Search for New Non-standard Decays of the SM-like Higgs at the LHC

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Outline

- Motivation
- Dark Light Higgs (DLH) Model
- DLH Search
  - -Di-Muon channel
  - -B-bbar channel
  - -Di-Tau channel
- Conclusion

Motivation

- If we do not discover the Standard Model (SM) higgs in the future, we might guess that higgs decays in some new non-standard ways
- Non-standard higgs decay modes are also theoretically motivated by many extensions of the SM
- Usually, searching for light higgs is difficult, we provide some new approaches to look for SM-like and light higgese.

Dark Light Higgs Scenario

Draper, Liu, Wagner, Wang, Zhang, PRL. 106 121805 (2011)

$$\mathbf{W} = \lambda \mathbf{N}\mathbf{H_u}\mathbf{H_d} + \frac{1}{3}\kappa \mathbf{N}^3,$$

$$\begin{aligned} V_{soft} &= m_{H_d}^2|H_d|^2 + m_{H_u}^2|H_u|^2 + m_N^2|N|^2 \\ &\quad - (\lambda A_\lambda H_u H_d N + h.c.) + \left(\frac{\kappa}{3}A_\kappa N^3 + h.c.\right) \end{aligned}$$

- κN^3 explicitly breaks Peccei-Quinn symmetry
- Dark light higgs scenario:

nearly PQ limit of NMSSM

($\kappa/\lambda \to 0$, $A_\kappa \to 0$, moderate or small λ)

- Three CP-even higgs (h_1,h_2, h_3); two CP-odd higgs (a_1, a_2)

Masses of the Higgs

h2 is SM-like: $h_2 \sim h_u + h_d \cot\beta - \frac{2\varepsilon v m_Z}{m_Z^2 + \mu^2} h_n$ $\varepsilon = \frac{\lambda\mu}{m_Z}\left(\frac{A_\lambda}{\mu\tan\beta} - 1\right)$

h1 is the lightest CP-even scalar:

$$m_{h_1}^2 \approx -4\varepsilon^2 v^2 + \frac{4\lambda^2 v^2}{\tan^2\beta} + \frac{\kappa A_\kappa \mu}{\lambda} + \frac{4\kappa^2\mu^2}{\lambda^2}$$

And Loop correction: $\Delta m_{h_1}^2 \approx \frac{\lambda^2\mu^2}{2\pi^2} \log\frac{\mu^2\tan^3\beta}{m_Z^2}$

A light CP-odd Higgs a_1: $m_{a_1}^2 \approx -\frac{3\kappa A_\kappa \mu}{\lambda}$

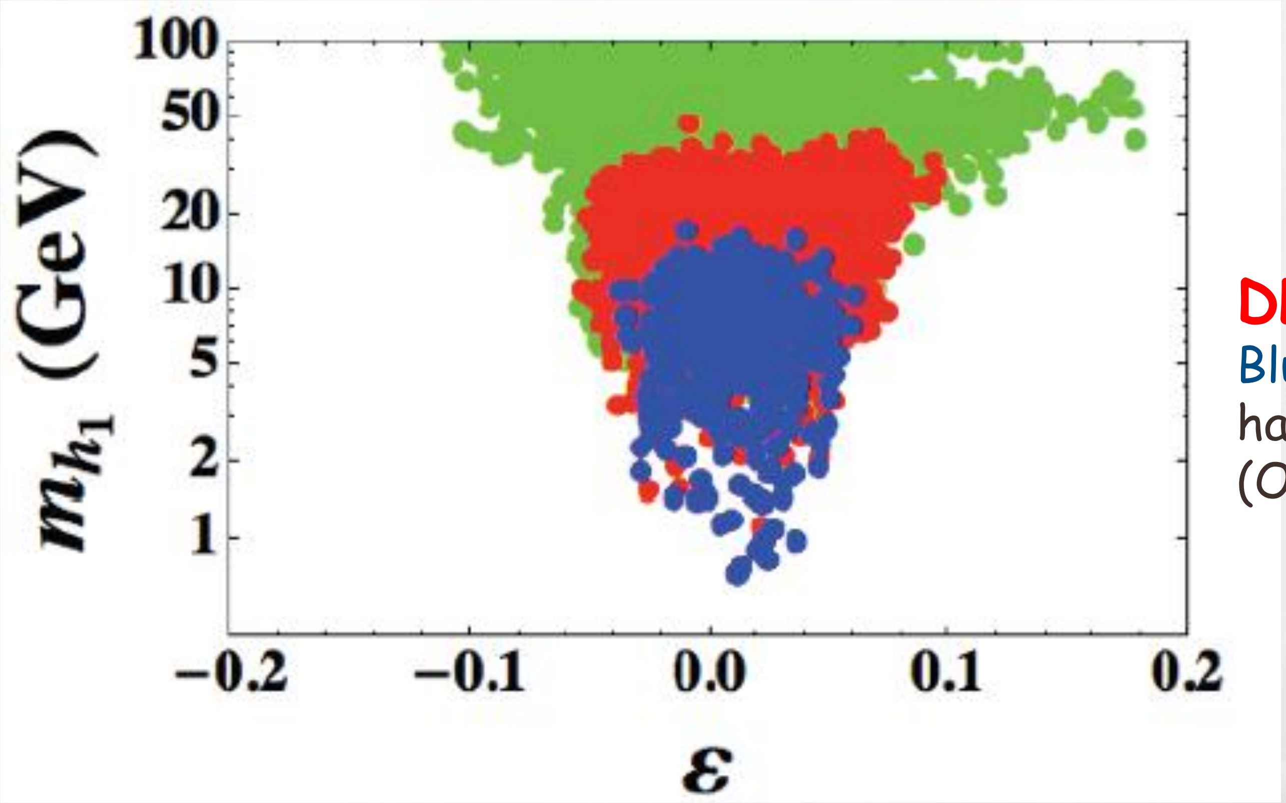
A lightest neutralino χ_1: $m_{\chi_1} \approx \frac{\lambda^2 v^2}{\mu}\sin 2\beta + \frac{2\kappa\mu}{\lambda}$

χ_1 is the dark matter particle

B. A. Dobrescu et al., Phys. Rev. D 63, 075003 (2001);
R. Dermisek et al., Phys. Rev. Lett. 95, 041801 (2005)

Comparison: in the R-symmetry limit, h_1 and χ_1 are typically not so light and h_1 is SM-like

Parameter Scan



DLH Senario:
Blue, Red Points
have mass range
(O(0.1)-O(10))GeV

Vacuum stability sets a small upper bound on ε

No points near ε->0 because of the vacuum stability requirement

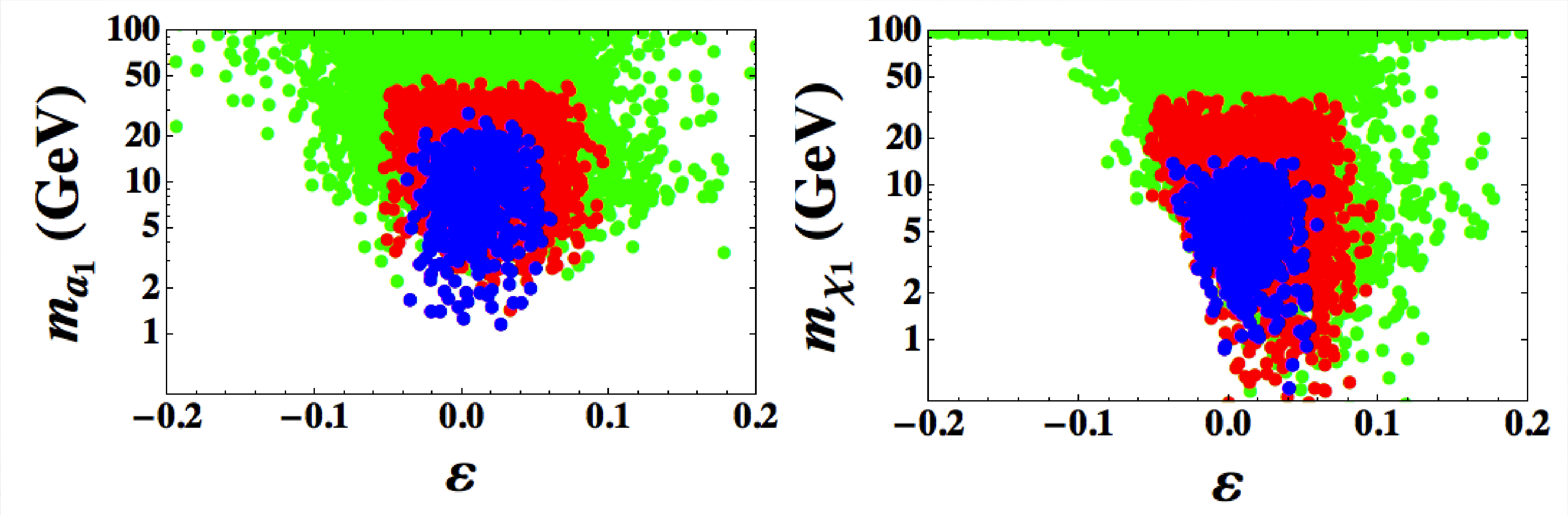
$5 \leqslant \tan\beta \leqslant 50,\ 0.05 \leqslant \lambda \leqslant 0.5,\ 0.0005 \leqslant \kappa \leqslant 0.05, -0.8 \leqslant \varepsilon' \leqslant 0.8,\ \ -40\text{GeV} \leqslant A_\kappa \leqslant 0,\ 0.1\text{TeV} \leqslant \mu \leqslant 1\text{TeV}$

$\lambda < 0.30,\ \kappa/\lambda < 0.05,\ \mu < 400\text{GeV}$

$\lambda < 0.15,\ \kappa/\lambda < 0.03,\ \mu < 250\text{GeV}$

Parameter Scan (cont.)

