Title: Search for New Non-standard Decay Modes of SM-like Higgs at the LHC

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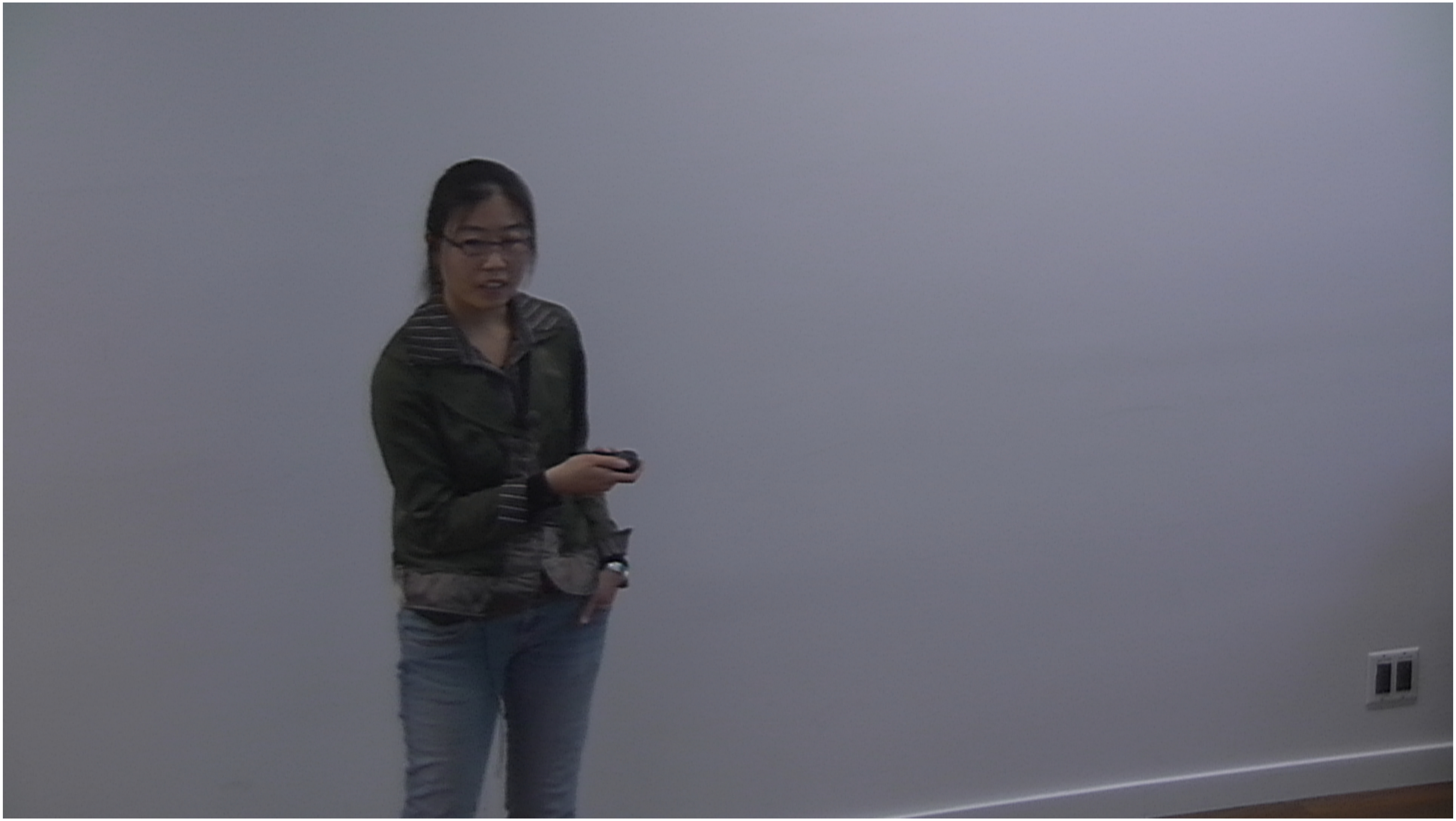
Abstract: We present strategies of searching for supersymmetric non-standard decays of Standard Model (SM)-like Higgs bosons (h2) at the Large Hadron Collider (LHC), motivated by "Dark Light Higgs" (DLH) scenario. The DLH sccenario represents a limit of the nearly-Peccei-Quinn-symmetric Next-to-Minimal Supersymmetric Standard Model, where there naturally co-exist two light singlet-like particles: a scalar (h1), a pseudoscalar (a1), and a light singlino-like DM candidate (\chi_1), all with masses of order 10 GeV or below. In this scenario, the SM-like Higgs boson typically decays dominantly into a pair of neutralinos, allowing themselves to be as light as below 100 GeV. We systematically study the searches of both the SM-like and the light Higgs bosons at the LHC, using the supersymmetric non-standard decay chains: h2 -> \chi_1 \chi_2, \chi_2 -> \chi_1 (h1, a1) with the h1 or a1 further decayed into a pair of fermions (including diMuon, diTau and b bbar, etc).



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

Jinrui Huang
UC Irvine

Work with Tao Liu, Shufang Su, Liantao Wang, Felix Yu

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Perimeter Institute

Dec. 6th 2011

Outline

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

Dark Light Higgs Scenario

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

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

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

- 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 Higgses

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, **Singlet Like**:

$$m_{h_1}^2 \approx -4\varepsilon^2 v^2 + \frac{4\lambda^2 v^2}{\tan^2\beta} + \frac{\kappa A_\kappa \mu}{\lambda} + \frac{4\kappa^2\mu^2}{\lambda^2} \qquad \Delta m_{h_1}^2 \approx \frac{\lambda^2\mu^2}{2\pi^2}\log\frac{\mu^2\tan^3\beta}{m_Z^2}$$

(Loop correction)

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

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

dark matter particle

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

B. A. Dobrescu et al., PRD 63, 075003 (2001);
R. Dermisek et al., PRL 95, 041801 (2005).

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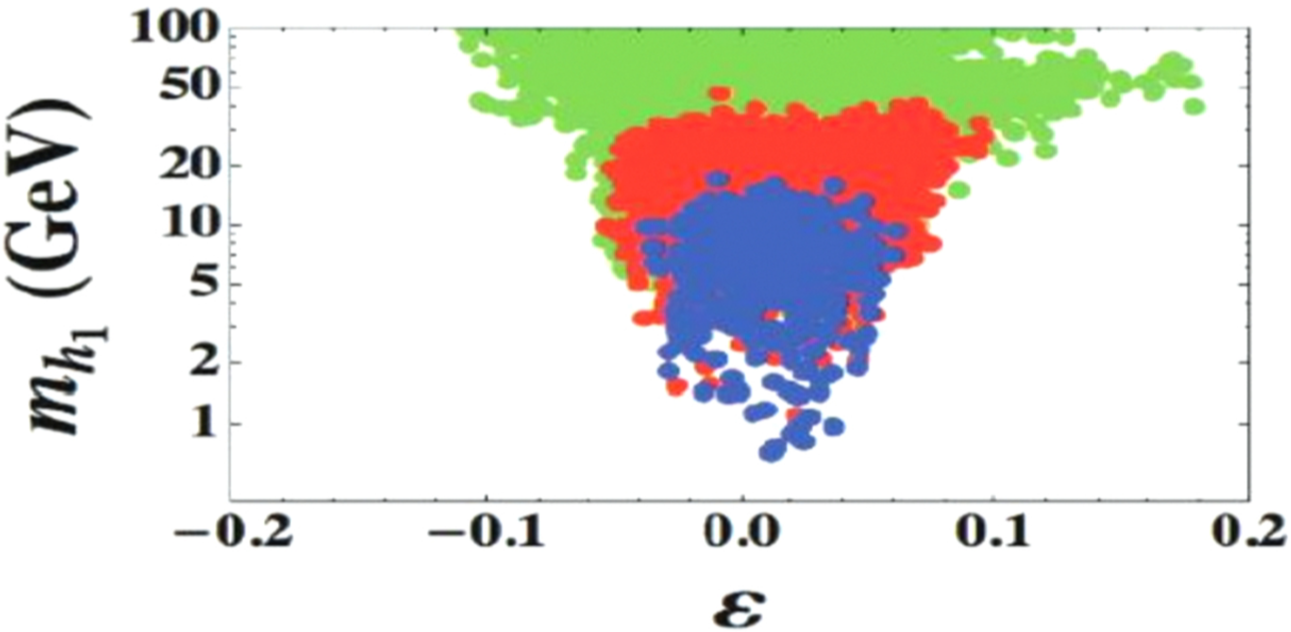
Parameter Scan



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

Vacuum stability sets a small upper bound on ε

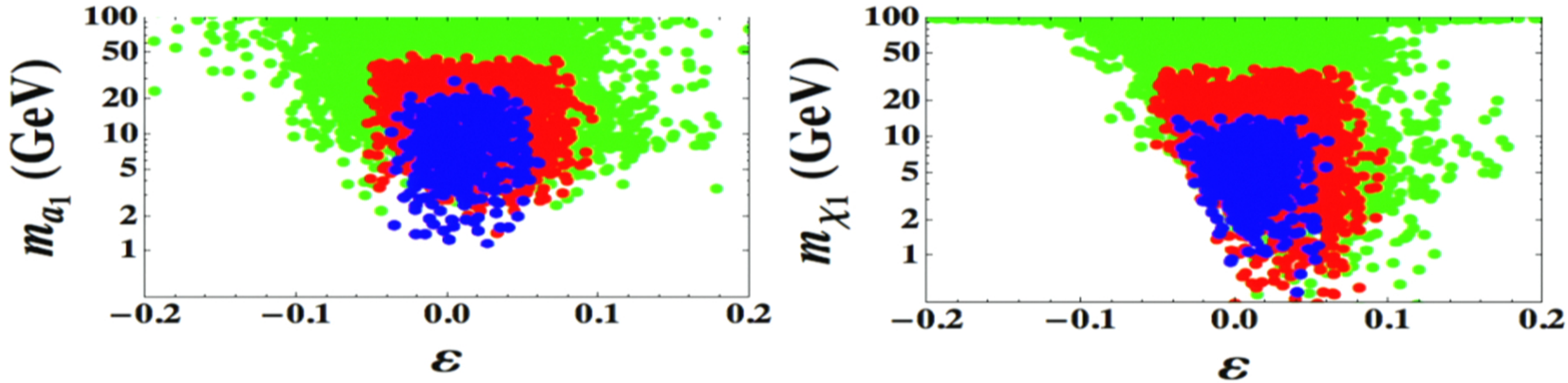
No points near ε->0 because of the vacuum stability requirement

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

$\lambda < 0.30,\ \kappa/\lambda < 0.05,\ \mu < 400\text{GeV}$ $\lambda < 0.15,\ \kappa/\lambda < 0.03,\ \mu < 250\text{GeV}$

Parameter Scan (cont.)

