A very light decaying particle search at the LHC

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- Possible reasons that we have not been able to observe a new physics yet…

1. New physics is beyond the LHC reach.
   - We need a new machine, VLHC, 100TeV, etc…

2. New physics is located at a “blind spot”.
   -Need to have High luminosity machines…

3. Signals from New physics are hiding (disguising) behind (as) backgrounds. (Not enough big MET to separate signals)
   - Need to have precise SM (cross-section) measurement
     in theory side($N^{Enough}LO$),
     in experimental side(well-controlled samples)

4.…

- In this talk, I will focus on a case in

  "3. Signals from New physics are hiding (disguising) behind (as) backgrounds."

  based on recent papers, ongoing projects

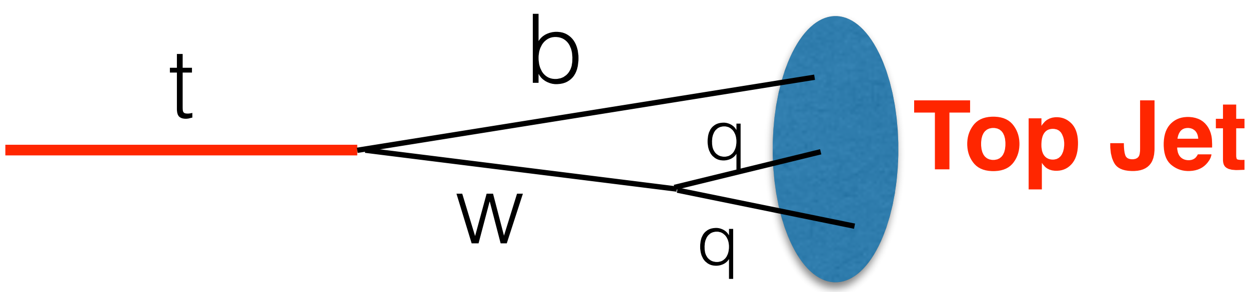
  1." Dark decay of Top quark" (PRD D89(2014) 074007) with HS Lee and KC Kong.

  2. "Search for dark Z' in a rare decay of top quark using M2 variables" (arxiv: 1411.0668) with HS Lee and DJ Kim

  3. "125GeV Higgs decay into Z and a Lepton-Jet" (arxiv:1412.OOOO) with HS Lee et.al.

  4. lepton-jet from light pseudo-scalar decay in NMSSM (arxiv:1412.0000)

signature at the LHC

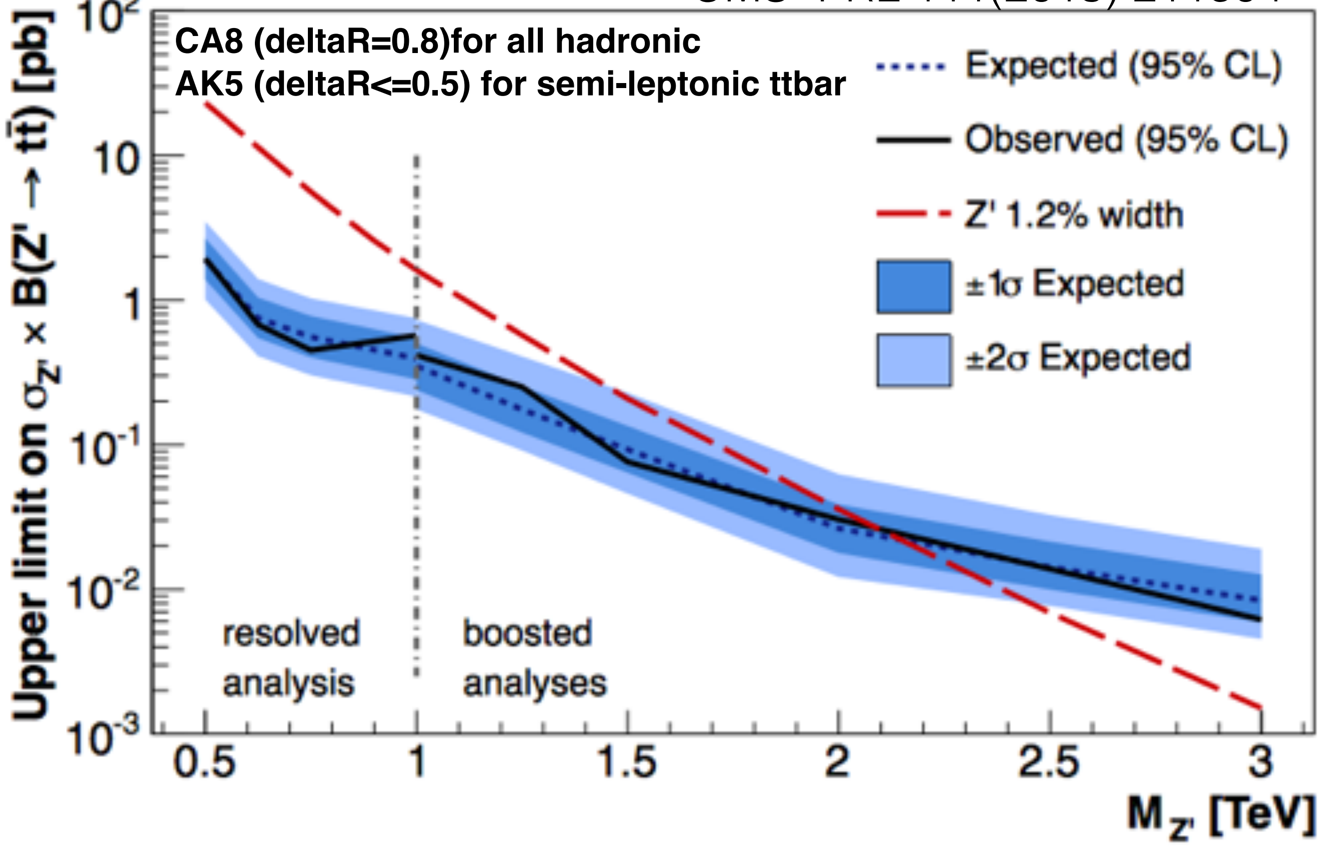


Heavy object, like top-quark need to have high pt (1TeV) to have all sub particles are included within deltaR<0.4

SJ Lee et.al. (arxiv:0810.0934) Top Jets at LHC

- Massive objects (top, higgs) require a large Pt to have collimated children

CMS- PRL 111(2013) 211804



- To tag this top-jet, we need to look into substructure (properties) of this “jet”.

signature at the LHC

- Similarly, we may have a new type of signature from a light decaying particle.

