The Top portal to discovery at the Large Hadron Collider

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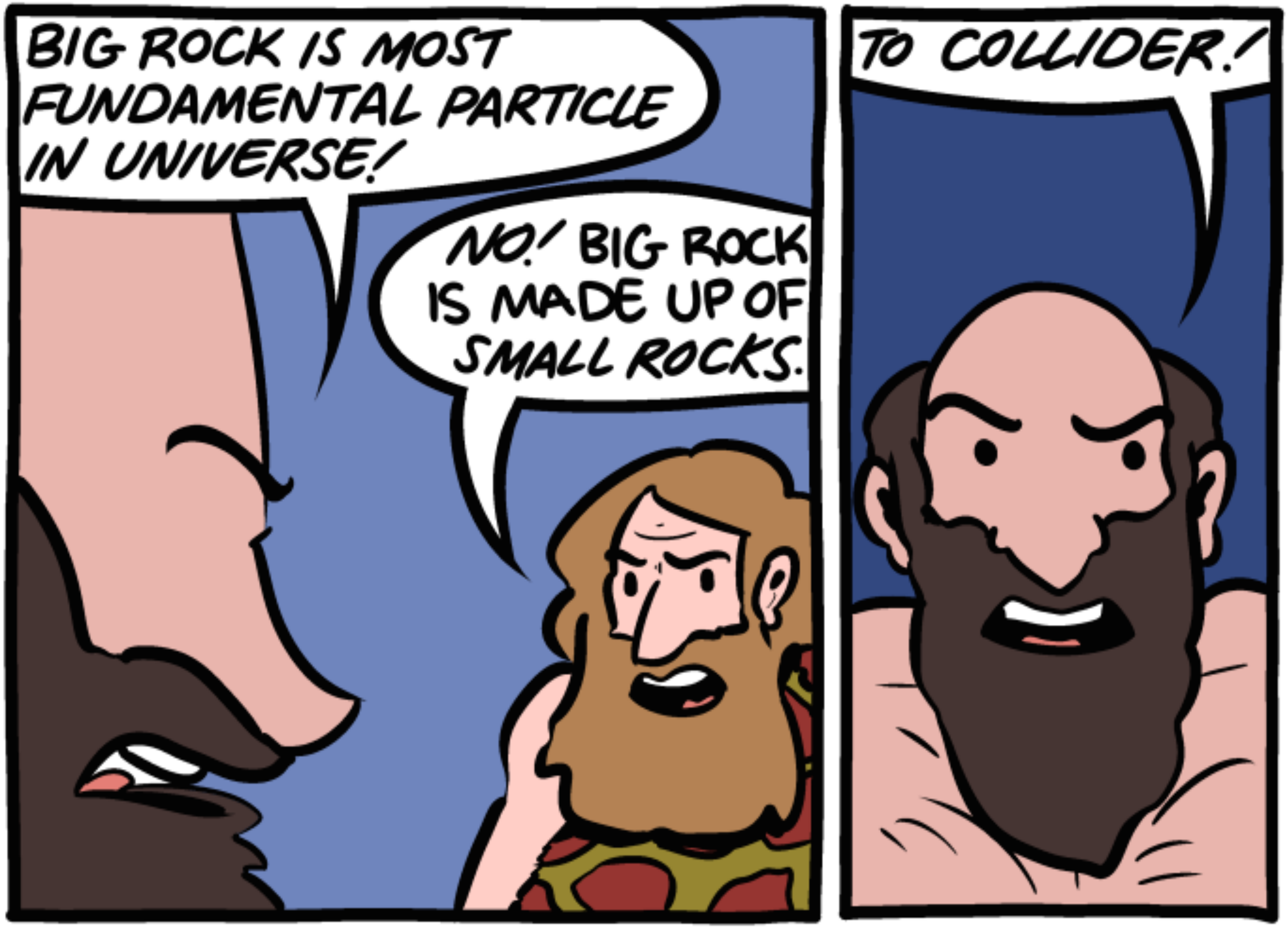
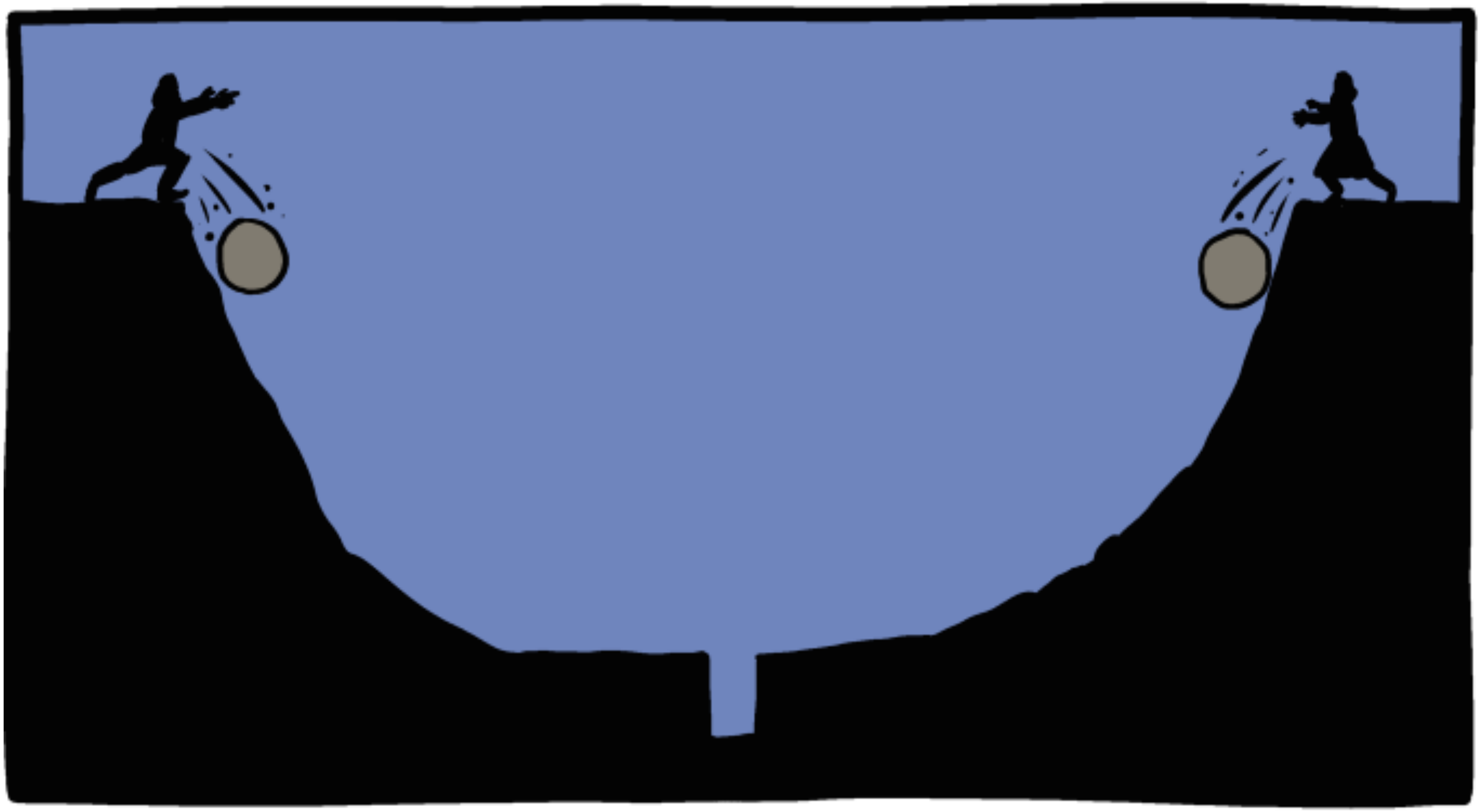
Curiosity



src: http://www.smbc-comics.com

Curiosity



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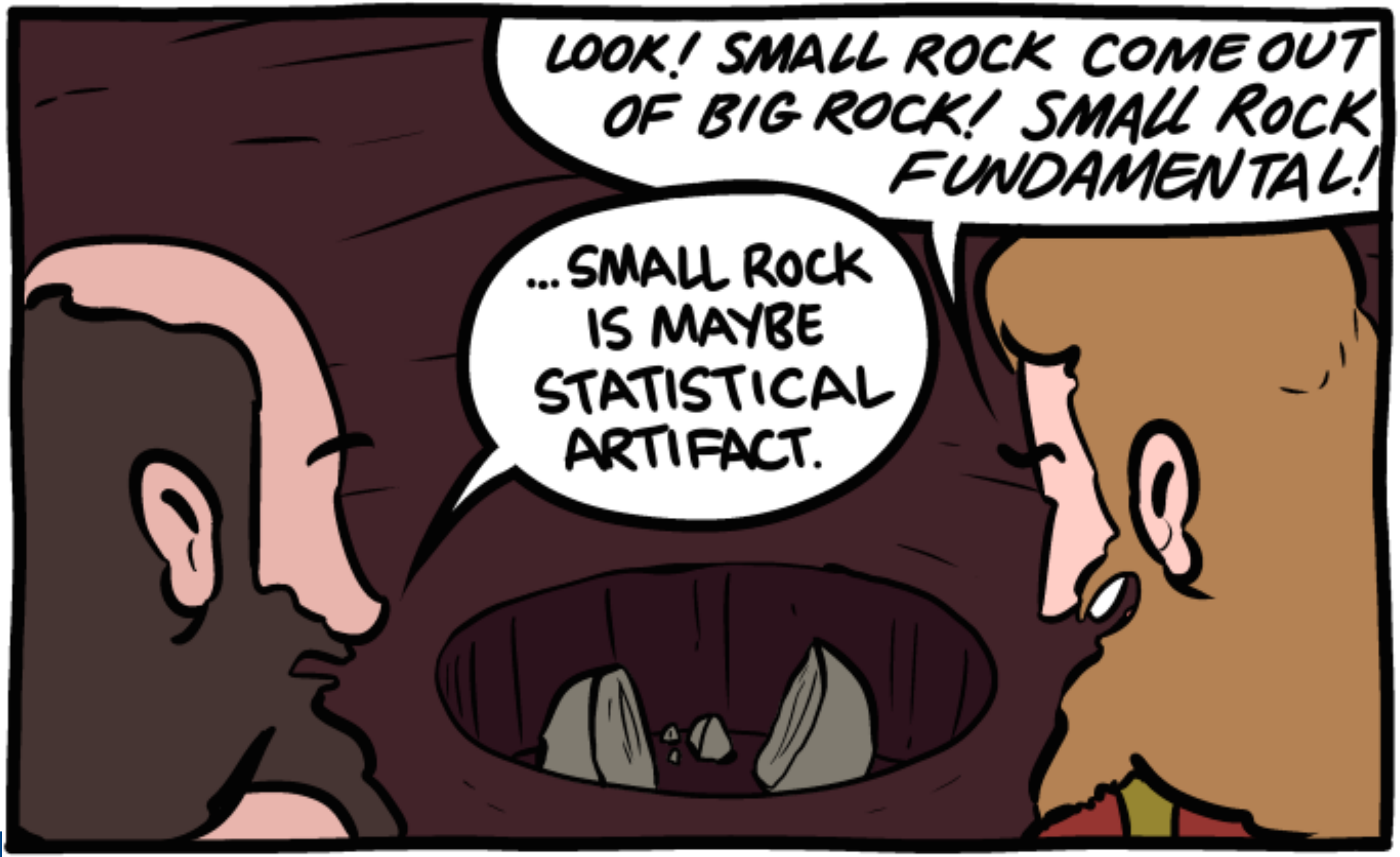

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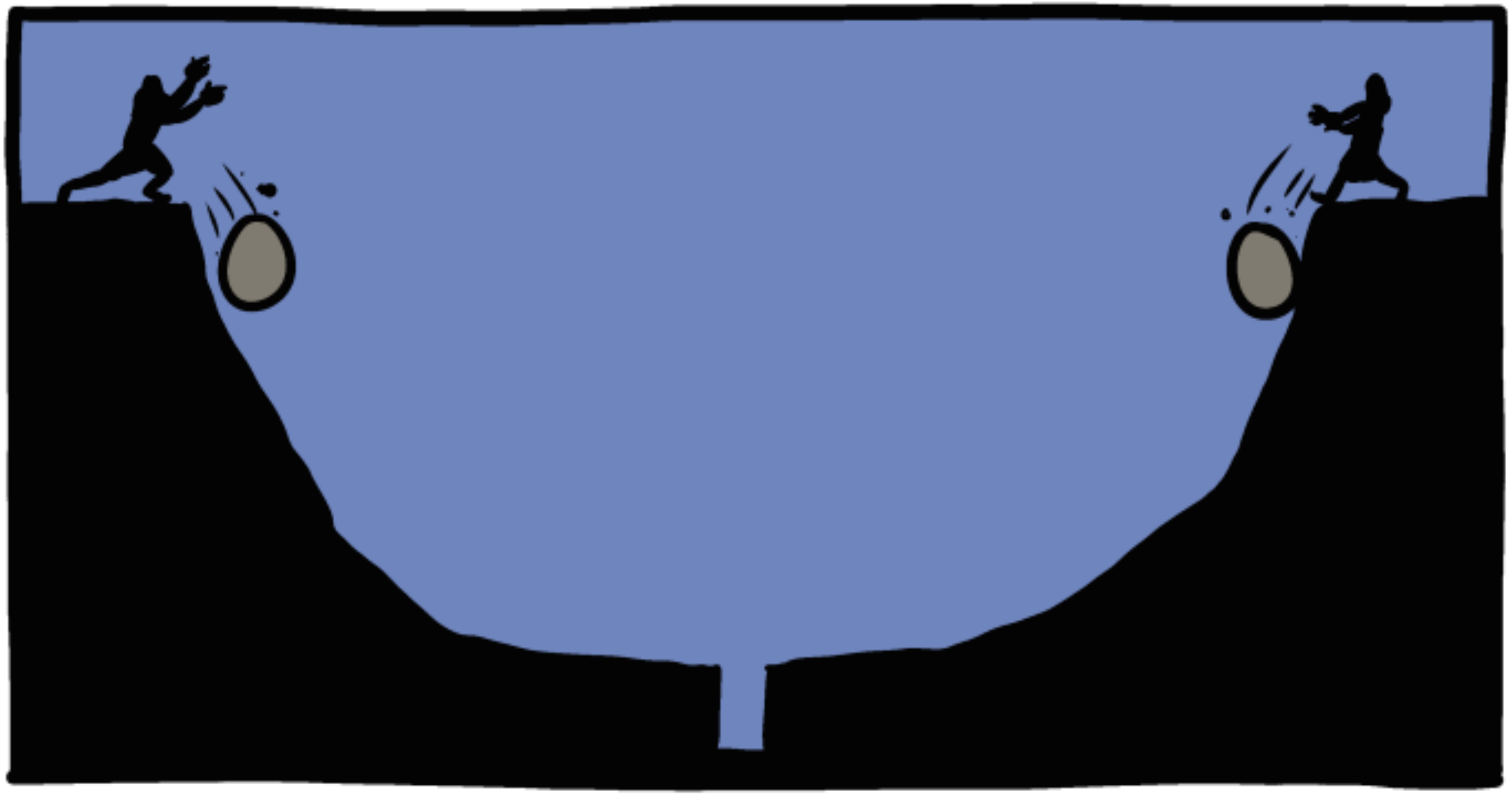
Curiosity



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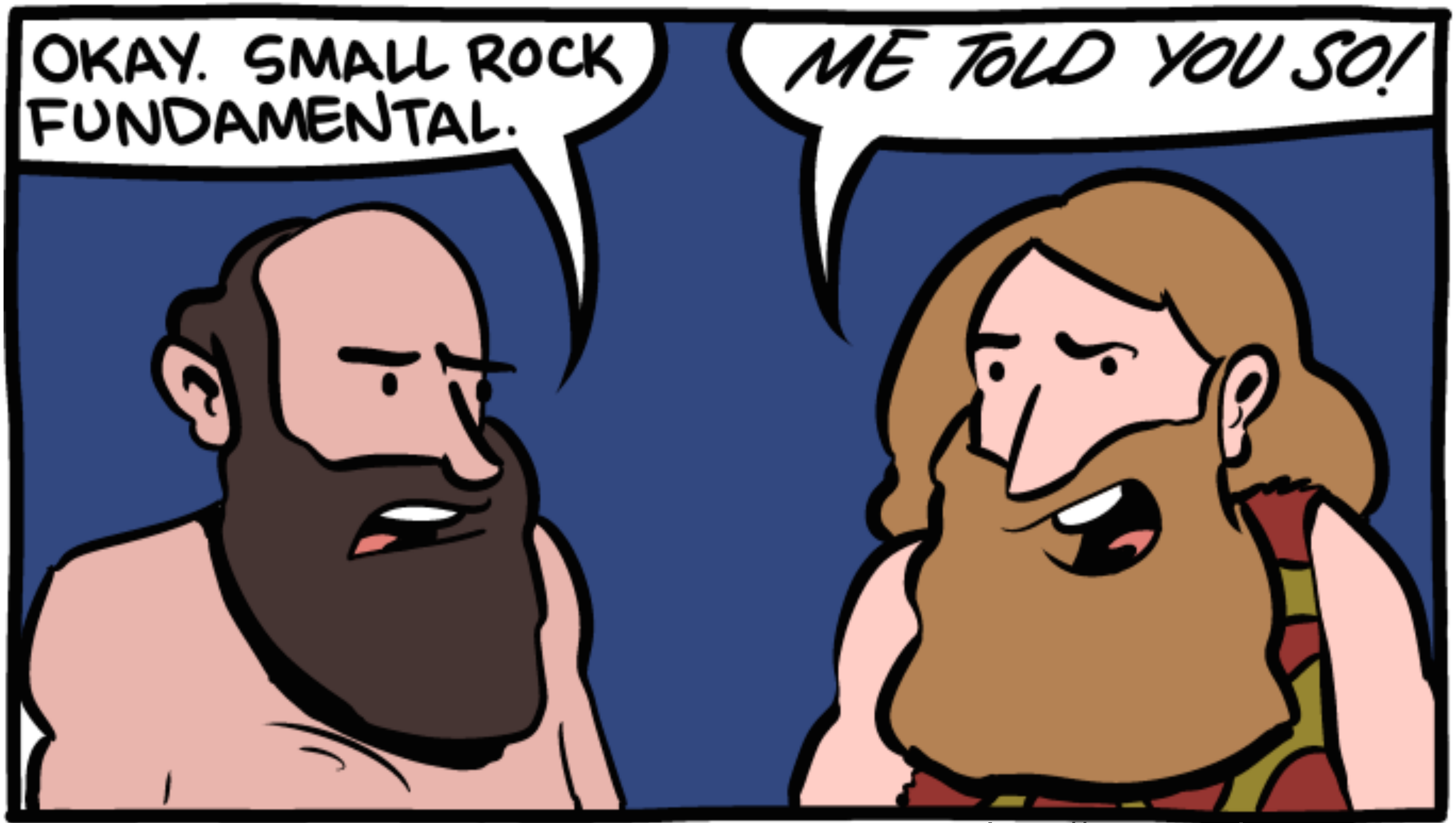
Curiosity



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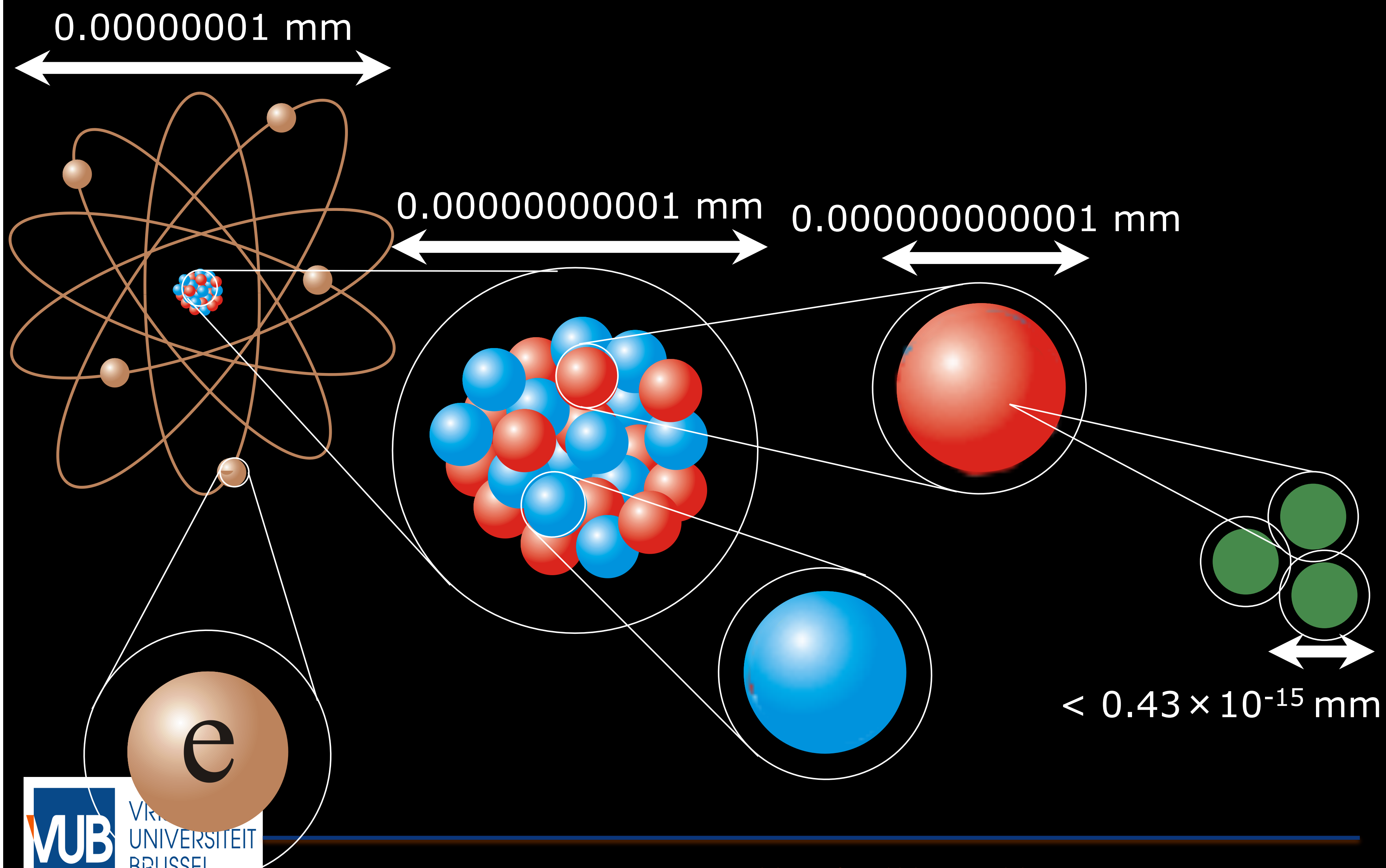
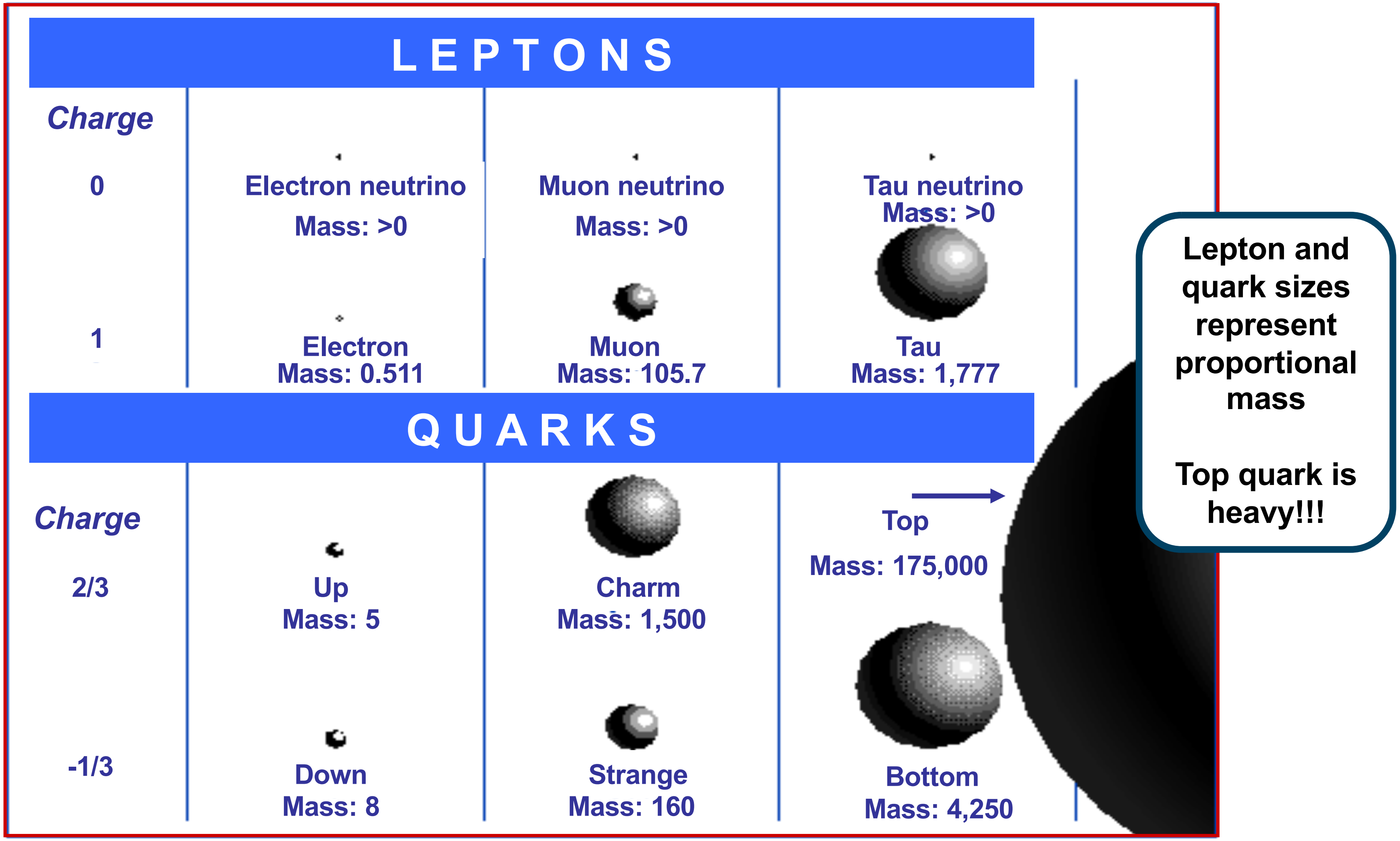


0.00000001 mm
0.00000000001 mm
0.000000000001 mm
e
< 0.43 × 10-15 mm

The building blocks of matter



Masses are in millions of Electron Volts [MeV/c^2]

