Jet Production in Association with Vector Bosons at CMS

Matteo Marone
on behalf of the CMS Collaboration

UNIVERSITÀ DEGLI STUDI DI TRIESTE

Istituto Nazionale di Fisica Nucleare
Sezione di Trieste

IHEP, Protvino (RUS) 22 November 2012

Outline

- Motivations

- CMS Detector and Particle Reconstruction
- Common Analysis Tools used in Vector Boson + Jets

- Topics in this presentation:
  - Rate of Jets Produced in Association with W and Z Bosons in pp Collisions at $\sqrt{s}$ = 7 TeV
  - Measurement of the Z+b Jet Cross Section
  - Azimuthal Correlations and Event Shapes in Z + Jets Production

---

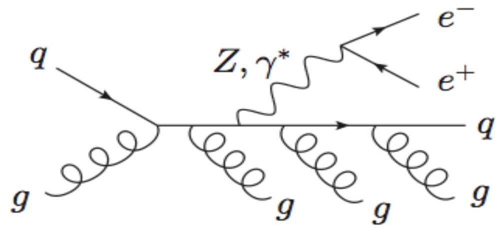
- Conclusions

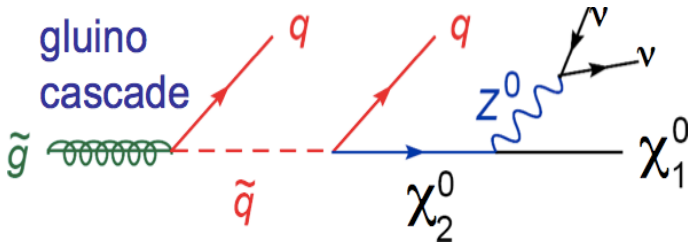
Physics Motivations

The associated production of a boson and jets is a test of the Standard Model (SM)

- Test the perturbative Quantum Chromodynamics predictions (pQCD)
    - NLO calculation available for the Z/W boson
    - Data driven method to tune different theoretical models of the process

- SM Background to New Physics processes
    - Huge variety of processes involving multiple jets in searches
    - SUSY (gluino cascades), Dark Matter, 4th generation





- SM Background to Higgs Physics (HZ with H to bb pair, ZZ to lepton+jets...)

- Constraints to Parton Density Function (PDF), at various center of mass energies

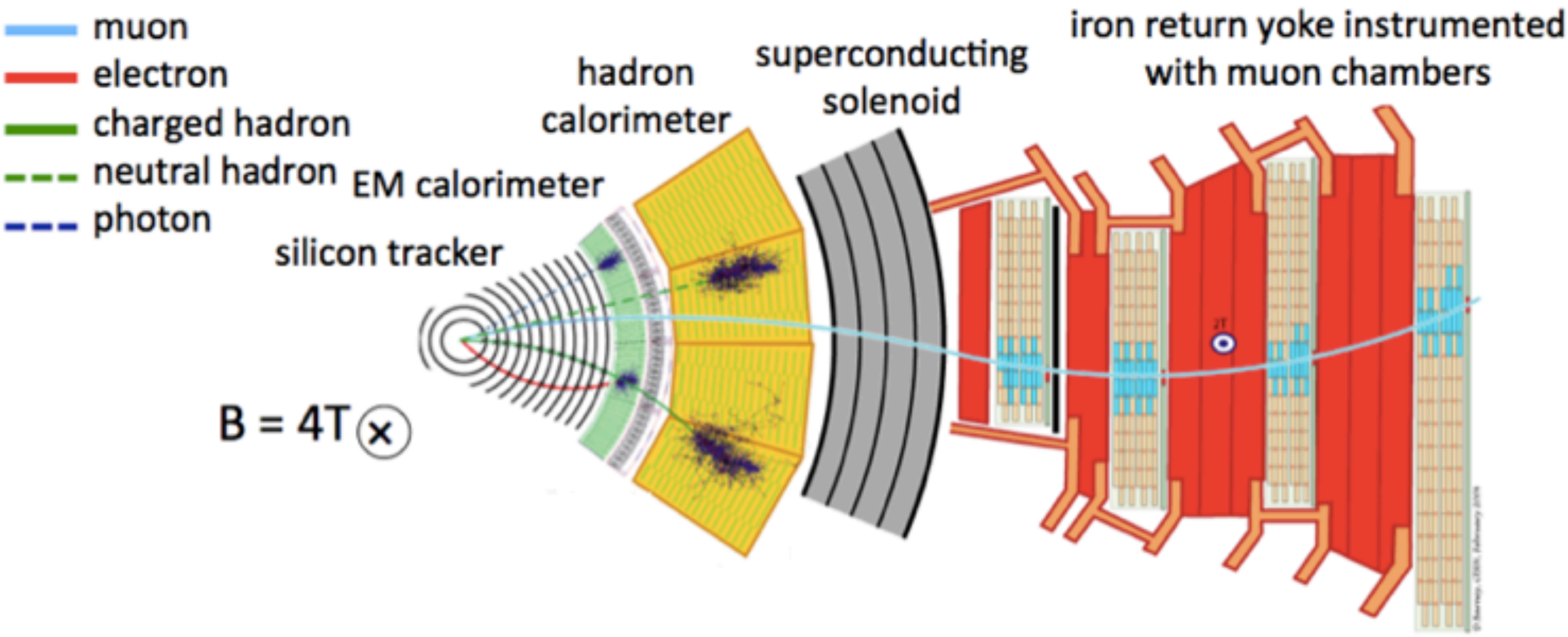
Other motivations

- Can be also useful for detector calibrations:
  - Jets recoiling against a Z can be utilized to calibrate the jet energy

- It is an important test bench to probe a wide number of MC generators:
  - Leading Order (LO) MC + Matching Parton Shower (PS):
    - Alpgen, MadGraph, Sherpa
  - Fixed Order Next-to-Leading Order (NLO):
    - aMC@NLO, BlackHat
  - Fixed Order NLO + PS:
    - Powheg, Pythia (Z+>=1 Jet)

	3+ years ago	today
W/Z	NNLO	NNLO
V+1j	NLO	NLO+PS
V+2j	NLO	NLO
V+3j	LO	NLO
V+4j	LO	NLO
V+5j	LO	NLO soon

CMS Detector



- Significant improvement due to Particle Flow Algorithm that uses information from all sub-detectors
  - muons, electrons, photons, charged and neutral hadrons
  - the list is used to reconstruct higher level objects like jets, MET
    - **electrons**: tracks matched to clusters in EM calorimeter
    - **muons**: minimum ionizing tracks, penetrate deep into muon system
    - **jets / H_T**: constructed with combined tracking + calo info
    - **MET**: constructed with combined tracking + calo info, hermetic detector

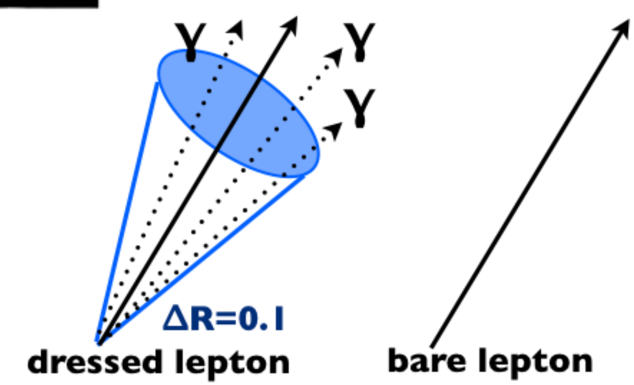
General Strategy

- In order to measure cross sections, the following quantities have to be evaluated:

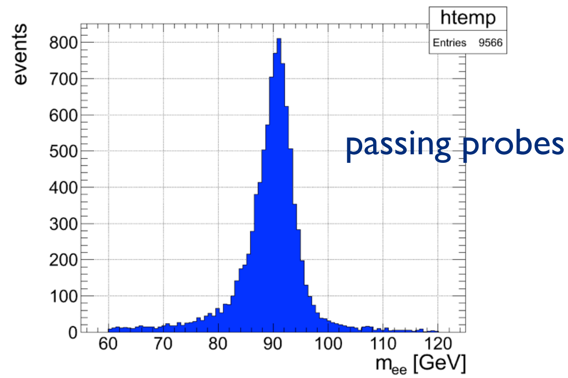
$$\frac{d\sigma}{dx} = \frac{\left(N_{data} - N_{bkg}\right)}{\varepsilon \times L \times \Delta x}$$

- Estimate background contribution and efficiencies
- Unfold in order to bring back results at particle level

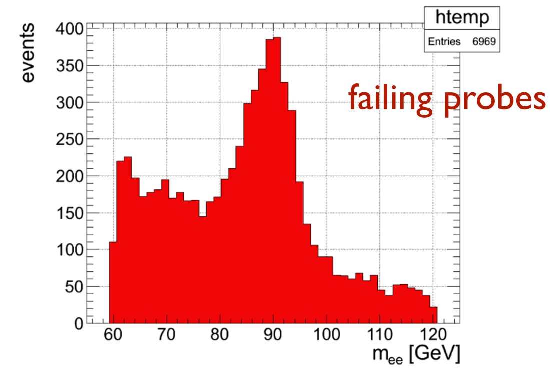
- Apply photon and lepton recombination

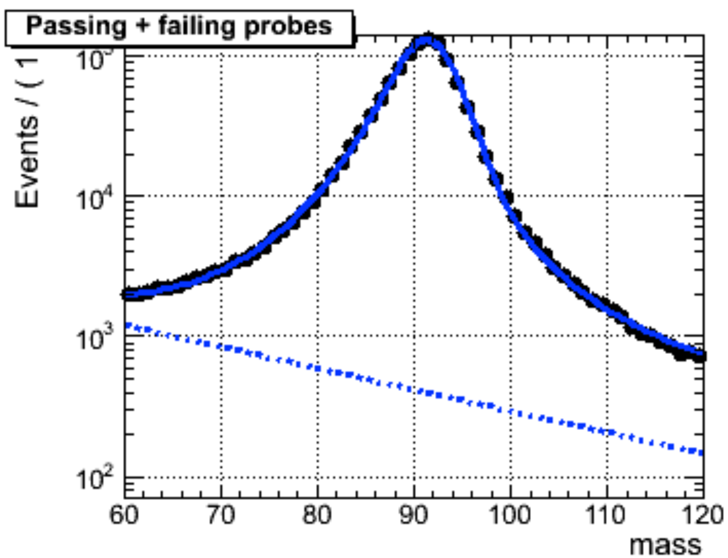


Tag And Probe (TAP) Method



- Efficiencies evaluated with the data driven Tag & Probe method:
  - select Z candidates sample by requiring a “tag” electron with very tight requirements
  - the second "probe" electron is used to test the event selection efficiency. The invariant mass of the two electrons is then computed in a window around the Z mass
  - filled different distributions for **passing** and **failing**