- Usually to tag resonance from Standard model backgrounds, our preference

  muon > electron > photon

  and we require “**isolated**” objects since jets can have leptons/photons inside their cone.

  *Please remember the main BKG for SUSY tri-lepton searches is ttbar, one lepton from b-jet.

“isolated leptons” ?

For an example, if a very light particle decays into two leptons,

$$m^2_{\ell^+\ell^-} = 2P_{T(\ell+)}P_{T(\ell-)}(\cosh\Delta\eta_{(\ell+\ell-)} - 1) \simeq P_{T(\ell+)}P_{T(\ell-)}\Delta R^2_{(\ell+\ell-)}$$

with observation $\Delta R \simeq \Delta\eta$

With $P^{\rm min}_{T(\mu)} = 5\ {\rm GeV}$ for a moderate tagging efficiency and isolation cut of DeltaR>0.3

$$m_{\mu\mu} > \sqrt{2P^{\rm min}_{T(\mu)}P^{\rm min}_{T(\mu)}(\cosh(0.3) - 1)} \simeq 1.5\ {\rm GeV}.$$

We **can not** access a particle of a mass below 1.5GeV with conventional “isolated leptons”. It looks like a jet if we don’t look into it in details. (If we require larger PT, then situation gets worse.)

a new object for a light particle

- “Lepton-Jet” was proposed by Nima and Neal Weiner in arxiv:0810.0714 for a dark photon.

- After this paper, CMS/ATLAS collaboration studies this new type of object in a limited region of new physics searches.

- But this new object needs to be considered with an equal status, just like, for example, tau-jet and b-jet.

- I will take two examples of a new physics, one concrete example and one-ongoing project.

1. light dark force mediator

- A new U(1) force is introduced as a dark force, Zd
- Zd is coupled to Standard Model particles through a gauge kinetic mixing with $U(1)_Y$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z'^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$$

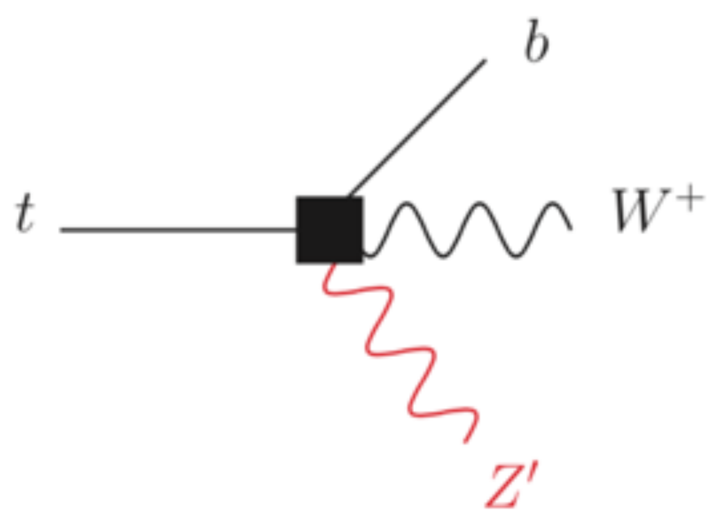
- Zd gets mass through additional higgs fields. Depending on SU(2) structure of this new higgs field, it can mix with Z boson.

$$\mathcal{L}_{\text{dark } Z} = -\left(\varepsilon e J^{\mu}_{em} + \varepsilon_Z g_Z J^{\mu}_{\text{NC}}\right) Z'_{\mu}$$

- By noticing uncertainties for top quark decay width measurements, we started to look into top channel as one of chances to probe/test a dark force carrier. Theoretically $\Gamma_t = 1.329\, GeV$
  - current CMS measurement,
  (2% deviation with O(10)% uncertainties)

$$\Gamma_t = 1.36 \pm 0.02(\mathrm{stat})^{+0.14}_{-0.11}(\mathrm{syst})\, GeV$$

Additional top-quark decay channel



(i) $t \to bH^+ \to bW + Z'$
(through $H^{\pm}W^{\mp}Z'$ coupling),
(ii) $t \to bH^+ \to bW + h \to bW + Z'Z'$
(with a light non-SM Higgs boson h),
(iii) $t \to bW^* \to bW + Z'$
(through $Z'WW$ coupling),
(iv) $t \to bW^* \to bW + h \to bW + Z'Z'$
(through hWW coupling).