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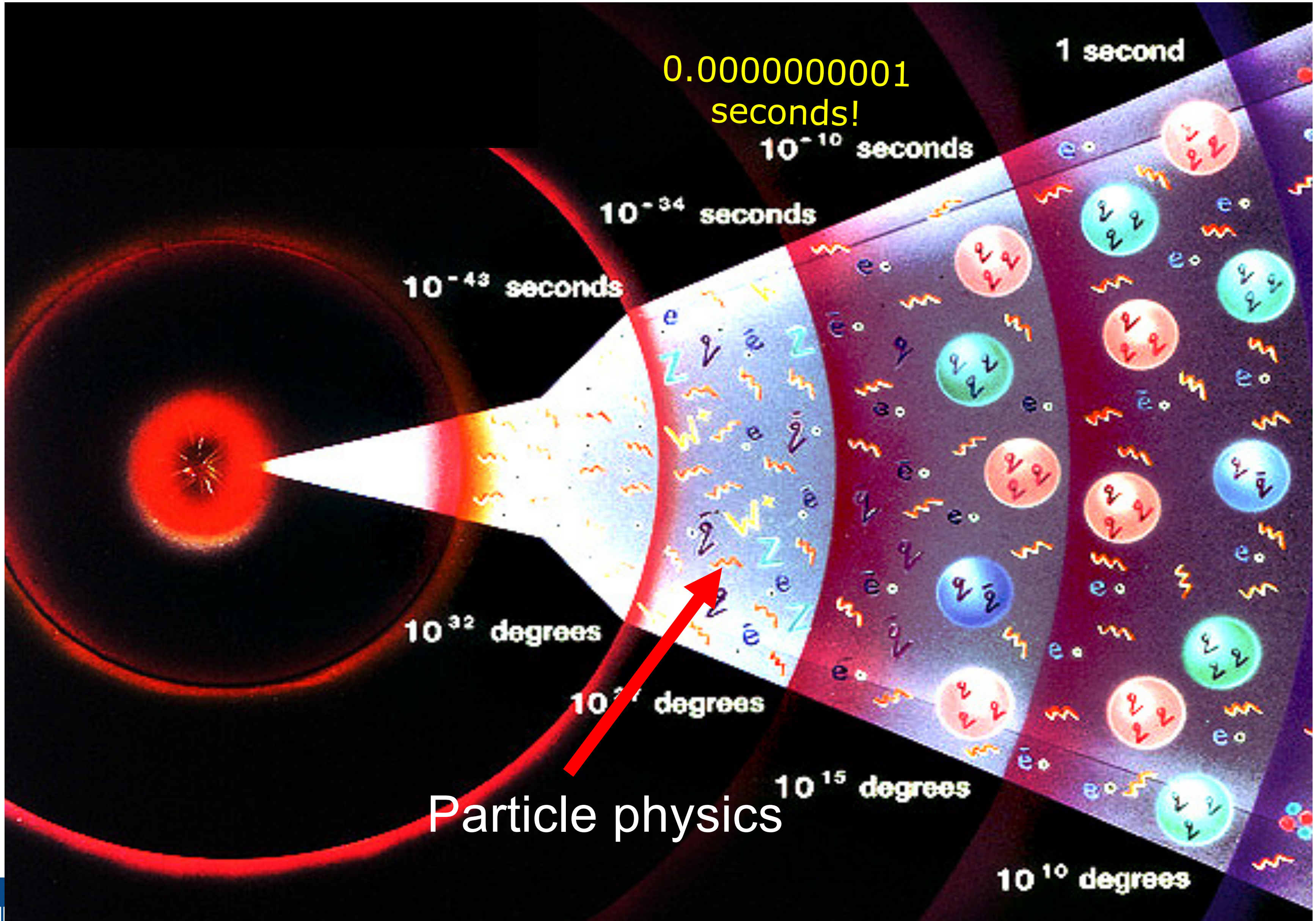
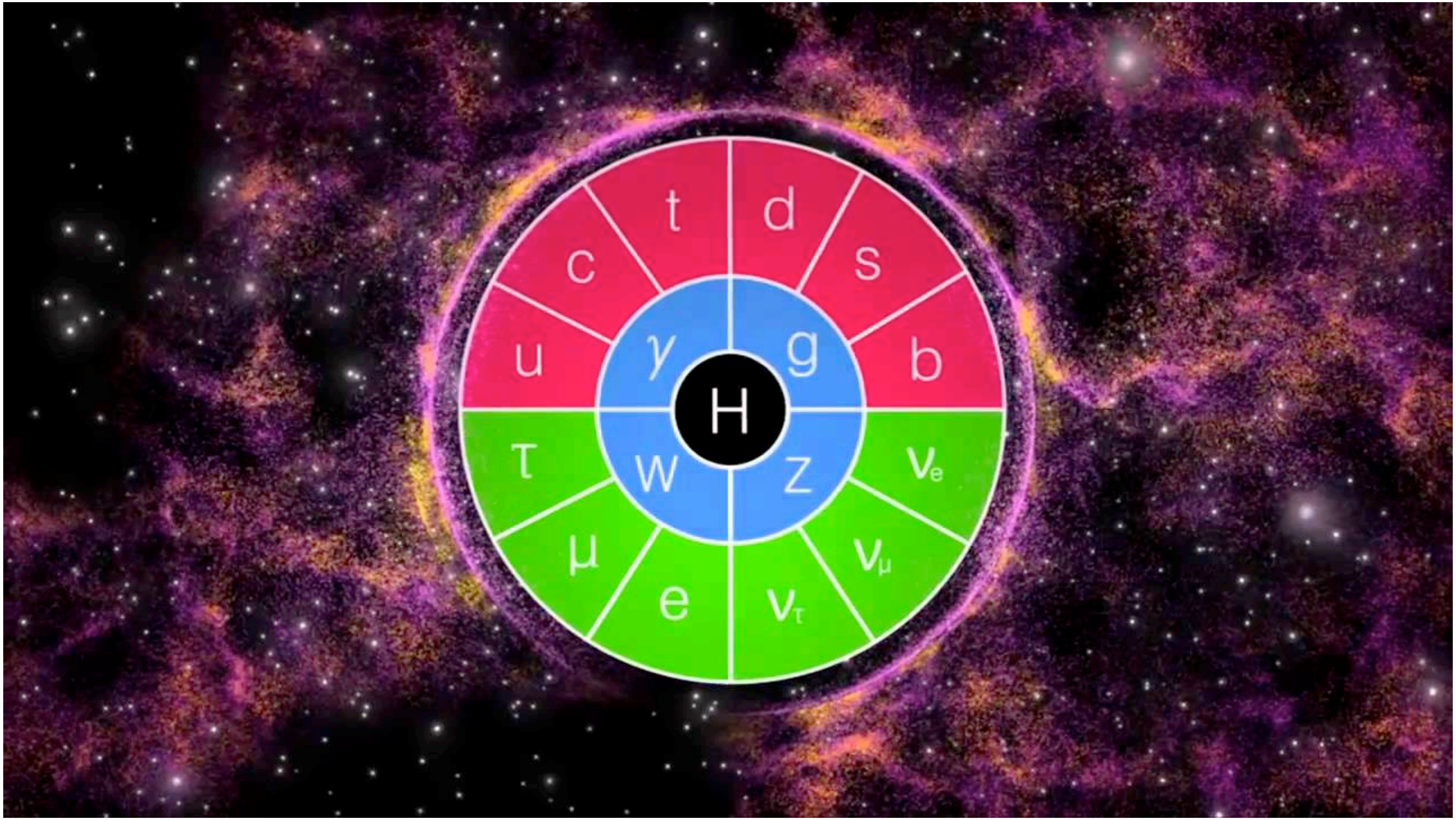
The Big Bang...



0.0000000001
seconds!
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{15} degrees
10^{10} degrees
Particle physics

The Standard Model!



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$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$

$$\frac{1}{2}ig^2_s(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$

$$\frac{1}{2}m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c^2_w}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$

$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu -$$

$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu -$$

$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$

$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$

$$g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$

$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$

$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$

$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$

$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$

$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$

$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$

$$\frac{1}{4}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$

$$g^1 s^2_w A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j -$$

3

$$\bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$

$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w -$$

$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$

$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$

$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4

$$\frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$

$$m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$

$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$

$$\frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

5

$$\frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$

$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$

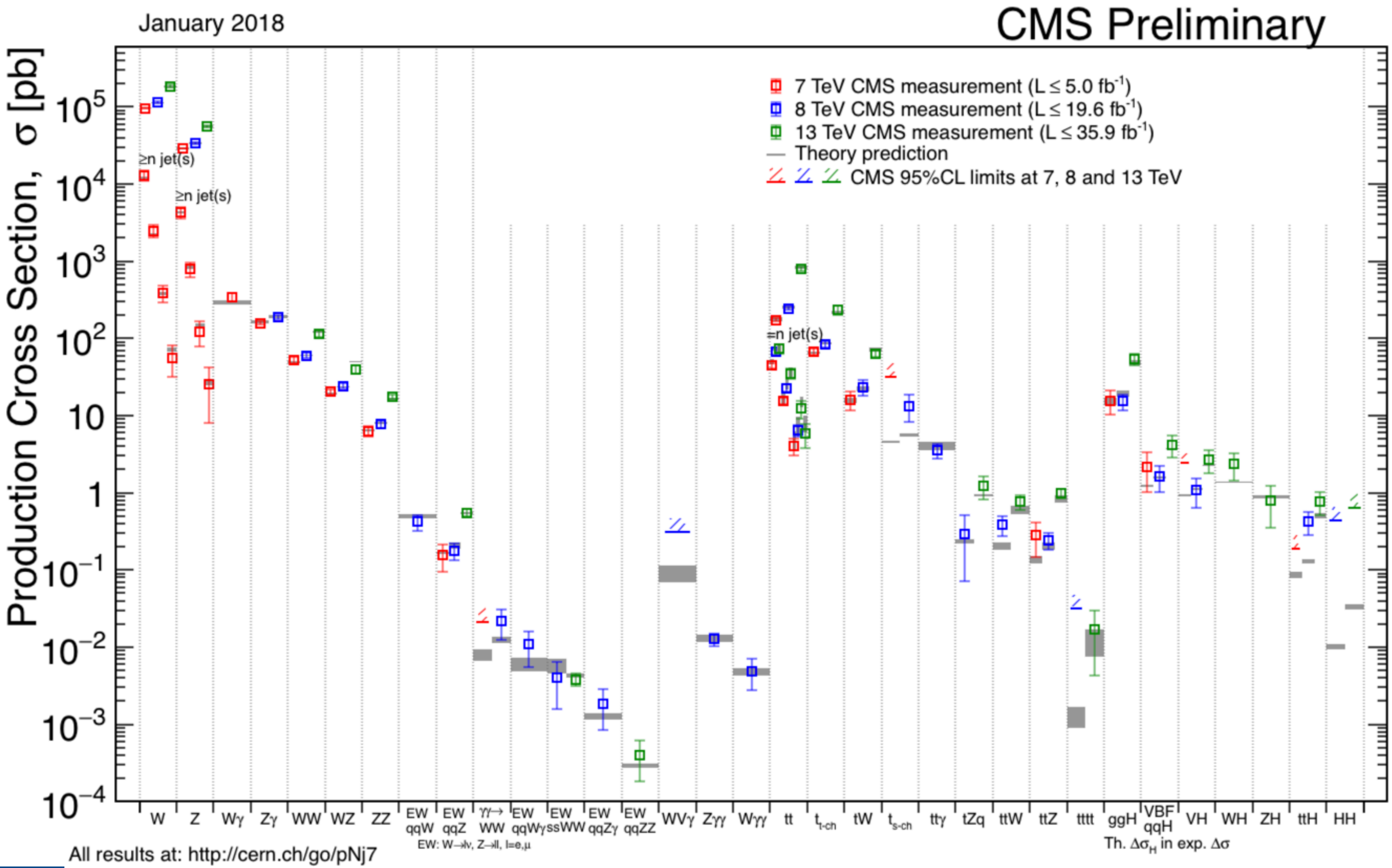
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$

$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H] +$$

$$\frac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$

$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Standard Model at the LHC: orders of magnitude



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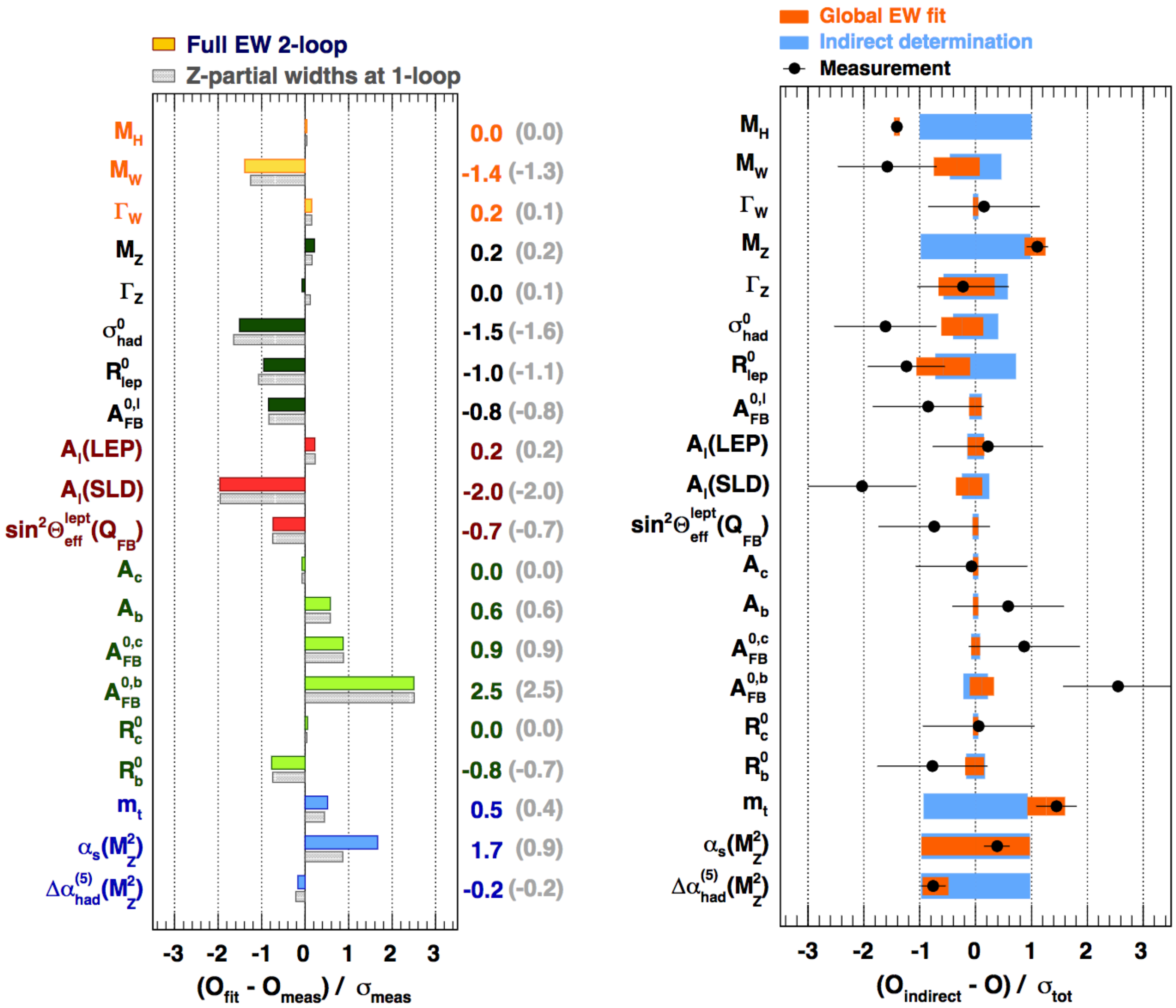
Standard Model (scarily) good at describing everything



See also:
arXiv:1407.3792
(Gfitter group)

Problems with the Standard Model

- Matter vs antimatter asymmetry
  - Standard Model cannot provide enough CP violation to explain dominance of matter
- Dark Matter
  - if it exists, it is very likely not described by the Standard Model
  - Neither is dark energy
- Standard Model neutrinos are massless
  - The 2015 Nobel Prize (Kajita and McDonald) was for neutrino oscillations, directly proving that neutrinos have mass
- Gravity is not included

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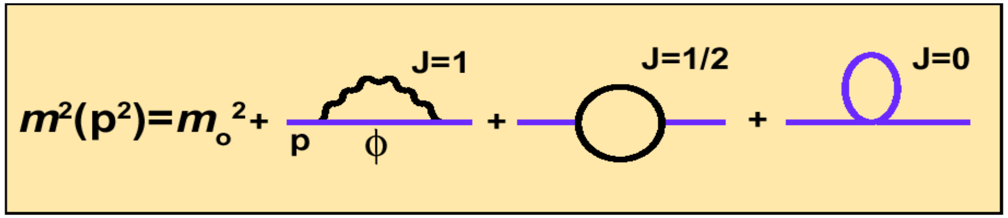
Problems with the Standard Model

- **Foremost: how can the mass of the Higgs boson be anything “small”?**
  - **It should “resist” itself (since it couples to mass, it should couple to itself as well)**
  - **Its mass should be almost infinite!**
- **Quadratic divergence in the Higgs mass**



$$m^2(p^2) = m^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2$$

  - **Why is the Higgs mass so low? What is the mechanism?**
  - **Strong dependence of Physics(Λ_{EWK}) on Physics(Λ_{PL})**
    - **It’s like saying that to describe the Hydrogen atom one needs to know about the quarks inside the proton (not true!)**
    - **Implies extreme fine-tuning (ETF) of parameters**

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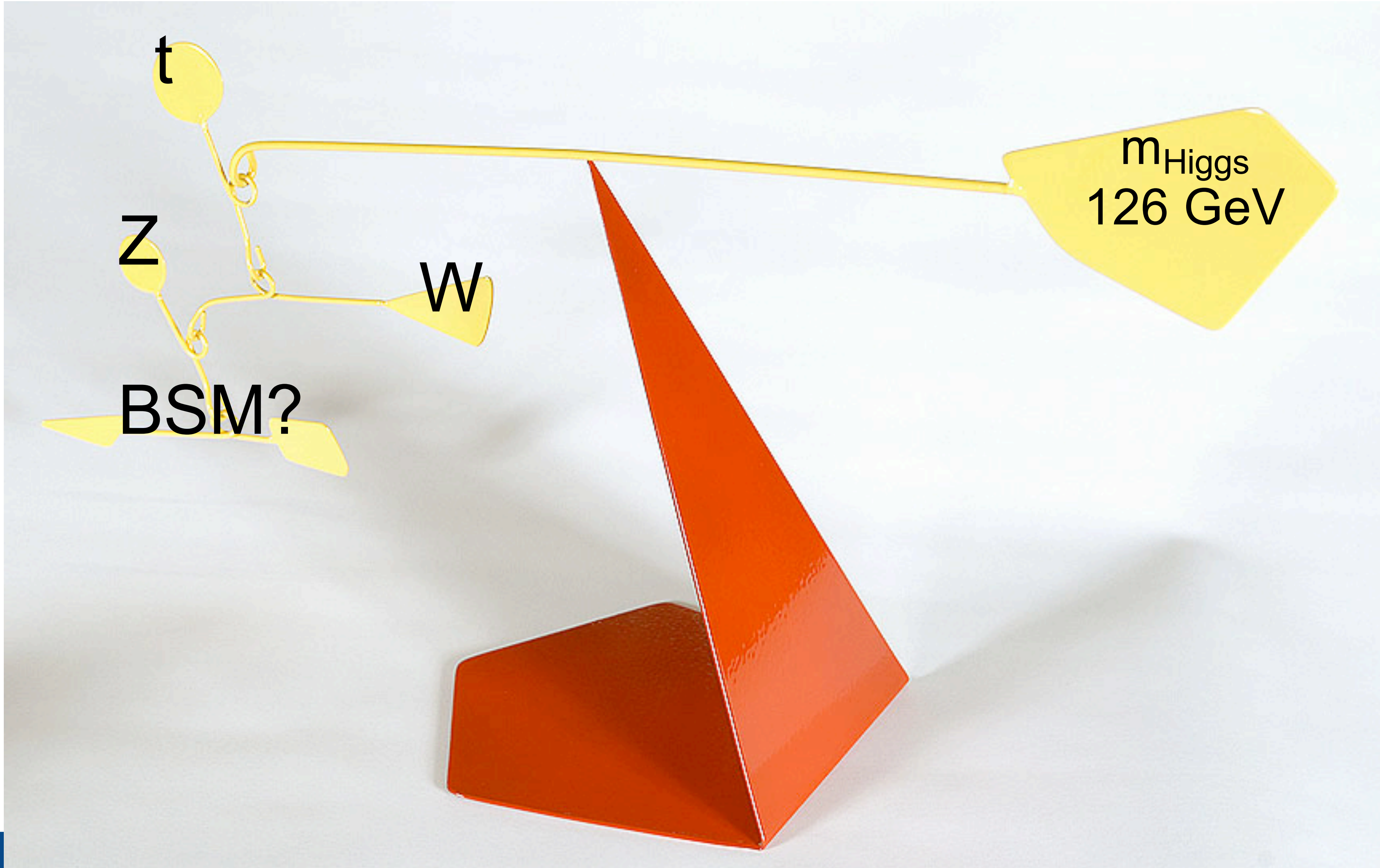
Little Hierarchy problem, Naturalness



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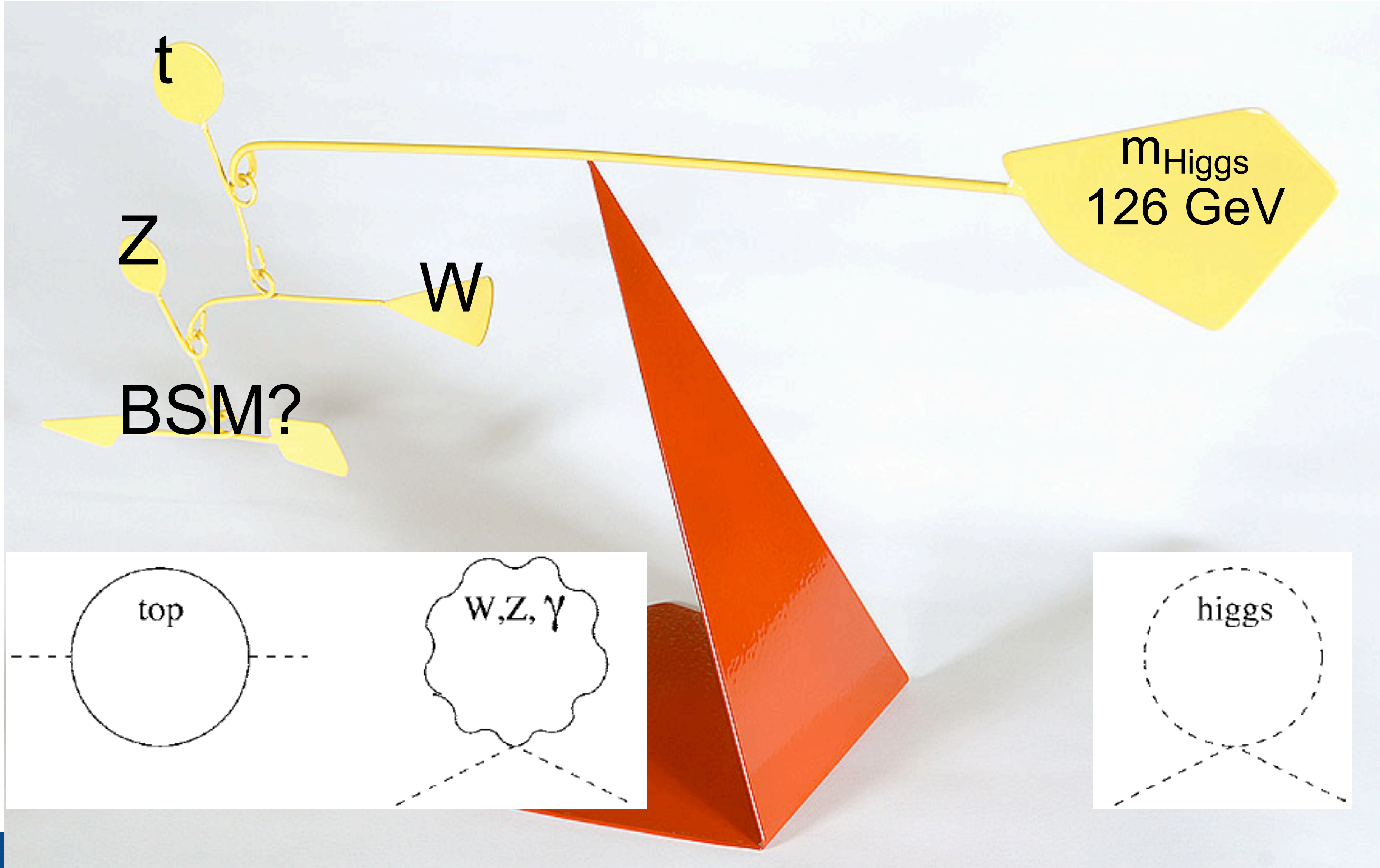
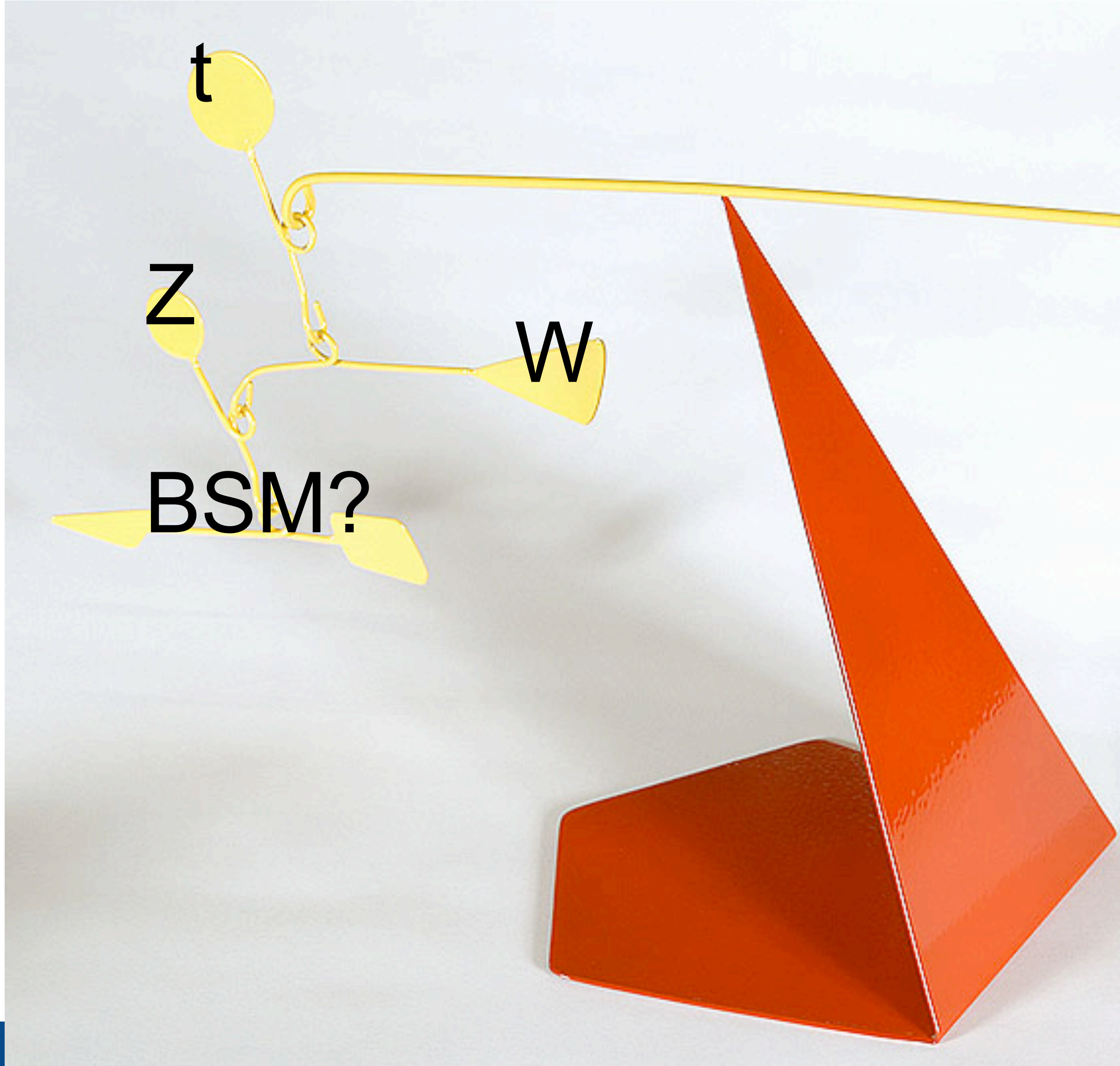
Little Hierarchy problem, Naturalness