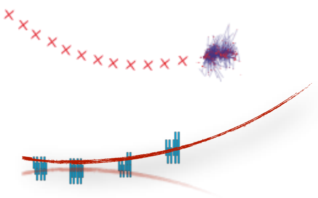


$$\varepsilon = \frac{n^{(pass)}_{signal}}{n^{(pass)}_{signal} + n^{(fail)}_{signal}}$$

- Perform a **simultaneous** fit to the “passing” and “failing” distributions to extract the efficiencies

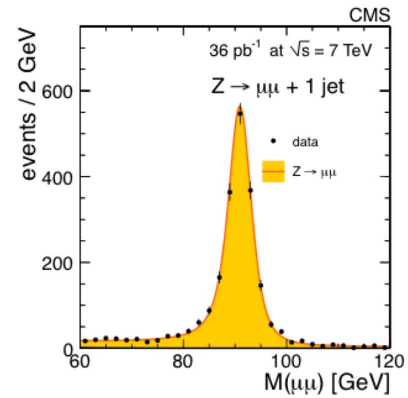
Event and Jet Selection

Leptons



- Electrons: p_T > 20 GeV, $|\eta|$<2.4 (no crack)
- Muons: p_T > 20 GeV, $|\eta|$<2.4
- Subtract PU ("ρ Fast Jet Method")
- Isolation Criteria

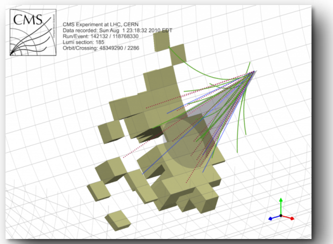
Bosons



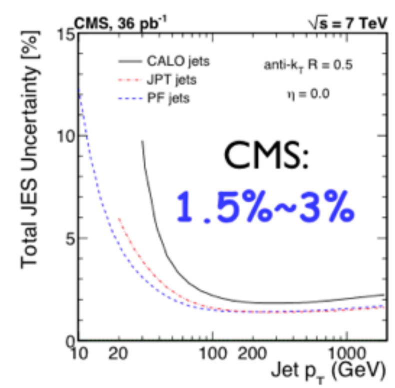
- Z: Lepton opposite charge, cuts on lepton invariant mass
- W: cut on missing energy (using M_T variable)

$$M_T=\sqrt{(2p_{TL}\not{E}_T\,(1-\cos\Delta\Phi))}$$

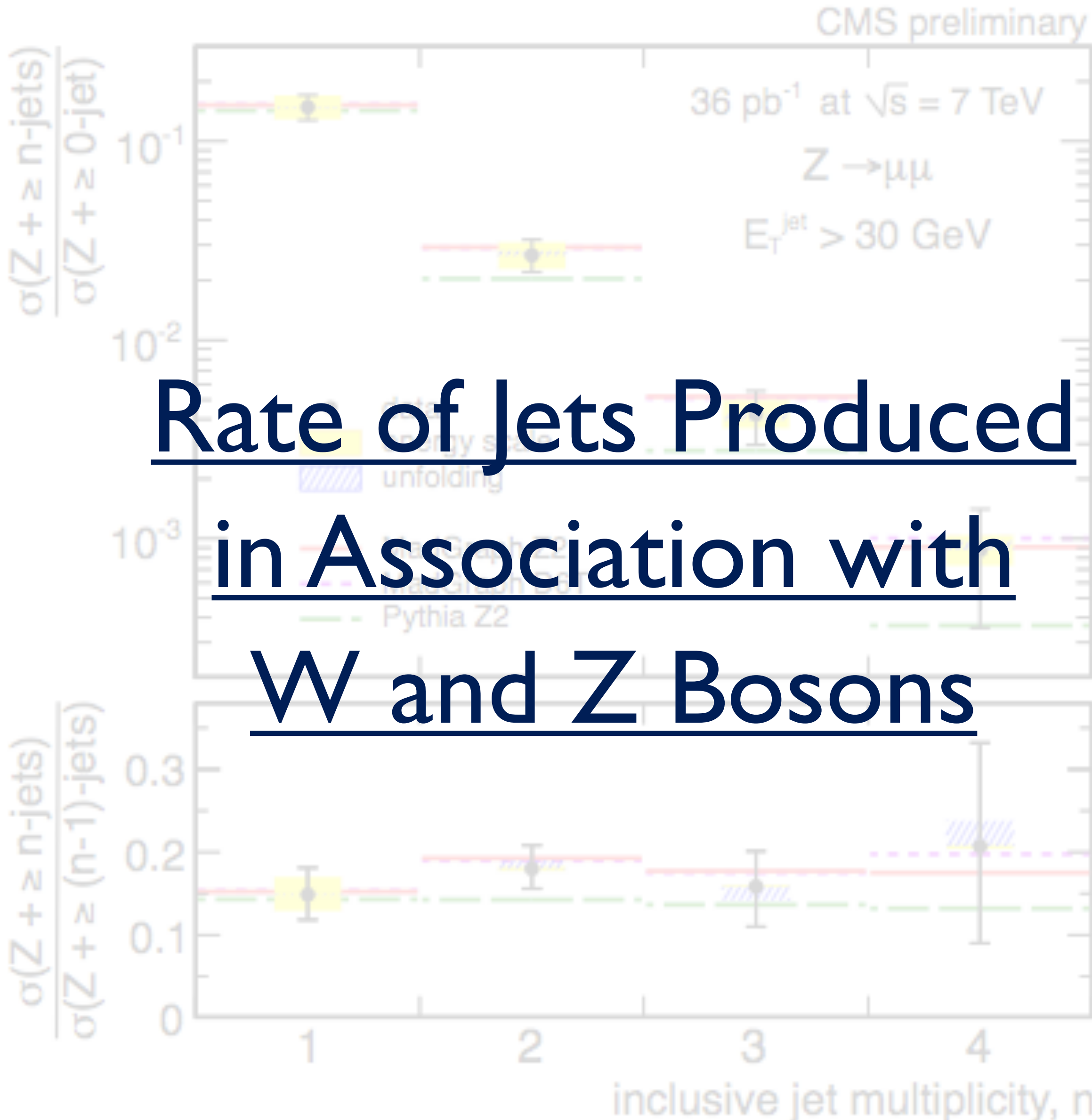
Jets Selection



- Correct for the Jet Energy Scale
- Anti-KT jets in $|\eta|$ < 2.4 (2.1) ΔR=0.5
- Separation lepton-jet required



Rate of Jets Produced in Association with W and Z Bosons



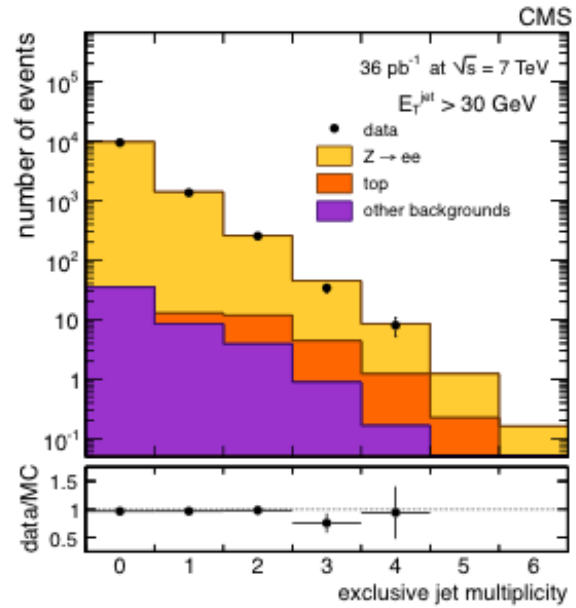
Analysis Peculiarities

Data luminosity: 36/pb
Jets > 30 GeV

Background
Signal

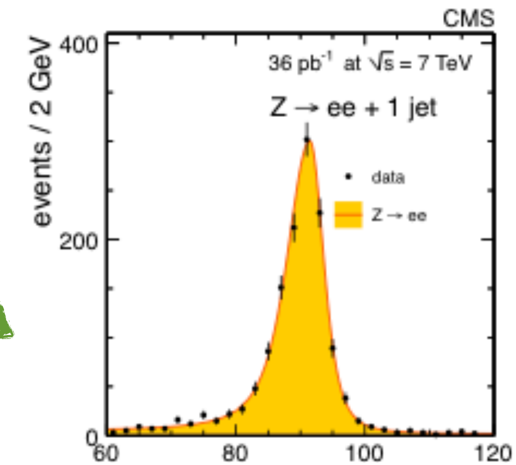
Generator	Process	σ (pb)
MADGRAPH	$W \to \ell\nu$	3.1×10^4 (NNLO)
MADGRAPH	$Z \to \ell^+\ell^-$	3.0×10^1 (NNLO)
MADGRAPH	$t\bar{t}$	1.6×10^2 (NLO)
MADGRAPH	single top tW channel	1.1×10^1 (LO)
MADGRAPH	single top s and t channels	3.5 (NLO)
PYTHIA	$W \to e\nu$	8.2×10^3 (NNLO)
PYTHIA	$W \to \mu\nu$	7.7×10^3 (NNLO)
PYTHIA	$W \to \tau\nu$	1.0×10^4 (NNLO)
PYTHIA	$Z \to \ell^+\ell^-$	5.0×10^3 (NNLO)
PYTHIA	Inclusive μ QCD	3.4×10^5 (LO)
PYTHIA	EM-enriched QCD	5.4×10^6 (LO)
PYTHIA	b/c $\to$ e	2.6×10^5 (LO)
PYTHIA	γ+jet	8.5×10^7 (LO)

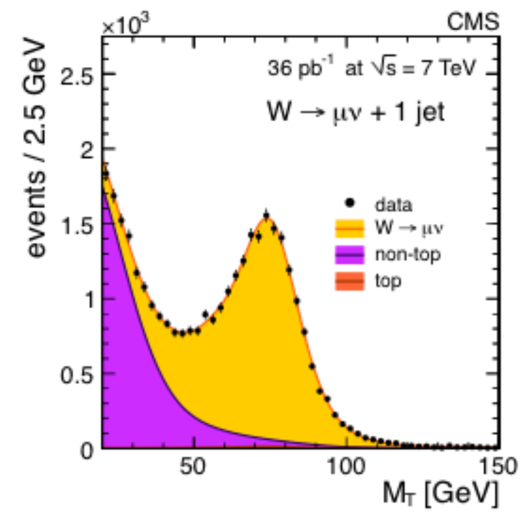
- The following observables are presented:
  - W and Z (called "V") + N jets cross section (σ) over the inclusive σ_W or σ_Z
  - $\sigma_{(V+(n-1)\ jets)}/\sigma_{(V+n\ jets)}$
  - "Berends-Giele" Scaling
  - Ratio of the W to Z σ Vs Jet Multiplicity
  - W charge asymmetry Vs Jet Multiplicity
- In general, "ratios" preferred to reduce total uncertainties



Analysis Procedure

- Results quoted within the acceptance (no correction)
- Efficiencies extracted from data using TAP method (see previous slide)
- Signal and background yields estimated using a **Maximum-Likelihood** fit at the M_{ll} (Z) or M_T (W):
  - number of the initial observed events inserted as constraint normalization
  - prob. distributions in the fit are asymmetric Gaussian with tails
    - parameters derived from simulation or from control data samples



