

Production of Top Pair Events with Additional Radiation

Christian Schwanenberger

DESY

formerly: University of Manchester

on behalf of the ATLAS Collaboration



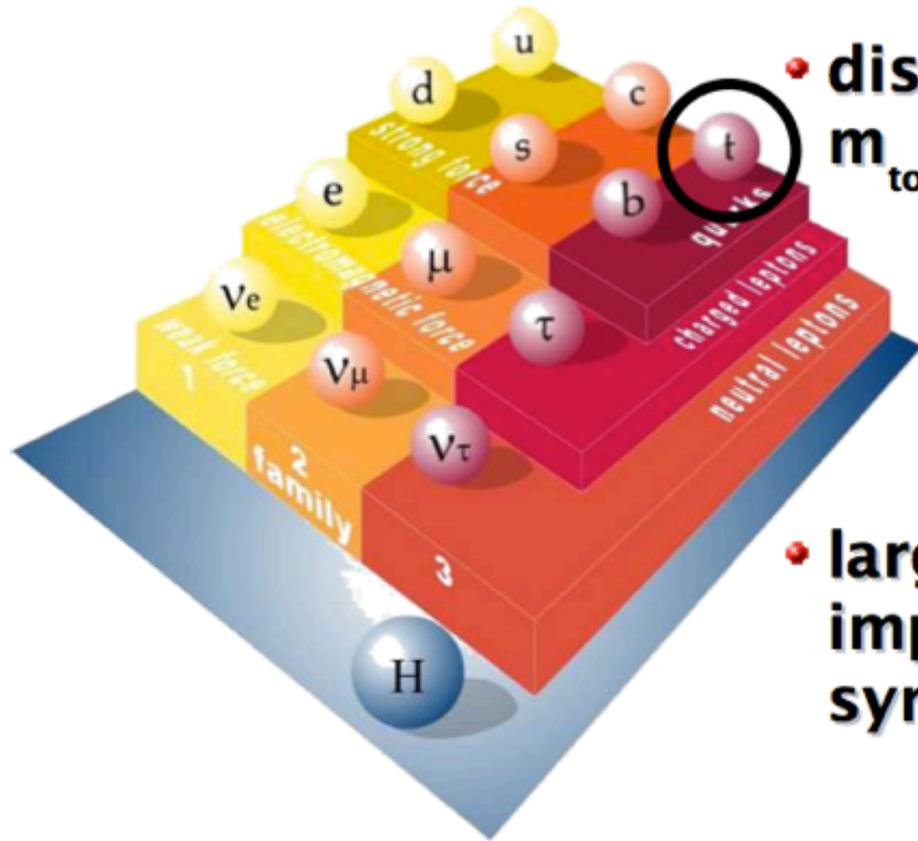
**XXIII. International Workshop on DIS and
Related Subjects: DIS 2015**

**MANCHESTER
1824**

Dallas, April 29, 2015

 **THE ROYAL
SOCIETY**
CELEBRATING 350 YEARS

The Top Quark

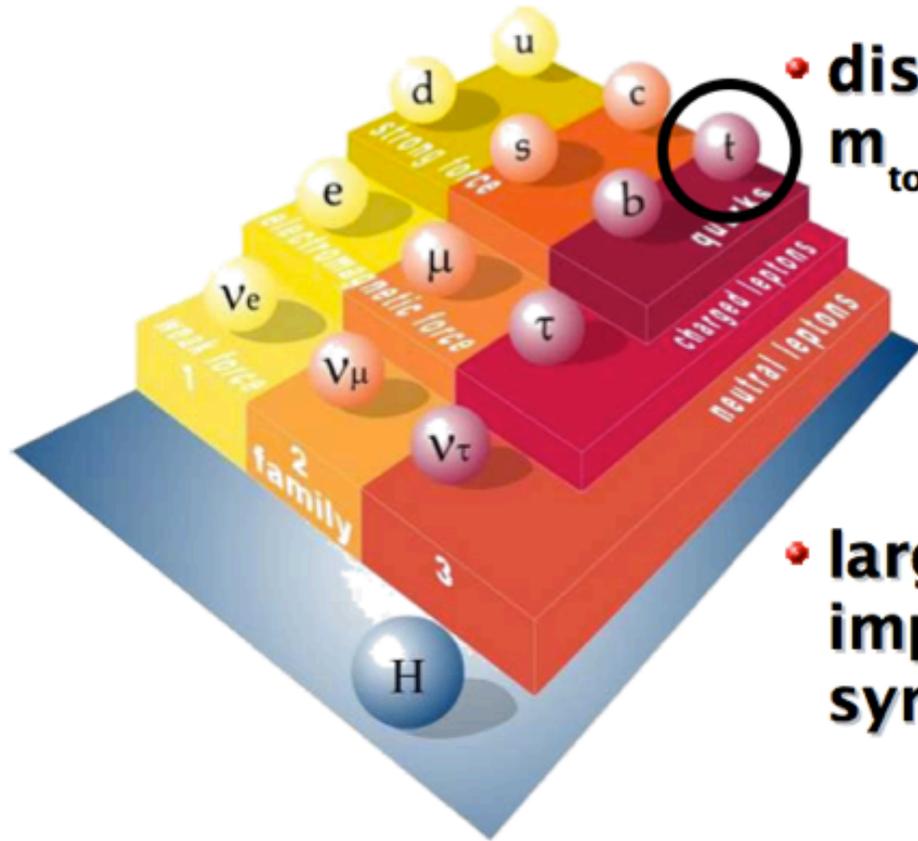


- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: $m_{\text{top}} \sim$ gold nucleus

- large coupling to Higgs boson ~ 1 : important role in electroweak symmetry breaking?

Is the top quark the particle as predicted by the SM?

The Top Quark



- needed as isospin partner of bottom quark
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- large coupling to Higgs boson ~ 1 : important role in electroweak symmetry breaking?

Is the top quark the particle as predicted by the SM?

- top quark and strong and EW interaction
- $t\bar{t}$ +jets, $t\bar{t}\gamma$, $t\bar{t}Z$, $t\bar{t}W$ production

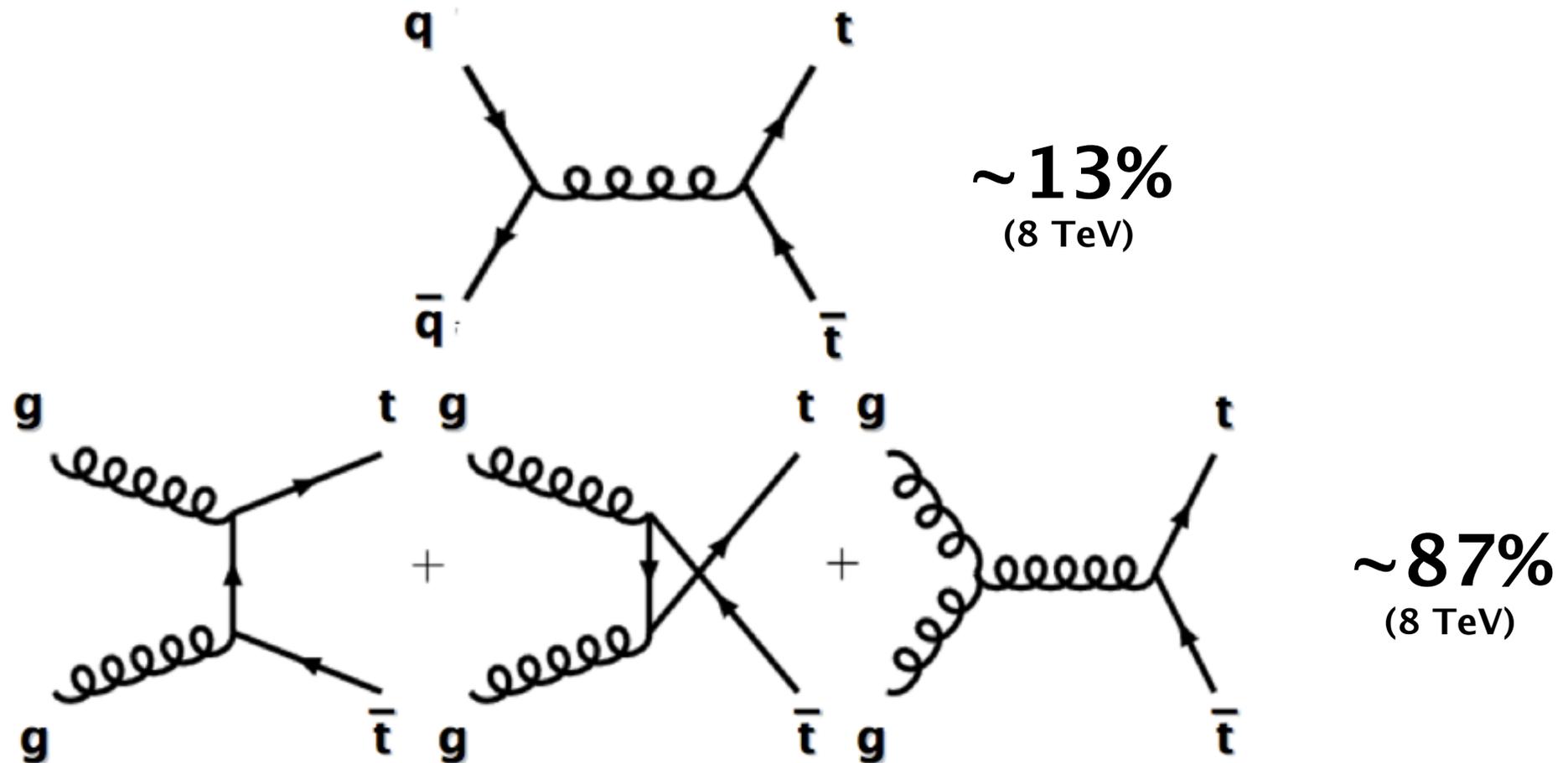
Content

Introduction
 $t\bar{t}$ +jets
 $t\bar{t}$ +gamma
 $t\bar{t}Z$, $t\bar{t}W$
Summary

Content

Introduction

Top Quark Pair Production



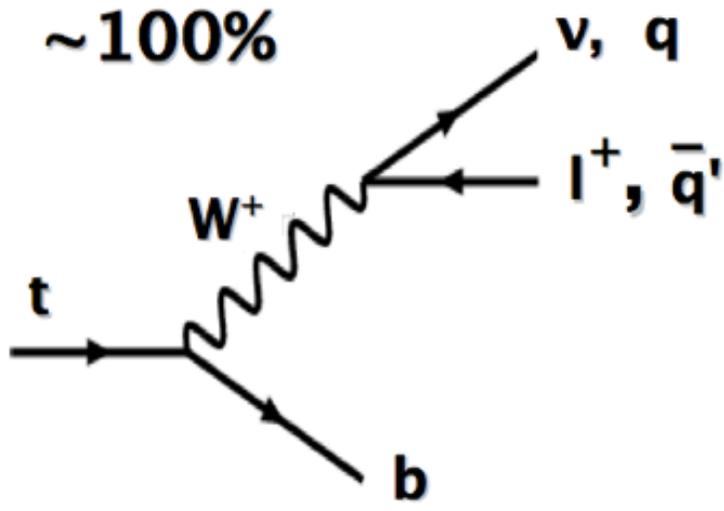
Top Quark Pair Signatures

τ 's
14%

alljets
46%

Top Pair Decay Channels

top decay:



- high p_T leptons, missing E_T
- jets
- b-jets

$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$		tau+jets
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
e^-	$e\tau$	$e\mu$	$e\tau$	electron+jets	
W^- decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$

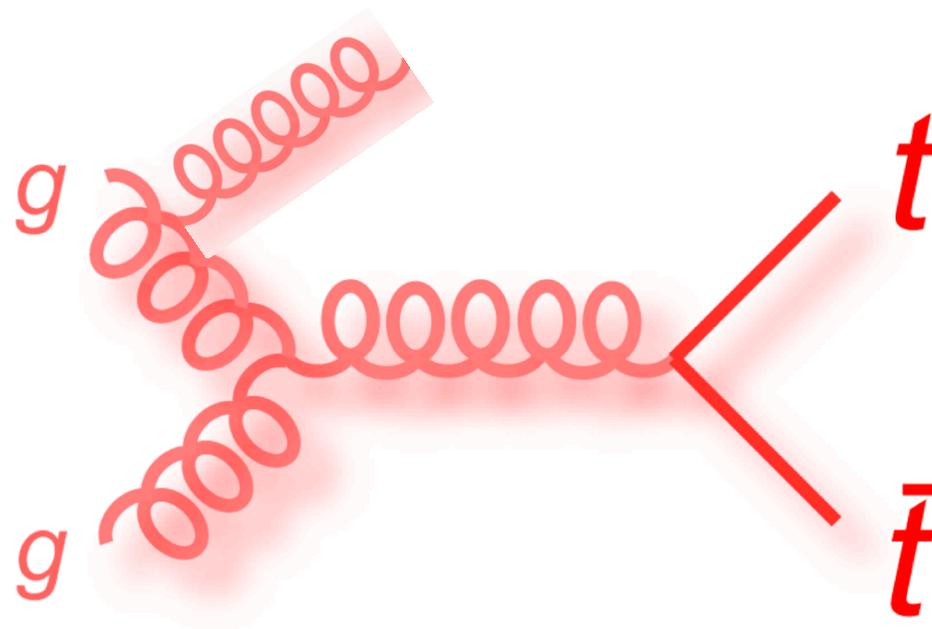
dilepton (e/ μ)
6%

e/ μ +jets
34%

Content

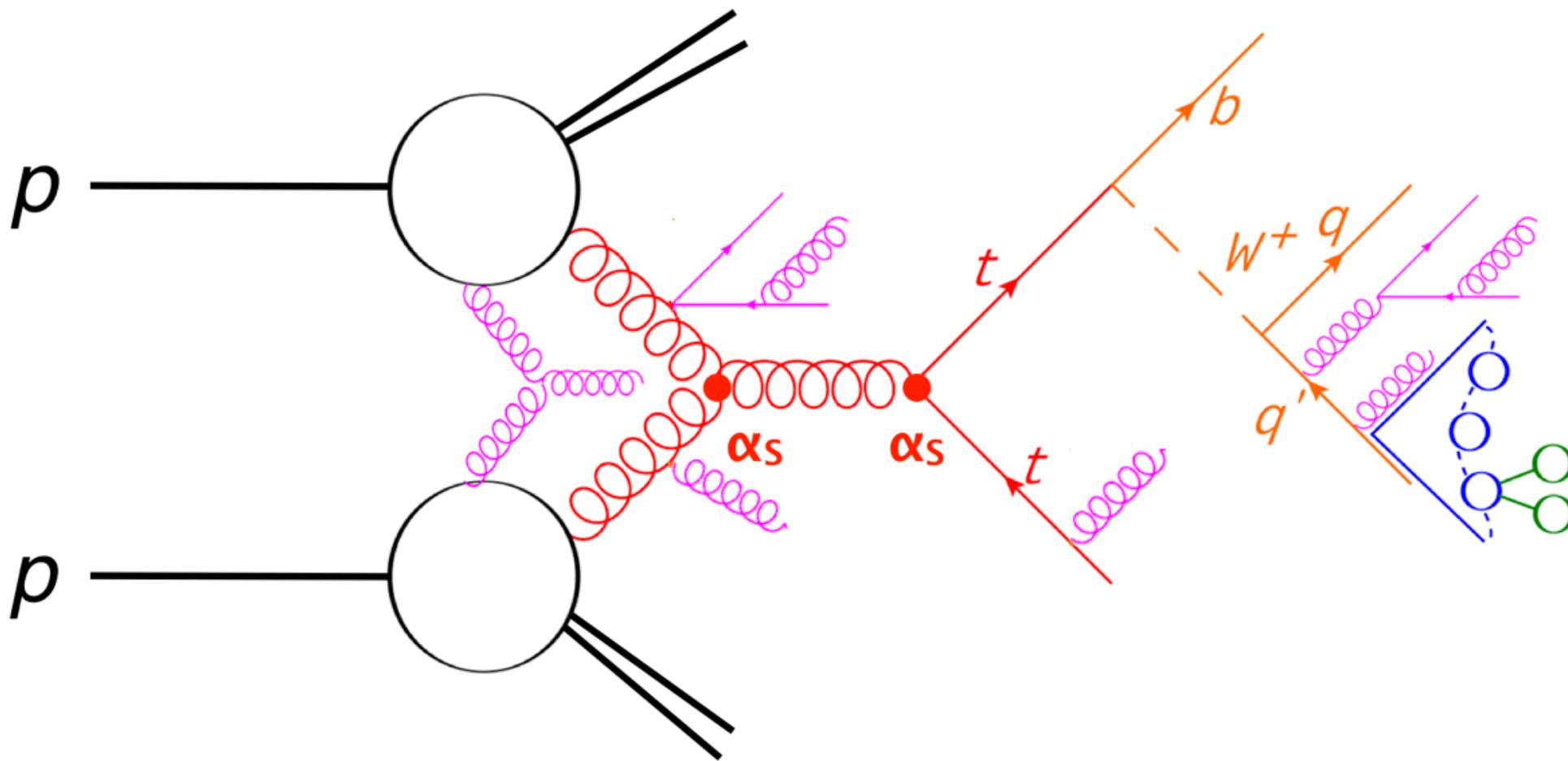
Introduction

$t\bar{t}$ +jets



“Revolution” in Phenomenology

- LO QCD+parton shower generators
Pythia, Herwig, ...