Light pseudoscalar and neutralino masses

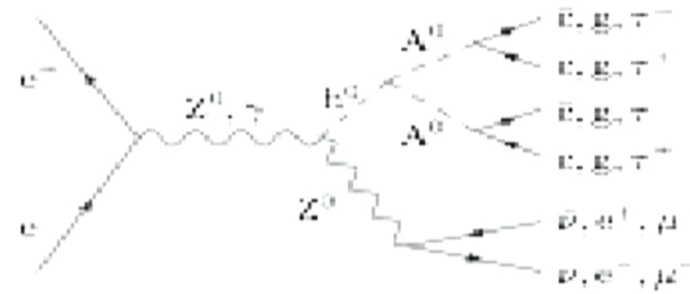


Constraints from h2->h1h1,a1a1

- LEP searches:

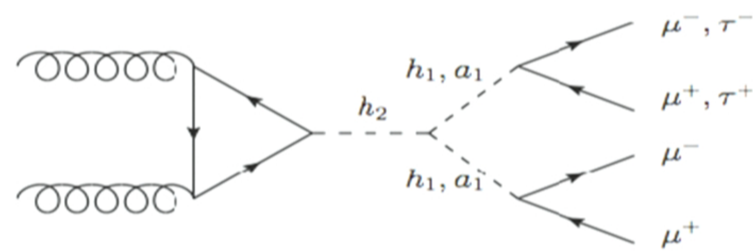
(1) ($h_2 \rightarrow a_1 a_1$) $a_1 \rightarrow 2b$ (S. Schael et al. [ALEPH, DELPHI, L3, and OPAL Collaborations], Eur. Phys. J. C 47(2006); S. Schael et al. [ALEPH Collaboration], JHEP 1005 (2010));

(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:

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

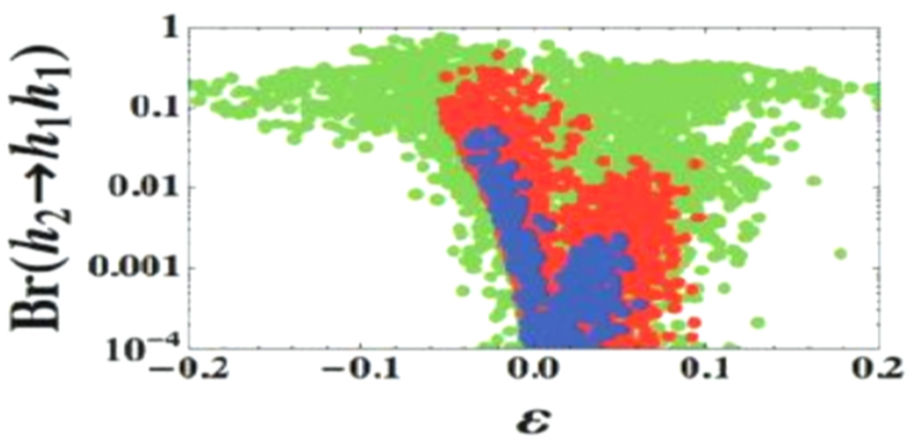


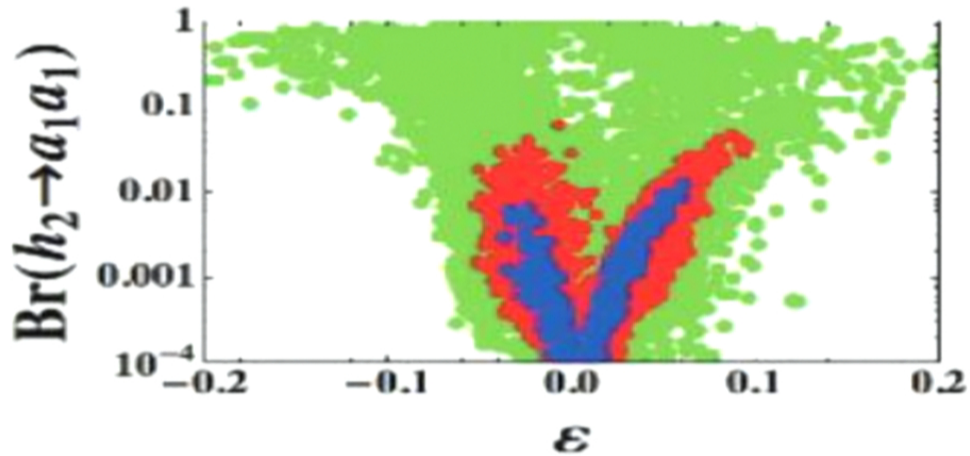
h2->h1h1, a1a1 modes

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

Exp. Constraints can be easily satisfied.

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





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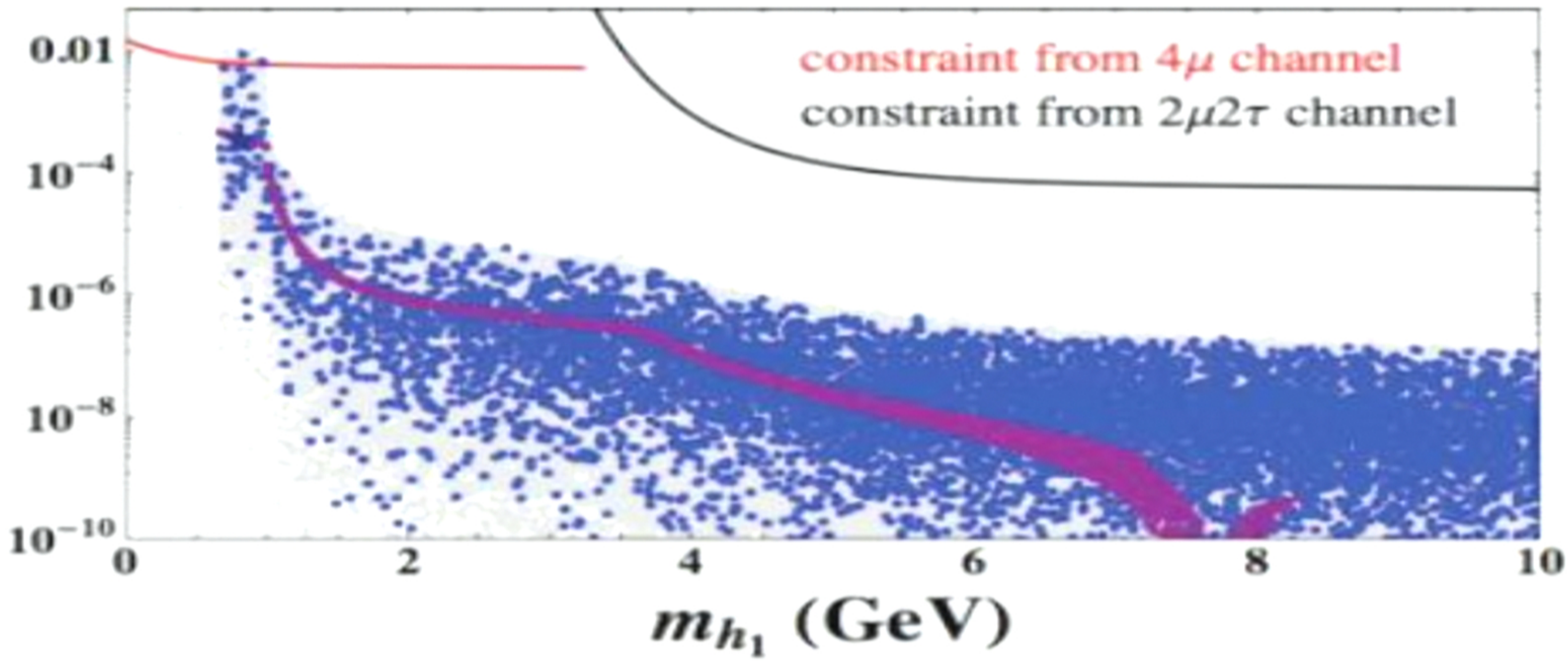
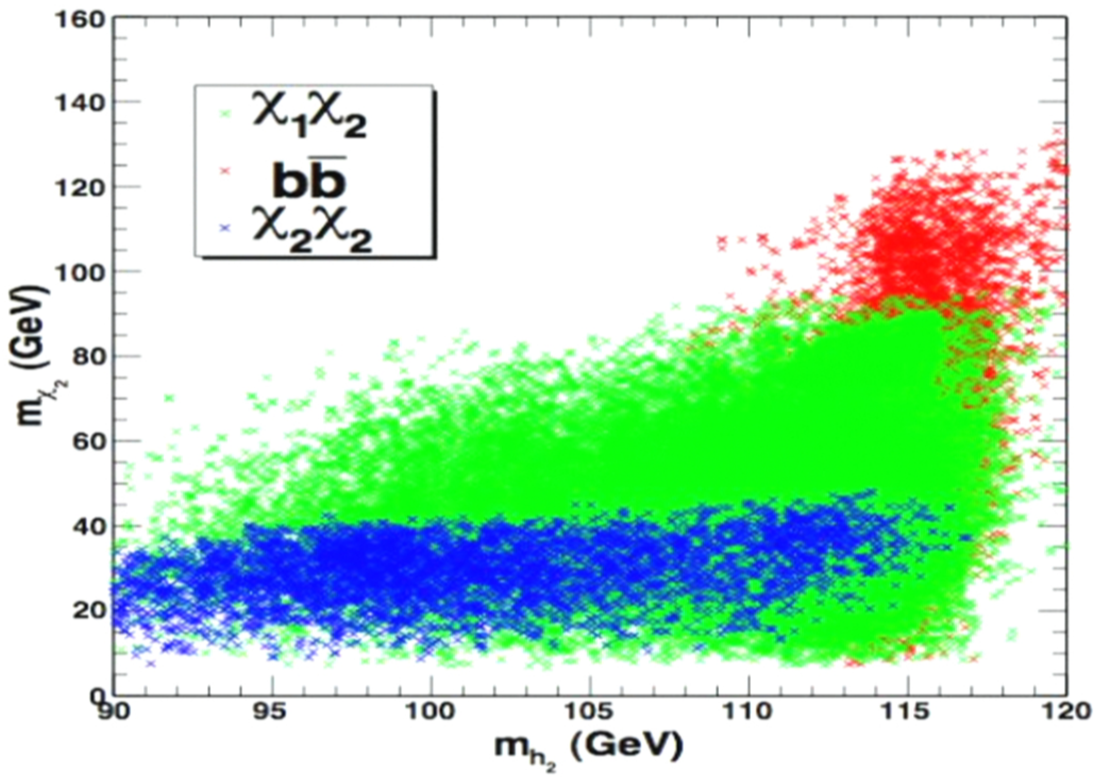
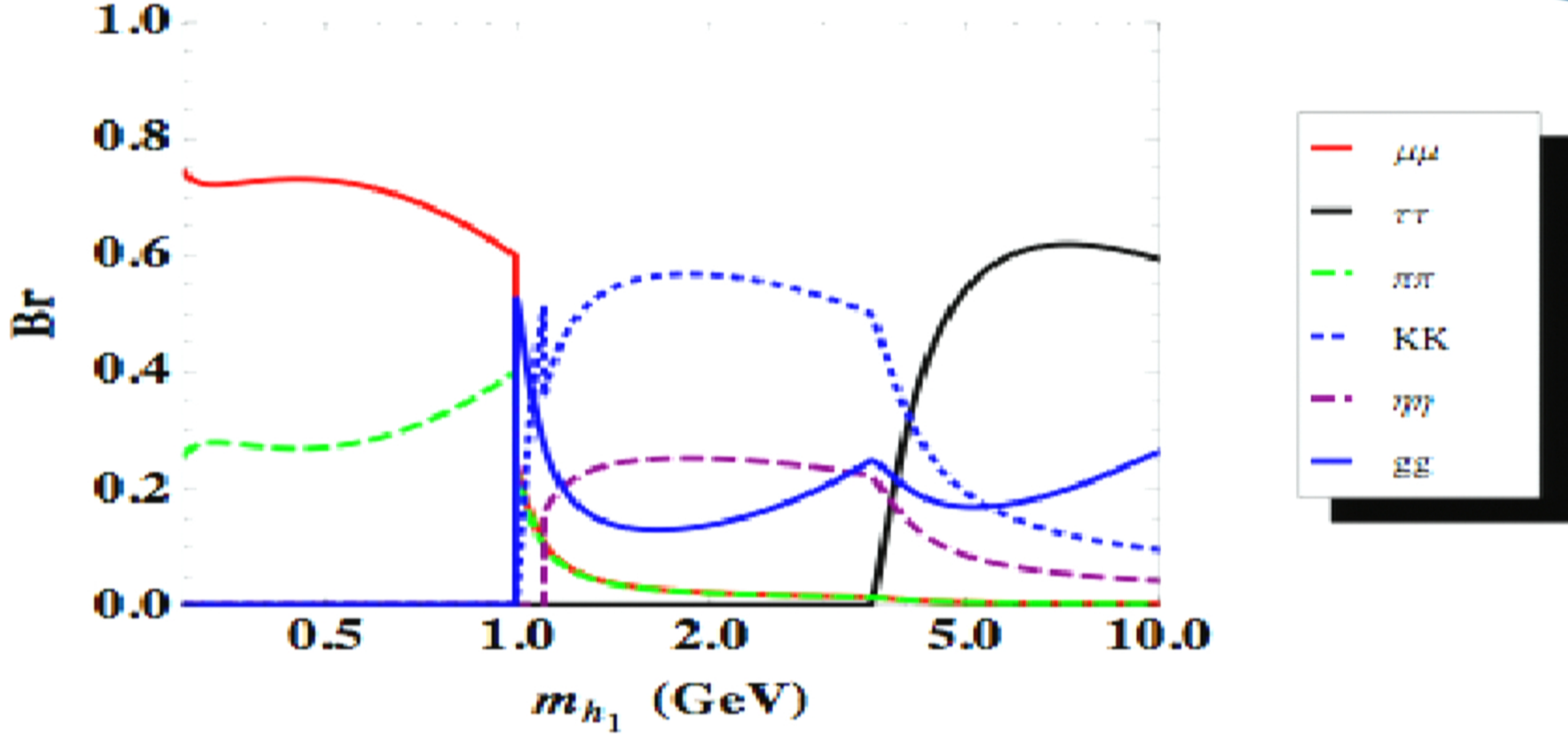