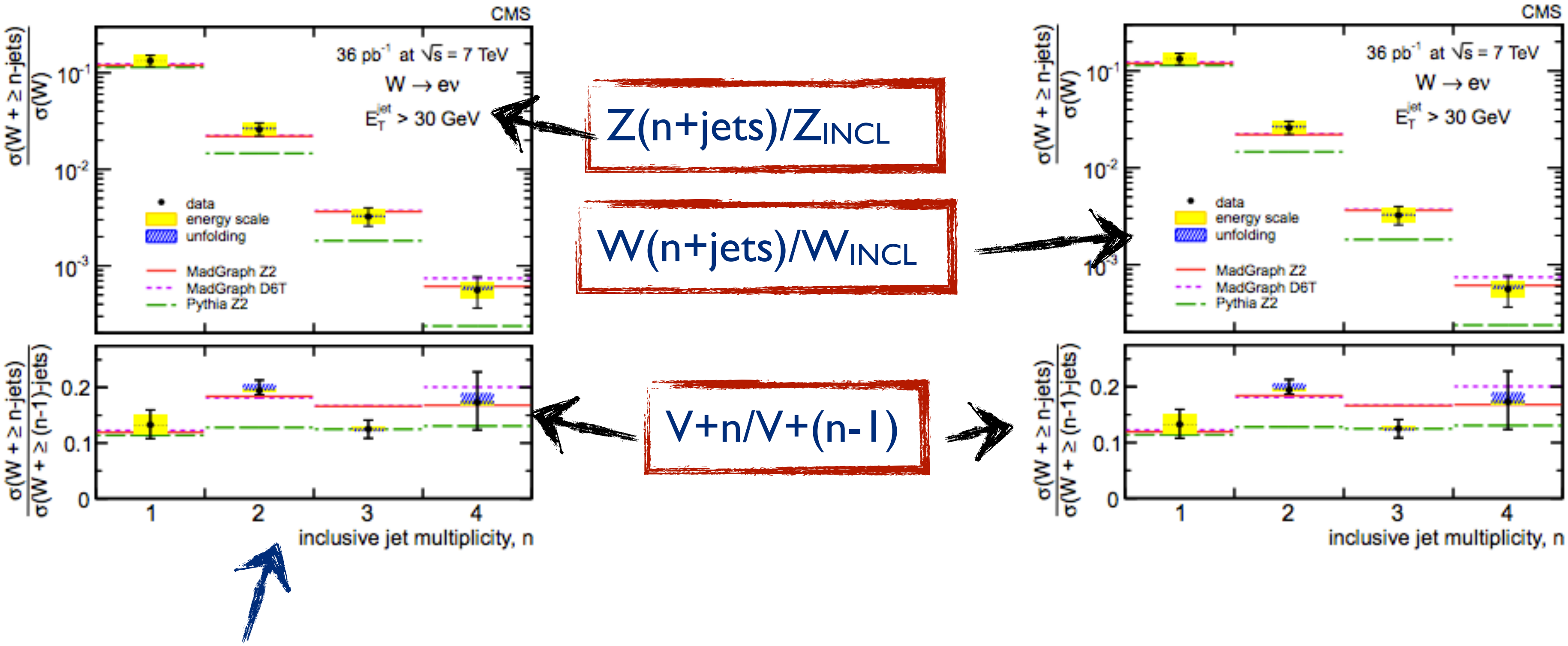


Distributions are then **unfolded** from detector effect using two different algorithms:
- Bayes
- Single Value Decomposition

MadGraph used to train the response matrix

Main systematics:
- Jet Energy Scale **5-15%**
- Unfolding < **10** %
- Sel. Efficiency < **3-4%**
- Signal Extraction **1-10%**

Results (1)



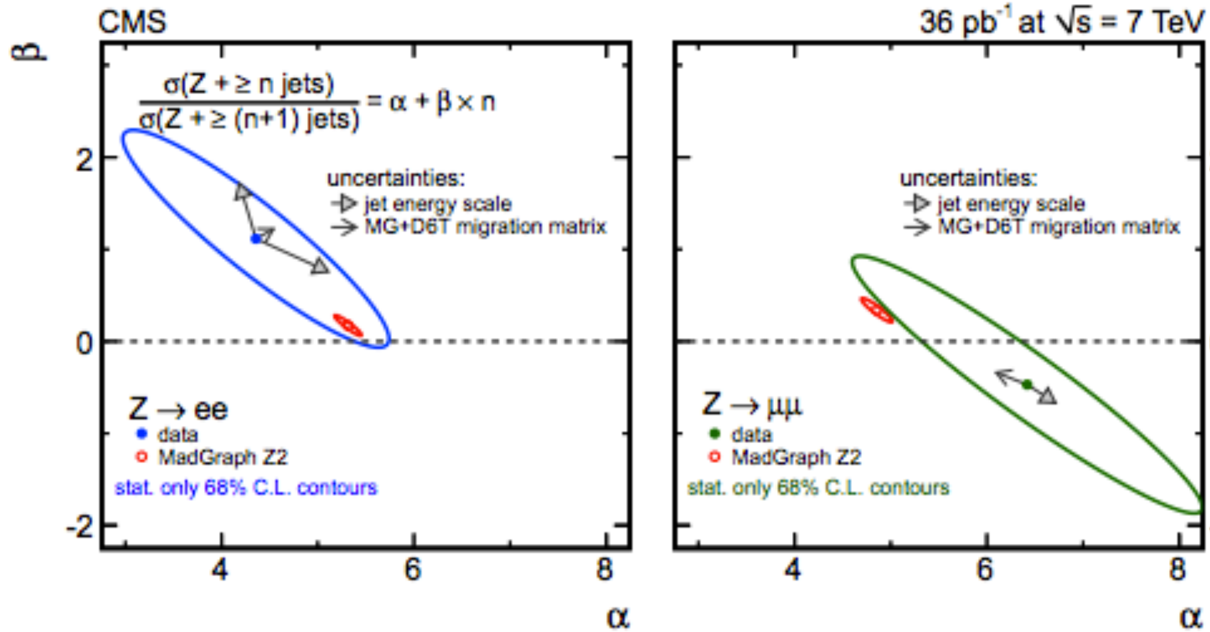
• For n ≥ 2 jets, the Pythia pure parton shower simulation fails to describe the data, while the MadGraph simulation agrees well with the experimental spectrum.

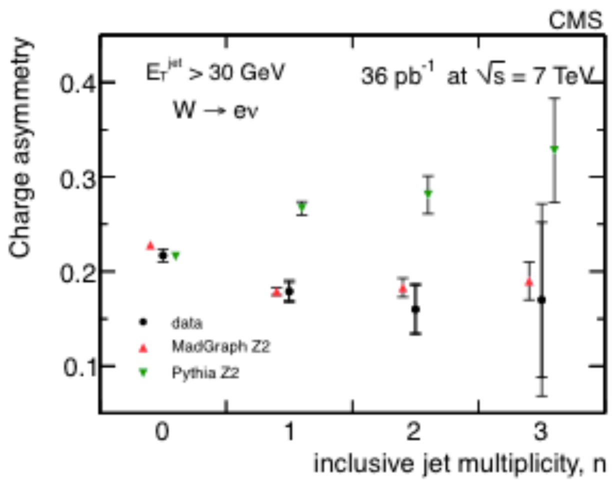
• Because of the jet E_T threshold, underlaying event tuning (----- or ——) play a negligible role

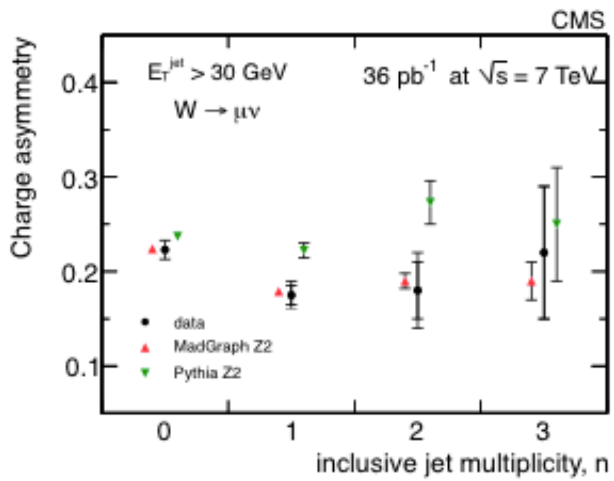
Results (2)

Berends-Giele

- Observable used to test the constant scaling law of Z(N-1)/Z(n) = α
- Inserted additional parameter (β) to allow for possible deviation
- Good Agreement MC/DATA, β compatible with 0







W Asymmetry Vs Jet Multiplicity

- Good Agreement with MadGraph, bad with Pythia

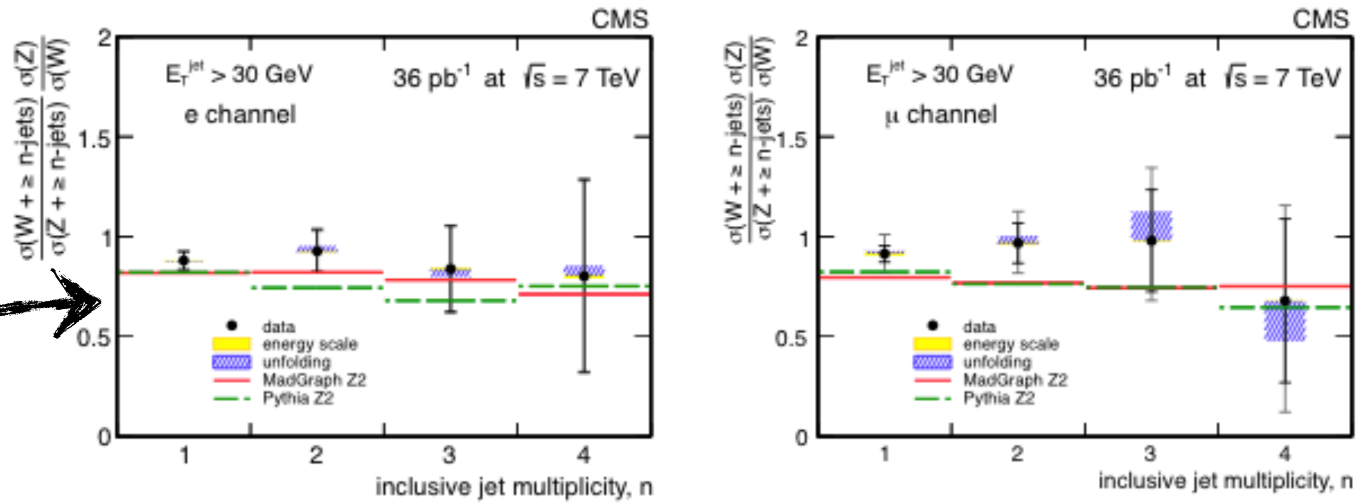
$$A_W = \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)}$$

Results (3)

