Multilepton dark matter signals

J. A. Aguilar Saavedra

Instituto de Física Téorica, Madrid

Multidark workshop, May 24th 2022

Project PID2019-110058GB-C21 funded by

I will talk about multilepton signals at LHC

Multilepton dark matter signals

Conspicuously, these are associated to DM.

Not your average DM signal!

The models: common features

U(1)′ extension of the SM → new Z' boson

Additional scalar $SU(2)_L \times U(1)_Y$ singlet(s) to give the Z' a mass

The Z' boson is leptophobic: avoid strong constraints from $Z' \to \ell\ell$ at LHC

→ new fermions required for anomaly cancellation

Several simple possibilities. Model with extra leptons: DM candidate

- All quark fields have the same U(1)′ hypercharge Y_q'
- Heavy lepton doublet $\psi_{L,R} = \begin{pmatrix} \psi^0 \\ \psi^- \end{pmatrix}_{L,R}$ $-Y_L' = Y_R' = 9/2\, Y_q'$
- Heavy neutral singlet $\chi^0_{L,R}$ $Y_L' = -Y_R' = 9/2\, Y_q'$
- Heavy charged singlet $\chi^-_{L,R}$ $Y_L' = -Y_R' = 9/2\, Y_q'$
- New scalar singlet(s) have $Y' = 9\, Y_q'$

Model variants

Minimal model: just one scalar singlet — Caron, Casas, Quilis, Rd Austri, 1807.07921

→ study of allowed parameter space to accommodate DM

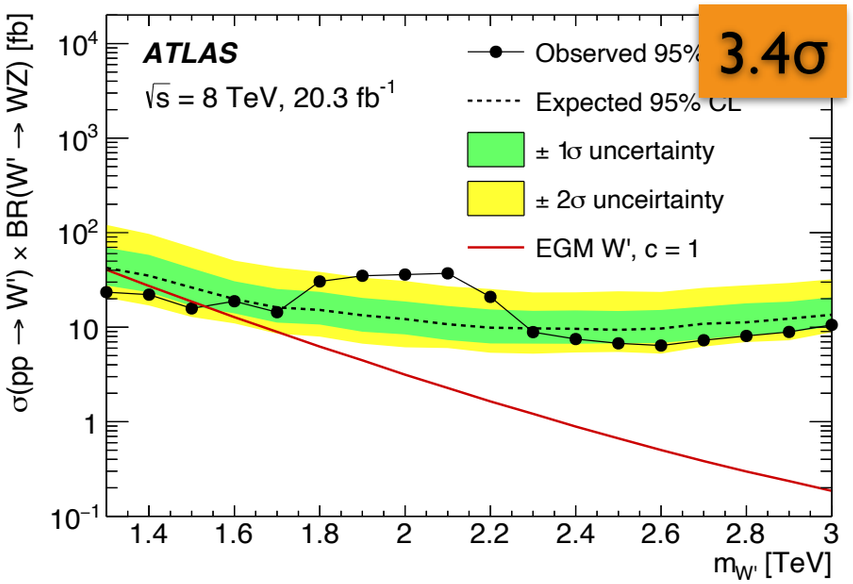
Model with two singlets: — JAAS, Joaquim, 1905.12651

