CKM2016

9th International Workshop on the CKM Unitarity Triangle

TIFR, Mumbai

Nov. 28 – Dec. 2, 2016

WG6: High-Energy Flavor Physics

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CMS ATLAS EXPERIMENT DØ CDF LHCb

Image: https://en.wikipedia.org/wiki/Bandra-Worli_Sea_Link
Designed by Saurabh Sandilya

The CKM 2016 Indian Tasting Menu!

WG 1

WG 2

WG 3

WG 4

WG 5

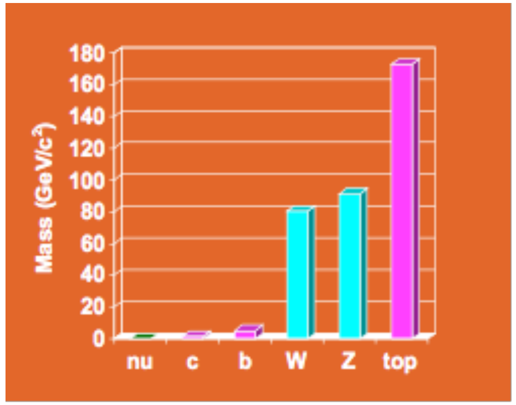
WG 6 →

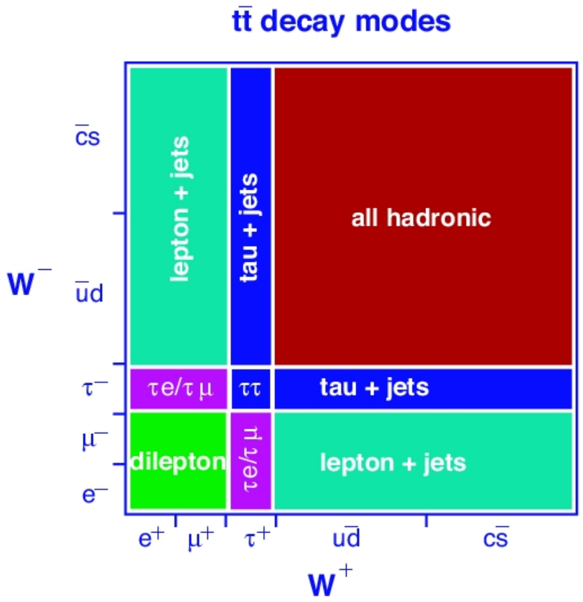
WG 7

Shikanji sorbet

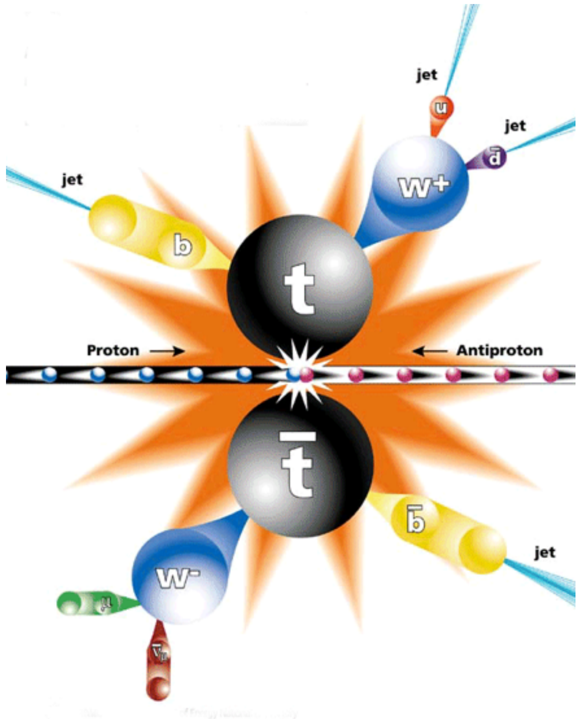
The top quark is special!

- May be not a normal quark…
- Top decays before it feels non-perturbative strong interaction
- LHC is a top quark factory: at 13 TeV about 2 tops every second!

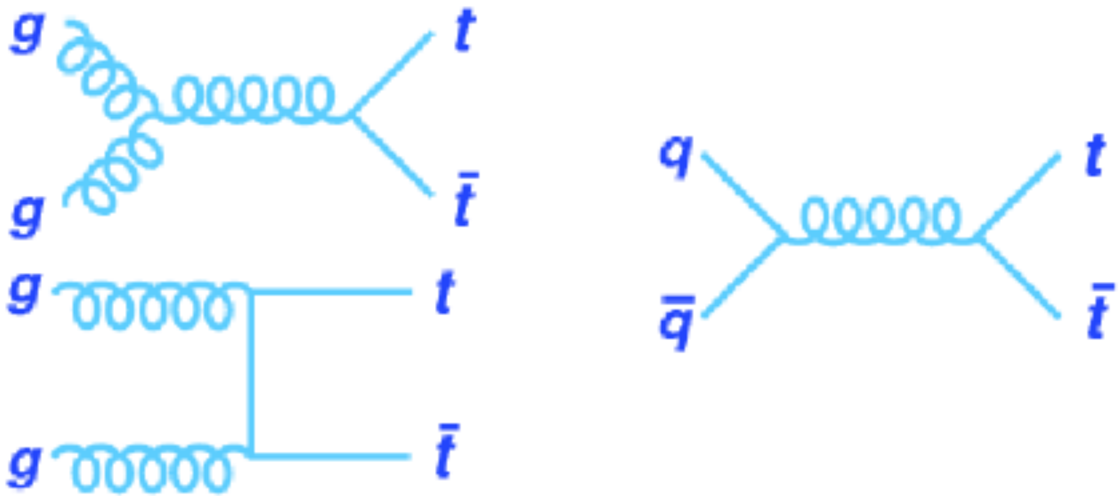




(not inc. τ)	BR	background
dilepton	~5%	low
lepton + jets	~30%	moderate
all hadronic	~44%	high



Top quark pair cross-sections



Partonic cross section

- Partonic cross sections are perturbatively calculable order by order in α_s

$$\hat{\sigma}^{i\,j\to t\bar{t}}(\alpha_s,\mu_F,\mu_R) = \alpha_s(\mu_R)^2\Big\{\hat{\sigma}^{LO} + \frac{\alpha_s}{2\pi}\hat{\sigma}^{NLO}(\mu_F,\mu_R) + \left(\frac{\alpha_s}{2\pi}\right)^2\hat{\sigma}^{NNLO}(\mu_F,\mu_R) + \mathcal{O}(\alpha_s^3)\Big\}$$

- full NNLO

$$d\hat{\sigma}^{NNLO} = d\hat{\sigma}^{VV} + d\hat{\sigma}^{RV} + d\hat{\sigma}^{RR} \qquad \mathcal{O}(\alpha_s^4)$$

- NNLO cross sections beyond the known threshold expansions was essential and the missing ingredients involved
  - double-real
  - real-virtual

• LO	$i\,j \to t\bar{t}$	$ij \equiv q\bar{q};\ gg$	$\mathcal{O}(\alpha_s^2)$
• NLO	$i\,j \to t\bar{t} + X_1$	$ij \equiv q\bar{q};\ gg;\ q(\bar{q})g$	$\mathcal{O}(\alpha_s^3)$
• NNLO	$i\,j \to t\bar{t} + X_2$	$ij \equiv qq'(\bar{q}');\ gg;\ q(\bar{q})g$	$\mathcal{O}(\alpha_s^4)$

X_1 **one** additional parton $\qquad$ X_2 **two** additional parton

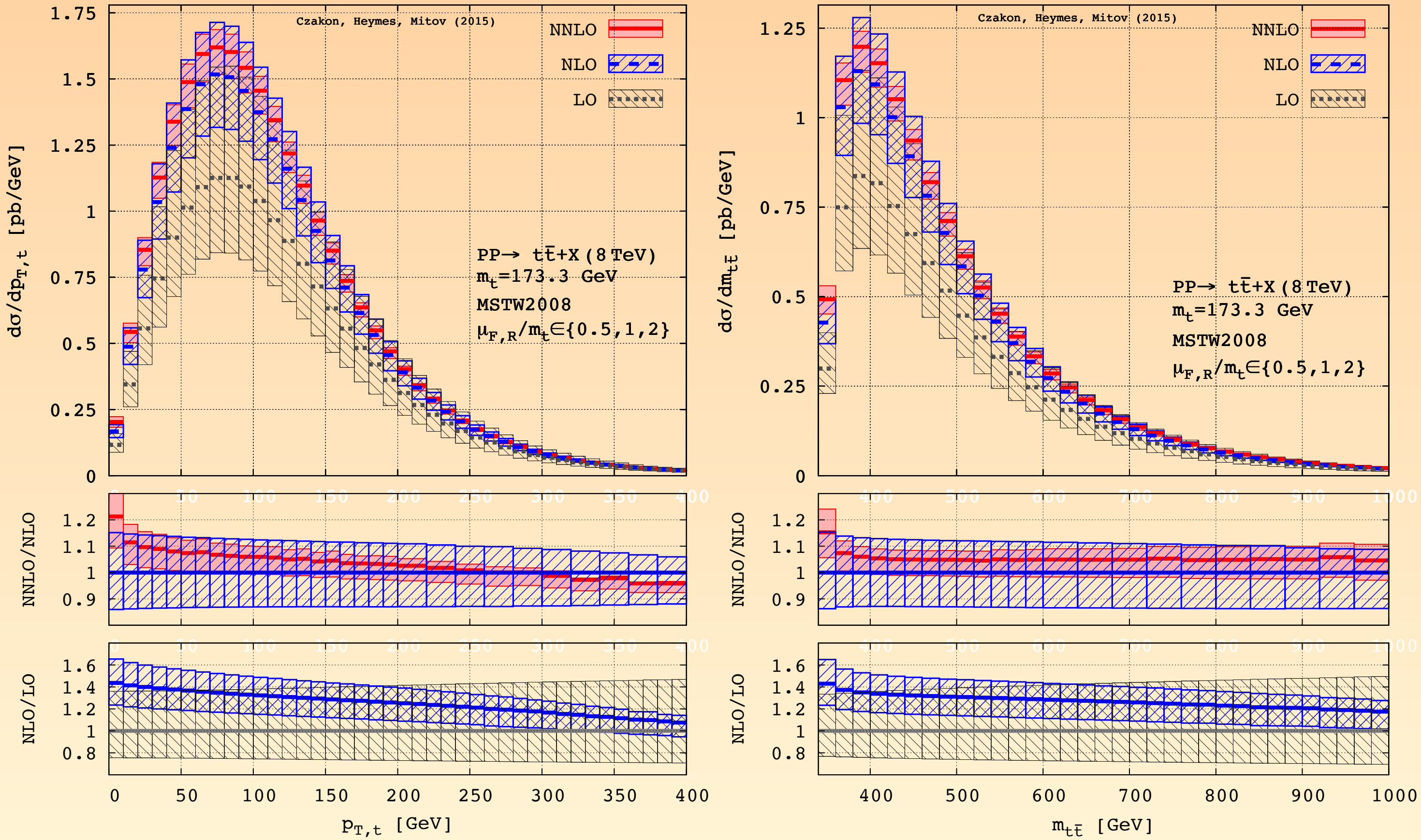
- New channels open up, as one goes higher up in the perturbative order
- Important development is the development of sector-improved residue subtraction scheme (STRIPPER) to handle the NNLO computations.

Czakon (2010); (2011); Czakon, Heymes (2015)

Prof Prakash Matthews

p_T^t and $m_{t\bar{t}}$ distribution to NNLO

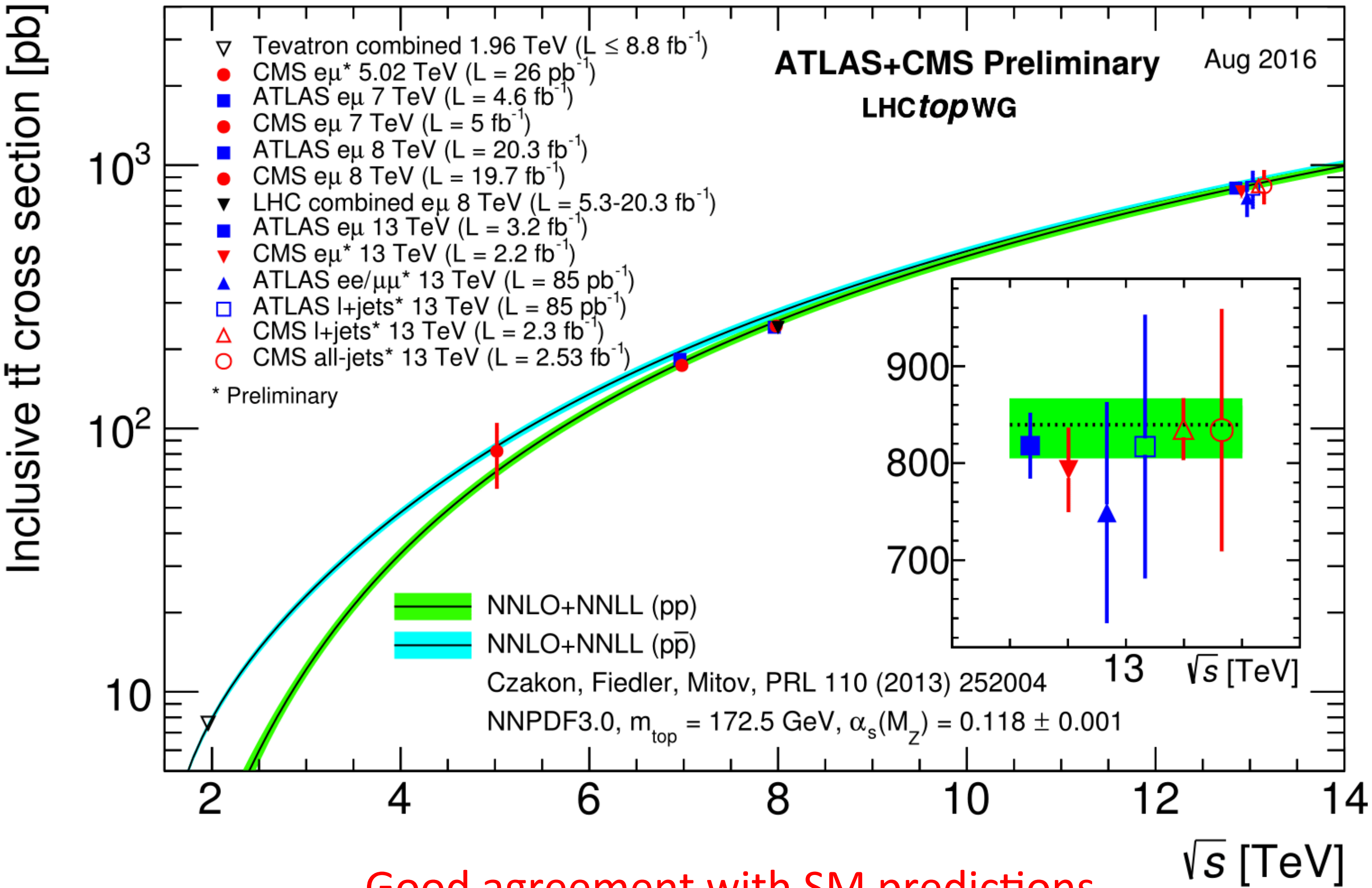
- Scale variation for each perturbative order, with NLO, NNLO K-factors



- Consistent reduction in scale variation with successive perturbative order and NNLO corrections are contained within the NLO error band
- Result includes all partonic channels contribution to NNLO and does not resort to leading color approximation

Prof Prakash Matthews

Summary



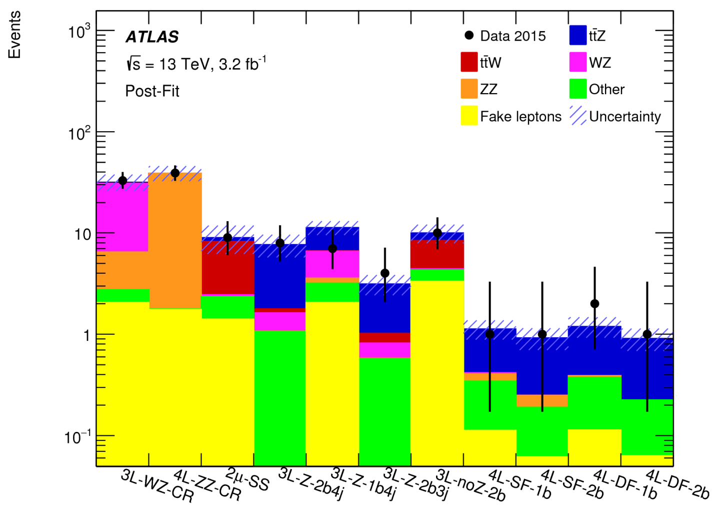
Good agreement with SM predictions

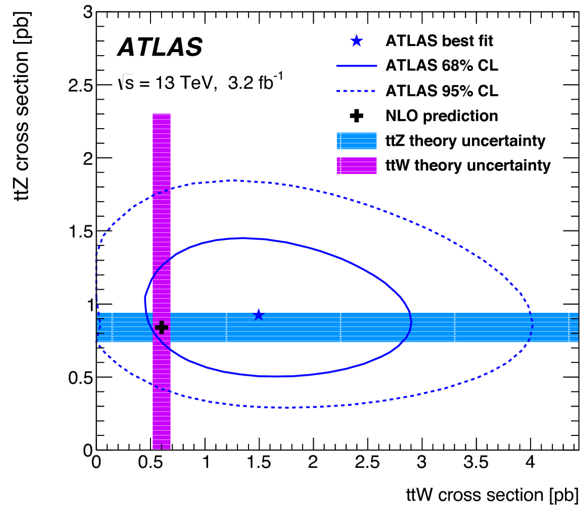
More precision expected at 13 TeV with 2016 data

Arun Nayak

ttW, ttZ @ 13 TeV

ATLAS: arXiv:1609.01599 (Submitted to EPJC) 3.2 fb^{-1} of 2015 data





ATLAS Results:

$\sigma_{ttZ} = 0.9 \pm 0.3$ pb

$\sigma_{ttW} = 1.5 \pm 0.8$ pb

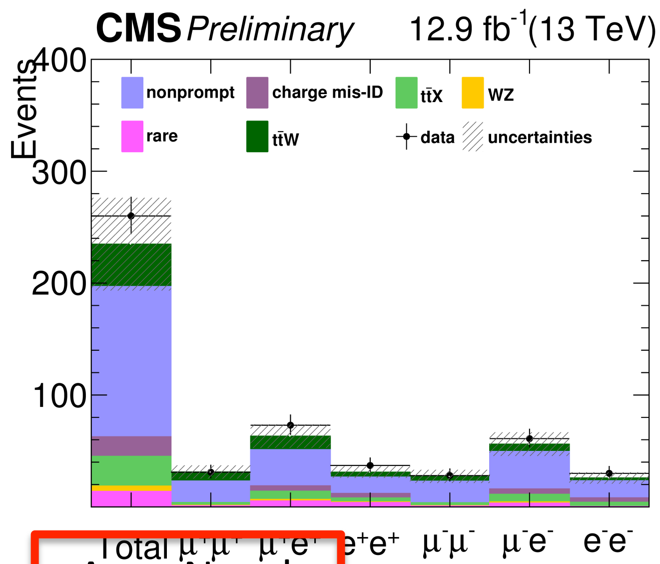
CMS Results:

$\sigma_{ttZ} = 0.7\ ^{+0.16}_{-0.15}$ (stat) $^{+0.14}_{\ 0.12}$ (syst) pb

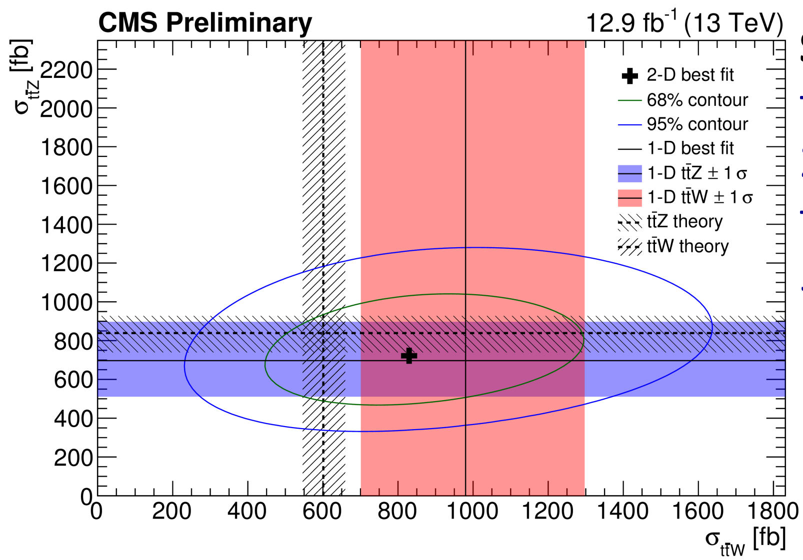
$\sigma_{ttW} = 0.98\ ^{+0.23}_{-0.22}$ (stat) $^{+0.22}_{-0.18}$ (syst) pb

CMS: CMS-PAS-TOP-16-017

12.9 fb^{-1} of 2016 data



Arun Nayak



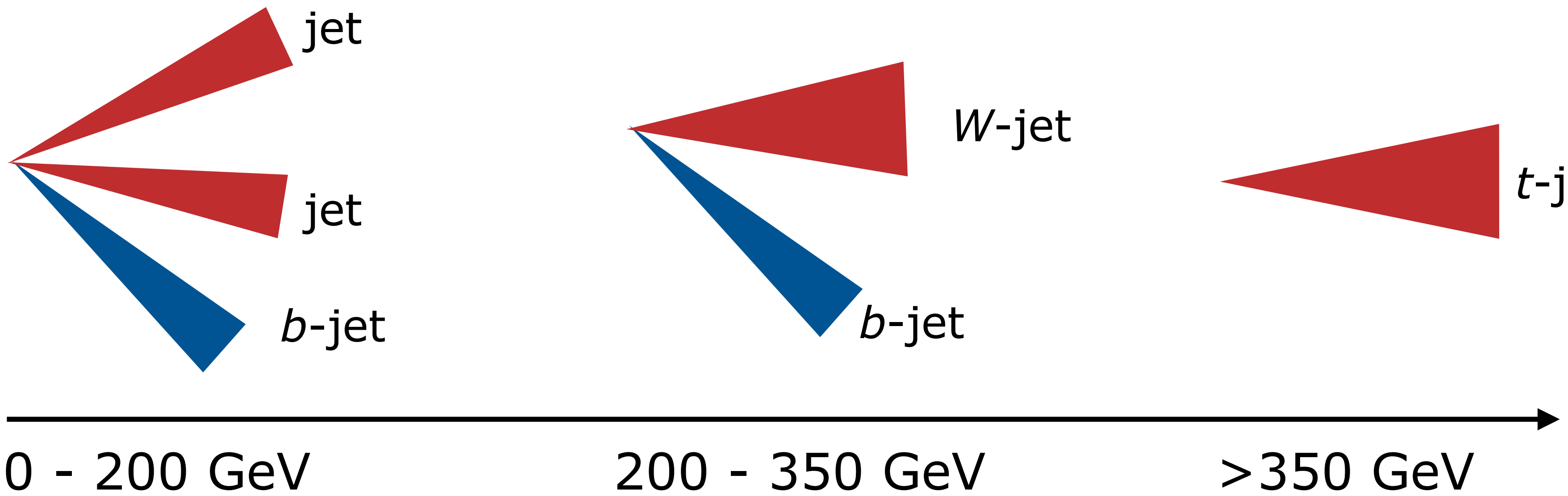
Signal Significance:

ttW: 3.9σ (obs) / 2.6σ (exp)

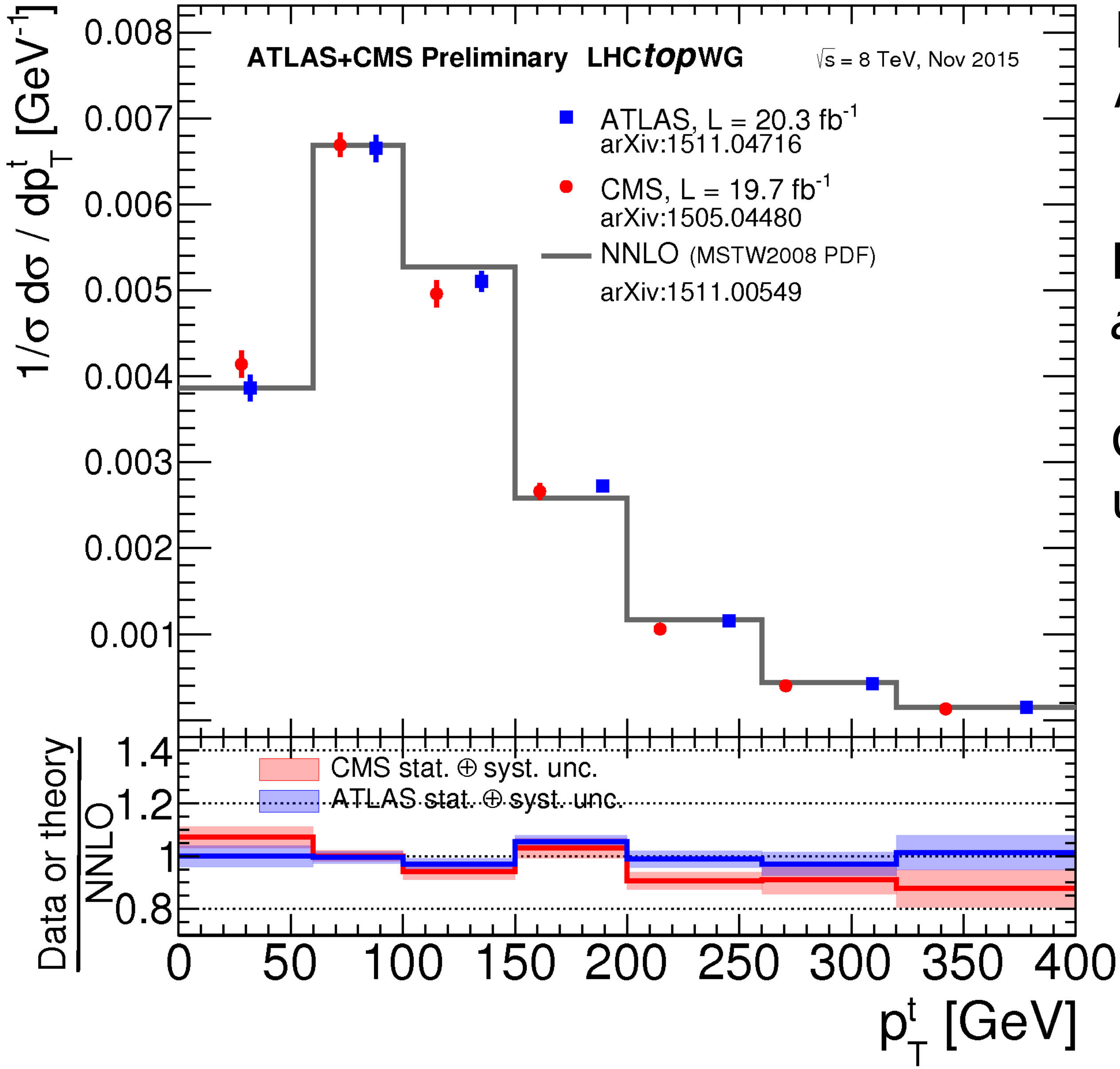
ttZ : 4.6σ (obs) / 5.8σ (exp)

Top quark p_T, y

- Top p_T probably the most important observable
- Sensitive to final state radiation
- Measurement up to ~1 TeV spans different **kinematic regimes**, thus **reconstruction methods**
- Many sources indicate data/theory disagreement at high-p_T



ℓ+jets, Parton level



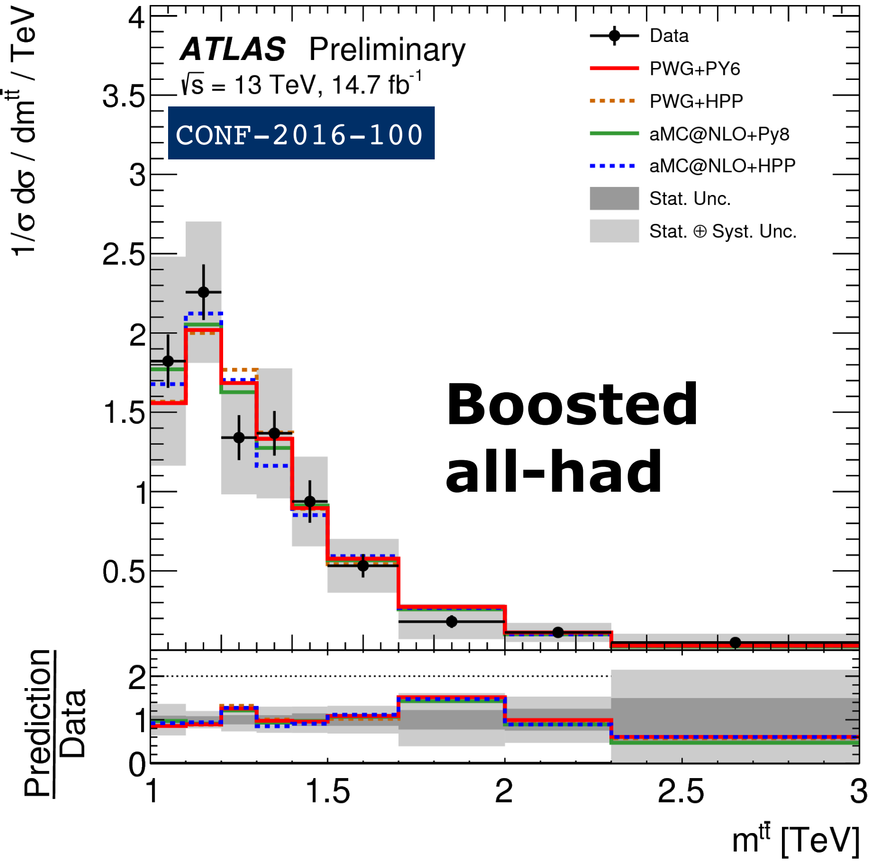
Run 1
ATLAS+CMS legacy

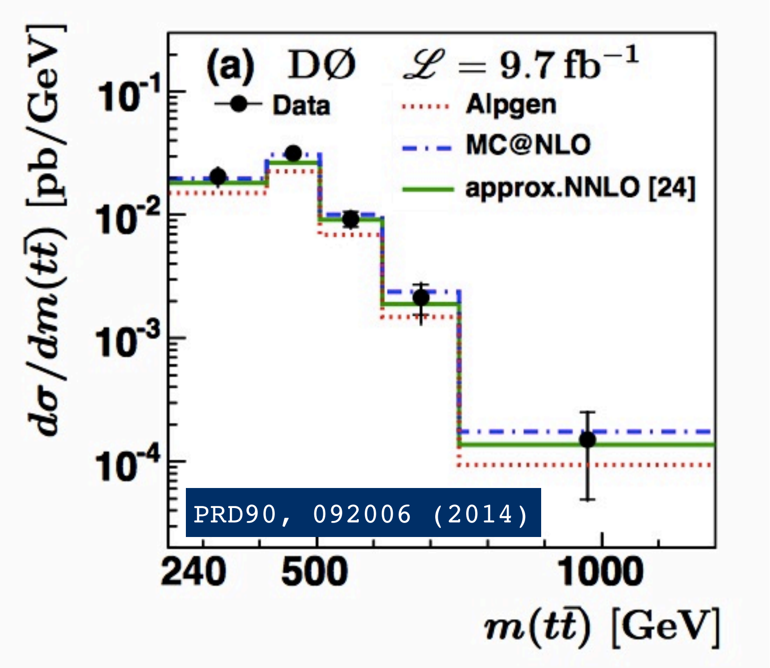
NNLO corrections *are* important!

