High and low energy probes of light Z' bosons

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Outline

Question(s) I want to ask:

SU(2) × U(1) gauge symmetry is the only gauge symmetry at the low scale?
Room for light (≲100GeV) gauge bosons?

If so, how to probe them?
And in particular what is the role of the Higgs boson?

What are the virtues of these new gauge bosons?

Outline

1. Introduction:

- Present searches for neutral gauge bosons

2. Kinetically mixed Z dark gauge boson

- Present bounds
- Role of the Higgs boson in probing the model: exotic Higgs decays

3. L_μ-L_τ model

- Interesting effects in flavor physics
- Diversity of low and high energy probes of the model:
  EWPTs, $(g-2)_\mu$, $Z \longrightarrow 4\mu$, neutrino trident production

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  EWPTs, $(g-2)_\mu$, $Z \longrightarrow 4\mu$, neutrino trident production

- Exotic decays of the 125 GeV Higgs boson
  D. Curtin, R. Essig, S.G., P. Jaiswal, A. Katz, T. Liu, Z. Liu, D. McKeen, J.Shelton, M. Strassler, Z. Surujon, B. Tweedie, Y-M. Zhong, 1312.4992
- D.Curtin, R.Essig, S.G., J.Shelton, in preparation
- Dressing L_μ - L_τ in color
  W.Altmannshofer, S.G., M.Pospelov, I.Yavin, 1403.1269 + in preparation

Z' models

- Naturally arising in Grand Unified Theories
(e.g. $E_6 \longrightarrow SO(10) \times U(1)_\psi \longrightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$)

- Models of compositeness or extra dimensions give raise to excited Z bosons: „sequential Z' bosons“

From where

- A new U(1)' symmetry can address the μ problem of the MSSM, since it can forbid the appearance of a μ term

- In Susy models, a new U(1)' symmetry can give a sizable tree level contributions to the Higgs mass, through new non-decoupling D-terms

Naturalness

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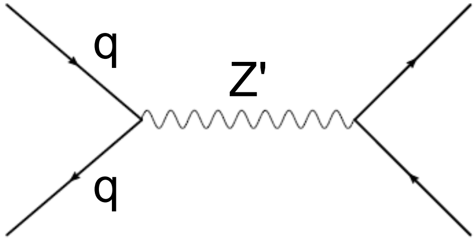
Naturalness

- Used in neutrino model building
- „Dark“ gauge bosons can arise in models for thermal dark matter
- A U(1)' Susy model can provide a sufficiently large first order phase transition for Electroweak baryogenesis
- Easy to get sizable effects in $(g-2)_\mu$ if the Z' is quite light

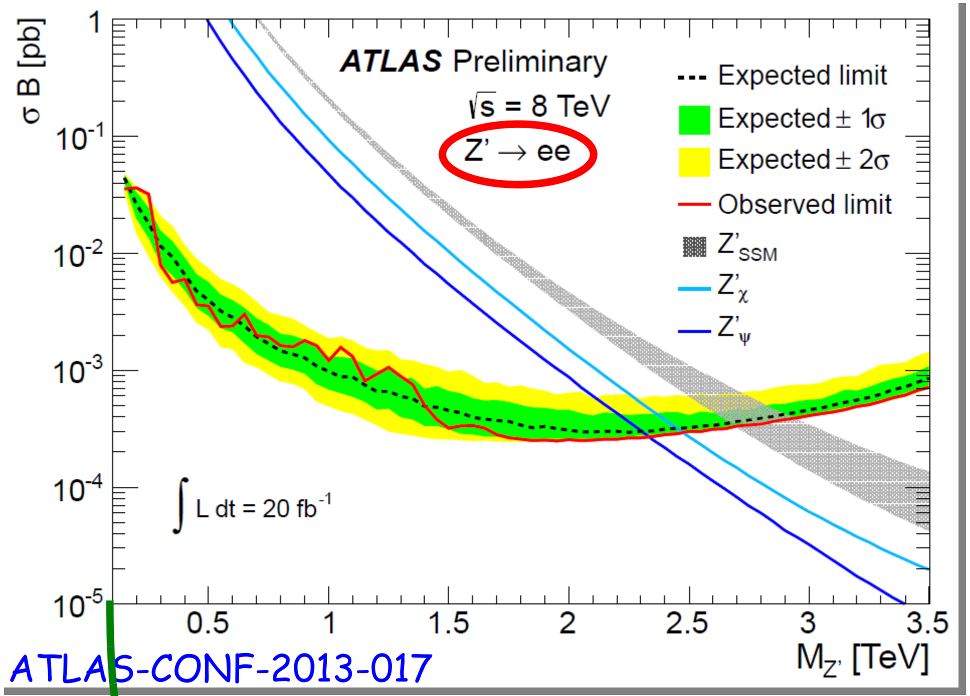
Pheno

Z' searches

Plenty of LHC searches for TeV-scale Z'



Di-lepton resonances:



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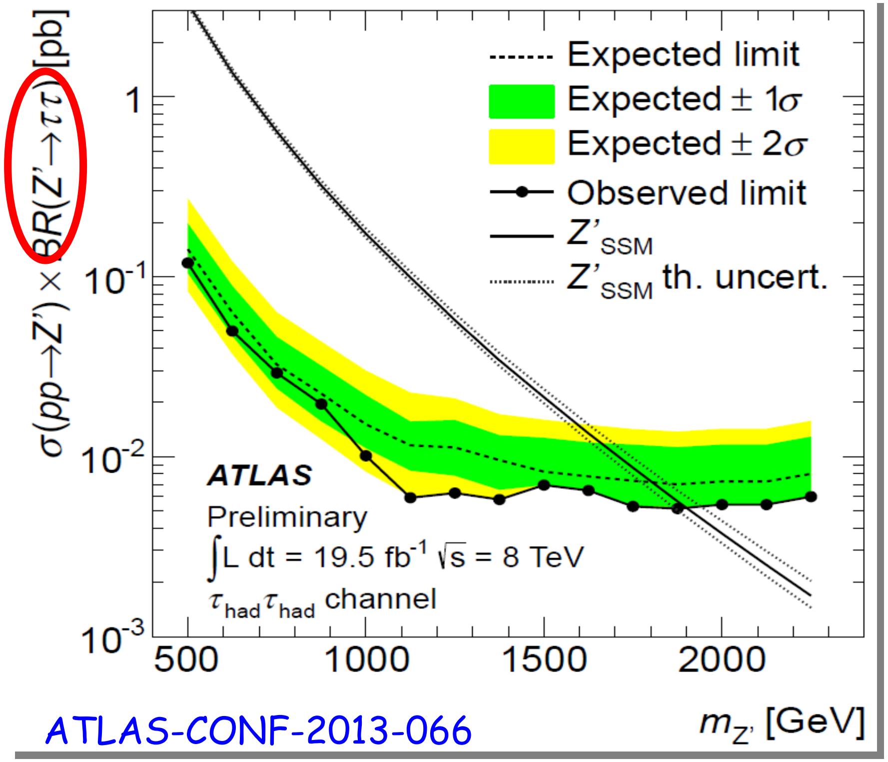

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Below 100 GeV, limits from LEPII: $e^+e^- \to ff$

(for couplings of at least 10^{-2})

Z' searches

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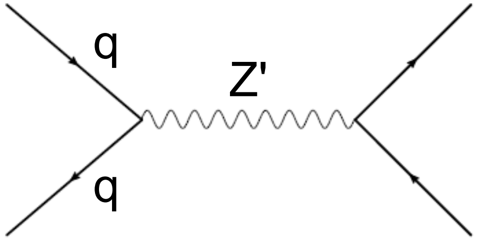
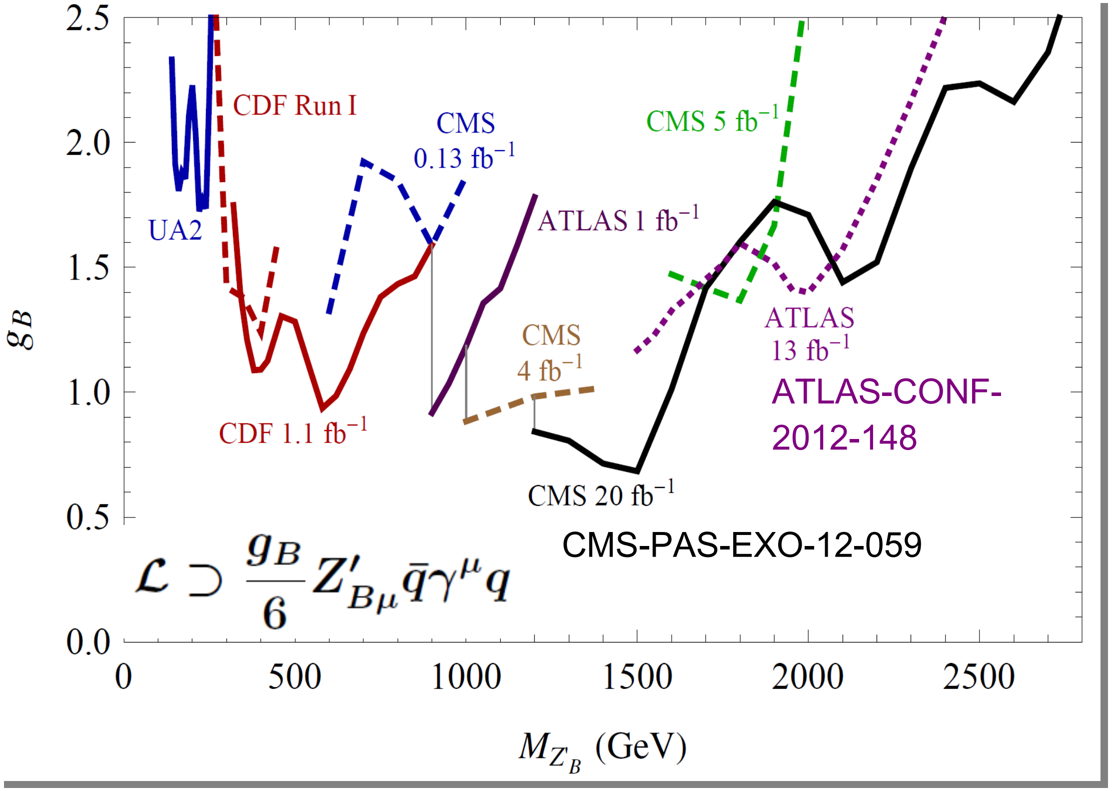


Di-jet/top resonances:

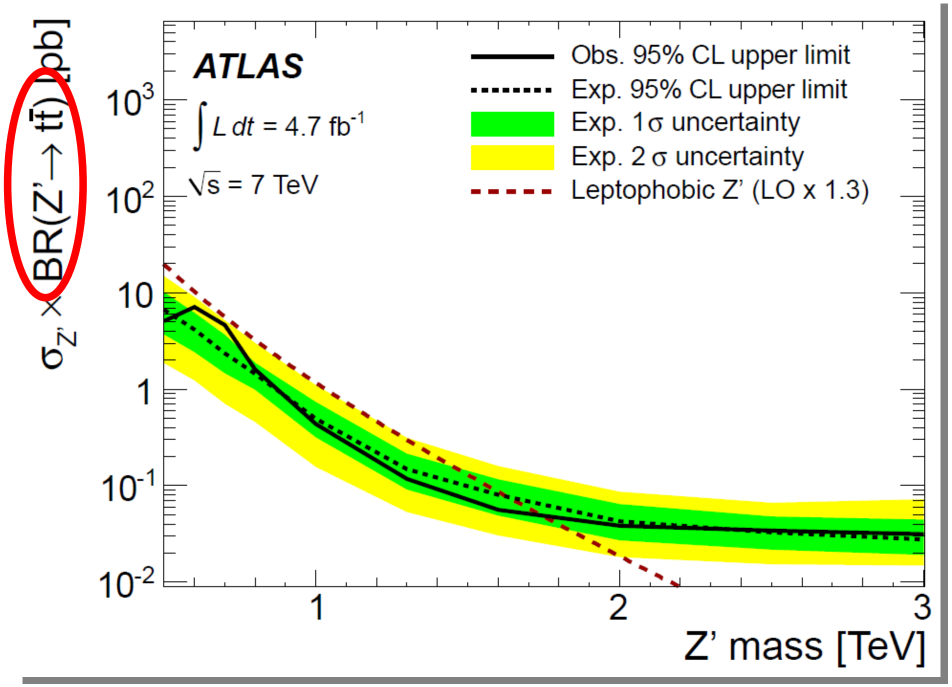


$$\mathcal{L} \supset \frac{g_B}{6} Z'_{B\mu} \bar{q} \gamma^\mu q$$

ATLAS-CONF-2012-148

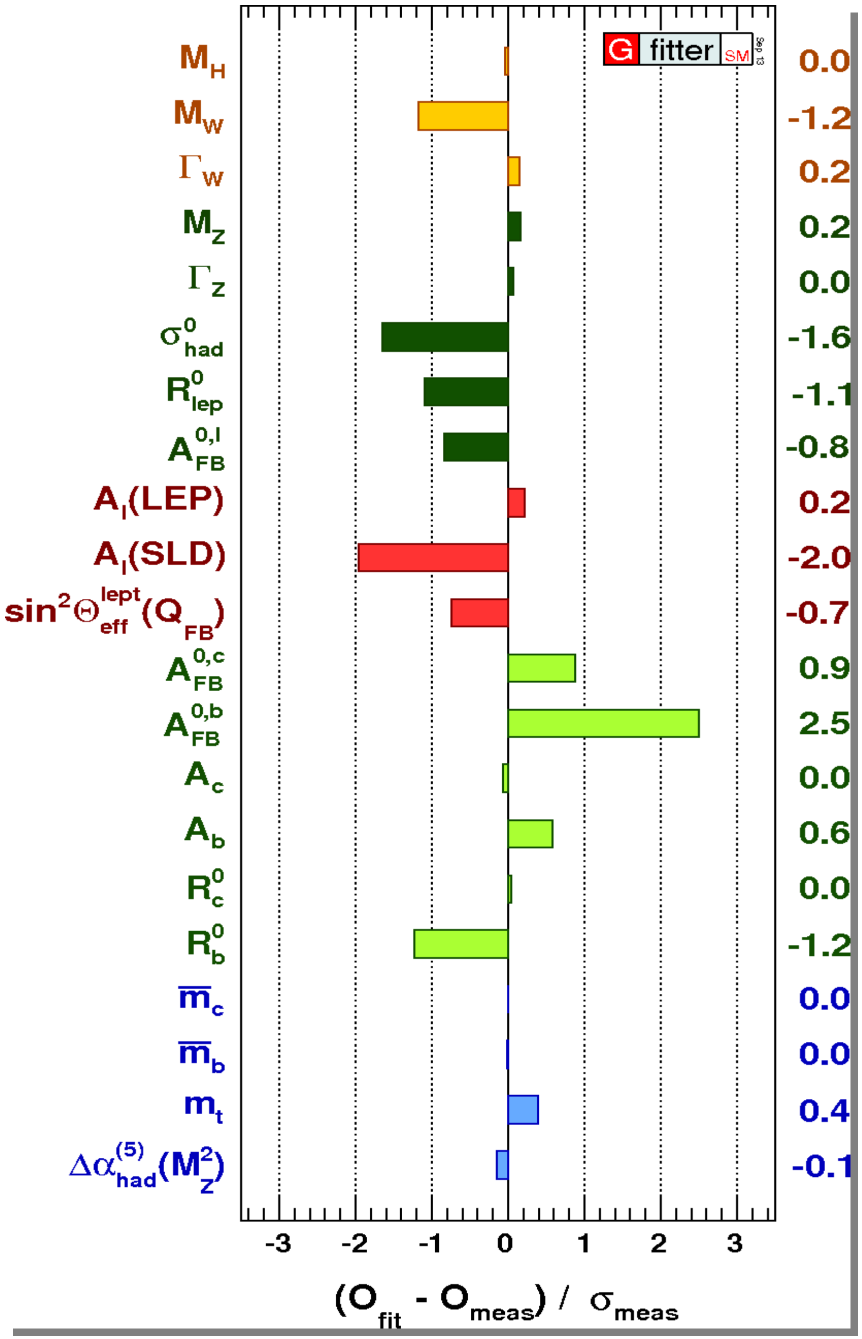
CMS-PAS-EXO-12-059

Dobrescu, Yu, 1306.2629



1305.2756

Z' „indirect“ searches

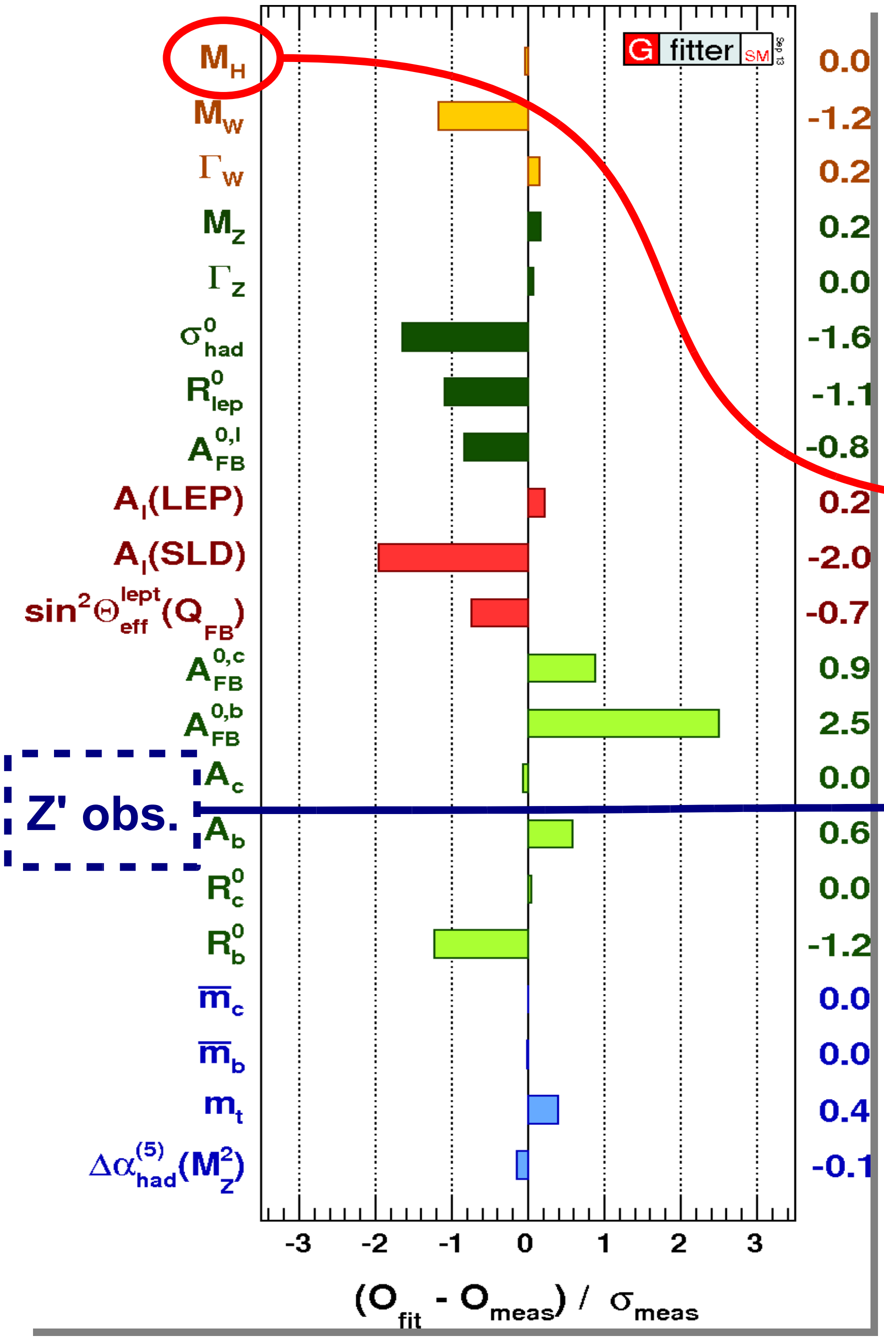


Starting from the 90s, LEP, SLD, Tevatron lead a very successful program of measurement of electroweak precision observables (EWPO).

p-value = 0.21

See also Batell, S.G., L.T.Wang 1209.6382

Z' „indirect" searches



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Last ingredient to complete the SM: the Higgs mass

Is the ew sector of nature now complete?