→ Minimal stealth boson model: study SB signatures from Z´ decay

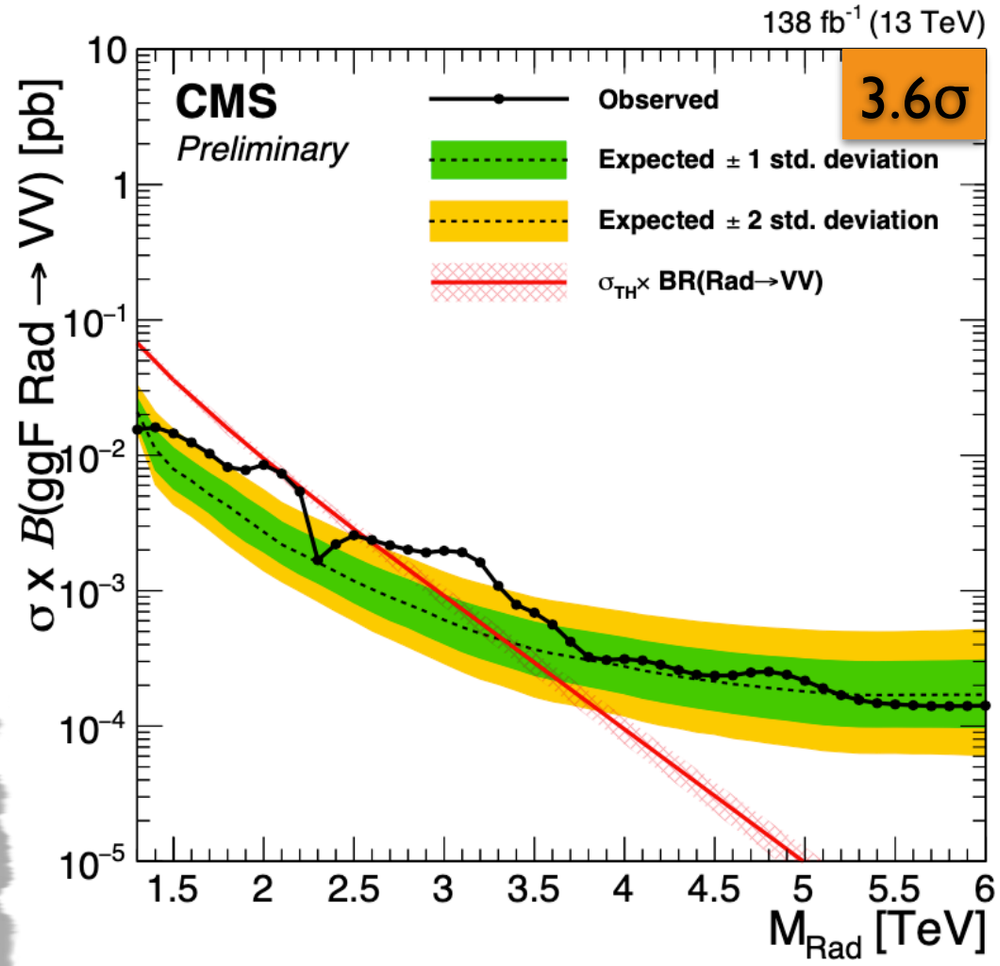
Model with 2 scalar doublets + singlet: — JAAS, Joaquim, Seabra, 2206.xxxxx

→ Further study of SB and multiboson signals from Z´ decay

Interlude: why would I want SB signatures?



