AFB as a discovery tool for Z’ bosons at the LHC

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• New heavy vector resonances: Drell-Yan processes at the LHC
• Beyond commonly used approximations: Interference and FW effects
• Interpretation of exp. results: Mass bounds on Z’-bosons
• A newly proposed observable: Forward-Backward Asymmetry as a Z’ hunter

based on papers by:
E. A., Belyaev, Fiaschi, Mimasu, Moretti, Shepherd-Themistocleous (NExT)

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New Heavy vector resonances

- Most common scenarios predict a single $Z'$ or $W'$:
  An extra heavy neutral vector boson, $Z'$ or $W'$ can come from weakly interacting theories with at least a light elementary higgs boson:

  $Z'$: $E_6$, Left-Right, SSM

  $W'$: Left-Right, SSM

- More complicated models can predict multi-resonances:
  A tower of extra heavy vector bosons, $Z'_n$ and $W'_n$, can come from extended gauge groups and strongly interacting theories:

  $Z$'s and $W$'s: Composite Higgs, (N)MWT, ED

The Drell-Yan channel is the favoured process for ALL models.

We focus on the single $Z'$ search in DY within weakly interacting theories with a light elementary Higgs.
### $Z'\,$-boson at the LHC in DY

Narrow width Benchmark models

[E.A., Belyaev, King, Fedeli, Shepherd-Themistocleous, arXiv:1010.6058]

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<th>$g^u_V$</th>
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Z’ searches at the LHC in DY: tools and methods

Great accuracy at QCD and/or EW NLO and beyond, mass scale dependent K-factors are implemented in several tools:
NLO QCD via MC@NLO [Frixione et al.] and POWEG [Alioli et al.]
NLO+NLL [Jezo, Lyonnet et al. ‘14]
NLO EW via HORACE [Carloni Calame et al. ’05]

At LO, great ferment on Interference and Finite Width (FW) effects in theoretical studies:
Higgs [E.A. ‘08, Campbell, Ellis et al. ‘11, Kauer, Passarino ’12, Denner et al. ‘14]
Z’ and W’ [E.A. et al. ’12, Bella et al., Jeso et al. ‘14]

First attempts to deal with Interference and FW effects in experimental analyses at the LHC. They are model-dependent and CPU consuming, so different strategies are adopted:
W’ [CMS ‘14]
Z’ [ATLAS ‘15, CMS ‘15]

Focus on Z’ searches at LO: where do we stand?
SSM $Z'$ Drell-Yan production @ the LHC
Non-interferred model vs complete SSM

[E.A., Becciolini, Belyaev, Fiaschi, Moretti, Shepherd-Themistocleous, arXiv:1304.6700]
Narrow width $Z'$ at the LHC in all models: search strategy & theoretical accuracy

Impose the cut $|M(ll)-M_{Z'}| < 5\% E_{\text{coll}}$ to be as much as possible model-independent. Interference effects are in fact below $O(10\%)$, i.e. comparable with NLO EW+QCD uncertainties. [E.A., Becciolini, Belyaev, Fiaschi, Moretti, Shepherd-Themistocleous, 2013]

Implemented in the last CMS analysis on dilepton states, arXiv:1412.6302
Limits on Narrow width Z’ from CMS

pp → γ, Z, Z’ → ee, μμ with |M(II)−M_{Z'}| < 5% E_{coll}

Similar limits have been obtained by Jezo et al., arXiv:1410.4692
Projection on Narrow width $Z'$ @ 13 TeV

$pp \rightarrow \gamma, Z, Z' \rightarrow ee, \mu\mu$ with $|M(ll) - M_{Z'}| < 5\% E_{\text{coll}}$

Search window in the next Run II: $2.5\text{ TeV} < M_{Z'} < 6.5\text{ TeV}$
Realistic prospects for $Z'$ @ 13 TeV

- At low luminosity a $Z'$ evidence could not be that convincing
- At high luminosity the PDF error could spoil the significance
Realistic prospects for $Z'$ @ 13 TeV
A wide $Z'$-boson

$Z'$ bosons could be wide and appear as broad resonances spread over the SM background leading to a difficult interpretation of the excess of events.

