First results on high-precision constraints on Z-Z' mixing with ATLAS and CMS diboson production data at the LHC at 13 TeV and predictions for RUN II

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Outline

- "Classical" models of ***Z′***-bosons: (SSM, E6, LR, ALR)
- DY as a principal ***Z′*** discovery channel:

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

- Study the potential of the LHC to observe of ***Z-Z′*** mixing effects in

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

Main goal – quantify sensitivity of W^+W^- pair production to

$M_{Z'}$ and ***Z-Z′*** mixing angle using ATLAS and CMS data at 13 TeV

- Comparison with current limits (from EW data) and ILC potential
- Conclusions

based on: **Phys.Rev.D (2017)** and recent results.

Other relevant refs.: Phys.Rev.D(2014), Phys.At.Nucl.(2015), Phys.Part.Nucl.Lett.(2016).

Introduction

Here, we study

(**i**) 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.

(**ii**) we will present the Z' exclusion region

in the Z-Z' mixing parameter $\xi (\equiv \sin\phi)$ and Z' mass plane, (ξ - $M_{Z'}$), **for the first time** by using data comprised of pp collisions and recorded by the ATLAS and CMS detectors at the LHC(13 TeV) with integrated luminosities of ≈ 36/fb.

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):

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

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

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
$g_L^{f\prime}/g_{Z}^{\prime}$	$3A+B$	$3A+B$	$-A+B$	$-A+B$
$g_R^{f\prime}/g_{Z}^{\prime}$	0	$A-B$	$A-B$	$-3A-B$
Left-Right model (LR)				
$g_L^{f\prime}/g_{Z}^{\prime}$	$\frac{1}{2\,\alpha_{LR}}$	$\frac{1}{2\,\alpha_{LR}}$	$-\frac{1}{6\,\alpha_{LR}}$	$-\frac{1}{6\,\alpha_{LR}}$
$g_R^{f\prime}/g_{Z}^{\prime}$	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)				
$g_L^{f\prime}/g_{Z}^{\prime}$	$-\frac{1}{2}+s_W^2$	$-\frac{1}{2}+s_W^2$	$-\frac{1}{6}s_W^2$	$-\frac{1}{6}s_W^2$
$g_R^{f\prime}/g_{Z}^{\prime}$	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.

In general, such ***Z-Z′*** mixing effects reflect
(i) the underlying gauge symmetry and/or
(ii) the Higgs sector of the model.

- We set $\rho_0=1$ which corresponds to a Higgs sector with only SU(2) doublets and singlets $\Rightarrow$ **two** free parameters: ϕ and M_2

- **one** free parameter - in specific "minimal-Higgs models",

$$\phi = -s_W^2 \frac{\sum_i \langle \Phi_i^2 \rangle \; I_{3L}^i Q_i'}{\sum_i \langle \Phi_i^2 \rangle \; (I_{3L}^i)^2} = C \frac{M_1^2}{M_2^2}.$$

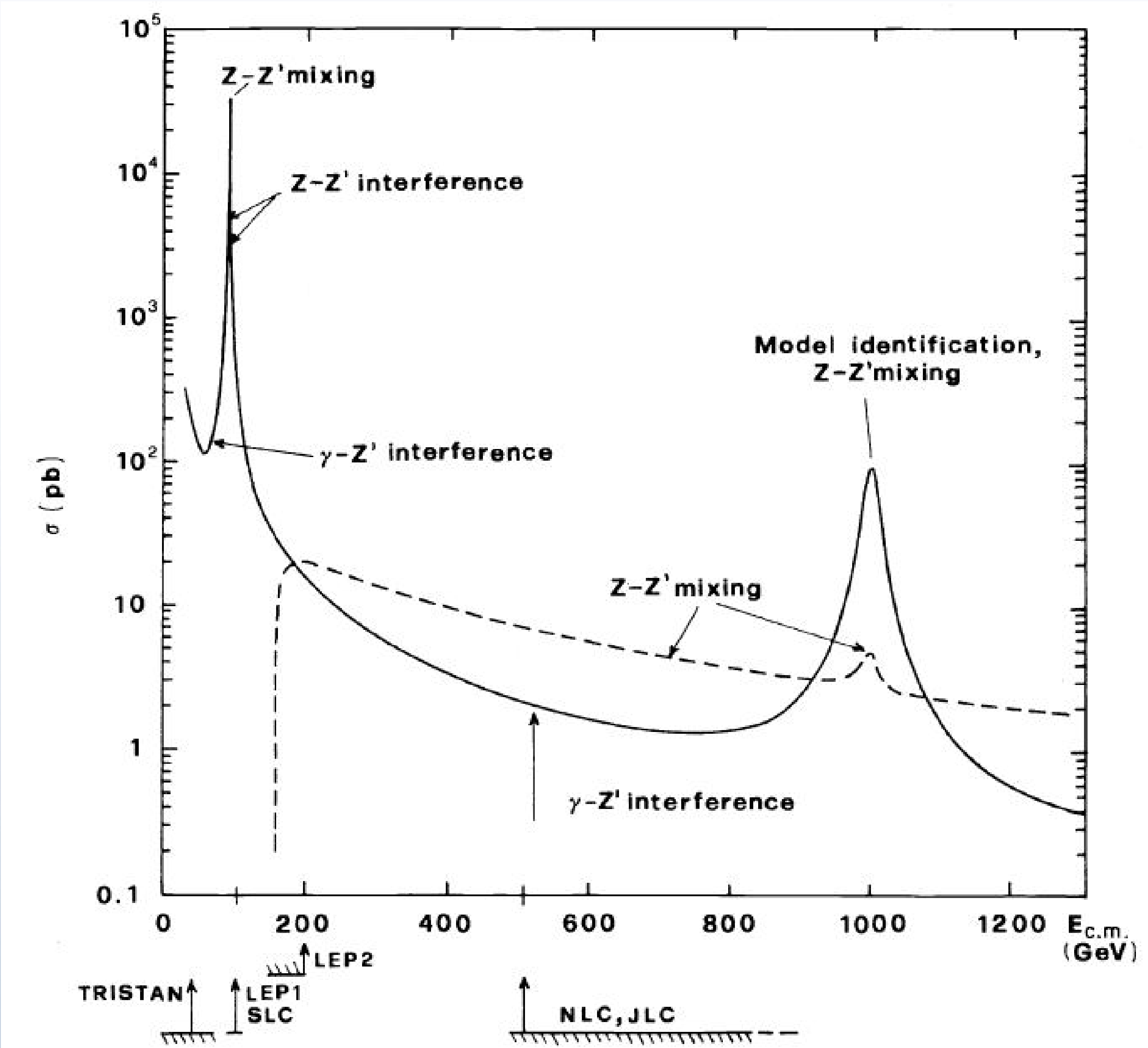
Here, Φ_i are the Higgs vacuum expectation values spontaneously breaking the symmetry, and Q_i' are their charges with respect to the additional U(1)'.

