Inclusive and Differential $t\bar{t}$ Cross Section Measurements

Luca Scodellaro
Instituto de Fisica de Cantabria - CSIC
On behalf of the ATLAS and CMS Collaborations

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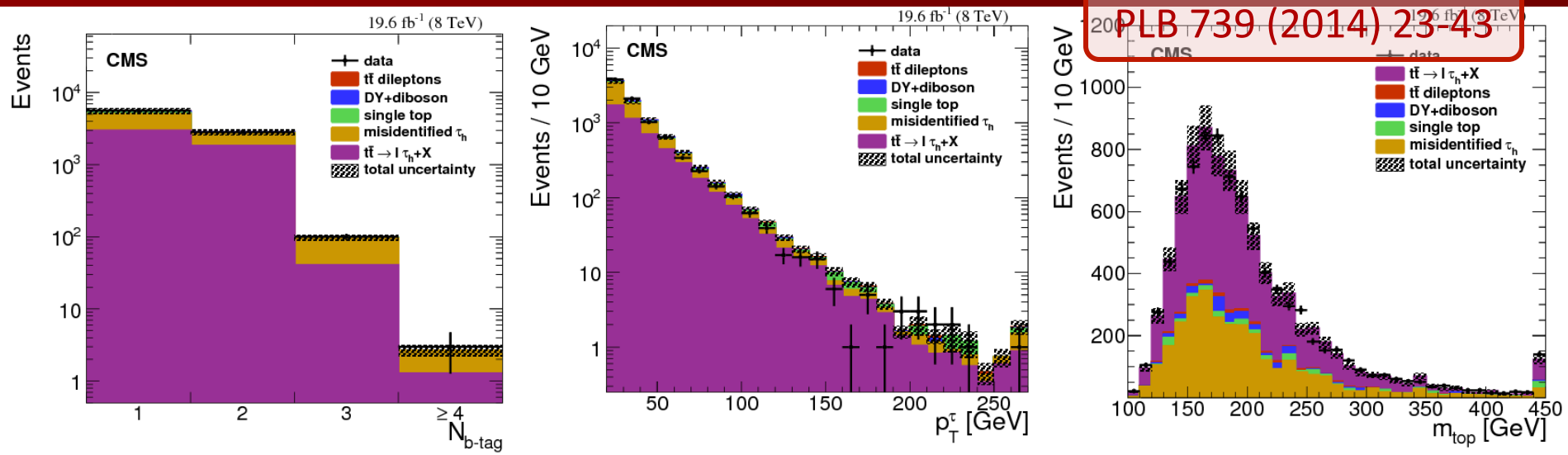
Outline

- Inclusive top pair production cross section:
  - Recent measurements at ATLAS and CMS
  - Measurements in the $t\bar{t} \rightarrow e\mu$ + jets channel
  - Combination of the results in the $t\bar{t} \rightarrow e\mu$ + jets channel at 8 TeV
- Differential $t\bar{t}$ cross sections:
  - Measurements in full and fiducial phase spaces
  - Particle level construction of parton-level observables (pseudo-top)
  - Differential cross section for boosted top production
- Links to public results from the ATLAS and CMS Collaborations:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Inclusive Cross Section Measurements

CMS: $t\bar{t}$ Cross Section in $e\tau/\mu\tau$ Events

PLB 739 (2014) 23-43



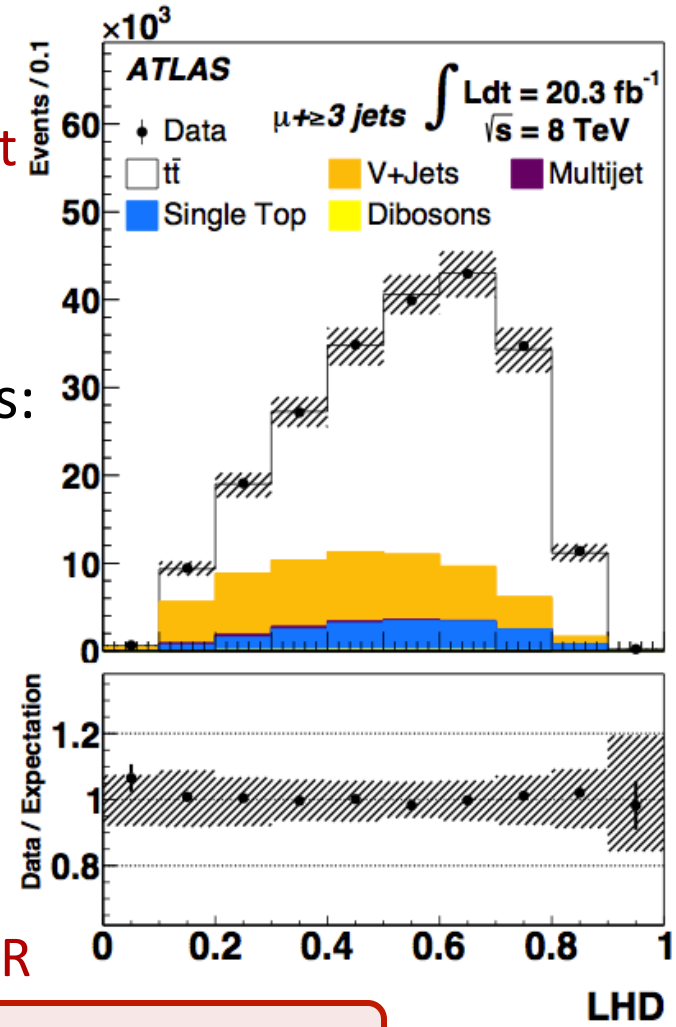
- Cross section measurement in 19.6 fb^{-1} of data at $\sqrt{s}$ = 8 TeV
  - One hadronically decaying tau τ_h, opposite charged isolated *e* or μ
  - Large E_T^{miss}, at least two jets of which at least one b-tagged
- Dominant background from misidentified τ_h (tt→l+jets and W+jets):
  - Misidentification probability measured as a function of jet p_T, η and width
  - Main systematics come from tau jet idetification (6.0%) and from tau misidentification background (4.3%)

$$\sigma_{tt} = 257 \pm 3\ (stat) \pm 24\ (syst) \pm 7\ (lum)\ pb$$

ATLAS: $t\bar{t}$ Cross Section in l+jets Events

arXiv:1504.04251v1

- Measurement in l+jets events selected in 20.3 fb^{-1} of data at $\sqrt{s}$ = 8 TeV:
  - Exactly one lepton, ≥3 jets, ≥1 b-tagged jet
  - E_T^{miss}>30 GeV and $m_T(W)$>30 GeV
- Signal extracted by a fit to a likelihood discriminant built from kinematic variables:
  - Lepton pseudorapidity η_l and event transformed aplanarity $\mathcal{A}' = \exp(-8\mathcal{A})$
  - Dominant background (V+jets) also extracted from the fit, other backgrounds fixed to MC or data-driven expectations
- Largest systematics from signal modeling
  - PDF, MC generator, parton shower, ISR/FSR

