

HIGGS DECAYS TO DARK SECTOR

JURE ZUPAN

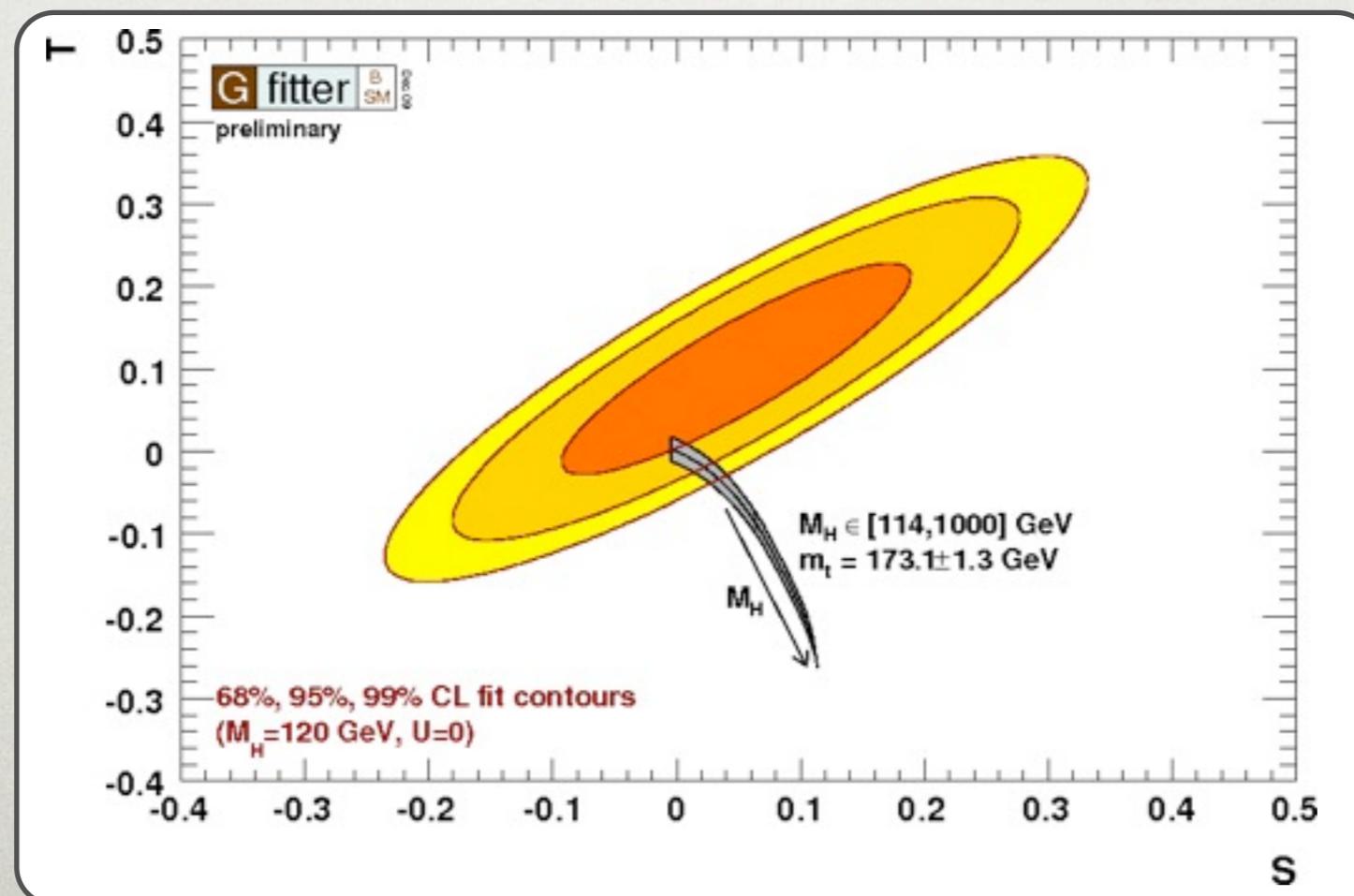
based on work with Falkowski, Ruderman, Volansky (1002.2952, 1007.3496)

AIM

- solutions to hierarchy problem (MSSM,...) have still some fine tuning: little hierarchy problem
 - i.e. $m_h > 115$ GeV exp. for \sim SM higgs
- can $higgs \rightarrow dark\ sector$ alleviate this problem?
 - i.e. make LEP / Tevatron bounds looser, so that lighter higgs possible
- YES: $higgs \rightarrow lepton\ jets$
 - how to see them (@LEP, @Tevatron, @LHC)?

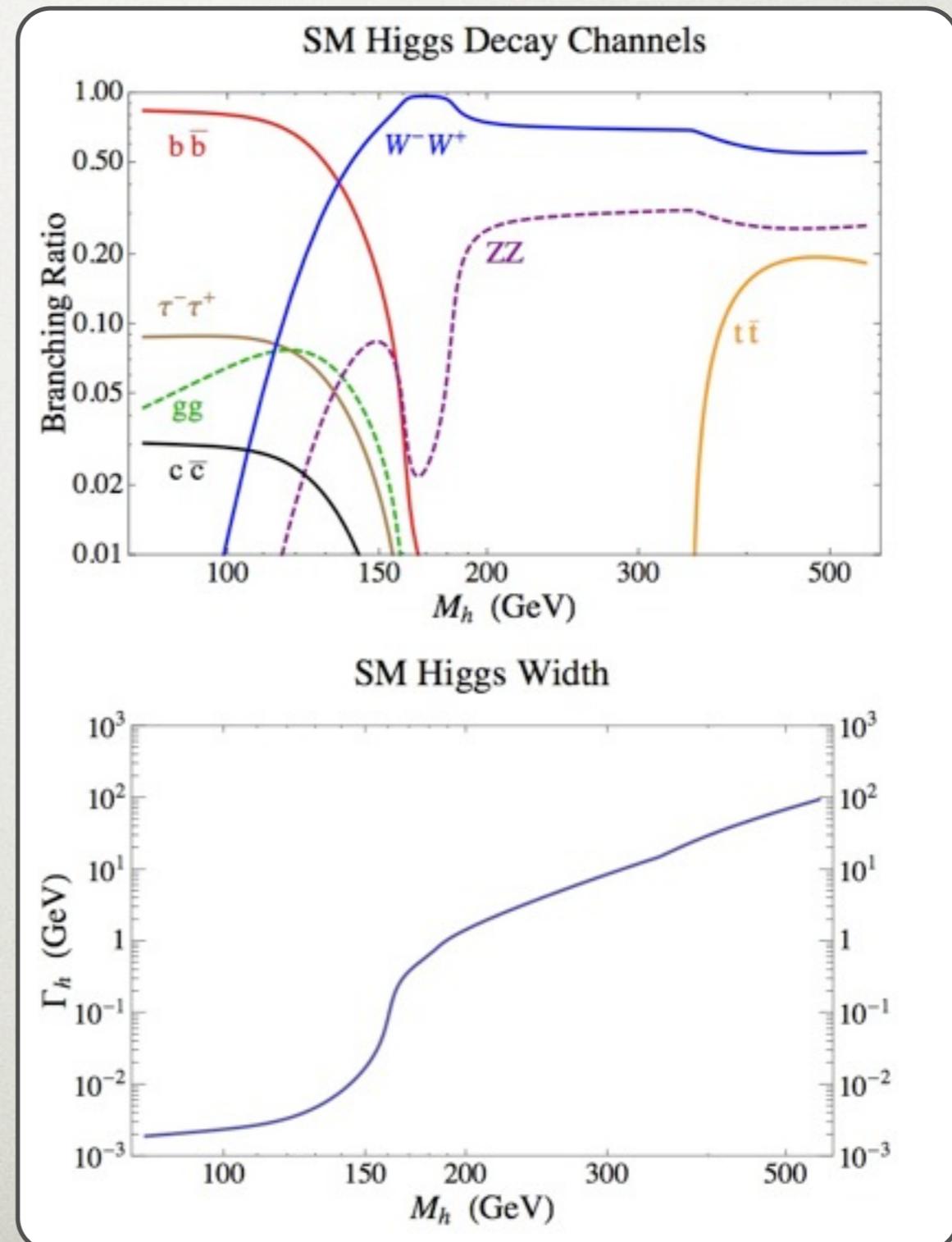
WHAT DO WE KNOW ABOUT HIGGS BOSON?

- *light* higgs suggested by electroweak precision tests
- likely there exists a light scalar that couples to W and Z in a similar way as SM higgs after EWSB, $\sim m_V V_\mu V^\mu h$
- note: there is no exp. info on higgs-to-fermion couplings!



EXP. CONSTRAINTS

- The LEP constr. imply
 - either higgs mass above 114.4 GeV
 - or higgs decays in a nonstandard way
- note: below W threshold the decay width is small



HIGGS DECAYING TO DARK SECTOR

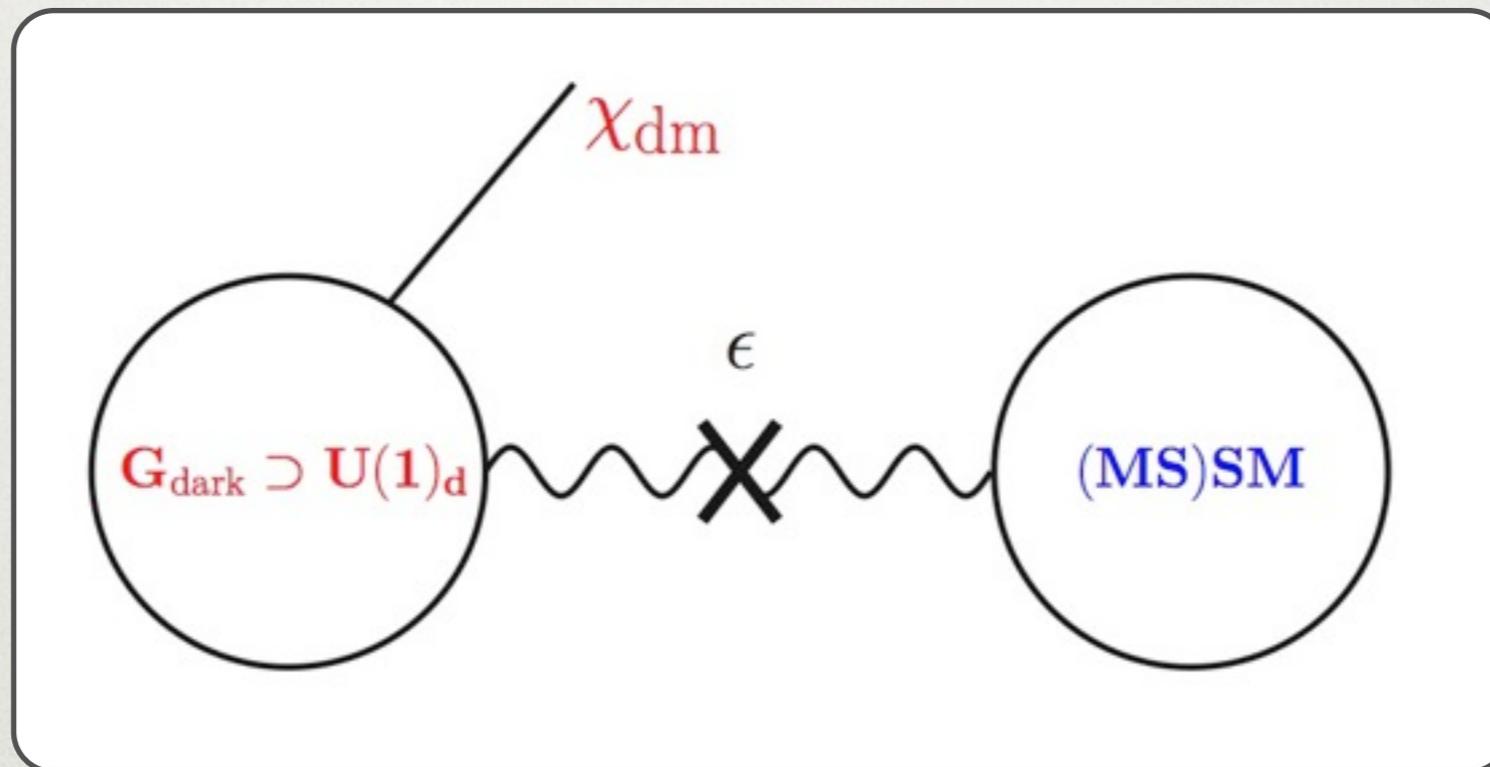
- entertain the possibility that higgs decays predominantly to dark sector
- higgs couples to dark sector (directly or indirectly) and $h \rightarrow \text{dark sector}^*$ dominates
 - not unlikely, given $y_b \sim 0.02$
- *dark sector:
 - option 1: dark sector only decays into dark sector
 - signature $h \rightarrow \text{missing } E_T$
 - LEP bound is $m_h > 115 \text{ GeV}$
 - option 2: also decays to visible sector

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GENERAL SETUP

- our models supersymmetric (no little hierarchy)



