Looking for Dark forces with multi-leptons

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Perimeter Institute for Theoretical Physics

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High energy theory seminar

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Outline

1. Introduction:

- The long quest for new massive gauge bosons
- New „dark“ gauge bosons for Dark Matter/Neutrino phenomenology

2. A kinetically mixed dark gauge boson

- Interplay between EWPMs, Drell-Yan production and Higgs exotic decays

New experiments to test new light „dark forces“

3. Gauging the L_μ-L_τ number

- Role of neutrino experiments to probe new Z' gauge bosons (past: CCFR, future: LBNE)

- 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, 14xx.xxxx
- Dressing L_μ - L_τ in color
  W.Altmannshofer, S.G., M.Pospelov, I.Yavin, 1403.1269 + 1406.2332

The long quest for new forces

	EM	Weak	Strong	New Force?
Quarks	✓	✓	✓	?
Leptons	✓	✓	—	?
Neutrinos	—	✓	—	?
Dark Matter?	—	?	—	?

- Naturally arising in Grand Unified Theories, models of compositeness or extra dimensions, ...

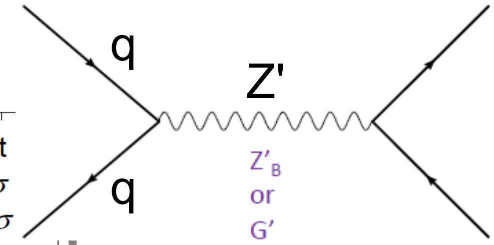
- In SUSY models, they can address the μ problem, they can give a sizable tree level contribution to the Higgs mass

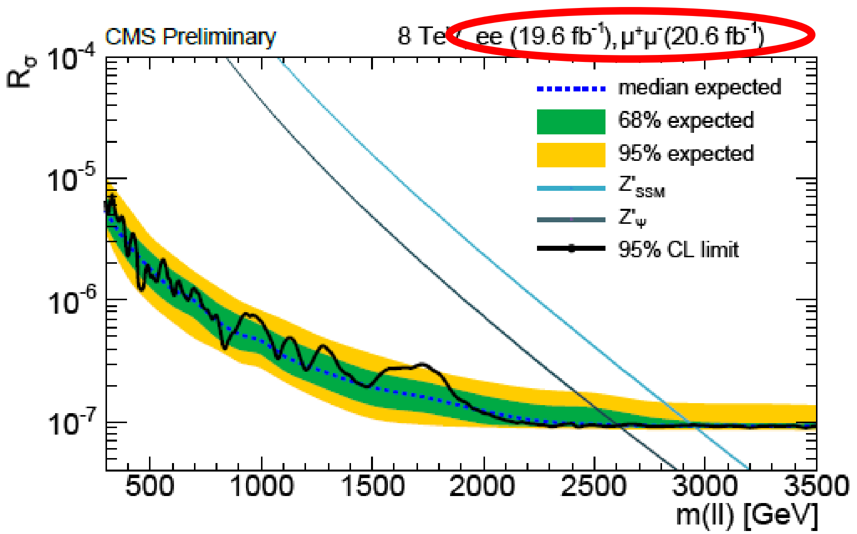
- Used in neutrino model building, dark matter model building, electroweak baryogenesis, to solve the long standing discrepancy in $(g-2)_\mu$

WHY?

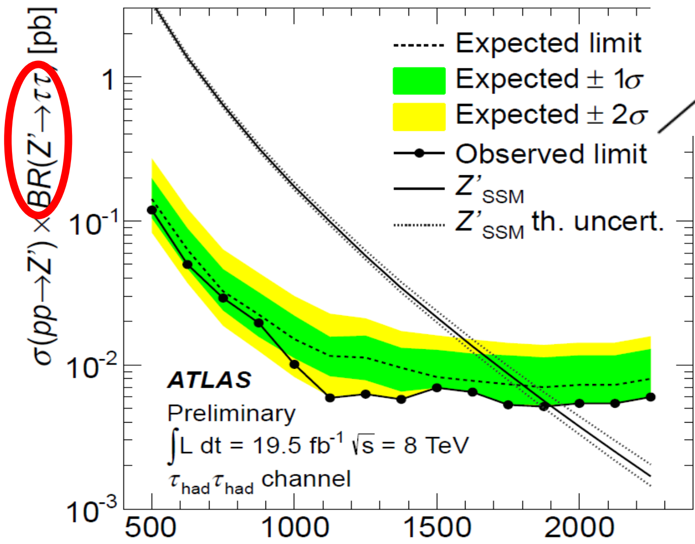
Z' searches @ colliders

Multi-hundred GeV/TeV - scale Z'

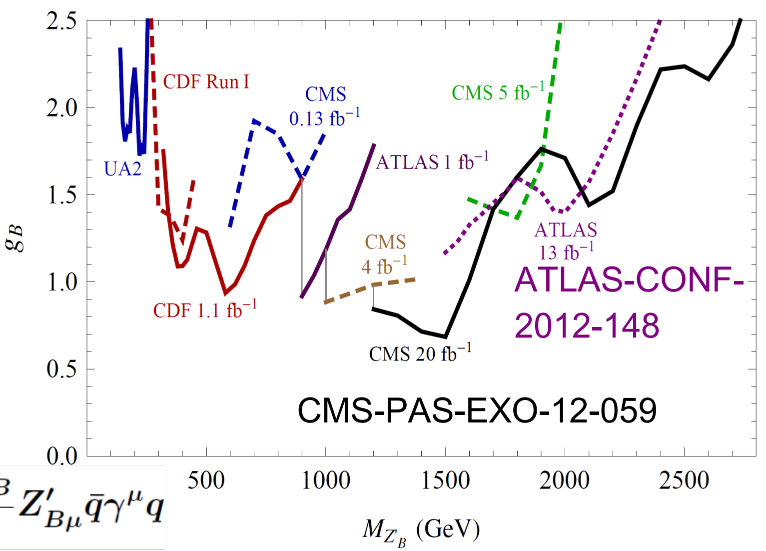




CMS PAS EXO-12-061

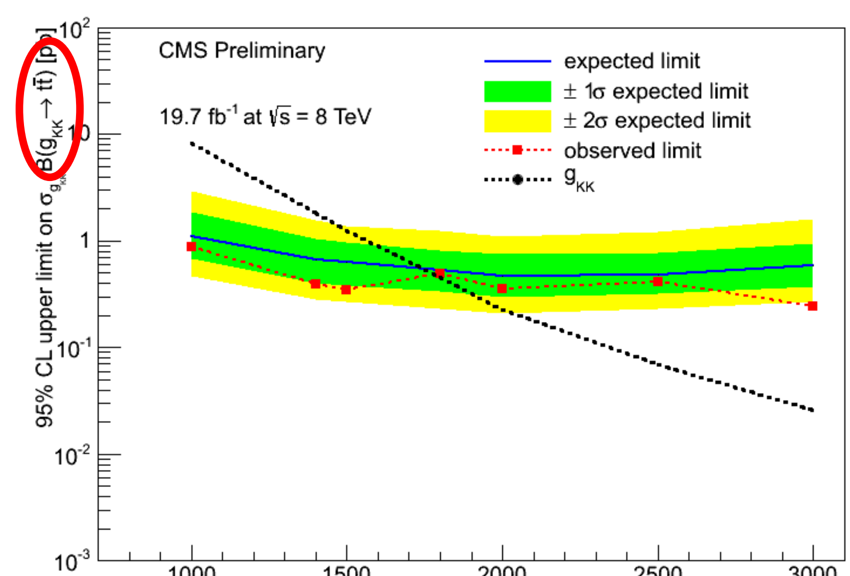


ATLAS-CONF-2013-066



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

Dobrescu, Yu, 1306.2629



CMS-PAS-B2G-12-007

Well-hidden gauge bosons

1.

g,W,Z,γ

Known forces

?

„Dark sectors“ forces, particles, dark matter

Vector portal

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

	EM	Weak	Strong	New Force?
Quarks	✓	✓	✓	-
Leptons	✓	✓	–	-
Neutrinos	–	✓	–	-
Dark Matter?	–	–	–	✓

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Leptons	✓	✓	–	-
Neutrinos	–	✓	–	-
Dark Matter?	–	–	–	✓

2.

	EM	Weak	Strong	New Force?
Quarks	✓	✓	✓	-
Leptons	✓	✓	–	✓no 1st gen.
Neutrinos	–	✓	–	✓no 1st gen.
Dark Matter?	–	?	–	?

Gauging $L_\mu - L_\tau$ symmetry

Neutrino mass model building, Heeck, Rodejohann, 1107.5238

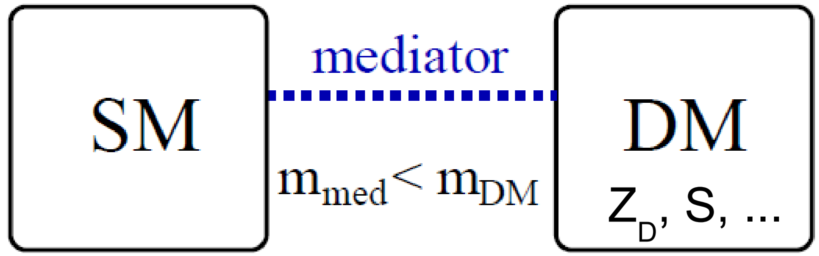
	EM	Weak	Strong	New Force?
Quarks	✓	✓	✓	-
Leptons	✓	✓	—	-
Neutrinos	—	✓	—	-
Dark Matter?	—	—	—	✓

Kinetically mixed Z'

- Higgs phenomenology
- Drell-Yan production
- EWPMs

A DM-motivated framework

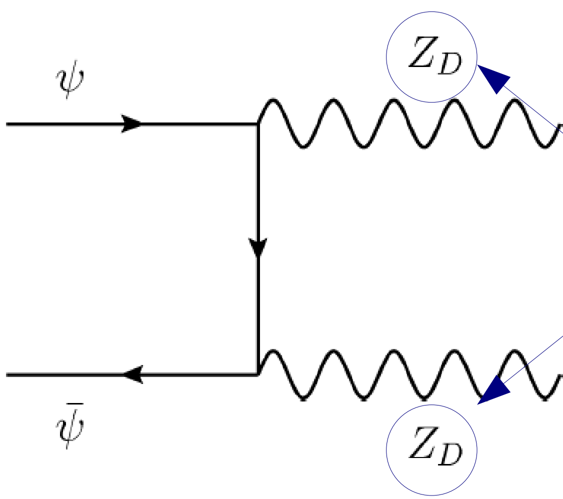
DM does not interact „directly“ with our SM world,
but only „indirectly“



Pospelov et.al. 0711.4866
Feldman et al 0702123

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

For a recent study, see
Cline et al. 1405.7691



They ultimately decay to SM states thanks to the kinetic mixing „**portal**“

The simplified model

$$\mathcal{L} = -\frac{1}{4}\hat{V}_{\mu\nu}\hat{V}^{\mu\nu} - \frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} + \frac{\epsilon}{2\cos\theta}\hat{V}_{\mu\nu}\hat{B}^{\mu\nu} + \\ + \frac{1}{8}w^2 g_D^2 (\hat{V}_{\mu\nu})^2 + \frac{1}{8}v^2(-g\hat{W}^3_\mu + g'\hat{B}_\mu)^2 + \\ + \zeta|S|^2|H|^2$$

(+ Interactions with Dark Matter)

Breaking of the U(1)' symmetry in the dark sector $S \to \langle S \rangle \equiv w$

In GUT theories, the kinetic mixing operator is generated at one loop

$$\epsilon \sim \frac{g_1 g'}{16\pi^2}\log\left(\frac{M_1}{M_2}\right) \sim (10^{-3} - 10^{-4})\log\left(\frac{M_1}{M_2}\right)$$

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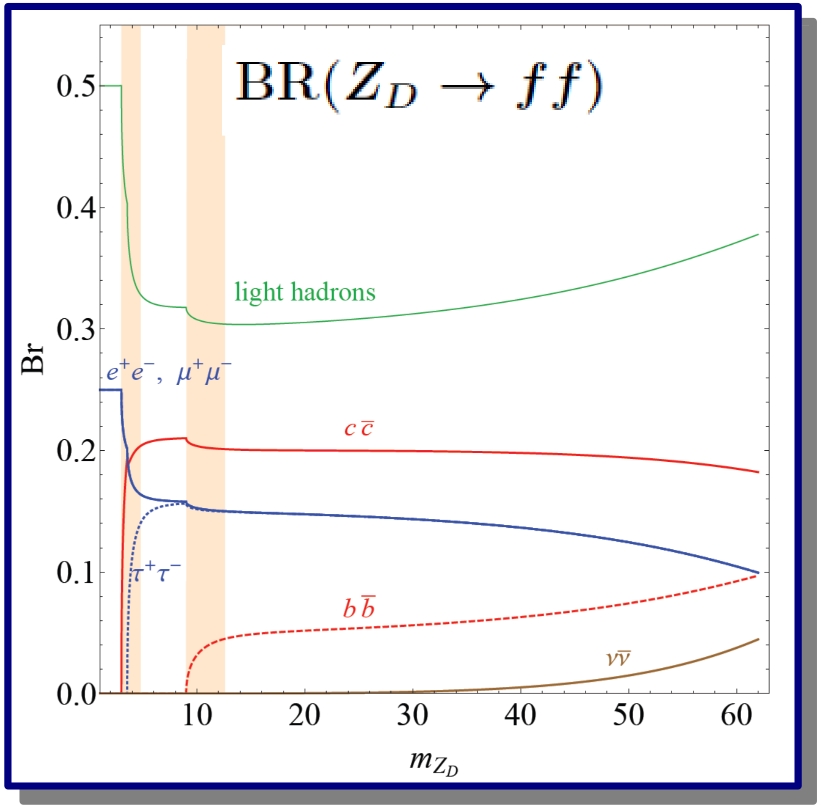
If m_s, $m_{DM} > m_{ZD}$, the Z_D pheno depends only on ϵ, m_{ZD}

„Minimal model“

- $m_{Z_D} \ll m_Z \Rightarrow Z_D \bar{f} f \propto \epsilon Q$
  $m_{Z_D} \sim m_Z \Rightarrow Z_D \bar{f} f \propto \epsilon(T_3 - Q s_W^2)$
- $\Gamma_{Z_D} \propto \epsilon^2 m_{Z_D}$

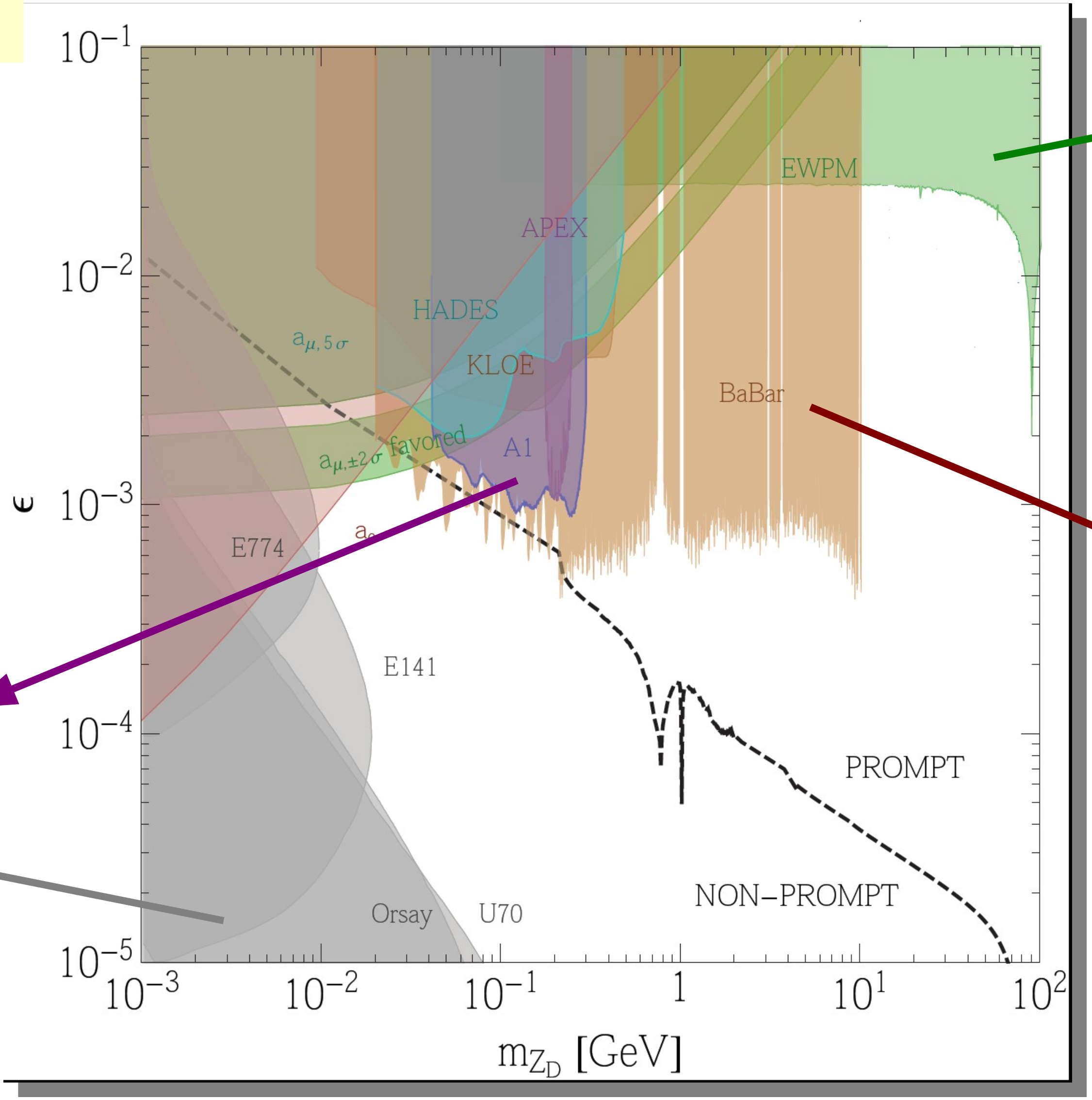
Z_D decays prompt ($c\tau < 1\mu m$) for $\epsilon \geq$ few*10^{-5} and $m_{ZD} \geq 10$ GeV



Overview of the existing bounds for Z_D

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

„Minimal model"