h_2 decay modes

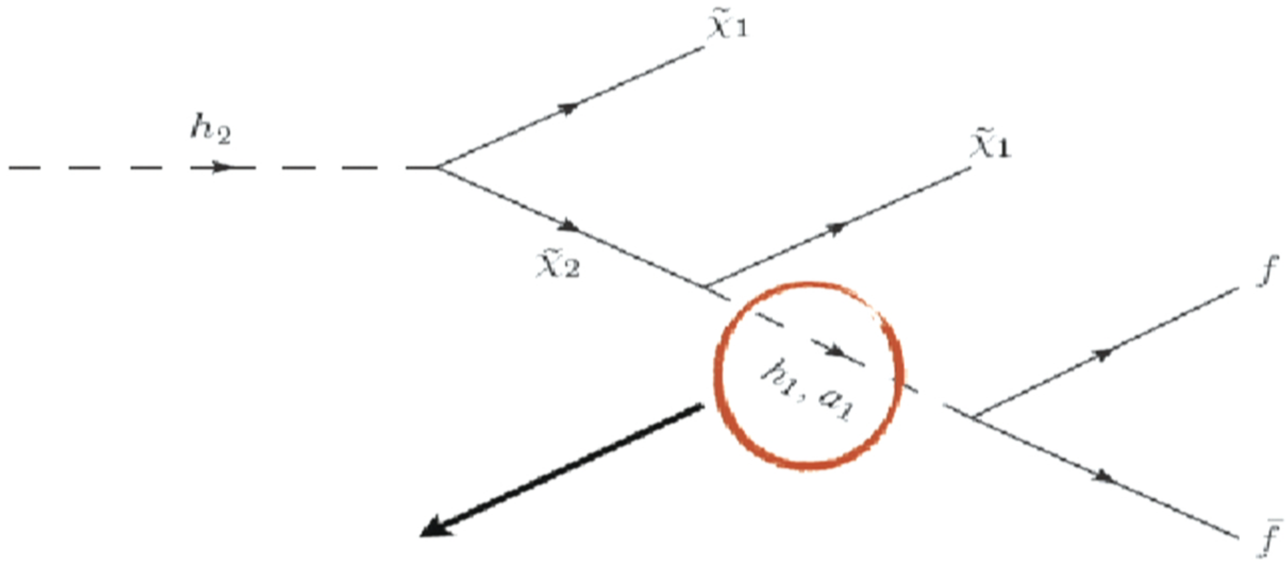


- $h_2 \to \chi_1\ \chi_2$ is typically dominant as long as it is kinematically allowed, and it is corresponding to the GREEN points.
- $h_2 \to bb$ mode can be dominant sometimes, but NOT generic.

h_1 decay modes



Dark Light higgs search



On-shell resonance

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

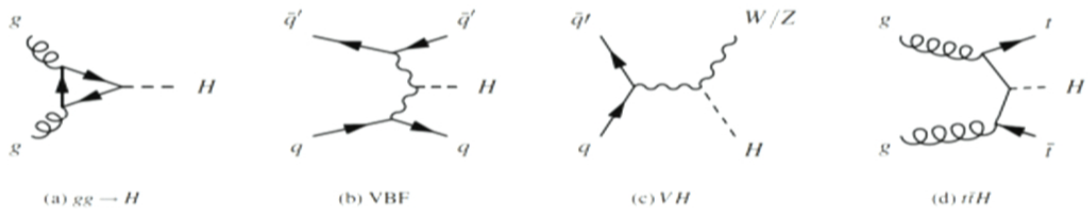
-$m_{\chi 1}$ = 10GeV

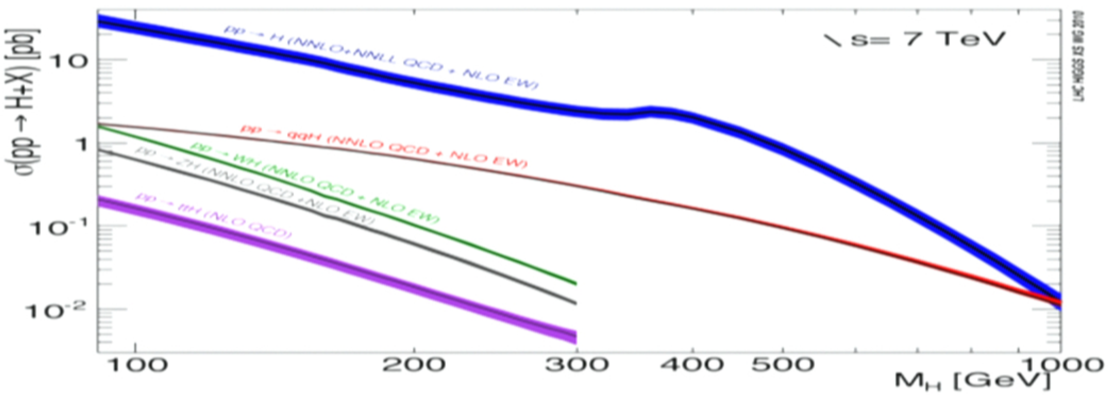
-m_{h1} = 1GeV($\mu\mu$)

6GeV ($\tau\tau$)

15GeV(bb)

SM Higgs Production





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

Handbook of LHC Higgs, CERN-2011-002

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

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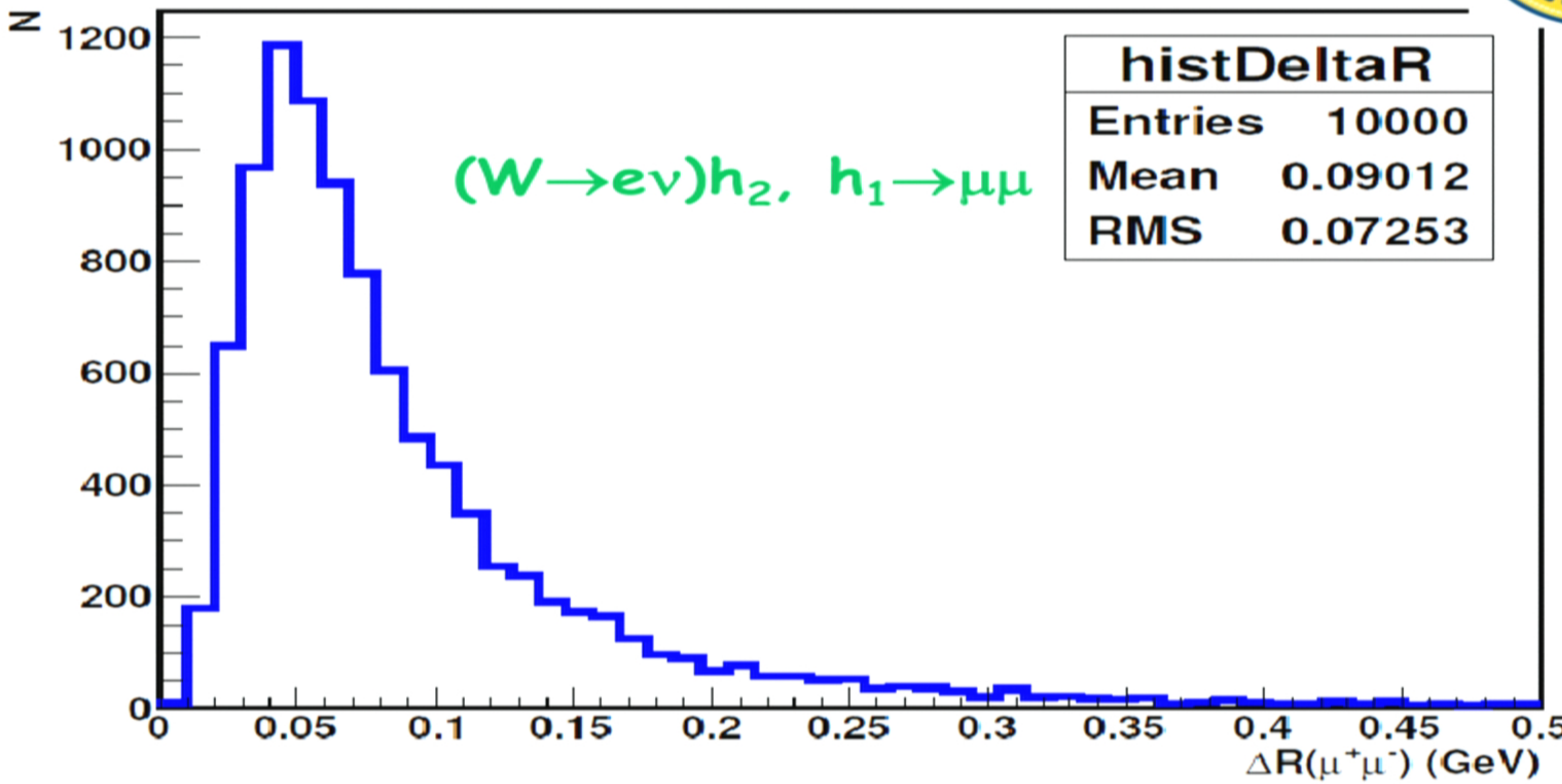
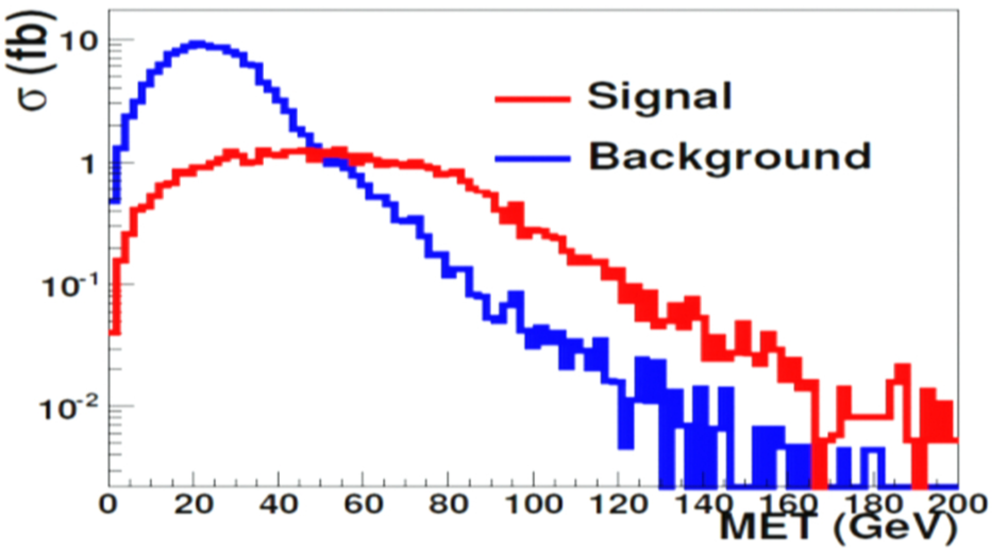
ΔR(μμ)

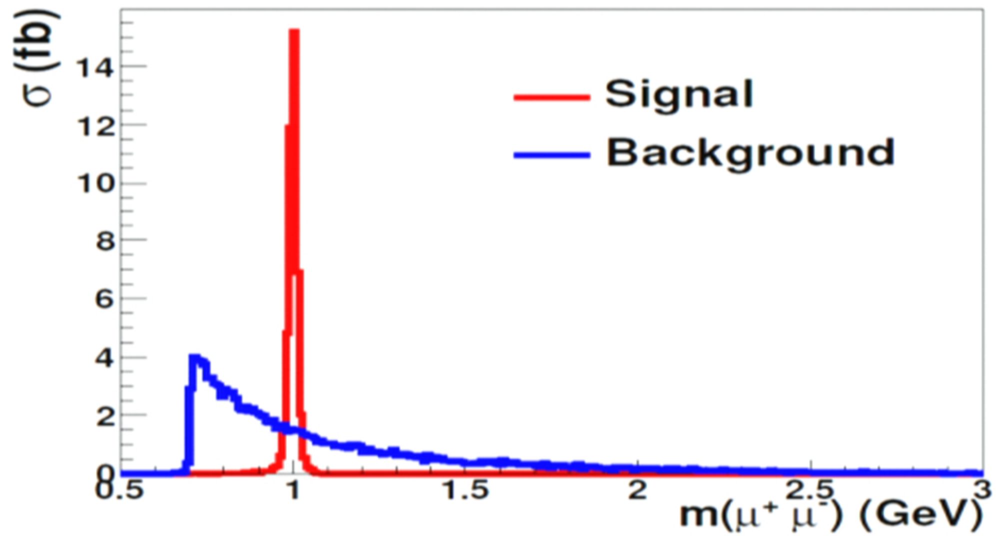

N
histDeltaR
Entries 10000
Mean 0.09012
RMS 0.07253
(W→eν)h₂, h₁→μμ
0 200 400 600 800 1000 1200
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5
ΔR(μ⁺μ⁻) (GeV)