**Benchmark models:**
- **wide SSM**
  [Altarelli et al., Z. Phys. C45, 109 (1989)]
- **Non-Universal SM**

These reasons motivate the introduction of the Forward Backward Asymmetry (AFB) as a new observable for the $Z'$ boson search
Forward-Backward Asymmetry (AFB)

\( A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \)

is defined in the CM of the hard-scattering where the Forward and Backward directions are taken with respect to the incoming quark.

\( A_{FB} \) can be reconstructed at the LHC via the boost variable i.e. the rapidity of the dilepton system:

\[ Y_{ll} = 0.5 \log \left( \frac{E_{ll} + P_{ll}}{E_{ll} - P_{ll}} \right) \]

Usually adopted for distinguishing between different Z' models

[Dittmar, Nicollerat, Djouadi 03; Petriello, Quackenbush 08, Rizzo]

It is here proposed as a primary search observable.
The probability of guessing the correct direction of the initial quark depends on both the $Y_{\parallel}$ cut and the $Z'$ boson mass (or energy scale).

At Run II, the $Y_{\parallel}$ cut can be relaxed.

The qq luminosity rapidly decreases with the $Y_{\parallel}$ cut for $M_{Z'} > 2500$ GeV.

The acceptance rapidly decreases with increasing $Y_{\parallel}$ cut and $M_{Z'}$. 

Reconstructed AFB and $Y_{\parallel}$ cut
Forward-Backward Asymmetry (AFB)

\[ A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \]

The statistical error is:

\[ \delta A_{FB} = \left[ \frac{1 - A_{FB}^2}{N_{evt}} \right]^{1/2} \]

Delicate balance between aiming to reconstruct the true shape of AFB via the \( Y_{ll} \) cut and preserving high acceptance i.e. high statistics (Nevt).

Our finding: no \( Y_{ll} \) cut maximizes the significance for \( M_{Z'} > 2500 \) GeV

[E.A., Belyaev, Fiaschi, Moretti, Shepherd-Themistocleous, arXiv:1503.02672]
AFB as a \( Z' \) search tool in DY

\[ pp \rightarrow \gamma, Z, Z' \rightarrow ee, \mu\mu \]

[\cite{Belyaev:2015cna}]

The interference \( Z' \) – SM is an intrinsic ingredient of \( A_{FB} \).
AFB as a $Z'$ search tool in DY
$pp \rightarrow \gamma, Z, Z' \rightarrow ee, \mu\mu$

- The true $A_{FB}$ can give rise to a significance much bigger than the bump.
- The reconstruction of the $A_{FB}$ depletes it, but still the significance remains sizeable.
AFB as a $Z'$ search tool in DY

$pp \rightarrow \gamma, Z, Z' \rightarrow ee, \mu\mu$

First 2 years of Run II: collected Lum = 30 fb$^{-1}$

An evidence in the bump search can be reinforced by a further evidence in an independent and differently shaped observable, i.e. the off-peak $A_{FB}$.
AFB and PDF's error in DY at high scales

\[ pp \to \gamma, Z, Z' \to ee, \mu\mu \]

Hessian PDF uncertainty

Cteq6.6 gives a central value and 40 error sets. The symmetric error on the dilepton invariant mass distribution is:

\[ \Delta (d\sigma/dm_{ll}) = \left[ \sum |(d\sigma/dm_{ll})^+_i - (d\sigma/dm_{ll})^-_i| \right]^{1/2} \]

\((d\sigma/dm_{ll})^+_i\) is the value of the observable using the PDF error set corresponding to the + direction of the eigenvalue \( i \).

- The error on the dilepton invariant mass distribution is dominated by the PDF's uncertainty on peak.
- The error on the off-resonance A_{FB} is dominated by the statistics over the full invariant mass range as the PDF's uncertainty is largely cancelled in the ratio

\[ \Delta A_{FB} = 0.5 (1 - A^2_{FB}) |\Delta(d\sigma_F/dm_{ll}) - \Delta(d\sigma_B/dm_{ll})| \]
AFB as a Z’ search tool in DY  
$pp \rightarrow \gamma, Z, Z' \rightarrow ee, \mu\mu$

Dilepton invariant mass distribution

Reconstructed $A_{FB}$

If statistical and PDF errors are combined linearly, the significance in the bump search rapidly drops, making the AFB quite competitive.
Relative errors on the signal cross section

$\sqrt{s} = 13$ TeV
$\text{Lum} = 300$ fb$^{-1}$

- E6–$\gamma$
- E6–I
- GLR–LR
- GSM–SM

A PDF’s refitting procedure could in principle reduce the error on the cross section. The procedure could be however scale and New Physics dependent.