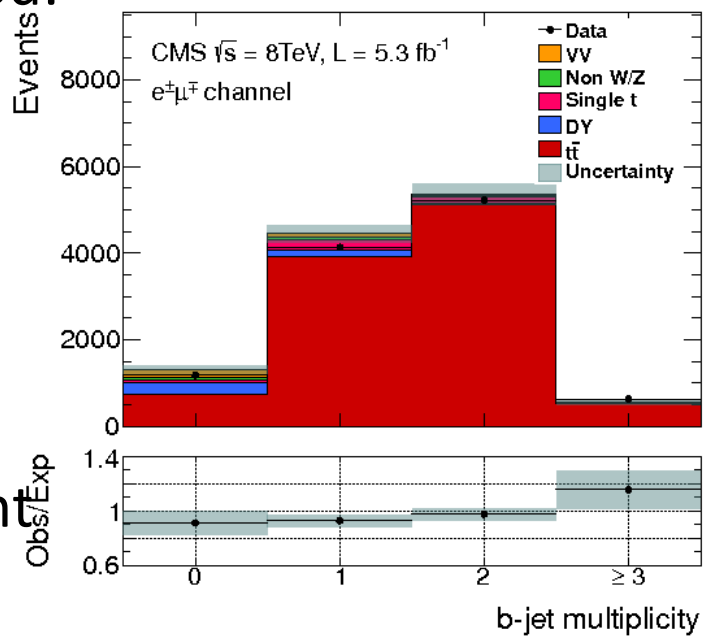


$$\sigma_{tt} = 260 \pm 1\ (stat)\ ^{+20}_{-21}\ (syst) \pm 8\ (lum) \pm 4\ (beam)\ pb$$

CMS: $t\bar{t}$ Cross Section in Dilepton Events

JHEP 02 (2014) 024

- Simple but robust cut-and-count method:
  - 5.3 fb^{-1} of data at $\sqrt{s}$ = 8 TeV
- Event selection:
  - Data collected by dilepton triggers
  - Two opposite charge leptons (*e* or *μ*)
  - At least two jets and one b-tagged jet
- Signal purity ~90% after tag requirement
  - Residual background estimated by a mixture of MC and data driven methods
- Combination of *ee*, *μμ* and *eμ* channels in agreement with SM prediction:



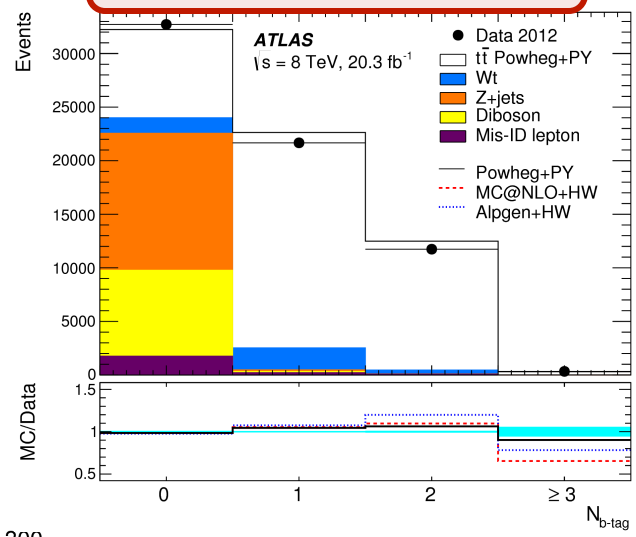
Main systematics (*eμ*)	%
Trigger efficiency	1.5
Lepton efficiency	1.7
Jet energy scale	2.2
Signal modeling	2.8

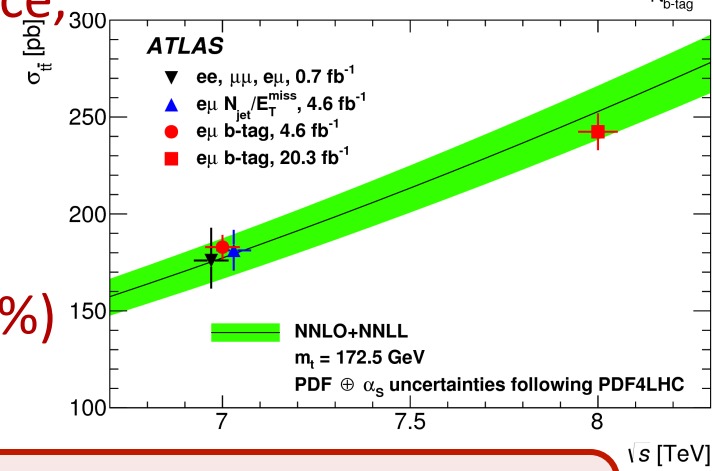
σ_{tt} = 239.0 ± 1.2 (stat) ± 11.3 (syst) ± 6.2 (lum) pb

ATLAS: $t\bar{t}$ Cross Section in the $e\mu$ Channel

EPJ C74 (2014) 3109

- Event selection:
  - Data collected by single lepton triggers
  - Opposite charge electron-muon pair
  - Exactly one or two b-tagged jets
- Method: simultaneous determination of
  - top pair production cross section
  - Probability for the b-jet to be in acceptance, being reconstructed and b-tagged
- Allows for reduced detector uncertainty
  - Main systematics from signal modeling: generator/hadronization (1.4%), PDF (1.1%)



