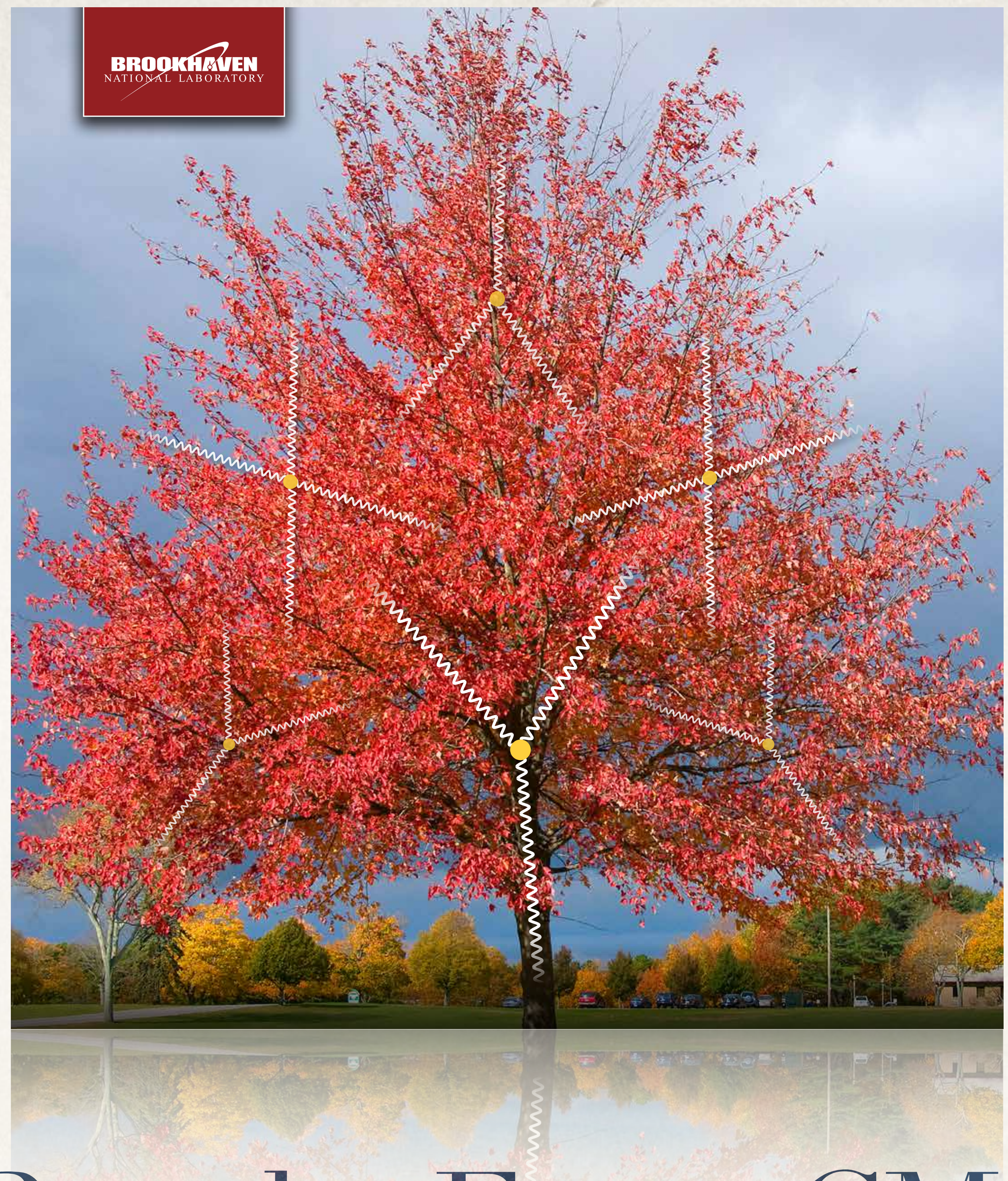


VBF-V Results From CMS

Yiwen Wen, Peking University

On behalf of CMS experiment

October 29, Multi-boson Interaction Workshop

Motivation

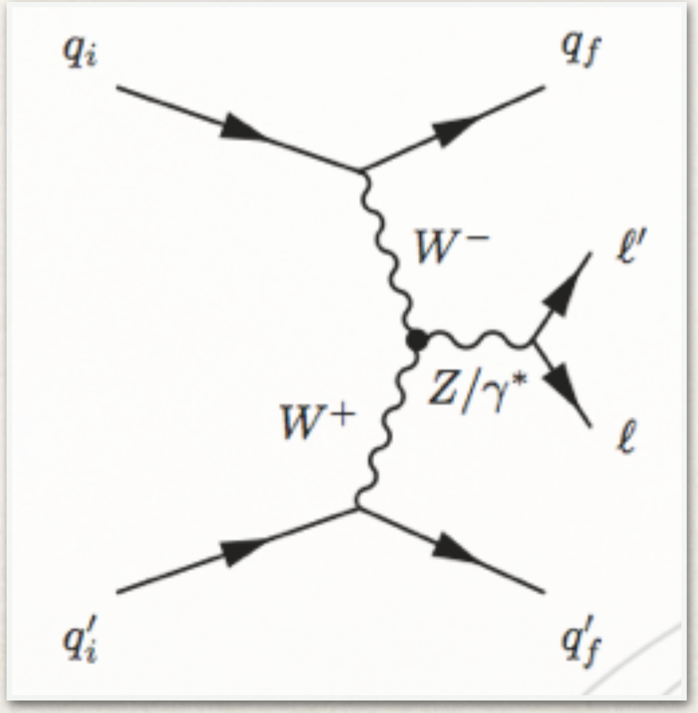
- **Standard Model** achieved great success: good agreement between theoretical expectation and data. Found a new 125 GeV **Higgs-like** particle
- **Vector boson fusion(VBF)** provides a unique channel to probe the mechanism of electroweak symmetry breaking in LHC
- Give independent access to **triple gauge couplings**
- Allows us to study the **rapidity gap,** crucial to **VBF higgs search**
- The events are **rare**. The LHC is the first hadron collider to probe VBF process

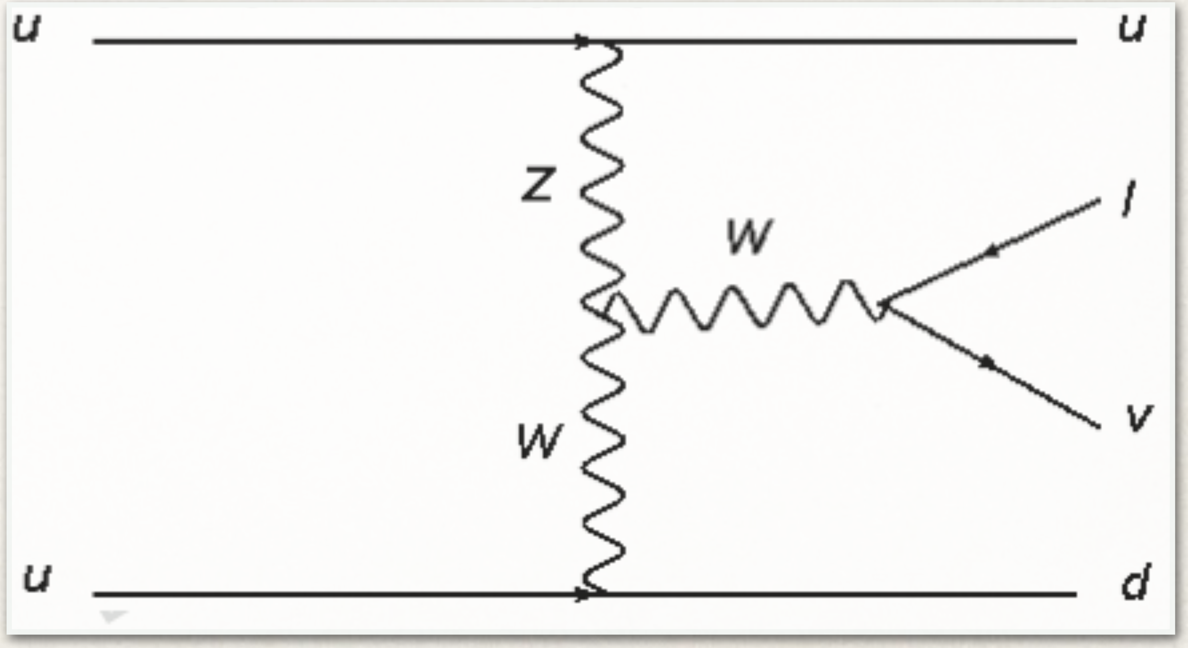
VBF-V measurement in CMS

- Electroweak vector boson production with 2 jets

EWK Z+2 jets@7TeV (JHEP 10 (2013) 062)

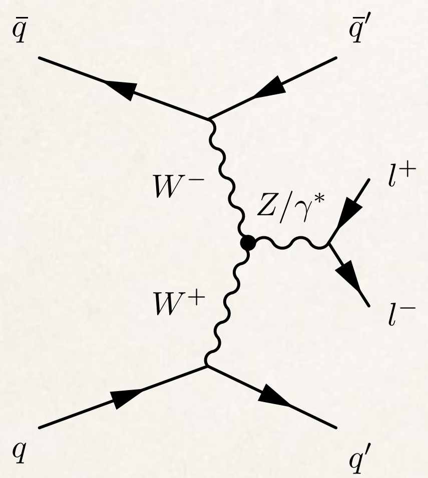
EWK Z+2 jets@8TeV (**today's topic**)[CMS-PAS-FSQ-12-035](arXiv:1410.3153, Submited to EPJC)





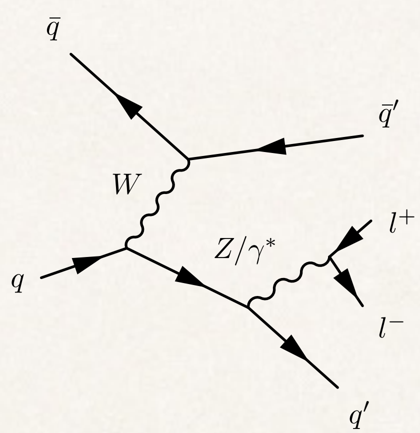
EWK Z+ 2jets characteristics

We are interested in pure electroweak production Z+2jets with final state of lljj (l=e, μ), of order of α^4_{EM}