Coupling constants

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

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

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



Total cross sections of $e^+e^- \rightarrow$ hadrons (solid line) and $e^+e^- \rightarrow W^+W^-$ (dashed line) vs energy.

Z' from E_6 (χ model) $M_{Z'} = 1$ TeV and a Z-Z' mixing angle 3×10^{-3} rad

Search for W^+W^- resonances

Direct searches for a heavy W^+W^- resonances

(RS graviton, Z' and W' bosons, scalar particles) by:

- **Tevatron** **with CDF** and **D0** collaborations by using the *leptonic*, *semi-leptonic* and *hadronic* final states.
- **LHC** **with ATLAS** and **CMS** collaborations at collider energies 7-8 TeV (**Run I**) and 13 TeV (**Run II**) set mass limits on heavy resonances.

Current limits:

- **2 free** parameters case:

on Z′ mass from LHC(13 TeV) in Drell-Yan
$M_{Z'} > 3.7 - 4.5$ TeV (95% C.L.) depending on the model

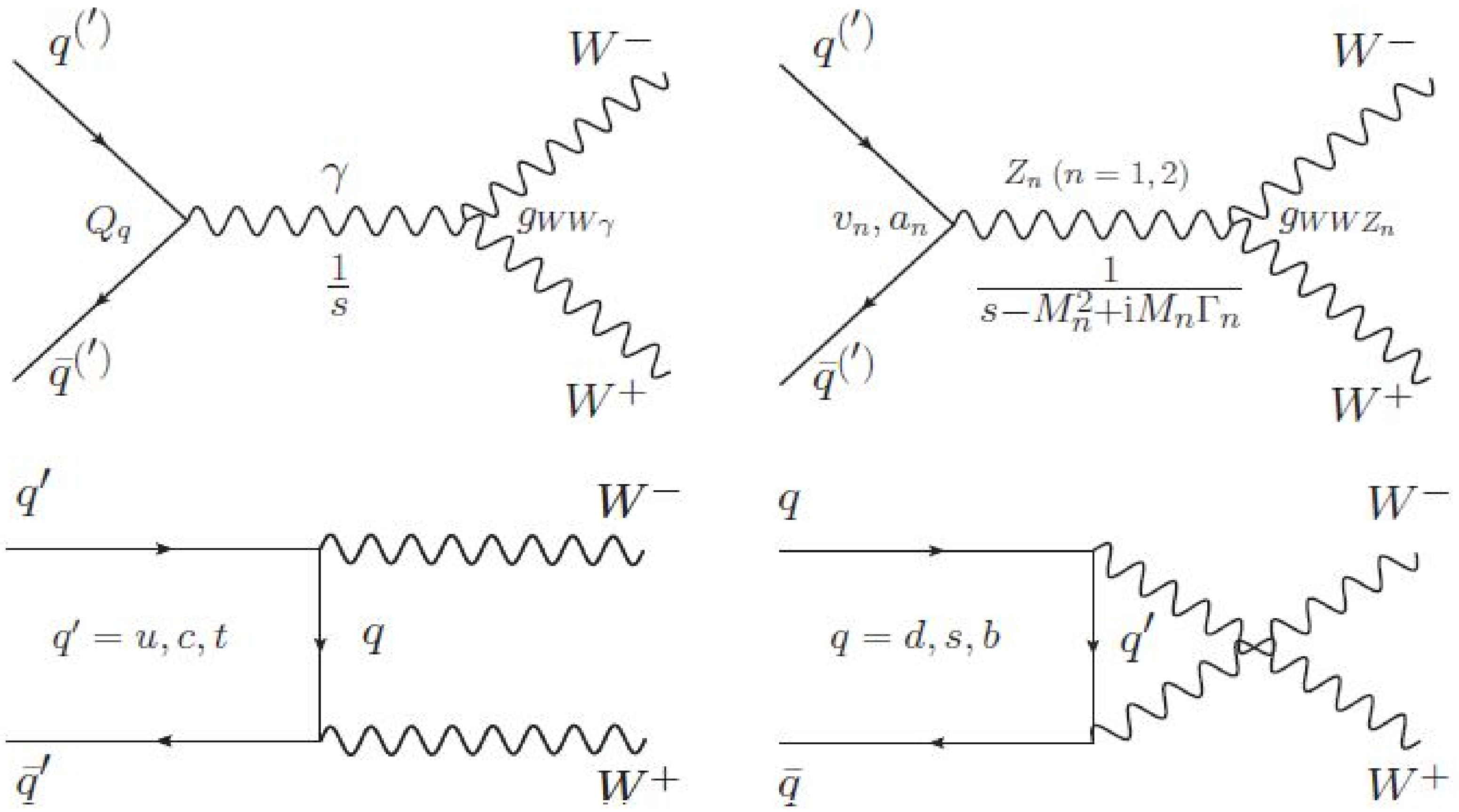
EW: *Z-Z′* mixing angle (mostly from LEP1 and SLC): $|\phi| < few \cdot 10^{-3}$