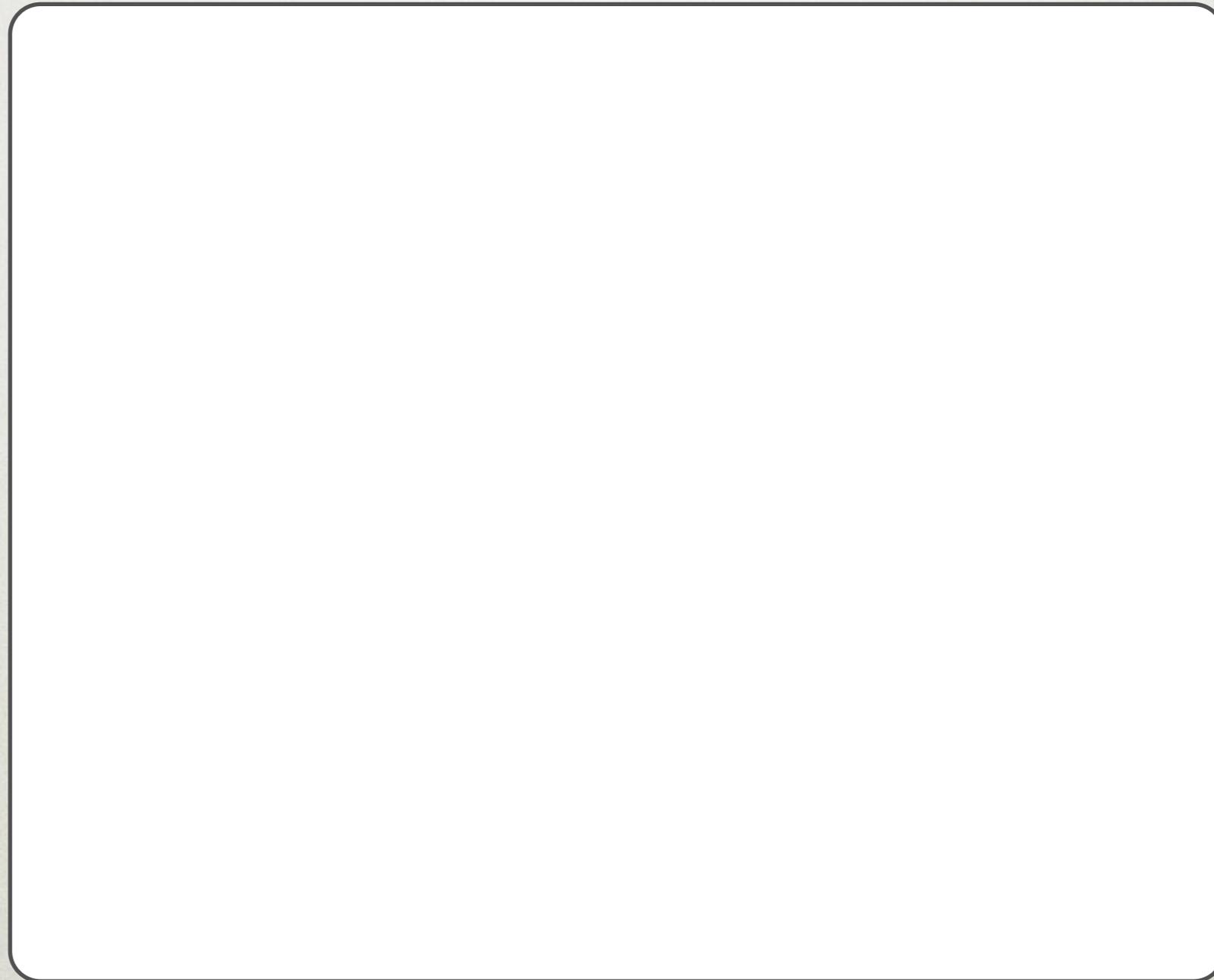
- G_{dark} is broken at GeV (we will use $G_{\text{dark}}=U(1)_d$)
- the cross-talk is done through kinetic mixing

$$\mathcal{L} \supset \frac{\epsilon}{2} b_{\mu\nu} B^{\mu\nu} \quad \epsilon \lesssim 10^{-3}$$

CASCADES

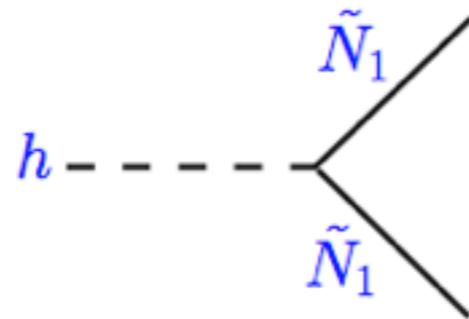
- one can potentially avoid LEP and Tevatron bounds, if $h \rightarrow$ *many body final states*
 - no dedicated searches
 - BUT: have to check other searches
- such decays naturally arise in our setup
 - $h \rightarrow$ *hidden sector*
 - cascade in hidden sector
 - then decay back to visible sector

SAMPLE DECAY



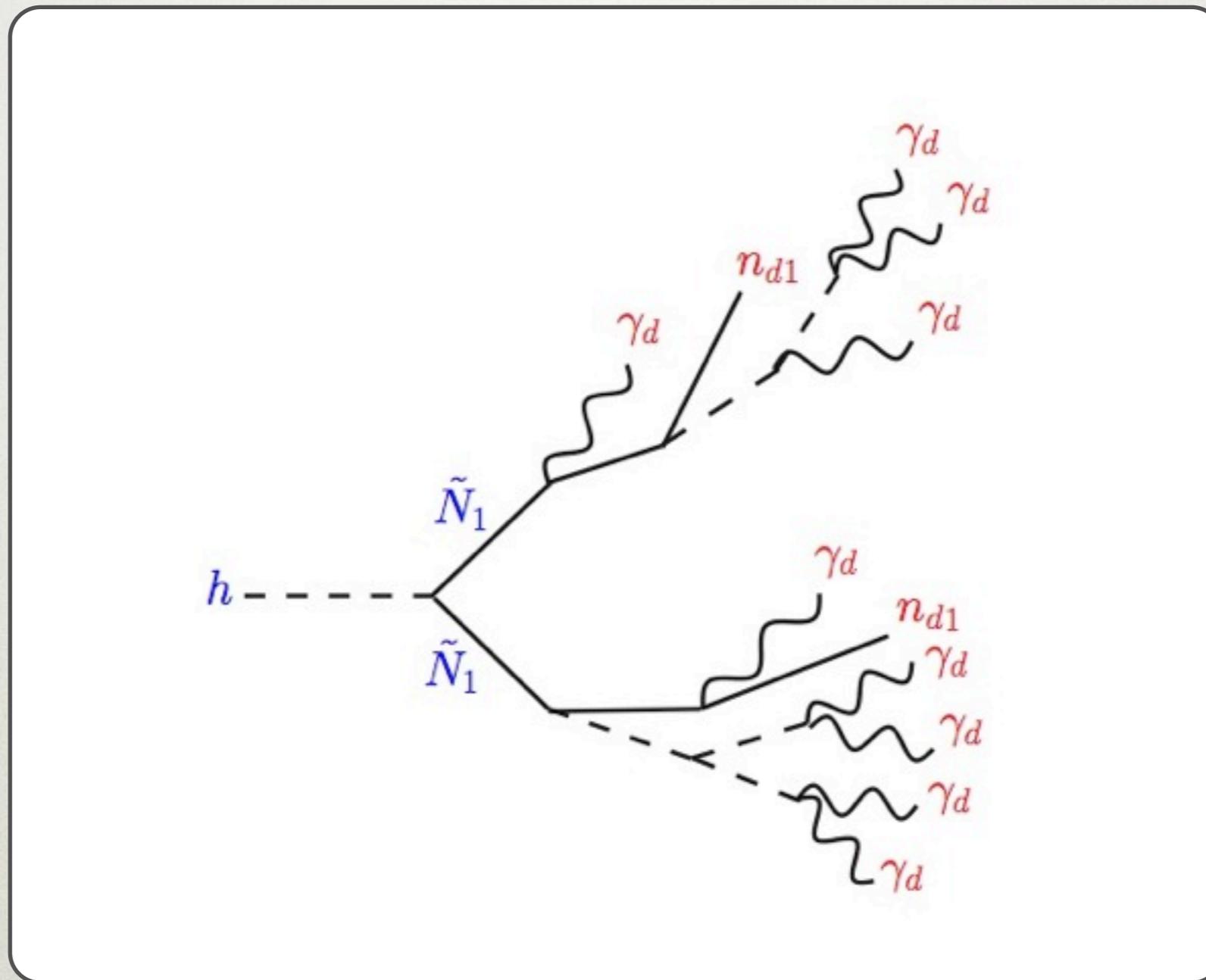
- results in many leptons and MET

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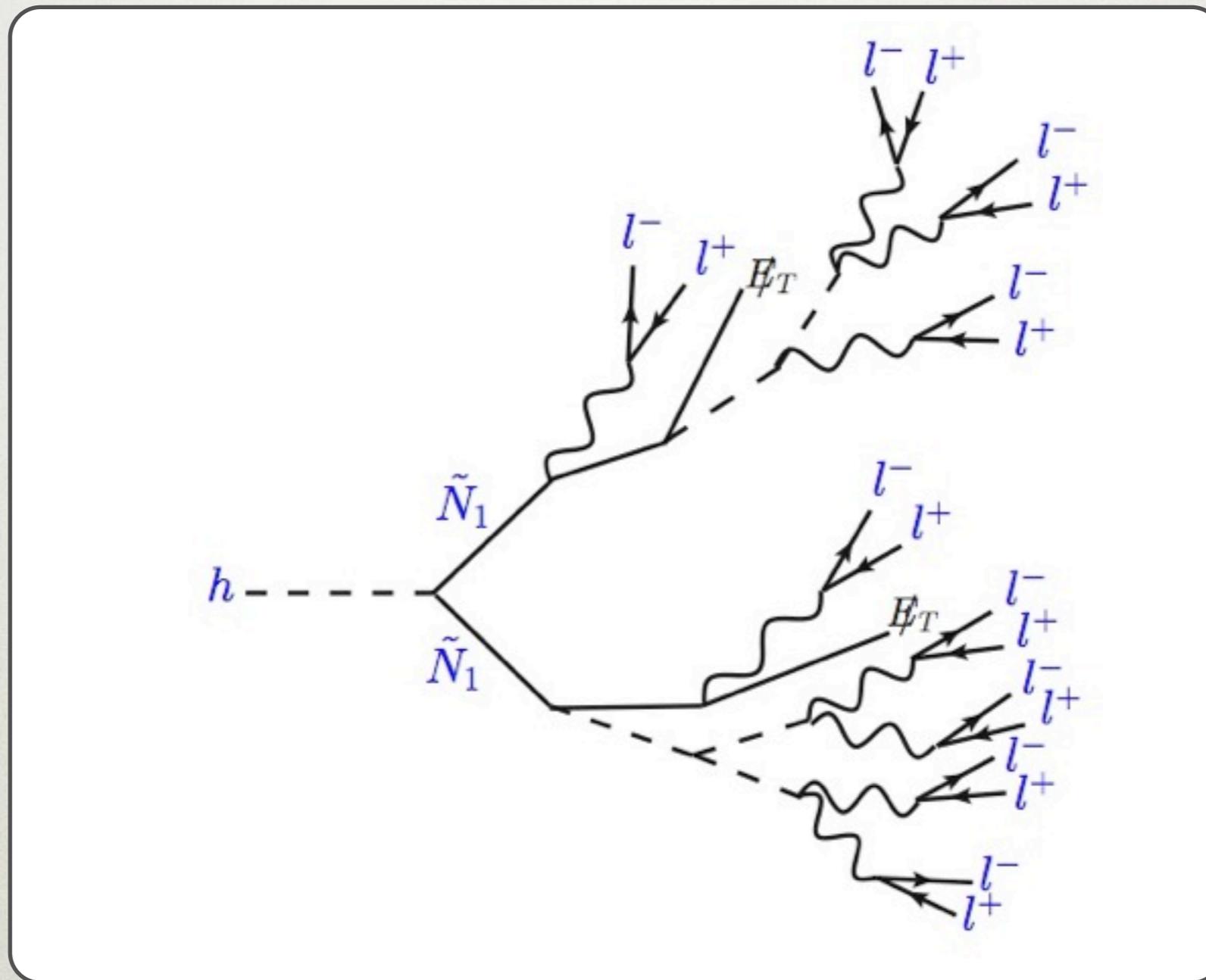
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SAMPLE DECAY



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DECAYING TO HIDDEN SECTOR

- will assume that higgs does not couple directly to hidden / dark sector
 - LSP decays due to kinetic mixing
- we want: higgs decaying to neutral particles in (N)MSSM
- three choices
 - neutralino portal
 - sneutrino portal
 - singlet portal

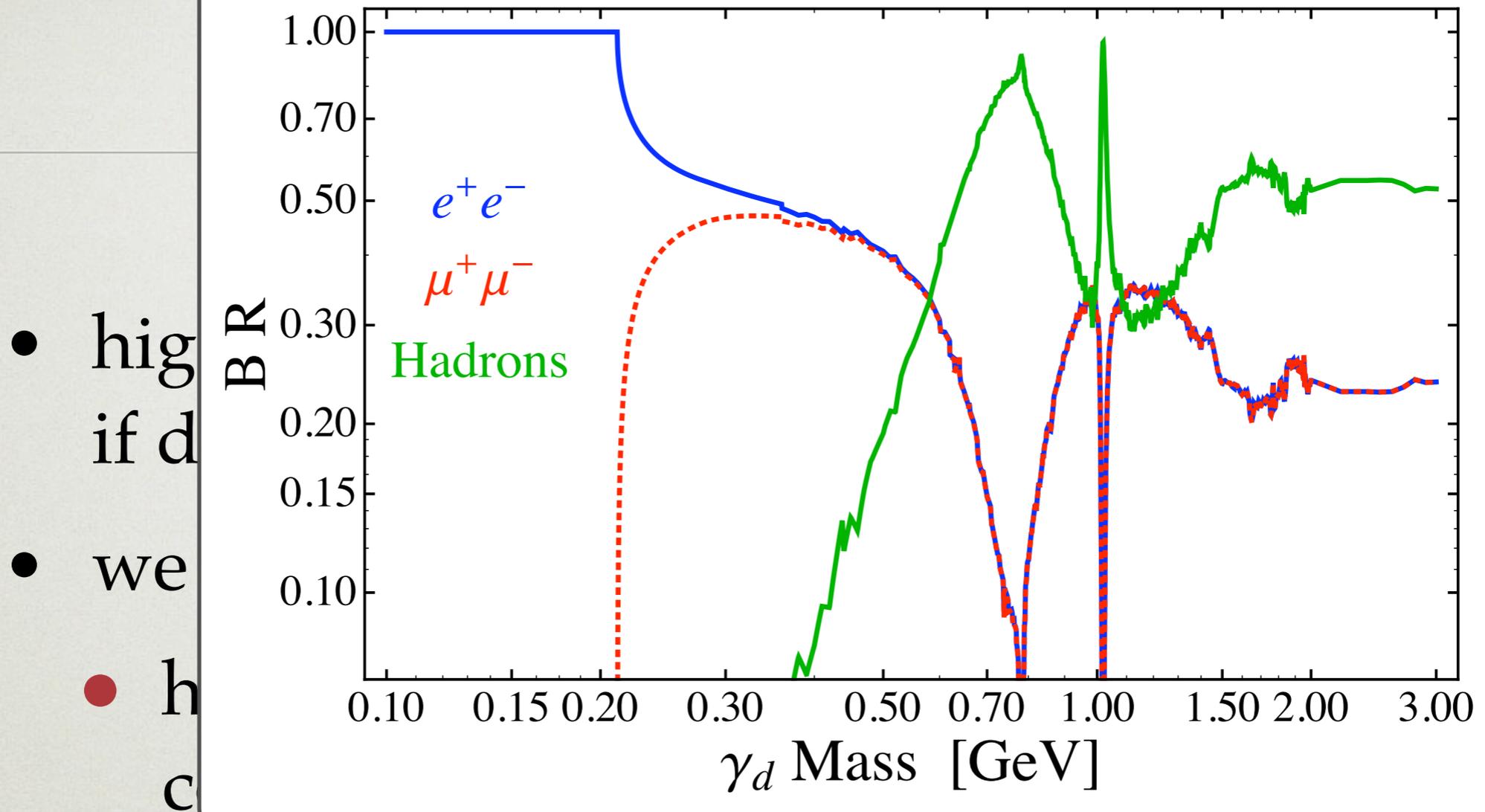
[Falkowski, Ruderman, Volansky, JZ, 1002.2952](#)