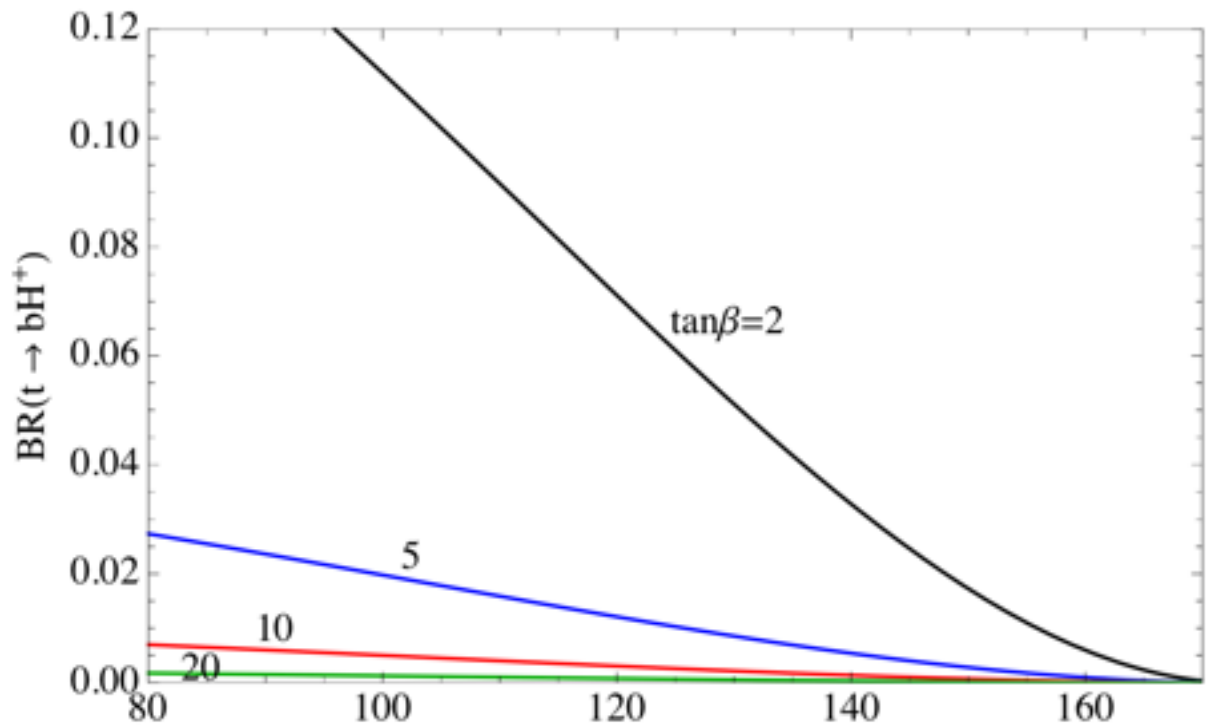
- For typical 2HDM, due to $H^+ \to \nu_\tau + \tau^+$channel, there are severe bound.
- We study (i) at the LHC where SM-like higgs is a lighter higgs doublet.

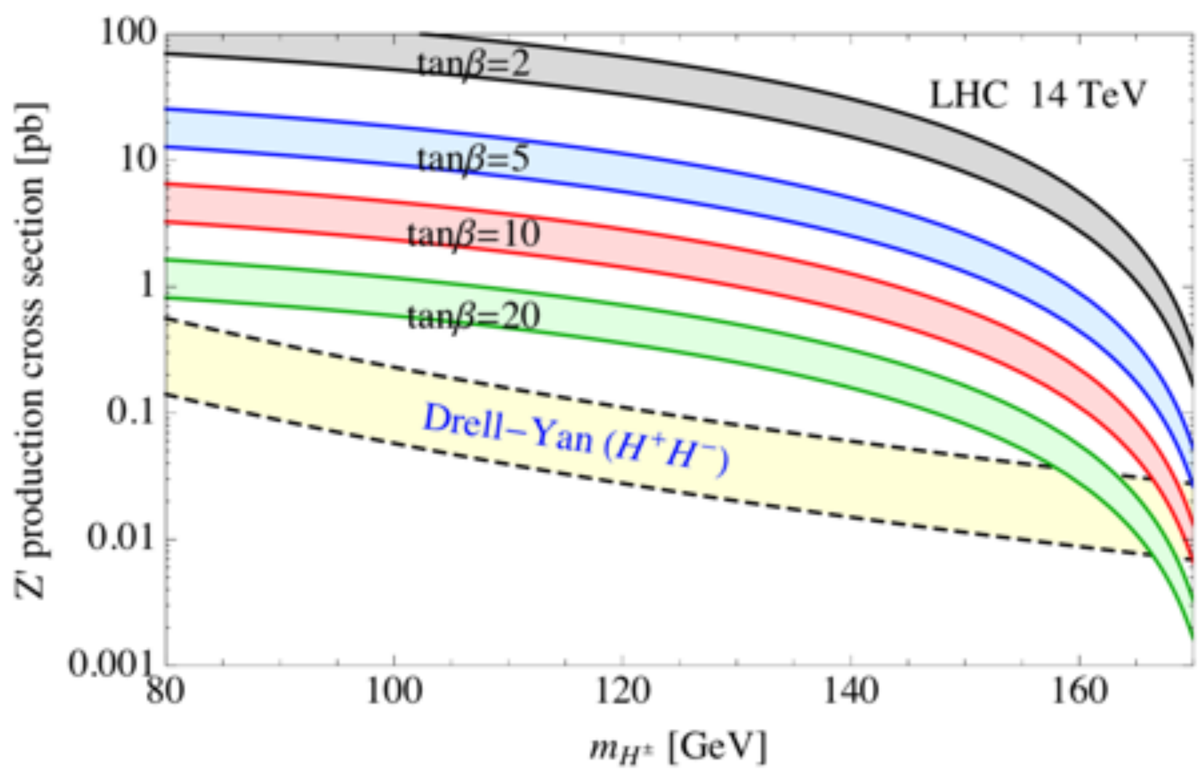
$$\Gamma(H^{\pm} \to WZ') \simeq \frac{m_{H^{\pm}}^3}{16\pi v^2} (\sin\beta\cos\beta_d)^2 \left(1 - \frac{m_W^2}{m_{H^{\pm}}^2}\right)^3$$