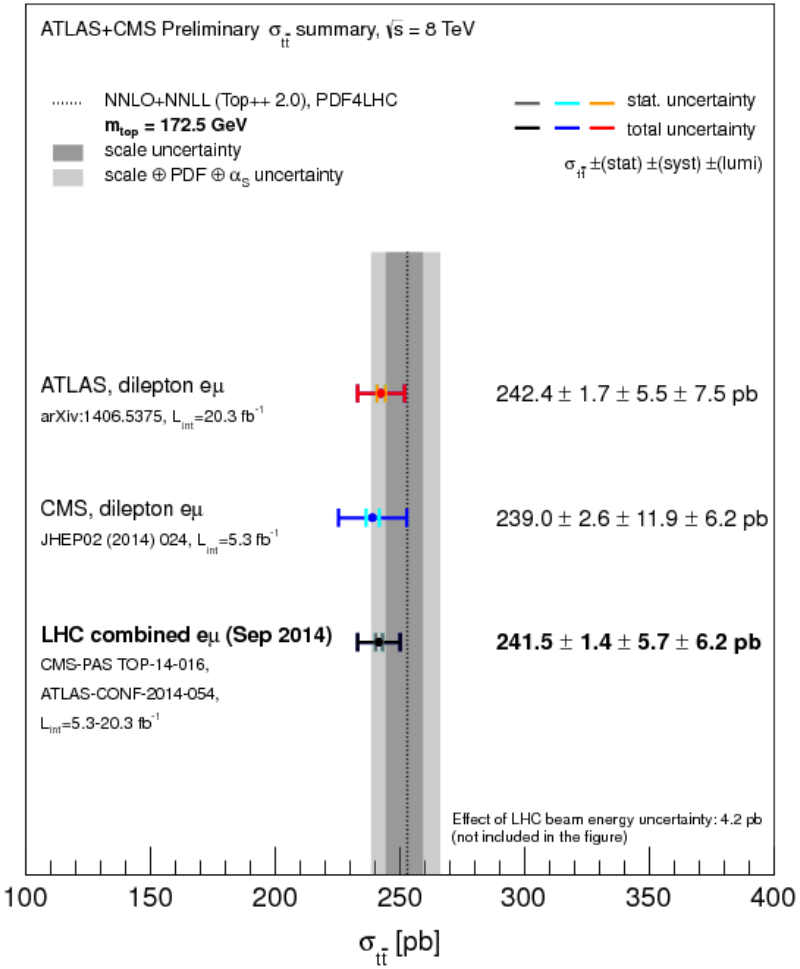


σ_{tt} = 182.9 ± 3.1 (stat) ± 4.2 (syst) ± 3.6 (lum) ± 3.3 (beam) pb (√s= 7 TeV)
σ_{tt} = 242.4 ± 1.7 (stat) ± 5.5 (syst) ± 7.5 (lum) ± 4.2 (beam) pb (√s = 8 TeV)

Combination of Results in the $e\mu$ Channel

CMS PAS TOP-14-016
ATLAS-CONF-2014-054

- Combination performed through the Best Linear Unbiased Estimator:
  - Results stable vs different choices of correlations of systematics between the two experiments
- Combined cross section reaches an accuracy of 3.5%:
  - Main systematic uncertainties come from beam modeling (1.4%) and luminosity determination (2.1%)
- Experimental uncertainty smaller than theoretical one (5.5%)



Differential Cross Section Measurements

Differential Cross Section Measurements

- Measuring the $t\bar{t}$ cross section as a function of the kinematic properties of the top quark or its decay products allows to:
  - Probe perturbative QCD calculations
  - Test different generator and showering models
  - Tune PDF sets and MC parameters on data

- Key ingredients of the differential cross section measurements:
  - Kinematic fit to reconstruct the kinematic properties of the top quarks and their decay products
  - Unfolding the observed distributions from the reconstruction level to the parton or particle level:
    - ✧Correct for acceptance and detector effects
    - ✧Directly compare to predictions from theory

Differential Cross Section in Full Phase Space

- Extrapolation to full phase space at parton level:

$$\frac{d\sigma}{dX_j} \equiv \frac{1}{\Delta X_j} \cdot \frac{\sum_i \mathcal{M}_{ji}^{-1}[D_i - B_i]}{\mathrm{BR} \cdot \mathscr{L} \cdot \epsilon_j}$$

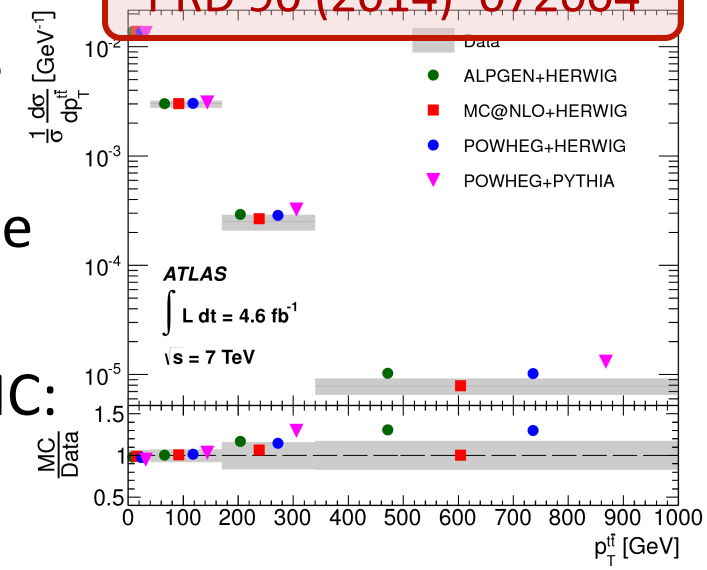
  - Results unfolded to parton level correcting for hadronization and detector effects
  - Extrapolation to part of the phase space out of acceptance through simulation

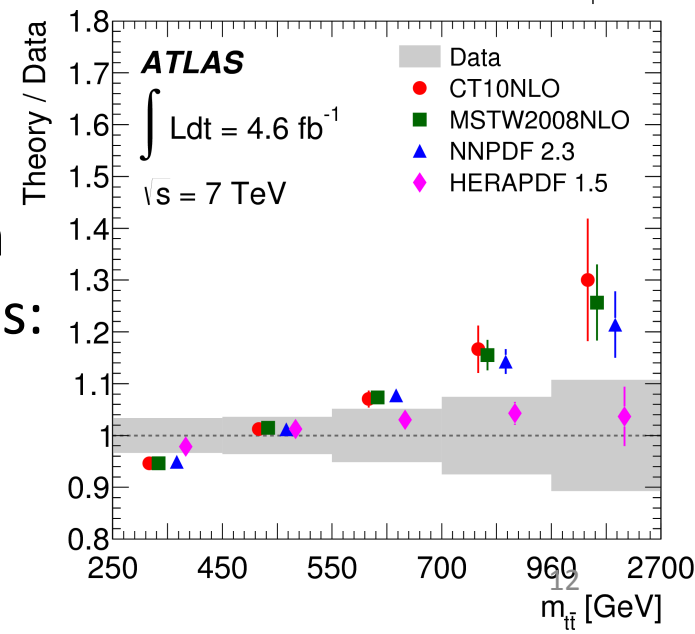
- Model dependent measurement, but can be directly compared to perturbative QCD calculations

