Top-quark production

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for the ATLAS Collaboration

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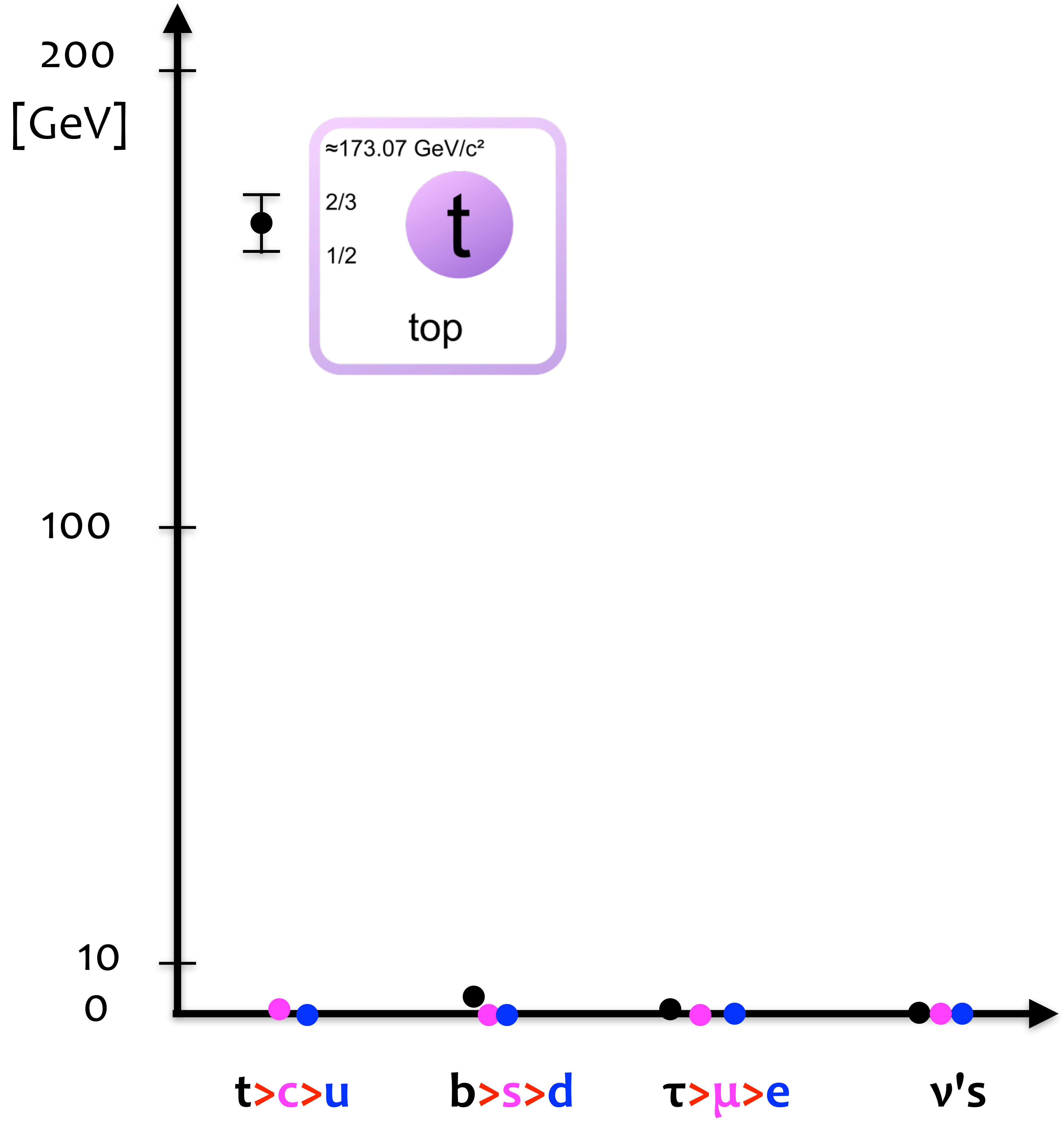
ATLAS EXPERIMENT

The most massive known elementary building block of matter

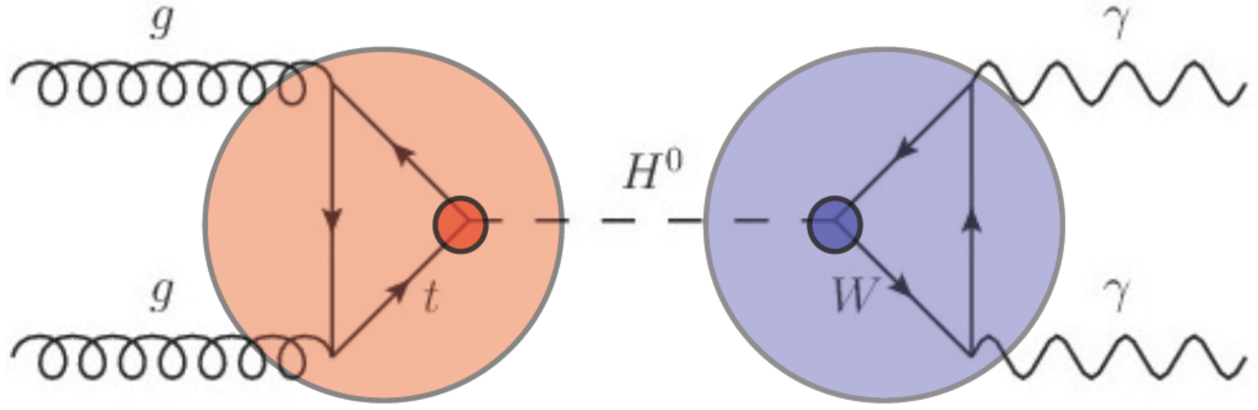


The top quark

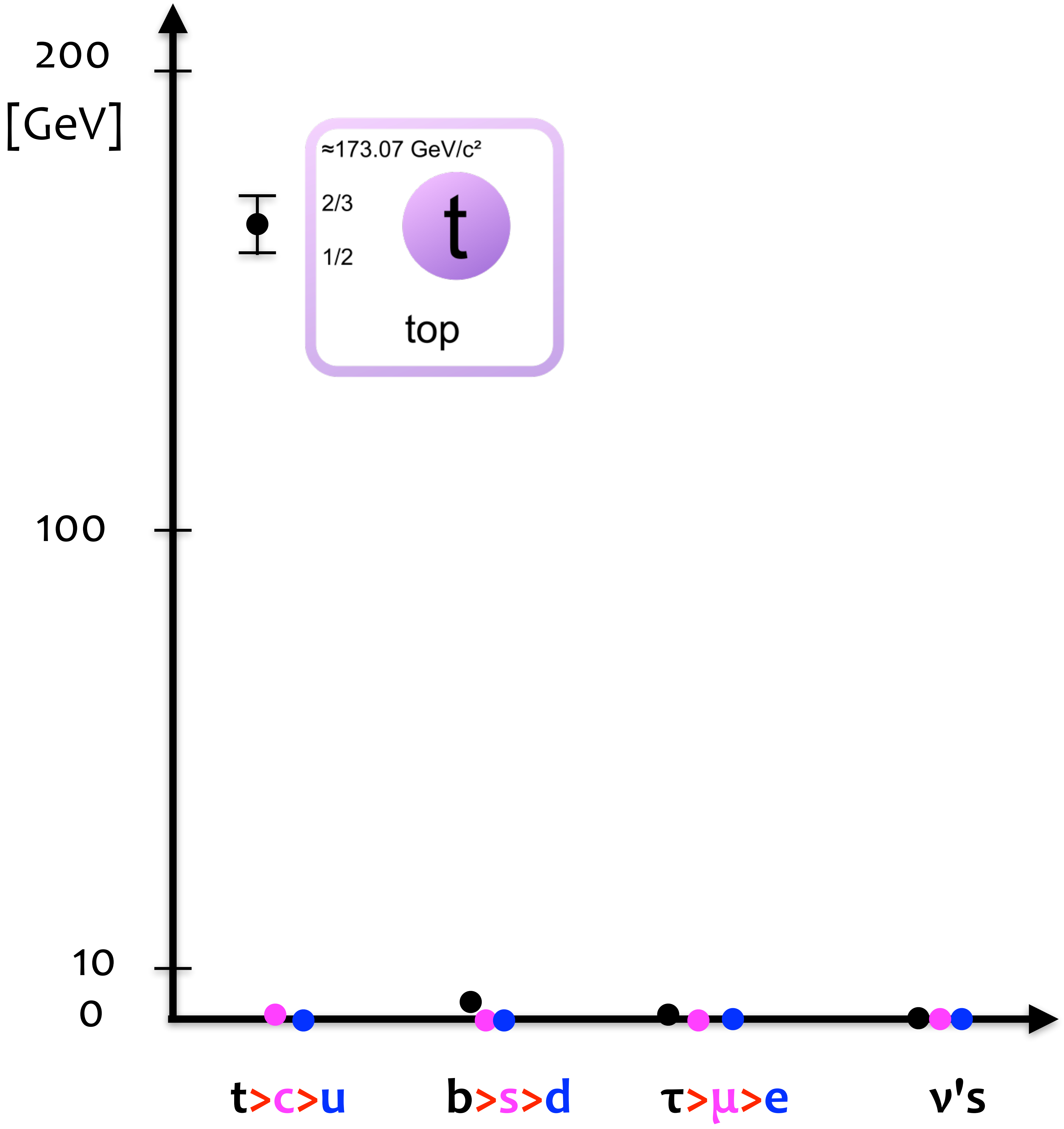
The most massive known elementary building block of matter

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

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



- role in loop diagrams
- large Yukawa coupling $y_t \sim 1$



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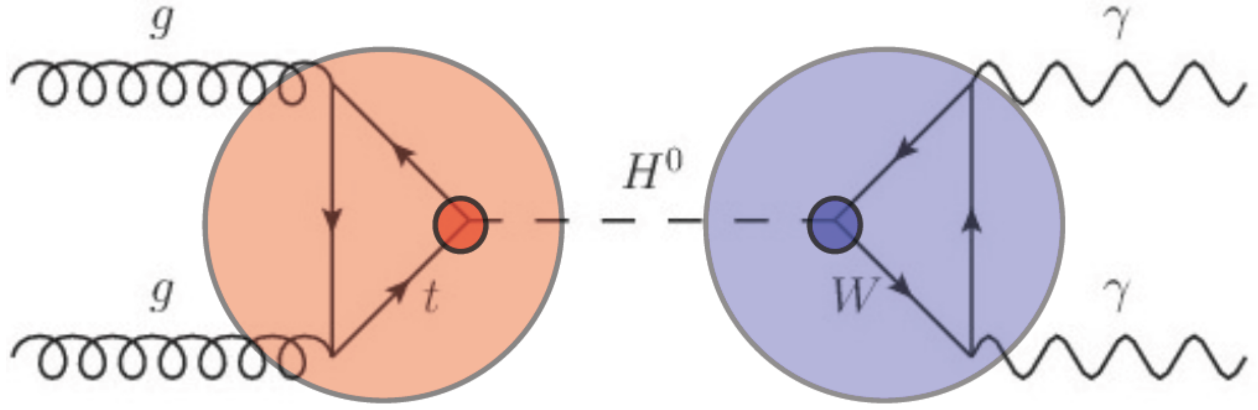
- **short lifetime**
- **τ_{top} = 4 · 10^{-25} s → no bound states**



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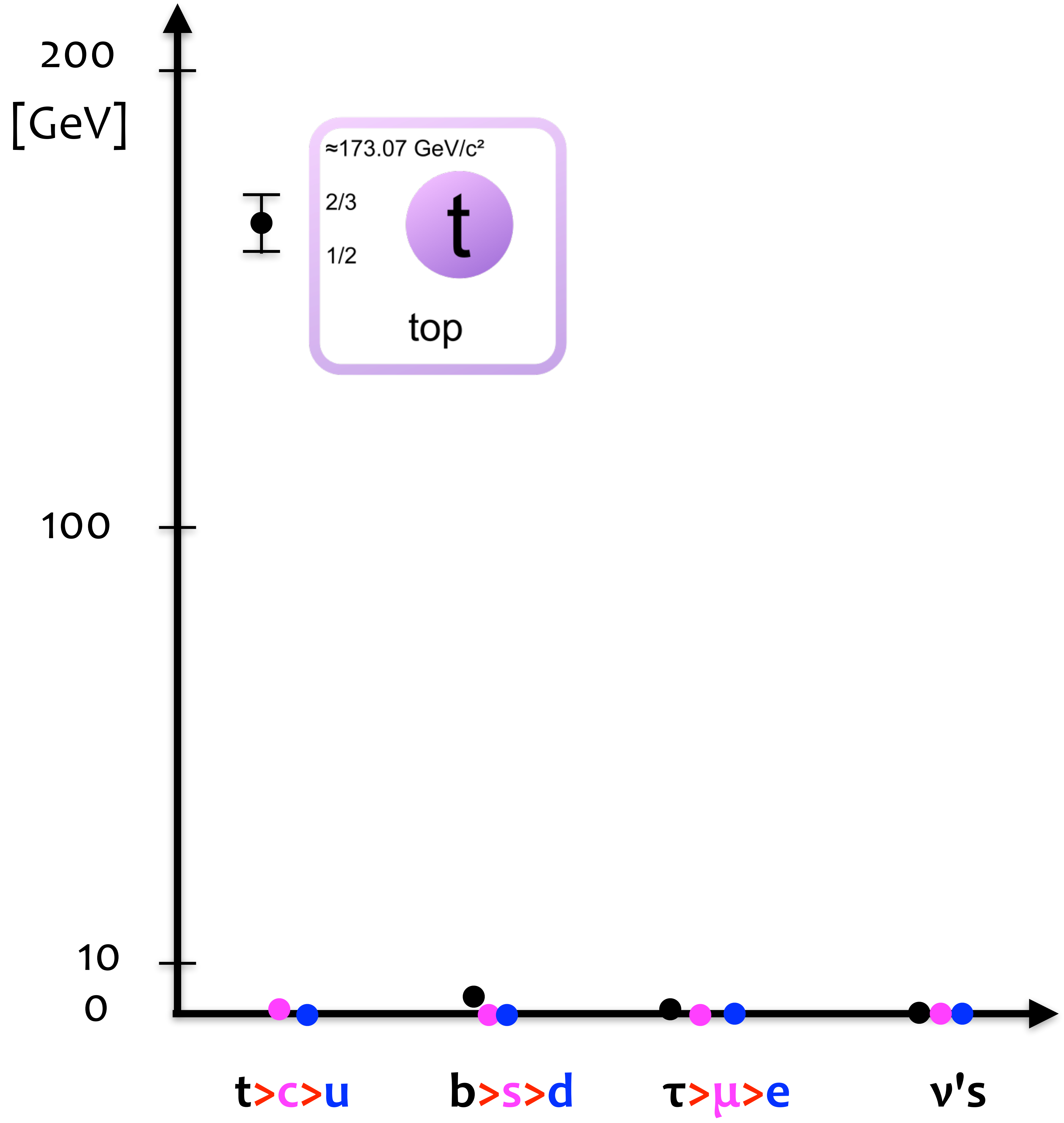
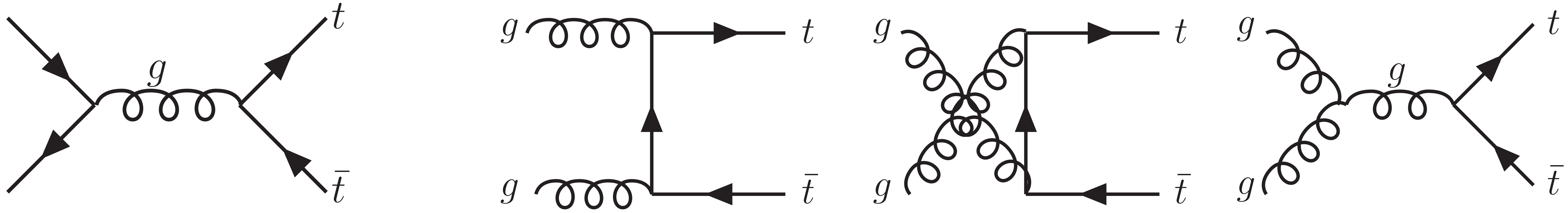


Top quark physics at hadron colliders

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

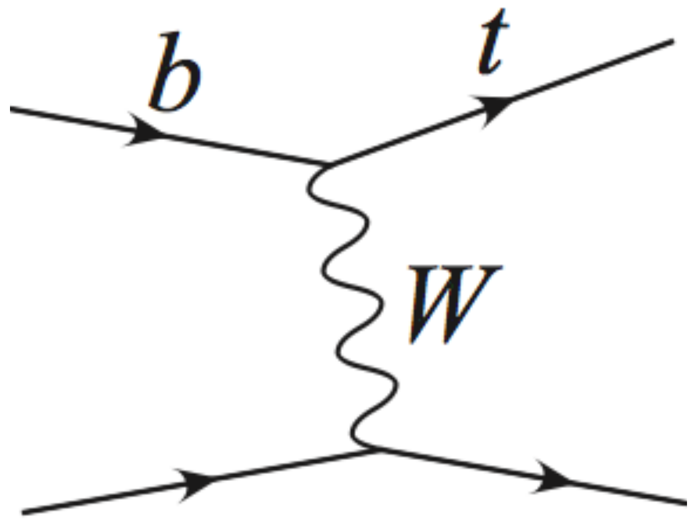
Top-quark production

Top-quark pairs via strong interaction

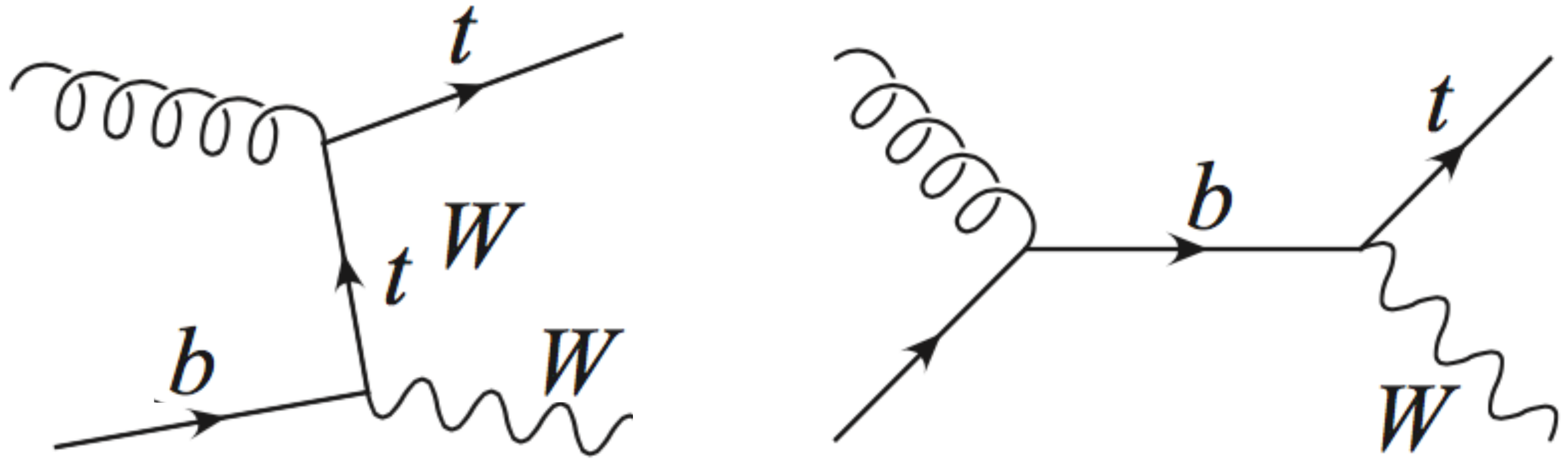


830 pb @ 13 TeV

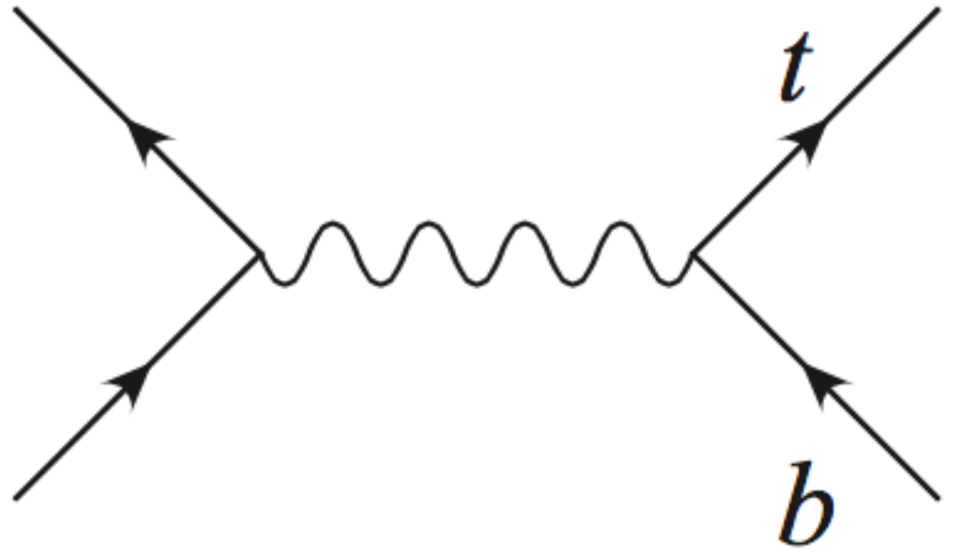
Single-top quarks via weak interaction



***t*-channel**
210 pb @ 13 TeV

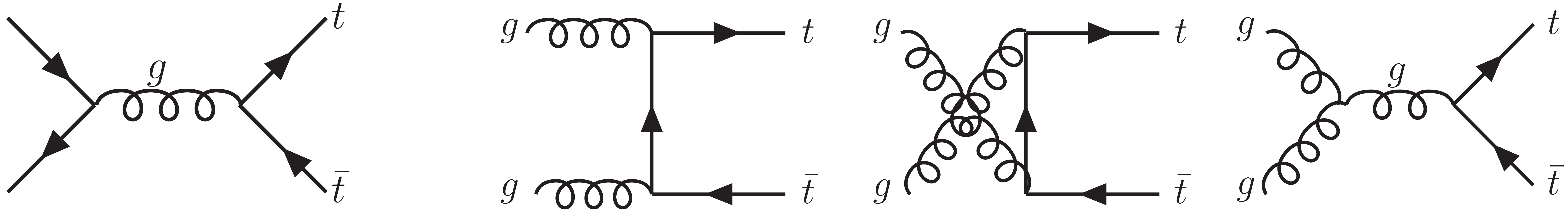


***Wt* channel**
72 pb @ 13 TeV



***s*-channel**
11 pb @ 13 TeV

Top-quark pairs via strong interaction

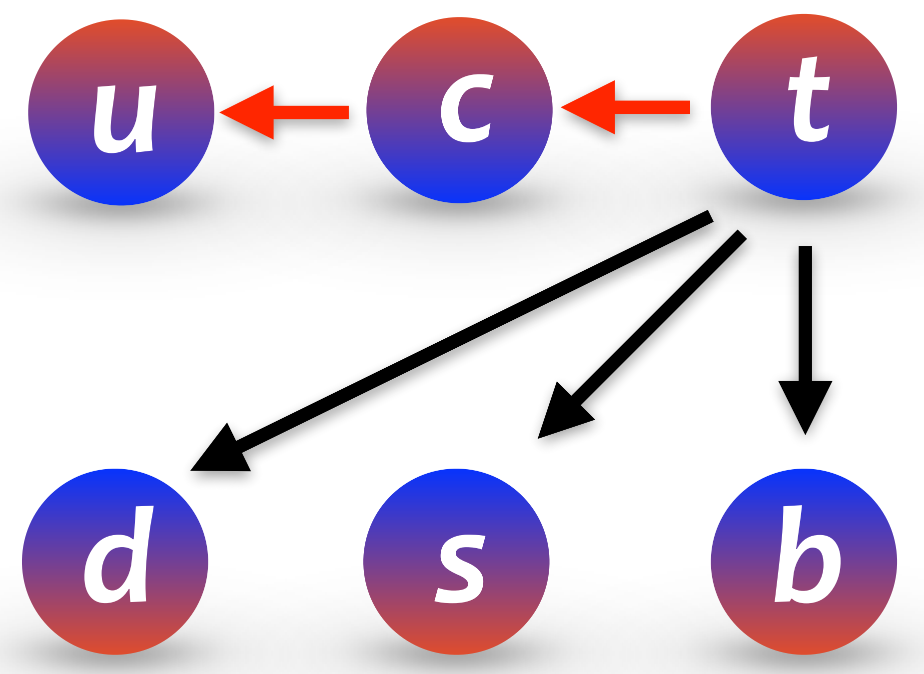


830 pb @ 13 TeV

Top-quark pair signatures

Weak decay

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



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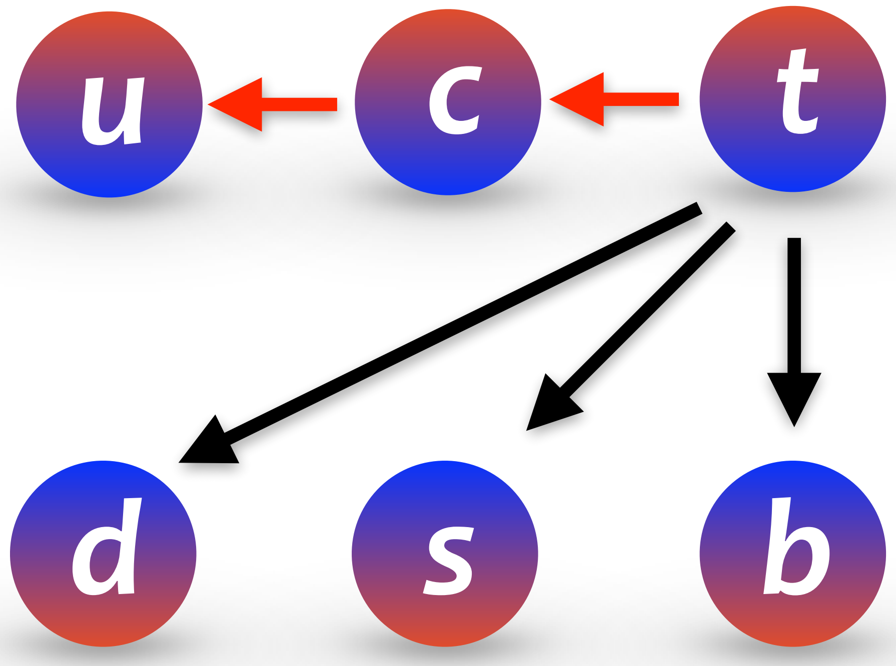