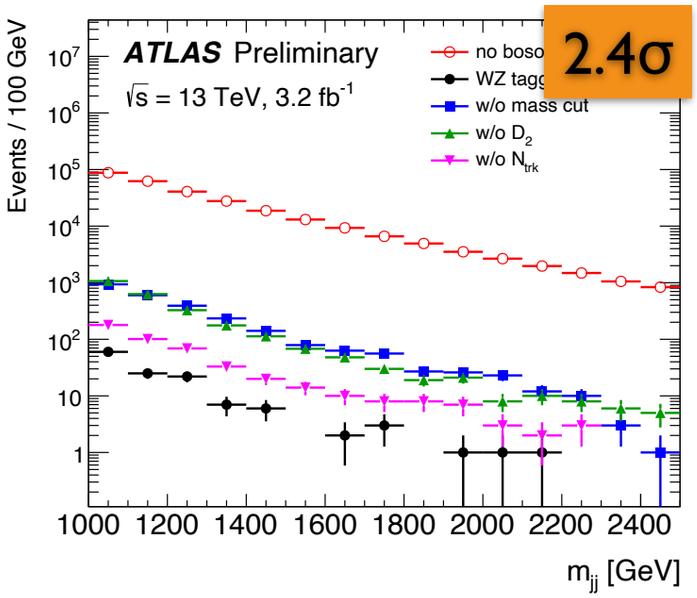
3.4σ



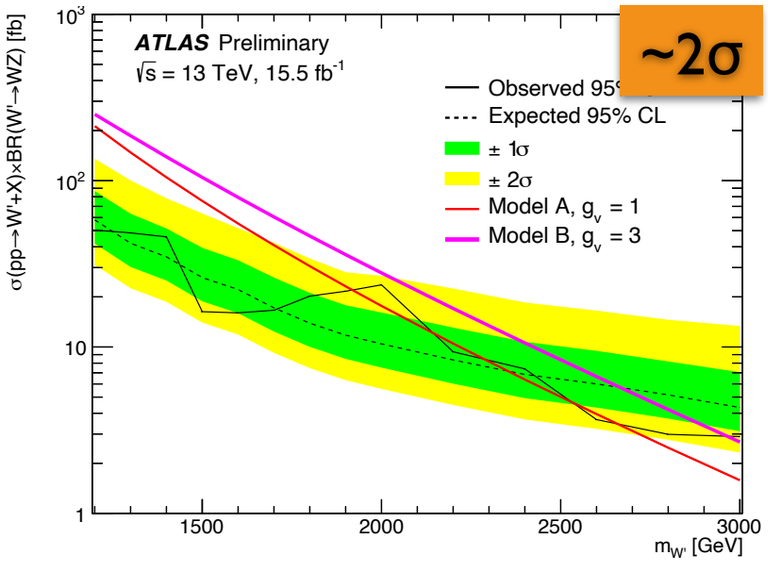
3.6σ

Naive combination: 5.8σ

Fisher combination: 5.1σ



2.4σ



~2σ

The models: new leptons

Heavy leptons do not have Yukawa interactions with the SM ones, they are forbidden by the U(1)´ gauge symmetry. They only couple among themselves

$$\begin{aligned}\mathcal{L}_Y = &- y_1(\bar{\psi}^0_L\ \bar{\psi}^-_L)\chi^-_R\phi - y_2(\bar{\psi}^0_L\ \bar{\psi}^-_L)\chi^0_R\tilde{\phi} \\ &- y_3\bar{\chi}^-_L(\psi^0_R\ \psi^-_R)^T\phi^\dagger - y_4\bar{\chi}^-_L(\psi^0_R\ \psi^-_{1R})^T\tilde{\phi}^\dagger \\ &- y_5(\bar{\psi}^0_L\ \bar{\psi}^-_L)(\psi^0_R\ \psi^-_R)^T S^* - y_6\bar{\chi}^-_L\chi^-_R S - y_7\bar{\chi}^0_L\chi^0_R S\end{aligned}$$

We assume a dark lepton number so that Majorana terms

$$\mathcal{L}_M = - y_8\bar{\chi}^0_L(\chi^0_L)^c S - y_9\overline{(\chi^0_R)^c}\chi^0_R S$$

are absent.

The models: new leptons

Mass eigenstates are mixture of doublets and singlets

$$\begin{pmatrix} N_1 \\ N_2 \end{pmatrix} = \begin{pmatrix} \cdot & \cdot \\ \cdot & \cdot \end{pmatrix} \begin{pmatrix} \chi^0 \\ \psi^0 \end{pmatrix}$$

$$\begin{pmatrix} E_1 \\ E_2 \end{pmatrix} = \begin{pmatrix} \cdot & \cdot \\ \cdot & \cdot \end{pmatrix} \begin{pmatrix} \chi^- \\ \psi^- \end{pmatrix}$$

Therefore, there are heavy-heavy [flavour-changing] couplings to the Z , W and H bosons.