- When SM-like higgs is a heavier higgs doublet, (ii) channel is dominant and we can extend our studies at the LHC in this case

Additional top-quark decay channel

$$\mathrm{BR}(t \to bH^+) \simeq \frac{\Gamma_{t\to bH^+}}{\Gamma_{t\to bW} + \Gamma_{t\to bH^+}} \approx \left(\frac{m_t^2 - m_{H^\pm}^2}{m_t^2 - m_W^2}\right)^2 \frac{1/\tan^2\beta}{1 + 2m_W^2/m_t^2}$$





- To be model-independent search, we parameterize model-dependency into X and Y as following,

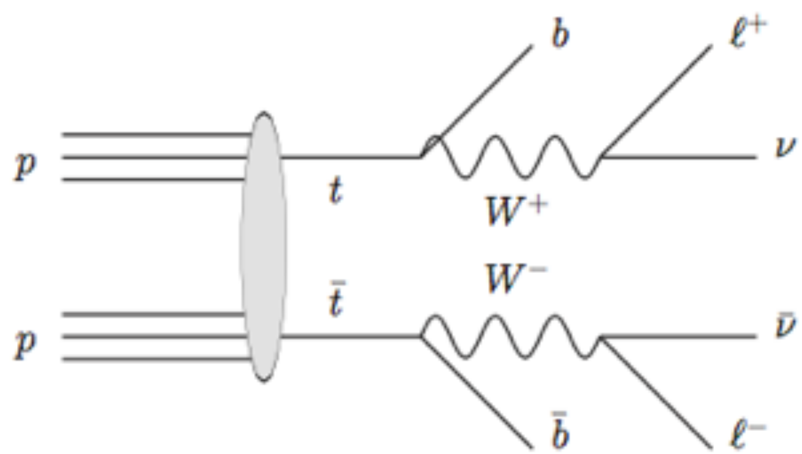
$$X = \mathrm{BR}(t \to bH^+)\, Y$$

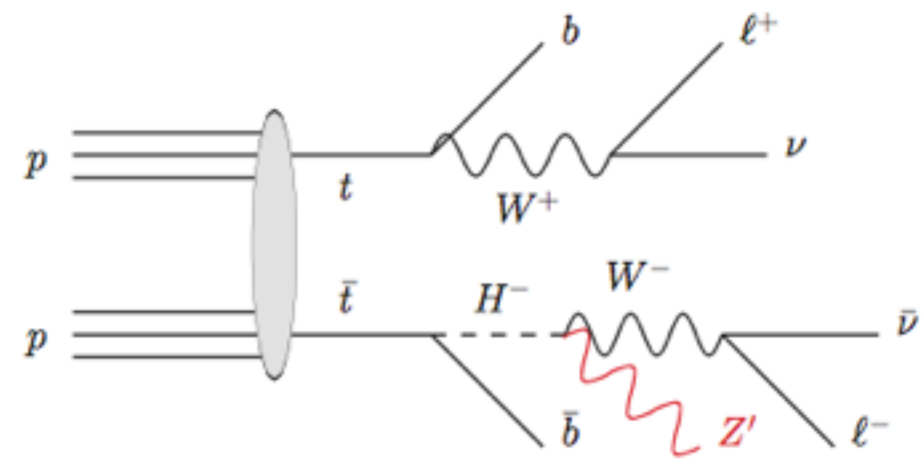
$$Y \equiv \mathrm{BR}(H^\pm \to W + Z'\mathrm{s})$$

The value $X = 0.001$ can be obtained, for example, for $m_{H^\pm} = 100$ GeV (with $\tan\beta \simeq 20$, $Y \simeq 0.8$), $m_{H^\pm} = 140$ GeV (with $\tan\beta \simeq 10$, $Y \simeq 0.9$), and $m_{H^\pm} = 160$ GeV (with $\tan\beta \simeq 5$, $Y \simeq 1$).

- In (i), there can be another dark Z channels through DY-process of charged higgs pair. But this channel is less by more than factor 10 compared to tab process

