Top-quark physics

Markus Cristinziani*
Universität Bonn

ATLAS EXPERIMENT

CDF II

CMS

DØ

XXXVI
PHYSICS IN COLLISION

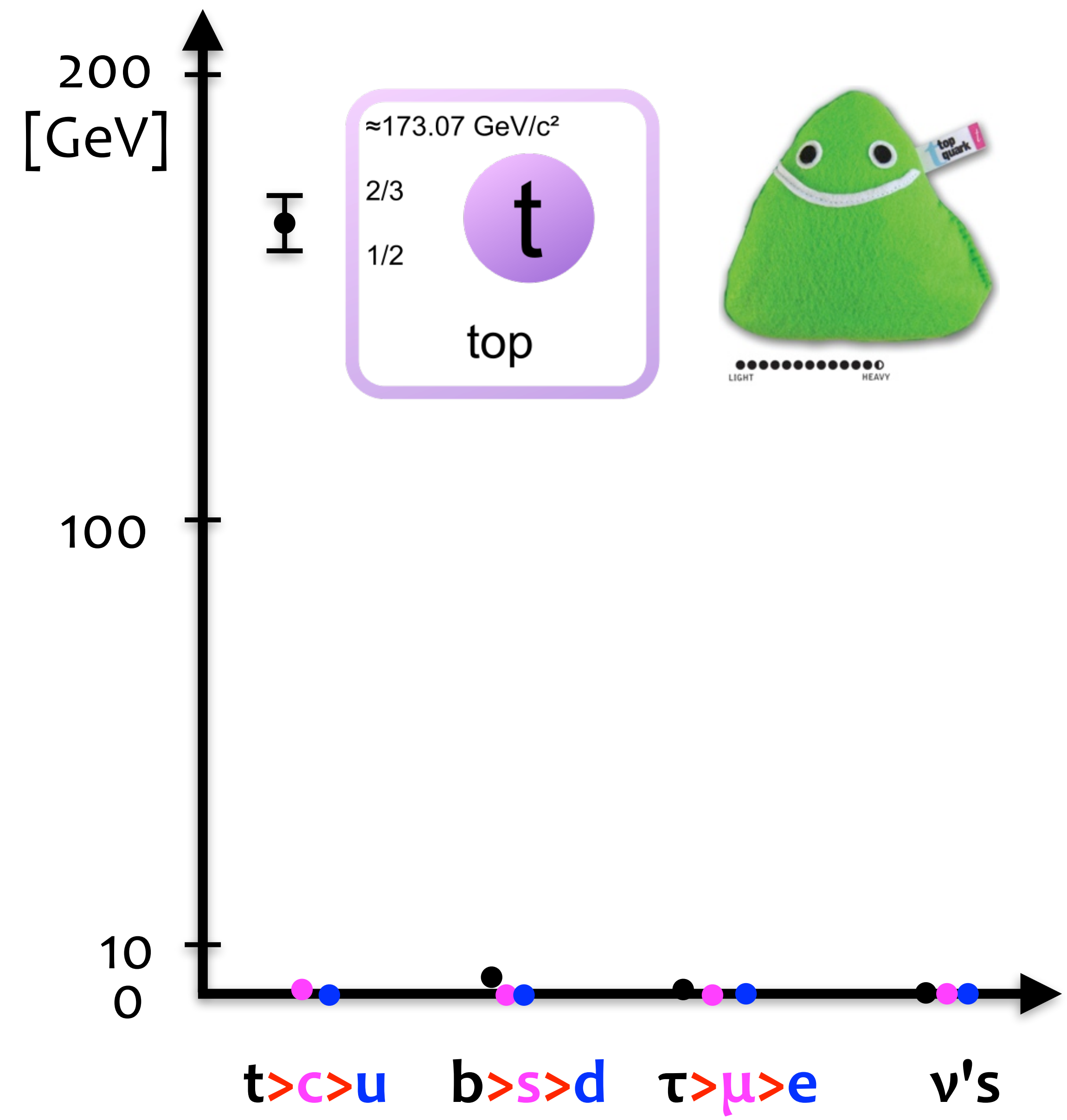
XII[th] Rencontres du Vietnam
International Center for Interdisciplinary Science and Education, [ICISE]
Quy Nhon, Vietnam, September 13 - 17, 2016

* supported by the European Research Council under contract ERC-CoG-617185

erc

The top quark

Most massive elementary particle



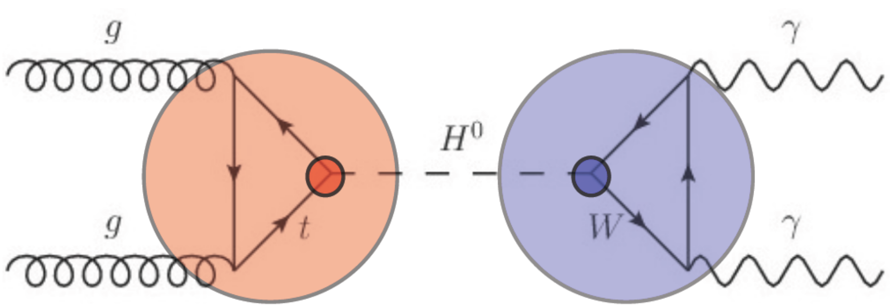
The top quark

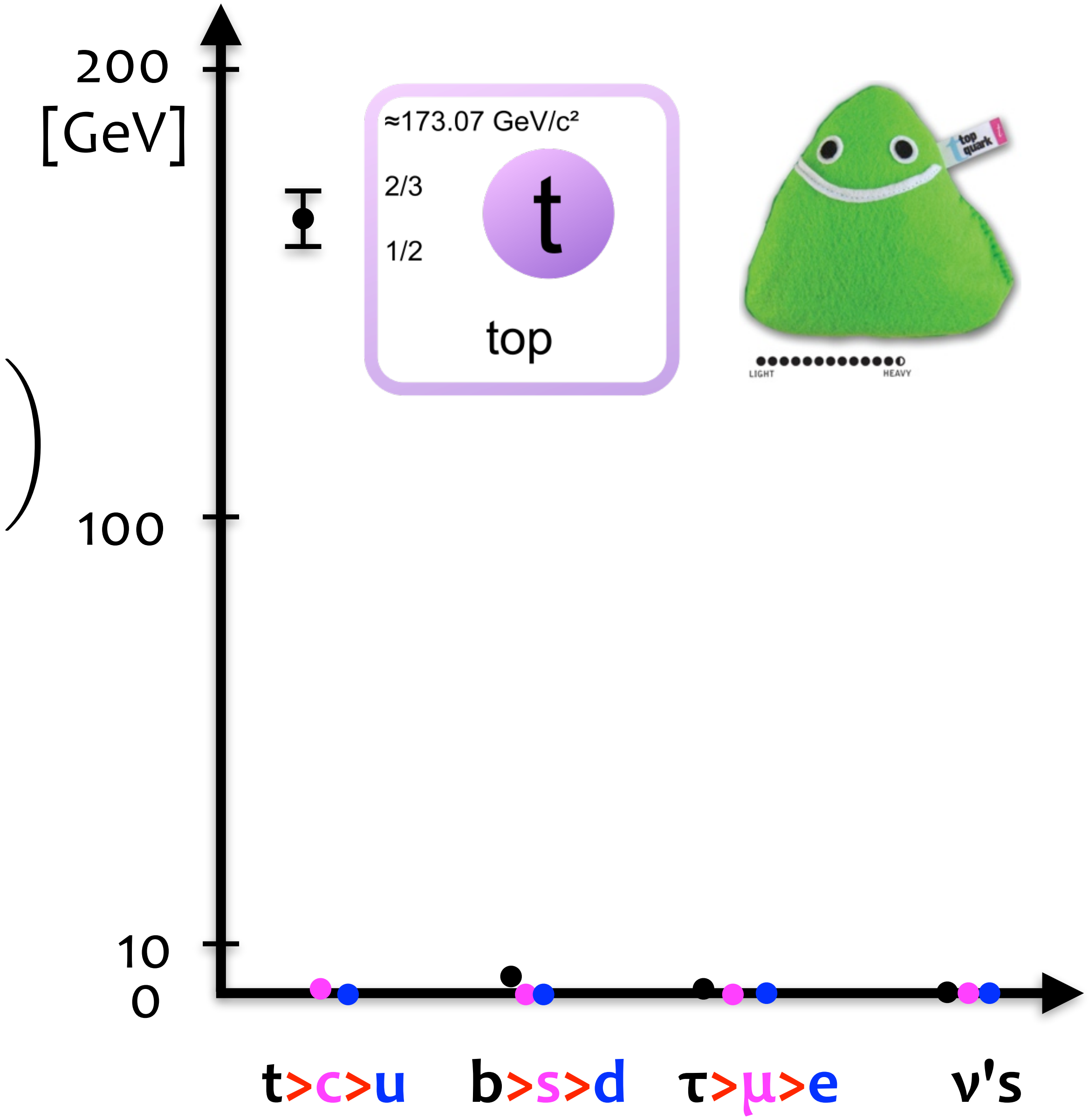
Most massive elementary particle

- **short lifetime**
- **$\tau_{top} = 4 \cdot 10^{-25}\,s \rightarrow$ no bound states**

$$\Gamma_t \sim \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{m_W^2}{m_t^2}\right)$$

- **role in loop diagrams**



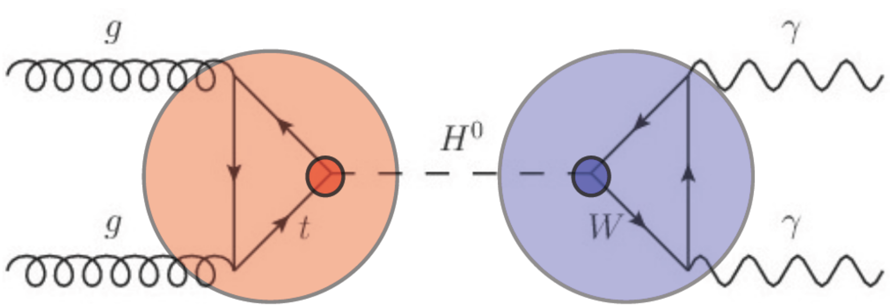


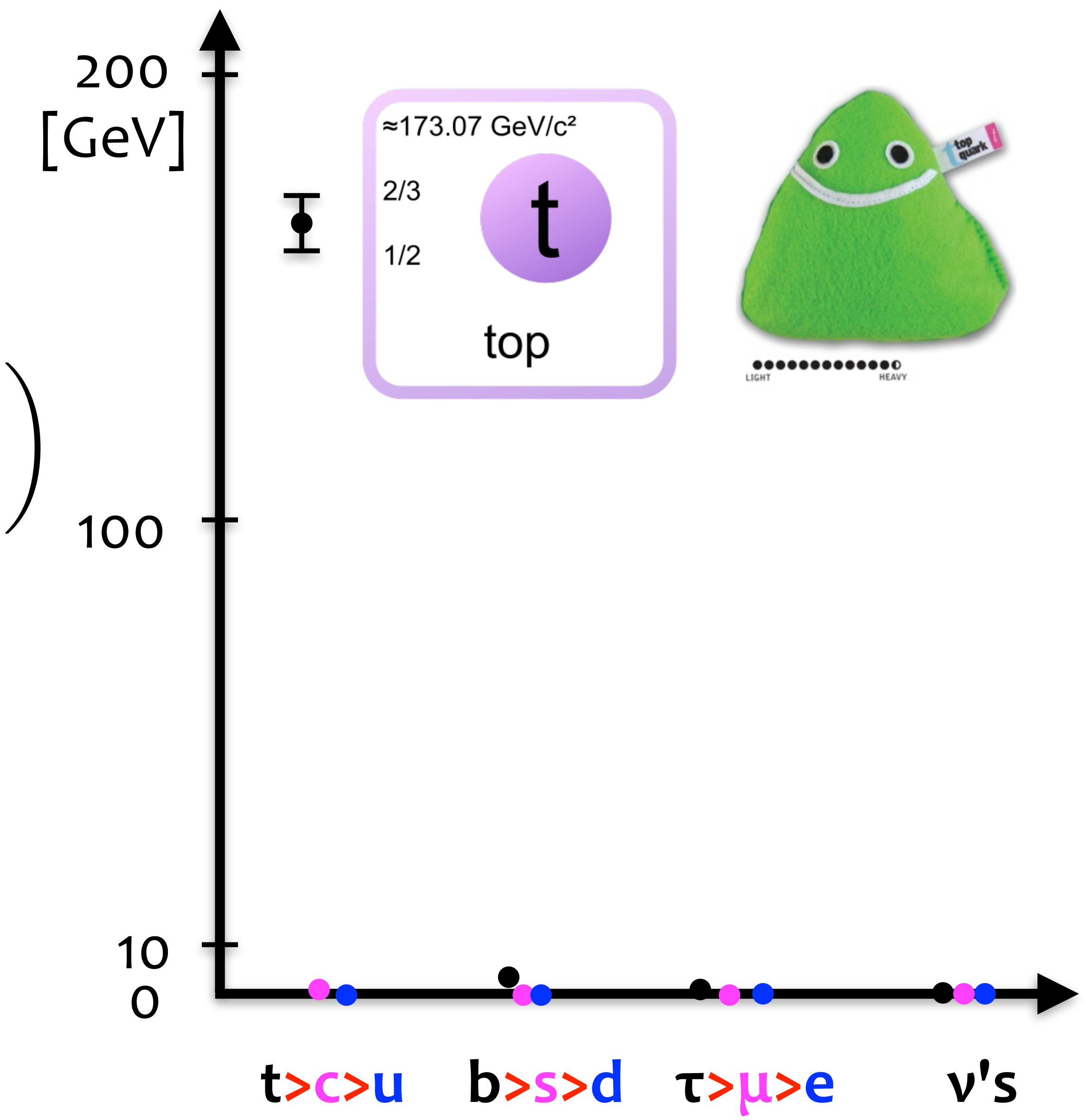
Most massive elementary particle

- short lifetime
- $\tau_{top} = 4 \cdot 10^{-25}\,s \rightarrow$ no bound states

$$\Gamma_t \sim \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{m_W^2}{m_t^2}\right)$$

- role in loop diagrams





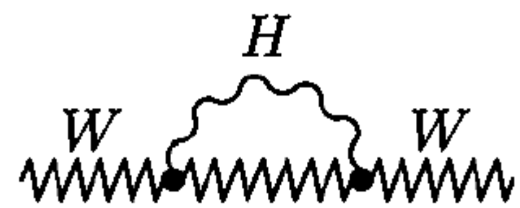
Top quark physics at hadron colliders

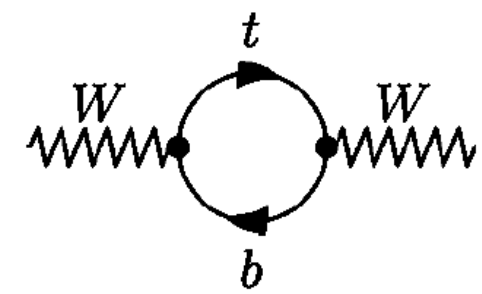
- test Standard Model
- search for new resonances or interactions
- important background to new physics searches

Top-quark mass

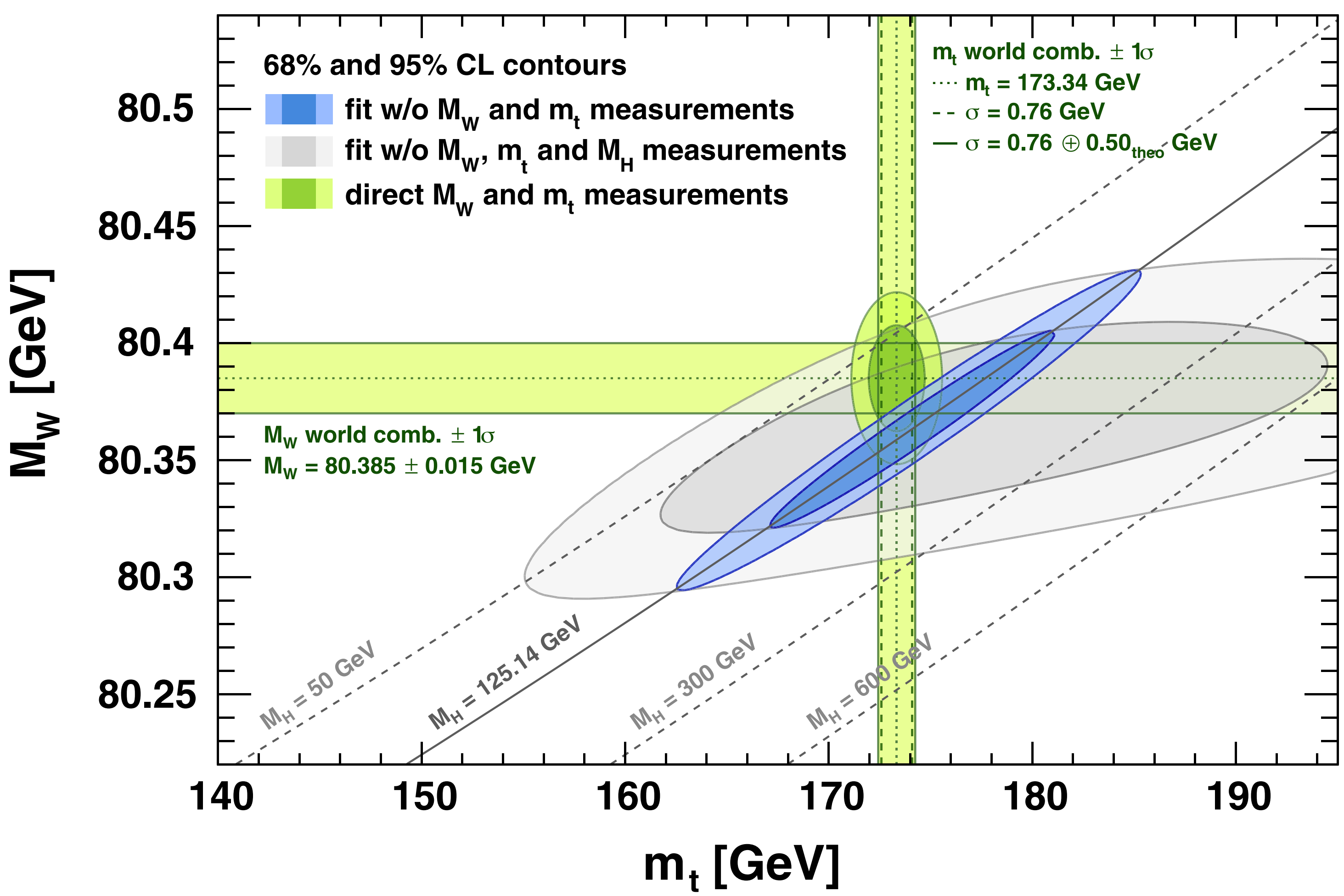
Fundamental parameter of theory

- related to other electroweak parameters
- precise determination allows for stringent tests of SM





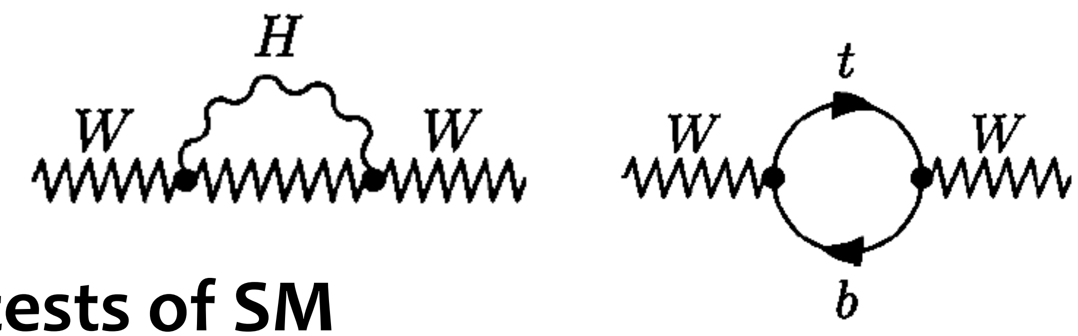
Eur. Phys. J. C74 (2014) 3046



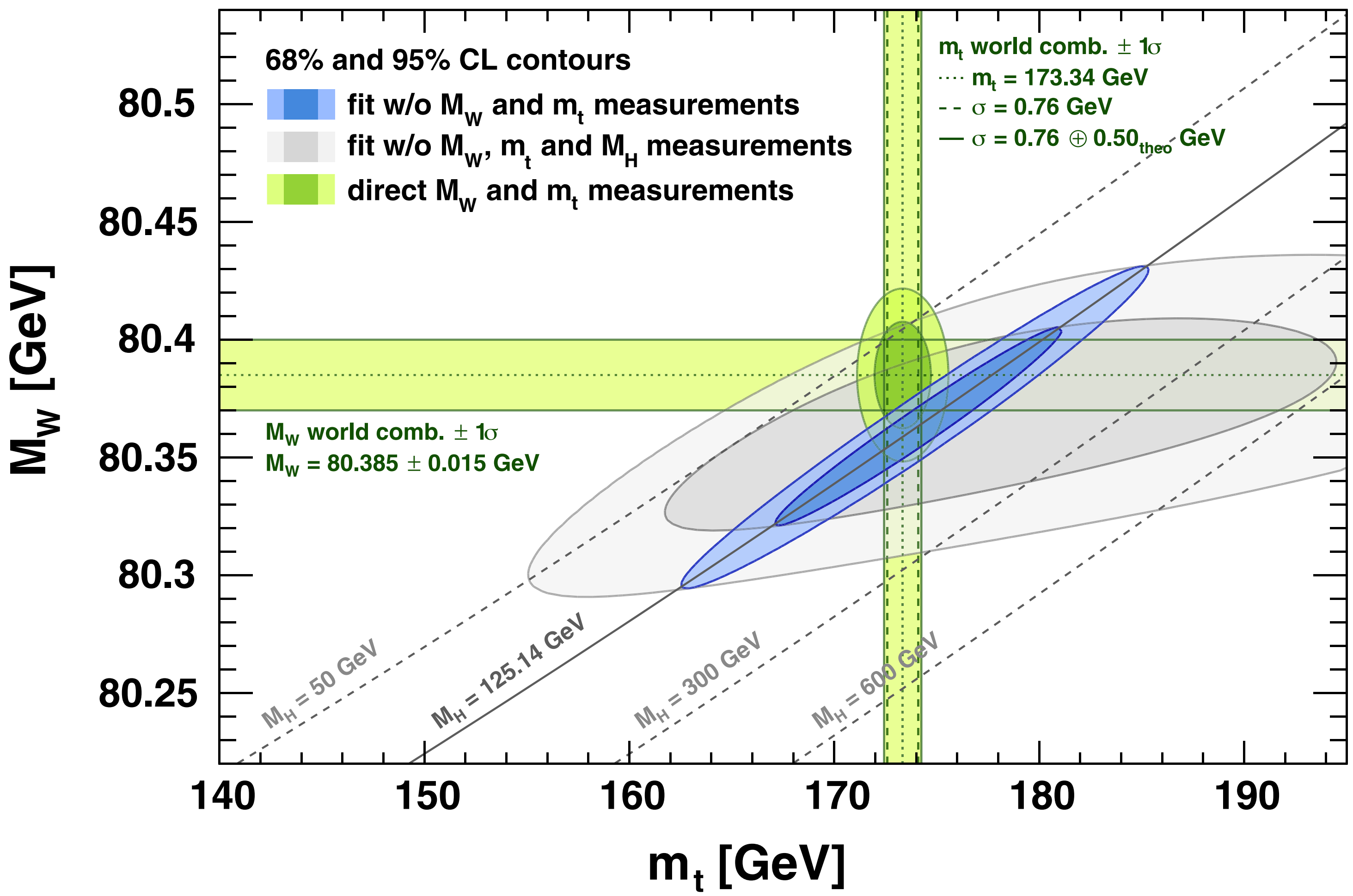
Top-quark mass

Fundamental parameter of theory

- related to other electroweak parameters
- precise determination allows for stringent tests of SM

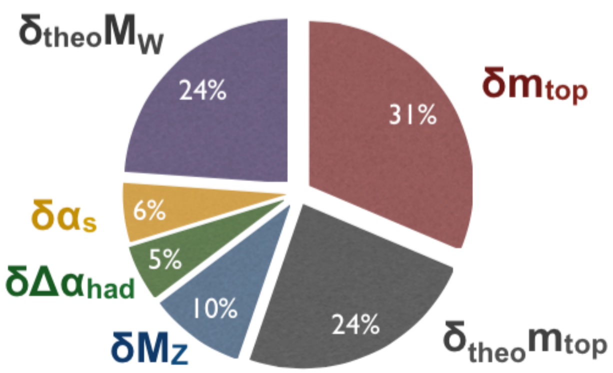


Eur. Phys. J. C74 (2014) 3046



Error on m_W prediction

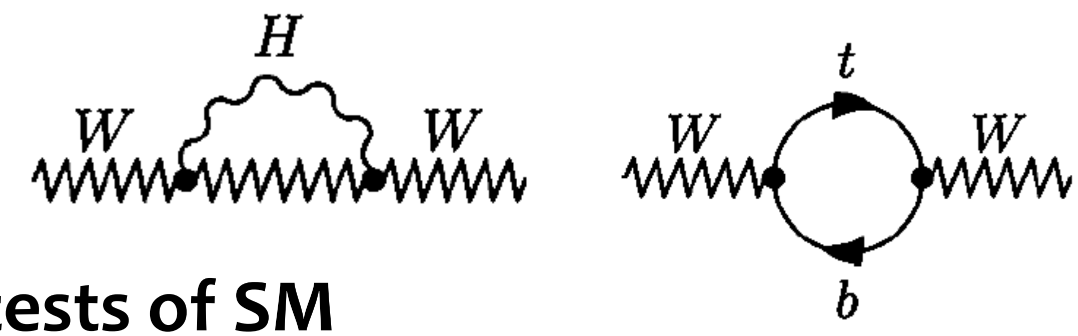
Phys. Rev. D69 (2004) 053006



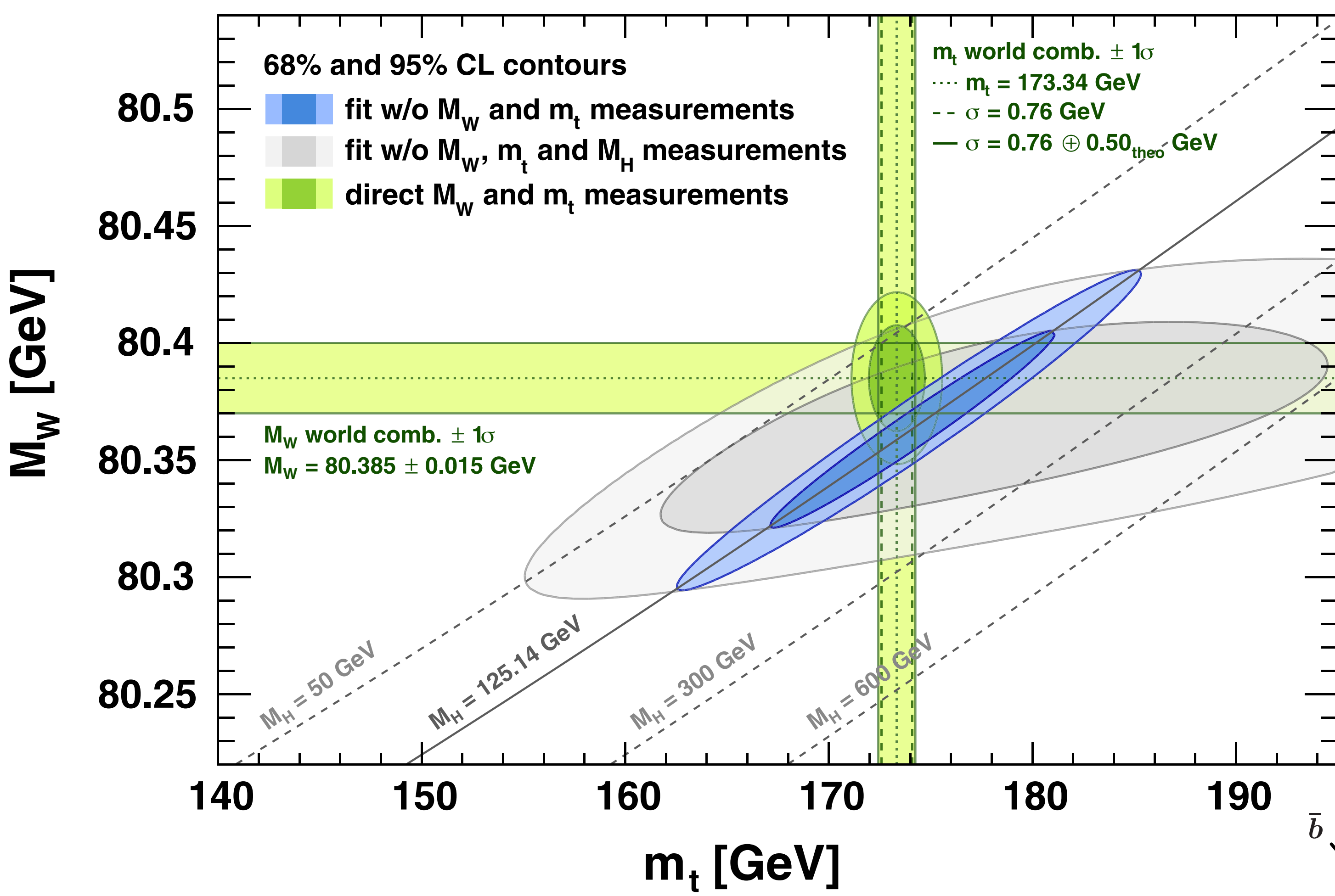
Top-quark mass

Fundamental parameter of theory

- related to other electroweak parameters
- precise determination allows for stringent tests of SM

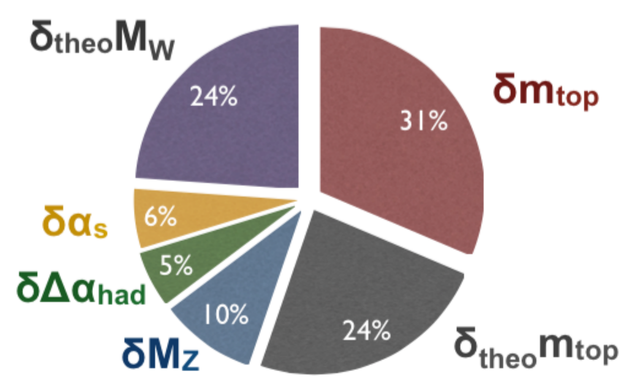


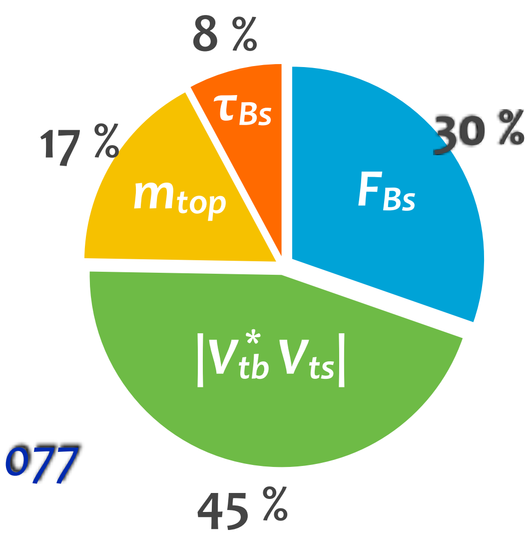
Eur. Phys. J. C74 (2014) 3046



Error on m_W prediction

Phys. Rev. D69 (2004) 053006

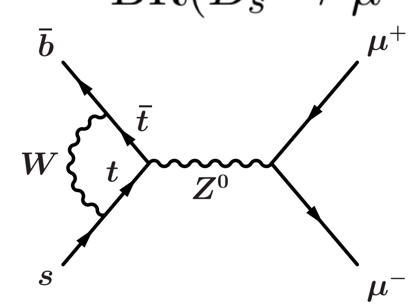




JHEP 07 (2013) 077

Error on $B_s \to \mu\mu$ prediction

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = 3.25 \times 10^{-9} \left(\frac{M_t}{173.2\,\mathrm{GeV}}\right)^{3.07} \left(\frac{F_{B_s}}{225\,\mathrm{MeV}}\right)^2 \left(\frac{\tau_{B_s}}{1.500\mathrm{ps}}\right) \left|\frac{V_{tb}^* V_{ts}}{0.0405}\right|^2$$



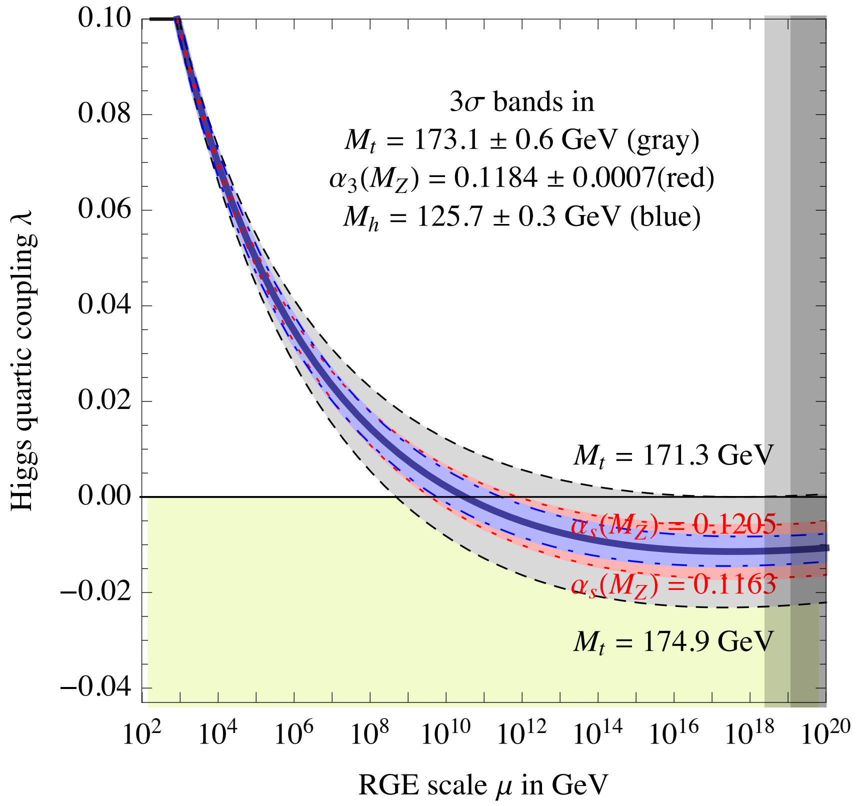
Top-quark mass

Higgs potential

$$V(\phi) = \frac{1}{2}\mu^2(\phi^\dagger\phi) + \frac{1}{4}\lambda(\phi^\dagger\phi)^2$$

Higgs potential

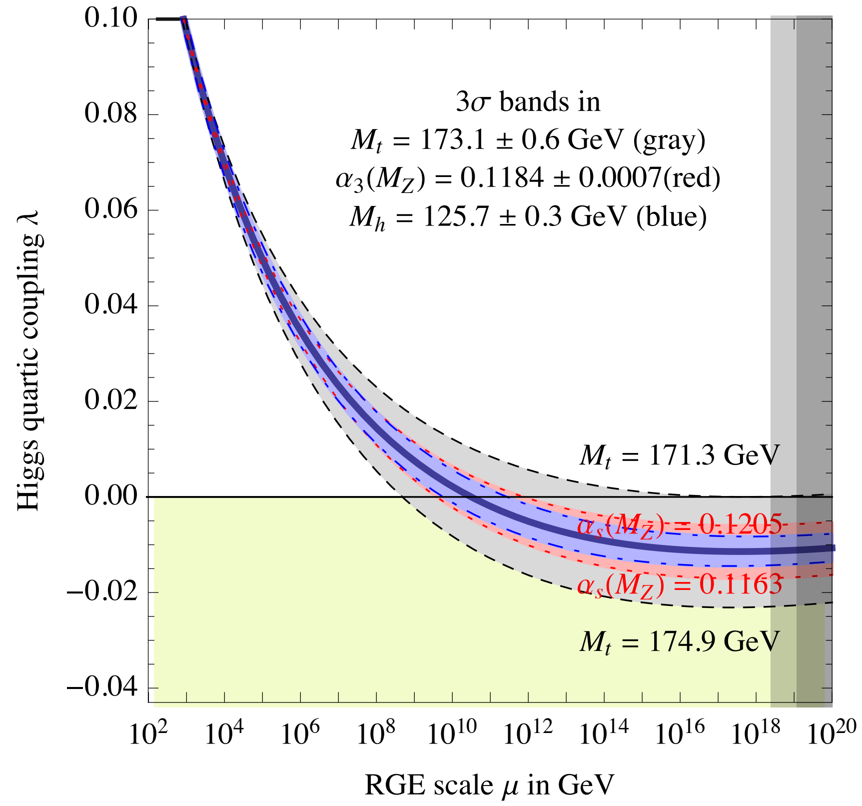
$$V(\phi) = \frac{1}{2}\mu^2(\phi^\dagger\phi) + \frac{1}{4}\lambda(\phi^\dagger\phi)^2$$



Top-quark mass

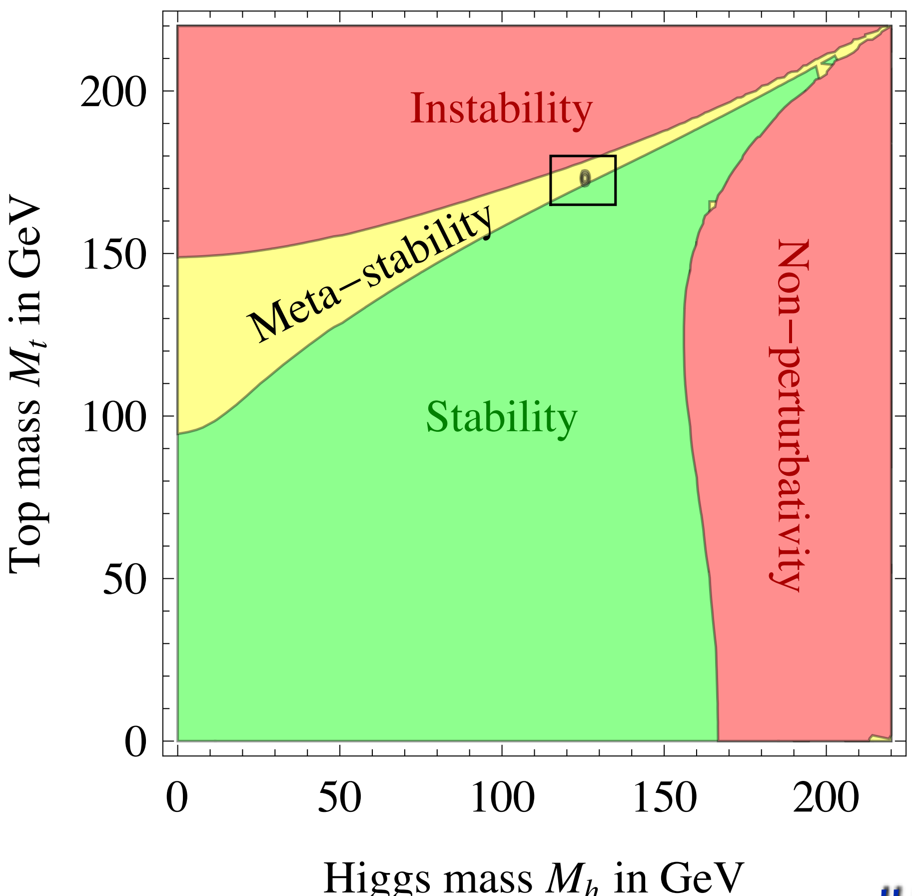
Higgs potential

$$V(\phi) = \frac{1}{2}\mu^2(\phi^\dagger\phi) + \frac{1}{4}\lambda(\phi^\dagger\phi)^2$$



Vacuum stability

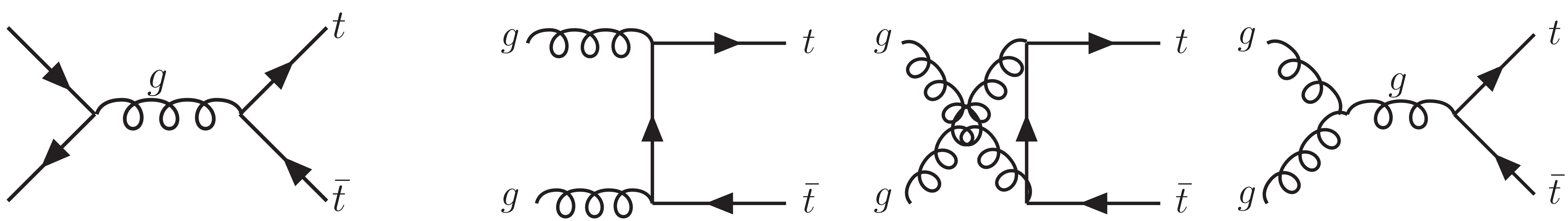
- depends critically on m_{top}
- $\lambda(\mu)\rightarrow 0$, $\lambda(\mu)=0$ or even $\lambda(\mu)<0$ at a scale $\mu < m_{Pl}$



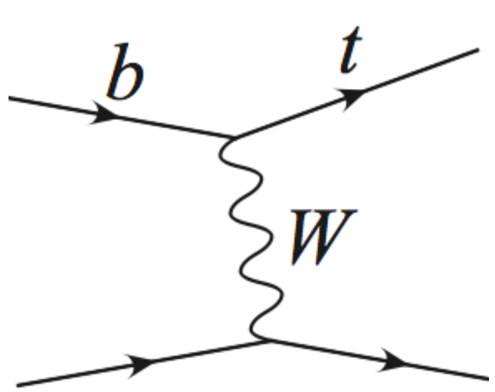
JHEP08 (2012) 098

Top-quark production

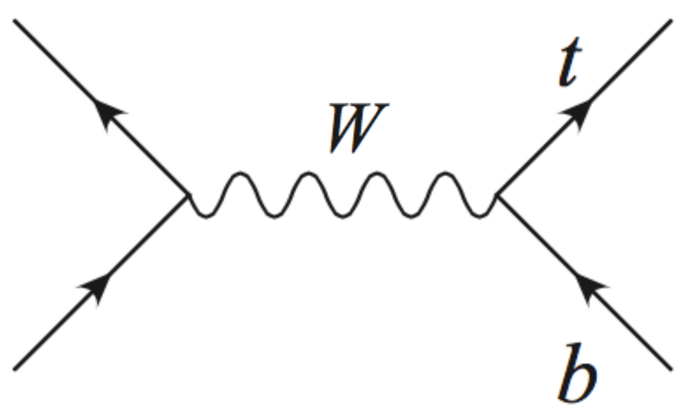
Top-quark pairs via strong interaction



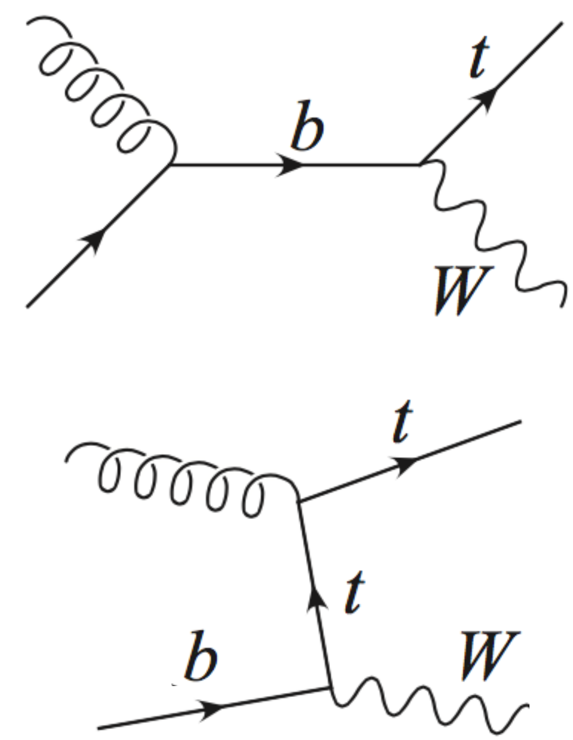
Single-top quarks via weak interaction



t-channel



s-channel

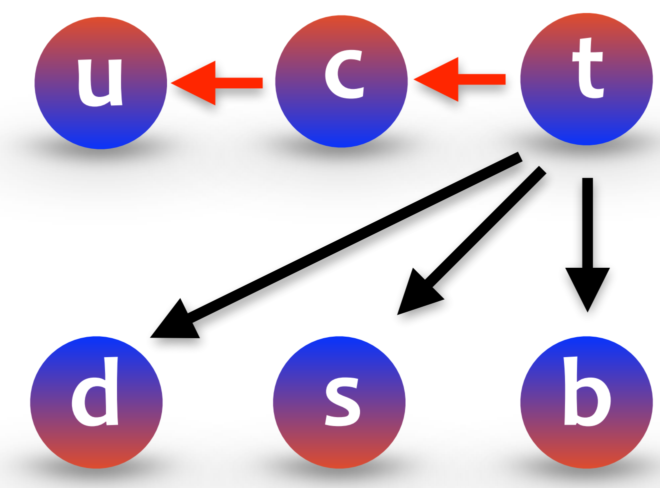


Wt channel

Top-quark decays

Weak decay

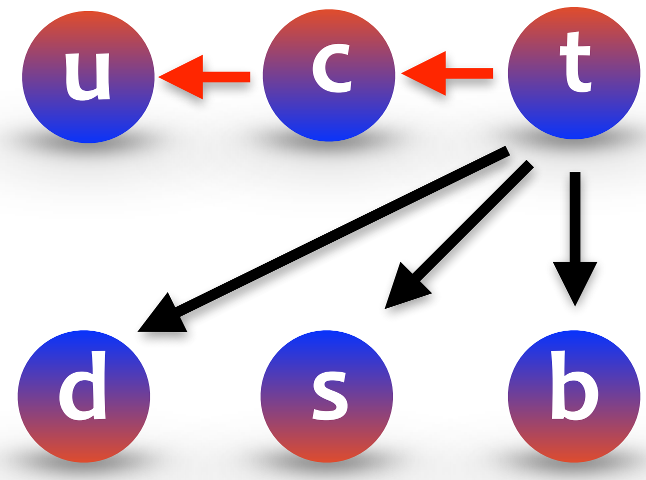
- governed by CKM matrix, BF($t \to Wb$) ~ 1
- no FCNC transitions at tree level

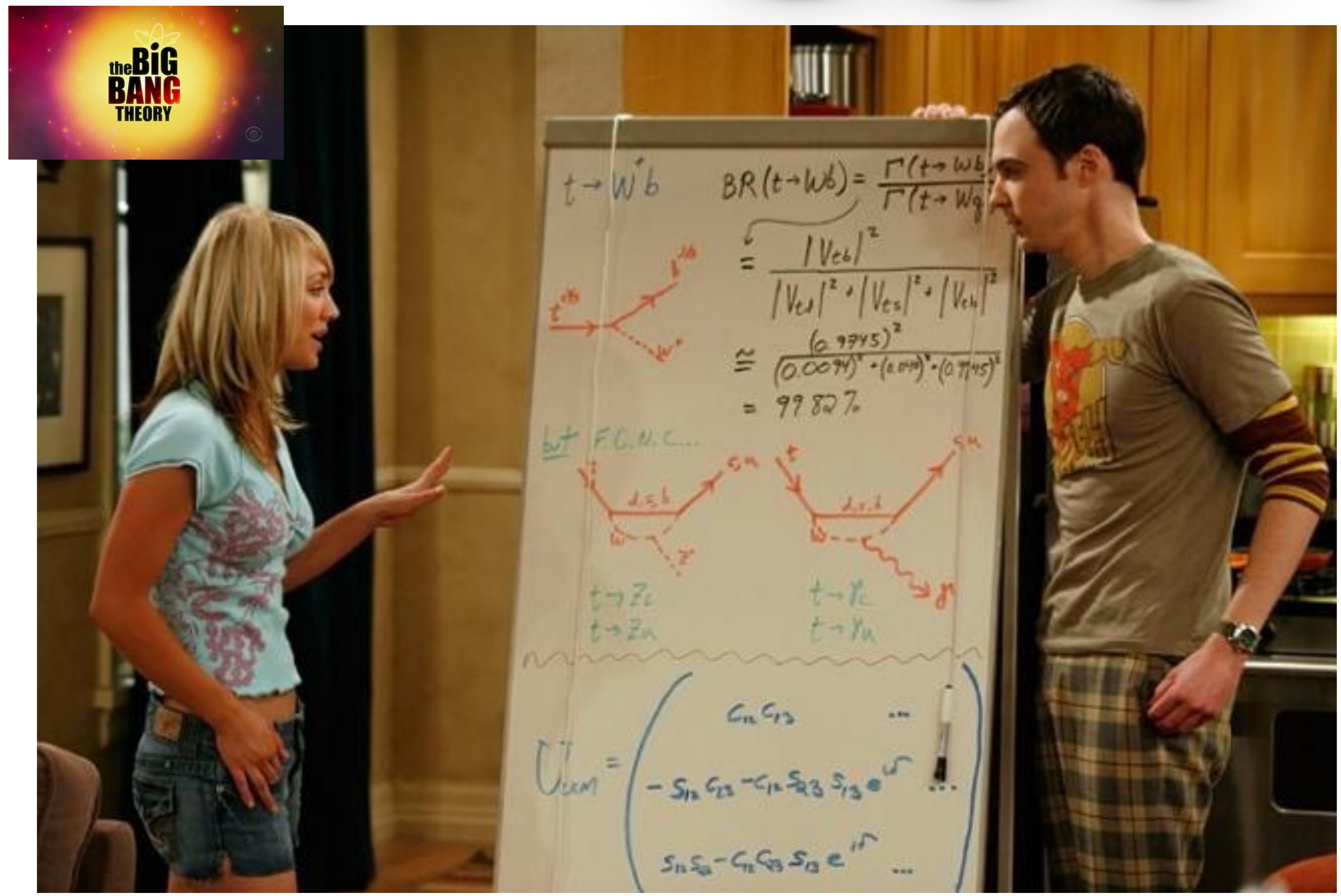


Top-quark decays

Weak decay

- governed by CKM matrix, BF($t \to Wb$) ~ 1
- no FCNC transitions at tree level

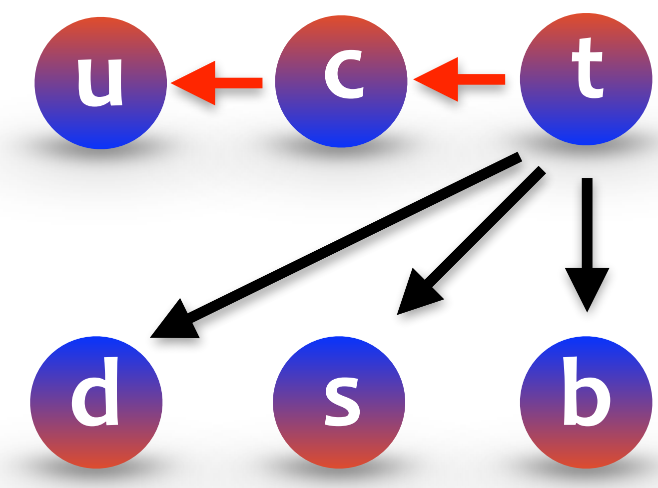


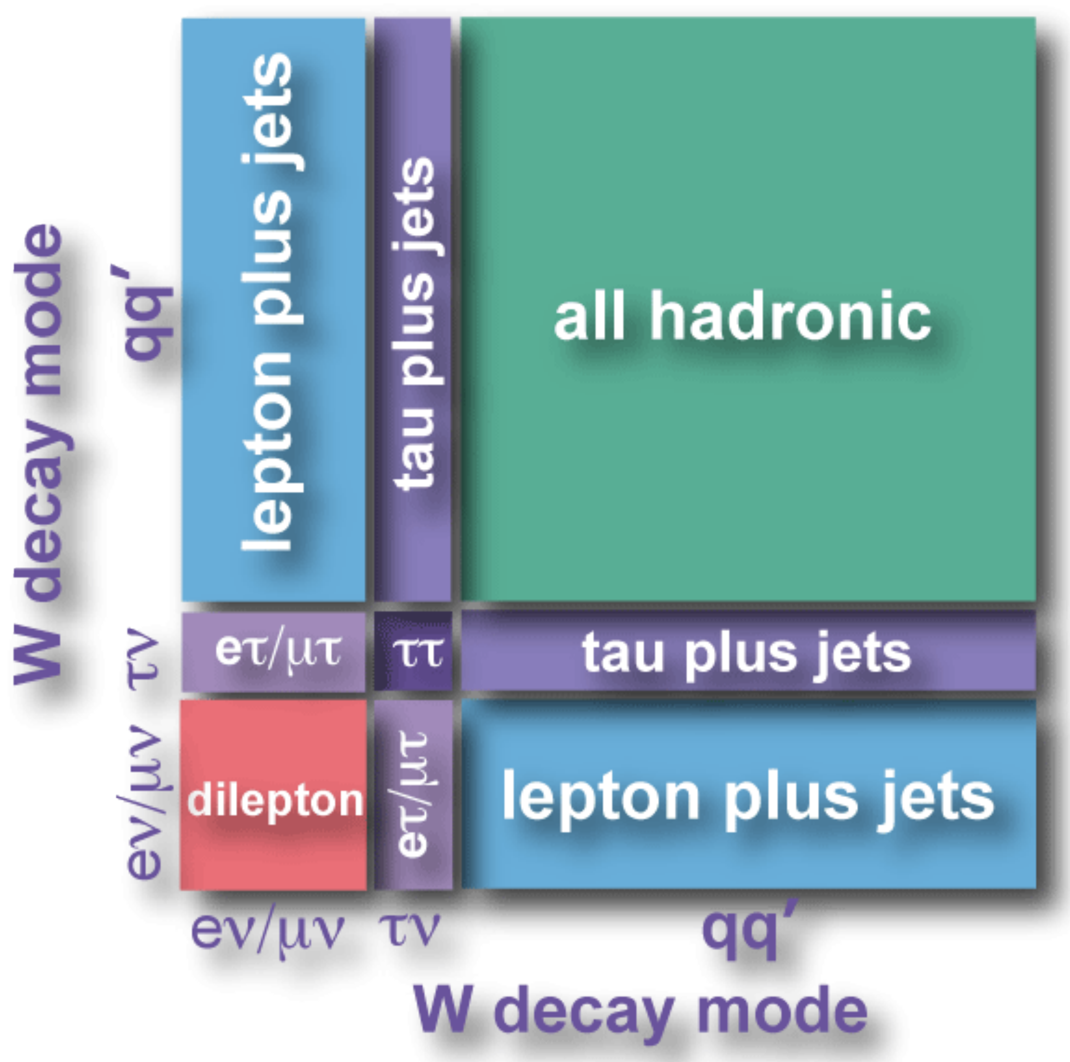


Top-quark decays

Weak decay

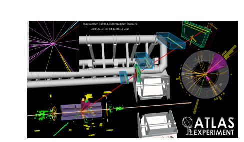
- governed by CKM matrix, BF($t \to Wb$) ~ 1
- no FCNC transitions at tree level
- $W \to \ell\nu$, $\tau_{\text{had}}\nu$ or $q\bar{q}$