- **1 free** parameter case: Altarelli reference model

$M_{Z'} > 3.5$ TeV, $|\phi| = (M_W / M_{Z'})^2 < few \cdot 10^{-4}$

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

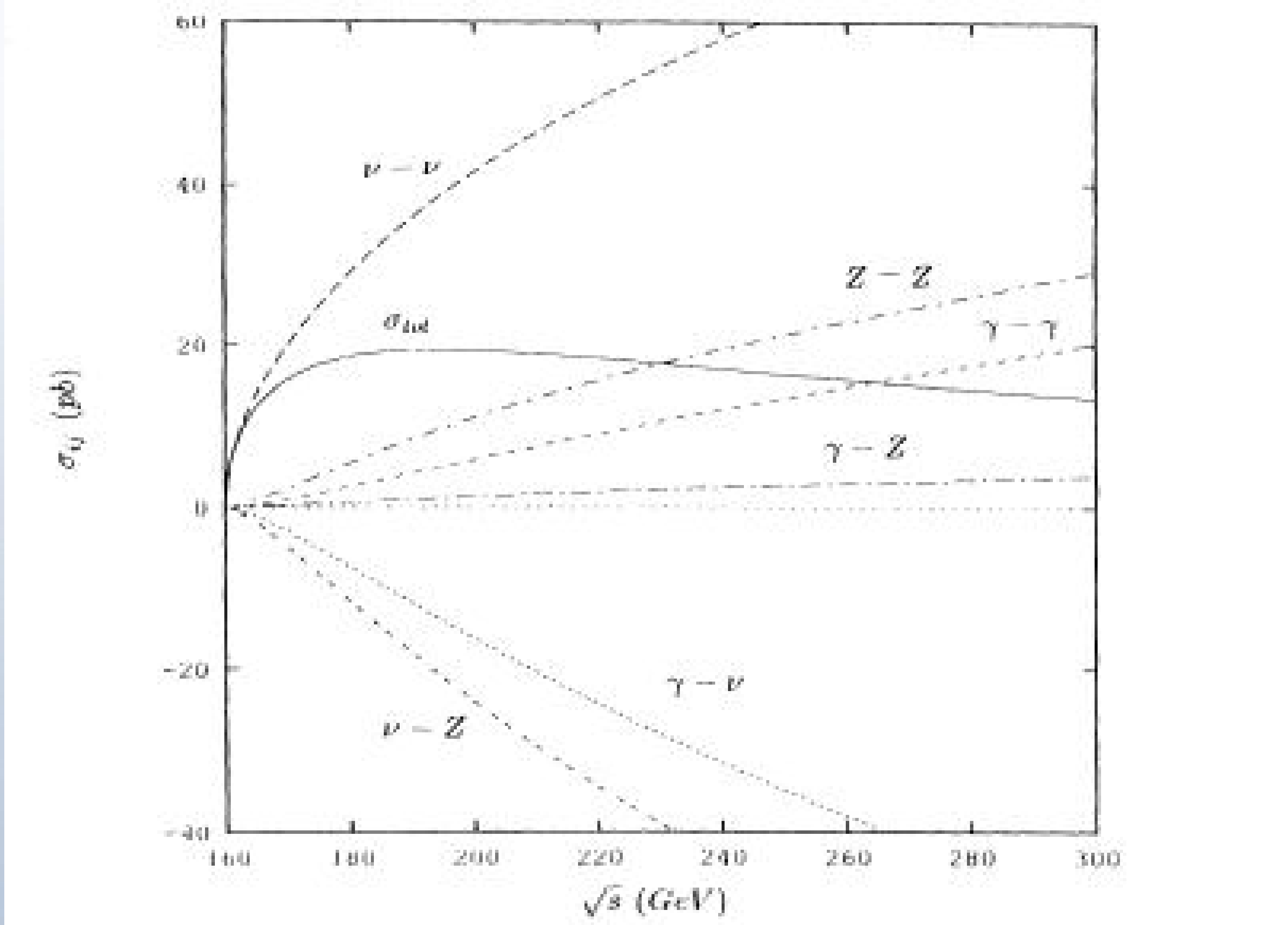
Diagrams of the subprocess $qq \to WW$ in the framework of extended gauge models are presented below.