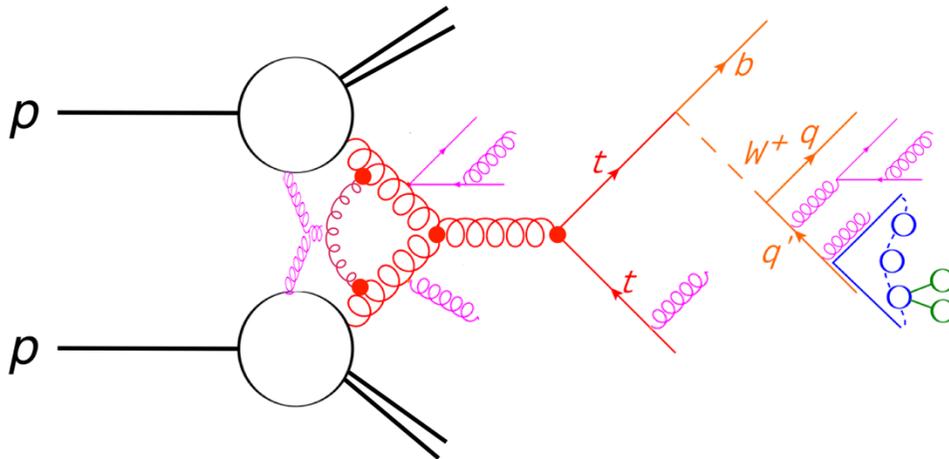
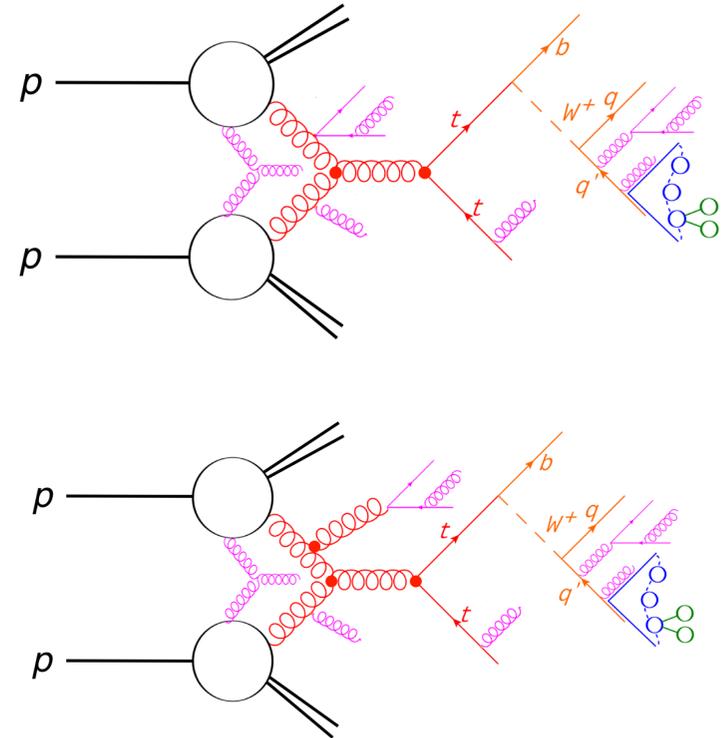


“Revolution” in Phenomenology

- LO QCD+parton shower generators
Pythia, Herwig, ...

- LO multileg generators matched with parton shower
Alpgen+Pythia, Alpgen+Herwig, ...

- NLO+parton shower generators
Powheg+Pythia, MC@NLO+Herwig, ...



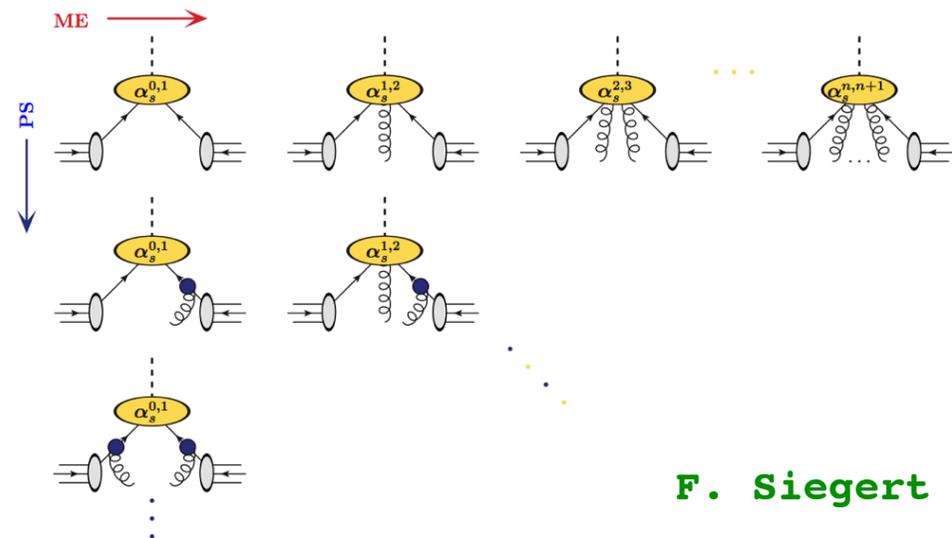
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- NLO+LO multileg generators matched with parton showers



F. Siegert

“Revolution” in Phenomenology

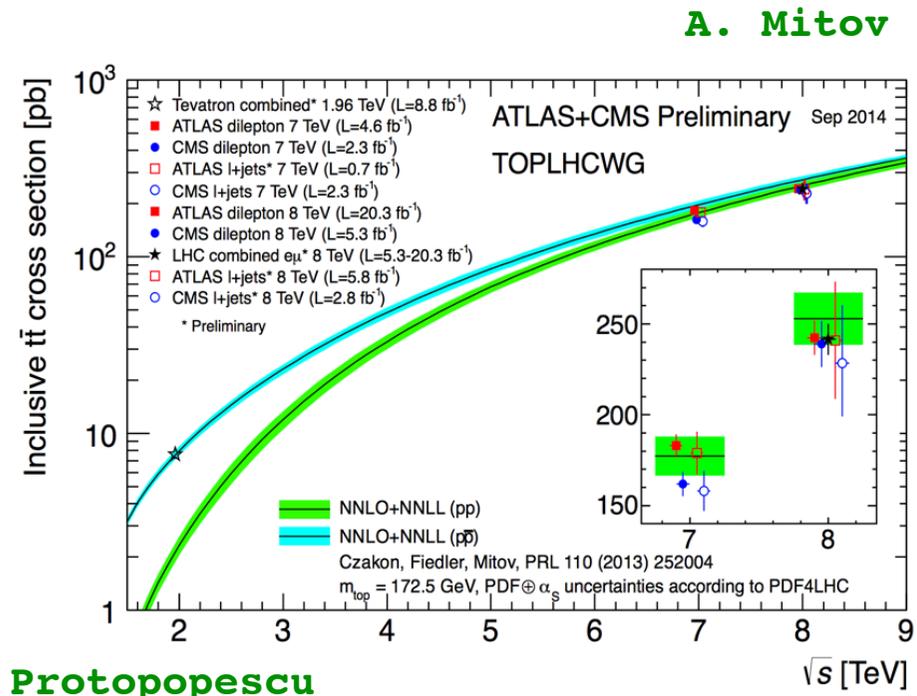
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- NNLO QCD calculations
normalisation



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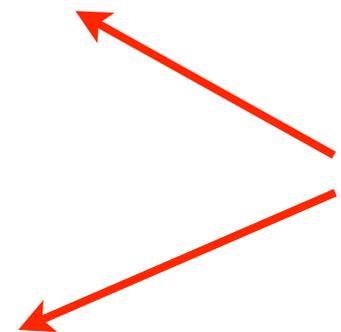
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**this analysis:
 $t\bar{t}$ +jets**

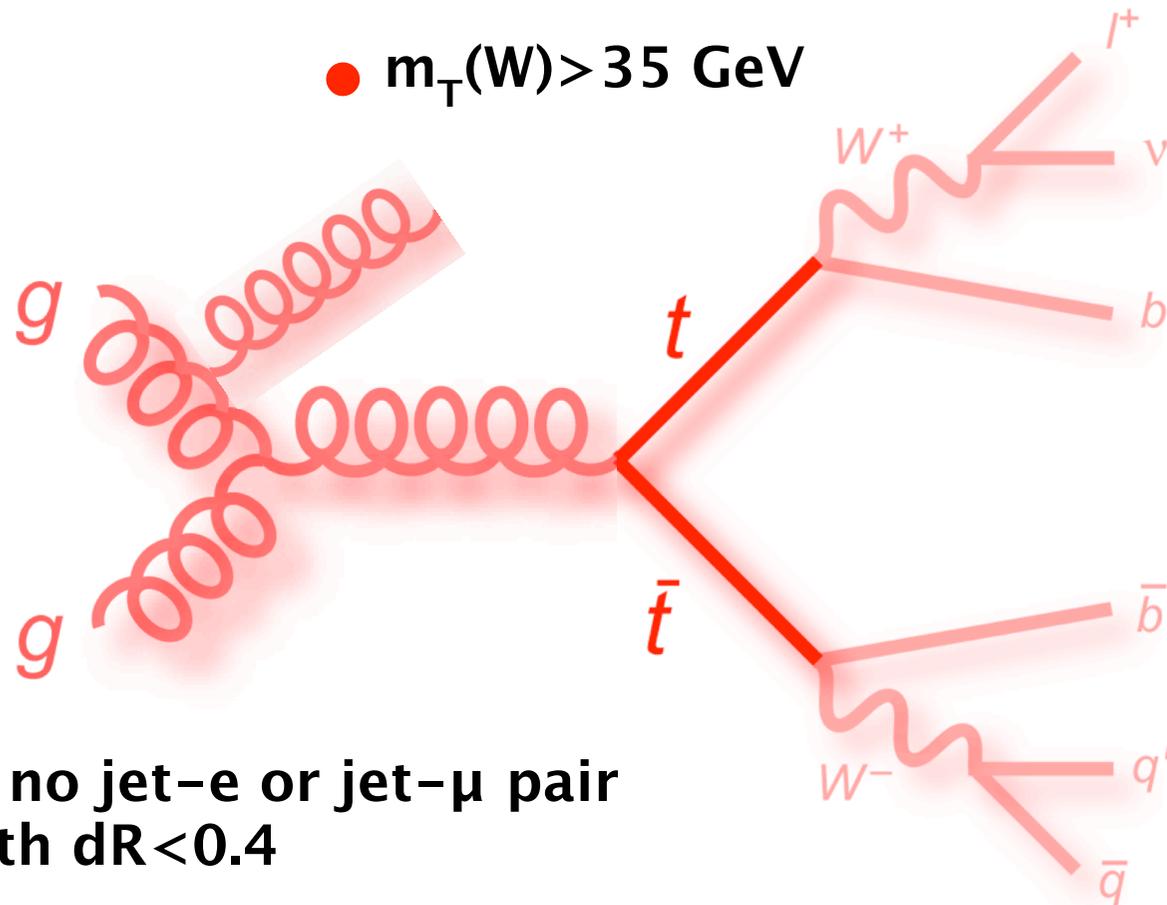


**very important
measurements to study
higher orders QCD in a
top quark environment!**

Fiducial Kinematic Phase Space

- no additional e or μ with $p_t > 15$ GeV & $|\eta| < 2.5$

- $m_T(W) > 35$ GeV



- no jet- e or jet- μ pair with $dR < 0.4$

- no jet-jet pair with $dR < 0.5$

- exactly one isolated e or μ with $|\eta| < 2.5$, $p_t > 25$ GeV (including clustering with γ in cone $\Delta R = 0.1$)

- $E_{t,miss} > 30$ GeV

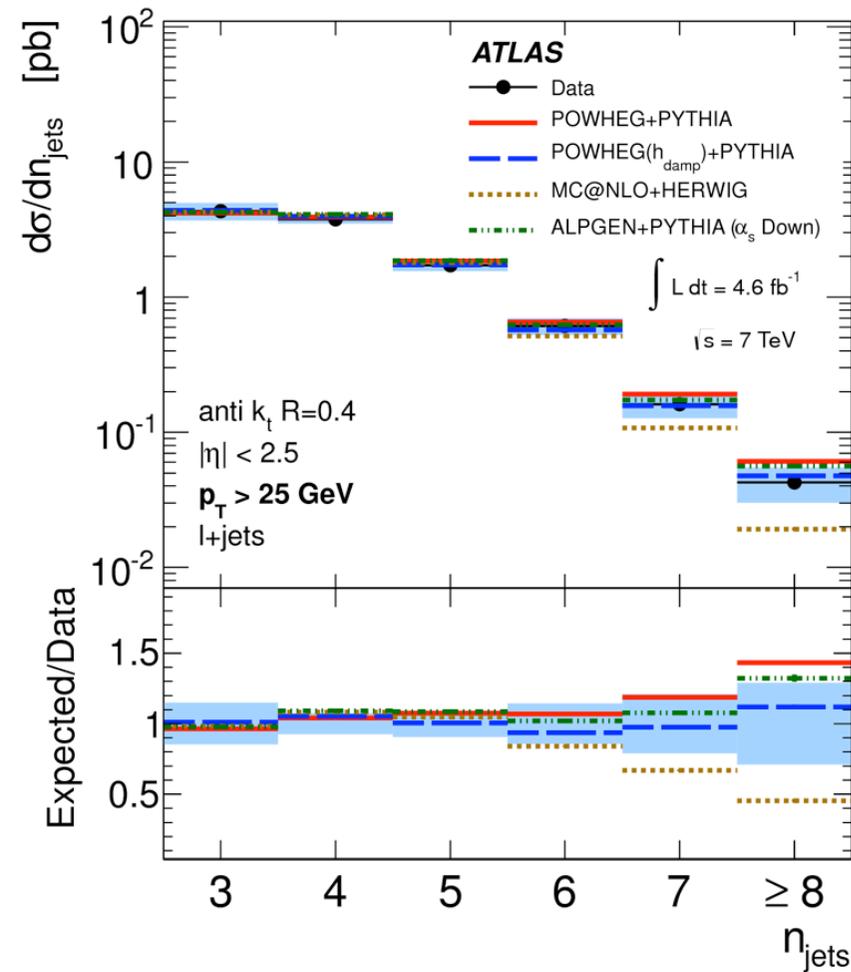
- ≥ 3 Jets with $p_t > 25$ GeV & $|\eta| < 2.5$ incl. ≥ 1 b-tagged jet

- jets: anti- k_t $R = 0.4$, clusters all but prompt particles (i.e. e , μ , ν from hadronic decays are inside jets)

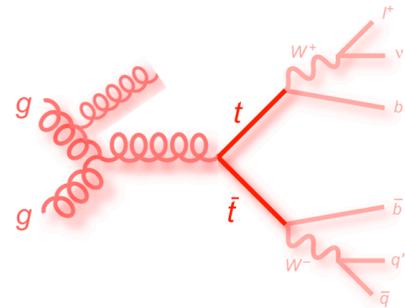
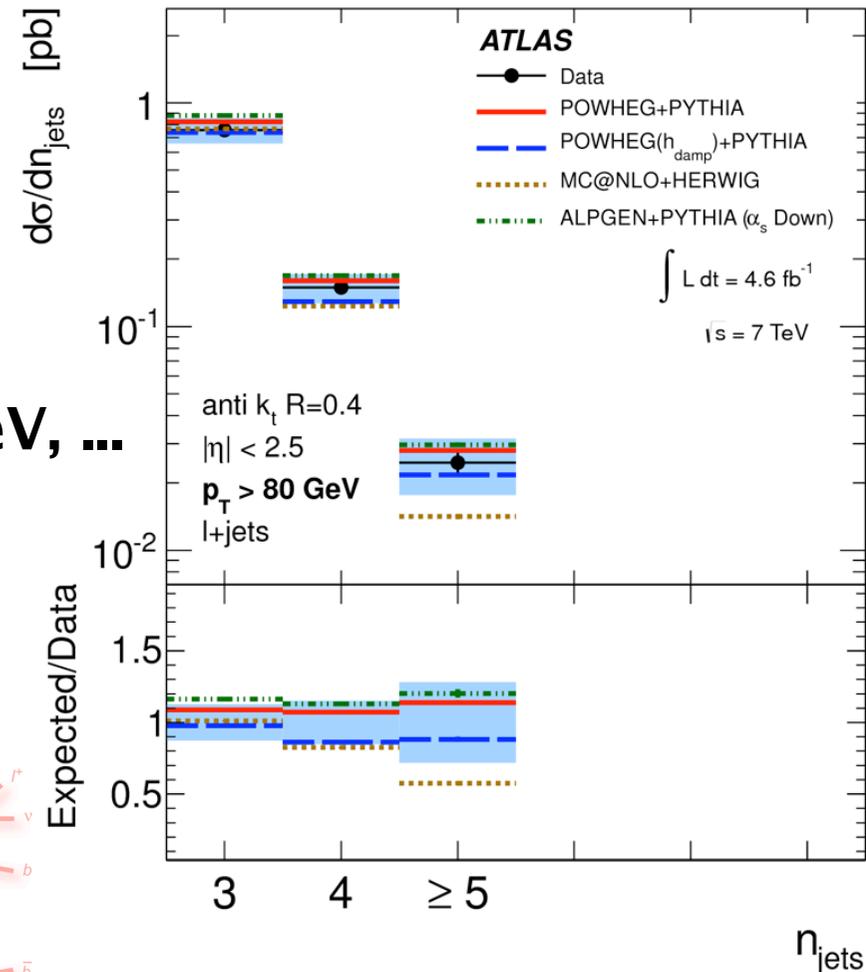
- background subtraction
- corrections to particle level
- reduced dependence on MC model

Jet Multiplicities

- uncertainties dominated by JES and MC modeling of QCD radiation



... 40, 60 GeV, ...