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

Hook, Izaguirre, Wacker, 1006.0973

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

1406.2980

Fixed target/ beam dump experiments

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

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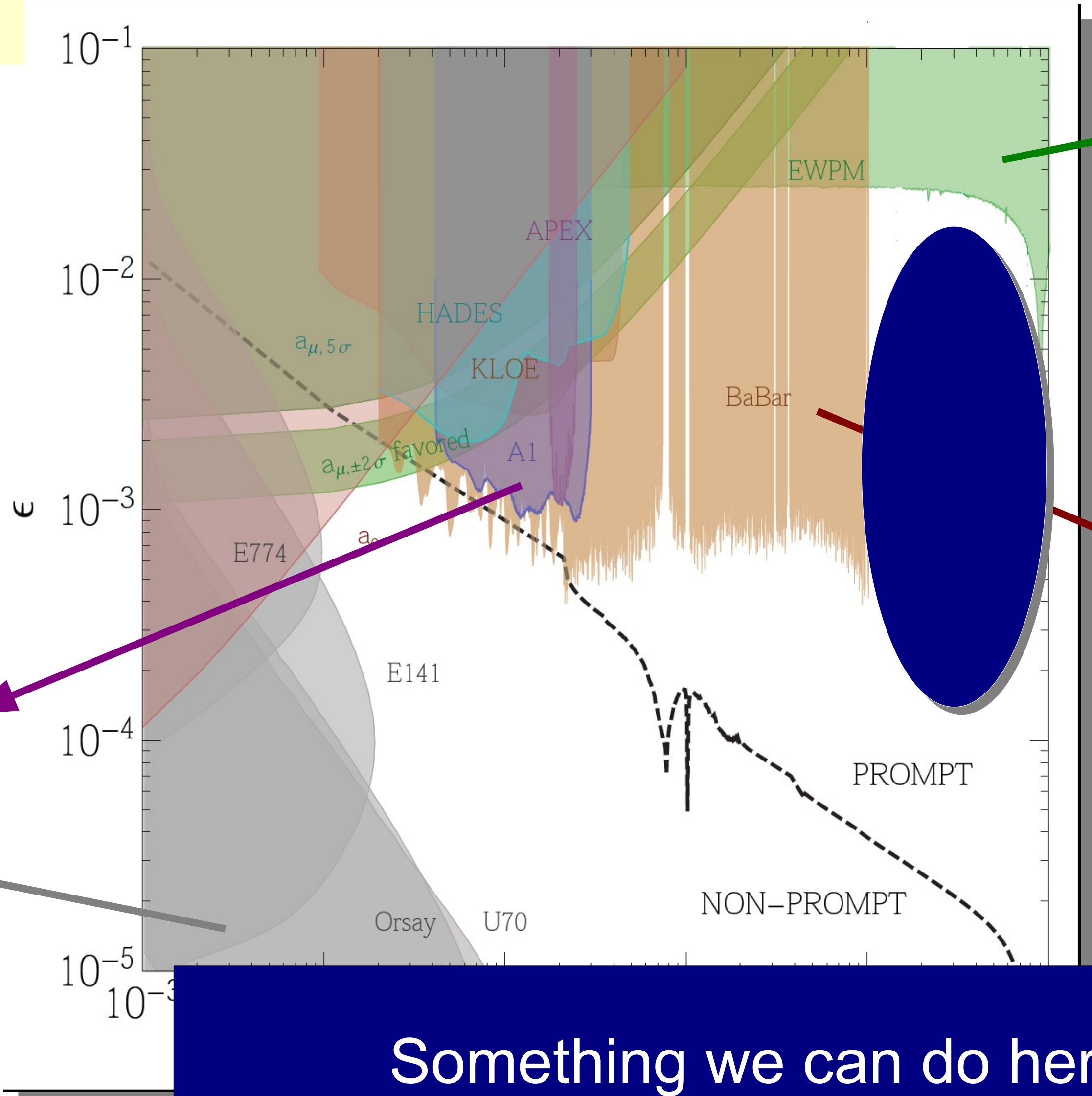

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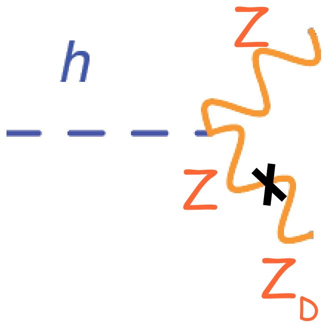
Fixed target/ beam dump experiments

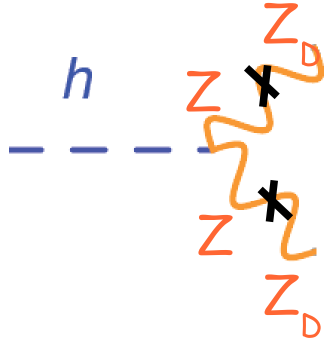
Something we can do here?

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

Here it comes the Higgs...

1. In the „Minimal model“:





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

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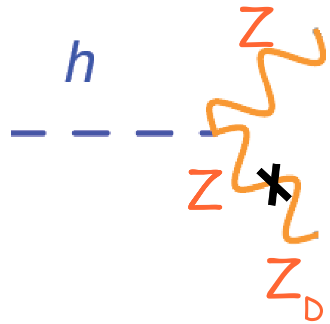

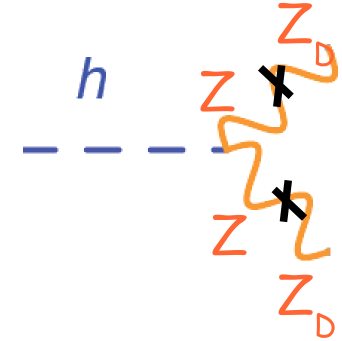

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2. In the „Next to Minimal model“:

The Higgs will generically mix with the scalar responsible of U(1)' breaking

$$\zeta |S|^2 |H|^2$$

- Higgs „SM pheno“ changes:
  all Higgs couplings to SM fermions and gauge bosons will be suppressed by cos(α)
- Set of new possible Higgs decays

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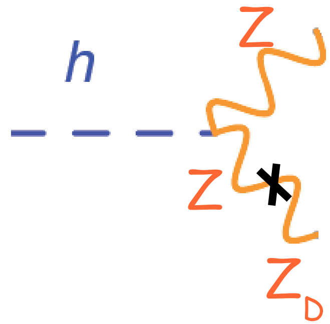

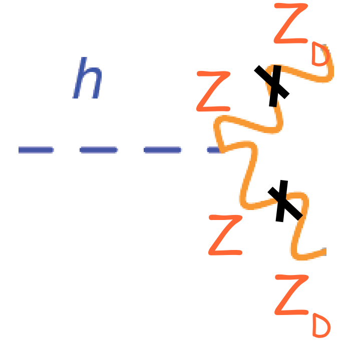

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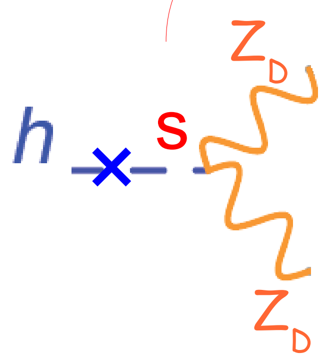
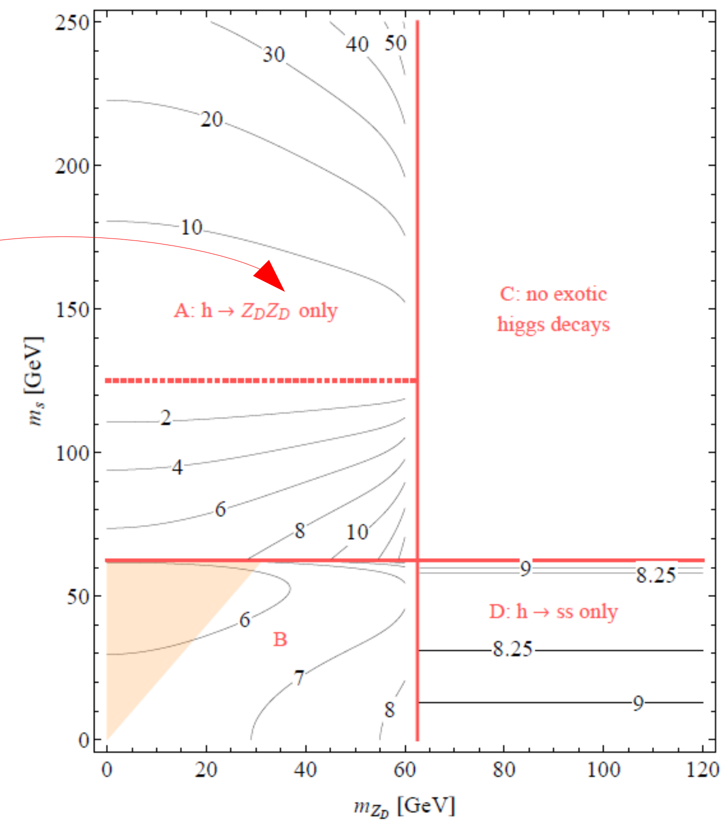




S.Gori

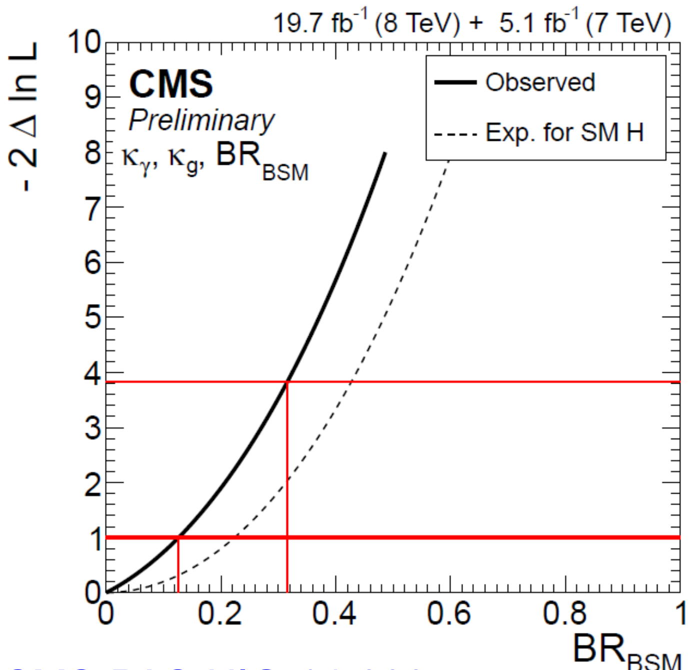
„Hidden" exotic decays

Exotic decays will contribute to the Higgs width

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

Too small to be measured directly, except at a muon collider where the Higgs can be produced as a resonance

Now



CMS-PAS-HIG-14-009

+

Off-shell interference in H ⟶ ZZ

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

CMS PAS HIG-14-002

Based on
Caola, Melnikov, 1307.4935
Campbell, Ellis, Williams
1311.3589, 1312.1628

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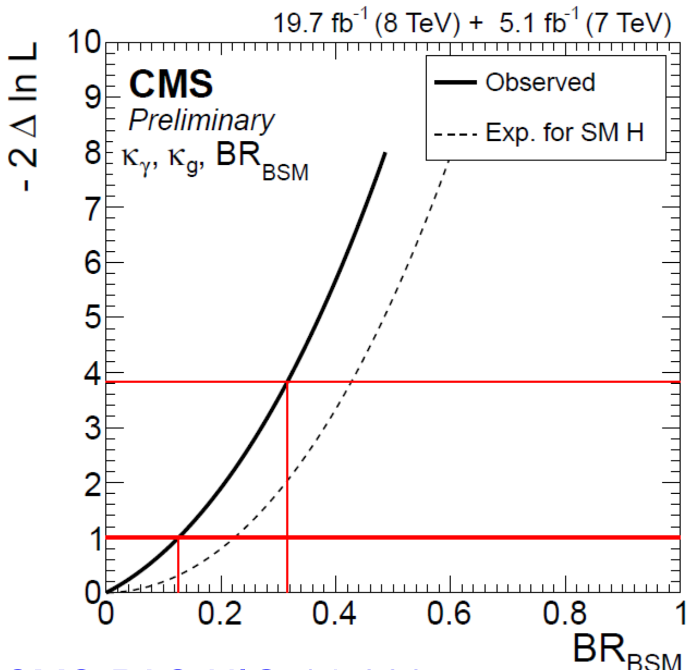

CMS-PAS-HIG-14-009

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CMS PAS HIG-14-002

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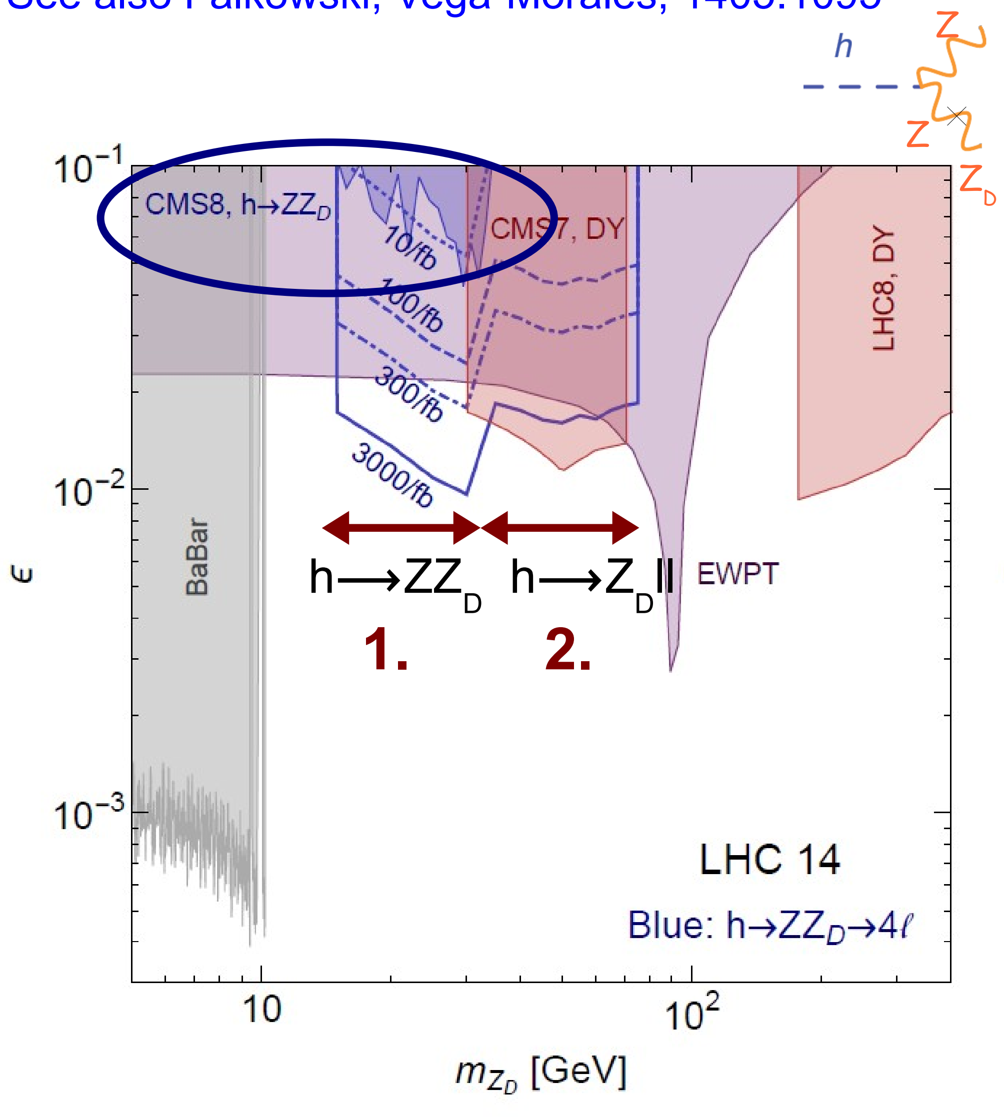
Future

In general the extraction of the Higgs width at hadron colliders is difficult.
It has to rely on some assumption (e.g. $\kappa_Z, \kappa_W \leq 1$)
Typically ~10% at 300 fb^{-1}, ~5% at 3000 fb^{-1} LHC

Small branching ratios are difficult to discover in this way
Importance of looking directly for Higgs exotic decays

„Minimal“ model and Higgs decays

See also Falkowski, Vega-Morales, 1405.1095



Curtin, Essig, SG, Shelton, appearing soon

$120\,\mathrm{GeV} < m_{4\ell} < 130\,\mathrm{GeV}$

No SFOS lepton pair with m_{ll} < 12GeV

1. $|M_1 - m_Z| \;<\; 15\,\mathrm{GeV}$
2. $|M_1 - m_Z| \;>\; 15\,\mathrm{GeV}$

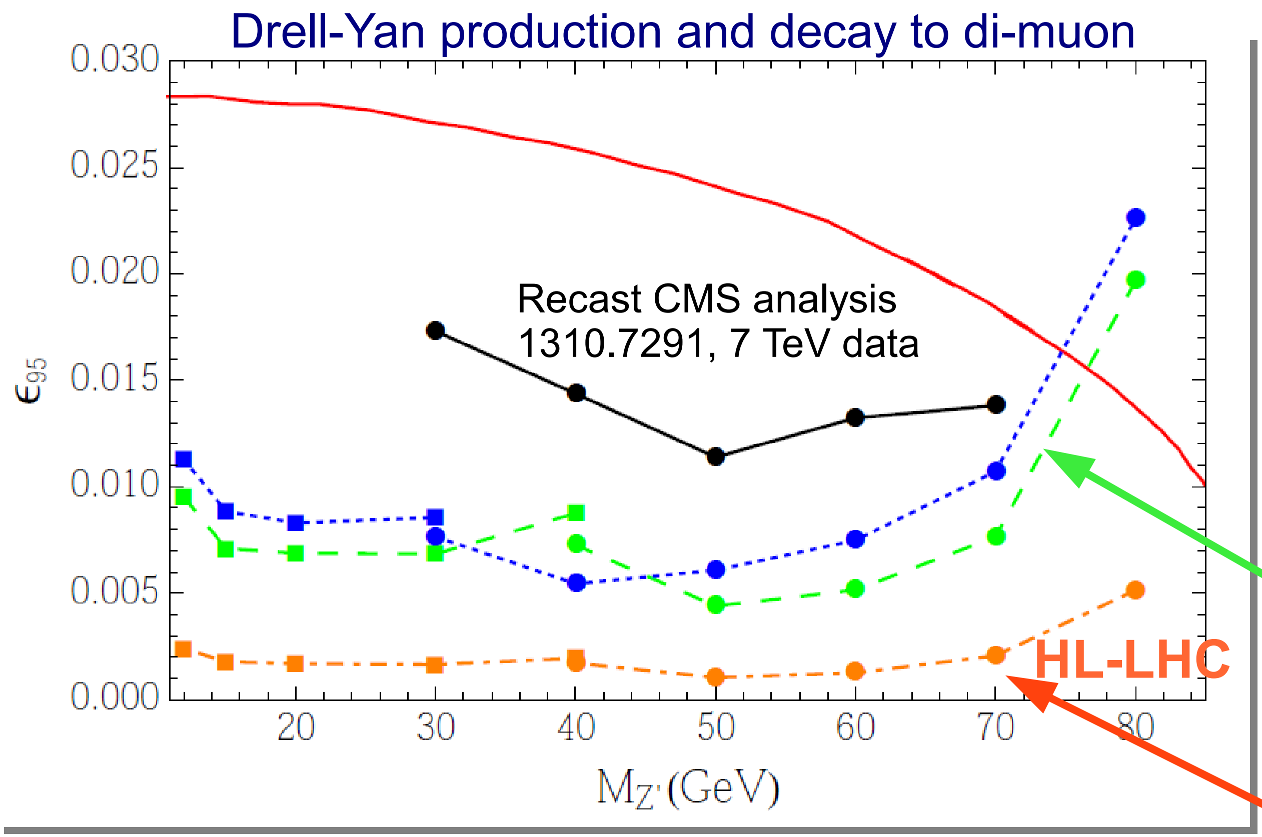
Bump hunt in the SFOS dilepton invariant mass