Charged heavy leptons also have diagonal couplings to the photon.

Multilepton signals

The new matter content is fixed by anomaly cancellation conditions, and gives rise to its own signals.

- Direct production: multileptons + MET. Signals similar to SUSY, with $E_1^{\pm}, E_2^{\pm} \sim \chi_1^{\pm}, \chi_2^{\pm}$ and $N_1, N_2 \sim \chi_1^0, \chi_2^0$.
- Production from Z' decay: novel uncovered signals.

The decay modes of the new leptons are just what one expects for mass eigenstates that couple to gauge and Higgs bosons

$$E_2 \to E_1 Z^{(*)}, \quad E_2 \to E_1 H^{(*)}$$

$$N_2 \to N_1 Z^{(*)}, \quad N_2 \to N_1 H^{(*)}$$

$$E_i \to N_j W^{(*)}, \quad N_2 \to E_i W^{(*)}$$

[if kinematically allowed]

Multilepton signals - II

Parameter space studied:

- Heavy leptons not very light, so that direct production has small cross section

This is not really a need: assumed just in order to show that the new signals are interesting by themselves, and could appear when nothing else is seen

- Heavy leptons not very heavy either, so that Z' can decay into pairs. Z' boson of 2-3 TeV, in order to have sizable cross section at LHC

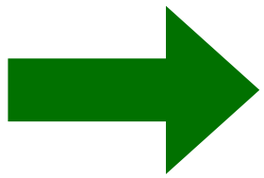
$N_l\ N_l \rightarrow Z'\ Z'$ does not contribute to DM annihilation

$N_l\ N_l \rightarrow Z' \rightarrow q\ q$ does not contribute enough to DM annihilation because of direct limits on $g_{Z'}$

Multilepton signals - III

Reproducing relic density

- N_1 must coannihilate with other heavy leptons



Small mass gap between N_1 and N_2 (at least)