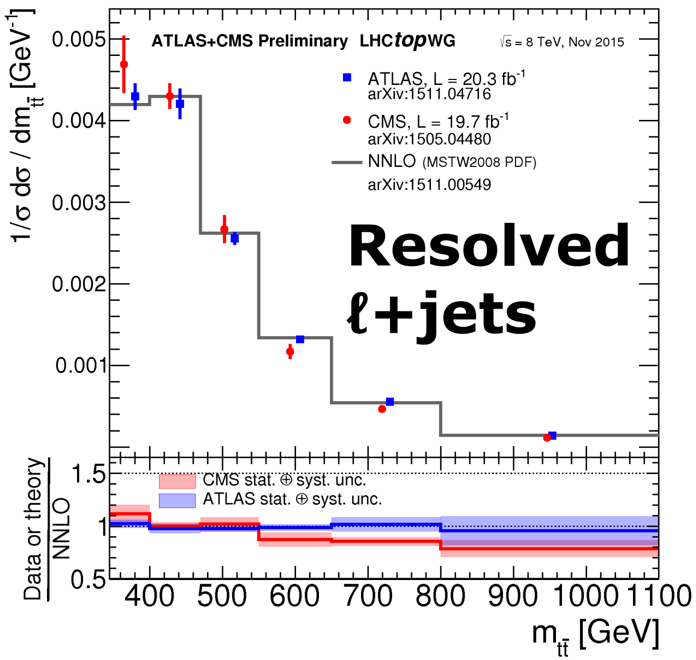
Good agreement up to high p_T

$t\bar{t}$ system invariant mass

Data/MC **seems well-modelled**
Resolution limits bump hunting
All-Hadronic boosted promising
(no neutrinos, only two jets)



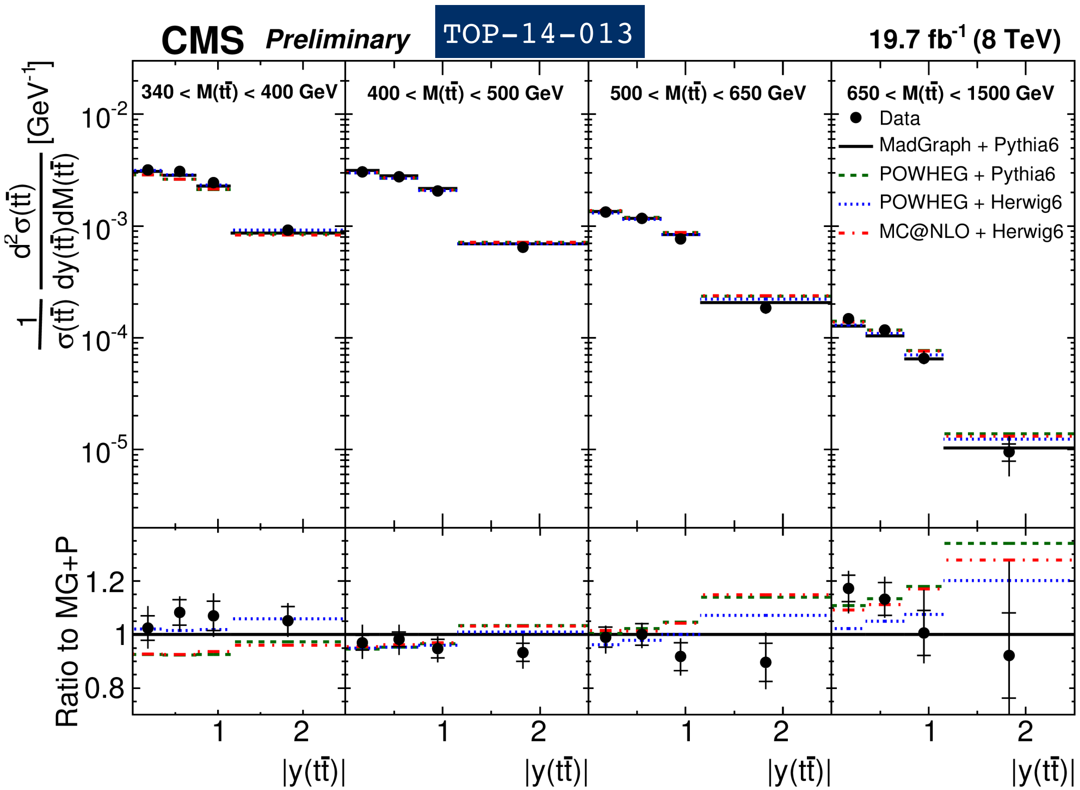


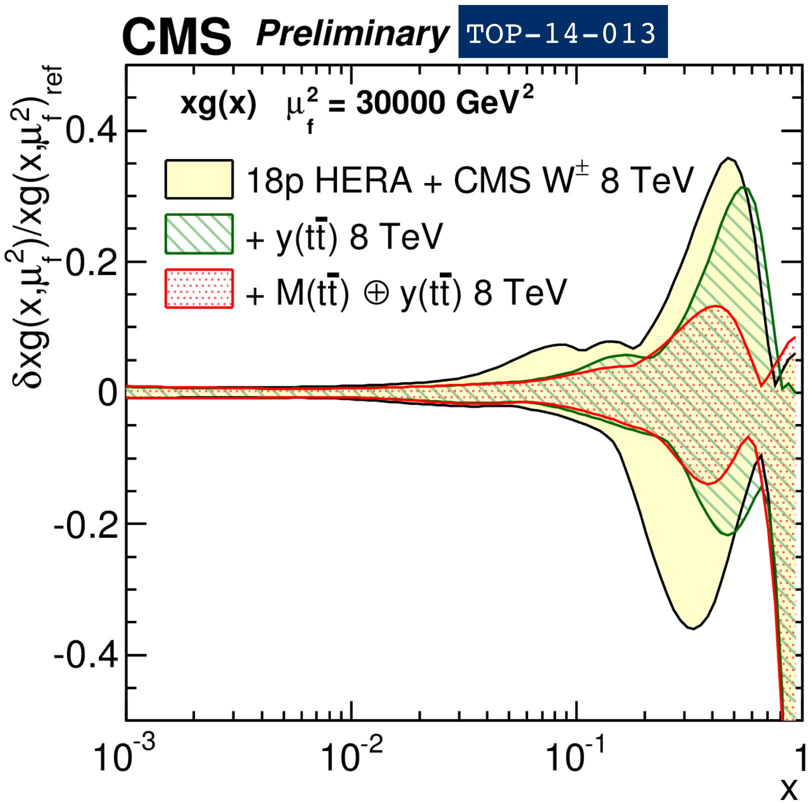


$t\bar{t}$ system rapidity

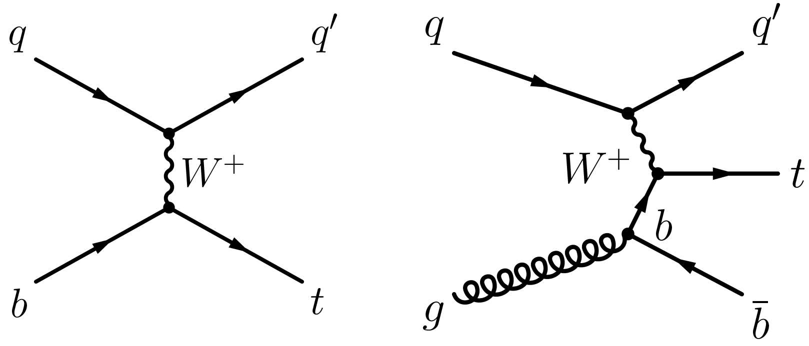
Double-differential measurement constrains **gluon PDF**

$$x = \frac{M(t\bar{t})}{\sqrt{s}} e^{\pm y(t\bar{t})}$$



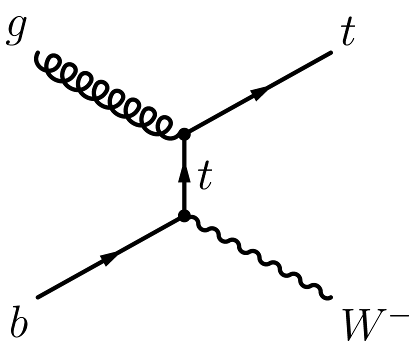


Fit PDF

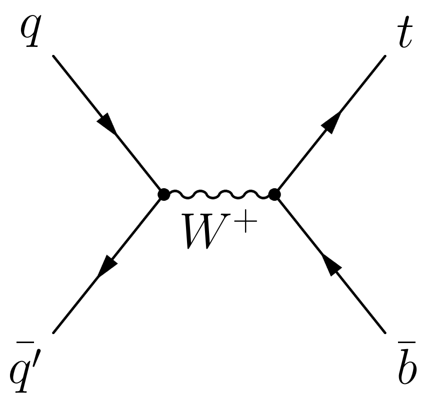


t - channel

Single top production and V_{tb}



tW - channel



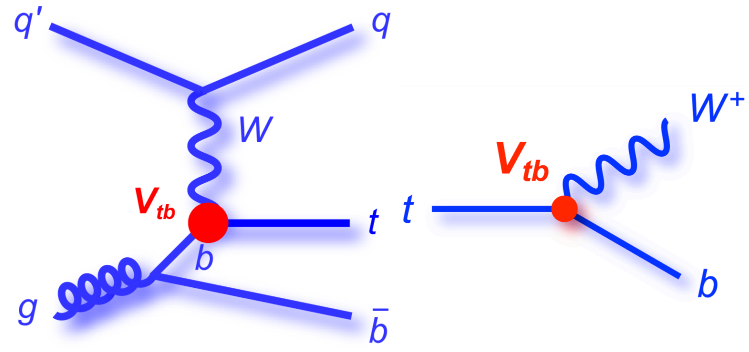
s - channel

V_{tb} using single top

- V_{tb} appears in production and decay of the top quark

$$\sigma \propto |V_{tb}|^2$$

$$|V_{tb}|^{meas.} = \sqrt{\frac{\sigma_{exp.}}{\sigma_{theory}}}$$



- σ_{theory} in SM ➛ $|V_{tb}| \approx 1$, $|V_{tb}| >> |V_{td}|, |V_{ts}|$

- Questions regarding CKM matrix:

➛ Is it a 3x3 matrix? Why not 4x4 or even larger?

➛ Is it unitary?

$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$?

Soureek Mitra & Jyothsana Rani Komaragiri

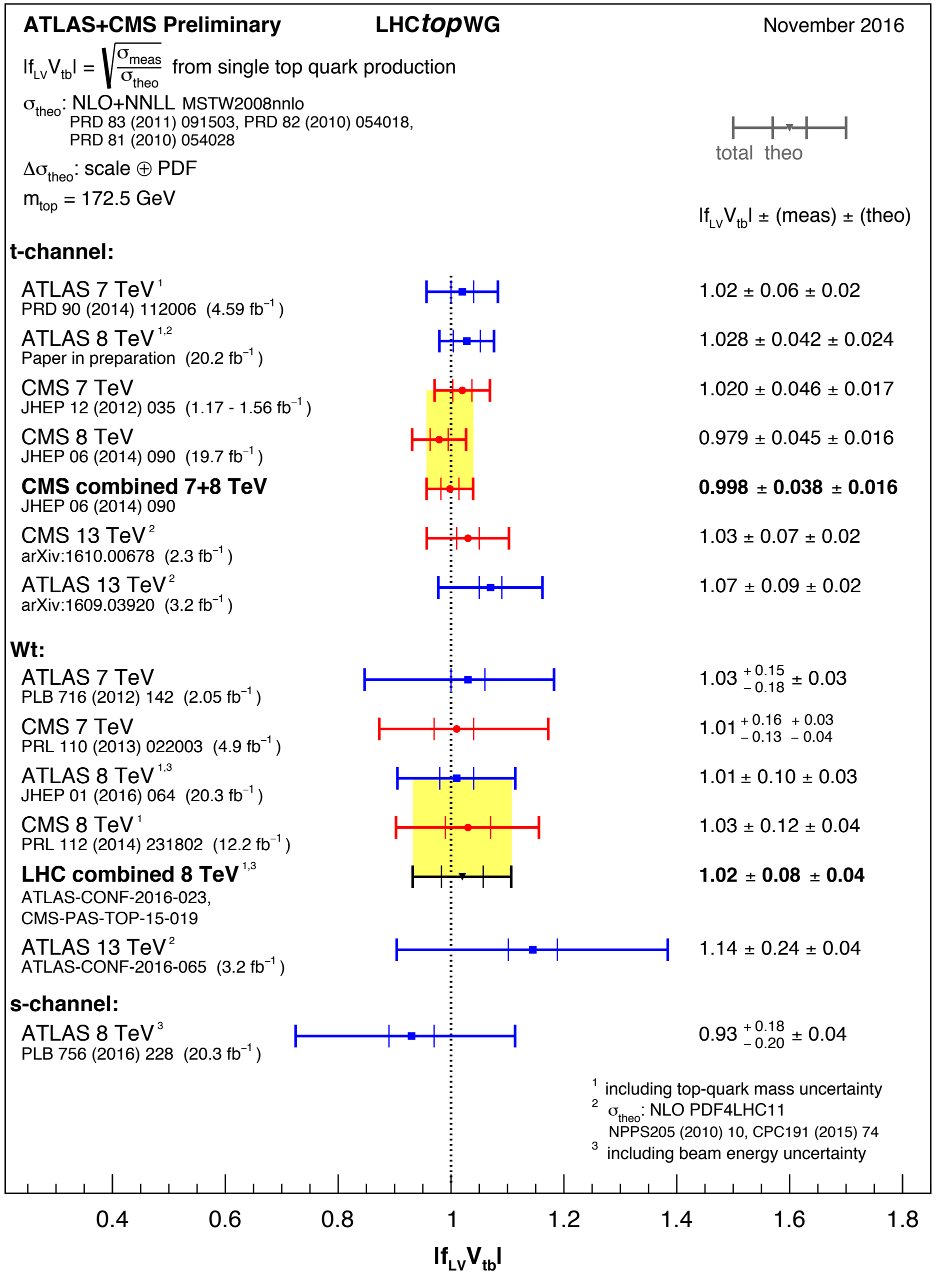
Direct Measurements: see other talks

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Ratio Constrained from Bs oscillations

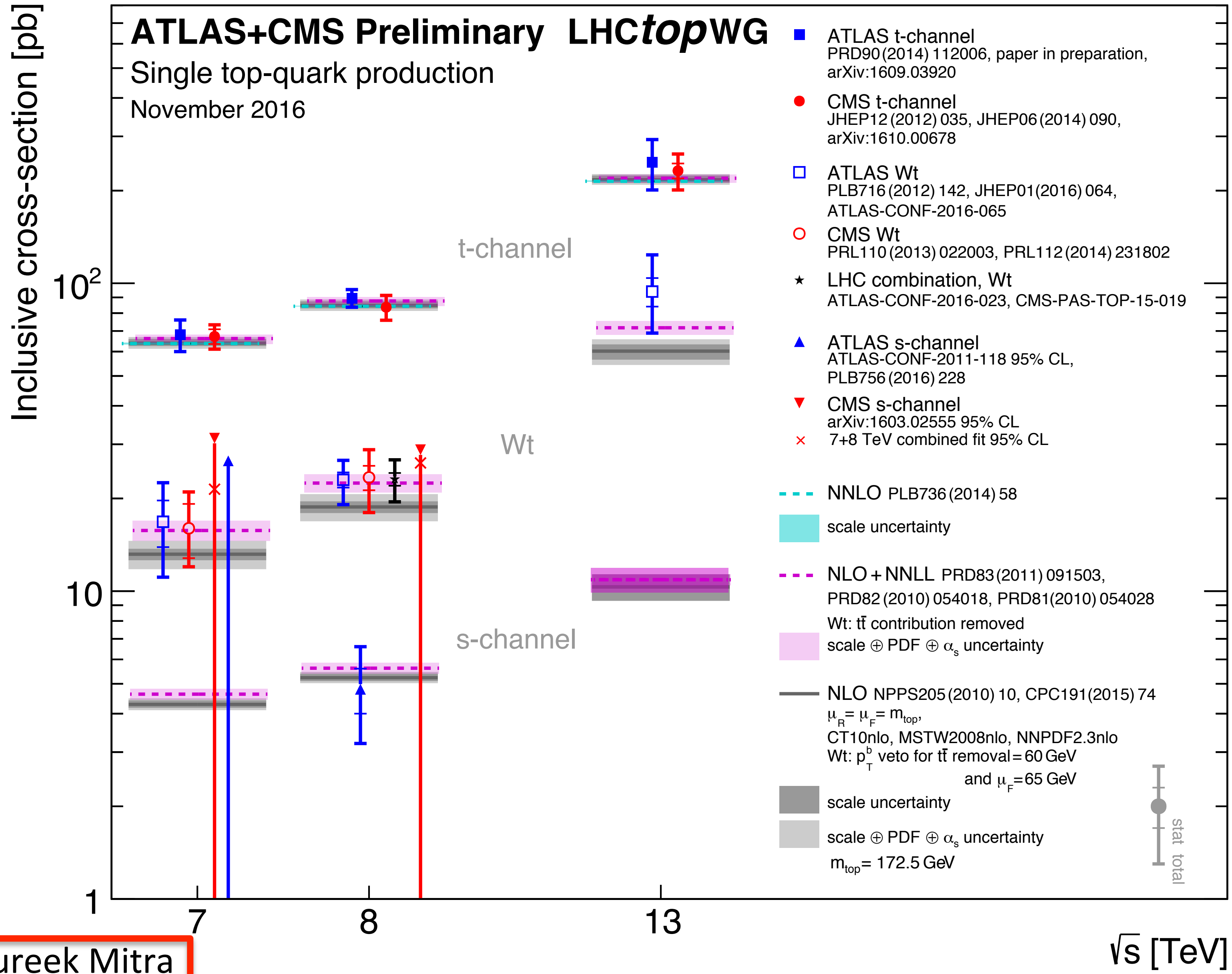
Measured under certain assumptions

Summary of V_{tb} measurements



Soureek Mitra

Summary of cross-section measurements



Soureek Mitra

Top quark properties

Properties of the top produced in the processes involving the new BSM particles can be different from the top quarks produced via the SM processes and can carry the imprint of the BSM.

Since all the BSM options address the issue of EWSB, in many of them, the couplings of the top quark to the new particles can have a different chiral structure than the SM case.

Recall that **at the LHC** all the SM $t\bar{t}$ production via QCD will produce unpolarized top quarks! Only the single top will be polarized and the polarization completely predicted!

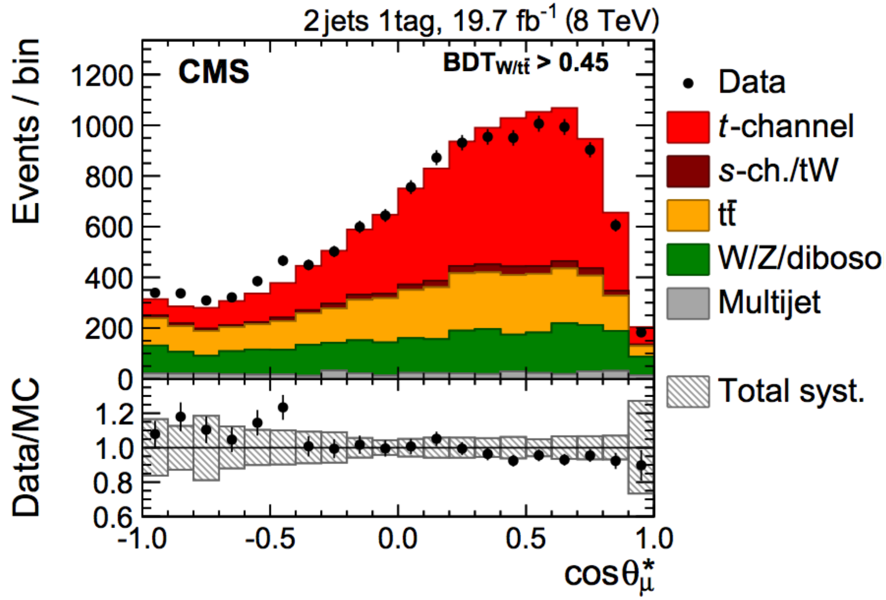
Hence polarization of the produced top quarks can be a very important discriminator of BSM physics.

Prof Rohini Godbole

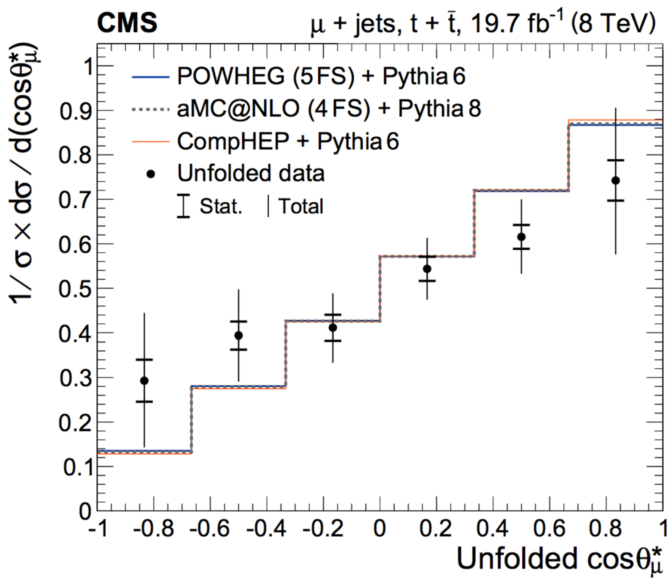
Top polarization in t - channel

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_X^*} = \frac{1}{2}(1 + P_t^{(\vec{s})}\alpha_X\cos\theta_X^*) = \left(\frac{1}{2} + A_X\cos\theta_X^*\right) \quad A_X \equiv \frac{1}{2}P_t\,\alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

- θ_X^* = Angle between muon and light quark in top rest frame
- P_t : Top polarization , $\boldsymbol{\alpha}_X = 1$ in SM
- 2J1T event selection
- Fit BDT discriminant to determine signal and background normalization
- Cut on BDT output to select signal enriched region
- Unfolding to correct for detector effects



A_μ^{meas} = 0.26 ± 0.03 (stat.) ± 0.10 (syst) = 0.26 ± 0.11
A_μ^{SM} = 0.44
=> Measured value ~2σ away from SM prediction



- JES, JER, W+ heavy flavor jets modeling, Q^2 scale, PDF etc. are the main source of uncertainties

JHEP 04 (2016) 073

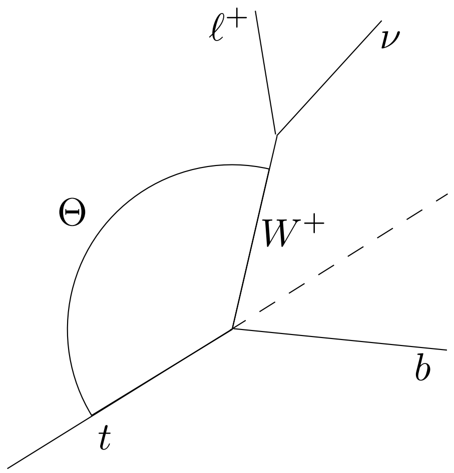
Soureek Mitra

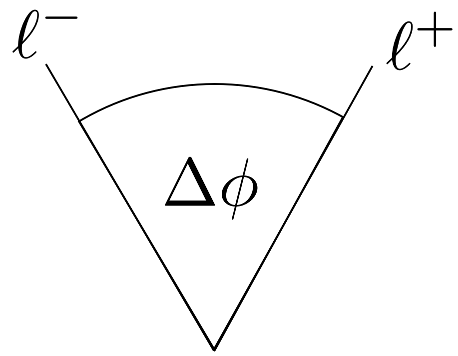
Spin Correlations

- Top lifetime is less than the timescale of QCD interaction
  - Top spin at production is conserved through to the decay

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 + B_1\cos\theta_1 + B_2\cos\theta_2 + C_{\text{helicity}}\cos\theta_1\cdot\cos\theta_2)$$

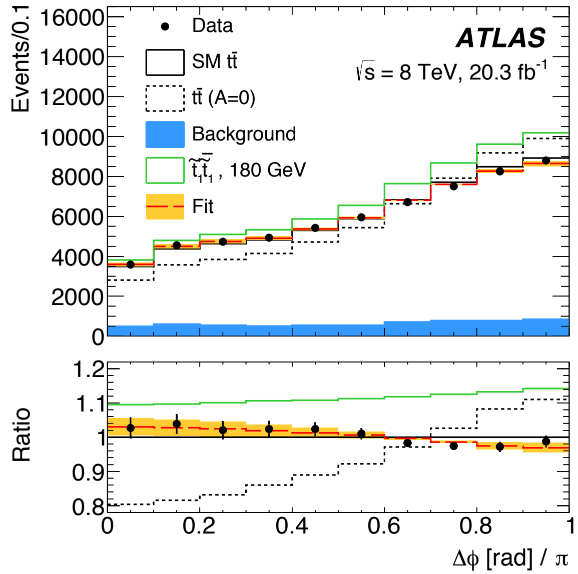
- $C_{\text{helicitiy}} = -A_{\text{helicity}}\alpha_1\alpha_2$
- α Spin analyzing power: $\alpha_{\ell^+} = +0.998$, $\alpha_d = -0.966$, $\alpha_b = -0.393$
- $A_{\text{helicity}} = \frac{N_{\text{like}} - N_{\text{unlike}}}{N_{\text{like}} + N_{\text{unlike}}}$
- NLO QCD Prediction $A = 0.31$ (dilepton)
- Sensitivity also through $\Delta\phi$ between leptons





ATLAS: Spin correlation at 8TeV in Dilepton

Phys Rev Lett 114, 142001 (2015)



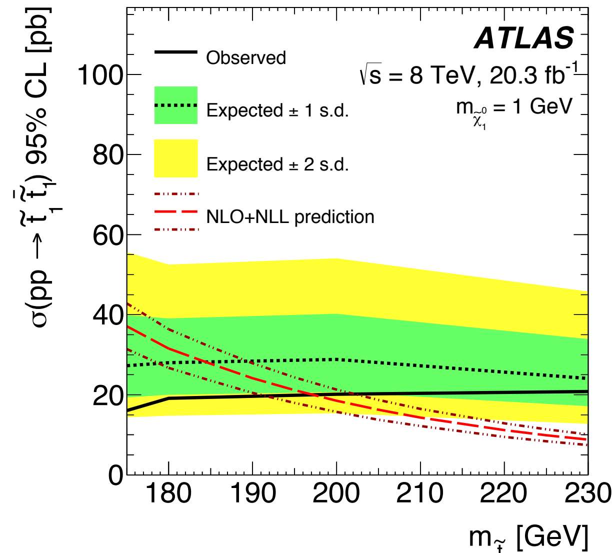
Fit to $\Delta\Phi$ Distribution:

$$\Delta\Phi = f_{SM} \cdot SM + (1 - f_{SM}) \cdot no\ corr.$$

Final Result:

$$f_{SM} = 1.20 \pm 0.05(\text{stat.}) \pm 0.18(\text{syst.})$$

$$A_{\text{helicity}} = 0.38 \pm 0.04$$



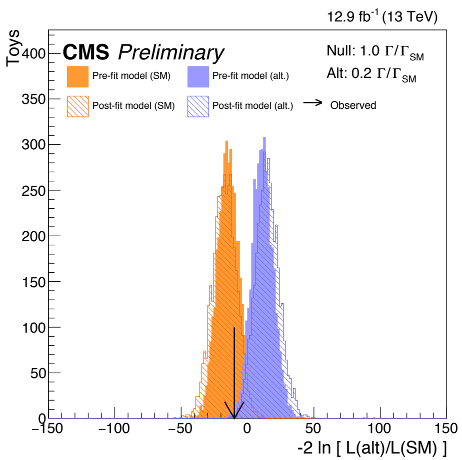
Search for stops with $\tilde{t}_1 \to t\tilde{\chi}^0_1$

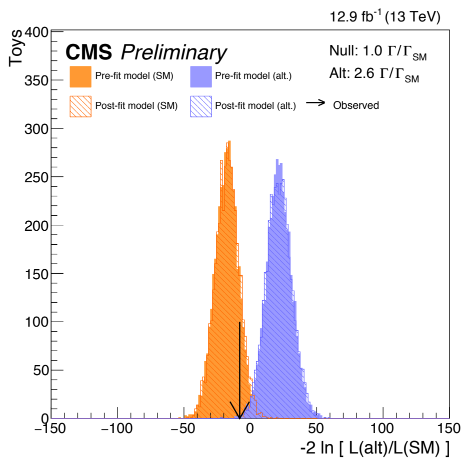
Assuming $BR(\tilde{t}_1 \to t\tilde{\chi}^0_1) = 100\%$: top squark masses are excluded between top mass and 191 GeV at 95%C.L.

