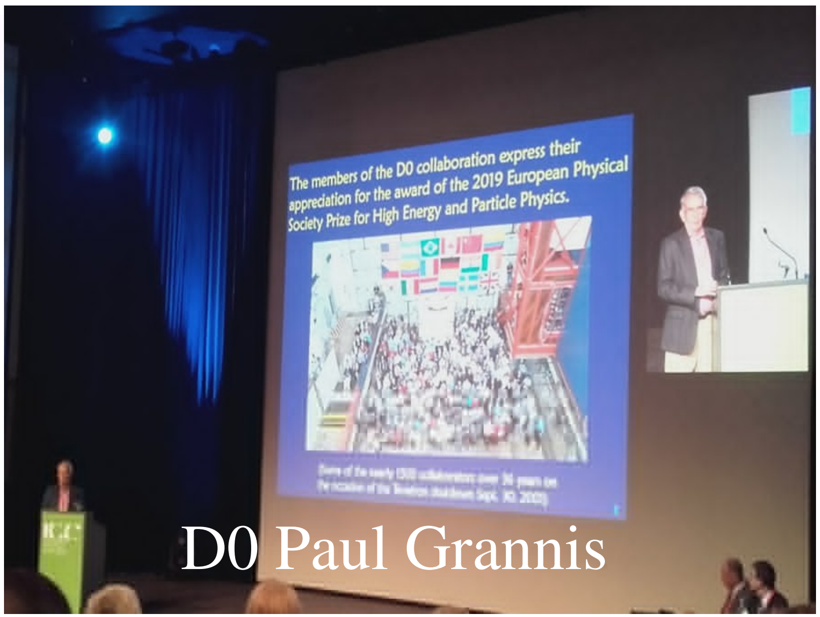
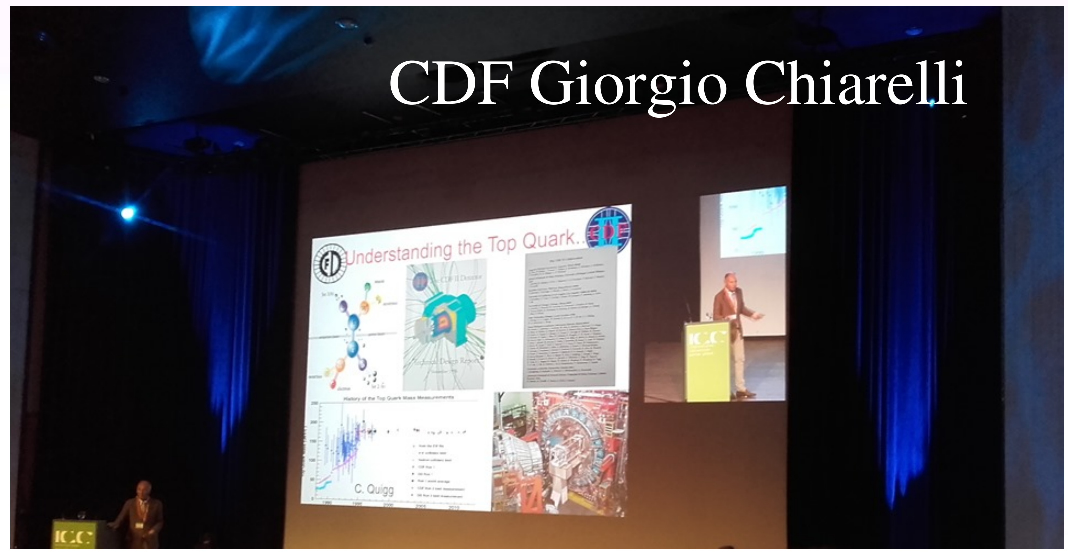
Top quark: SM measurements and selected BSM results

European Physical Society
High Energy and Particle Physics Division

The **2019 High Energy and Particle Physics Prize of the EPS** for an outstanding contribution to High Energy Physics is awarded to the **CDF and D0 Collaborations** for the discovery of the top quark and the detailed measurement of its properties.

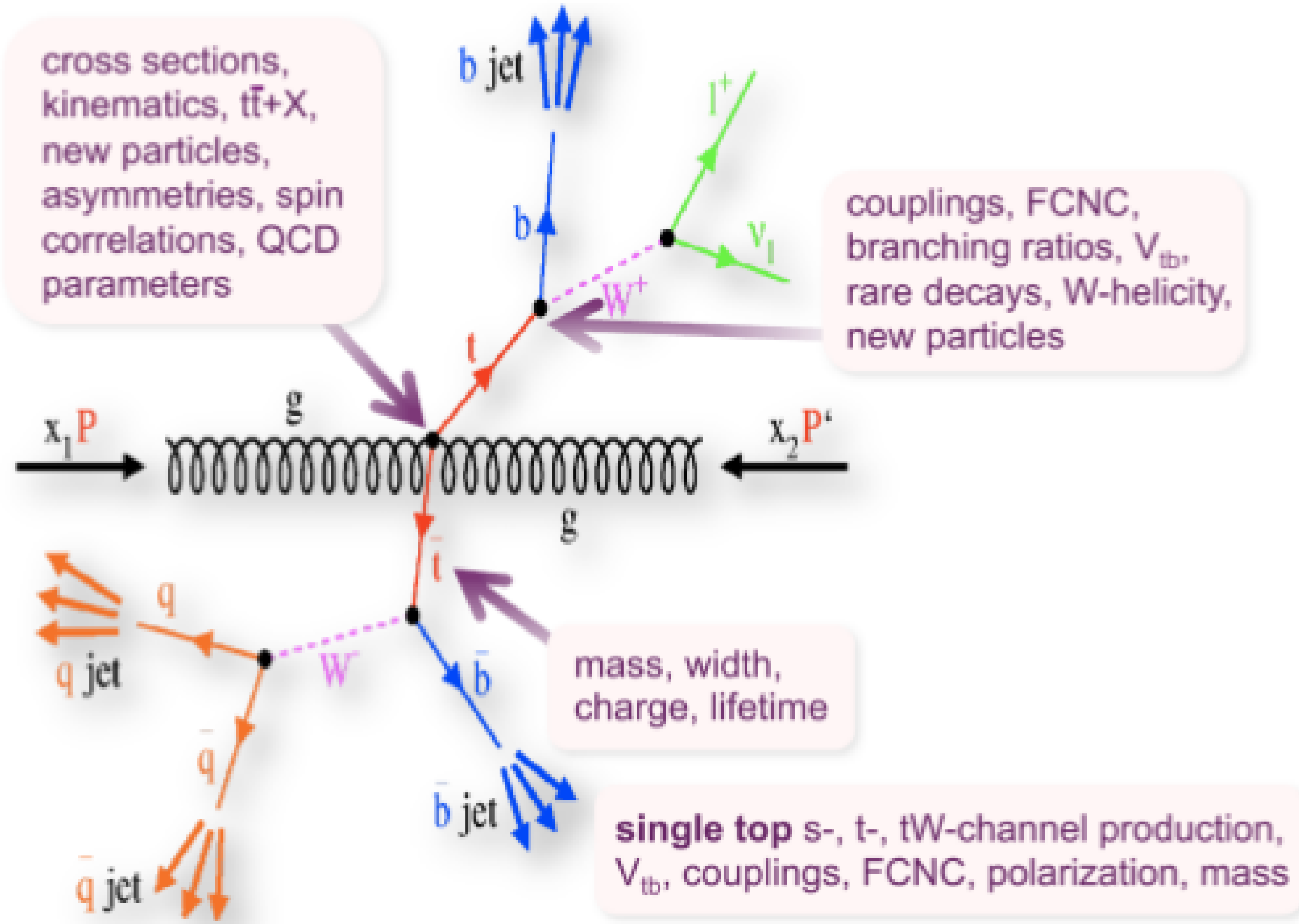




PIC2019, Taipei, ROC, September 17

Anna Lipniacka, University of Bergen
on behalf of
ATLAS & CMS

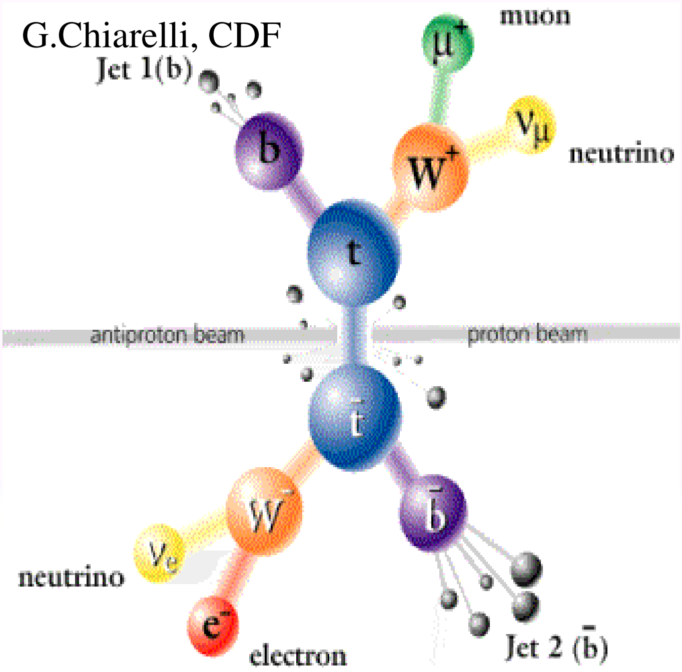
Top quark measurements and selected BSM results



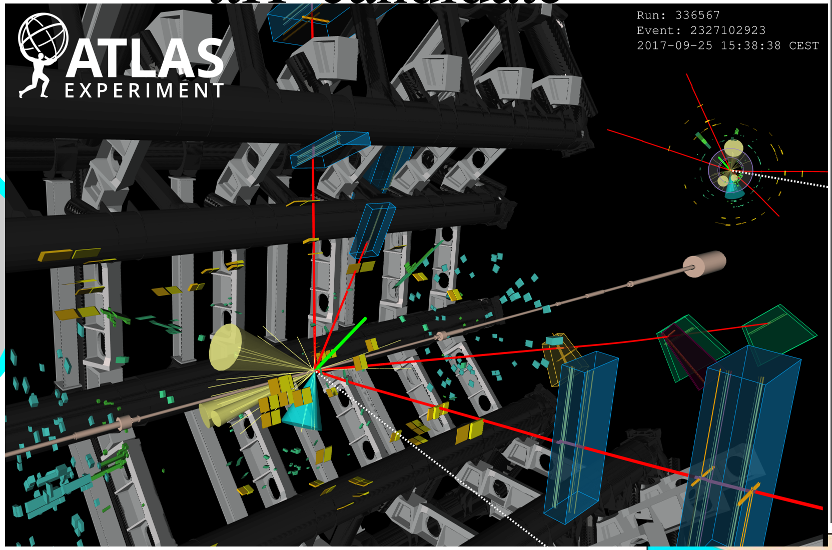
Drawing: M. Aldaya

Top quark measurements and selected BSM results

- Introduction
- Top quark mass
- Top quark and the Higgs boson
  Four Tops ? ttH
- Probing EW couplings:
  single top,
  top quark width,
  ttZ, ttγ, asymmetries
- BSM:
  The top and the stop
- Summary and perspective



ttH candidate



Introduction

Particle	Produced in 139 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.7 million	
Top quark	275 million	
Z boson	2.8 billion	($\to \ell\ell$, 290 million)
W boson	12 billion	($\to \ell\nu$, 3.7 billion)
Bottom quark	~40 trillion	(significantly reduced by acceptance)

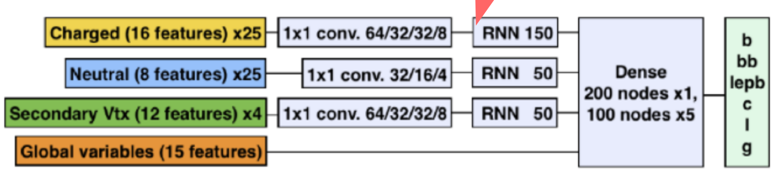
Run2 will set the standards for some time. Need to exploit it optimally

Coherent data and MC sample for all of Run-2

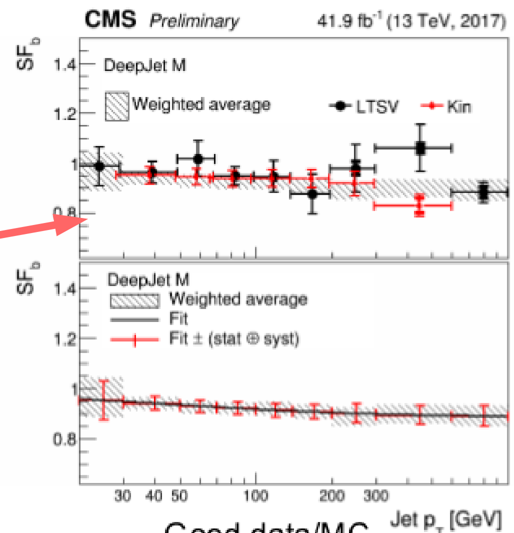
Widespread use of machine learning techniques for particle reconstruction & identification

Dedicated improvements and calibrations of low-momentum leptons, hadronic taus, low & high momentum b-tagging, boosted hadronic objects,

- Examples: “DeepJet” b-tagging, neural networks for the ttH(H->bb) analysis

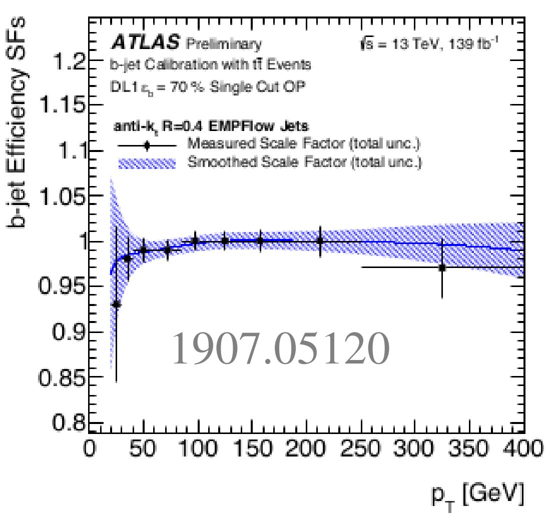


CMS DP-2018/058



Good data/MC agreement at better performance

Data-driven energy calibration of b-jet tagging efficiency



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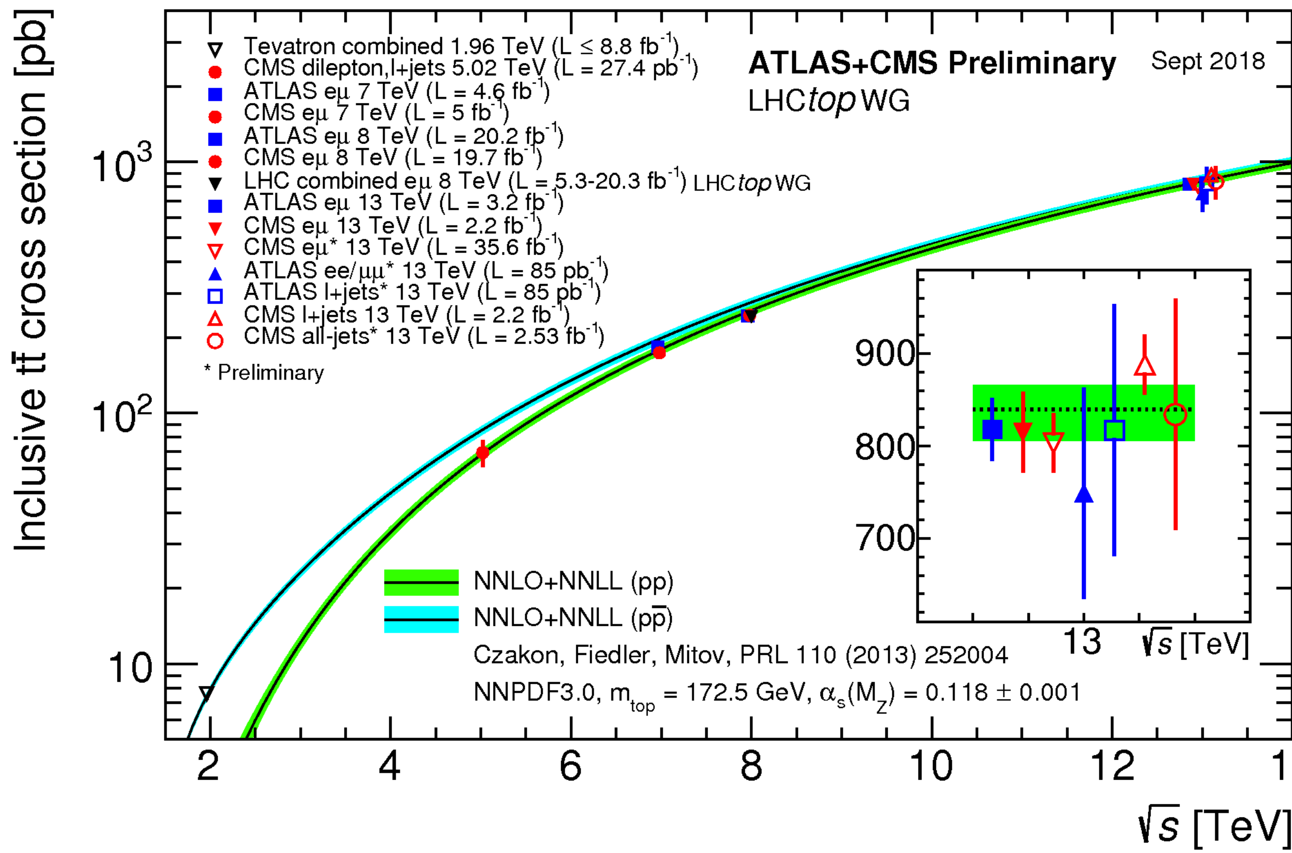
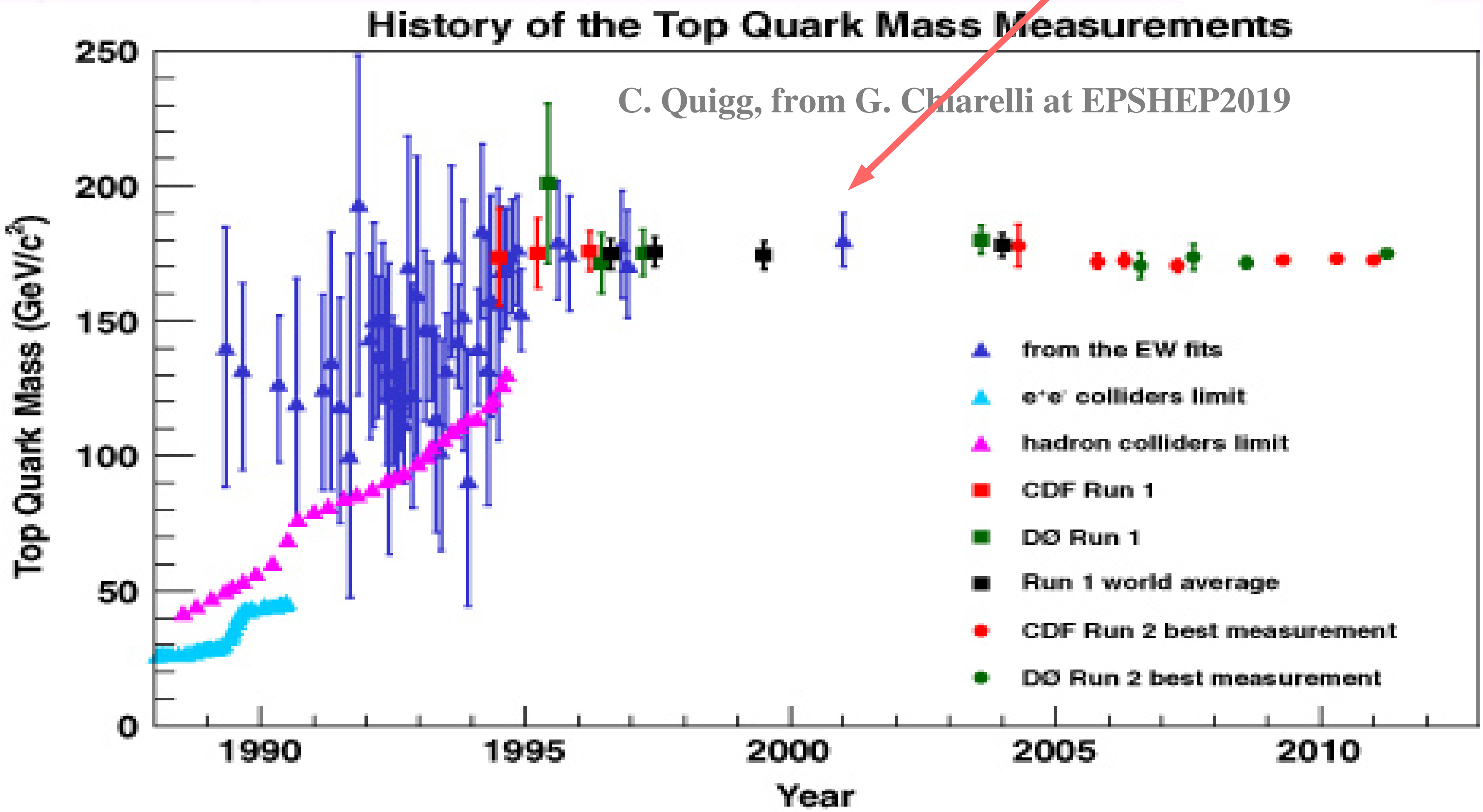
Precision of theoretical calculations matters more then ever