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

Example: gauge cancellation mechanism in SM

for e+e- →W+W-



CROSS-SECTION

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

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 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

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

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

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'.

Total cross section in NWA

$$\boxed{\Gamma_2 << \Delta M}$$

$$\sigma(pp \to Z_2 \to W^+W^-)_{fid} = \int\limits_{M_2-\Delta M/2}^{M_2+\Delta M/2} dM \int\limits_{-Y}^{Y} dy \int\limits_{-z_{cut}}^{z_{cut}} dz \frac{d\sigma^{Z_2}}{dM\, dy\, dz} =$$

$$= A_{WW} \times \underbrace{\sigma(pp \to Z_2) \times Br(Z_2 \to W^+W^-)}_{in\ \ total\ phase\ space}$$

$$\sigma(pp \to Z_2) - ? \qquad Br(Z_2 \to W^+W^-) - ?$$

Experimental <u>mass resolution</u>: $\boxed{\Delta M \approx 5\% \cdot M_2}$

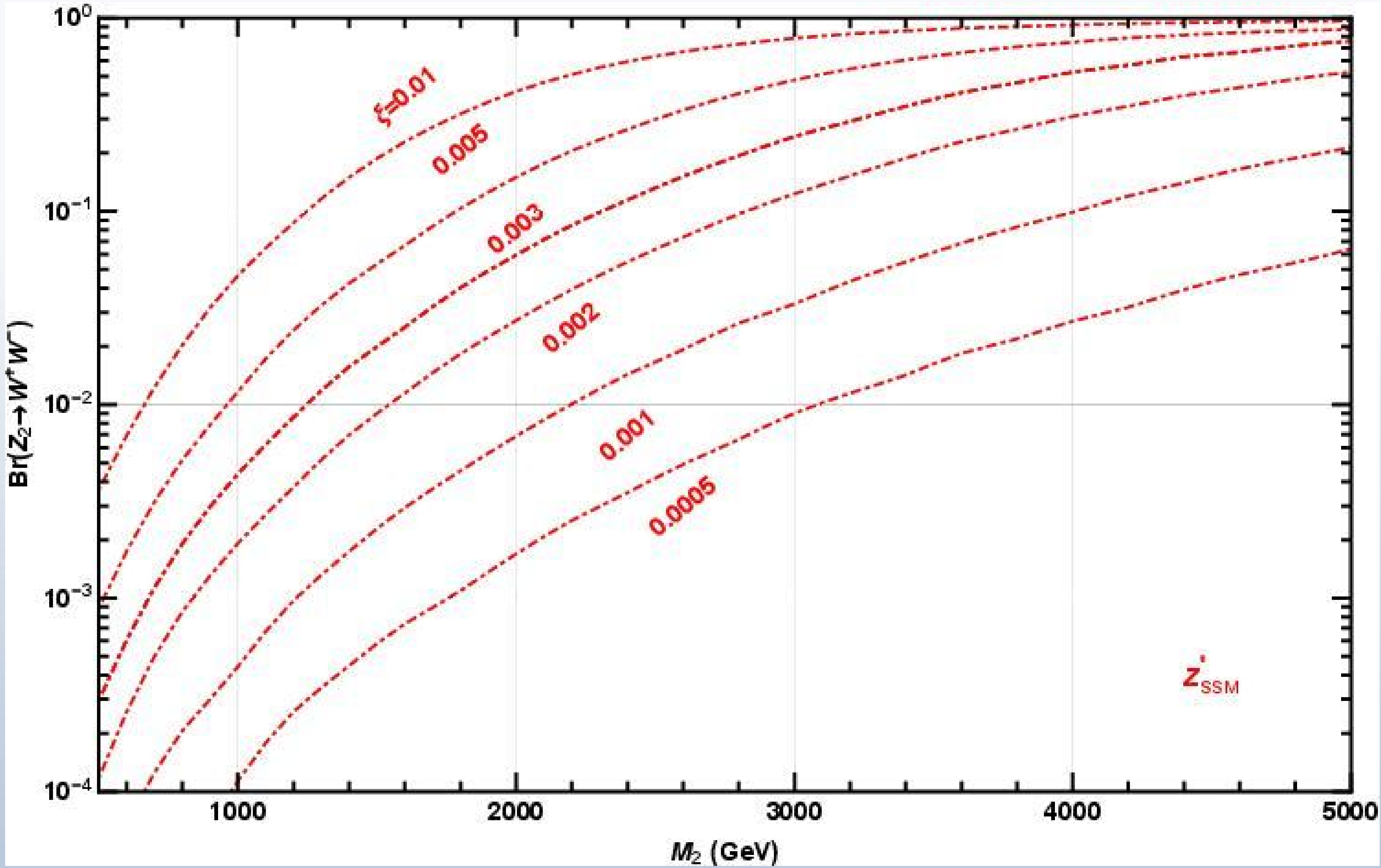
ArXiv: 1705.09171 CMS
1606.04833 ATLAS
(hep-ex)

$$\Gamma_2 = \sum_{ff} \Gamma_2^{ff} + \Gamma_2^{WW} + \Gamma_2^{Z_1 H}$$

$$SSM: \quad \sum_{ff} \Gamma_2^{ff} = 0.03 \cdot M_2 \quad (SM: f = \nu, l, q)$$