MET + m(μμ)

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

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





Cut-Flow-Table

Basic Cuts	MET Cut	$m(\mu\mu)$
Reco (l); $\lvert\eta_l\rvert \leq 2.4$; $PT\mu \geq 10$GeV; $PT_{l3} \geq 20$GeV; $\Delta R(\mu\mu) < 0.2$; $PT_{iso}(\mu) < 5$GeV	MET $\geq$ 40GeV	0.9GeV $\leq m(\mu\mu) \leq$ 1.1GeV

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

Cut	Signal (0.162 pb)	Background (11.3 pb)
Basic Cuts	27.926%	1.2328%
MET	18.3396%	0.1764%
$m(\mu\mu)$	18.1546%	0.0365%

Note: Some preselection cuts have been applied

Cut-Flow-Table

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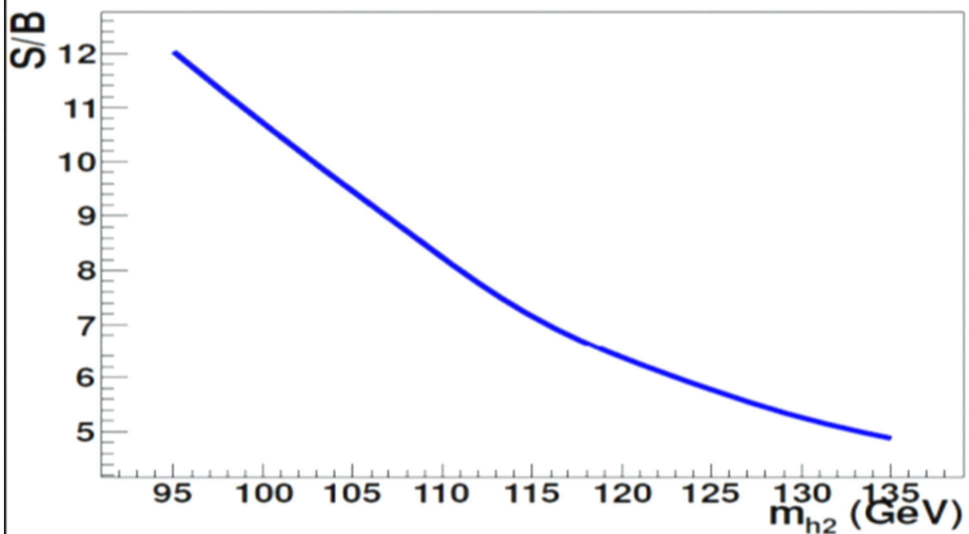
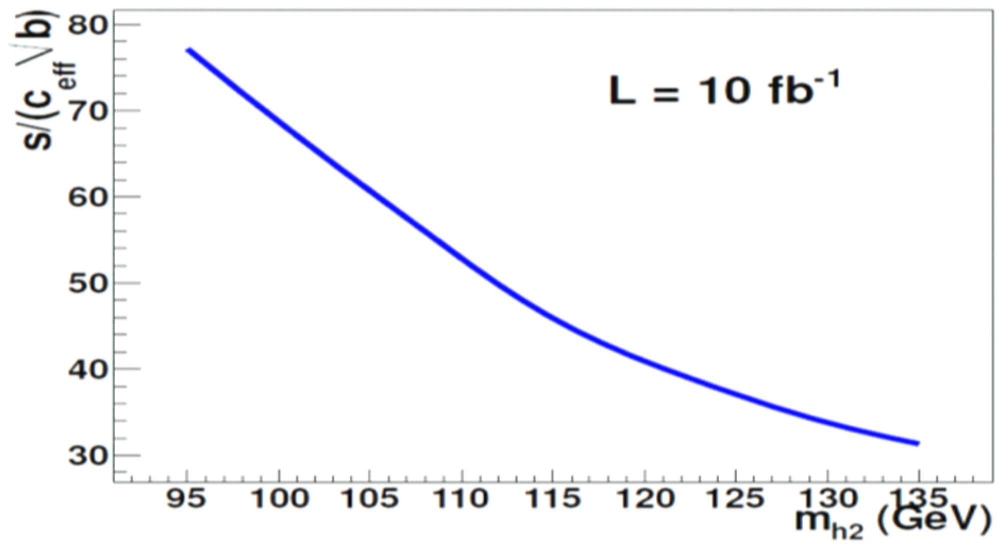
Discovery Potential

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

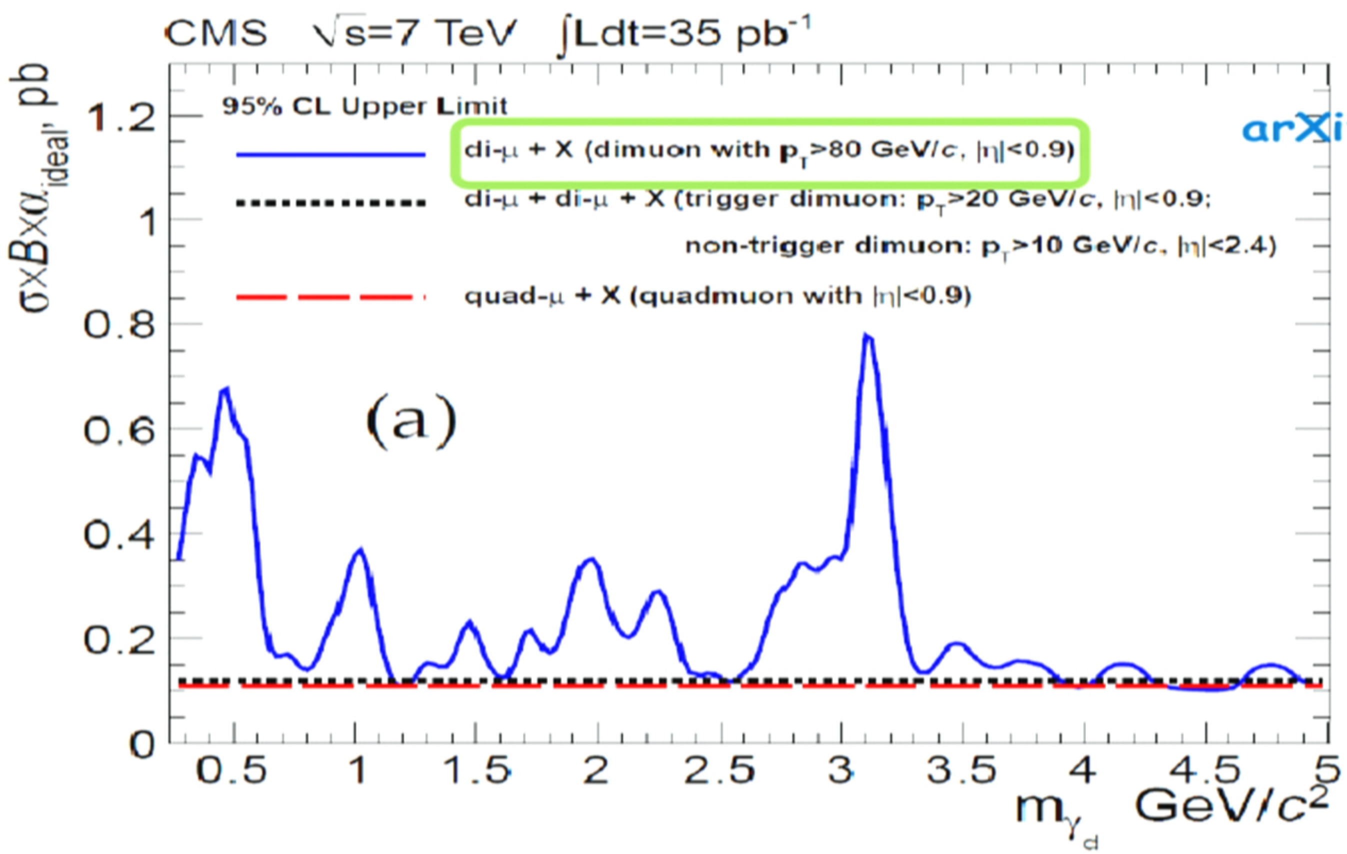




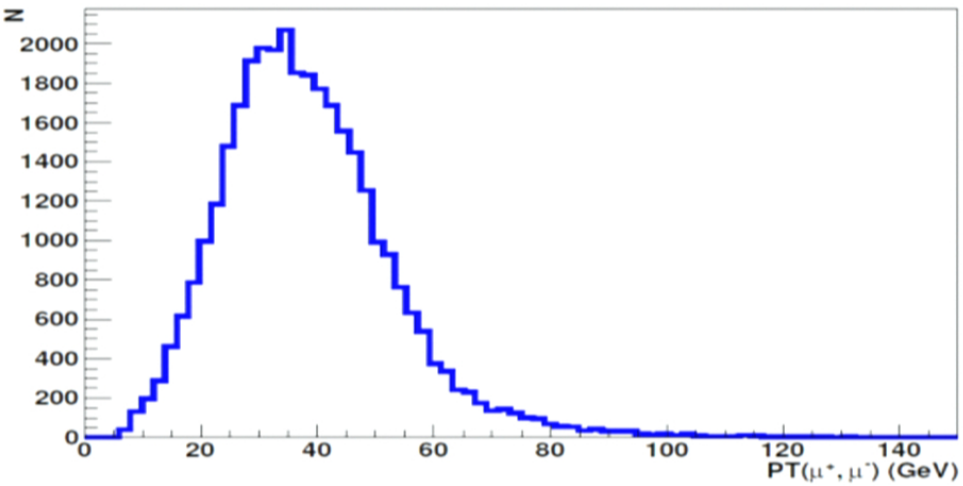
C_{eff} includes Branching ratio, K factors, etc