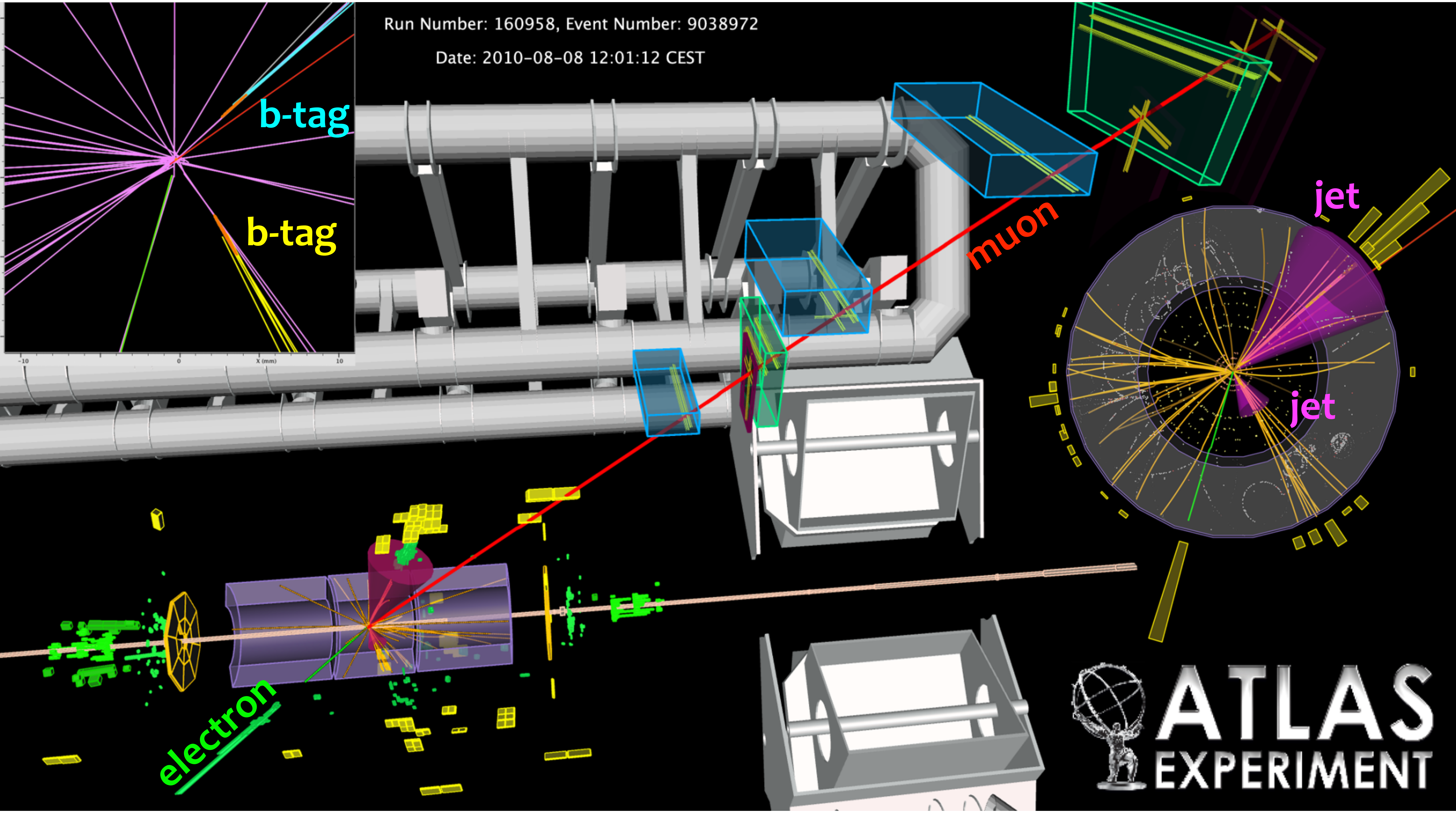


$t\bar{t}$ final states

- all hadronic (2b, 4q)
- with a τ_{had} lepton
- single lepton (2b, 2q, 1ℓ, 1ν)
- dilepton (2b, 2ℓ, 2ν)

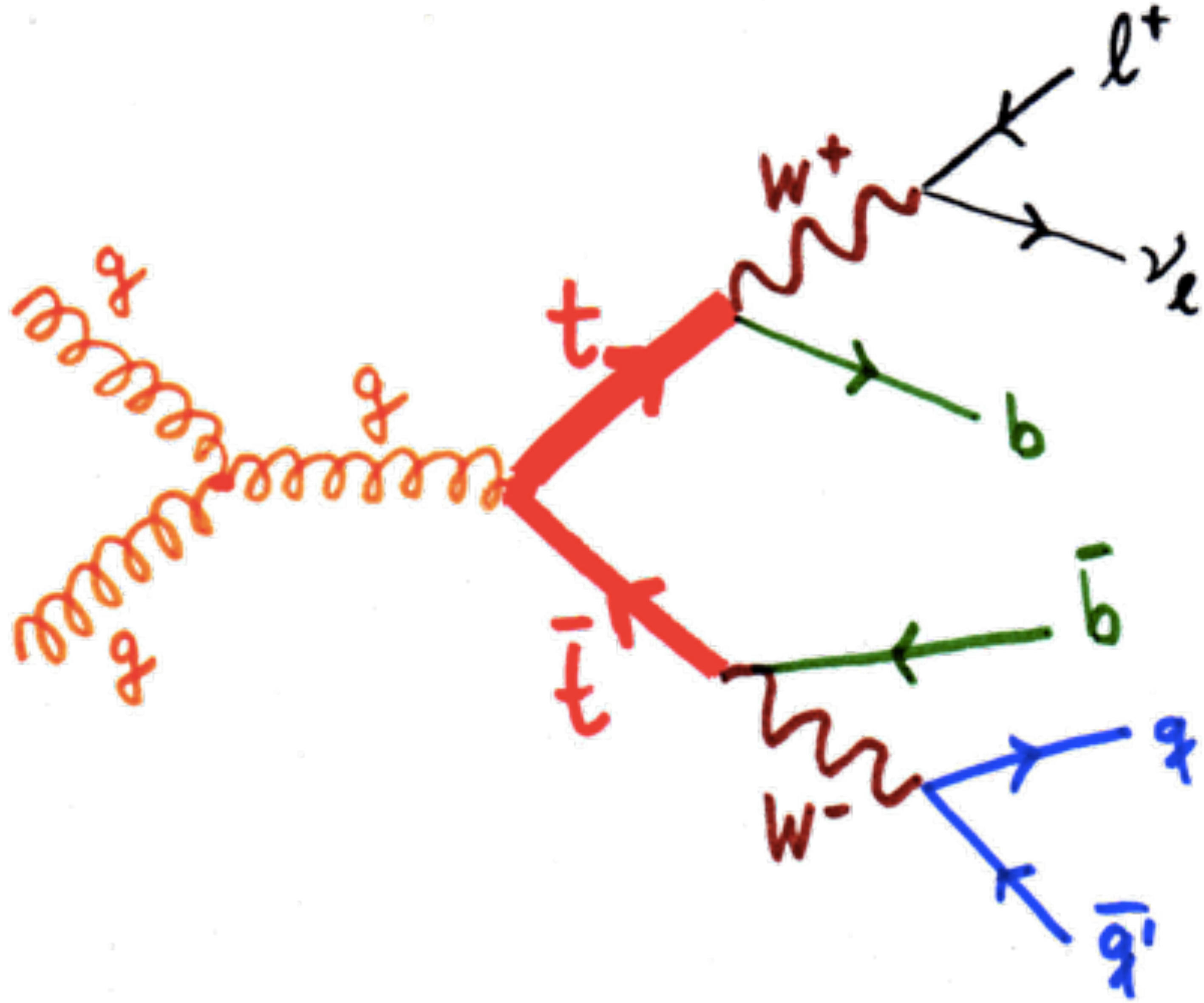


A $t\bar{t}$ event in ATLAS

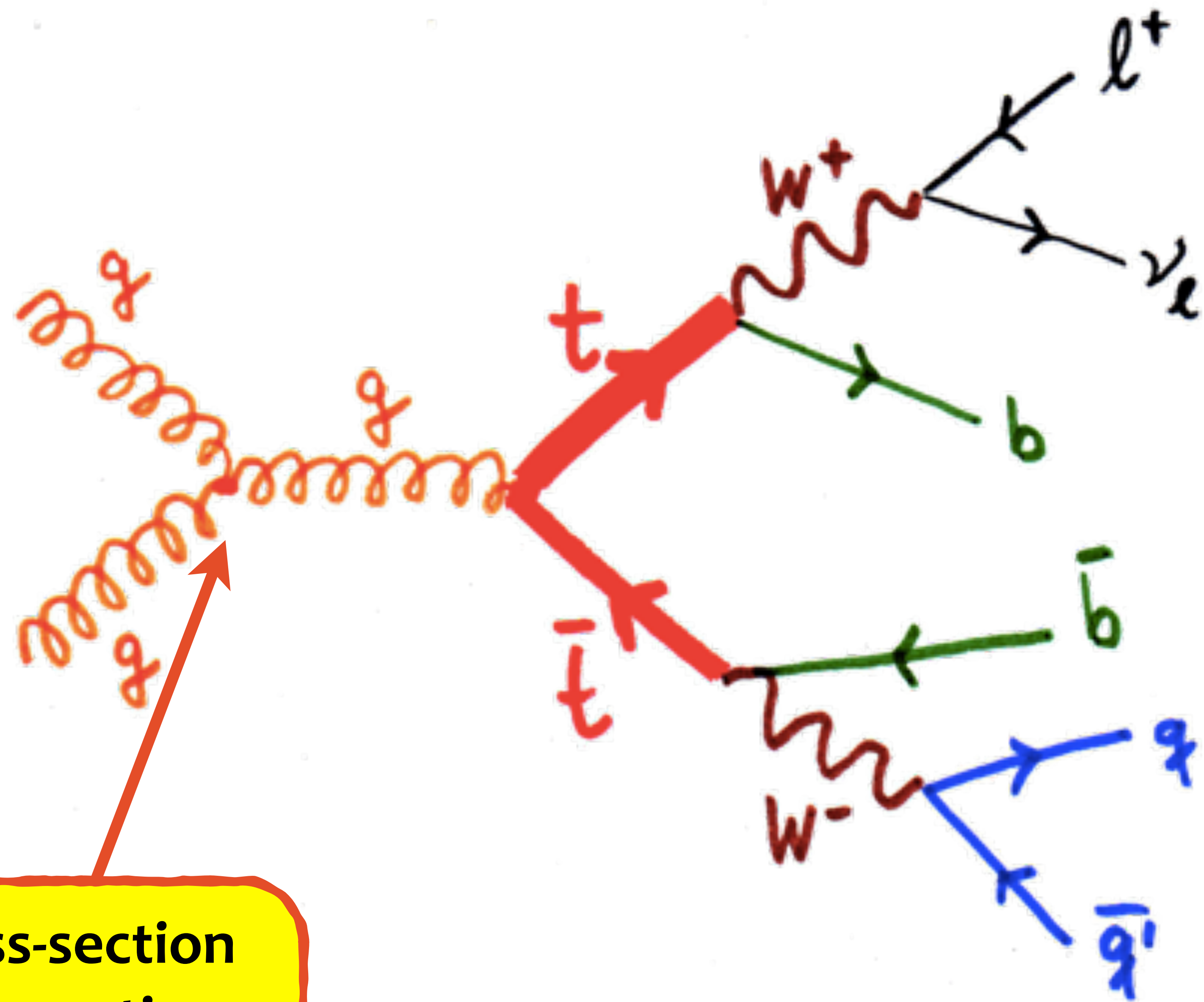


First dilepton candidate: $t\bar{t} \rightarrow W^{+}b\, W^{-}\bar{b} \rightarrow e^{+}\nu_{e}\, b\, \mu^{-}\, \bar{\nu}_{\mu}\bar{b}$

Top-quark physics overview



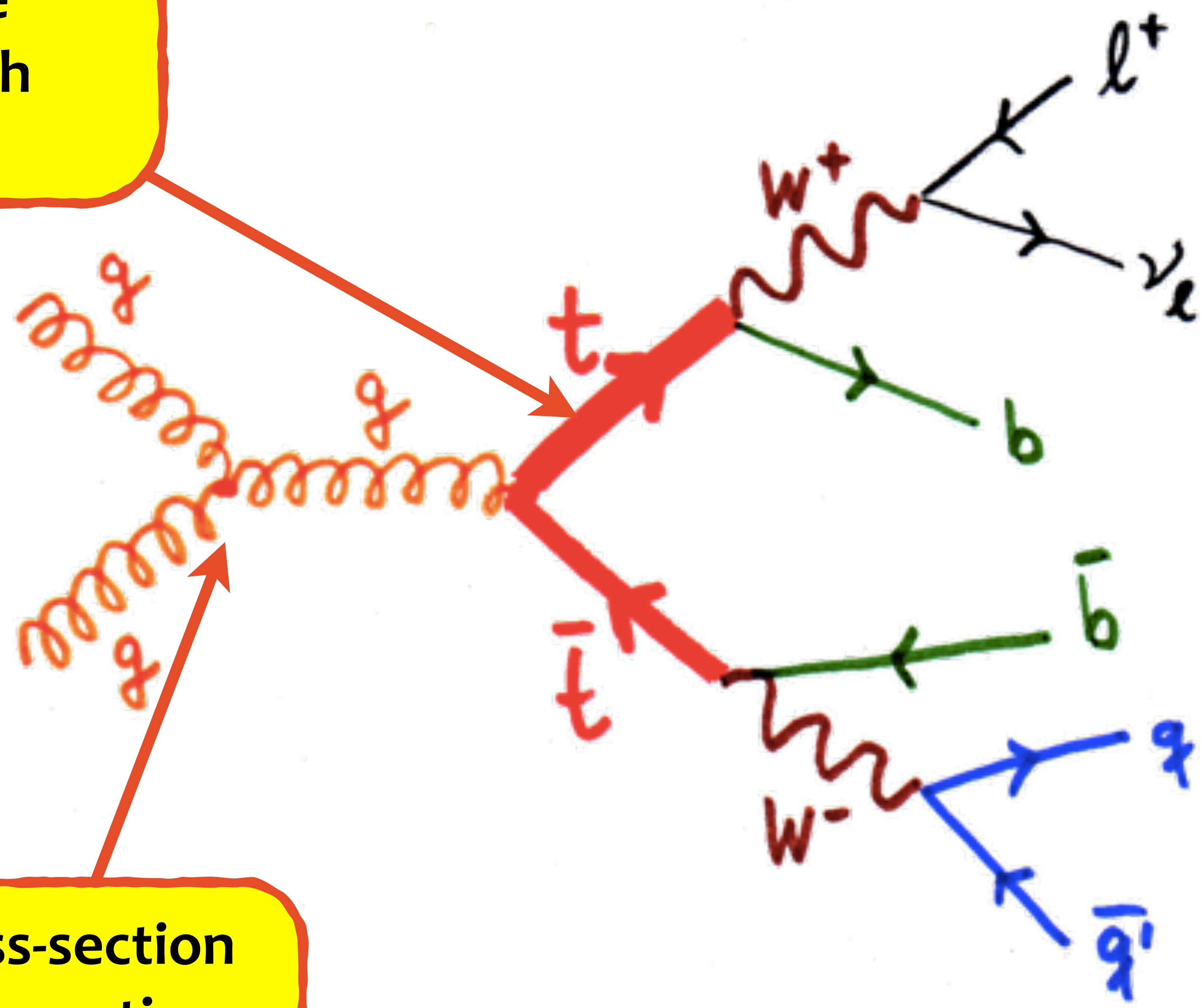
Top-quark physics overview



prod. cross-section
prod. kinematics
resonances
new particles

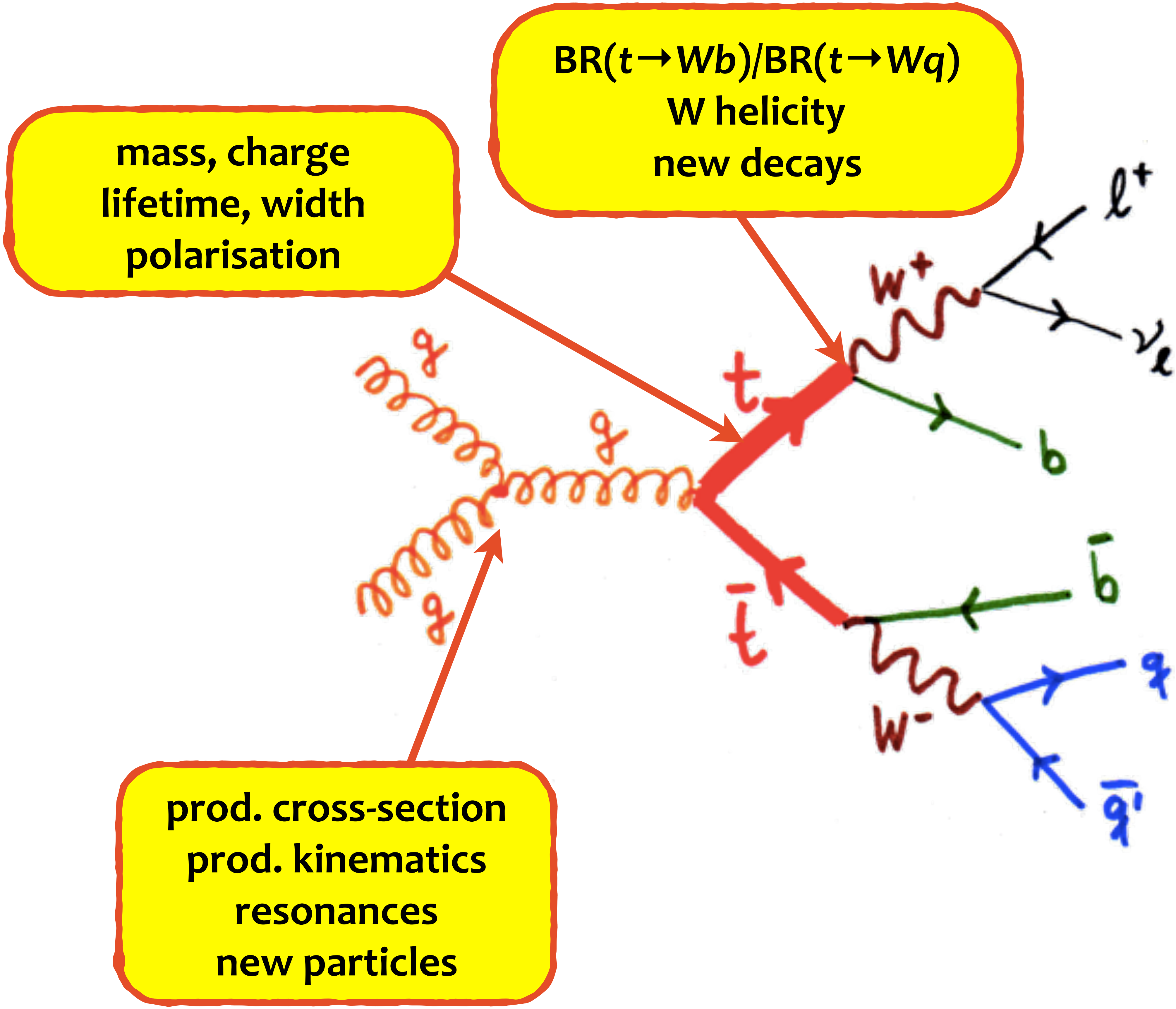
Top-quark physics overview

mass, charge
lifetime, width
polarisation



prod. cross-section
prod. kinematics
resonances
new particles

Top-quark physics overview



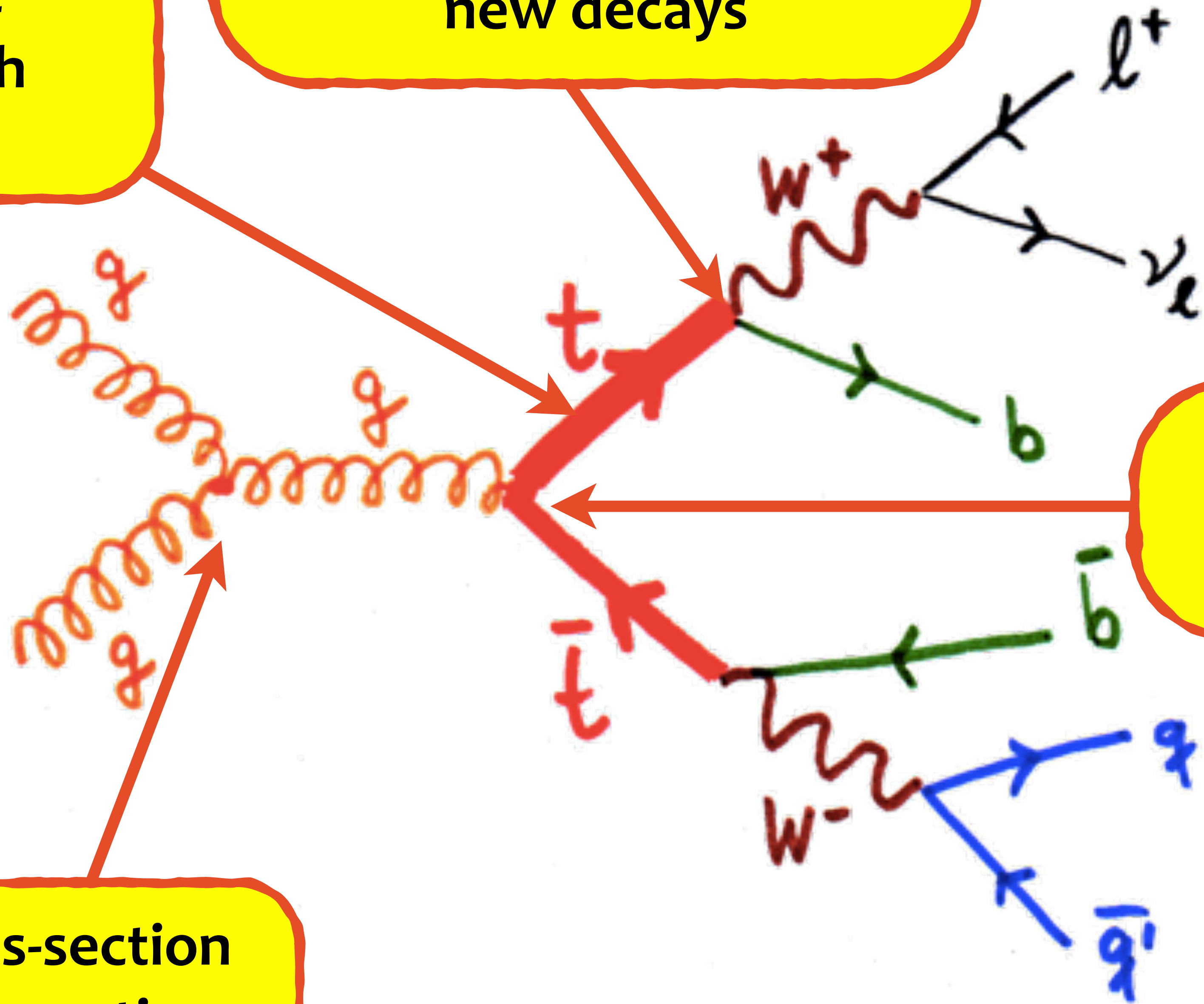
Top-quark physics overview

mass, charge
lifetime, width
polarisation

$BR(t\to Wb)/BR(t\to Wq)$
W helicity
new decays

spin correlations
charge asymmetry

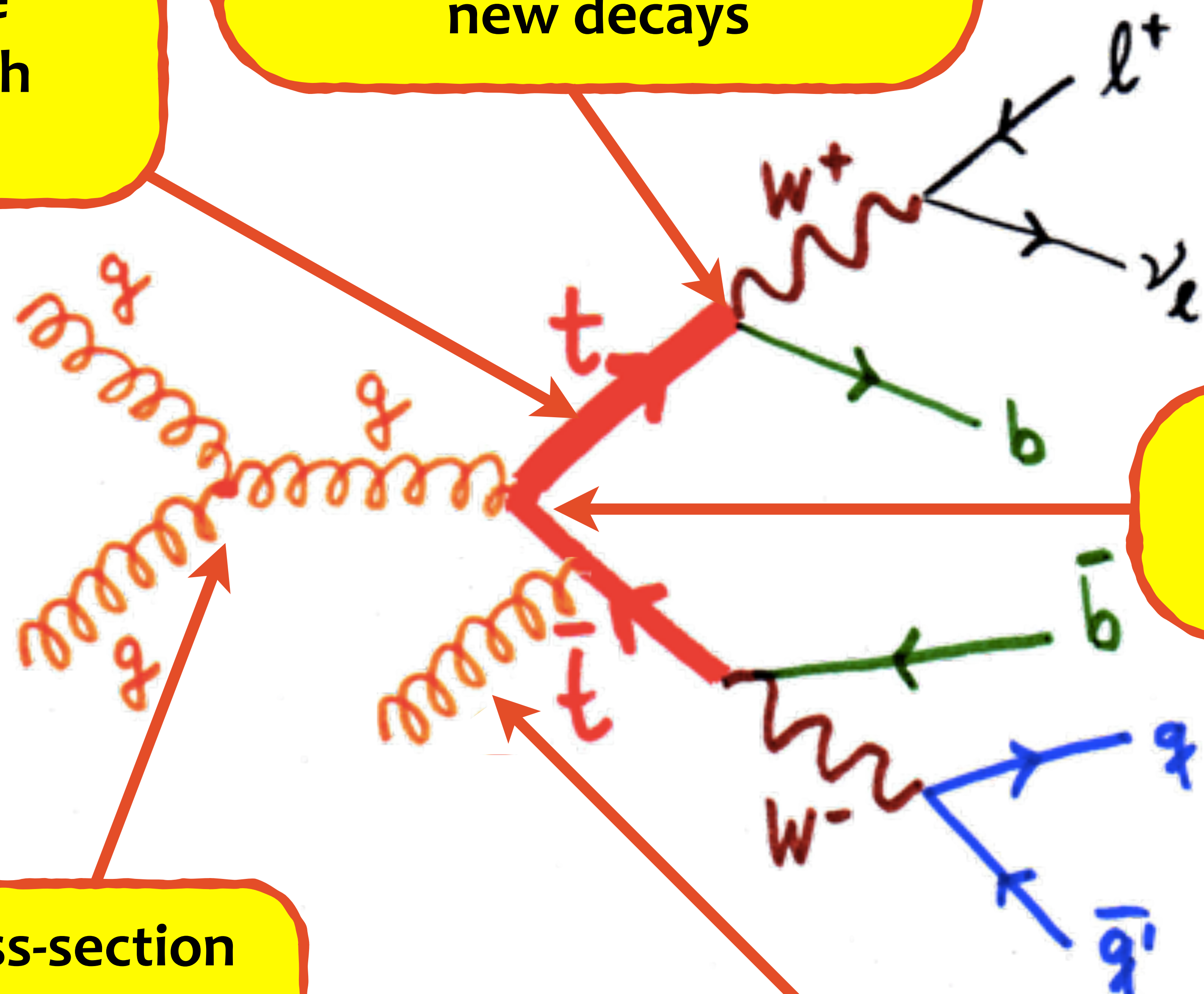
prod. cross-section
prod. kinematics
resonances
new particles



Top-quark physics overview

mass, charge
lifetime, width
polarisation

BR($t \to Wb$)/BR($t \to Wq$)
W helicity
new decays



spin correlations
charge asymmetry

prod. cross-section
prod. kinematics
resonances
new particles

extra radiation:
g, γ, Z, H

Outline

Production

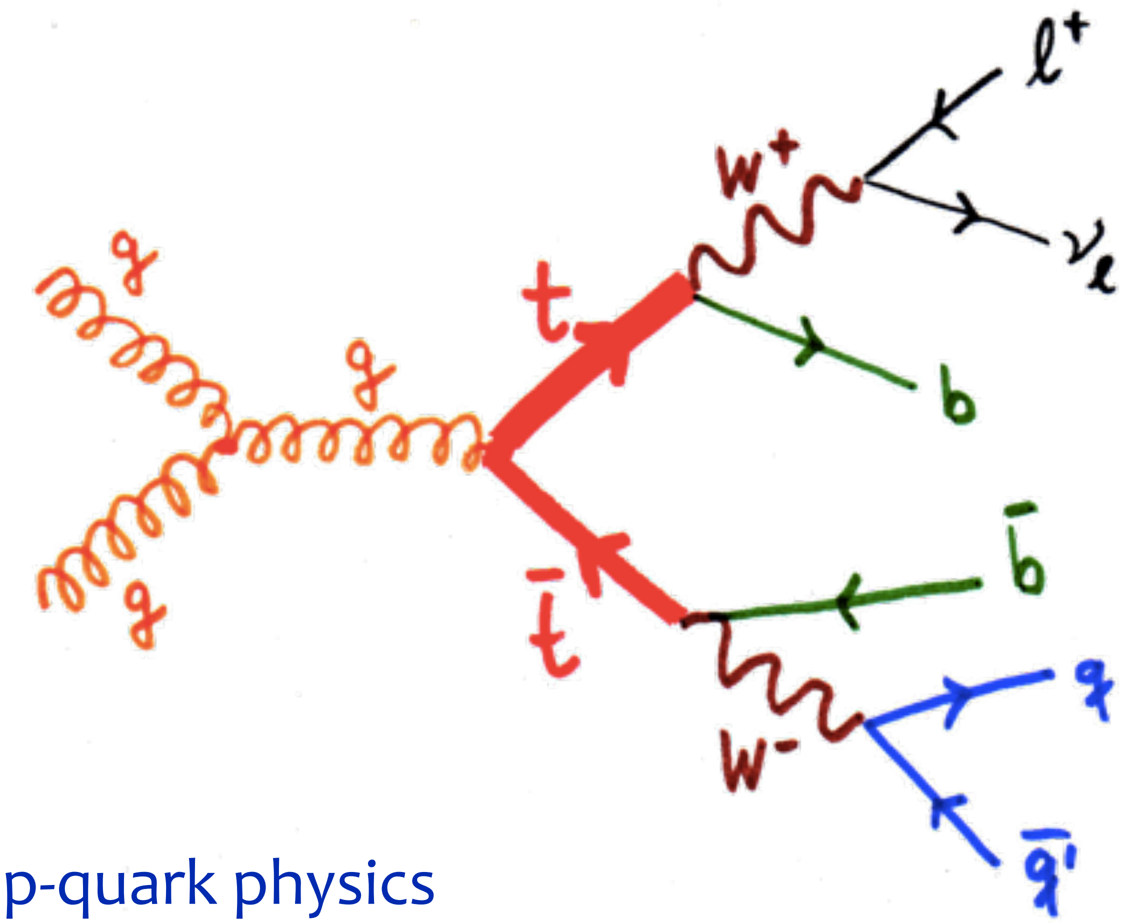
- $t\bar{t}$ production inclusive
- $t\bar{t}$ production differential
- $t\bar{t}$+jets, $t\bar{t}$+V
- single top

Properties

- mass
- spin, polarisation, helicity
- asymmetries

The XXXVI international symposium on Physics in Collision (PIC) is a conference whose focus is to update key topics in elementary particle physics in which new results have been published within the last year or are reasonably expected to be so before the symposium. The aim of the presentations is to encourage informal discussions of new experimental results and their implications. The topics at the symposium cover a wide range of physics subjects from experimental

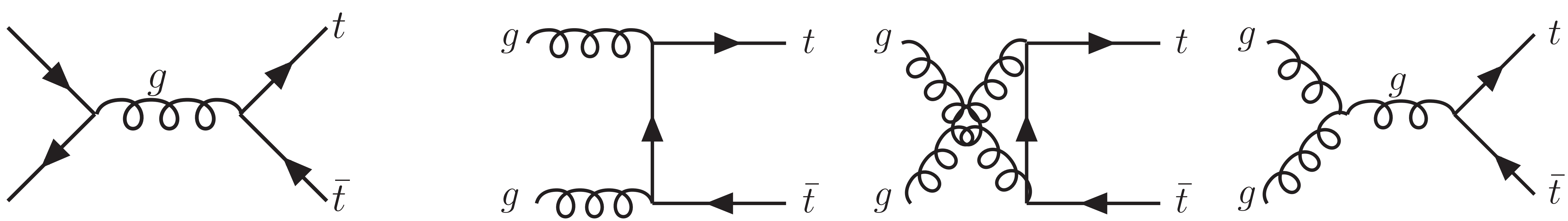
Quy Nhon



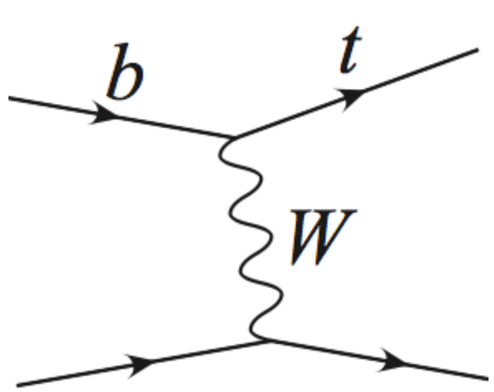
Since PIC2015:

39 papers and 26 preliminary results on top-quark physics
discussion mainly based on submitted papers

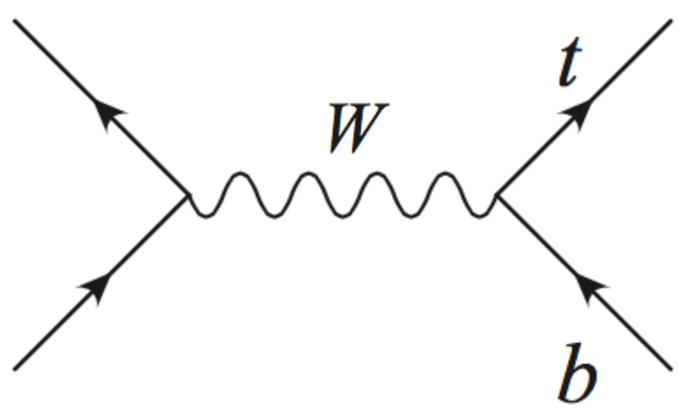
Top-quark pairs via strong interaction



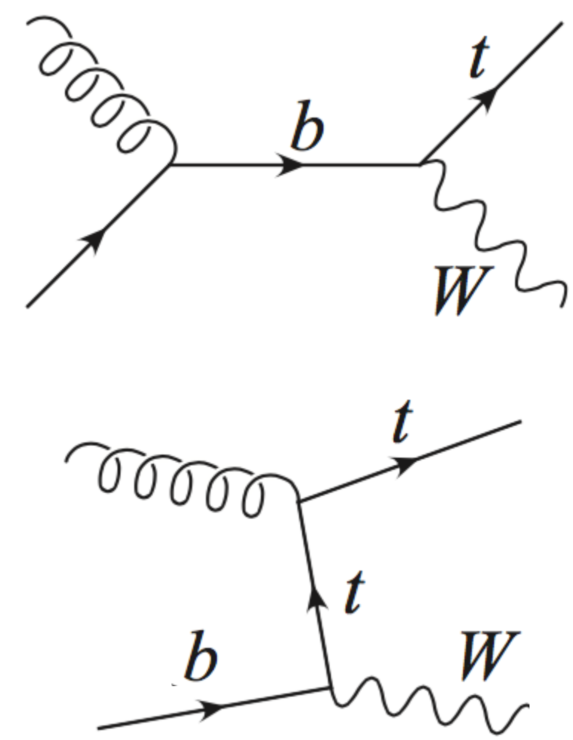
Single-top quarks via weak interaction



t-channel



s-channel

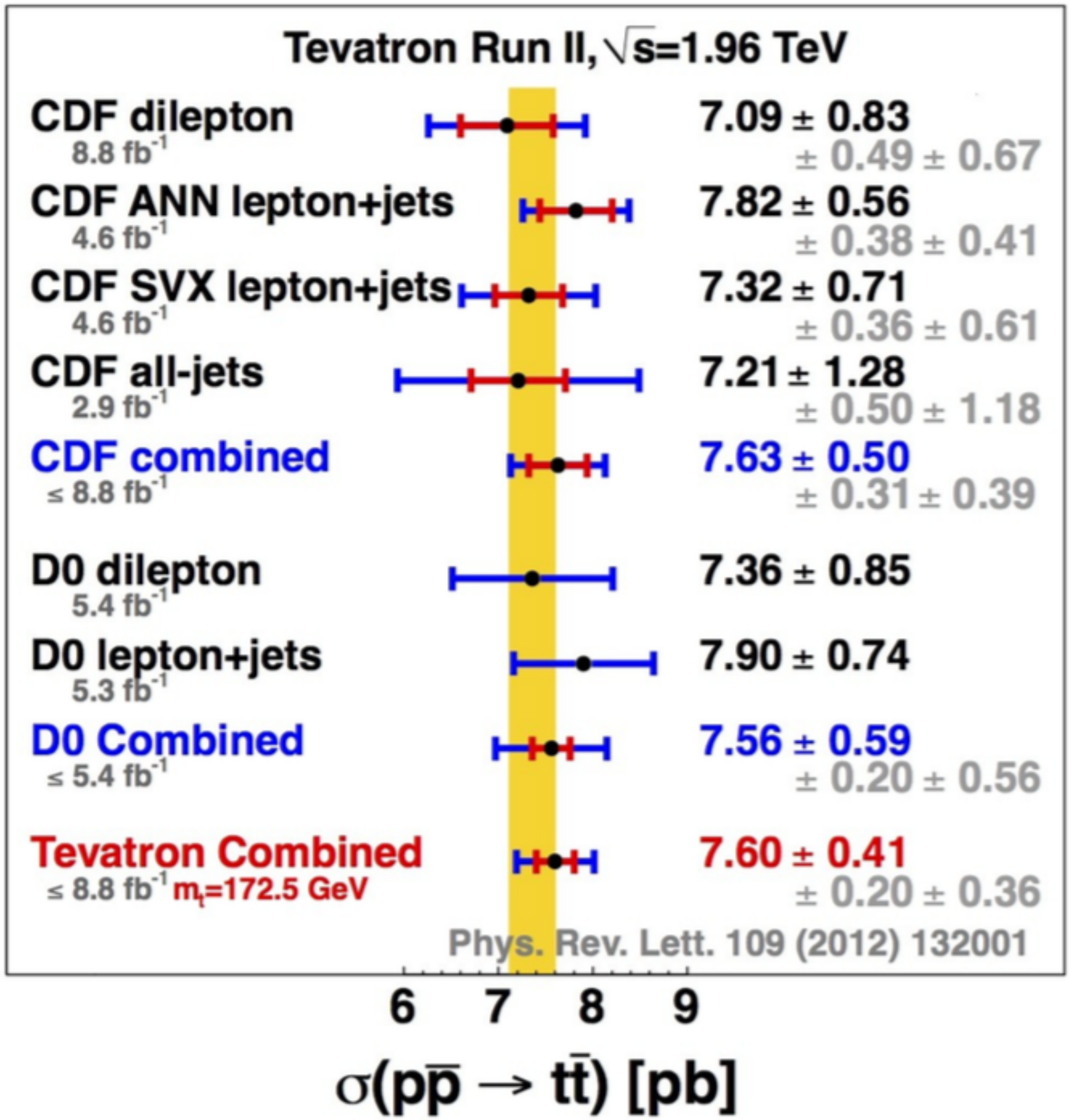


Wt channel

$t\bar{t}$ production at 1.96 TeV

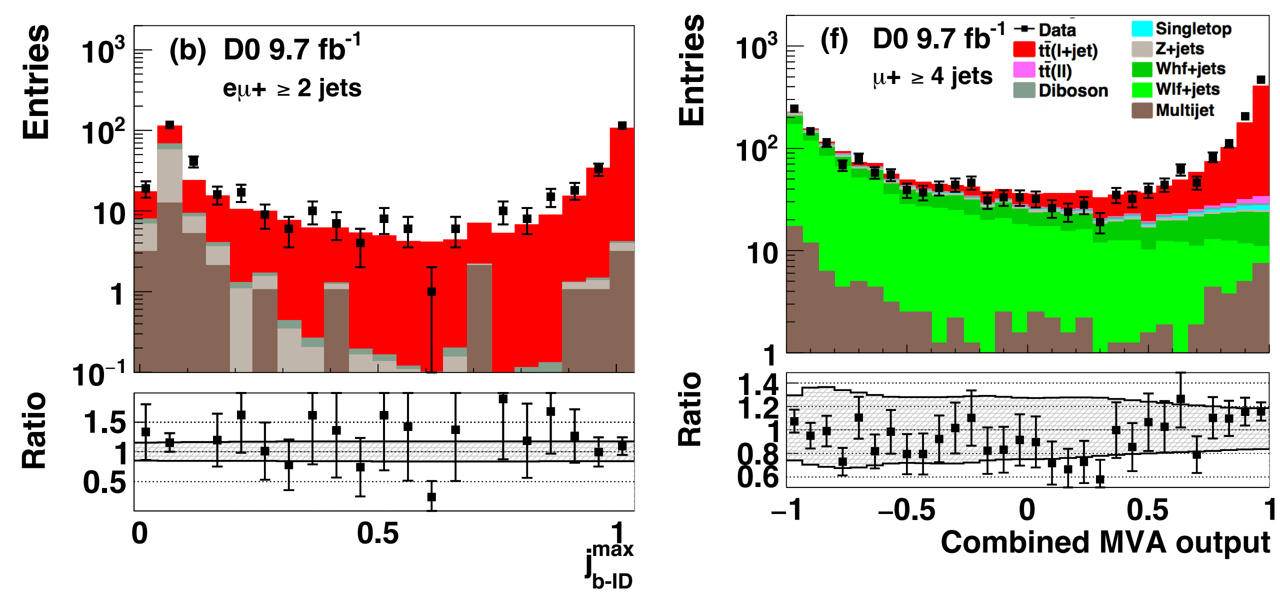
universitätbonn erc

arXiv:1605.06168, submitted to PRD



New D0 inclusive measurement

- full dataset, including combination
- dilepton
  - *b*-tag MVA
- *ℓ*+jets
  - *b*-tag MVA + topological discriminant
  - split in 2, 3, ≥ 4 jets

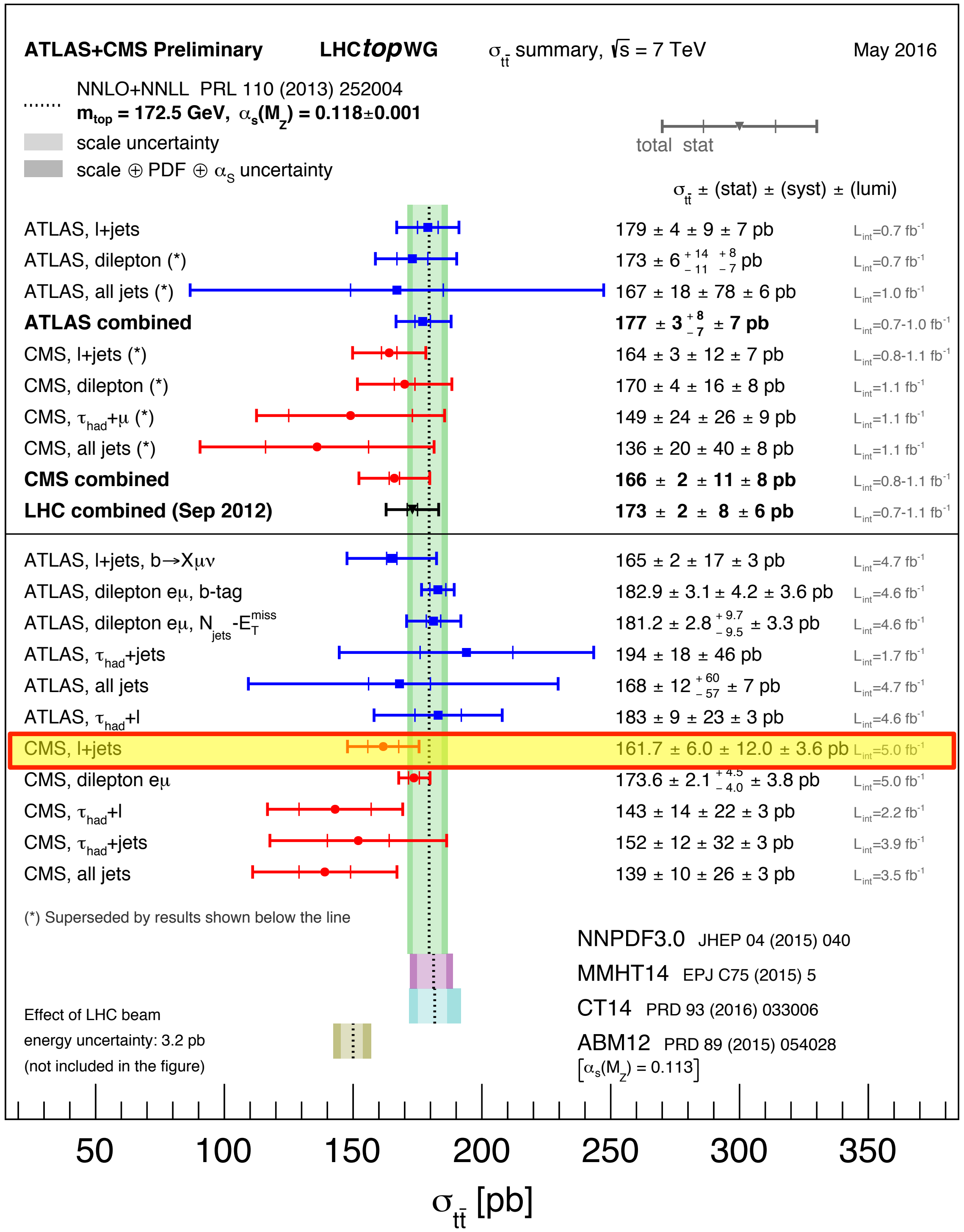


- $\sigma_{t\bar{t}} = 7.26 \pm 0.13_{stat}\,^{+0.57}_{-0.50}\,_{syst}$ pb
  - $\Delta\sigma/\sigma = 7\%$
  - largest syst. from hadronisation

$t\bar{t}$ production at 7 TeV

arXiv:1602.09024, submitted to EPJC

All channels (except for $\tau_h\tau_h$) explored



Re-analysis of 7 TeV $t\bar{t} \to \ell$+jets

- **better understanding of detector and systematic uncertainties**
  - dominated by jet energy scale and modeling
- **extracting ratio $R = \sigma_{8\text{TeV}}(t\bar{t})/\sigma_{7\text{TeV}}(t\bar{t})$**
  - $R_{meas} = 1.43 \pm 0.09$ ($R_{theo} = 1.429 \pm 0.004$)

Systematic uncertainty	7 TeV μ+jets (%)	e+jets (%)	corr.	comb.(%)
Jet energy scale	±4.8	±5.2	0.9	±4.4
Jet energy resolution	±1.4	±1.1	1.0	±1.1
E_T^{miss} unclustered energy	< 0.05	±0.3	1.0	±0.2
Pileup	±0.4	±0.6	1.0	±0.5
Lepton ID / Trigger eff. corrections	±1.4	±1.7	0.0	±0.8
b tagging method	±0.5	±0.6	1.0	±0.6
Background composition	±0.5	±0.4	1.0	±0.5
Factorization/renormalization scales	±3.7	±0.4	1.0	±2.1
ME-PS matching threshold	±2.0	±1.7	1.0	±1.8
Top quark p_T-reweighting	±1.1	±1.2	1.0	±1.1
Signal modeling for $\sigma_{t\bar{t}}$ ($\sigma_{t\bar{t}}^{vis}$)	±4.4(±2.2)	±4.4(±2.4)	1.0	±4.4(±2.3)
PDF uncertainties	±2.3	±1.9	1.0	±2.2
Sum for $\sigma_{t\bar{t}}$ ($\sigma_{t\bar{t}}^{vis}$)	±8.4(±7.5)	±7.7(±6.8)		±7.4(±6.4)
Integrated luminosity	±2.2	±2.2	1.0	±2.2
Total for $\sigma_{t\bar{t}}$ ($\sigma_{t\bar{t}}^{vis}$)	±8.7(±7.8)	±8.0(±7.1)		±7.7(±6.7)

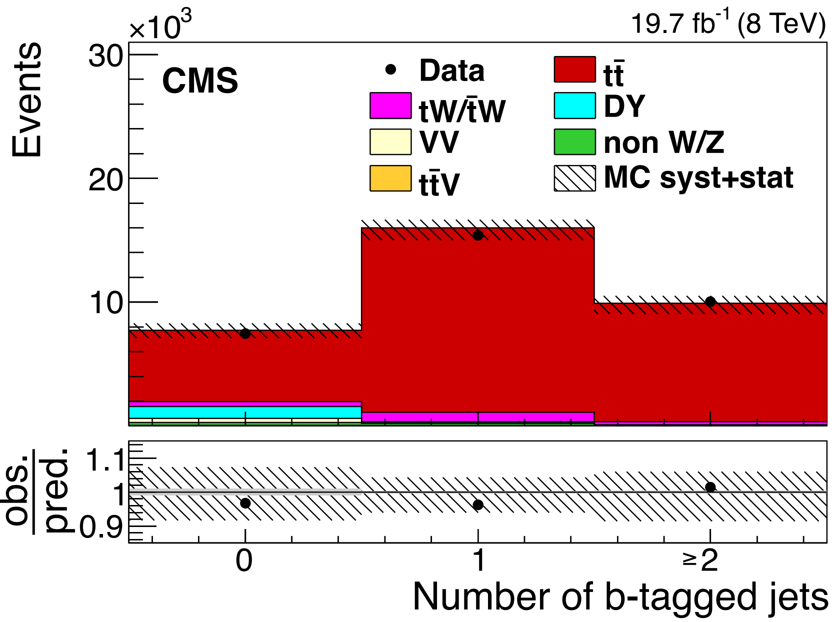
$t\bar{t}$ production at 8 TeV

universitätbonn erc

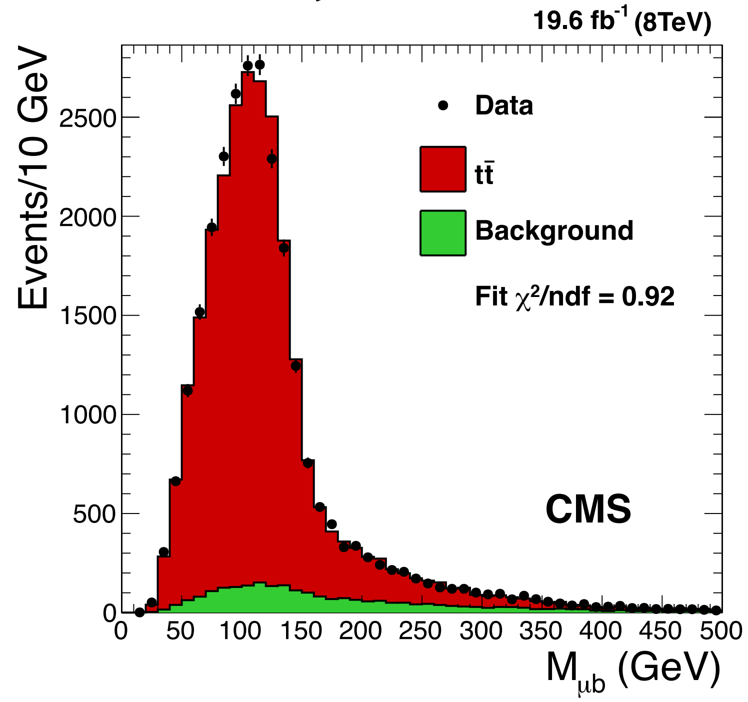
arXiv:1509.06076, EPJC 76 (2016) 128 | 1602.09024, submitted to EPJC | 1603.02303, JHEP 08 (2016) 029 | 1605.00116, submitted to PRD