Differential Cross Section in Full Phase Space

PRD 90 (2014) 072004

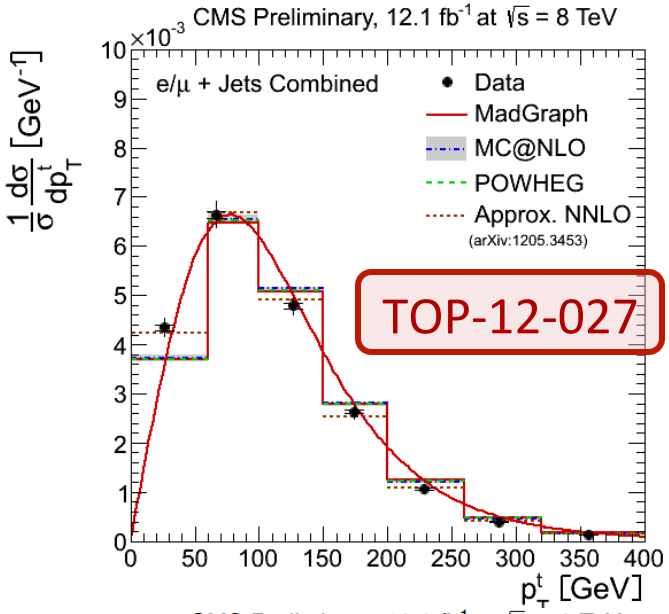
- ATLAS: differential cross sections in l+jets events at √s = 7 TeV
- Parton level quarks are defined before the decay and after QCD radiation
- Data have sufficient precision to probe MC:
  - No single generator performs best for all kinematic variables studied
  - Measured cross section lower than expected for high top-quark momentum
- Measurements also discriminate between NLO QCD predictions for different PDF sets:
  - HERAPDF1.5 generally shows better agreement with observed distributions

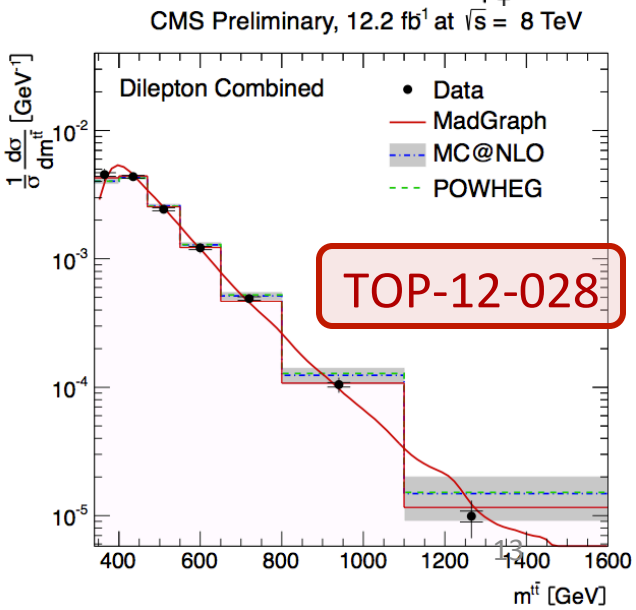




Differential Cross Section in Full Phase Space

- CMS: differential cross sections in l+jets and dilepton events at √s = 8 TeV
- Approximate NNLO calculation provides a better description of the top-quark transverse momentum spectrum
- $t\bar{t}$ mass distribution suggests a better agreement with data for MADGRAPH+PYTHIA than for POWHEG +PYTHIA and MC@NLO +HERWIG



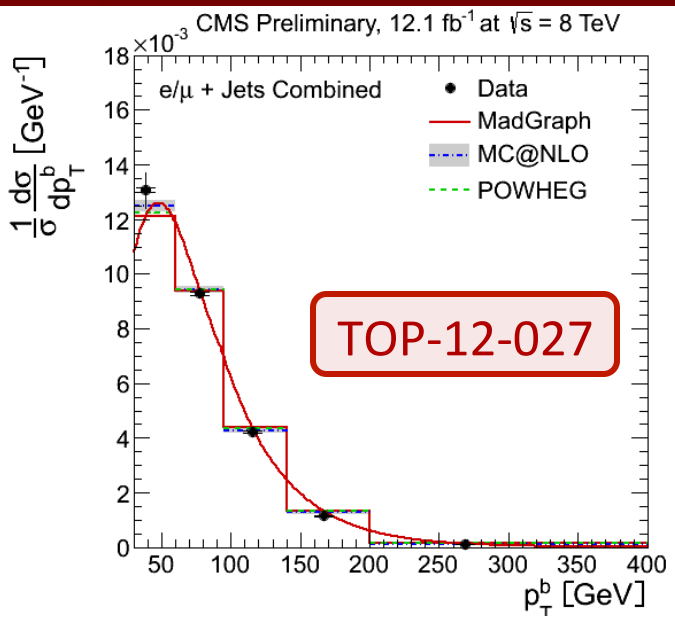


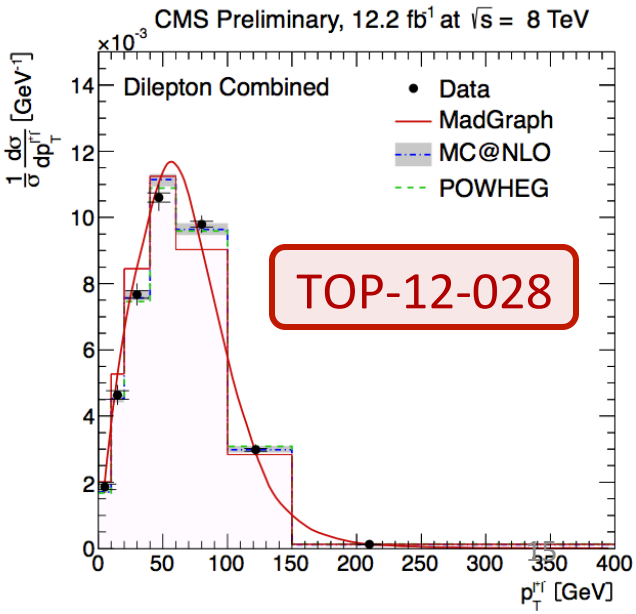
Differential Cross Section in Fiducial Region

