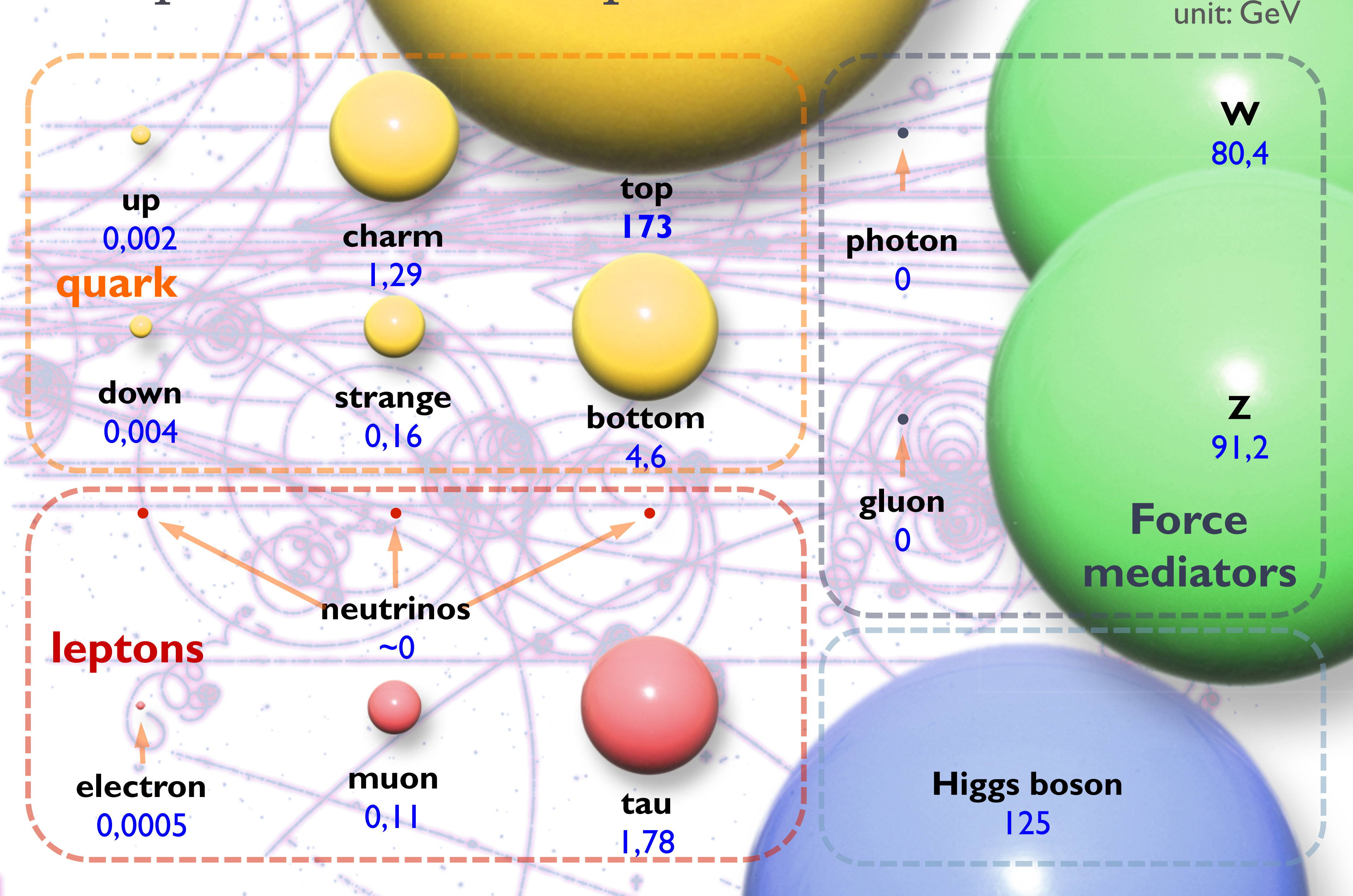
Top-quark results at LHC

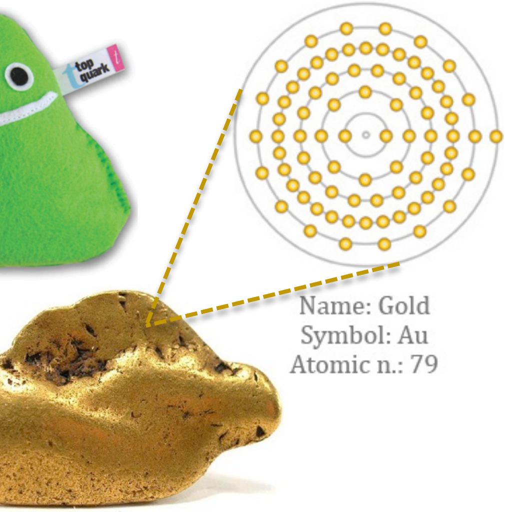
Luca Lista INFN Napoli


Happy 20th birthday!
CAVA

Top: the heaviest particle



Top: the heaviest particle



- Top is by far the heaviest quark and the heaviest particle ever observed
  - As heavy as a Au atom!
- Top mass is clos to the Electroweak scale

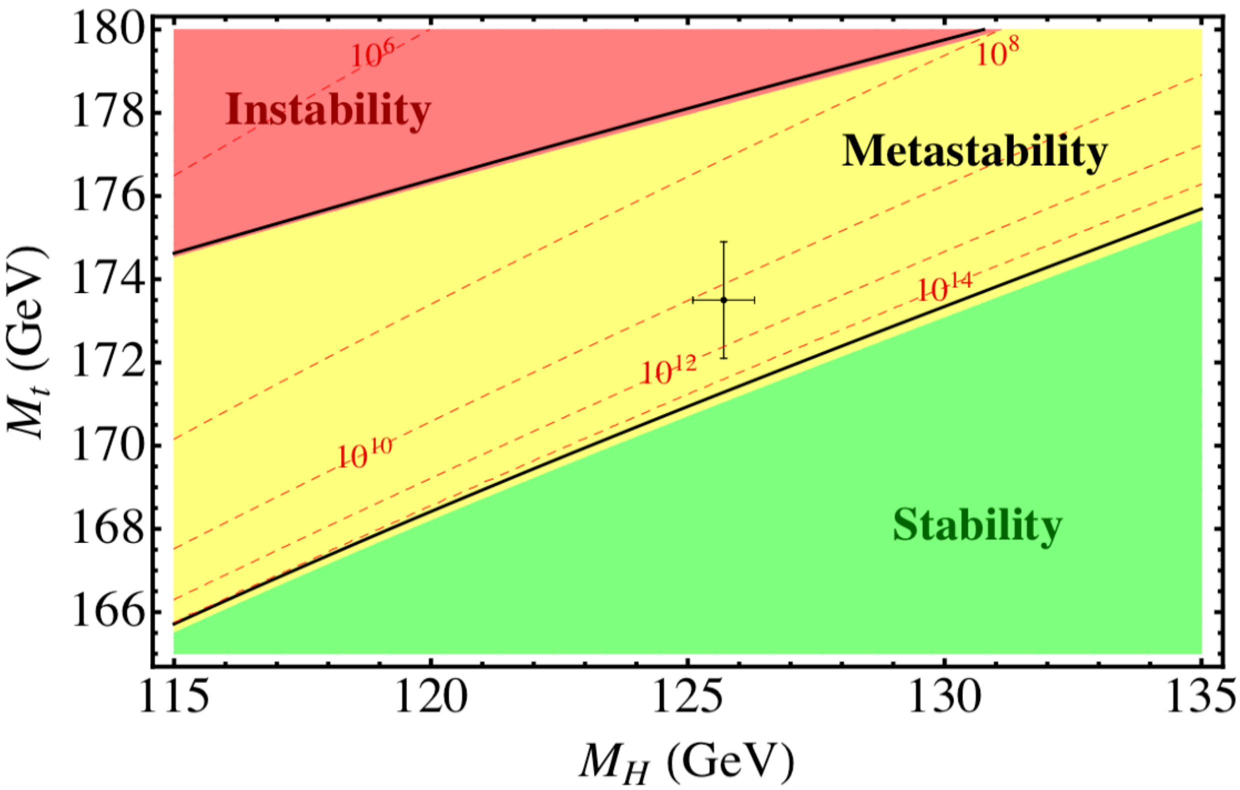
$$\mathcal{L}_{\mathrm{t}}^{\mathrm{SM}} = -\frac{1}{\sqrt{2}} Y_{\mathrm{t}}^{\mathrm{SM}}\, \bar{\mathrm{t}}\mathrm{t}\mathrm{H} \qquad Y_{\mathrm{t}}^{\mathrm{SM}} = \frac{\sqrt{2}m_{\mathrm{t}}}{v} \simeq \sqrt{2}\frac{173}{246} \simeq 0.995 \simeq 1!!!$$

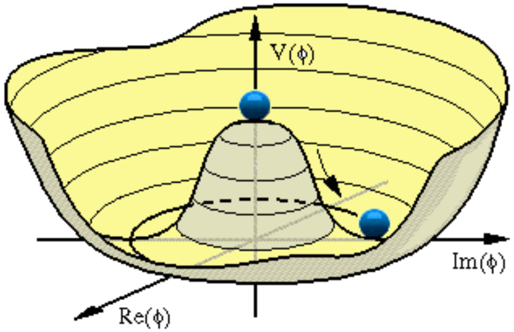
- Unlike all other quarks, it's heavier than the W, so it can decay into a real W: $\mathrm{t} \rightarrow \mathrm{Wq}$
- Top lifetime is shorter than the typical hadronization time

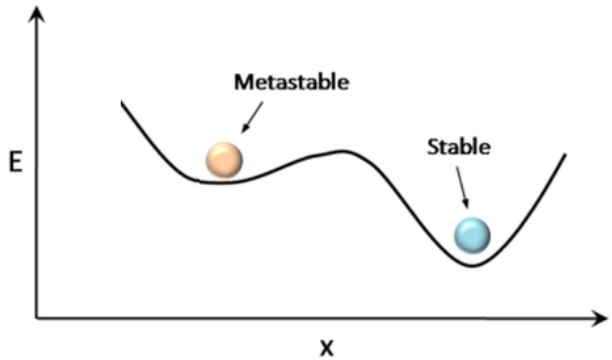
$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{M_W^2}{m_t^2}\right)^2\left(1+2\frac{M_W^2}{m_t^2}\right)\left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right] \Rightarrow \tau_{\mathrm{t}} \simeq 0.5\times 10^{-24}s$$

  - Top decays before top-flavored hadrons or tt-quarkonium-bound states can form ($\tau_{\mathrm{had}} \approx 10^{-23}\mathrm{s} \sim 20 \times \tau_{\mathrm{t}}$)
  - It's a unique opportunity to study "bare" quark properties

Top mass and Higgs field stability

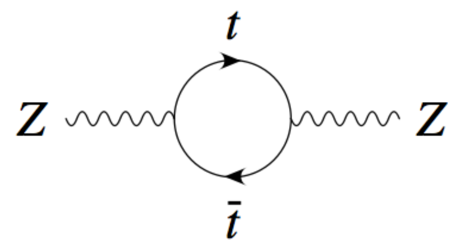


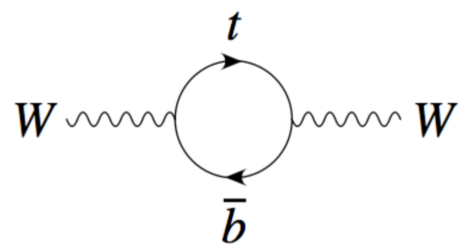




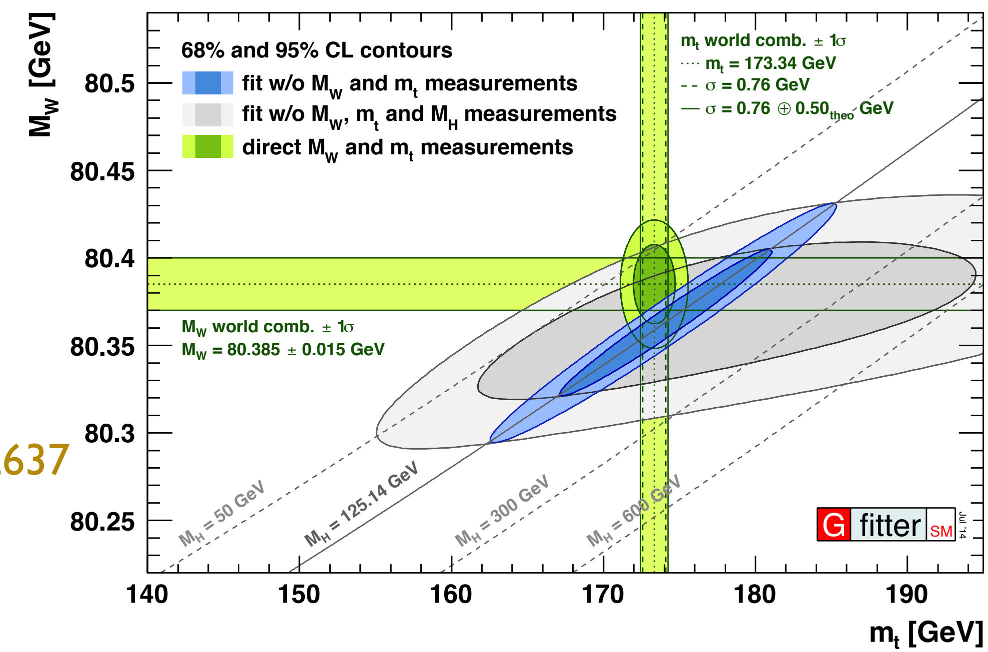
J. Elias-Miro et al., arXiv:1112.3022
O. Antipin, et al., arXiv:1306.3234

Top history timeline

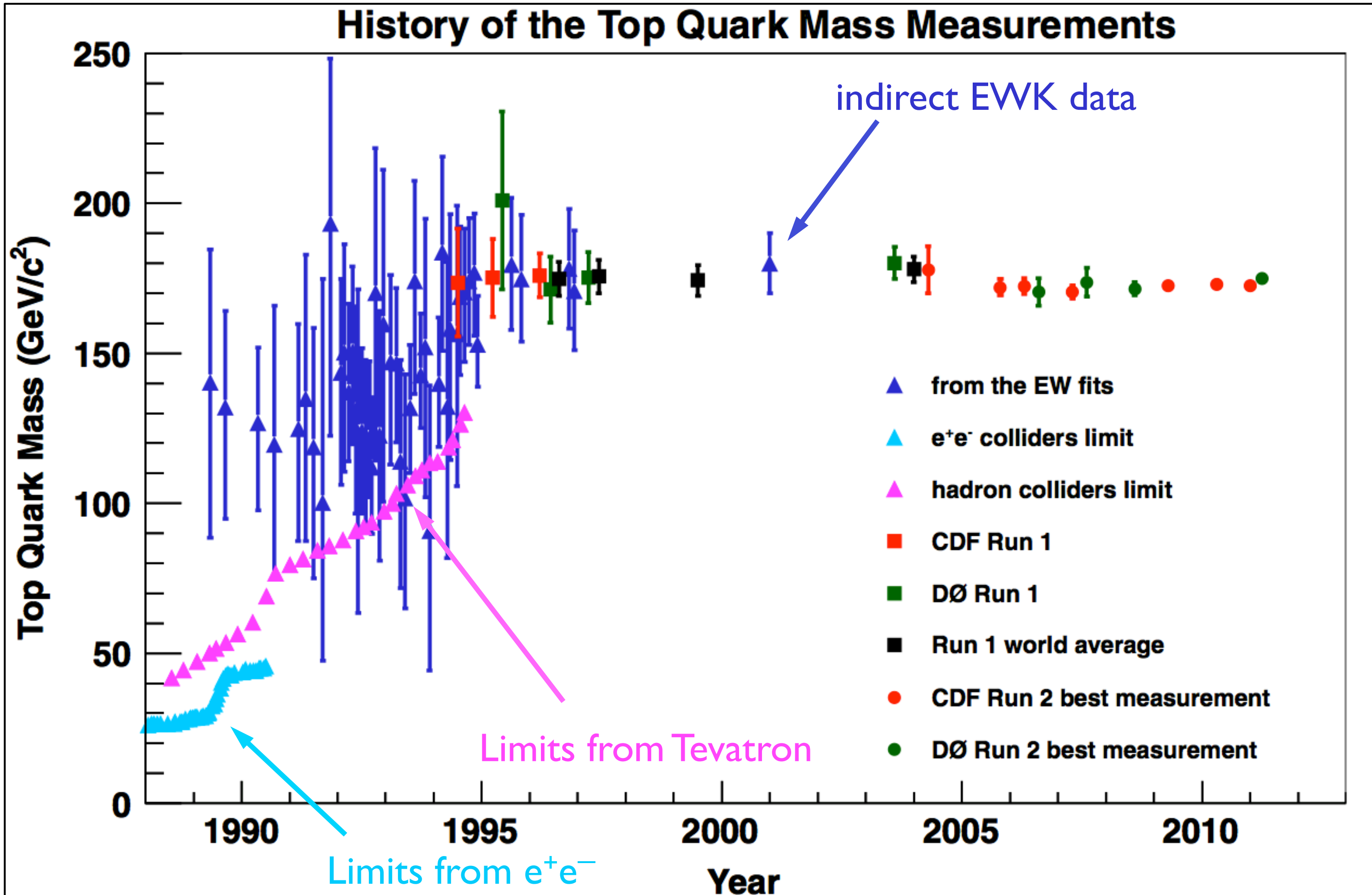




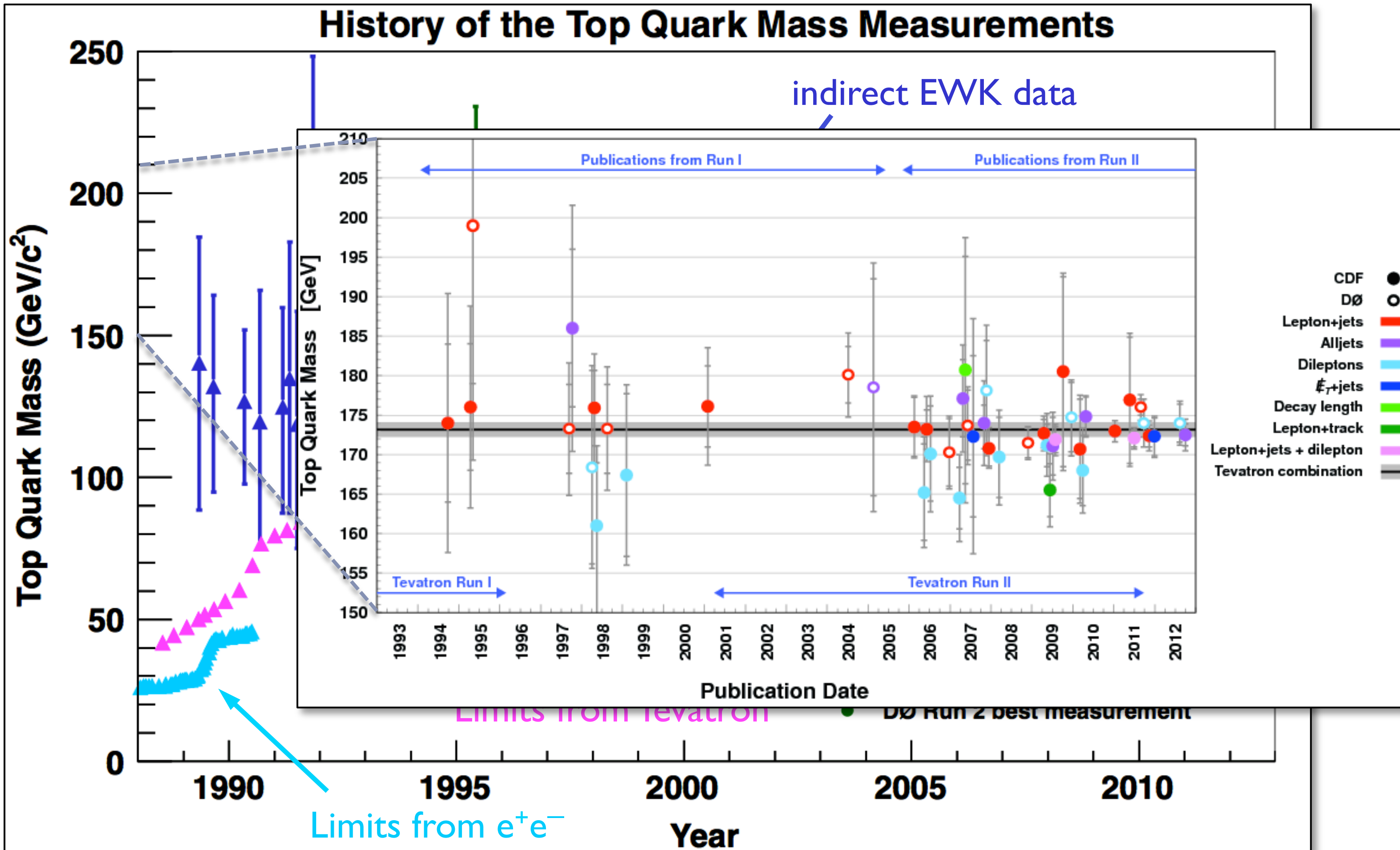
- 1977 – b-quark discovered, top quark hypothesizes as weak isospin partner and 6th quark to complete the three SM generations
- 1980-90's – direct search in e^+e^- colliders, increasing limits on the top mass
- ~1990 – indirect estimate of quark mass from LEP precision EWK measurements
  - Corrections $\Delta r \sim m_t^2$, $\ln(m_H)$ to EWK predictions
- 1995 – discovered at FNAL by CDF and D0 in direct top-pair production
  - 24th feb: papers submission: PRL 74, 2626–2631, PRL 74, 2632–2637



Top mass history



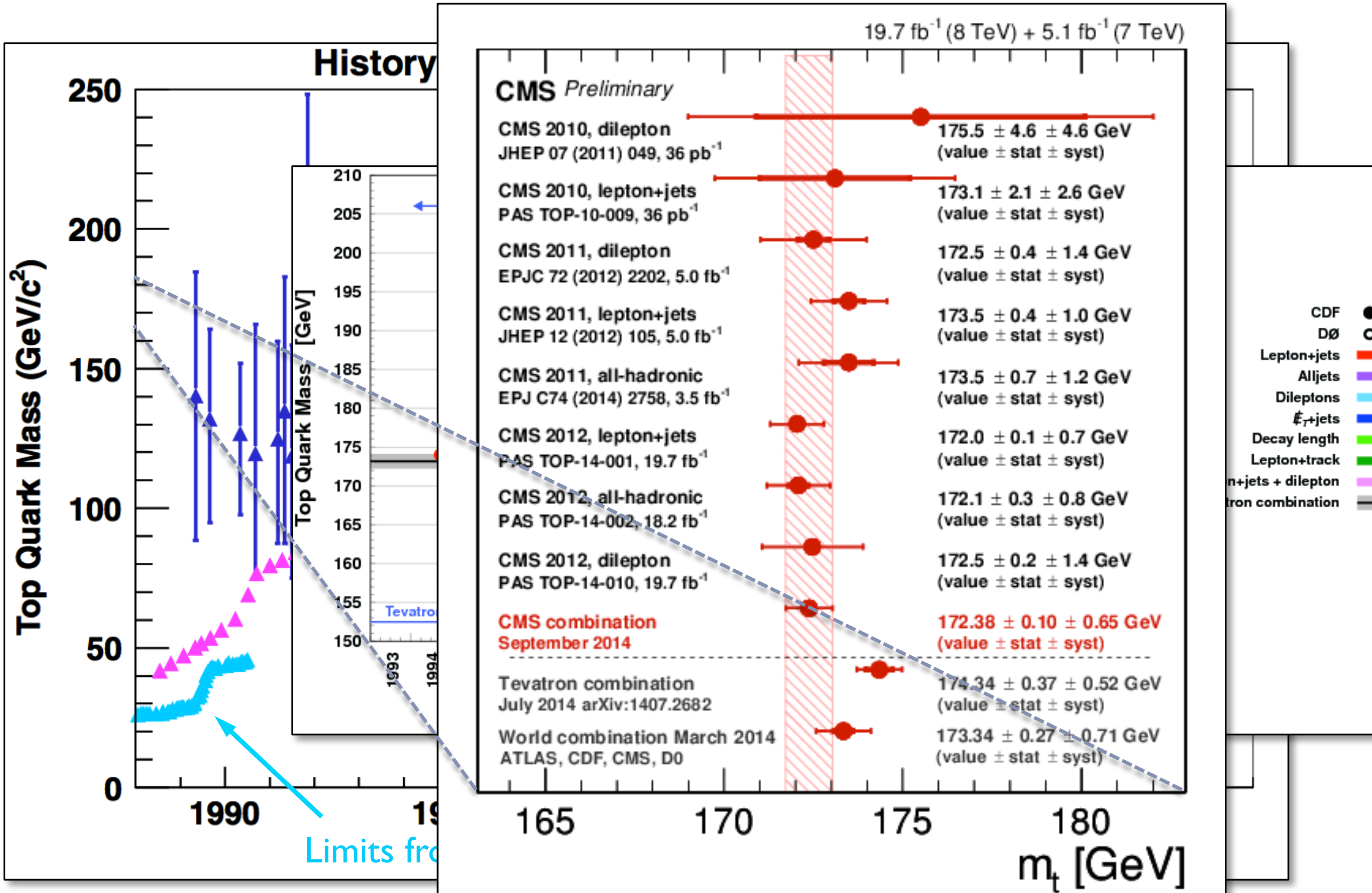
Top mass history (Tevatron)