- Simple benchmarks taking into account DM constraints

$$N_1 \sim \chi^0$$

$$N_2 \sim \psi^0\,, \quad E_1 \sim \psi^- \qquad \text{nearly degenerate}$$

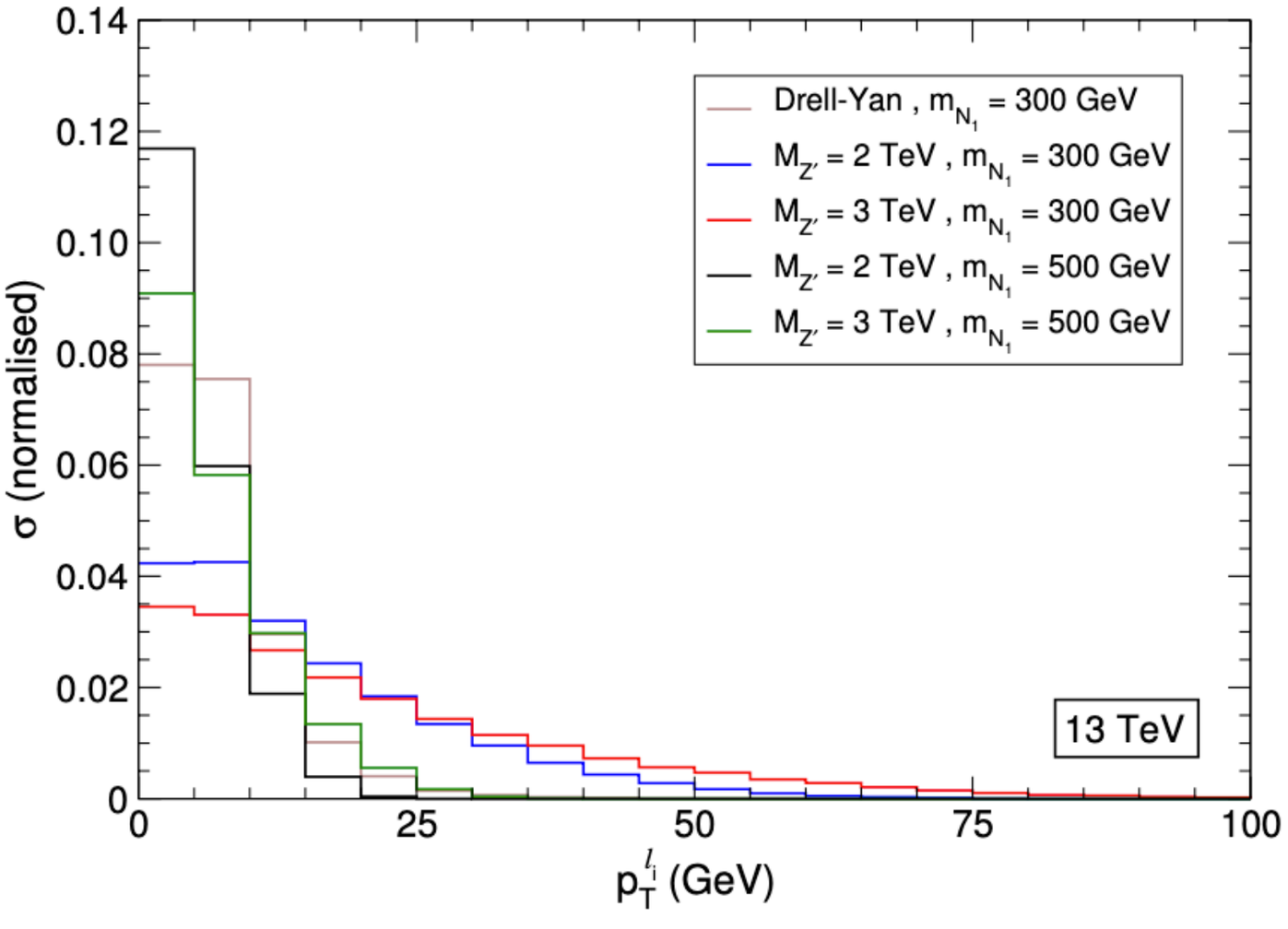
$$E_2 \sim \chi^- \qquad \text{heavier}$$

- The most interesting signal is $Z' \to N_2\, N_2$, with $N_2 \to N_1\, \ell\ell$

4-lepton signal: general features

Because of small $N_2 - N_1$ mass difference:

- The lepton pair has small invariant mass $m_{\ell\ell} \leq m_{N_1} - m_{N_1}$
- The leptons have small energy in N_2 rest frame $E^*_\ell \leq \frac{m^2_{N_2} - m^2_{N_1}}{2m_{N_2}}$
- The leptons have *small* p_T in LAB frame

