Determination of Z'-boson parameters with ATLAS diboson resonance production data at the 13 TeV LHC

XXIV International Seminar
Nonlinear Phenomena in Complex Systems
May, 16 - 19, 2017 : Minsk, JIPNR - Sosny

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Introduction

Heavy neutral gauge ***Z′***-bosons, are predicted by many theoretical schemes of physics beyond the SM (GUT, left-right symmetric models etc.), and their properties represent important tests of such extended models.

After the discovery of a ***Z′*** boson at the LHC via the DY process

$$pp \to Z' \to l^+ l^- + X$$

some diagnostics of its couplings and ***Z-Z′*** mixing needs to be done in order to identify the correct theoretical framework.

Here, we study the potential of the LHC to discover ***Z-Z'*** mixing effects in the process

$$pp \to Z' \to W^+W^- + X$$

and compare it with current one (from the EW precision data) as well as with that expected at the ILC.

We discuss the feasibility of observing Z' boson in the W-pair production at the LHC, which in contrast to DY process is **not the principal discovery channel**, but can help to understand the origin of new gauge bosons.

Direct searches for a heavy W^+W^- resonances (R=RS graviton, Z' and W' bosons, scalar particle) by:

- the CDF and D0 collaborations at the **Tevatron** using the $e\nu e'\nu'$ and $e\nu jj$ final states.

- the direct W^+W^- resonance search by the ATLAS and CMS collaborations using the $e\nu e'\nu'$ and $e\nu jj$ final state at the collider energies of $\sqrt{s}$=8 TeV and 13 TeV set mass limits on M_R such resonances.

Current limits on Z′ mass from LHC in Drell-Yan:

M(Z′) > 3 – 4 TeV (depending on a model).

Z-Z′ mixing angle (mostly from LEP1 and SLC): $|\phi| < few \cdot 10^{-3}$

Models of Z′-bosons:

The list of ***Z′***-models that will be considered in our analysis is the following:

1) E_6 models: $E_6 \to SO(10)\times U(1)_\psi \to SU(5)\times U(1)_\chi \times U(1)_\psi$

$$Z'(\beta) = \chi\cos\beta + \psi\sin\beta$$

three popular possible U(1) Z′ scenarios originating from the exceptional group E_6 breaking:

$$\chi-\text{model}\ \ (\cos\beta = 0);\ \psi-\text{model}\ (\cos\beta = 1);\ \ \eta-\text{model}\ (\tan\beta = -\sqrt{5/3})$$

2) Left-Right models (LR): $SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$J^\beta_{LR} = \sqrt{\frac{5}{3}}\left(\alpha_{LR} J^\beta_{3R} - \frac{1}{2\alpha_{LR}} J^\beta_{B-L}\right), \quad \alpha_{LR} \equiv \sqrt{\frac{c_W^2}{s_W^2}\frac{g_R^2}{g_L^2} - 1}, \quad \sqrt{\frac{2}{3}} \le \alpha_{LR} \le \sqrt{\frac{c_W^2}{s_W^2} - 1}$$

3) Alternative Left-Right model (ALR).

4) Sequential Standard Model (SSM), where the couplings to fermions are the same as those of the SM Z.

Left-handed and right-handed couplings of the first generation of SM fermions to the *Z'* gauge bosons

E_6 model				
fermions (f)	ν	e	u	d
$g_L^{f'}/g_{Z'}$	$3A+B$	$3A+B$	$-A+B$	$-A+B$
$g_R^{f'}/g_{Z'}$	0	$A-B$	$A-B$	$-3A-B$
Left-Right model (LR)				
$g_L^{f'}/g_{Z'}$	$\frac{1}{2\,\alpha_{LR}}$	$\frac{1}{2\,\alpha_{LR}}$	$-\frac{1}{6\,\alpha_{LR}}$	$-\frac{1}{6\,\alpha_{LR}}$
$g_R^{f'}/g_{Z'}$	0	$\frac{1}{2\,\alpha_{LR}}-\frac{\alpha_{LR}}{2}$	$-\frac{1}{6\,\alpha_{LR}}+\frac{\alpha_{LR}}{2}$	$-\frac{1}{6\,\alpha_{LR}}-\frac{\alpha_{LR}}{2}$
Alternative Left-Right model (ALR)				
$g_L^{f'}/g_{Z'}$	$-\frac{1}{2}+s_W^2$	$-\frac{1}{2}+s_W^2$	$-\frac{1}{6}s_W^2$	$-\frac{1}{6}s_W^2$
$g_R^{f'}/g_{Z'}$	0	$-\frac{1}{2}+\frac{3}{2}s_W^2$	$\frac{1}{2}-\frac{7}{6}s_W^2$	$\frac{1}{3}s_W^2$

