# Standard Model WW/WZ→lνjj measurement at $\sqrt{s}$=8 TeV with the ATLAS detector.

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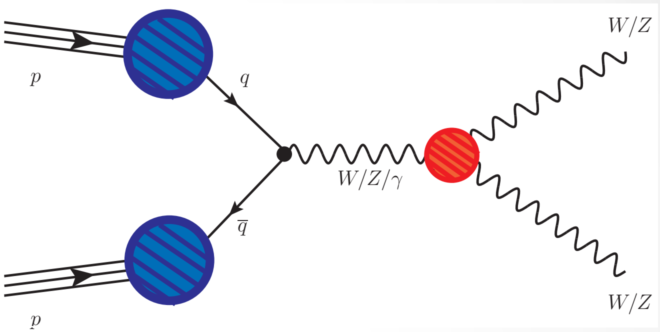
# Overview

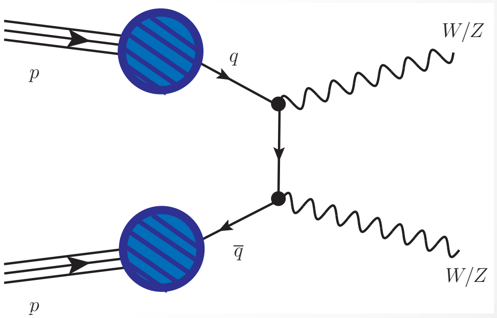
- Motivations and previous measurements.
- 8 TeV analysis strategy
  - Cross section measurement
  - Anomalous Triple Gauge Coupling (aTGC)

# Semileptonic diboson production

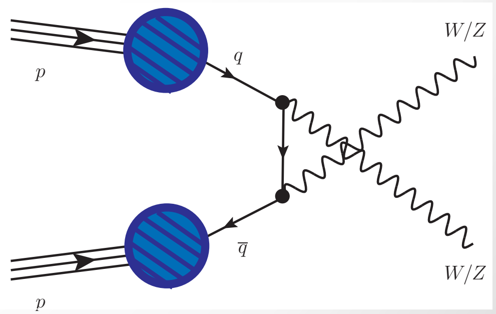
- Associated production of a gauge bosons pair: WW or WZ
  - A *W* decays to e $\nu$ or $\mu$ $\nu$. The other *W* or *Z* decays to a jet pair.



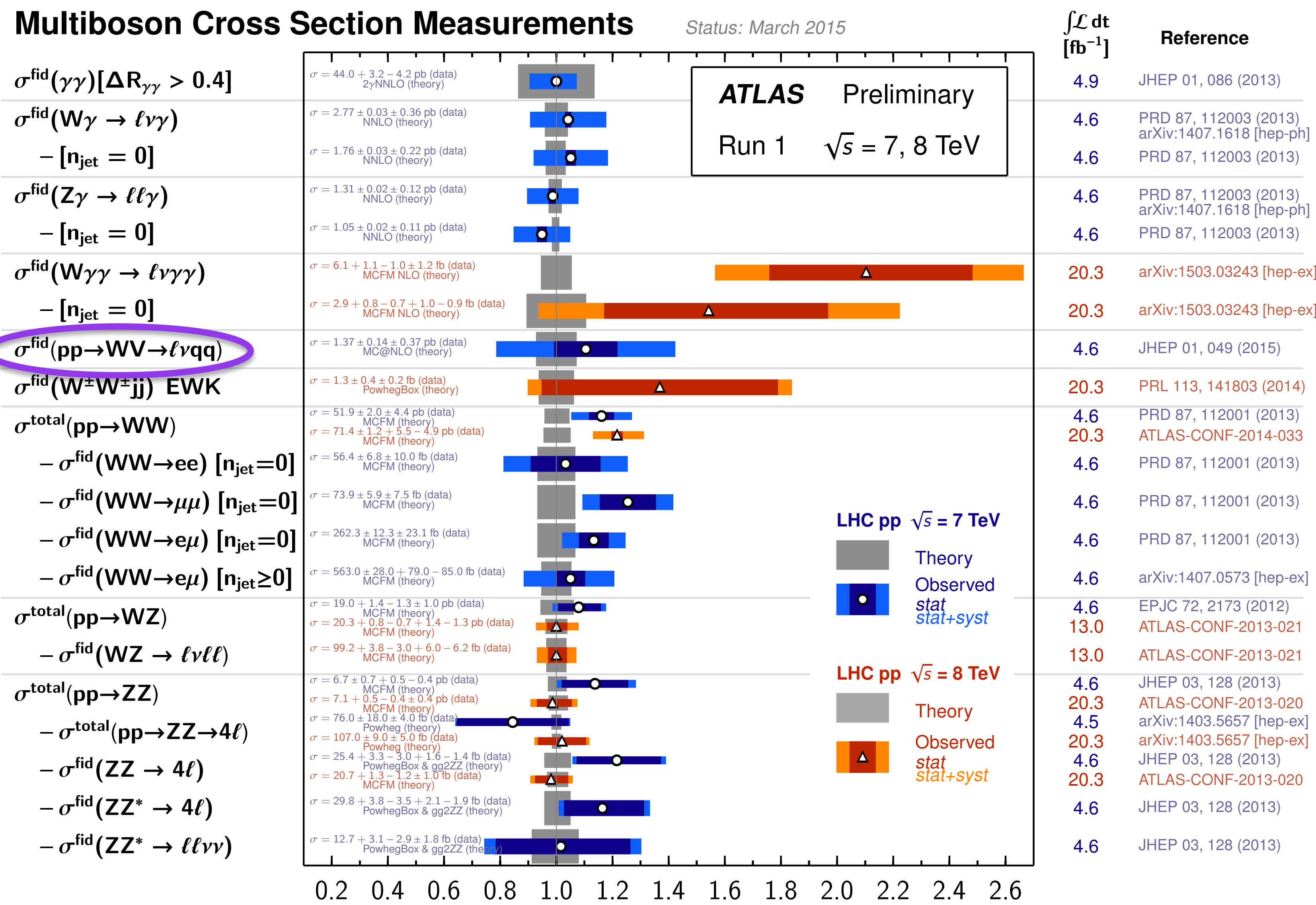

- Interactions between vector bosons:
  - Test of non-Abelian electroweak gauge symmetry
  - Possible anomalous coupling due to new physics




- Main background to Higgs physics:
  - WH/ZH, H→WW
- Detecting di-jet resonances: a key technique for future (and present) analysis at hadron colliders.



# A wide analysis effort



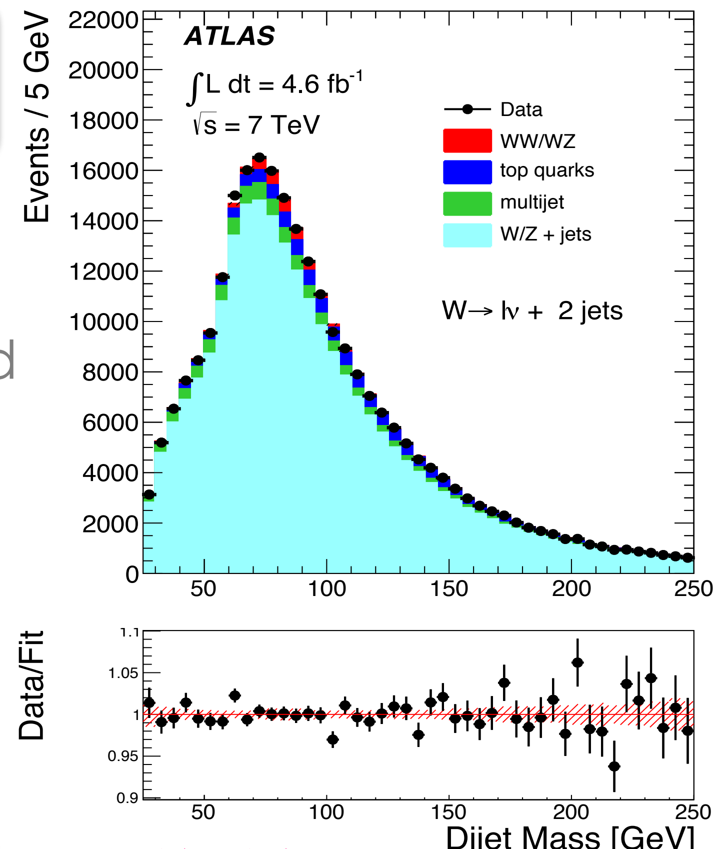
# WW/WZ→lνjj 7 TeV measurement

- In agreement with Standard Model.
  - Cross section: systematic dominated
  - aTGC: statistics dominated

$$7\ \mathrm{TeV}: \int L dt \simeq 5\ \mathrm{fb}^{-1}$$
$$8\ \mathrm{TeV}: \int L dt \simeq 20\ \mathrm{fb}^{-1}$$

$$\sigma^{measured}_{WW+WZ}(7\ \mathrm{TeV}) = 68 \pm 7(\mathrm{stat.}) \pm 19(\mathrm{syst.})\ \mathrm{pb}$$
$$\sigma^{expected}_{WW+WZ}(8\ \mathrm{TeV}) \simeq 80.13 \pm 8\%\ \mathrm{pb}$$

- At 8 TeV:
  - gain sensitivity in aTGC measurement.
  - larger fraction of W/Z bosons produced with a Lorentz boost
  - better modelling of close-by jets topologies
  - Possible to separate signal peak from background peak.
  - Parallel analysis: highly boosted topology

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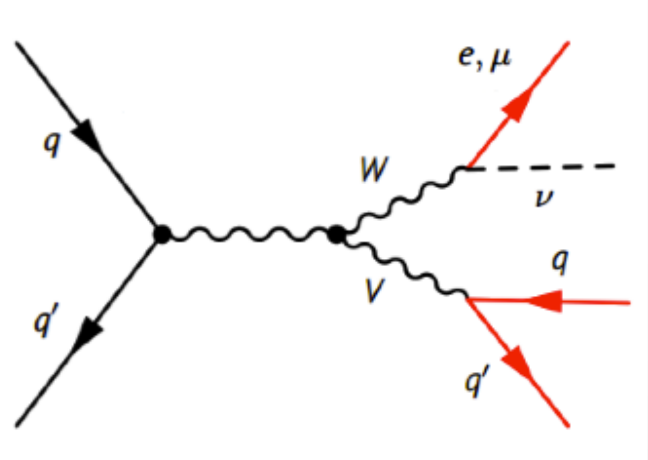
# 8 TeV analysis

- Collaboration between several institutions.
- We followed the same strategy adopted at 7 TeV:
  - select l $\nu$ jj events
  - MonteCarlo simulation of signal and background
  - fit of the jet-jet invariant mass spectrum to extract the signal cross section

