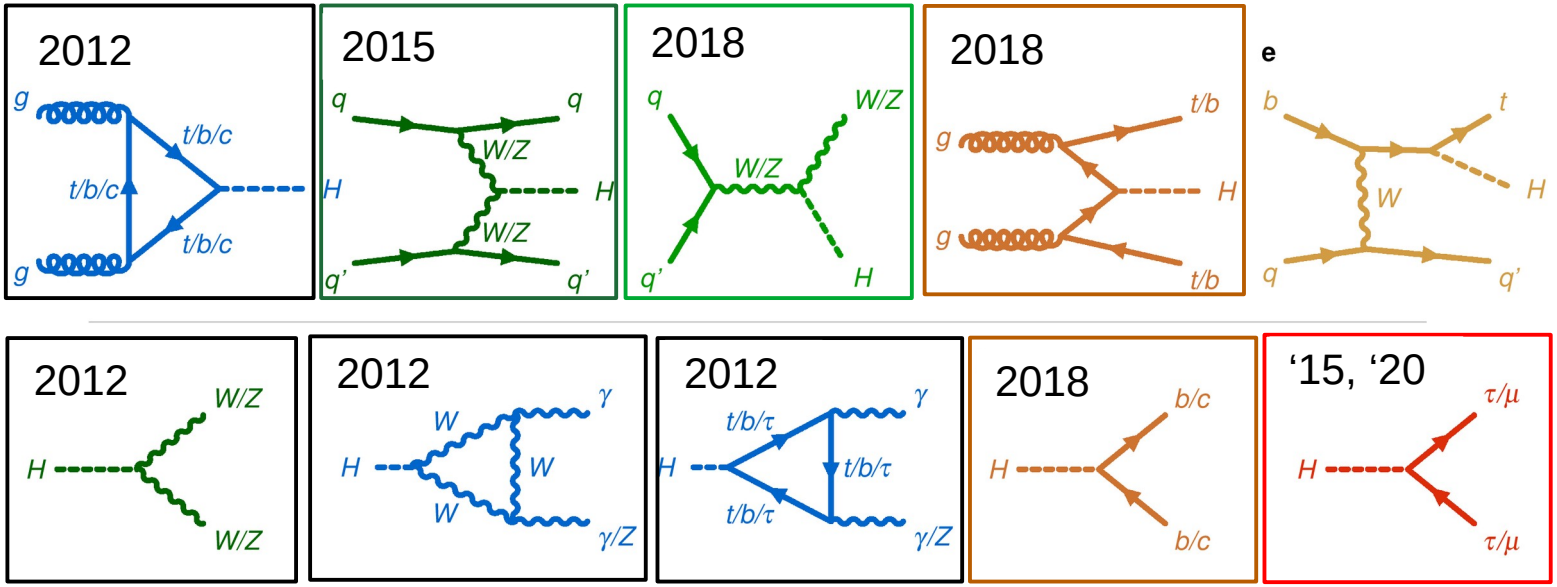
marcel.vos@ific.uv.es

Top and Higgs



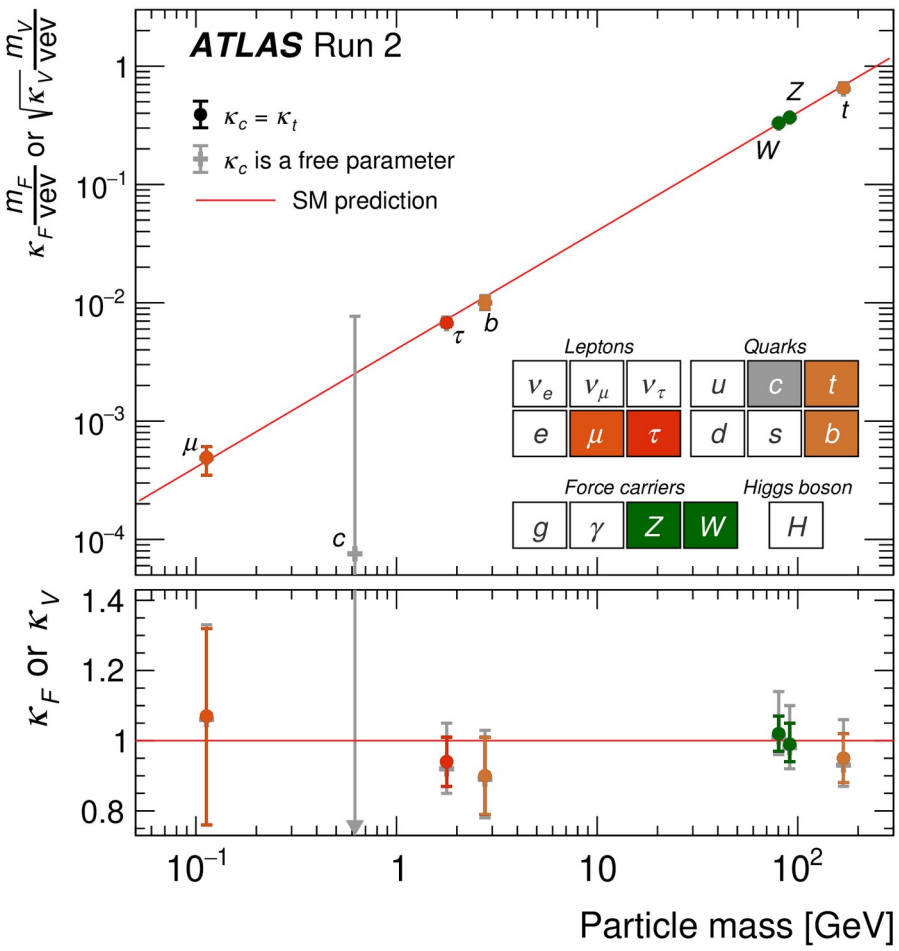
Higgs boson discovery and beyond

The Higgs boson was discovered in 2012 with one out of four accessible production modes and two decay modes.



2015: Vector-boson-fusion, H→ ττ (fermions!)
2018: Associated ttH production, H→bb decay
2020: evidence H→ μμ (2nd gen.)
Still missing: charm, tH production, self-coupling…

Higgs boson summary



Fabiola Giannotti: we got very lucky (many couplings accessible at the LHC)

John Ellis: it looks and quacks like a Higgs boson

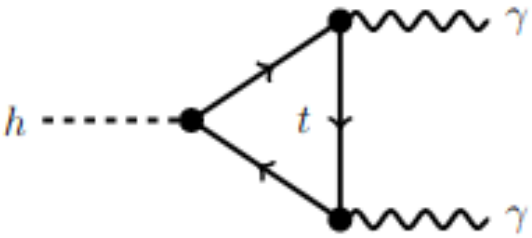
All measurements so far compatible with simplest Higgs particle within uncertainties

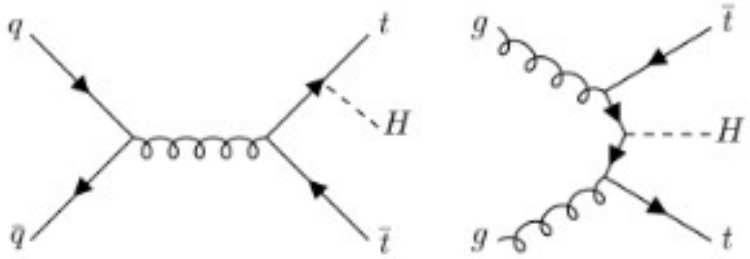
Experimental status:
ATLAS & CMS, Nature, arXiv:2207.00043/92

Theory review:
Salam, Wang, Zanderighi, arXiv:2207.00478

The top Yukawa coupling at the LHC

H(125) observation in **2012** in gg → H, H→ γγ implicitly establishes Higgs-top coupling





Explicit confirmation in **2018** with the observation of pp → ttH production

Global fit to LHC data in **2021** (Ellis et al.) combine “indirect” constraints from gg → H or H → γγ with “direct” result from ttH

Precision top Yukawa

SM prediction

$m_t = y_t\, v$

Largest coupling to the Higgs boson in the SM

ATLAS ttH (H→bb)

$0.84^{+0.30}_{-0.46}$

Direct measurements in associated production, arXiv:2303.05974

ATLAS Higgs

$0.94^{+0.11}_{-0.11}$

ATLAS Higgs, incl. H→ γγ (Nature 2022)

ATLAS tttt

$1.48^{+0.23}_{-0.29}$

ATLAS tttt (+ ttH background), arXiv:2303.15061

CMS tt production

$1.16^{+0.24}_{-0.35}$

EW corrections in tt production

Cornering the top Yukawa coupling. Direct bound from ttH. Indirect bounds from H→γγ and gg→H, tttt, and tt production.

The Higgs boson at the LHC

We now have enough data to start filling the PDG data sheet on the H^0 boson

Top-Higgs interaction is standard/minimal within uncertainties

Switch to bottom quark coupling for a slight digression

Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022)

H^0 $J = 0$

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)

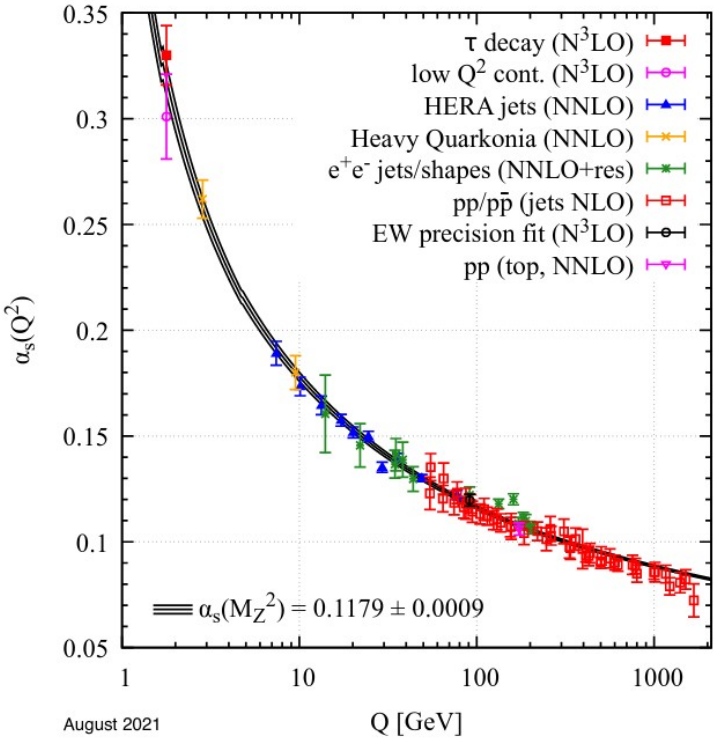
H^0 Signal Strengths in Different Channels

Combined Final States $= 1.13 \pm 0.06$
$WW^* = 1.19 \pm 0.12$
$ZZ^* = 1.01 \pm 0.07$
$\gamma\gamma = 1.10 \pm 0.07$
$c\bar{c}$ Final State $= 37 \pm 20$
$b\bar{b} = 0.98 \pm 0.12$
$\mu^+\mu^- = 1.19 \pm 0.34$
$\tau^+\tau^- = 1.15^{+0.16}_{-0.15}$
$Z\gamma < 3.6$, CL = 95%
$\gamma^*\gamma$ Final State $= 1.5 \pm 0.5$
$t\bar{t}H^0$ Production $= 1.10 \pm 0.18$
tH^0 production $= 6 \pm 4$
H^0 Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV $= 56 \pm 4$ pb

Running couplings

Scale evolution of the strong coupling predicted by QCD:

$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots)$$



Precise determinations from 1 GeV to > 1 TeV!

Reference $\alpha_s(m_Z) = 0.118 \pm 0.001$ (PDG, <1%)

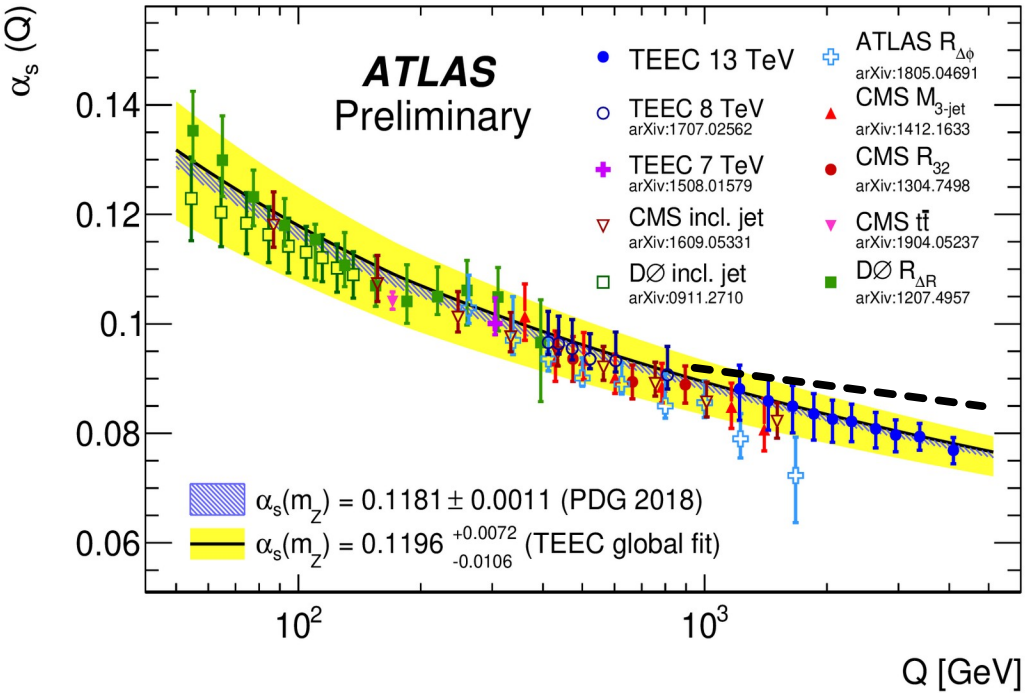
This plot collects α_s value extracted from measurements of many observables in several processes over a broad energy range

Running couplings

Scale evolution of the strong coupling predicted by QCD:

$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots)$$

The LHC extends the range: precise determinations up to 4 TeV!