For heavy Z_2: $\Gamma_2^{WW} \approx \Gamma_2^{Z_1 H} \sim \xi^2 \; (\equiv \sin^2 \phi)$ **Equivalence theorem**

$$\Gamma_2^{WW} = \frac{\alpha \cot^2 \theta_W}{48} M_2 \left(\frac{M_2}{M_W}\right)^4 \left(1 - 4\frac{M_W^2}{M_2^2}\right)^{3/2} \left[1 + 20\frac{M_W^2}{M_2^2} + 12\frac{M_W^4}{M_2^4}\right] \xi^2$$



Br(Z₂→W⁺W⁻)
M₂ (GeV)
1000
2000
3000
4000
5000
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
ξ=0.01
0.005
0.003
0.002
0.001
0.0005
Z'SSM

SIGNAL AND BACKGROUNDS

- Pure leptonic decay

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

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

- higher cross section then pure leptonic one;

- 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
- $\left|\eta^{W\to jj}\right| < 2.0$: hadronic W must be central

Constraints on Z′

N_{SM} and $N_{Z'}$ number of background and signal events.

Criterion: $N_{Z'} = 2\sqrt{N_{SM}}$ or **3 events**,

whichever is larger (reach at the 95% C.L.)

$$N_{Z'} = N_{data} - N_{bkg} = L_{\text{int}} \cdot \varepsilon \cdot A_{WW} \cdot \underbrace{\sigma(pp \to Z') \times Br(Z' \to W^+W^-)}$$

theoretical resonant production cross section $\bullet\, Br$
extrapolated to the total phase space

N_{data} *and* $N_{bkg} (= N_{SM})$ are the number of observed data events and estimated background events, respectively.

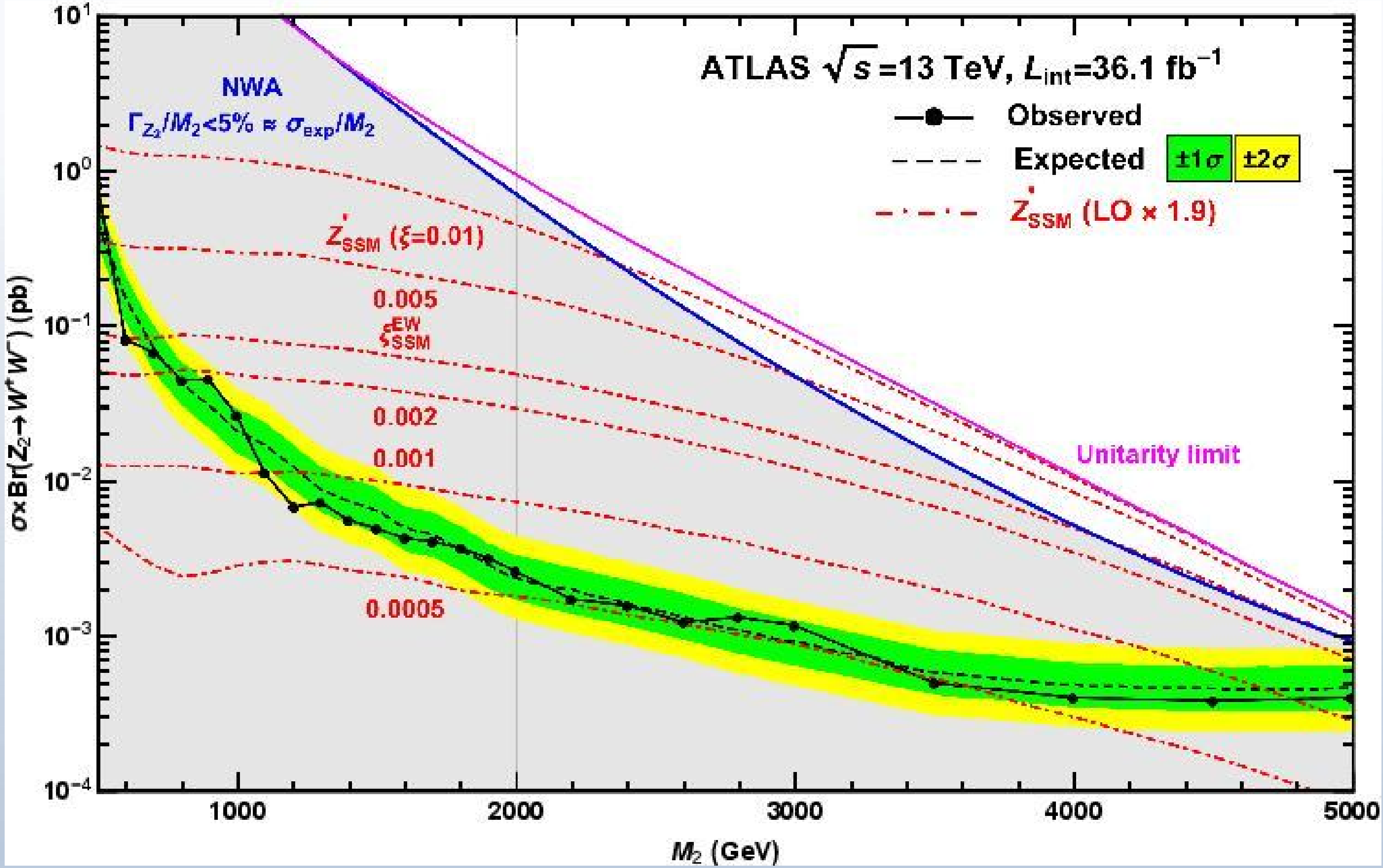
- I L_{int} integrated luminosity,

- $\varepsilon \cdot A_{WW}$ overall kinematic and geometric acceptance times trigger, reconstruction and selection efficiencies, is defined as the number of signal events passing the full event selection divided by the number of generated events,