- Fiducial cross section measurements:
  - Unfolding to particle level in the experimentally accessible region
  - Correcting mostly for detector effects
  - Reduced model dependence
- ATLAS and CMS agreed on a common definition of particle level objects for fiducial cross section measurements (TopLHC working group):
  - Leptons: stable *e* and μ not coming from hadron decays and dressed with photons if $\Delta R<0.1$
  - E_T^{miss}: defined by the sum of all neutrinos excluding the ones coming from hadron decays
  - Jets: reconstructed by the anti-k_t algorithm on all stable particles but dressed leptons
  - b-jets: jets containing a *ghost* B hadron
    - ✓ B hadrons are made ghost by scaling down their momentum to negligible values and then added to the list of stable particles for jet-clustering

Differential Cross Section in Fiducial Region

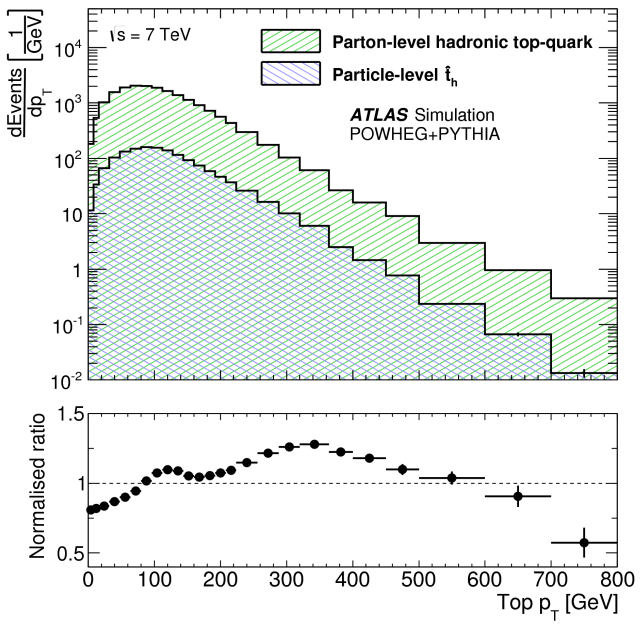
- CMS: differential cross sections in l+jets and dilepton events at √s = 8 TeV
- Not yet based on TopLHC particle level object definition:
  - Stable (status code 1) leptons from W decays, not dressed by photons
  - b-jets: particle level jets containing the decay products of a B hadron
- MC@NLO+HERWIG and POWHEG+PYTHIA predictions take into account $t\bar{t}$ spin correlations and suggest a better description of the lepton-pair observables

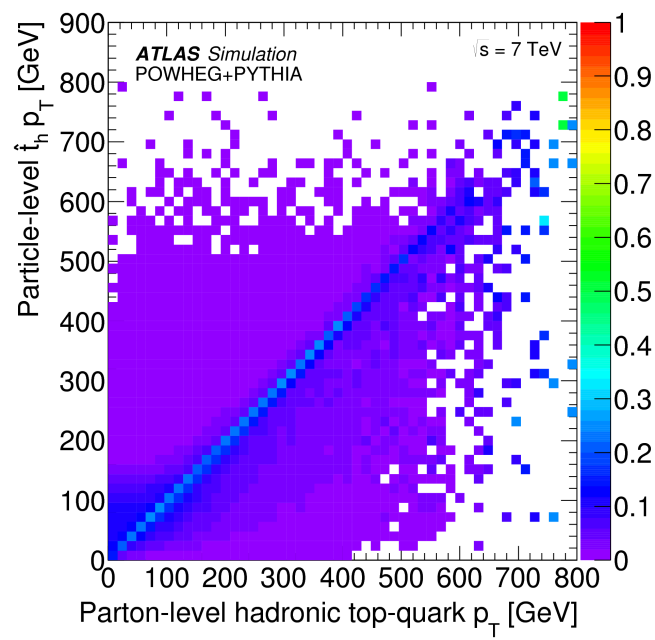




Differential Cross Section with Pseudo-Top

- ATLAS: using particle-level objects as defined in the TopLHC working group to construct pseudo-tops which:
  - Avoid large model-dependent extrapolations to parton-level top quarks and to full phase space
  - Remain strongly correlated with corresponding partons from QCD calculations



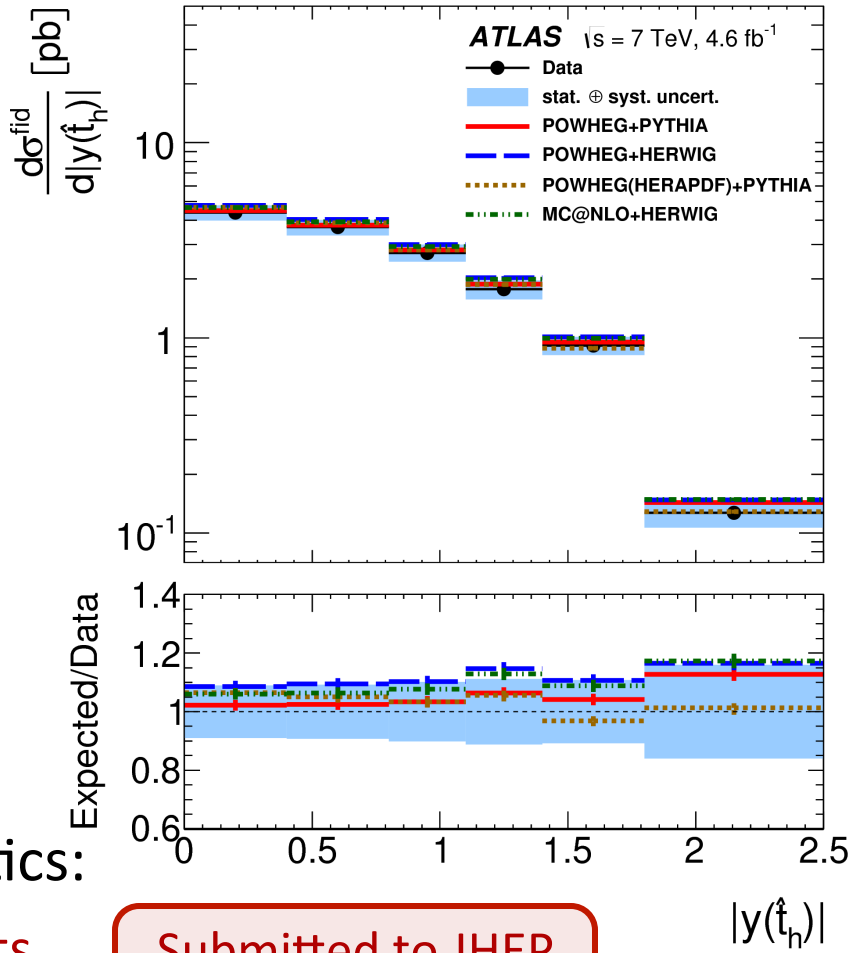


Differential Cross Section with Pseudo-Top

- ATLAS: differential cross section as a function of pseudo-top variables in the l+jets channel at √s = 7 TeV