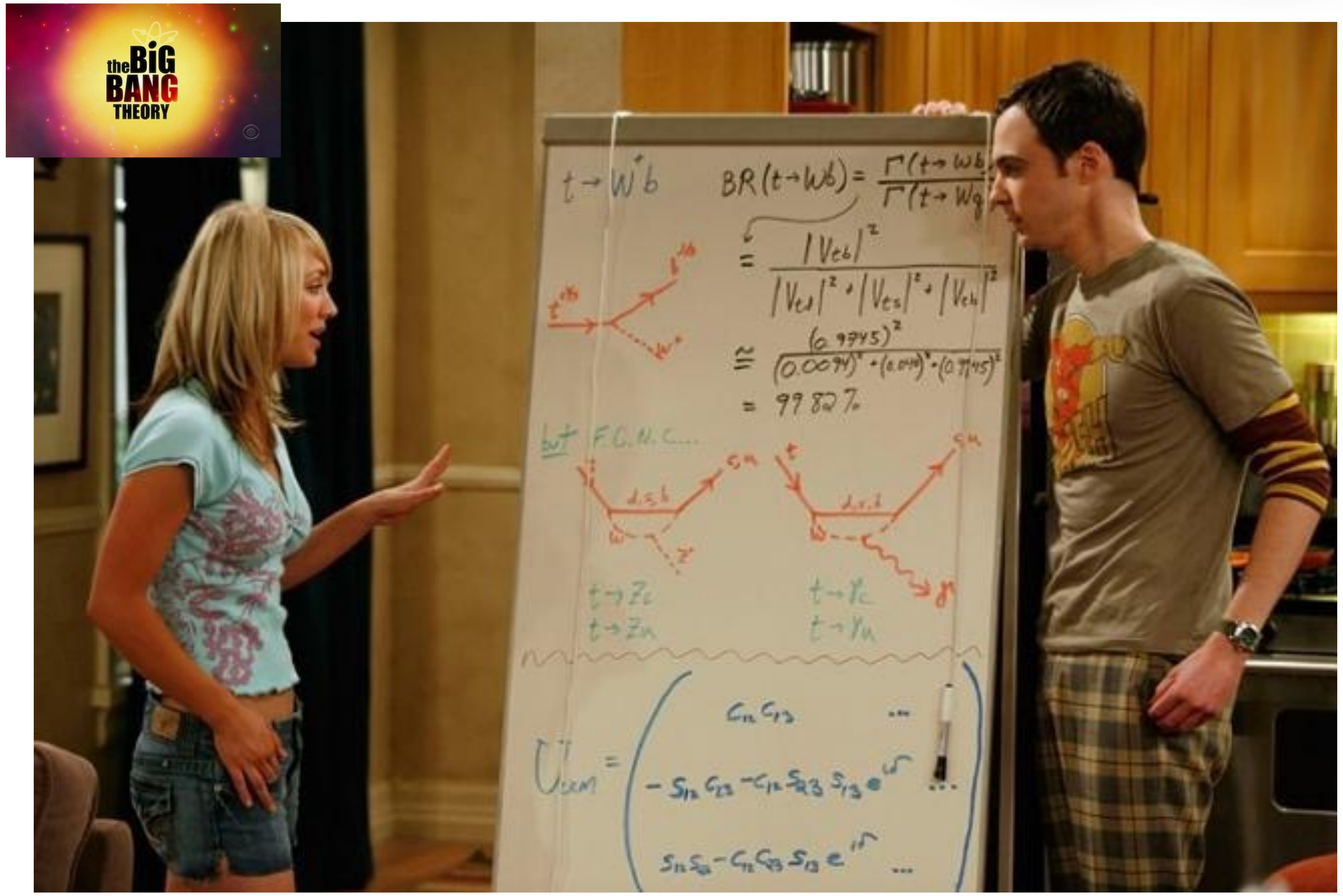

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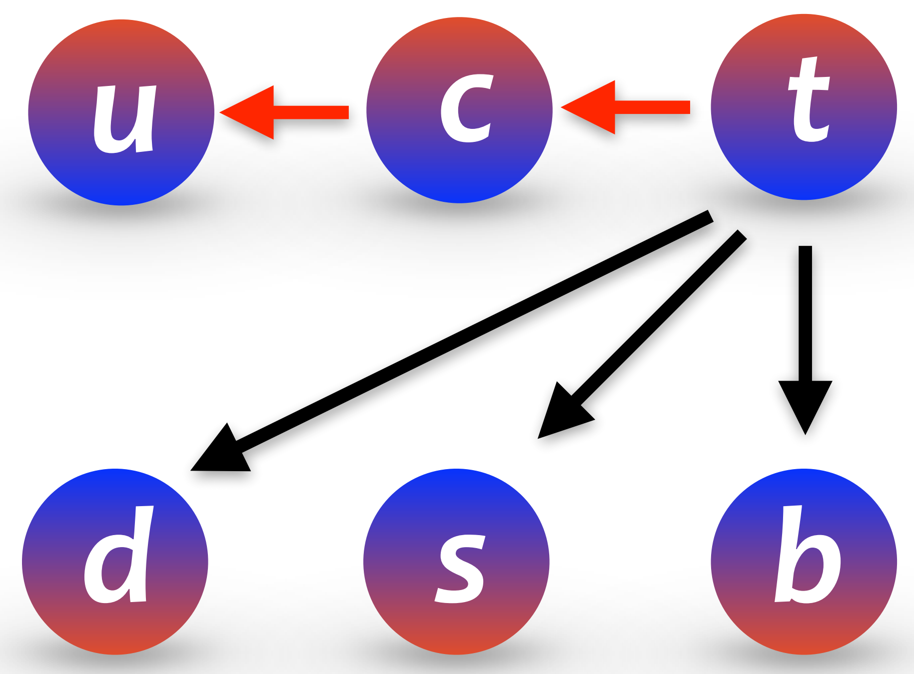
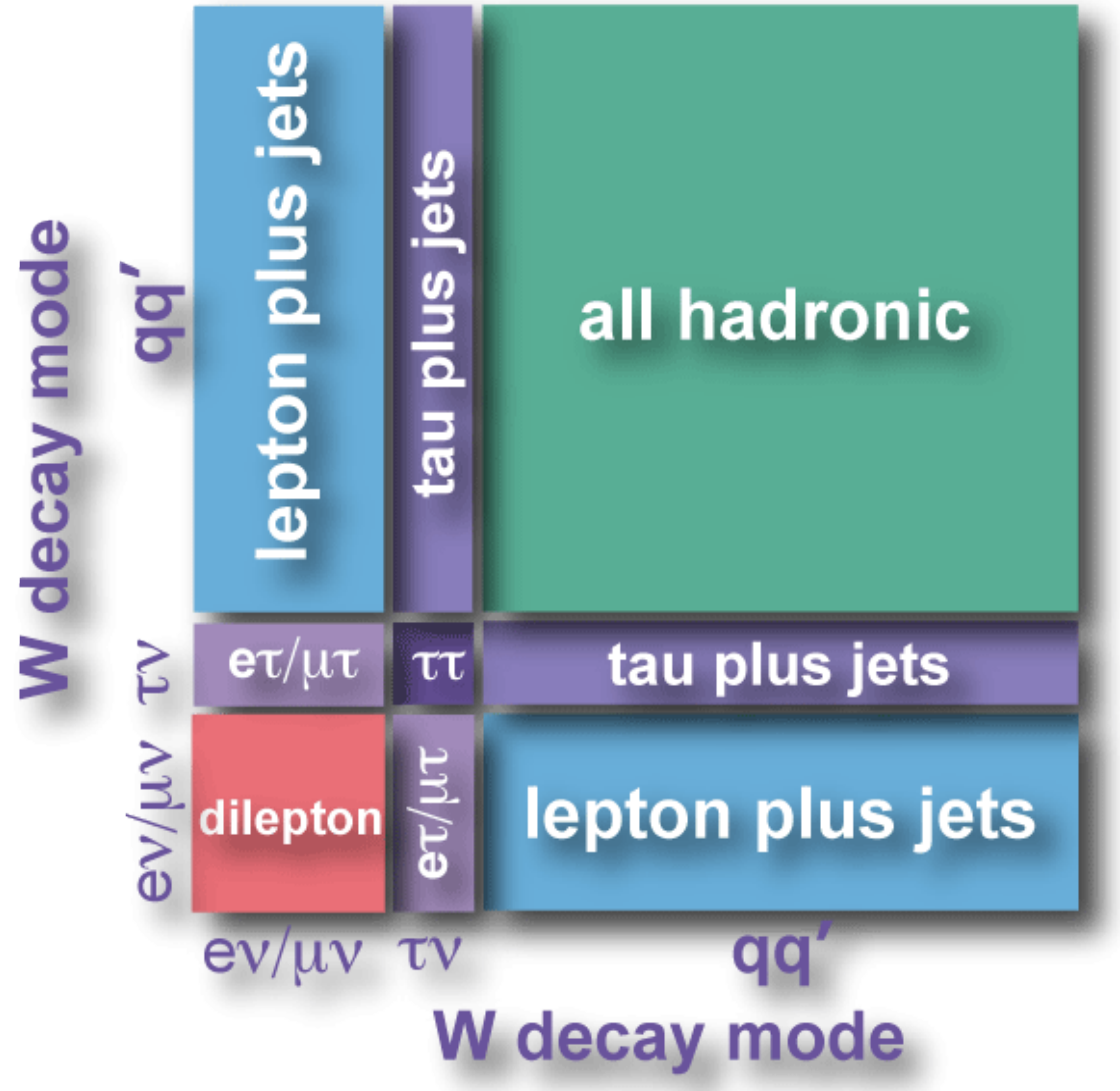
- $W \to \ell\nu$, $\tau_{\text{had}}\nu$ or $q\bar{q}$

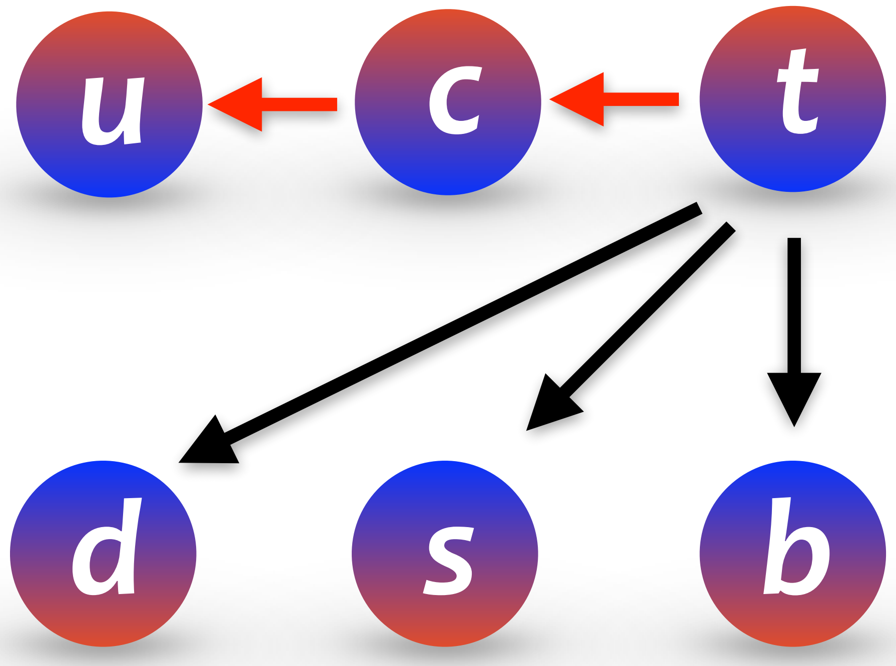




$t\bar{t}$ final states

- Dilepton: $2b$, 2ℓ, 2ν
- Lepton+jets: $2b$, $2q$, 1ℓ, 1ν
- All hadronic: $2b$, $4q$
- With τ_{had} leptons

Top-quark pair signatures



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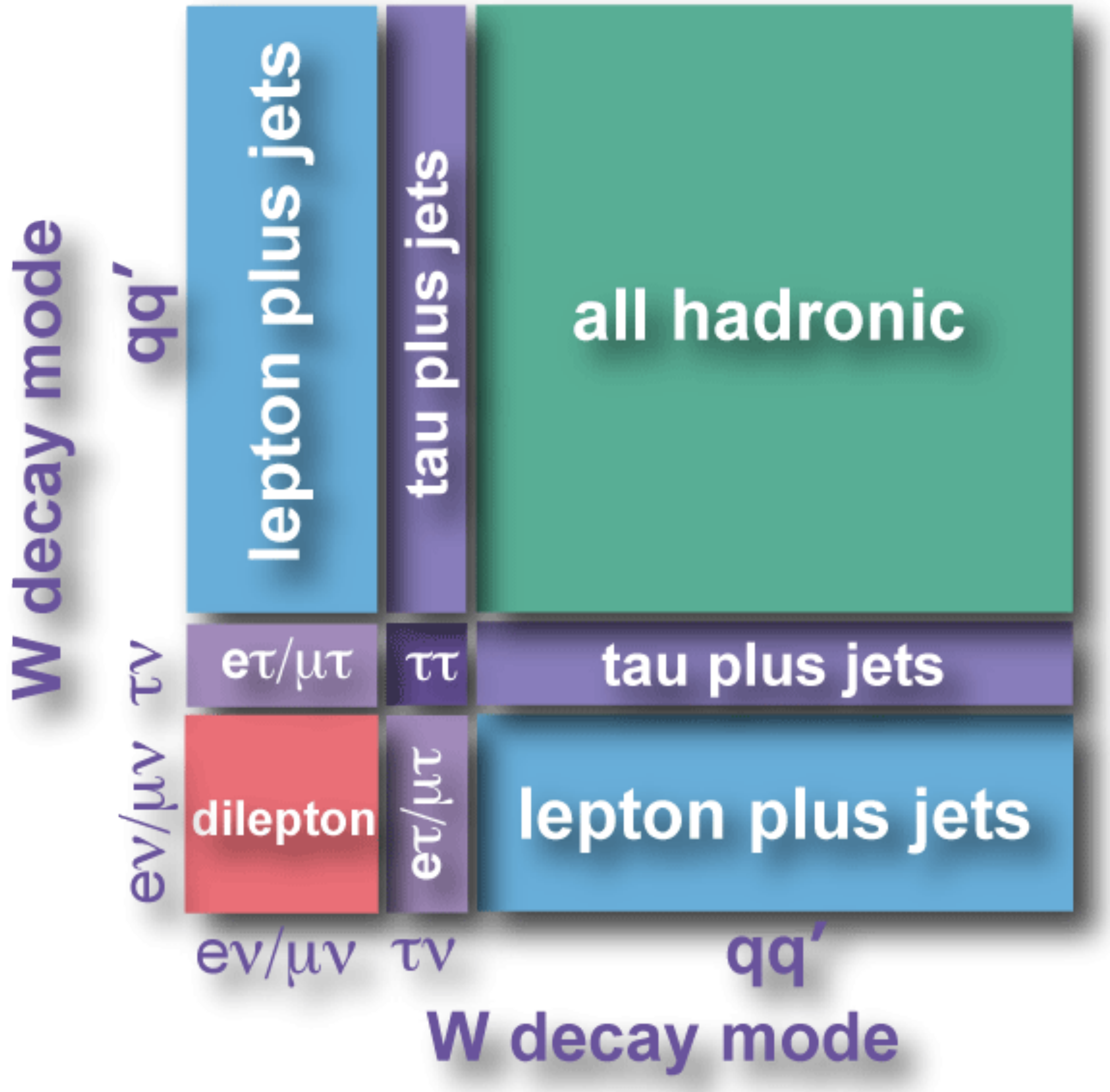

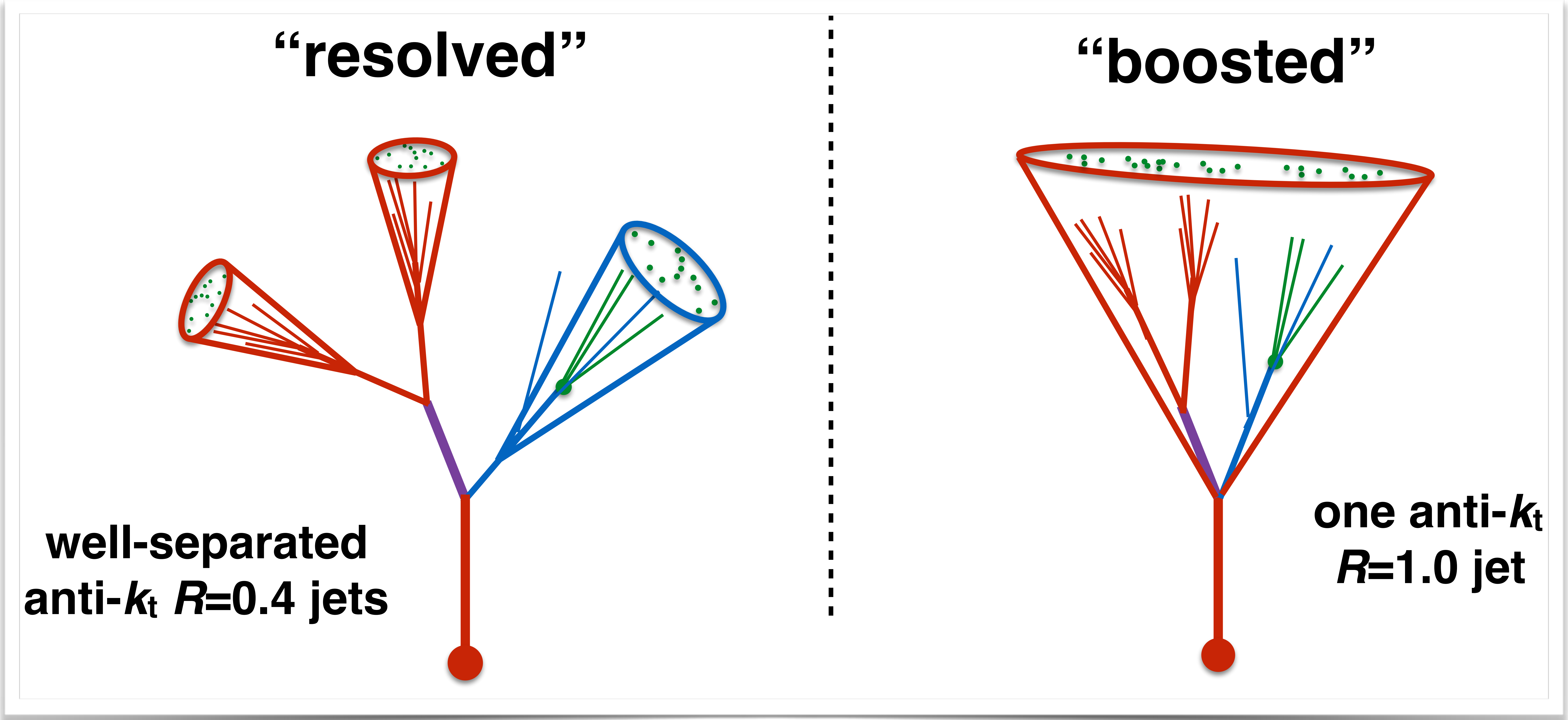

Inclusive $t\bar{t}$ production cross section

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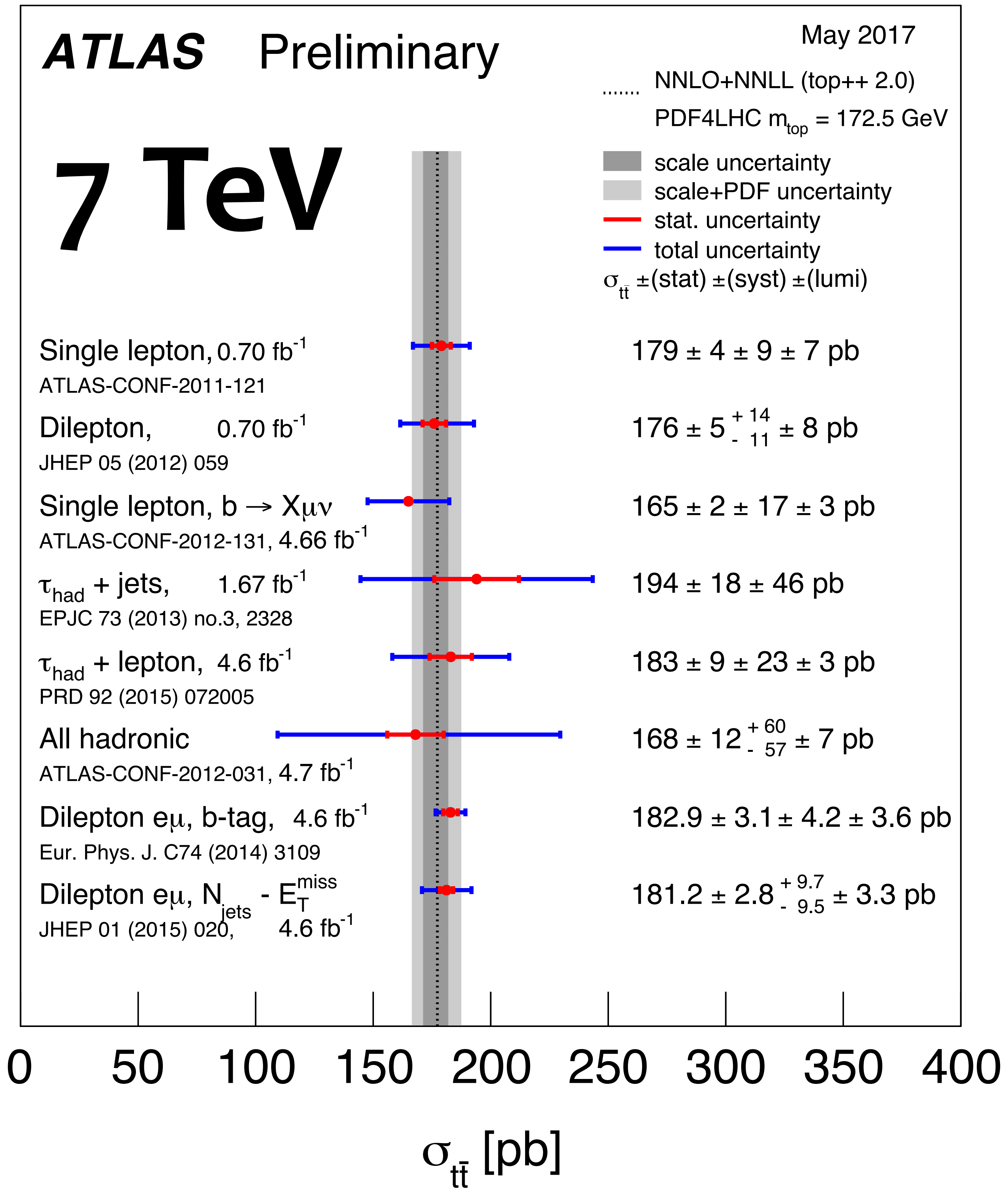
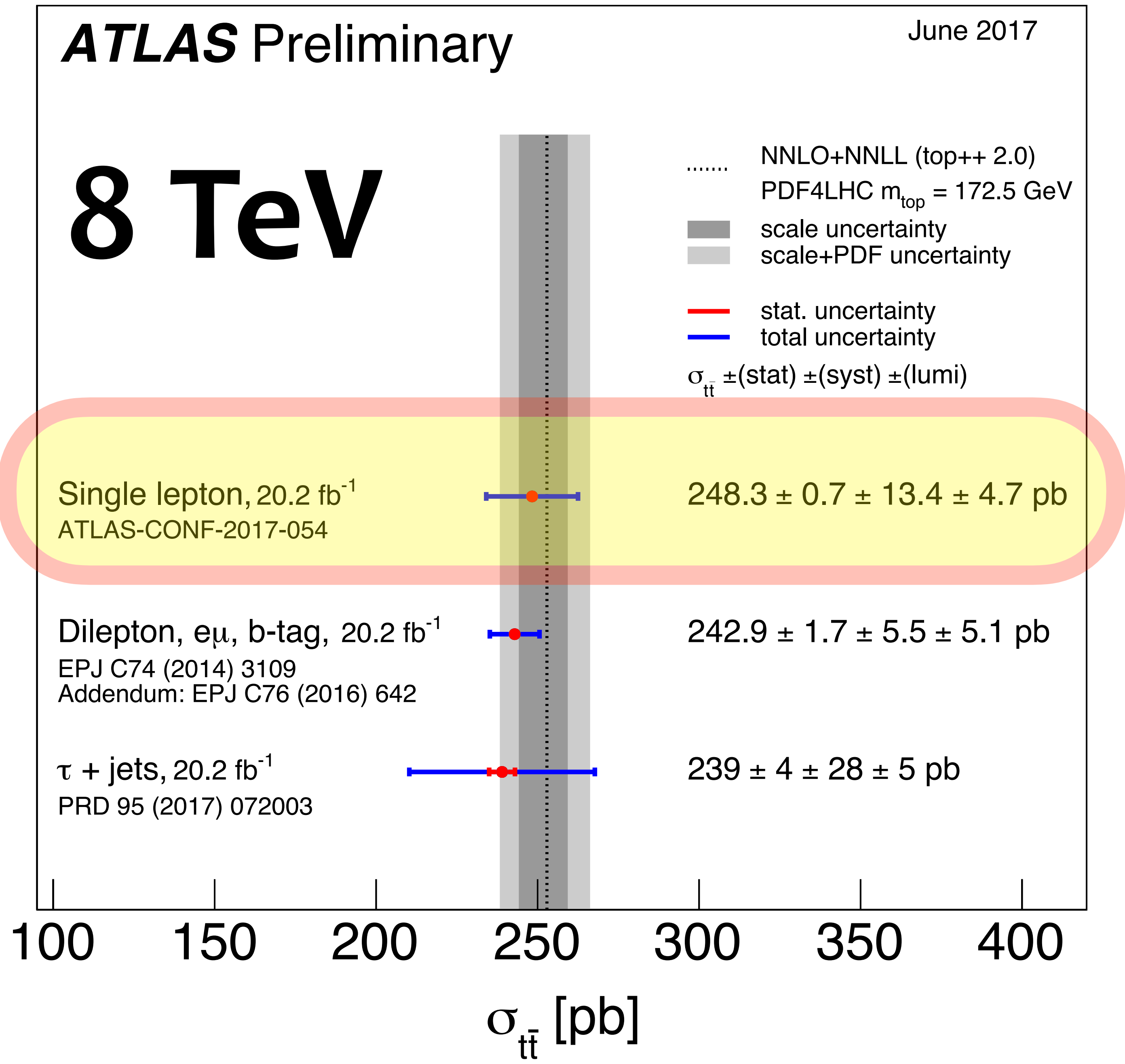
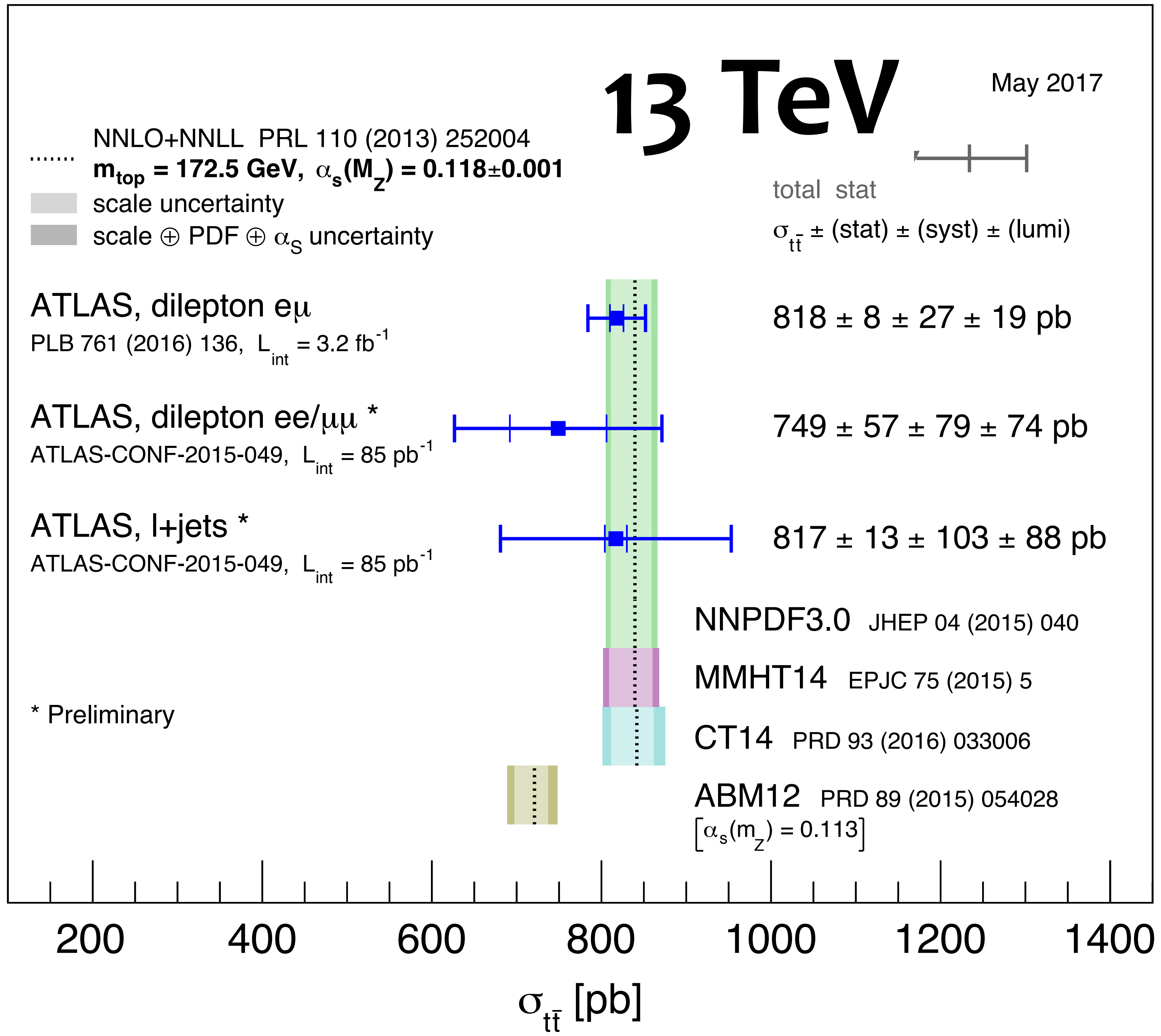
Several measurements at 3 collision energies