ATLAS-CONF-2020-025

Massive new states with colour charge alter the evolution:
Llorente & Nachman, NPB 936 (2018) 106
Becciolini et al., PRD91 (2015) 015010
Kaplan, Schwartz, PRL 101 (2008) 02202

Running constants

Quark masses – parameters of the QCD Lagrangian – **must run too**

$$\frac{\partial m_q(\mu)}{\partial \log(\mu^2)} = \gamma_m[\alpha_s(\mu)]\, m_q(\mu)$$

Anomalous mass dimension

Experimental studies of “running” (some evidence that indeed it works):

- charm quark mass, HERA [Ghizko et al., PLB775 (2017)]

- bottom quark mass, DELPHI,SLD,ALEPH,OPAL, see cf. Kluth [hep-ex/0603011])

- top quark mass, CMS[PLB803 (2020)] (see also Catani et al., JHEP08 (2020))

Higgs decays and the bottom quark mass

The Higgs decay to bottom quarks:

- quadratic dependence on m_b

- EW process, rate decoupled at LO from strong coupling α_s

- precise predictions available --->

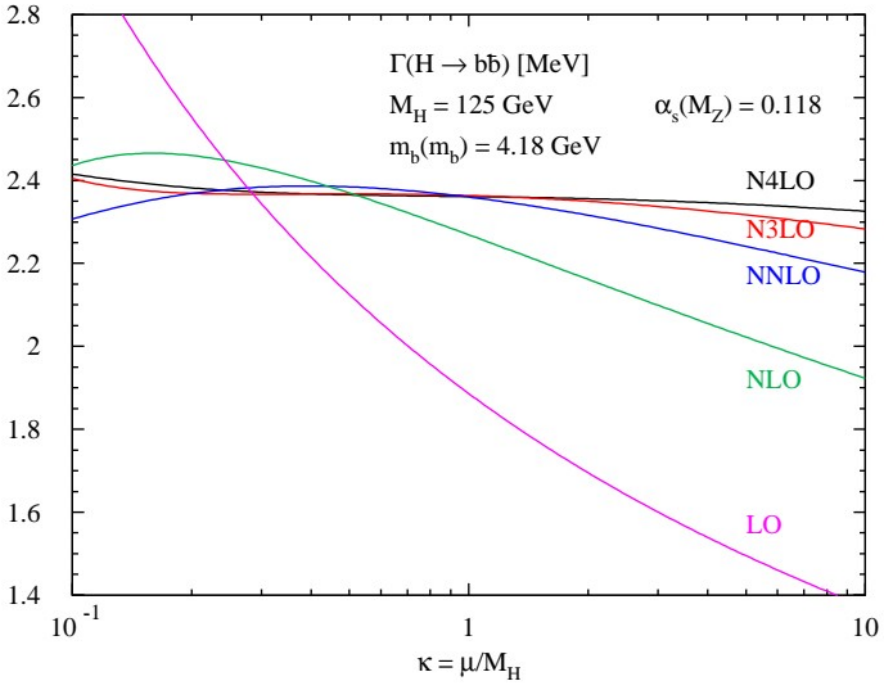
- **well-defined natural scale m_h**

QCD series for $\Gamma(H \to bb)$ for $\mu = m_H$:

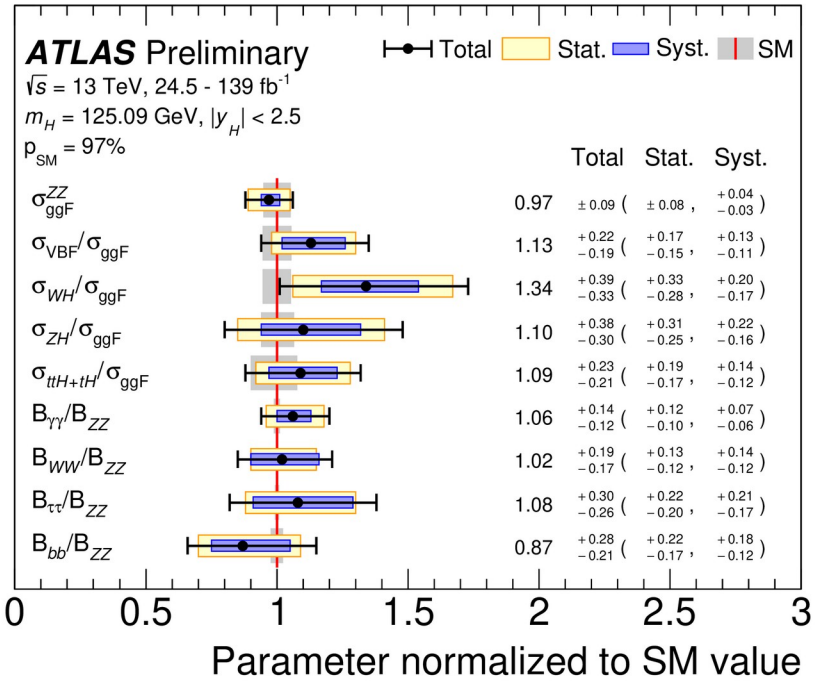
$$1 + \delta_{\rm QCD} = 1 + 0.2030 + 0.0374 + 0.0019 - 0.0014.$$

And for $\mu = m_b$:

$$1 + \delta_{\rm QCD} = 1 - 0.5665 + 0.0586 + 0.1475 - 0.1274.$$



We proudly present: $m_b(m_h)$



The bottom quark mass at the scale of the Higgs boson mass is extracted from ATLAS+CMS measurements of H→ bb / H→ ZZ

$$m_b(m_h) = 2.60^{+0.36}_{-0.30}\ \text{GeV} + 0.06\ \text{GeV theory uncertainty}$$

Theory uncertainty includes:
- scale variations + EW corrections (0.3-0.5%, YR *arXiv:1610.07922)*
- parametric uncertainty α_s (± 0.001 → 0.2%)
- parametric uncertainty m_H (± 240 MeV → 3%)

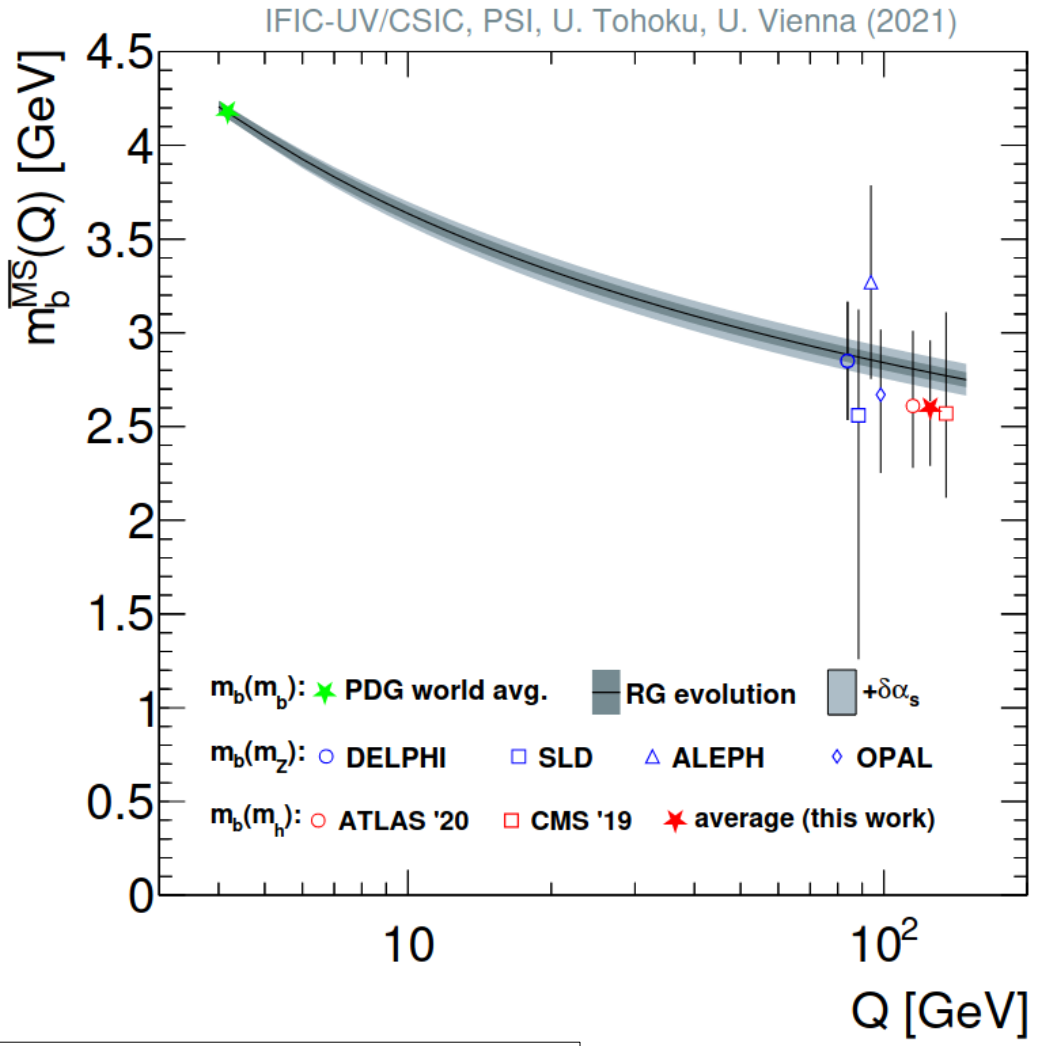
Running of the bottom quark mass

RG evolution from Revolver package, arXiv:2102.01085

Quark masses are not predicted by the SM, but QCD (RGE) does give a prescription for their scale evolution

Collecting measurements at different energies:

- $m_b(m_b)$ world average from low-energy expts
- $m_b(m_Z)$ from LEP experiments and SLD
- $m_b(m_H)$ from LHC Higgs measurements



LHC $m_b(m_h)$ today is as precise as LEP $m_b(m_Z)$

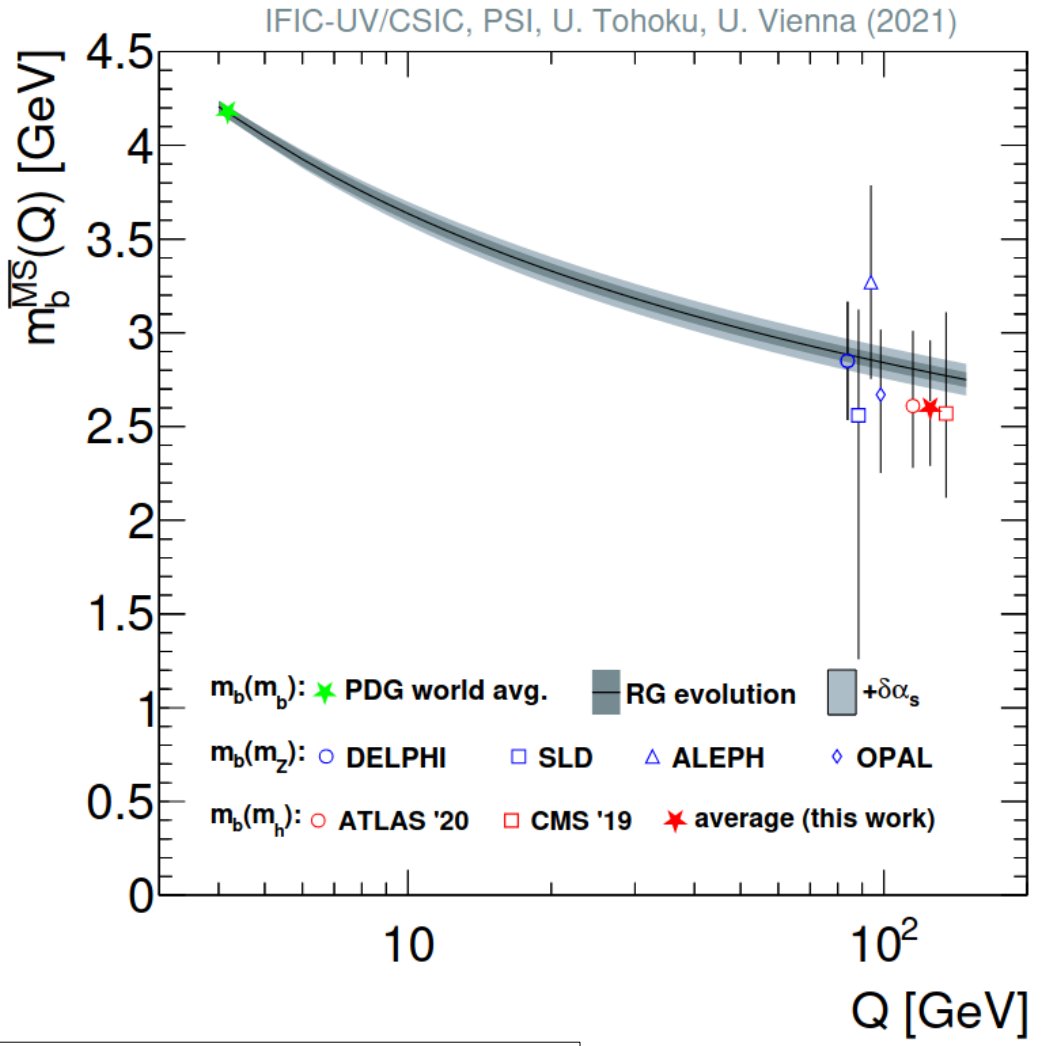
Running of the bottom quark mass

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Uncertainties on evolution:

- reference $m_b(m_b)$ → PDG
- $\alpha_s \pm 0.001$ (PDG $\alpha_s(m_Z)$ ■)
- $\alpha_s \pm 0.004$ (BSM evolution ■)
- missing higher orders (negligible)



LHC $m_b(m_h)$ today is as precise as LEP $m_b(m_Z)$

Bottom quark mass mb(mH)

Reference mb(mb)

$m_b(m_b) = 4.18^{+0.03}_{-0.02}$

PDG world average based on low-energy exp. and lattice

Evolution to high scale

$m_b(m_H) \sim 2.79$

Expected mass at high scale RGE evolution (Revolver)

ATLAS Higgs

$m_b(m_H) = 2.60^{+0.36}_{-0.30}$

from Higgs decay rates PRL128 (2022)

HL-LHC projection

$m_b(m_H) = X \pm 0.06$

HL-LHC projections of Higgs measurements

Higgs factory projection

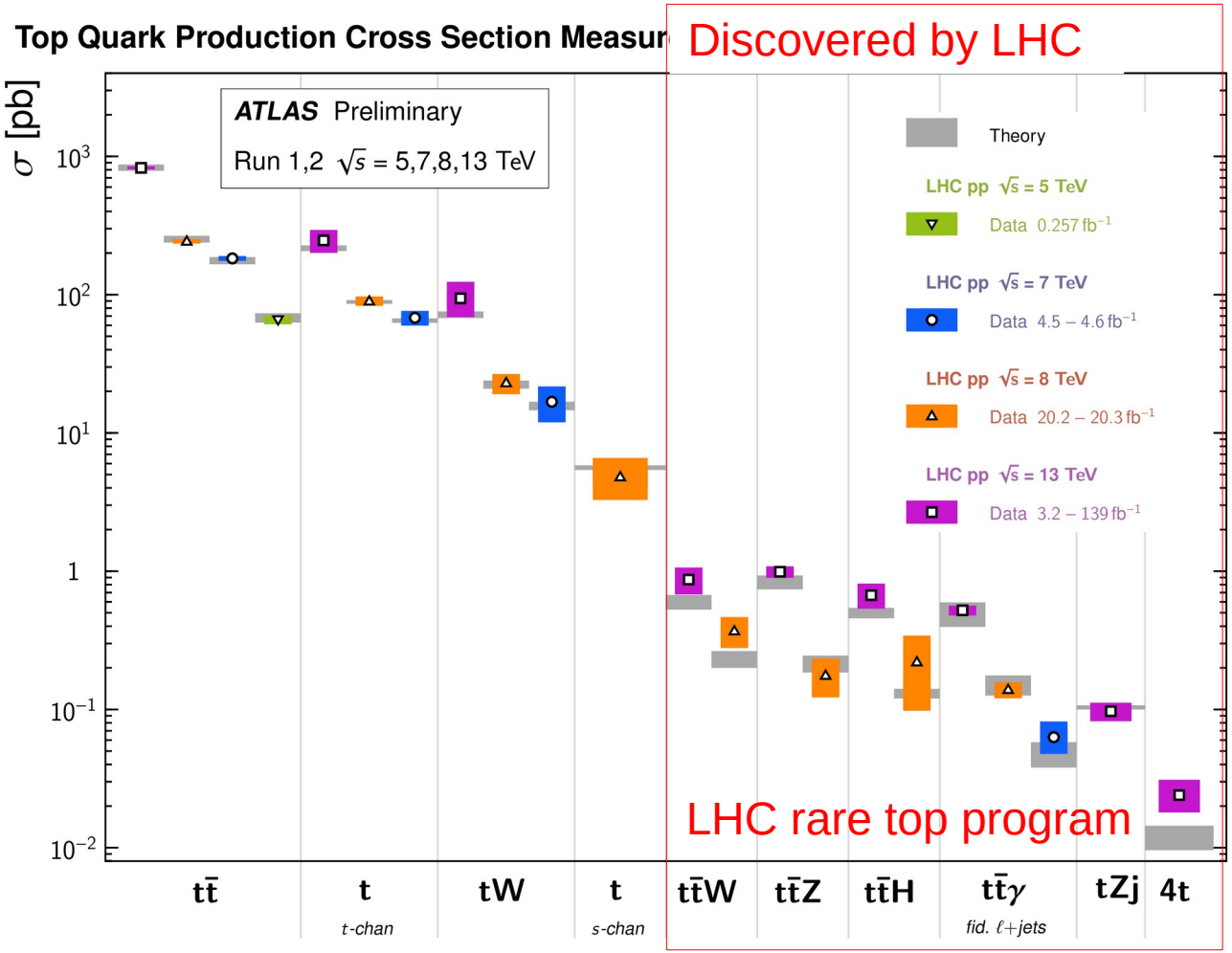
$m_b(m_H) = X \pm 0.01$

Higgs factory (ILC 250+500)

Today: observation of the scale evolution of the bottom quark mass
Future: competitive bottom quark mass at high scale!

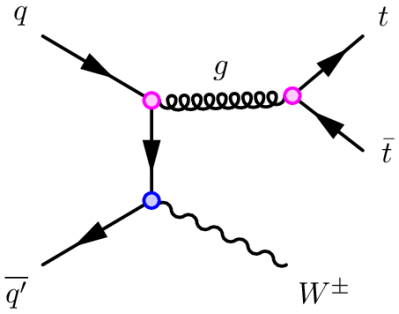
More Standard THEORY* processes

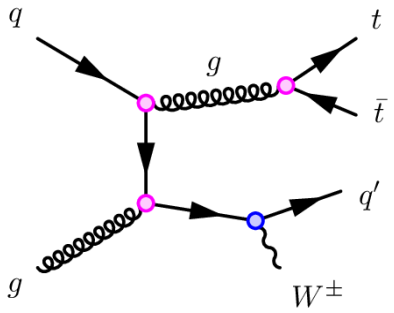
** Paris Sphicas, ICHEP2020*

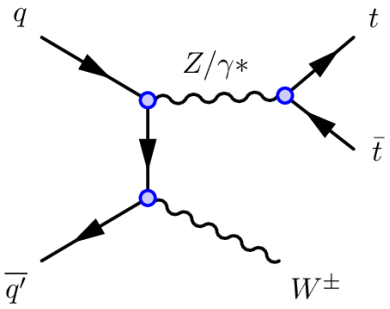


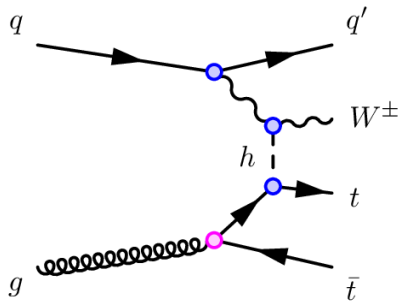
marcel.vos@ific.uv.es

New rare processes: ttW









LO QCD ($\alpha\alpha_s^2$)

$q\bar{q}$ initial state

363 fb ± 20%

+NLO QCD ($\alpha\alpha_s^3$)

qg production opens up

544 fb ± 11%

+Tree-level EW (α^3)

+Mixed QCD/EW ($\alpha^3\alpha_s$)

t-W scattering

577 fb ± 11%

Numbers from JHEP 02 (2018) 031. See JHEP 08 (2019) 039 for resummation, EPJC 81 (2021) for off-shell contribution and JHEP 11 (2021) 029 for

A complex process made up of well-known gt$\bar{t}$ (o) and tWb (o) couplings

The most important source of same-sign and three-lepton events

"Surprisingly" large (50%) QCD correction, and allegedly sub-dominant EW corrections

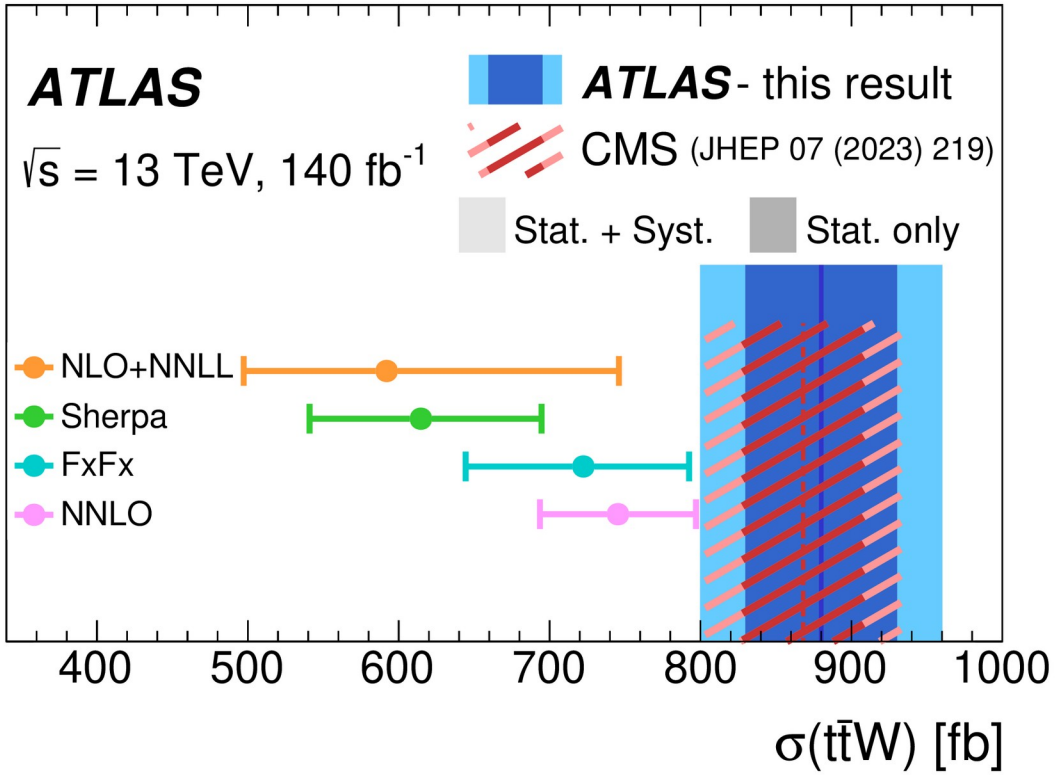
Reference cross section recently updated to 720 ± 80 fb (Frederix & Tsinikos)

The gg→ ttW+j channel opens up at NNLO; eagerly awaiting numerical results

New rare processes: ttW

ATLAS: 880 ± 50 (stat) ± 70 (syst) **arXiv:2401.05299**

CMS: 870 ± 40 (stat) ± 51 (syst) fb **arXiv:2208.06485**



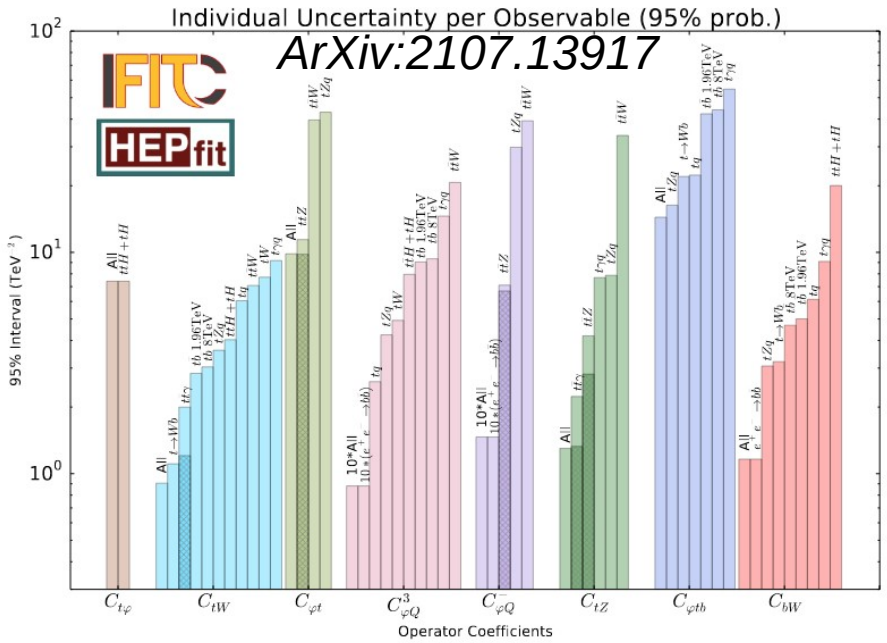
Both ATLAS and CMS see a slight excess (1.5 sigma each)
CMS measured a smaller asymmetry; not confirmed by ATLAS