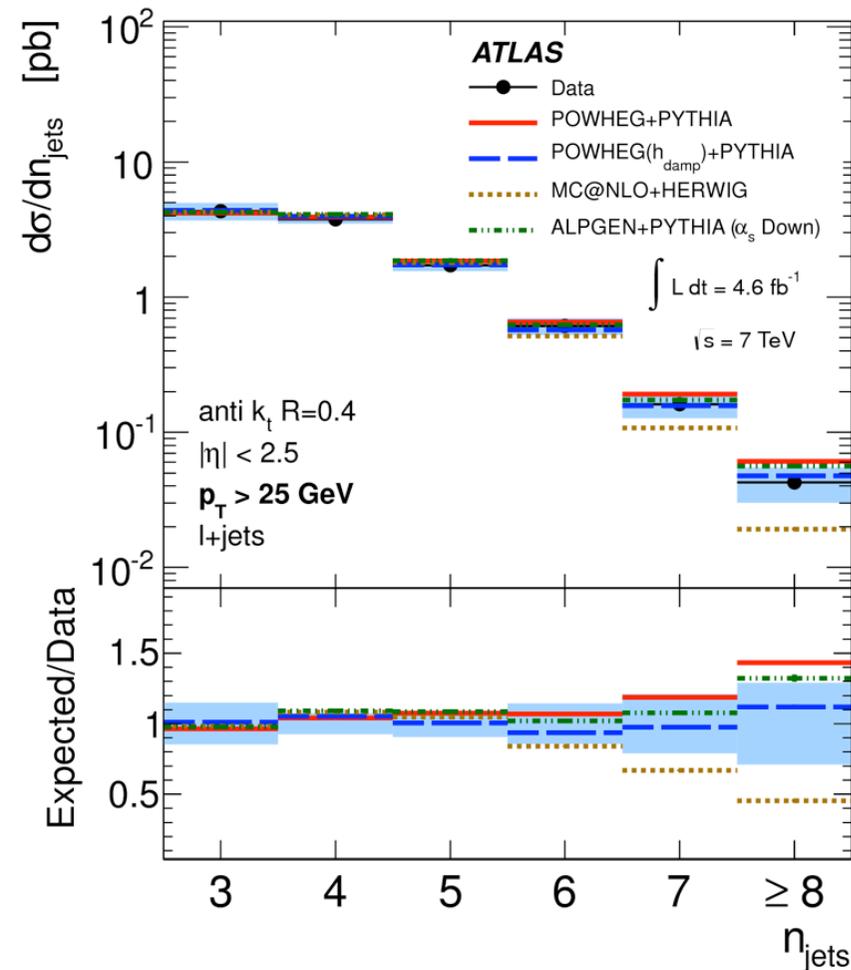


JHEP 1501, 020 (2015)

→ high sensitivity on higher order QCD modeling of MC generators

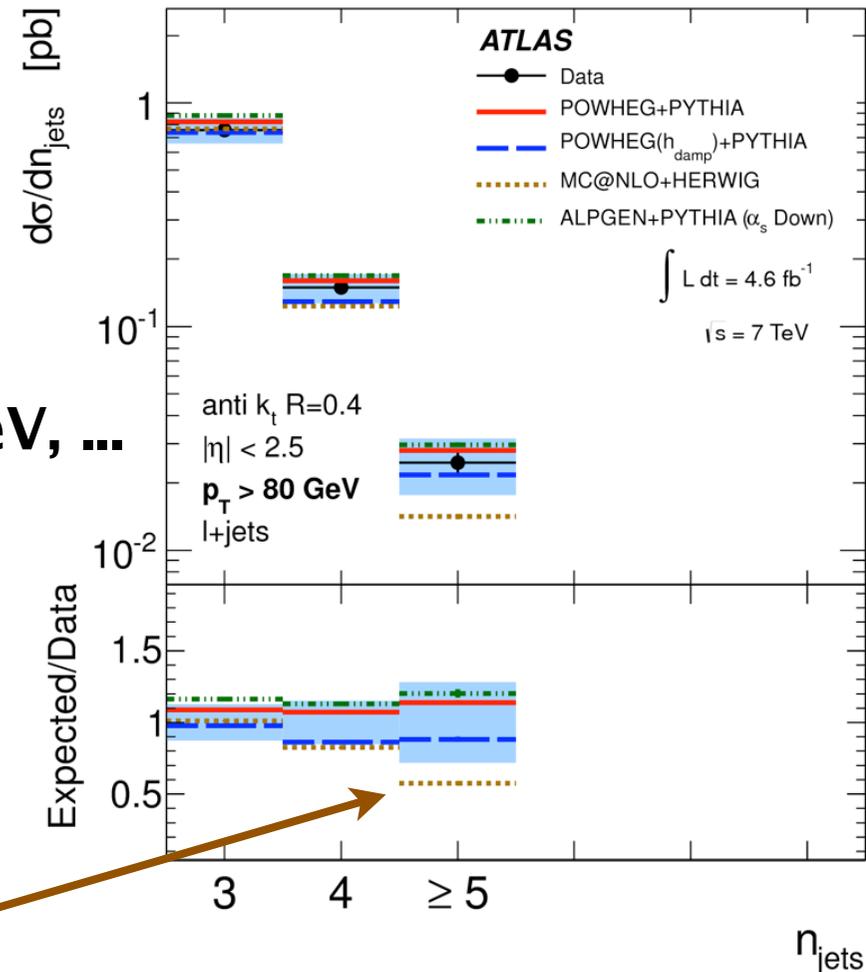
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ALPGEN+Pythia ok

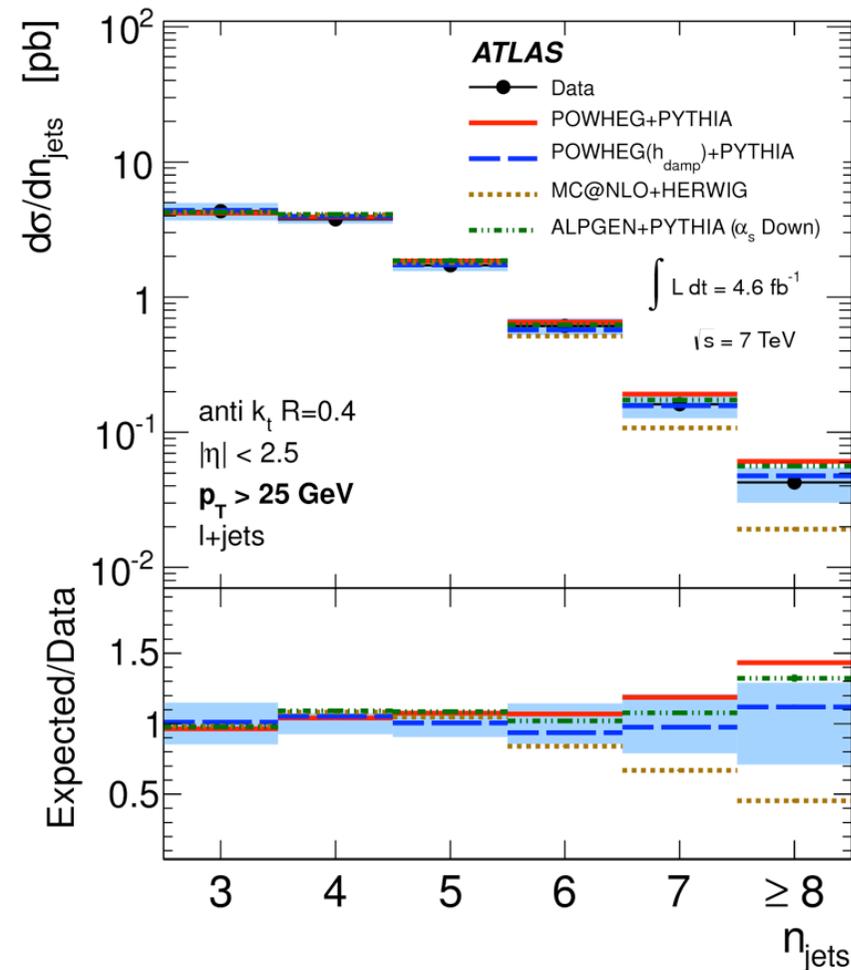
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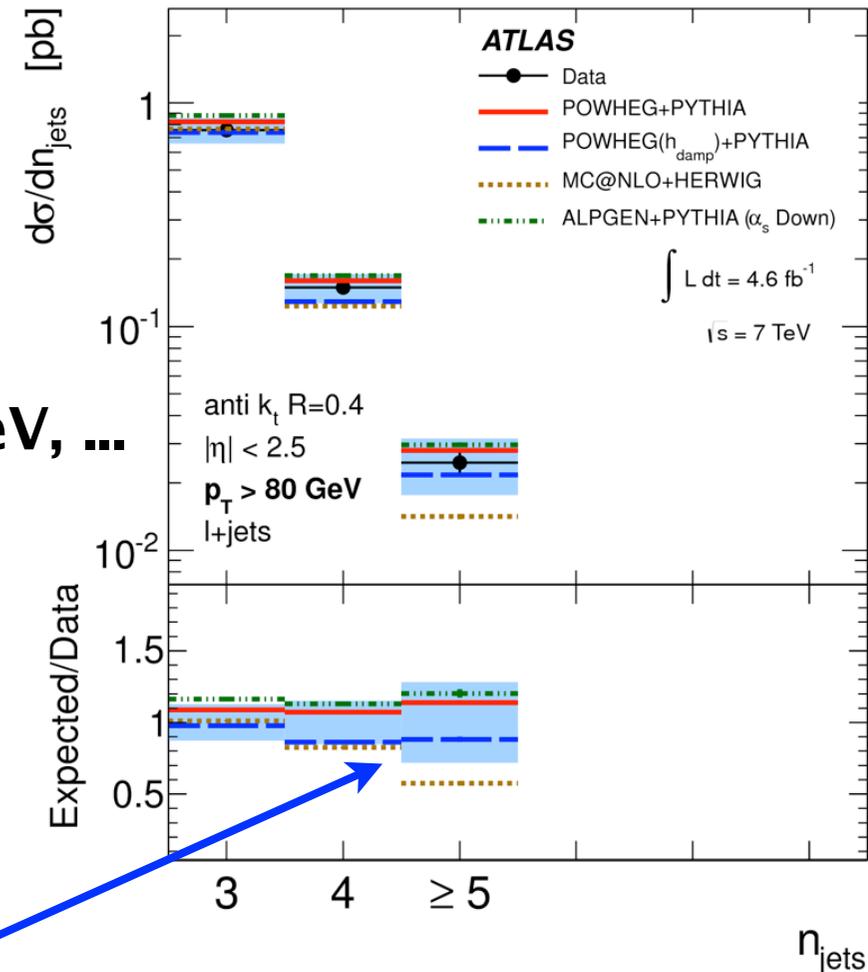
MC@NLO+Herwig disfavoured (since those come mostly from parton showers)

Jet Multiplicities

- Uncertainties dominated by JES and MC modeling of QCD radiation

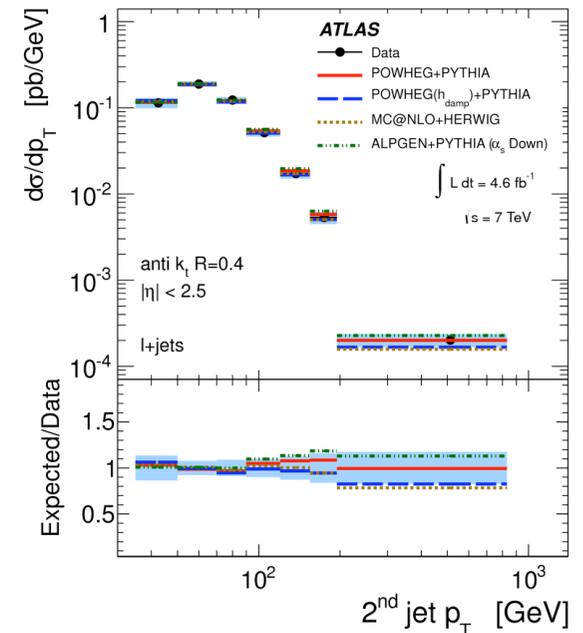
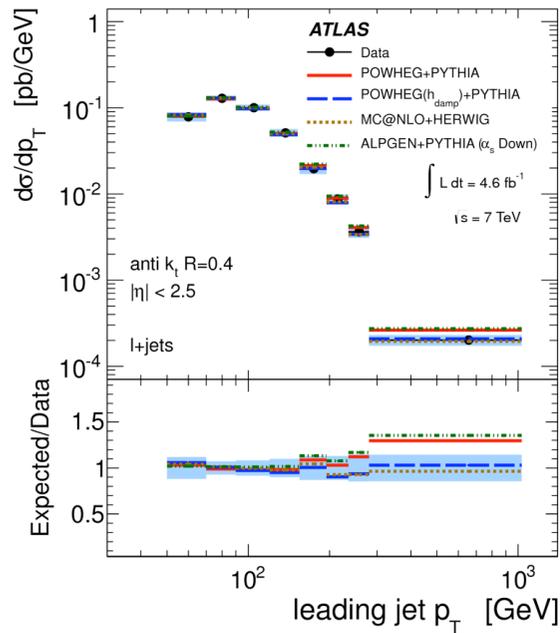


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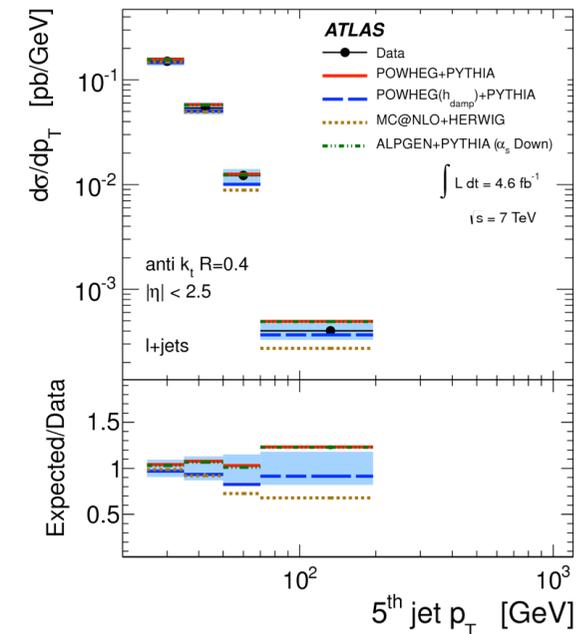
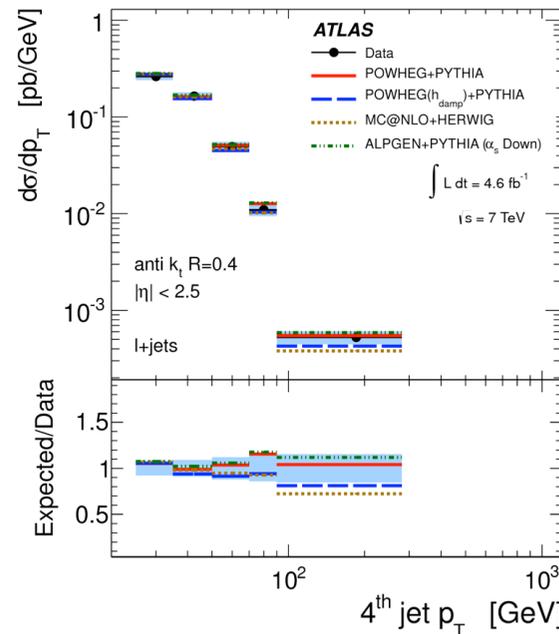
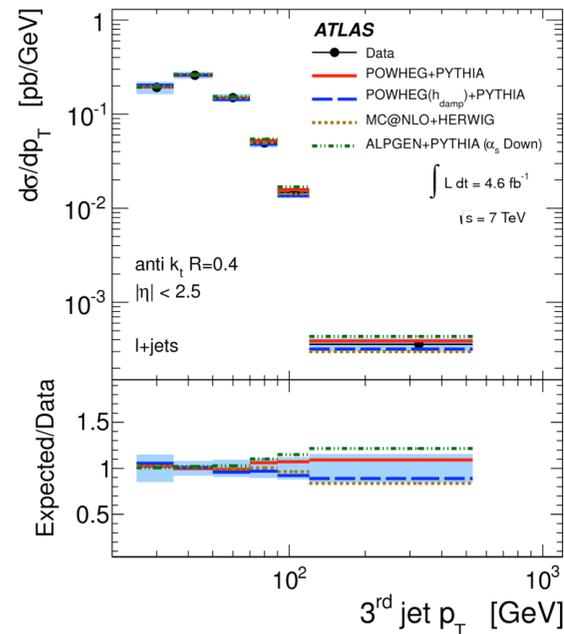


Powheg+Pythia with damping of the hardest emissions is best (high n_{jets} still get large contributions from the matrix element)

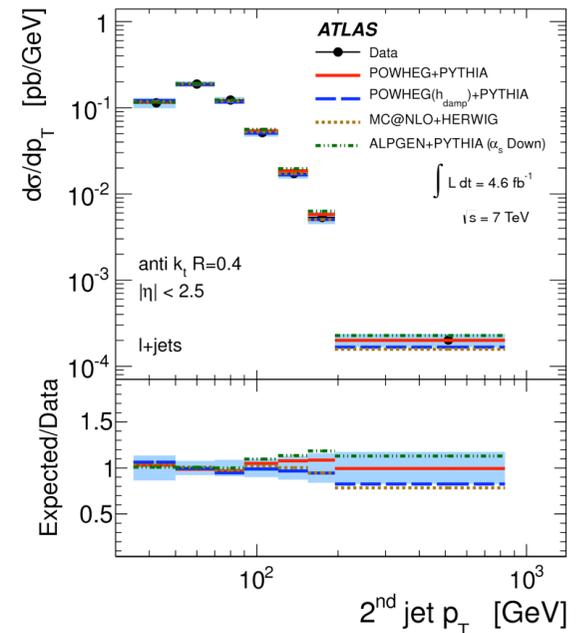
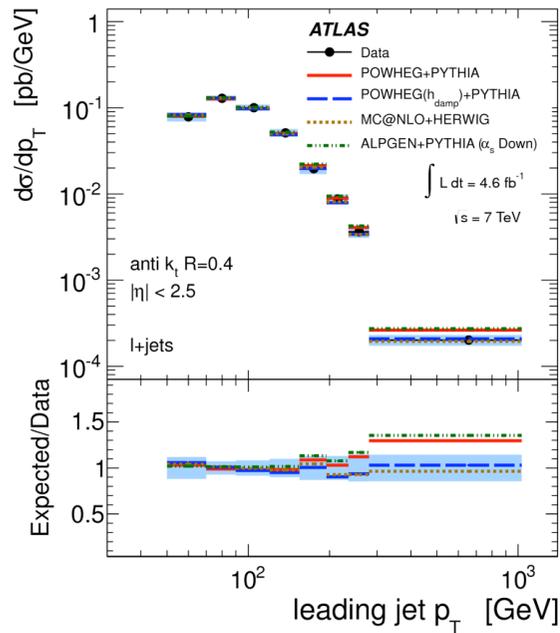
Differential: Jet p_T