Dark Photon Search

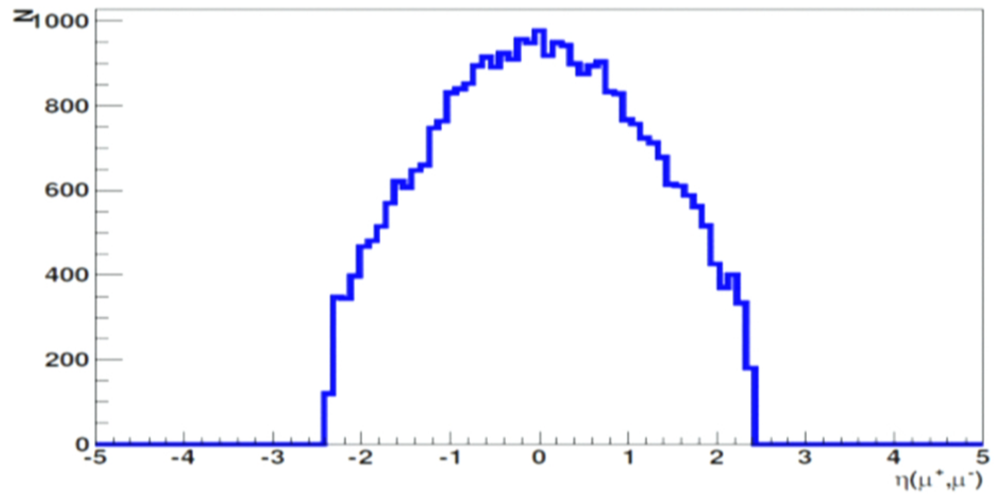
arXiv:1106.2375



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

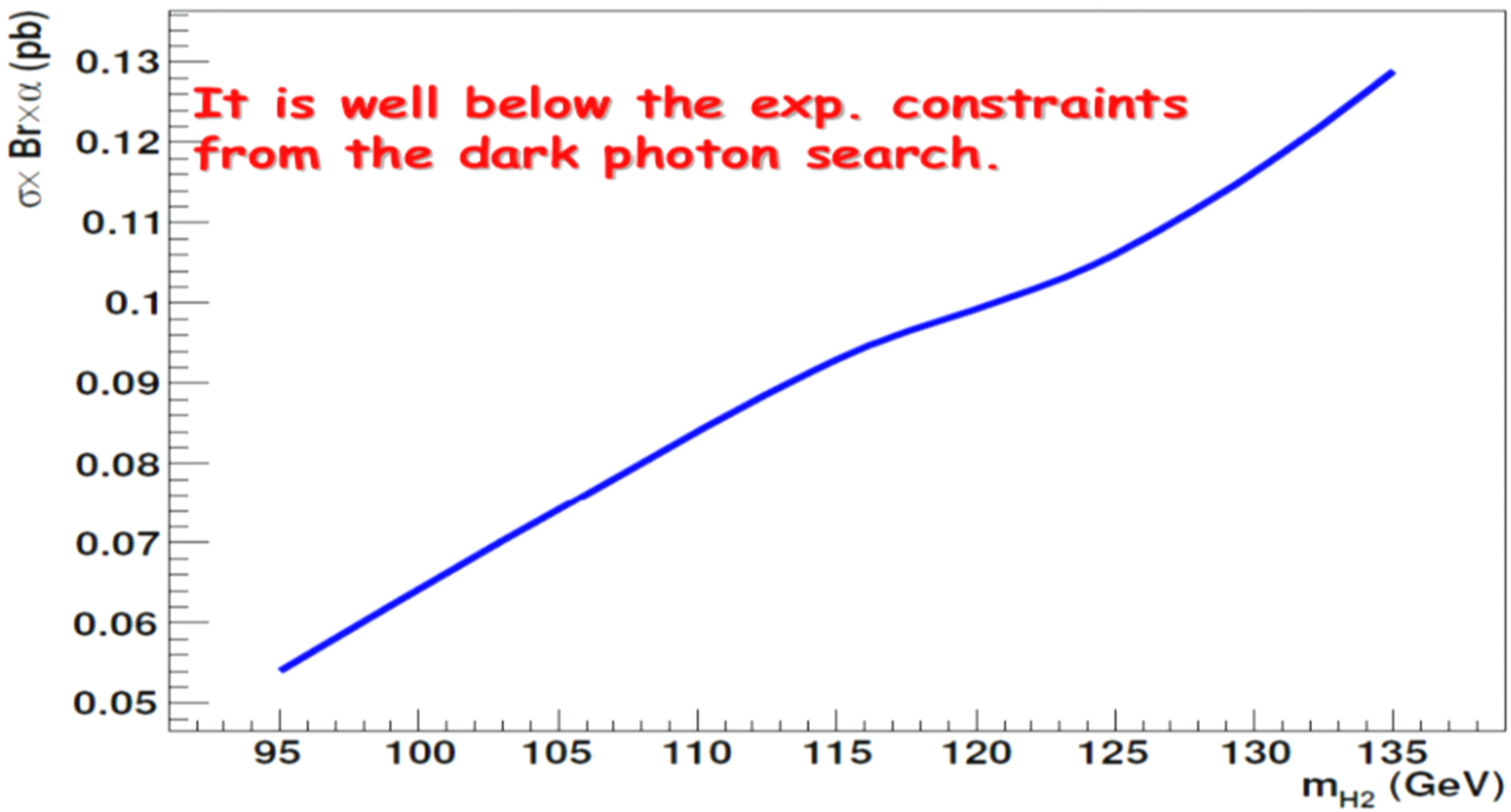


PT (μμ) > 80GeV



|η(μμ)| < 0.9

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



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 + $\ell+\ell-$+ MET
  -can use Z mass window cut to control ttbar fully leptonic background
  -remaining Zg($g \rightarrow$ bb) background is reduced by MET requirement
- tth_2: bb(+bb) + ℓ+MET or bb(+bb) + $\ell+\ell-$+ 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 3+jets
  - ttbar+jets for 0, 1, and 2+jets

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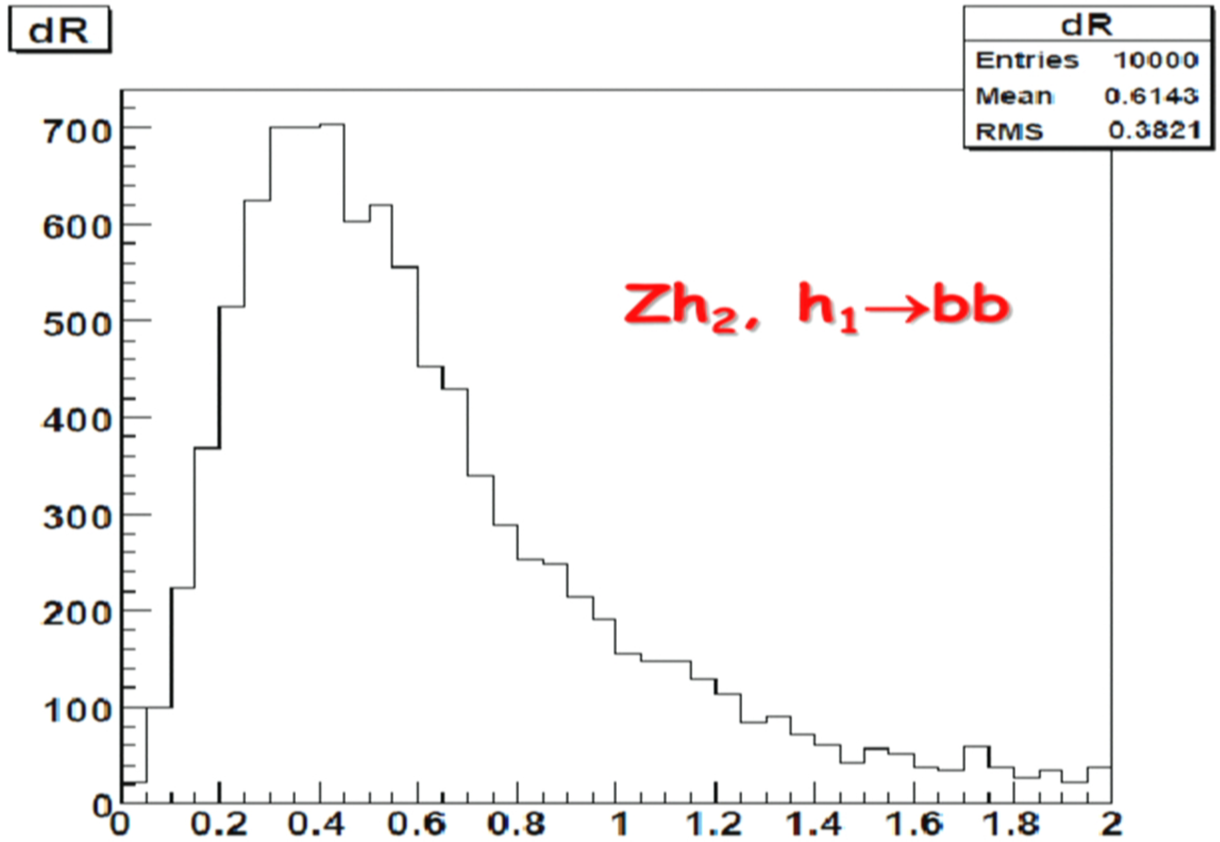
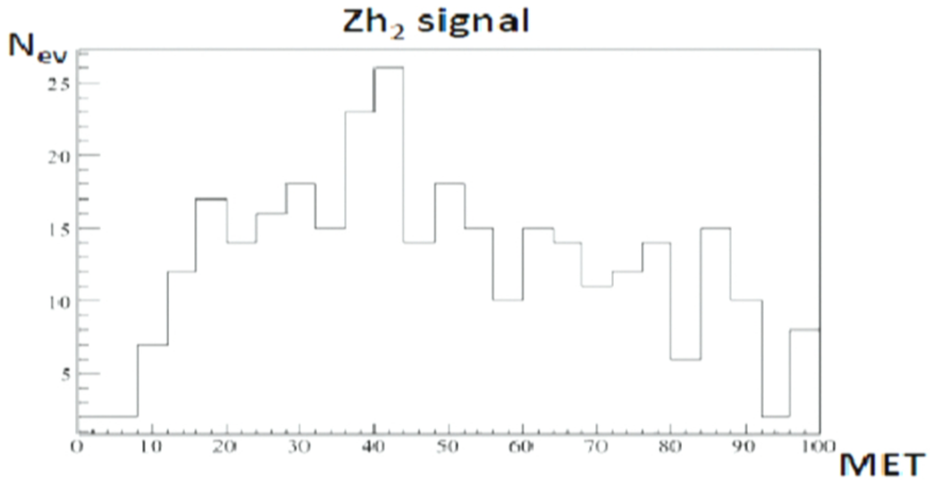
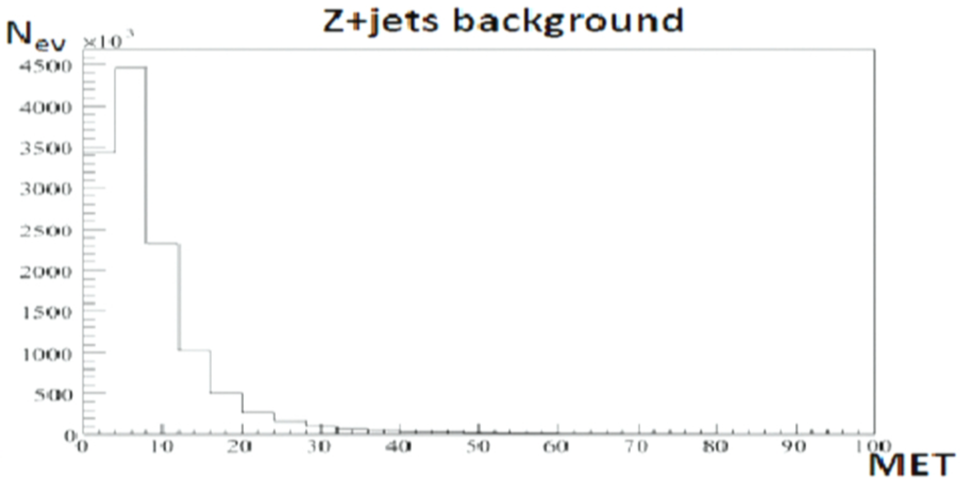
ΔR(bb)


dR
dR
Entries 10000
Mean 0.6143
RMS 0.3821
700
600
500
400
300
200
100
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Zh2, h1→bb

