$t\bar{t}$ Analyses at ATLAS

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EPD seminar

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Outline (Time-line)

Hadron Collider → q/g → $t\bar{t}$ → decay

↓

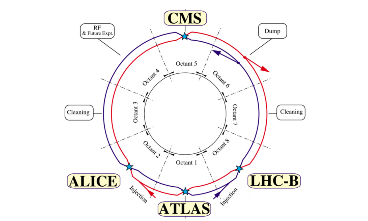
observable decay products → ATLAS → Reconstruction $e/\nu/\gamma/\mu$/jet → Selection $t\bar{t}$ sample

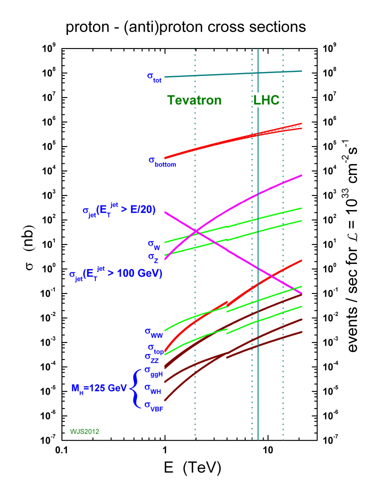
→ Measurements / Interpretation
- Xsec
- mass
- spin
- QED/QCD
- ....

Large Hadron Collider

Proton-proton collision

- 7 TeV designed beam energy (up to now: 3.5/4/6.5 TeV)
- colliding quarks and gluons
- factory of H/W/Z/top/...
- general: ATLAS and CMS
- b physics: LHCb
- heavy ion: ALICE





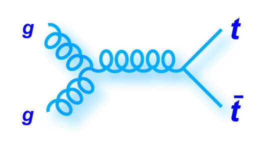
$t\bar{t}$ Production @LHC

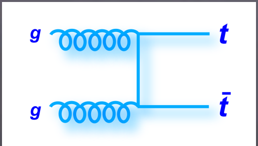
Top quark: the known heaviest elementary particle ($\sim$ 170 GeV)

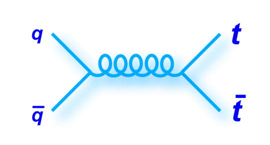
- mass at the EW breaking scale, large yukawa coupling with Higgs, short life time, ...

$t\bar{t}$ production mechanism at LHC

- LO: $gg \to t\bar{t}$ (main, e.g. 90% when $\sqrt{s}$=13 TeV) and $q\bar{q} \to t\bar{t}$ (different parton density functions (PDF) $f(x, Q^2)_p^{q/g}$: probability of parton q/g with energy fraction x of the proton energy)
- current best $\sigma_{\text{total}} = \sigma(pp \to t\bar{t})$ of $\sqrt{s}$ =13 TeV: 832^{+46}_{-51} pb @NNLO + NNLL (soft gluon) in QCD (PRL110(2013)252004)



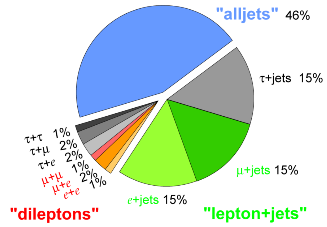




$t\bar{t}$ Decay

$t \to W^+ b$ almost all cases

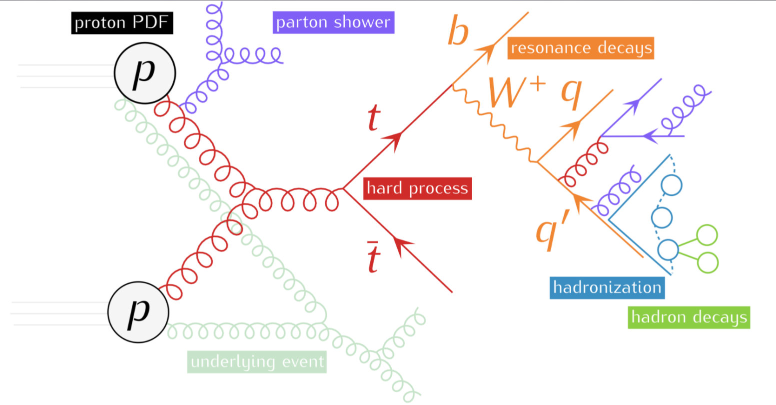
- decay in $5{\times}10^{-25}$s, before hadronization (10^{-23})
- $W \to \ell\nu(\ell = e/\nu/\tau) \sim 30\%$ cases, $W \to q\bar{q}' \sim 70\%$ cases



$t\bar{t}$ decay categorized according to number of leptons

- "dilepton" channel: 2 leptons with opposite sign (OS) of charge, 2 neutrinos, b and $\bar{b}$ quarks
- "single lepton" channel: 1 lepton, 1 neutrino, a pair of light quarks, b and $\bar{b}$ quarks
- "all hadronic" channel: two pairs of light quarks, b and $\bar{b}$ quarks
- more lepton $\to$ smaller cross-section but cleaner signal

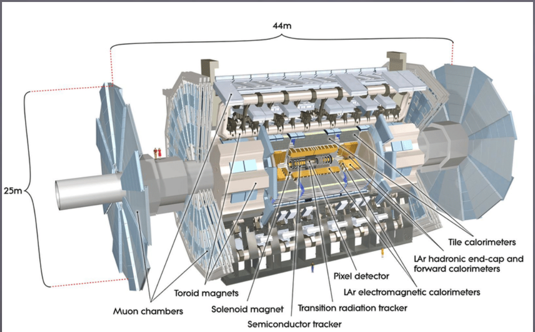
Not Just $t\bar{t}$



- underlying events: beam remnant, multiple parton interaction
- parton shower (PS): initial/final state QCD radiation
- PS down to hadron scale → hadronization and hadron decays
- Pile-up: (soft) events from other *pp* collision

ATLAS Detector

$t\bar{t}$ final state: leptons (e/μ), neutrinos, hadrons



Electron/Photon

* Inner detector track(s) + Electromagnetic calorimeter energy deposit

Muon

* Inner detector track + Muon spectrometer track

Hadron

* Inner detector track + Hadronic calorimeter energy deposit

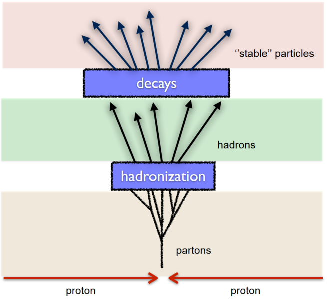
Neutrinos

* cannot measure directly → infer from momentum imbalance, but p_z (beam direction) unknown → called missing E_T (MET)
* cylindrical system: azimuthal ϕ (0∼ 2π), $\eta = \ln \tan \frac{\theta}{2}$ (-5∼5/1∼179 degrees)