$$A = \cos\beta/2\sqrt{6},\ B = \sqrt{10}\sin\beta/12$$

$$\alpha_{LR} = \sqrt{\frac{2}{3}} \equiv E_6(\chi)$$

Z-Z′-mixing

The mass eigenstates Z_1 and Z_2 are:

$$Z_1 = Z\cos\phi + Z'\sin\phi$$

$$Z_2 = -Z\sin\phi + Z'\cos\phi$$

$$\tan^2\phi = \frac{M_Z^2 - M_1^2}{M_2^2 - M_Z^2} \simeq \frac{2M_Z\Delta M}{M_2^2}$$

$$\Delta M = M_Z - M_1 > 0,$$ mass shift due to Z-Z′ mixing.

Coupling constants

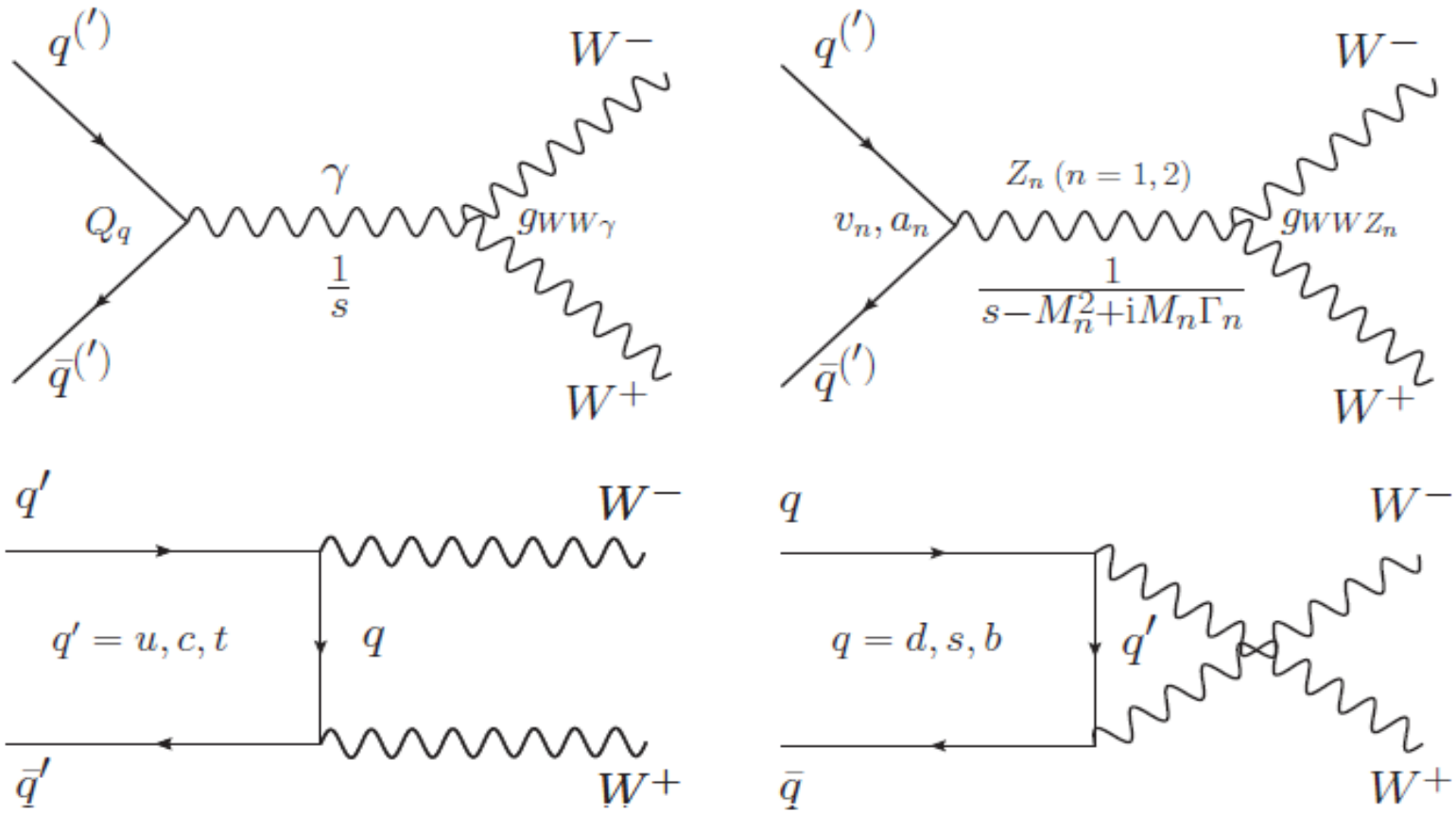
$$v_{1f} = v_f \cos\phi + v'_f \sin\phi \ , \quad a_{1f} = a_f \cos\phi + a'_f \sin\phi \ ,$$
$$v_{2f} = -v_f \sin\phi + v'_f \cos\phi \ , \quad a_{2f} = -a_f \sin\phi + a'_f \cos\phi,$$