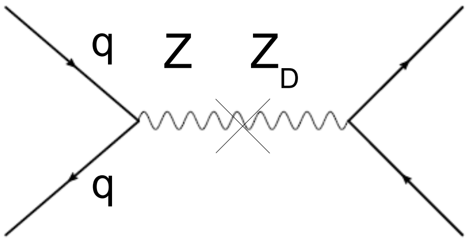
$$|M_2 - m_{Z_D}| < \begin{cases} 0.02 M_2 & \text{(electrons)} \\ 2.5(0.026\ \mathrm{GeV} + 0.013 M_2) & \text{(muons)} \end{cases}$$

for muons, we are using the (pessimistic) mass resolution for forward muons: η_μ>0.9

BR($h \longrightarrow ZZ_D$)~10^{-4}
can be tested at the HL-LHC

Drell-Yan production





Leading (sub-leading) muon with p_T > 14 (9) GeV

Proposed search with 8 TeV data p_T > 20 (10) GeV

Assuming the same trigger threshold as for the 8 TeV

Hoenig, Samach, Tucker-Smith, 1408.1075

Search for a light (5.5-14 GeV) pseudoscalar Higgs in the di-muon channel:

$\varepsilon < 2\times10^{-3}$ at $m_{ZD} \sim 12$ GeV,

CMS, 1206.6326

Complementarity with EWPMs

Because of kinetic mixing, the Z_D mixes with the SM Z boson

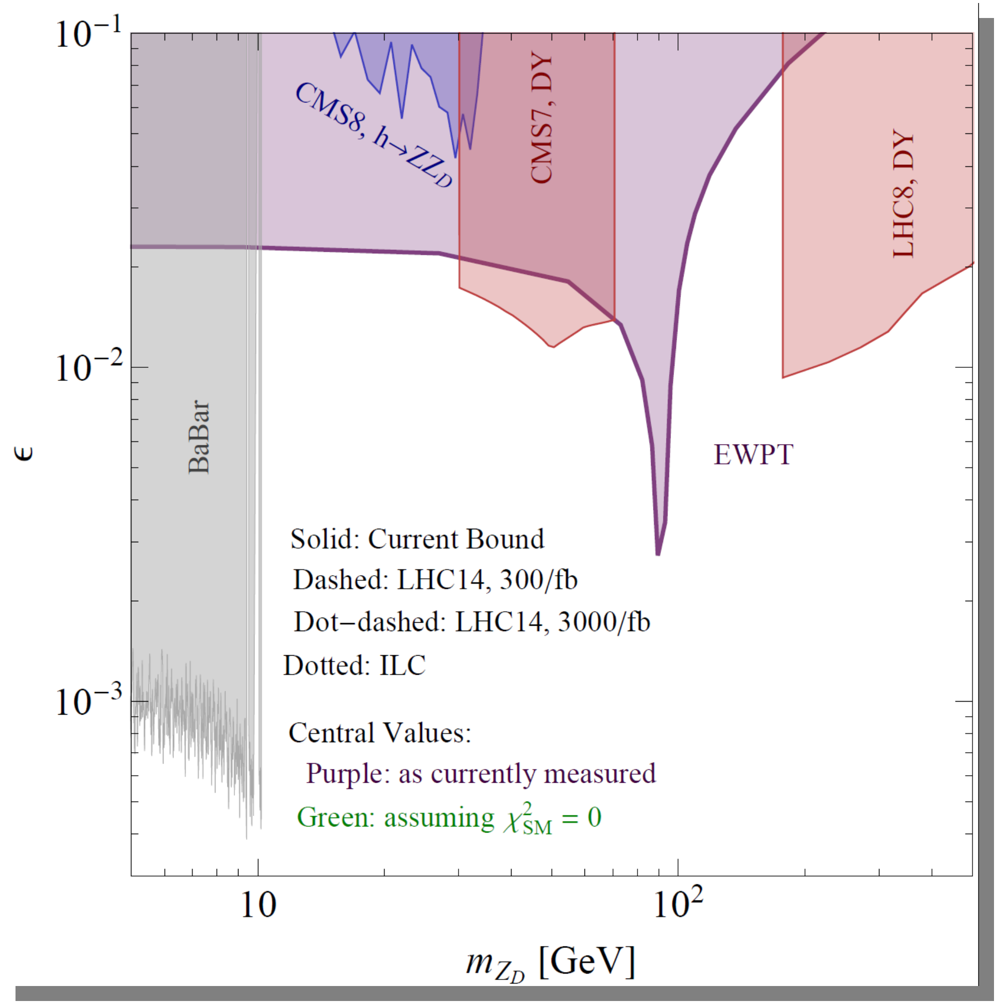
Effects on the Z phenomenology

- Tree level shift in the Z mass;

$$m_Z^2 \sim m_{Z0}^2 (1 + \epsilon^2 \tan^2\theta)$$

- Modification of the Z couplings

$$\sim (Zf\bar{f})_{\rm SM} \left(1 + \epsilon^2 \frac{\tan^2\theta}{2} \cdot \frac{T_3 - Q(1+\cos^2\theta)}{T_3 - Q\sin^2\theta}\right)$$



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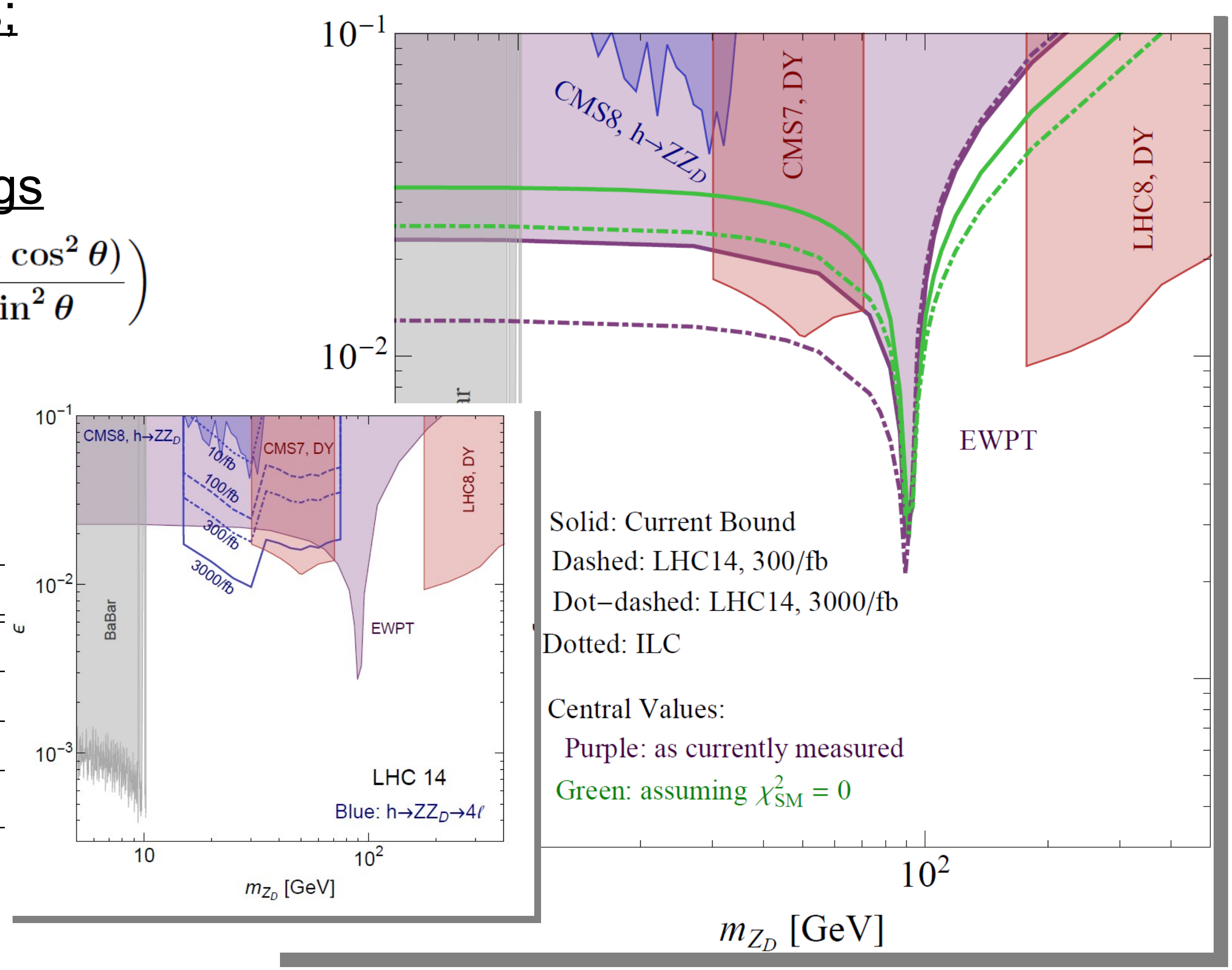
	Now	Future HL-LHC
δm_W	15 MeV	5 MeV
δm_h	0.24 GeV	0.05 GeV
δm_t	0.76 GeV	0.2 GeV
$\delta\Delta\alpha_{\rm had}^{(5)}$	$10 \cdot 10^{-5}$	$4.7 \cdot 10^{-5}$

Babar expectation



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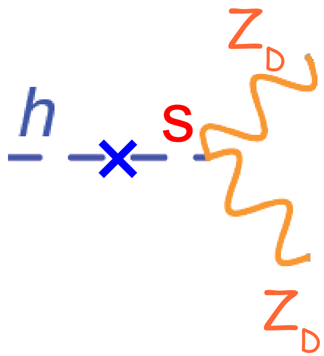
An un-explored „Next-to-Minimal“ model

If ε is small ($<10^{-3}$) all constraints are washed out



$$V(H,S) \supset \zeta |S|^2 |H|^2$$

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

Responsible for the decay of Z_D back to the SM

Free parameters:

$$m_{Z_D},\ m_s,\ \epsilon,\ \kappa' \equiv \zeta \frac{m_h^2}{|m_h^2 - m_s^2|}$$

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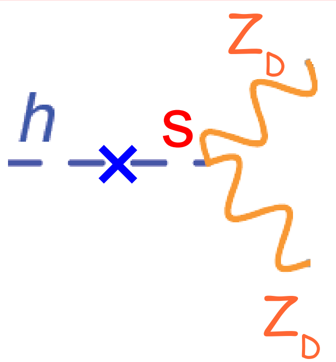

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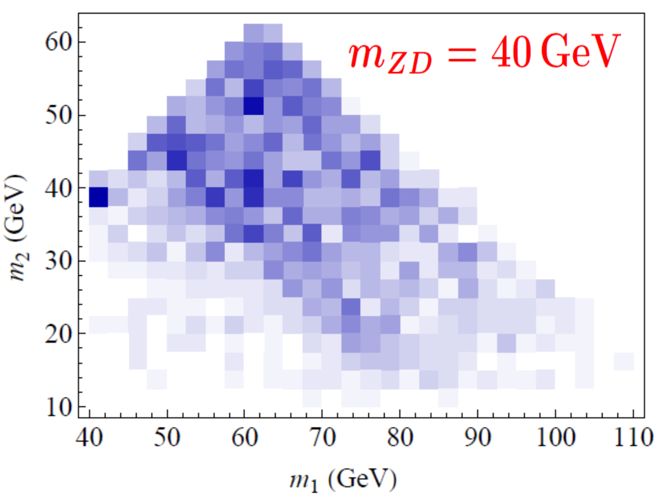
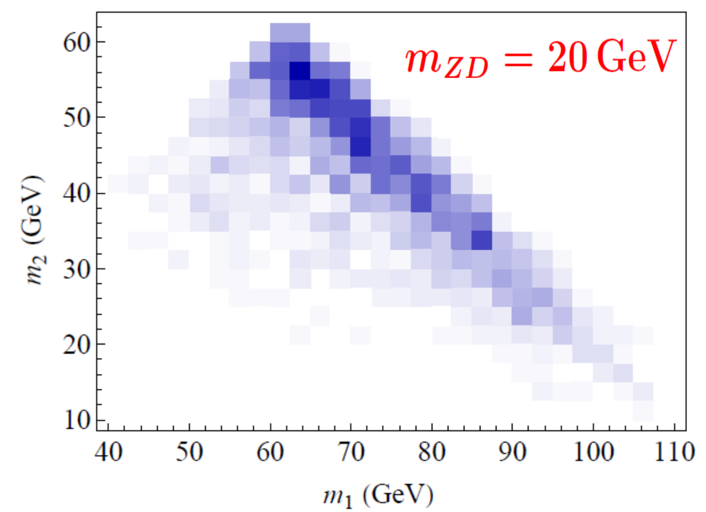
Recast CMS-ATLAS h→ZZ*→4l:

Our signal



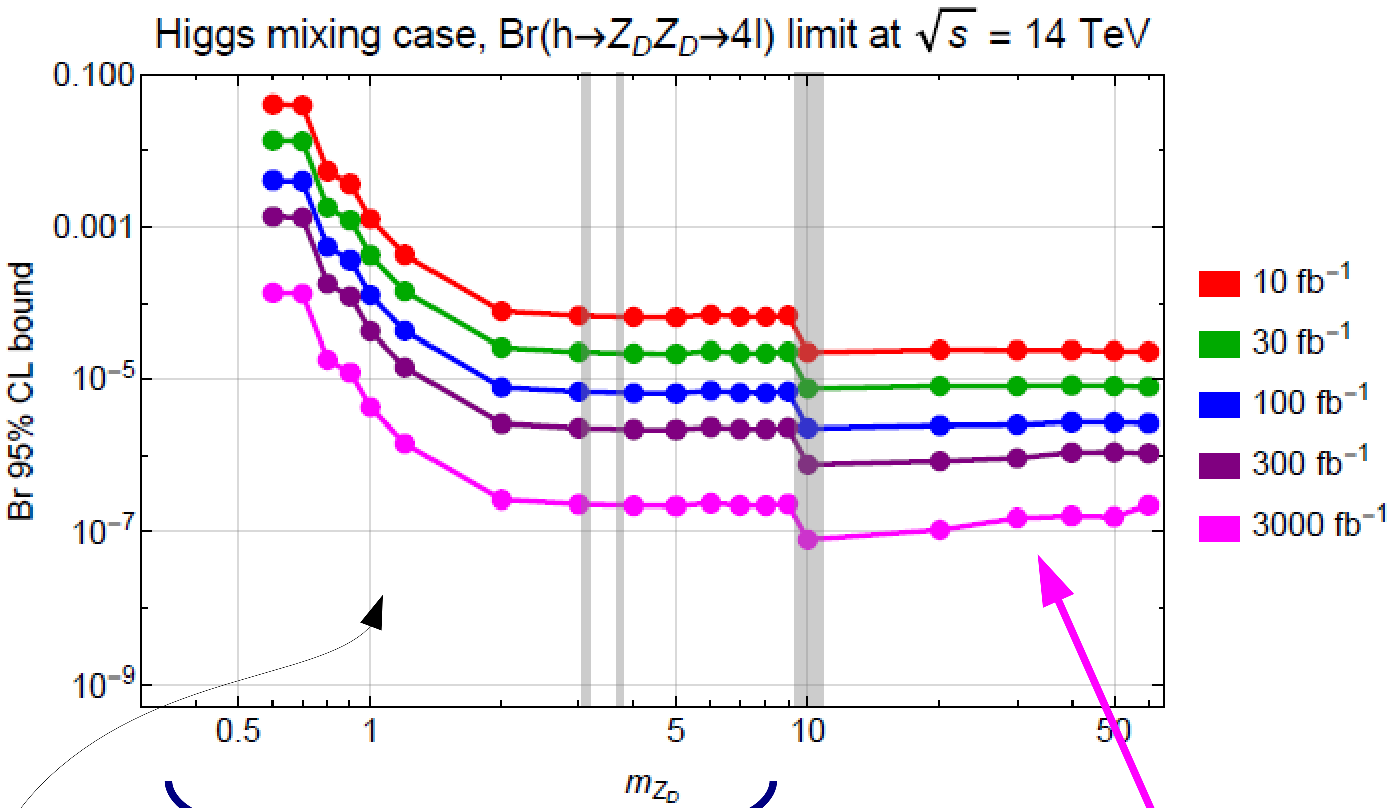
m_1 in (40-120) GeV,
m_2 in (12-120) GeV

Because of mispairing:



$BR(h \to Z_D Z_D \to 4l) \leq$ few*10^{-5}, at best

A dedicated analysis



Two di-lepton resonances
at the same mass;

$\Delta R_{\mu\mu}$>0.05,
ΔR_{ee}>0.02,

Only di-muon channel at low mass (< 10 GeV)

HL is crucial
since the search is almost background free/ statistically limited

This corresponds to set a bound on the Higgs mixing with another scalar at the level of

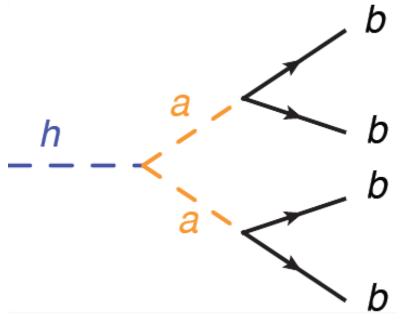
$$\kappa' \sim \text{few} \cdot 10^{-5}$$

See also CMS PAS HIG-13-010
for h ⟶ aa ⟶ 4μ with $m_a < 2m_\tau$

A lucky search

Main limitation for the search of Higgs exotic decays:

soft objects coming from the decay of a (light) Higgs



$$p_T^j \lesssim 30\,\mathrm{GeV}$$

Possible problem in triggering, especially in going to higher energies!

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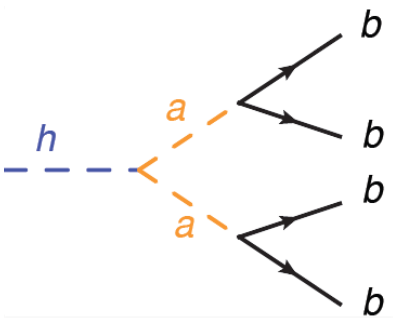
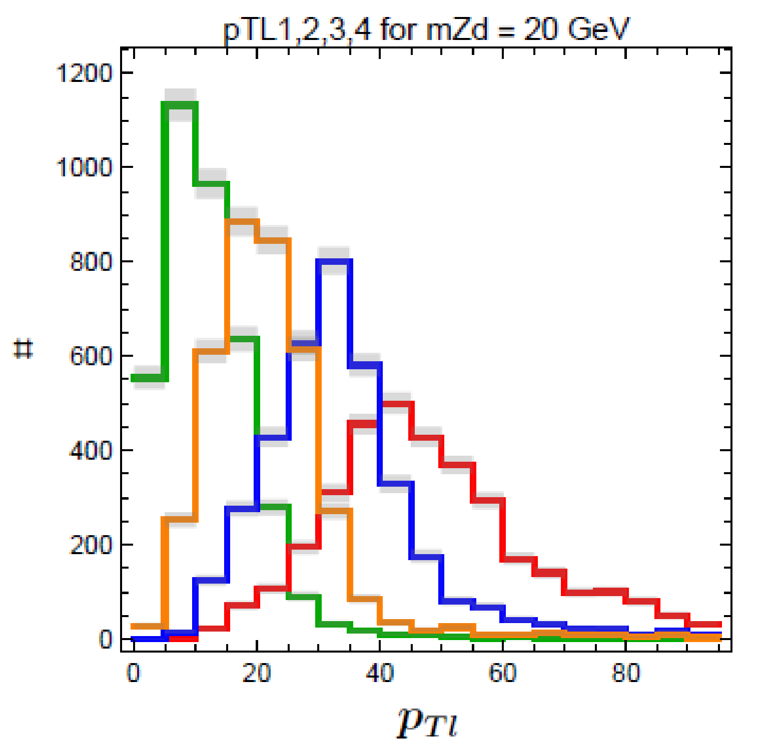


$$p_T^j \lesssim 30\,\mathrm{GeV}$$

Possible problem in triggering, especially in going to higher energies!

