Black Holes and BSM Scenario at the LHC

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On behalf of

The CMS Collaboration

&

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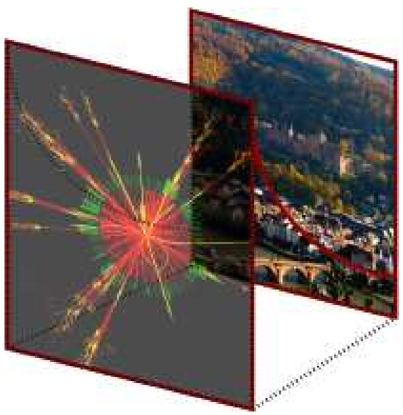


Motivation

- Hierarchy problem is one of the outstanding challenges in particle physics

- Hierarchy problem (both forces involve constants of nature):
  - Electroweak energy scale (~1 TeV)
  - Planck energy scale ($\sim 10^{16}$ TeV)

- SUSY and ED could address the hierarchy problem
  - ADD model: a large volume extra dimensions
  - RS model: a single warped extra dimension

- Consequences of the existence of ED is the production of black hole (BH)

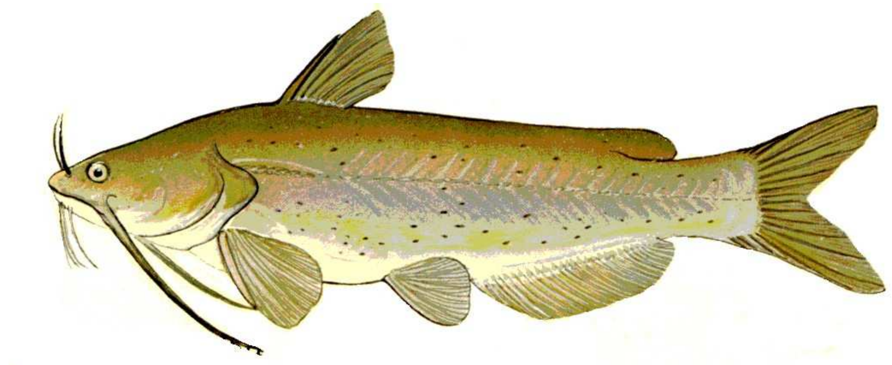
- Much effort has been made to observe BH production in fundamental Planck scale of $M_\star \sim$1 TeV

CATFISH: Black Hole Generator

- BH generators: Truenoir, Charybdis, CATFISH, and BlackMax

- We wrote a BH MC generator called “CATFISH”

  CATFISH (Collider grAviTational FIeld Simulator for black Holes)

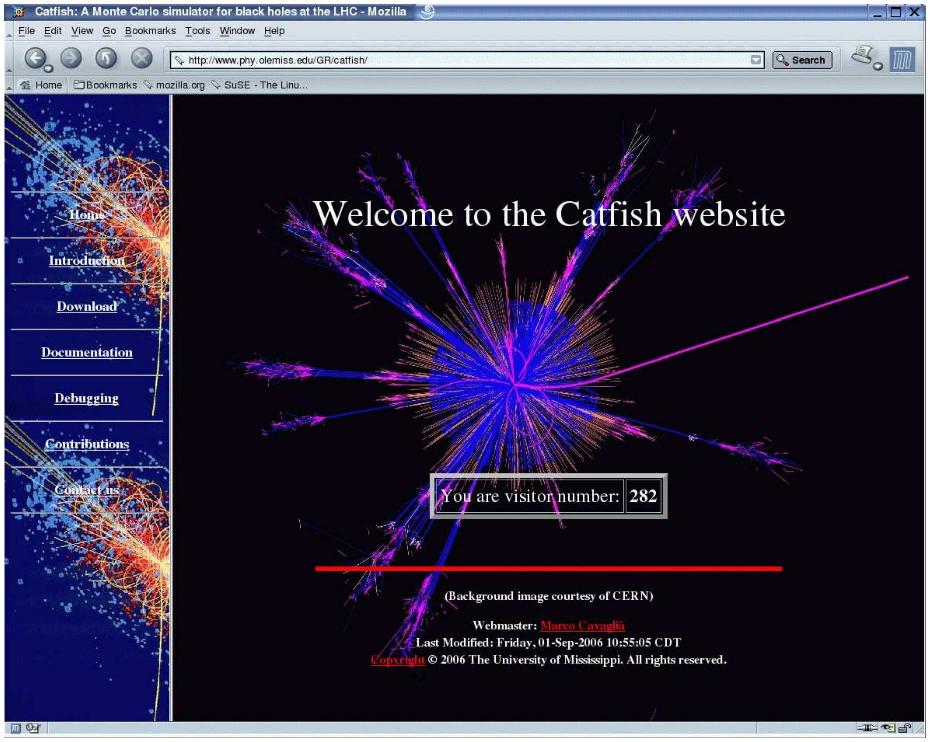


CATFISH authors: M. Cavaglià, R. Godang, L. Cremaldi, D. Summers

- Published Journal of High Energy Physics, JHEP06, 055, 2007

- Published Computer Physics Communications 177, 506, 2007

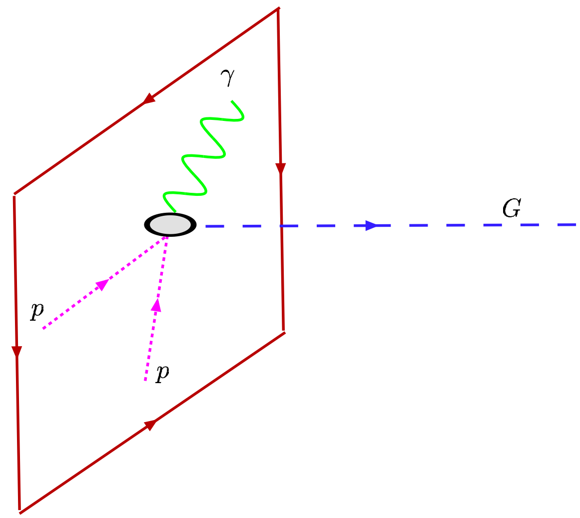
CATFISH Website



- ☐ **CATFISH: http://www.phy.olemiss.edu/GR/catfish/**
- ☐ **CATFISH features including :**
  - **Different final BH decay modes with possibility of remnant formation**
  - **Graviton field emissivities**
  - E^{miss} **due to** ν**, gravitons, BH remnant, inelastic effect during BH formation**