Room for another ingredient an electro-weakly coupled neutral gauge boson?

p-value = 0.21

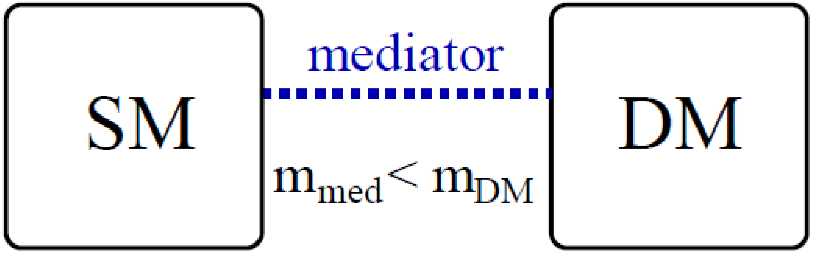
See also Batell, S.G., L.T.Wang 1209.6382

Kinetically mixed Z'

Secluded models for dark matter

Pospelov et.al. 0711.4866
Feldman et al 0702123

Mechanism:


SM

mediator

$m_{med} < m_{DM}$

DM

Suppression of DM direct detection signals,
but still possible to have a thermal DM candidate

The only link between
the SM and the dark sector:

$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta}\hat{B}_{\mu\nu}\hat{Z}_D^{\mu\nu}$$

+ mass term for Z_D
coming from Stueckelberg
mechanism / dark Higgs
that breaks the U(1)' symmetry

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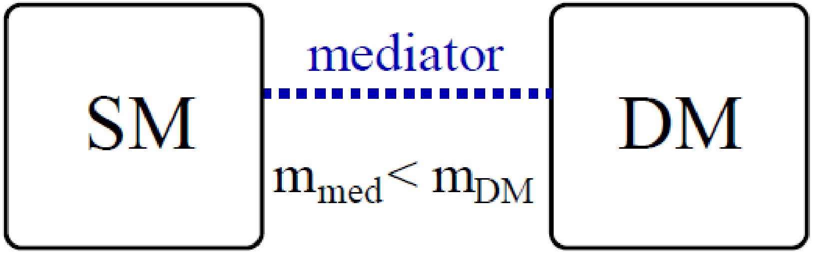

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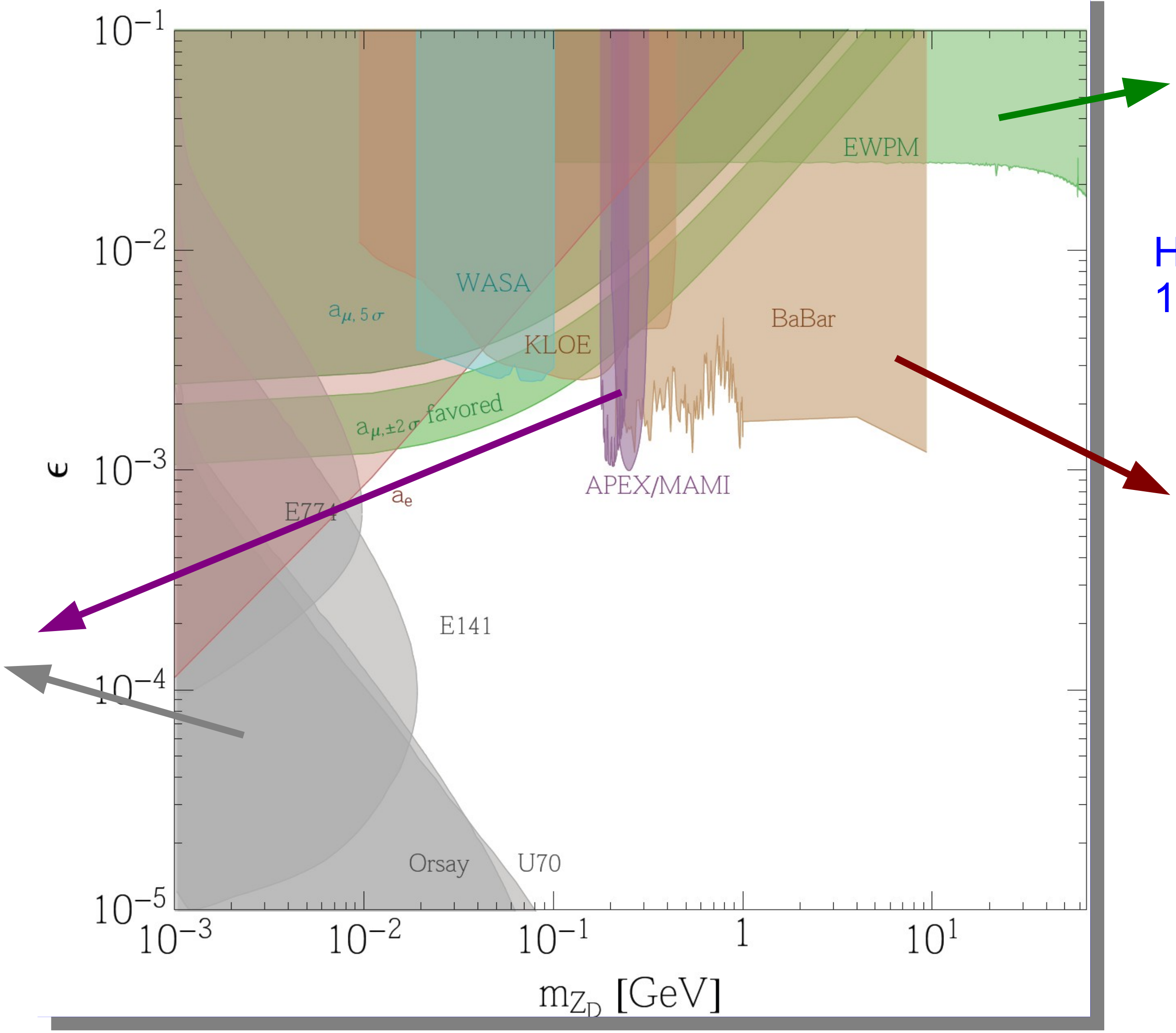
NP effects on the Z boson:

- Tree level shift in the Z mass: $m_Z^2 \sim m_{Z0}^2(1+\epsilon^2\tan^2\theta_W)$
- Modification of the Z couplings $\sim (Zf\bar{f})_{\text{SM}}\left(1+\epsilon^2\frac{\tan^2\theta}{2}\cdot\frac{T_3-Q(1+\cos^2\theta)}{T_3-Q\sin^2\theta}\right)$

How to probe the model

A plethora of probes of the model



Mainly driven by
the tree level
shift in the
Z boson mass

Hook, Izaguirre, Wacker,
1006.0973

$$e^+e^- \to \gamma Z_D$$

Fixed targed
experiments

Curtin, Essig, S.G., Jaiswal, Katz, Liu, Liu, McKeen,
Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992

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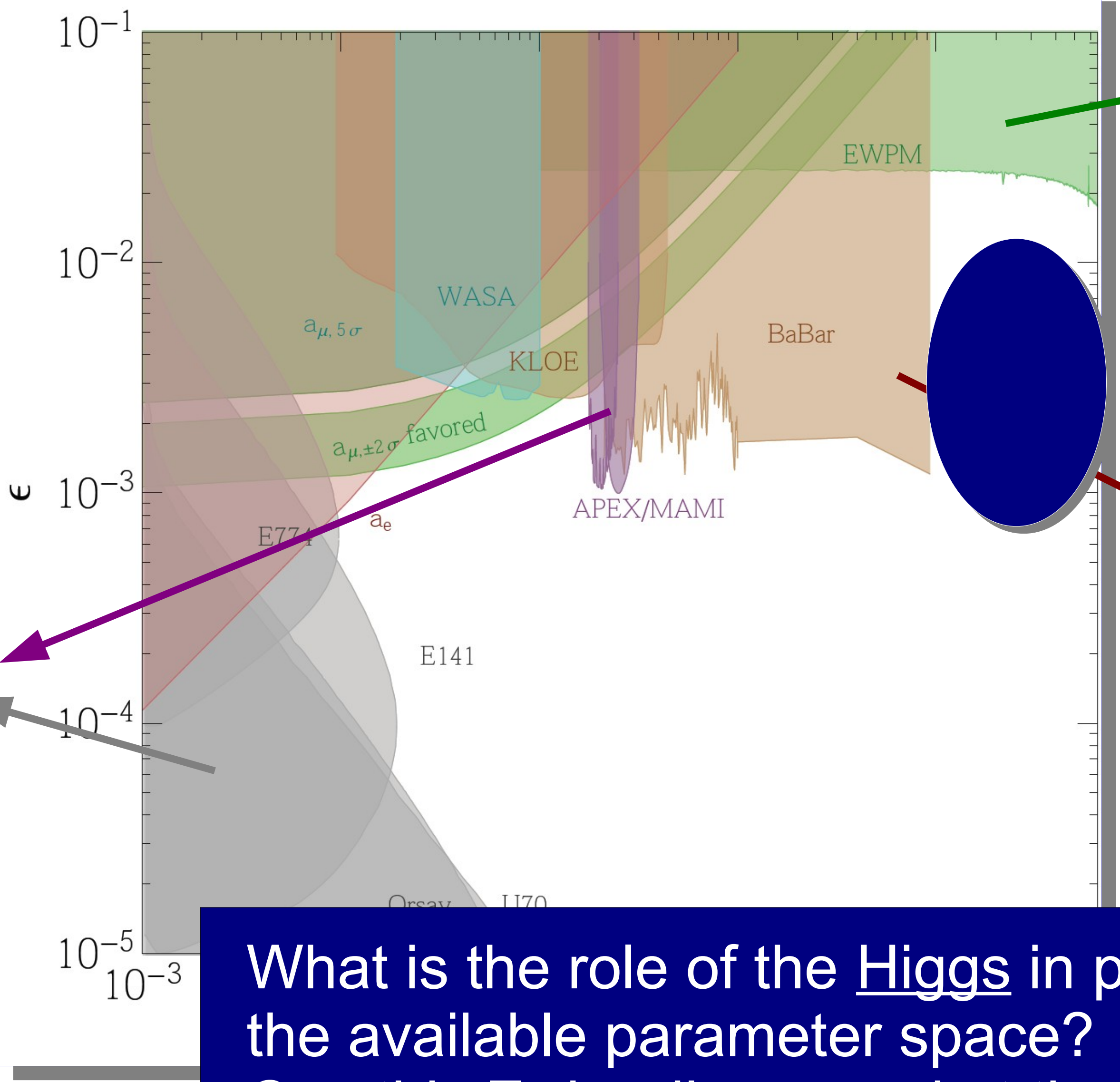

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Hook, Izaguirre, Wacker, 1006.0973

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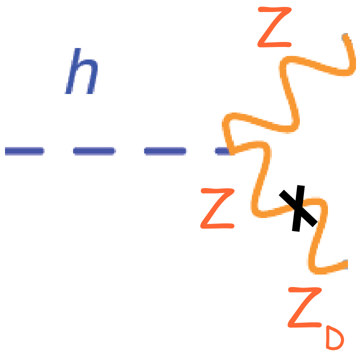
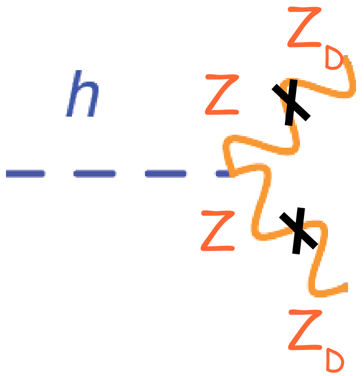
Fixed targed experiments

What is the role of the <u>Higgs</u> in probing the available parameter space?
Can this Z_D be discovered at the <u>LHC</u>?

, McKeen,
Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992

A four lepton Higgs signature





$$hZZ_D \sim 2\epsilon\tan\theta\frac{m_{ZD}^2}{v}$$

$$hZ_DZ_D \sim \epsilon^2\tan^2\theta\frac{m_{ZD}^4}{m_Z^2 v}$$

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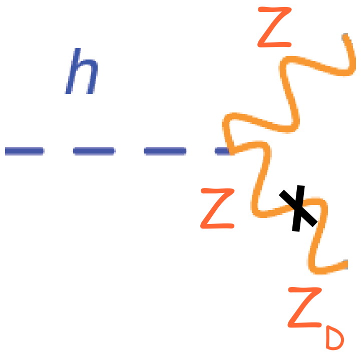

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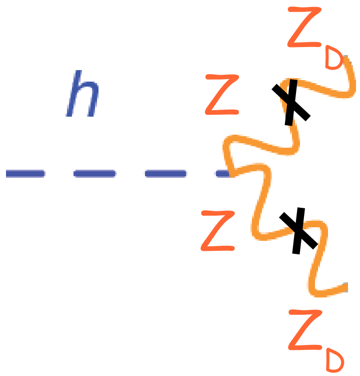

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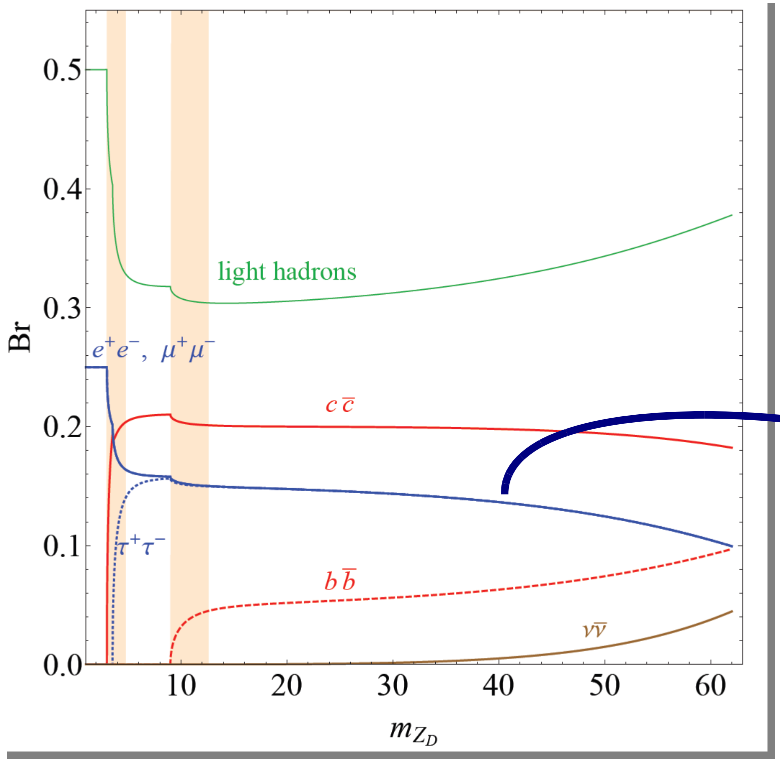


For m_{ZD} > 𝒪(100MeV),
ε > 𝒪(10^{-4}) gives rise to
promptly decaying
dark Z bosons (cτ<1μm)

Sizable branching ratio into two leptons

➡ Higgs four lepton signature!