Invisible Z' decays

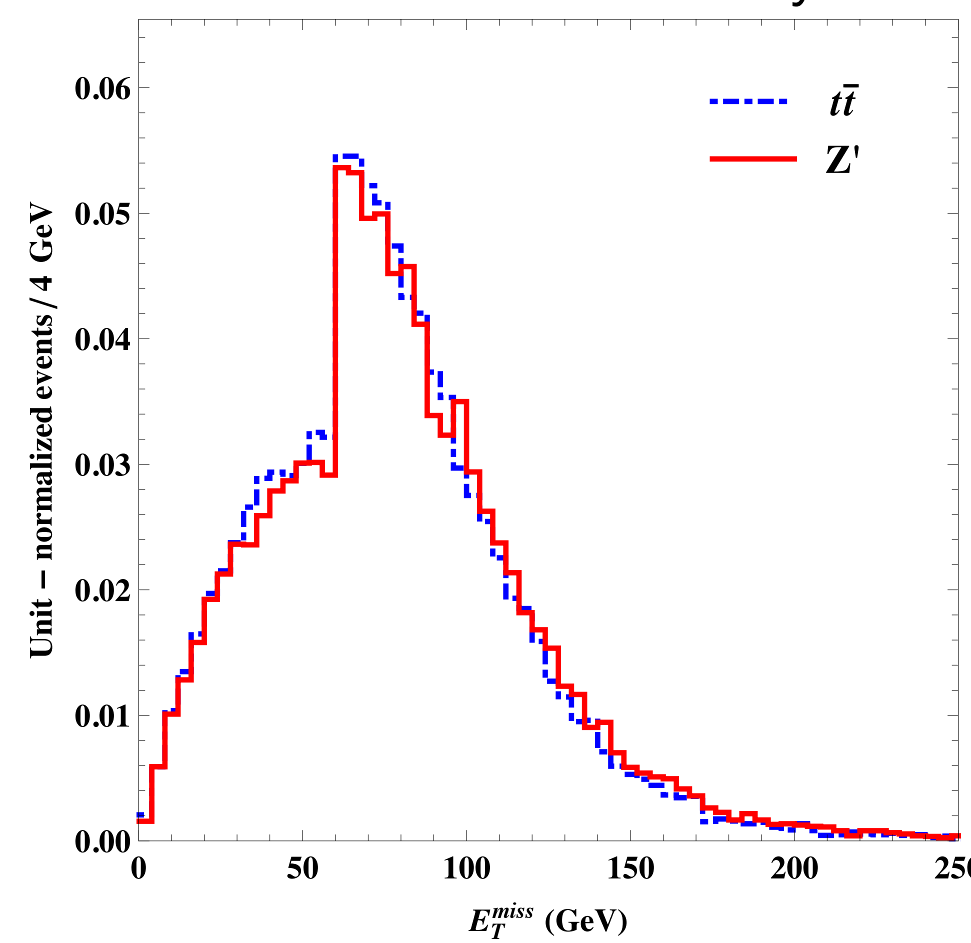




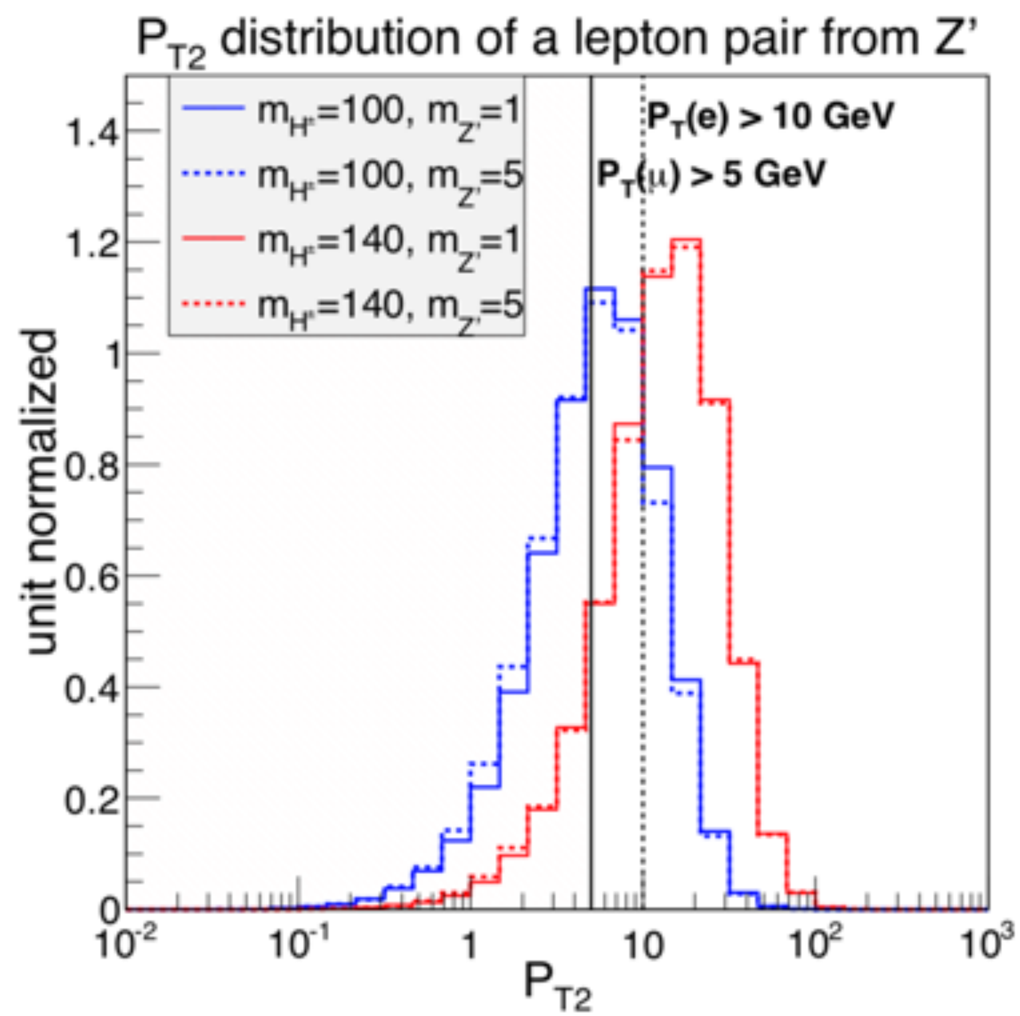
- In this case, a "tailored" variable for t-tbar can help to distinguish a new physics from t-tbar bkg.Assumed that events from t-tbar di-lepton channel, We try to reconstruct neutrino momentum from t/t-bar decays with Mtop1= Mtop2, Mw1 = Mw2