Little Hierarchy problem, Naturalness



If fine tuning <=10%:
Restrictions:
Λ_{quarks} ~< 2 TeV
Λ_{gauge} ~< 5 TeV

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17 SM parameters do not constrain creativity

creativity is definitely subject to fashion

- SUSY in all it's variations
    - GMSB
    - MSSM, CMSSM etc
- New strong interactions?
    - Technicolor; excited quarks; compositeness; new "contact" interactions
- Exotica:
    - leptoquarks?
    - New "forces"?
    - New resonances (W-Z-like)
    - More generations?
        - Fourth generation (b'/t')
    - Gravity descending at the TeV scale?
    - New resonances; missing stuff; black holes; SUSY-like signatures [Universal Extra dimensions]
- SUSY-inspired exotica:
    - Long-lived massive (new) particles?
- Some true inspirations: "hidden valleys"?

src: H.Murayama

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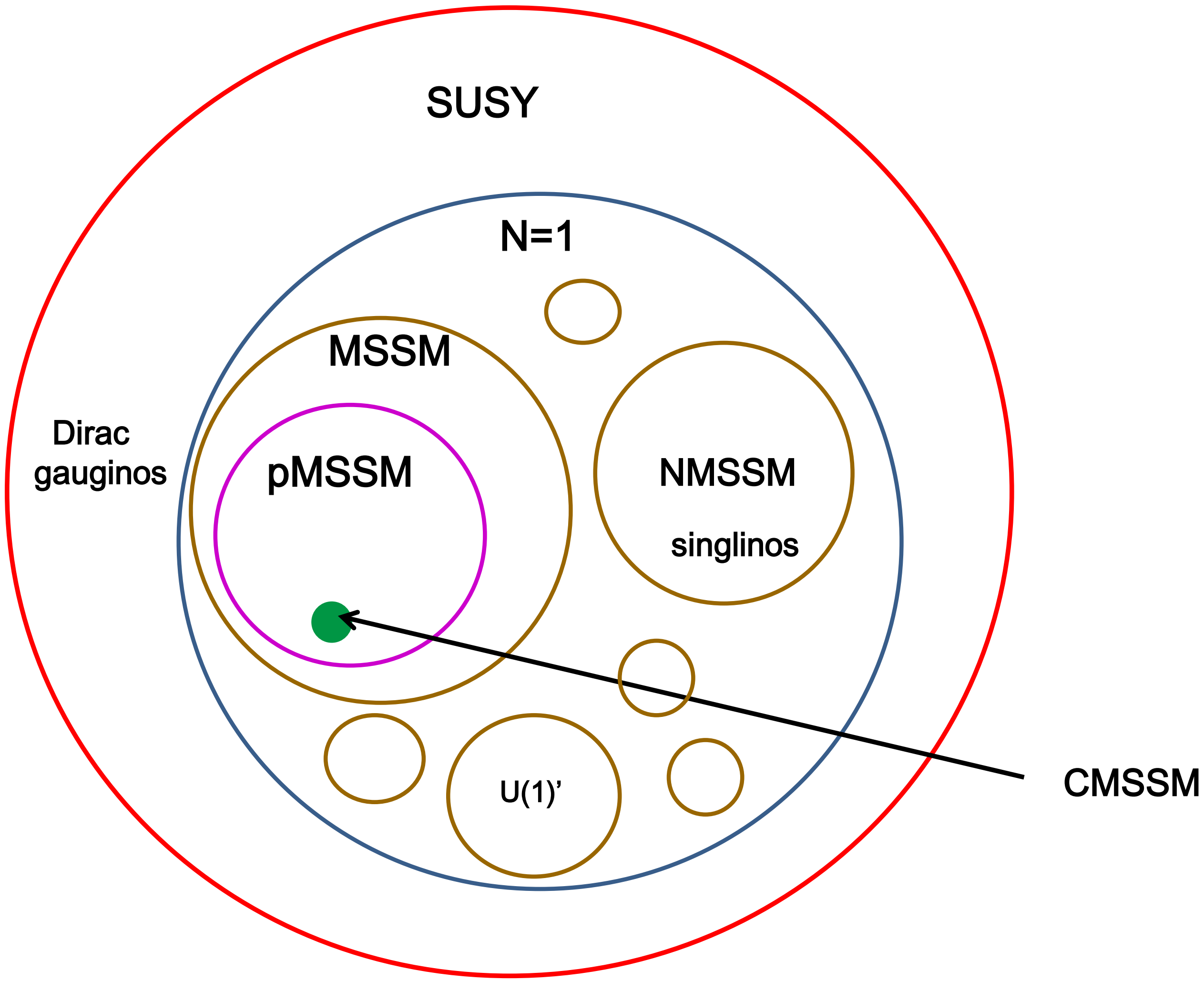
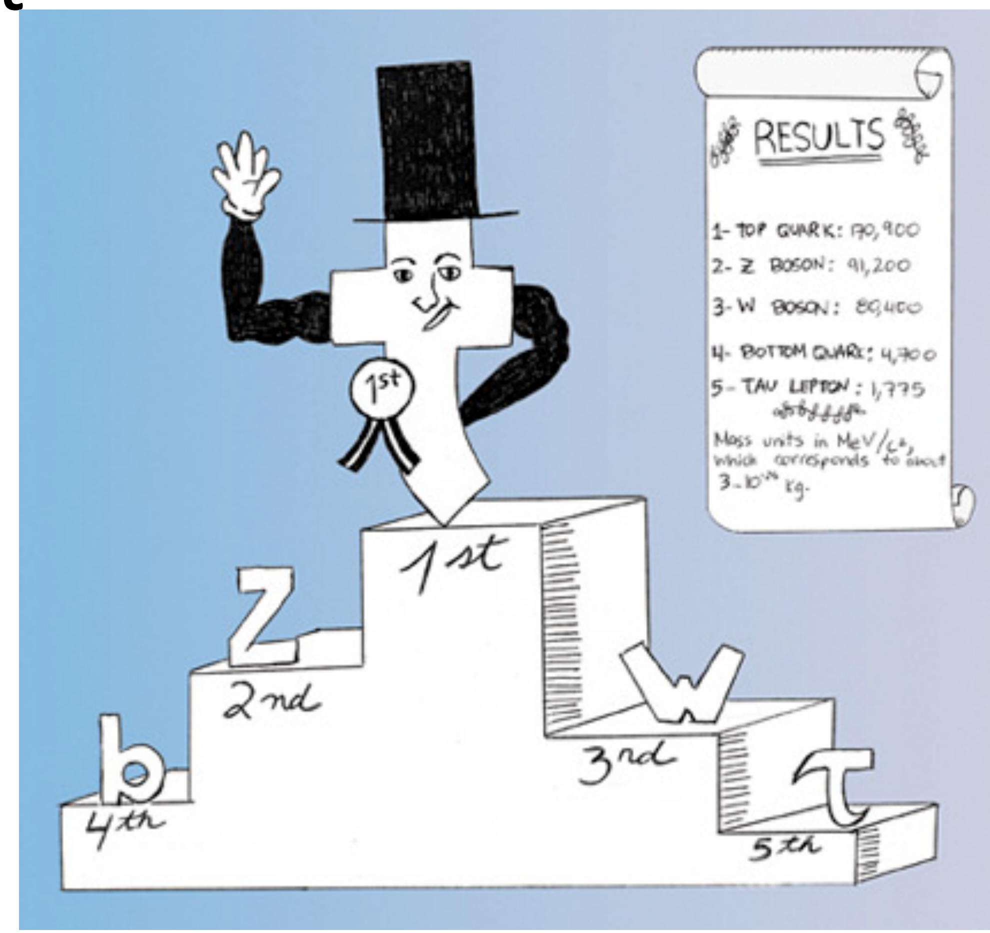
Supersymmetry or SUSY



Top quark – special?

- Many models predict that top is special in order to explain large mass

- Or top quark has special role because of its large mass



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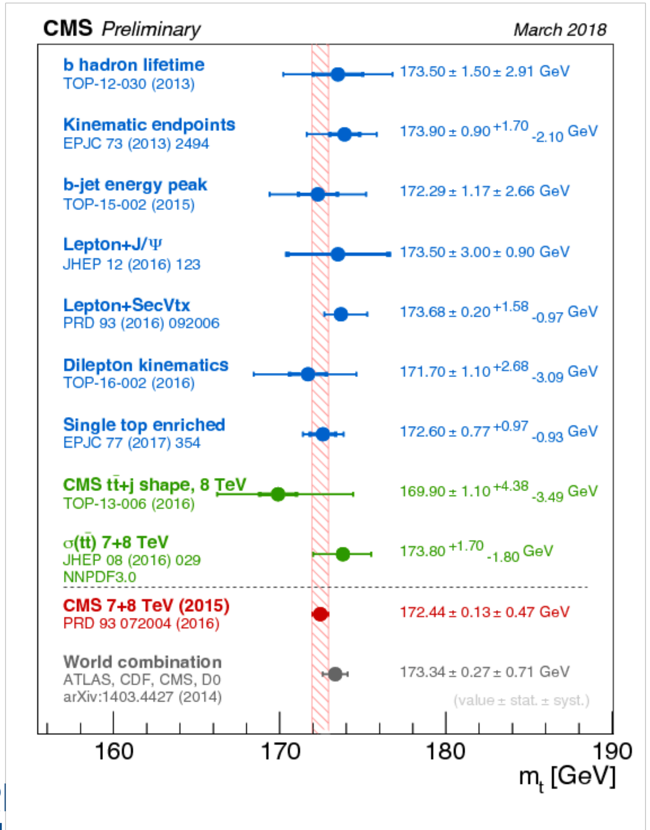
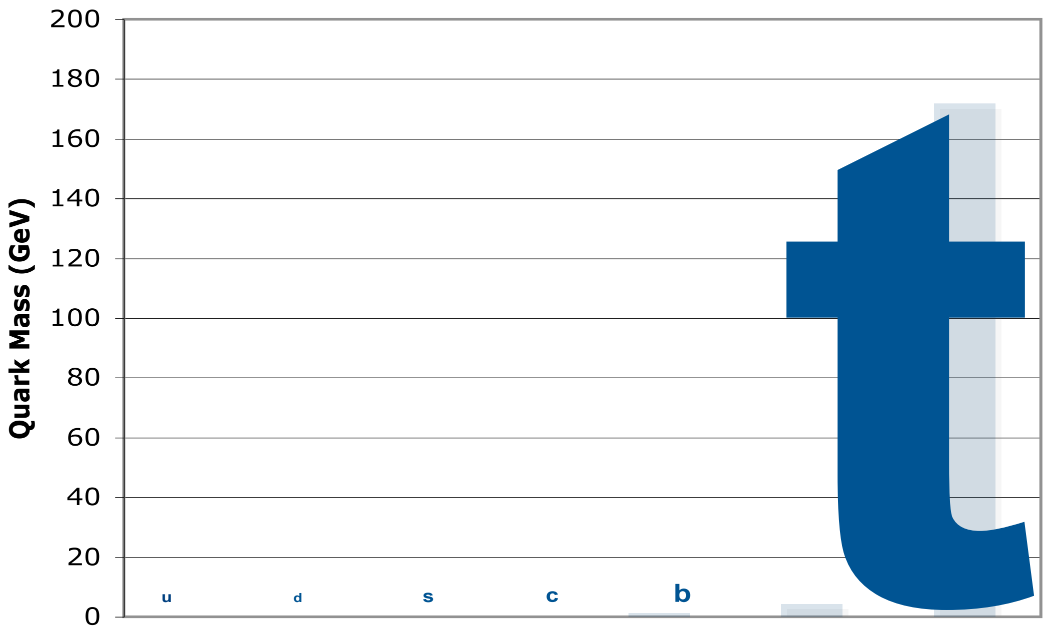
The top quark

- First evidence 1994, CDF
- Discovery by D0 and CDF in 1995
- Heaviest known fundamental particle, $m_t \approx 172.5$ GeV/c^2
- Lifetime ~5×10^{-25} s → no hadronization before decay

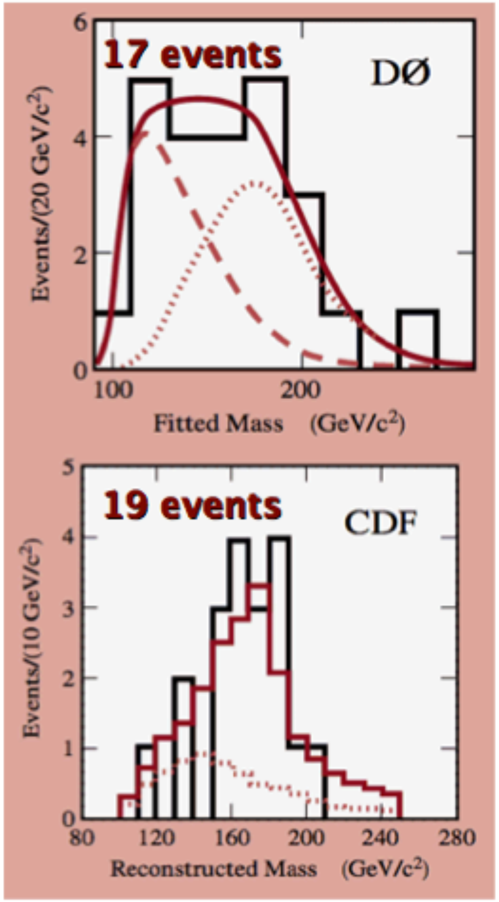




History of the top quark

discovery

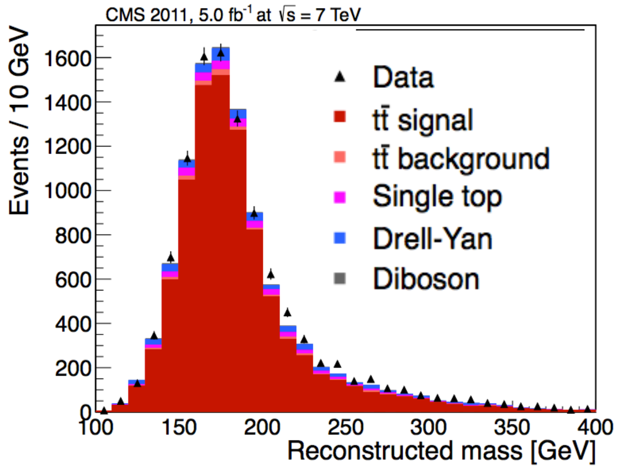
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

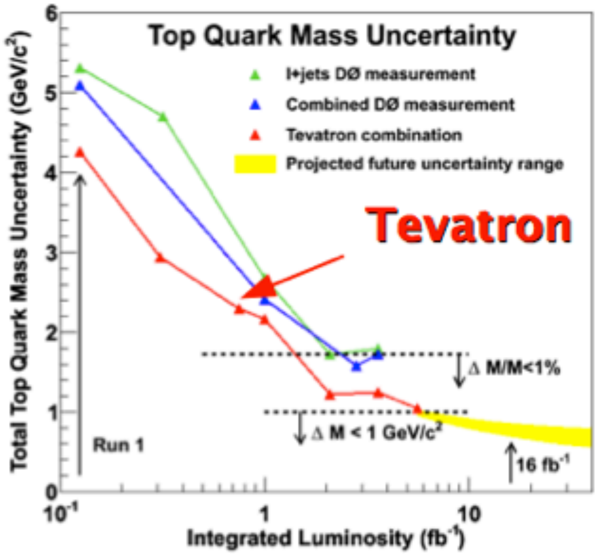
today

10000s of events



LHC: top quark factory

precision



searches

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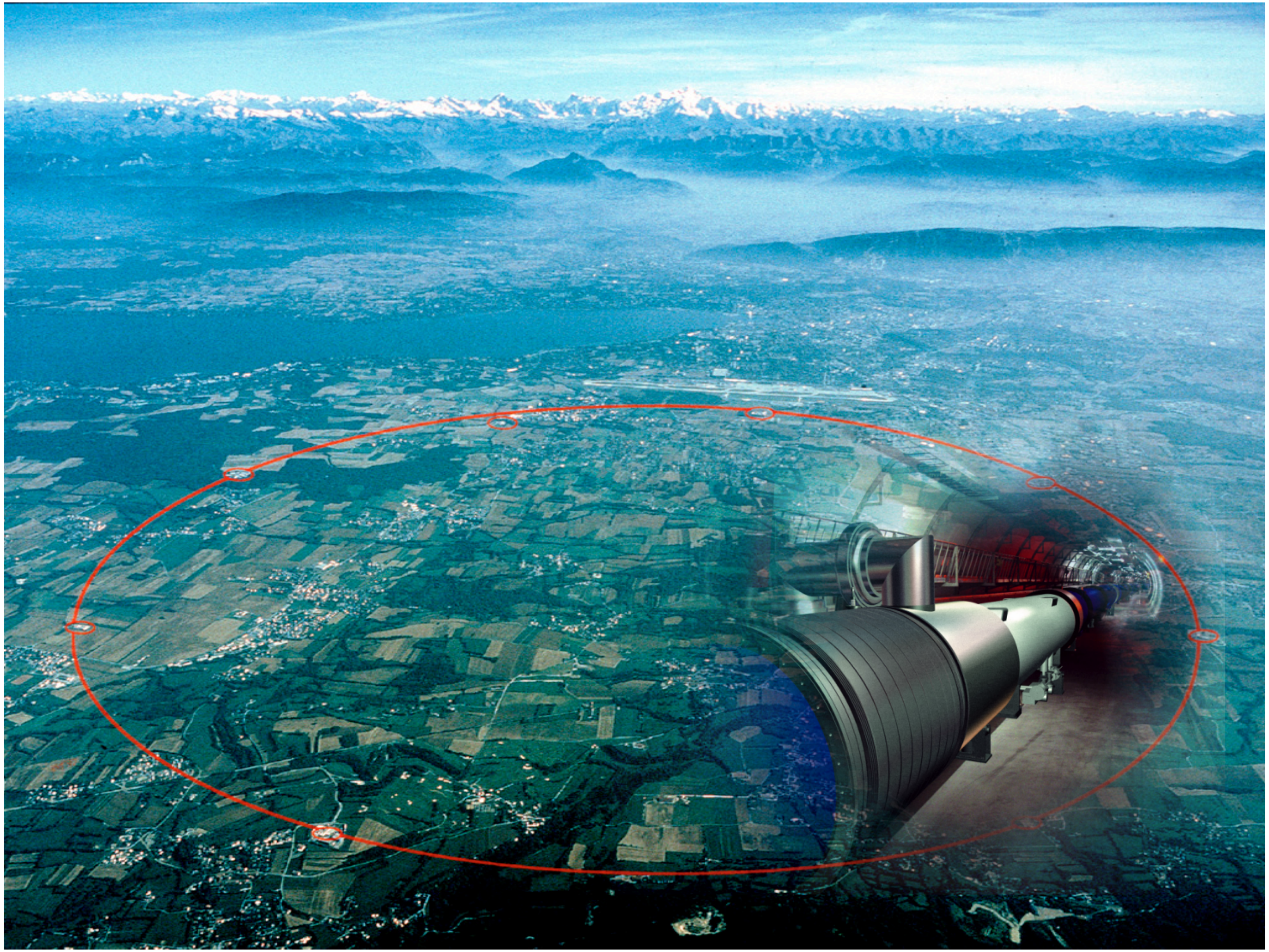
The Large Hadron Collider



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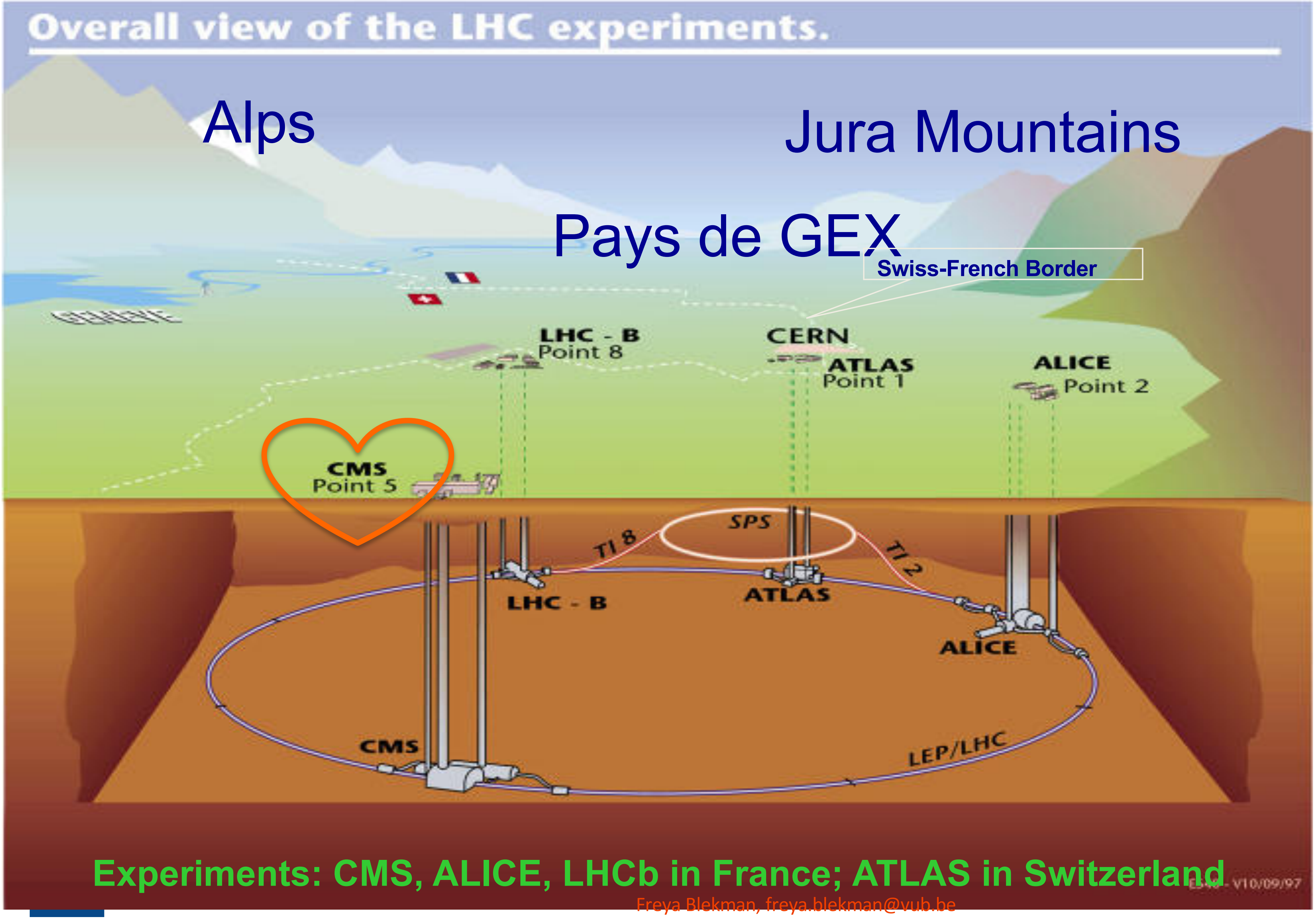
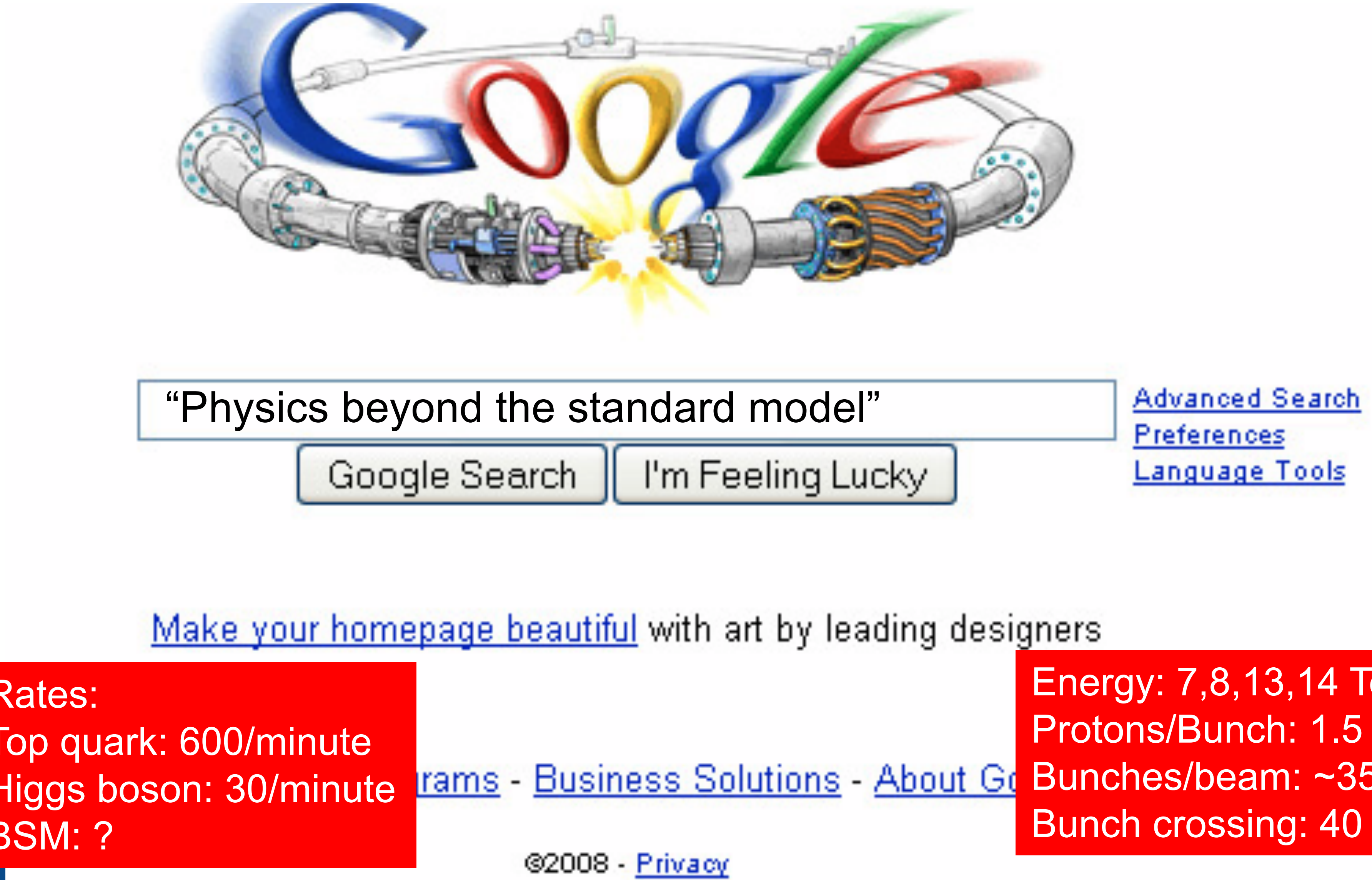


Experiments: CMS, ALICE, LHCb in France; ATLAS in Switzerland

LHC: search engine



Rates:
Top quark: 600/minute
Higgs boson: 30/minute
BSM: ?