Recent measurements in four channels

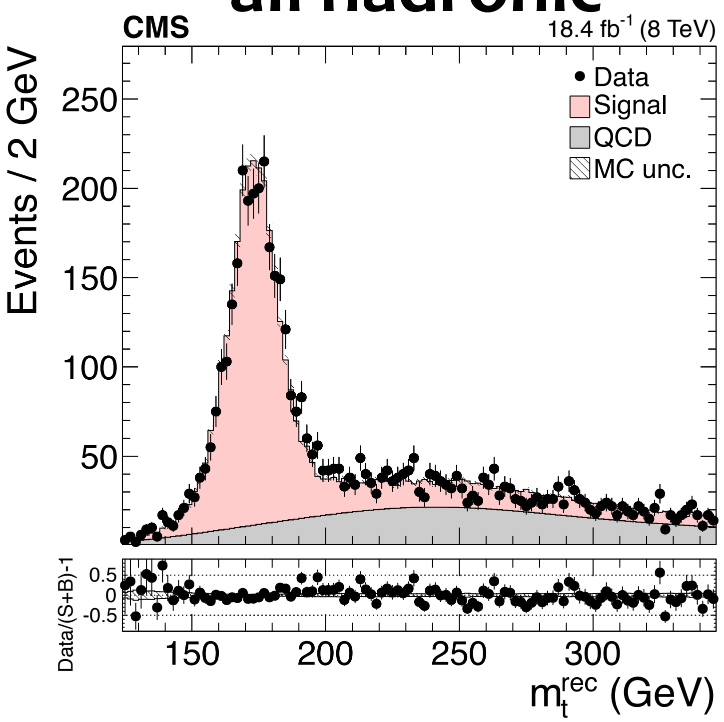
dilepton



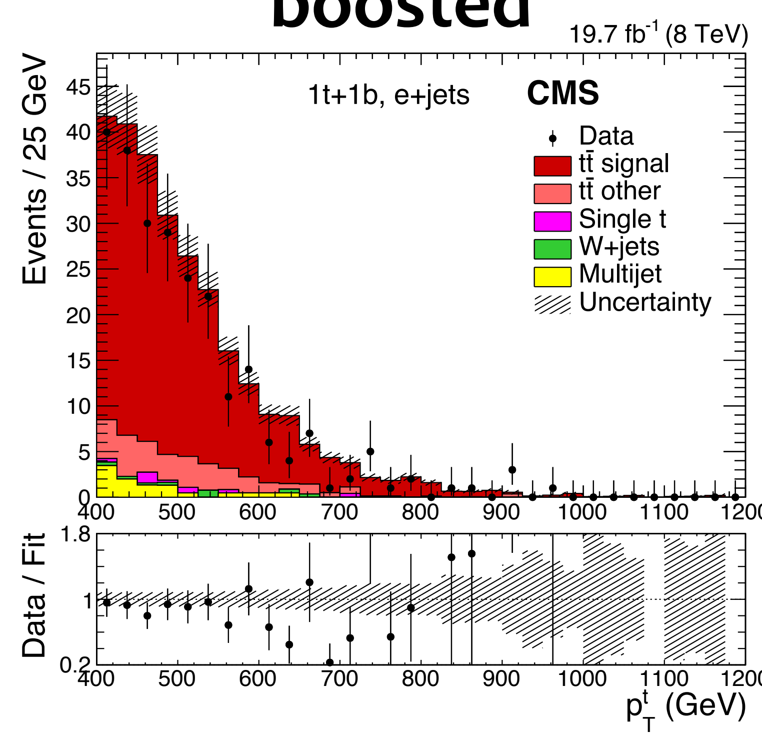
ℓ+jets

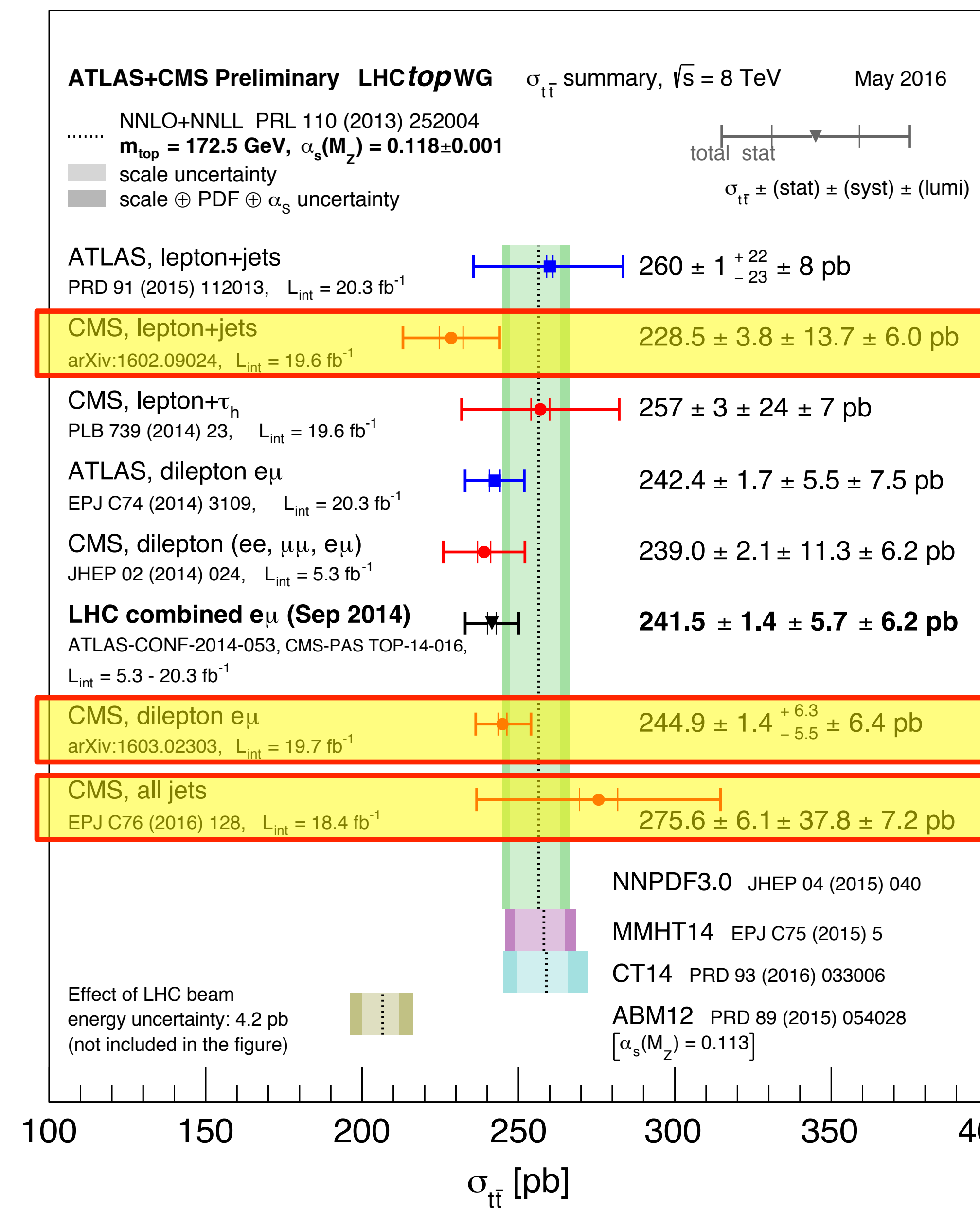


all hadronic



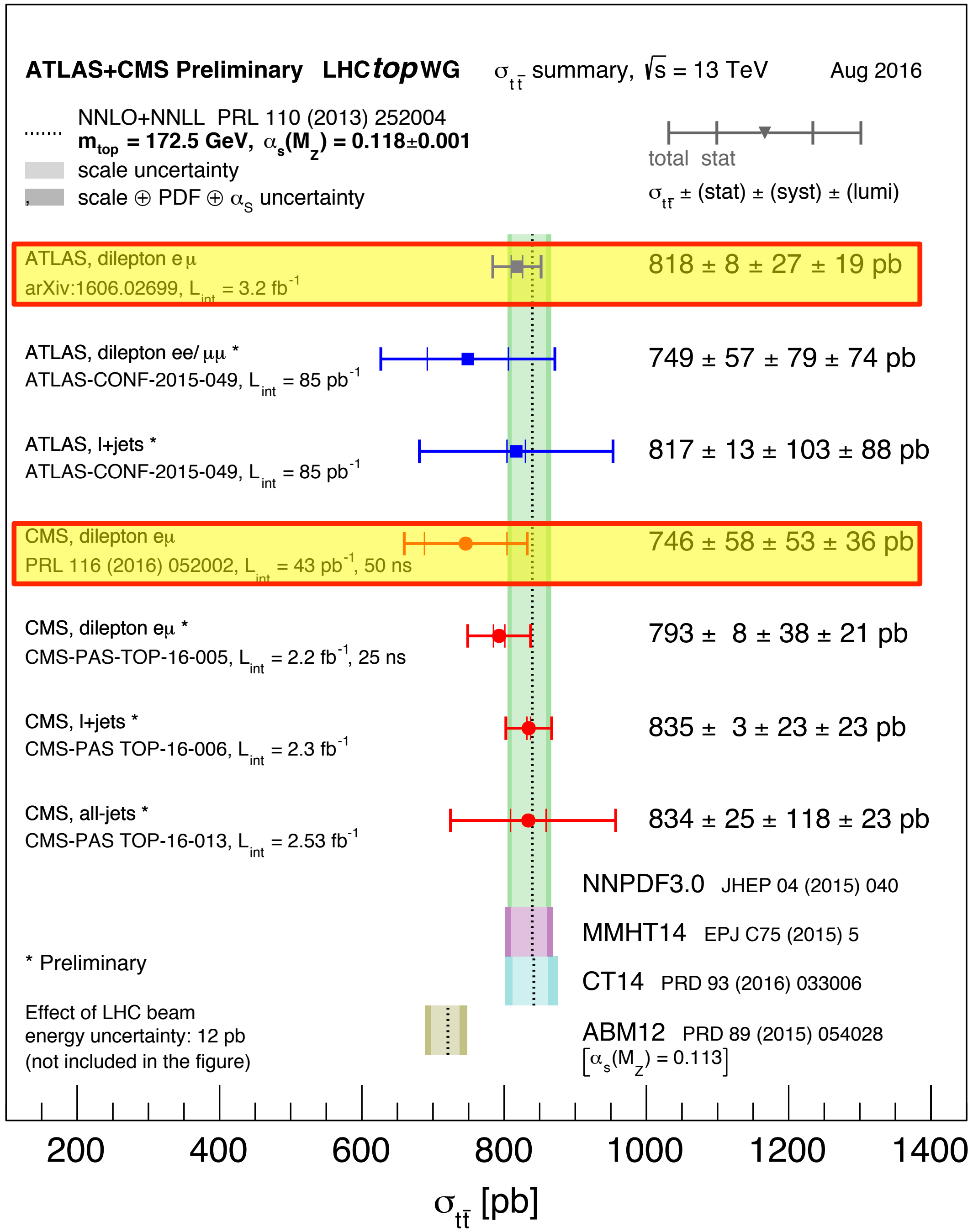
boosted





$\Delta\sigma/\sigma = 3.5\%$

$t\bar{t}$ production at 13 TeV



$\Delta\sigma/\sigma = 3.9\%$

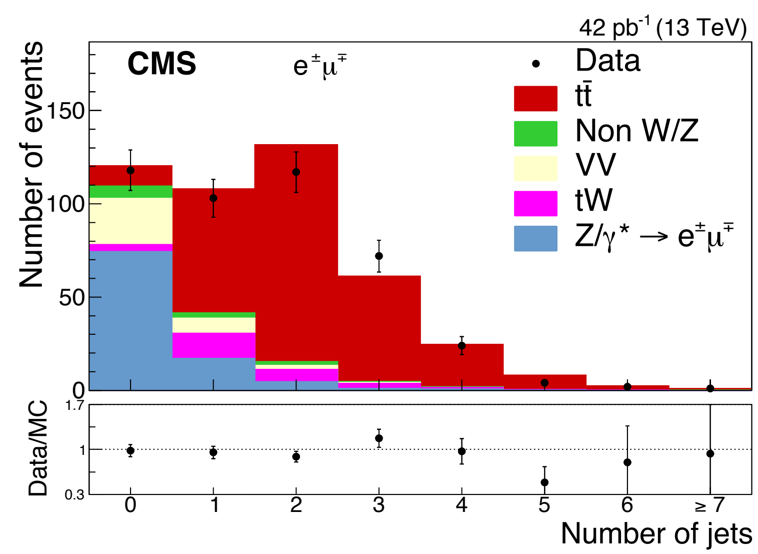
Count number of $e\mu$ events with

- exactly one (N_1) and two (N_2) b-tags
- simultaneously extract $\sigma_{t\bar{t}}$ and ϵ_b

$$N_1 = L\sigma_{t\bar{t}}\ \epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\rm bkg}$$

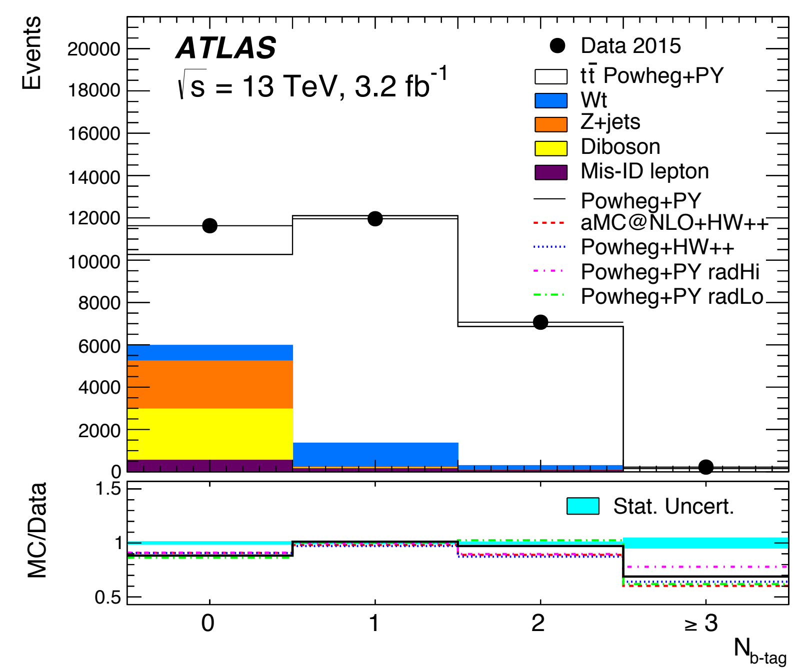
$$N_2 = L\sigma_{t\bar{t}}\ \epsilon_{e\mu}C_b{\epsilon_b}^2 + N_2^{\rm bkg}$$

arXiv:1510.05302, PRL 116 (2016) 052002



$\Delta\sigma/\sigma = 12\%$

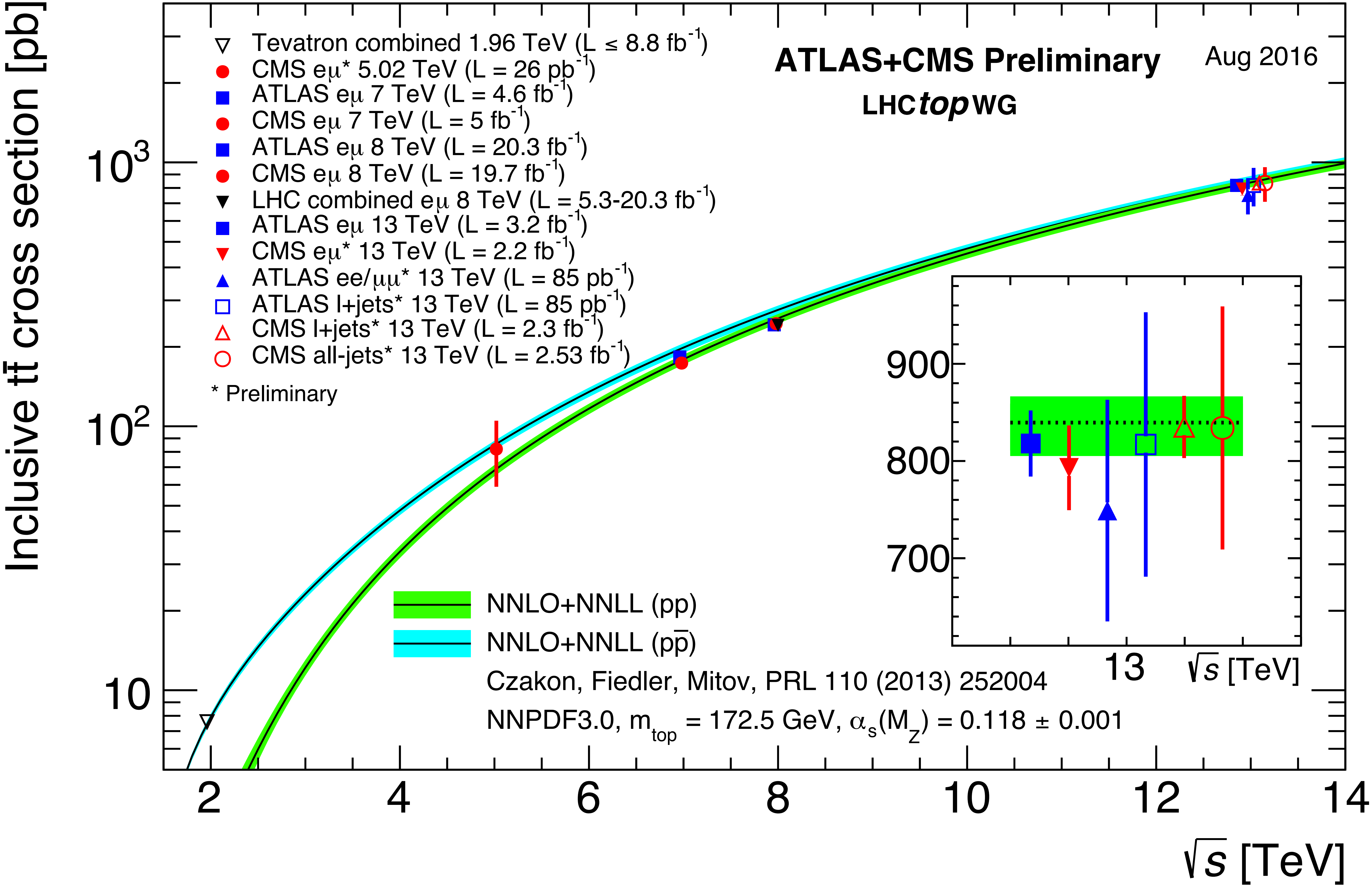
arXiv:1606.02699, PLB 761 (2016) 136



$\Delta\sigma/\sigma = 4.4\%$

Preliminary measurements also in ℓ+jets and all hadronic channels

$t\bar{t}$ inclusive production summary



$t\bar{t}$ differential cross section

Motivation

- detailed test of pQCD, constrain PDF and MC parameters
- background for Higgs, rare processes and many BSM searches

$t\bar{t}$ differential cross section

Motivation

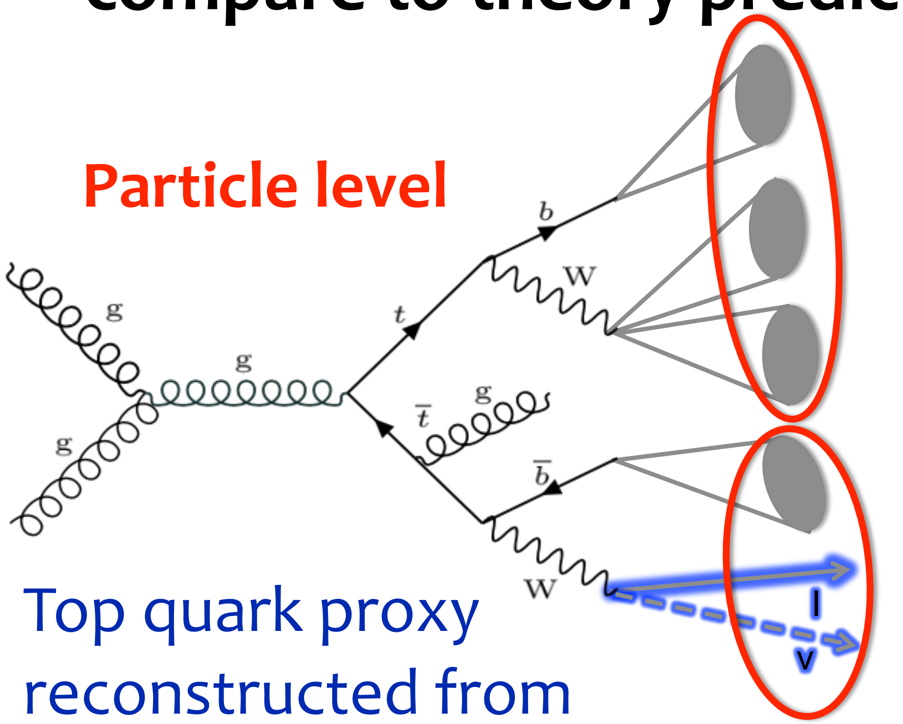
- detailed test of pQCD, constrain PDF and MC parameters
- background for Higgs, rare processes and many BSM searches

General analysis strategy

- tight event selection → pure $t\bar{t}$ sample
- $t\bar{t}$ system / top quark kinematic reconstruction
- background subtraction
- corrections: acceptance, resolution → unfolding
- compare to theory predictions at particle or parton level

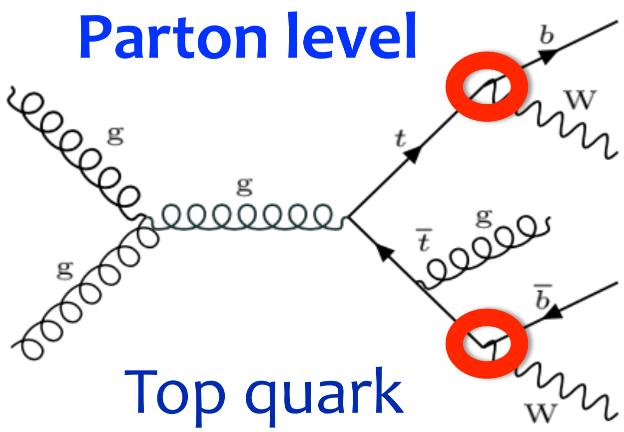
$$\frac{1}{\sigma}\frac{d\sigma_i}{dX} = \frac{1}{\sigma}\frac{\text{unfold}(s_i^X - b_i^X)}{\Delta_i^X \cdot \int \mathcal{L}dt}$$

Particle level



Top quark proxy reconstructed from decay products after hadronisation

Parton level



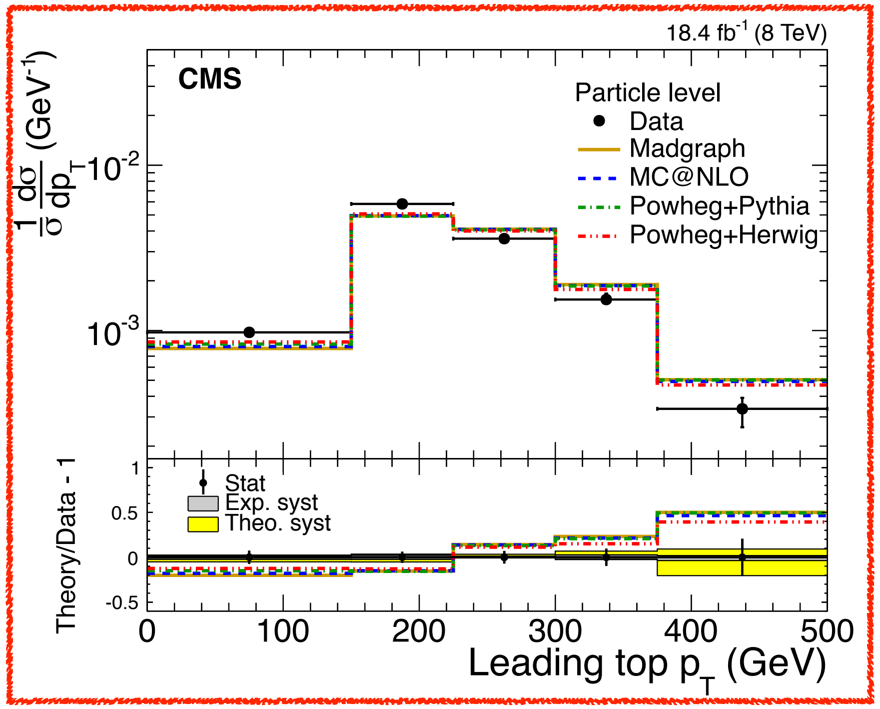
Top quark after radiation, but before decay

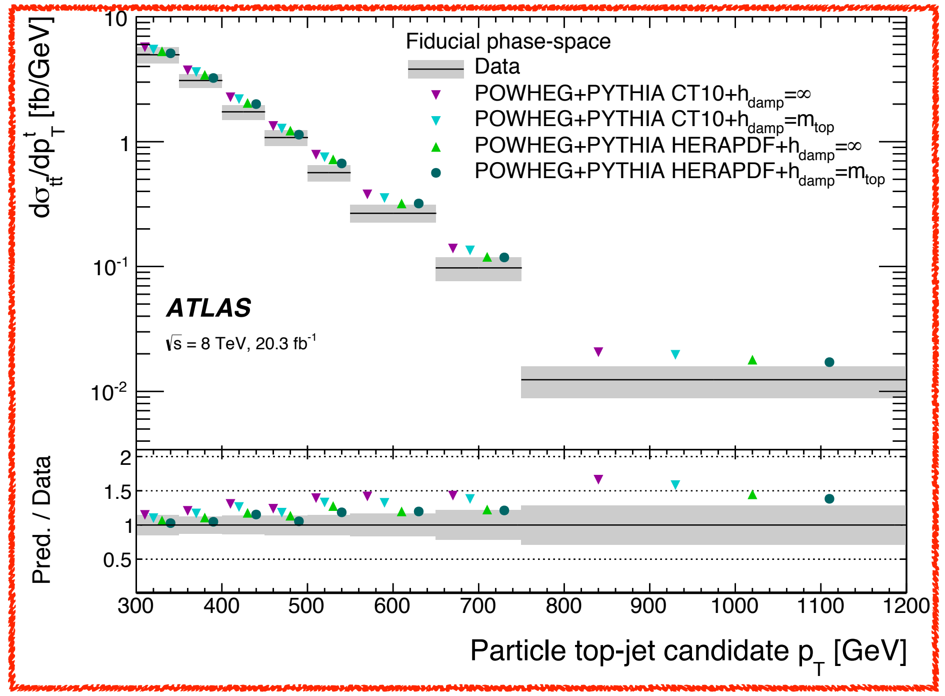
$t\bar{t}$ differential – top quark p_T

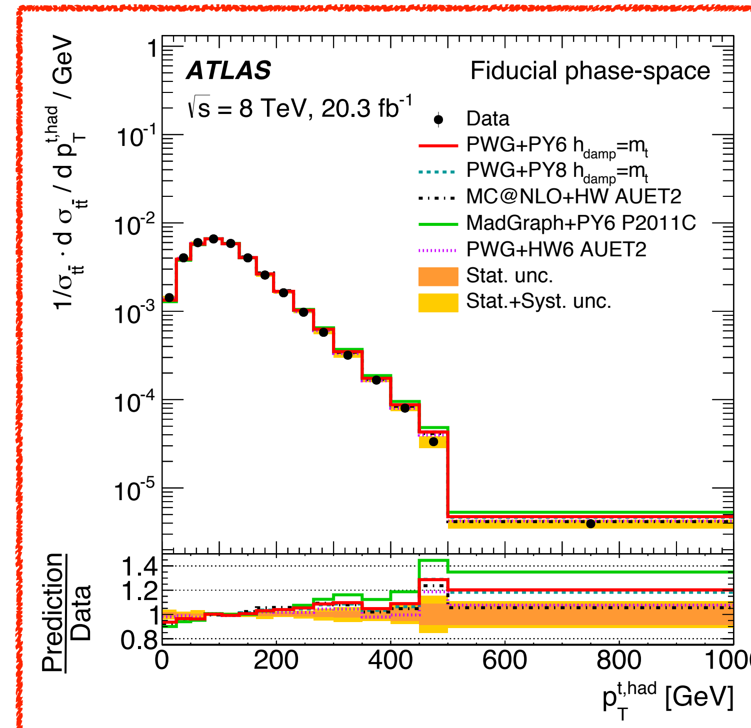
Mis-modeling of top p_T spectrum confirmed in all decay channels

arXiv:1509.06076, EPJC 76 (2016) 128 | *arXiv:1510.03818, PRD 93 (2016) 032009* | *arXiv:1511.04716, submitted to EPJC*

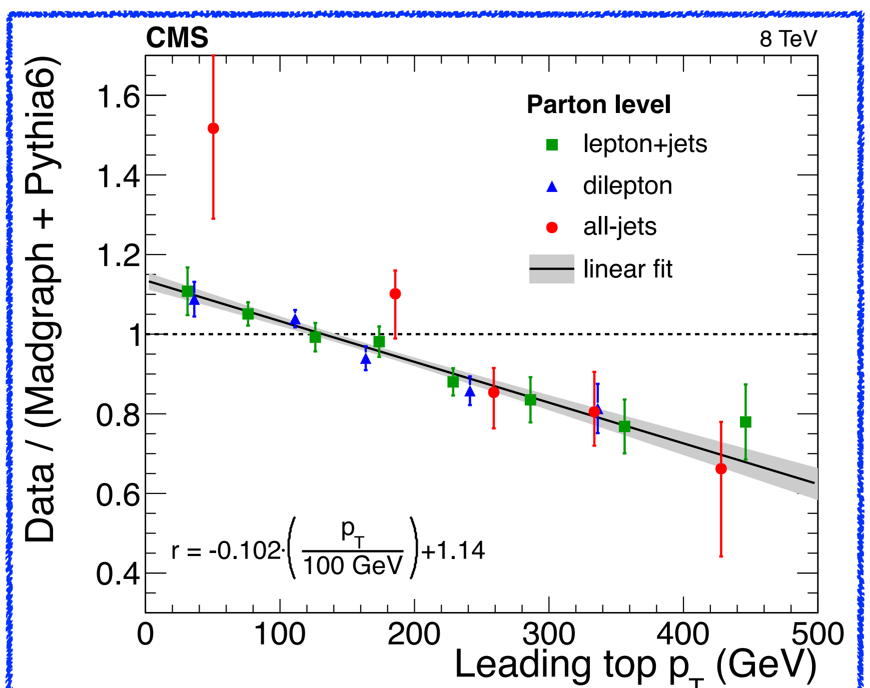
all-hadronic channel | **boosted top R=1 jets p_T > 300 GeV** | **ℓ+jets channel comprehensive study**

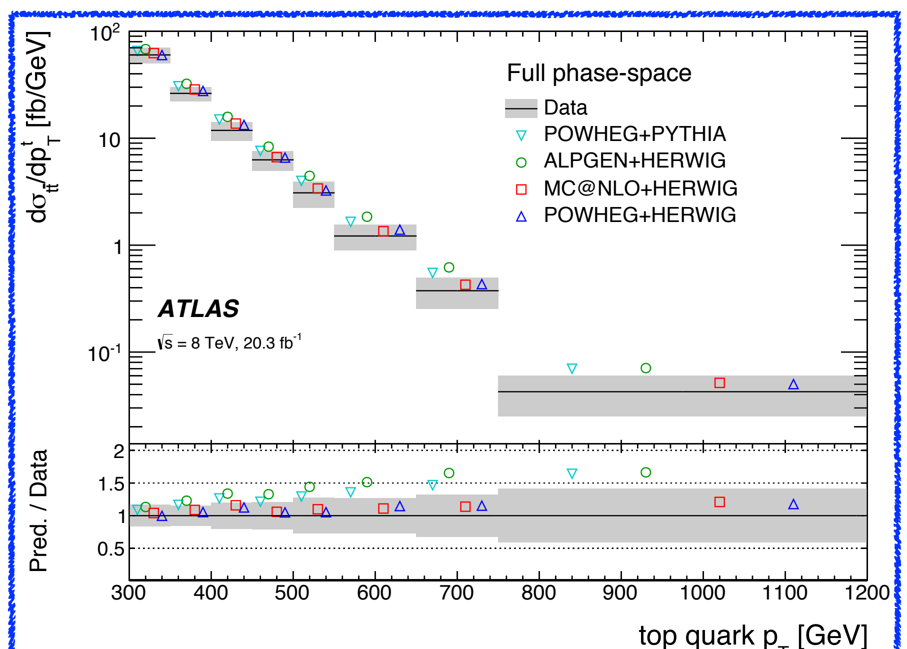


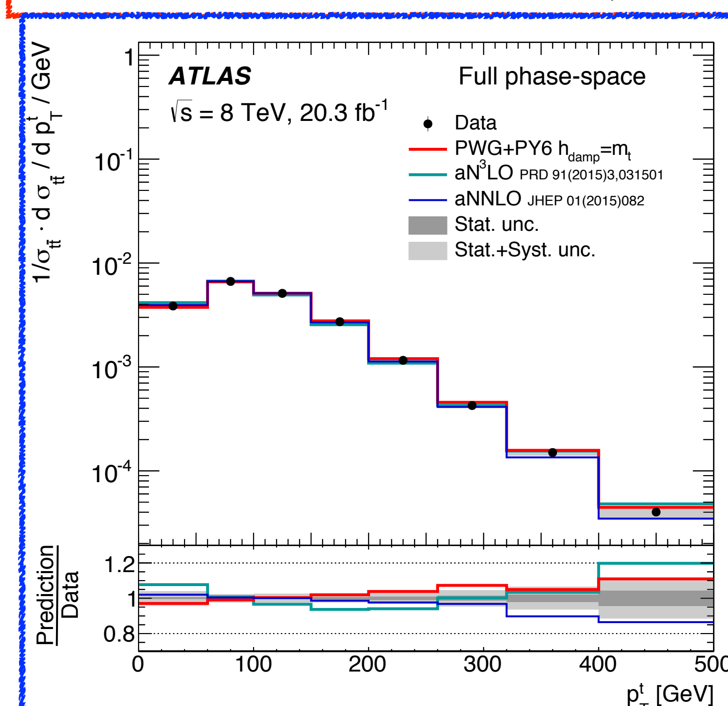




Particle-level







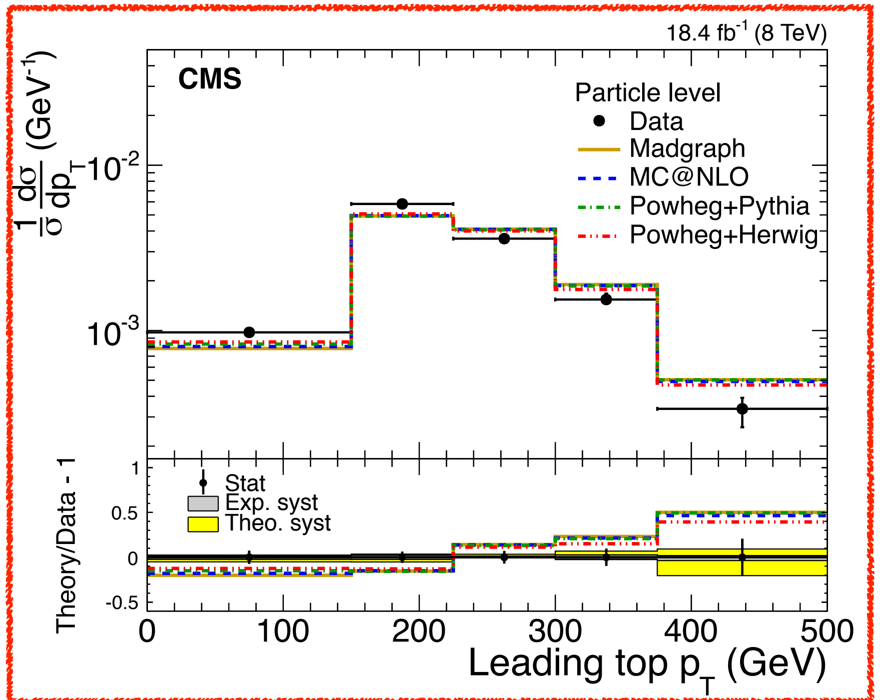
Parton-level

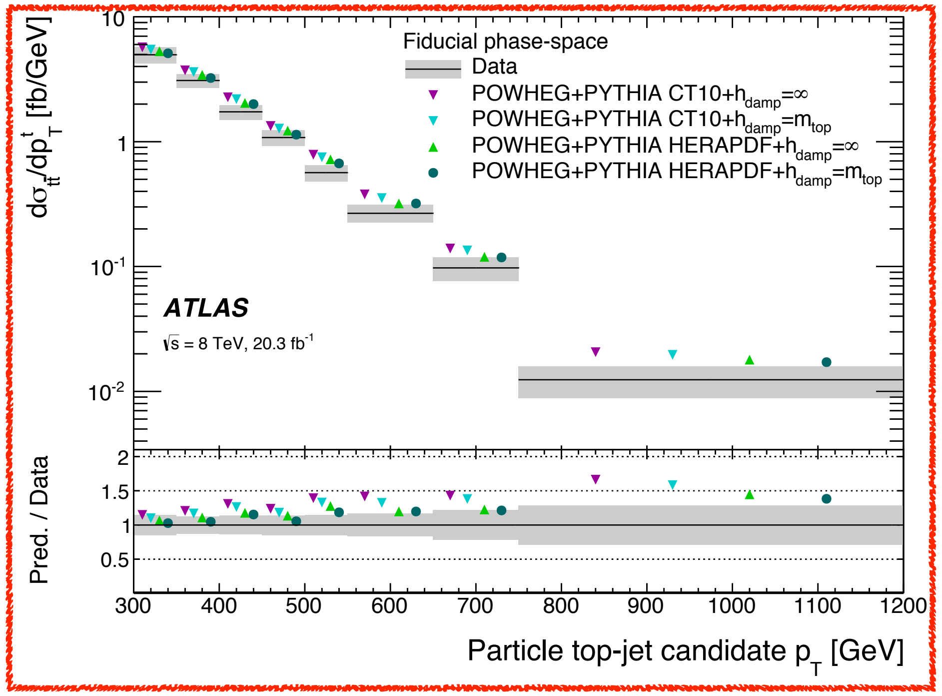
$t\bar{t}$ differential – top quark p_T

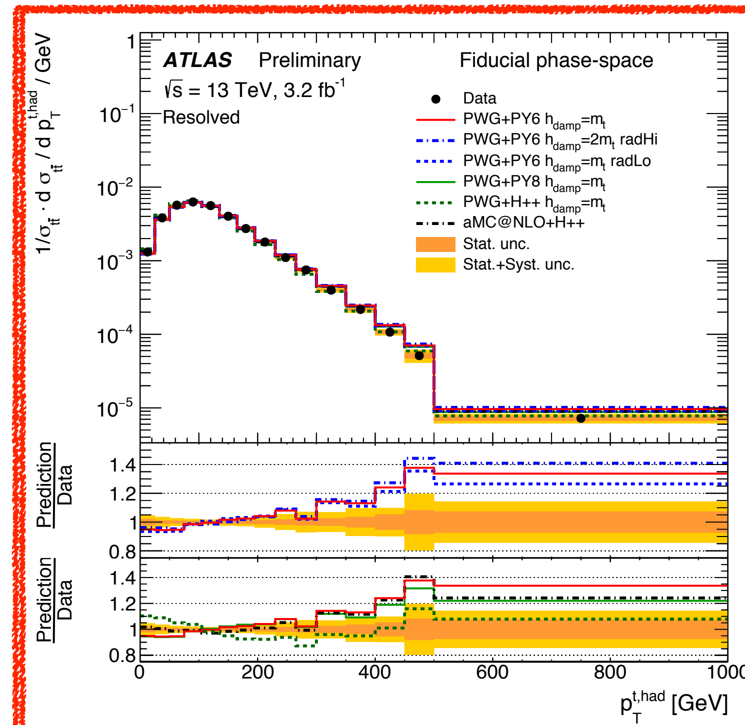
Mis-modeling of top p_T spectrum confirmed in all decay channels

arXiv:1509.06076, EPJC 76 (2016) 128 arXiv:1510.03818, PRD 93 (2016) 032009

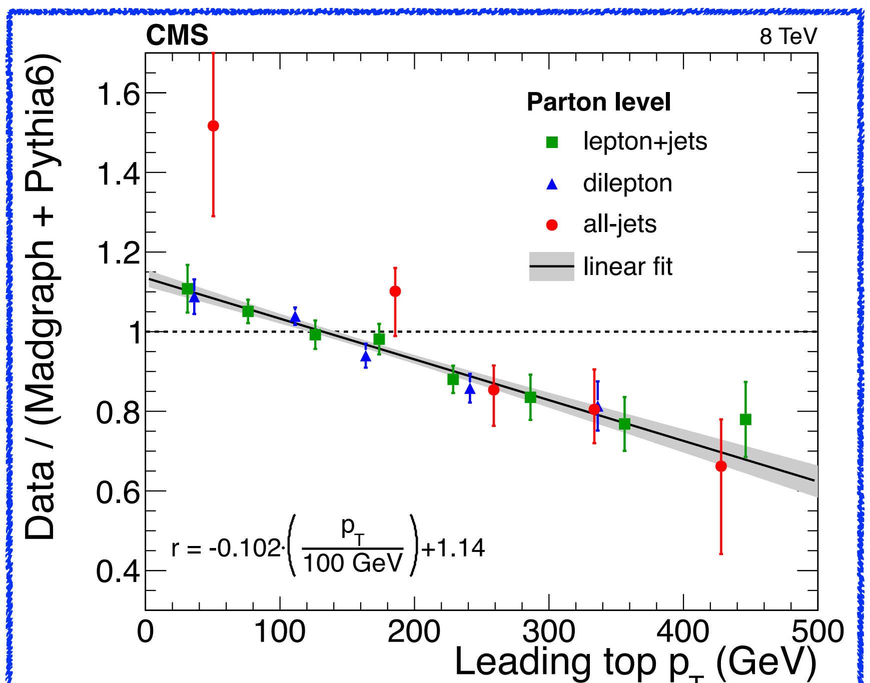
all-hadronic channel **boosted top R=1 jets p_T > 300 GeV** **ℓ+jets channel 13 TeV** ATLAS-CONF-2016-040

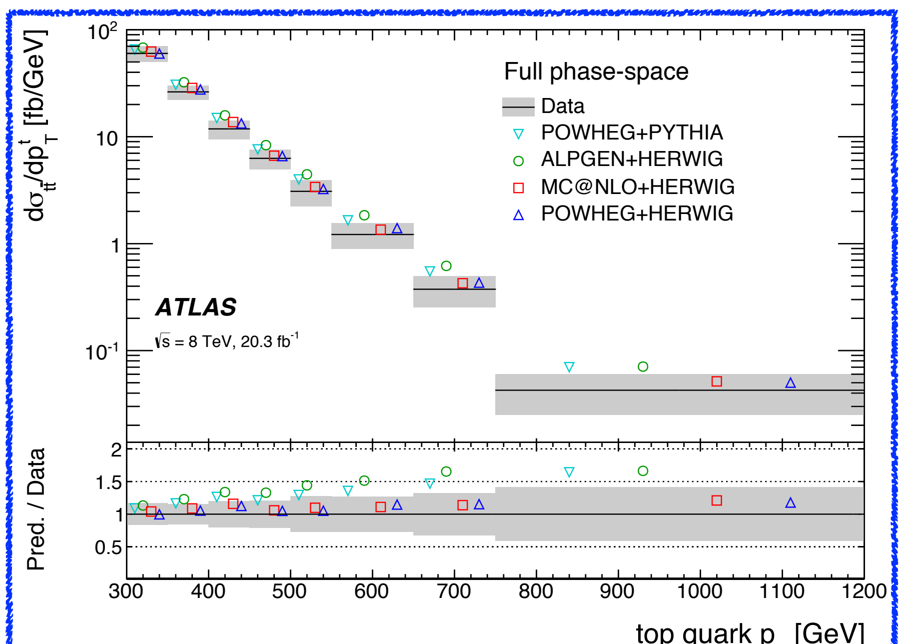


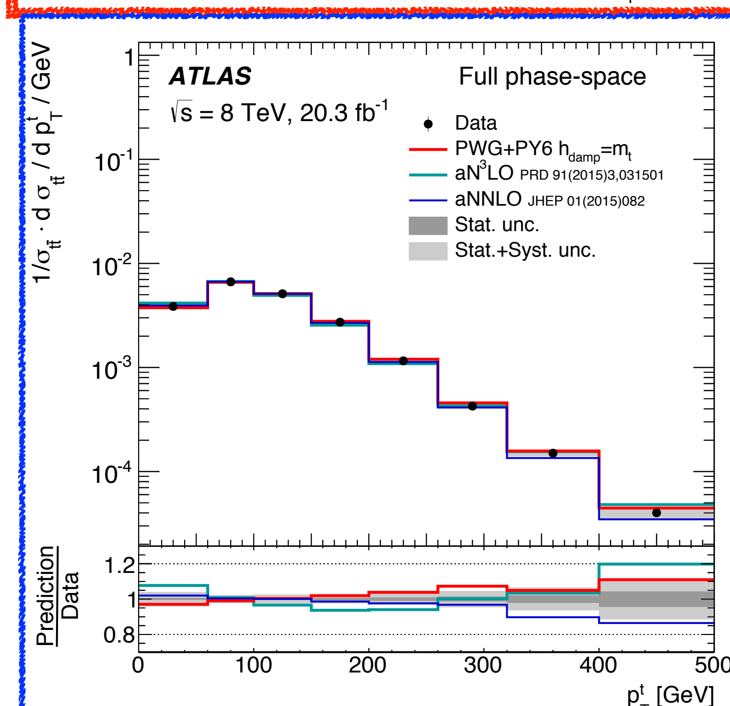




Particle-level







Parton-level

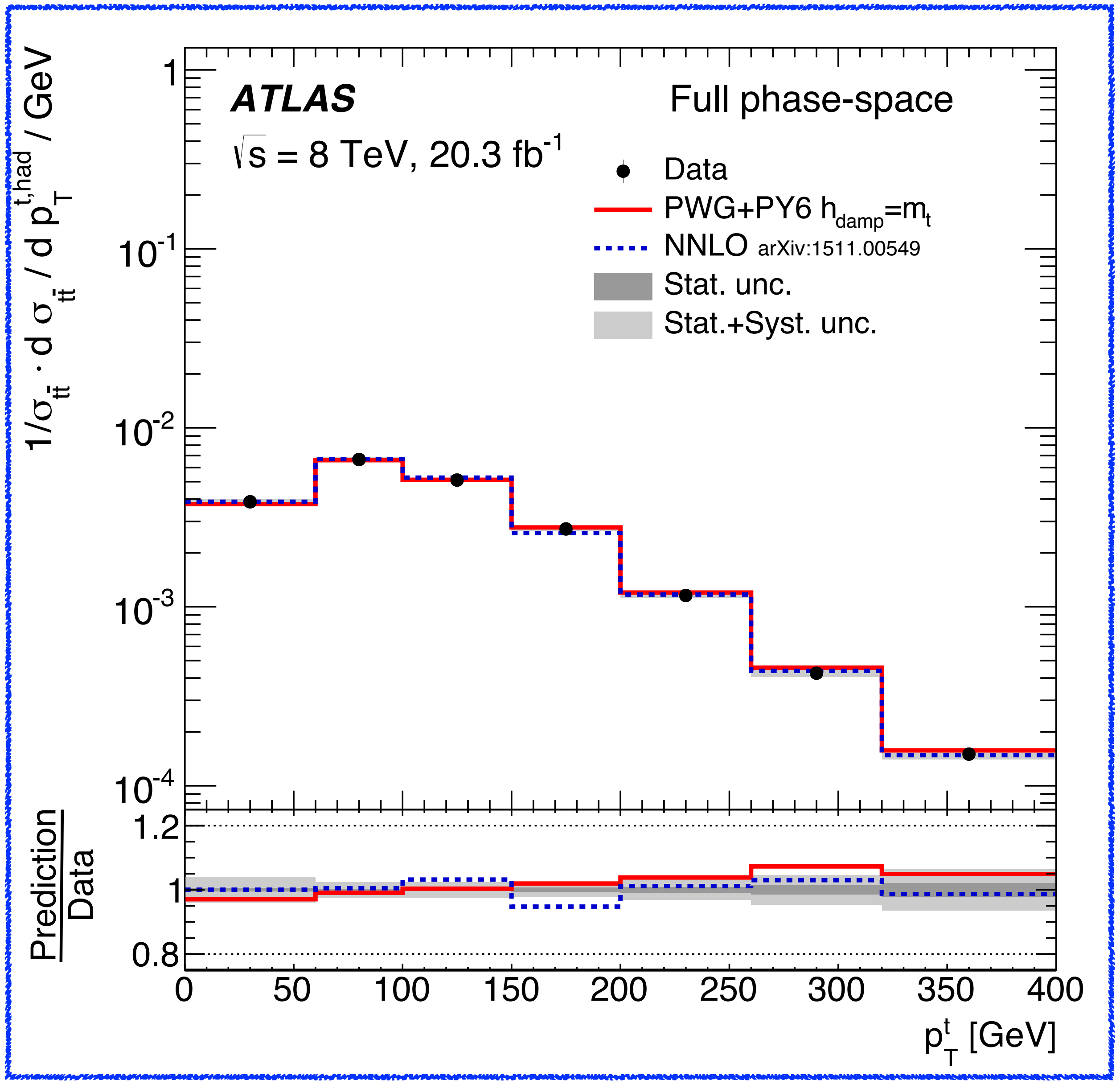
$t\bar{t}$ differential – top quark p_T

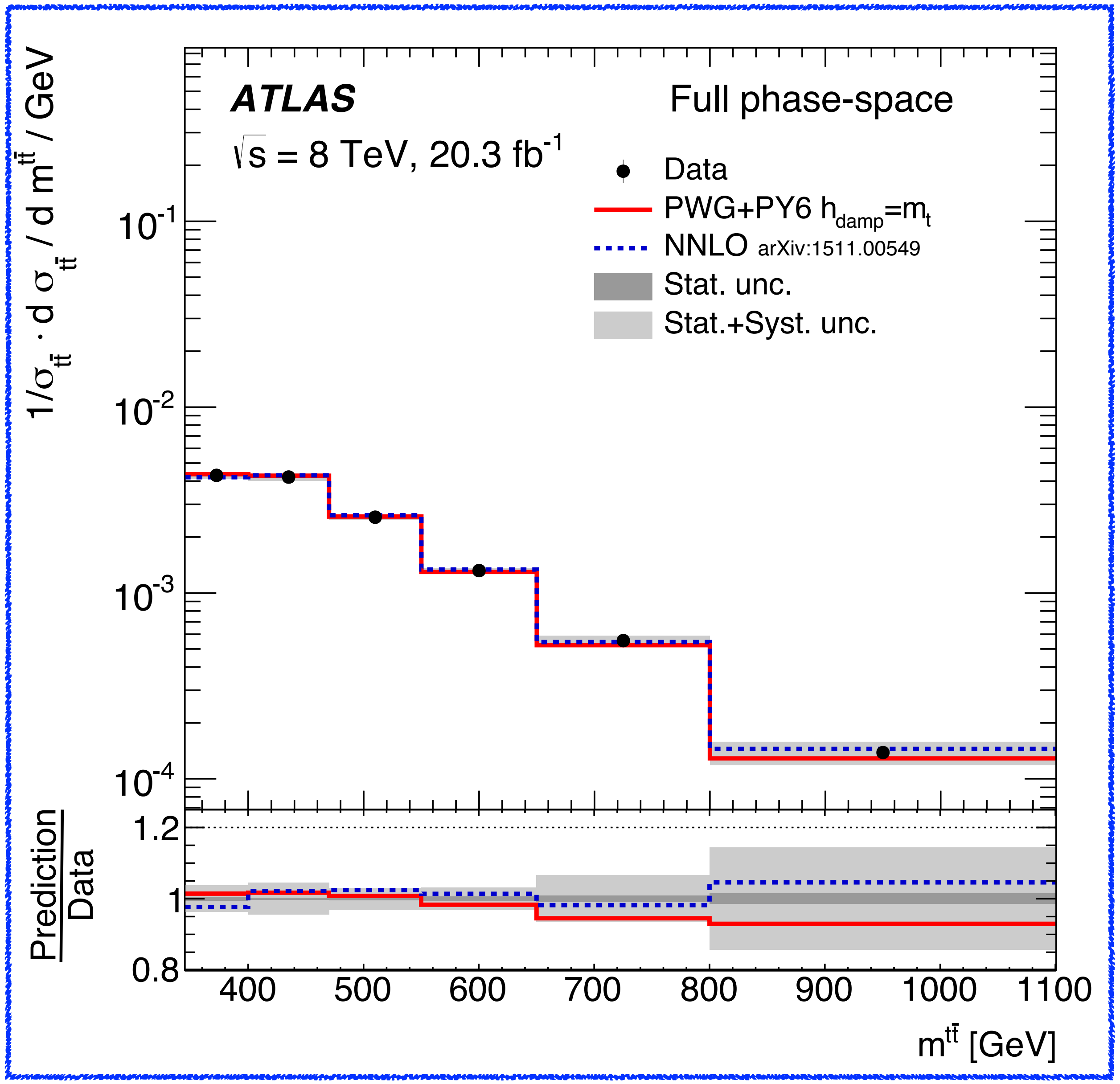
Full NNLO $t\bar{t}$ differential calculation available