Jet

Proxy of QCD parton

- a QCD parton $\rightarrow$ a bunch of collimated stable particles
- collect these stable particles $\rightarrow$ jet
- "reverse-engineer" of the original parton kinematics



Jet algorithm: e.g. anti-k_T

- infrared/collinear radiation safe, robust against underlying events and pile-up
- circular cone shape: $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2)} = 0.4$, in (η, ϕ) plane

Identify b-quark/b-jet: b-tagging

- e.g. displaced decay vertex (wrt hard event vertex): b-hadron flies $\sim$1 mm before decays

Typical Selection

Object kinematics selection

- high pT (e.g. pT $>$ 25 GeV) and central $|\eta|$ (e.g. $|\eta| < 2.5$)
- remove electron/photon in crack region between barrel/endcap

Lepton/photon isolation

- additional E/p in a cone of $\Delta R = X$ around the object
- small (large) isolation for prompt (non-prompt/jet-fake) lepton/photon

Primary vertex (PV) selection

- formed by fitting tracks, choose the one with max $\sum_{trk} p_T^2$

Lepton impact parameter selection

- track close to PV in beam direction and transverse plane

Pile-up jet suppression

- pile-up jet has more tracks NOT from PV

Typical Selection

Event selection

- single lepton channel: 1 lepton, MET, $\geq$ 4 jets, $\geq$ 1 b-jet
- dilepton channel: 2 leptons with OS, MET, $\geq$ 2 jets, $\geq$ 1 b-jet
- use $\geq$ instead of "==" to account for additional jet from QCD radiation and inefficiency of b-tagging

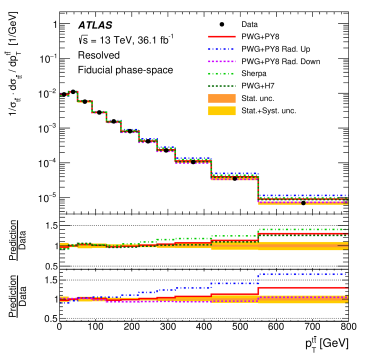
Background suppression

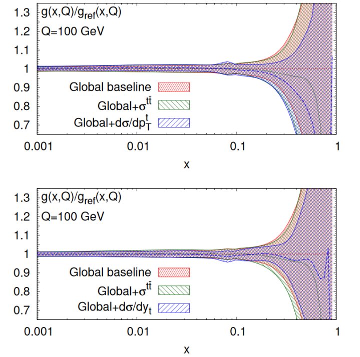
- single top, W/Z+jets, diboson (WW/WZ/ZZ), non-prompt and fake leptons
- single lepton channel: transverse W mass $m_T^W = \sqrt{2p_T^\ell p_T^\nu(1 - \cos\Delta\phi} > 30$ GeV, for events with fake lepton or MET or not containing W intermediate state
- dilepton channel: lepton pair invariant mass $m_{\ell\ell} > 10$ GeV and $\notin$ [85,95] GeV, for low-mass Drell-Yan (DY) and Z+jets events

$t\bar{t}$ Analyses

Inclusive and differential $t\bar{t}$ cross-sections

- challenge pQCD calculation and check MC generators (e.g. too hard MC $t\bar{t}$ pT, arxiv:1908.07305)
- sensitivity to large-x gluon PDF (JHEP04(2017)044), m_t
- background to rare SM process / BSM search





$t\bar{t}$ Analyses

Top quark mass (m_t): fit to observables sensitive to m_t

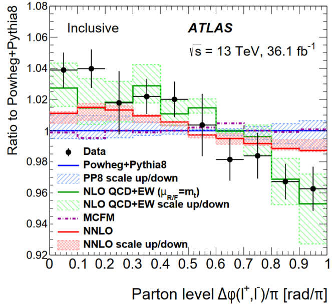
- key SM parameter, vacuum stability, mass definition

$t\bar{t}$ charge asymmetry: tiny effect, sensitive to BSM

- SM: top closer to beam direction than anti-top in average

$t\bar{t}$ spin correlation (Arxiv:1903.07570)

- top life time much smaller than spin decorrelation time
- spin correlation propagated to decay products
- deviation from NNLO prediction in ATLAS



$t\bar{t}$ Analyses

Flavor-changing neutral current (FCNC)

- $t \to Xq$, where $X = H/Z/g/\gamma$ and q a light up-type quark

$t\bar{t}$ associated production with X

- $X = H/Z/\gamma$, top neutral couplings, $t\bar{t}\gamma$ (in this talk)
- $X =$ (heavy-flavor) jets (in this talk): test pQCD and tune MC, important background process

$t\bar{t}$ as background (in this talk)

- $H \to WW$ and WW measurements

More not covered here

- jet substructure, top polarisation, single-top production, ...

$t\bar{t}$ + Jets in $e\mu$ Channel

Introduction

$\alpha_S \sim 0.1$: normal to have QCD radiation, i.e. additional jets, in $t\bar{t}$ production/decay

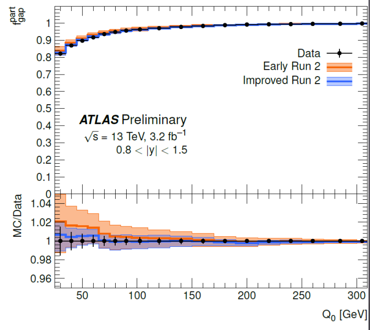
- resolved jet with hard p_T, otherwise not easy to measure/predict

Why interested in $t\bar{t}$ + jets?

- testing pQCD at top mass scale
- test/tune MC generator (ATL-PHYS-PUB-2018-009)
- background to other analyses

Why in $e\mu$ channel?

- clean signal sample with tiny background



Predictions & Experiments

Theoretical predictions

- $t\bar{t}+$ 1 jet:
- NLO prediction: PRL98(2007)262002, NPB840(2010)129-159
- interfaced to PS: JHEP04(2015)114
- non-resonance and off-shell: PRL116(2016)052003
- $t\bar{t}+$ 2 jets:
- NLO prediction: PRL104(2010)162002
- implementation in PS: PLB06(2015)060

Experimental measurements (ATLAS)

- 7 TeV dilepton: EPJC72(2012)2043
- 7 TeV single lepton: JHEP01(2015)020
- 8 TeV dilepton of emu: JHEP09(2016)074
- 13 TeV dilepton of emu (partial dataset): EPJC77(2017)220
- 13 TeV single lepton (partial dataset): JHEP10(2018)159

Analysis Overview

Selection: 1 pair of OS e and μ, $\geq$2 b-jets

- high signal ($t\bar{t}$) purity: $> 95\%$, Wt (MC) and fake lepton (data-driven) background
- additional jets are measured: jet not corresponding to the two b-jets from top decay