- stringent tests of QCD with heavy quarks
- can be sensitive to potential new physics
- but also: top quark mass in well defined renormalisation scheme







$t\bar{t}$ production in ℓ+jets channel at 8 TeV

Split selection in 3 signal regions

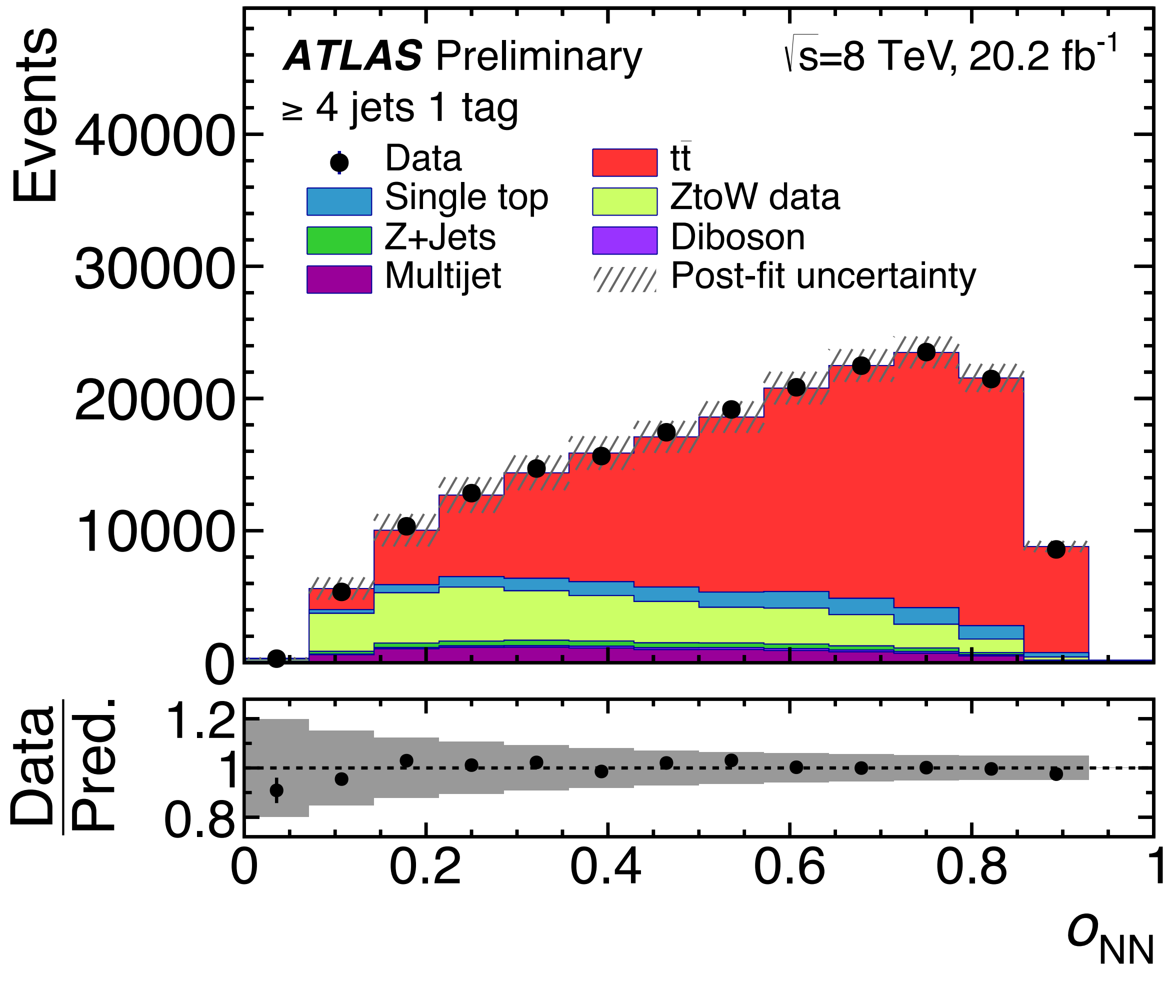
- different backgrounds
- sensitive to additional radiation

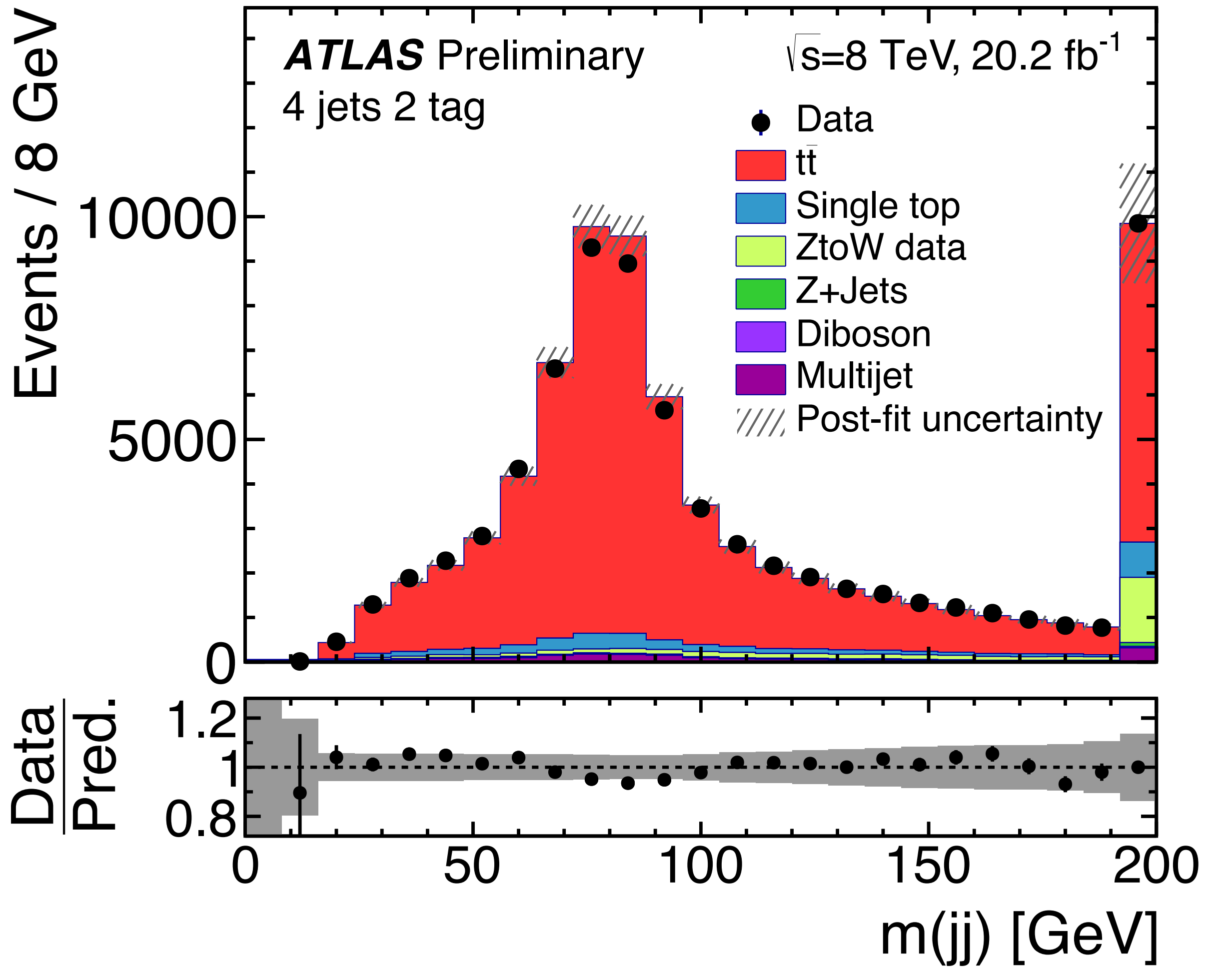
Analysis

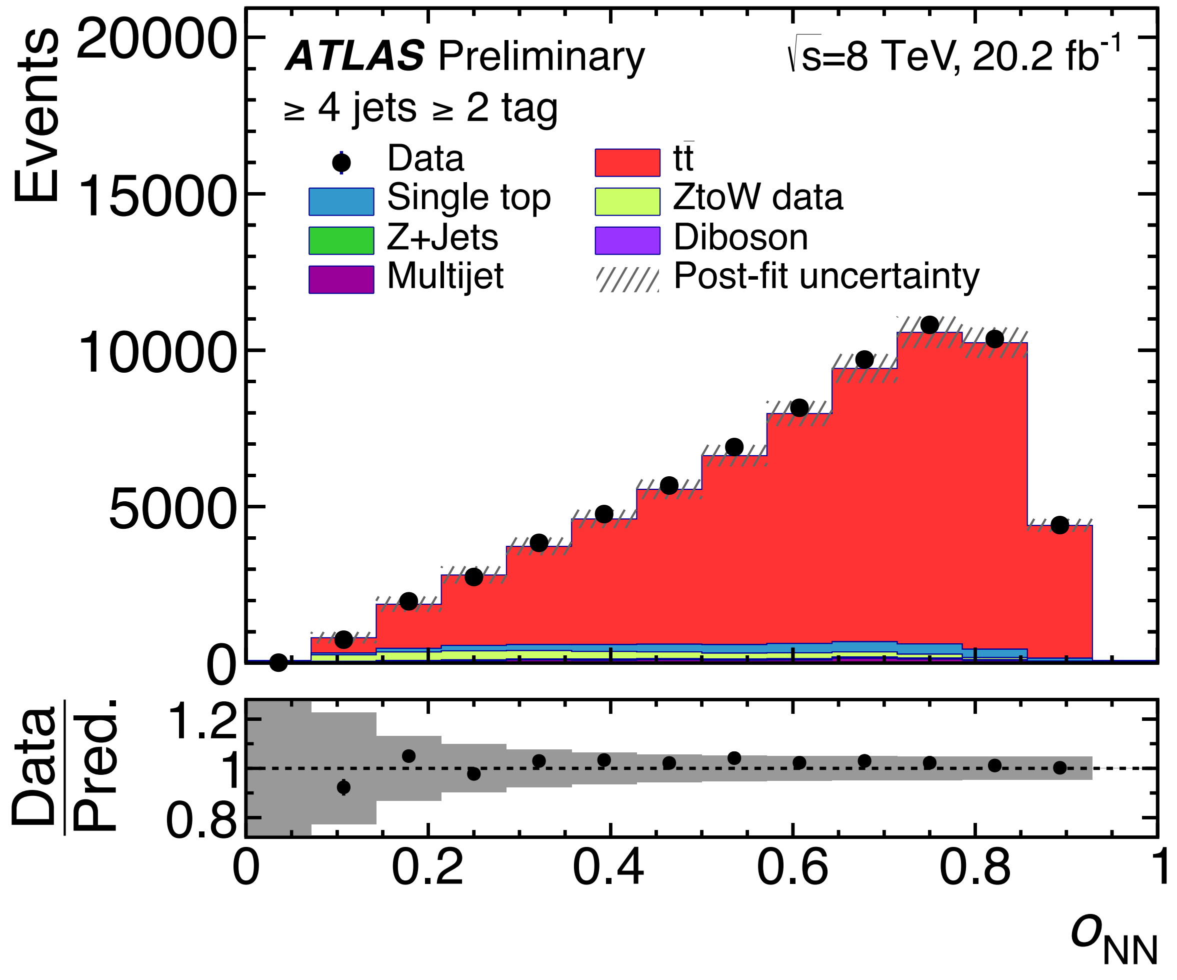
- *W*+jets background shape modelled using *Z*+jets in data
- multi-jet from data, including normalisation
- neural network with kinematic observable inputs
- likelihood fit with nuisance parameters

Result

- $\sigma_{t\bar{t}} = 248.3 \pm 0.7_{stat} \pm 14.2_{syst}$ pb
- dominant uncertainties
  - MC modelling
  - jet energy scale, b-tagging

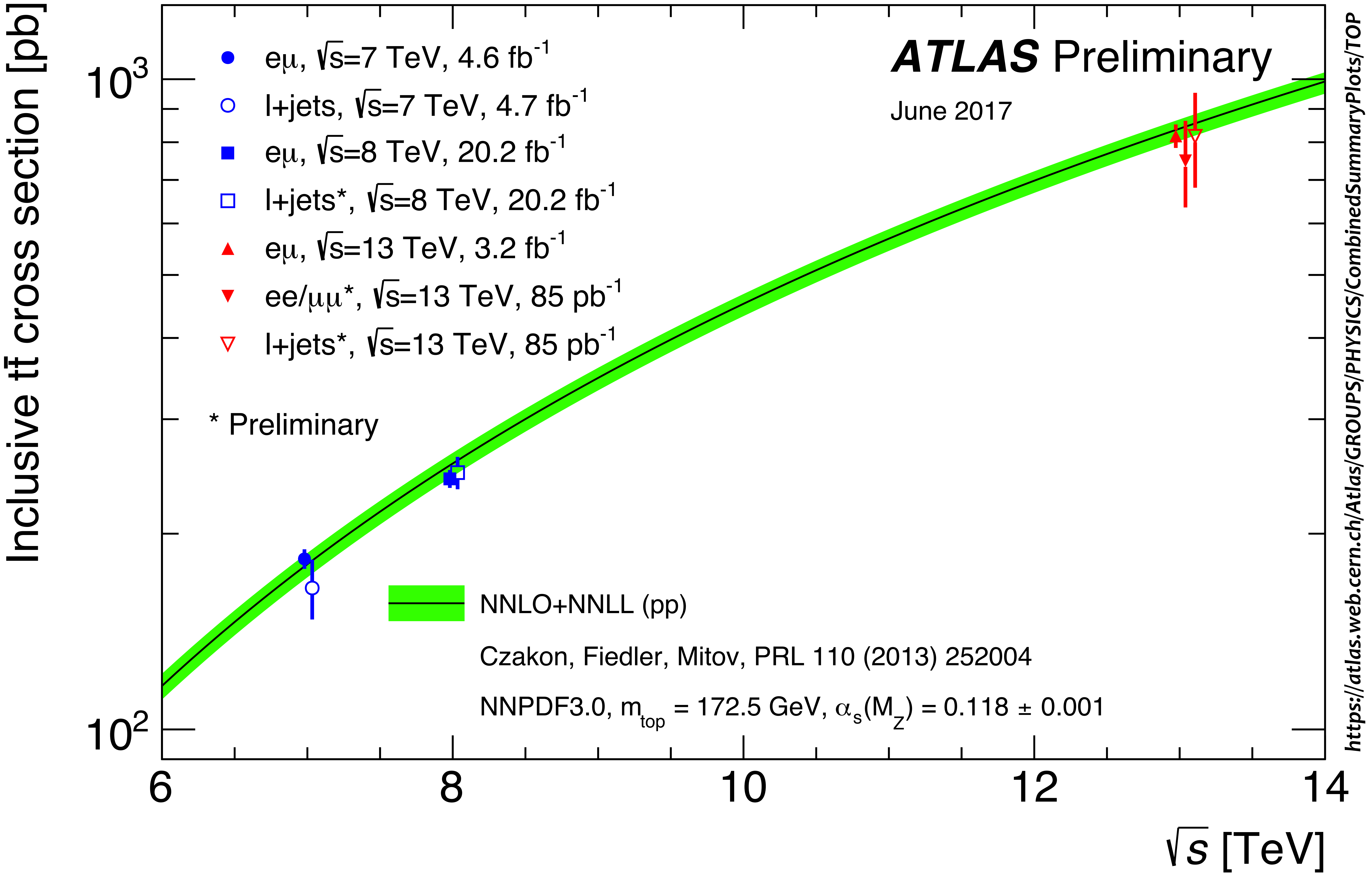






ATLAS-CONF-2017-054

$t\bar{t}$ inclusive production summary



Most precise measurements at 7, 8 and 13 TeV compared to calculations

Motivation

- detailed test of pQCD, constrain PDF and MC parameters

$t\bar{t}$ differential cross section

Motivation

- detailed test of pQCD, constrain PDF and MC parameters

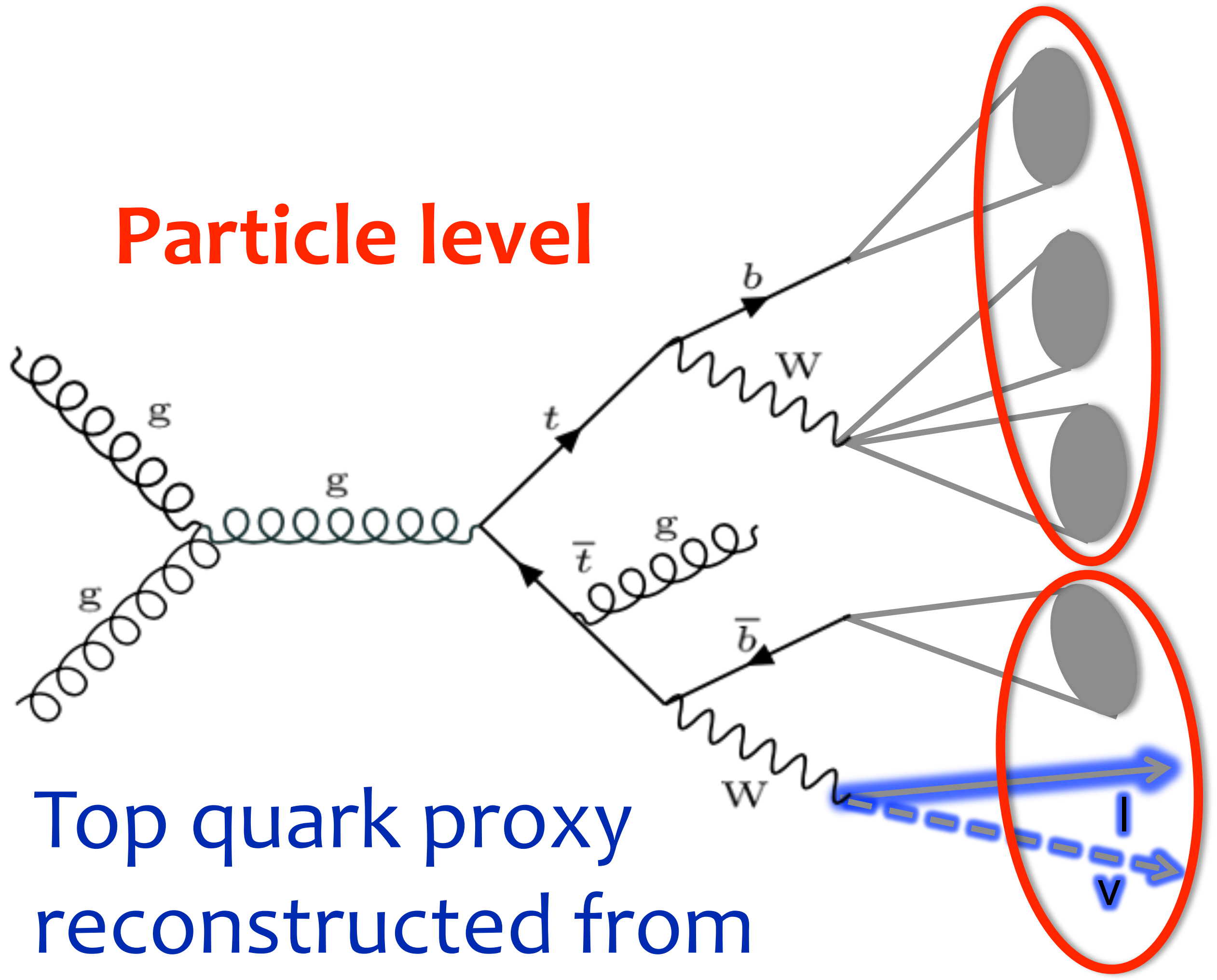
General analysis strategy

- tight event selection → pure $t\bar{t}$ sample
- $t\bar{t}$ / top quark kinematic reconstruction
- background subtraction
- corrections: acceptance, resolution → unfolding