M. Czakon, D. Heymes and A. Mitov
arXiv:1511.00549, PRL 116 (2016) 082003

- Top quark p_T and y
- Top quark pair $m_{t\bar{t}}$
- Very good agreement with measurements

arXiv:1511.04716, submitted to EPJC

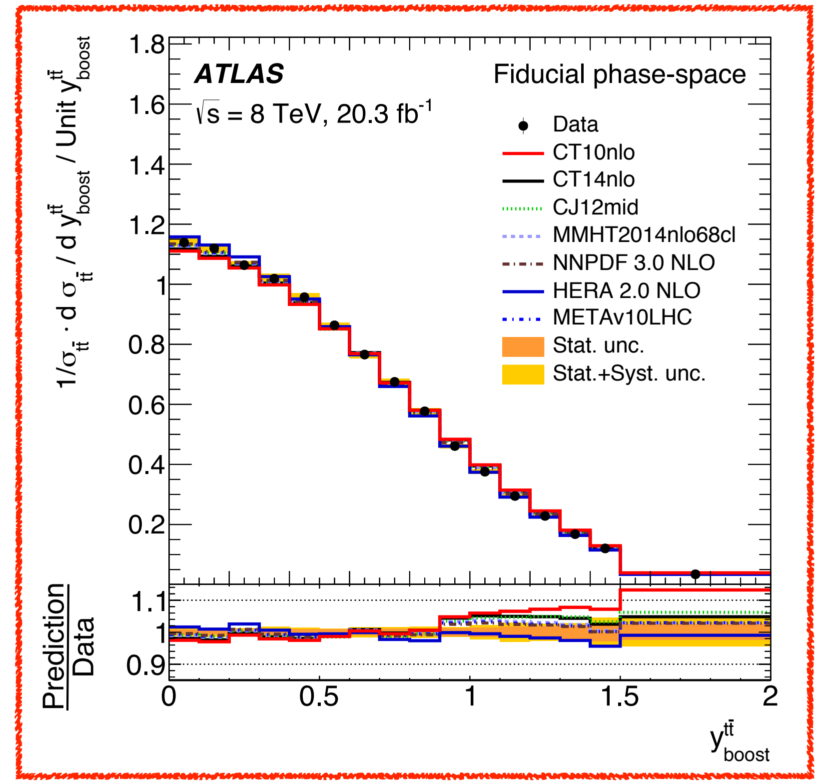




Comprehensive analysis of kinematics

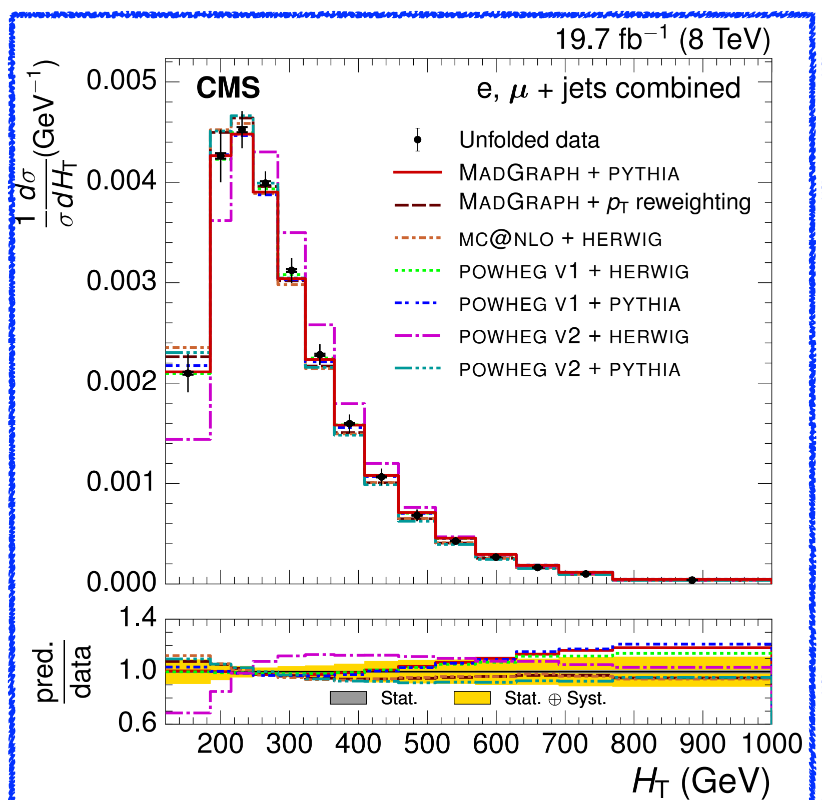
arXiv:1511.04716, submitted to EPJC

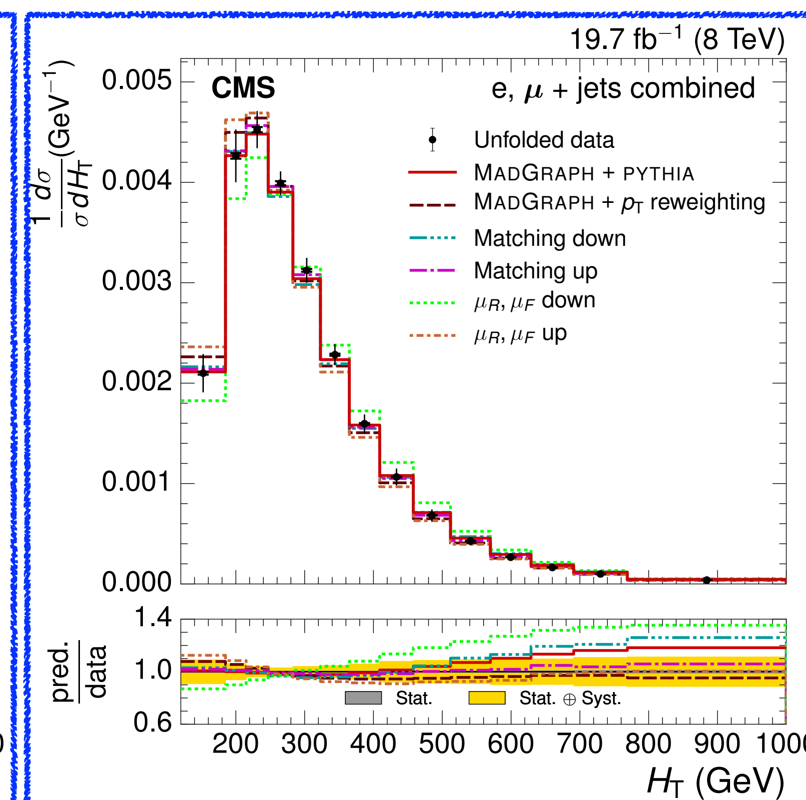
- hadronic top quark p_T and $|y|$
- $t\bar{t}$ system : $m_{t\bar{t}}$, $p_{T,t\bar{t}}$ and $|y_{t\bar{t}}|$
- $\chi^{t\bar{t}}$ and $y_{boost}^{t\bar{t}}$
  - → hard scattering interaction
- $\Delta\varphi^{t\bar{t}}$, $|p_{out}{}^{t\bar{t}}|$, $H_T{}^{t\bar{t}}$, R_{Wt}
  - → emission of radiation along the $t\bar{t}$ pair



arXiv:1607.00837, submitted to PRD

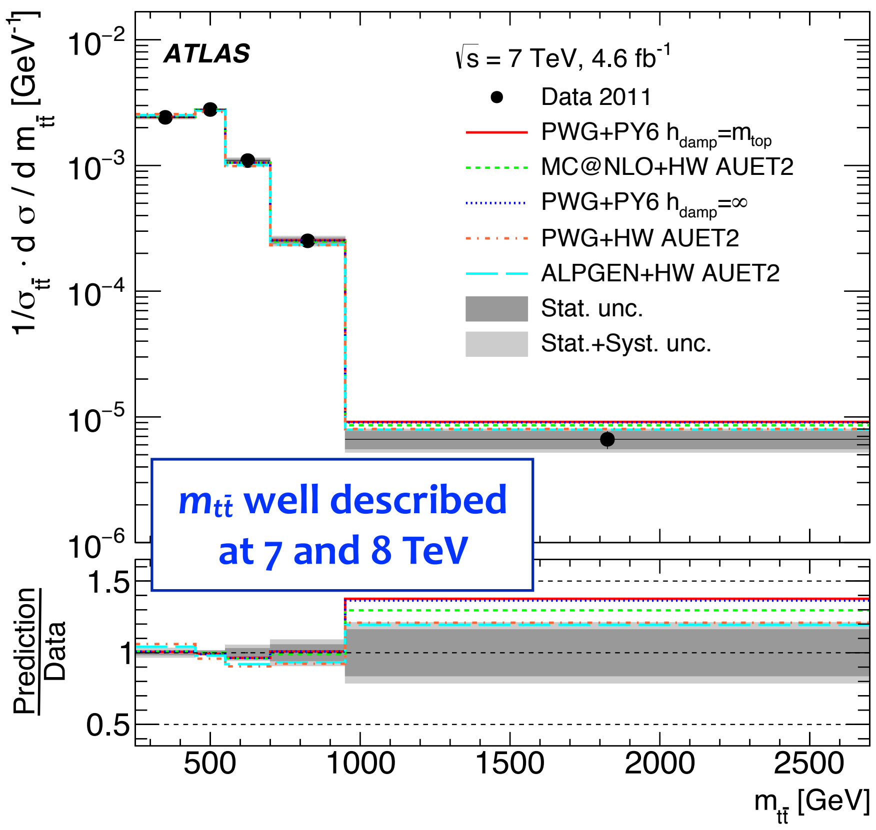
- $E_T{}^{miss}$, H_T, S_T, $p_T(W)$
  - compare generators
  - compare parameter choices





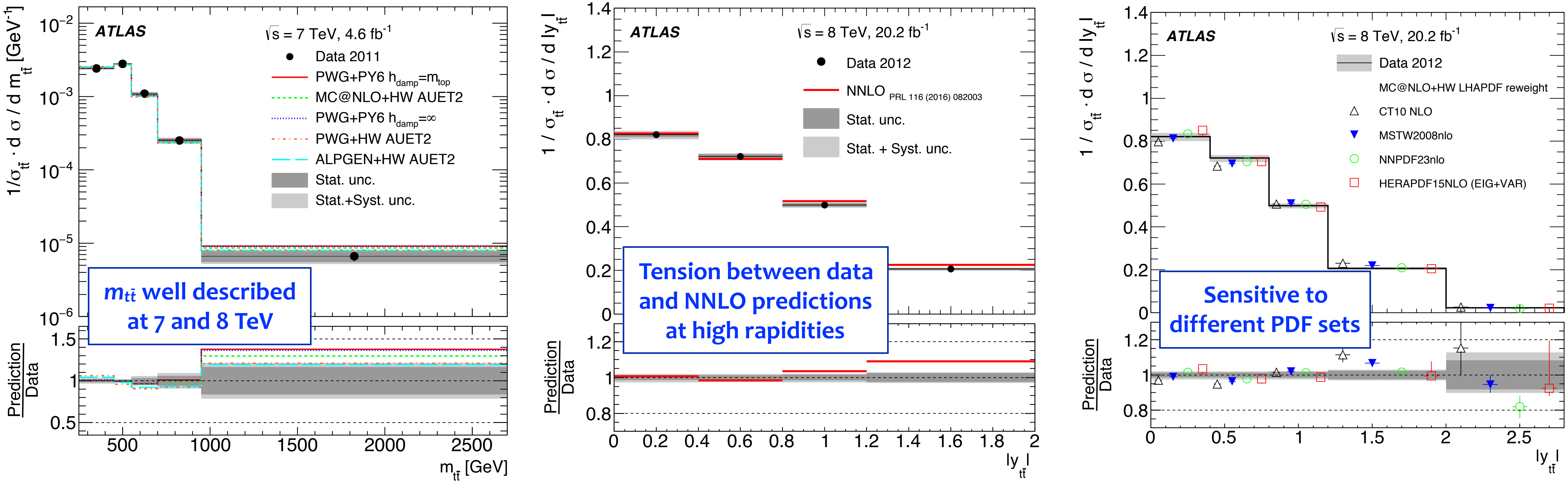
$t\bar{t}$ differential – dilepton channel

arXiv:1607.07281, submitted to PRD



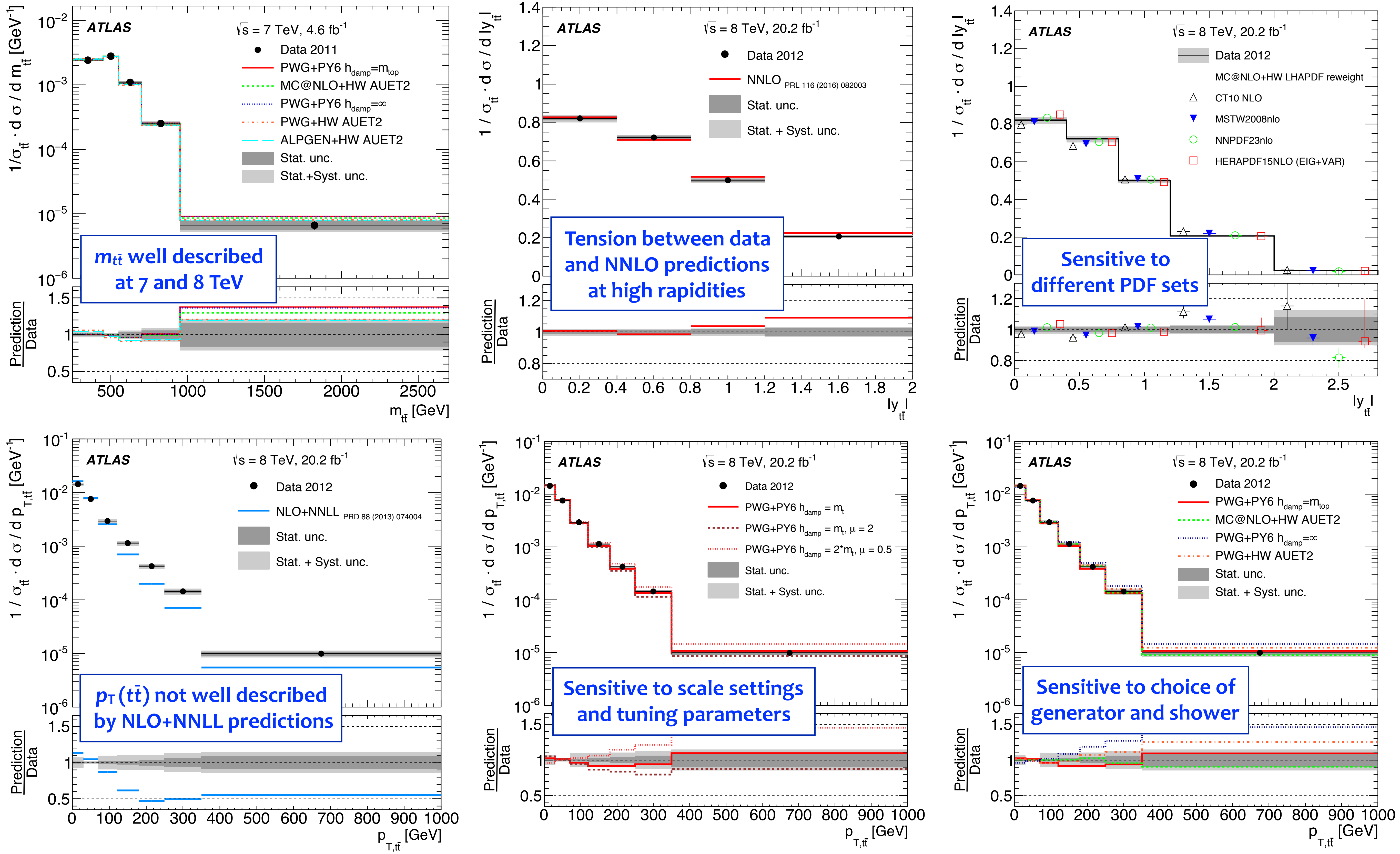
$t\bar{t}$ differential – dilepton channel

arXiv:1607.07281, submitted to PRD



$t\bar{t}$ differential – dilepton channel

arXiv:1607.07281, submitted to PRD



$t\bar{t}$+jets – dilepton channel

universitätbonn erc

Counting number of jets

- with different jet p_T thresholds

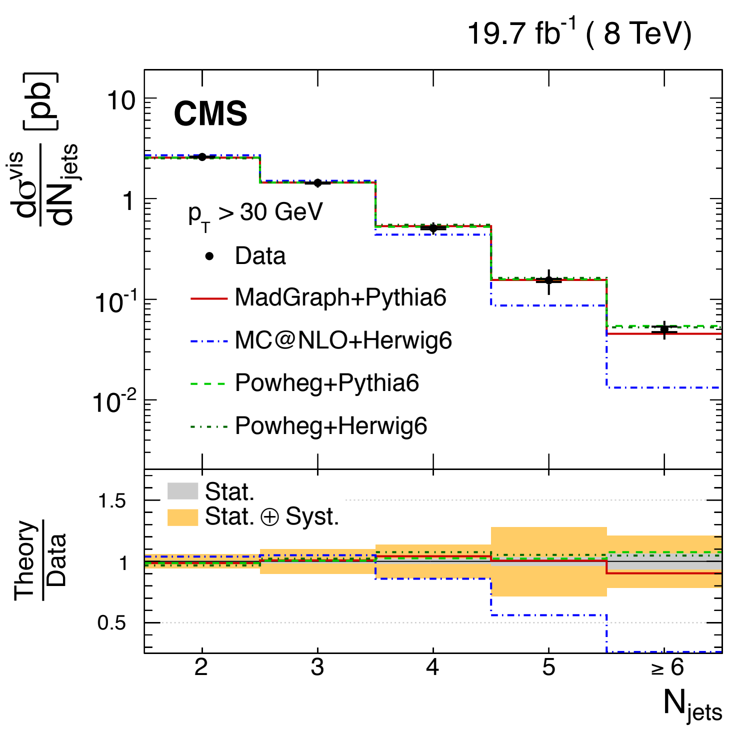
Characterise additional jets

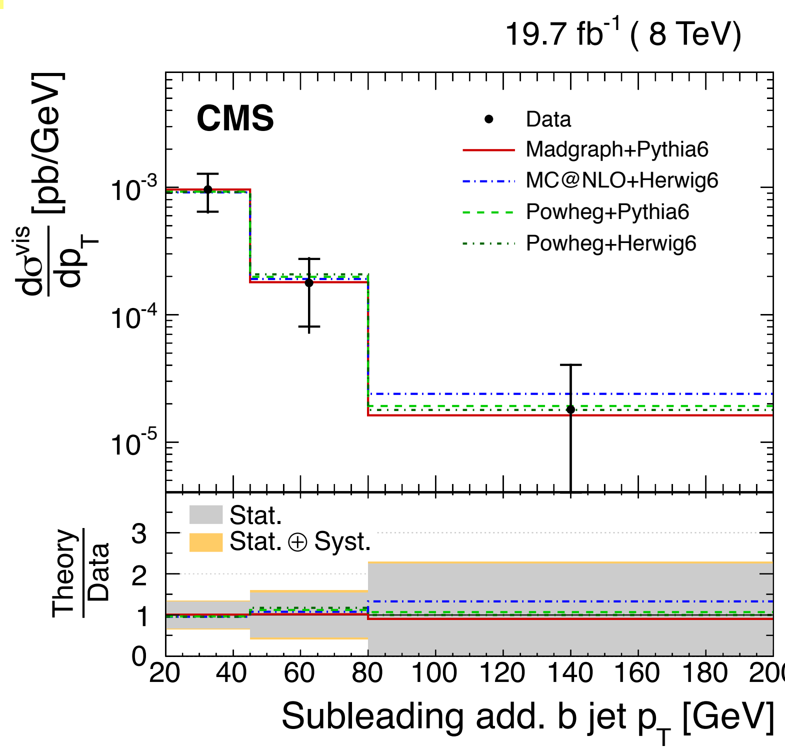
- p_T, $|\eta|$, ΔR_{jj}, m_{jj}

Include gap fraction measurements

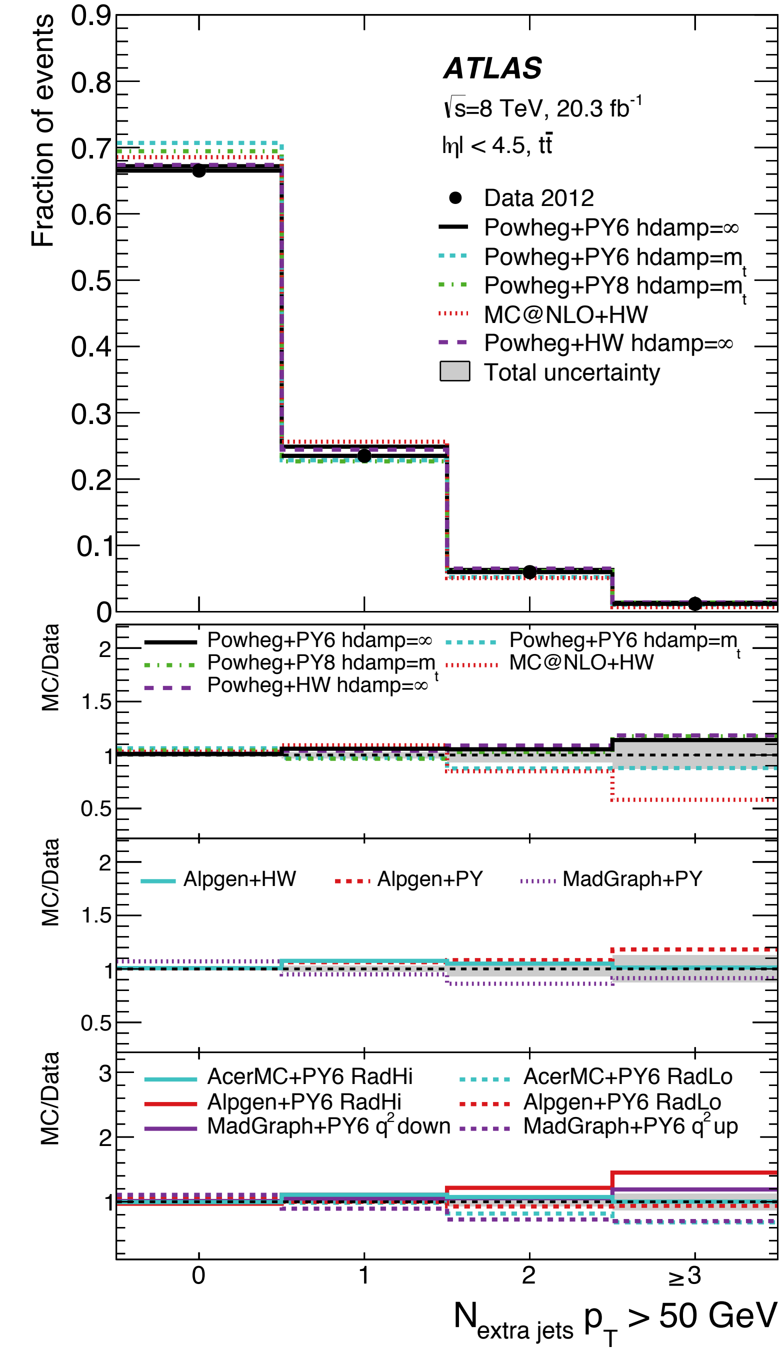
- events without additional jets above threshold

arXiv:1510.03072, EPJC 76 (2016) 379





arXiv:1606.09490, submitted to JHEP

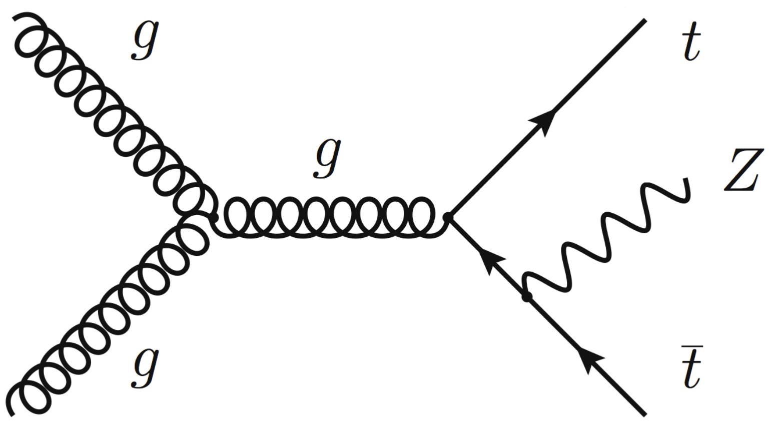


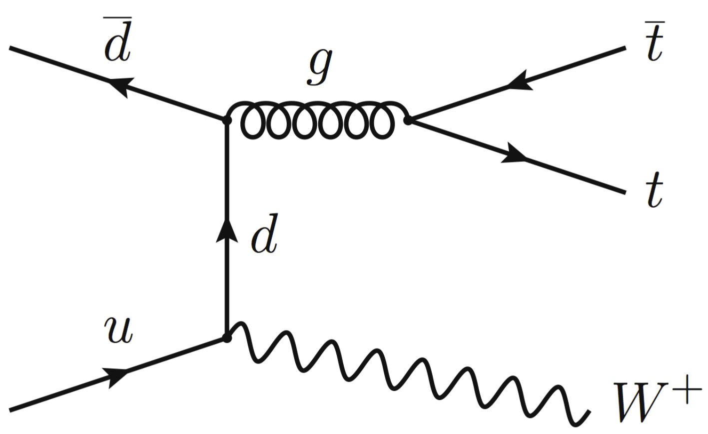
- All distributions well modelled with appropriate parameter choices

$t\bar{t}Z$ and $t\bar{t}W$

Couplings of top quark to Z are largely unexplored

- **production sensitive to new physics**
- **$t\bar{t}Z$ and $t\bar{t}W$ backgrounds to new physics searches and $t\bar{t}H$**

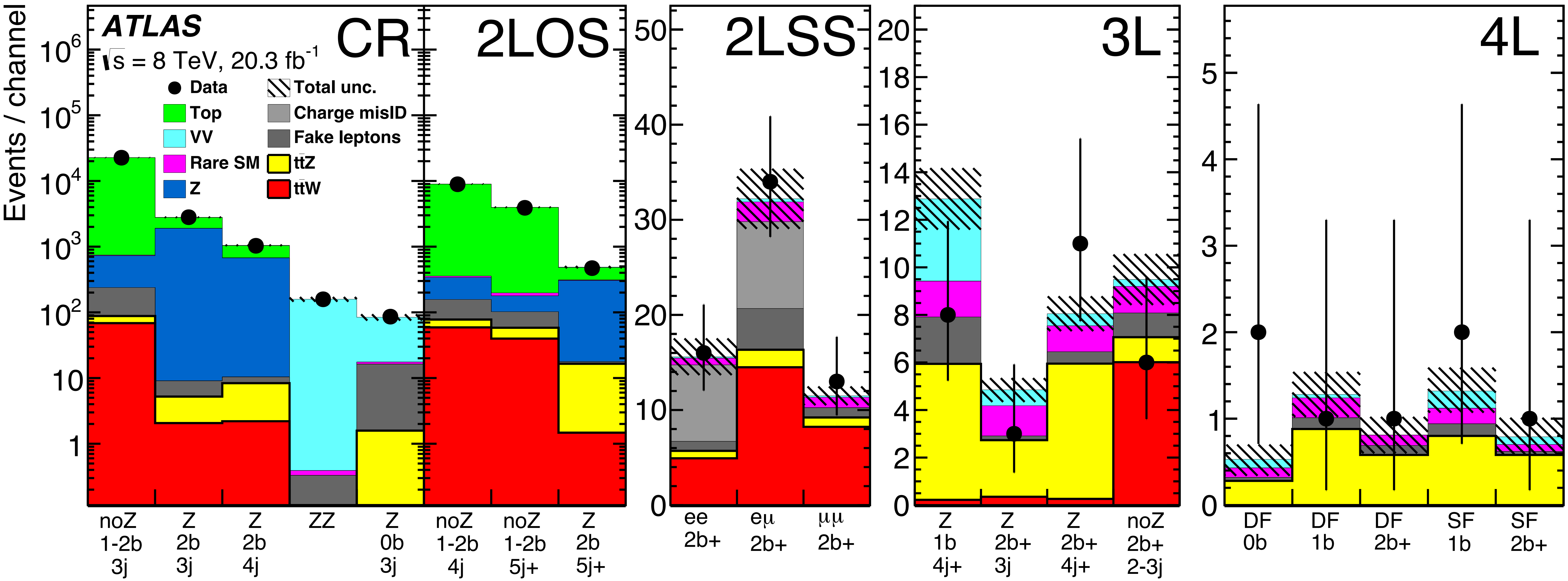




Four signal regions: 2ℓ OS, 2ℓ SS, 3ℓ, 4ℓ

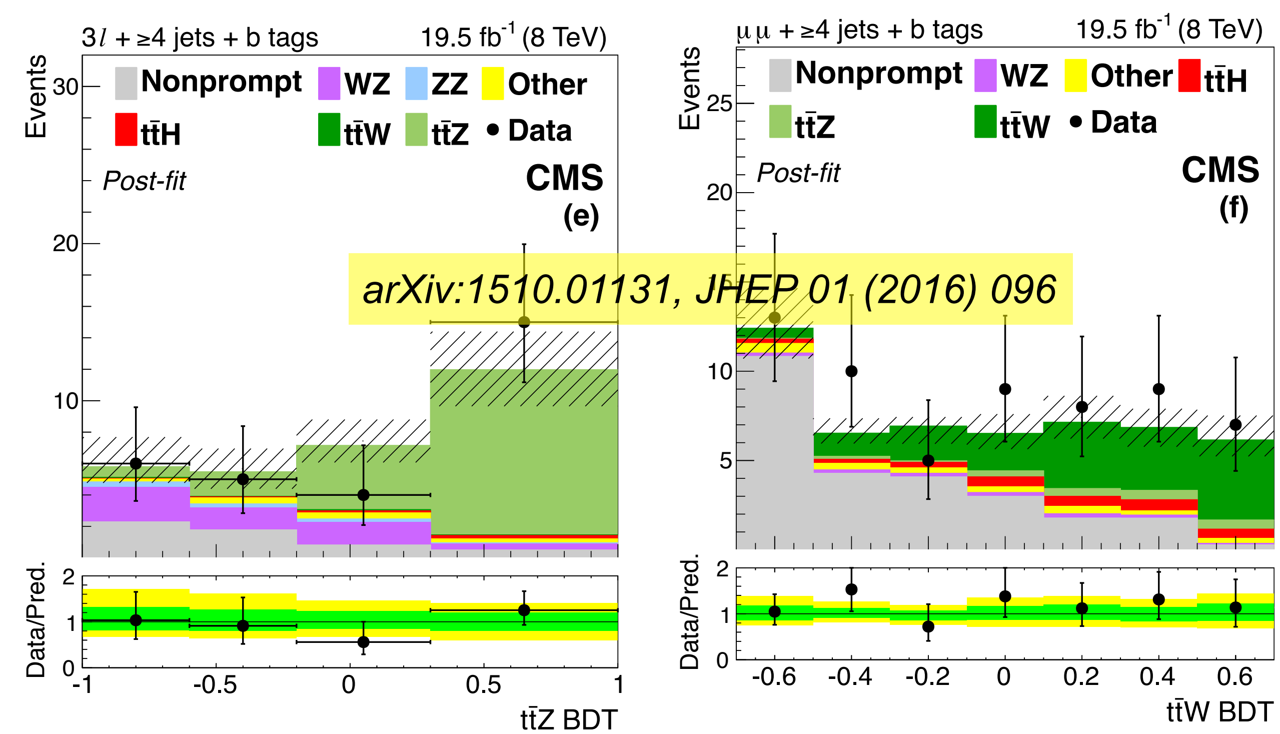
- **extract $t\bar{t}Z$ and $t\bar{t}W$ simultaneously in a binned profile likelihood fit**
- **increase sensitivity by splitting channels according to**
  - number of jets and *b*-jets
  - relative lepton flavour (*Z* or not-*Z* like), $m_{\ell\ell}$
  - E_T^{miss} or H_T
- **profile likelihood technique, statistical uncertainty dominates**

$t\bar{t}Z$ and $t\bar{t}W$ fit to data



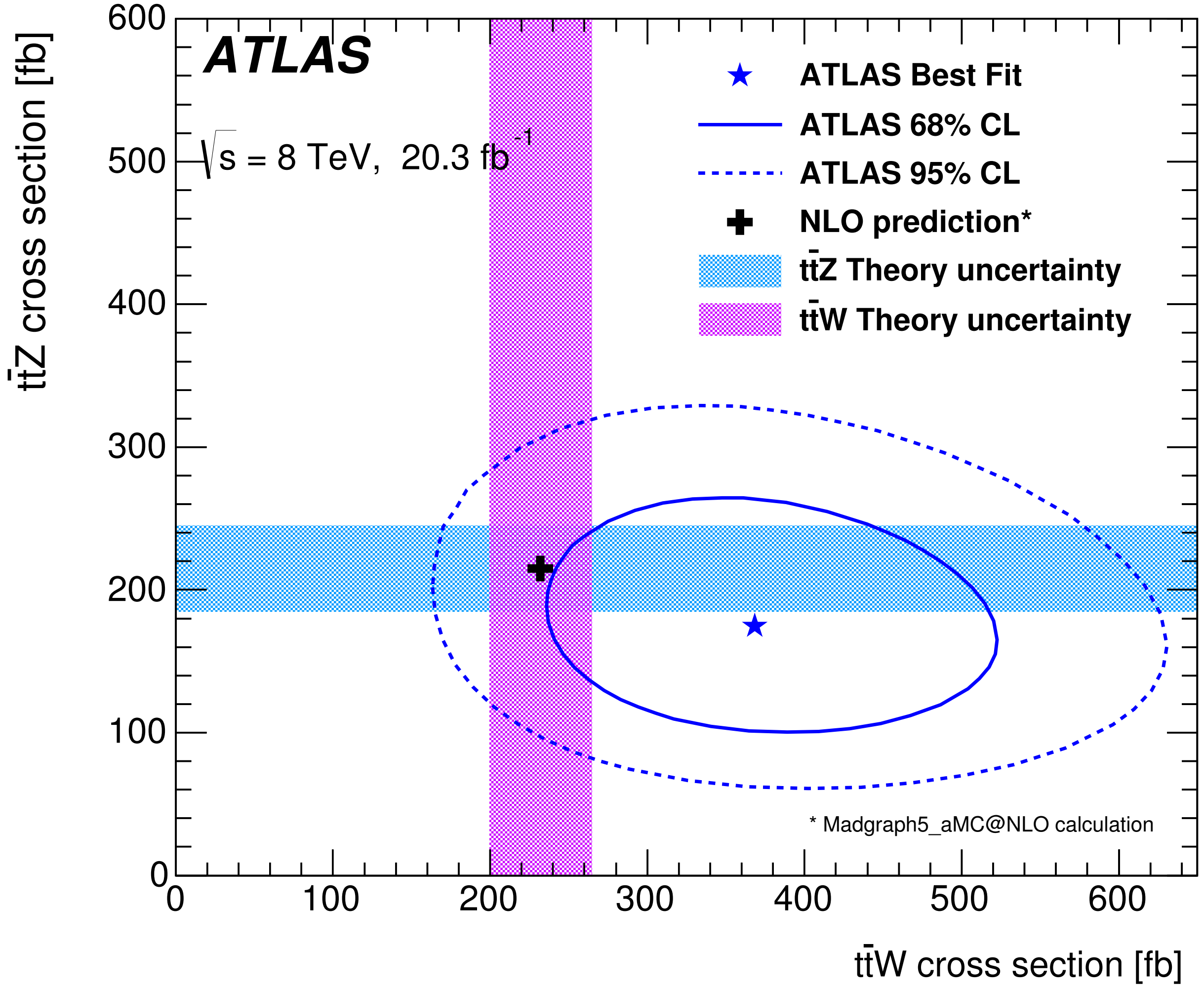
arXiv:1509.05276, JHEP 11 (2015) 172

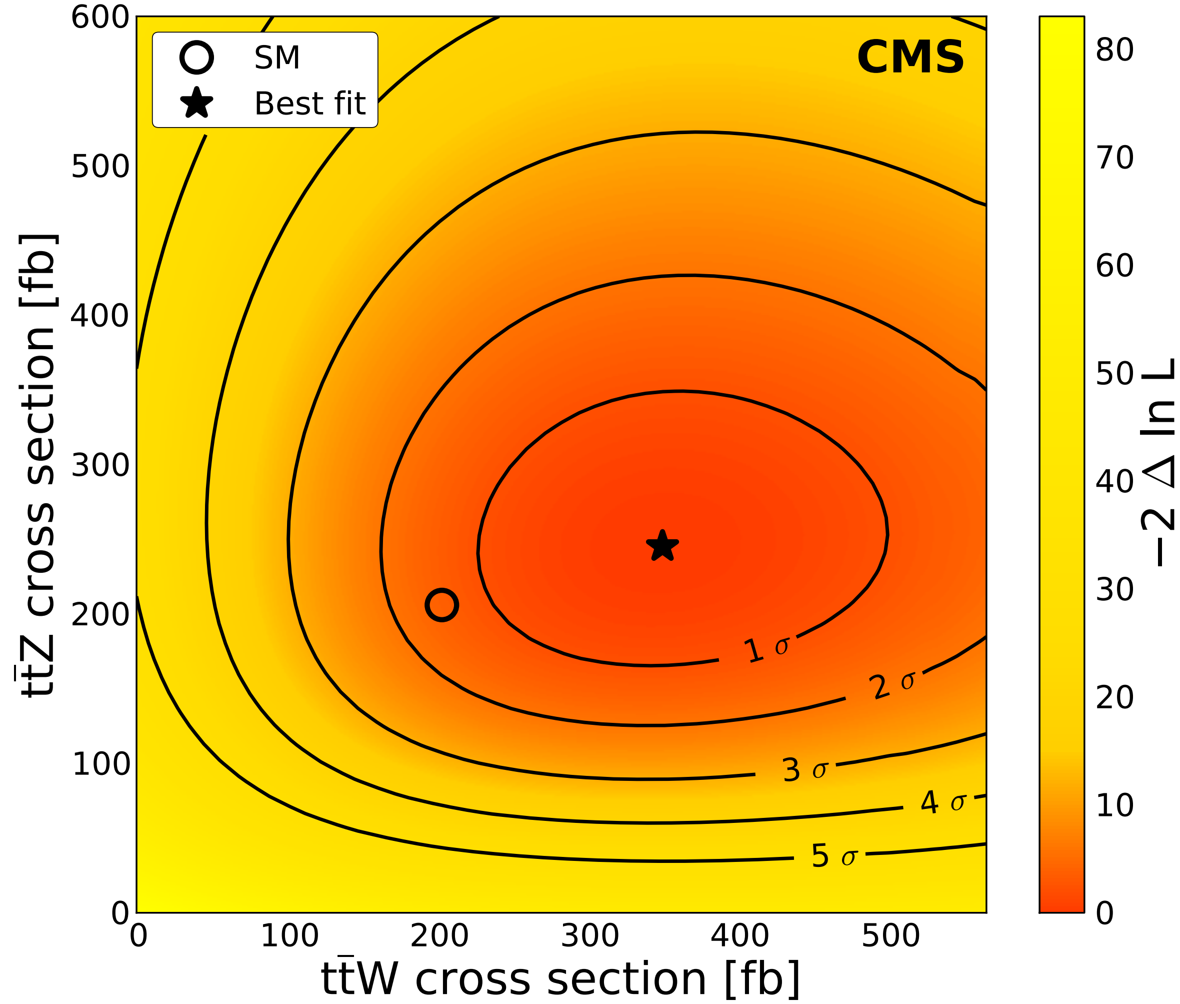
- **additionally attempt full (partial) $t\bar{t}Z/W$ reconstruction**
  - match reconstructed objects to W, Z, $t\bar{t}$
  - combine into linear discriminant
  - choose best permutation
- **combine information into BDT** →
  - using kinematic quantities



arXiv:1510.01131, JHEP 01 (2016) 096

→ **associated $t\bar{t}Z$ and $t\bar{t}W$ production established at 8 TeV**





Channel	$t\bar{t}W$ significance Expected	$t\bar{t}W$ significance Observed	$t\bar{t}Z$ significance Expected	$t\bar{t}Z$ significance Observed
2ℓOS	0.4	0.1	1.4	1.1
2ℓSS	2.8	5.0	-	-
3ℓ	1.4	1.0	3.7	3.3
4ℓ	-	-	2.0	2.4
Combined	3.2	5.0	4.5	4.2

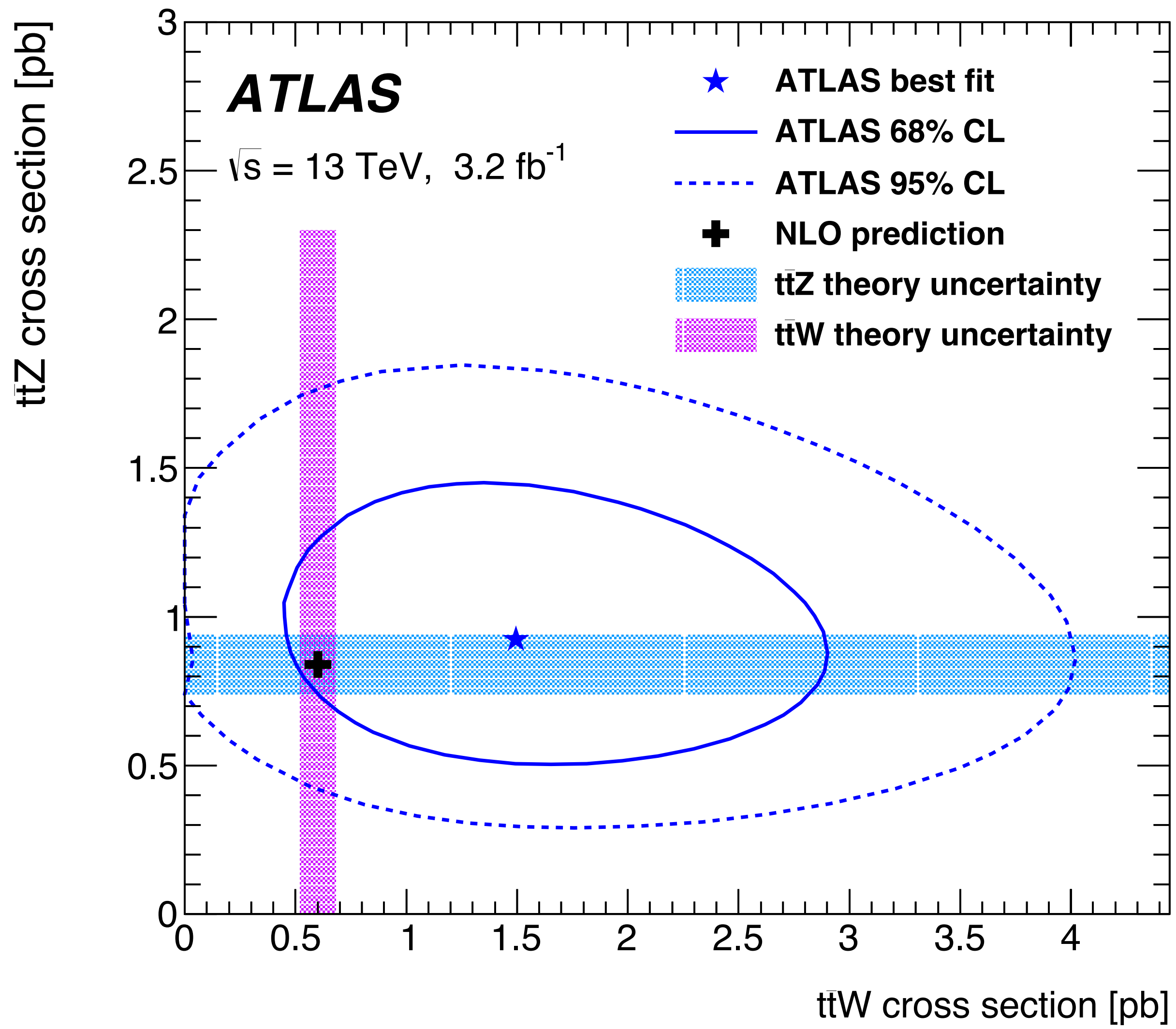
$t\bar{t}W$ Channels	Significance Expected	Significance Observed
SS	3.4	4.9
3ℓ	1.0	1.0
SS + 3ℓ	3.5	4.8

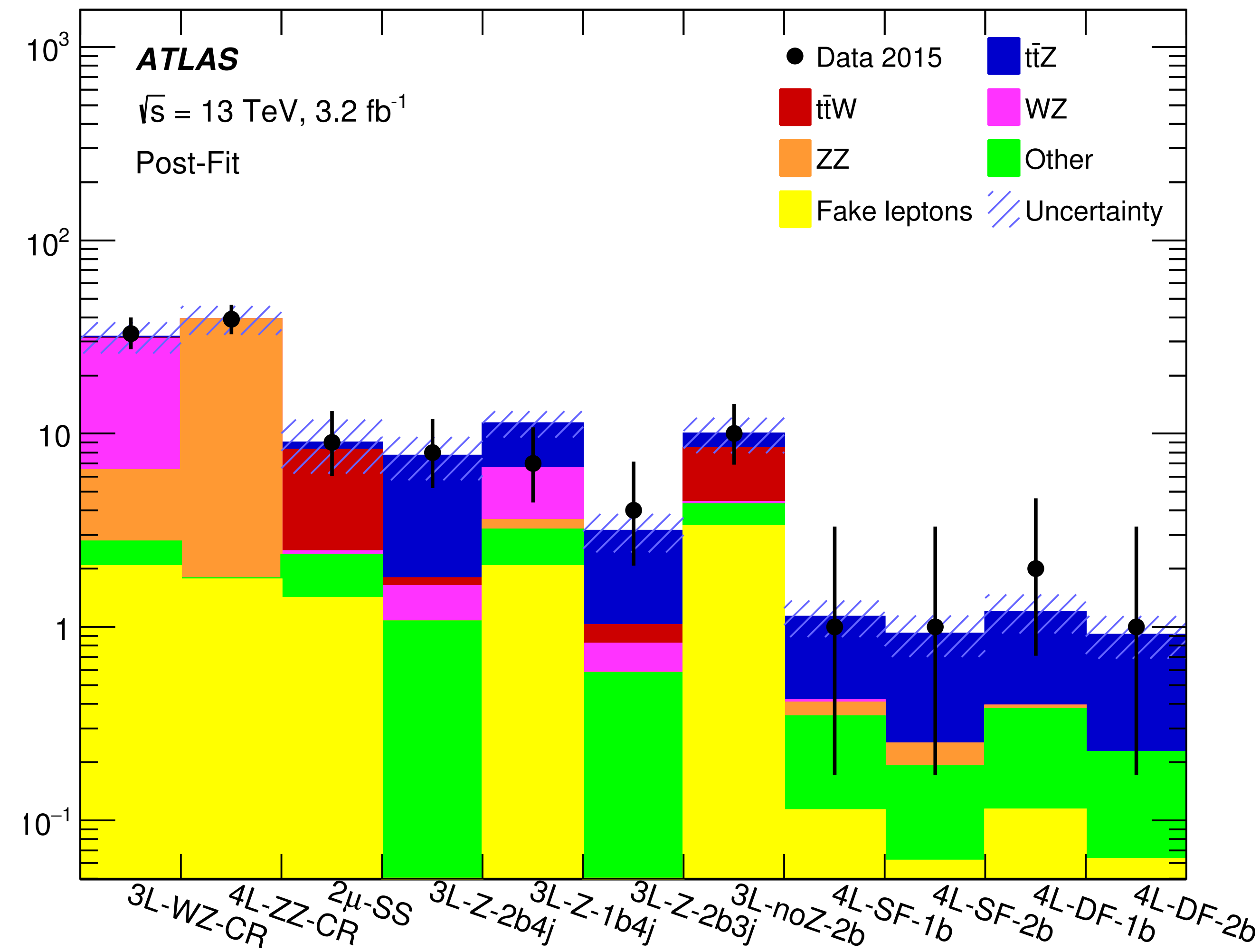
$t\bar{t}Z$ Channels	Significance Expected	Significance Observed
OS	1.8	2.1
3ℓ	4.6	5.1
4ℓ	2.7	3.4
OS + 3ℓ + 4ℓ	5.7	6.4

$t\bar{t}Z$ and $t\bar{t}W$ results

→ associated $t\bar{t}Z$ and $t\bar{t}W$ production established at 8 TeV

arXiv:1609.01599, submitted to EPJC



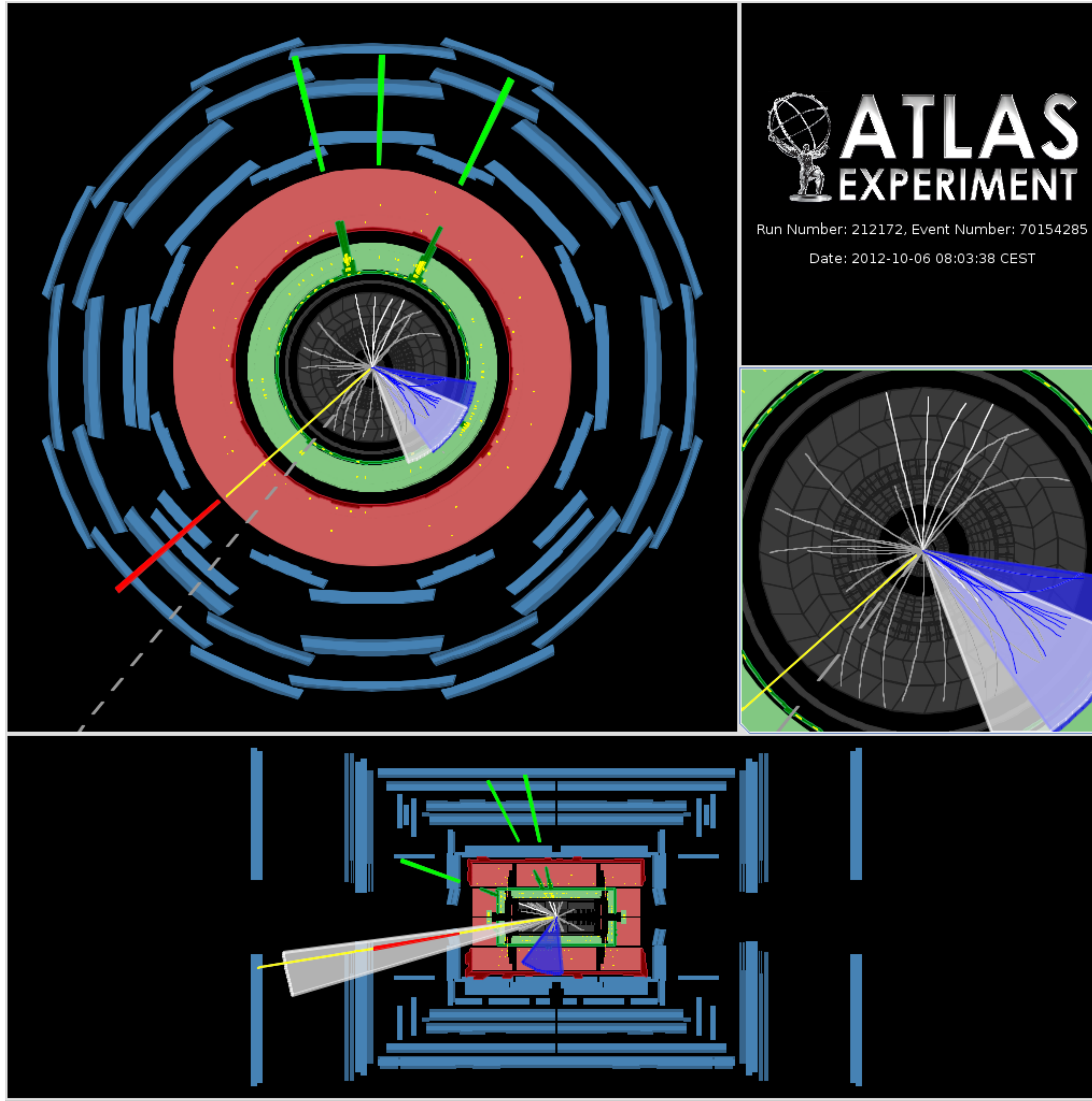


→ now also measured at 13 TeV with 2015 data

- $\sigma_{t\bar{t}Z} = 0.9 \pm 0.3$ pb (3.9σ)
- $\sigma_{t\bar{t}W} = 1.5 \pm 0.8$ pb (2.2σ)

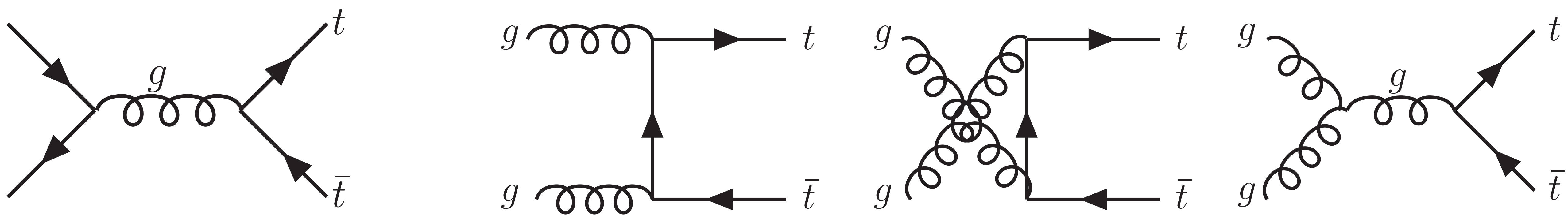
$t\bar{t}Z$ candidate

- 4 leptons: $\mu^- e_1^+ e_2^- e_3^+$
- $m(e_2 e_3)$ = 94 GeV
- 2 jets p_T > 50 GeV
- both b-tagged
- E_T^{miss} = 57 GeV