LEPTON JETS

- higgs can avoid detection at LEP&Tevatron, if decay channels unconstrained by searches
- we focus on one such case: *lepton jets*
 - high multiplicity clusters of boosted, collimated leptons
- lepton jets arise, if $m_{\gamma d} < 2m_{\pi}$
- also - there has to be mass gap between higgs and its decay products (to obtain boost)

Arkani Hamed, Weiner, 0810.0714

γ_d Branching Ratio



- high BR to e^+e^- if $m_{\gamma_d} < 2m_\pi$
- we can see γ_d if $m_{\gamma_d} > 2m_\pi$
- hadron jets arise, if $m_{\gamma_d} < 2m_\pi$
- also - there has to be mass gap between higgs and its decay products (to obtain boost)

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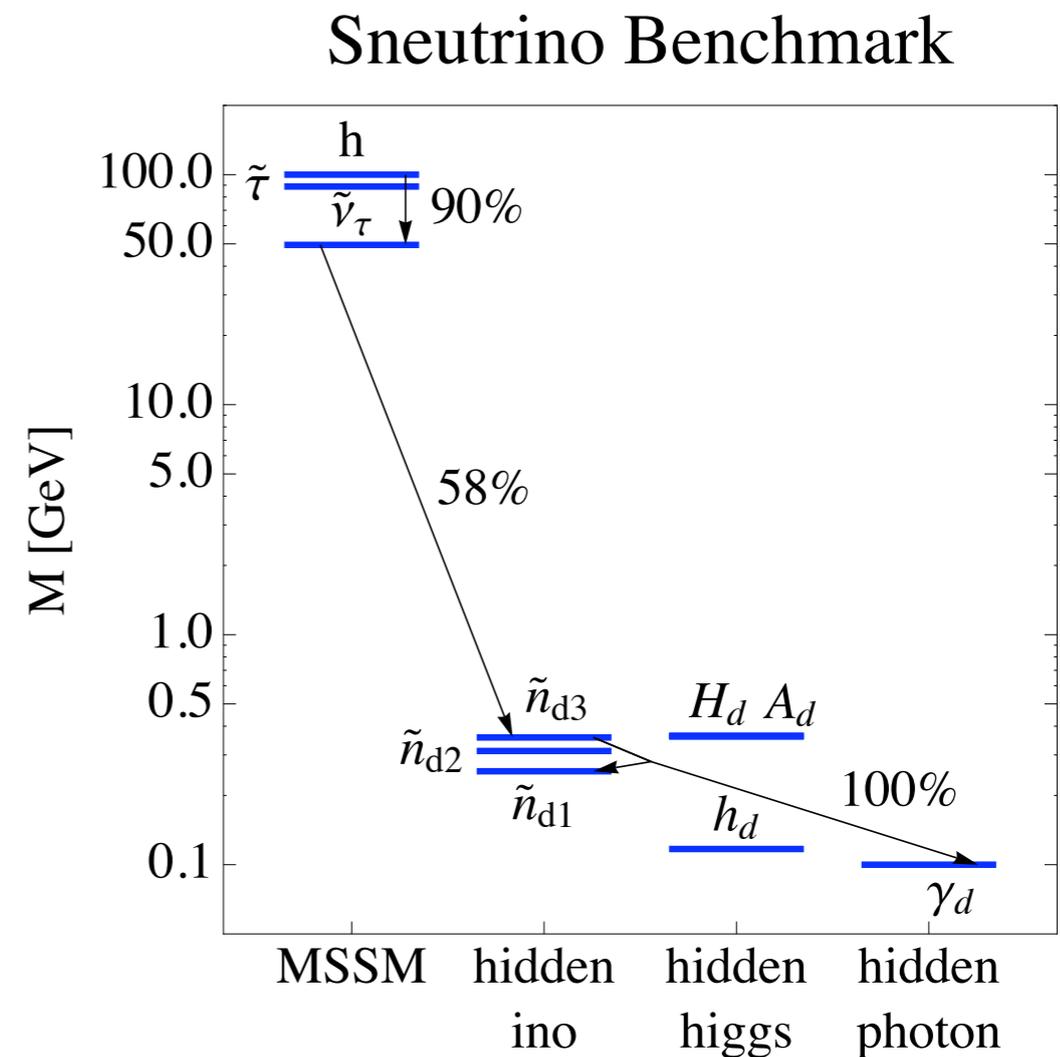
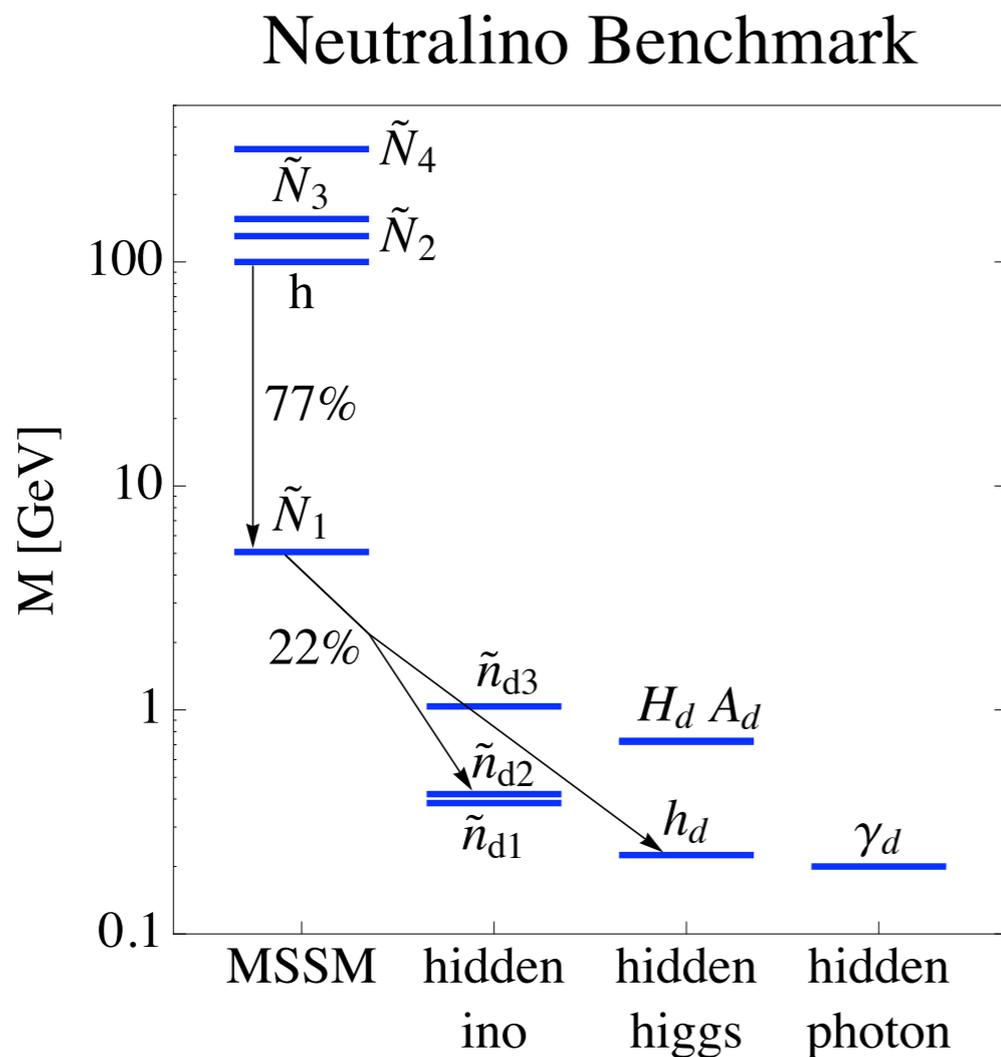
BENCHMARK MODELS