Ratio W/Z

Vs

Jet Multiplicity

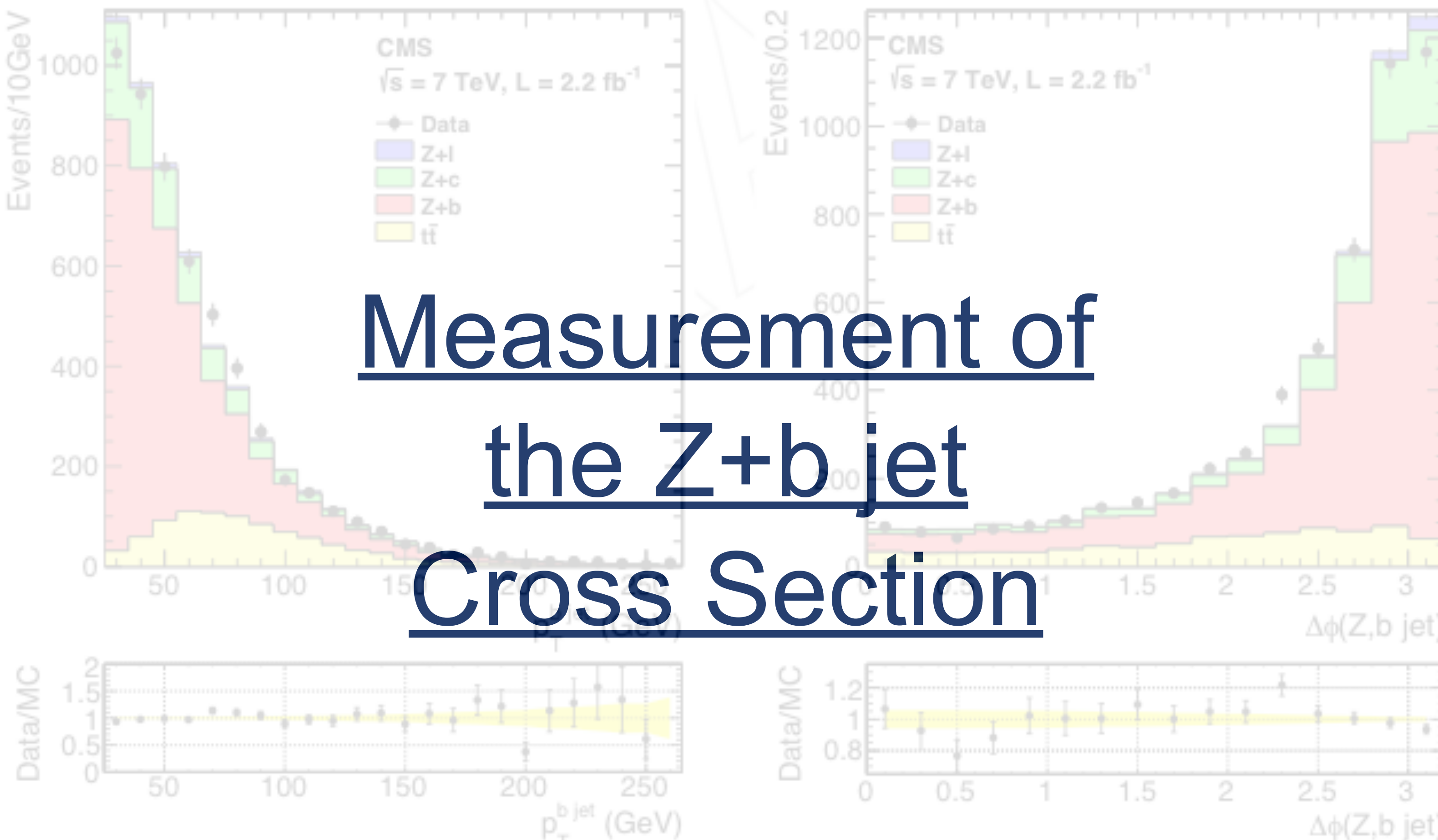


- Systematic uncertainties (int. luminosity and jet energy scale) cancel in the ratio.

- The maximal difference observed between the measured and expected values is at the level of one standard deviation

- <u>This analysis is being updated at 5/fb, adding differential cross sections (jet P_T,H_T, η)</u>

Measurement of the Z+b jet Cross Section



Analysis Details

- Data: 7 TeV data (2.2/fb)
- Jet P_T >25 GeV, $|\eta|$ < 2.1 (to optimize the "b-tagging")

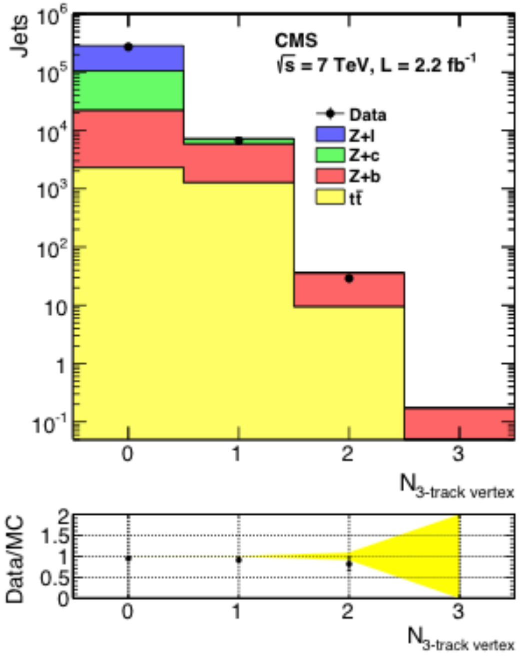
- Aim to measure the inclusive cross section $Z/\gamma^*(ll)$ + b-jets, regardless additional non-b-flavoured jets

↓

- Jets from b are tagged taking advantage of the long b-hadron lifetime, using the "Simple Secondary Vertex" discriminator (based on decay length significance)

- Z+Jets sample is divided in 3 subsamples:
  - underlaying production of b jets (Z+b)
  - underlaying production of c jets (Z+c)
  - underlaying production of "light" u,s,d jets (Z+l)

- Background:
  - ttbar
  - QCD multijet, W+Jets, WW and WZ negligible
  - Irreducible ZZ and associated production of W and t negligible



Cross Section @ Hadron Level

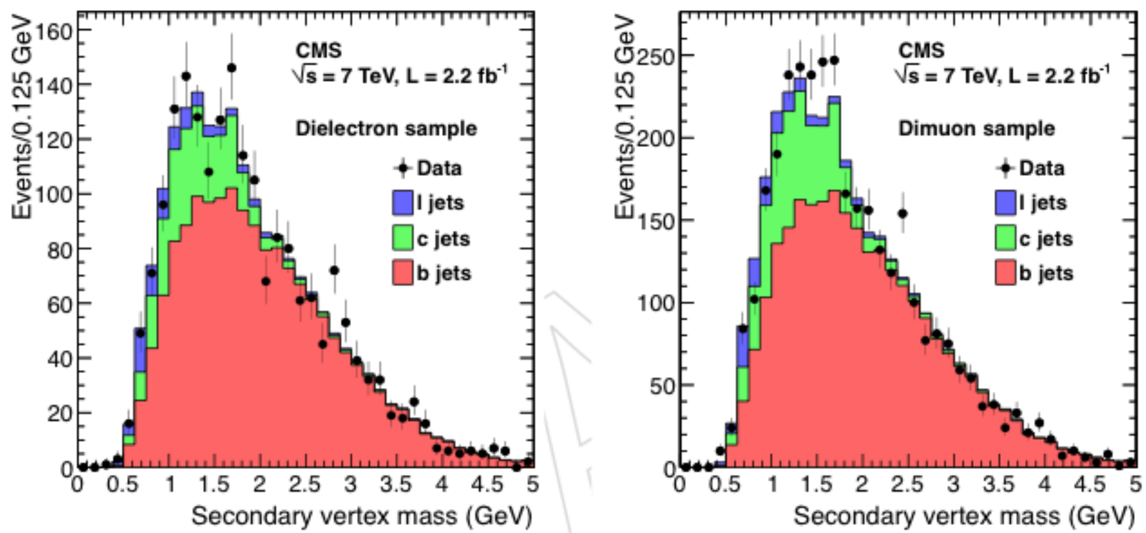
- The cross section for the production of a Z/γ^* boson in association with at least 1 hadron-level b is given by:

$$\sigma_{\text{hadron}}(Z/\gamma^* + b, Z/\gamma^* \to \ell\ell) = \frac{N(\ell\ell + b) \times (\mathcal{P} - f_{t\bar{t}})}{\mathcal{A}_\ell \times \mathcal{C}_{\text{hadron}} \times \varepsilon_\ell \times \varepsilon_b \times \mathcal{L}}$$

- **A_l**: Acceptance (Sherpa,MCFM)
- **ε_b**: B-tagging efficiency (MC correct to match data)
- **ε_l**: Lepton efficiency
- **C_{hadron}**: Correction factor for detector resolution (comparison event yield/generator level)

- **Purity (P)**: estimated from the secondary vertex mass distribution, extracting the P from data using a template trained on MC.
- **F_{tt}** is the fraction of tt events, because real b arise from tt.
  tt extrapolated from sideband

Variable	Electron	Muons
Purity	83.4±3.6	81.5±2.9
F_{tt}	18.7+2.2	18.4±2.3
ε_b	35.3±3.5	34.9±3.5
ε_{Lepton}	63.2 ± 2.6	84.4±1.7
C_{Hadron}	$84.2^{+5.8}_{-0.6}$	$95^{+6.6}_{-0.5}$
A_L	$55^{+3.6}_{-2.1}$	$57.2^{+3.7}_{-2.4}$



Results

- Final Cross section is:

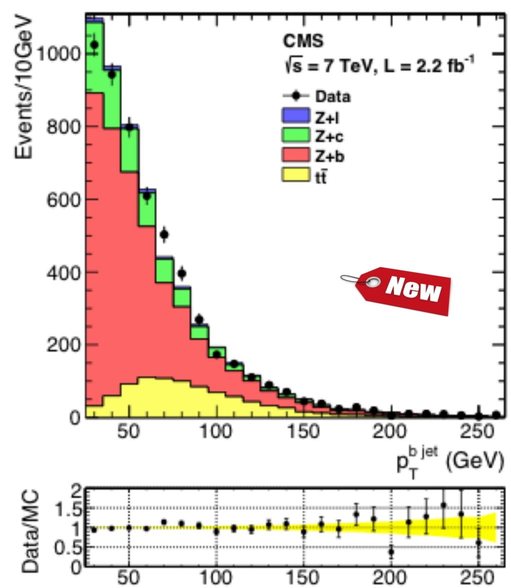
Electrons | Muons | Combination

$$\sigma_{\text{hadron}}(Z/\gamma^* + b, Z/\gamma^* \to \ell\ell)\ (\text{pb}) \;\Big|\; 5.61 \pm 0.13 \pm 0.73^{+0.24}_{-0.53} \;\Big|\; 5.97 \pm 0.10 \pm 0.73^{+0.25}_{-0.57}$$