Fake lepton background

- varied selection: SS e and $\mu \rightarrow$ fake lepton control region

Pile-up additional jet background:

- 1. vary pile-up simulation
- 2. revert pile-up suppression $\rightarrow$ pile-up jet control region

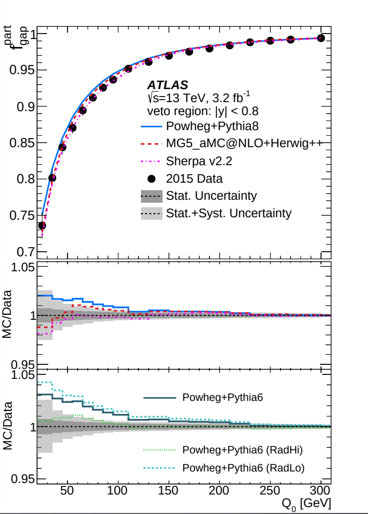
Unfolding: iterative Bayesian

- from observed distribution to truth distribution: strip off detector/pile-up effects

Observables

Gap fraction (here), p_T spectrum, jet multiplicity

- fraction of events with 0 additional jet of $p_T > X$ and $|\text{rapidity}| \in [Y,Z]$ over all events
- sensitive to 1st real emission by matrix element (pQCD) and parton shower (non-pQCD) and their matching
- upgraded version: allow additional jets, but p_T sum of additional jets $< X$, sensitive to all emission
- analysis ongoing (results here from last published analysis)



Heavy-flavor Additional Jet

Why heavy-flavor jet:

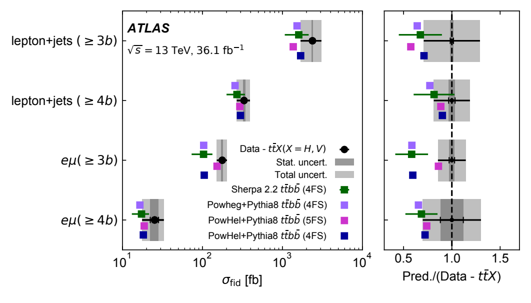
- multi-scale problem: p_T of jet and b mass: hard to predict/model, see Frank Siegert's talk in TOP2019

Feature on top of $t\bar{t}$ + jets measurement

- measure relative fraction of b/c/light-flavor jet out of all additional jets by fitting b-tagging score

Observed heavy flavor more than MC predictions

- JHEP04(2019)046
- systematics: b-tagging and fit of its score, $t\bar{t}$ modelling



Issues of Previous Analyses

Jet order swapping

- an observed subleading jet could be the leading truth jet due to resolution effect (20% case)
- previously discarded, now enter the unfolding

Optimization of unfolding algorithm

- comparison with other unfolding methods: e.g. TUnfold

New observables

- e.g. recoil of the leading additional jet wrt $t\bar{t}b\bar{b}$ system

Large systematics

- jet (to PFlow) and b-tagging (to new tagger) performance expected to be improved
- new $t\bar{t}$ modelling benchmarks

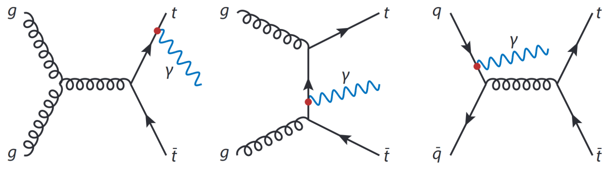
$t\bar{t}$ + Photon

JHEP11(2017)086, EPJC79(2019)382, ATLAS-CONF-2019-042
ATL-PHYS-PUB-2018-049

$t\bar{t}\gamma$ Process @LHC

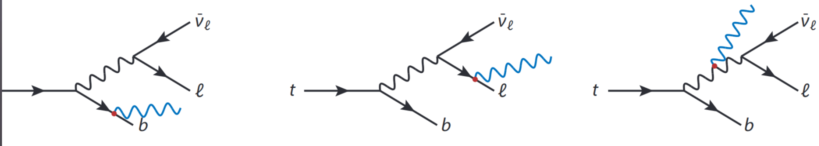
Radiative production

- a photon radiation on top of $t\bar{t}$ production: e.g. top quark, initial charged parton



Radiative decay

- photon radiation during top decay: e.g. W boson, final state charged particle



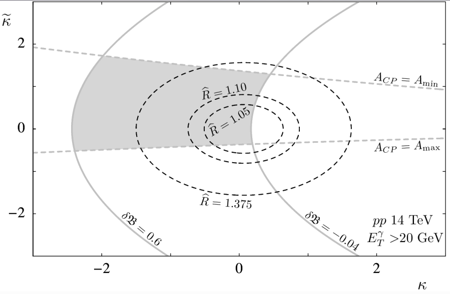
Why Measuring $t\bar{t}\gamma$

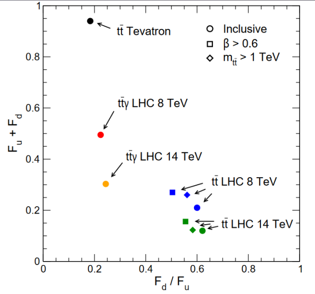
Probe the structure of $t\gamma$ coupling

- electric ($\tilde{\kappa}$) and magnetic (κ) dipole moments: PRD71(2005)054013 PRD87(2013)074015 (by $t\bar{t}\gamma/t\bar{t}$ ratio),
- EFT dimension-6 operators O^{33}_{uW}, $O^{33}_{uB\phi}$: NPB812(2009)181

Enhanced $t\bar{t}$ charge asymmetry in $t\bar{t}\gamma$ process

- JHEP04(2014)188, EPJC79(2019)189





Predictions & Experiments

Theoretical predictions

- LO calculation: PRD64(2001)094019, PRD71(2005)054013
- NLO QCD: PRD80(2009)014022, PRD83(2011)074013
- NLO EW: PLB766(2017)102
- $e\nu\mu\nu b\bar{b}\gamma$ in NLO QCD: JHEP10(2018)158

Experimental measurements

- evidence: CDF PRD84(2011)031104
- observation: ATLAS 7 TeV PRD91(2015)072007,
- measurements: CMS 8 TeV JHEP10(2017)006,
  ATLAS 8 TeV JHEP11(2017)086,
  ATLAS 13 TeV (36 fb^{-1}) EPJC79(2019)382,
  ATLAS 13 TeV (139 fb^{-1}) $e\mu$ channel ATLAS-CONF-2019-042