BENCHMARK MODELS

- we choose three benchmark spectra

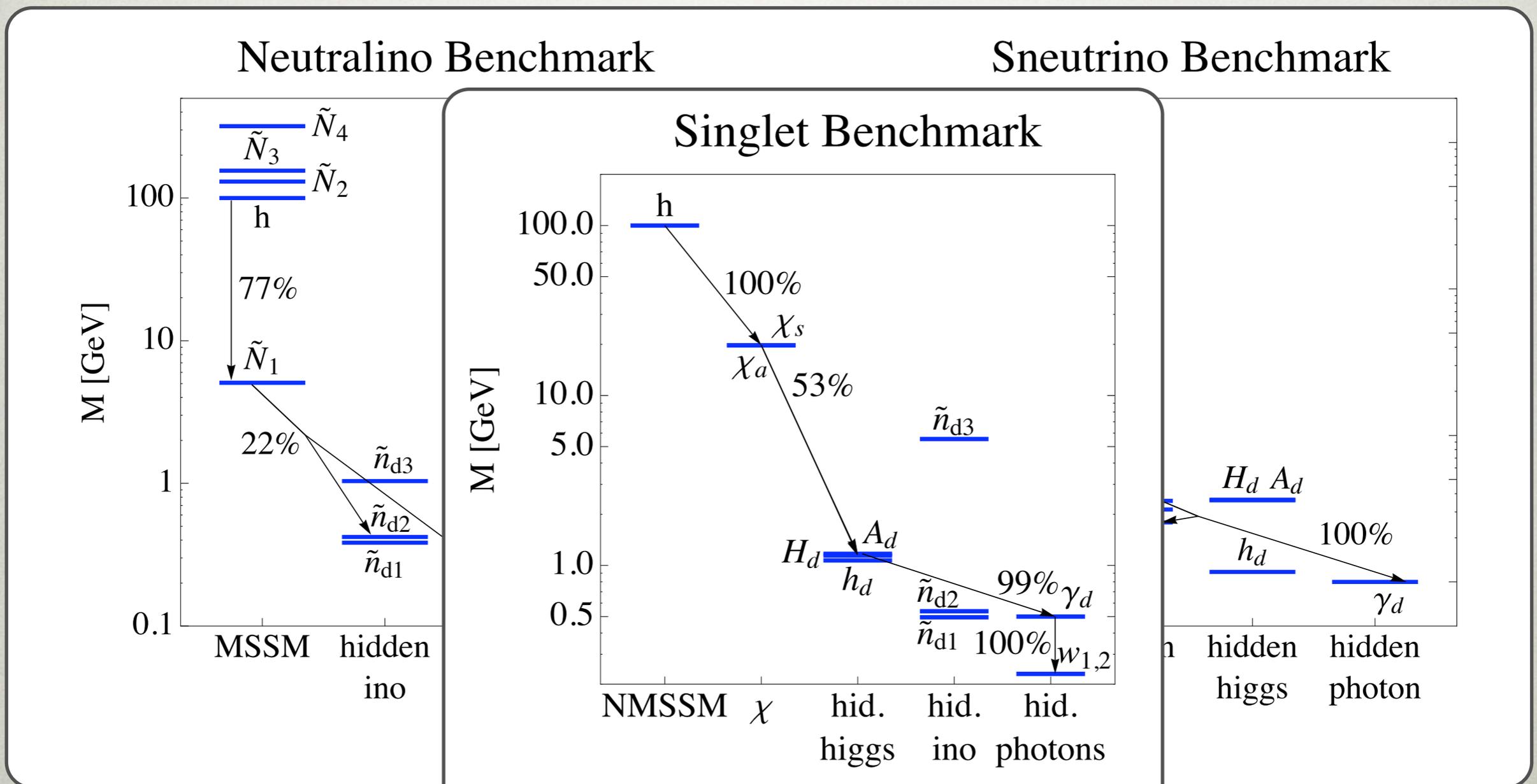
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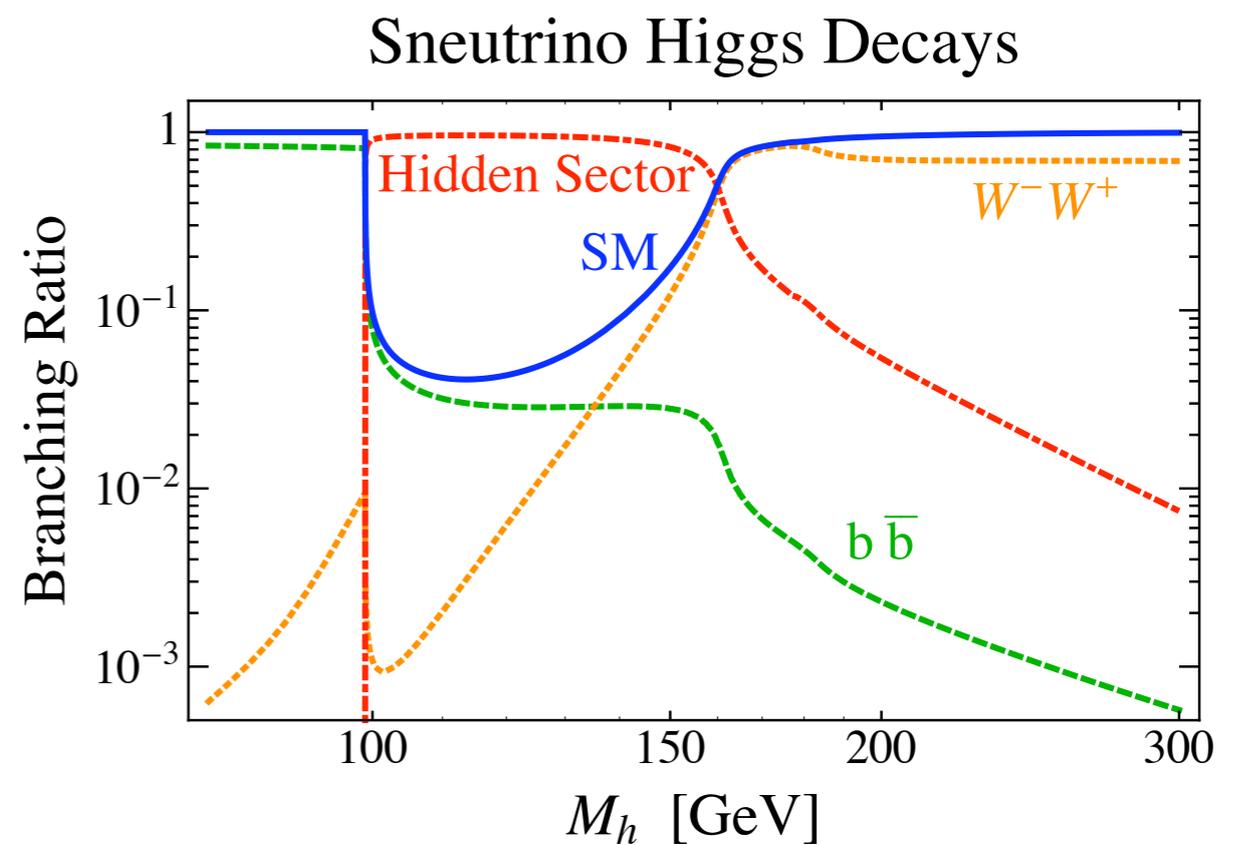
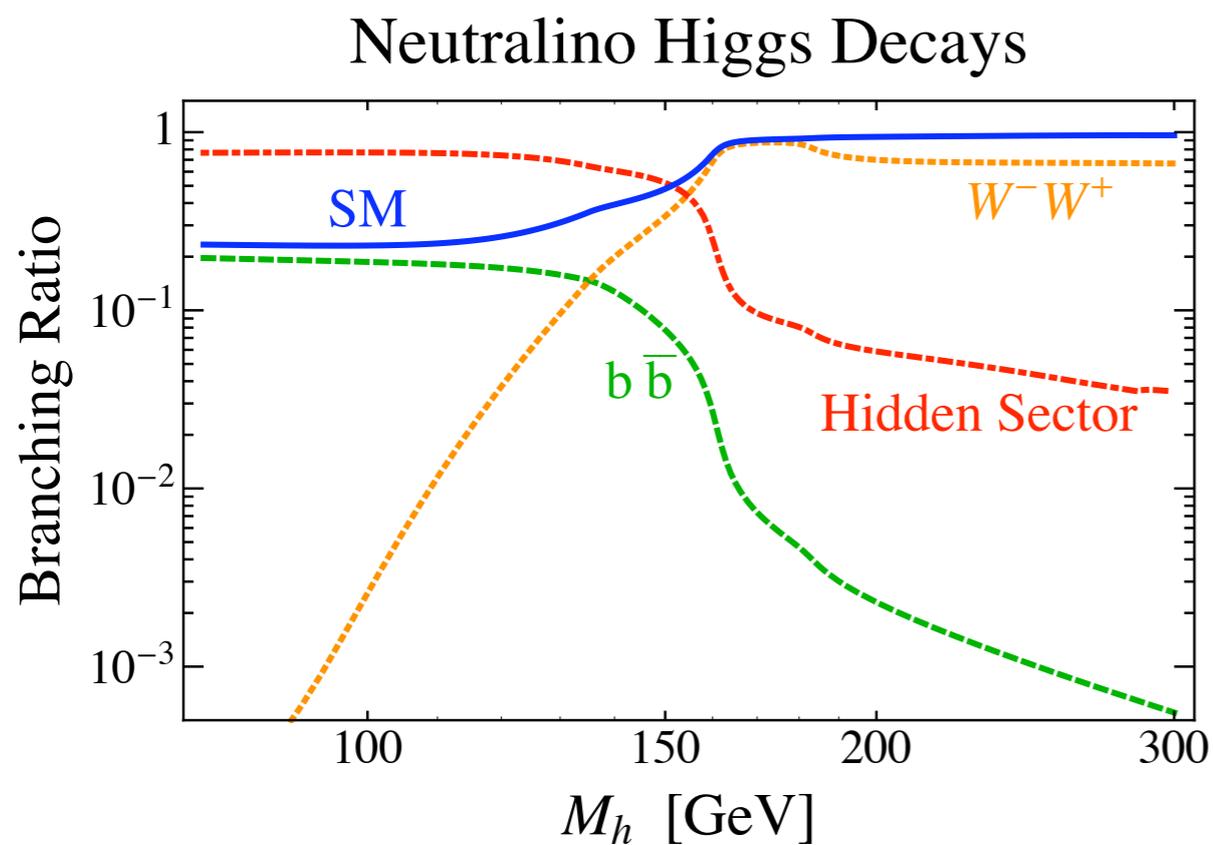
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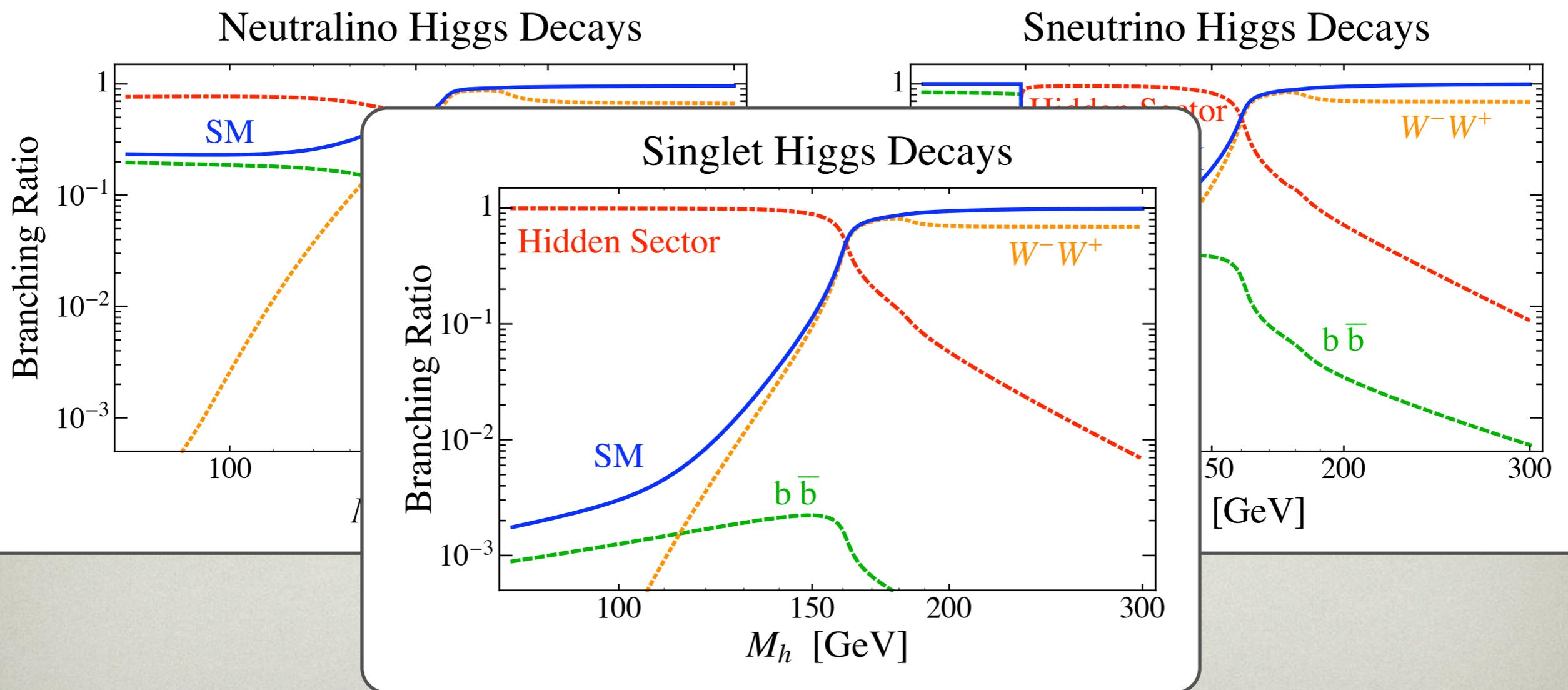
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BENCHMARK MODELS

- we choose three benchmark spectra
- take $m_h=100$ GeV
- test against LEP-1, LEP-2, Tevatron searches
- before any cuts one has
 - $O(100 \text{ higgs evnts/exp}) @ \text{LEP-2}$
 - $O(10^4 \text{ higgs evnts/exp}) @ \text{Tevatron}$

BENCHMARK MODELS

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- before any cuts one has

- Many events, so isn't
- this excluded trivially?! on

CAN LEPTON JETS REALLY HIDE THE HIGGS?

- $O(100)$ higgses / exp @ LEP-2:
 - preliminary selection cuts reduce this by order of magnitude
 - usually hadronic events identified by charged tracks \Rightarrow hidden in hadronic bckg.
 - need dedicated searches

CAN LEPTON JETS REALLY HIDE THE HIGGS?

- $O(10^4)$ events @ Tevatron
 - large QCD bckg., cannot search 'by eye'
 - still, there are many leptons...
 - but Tevatron searches require them to be isolated
 - in lepton jets this not true
 - need dedicated searches

LEPTON JET MONTE CARLO

Falkowski, Ruderman, Volansky, JZ, 1002.2952

- we simulated $h \rightarrow \text{lepton jets}$ at LEP and Tevatron using Monte Carlo
 - Madgraph for higgs production and decay
 - Bridge for cascade decays
 - SlowJet (our Mathematica code) for event analysis
- this is “theoretists simulation”: no detector effects, to get precise limits this would be needed

RELEVANT EXPERIMENTAL SEARCHES

LEP-1 searches							
Search	Ref.	Obs.	Bckg.	Neutr.	Sneutr.	Singlet	Max.
Monojets	[42]	3	2.8	< 1	0	0	6.6
Acoplanar	[41]	0	0.2	< 1	0	0	3.8
LEP-2 searches							
Search	Ref.	Obs.	Bckg.	Neutr.	Sneutr.	Singlet	Max.
$H \rightarrow 4\tau$	[12]	2	5.09	1	15	1	5.0
$H \rightarrow \cancel{E}$	[36]	8	11	2	5	3	7.5
$H \rightarrow WW^*2c$	[52]	0	0.3	2	< 1	2	3.8
$H \rightarrow WW^*2t$	[52]	1	1.2	1	1	3	5.0
6l	[55]	1	1.1	< 1	4	< 1	5.0
$2j + \cancel{E}$ (OPAL)	[56]	13	19.8	8	35	7	7.8
$2j + \cancel{E}$ (ALEPH)	[57]	19	15.9	7	3	1	14.5
$2j + 2l + \cancel{E}$	[57]	5	3	2	4	5	9.0
Tevatron searches							
Search	Ref.	Obs.	Bckg.	Neutr.	Sneutr.	Singlet	Max.
Dark photon	[59]	7	8	~ 1	< 1	< 1	7.9
$H \rightarrow 4\mu$	[60]	2	2.2	0	0	2	5.8
Unified 3l	[44]	1	1.47	< 1	< 1	< 1	3.7
Low p_T 3l	[45]	1	0.4	< 1	< 1	< 1	5.4
Like-sign 2l	[43]	13	7.8	1	< 1	< 1	14.7

RELEVANT EXPERIMENTAL SEARCHES

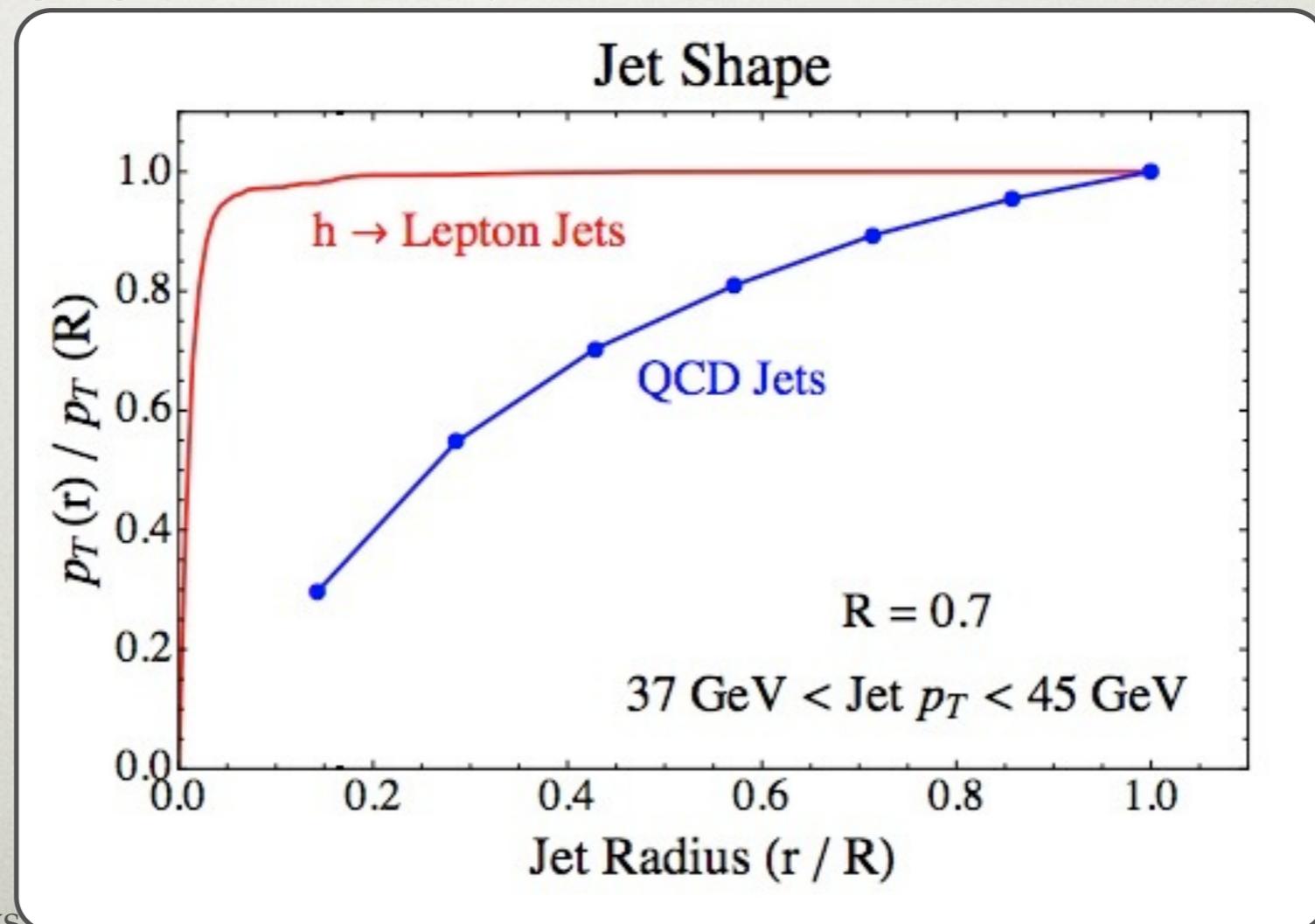
- two out of three benchmarks survive
- of course these are just benchmarks
- the *higgs* \rightarrow *lepton jets* framework is more general
- many knobs to turn
 - multiplicity, mass gaps, final states...
- can one search for large classes of models at once?