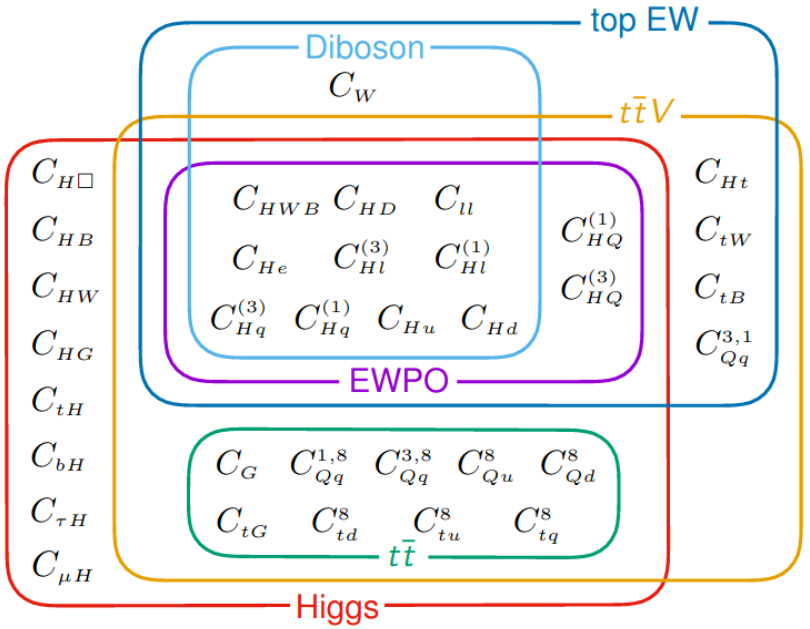
Top couplings at the LHC

Tevatron and LHC have characterized top quark QCD couplings precisely

Charged-current tWb interaction constrained by single top and W-helicity

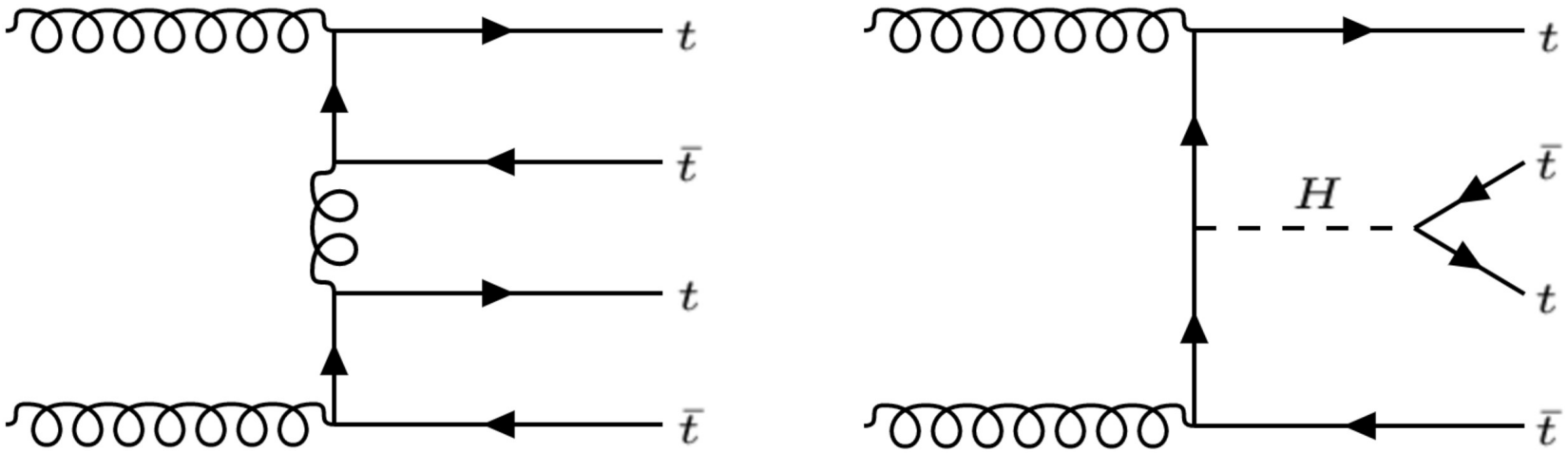
Couplings with γ/Z/H probed directly in top+X production for the first time
- ttZ, tZq, ttγ, tγq, ttH, ttW observed in run 2





Constraining electro-weak couplings that were not probed directly before (as the top quark escaped scrutiny at LEP) and the top Yukawa coupling

New rare processes: tttt



A simple process that probes uncharted tttt and ttH couplings

Standard Model prediction: extremely rare at O(10 fb)

SM prediction NLO QCD + EW: 12 fb ± 20% (Frederix et al., arXiv:1711.02116). NNLL resummation 13.4 fb +7%-14% (van Beekveld et al., arXiv:2212.03259)

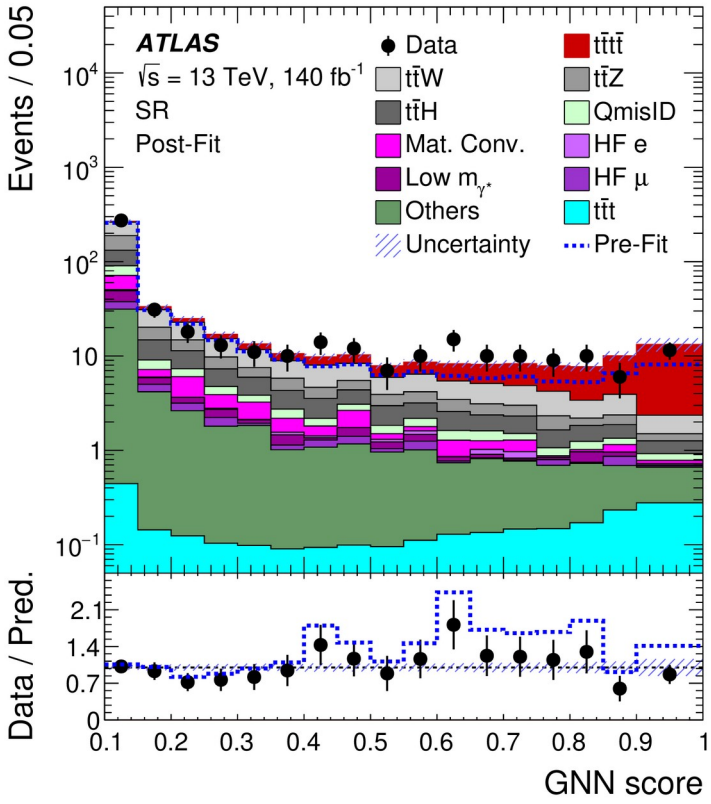
Strong enhancement possible in SUSY, 2HDM, compositeness scenarios

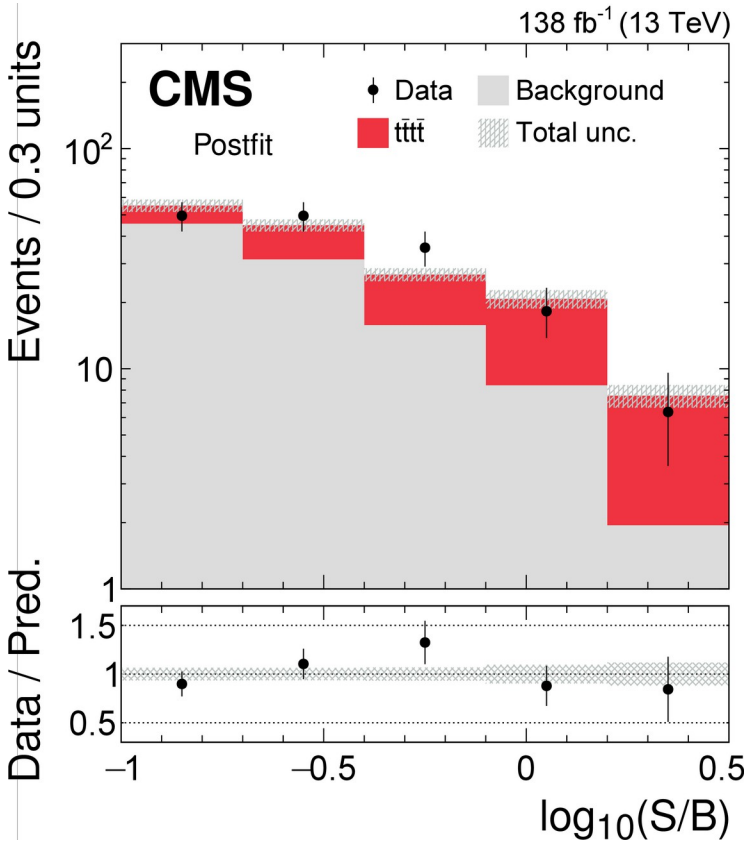
Lillie, Shu, Tait (2008): "We find that a composite top can result in an enhancement of the tttt production rate at the LHC (of as much as 10^3 compared to the Standard Model four top rate)".

ATLAS: arXiv:2303.15061

Observation of four-top-quark production

After 4 years of data taking and another 5 years analyzing the data…





ATLAS and CMS announced the observation on the same day (Moriond ‘23)

Precision

SM prediction

13.4 fb

Tiny Standard Model rate (van Beekveld et al.)

ATLAS

$22.5^{+6.6}_{-5.5}$ fb

ATLAS refined same-sign & multi-lepton analysis:
6.1 sigma from background-only hypothesis

CMS

$17.9^{+4.4}_{-4.1}$ fb

CMS refined same-sign & multi-lepton analysis:
5.5 sigma from backround-only hypothesis

Run 3 and beyond

????

Differential measurements, improved modelling, specific analysis aimed at 3-top-quark production

Four-top production observed by ATLAS and CMS at Moriond ‘23

Top and the foundations of Quantum Mechanics



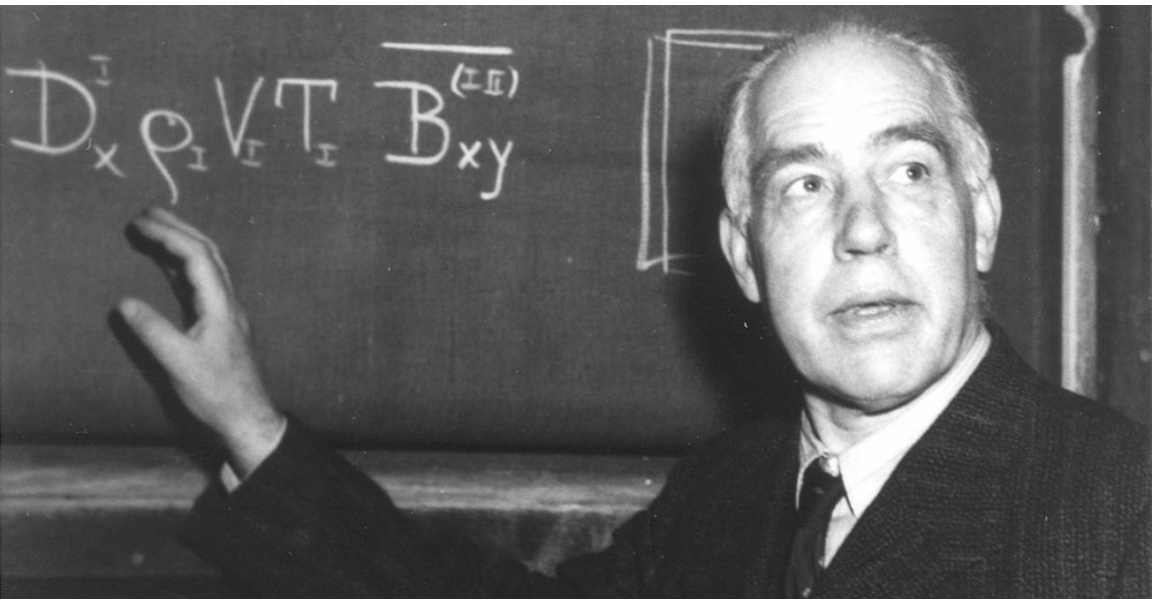
EINSTEIN ATTACKS QUANTUM THEORY

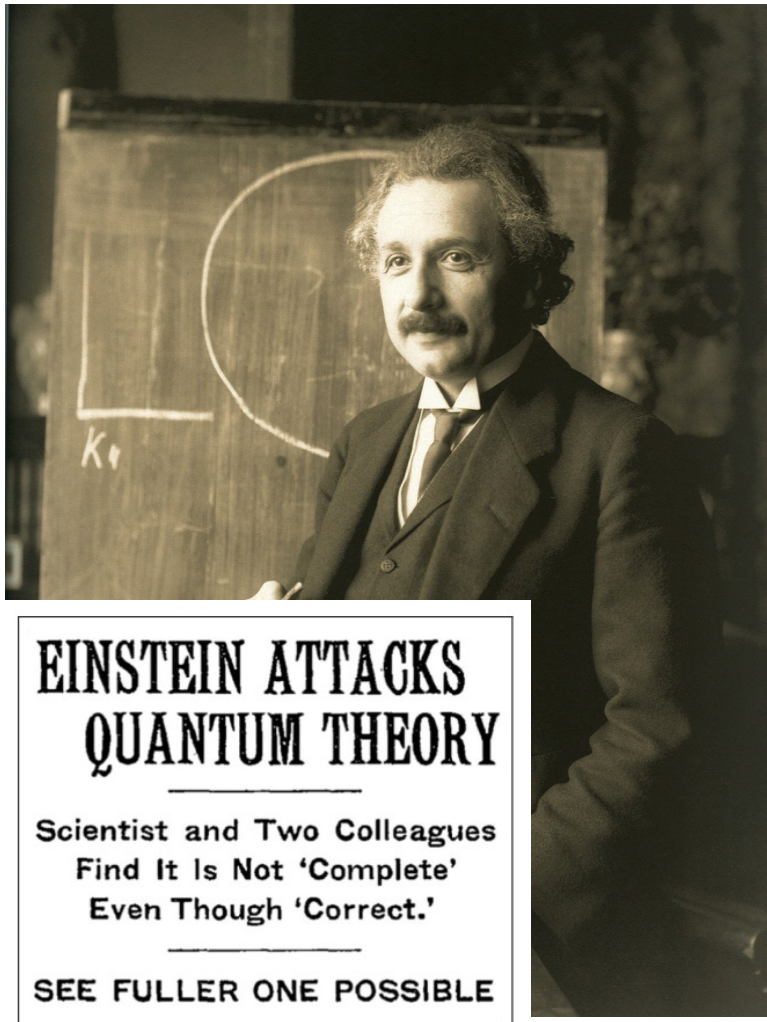
Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

Foundations of quantum mechanics





Philosophical debate among founders of quantum mechanics (and hence modern physics)