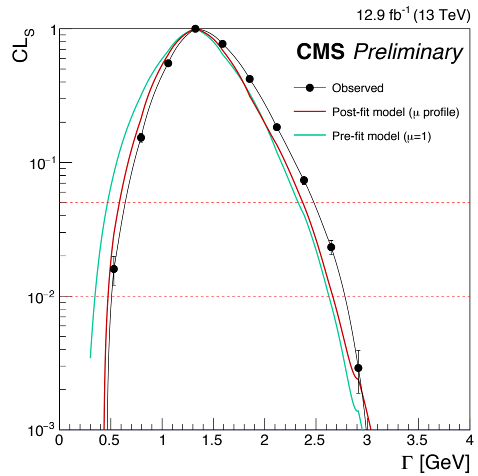
CMS: Measurement of the top width at $\sqrt{s} = 8\,\text{TeV}$

CMS-TOP-16-019

- Using $t\bar{t}$ and tW decay events with 2 charged leptons
- Reconstruct $M_{\ell b}$ distribution and use for hypothesis tests
- $N_{\text{signal}} = \mu[(1 - x) \cdot N_{\text{SM}} + x \cdot N_{\text{alt}}]$
- Measure hypthesis seperation with CL_s criterium



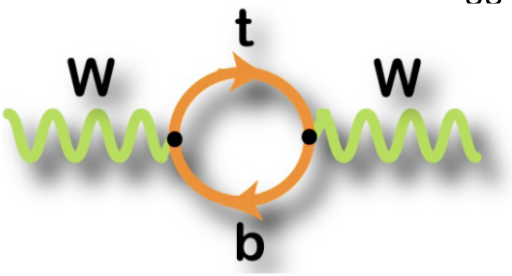




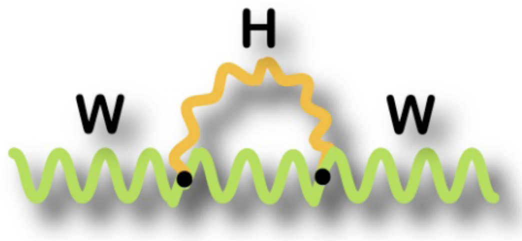
- Binary hypothesis test: $0.6 \leq \Gamma_t \leq 2.5\,\text{GeV}$ at the 95 % C.L., with expected bounds of $0.6 \leq \Gamma_t \leq 2.4\,\text{GeV}$ with $m_t = 172.5\,\text{GeV}$
- First direct measurement at LHC and most precise direct bound on top width

Top quark mass

- Special role in EW symmetry breaking?
  - M_W related to m_t & M_{Higgs}:

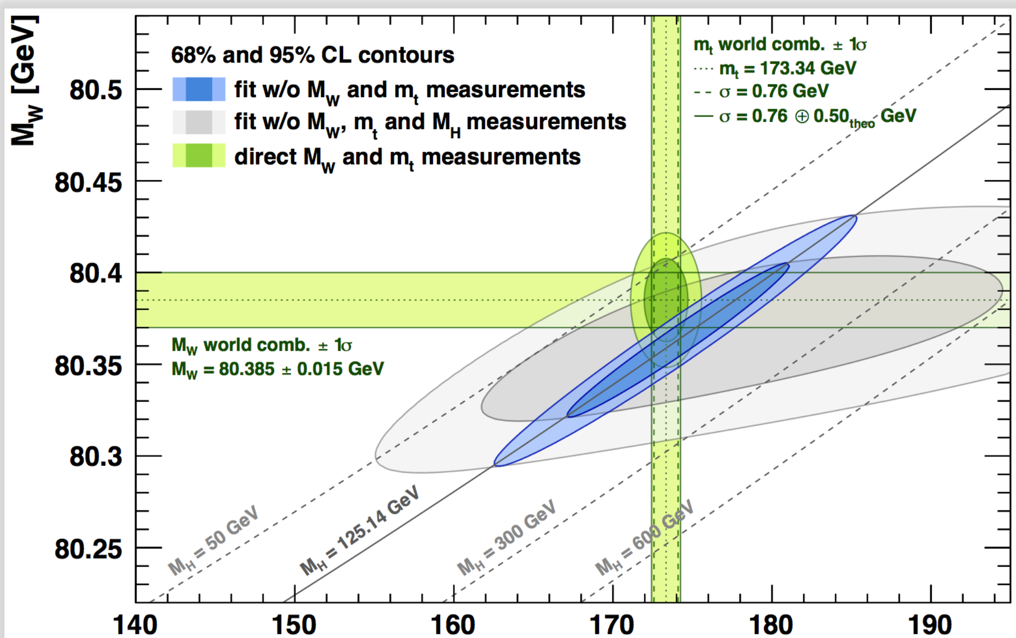


$\Delta M_W \propto M_{top}^2$



$\Delta M_W \propto \ln M_H$

  - Overconstrain M_W, m_t, M_{higgs}
    Consistency check of the SM!



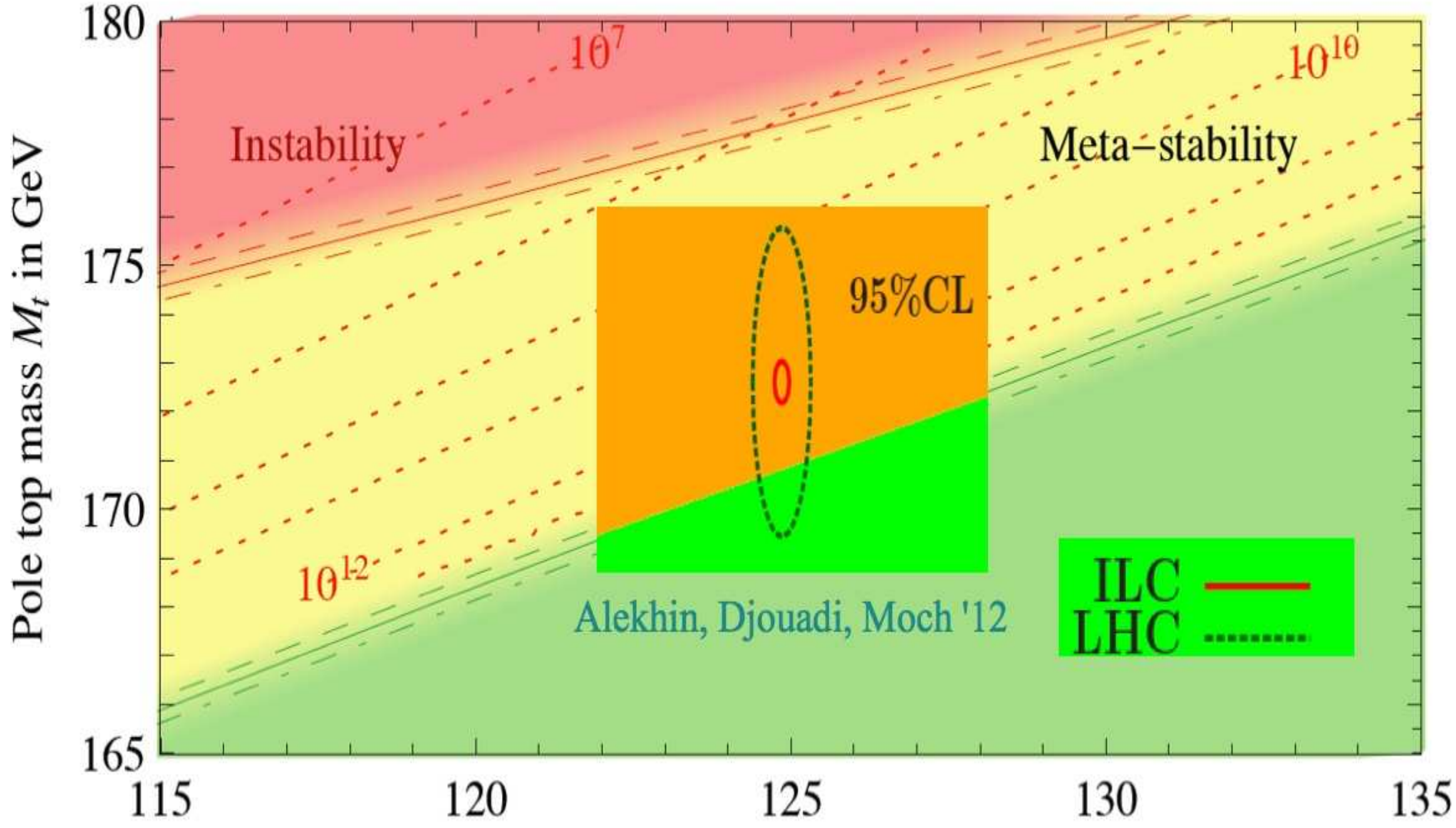
Gfitter Coll., EPJC, **74** 3046 (2014)

Vacuum stability bounds imply that unless M_h is large enough SM will become inconsistent at some large scale Λ!

The mass is just large enough to make us suspect that SM is all there is! ie. it **may** remain consistent all the way to Planck scale!

$M_h = 125$GeV is really critical, in all senses of the word. Knowledge of M_t crucial here.

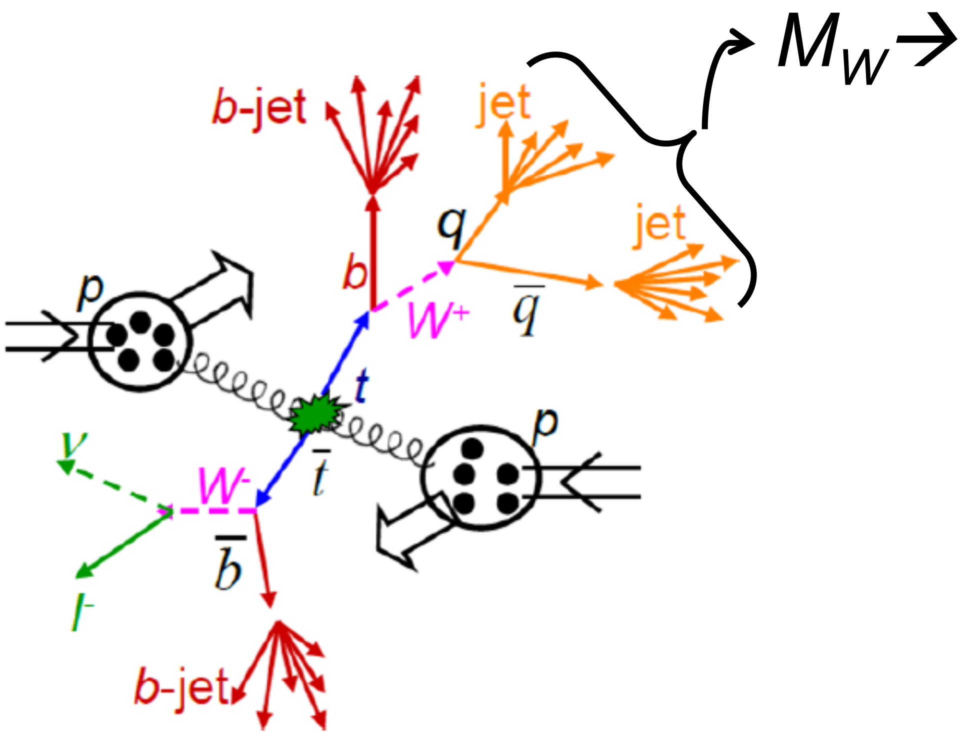
Prof Rohini Godbole

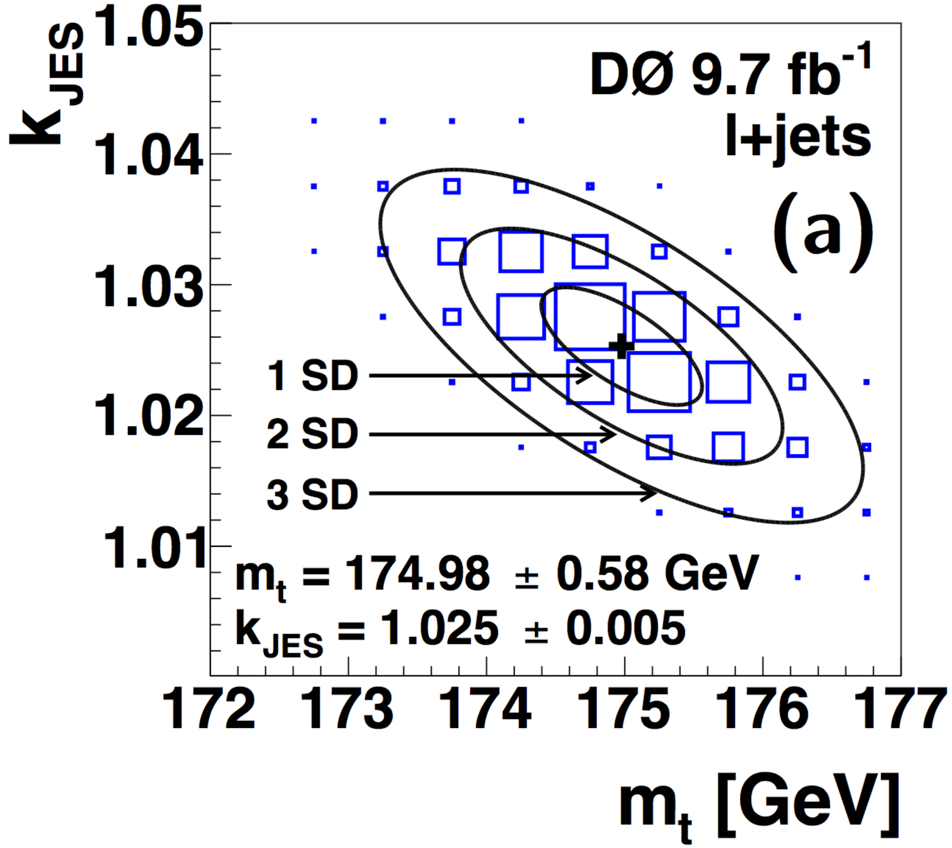


M_h value indeed critical.

Prof Rohini Godbole

- **In-situ calibration of JES:**





- **Result:**

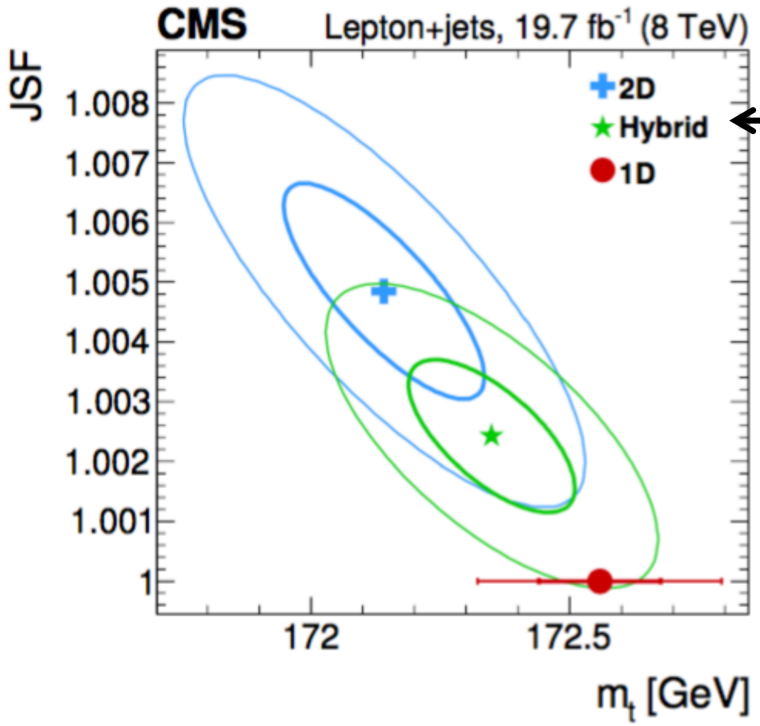
$$m_t = 174.98 \pm 0.58\ (\text{stat} + \text{JES}) \pm 0.49\ (\text{syst})\ \text{GeV}$$

- **Dominant uncertainties:**
  - Hadronisation and underlying event (0.26 GeV)
  - Residual JES (0.21 GeV)
  - b-quark JES (0.16 GeV)

$$\Delta m_t / m_t = 0.43\%!$$

Most precise Tevatron result

- **Result:** $m_t^{hyb} = 172.35 \pm 0.16\,(\text{stat+JSF}) \pm 0.48\,(\text{syst})\ \text{GeV}$



Most precise LHC result: $\Delta m_t/m_t = 0.30\%!$

"Hybrid": *in-situ JES and standard JES constraints*

Experimental uncertainties	
Method calibration	0.04
Jet energy corrections	
– JEC: Intercalibration	+0.01
– JEC: In situ calibration	+0.12
– JEC: Uncorrelated non-pileup	−0.10
– JEC: Uncorrelated pileup	−0.04
Lepton energy scale	+0.01
E_T^{miss} scale	+0.04
Jet energy resolution	−0.03
b tagging	+0.06
Pileup	−0.04
Backgrounds	+0.03
Modeling of hadronization	
JEC: Flavor-dependent	
– light quarks (u d s)	+0.05
– charm	+0.01
– bottom	−0.32
– gluon	−0.08
b jet modeling	
– b fragmentation	<0.01
– Semileptonic b hadron decays	−0.16
Modeling of perturbative QCD	
PDF	0.04
Ren. and fact. scales	−0.09 ± 0.07
ME-PS matching threshold	+0.03 ± 0.07
ME generator	−0.12 ± 0.08
Top quark p_T	+0.02
Modeling of soft QCD	
Underlying event	+0.08 ± 0.11
Color reconnection modeling	+0.01 ± 0.09
Total systematic	0.48
Statistical	0.16
Total	0.51

- **Dominant uncertainties:**
  - *b*-quark JES (0.32 GeV)
  - JES (0.16 GeV)
  - tt event generator (0.12)

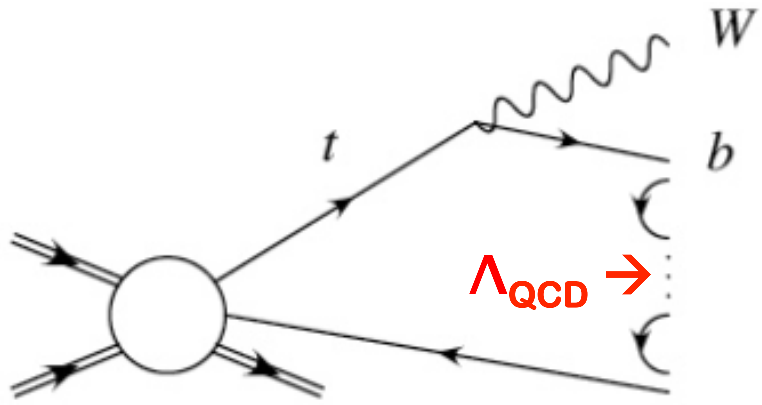
[1] *PRD **93**, 072004 (2016)*

- m_t is not an observable but a SM parameter
  - → inferred from its effect on kinematic observables
  - → not well-defined concept at LO
- **Pole mass concept:**

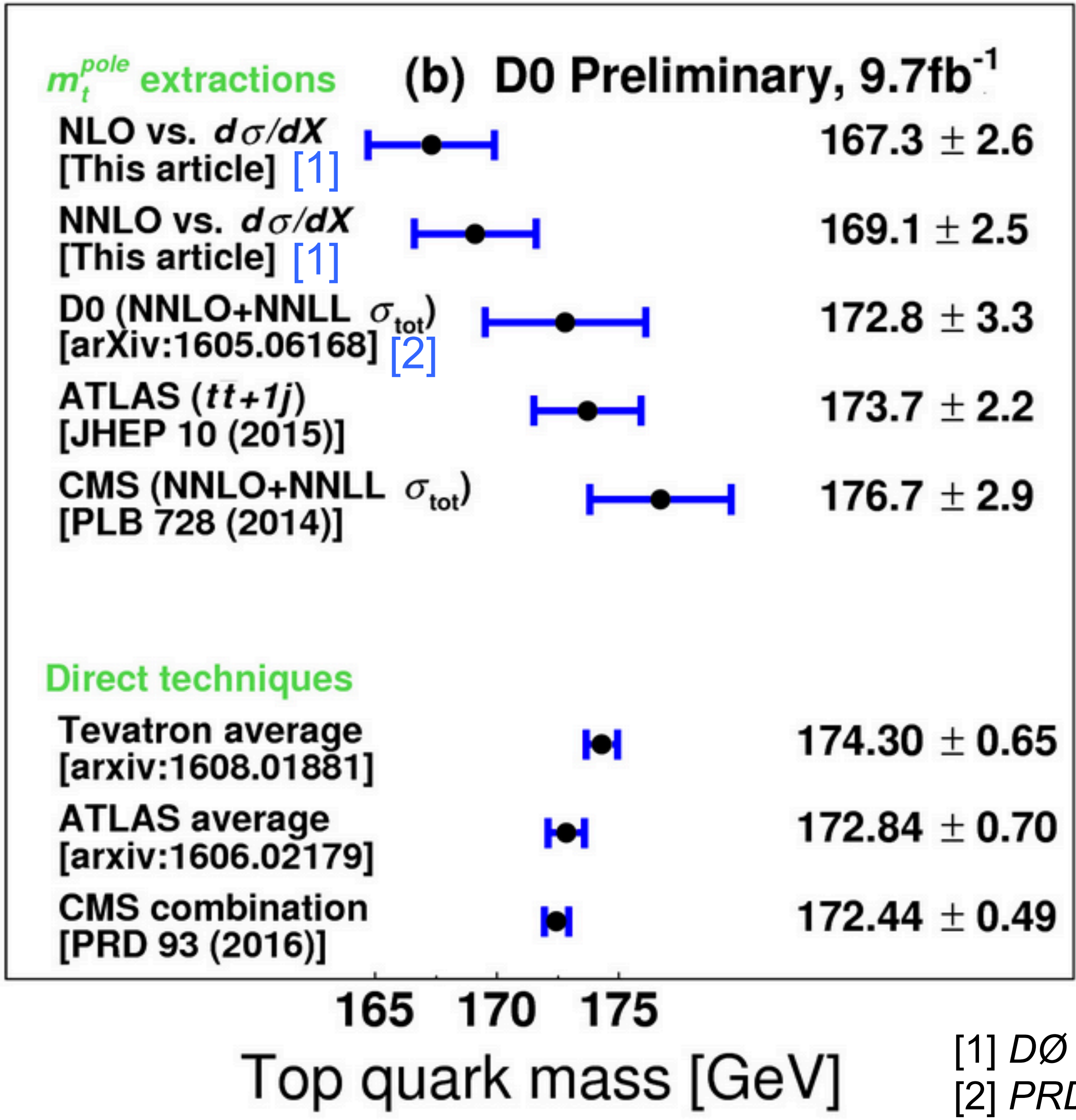
$$\frac{i\,(\not{p}_t + m_t)}{p_t^2 - m_t^2} = \frac{i}{\not{p}_t - m_t}$$

← *"Pole" in the top quark propagator*

  - Not exact (but hadronisation effects small, o(Λ_{QCD}))
  - Direct measurements (shown so far):
    - m^{MC} (neither MS, nor pole mass)
    - "Close" to pole mass (≈0.5 GeV)
    - True also for "NLO generators", e.g. Powheg
      - Top decay not simulated at NLO



- **Next slides:**
  - Measurements of m_t in the pole mass scheme

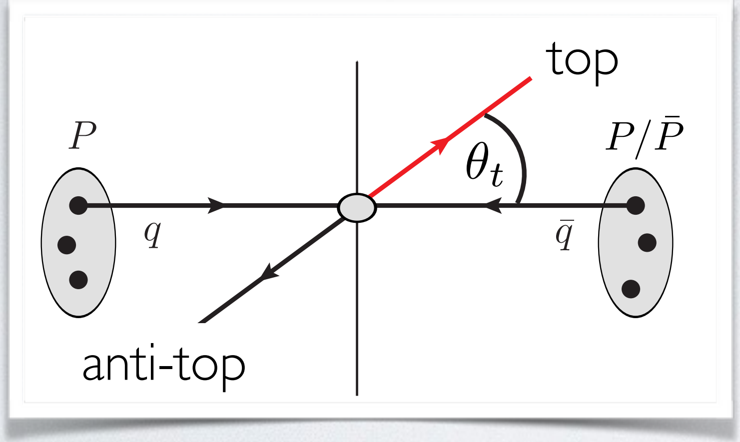


Only most precise m_t^{pole} measurements up to ICHEP 2016 shown

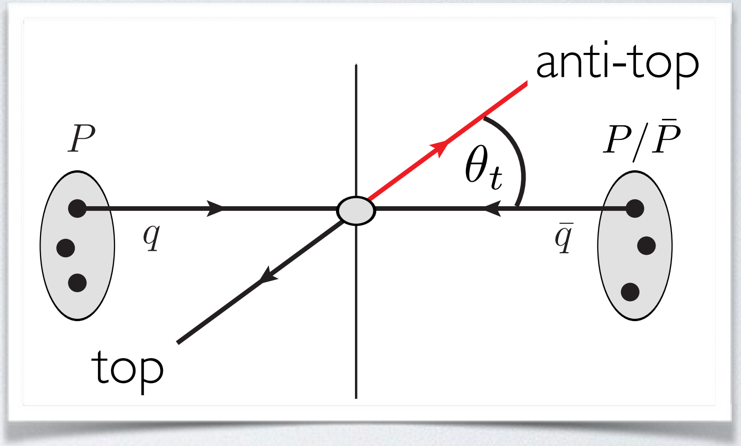
[1] *DØ note 6473 (2016)*
[2] *PRD 94 092004 (2016)*