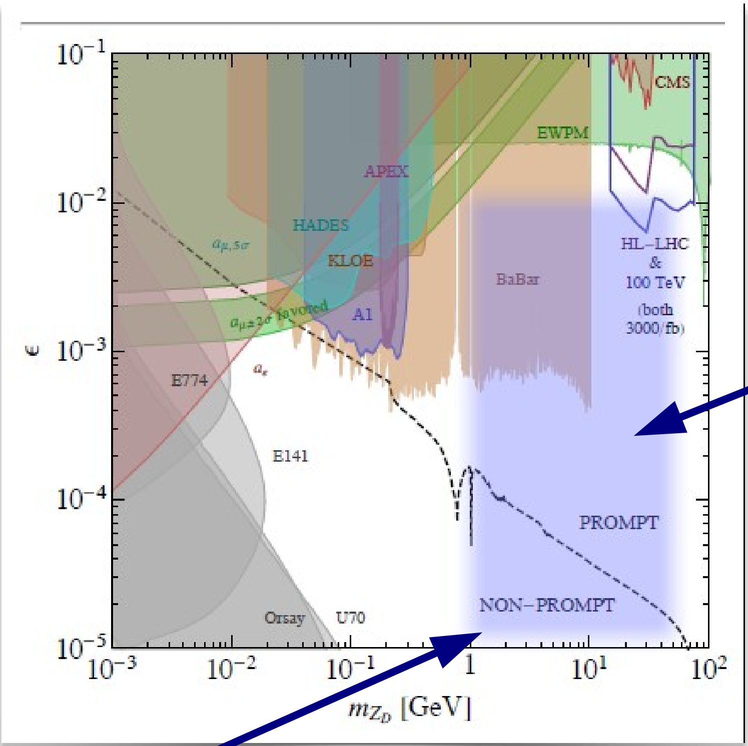
In our four lepton case, we use 8 TeV thresholds: $p_{Tl} > 20$ (10) GeV

Still, even raising a bit the thresholds would not affect much the reach



A non-promptly decaying Z_D

What if the kinetic mixing is very small $\epsilon \lesssim 10^{-4} - 10^{-5}$
and Z_D does not decay promptly?



Probed by $h \to Z_D Z_D$

Accessible?

 S.Gori

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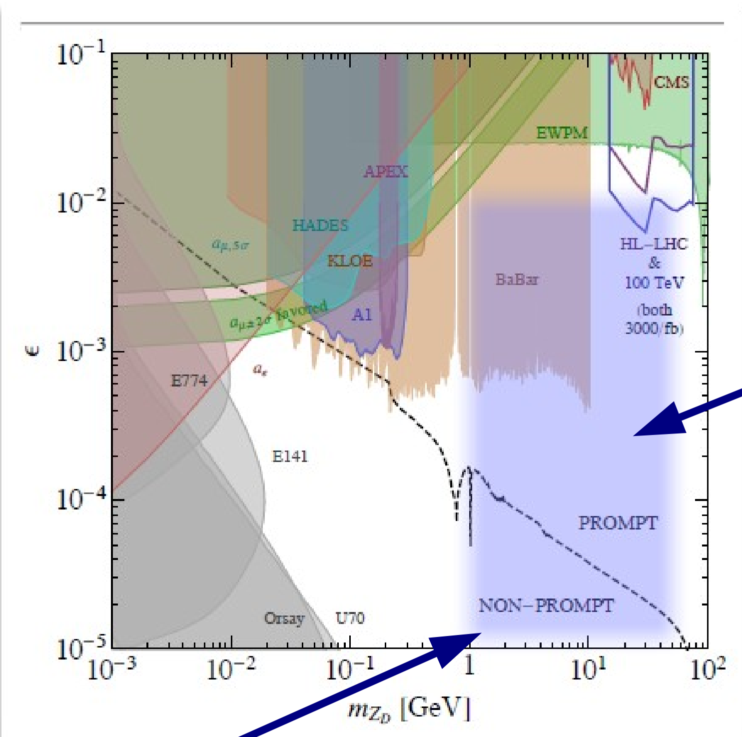
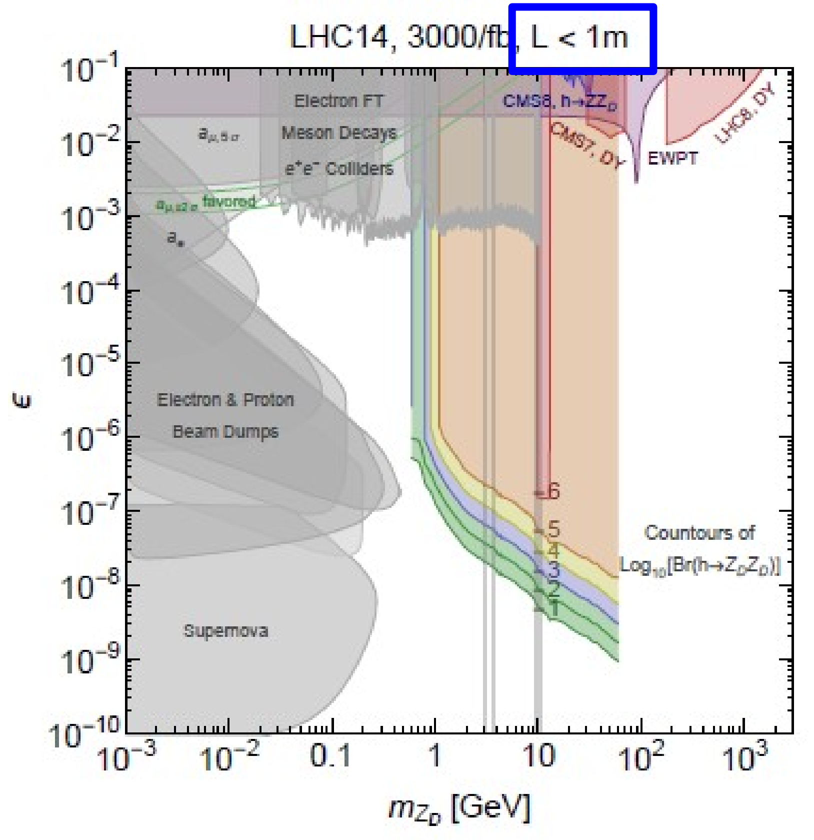


Probed by $h \to Z_D Z_D$

Accessible?

Let´s estimate...



Probabilty for Z_D to decay inside the detector

The BR we measure

$$\text{BR}_{\text{eff}} = \text{BR}(h \to Z_D Z_D)\, P(L, \sqrt{s}, m_{Z_D}, \epsilon)$$

	EM	Weak	Strong	New Force?
Quarks	✓	✓	✓	-
Leptons	✓	✓	—	✓no 1st gen.
Neutrinos	—	✓	—	✓no 1st gen.
Dark Matter?	—	?	—	?

A anomaly free L_μ-L_τ gauge symmetry

- $(g-2)_\mu$
- LHC bounds
- EWPMs
- Trident di-muon production

A well motivated gauge symmetry

„Benchmark theory“

L_μ-L_τ gauge symmetry

(one of the few anomaly free)

See e.g.
Salvioni, Strumia, Villadoro, Zwirner, 0911.1450

1. It can generate a hierarchy between neutrino masses and mixing, in agreement with data

- Before breaking the gauge symmetry: Θ_{23} = maximal, $\Theta_{13} = \Theta_{12} = 0$, and two neutrinos are degenerate in mass.

See e.g.
Heeck, Rodejohann, 1107.5238

- In seesaw models, with the breaking of the gauge symmetry Θ_{13} , Θ_{12} non zero and (small) splitting between the two degenerate neutrinos

2. It can address the anomaly in the flavor violating B-meson decay: $B \to K^* \mu\mu$: $\sim 3.5\sigma$

Altmannshofer, SG, Pospelov, Yavin, 1403.1269

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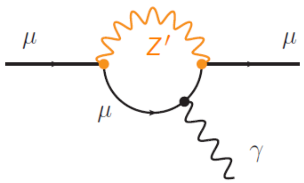
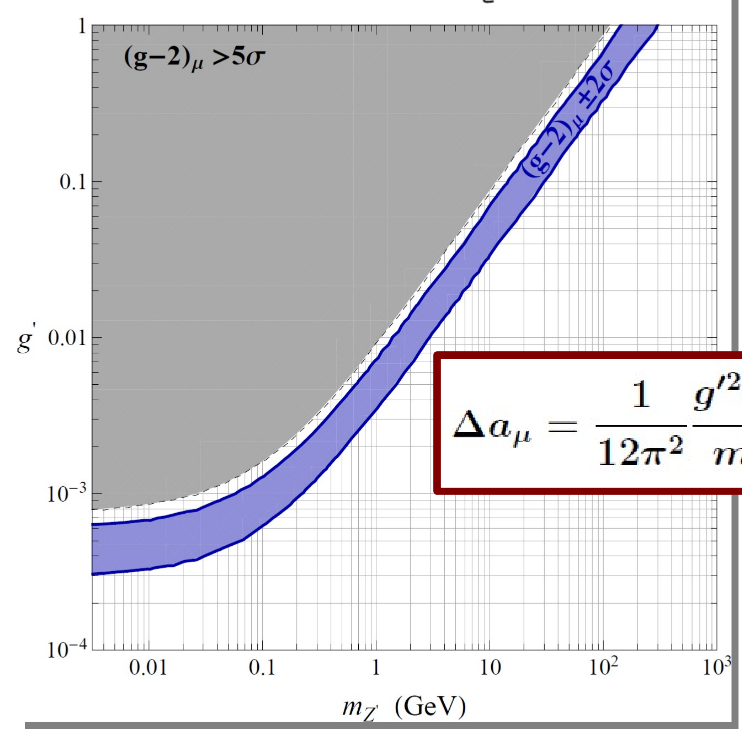




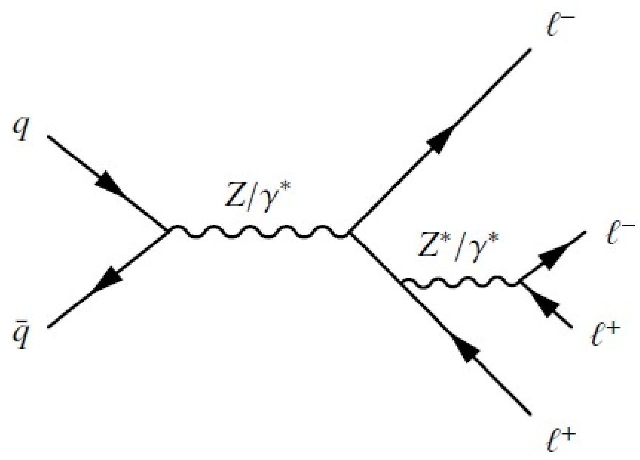
$$\Delta a_\mu = \frac{1}{12\pi^2}\frac{g'^2 m_\mu^2}{m_{Z'}^2}$$

2. It can address the anomaly in the flavor violating B-meson decay: $B \to K^* \mu\mu$: ~3.5σ
Altmannshofer, SG, Pospelov, Yavin, 1403.1269

3. It can address the anomaly in $(g-2)_\mu$: 3.2σ

A LHC multi-lepton opportunity

Measurement of the branching ratio of $Z \longrightarrow 4l$



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

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

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)

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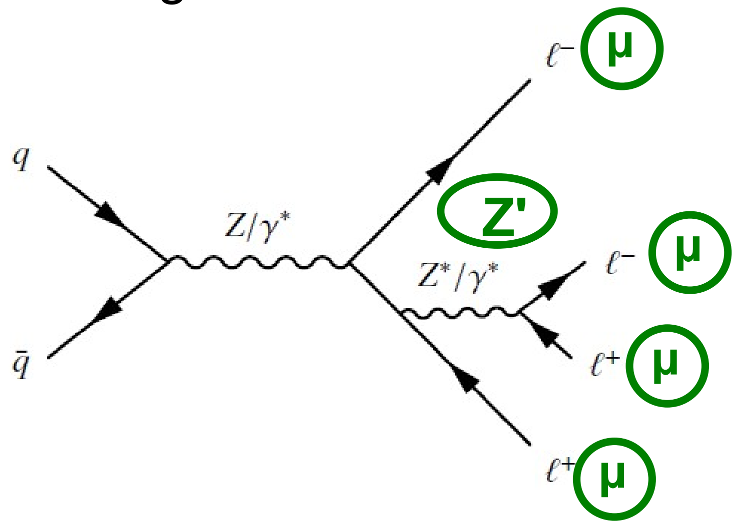

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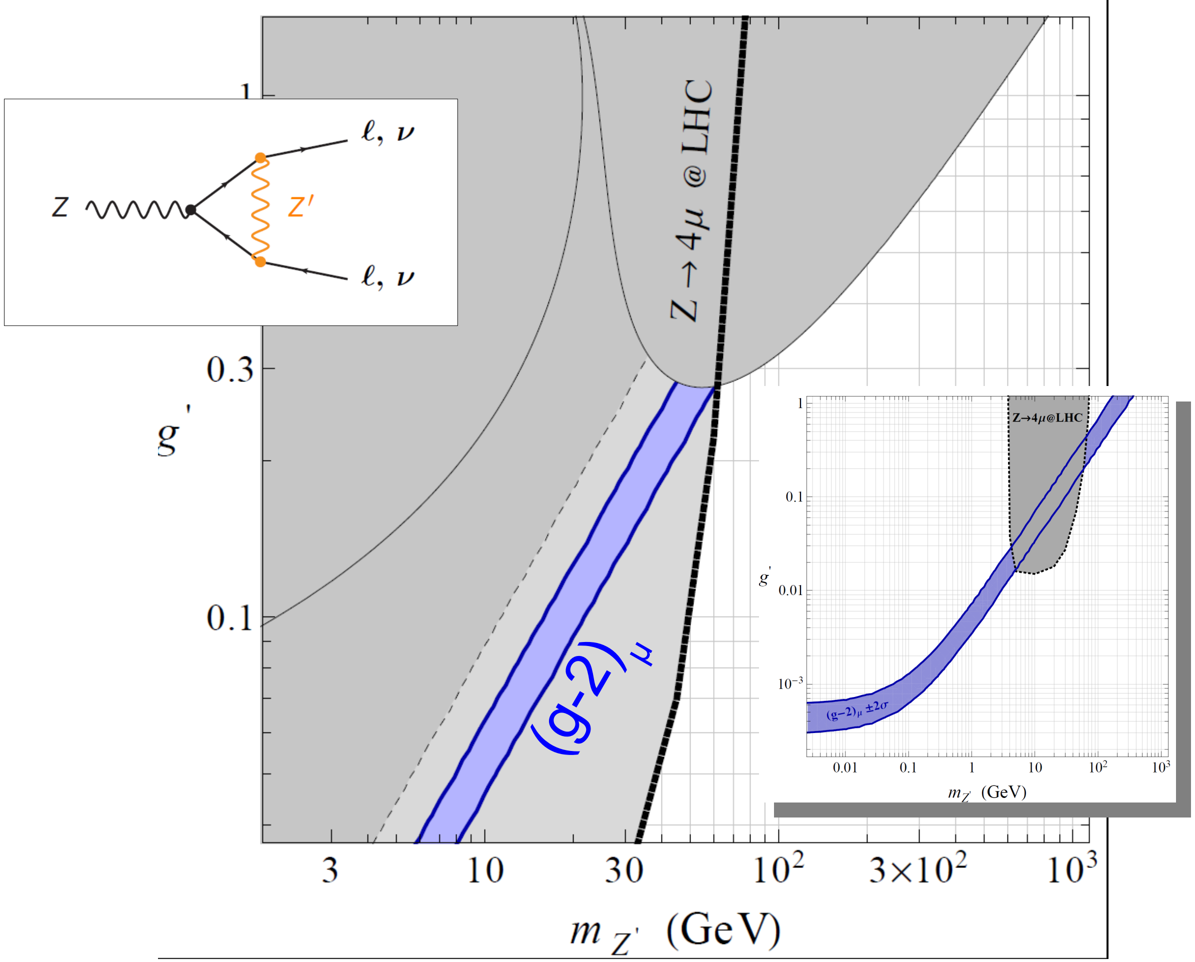
ATLAS (CONF-2013-055),
see also CMS (1210.3844)

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

Altmannshofer, SG, Pospelov, Yavin, 1403.1269



See also
Harigaya et.al.
1311.0870

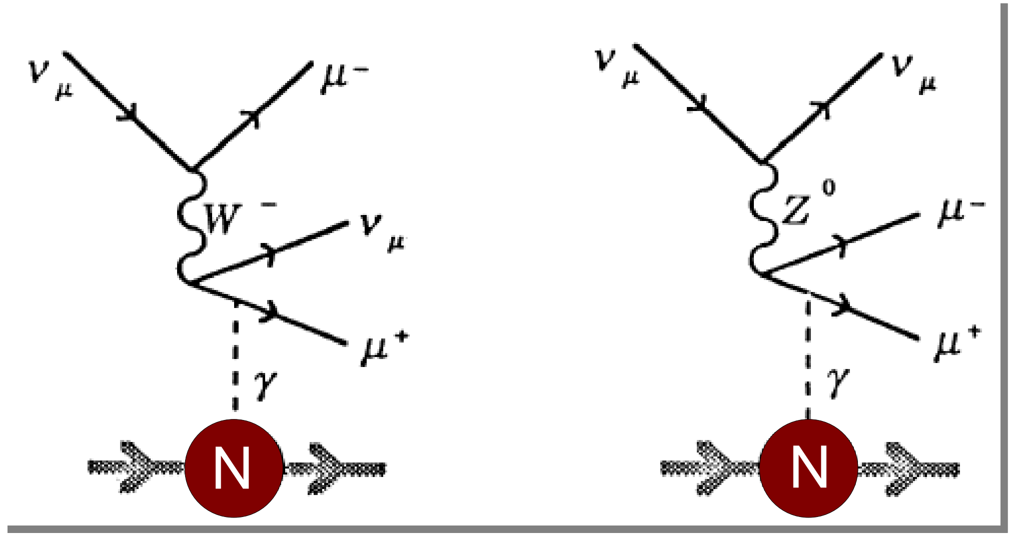
Neutrino trident di-muon production

Early 90s experiments:

- First observed by CHARMII experiment at CERN (55±16 events) (CERN-EP/90-75)

~20 GeV of neutrino/antineutrino mean energy

Difficult measurement since **small cross section**:
~5-6 orders of magnitude smaller than the inclusive neutrino-nucleus cross sec.