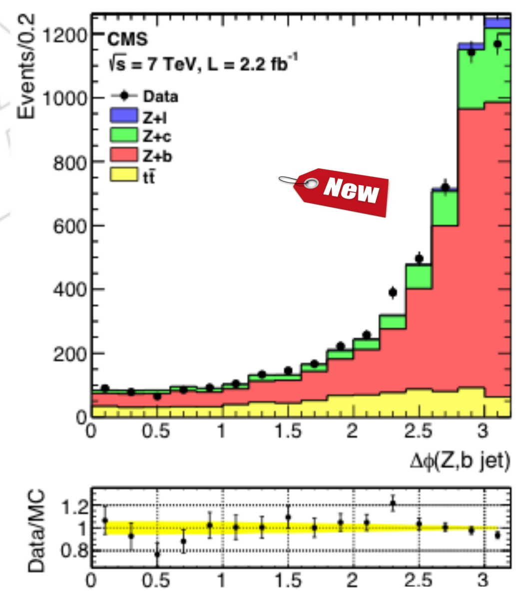
$$5.84 \pm 0.08\,(\text{stat.}) \pm 0.72\,(\text{syst.})^{+0.25}_{-0.55}(\text{theory})\ \text{pb} \leftarrow \sigma_{\text{parton}}^{\text{MCFM}} = 4.73 \pm 0.54\ \text{pb},$$

New

- Main systematics are:
  - b-jet purity ~5%
  - b tagging efficiency 10%
  - Luminosity 2.2%
  - tt contribution 3%
  - Jet Energy Scale 3%
  - Trigger and Lepton sel. 4%



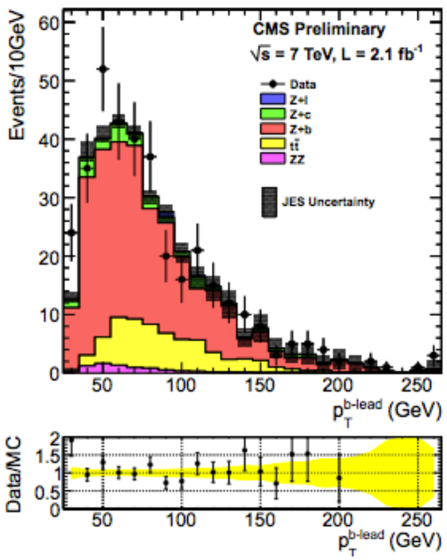
$P_T^{b\text{-jet}}$ (GeV)

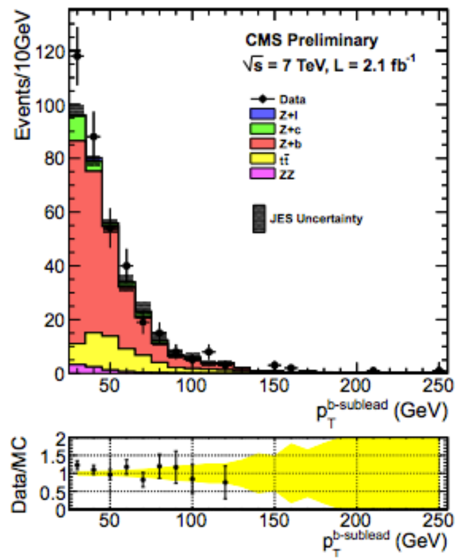


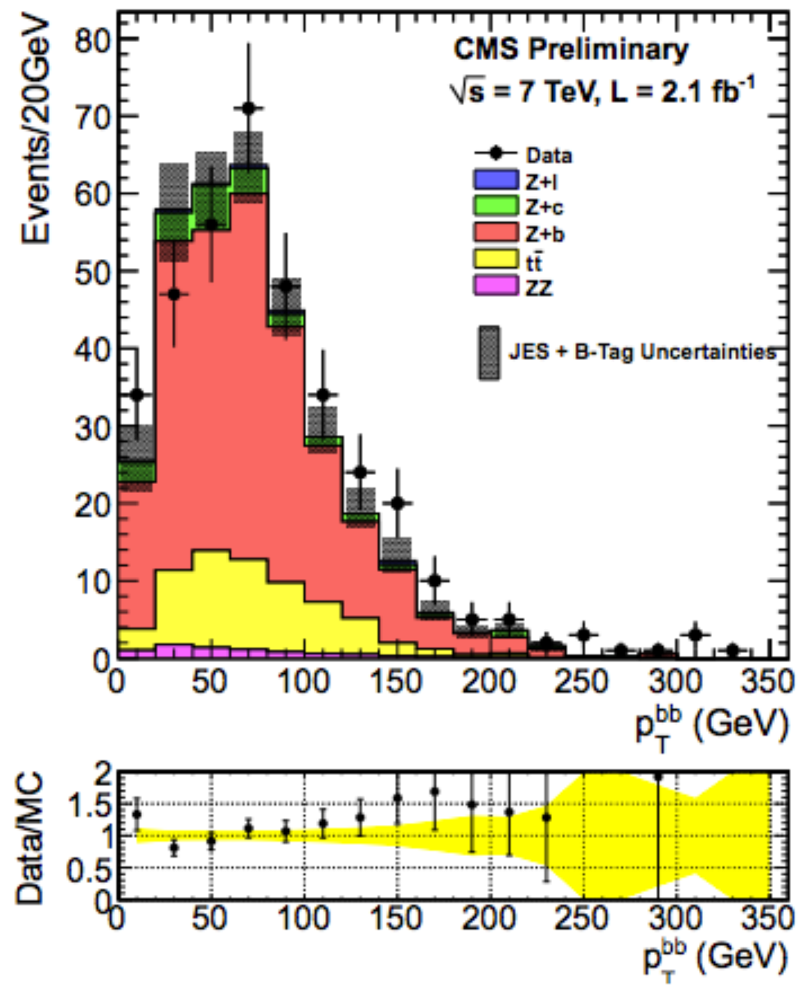
ΔΦ(Z, b-jet)

Z+bb Analysis

- Cross section for one Z boson in association with exactly one or at least two b quarks

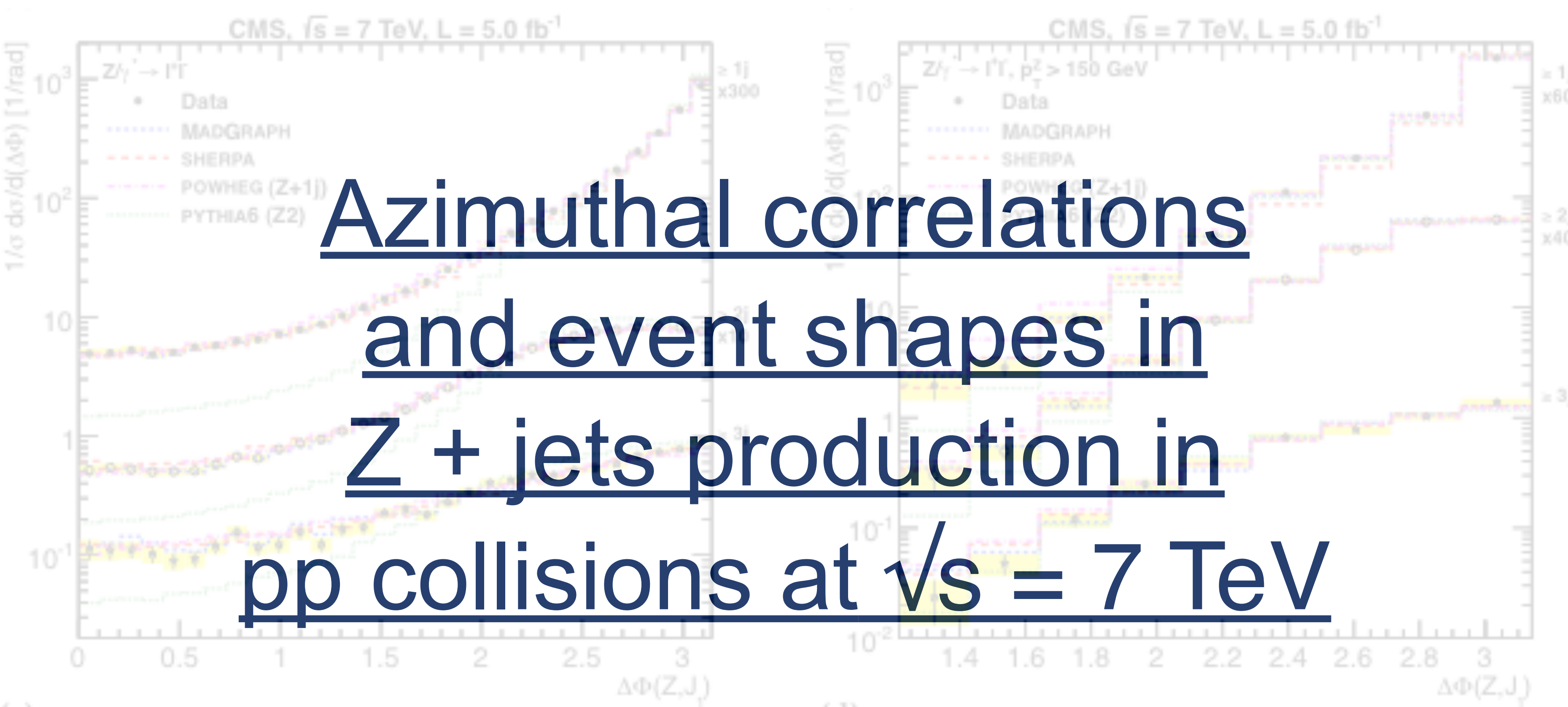






Multiplicity Bin	Electrons	Muons
σ_{hadron}(Z+1b) (pb)	3.25±0.08±0.29 ±0.06	3.47±0.06±0.27 ±0.11
σ_{hadron}(Z+2b) (pb)	0.39±0.04±0.07 ±0.02	0.36±0.03±0.07 ±0.03

Azimuthal correlations and event shapes in Z + jets production in pp collisions at √s = 7 TeV



Analysis Peculiarities

- Data: 5.0/fb taken at 7 TeV from 2011 data
- Event Selection: Jets > 50 GeV

- MC "Signal" (named "Z+Jets"):
  - MadGraph (up to the fourth jets + pythia)
  - SHERPA (up to the fourth jet)
- MC Backgrounds:
  - ttbar
  - W+Jets
  - dibosons (WW,WZ,WW)

- Studies published by the Tevatron (D0) and ATLAS: extended the frontier to higher jet multiplicity (three jets)
- Theory/data comparison for boosted Z bosons (p_T>150 GeV) -> **phase space very critical for searches for new phenomena** based on large imbalanced system *New*
- First study of variables categorizing the topological structure of Z+Jets ("Event Shapes") suitable to **tune parton shower** or fragmentation functions. *New*