← **AlpGen+Pythia and Powheg+Pythia disfavoured**

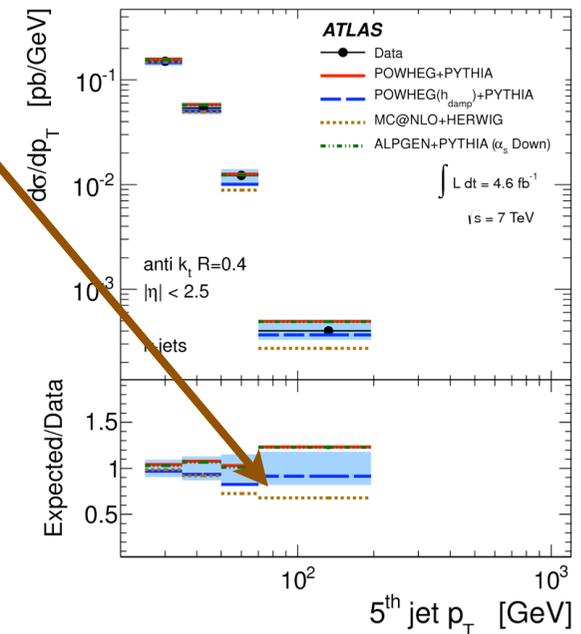
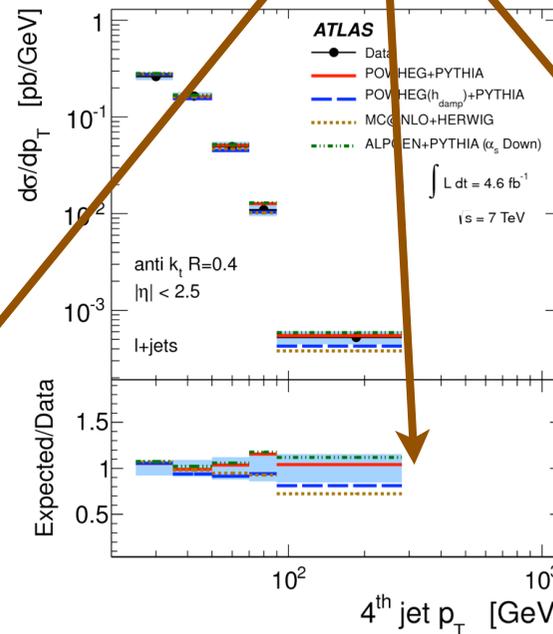
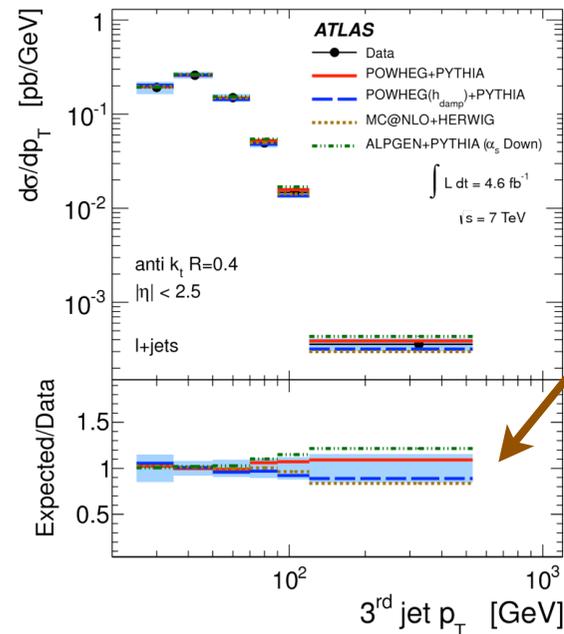


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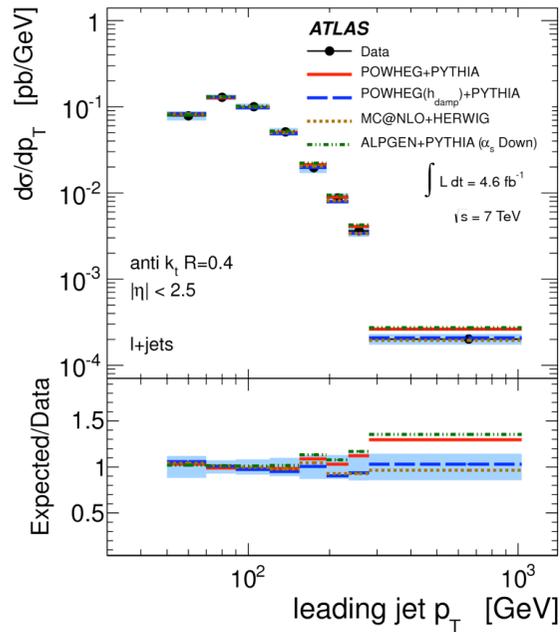


→ multileg MEs are needed!

MC@NLO+Herwig too soft



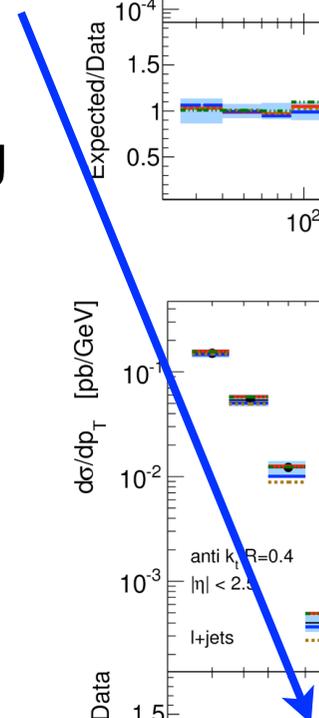
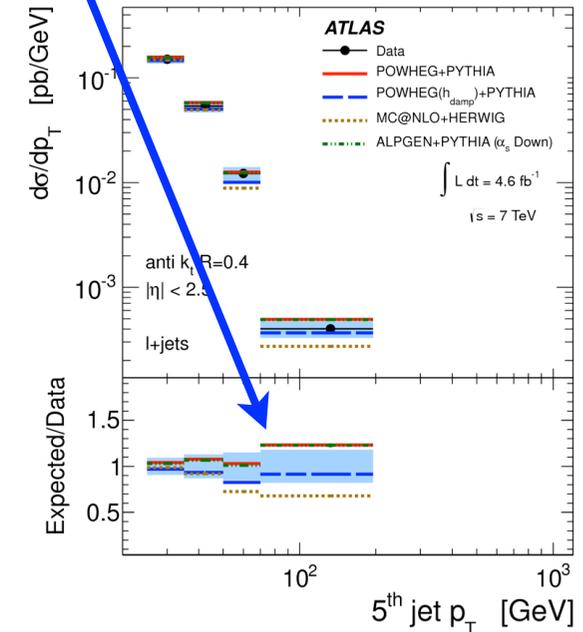
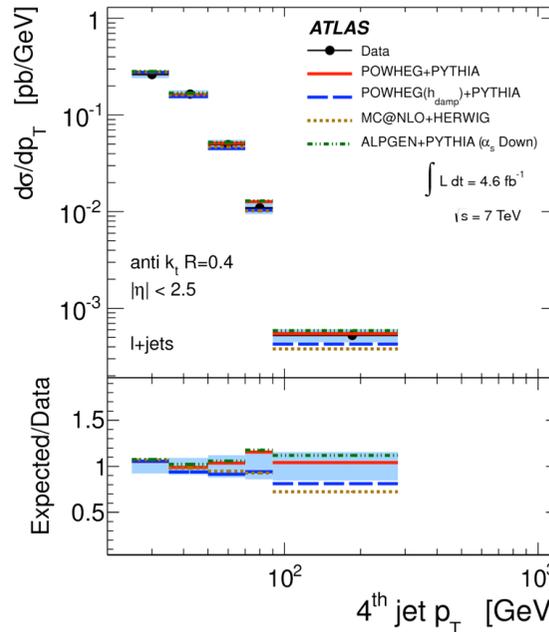
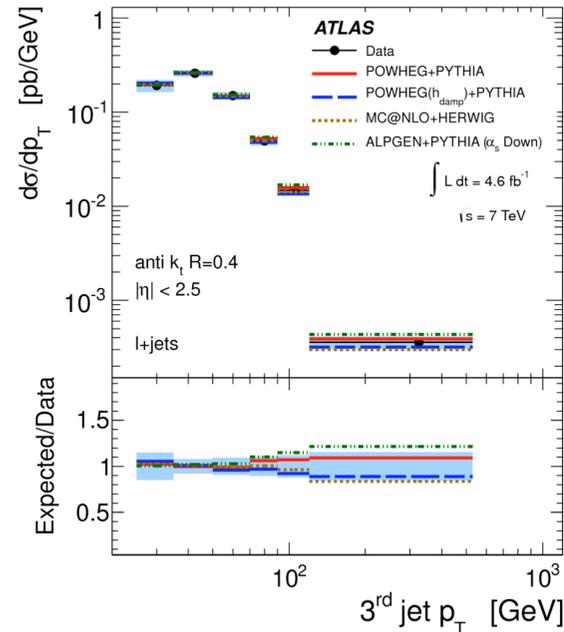
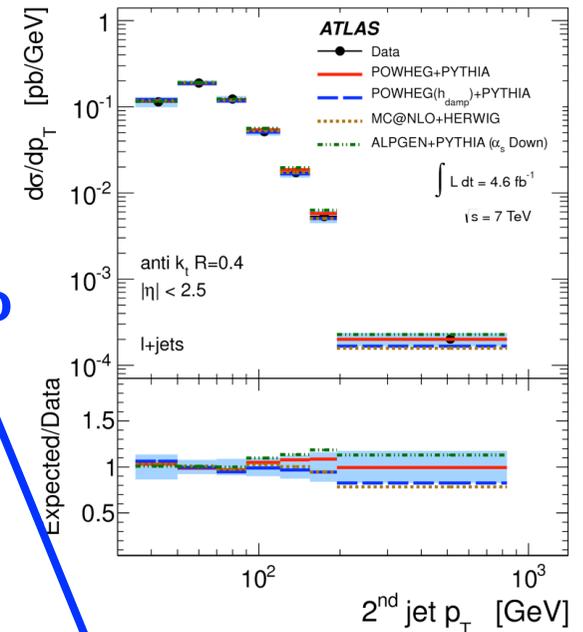
Differential: Jet p_T



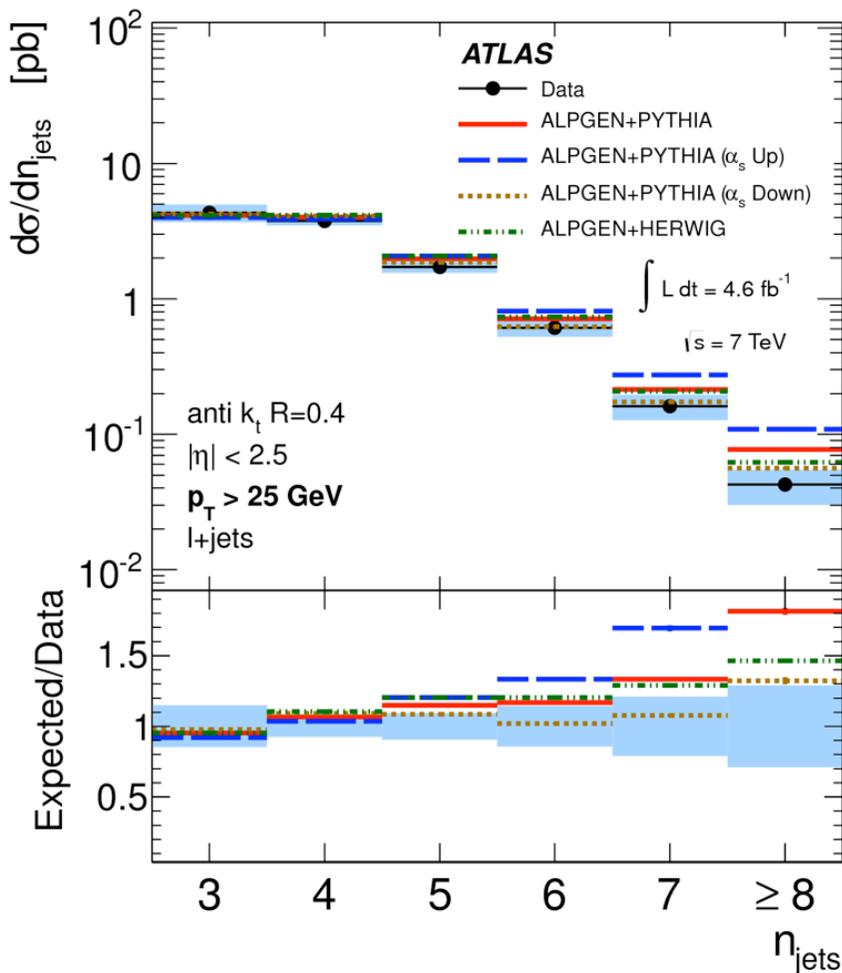
Powheg+Pythia in reasonable agreement

Powheg+Pythia with damping softer, due to damping of hardest emission

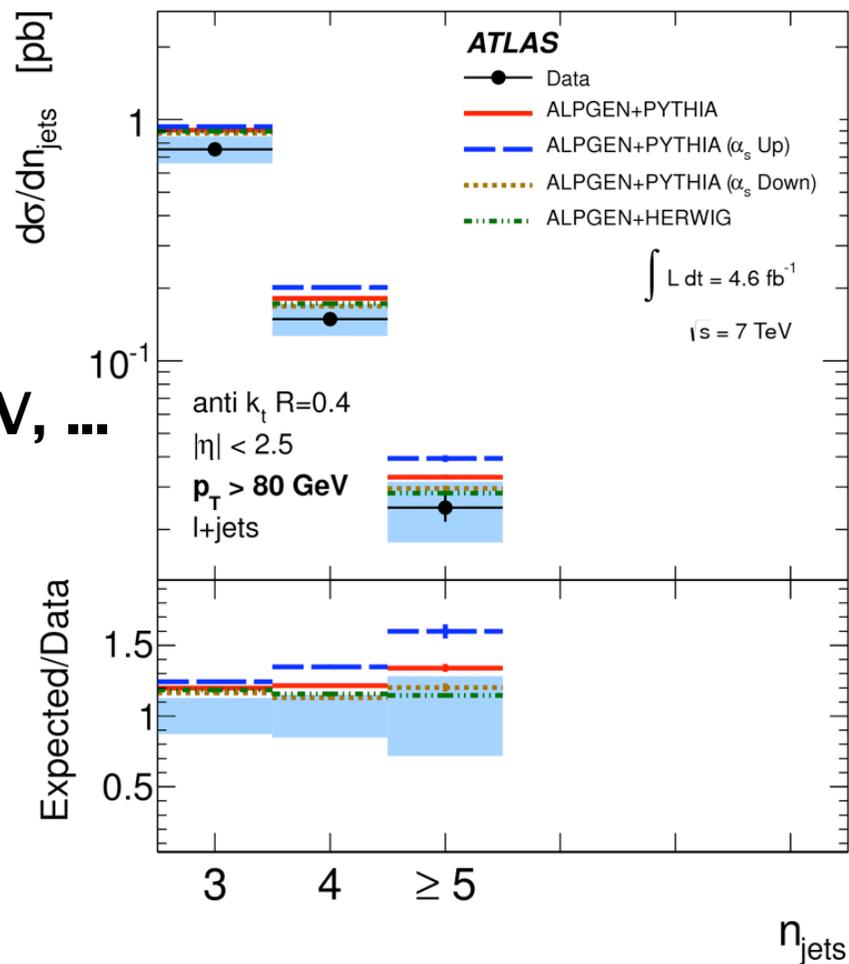
→ matter of tuning ($h_{damp}=m_{top}$ works best)



Strong Coupling and Parton Showers



... 40, 60 GeV, ...



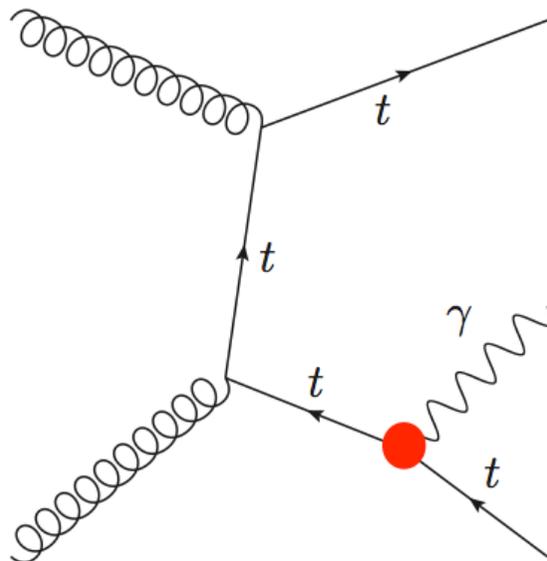
- high sensitivity on α_s and parton showers
- very valuable for improving models and reduce uncertainties
- used for MC tuning: [ATL-PHYS-PUB-2015-007](#)
- improves our understanding of higher order QCD calculations

Content

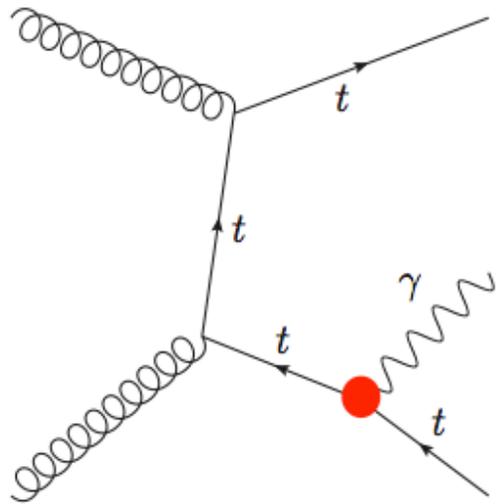
Introduction

$t\bar{t}$ +jets

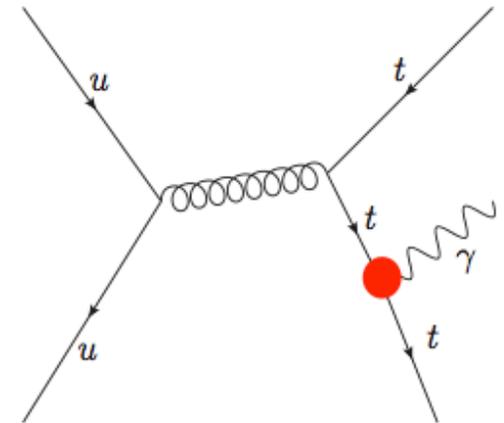
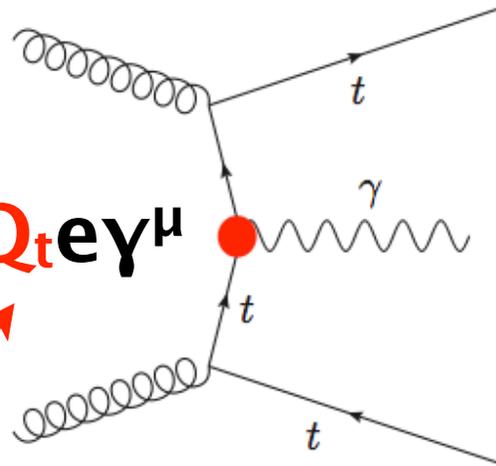
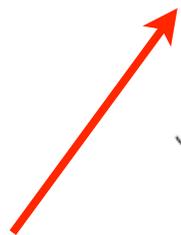
$t\bar{t}$ +photon