Extra Dimensions

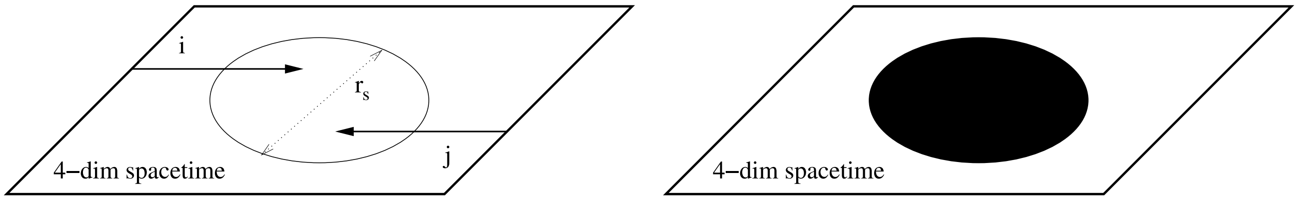
- In large extra dimensions at TeV energy-scale (Planck scale), Gravitons can propagate in $n = D - 4$ extra dimensions



- The BH is characterized by the Schwarzschild radius

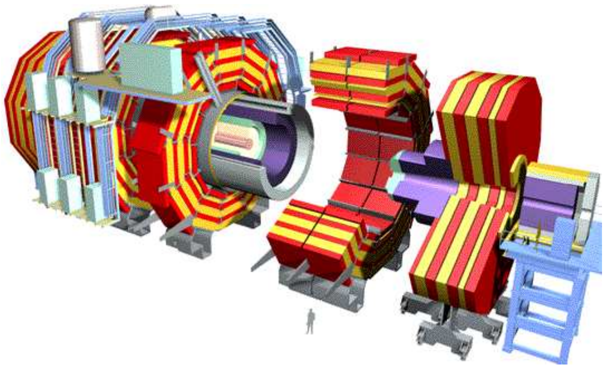
$$r_s = \frac{1}{\sqrt{\pi} M_\star} \left[\frac{8\Gamma\left(\frac{n+3}{2}\right)}{(2+n)} \right]^{\frac{1}{n+1}} \left(\frac{M_{BH}}{M_\star} \right)^{\frac{1}{n+1}}$$

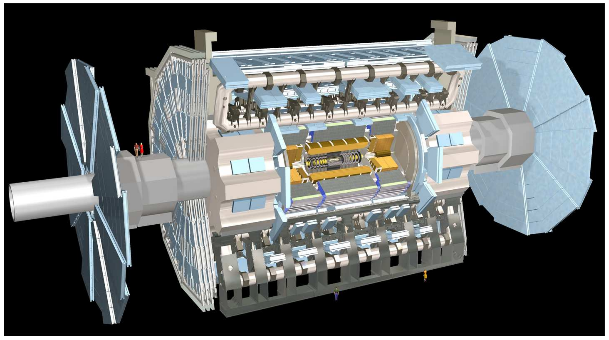
- If the impact parameter $b < r_s$, $\rightarrow$ an Event Horizon is formed



Extra Dimensions

☐ **Mini Black hole production at LHC**





☐ **At TeV-energy scale, LHC could observe BH production:**

1. $E_{observable} \ll M_\star$: **Gravitons escapes into extra dimensions**

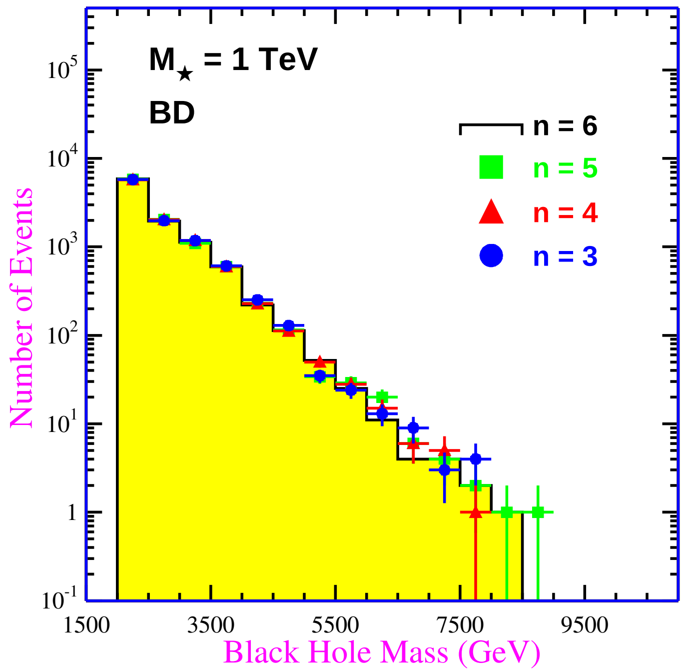
☐ $pp \longrightarrow$ **Jet + Gravitons** $\longrightarrow$ **Jet +** E_T^{miss}

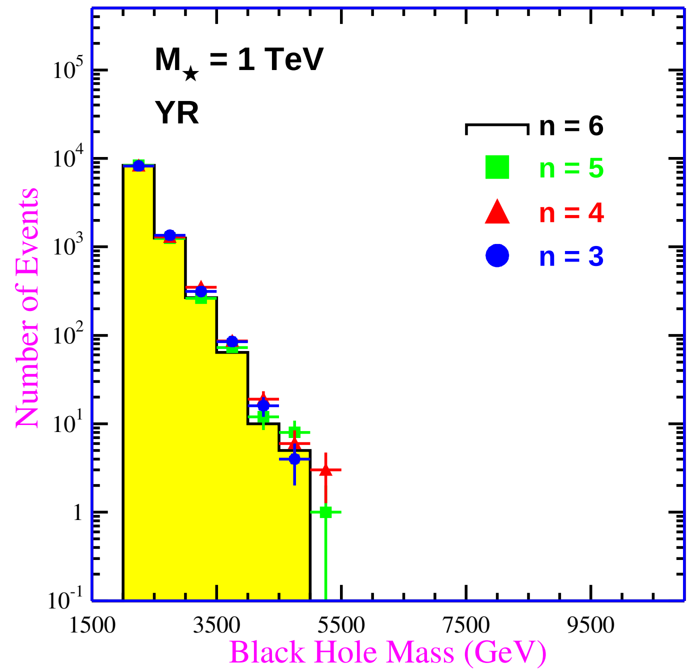
2. $E_{observable} \gg M_\star$: **Mini BH production**

☐ $pp \longrightarrow$ **BH** $\longrightarrow$ **spectacular decays (High P_T leptons, Jets)**