Light pseudoscalar and neutralino masses

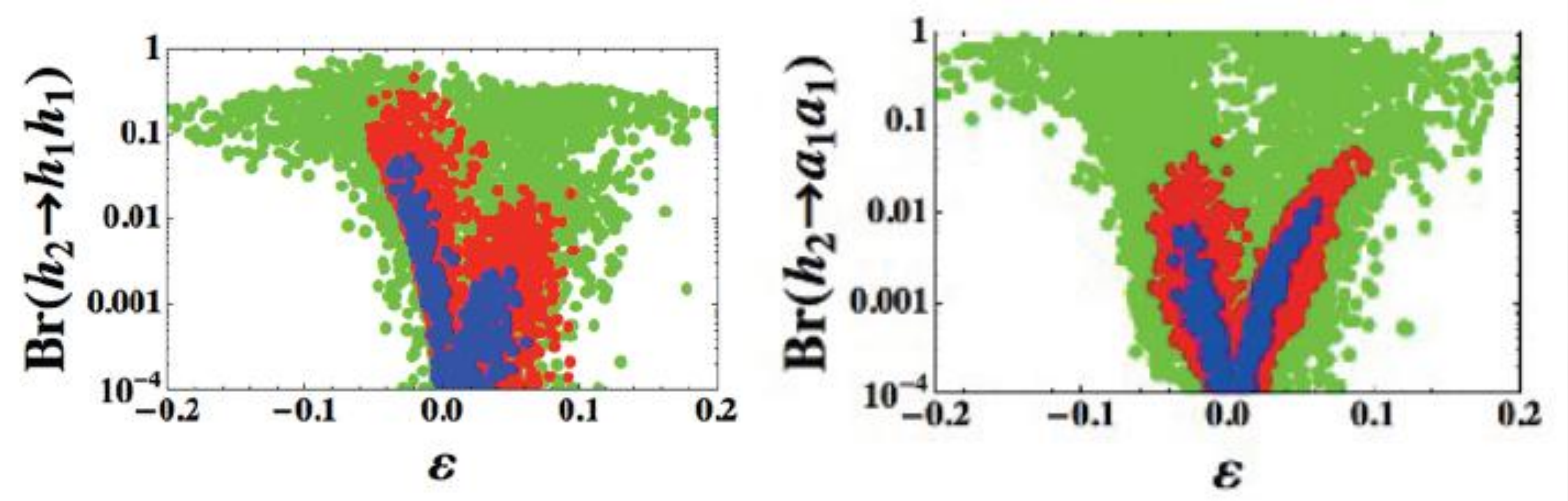


h2->h1h1, a1a1 modes

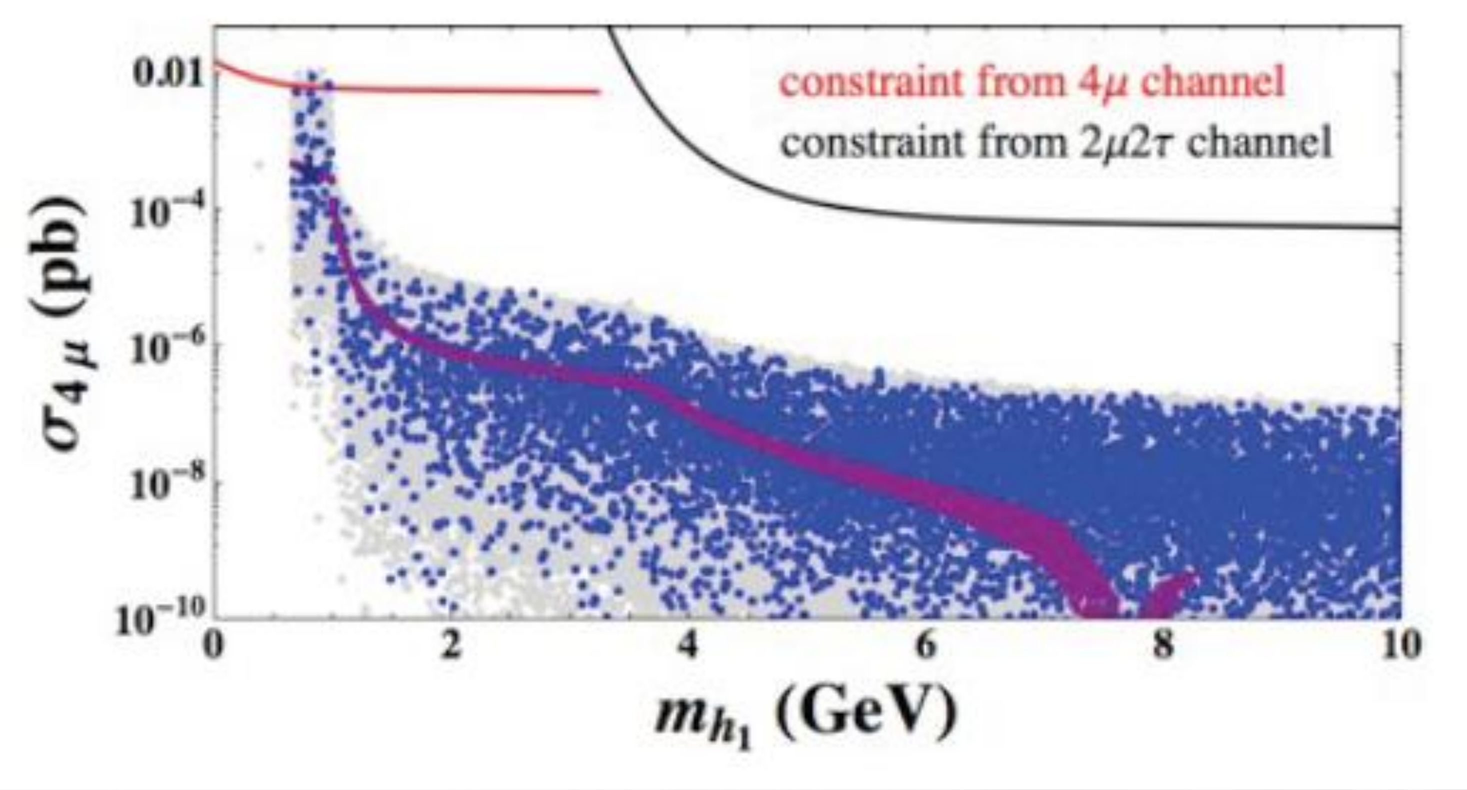
DLH scenario has h2->h1 h1 and h2->a1 a1 decay channels as well, but highly suppressed

Exp. Constraints can be easily satisfied.

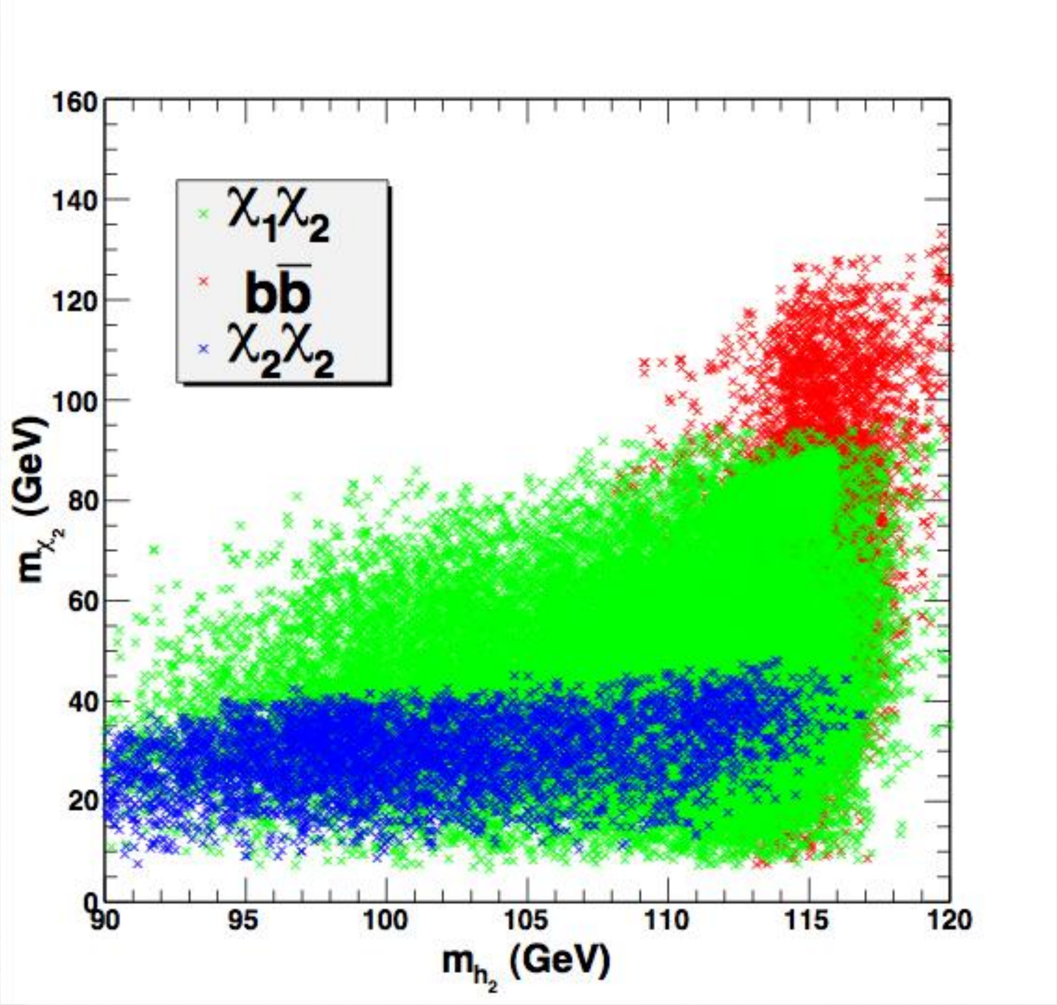
$$|y_{h_2 h_1 h_1}| = |y_{h_2 a_1 a_1}| = \frac{\lambda v m_Z \varepsilon}{\sqrt{2}\mu}$$



Constraints from h2->h1h1,a1a1

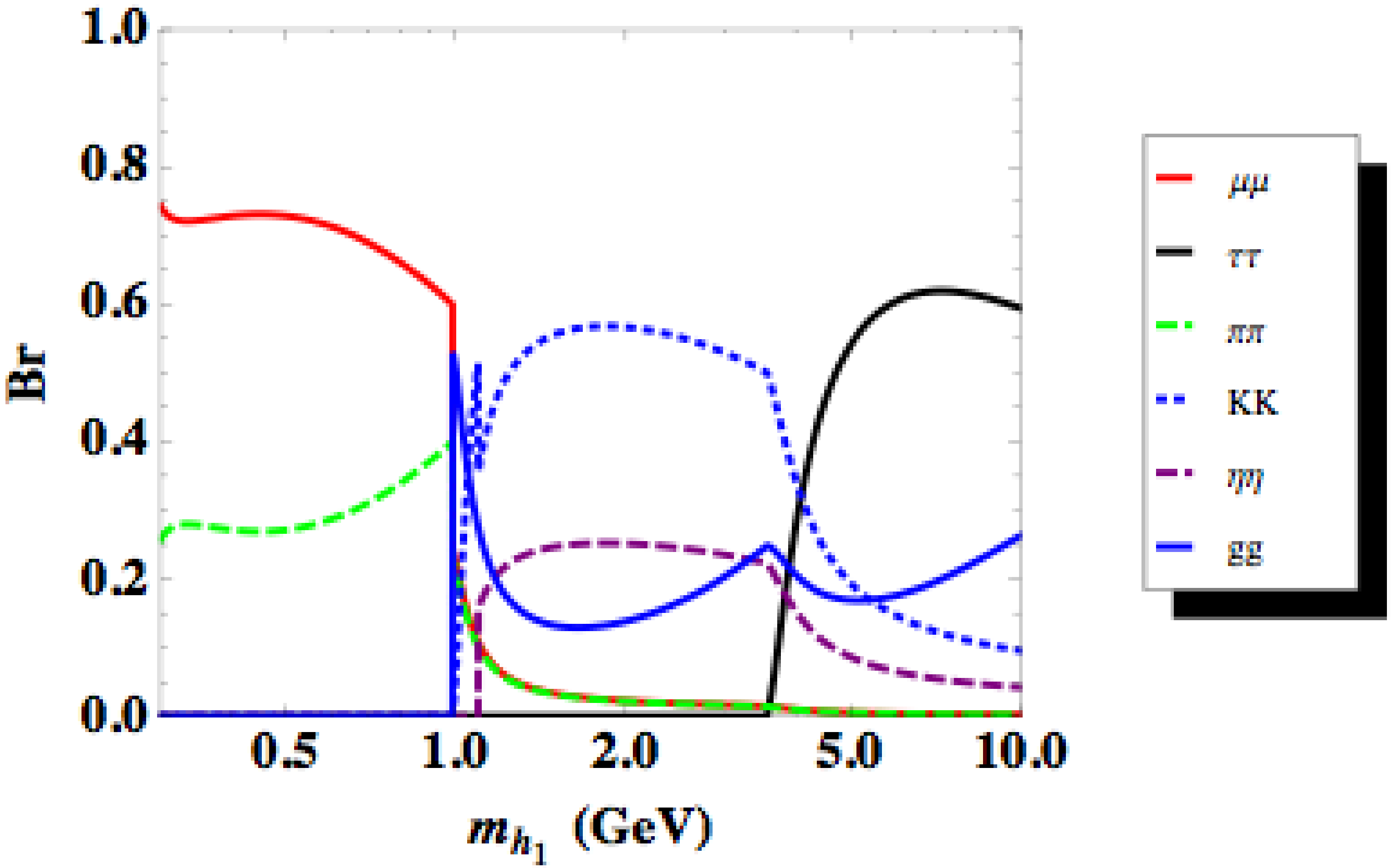


h_2 decay modes

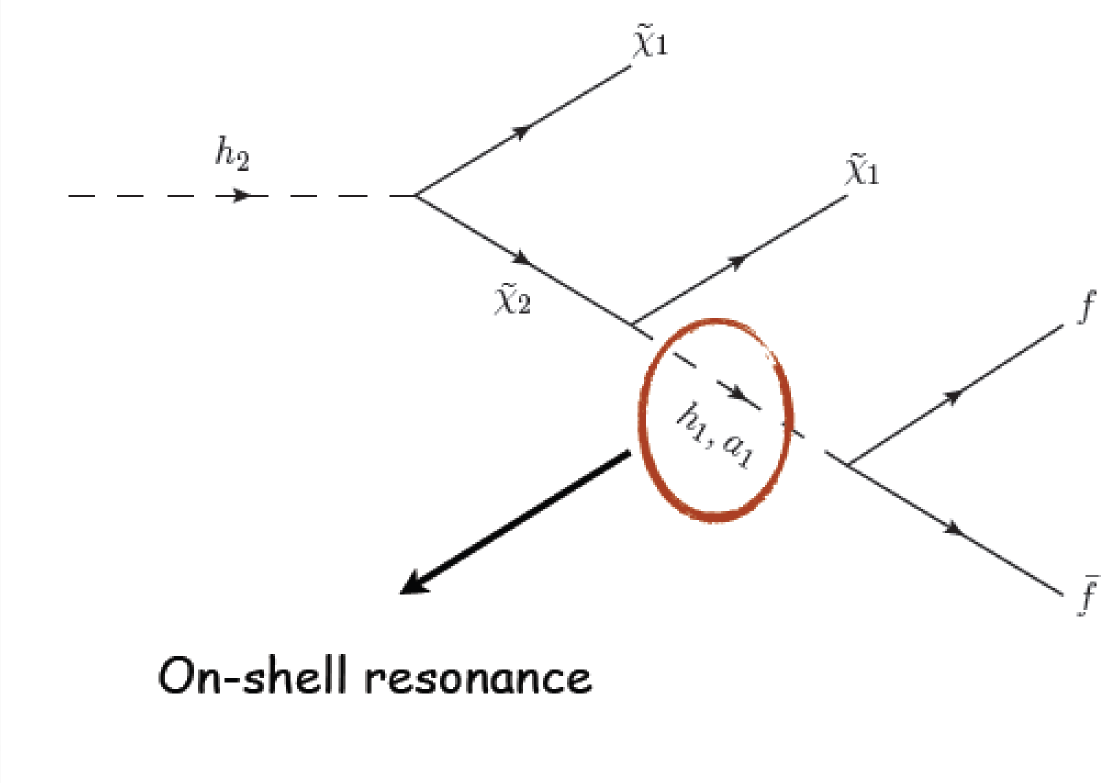


- **$h_2 \to \chi_1\ \chi_2$** is typically dominant as long as it is kinematically allowed, and it is corresponding to the **GREEN** points.
- **$h_2 \to bb$** mode can be dominant sometimes, but NOT generic.