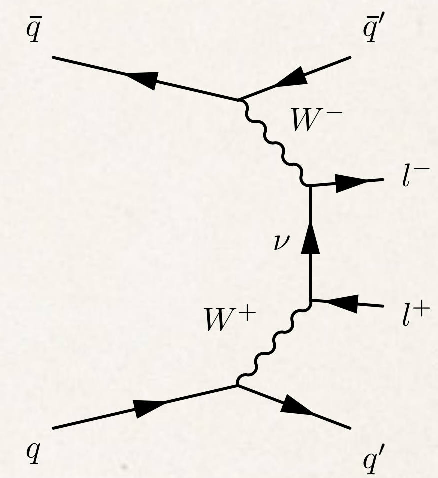
VBF

$+$



Z-Bremsstrahlung

$+$

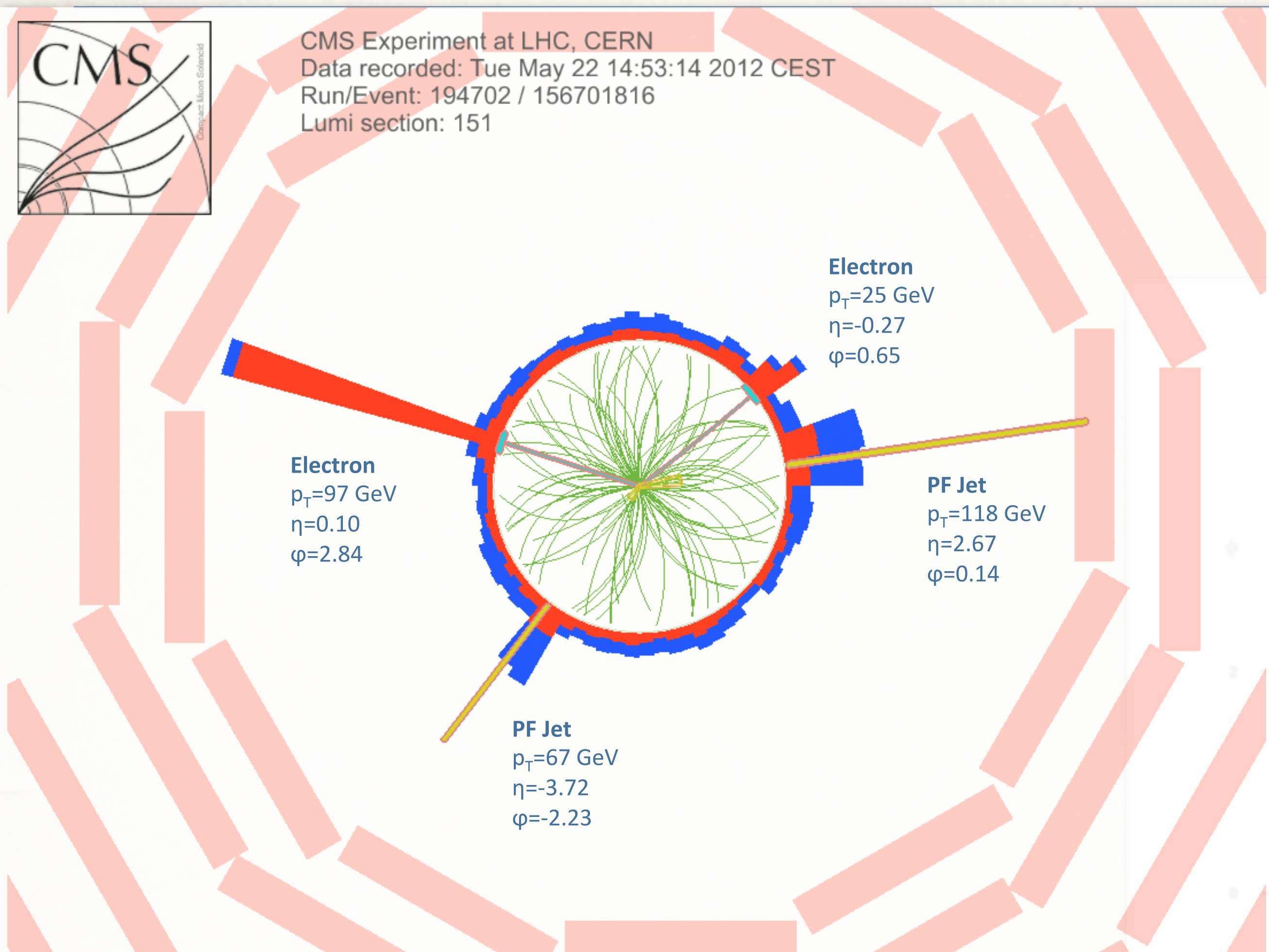


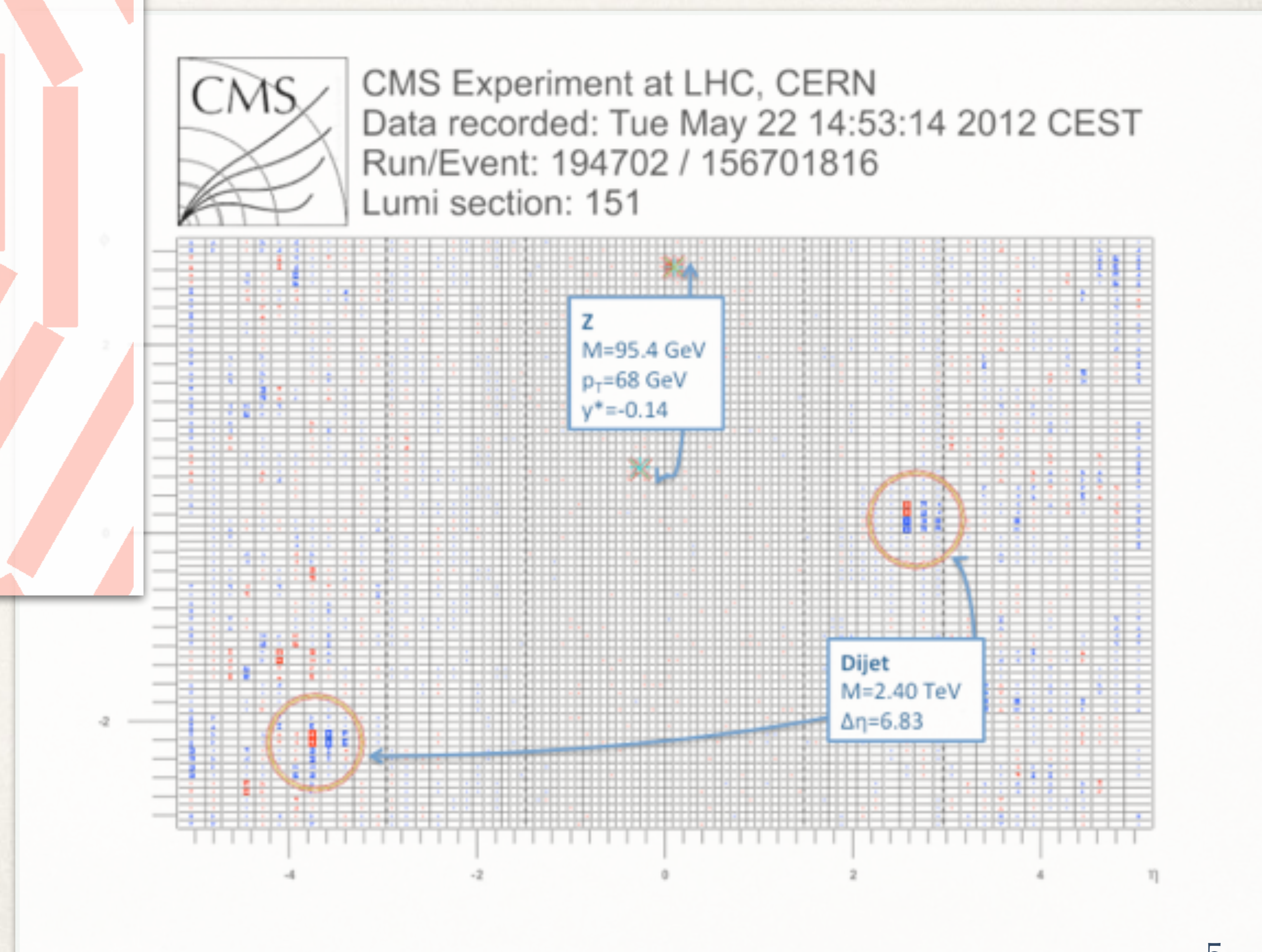
Multiperipheral

Key signatures :

- **Two isolated leptons in the central region of detector with M(ll) at the Z-peak**
- **Two well separated high-Pt forword/backword jets with large invariant mass Mjj**
- **Low central hadronic activity**

Event display





high Mjj and tag jets
Δη

Part I) Cross-section Measurement

How to analyze?

- Signal is covered by Drell-Yan background
  - Use Boosted Decision Tree method(BDT)
  - Confirm signal in ee and dimuon modes
  - Use different methods of jet reconstruction
  - Modeling background use different methods: MC based and Data-driven

- The Measurement use the full 8TeV data set corresponding to an integrated luminosity of **19.7/fb**

In this Analysis:

A:Particle Flow(PF) jet — MC-based background

B: Jet Plus Track(JPT) jet — MC-based background

C: PF jet —Data driven background

Event selection and signal extraction

Signal selections

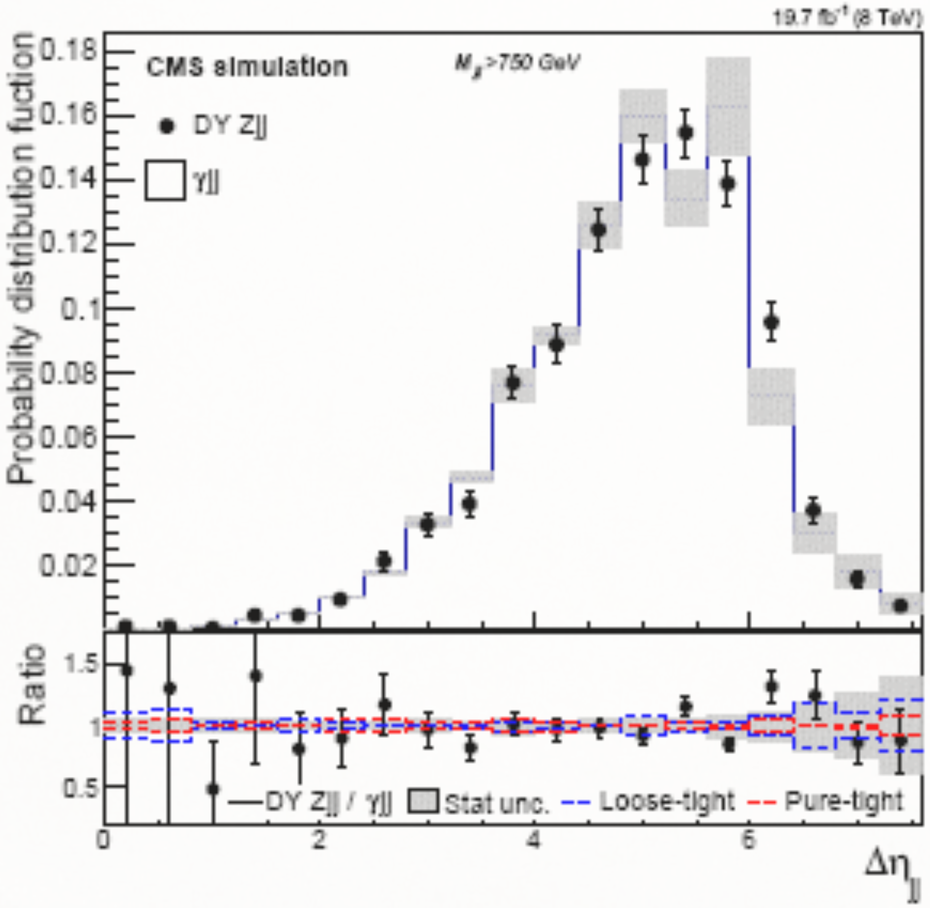
- Two opposite charged, isolated leptons
- Lepton pT > 20 GeV, $|\eta|<2.4$
- $|m_{ll}-m_Z| < 15$ GeV
- At least 2 jets in $|\eta| < 4.7$ with leading (subleading) pT > 50 (30) GeV

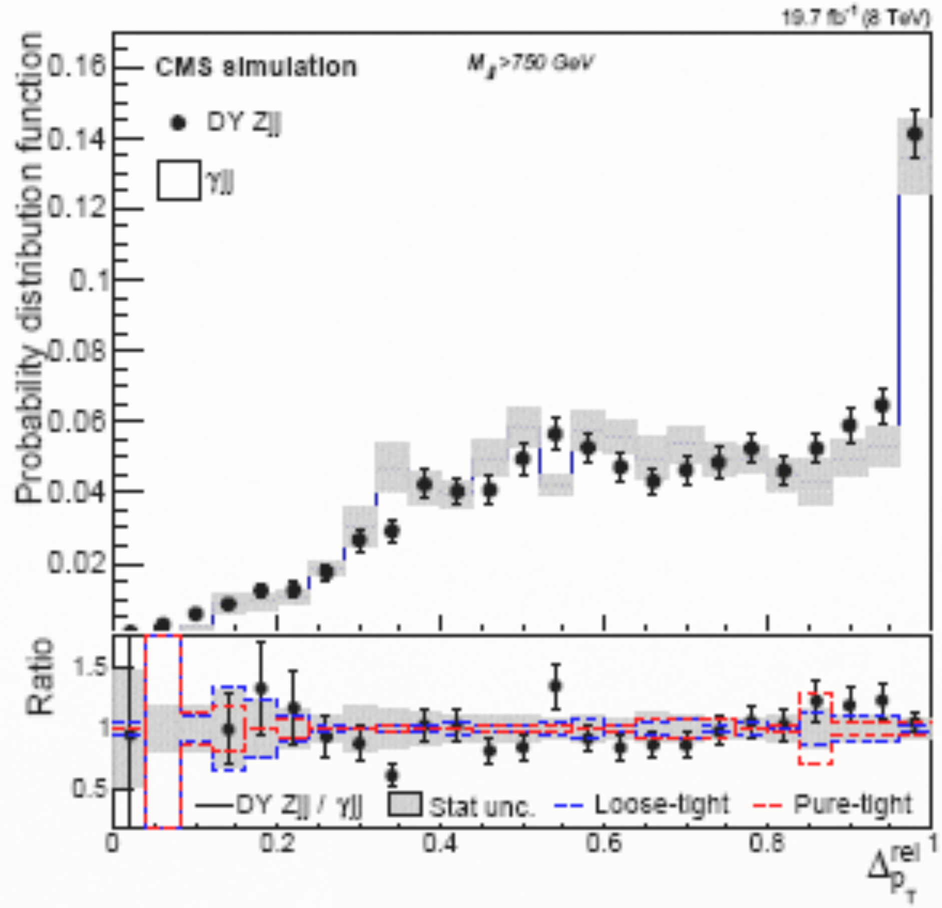
Background Modeling

- MC-based
  - Introduce NLO reweighting by comparing MCFM(NLO) to MADGRAPH(LO) with showering -> Reweight MADGRAPH simulation event by event
  - the difference between nominal MADGRAH and the reweight one is assigned as a systematic uncertainty for the DY Zjj background
- Data driven:
  - In data, Select γ+2jets -> mimic the kinematic distributions of the tag jets
  - reweighting the pT(γ) to pT(Z) can mitigate the difference
  - subtracting the EWK γ+2jets (from simulation) obtain the final DY Z+2jets
  - 30% normalization uncertainty assigned to the residual process
  - Cut harder: pT(Z or γ) > 50GeV, Mjj> 450 GeV and rapidity $|y(Z \text{ or } \gamma)| < 1.442$, considering multijet fake photon

data-driven methord: MC validation

- γ+2 jets agree well with Drell-Yan Z+2 jets in Simulation.
- The difference between the samples observed after PDF variations is assigned as uncertainty. “tight” and “loose” photon selections are compared and the difference is taken as extra uncertainty





Ratio between the pT of the dijet to the scalar sum of tag jets pT:

$$\Delta^{\mathrm{rel}}_{p_\mathrm{T}} = \frac{|\vec{p}_{\mathrm{Tj}_1} + \vec{p}_{\mathrm{Tj}_2}|}{|\vec{p}_{\mathrm{Tj}_1}| + |\vec{p}_{\mathrm{Tj}_2}|}.$$

Event selection and signal extraction

- MVA discriminator built with the listed variables in analysis
- A)and B) making use of the dijet and Z boson kinematics. C) uses solely dijet-related
- Signal strengths fitted from discriminator output.

event balance variable:

$$R\left(p_T^{hard}\right)=\frac{\left|\vec{p}_T(j_1)+\vec{p}_T(j_2)+\vec{p}_T(Z)\right|}{p_T(j_1)+p_T(j_1)+p_T(Z)}$$

difference between the rapidity of Z and the average rapidity of two tag jets

$$y^*=y(Z)-\frac{y(j_1)+y(j_2)}{2}$$

$$z^*=\frac{y^*}{\Delta y_{jj}}$$

	Analysis A	Analysis B	Analysis C
Channels	ee, $\mu\mu$	$\mu\mu$	ee, $\mu\mu$ binned in M_{jj}
Selection	$p_{Tj_1,j_2} > 50, 30$ GeV; $Rp_T^{hard} < 0.14$; $\lvert y^* \rvert < 1.2$; $M_{jj} > 200$ GeV	$p_{Tj_1,j_2} > 50, 30$ GeV; $Rp_T^{hard} < 0.14$; $\lvert y^* \rvert < 1.2$; $M_{jj} > 200$ GeV	$p_{Tj_1,j_2} > 50, 30$ GeV; $p_{TZ} > 50$ GeV; $\lvert y_Z \rvert < 1.4442$; $M_{jj} > 450$ GeV
Jets	PF	JPT	PF
Variables used			
M_{jj}	•	•	•
p_{Tj_1}, p_{Tj_2}		•	•
η_{j_1}, η_{j_2}			•
$\Delta_{rel}(jj)=\frac{\lvert\vec{p}_{Tj_1}+\vec{p}_{Tj_2}\rvert}{p_{Tj_1}+p_{Tj_2}}$			•
$\Delta\eta_{jj}$		•	
$\lvert\eta_{j_1}\rvert+\lvert\eta_{j_2}\rvert$	•	•	•
$\Delta\phi_{jj}$		•	•
$\Delta\phi_{Z,j_1}$		•	
y_Z	•	•	
z_Z^*	•		
p_{TZ}	•	•	
Rp_T^{hard}		•	
q/g discriminator	•		•
DY Zjj model	MC-based	MC-based	from data