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

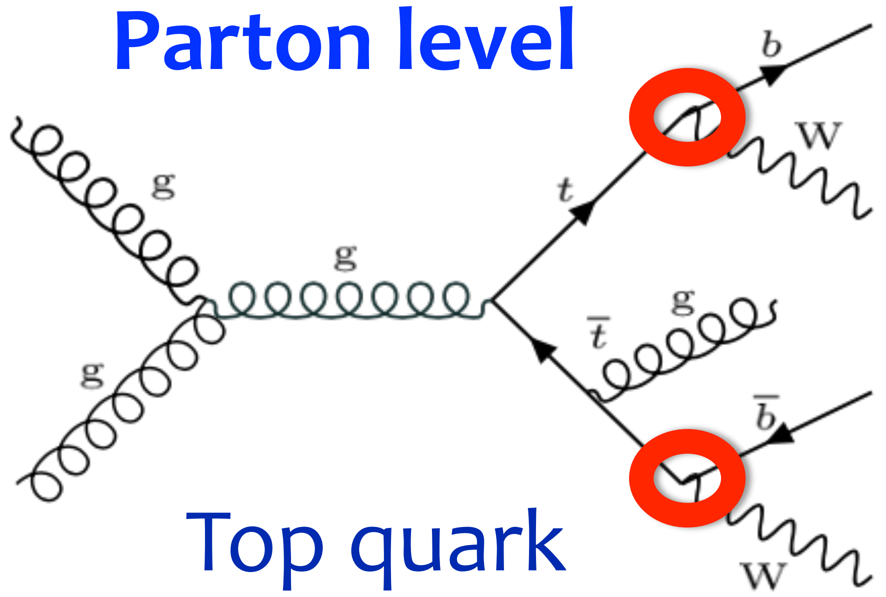
- X = p_T, η of top-quark; p_T, η, $m_{t\bar{t}}$ of top-quark pairs, …
- compare to theory predictions at particle of parton level

Particle level



Top quark proxy
reconstructed from
decay products after hadronisation

Parton level



Top quark
after radiation, but before decay

$t\bar{t}$ differential cross section

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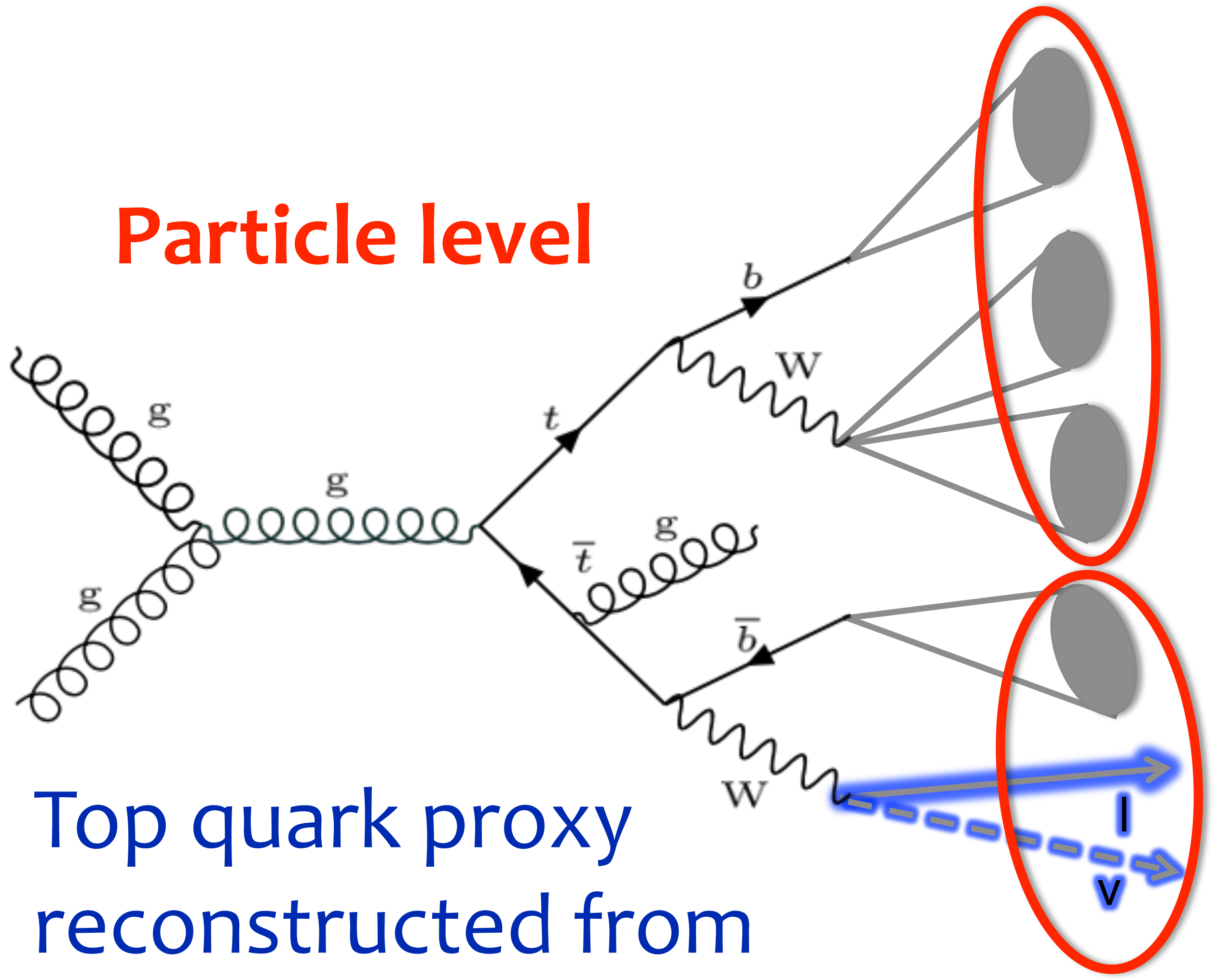

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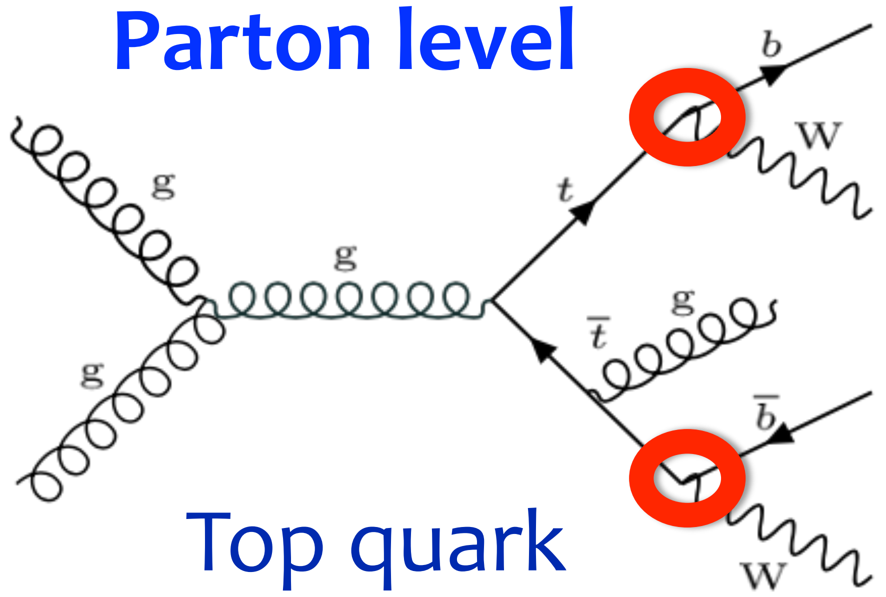

Top quark
after radiation, but before decay

Results at 7, 8 and 13 TeV

EPJ C73 (13) 2261, PR D90 (14) 072004, JHEP 06 (15) 100 [7 TeV] — EPJ C76 (16) 538, PR D93 (16) 032009 [8 TeV] — EPJ C77 (17) 292, ATLAS-CONF-2017-044, 1708.00727 [13 TeV]

$t\bar{t}$ ℓ+jets differential 13TeV 3.2 fb^{-1}

Analysis

- Resolved and boosted regime
- full phase space parton or particle level
  - avoids model-dependent extrapolations
- absolute and relative distributions
- top and $t\bar{t}$ system

Findings

- generally modelling ok

1708.00727

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Analysis

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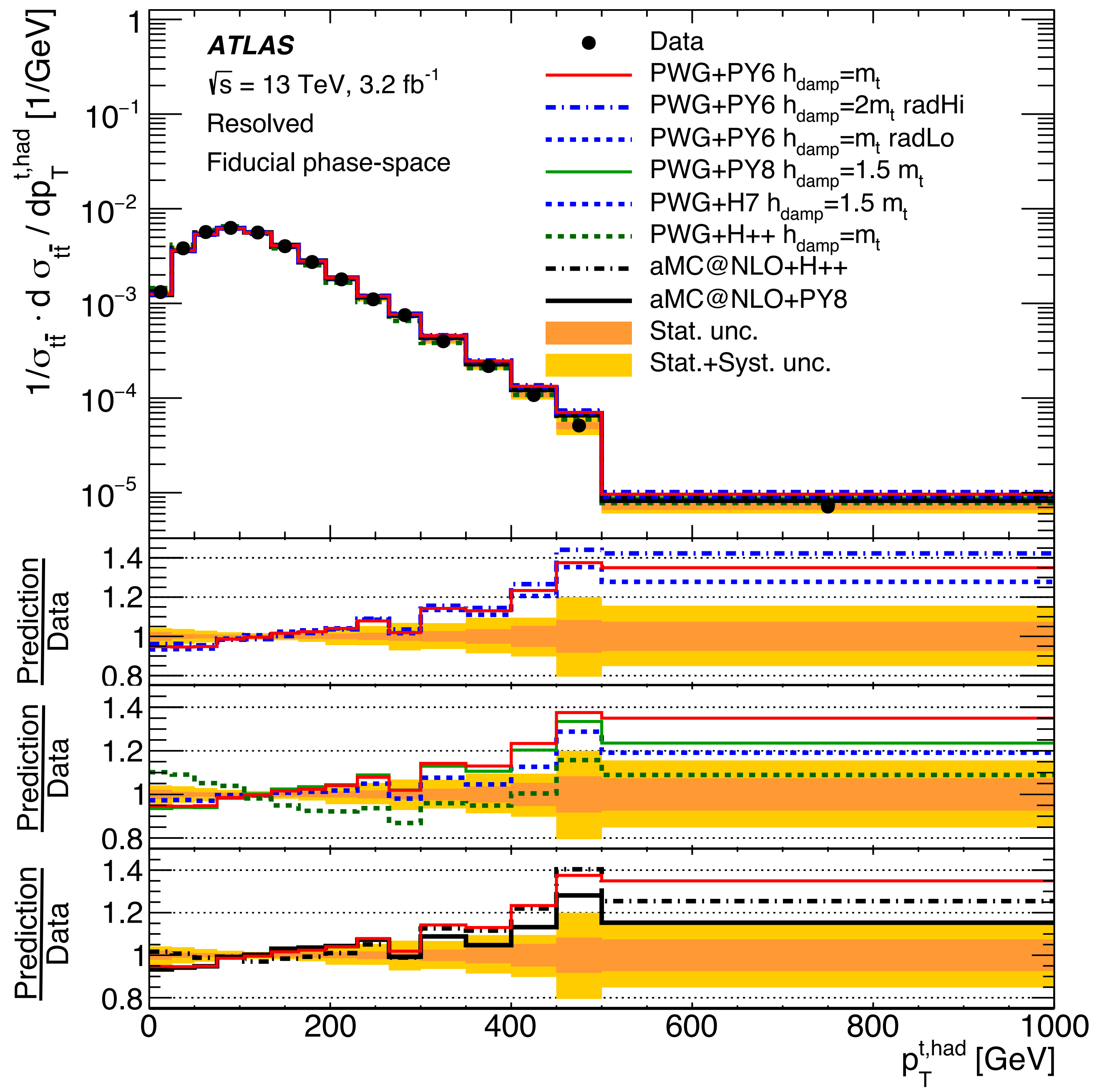
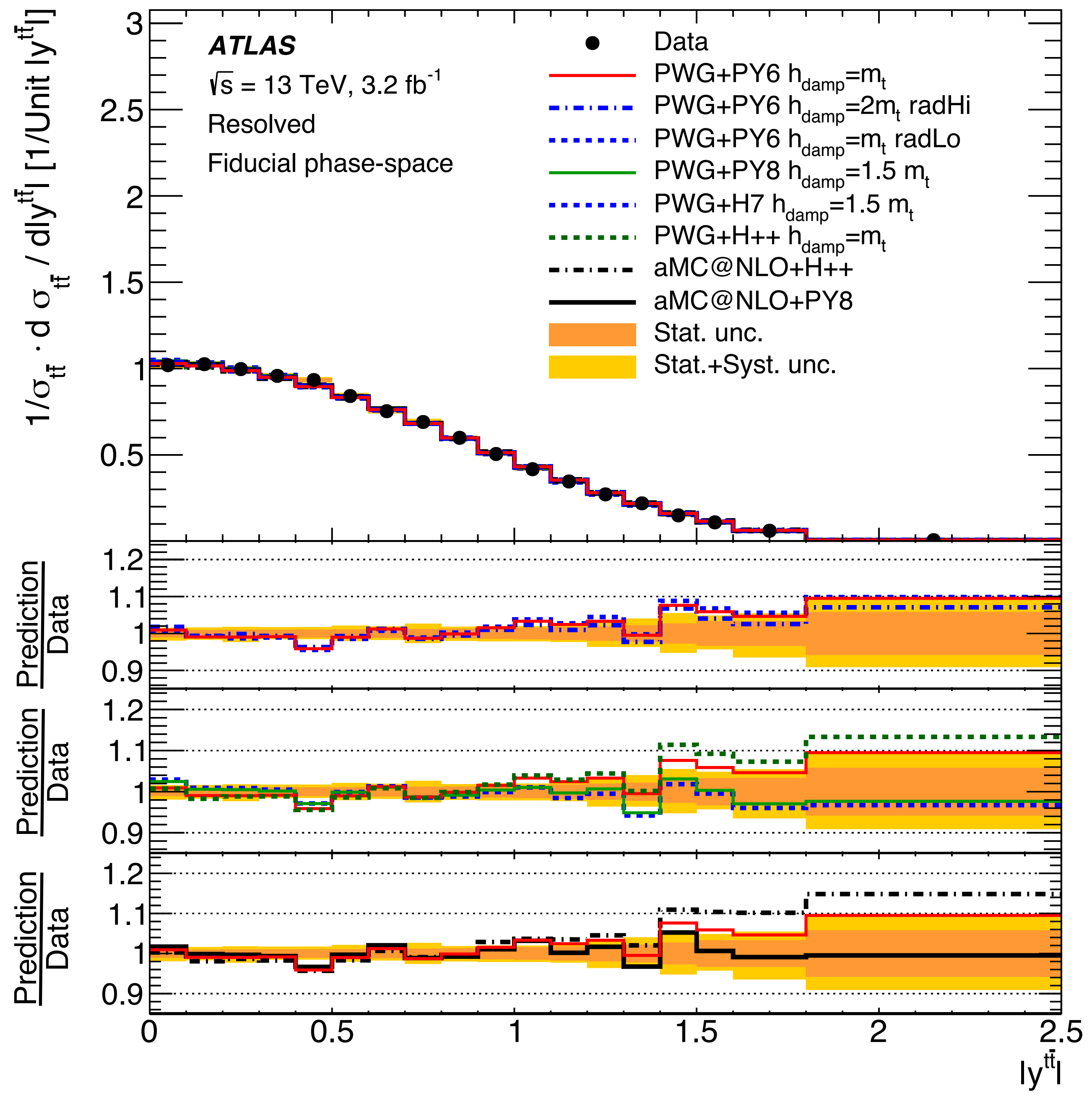
- **full phase space parton or particle level**
  - avoids model-dependent extrapolations
- **absolute and relative distributions**
- **top and $t\bar{t}$ system**

Findings

- **generally modelling ok**
- **p_T (top) not well described**
  - Powheg+Herwig7 best description
- **$y(t\bar{t})$ not well described**
  - sensitive to different PDFs





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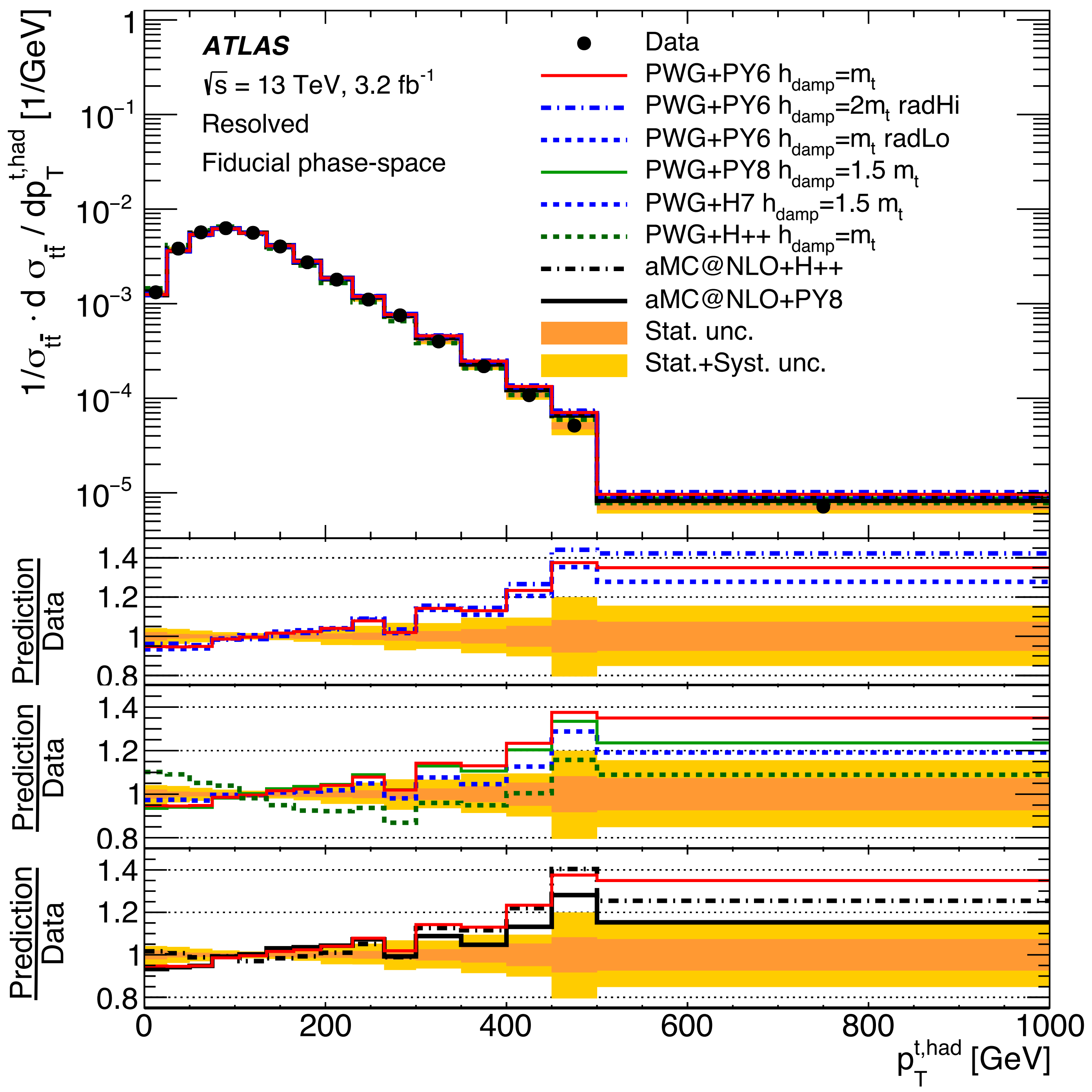
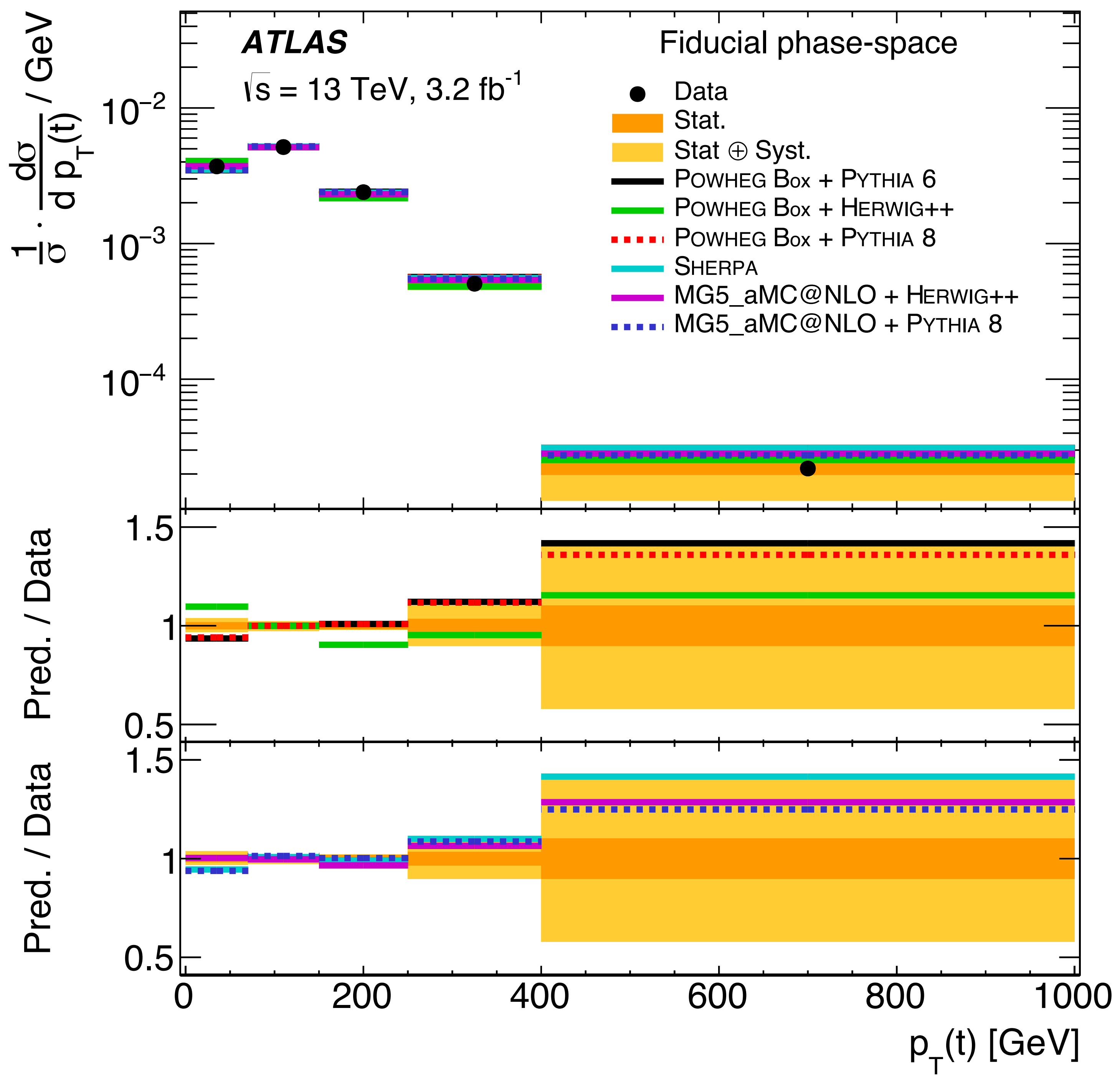
$t\bar{t}$ modelling of top p_T distribution

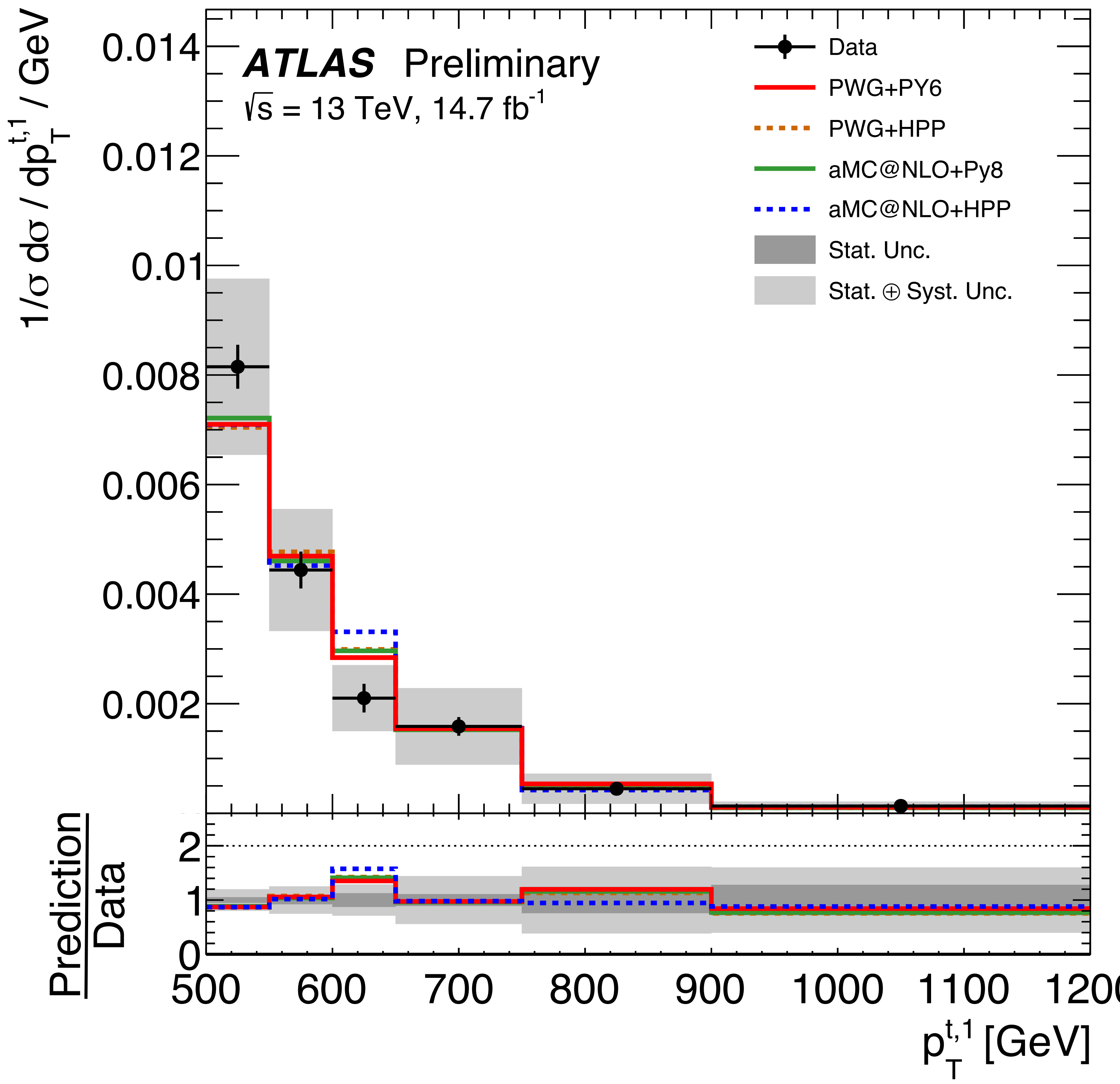
ℓ +jets 13 TeV



dilepton 13 TeV



all hadronic 13 TeV



p_T (top) not well described

- already observed at 7 and 8 TeV, ATLAS and CMS
- ewk corrections and foremost full NNLO calculations needed for data/MC agreement
- observe in ℓ+jets, dilepton and all hadronic channels also at 13 TeV