MET distribution Comparison

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



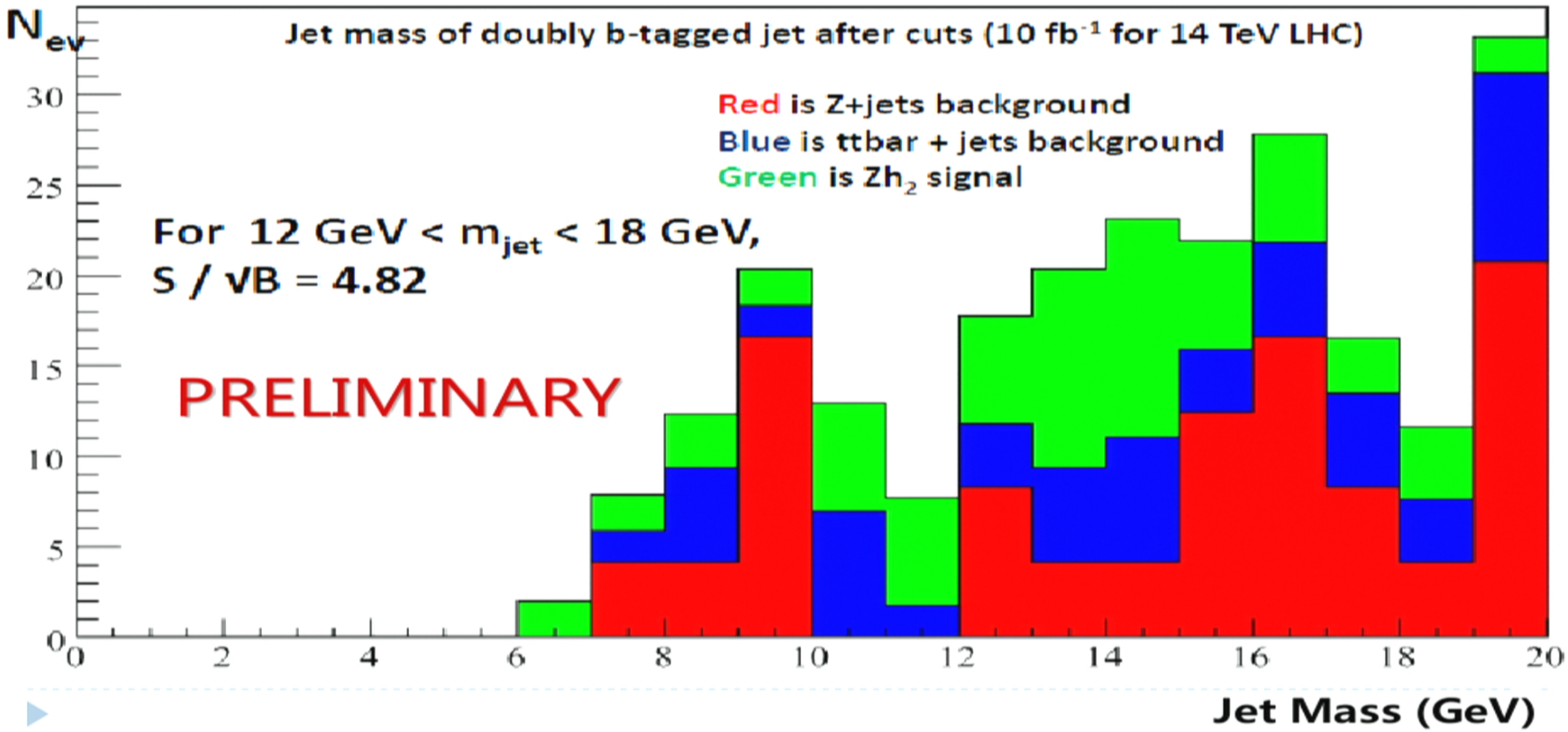


Cut-Flow-Table

Cut	Zh_2, $Z \to ll$ (0.114pb)	Z+jets, $Z \to ll$ (3002pb)	tt +jets (88.4pb)
=2l, Pt>20GeV	48.291%	51.775%	31.097%
Same flavor	48.028%	51.578%	15.544%
Opp. sign	47.940%	51.537%	14.364%
$\lvert m_{ll}-m_z \rvert <5$GeV	37.248%	40.527%	1.056%
MET>40GeV	24.803%	1.015%	0.829%
Doubly b-tagged jet, P_T >20GeV	10.692	1.7433E-5	0.104%
$\lvert P_T(h_2^*) - P_T(ll) \rvert < 15$GeV	7.274%	7.6095E-6	0.025%
N_{evt} ($10fb^{-1}$ @ 14TeV)	83	55	127

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

Jet mass

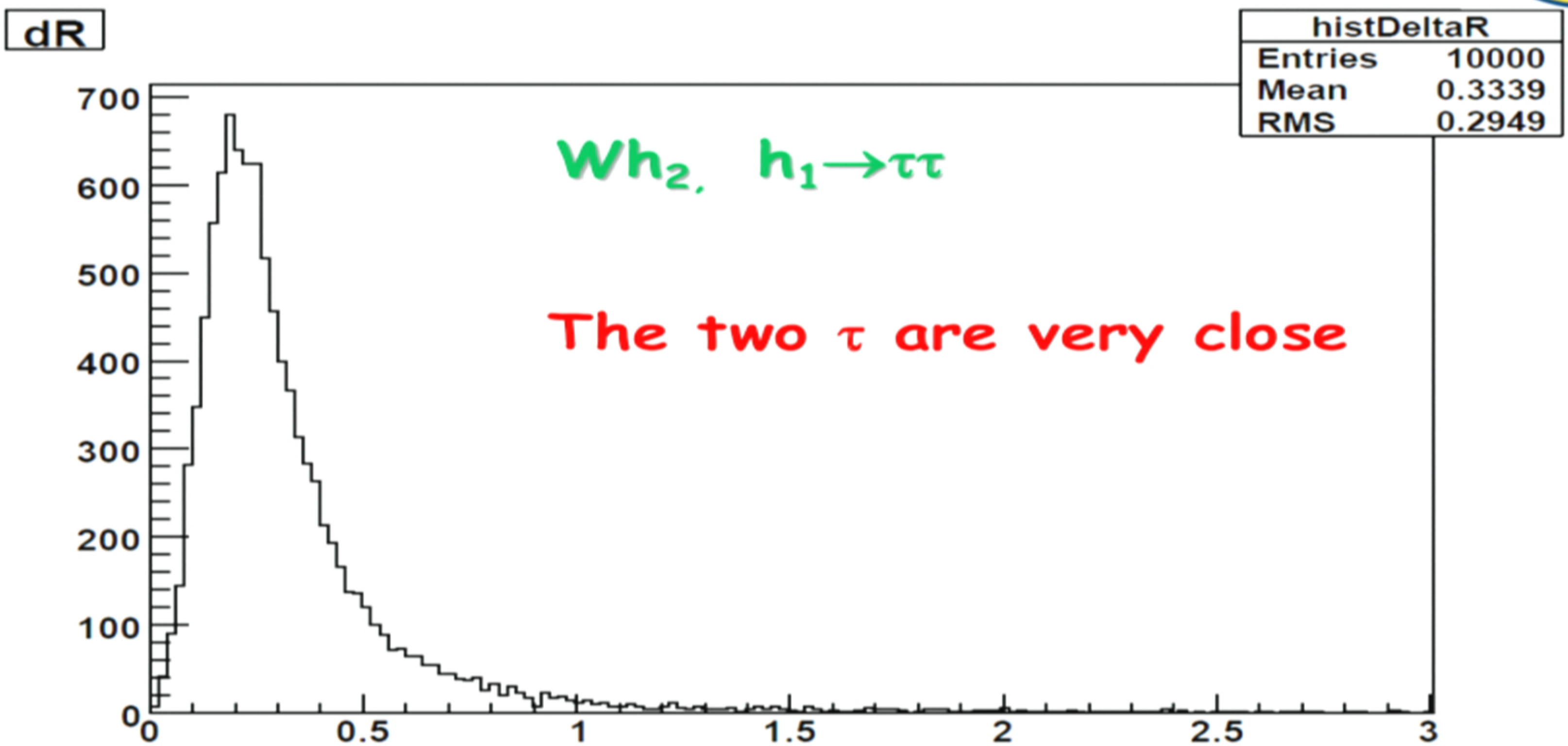


Jet mass of doubly b-tagged jet after cuts (10 fb⁻¹ for 14 TeV LHC)
Red is Z+jets background
Blue is ttbar + jets background
Green is Zh_2 signal
For 12 GeV < m_{jet} < 18 GeV,
S / √B = 4.82
PRELIMINARY
N_{ev}
0
5
10
15
20
25
30
0
2
4
6
8
10
12
14
16
18
20
Jet Mass (GeV)