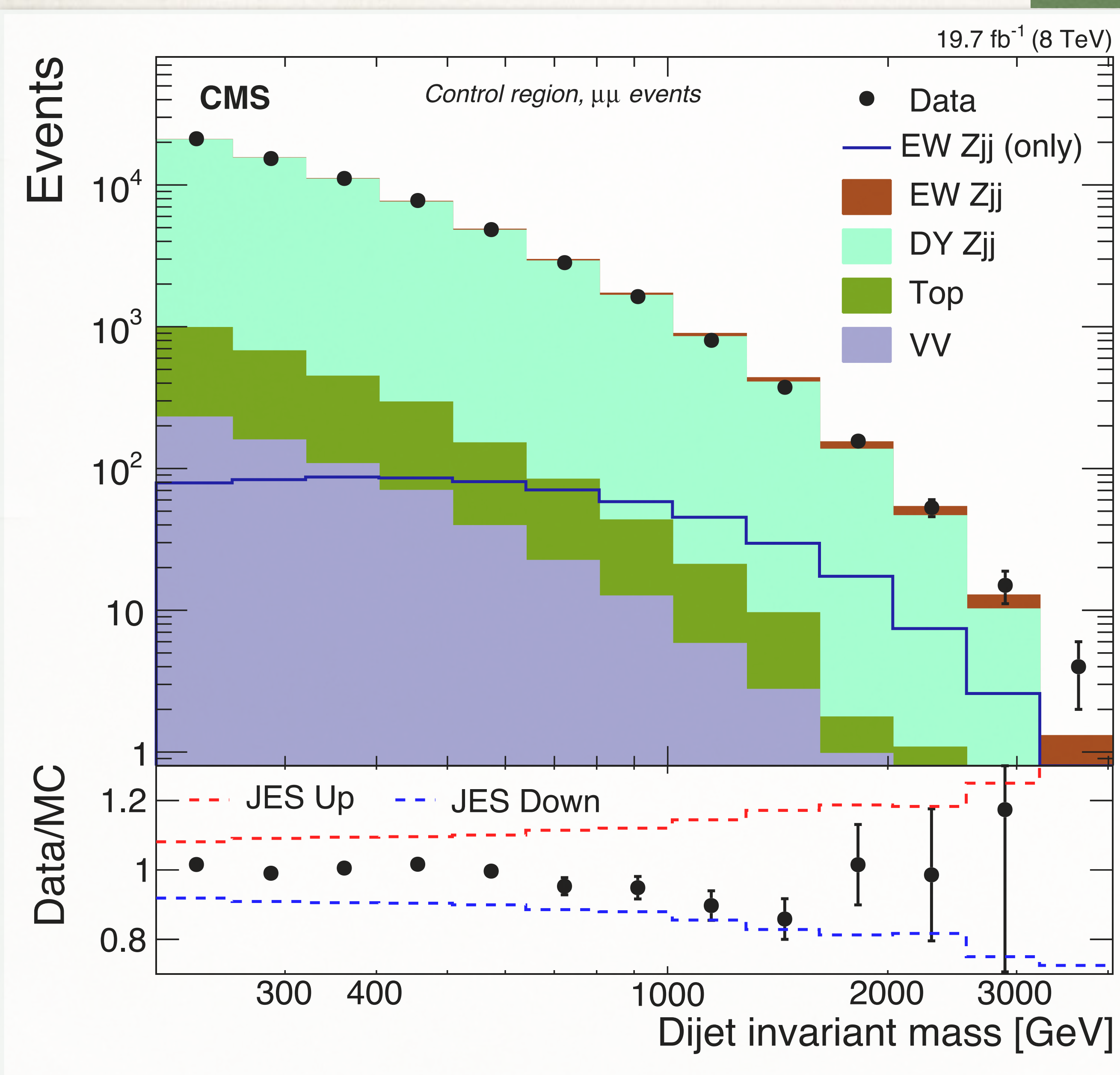
A)MC-based predictions for background

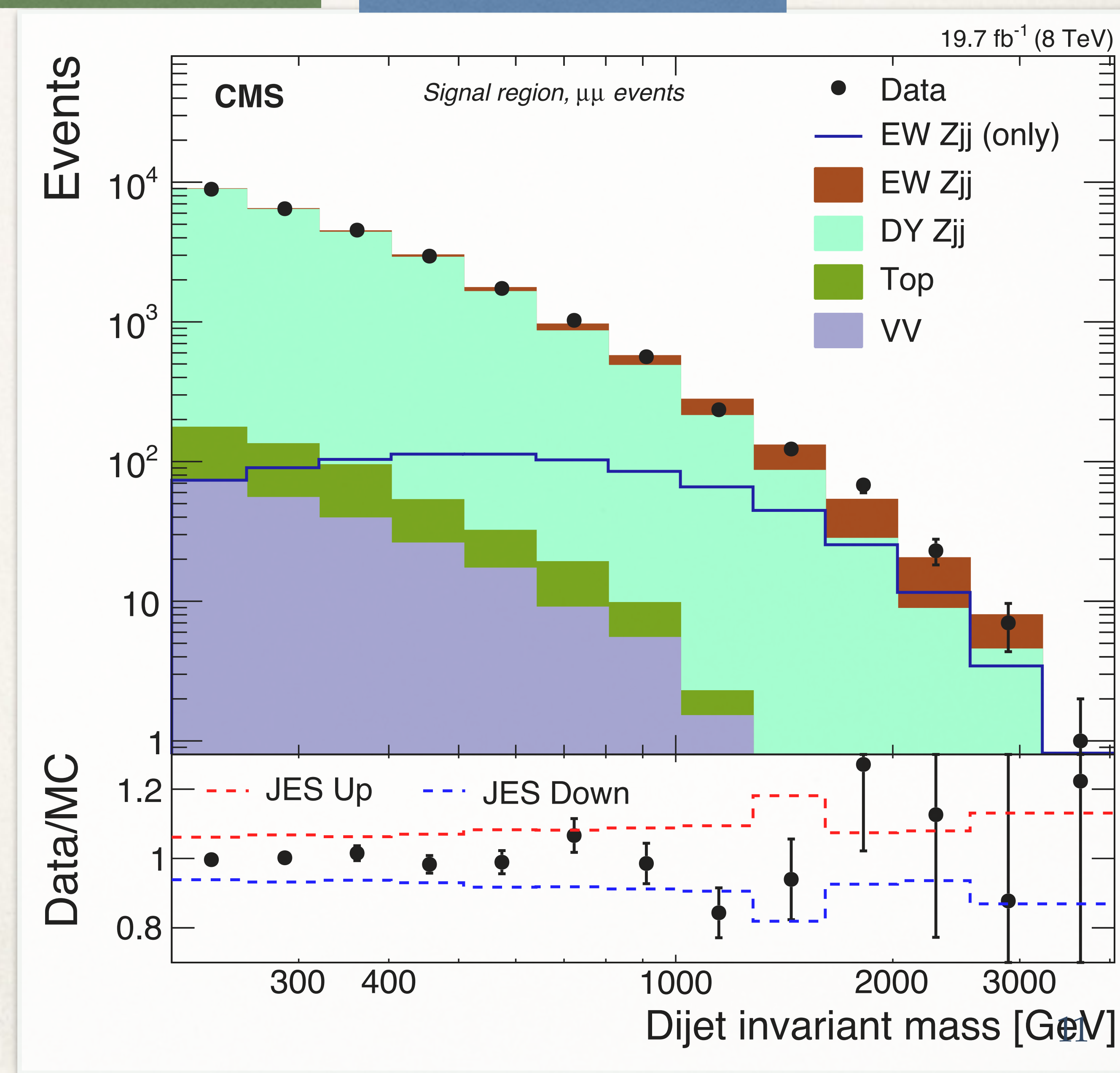
motivated by the fact that the signal is expected to have the Z boson balanced with respect to the dijet system in the transverse plane.

dimuon channel Mjj distribution

signal region: R(Pt)<0.14

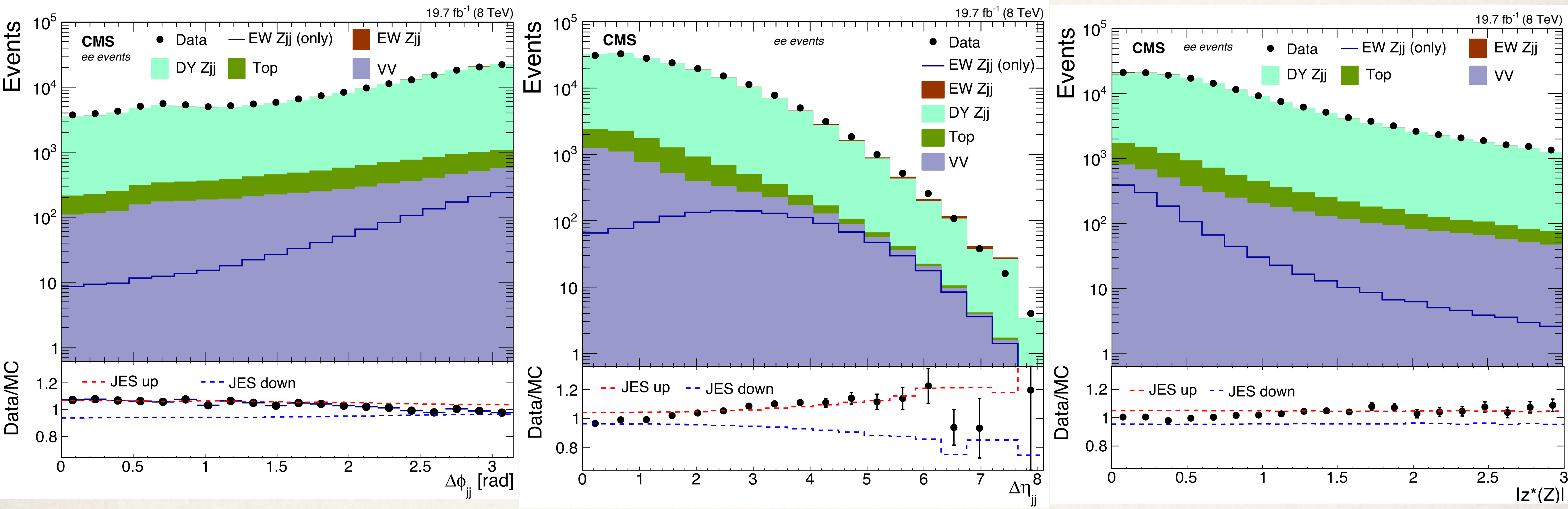
control region: R(Pt)>0.14





A)MC-based predictions for background

angle-related variables distribution



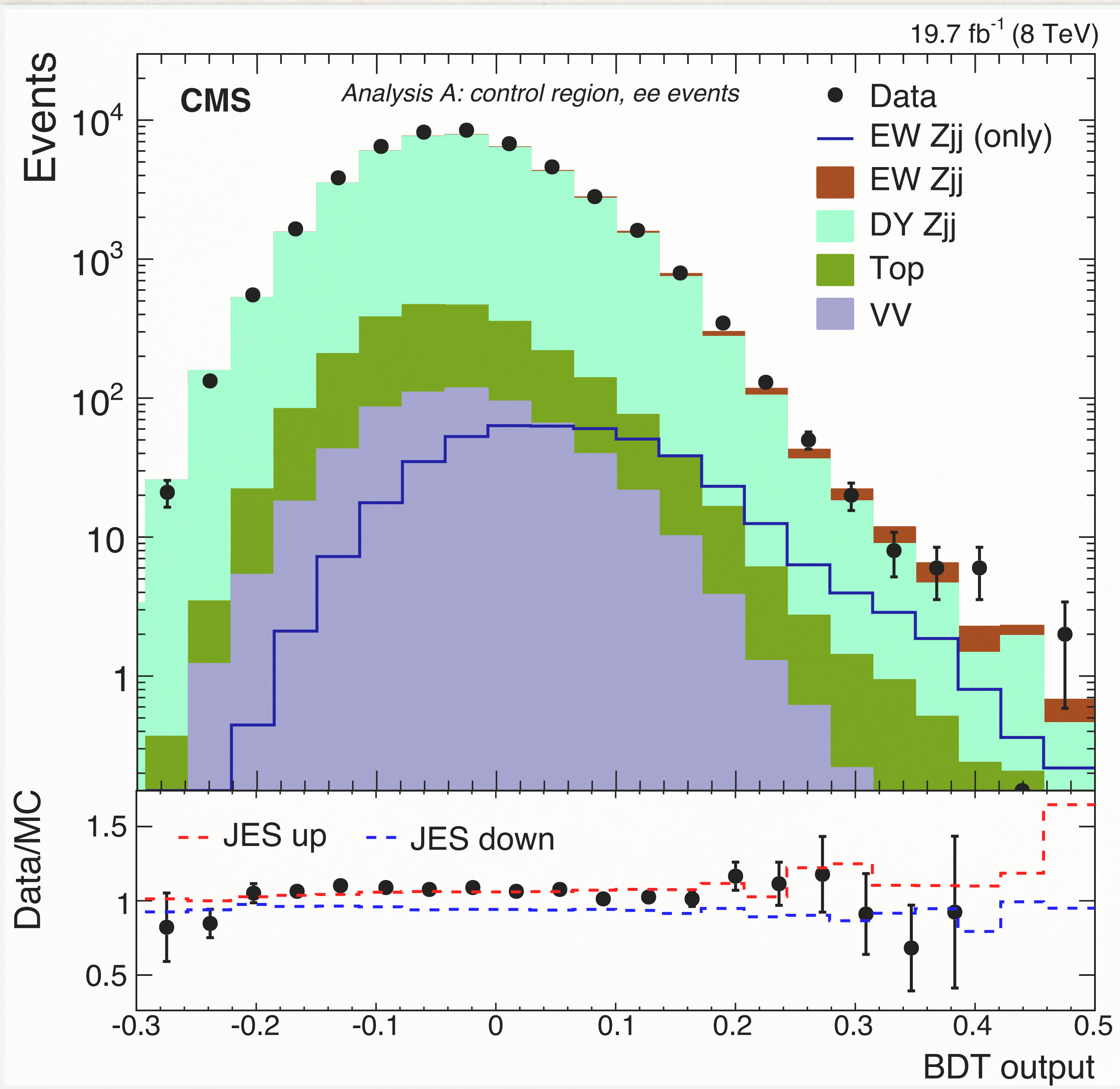
Well agreement with the prediction!