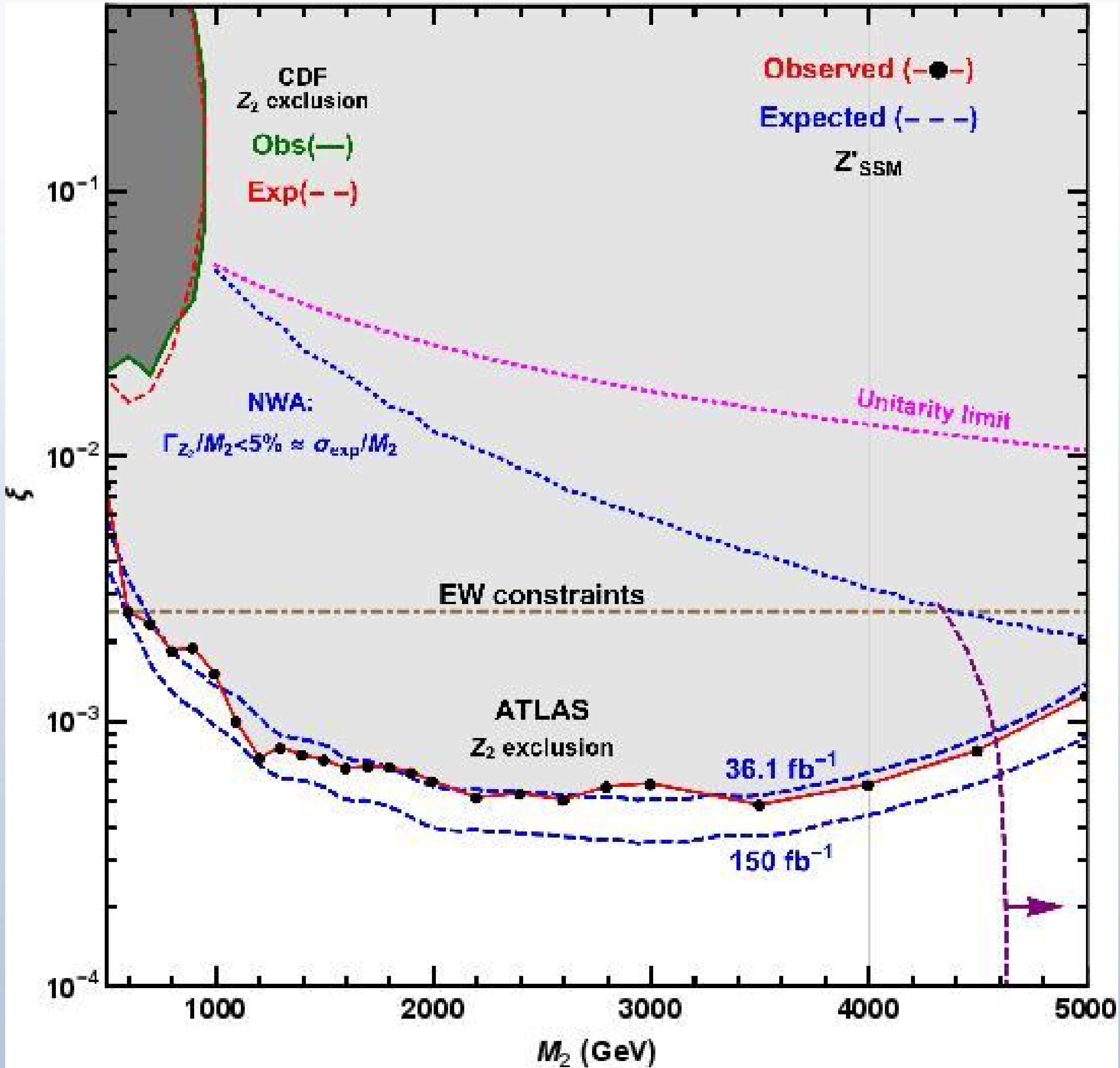
- 95% C.L. upper limit $(\sigma_{95\%} \times Br) \simeq (L_{\text{int}} \cdot \varepsilon \cdot A_{WW})^{-1} \cdot 2\sqrt{N_{bkg}}$