- Observed distributions show some sensitivity to PDF sets and parton shower models:
  - POWHEG(HERAPDF)+PYTHIA provides generally the best representation

- Measurements limited by systematics:
  - b-tagging, jet energy measurements, initial/final state parton shower

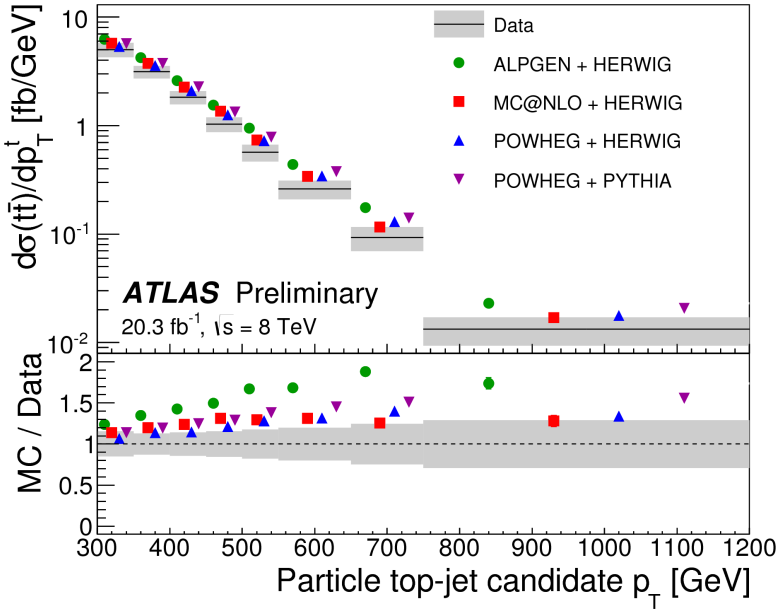


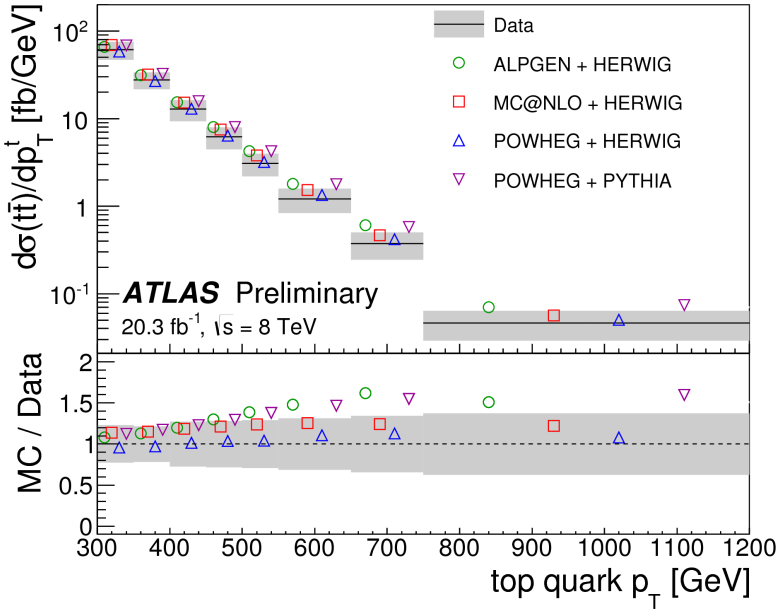
Submitted to JHEP
arXiv:1502.05923

Differential Cross Section of Boosted Tops

ATLAS-CONF-2014-057

- First differential cross section measurement for boosted top:
  - Using lepton + jets events in √s = 8 TeV data
  - Hadronic top decay reconstructed as jet with R=1.0 with substructures
- Unfolding to fiducial (particle-level) and full (parton-level) phase space
  - JES for large-R jets main systematic for particle-level measurements
  - Signal modeling uncertainty much larger for results at parton level
- NLO and LO+parton shower MC predictions overestimate data





Overview of Differential Cross Sections

Observables	Full phase space (parton level)	Fiducial phase space (particle level)
top quark, ttbar system	ATLAS (L+J) 7TeV PRD90, (2014) 072004 CMS (L+J) 7TeC EPJ C73 (2013) 2339 CMS (L+J) 8TeV CMS PAS TOP-12-027 CMS (LL) 8TeV CMS PAS TOP-12-028	ATLAS (L+J) 7TeV arXiv:1502.05923 CMS (LL) 8TeV CMS PAS TOP-12-028
Final state particles		CMS (L+J) 8TeV CMS PAS TOP-12-027 CMS (LL) 8TeV CMS PAS TOP-12-028
Global event variables	CMS (L+J) 7TeV CMS PAS TOP-12-019 CMS (L+J) 8TeV CMS PAS TOP-12-042	
ttbar+jets	CMS (LL) 8TeV CMS PAS TOP-12-041	ATLAS (LL) 7TeV EPJ C72 (2012) 2043 ATLAS (L+J) 7TeV JHEP01(2015)020 ATLAS (L+J) 7TeV PHYS-PUB-2015-002 CMS (L+J/LL) 7TeV EPJ C74 (2014) 3014 CMS (LL) 8TeV CMS PAS TOP-12-041
Boosted top		ATLAS (L+J) 8TeV ATLAS-CONF-2014-057