BH Mass

☐ **BH Mass distribution for fundamental Planck scale $M_\star = 1$ TeV, $n_p = 2$**



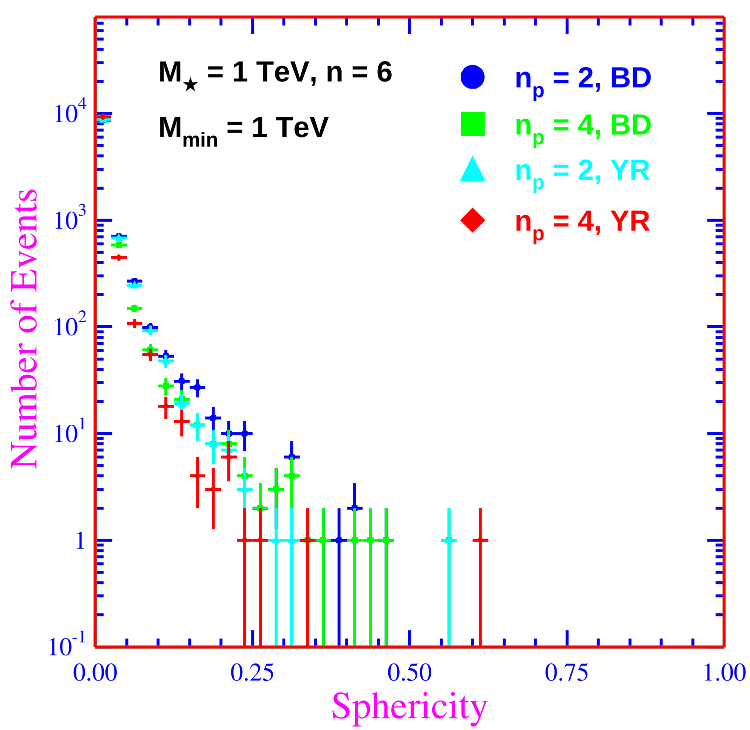


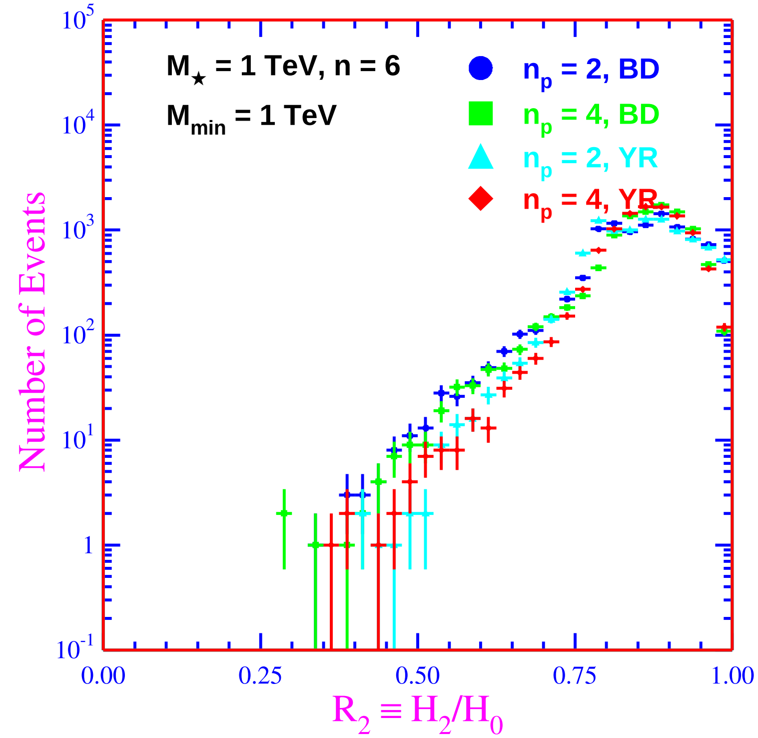
☐ **CATFISH MC results :**

- **(left) Black Disk model (BD) $\Longrightarrow$ no Gravitons loss**
- **(right) Yoshino-Rychkov TS model (YR) $\Longrightarrow$ with Gravitons loss**

BH Events Shape

- BH events are expected to be highly spherical due to the spherical nature of Hawking radiation