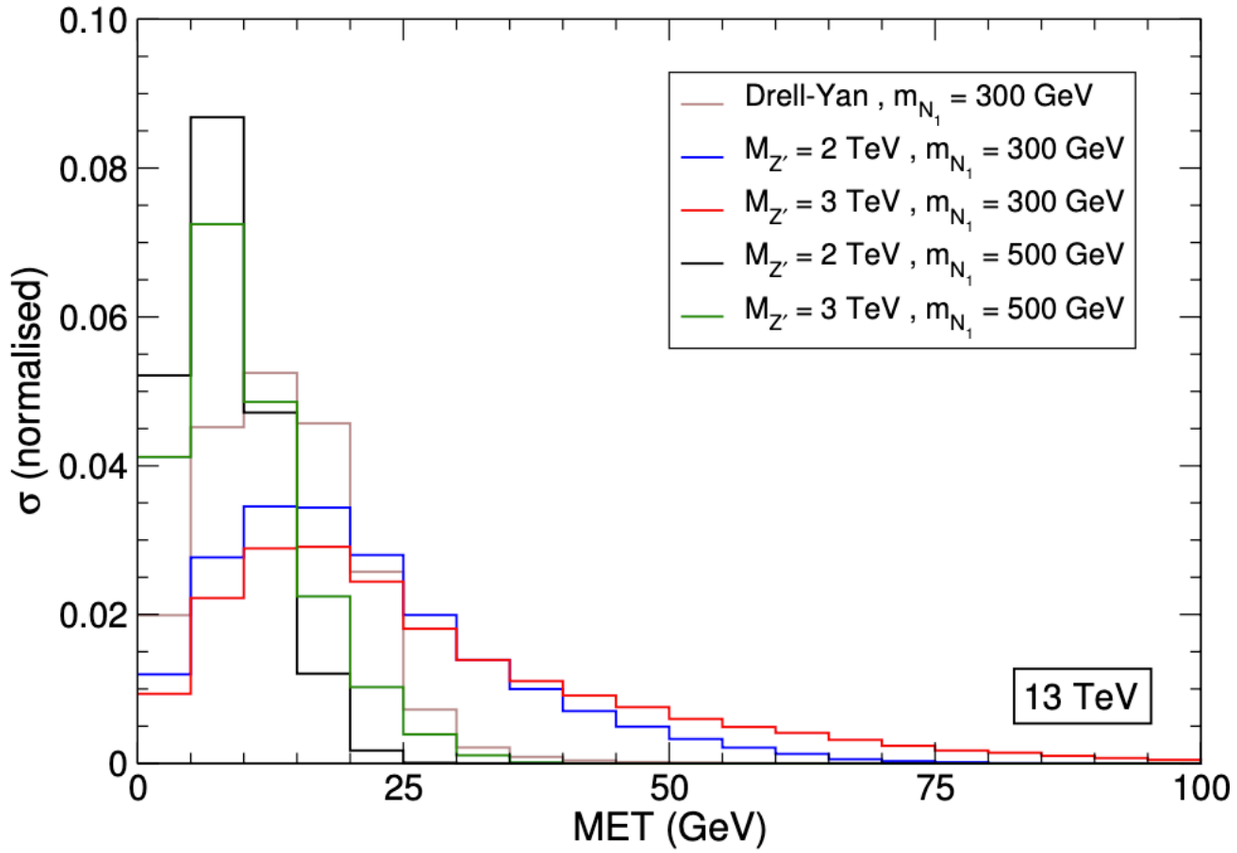


small if one considers that they are produced from a multi-TeV resonance (!)

4-lepton signal: general features

Because of small $N_2 - N_1$ mass difference:

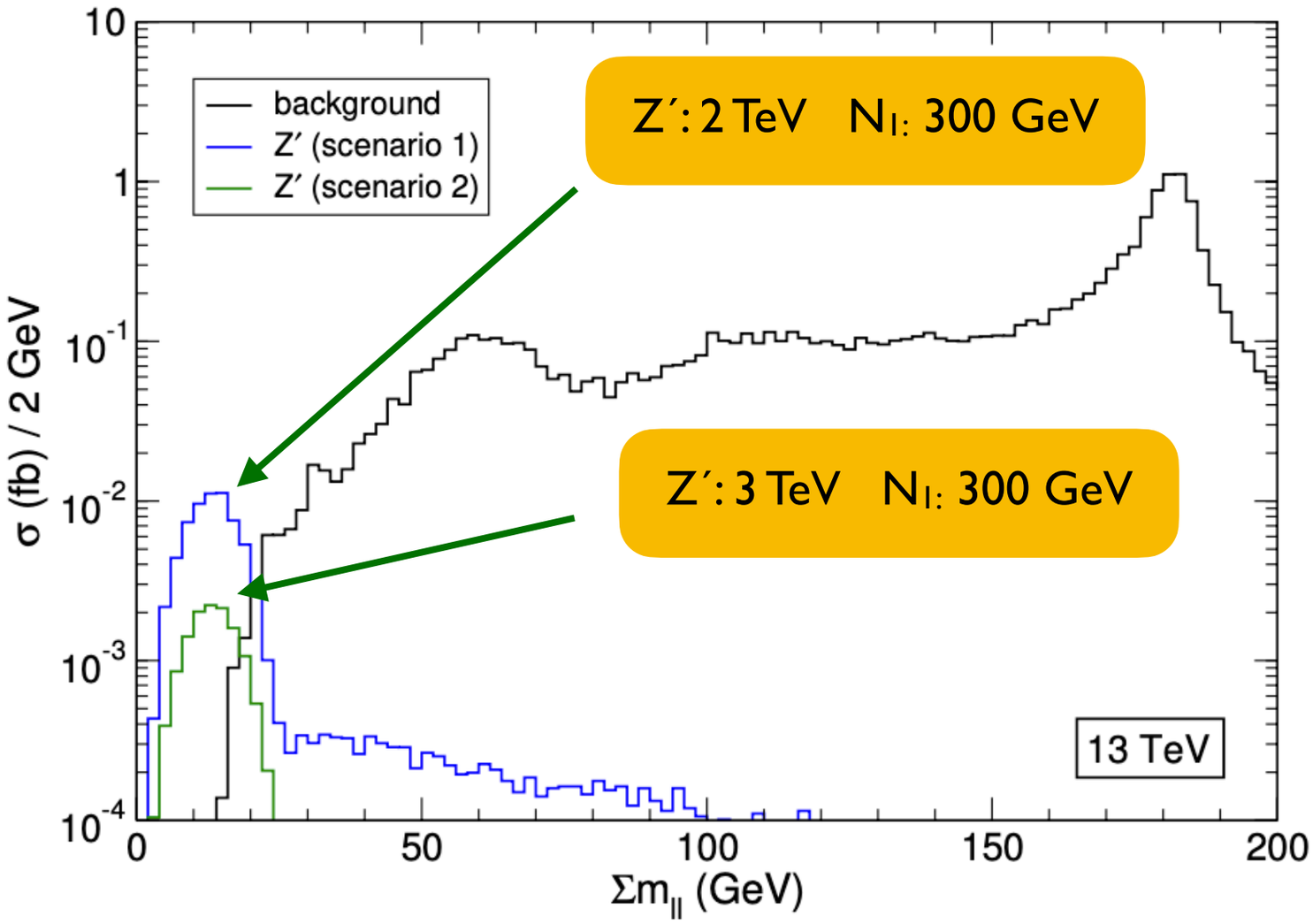
- The two N_1 are nearly back-to-back, and the MET is small (!)



low-p_T leptons, small MET, seems a nightmare scenario to look for a signal!

4-lepton signal: prospects

Conspicuously, the SM background for 4 leptons forming two pairs of small invariant mass is quite small