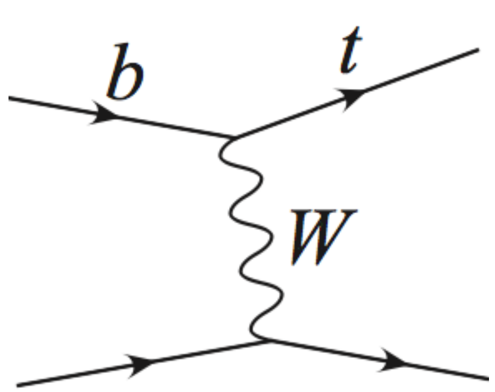


Top-quark production

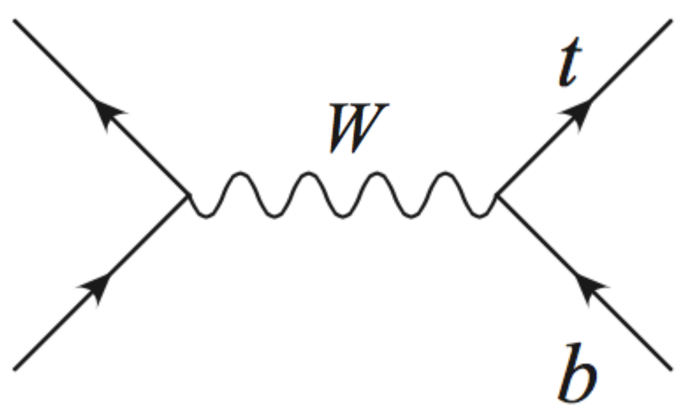
Top-quark pairs via strong interaction



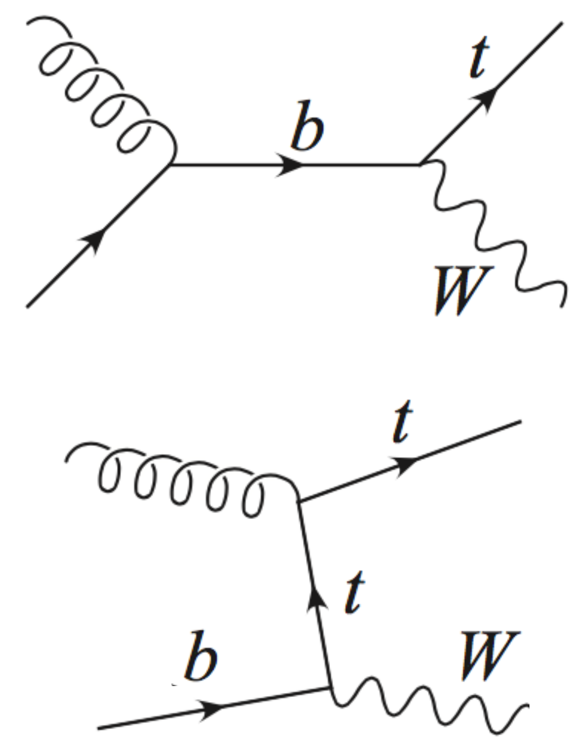
Single-top quarks via weak interaction



t-channel



s-channel

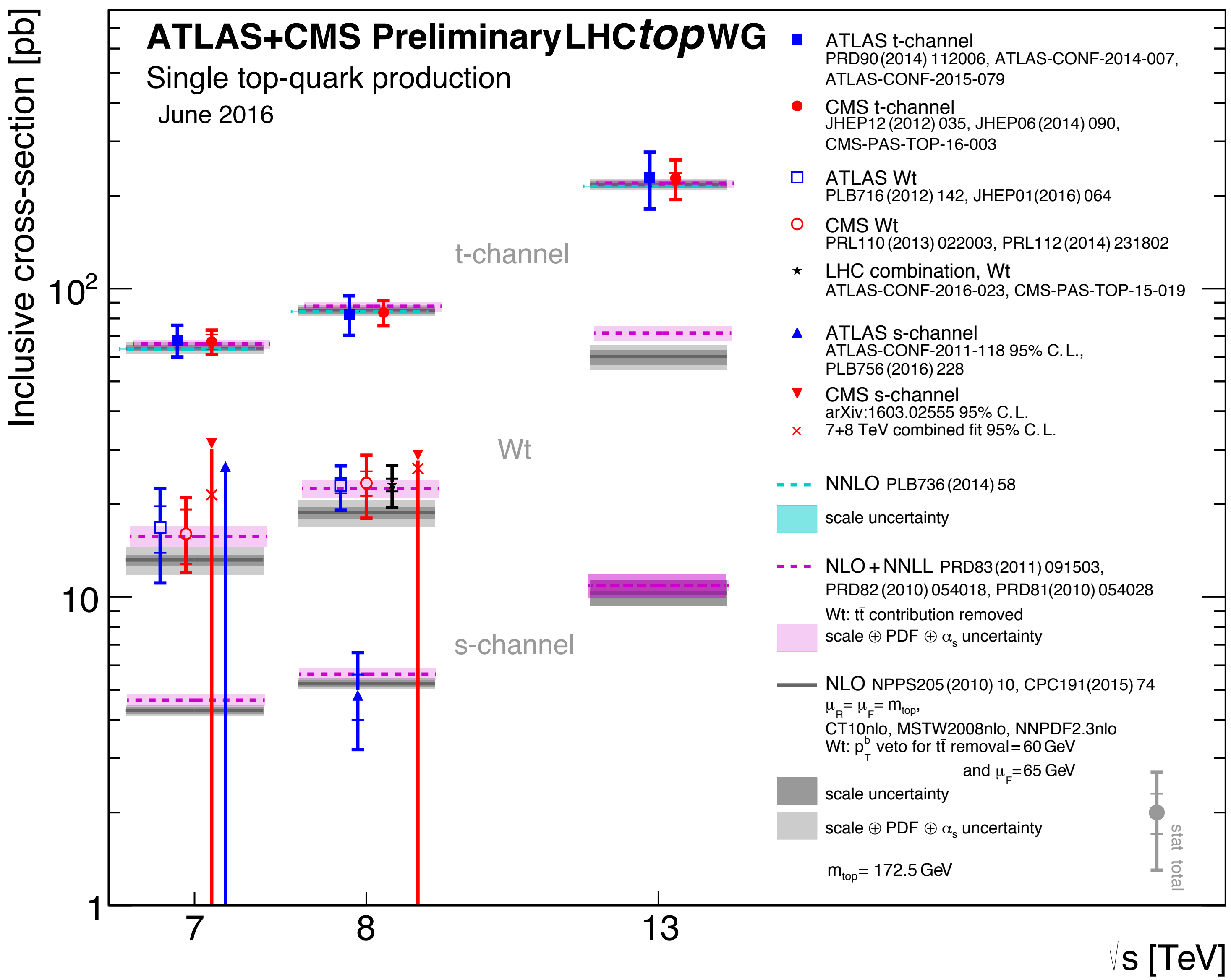


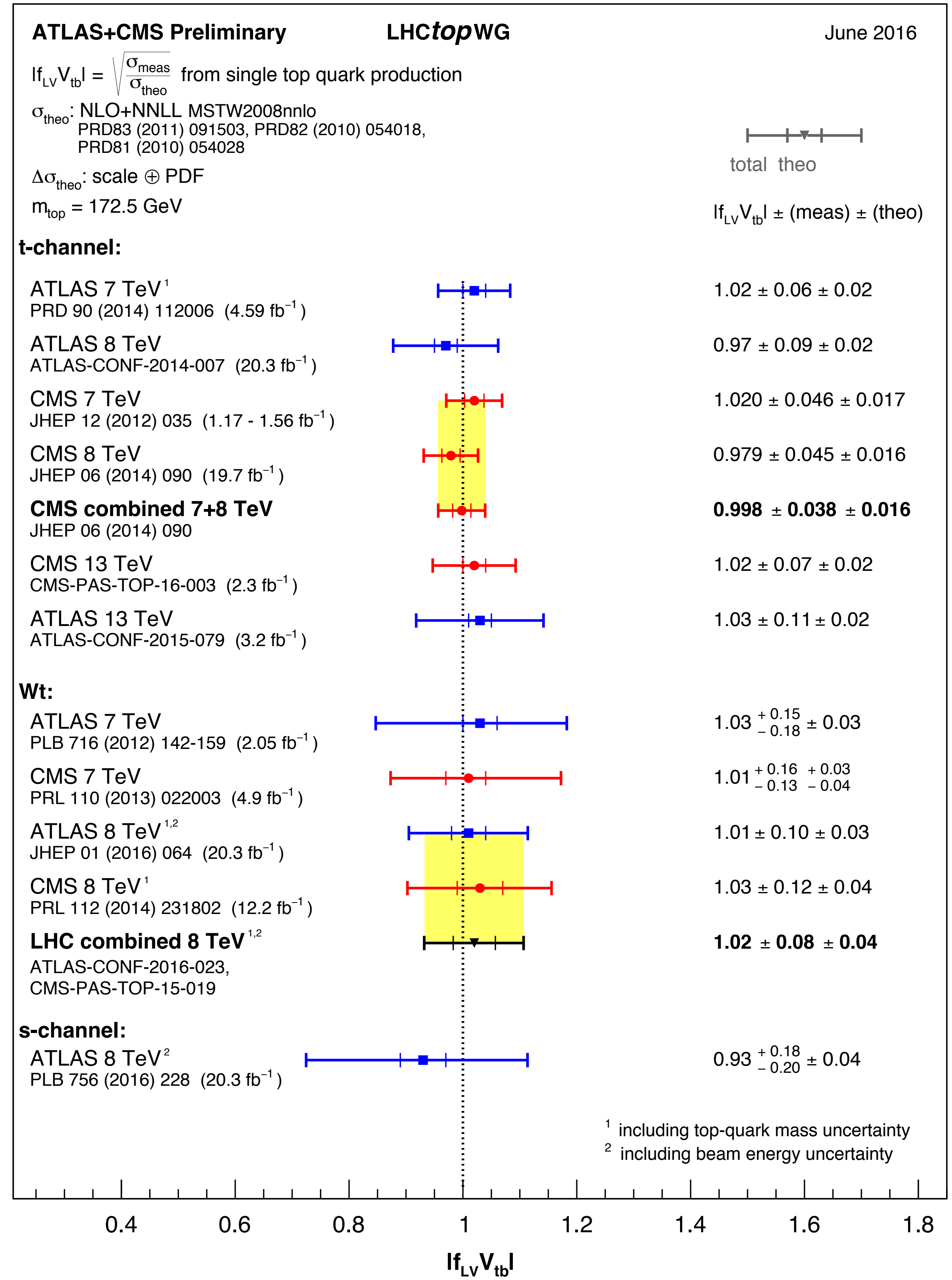
Wt channel

Single top quark production

At LHC 7–13 TeV

- **t-channel well measured**
- ***Wt* recently established, LHC combination**
- **s-channel: first evidence**

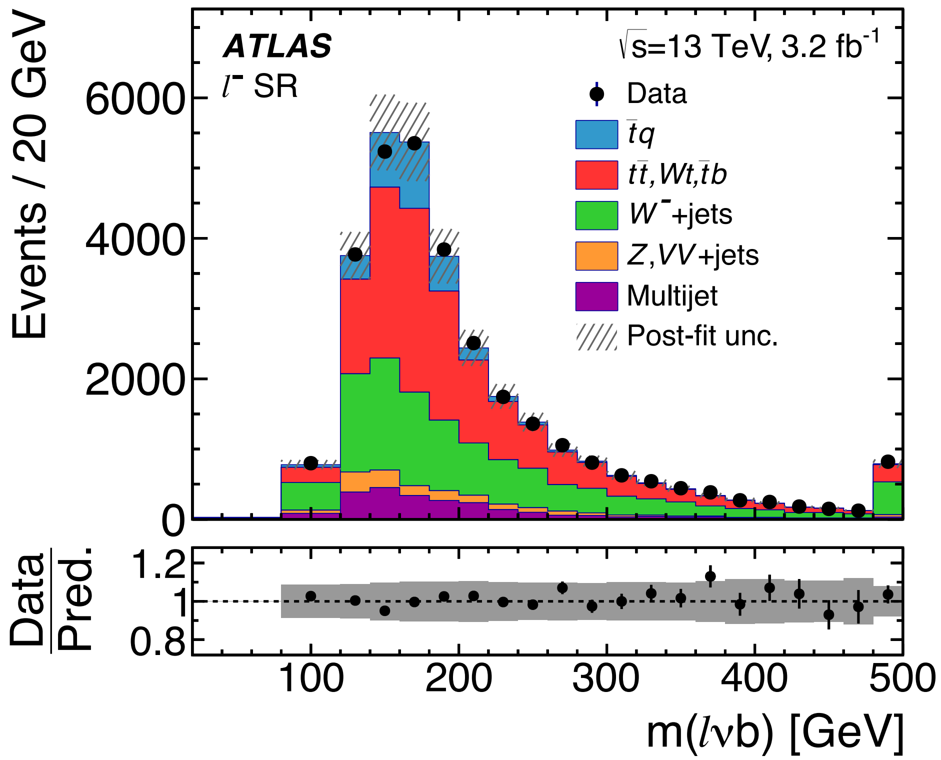


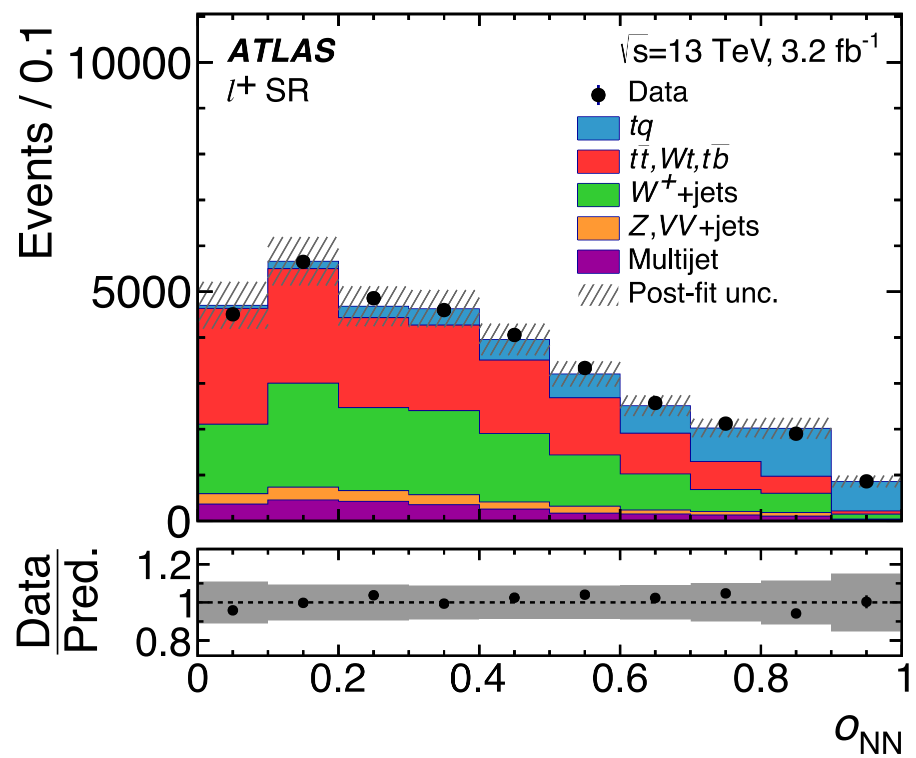


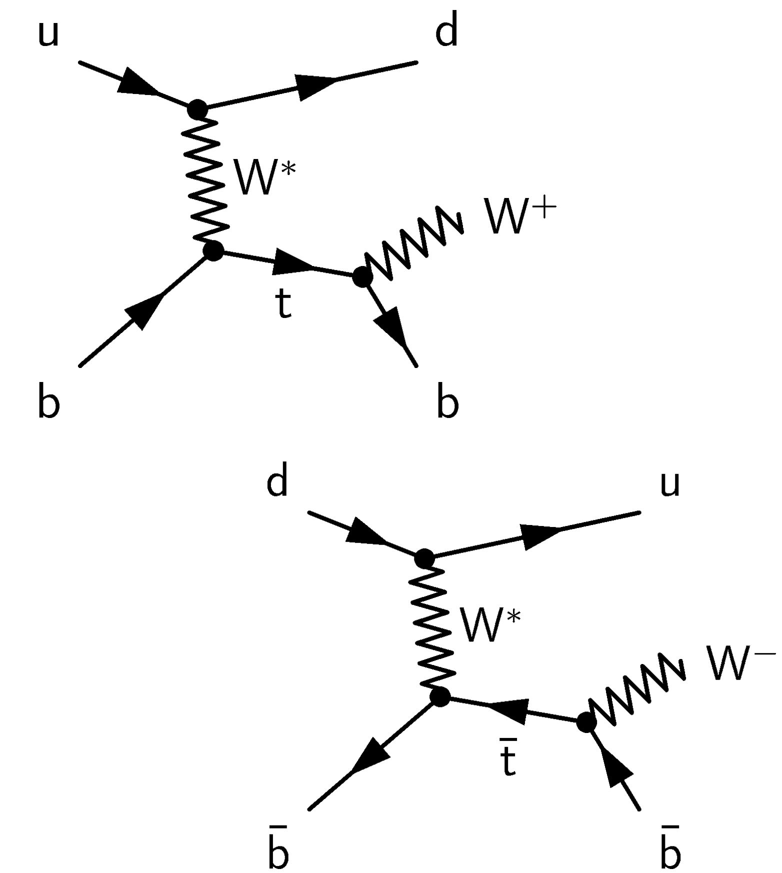
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots arXiv:1609.03920, submitted to JHEP

13 TeV measurement with 2015 data

- neural network with m(ℓνb), m(jb), …

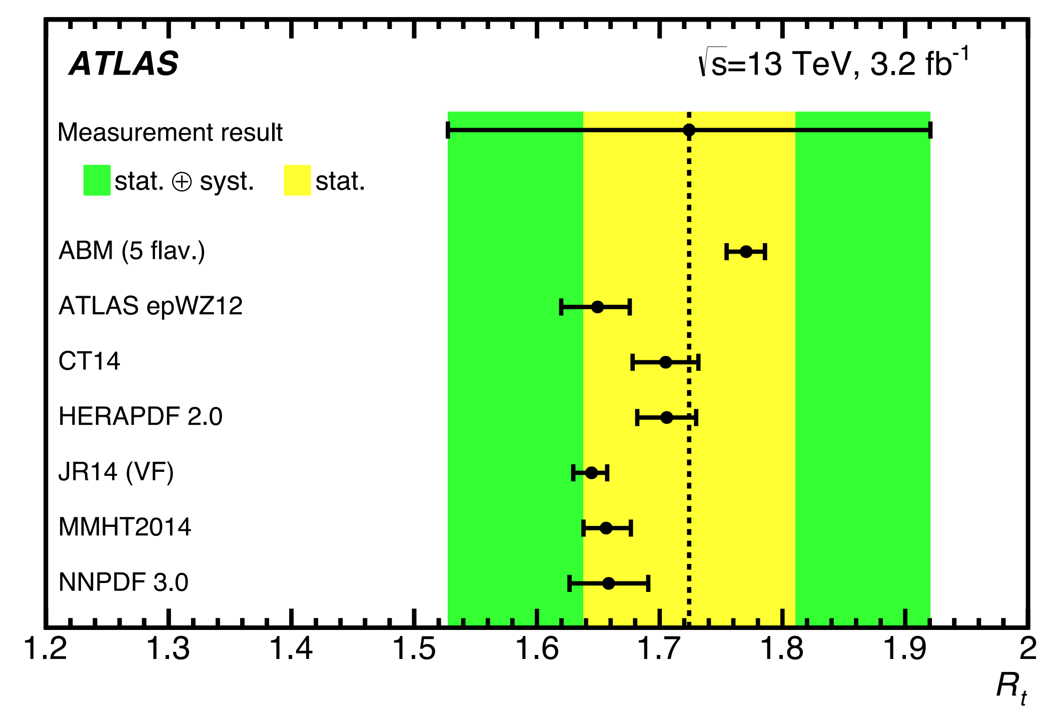






Results

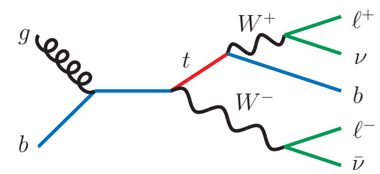
- $\sigma(t) = 156 \pm 5_{stat} \pm 27_{syst}$ pb
- $\sigma(\bar{t}) = 91 \pm 4_{stat} \pm 18_{syst}$ pb
- $\sigma(t+\bar{t}) = 247 \pm 46$ pb
- $R_t = \sigma(t)/\sigma(\bar{t}) = 1.72 \pm 0.09_{stat} \pm 0.18_{syst}$



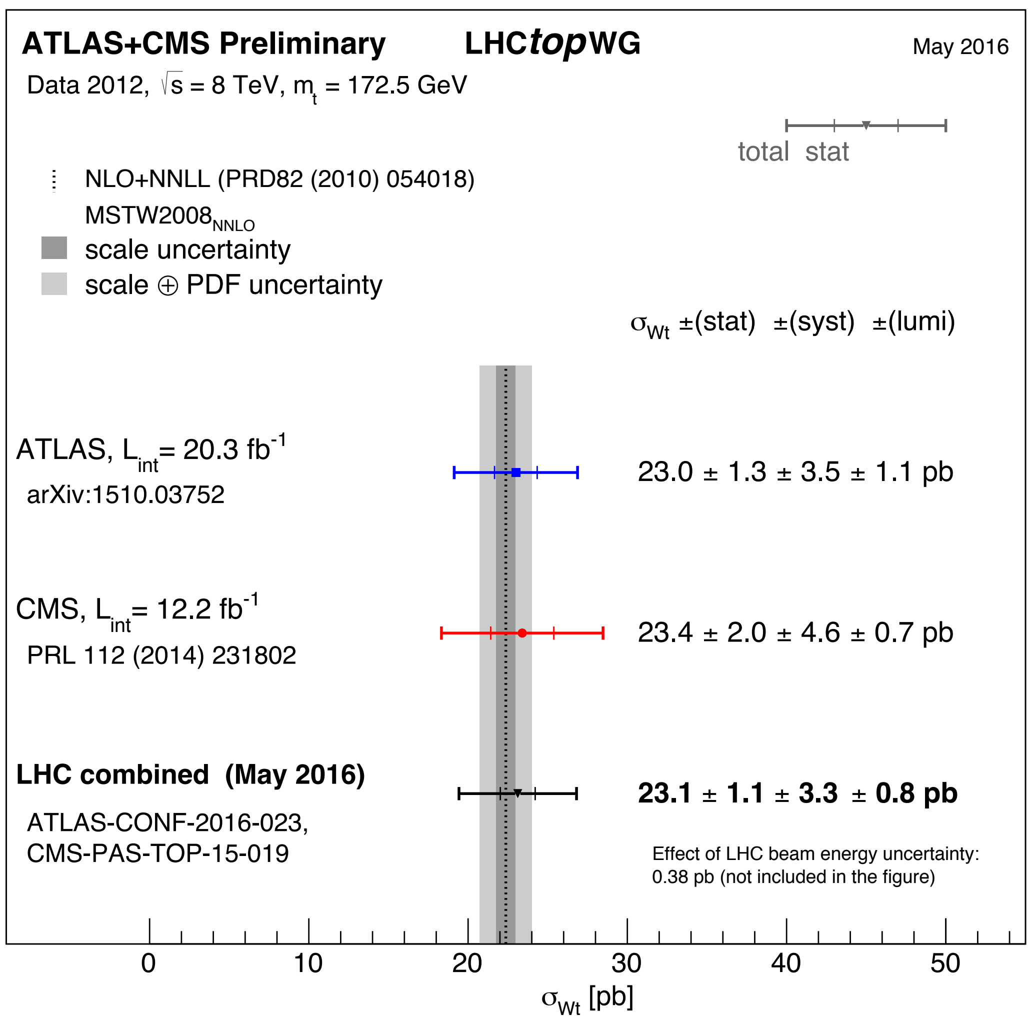
Single top – *Wt* channel

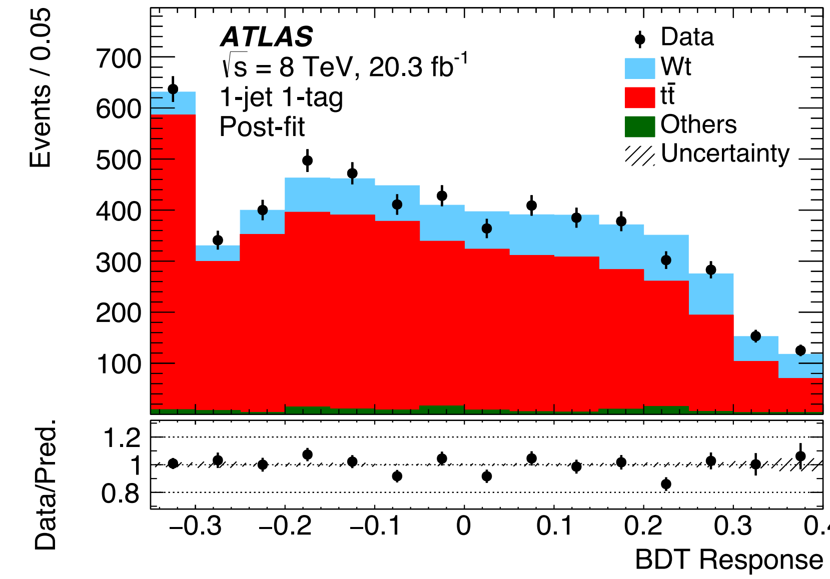
arXiv:1510.03752, JHEP 01 (2016) 064

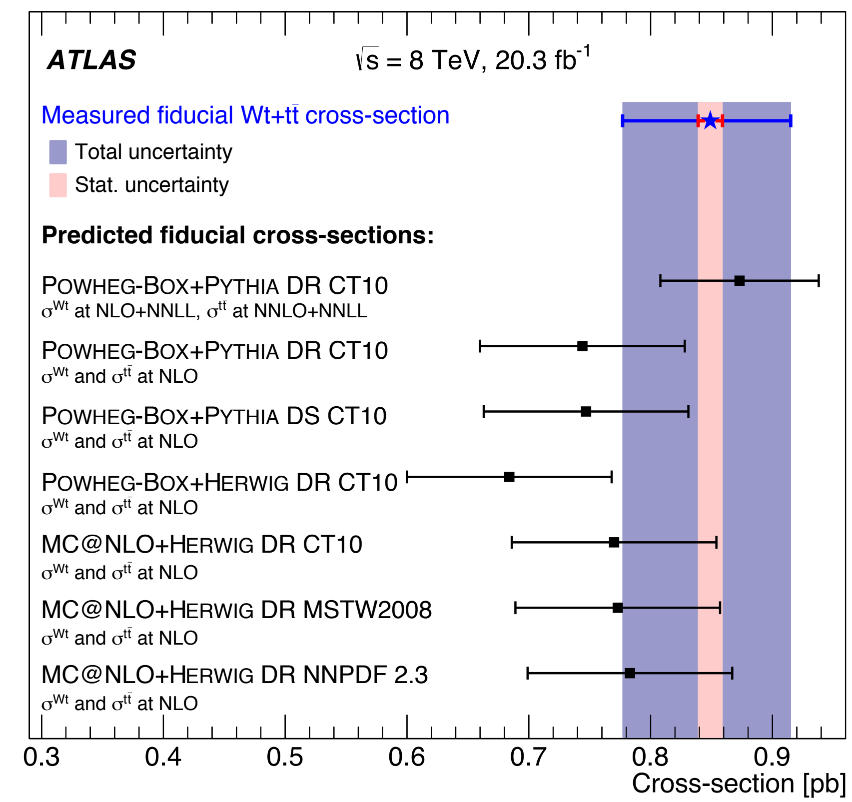
Dilepton selection with 1 *b*-tag



- main background $t\bar{t}$
- fit to BDT discriminants in signal and background regions



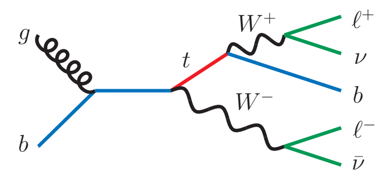




- **7.7σ significance** σ_{Wt} (8 TeV) = $23.0 \pm 1.3\,(\text{stat.})^{+3.2}_{-3.5}\,(\text{syst.}) \pm 1.1\,(\text{lumi.})$ pb

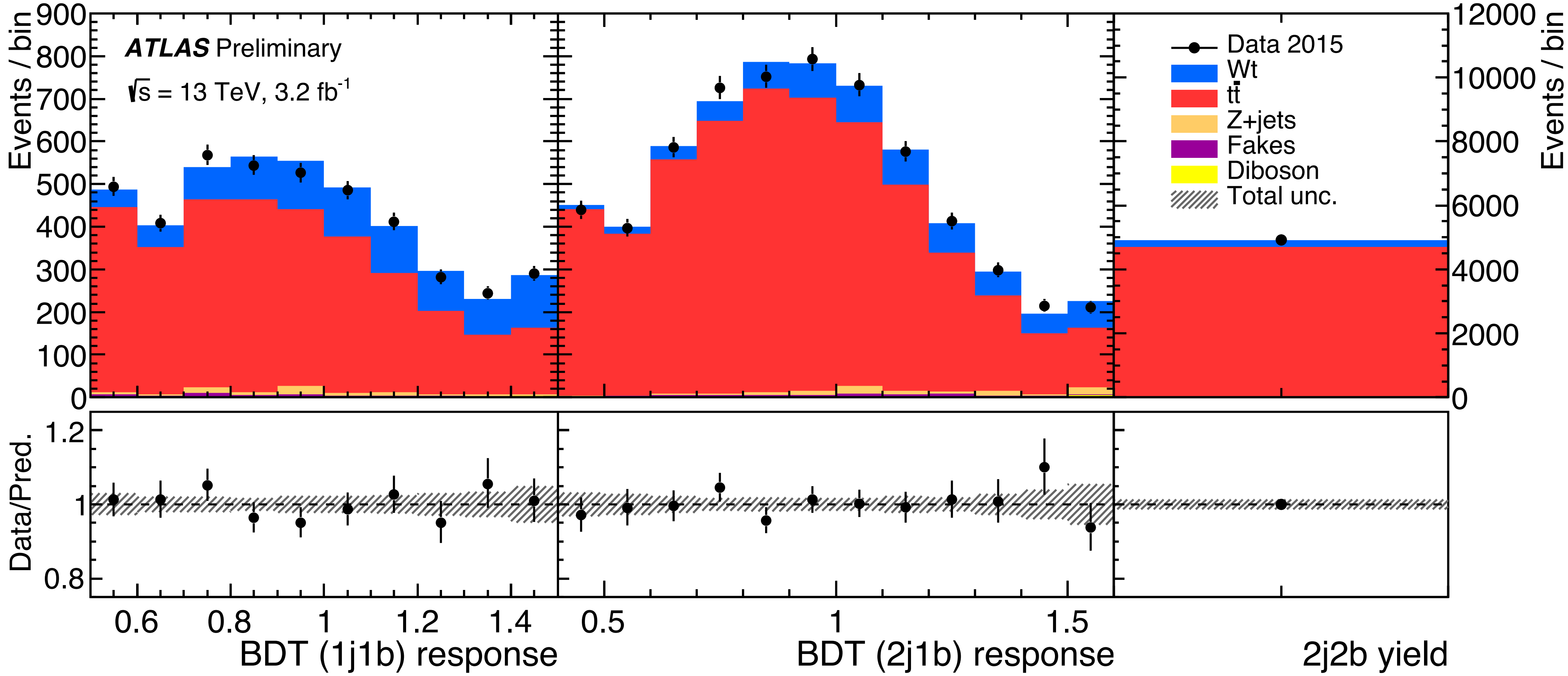
Single top – *Wt* channel

Dilepton selection with 1 *b*-tag



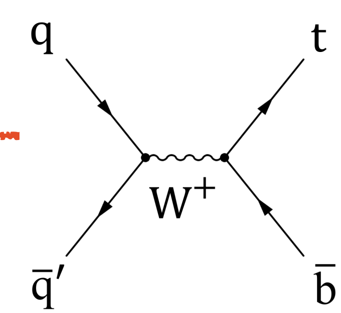
- **main background $t\bar{t}$**
- **fit to BDT discriminants in signal and background regions**

ATLAS-CONF-2016-065



- **7.7σ significance** **σ_{Wt} (8 TeV) =** $23.0 \pm 1.3\,(\text{stat.})^{+3.2}_{-3.5}\,(\text{syst.}) \pm 1.1\,(\text{lumi.})$ pb
- **4.5σ significance** **σ_{Wt} (13 TeV) =** $94 \pm 10\,(\text{stat.})^{+28}_{-23}\,(\text{syst.})$ pb

Single top – s-channel



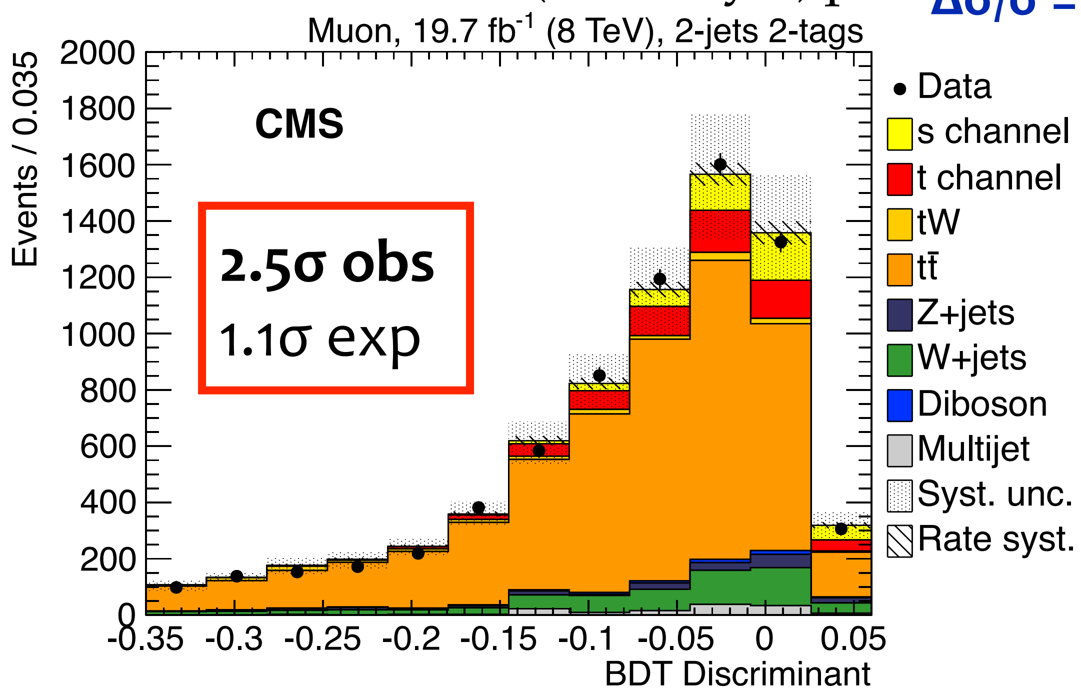
arXiv:1603.02555, submitted to JHEP
arXiv:1511.05980, PLB 756 (2016) 228

Evidence of s-channel production

- rare in pp collisions — grows much slower with $\sqrt{s}$ than other top production
- CMS multivariate discriminator, ATLAS matrix-element approach

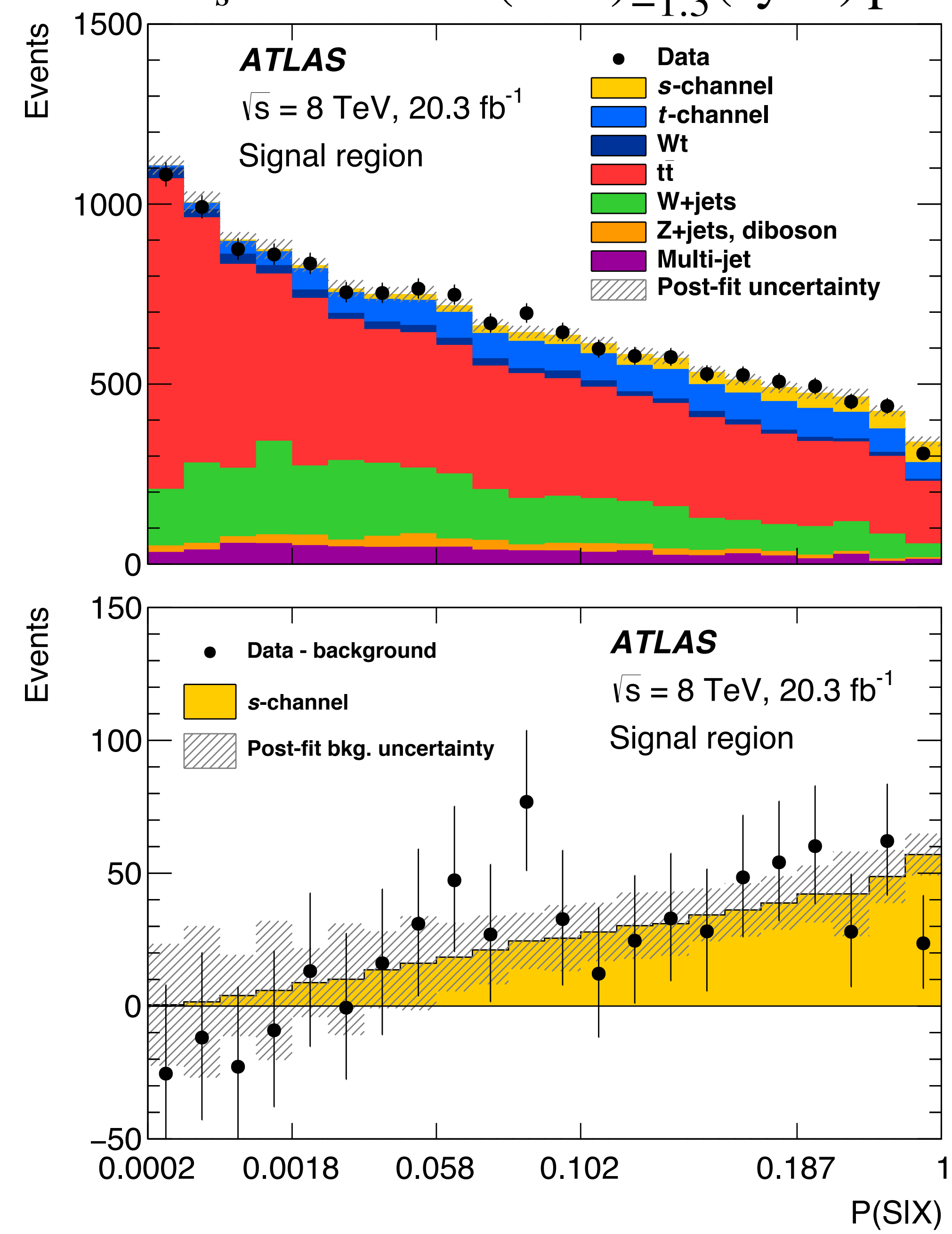
$$\sigma_s = 13.4 \pm 7.3\,(\text{stat} + \text{syst})\,\text{pb}$$

Δσ/σ = 54%



$$\sigma_s = 4.8 \pm 0.8(\text{stat.})^{+1.6}_{-1.3}(\text{syst.})\,\text{pb}$$

Δσ/σ = 37%



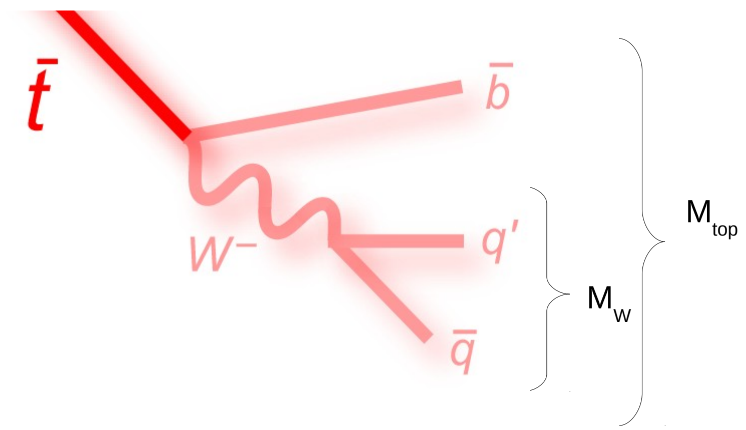
3.2σ obs
3.9σ exp

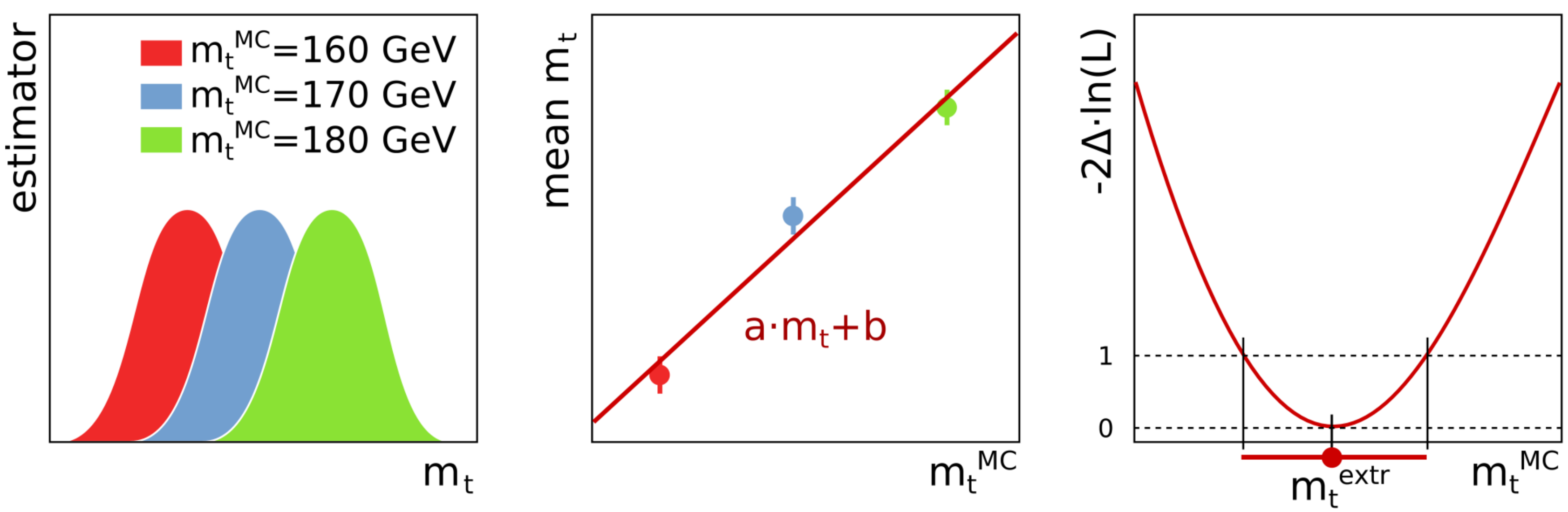
Source	Δσ/σ (%) ATLAS	Δσ/σ (%) CMS
Statistics	12	11
Luminosity	5	6
MC statistics	12	-
Jet/MET	13	19
b-tagging	8	16
Backgrounds	8	19
tt/single top (t,s) models	13	33

m_{top} – measurement basics

Template method

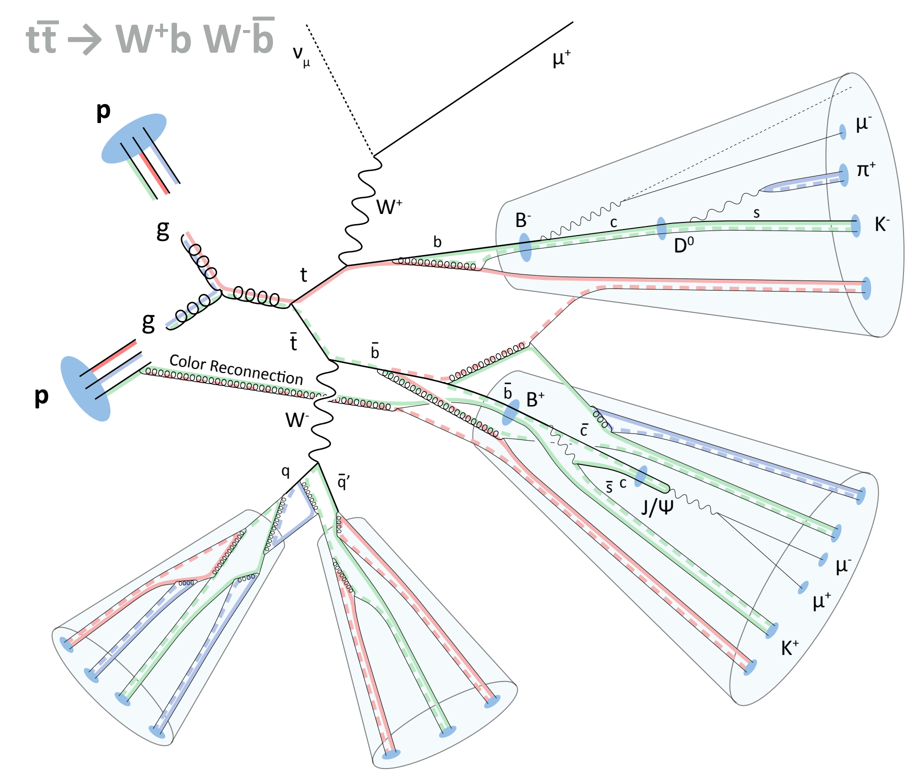
- chose an appropriate estimator for m_t
  - e.g. $m(q\bar{q}b)$
- parameterise estimator as function of m_t^{MC}
- perform maximum likelihood fit to data





Here: measuring the "Monte-Carlo" mass

- theoretical uncertainty up to 1 GeV when translating to a well defined top mass



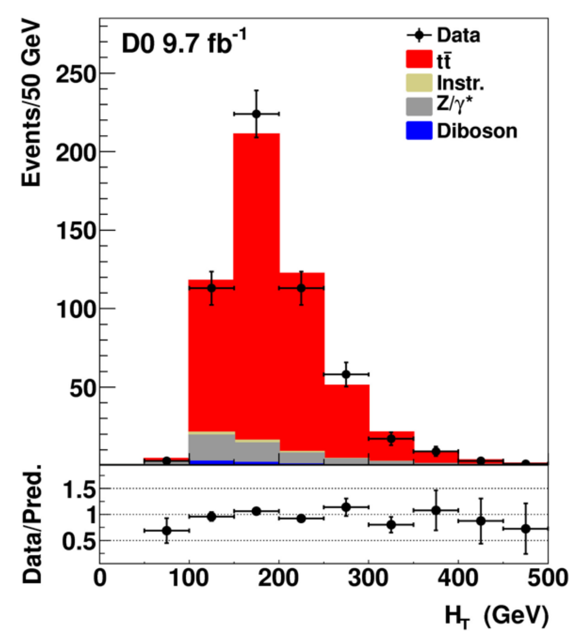
Goal in all analyses

- Try to understand/reduce impact of systematics

m_{top} – Tevatron update

Dilepton channel measurements

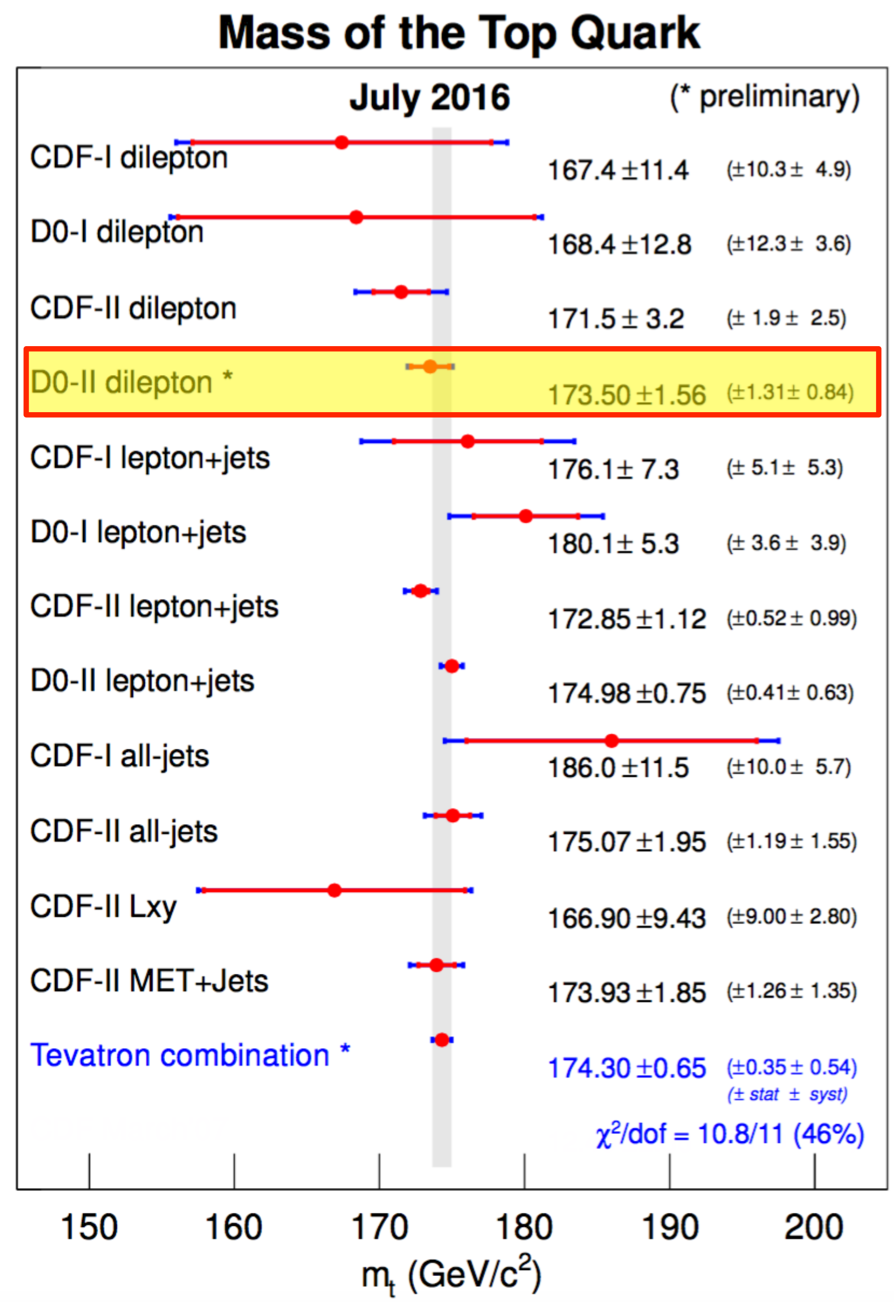
- matrix-element method *arXiv:1606.02814, PRD 94 (2016) 032004*
- neutrino weighting
- → statistical combination of the two



New Tevatron combination

- $\Delta m_{top} / m_{top} = 0.37\%$

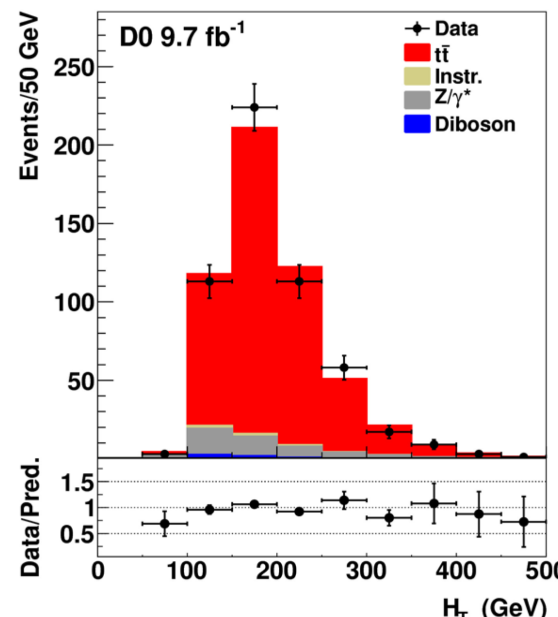
arXiv:1608.01881, TEWWG



m_{top} – Tevatron update

Dilepton channel measurements

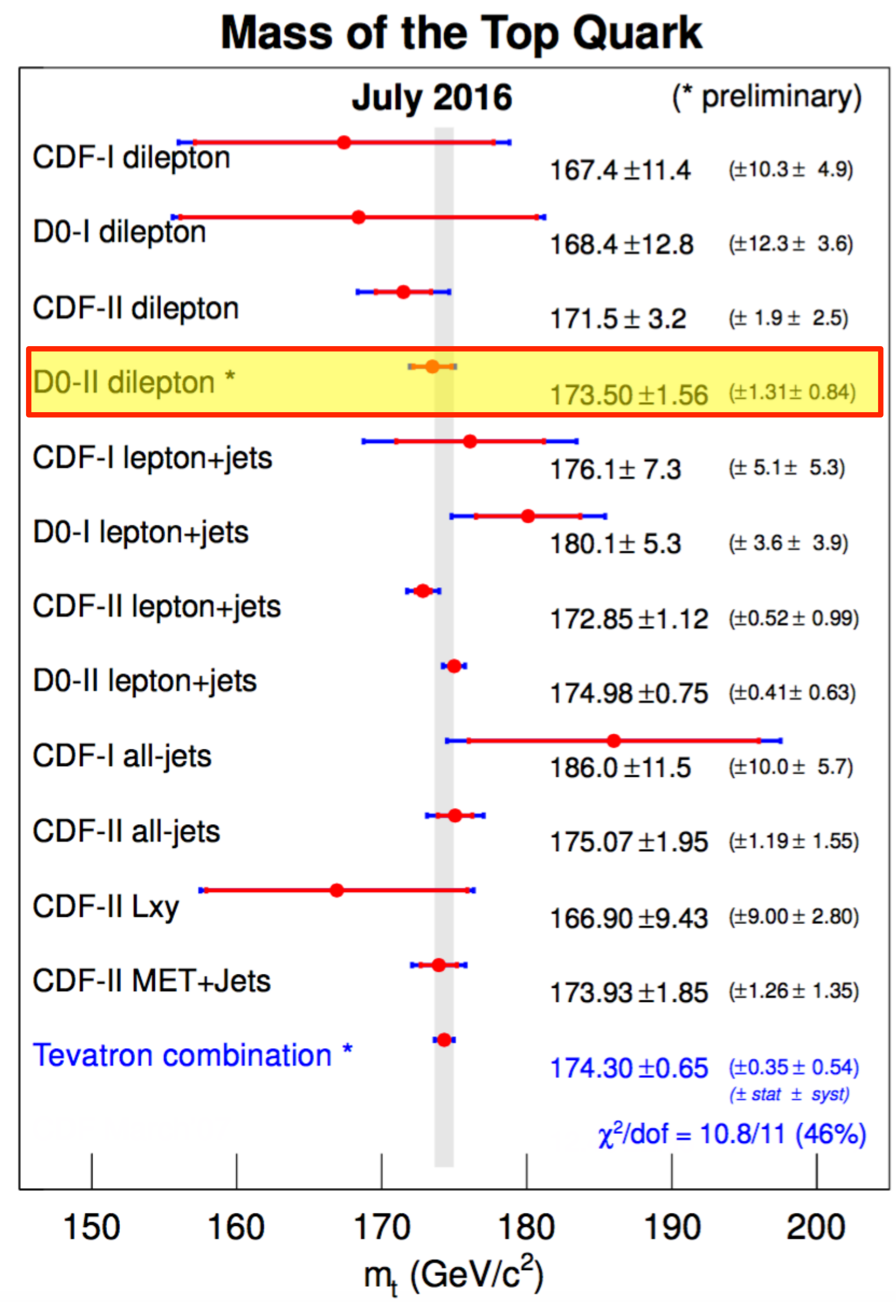
- matrix-element method *arXiv:1606.02814, PRD 94 (2016) 032004*
- neutrino weighting
- → statistical combination of the two