$t\bar{t}\gamma$ Production

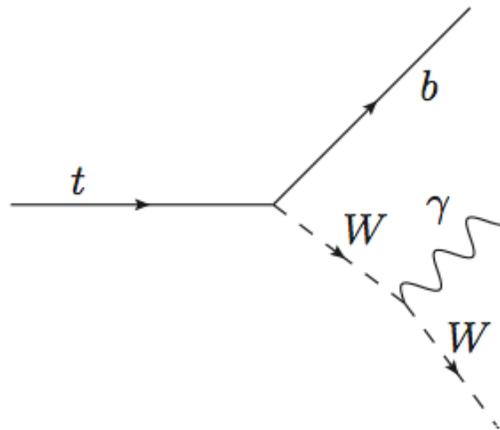
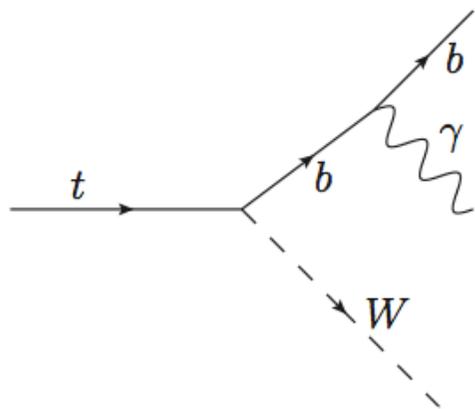


$$-iQ_t e \gamma^\mu$$

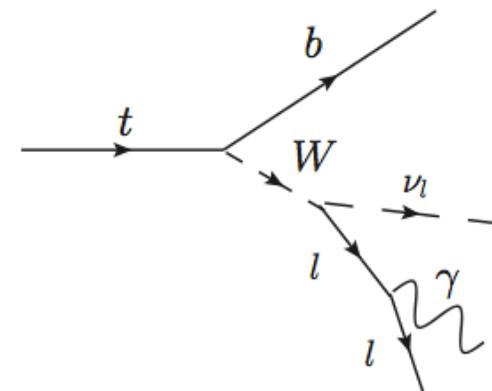


- measure top quark charge
- search for anomalous couplings

photons not radiated off the top quark:

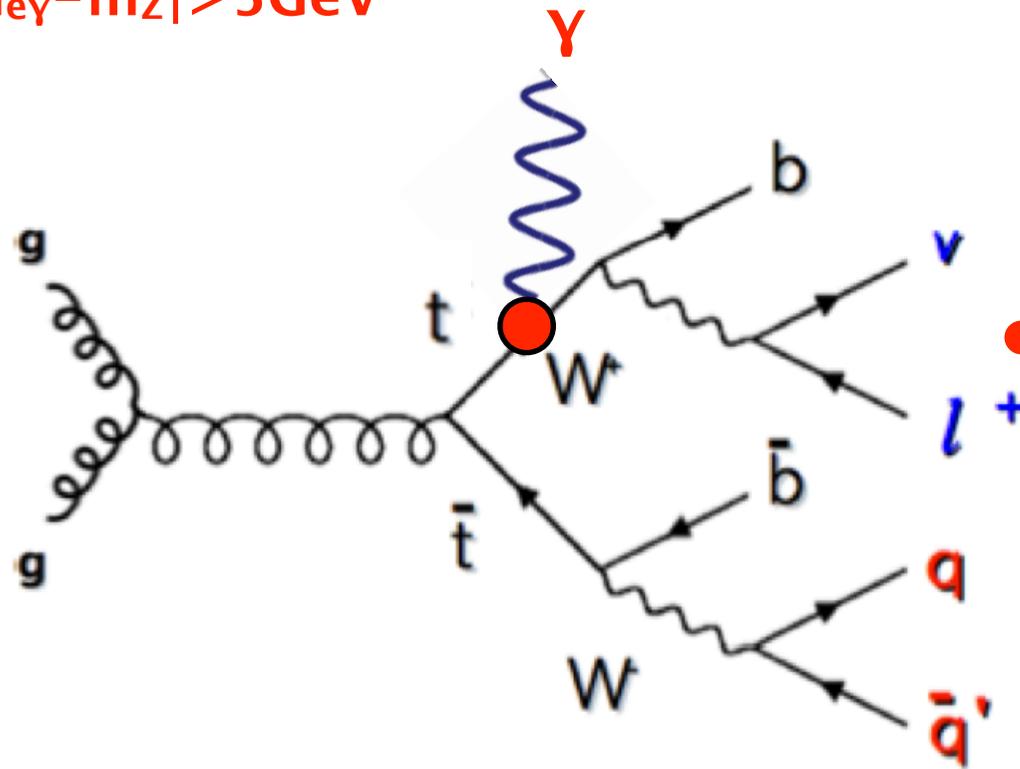


interference taken into account



Selection and Fiducial Phase Space

- ≥ 1 isolated photon with $p_t > 20$ GeV & $|\eta| < 2.37$, $|m_{e\gamma} - m_{z\gamma}| > 5$ GeV



- no jet-e ($dR < 0.2$) or jet- μ ($dR < 0.4$) or jet- γ ($dR < 0.5$) or lepton- γ pair ($dR < 0.7$) (reduce lepton FSR)

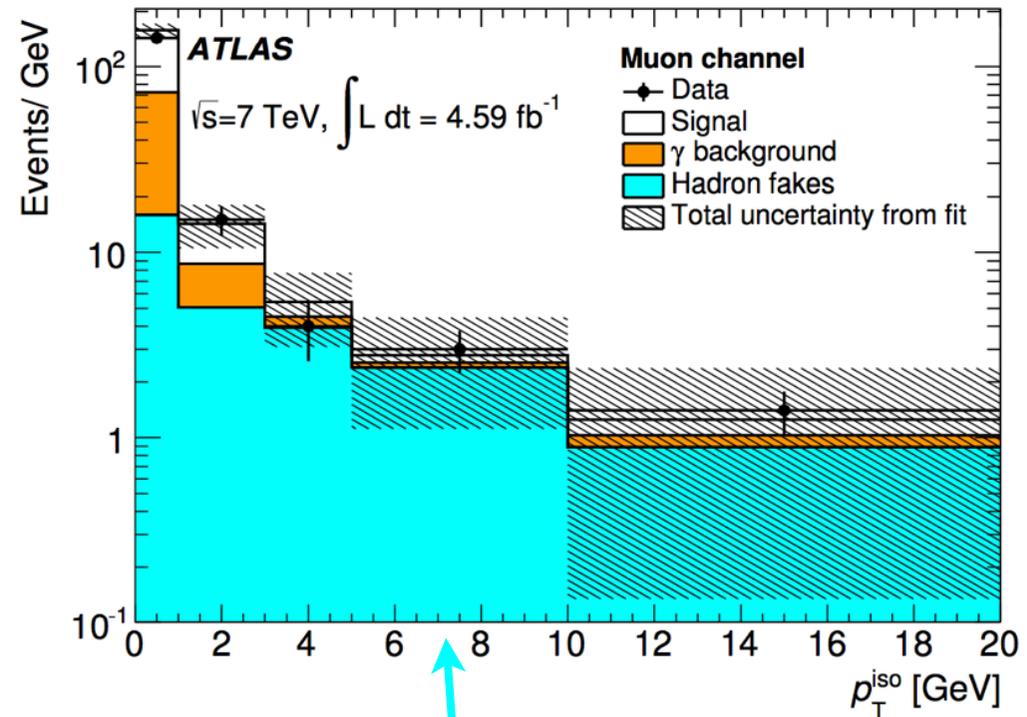
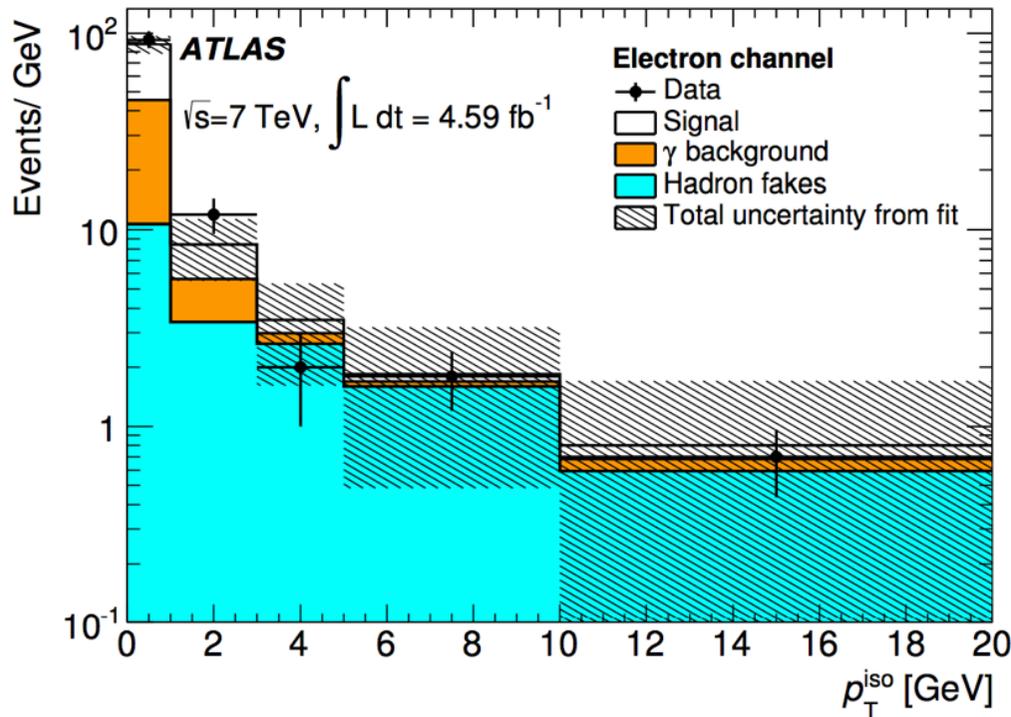
“standard” lepton+jets selection

- ≥ 4 Jets with $p_t > 25$ GeV & $|\eta| < 2.5$ incl. ≥ 1 b-tagged jet
- $E_{t,miss} > 30$ GeV
- $m_T(W) > 35$ GeV
- exactly one e or μ with $|\eta| < 2.5$, $p_t > 25$ GeV, e, μ : including clustering with γ in cone $\Delta R = 0.1$
- jets: anti- k_t $R = 0.4$, clusters all but prompt particles (i.e. e, μ , ν from hadronic decays are inside jets)

$t\bar{t}\gamma$ Cross Section

- **template fit using track-isolation distribution to discriminate**

p_T^{iso} : the scalar sum of the transverse momenta of selected tracks in a cone of $\Delta R = 0.2$ around the photon candidate



prompt photon backgrounds:
data driven and MC simulation

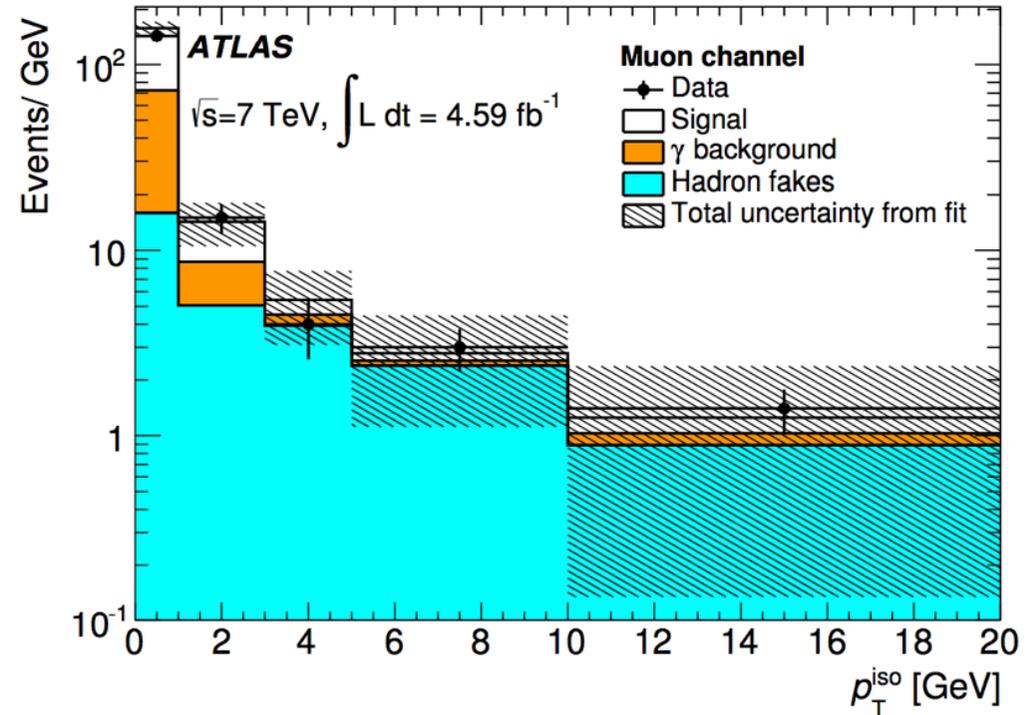
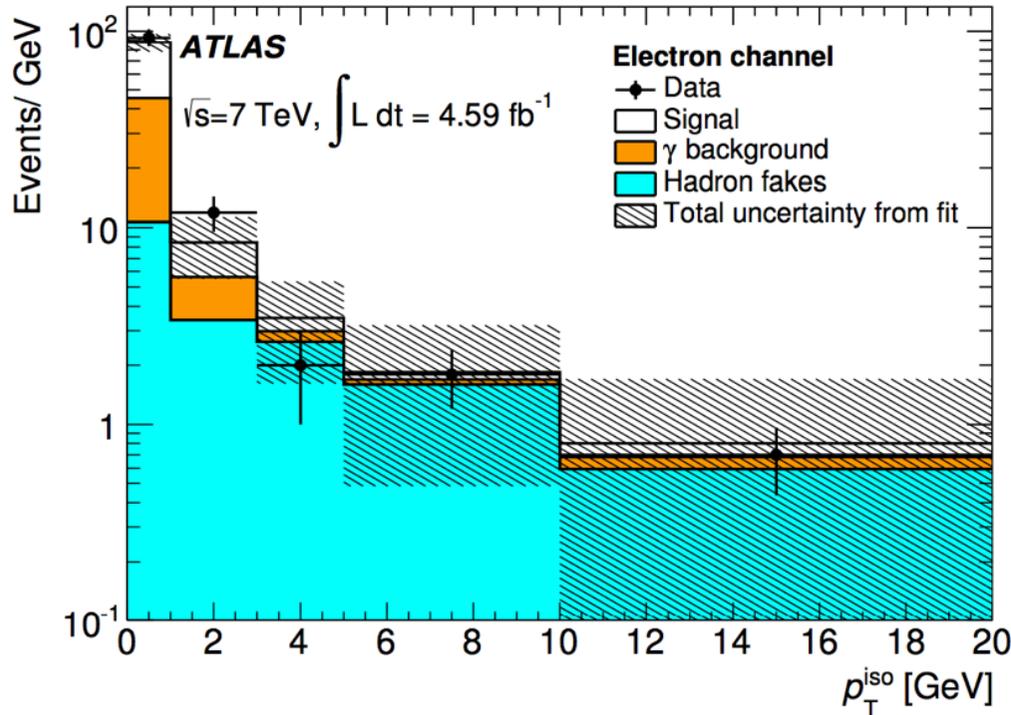
$e \rightarrow \gamma$ misidentification
Multijet + γ
 $W\gamma$ + jets
Single top + γ
 $Z\gamma$ + jets
Diboson

hadrons misidentified as photons,
neutral hadron decays to diphotons:
multijets data sample

$t\bar{t}\gamma$ Cross Section

- **template fit using track-isolation distribution to discriminate**

p_T^{iso} : the scalar sum of the transverse momenta of selected tracks in a cone of $\Delta R = 0.2$ around the photon candidate



$$\sigma_{t\bar{t}\gamma}^{\text{fid}} \times \text{BR} = 63 \pm 8(\text{stat.}) \begin{matrix} +17 \\ -13 \end{matrix} (\text{syst.}) \pm 1 (\text{lumi.}) \text{ fb}$$

SM: 48 ± 10 fb

→ in agreement with **SM prediction**

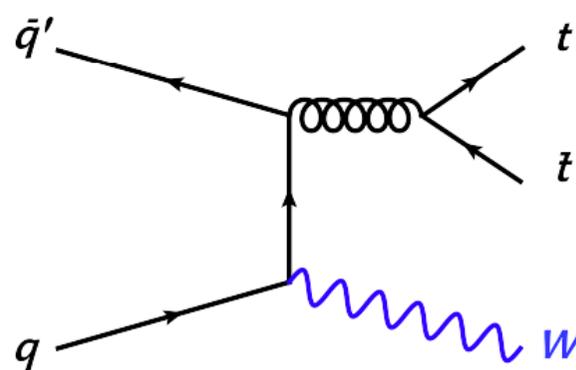
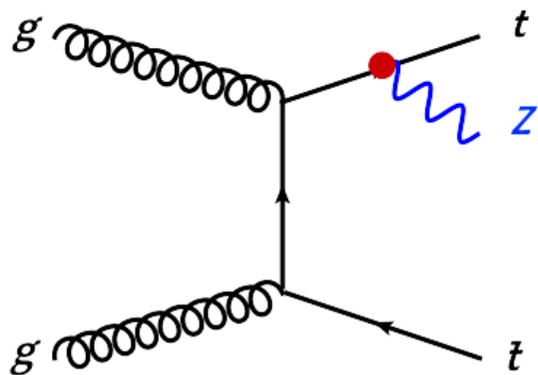
→ **observation** with significance of 5.3σ

arXiv:1502.00586 [hep-ex]

Content

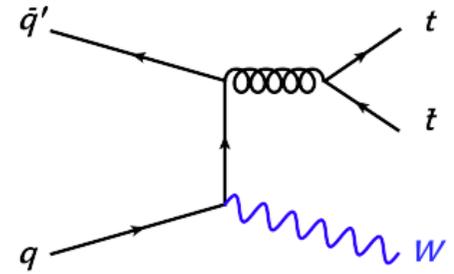
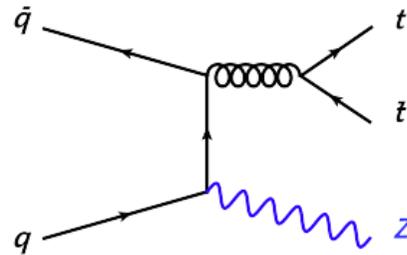
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 $t\bar{t}$ +photon
 $t\bar{t}Z, t\bar{t}W$