$$g_{WWZ_1} = \cos\phi \ g_{WWZ} \ ,$$
$$g_{WWZ_2} = -\sin\phi \ g_{WWZ}$$

$$g_{WW\gamma} = 1 \ , \quad g_{WWZ} = \cot\theta_W \ .$$

$pp \to \gamma, Z_1, Z_2 \to W^+W^- + X$

Diagrams of the subprocess $qq \to WW$ in the framework of extended gauge models are presented below.



Feynman diagrams for $q\bar{q} \to \gamma, Z_1, Z_2 \to W^+W^-$ process in the Born approximation

CROSS-SECTION

$$\frac{d\sigma_{q\bar{q}}}{dM\ \ dy\ \ dz} = K\frac{2M}{s}\ \sum_q [\, f_{q/P_1}(\xi_1)\, f_{\bar{q}/P_2}(\xi_2) + f_{\bar{q}/P_1}(\xi_1)\, f_{q/P_2}(\xi_2)]\ \frac{d\hat{\sigma}_{q\bar{q}}}{dz},$$

where

$z = \cos\theta,$ y diboson rapidity,

$f_{\bar{q}/P_1}(\xi_1);\ f_{q/P_2}(\xi_2)$ pdfs,

$\xi_{1,2} = (M/\sqrt{s})\cdot\exp(\pm y)$ parton fractional momenta (CTEQ-6L1)

K factor (=1.2) accounts NLO QCD corrections

μ_F factorization scale enters through pdf ($\mu_F^2 = M^2 = \hat{s} = \xi_1\xi_2\, s$)

Experimental rapidity cut $|\, y\,| < 2.5$

RESONANT CROSS SECTION:

PARTON LEVEL

$$\frac{d\hat{\sigma}_{q\bar{q}}^{Z_2WW}}{d\cos\theta} = \frac{1}{3}\frac{\pi\alpha^2\cot^2\theta_W}{16}\beta_W^3(v_{2,q}^2 + a_{2,q}^2)\frac{\hat{s}}{(\hat{s}-M_2^2)^2 + M_2^2\Gamma_2^2}\sin^2\phi$$

$$\times[\frac{\hat{s}^2}{M_2^4}\sin^2\theta + 4\frac{\hat{s}}{M_2^2}(4-\sin^2\theta) + 12\sin^2\theta]$$

Dominant term $\propto \frac{M^4}{M_W^4}\sin^2\theta$ enhances sensitivity to ϕ **!**

It corresponds to the production of longitudinally polarized W's, $Z_2 \to W_L^+ W_L^-$.

"Violation" of gauge cancellation mechanism by Z'.