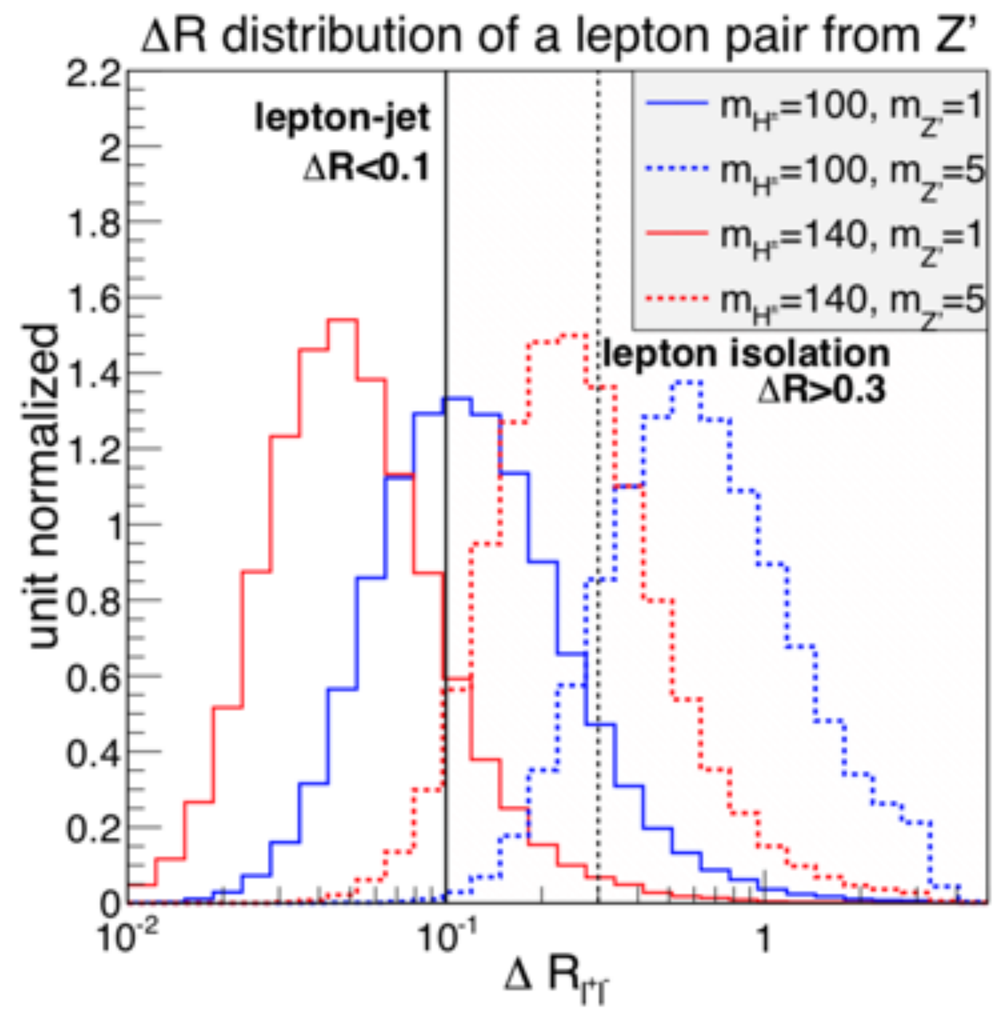
	BP1	BP2	BP3	BP4	BP5
c_1 (GeV)	115(111)	119(112)	115(111)	125(125)	137(137)
c_2 (GeV)	79(79)	83(77)	88(80)	89(84)	89(94)
$X(\times 10^{-3})$	6.7 (2.2)	6.5 (2.1)	6.5 (2.1)	8.2 (2.6)	10.4 (3.3)

Discovery potential for four benchmark points – BP1: $m_{H^\pm} = 130$ GeV and $m_{Z'} = 1$ GeV, BP2: $m_{H^\pm} = 130$ GeV and $m_{Z'} = 20$ GeV, BP3: $m_{H^\pm} = 130$ GeV and $m_{Z'} = 5$ GeV , BP4: $m_{H^\pm} = 120$ GeV and $m_{Z'} = 5$ GeV, BP5: $m_{H^\pm} = 110$ GeV and $m_{Z'} = 5$ GeV – with integrated luminosities of 300 fb^{-1} (3000 fb^{-1}) at $\sqrt{s} = 14$ TeV.



Characteristics of signals @LHC





- Simple kinematics helps us to understand why we need to use lepton-jet, based on threshold production assumption for t-tbar.

$$\Delta R^{(\mathrm{peak})} \sim \cosh^{-1}\left(\frac{2m_{Z'}^2}{(E_\ell^{(\mathrm{cusp})})^2}+1\right)$$

$$E_\ell^{(\mathrm{cusp})} \equiv \frac{m_{Z'}}{2} e^{|\eta_{Z'}-\eta_{H^\pm}|},$$

$$P_T^{\mathrm{peak}} \equiv \frac{1}{2} E_\ell^{(\mathrm{cusp})}$$

analysis

- Our irreducible BKG is ttbar+dilepton.
- To remove another SM BKG, we follow/mimic cuts from CMS t-tbar cross section measurements.
- We take all hadronic, semi-lepton and di-lepton t-tbar channels with an additional requirement of Lepton-Jet (LJ) as followings,

1. At least two same flavor leptons with $P_T > 10$ GeV (electron), 5 GeV (muon) and in a cone of $\Delta R < 0.1$.
2. Isolation: Hadronic and leptonic isolation of $\sum P_T < 3$ GeV in $0.1 < \Delta R < 0.4$.
3. Invariant mass cut on the lepton-jet: $|m_{\rm LJ} - m_{Z'}| < 0.2 \times m_{Z'}$.

Results of simulations

- With previous 8TeV LHC with 20fb^{-1}

$m_{Z'}$ [GeV]	$m_{H^\pm}$ 100 GeV	140 GeV	160 GeV	BKG
1	40.0	86.2	58.1	69.6
2	8.2	59.9	47.8	5.0
5	0.1	5.0	9.1	0.3

Expected number of events in each lepton-jet bin (20% window of the Z' mass) with two b-tagging in 8 TeV LHC 20 fb^{-1}. We set $X = 0.001$ and $\mathrm{BR}(Z' \to \ell^+\ell^-) = 0.2$. Signal events were obtained with high order $\sigma_{t\bar{t}}$ with the branching ratio, and the background events were obtained with tree-level simulation with $K_{\rm bkg} = 2$.

Estimated number of events from BKG is only 5!