Energy: 7,8,13,14 TeV
Protons/Bunch: 1.5 10^{11}
Bunches/beam: ~3500
Bunch crossing: 40 MHz

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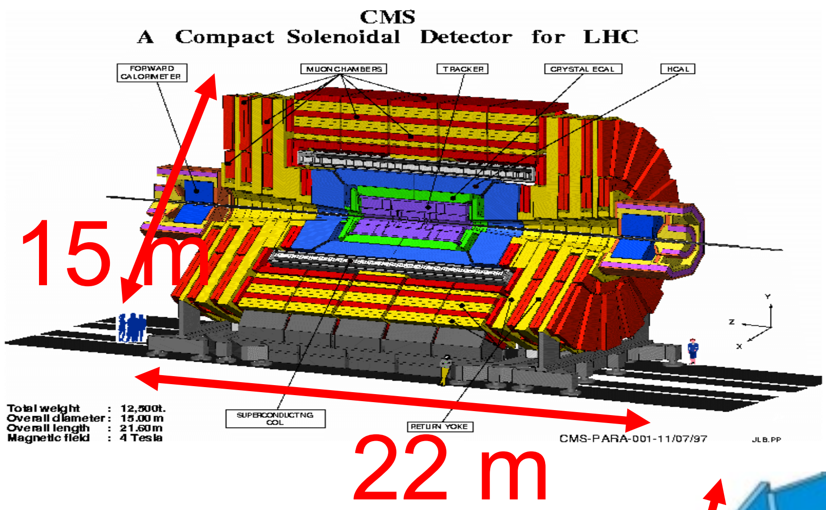
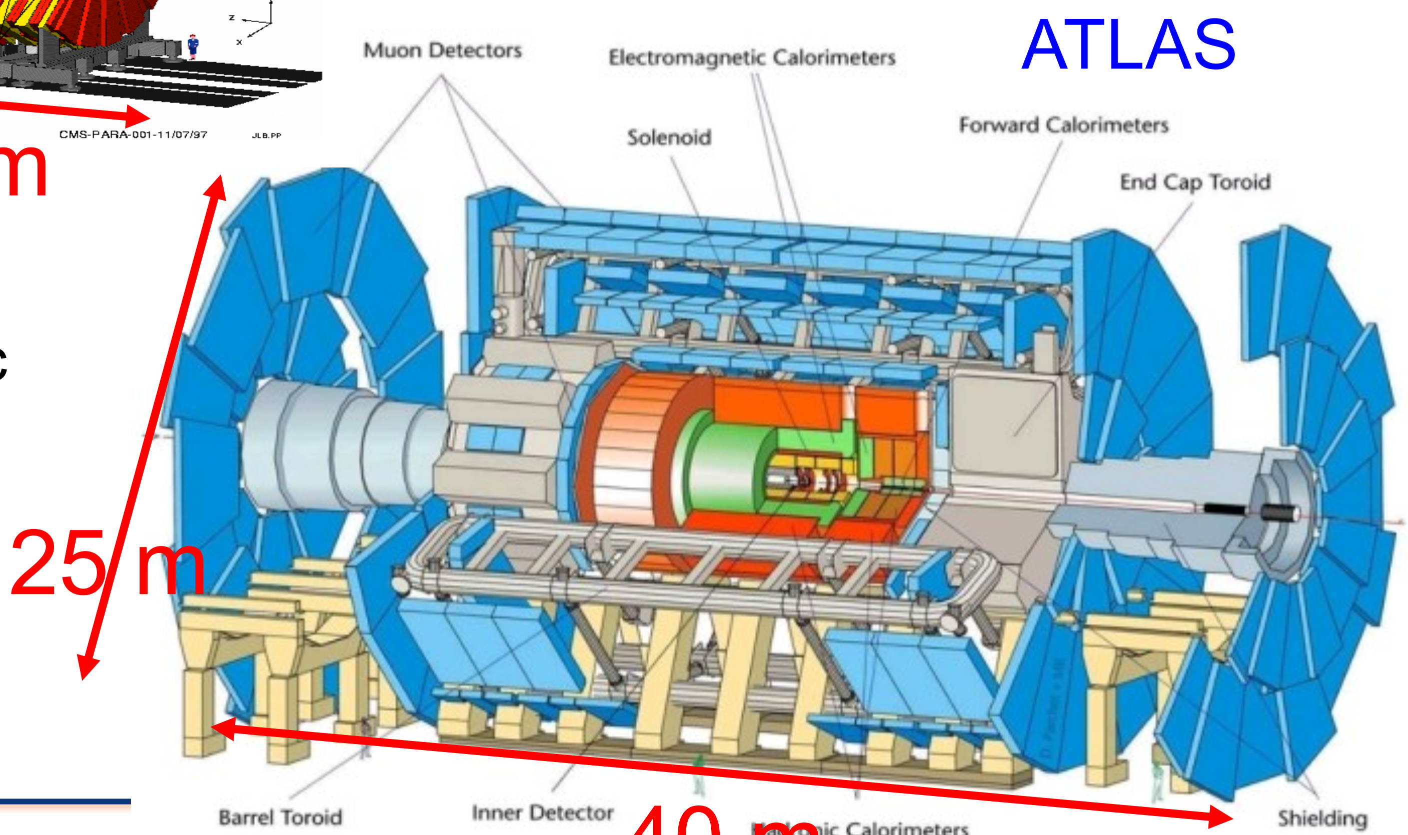
General Purpose Detectors (GPD)

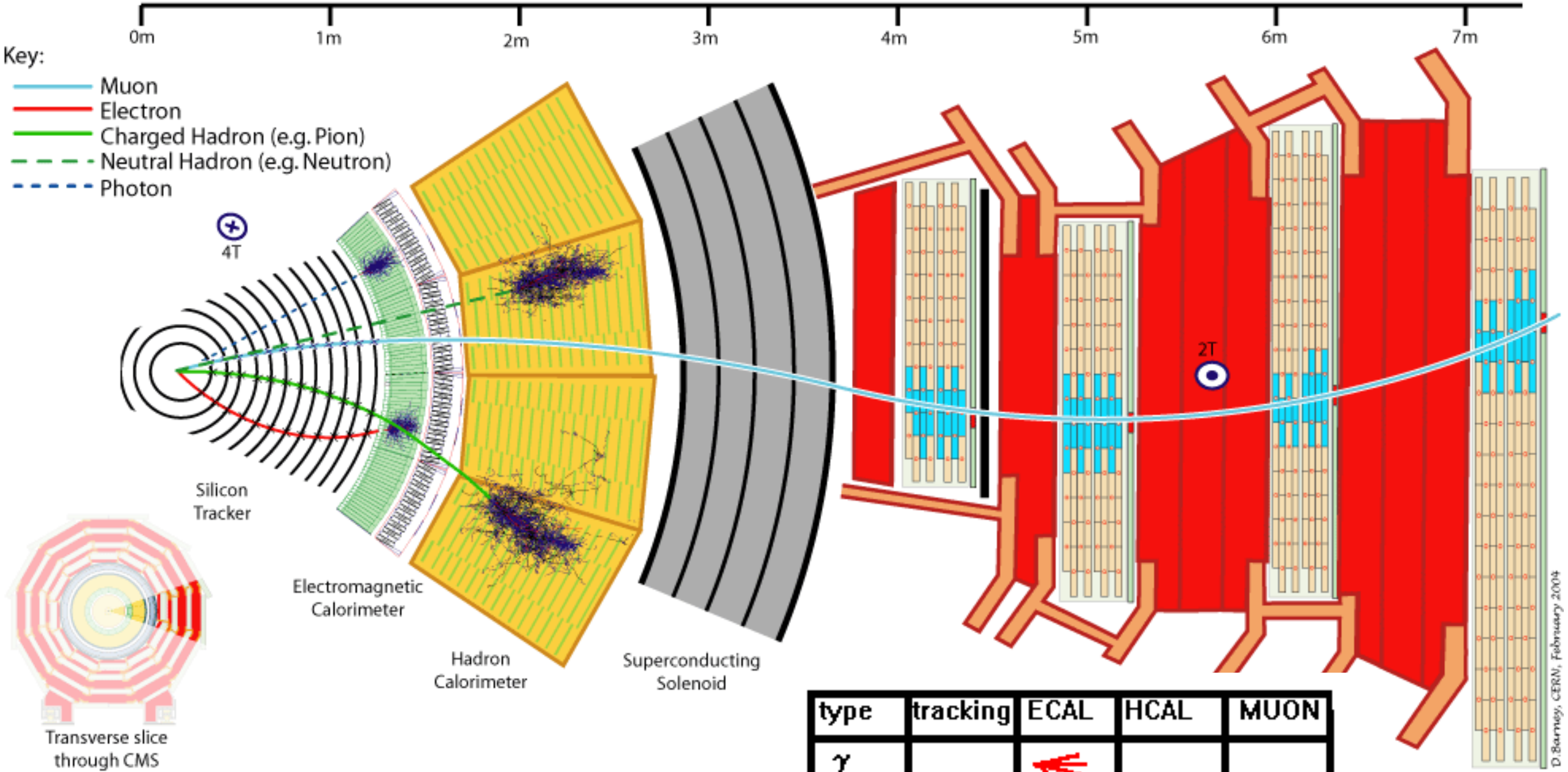


- Compared to the ATLAS experiment CMS is much smaller
- CMS weighs 12,000 tons *vs.* 7,500 tons for ATLAS

- ATLAS has a toroidal magnetic field for their muon system



CMS Slice



type	tracking	ECAL	HCAL	MUON
γ				
e				
μ				
Jet				
Et miss				

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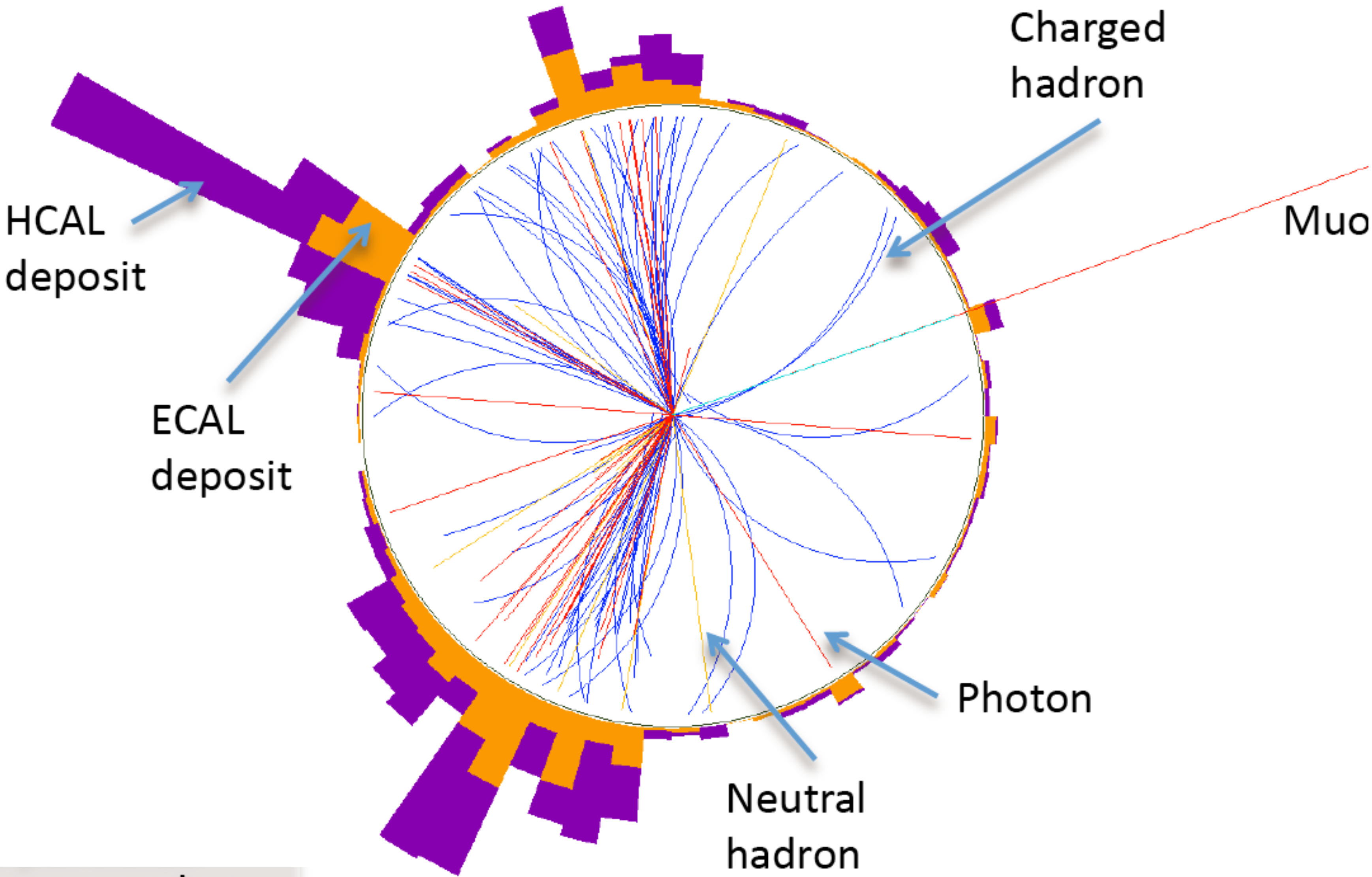
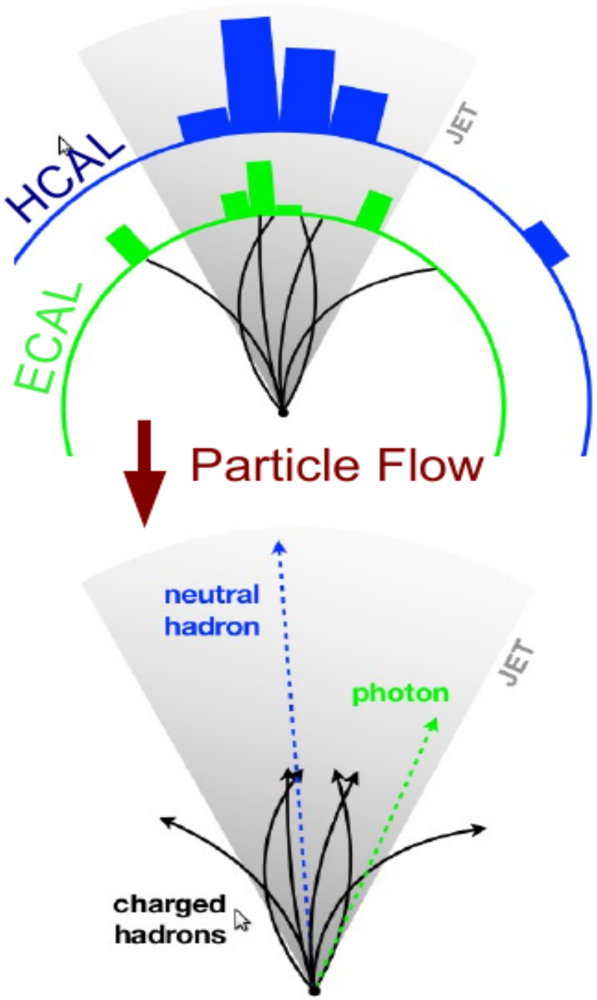
Particle flow



om a generator

Particle flow in practice



- PF combines information from all subdetectors in a global event description
  - reconstruct 'particles' such as charged/neutral hadrons, photons, muons, electrons
- These particles are used to construct composite objects such as jets, taus, missing transverse energy
  - Reject tracks from non-leading collisions before creating composite objects
  - And make assumptions for background from neutral particles
- Widely used in CMS, LHCb
  - CMS: big improvements in energy resolution jets, MET, tau identification,

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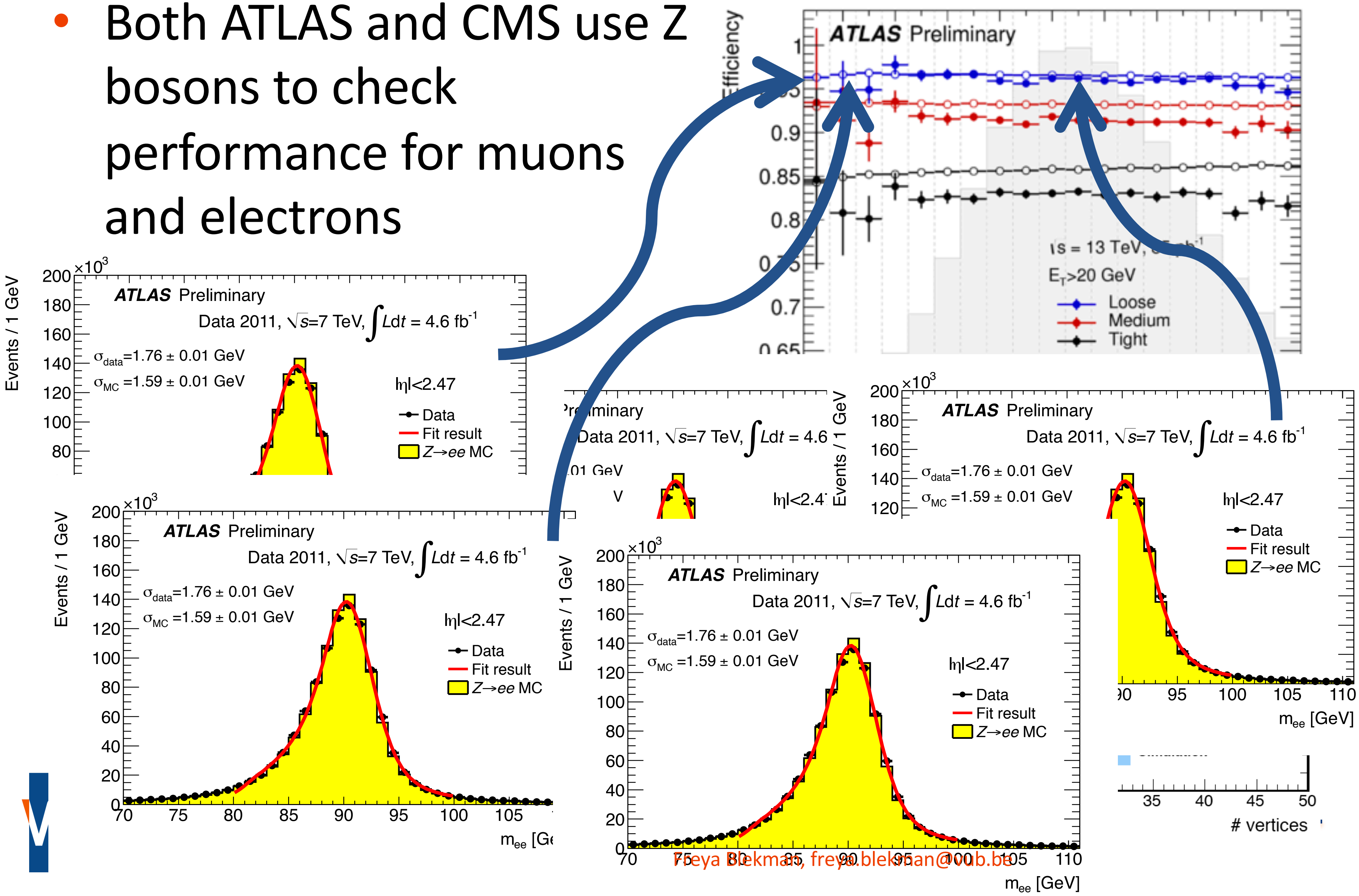
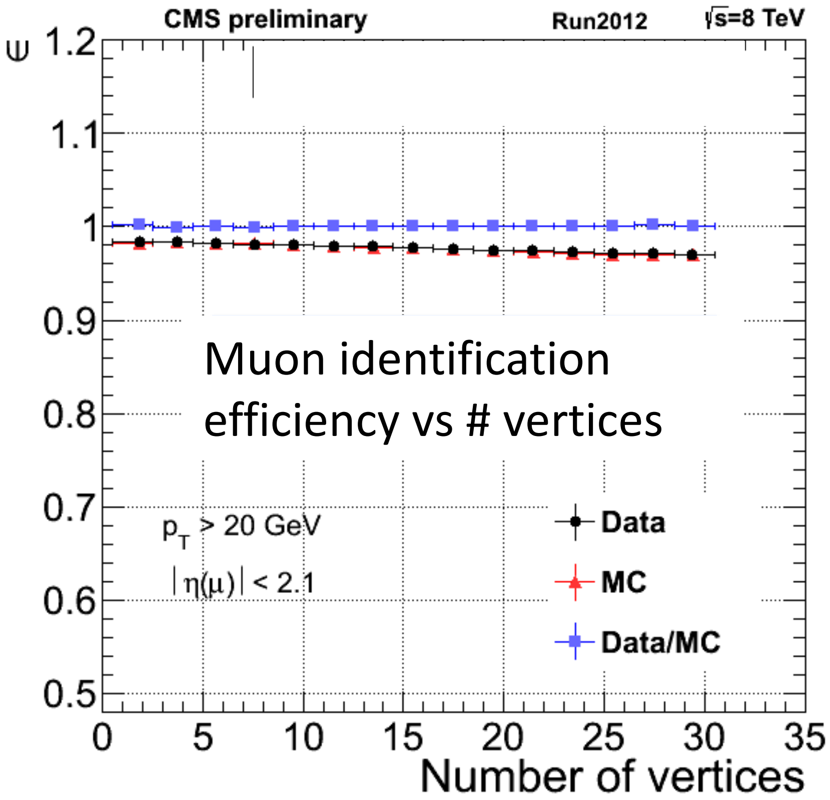
electrons

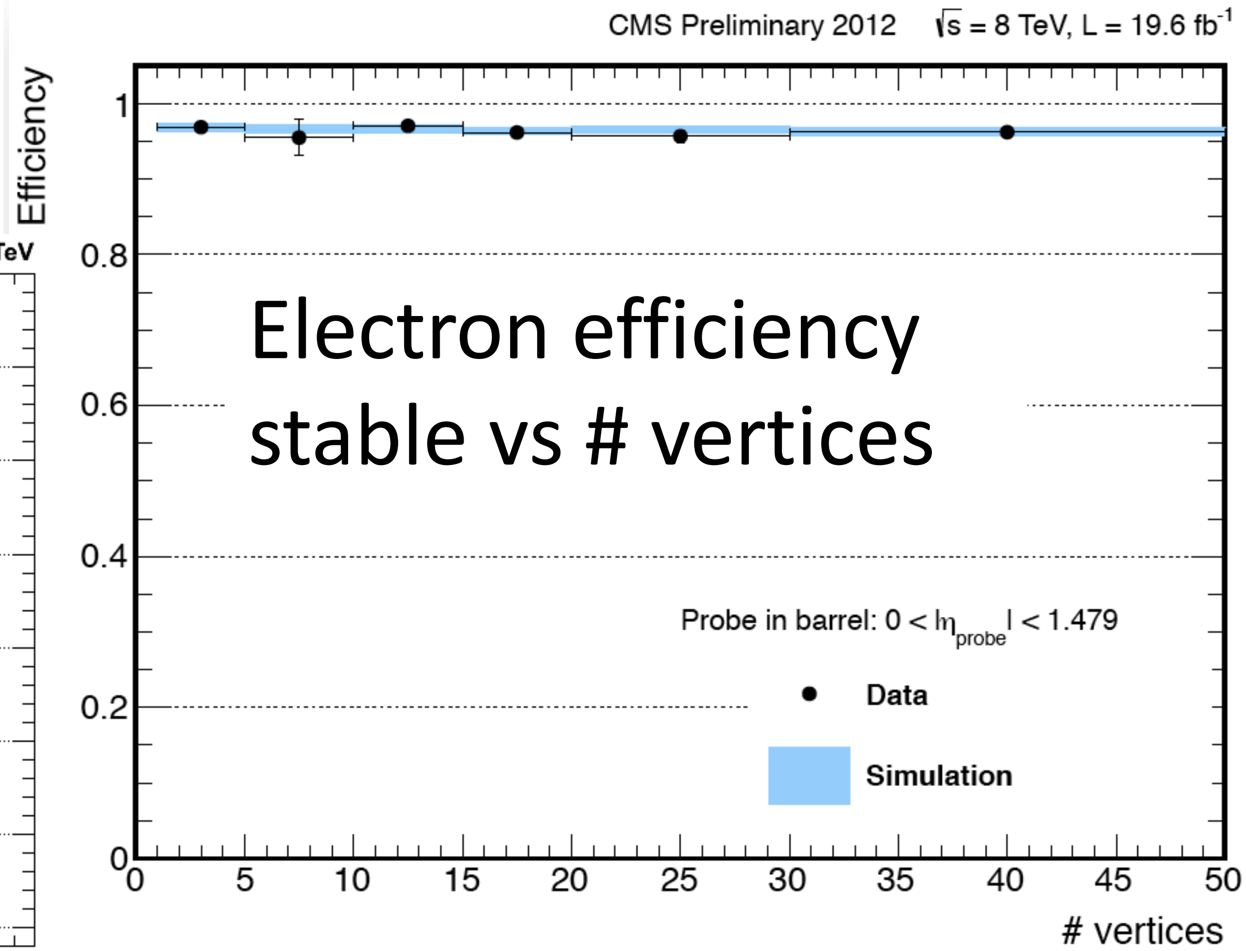
- Both ATLAS and CMS use Z bosons to check performance for muons and electrons



leptons



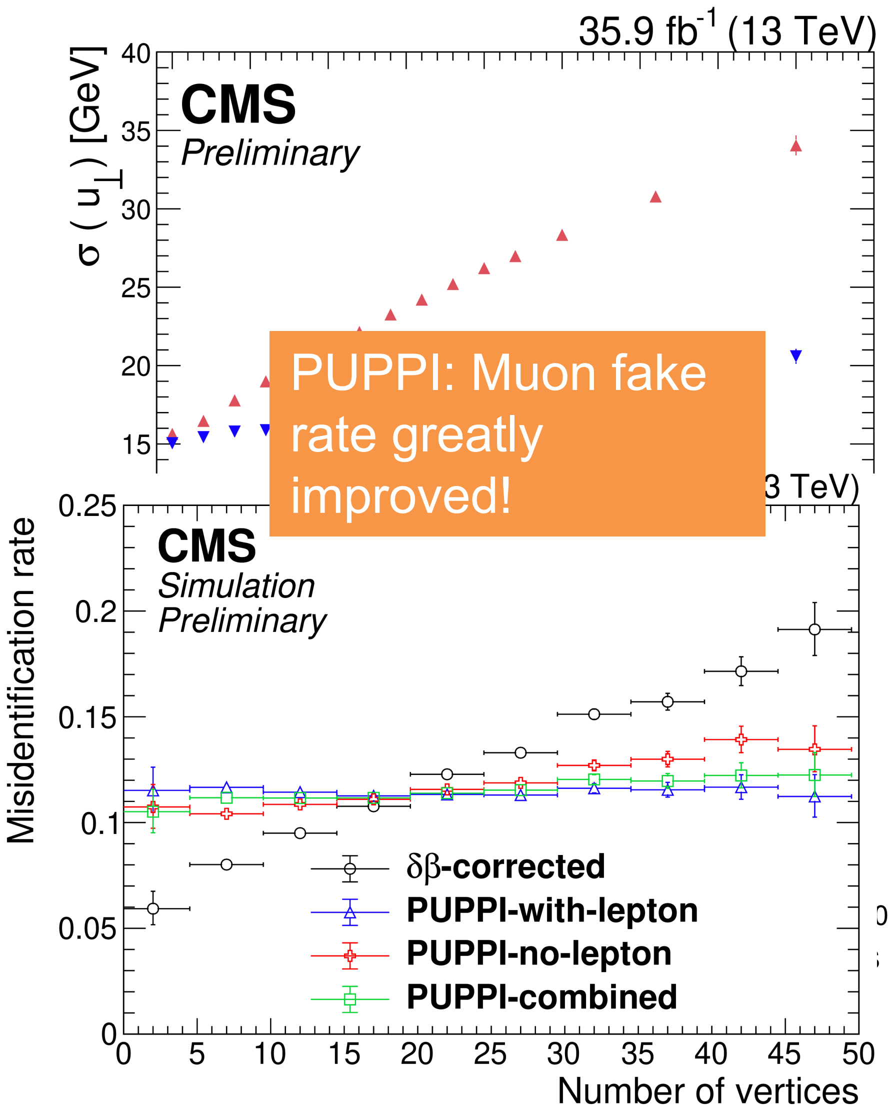
Muon identification efficiency vs # vertices



Electron efficiency stable vs # vertices

- Substantial effort necessary to achieve this stability

Missing ET



- Particle flow extremely powerful approach for missing ET reconstruction
- Missing ET sensitivity to PU irreducible
  - But well reproduced in MC
  - New tricks are appearing, for example PUPPI