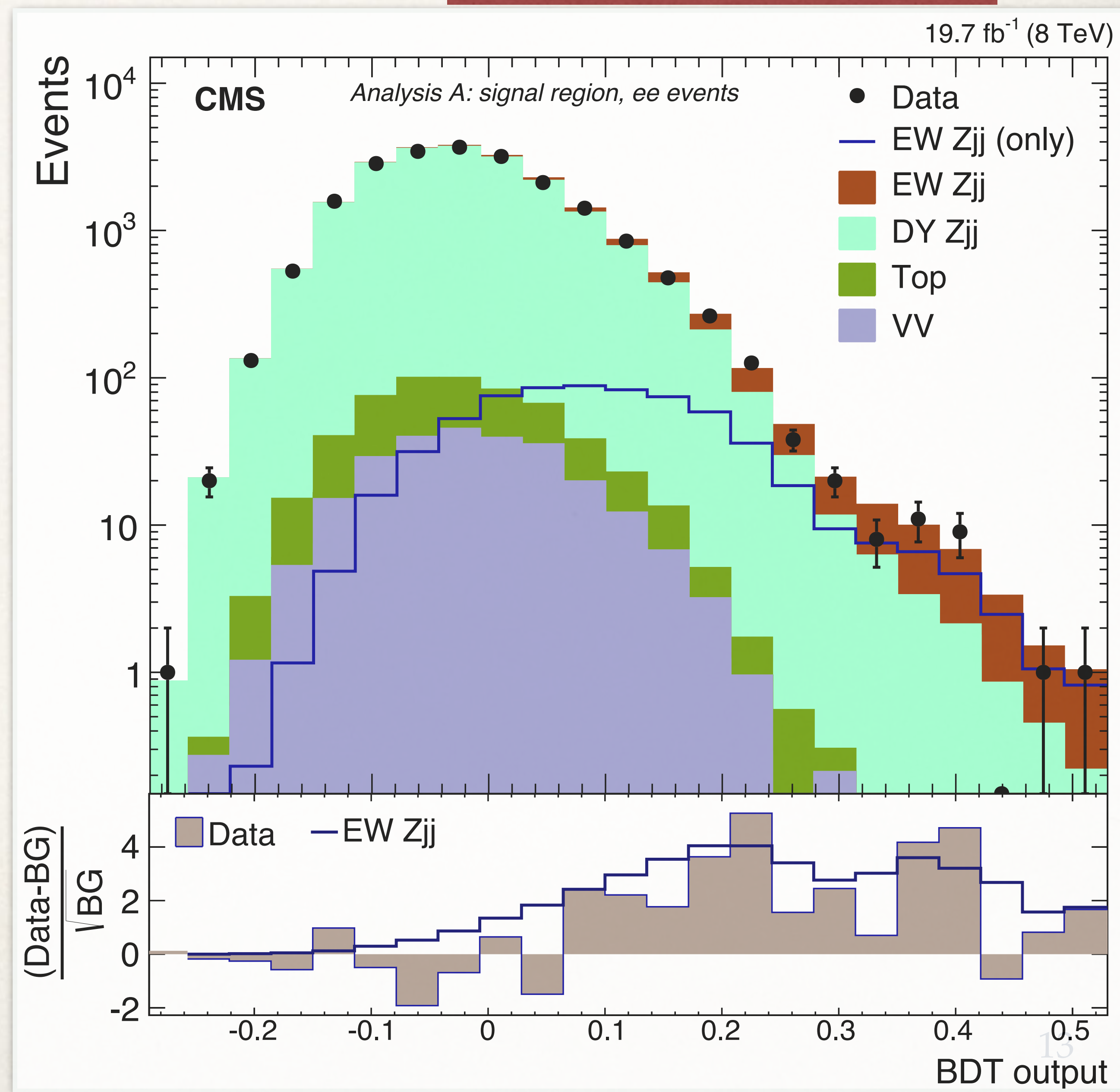
(A)PF+MC-based results

Analysis **A**: ee channel BDT output

signal region:
R(Pt)<0.14

Signal strength:
μ=0.82 ± 0.11 ± 0.19



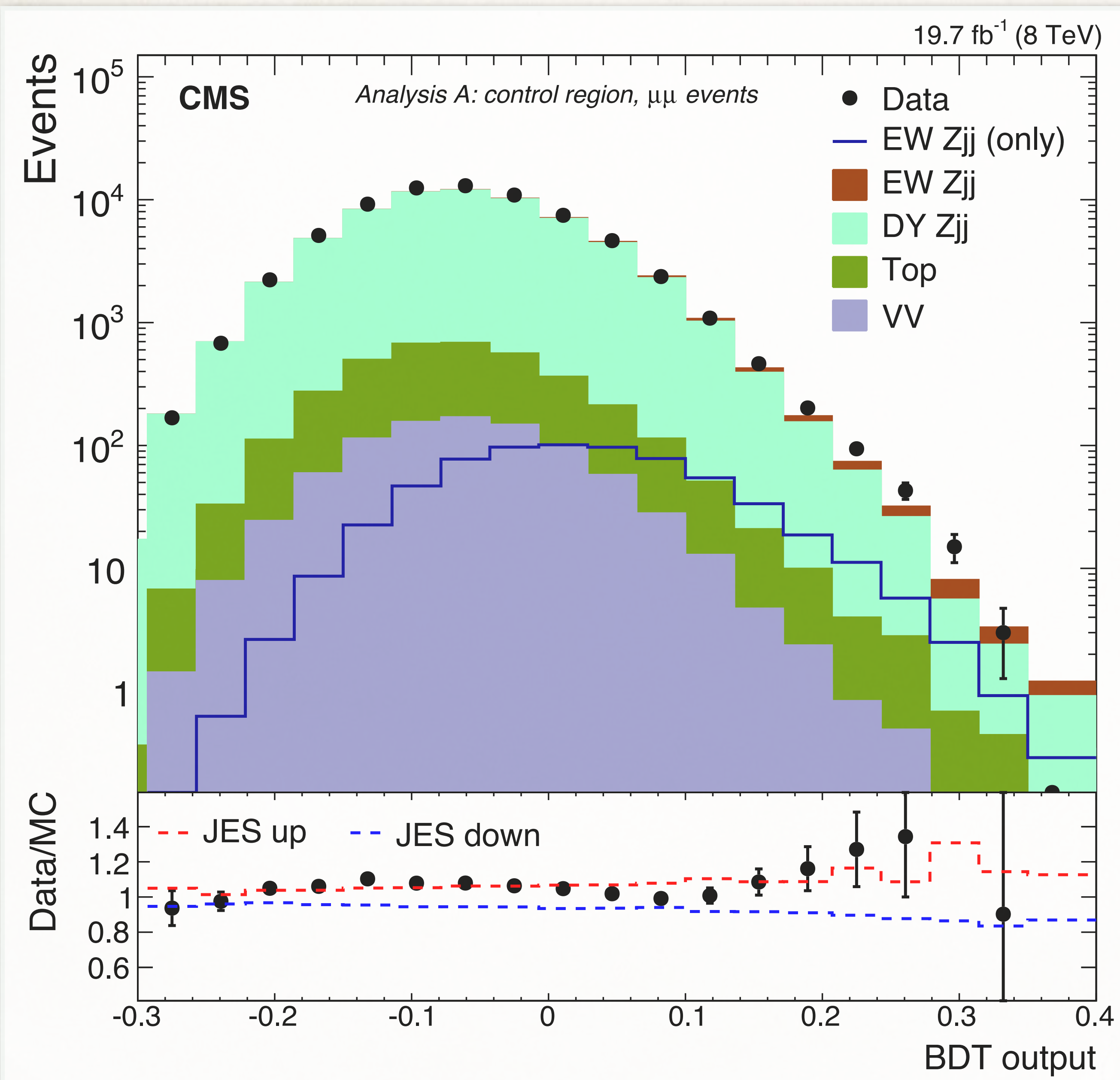


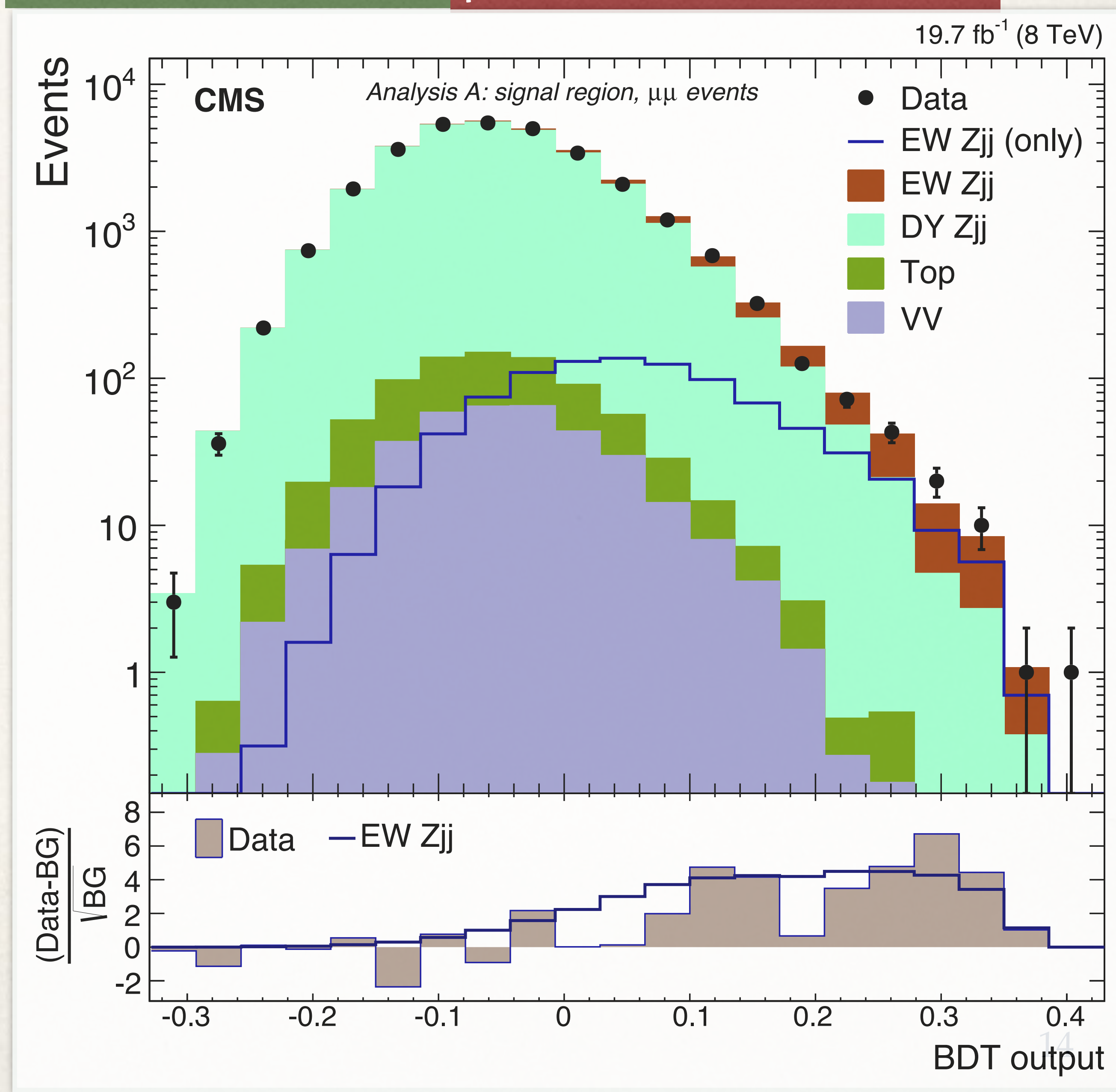
(A)PF+MC-base results

Analysis **A**: dimuon channel BDT output

signal region:
R(Pt)<0.14