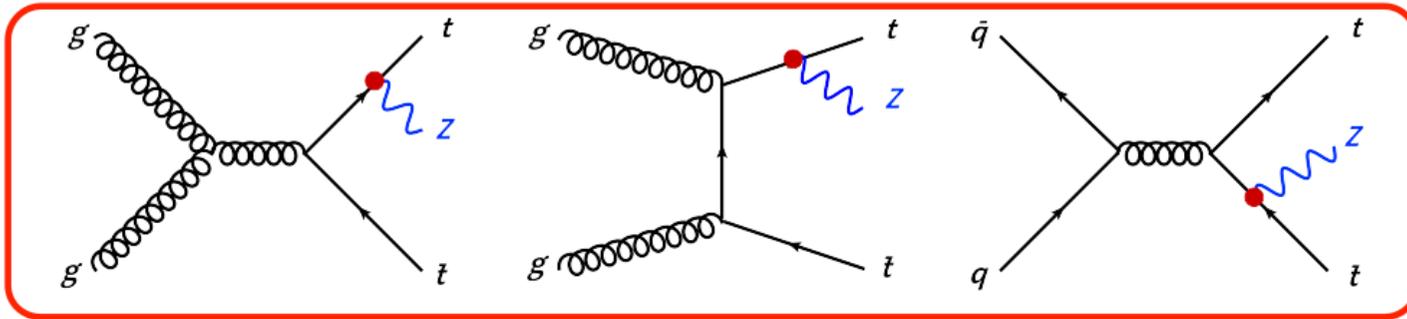


$t\bar{t}Z$ and $t\bar{t}W$ Production

ISR



FSR

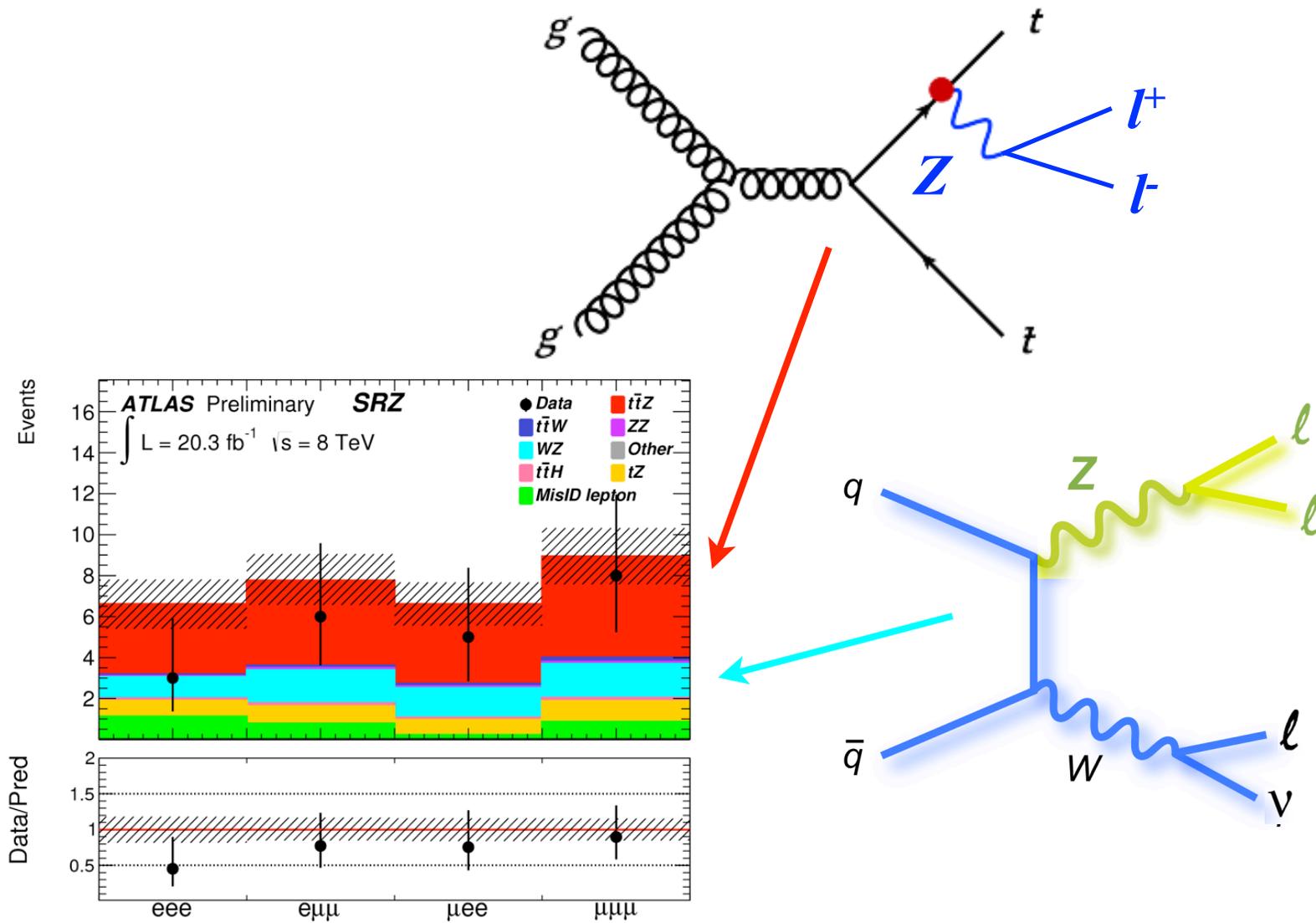


$$-i \frac{e}{\sin\theta_W \cos\theta_W} (T_3 - \sin^2\theta_W Q_t) \gamma^\mu$$



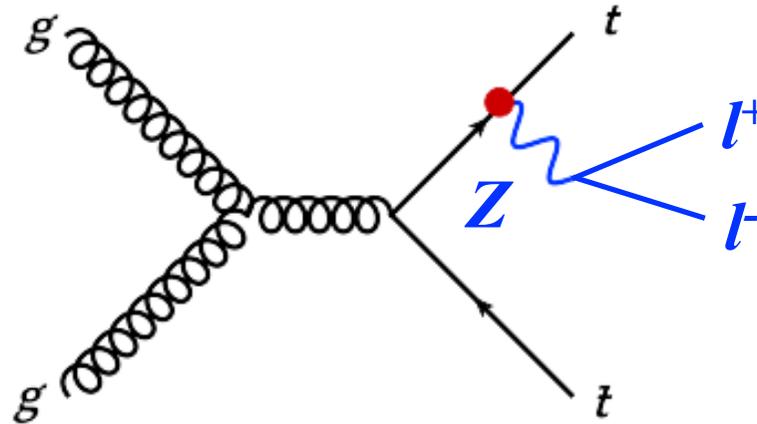
- measure **3rd component of weak isospin**
 - search for anomalous couplings in $t\bar{t}Z$ vertex (basically unexplored)
- both processes are important backgrounds to searches (e.g. $t\bar{t}H$ in multilepton events)

Three Lepton Channel

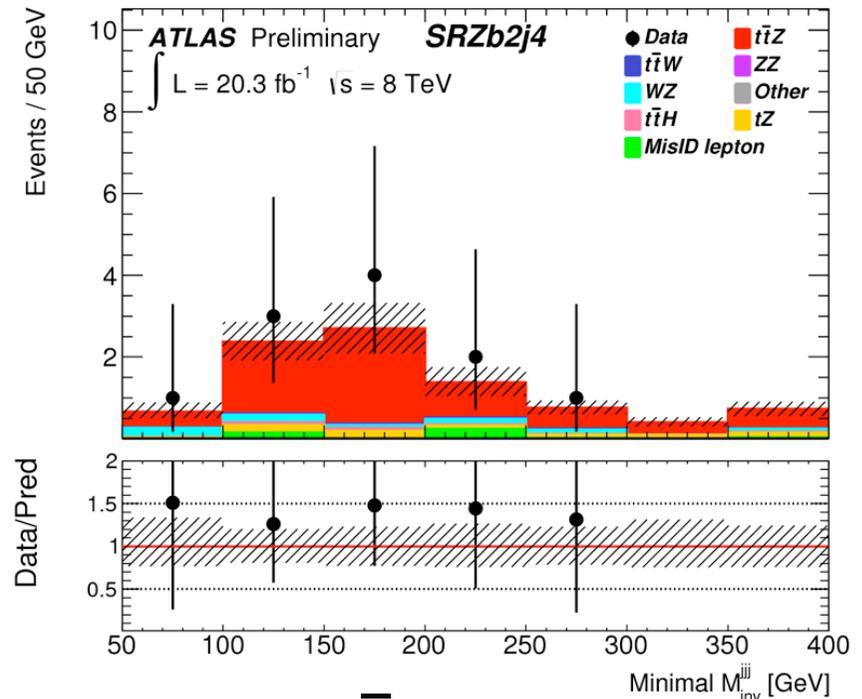
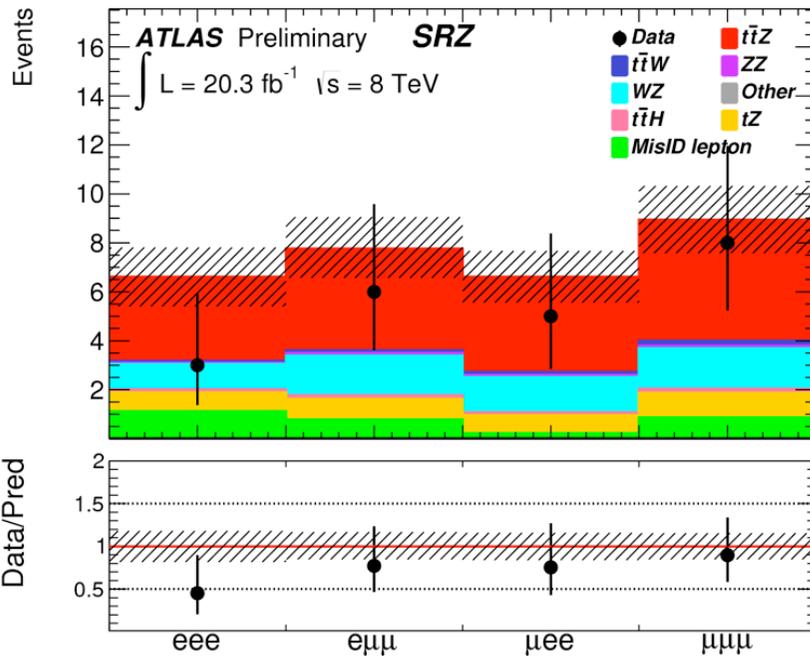


+ same channels with Z-veto to enhance $t\bar{t}W$ production

Three Lepton Channel

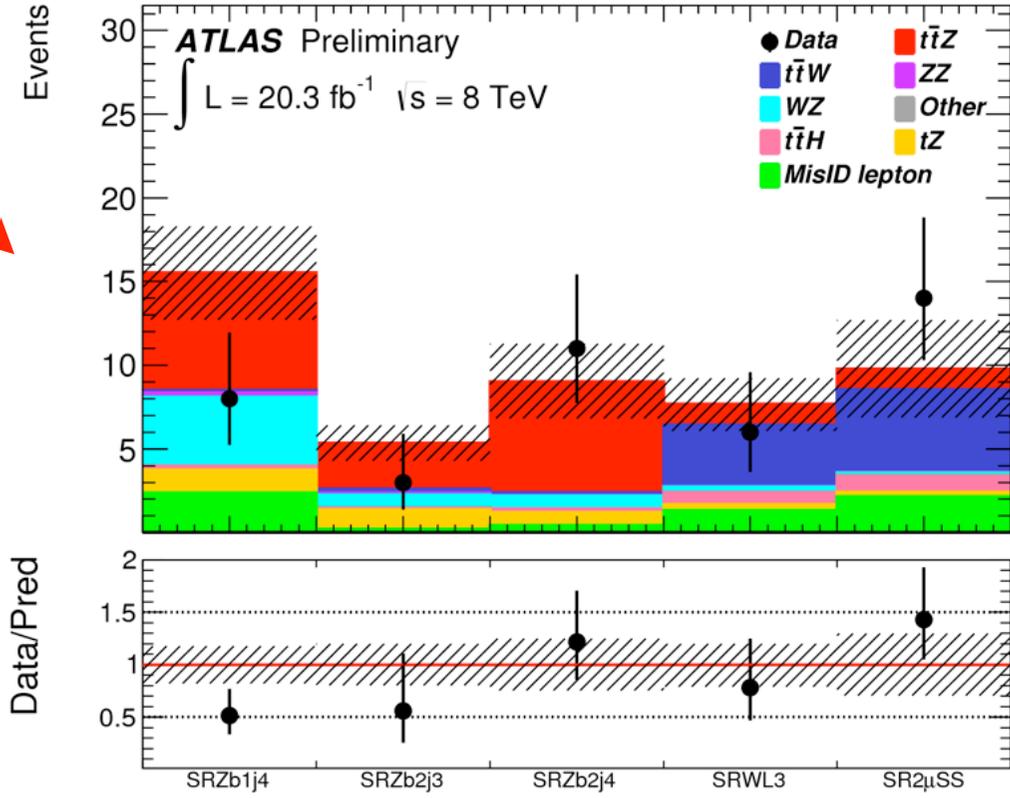
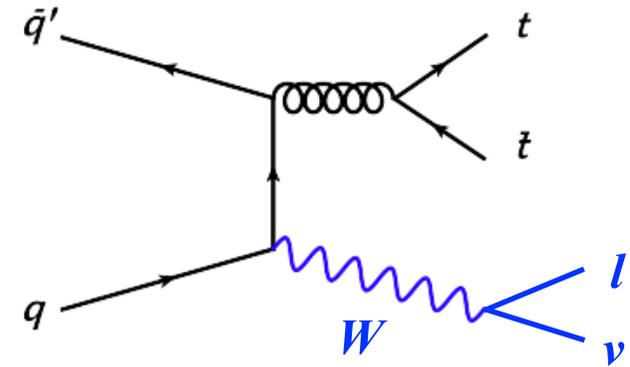
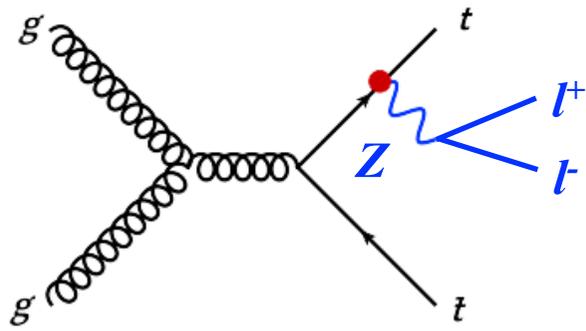


4 jets, 2 b-jets



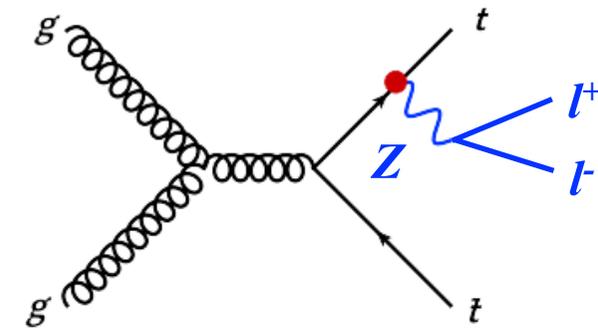
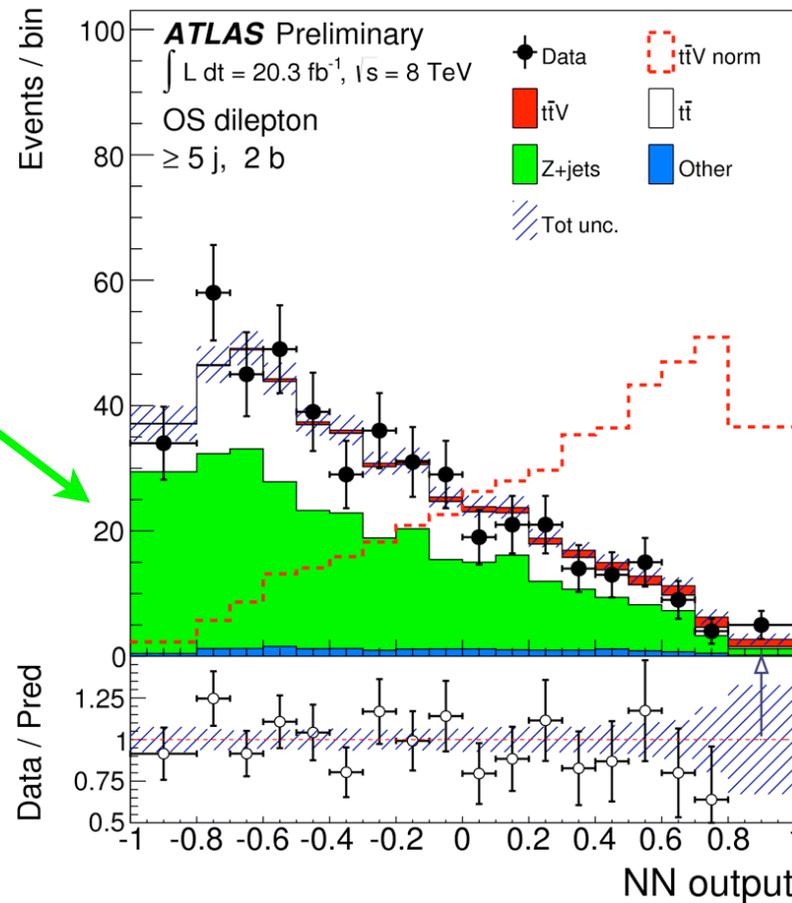
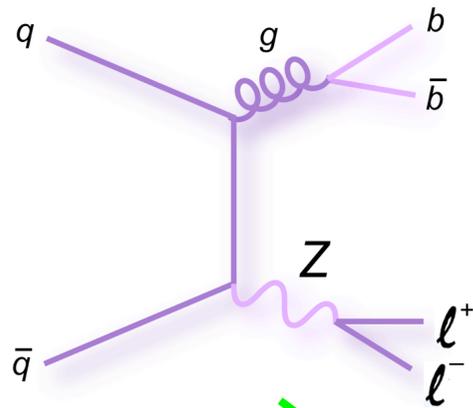
- + same channels with Z-veto to enhance $t\bar{t}W$ production
- + different bins in n_{jets} and n_{bjets}