The top quark mass

A bit of history
Results
How do we measure it?
What do we learn from the top quark mass?

Precision tests of SM consistency

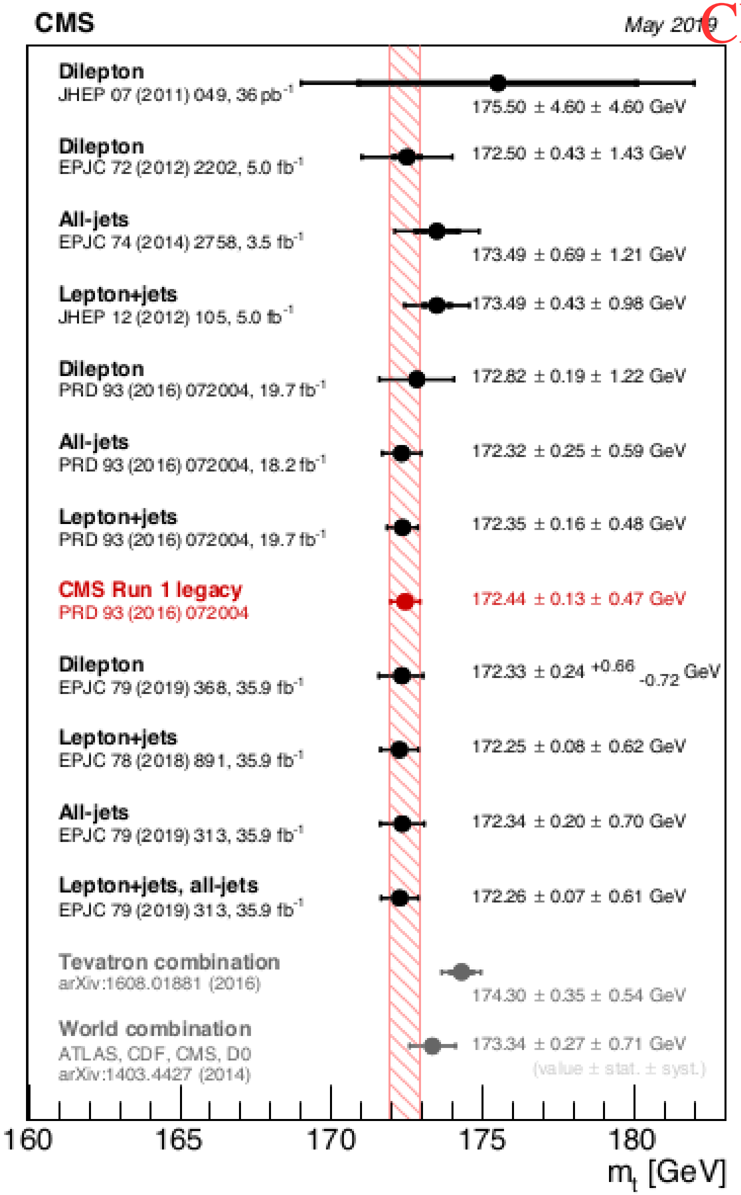


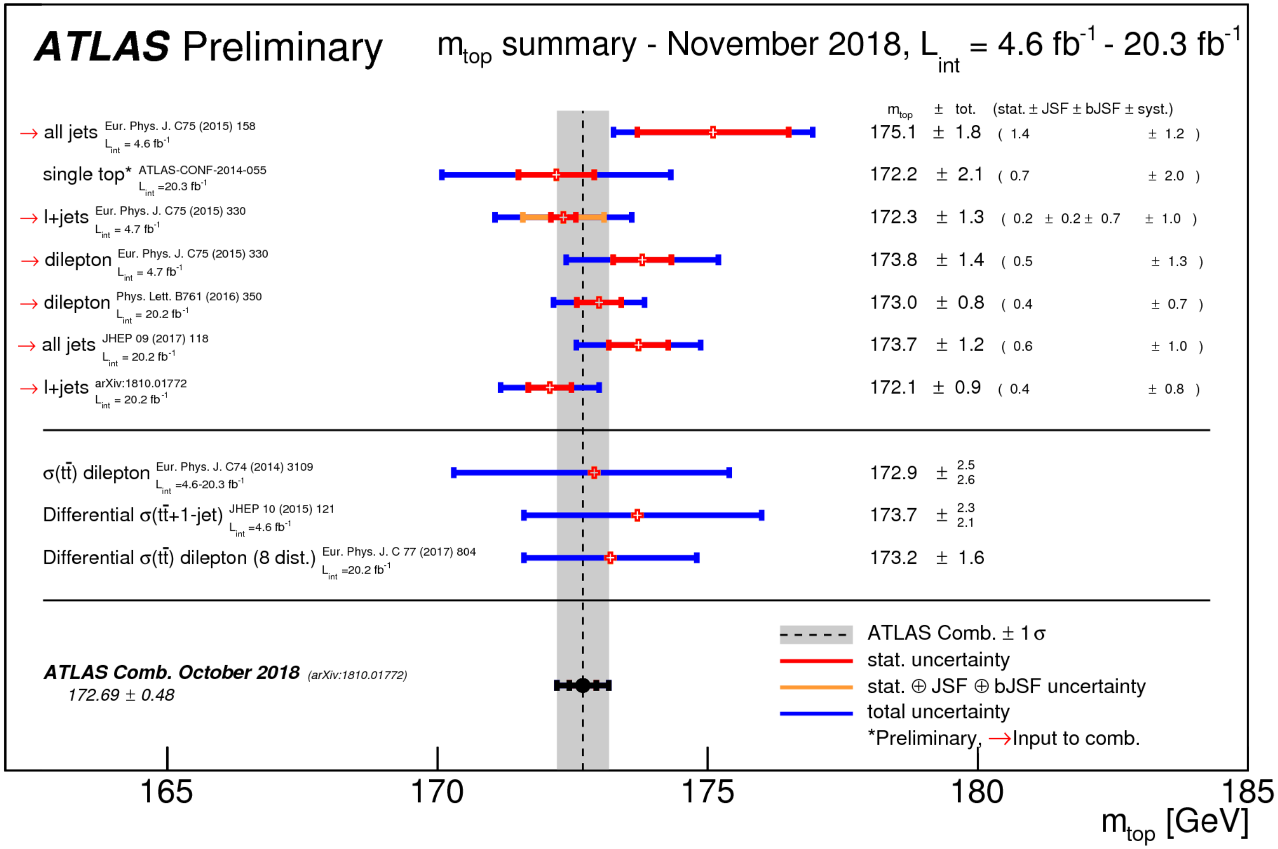
The top quark mass

Results

ATLAS combination, 2018 172.7 +- 0.25 +- 0.41 GeV

CMS Run 1 legacy 172.4 +- 0.10 +- 0.50 GeV





The top quark mass

How do we measure it ?

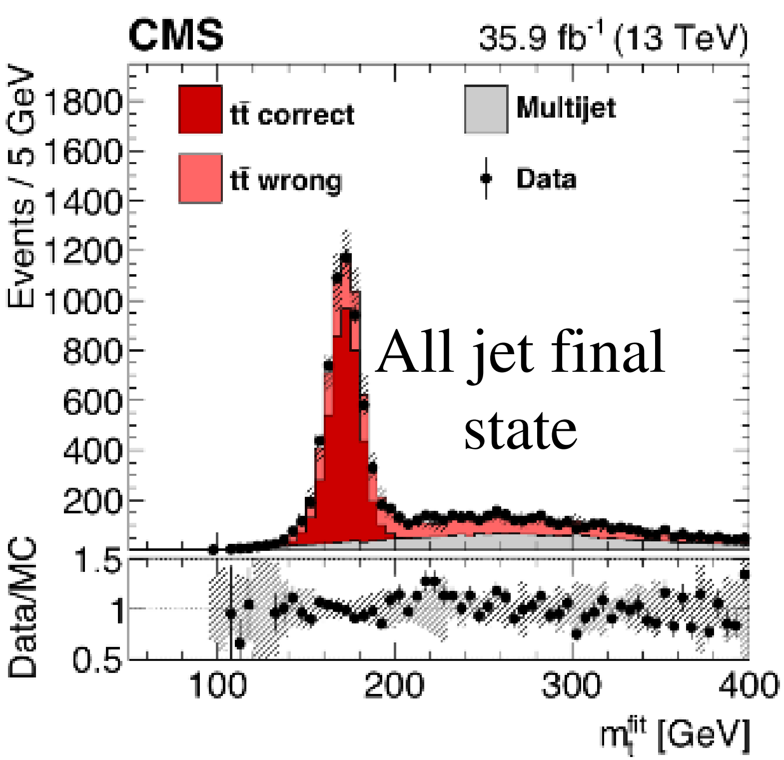
* Direct measurement from top decay products.

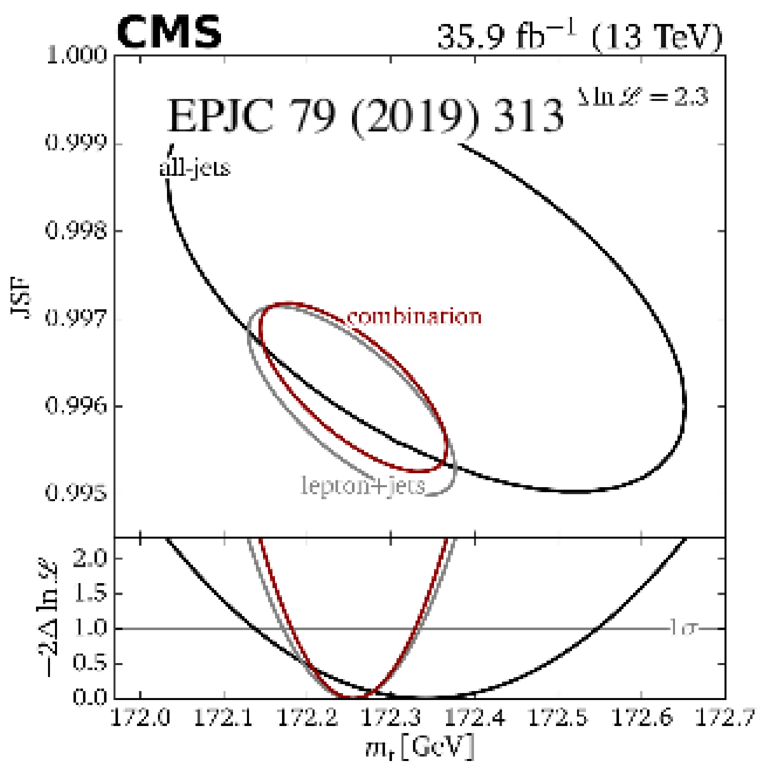
→ MC mass m_t^{MC} as defined in Monte Carlo

→ experimentally, highest sensitivity <500 MeV

→ improved understanding of non-perturbative effects needed for increased precision

$$m_t = 172.25 \pm 0.08\ (\text{stat+JSF}) \pm 0.62\ (\text{syst})\ \text{GeV}$$





The top quark mass

How do we measure it ?

* Indirect measurements sensitive observables (cross-sections) + theory

→ Use a well defined scheme(m_t^{pole} , $m_t(m_t)$)

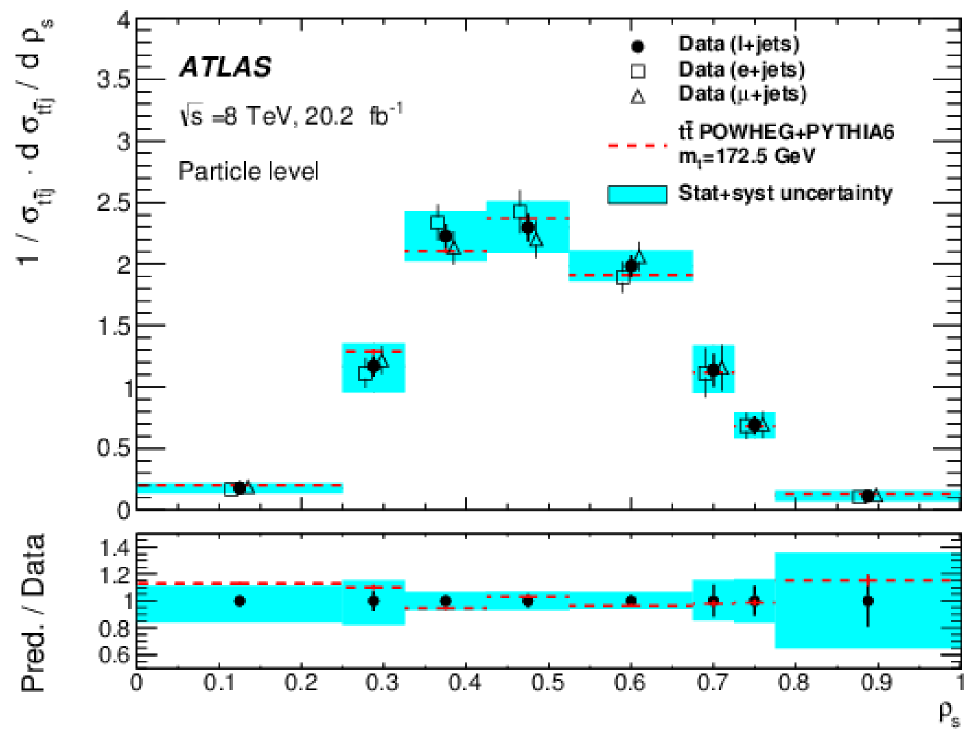
→ approaching < 1 GeV precision

* Combine different measurements to constrain uncertainties

Most precise yet from tt+1j at 8 TeV +NLO **arXiv:1905.02302**

$$m_t^{\rm pole} = 171.1 \pm 0.4({\rm stat}) \pm 0.9({\rm syst})\ ^{+0.7}_{-0.3}({\rm theo})\ {\rm GeV}$$