Reference: CMS PAS JME-19-001

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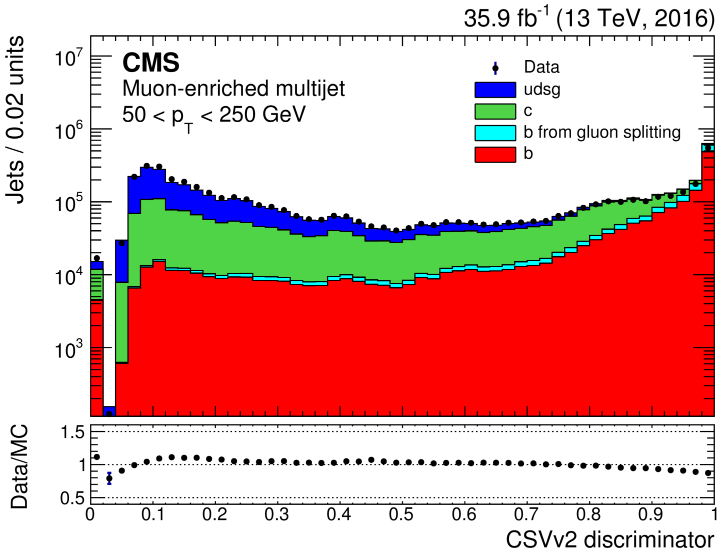
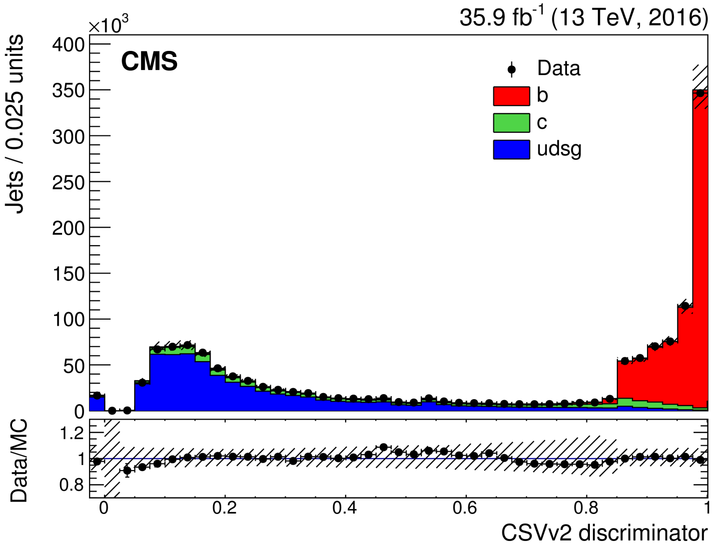
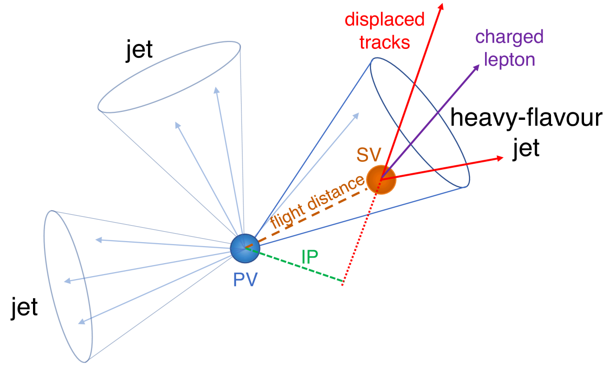
Jets with b-tagging





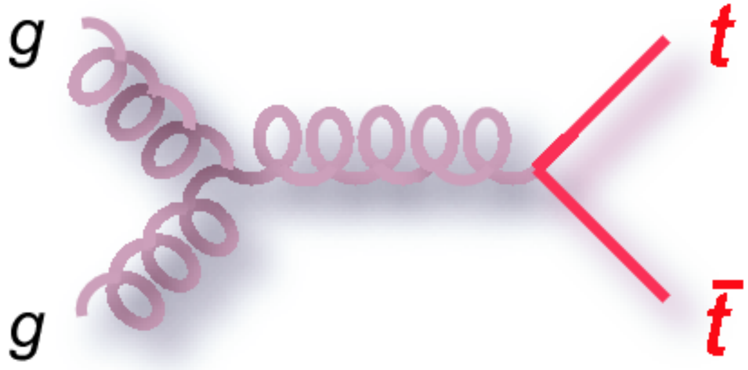


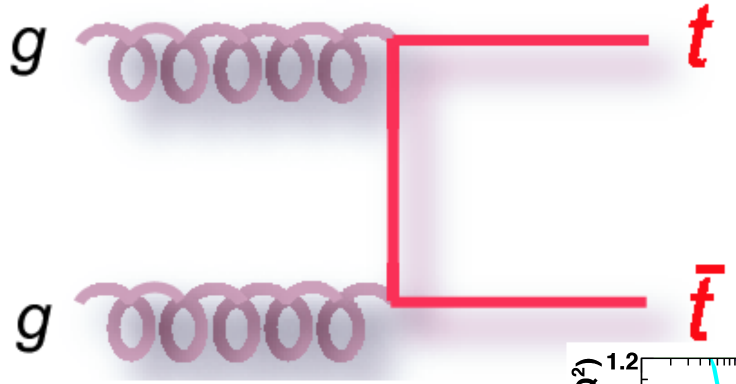
- Long lifetime of b-hadrons in b-jets
  - $\tau = 1.512 \times 10^{-12}$ s
  - $c\tau = 455.4\ \mu m$
- Combination of lifetime information in MVA
- Efficiency measured in top and QCD events (data) using multiple methods

arXiv:1712.07158

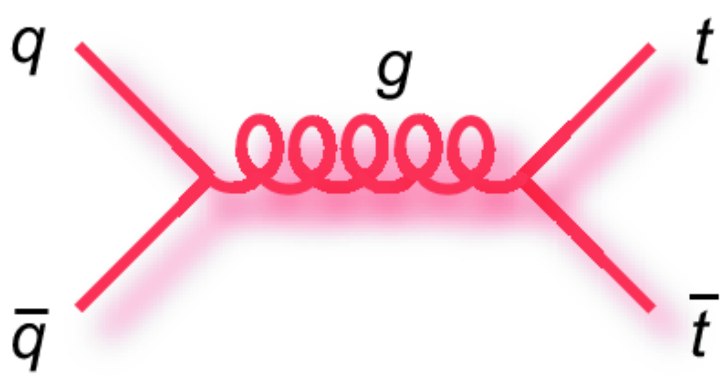
Top pair production at the LHC

- Pair production in 13 TeV pp collisions:

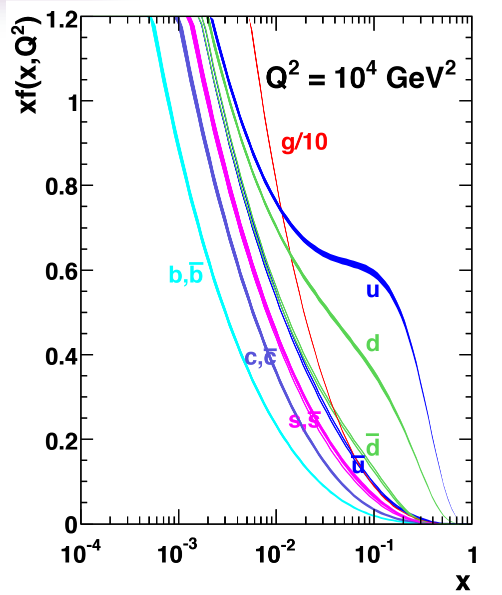




~95%

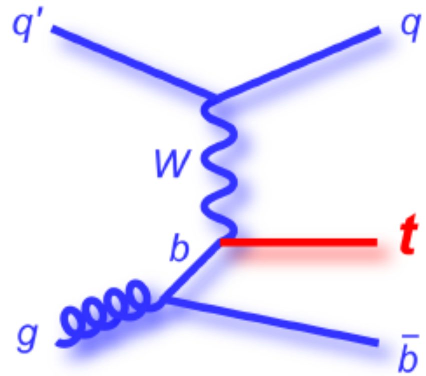


~5%

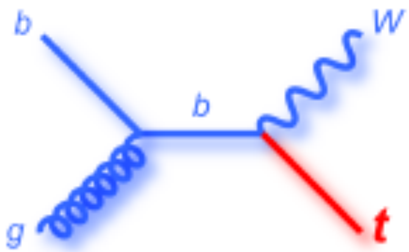


MSTW08:Eur.Phys.J.C63:189-285

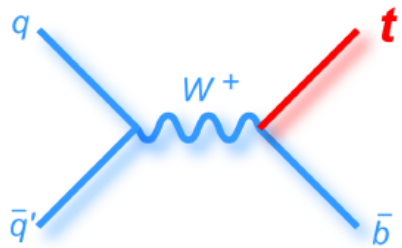
Single Top production



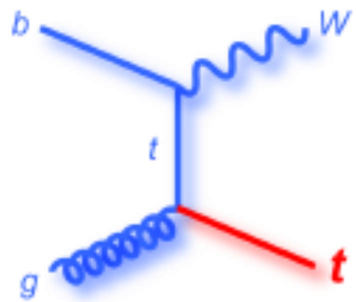
t-channel



tW-channel

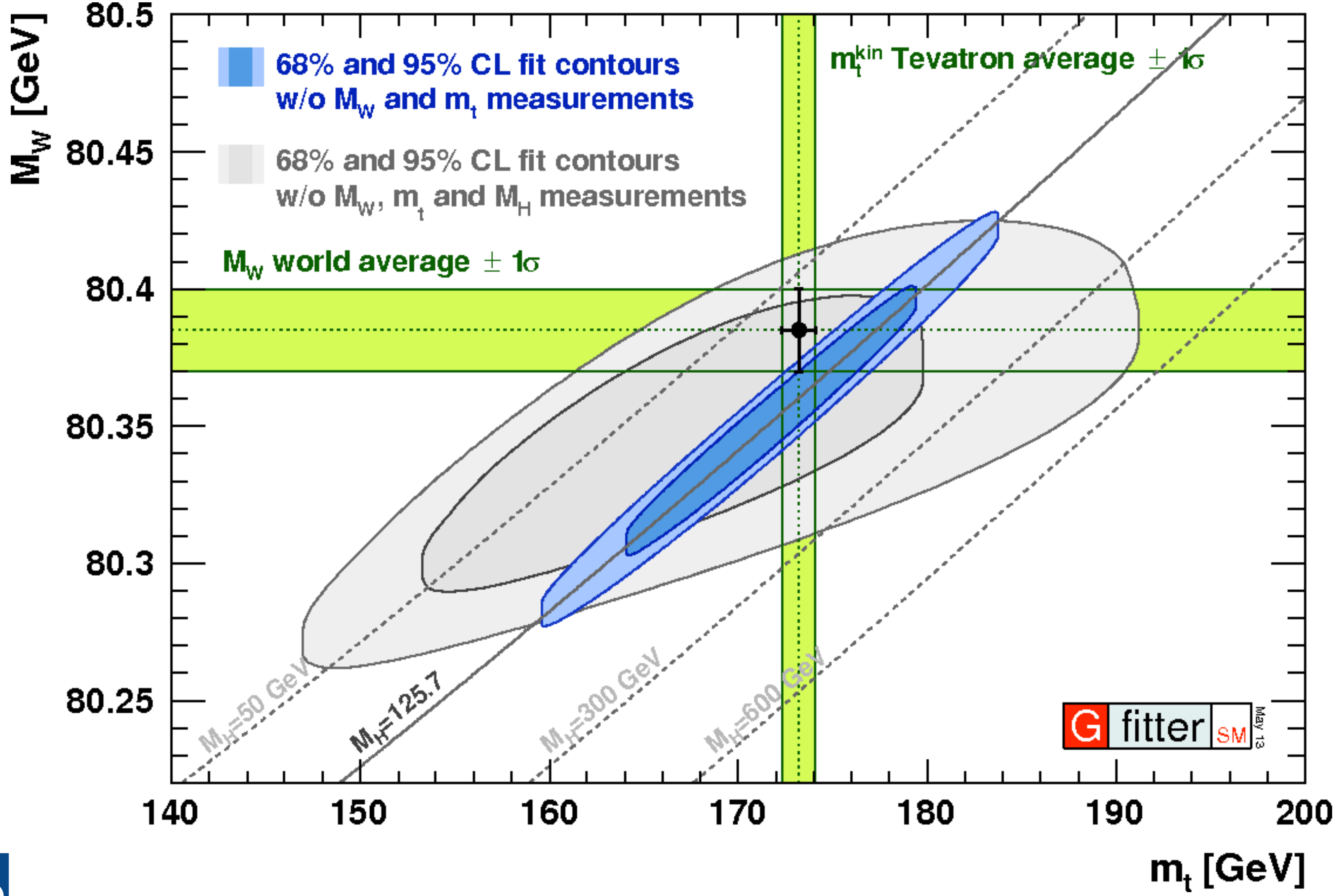


s-channel



- Electroweak production of top quarks
- Dominant channels at LHC @ 13 TeV:
  - t-channel: 217 pb
  - tW channel: 72 pb
  - s-channel: 11 pb

Top quark mass in Standard Model



Top quark and new physics

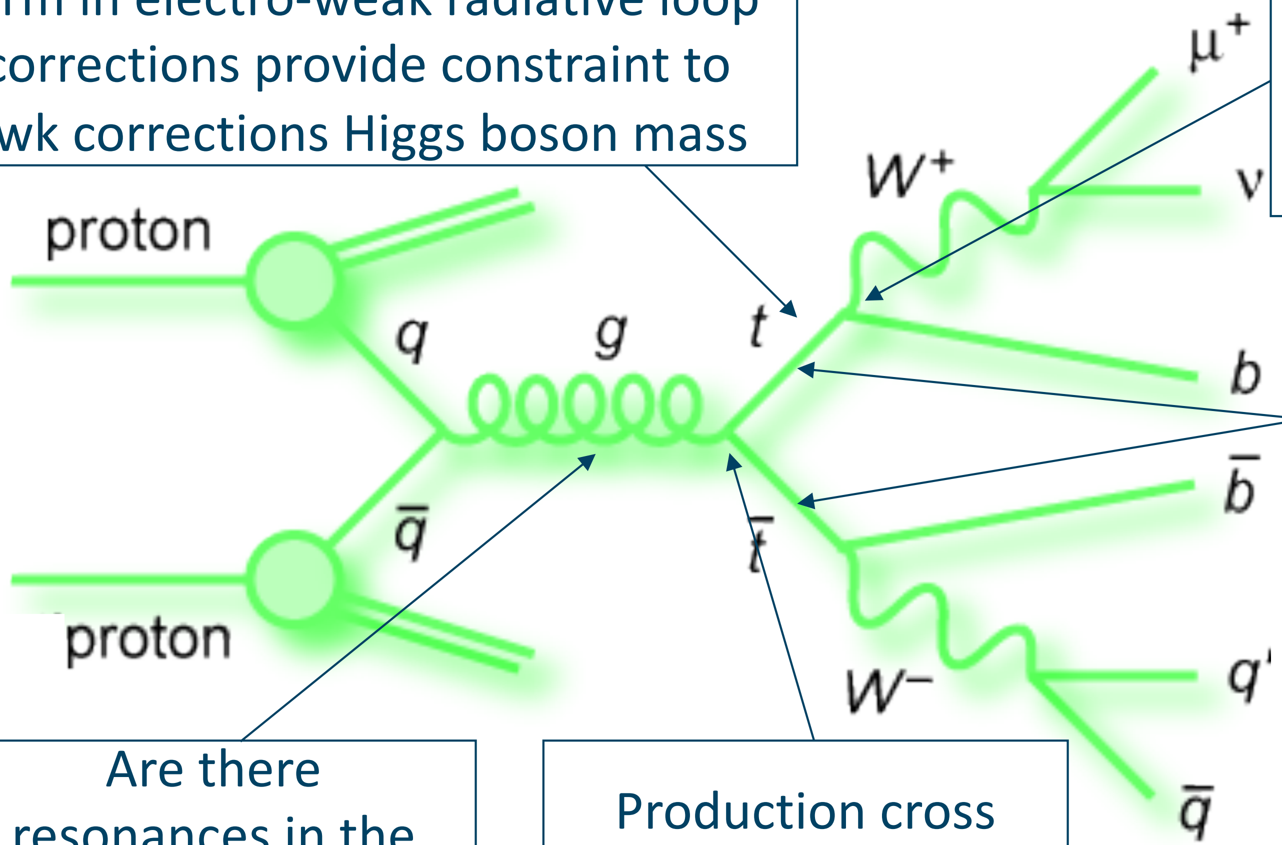
- Standard model predicts top kinematics
- Top physics = SM cross check
- Deviations are signs of new physics
- This new physics is at large mass scales, making it a good candidate to fix the holes in the SM

$$\left(\begin{array}{l}\text{Top pair production rate}\\ \text{Top mass}\\ \text{Single top production rate}\\ B(t\to Wb)\\ |V_{tb}|\\ \text{W helicity}\\ \text{Top polarization}\\ \text{Anomalous couplings}\\ \text{Spin correlations}\\ \text{Rare decays}\\ \text{Top width}\\ \quad\ldots\end{array}\right)$$

Why top physics is interesting?

Measure top quark mass - dominant term in electro-weak radiative loop corrections provide constraint to ewk corrections Higgs boson mass

BR($t \rightarrow Wb$)≈1 in SM. Measurement of V_{tb} is test standard model



Spin of W boson is direct probe of top spin and the only way to measure spin correlations in unbound quarks

Are there resonances in the top quark pair spectrum?

Production cross section can be accurately predicted by QCD calculations

Are there other objects that decay to b quarks and W bosons?

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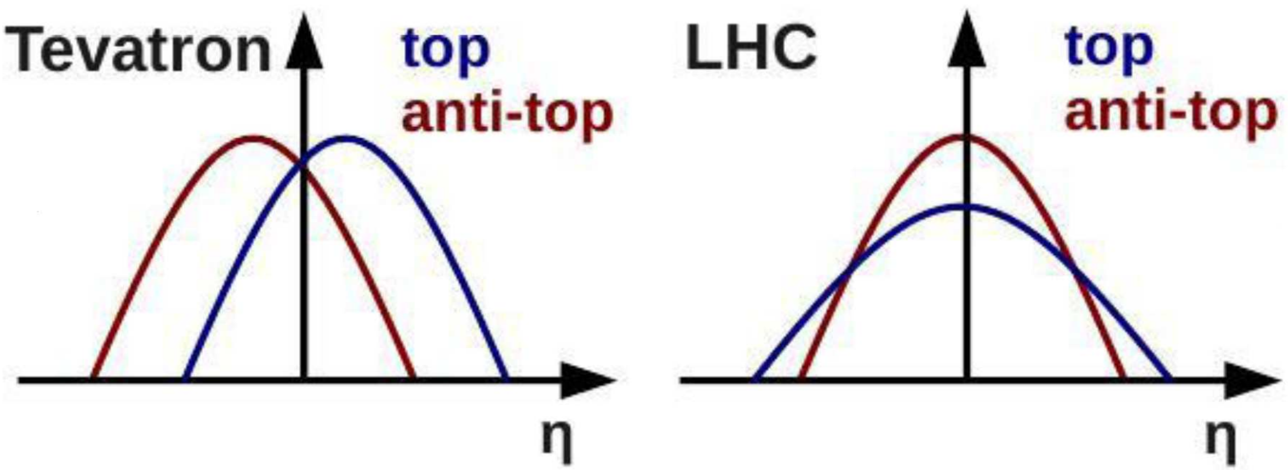
History: Top asymmetries: forward-backward



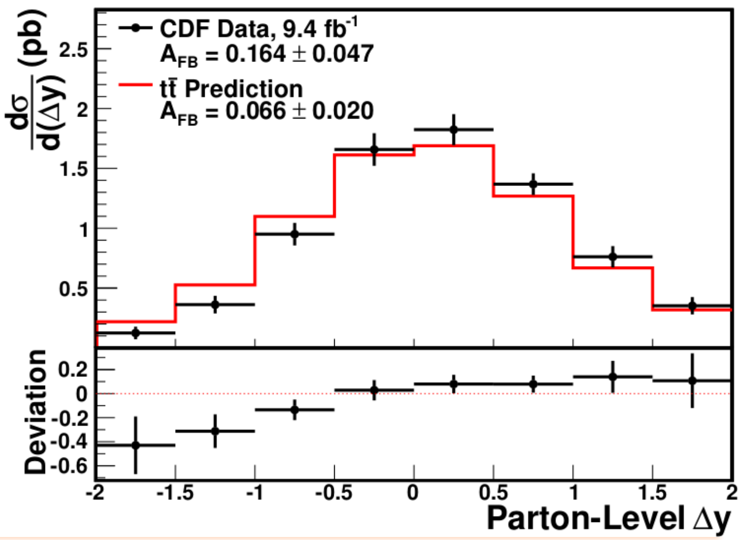
- New physics in production can alter angular distributions

$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

with $\Delta y = y_t - y_{\bar{t}}$

- At Tevatron in 2004-2008:

2.5 S.D. deviation from SM



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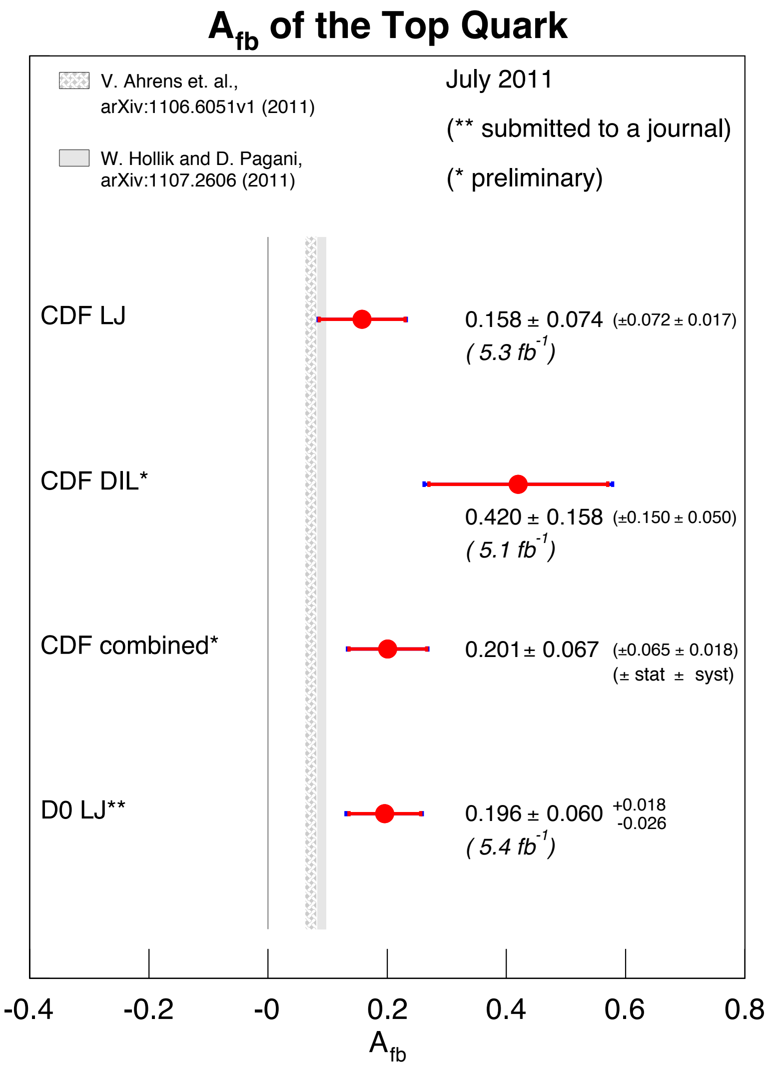
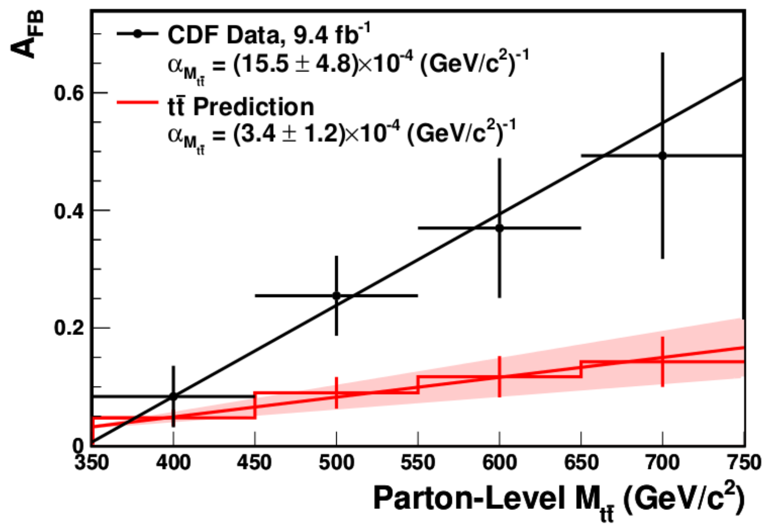
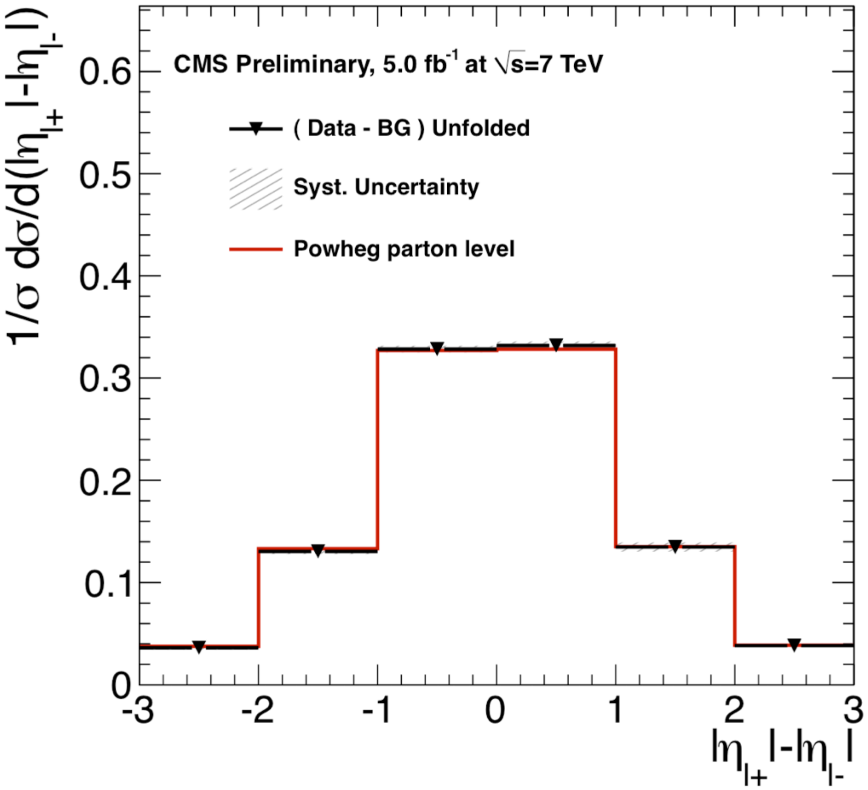
AFB details





- AFB deviations largest at high m(ttbar)
- No effect at the LHC!!!