Luca Lista

Padova, 26-02-2015

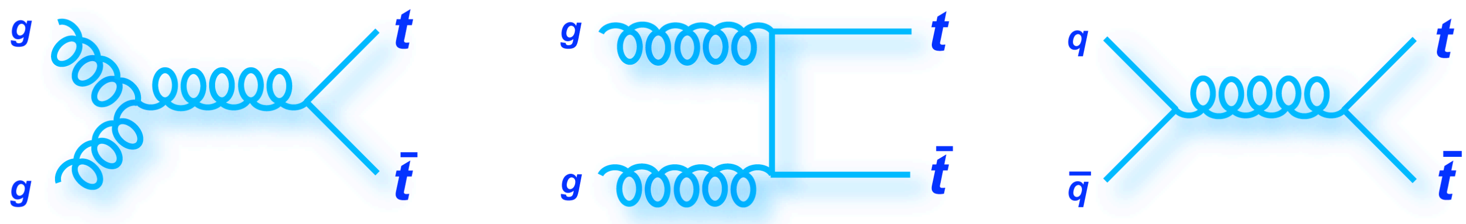
Top mass history (LHC)



Top production at hadron colliders

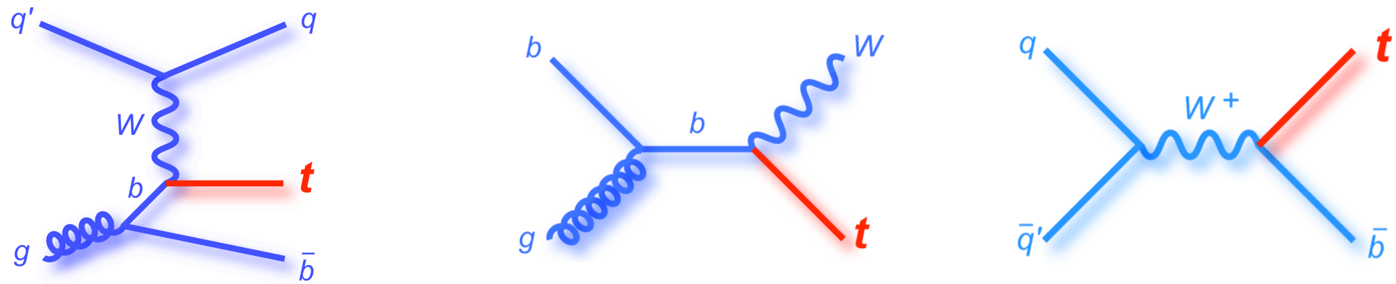
Czakon, et al.: PRL110(2013)252004
Cacciari et al.: PLB710,612 (2012)
Baernreuther et al.: PRL109,132001 (2012)
Czakon, Mitov: arXiv:1207.0236 (2012), arXiv:1210.6832 (2012)
N. Kidonakis: PRD83(2011)091503, PRD81(2010)054028 (2010), PRD82(2010)054018, arXiv:1205.3453

top-pair strong production gg dominates at LHC (85%) over qqbar (15%)



single-top electroweak production

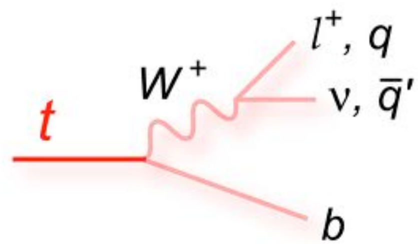
t channel | t W channel | s channel



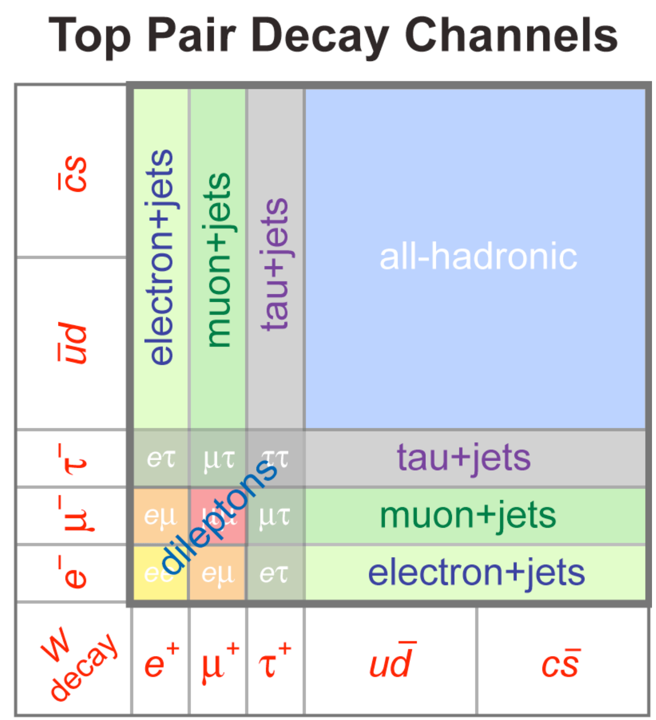
		t ch.	tW ch.	s ch.	$t\bar{t}$
Tevatron (**p$\bar{\text{p}}$**)	2 TeV	2.08pb	0.25pb	1.05pb	7.08pb
LHC (**pp**)	7 TeV	64.6pb	15.6pb	4.59pb	172pb
	8 TeV	87.6pb	22.2pb	5.55pb	249pb
	14 TeV	248pb (×3.2)	84.8pb (×3.8)	11.9pb (×2.1)	954pb (×3.9)

Top decay and final-state particles

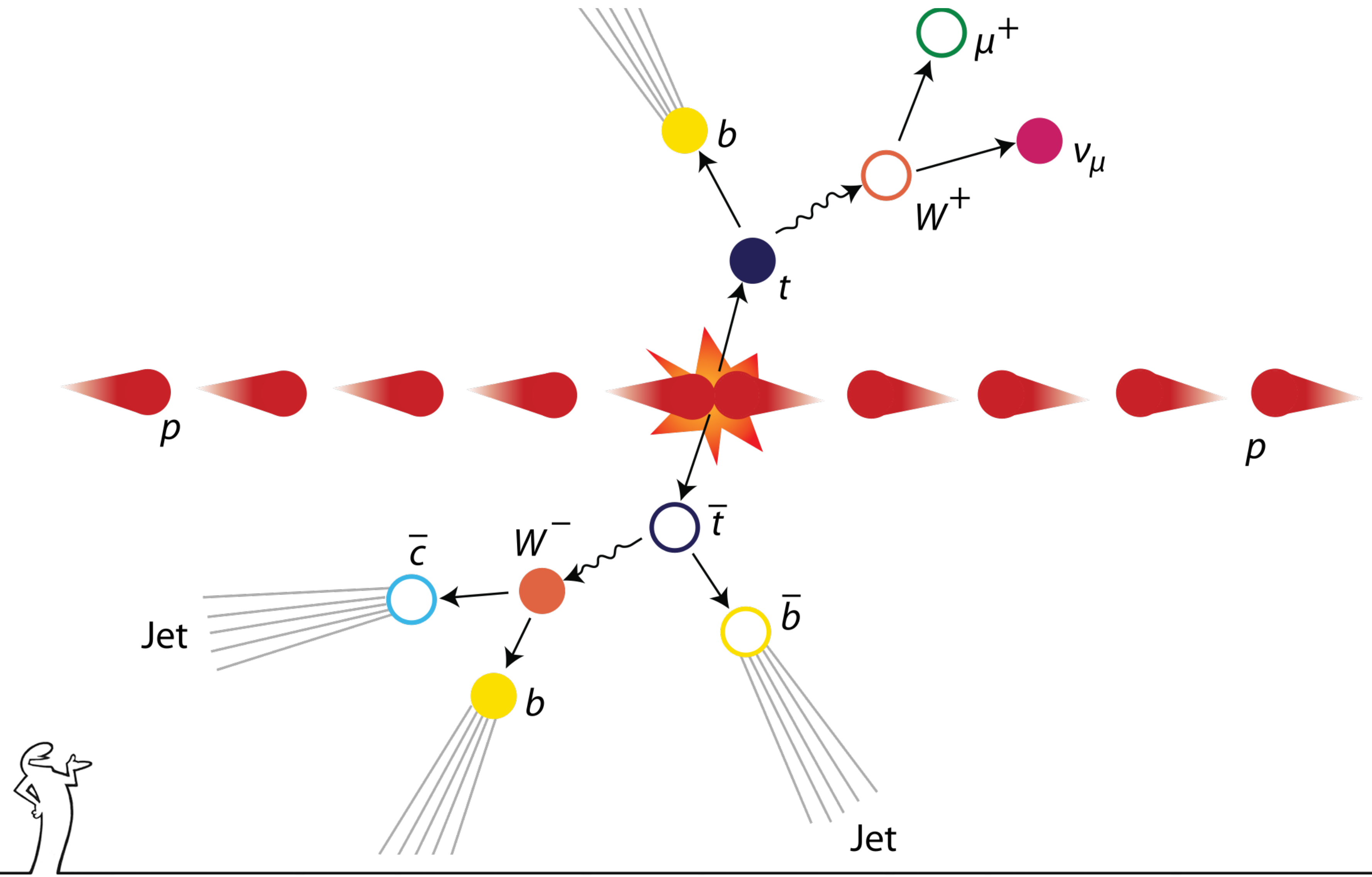
- The SM values for top coupling to other quarks (Cabibbo-Kobayashi-Maskawa matrix elements) are:
  $|V_{tb}| \approx 1$, $|V_{td}| \approx 4\times10^{-3}$, $|V_{ts}| \approx 4\times10^{-2}$
  → Top quark decays ~100% of the times to Wb
- W decays from $t \to Wb$ dictate top event signature
- Hadronic W decay:
  - Non-b jets are present in the event
- Leptonic W decay
  - Neutrinos accompany leptons
- Possible final states of a $tt^{bar} \to WWbb$ events:
  - Dileptonic (e, μ): ~5%
  - Leptons + jets (e, μ): ~30%
  - All hadronic: ~45%
- Two or more hadronic jets from b-quark fragmentation are present in a tt^{bar} event



W^+ DECAY MODES	Fraction (Γ_i/Γ)
$\ell^+\nu$	(10.80 ± 0.09) %
$e^+\nu$	(10.75 ± 0.13) %
$\mu^+\nu$	(10.57 ± 0.15) %
$\tau^+\nu$	(11.25 ± 0.20) %
hadrons	(67.60 ± 0.27) %

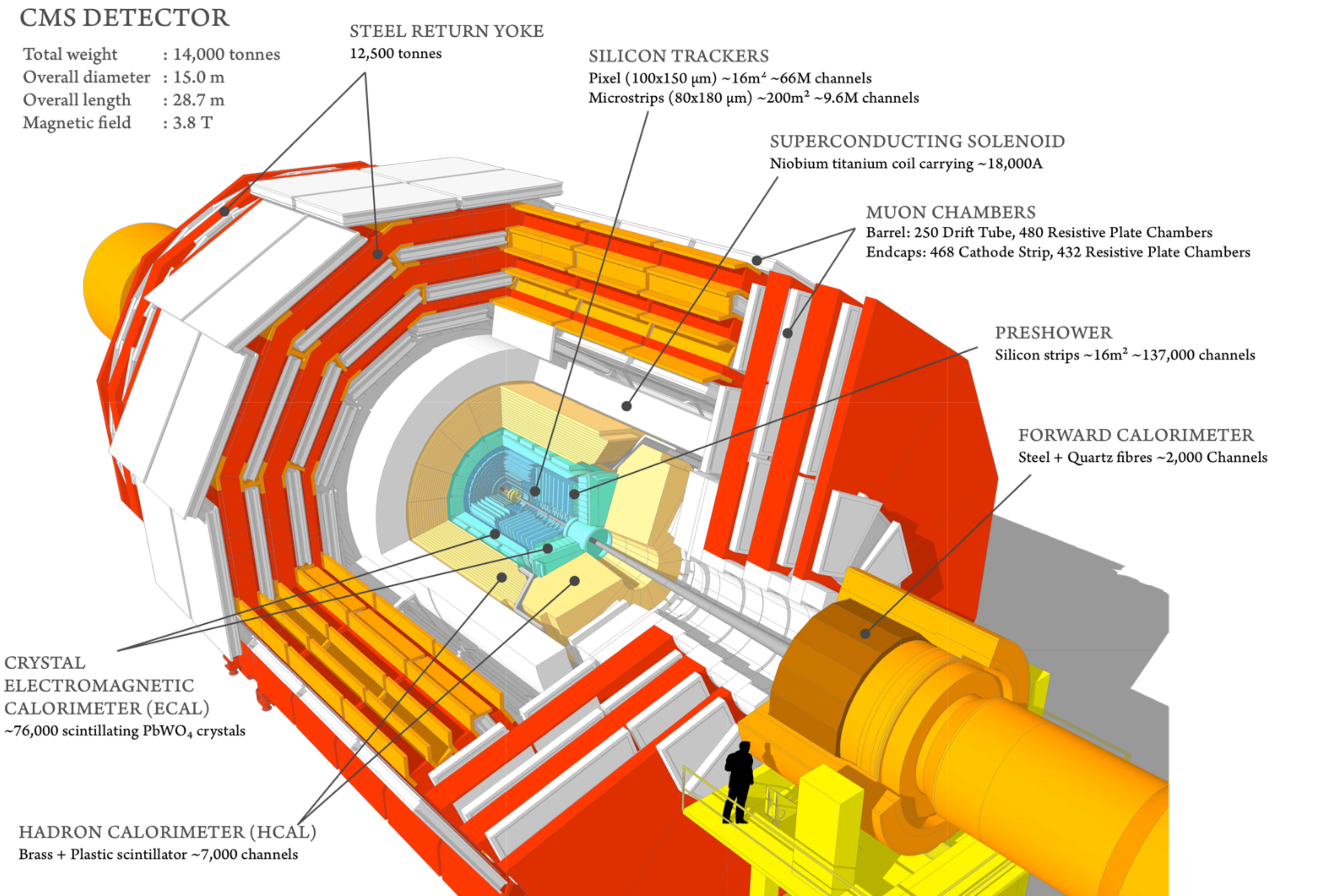


Typical $t\bar{t}$→lepton + jets event at LHC

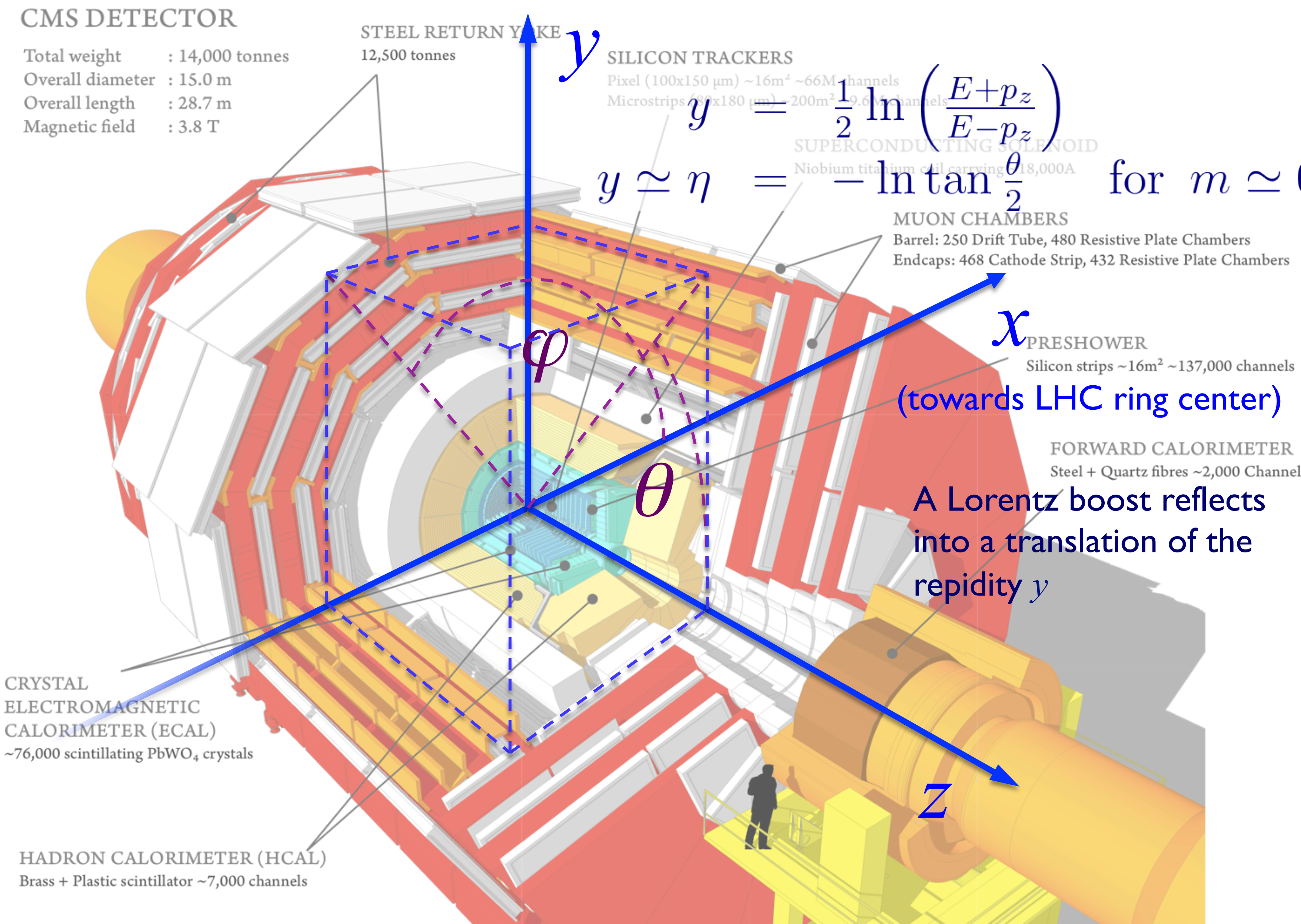


LHC experiments: CMS

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic Field : 3.8 T



Reference system, (pseudo)rapidity

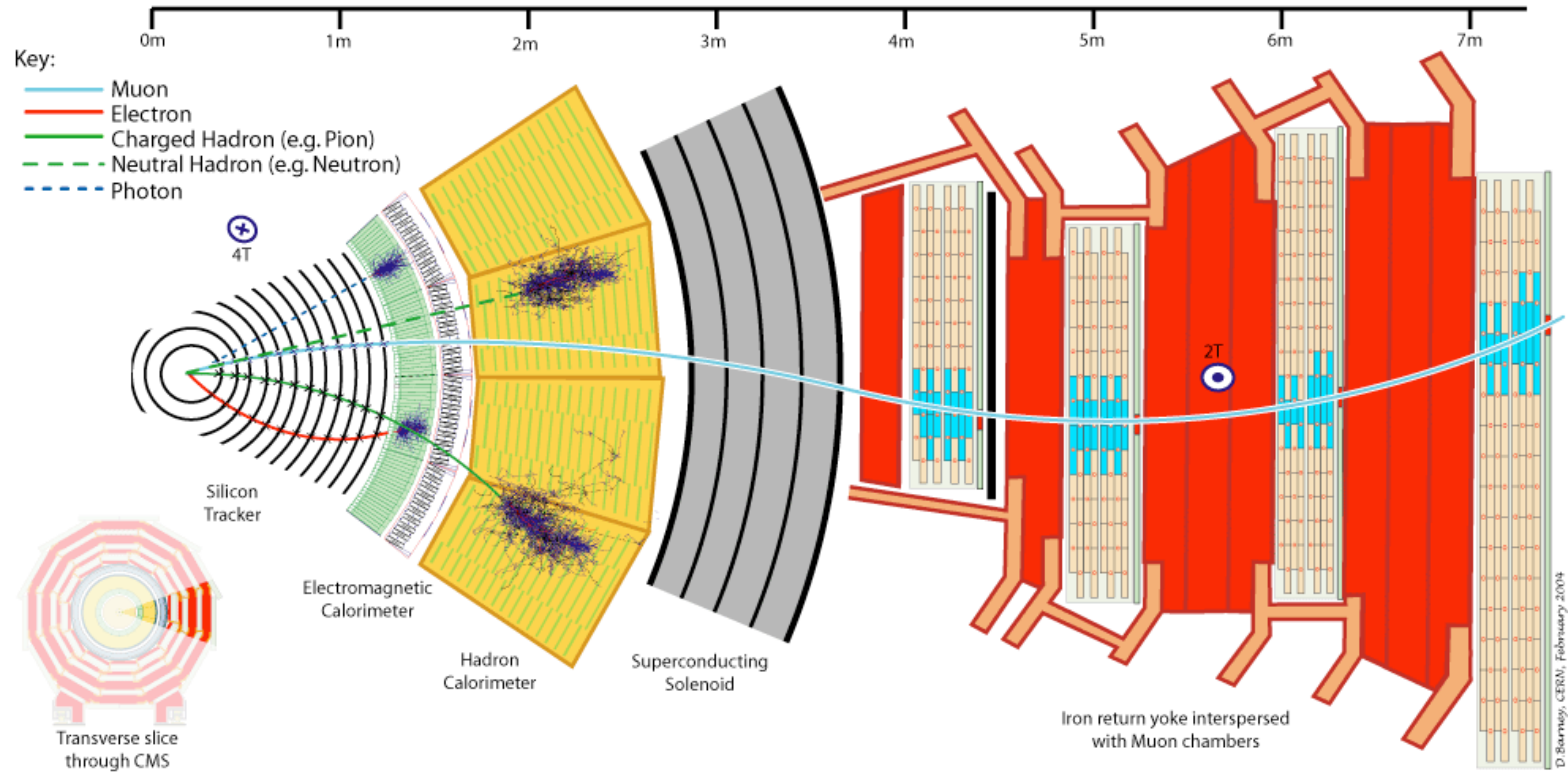


$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

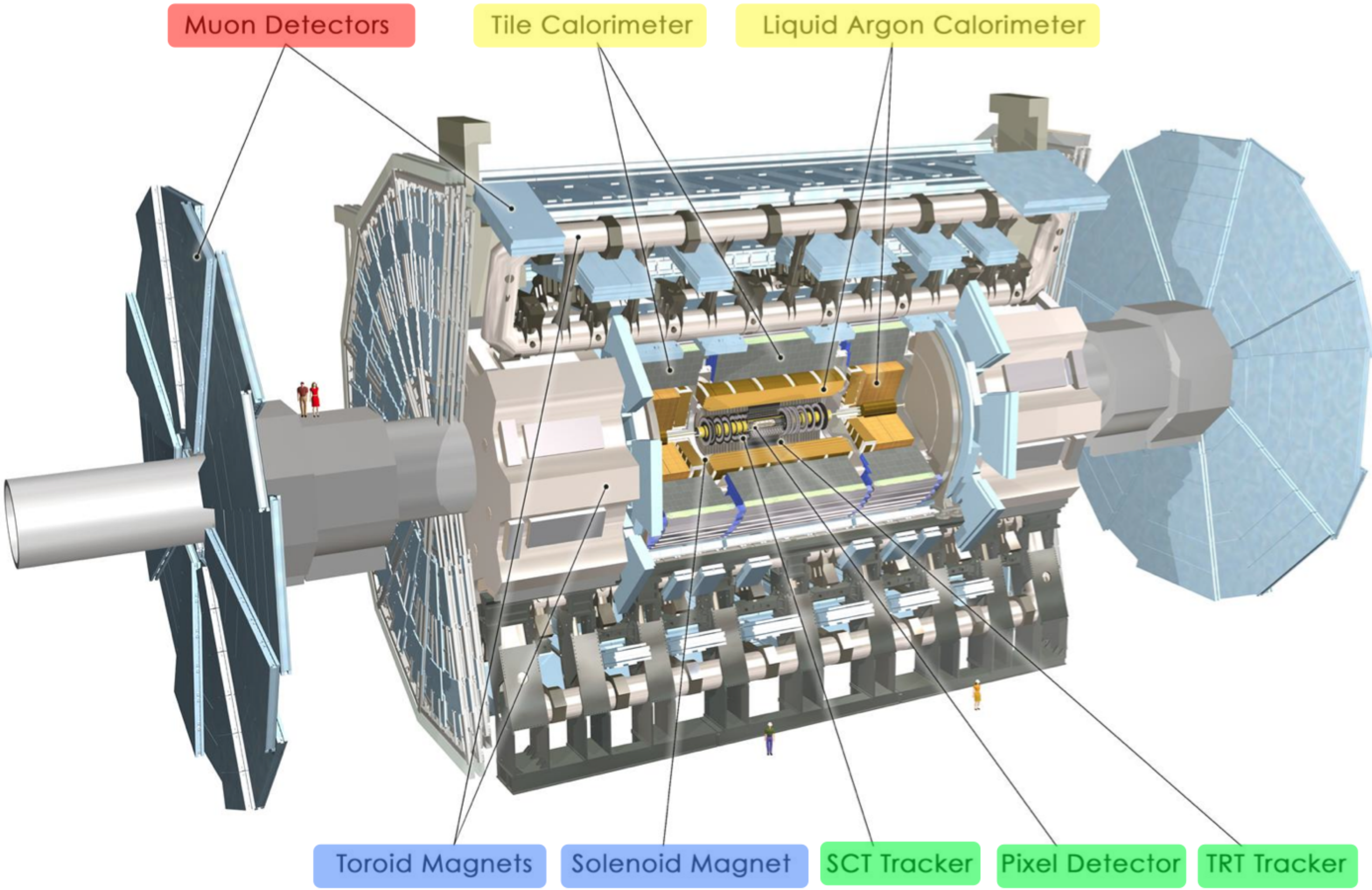
$$y \simeq \eta = -\ln\tan\frac{\theta}{2} \quad \text{for } m \simeq 0$$