1708.00727, EPJC 77 (2017) 299, ATLAS-CONF-2016-100

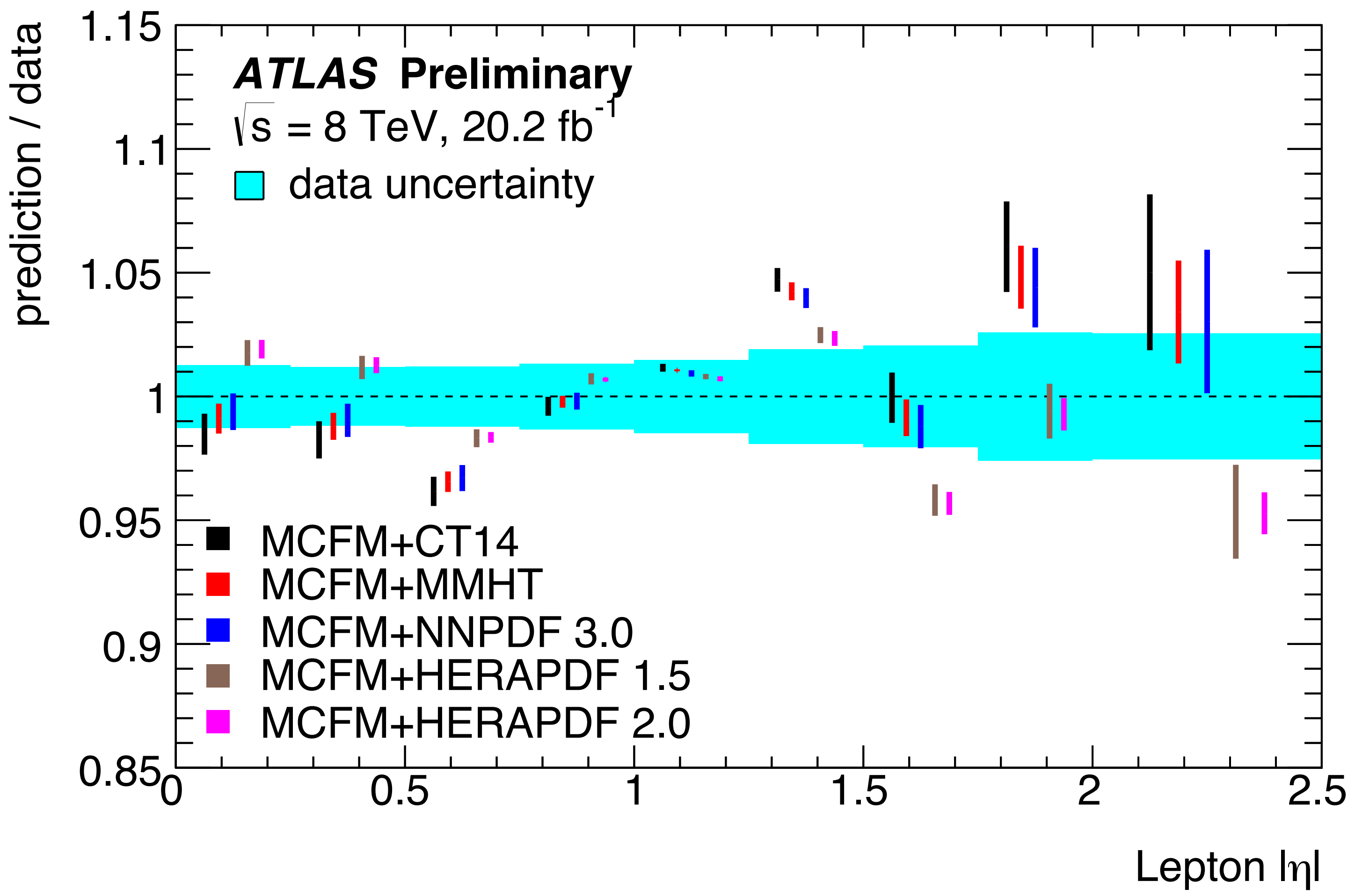
$t\bar{t}$ $e\mu$ differential: lepton observables

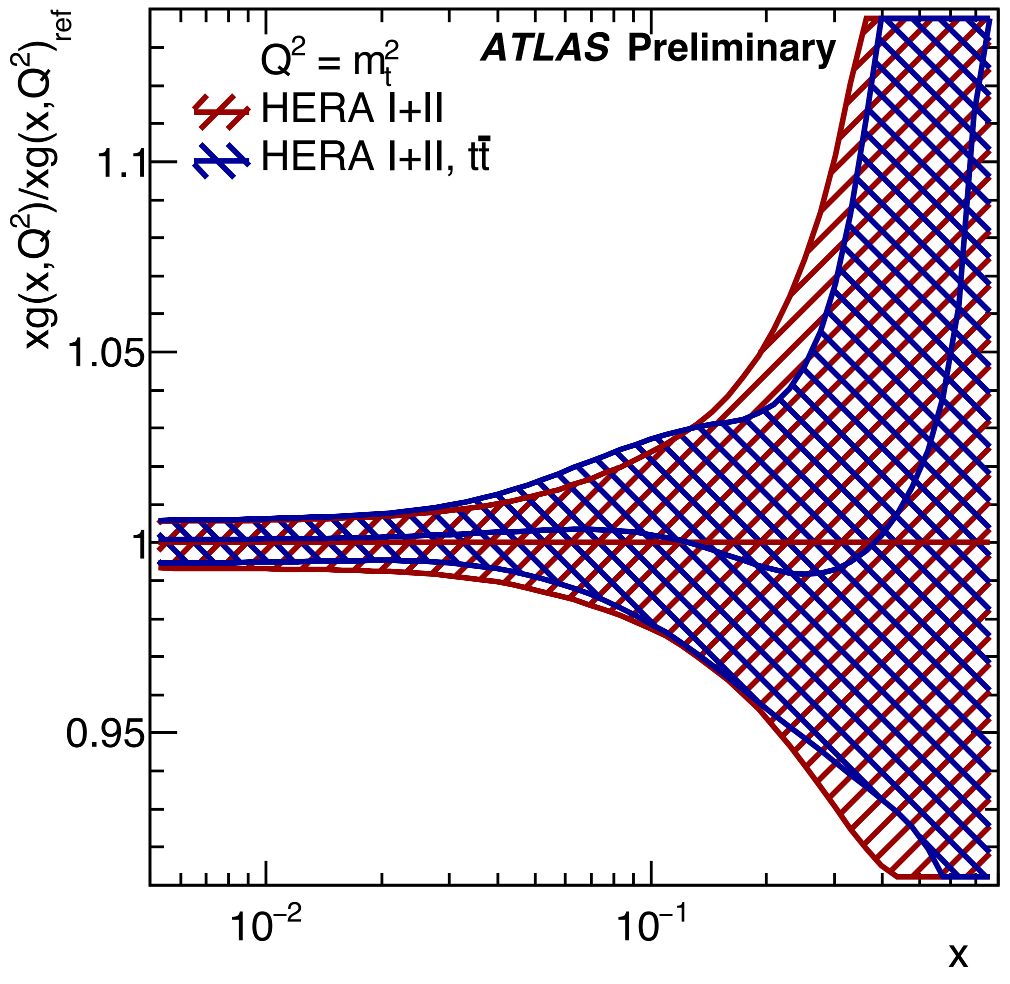
Fiducial lepton and dilepton distributions compared to

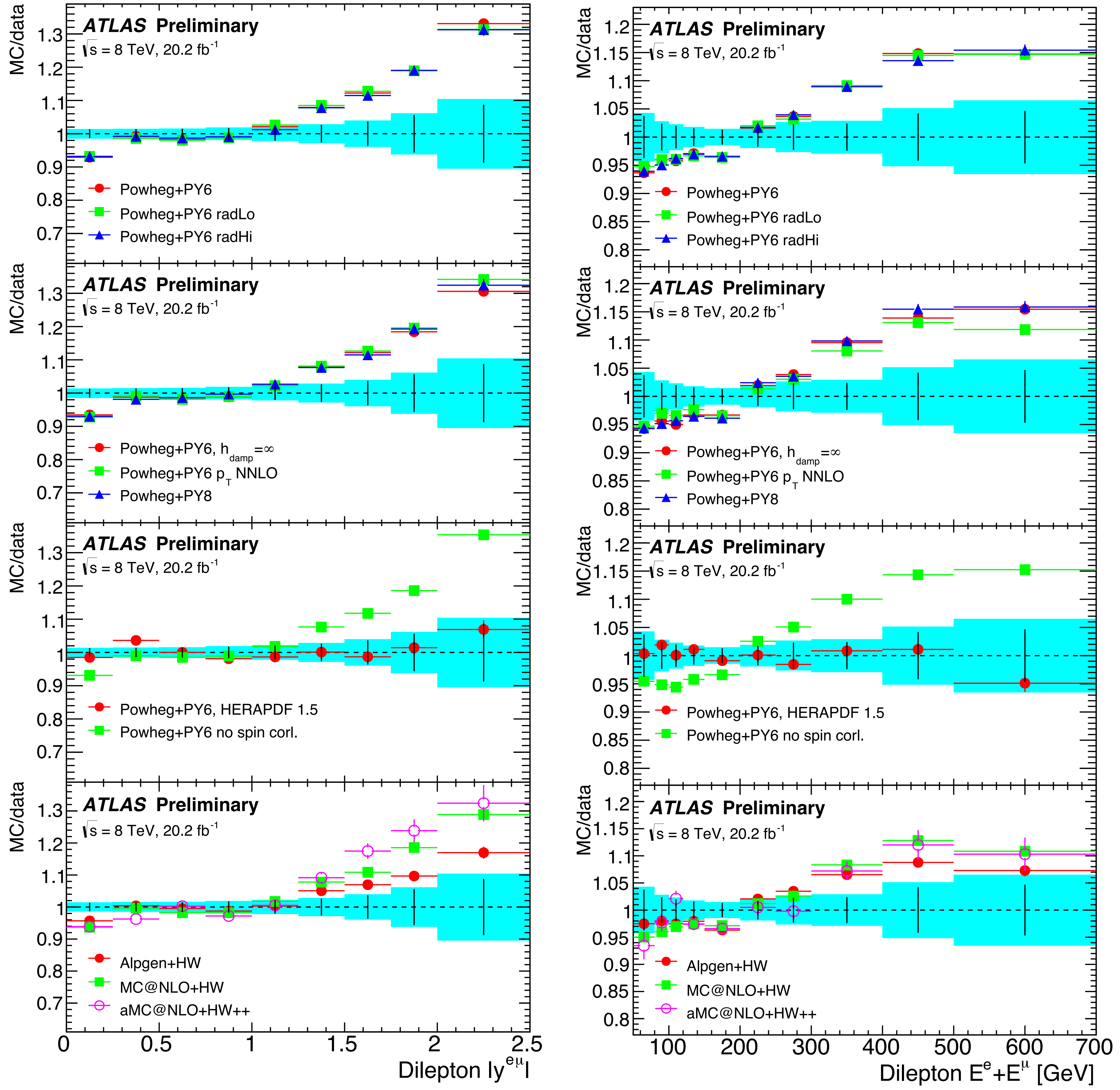
- $t\bar{t}$ NLO and LO multileg generators
- parton shower and hadronisation

Results

- in general good agreement
- sensitive to gluon PDF





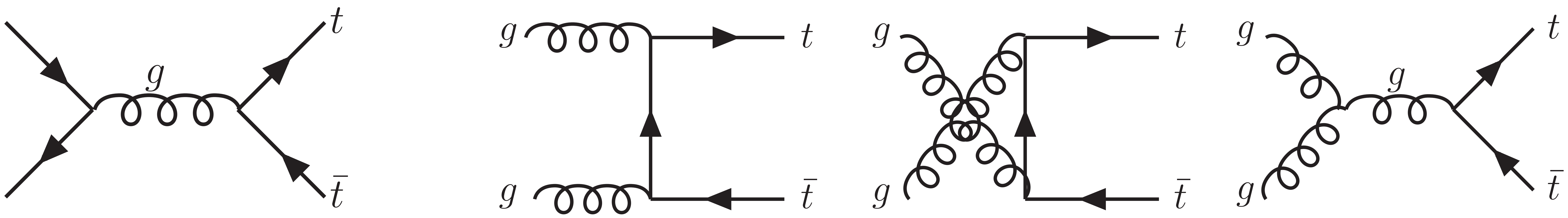


- pole mass, $\delta m_t < 2$GeV (see next talk)

ATLAS-CONF-2017-044

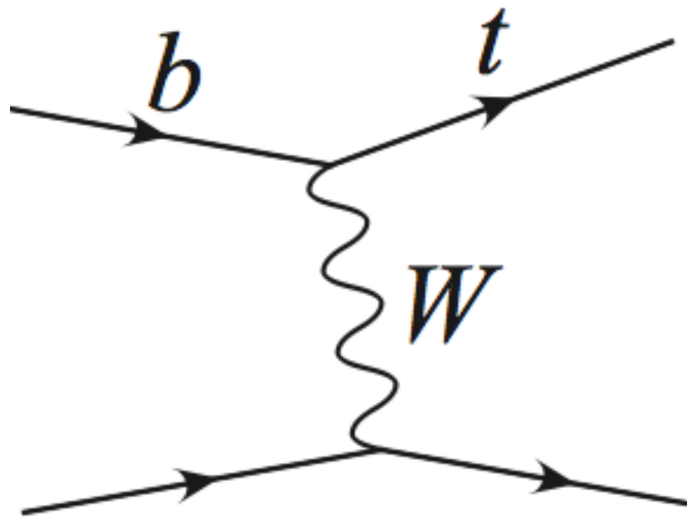
Top-quark production

Top-quark pairs via strong interaction



830 pb @ 13 TeV

Single-top quarks via weak interaction



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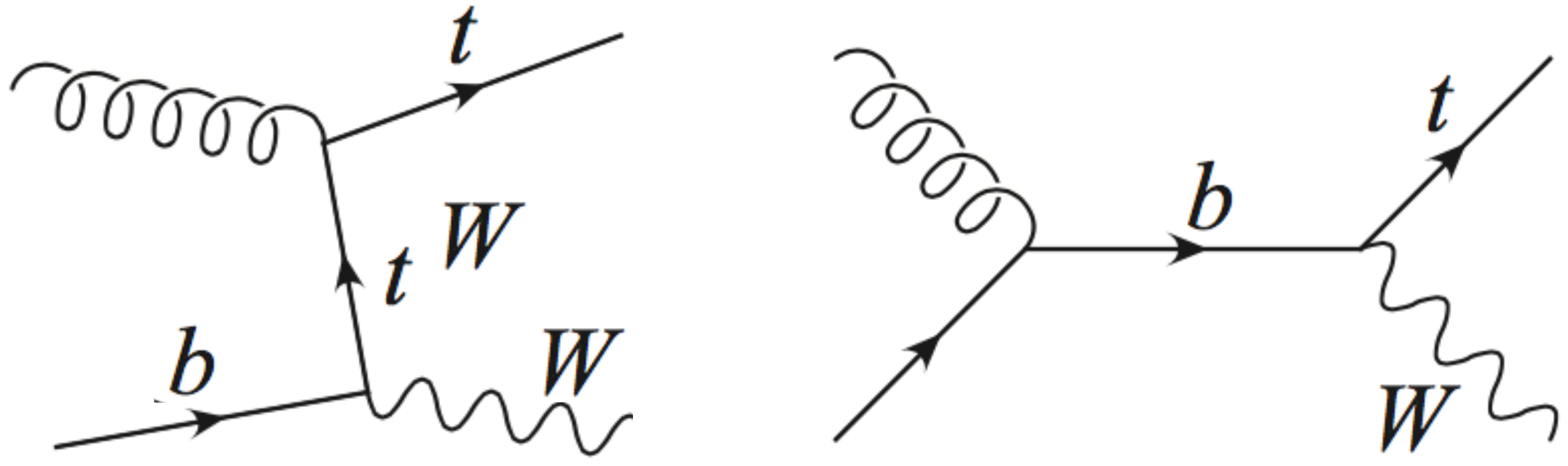
210 pb @ 13 TeV



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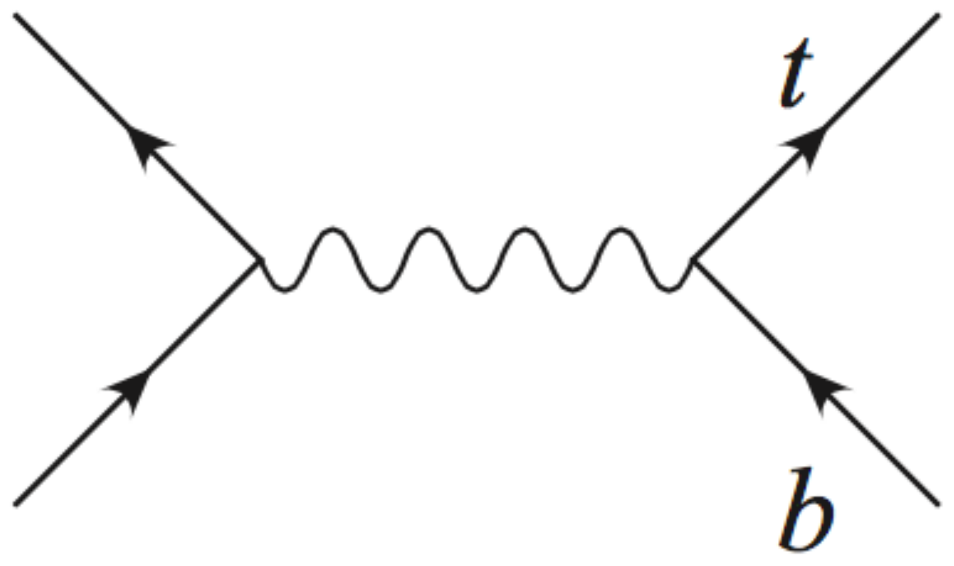

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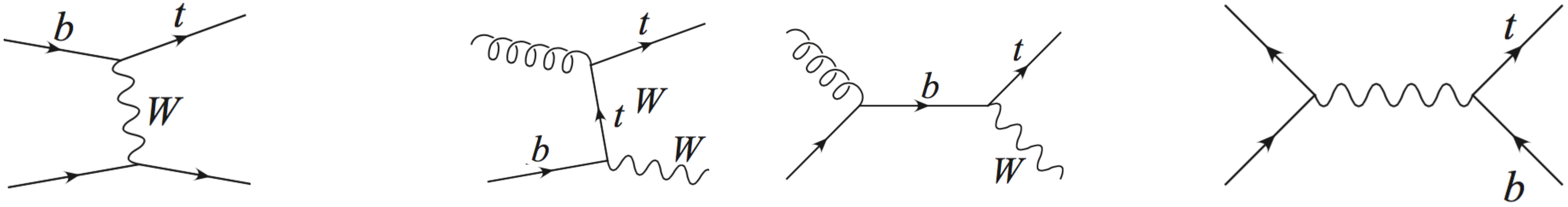


t-channel	*Wt* channel	*s*-channel
210 pb @ 13 TeV	72 pb @ 13 TeV	11 pb @ 13 TeV

t-channel at 8 TeV: fiducial

Signature

- ℓ + E_T^{miss} + b-tag + forward jet

Backgrounds

- $t\bar{t}$, W+jets, multi-jets

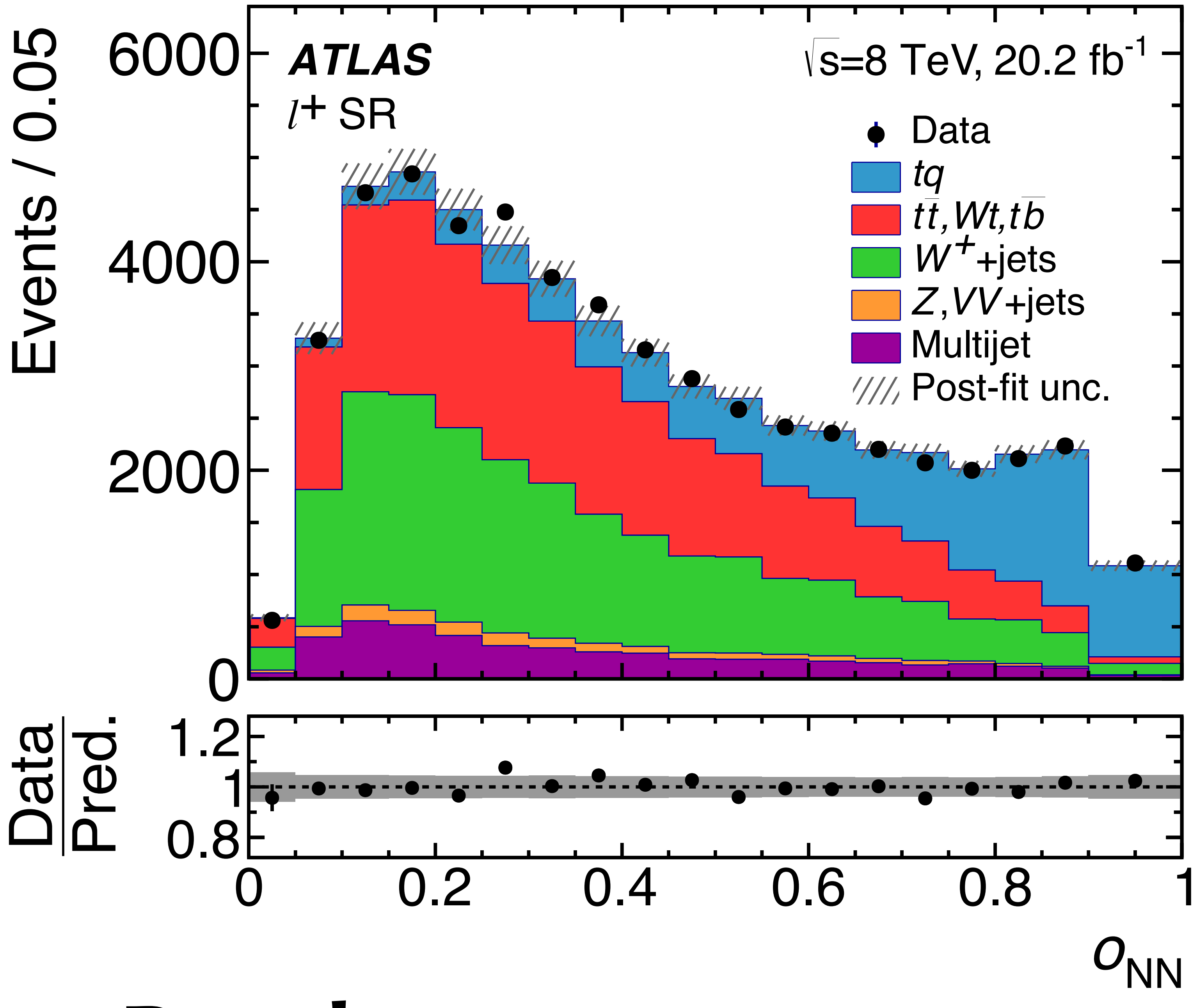
Neural networks to enhance S/B

Separate cross-section

- for ℓ^+ and ℓ^-

Fiducial

- fiducial cross section to reduce systematic uncertainties
- fiducial volume defined using stable particles with cuts close to selection



- **Results**
  - σ_{tq}(fid.) = 9.87 pb ± 5.8%
  - $\sigma_{\bar{t}q}$(fid.) = 5.77 pb ± 7.8%
- **Uncertainties**
  - systematically dominated: JES, NLO matching choice, lepton reconstruction