Einstein (and common sense):
Particles have properties

Bohr (and quantum mechanics):
Quantum probabilities are all there is to know

1935: Einstein-Podolsky-Rosen thought experiment

EINSTEIN ATTACKS QUANTUM THEORY

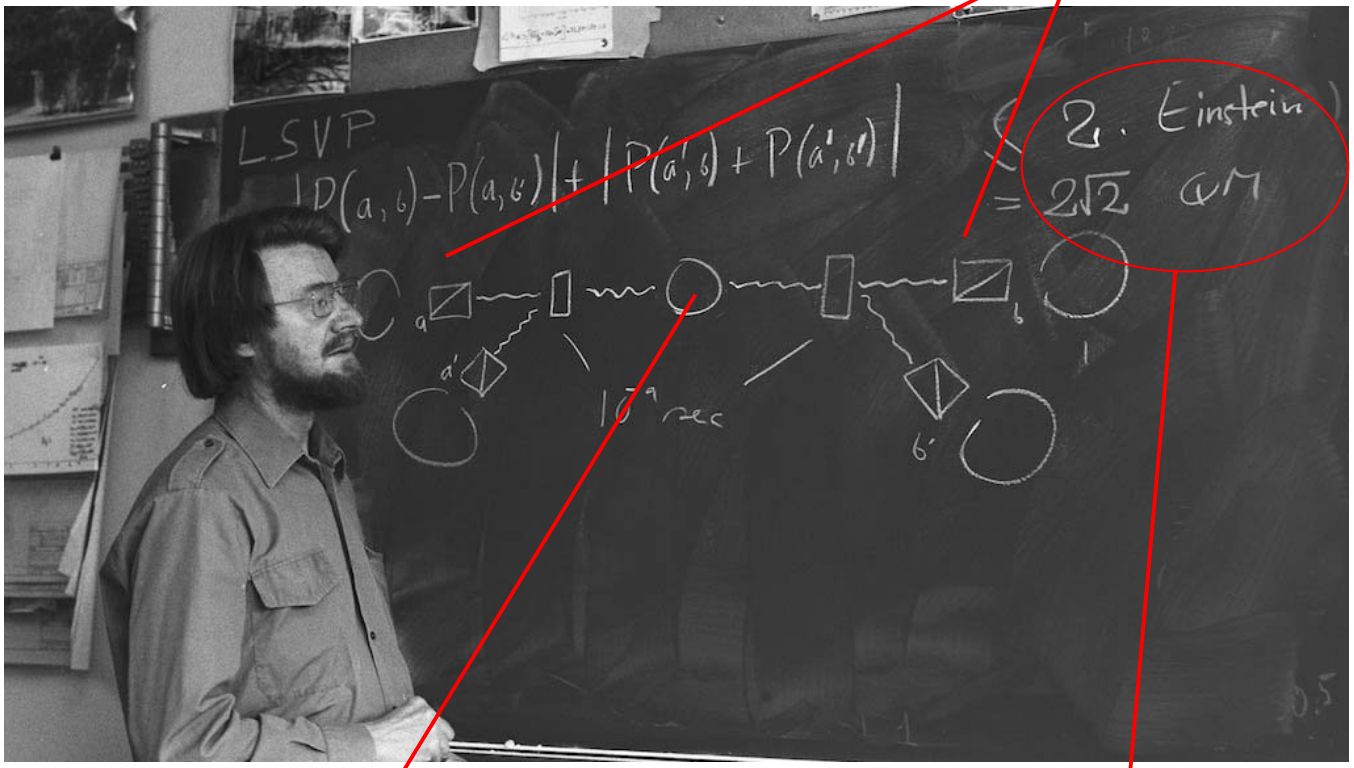
Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

Bell-style experiments

Two well-separated & independent detectors



Source of quantum-correlated “entangled” photons

Outcome of the Bell tests decides between “Einstein” (local realistic theory with hidden variables) and “Bohr” (probablistic interpretation of QM)

Experimental quantum information

1970s-now: Aspect, Clauser, Zeilinger and many others designed and performed experiments that can test Bell inequalities

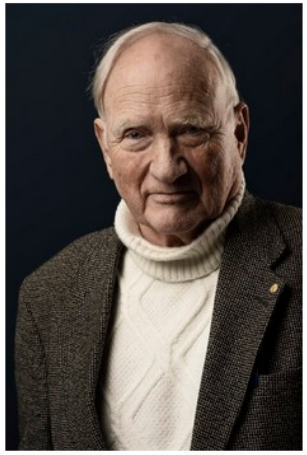
The result: Bohr was right, Einstein and common sense were wrong

A triumph of emprical science: settle a philosophical debate with an experiment

2022 Nobel prize “for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"



© Nobel Prize Outreach. Photo: Stefan Bladh
Alain Aspect
Prize share: 1/3



© Nobel Prize Outreach. Photo: Stefan Bladh
John F. Clauser
Prize share: 1/3

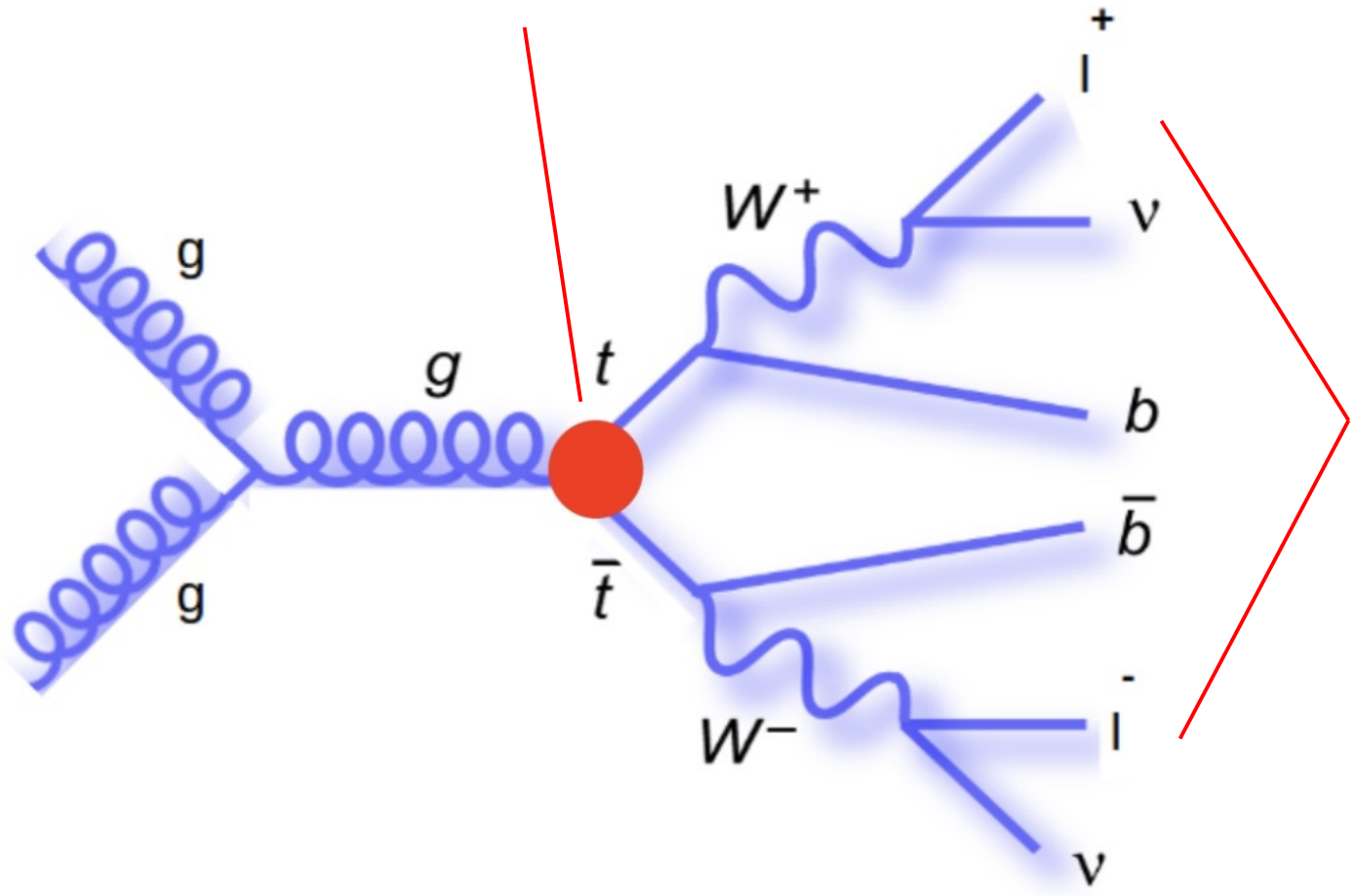


© Nobel Prize Outreach. Photo: Stefan Bladh
Anton Zeilinger
Prize share: 1/3

High energy collisions

Afik & de Nova, EPJPlus
ATLAS, arXiv:2311.07288

Source of entangled particles: pp → $t\bar{t}$

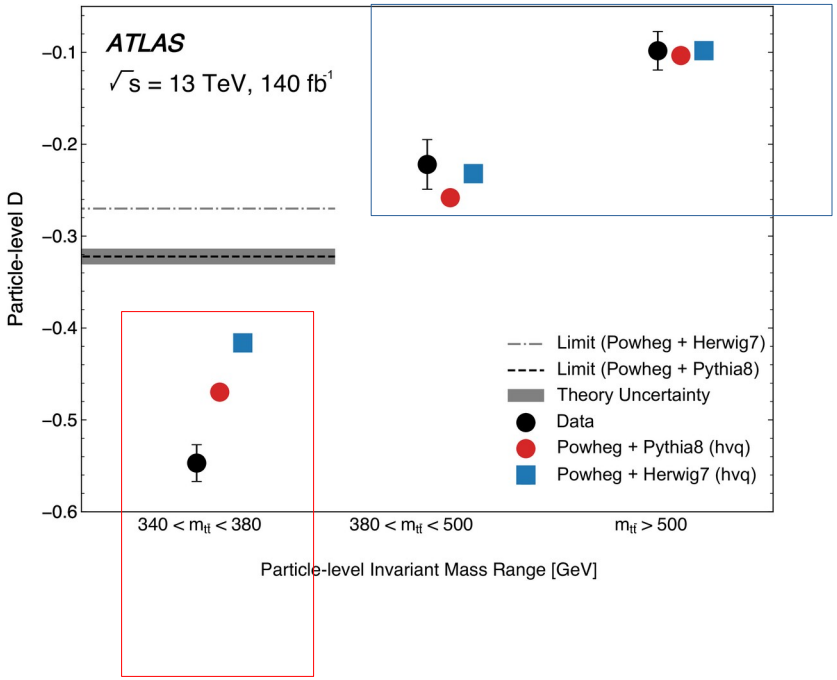


Two polarimeters:
top quark decay
t → Wb, W → $l^{\pm}\nu$

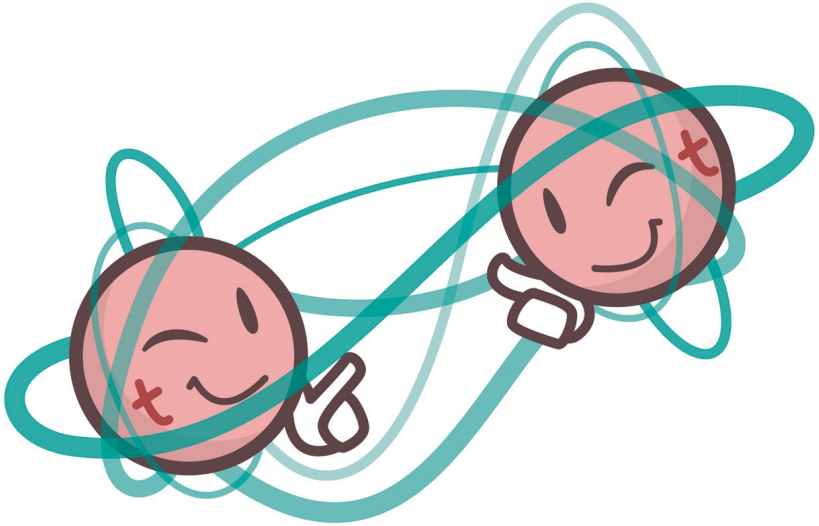
Entanglement: one calls a mixed state of two systems entangled if it cannot be written as a convex combination of product states...
Horodecki, Horodecki, Horodecki & Horodecki, RMP81 (2009), arXiv

Observation of entanglement

ATLAS, TOP23, September ‘23



D != 0 top spins are correlated
(nice, but known since 2013)



D < -1/3 top spin correlations are “quantum”
(new! Opens the door to QI@LHC)