h_1 decay modes



Dark Light higgs search



Signal: Collimated Fermion pairs + MET

Benchmark points

- **Assumption:**

$Br(h_2 \to \chi_1 \chi_2)=100\%$, $Br(\chi_2 \to \chi_1 h_1) = 100\%$, $Br(h_1 \to ff) = 100\%$

- **Parameters:**

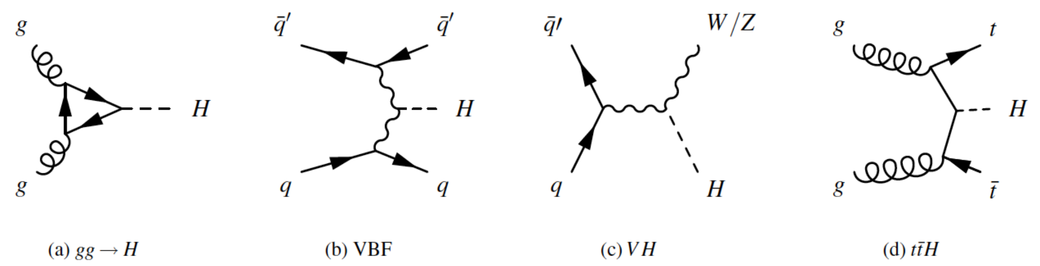
-m_{h2} = 115GeV (95GeV~135GeV)

-$m_{\chi 2}$ = 80GeV

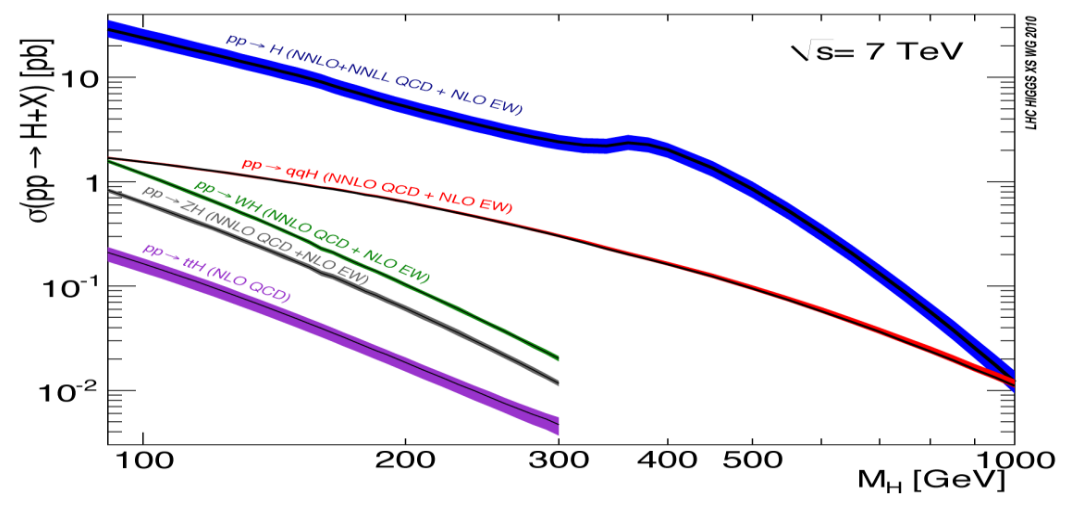
-$m_{\chi 1}$ = 10GeV

-m_{h1} = 1GeV($\mu\mu$)
6GeV ($\tau\tau$)
15GeV(bb)

SM Higgs Production



(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$



h_2 (m_{h2} = 115GeV)	σ (pb) @ 7TeV	σ (pb) @ 14TeV
Gluon Funsion	18.35	59.37
W/Z Funsion	1.393	4.771
Wh_2	0.7546	1.952
Zh_2	0.4107	1.130
ttbar h_2	0.1106	0.7699

Di-Muon Channel @ 7TeV

- Fairly Straight-forward:

  Two close muons + MET + narrow invariant dimuon mass peak around m_{h1}

- Zh_2 with $Z \to ll$, $h_1 \to \mu\mu$

  Almost no irreducible background

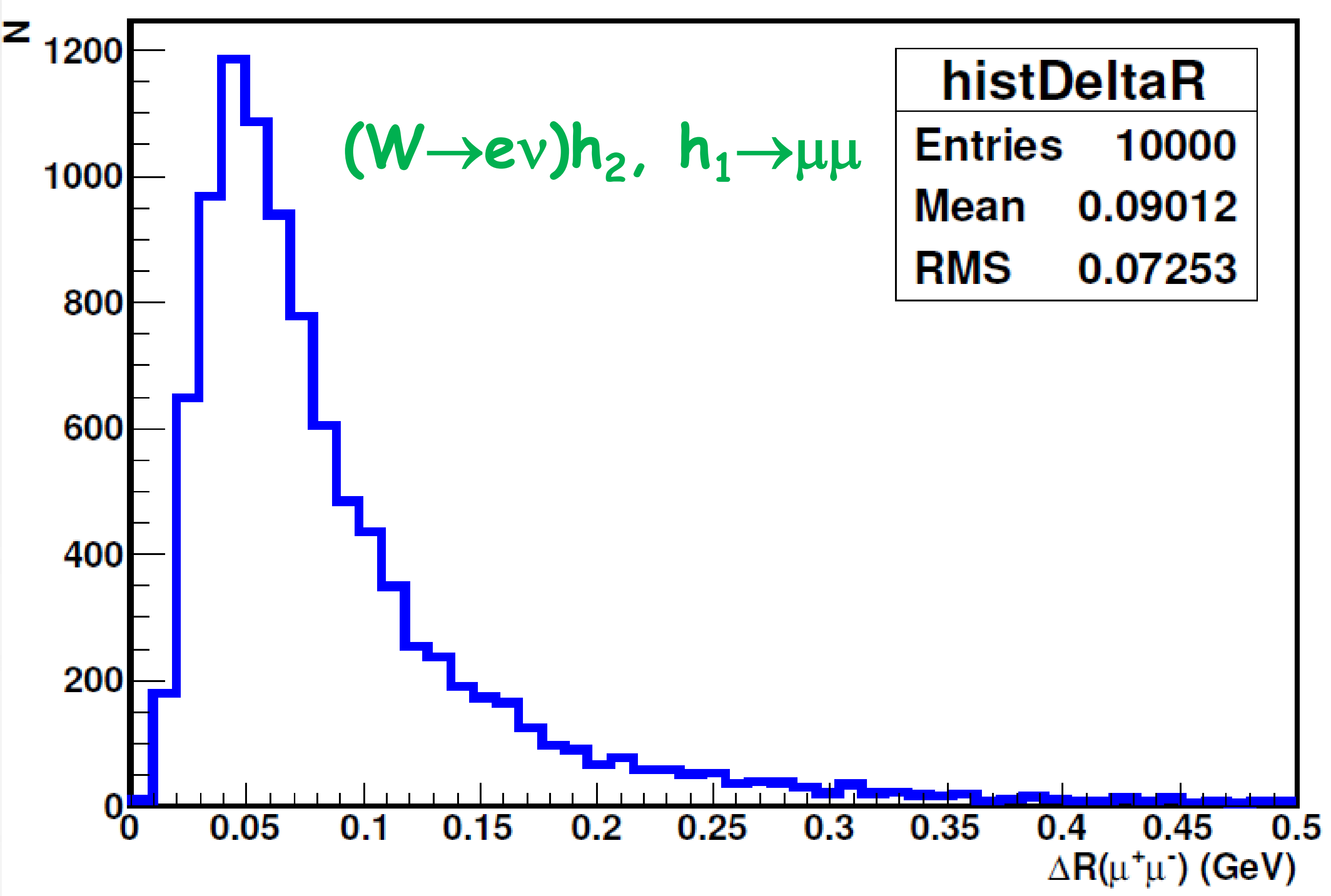
- Wh_2 with $W \to l\nu$, $h_1 \to \mu\mu$

  Also very easy to be discovered and the dominant background is from $W+(\gamma^* \to \mu\mu)$

- Event Generation

  MG5/ME4 + pythia + PGS

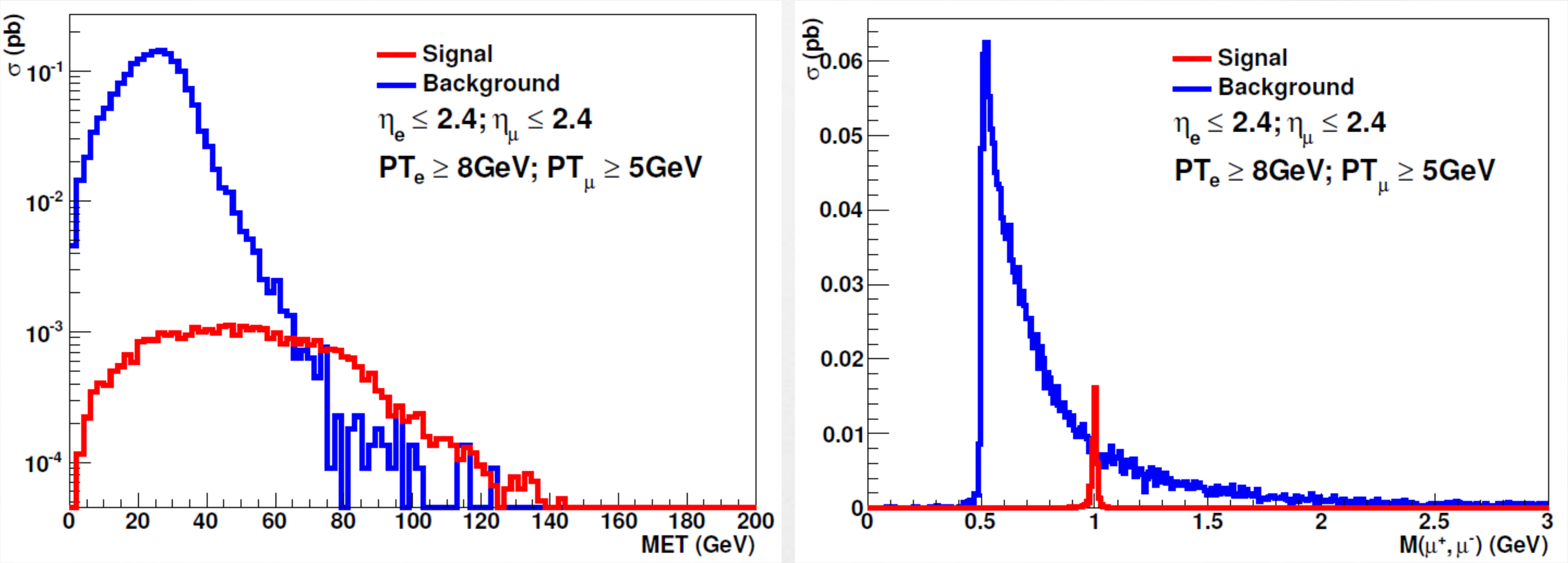
$\Delta R(\mu\mu)$


N
1200
1000
800
600
400
200
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
$\Delta R(\mu^+\mu^-)$ (GeV)
$(W\rightarrow e\nu)h_2,\ h_1\rightarrow\mu\mu$
histDeltaR
Entries 10000
Mean 0.09012
RMS 0.07253

MET + m(μμ)

The two most effective variables that can reduce the SM background are **MET** and **m(μμ)**

$(W \rightarrow e\nu)h_2,\ h_1 \rightarrow \mu\mu$



Cut-Flow-Table

η_l Cut	Pt_l Cut	MET Cut	$m(\mu\mu)$
$\eta_{e,\mu} \le 2.4$	$Pt_e \ge 8$GeV, $Pt_\mu \ge 5$GeV	MET > 30GeV	$0.9\text{GeV} \le m(\mu\mu) \le 1.1\text{GeV}$

$(W\to e\nu)h_2,\ h_1\to\mu\mu$

Cut	Signal	Background 4.5179+6.7256 pb
Reco+η_l	55.57%	26.89%
Pt_l	47.74%	15.02%
MET	37.29%	4.19%
$m(\mu\mu)$	36.85%	0.40%