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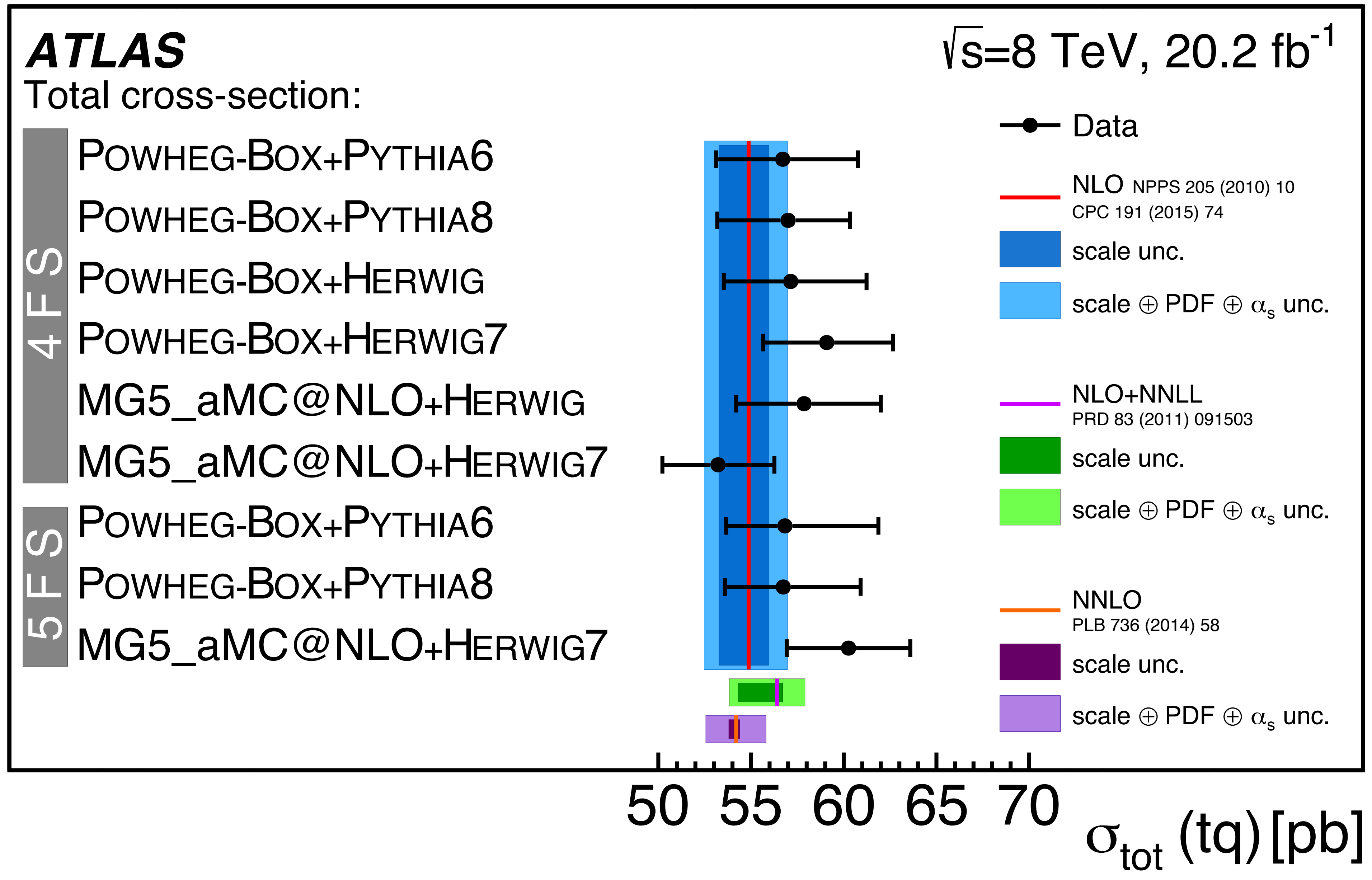
t-channel at 8 TeV: total cross section

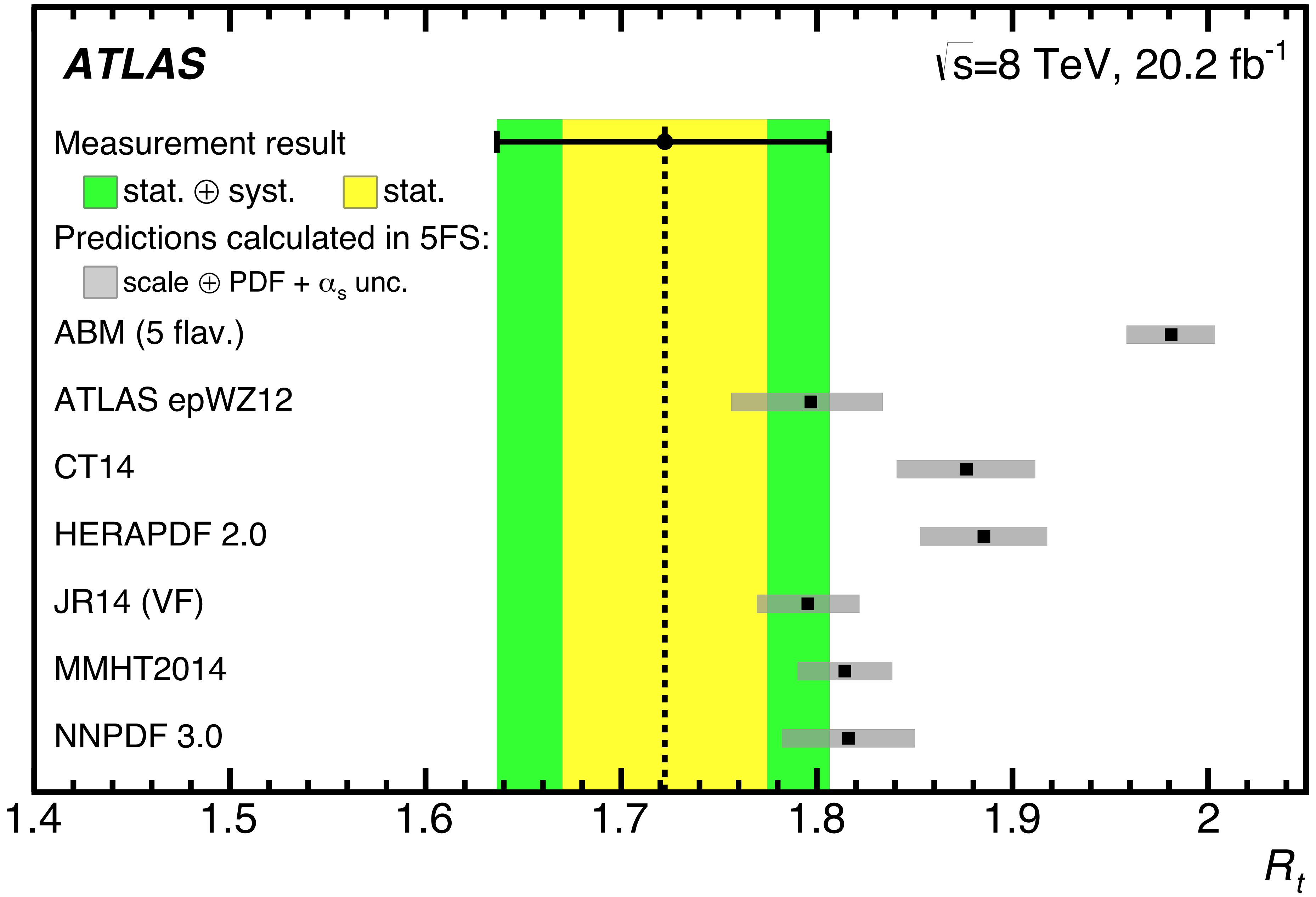
Total cross section

- fiducial cross section extrapolated to full phase space
- $\sigma(\text{tot}) = N_{\text{tot}}/N_{\text{fid}} \cdot \sigma(\text{fid})$
  - $\sigma_{tq}(\text{tot}) = 56.7^{+4.3}_{-3.8}$ pb
  - $\sigma_{\bar{t}q}(\text{tot}) = 32.9^{+3.0}_{-2.7}$ pb
- compared to different generators



Ratio R_t

- $R_t = \sigma_{tq}/\sigma_{\bar{t}q} = 1.72 \pm 0.09$



- without unitarity assumption
- $|f_{LV} \cdot V_{tb}|^2 = \sigma_{\text{meas}} / \sigma_{\text{pred}} = 1.029 \pm 0.048$

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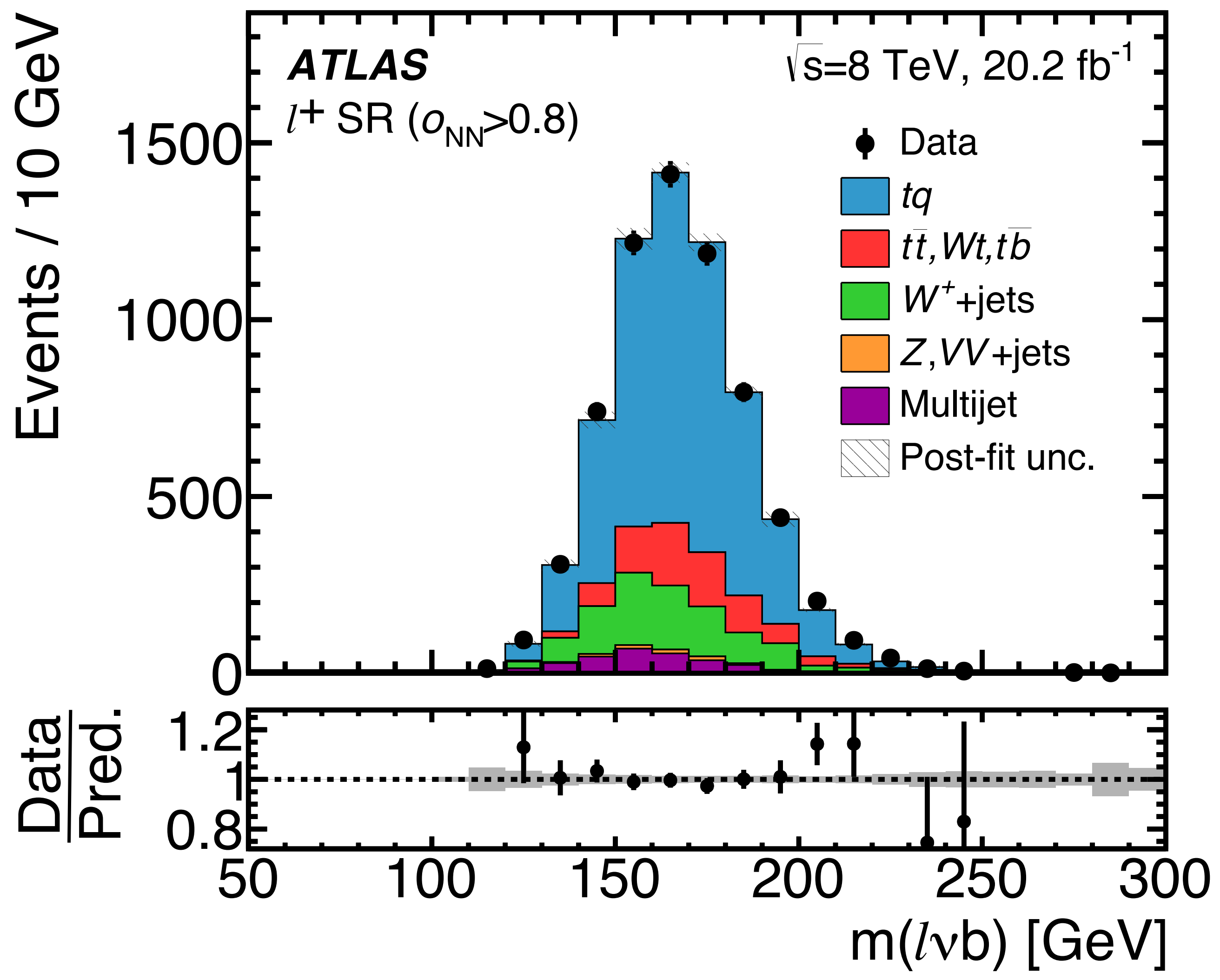
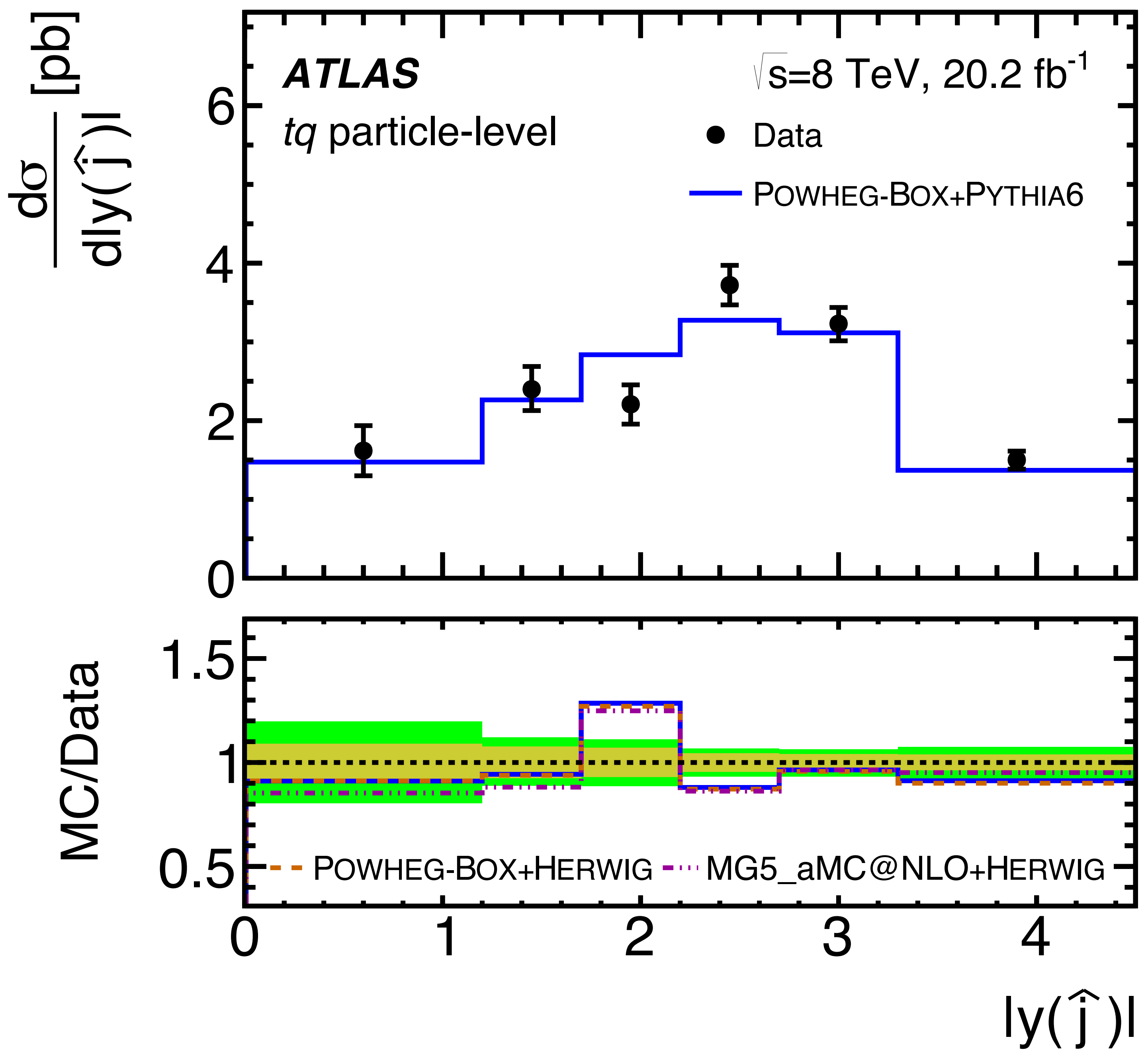
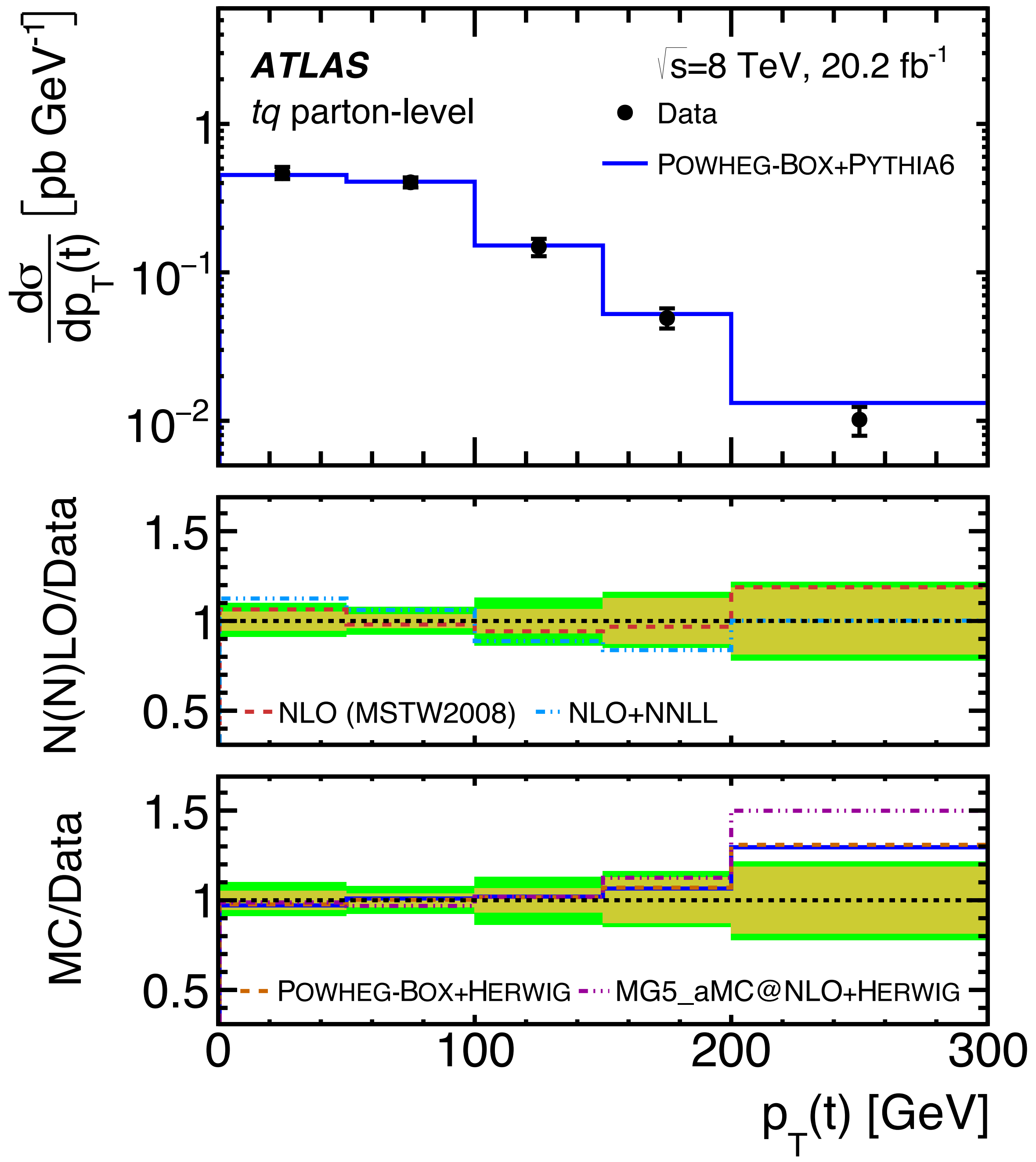
Region with enhanced purity

- select events with $O_{NN} > 0.8$







Unfolded distributions

- parton level
  - $p_T(t)$, $|y(t)|$ for $t/\bar{t}$
- particle level
  - $p_T(t)$, $|y(t)|$, $p_T(j)$, $|y(j)|$ for $t/\bar{t}$

- good agreement with NLO predictions
- main sources of systematics
  - similar to fiducial measurement

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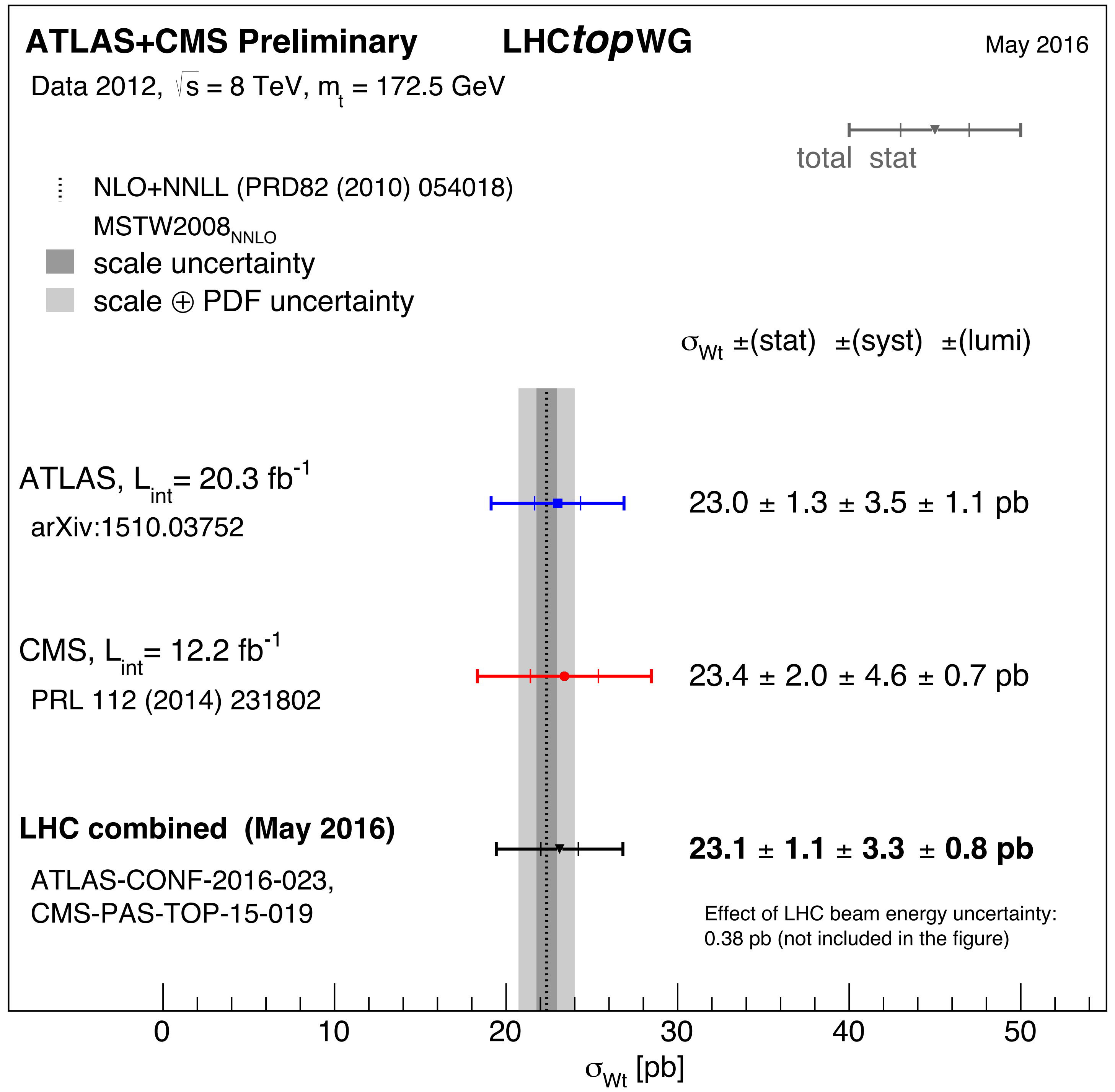
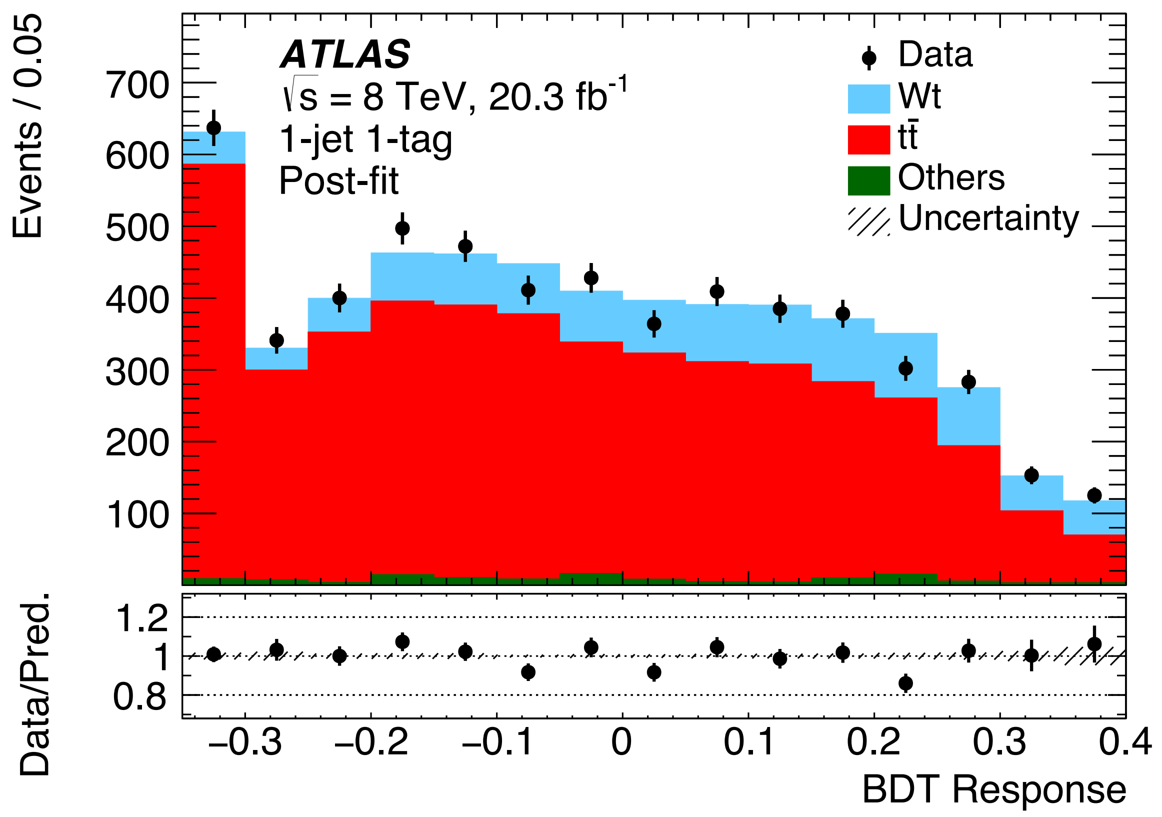
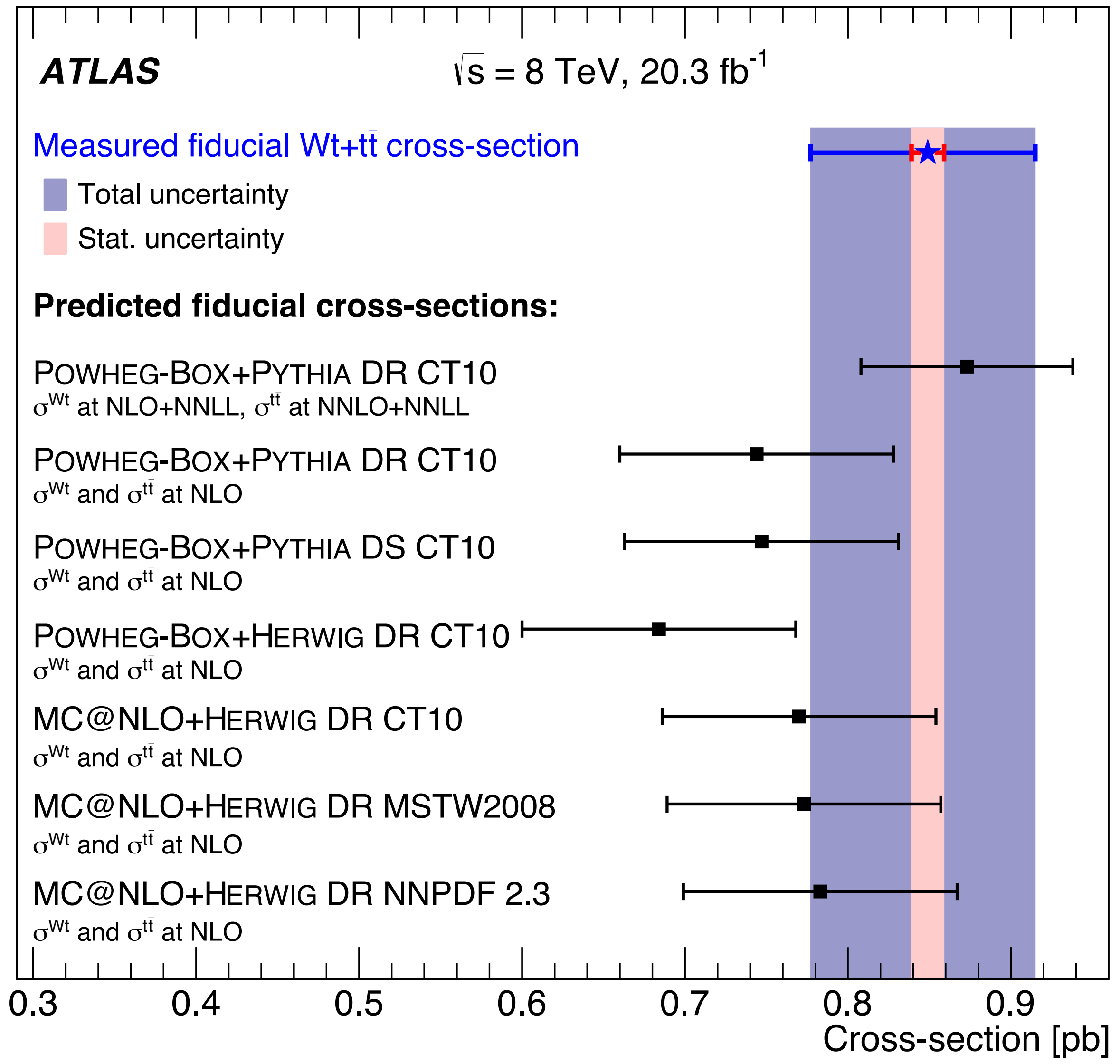
Dilepton selection with 1 *b*-tag