Curtin, Essig, S.G., Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992

Higgs width: direct measurement

CMS PAS HIG-14-002

F. Caola, K. Melnikov (1307.4935)
J. Campbell et al. (1311.3589)

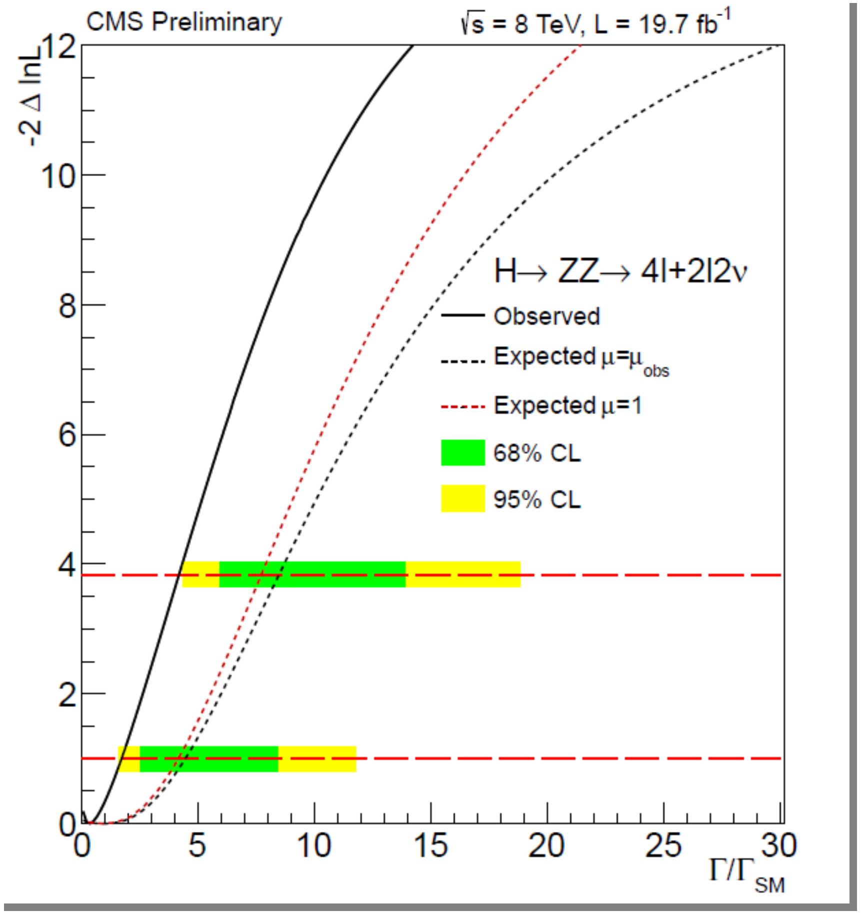
Very interesting new CMS measurement

In a nutshell:

$$\left\{\begin{array}{l} \sigma^{\rm on-peak}_{gg\to H\to ZZ} = \dfrac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot {\rm BR})_{\rm SM} \equiv \boxed{\mu}(\sigma\cdot {\rm BR})_{\rm SM} \\[2ex] \dfrac{\sigma^{\rm off-peak}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa_g^2\kappa_Z^2\dfrac{\sigma^{\rm off-peak,\,SM}_{gg\to H\to ZZ}}{dm_{ZZ}} \equiv \boxed{\mu r}\dfrac{\sigma^{\rm off-peak,\,SM}_{gg\to H\to ZZ}}{dm_{ZZ}} \end{array}\right.$$

$$\begin{aligned} \kappa_g &= g_{ggH}/g^{\rm SM}_{ggH} \\ \kappa_Z &= g_{HZZ}/g^{\rm SM}_{HZZ} \\ r &= \Gamma_H/\Gamma^{\rm SM}_H \end{aligned}$$

$$\boxed{\Gamma_H < 4.2(8.5)\,\Gamma_{H,\rm SM}}$$

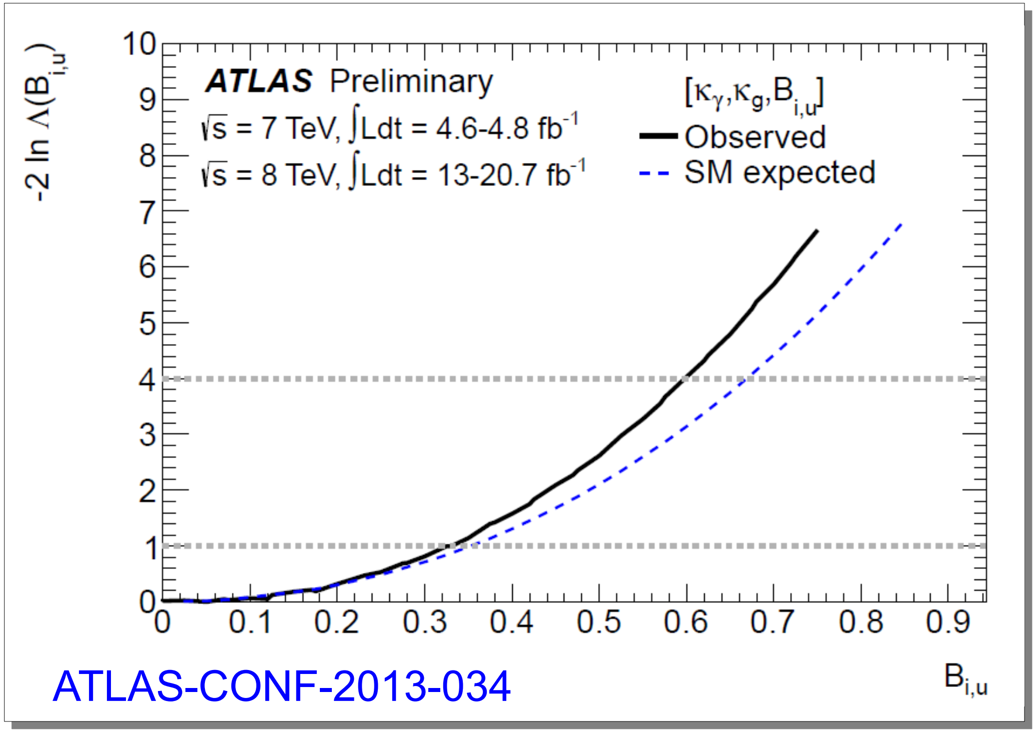


Combining the 4l and the 2l2v channels

Higgs width: indirect measurement

Constraint from the fit of the SM Higgs couplings

NOW



ATLAS-CONF-2013-034

$$\mathrm{BR}(h \to \mathrm{inv,\ undet}) \lesssim 60\% \quad @\, 95\%\ \mathrm{C.L.}$$

The exact value depends on the fit.
Still typically values below (20-30)%
are uncostrained

Assumptions going into this fit:
Only NP effects modifying

1. the coupling of the Higgs to photons (k_γ)
2. the coupling of the Higgs to gluons (k_g)
3. the total width of the Higgs

Higgs width: indirect measurement

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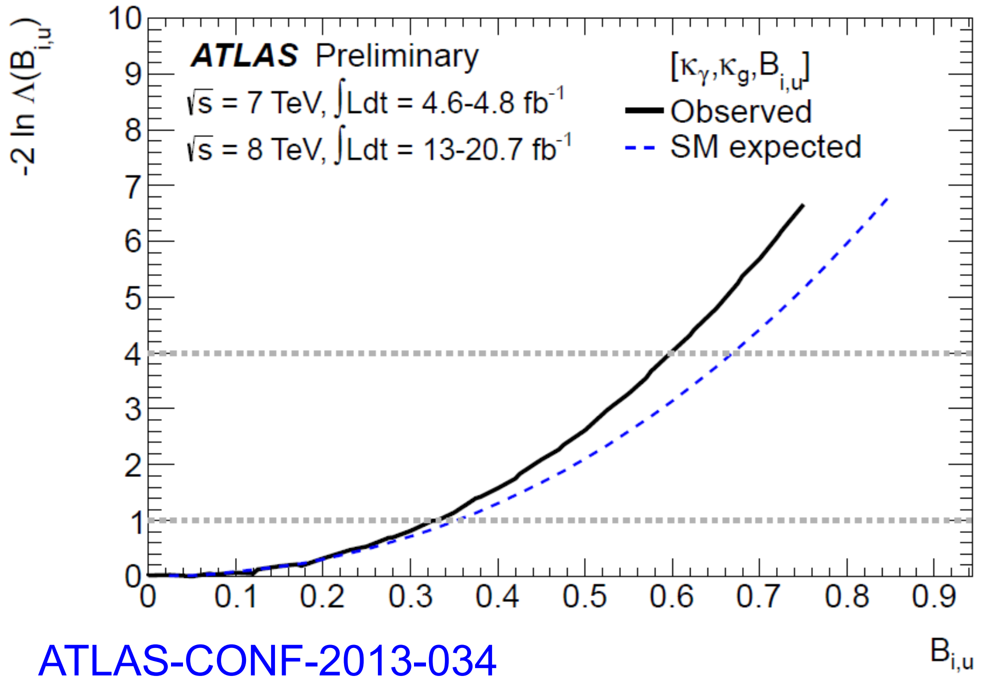

ATLAS-CONF-2013-034

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FUTURE

With 300fb^{-1} LHC data, the expected bound on the „extra width“ is at the level of ~10%

See e.g. Peskin, 1207.2516

Higgs width: indirect measurement

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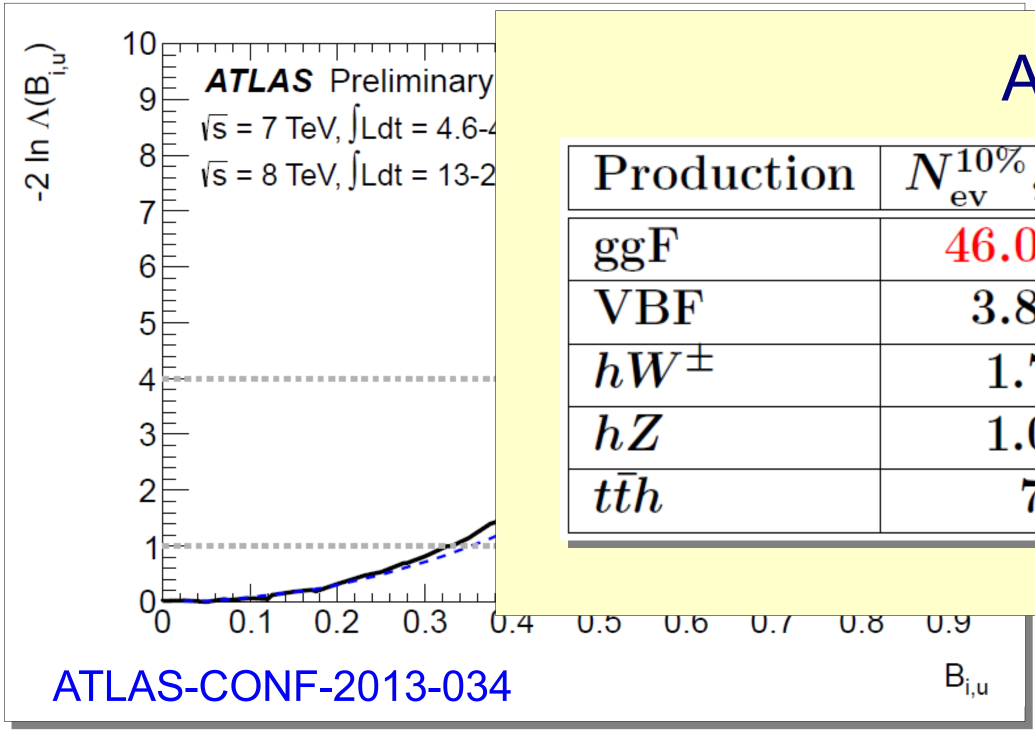

ATLAS-CONF-2013-034

A lot of events!

Production	$N_{ev}^{10\%}$, Now (14 TeV)
ggF	46.000 (1500.000)
VBF	3.800 (125.000)
$hW^\pm$	1.700 (45.000)
hZ	1.000 (27.000)
$t\bar{t}h$	70 (18.000)

Leptonic W,Z

→ ~360 (9500)

→ ~70 (1900)

ns (k_γ)

s (k_g)

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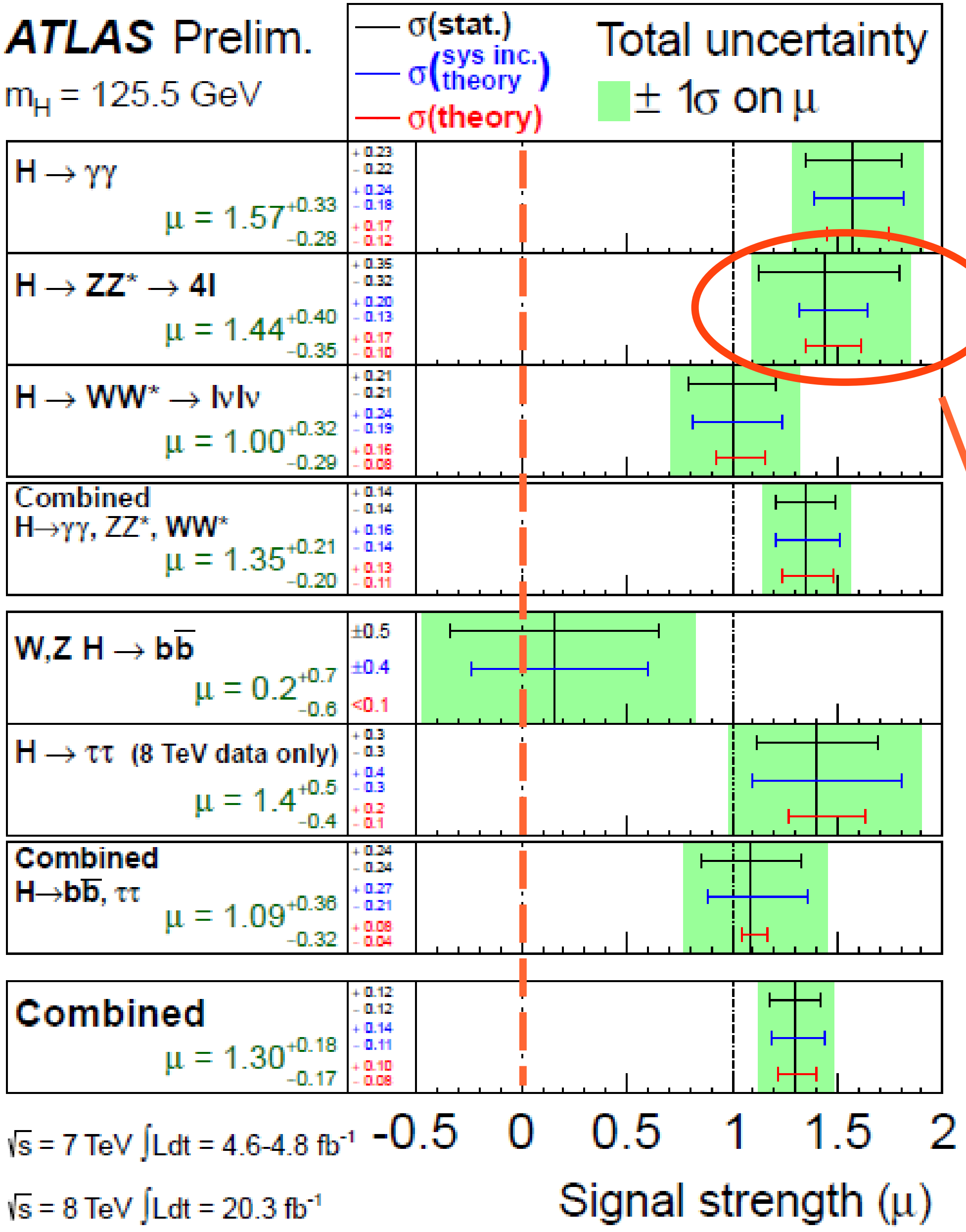
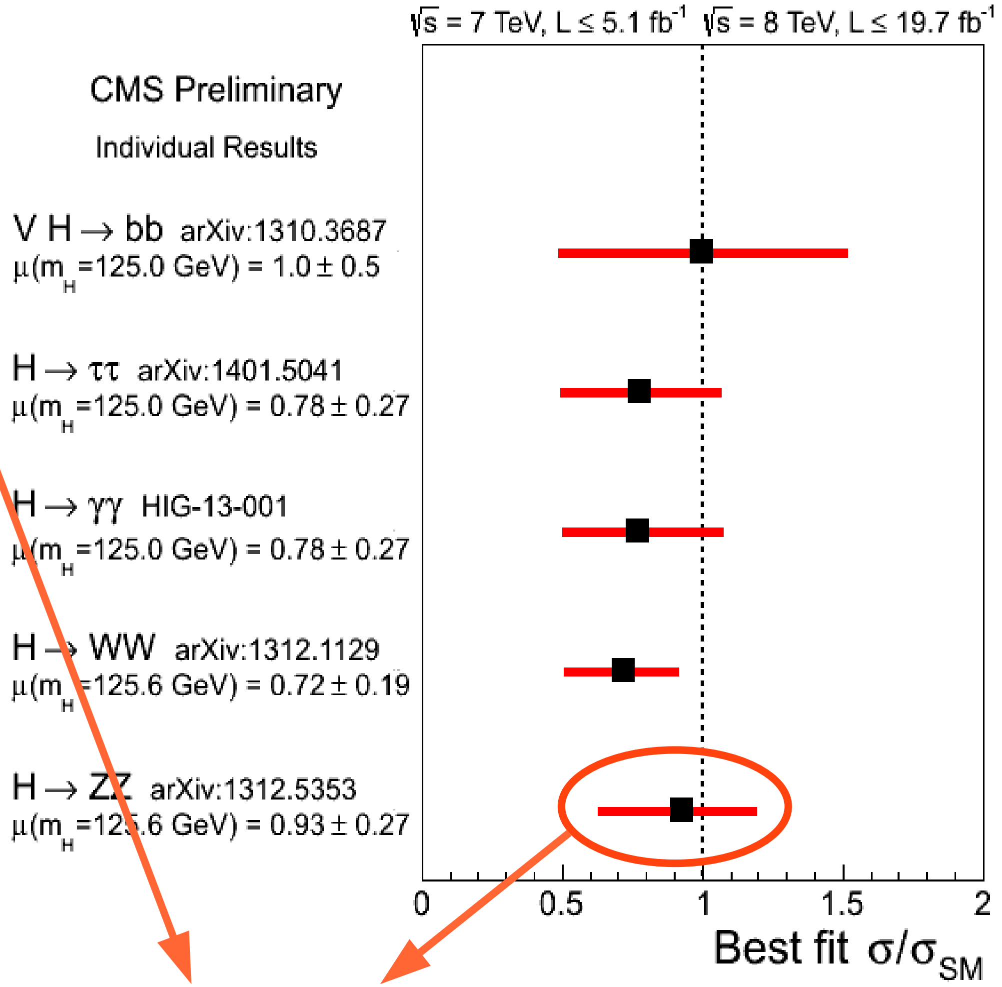
Importance of the ZZ channel

ATLAS-CONF-2014-009



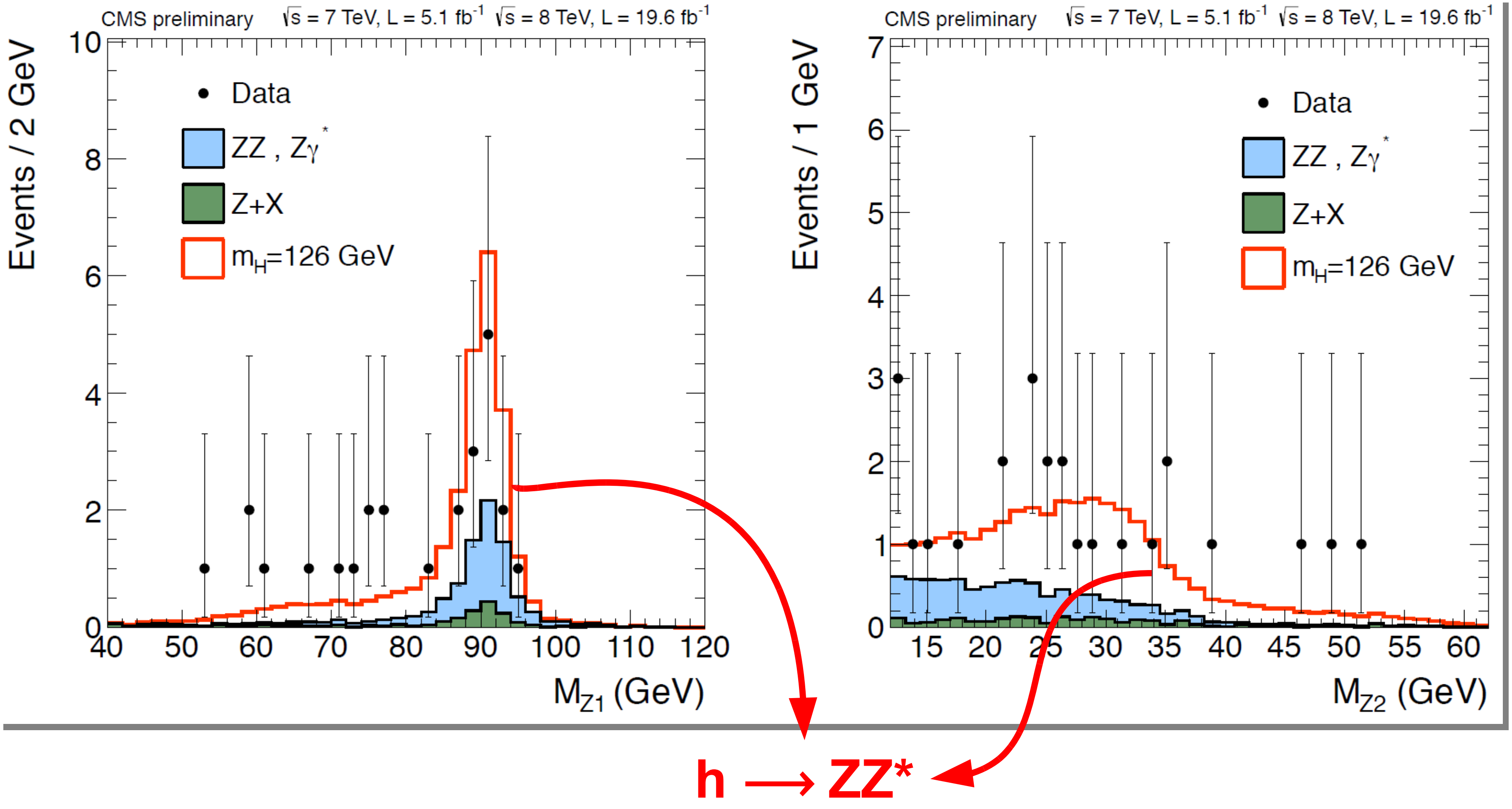


6.6 σ significance @ ATLAS
6.8 σ significance @ CMS

LHC measurement of Higgs to four leptons

Latest results with the full (7+8) TeV LHC dataset:
CMS PAS HIG-13-002, ATLAS-CONF-2013-013