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

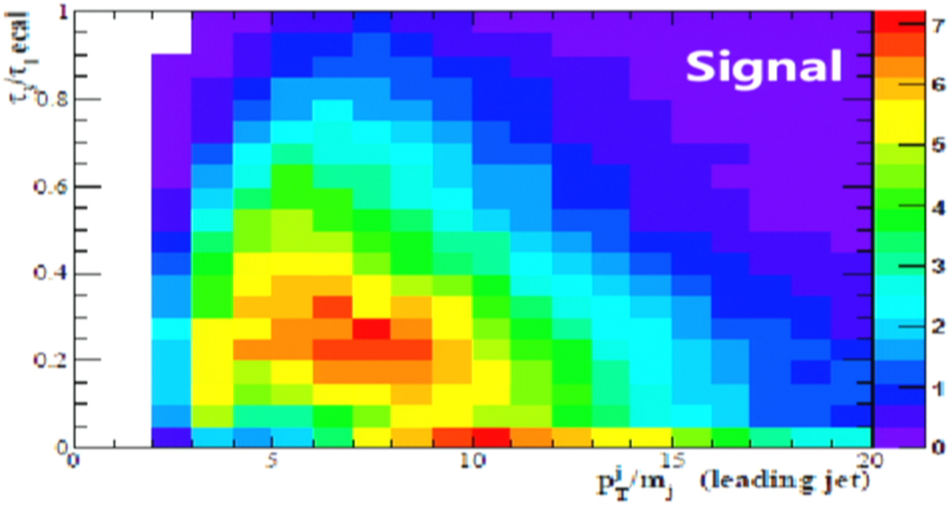
$\Delta R(\tau\tau)$

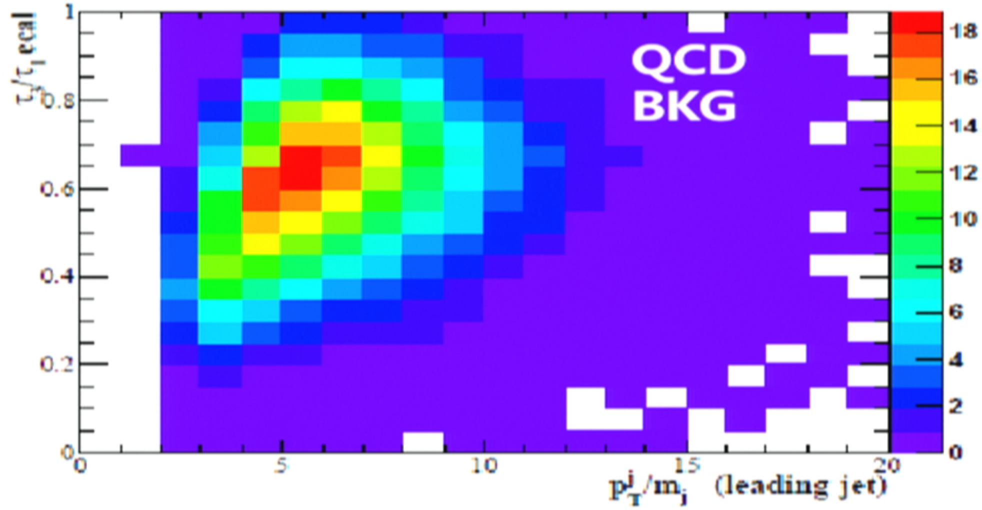


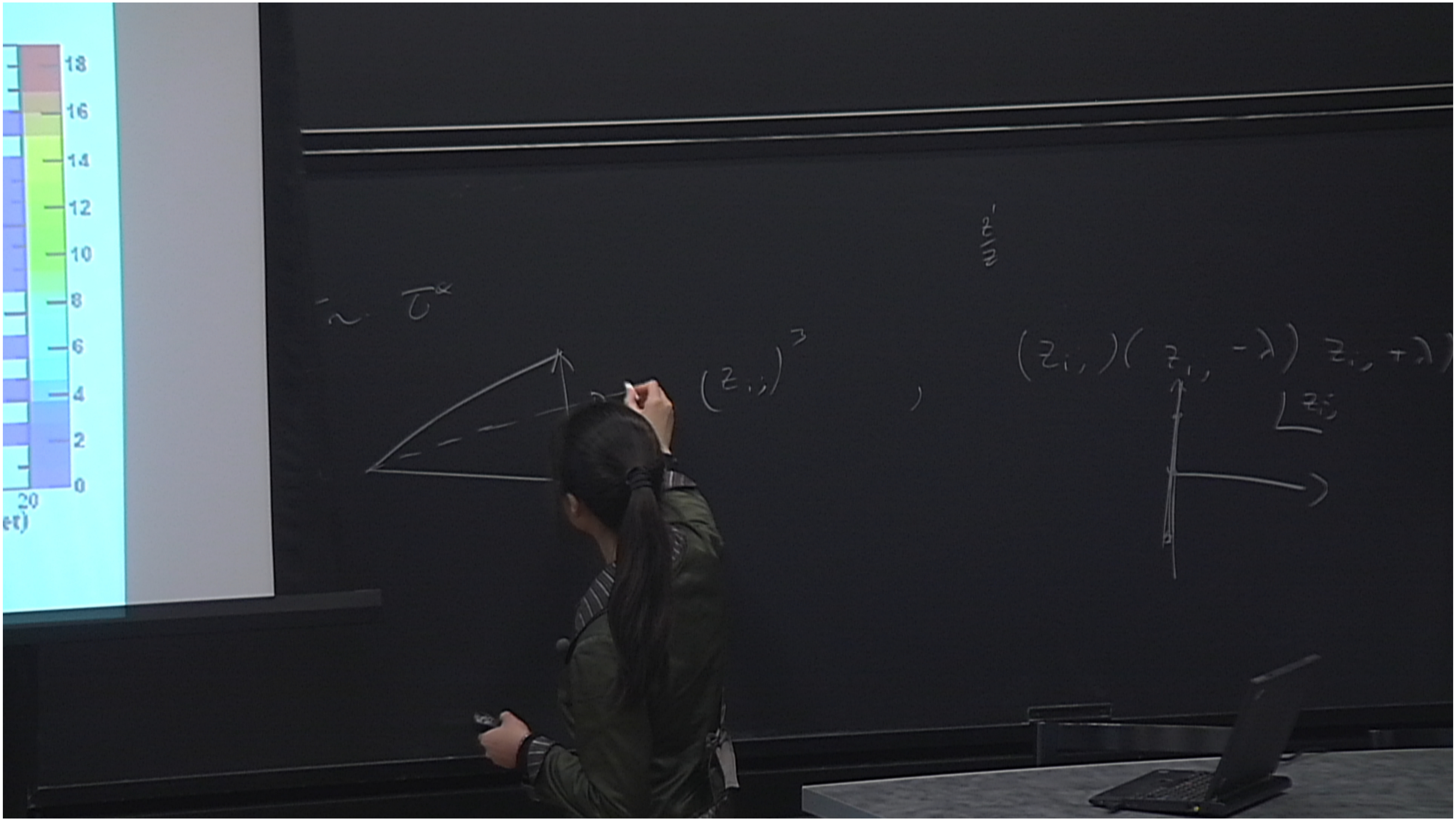
Di-Tau jet identification

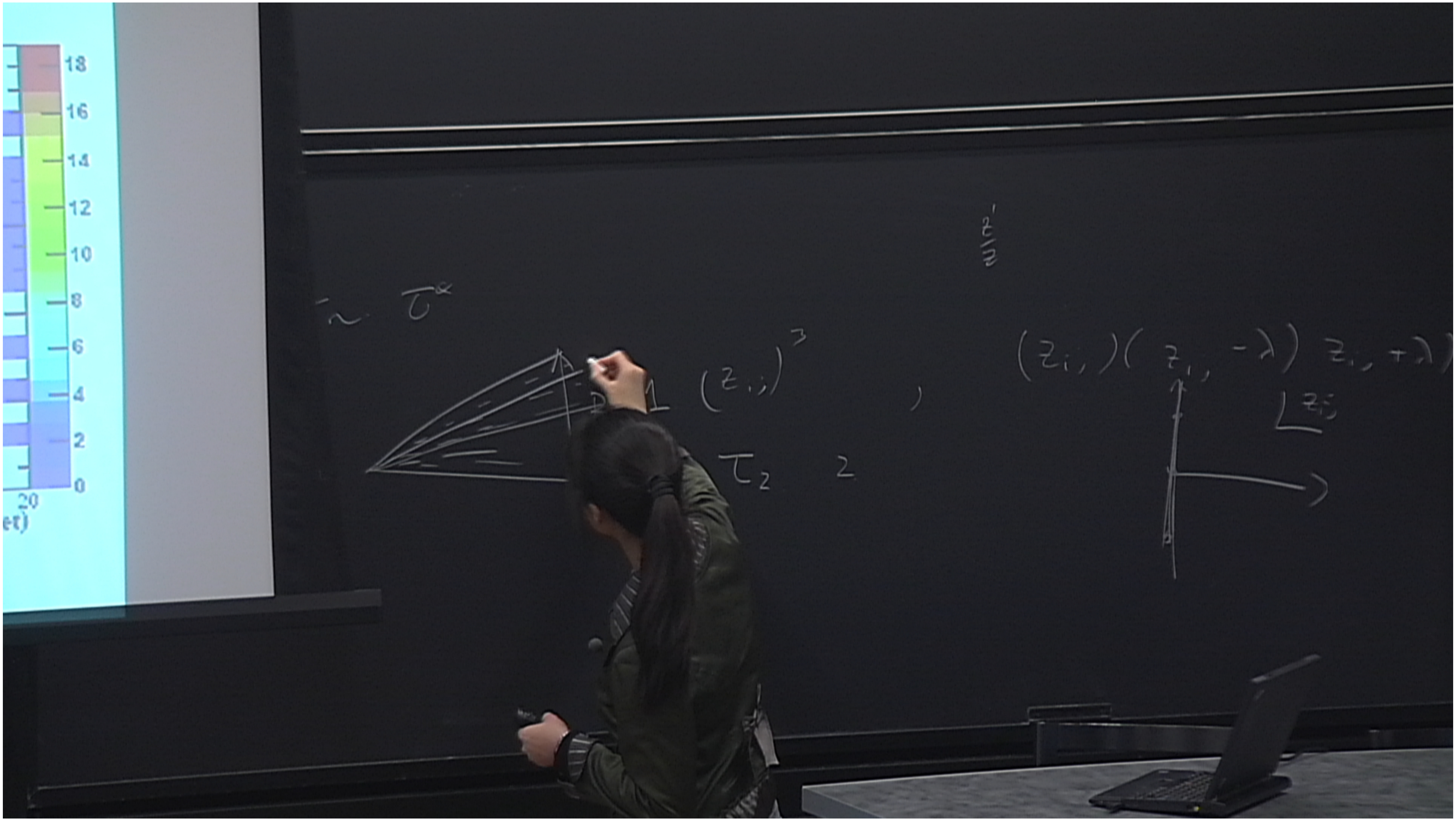
N-Subjettiness: C. Englert, T. Roy, M. Spannowsky, arXiv:1106.4545; J. Thaler, K. Van Tilburg, JHEP 1103 (2011) 015.

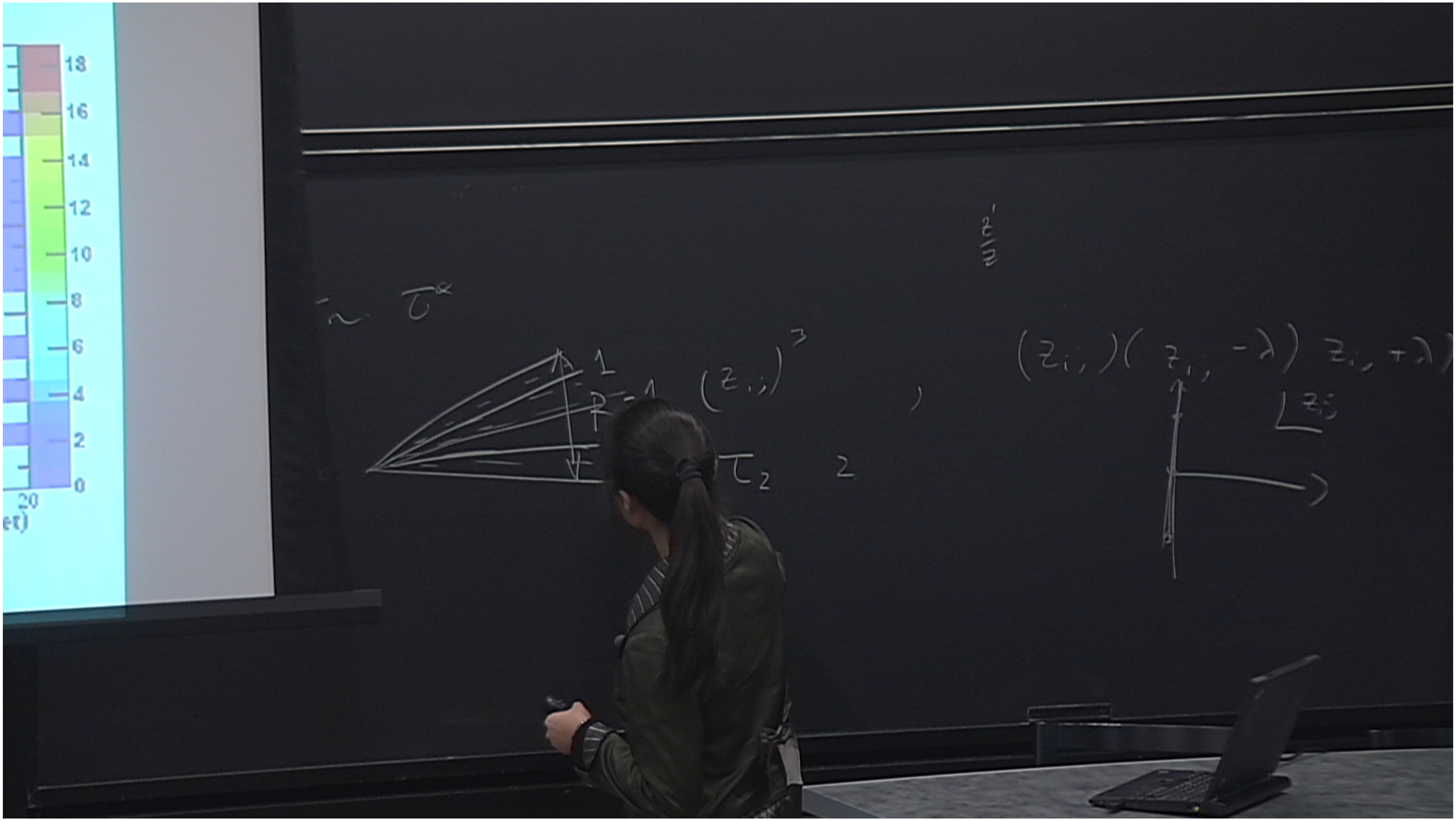
$$\tau_N = \frac{\sum_k P_{T,k} \min(\Delta R(1,k),\ldots,\Delta R(N,k))}{\sum_k P_{T,k} R}$$