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~20 GeV of neutrino/antineutrino mean energy

- 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

- No conclusive evidence from the NuTeV experiment at Fermilab (Phys.Rev.D 61, 092001)

Difficult measurement since **small cross section**:
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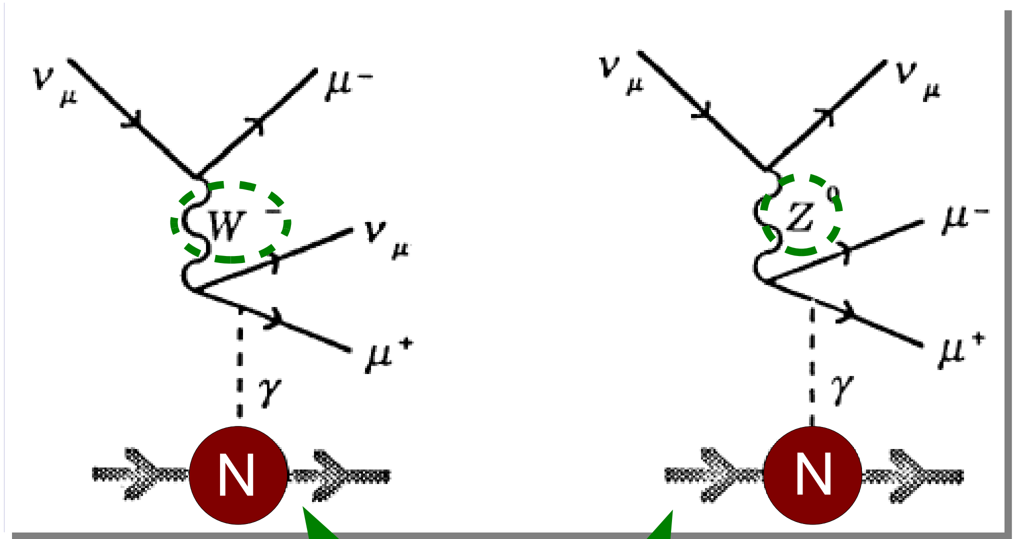
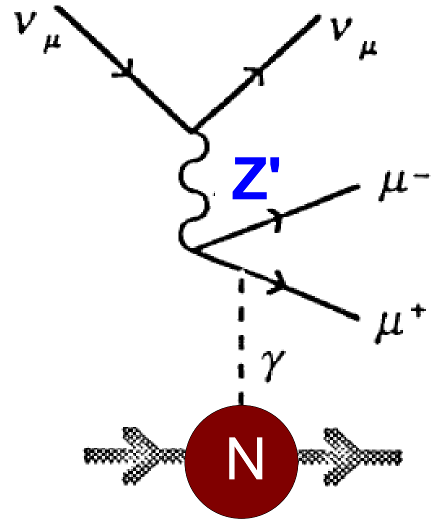


SM prediction is ~60% W contribution

$$\sigma_{\rm CHARMII}/\sigma_{\rm SM} = 1.58 \pm 0.57\ ,$$
$$\sigma_{\rm CCFR}/\sigma_{\rm SM} = 0.82 \pm 0.28\ .$$

Z' & the trident production

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



Threshold for CCFR with ~160GeV neutrinos

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

$$\frac{\sigma}{\sigma_{\mathrm{SM}}} \simeq \frac{1 + \left(1 + 4s_W^2 + 2(g')^2 v^2/m_{Z'}^2\right)^2}{1 + (1 + 4s_W^2)^2}$$

- For $m_{Z'} \lesssim 5\,\mathrm{GeV}$,
  computation of the full 2 $\longrightarrow$ 4(3) process

In particular, in the limit $m_{Z'} \ll m_\mu$

$$\sigma^{(Z')} \simeq \frac{1}{m_\mu^2} \frac{7g'^4\alpha}{72\pi^2} \log\left(\frac{m_\mu^2}{m_{Z'}^2}\right)$$

$$\sigma_{\mathrm{CCFR}}/\sigma_{\mathrm{SM}} = 0.82 \pm 0.28$$

Altmannshofer, SG, Pospelov, Yavin, 1406.2332

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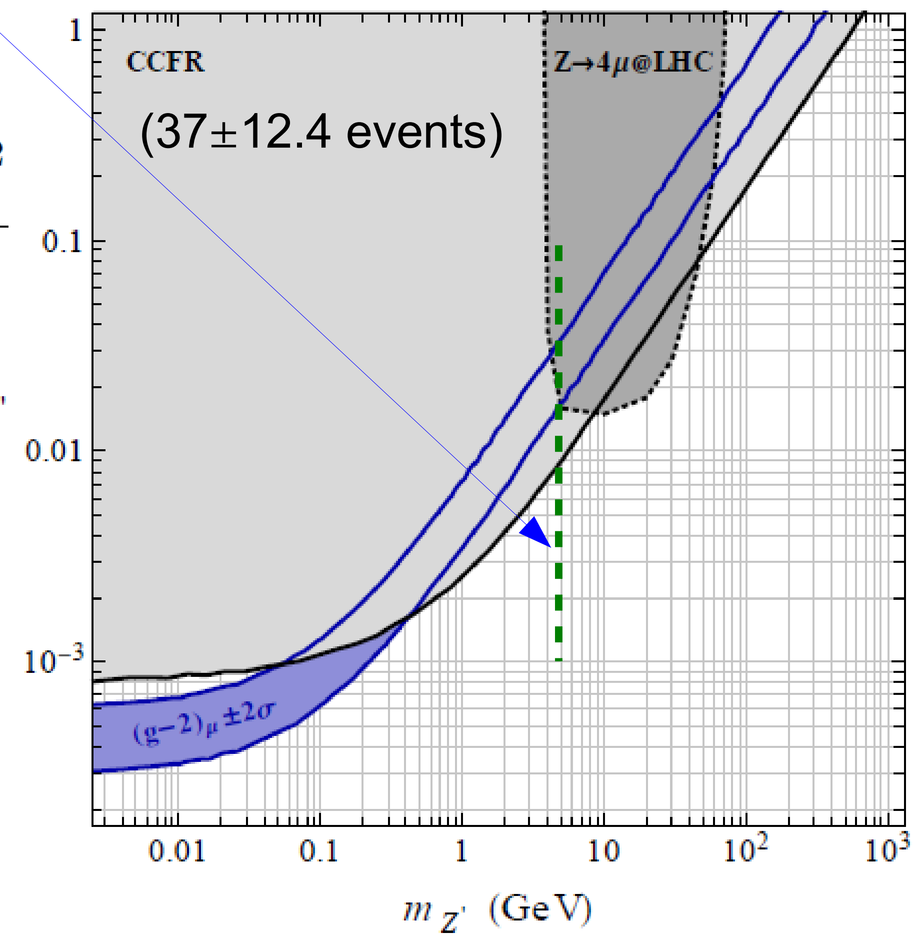
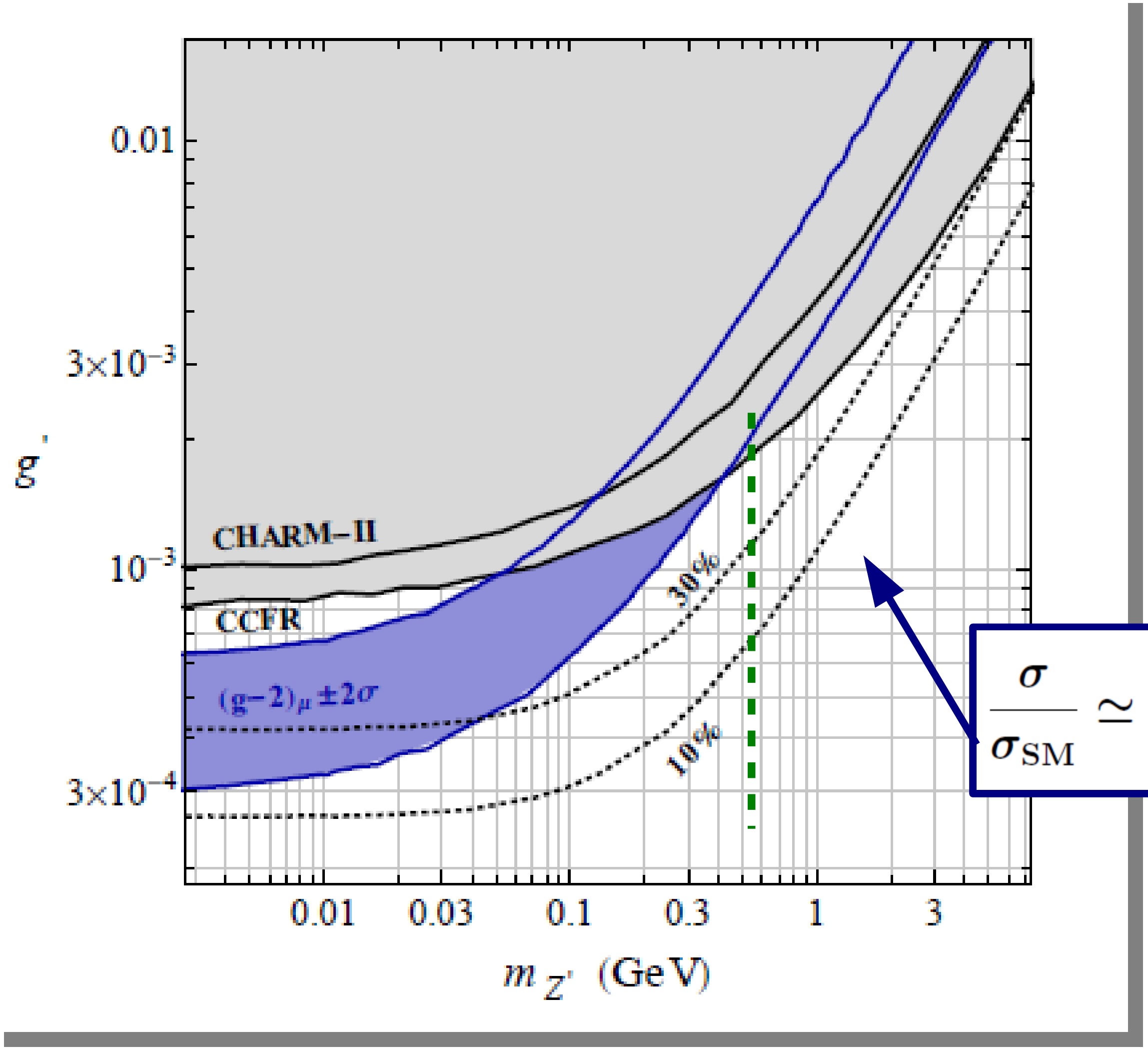


Altmannshofer, SG, Pospelov, Yavin, 1406.2332

Great future prospects

Example for 5 GeV neutrinos on Argon



$$\frac{\sigma}{\sigma_{\rm SM}} \simeq \frac{1+\left(1+4s_W^2+2(g')^2v^2/m_{Z'}^2\right)^2}{1+\left(1+4s_W^2\right)^2}$$

Great opportunity for low energy neutrino experiments!

Z' @ future neutrino experiments

What are the prospects for measuring this process at the near detector of LBNE?

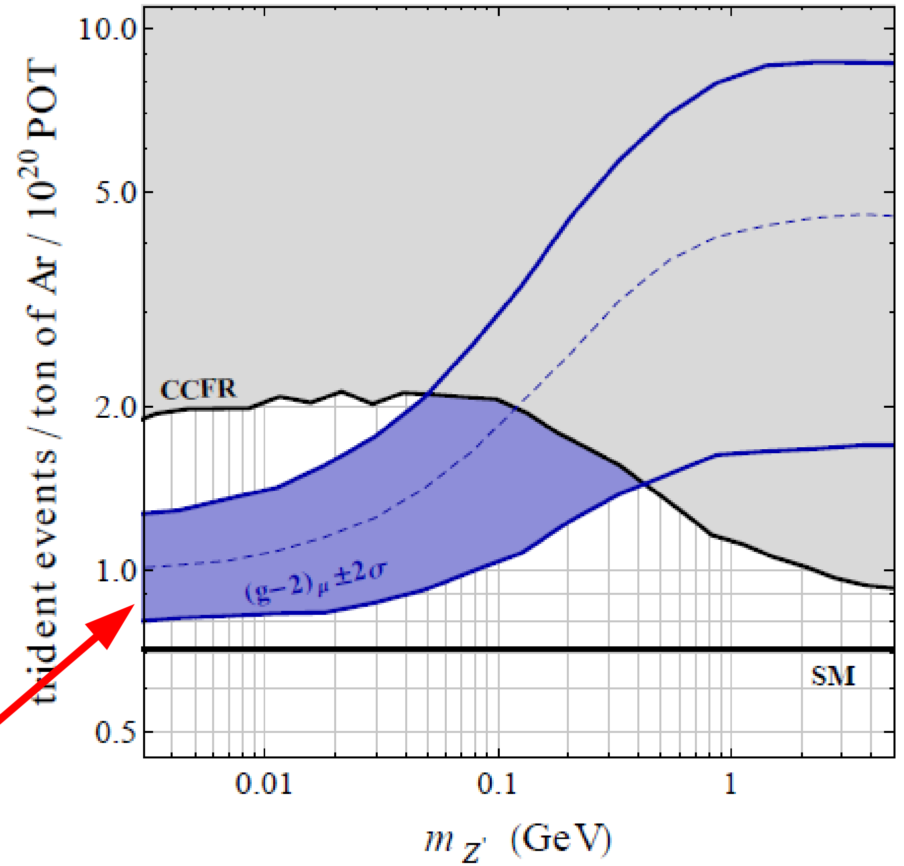
- Huge detector: 18ton Argon
- Huge number of protons on target: $6*10^{20}$ POT/year
- Huge rate for the charge current: ~26 M/year
- Neutrinos with a smaller energy: (2-5)GeV

LBNE collaboration, 1307.7335

Assumed CC events: ~ 236 K/ton/10^{20}POT

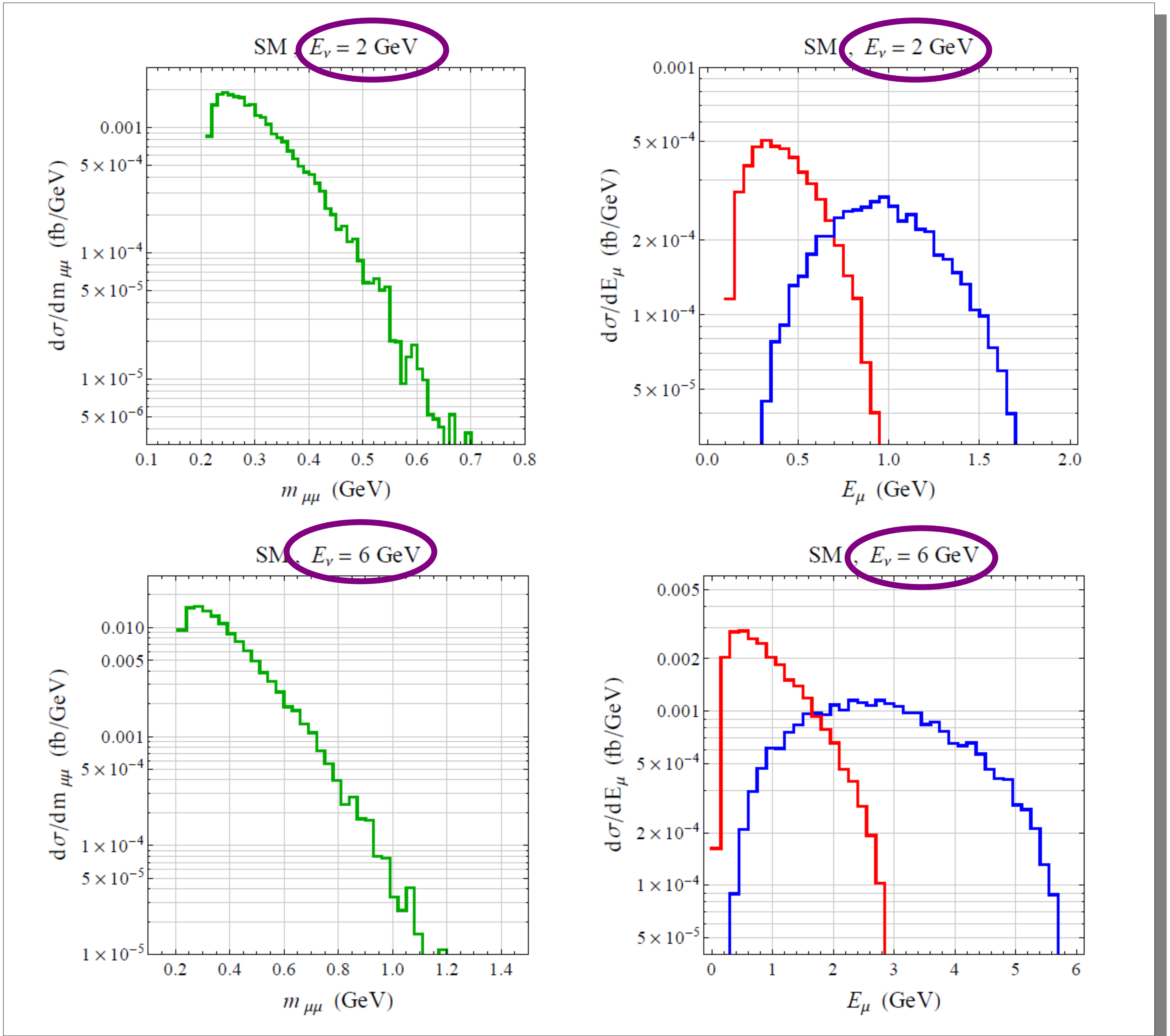
This corresponds to ~100 signal events/year

Altmannshofer, SG, Pospelov, Yavin, 1406.2332



An interesting analysis

Work
in
progress...