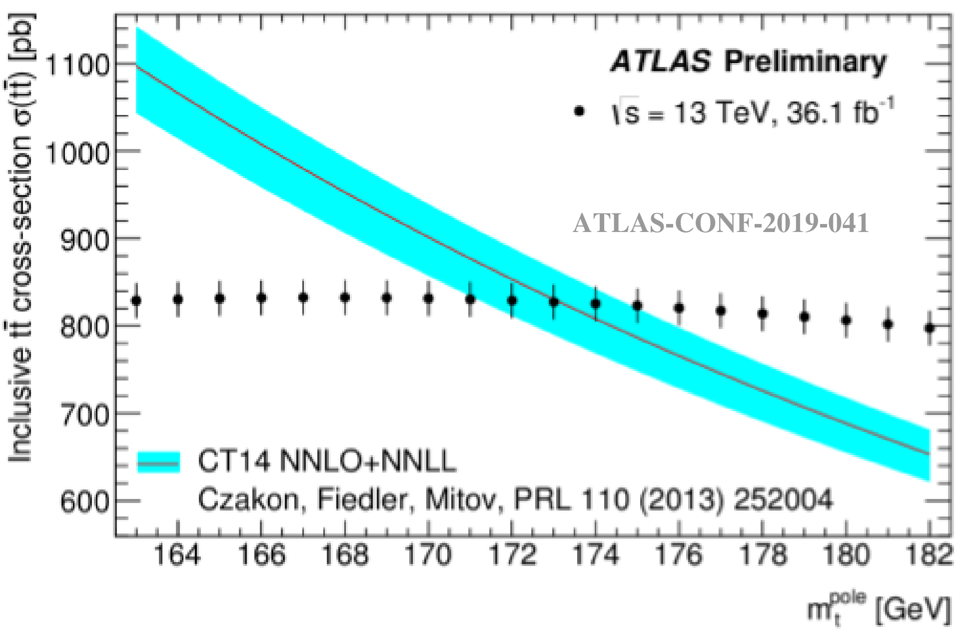
$$m_t(m_t) = 162.9 \pm 0.5\ ({\rm stat}) \pm 1.0\ ({\rm syst})\ ^{+2.1}_{-1.2}\ ({\rm theo})\ {\rm GeV}$$



$$\rho_s = \frac{170\ \ GeV}{m_{t\bar{t}+1j}}$$

New 13 TeV measurement using only the inclusive σ(tt) and NNLO+NNLL theory achieved

$$m_t^{\rm pole} = 173.1^{+2.0}_{-2.1}\ {\rm GeV}$$



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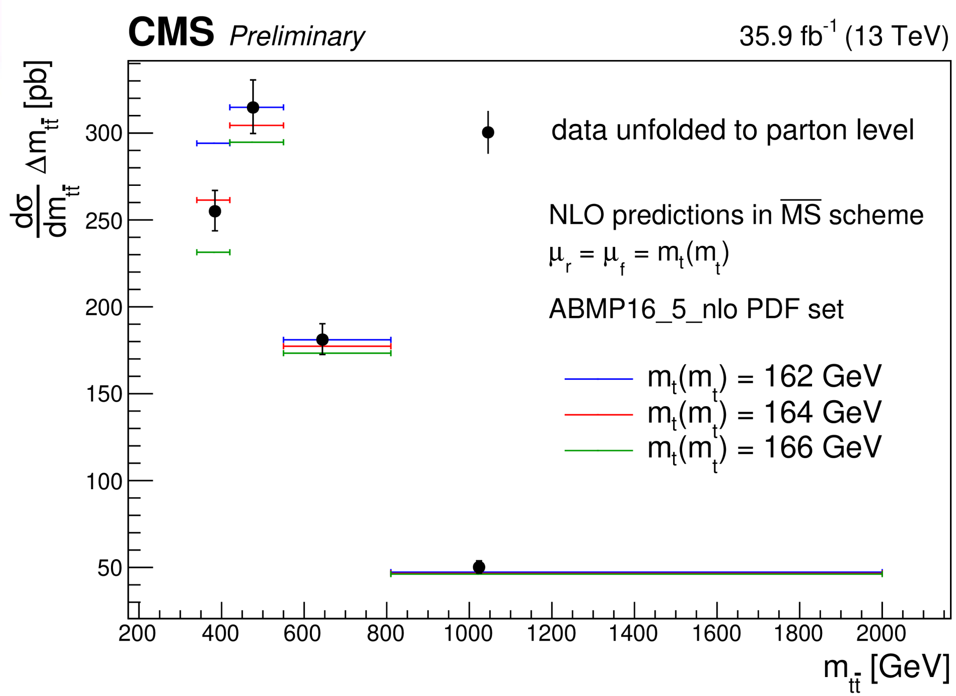
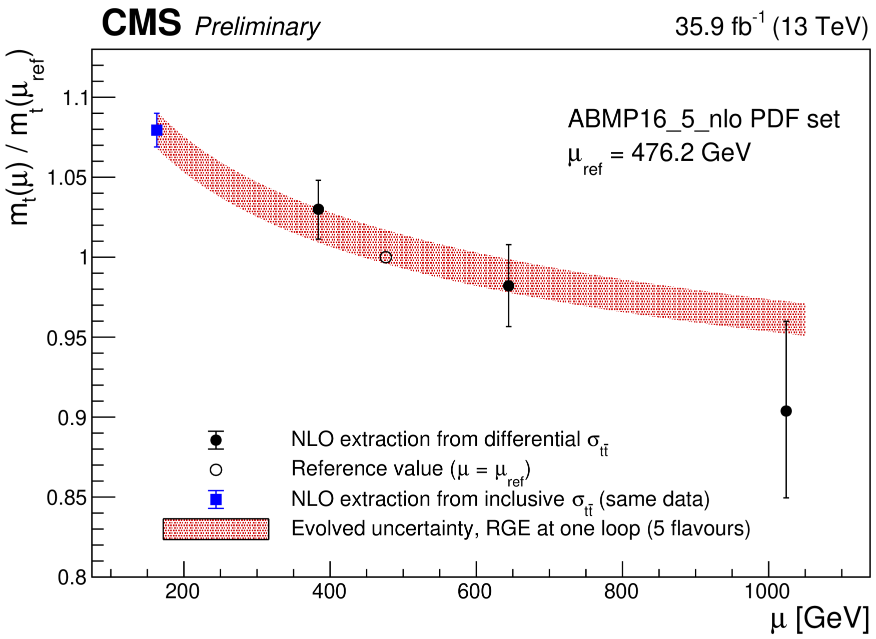
Running mass from differential x-section CMS-PAS-TOP-19-007





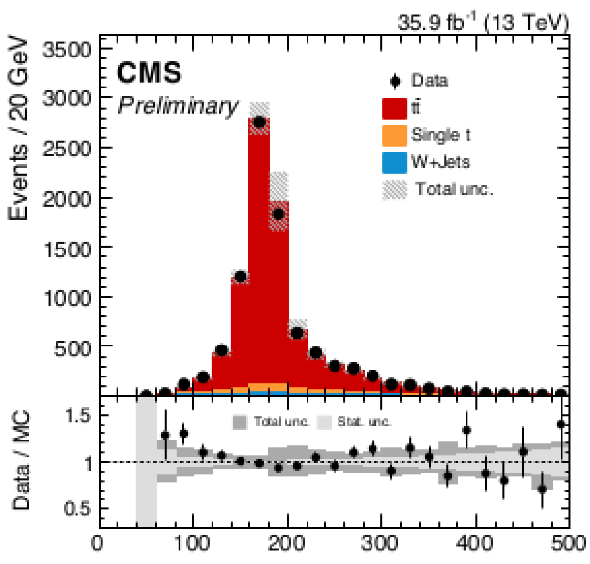
The top quark mass

How do we measure it ?

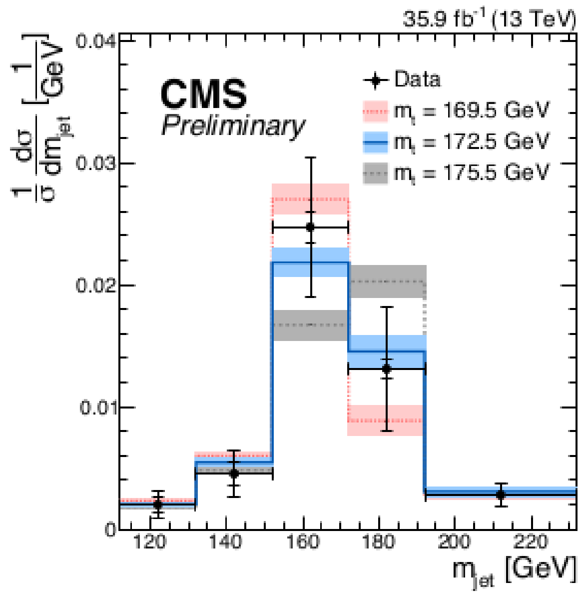
Measurement of m(jet) in top quark decays

Jet mass in decays of boosted top quarks

- Alternative approach to measuring m(t): jet mass of highly boosted top quarks (p_T>400GeV)
- Reconstruction of large (R=1.2) jets, and 3 subjets / jet using the XCone algorithm
  - one leptonic top decay is required, and jet with max. distance to lepton is chosen



Unfold to particle level



Extracted value for m(t) = 172.56 ± 2.47 GeV

Uncertainty similar to the ones from threshold production!

TOP-19-005 NEW!

The top quark mass , fundamental parameter of SM

What do we learn from it ? ***Top mass as a link from Lagrangian to data*** *(Tilman Plehn , summary TOP2018)*

– new physics inspiration:

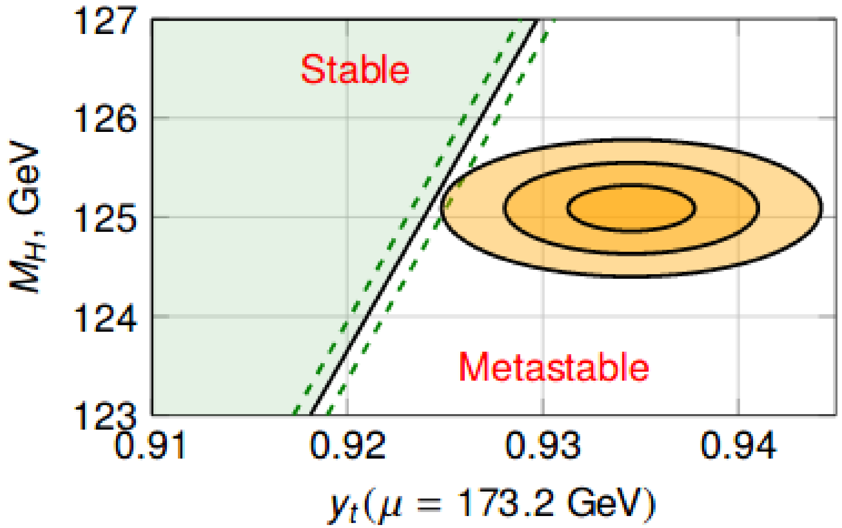
electroweak precision data
vacuum stability
hierarchy problem

impact from future LHC measurement?

– actually, field theory question
related to large-n_F loop diagrams [renormalons]

arXiv:1205.2893

tH coupling



The top quark mass , fundamental parameter of SM

What do we learn from it ?

(Tilman Plehn summary, TOP2018 list of "theory concerns")

Top mass as a link from Lagrangian to data

Tick the correct statements:

- ☐ Direct top mass measurements measure the Pole Mass.
- ☐ Direct top mass measurements measure the Monte Carlo Mass.
- ☐ Direct top mass measurements measure the Monte Carlo Mass. but you can pretend that it is the pole mass, just inflate the error a bit.
- ☐ The top is the only SM particle with more than one mass.
- ☐ You should use only leptons to avoid hadronization uncertainty.
- ☐ You should use at least NLO calculations to measure the pole mass.
- ☐ The top pole mass has renormalons, you should stay away from it.
- The MC mass differs from the pole mass by
  ☐ terms of order $m\alpha_s$; ☐ terms of order Λ_{QCD}; ☐ terms of order $\alpha_s\Gamma_t$.
- The Pole Mass renormalon ambiguity is
  ☐ ≈ 1GeV; ☐ ≈ 250 MeV; ☐ ≈ 200 MeV; ☐ ≈ 110 MeV.

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + \Delta_m^{\mathrm{pert}} + \Delta_m^{\mathrm{non-pert}} + \Delta_m^{\mathrm{MC}}$$

pQCD contribution:

- Perturbative correction
- Depends on MC parton shower setup

Non-perturbative contribution:

- Effects of hadronization model
- May depend on parton shower setup

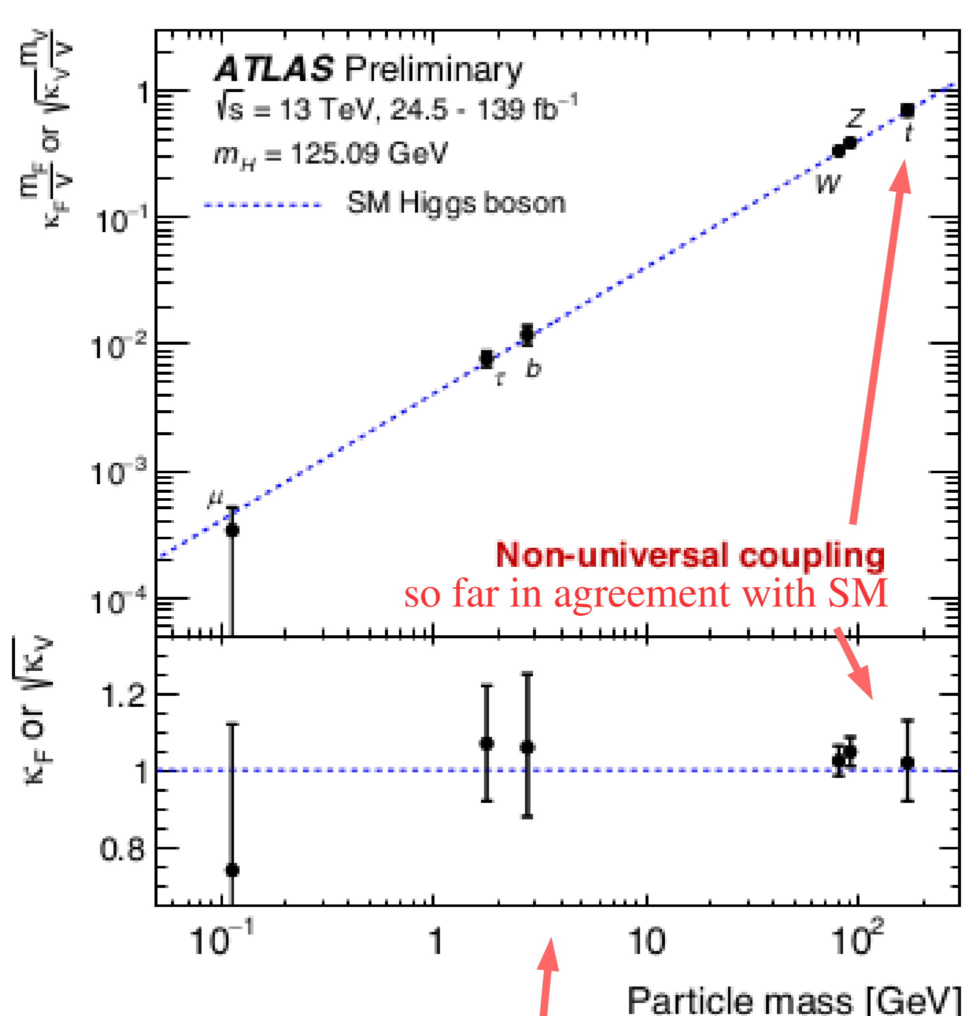
Monte Carlo shift:

- Contribution arising from systematic MC uncertainties
- E.g. color reconnection, b-jet modeling, finite width, ...
- Should be covered by 'MC uncertainty' or better negligible

The top quark and the Higgs boson

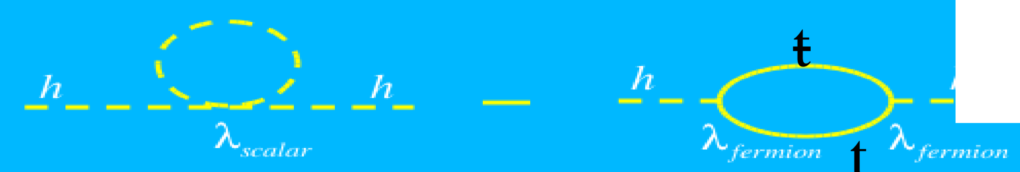
Top quark Yukawa coupling

- Largest in the SM: $y_t = \sqrt{2}\, m_t / v \approx 1$
- Sensitive to potential New Physics



Indirect measurement of y_t, details in arxiv 1909.02845
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/

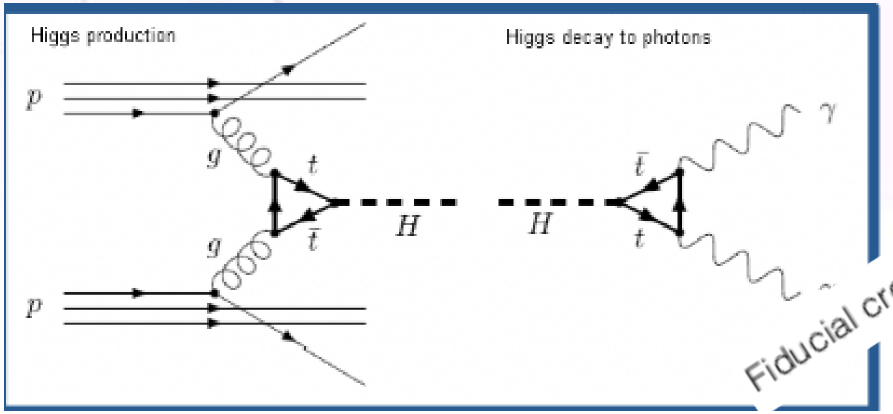
Linked to the hierarchy problem.
Are there any scalar partners?