Signal strength:
μ=0.86 ± 0.10 ± 0.18



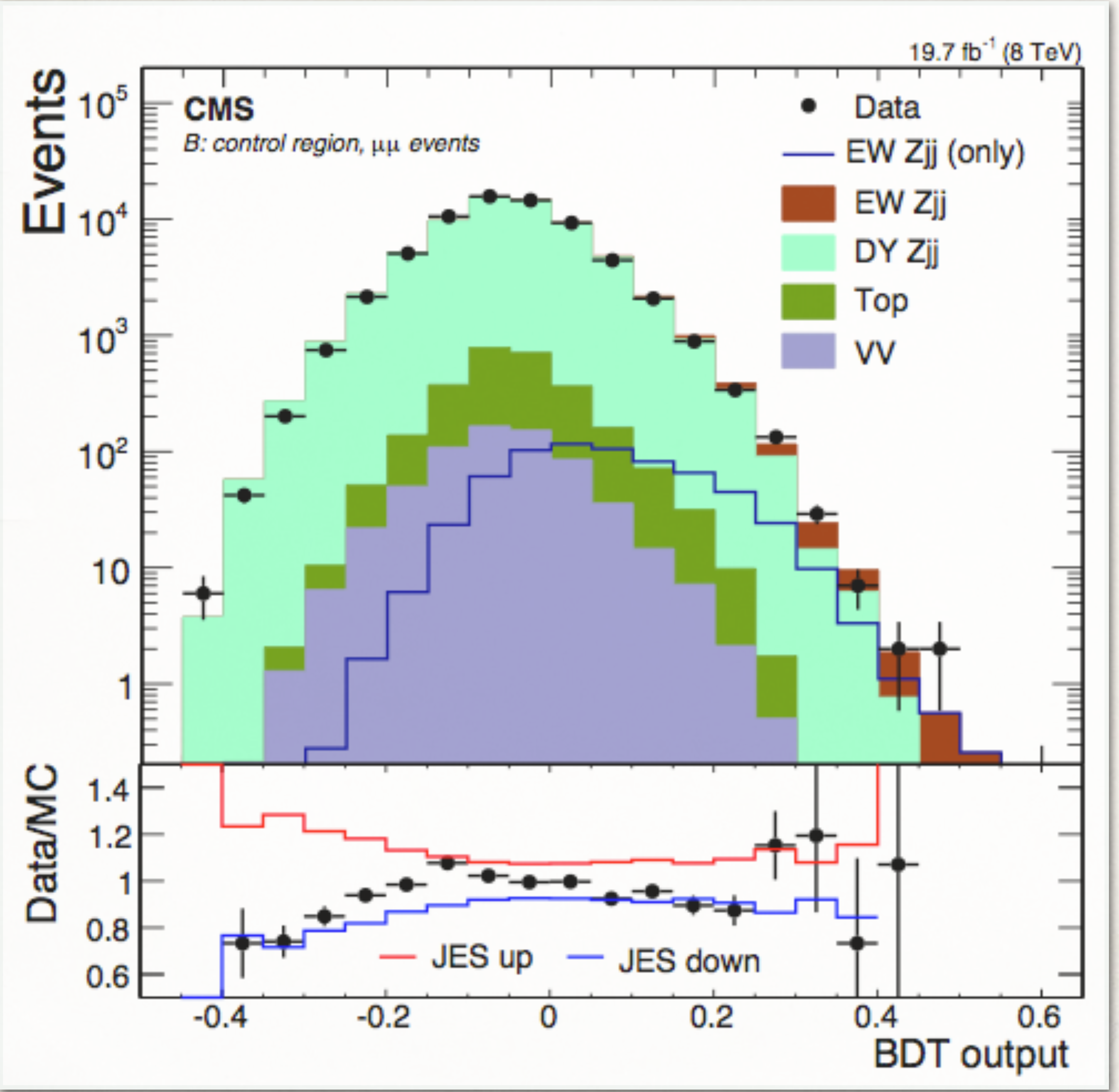


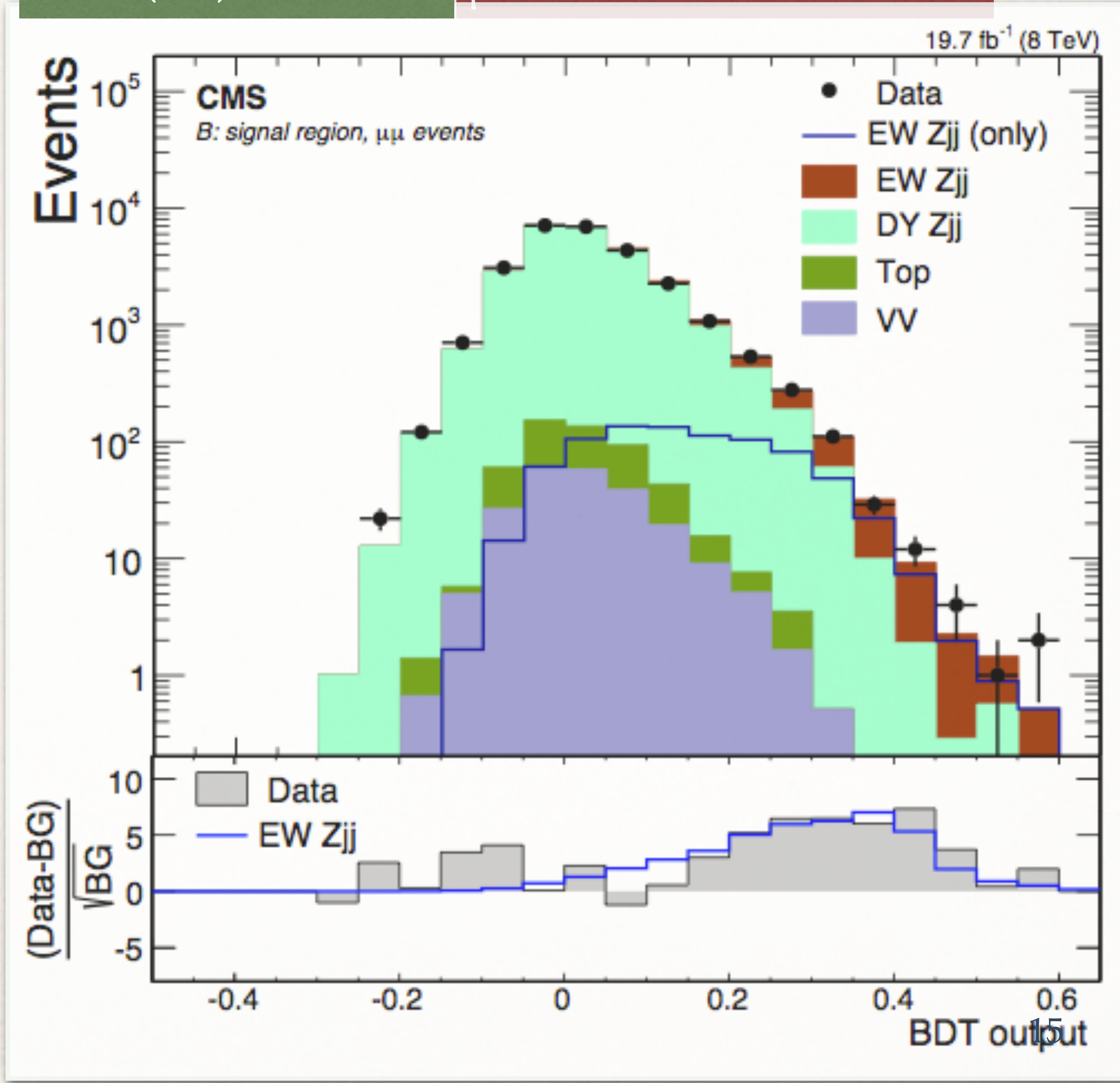
(B)JPT + MC based results

Analysis **B**: dimuon channel BDT output

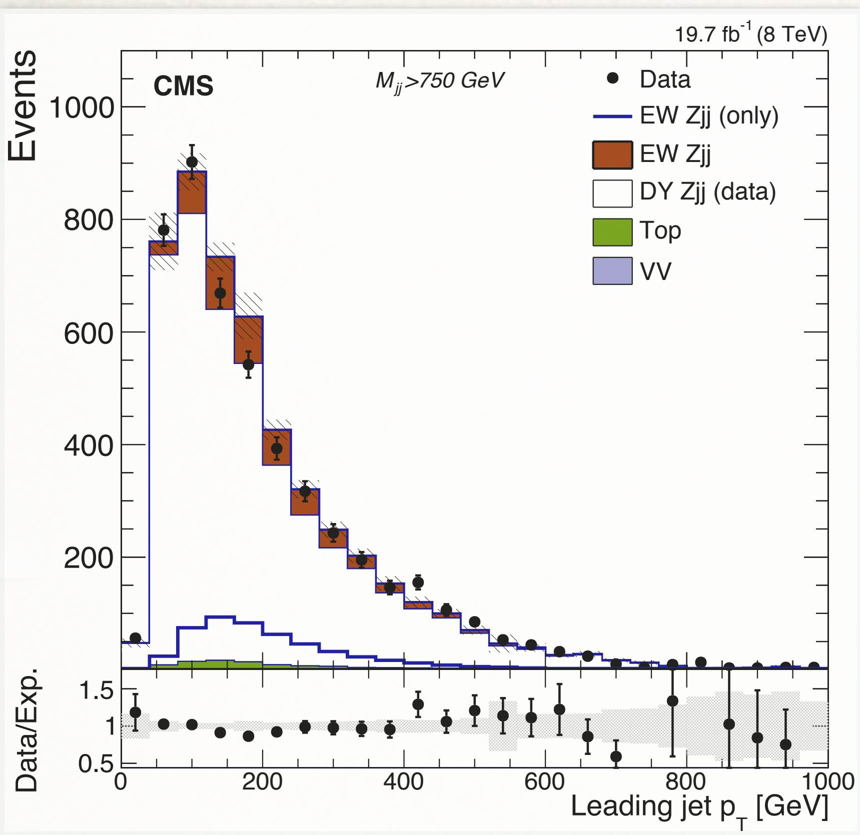
signal region: R(Pt)<0.14

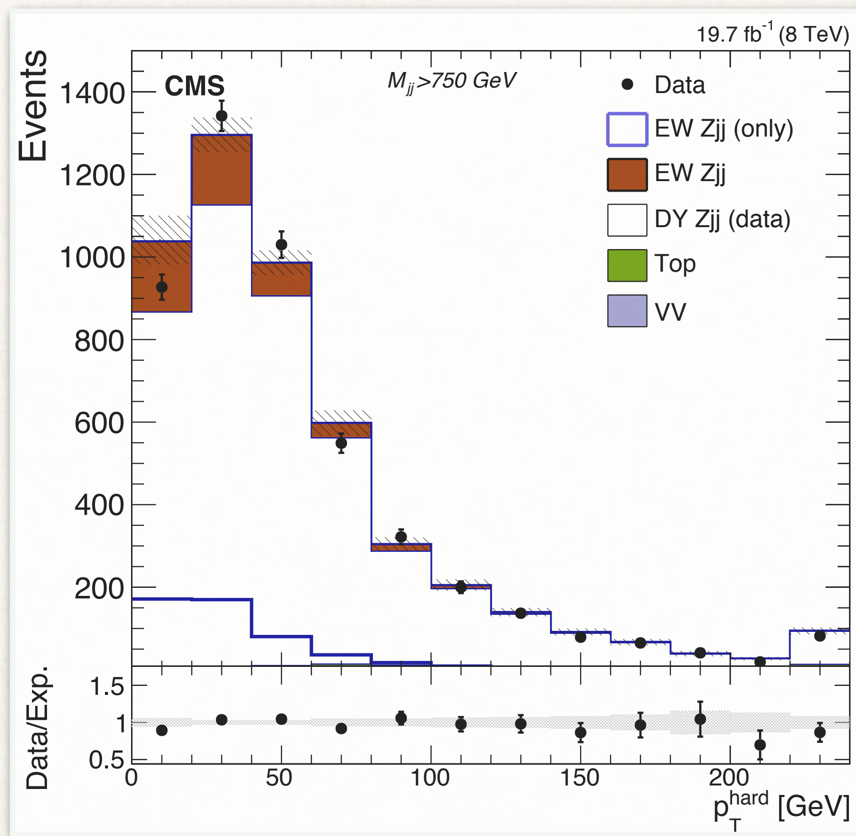
Signal strength: $\mu=0.89 \pm 0.09 \pm 0.17$