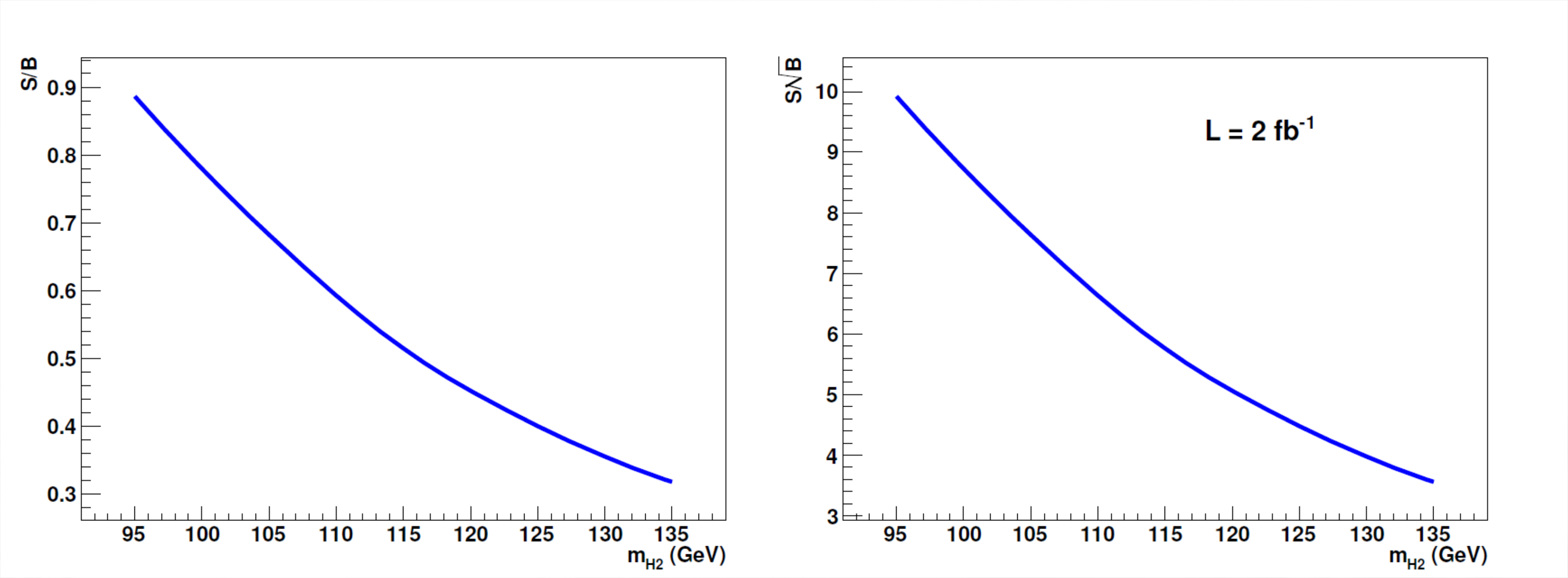
$(W\to \mu\nu)h_2,\ h_1\to\mu\mu$

Cut	Signal	Background 4.5649+6.8047 pb
Reco+η_l	60.17%	29.01%
Pt_l	51.34%	16.23%
MET	40.42%	5.38%
$m(\mu\mu)$	39.73%	0.55%

Note: Some preselection cuts have been applied

Discovery Potential

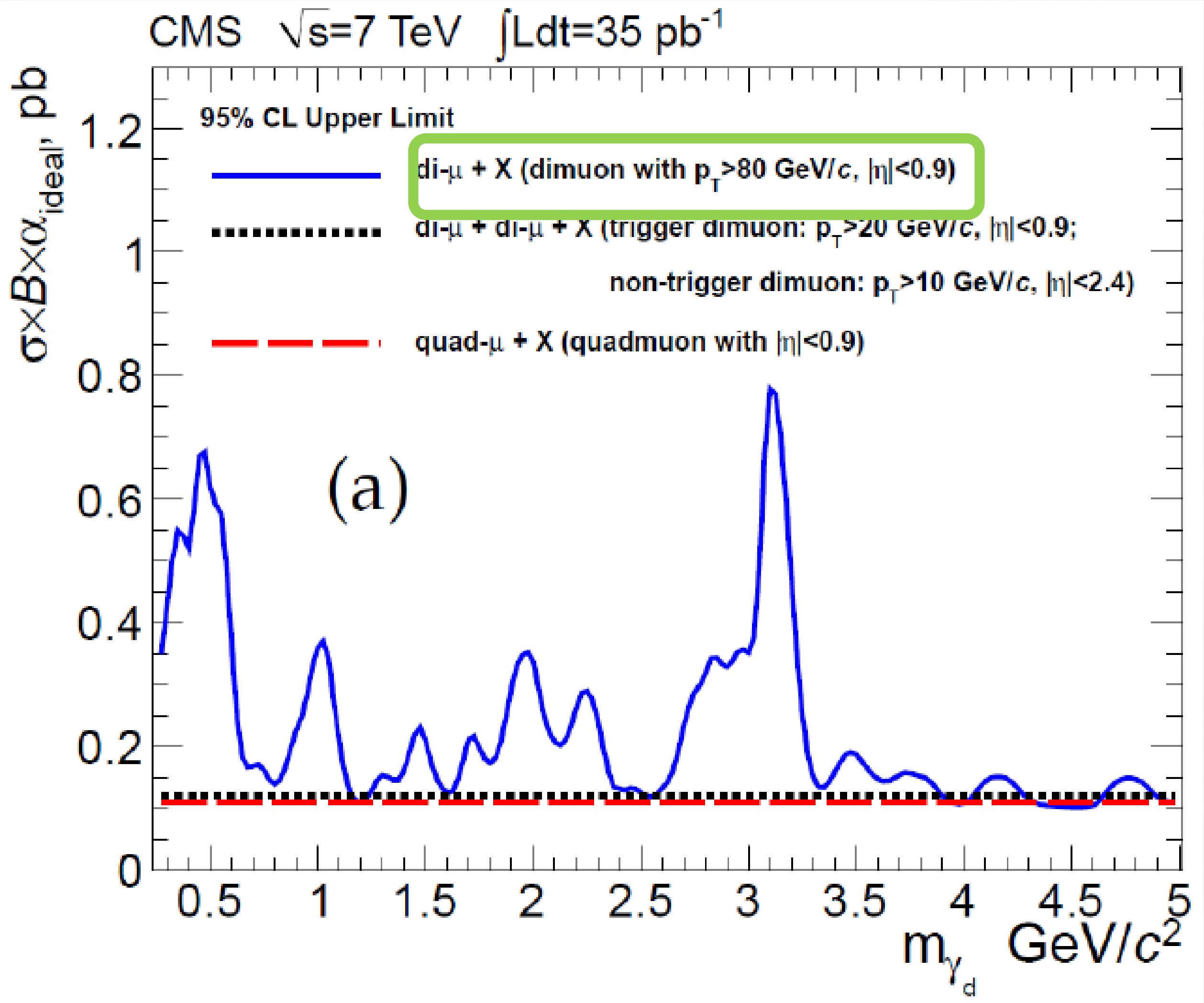
$(W \to e\nu)h_2,\ h_1 \to \mu\mu$



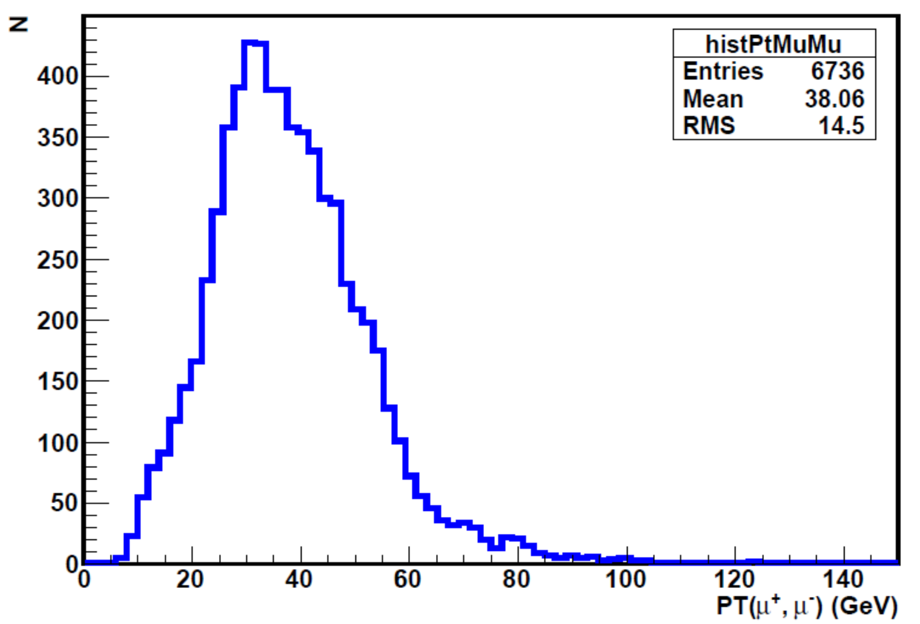
Similar for other h_2 production in dimuon channels