Asymmetries in top quark sector

CHARGE ASYMMETRY FOR PEDESTRIANS

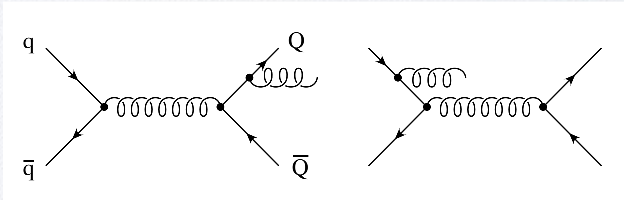


$\neq$

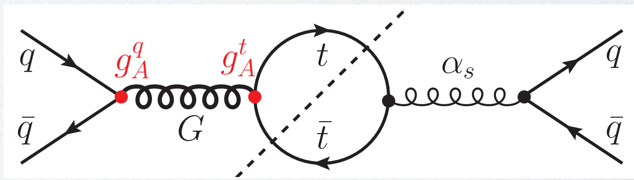


$$d\sigma_A = d\sigma_{t\bar{t}}(p_t, p_{\bar{t}}) - d\sigma_{t\bar{t}}(p_t, p_{\bar{t}})$$

Test strong interactions beyond leading order:



Test new interactions at leading order:



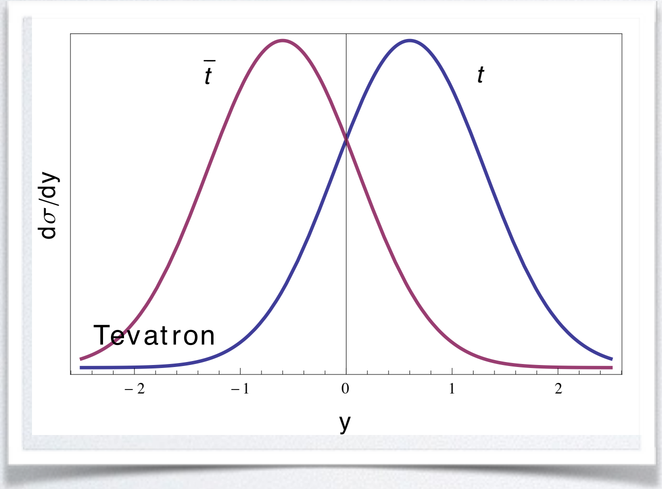
Susanne Westhoff

WHAT WE OBSERVE

rapidity asymmetries

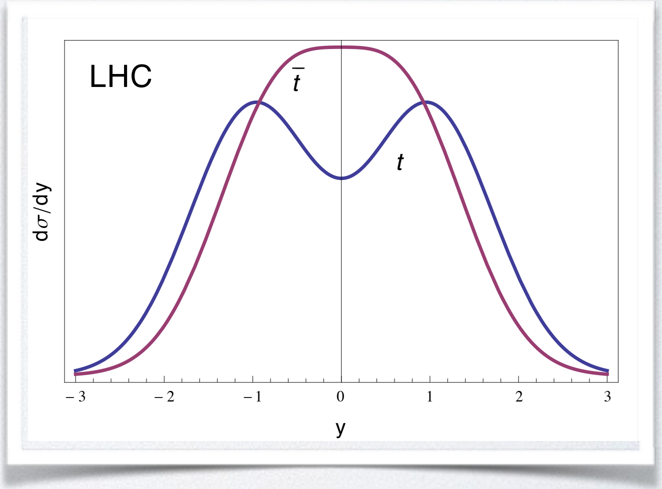
$$A_y = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}$$

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



$A_y \approx 12\%$

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



$A_y \approx 1\%$

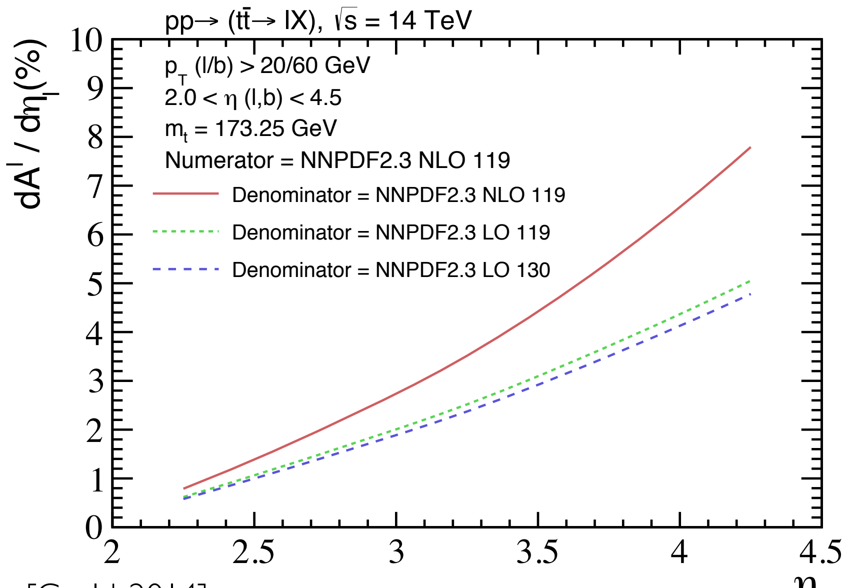
Susanne Westhoff

HOW ABOUT LHCB?

Charge asymmetry of $t \to b\,\ell^+\nu_\ell$ leptons in forward region:

$$\frac{dA_\ell}{d\eta_\ell} = \frac{d\sigma_{\ell^+ b}/d\eta_\ell - d\sigma_{\ell^- b}/d\eta_\ell}{d\sigma_{\ell^+ b}/d\eta_\ell + d\sigma_{\ell^- b}/d\eta_\ell}$$

[Kagan, Kamenik, Perez, Stone, 2011]



[Gauld, 2014]

Top-pair cross section just measured with 4.9 sigma significance.

[LHCb collaboration, 2016]

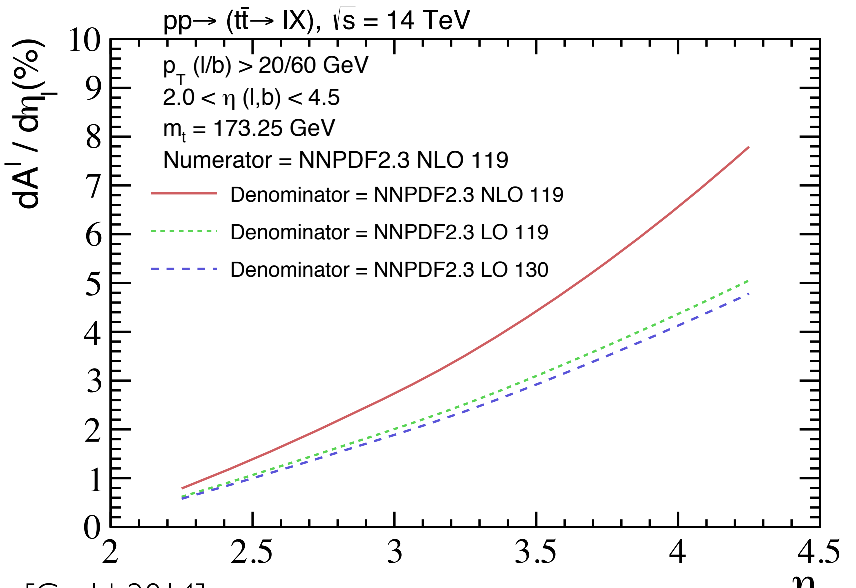
Need to tame background from (mistagged) Wj, Zj, single top.

HOW ABOUT LHCB?

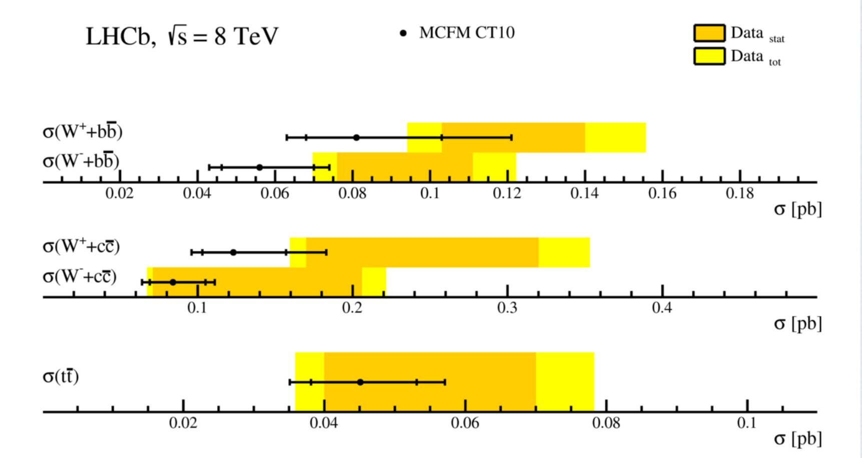
Charge asymmetry of $t \to b\,\ell^+ \nu_\ell$ leptons in forward region:

$$\frac{dA_\ell}{d\eta_\ell} = \frac{d\sigma_{\ell^+ b}/d\eta_\ell - d\sigma_{\ell^- b}/d\eta_\ell}{d\sigma_{\ell^+ b}/d\eta_\ell + d\sigma_{\ell^- b}/d\eta_\ell}$$

[Kagan, Kamenik, Perez, Stone, 2011]



[Gauld, 2014]



LHCB-PAPER-2016-038

Need to tame background from (mistagged) Wj, Zj, single top.

ENERGY ASYMMETRY

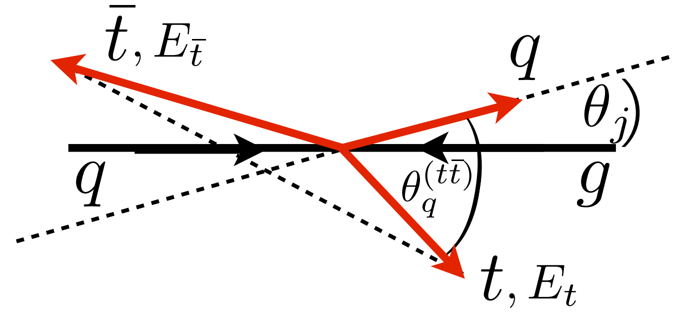
[Berge, SW, 2013]

Top-antitop **energy difference** in top-pair + jet production:

$$A_E = \frac{\sigma_{t\bar{t}j}(\Delta E > 0) - \sigma_{t\bar{t}j}(\Delta E < 0)}{\sigma_{t\bar{t}j}(\Delta E > 0) + \sigma_{t\bar{t}j}(\Delta E < 0)}$$

$\Delta E = E_t - E_{\bar{t}}$
(parton frame)

$$E_t < E_{\bar{t}} \leftrightarrow \cos\theta_q^{(t\bar{t})} > 0$$

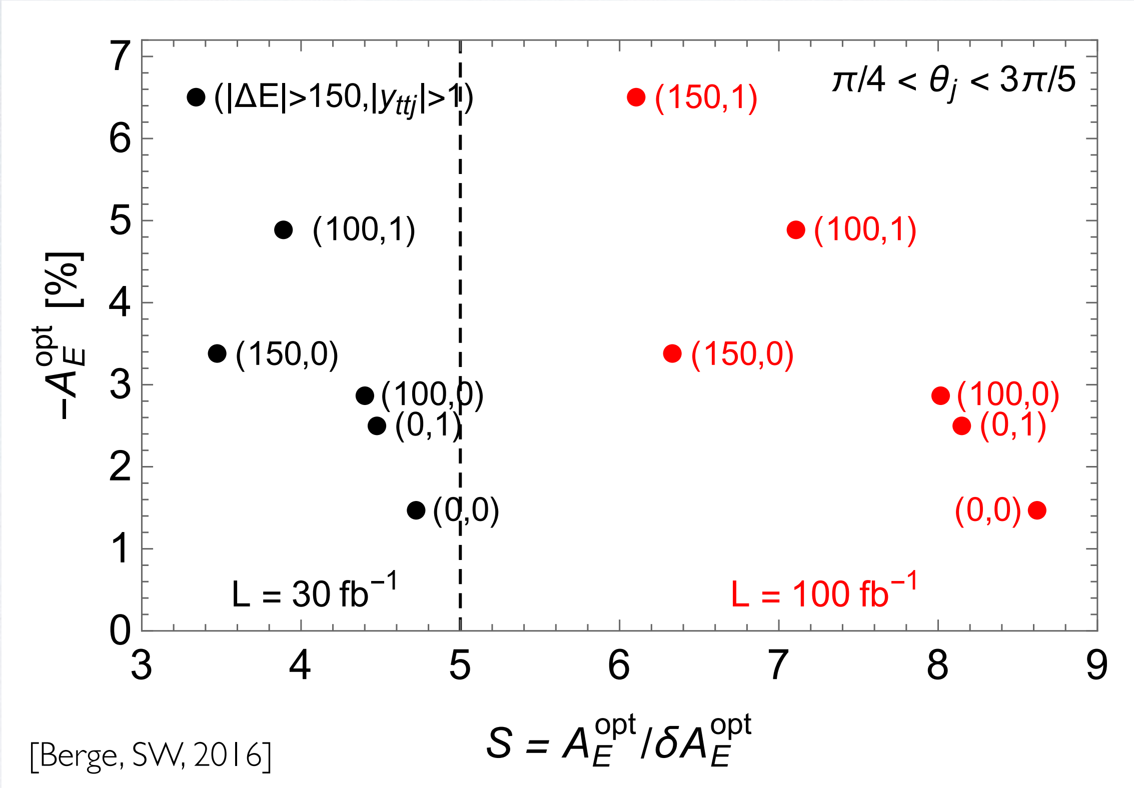


energy asymmetry in *qg* frame = angular asymmetry in *t$\underline{t}$* frame

Susanne Westhoff

OBSERVATION PROSPECTS FOR LHC RUN II

Now 2018



Statistical significance S, assuming acceptance × efficiency = 8%.

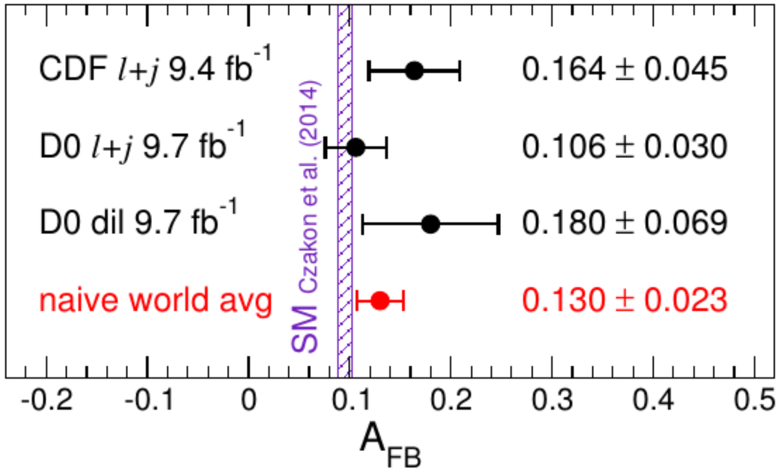
Susanne Westhoff

Forward-backward asymmetry - Rev.Mod.Phys. 87 (2015) 421-455

- The Tevatron is a $p-\bar{p}$ machine
- The forward-backward (FB) $t\bar{t}$ asymmetry is defined by the rapidity, y, of the top- and anti-top-quarks, where $\Delta y = y_t - y_{\bar{t}}$
- The FB asymmetry is expressed as:

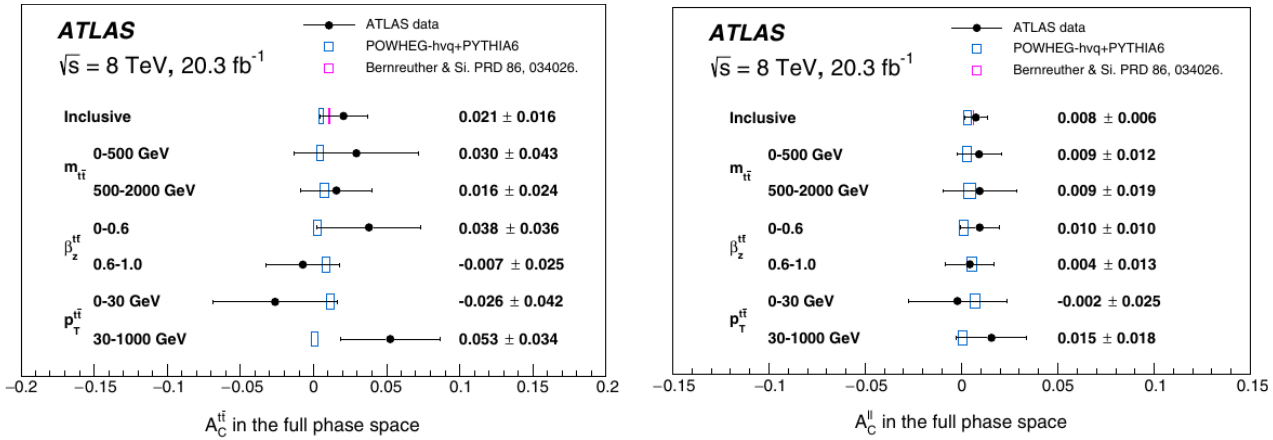
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

- A Summary of the full Tevatron Run2 inclusive A_{FB} results

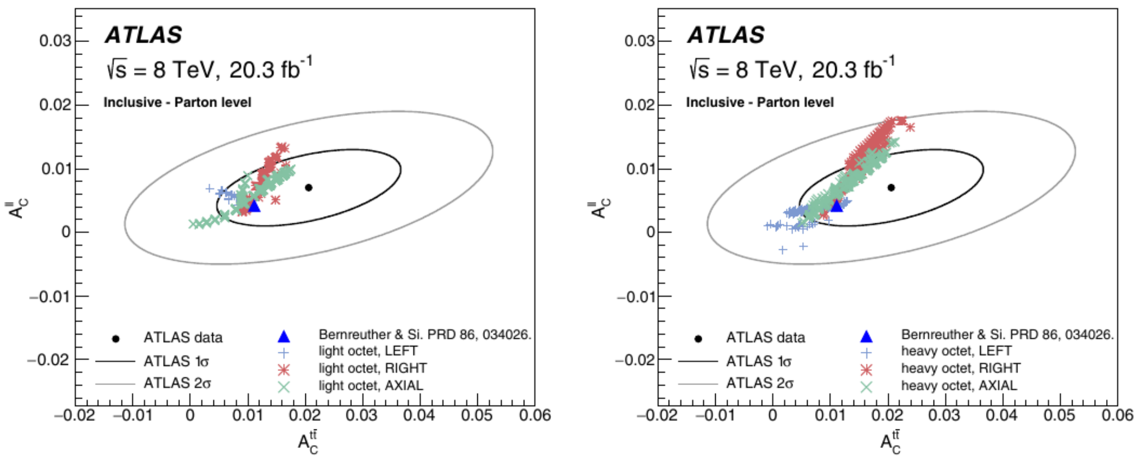


ATLAS dilepton results - Phys. Rev. D 94, 032006 (2016)

- A_c and A_c^{lep} for different bins of $m_{t\bar{t}}$, $|\beta_{z,t\bar{t}}|$ and $p_{\mathrm{T}}^{t\bar{t}}$



- A_c Vs A_c^{lep}, shown for a selection of BSM theories

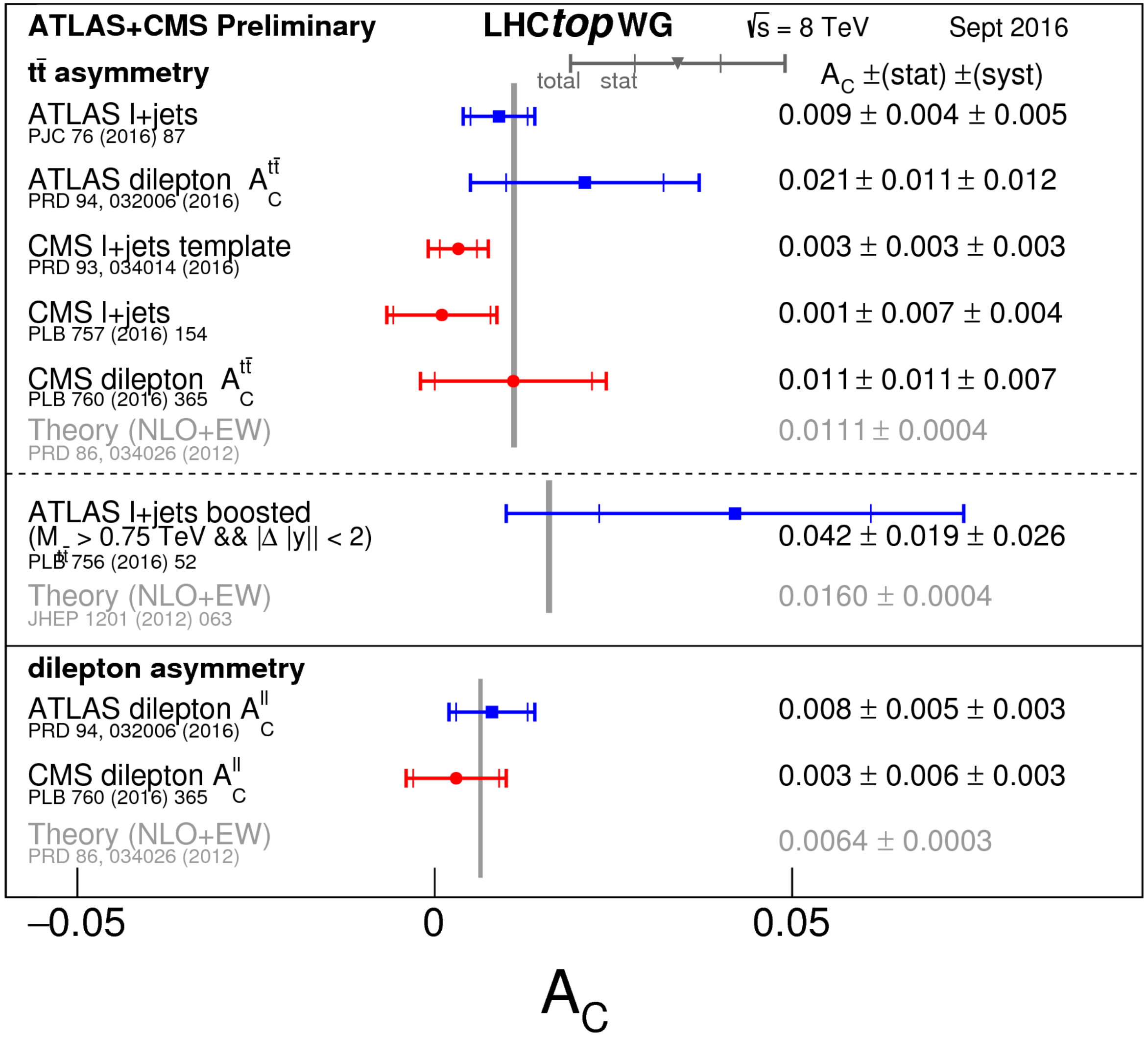


John Morris

- Results are consistent with the Standard Model
- BSM models are not excluded

Summary of A_c

- A summary of all inclusive measurements of A_c



John Morris

CP violation at CMS - CMS TOP-16-001

- First measurement of CP violation using $t\bar{t}$ events
- Based on the T-odd triple product correlations
- Semi-leptonic $t\bar{t}$ event selection
  - Similar event selection to CMS ℓ+jets A_c analysis
- 4 CP-sensitive observables, O_i.
- CP-asymmetry expressed as:

$$A_{CP}(O_i) = \frac{N(O_i > 0) - N(O_i < 0)}{N(O_i > 0) + N(O_i < 0)}$$

- Any non-zero $A_{CP}(O_i)$ would hint a BSM physics

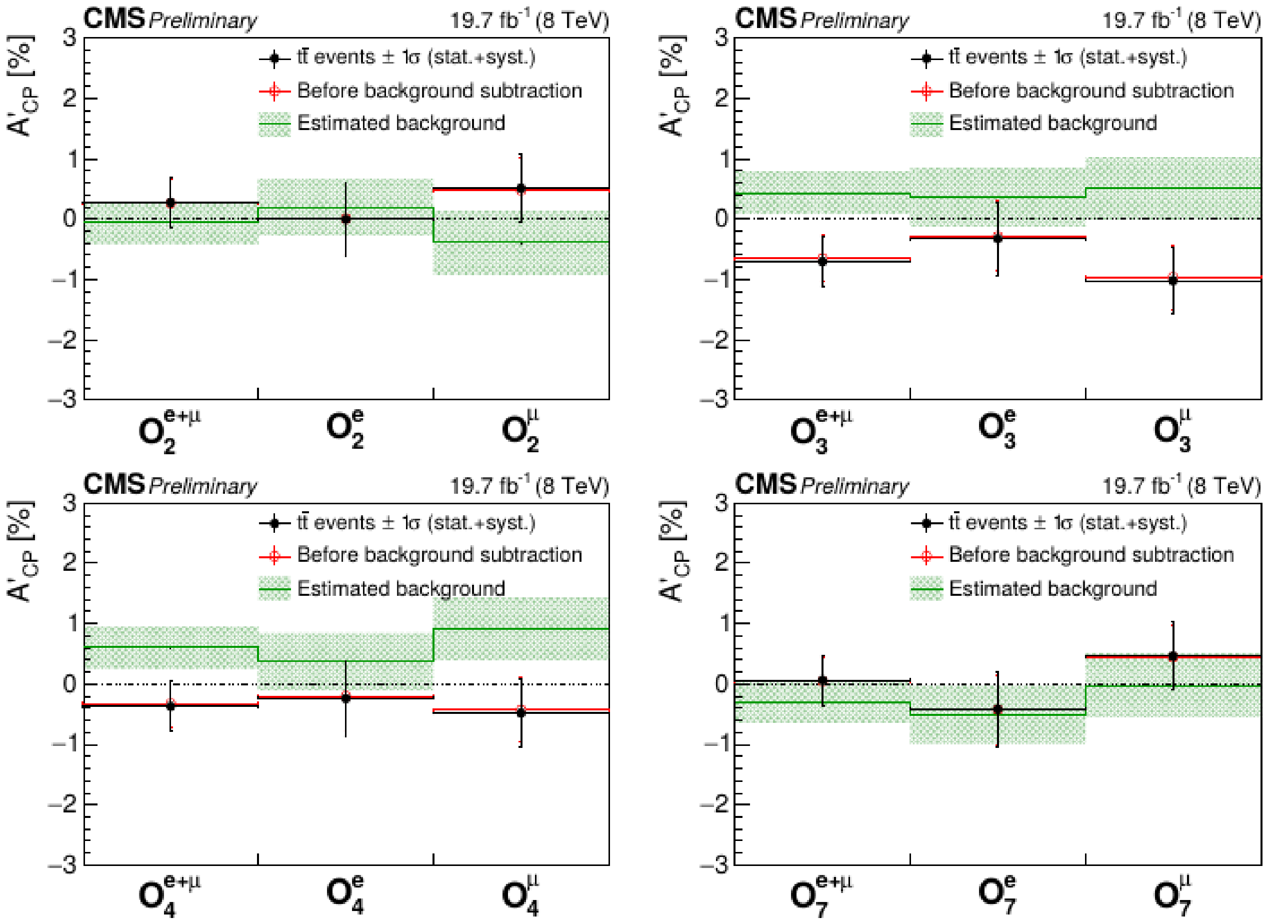
$$O_2 = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{b\bar{b}\ CM} \propto Q_\ell \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

$$O_4 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

$$O_7 = q \cdot (p_b - p_{\bar{b}}) \epsilon(P, q, p_b, p_{\bar{b}}) \xrightarrow{lab} \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z (\vec{p}_b \times \vec{p}_{\bar{b}})_z .$$

CP violation at CMS - CMS TOP-16-001



- Measured asymmetries show no evidence for CP-violation
- In agreement with Standard Model prediction

CP violation at ATLAS - arXiv:1610.07869 (Submitted to JHEP)