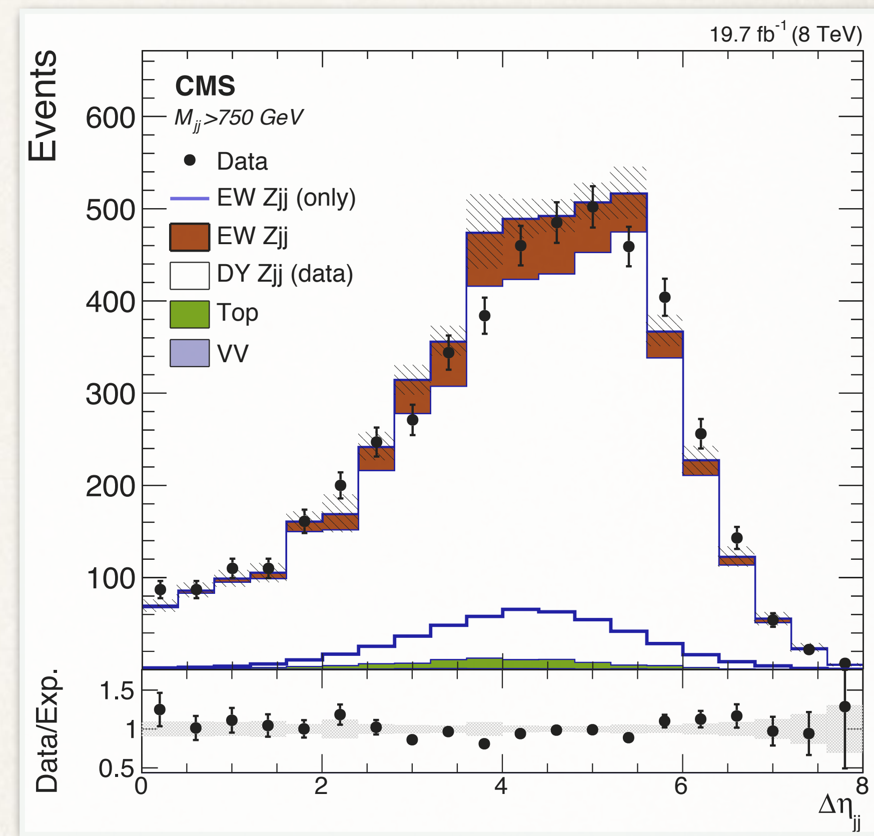




C)data-based prediction for background





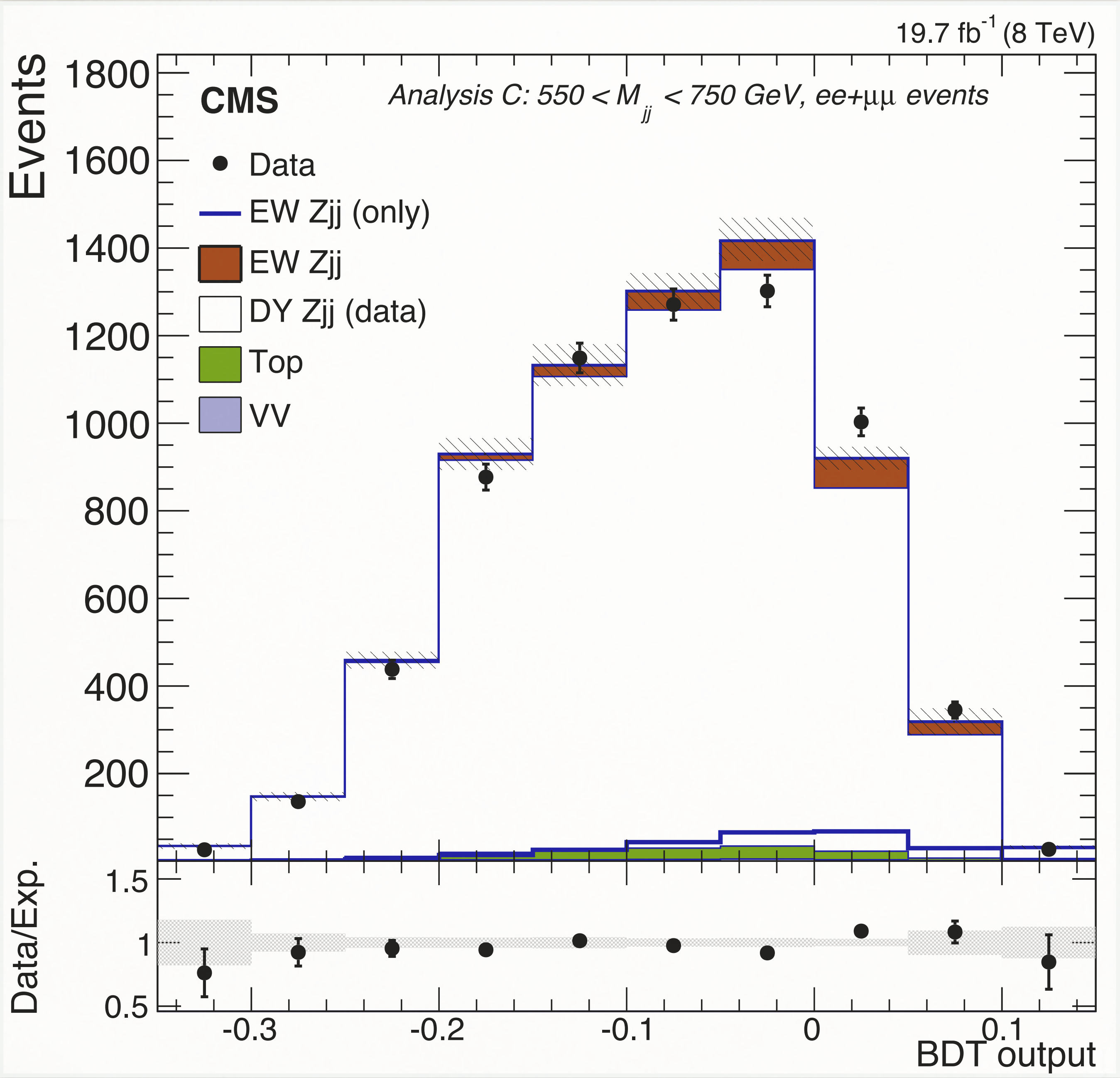


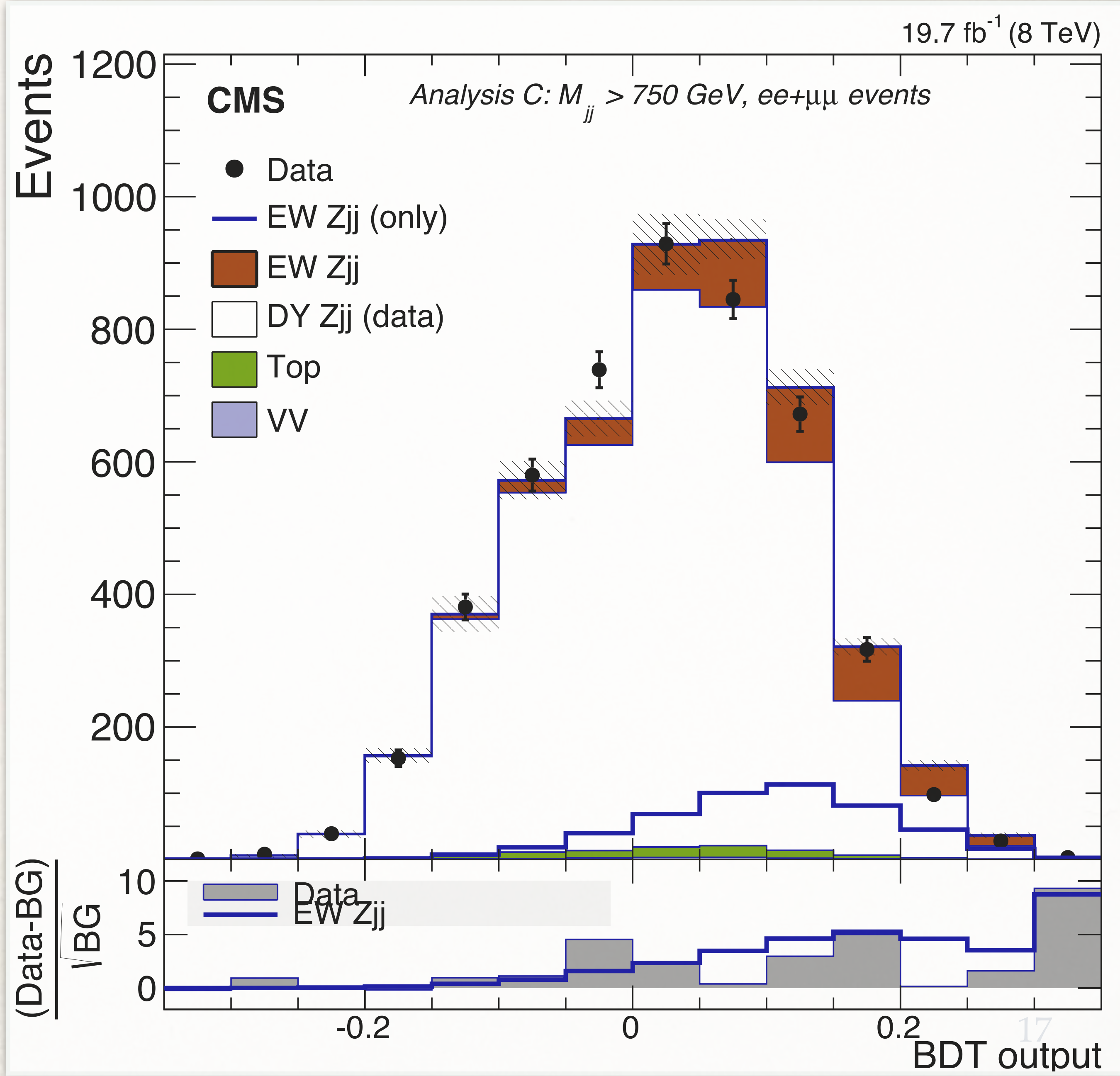
Good agreement with the prediction!

(C)PF + data-driven based results

Analysis **C**: BDT output in different Mjj categories

Signal strength:
$\mu = 0.88 \pm 0.16 \pm 0.18 (ee+\mu\mu)$

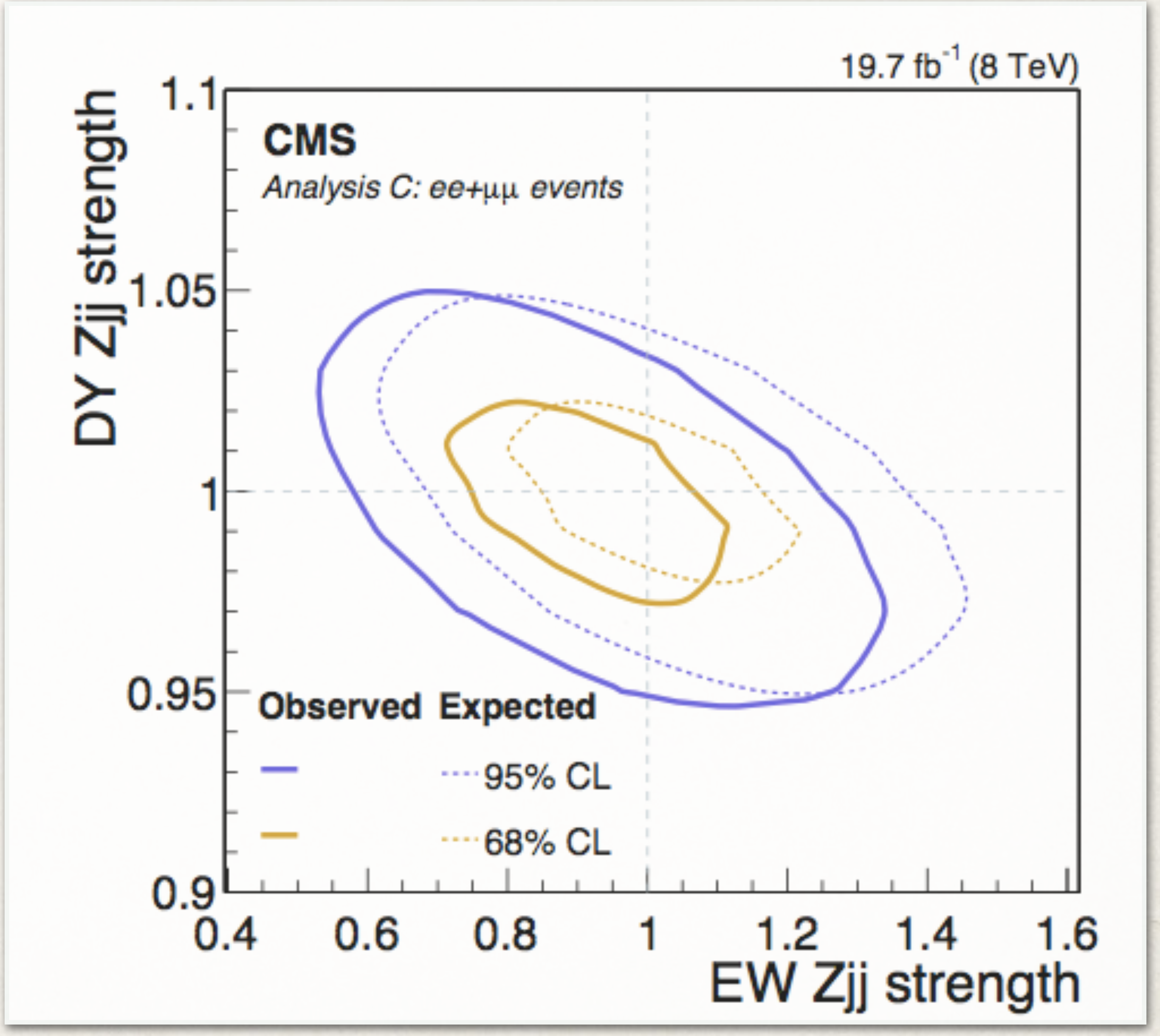




(C)PF + data-driven based results

Analysis **C:** The CL interval

The 68% and 95% confidence levels (CL) obtained for the combined fit of the EW Zjj and DY Zjj strengths are shown. Good agreement is found with the SM prediction for both components, as well as with the expected magnitude of the CL interval



Results and uncertainty

	Analysis A			Analysis B	Analysis C		
	ee	$\mu\mu$	ee + $\mu\mu$	$\mu\mu$	ee	$\mu\mu$	ee + $\mu\mu$
Luminosity	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Trigger/lepton selection	0.04	0.04	0.04	0.04	0.04	0.04	0.04
JES+residual response	0.06	0.05	0.05	0.04	0.06	0.05	0.05
JER	0.02	0.02	0.02	0.02	0.04	0.04	0.03
Pileup	0.01	0.02	0.02	0.01	0.01	0.01	0.01
DY Zjj	0.07	0.05	0.07	0.08	0.14	0.12	0.13
q/g discriminator	<0.01	<0.01	<0.01	—	<0.01	<0.01	<0.01
Top, dibosons	0.01	0.01	0.01	0.01	<0.01	<0.01	<0.01
Signal acceptance	0.03	0.04	0.04	0.04	0.06	0.06	0.06
DY/EW Zjj interference	0.14	0.14	0.14	0.13	0.06	0.08	0.08
Systematic uncertainty	0.19	0.18	0.19	0.17	0.17	0.17	0.18
Statistical uncertainty	0.11	0.10	0.07	0.09	0.24	0.21	0.16
$\mu = \sigma/\sigma_{\text{th}}$	0.82	0.86	0.84	0.89	0.91	0.85	0.88

method A(ee+μμ) signal strength

$\mu = 0.84 \pm 0.07\ (\text{stat}) \pm 0.19\ (\text{syst})$

$\sigma = 174 \pm 15\ (\text{stat}) \pm 40\ (\text{syst})$ fb

Signal significance > 5σ

in agreement with the SM prediction σ_{LO}(EW lljj) = 208 ± 18 fb.

More on EWK and DY Interference study

- Three Samples (EWK, DY and Mixed Zjj) are generated via MadGraph, with **fixed QCD scale at MZ.**

- The interference effect is parameterized at parton level from these samples and fed into final fitting procedure. Inspired on the **Born-level matrix** elements： total yield:

$$\hat{N}^{\ell\ell jj}(\mu, v) = \mu N_{\mathrm{EW\ Zjj}} + \sqrt{\mu v} N_{\mathrm{I}} + v N_{\mathrm{DY\ Zjj}}$$

where $N_{\mathrm{EW\ Zjj}}$, $N_{\mathrm{DY\ Zjj}}$ are the yields for the EW Zjj and DY Zjj processes, and N_{I} is the expected contribution from the interference to the total yield.