New Tevatron combination

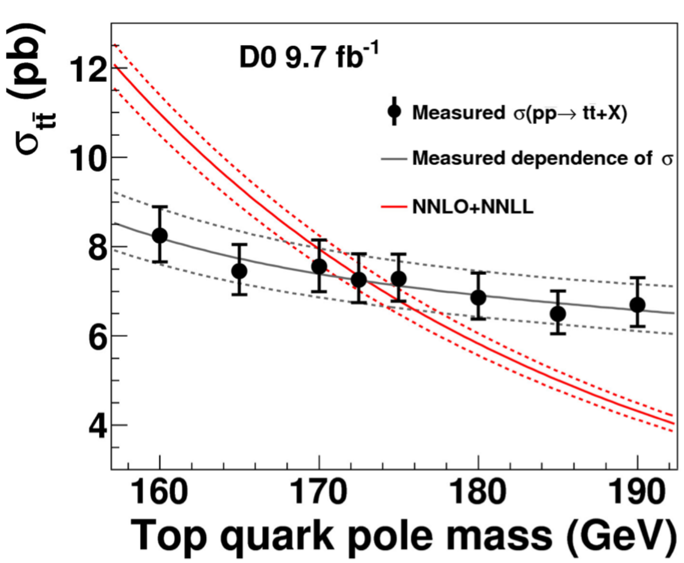
- $\Delta m_{top} / m_{top} = 0.37\%$

arXiv:1608.01881, TEWWG



Exploit $\sigma_{t\bar{t}} = \sigma_{t\bar{t}}(m_{top})$

- well defined renormalisation scheme



arXiv:1605.06168, submitted to PRD

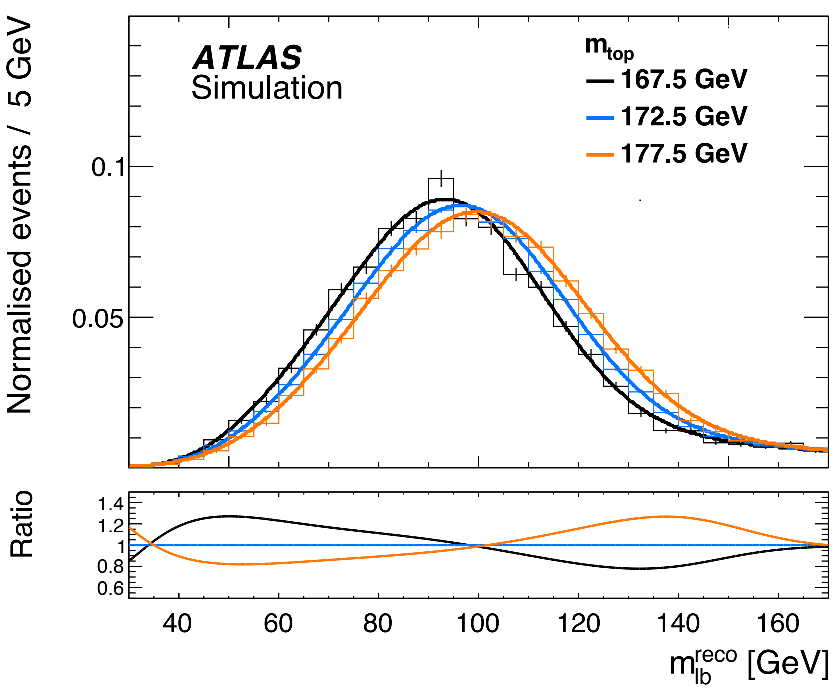
$$m_t = 172.8 \pm 1.1\,(\text{theo.})\,^{+3.3}_{-3.1}\,(\text{exp.})\,\text{GeV}$$

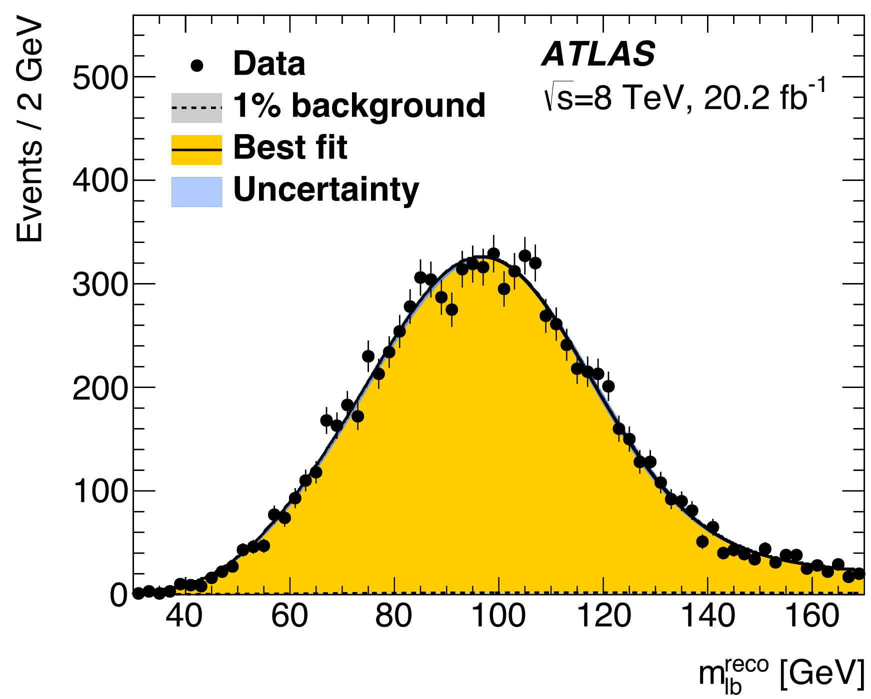
m_{top} – template method at the LHC

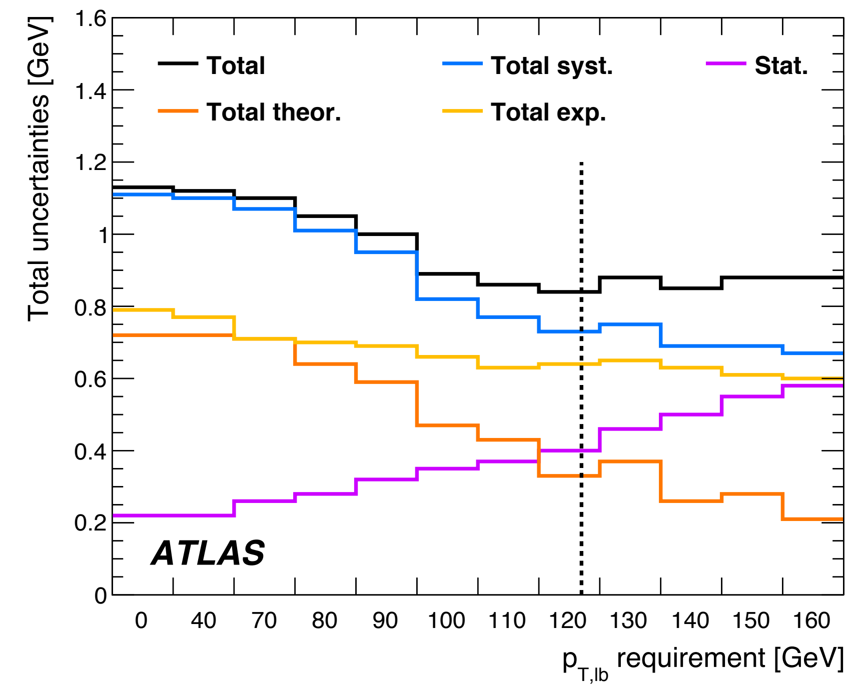
arXiv:1606.02179, submitted to PLB

ATLAS dilepton

- **cannot directly reconstruct top mass, choose estimator $m_{\ell b}$**
- **optimise total uncertainty through cut on minimal average $p_{T,\ell b}$**
  - cleaner event reconstruction leads to reduced systematics



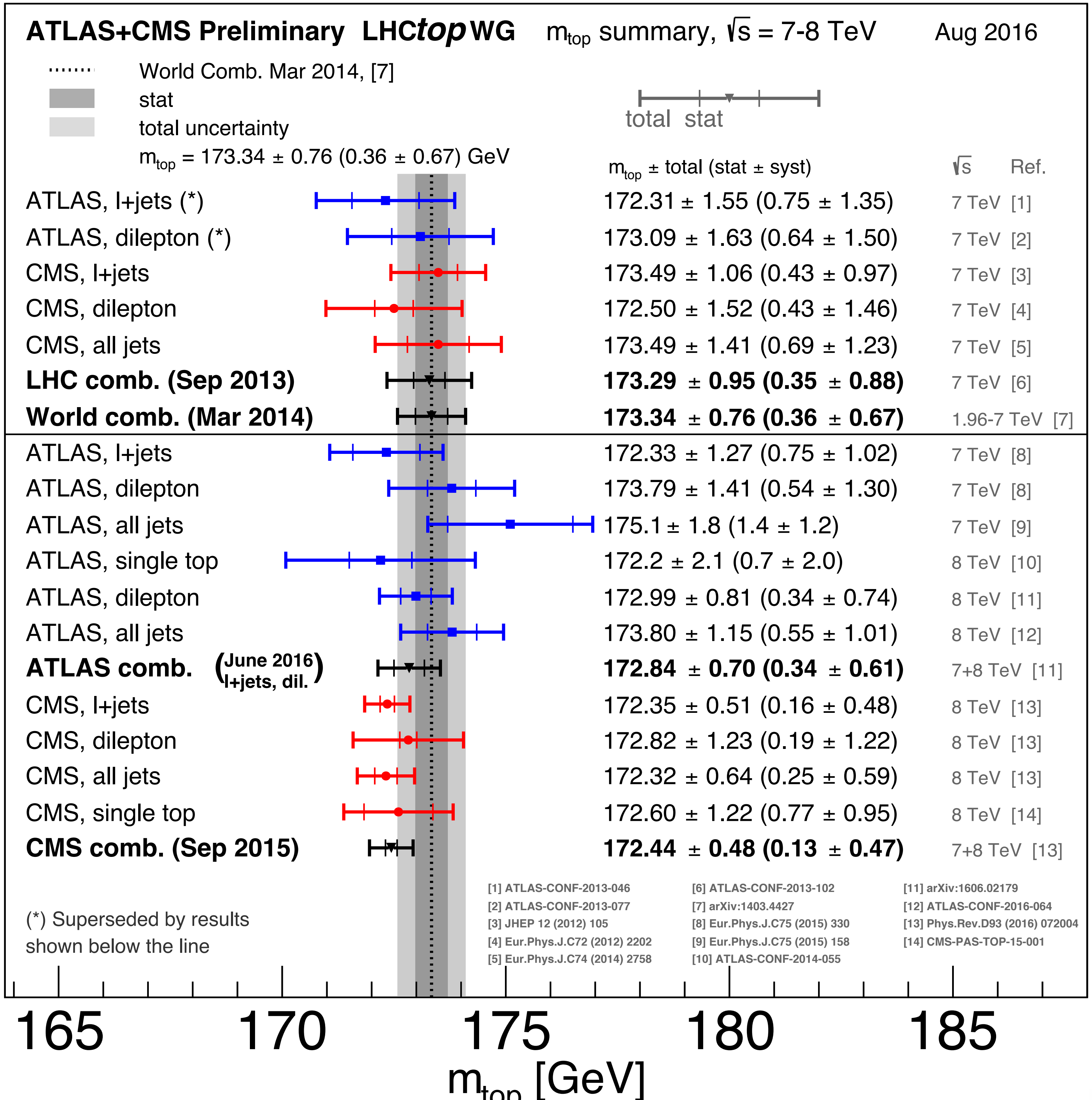


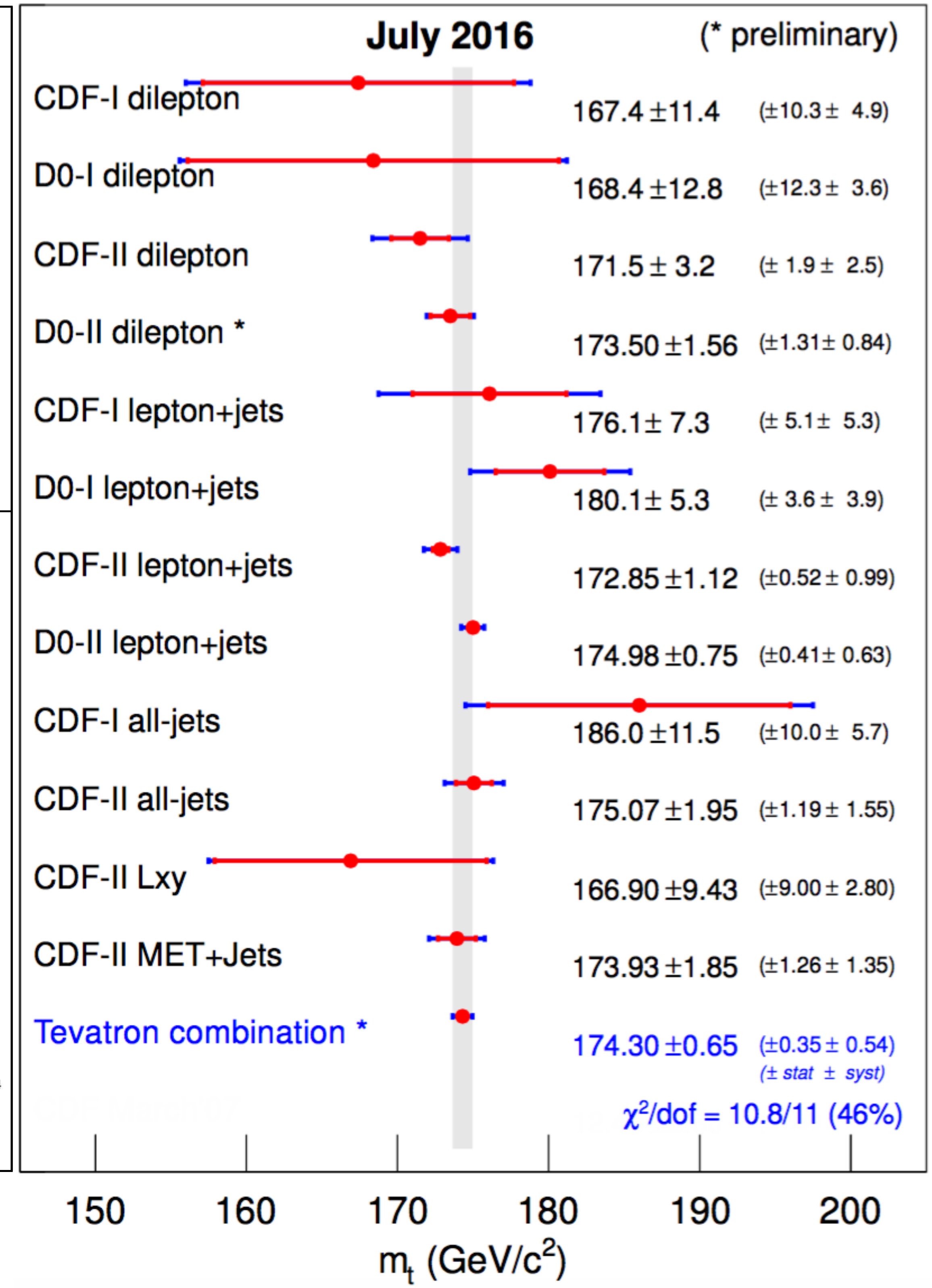


Resulting in $m_{top} = 172.84 \pm 0.34_{stat} \pm 0.61_{syst}$ GeV

- **→ best single measurement in the dilepton channel**
- **systematics dominated by jet energy scale uncertainty**
- **$\Delta m_{top} / m_{top} = 0.40\%$**

m_{top} – current summary

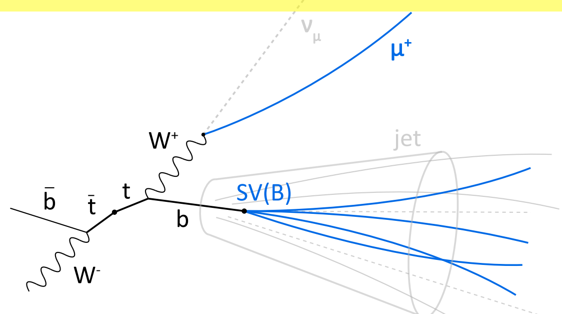




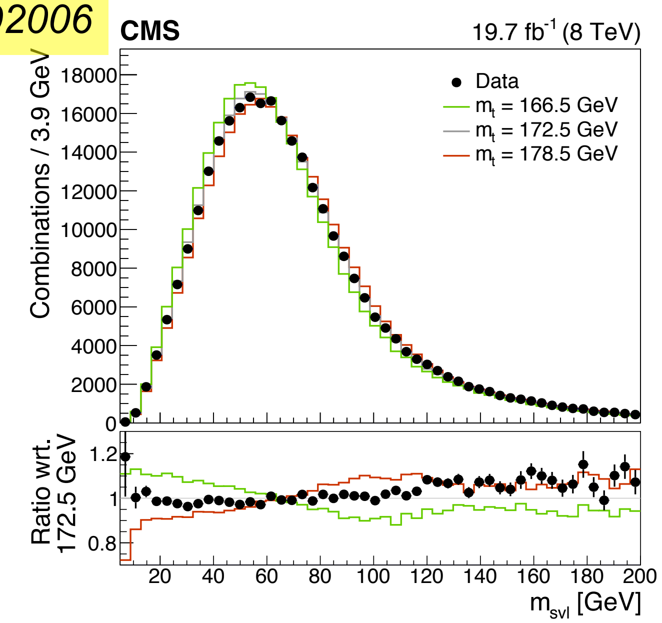
Using tracks and leptons

- **reduced experimental uncertainties**
  - reconstruct secondary vertex from b-hadron decay
  - $m(\mathrm{SV},\ell)$ is sensitive to m_{top}
  - better momentum resolution
  - smaller corrections compared to jets
  - split in bins of SV-track multiplicity

arXiv:1603.06536, PRD 93 (2016) 092006



$$m_t = 173.68 \pm 0.20(\mathrm{stat}) {}^{+1.58}_{-0.97}(\mathrm{syst})\ \mathrm{GeV}$$



- **Systematic uncertainties**
  - experimental are <500 MeV
  - *b*-fragmentation (−0.54; +1.00 GeV)
  - top quark p_T (0.82 GeV)

m_{top} – novel extraction techniques

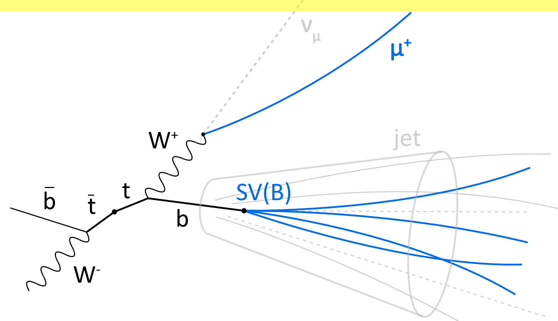
universitätbonn erc

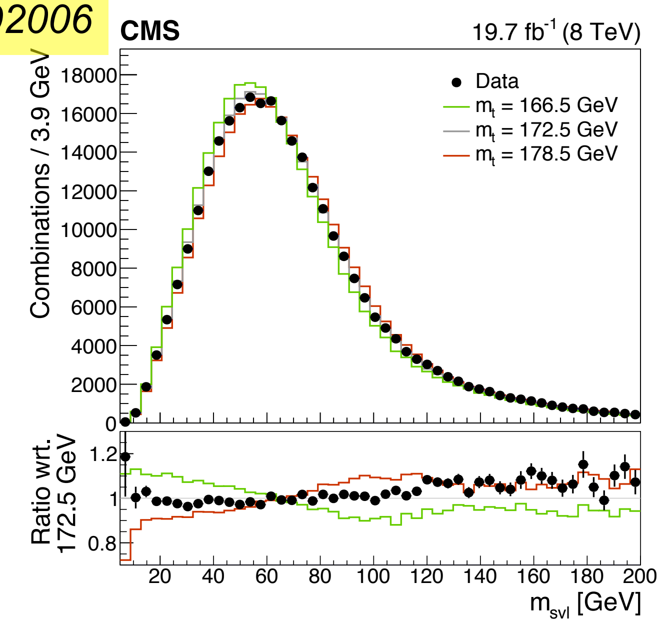
arXiv:1608.03560, submitted to JHEP

Using tracks and leptons

- **reduced experimental uncertainties**
  - reconstruct secondary vertex from b-hadron decay
  - *m*(SV,ℓ) is sensitive to m_{top}
  - better momentum resolution
  - smaller corrections compared to jets
  - split in bins of SV-track multiplicity

arXiv:1603.06536, PRD 93 (2016) 092006



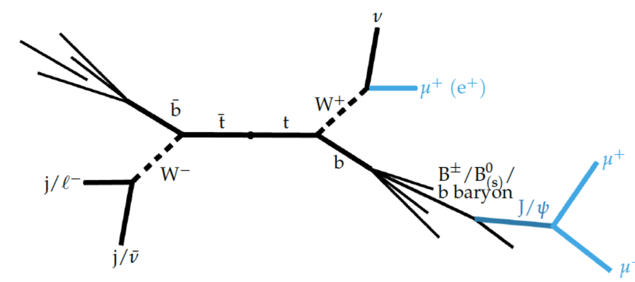


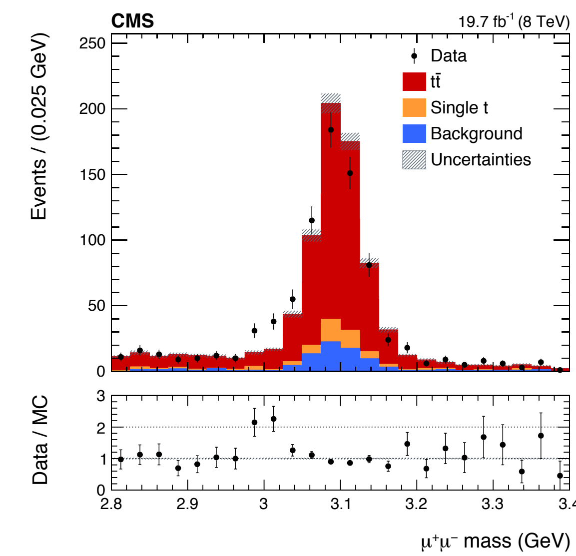
$$m_t = 173.68 \pm 0.20(\text{stat}) {}^{+1.58}_{-0.97}(\text{syst})\ \text{GeV}$$

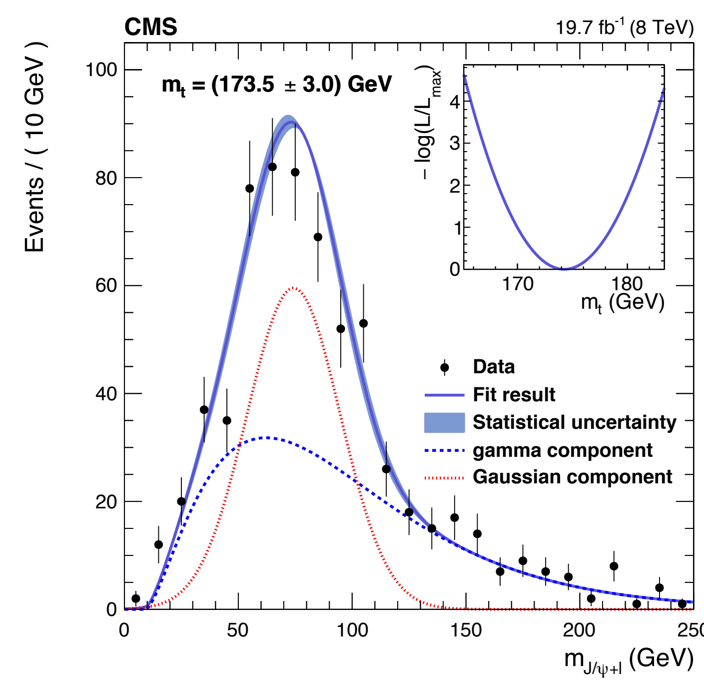
- **Systematic uncertainties**
  - experimental are <500 MeV
  - *b*-fragmentation (–0.54; +1.00 GeV)
  - top quark p_T (0.82 GeV)

Using *J/ψ* mesons

- **Select $t\bar{t}$ events with $B \to J/\psi \to \mu\mu$**
  - reconstruct $m(\ell, J/\psi)$, small BR, 666 events selected







$$m_t = 173.5 \pm 3.0\,(\text{stat}) \pm 0.9\,(\text{syst})\,\text{GeV}.$$

- **Systematics mainly**
  - *b*-fragmentation and top modeling

$t\bar{t}$ spin correlations

In QCD the spin of heavy quarks is correlated at production

Very short lifetime

- $\tau_{\text{top}} < \tau_{\text{hadronisation}} < \tau_{\text{spin-decorrelation}}$
- **information of spin propagates to the daughter particles**
  - direct measurement with charged leptons
  - can be studied with or without reconstruction of $t\bar{t}$ system

Spin correlation strength

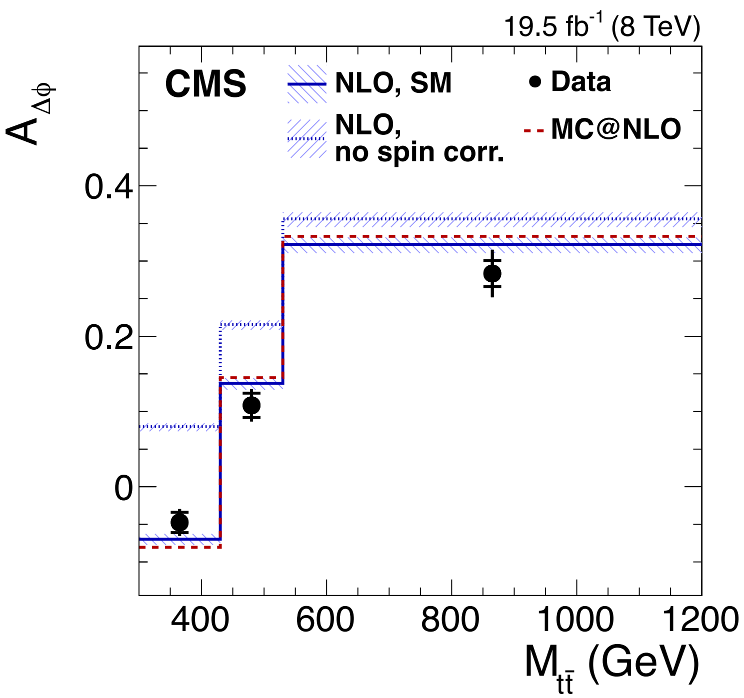
- **dependent on the observables, production mechanisms and energy**
- **can be extracted from angular variables (dilepton $\Delta\varphi_{\ell\ell}$, cos ϑ)**

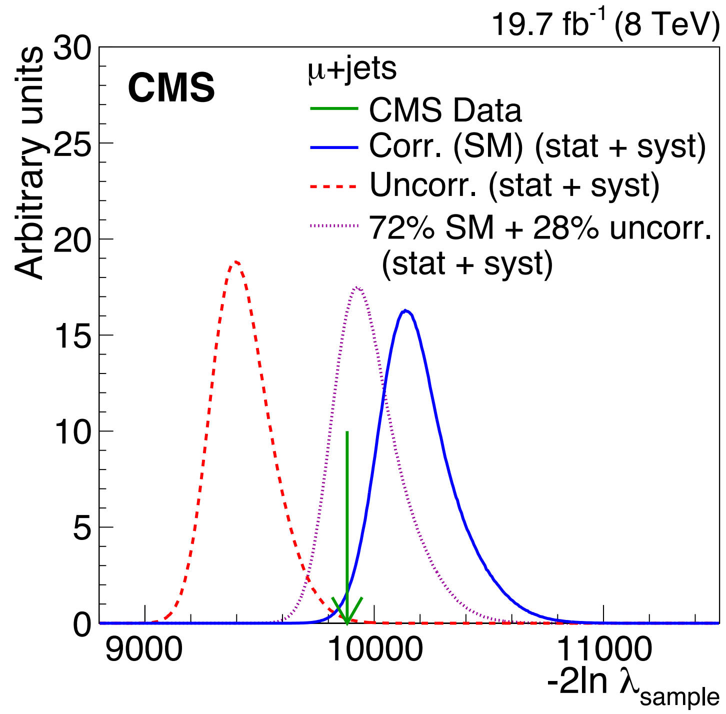
$t\bar{t}$ spin correlations at LHC

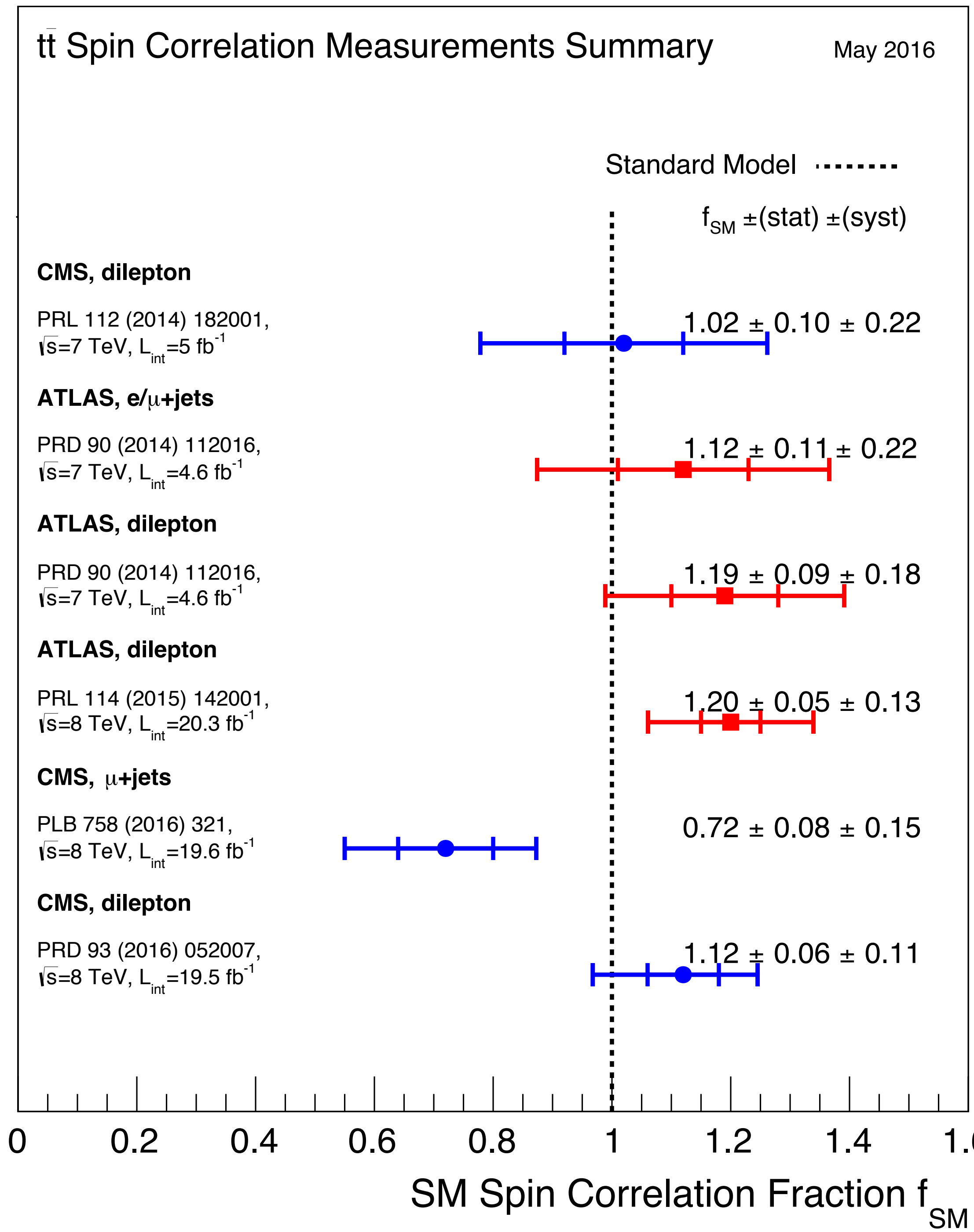
in $t\bar{t}$ dilepton

arXiv:1601.01107, PRD 93 (2016) 052007

- **observables formed by angles between the two leptons**
- **also differential**







in $t\bar{t}$ μ+jets

arXiv:1511.06170, PLB 758 (2016) 321

- **using matrix-element method**
- **calculate sample likelihood for two hypotheses**

$t\bar{t}$ spin correlations at Tevatron

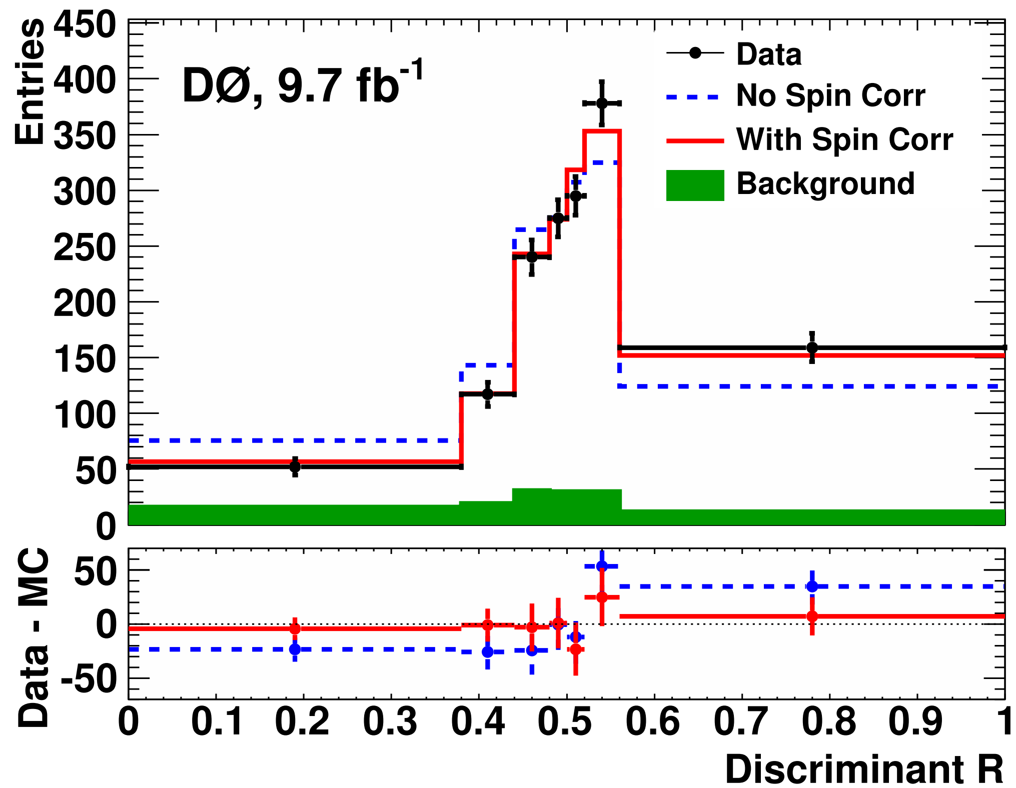
Different physics at Tevatron and LHC

- $p\bar{p}$ vs pp → $q\bar{q}$ vs gg (like helicity gluons) at different energies
- → spin correlation at both interesting and complementary.

arXiv:1512.08818, PLB 757 (2016) 199

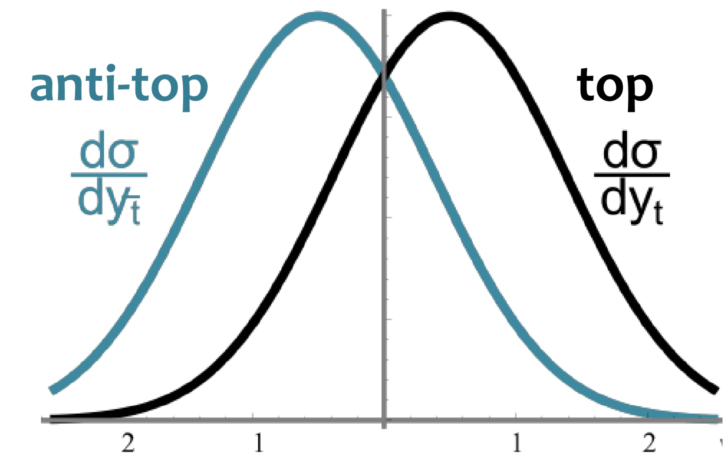
Tevatron matrix-element technique

- Evidence (4.2σ) for spin-correlations in agreement with SM prediction
- extract $gg \to t\bar{t}$ fraction in absence on BSM: $f_{gg} = 0.08 \pm 0.16$

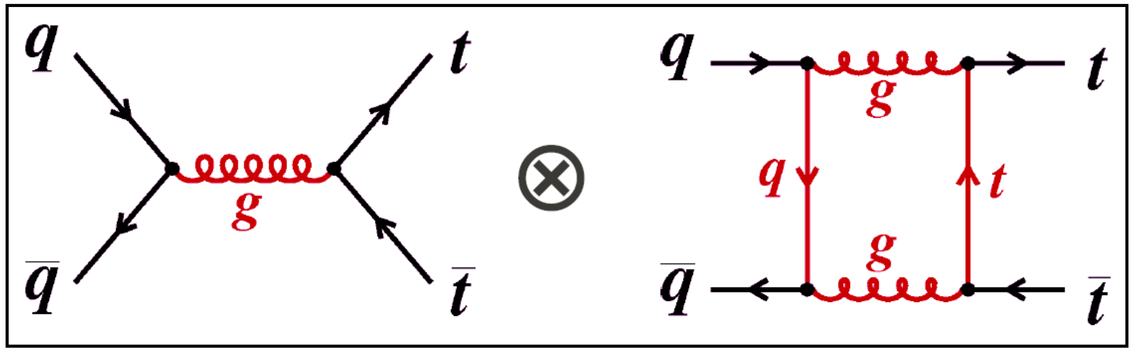


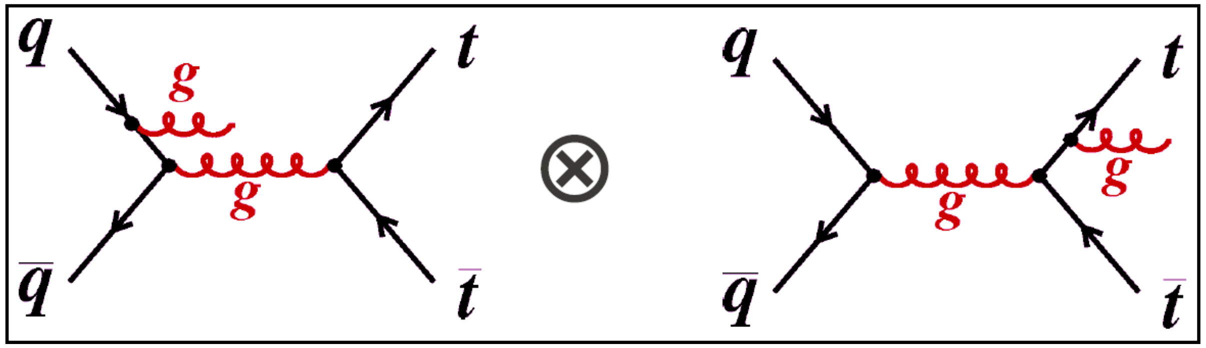
At Tevatron, $p\bar{p} \to t\bar{t}$ production

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



- **top quark preferentially follows p beam direction**
- **asymmetry zero at LO, but appears at $O(\alpha_s^3)$**
    - interference between Born vs box diagrams and ISR vs FSR in $t\bar{t}$+gluon

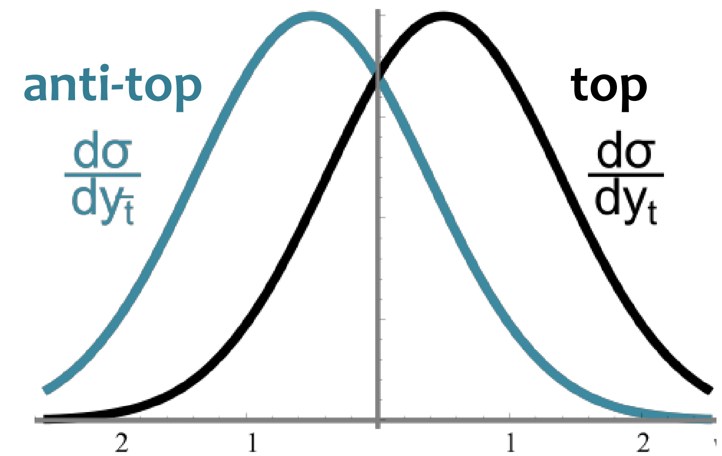




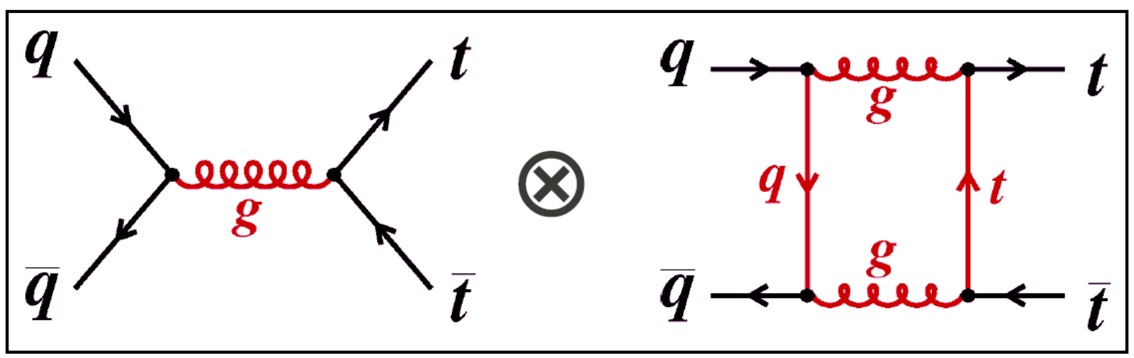
$t\bar{t}$ forward-backward asymmetry A_{FB}

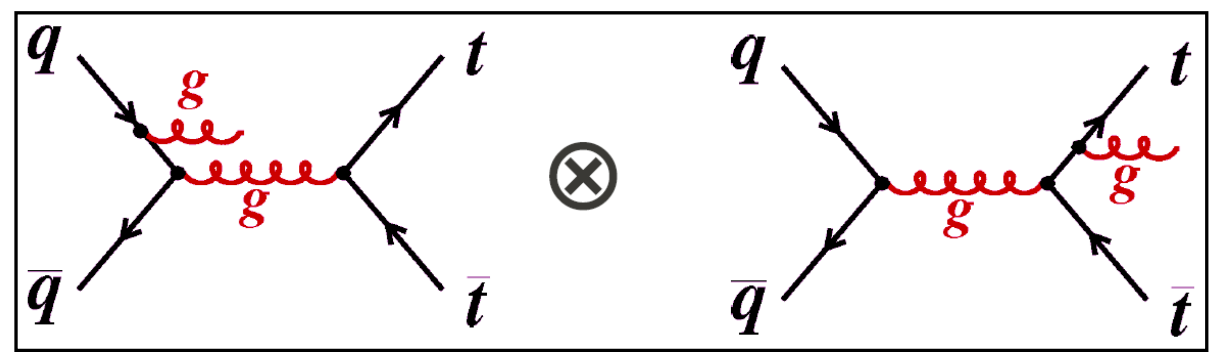
At Tevatron, $p\bar{p} \to t\bar{t}$ production

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



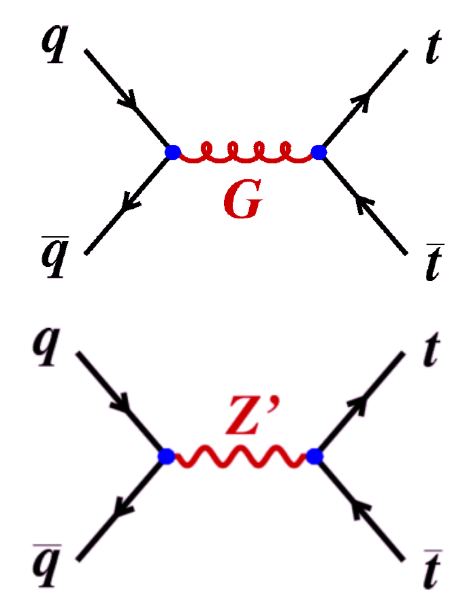
- top quark preferentially follows p beam direction
- asymmetry zero at LO, but appears at $O(\alpha_s^3)$
  - interference between Born vs box diagrams and ISR vs FSR in $t\bar{t}$+gluon





Until 2013 A_{FB} unexpectedly large (SM ~10%)

- larger than expected in SM, especially at high $m_{t\bar{t}}$
- A_{FB} = (17±4)%
- A_{FB} = (30±7)% for m($t\bar{t}$)>450GeV (CDF)
- → many new physics scenarios proposed to explain this

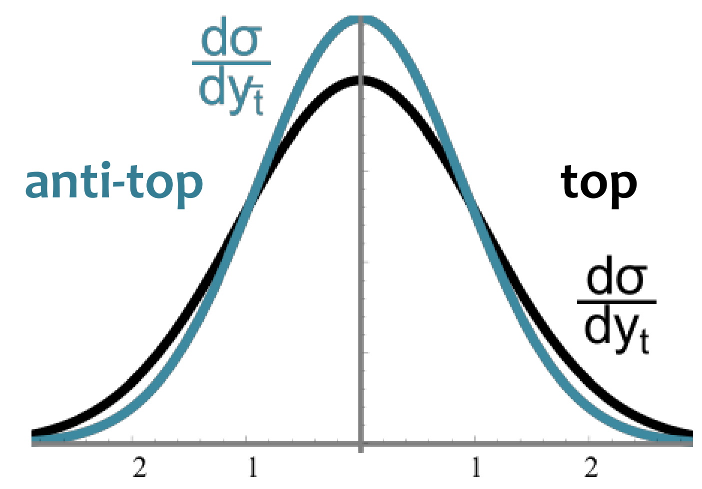


$t\bar{t}$ charge asymmetry – A_C

LHC collides pp, not $p\bar{p}$ — no A_{FB}

- but can define analogously a charge asymmetry

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



- SM prediction for inclusive A_C is 1.1%
  - much smaller effect than at Tevatron (gg dominates)

In dilepton channel

- can additionally define a dilepton asymmetry

$$A_C^{\ell\ell} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)} \qquad \Delta|\eta| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$$

- SM prediction is 0.6%

A_{FB} measurements at Tevatron

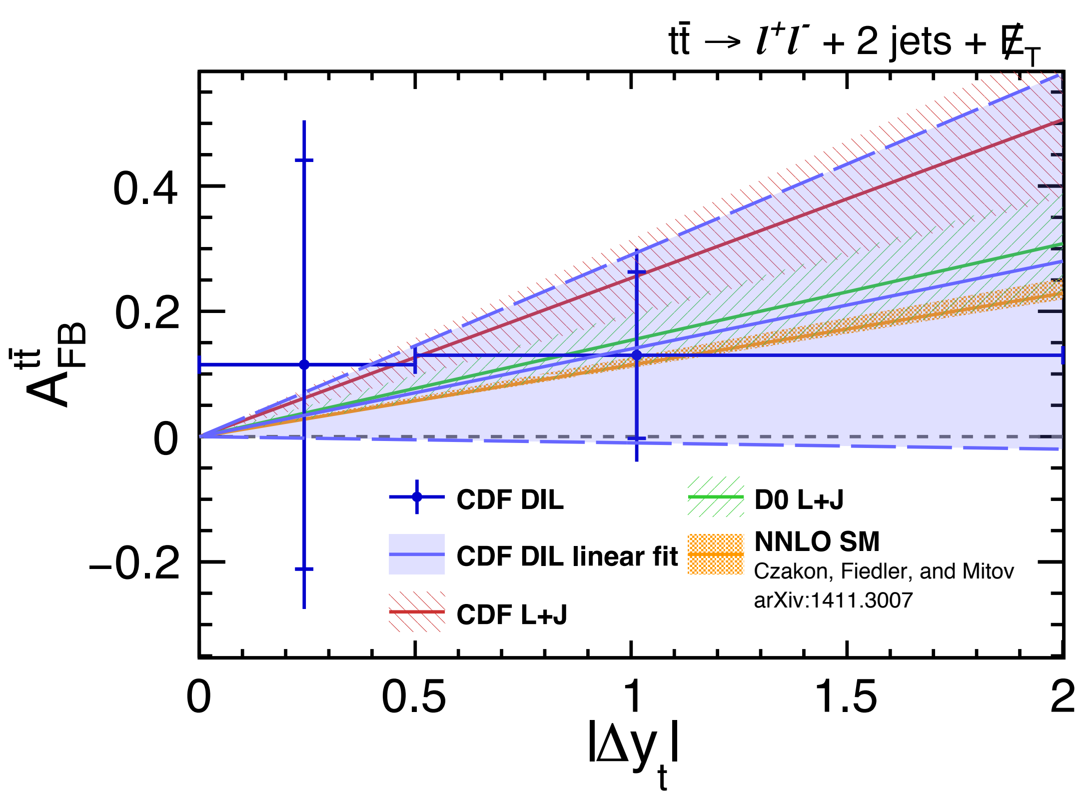
Measurements at Tevatron and LHC are complementary

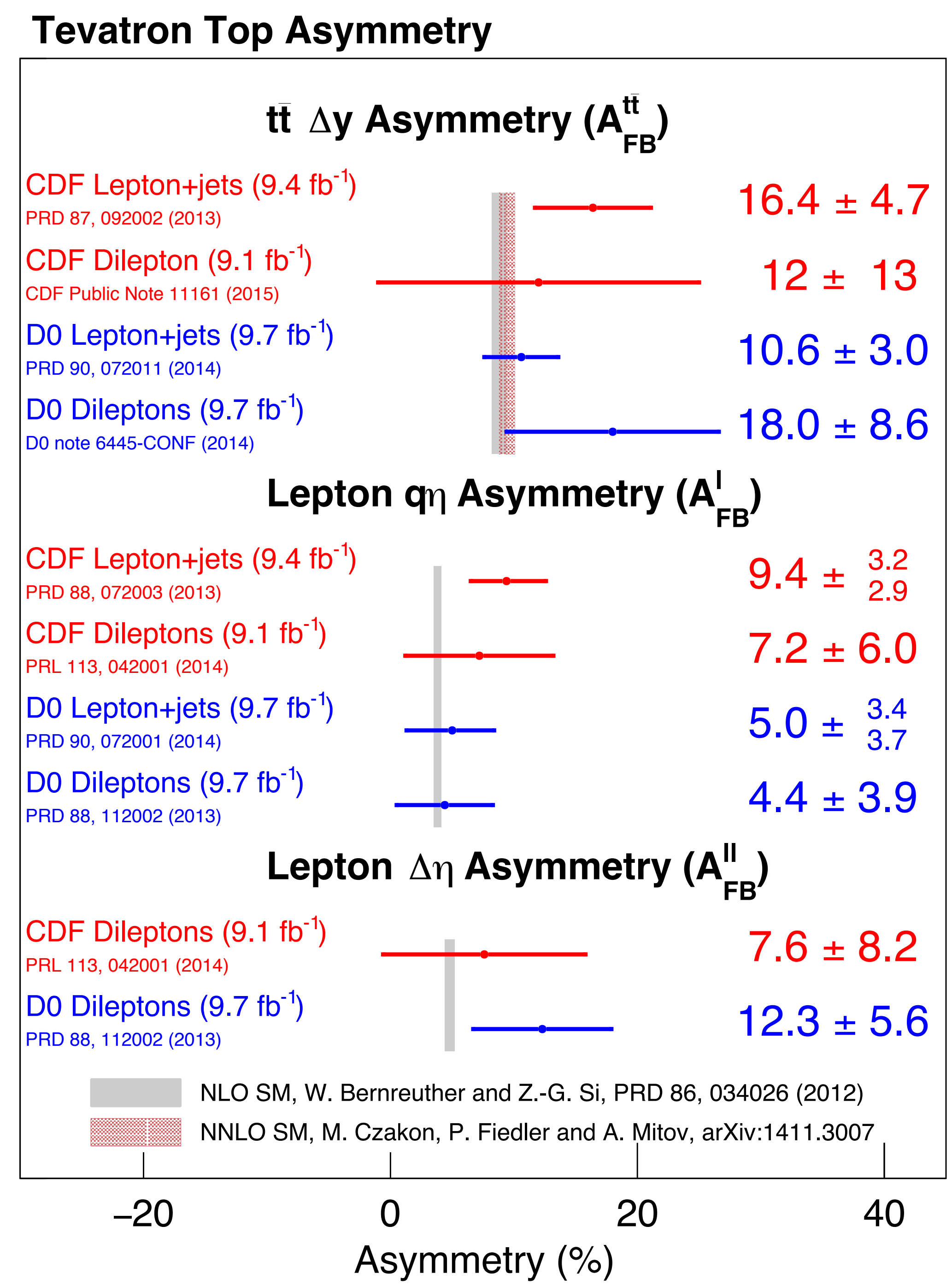
- **SM predictions at NLO (QCD+EWK) A_{FB} ~ 10%**
- **differential theory calculation at NNLO+NNLL available** *arXiv:1601.05375, JHEP 05 (2016) 034*