Observable Quantities

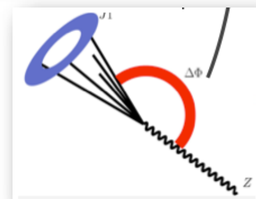
- Differential cross section as a function of:
  - azimuthal angles $\Delta\Phi(Z,J_i)$ i = 1,2,3
  - $\Delta\Phi(J_i,J_k)$ i,k = 1,2,3
  - transverse thrust

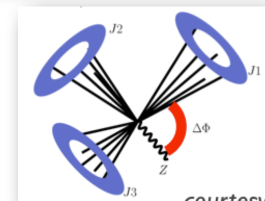
A. Banfi, G.P. Salam, G. Zanderighi, JHEP 0408 (2004) 062

$$\tau_\perp \equiv 1 - \max_{\vec{n}_\tau} \frac{\sum_i |\vec{p}_{T,i} \bullet \vec{n}_\tau|}{\sum_i p_{T,i}}$$

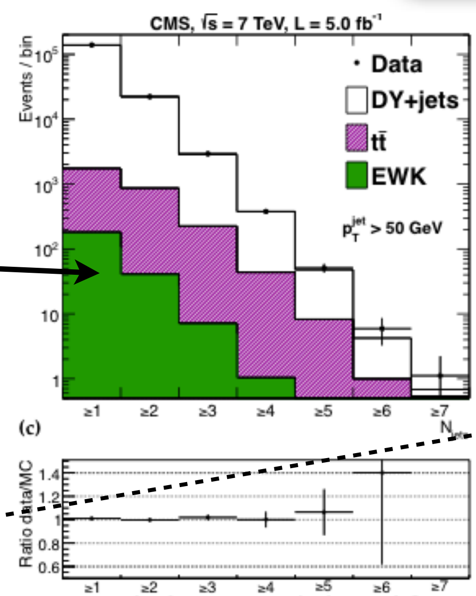
Pencil-like: $\tau_\perp \sim 0$ Spherical: $\tau_\perp \sim 1 - 2/\pi$

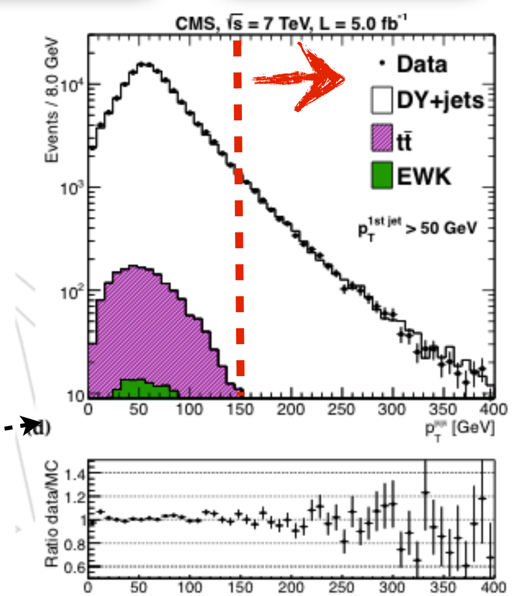
In the limit of a **perfectly balanced** (pencil-like) Z + 1 Jet tends to **zero**. With additional jets, the value increases. The largest possible value is reached in the limit of a spherical, homogeneously-distributed event.





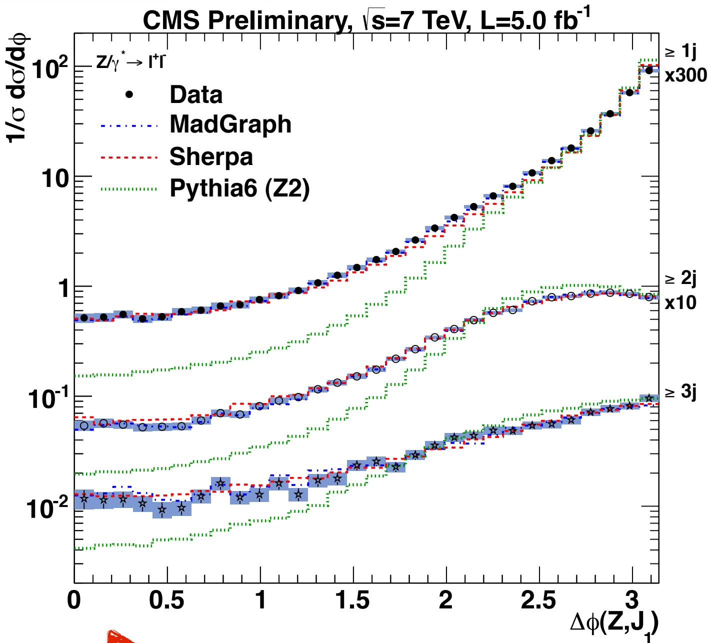
To investigate the dependence of the topological properties on the complexity of the final state, events categorized as a function of the Jet Multiplicity.

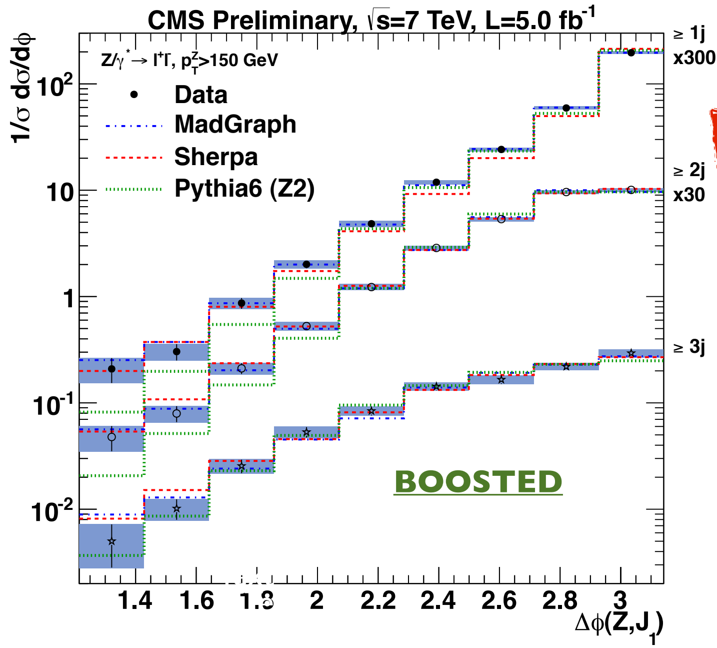




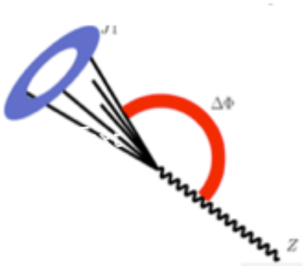
Measurement performed also in the boosted regime ($Z(P_T) > 150$ GeV)

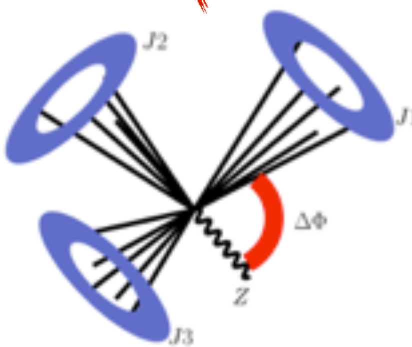
Results (1)





$\Delta\Phi(Z,J_i)$ as a function of the Jet Multiplicity, with/without the Z(Pt)>150 GeV cut



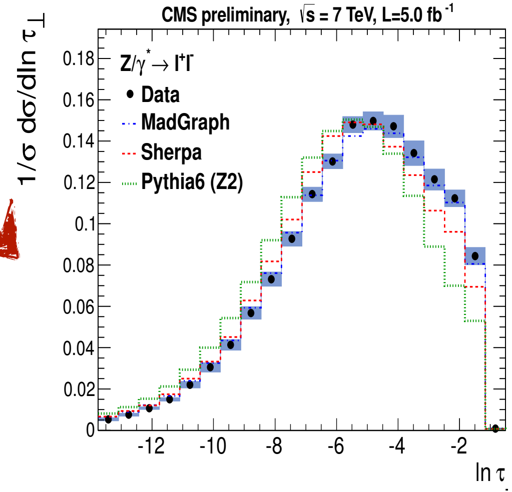


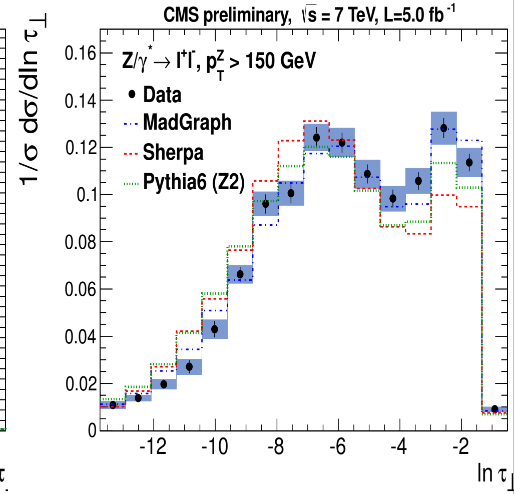
- Overall the measured distributions agree within uncertainties with MadGraph
- Sherpa 10% overshoot
- For Z(PT)> 150 GeV, system more isotropic

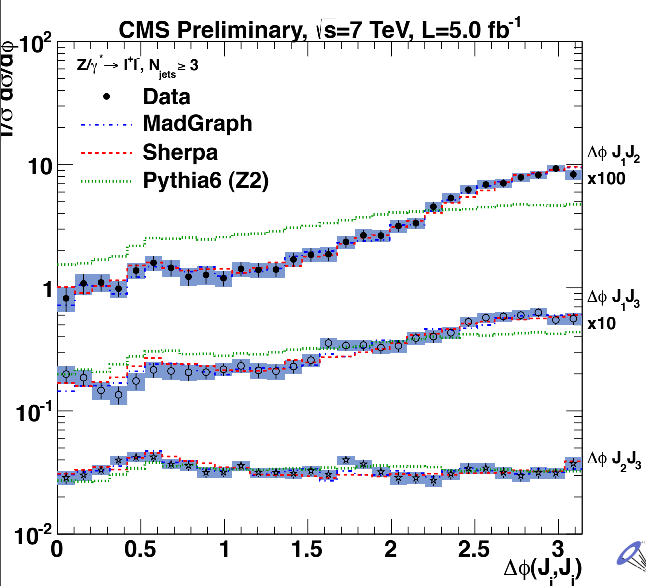
Results (2)

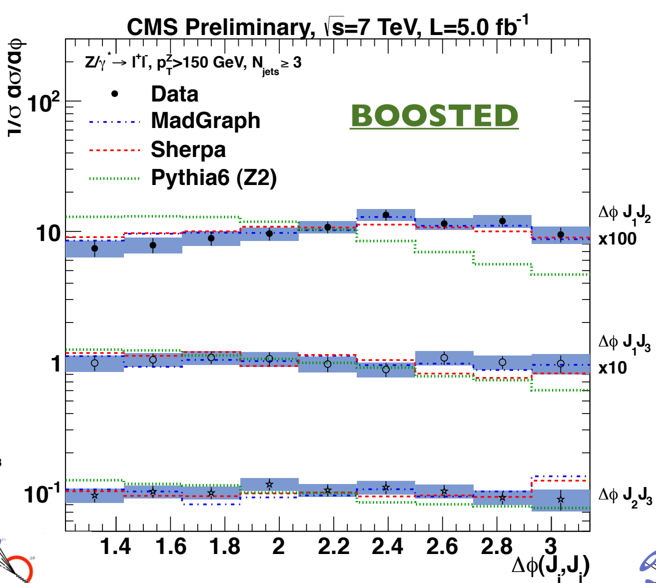
$\Delta\Phi(J_j,J_i)$ as a function of the Jet Multiplicity, with/without the Z(Pt)>150 GeV cut