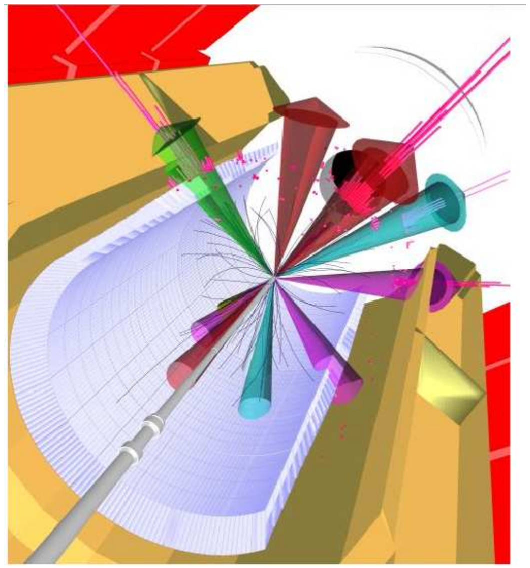


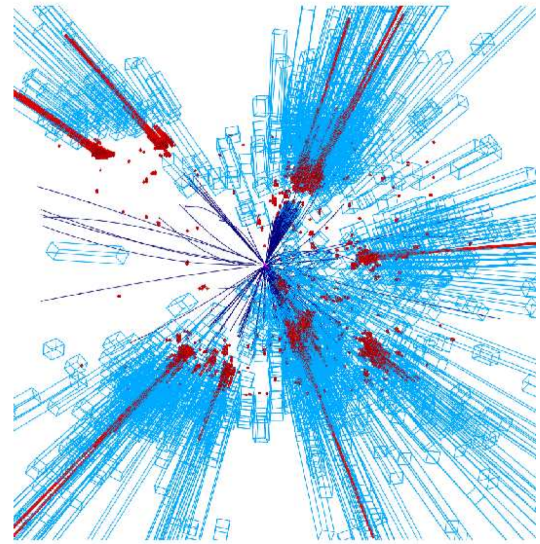


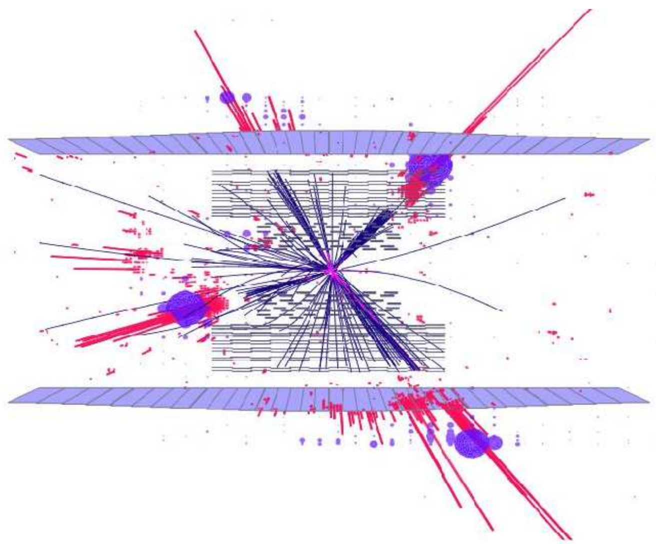
- Experimentally one needs to distinguish between BH events shape with $q\bar{q}$ events as BH-backgrounds (back-to-back events shape)

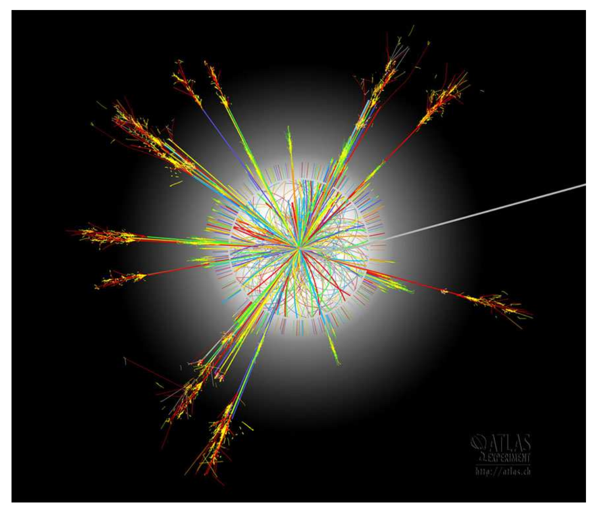
  - (left) Sphericity BH events shape $\longrightarrow S > 0.30$ (depends on M_{min})
  - (right) Fox-Wolfram moment $\longrightarrow R_2 < 0.50$

Black Hole Events at CMS and ATLAS









$E_{observable} \gg M_\star$: **Mini black hole production at LHC**

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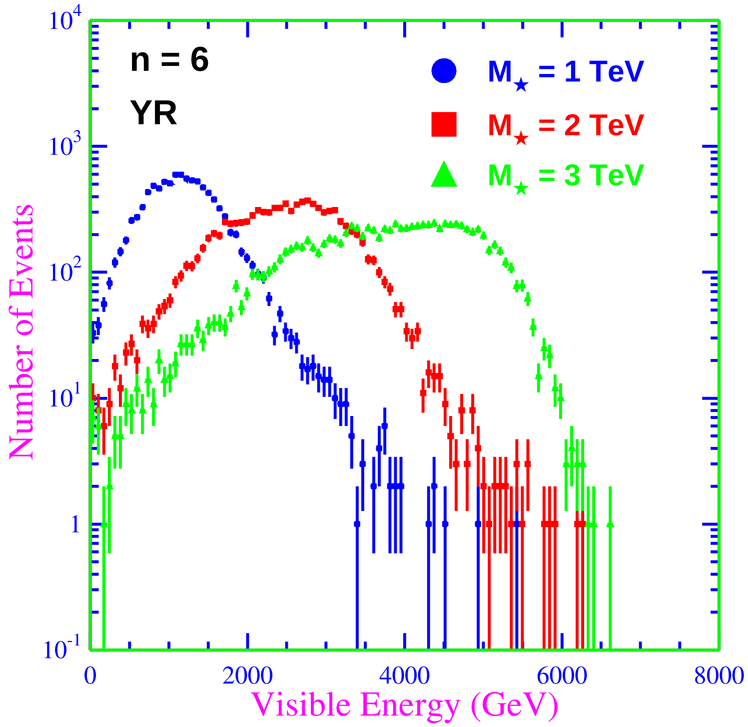
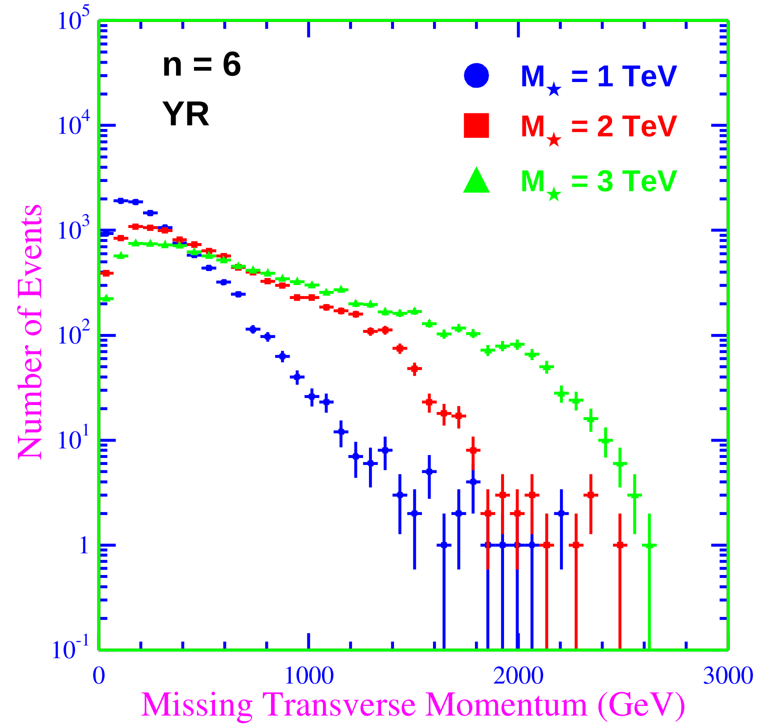
Effects of Fundamental Scale