Three Lepton + Same Sign Dilepton



→ counting analysis

Opposite Sign Dilepton



+ same channels with Z-veto
 + different bins in n_{jets} and n_{bjets}

→ neural network analysis

Content

Introduction
 $t\bar{t}$ +jets
 $t\bar{t}$ +photon
 $t\bar{t}Z$, $t\bar{t}W$
Summary

Summary

interaction between top quark and strong and EWK force carriers

- $t\bar{t}$ +jets: many different observables related to QCD radiation have been measured (fiducial phase space): results show discriminating power between some MC models allowing first **MC optimisations**
- **first observation** of $t\bar{t}\gamma$ production: in agreement with SM
- **evidence** for $t\bar{t}Z$ and $t\bar{t}W$ production: in agreement with SM

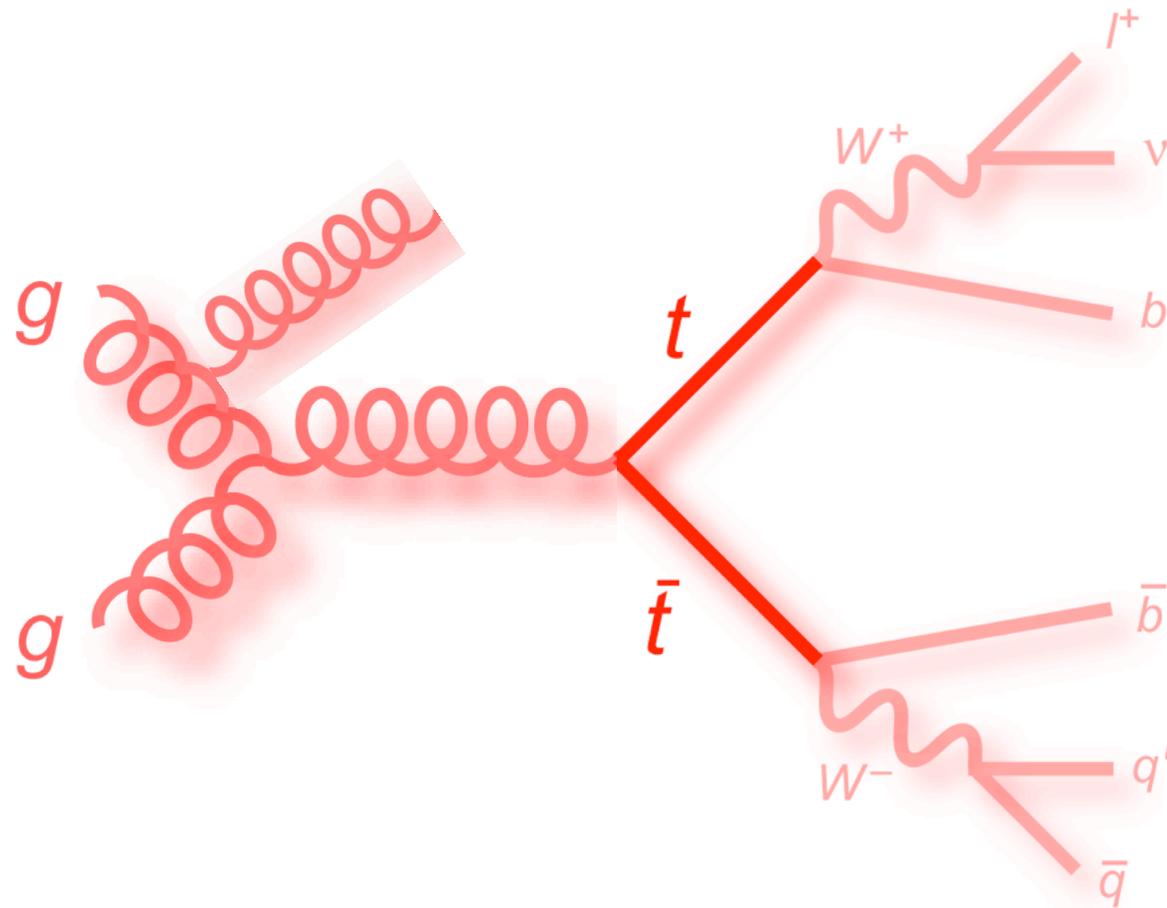
→ **important improvements to understand strong and EWK interactions of top quark**

- for $t\bar{t}$ +jet production: 13 TeV data will offer potential for smaller uncertainties and allow to probe more extreme parts of the phase space
- for $t\bar{t}\gamma$, $t\bar{t}Z$ and $t\bar{t}W$ production: 13 TeV data will allow precise measurements of cross sections and EW couplings and sensitive searches for anomalous contributions

→ **exciting prospects for Run-II**

Backup

Fiducial Object Definition



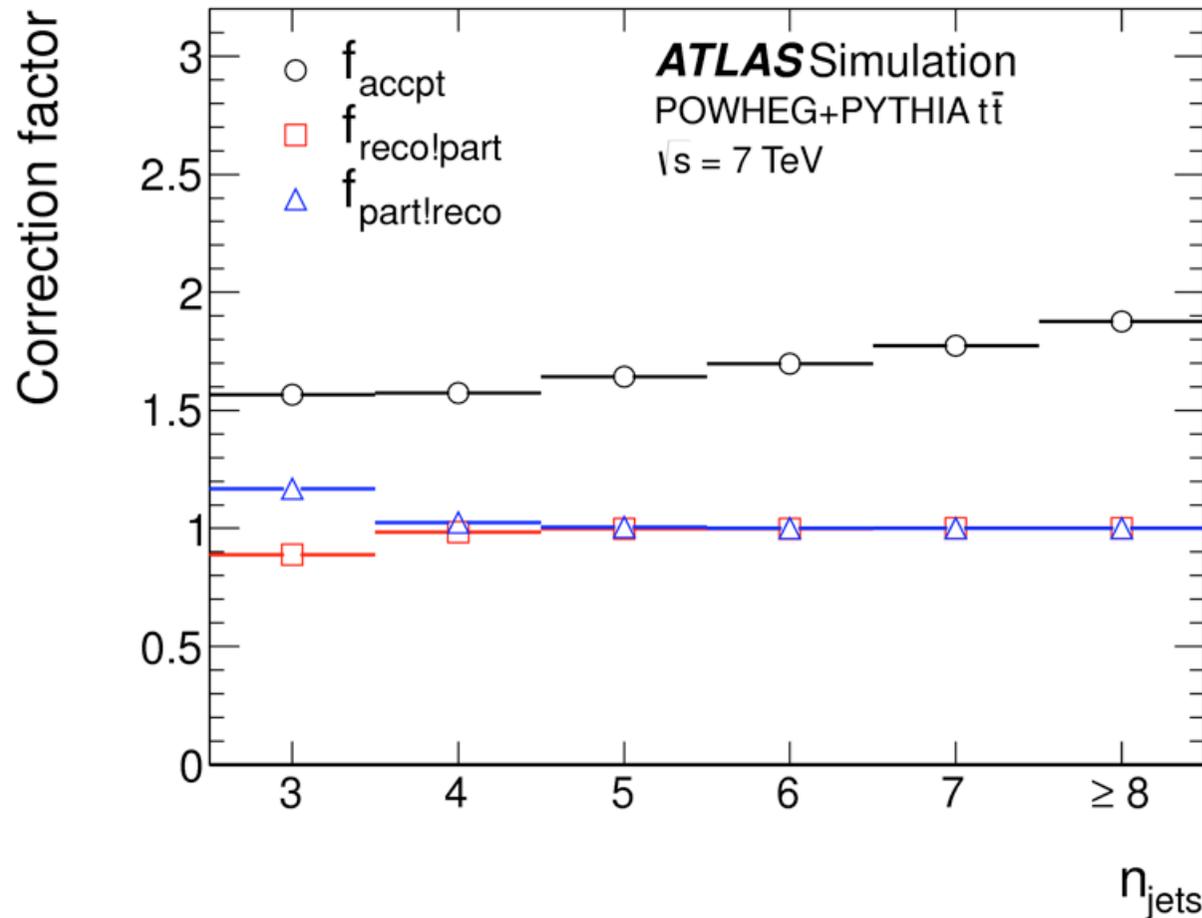
- e, μ : including clustering with γ in cone $\Delta R=0.1$

- b -jets: if stable B -hadron with initial $p_t > 5\text{GeV}$, ghost matched to the jet (corresponding to non-prompt B s from EW decays)

- jets: anti- k_t $R=0.4$, clusters all but prompt particles (i.e. e, μ, ν from hadronic decays are inside jets)

Correction to Particle Level

global efficiency correction factors+iterative Bayesian unfolding:

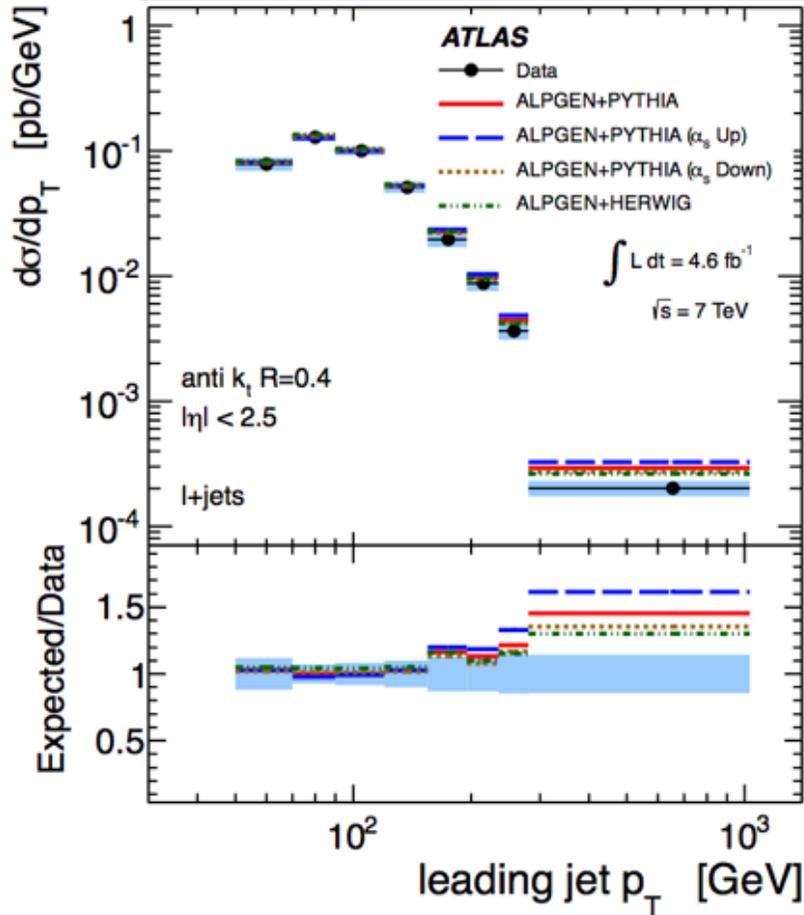


$f_{\text{accpt}} = \frac{\text{\# events @ particle level in fiducial volume}}{\text{\# events @ reco level in fiducial volume}}$
 $f_{\text{reco!part}} = \frac{\text{\# events reco jets no particle jets}}{\text{\# events reco jets}}$
 $f_{\text{part!reco}} = \frac{\text{\# events particle jets no reco jets}}{\text{\# events particle jets}}$

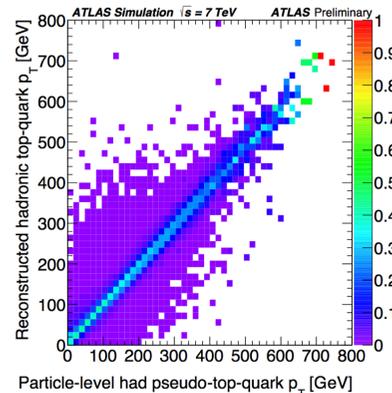
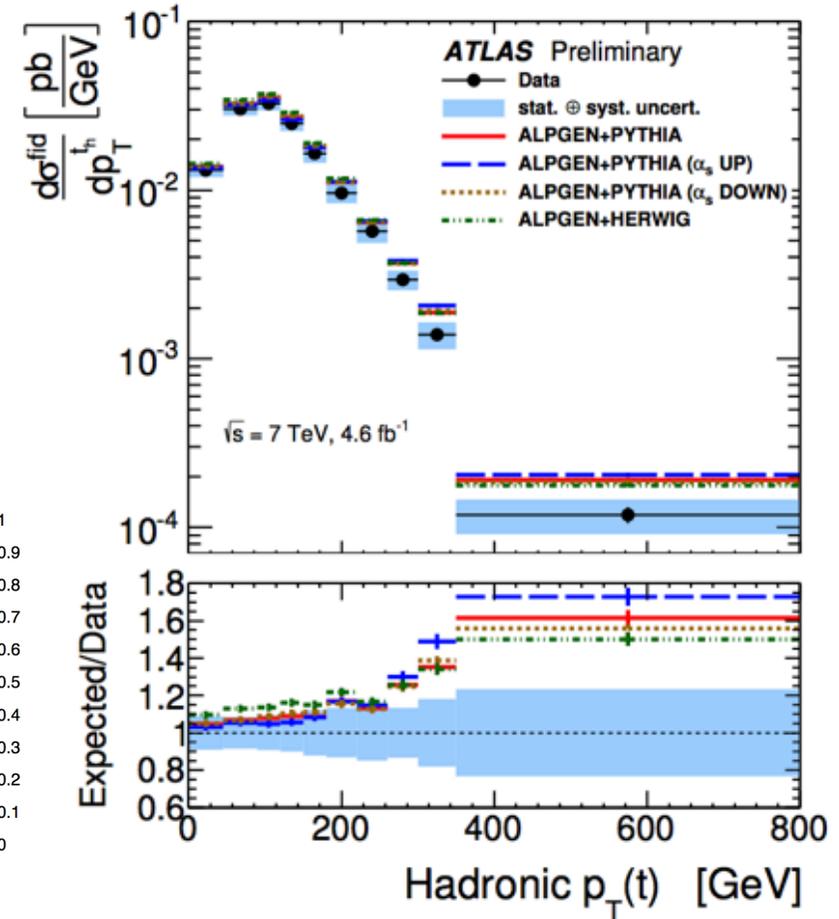
- considerably large factors to correct for detector effects
- reduced dependence on MC model

Top decay products: pseudo-top

Fiducial phase space:
 ≥ 1 b-jet, 1 lepton, ≥ 3 jets,
 1^{st} jet $p_T > 50$ GeV, 2^{nd} jet $p_T > 35$ GeV

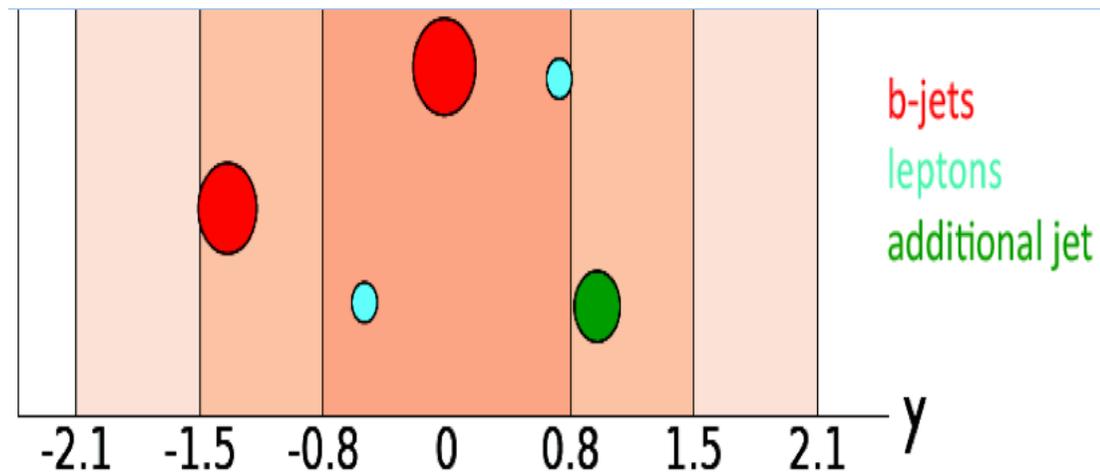
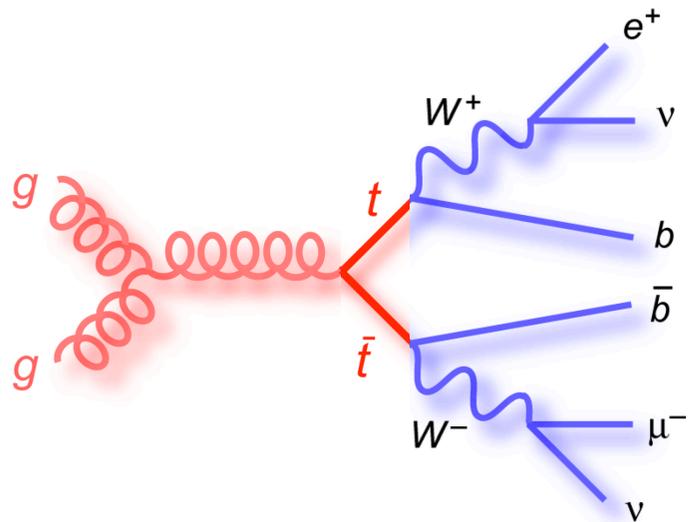


Fiducial phase space:
 2 b-jets, 1 lepton, ≥ 4 jets

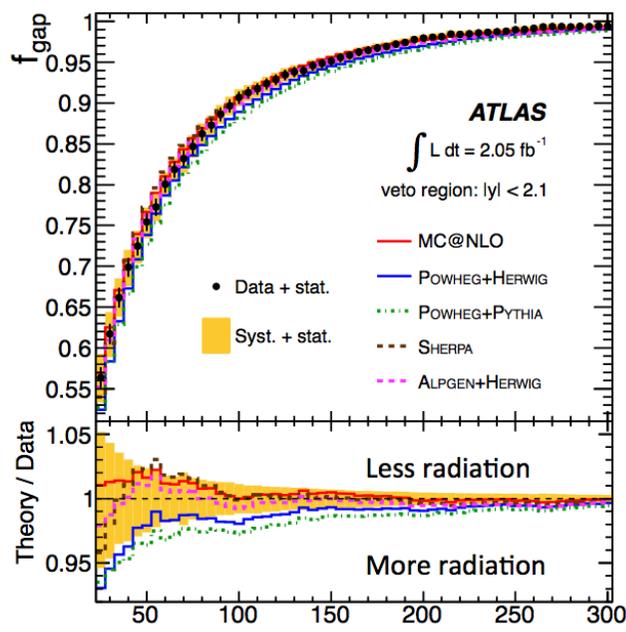


→ reconstruct tops on particle level
 → very valuable for theorists today and in future