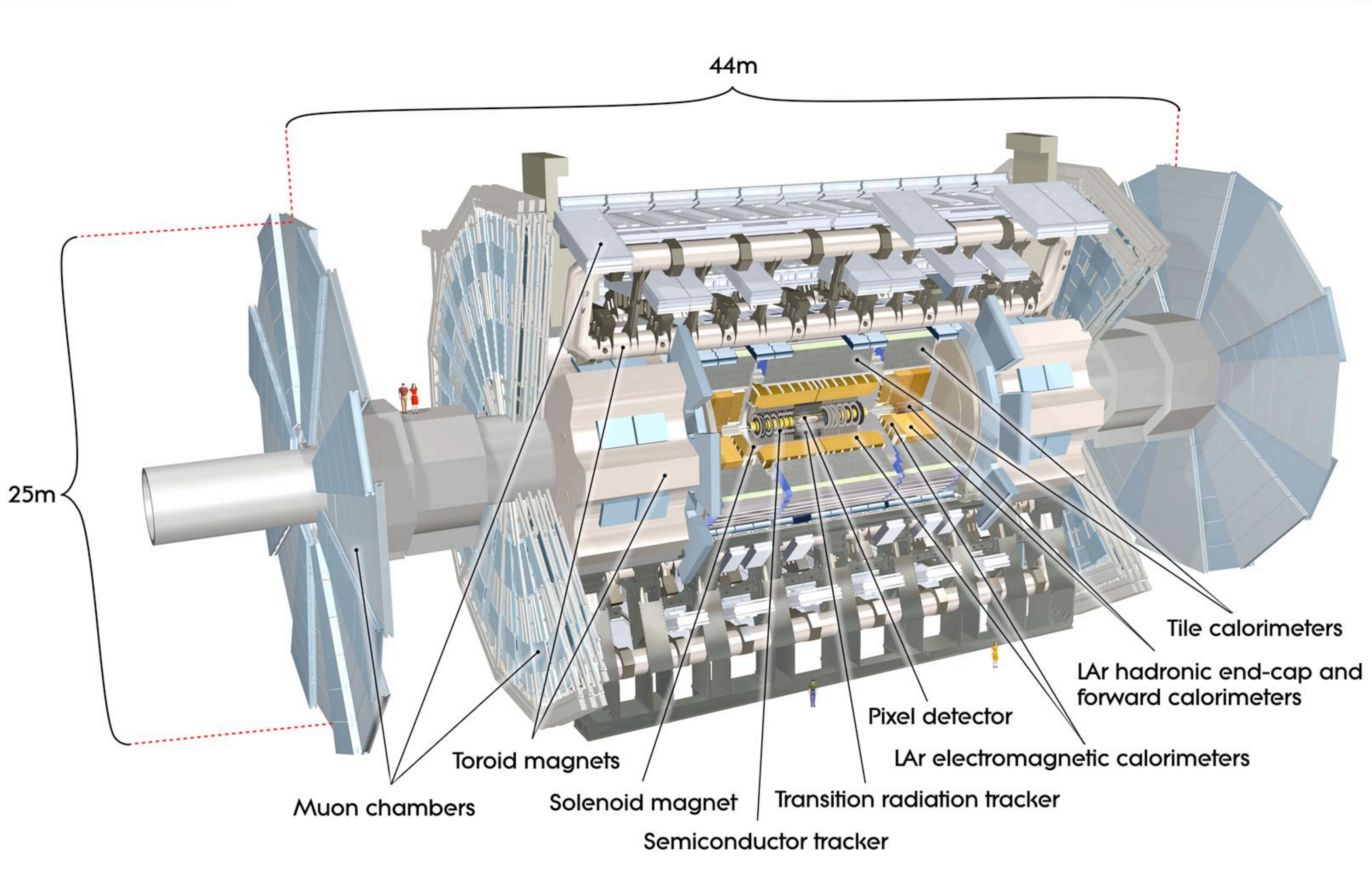
Background contribution:

- W + jets
- top/anti-top production
- single top production
- Z + jets
- QCD multijet

- W+jets is the largest contribution

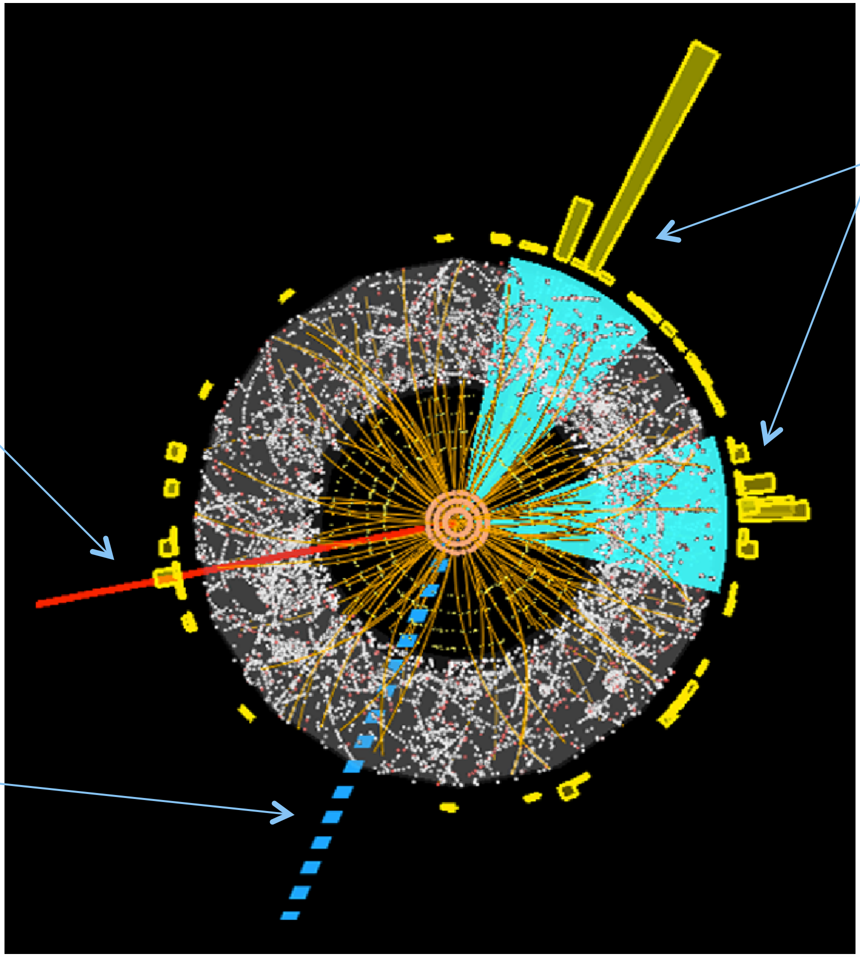


# The ATLAS detector



# Physics objects

- ELECTRON / MUON
  - good reconstruction quality
  - $p_T > 30$ GeV
  - central $\eta$ region
  - impact parameter
  - isolation



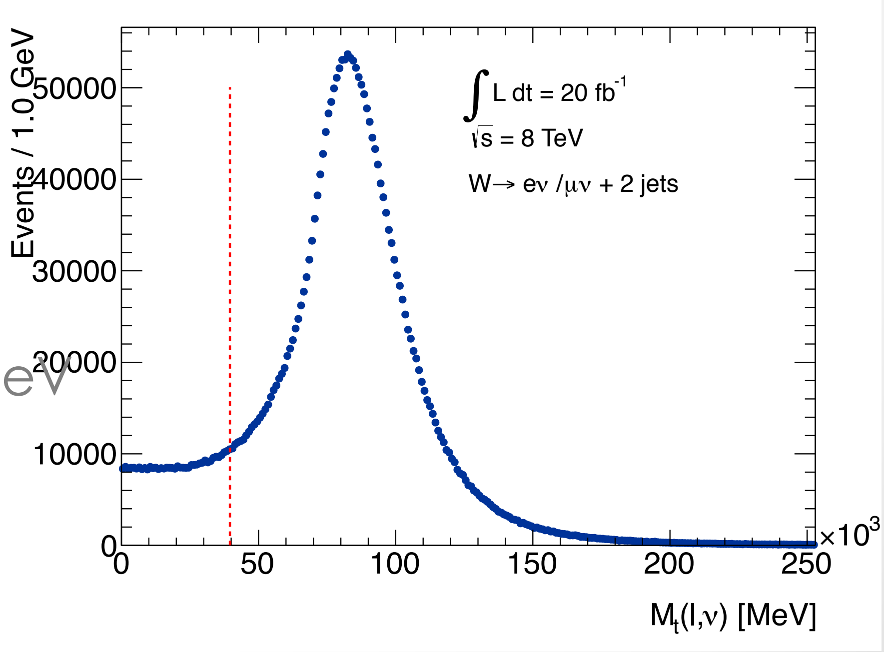
- JETS
  - Anti_Kt, R=0.4
  - $p_T > 25$ GeV
  - central $\eta$ region
  - reject jets originating from PileUp

- $E_T^{miss}$
  - complementary sum of $p_T$ of all particles in the event
  - $E_T^{miss} > 40$ GeV

# Event selection

- Preselection:
  - Un-prescaled trigger on a single lepton
  - Detector based quality criteria
  - One primary vertex, at least three associated tracks

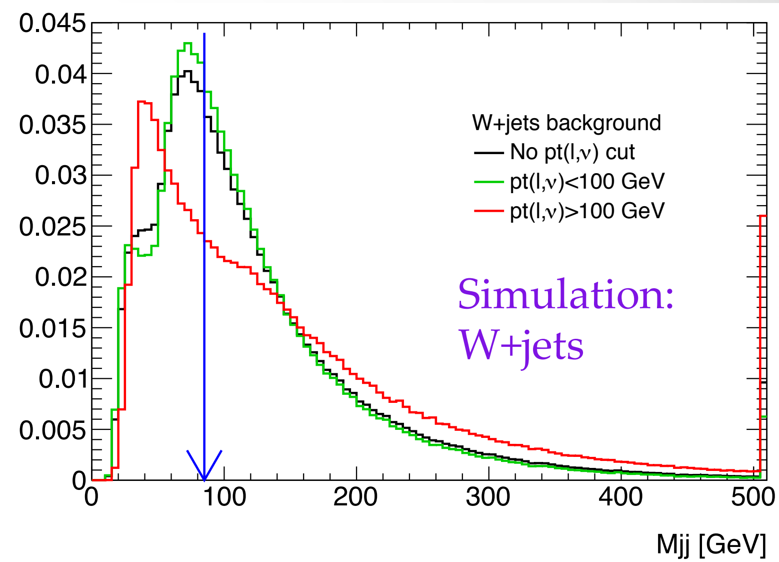
- Select leptonic W decay:
  - exactly one selected lepton,
  - not overlapping with jets.
  - $E_T^{miss} > 40$ GeV
  - Transverse mass: $M_T(l,E_T^{miss})>40$ GeV

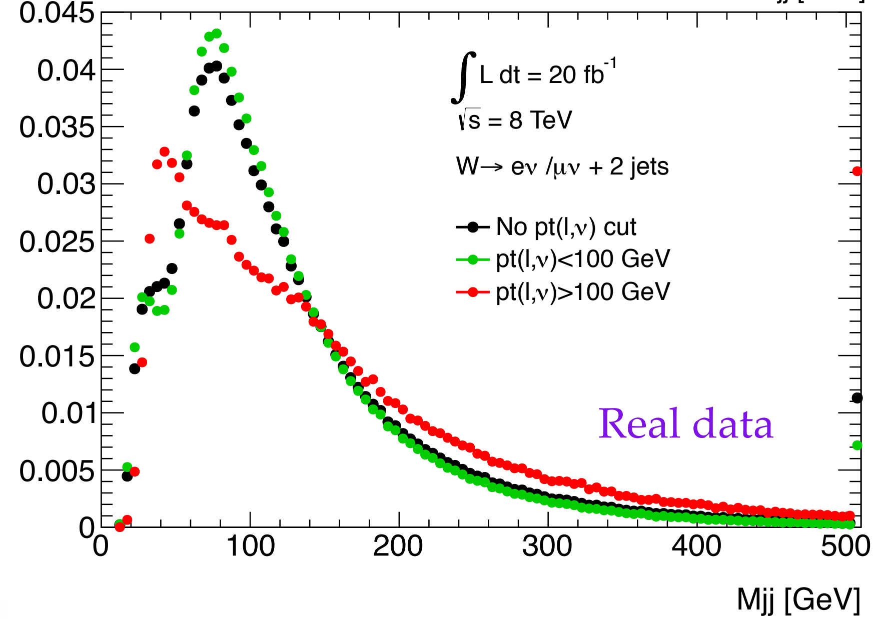



- Select hadronic W/Z decay:
  - exactly two selected jets
  - optimized cuts to reduce background (next)