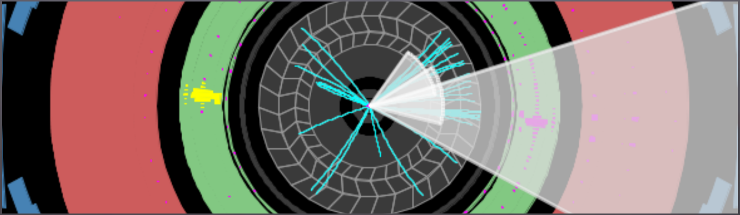
Analysis Overview

A lot in common with typical $t\bar{t}$ analysis

- similar event selection and background sources: e.g. W+jets ($W\gamma$+jets)to $t\bar{t}$ ($t\bar{t}\gamma$) analysis in single lepton channel

Prompt photon v.s. fake photon or non-prompt photon

- prompt photon directly from ME: e.g. $t\bar{t}\gamma$
- j$\rightarrow\gamma$ fake: jet misidentified as photon; photon from jet fragmentation or hadron decay (non-prompt photon)
- $e\rightarrow\gamma$ fake: electron misidentified as photon (missing track, failed track/calo. matching, fake photon-conversion vertex); photon from hard electron brem. (non-prompt photon)



Analysis Overview

No total $t\bar{t}\gamma$ cross-section

- soft/collinear photon radiation $\rightarrow$ divergence $\rightarrow$ only fiducial cross-section is well defined

Typical phase space

- lower bound to: photon p_T, ΔR (photon, charged final state particle), invariant mass (photon, charged final state particle)
- photon isolation: upper bound of p_T sum of nearby particles, Frixione isolation (PLB429(1998)369-374)

MC simulation

- full simulation (currently employed, only in LO): radiative production + radiative decay + their interference
- normalize to NLO theory calculation

Event Selection

$t\bar{t}$ leptonic decay channels were analyzed

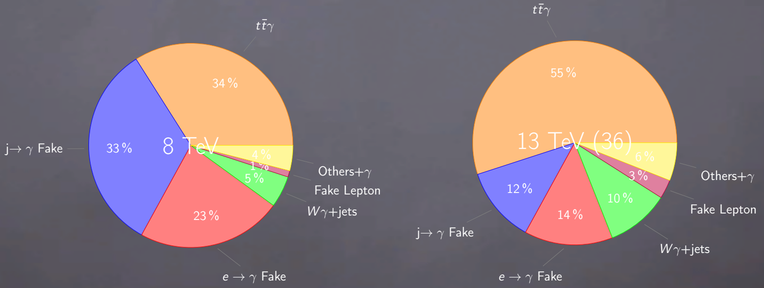
- event selection factorized into $t\bar{t}$ and photon (shown here) parts
- suppress fake photon and photon from non-$t\gamma$ vertex
- fiducial cross-section defined in similarly selected phase space at particle level (but removing Z-mass and MET cuts)

	8 TeV	13 TeV (36)	13 TeV (139)
Channel	single lepton	all leptonic	dilepton
Photon $p_T$cut	15 GeV	20 GeV	
$e \to \gamma$ in single electron	$\lvert m(e,\gamma) - m_Z \rvert > 5$ GeV		
$Z\gamma$ in dilepton		$\lvert m(\ell,\ell,\gamma) - m_Z \rvert > 5$ GeV	
Min. $\Delta R(\gamma, j)$	0.5	0.4	
Min. $\Delta R(\gamma, \ell)$	0.7	1.0	0.4

Event Yields

Single lepton channel: ∼3000 and ∼12000 events selected for 8 TeV and 13 TeV (36) analyses

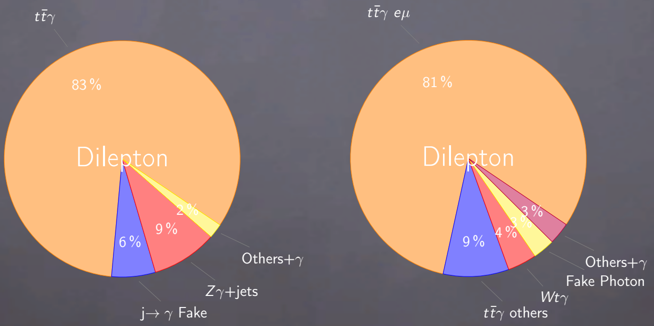
- large statistics, complicated backgrounds
- isolation not applied but fitted in 8 TeV → much larger j→ γ



Event Yields

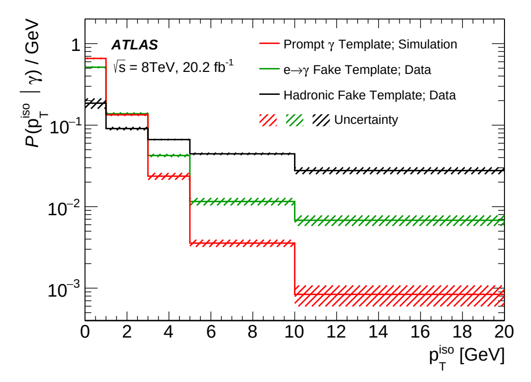
Dilepton channel: $\sim$ 900 and $\sim$3000 events selected for 13 TeV (36) and 13 TeV (139, $e\mu$) analyses

- smaller statistics, higher signal purity
- changed signal definition at 13 TeV (139, $e\mu$)



j→ γ Background (8 TeV)

Source: mainly from $t\bar{t}$ + jets, then any jet → γ



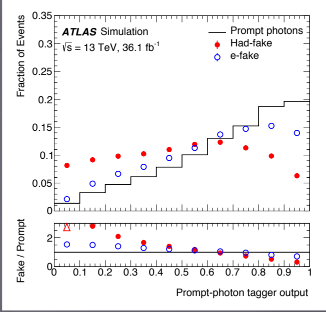
Isolation template method

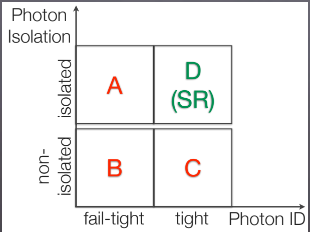
- j→ γ template from multi-jet data
- $e \to \gamma$ template from data-driven method
- signal template from MC

$j \to \gamma$ Background (13 TeV 36)

Prompt photon tagger (PPT)

- neural network (NN) trained with characteristic quantities of shower shape on calo.: e.g. lateral spread of energy deposit
- shape fed into another signal NN





Normalization by “ABCD“ method

- reverse shower-shape and/or isolation cuts to construct 3 $j \to \gamma$ control regions
- $D_{\text{est.}} = \frac{A_{\text{est.}}}{B_{\text{est.}}} \times C_{\text{est.}}$
- non-closure corrected by MC