A Lorentz boost reflects into a translation of the repidity y

Detecting final-state particles

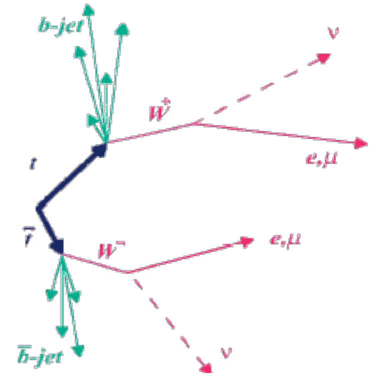


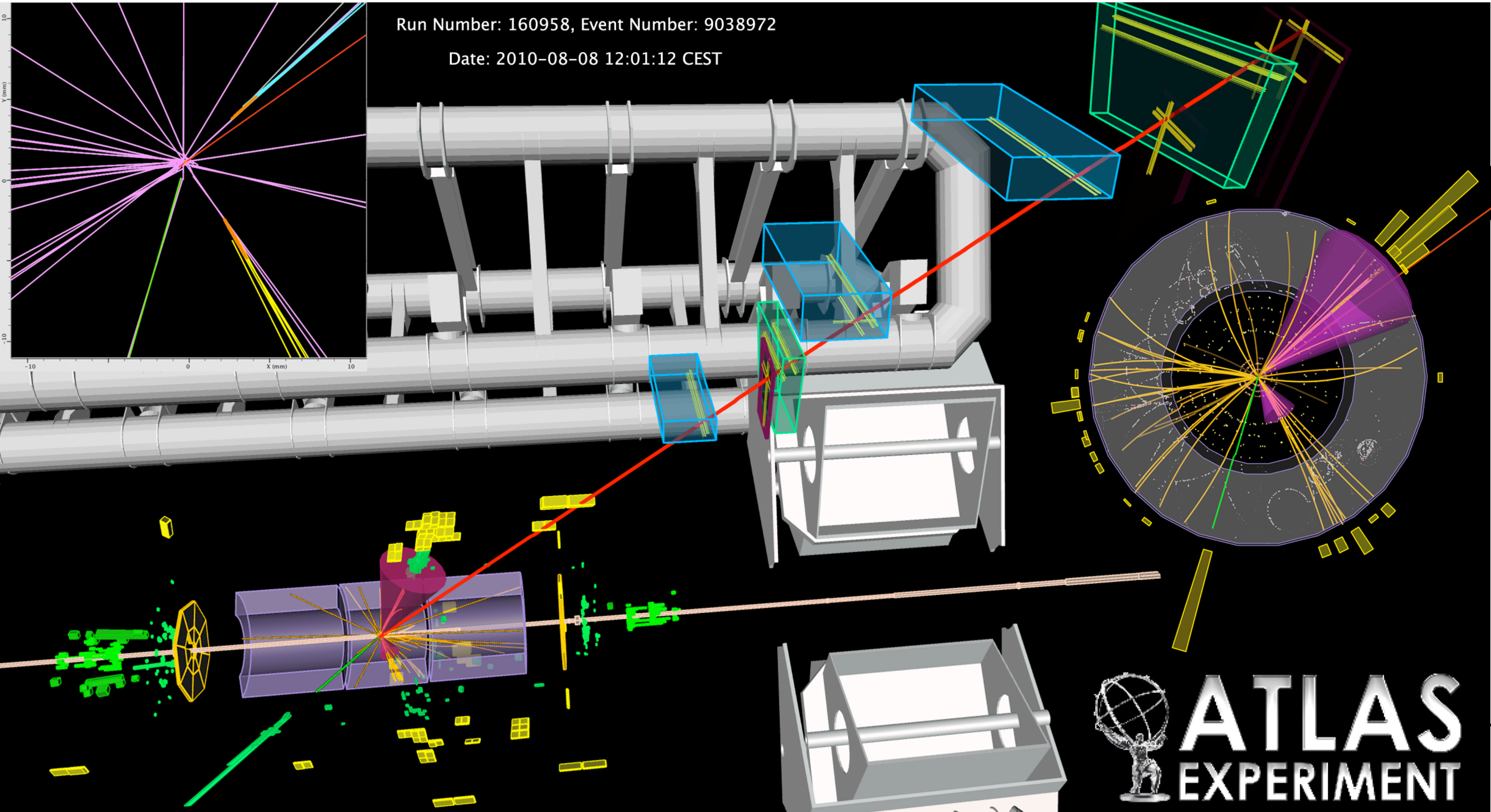
LHC experiments: ATLAS



A top candidate event

- $t \rightarrow (W^+ \rightarrow e^+\nu)b$, $\bar{t} \rightarrow (W^- \rightarrow \mu^-\nu)\bar{b}$





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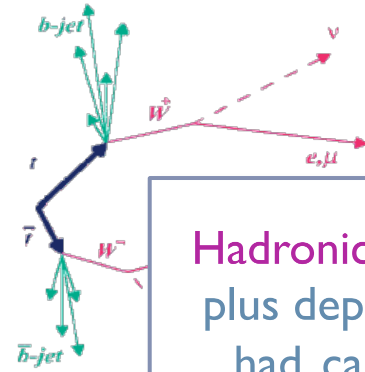

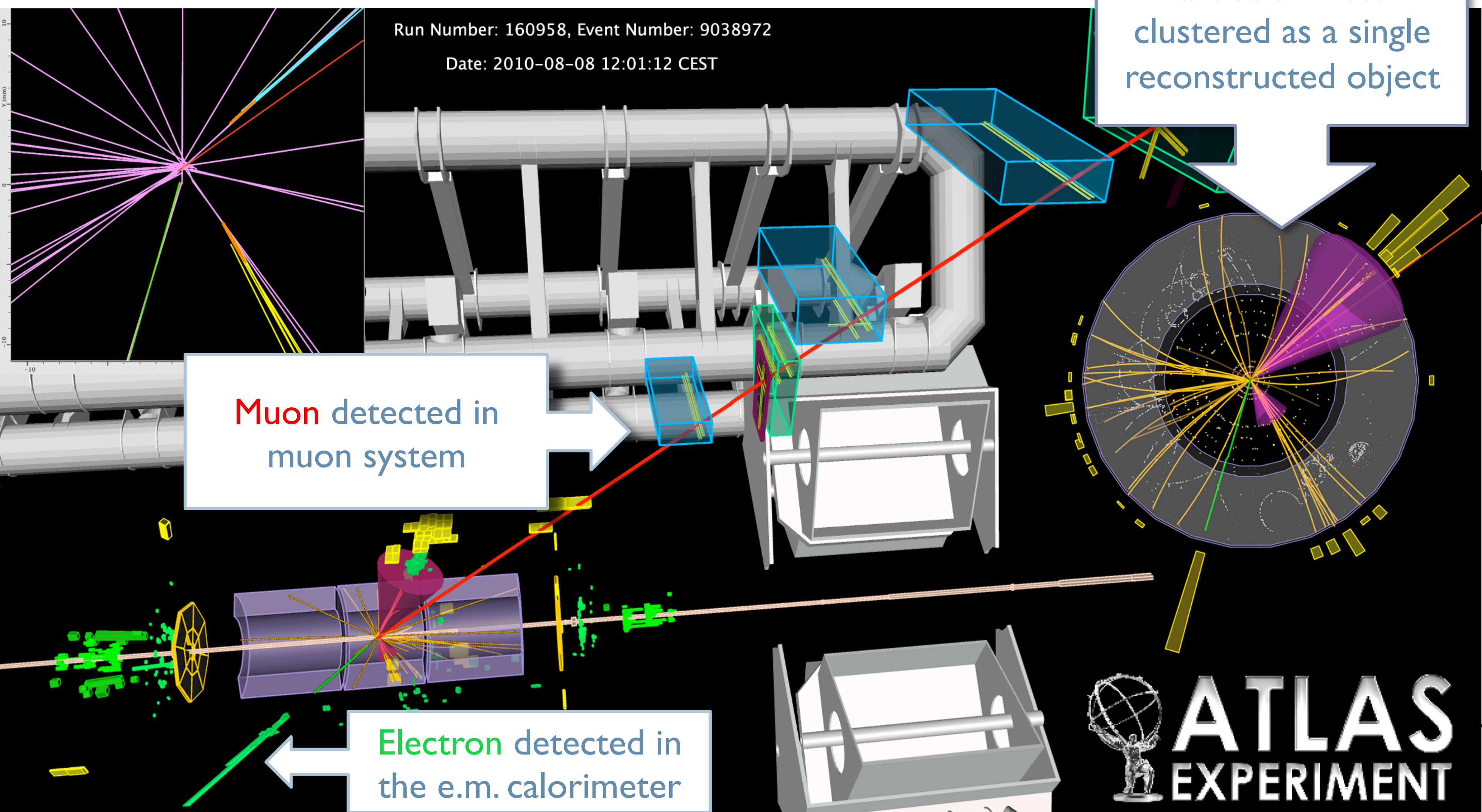

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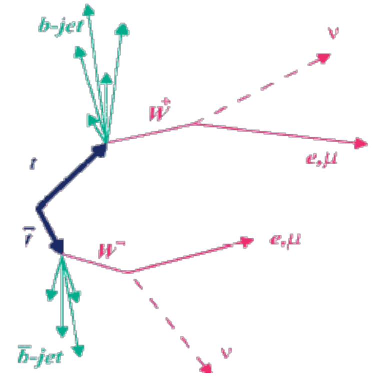
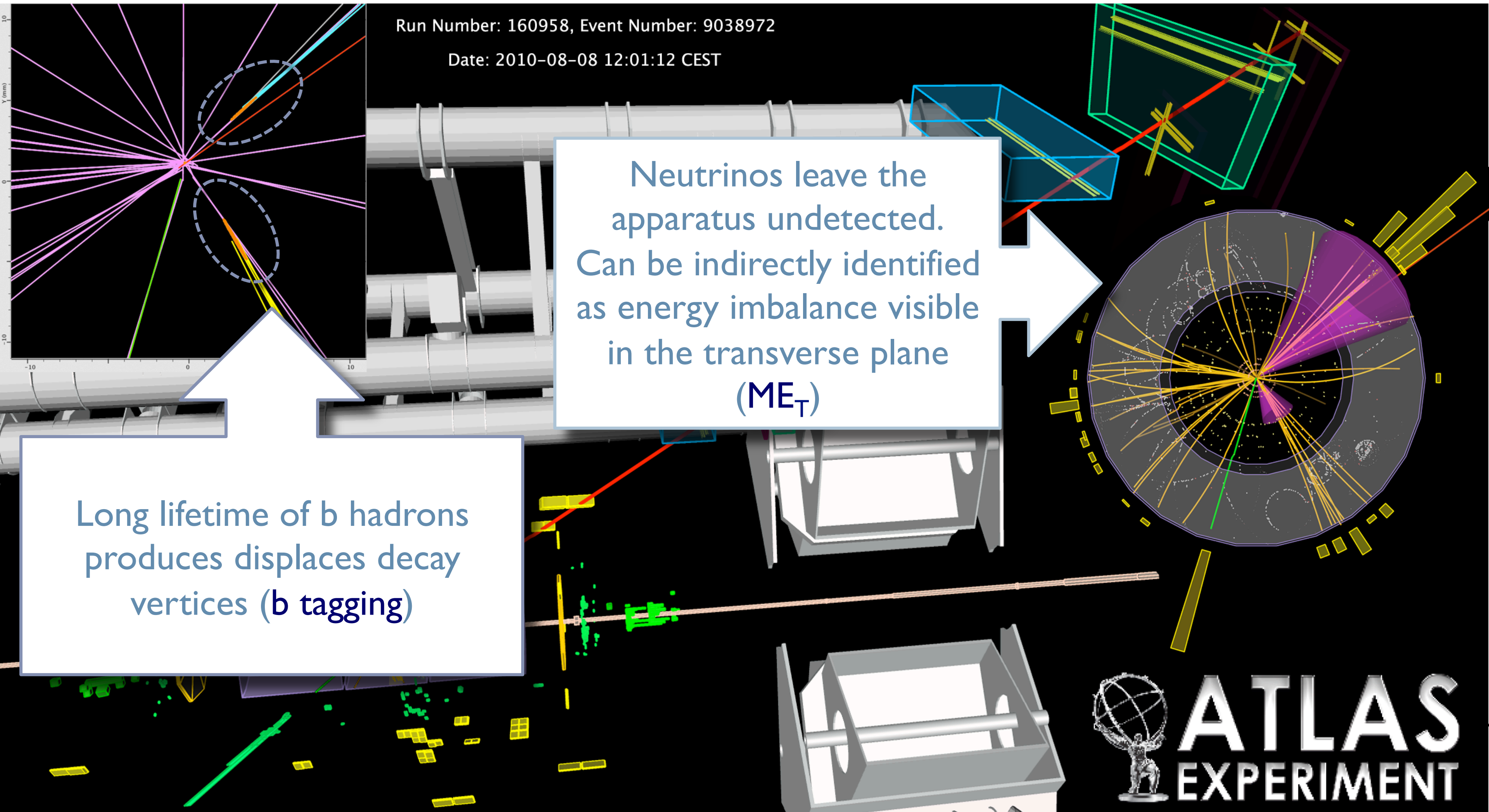


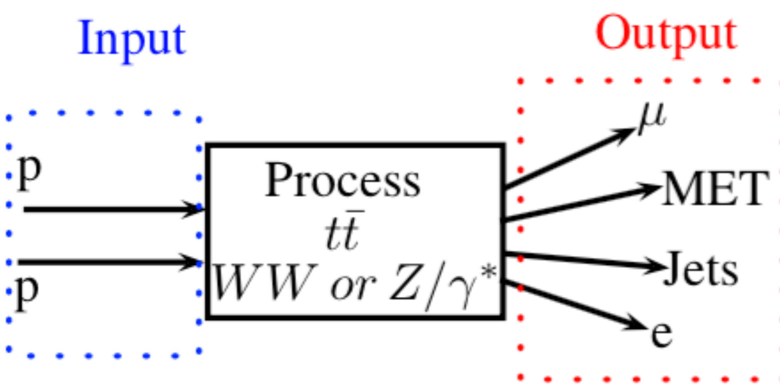


Neutrinos leave the apparatus undetected. Can be indirectly identified as energy imbalance visible in the transverse plane (ME_T)

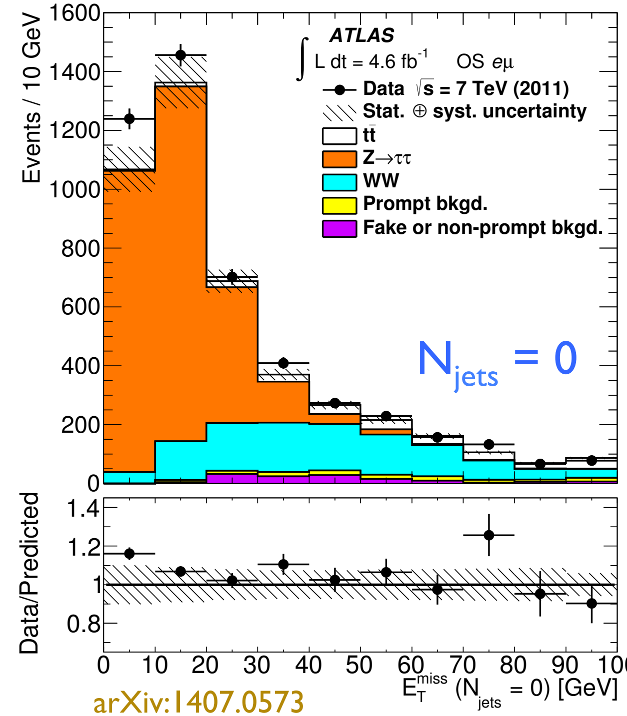
Long lifetime of b hadrons produces displaces decay vertices (b tagging)

Top-antitop cross section

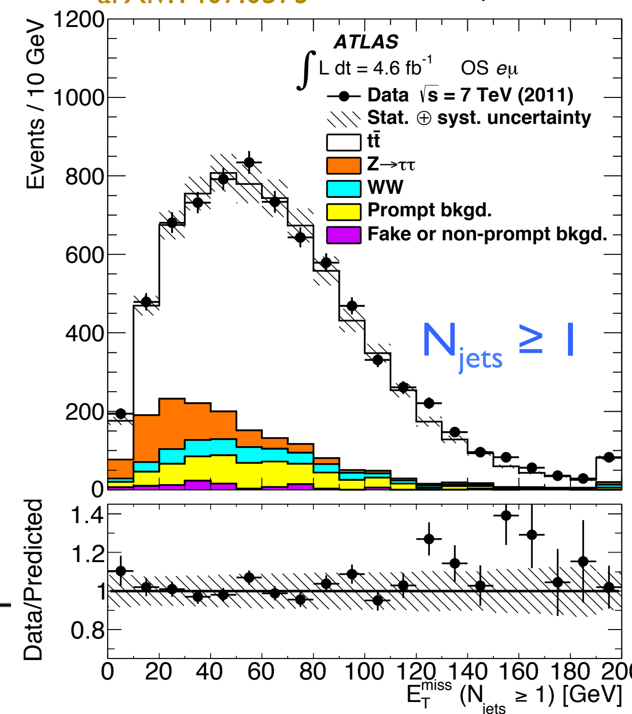
- Most precise measurements performed in the dileptonic channel
  - In particular, $e\mu$ less affected by Drell–Yan contamination ($Z^{(*)}\rightarrow e^+e^-$, $Z^{(*)}\rightarrow \mu^+\mu^-$)
- Main residual backgrounds with $e+\mu$+jets+ME_T in the final state: W^+W^-, $Z/\gamma^*\rightarrow\tau^+\tau^-$,



- Number of signal (tt^{bar}) and background (WW and Z/γ^*) events can be determined simultaneously from data using the distributions of ME_T and N_{jets}



arXiv:1407.0573



Top-antitop cross section

- From the signal yield in data, a fiducial cross section is first determined within kinematic boundaries
  - $E_T(e) > 25$ GeV, $|\eta(e)| < 2.47$ (excl. $1.37<|\eta(e)|<1.52$)
  - $p_T(\mu) > 20$ GeV, $|\eta(\mu)| < 2.5$
  - $p_T(\text{jet}) > 40$ GeV, $|\eta(\text{jet})| < 2\text{-}5$
- The fiducial cross section is then extrapolated to the entire phase space assuming the acceptance from the a generator simulation (MC@NLO)

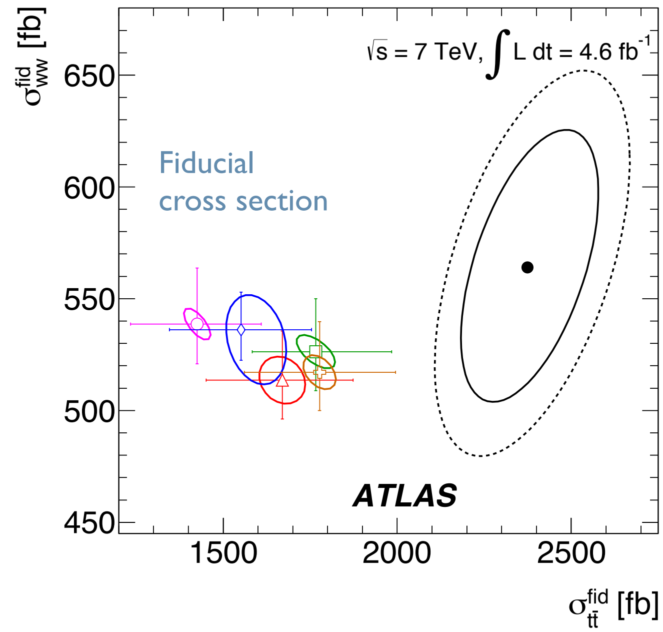
$$\sigma_{t\bar{t}}^{\text{tot}} = \frac{N^{\text{evt}}}{\varepsilon \times \mathcal{A} \times \mathcal{B} \times \mathcal{L}} = \frac{\sigma_{t\bar{t}}^{\text{fid}}}{\mathcal{A} \times \mathcal{B}}$$

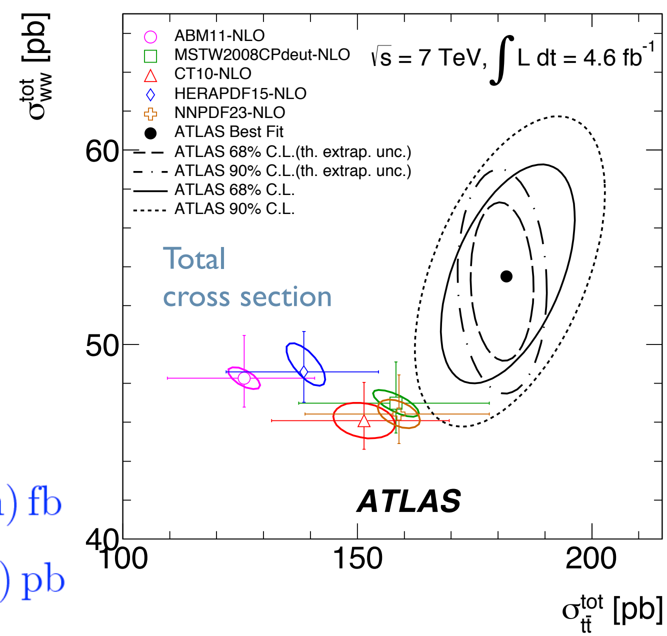
efficiency; acceptance (kinem. + geom.); branching fraction; integrated LHC luminosity

- Results:

$$\sigma_{t\bar{t}}^{\text{fid}} = 2730 \pm 40(\text{stat.}) \pm 140(\text{syst.}) \pm 50(\text{lumi.}) \pm 50(\text{beam})\ \text{fb}$$

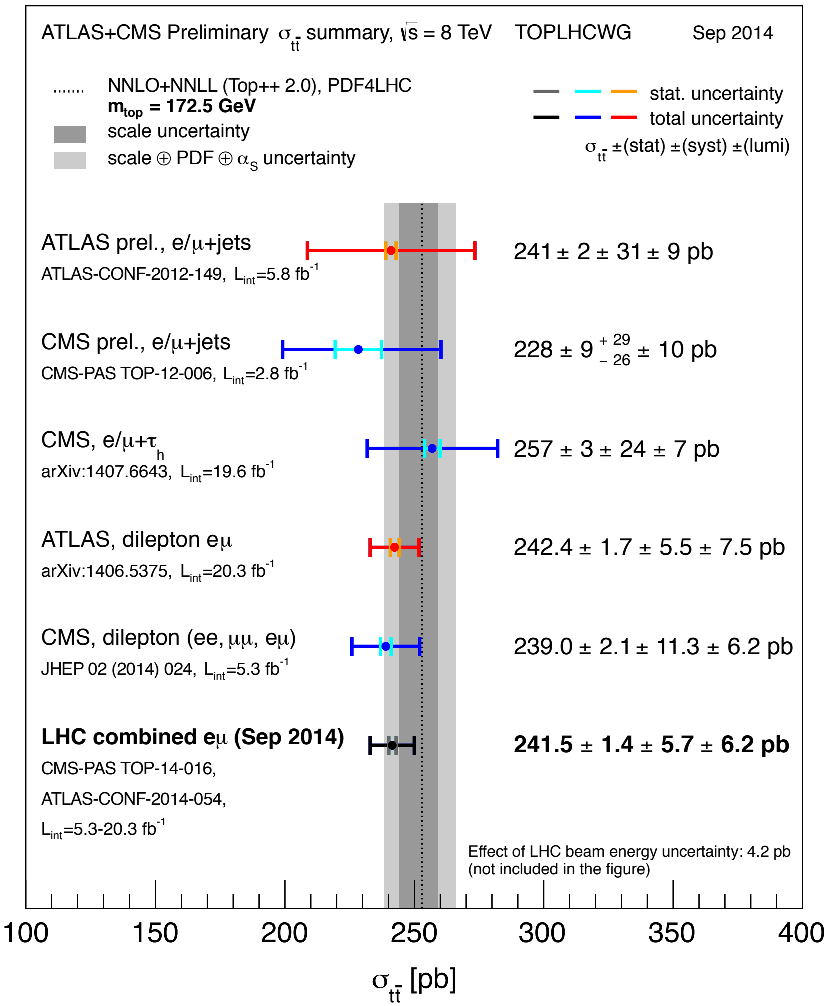
$$\sigma_{t\bar{t}}^{\text{tot}} = 181.2 \pm 2.8(\text{stat.})^{+9.7}_{-9.5}(\text{syst.}) \pm 3.3(\text{lumi.}) \pm 3.3(\text{beam})\ \text{pb}$$