# Further di-jet event selection

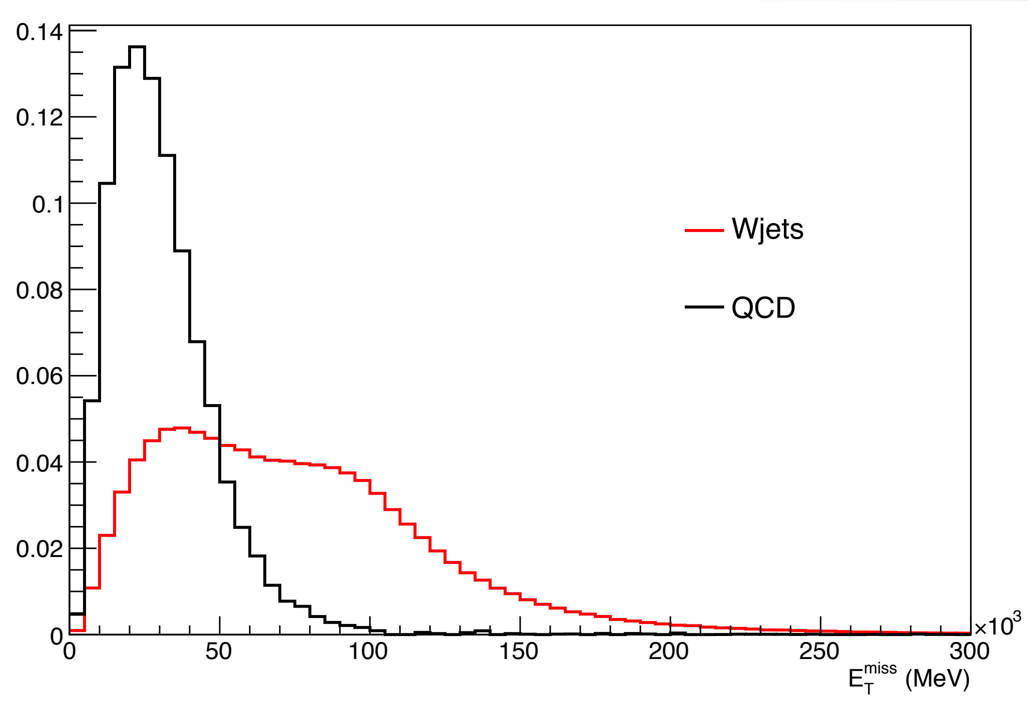
- Reduce QCD background:
  - $\Delta\Phi(j_{lead}, E_T^{miss}) > 0.8$
- Increase signal over background ratio:
  - $\Delta\eta(j_{lead}, j_{sublead}) < 1.5$
- Separate signal peak from background peak:
  - $p_T(W) > 100$ GeV
    $(p_T(W) = |\mathbf{p}_T(l) + \mathbf{E}_T^{miss}|)$



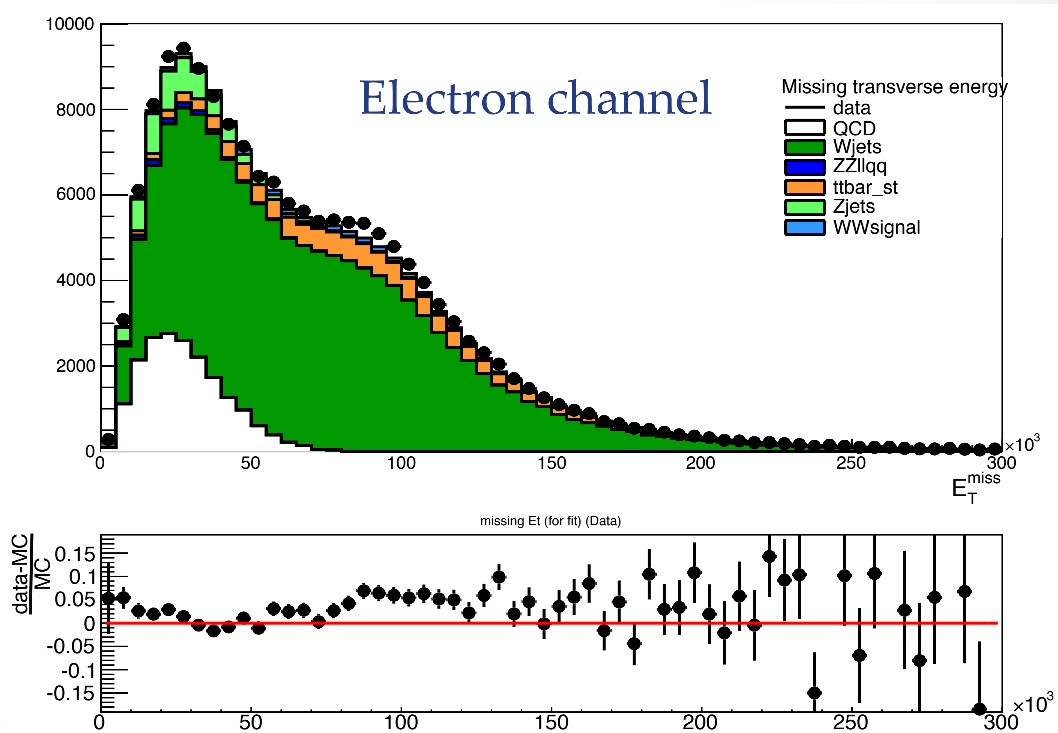
# QCD background modelling

- W/Z+jets and top background described with MonteCarlo generators.
- QCD multijet: MonteCarlo modelling not sufficiently good
  - data-driven estimation
    - Shape: QCD enriched sample from modified event selection
    - Normalization: fit $E_T^{miss}$ spectrum.
- $E_T^{miss}$:
  - provides good discrimination between QCD multijet and W+jets (main spectrum component)



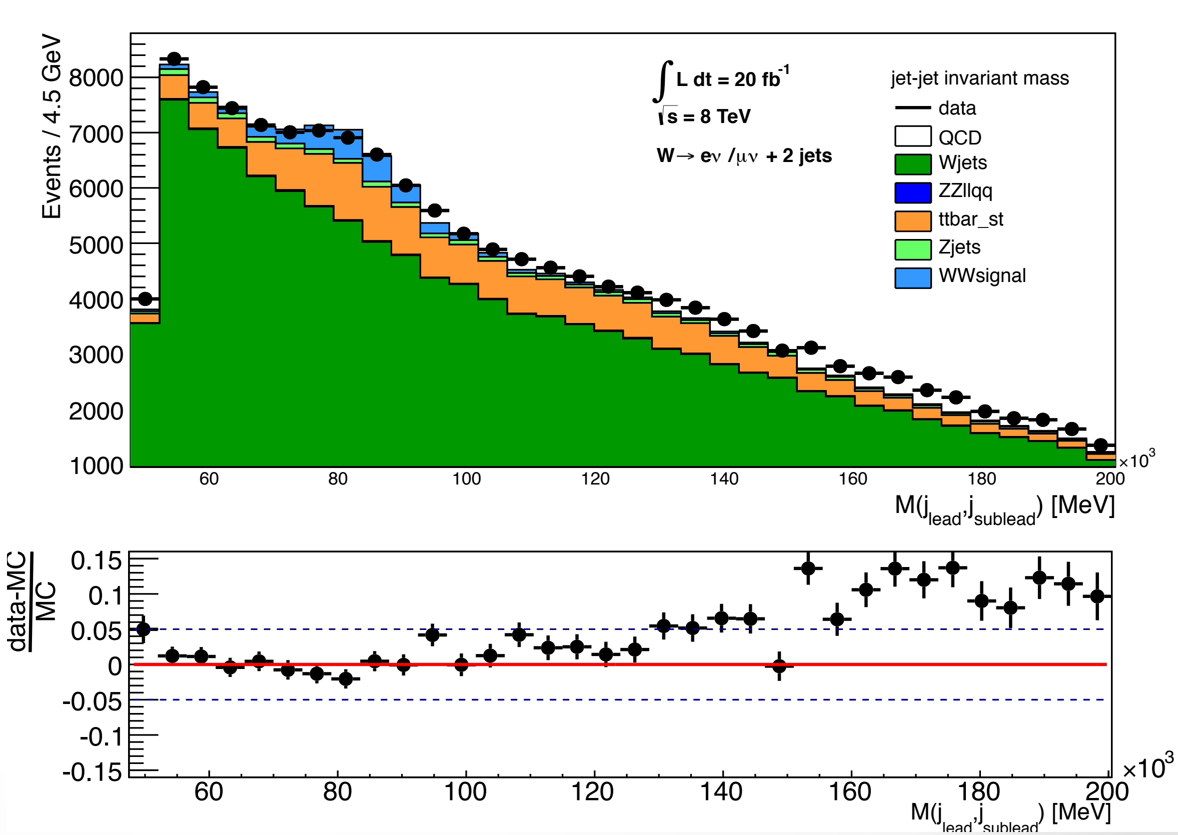
# QCD normalization extraction

- Full selection but the $E_T^{miss}$ > 40 GeV cut
- Full MonteCarlo template plus QCD enriched sample fitted to data
  - W/Z+jets and QCD normalization are the free parameters of the fit
- Fit results:
  - Data/MonteCarlo agreement not perfect (improvement ongoing)
  - Correction to W/Z+jets normalization is small (few percents)



# Di-jet invariant mass spectrum

- Full selection applied
- The signal peak is now clearly visible
- Disagreement in the high mass tail:
  - further investigation needed
- Systematic uncertainties to be added
  - Dashed lines give an idea of the order of magnitude



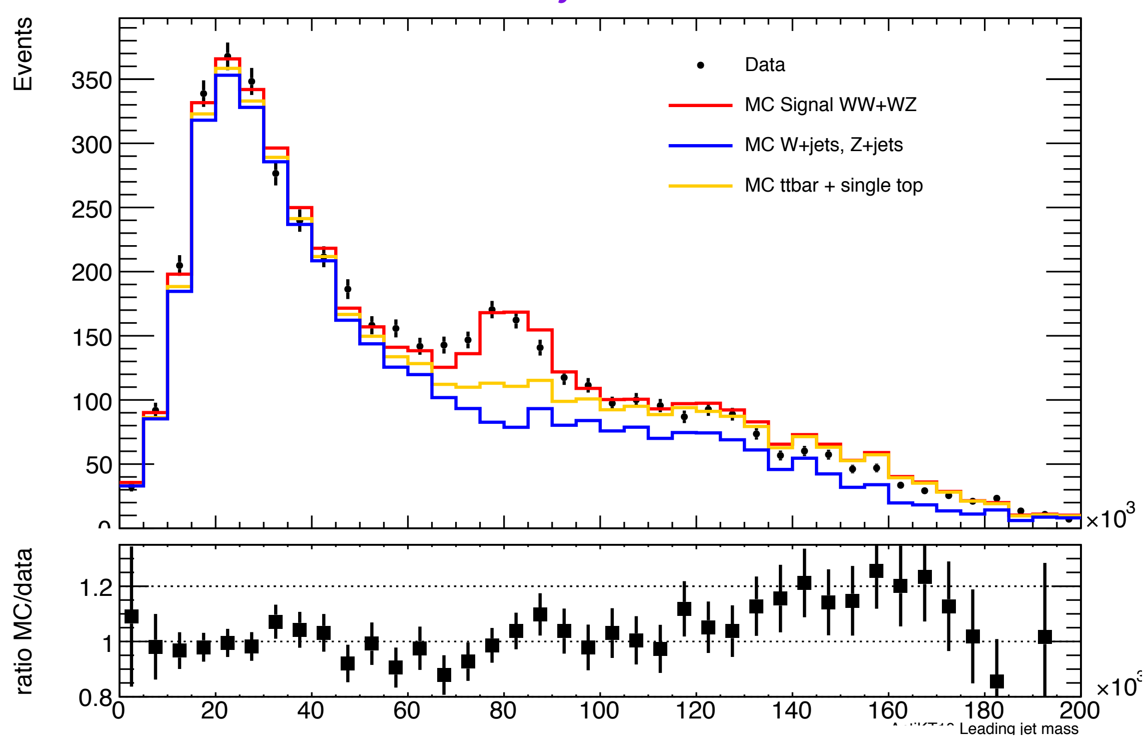
# Boosted channel

- W produced with a large boost: decays into quark pair with small angular separation.
  - Single large jet (*fat jet)* instead of a jet pair.