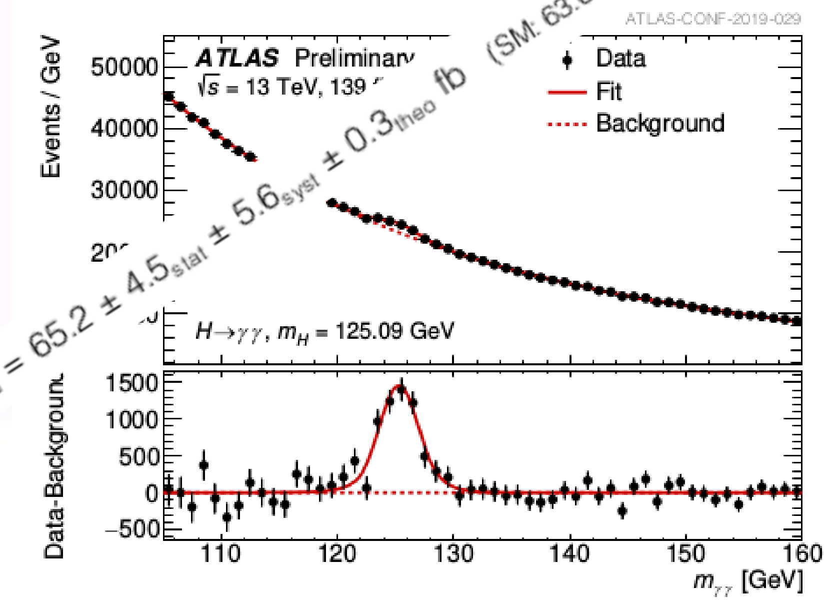
$$\delta m_h^2 = \frac{1}{8\pi^2}\left[\lambda_{scalar}^2 - \lambda_{fermion}^2\right]\Lambda^2 + \ldots$$

The top quark and the Higgs boson

Indirect measurement

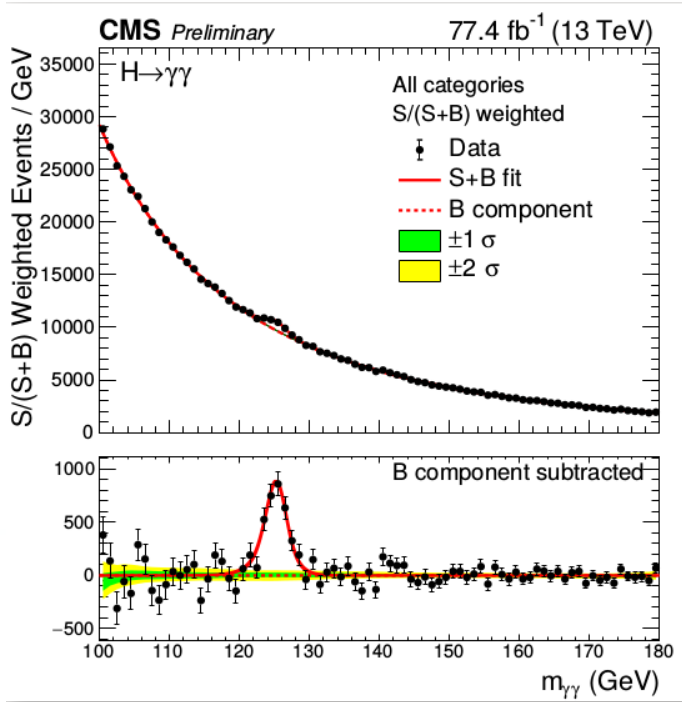


Fiducial cross section $\sigma_{fid} = 65.2 \pm 4.5_{stat} \pm 5.6_{syst} \pm 0.3_{theo}$ fb (SM: 63.6 ± 3.3 fb)



Raw spectrum, no categories, no weighting — beautiful Higgs boson signal

CMS HIG-18-029

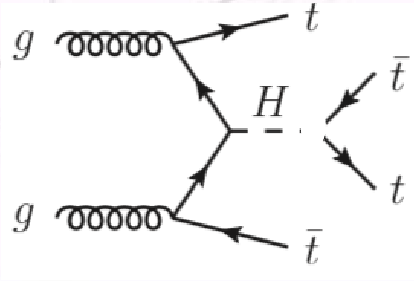


The top quark and the Higgs boson

Top quark measurements and selected BSM, PIC2019

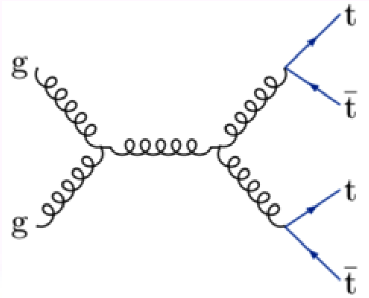
Top Yukawa coupling

Direct assessment **tttt (4 tops)**

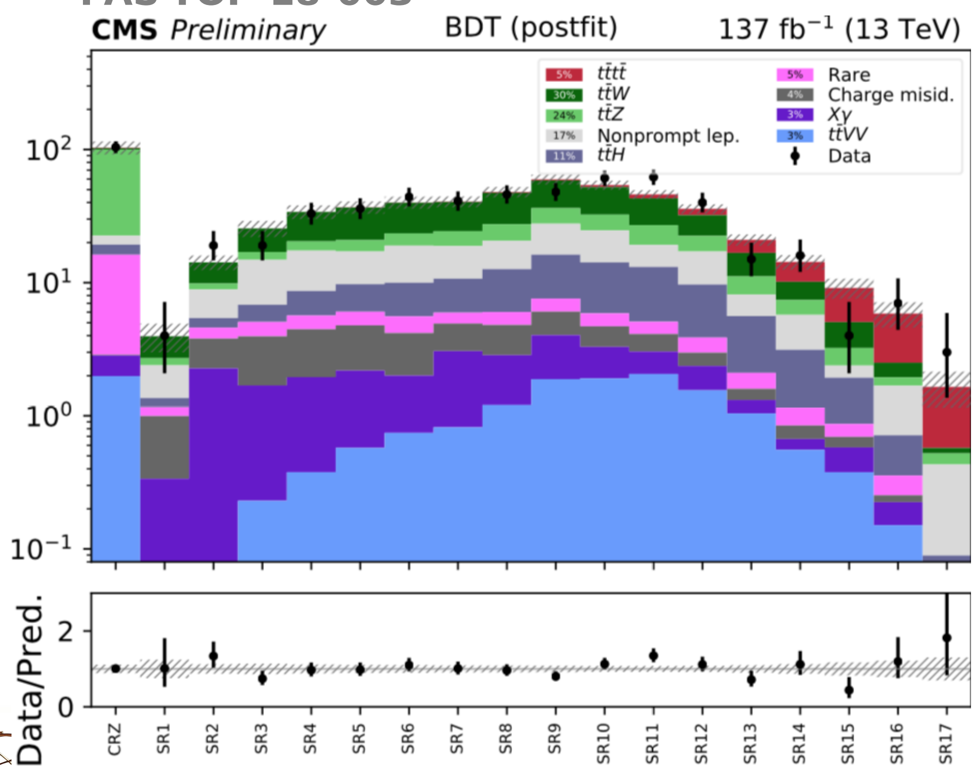


Not yet observed : σ^{NLO}_{tttt} (SM) ~ 12 fb

Sensitive to BSM effects.



PAS-TOP-18-003



same sign dileptons + (≥ 3 l)+(jets): fit many signal and control regions

signal significance **2.6 (2.7) σ** obs(exp.)

Top Yukawa coupling: $|y_t/y^{SM}_t| < 1.7$ @ 95%

complementary to coupling extraction in ttH & tH

(Indirect from tt kinematic:

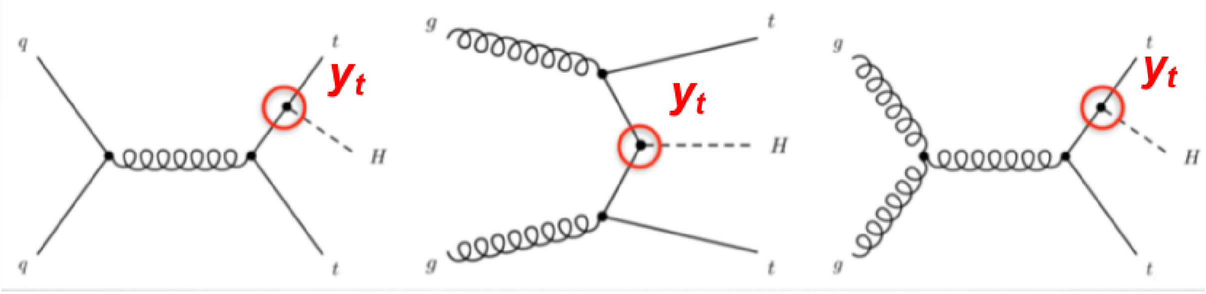
- **$|y_t/y^{SM}_t| < 1.6$ @ 95%**
- **CMS-TOP-17-004)**

The top quark and the Higgs boson

Top Yukawa coupling

Direct measurement

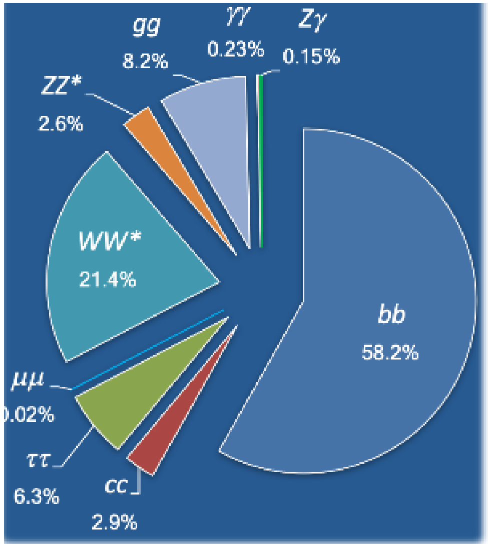
ttH production provides **direct probe of y_t**



Lots of final states, small cross-section.

$\sigma_{ttH} \sim 0.507\ pb$

Higgs branching fractions x top pair branching fractions



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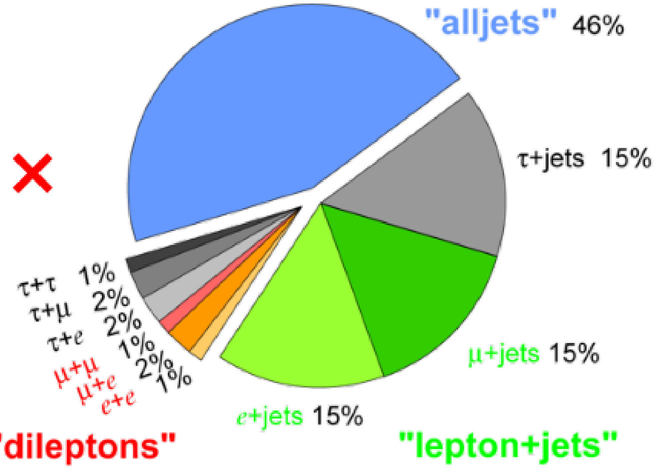
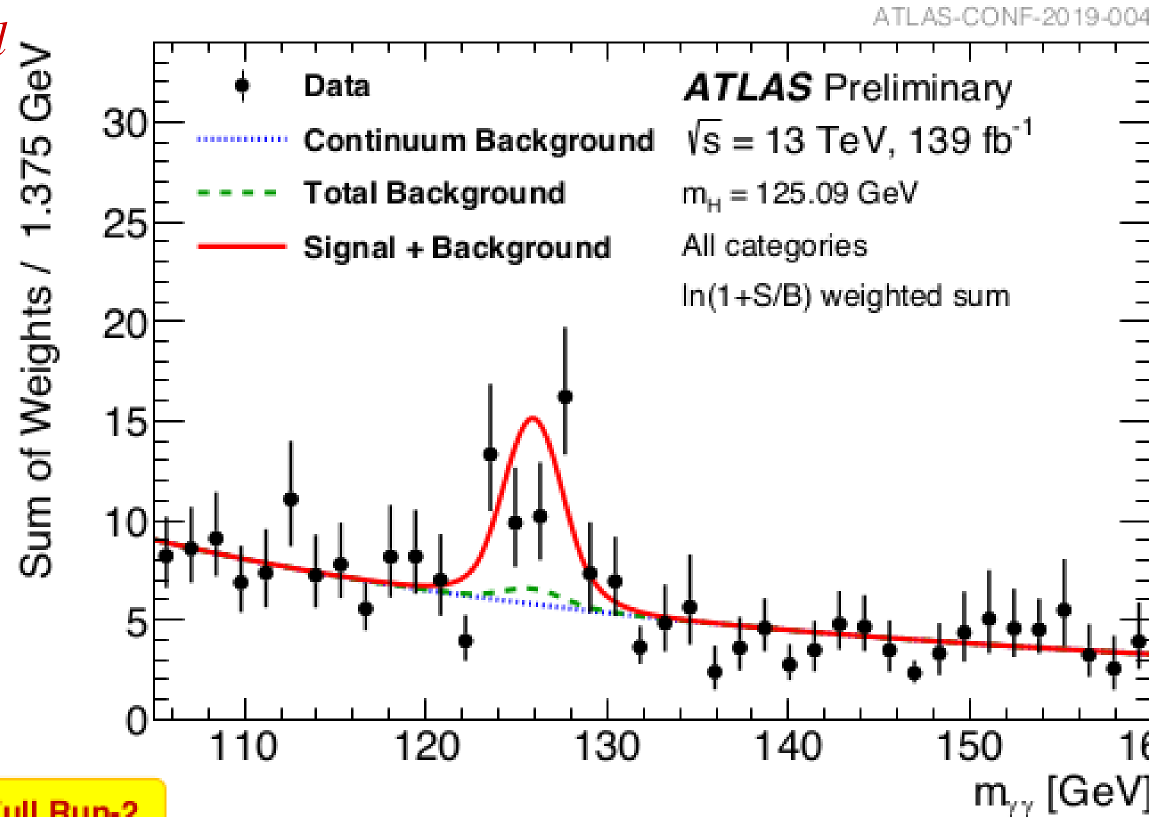


The top quark and the Higgs boson

Top Yukawa coupling, ttH,

First observation of SINGLE ttH channel with 4.9 σ (4.2 σ exp)

Analyze full Run-2 dataset with updated photon-ID, energy and jet calibrations



Note:

- *Events weighted by purity*
- *Non-ttH Higgs boson processes from MC samples normalized to their expected SM cross sections times the expected SM branching ratio to di-photons with a Higgs boson mass of 125 GeV*

Full Run-2

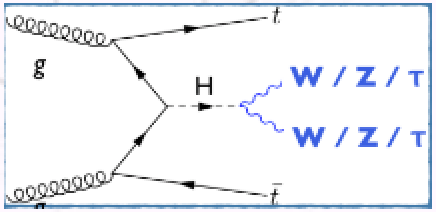
$$\sigma_{\mathrm{ttH}} \times B_{\gamma\gamma} = 1.59 \,^{+0.38}_{-0.36}(\mathrm{stat.}) \,^{+0.15}_{-0.12}(\mathrm{exp.}) \,^{+0.15}_{-0.11}(\mathrm{theo.})\ \mathrm{fb}$$

$$\frac{\sigma_{\mathrm{ttH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ttH}}} = 1.38 \ \pm^{0.33}_{0.31}\ (\mathrm{Stat.})\ \pm^{0.13}_{0.11}\ (\mathrm{exp.})\ \pm^{0.22}_{0.14}\ (\mathrm{theo.})$$

The top quark and the Higgs boson

ttH, example multilepton analysis:

PHYS. REV. D **97,** 072003 (2018)

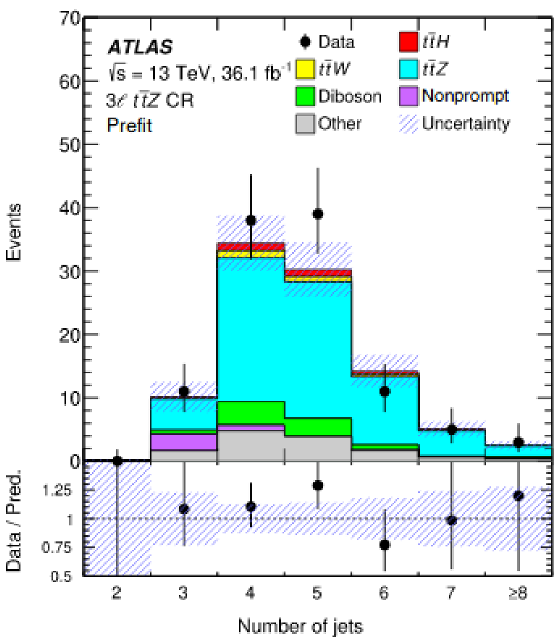


Irreducible backgrounds, tt V and VV, estimated in MC and validated in data .

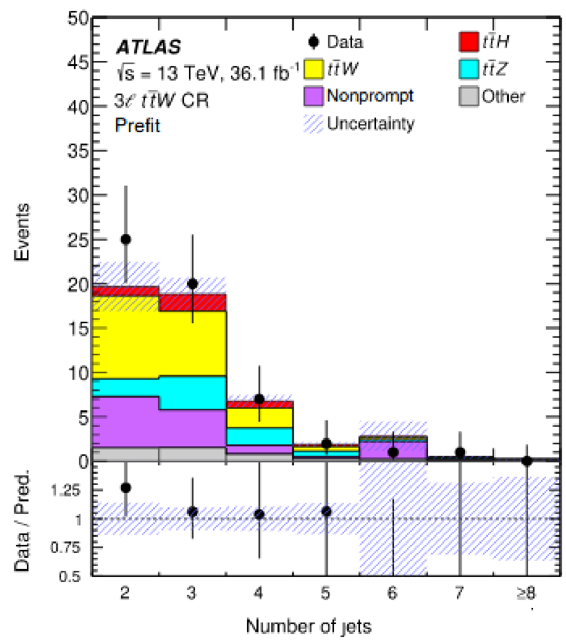
ttZ, ttW, tt γ
are interesting processes
by themselves and give direct
access to the top electroweak
coupling

validation

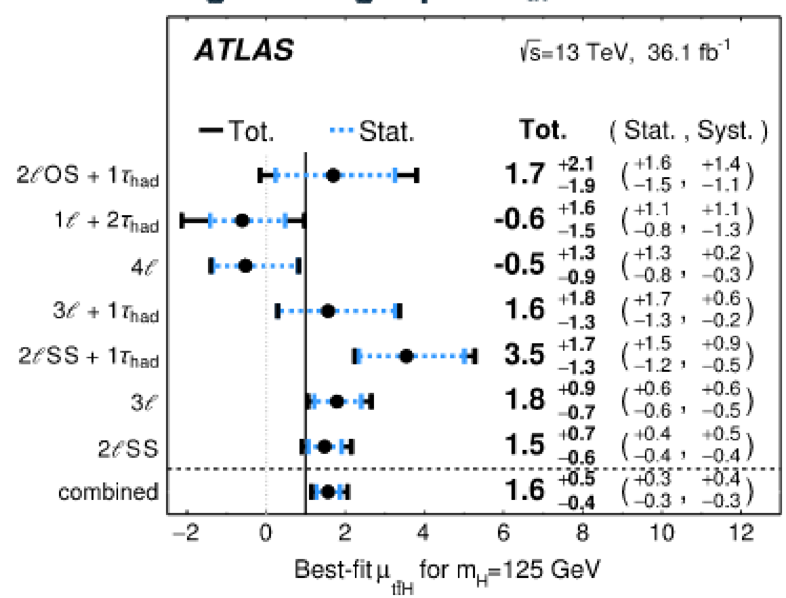
ttZ



ttW



Signal strength: $\mu=\sigma/\sigma_{SM}$



Significance: 4.1σ (expected 2.8σ)

The top quark and the Higgs boson

The top Yukawa coupling, combined fit.