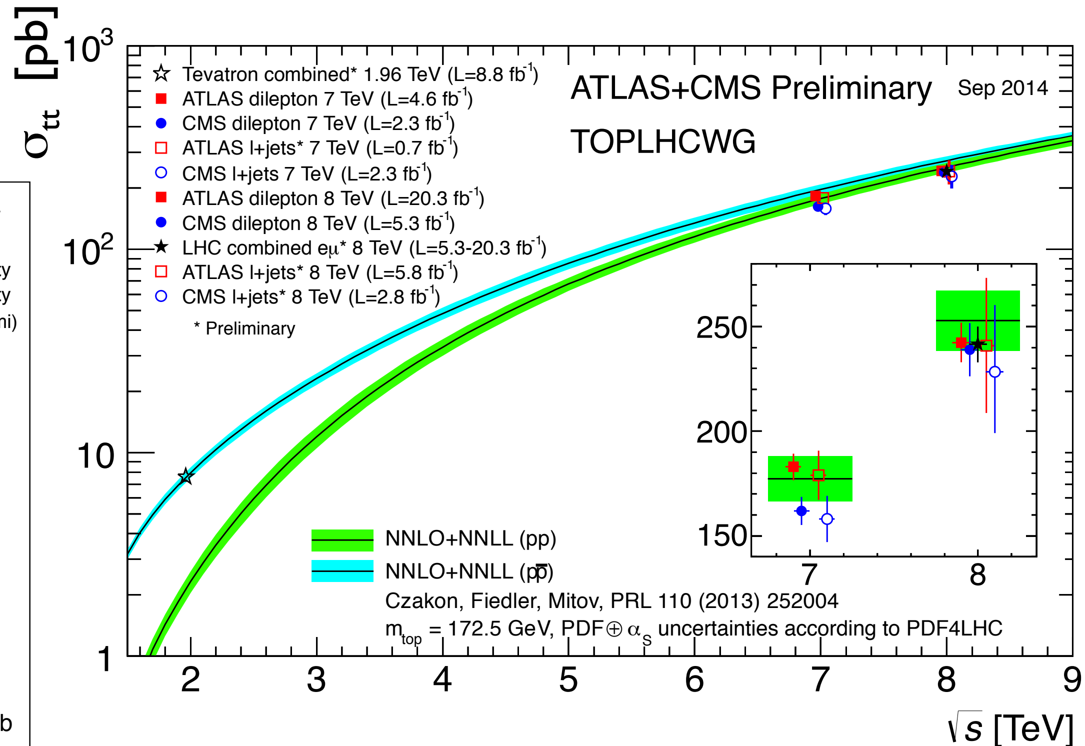


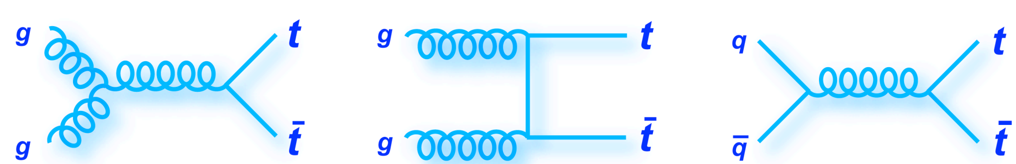


$t\bar{t}$ results and LHC combination

- Results in agreement with theory predictions

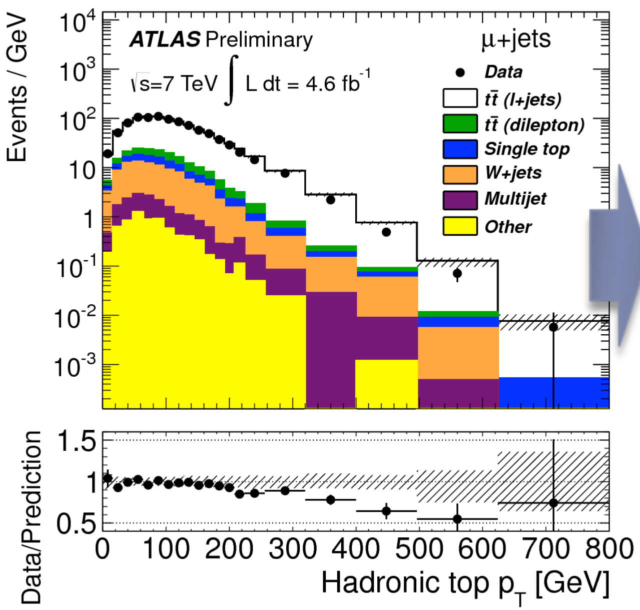


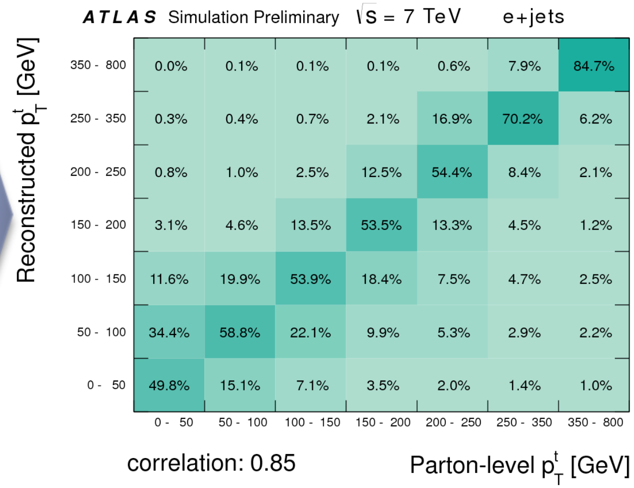


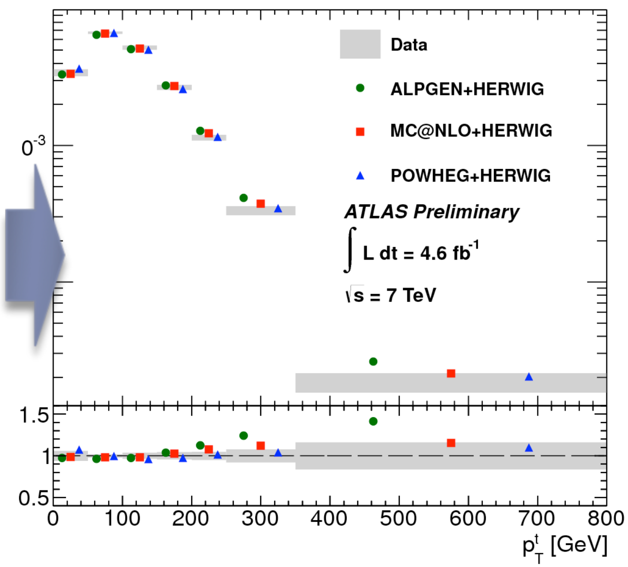


Differential measurements

- Subtract background + unfold experimental removing instrumental effects by correcting bin-by-bin migrations





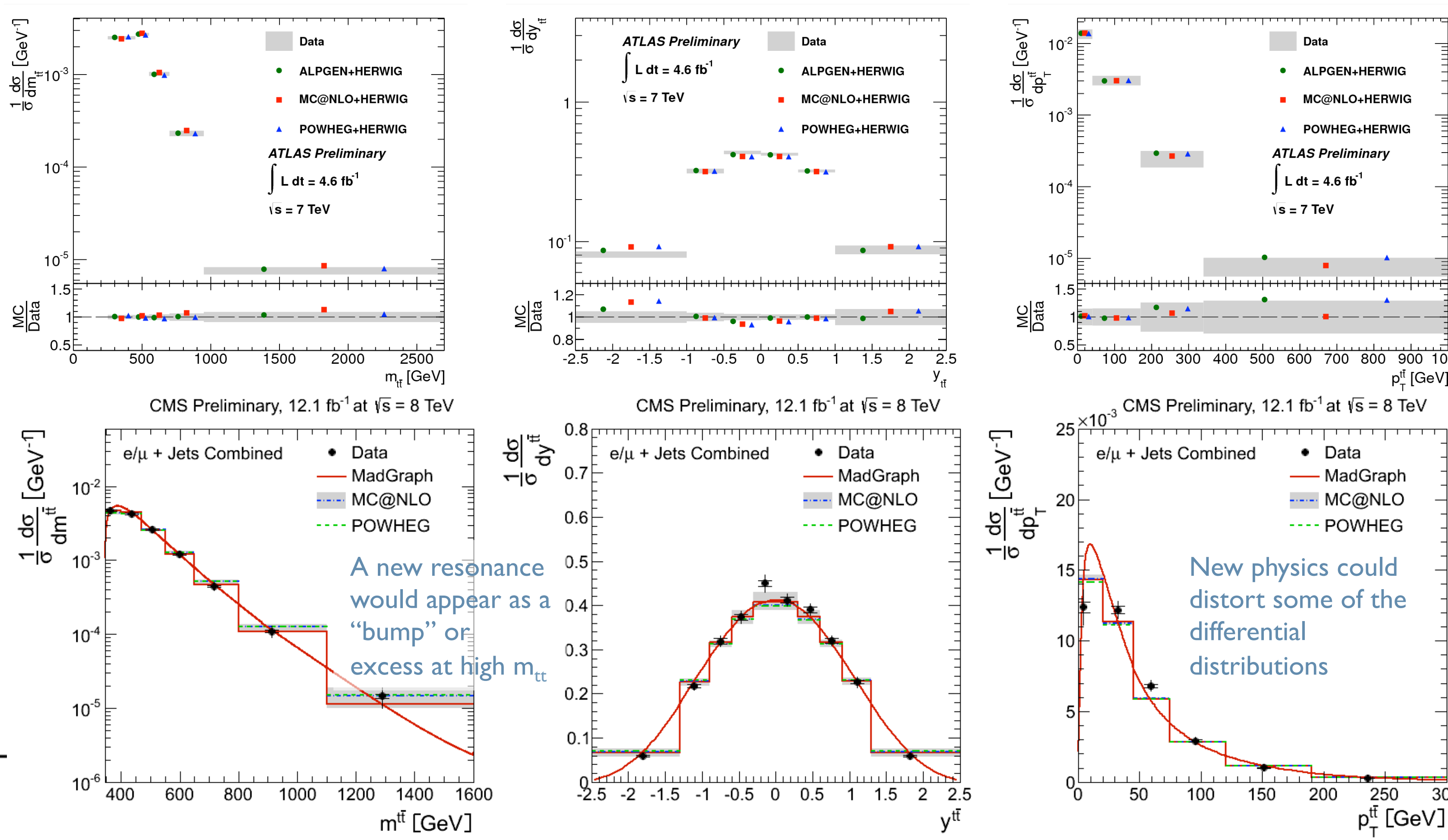


- Precise measurements of top-quark distributions are a crucial task:
  - Tests of perturbative QCD in different phase space regions
  - Enhance sensitivity to New Physics in top processes
  - Control background for Higgs, rare processes and many Beyond-Standard-Model searches

$t\bar{t}$ pair: m_{tt}, y_{tt}, p_T^{tt}

ATLAS-CONF-2013-099 (l+jets, 7 TeV)
ATLAS: EPJC73 (2013) 2339 (dileptons, 7 TeV)
CMS-PAS TOP-12-027 (l+jets, 8 TeV)
CMS-PAS TOP-12-028 (dileptons, 8 TeV)

- Potentially sensitive to new physics!
- Many distribution studied, good agreement with theory predictions so far



A new resonance would appear as a "bump" or excess at high m_{tt}

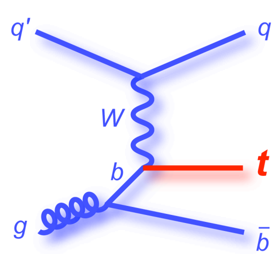
New physics could distort some of the differential distributions

Single-top production

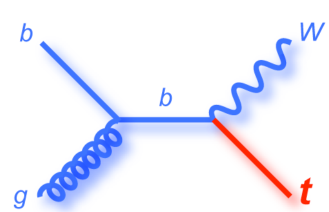
- Electroweak top-production
- Unique opportunity to study the Wtb vertex at production
  - May be sensitive to new physics
    - *t*-channel: Flavour-changing neutral currents
    - *s*-channel: W', H^+, …
  - Measure $|V_{tb}|$ in the production vertex
    - New physics may be not accessible in decay if new particles are too heavy
  - Possibly constrain proton's PDF

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{uX}? \\ V_{cd} & V_{cs} & V_{cb} & V_{cX}? \\ V_{td} & V_{ts} & V_{tb} & V_{tX}? \\ V_{Yd}? & V_{Ys}? & V_{Yt}? & V_{YX}? \end{pmatrix}$$

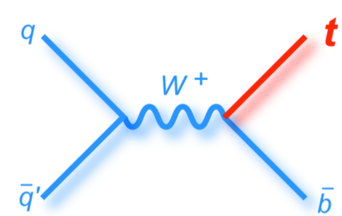
t channel



t W channel

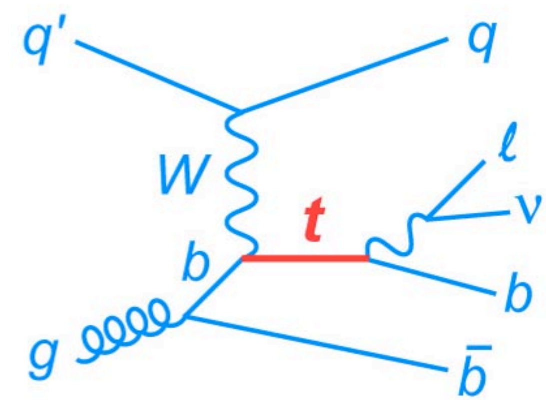


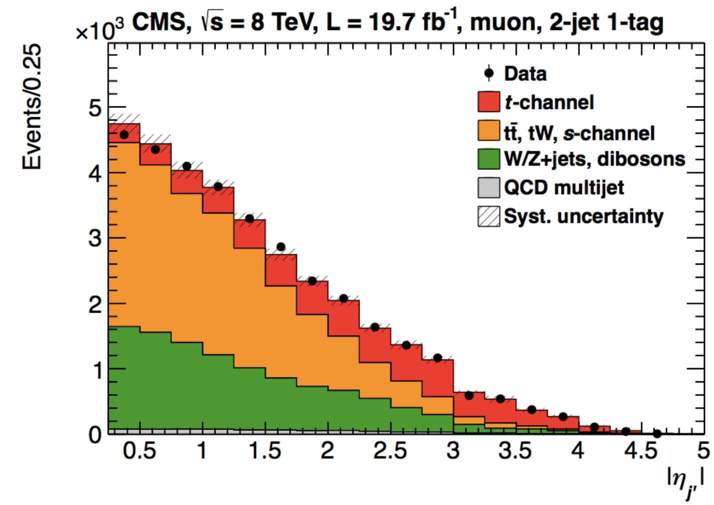
s channel

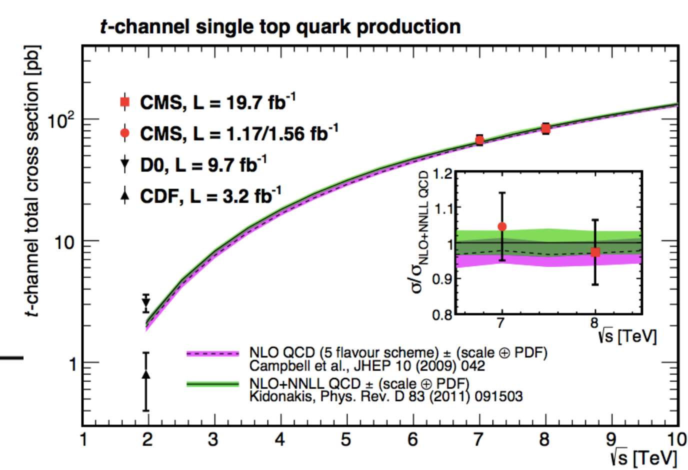


t channel: CMS

- Signal selection: one e or μ, two jets of which one b tagged, one forward
- Number of signal and background (W+jets, $t\bar{t}$) events determined from a fit to the $|\eta_{j'}|$ distribution
- Distributions for W+jets and $t\bar{t}$ are determined from control regions in data (*n*-jets, *m*-b tags)
  - $\sigma_{t\text{-ch.}} = 83.6 \pm 2.3(\text{stat}) \pm 7.4(\text{syst})$ pb
  - $R_{8/7} = 1.24 \pm 0.08(\text{stat}) \pm 0.12(\text{syst})$
- Largest uncertainty: signal modeling (generator), jet energy scale



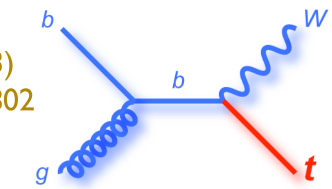




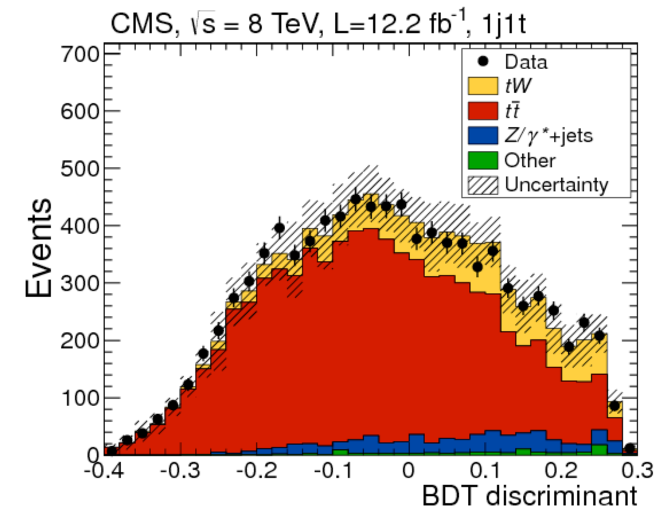
JHEP06(2014)090
CMS PAS TOP-12-002/ATLAS-COM-CONF-2013-061

tW, s-ch. production

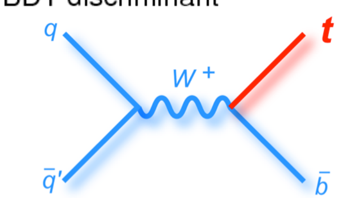
7 TeV: Phys.Rev.Lett 110, 022003 (2013)
8 TeV: Phys. Rev. Lett. 112 (2014) 231802



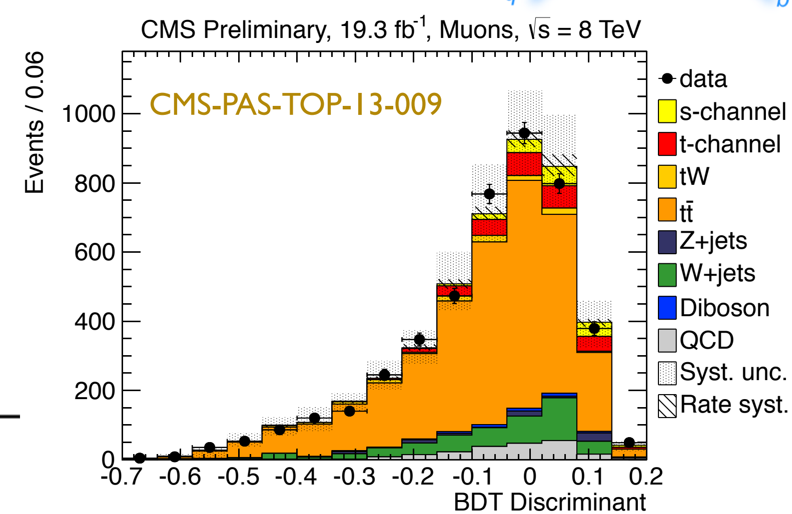
- More rare modes affected by large background due to tt^{bar} events
- Probe different production modes
- Multivariate discriminators (Boosted Decision Trees) adopted to enhance the signal/ background separation.



- tW (12.2fb^{-1}, 8TeV):
  $\sigma_{tW} = 23.4^{+5.5}_{-5.4}$ pb
  significance: 6.1σ obs. ($5.4^{+1.5}_{-1.4}$σ exp.)



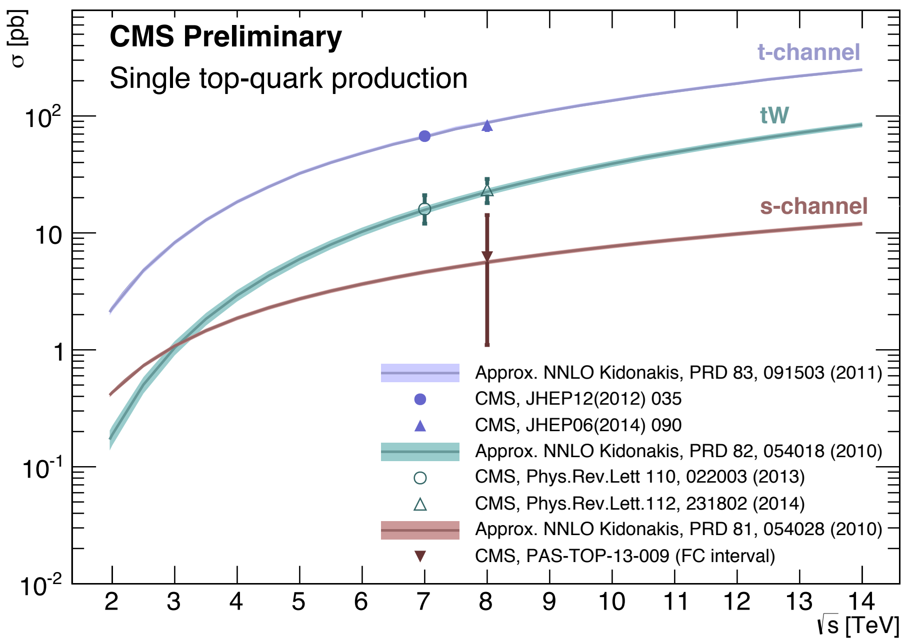
- s-ch. (19.3fb^{-1}, 8TeV):
  $\sigma_{s\text{-ch.}} < 11.5$ pb = 2.1× σ SM, 95%CL
  - Assuming SM signal:
    $\sigma_{s\text{-ch.}} = 6.2^{+8.0}_{-5.1}$ pb (68% FC int.)
  - Significance: 0.9σ exp, 0.7σ obs

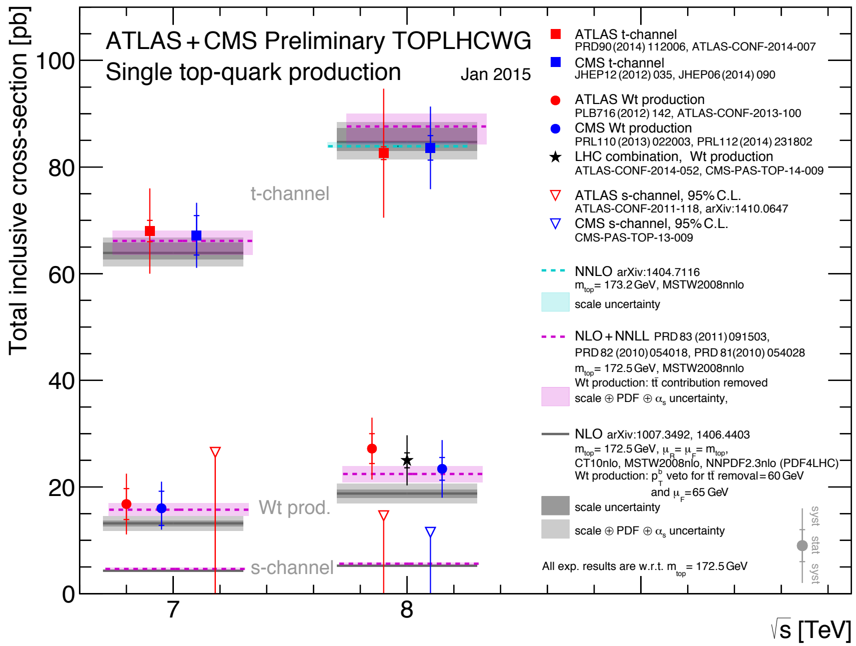


- Main limitation to both channel is the modeling of the very large tt^{bar} background

Single top LHC cross sect. summary

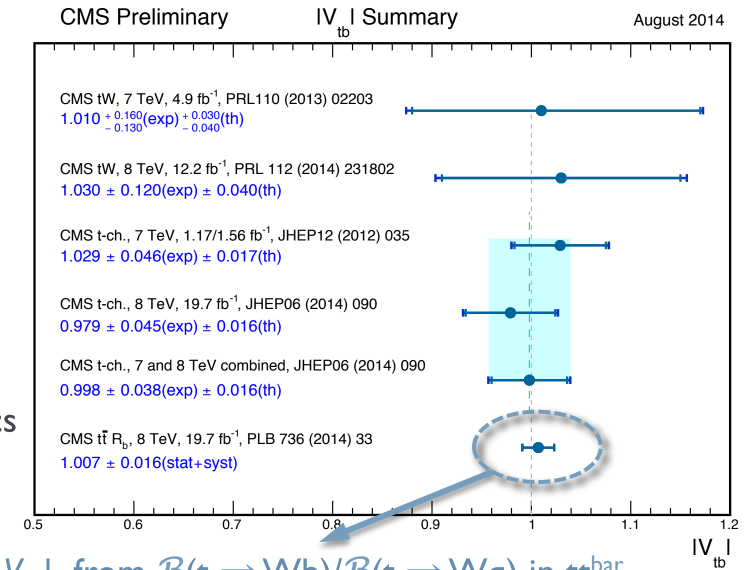
- All measurements are in agreement with theory calculations (reached the NNLO or approx. NNLO)