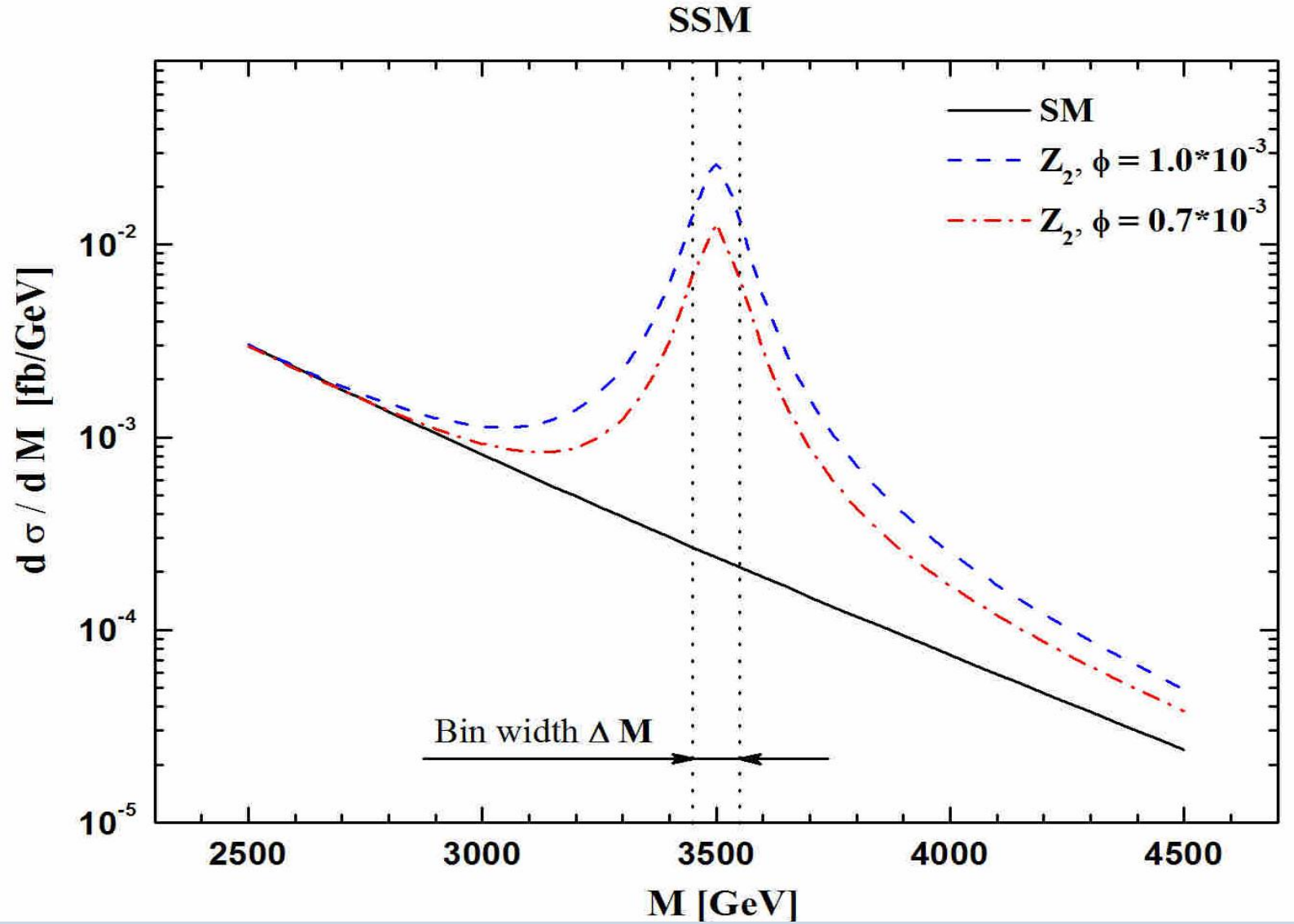


FIG. 2: Invariant mass distribution of $W^{\pm}$ pairs in process $p + p \to W^+W^- + X$ in the SM (solid curve) and for $Z'_{\rm SSM}$ model with $Z - Z'$ mixing angle of $\phi = 10^{-3}$ (dashed line) and $\phi = 0.7 \cdot 10^{-3}$ (dash-dotted line) at the LHC with $\sqrt{s} = 14$ TeV.

SIGNAL AND BACKGROUNDS

- Pure leptonic decay

$$pp \to W^+W^- + X \to l\nu\, l'\nu' + X \quad (l = e, \mu)$$

Here we focus on

- Semileptonic process: $pp \to W^+W^- + X \to l\nu\, jj + X$

- higher cross section;

- allows the reconstruction of the invariant mass of the WW system;

- large QCD background.

Semileptonic process $pp \to W^+W^- + X \to l\nu\ jj + X \quad (l = e, \mu)$

Background reduction

(i) W+jets with W→$l\ \nu$

(ii) t $\bar{t}$ pair production, pp→ t $\bar{t}$ → Wb Wb

using jet veto in the central region.

(iii) WW and WZ continuum (low rate) but irreducible in central region

Set of cuts:

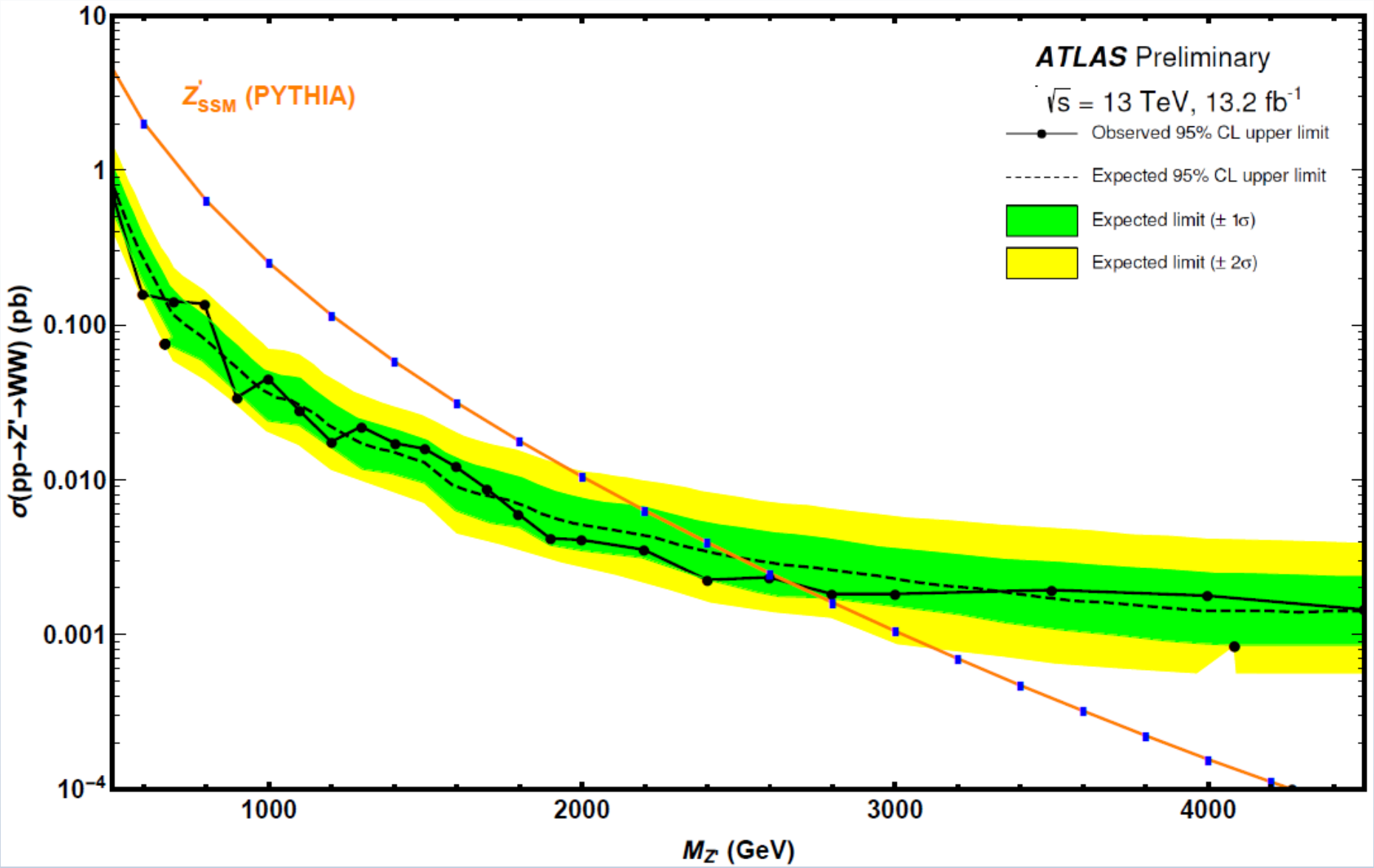
- Lepton cuts P_T^l, $P_T^{miss} > m_{Z'}/10$ (GeV/c) and $|\eta_l| < 2.0$
- High P_T^W cuts: $P_T^{W\to l\,\nu}, P_T^{W\to jj} > m_{Z'}/3$ (GeV/c)
- $M_{W\to jj} = M_W \pm 15$ GeV/c²
- $|\eta^{W\to jj}| < 2.0$: hadronic W must be central