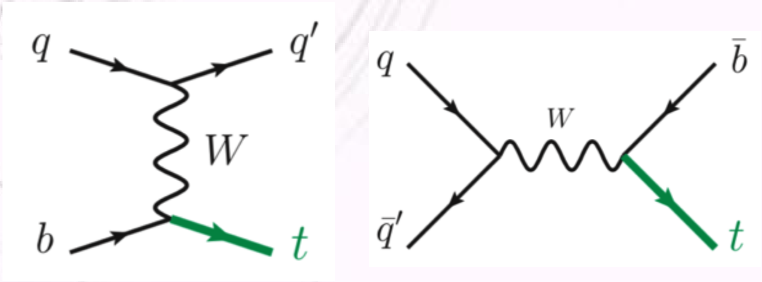
Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
VH, $H \to b\bar{b}$	79.8
VBF, $H \to b\bar{b}$	24.5 – 30.6
$H \to \mu\mu$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1
$H \to$ invisible	36.1
Off-shell $H \to ZZ^* \to 4\ell$ and $H \to ZZ^* \to 2\ell 2\nu$	36.1

arxiv 1909.02845

$y_t/y_t^{SM} = 1.02^{+0.11}_{-0.10}$ → Allowing only SM particles in the loops

$y_t/y_t^{SM} = 1.18^{+0.23}_{-0.23}$ → Allowing one BSM contribution

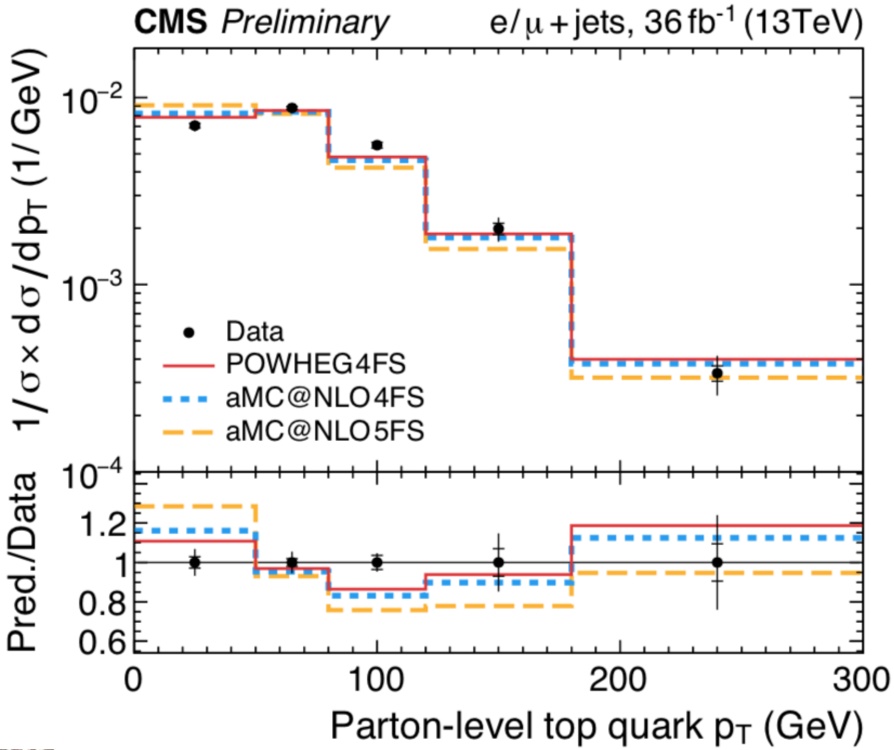
Probing the tWb coupling: single top

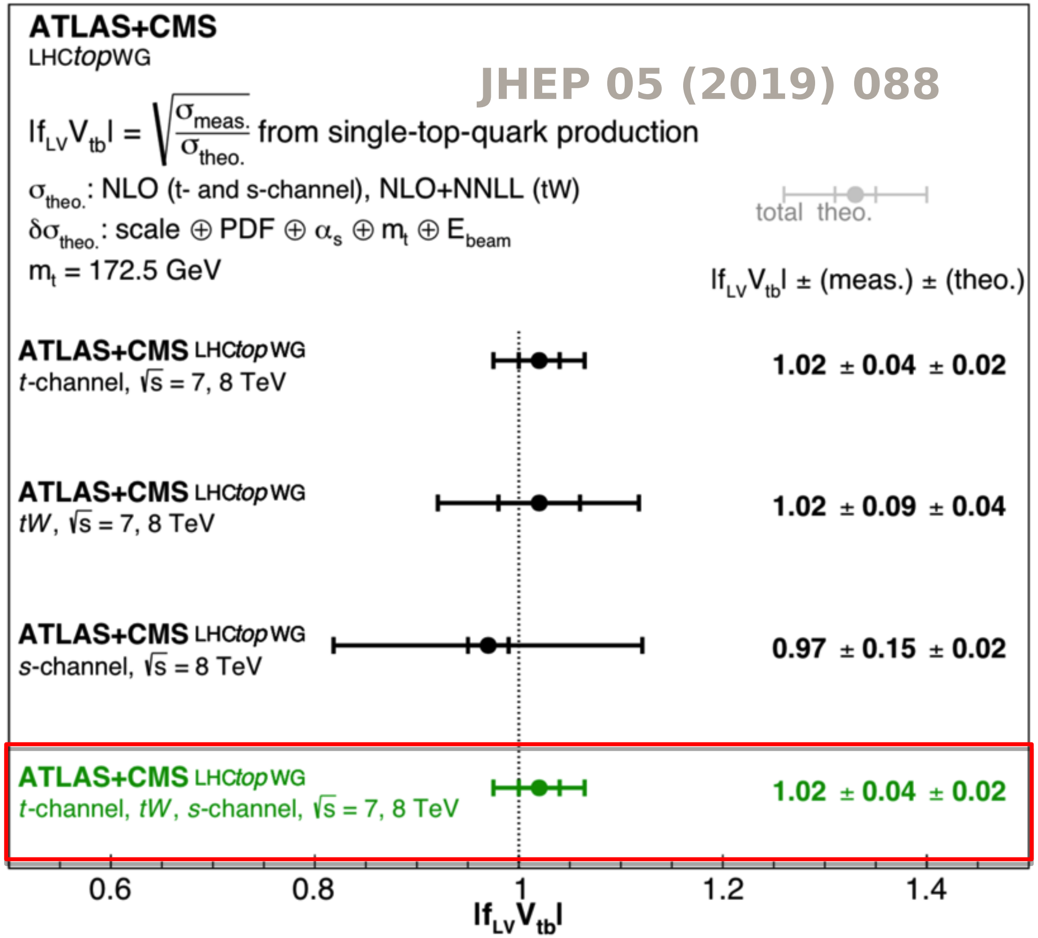


LHC best combined precision 7@8TeV:
ATLAS+CMS X-section: **~ 7%** (t-channel)

NLO+NLL predictions **~ 3 %** (t-channel)

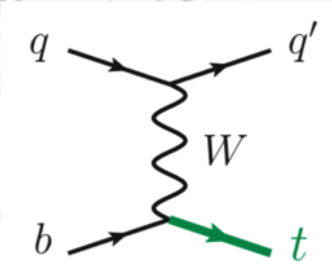
| f_{LV} * V_{tb} | = 1 within ~ 4%

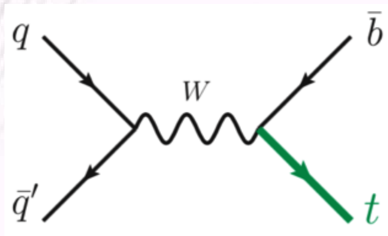




(f_{LV} form factor for BSM contributions)

Probing the tWb coupling: single top





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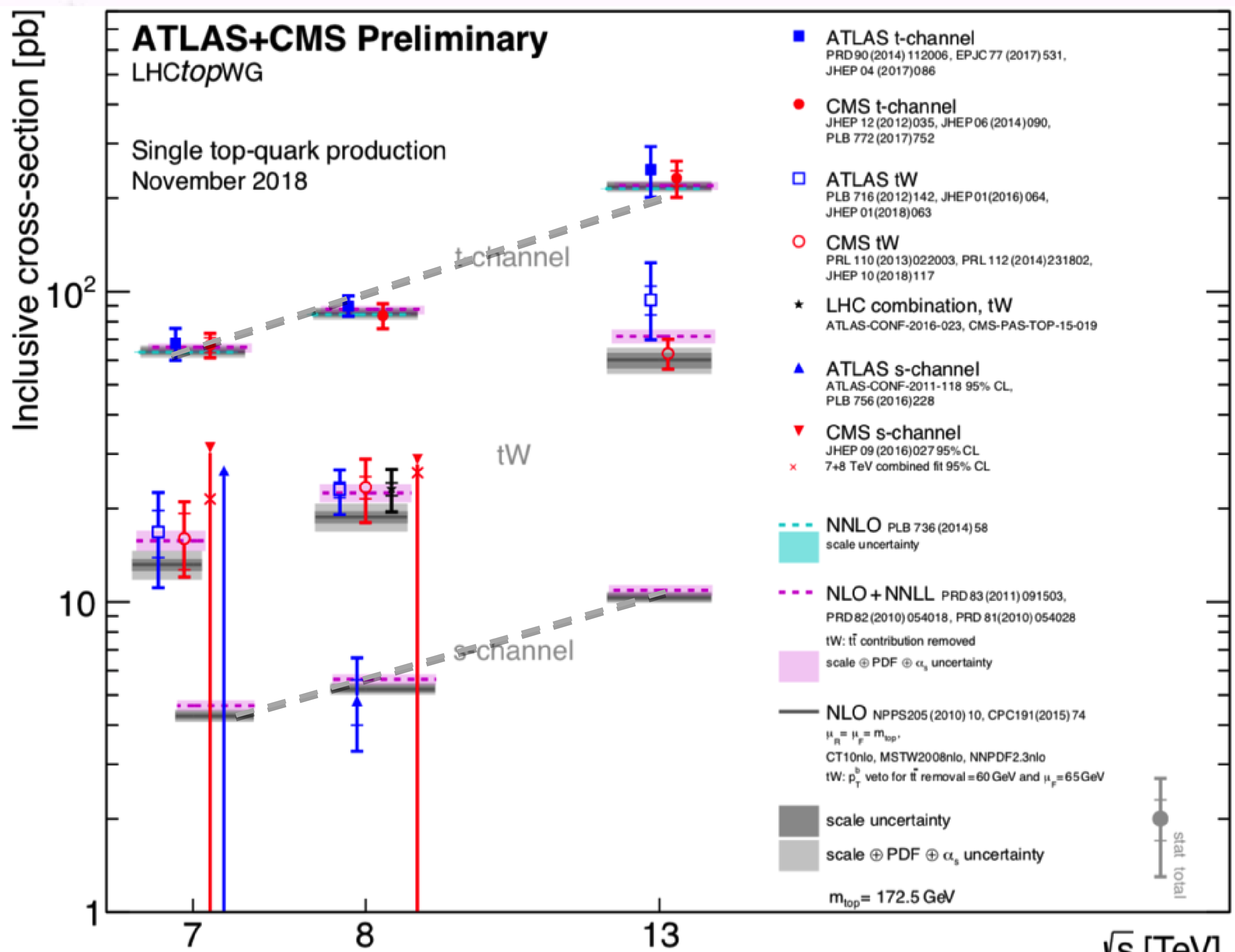
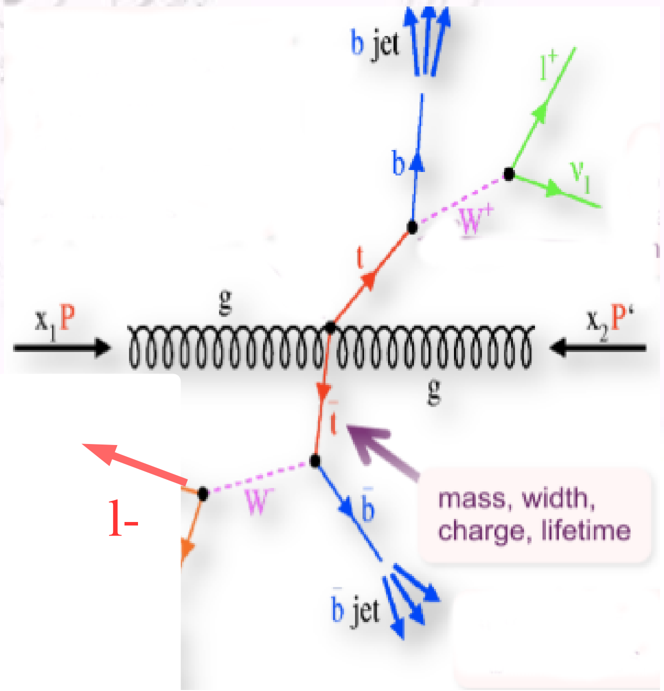
NLO+NLL predictions ~ **3 %** (t-channel)

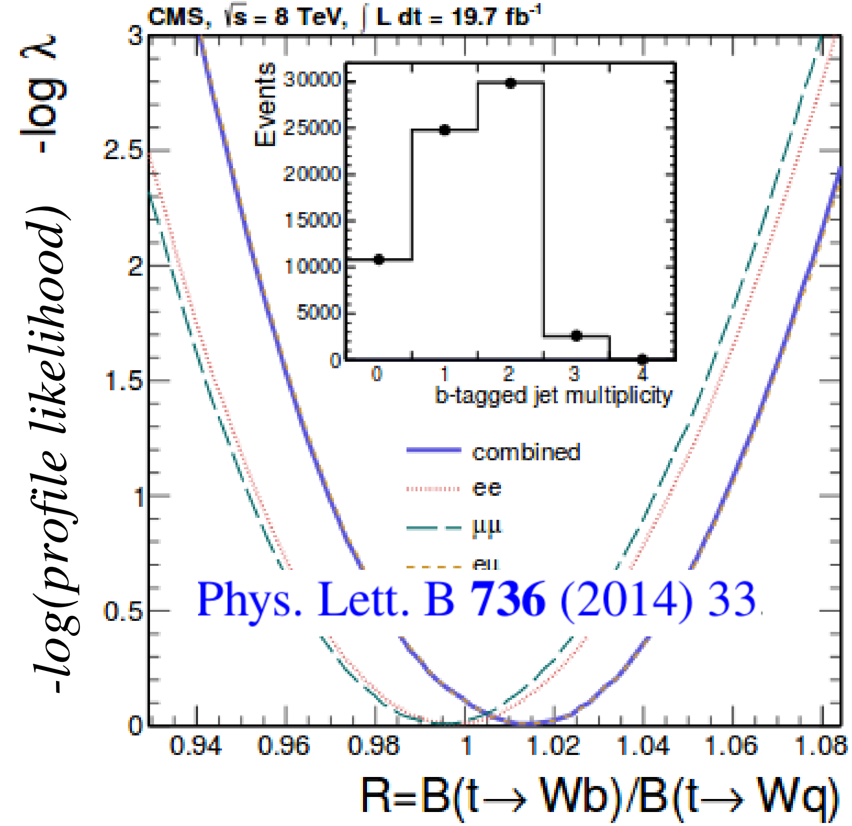


Probing the tWb coupling: the top quark width



Most precise indirect measurement, CMS measuring:

$$\mathcal{R} = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$$

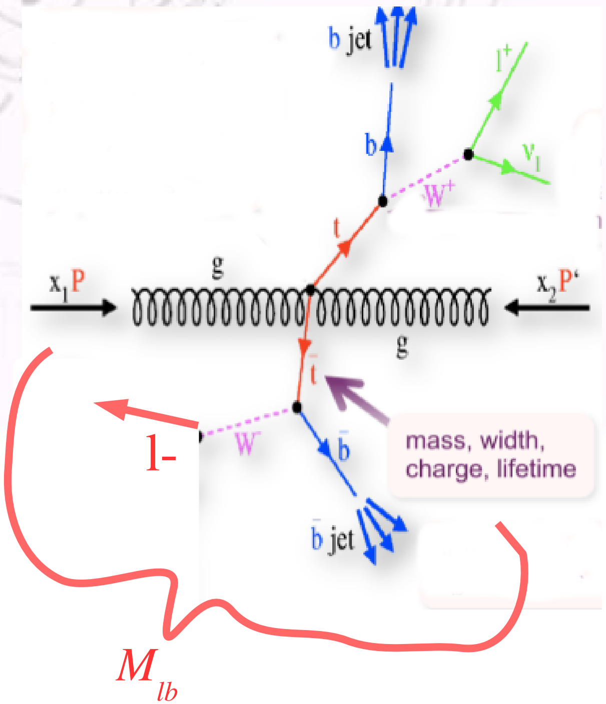


Phys. Lett. B **736** (2014) 33

assuming SM : $\Gamma(t \to Wb) = 1.329$ GeV $\to$ $\Gamma_t = 1.36 \pm 0.02(\text{stat})^{+0.14}_{-0.11}(\text{syst})$ GeV

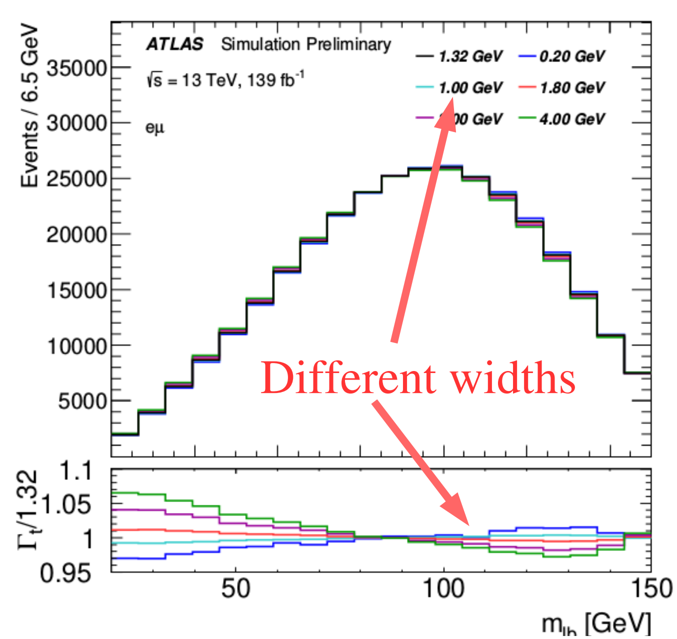
with f_{LV}= 1 R gives: $|V_{tb}| = 1.007 \pm 0.016\,(\text{stat.+syst.})$

The top quark width, direct



Profile-likelihood template fit to M_{lb}

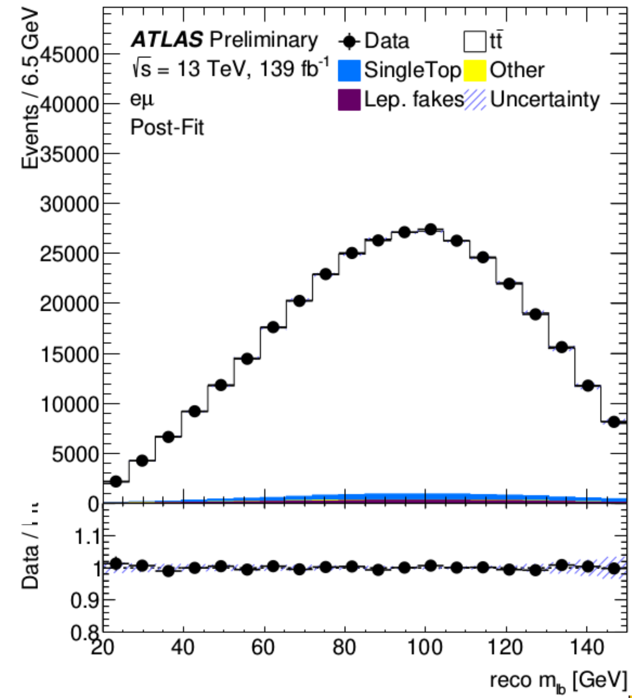
ATLAS-CONF-2019-038



$$\Gamma = 1.94 \pm 0.5 \;\; GeV \left(\;\; for \;\; m_t = 172.5 \;\; GeV \right)$$