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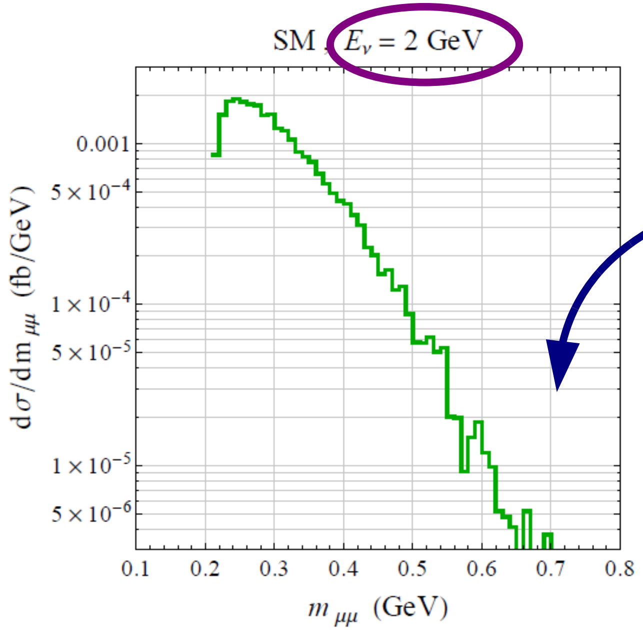
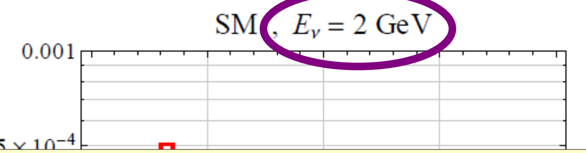
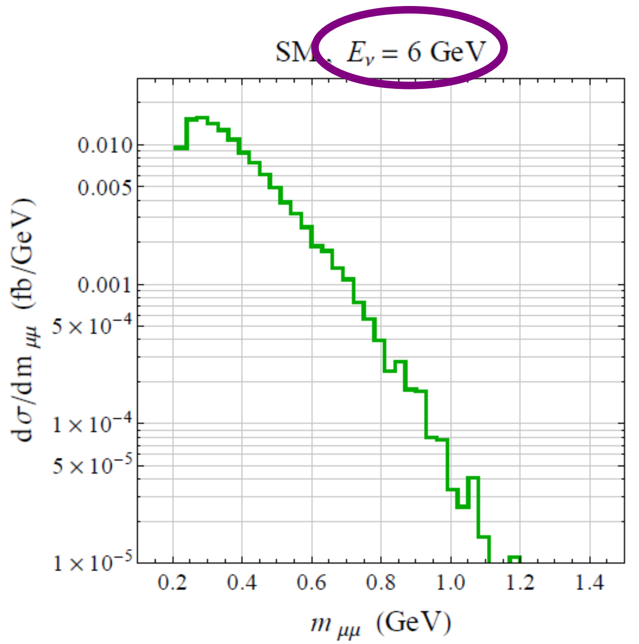


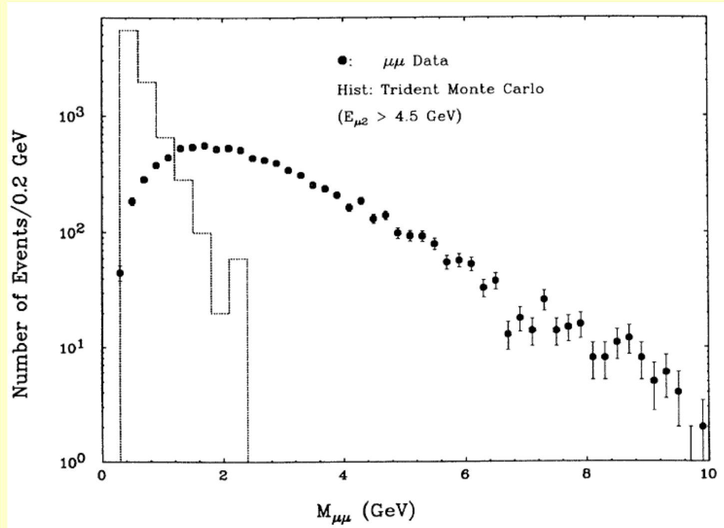




Charm background

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

should come at
higher invariant masses



From CCFR, Phys.Rev.Lett. 66, 3117

0 1 2 3 4 5 6
E_μ (GeV)

Work
in
progress...

 S.Gori

Conclusions & lessons

Great opportunity to test new light forces using multi-lepton signatures!

Hadron machines

- Interesting possibility of testing Z_D gauge bosons using new Higgs boson decays
- We will incredibly benefit from the High-Luminosity LHC, since the signature is very clean
- We can set bounds BR($h \to Z_D Z_D \to 4l$) ~ few*10^{-7} !

Neutrino facilities

The new force will generically couple to the neutrinos.

Possibility of totally closing the $(g-2)_\mu$ window at the LBNE

Going to higher energy?

What we will gain on the Higgs exo. decays going to higher energy?

Huge productions!

	$\sqrt{S}$=14 TeV	$\sqrt{S}$=33 TeV	$\sqrt{S}$=100 TeV
ggF	50.4 pb	178 pb	740 pb
VBF	4.4 pb	17 pb	82 pb
WH	1.6 pb	4.7 pb	16 pb
ttH	.62 pb	4.6 pb	38 pb
HH	.034 pb	.2 pb	1 pb

Higgs cross section working group

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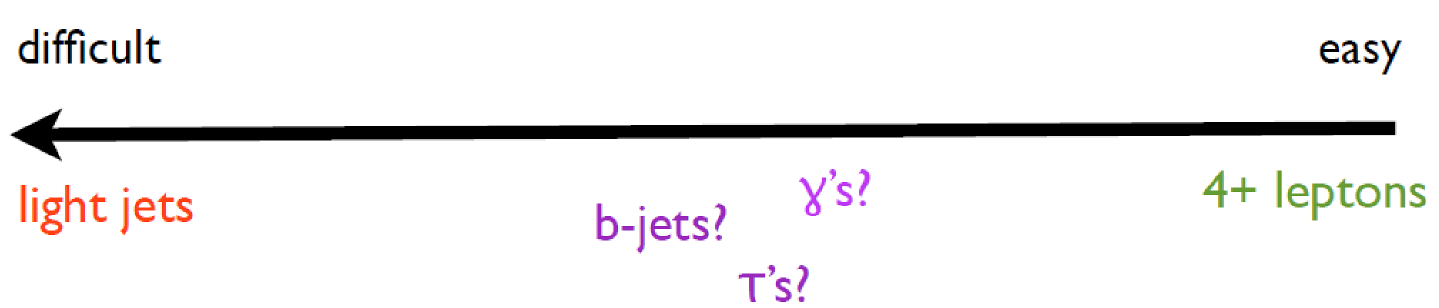
Higgs cross section working group

1. Difficult decay modes
Benefit from having „accessible“ Higgs production in association with tops, Z bosons, ...

2. Clean decay modes
At the high-lumi LHC, we cannot expect to be able to put bounds on $BR_{exo} \leq 10^{-6}$-10^{-7} because of the lack of statistics



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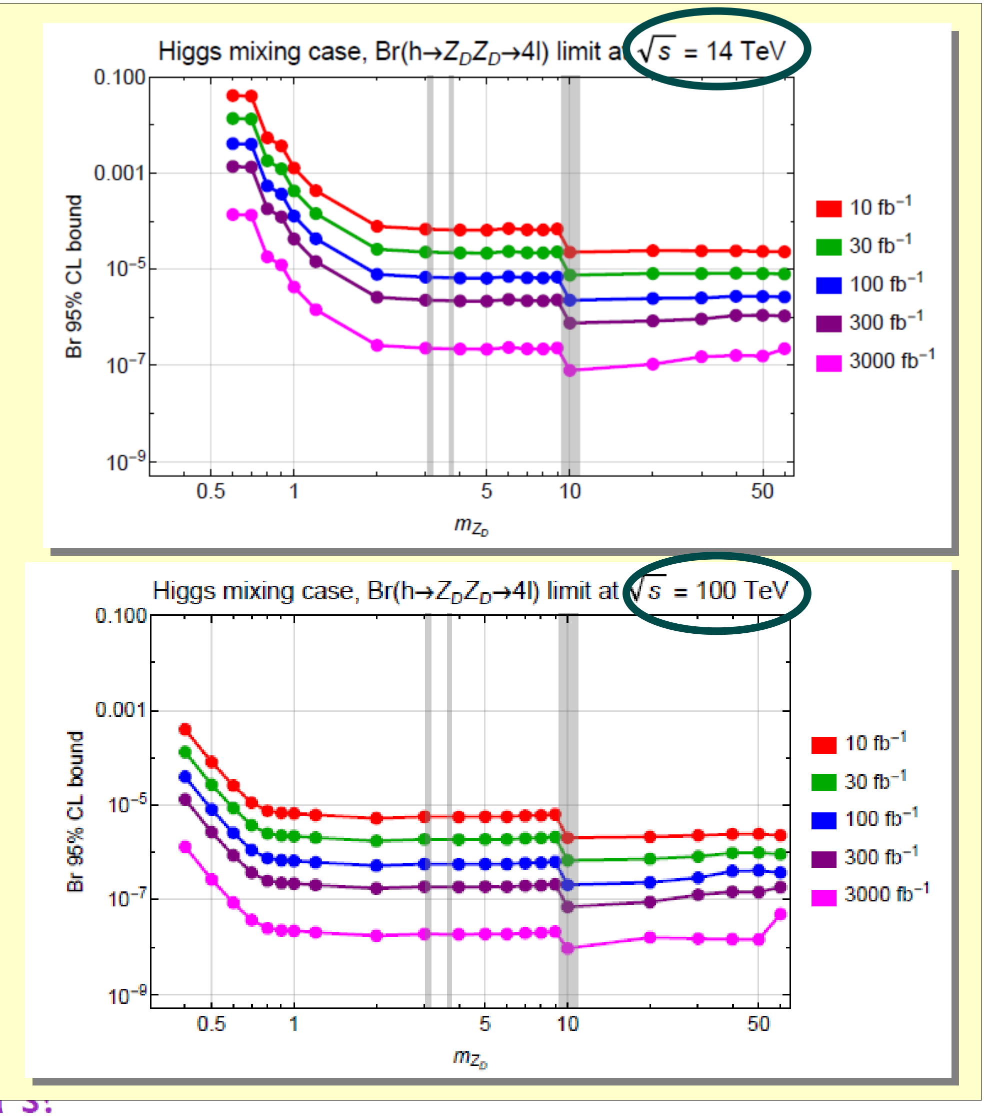


1. Difficult decay modes

Benefit from having „accessible" Higgs production in association with tops, Z bosons, ...

difficult

light jets

b-jets?

Our assumptions

1. The observed 125 GeV is SM-like

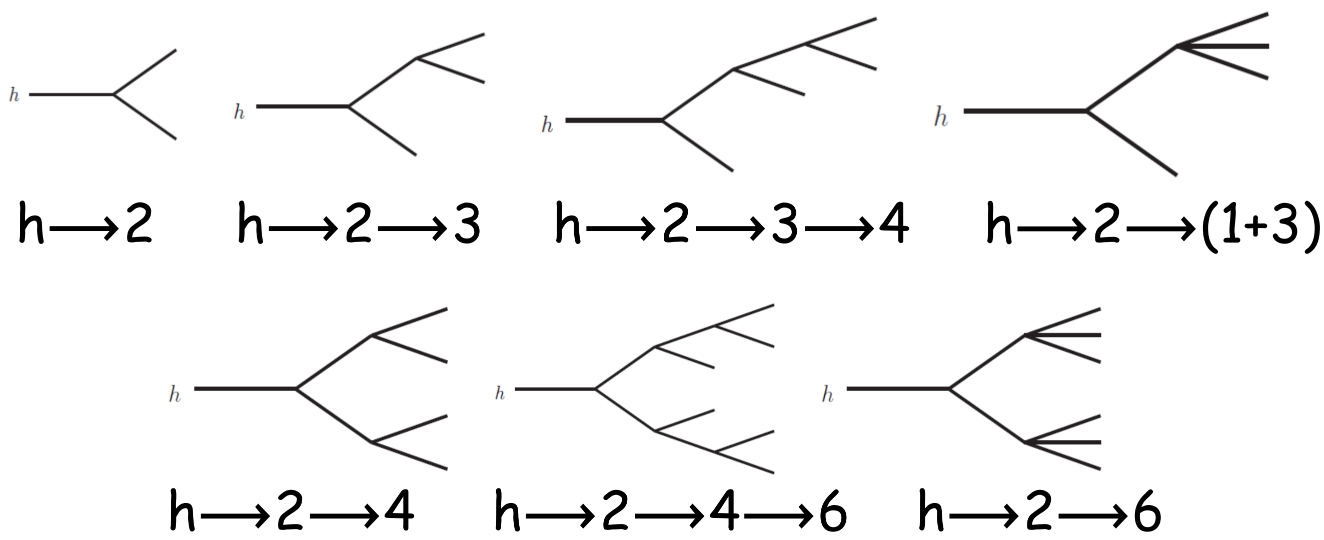
• In particular its production cross section in the several channels is the one of the SM Higgs

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

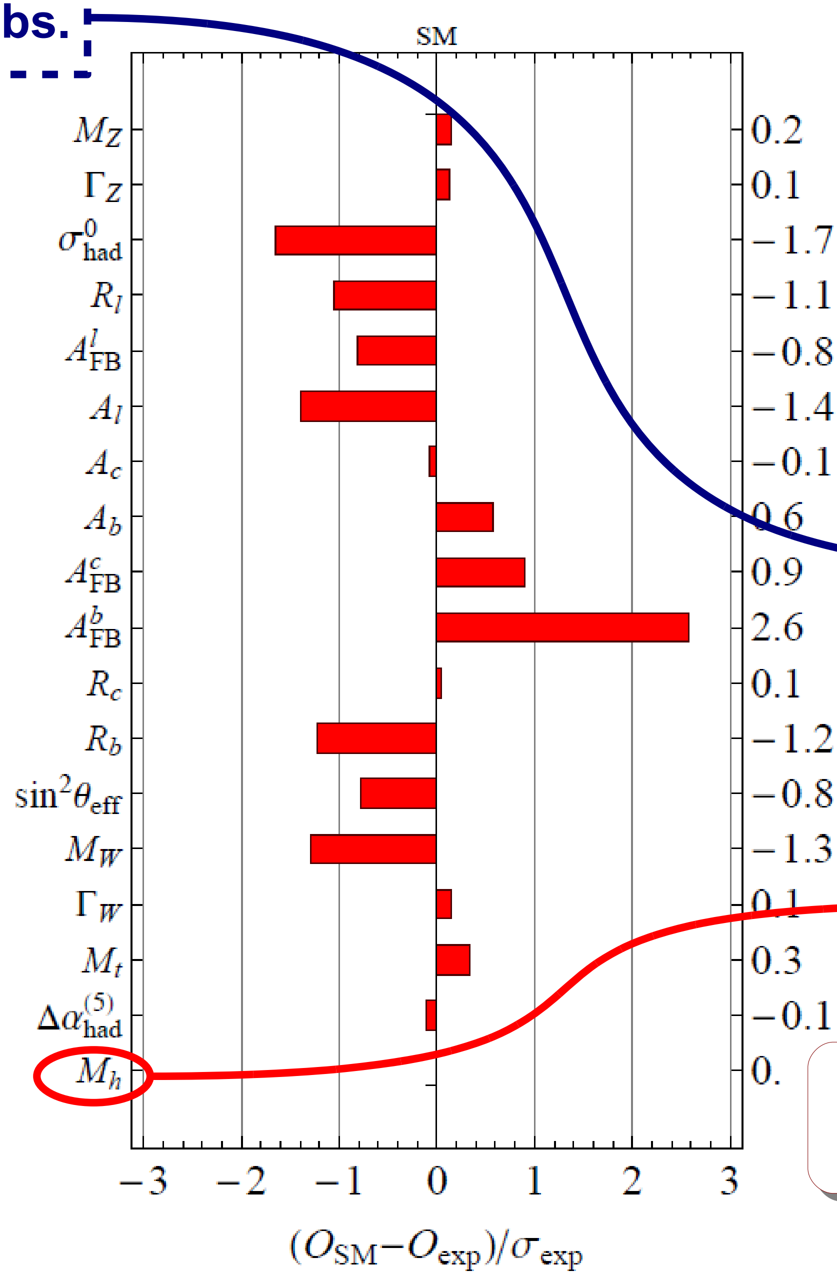
• 3-body decays are possible, but require new light states with substantial coupling to h to overcome phase space suppression



h→MET	h→$Z_D Z_D$→4l
h→4b	h→γ+MET
h→2b2τ	h→2γ+MET
h→2b2μ	h→4l+MET
h→4τ, 2τ2μ	h→2l+MET
h→4j	h→one lepton jet
h→2γ2j	h→two lepton jets
h→4γ	h→bb+MET
h→ZZ_D→4l	h→ττ+MET

Z' „indirect“ searches

Z' obs.



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

Is the ew sector of nature now complete?

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

Last ingredient to complete the SM: the Higgs mass

p-value = 0.21

My fit, following the Gfitter procedure

Higgs width: direct measurement

CMS PAS HIG-14-002

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

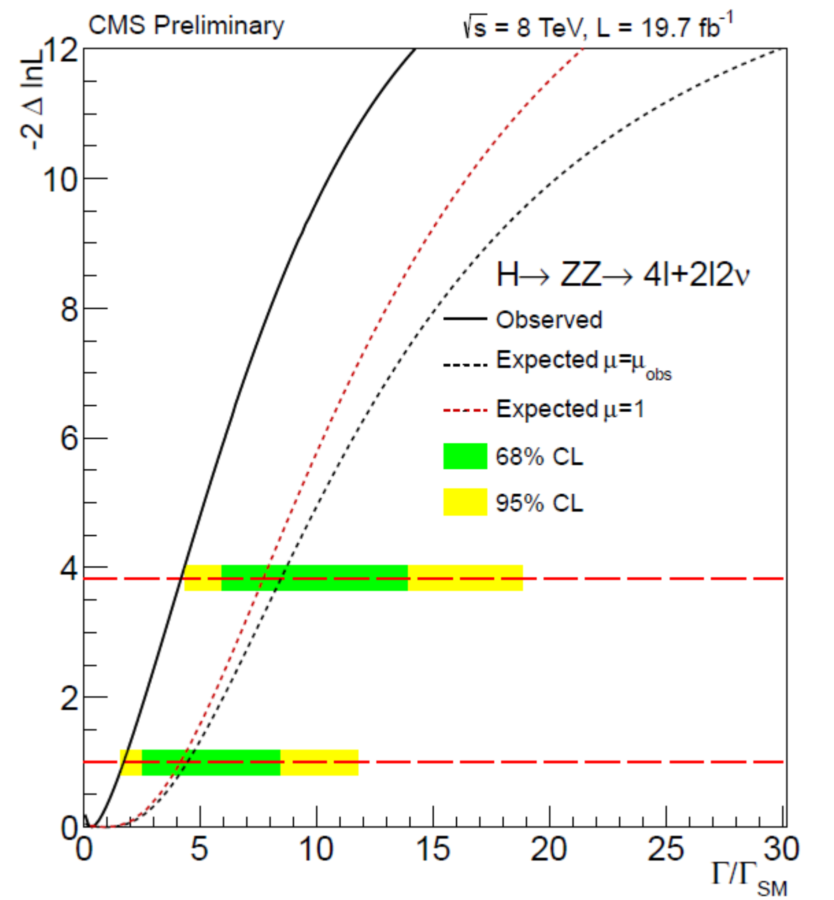
Very interesting new CMS measurement

In a nutshell:

$$\begin{cases} \sigma_{gg\to H\to ZZ}^{\mathrm{on-peak}} = \dfrac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot\mathrm{BR})_{\mathrm{SM}} \equiv \mu(\sigma\cdot\mathrm{BR})_{\mathrm{SM}} \\ \dfrac{\sigma_{gg\to H\to ZZ}^{\mathrm{off-peak}}}{dm_{ZZ}} = \kappa_g^2\kappa_Z^2\dfrac{\sigma_{gg\to H\to ZZ}^{\mathrm{off-peak,\,SM}}}{dm_{ZZ}} \equiv \mu r\dfrac{\sigma_{gg\to H\to ZZ}^{\mathrm{off-peak,\,SM}}}{dm_{ZZ}} \end{cases}$$