- Visible energy and missing transverse momentum for n = 6, $n_p = 4$, YR

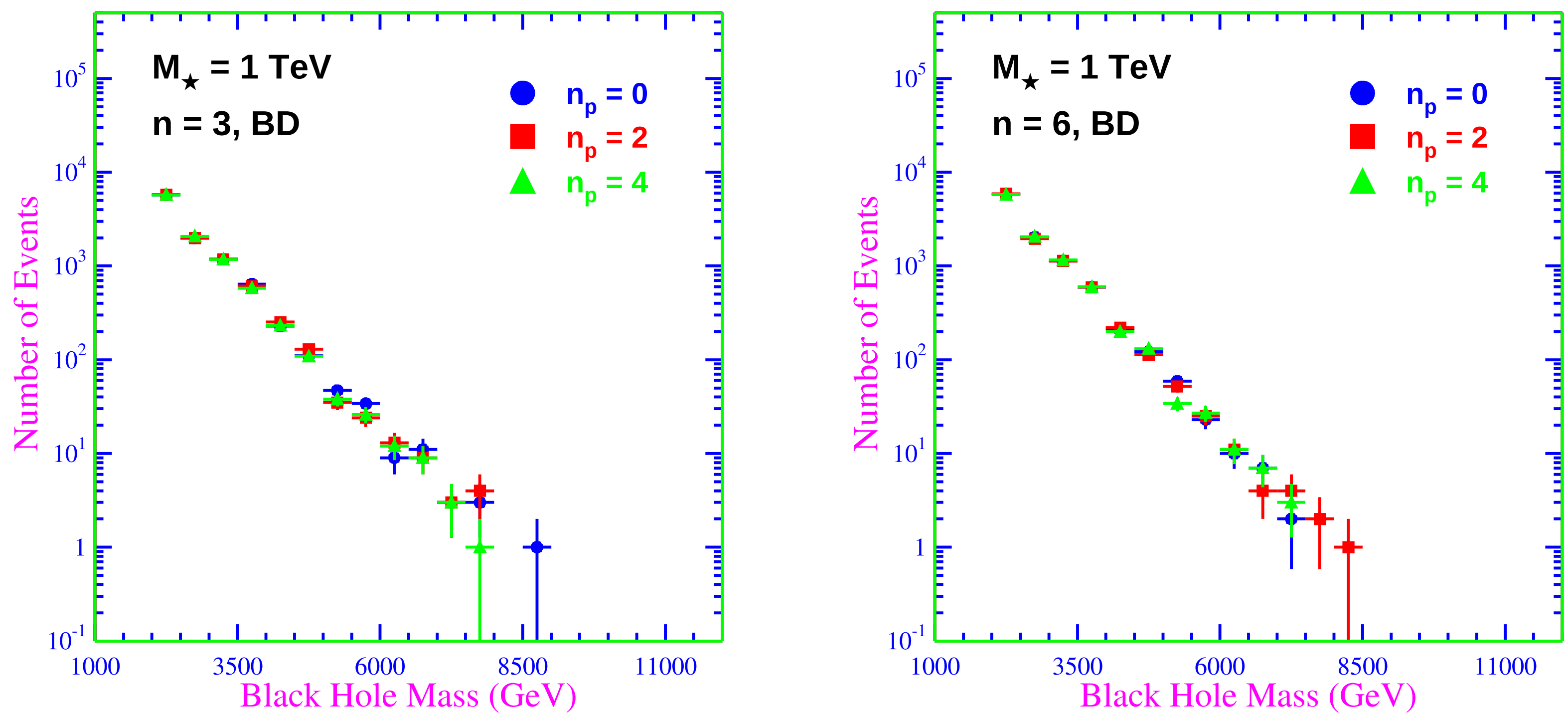




- Increasing $M_\star$ leads to higher M_{min} ($M_{min} = 2M_\star$) :
  - Larger visible energy in Hawking phase
  - Larger missing transverse momentum
- $M_\star$ could be measured to a certain degree of precision at LHC

Effects of Final BH Decay

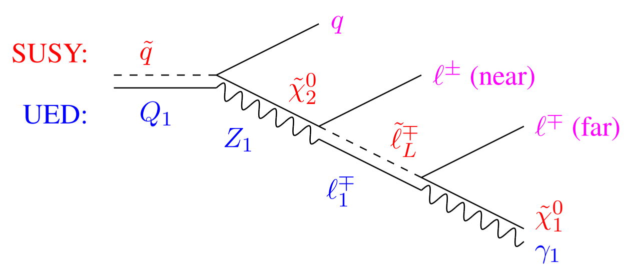
- BH Mass distribution for $M_\star = 1$ TeV, (n =3 or 6), BD



- The initial BH mass is obviously unaffected by the detail of final decay
  - (left) We vary number of quanta at the end of BH decay for $n = 3$
  - (right) We vary number of quanta at the end of BH decay for $n = 6$
- This is a nice consistency check of CATFISH generator

BH Vs SUSY

- **How do we distinguish between SUSY and BH events?**
- **SUSY and Universal Extra Dimensions (UED) has twin diagrams**



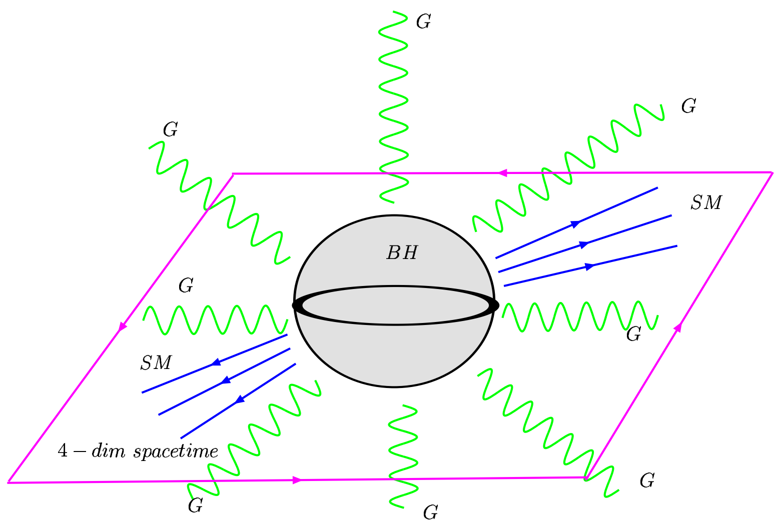
- **SUSY:** $\tilde{q} \to q\tilde{\chi}_2^0 \to q\ell^\pm\tilde{\ell}_L^\mp \to q\ell^+\ell^-\tilde{\chi}_1^0$
- **UED:** $Q_1 \to qZ_1 \to q\ell^\pm\ell_1^\mp \to q\ell^+\ell^-\gamma_1$
- **Both modes produce SM particles:** $q\ell^+\ell^-\not{E}_T$ **(KEY)**
- **SUSY: slepton is a scalar particle → no spin correlation between SM leptons**
- **UED: slepton is replaced by a KK lepton → it is a fermion**
- **Expected a different shape in the dilepton invariant mass distribution**