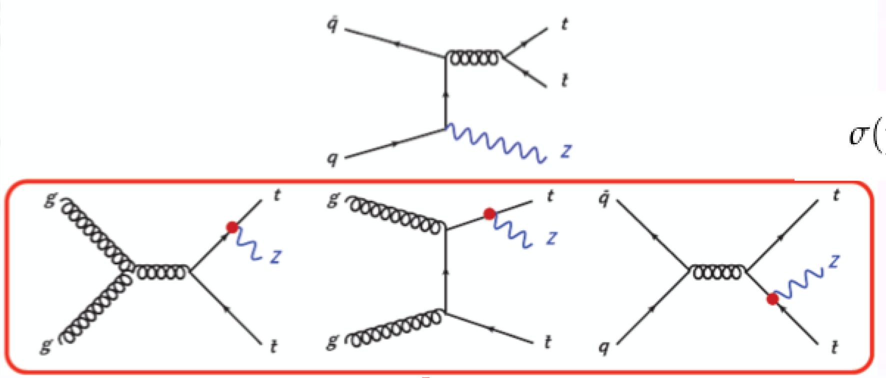
	m_t = 172 GeV		m_t = 172.5 GeV		m_t = 173 GeV	
	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]	Mean [GeV]	Unc. [GeV]
Measured	2.01	+0.53 −0.50	1.94	+0.52 −0.49	1.90	+0.52 −0.48
Theory	1.306	< 1%	1.322	< 1%	1.333	< 1%

top width



Probing the top EW coupling: ttZ

$t\bar{t}Z$ (ISR and FSR)

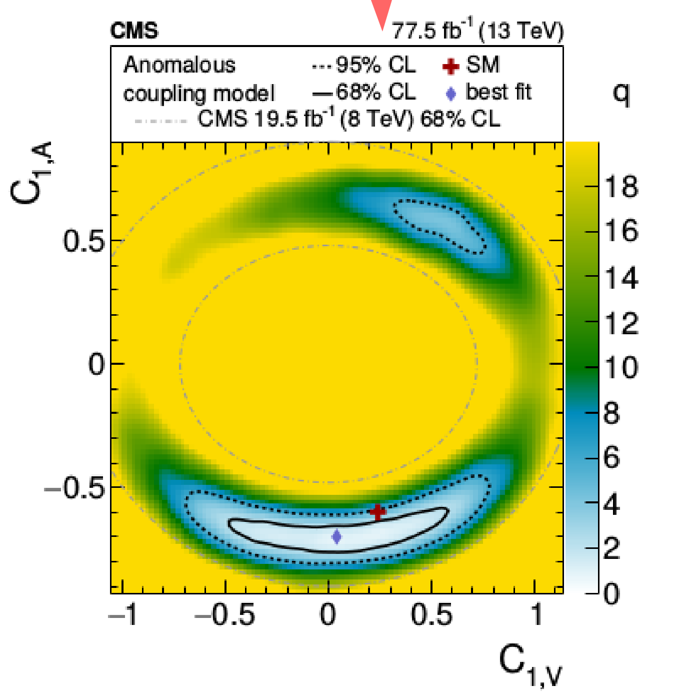


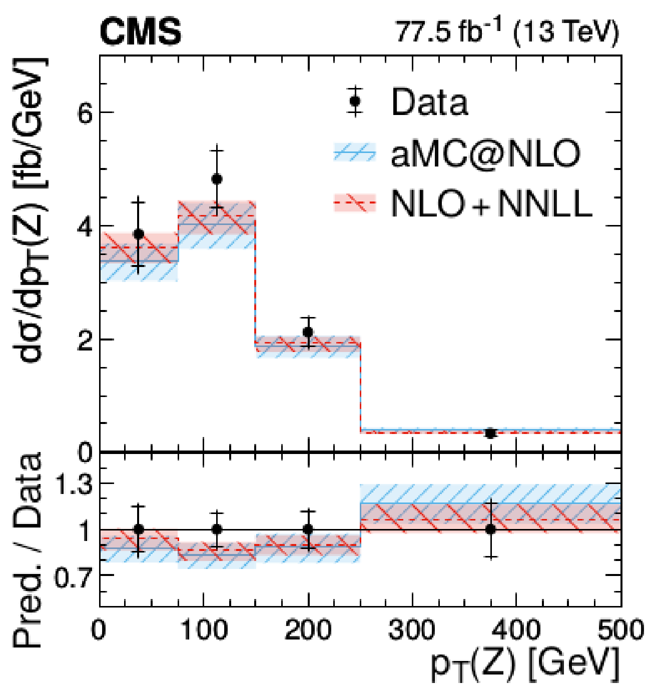
4 and 3 lepton channel, CMS

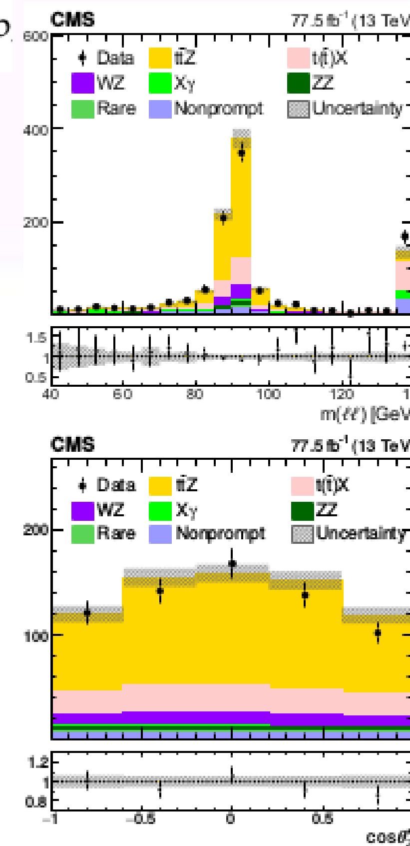
arXiv:1907.11270v1

$$\sigma(pp \rightarrow t\bar{t}Z) = 0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})\,\text{pb}$$

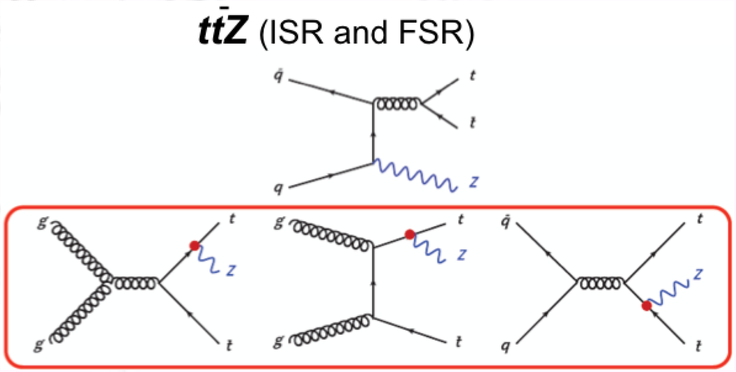
SM prediction of 0.84 ± 0.10 pb at NLO



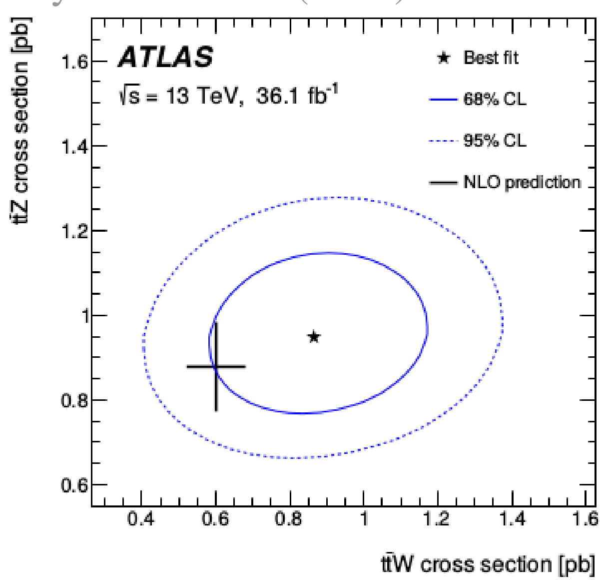




Probing the top EW coupling: ttZ



Phys. Rev. D 99 (2019) 072009



$$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08_{\text{stat.}} \pm 0.10_{\text{syst.}}\ \text{pb and } \sigma_{t\bar{t}W} = 0.87 \pm 0.13_{\text{stat.}} \pm 0.14_{\text{syst.}}\ \text{pb}$$

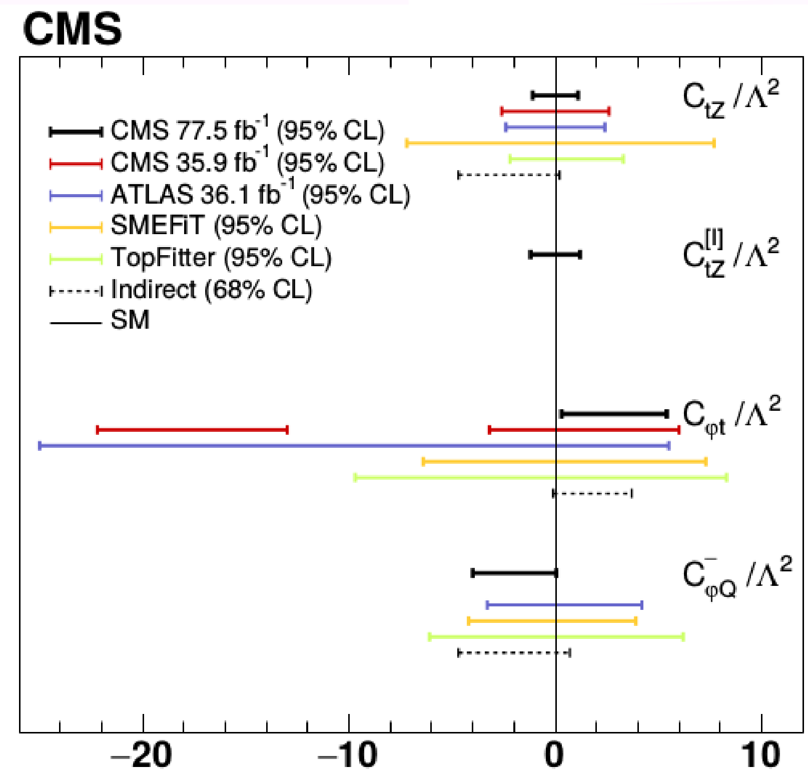
4 and 3 lepton channel, CMS

$$\sigma(pp \to t\bar{t}Z) = 0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})\ \text{pb}$$

SM prediction of 0.84 ± 0.10 pb at NLO

NNLL +0.02

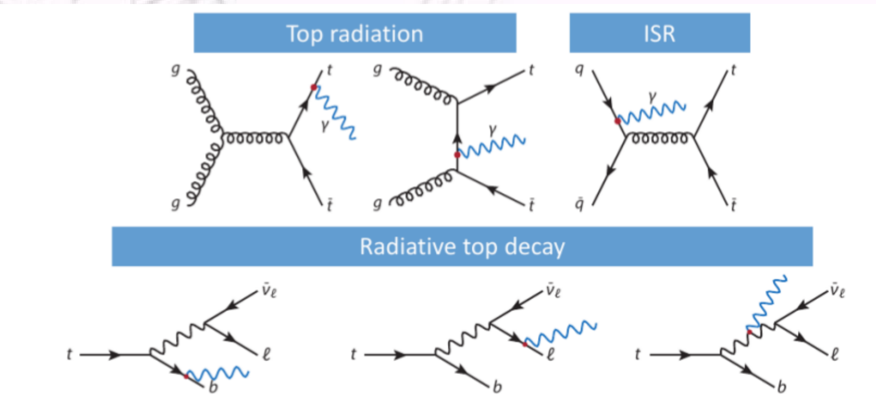
arXiv:1907.11270v1



(SMEFT , SM Effective Theory)

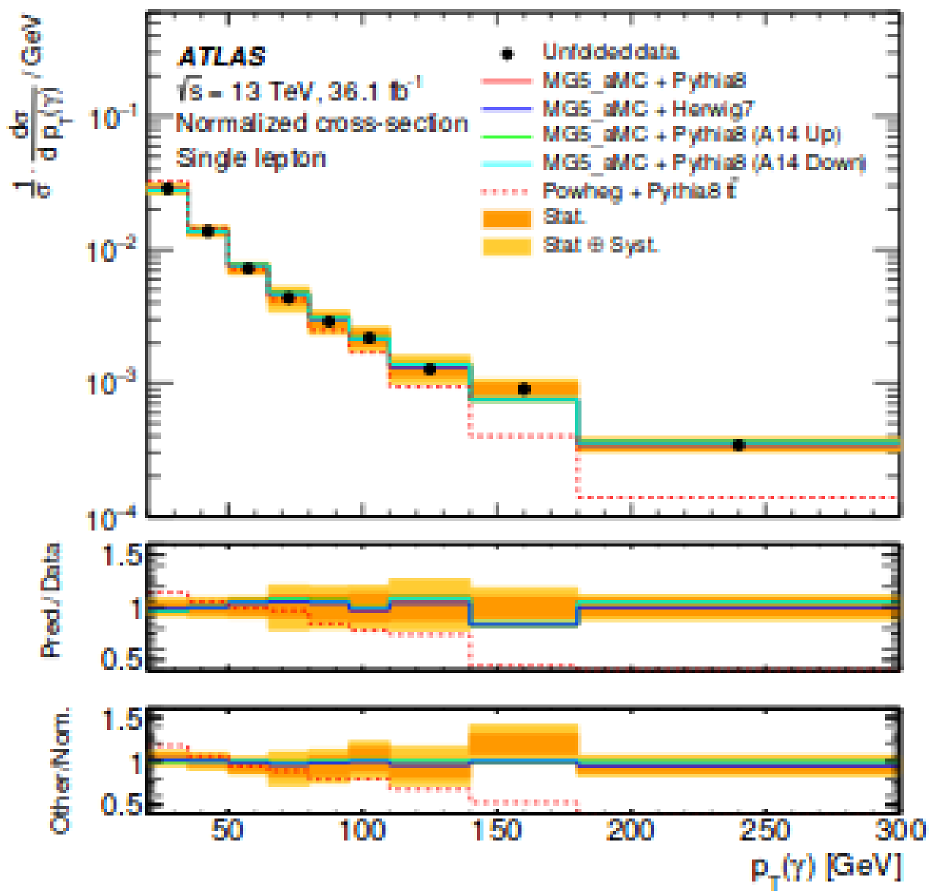
Λ , scale of BSM physics

Probing the top EW coupling: $t\bar{t}\gamma$

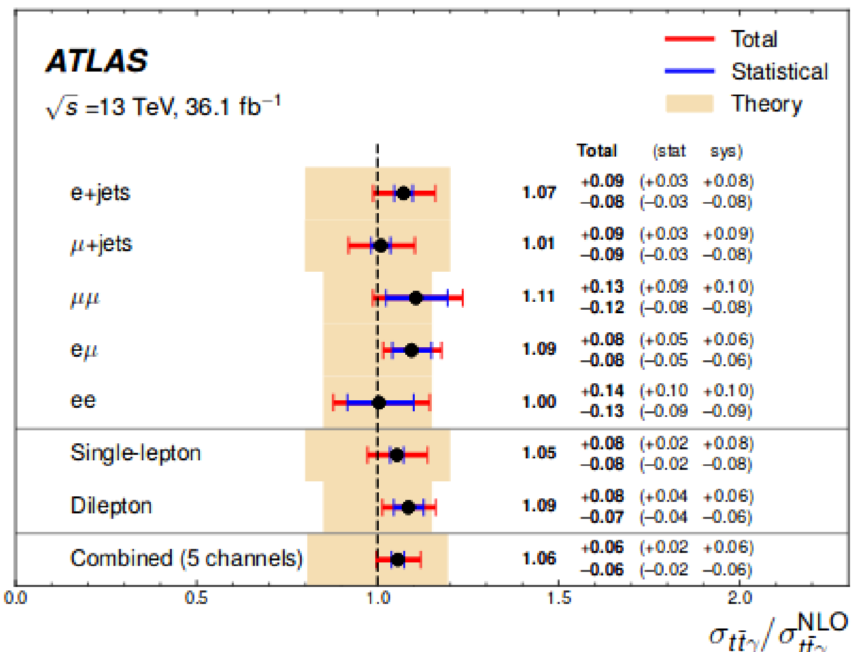


ATLAS single lepton and dilepton channel

Eur. Phys. J. C 79 (2019) 382

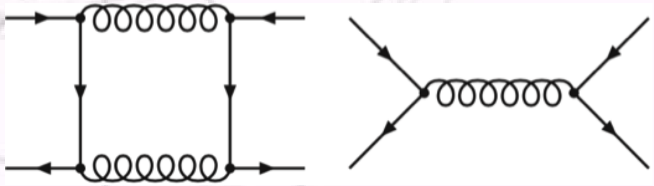


Fiducial x-section accuracy and the theory error comparable



Top quark measurements and selected BSM, PIC2019

tt, top charge asymmetry, A_C



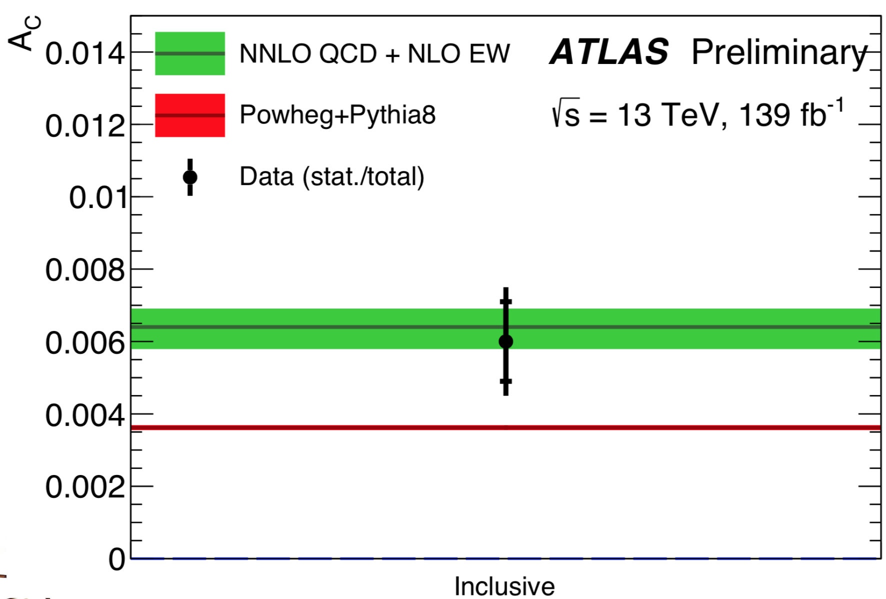
•SM : A_C results from the interference of HO amplitudes in qq and qg initial states : t prefers q direction. Small effect, enhanced @ high tt mass (**m_{tt}**) and longitudinal tt boost (**β_{tt}**).