- 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

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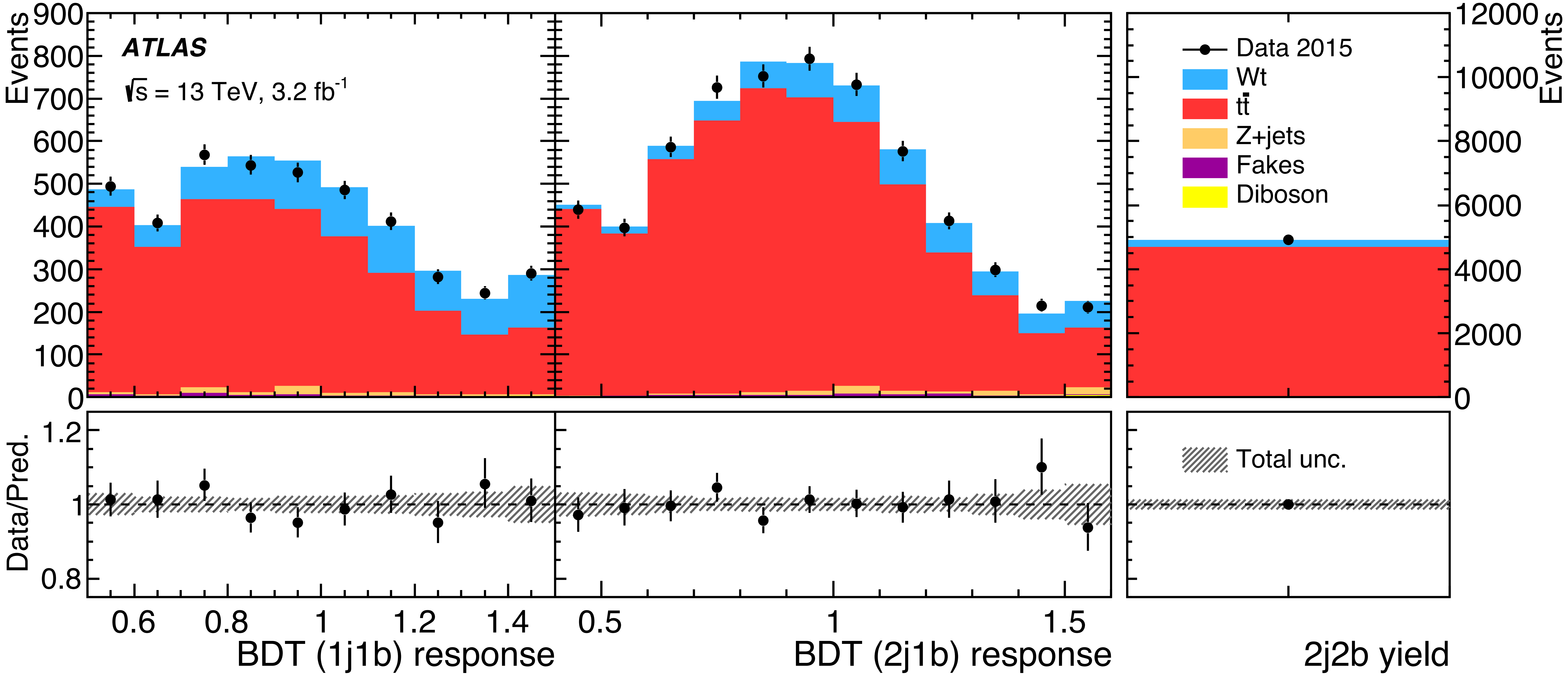
Dilepton selection with 1 *b*-tag

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



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

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1612.07231

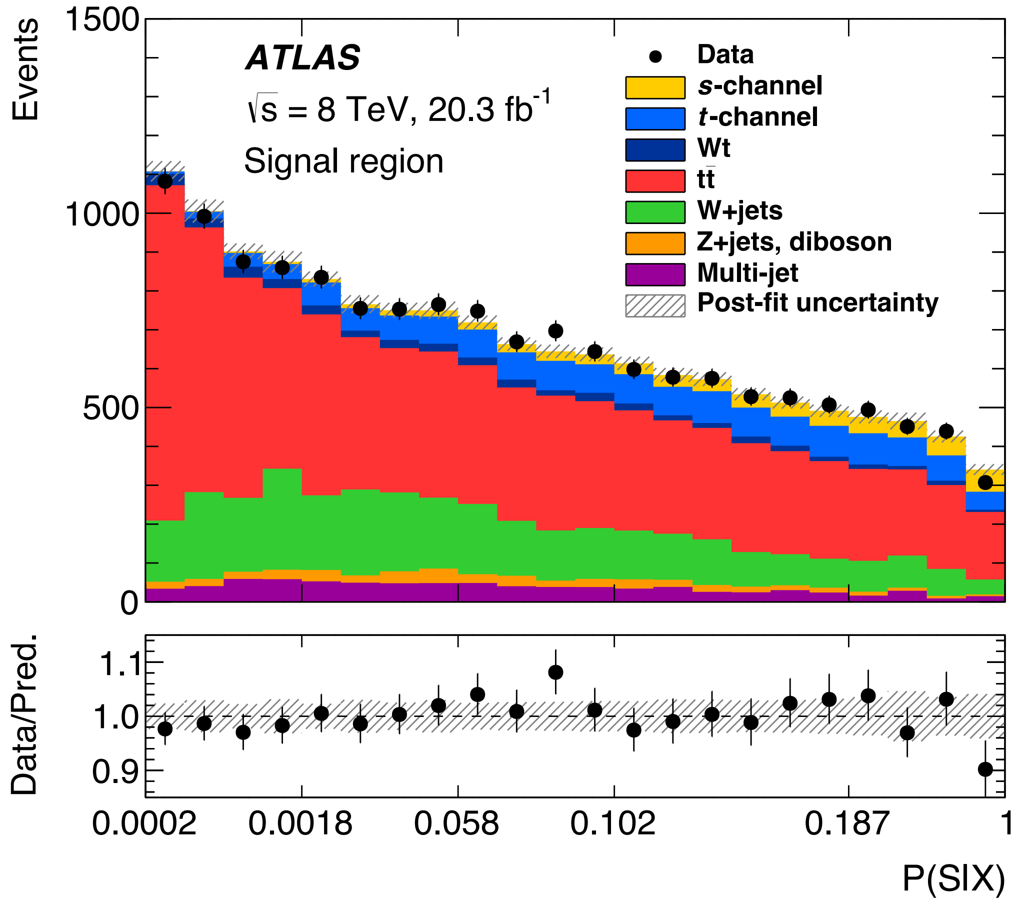
Single top – *s*-channel

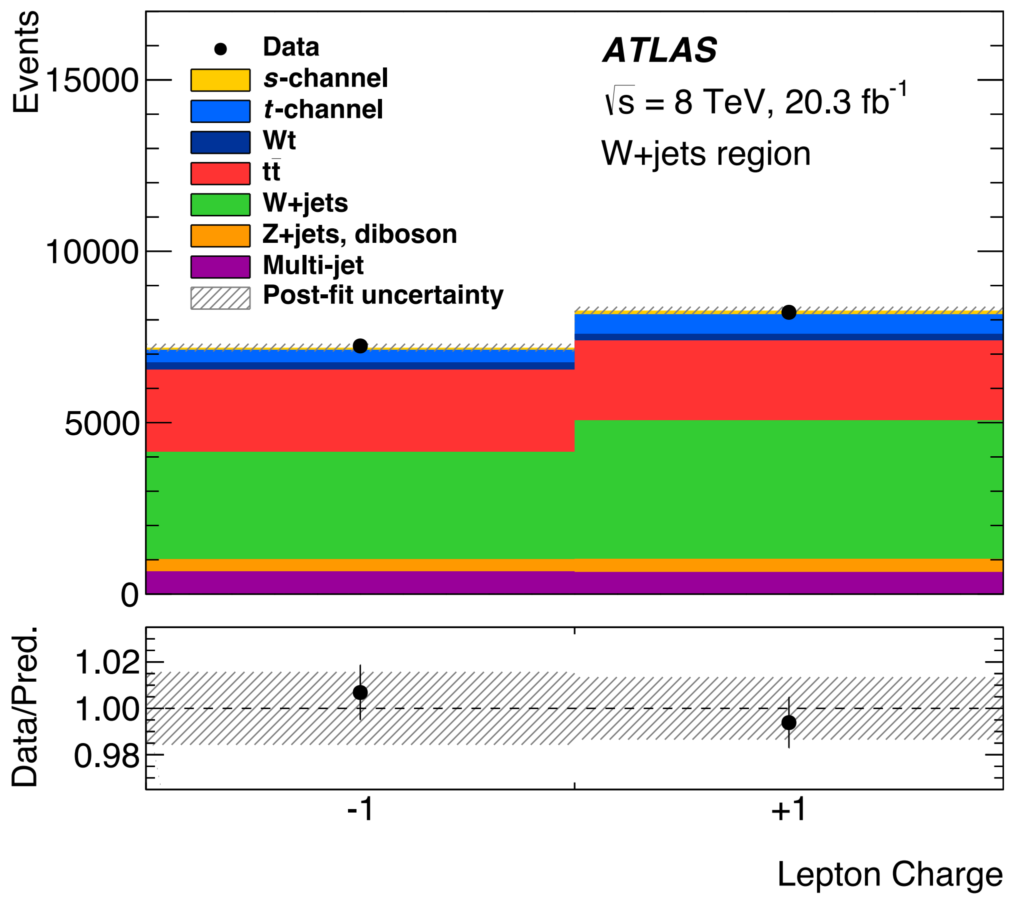
Motivation

- **SM process not yet seen, other resonances may decay to *tb***

Strategy

- ***2j2b* (SR), *2j1b* (*t*-channel, *W*+jets)**
- **matrix-element method employed**
- **combined ML fit to SR and CR**

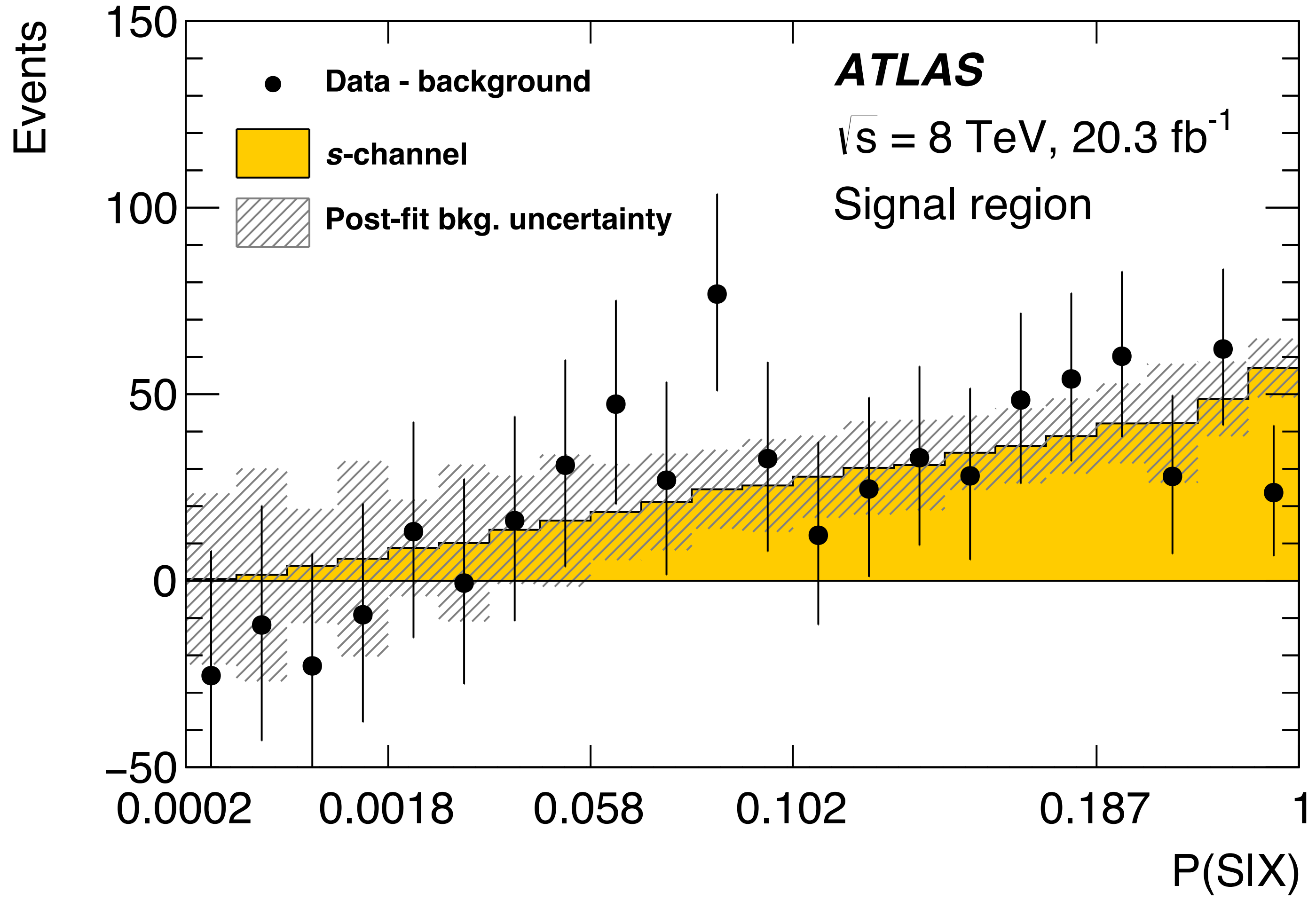




- **lepton charge discriminates *W*+jets**

First evidence at LHC

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



- **expected significance 3.9σ**
- **observed significance 3.2σ**

Main systematics

- **jet energy resolution, modelling, *b*-tagging**

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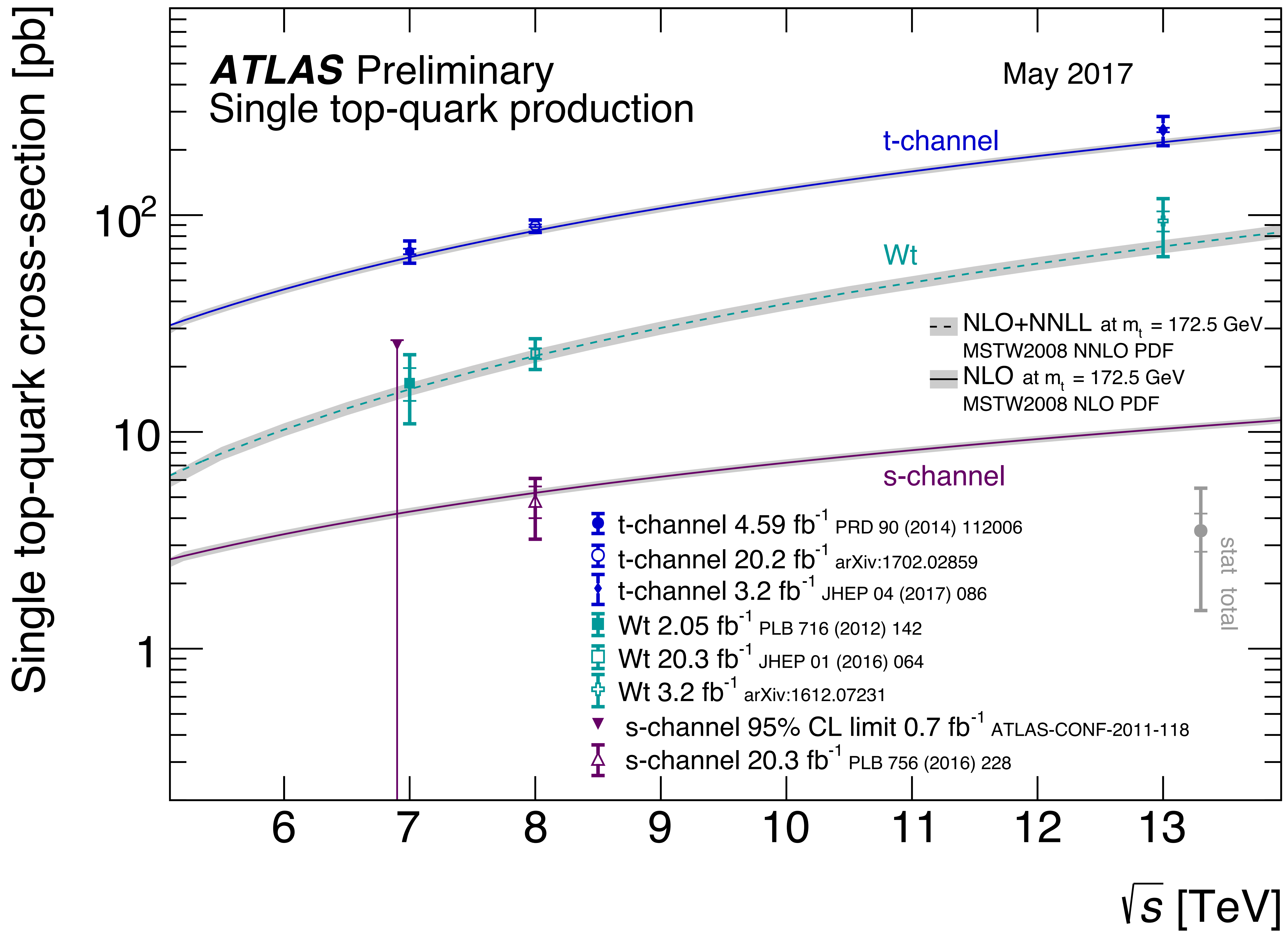
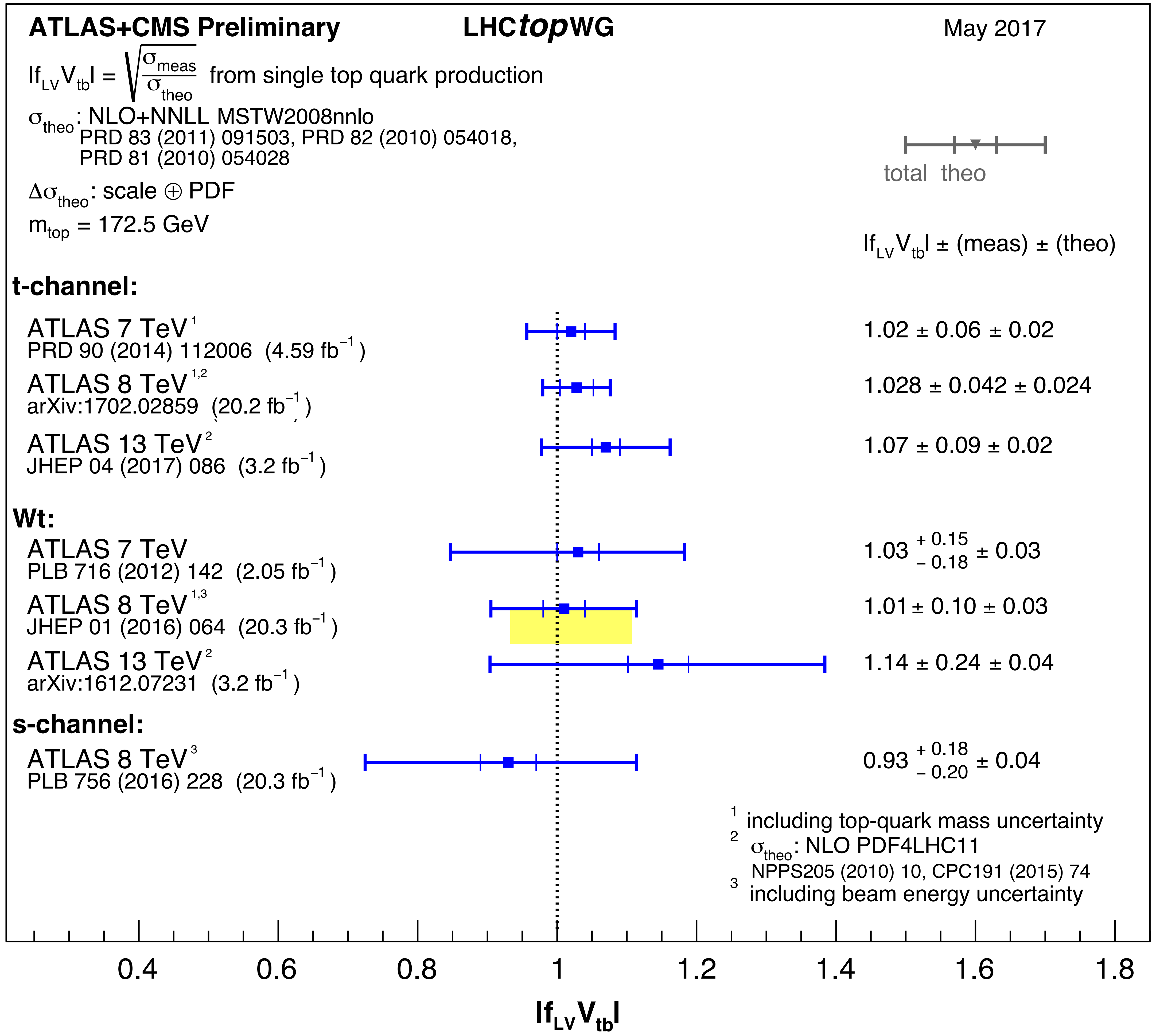
Summary single top production

- good agreement with NLO calculations
- from $\sigma_{meas.}/\sigma_{theo.} = |f_{LV} \cdot V_{tb}|^2 \rightarrow$ can extract $|V_{tb}|$ with 5% uncertainty