$e \to \gamma$ Background

Mainly for single lepton channel and from $t\bar{t} \to e\ell$ and $Z \to ee$

Tag & probe method utilizing $Z \to ee$ decay

- tag: a well identified electron triggered the event
- probe: an electron or photon object back-to-back w.r.t the tag, and invariant mass of (tag,probe) close to Z peak
- fake rate: probe-photon / probe-electron
- non-Z background in one template: fit m(T,P): double-sided Crystal-ball (Z) + polynomial (non-Z)

8 TeV

- apply fake rate to another CR: replacing SR photon requirement by electron requirement

13 TeV (36): more decomposed/detailed study

- probe-photon composition studied with MC $\to$ $Z\gamma$ subtracted
- fake rate data/MC: 0.8$\sim$2.1, large correction in central eta region

$V\gamma$+jets and Fake Lepton

$V\gamma$+jets ($V = W/Z$)

- $W\gamma$+jets in single lepton channel: control region in 8 TeV while floated in 13 TeV (36)
- $Z\gamma$ from MC but checked in dedicated validation regions (only 13TeV 36)

Fake lepton

- source: lepton from heavy flavor decay in jet, jet misidentification
- single lepton channel: select loosely and tightly identified leptons

$$N^{\text{loose}} = N^{\text{loose}}_{\text{real}} + N^{\text{loose}}_{\text{fake}}$$

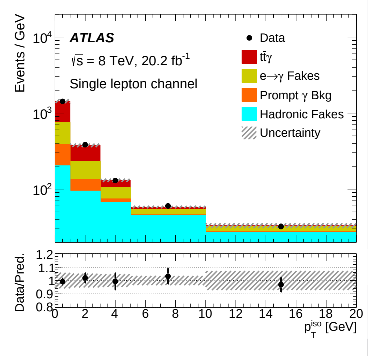
$$N^{\text{tight}} = N^{\text{tight}}_{\text{real}} + N^{\text{tight}}_{\text{fake}} = \epsilon_{\text{real}} N^{\text{loose}}_{\text{real}} + \epsilon_{\text{fake}} N^{\text{loose}}_{\text{fake}}$$

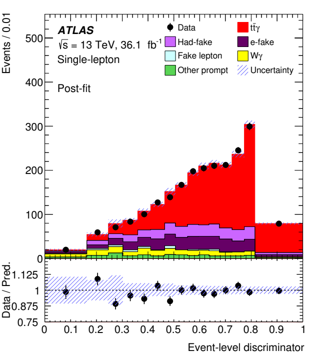
- with measured ϵ_{real} and ϵ_{fake}, solve equation for $N^{\text{tight}}_{\text{fake}}$
- 8 TeV with assumed 50% systematics $\rightarrow$ 13 TeV with dedicated sys. study
- dilepton channel: one true + one fake, negligible, checking same-charge lepton-pair events

Fit in Single Lepton Channel

8 TeV fit isolation, 13 TeV fit NN trained with

- jet multiplicity, jet p_Ts, b-tagging scores, MET
- PPT, photon-lepton invariant mass

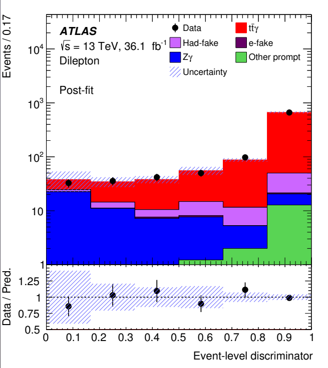


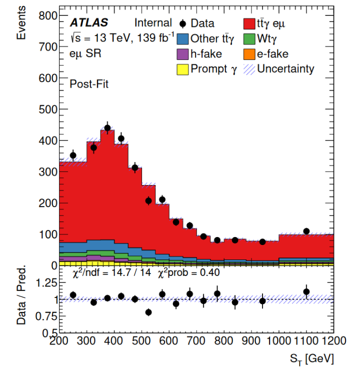


Fit in Dilepton Channel

13 TeV (139) fit S_T, 13 TeV (36) fit on NN trained with Extract fiducial cross-section by fitting NN trained with

- jet multiplicity, jet p_Ts, b-tagging scores, MET
- dilepton invariant mass



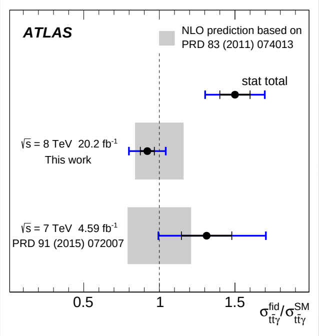


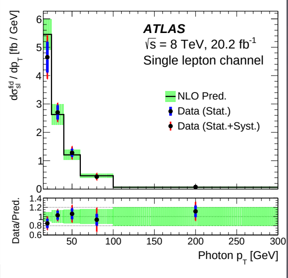
Cross-sections (8 TeV)

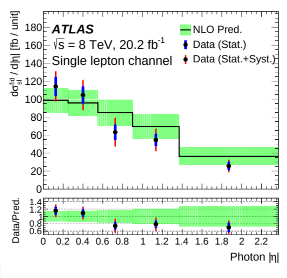
Measured v.s. NLO theory (PRD83(2011)074013)

- $\sigma_{\text{fid}}^{\text{SL}} = 139 \pm 7(\text{stat.}) \pm 17(\text{sys.})$ fb
- systematics: fake photon, JES, $W\gamma$

Differential cross section measured via bin-by-bin unfolding



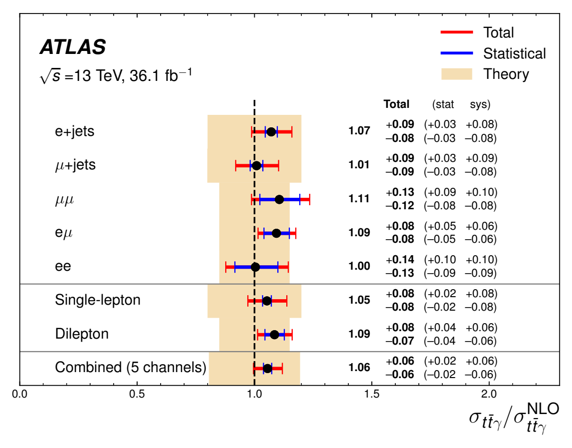




Fiducial Crosssection (13 TeV)

Measured (36 fb^{-1}) v.s. NLO theory (PRD83(2011)074013)

- $\sigma_{\mathrm{fid}}^{\mathrm{SL}} = 521 \pm 9(\mathrm{stat.}) \pm 41(\mathrm{sys.})$ fb
- $\sigma_{\mathrm{fid}}^{\mathrm{DL}} = 69 \pm 3(\mathrm{stat.}) \pm 4(\mathrm{sys.})$ fb
- systematics: JES, $t\bar{t}\gamma/t\bar{t}$ modelling, Pileup, Lumi., PPT in SL