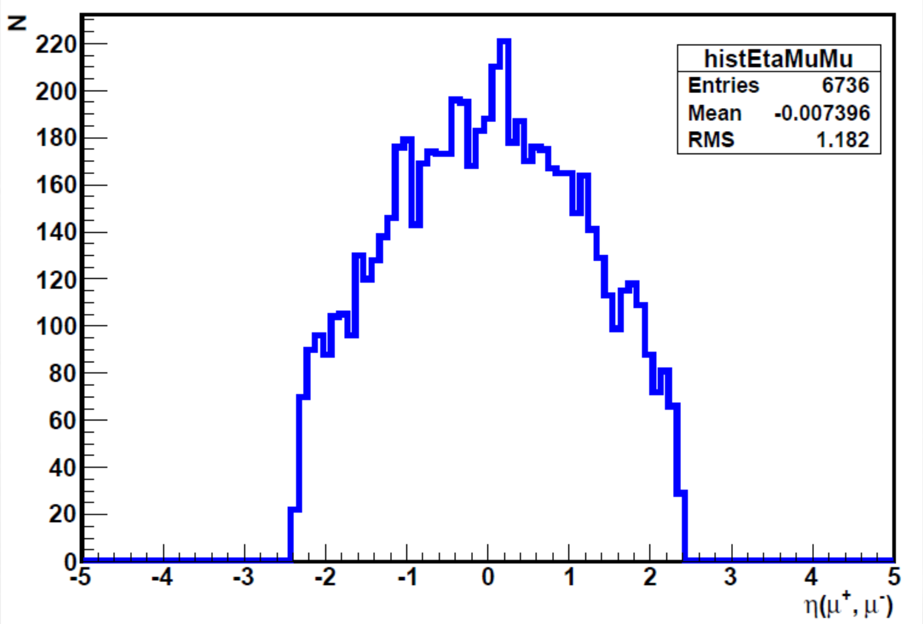
Dark Photon Search

arXiv:1106.2375



Check $gg \rightarrow h_2$, $h_1 \rightarrow \mu\mu$

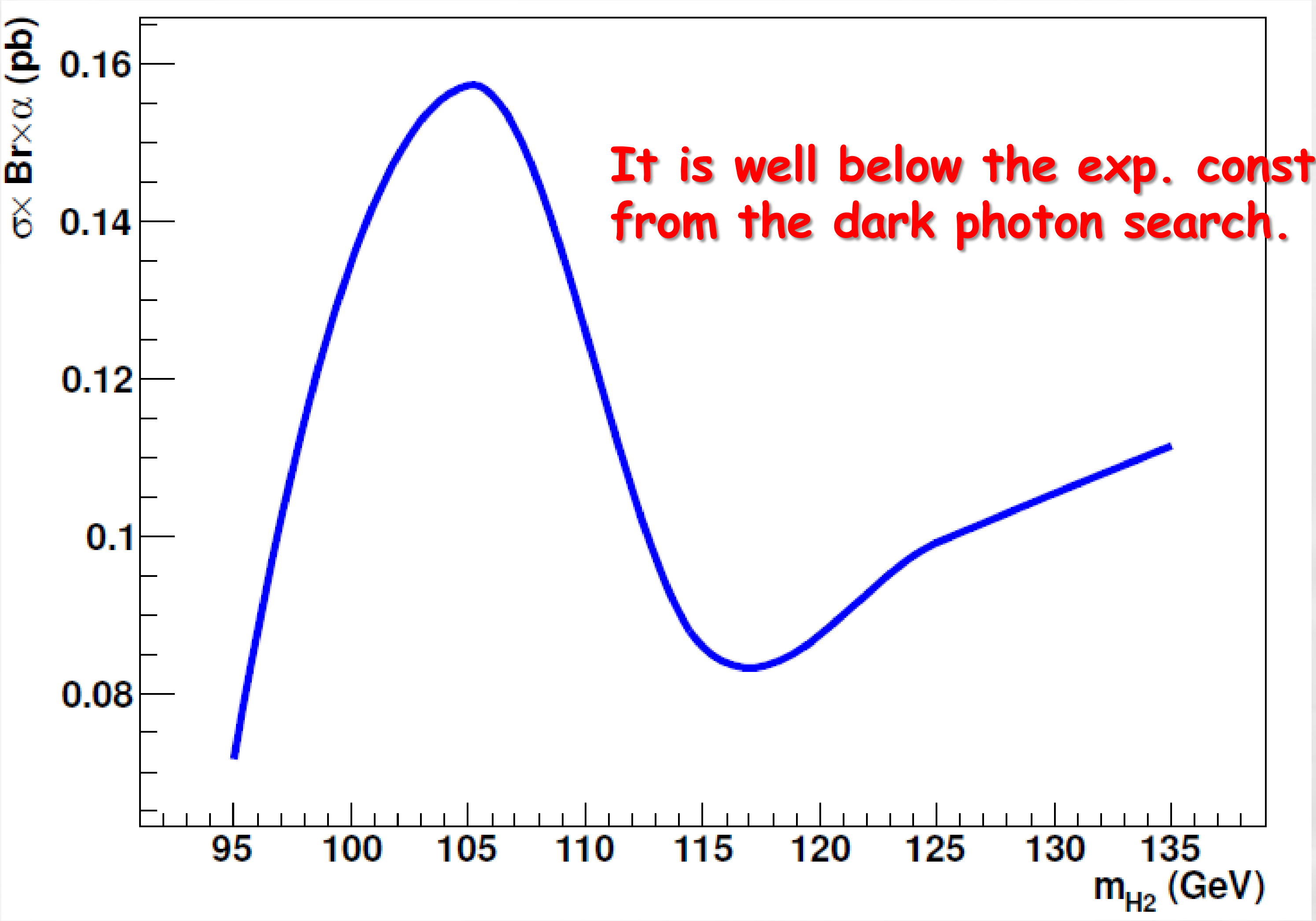




$PT(\mu\mu) > 80GeV$

$|\eta(\mu\mu)| < 0.9$

Check $gg \to h_2$, $h_1 \to \mu\mu$ (Cont.)



It is well below the exp. constraints from the dark photon search.

B-bbar channel @ 14TeV

- Bbbar channel is much more difficult
- ggfusion: bb + MET signal
  -overwhelmed by ttbar background
- VBF: bb + jets + MET
  -overwhelmed by ttbar background
- Wh_2: bb + ℓ+MET
  -overwhelmed by ttbar semileptonic background
- Zh_2: bb + ℓ+ℓ-+ MET
  -can use Z mass window cut to control ttbar fully leptonic background
  -remaining Zg(g → bb) background is reduced by MET requirement
- tth_2: bb(+bb) + ℓ+MET or bb(+bb) + ℓ+ℓ-+ MET
  -can isolate inclusive ttbar sample, and use MET and additional b-tag requirements to isolate signal

Zh_2($t\bar{t}h_2$), ($h_1 \to bb$)

- Zh_2 is the more promising channel
- Event Generation

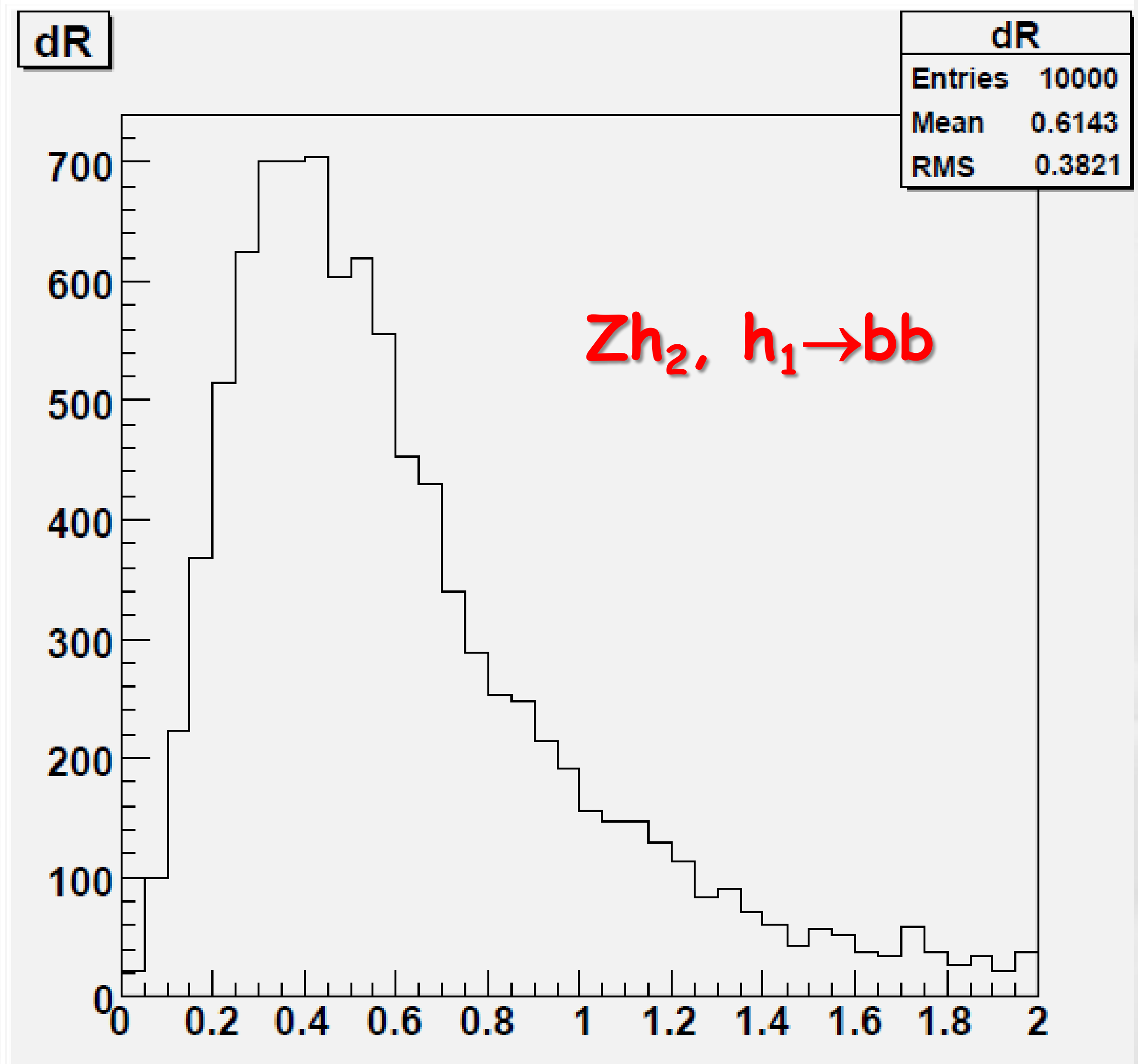
Generate events using MG5/ME4, shower and hadronize with Pythia,cluster with FastJet (anti-kT with R = 1)

Minimal detector simulation

Background

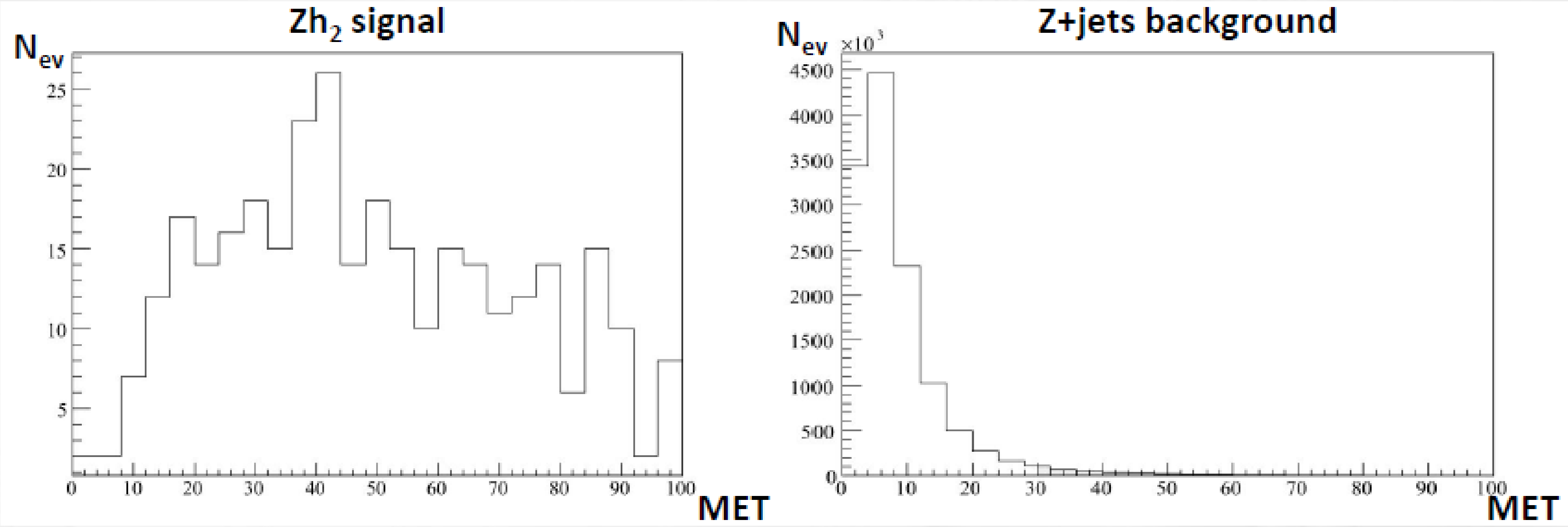
- Backgrounds
  - Z+jets
  - ttbar+jets
- Generate background using MG5/ME4
  - Z+jets for 0, 1, 2, and 3jets
  - ttbar+jets for 0, 1, and 2jets

ΔR(bb)


dR
dR
Entries 10000
Mean 0.6143
RMS 0.3821
Zh$_2$, h$_1$→bb
0
100
200
300
400
500
600
700
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

MET distribution Comparison

$10fb^{-1}$ @ 14TeV

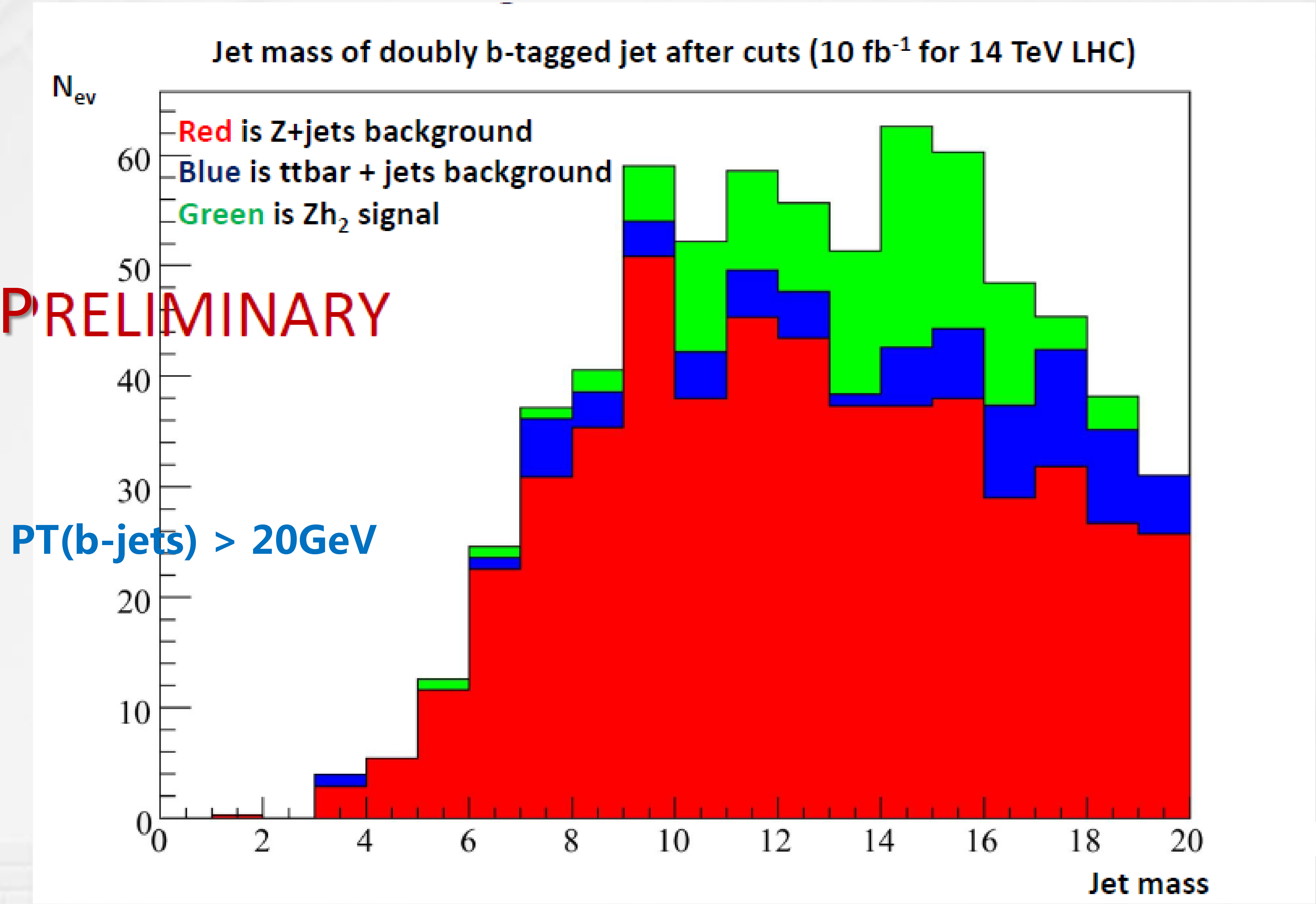


Cut-Flow-Table

Cut	Zh_2, $Z \rightarrow ll$ (0.076pb)	tth_2 (0.027pb)	Z+jets, $Z \rightarrow ll$ (2001pb)	tt +jets (833pb)
=2l, Pt>20GeV	73.28%	60.54%	79.653%	6.115%
Same flavor	73.11%	30.24%	79.643%	3.071%
Opp. sign	73.06%	29.18%	79.64%	2.311%
$\lvert m_{ll}-m_z \rvert<5$GeV	54.11%	2.03%	62.717%	0.151%
MET>40GeV	37.27%	1.72%	0.806%	0.111%