- CP Violation occurs in neutral B-meson decays
- $t\bar{t}$ events offer an alternative b-quark production mechanism compared to b-factories such as BaBar and Belle
- Hard lepton from W-boson decay in semileptonic $t\bar{t}$ allows determination of b-quark charge ($t \to bW^+ \to b\ell^+\nu$)
- Charge of soft muon from ($b \to X\mu\nu$) probes decay chain
  - Tag jets containing a soft muon (SMT algorithm)
- Inclusive top decay chains which produce 2 leptons

- Same Sign
- $t \to \ell^+\nu\,(b \to \bar{b}) \to \ell^+\ell^+X$
- $t \to \ell^+\nu\,(b \to c) \to \ell^+\ell^+X$
- $t \to \ell^+\nu\,(b \to \bar{b} \to c\bar{c}) \to \ell^+\ell^+X$

- Opposite Sign
- $t \to \ell^+\nu b \to \ell^+\ell^-X$
- $t \to \ell^+\nu\,(b \to \bar{b} \to \bar{c}) \to \ell^+\ell^-X$
- $t \to \ell^+\nu\,(b \to c\bar{c}) \to \ell^+\ell^-X$

- These processes are sensitive to CPV in $B_q - \bar{B}_q$ $(q = d, s)$ mixing, semileptonic b and c decays and $b \to c$
- Theory paper: **PRL 110,232002 (2013)**

CP violation at ATLAS - arXiv:1610.07869 (Submitted to JHEP)

- Use semileptonic $t\bar{t}$ events in which B-hadron decays to a muon
- Consider number of SMT muons, N^{ab}, where:
  - a : Charge of W-lepton $\Rightarrow$ identifies initial charge of b
  - b : Charge of SMT Muon $\Rightarrow$ probes final state for CPV
- Consider probability of initial b decaying to a lepton ℓ

$$P\left(b \to \ell^+\right) = \frac{N\left(b \to \ell^+\right)}{N\left(b \to \ell^-\right) + N\left(b \to \ell^+\right)} = \frac{N^{++}}{N^{+-} + N^{++}} = \frac{N^{++}}{N^+}$$

$$P\left(\bar{b} \to \ell^-\right) = \frac{N\left(\bar{b} \to \ell^-\right)}{N\left(\bar{b} \to \ell^-\right) + N\left(\bar{b} \to \ell^+\right)} = \frac{N^{--}}{N^{--} + N^{-+}} = \frac{N^{--}}{N^-}$$

$$P\left(b \to \ell^-\right) = \frac{N\left(b \to \ell^-\right)}{N\left(b \to \ell^-\right) + N\left(b \to \ell+\right)} = \frac{N^{+-}}{N^{+-} + N^{++}} = \frac{N^{+-}}{N^+}$$

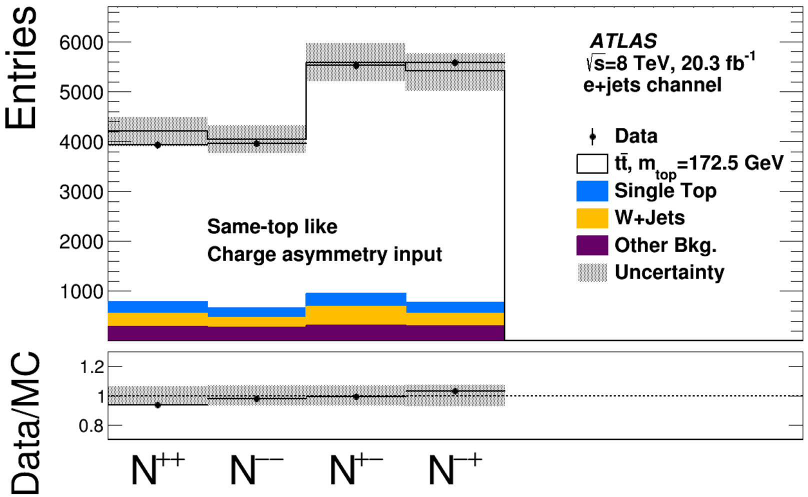
$$P\left(\bar{b} \to \ell^+\right) = \frac{N\left(\bar{b} \to \ell^+\right)}{N\left(\bar{b} \to \ell^-\right) + N\left(\bar{b} \to \ell^+\right)} = \frac{N^{-+}}{N^{--} + N^{-+}} = \frac{N^{-+}}{N^-}$$

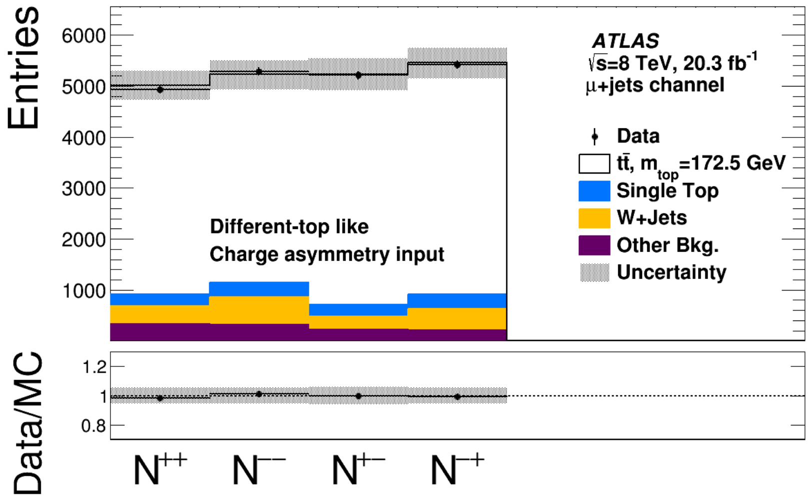
- Measure same- and opposite-sign charge asymmetries:

$$A^{ss} = \frac{P\left(b \to \ell^+\right) - P\left(\bar{b} \to \ell^-\right)}{P\left(b \to \ell^+\right) + P\left(\bar{b} \to \ell^-\right)} \qquad A^{os} = \frac{P\left(b \to \ell^-\right) - P\left(\bar{b} \to \ell^+\right)}{P\left(b \to \ell^-\right) + P\left(\bar{b} \to \ell^+\right)}$$

$$A^{ss} = \frac{\left(\frac{N^{++}}{N^+} - \frac{N^{--}}{N^-}\right)}{\left(\frac{N^{++}}{N^+} + \frac{N^{--}}{N^-}\right)} \qquad A^{os} = \frac{\left(\frac{N^{+-}}{N^+} - \frac{N^{-+}}{N^-}\right)}{\left(\frac{N^{+-}}{N^+} + \frac{N^{-+}}{N^-}\right)}$$

CP violation at ATLAS - arXiv:1610.07869 (Submitted to JHEP)





	Data (10^{-2})	MC (10^{-2})	Existing limits (2σ) (10^{-2})		SM prediction (10^{-2})	
A^{ss}	-0.7 ± 0.8	0.05 ± 0.23	-		$< 10^{-2}$	[19]
A^{os}	0.4 ± 0.5	-0.03 ± 0.13	-		$< 10^{-2}$	[19]
A^{b}_{mix}	-2.5 ± 2.8	0.2 ± 0.7	< 0.1	[95]	$< 10^{-3}$	[96] [95]
$A^{b\ell}_{\text{dir}}$	0.5 ± 0.5	-0.03 ± 0.14	< 1.2	[94]	$< 10^{-5}$	[19] [94]
$A^{c\ell}_{\text{dir}}$	1.0 ± 1.0	-0.06 ± 0.25	< 6.0	[94]	$< 10^{-9}$	[19] [94]
A^{bc}_{dir}	-1.0 ± 1.1	0.07 ± 0.29	-		$< 10^{-7}$	[97]

- All results are consistent with the Standard Model
- Largest uncertainty on all results is statistical
- First ever measurement of $A^{\text{bc}}_{\text{dir}}$
- Strengthens 2σ limit on $A^{c\ell}_{\text{dir}}$, equivalent limit for $A^{b\ell}_{\text{dir}}$

BFF: Top & Higgs

Hunting the Higgs-top Yukawa coupling

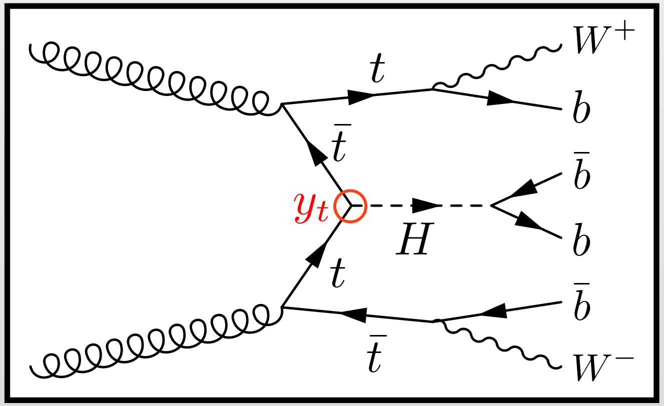
Direct measurement

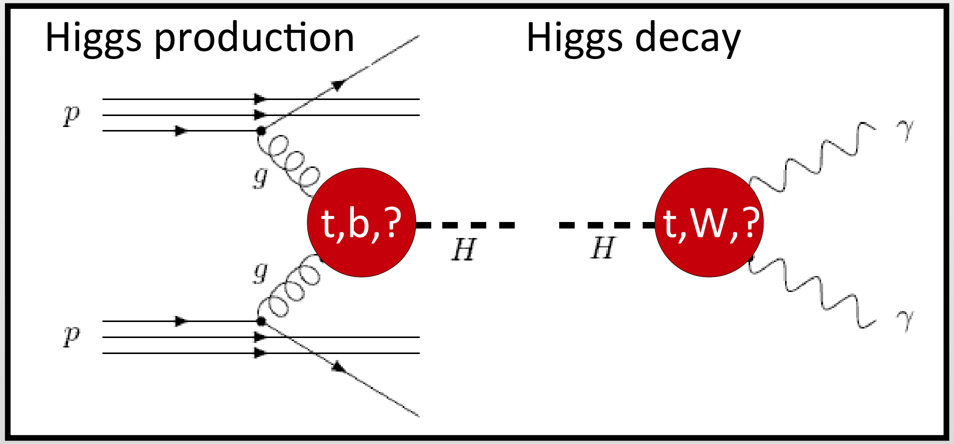
- **Direct** measurement **in $t\bar{t}H$** production

Sensitive to y_t^2

Indirect constraints:

- loops in **ggF** and **H → γγ** vertices;
  - assuming only SM particles contributing to the loops.





- **tH production**: interference between top-mediated and W-mediated diagrams;

Sensitive to y_t

- **H → γγ**: interference between top quark and W boson in the loop;
- **ZH production and H->Zγ**: interference between top quark and W-boson contribution in the loop.

Coupling measurement methodology

Assumptions:

arXiv:1307.1347

- Observed signal originates from the **single resonance**;
- **Narrow width** approximation: $(\sigma \cdot BR)(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$
- Parametrise deviations with only **coupling strength modifiers {κx}.**

Procedure:

- Scale SM cross-section and partial widths as a function of parameters {κx}:

$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \; \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

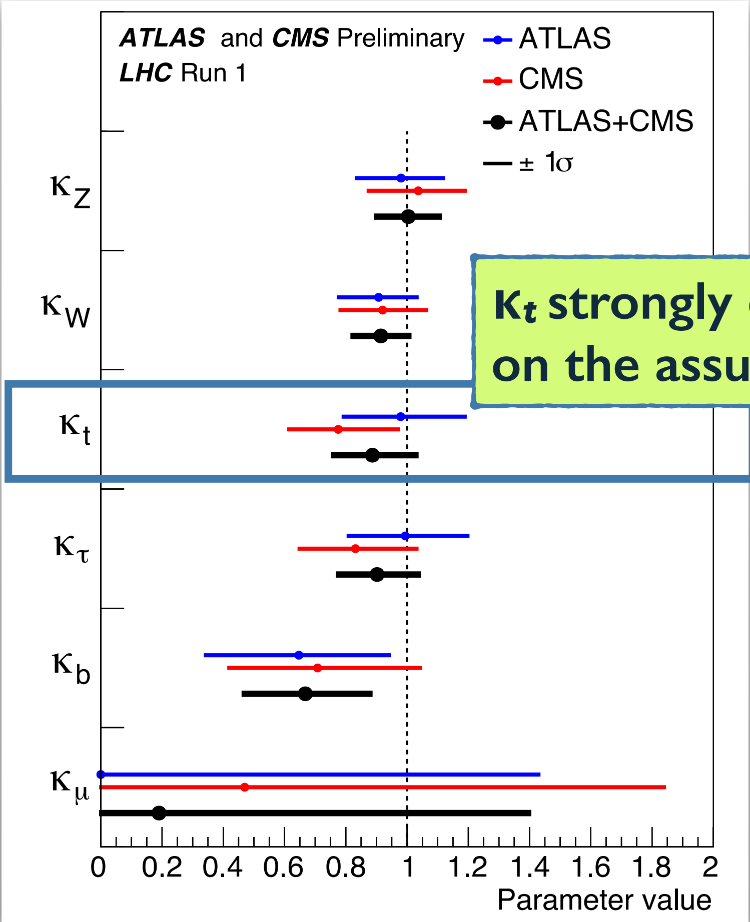
- In case of loop processes κ_x can be expressed as a function of more fundamental κ_y;
- If BSM decays are allowed, scale down all SM decays uniformly.

Tested many scenarios:

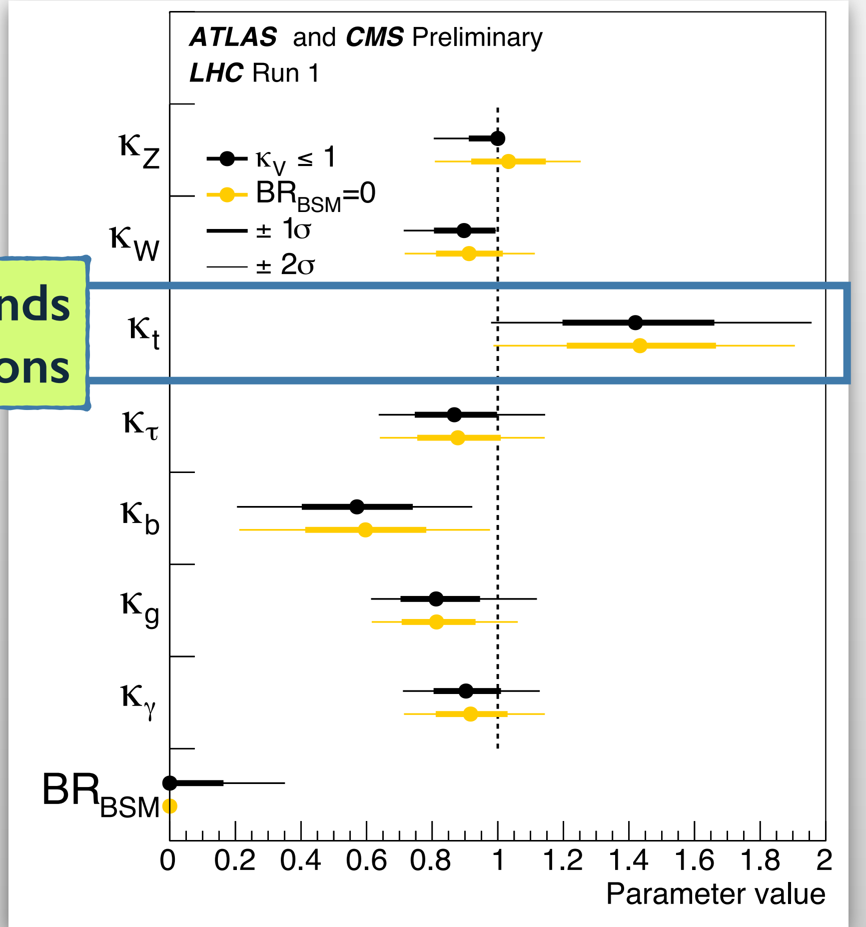
- **Fermion versus vector boson** couplings, up quark VS down quark couplings: also provide constraints on BSM
- **Generic model** - simultaneous fit of all modifiers, etc…

Top Yukawa coupling - ATLAS+CMS Run I

- parameterisation assuming the absence of BSM particles in the loops, $BR_{BSM} = 0$, $\kappa_j > 0$;
- two parameterisations allowing loop couplings, with either $\kappa_{V(W,Z)} \leq 1$ or $BR_{BSM} = 0$;



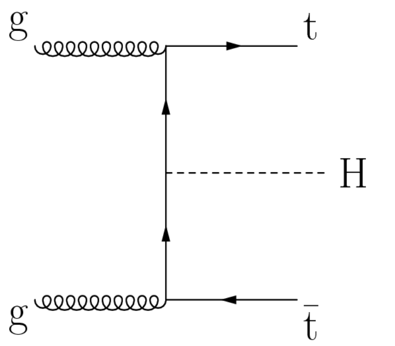
κt strongly depends on the assumptions



$t\bar{t}H$ - final states

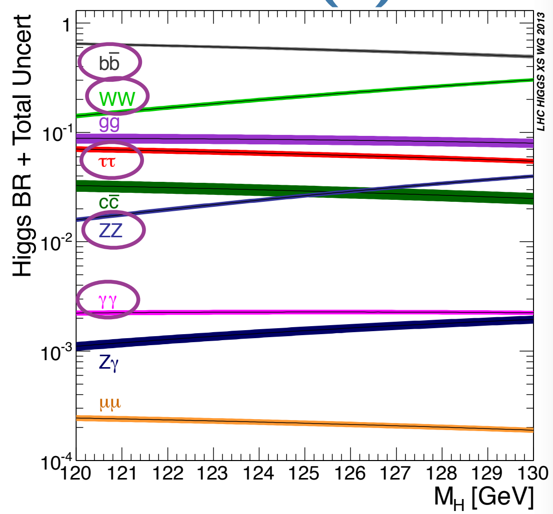
Large BR
Large background

ttH production

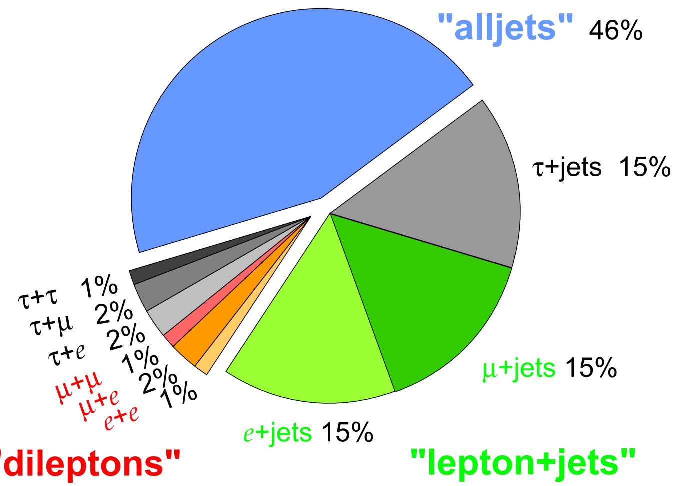


$\sigma(t\bar{t}H) = 507 fb^{-1}$ @ 13TeV
$1\%\sigma(H)$

BR(H)



BR($t\bar{t}$)

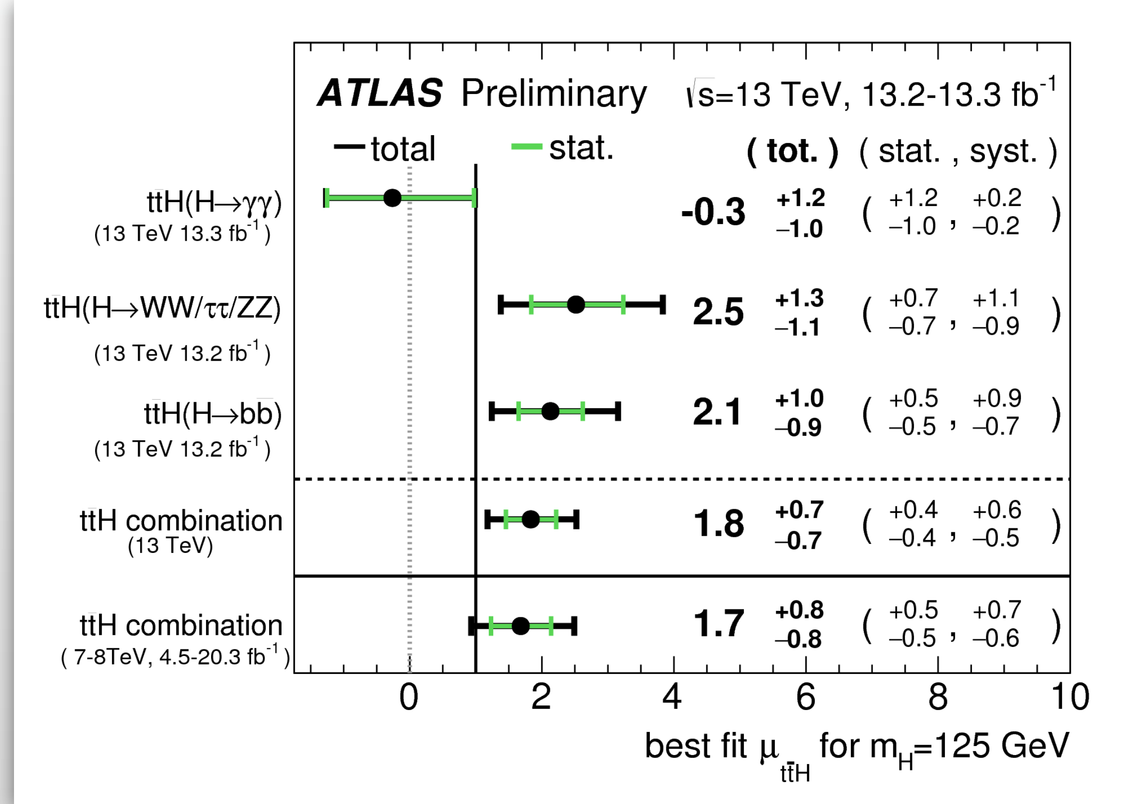


Small BR
Purity and precision

Broad spectrum of analyses covering multiple final states:

- generally combine low BR Higgs decay with high BR $t\bar{t}$ decay and vice-versa;
- $t\bar{t}$ decay products help selection of signal and the reduction of non-$t\bar{t}$ backgrounds, but combinatorics increased when attempting to reconstruct the Higgs boson candidate.

$t\bar{t}H$ combination and summary



Run1 precision already reached with ~13fb^{-1} of Run 2 data!
No significant deviations from the SM observed at both experiments.
Stay tuned for the new results from CMS and ATLAS using full 2015+2016 statistics ~ 35fb^{-1}

New Physics searches: FCNC

- Flavor-Changing Neutral Current (FCNC) changes the flavor of a fermion current without altering its electric charge.
- In the top quark sector :

FCNC decays:

t $\rightarrow$ u + γ

t $\rightarrow$ c + γ

t $\rightarrow$ u + Z

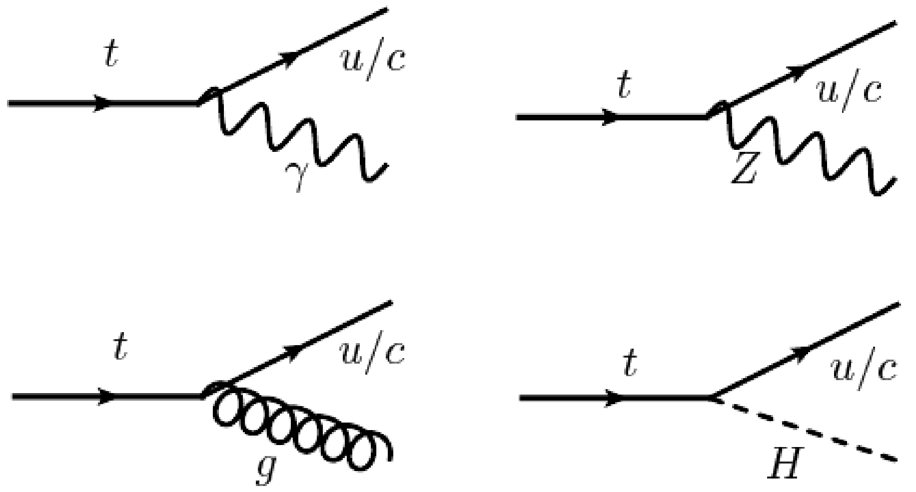
t $\rightarrow$ c + Z

t $\rightarrow$ u + g

t $\rightarrow$ c + g

t $\rightarrow$ u + H

t $\rightarrow$ c + H

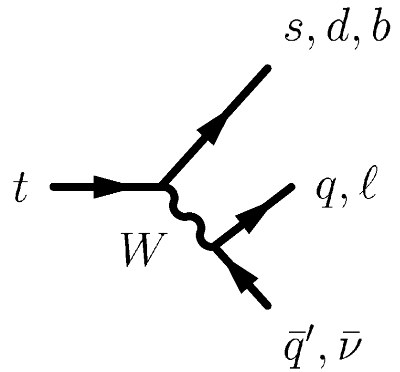


Charged current decays:

t $\rightarrow$ b + W ($BR \sim 100\%$)

t $\rightarrow$ s + W ($BR \sim 0.18\%$)

t $\rightarrow$ d + W ($BR \sim 0.02\%$)



Sandeep Bhowmik

FCNC in BSM

- Many models for new physics predict new contributions to top FCNCs that are orders of magnitude in excess of SM expectations.

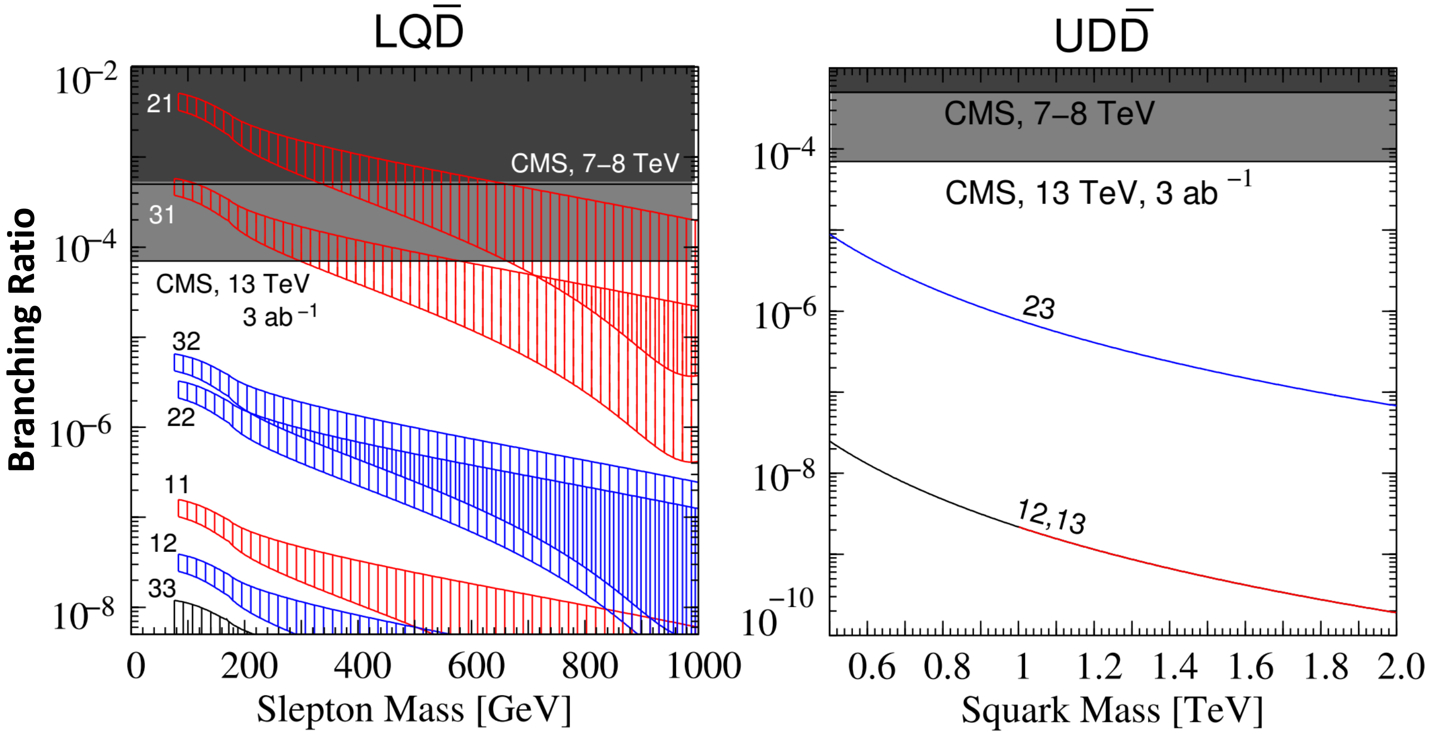
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to u + \gamma$	4×10^{-16}	-	-	$\leq 10^{-8}$	$\leq 10^{-9}$	-
$t \to c + \gamma$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to u + Z$	7×10^{-17}	-	-	$\leq 10^{-7}$	$\leq 10^{-6}$	-
$t \to c + Z$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to u + g$	4×10^{-14}	-	-	$\leq 10^{-7}$	$\leq 10^{-6}$	-
$t \to c + g$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to u + H$	2×10^{-17}	6×10^{-6}	-	$\leq 10^{-5}$	$\leq 10^{-9}$	-
$t \to c + H$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

- The branching ratio (BR) : the ratio of the flavor-violating partial width relative to the dominant top quark partial width, $t \to b + W$.