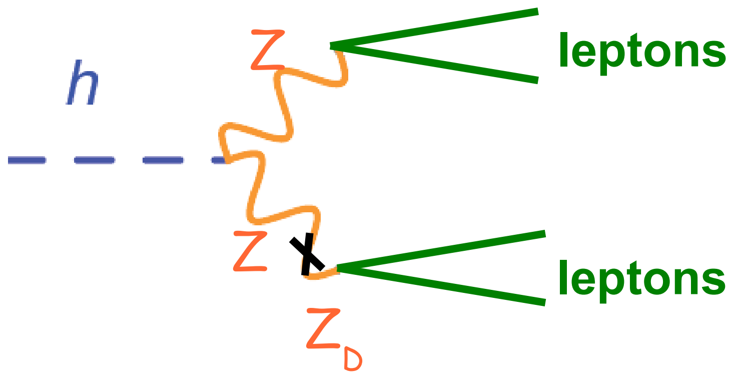
$$\kappa_g = g_{ggH}/g_{ggH}^{\mathrm{SM}}$$
$$\kappa_Z = g_{HZZ}/g_{HZZ}^{\mathrm{SM}}$$
$$r = \Gamma_H/\Gamma_H^{\mathrm{SM}}$$

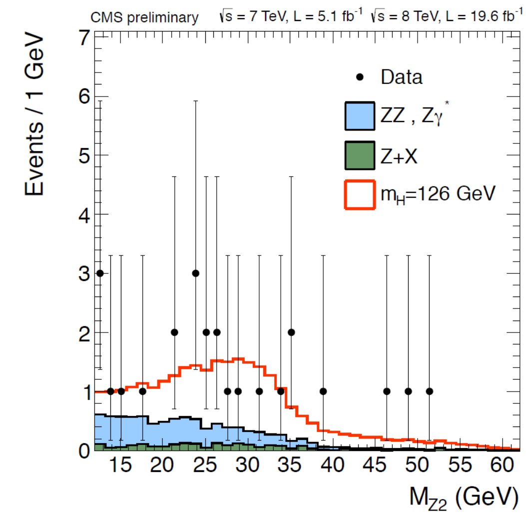
$\Gamma_H < 4.2(8.5)\ \Gamma_{H,SM}$



Combining the 4l and the 2l2v channels

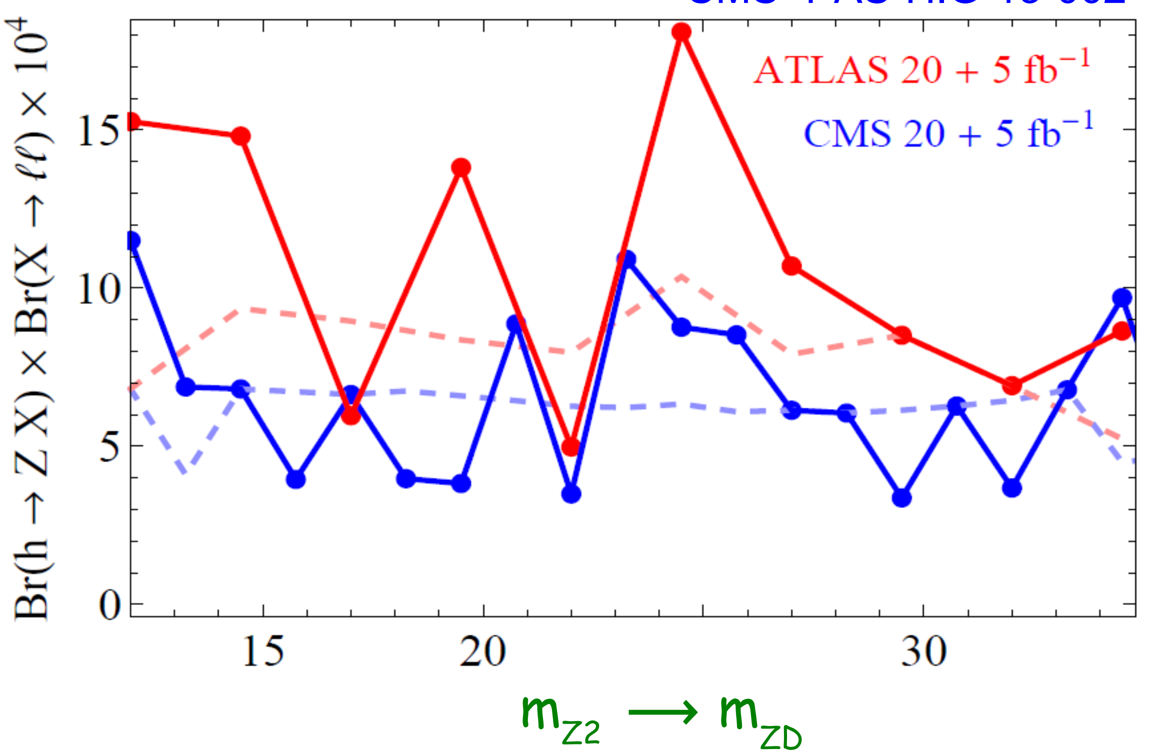
Present bound

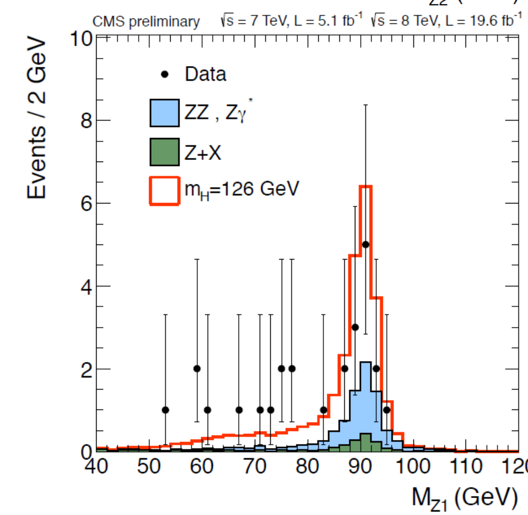




Counting experiment:

ATLAS-CONF-2014-009,
CMS- PAS-HIG-13-002





Bound from the CMS, ATLAS h⟶ZZ* analysis

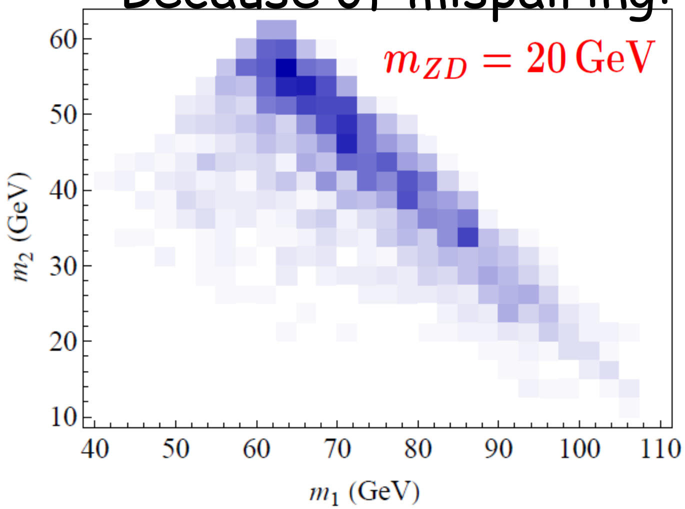
$BR(h \longrightarrow ZZ_D) \sim 10^{-3}$ are already probed with the present (un-dedicated) (7+8) TeV LHC searches

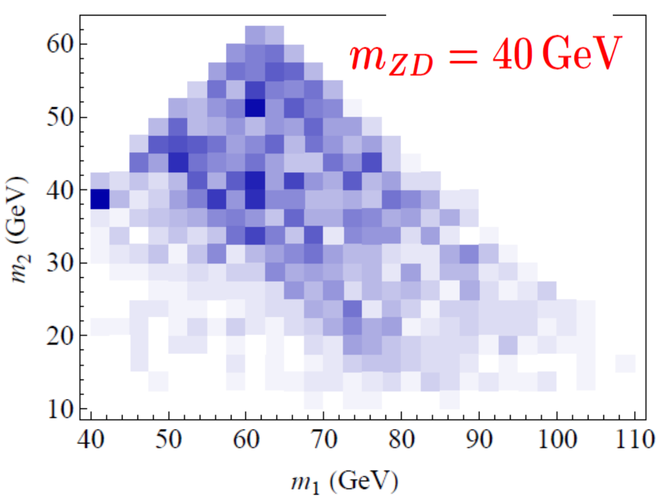
Setting bounds on $Z_D Z_D$: present

Bounds coming from SM $h \to ZZ^* \to 4l$ searches at the LHC
CMS PAS HIG-13-002, ATLAS-CONF-2013-013

Because of mispairing:

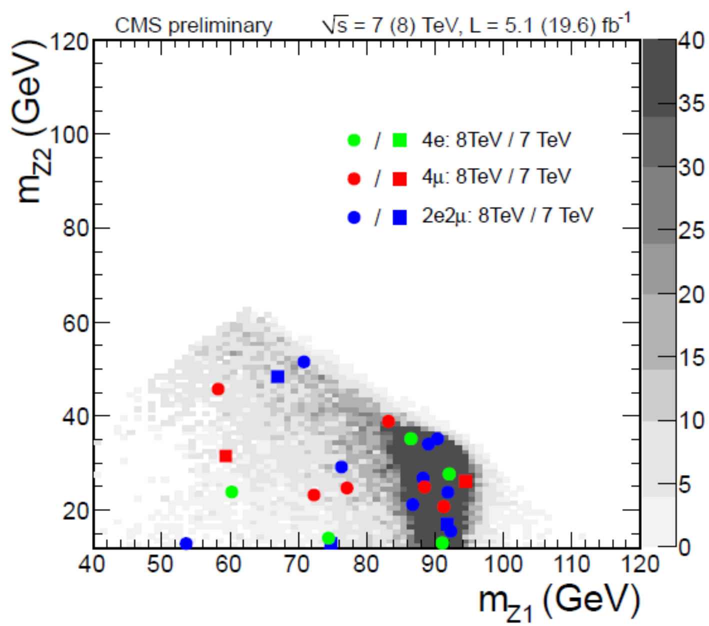
Our signal





40 GeV < m_1 < 120 GeV,
12 GeV < m_2 < 120 GeV

To compare to the experimental data:



CMS PAS HIG-13-002

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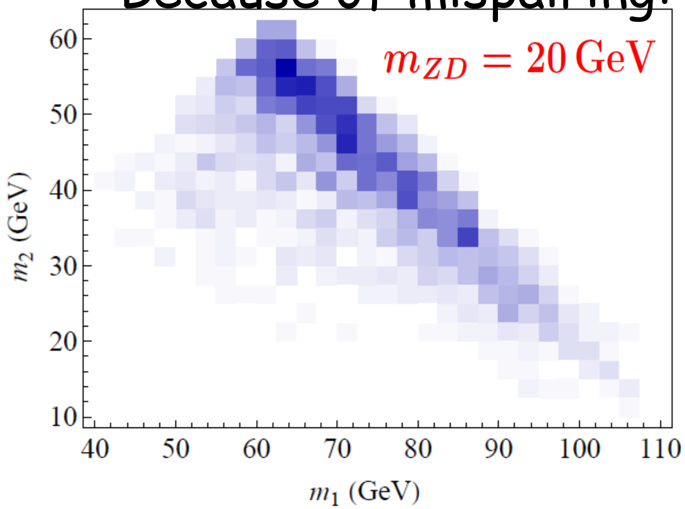

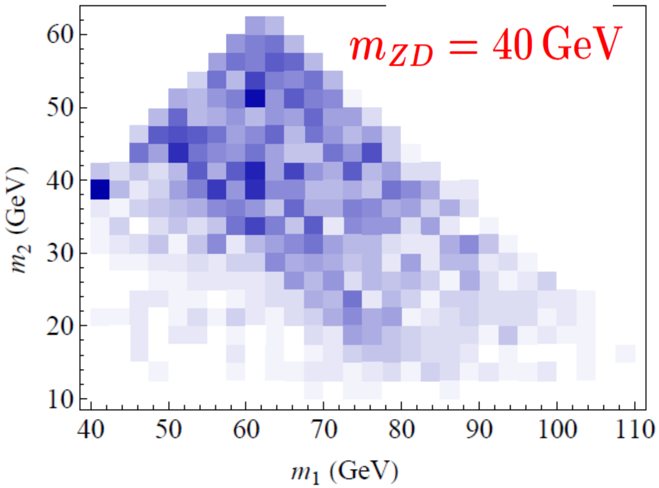

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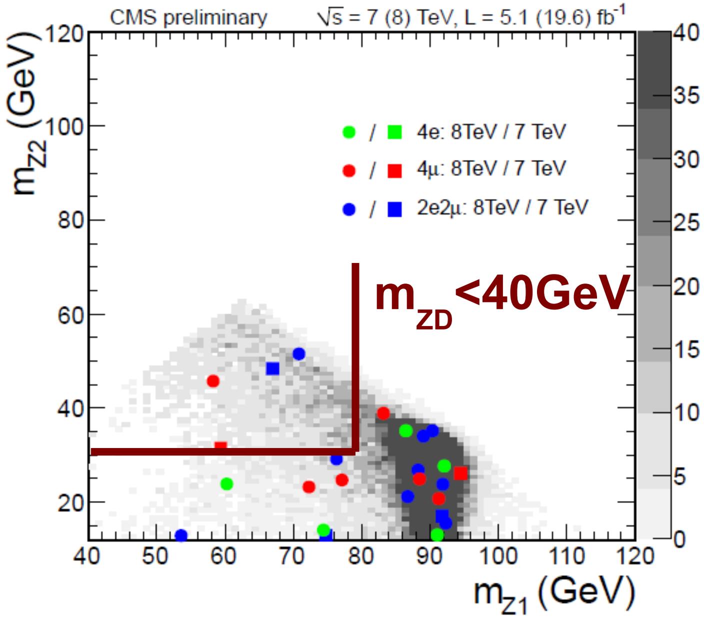


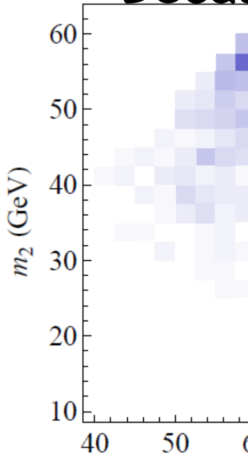
CMS PAS HIG-13-002

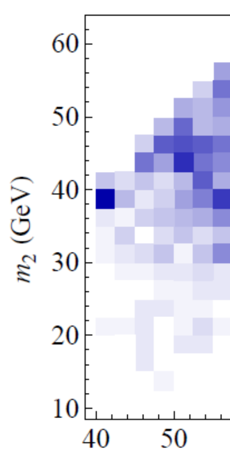
For m_{ZD}>40GeV:
m_{ZD} ± 5 GeV

Setting bounds on $Z_D Z_D$: present

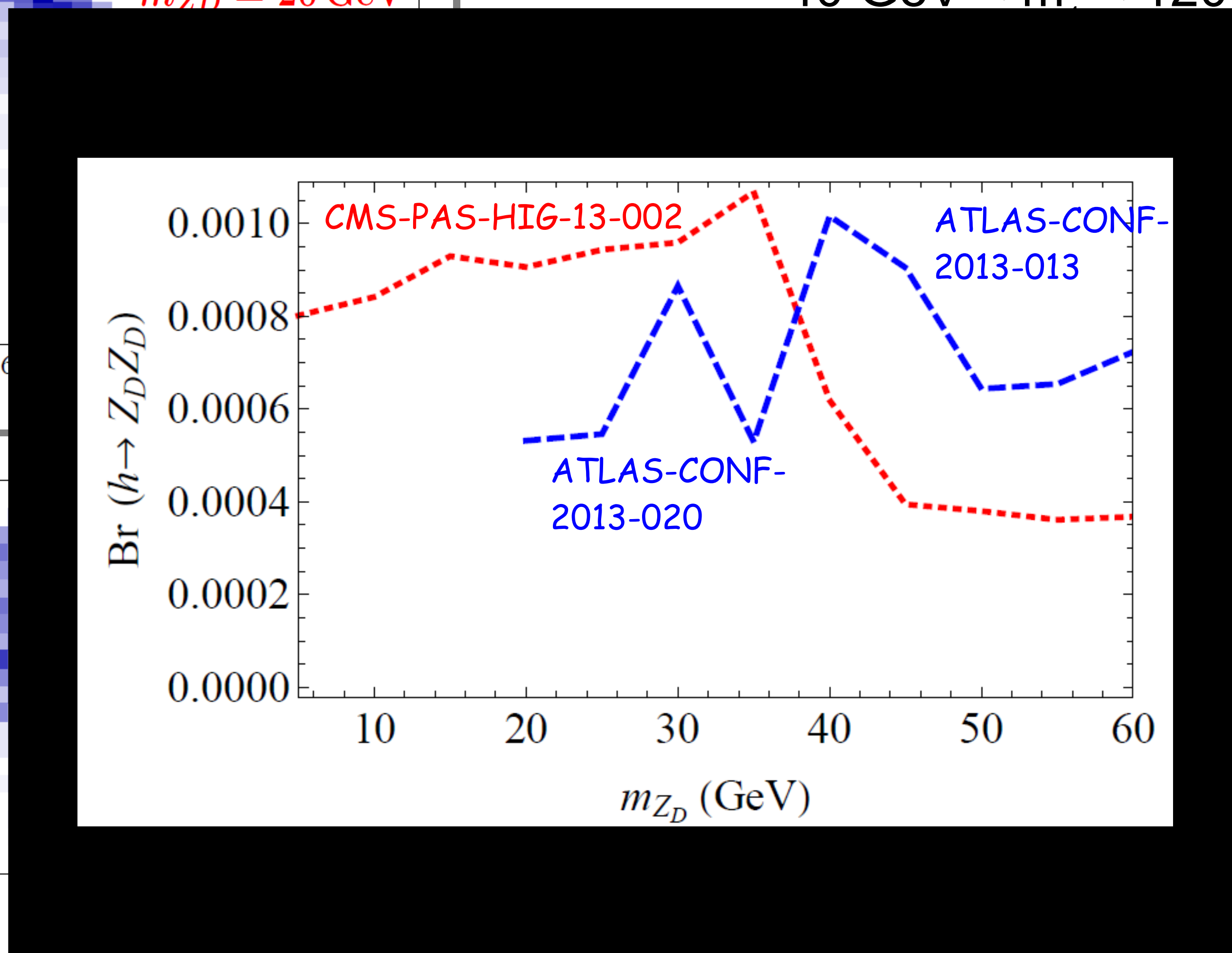
Bounds coming from SM h → ZZ*→ 4l searches at the LHC
CMS PAS HIG-13-002, ATLAS-CONF-2013-013

Because of mispairing:





Our signal



40 GeV < m_ < 120 GeV,
GeV

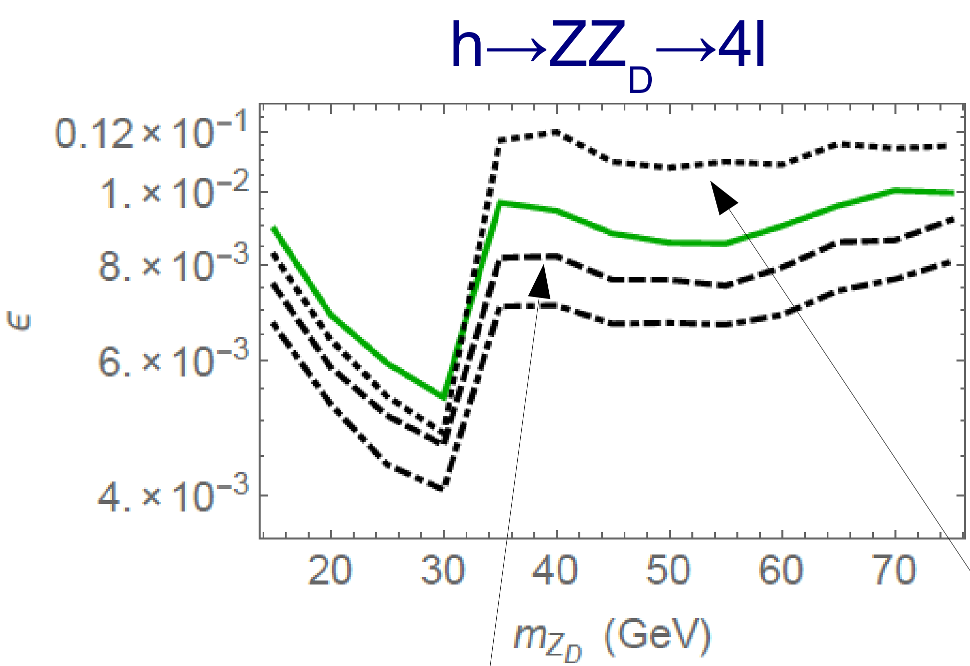
ntal data:

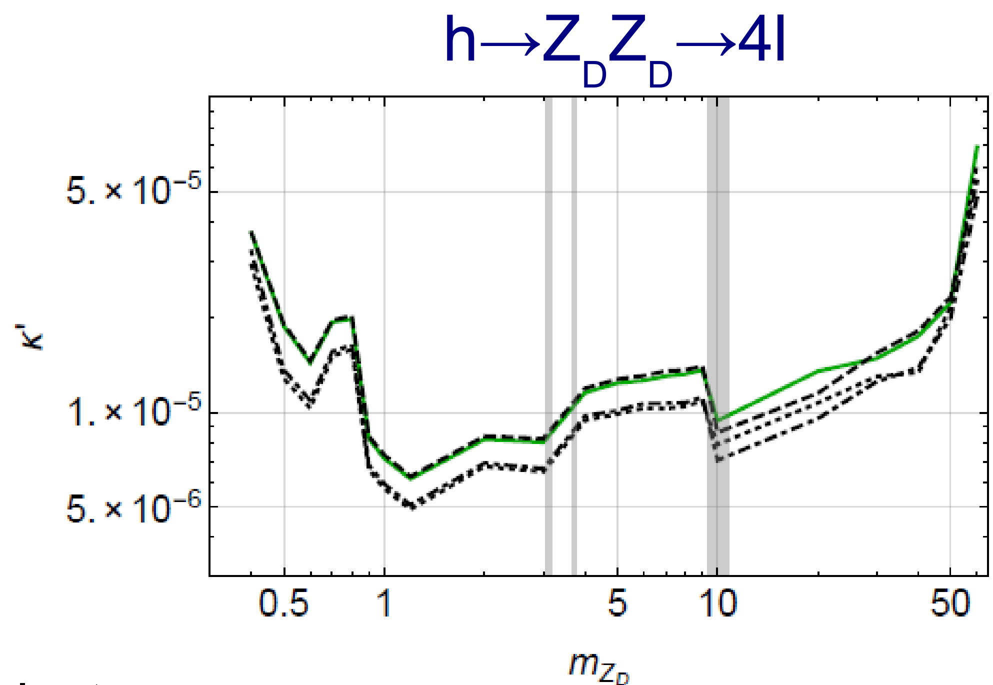
For m_{ZD}>40GeV:
m_{ZD} ± 5 GeV

CMS PAS HIG-13-002

Importance of detector design

Reach at 100 TeV, with 3000 fb^{-1}





Increased lepton acceptance |η|<4

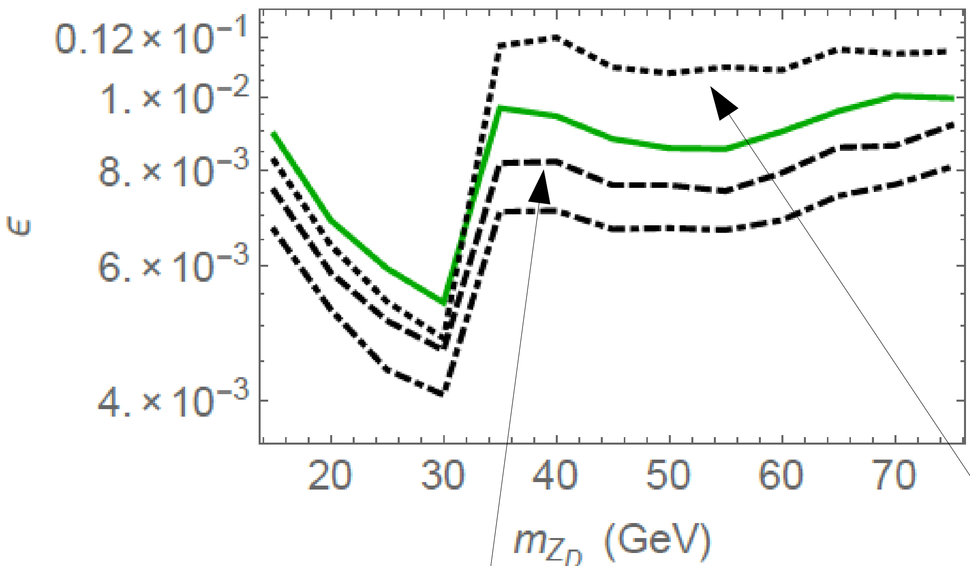
Improved mass resolution

$$|M_{\ell\ell} - m_{Z_D}| < 0.015\, M_{\ell\ell}$$

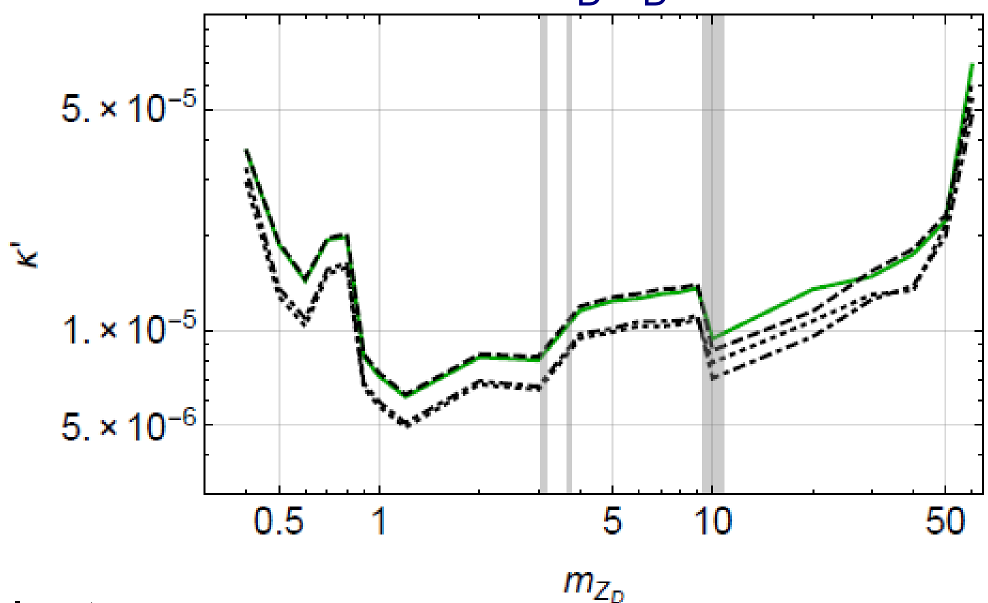
Importance of detector design

Reach at 100 TeV, with 3000 fb^{-1}

$h \to Z Z_D \to 4l$



$h \to Z_D Z_D \to 4l$



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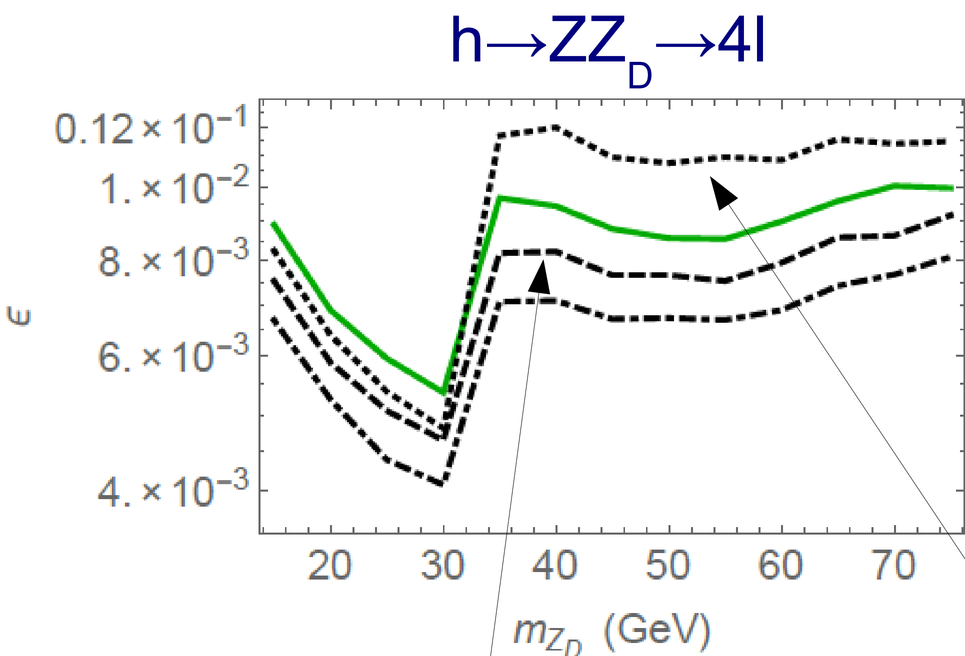

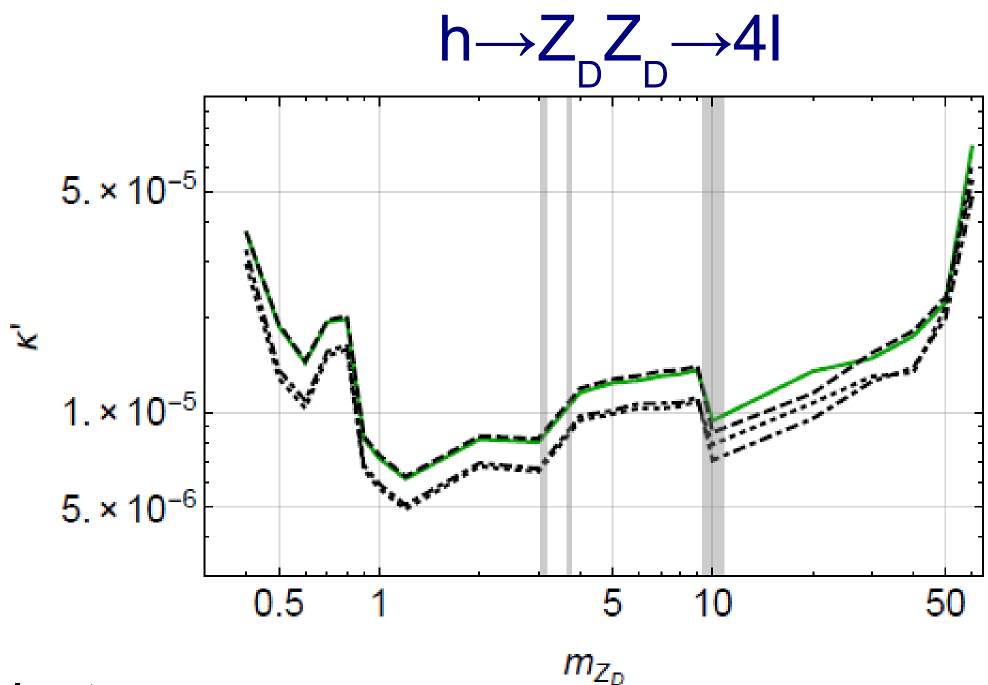

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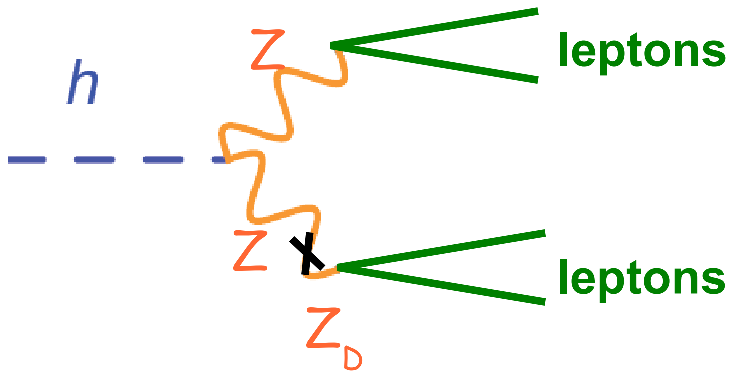
Present bound ZZ_D



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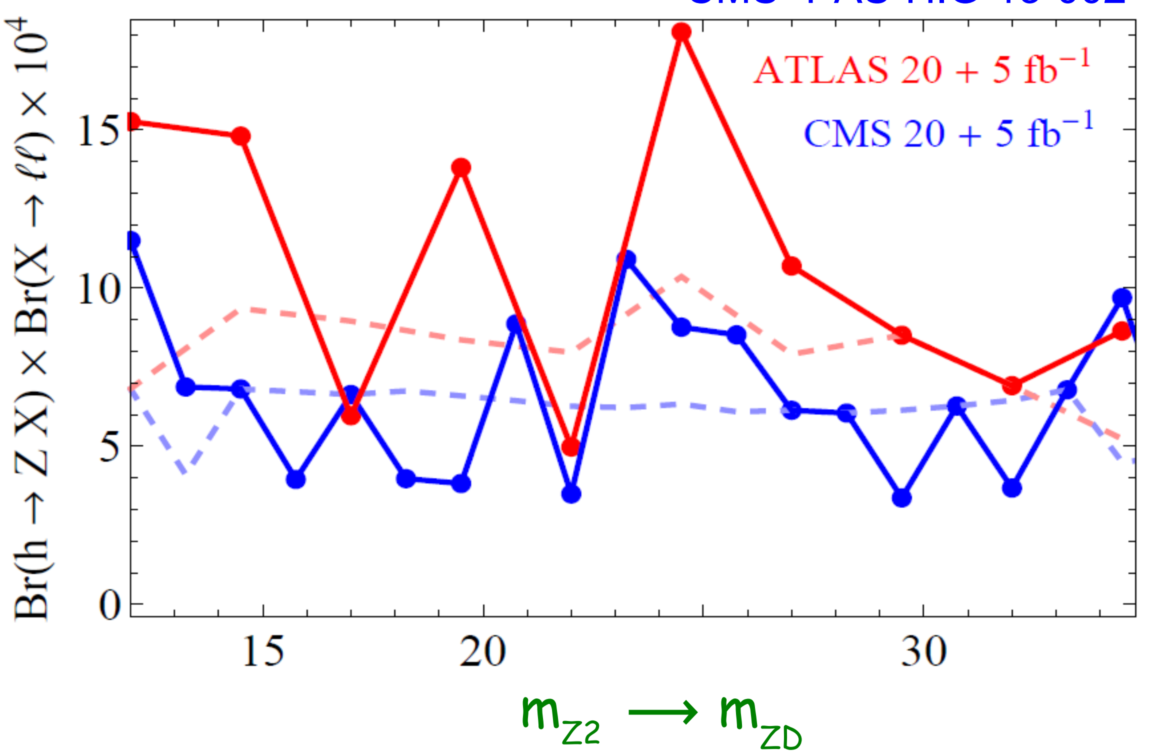
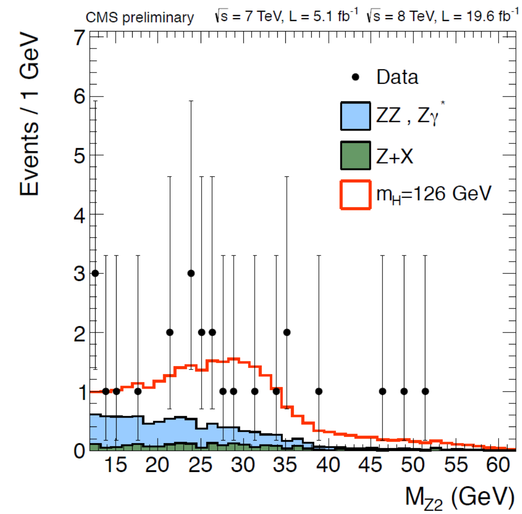
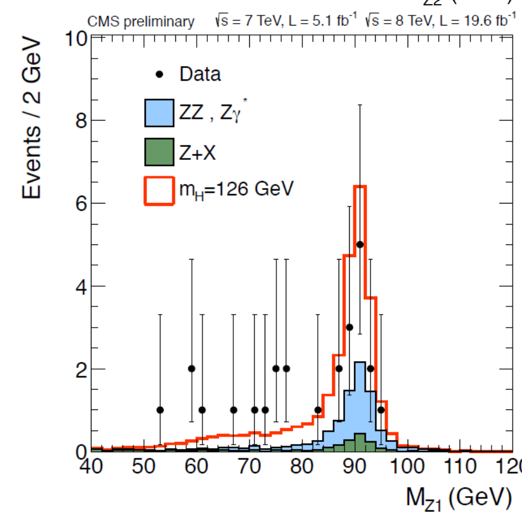
CMS- PAS-HIG-13-002







Bound from the CMS, ATLAS h⟶ZZ* analysis

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

The final aim

$h \longrightarrow ZZ_D$, $h \longrightarrow Z_D Z_D$

Exotic scorecard

	jj	bb	$\tau\tau$	ll	$\nu\nu$
jj					
bb					
$\tau\tau$					
ll					
$\nu\nu$					

Prospects?

Initial attempt for $h \longrightarrow Z_D Z_D$ (by theorists)

Decay Mode $\mathcal{F}_i$	Projected/Current 2σ Limit on $\mathrm{BR}(\mathcal{F}_i)$ 7+8 [14] TeV	Production Mode	$\frac{\mathrm{BR}(\mathcal{F}_i)}{\mathrm{BR}(non-SM)}$	Limit on $\frac{\sigma}{\sigma_{\mathrm{SM}}} \cdot \mathrm{BR}(\text{non-SM})$ 7+8 [14] TeV
$jjjj$	> 1 [0.1*]	W	0.25	> 1 [0.4*]
$\ell\ell\ell\ell$	$4 \cdot 10^{-5}$	G	0.09	$4 \cdot 10^{-4}$
$jj\mu\mu$	$0.002 - 0.008$ $[(5 - 20) \cdot 10^{-4}]$	G	0.15	$0.01 - 0.06$ $[0.003 - 0.01]$
$b\bar{b}\mu\mu$	$(2 - 7) \cdot 10^{-4}$ $[(0.6 - 2) \cdot 10^{-4}]$	G	0.015	$0.01 - 0.05$ $[0.003 - 0.01]$

Curtin, Essig, SG, Jaiswal, Katz, Liu, Liu, Mckeen, Shelton, Strassler, Surujon, Tweedie, Zhong, 1312.4992