In CMS dilepton analysis, there is m(ll) > 20GeV analysis cut for dilepton t-tbar channel. Only 4 signal events can survive from such analysis.
New physics "**was" buried** by BKG,

$$\Delta N_{\rm BKG} \simeq 591$$

Results of simulations

- LHC Run 2 expectation with 14TeV energy,

$m_{Z'}$ [GeV]	$m_{H^\pm}$		
	100 GeV	140 GeV	160 GeV
1	$7.8\,\mathrm{fb}^{-1}$	$1.9\,\mathrm{fb}^{-1}$	$3.4\,\mathrm{fb}^{-1}$
2	$14.5\,\mathrm{fb}^{-1}$	$0.7\,\mathrm{fb}^{-1}$	$1.0\,\mathrm{fb}^{-1}$
5	-	$7.3\,\mathrm{fb}^{-1}$	$3.5\,\mathrm{fb}^{-1}$

Required luminosity for 14 TeV LHC to see the likelihood ratio $S_{\mathrm{cL}} = 5$ (corresponding to 5σ discovery).

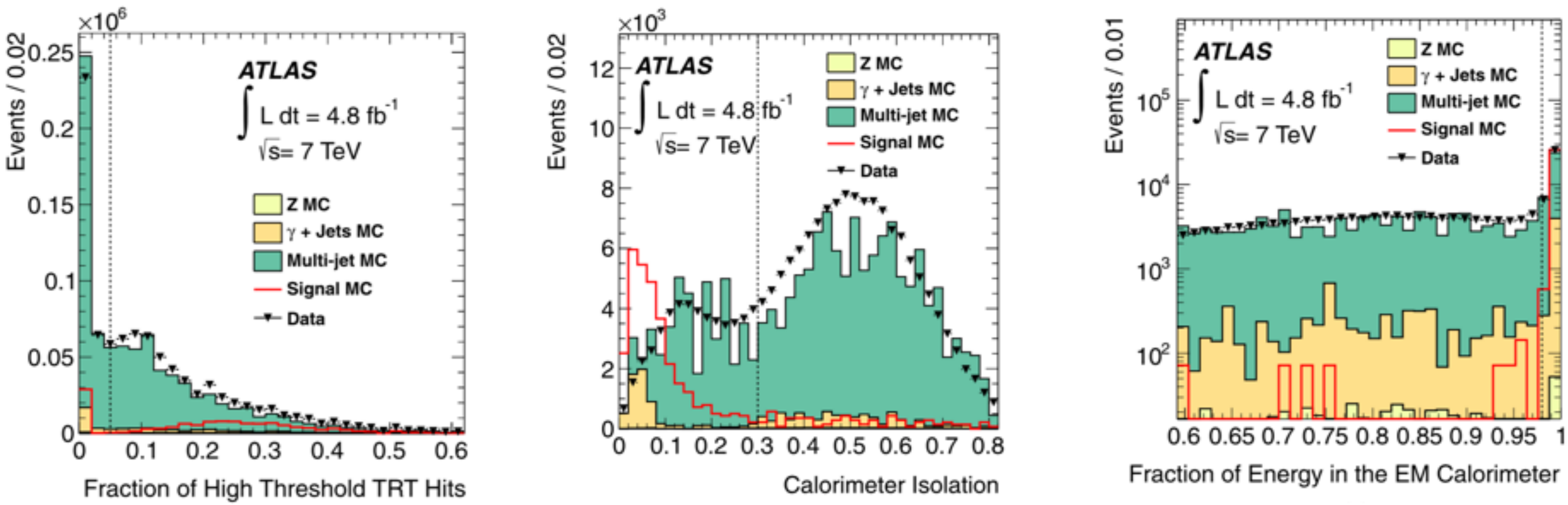
$$S_{\mathrm{cL}} = \sqrt{2N_{\mathrm{obs}} \log\left(1 + N_{\mathrm{sig}}/N_{\mathrm{bkg}}\right) - 2N_{\mathrm{sig}}}$$

technical problem

- In Lepton-jet analysis, there are two type
  1. electron-jet
  2. muon-jet

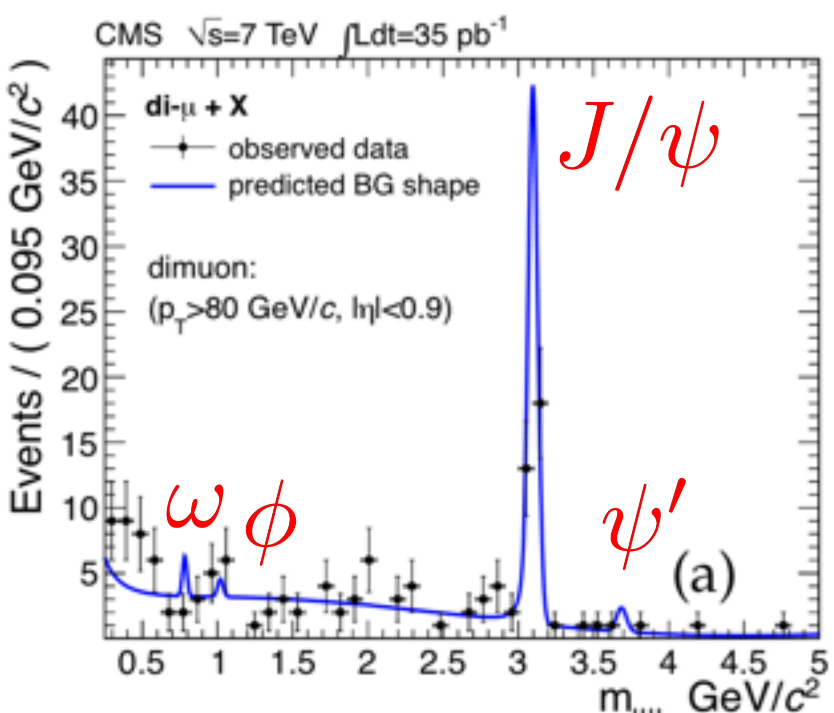
  Unlike muon which is the best object@LHC, study of collimated electrons have a difficulties @ E-cal.