- Parallel analysis: common leptonic selection.
  - One fat jet with $p_T$>250 GeV

- Jet substructure analysis:
  - energy correlation between jet constituents.

[Courtesy, David Freeborn, UCL]



# Signal yield extraction

- Binned Maximum Likelihood fit of the invariant mass spectrum.
  - Systematic uncertainties on shape and normalization of simulated templates are taken into account in the fit.

- Extracted parameter: number of WW+WZ events $N_{meas.}$
  - The ratio $\sigma_{WW}/\sigma_{WZ}$ is fixed at the theoretical value.

- Preliminary fit tests ongoing. First results expected in a short time.

# Cross section computation

- From the fit event yield, cross section is measured in the *fiducial phase space*.

$$\sigma_{fid} = \frac{N_{meas}}{\mathcal{L} \cdot D \cdot \mathcal{B}}$$

<u>Fiducial phase space</u>:

- Kinematic region accessed by the analysis.
- Defined applying event selection to MonteCarlo particle-level objects.

- $D = f_{fid}^{WW} C^{WW} + (1 - f_{fid}^{WW}) C^{WZ}$
  - $C^{WW}$ and $C^{WZ}$: correction factors for WW and WZ channels
  - $f^{WW}$: ratio between WW and WW+WZ theoretical fiducial cross sections.

$$C^{WW} = \frac{N_{WW}^{reco,selected}}{N_{WW}^{inFiducial}}$$

$$D = 0.88 \pm 0.03 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$$

# Systematic uncertainties

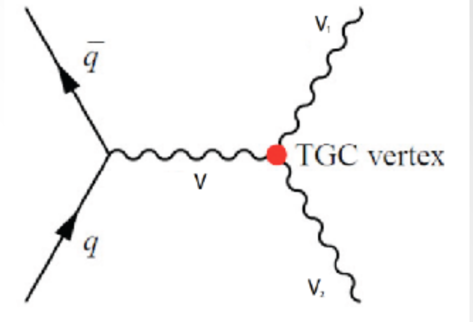
- Systematics affect both template's normalization and shape
    - Systematic on signal normalization not included in the fit: D factor uncertainty

- Systematic sources:
    - physic objects measurements:
        - largest contribution: Jet Energy Scale (~4%)
        - studied in detail by dedicated analysis
    - MonteCarlo modelling:
        - largest contribution: signal shape, W+jets
        - comparison between generators

- Full set of systematics under implementation.

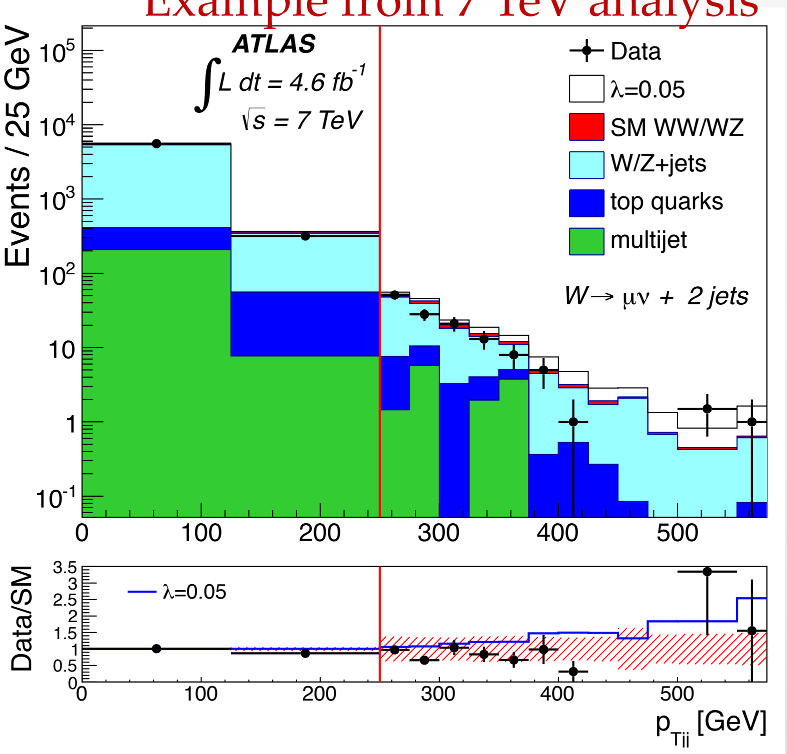
# anomalous Triple Gauge Couplings (aTGC)

- Contribution from new physics processes: vector boson couplings may deviate from Standard Model.




- Model-independent extension of Standard Model Lagrangian
  - aTGC parameters to be evaluated from data
- Most sensitive variable:
  - $p_{Tjj} = |\mathbf{p}_T(j_{lead}) + \mathbf{p}_T(j_{sublead})|$
  - larger effects expected in high-$p_T$ tail
- Limits expected to improve by a factor 2 at 8 TeV

Example from 7 TeV analysis

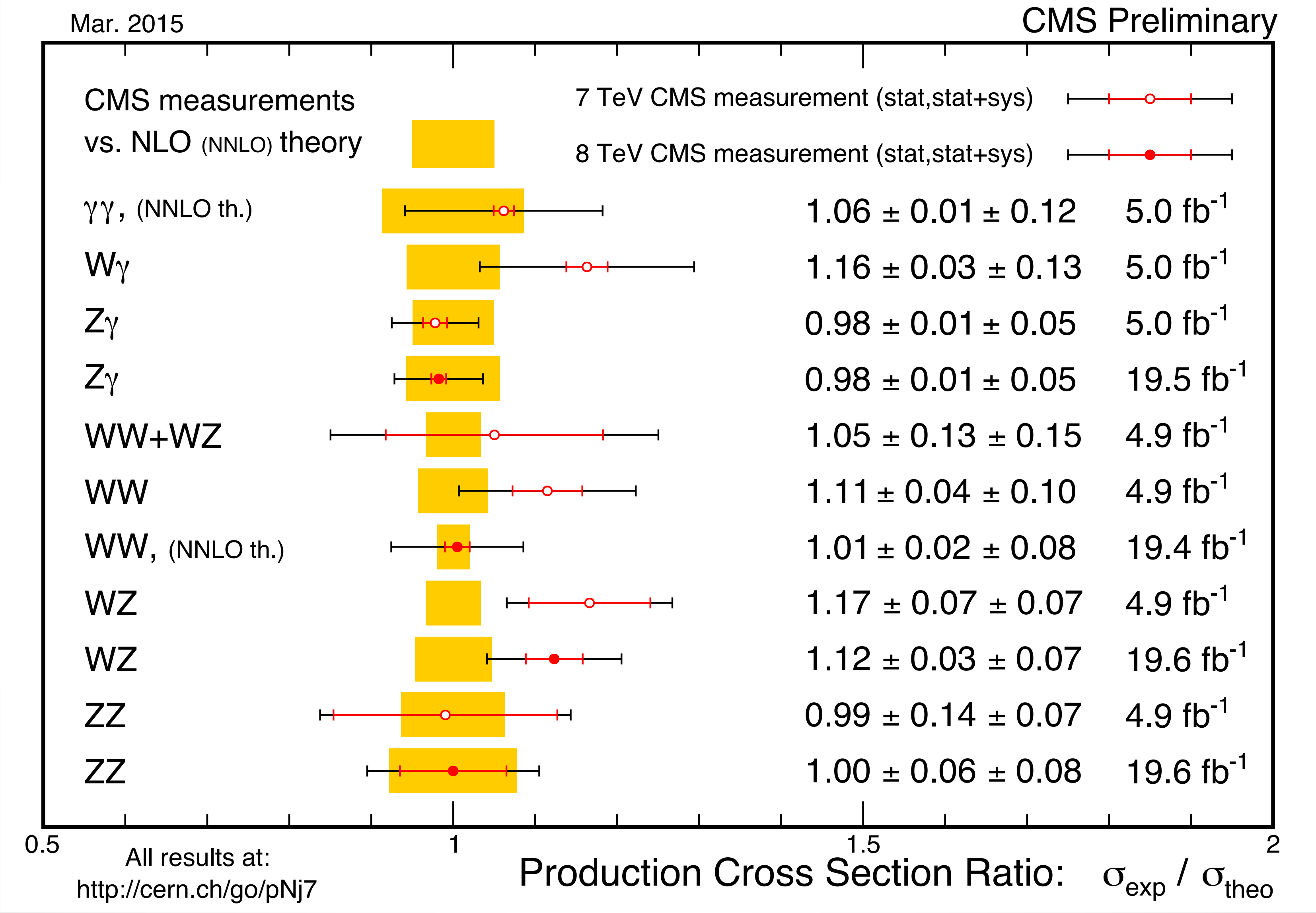


# Conclusions

- Standard Model WW/WZ→l $\nu$ jj measurement at 8 TeV
  - The analysis is difficult because of large background (W +jets production)
- Larger statistics exploited to improve signal discrimination from background with respect to 7 TeV analysis.
- Cross section is extracted from a binned Maximum Likelyhood fit to data.
  - First results available in a short time.
- Evaluation and implementation of the full set of systematics is proceeding.