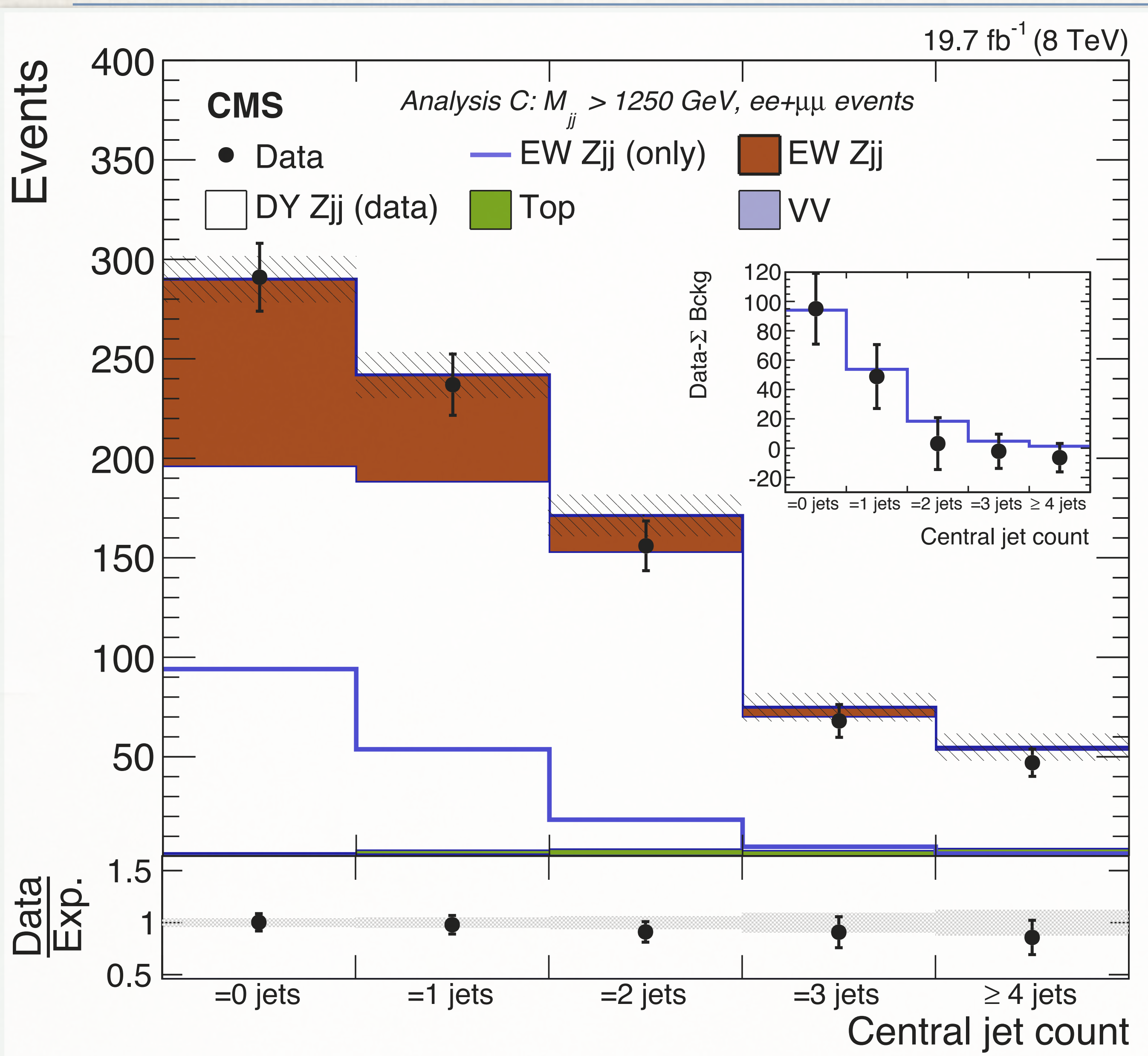
- The difference observed in the fit without interference relative to the nominal result is used to **estimate the uncertainty** due to the interference.

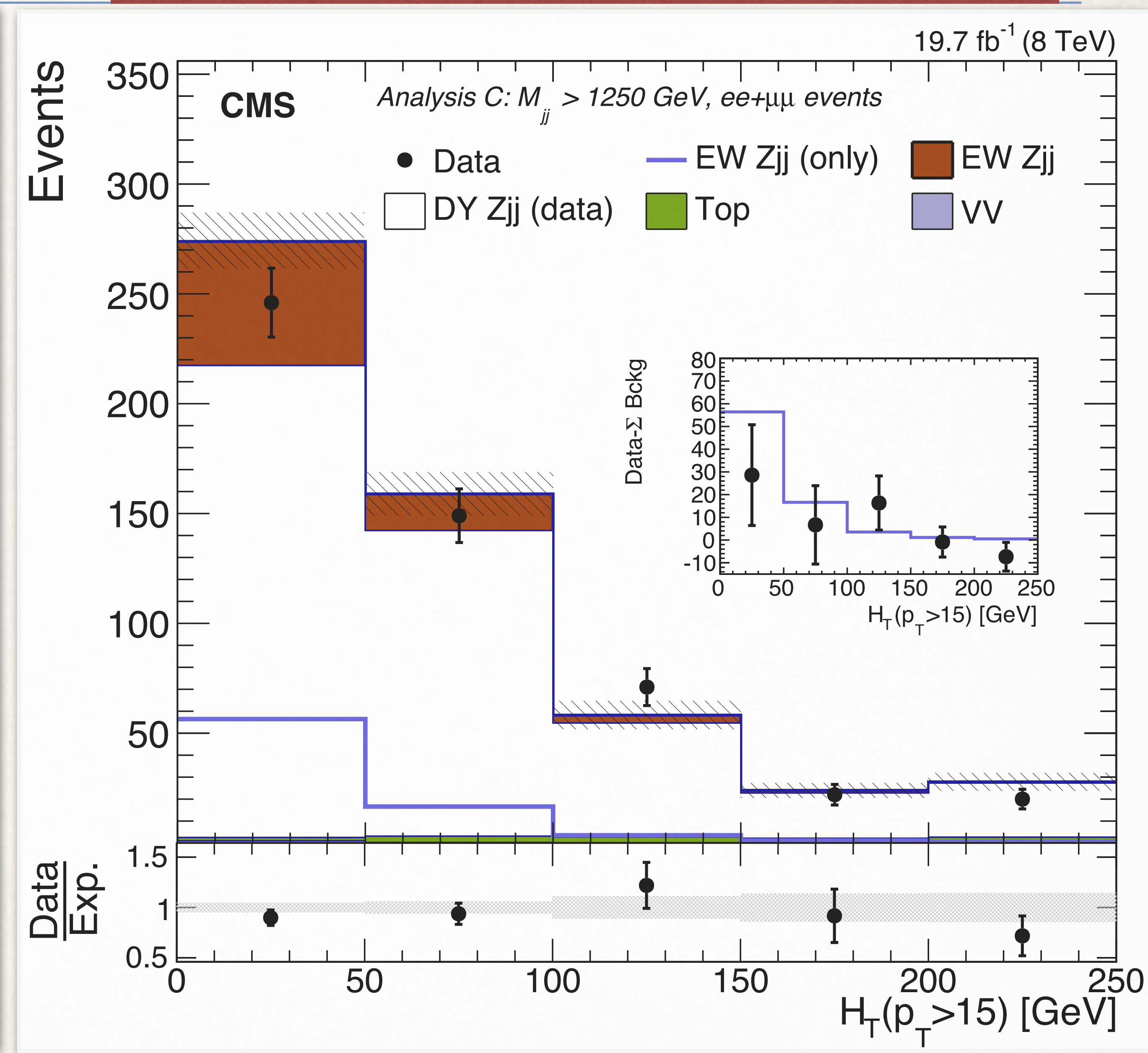
- **Method C less affected by interference** due to tighter selection criteria

Part II) Central Jet activity Measurement

Study of the jet properties in high purity region

providing the most striking evidence for EWK Z jj production with a clear sign of the suppression of central jet activity.

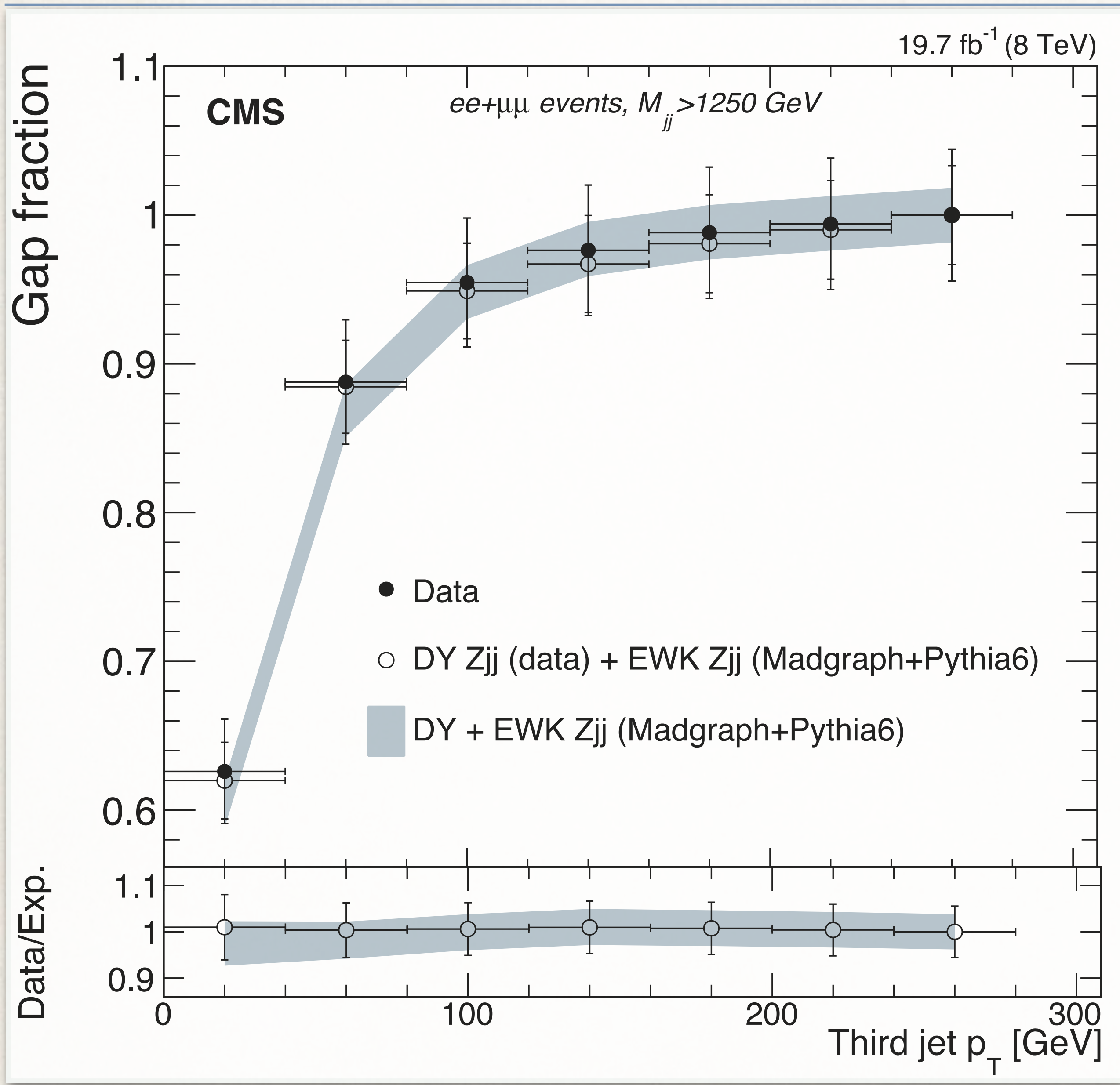




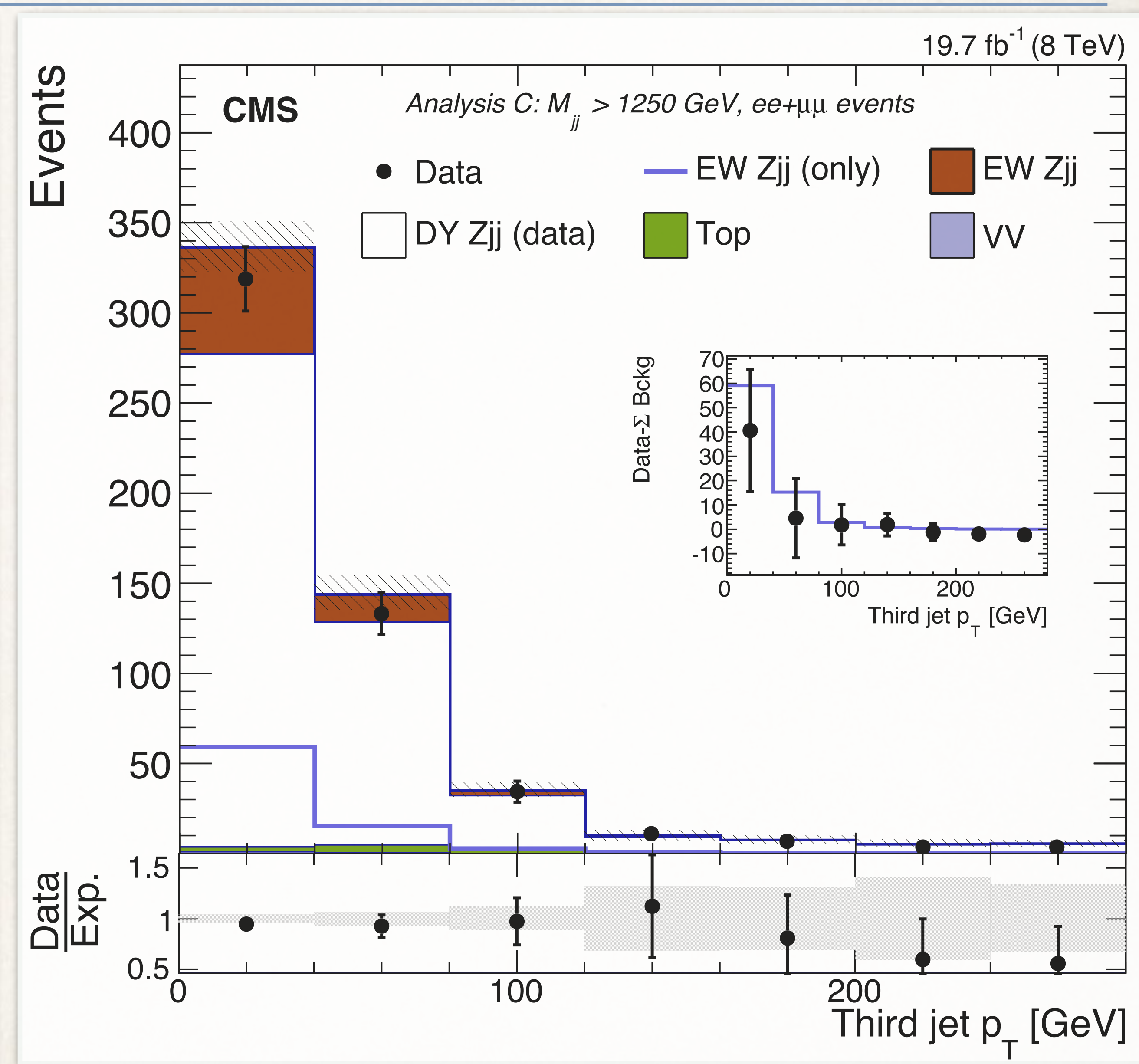
Additional jet multiplicity within the tag jets gap Δηjj