Fiducial Crosssection (13 TeV)

139 fb^{-1} $e\mu$ v.s. 36 fb^{-1} $e\mu$

- compare directly with $e\nu\mu\nu b\bar{b}\gamma$ NLO calculation in JHEP10(2018)158: 1. excluded signal with a e/μ from prompt τ decay; 2. unfold to parton level instead of particle level
- $t\bar{t}\gamma$ in non-$e\mu$ channels and $Wt\gamma$ as dominant backgrounds

Fiducial region: strictly $e\mu$, not including τ lepton decay

- similar p_T/η cuts on e/$\mu/\gamma/b/\bar{b}$-jets as before
- $\Delta R(\ell, \gamma)$, $\Delta R(e, \mu)$, $\Delta R(\ell, b/\bar{b}\text{-jets})$, $\Delta R(\text{b-jet}, \bar{b}\text{-jet}) > 0.4$

Fiducial cross-section

- measured: $44.2 \pm 0.9(\text{stat})^{+2.6}_{-2.4}(\text{sys})$ fb
- theory: $39.50^{+0.56}_{-2.18}(\text{scale})^{+1.04}_{-1.18}(\text{PDF})$ fb
- dominant systematics: MC modelling of $t\bar{t}\gamma$ and $Wt\gamma$

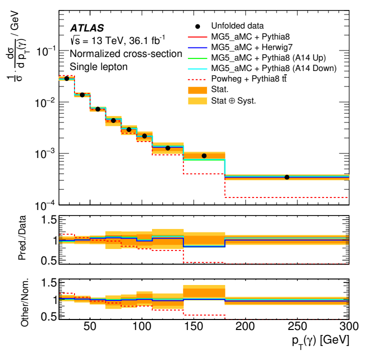
Notes

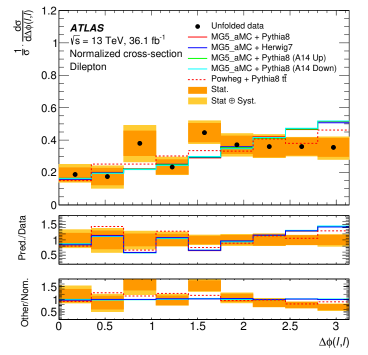
- theory includes $Wt\gamma$ and non-resonant, while measurement is $t\bar{t}\gamma$ only

Differential Cross-section

13 TeV 36 fb^{-1}: unfold pre-fit observables with Iterative Bayesian method

- photon p_T and $|\eta|$, min. $\Delta R(\ell, \gamma)$, dilepton $\Delta\phi$ and $\Delta\eta$
- compared to signal MC + its PS/ISR variations
- $t\bar{t}\gamma$ by $t\bar{t}$ + parton shower (PS) has softer p_T

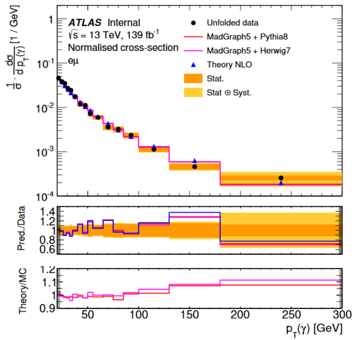


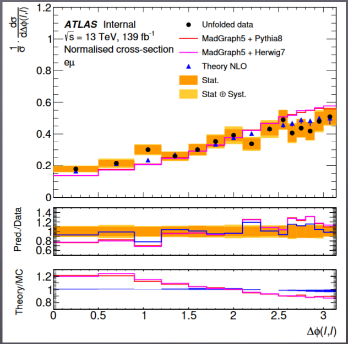


Differential Cross-section

13 TeV 139 fb^{-1}: unfold pre-fit observables with Iterative Bayesian method

- photon p_T and $|\eta|$, min. $\Delta R(\ell, \gamma)$, dilepton $\Delta\phi$ and $\Delta\eta$
- compared to signal MC + its PS variations and NLO theory including non-resonant/off-shell

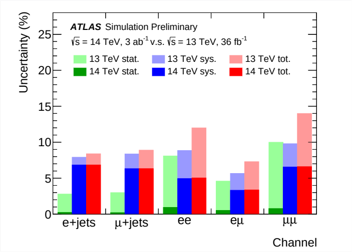


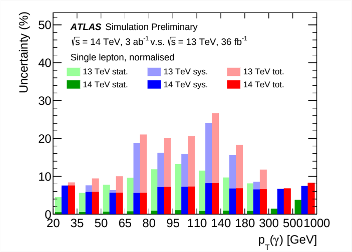


HL-LHC Projection

HL-LHC: 14 TeV 3000 fb^{-1}

- projected from 13 TeV 36 fb^{-1} analysis
- same experimental and half theoretical uncertainties
- also the first $t\bar{t}\gamma$ EFT interpretation: limit an order of magnitude lower than current limit





$t\bar{t}$ as Background

PRD92(2015)012006, PLB763(2016)114

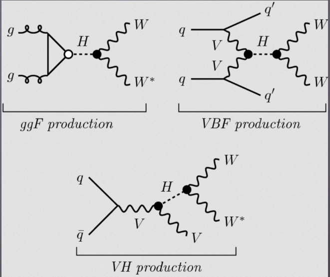
HWW Analysis

Signal: $H \to WW^* \to \ell\nu\ell\nu$

- 2 OS leptons and MET, 2 fwd jets (if VBF)
- observe Higgs, probe its properties: spin, off-shell coupling

Sub-channels and backgrounds

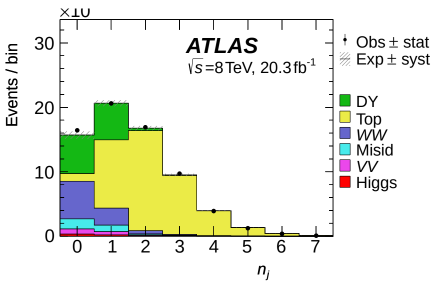
- $0/1/\geq 2$j, same/different flavor leptons, ggF/VBF enriched
- significance dominated by 0j DF leptons
- backgrounds: *WW*, top, non-prompt and fake leptons, diboson, DY

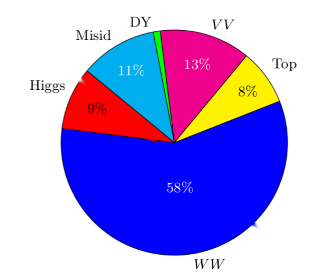


Top Background in 0J $e\mu$

Small background but comparable as signal → its precision limit the lower limit of signal measurement precision

- estimation: Jet Veto Survival Probability (JVSP) method
- MC based sys of > 20% v.s. JVSP sys of $\sim$ 8%