Wtb vertex: triple differential decay rate

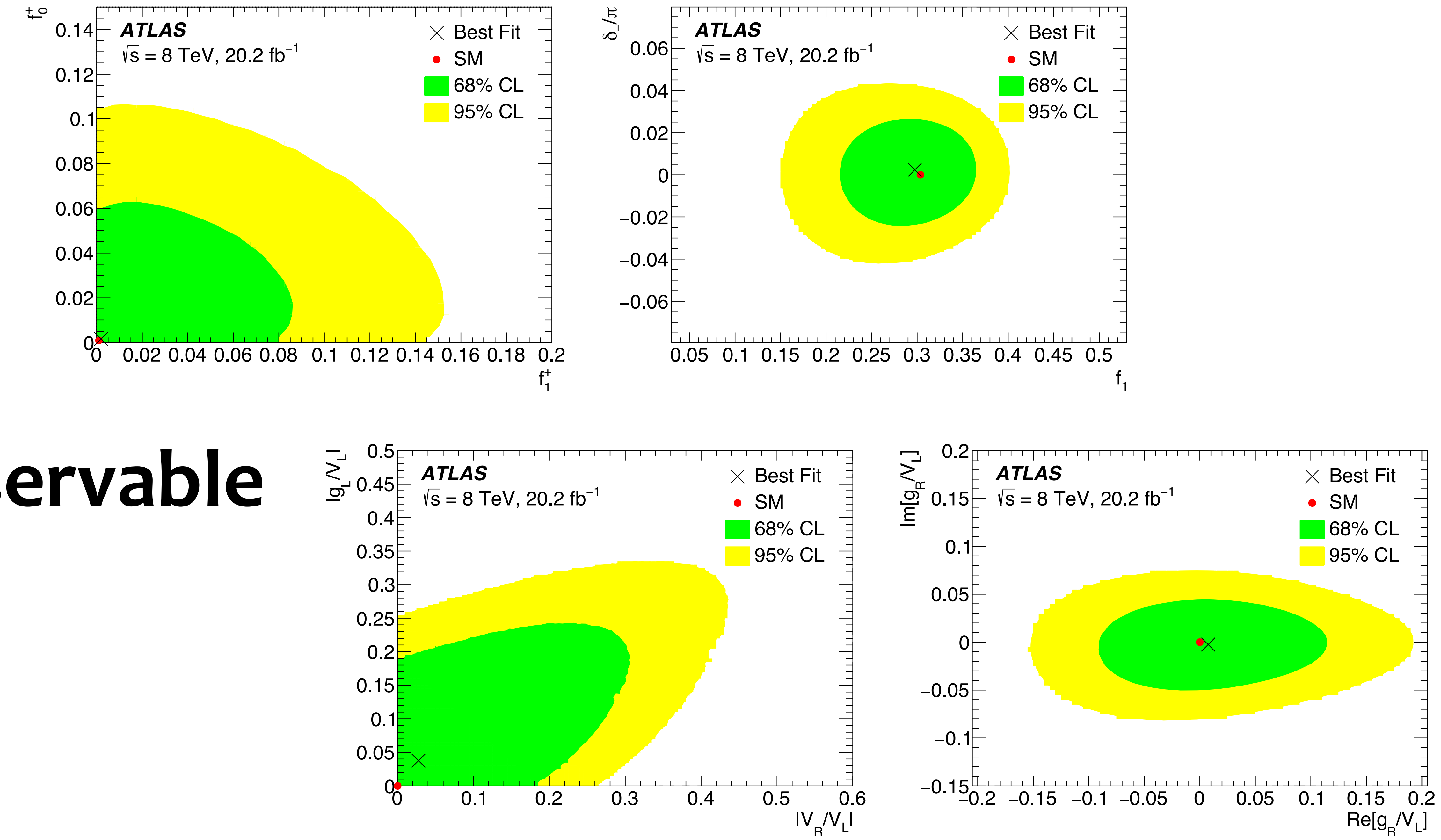
Normalised triple-differential ($\vartheta,\vartheta^*,\varphi^*$) decay rate of top quarks

- complete description of anomalous couplings in *Wtb* + top polarisation
- relate to helicity amplitudes in $t \to Wb$

$$\frac{1}{N}\frac{\mathrm{d}^3N}{\mathrm{d}(\cos\theta)\mathrm{d}\Omega^*} = \sum_{k=0}^{1}\sum_{l=0}^{2}\sum_{m=-k}^{k} a_{k,l,m}\sqrt{2\pi}Y_k^m(\theta,0)Y_l^m(\theta^*,\phi^*).$$

9 $a_{k,l,m}$ = 0, parameterised by

- 3 amplitude fractions f_1, f_1^+, f_0^+
- 2 phases δ_- : can imply CP violation, δ_+ not observable
- a nuisance parameter



Strategy and results

- global fit with all correlations
- extraction of limits on anomalous couplings
- no assumptions on values of the other couplings

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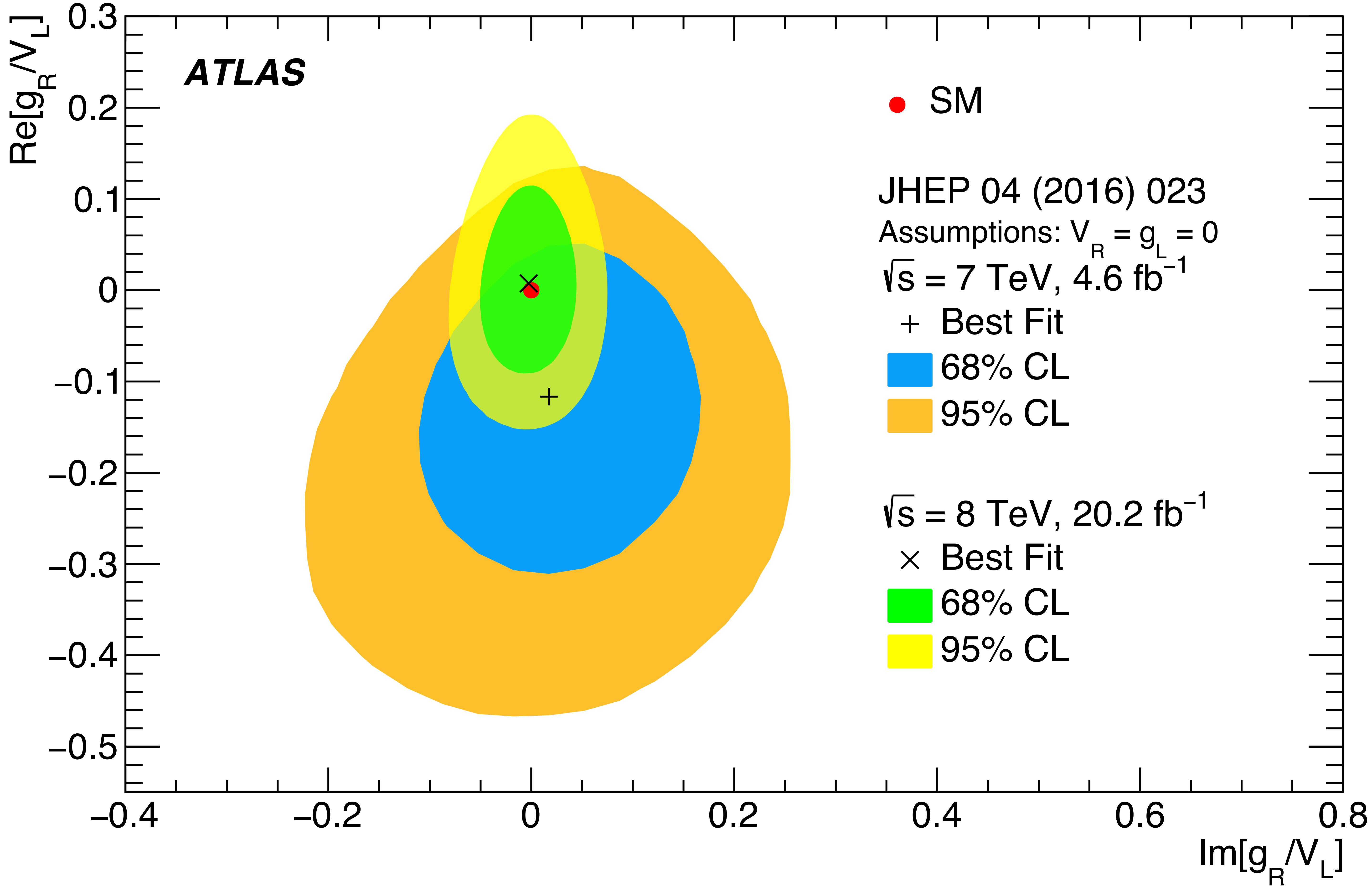
Wtb vertex: triple differential decay rate

Normalised triple-differential ($\vartheta,\vartheta^*,\varphi^*$) decay rate of top quarks



- no assumptions on values of the other couplings

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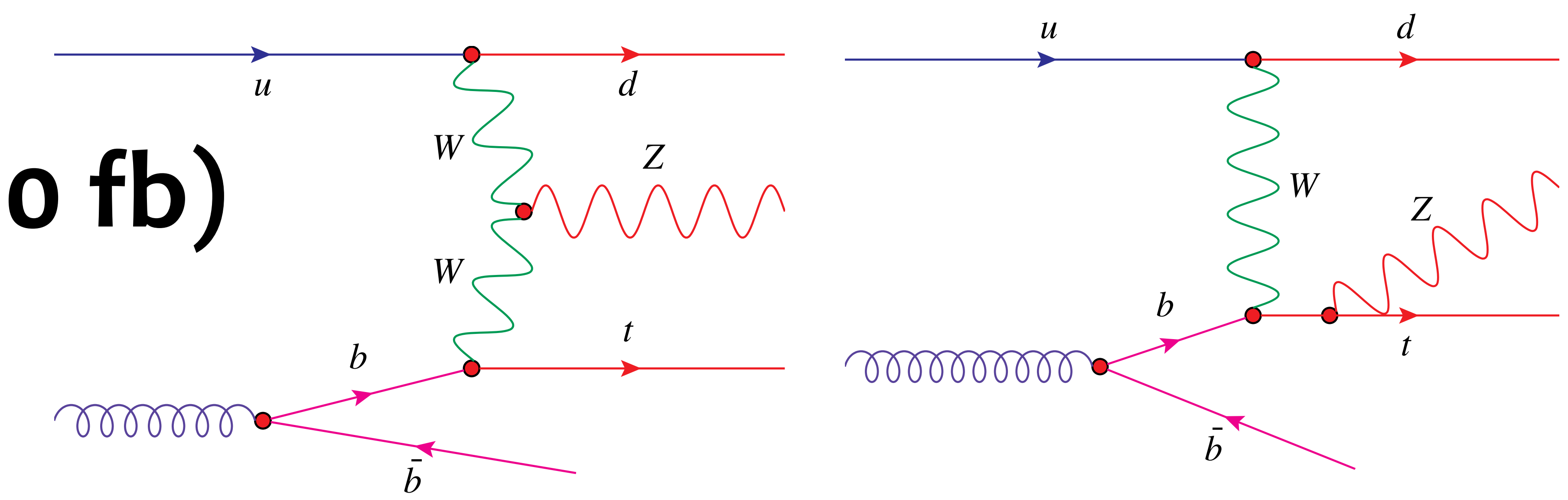
Associated single top production: *tZq*

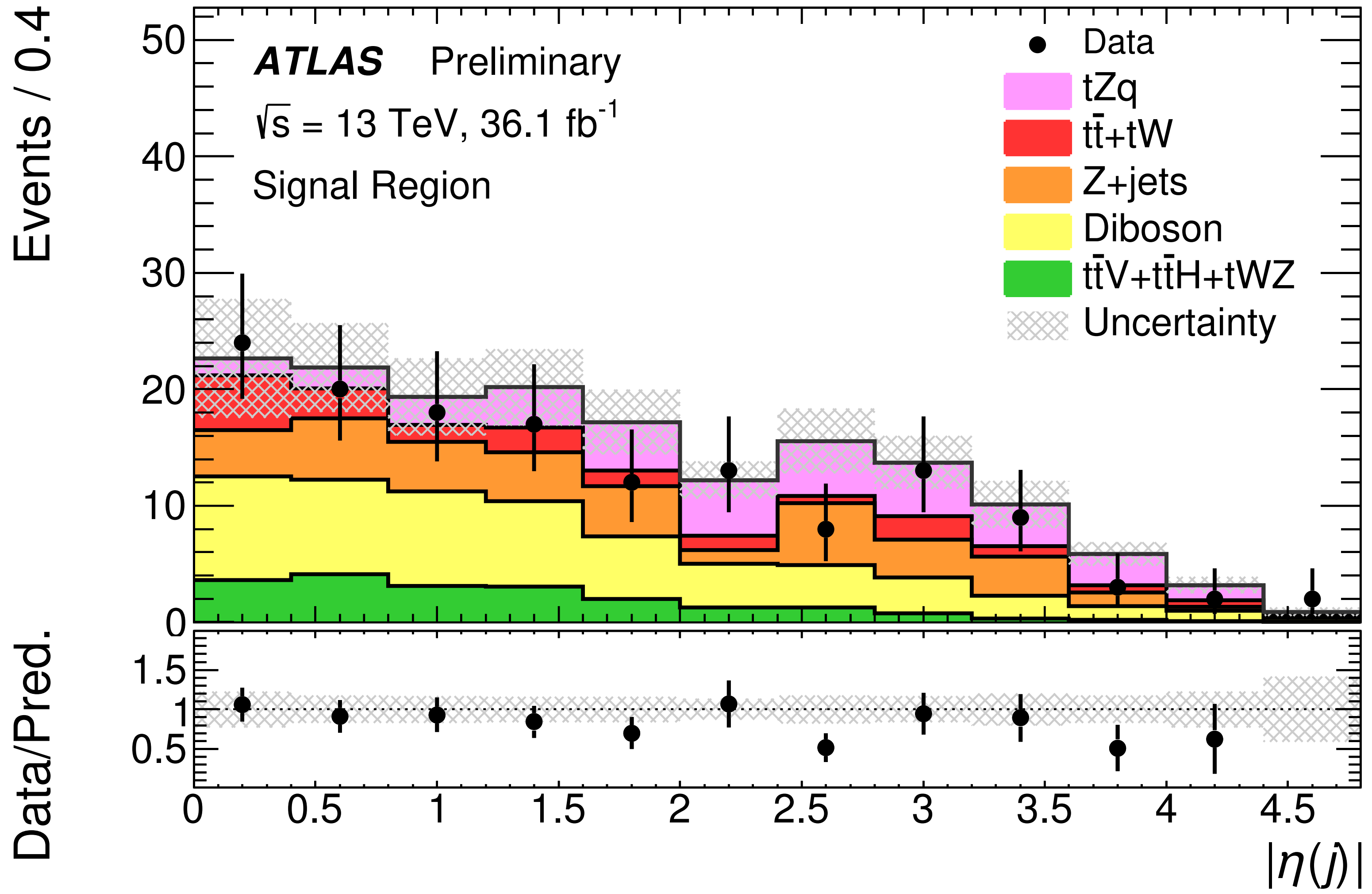
Motivation

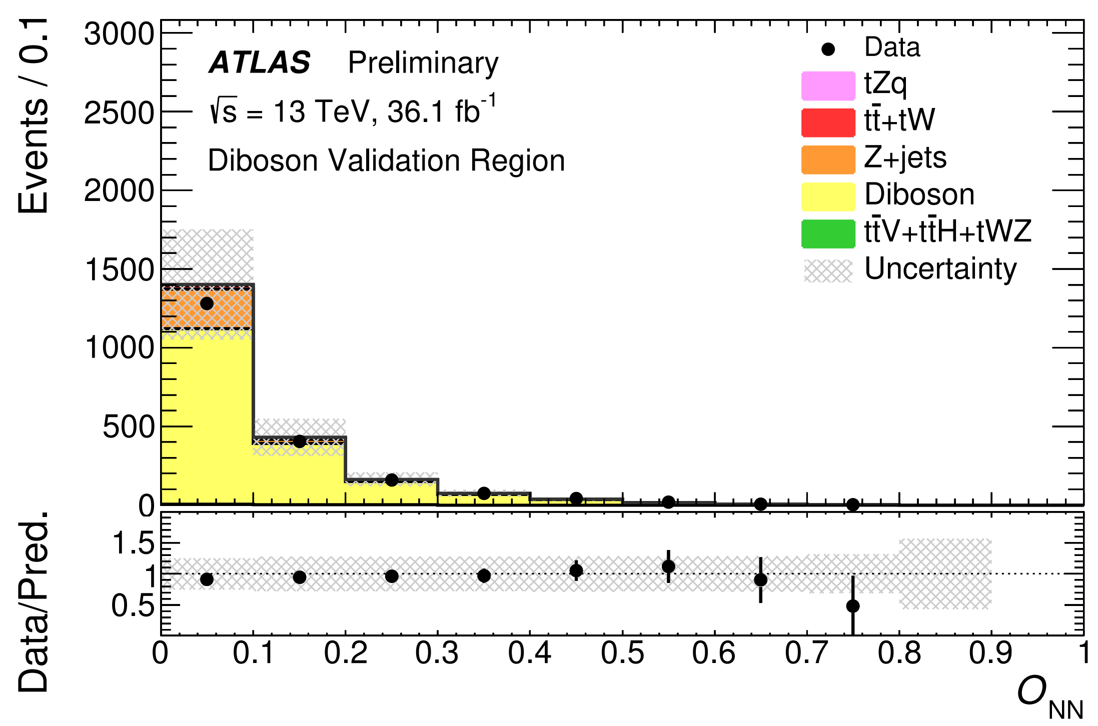
- electroweak process, not yet observed (800 fb)
- sensitive to *tZ* and *WWZ* coupling
- first step on the way to measure *tH*

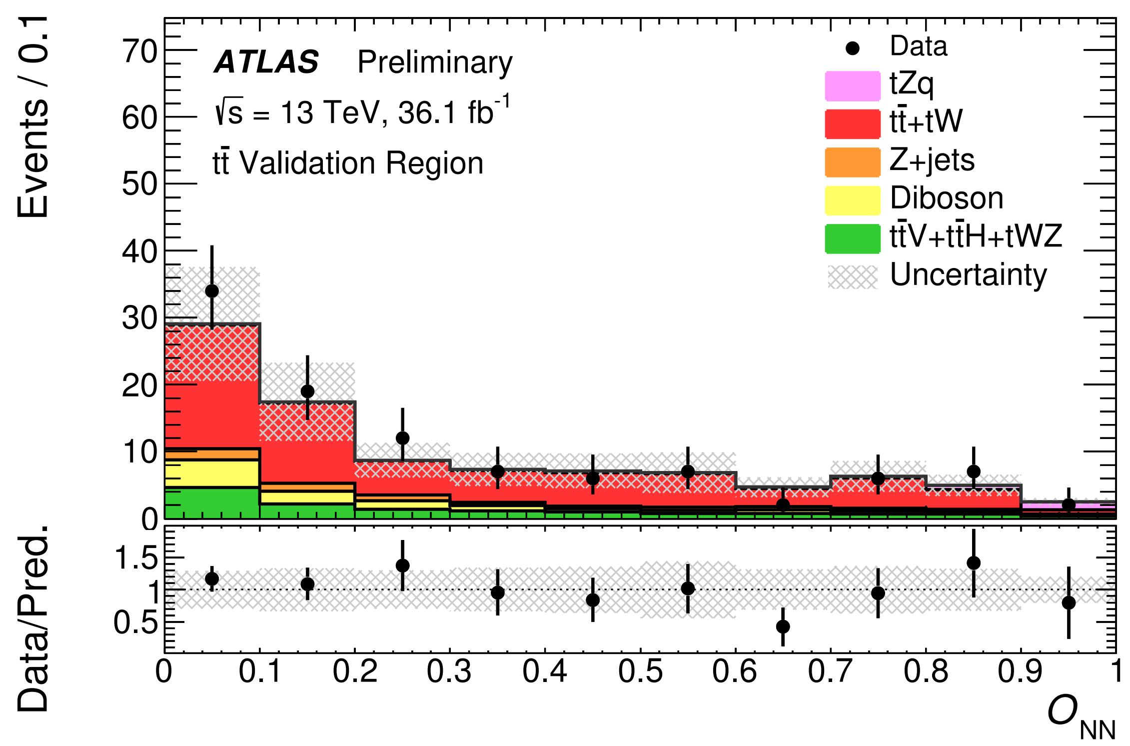


Analysis outline

- SR: 3 leptons ($m_{ll} \sim m_Z$), 1 central *b*-tag + 1 jet
- 10 variables used as input to NN to enhance S/B
- background under control with validation regions







- diboson: no b-tagged jet

$t\bar{t}$: !($m_{ll} \sim m_Z$)

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tZq results

Dominant systematic uncertainty

- *tZq* radiation: hard scatter and parton shower scales

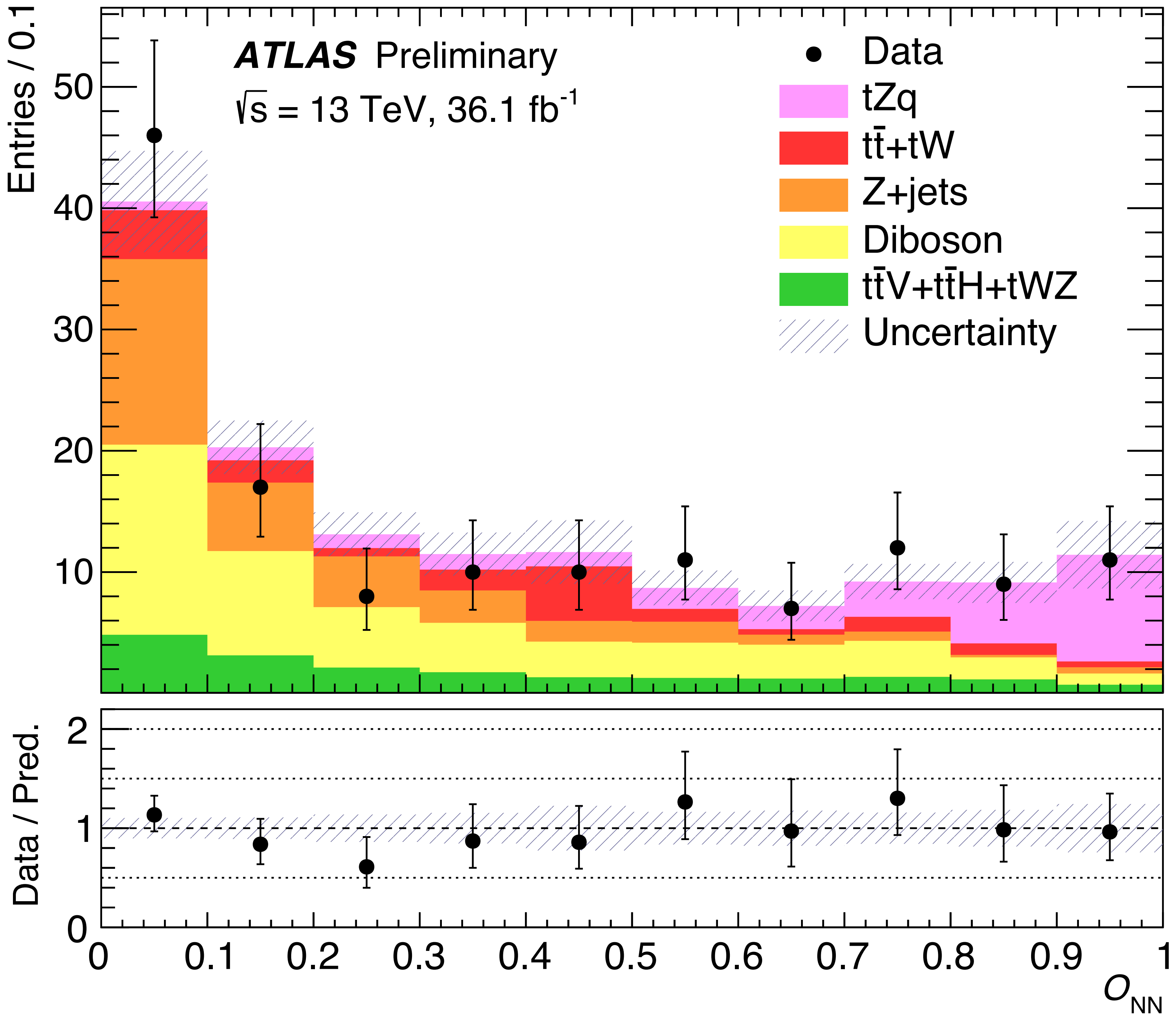
Fit setup

- binned ML fit to full NN distribution in SR
- $t\bar{t}$ and diboson normalisation from CRs
- Z+jets data-assisted MC correction

Results

- $\sigma_{tZq} = 600 \pm 170_{\text{stat}} \pm 140_{\text{syst}}$ fb
- expected significance 5.4σ
- observed significance 4.2σ

Channel	Number of events	
	Asimov dataset	Real data
tZq	35 ± 9	26 ± 8
$t\bar{t} + tW$	18 ± 7	17 ± 7
$Z+$jets	37 ± 11	34 ± 11
Diboson	53 ± 13	48 ± 12
$t\bar{t}V + t\bar{t}H + tWZ$	20 ± 3	19 ± 3
Total	163 ± 12	143 ± 11



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Summary

Millions of top-quarks produced at LHC

- comprehensive program at ATLAS to measure $t\bar{t}$ and single top production

Top-quark pairs

- inclusive cross-section compared to NNLO calculations
- differential cross-section helps MC tuning, to extract gluon PDF, …

Single top

- all three channels now seen
- *t*-channel differential distribution allows also to probe *Wtb* structure
- first evidence of *tZq* process shown