$|V_{tb}|$ from single top

- The $|V_{tb}|$ measurement in single-top events provides a unique opportunity to directly probe the top production Wtb vertex: $|V_{tb}| = \sqrt{(\sigma/\sigma^{th}(|V_{tb}|=1))}$, assuming $|V_{tb}| \gg |V_{ts}|, |V_{td}|$ or equivalently $\mathcal{B}(t\rightarrow Wb) = 1$
  - Deviations from the SM are potentially sensitive to new physics
- Eight measurements in the *t* channel and in tW, the latter with less precision



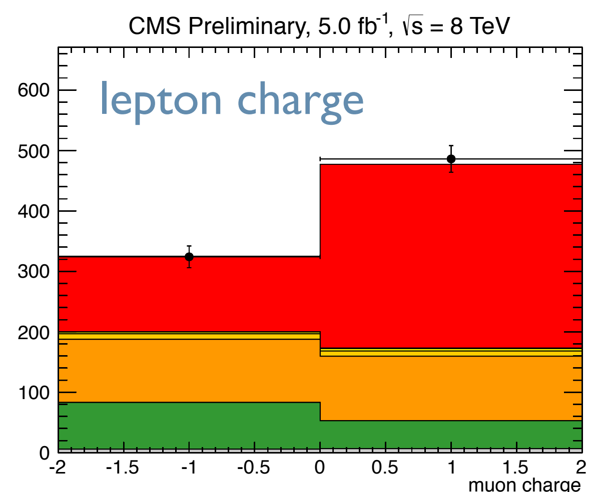
$|V_{tb}|$ from $\mathcal{B}(t\rightarrow Wb)/\mathcal{B}(t\rightarrow Wq)$ in $t\bar{t}$

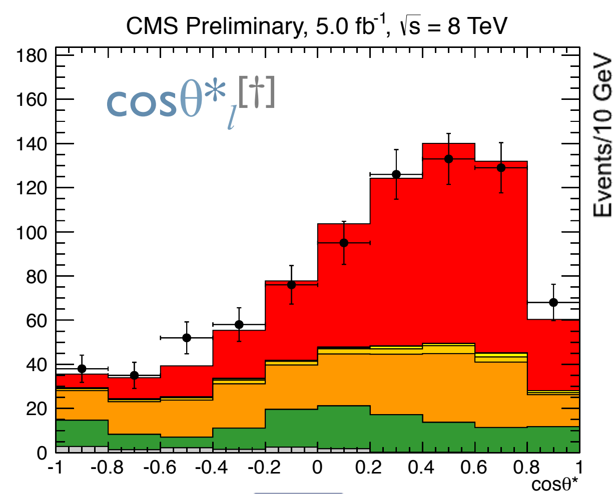
- ATLAS:
  - 7 TeV: $|V_{tb}| = 1.13^{+0.14}_{-0.13}$ (t-ch., 11.9%)
    $|V_{tb}| = 1.03^{+0.16}_{-0.19}$ (tW, 17.0%)
  - 8 TeV: $|V_{tb}| = 0.97 \pm 0.01(\text{stat})^{+0.06}_{-0.07}(\text{syst}) \pm 0.6(\text{gen+PDF})^{+0.02}_{-0.01}(\text{th}) \pm 0.01(\text{lumi})$
    $= 0.97^{+0.09}_{-0.10}$ (t-ch., 9.8%)
    $|V_{tb}| = 1.10 \pm 0.12(\text{exp}) \pm 0.03(\text{th})$ (tW, 11.2%)
- CMS:
  - 7 TeV: $|V_{tb}| = 1.020 \pm 0.046(\text{exp}) \pm 0.017(\text{th})$ (t-ch. 4.8%)
    $|V_{tb}| = 1.01^{+0.16}_{-0.13}(\text{exp})^{+0.03}_{-0.04}(\text{th})$ (tW, 14.8%)
  - 8 TeV: $|V_{tb}| = 0.979 \pm 0.045(\text{exp}) \pm 0.016(\text{th})$ (t-ch. 4.9%)
    $|V_{tb}| = 1.03 \pm 0.12(\text{exp}) \pm 0.04(\text{th})$ (tW 12.3%)

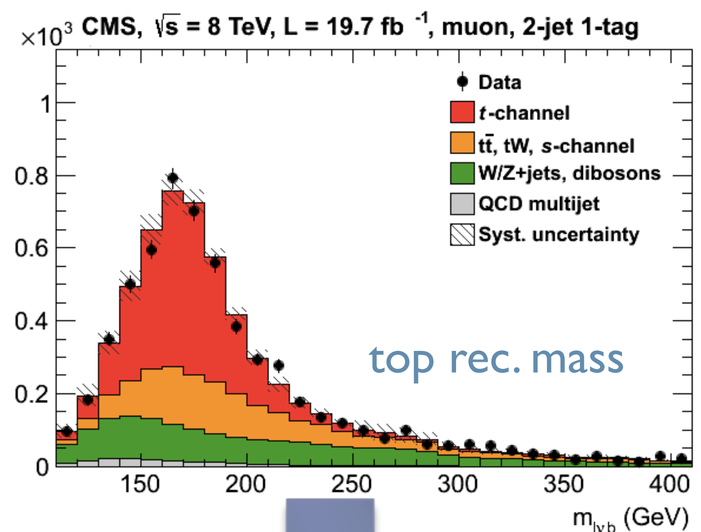
  t-ch. 7 TeV and 8 TeV combined: $|V_{tb}| = 0.998 \pm 0.038(\text{exp}) \pm 0.016(\text{th})$ (7+8 TeV t-ch., comb.: 4.1%)

t-channel: distributions

- The t-channel data sample is large enough to study distributions
  - → differential cross section measurements
- Signal can be enhanced by requiring e.g.: large forward jet pseudorapidity: $|\eta_{j'}| > 2.0$







Top/antitop σ ratio, ATLAS-CONF-2012-056, JHEP06(2014)090

Top polarization, CMS-PAS-TOP-13-001
W helicity, JHEP 01 (2015) 053

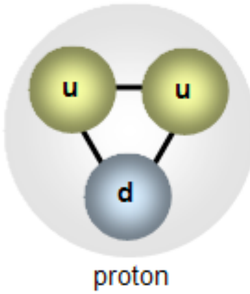
Top mass, ATLAS-CONF-2014-055

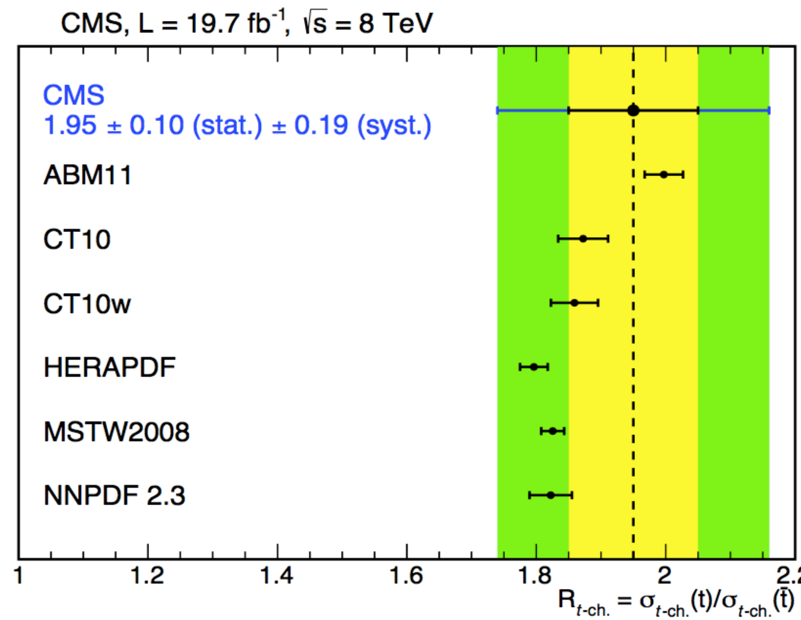
[†] $\theta*_l$ = angle between lepton in W rest frame and the W in top rest frame.

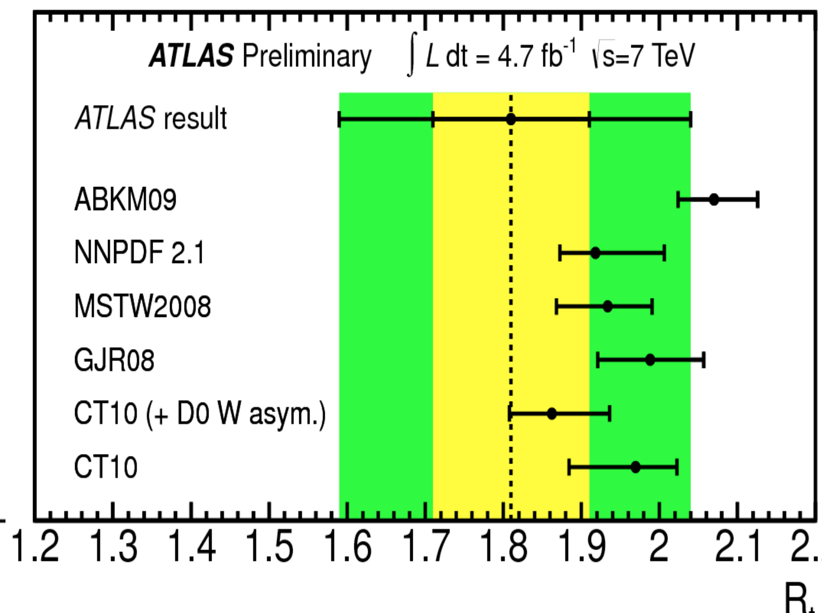
7 TeV: ATLAS-CONF-2012-056
8 TeV: CMS: JHEP06(2014)090

Top/antitop ratio

- $R_t = \sigma_t(t)/\sigma_t(t^{bar})$ is potentially sensitive to the proton's PDF
- ATLAS, 7 TeV:
  - $\sigma_t(t) = 53.2 \pm 10.8$ pb, $\sigma_t(t^{bar}) = 29.5\ ^{+7.4}_{-7.5}$ pb
  - $R_t = 1.81\ ^{+0.23}_{-0.22}$
- CMS, 8 TeV:
  - $\sigma_t(t) = 53.8 \pm 1.5(\text{stat}) \pm 4.4(\text{syst})$ pb, $\sigma_t(t^{bar}) = 27.6 \pm 1.3(\text{stat}) \pm 3.7(\text{syst})$ pb
  - $R_t = 1.95 \pm 0.10(\text{stat}) \pm 0.19(\text{syst})$
- Approaching the precision necessary to discriminate between different PDF models
  - Main sources of uncertainty: jet energy scale, signal modeling







Top quark polarization

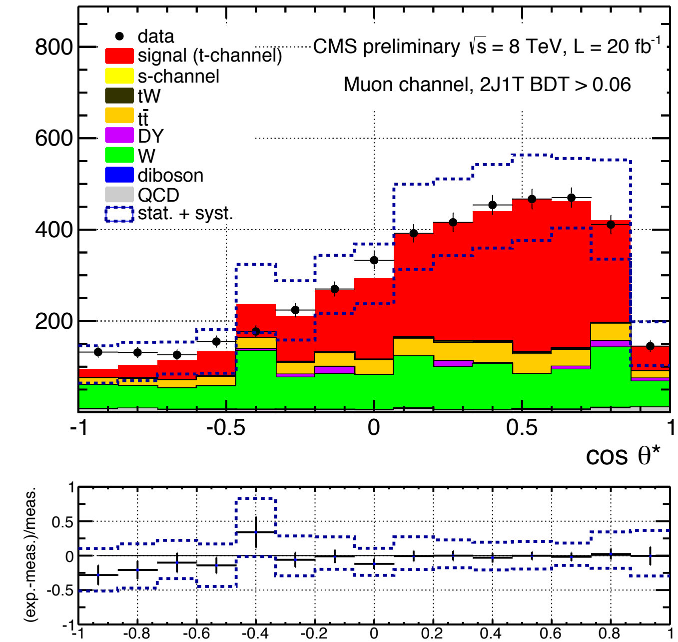
- Test of parity violation in the SM performed on a "free" quark at the production vertex
  - The top quark from electroweak production is 100% polarized due to the *V–A* structure of the interaction at the Wtb production vertex

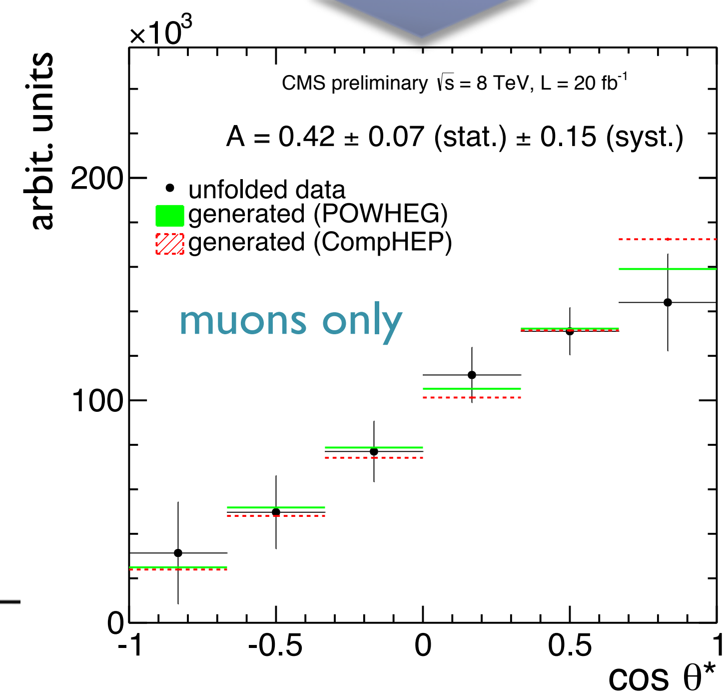
- In the SM $P_t = 1$: $$A_l = \frac{1}{2}P_t = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

- The cos θ *[†] distribution is obtained in a signal-enriched sample after unfolding the experimental effects, and compared to:

$$\frac{d\Gamma}{d\cos\theta^*} = \frac{\Gamma}{2}(1 + P_t \cos\theta^*)$$

- Measured top polarization:
  $P_t = 0.82 \pm 0.12(\text{stat}) \pm 0.32(\text{syst})$, e+μ combined

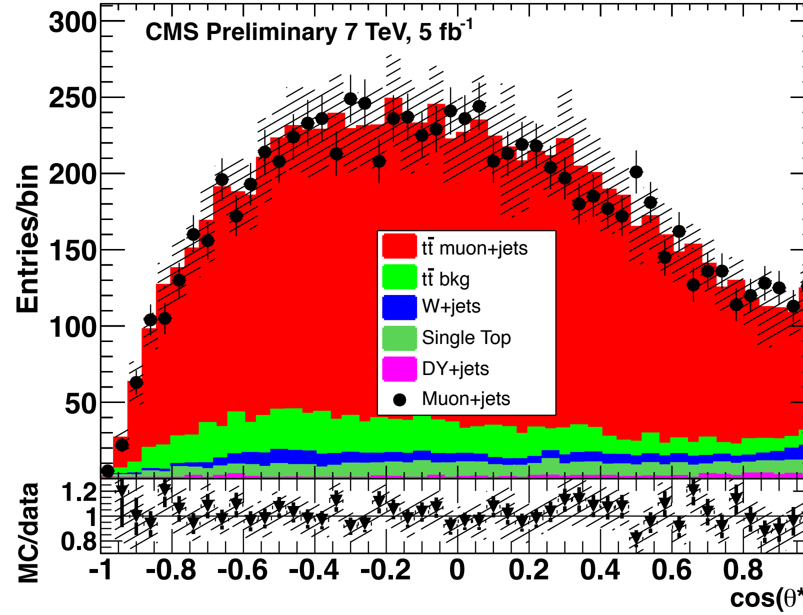




[†] θ^*_l = angle between lepton in W rest frame and the W in top rest frame.

W polarization in $t\bar{t}$

- Test of parity violation in the SM performed on a "free" quark at the decay vertex
  - Top quarks are produced unpolarized in strong interactions
  - The t→Wb decay induces a W polarization due to the *V–A* structure of weak charged current



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{4}\sin^2\theta^* F_0$$

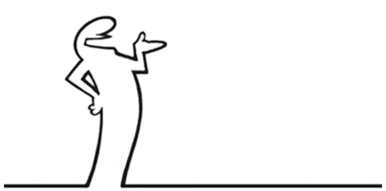
$\theta*$ = angle between lepton in the W rest frame and W in the top rest frame

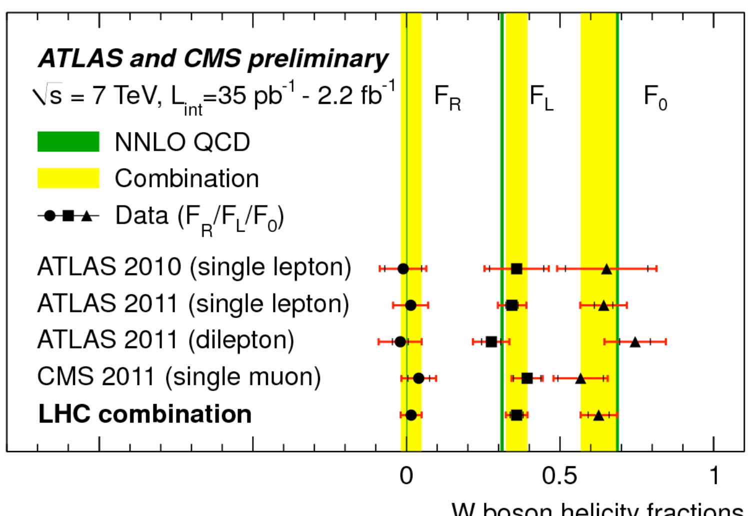
CMS-PAS-TOP-11-020
JHEP 1206 (2012) 088
ATLAS-CONF-2013-033/
CMS-PAS-TOP-12-025

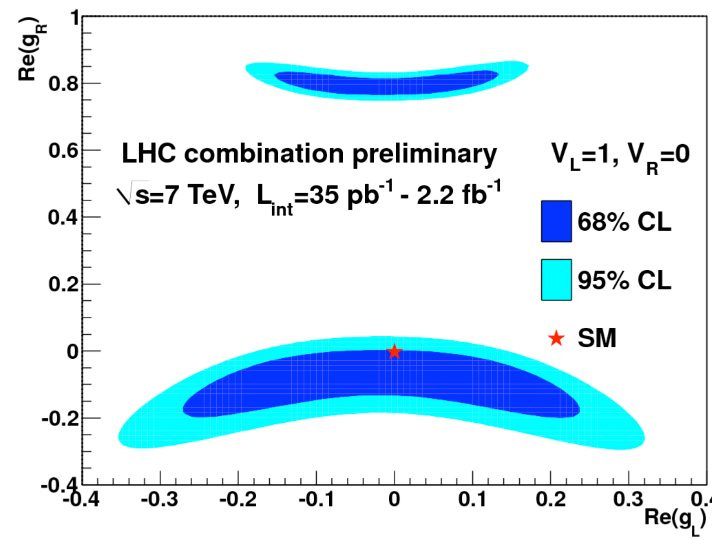
- Anomalous tWb couplings can be probed:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)tW^-_\mu - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(g_L P_L + g_R P_R)\, t\, W^-_\mu + \text{H.c.}$$

Also studied in single top
JHEP 01 (2015) 053







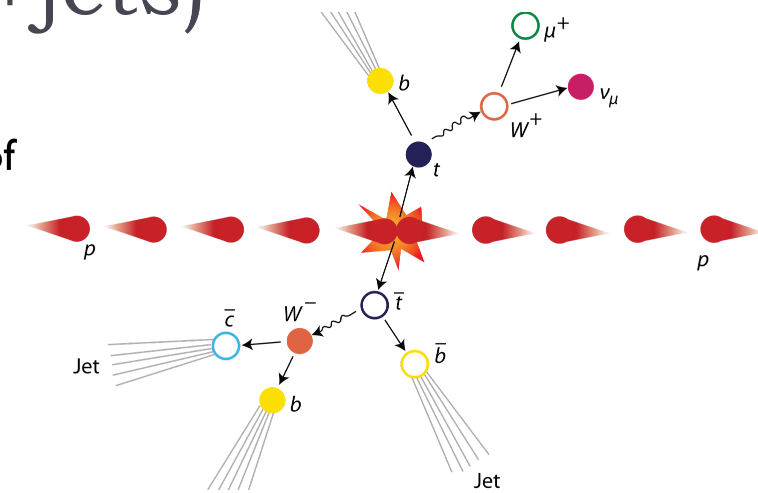
Top-quark mass (CMS, *l*+jets)

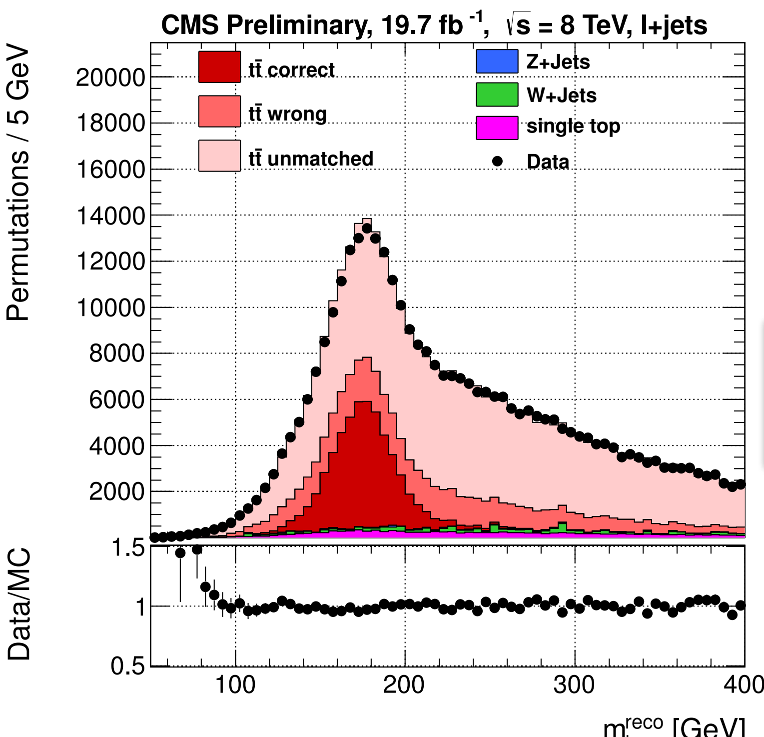
- Signal selection: one lepton, ≥4 jets, ≥2 b-tagged jets
- Kinematic fit: m_W constraint on both W, equal mass of decaying heavy particles; goodness-of-fit from χ^2:

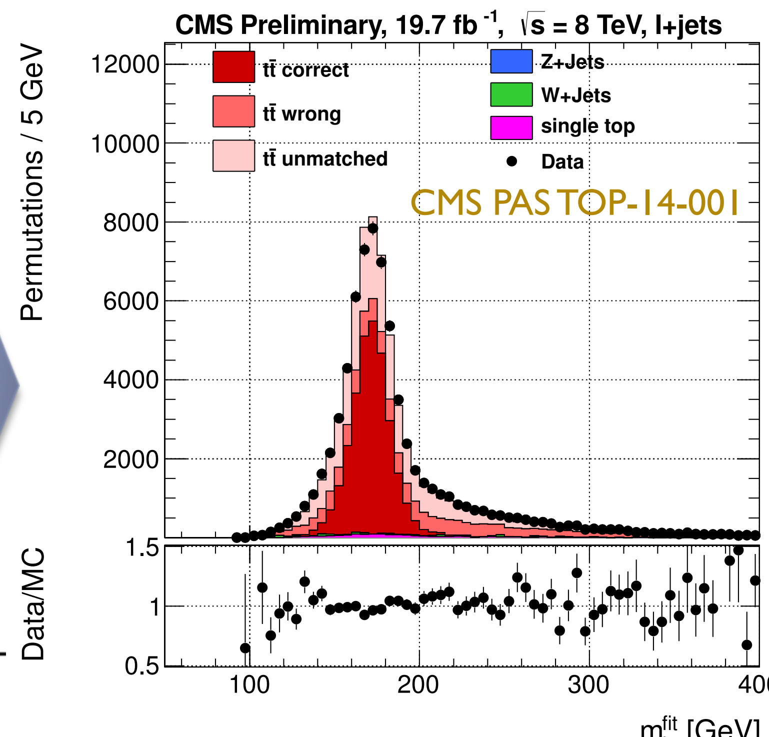
$$P_{\mathrm{gof}} = P\left(\chi^2\right) = \exp\left(-\tfrac{1}{2}\chi^2\right)$$

- Weight possible permutations by χ^2 probability (at least $P(\chi^2)>0.2$ required)

$$\mathcal{L}\left(m_t, \mathrm{JES}|\mathrm{sample}\right) \propto \prod_{\mathrm{events}} \left(\sum_{i=1}^{n} c\, P_{\mathrm{gof}}(i)\, P\left(m_{t,i}^{\mathrm{fit}}, m_{W,i}^{\mathrm{reco}} | m_t, \mathrm{JES}\right)\right)^{w_{\mathrm{event}}}$$







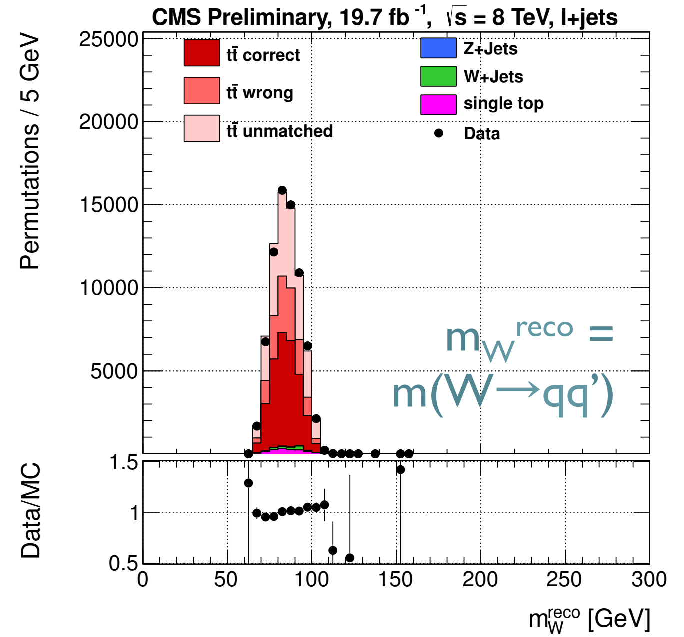
Top-quark mass (cont.)