SEARCH STRATEGIES

POSSIBLE SEARCH STRATEGIES

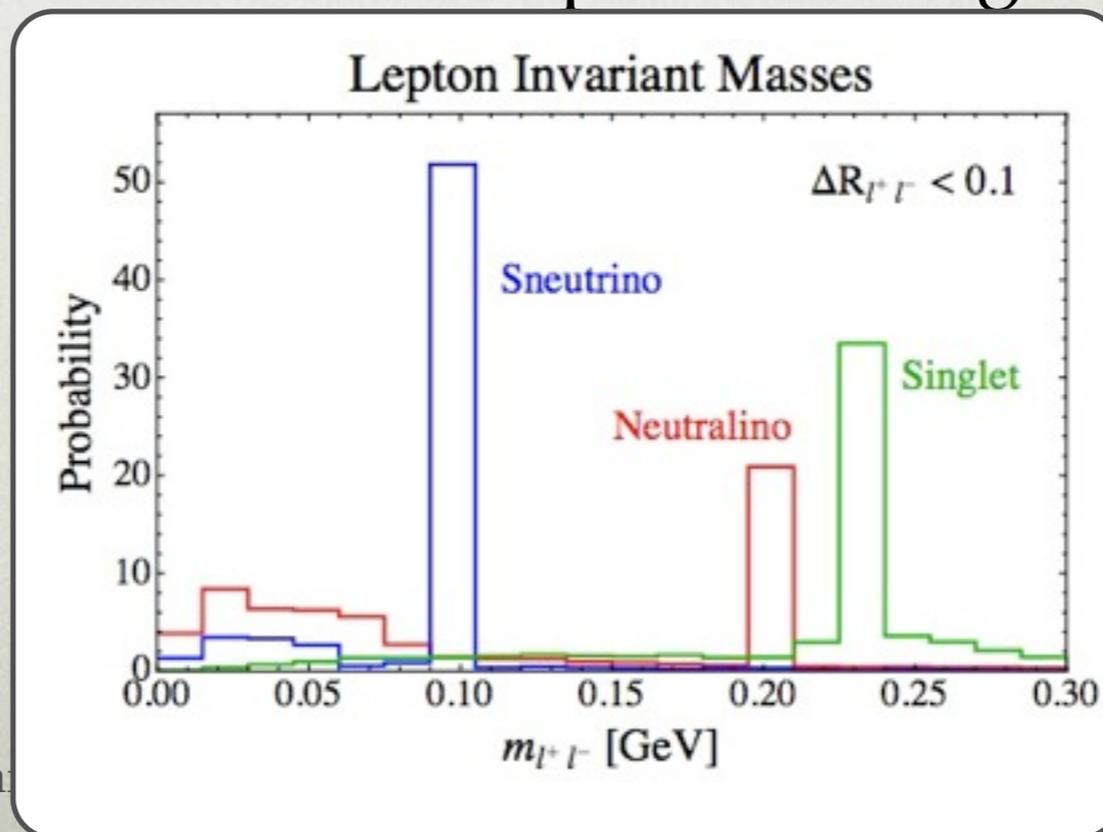
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- event shapes
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- lepton pair invariant mass
 - in dark photon case can be quite striking

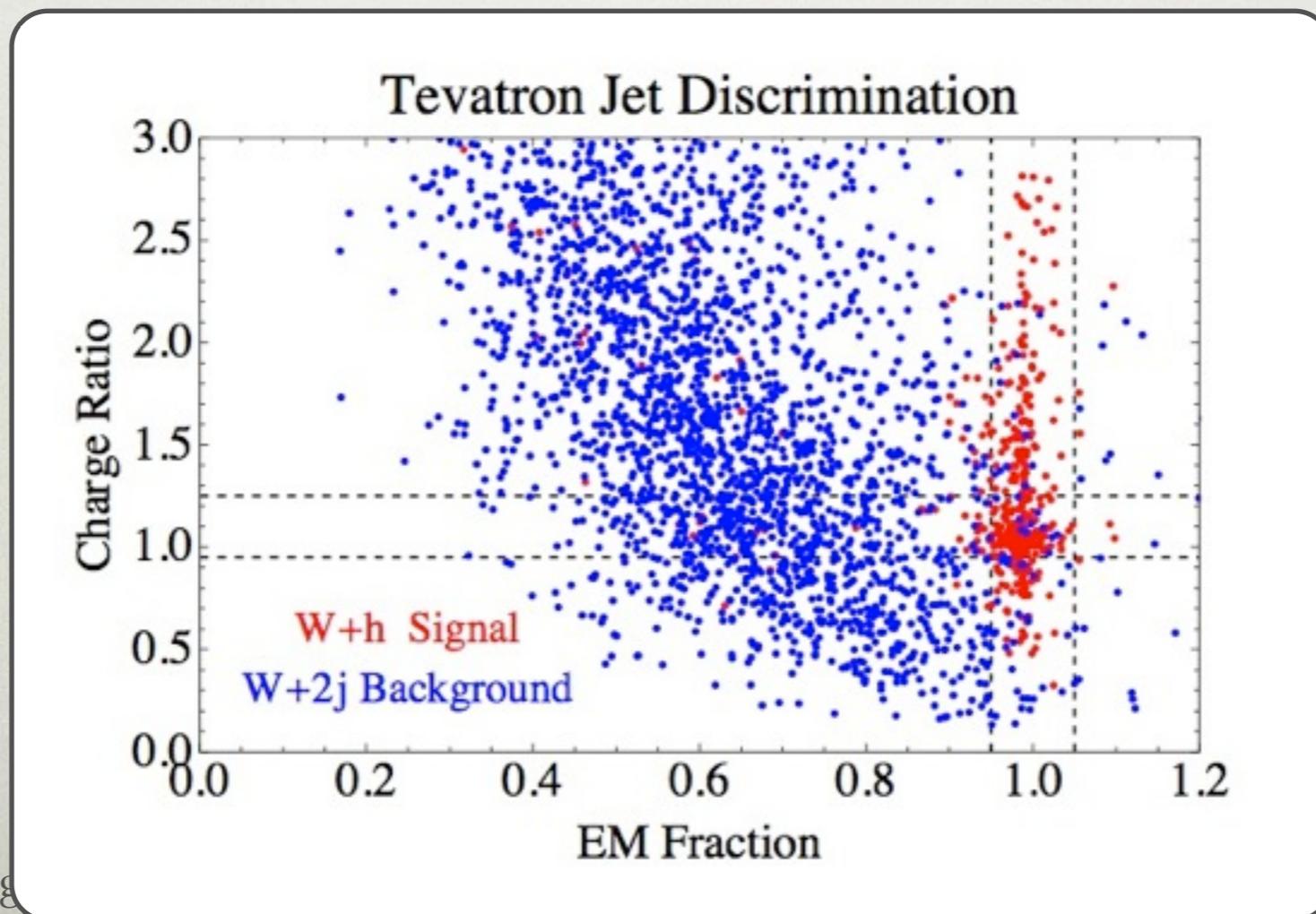


POSSIBLE SEARCH STRATEGIES

- event shapes
 - simple U(1) lepton jets much more collim. than QCD jets
 - but strongly interacting hidden sectors (hidden showering) gives wider jets
- lepton pair invariant mass
 - in dark photon case can be quite striking
- common feature: need to allow for many leptons in jets
 - can we also use it to control bckg?

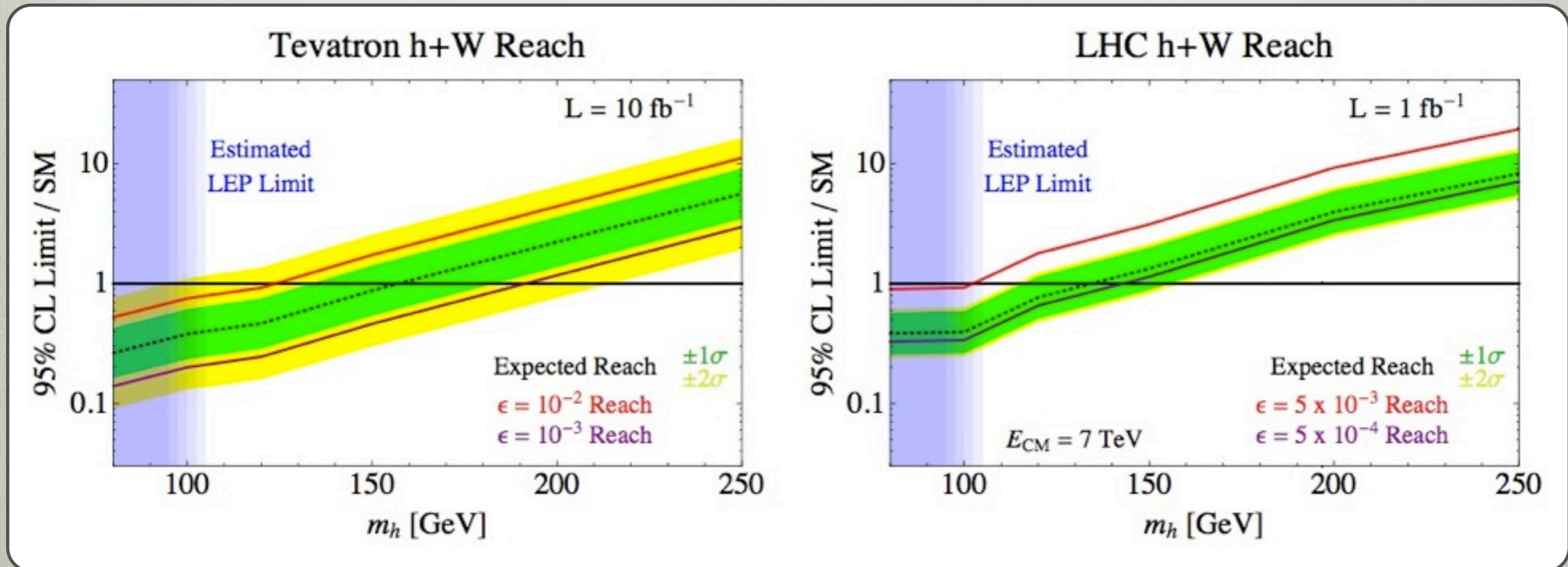
MORE MODEL INDEPENDENT?

- two discrim. that don't rely on details of the cascade
 - “em fraction” $f_{em} = E_{em}/E_{tot}$ (=1 for eLJ)
 - “charge fraction” $f_{ch} = E_{ch}/E_{tot}$ (=1 for eLJ)
- QCD rejection of $\sim 10^{-3}$ / jet possible [Falkowski, Ruderman, Volansky, JZ, 1007.3496](#)



REACH

- light higgs can be probed now!
 - choose a simple 3-step benchmark: avoids D0 search
- Tevatron higher reach than early LHC



CONCLUSIONS

- $h \rightarrow \text{lepton jets}$ can alleviate little hierarchy (lower higgs mass)
 - models + exp. signatures / constraints
- discussed how to find them at LHC, Tevatron, LEP
 - exciting is that searches are within reach

BACKUP SLIDES

GENERAL FEATURES

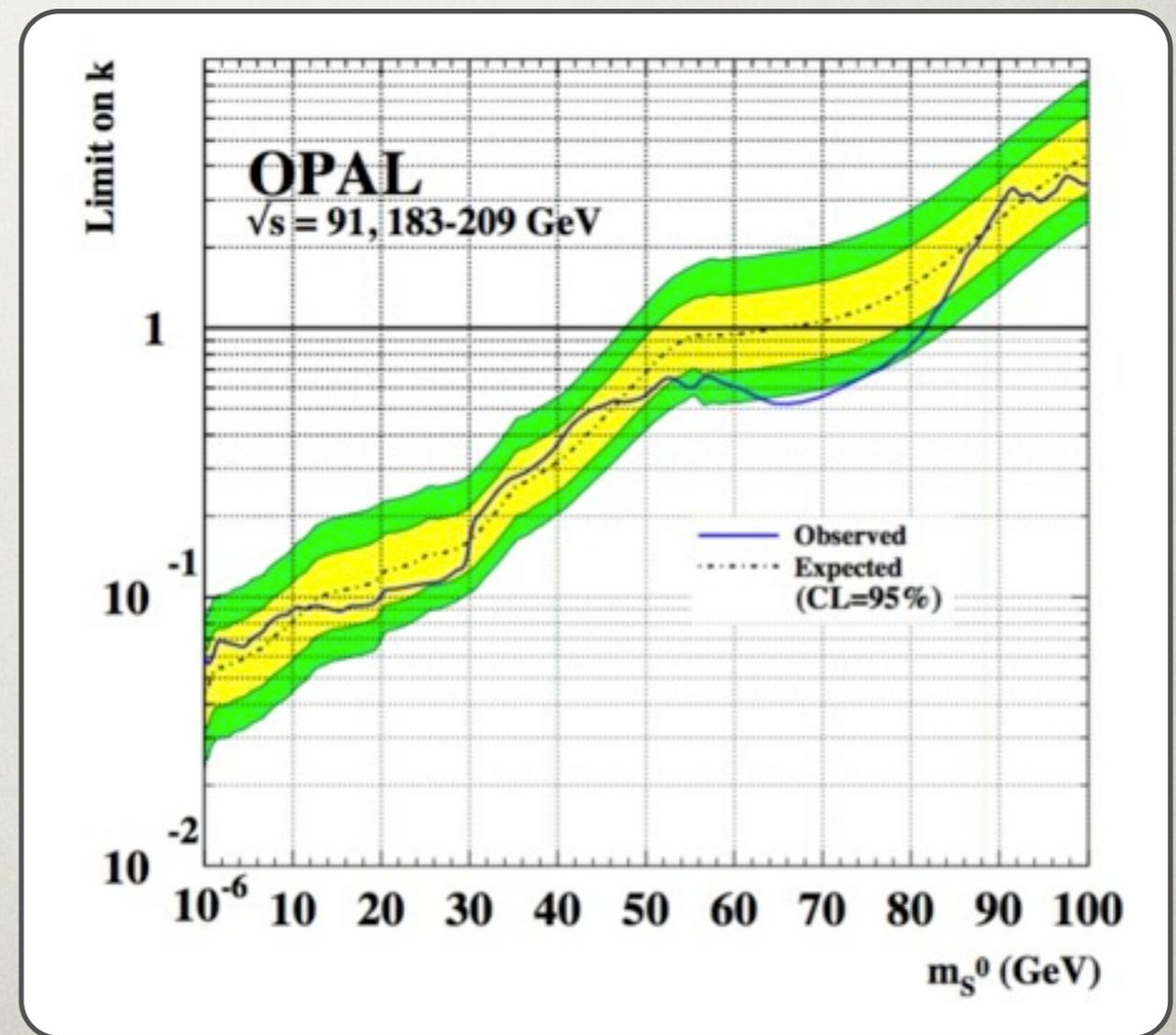
- constraints are in general avoided, if higgs decay has
 - two-jet topology (higgs decays to two lepton jets)
 - high lepton multiplicity (at least 4 lepton per lepton jet)
 - all electron or very high multiplicity