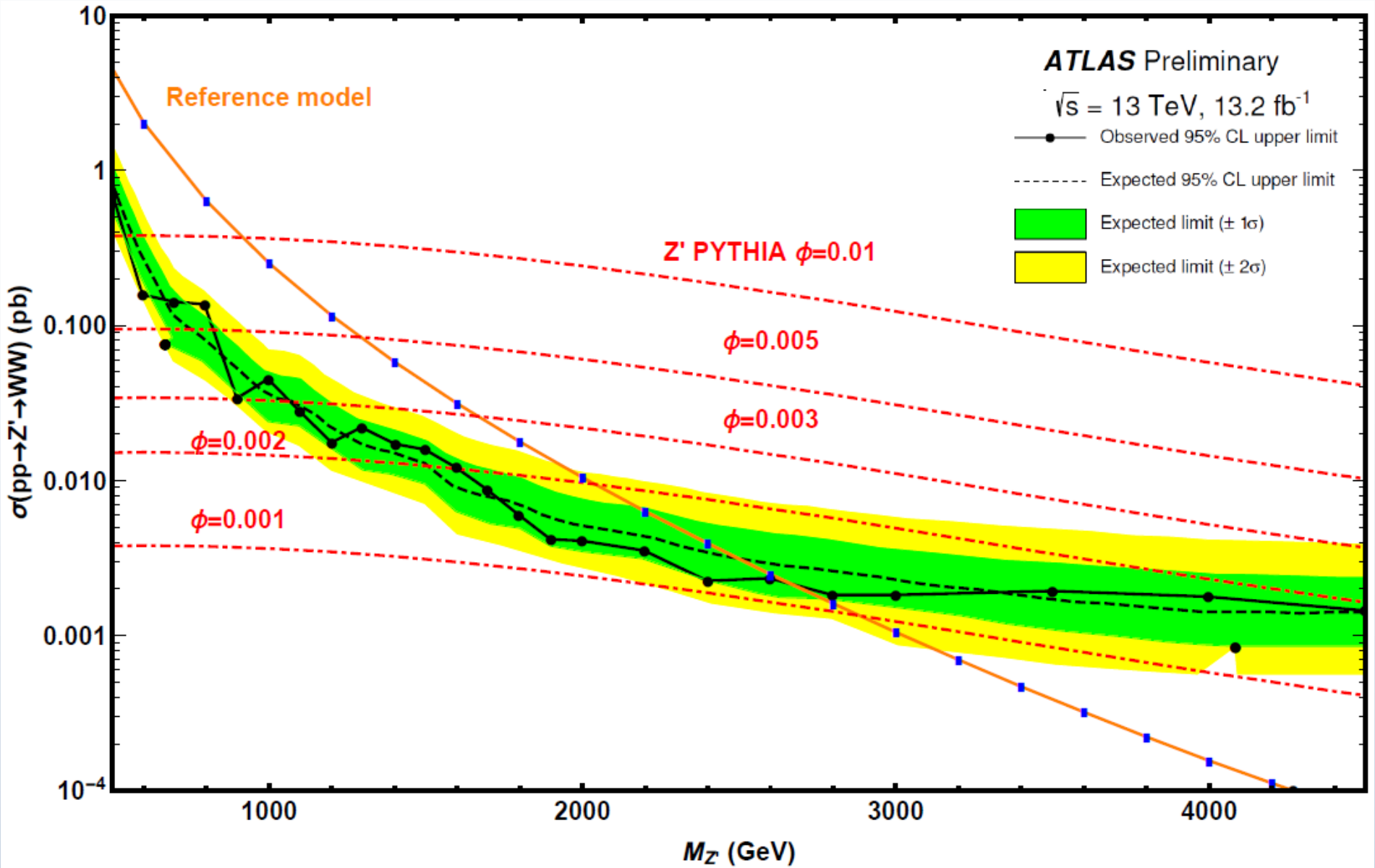
Discovery reach on Z-Z′ mixing angle at 95% C.L. in different processes and experiments

Collider, process	$\lvert\phi\rvert$	Z'_χ	Z'_ψ	Z'_η	$Z'_{\rm SSM}$	@ $M_{Z'}$
LEP2, $e^+e^- \to W^+W^-$	$\lvert\phi\rvert, 10^{-2}$	6	15	50	7	$\geq$ 1 TeV
Tevatron, $p\bar{p} \to W^+W^- + X$	$\lvert\phi\rvert, 10^{-2}$	–	–	–	2	0.4–0.9 TeV
electroweak (EW) data	$\lvert\phi\rvert, 10^{-3}$	1.6	1.8	4.7	2.6	–
ILC (0.5 TeV), $e^+e^- \to W^+W^-$	$\lvert\phi\rvert, 10^{-3}$	1.5	2.3	1.6	1.2	$\geq$ 3 TeV
ILC (1.0 TeV), $e^+e^- \to W^+W^-$	$\lvert\phi\rvert, 10^{-3}$	0.4	0.6	0.5	0.3	$\geq$ 3 TeV
LHC (8 TeV), $pp \to W^+W^- \to l\nu l'\nu'$	$\lvert\phi\rvert, 10^{-3}$	–	–	–	5.2	3 TeV
LHC (14 TeV), $pp \to W^+W^- \to l\nu jj$	$\lvert\phi\rvert, 10^{-3}$	1.7	1.2	1.1	1.7	3 TeV
LHC (14 TeV), $pp \to W^+W^- \to l\nu l'\nu'$	$\lvert\phi\rvert, 10^{-3}$	0.4–0.8	0.3–0.6	0.3–0.6	0.5–0.9	3–4.5 TeV