Improving large-x PDF’s uncertainties is mandatory for high energy DY.

Errors on the reconstructed $A_{FB}$

The PDF’s error on $A_{FB}$ is always smaller than the statistical one over the full range of $Z'$ boson masses can be searched for during Run II.

$A_{FB}$ is much more robust than the total cross section as to PDF’s.
AFB as a $Z'$ search tool in DY

A wide $Z'$-boson

A shape-analysis of the AFB would support the interpretation of any excess of data in the invariant mass distribution.
• We have discussed the importance of interference effects in searches for extra heavy Z’ bosons. The impact of Interference and Finite Width effects on presentation of experimental results, data interpretation and mass bound extraction can be important for Z’ searches. Last analyses by ATLAS and CMS have imported these findings and account for such effects even if with different strategies.

• Interferences are intrinsic to the Forward-Backward Asymmetry. In order to maximize the LHC potential in searching for new Z’s, our proposal is to promote the $A_{FB}$ to be a primary observable.

• The $A_{FB}$ can in fact give rise to a significance comparable to or even bigger than that one expected from the default bump search.

• The $A_{FB}$ is moreover much more robust against PDF’s uncertainties.

Improving large-x PDF’s uncertainties is mandatory for high energy DY.
extra slides
Z' @ the LHC in all models: size and sign of interference effects

Strategy #1: New dedicated analysis to distinguish between Z’ models
Strategy #2: interference below theoretical uncertainties via cuts i.e. quasi-model independent analysis as in the current scheme
Z’ @ the LHC in all models: NWA vs FW

[E.A., Becciolini, Belyaev, Moretti, Shepherd-Themstocleous, arXiv:1304.6700]

\[
\left( \frac{\sigma_{\text{NWA}} - \sigma_{Z'}}{\sigma_{Z'}} \right)
\]

\[
\left( \frac{\sigma_{\text{NWA}} - \sigma_{\text{BSM}}}{\sigma_{\text{BSM}}} \right)
\]

Results in NWA cannot be reproduced exactly when interference is included, or the NWA can only be valid up to some accuracy.

Strategy #2 : NWA accuracy below theoretical uncertainties via cuts
W’ and Z’ searches at the LHC in DY

Latest analyses in the Drell-Yan channel

**ATLAS:**
- Z’ search in the dilepton invariant mass distribution, arXiv:1209.2535
  interference included only for Kaluza-Klein Z’s in ED theories as suggested by [Bella et al, arXiv:1004.2432]
- W’ search in the dilepton transverse mass distribution, arXiv:1209.4446
  no interference included

**CMS:**
- Z’ search in the dilepton invariant mass distribution, arXiv:1212.7165
  no interference included
- W’ search in the dilepton transverse mass distribution, arXiv:1204.4764
  interference included as suggested by [E.A. et al, arXiv:1110.0713]
  see talk by Philipp Millet

\[ M_{Z'} > 2.22 \text{ TeV} \quad \text{and} \quad M_{W'} > 3.10 - 3.35 \text{ TeV} \]
Our point: the impact of Interference and Finite Width effects on presentation of exp. results, data interpretation and mass bound extraction can be sizeable for Z’ searches.
Forward-backward asymmetry $A_{FB}$ in $pp \rightarrow l^+l^-$

(Dittmar, Nicollerat, Djouadi 03; Petriello, Quackenbush 08)

Forward-backward asymmetry $A_{FB}$ in $pp \rightarrow l^+l^-$

$M_{Z'1} = 1.0 \text{TeV}$

$M_{Z'2} = 1.3 \text{TeV}$

$M_{Z'(SM-like)} = 1.3 \text{TeV}$

$A_{FB} = \left[ \frac{d\sigma^F}{dM_{\text{inv}}} - \frac{d\sigma^B}{dM_{\text{inv}}} \right] / \left[ \frac{d\sigma^F}{dM_{\text{inv}}} + \frac{d\sigma^B}{dM_{\text{inv}}} \right]$