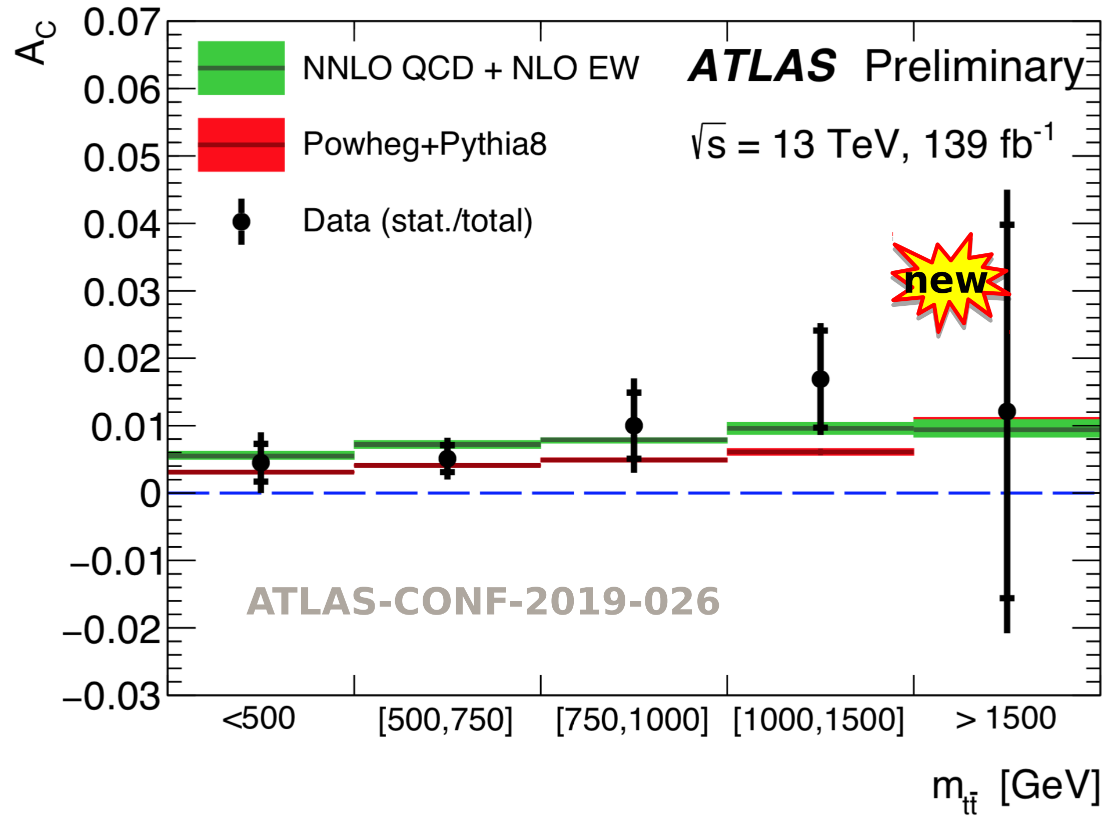
ATLAS full Run 2 analysis lepton-jet topology

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} = 0.0060 \pm 0.0011_{stat} \pm 0.0010_{sys}$$

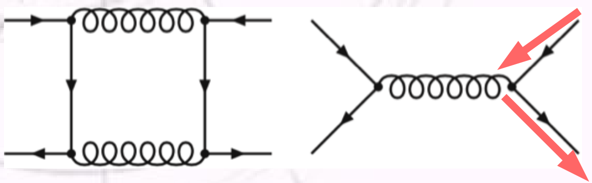
Non-zero at 4σ — first evidence at LHC

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





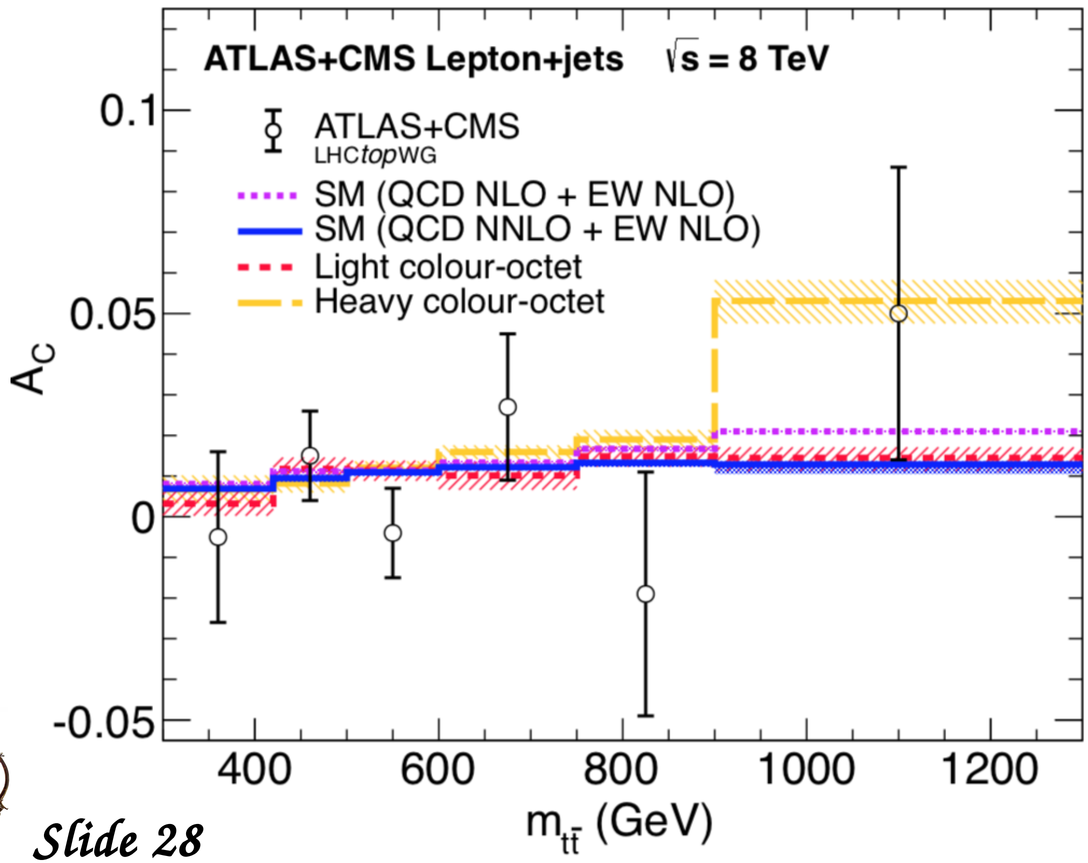
tt, top charge asymmetry, A_C

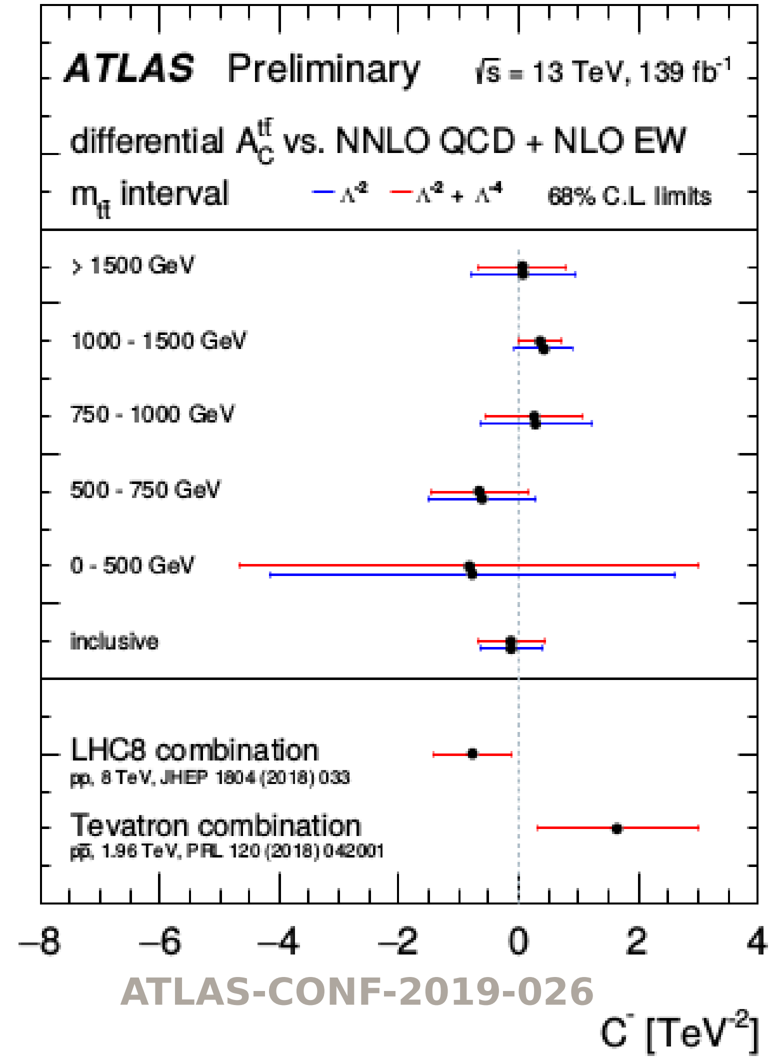


BSM Limits: on coeff. dim-6 EFT operators C^{-}/Λ^2

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

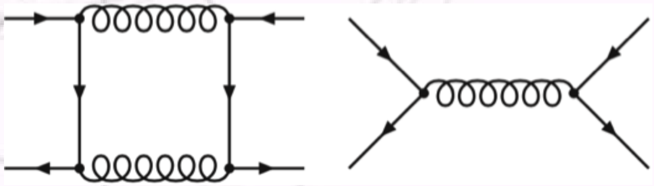
Run 1 results arxiv 1709.05327





ATLAS-CONF-2019-026

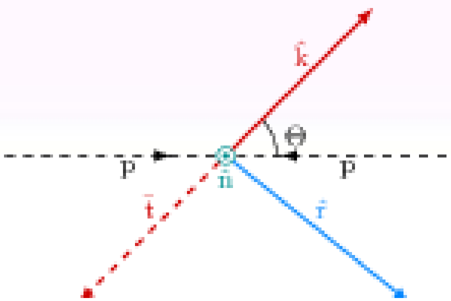
tt spin correlations



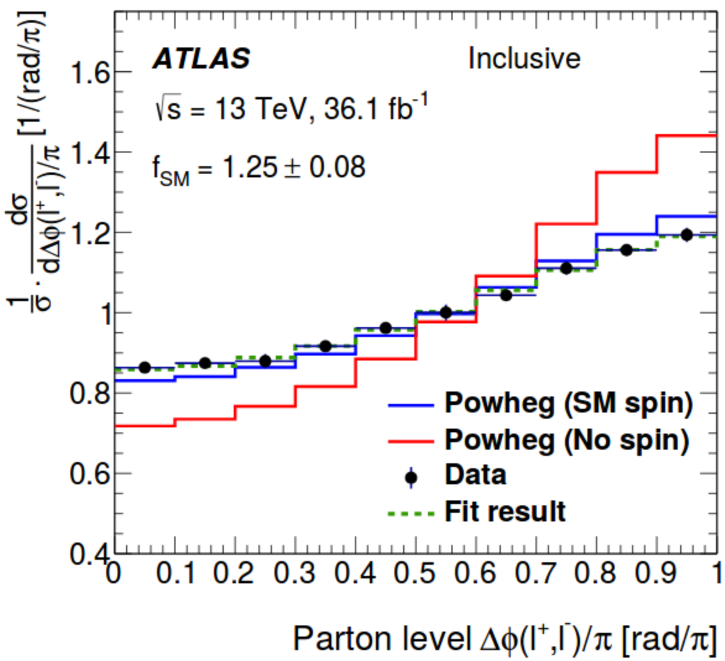
- QCD parity-invariant, top quarks are not polarized, but spins are correlated. Possible BSM effects.

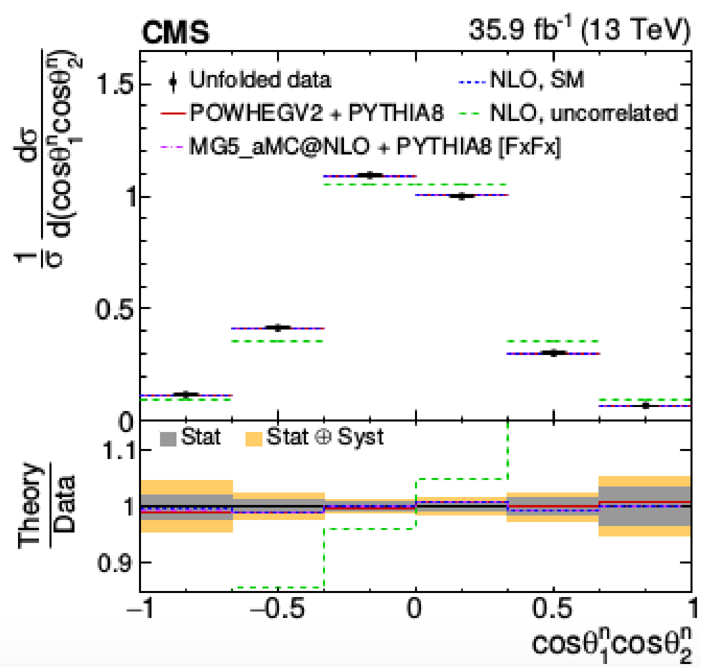
Possible spin correlation sensitive variables (leptonic topologies):

ATLAS : $\Delta\phi_{l^+l^-}$, $\Delta\eta_{l^+l^-}$ arxiv 1903.07570

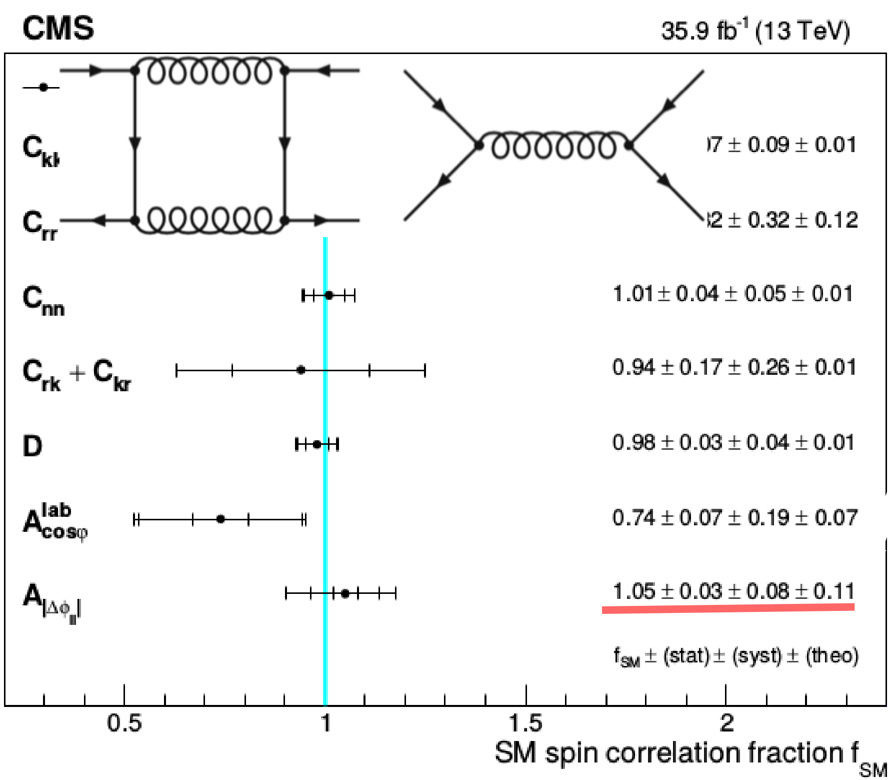


CMS : angles in the scattering plane and perpendicular plane
arxiv 1907.03729



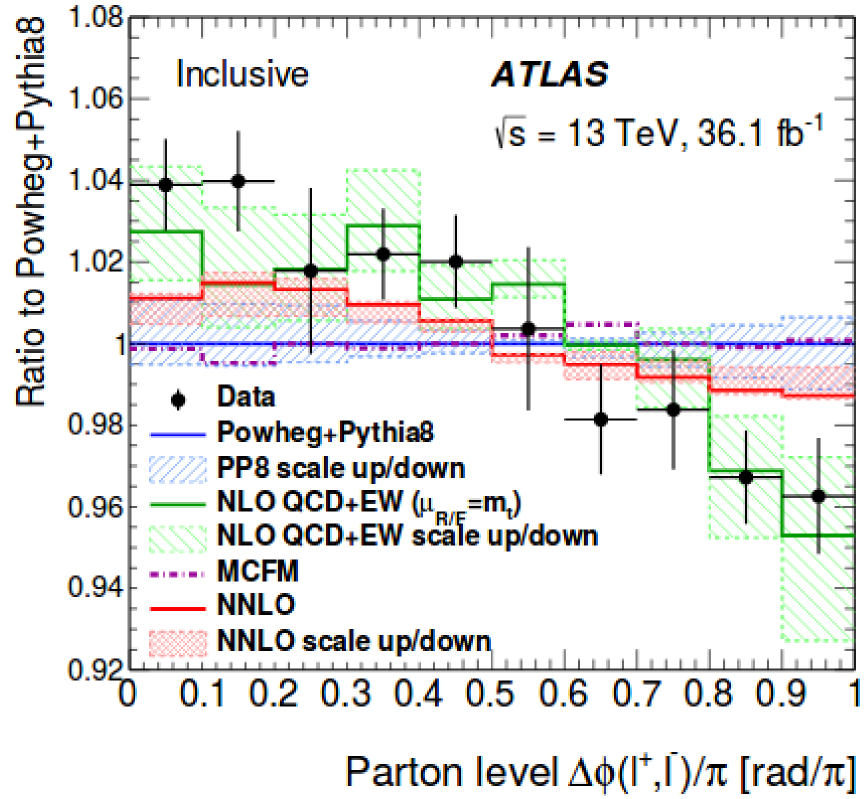


tt spin correlations



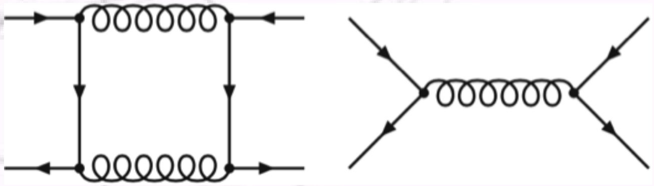
- BSM or NNN..LO ?
  ATLAS, more spin correlation than in SM ?:

f_{SM} ± (stat.,syst.,theory)	Significance (excl. theory uncertainties)
1.249 ± 0.024 ± 0.061 ± 0.040	3.2 (3.8)