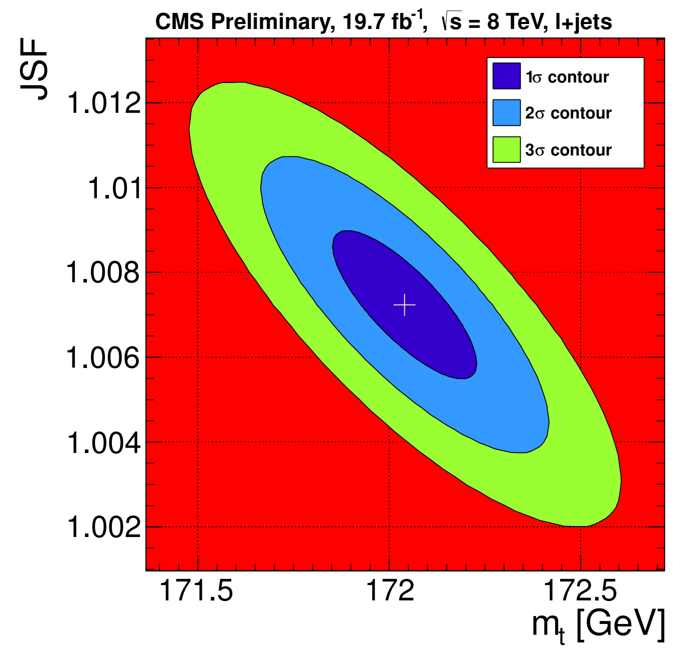
- Simultaneous fit of m_t and of jet energy scale from reconstructed W-mass distribution (hadonic W)

$$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\,\text{GeV},$$
$$\text{JSF} = 1.007 \pm 0.002\,(\text{stat.}) \pm 0.012\,(\text{syst.}).$$

- Reached ultimate Tevatron precision
  - Most precise measurement by D0: m_t = 174.98 ± 0.76 GeV (arXiv:1405.1756, l+jets)

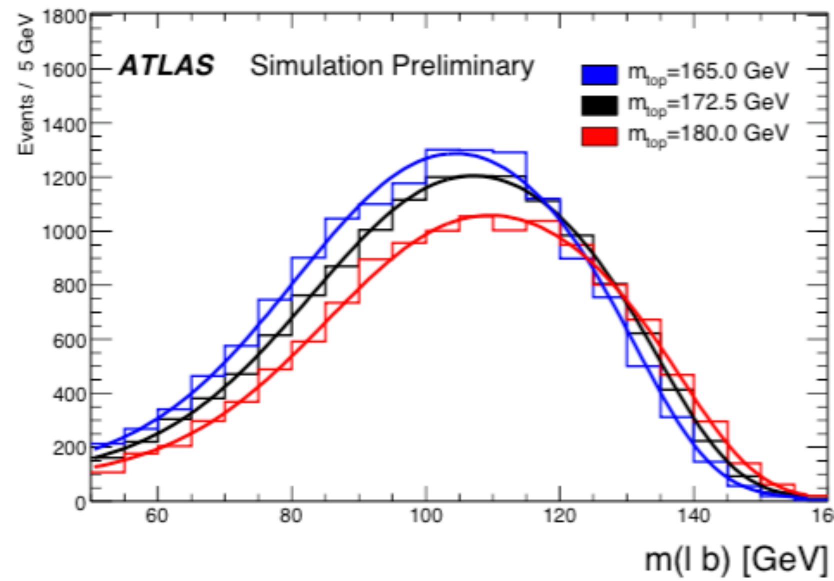
	δm_t^{2D} (GeV)
Experimental uncertainties	
Fit calibration	0.10
p_T- and η-dependent JES	0.18
Lepton energy scale	0.03
MET	0.09
Jet energy resolution	0.26
b tagging	0.02
Pileup	0.27
Non-$t\bar{t}$ background	0.11
Modeling of hadronization	
Flavor-dependent JSF	0.41
b fragmentation	0.06
Semi-leptonic B hadron decays	0.16
Modeling of the hard scattering process	
PDF	0.09
Renormalization and factorization scales	0.12±0.13
ME-PS matching threshold	0.15±0.13
ME generator	0.23±0.14
Modeling of non-perturbative QCD	
Underlying event	0.14±0.17
Color reconnection modeling	0.08±0.15
Total	0.75

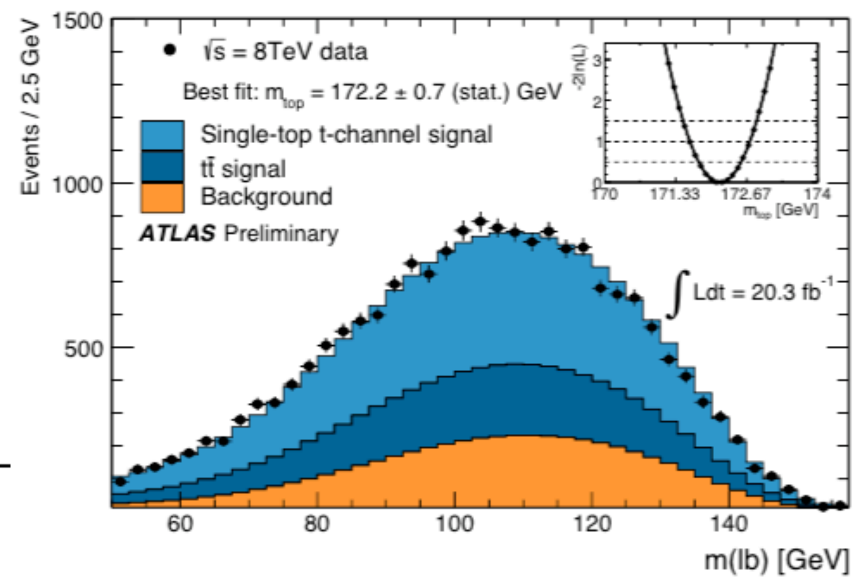




Top-quark mass from single top

- Theoretical uncertainties complementary to $t\bar{t}$ measurements
  - Color reconnection effect different in electro-weak and strong processes
- Event selection similar to *t*-channel cross section analysis (Neural Network, for ATLAS)
- Sample composition: ~50% single top, ~23% $t\bar{t}$
- Mass measured from the distribution of the lepton+b invariant mass
  - Varied for both single-top and $t\bar{t}$
- Precision still limited mainly by jet energy scale (1.5 GeV), *t*-channel hardronization model (0.7 GeV), backgrounds (0.6 GeV)

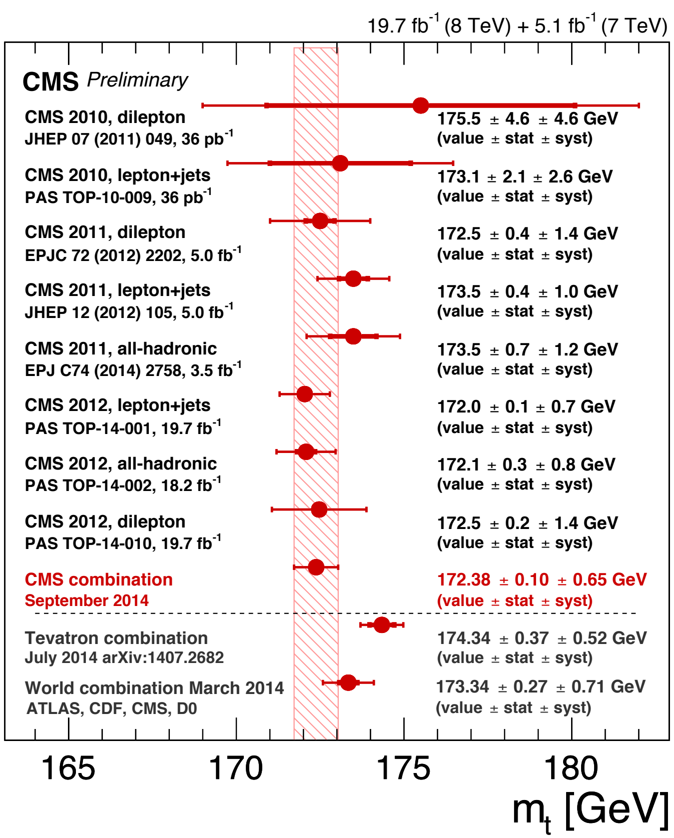


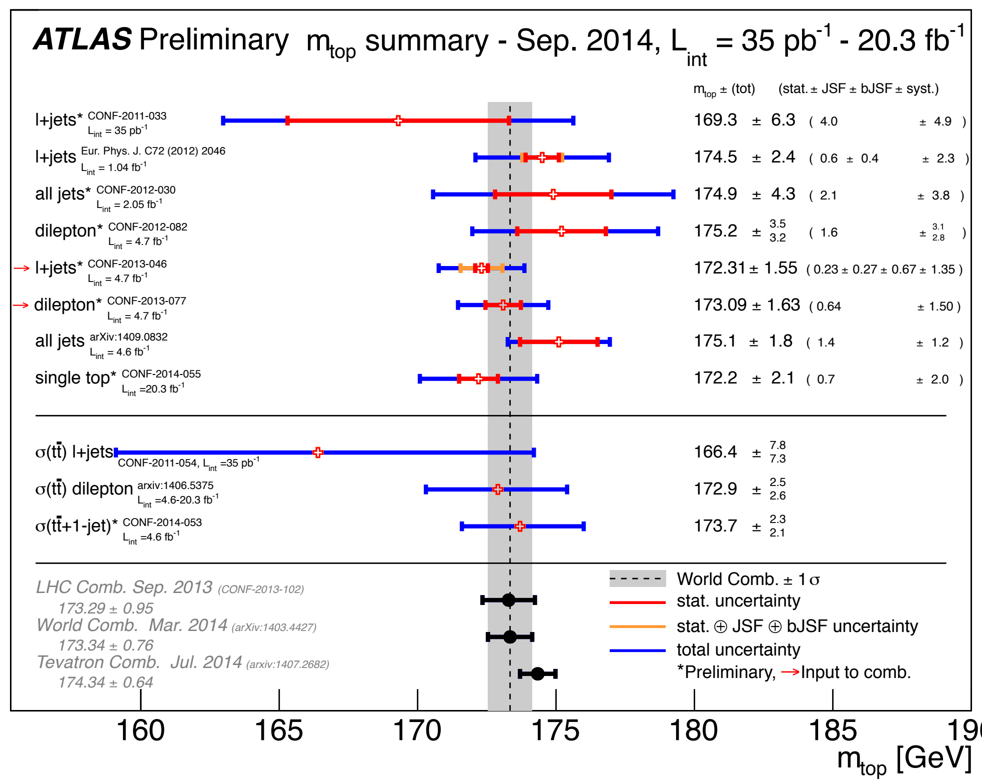


$m_t = 172.2 \pm 0.7$ (stat.) ± 2.0 (syst.) GeV

Top-quark mass combinations

- World combination released, including Tevatron results
- Should be updated with latest CMS measurement





Charge and FB asymmetries

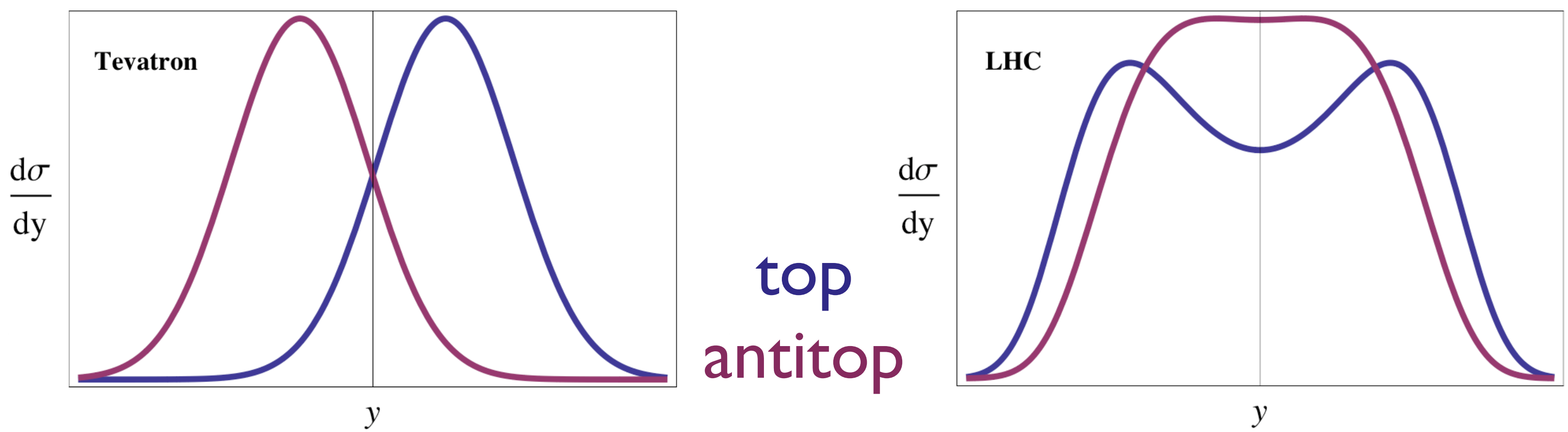
- Hints of FB asymmetry reported since long by Tevatron (mainly CDF)
- In the SM no forward-backward asymmetry is expected in $gg \to t\bar{t}$ processes
- Small asymmetry in $q\bar{q} \to t\bar{t}$ due to interference of higher order diagrams (ISR + FSR)
- The exchange of exotic particles may enhance the asymmetry
- LHC data not directly comparable to Tevatron: symmetric pp initial state vs asymmetric $p\bar{p}$
- Charge asymmetry measured at LHC instead of forward-backward asymmetry, measured at Tevatron
- Either top or lepton y used as direction

$$\Delta|y| = |y_{t}| - |y_{\bar{t}}|$$

$$\Delta|y| = |y_{\ell+}| - |y_{\ell-}|$$

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

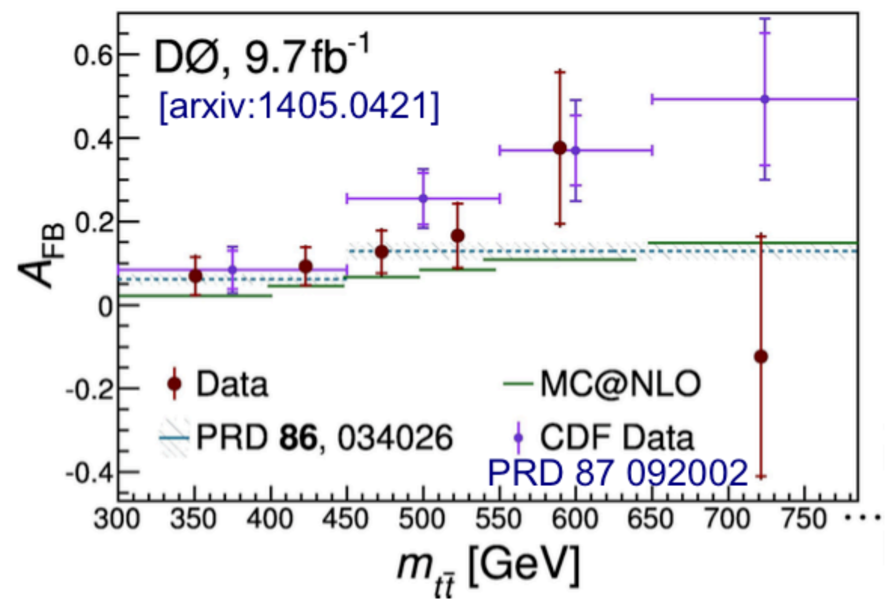
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$



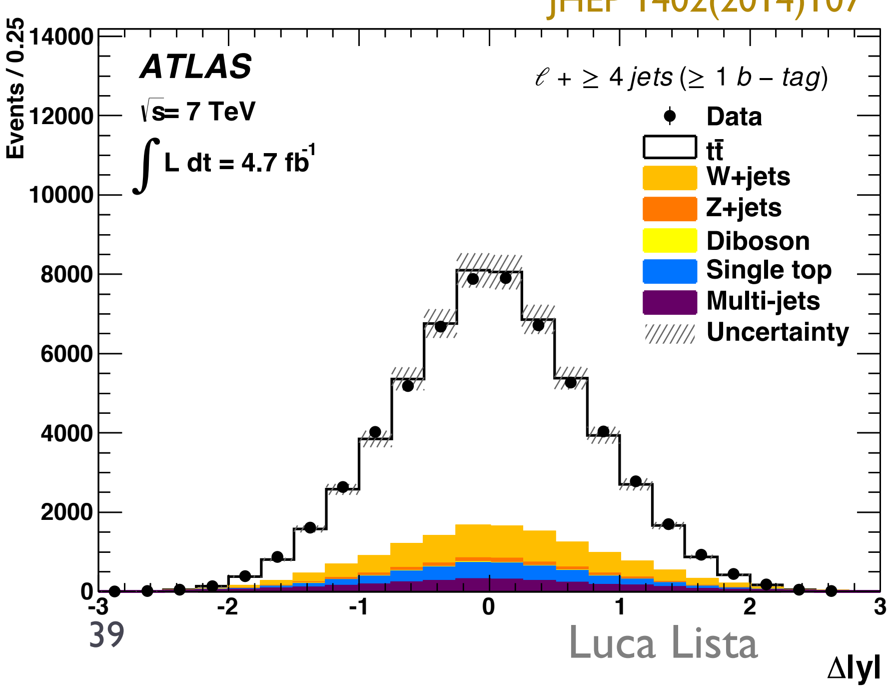
A_{FB}, A_C (cont.)

- SM prediction for A_{FB} at Tevatron is zero at LO (appears at $\mathcal{O}(\alpha_s^3)$)
- Historically A_{FB} larger than SM for large m_{tt} at Tevatron, though recent measurements are less pronounced
  - Also theory predictions "moved" towards data
- SM prediction for A_C at LHC is ~1%
- Best measured by ATLAS and CMS (and their combination) in the *l*+jets channel

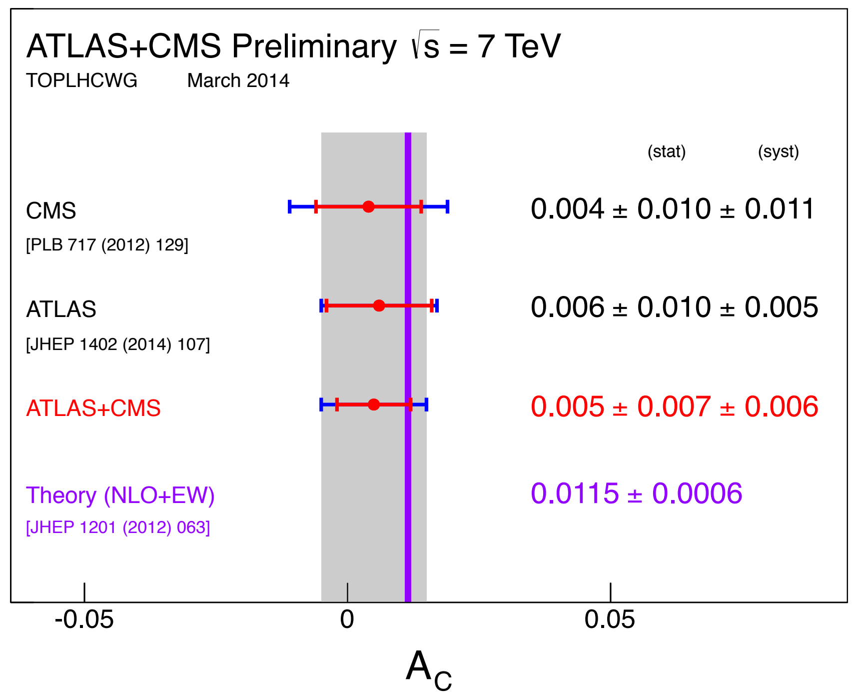
PRD90(2014)072011



JHEP 1402(2014)107

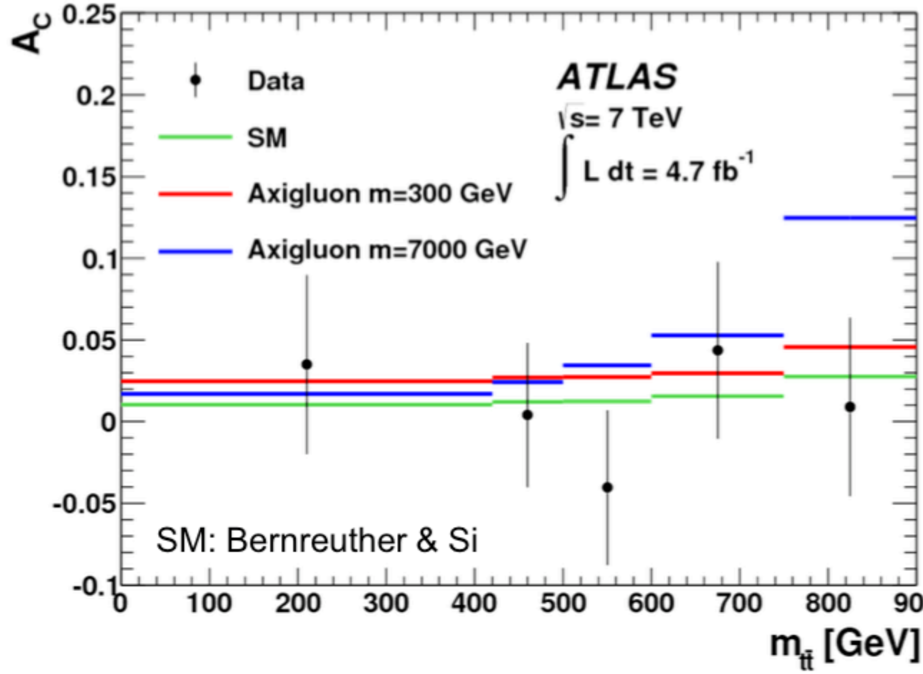


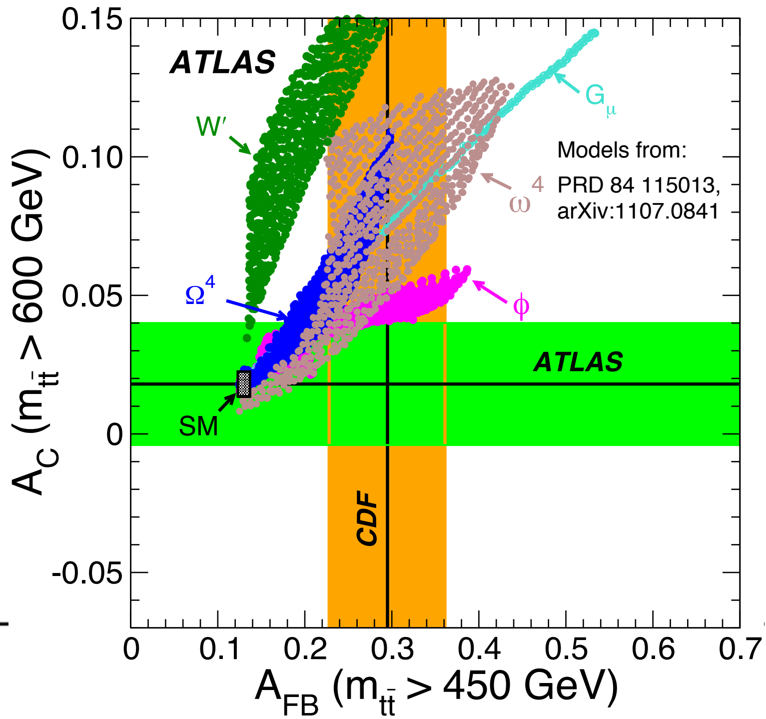
CMS PAS TOP-14-006/ATLAS-CONF-2014-012

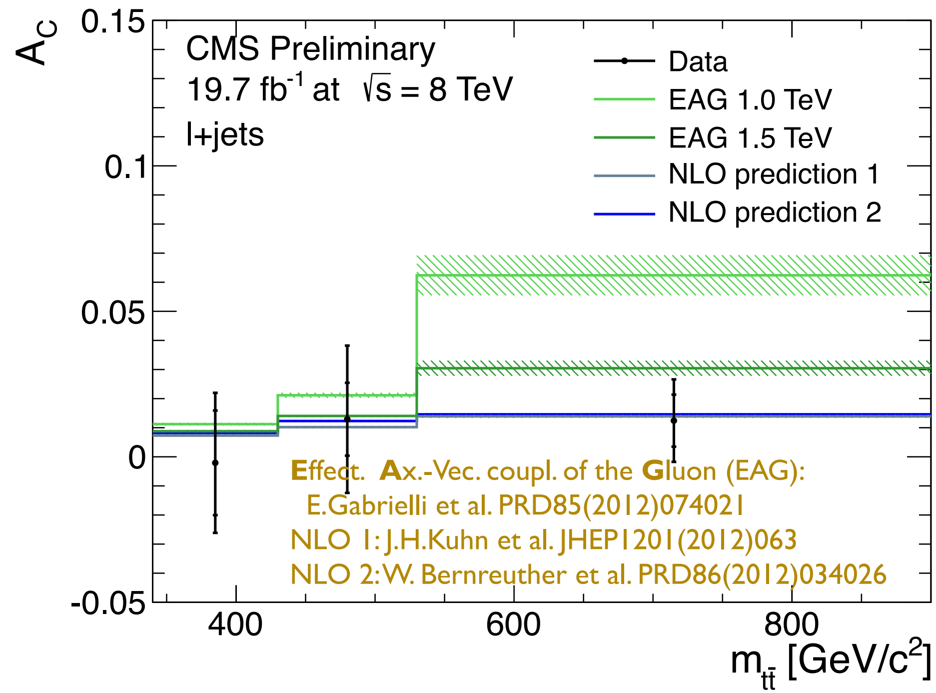


A_{FB}, A_C (differential)