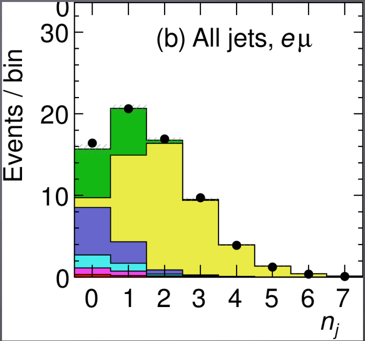
Definition of JVSP

JVSP ≡ Jet Veto Survival Probability

- Probability of top quark background surviving jet veto
- Jet veto: veto event which has any jet with $p_T > 25$ GeV

$$N_{\mathrm{top,0j}} = N_{\mathrm{top,inc.}} \times \mathrm{JVSP}$$

- $N_{\mathrm{top,inc.}}$, jet inclusive top quark event, easy to control
- $N_{\mathrm{top,0j}}$, 0 jet top quark event, quantity of interest, sensitive to theoretical and experimental errors because of JVSP



Formulation of JVSP

Leading Order (LO) picture

$$\text{JVSP} \equiv P_2 = P_{b1} \times P_{b2} \equiv P_1^2$$

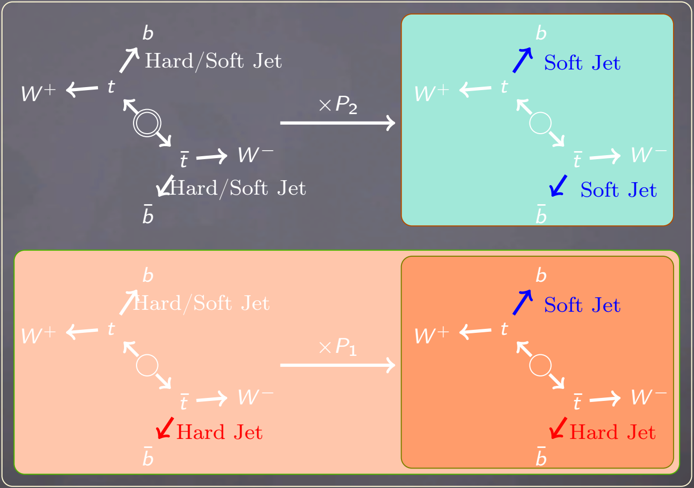
- For convenience, JVSP is denoted as P_2
- P_{b1} and P_{b2} are the probabilities of the 1st and 2nd b-jet to have $p_T < 25$ GeV
- Assume no correlation (2% precision) between P_{b1} and P_{b2} $\rightarrow$ they are denoted as P_1

P_1 can be measured with data

- Denote jet with p_T below/above 25 GeV as soft/hard jet
- 1 hard jet (also b-tagged) as tag of top quark event, the other jet as probe

$$P_1 = \frac{N_{1hard+1soft}}{N_{\geq 1hard}}$$

Illustration of P_1/P_2



Beyond LO of JVSP

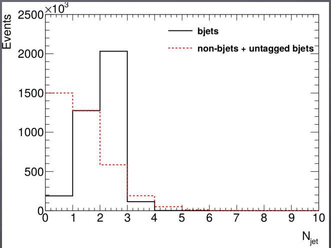
At beyond LO, QCD radiation modifies JVSP (P_2)

$$P_2 = P_1^2 \times P_r$$

- P_r: probability of the rest jets to be soft, predicted by MC

$$P_r^{MC} = \frac{P_2^{MC}}{P_1^{MC,2}}$$

$$\begin{aligned} P_2^{data} &= P_1^{data,2} \times P_r^{MC} \\ &= P_2^{MC} \times \left(\frac{P_1^{data}}{P_1^{MC}}\right)^2 \end{aligned}$$



Extend P_1 definition to absorb P_r to reduce residual dependency on MC

Systematics of JVSP

Top quark modelling systematics (of $\frac{P_2^{MC}}{P_1^{MC,2}}$)

- 3.3% parton shower (PS) uncertainty: fHerwig v.s. Pythia6
- 1.2% matrix element (ME) uncertainty: POWHEG v.s. MC@NLO
- 1.6% PDF uncertainty: CT10 v.s. 1) CT10 eigenvector error sets 2) MSTW 3) NNPDF
- 0.7% QCD scale uncertainty, $t\bar{t}/Wt$ interference uncertainty, ...

Other systematics

- 4.6% experimental uncertainty, dominated by jet energy scale/resolution (JES/JER)
- 1.5% non-top event subtraction uncertainty

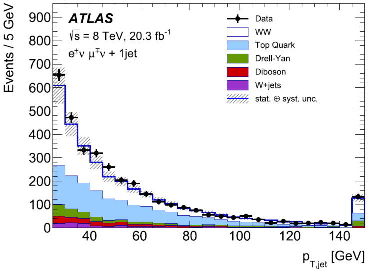
Other checks

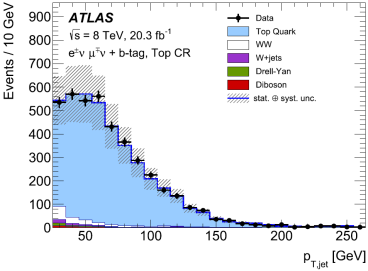
- Varying 1) definition of the probing jet 2) exponent of 2, ...
- Results are stable against these checks

WW+1j Measurement

Test SM

- pQCD calculation available for NLO+NNLL (by the time)
- 1.4σ tension of obs./pred. total xsec. (from 0 jet fiducial)
- top background largest even after *b*-veto
- "in-situ" method for top background: 5% sys





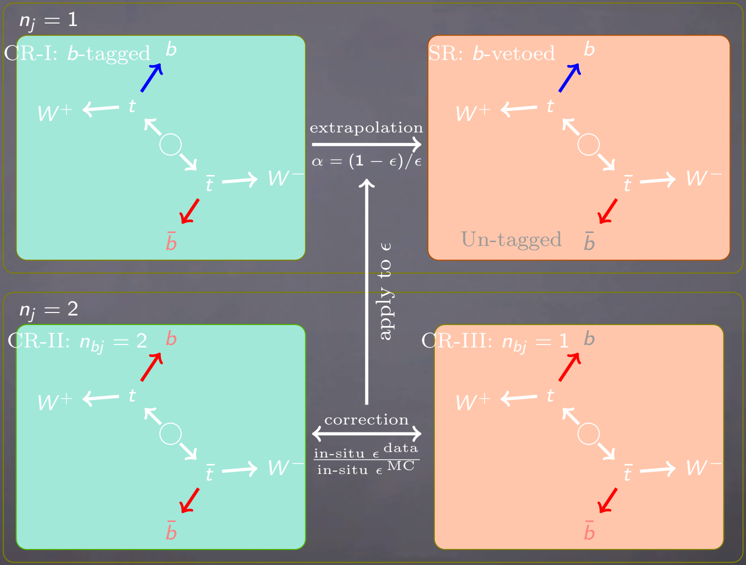
"In-situ" Method

Measure the b-tagging efficiencies in the situation

$$N^{\text{bveto}}_{\text{after}} = N^{\text{bveto}}_{\text{before}} \times \epsilon_{\text{bveto}}$$
$$= \frac{N^{\text{btag}}_{\text{after}}}{\epsilon_{\text{btag}}} \times (1 - \epsilon_{\text{btag}})$$