Latest result CDF dilepton events

- **overall agreement with SM**

arXiv:1602.09015, PRD 93 (2016) 112005





A_C measurements at LHC

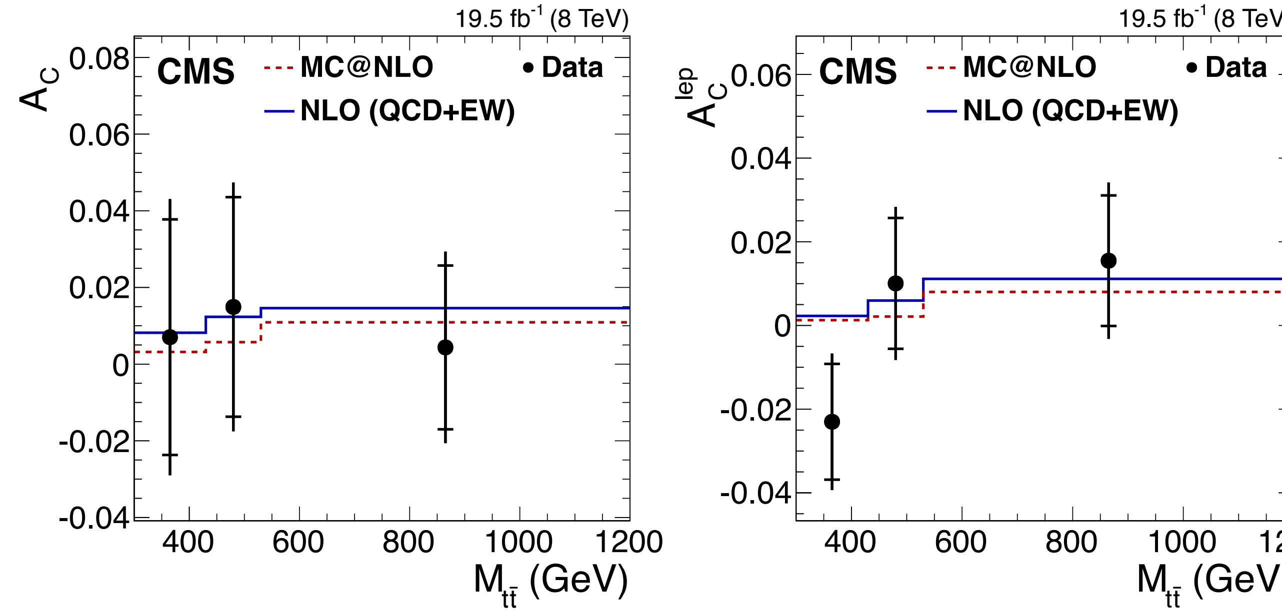
Most recent: 8 TeV dilepton channel

- **template fit, as function of $m_{t\bar{t}}$, $y_{t\bar{t}}$ and $p_{T,t\bar{t}}$**

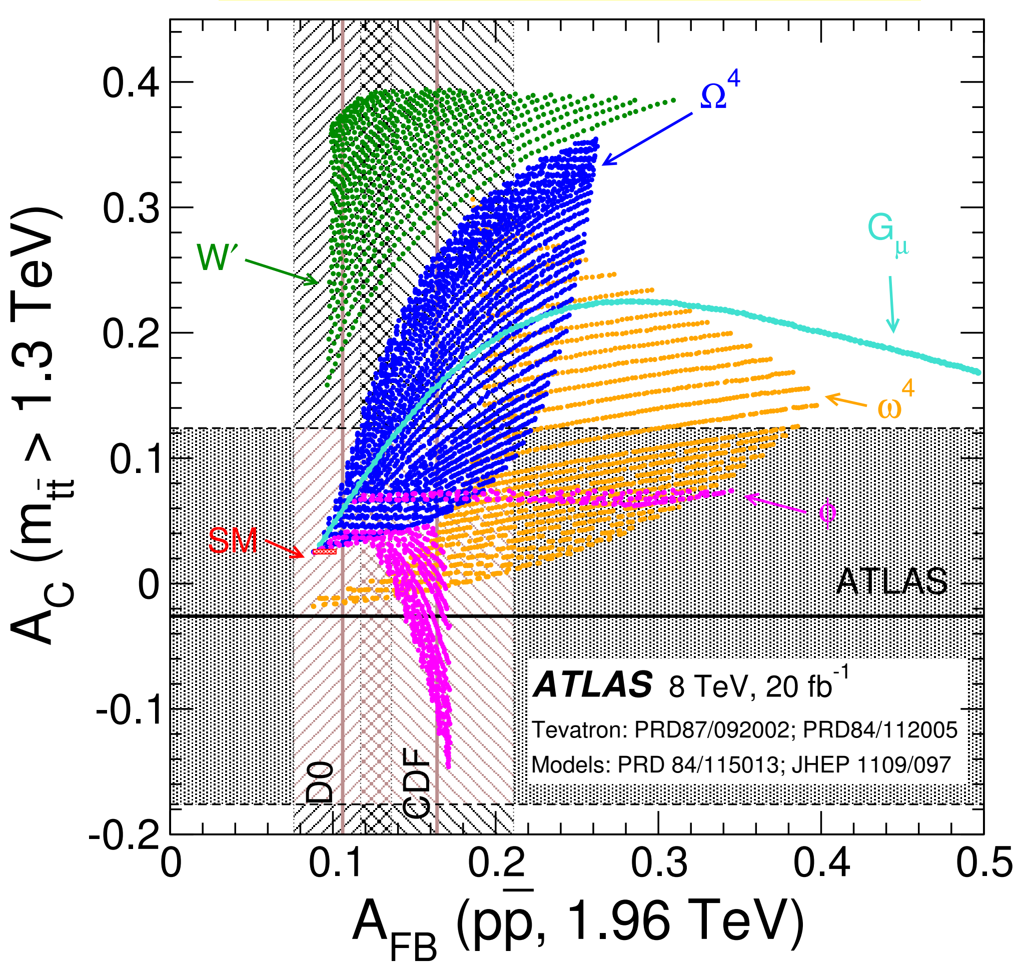
arXiv:1603.06221, PLB 760 (2016) 365

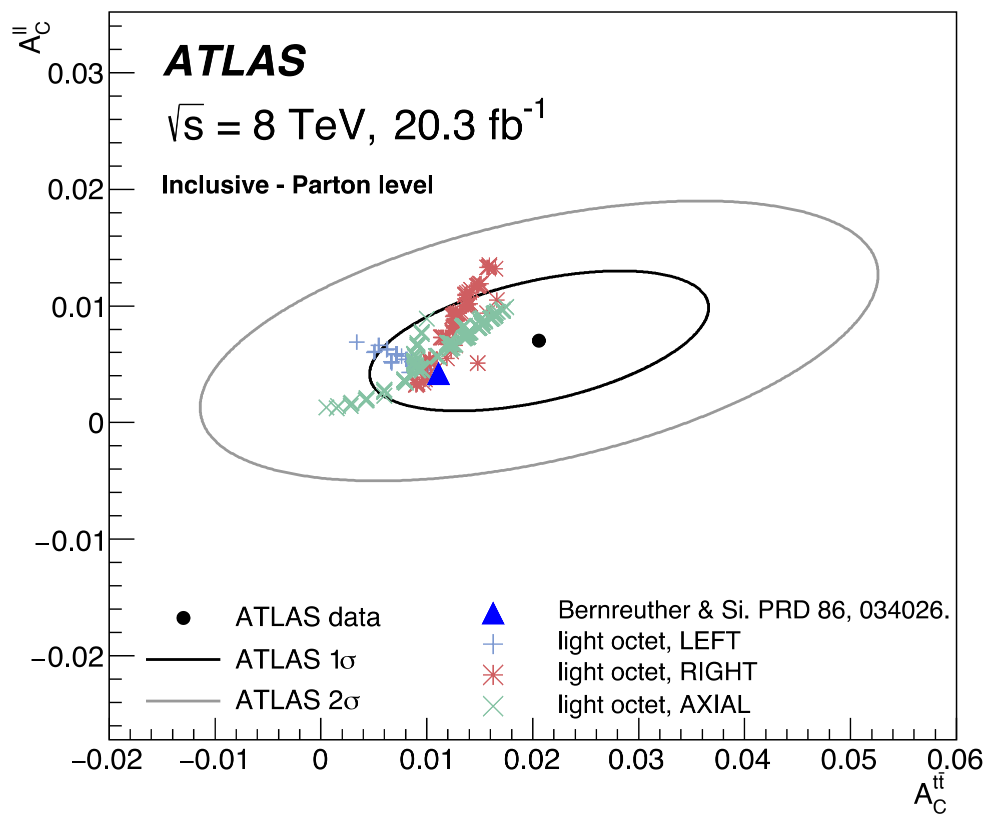
arXiv:1604.05538, PRD 94 (2016) 032006

Variable	CMS	ATLAS	NLO (QCD+EWK)
A_C $t\bar{t}$	1.1 ± 1.1 ± 0.7	2.1 ± 1.6	1.11 ± 0.04
A_C lep	0.3 ± 0.6 ±0.3	0.8 ± 0.6	0.64 ± 0.03



arXiv:1512.06092, PLB 756 (2016) 52





The *Wtb* vertex

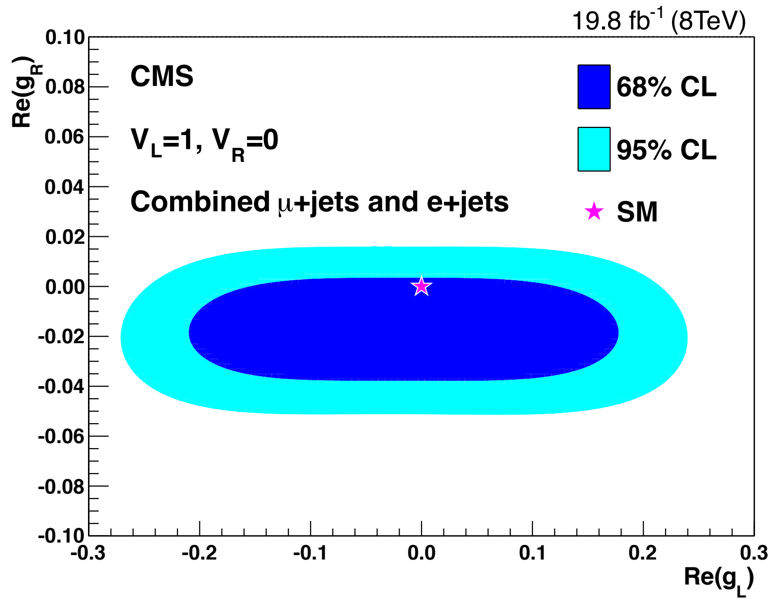
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_L P_L + g_R P_R\right) t W_{\mu}^{-}$$

W boson helicity

- *ℓ*+jets channel
- interpret as limits on g_R vs g_L

Variable	CMS	NNLO
F_0	68.1 ± 1.2 ± 2.3	68.7 ± 0.5
F_L	32.3 ± 0.8 ± 1.4	31.1 ± 0.5
F_R	-0.4 ± 0.5 ± 1.4	0.17 ± 0.01

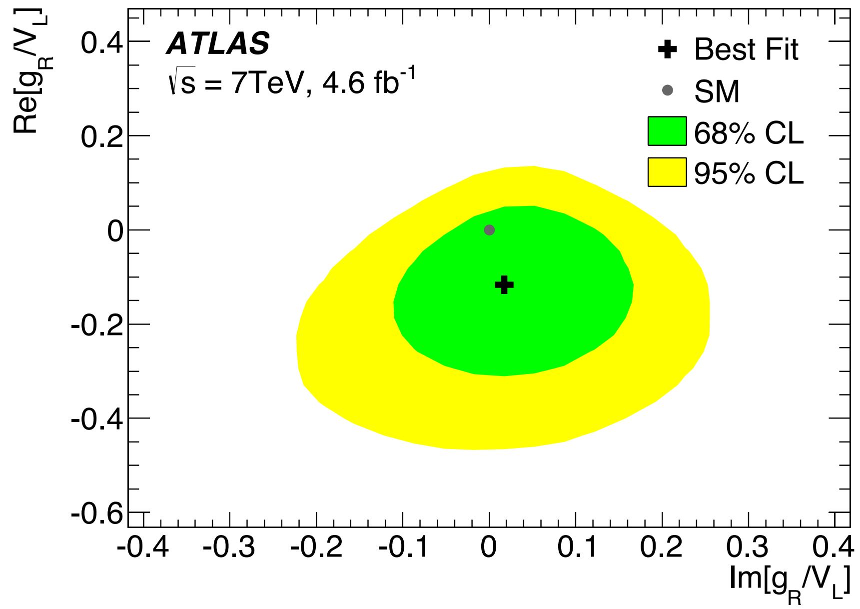
arXiv:1605.09047, submitted to PLB



t-channel

- double differential angular distributions
- interpret as limits on g_R/V_L

arXiv:1510.03764, JHEP 04 (2016) 023



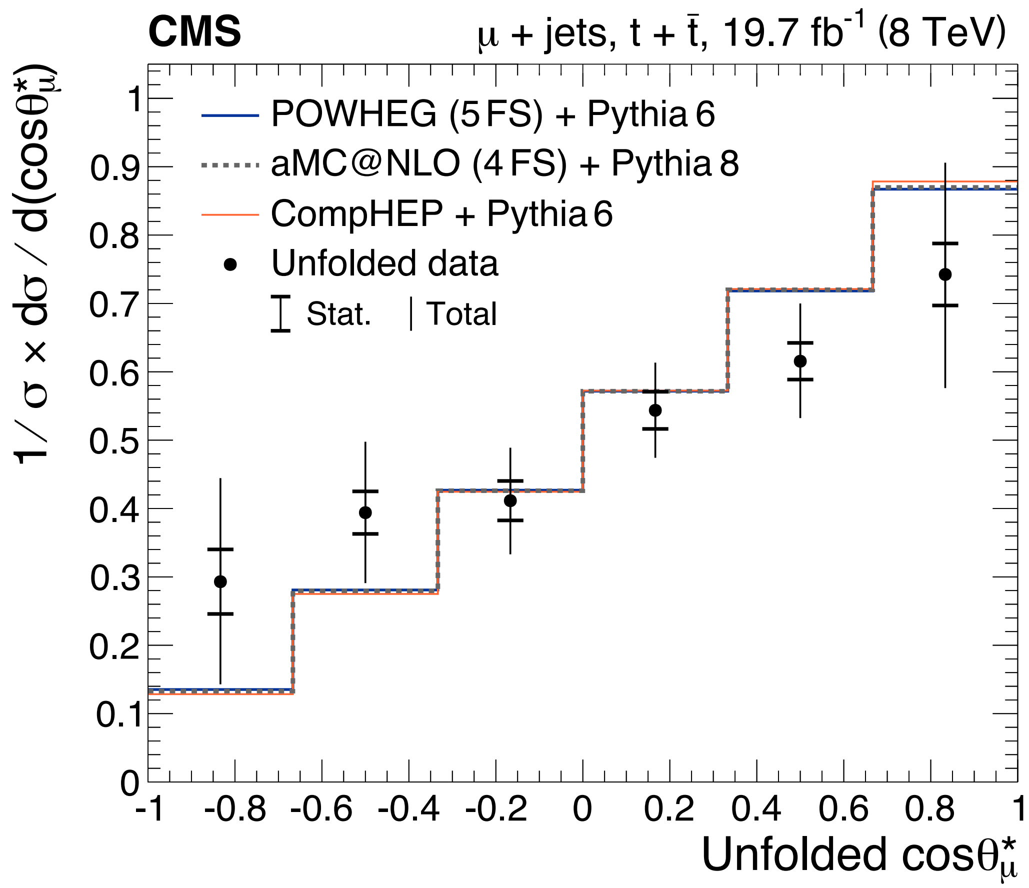
Top-quark polarisation

t-channel polarisation

- top-quark spin asymmetry sensitive to polarisation
- *p*-value of 4.6% SM (2.0σ)

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_X} = \frac{1}{2}(1 + P_t^{(\vec{s})}\alpha_X \cos\theta^*_X) = \left(\frac{1}{2} + A_X \cos\theta^*_X\right)$$

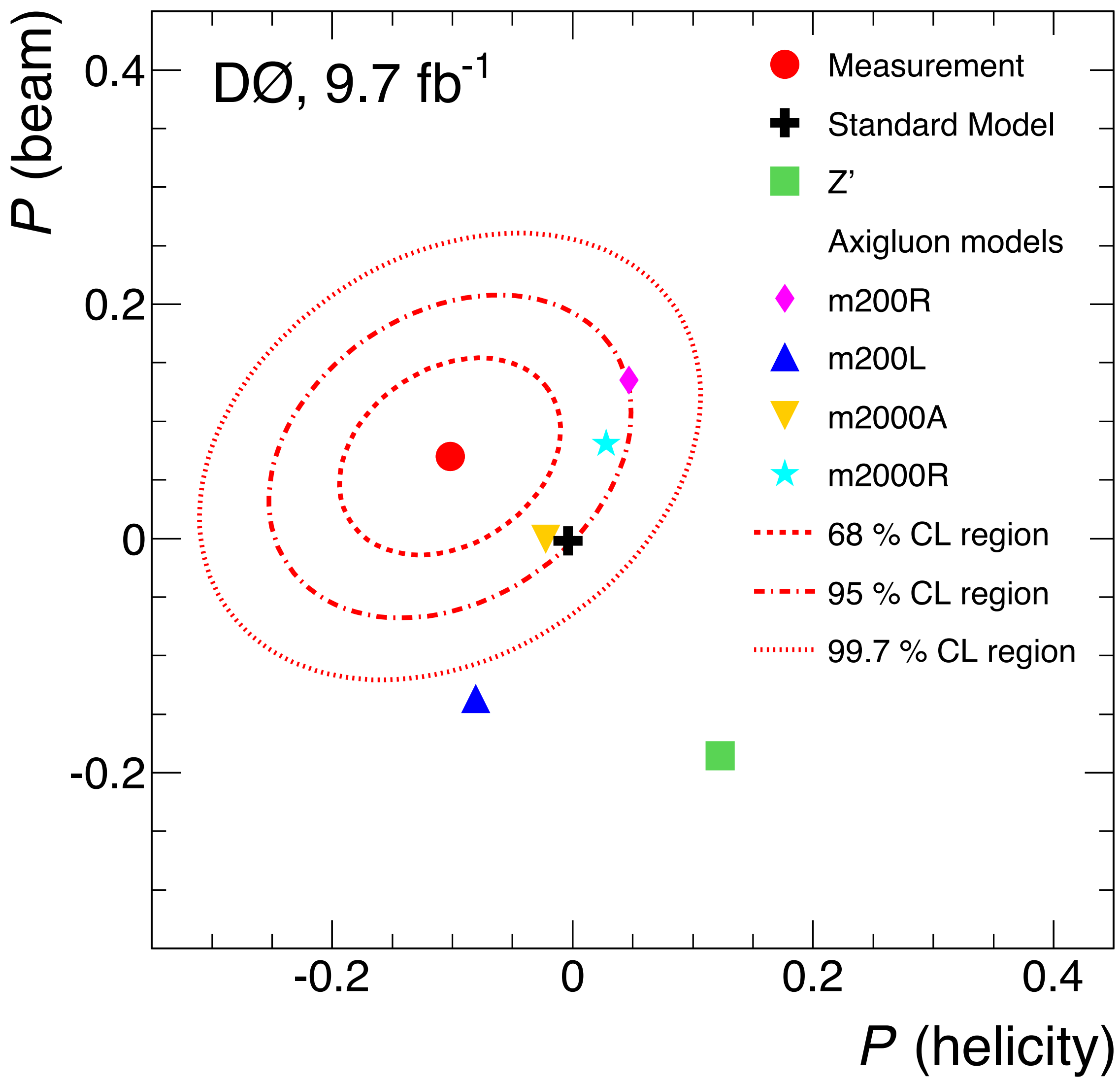
arXiv:1511.02138, JHEP 04 (2016) 073



$t\bar{t}$ top polarisation

- performed also at Tevatron
- compared with BSM models

arXiv:1607.07627, submitted to PRL



Much more in the pipeline …

More preliminary results released in 2016 by ATLAS and CMS

- **5 TeV**
  - $t\bar{t}$ inclusive (**16-015**)
- **8 TeV**
  - $t\bar{t}$ dilepton double differential (**14-013**)
  - $t\bar{t}$+jets (**15-006**)
  - search for tZ and FCNC in tZ (**12-039**)
  - mass dilepton (**15-008**), tt+1jet (**13-006**), leptonic observables (**16-002**), single top (**15-001**), all hadronic (**16-064**)
  - search for CP violation (**16-001**)
- **13 TeV**
  - inclusive $t\bar{t}$ $e\mu$ (**16-005**), ℓ+jets (**16-006**), all hadronic (**16-013**)
  - $t\bar{t}$ differential dilepton (**16-007, 16-011**), ℓ+jets (**16-008**)
  - $t\bar{t}b\bar{b}/t\bar{t}jj$ (**16-010**) and search for $t\bar{t}t\bar{t}$ production (**16-016**, **16-020**)
  - $t\bar{t}\,W$, $t\bar{t}Z$ (**16-017**)
  - t-channel inclusive (**16-003**), differential (**16-004**)
  - tZ (**16-009**)

… and **TOP2016** starts this Monday
with many new results anticipated

top 2016
OLOMOUC, CZECH REPUBLIC
9th International Workshop on Top Quark Physics
19 - 23 September 2016

Conclusion

Top physics is currently a very active field

- more than 150 LHC papers so far, 65 results released in the last year

$t\bar{t}$ precision measurements include

- 3.5% $t\bar{t}$ total cross-section
- 0.28% top quark mass
- modelling in differential measurements

New production mechanisms established, for instance

- $t\bar{t}\gamma$, $t\bar{t}b\bar{b}$, $t\bar{t}W$, $t\bar{t}Z$, single top Wt and s-channel

Searches for new processes involving top quarks

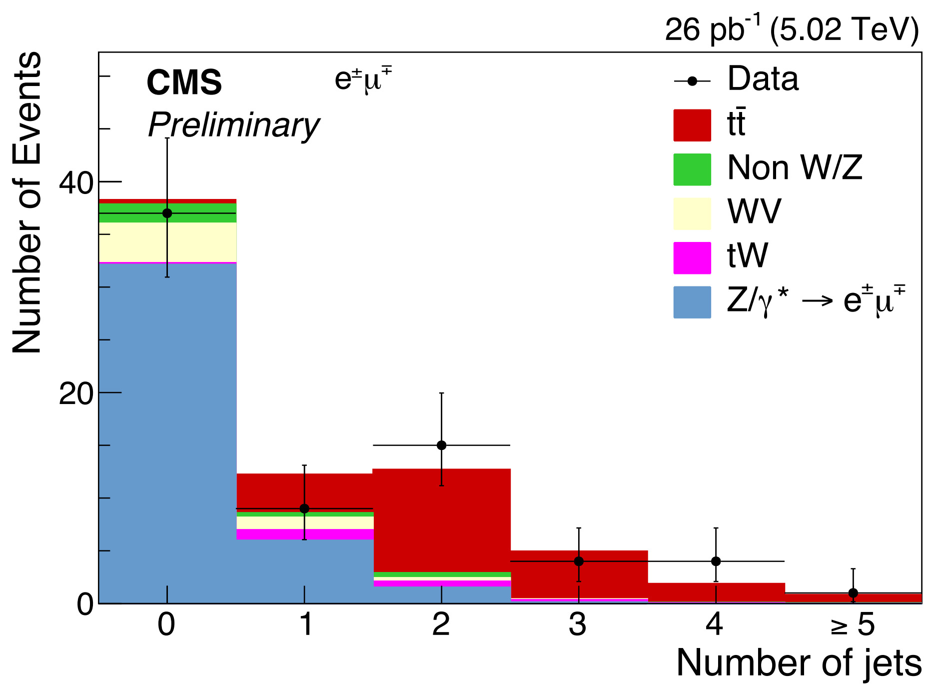
- $t\bar{t}H$, FCNC top quark decays, $t\bar{t}$ resonances, stop production, …

Expect even better sensitivity

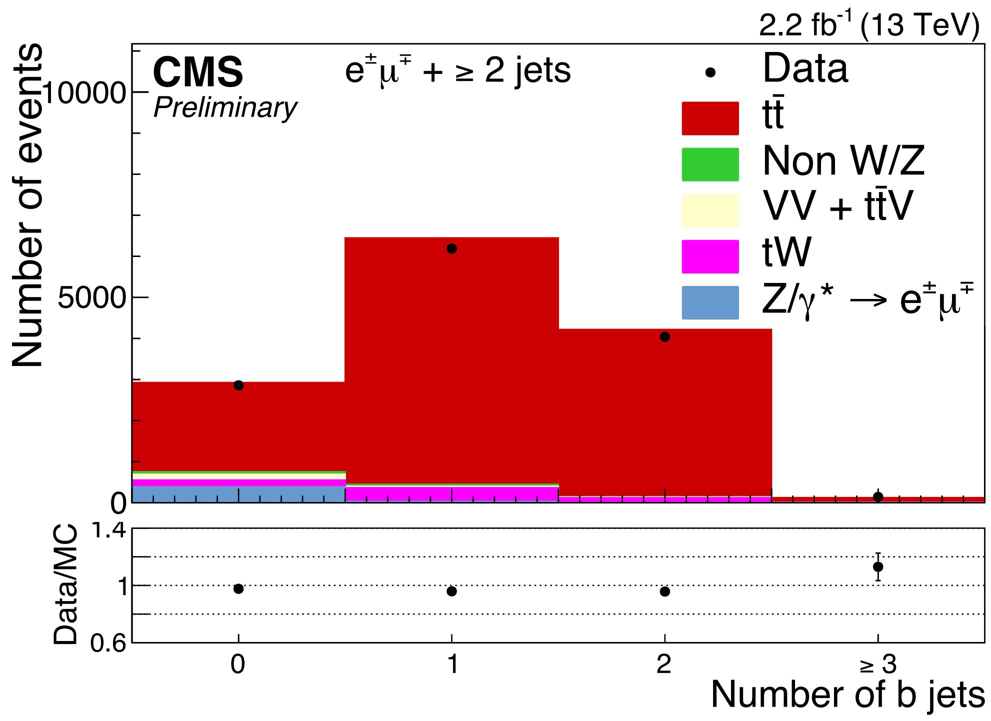
- with full 13 TeV dataset and ultimately with 3000/fb (HL-LHC)

Preliminary I: inclusive $\sigma_{t\bar{t}}$

5.02 TeV



13 TeV eμ channel



CMS PAS TOP-16-015

first measurement at this energy
expect 73% gg–initiated
data collected in Nov.2015
eμ channel + jets
$\sigma(t\bar{t})$ = 82 ± 23 pb

CMS PAS TOP-16-005

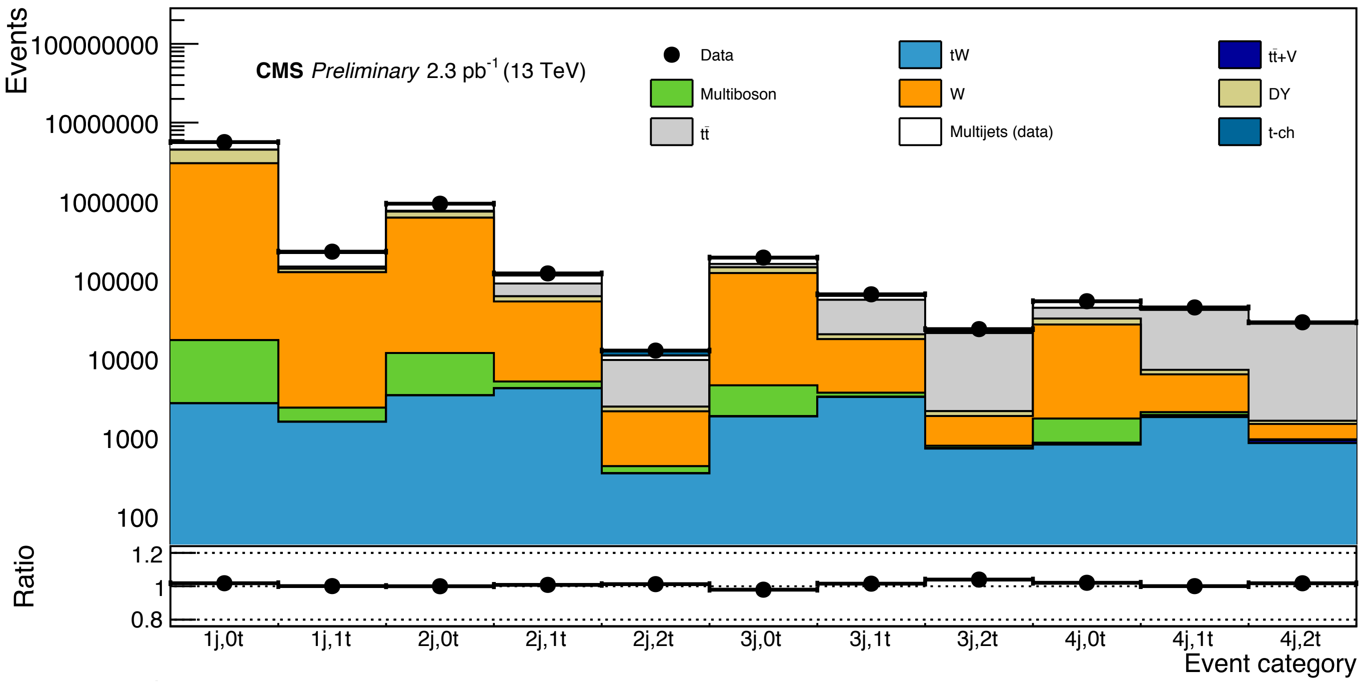
updated to 2.2fb^{-1}

$\sigma(t\bar{t}) = 793 \pm 8_{stat} \pm 38_{syst} \pm 21_{lumi}$ pb

Systematics dominated by ℓ efficiencies,
jet energy scale and $t\bar{t}$ NLO generator choice

Preliminary II: inclusive $\sigma_{t\bar{t}}$

13 TeV ℓ+jets channel

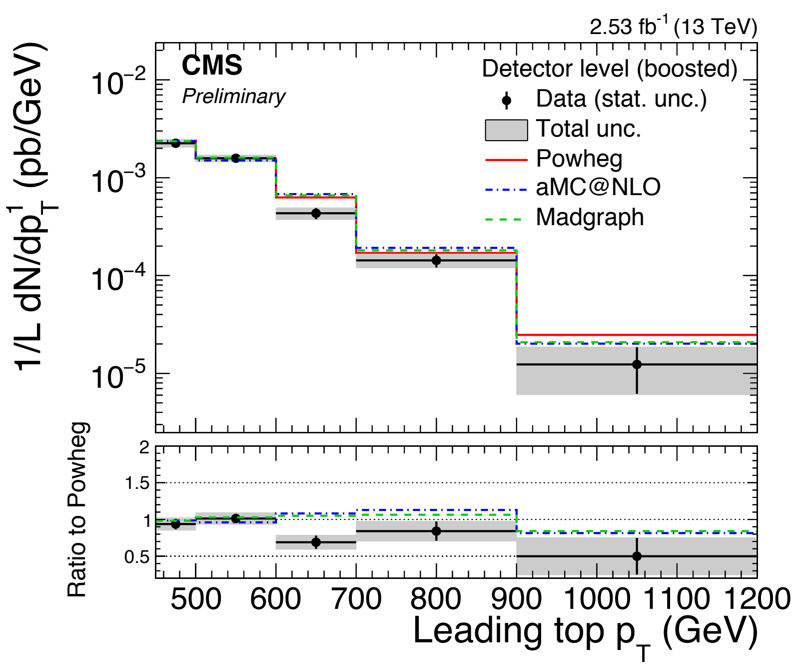


CMS PAS TOP-16-006

very inclusive 1ℓ + ≥ 1jet selection
fit to $m_{\ell b}$
$\sigma(t\bar{t})$ = 835 ± 32 pb

Also extract top pole mass
172.3 ± 2.5 GeV

13 TeV all hadronic



CMS PAS TOP-16-013

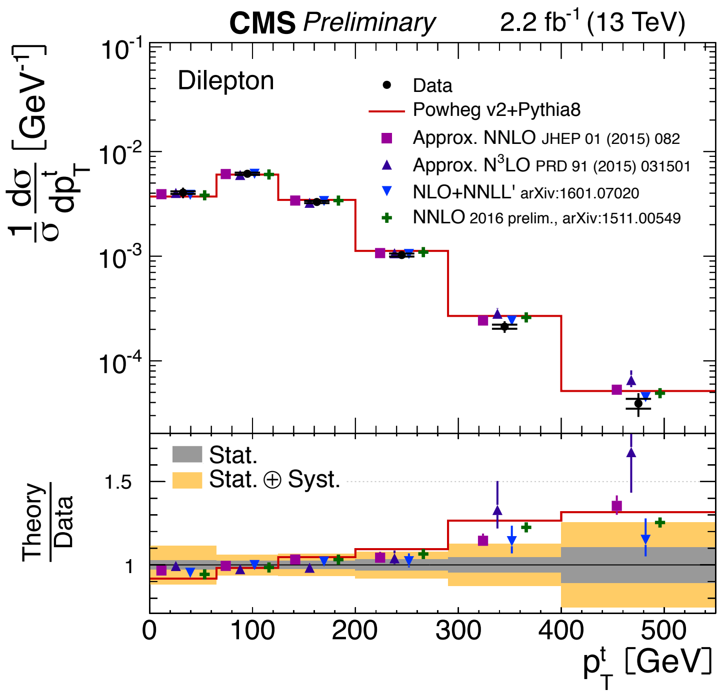
total $\sigma(t\bar{t})$ = 834 ± 116 pb
also differential, resolved and boosted
results also at parton level

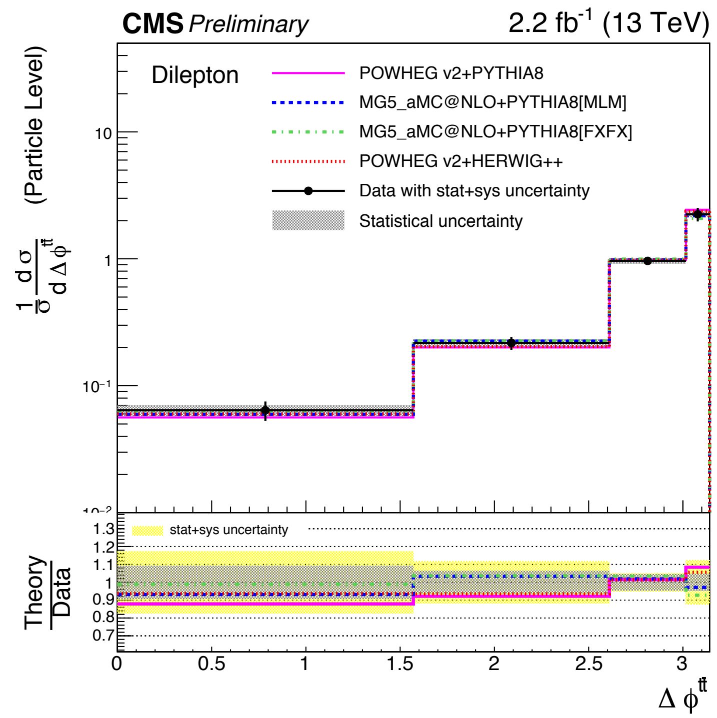
p_T(top) significantly softer than predictions

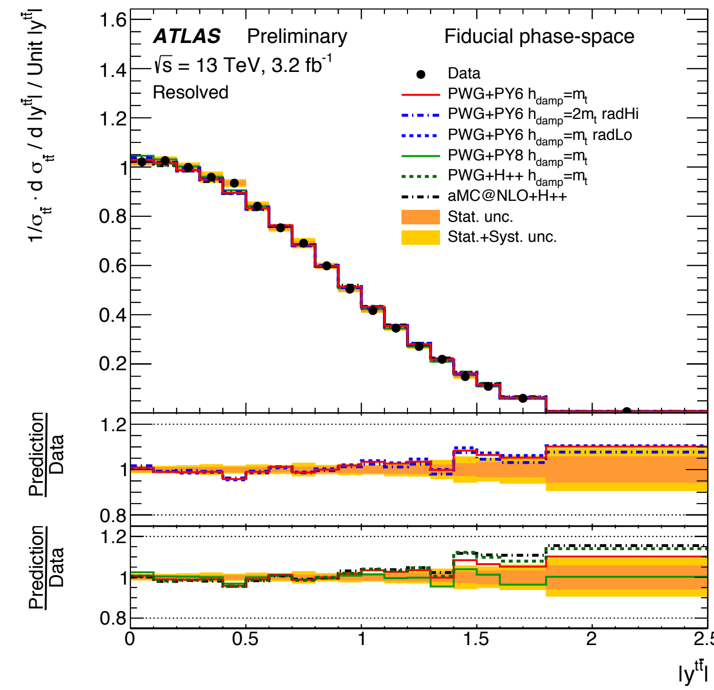
Preliminary III: differential $\sigma_{t\bar{t}}$

13 TeV dilepton

13 TeV ℓ+jets channel







CMS PAS TOP-16-011

as a function of top, $t\bar{t}$ and of the number of jets

Broadly in agreement with predictions

CMS PAS TOP-16-007

Particle level distributions as a function of top, $t\bar{t}$, ℓ and b-jet kinematic properties

Agree with predictions

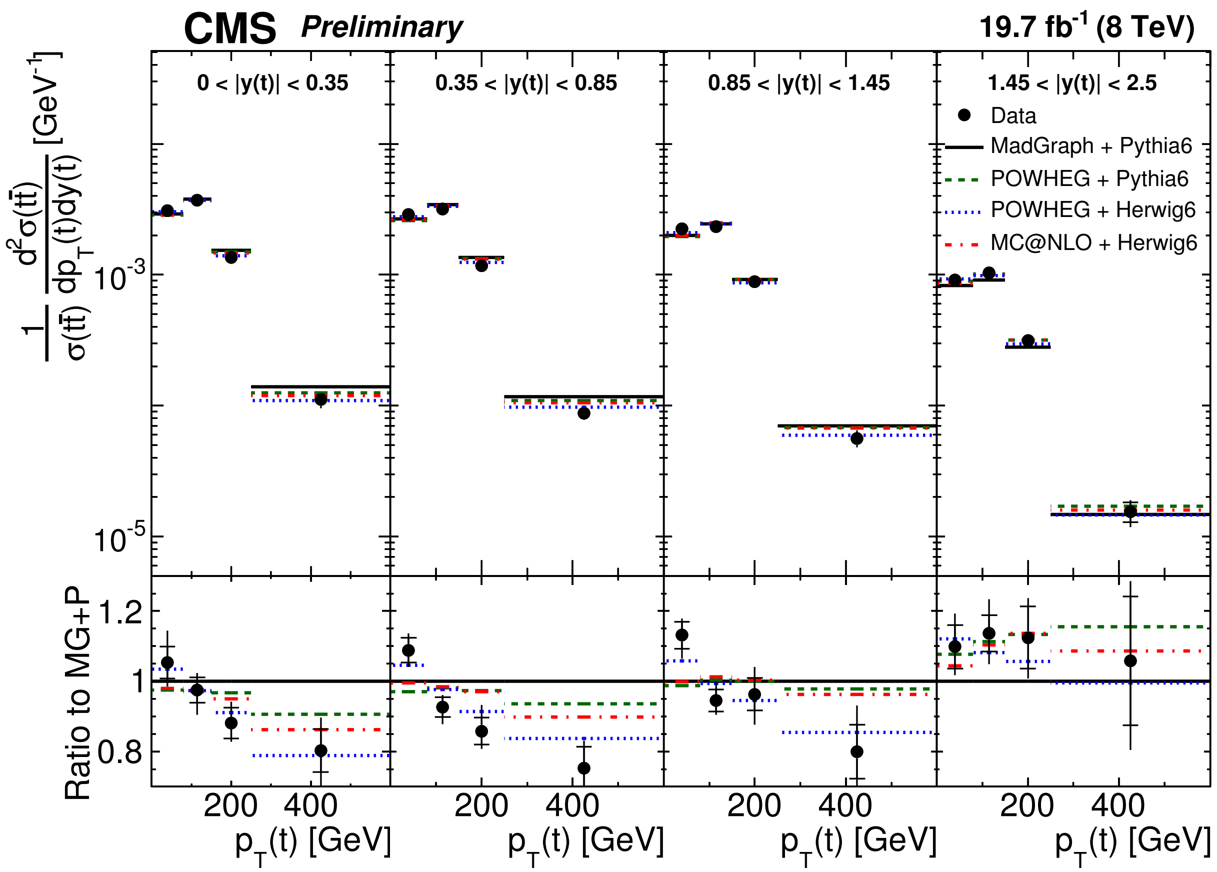
ATLAS-CONF-2016-040

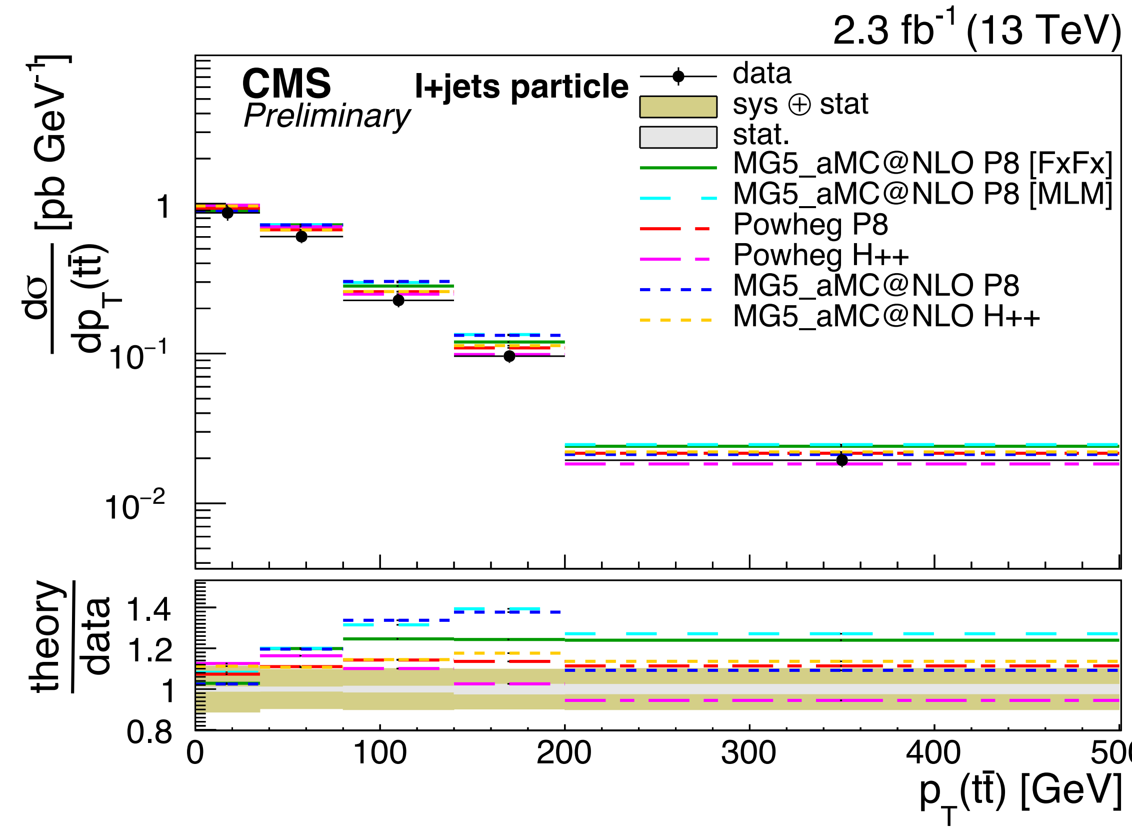
Resolved and boosted selection

Fair agreement with MC
Most generators predict a harder p_T(top)

Preliminary IV: differential $\sigma_{t\bar{t}}$

8 TeV double differential





CMS PAS TOP-14-013

dilepton eμ channel
various combinations of two observables
compared to NLO, aNNLO, Monte-Carlo predictions
impact on constraining gluon PDF is illustrated

Overall reasonable agreement

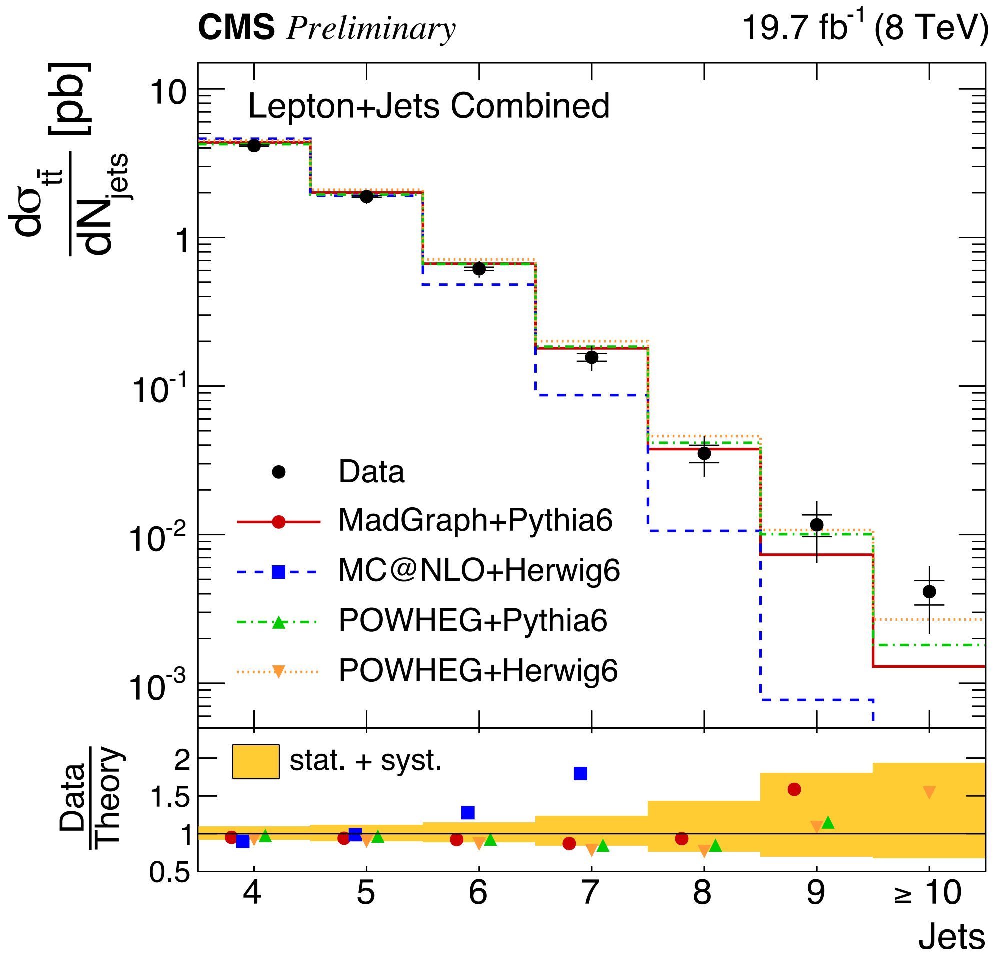
CMS PAS TOP-16-008

Particle and parton level as a function of top and $t\bar{t}$ kinematic variables

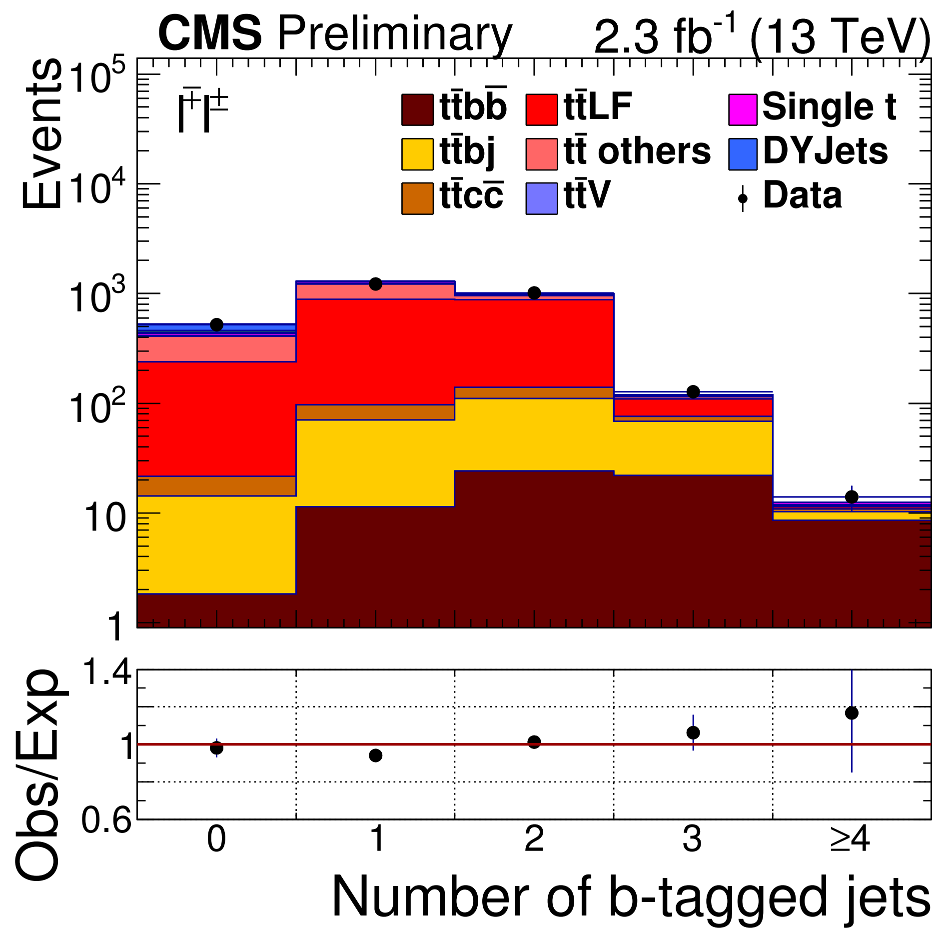
no significant deviation

Preliminary V: $t\bar{t}$+jets

8 TeV, $t\bar{t}$+jets



13 TeV, $t\bar{t}$+$b\bar{b}$



CMS PAS TOP-15-006

ℓ+jets
Fiducial and full phase space

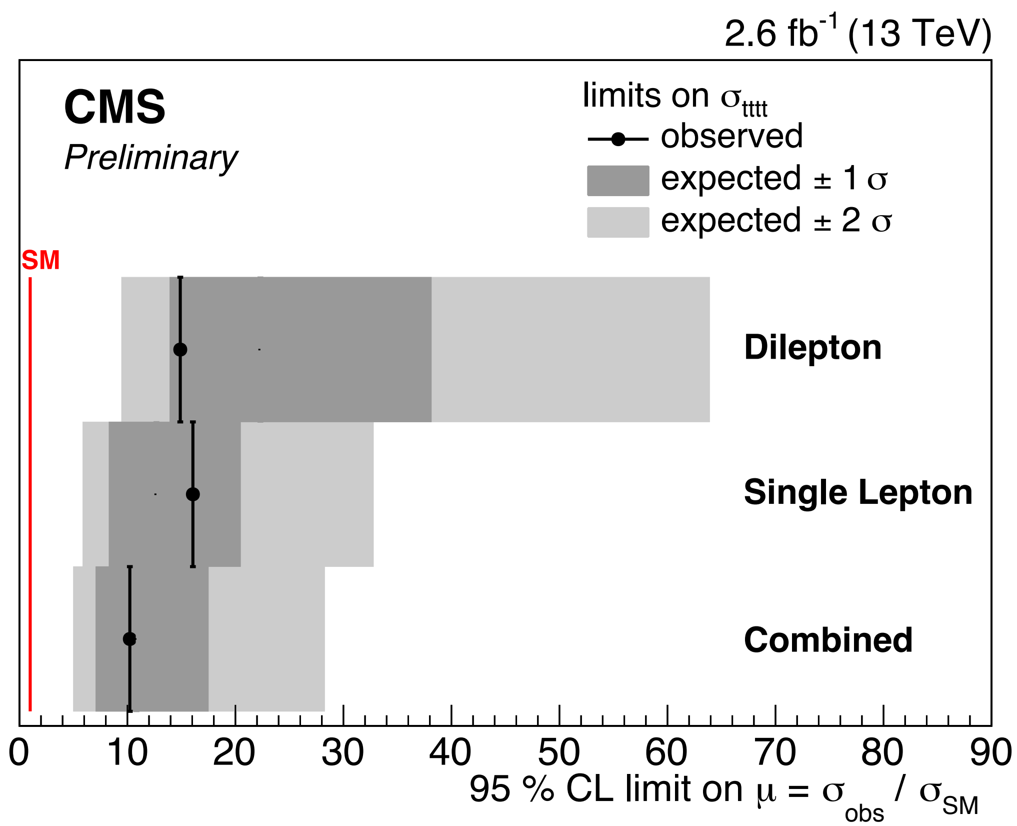
Good agreement with NLO predictions

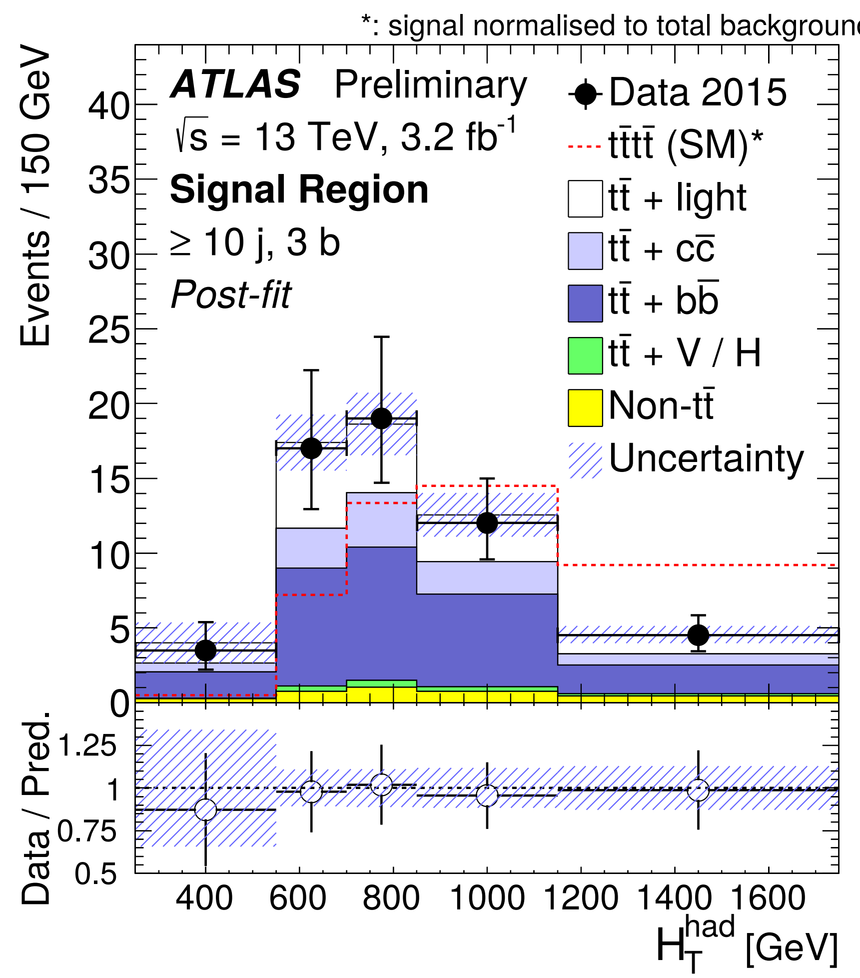
CMS PAS TOP-16-010

Select 2ℓ + ≥ 4jets
$\sigma(t\bar{t}\,b\bar{b})$ = 3.9 ± 1.4 pb
$\sigma(t\bar{t}\,b\bar{b})/\sigma(t\bar{t}\,jj)$ = (2.2 ± 0.6)%

Compatible with Powheg+Py

Search for $t\bar{t}$+$t\bar{t}$





CMS PAS TOP-16-016

SM expect 1.3 fb @ 13 TeV
Uses BDTs to suppress backgrounds

Upper limit 10.2 x $\sigma_{SM}(t\bar{t}t\bar{t})$ at 95%C.L.