Thrust variable with/without the Z(Pt)>150 GeV cut









- MadGraph agrees with data
- Sherpa & Pythia differs in the thrust (smaller values)

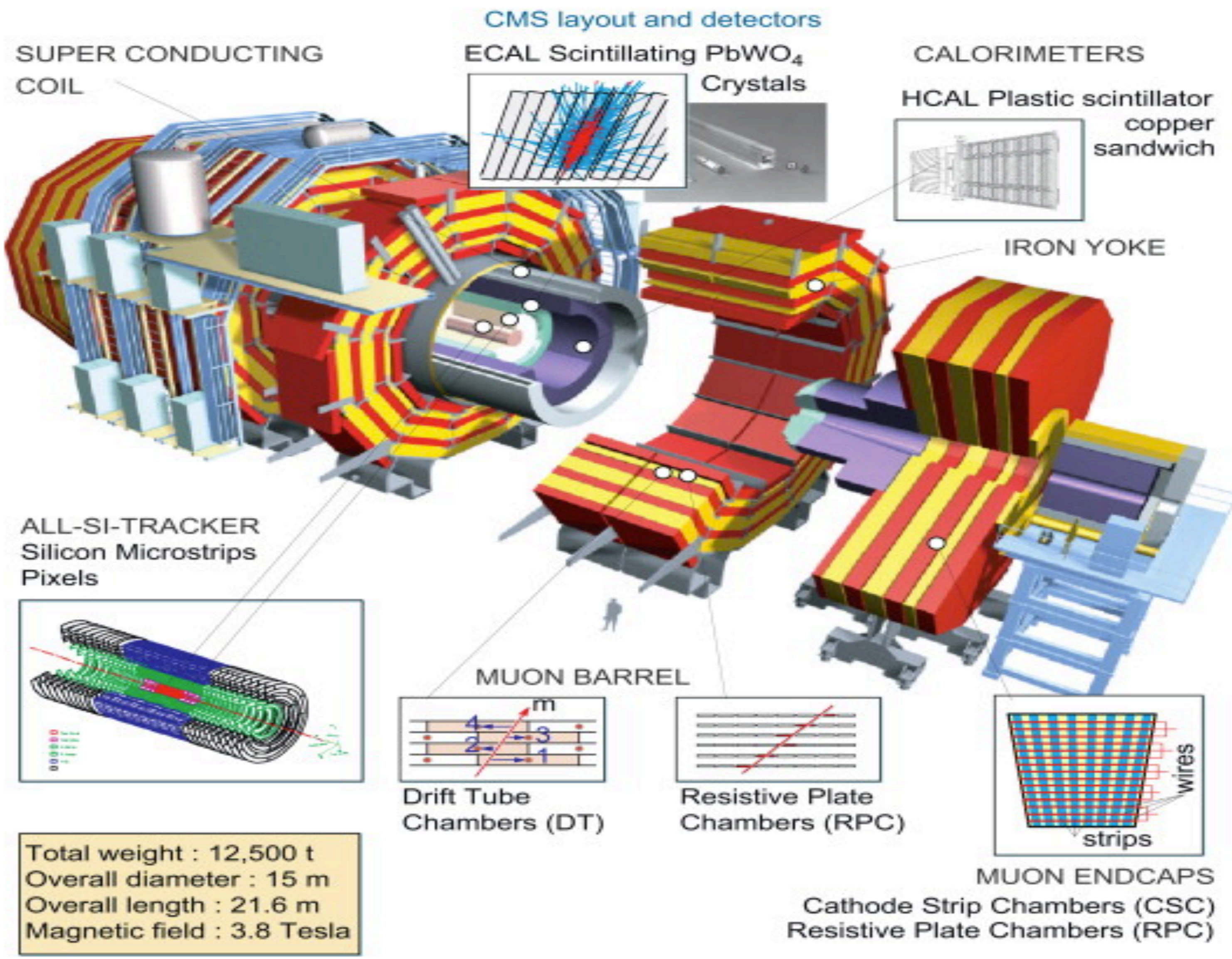
Conclusions

- Presented a selection of results on the production of vector bosons and jets. More details can be found here:
  - Jet Rate With W and Z Bosons → arXiv:1110:3226
  - Azimuthal correlation and event shape → (*)
  - Zb cross section measurement → arXiv:1204:1643
- In general, good agreement data/MC over a large number of observables investigated so far
- Several promising analyses will be carried on in the future, taking advantage from a higher statistics and center-of-mass energy

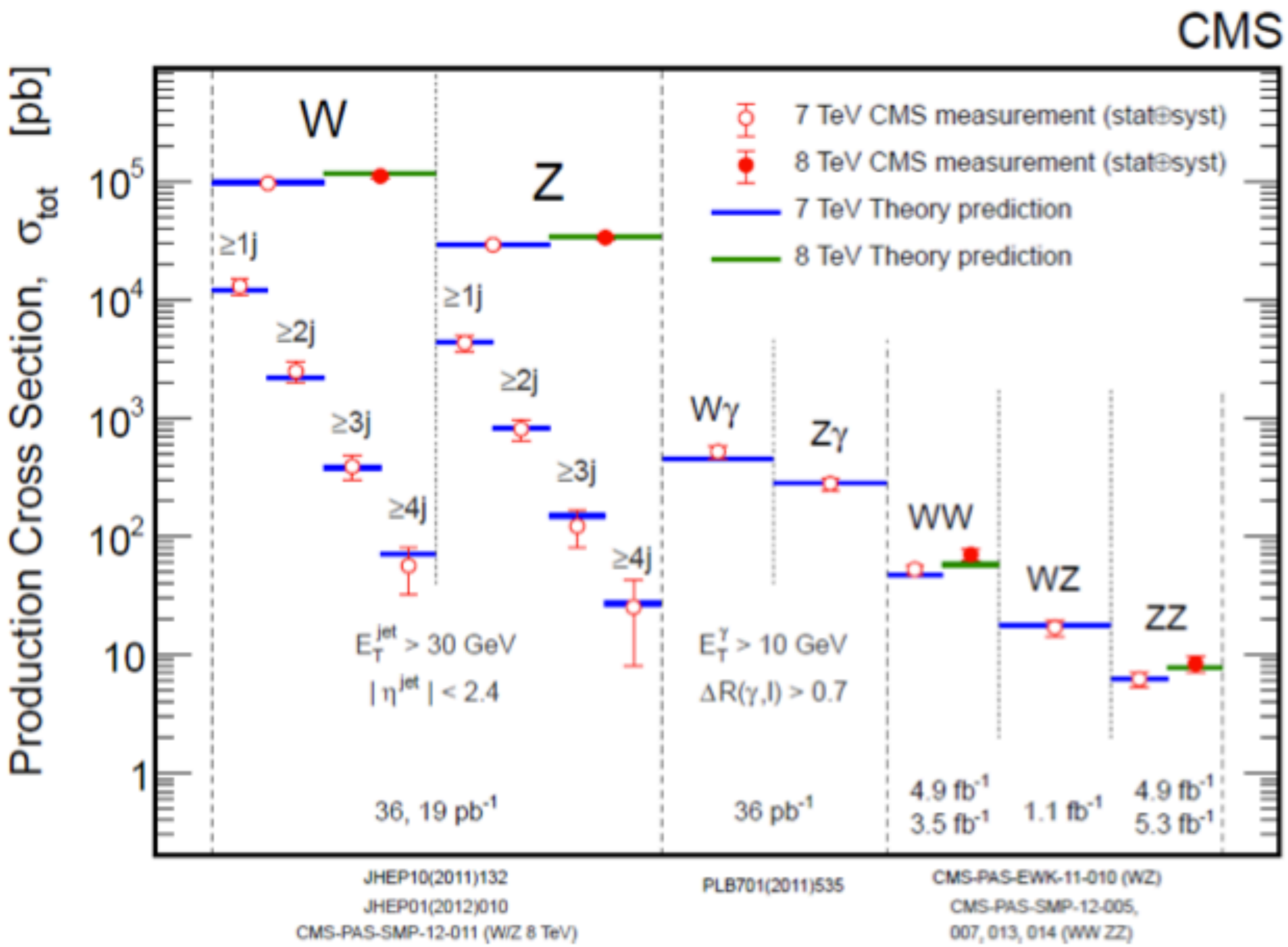
(*) https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11021?skin=drupal

Backup

CMS Detector

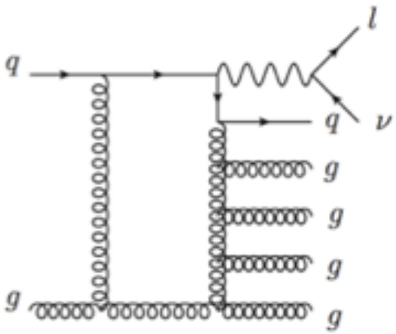


Standard Model @ CMS



Review of MC in the market

- LO matrix element + matching to parton shower (PYTHIA, HERWIG)
  - **ALPGEN**, **MADGRAPH**, **SHERPA** (CKKW or MLM matching)
- Fixed-order NLO calculation
  - **Blackhat-Sherpa**: NLO up to Z + ≥4 jets W + ≥5 jets
  - **Rocket + MCFM**: NLO up to W/Z + ≥3 Jets
  - **MCFM**: NLO up to W/Z + ≥2 Jets



- Fixed-order NLO + parton shower for Z+ ≥1 Jet
  - **POWHEG + PYTHIA**
- Resummation
  - **HEJ**: all-order resummation of perturbative contribution of wide angle emission (for ≥2 Jets)
- Approximate NNLO for Z+ ≥1 Jet
  - **LOOPSIM+MCFM**, JHEP 1009 (2010) 084
- NLO QCD ⊗ NLO EW
  - JHEP 1106 (2011) 069