Quantum entanglement observed in top quark pair production

Observation of entanglement – part 2

New: CMS entanglement **observation** at Moriond24

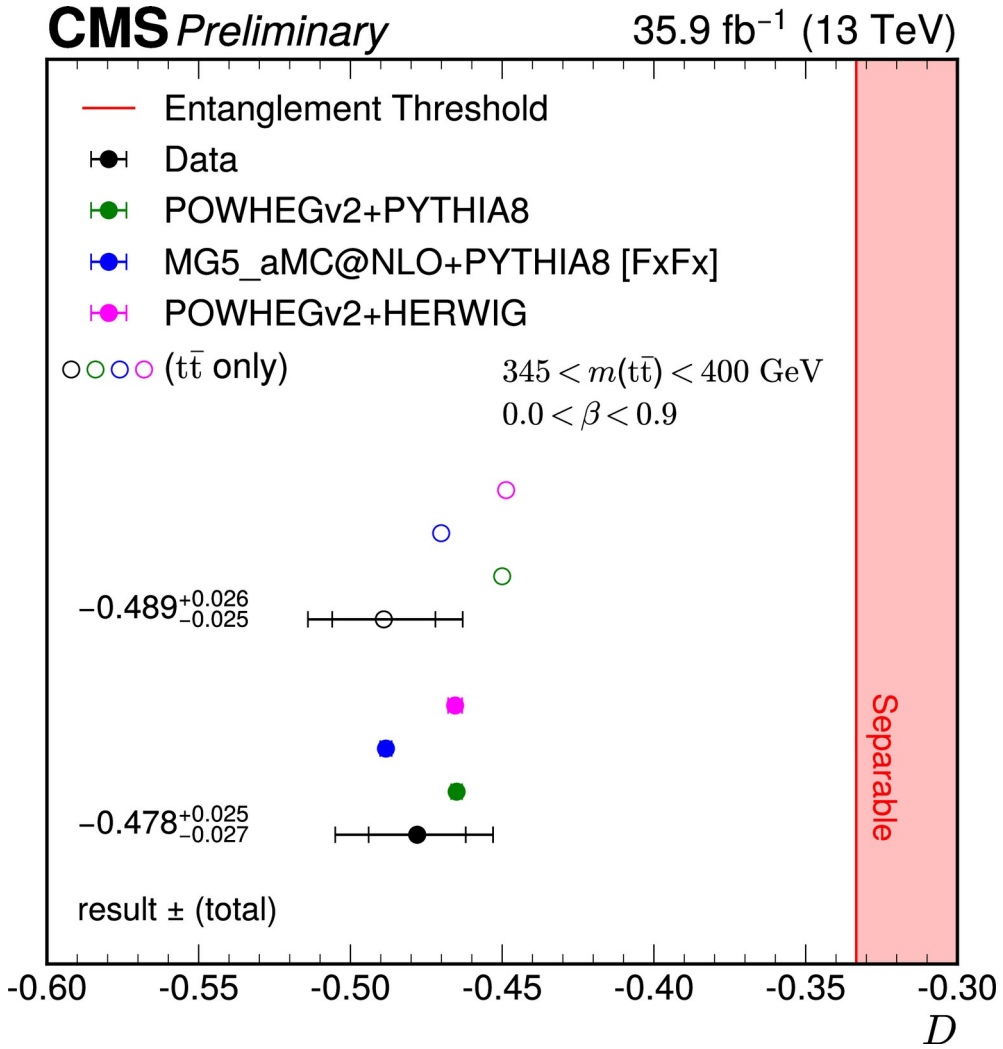
CMS-PAS-TOP-2023-001

D = -0.478 ± 0.026

In good agreement with MC

Toponium and especially MG5-FxFx have large impact on prediction

Note Powheg+Pythia8 prediction ($t\bar{t}$ only) is slightly below ATLAS PP8

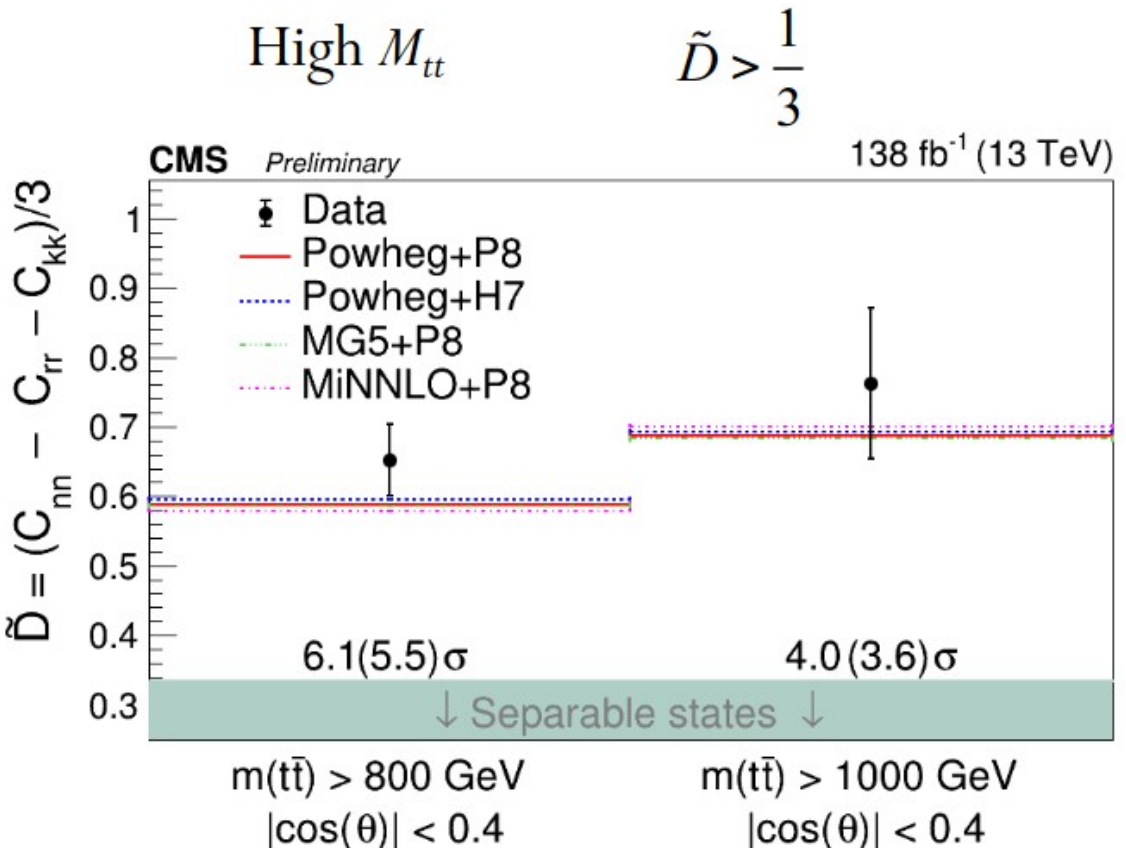


Observation of entanglement – part 3

New at LHCp24 in Boston:

CMS **observes entanglement** in boosted top quark pair production

Nice confirmation, but also:
- less affected by threshold uncertainties
- boosted top quark pairs are more space-like separated



Prospect studies: disclaimer

Prospect studies have a history of underestimating the potential of new facilities

- i.e. LEP prospects without vertex detectors (hence less precise Z→bb studies)
- i.e. impressive LHC top quark physics programme

HL-LHC prospects: from somewhat gloomy 3-pager in 2005…

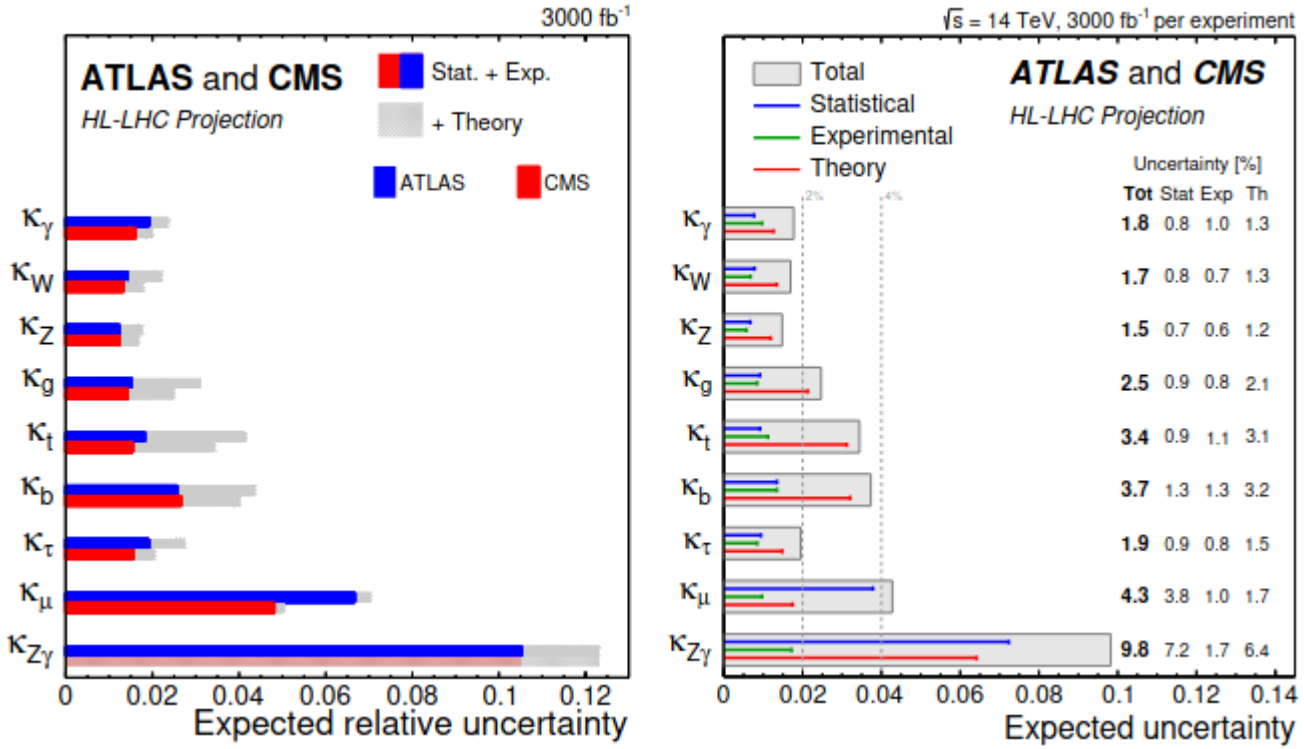
> **4.4 Top-quark physics**
>
> Given the large top quark cross-section, most of the top physics programme should be completed during the first few years of LHC operation [32]. In particular, the $t\bar{t}$ and the single-top production cross-sections should be measured more precisely than the expected theoretical uncertainties, and the determination of the top mass should reach an uncertainty (dominated by systematics) of $\sim$ 1 GeV, beyond which more data offer no obvious improvement.
>
> *HL-LHC primer, hep-ph/0204087*

… to 40 pages on boosted top, rare associated production processes, etc. in yellow report arXiv:1902.04070

Higgs boson summary

Projections for Higgs coupling measurements, derived in the “S2 scenario” and reported in the “kappa framework”

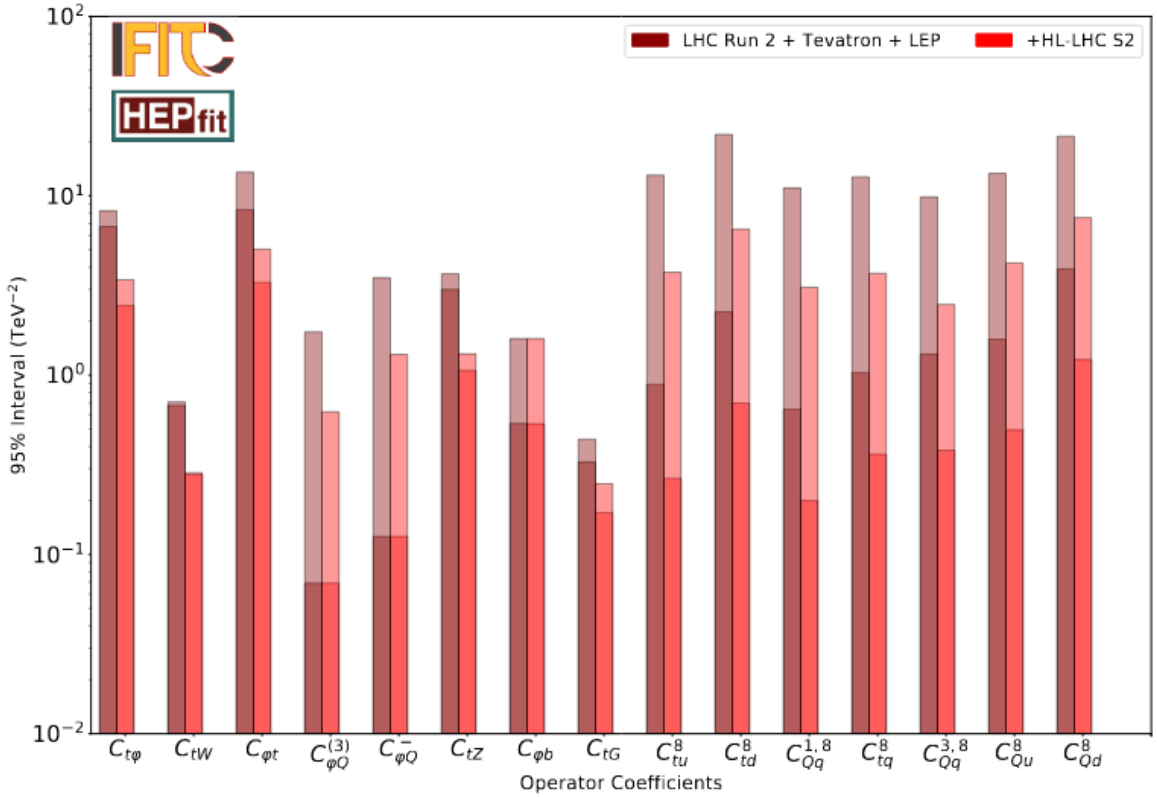
S2 assumes 3000/fb and progress on all fronts, halving theory uncertainties and scaling experimental uncertainties with 1/sqrt(L)



CERN Yellow Rep.Monogr. 7 (2019) 221-584, arXiv:1902.00134

Current SMEFT bounds from top program

Bounds on SMEFT Wilson coefficients still O(1) to O(10) for many operators
Still large correlations and many blind directions: add more measurements



From:
arXiv:2206.08326

Based on
JHEP12(2019)098

Individual bounds
Global bounds

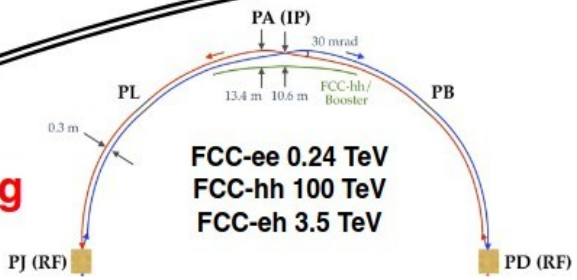
HL-LHC to gain factor 2-5 in all coefficients, with reasonable assumptions:

- *NNLO calculations appear for ttX and tqX production*
- *Modelling uncertainties improve by factor 2*
- *Progress in top quark pair production driven by boosted production*
- *Measurements improve as 1/sqrt(L_{int}): O(10%) now → O(few %) in 2037*