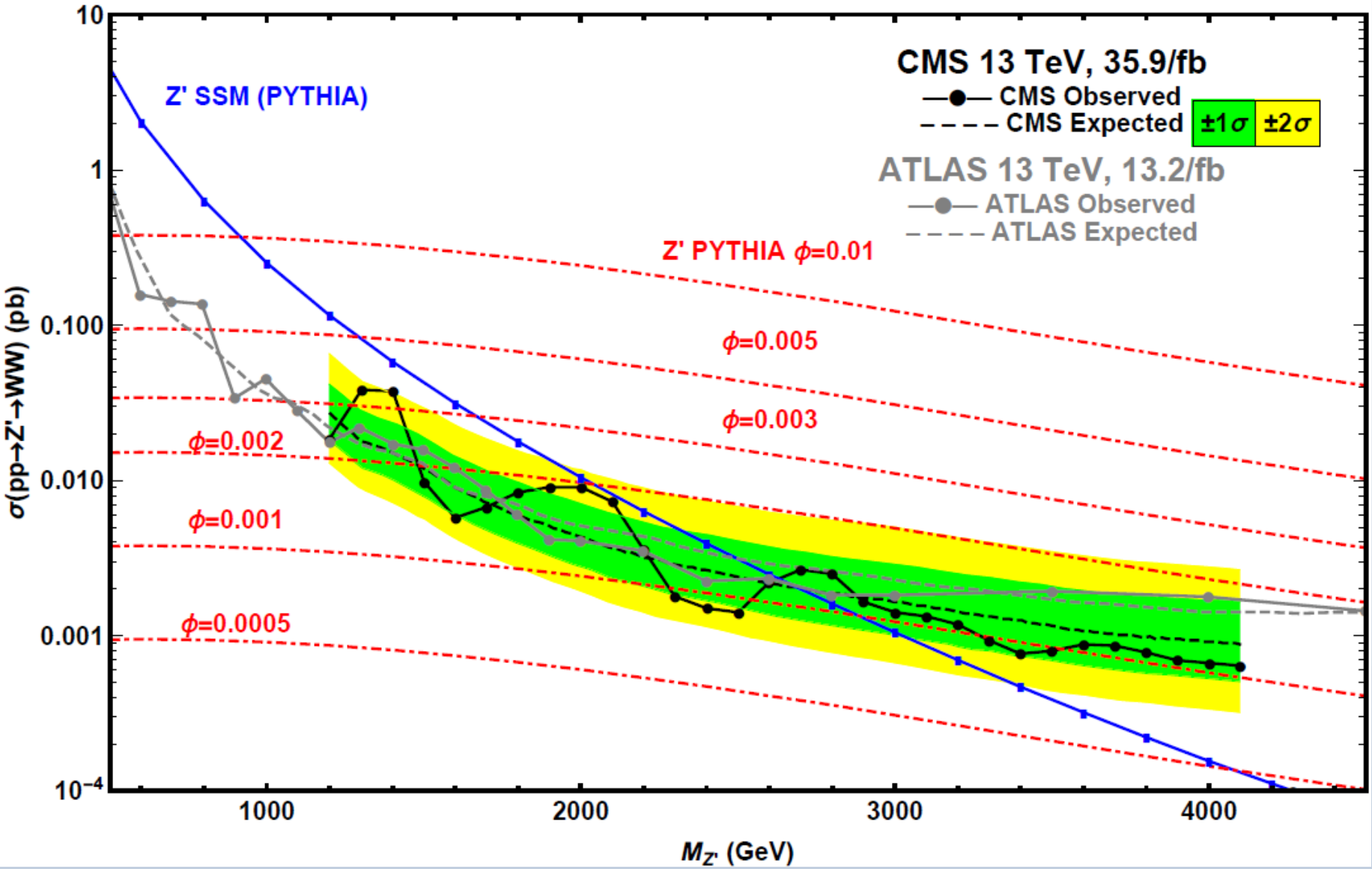
[Eur.Phys.J. 2012; Phys.Rev.D 2014; Phys.At.Nucl. 2015, Phys.Part.Nucl.Lett. 2016]