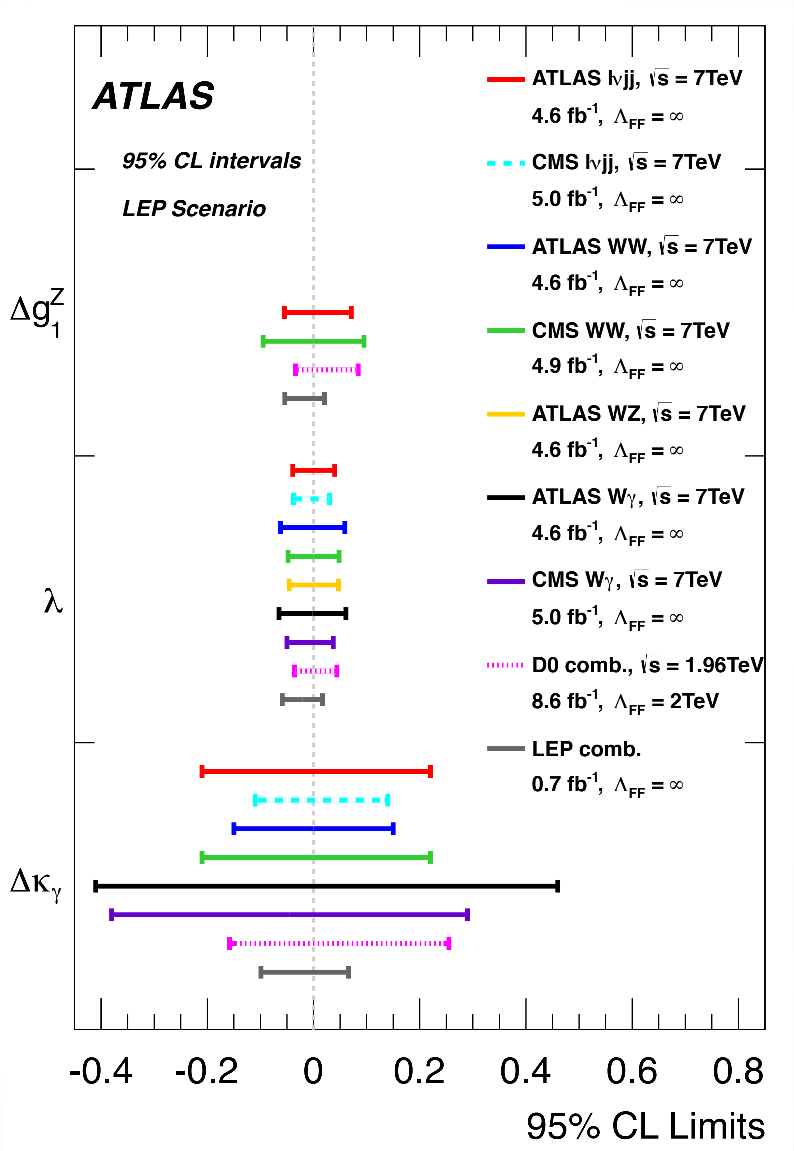
# Backup

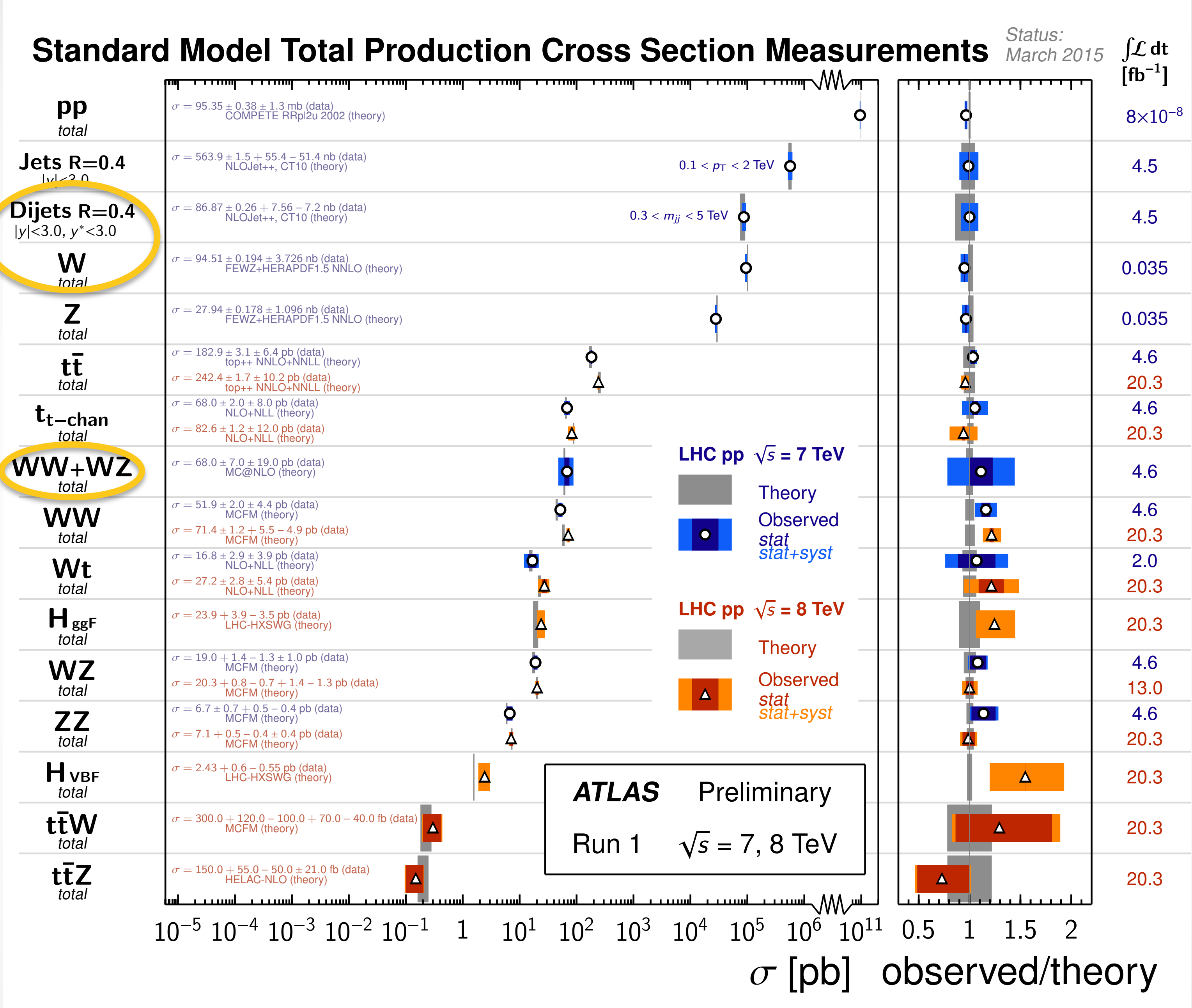
# CMS diboson results



# WW/WZ→lνjj 7 TeV measurement

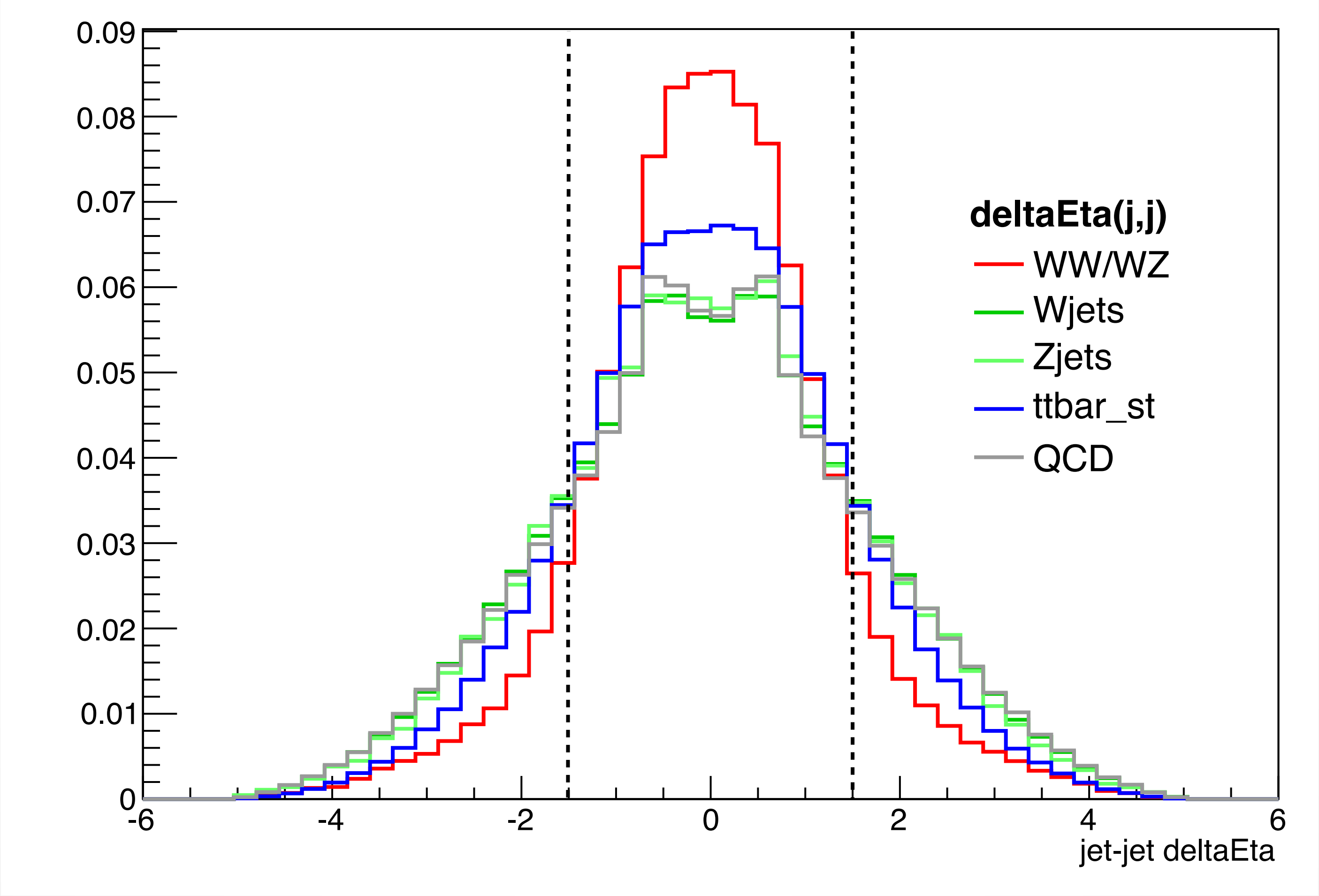
- Anomalous Triple Gauge Couplings:




Standard Model Total Production Cross Section Measurements
Status: March 2015
∫ℒ dt [fb⁻¹]
pp total
Jets R=0.4
Dijets R=0.4 |y|<3.0, y*<3.0
W total
Z total
tt̄ total
t t−chan total
WW+WZ total
WW total
Wt total
H ggF total
WZ total
ZZ total
H VBF total
tt̄W total
tt̄Z total
LHC pp √s = 7 TeV
Theory
Observed
stat
stat+syst
LHC pp √s = 8 TeV
Theory
Observed
stat
stat+syst
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
σ [pb]
observed/theory

# Di-jet event selection: jet-jet Δη

- Cut at: $\Delta\,\eta\,(j_{lead}, j_{sublead}) < 1.5$



# 8 TeV expectation

- Total expected cross section:

$$\sigma^{expected}_{WW+WZ}(8\ \text{TeV}) \simeq 80.13 \pm 8\%\ \text{pb}$$

- Expected cross section in the fiducial phase space:

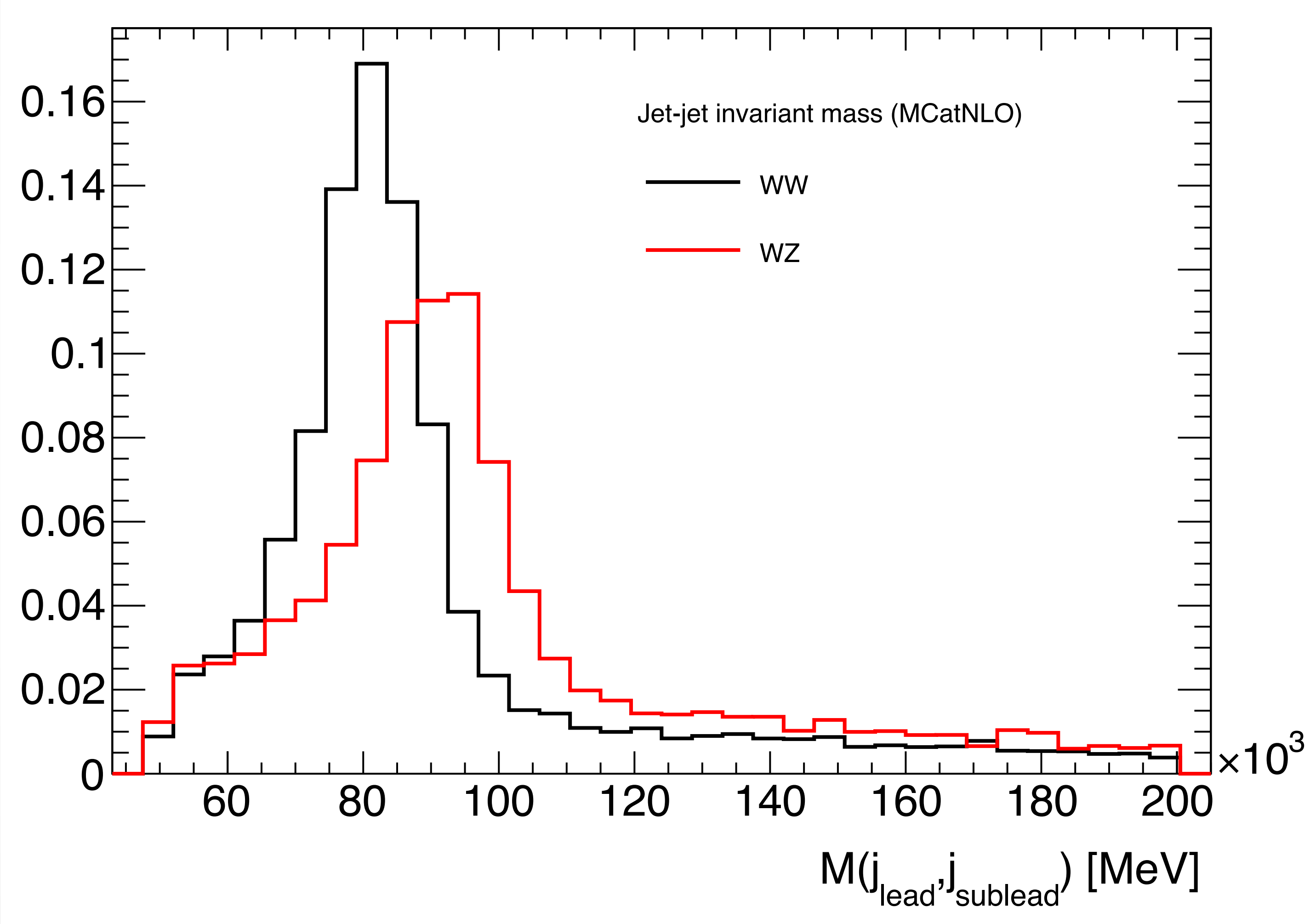
$$\sigma^{expected}_{fid}(8\ \text{TeV}) \simeq 0.41 \pm 0.01\ \text{pb}$$

**Fiducial phase space:**

- Kinematic region accessed by the analysis.
- Defined applying event selection to MonteCarlo particle-level objects.

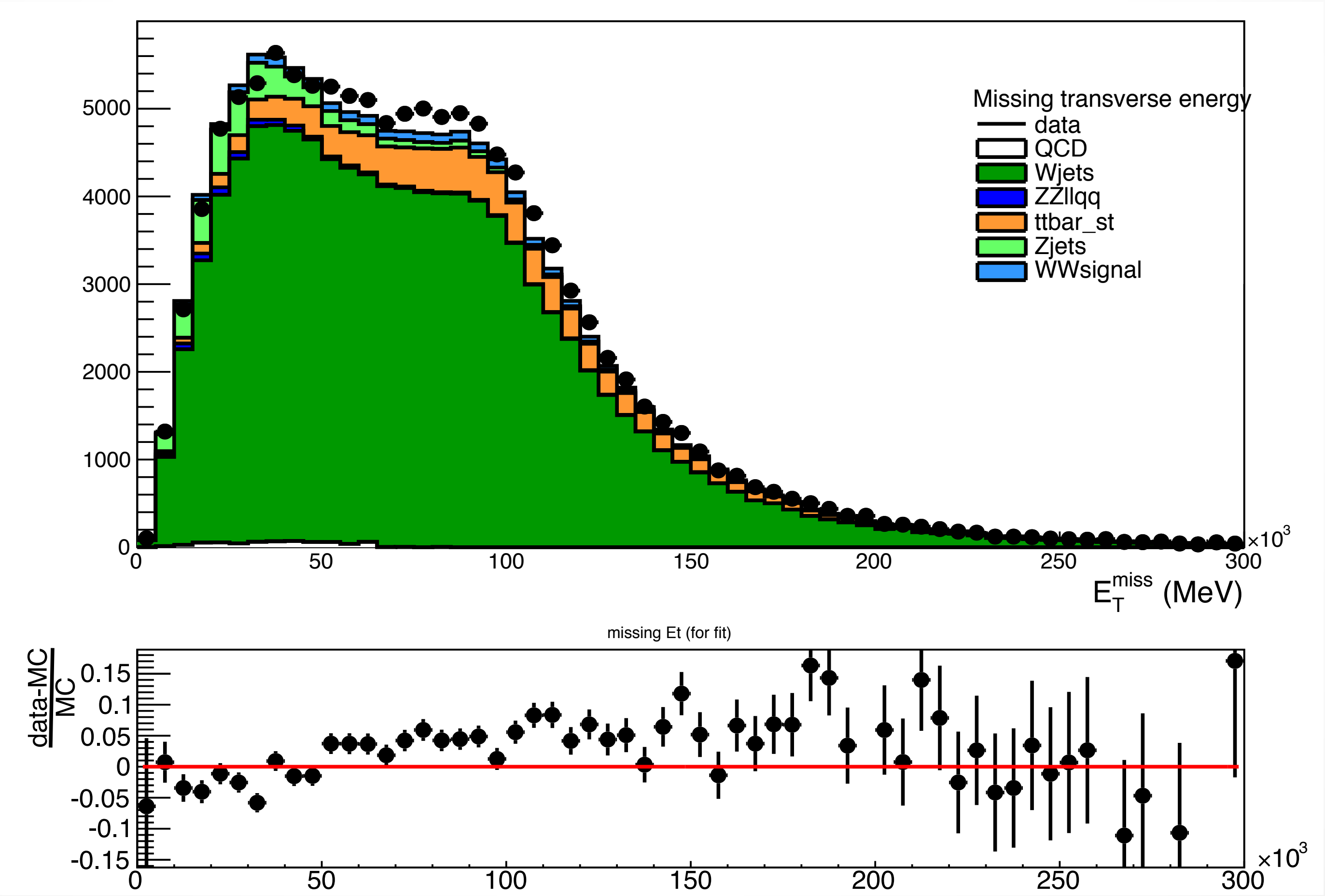
| **Expected signalevent yield after event selection** | |
|---|---|
| process | expected events |
| WW | 1459.49 |
| WZ | 365.146 |