Note: (80% b-tagging efficiency -cf. ATLAS-CONF-2011-100)

Invariant mass



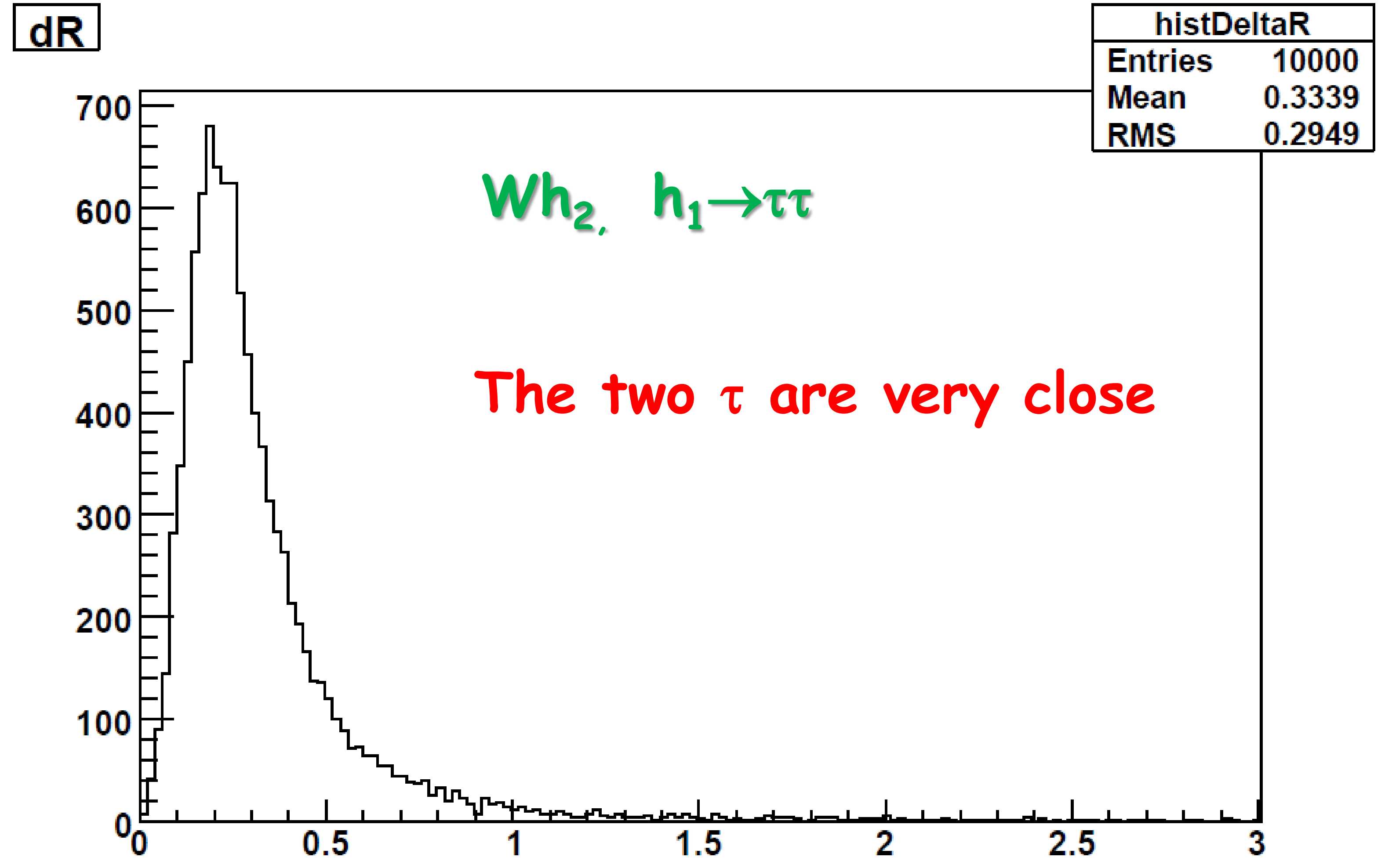
PRELIMINARY

PT(b-jets) > 20GeV

Di-tau Channel

- $\tau\tau$ channel is also much more difficult
- The two taus are very close to eath other and the tau decay products are fairly soft, and we can NOT use the standard approach to identify the taus
- We treat di-tau as one jet and look for the jet substructure

$\Delta R(\tau\tau)$



Wh_2, $h_1 \rightarrow \tau\tau$

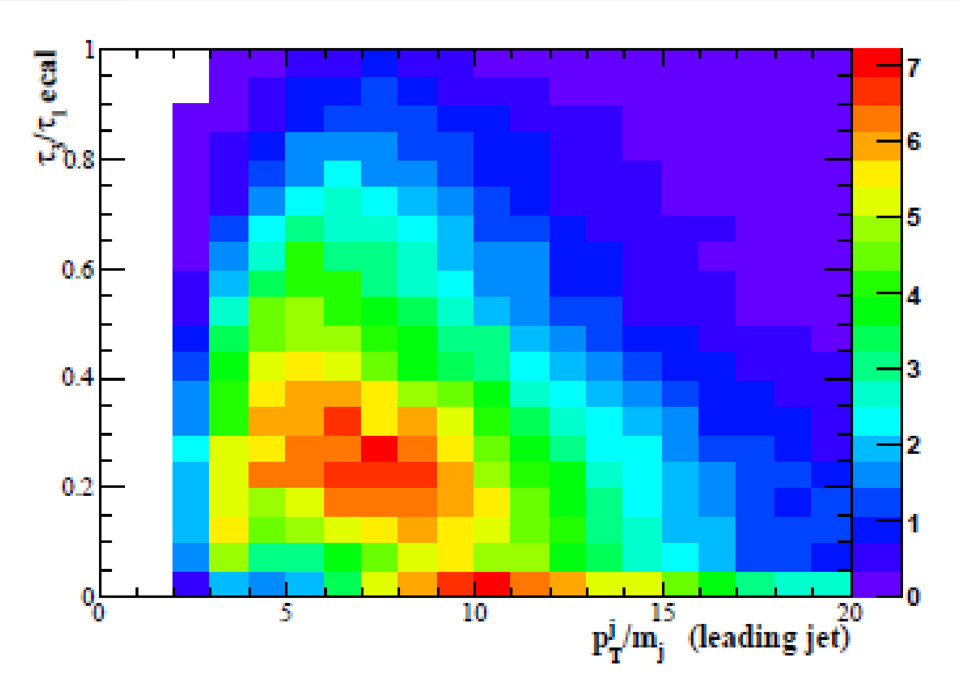
The two τ are very close

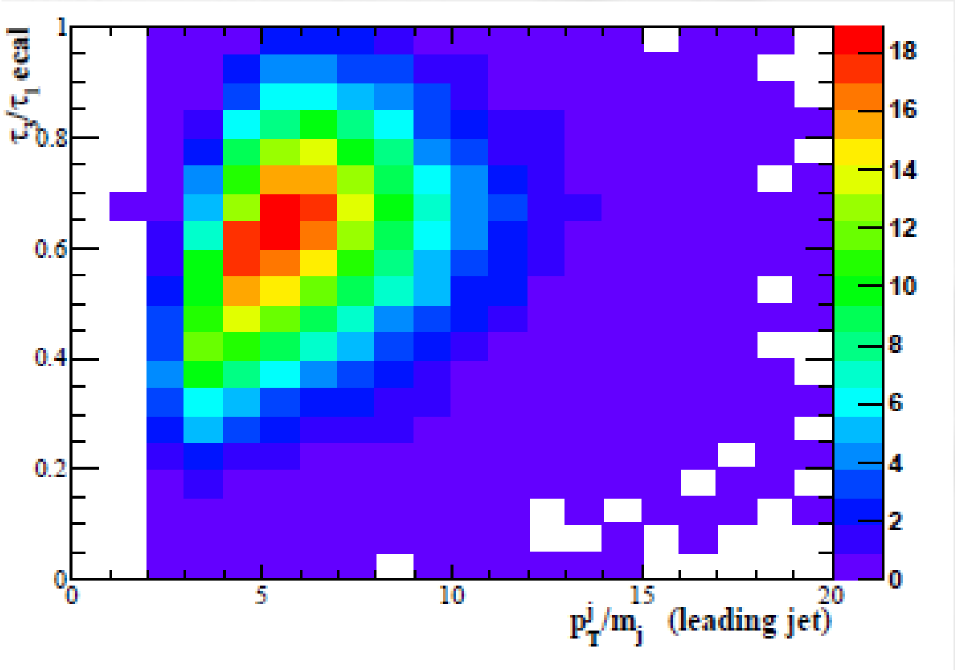
Di-Tau jet identification

C. Englert, T. Roy, M. Spannowsky, arXiv:1106.4545

N-Subjettiness:

$$\tau_N = \frac{\sum_k p_{T,k} \min\left(\Delta R(1,k), \ldots, \Delta R(N,k)\right)}{\sum_j p_{T,j}\, R}$$





Conclusions

- DLH scenario provides a theoretical framework for studying non-standard Higgs phenomenology
- Many interesting channels to consider

  -μμ and bb preliminary results presented

  -ττ is underway

  -aim to provide a comprehensive LHC search strategy for SM-like higgs and light scalar resonances.

Back Up

Long List of Exp. Constraints

Collider (LEP + Tevatron)

- (1) Direct searches for new particles at LEP;
- (2) Direct searches for new particles at the Tevatron;
- (3) Electroweak precision observables;
- (4) muon anomalous magnetic moment

Flavor physics and meson decay:

- (1) Constraints from B-system;
- (2) Constraints from K-system;
- (3) Constraints from charm system;
- (4) Upsilon decays

Cosmology:

- (1) Dark matter relic density;
- (2) Dark mater direct detection;
- (3) Dark matter indirect detection, cosmic rays;
- (4) Big bang nucleosynthesis, Cosmic Microwave Background

Radiation:

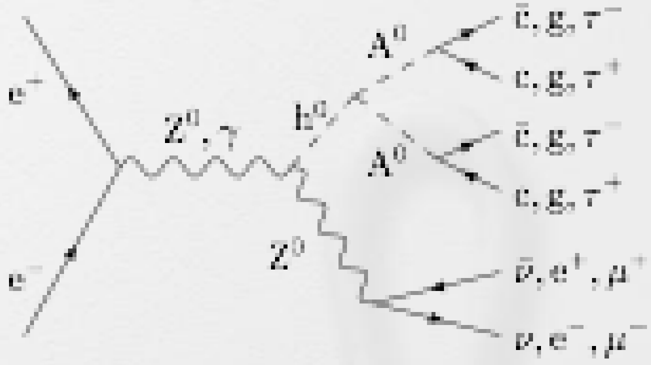
- ……

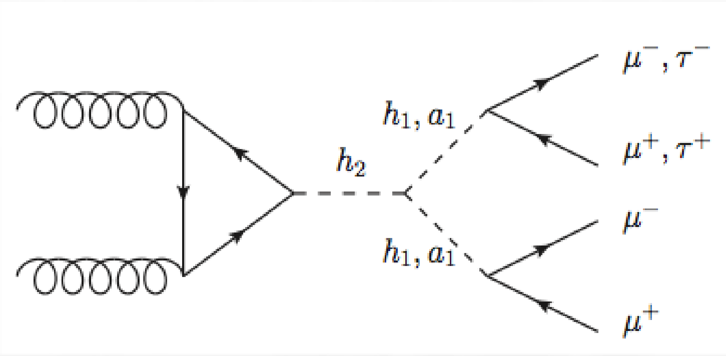
Constraints from h2->h1h1,a1a1

- LEP searches:

(1) ($h_2 \to a_1 a_1$) $a_1 \to 2b$ (S. Schael et al. [ALEPH, DELPHI, L3, and OPAL Collaborations], Eur. Phys. J. C 47(2006); S. Schael et al. [ALEPH Collaboration], JHEP 1005 (2010));

(2) Z-associated Higgs production, with Z leptonically decayed (S. Schael et al. [ALEPH Collaboration], JHEP 1005 (2010); G. Abbiendi et al. [The OPAL Collaboration], Eur. Phys. J. C 27, (2003)).