- Both total and differential (m_{tt}-dependent) measurement give no indication of deviations from SM predictions
- Limits can be set on new physics models





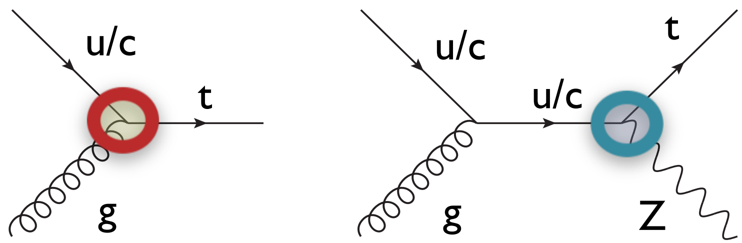


New physics in single top

- FCNC in single-top production may arise from several new physics scenarios affecting both production (u/c→t) and decay (e.g: u/c→tZ, tγ, tg)

$$\mathcal{L} = \sum_{q=u,c} \left[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t}\sigma^{\mu\nu} T_a (f_q^L P_L + f_q^R P_R) q \, G^a_{\mu\nu} \right.$$
gut, gct

$$\left. + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{Zqt}}{\Lambda} \bar{t}\sigma^{\mu\nu} (\hat{f}_q^L P_L + \hat{f}_q^R P_R) q \, Z_{\mu\nu} \right] + \text{h.c.}$$
Zut, Zct



ATLAS:

$\kappa_{gut}/\Lambda < 5.1\times10^{-3}\ \text{TeV}^{-1}$

$\kappa_{gct}/\Lambda < 1.1\times10^{-2}\ \text{TeV}^{-1}$

CMS:

$\kappa_{Zut}/\Lambda < 0.45\ \text{TeV}^{-1}$

$\kappa_{Zct}/\Lambda < 2.27\ \text{TeV}^{-1}$

$B(t\to gu) < 3.1\times10^{-5}$

$B(t\to gc) < 1.6\times10^{-5}$

$B(t\to Zu) < 5.1\times10^{-3}$

$B(t\to Zc) < 0.1140$

(95% CL)

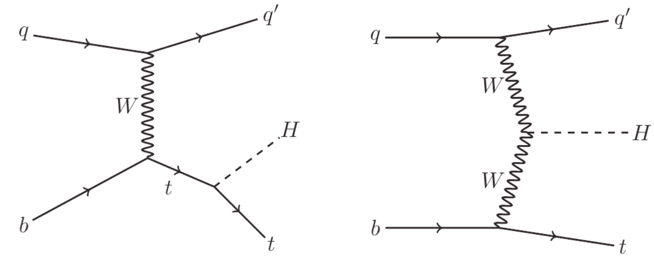
- ATLAS searches for FCNC in single top production with SM t→Wb decay (ATLAS-CONF-2013-063, 8 TeV)
- CMS looked for FCNC in associated tZ production (CMS PAS TOP-12-021, 7 TeV)
- ATLAS also looked for CP violation in the Wtb vertex using lepton angular distribution in single-top (ATLAS-CONF-2013-032, 7 TeV)
- No deviation from SM prediction spotted so far

$A_{FB}^{N} = 0.031 \pm 0.065(\text{stat.})^{+0.029}_{-0.031}(\text{syst})$

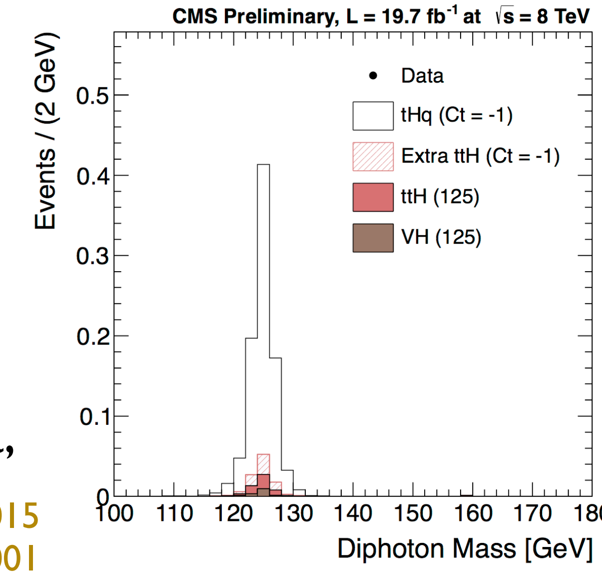
anomalous tensor coupling:

$-0.2 < \Im(g_R) < 0.3$, 95%CL

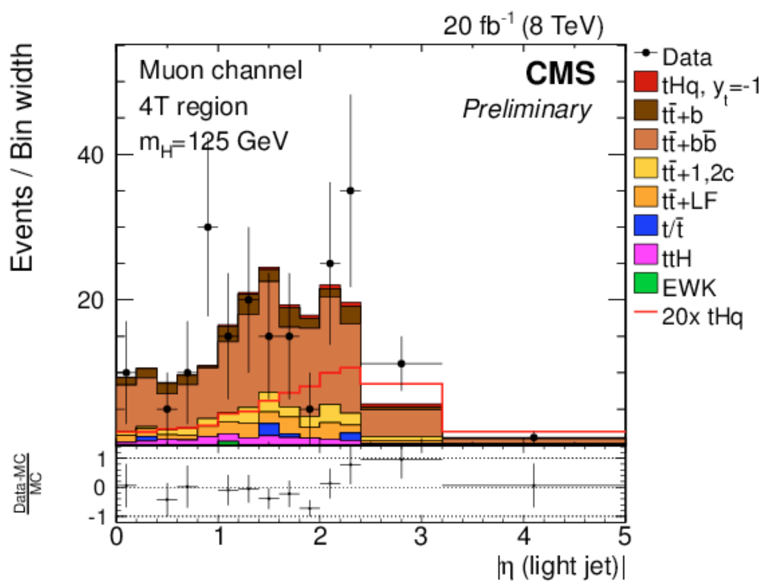
Single top and exotic Higgs

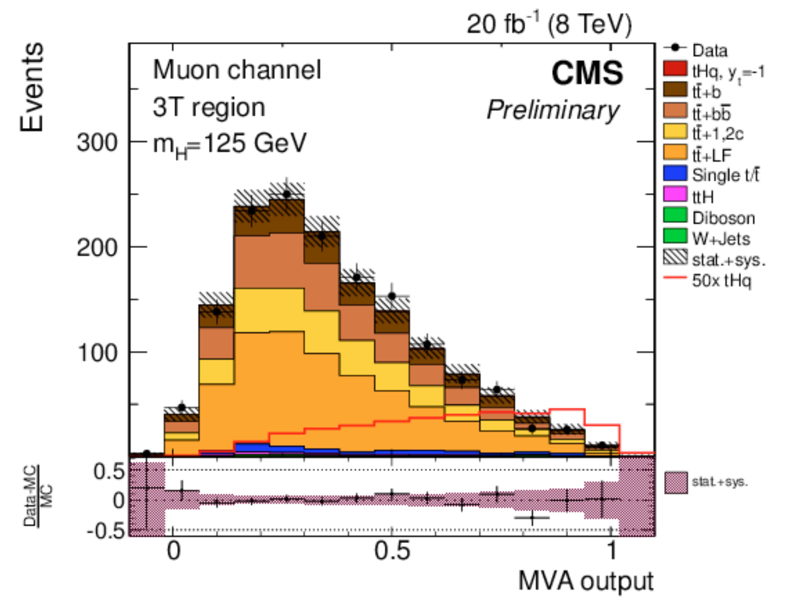


- Probe Higgs anomalous coupling to top quark ($y_t = -1$), due to interference of diagrams with ttH and WWH vertices
- Upper limits to cross section set:
  - σ(tHq, H→bb) < 7.6×σ(y_t=−1), 5.1 exp., 95%CLs
  - σ(tHq, H→γγ) < 4.1×σ(y_t=−1), 4.1 exp., 95%CLs
- May probe up to SM Higgs coupling with run-II data, complementing ttH search



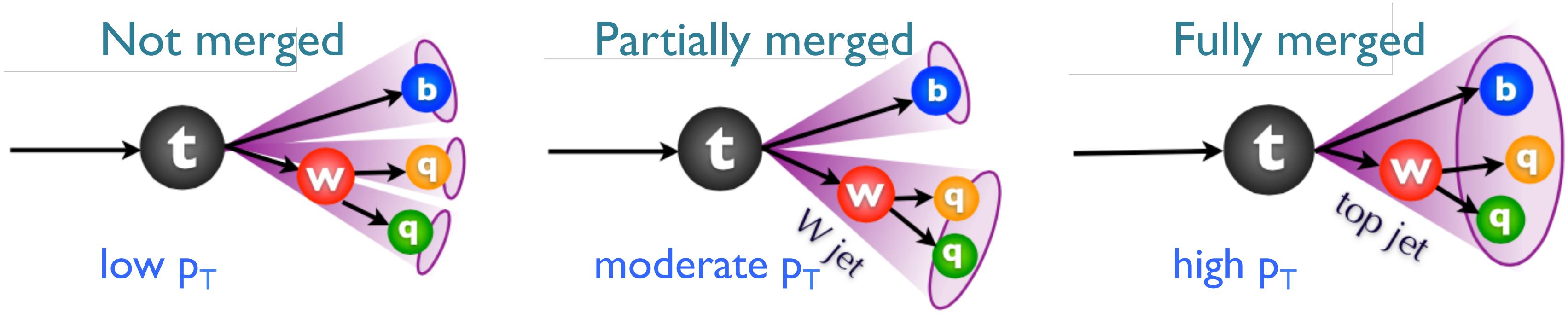
CMS PAS HIG-14-015
CMS PAS HIG-14-001





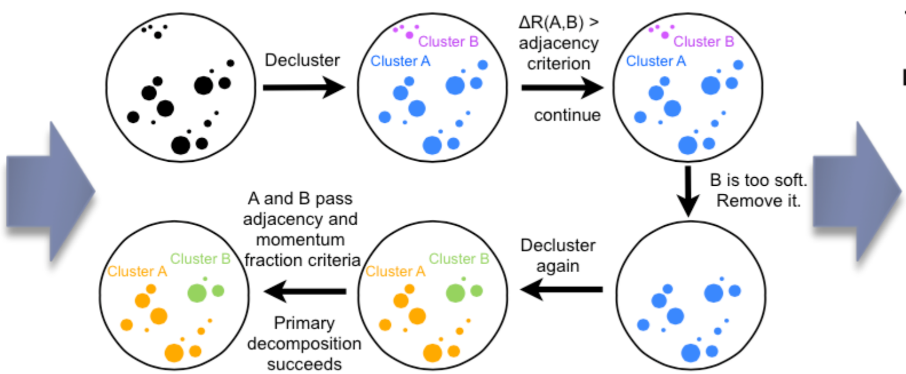
Top reconstruction at high energy

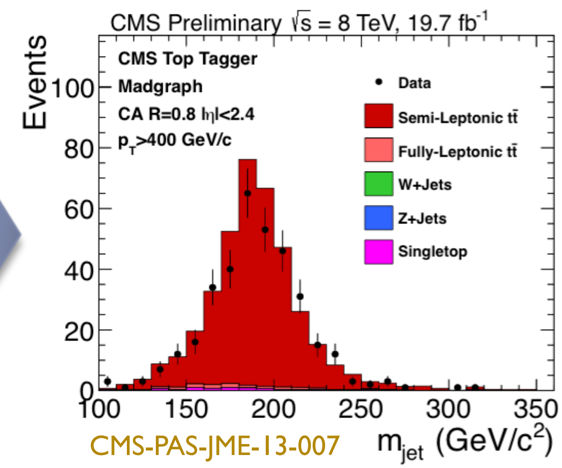
- The high-energy LHC regime forces top decays to be reconstructed in the same hadronic jet
- Important to measure high-p_T ends of SM processes, for top-quark from exotic decays having large boost and for run-II data at 13-14 TeV



- Dedicated algorithms identify jet substructures and identify top decay products (top taggers)

CMS Top Tagger
Kaplan et al., arXiv:0806.0848

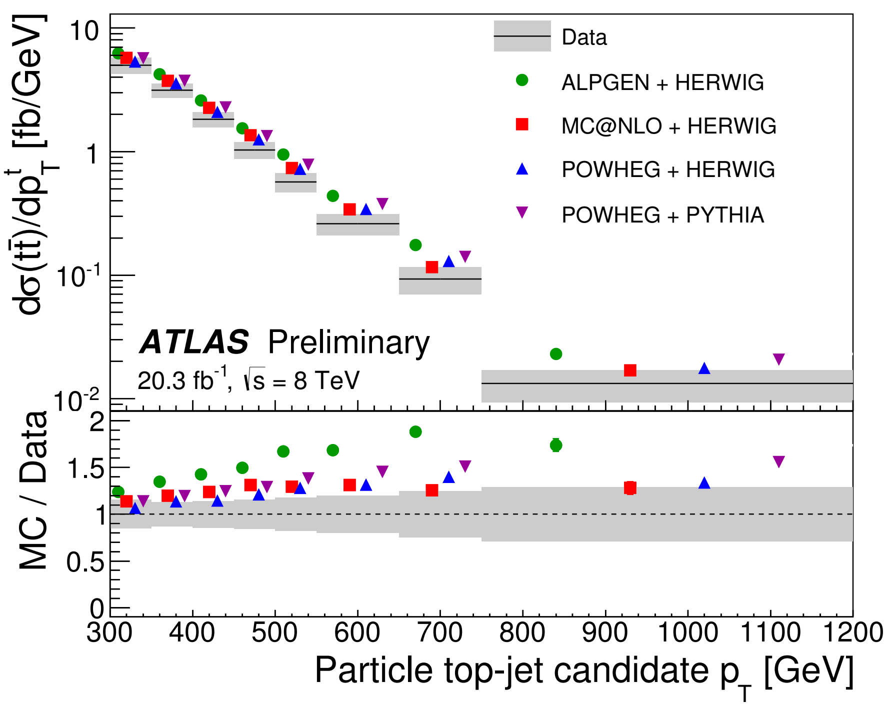




CMS-PAS-JME-13-007

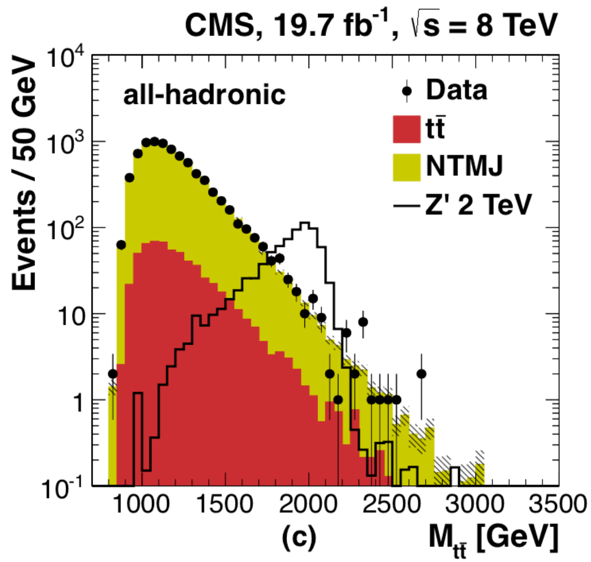
Boosted top in SM processes

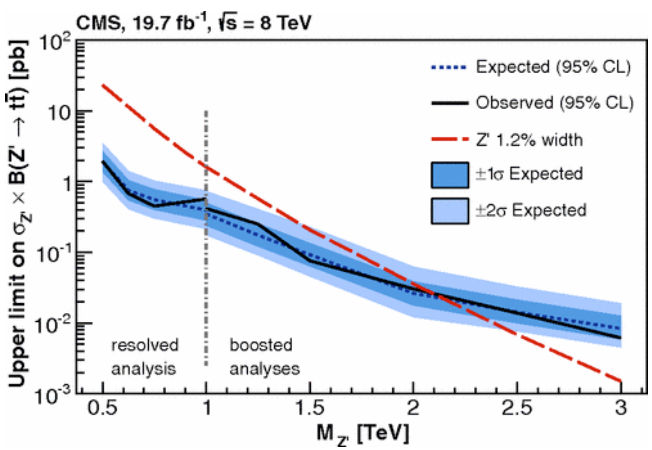
- ATLAS measured tt^{bar} differential cross section using boosted techniques at high top p_T (in *l*+jets)
- Background to may new physics searches
- Simulation does not reproduce well the high-p_T regime



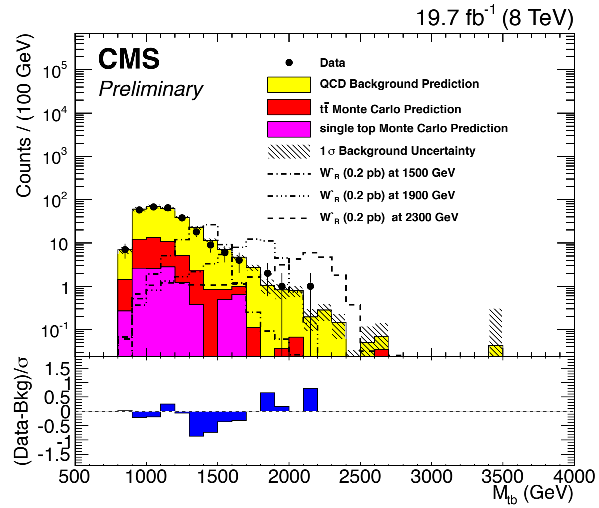
Boosted tops and new physics

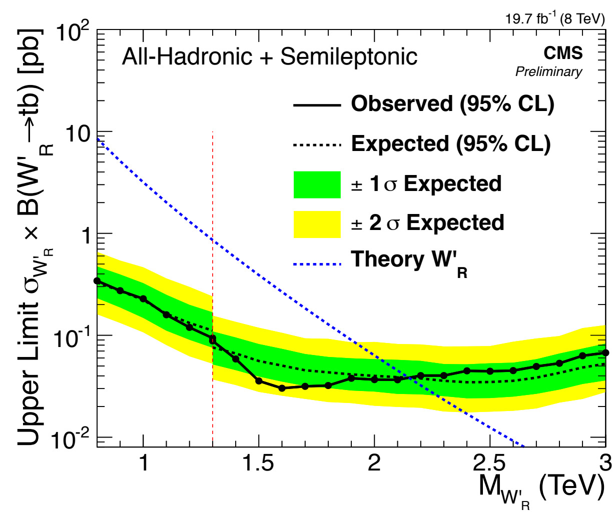
Search for $t\bar{t}$ resonances (Z')
PRL 111(2013)211804



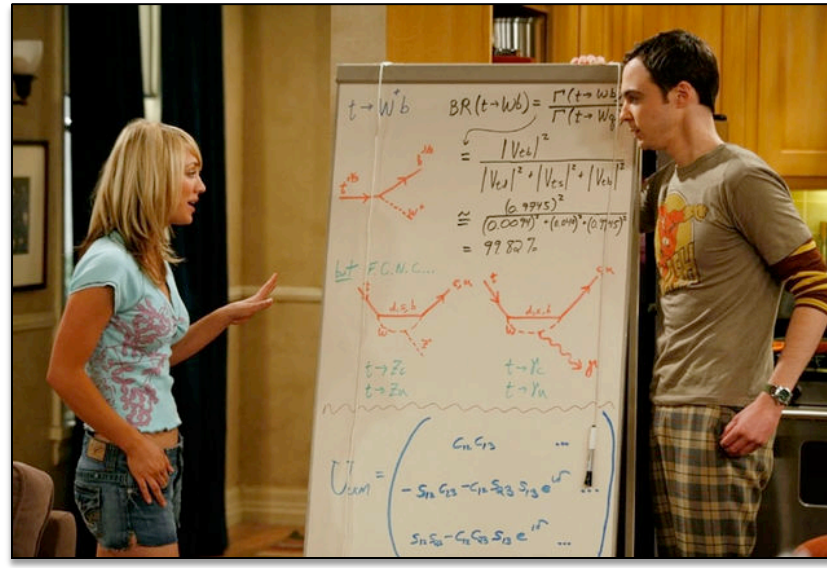


Search for tb resonances (W')
CMS-PAS-B2G-12-009



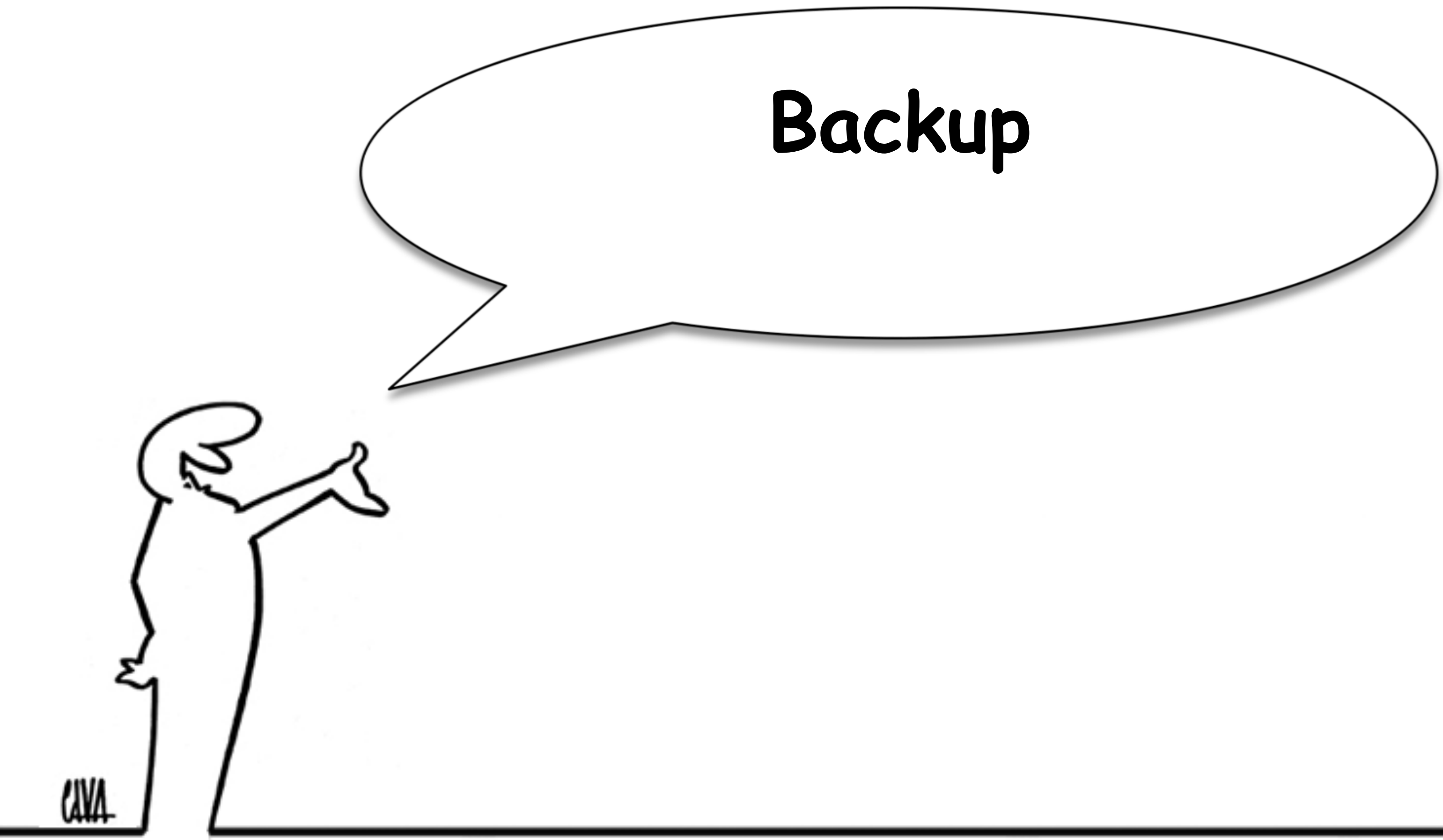


Conclusions



- After 20 years from its discovery, the top quark field is very active and rich in new results
- LHC reached very good precision in many measurements, ranging from production cross section and distributions to top-quark properties
- Top can couple to new physics but so far no hint of deviations from the SM has been identified
- Advanced analysis technique have been developed to exploit in an optimal way the forthcoming 13−14 TeV LHC

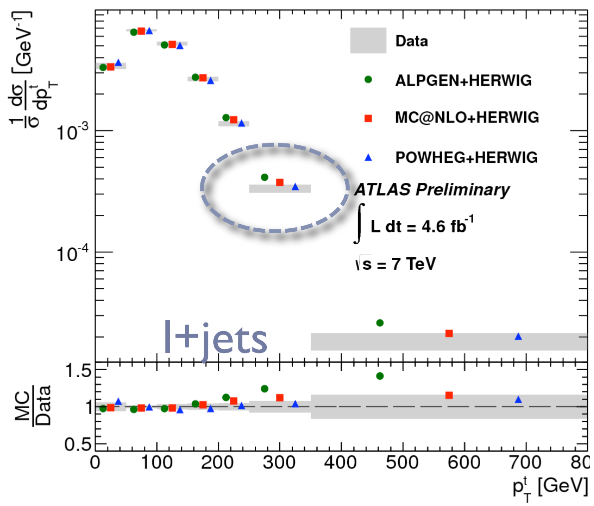
Stay tuned for new results from LHC run-II !