# WW/WZ comparison

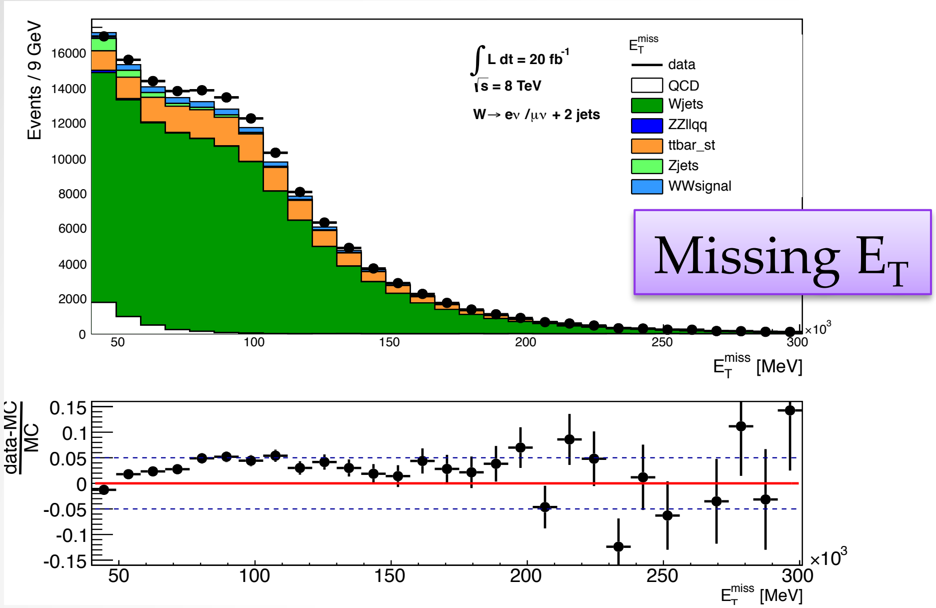


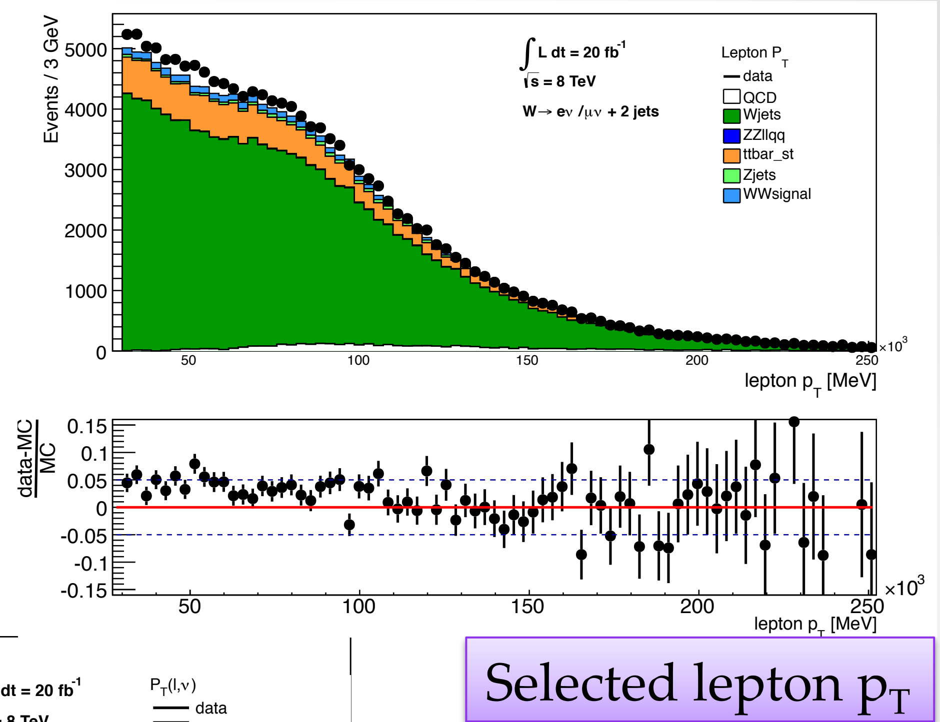
# QCD normalization extraction

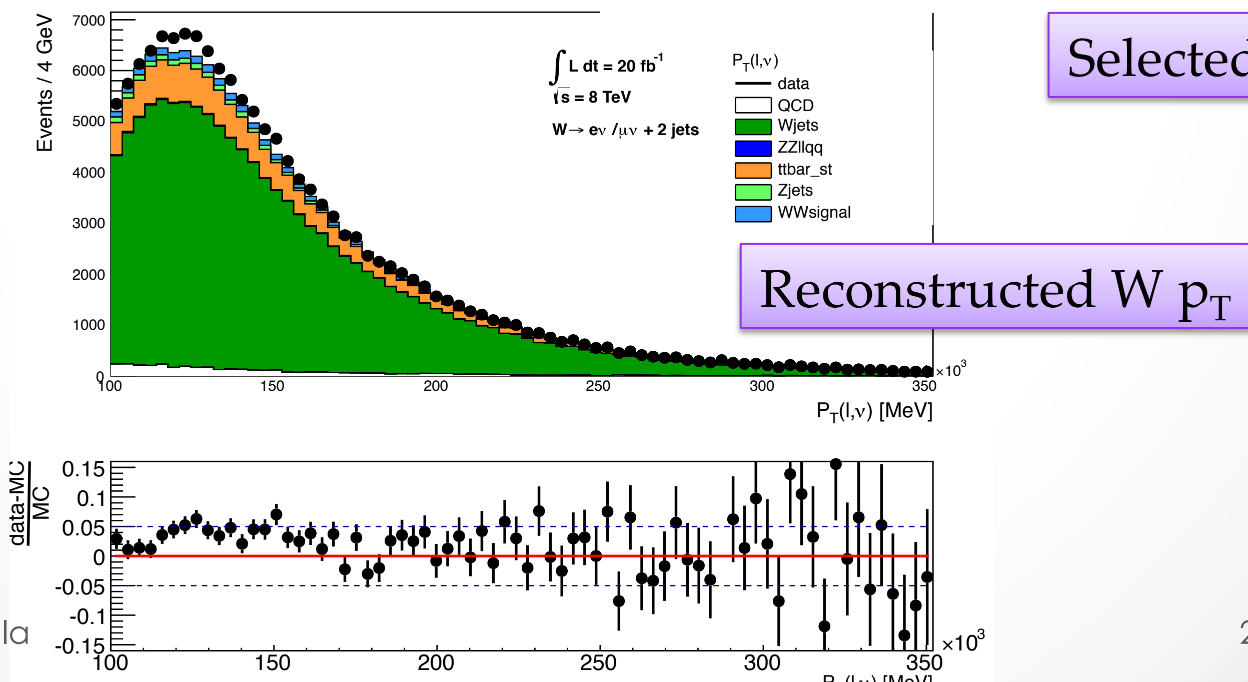
## Muon channel



# Kinematic distributions after full selection



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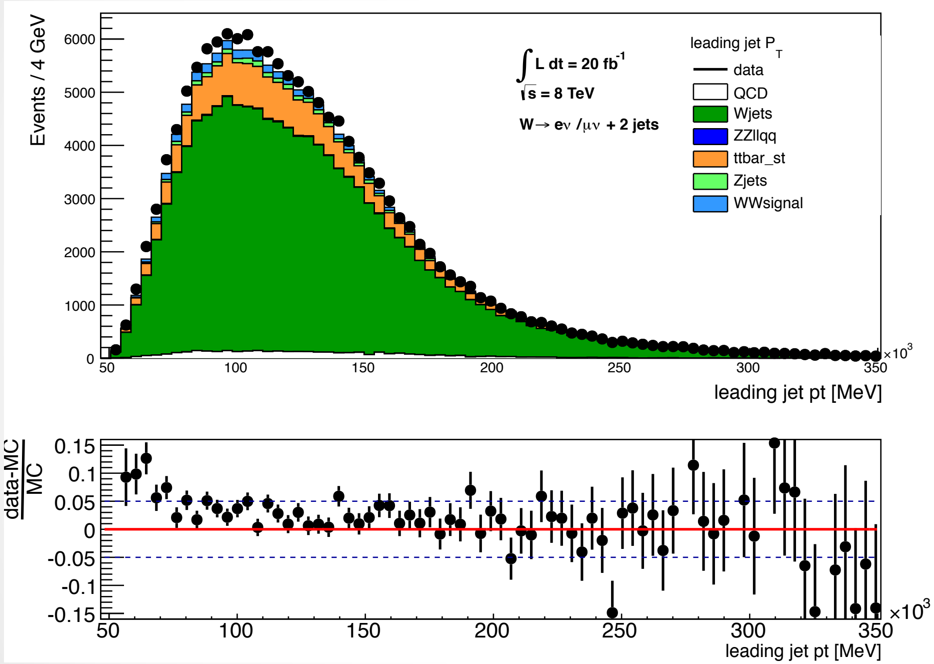
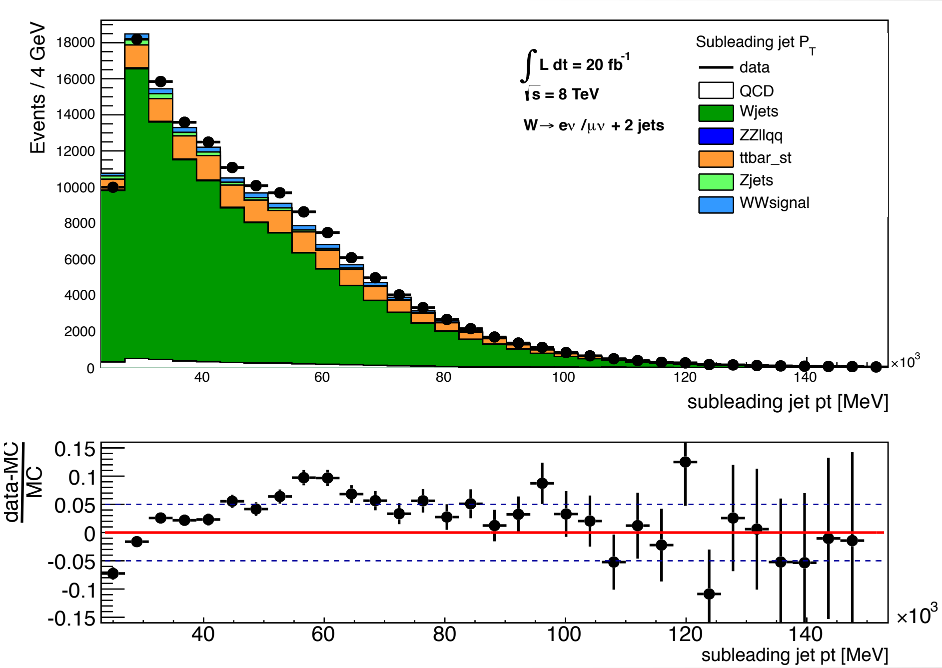
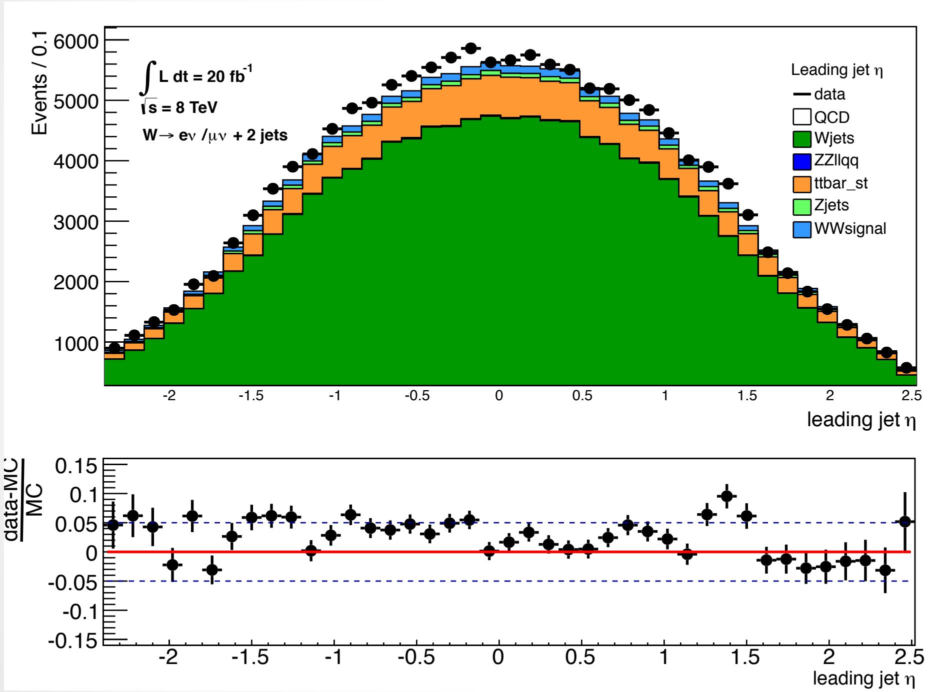