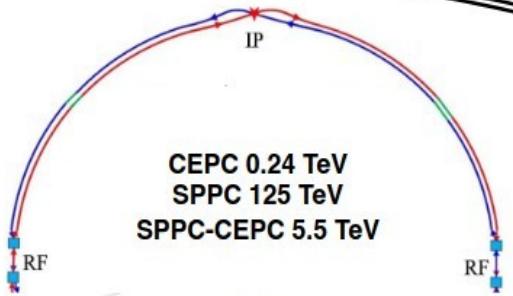
Possible projects…

Future collider proposals: 0.125 – 500 TeV; e+e-, hh, eh, μμ, γγ, …

- **Storage ring colliders**
- **Linear colliders**
- **ERL colliders**
- **Muon collider**
- **Wakefield colliders**



FCC-ee 0.24 TeV
FCC-hh 100 TeV
FCC-eh 3.5 TeV

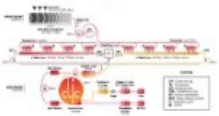


CEPC 0.24 TeV
SPPC 125 TeV
SPPC-CEPC 5.5 TeV

Collider-in-the-sea 500 TeV



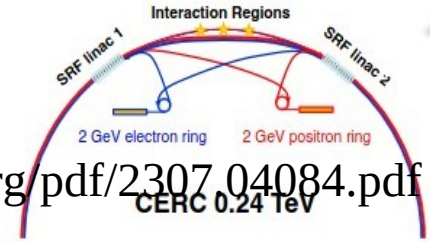
ILC 0.25 TeV



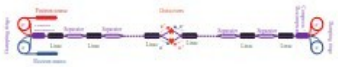
CLIC 0.24 TeV



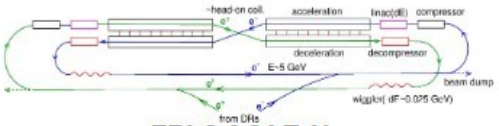
CCC 0.25 TeV



CERC 0.24 TeV

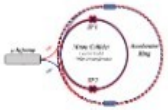


ReLiC 0.24 TeV

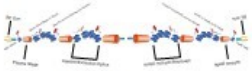


ERLC 0.24 TeV

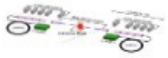
https://arxiv.org/pdf/2307.04084.pdf



MC 10 TeV



PWFA 15 TeV



LWFA 15 TeV



SWFA 3 TeV

10 km

The future collider landscape

European, American and Asian strategies agree on big picture

— e+e- Higgs factory first:

large circular colliders: FCC-ee (CERN) and CEPC (China)

linear colliders: ILC (Japan?), CLIC (CERN), CCC (US)

— exploration of the energy frontier next:

large pp collider: FCC-hh (CERN), SPPC (China)

muon collider: μ-collaboration (CERN+US)

plasma: accelerator R&D (EUPRAXIA, AWAKE), collider studies (i.e. ALEGRO)

Snowmass report

The proposed plans in five-year periods starting in 2025 are given below.

For the five-year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs Factory Detector R&D program,
3. Develop an initial design for a first-stage TeV-scale Muon Collider in the U.S.,
4. Support critical Detector R&D towards EF multi-TeV colliders.

For the five-year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support the construction of an e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for Detector R&D for energy frontier multi-TeV colliders.

European strategy update

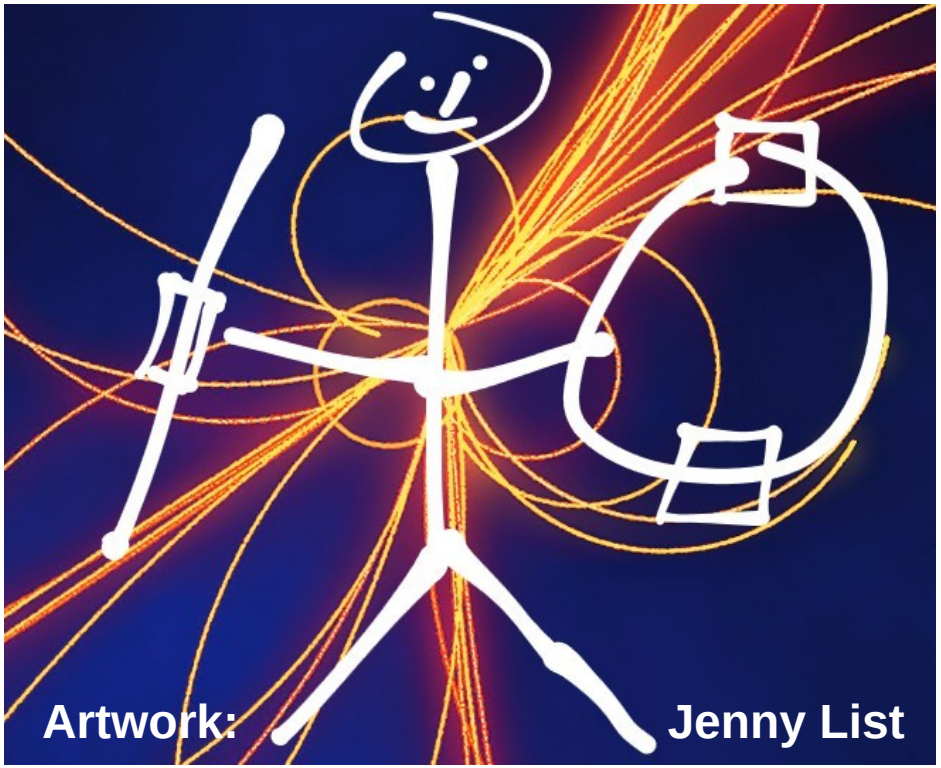
3 !

High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

So, a Higgs factory. Would you like that circular or linear?

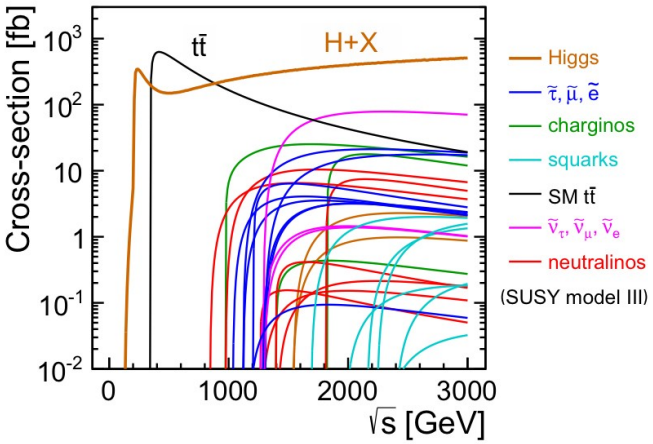
- Circular machines provide superior luminosity at LEP energies (i.e. TeraZ Z-pole run)
- All machines can do excellent Higgs physics and can reach the $t\bar{t}$ threshold
- Upgraded linear colliders access di-Higgs, ttH, and “energy-growth” in new physics

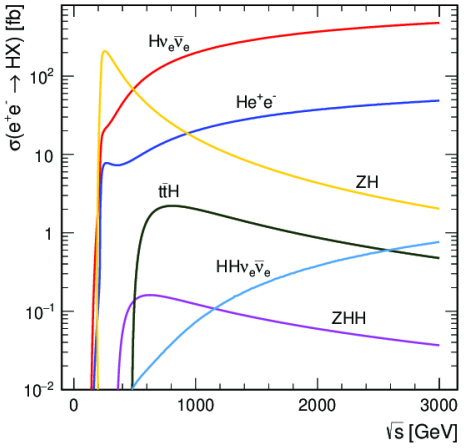


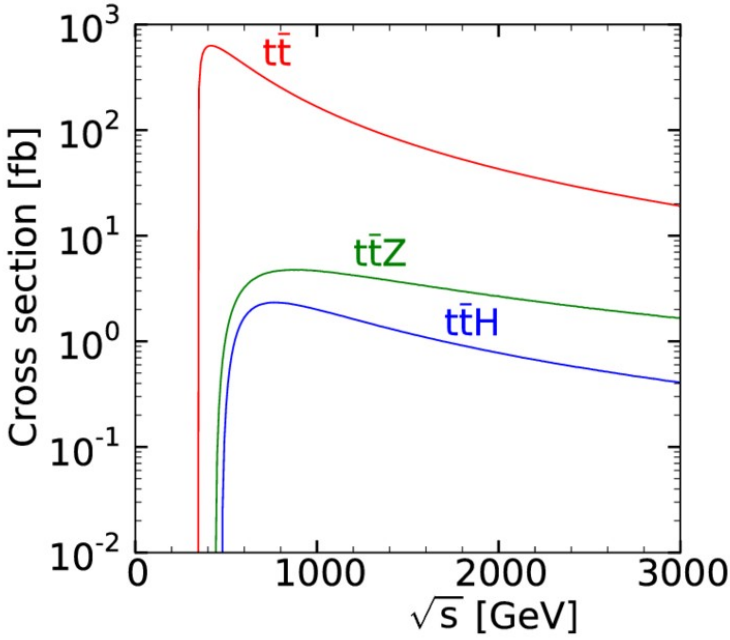
The scientific choice is essentially Z-pole vs. energy upgrade, the rest is “just” politics

Energy reach: top production thresholds

The ideal facility covers a broad energy range.







Z-pole measurements at 91 GeV

Higgs coupling measurements at 250 GeV

Top physics thresholds: ~ 350 GeV for pair production
~ 550 GeV for ttH
~ few TeV for VBF tt production, single top

Precision

Remember that ATLAS $t\bar{t}$ cross section with <2% uncertainty?

Main bottle neck at the LHC today remains NNLO+NNLL theory

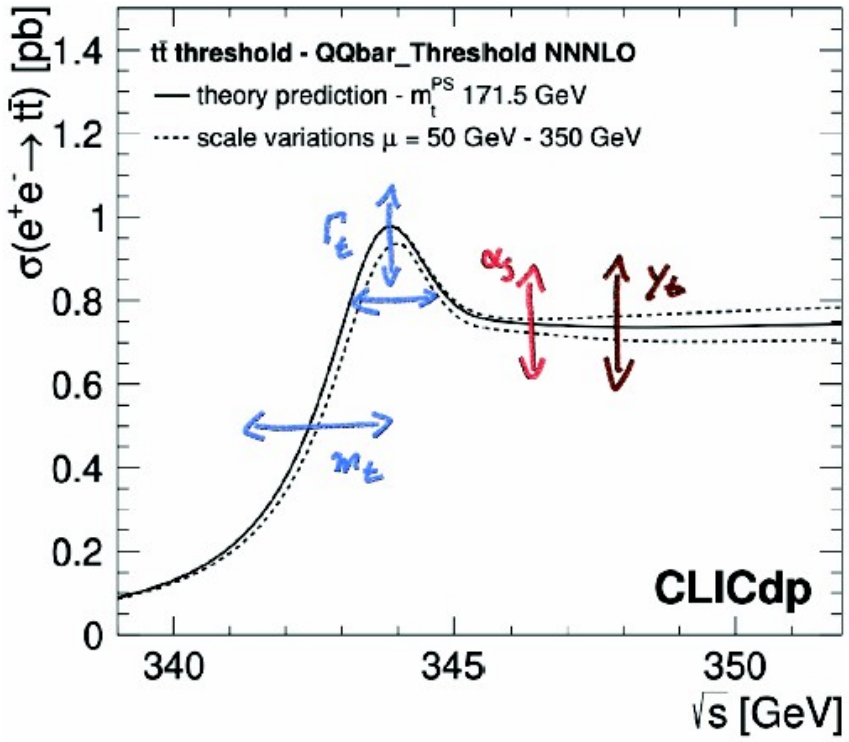
At an e+e- collider realistic statistical uncertainties are O(few ‰)
→ *See e.g. CLIC top paper, arXiv:1807.02441*

Experimental systematic uncertainties can be controlled to that level
→ *requires work on techniques, calibrations and MC*

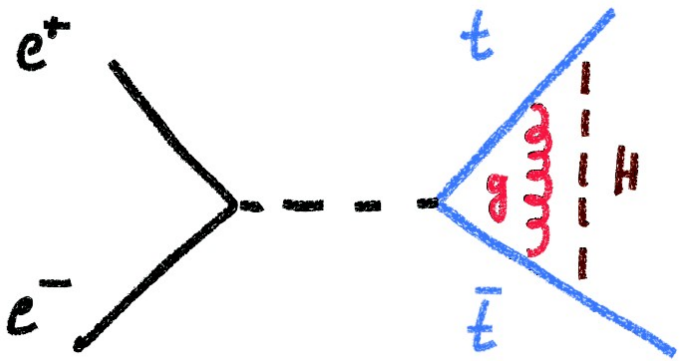
Theoretical uncertainties can be made small enough
→ *partial NNNLO QCD is available today*

e+e- threshold scan

A scan of the e^+e^- center-of-mass energy through the pair production threshold allows for the ultimate mass measurement *(Gusken & Kuhn '85, Peskin & Strassler '91)*
Experimental studies: Martinez & Miquel, hep-ph/020735, Seidel et al., arXiv:1303.3758
Part of the operation plan for all e+e- collider projects: Higgs & top factory!