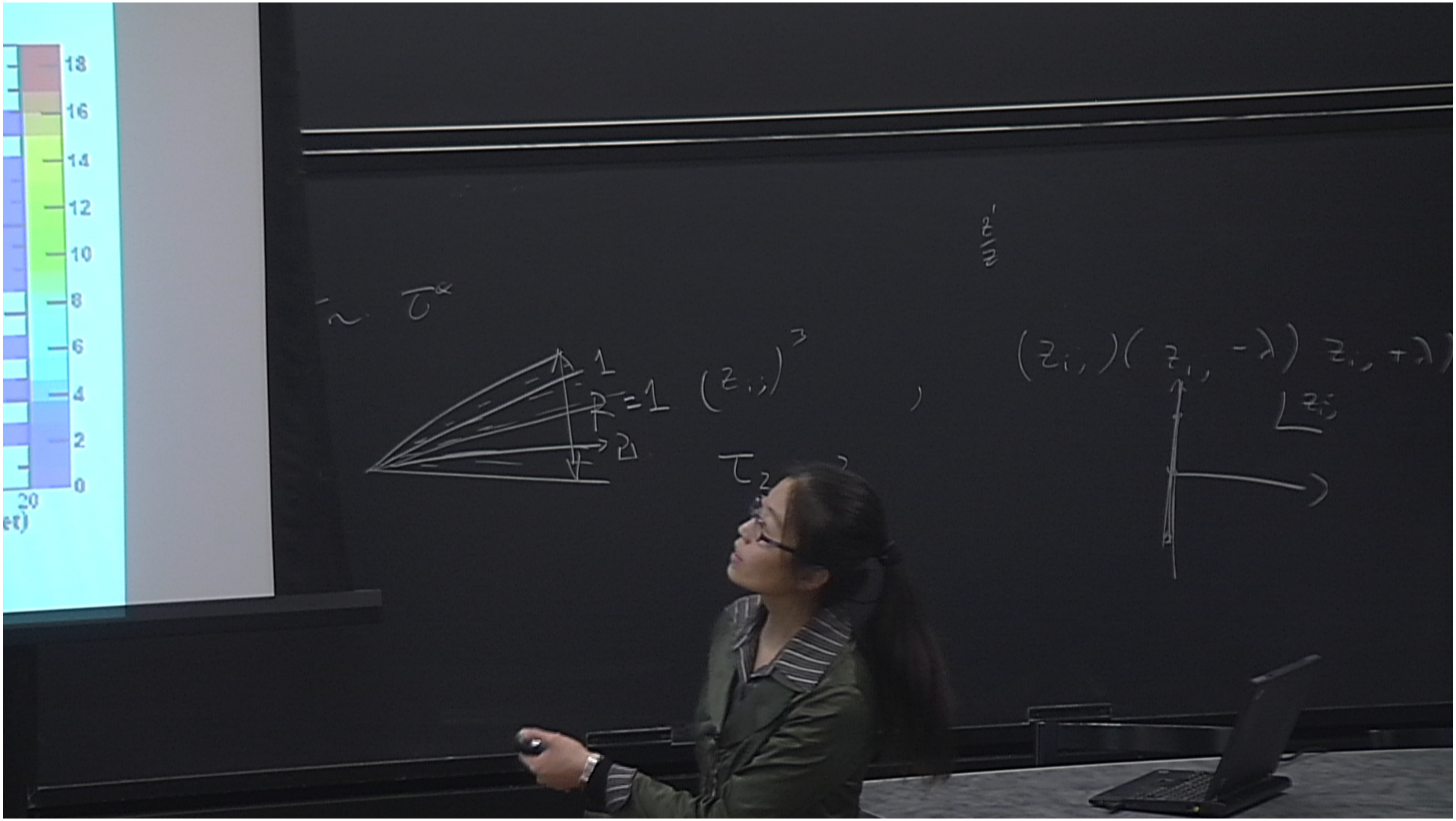











18
16
14
12
10
8
6
4
2
0
20

Conclusions

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

  -$\mu\mu$ and bb preliminary results presented

  -$\tau\tau$ is underway

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

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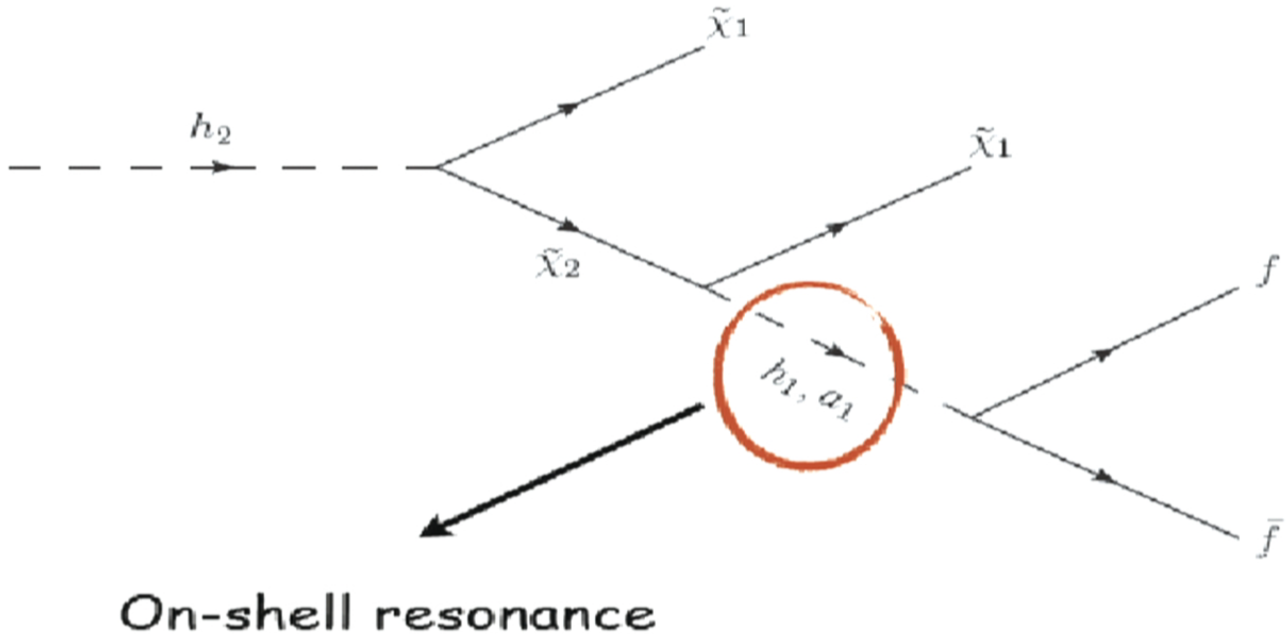
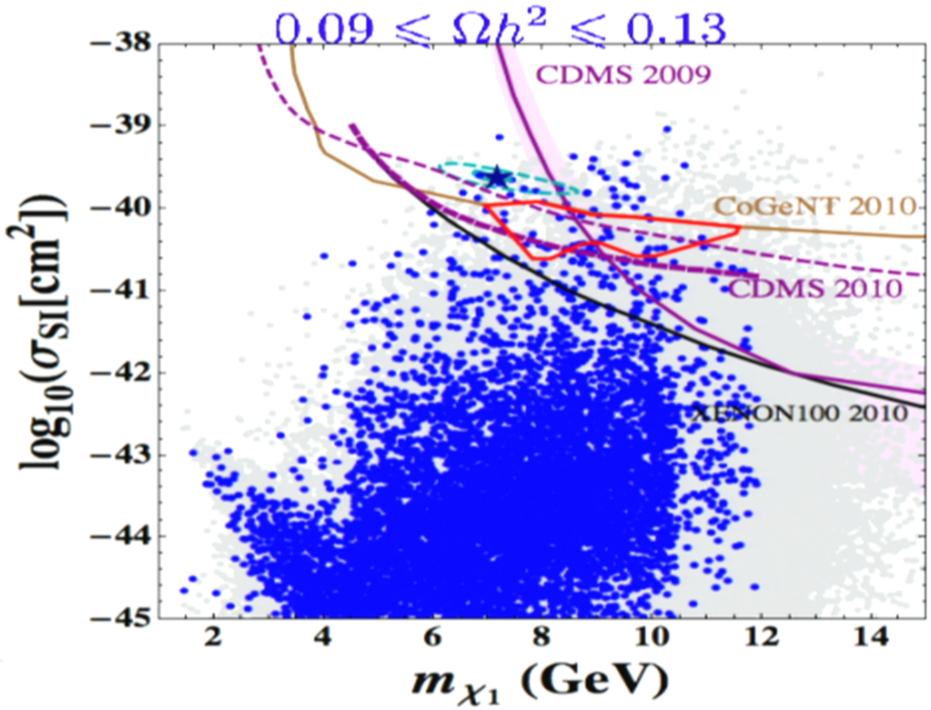
Dark Light higgs search



Signal: Collimated Fermion pairs + MET

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



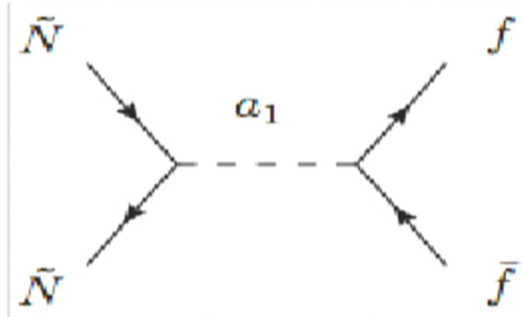
$$0.05 \leqslant \lambda \leqslant 0.15, \quad 0.001 \leqslant \kappa \leqslant 0.005,$$
$$|\varepsilon'| \leqslant 0.25, \quad -30\text{GeV} \leqslant A_\kappa \leqslant -15\text{GeV},$$
$$5 \leqslant \tan\beta \leqslant 50, \ 100\text{GeV} \leqslant \mu \leqslant 250\text{GeV}$$

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}

Breit-Wigner Effect



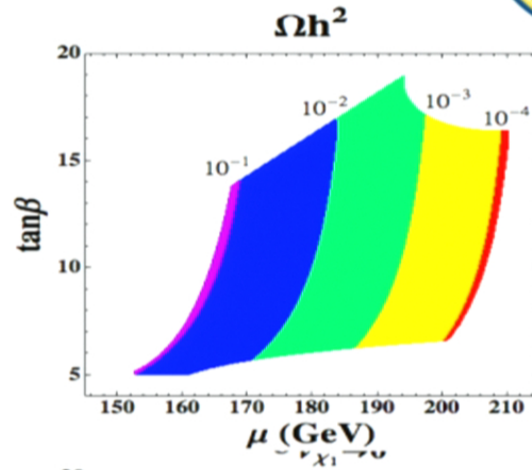
Thermal average of the LSP annihilation xection

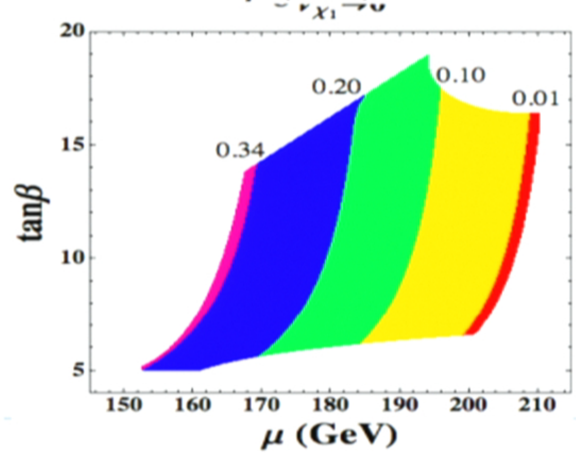
$$\sigma_{f\bar{f}} v_{\chi_1} \approx \frac{3\,|g_{a_1\chi_1\chi_1}\, g_{a_1 f f}|^2 (1 - m_f^2/m_{\chi_1}^2)^{1/2}}{32\pi m_{\chi_1}^2 \left(\delta^2 + \left|\frac{\Gamma_{a_1} m_{a_1}}{4 m_{\chi_1}^2}\right|^2\right)}$$

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

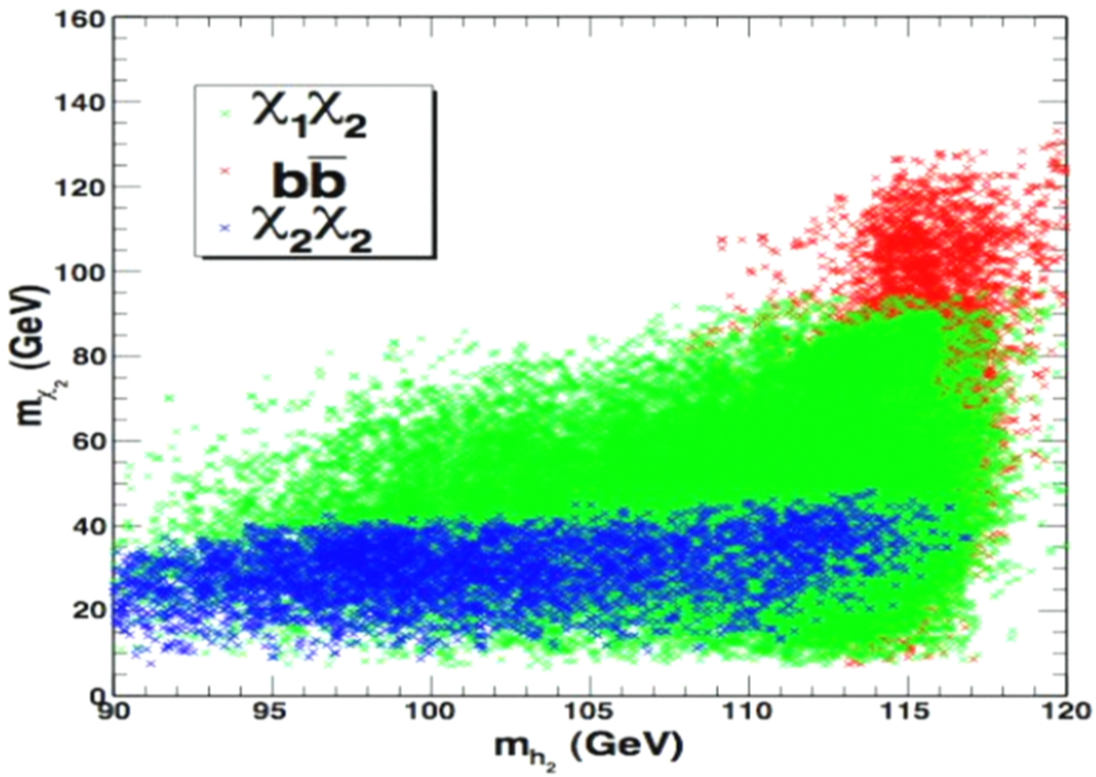
Relic density

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





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.