Sandeep Bhowmik

Reference: Snowmass 2013 Top quark working group report, arXiv:1311.2028

RPV SUSY Results - $t \to c\,Z$



Bounds (@ 20 fb^{-1})

$B(t \to cZ) < 5.0 \times 10^{-4}$

Projections (@ 3000 fb^{-1})

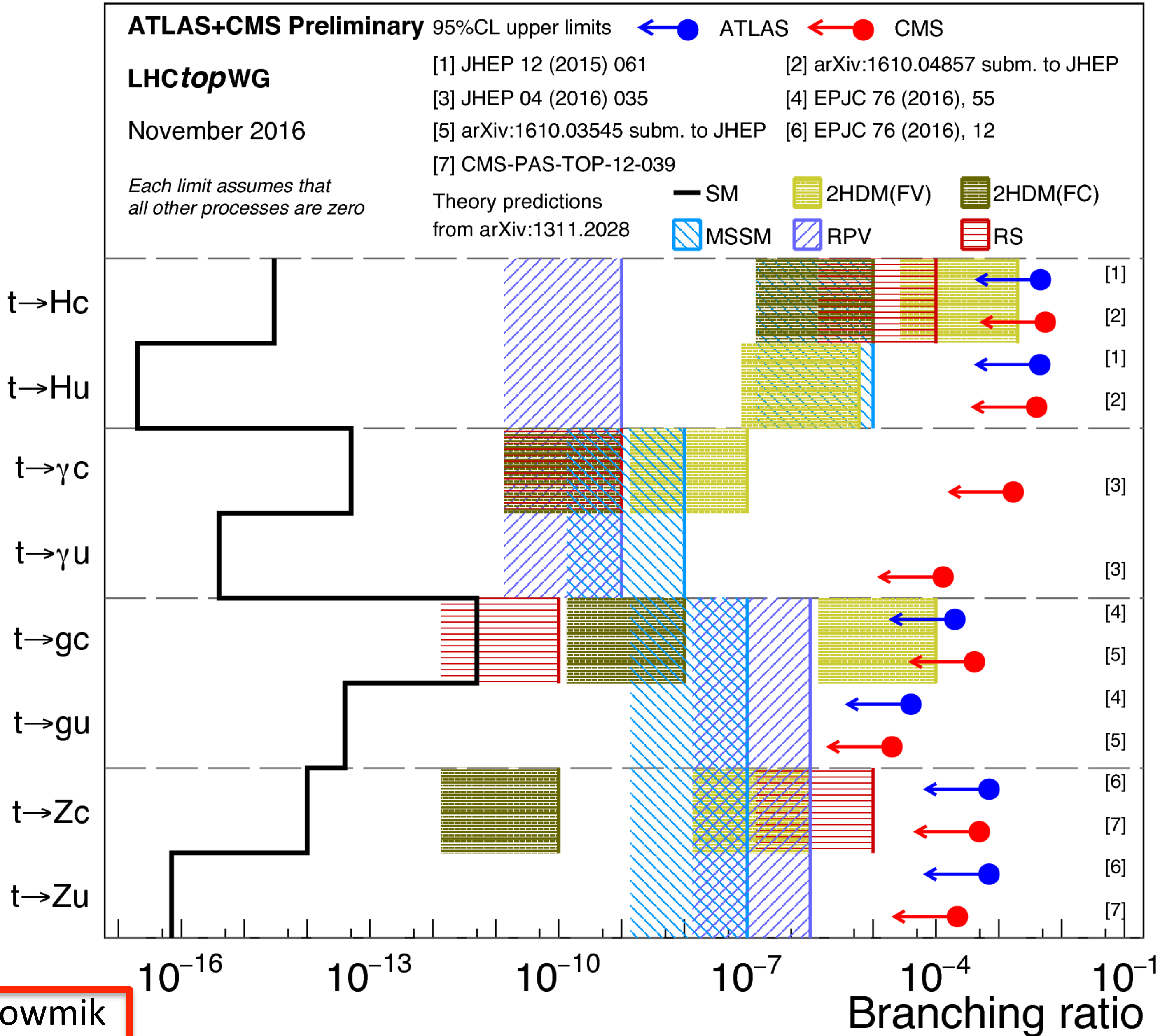
$B(t \to cZ) < 7.0 \times 10^{-5}$

hep-ex/1311.2028

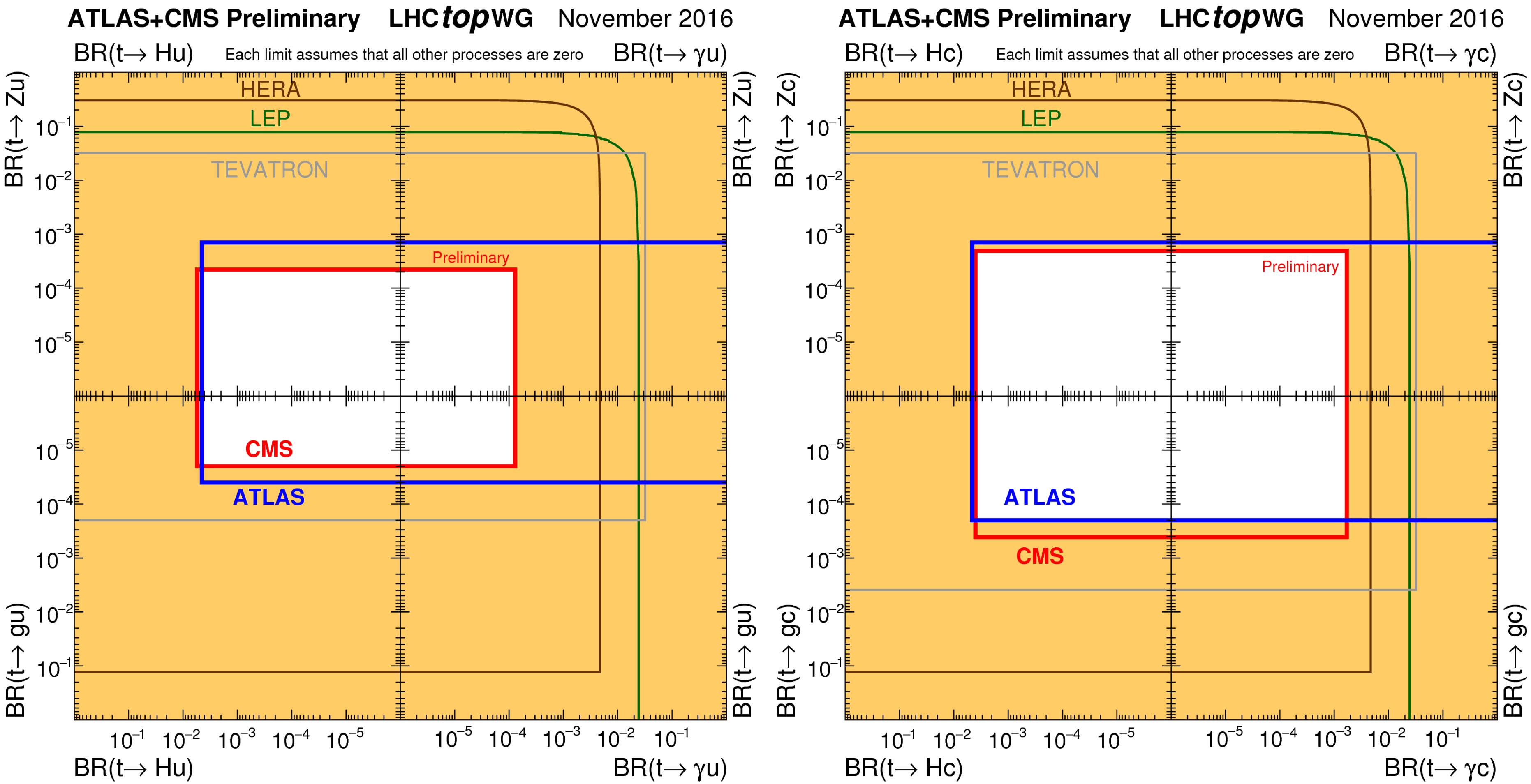
- Range of parameters for which top to charm and Z-boson would be visible
- Detection would be signal for RPV-SUSY – but not uniquely

Debjyoti Bardhan

Summary



Sandeep Bhowmik

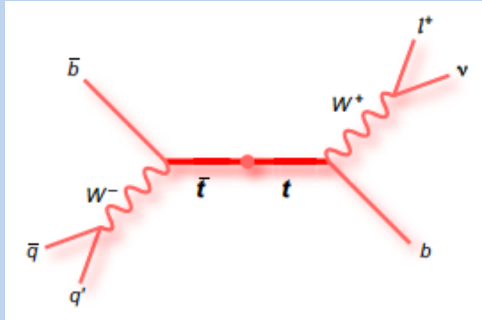


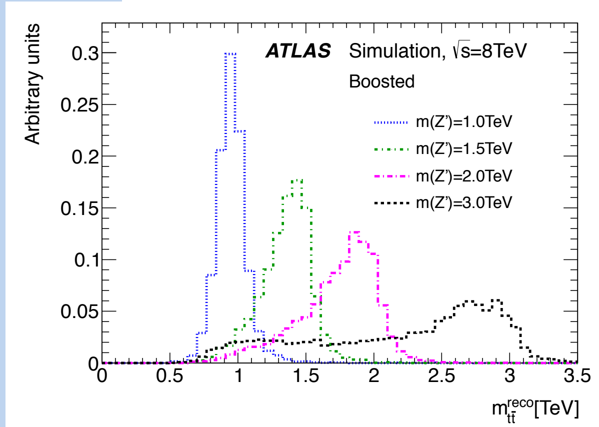
Sandeep Bhowmik

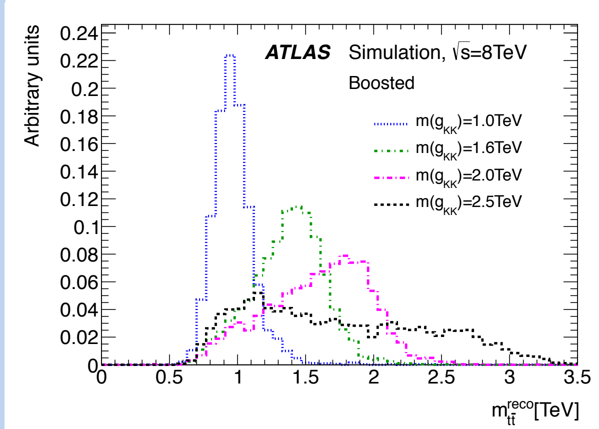
New Physics searches: Resonances

Physics

- Many BSM predict high mass particles decaying to ttbar because of its yukawa coupling ~1
- Experiments search for resonances on top of non-resonant standard model backgrounds
  - Analysis is a generic bump-hunt looking for significant deviations from the SM
- Interpret in terms of physics models to establish limits:
  - Techicolour Z' - spin-1 colour singlet
  - Extra dimension models Kaluza-Klein gluons – spin -1 colour octet
  - Extra dimensions Kaluza-Klein gravitons – spin-2 colour singlets
  - Heavy Higgs – spin-0 scalar
- In general interference is not implemented in the models, except for search for heavy Higgs' bosons

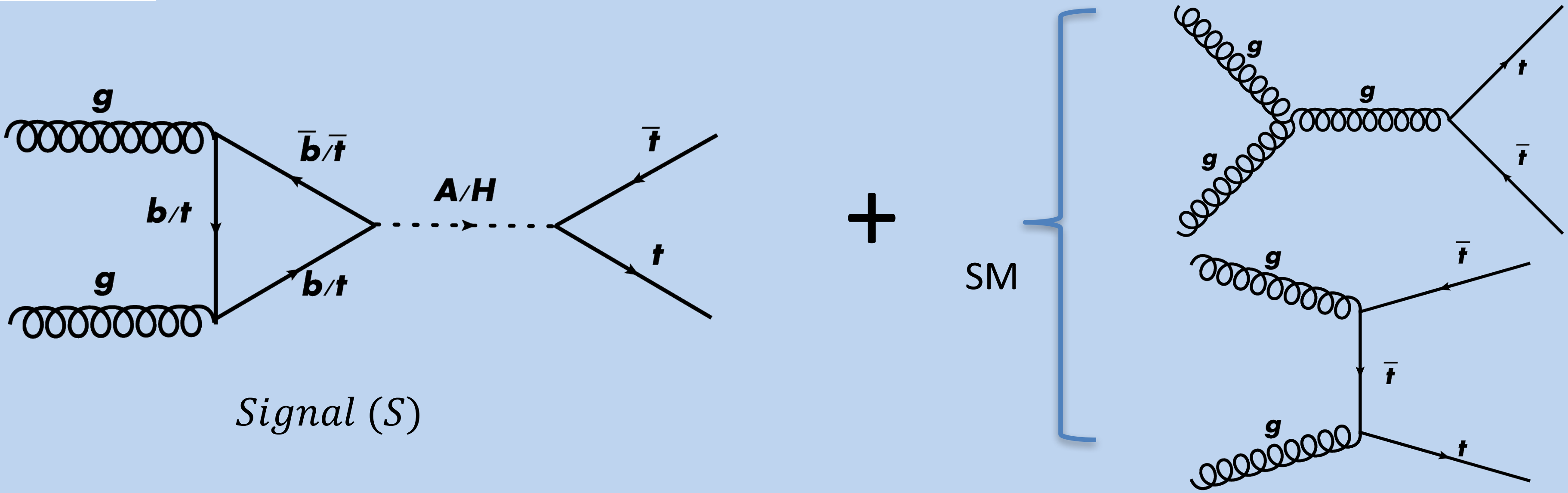






Revisiting the search for heavy scalars: including interference

ATLAS-CONF-2016-073



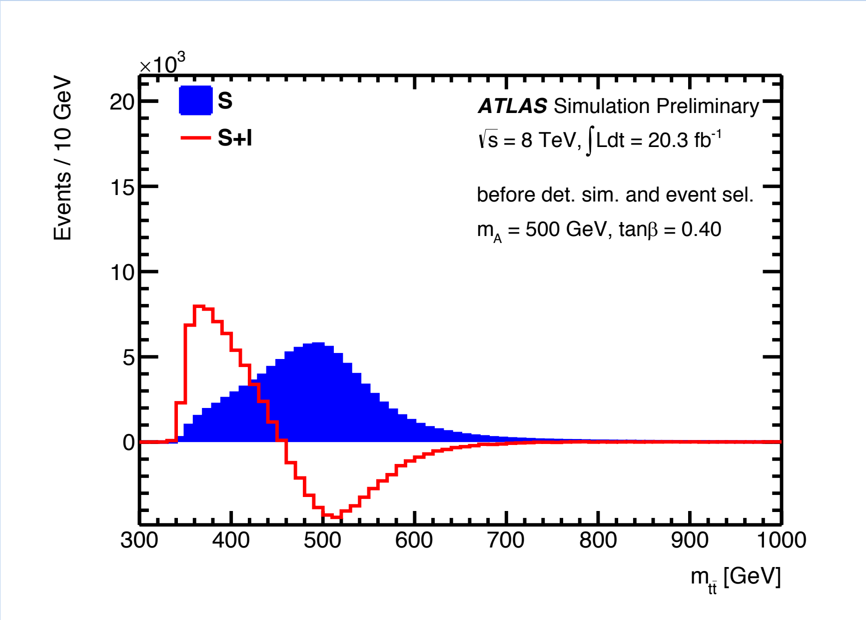
Signal (S)

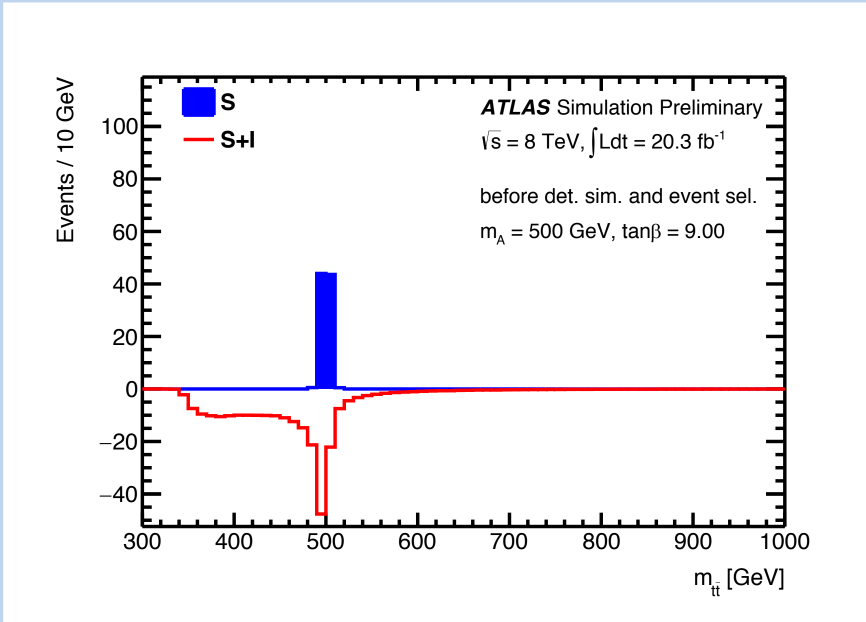
Background (B)

- Interference between gluon initiated signal and background
- Previous analyses assume no interference, but processes with gluon initial state will interfere with SM top production
- New analysis reinterprets in terms of 2HDM type-II H/A->ttbar
- Probe mass range 400<M<800 GeV and low tanβ
  - Events are tested against boosted and resolved categories, if both treat as resolved

Effect of interference

- Modify Madgraph5_aMC@NLO to generate events without SM ttbar background i.e. generate signal+interference only
  - Keep good description of background at NLO (Powheg+Pythia)
  - Efficient generation
  - Cross check with full S+I+B generation

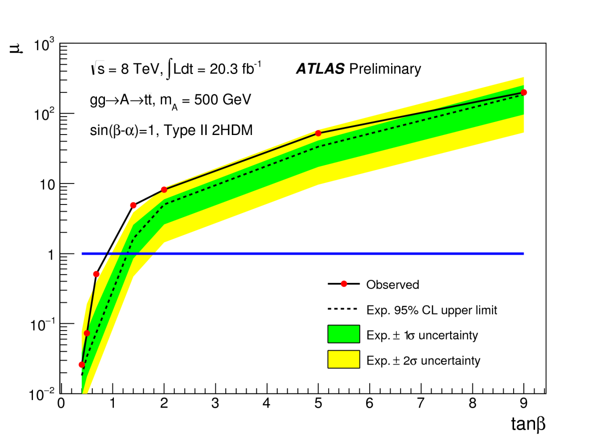




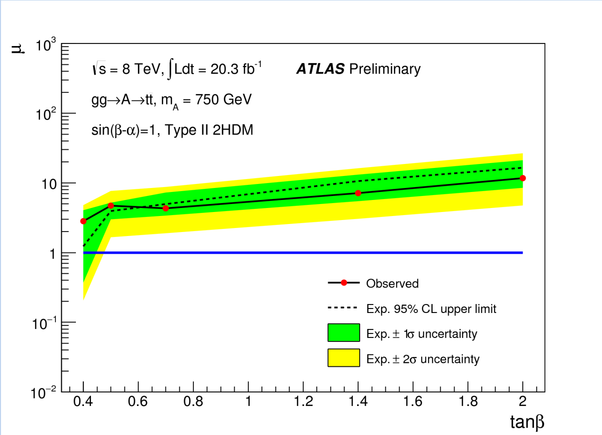
Parton level simulation

Scalar limits

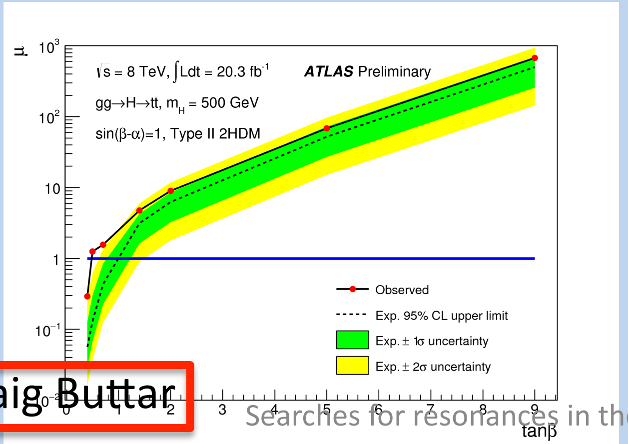
- Limits are set parameterising S+I and S as function of $\sqrt{\mu}$
  - $\mu S + \sqrt{\mu} I + B = \sqrt{\mu}(S + I) + (\mu - \sqrt{\mu})S + B$
  - (μ=1 for 2HDM type II)

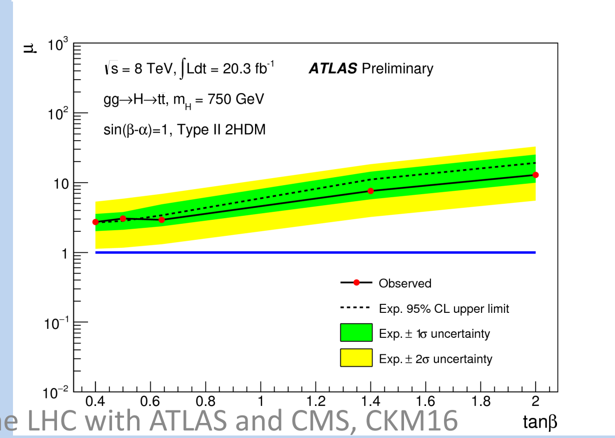


$M_{H/A}$=500GeV Excluded region for pseudoscalar: tanβ<0.85 For scalar tanβ<0.45

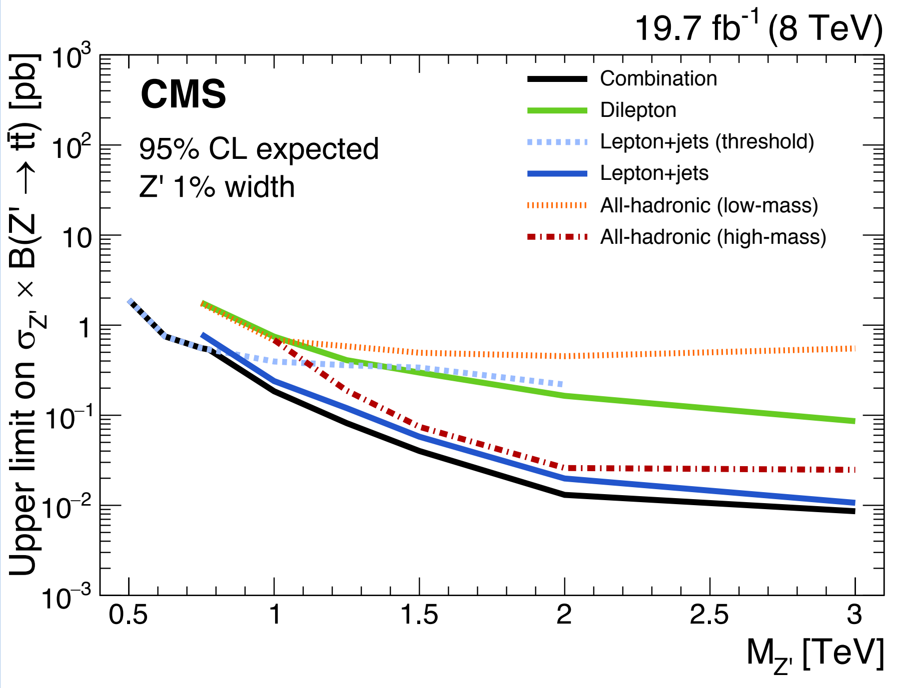


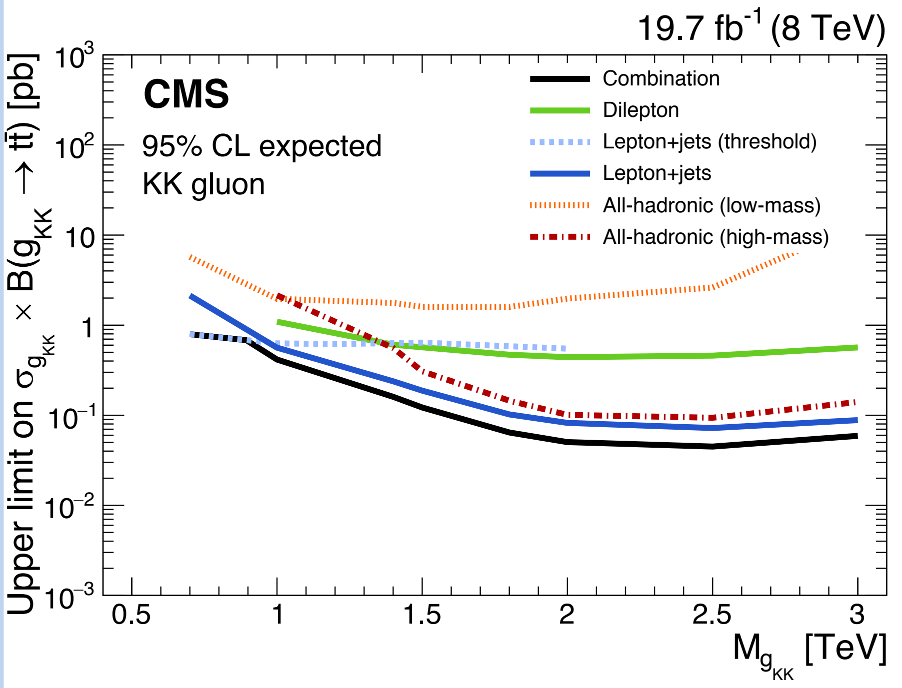
No limit on tanβ for $M_{H/A}$=750GeV



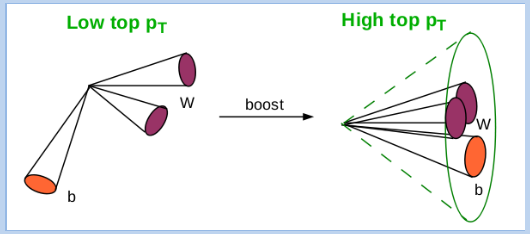


Results at 8TeV



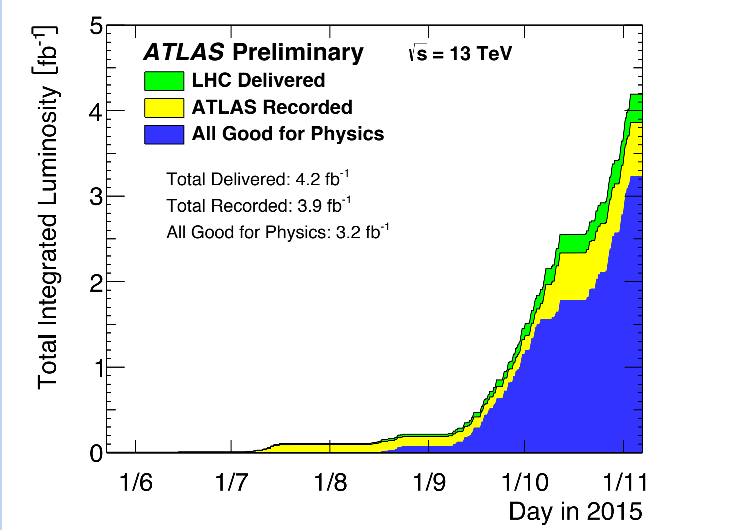


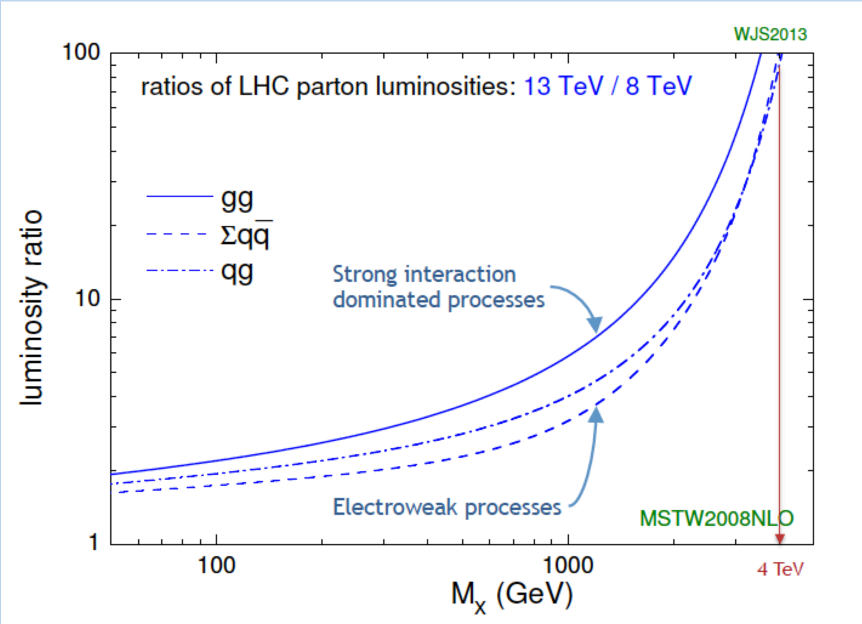
95% CL upper limits on cross-section X branching ratio for Z’ and KK gluon