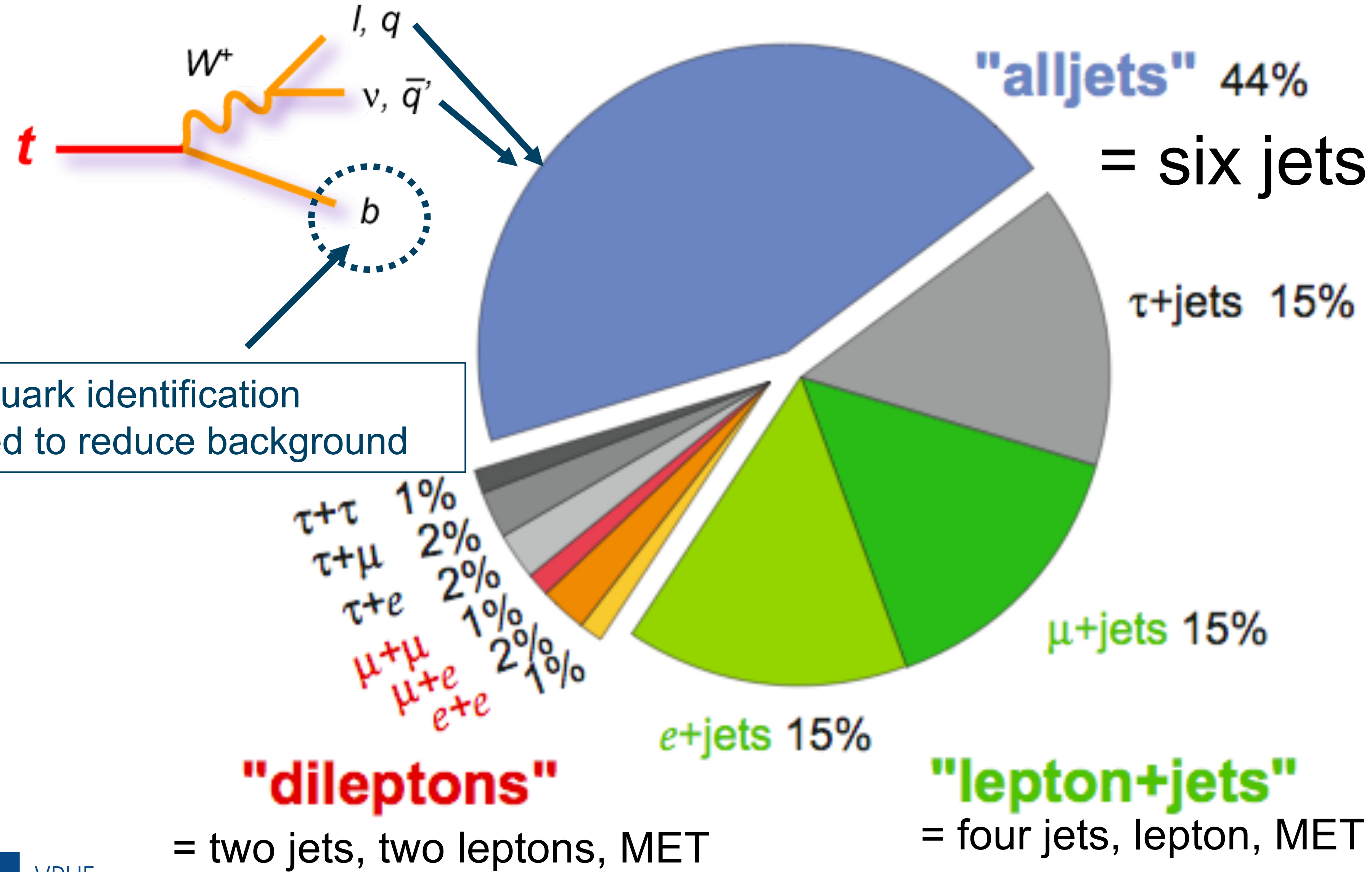
A_{FB} – portal to new physics?



CDF and D0 measured values not consistent with Standard Model

- Depending on how you calculate it: 2.5 to 4.0 sigma from SM
- In multiple decay channels and across multiple experiments
  - Compelling to explain as new physics?
  - History lesson: No BSM, ☹ just not enough orders in SM theory prediction!

Top pair branching fractions



B-quark identification
used to reduce background

Top physics: decay channel choice

- Difficulty of isolation of top quark events inversely proportional to the complexity of the mass reconstruction

	Isolation signal	Reconstruction
Di-lepton	Relatively easy	Two neutrinos, ambiguities
Lepton+jets	Reasonable	One neutrino, use missing transverse energy
All-hadronic	Very difficult	Possibility to observe top as 'peak' in invariant mass spectrum, no energetic neutrinos

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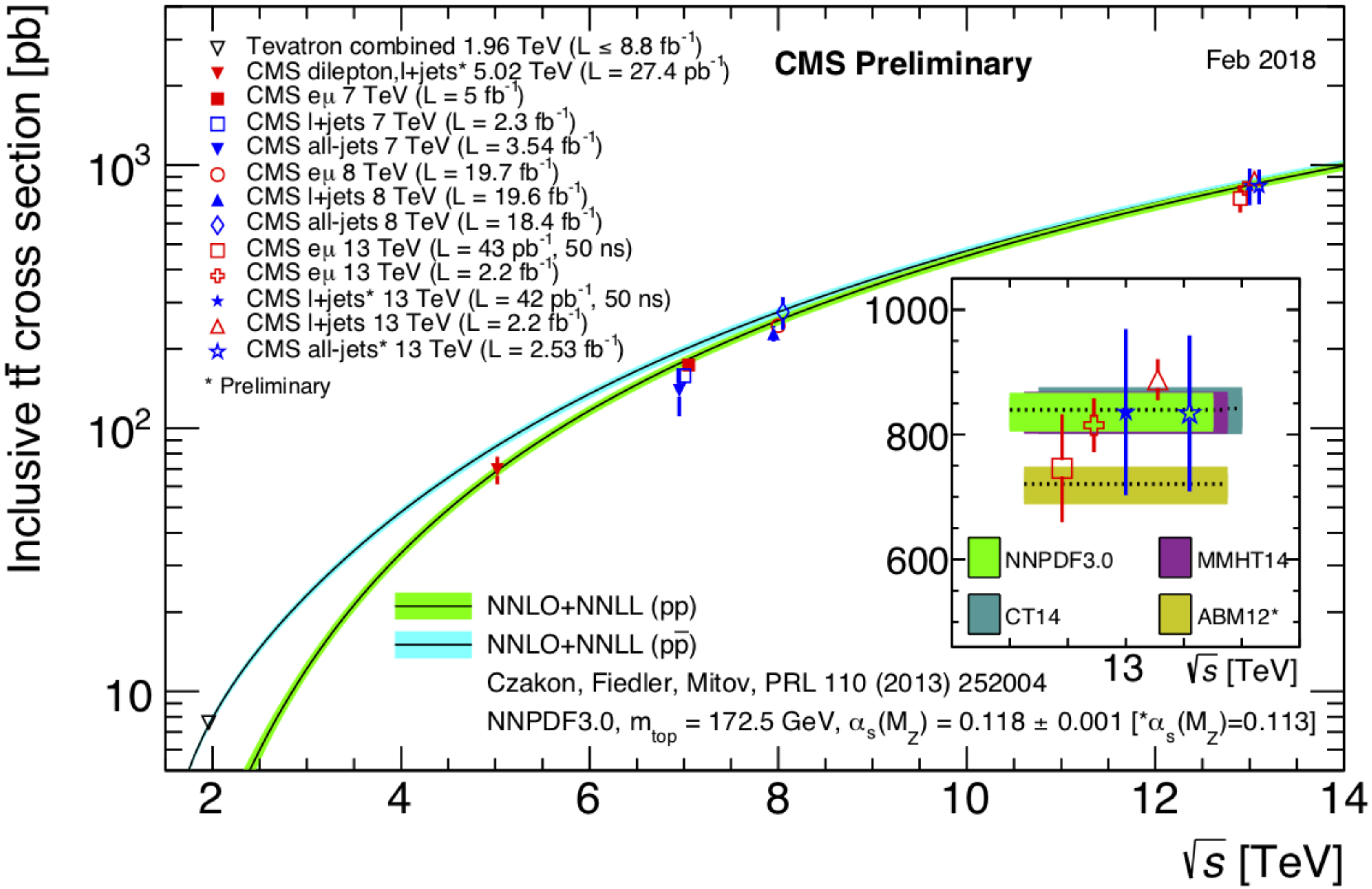
Top pair production

Production cross section overview



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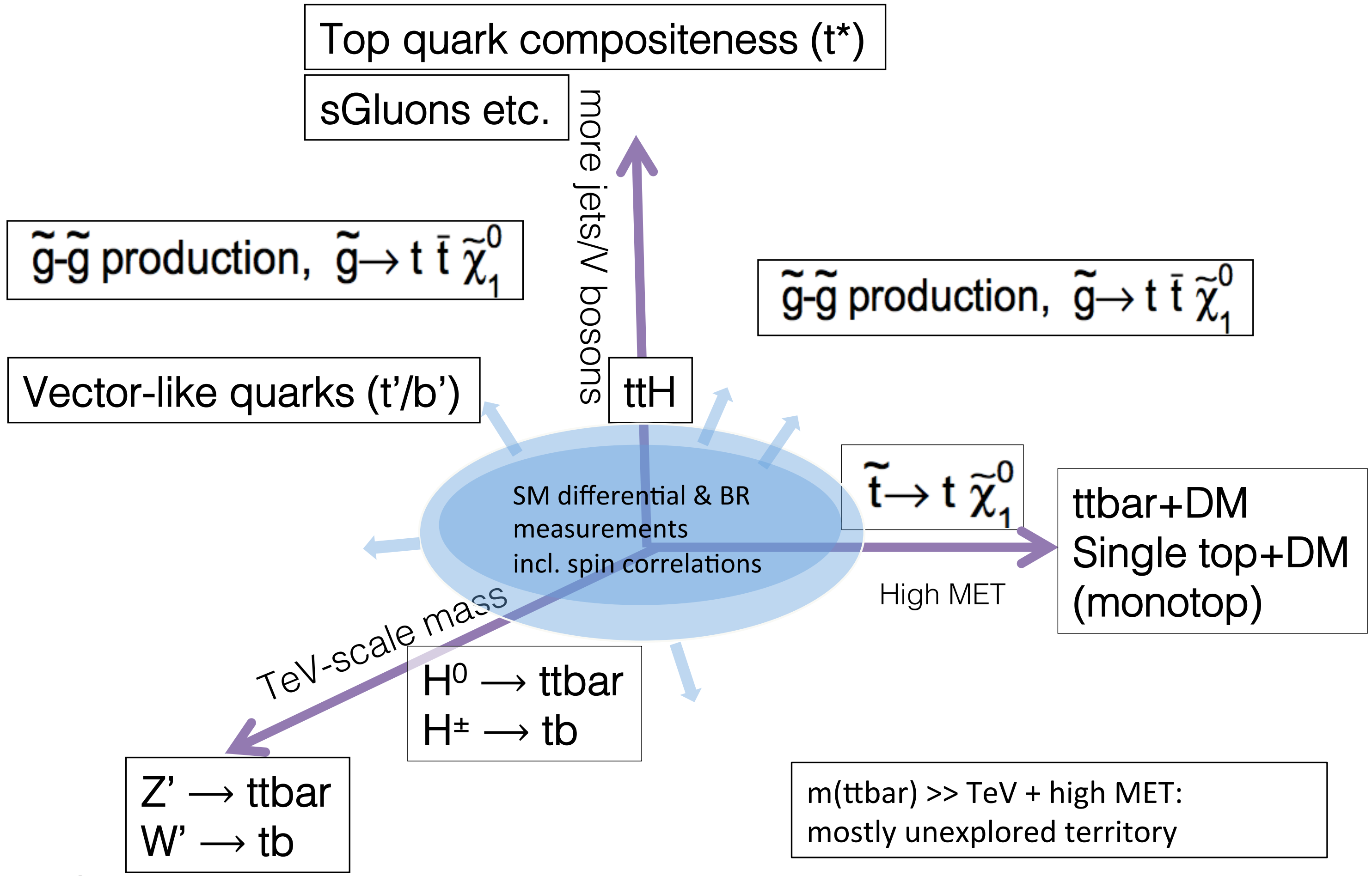
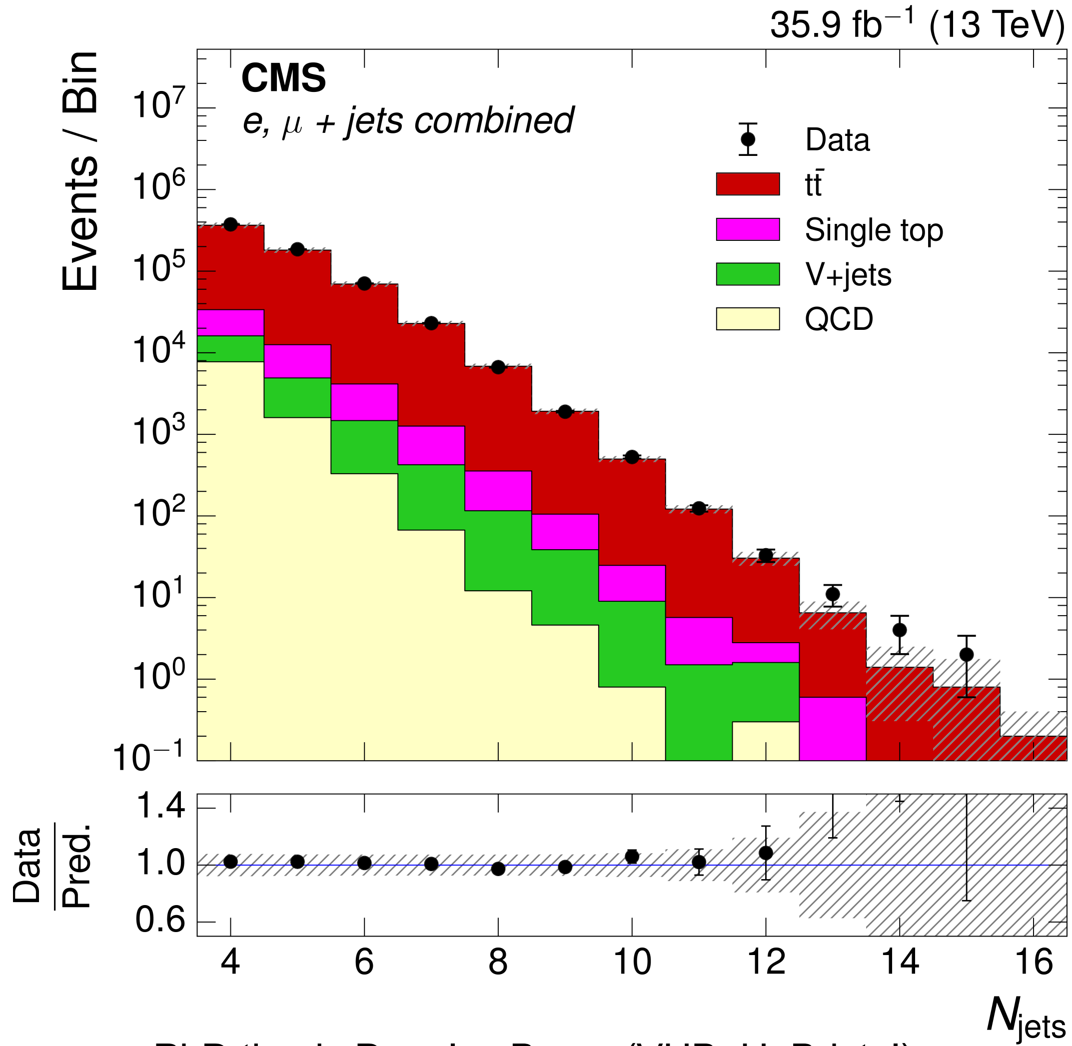
BSM signatures in the ttbar phase space



See also: Czakon et al. arXiv:1501.01112

Differential cross sections

- As top quark production is a (mostly) Quantum-Chromodynamic process, substantial additional jet multiplicity is expected



PhD thesis Douglas Burns (VUB, UoBristol)
src: TOP-16-014 arXiv1803.03991 (JHEP)

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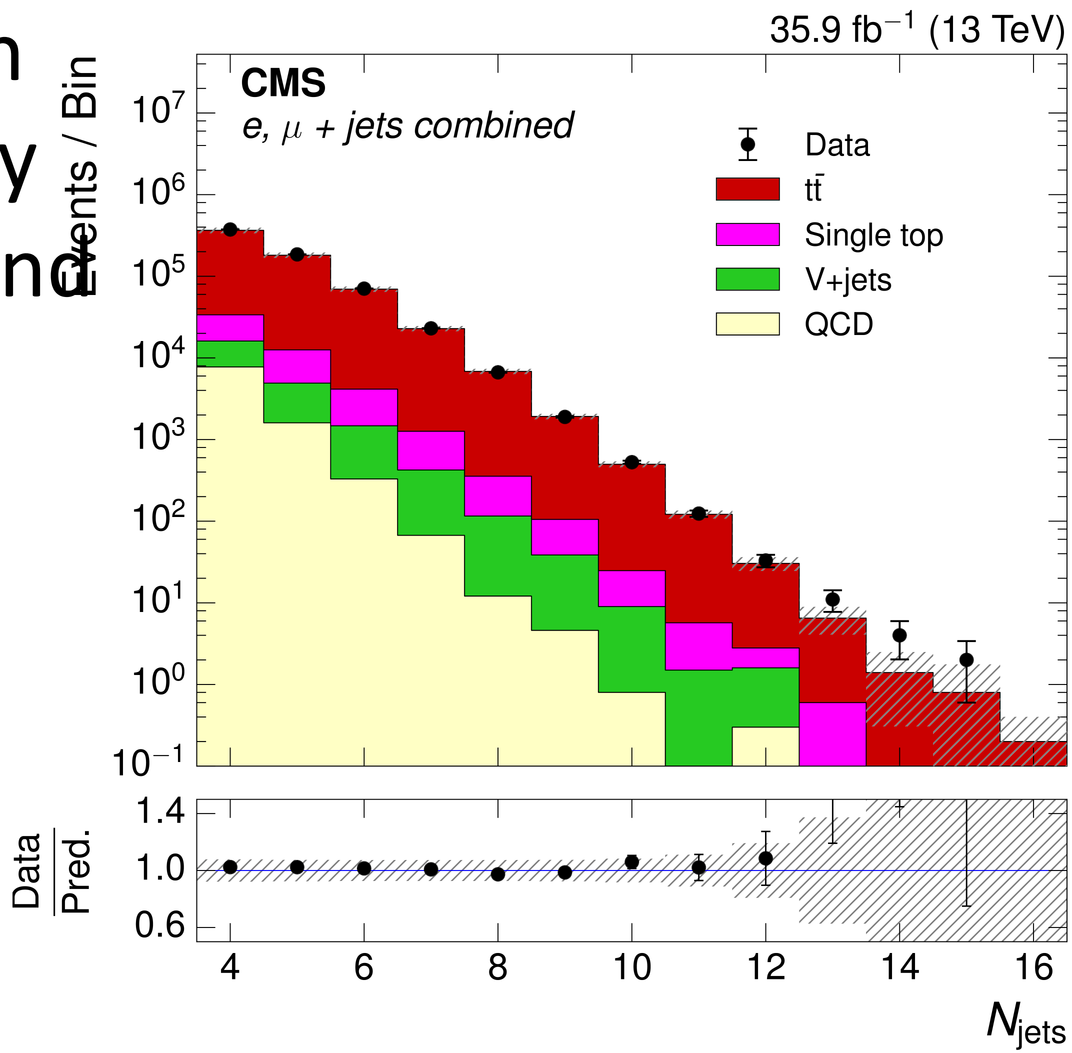
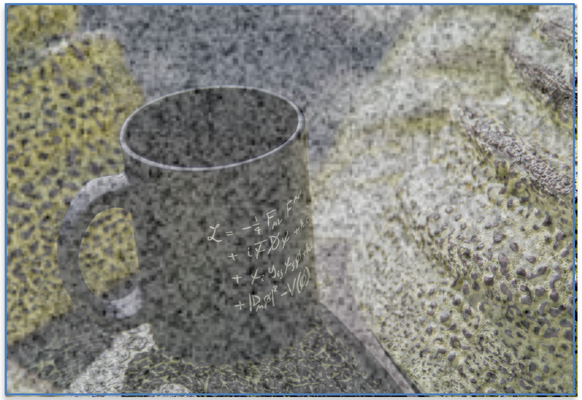
Differential cross sections

- Top quark production at high jet multiplicity is the main background for many direct searches for new physics
- **Important to understand in detail**



src: TOP-16-014 arXiv1803.03991 (JHEP)

Differential cross sections -unfolding



physics is ‘smeared’ by detector resolution

Knowledge of smearing used to ‘unsmear’. This is called *unfolding*

Unfolded picture is allows understanding of physics without (most) detector effects

src: TOP-16-014 arXiv1803.03991 (accepted JHEP)

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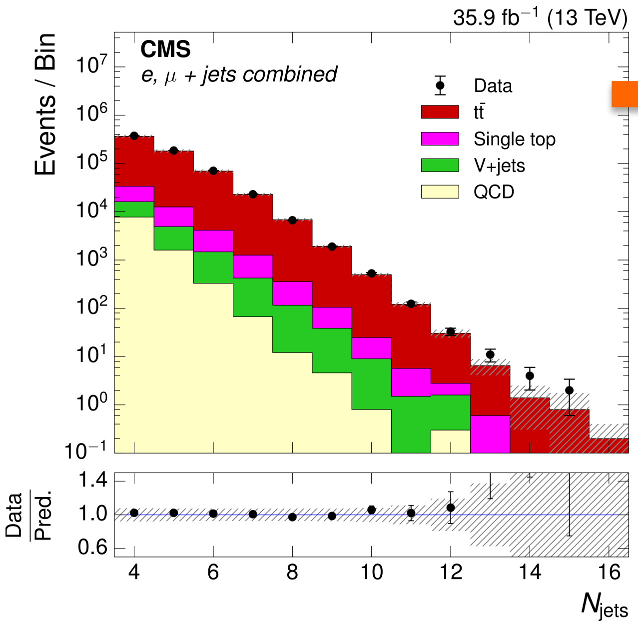
Differential cross sections -unfolding



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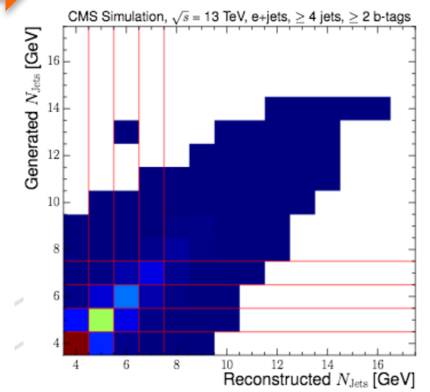

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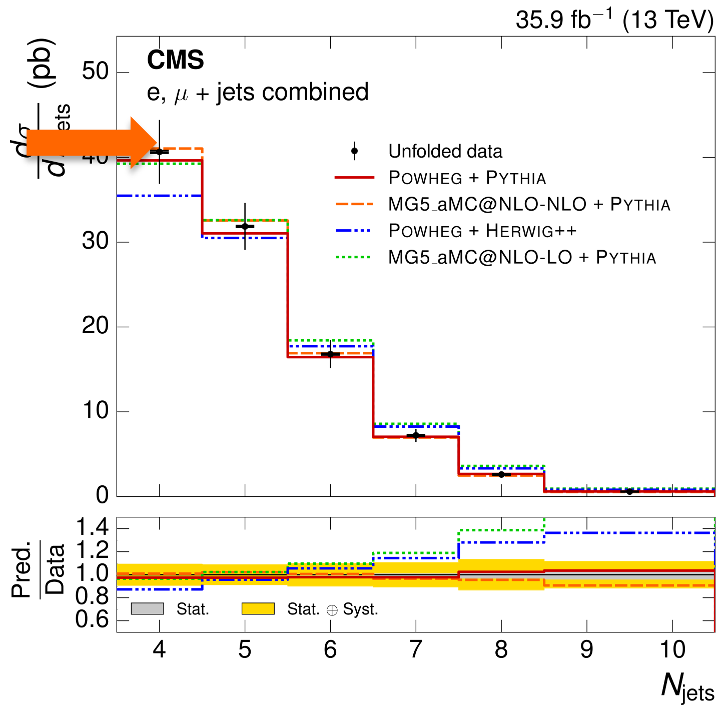

Unfolded picture is allows understanding of physics without (most) detector effects

src: TOP-16-014 arXiv1803.03991 (JHEP)

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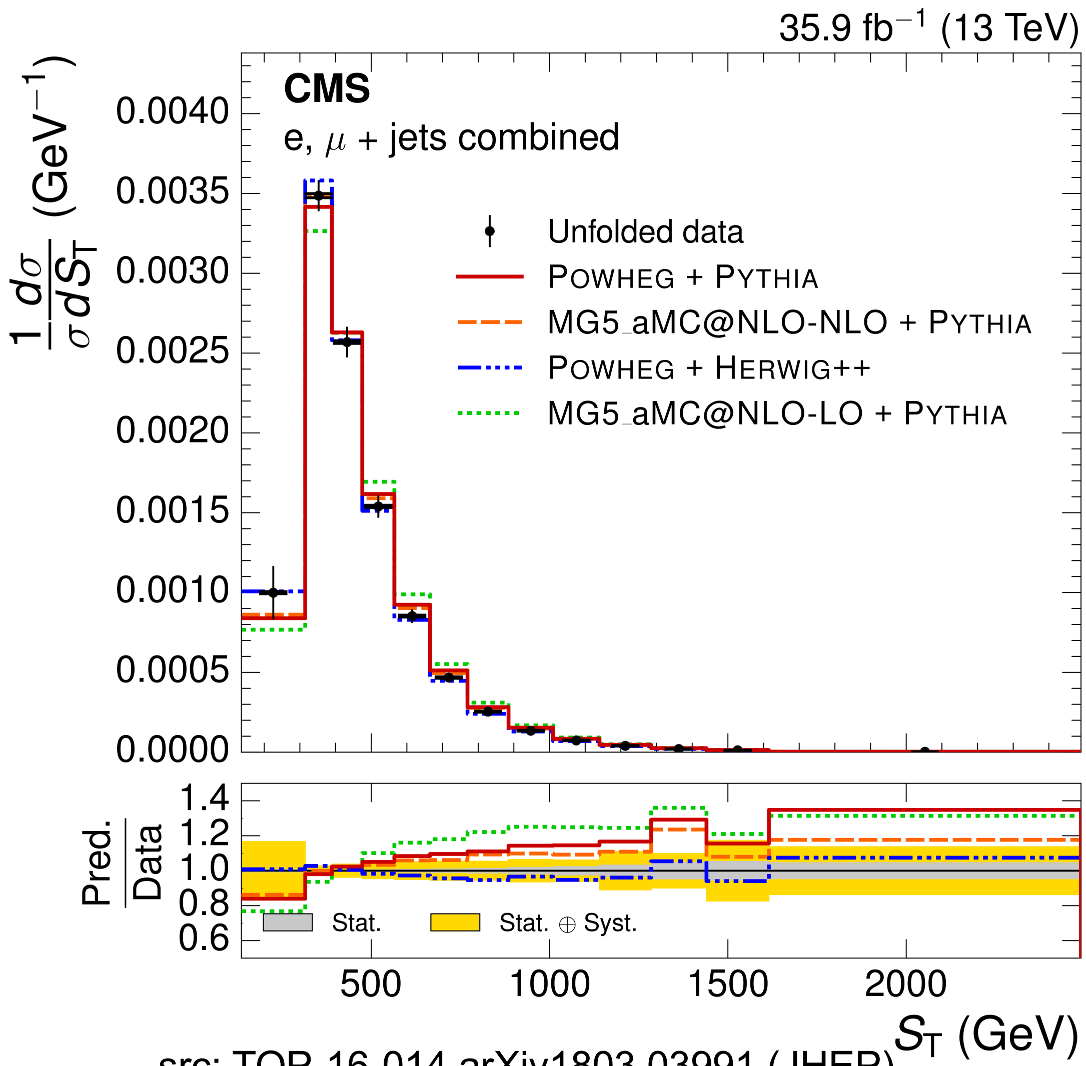
Differential cross sections: event kinematic information

- Useful for:
  - Tuning/checking QCD NNLO calculations
  - Improvement background simulation searches
  - Improvement understanding quark content proton (i.e. parton density functions)