EXPERIMENTAL CONSTRAINTS

- experimental constraints depend on the assumed dominant higgs decay

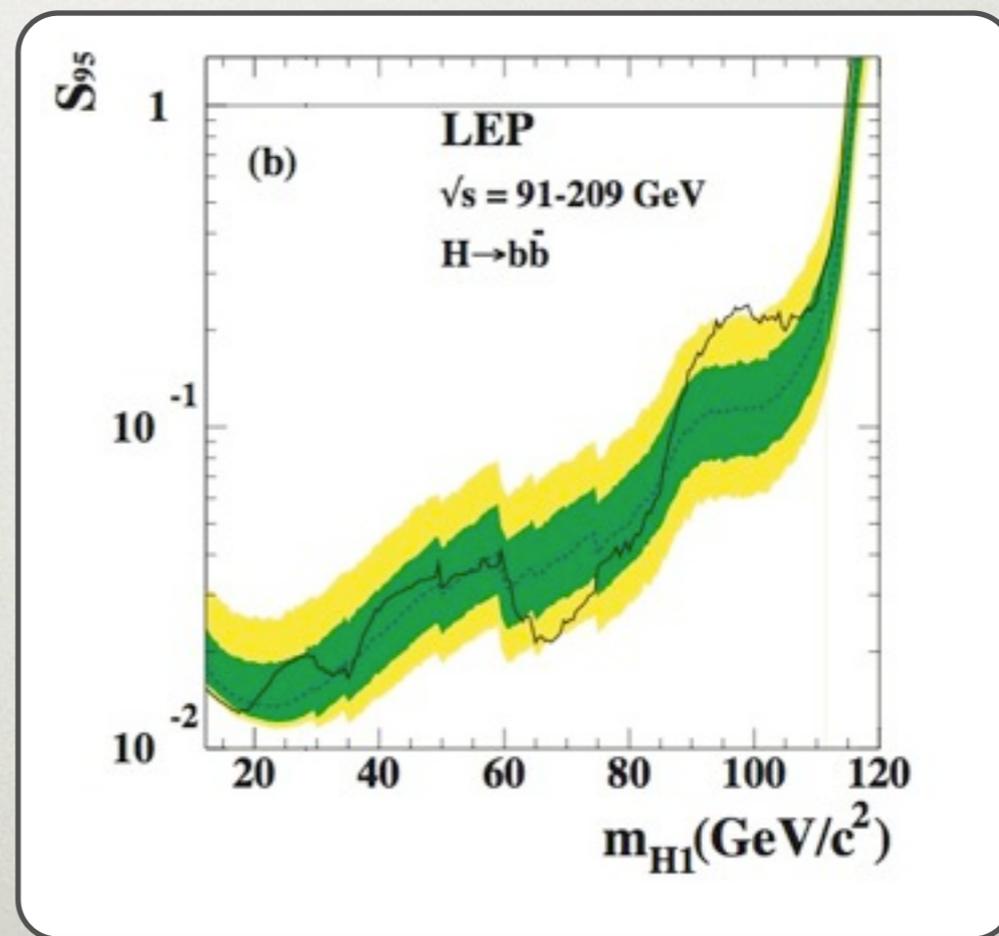
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- a model indep. bound: $m_h > 82 \text{ GeV}$



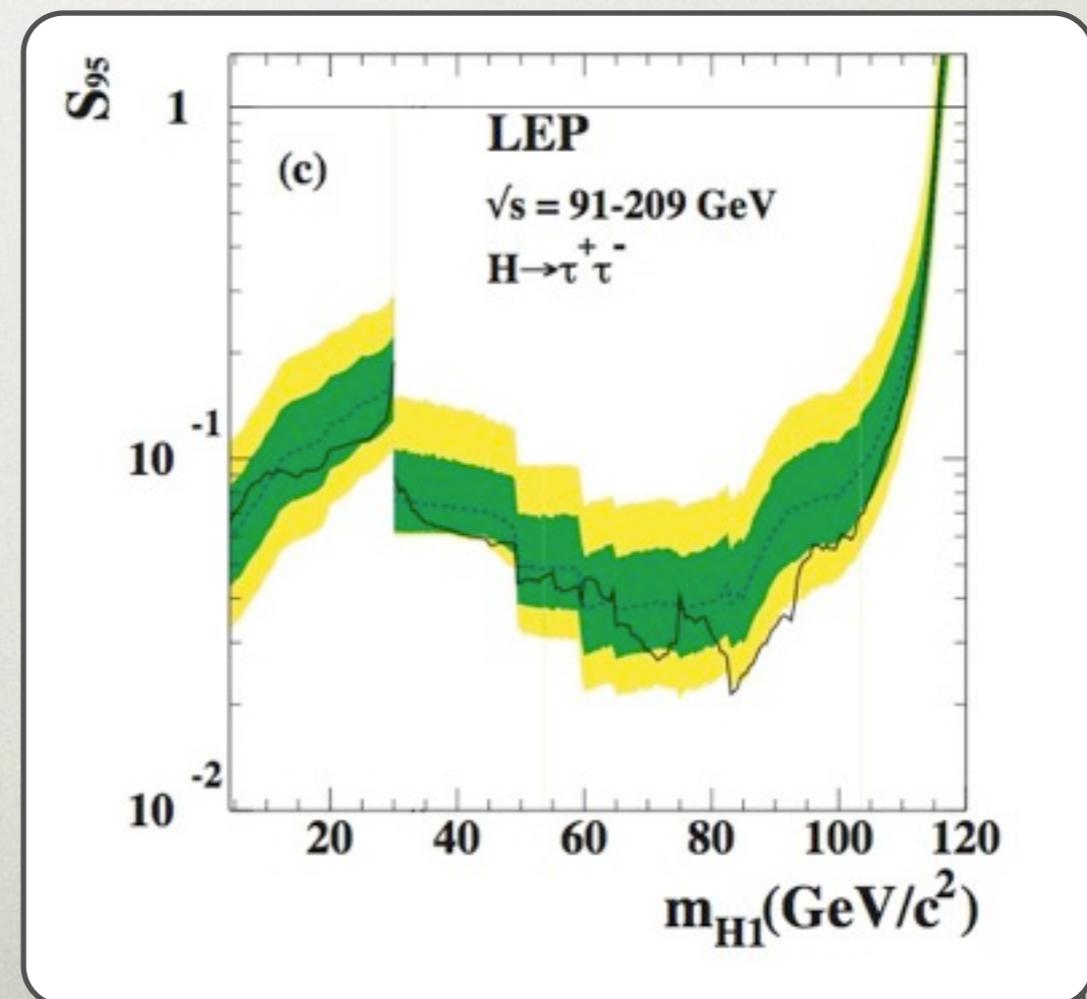
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- for $h \rightarrow bb$ the bound is $m_h > 115 \text{ GeV}$
- for $m_h \sim 100 \text{ GeV}$
 $\Rightarrow \text{Br}(h \rightarrow bb) < 20\%$



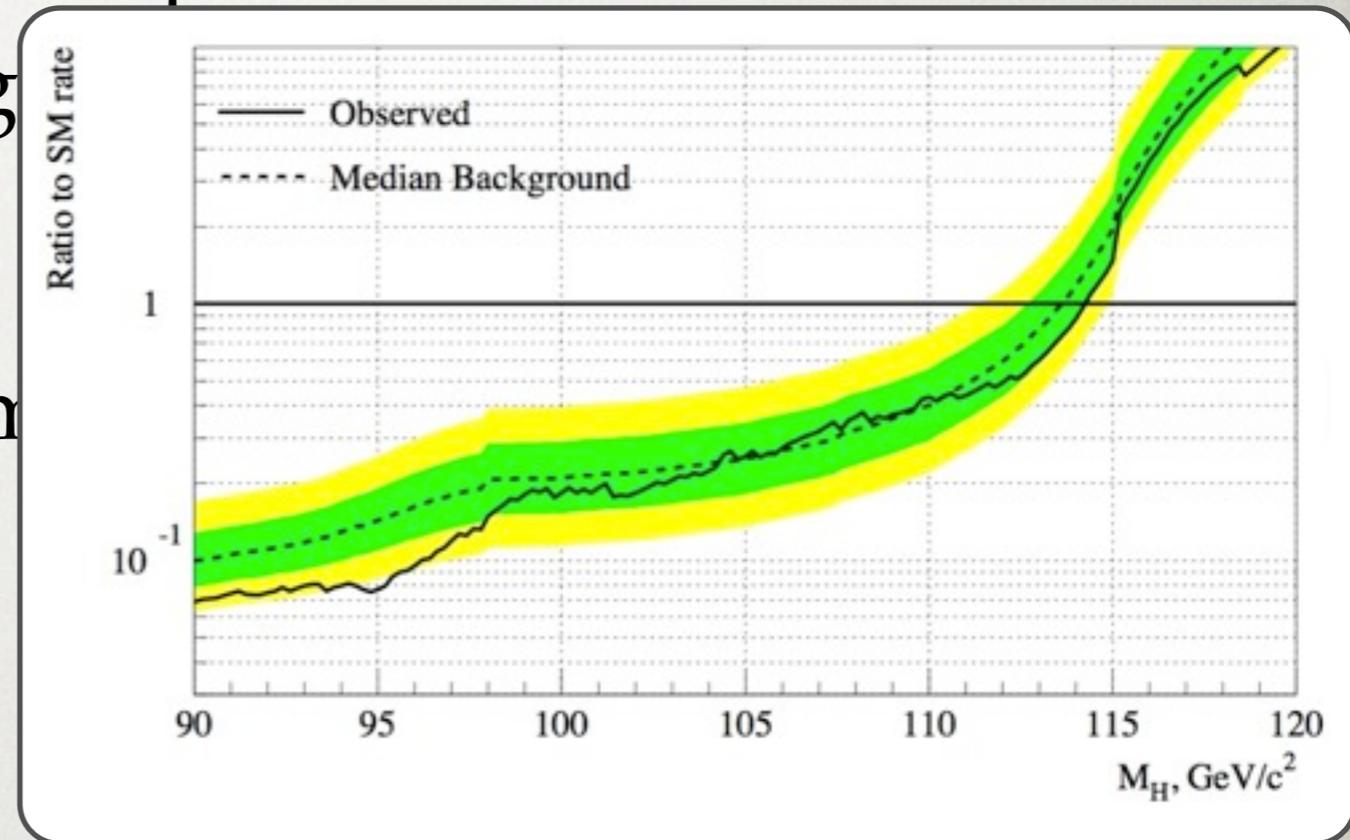
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- for $h \rightarrow bb$ the bound is m
 - for $m_h \sim 100$ GeV
 $\Rightarrow \text{Br}(h \rightarrow bb) < 20\%$
- similar for $h \rightarrow \tau\tau$
- invisible h: $m_h > 115$ GeV
 - for $m_h \sim 100$ GeV $\Rightarrow \text{Br}(h \rightarrow \text{MET}) < 15\%$



HIDING HIGGS IN NMSSM

- NMSSM=MSSM+a singlet

[Dermisek, Gunion, 2005](#)

$$W \supset \lambda S H_u H_d + \kappa S^3$$

- two new higgses beyond MSSM (s, a)

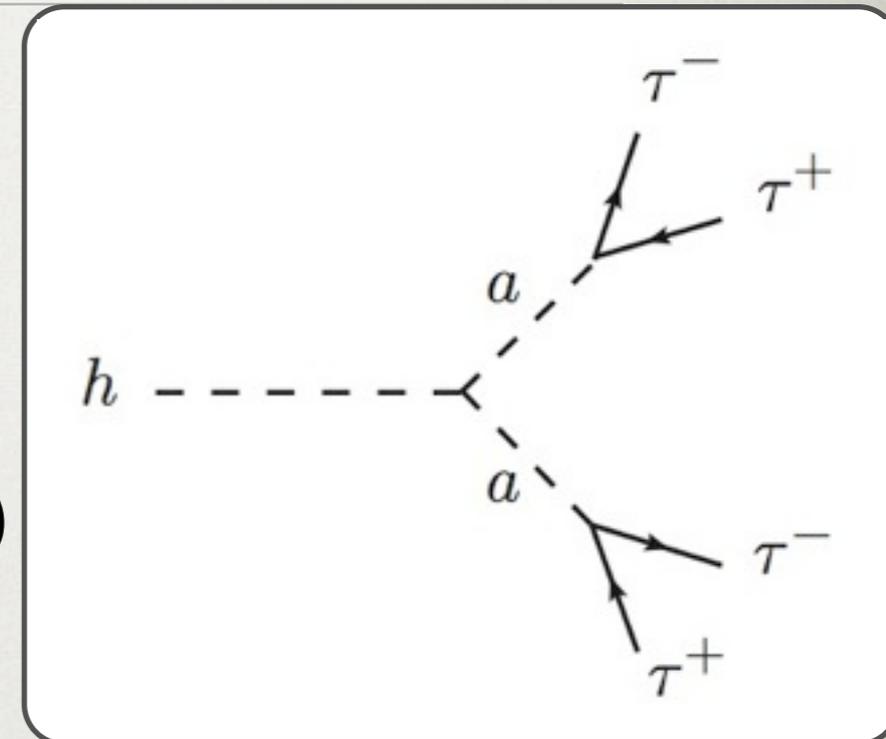
- pseudoscalar a naturally light

- for $m_a < 2m_b$ the dominant decay can be $h \rightarrow 2a \rightarrow 4\tau$

- before this year the bound only $m_h > 85$ GeV

- reanalysis by Aleph, $m_h > 107$ GeV @95% CL (for $10 \text{ GeV} > m_a > 4 \text{ GeV}$)

[Aleph, 1003.0705](#)



ARRIVING FROM HIDDEN SECTOR

- the kinetic mixing Lagrangian for dark photon

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} b_{\mu\nu} b^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\epsilon}{2} \cos \theta_W b^{\mu\nu} F_{\mu\nu}$$
$$V \supset \frac{1}{2} m_b^2 b^2 + b_\mu J_{\text{dark}}^\mu + A_\mu J_{\text{EM}}^\mu$$

- the dark photon-photon mixing term is removed by photon field redefinition

$$A_\mu \rightarrow A_\mu + \epsilon \cos \theta_W b_\mu$$

- dark photon couples to EM current, $\epsilon b_\mu J_{\text{EM}}^\mu$
- Br's of light photon to visible are fixed!