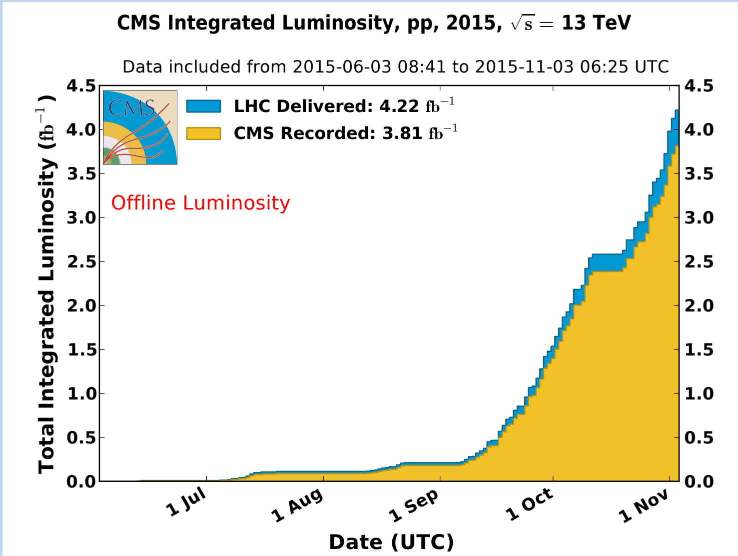


Run-2 at 13TeV

- 2015 very successful for rebooting LHC at 13TeV, and ATLAS & CMS after long shutdowns
  - 2016 luminosities:
    ATLAS: $36fb^{-1}$
    CMS:$32.87fb^{-1}$ (preliminary)
- Significant increase in parton luminosity of heavy particles
  - >10 increase for ~3TeV mass object







Summary of results at 8 and 13 TeV

13TeV		Mass limit (95% CL upper limit on σxBr)
ATLAS 3.2fb^{-1} semi-leptonic	Z' 1.2% width	0.7<M<2.0 TeV
CMS 2.6fb^{-1} all-hadronic	Z' 1% width	1.2<M<1.6 TeV
	RS KK-gluon	1.0<M<2.5 TeV (17pb @ 1TeV– 0.25pb @ 4TeV)
CM 2.6fb^{-1} semi-leptonic	Z' 1% width	0.6<M<2.1 TeV
	RS KK-gluon	0.5<M<2.9 TeV 73.4pb @ 0.5TeV– 0.22pb @ 4TeV)
8TeV		
ATLAS 20.3fb^{-1} semi-lpetonic	Z' 1.2% width	M<2.0 TeV
	RS KK-gluon	M<2.3TeV (4.8pb @ 0.4TeV – 0.09 pb @ 3TeV
CMS 19.7fb^{-1} (Combined)	Z' 1% width	M<2.4TeV
	RS KK-gluon	M<2.7 TeV (17pb @ 0.7TeV– 0.059pb @ 3TeV)

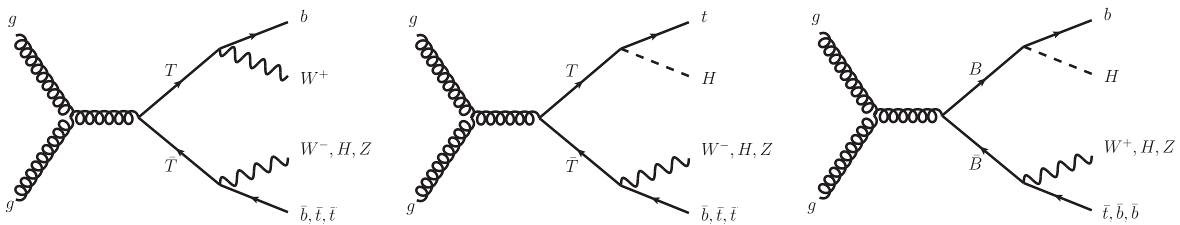
CMS result at 8TeV, combination of di-leptonic, semi-leptonic, all-hadronic channels

Other New Physics searches

Search for VLQs

ATLAS

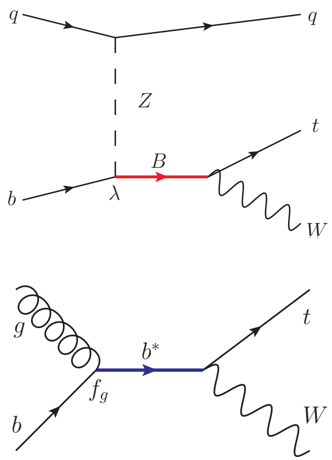
- Pair produced VLQs decaying via $T\bar{T}$->Ht+X, $T\bar{T}$->Wb+X, $B\bar{B}$->Hb+X in the lepton plus jets final state.

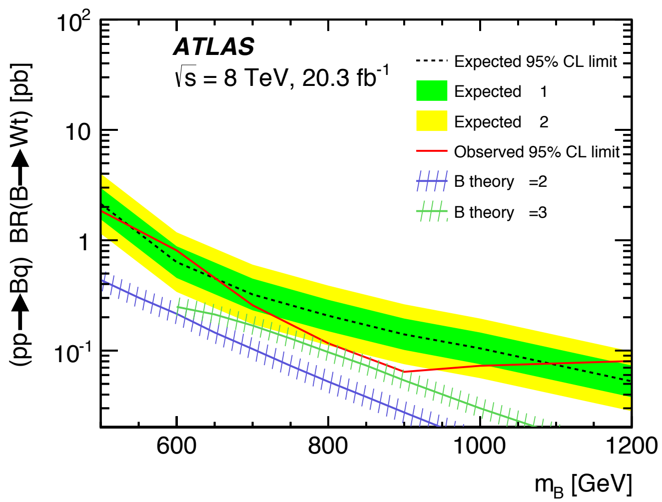


M_T > 730-950 GeV

M_B > 575-813 GeV

- Singly produced VLQs or excited quarks decaying through top quark.





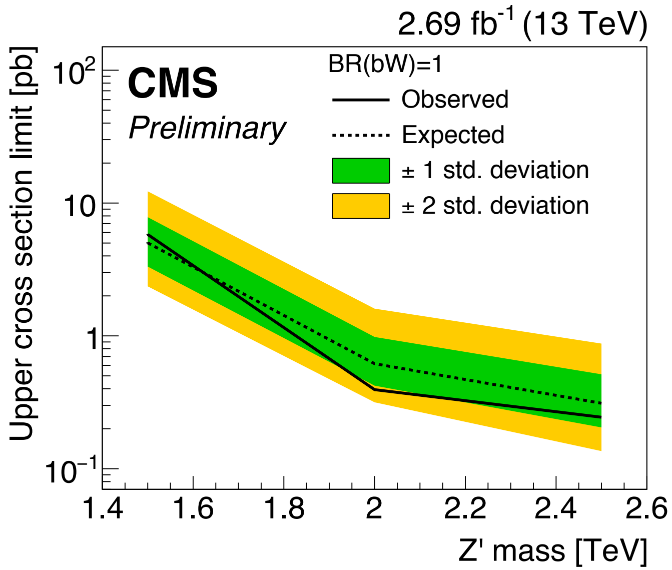
M_{b^*} > 1.5 TeV

Refer: JHEP 08 (2015) 105, JHEP 02 (2016) 110

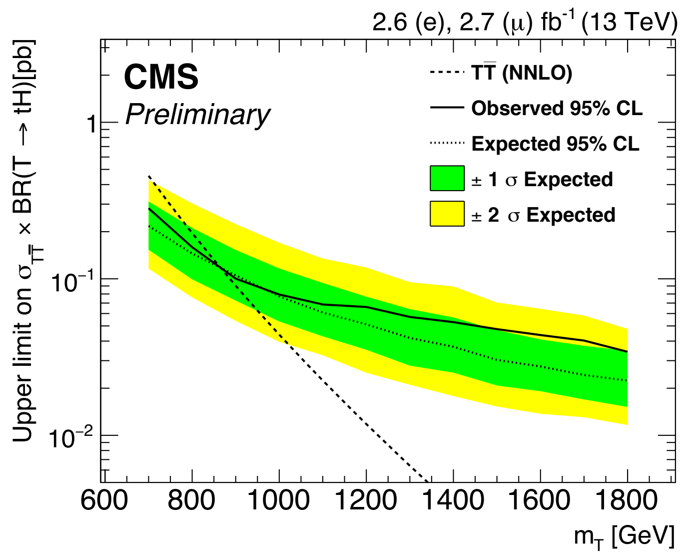
Pallabi Das

Search for VLQs

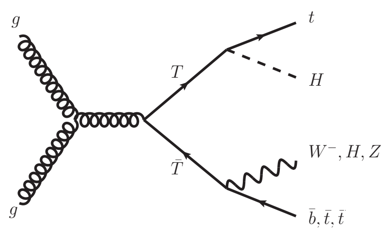
- Z′->T′t->WbWb, where T′ is a heavy vector like top partner.
- T′ and Z′ invariant mass reconstructed in all hadronic final state.



σ < 0.13-11 pb



- Pair produced VLQs decaying via TT̄->Ht+X.



M_T > 860 GeV

Refer: CMS PAS B2G-16-011, B2G-16-013

Two ways to distinguish between MSSM and NMSSM through $B - \bar{B}$ observables:

1. Different predictions - common parameter space:

Squarks, charginos, gluinos and effectively charged Higgs diagrams are identical in the two-models. Thus there are only two sources, both effective for **large** $\tan\beta$:

- Neutralinos: Neutralino-gluino diagrams can be important at large $\tan\beta, \lambda(\sim \kappa)$ and small μ_{eff} in models with significant gluino-gluino MSSM-background.
- Double Penguins: Neutral Higgs diagrams can be significant obviously at large $\tan\beta$ and light singlet masses (CP-even/odd).

Both effects decouple for $\lambda \to 0$ and/or large μ_{eff} since this is effectively the MSSM-limit.

2. Common predictions - different allowed parameter space:

Translate Higgs and Heavy Higgs measurements into different bounds on the $\tan\beta - M_A(M_{H^\pm})$ planes of the two models. Using these planes for low $\tan\beta$ MFV one can distinguish between the two models through their maximal NP-contribution in ΔM_q.

Effective Field Theory in top sector

The Standard Model EFT

- Resurgence of model-independent frameworks to go beyond SM

(κ framework, anomalous couplings, form factors…)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i O_i}{\Lambda^2} \quad (+\ldots)$$

Why bother with Effective Field Theory?

- completely general
- can be matched to UV completions
- radiative corrections calculable
- allows contact interactions
- allows power counting
- keeps gauge invariance manifest
- differential distributions
- …

EFT: Which Lagrangian best describes the currently available data?

Relevant operators

$$O_{qq}^1 = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$$
$$O_{qq}^3 = (\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$$
$$O_{uu} = (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$$
$$O_{qu}^8 = (\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$$
$$O_{qd}^8 = (\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$$
$$O_{ud}^8 = (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$$

$$O_{uW} = (\bar{q}\sigma^{\mu\nu}\tau^I u)\tilde{\phi}W_{\mu\nu}^I$$
$$O_{uG} = (\bar{q}\sigma^{\mu\nu}\lambda^A u)\tilde{\phi}G_{\mu\nu}^A$$
$$O_G = f_{ABC}G_\mu^{A\nu}G_\nu^{B\lambda}G_\lambda^{C\mu}$$
$$O_{\tilde{G}} = f_{ABC}\tilde{G}_\mu^{A\nu}G_\nu^{B\lambda}G_\lambda^{C\mu}$$
$$O_{\phi G} = (\phi^\dagger\phi)G_{\mu\nu}^A G^{A\mu\nu}$$

$$O_{\phi q}^3 = i(\phi^\dagger\tau^I D_\mu\phi)(\bar{q}\gamma^\mu\tau^I q)$$
$$O_{\phi q}^1 = i(\phi^\dagger D_\mu\phi)(\bar{q}\gamma^\mu q)$$
$$O_{uB} = (\bar{q}\sigma^{\mu\nu}u)\tilde{\phi}B_{\mu\nu}$$
$$O_{\phi u} = (\phi^\dagger iD_\mu\phi)(\bar{u}\gamma^\mu u)$$
$$O_{\phi\tilde{G}} = (\phi^\dagger\phi)\tilde{G}_{\mu\nu}^A G^{A\mu\nu}$$

A handful of operators

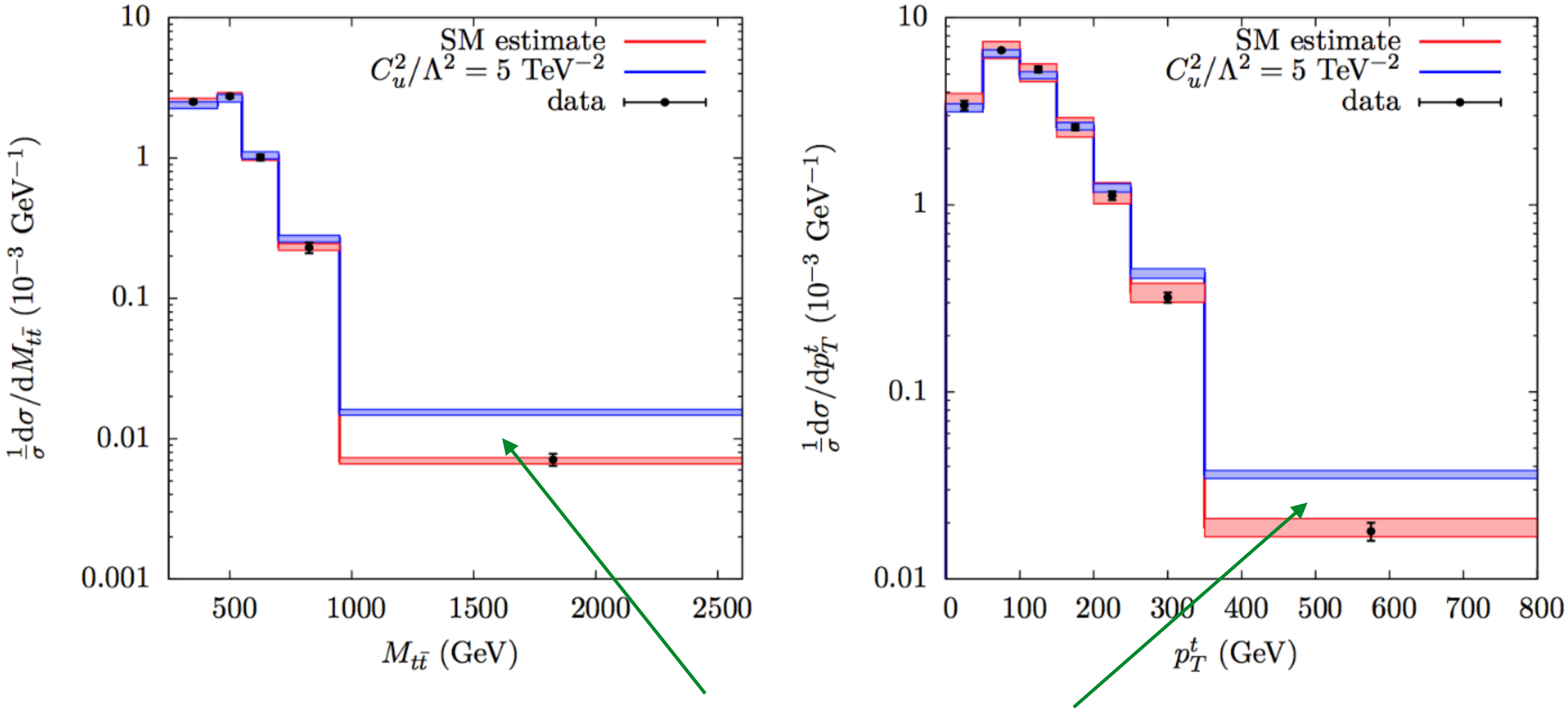
And many measurements…

GLOBAL FIT

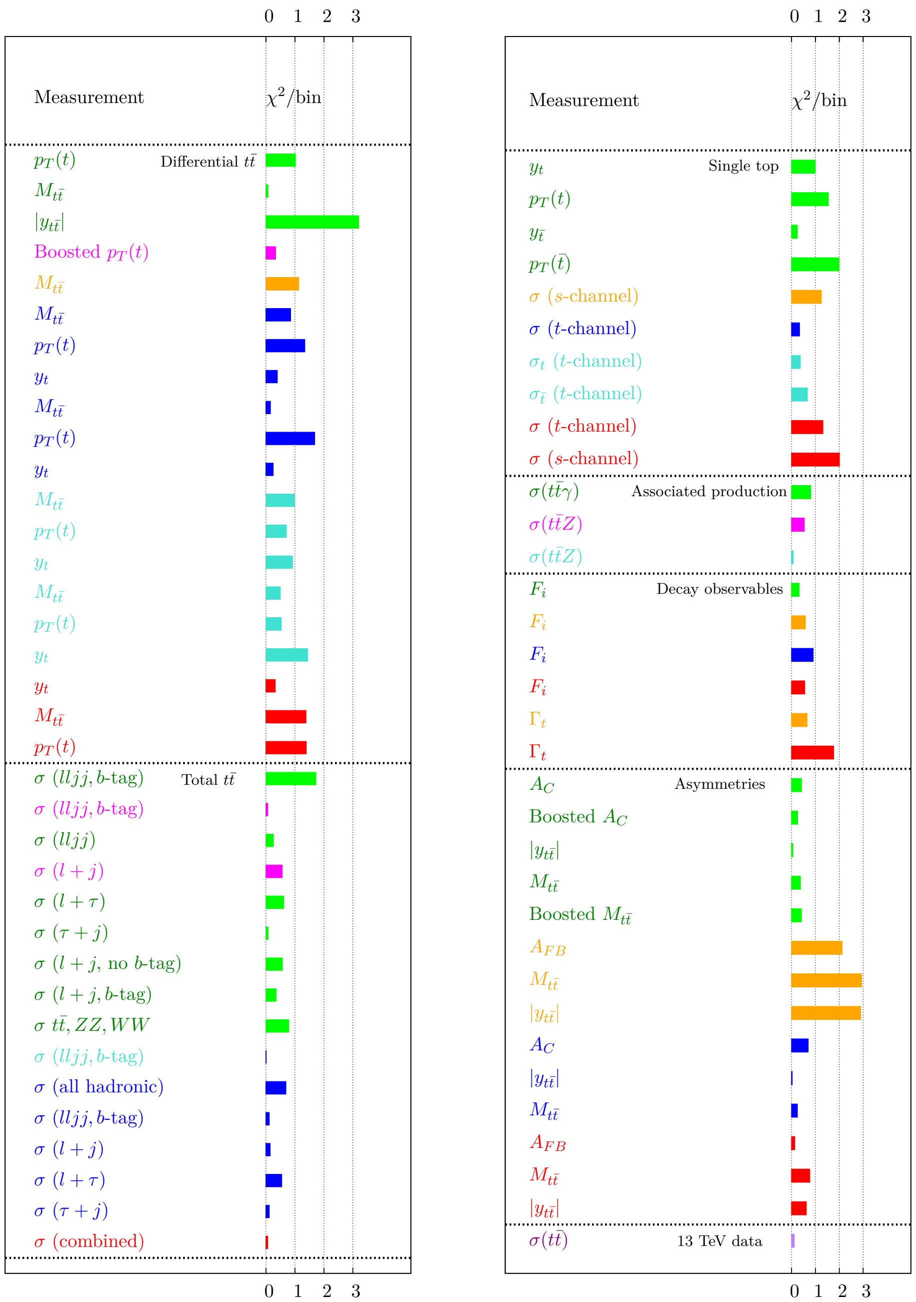
List of papers submitted to refereed journals

Full Title	Journal	Links	Status	Groups
NEW Measurement of the correlations between the polar angles of leptons from top quark decays in the helicity basis at $\sqrt{s}=7$ TeV using the ATLAS detector	Phys. Rev. D (RC)	Figures	Submitted: 2015/10/26	TOPQ
Measurement of the production cross-section of a single top quark in association with a W boson at 8 TeV with the ATLAS experiment	JHEP	Inspire, arXiv, Figures	Submitted: 2015/10/13	TOPQ
Measurement of the differential cross-section of highly boosted top quarks as a function of their transverse momentum in $√s$ = 8 TeV proton--proton collisions using the ATLAS detector	PRD	Inspire, arXiv, Figures	Submitted: 2015/10/13	TOPQ
Search for anomalous couplings in the Wtb vertex from the measurement of double differential angular decay rates of single top quarks produced in the t-channel with the ATLAS detector	JHEP	Inspire, arXiv, Figures	Submitted: 2015/10/13	TOPQ
Search for the production of single vector-like and excited quarks in the Wt final state in pp collisions at $√s = 8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	Submitted: 2015/10/09	EXOT / TOPQ
Search for flavour-changing neutral current top quark decays $t\to Hq$ in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	Submitted: 2015/09/20	TOPQ / HIGG
Measurement of the $t\bar{t}W$ and $t\bar{t}Z$ production cross sections in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	Submitted: 2015/09/17	TOPQ
Measurement of the charge asymmetry in top-quark pair production in the lepton-plus-jets final state in pp collision data at $√s=8$ TeV with the ATLAS detector	EPJC	Inspire, arXiv, Figures	Submitted: 2015/09/08	TOPQ
Search for single top-quark production via flavour changing neutral currents at 8 TeV with the ATLAS detector	EPJC	Inspire, arXiv, Figures	Submitted: 2015/09/01	TOPQ
Measurements of fiducial cross-sections for $t\bar{t}$ production with one or two additional b-jets in pp collisions at $\sqrt{s}$=8 TeV using the ATLAS detector	EPJC	Inspire, arXiv, Figures	Submitted: 2015/08/27	TOPQ
Search for flavour-changing neutral current top-quark decays to qZ in pp collision data collected with the ATLAS detector at $√s=8$ TeV	EPJC	Inspire, arXiv, Figures	Submitted: 2015/08/24	TOPQ
PUBLISHED Determination of the top-quark pole mass using $t t̄$ +1-jet events collected with the ATLAS experiment in 7 TeV pp collisions	JHEP	Inspire, arXiv, Figures	JHEP 10 (2015) 121, (Submitted: 2015/07/07)	TOPQ
PUBLISHED Measurement of colour flow with the jet pull angle in $t\bar{t}$ events using the ATLAS detector at $\sqrt{s}=8$ TeV	PLB	Inspire, arXiv, Figures	Physics Letters B (2015) 475-493, (Submitted: 2015/06/18)	TOPQ
PUBLISHED Measurement of the top quark branching ratios into channels with leptons and quarks with the ATLAS detector	PRD	Inspire, arXiv, Figures	Phys. Rev. D 92, 072005 (2015), (Submitted: 2015/06/16)	TOPQ
PUBLISHED A search for $t\bar{t}$ resonances using lepton-plus-jets events in proton--proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	JHEP08 (2015) 148, (Submitted: 2015/05/26)	TOPQ / EXOT
PUBLISHED Search for production of vector-like quark pairs and of four top quarks in the lepton-plus-jets final state in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	JHEP 08 (2015) 105, (Submitted: 2015/05/16)	EXOT / TOPQ
Analysis of events with b-jets and a pair of leptons of the same charge in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	Accepted (Submitted: 2015/04/17)	EXOT / TOPQ
PUBLISHED Measurement of the top pair production cross-section in 8 TeV proton--proton collisions using kinematic information in the lepton+jets final state with ATLAS	PRD	Inspire, arXiv, Figures	Phys. Rev. D 91, 112013 (2015), (Submitted: 2015/04/16)	TOPQ
PUBLISHED Measurement of the top quark mass in the $t\bar t \to {\rm lepton+jets}$ and $t\bar t \to {\rm dilepton}$ channels using $\sqrt{s}=7$ TeV ATLAS data	EPJC	Inspire, arXiv, Figures	Eur. Phys. J. C (2015) 75:330, (Submitted: 2015/03/18)	TOPQ
PUBLISHED Search for vector-like B quarks in events with one isolated lepton, missing transverse momentum and jets at $\sqrt{s}=$ 8TeV with the ATLAS detector	PRD	Inspire, arXiv, Figures	Phys. Rev. D 91, 112011 (2015), (Submitted: 2015/03/18)	EXOT / TOPQ
PUBLISHED Differential top--antitop cross-section measurements as a function of observables constructed from final-state particles using pp collisions at $\sqrt{s}=7$ TeV in the ATLAS detector	JHEP	Inspire, arXiv, Figures	JHEP 06 (2015) 100, (Submitted: 2015/02/20)	TOPQ
PUBLISHED Observation of top-quark pair production in association with a photon and measurement of the $t\bar{t}\gamma$ production cross section in pp collisions at $\sqrt{s}=7$ TeV using the ATLAS detector	PRD	Inspire, arXiv, Figures	Phys. Rev. D 91, 072007 (2015), (Submitted: 2015/02/02)	TOPQ
PUBLISHED Measurement of the ttbar and lepton charge asymmetry in dilepton events in √s=7 TeV data with the ATLAS detector	JHEP	Inspire, arXiv, Figures	JHEP 05 (2015) 061, (Submitted: 2015/01/29)	TOPQ
PUBLISHED Measurement of spin correlation in top-antitop quark events and search for stop quark pair production in proton-proton collisions at √s = 8 TeV using the ATLAS detector	PRL	Inspire, arXiv, Figures	Phys. Rev. Lett. 114, 142001 (2015), (Submitted: 2014/12/15)	TOPQ / SUSY
PUBLISHED Search for invisible particles produced in association with single-top-quarks in proton-proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector	EPJC	Inspire, arXiv, Figures	Eur. Phys. J. C (2015) 75:79, (Submitted: 2014/10/20)	TOPQ / EXOT
PUBLISHED Search for $W' \to t\bar{b}$ in the lepton plus jets final state in proton-proton collisions at a centre-of-mass energy of $\sqrt{s}$ = 8 TeV with the ATLAS detector	PLB	Inspire, arXiv, Figures	Physics Letters B 743 (2015) 235-255, (Submitted: 2014/10/15)	TOPQ / EXOT
PUBLISHED Search for s-channel single top-quark production in proton-proton collisions at $\sqrt{s}$=8 TeV with the ATLAS detector	PLB	Inspire, arXiv, Figures	Phys.Lett. B740 (2015) 118, (Submitted: 2014/10/02)	TOPQ
PUBLISHED Search for pair and single production of new heavy quarks that decay to a Z boson and a third-generation quark in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	JHEP 11 (2014) 104, (Submitted: 2014/09/19)	EXOT / TOPQ
PUBLISHED Measurement of the top-quark mass in the fully hadronic decay channel from ATLAS data at sqrt(s) = 7 TeV	EPJC	Inspire, arXiv, Figures	Eur. Phys. J. C (2015) 75:158, (Submitted: 2014/09/02)	TOPQ
PUBLISHED Search for W' →tb →qq'bb decays in pp collisions at √s=8 TeV with the ATLAS detector	EPJC	Inspire, arXiv, Figures	Eur. Phys. J. C (2015) 75:165, (Submitted: 2014/08/05)	EXOT / TOPQ

Michael Russell



Most sensitivity in the tails



Run I SUMMARY

SM a good fit everywhere?