The four leptons are divided in 2 SFOS pairs:
the leading pair „Z1“ and the subleading pair „Z2“



$h \to ZZ^*$

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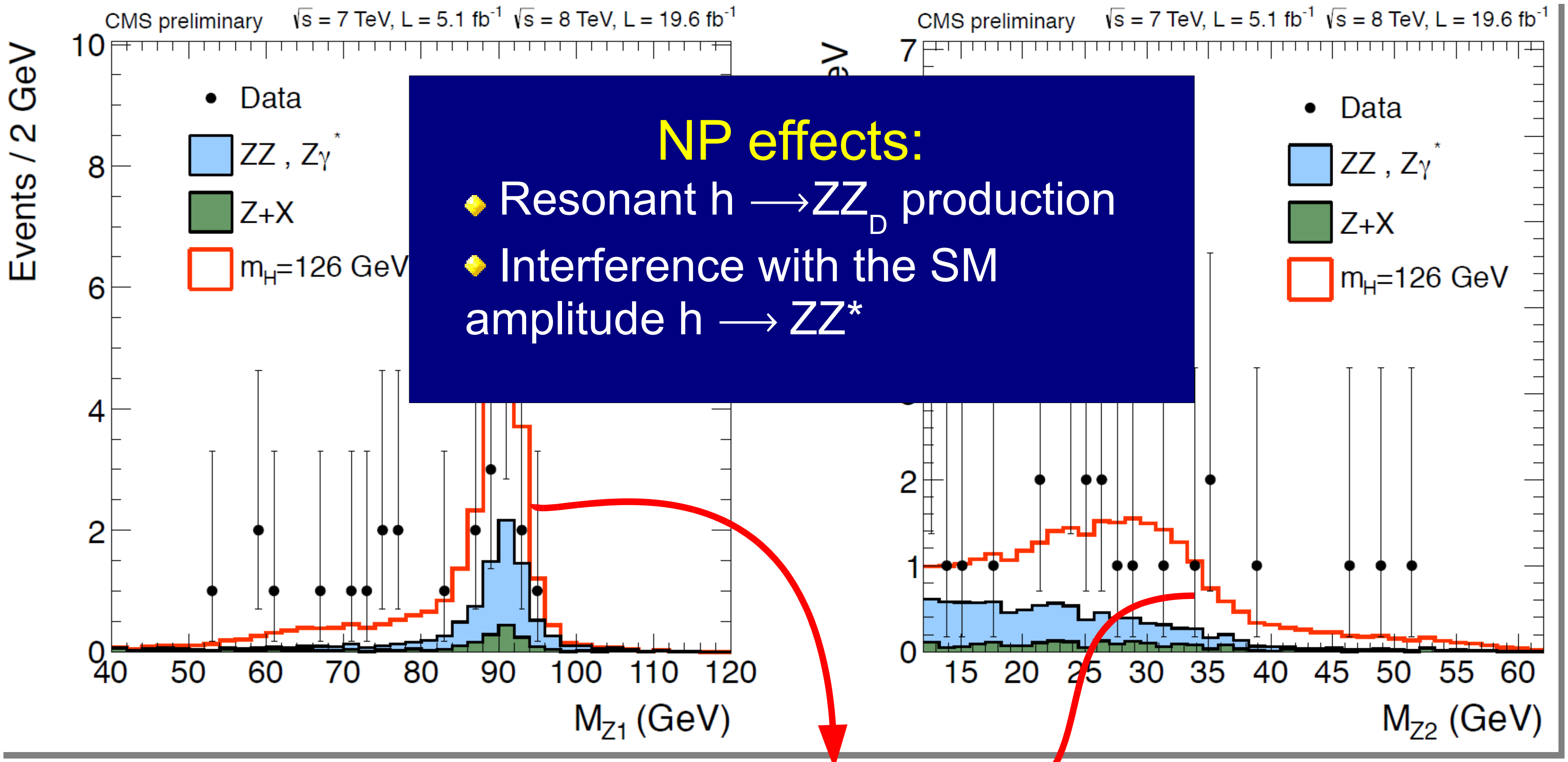


NP effects:

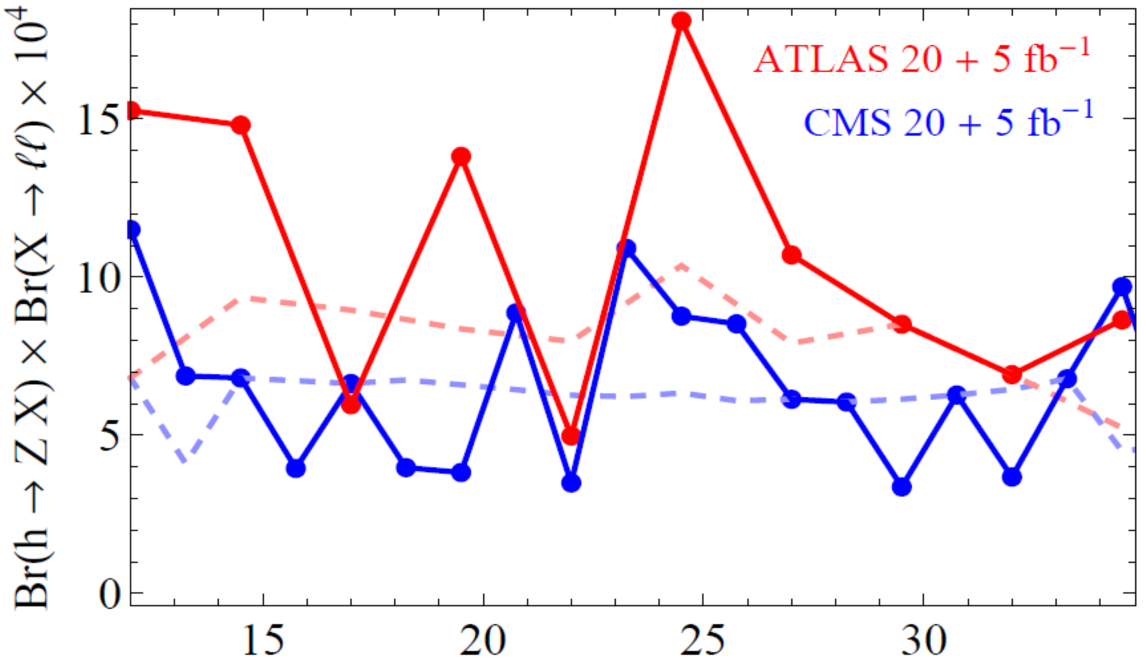
- Resonant $h \longrightarrow ZZ_D$ production
- Interference with the SM amplitude $h \longrightarrow ZZ^*$

$h \longrightarrow ZZ^*$

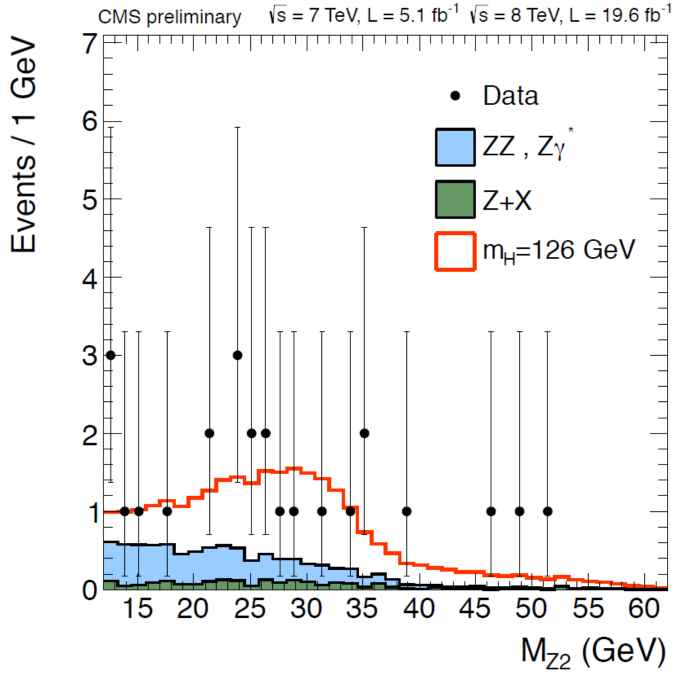
Bound on the resonant ZZ_D production (1)

Assuming the same efficiency as for events genuinely coming from h⟶ZZ*

Counting experiment:



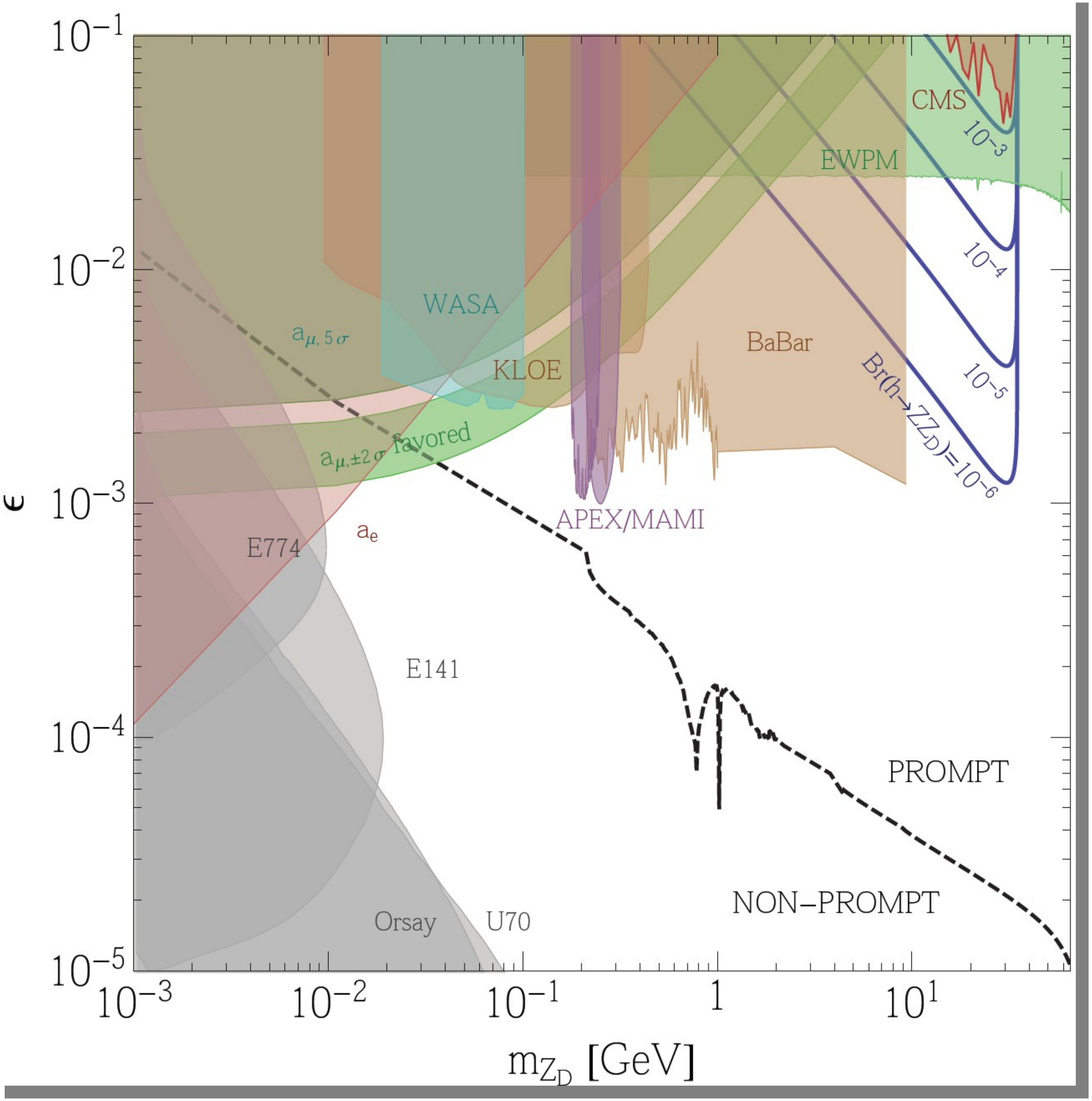
$m_{Z2} \longrightarrow m_{ZD}$



$BR(h \longrightarrow ZZ_D) \sim 10^{-3}$ are already probed with the present (un-dedicated) 7+8 TeV LHC searches

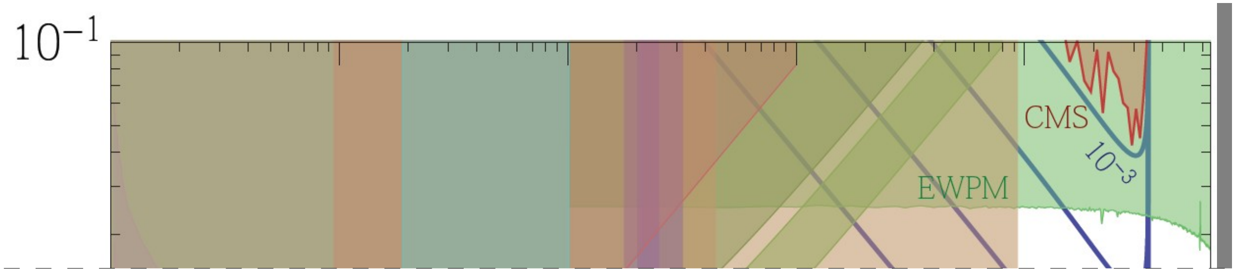
Given the ≤3% dilepton mass resolution and the CMS binning of 1.25 GeV

Bound on the resonant ZZ_D production (2)



The Higgs bound is already approaching the bound coming from ~20 years of EWPTs!

Future: EWPTs vs Higgs to four leptons



D.Curtin, R.Essig, S.G., J.Shelton, in preparation

- EW precision measurements will improve:

	Present	Tevatron full dataset	LHC14, 300 fb^{-1}	LHC14, 3000 fb^{-1}
ΔM_W (MeV)	15	9	8	5

	Present	LHC14, 300 fb^{-1}
ΔM_H (GeV)	0.4	0.1

We do not expect a significantly stronger bound from EWPTs

- What about LHC h⟶ZZ$_D$ dedicated searches?

And in particular what about the shape of the two invariant mass distributions in the case of off-shell Z$_D$? (interference effects with h⟶ZZ*)

Dedicated searches at LHC14 can improve the bound on the branching ratio by more than 1order of magnitude
Davoudiasl et al.1304.4935

A anomaly free
L_μ-L_τ gauge symmetry

A gauge symmetry for neutrino physics

L_μ-L_τ is one of the few anomaly free gauge groups.
Arbitrary linear combinations of Y and B-L, with $L=L_e+L_\mu+L_\tau$
(not necessarily family independent)

- The associated Z' couples directly with muons → $(g\text{-}2)_\mu$

- Neutrino model building:
  - Before breaking the gauge symmetry:

$$\begin{cases} \Theta_{23} = \text{maximal},\ \Theta_{13} = \Theta_{12} = 0 \\ \text{Two neutrino are degenerate in mass. The third one is split in mass} \end{cases}$$

  - In seesaw models, breaking the gauge symmetry with a additional scalar induces corrections

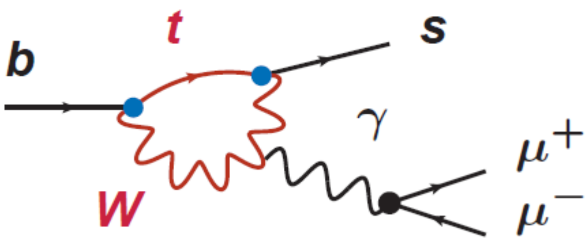
$$\begin{cases} \sin\theta_{13} = \mathcal{O}\left(\frac{\langle S\rangle}{M_N}\right) \\ \sin\theta_{23} = \frac{1}{\sqrt{2}} + \mathcal{O}\left(\frac{\langle S\rangle^2}{M_N^2}\right) \end{cases}$$

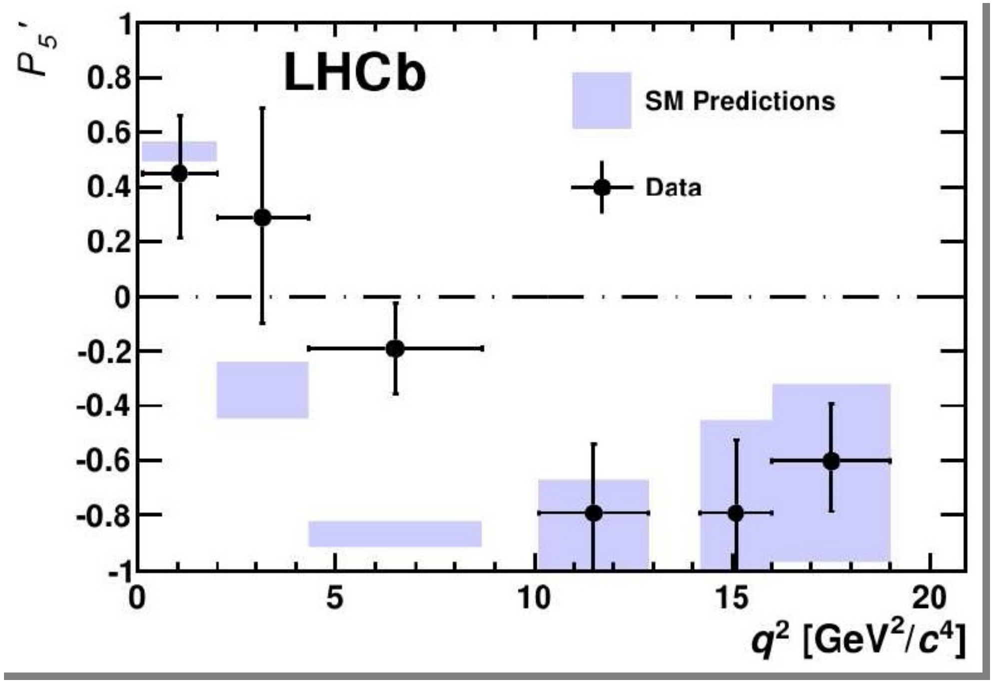
See e.g.
Heeck, Rodejohann, 1107.5238

The two degenerate neutrinos acquire a split proportional to $\frac{\langle S\rangle^2}{M_N^2}$

LHCb measurement of B⟶K*μμ

Latest $B \to K^*$μμ results from LHCb (with 1fb^{-1})
1308.1707





3.7 σ discrepancy

in the 4.3 GeV^2< q^2 < 8.68 GeV^2 bin, with respect to the SM

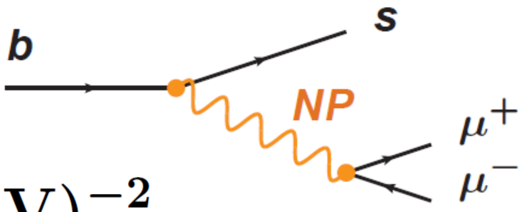
- Statistical fluctuation? (full data set probably this summer)
- Underestimated SM uncertainties? (see Jager et al. 1212.2263)
- New Physics?