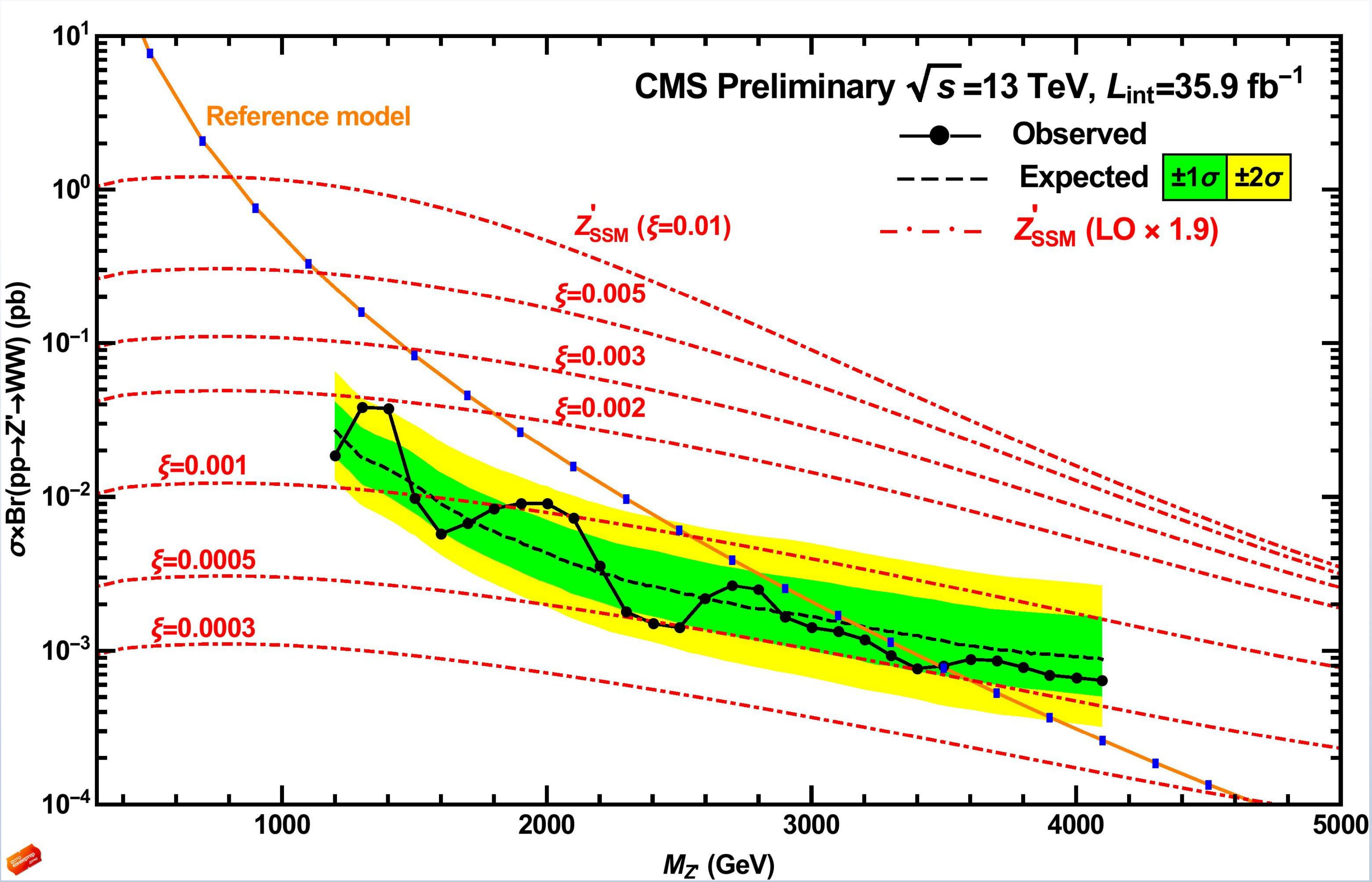
Observed in experiment

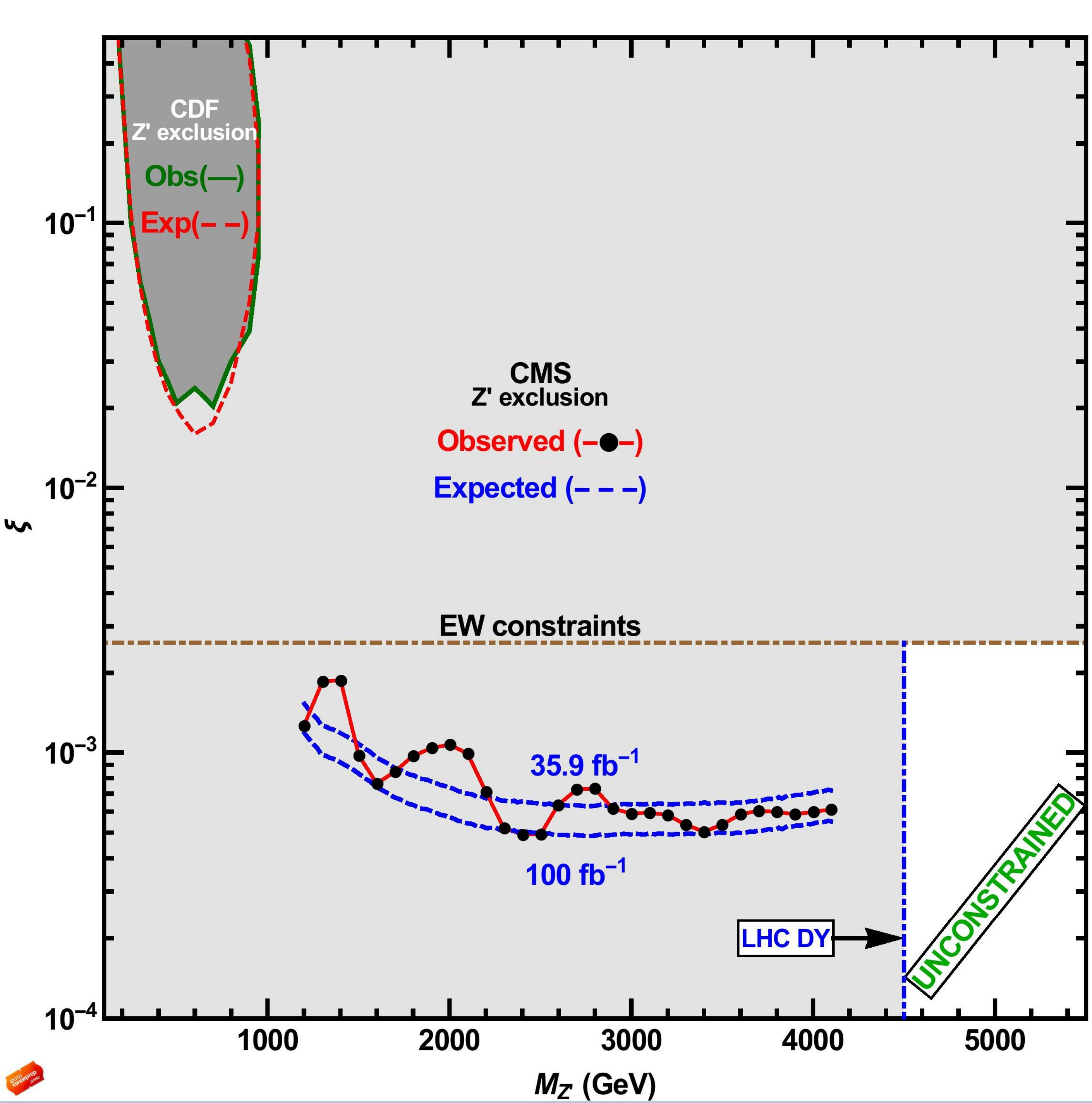
Observed and expected 95% C.L. upper limits on $\sigma \times Br(W^+W^-)$ as a function of Z_2 mass.
Theoretical cross sections $\sigma(pp \to Z_2) \times Br(Z_2 \to W^+W^-)$ f or SSM and reference model are calculated from PYHTHIA8 $\sigma_{\exp} (\simeq \Delta M)$