ATLAS collaboration, Physics Letters B 719 (2013) 299–317

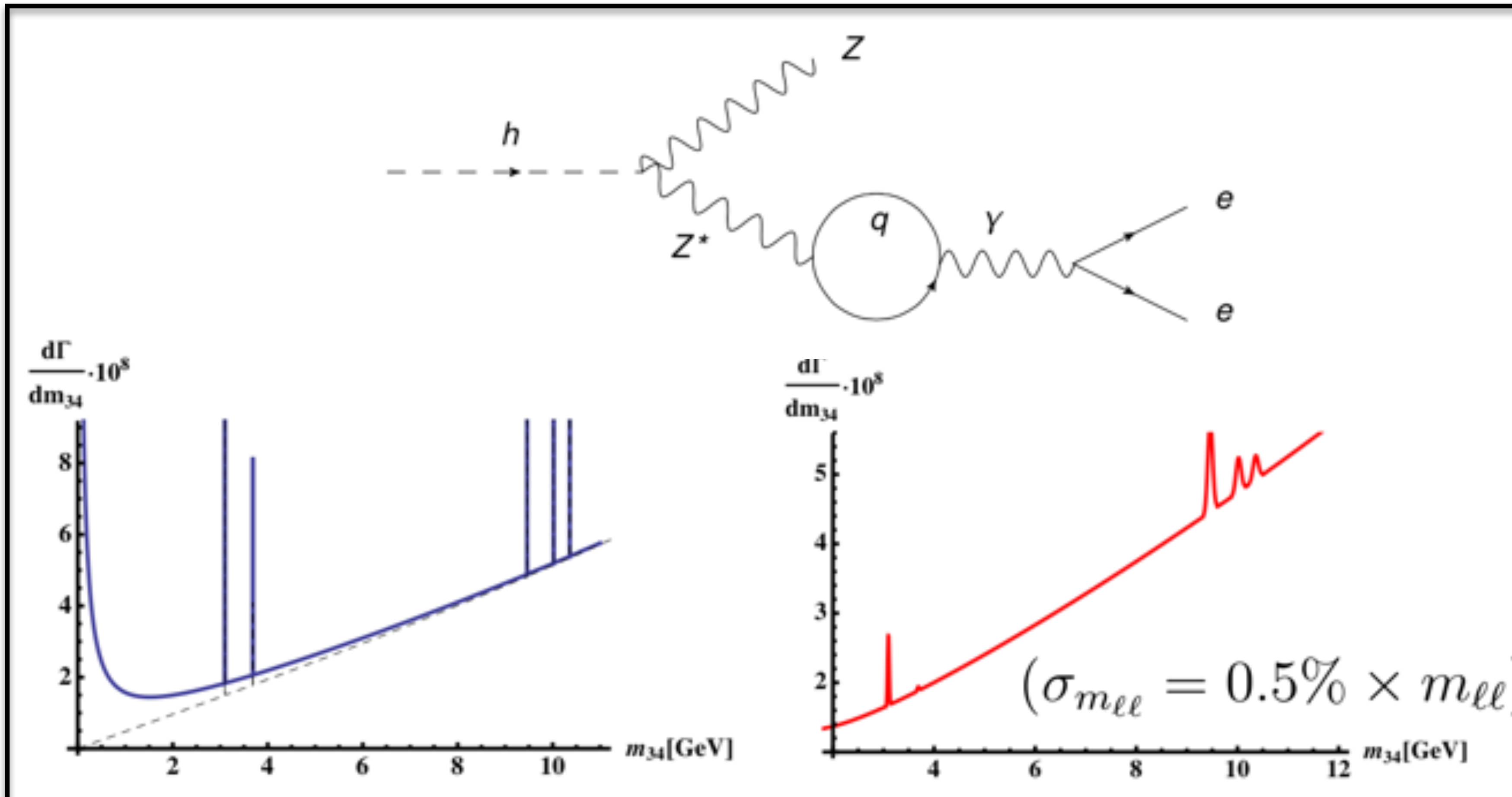


Standard model BKG

- One of the biggest SM BKGs is the leptons from mesons.



CMS-EXO-11-013



Gino Isidori et.al. arXiv:1403.2648

$$\sigma(m_{\mu\mu}) = 0.026\ \mathrm{GeV}/c^2 + 0.0065\, m_{\mu\mu} \text{ for barrel } (|\eta^{\mu\mu}| < 0.9)$$

$$|\ 0.026\ \mathrm{GeV}/c^2 + 0.013\, m_{\mu\mu}$$

2. a light scalar in NMSSM

- Supersymmetric models have been one of favorite bench mark models @ LHC
  (SUSY provides various signature sets depending on mass hierarchies.)

- For a different model, we can recast results from SUSY. (e.g.matrix element reweighting)

- But conventional SUSY models does not provide this interesting object (LJ).

- Next to Minimal SUSY can do…. This is an interesting bench mark study model.

- Please stay tunned.

Conclusion

- CMS/ATLAS have started to use Lepton-Jet (LJ) motivated by dark photon searches.
- But LJ has not been promoted to a “signature” in various analyses.
- As we see, some interesting new signal may be lost previous collider searches.
  - We are also studying H to Z’ Z with one LJ and two leptons. Signals from this channel have been neglected by lower invariant mass cut (mll> O(10) GeV)
- A LJ is one of “characteristic” signature for light decaying particles.

- Another version of LJ with displaced vertices studied by ATLAS, CERN-PH-EP-2014-209