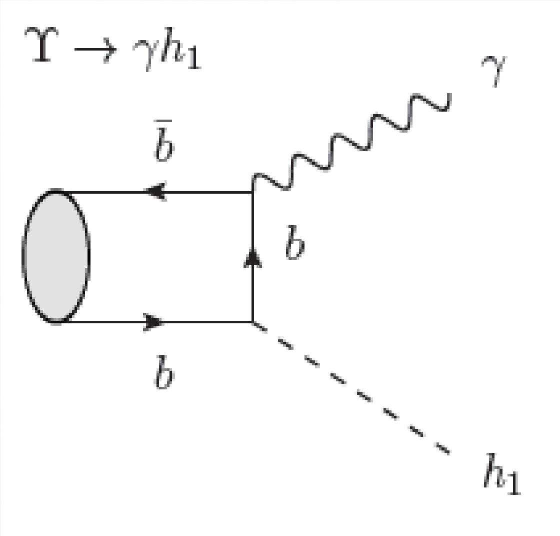
- Tevatron searches:

$h_2 \to a_1 a_1, h_1 h_1 \to 4\mu$, $2\mu\ 2\tau$ (V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 103 (2009))

Upsilon Meson Decays

- Because of its bottom quark Yukawa coupling, Upsilon meson decay adds stronger constraints, comparing with other meson decays
- The relevant decay chain is (the decay chain of is similar)(CLEO Collaboration, Phys Rev Lett 101,151802 (2008); BABAR Collaboration, Phys. Rev. Lett 103, 081803 (2009)):

$$\Upsilon \rightarrow \gamma + h_1 \quad \Upsilon \rightarrow \gamma + \bar{X} + X, \quad X = \mu, \pi, K\ldots$$



Upsilon->photon+h_1

- The decay width is normalized by $\Gamma(Y \to e^+ e^-)$ (D. McKeen, Phys Rev D 79, 015007 (2009))

$$\frac{\Gamma(\Upsilon \to \gamma h_1)}{\Gamma(\Upsilon \to e^+ e^-)} = \frac{\lambda_d^2 m_b^2 G_F}{\sqrt{2}\pi\alpha}\left(1 - \frac{m_{h_1}^2}{m_\Upsilon^2}\right) C_S(x)$$

- λ_d(= mixing angle in h1* tanb) and λ_u is defined as

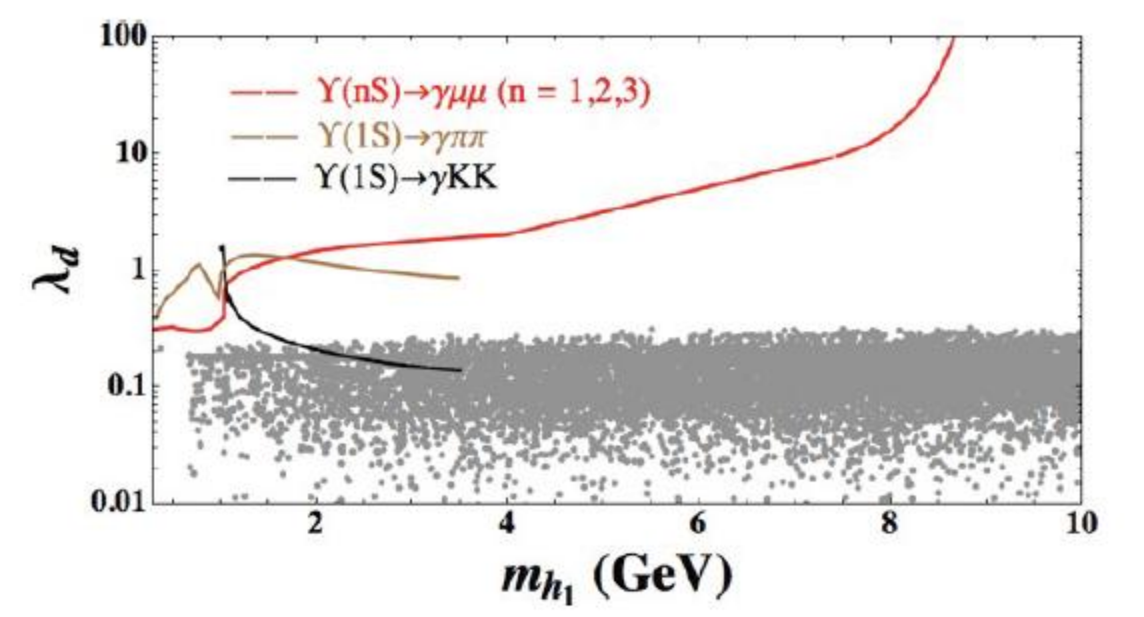
$$\mathcal{L} = -\frac{h_1}{\sqrt{2}}\left(\lambda_d m_l \bar{l} l + \lambda_d m_d \bar{d} d + \lambda_u m_u \bar{u} u\right)$$

- In the DLH scenario, we have

$$\lambda_d \approx \frac{v}{\mu}\left(\lambda + \frac{2\varepsilon\mu}{m_Z}\right), \quad \lambda_u \approx \frac{2\varepsilon v}{m_Z}$$

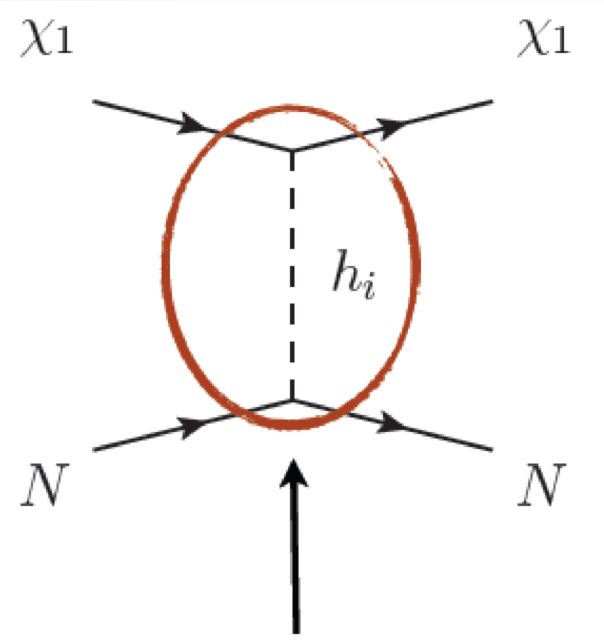
- λ_d is small, so the branching ratio $\Gamma(Y \to \gamma h_1)$ is small

Constraints on λ_d



Quite generally, these constraints are weak in the DLH scenario.
Below the Kaon threshold, the most important constraint is from the muon channel.
Above the Kaon threshold, the Kaon channel gives a stronger constraint due to a larger Yukawa coupling to strange quarks.

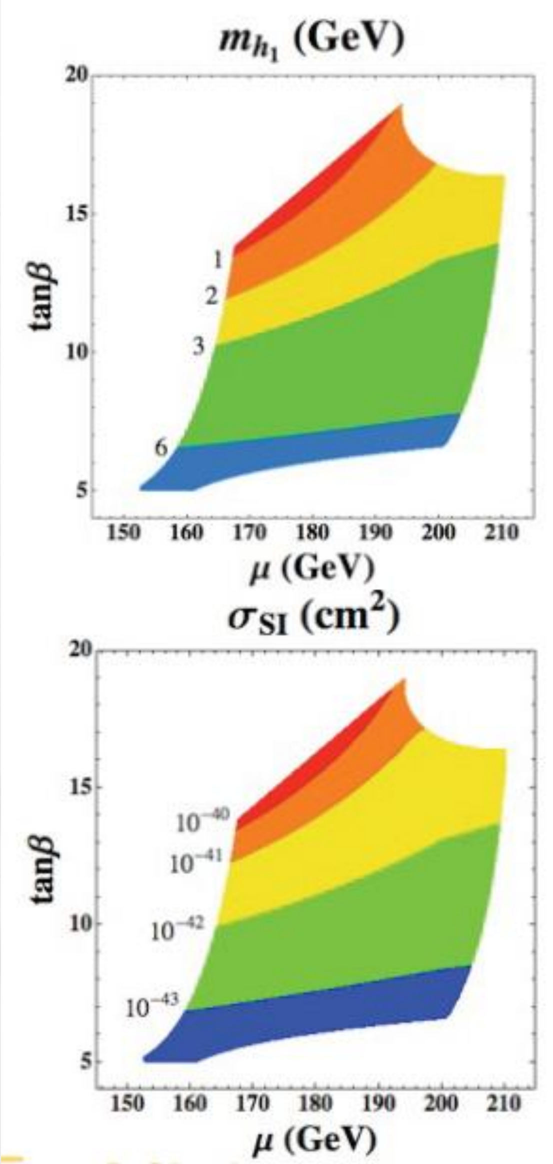
A Novel SUSY Light DM Scenario



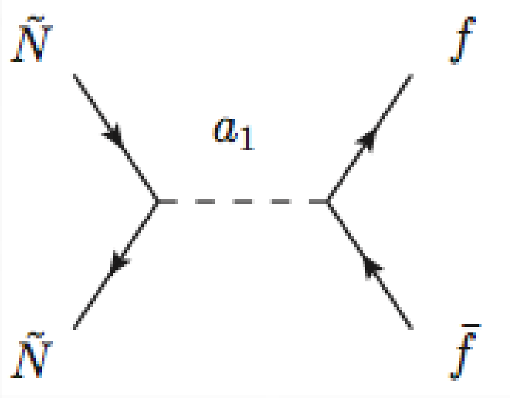
a t-channel process is dominant in spin-independent direct-detection

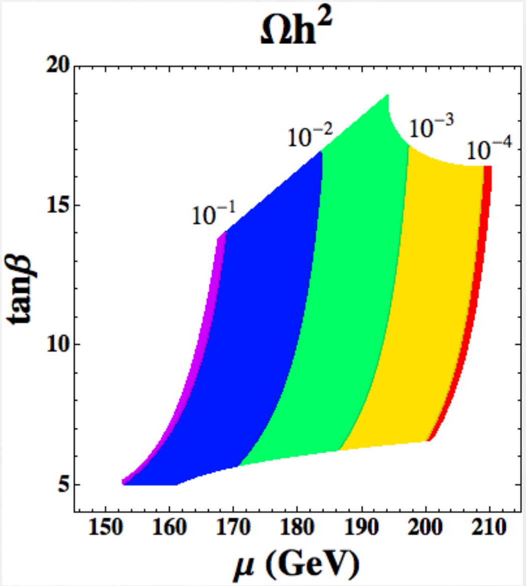
⇒σ will be strongly enhanced by a small m_{h1}

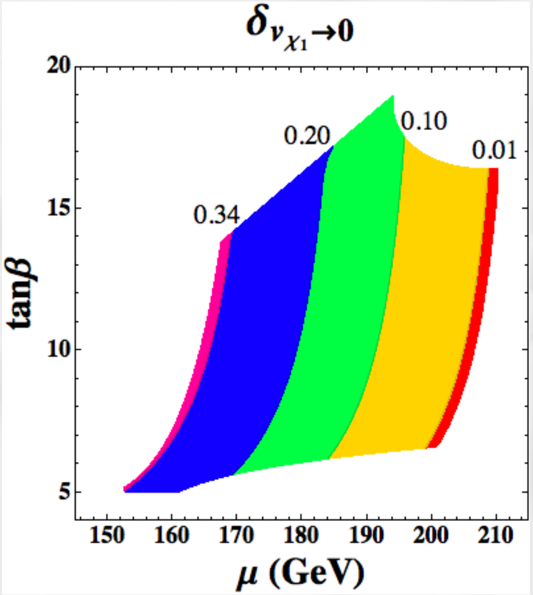
$$\sigma_{\rm SI} \approx \frac{\left[\left(\frac{\varepsilon}{0.04}\right) + 0.46\left(\frac{\lambda}{0.1}\right)\left(\frac{v}{\mu}\right)\right]^2 \left(\frac{y_{h_1\chi_1\chi_1}}{0.003}\right)^2}{\left(\frac{m_{h_1}}{1\text{GeV}}\right)^4} \times 10^{-40}\text{cm}^2$$