Rho Fast-Jet Method

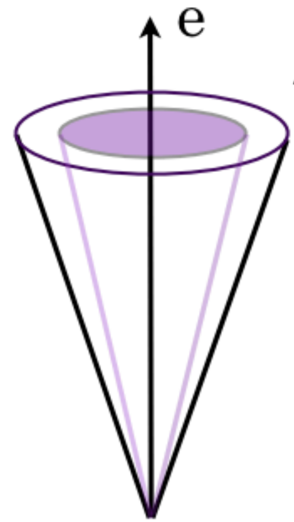
Isolation

$$Iso = [\sum_{ECAL,HCAL,TRK}^{\Delta R<0.3} E_T] - p_T^e$$

Isolation pile-up corrected

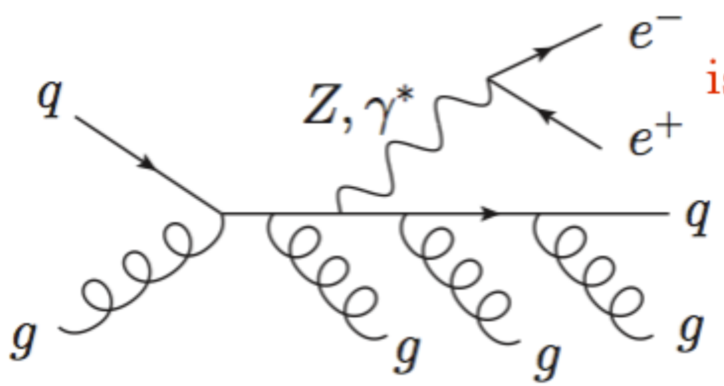
Rho FastJet Method

$$Iso_{PUR} = Iso - \rho S$$



$\Delta R = [(\Delta\eta)^2 + (\Delta\phi)^2]^{1/2}$

- ρ = *energy density*
  energy per unit of area in the jet
  (PU energy event by event)
- S = *effective area*
  jet area weighted with iso dependence wrt vtxs



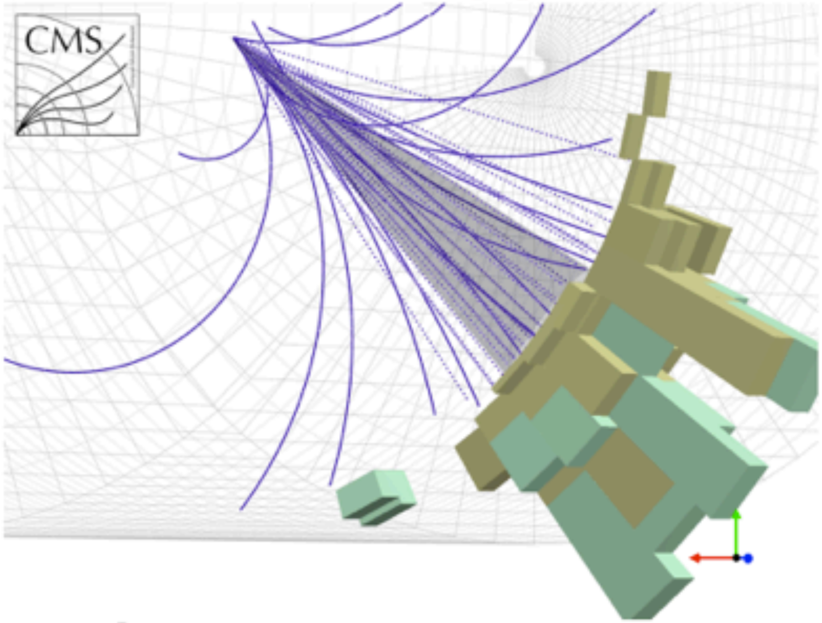
isolated electrons

jet energy

Jet Energy Corrections

Jet reconstruction in CMS: Particle Flow
combines information from all CMS sub-detectors

- simply:
  Jets energy is difficult to measure.
- Main issue: correct the jet energy



HCAL response

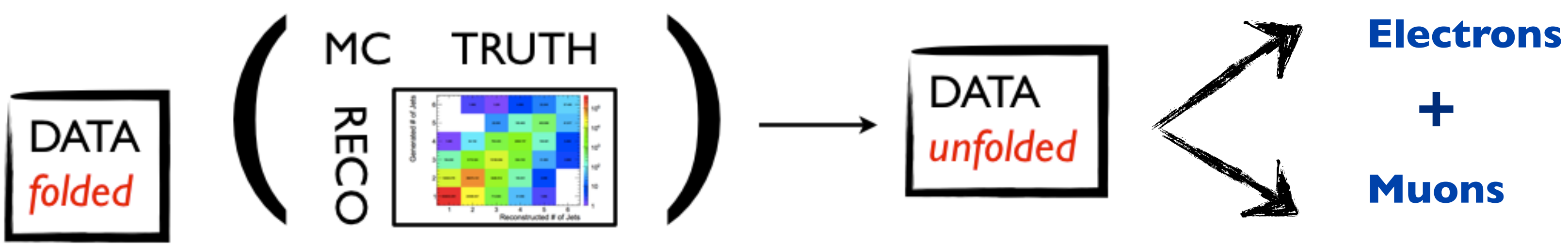
In CMS decompose correction into indipendent factor then apply in a fixed sequence (levels)

RECO JET → CALIB JET

LVL1	Offset	pile-up removal
LVL2	Relative	jet response uniform with η
LVL3	Absolute	CaloJet pT uniform to particle level
LVL4	EM	jet response in e.m. energy component
LVL5	Flavour	flavour dependence
LVL6	Parton Jet	<CaloJet pT = parton pT>

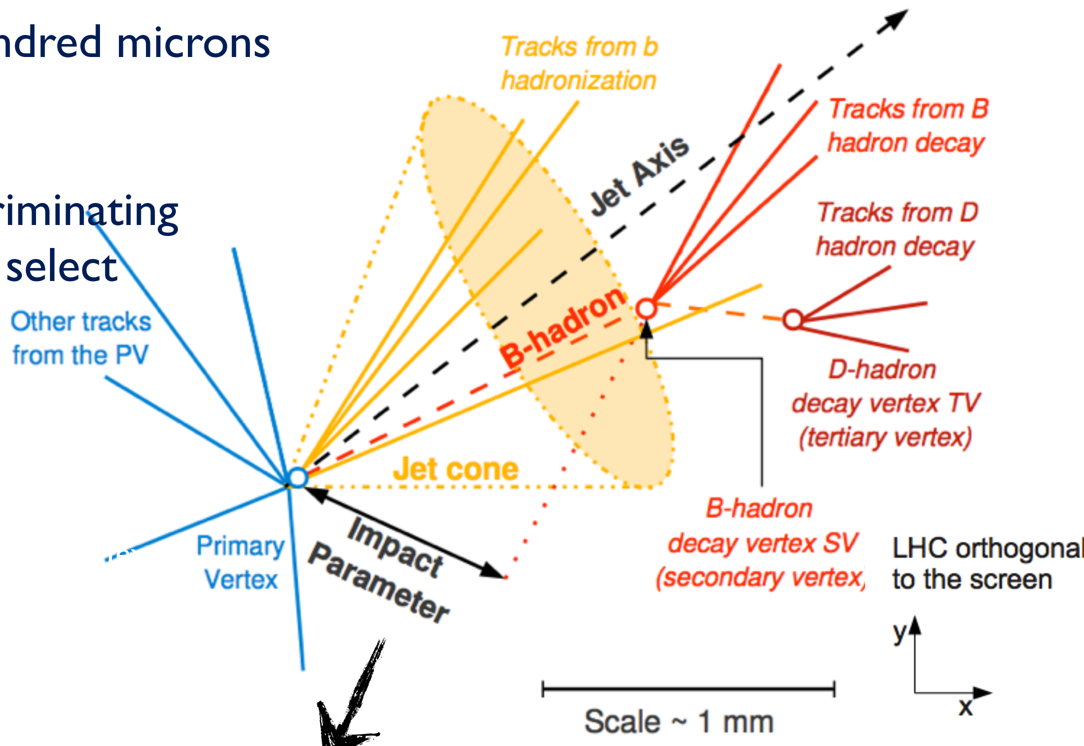
From detector to particle level

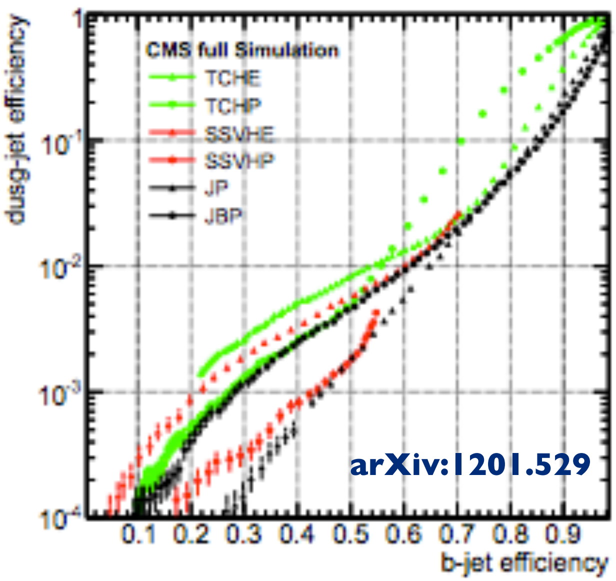
- After the event selection, the following steps are done:
  - **Background subtraction**:
    - Via MC prediction for minor backgrounds (dibosons and W+Jets).
    - TTbar prediction cross checked using a eμ sample in data
  - **Unfolding:** background subtracted events (detector level) are mapped at particle level through the unfolding procedure and efficiency correction.
    - Generated jets are formed in the <u>same way</u> as the detector (including FSR)
  - **Combination** done using the best linear unbiased estimator

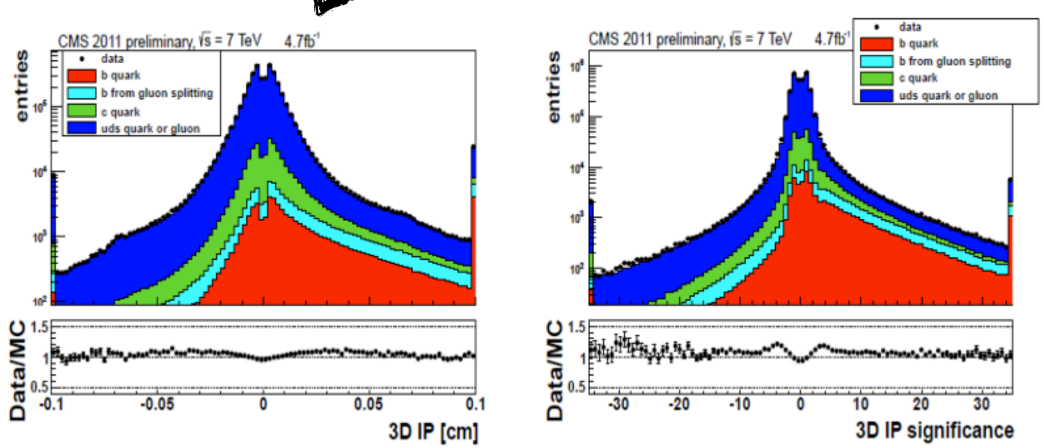


B Tagging in a nutshell

- Typical IP order of magnitude is few hundred microns (IP uncertainty ~10-100 um)
- Use Track IP significance $S = IP / \sigma_{IP}$
- In the SSV algorithm S is used as a discriminating variable on which the user can cut on to select different regions in the efficiency versus purity phase space.







Analysis Working Point: (mis)tagging fakes (udsg) jets estimated to be 1%