C2019

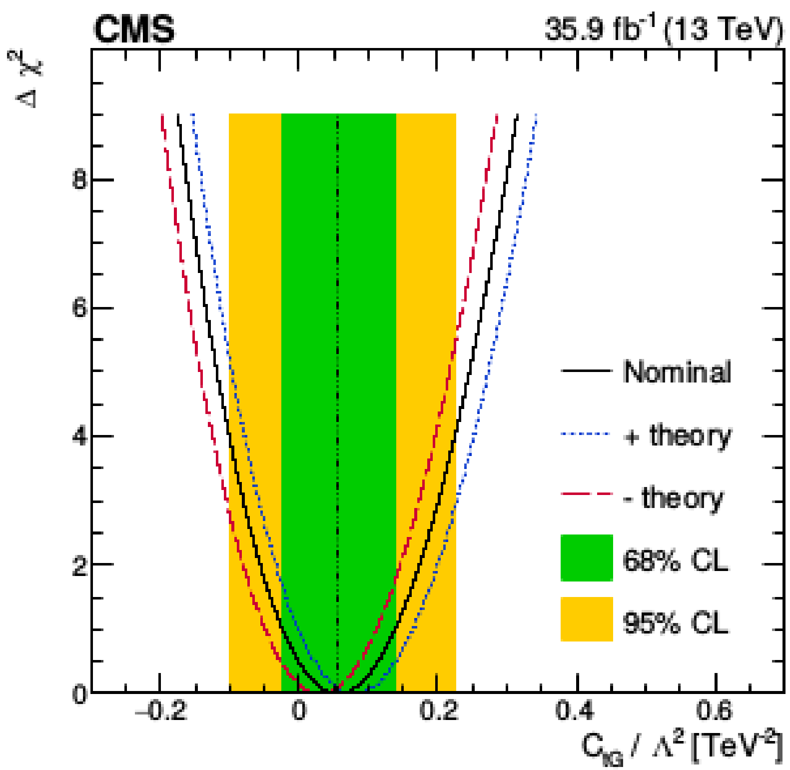
tt spin correlations

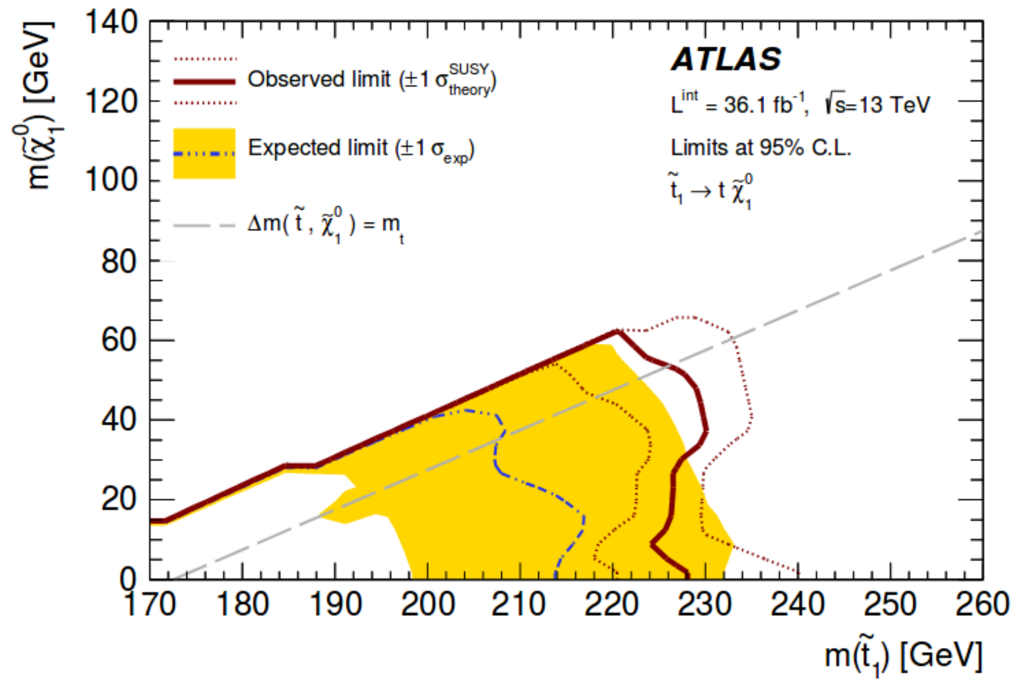


- BSM limits

Anomalous Chromomagnetic Dipole Moment

stop quark in the “corridor “





Is there a stop around the corner? Large Xt could make the stop the lightest squark.

In MSSM The **Higgs boson mass is mass related mostly to stop squark mass and mixing Xt**

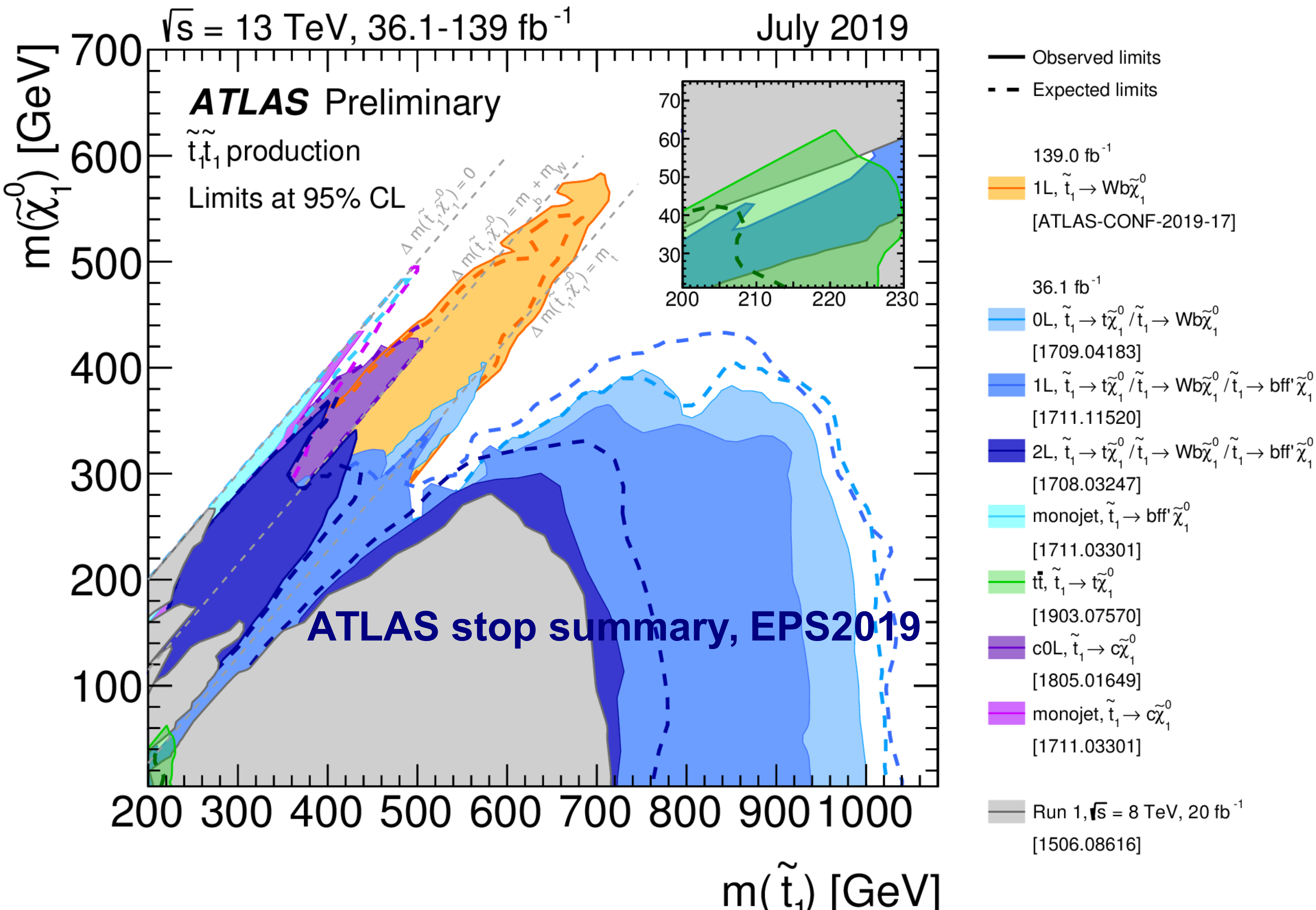
$$\Delta m_h^2 \approx \frac{3m_t^4}{2\pi^2 v^2} \ln \frac{M_S^2}{m_t^2} + \frac{3m_t^4}{2\pi^2 v}\left[\frac{X_t^2}{M_S^2} - \frac{X_t^4}{12 M_S^4}\right]$$

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

$$X_t = A_t - \mu \cot\beta$$

$$\tilde{t}_L, \tilde{t}_R \rightarrow \tilde{t}_1, \tilde{t}_2$$

Large Xt favors a light stop state (stop 1). This "promotes" gluino decays via stop, and "top"- rich final states, mediated by **stop→ LSP+top**



New results from CMS :stop CMS-PAS-SUS-19-009, gluino with tops: CMS-PAS-SUS-19-009

Summary and prospects

LHC Top quark physics is in precision era.

-Top quark mass experimental precision ~0.3% and coupling precision reaches 4%.

-More to come soon from the full analysis of Run 2.

Will theory be up to the task?

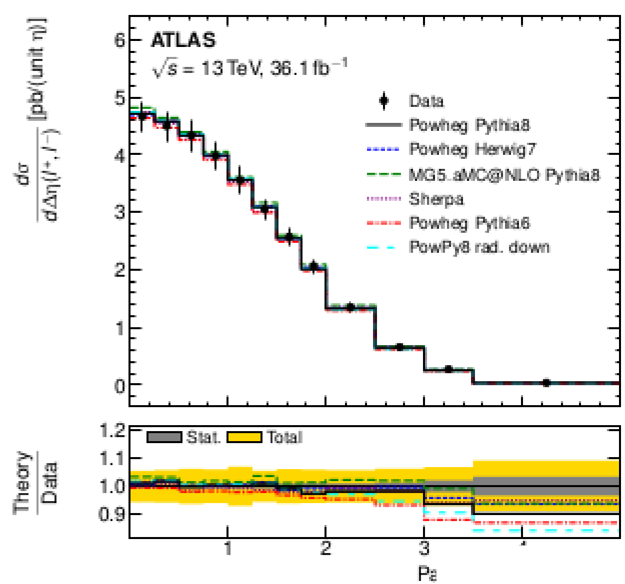
-Advances beyond QCD (N)NLO crucial.

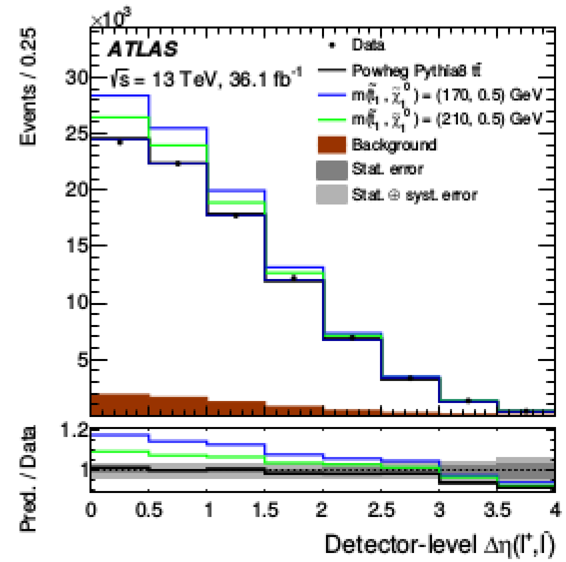
-EW NLO cannot be ignored.

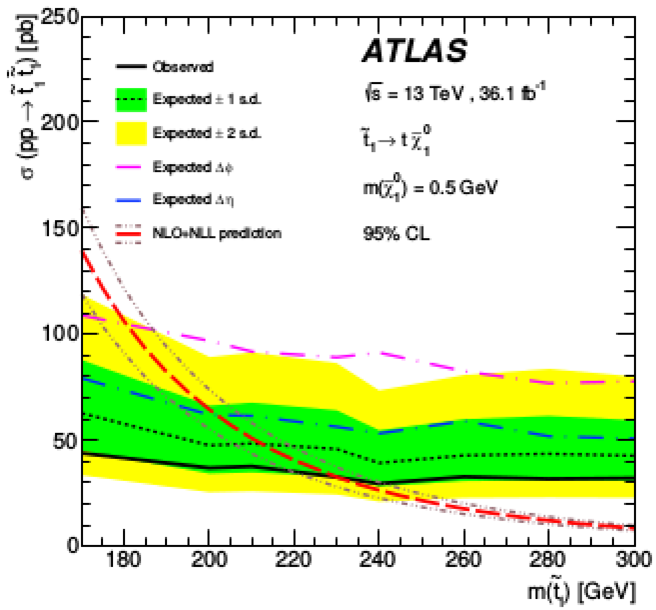
-Needed to pin-point the energy scale of BSM physics .. that still remains hidden

backup

The spin correlation susy interpretation







stop limit sensitive mostly to Δ η distribution, in agreement with SM

The MSSM

Particles in Minimal SUSY

One fermionic/bosonic partner to the SM fermions/bosons with SM coupling

particle	spin	sparticle	spin	name
$l = e, \mu, \tau, \nu$	1/2	$\tilde{l}_R, \tilde{l}_L$	0	slepton
$q = u, d, s, c, b, t$	1/2	$\tilde{q}_R, \tilde{q}_L$	0	squark
g	1	$\tilde{g}$	1/2	gluino
γ	1	$\tilde{\gamma}$	1/2	photino
$W^{\pm}$	1	$\tilde{W}^{\pm}$	1/2	wino
Z	1	$\tilde{Z}$	1/2	zino
H_1^0, H_2^0	0	$\tilde{H}_1^0, \tilde{H}_2^0$	1/2	higgsino
$H^{\pm}$	0	$\tilde{H}^{\pm}$	1/2	higgsino

$$R\ parity, R = -1^{2J+3B+L}, R=-1\ for\ Sparticles, R=1\ for\ particles$$

Gauge Eigenstates		Mass Eigenstates	
$\tilde{W}^{\pm}, \tilde{H}^{\pm}$	$\longleftrightarrow$	$\tilde{\chi}^{\pm}_{1,2}$	(Charginos)
$\tilde{B}, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0$	$\longleftrightarrow$	$\tilde{\chi}^0_{1,2,3,4}$	(Neutralinos)

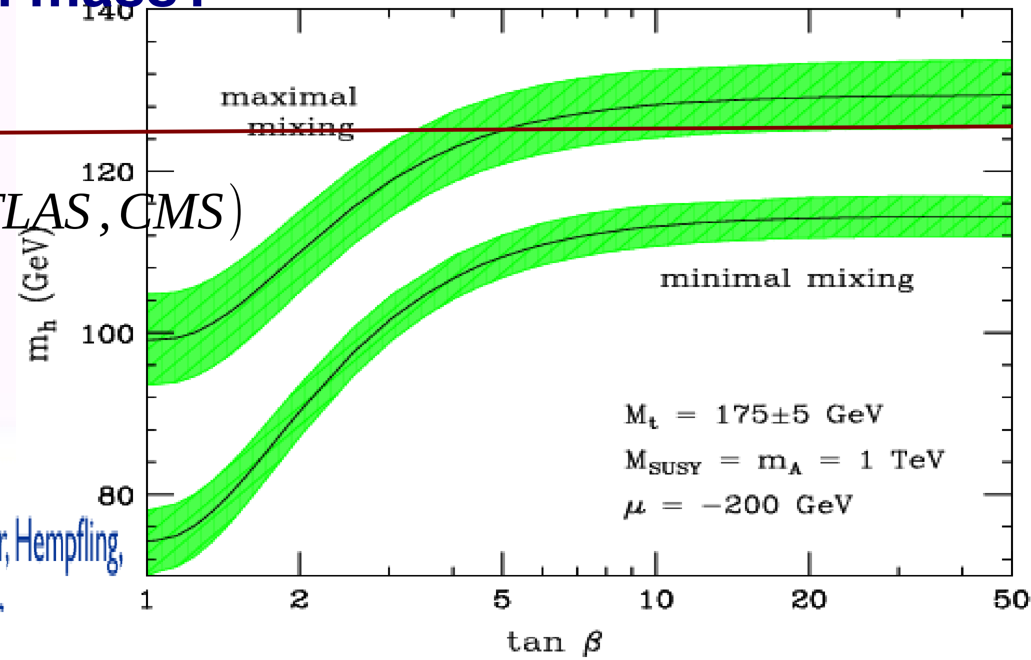
Fermion Eigenstates		Mass Eigenstates	
$\tilde{t}_R, \tilde{t}_L$	$\longleftrightarrow$	$\tilde{t}_1, \tilde{t}_2$	(stop)
$\tilde{b}_R, \tilde{b}_L$	$\longleftrightarrow$	$\tilde{b}_1, \tilde{b}_2$	(sbottom)
$\tilde{\tau}_R, \tilde{\tau}_L$	$\longleftrightarrow$	$\tilde{\tau}_1, \tilde{\tau}_2$	(stau)

$\tan\beta = v2/v1$

If R-parity conserved, LSP is a Dark Matter candidate.

SUSY and top relation? What is the reason for the Higgs boson mass?

$M_h = 125.09 \pm 0.xx(stat) \pm 0.11(syst)\ \ GeV\,(ATLAS, CMS)$



Long list of two-loop computations: Carena, Degrassi, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, C.W. Weiglein, Zhang, Zwirner

There are 5 Higgs bosons in the Minimal Supersymmetric SM, the lightest one is lighter than ~130 GeV Its mass related mostly to stop squark mass (Ml, Mr) and mixing Xt

$$\Delta m_h^2 \approx \frac{3m_t^4}{2\pi^2 v^2} \ln \frac{M_S^2}{m_t^2} + \frac{3m_t^4}{2\pi^2 v}\left[\frac{X_t^2}{M_S^2} - \frac{X_t^4}{12 M_S^4}\right]$$

$$\delta m_h^2 = \frac{1}{8\pi^2}\left[\lambda_{scalar}^2 - \lambda_{fermion}^2\right]\Lambda^2 + \ldots$$

Golfand, Likhtman, JETP Lett. 1971
Volkov, Akulov, Phys.Lett. B, 1973
Wess, Zumino, Nucl. Phys. B, Phys. Lett. B, 1974

In SUSY, the mass correction proportional to SUSY breaking.