NEUTRALINO PORTAL

- susy \Rightarrow mixing also in gaugino sector

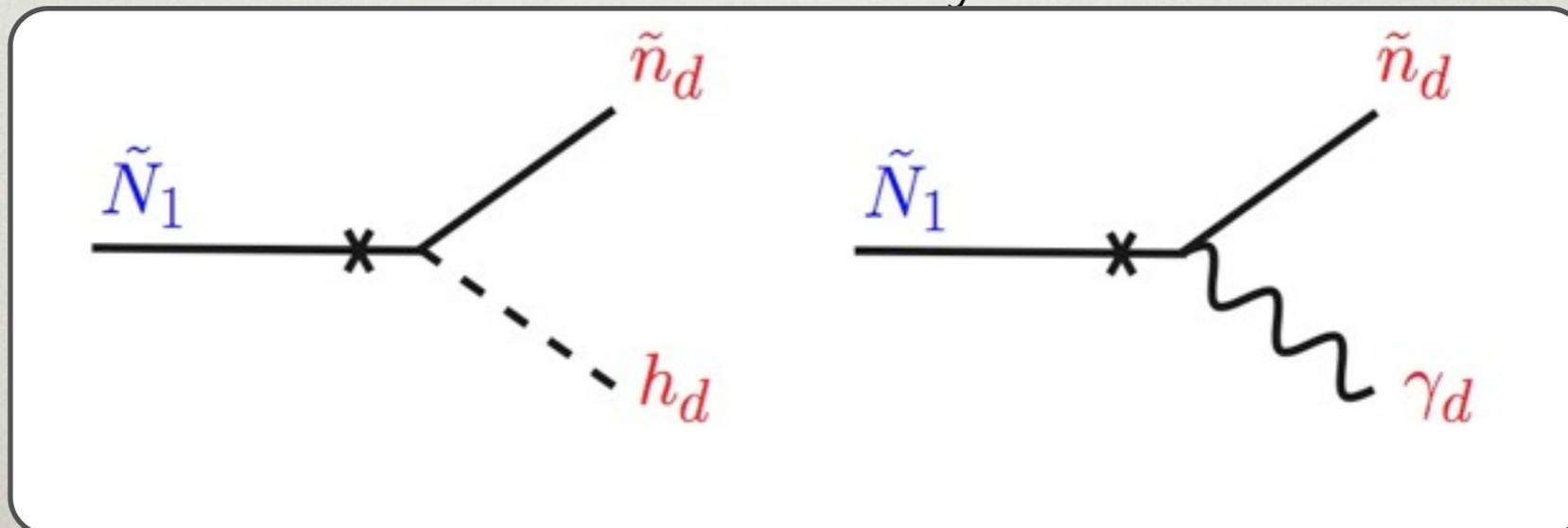
$$\mathcal{L}_{\text{gaugino}} \supset -2i\epsilon \lambda_{\tilde{b}} \bar{\sigma}^\mu \partial_\mu \lambda_{\tilde{B}} + \text{h.c.}$$

- shift hidden gaugino to diag. \Rightarrow visible gaugino couples to hidden current

$$\lambda_{\tilde{b}} \rightarrow \lambda_{\tilde{b}} + \epsilon \lambda_{\tilde{B}}$$

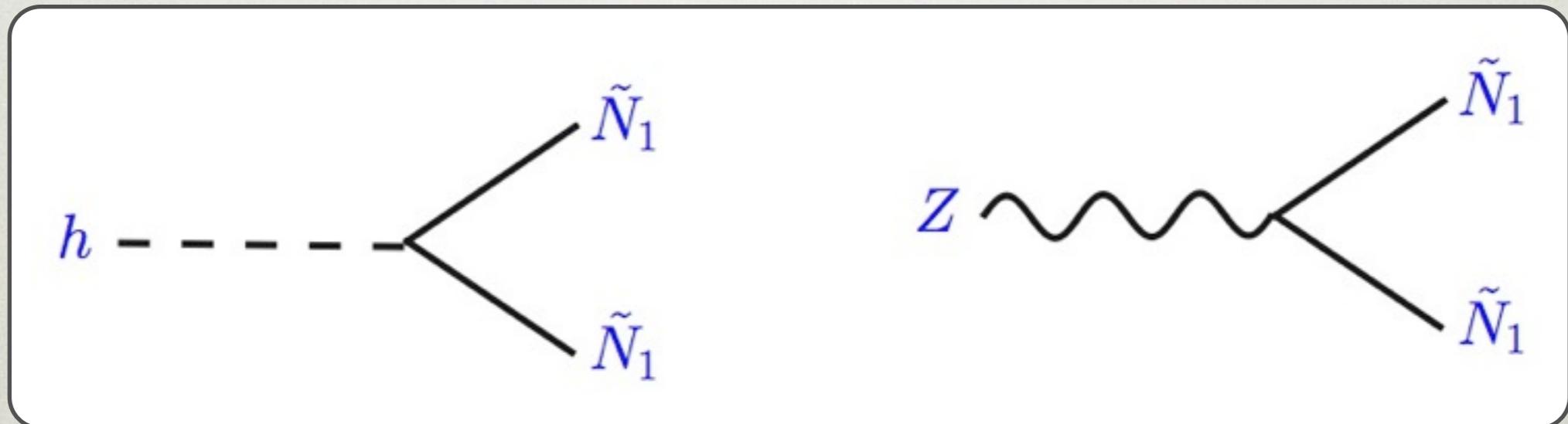
$$V \supset \epsilon \lambda_{\tilde{B}} \tilde{J}_b$$

- MSSM neutralinos can decay to hidden sector



NEUTRALINO PORTAL

- higgs decays to pair of MSSM neutralinos, $h \rightarrow 2\tilde{N}_1$, if $2m_{\tilde{N}_1} < m_h$
- for $2m_{\tilde{N}_1} < m_Z$ Z also decays to \tilde{N}_1
 - consistent with LEP1, if $Br(Z \rightarrow 2\tilde{N}_1) < 10^{-3}$



- possible, if neutralino mostly bino, since then

$$Br(Z \rightarrow 2\tilde{N}_1) \propto (\theta_{\tilde{N}_1\tilde{H}})^4 \quad Br(h \rightarrow 2\tilde{N}_1) \propto (\theta_{\tilde{N}_1\tilde{H}})^2$$

SNEUTRINO PORTAL

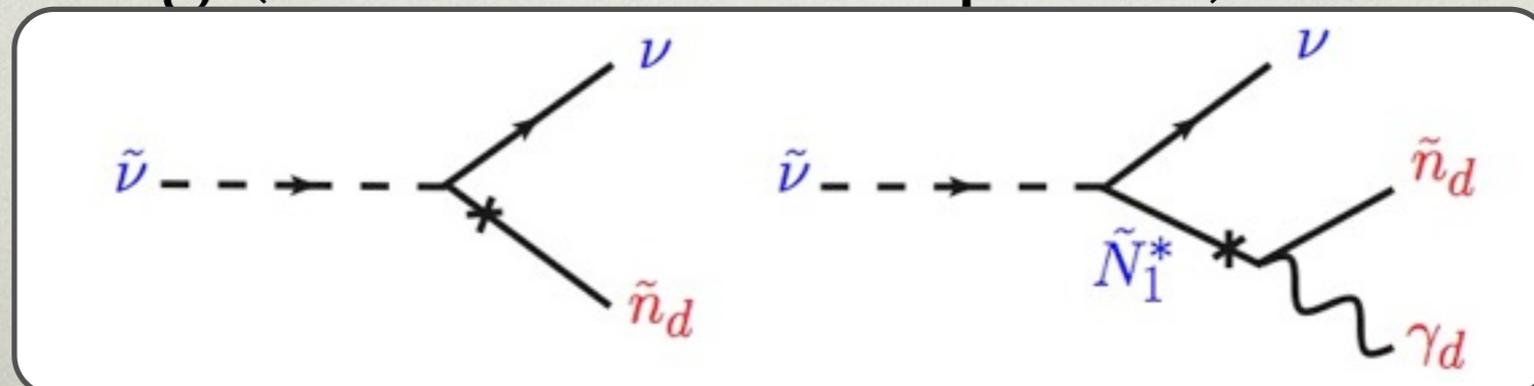
- higgs-snu-snu coupling from D terms, is large

$$D_1 = \frac{g_1}{2} (|H_u|^2 - |H_d|^2 - |\tilde{\nu}_i|^2 + \dots)$$

$$D_2^a = \frac{g_2}{2} (H_u T^a H_u^* + H_d T^a H_d^* + \tilde{L}_i T^a \tilde{L}_i^*)$$

$$V \supset \frac{1}{2} D_1^2 + \frac{1}{2} D_2^2$$

- LEP1: Z should not decay to it $\Rightarrow m_Z < 2m_{\tilde{\nu}} < m_h$
- $h \rightarrow \tilde{\nu}\tilde{\nu}$ dominates over $h \rightarrow b\bar{b}$
- the decay to hidden sector is from kinetic mixing (as in neutralino portal)



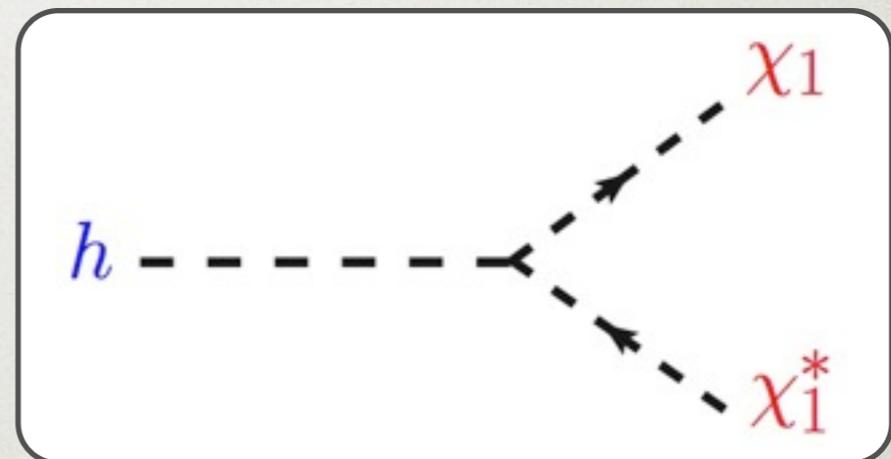
SINGLET PORTAL

- NMSSM+two chiral fields $\chi, \bar{\chi}$ with hidden $U(1)_d$ charges ± 2

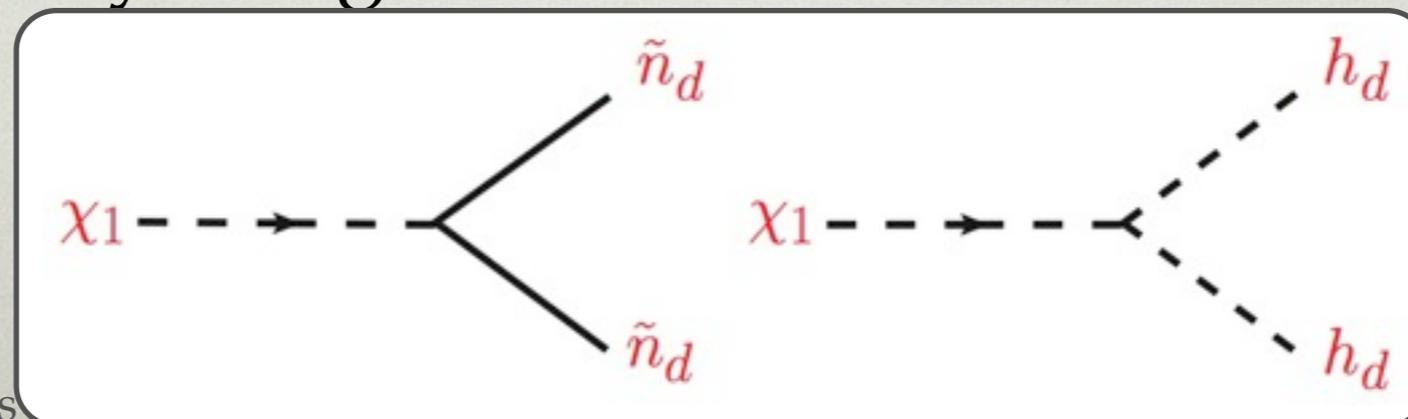
$$W \supset S H_u H_d + S \chi \bar{\chi} + \chi \bar{h}^2 + \bar{\chi} h^2$$