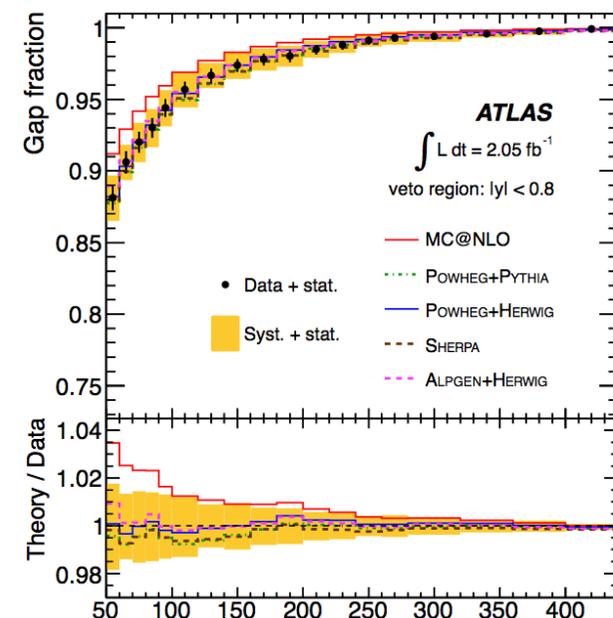
Jet Veto (“Gap Fraction”) Analysis



→ complementary since mostly sensitive to first emission

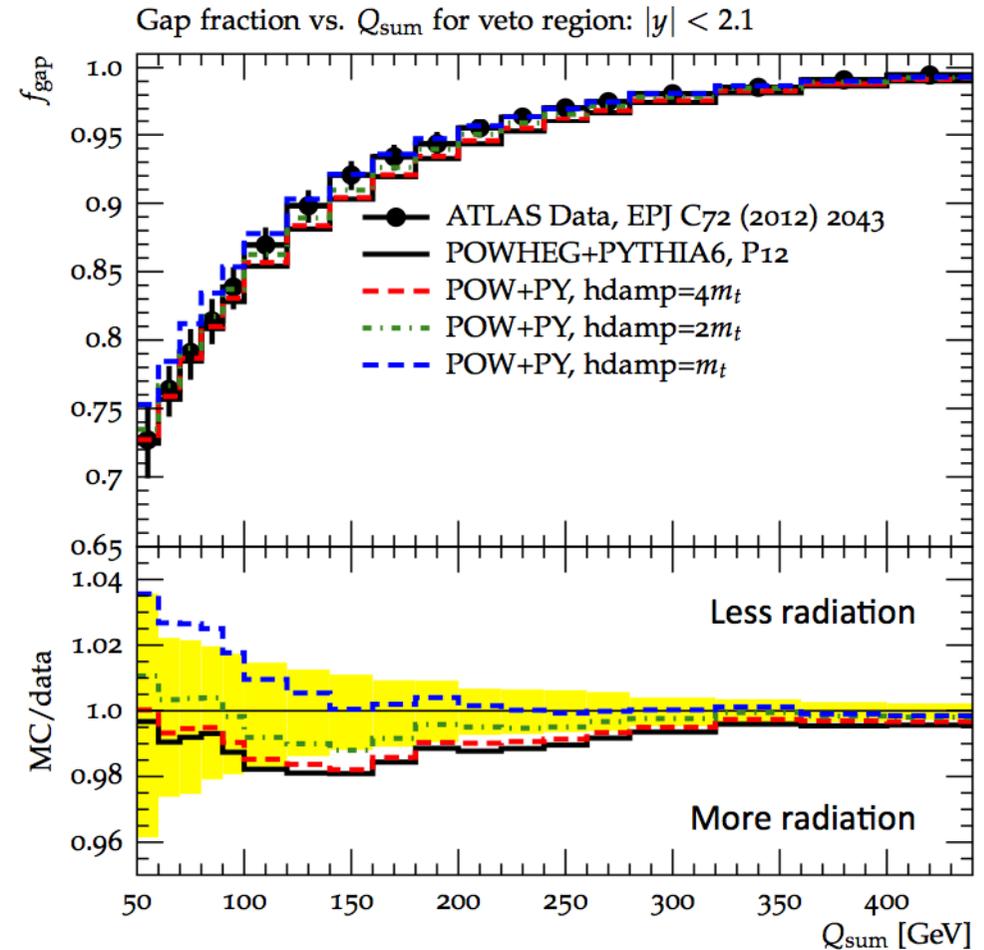
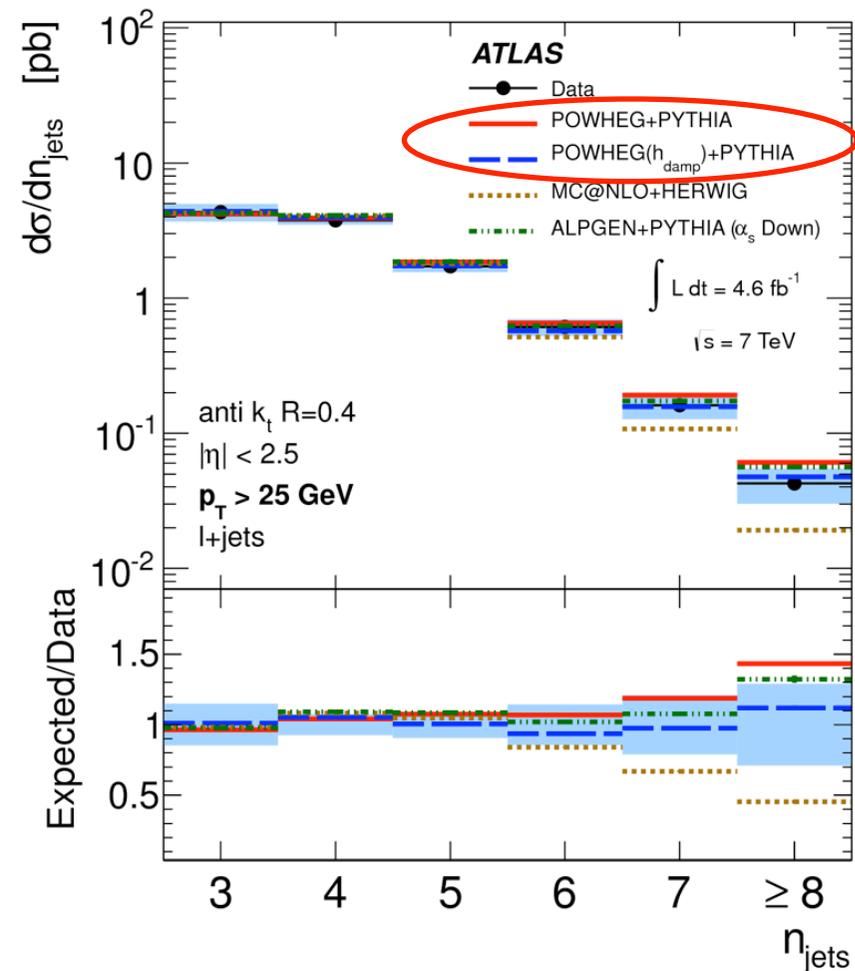


p_t threshold for first additional jet



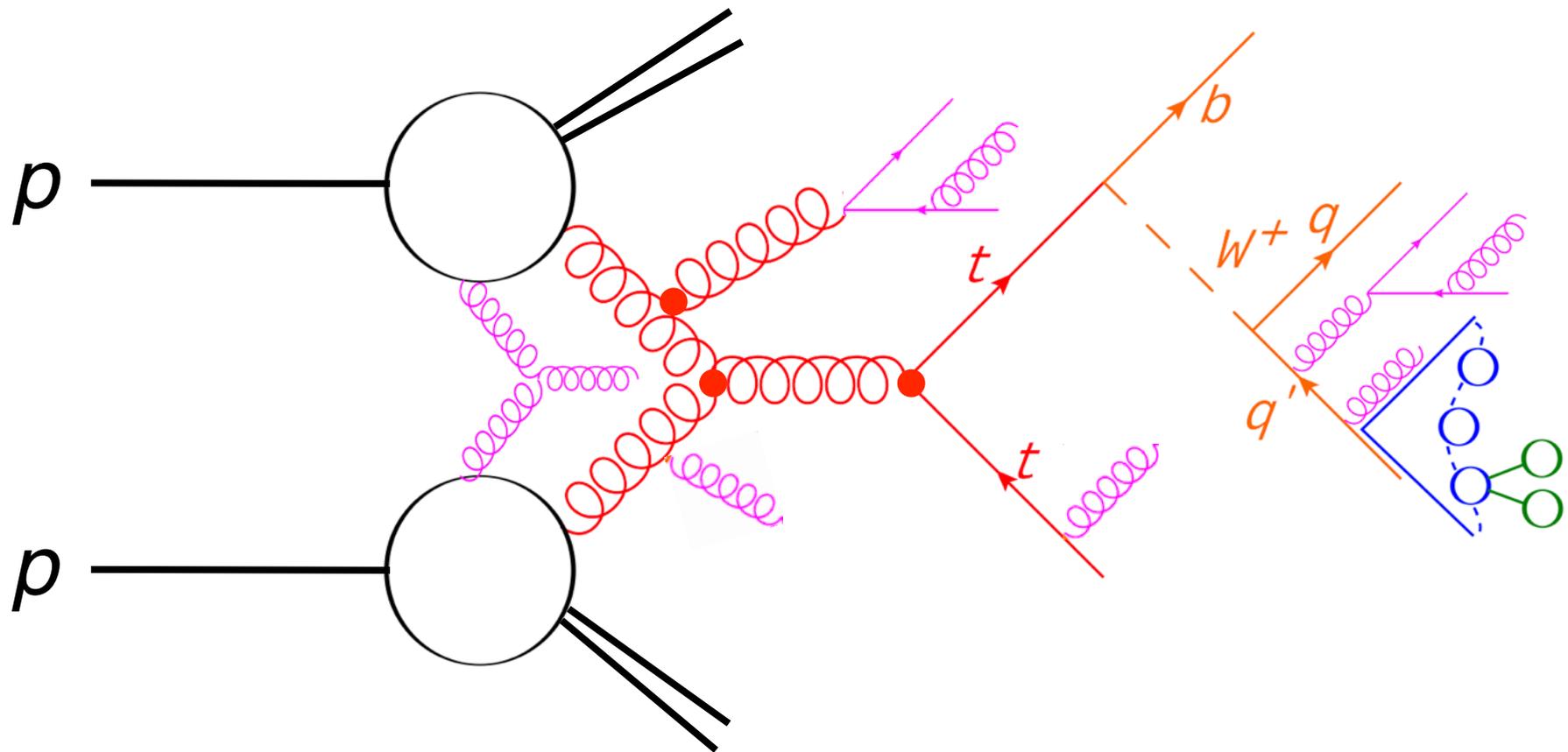
p_t threshold of p_t sum of additional jet

Radiation Hardness

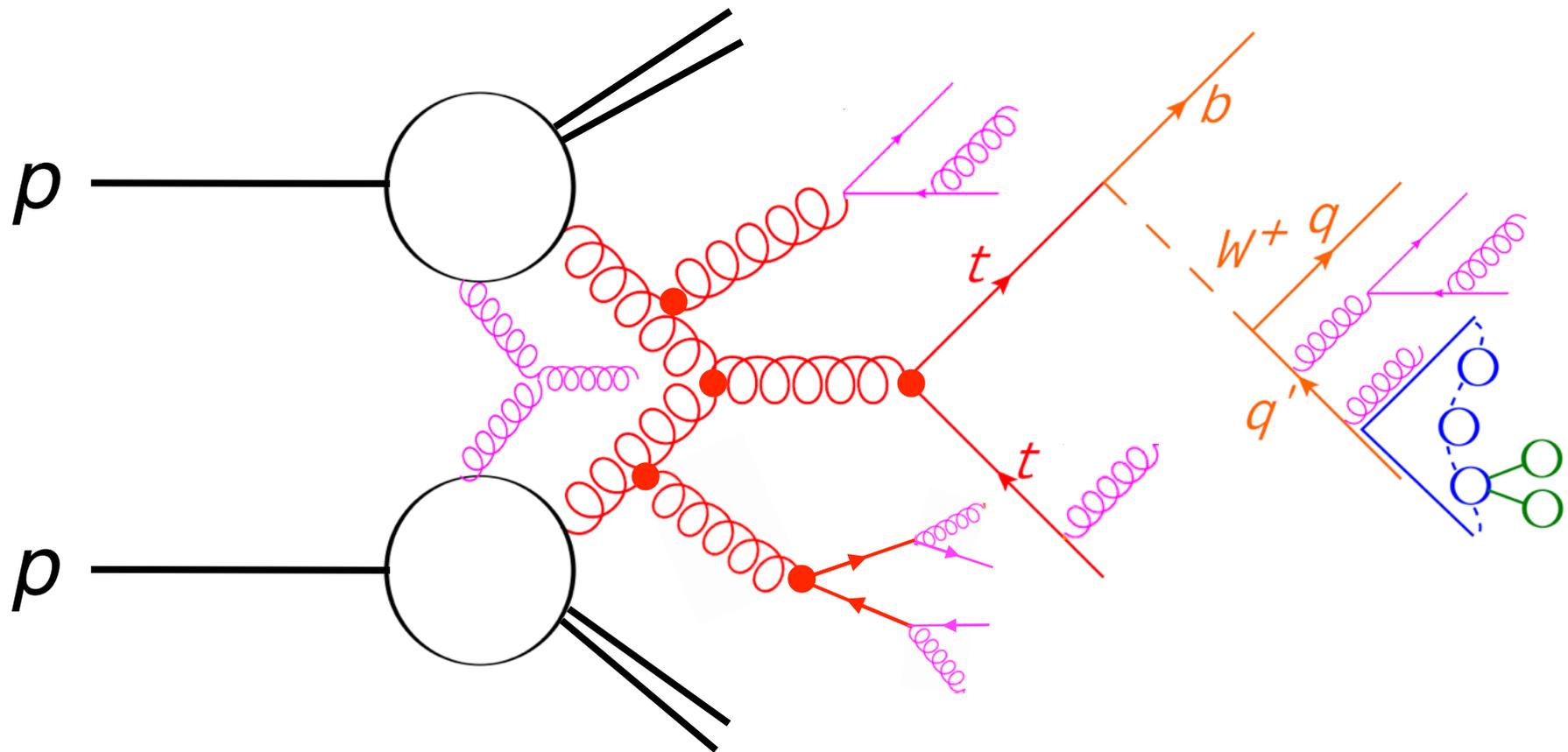


- measurements are sensitive to model parameter h_{damp} to regulate hardness of first radiation: $h_{\text{damp}} \sim m_{\text{top}}$ is best
- very important to model QCD processes

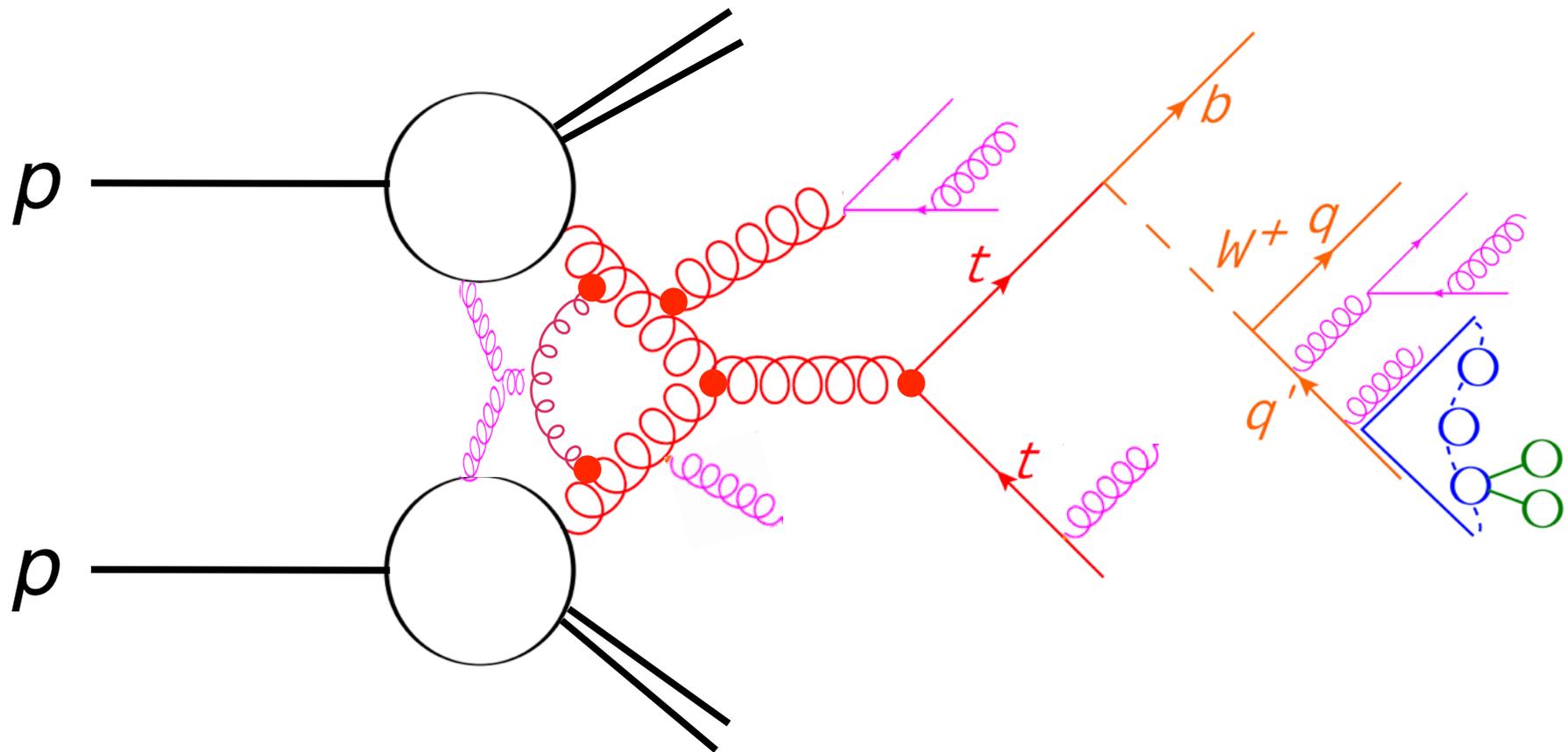
Top pair event generation



Top pair event generation



Top pair event generation



Top pair event generation