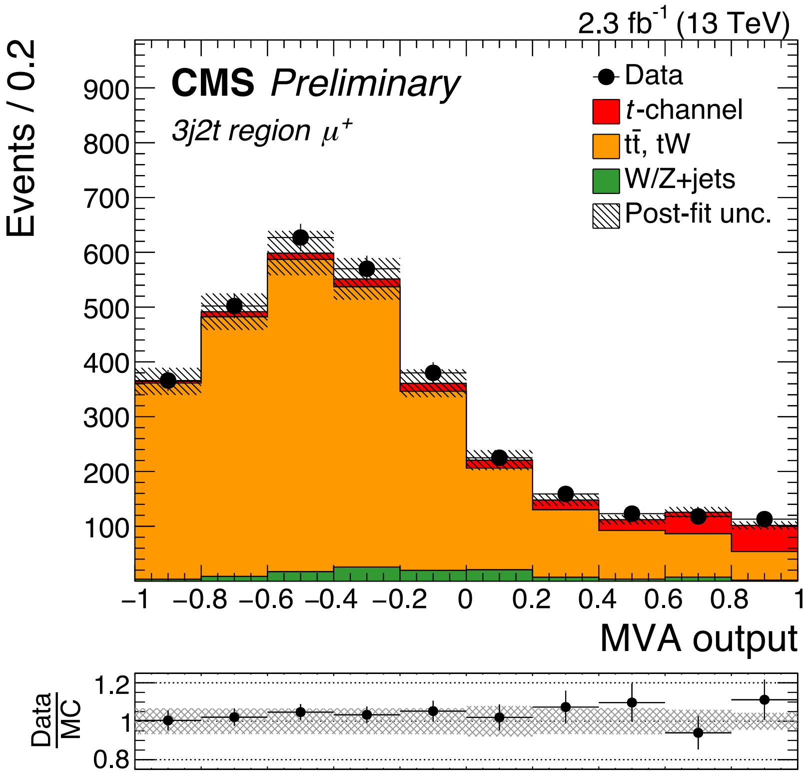
ATLAS-CONF-2016-020

Single lepton channel
Split in several categories

Upper limit 21 x $\sigma_{SM}(t\bar{t}t\bar{t})$ at 95%C.L.

Preliminary VII: single top

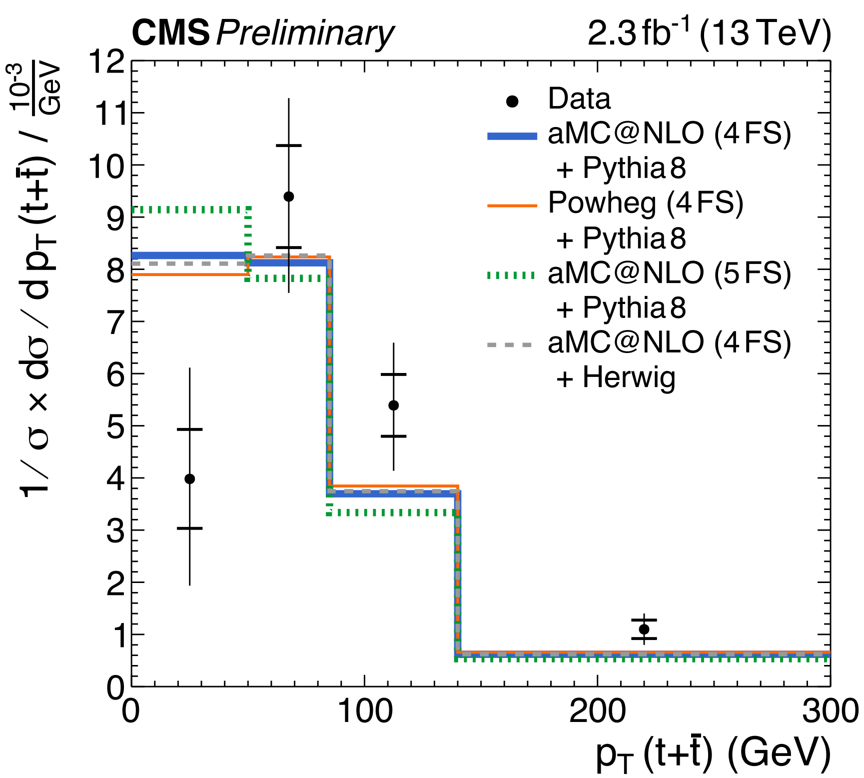
t-channel @ 13 TeV



CMS PAS TOP-16-003

μ+jets signature

$\sigma(t) = 142 \pm 23$ pb, $\sigma(\bar{t}) = 81 \pm 15$ pb
$\sigma(t+\bar{t}) = 228 \pm 33$ pb, $|V_{tb}| = 1.02 \pm 0.07$



CMS PAS TOP-16-004

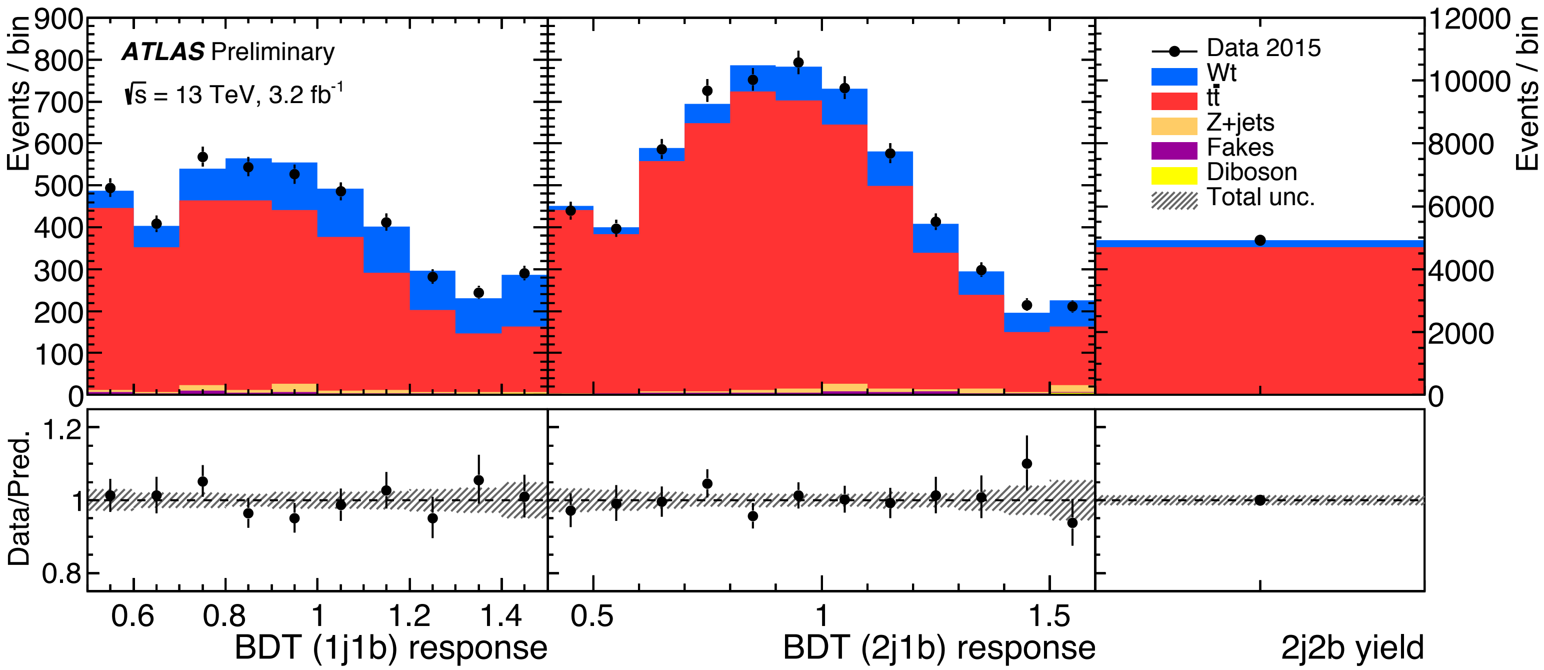
μ+jets signature

Parton level,
compared to Monte Carlo (NLO+PS)

General agreement within uncertainties

Preliminary VIII: single top

Wt channel @ 13 TeV

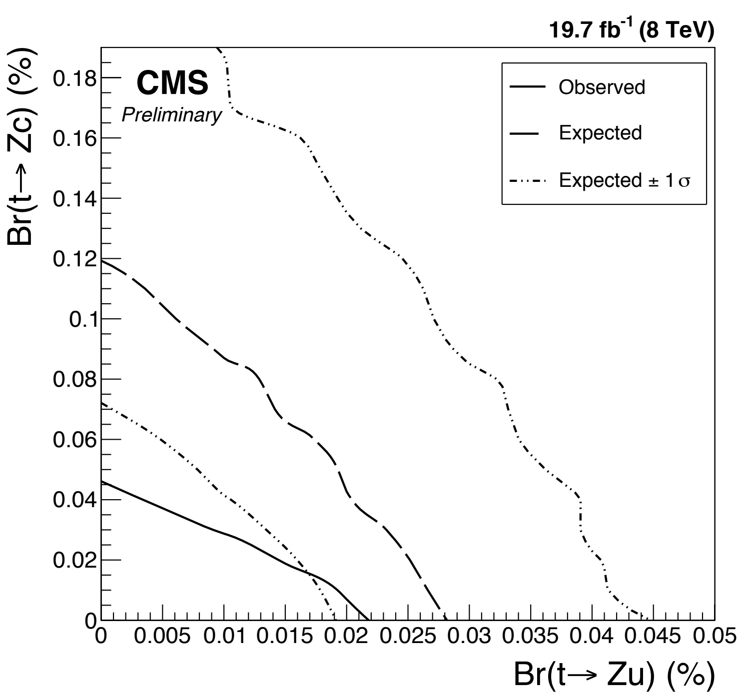


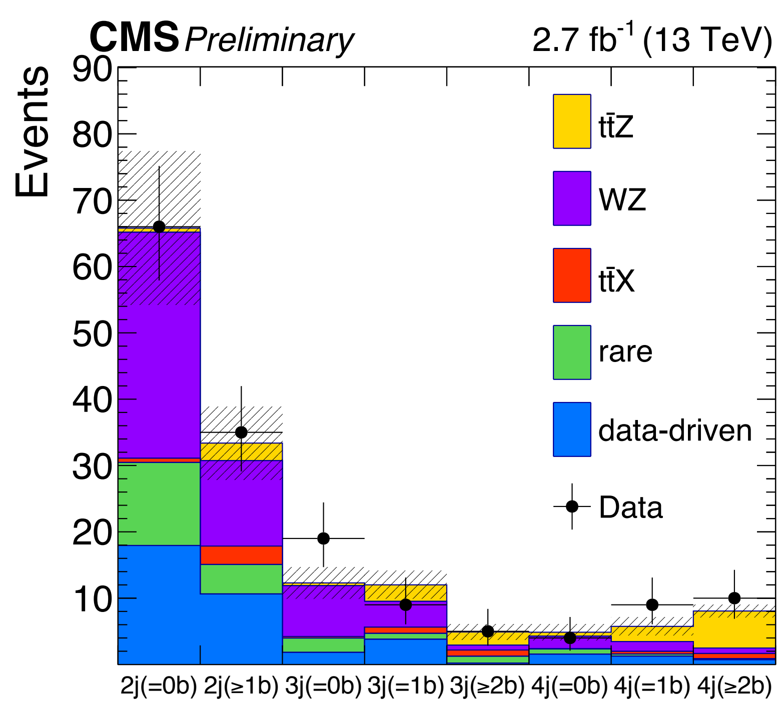
ATLAS-CONF-2016-065

Using BDT to separate from $t\bar{t}$

$$\sigma_{Wt} = 94 \pm 10\,(\text{stat.})^{+28}_{-23}\,(\text{syst.})\ \text{pb}$$

Search for tZ



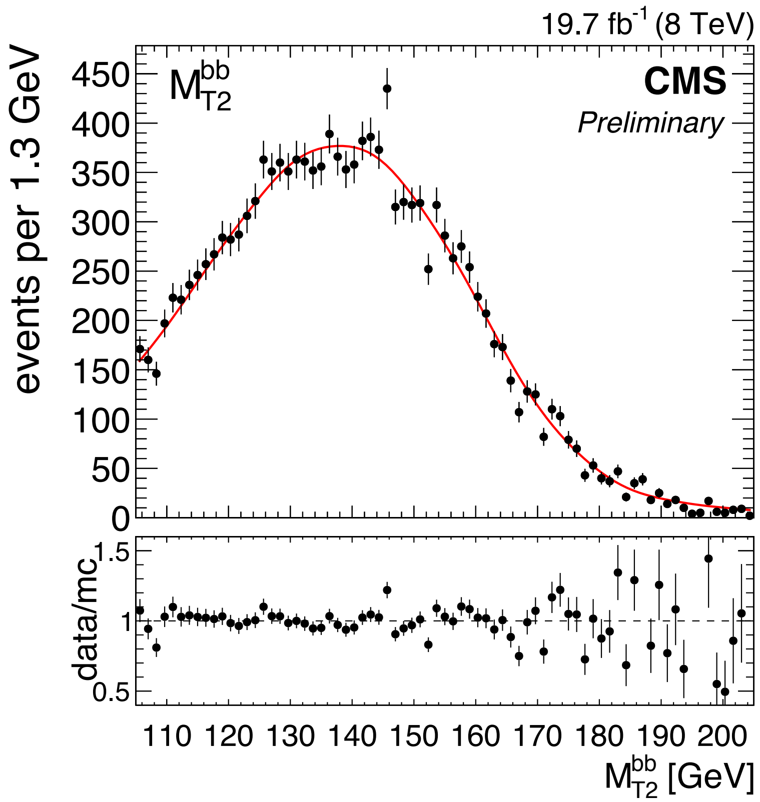


CMS PAS TOP-12-039

SM expect 236^{+19}_{-16} fb @ 8 TeV
measured $\sigma(tZq \rightarrow 3\ell)$ at 2.4σ
FCNC $t \rightarrow Zc$

Preliminary IX: m_{top}

Dilepton



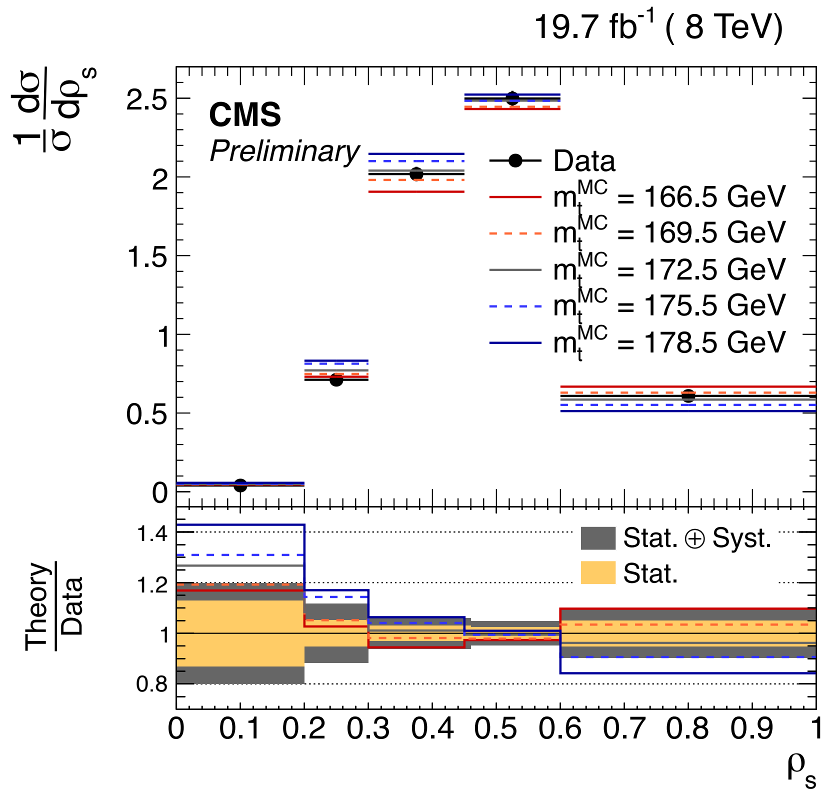
CMS PAS TOP-15-008

Using $m_{b\ell}$, m_{T2}, $m_{b\ell\nu}$ observables

Shape sensitive to m_{top}

$172.22 \pm 0.18\ \text{(stat)}\ ^{+0.89}_{-0.93}\ \text{(syst) GeV}$

$t\bar{t}$ + jet



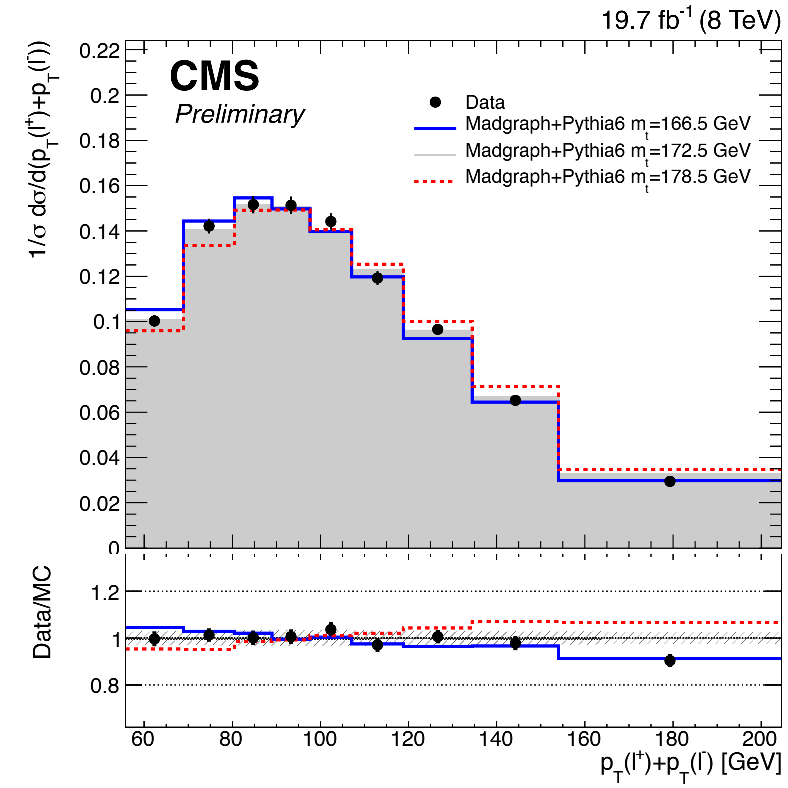
CMS PAS TOP-13-006

Using normalised invariant mass distribution of the $t\bar{t}$+jet system

Also extract from differential σ Dilepton channel

$169.9 \pm 1.1\ \text{(stat)}\ ^{+2.5}_{-3.1}\ \text{(syst)}\ ^{+3.6}_{-1.6}\ \text{(theo) GeV}$

leptonic observables



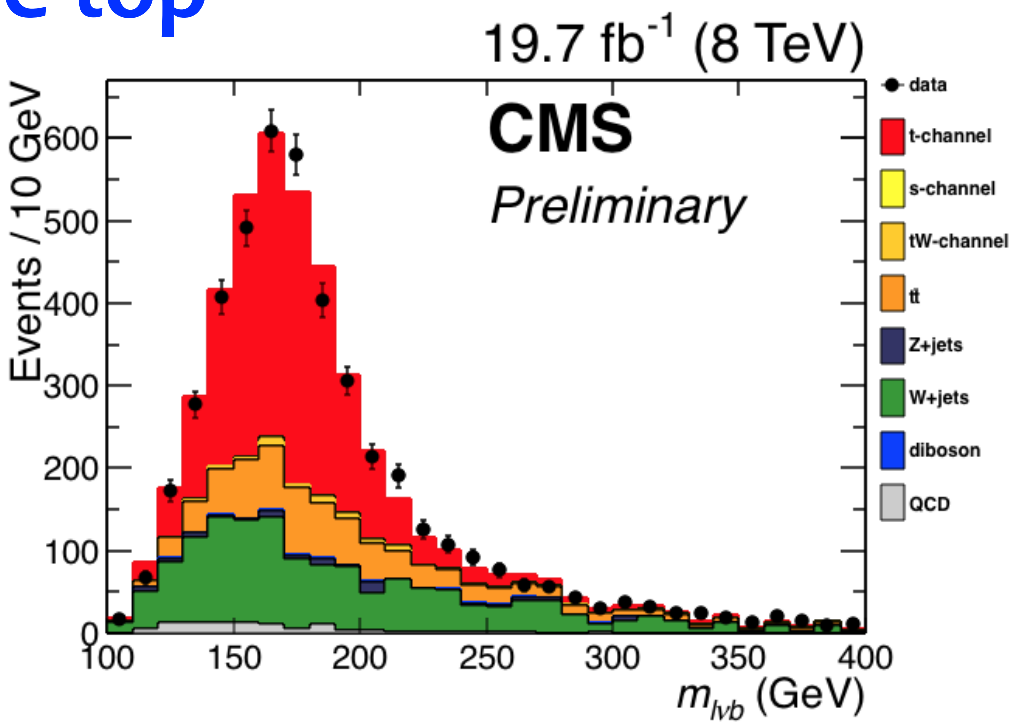
CMS PAS TOP-16-002

Novel technique, eμ channel several observables studied using $p_T(\ell\ell)$

$$171.7\ \pm 1.1\ \text{(stat.)} \pm 0.5\ \text{(exp.)}\ ^{+2.5}_{-3.1}\ \text{(th.)}\ ^{+0.8}_{-0.0}\ (p_T(t))\ \text{GeV}$$

Preliminary X: m_{top}

single top

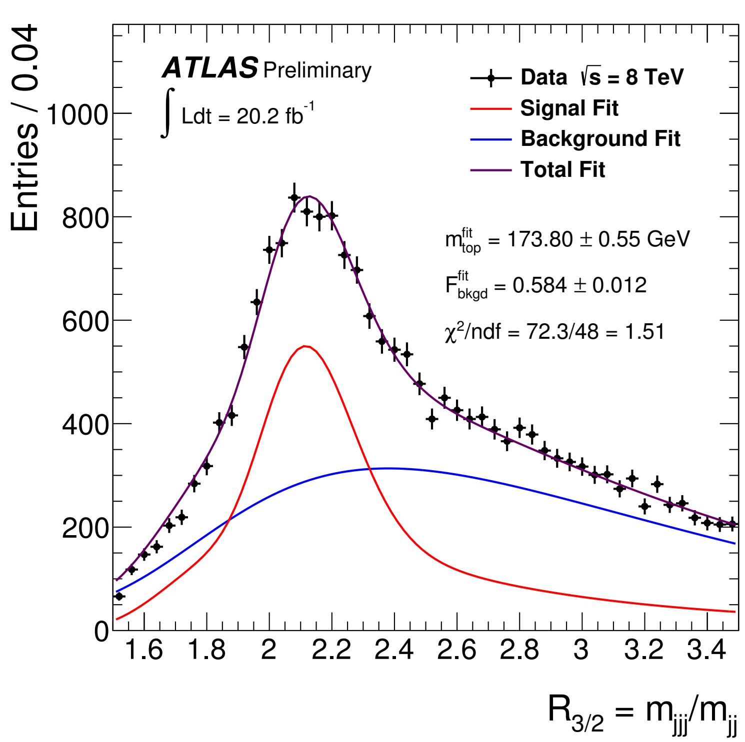


CMS PAS TOP-15-001

Using single top t-channel
µ channel
Selection aiming suppression of $t\bar{t}$

$$172.60 \pm 0.77\ (\text{stat})\ ^{+0.97}_{-0.93}\ (\text{syst})\ \text{GeV}.$$

all hadronic



ATLAS-CONF-2016-064

Events reconstructed with χ^2 method
Multi-jet background data-driven

Template fit to $R_{3/2} = m_{jjb}/m_{jj}$

$$173.80 \pm 0.55\ \ (\text{stat.}) \pm 1.01\ \ (\text{syst.})\ \ \text{GeV}$$

LHCb joins the top family

PRD 115 (2015) 112001

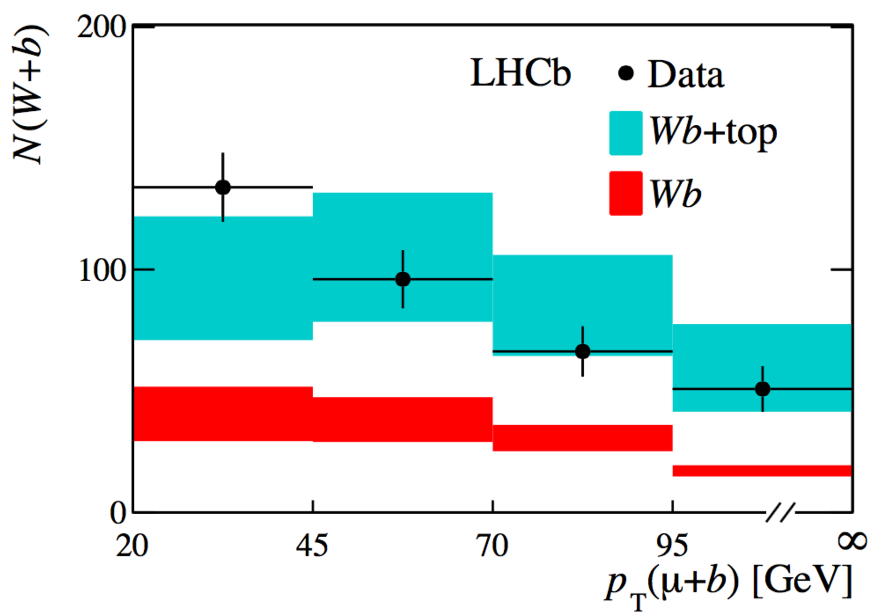
Forward region interesting

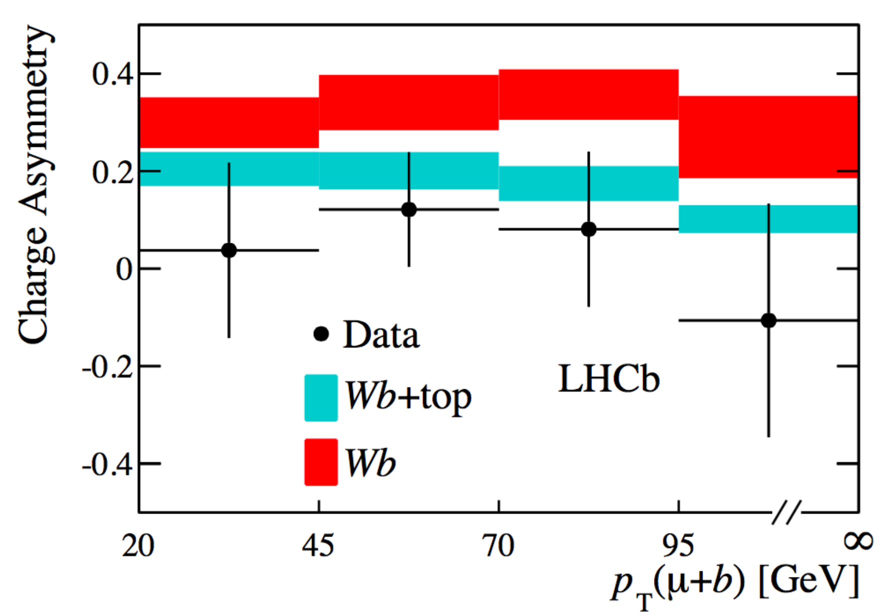
- enhanced sensitivity to BSM ($q\bar{q}$ and qg production)
- constrain PDF at large x → improves background to high-mass particles

LHCb observation

- can identify W bosons and tag b- and c-jets → combine to top quark search
- likelihood fit of $N(\mu b)$ and $A(\mu b)$ in fiducial region
- Wb-only hypothesis is excluded at 5.4 σ

$$\mathcal{A}(Wq) = \frac{\sigma(W^+q) - \sigma(W^-q)}{\sigma(W^+q) + \sigma(W^-q)}$$





compatible with MCFM NLO

$$p_T(\mu) > 25\,\text{GeV},\ 2.0 < \eta(\mu) < 4.5$$
$$\Delta R(\mu, b) > 0.5,\ \text{and}\ p_T(\mu + b) > 20\,\text{GeV}$$
$$50 < p_T(b) < 100\,\text{GeV},\ 2.2 < \eta(b) < 4.2$$

$$\sigma(\text{top})[7\,\text{TeV}] = 239 \pm 53\,(\text{stat}) \pm 38\,(\text{syst})\ \text{fb}\,,$$
$$\sigma(\text{top})[8\,\text{TeV}] = 289 \pm 43\,(\text{stat}) \pm 46\,(\text{syst})\ \text{fb}\,.$$

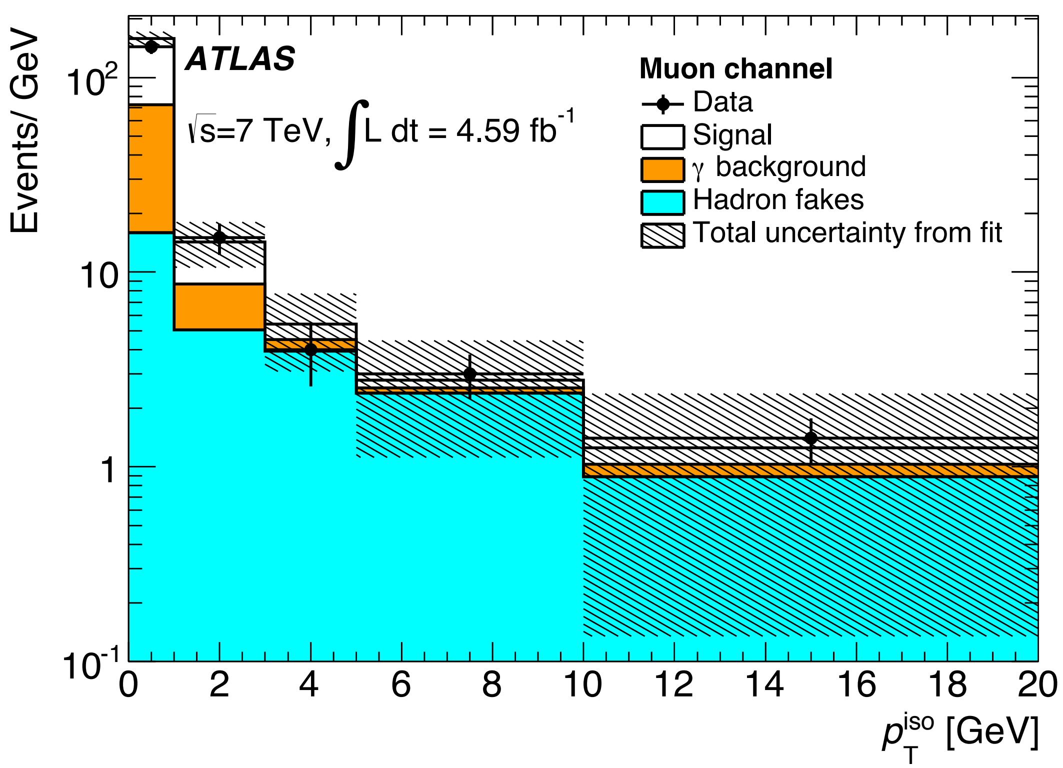
PRD 91 (2015) 07207

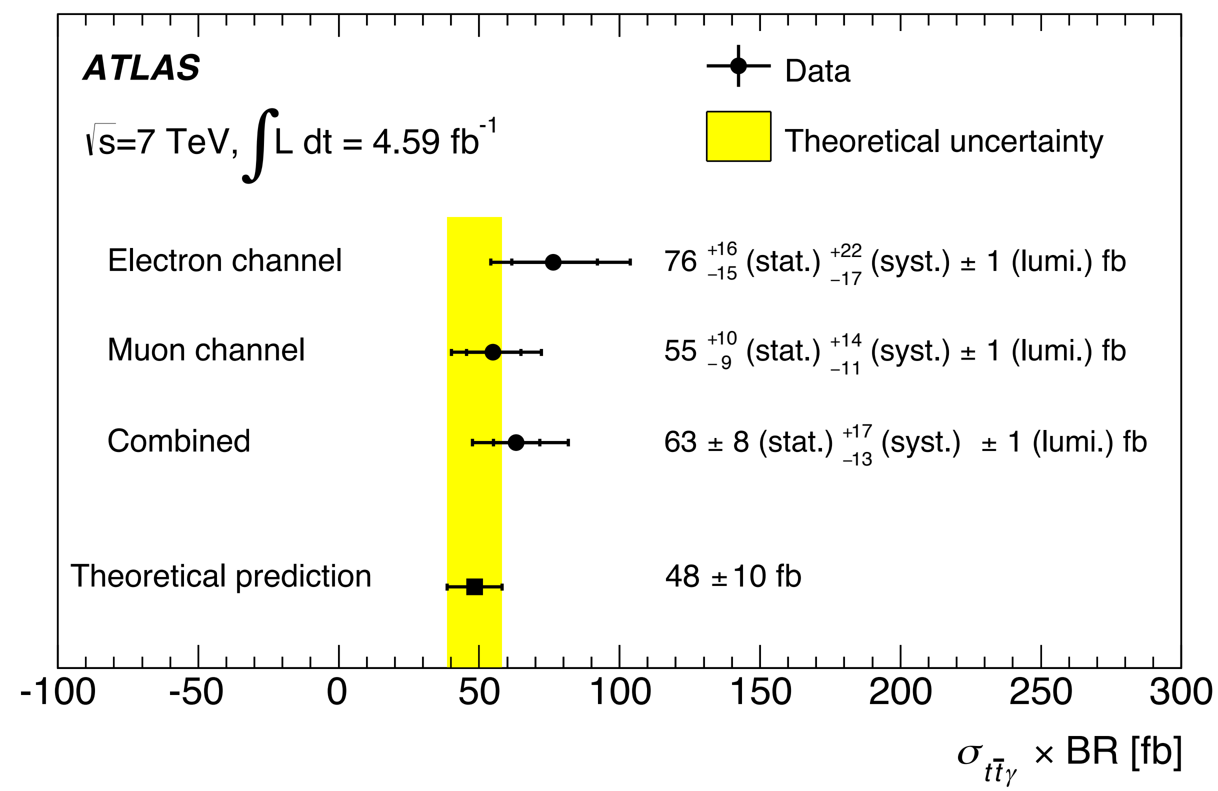
Observation in 7 TeV data

- sensitive to $t\gamma$ coupling and to anomalous $t^* \to t\gamma$

Fiducial cross section measurement at particle level

- with generator cuts $p_T(\gamma) > 20$ GeV and $\Delta R(\gamma, \ell) > 0.7$
- template fit to photon isolation variable in ℓ+jets+γ channel
- suppress misidentified γ from $Z \to ee$: $|m_{e\gamma} - m_Z| > 5$ GeV





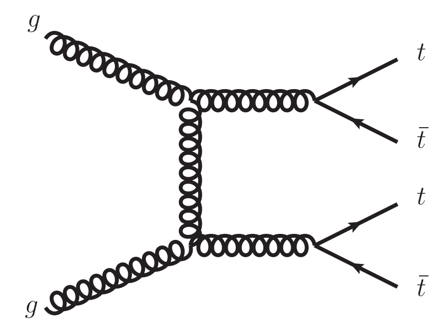
- jet energy scale and *b*-tagging efficiency are main systematics

Null hypothesis excluded at 5.3 σ

$t\bar{t}t\bar{t}$

$\sigma_{t\bar{t}t\bar{t}}$ ~ 1 fb (8 TeV) 1.3fb (13 TeV)

- main background is $t\bar{t}$+jets



JHEP 11 (2014) 154
JHEP 10 (2015) 150
JHEP 08 (2015) 105

CMS PAS TOP-16-016
ATLAS-CONF-2016-020

Searches

- Dedicated searches with ℓ + ≥ 6 jets, ≥ 2 *b*-tags, large H_T
- Generic searches targeting several exotic final states: ℓ+jets and same-sign 2ℓ

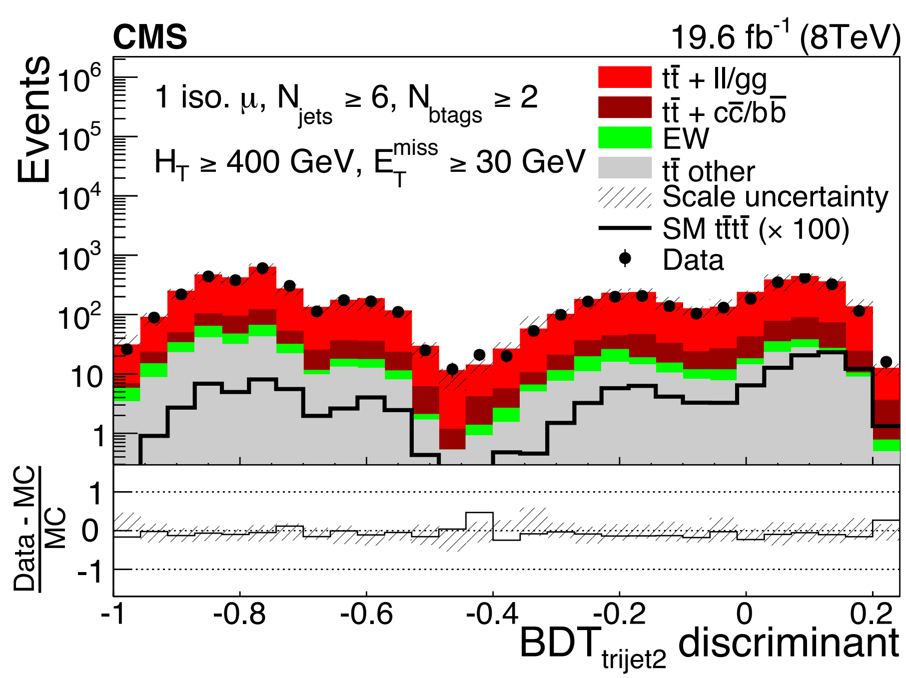
Strategies

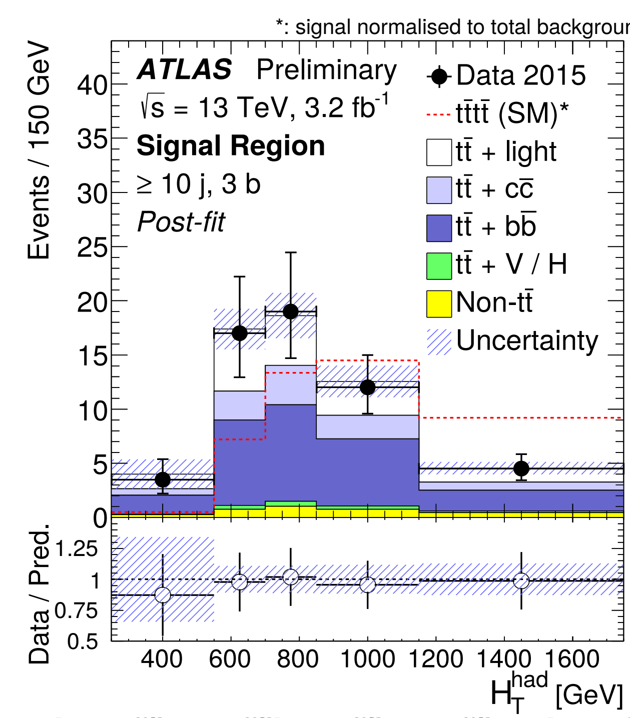
- use BDT classifier with top content, event activity and *b*-jet content

Limits in terms of $\mu = \sigma_{obs}/\sigma_{SM}$

- 95% C.L. exclusion limits

Experiment	Channel	Energy	Observed
CMS	ℓ+jets	8 TeV	32
ATLAS	same sign 2ℓ	8 TeV	70
ATLAS	ℓ+jets	8 TeV	23
CMS	2ℓ and ℓ+jets	13 TeV	10.2
ATLAS	ℓ+jets	13 TeV	21





CP violation in $t\bar{t}$ events

Tiny in the SM, but new physics can enhance CP violation

CMS PAS TOP-16-001

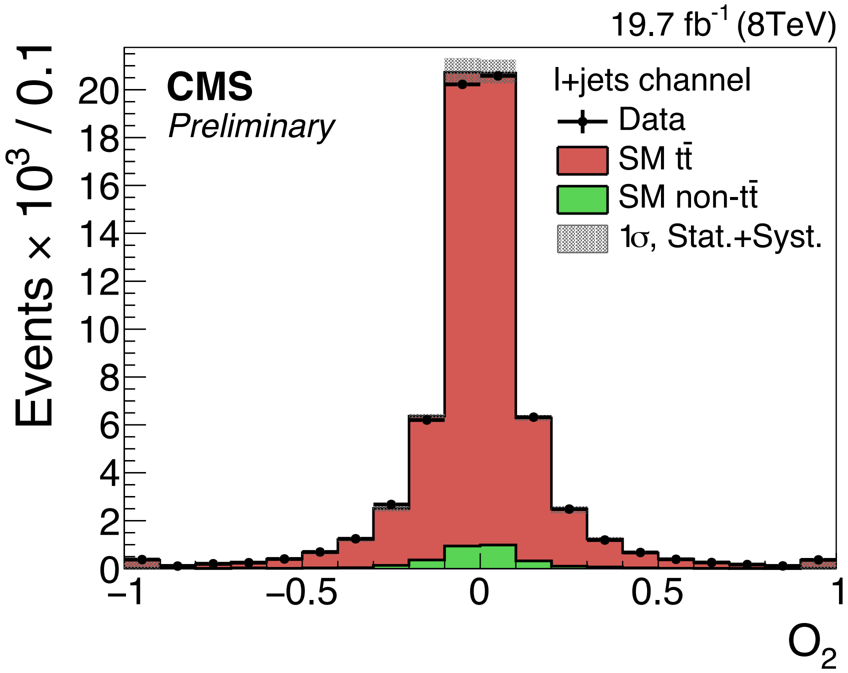
- **anomalous couplings in $t\bar{t}$ production and W decays**
- **measure with 4 T-odd triple-product observables (O_i)**
  - assume CPT conservation
  - observables calculated by the composition of decays' momenta of $t\bar{t}$ ℓ+jets channel
  - present with asymmetry parameter A_{CP}

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

Results consistent with SM

- **final A_{CP} after background subtraction are zero as in SM**
- **systematic uncertainties mostly canceled**

$A'_{CP}(O_i)$	e+jets	μ+jets	ℓ+jets
O_2	$-0.01 \pm 0.61 \pm 0.01$	$+0.50 \pm 0.56 \pm 0.02$	$+0.27 \pm 0.41 \pm 0.01$
O_3	$-0.34 \pm 0.61 \pm 0.02$	$-1.03 \pm 0.56 \pm 0.04$	$-0.71 \pm 0.41 \pm 0.03$
O_4	$-0.24 \pm 0.61 \pm 0.02$	$-0.49 \pm 0.56 \pm 0.04$	$-0.38 \pm 0.41 \pm 0.03$
O_7	$-0.42 \pm 0.61 \pm 0.00$	$+0.46 \pm 0.56 \pm 0.01$	$-0.06 \pm 0.41 \pm 0.01$



Definitions of kinematic quantities

$y_{boost}^{t\bar{t}} = (y^{t,1}+y^{t,2})/2$

- longitudinal motion of the $t\bar{t}$ system in lab frame

$\chi^{t\bar{t}} = \exp(2|y^*|)$

- production angle, with y* (and –y*) the top rapidity in the CM frame
- many BSM signals expected to peak at low $\chi^{t\bar{t}}$ values

Out-of-plane momentum

- projection of the top-quark momentum onto the direction perpendicular to a plane defined by the other top quark and the beam axis (z) in lab frame

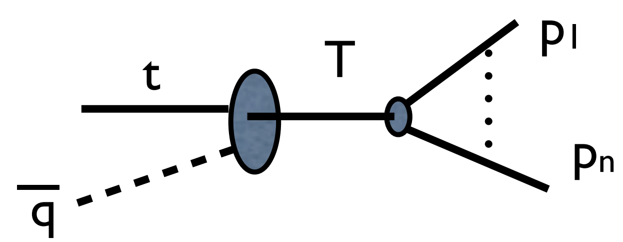
$$\left|p_{\text{out}}^{t\bar{t}}\right| = \left|\vec{p}^{\,t,\text{had}} \cdot \frac{\vec{p}^{\,t,\text{lep}} \times \hat{z}}{|\vec{p}^{\,t,\text{lep}} \times \hat{z}|}\right|$$

Ratio of p_T of the W boson and corresponding top quark

$$R_{Wt} = p_{\text{T}}^{W,\text{had}} / p_{\text{T}}^{t,\text{had}}$$

What top mass do we measure?

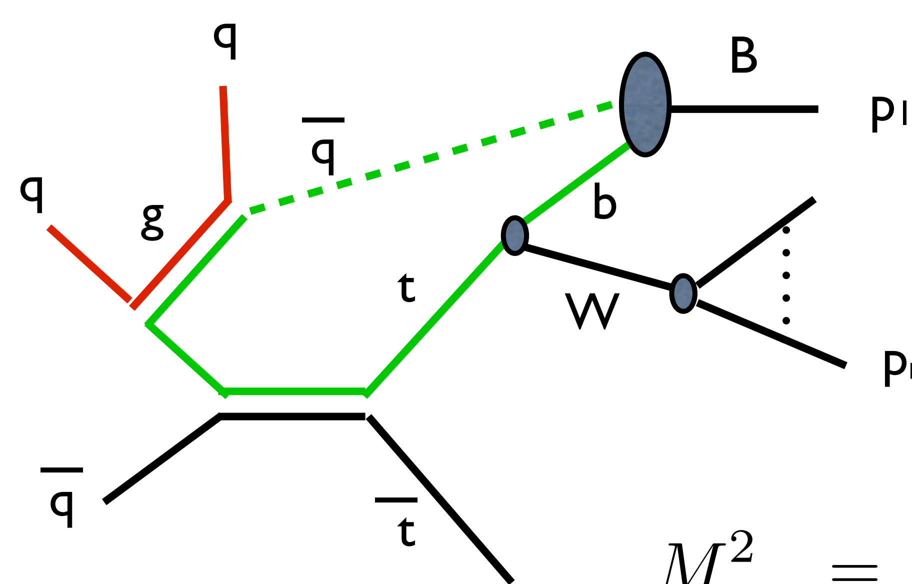
If Γ_{top} were < 1 GeV, top would hadronize before decaying. Same as b-quark



$$m_T^2 = \left(\sum_{i=1,\ldots,n} p_i\right)^2$$

$m_t = F_{lattice/potential\ models}(m_T, \alpha_{QCD})$

But Γ_{top} is > 1 GeV, top decays before hadronizing. Extra antiquarks must be added to the top-quark decay final state in order to produce the physical state whose mass will be measured



$$M_{exp}^2 = \left(\sum_{i=1,\ldots,n} p_i\right)^2$$

As a result, M_{exp} is not equal to m^{pole}_{top}, and will vary in each event, depending on the way the event has evolved.

The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_{top}) \sim 1$ GeV

Goal:
- correctly quantify the systematic uncertainty
- identify observables that allow to validate the theoretical modeling of hadronization in top decays
- identify observables less sensitive to these effects

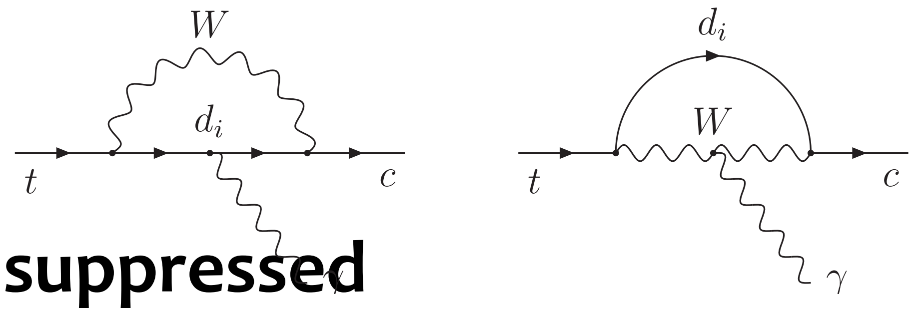
from M. Mangano, TOP2013

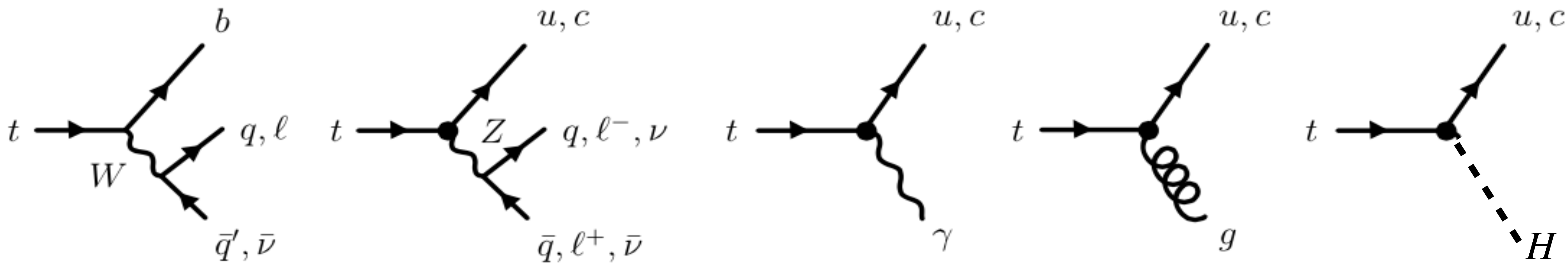
Top FCNC decays

universitätbonn erc

In Standard Model

- ~100% t→Wb, with CKM suppressed t→Ws, Wd
- t→Xq with X = neutral boson and q = u,c is very suppressed





J.Aguilar-Saavedra, Acta Phys.Polon. B35 (2004) 2695-2710

Beyond Standard Model

	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	—	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

FCNC current limits