Calculation: Beneke et al.
Art-work: Frank Simon

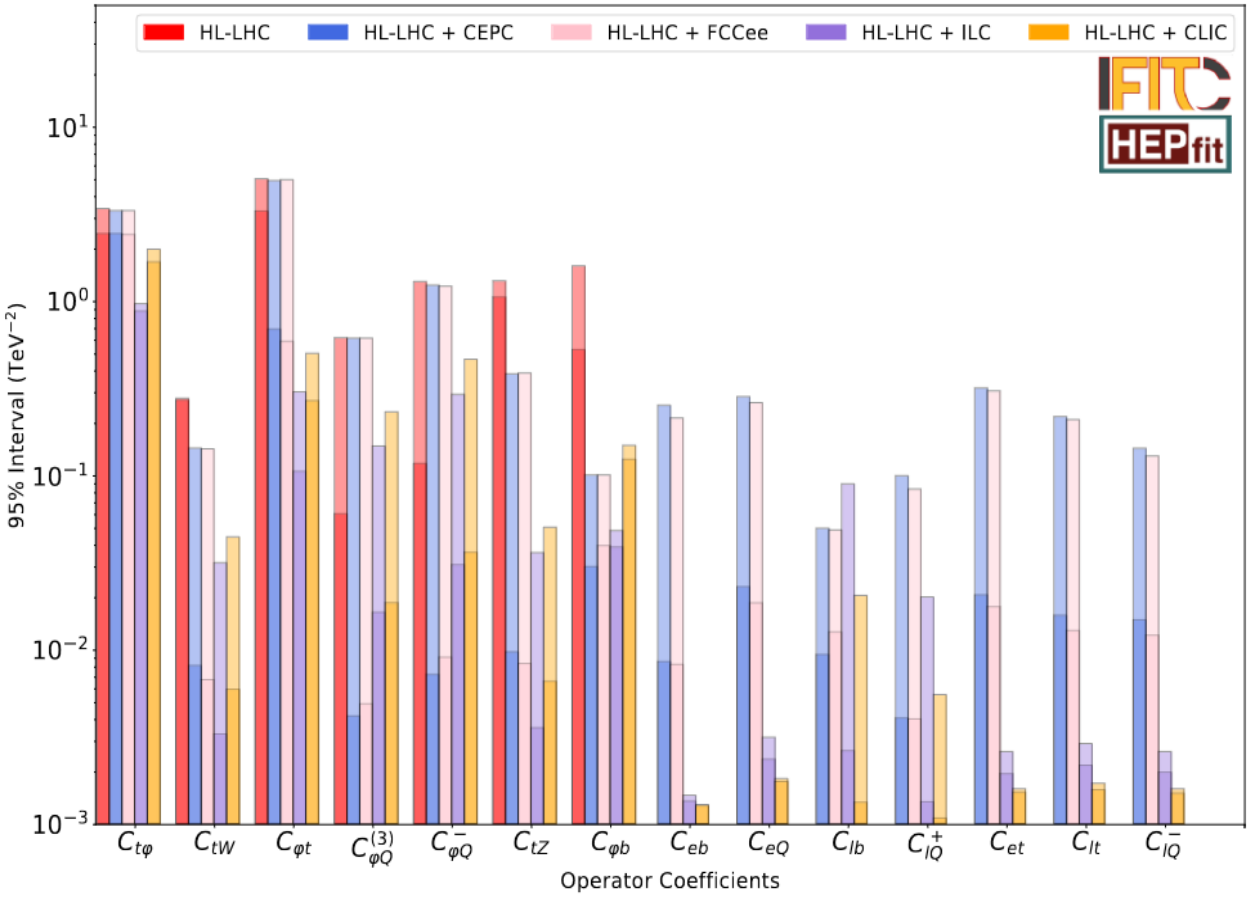


The threshold position is sensitive to the top quark mass, the shape to the width
The normalization is sensitive to strong coupling and top quark Yukawa coupling
Just measure the cross section vs. sqrt(s) shape and derive all parameters

SMEFT fit HL-LHC + e+e- collider

EFT for e+e-: Durieux et al. , arXiv:1807.02121
top EW fit HL-LHC/e+e-: Durieux et al., arXiv:1907.10619
Snowmass top couplings, arXiv:2205.02140
Global SMEFT fit, J. De Blas et al., arXiv:2206.08326
Snowmass report, Schwienhorst et al., arXiv:2209.11267

four-quark operators (qqtt): no progress
two-fermion top-boson: O(1) → O(0.1)
Two-lepton-two-top (lltt): XXX → O(10^{-1} - 10^{-3})



Snowmass SMEFT fit based on Durieux et al., with updated operating scenarios

Summary

The LHC is delivering great top quark physics!
A broad program: precision measurements in the classical top production processes and exploration of new rare processes and unexplored couplings

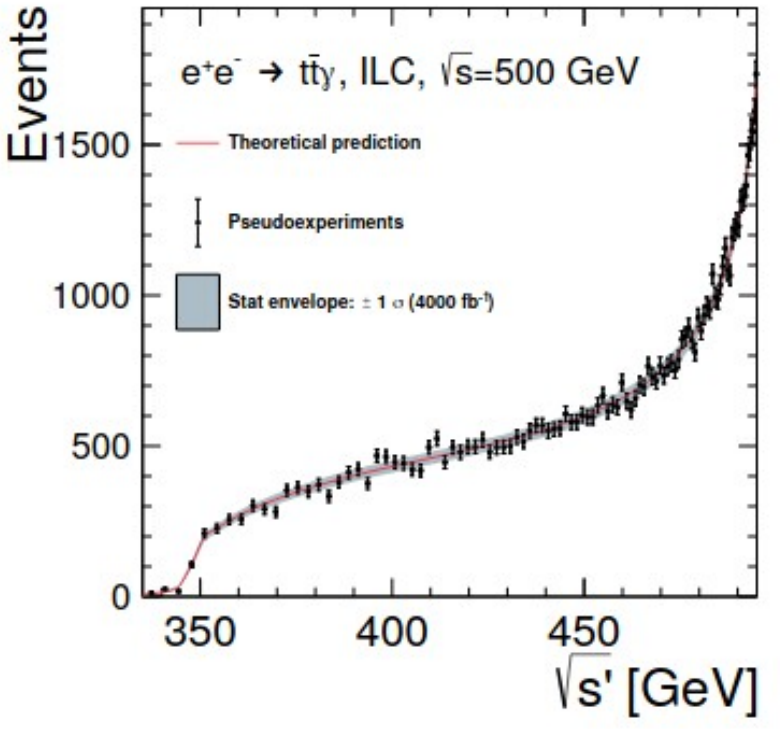


The top quark physics programme:
- LHC precision measurements exceed expectations and continue to improve
- Close ties between the top quark and the Higgs boson confirmed
- Rare processes yield first results on top EW couplings and 4-top vertex

Unorthodox use of LHC data tests internal consistency of the SM
- confirm “running” of the bottom quark mass with Higgs data
- explore the foundations of quantum mechanics with Bell-style experiments

HL-LHC and e+e- collider bring order of magnitude improvement in precision

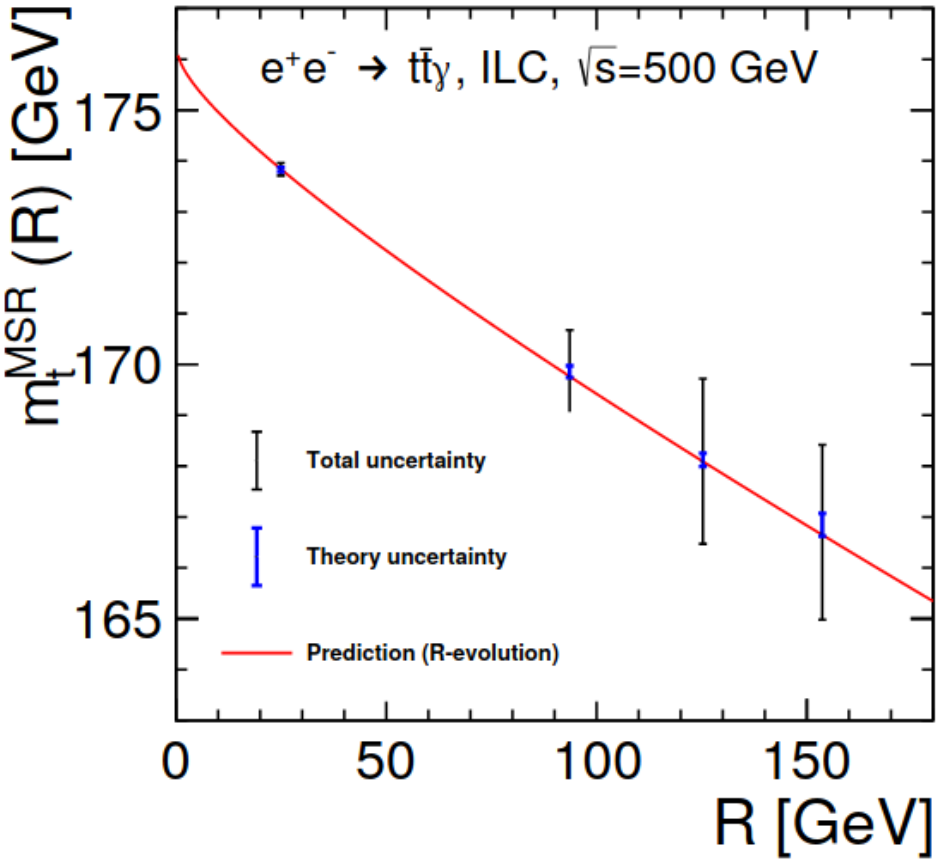
Going full circle: top quark mass from radiative events



Radiative "return to threshold" in e+e- → ttγ events

Extract short-distance mass with rigorous interpretation and competitive precision:

CLIC380 (1/ab): 50 MeV (theory), 110 MeV total
ILC500 (4/ab): 50 MeV (theory), 150 MeV total

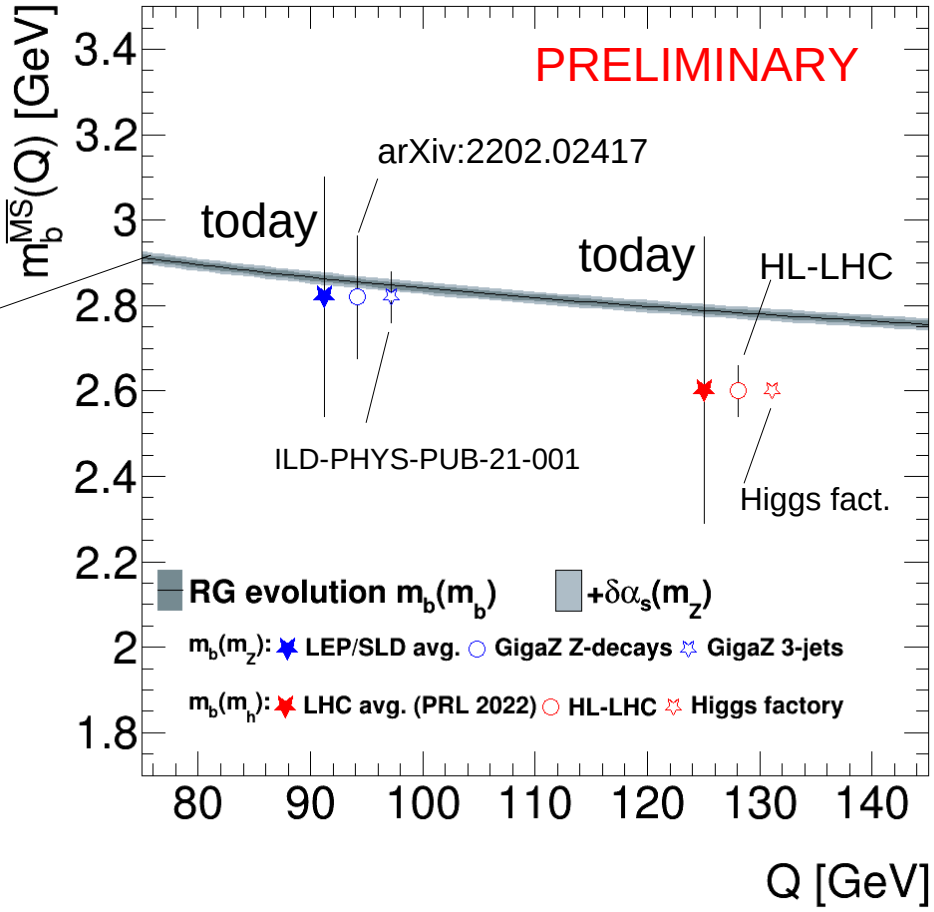


5σ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone

Future prospects – the complete picture

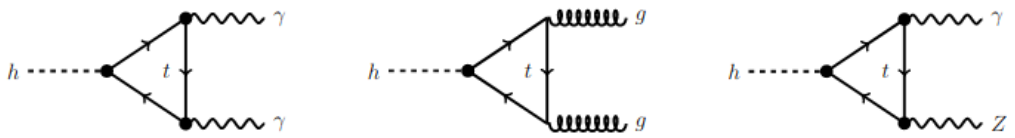
Currently working to collect complete prospects:
$\alpha_s(m_b)$, $\alpha_s(m_Z)$, $\alpha_s(m_H)$, $m_b(m_b)$, $m_b(m_Z)$, $m_b(m_H)$
Snowmass White Paper, arXiv:2203.XXXXX

Projected evolution from m_b scale
$m_b(m_b)$ < 10 MeV [Mateu/Hoang]
$\alpha_s(m_b)$ < 0.5%) [FLAG]
$\alpha_s(m_Z)$ < 0.1% [d'Enterria/FCCee]
See report α_s workshop 2022



The next years at the LHC will see rapid progress in $m_b(m_H)$; the Higgs factory will further improve $m_b(m_H)$ and $\alpha_s(m_Z)$

The top Yukawa coupling at a lepton collider



250 GeV run offers "indirect" sensitivity to the top Yukawa

$\Delta y/y < 1\%$ from $H \rightarrow gg$ — *Mitov et al., arXiv:1805.12027*

$\Delta y/y < 1\%$ from $H \rightarrow \gamma\gamma$ — *Jung et al., arXiv:2006.14631*

Assuming the SM for all other couplings

500+ GeV run offers a "direct" measurement in ttH production

<3% precision — *Price et al., arXiv:1409.7157*

robust in global analysis — *Jung et al.,arXiv:2006.14631*

Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	12.2	5.06	3.14	2.60	1.48	2.96
	Indiv. fit	10.2	3.70	2.82	2.34	1.41	2.52

Top-SMEFT fit on prospects, de Blas et al., 2206.08326