Z' exclusion regions (95%C.L.) in the two-dimensional plane of (M_2 , ξ) obtained from CDF (Tevatron), precision electroweak (EW) data and LHC(13 TeV) data. Exclusion plots with 150/fb of data correspond to an extrapolation of the expected sensitivity.




CMS Preliminary √s =13 TeV, L_int=35.9 fb⁻¹
Reference model
Observed
Expected ±1σ ±2σ
Z'_SSM (ξ=0.01)
Z'_SSM (LO × 1.9)
ξ=0.005
ξ=0.003
ξ=0.002
ξ=0.001
ξ=0.0005
ξ=0.0003
σ×Br(pp→Z'→WW) (pb)
M_Z' (GeV)
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
1000
2000
3000
4000
5000


CDF
Z' exclusion
Obs(—)
Exp(- -)
CMS
Z' exclusion
Observed (–●–)
Expected (- - -)
EW constraints
35.9 fb^{-1}
100 fb^{-1}
LHC DY
UNCONSTRAINED
10^{-1}
10^{-2}
10^{-3}
10^{-4}
ξ
1000
2000
3000
4000
5000
$M_{Z'}$ (GeV)

Exclusion regions (95% C.L.) on Z-Z′ mixing in different processes and experiments

Collider, process / Z' model	$\|\xi\|$	SSM	χ	ψ	η	$M_{Z'}$, TeV
LEP2, $e^+e^- \to W^+W^-$	10^{-2}	7	6	15	50	>1
Tevatron, $p\bar{p} \to W^+W^- + X$	10^{-2}	2	–	–	–	< 0.9
Electroweak (EW) data	10^{-3}	2.6	1.6	1.8	4.7	–
LHC@13TeV $pp \to W^+W^- + X$ (this work) **from data** 36/fb	10^{-3}	0.48	0.59	0.47	0.42	<dis.
Extrapolated sensitivity for 150/fb	10^{-3}	0.34	0.42	0.34	0.30	<dis.
ILC@0.5TeV $e^+e^- \to W^+W^-$	10^{-3}	1.2	1.5	2.3	1.6	>3
ILC@1 TeV $e^+e^- \to W^+W^-$	10^{-3}	0.3	0.4	0.6	0.5	>3

Scaling low

$$|\xi| \sim L_{\text{int}}^{-1/4}$$

- Run2 (36/fb) → Run2(150/fb):
improvementfactor for mixing constraints ≈ 1.4

-Run2 (36/fb) vs HL-LHC (3000/fb):
improvement factor for mixing constraints ≈ 3

Concluding remarks

- If a new Z2 (Z′) boson exists in the mass range ~ 4– 5 TeV, its discovery is possible at the LHC in the Drell—Yan process at nominal energy and luminosity.

- Detection of the $Z2 \rightarrow W^+W^-$ mode is eminently possible and would give valuable information on the $Z - Z'$ mixing.

- Present analysis of the $Z - Z'$ mixing is based on current pp collision data collected by the ATLAS and CMS experiments at the LHC(13 TeV) with integrated luminosities of ≈ 36/fb.

- We presented the Z' exclusion region in the ξ-$M_{Z'}$ plane **for the first time** by using these data.

- We derived **large improvement** over previously published results obtained at the Tevatron, and precision electroweak data (EW); we obtained the most stringent exclusion limits to date on the $(\xi$-$M_{Z'})$.

- Further improvement: at **Run 2** LHC (13 TeV) with 150/fb, at **Run 3** LHC (14 TeV) with 300/fb and at **HL-LHC** (14 TeV) with 3000/fb.