Leading jet $p_T$

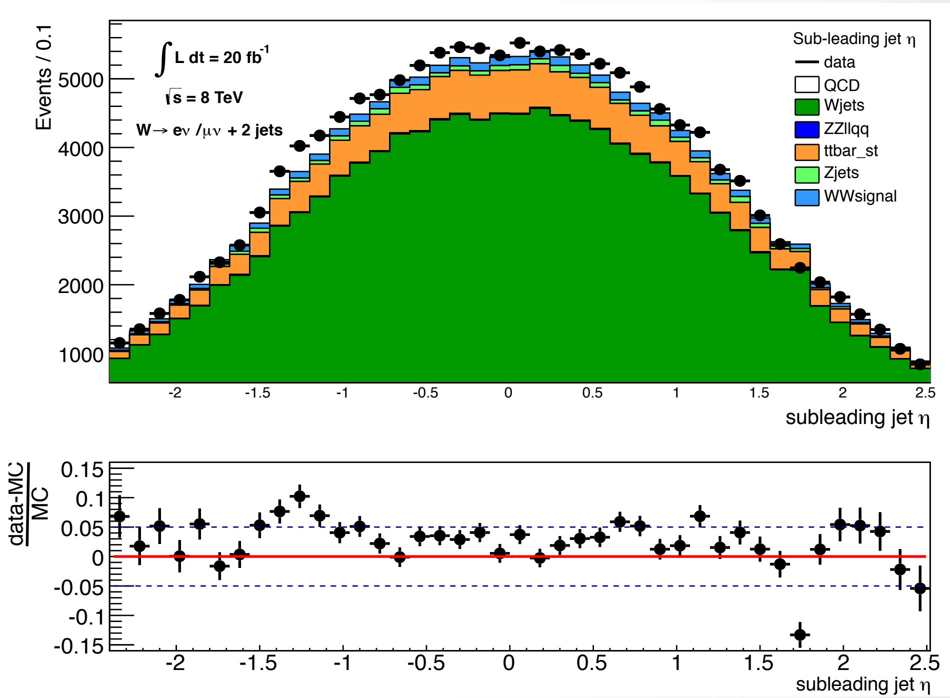



Sub-leading jet $p_T$

# Kinematic distributions after full selection

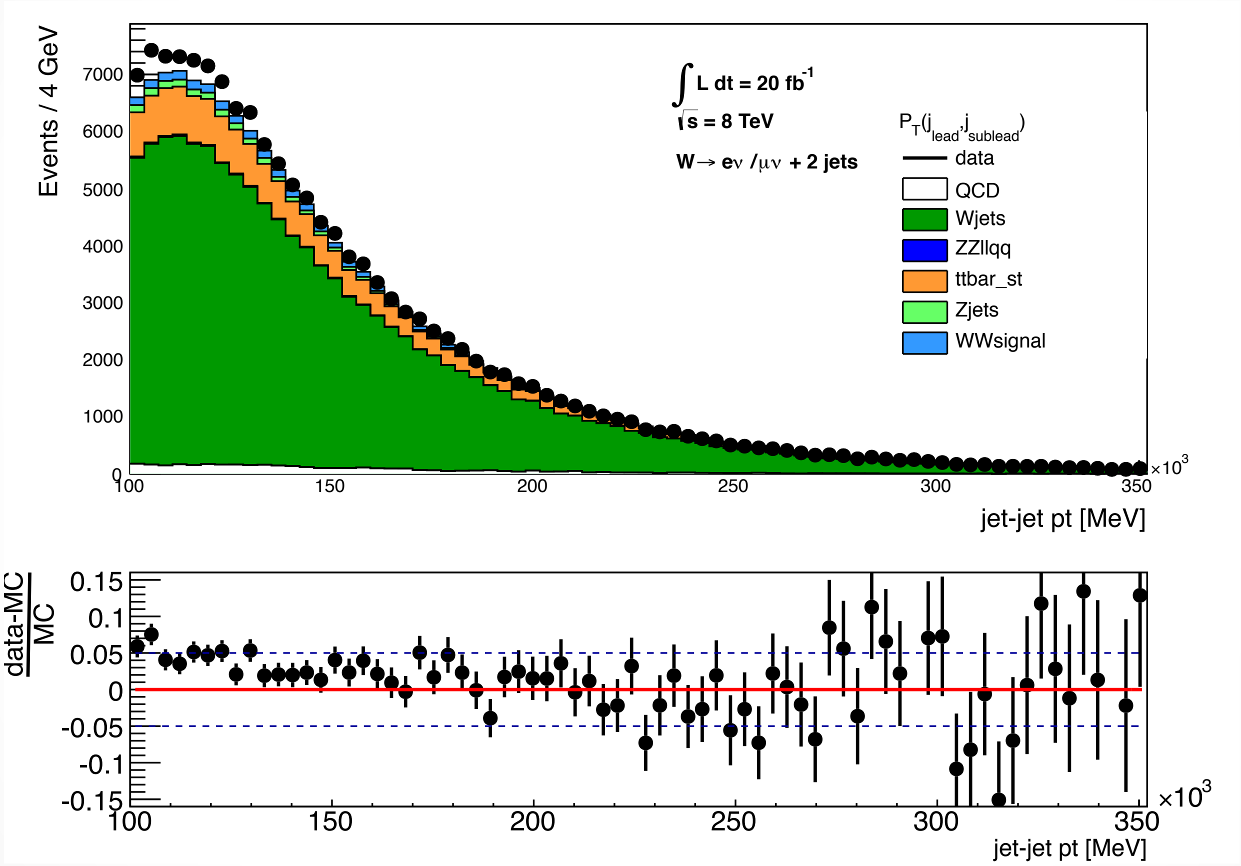



Leading jet η




Sub-leading jet η

# Kinematic distributions after full selection

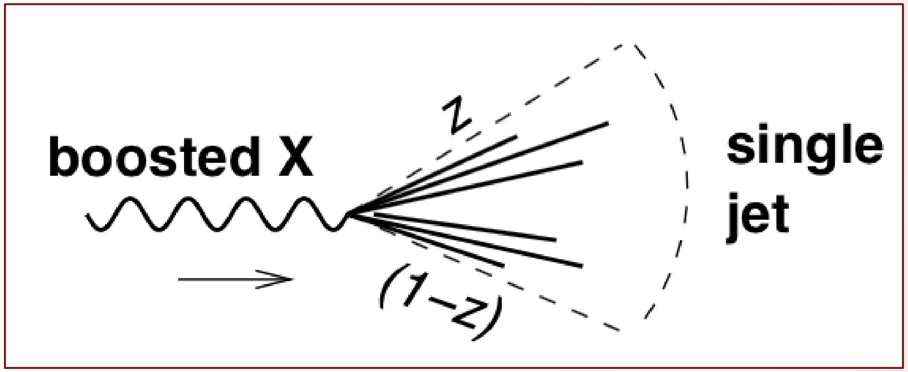



Di-jet $p_T$

# Boosted topology

- Assume an heavy particle X decaying to two jets of momentum $\mathbf{p}_1$ and $\mathbf{p}_2$
  - $z = p_1/p_X$
- Minimal angular separation between decay products is roughly:

$$\Delta R_{min} \sim \frac{M_X}{p_{t_X}} \frac{1}{\sqrt{z(1-z)}}$$




- If $\Delta R_{min} < R_{jet}$ the two jets from X decay cannot be resolved.
  - $R_{jet}$ = radius parameter of the used jet reconstruction algorithm.
  - In our case $R_{jet} = 0.4$

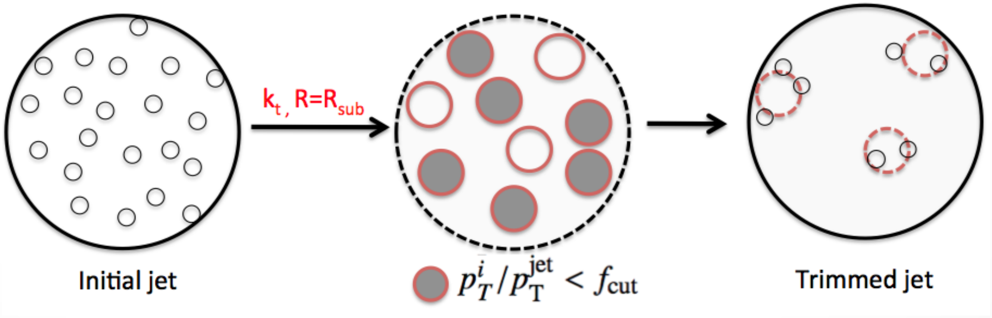
# Boosted selection

- Preselection and leptonic W selection: common to resolved channel
- Hadronic W/Z selection
  - Jets reconstructed with Anti-Kt, R=1
  - Trimming algorithm applied before any selection/ calibration
  - Exactly one jet satisfying:
    - $p_t > 250$ GeV
    - $|\eta| < 2.4$
  - Top background rejection
    - Discard events with 'small' (Anti-Kt r=0.4) jets passing the resolved selection and not overlapping with the selected fat jet.
  - Cut on jet substructure variables
    - $D_2 < 0.8$ (see next)

# Jet trimming

- *Trimmed* fat jets are used for the boosted analysis.

- A trimming algorithm takes as input the constituents of a jet
  - It reconstructs sub-jets using the Kt algorithm with radius parameter $R_{subjet} < R_{jet}$
  - Sub-jets carrying a fraction of the jet $p_t$ smaller than $f_{cut}$ are removed from the jet.




- In this analysis: $R_{subjet}$ =0.2 and $f_{cut}$=0.5

# Jet substructure analysis: $D_2$

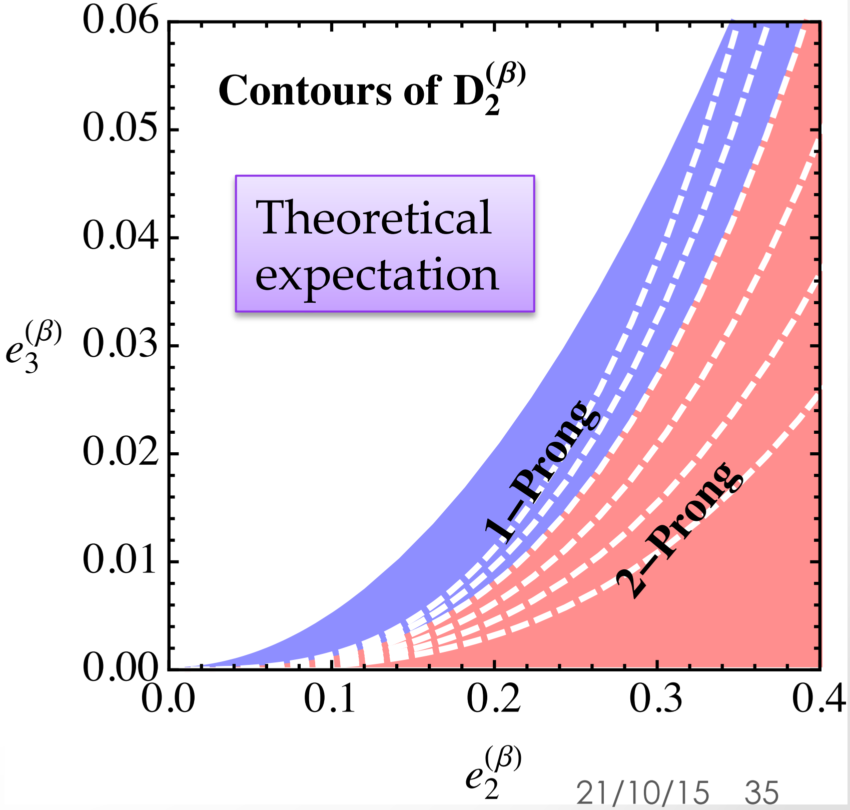
- $D_2$ is the ratio between 2-point ($e_2$) and 3-point ($e_3$) energy correlations functions between jet constituents
  - $\beta$ =1 in this analysis.

$$e_2^{(\beta)} = \frac{1}{p_{T_J}^2} \sum_{1\leq i<j\leq n_J} p_{T_i} p_{T_j} \Delta R_{ij}^{\beta}$$

$$e_3^{(\beta)} = \frac{1}{p_{T_J}^3} \sum_{1\leq i<j<k\leq n_J} p_{T_i} p_{T_j} p_{T_k} \Delta R_{ij}^{\beta} \Delta R_{jk}^{\beta} \Delta R_{ik}^{\beta}$$

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$

arXiv:1409.6298



# Systematics: detail

| Systematic uncertainty | Effect: (Shape/Normalization) | Included in: (Fit/$D$ factors) |
|---|---|---|
| Luminosity | N | - |
| **Physics objects** | | |
| Jet Energy Scale (JES) | SN | F/D |
| Jet Energy Resolution (JER) | SN | F/D |
| Jet Vertex Fraction (JVF)* | SN | F/D |
| Lepton momentum scale/resolution | SN | F/D |
| Lepton reconstruction/selection efficiency | N | F/D |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ scale/resolution | SN | F/D |
| **Background modelling** | | |
| $W/Z$+jets: scale variations | S | F |
| $W/Z$+jets: generator | S | F |
| $W/Z$+jets: parton shower | S | F |
| $W/Z$+jets: data-reweighting** | S | F |
| $\sigma_{WW}/\sigma_{WZ}$ ratio | S | F |
| $t\bar{t}$ cross section | N | F |
| $t\bar{t}$: generator - parton shower - ISR/FSR | SN | F |
| Single top cross section: $\sigma_{st}/\sigma_{t\bar{t}}$ | SN | F |
| Multijet normalization | N | F |
| Multijet shape | S | F |
| $\sigma_{ZZ}$ uncertainty | N | F |
| **Signal modelling** | | |
| $WW/WZ$ scale variations | SN | F/D |
| $WW/WZ$ generators | SN | F/D |
| $WW/WZ$ PDF | SN | F/D |

# Systematic uncertainties

- Example of signal shape systematic study: comparison between different generators.