Flavor structure of the L_μ-L_τ gauge theory(1)

Considering constraints from

$B_s \to \mu\mu$, $b \to s\gamma$, $B \to K\mu\mu$ and from the other observables in $B \to K^*\mu\mu$,

the best fit arises for



$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma^\alpha P_{L(R)} b)(\bar{\mu}\gamma_\alpha \mu), \;\; \mathrm{Re}(C_9^{(\prime)}) \sim \mp(35\,\mathrm{TeV})^{-2}$$

Vector coupling with muons

Axial-vector coupling with quarks

Altmannshofer, Straub, 1308.1501

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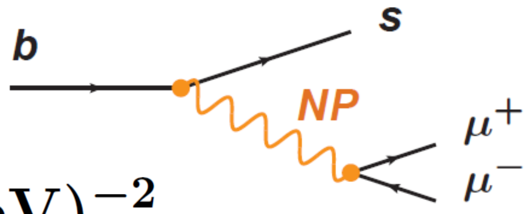

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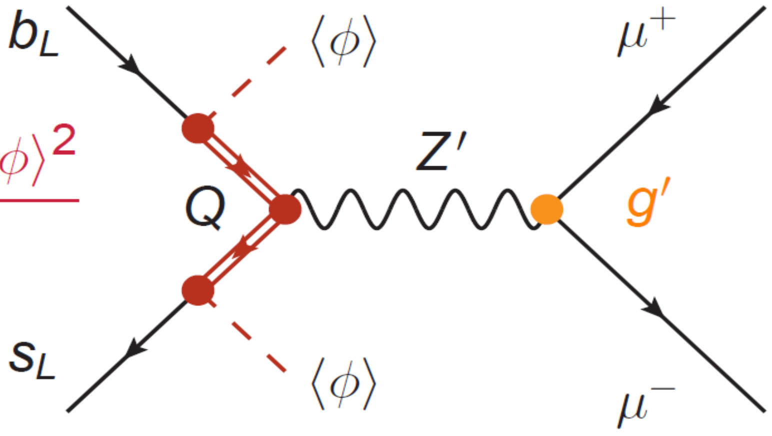
Vector coupling with muons

Axial-vector coupling with quarks

Altmannshofer, Straub, 1308.1501

Couple the Z' to quarks only indirectly, by mixing with
heavy vector-like fermions charged under $U(1)'$ e.g. Fox, Liu, Tucker-Smith, Weiner 1104.4127

$$\frac{g' Y_{Qb} Y^*_{Qs} \langle\phi\rangle^2}{2m_Q^2}$$



NP effect independent of the
Z' mass and gauge coupling

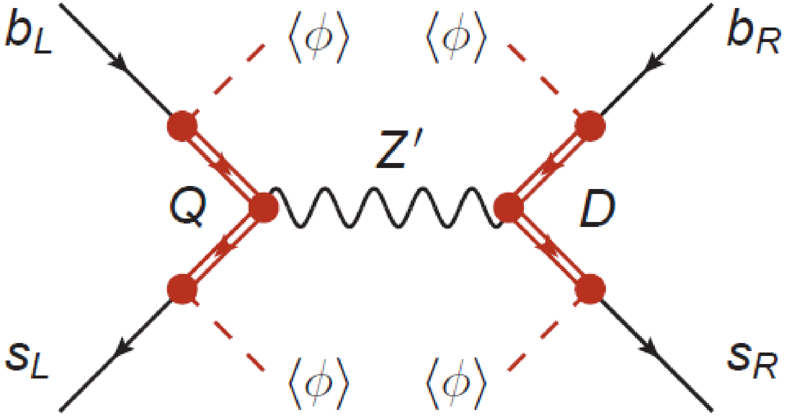
$$C_9 \sim \frac{Y_{Qb} Y^*_{Qs}}{2m_Q^2}, \quad C'_9 \sim -\frac{Y_{Db} Y^*_{Ds}}{2m_D^2}$$

Altmannshofer, S.G.,
Pospelov, Yavin, 1403.1269

Flavor structure of the L_μ-L_τ gauge theory(2)

Altmannshofer, S.G.,
Pospelov, Yavin, 1403.1269

The Z' leads also to contributions to B_s meson mixing



$$M_{12}^s \propto (\mathbf{Y}_{Qb}\mathbf{Y}_{Qs}^*)(\mathbf{Y}_{Db}\mathbf{Y}_{Ds}^*)\frac{v_\phi^2}{m_Q^2 m_D^2}$$

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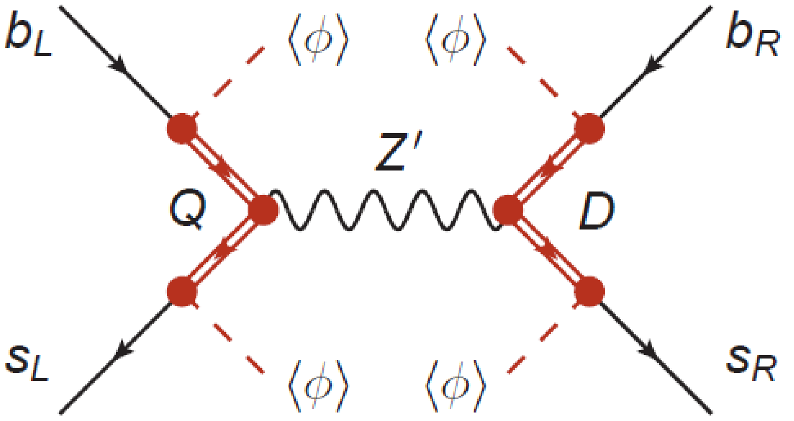

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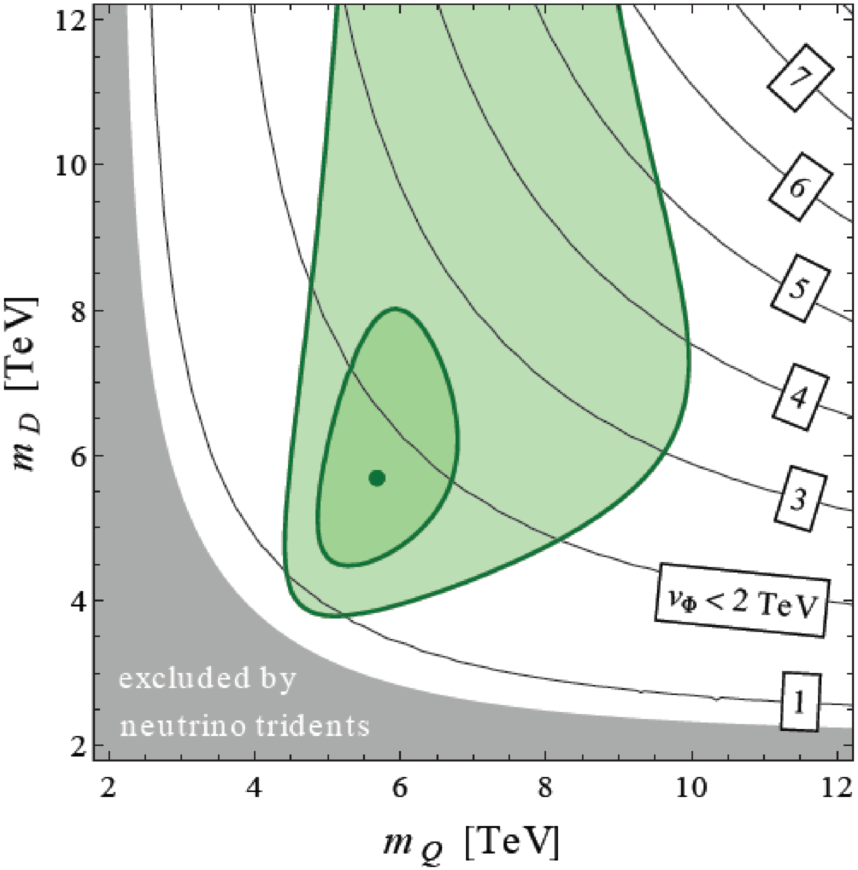
Same parameter dependence as in B → K*μμ

To fit the central value of B → K*μμ, one needs $v_\phi \lesssim 1.8\,\text{TeV}$

→ **Light Z', $m_{Z'} = g' v_\phi$**

Altmannshofer, S.G., Pospelov, Yavin, 1403.1269

$\mathrm{Re}(Y_{Db}Y_{Ds}^*) = \mathrm{Re}(Y_{Qb}Y_{Qs}^*) = \lambda^2$



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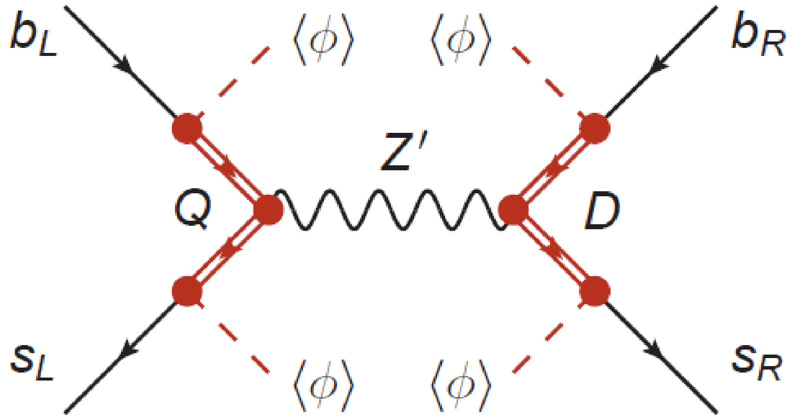

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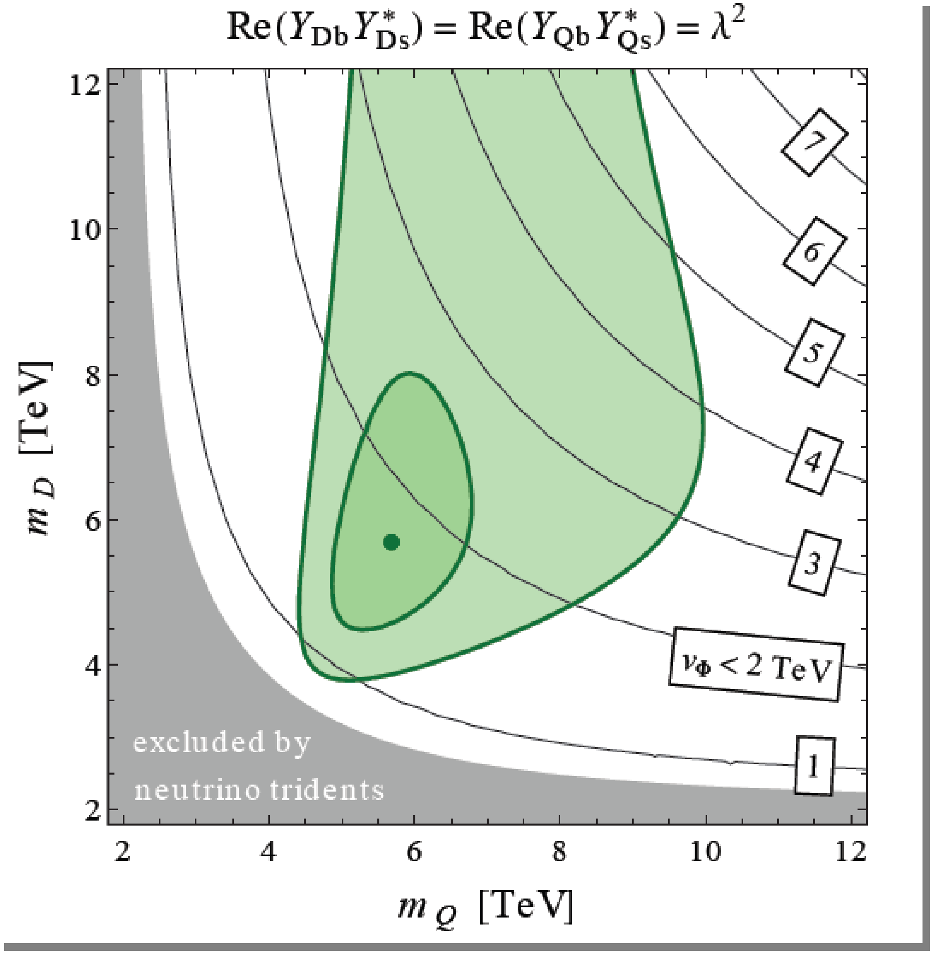
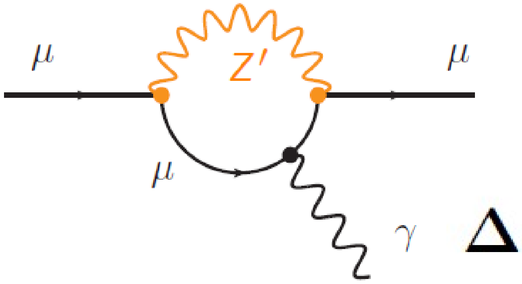


Note:

Kaon mixing strongly constrains the couplings to first generation quarks tiny Z' production at the LHC!

Probing Z' through its couplings to leptons

1. Anomalous magnetic moment of the muon

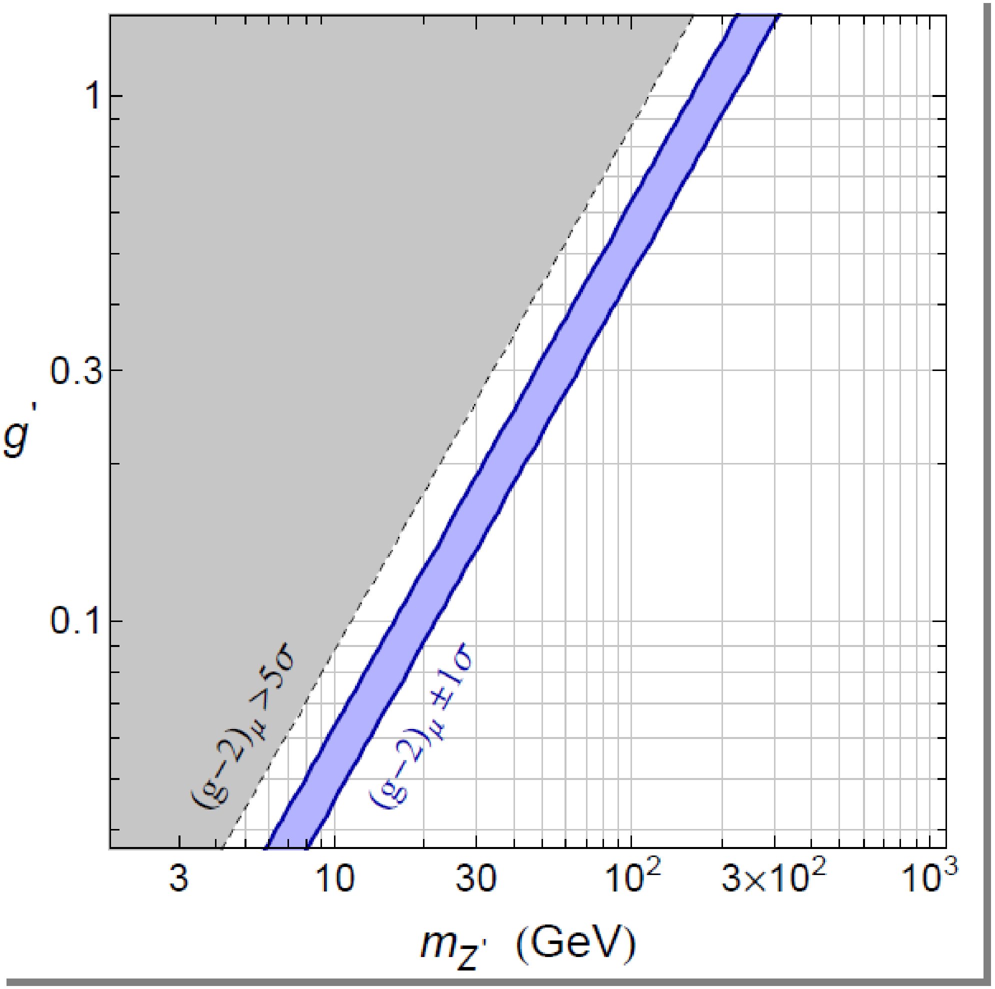


$$\Delta a_\mu \simeq \frac{1}{12\pi^2}\frac{m_\mu^2}{v_\phi^2}$$

To reach the central value of the measurement:

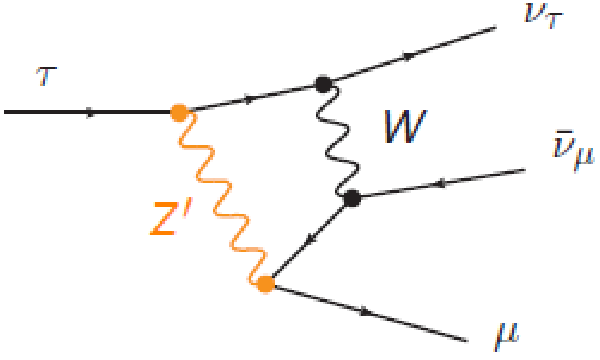
$$\Delta a_\mu = (2.9 \pm 0.9) \times 10^{-9}$$

$$v_\phi \simeq 180\,\mathrm{GeV}$$



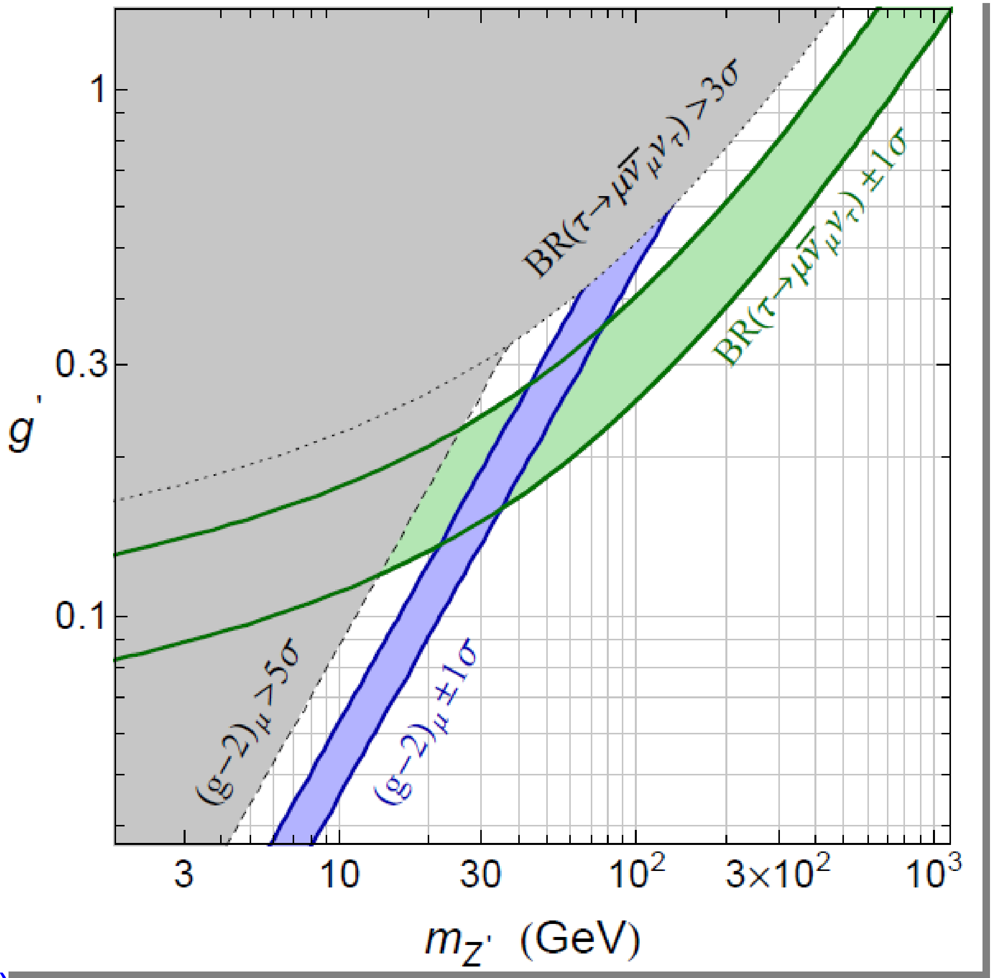
Probing Z' through its couplings to leptons

2.Tau decays



$$\frac{\mathrm{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}{\mathrm{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)_{\mathrm{SM}}} \simeq 1 + \Delta$$

$$\Delta = \frac{3(g')^2}{4\pi^2}\,\frac{\log(m_W^2/m_{Z'}^2)}{1 - m_{Z'}^2/m_W^2}$$



Combining the SM prediction (Pich 1310.7922)
with exp. measurement (PDG + Belle 1310.8503)

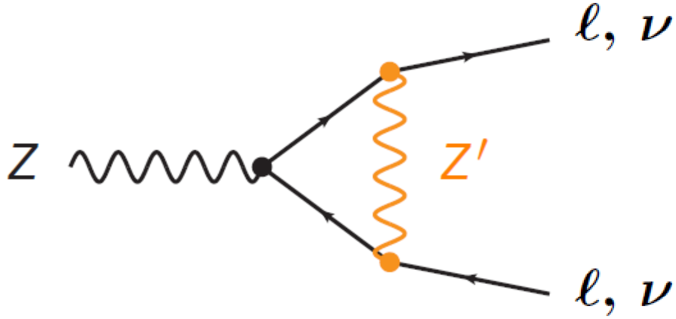
$$\Delta = (7.0 \pm 3.0) \times 10^{-3}$$

New more precise measurement
of the τ life time

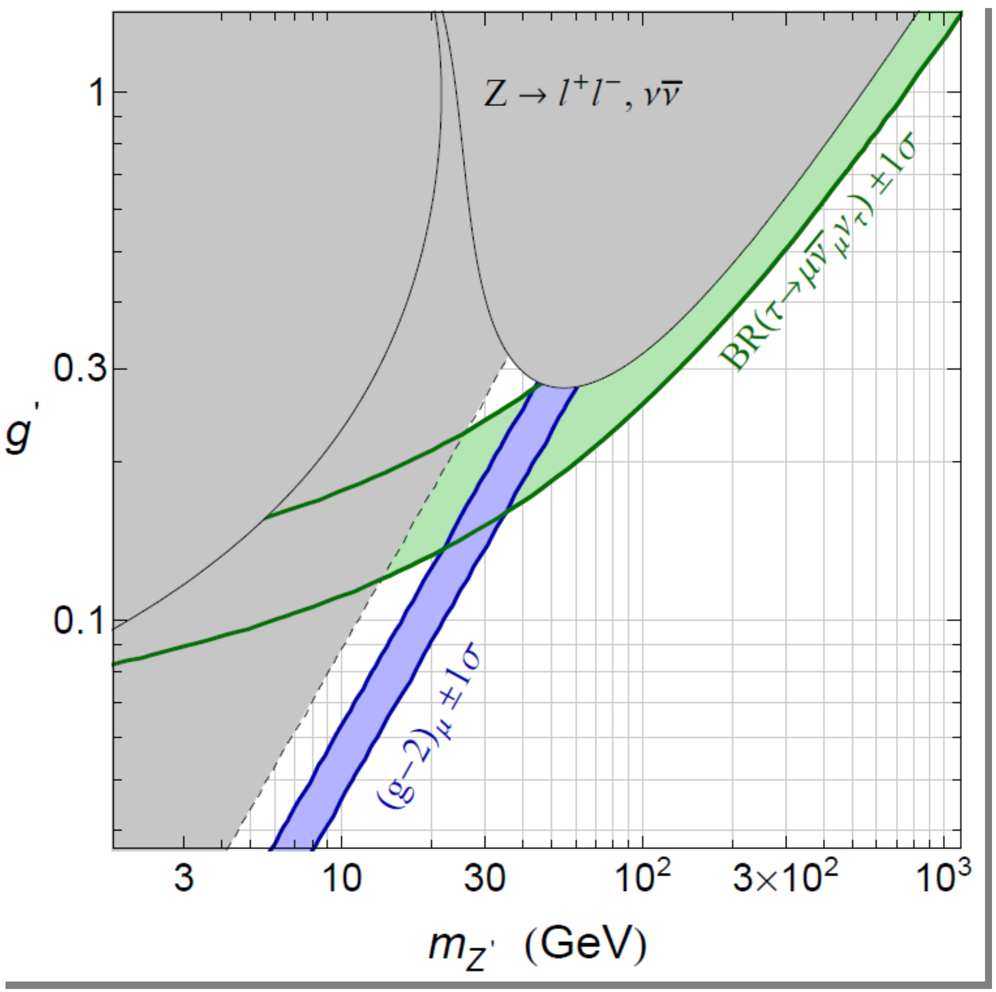
Probing Z' through its couplings to leptons

3.EW precision measurements

Modifications of the Z couplings to muons, taus and neutrinos

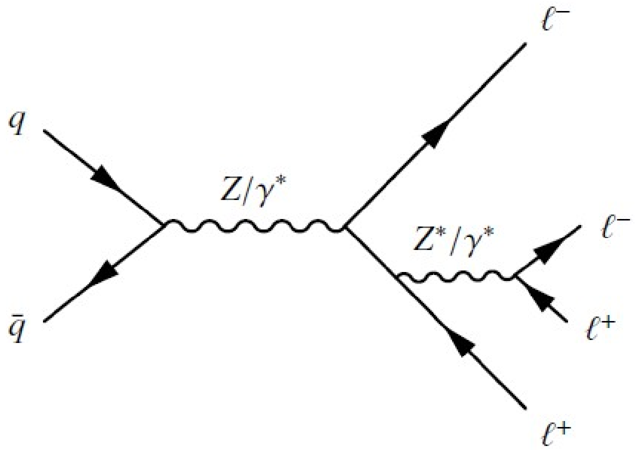


Axial vector couplings with muons and taus are measured at the 0.1% level at LEPII!



Probing Z' through its couplings to leptons

4. Measurement of the Z decaying into four leptons



In the SM:

The branching ratio in the phase space M_{ll}> 4GeV and 76GeV< M_{4l}< 106GeV is given by

$BR(Z\longrightarrow 4l)_{SM}=(4.37\pm 0.03)\times 10^{-6}$

To be compared to the measured value

$BR(Z\longrightarrow 4l)_{exp}=(4.2\pm 0.4)\times 10^{-6}$

ATLAS (CONF-2013-055),
see also CMS (1210.3844)

Probing Z' through its couplings to leptons

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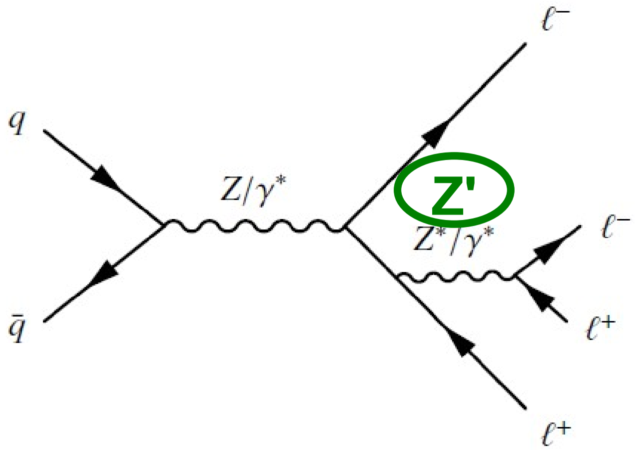

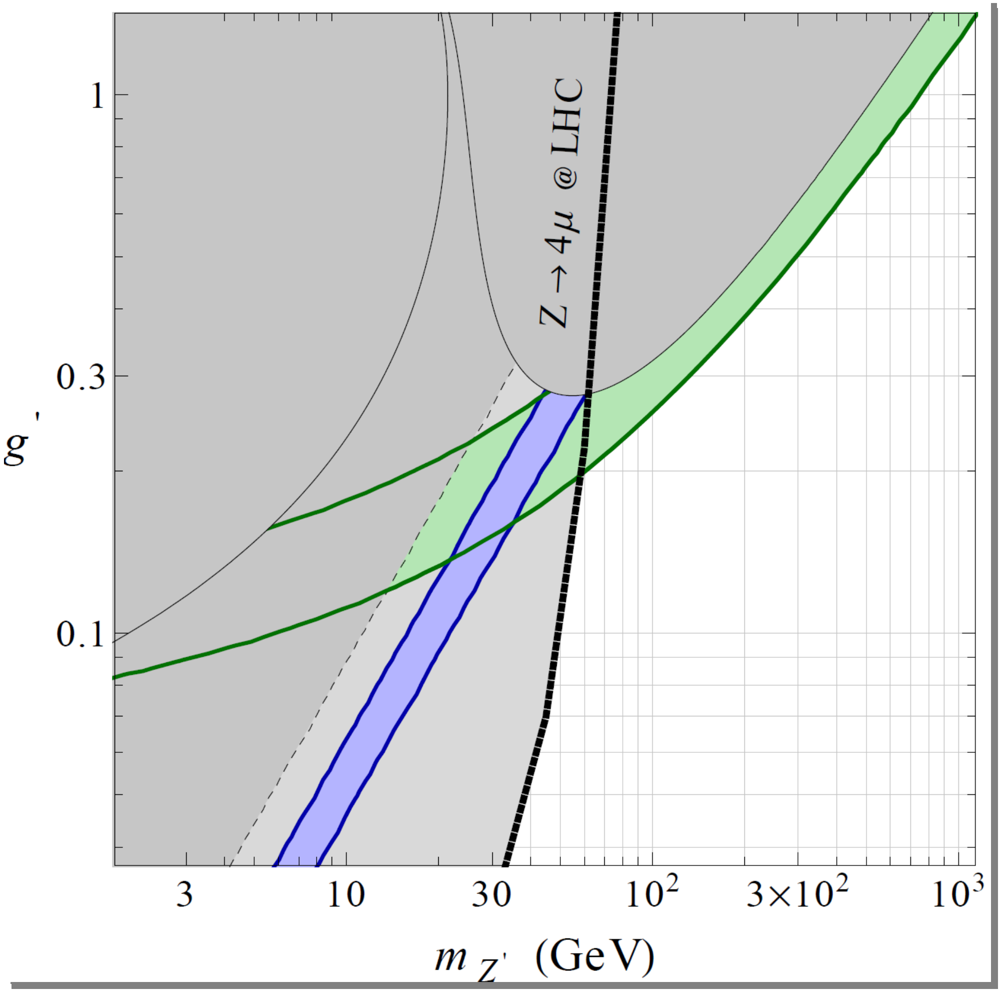

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Our Z' contribute to the four muon bin: 78 events expected and 77 observed

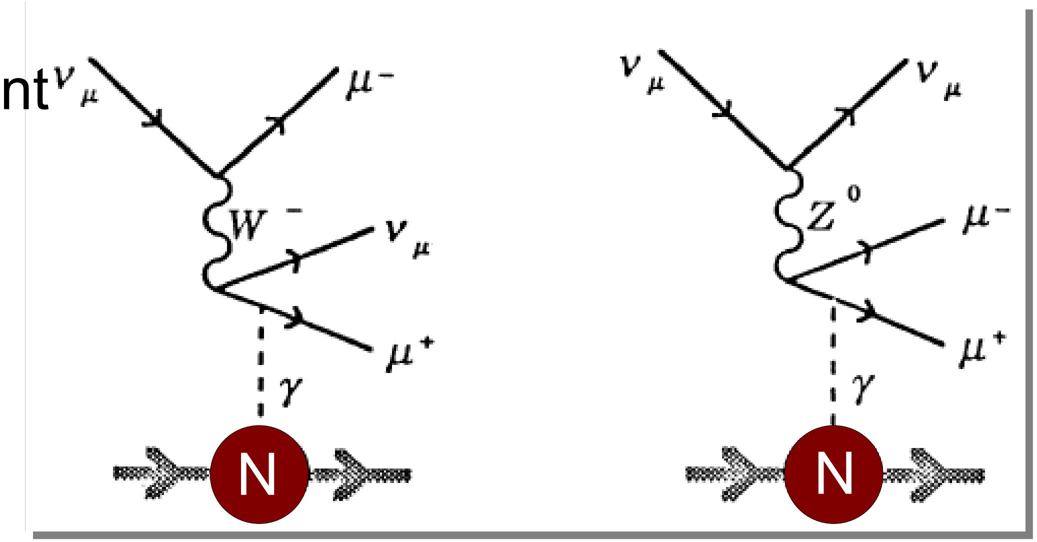
Z' @ neutrino experiments

Neutrino trident muon pair production

- First observed by CHARMII experiment at CERN (55±16 events)

(CERN-EP/90-75)

~20 GeV of neutrino/antineutrino mean energy



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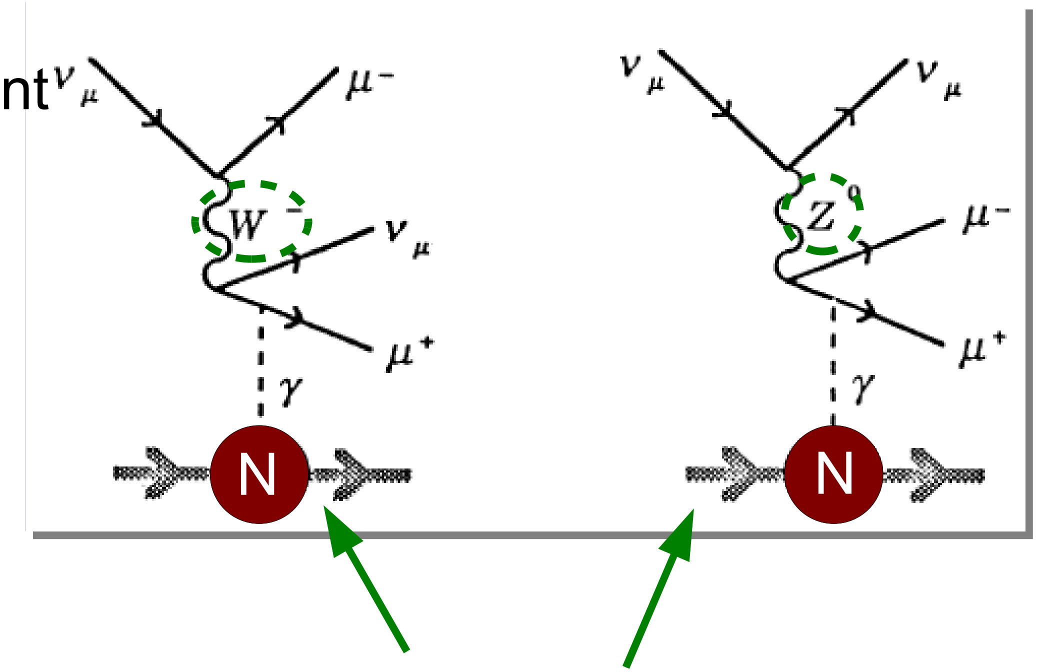

SM prediction is ~60% W contribution

- Later confirmed by the CCFR (Columbia, Chicago, Fermilab, Rochester) experiment at Fermilab (Phys.Rev.Lett. 66, 3117)

~160 GeV of neutrino/antineutrino mean energy

First demonstration of the W-Z destructive interference

Data	SM	Only W
37.0 ± 12.4	45.3 ± 2.3	78.1 ± 3.9

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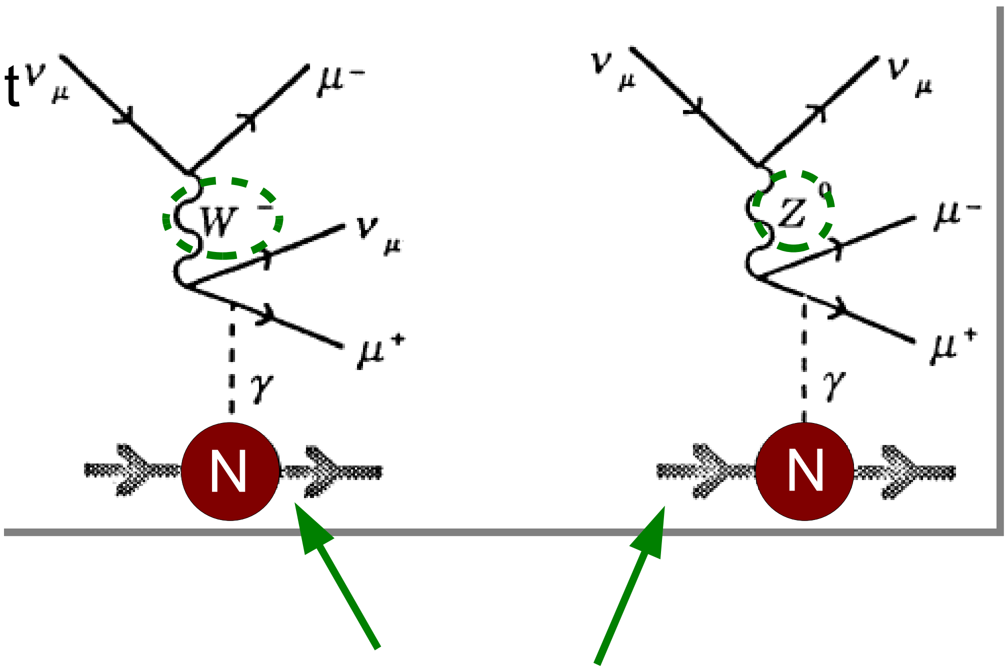