- $\chi, \bar{\chi}$ obtain masses from S vev
- higgs decays through F-term of a singlet

$$V \supset |F_S|^2 = |H_u H_d + \chi \bar{\chi}|^2$$



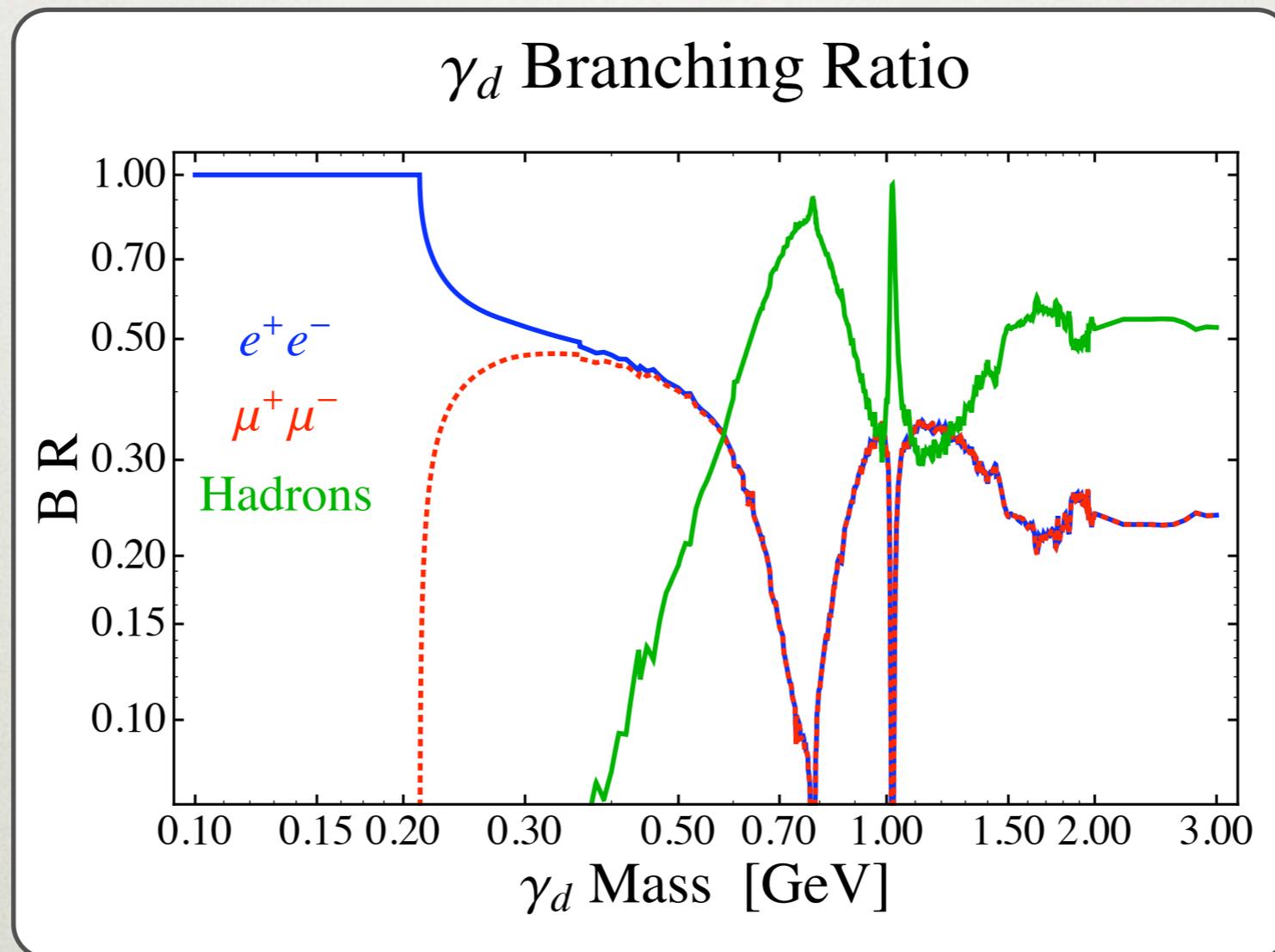
- χ 's decay to lighter hidden sector states



EXPERIMENTAL OBSERVABLES

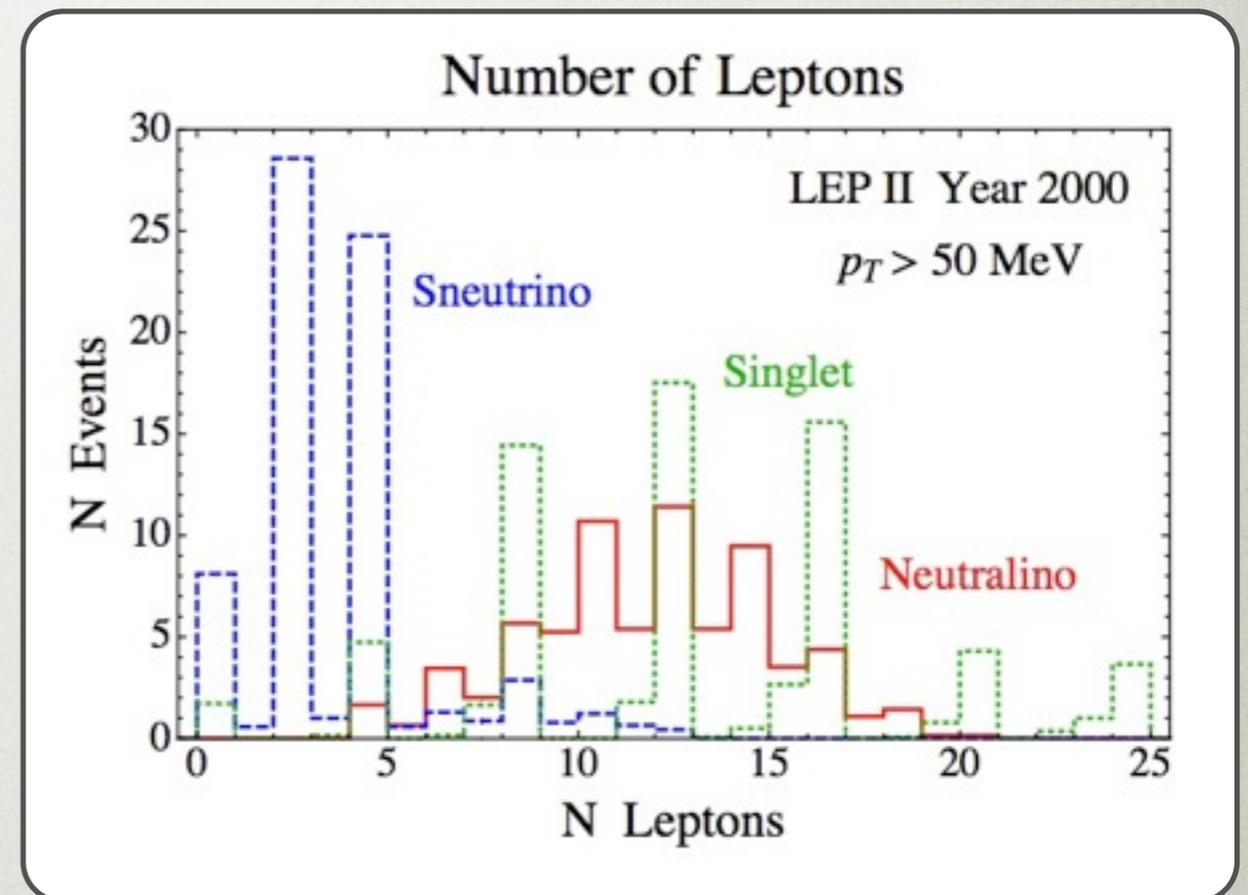
EXPERIMENTAL OBSERVABLES

- visible final states: electrons vs. muons



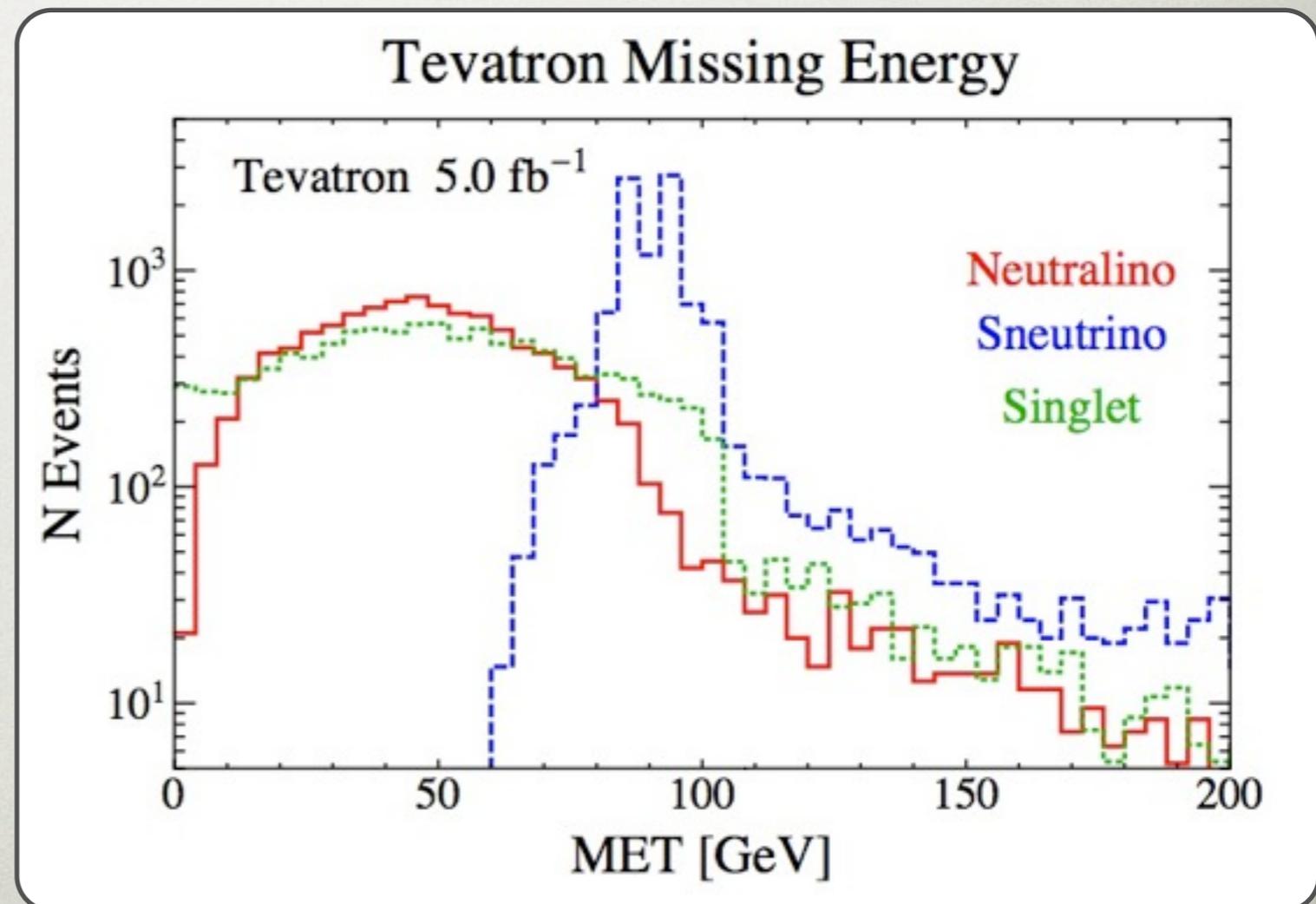
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- lepton multiplicity (depends on the hidden spectrum strongly)



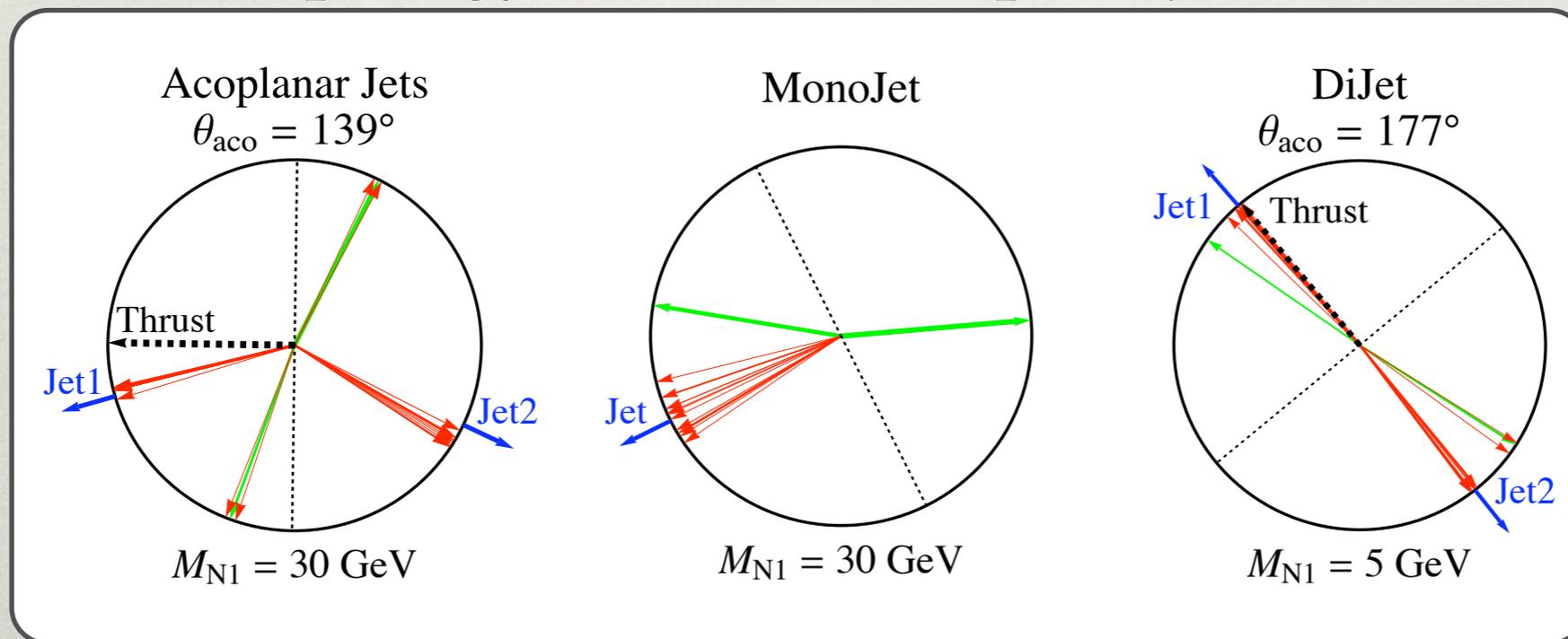
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- event topology: number of lepton jets and distr.



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- visible final states: electrons vs. muons
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- missing energy
- event topology: number of lepton jets and distr.
- lepton isolation