Hawking's Evaporation

☐ **The Black Holes emits into two modes :**

1. **Along the brane (brane mode (4D)): Standard Model fields**
2. **Into the extra dimensions (bulk mode (n)): Gravitons (invisible)**

☐ **Hawking radiation**



☐ **BH events are more spherical than SUSY**

due to the isotropic nature of the BH decays

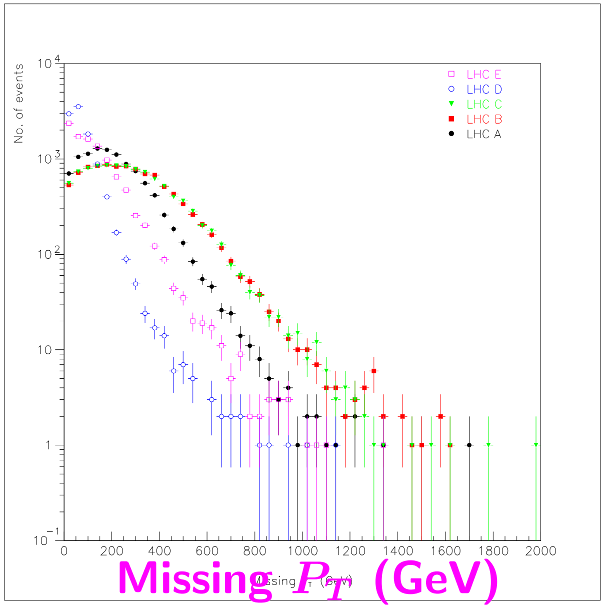
mSUGRA Parameters

mSUGRA scalar and gaugino masses are in GeV

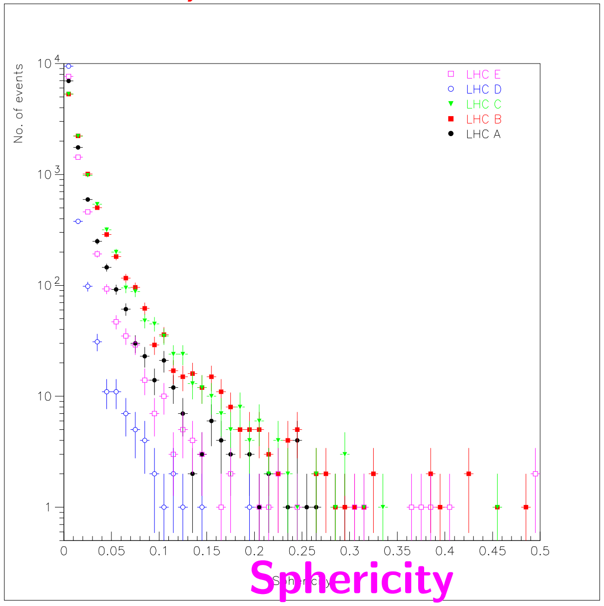
Type	m_0	$m_{1/2}$	A_0	$tan\beta$	μ
A	100	300	300	2.1	+
B	400	400	0	2.0	+
C	400	400	0	10.0	+
D	200	100	0	2.0	-
E	800	200	0	10.0	+

- ☐ No significant difference between SUSY type

  (A. Roy & M. Cavaglia, PRD 77, 064029, 2008)



Missing P_T (GeV)



Sphericity

- ☐ Any type [A-E] can be used as SUSY benchmark

SUSY OSSF Dilepton

- The Opposite-sign, Same-Flavor (OSSF) dilepton is a dominant MSSM interaction in SUSY (PYTHIA and ISAJET)

$$\tilde{\chi}^0_2 \rightarrow l^{\pm} \quad \tilde{l}$$
$$\rightarrow \quad l^{\mp} \; \tilde{\chi}^0_1$$

- The maximum dilepton invariant mass (On-shell point):

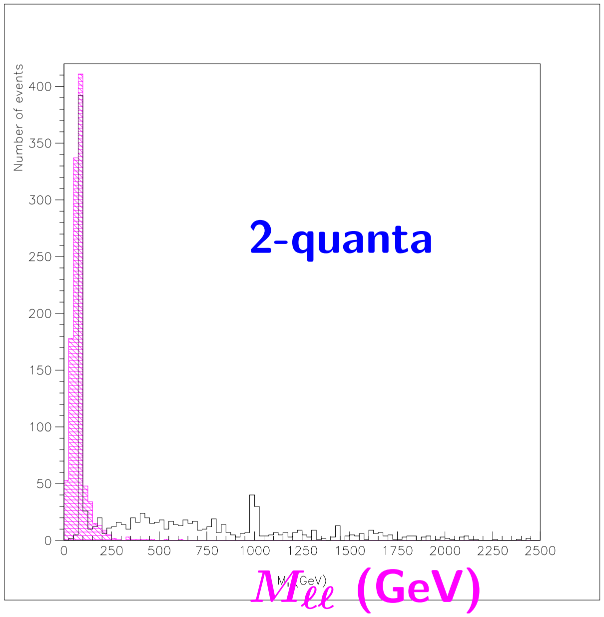
$$M_{ll}^{max} = m_{\tilde{\chi}^0_2} \sqrt{\left(1 - \frac{m^2_{\tilde{l}}}{m^2_{\tilde{\chi}^0_2}}\right)\left(1 - \frac{m^2_{\tilde{\chi}^0_1}}{m^2_{\tilde{l}}}\right)} \sim 90 \text{ GeV}$$

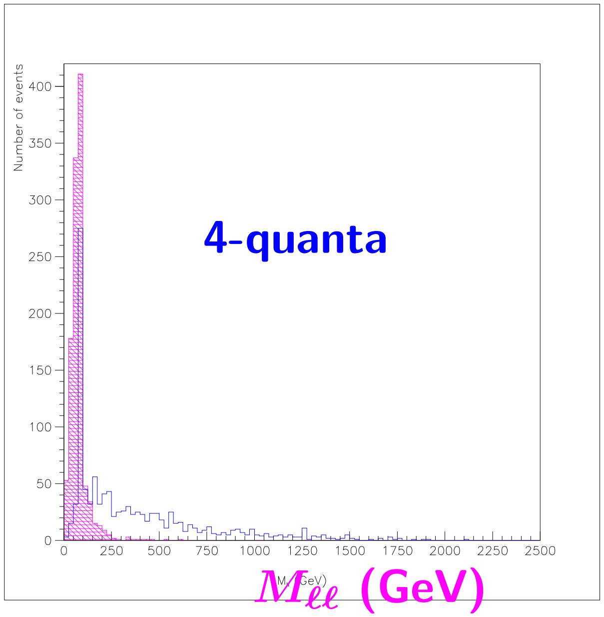
- The dominant SM backgrounds:
  - W + jets
  - Z + jets
  - $t\bar{t}$ + jets
  - diboson
  - dijets