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First demonstration of the W-Z destructive interference

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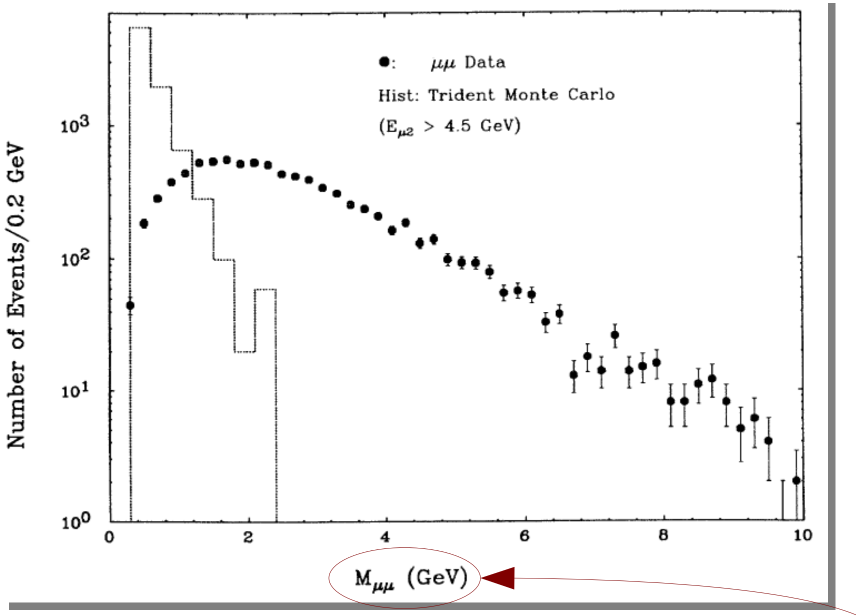
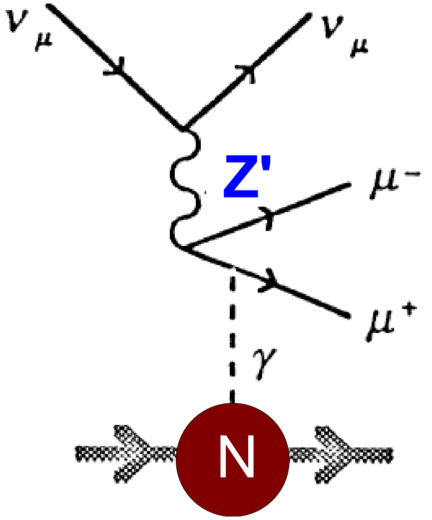
Difficult measurement since small cross section:
~5 orders of magnitude smaller than the inclusive neutrino-nucleus cross section



Main discriminant with respect to the charm background

$$\nu + (d,s) \to \mu^- + c$$

A powerful probe of Z' interactions (1)



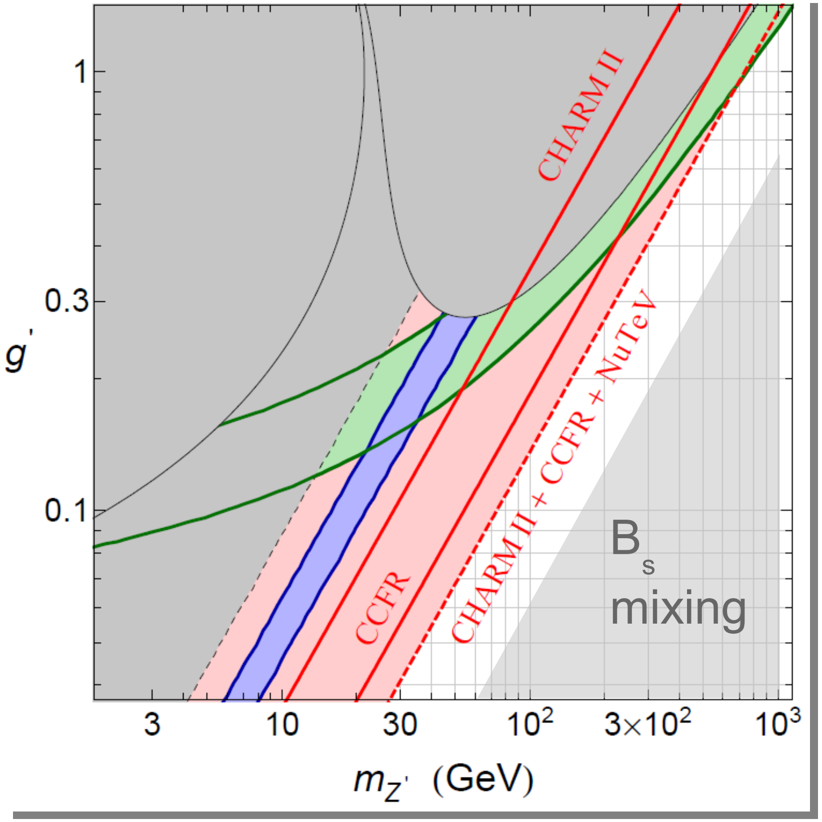
- The Z' contribution interferes constructively with the SM W contribution

- For $m_{Z'} \gtrsim 5\,\mathrm{GeV}$, the four fermion interaction approximation is good

$$\frac{\sigma}{\sigma_{\rm SM}} \simeq \frac{1 + \left(1 + 4s_W^2 + 2v^2/v_\phi^2\right)^2}{1 + (1 + 4s_W^2)^2}$$

- To be compared to

$$\sigma_{\rm CHARM-II}/\sigma_{\rm SM} = 1.58 \pm 0.57\ ,$$
$$\sigma_{\rm CCFR}/\sigma_{\rm SM} = 0.82 \pm 0.28\ ,$$
$$\sigma_{\rm NuTeV}/\sigma_{\rm SM} = 0.67 \pm 0.27^{*}.$$



(*) Later NuTeV publication does not confirm the original measurement hep-ex/9909041

A powerful probe of Z' interactions (2)

- At low mass $m_{Z'} < 5\,\mathrm{GeV}$, one should compute the full $2 \longrightarrow 4$ process (including the Z' full propagator)

- The Weizsaecker-Williams method of equivalent photons can be used:
Effectively it is a $2 \longrightarrow 3$ process initiated by a photon-neutrino scattering, with very small photon momentum

Cuts applied:

$E_{\mu 1} > 9$ GeV, $E_{\mu 1} > 4.5$ GeV
$M_{\mu\mu} < 2.3$ GeV

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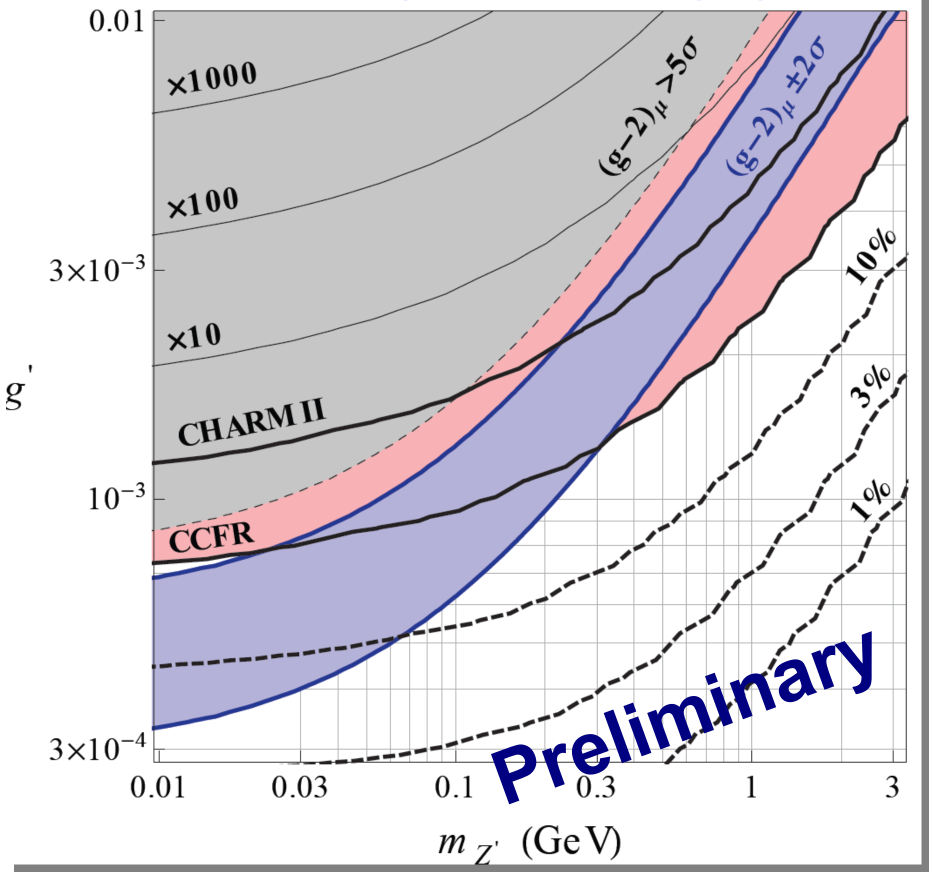
Altmannshofer, S.G., Pospelov, Yavin, in preparation



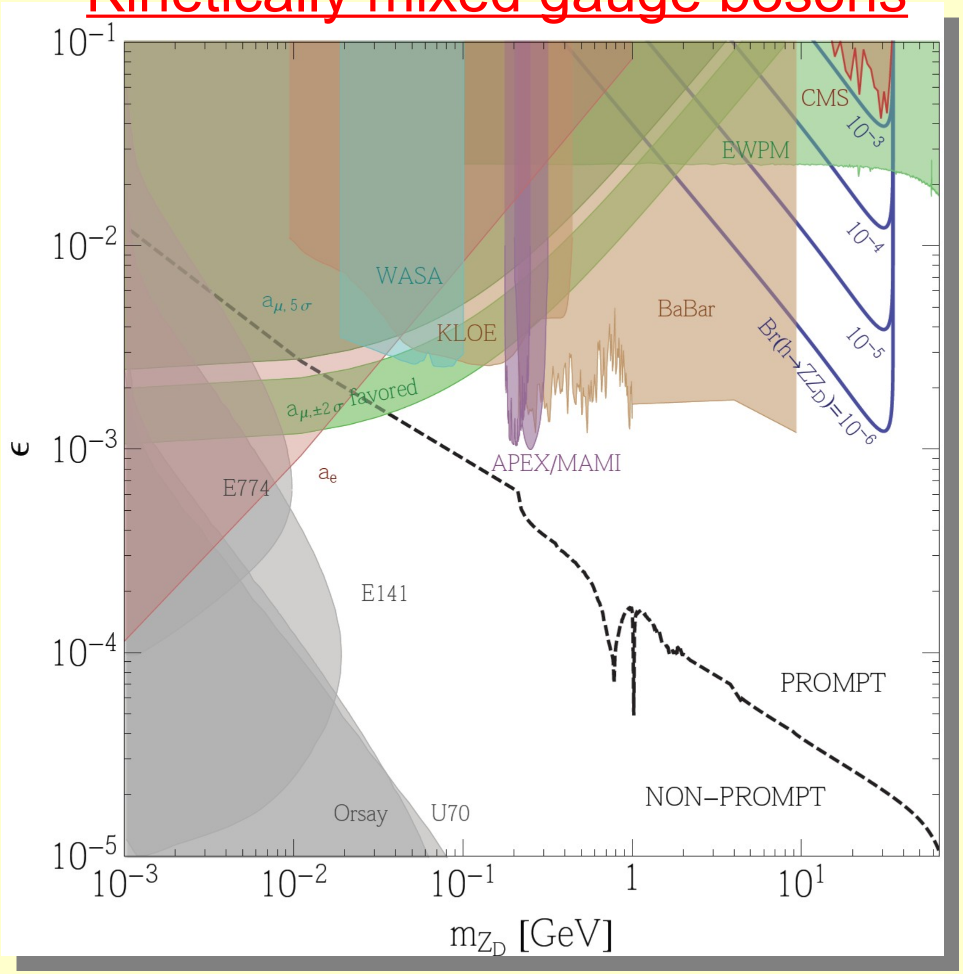
Z' coupled to muons
(and to the corresponding neutrino)
cannot explain $(g\text{-}2)_\mu$ if they are relatively massive ($m_{Z'} \gtrsim 300\,\mathrm{MeV}$)

Future neutrino experiments to further probe the Z' couplings to leptons and neutrinos? LBNE?

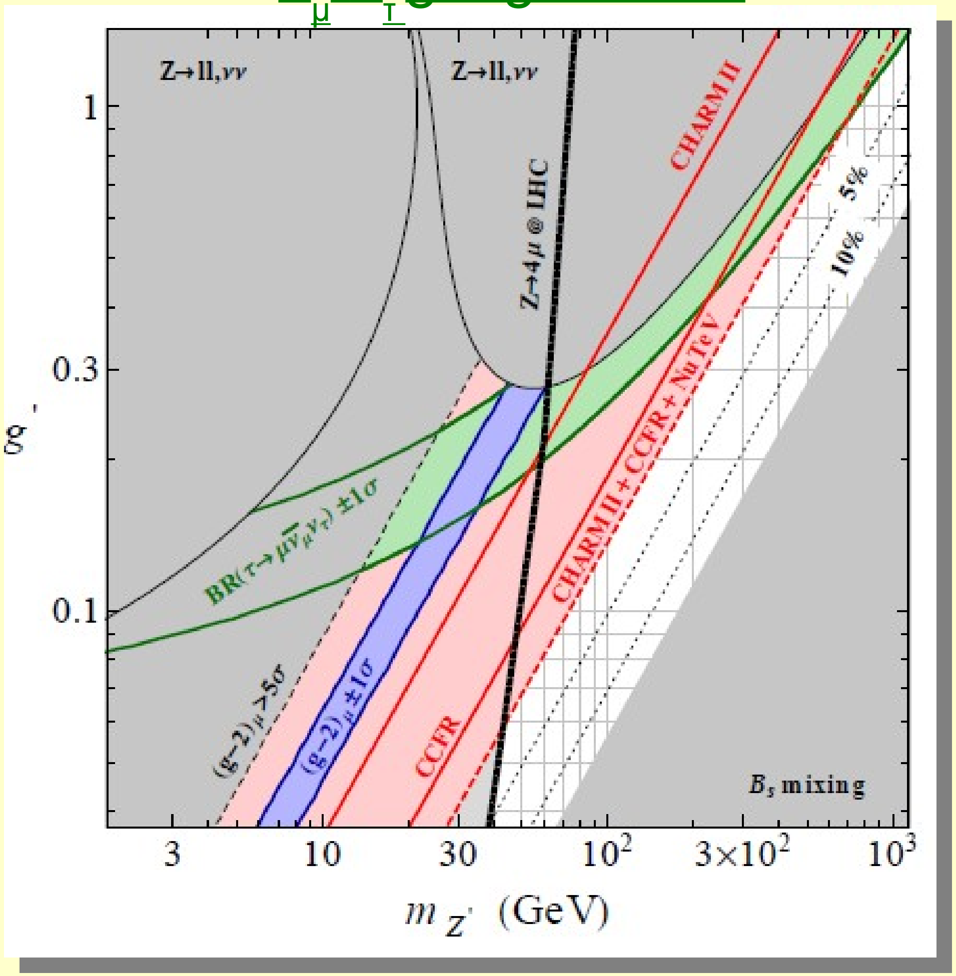
Conclusions

- Light (≲100GeV) new neutral gauge bosons Z' are a available possibility for NP theories
- Interesting complementarity of low (flavor/neutrino experiments) and high (Higgs and Z physics) energy experiments in testing the models

Kinetically mixed gauge bosons



L_μ-L_τ gauge boson



Our assumptions

1. The observed 125 GeV is SM-like

- In particular its production cross section in the several channels is the one of the SM Higgs

2. The Higgs decays promptly to new BSM particles that are either stable or promptly decaying

- we do not consider rare or nonstandard decays to SM particles

3. The Higgs decay is a 2-body decay

- 3-body decays are possible, but require new light states with substantial coupling to h to overcome phase space suppression

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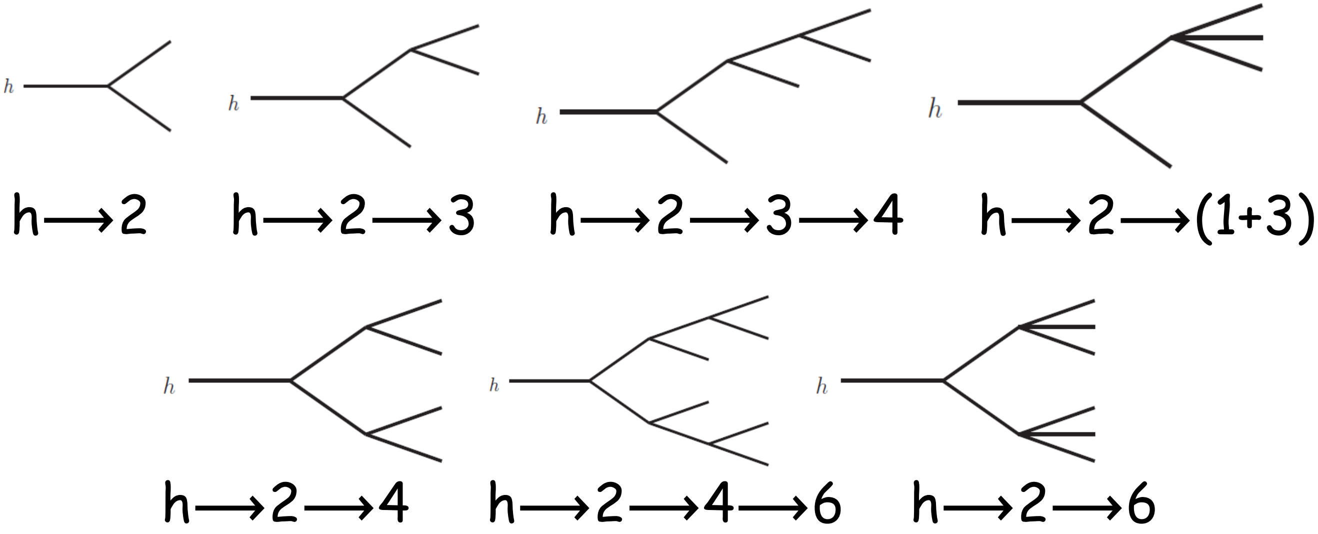

h⟶2 h⟶2⟶3 h⟶2⟶3⟶4 h⟶2⟶(1+3)

h⟶2⟶4 h⟶2⟶4⟶6 h⟶2⟶6

$h\to$MET
$h\to 4b$
$h\to 2b2\tau$
$h\to 2b2\mu$
$h\to 4\tau, 2\tau 2\mu$
$h\to 4j$
$h\to 2\gamma 2j$
$h\to 4\gamma$
$h\to ZZ_D\to 4l$
$h\to Z_D Z_D\to 4l$
$h\to\gamma$+MET
$h\to 2\gamma$+MET
$h\to 4l$+MET
$h\to 2l$+MET
$h\to$one lepton jet
$h\to$two lepton jets
$h\to bb$+MET
$h\to\tau\tau$+MET