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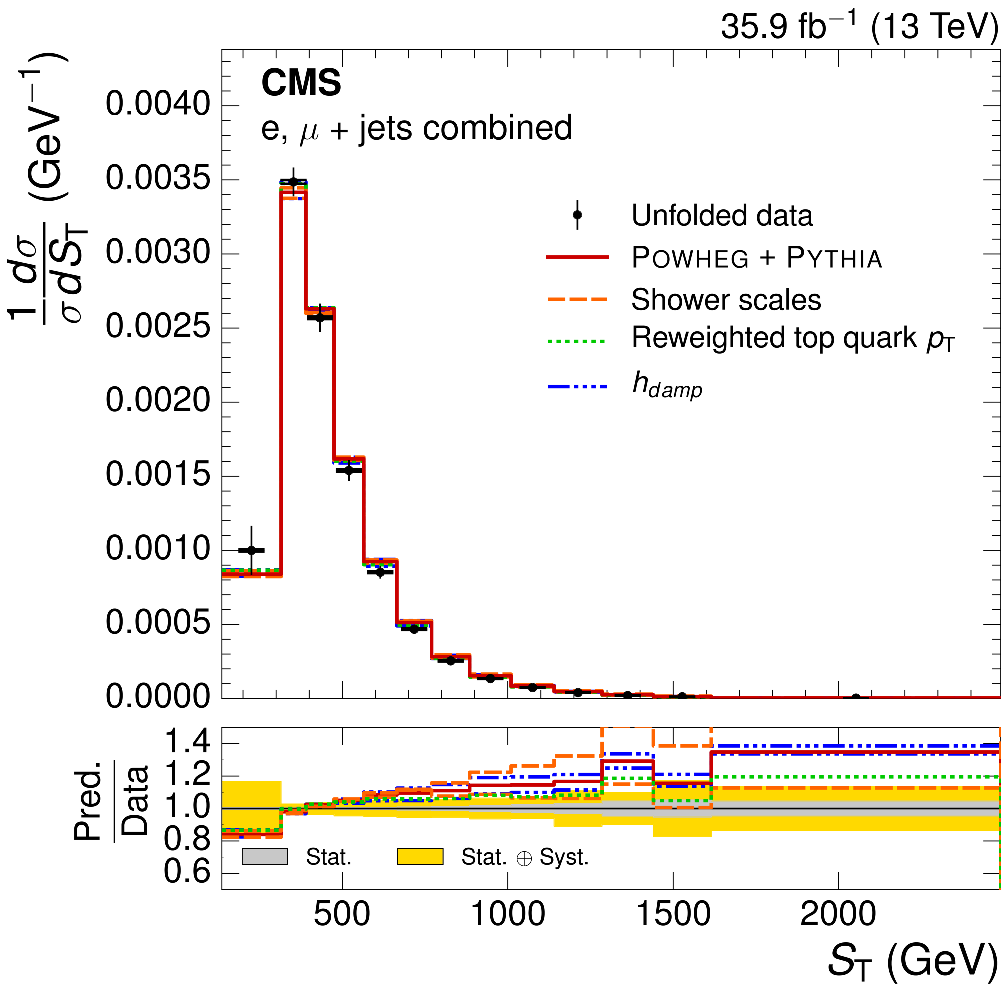

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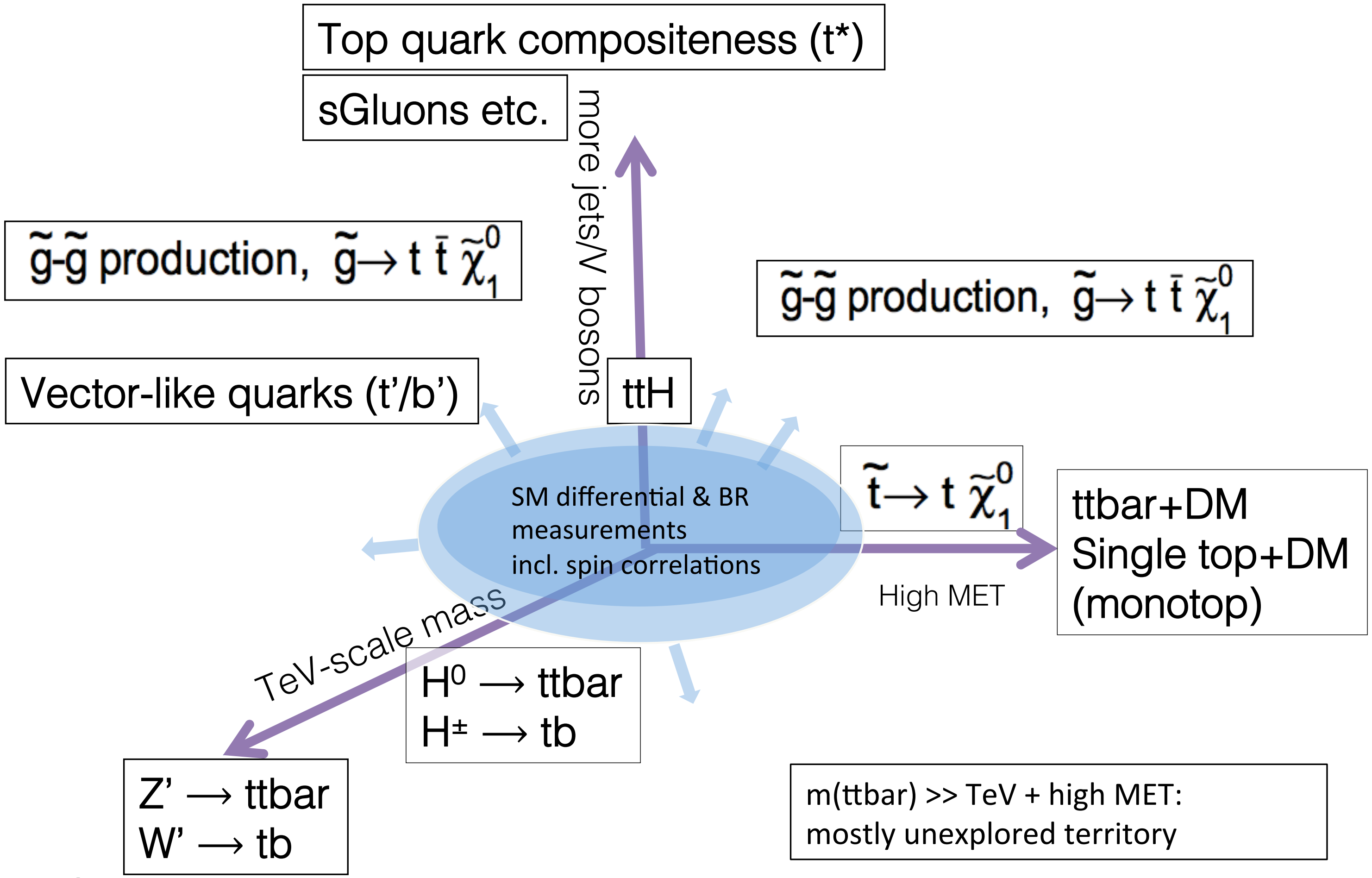
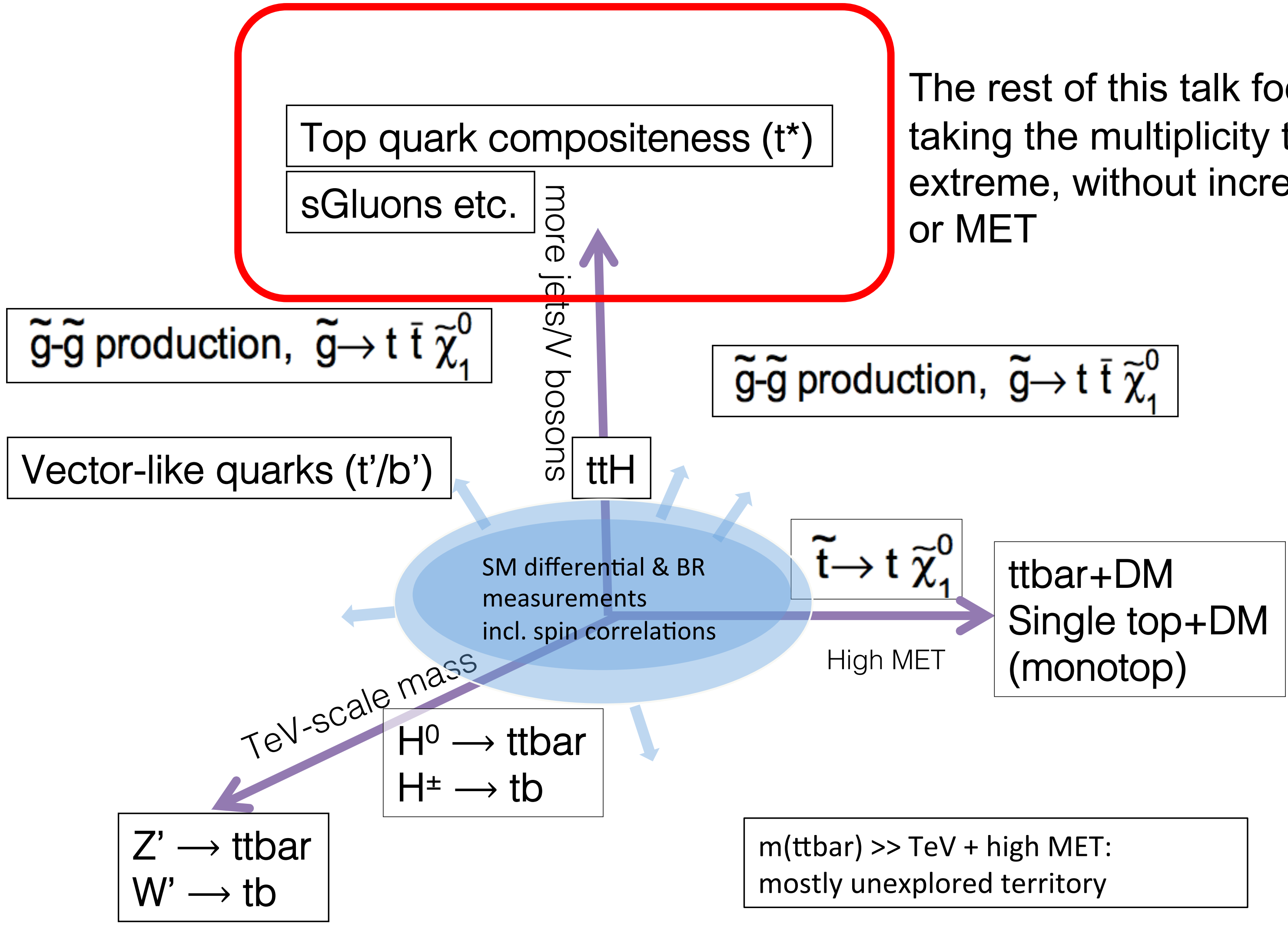
BSM signatures in the ttbar phase space



See also: Czakon et al. arXiv:1501.01112

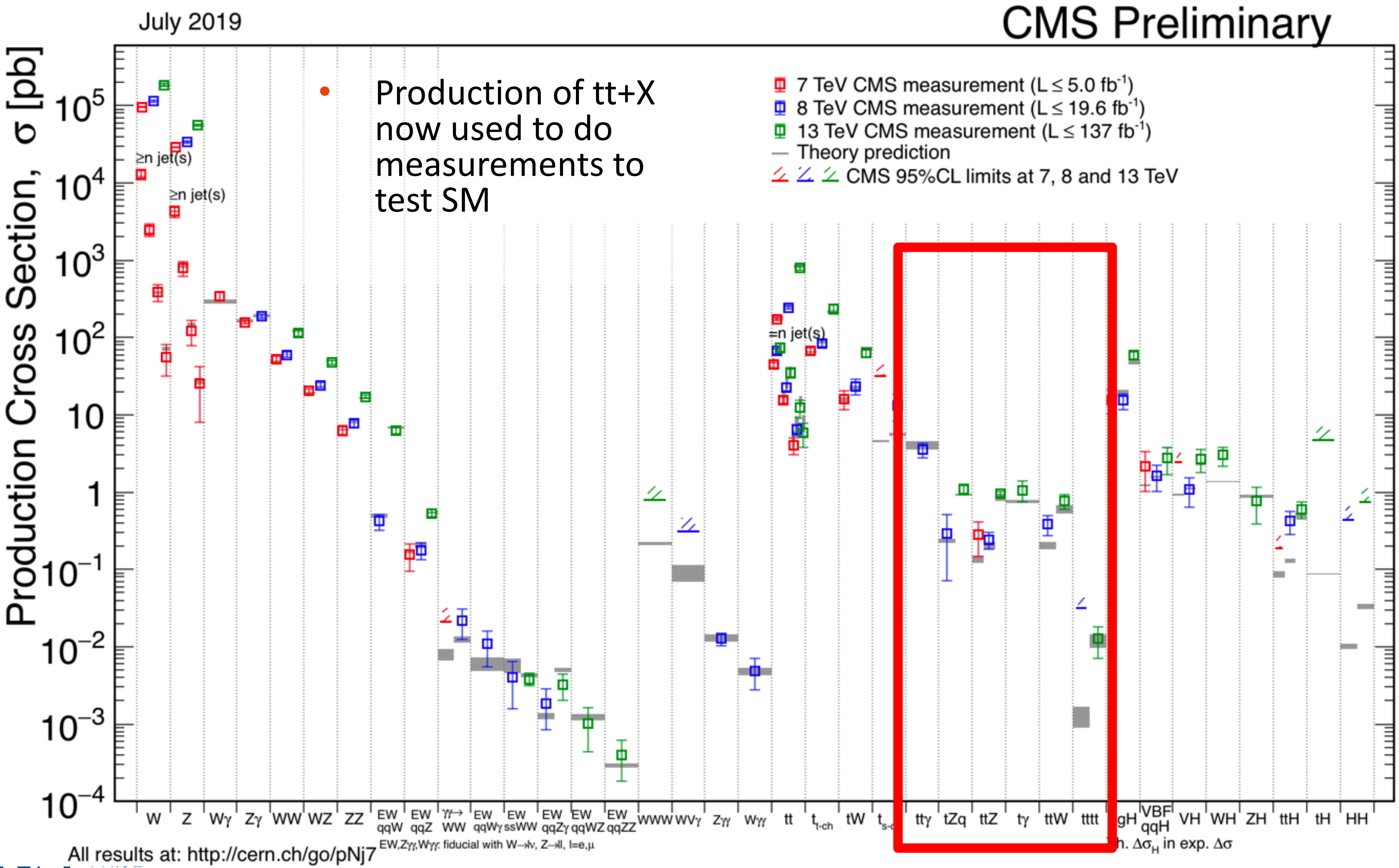
SM top quark production: a background



The rest of this talk focuses on taking the multiplicity to the extreme, without increasing scale or MET

See also: Czakon et al. arXiv:1501.01112

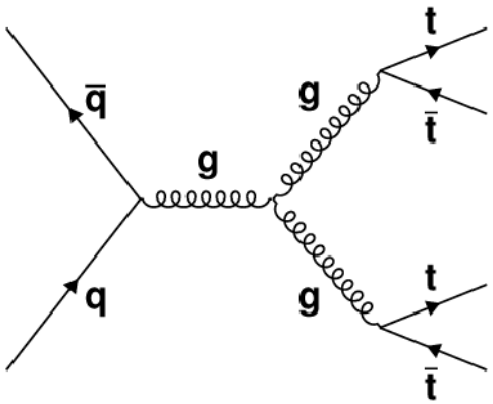
Top physics: rare decays



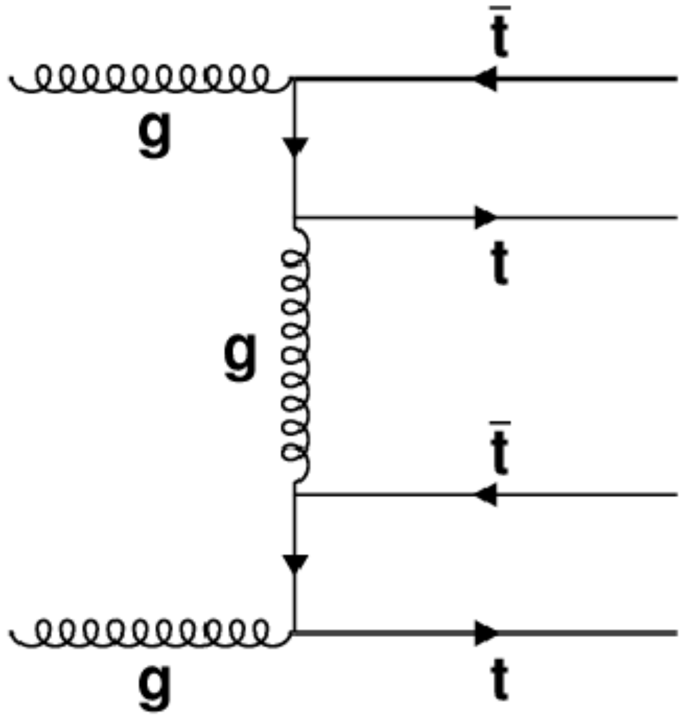
- Production of tt+X now used to do measurements to test SM

Rare decays: Four tops

- Four-top production in SM: gluon fusion dominates
- 9.2 fb cross section @ 13 TeV



small s-channel
contribution from qq fusion



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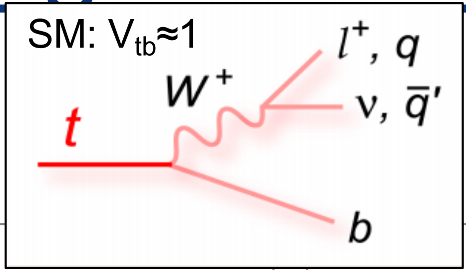
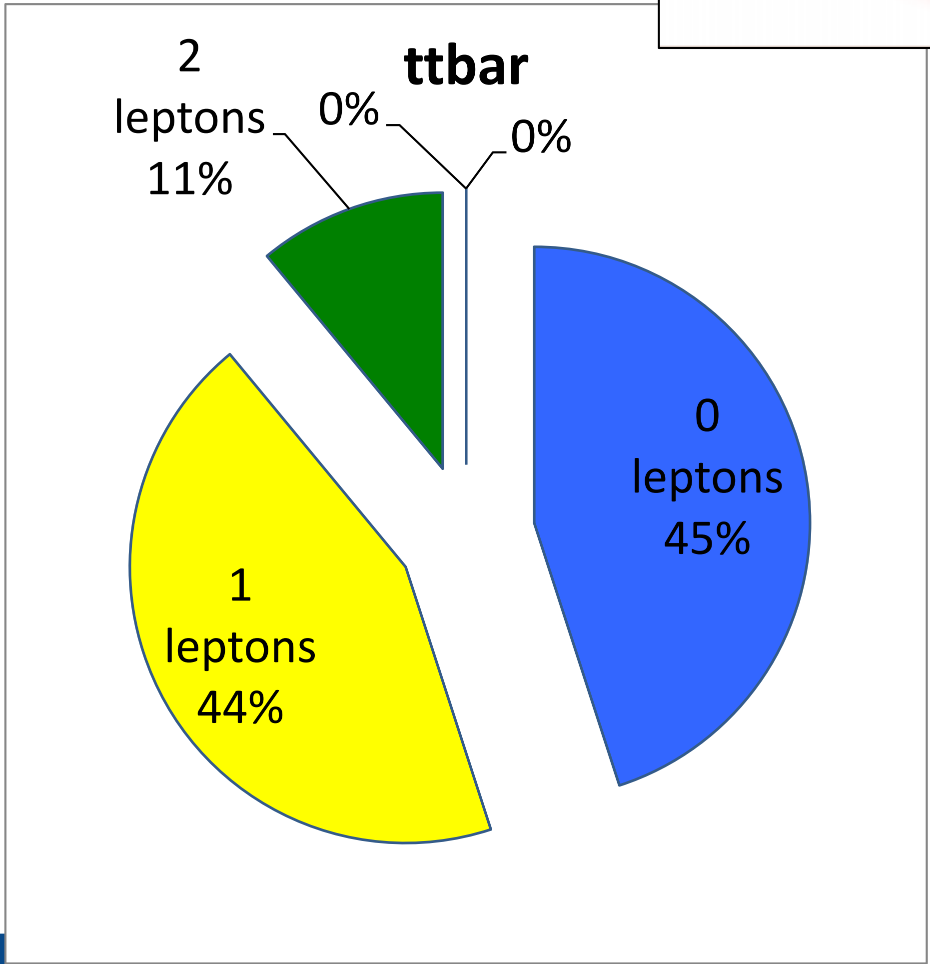
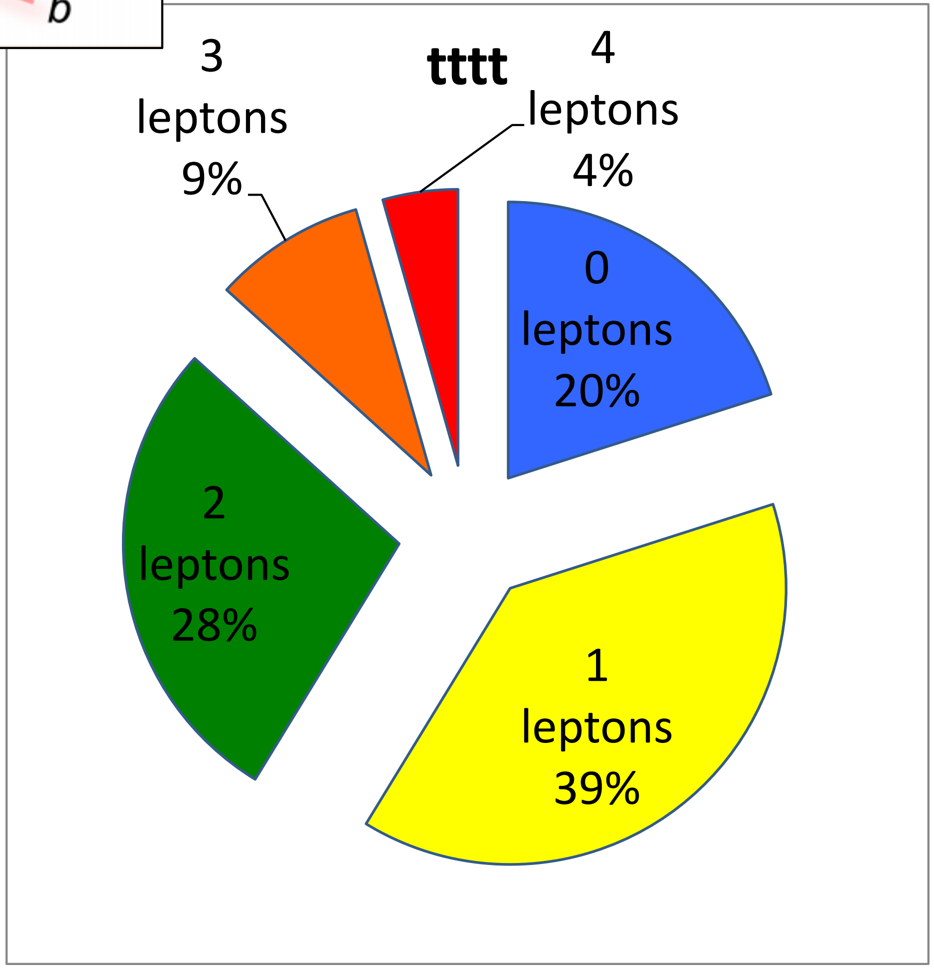
Branching ratio comparison







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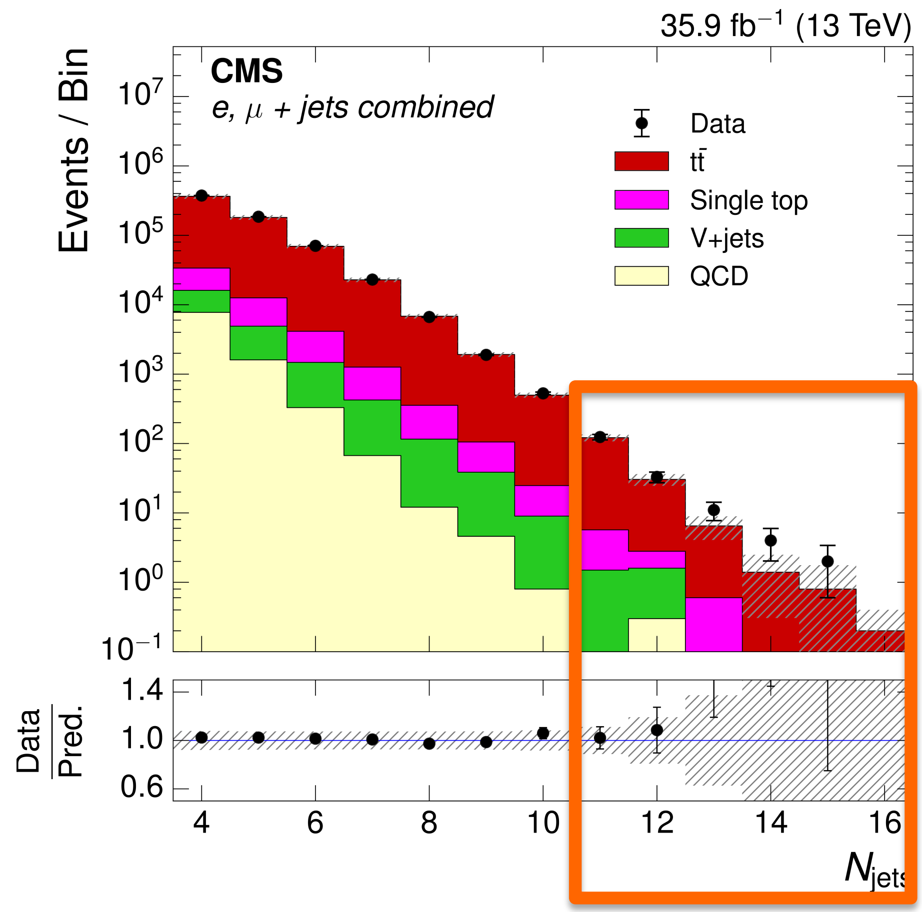
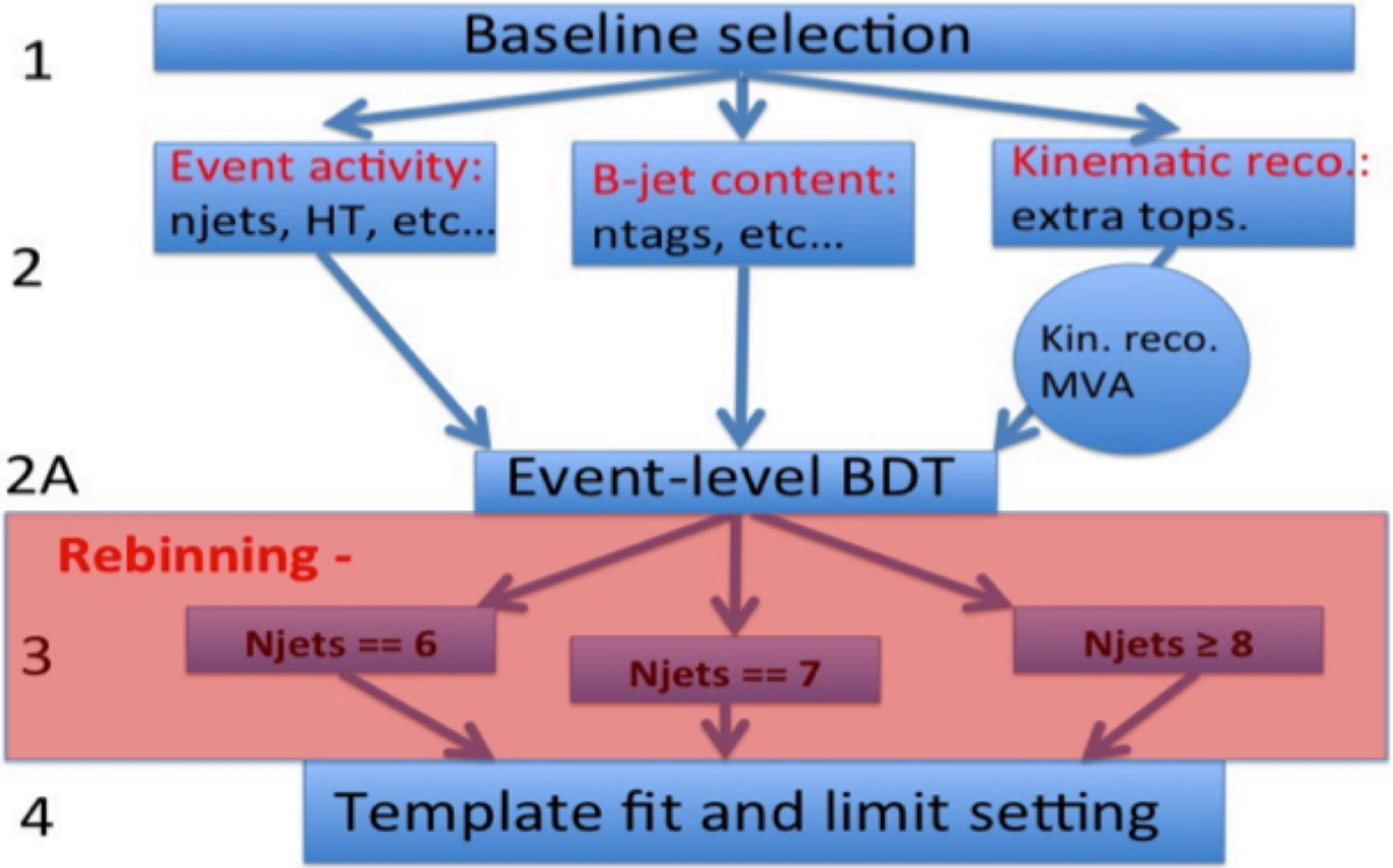
Four-top production: ‘needle in a hay stack’