Breit-Wigner Effect







Thermal average of the LSP annihilation xection

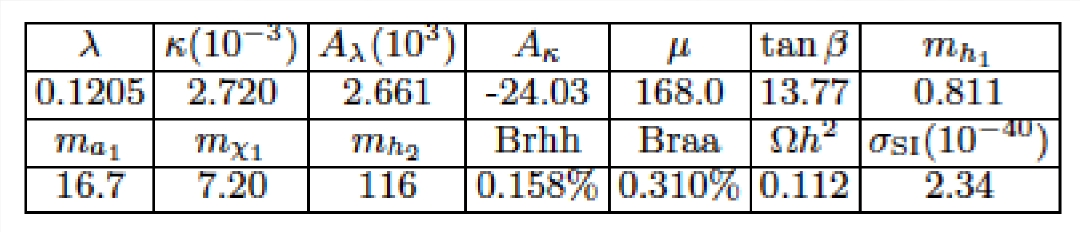
$$\sigma_{f\bar{f}} v_{\chi_1} \approx \frac{3\left|y_{a_1\chi_1\chi_1}\, y_{a_1 f\bar{f}}\right|^2 (1 - m_f^2/m_{\chi_1}^2)^{1/2}}{32\pi m_{\chi_1}^2 \left(\delta^2 + \left|\frac{\Gamma_{a_1} m_{a_1}}{4m_{\chi_1}^2}\right|^2\right)}$$

$$\delta \equiv |(1 - v_{\chi_1}^2/4)^{-1} - m_{a_1}^2/(4m_{\chi_1}^2)|$$

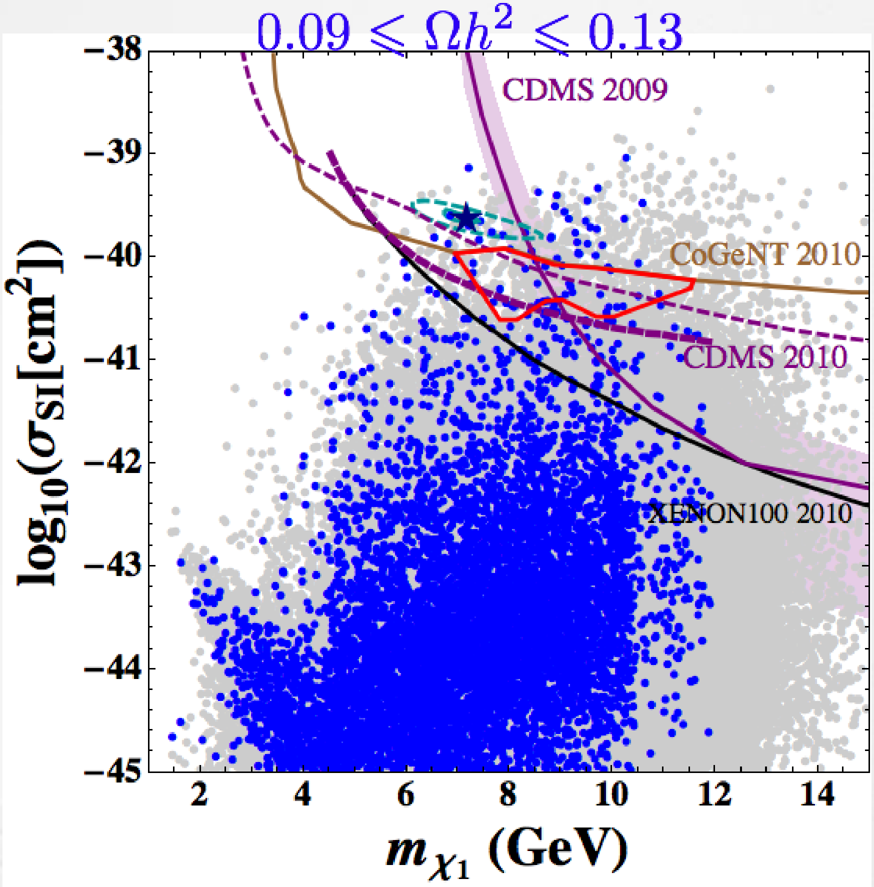
Relic density

$$\Omega h^2 \approx \frac{0.1\left(\frac{m_{a_1}}{15\mathrm{GeV}}\right)\left(\frac{\Gamma_{a_1}}{10^{-5}\mathrm{GeV}}\right)\left(\frac{\mu}{v}\right)^2\left(\frac{0.003}{\kappa}\right)^2\left(\frac{0.1}{\lambda}\right)^2}{\mathrm{erfc}\left(\frac{2m_{\chi_1}}{m_{a_1}}\sqrt{x_f \delta_{v_{\chi_1}\to 0}}\right)/\mathrm{erfc}(2.2)}$$

Numerical Results



λ	$\kappa(10^{-3})$	$A_\lambda(10^3)$	A_κ	μ	$\tan\beta$	m_{h_1}
0.1205	2.720	2.661	-24.03	168.0	13.77	0.811
m_{a_1}	m_{χ_1}	m_{h_2}	Brhh	Braa	Ωh^2	$\sigma_{SI}(10^{-40})$
16.7	7.20	116	0.158%	0.310%	0.112	2.34



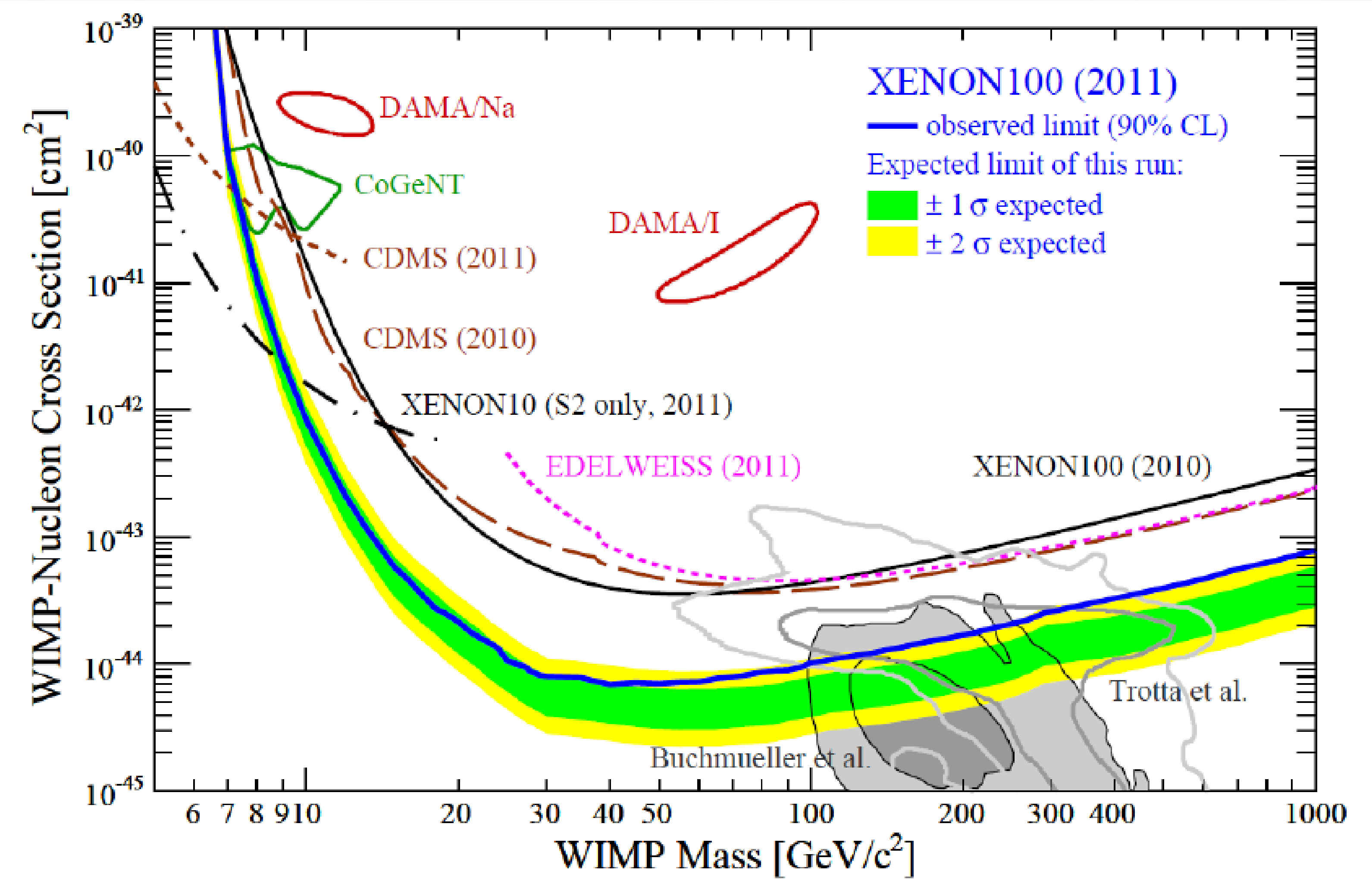
$$0.05 \leqslant \lambda \leqslant 0.15, \quad 0.001 \leqslant \kappa \leqslant 0.005,$$
$$|\varepsilon'| \leqslant 0.25, \quad -30\mathrm{GeV} \leqslant A_\kappa \leqslant -15\mathrm{GeV},$$
$$5 \leqslant \tan\beta \leqslant 50, \; 100\mathrm{GeV} \leqslant \mu \leqslant 250\mathrm{GeV}$$

All points have passed the current exp. bounds of flavor physics, meson decays, and collider exp.

The blue points fall in a 3 σ range of the observed relic density.

Their σ_{SI} can be as large as above 10^{-40} cm^{-2}

XENON100 Results (2011) (1104.2549)

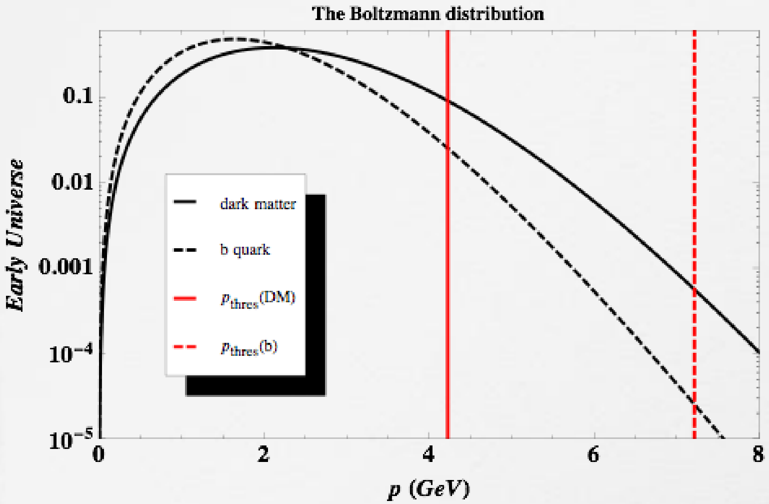


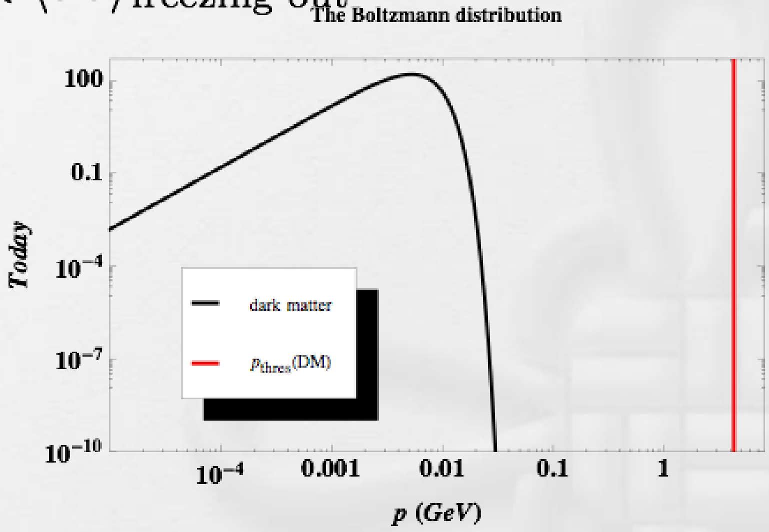
Constraints from Cosmic Ray Exps.

Bounds from indirect searches, e.g., Proton spectrum (O. Adriani etc., Nature Vol 458 607 (2009); O. Adriani etc., Phys Rev Lett 105, 121101 (2010)); gamma ray spectrum (Fermi LAT Collaboration, Phys Rev Lett 104, 101101 (2010))

But the DLH scenario is safe because there is a Breit-Wigner suppression effect in the Universe today.

$$\langle \sigma v \rangle_{\text{today}} \ll \langle \sigma v \rangle_{\text{freezing out}}$$





Resonance region (red solid line): dark matter particles in this region has a delta ~ 0, maximizing their annihilation