Higgs decays to two Z_D gauge bosons

A more difficult recast: $h \to Z_D Z_D \to 4\ell$

1. For very light Z_D ($2m_\mu$-$2m_\tau$), it easy:

CMS PAS HIG-13-010

(full 8 TeV data set)

Limits coming from the h ⟶ 4μ search

$$\mathrm{BR}(h \to Z_D Z_D \to 4\mu) < 4.7 \times 10^{-5}$$

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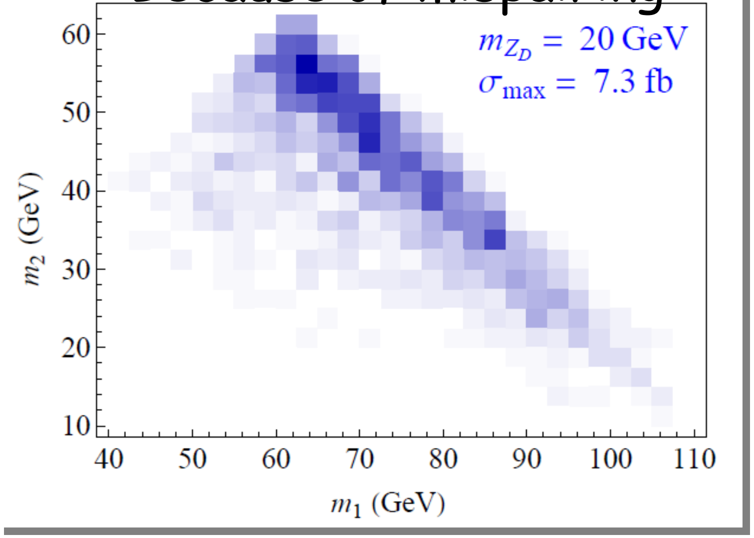
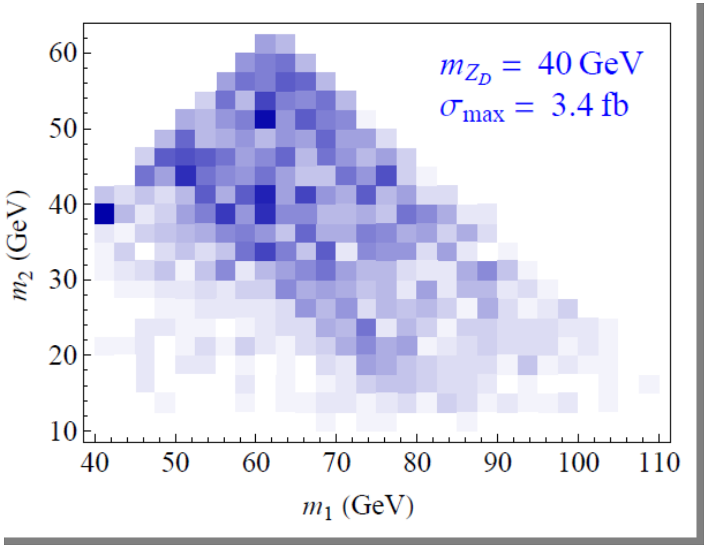
CMS-PAS-HIG-13-002
ATLAS-CONF-2013-013
ATLAS-CONF-2013-020

$40\ \mathrm{GeV} < m_1 < 120\ \mathrm{GeV},\ 12\ \mathrm{GeV} < m_2 < 120\ \mathrm{GeV}$

Because of mispairing:





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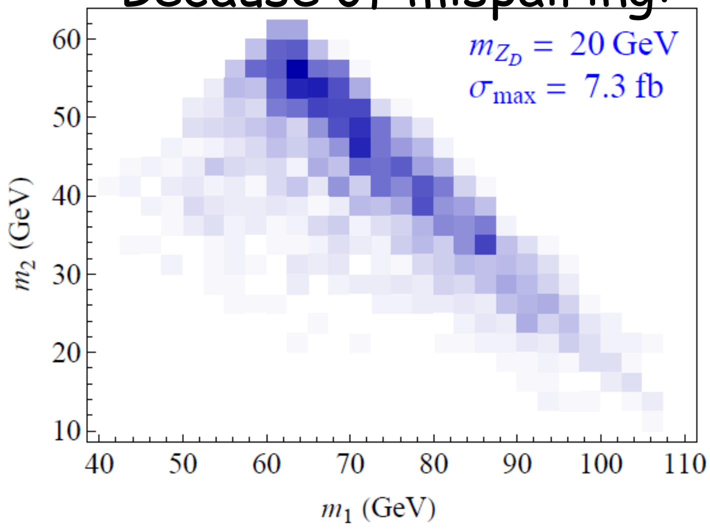

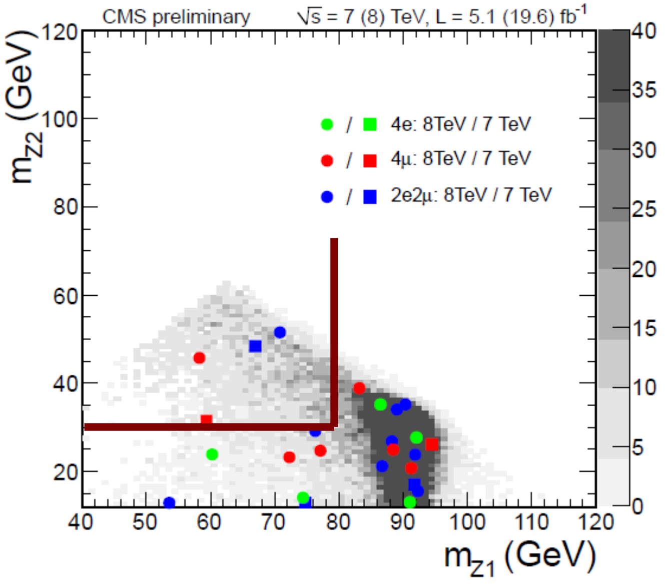

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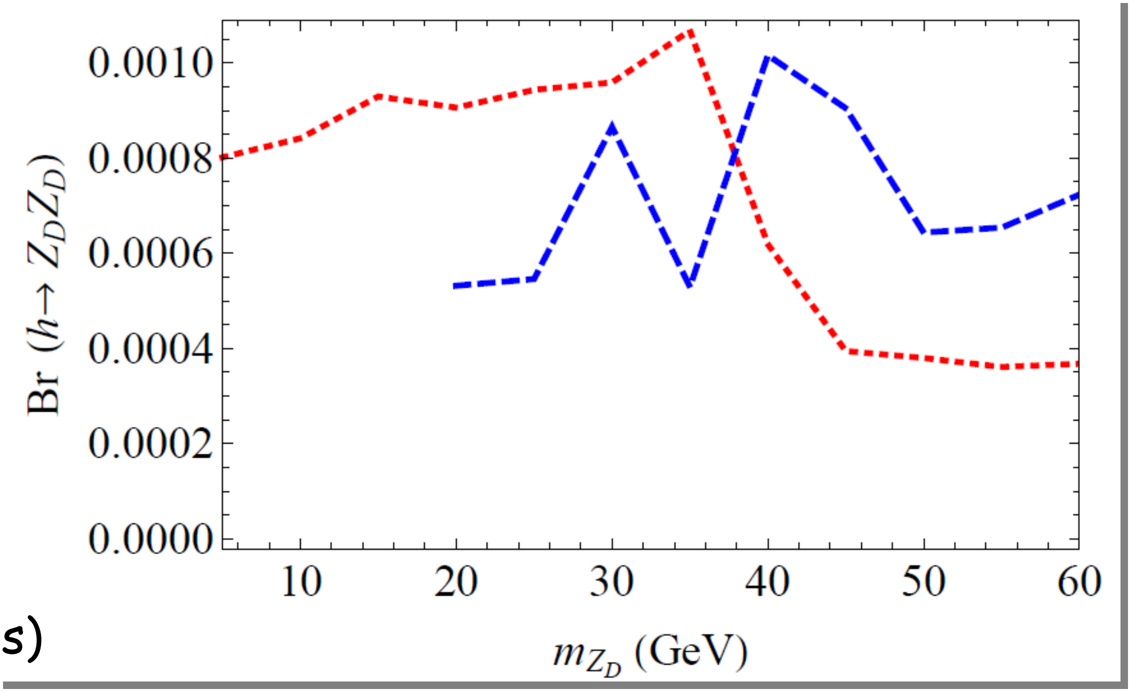
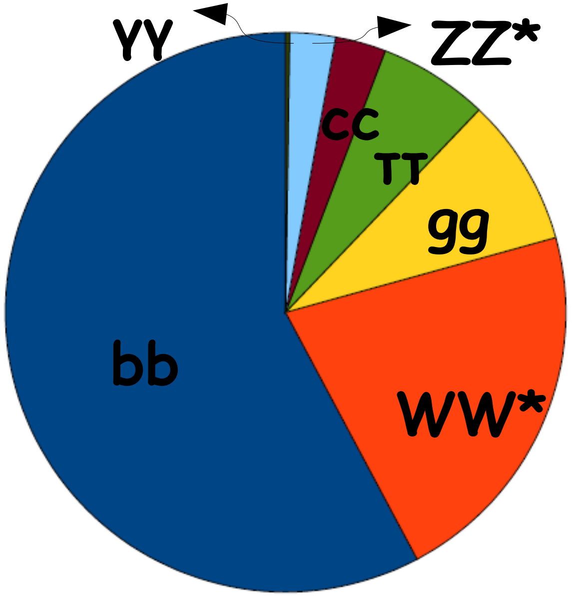


(having already unfolded the branching ratio of Z_D into leptons)

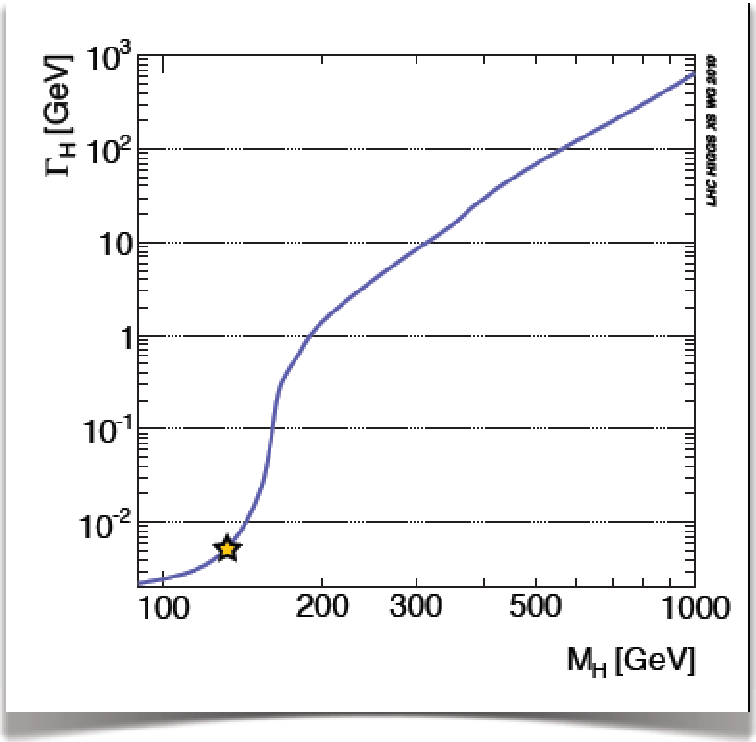
Exotic decays of the SM-like Higgs boson

A light Higgs, a lot to say:



But

not only



$$\Gamma_h^{\mathrm{SM}}(125\,\mathrm{GeV}) \sim 4.1\,\mathrm{MeV}$$

Even a small coupling to a light NP particle can lead to a sizable Higgs branching ratio for h ⟶ NP NP

A lot of events!

Production	$N_{\mathrm{ev}}^{10\%}$, Now (14 TeV)
ggF	46.000 (1500.000)
VBF	3.800 (125.000)
$hW^\pm$	1.700 (45.000)
hZ	1.000 (27.000)
$t\bar{t}h$	70 (18.000)

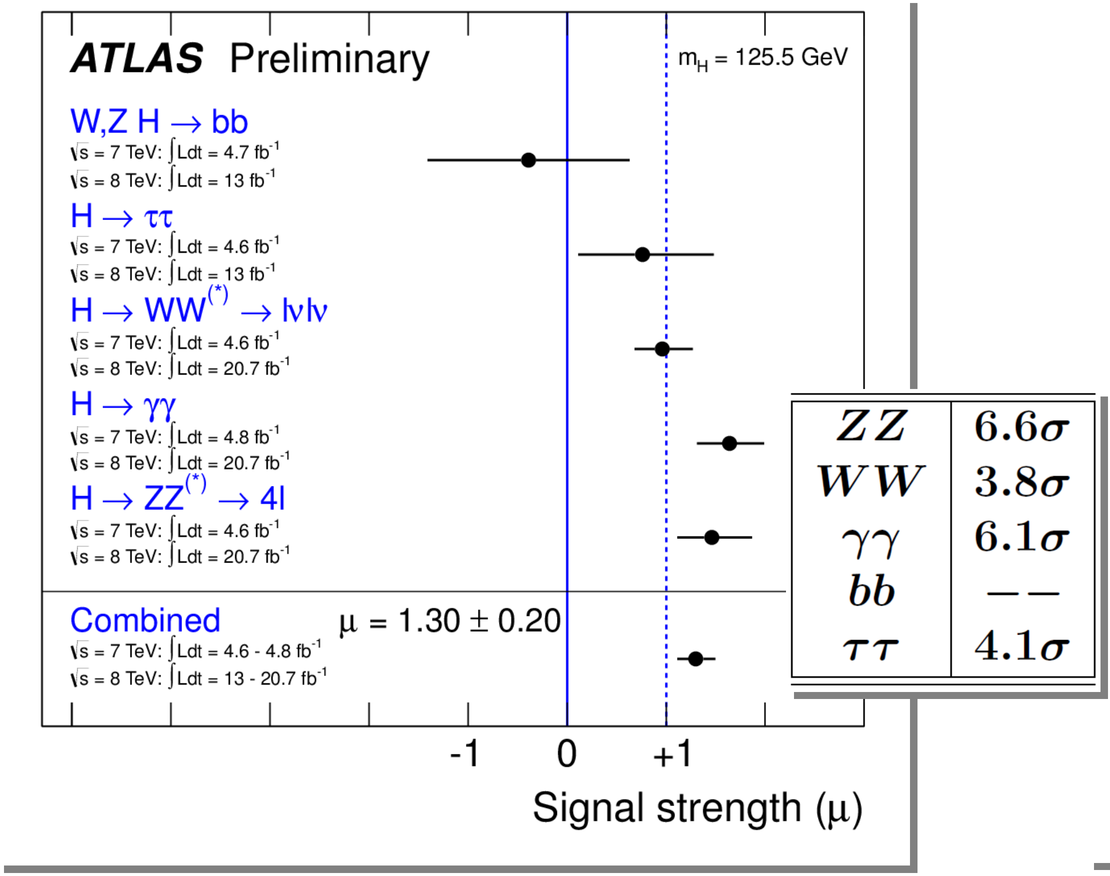
Leptonic W,Z

→ ~360 (9500)

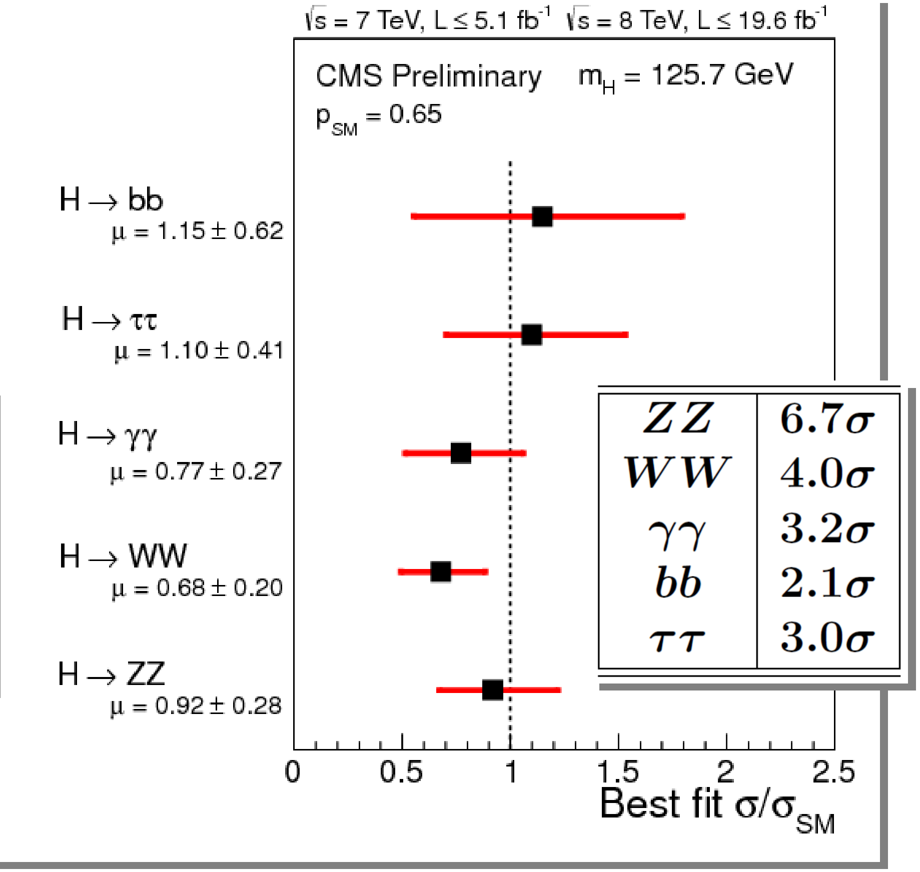
→ ~70 (1900)

Higgs: here you are!

Discovery of a weakly coupled Higgs boson



ZZ	6.6σ
WW	3.8σ
$\gamma\gamma$	6.1σ
bb	$--$
$\tau\tau$	4.1σ



ZZ	6.7σ
WW	4.0σ
$\gamma\gamma$	3.2σ
bb	2.1σ
$\tau\tau$	3.0σ

Now: evidence (≥3σ) in all channels but bb, at both ATLAS and CMS