- reverse b-veto to form top control region: $N^{\text{btag}}_{\text{after}}$
- measure ϵ_{btag} from $2b/2$jets and $1b/2$jets regions
- ϵ_{btag} measured in 2 jets region $\rightarrow$ bias of applying to 1 jet region considered

Illustration of “In-situ“



Summary

Overview of active top-quark related topics

- inclusive/fiducial/differential cross-sections
- top properties: charge, mass, spin
- $t\bar{t}$ event topology: charge asymmetry
- ...

Detailed presentation of

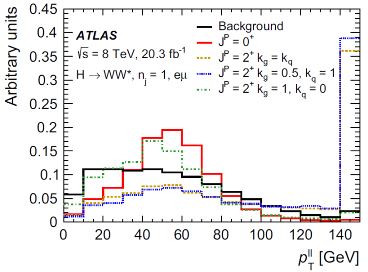
- ongoing: $t\bar{t}$ + (heavy-flavor) jet, important for almost all top-related analyses, plan to improve precision by addressing issues not considered in previous round
- $t\bar{t}\gamma$: from 8 TeV to 13 TeV full data set, close communication with theorists, far more advanced than CMS, precision from 28% at observation time down to 6%
- $t\bar{t}$ background in HWW/WW analyses: phase space of soft b-jet

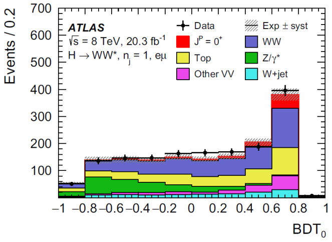
Backup

BDT for Higgs Spin in 1 Jet Channel

Four inputs: $p_T^{\ell\ell}$, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T

- 2-D BDTs: spin-0 v.s. backgrounds and spin-2 v.s. backgrounds
- 1 jet channel: non-universal coupling spin-2 models,





Jet Inclusive Off-shell Higgs Signal

Enhanced cross-section

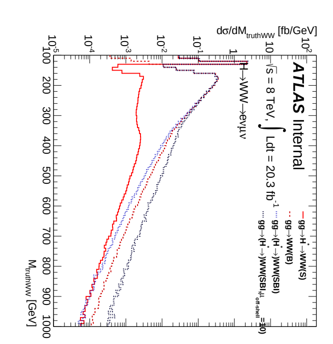
- phase space opened at 2* W mass
- sizable negative interference with non-resonant WW

Higgs decay width

- Combine on-shell and off-shell measurements

$$\sigma_{\text{on}} \propto \frac{\kappa^4}{\Gamma} \;\; \& \;\; \sigma_{\text{off}} \propto \kappa^4$$

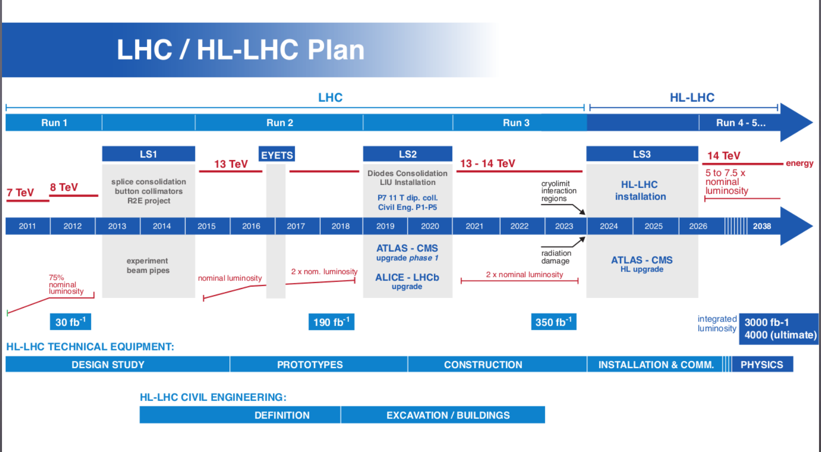
$$\Rightarrow \Gamma \propto \frac{\sigma_{\text{off}}}{\sigma_{\text{on}}}$$



Reference

top MC modelling:
https://indico.cern.ch/event/792576/contributions/3405534/

LHC Schedule



ATL-PHYS-INT-2014-037

In $n_j = 0$ Channel

Method	JVSP	Template	Extrapolation	In-situ
Methodology	$N_{\rm top}^{\rm inc.} \times {\rm JVSP}_{\rm SR}^{\rm MC} \times f_{\rm corr}$ $f_{\rm corr} = (\frac{{\rm JVSP}_{\rm CR}^{\rm data}}{{\rm JVSP}_{\rm CR}^{\rm MC}})^2$	CR $\rightarrow T_{n_j}(f_{\rm norm}^{\rm non\text{-}top})$ fit to n_j-inc SR	$\alpha = \frac{1}{\epsilon_{\rm SR}^{\rm MC}}$ $\leftarrow$	$\epsilon_{\rm SR}^{\rm MC}$ corrected with $\frac{\epsilon_{\rm CR}^{\rm data}}{\epsilon_{\rm CR}^{\rm MC}}$
Stat.	2.2	7.3	6.8	7.3
Exp.	4.6 (JES/JER)	17.5 (mis-b-tag)	13.6 (mis-b-tag)	9.0 (mis-b-tag)
Theo.	3.8 (PS)	4.4 (ME)	3.6 (ME)	1.9 (PDF)
Non-top	1.5	2.3	1.8	2.0
Total	6.5	19.6	15.7	11.9

- uncertainties in the table are evaluated at jet-veto or b-veto cut stage, slightly different from coupling paper
- JVSP has least stat. error; others much larger due to they use the small top CR: $n_j = 0 \& n_{bj[20,25]} \neq 0$
- JVSP not sensitive to b-tag, while others do
- In-situ has least theo. uncert.: large cancellation of systematics between $\epsilon_{\rm SR}^{\rm MC}$ and $\epsilon_{\rm CR}^{\rm MC}$
- Non-top includes WW / Z+jets with assumed 6% / 5% uncertainty
- Overall, JVSP suffers from much smaller uncertainty