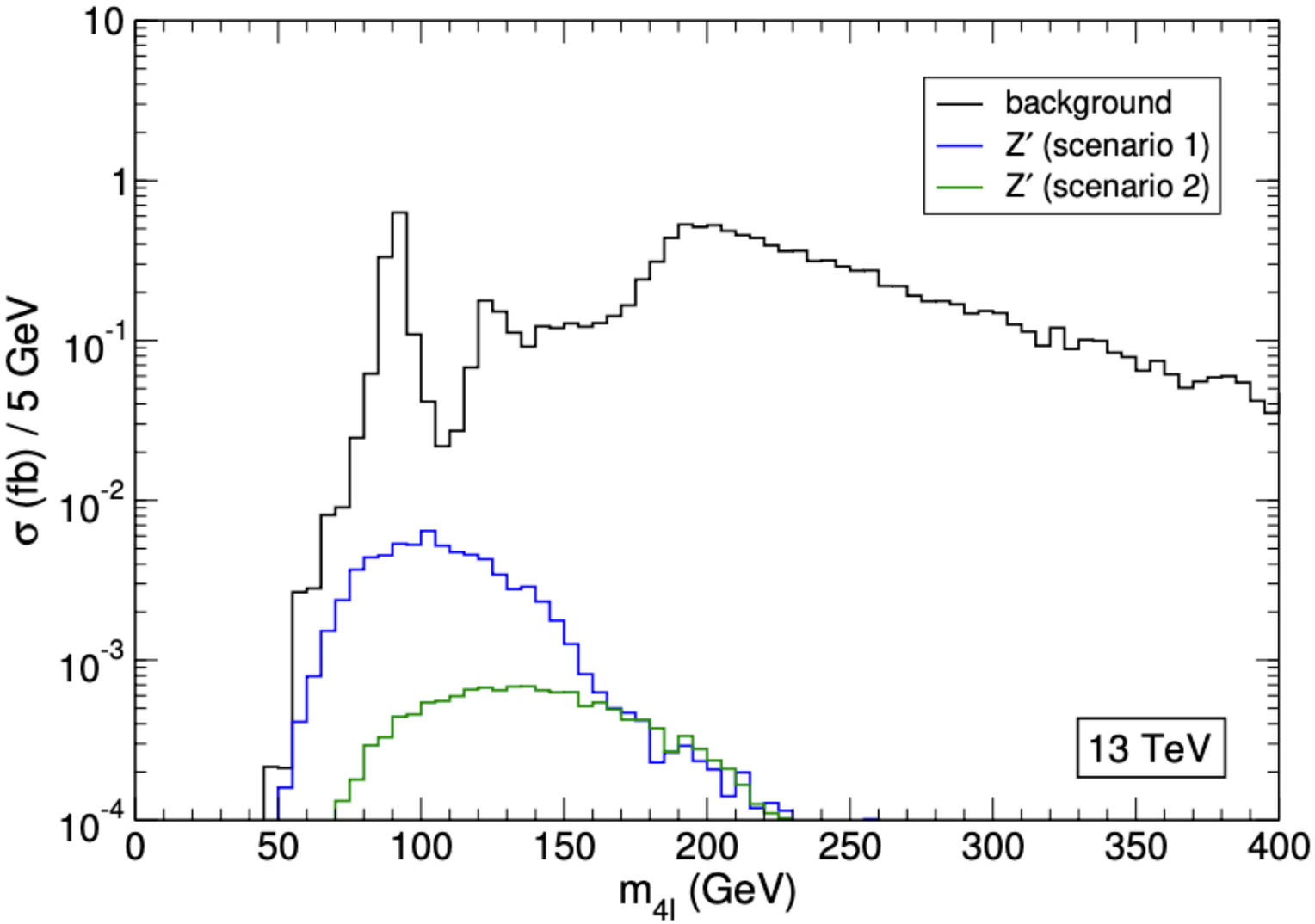


But obviously, such small signal in a corner of phase space is not seen without a dedicated search

4-lepton signal: prospects

This signal is similar to exotic Higgs decay $H \to a\,a$, $a \to \ell\ell$ [already covered]

but the 4-lepton invariant mass does not display a peak at M_H



4-lepton signal: prospects

The discovery prospects are good already with Run 2 data

150 fb^{-1} 13 TeV 300 fb^{-1} 14 TeV

	Run 2		Run 3	
B	0.78		1.60	
S (S1)	9.3	5.7σ	23.1	8.3σ
S (S2)	1.9	1.3σ	5.1	2.7σ

signals for $g_{Z'} \times Y_{q'} = 0.2$

3 ab^{-1} 14 TeV 15 ab^{-1} 27 TeV 30 ab^{-1} 100 TeV

	HL-LHC	HE-LHC	FCC
S1	0.069	0.022	8.3×10^{-3}
S2	0.14	0.035	0.012

value of $g_{Z'} \times Y_{q'}$ required for 5σ

End