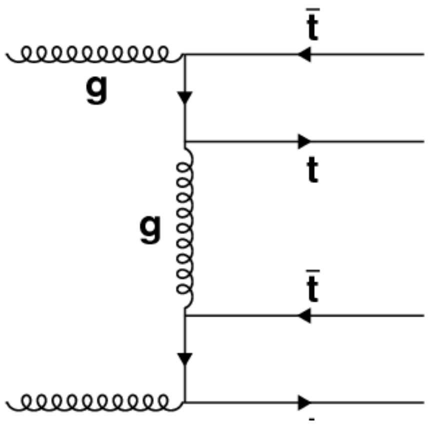
- Topology effectively looks like top quark production with extra jets or leptons
  - Example: 1 lepton+jets final state looks like top quark pair production with 6 (!) extra jets due to QCD radiation

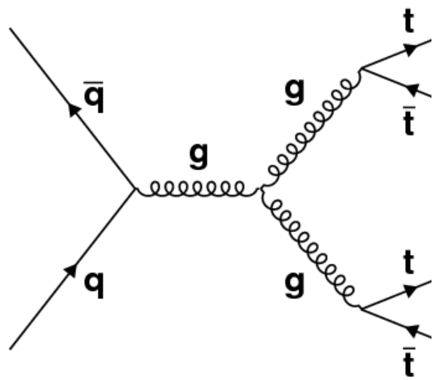


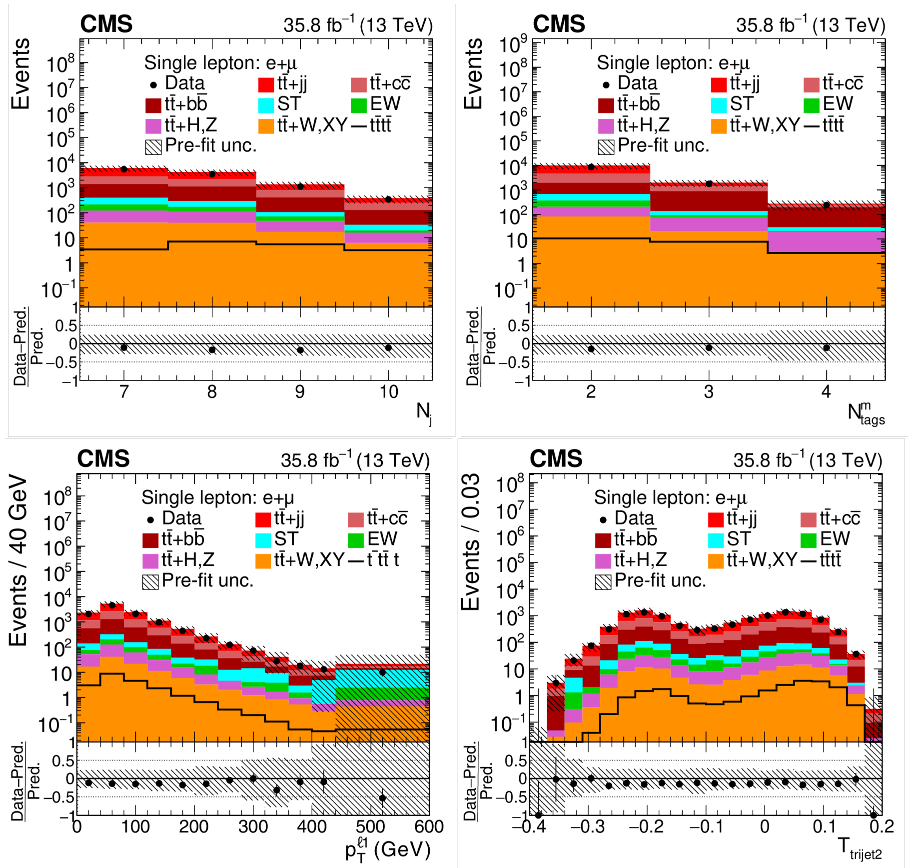
Search strategy for typical 'tough' LHC search



Four-top production: 'needle in a hay stack'





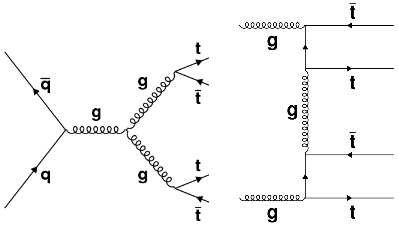


src:
TOP-16-016: arxiv:1702.06164 (JHEP)
PhD Lana Beck (VUB)
TOP-17-009: arxiv:1710.10614 (Eur.Phys.J.C)
TOP-19-017: arxiv:1906.02805 (subm. JHEP)

Production of tttt in SM: 9 fb!

Very sensitive to QCD-BSM

Results: Four tops



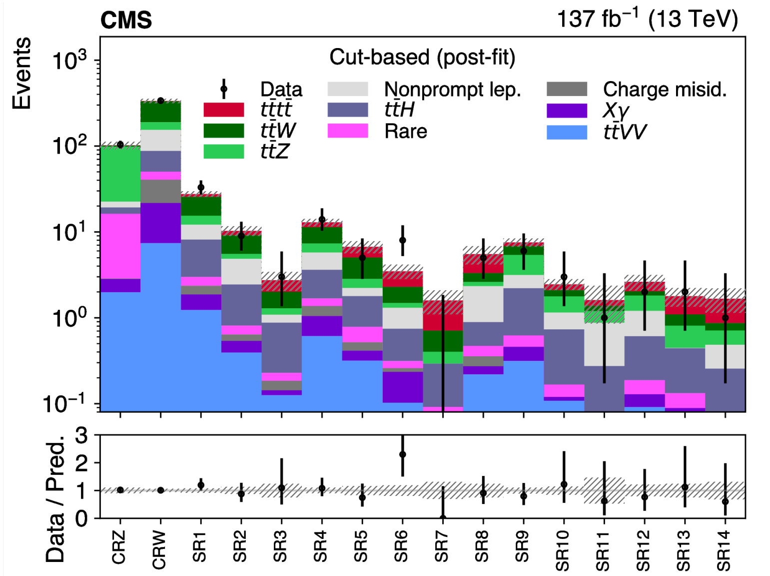
- Rare SM process enhanced by many BSM models such as MSSM,2HDM, ADD and some DM models
- NLO cross section 9.2 fb in SM
  - observation should be feasible in LHC Run 3 – or maybe even earlier?
    - Or earlier if enhanced by BSM…
- Results from Run II dataset using BSM search strategy
  - No identification of hadronic tops
  - Same-sign dileptons + b-tagged jets, or multileptons
  - CMS SS dlieptons: $12.6^{+5.8}_{-5.2}$ fb

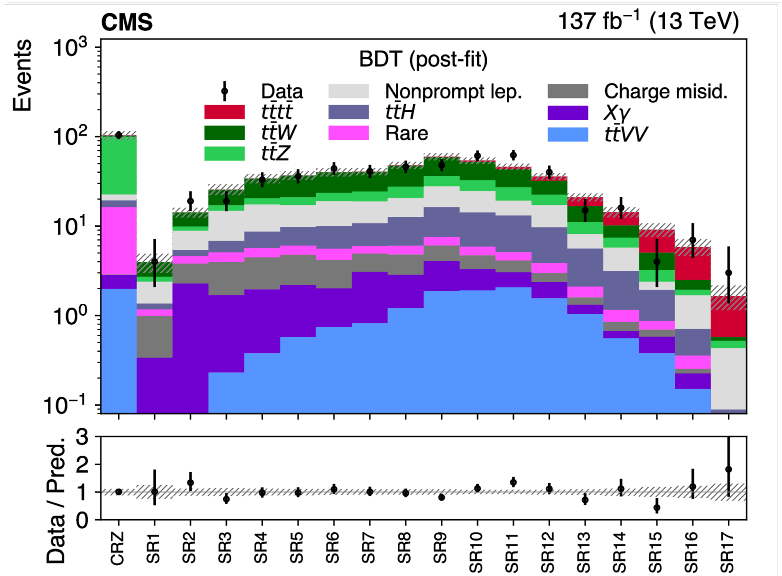
    (first 'observation' at 2.7σ!)

src:

TOP-19-017: arxiv:1906.02805 (subm. JHEP)

TOP-18-003 arxiv:1908.06463 (subm. EJPC)





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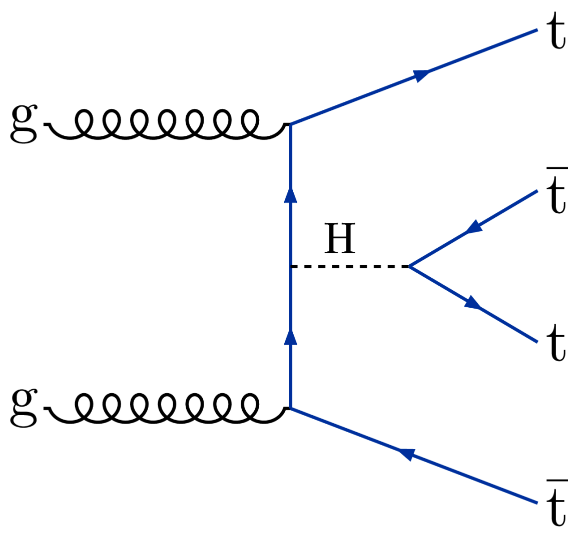
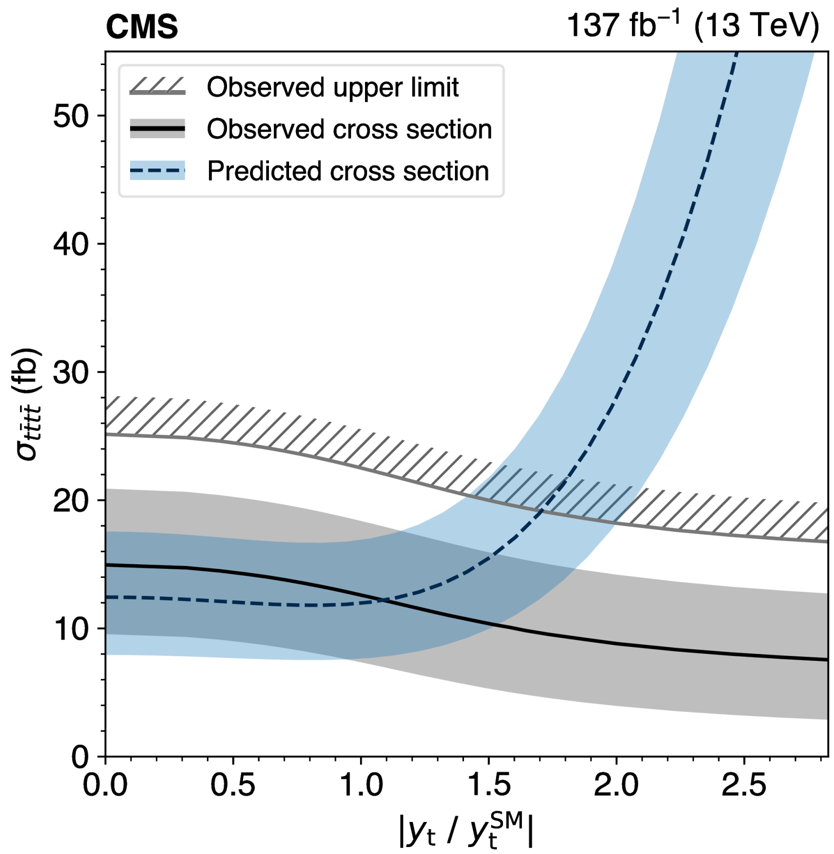
Learning more from the tttt cross section?



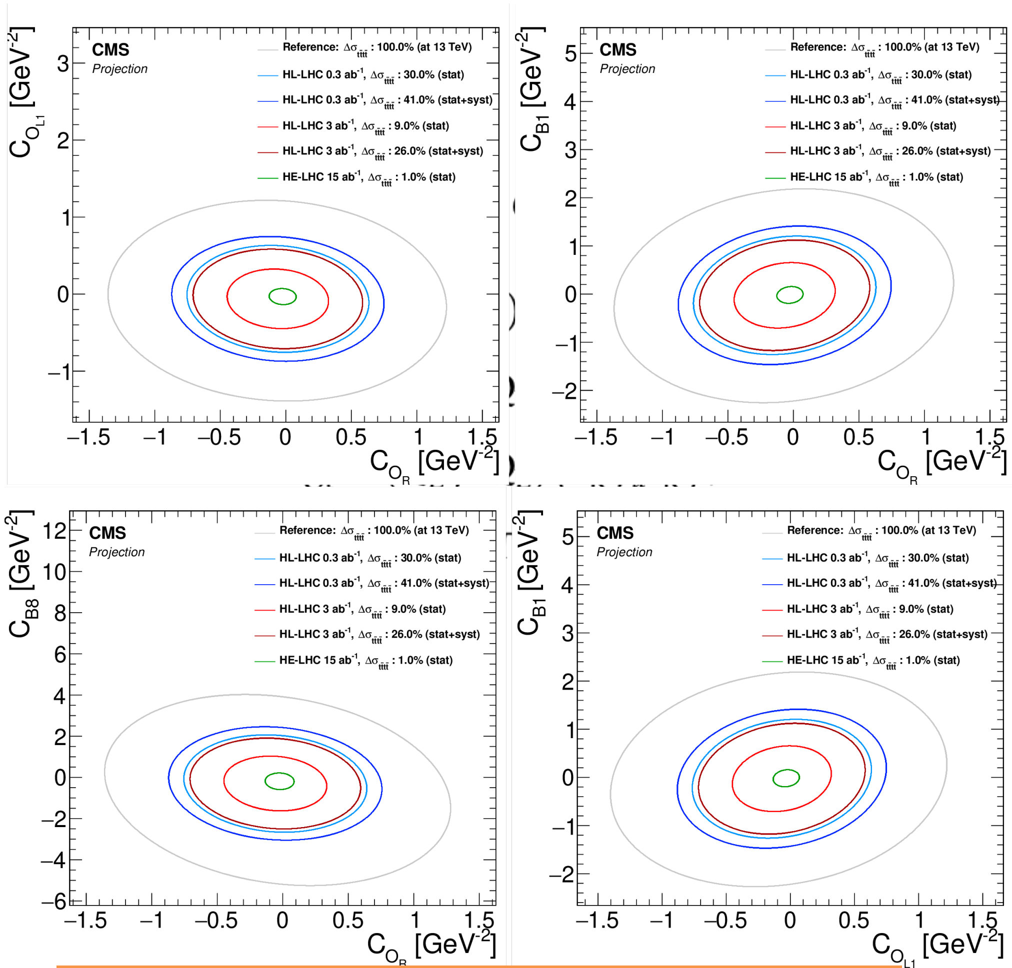
- tttt is sensitive to the coupling of higgs to top quarks!
- Direct link top yukawa coupling



- Many diagrams at lowest order in tttt production
- About 10-20% of the cross section comes from higgs production

src:
TOP-18-003 arxiv:1908.06463 (subm. EJPC)

Learning more from the tttt cross section?



- tttt is sensitive to the coupling of top quarks to gluons and other quarks!
- Effective field theory incl. operators not otherwise accessible
- Would be even more powerful once tttt is established, incl. dedicated measurements tuned for specific couplings

Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
[−2.0, 1.9]	[−2.2, 2.1]
[−2.0, 1.9]	[−2.2, 2.0]
[−3.4, 3.3]	[−3.7, 3.5]
[−7.4, 6.3]	[−8.0, 6.8]

src:

Projections for future LHC runs!

TOP-19-017: arxiv:1906.02805 (subm. JHEP)

CMS-PAS-FTR-18-031 (also in HL-LHC YR)

Numbers for σ_{tttt} < 36 fb (2016 dataset)

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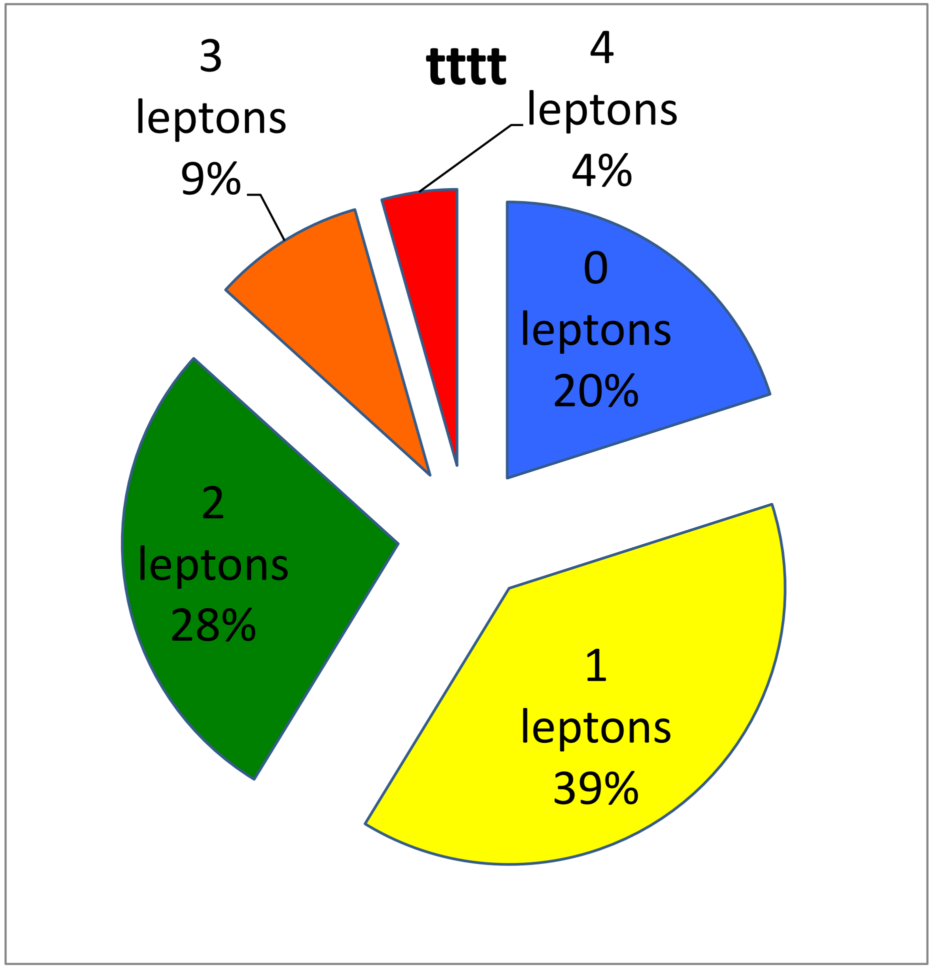
Other final states

- 1 lepton final state has largest branching ratio
- Analysis on Run3 large dataset coming very soon
  - Including the opposite-charge dilepton final state and single lepton final state
- **Stay tuned**



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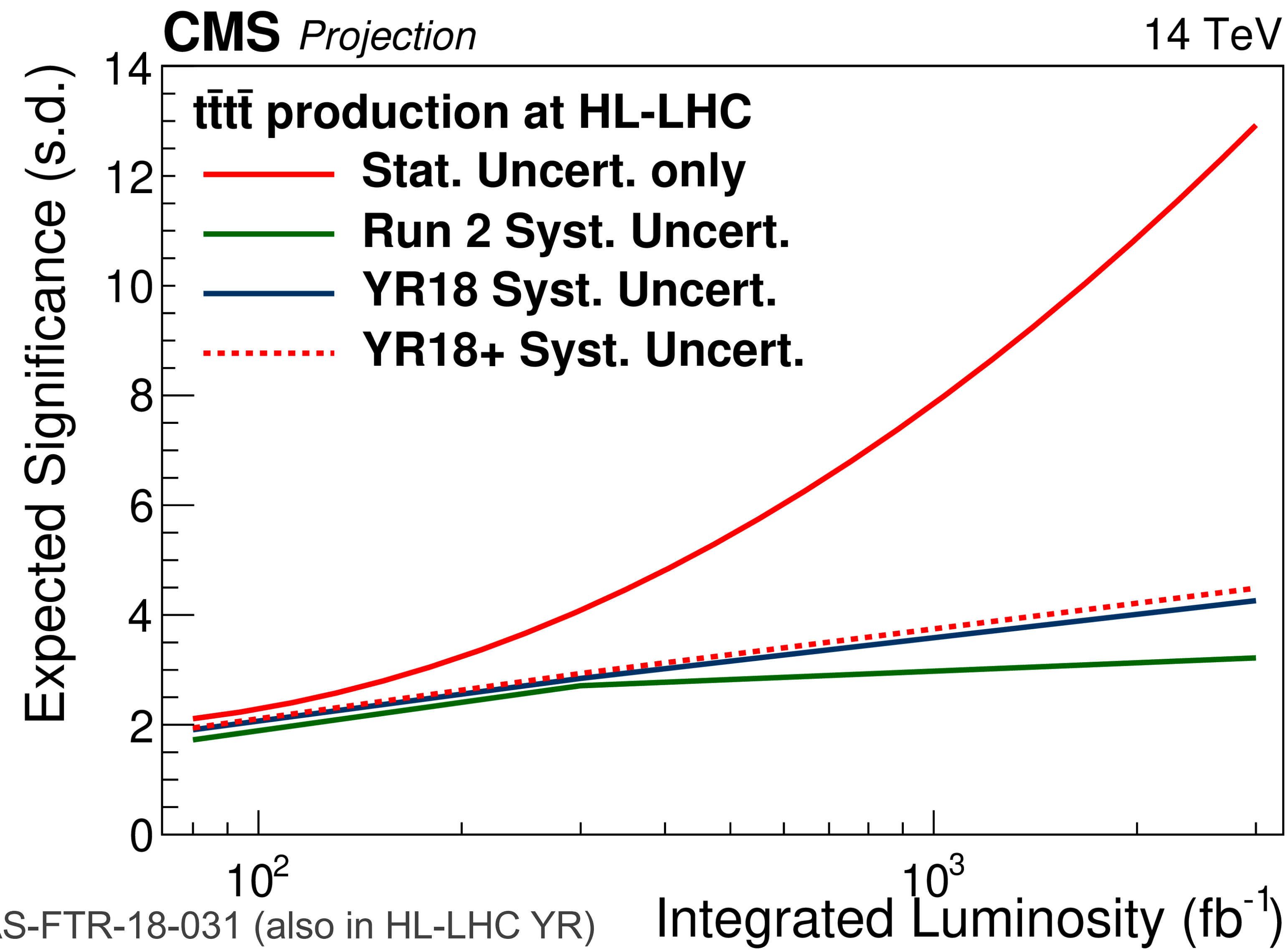
The future



src:
CMS-PAS-FTR-18-031 (also in HL-LHC YR)

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Lessons learned?

Check if BSM signatures have similar kinematics to SM process -> allows constraints, relatively easy reinterpretation even if complex (so sensitive) analysis

- Particularly useful if no direct search

- Same approach could be followed for Run II in lieu of direct sgluon->tt searches
    - Same for:
        - Composite Higgs or non-minimal SUSY H/A to tttt
        - Vector-like quarks if only >O(6) operators
        - Even some DM scenarios predict enhancements in tttt
- Targeted searches are almost always more sensitive
    - 4-top topology wealth of physics potential

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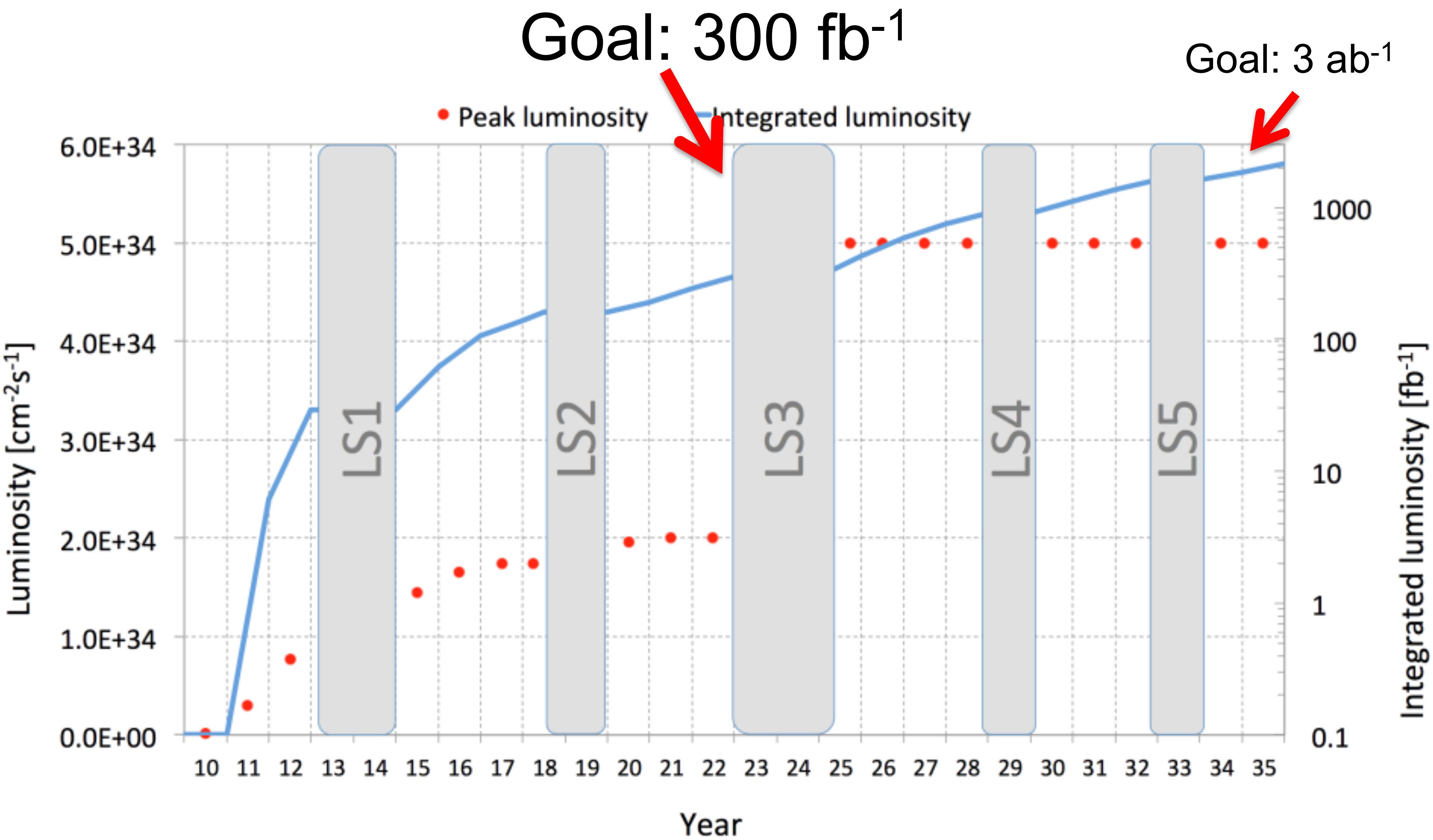
Data (=answers) will come!



Conclusion & Outlook

- Top quark has gone from discovery to senstive probe for new physics and standard model measurements
- Side note: CMS has dedicated direct searches program in the top sector too!
  - Top-like Exotica

    = Beyond two generations (B2G)