BH OSSF Dilepton

- Sources of isolated leptons in BH decays (CATFISH)
  - BH decays (most decays)
  - Z boson (small BR $\sim$ 0.034)
  - $t\bar{t}$ decays (rare)
  - Z and $t\bar{t}$ combination (small)

- BH (line) and SUSY (shaded) of dilepton invariant mass (2 or 4-quanta)

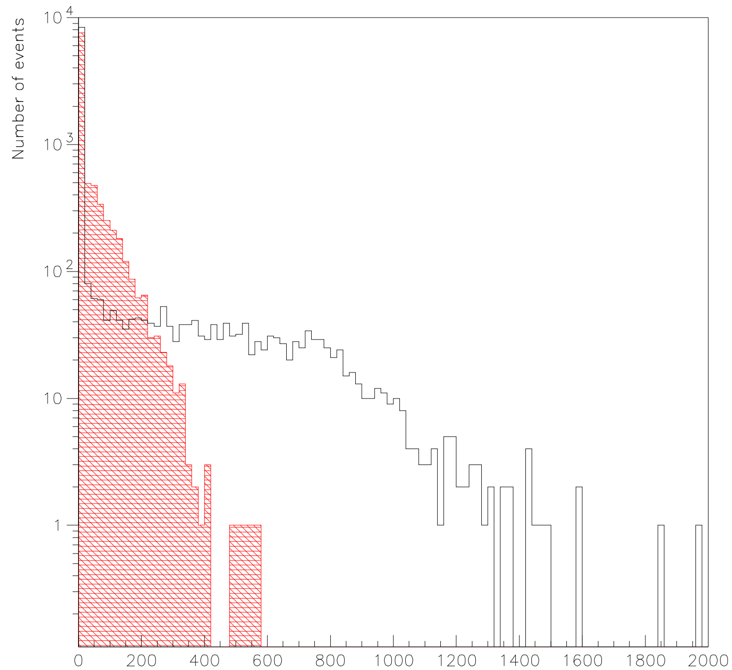




- BH peak ~ 90 GeV is due to $Z \longrightarrow$ dilepton
- BH 2-quanta peak ~ 1 TeV is due to final Hawking phase
- BH long tail is due to $t\bar{t}$ (rare) and mostly BH decays

BH Vs SUSY

- High P_T dilepton distribution can be used to disentangle between SUSY (shaded) and BH (solid) events



P_T of Isolated Leptons

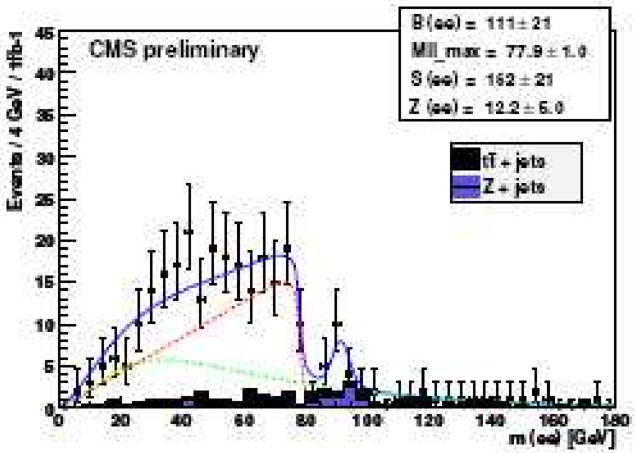
- SUSY variables: $m_0 = 100$, $m_{1/2} = 300$, $A_0 = 300$, $tan\beta = 2.1$, $\mu = +$

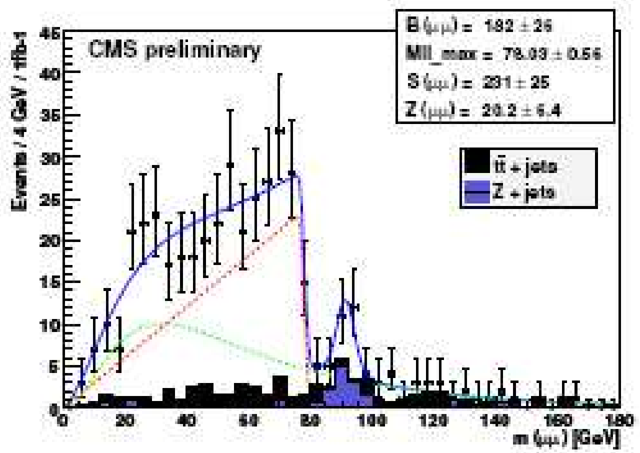
- The ratio of BH-to-SUSY of P_T dilepton is 1:5

- P_T (dilepton) > 600 GeV reduces the SUSY background substantially

CMS SUSY LM1 Dilepton, 14 TeV CM

- **LM1:** $m_0 = 60$ GeV$/c^2$, $m_{1/2} = 250$ GeV$/c^2$, $A_0 = 0$, $tan\beta = 10.0$, $\mu = +$





