heavy flavor and vector bosons associate production at CMS

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• motivations for studies on W/Z/γ*+ heavy flavor associated production at LHC

• Z/γ* + heavy flavor measurements:
  • Z/γ* + b inclusive cross-section ( 2.1 / fb ) ( arXiv:1204.1643 )
  • Z/γ* + bb cross-section ( 2.1 / fb ) ( CMS-PAS-SM-12-003 )
  • Z/γ* + BB angular correlation ( 4.6 / fb ) ( CMS-PAS-EWK-11-015 )

• W + heavy flavor measurements:
  • W + c cross-section ( 36 / pb ) ( CMS-PAS-EWK-11-013 )

• summary
$Z/\gamma^* + b(b)$ measurements: motivation

- $Z/\gamma^* + b(b)$ is one of the main backgrounds of Standard Model Higgs (ZH(bb)) and BSM searches

- $Z/\gamma^* + b(b)$ cross-section and dynamics test QCD processes and their description by Monte Carlo generators:

  - **variable flavor approach (5F)**
    - massless $b$-quarks:
      - Pythia
      - MadGraph (+ Pythia)
      - SHERPA
  
  - **fixed flavor approach (4F)**
    - massive $b$-quarks:
      - MadGraph (+ Pythia)
      - Alpgen
      - SHERPA

  - **NLO**
    - MCFM
    - fixed flavor approach massive $b$-quarks:
      - aMC@NLO
Z/γ* + b(b) analyses: event selection

- common **lepton** and **Z** selection except for:
  - 60 < M(ll) < 120 GeV for Z/γ*+b and Z/γ*+BB correlation analyses
  - 76 < M(ll) < 106 GeV for Z/γ*+bb measurement
- efficiency $\epsilon_l$ from MC simulation, rescaled to the efficiency measured on data with Tag&Probe technique

**inclusive cross-section measurements**

- jet selection: Particle Flow anti-$k_T$ (R=0.5), $p_T(j)>20$GeV, $|\eta(j)|<2.1$
- b-tagging: based on the identification of displaced secondary vertices
  - high b-purity (3 tracks at least): for Z/γ*+b measurement
  - high efficiency (2 tracks at least) for Z/γ*+bb analysis

**angular correlation measurement**

- no use of jets
- B hadrons identified through displaced secondary vertices
- reconstruction uses only charged tracks from the B decay
Z/γ* + b cross-section

\[ \sigma_{\text{hadron}}(Z/\gamma^*(ll) + b) = \frac{N_{ll+b} \cdot (P - f_{t\bar{t}})}{A_l \cdot C_{\text{hadron}} \cdot \epsilon_l \cdot \epsilon_b \cdot L} \]

- total number of selected data events \( N_{ll+b} \) corrected for
  - contamination from \( Z+udcsg \) (b-purity \( P \)): data-driven template fit of secondary vertex mass distribution of leading b-jet
  - contamination from top pair production \( f_{t\bar{t}} \): extrapolation of Z upper sideband into signal region
  - dilepton \( \epsilon_l \) and b-tagging efficiency \( \epsilon_b \): from simulation, rescaled to reproduce the efficiencies measured on data with Tag&Probe method
  - dilepton acceptance \( A_l \) and detector effects \( C_{\text{hadron}} \): from MC simulation

\[ \sigma_{\text{hadron}}(Z/\gamma^*(ll) + b) = 5.84 \pm 0.08 \text{(stat.)} \pm 0.72 \text{(syst.)} \pm 0.25^{+0.55}_{-0.72} \text{(theory)} \text{ pb} \]

- leptons and Z/γ*: \( p_T(l) > 20 \text{ GeV}, |\eta(l)| < 2.4, 60 < M(ll) < 120 \text{ GeV} \)
- b-jets: \( p_T(j) > 25 \text{ GeV}, |\eta(j)| < 2.1 \)

higher than NLO prediction by MCFM (corrected to hadron-level)

\[ \sigma_{\text{hadron}}(Z/\gamma^*(ll) + b) = 3.97 \pm 0.47 \text{ pb} \]
Z/γ*+ bb cross-section

1. background rejection

\[ N_{Z(\ell\ell)+bb}^{\text{signal}} = N_{Z(\ell\ell)+bb} \cdot (f_{bb} - f_{tt}) \cdot N_{ZZ} \]

- mis-tagged Z+bl and Z+cc: simultaneous fit of secondary vertex mass distribution for the two b-tagged jets
- top pair production \( f_{tt} \) reduced by tighter Z selection (76 < M(\ell\ell) < 106 GeV) and ME_T < 50 GeV cut, estimated with data-driven template fit of M(\ell\ell) distribution
- diboson \( N_{ZZ} \): from MC using the cross-section measured at CMS

2. correction for dilepton reconstruction and selection efficiency, acceptance, b-tag efficiency, detector resolution effects:

- set of unfolding matrices accounting for b multiplicity bin-to-bin migrations
**Z/γ*+ bb results**

\[
\sigma_{\text{hadron}}(Z/\gamma^*(ll) + 2b) = 0.37 \pm 0.02(\text{stat.}) \pm 0.07(\text{syst.}) \pm 0.11(\text{theory}) \text{ pb}
\]

fair agreement with tree-level prediction by MadGraph (5F) + Pythia within errors, measured cross-section **10% higher** than prediction

\[
\sigma(Z/\gamma^*(ll) + bb) = 0.33 \pm 0.01(\text{stat.}) \text{ pb}
\]
$\Delta R(B, B) = \sqrt{\Delta \phi^2 + \Delta \eta^2}$

B hadrons identification through the **Inclusive Vertex Finder**

- **no use of jets**
  - vertices from cascade B to charm decays merged into single B hadron candidate
    - no limitation from jet cone size, unprecedented sensitivity to very small angular separation between B hadrons
    - very good resolution in B hadron flight direction ($\Delta R(BB) \sim 0.02$) thanks to the excellent CMS performance in track and vertex reconstruction
    - sensitivity to low momentum B hadrons
normalized differential cross-section

\[\frac{1}{\sigma} \frac{d\sigma}{d\Delta R} \Rightarrow \frac{1}{\sigma_{\text{visible}}} \frac{N_i^{\text{data}} \cdot P_i^B}{\epsilon_i^B \cdot \epsilon_i^l \cdot A_i^l}, \quad i = \Delta R \text{ bin}\]

- detector-level number of $Z/\gamma^*+$BB signal events $N_i^{\text{data}}$
- estimated on data through extended maximum likelihood fit of M(II) distribution (rejection of background from top pair production, ~50% after selection)
- corrections:
  - dilepton acceptance, reconstruction and selection efficiency $\epsilon_i^l \cdot A_i^l$ estimated on simulation and rescaled to match the efficiencies measured on data
  - B hadron pair identification efficiency $\epsilon_i^B$ (10-15%), phase space and purity $P_i^B$ (80%), estimated on simulation

phase space definition

- leptons and $Z/\gamma^*$: transverse momentum $p_T(l) > 20$ GeV, pseudorapidity $|\eta(l)| < 2.4$, $60 < M(\Pi) < 120$ GeV
- B hadrons: $p_T(B) > 15$ GeV, $|\eta(B)| < 2.0$
Z/γ* + BB angular correlation result

- measured normalized ΔR(BB) distribution compared to MC expectation (hadron-level):
  - tree-level prediction by MadGraph(5F)+Pythia ([JHEP 0709 (2007) 028]) (including events from Z + B hadron pairs from Multiple Parton Interactions)
  - NLO prediction by aMC@NLO+Herwig ([JHEP 09 (2011) 061]) (not including Z + B hadron pairs from MPI)

reasonable agreement between data and Monte Carlo simulation, although data shows flatter trend compared to prediction
**motivation**

sensitivity to $s$ and $\bar{s}$ Parton Density Functions in the proton at electroweak scale

$$ R_c = \frac{\sigma(W + c + X)}{\sigma(W + j + X)} = \frac{N(W^+ + \bar{c}) + N(W^- + c)}{\epsilon_c \cdot N(W + j)} $$

- leptonic decay $W \rightarrow \mu \nu$ + one jet with $p_T(j) > 20$ GeV
- **b-tagging** applied to enhance charm component:
  - discriminator based on the secondary vertex flight distance significance (2 tracks required, efficiency $\epsilon_c$ 12%, estimated from MC simulation)
- backgrounds from **top pair production** and **single top**, $W + u d s g$ rejected through template fit of the b-tagging discriminant distribution

$$ R_c = 0.143 \pm 0.015 \text{(stat.)} \pm 0.024 \text{(syst.)} $$

**agreement with NLO predictions**
summary

- **Z/γ* + b** and **Z*/bb cross-sections** measured with 2.1/fb collected in 2011
  - **Z/γ* + b** cross-section 20% higher than NLO prediction by MCFM
  - **Z/γ* + bb** cross-section 10% higher than tree-level prediction by MadGraph (5F) with parton shower and hadronization by Pythia
  - some tensions between data and LO MC prediction in the kinematic distributions

- **Z/γ* + BB normalized differential cross-section** as a function of the **angular separation** of the B hadron pair measured with 4.6/fb collected in 2011
  - fair agreement with tree-level prediction by MadGraph(5F)+Pythia and NLO prediction by aMC@NLO+Herwig, though data show a flatter trend
  - measurement of the absolute differential cross-section and study of additional angular variables will help hopefully resolving the observed tension

- **ratio between W+c and W+light jet** cross-sections measured with 36/pb collected in 2010, result in good agreement with the NLO predictions

- the results shown will be updated with higher statistics and with further studies.