Conclusions

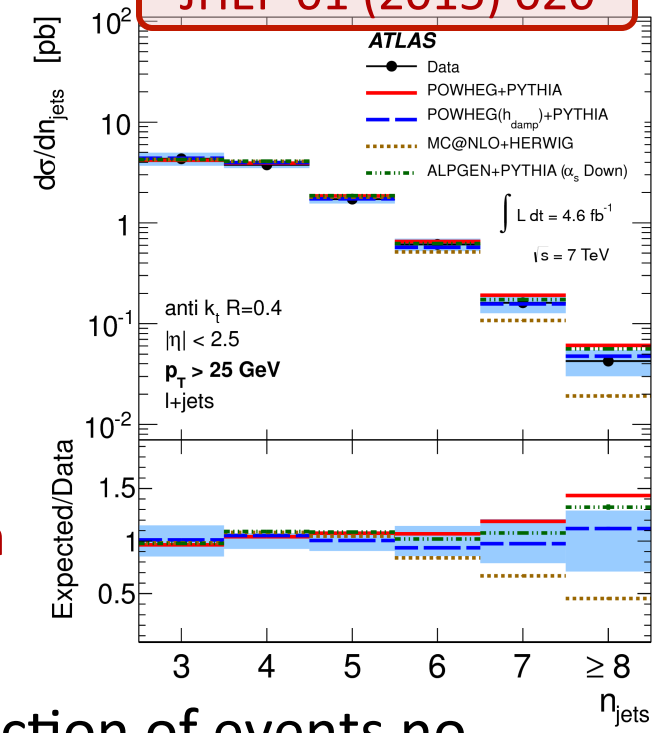
- Top pair production measurements at LHC are constraining the modeling of top pair production:
  - Some preference starts to emerge from data (HERAPDF1.5 generally shows better agreement with measuremens)
  - Yet no MC generators performs better than the other in all the kinematic region studied
  - High-p_T regime remains challenging
- Improving experimental precision requires careful definition of measured object and procedures:
  - ATLAS and CMS collaborations working to improve matching between particle level and reconstructed objects, synchronizing unfolding techniques, understand systematic correlations, etc.
  - This conference is a great opportunity to share new ideas with a wider community!
- 13 TeV era at LHC is a great challenge and opportunity

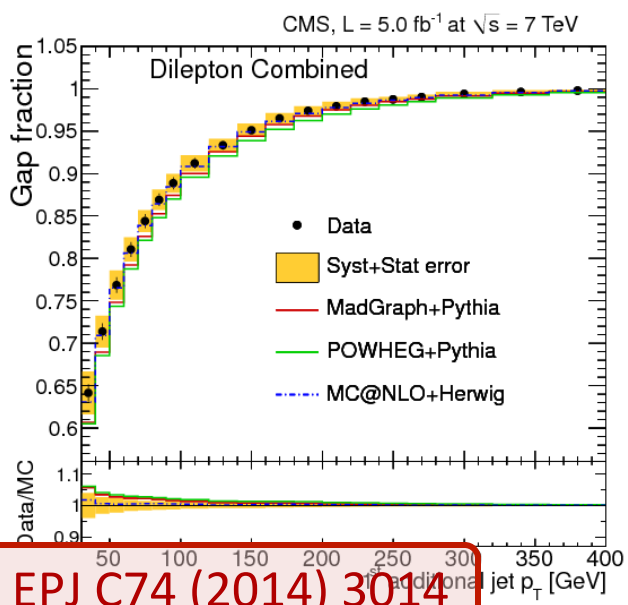
Backup Material

Jet Distributions in Top Pair Events

- Differential cross section as a function of jet multiplicity and jet p_T:
  - Several jet p_T thresholds used
- Probing higher order effects of different generators and shower models:
  - POWHEG+PYTHIA with tuning of hard radiation provides best overall description