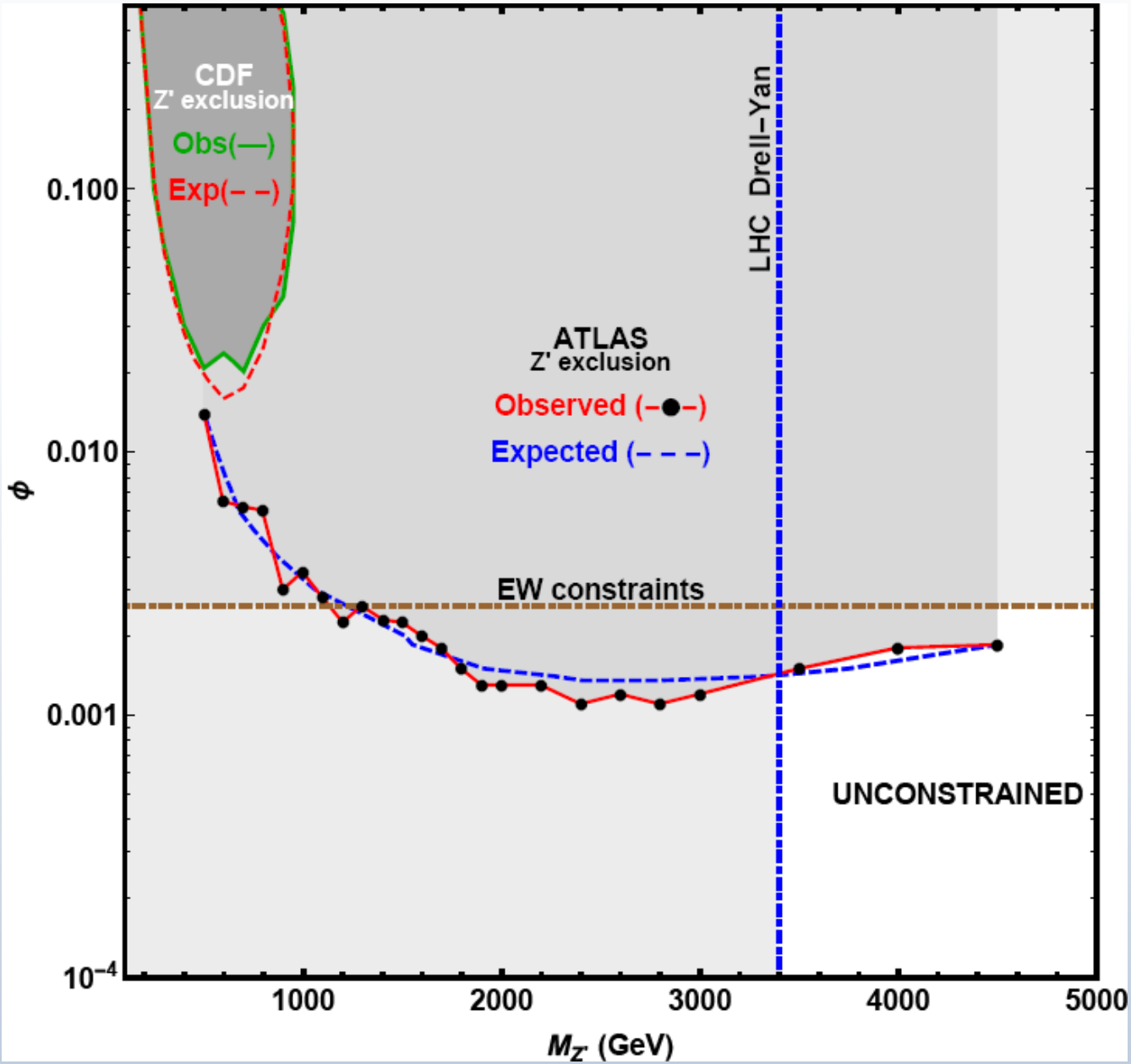
[ATLAS-CONF-2016-062]




ATLAS Preliminary
√s = 13 TeV, 13.2 fb-1
Observed 95% CL upper limit
Expected 95% CL upper limit
Expected limit (± 1σ)
Expected limit (± 2σ)
Reference model
Z' PYTHIA ϕ=0.01
ϕ=0.005
ϕ=0.003
ϕ=0.002
ϕ=0.001
σ(pp→Z'→WW) (pb)
10
1
0.100
0.010
0.001
10−4
1000
2000
3000
4000
MZ' (GeV)

[CMS PAS B2G-17-001]




CDF
Z' exclusion
Obs(—)
Exp(– –)
LHC Drell–Yan
ATLAS
Z' exclusion
Observed (–●–)
Expected (– – –)
EW constraints
UNCONSTRAINED
0.100
0.010
0.001
10^{-4}
ϕ
1000
2000
3000
4000
5000
$M_{Z'}$ (GeV)

Concluding remarks

New heavy neutral bosons Z' decaying to W+W- are predicted by many scenarios of new physics, including models with extended gauge sector such as SSM and others. The diboson production allows determining constraints on the Z' boson parameters such as Z-Z' mixing angle and Z' mass. We find that the present bounds on the Z-Z' mixing angle obtained with data comprised of 13.2/fb of proton-proton collisions at 13 TeV and recorded by ATLAS detector at the CERN LHC are quite competitive with those derived from the global analysis of the electroweak data.

[*Submitted to* **Nonlin. Phenom. Complex Syst. (2017)**]

Minsk
2017

Thank you for attention!