Ht within the tag jets gap Δηjj

Study of the jet properties in high purity region

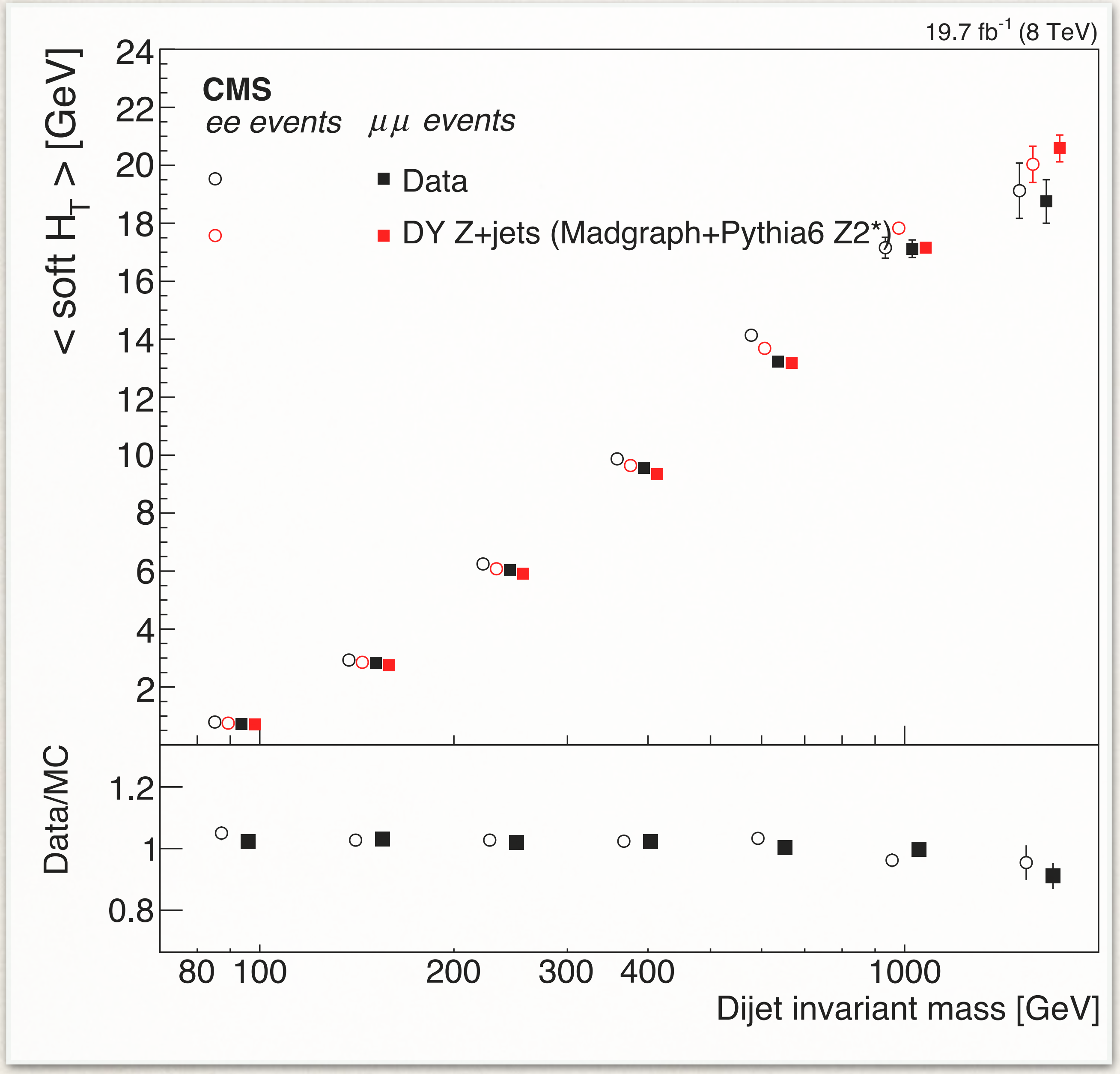


Gap fraction as a function of 3rd jet pT (gap fraction: fraction of events which do not have a third jet above a given threshold)

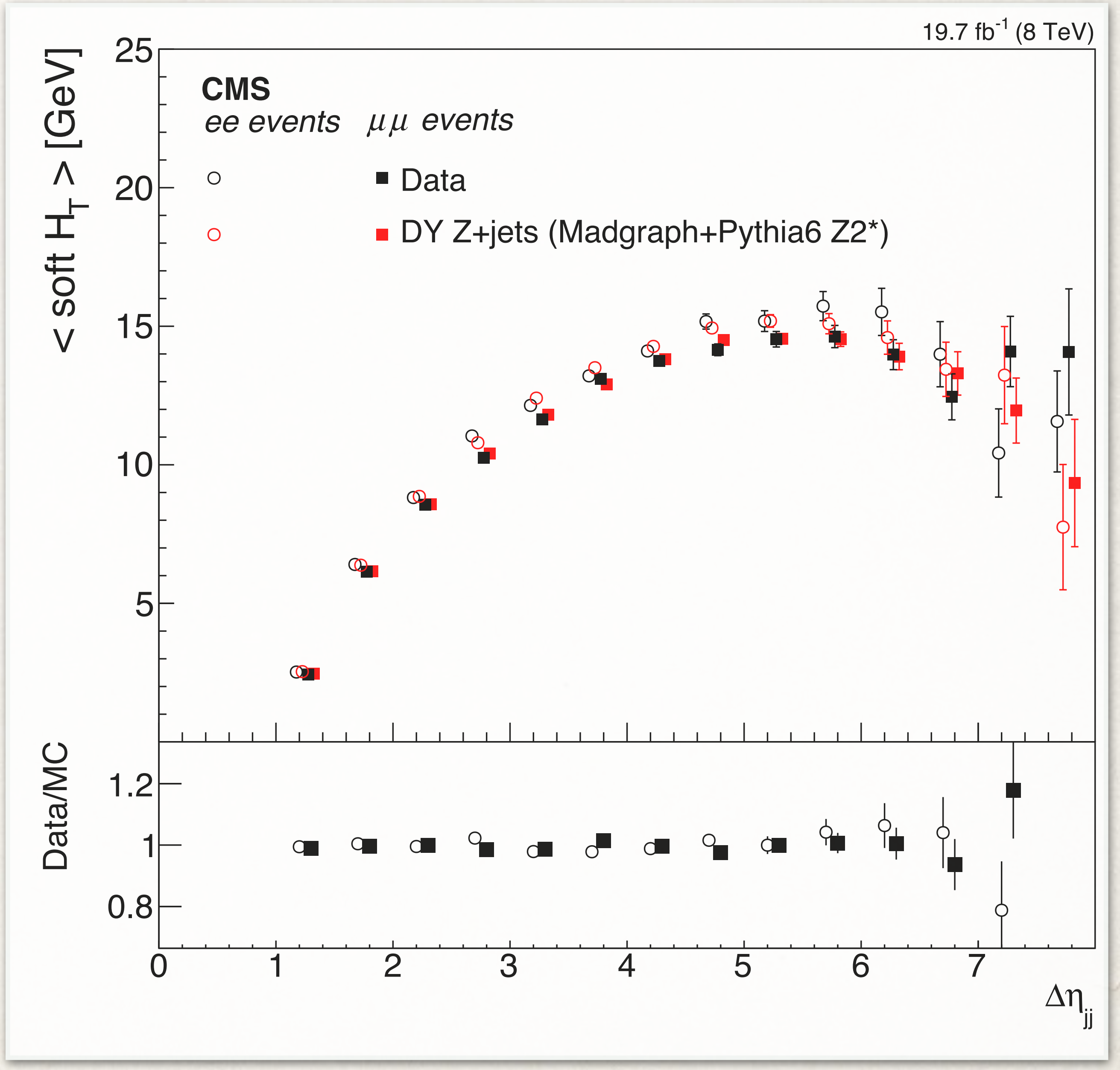


Third jet properties, insets shows the result of the direct bin-by-bin background subtraction

Study of charged hadronic activity and measurement of radiation pattern



Average H_T of the three leading soft track jets as a function of mjj



As function of $\Delta\eta jj$

Summary

- LHC Run I was successful. The first VBF process: EWK Z +2jets production has been observed at 8TeV LHC

  σ = 174 ± 15 (stat) ± 40 (syst) fb

  in agreement with theory σ_{th} 208±18 fb prediction

- Studies of the jet activity in the gap between 2 tag jets show generally good agreement with the Madgraph +PYTHIA predictions

- Vector boson fusion processes are going to be the hot topics at Run II of LHC

Back up

CMS Jets

- Calo jets: Jets are clustered from ECAL and HCAL towers
- Jet-plus-track(JPT) jets: Calorimeter jets are corrected with track information
- Particle Flow(PF) jets:Particles are reconstructed from all sub- detectors information, and then clustered to form jets
- Track Jets:Reconstructed from tracks only / associated to PV. Insensitive to pileup (used in measuring the activity in the dijet rapidity gap)

Event Yields

Channel	VV	Top	QCD Zjj	Total	EWK Zjj	Data
$\mu\mu$	41 ± 1	99 ± 8	$4213 \pm 48 \pm 450$	$\mathbf{4353 \pm 49 \pm 450}$	551 ± 4	**4902**

	Method A			Method B	Method C	
	ee	$\mu\mu$	ee+$\mu\mu$	$\mu\mu$	ee	$\mu\mu$
$\mu = \sigma/\sigma_{\text{th}}$	0.82	0.86	0.84	0.89	0.85	0.91
Statistical uncertainty	0.11	0.10	0.07	0.09	0.24	0.21
Systematic uncertainty	0.19	0.18	0.19	0.17	0.17	0.17
Luminosity	0.03	0.03	0.03	0.03	0.03	0.03
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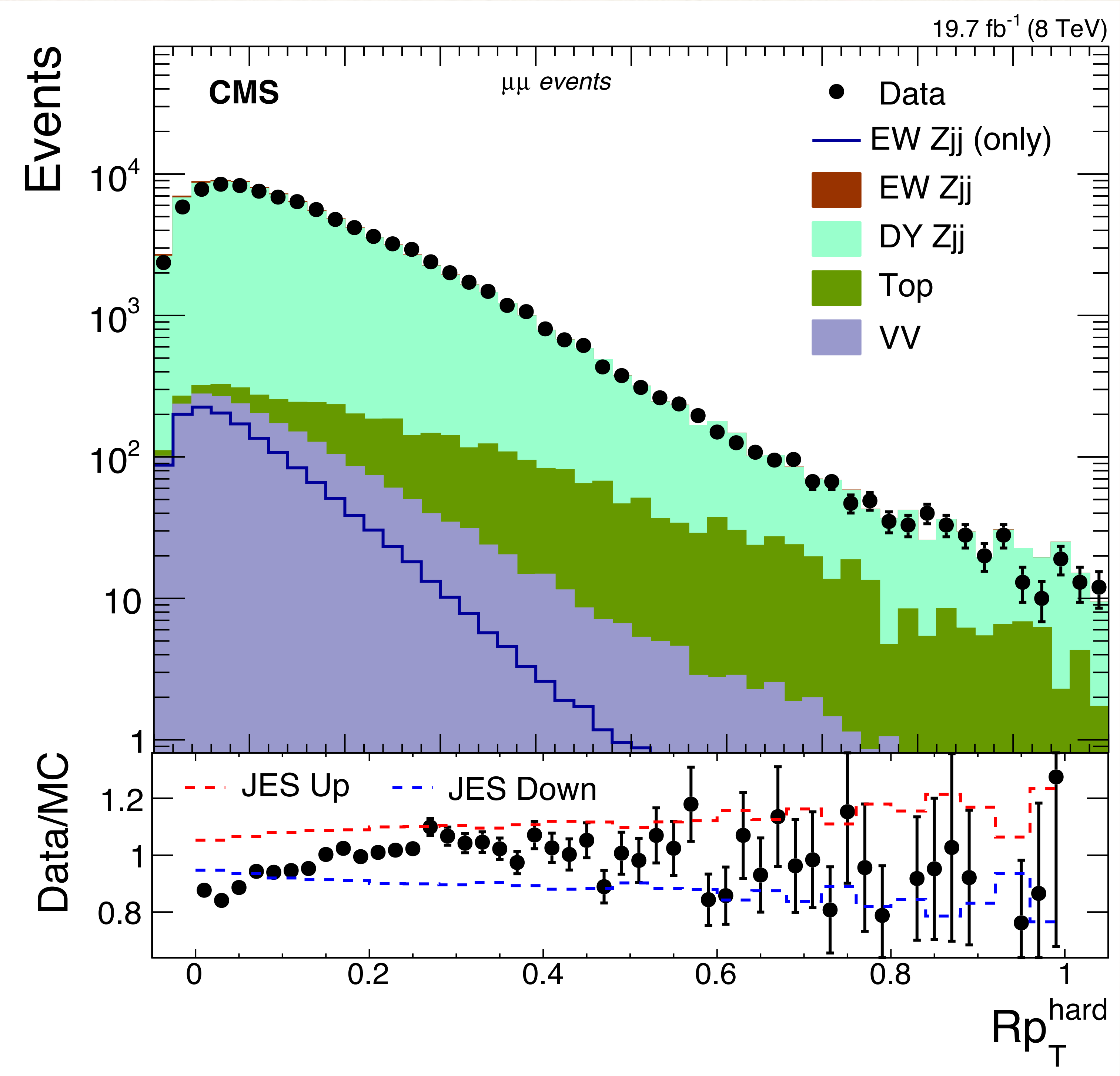
JER	0.02	0.02	0.02	0.02	0.04	0.04
Pileup	0.01	0.02	0.02	0.01	0.01	0.01
DY Zjj	0.07	0.05	0.07	0.08	0.14	0.12
q/g discriminator	< 0.01	< 0.01	< 0.01	-	< 0.01	< 0.01
Top, dibosons	0.01	0.01	0.01	0.01	< 0.01	< 0.01
Signal acceptance	0.03	0.04	0.04	0.04	0.06	0.06
DY/EW Zjj interference	0.14	0.14	0.14	0.13	0.06	0.08


19.7 fb^{-1} (8 TeV)
CMS
μμ events
Data
EW Zjj (only)
EW Zjj
DY Zjj
Top
VV
Events
Data/MC
JES Up
JES Down
Rp_T^{hard}