JHEP 01 (2015) 020



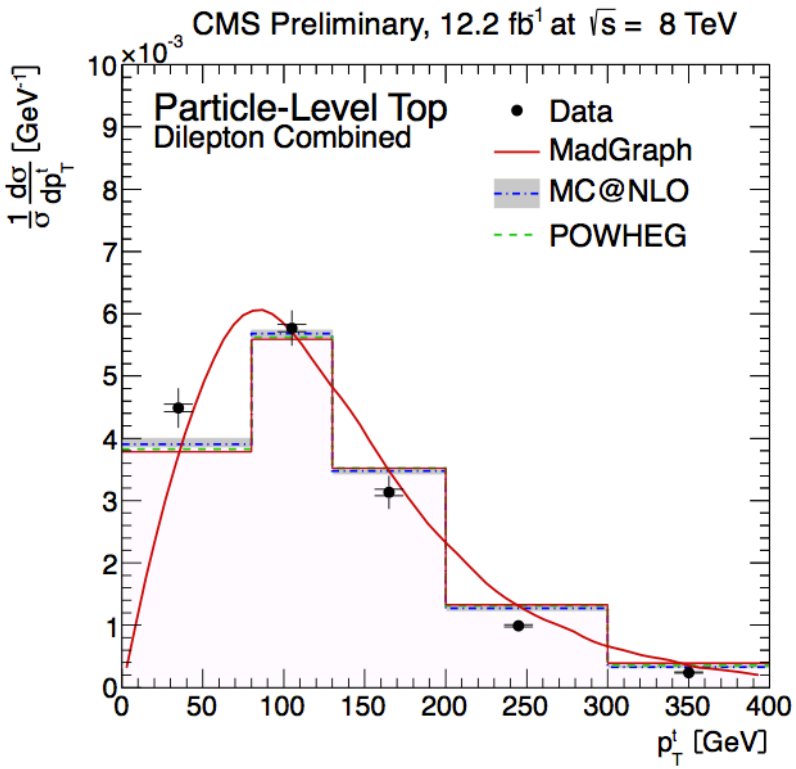


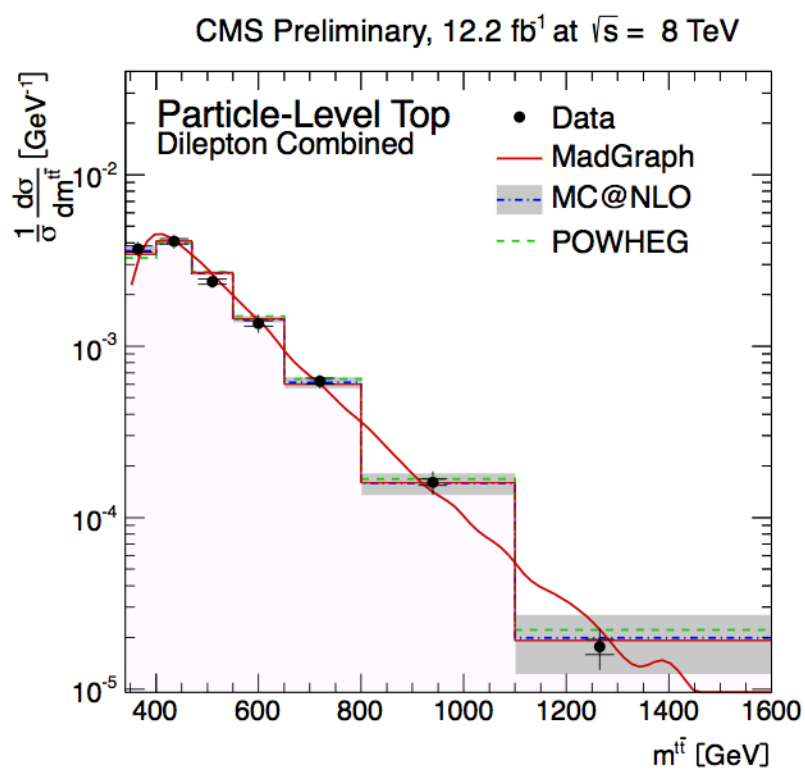
EPJ C74 (2014) 3014

- Gap fraction: fraction of events no containing additional jets:
  - Thresholds on leading additional jet p_T or scalar sum of the additional jets p_T
- Good agreement data vs MC:
  - MC@NLO+HERWIG seems more accurate

Differential Cross Section with Pseudo-Top

- CMS results for pseudo-top differential cross section
  - Similar reconstruction as in ATLAS
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PasTop12028AdditionalMaterial





Particle Level Objects

- The objects considered in the event record are stable particles (mean lifetime > 0.3×10^{-10}s) within the observable pseudorapidity range.
- **Photons**: photons used for final state definitions and for the definition of leptons (electron & muon) should not be from hadron decays. These removes the dependency on the underlying event.
- **Electron**: define 4-momentum from photons and electron within an anti-k_t R=0.1, where leptons (electron & muons) are considered for jet clustering. No isolation condition is imposed. In order to choose prompt leptons from W/Z decay in a way safe for all generators currently under consideration, the parent of the electron is required not to be a hadron or quark (u-b). (Expect that future sanitisation of generator record will remove the need for the quark requirement.)
- **Muon**: define 4-momentum from photons and muon within an anti-k_t R=0.1, where leptons (electron & muons) and photons are considered for jet clustering. No isolation condition is imposed. In order to choose prompt leptons from W/Z decay in a way safe for all generators currently under consideration, the parent of the muon is required not to be a hadron or quark (u-b). (Expect that future sanitisation of generator record will remove the need for the quark requirement.)

Particle Level Object (cont.)

- **E_T^{miss}/Neutrinos**: As an event level variable the missing transverse energy is calculated as the 4-vector sum of neutrinos from W/Z--boson decays. Tau decays are included. A neutrino is treated as a detectable particle and is selected for consideration in the same way as electrons or muons, i.e. the parent is required not to be a hadron or quark (u-b). (Expect that future sanitisation of generator record will remove the need for the quark requirement.)
- **Jets**: define with anti-k_t algorithm. Loop over all stable particles excluding the electrons, muons, neutrinos, and photons used in the definition of the selected leptons. This includes non-prompt muons and neutrinos for a proper b-jet energy scale. Use specific R parameter chosen by experiment: R=0.4 for ATLAS and R=0.5 for CMS.
- **b-jets**: A jet is a b-jet if any rescaled B-hadron is included in the jet. A rescaled B-hadron is treated as a stable B-hadron (that does not oscillate or decay to another B-hadron) for which the 4-momentum is scaled down by to the limit of floating point precision and added to the list of particles for jet-clustering as described above. Only B-hadrons with an initial $p_T > 5$ GeV are considered. This prescription provides an unambiguous way to associate a single jet with a B-hadron.
- **Further cuts in the event**: overlap removal, such as applied to reconstructed objects, does not make sense when the selected leptons are not included within jets. Instead, events where the leptons overlap with the selected jets should be discarded. For example, for a anti-k_t radius parameter of 0.4, events with dR(jet,el/mu) < 0.4 should be discarded.

Particle-Level Event Selection

Proposed event selection aiming at matching the event selection for particle-level objects with reconstructed objects

- **Single lepton channels (electron, muon)**:
  - Exactly one selected electron or muon with |eta| < 2.4 and p_T > 30 GeV
  - Not any other lepton (electron or muon) with |eta| < 2.5 and p_T > 15 GeV
  - Neutrino sum pt > 30 GeV
  - m_T(W), defined as sqrt(2*pt(l)*pt(v)*(1-cos(phi(l)-phi(v)))), > 30 GeV
  - At least two b-tagged jets in the region |eta| < 2.4 and p_T > 30 GeV
  - At least four jets in the region |eta| < 2.4 and p_T > 30 GeV
- **Dilepton channels (electron, muon)**:
  - At least two selected leptons (ee, eμ, μμ) with |eta|<2.4 and p_T>30 GeV
  - For same-flavour channels, neutrino sum p_T>60 GeV
  - At least two b-tagged jets in the region |eta| < 2.4 and p_T > 30 GeV

NB: the requirement of at least two b-tagging jets is for the study of pseudo-top-quark. Other analyses that study more inclusive kinematics may be more suited to require at least one b-tagged jet.

Pseudo Top Quark Definition

- **Single lepton events**:
  - Require exactly 1 electron or exactly 1 muon; no other leptons.
  - Require >=4 jets
  - Require >=2 b-jets
  - Select the two highest p_T b-jets as the b-jets to be used for the pseudo-top-quark definition.
  - Define the leptonic W by combining the lepton with the E_T^{miss} and solving for p_z assuming the W mass (highest p_z from two-fold ambiguity)
  - Combine the b-jet closest to the lepton with the leptonic W, to form the leptonic pseudo-top-quark.
  - Define the hadronic W from the two highest p_T jets that are not the two selected b-jets.
  - Combine the remaining b-jet with the hadronic W, to form the hadronic pseudo-top-quark.

Pseudo Top Quark Definition

- **Dilepton events**:
  - Require >=2 jets
  - Require >= 2 b-jets
  - Require exactly 2 opposite sign leptons (e,μ)
  - If leptons have the same flavor, require m(ll) > 20 GeV and |m(ll)-M_z| > 10GeV
  - Pseudo-Ws: consider only the 2 leading p_T selected neutrinos. The (nu,lep) pair that gives combined lepton-neutrino four momenta W1 and W2 with the minimal |m_W1-M_W_PDG|+|m_W2-M_W_PDG| is used to construct the pseudo-Ws from the dilepton decay.
  - Pseudo-top: the pair (b-jet_1, W) pair that gives the combined b-W four momenta ith the minimal |m_T1-M_top_PDG|+|m_T2-M_top_PDG| is used to construct the pseudo-top-quarks.