Backup

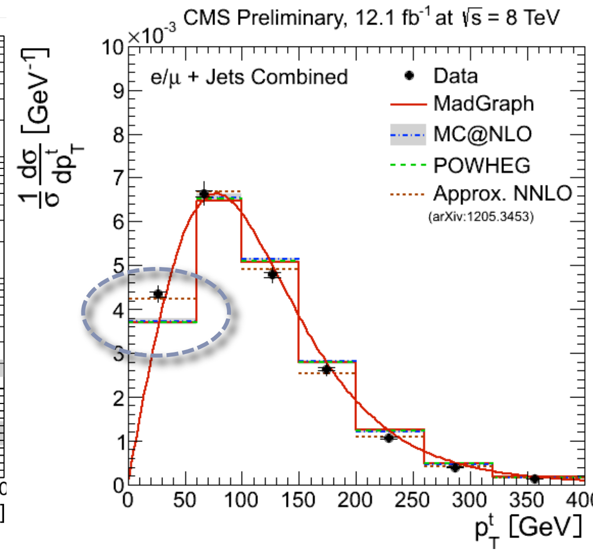
Top quark p_T, jet multiplicity

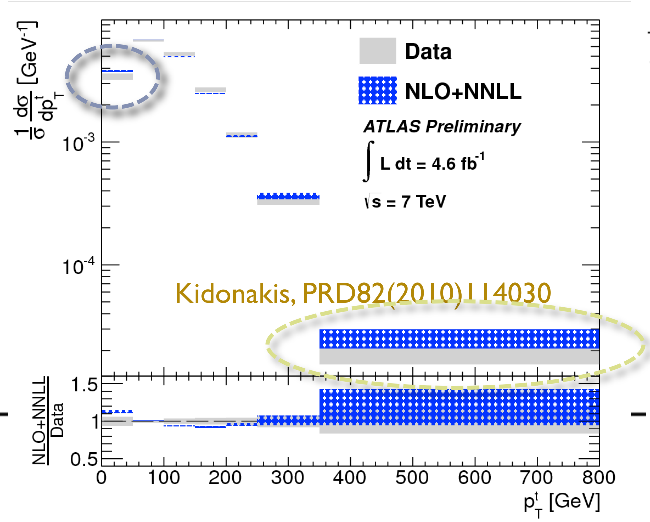
- Top p_T:
  - POWHEG best agrees with data
  - ATLAS reports ALPGEN, MC@NLO, and the NLO calculation above data for p_T > 200 GeV
  - CMS reports low-p_T spectrum not well reproduced, but in agreement with approx. NLO calculations
- Jet multiplicity:
  - MC@NLO+Herwig showering predicts lower jet multiplicity than observed

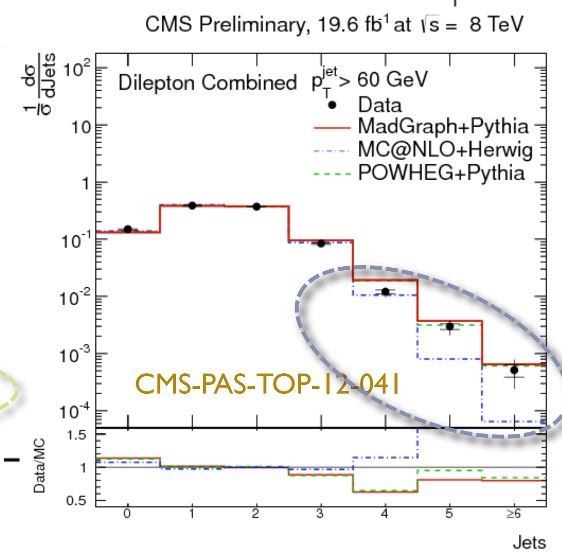
ATLAS-CONF-2013-099 (7 TeV)



CMS: EPJC73(2013)2339 (7 TeV)
CMS-PAS TOP-12-027 (l+jets, 8 TeV)
CMS-PAS TOP-12-028 (dileptons, 8 TeV)





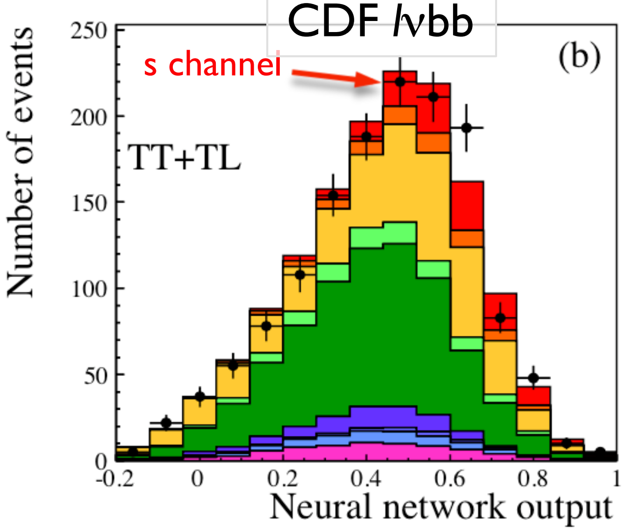


PRL112(2014)231803
PRL112(2014)231804
PRL112(2014)231805
PLB726(2013)656

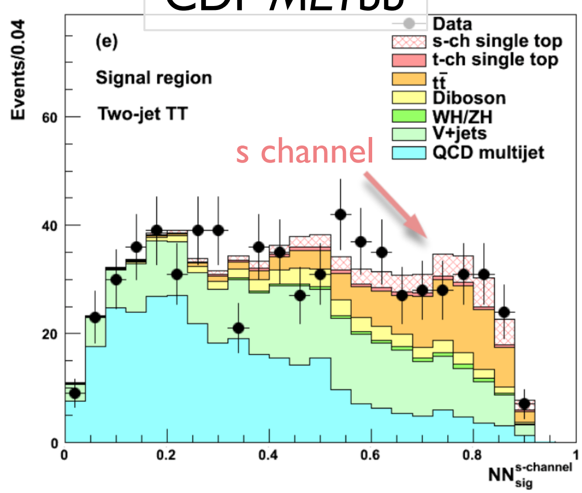
s channel at Tevatron

- Combination of three multivariate analyses by CDF and D0

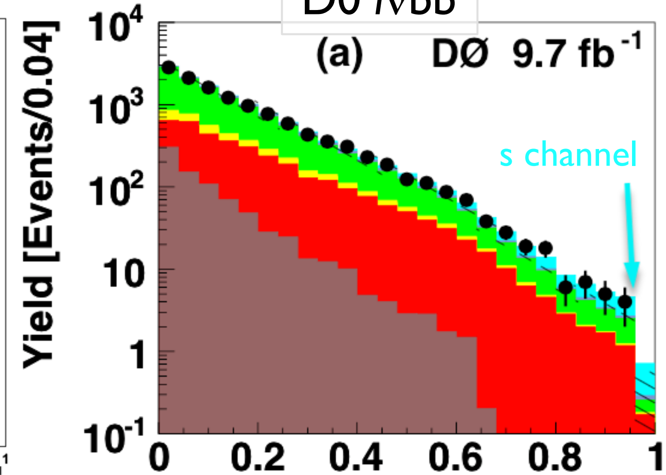
CDF *l*νbb



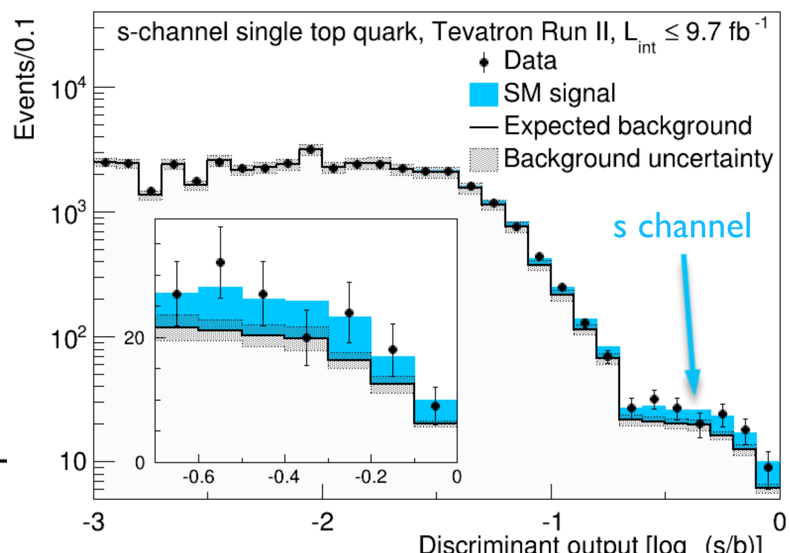
CDF *MET*bb

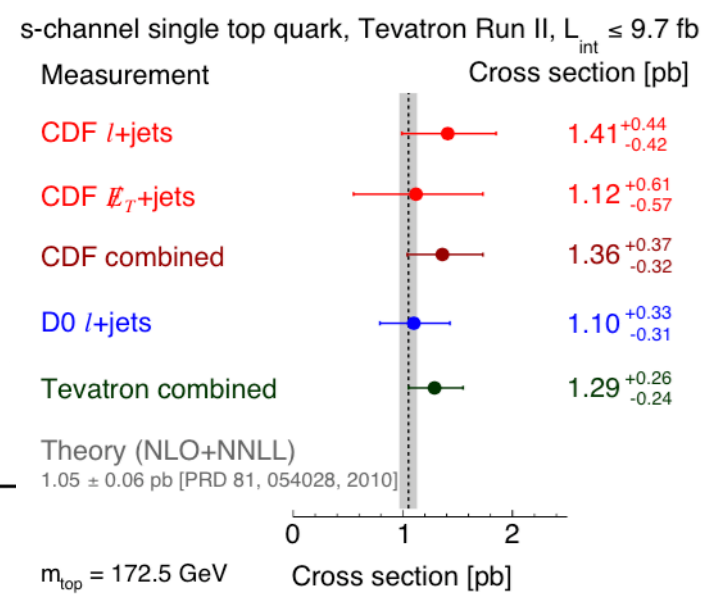


D0 *l*νbb



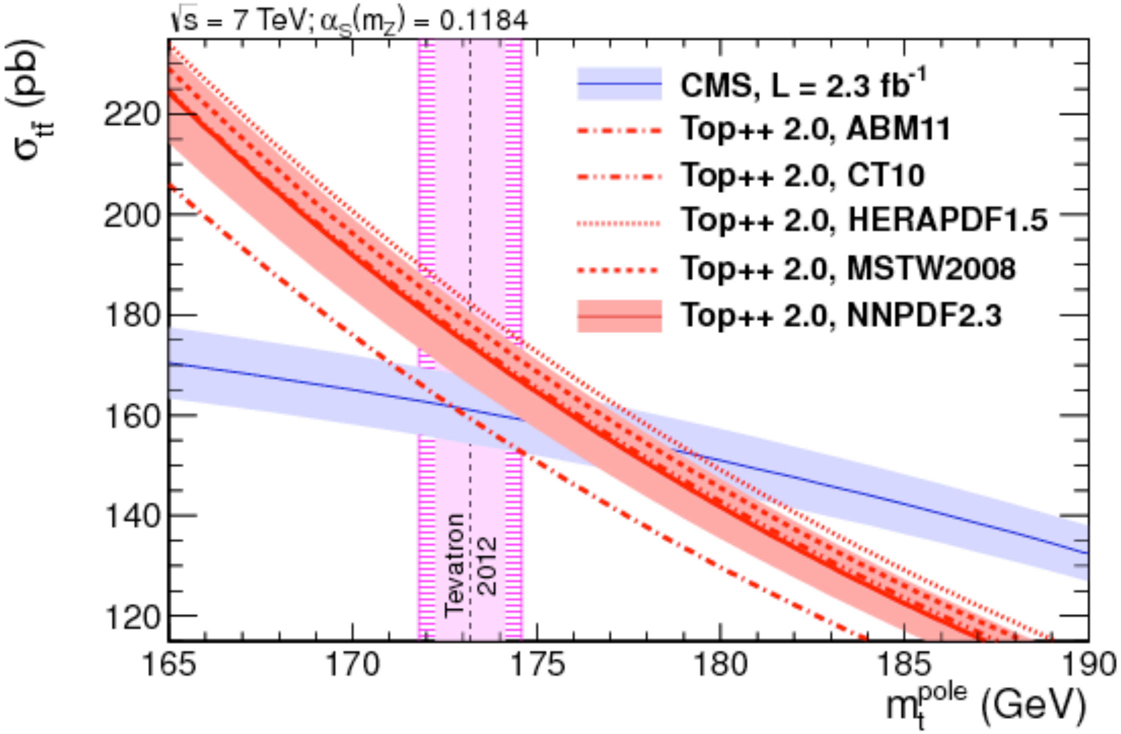
Bayesian posterior from the three observed discriminant distributions





Top-quark mass from cross section

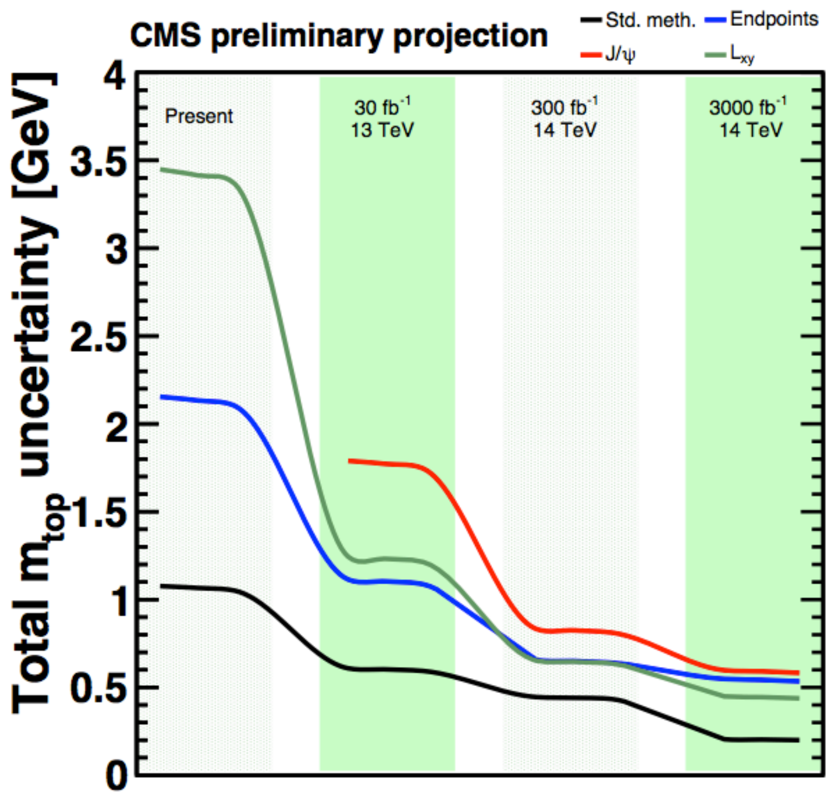
- Limited precision, but does not suffer from top mass definition from a renormalization scheme (*pole mass*)



- fixed $\alpha_s(m_Z) = 0.1184 \pm 0.0007$: $m_t^{pole} = 176.7^{+3.0}_{-2.8}$ GeV
- fixed $m_t = 173.2 \pm 1.4$ GeV: $\alpha_s(m_Z) = 0.1151^{+0.002}_{-0.0027}$

Perspectives on m_t for run–II and beyond

- Different assumptions done on uncertainty evolutions, including theory
  (PDF, cross sections, pole vs MC mass, …)



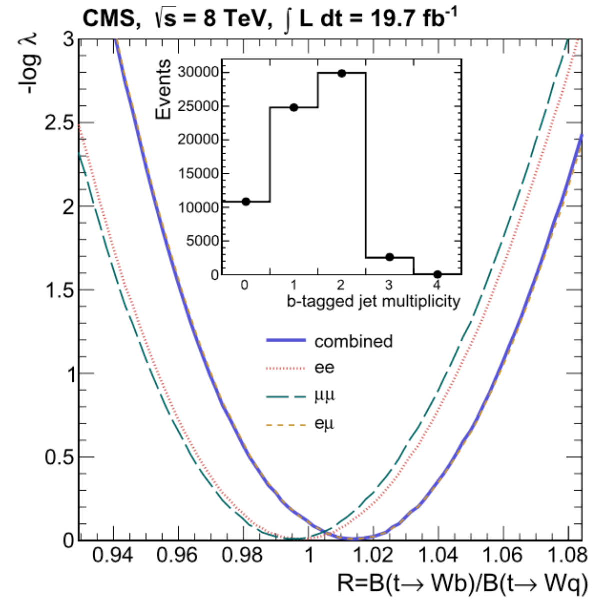
CMS-PAS-FTR-13-017

$\mathcal{B}(t \to Wb) / \mathcal{B}(t \to Wq)$ from $t\bar{t}$ and Γ_t

- $|V_{tb}|$ measured in $t\bar{t}$ from top decays
- $R = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq) = |V_{tb}|^2$
- Dilepton channel used (e or μ; Drell–Yan removed if $|M_Z - M_{ll}| < 15$ GeV or $ME_T < 40$ GeV)
- b flavour content of $t\bar{t}$ events probed counting the number of b jets after independent data-driven measurement of b-tagging efficiency
- Result:

  $R = 1.014 \pm 0.003\ (\text{stat.}) \pm 0.032\ (\text{syst.})$

  $|V_{tb}| > 0.975$, 95% CL



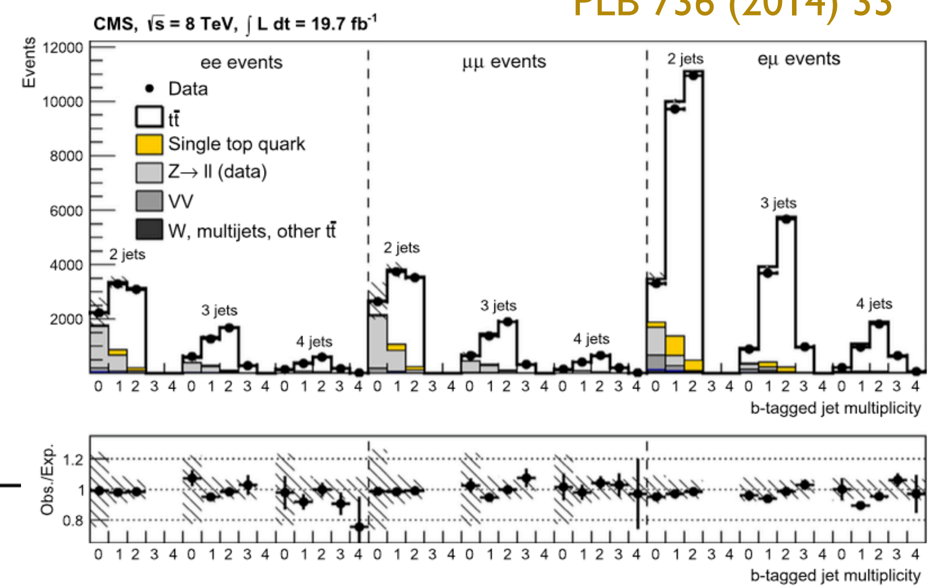
- Indirect measurement of Γ_t: including single-top t-channel cross-section measurement:

$$\Gamma_t = \frac{\sigma_{t\text{-ch.}}}{\mathcal{B}(t \to Wb)} \cdot \frac{\Gamma(t \to Wb)}{\sigma^{\text{theor.}}_{t\text{-ch.}}}$$

- Assuming the SM value $\Gamma(t \to Wb) = 1.329$ GeV (corresponding to $m_t = 172.5$ GeV), and $\sum_q B(t \to Wq) = 1$, hence $R = \mathcal{B}(t \to Wb)$:

  $\Gamma_t = 1.36 \pm 0.02\ (\text{stat.})^{+0.14}_{-0.11}\ (\text{syst.})$ GeV

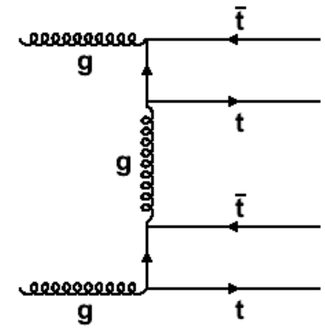
PLB 736 (2014) 33

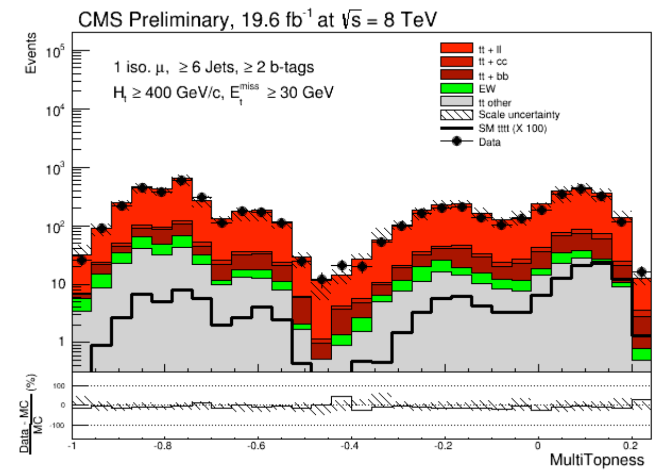


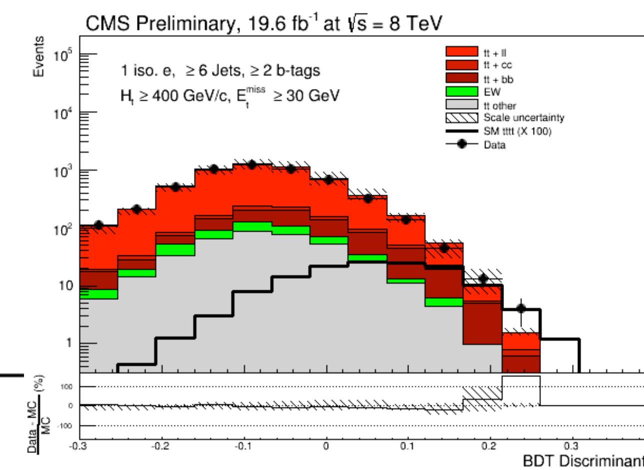
CMS-PAS-TOP-13-012
8 TeV, 20 fb^{-1}

Search for four tops

- SM process with very low cross section:
  - $\sigma^{SM}_{8TeV}(tttt) \approx 1$ fb(LO) + ~20÷30% (NLO)
    V. Barger et al., PLB687(2010)70
    M.W. G. Bevilacqua, JHEP1207(2012)111
- Production largely enhanced in several models beyond the SM
  - Composite top and Higgs, extra dimensions, supersymmetric cascade decay with multitop final states, …)
- Analysis strategy look for:
  - ① top decay to e or μ
  - ③ tops decay hadronically
    - 3-jet combinations scored as top decay using a dedicated BDT ("multitopness") against semileptonic $t\bar{t}$
    - Second BDT adding more event variables







- No significant excess observed:
- $\sigma(tttt) < 63$ fb (exp: 42^{+18}_{-13} fb) , 95%CL