No significant deviations at this stage

BUT

Early days in the LHC programme

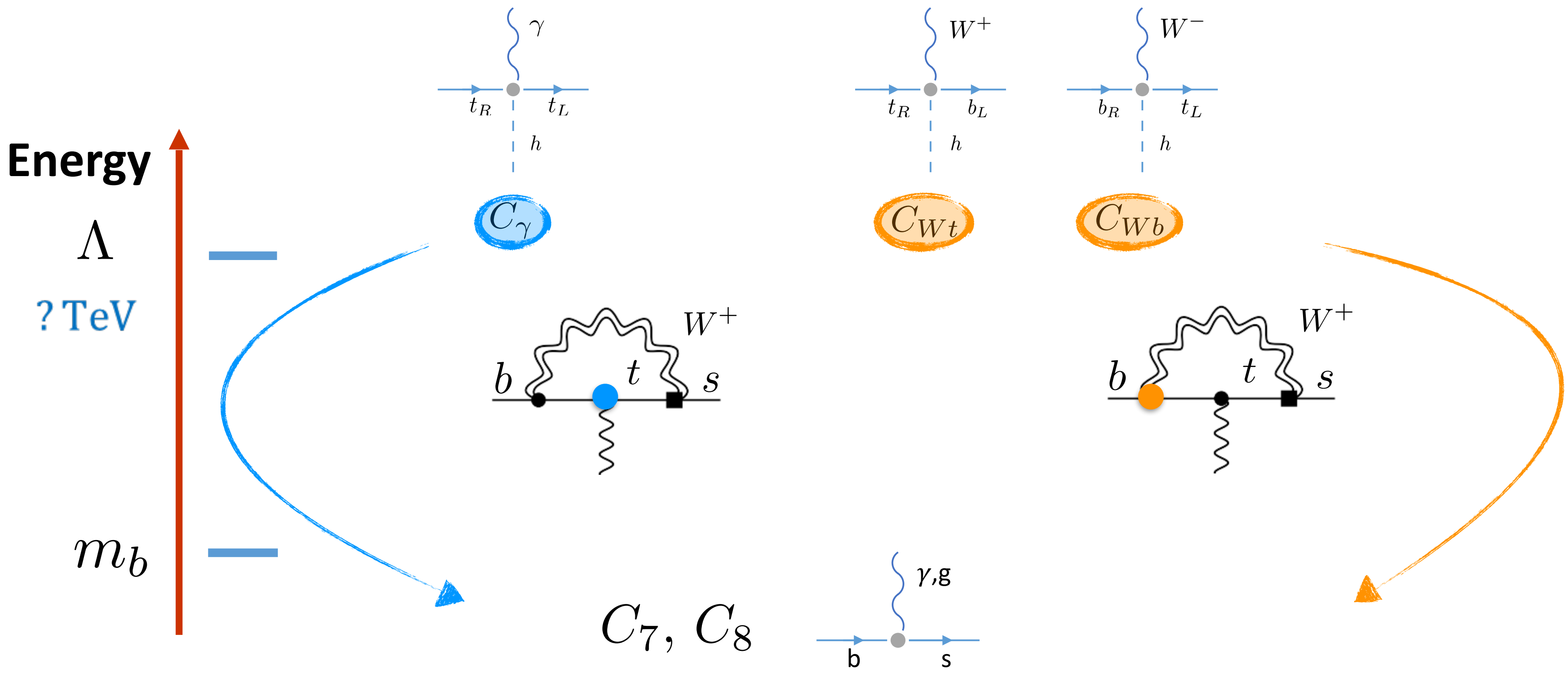
Many measurements statistics dominated

Many more measurements to come!

Michael Russell

Flavor physics

$b \to s\gamma$

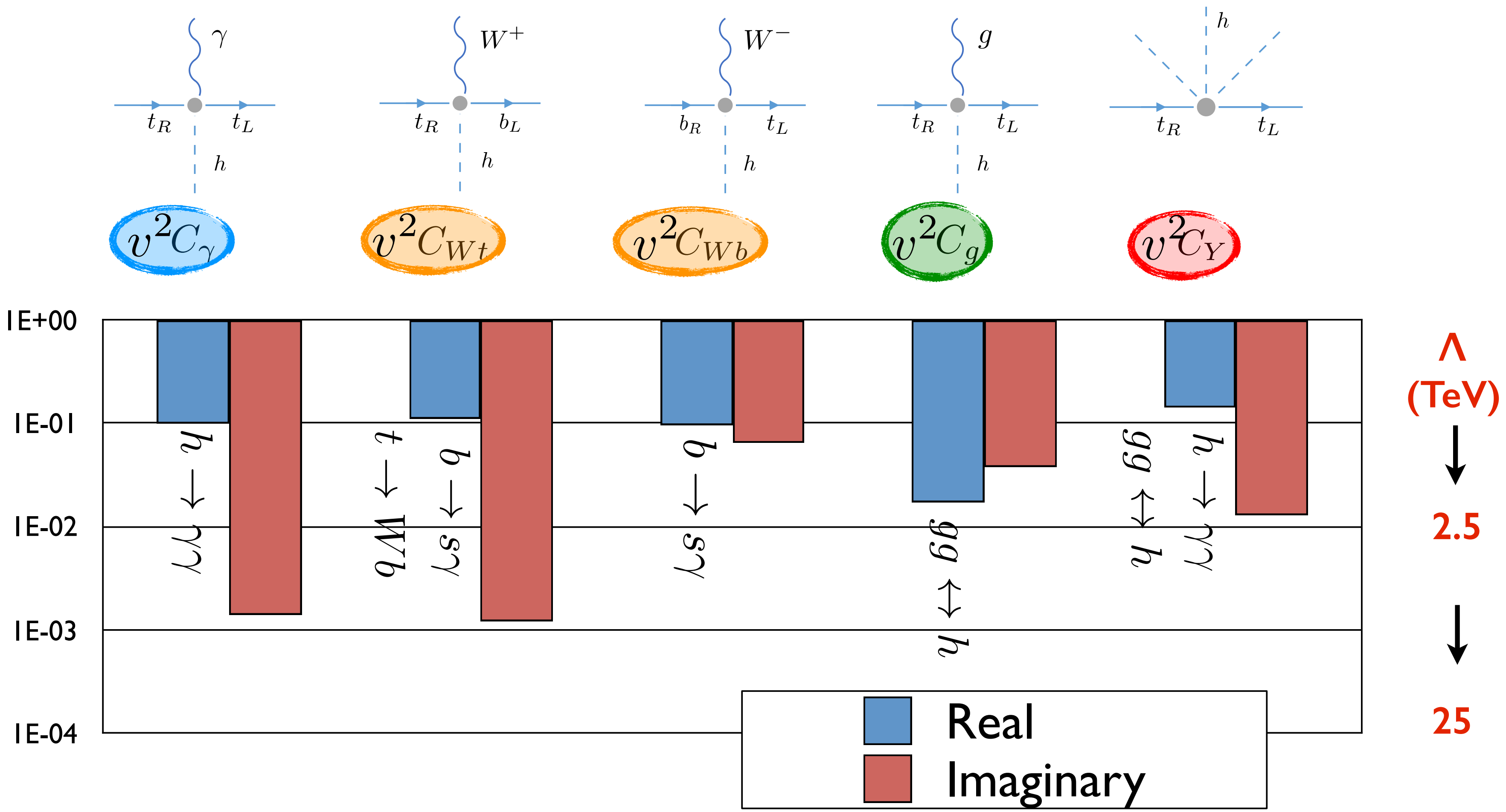


- Real parts contribute mainly to the branching ratio
- Imaginary parts mainly contribute to the CP asymmetry $A_{CP} \equiv \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)}$

Misiak et al, '07; Lunghi & Matias, '07; Kagan & Neubert, '99

Benzke, Lee, Neubert, Paz, '11

Constraints



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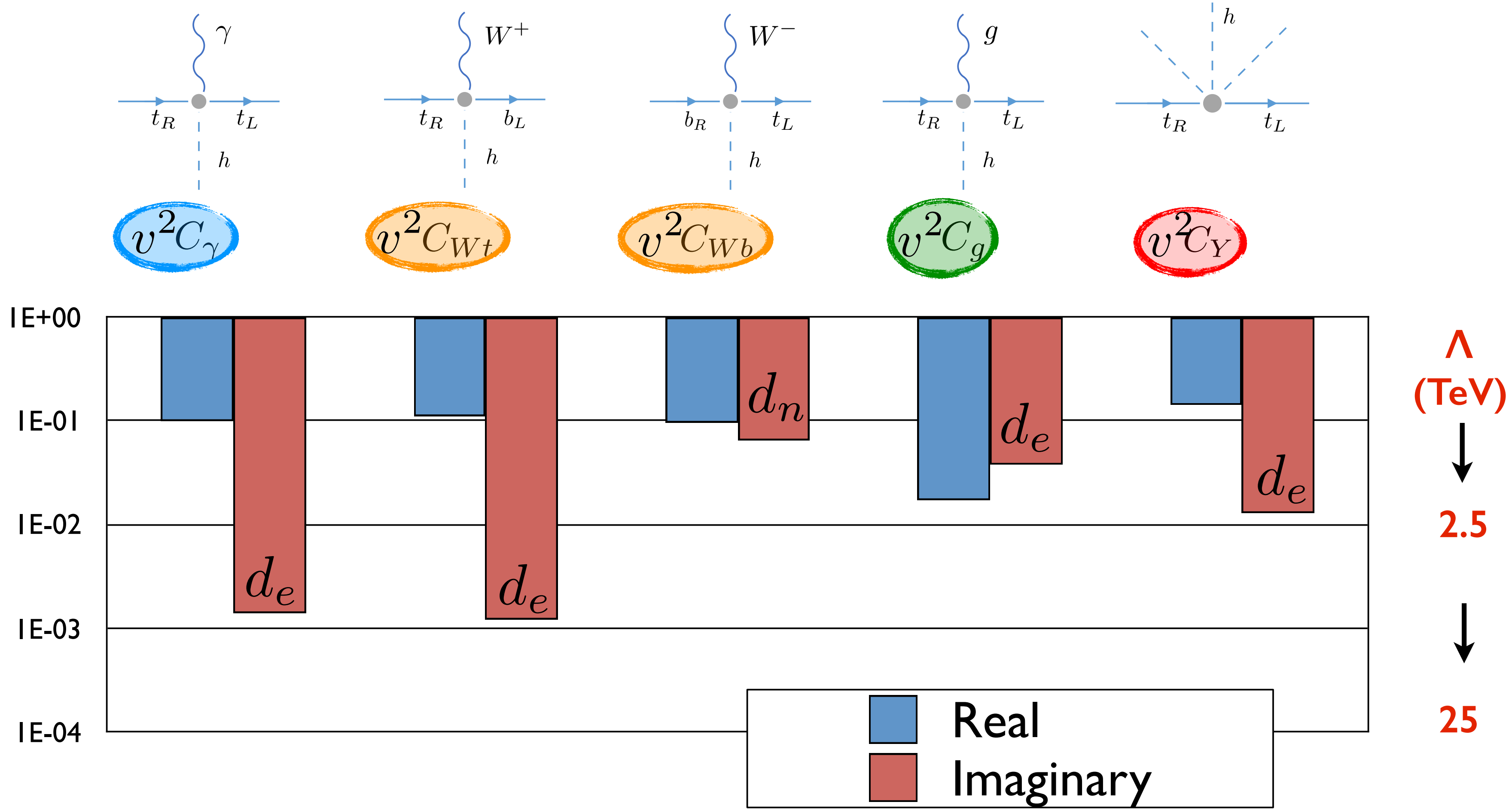

Conclusions

- High-Energy flavor physics in top and Higgs is complementary way of looking for NP
- Also interplay with precision probes like EDMs
- Some measurements are statistics limited
  - Run 2 (& 3 & 4 (HL-LHC)) will help
- Some are systematics limited
  - More stats will also help here
- Some Examples relevant to flavor:
  - Look for rare decays: measure V_{ts} directly!
  - Measure top Chromoelectric & Chromomagnetic dipole moment!
  - CPV in b physics using top:
    - With Run 2 will be systematics dominated
    - Can trade stats for syst reduction
    - Might be able to do a time dependent analysis!

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The CKM 2016 Indian Tasting Menu!

WG 1

WG 2

WG 3

WG 4

WG 5

WG 6

WG 7

A big thank you to all the speakers!
And to the audience for the interesting discussions!

Shikanji sorbet

Back up

In this paper, the first measurements of CP-violating asymmetries in $\mathrm{t\bar{t}}$ production and decay are presented. One of the top quarks is presumed to decay to a bottom (b) quark and a hadronically decaying W boson. The other top quark is required to decay to a b quark and a W boson that decays leptonically to an electron or muon and its associated neutrino. The analysis exploits T-odd, triple-product correlations, where T is the time-reversal operator. Several observables are measured, as proposed in Refs. [5–7], that take the form $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$, where $\vec{v}_i$ $(i = 1, 2, 3)$ are spin or momentum vectors. These triple-product observables are odd under the T transformation, and are thus also odd under the CP transformation if CPT conservation is valid, i.e. $\mathrm{CP}(O_i) = -O_i$, where O_i are the proposed observables. The presence of CPV would be manifested by a nonzero value of the asymmetry

$$A_{\mathrm{CP}}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)} \,. \tag{1}$$

The measurements of the asymmetry corrected for the effects of the detector (A_{CP}) and also without these corrections (A'_{CP}) are presented. The reason to present both A_{CP} and A'_{CP} values is that the corrections, called dilution factors (Section 8.1), could themselves be affected by physics beyond the SM [7]; no particular such new-physics process is considered in this paper.

Four observables that can be measured in the single-lepton + jets final state of $\mathrm{t\bar{t}}$ production and decay in proton-proton (pp) collisions are defined as:

$$\begin{aligned}
O_2 &= \epsilon(P, p_{\mathrm{b}} + p_{\mathrm{\bar{b}}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto (\vec{p}_{\mathrm{b}} + \vec{p}_{\mathrm{\bar{b}}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}), \\
O_3 &= Q_\ell\, \epsilon(p_{\mathrm{b}}, p_{\mathrm{\bar{b}}}, p_\ell, p_{j_1}) \xrightarrow{\mathrm{b\bar{b}}\,\text{CM}} \propto Q_\ell\, \vec{p}_{\mathrm{b}} \cdot (\vec{p}_\ell \times \vec{p}_{j_1}), \\
O_4 &= Q_\ell\, \epsilon(P, p_{\mathrm{b}} - p_{\mathrm{\bar{b}}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto Q_\ell\, (\vec{p}_{\mathrm{b}} - \vec{p}_{\mathrm{\bar{b}}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}), \\
O_7 &= q \cdot (p_{\mathrm{b}} - p_{\mathrm{\bar{b}}})\, \epsilon(P, q, p_{\mathrm{b}}, p_{\mathrm{\bar{b}}}) \xrightarrow{\text{lab}} \propto (\vec{p}_{\mathrm{b}} - \vec{p}_{\mathrm{\bar{b}}})_z (\vec{p}_{\mathrm{b}} \times \vec{p}_{\mathrm{\bar{b}}})_z.
\end{aligned} \tag{2}$$

The symbol $\rightarrow$ indicates the spatial frame chosen to simplify the triple product. The observables O_2, O_4, and O_7 are calculated in the laboratory (lab) frame, and O_3 in the $\mathrm{b\bar{b}}$ centre-of-mass frame ($\mathrm{b\bar{b}}$ CM), where b and $\mathrm{\bar{b}}$ indicate the bottom quark and antiquark jets from the t and $\mathrm{\bar{t}}$ decays, respectively. The symbol $\propto$ indicates proportionality. The symbol ϵ denotes the Levi–Civita symbol with $\epsilon_{0123} = 1$, which is contracted with four-vectors a, b, c, and d, i.e. $\epsilon(a, b, c, d) \equiv \epsilon_{\mu\nu\alpha\beta} a^\mu b^\nu c^\alpha d^\beta$. In these expressions, P is the sum of, and q the difference between, the four-momenta of the two initial-state protons; p and $\vec{p}$ are the four- and three-momenta, respectively, of the final-state particles; the subscript z indicates a projection along the direction of the counterclockwise rotating proton beam, defined to be the $+z$ direction in the CMS coordinate system; ℓ refers to the electron or muon from the leptonically decaying W boson; j_1 refers to the non-b quark jet originating from the hadronically decaying W boson with the highest transverse momentum (p_{T}); and Q_ℓ is the electric charge of ℓ. Note that the sign of the observable is the only information needed to measure A_{CP}.

The asymmetries A_{CP} computed from the above observables are predicted to be zero in the SM [5, 6]. However, in some new-physics scenarios [7], the effects of CPV can be sizable: $A_{\mathrm{CP}}(O_3)$ and $A_{\mathrm{CP}}(O_4)$ could be as large as 8%, while $A_{\mathrm{CP}}(O_2)$ and $A_{\mathrm{CP}}(O_7)$ are less sensitive to new physics and can reach 0.4% [7]. The sensitivity of the observables to CPV depends on whether distinguishable final-state objects are involved in their definition. For instance, the b quark jet charges need to be distinguished for O_3 and O_4, but not for O_2 and O_7.

$$A^{\mathrm{ss}} = r_b A_{\mathrm{mix}}^{b\ell} + r_c \left(A_{\mathrm{dir}}^{bc} - A_{\mathrm{dir}}^{c\ell}\right) + r_{c\bar{c}} \left(A_{\mathrm{mix}}^{bc} - A_{\mathrm{dir}}^{c\ell}\right)$$

$$A^{\mathrm{os}} = \widetilde{r}_b A_{\mathrm{dir}}^{b\ell} + \widetilde{r}_c \left(A_{\mathrm{mix}}^{bc} + A_{\mathrm{dir}}^{c\ell}\right) + \widetilde{r}_{c\bar{c}} A_{\mathrm{dir}}^{c\ell}$$

$$A_{\mathrm{mix}}^{b} = \frac{A^{\mathrm{ss}}}{r_b + r_{c\bar{c}}} = -0.025 \pm 0.021\,(\mathrm{stat.}) \pm 0.008\,(\mathrm{expt.}) \pm 0.017\,(\mathrm{model})\,,$$

$$A_{\mathrm{dir}}^{b\ell} = \frac{A^{\mathrm{os}}}{\widetilde{r}_b} = 0.005 \pm 0.004\,(\mathrm{stat.}) \pm 0.001\,(\mathrm{expt.}) \pm 0.003\,(\mathrm{model})\,,$$

$$A_{\mathrm{dir}}^{c\ell} = \frac{-A^{\mathrm{ss}}}{r_c + r_{c\bar{c}}} = 0.009 \pm 0.007\,(\mathrm{stat.}) \pm 0.003\,(\mathrm{expt.}) \pm 0.006\,(\mathrm{model})\,,$$

$$A_{\mathrm{dir}}^{bc} = \frac{A^{\mathrm{ss}}}{r_c} = -0.010 \pm 0.008\,(\mathrm{stat.}) \pm 0.003\,(\mathrm{expt.}) \pm 0.007\,(\mathrm{model})\,.$$

$$r_b = \frac{N_{r_b}}{N_{r_b} + N_{r_c} + N_{r_{c\bar{c}}}}, \qquad \widetilde{r}_b = \frac{N_{\widetilde{r}_b}}{N_{\widetilde{r}_b} + N_{\widetilde{r}_c} + N_{\widetilde{r}_{c\bar{c}}}},$$

$$r_c = \frac{N_{r_c}}{N_{r_b} + N_{r_c} + N_{r_{c\bar{c}}}}, \qquad \widetilde{r}_c = \frac{N_{\widetilde{r}_c}}{N_{\widetilde{r}_b} + N_{\widetilde{r}_c} + N_{\widetilde{r}_{c\bar{c}}}},$$

$$r_{c\bar{c}} = \frac{N_{r_{c\bar{c}}}}{N_{r_b} + N_{r_c} + N_{r_{c\bar{c}}}}, \qquad \widetilde{r}_{c\bar{c}} = \frac{N_{\widetilde{r}_{c\bar{c}}}}{N_{\widetilde{r}_b} + N_{\widetilde{r}_c} + N_{\widetilde{r}_{c\bar{c}}}}.$$

$$A_{\mathrm{mix}}^{b\ell} = \frac{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) - \Gamma\left(\bar{b} \to b \to \ell^- X\right)}{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) + \Gamma\left(\bar{b} \to b \to \ell^- X\right)},$$

$$A_{\mathrm{mix}}^{bc} = \frac{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) - \Gamma\left(\bar{b} \to b \to c X\right)}{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) + \Gamma\left(\bar{b} \to b \to c X\right)},$$

$$A_{\mathrm{dir}}^{b\ell} = \frac{\Gamma\left(b \to \ell^- X\right) - \Gamma\left(\bar{b} \to \ell^+ X\right)}{\Gamma\left(b \to \ell^- X\right) + \Gamma\left(\bar{b} \to \ell^+ X\right)},$$

$$A_{\mathrm{dir}}^{c\ell} = \frac{\Gamma\left(\bar{c} \to \ell^- X_L\right) - \Gamma\left(c \to \ell^+ X_L\right)}{\Gamma\left(\bar{c} \to \ell^- X_L\right) + \Gamma\left(c \to \ell^+ X_L\right)},$$

$$A_{\mathrm{dir}}^{bc} = \frac{\Gamma\left(b \to c X_L\right) - \Gamma\left(\bar{b} \to \bar{c} X_L\right)}{\Gamma\left(b \to c X_L\right) + \Gamma\left(\bar{b} \to \bar{c} X_L\right)},$$

	r_b	r_c	$r_{c\bar{c}}$	$\widetilde{r}_b$	$\widetilde{r}_c$	$\widetilde{r}_{c\bar{c}}$
Nominal	0.200	0.715	0.085	0.882	0.069	0.048
Relative uncertainty in %						
Hadron-to-muon branching ratio	+3.8 −3.2	+2.9 −2.3	+23 −30	+1.6 −1.3	+3.3 −3.3	+25 −31
b-hadron production	+1.8 −1.8	+0.5 −0.5	+0.3 −0.3	+0.2 −0.2	+1.9 −1.9	+0.2 −0.2
Additional radiation	±2.4	±0.6	±0.4	±0.1	±0.9	±1.1
MC generator	±0.2	±0.1	±0.1	±0.1	±0.5	±0.7
Parton shower	±6.8	±2.2	±2.6	±0.6	±12	±6.1
Parton distribution function	±0.1	±0.1	±0.9	±0.0	±0.3	±0.2
Total uncertainty	+8.4 −8.1	+3.7 −3.3	+23 −30	+1.7 −1.4	+13 −13	+25 −31

	$A^{ss}\left(10^{-2}\right)$		$A^{os}\left(10^{-2}\right)$	
Measured value	−0.7		0.41	
Statistical uncertainty	±0.6		±0.35	
Sources of experimental uncertainty				
Lepton charge misidentification	+0.002	−0.002	+0.001	−0.001
Lepton energy resolution	+0.09	−0.11	+0.07	−0.06
Lepton trigger, reco, identification	+0.004	−0.004	+0.002	−0.002
Jet energy scale	+0.10	−0.14	+0.08	−0.06
Jet energy resolution	+0.019	−0.019	+0.009	−0.009
Jet reco efficiency	+0.010	−0.010	+0.006	−0.006
Jet vertex fraction	+0.09	−0.09	+0.05	−0.05
Fake lepton estimate	+0.05	−0.05	+0.025	−0.025
Background normalisation	+0.002	−0.002	+0.001	−0.001
W+jets estimate (statistical)	+0.003	−0.002	+0.001	−0.002
Single-top production asymmetry	+0.016	−0.002	+0.001	−0.009
b-tagging efficiency	+0.008	−0.008	+0.004	−0.004
c-jet mistag rate	+0.020	−0.020	+0.013	−0.013
Light-jet mistag rate	+0.022	−0.023	+0.013	−0.012
SMT reco identification	+0.004	−0.004	+0.004	−0.004
SMT momentum imbalance	+0.06	−0.06	+0.04	−0.035
SMT light-jet mistag rate	+0.010	−0.009	+0.005	−0.005
Sources of modelling uncertainty				
Hadron-to-muon branching ratio	+0.04	−0.05	+0.026	−0.022
b-hadron production	+0.013	−0.008	+0.003	−0.008
Additional radiation	±0.4		±0.23	
MC generator	±0.05		±0.025	
Parton shower	±0.04		±0.017	
Parton distribution function	±0.22		±0.13	
Total experimental uncertainty	+0.19	−0.22	+0.13	−0.11
Total modelling uncertainty	+0.5	−0.5	+0.27	−0.27
Total systematic uncertainty	+0.5	−0.5	+0.30	−0.29

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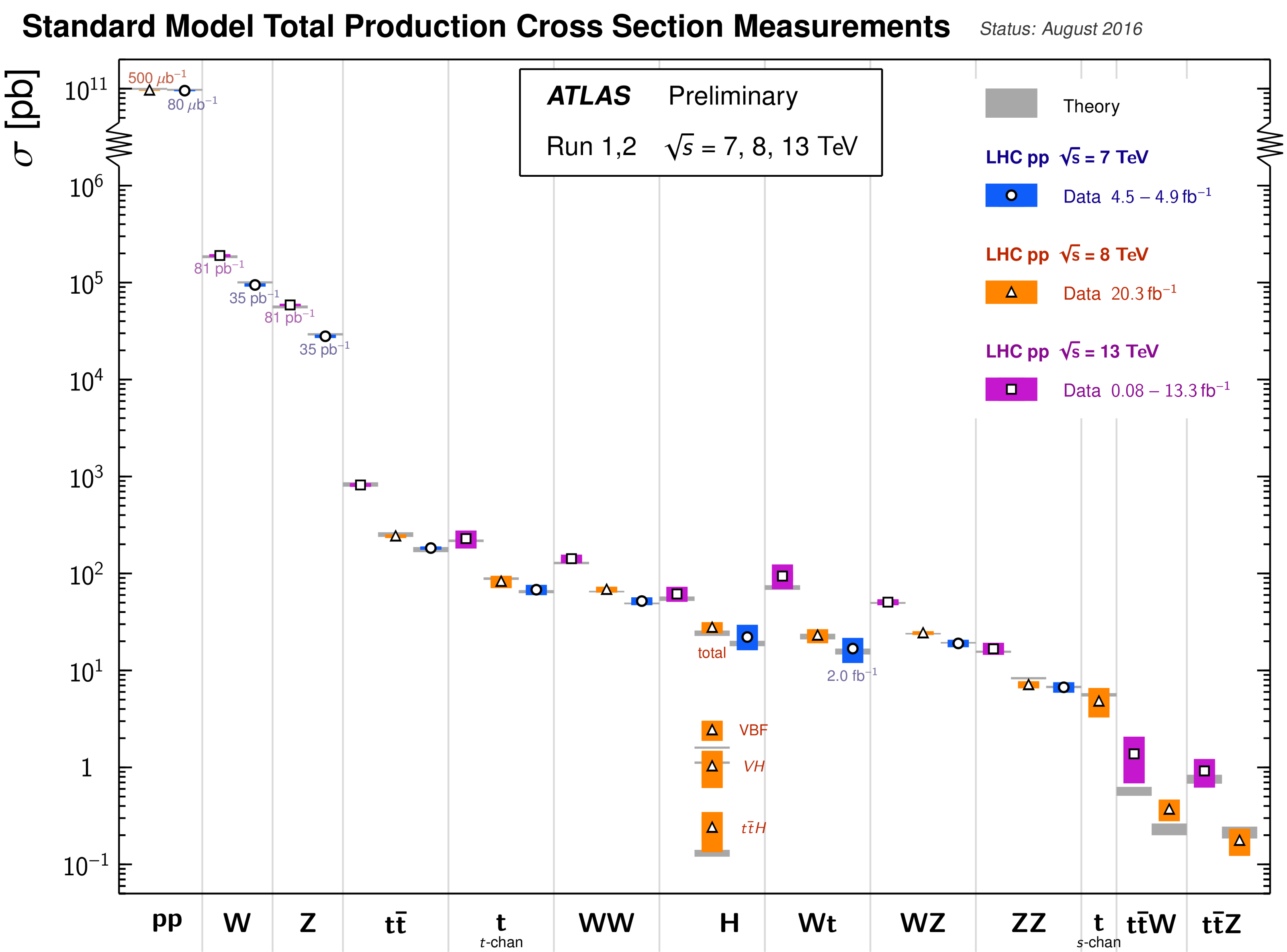

Standard Model Total Production Cross Section Measurements
Status: August 2016
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 13.3 fb⁻¹
σ [pb]
500 μb⁻¹
80 μb⁻¹
81 pb⁻¹
35 pb⁻¹
81 pb⁻¹
35 pb⁻¹
total
VBF
VH
tt̄H
2.0 fb⁻¹
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
WZ
ZZ
t
s-chan
tt̄W
tt̄Z