- **Signal (red), flavor-symmetric bkg, Z-peak bkg: Sample: 1 fb^{-1}**

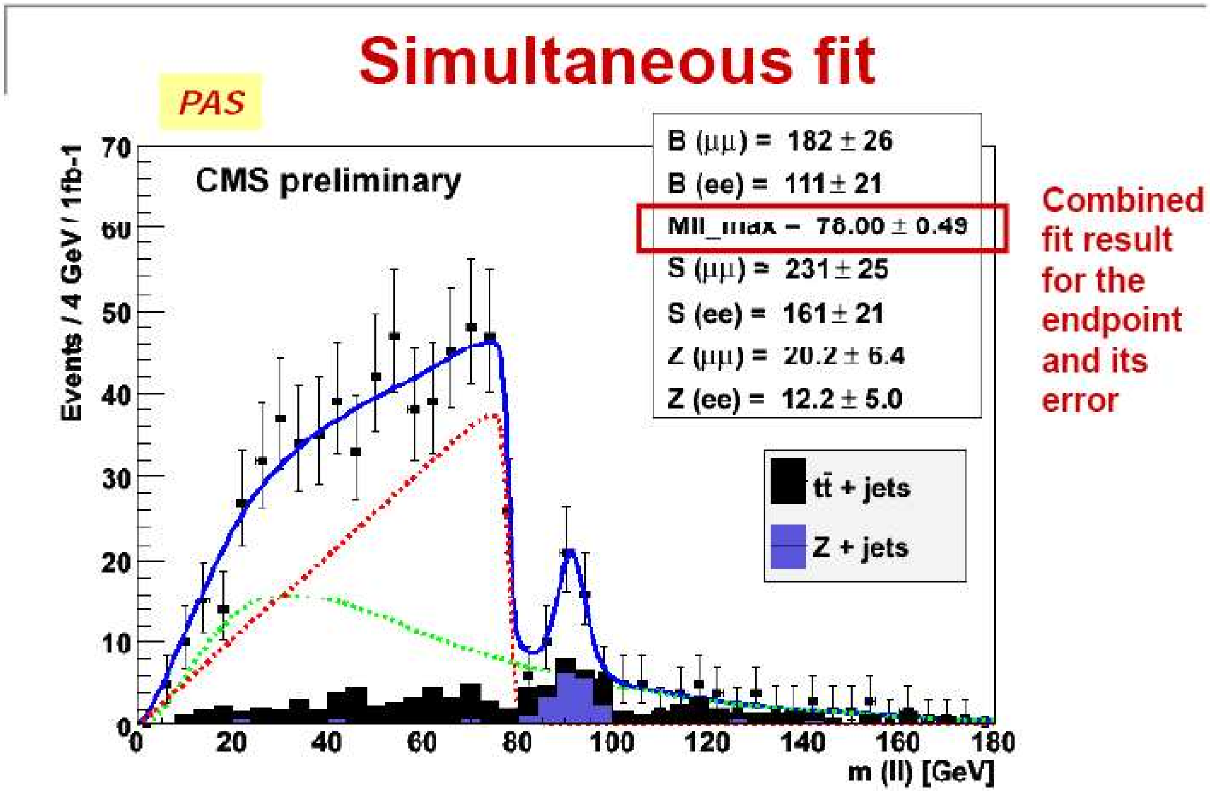
- $m_{\ell\ell}$ **distributions: dielectron (left) and dimuon (right)**
  - **At least two Opposite-sign, Same-Flavor:** $P_T^\ell > 10$ GeV, $|\eta^\ell| < 2.4$
  - **At least three jets:** $E_T^{jet} > 30$ GeV, $|\eta^{jet}| < 3$
  - **Missing Energy Transverse:** $M_T^{miss} > 200$ GeV

- **CMS MC result: (theoretical value = 78.15 GeV$/c^2$)**

$$M_{ee}^{max} = 77.90 \pm 1.0_{stat} \text{ GeV}/c^2 \qquad M_{\mu\mu}^{max} = 78.03 \pm 0.56_{stat} \text{ GeV}/c^2$$

CMS SUSY LM1 Dilepton, 14 TeV CM

- LM1: $m_0 = 60$ GeV/c^2, $m_{1/2} = 250$ GeV/c^2, $A_0 = 0$, $tan\beta = 10.0$, $\mu = +$



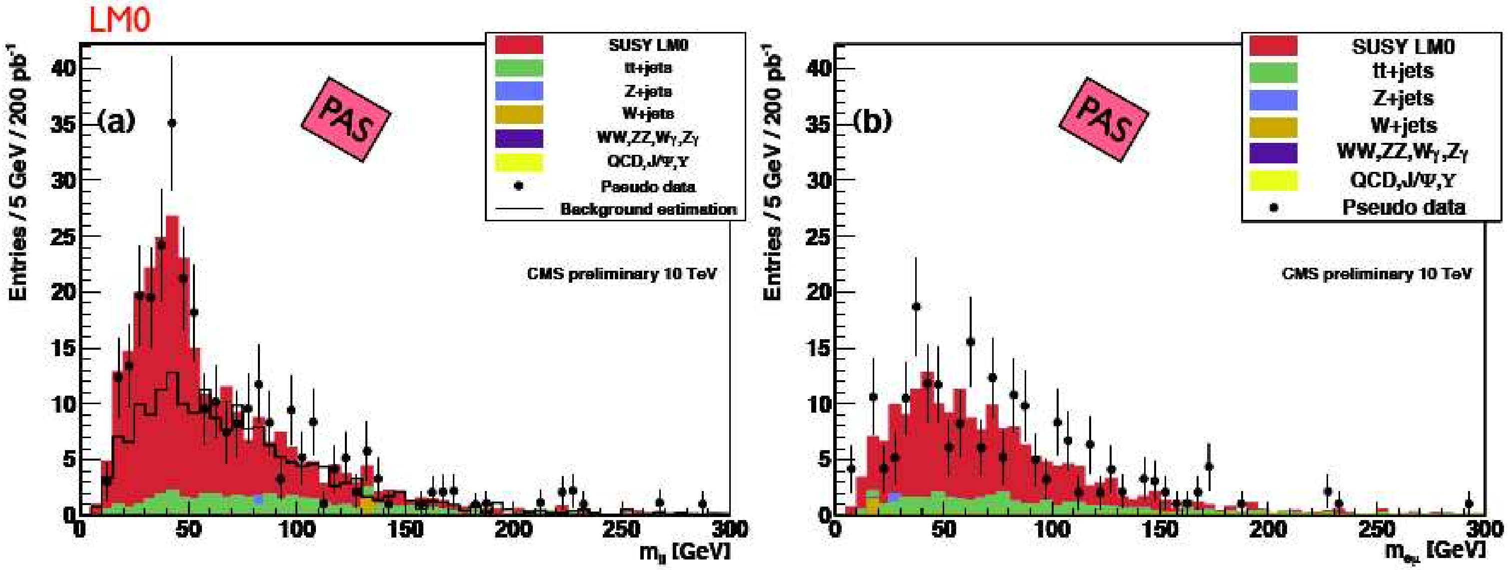
- FIT RESULTS : combined endpoint + # expected events:
  - S : signal, B : flavor-symmetric background, Z : susy+SM Z peak.

- Simultaneous fit of $m_{\ell\ell}$ distributions :

$$M_{\ell\ell}^{max} = 78.00 \pm 0.49_{stat} \pm 0.62_{syst} \text{ GeV}/c^2$$

CMS SUSY LMO Dilepton, 10 TeV CM

- **LMO:** $m_0 = 200$, $m_{1/2} = 160$, $A_0 = 400$ GeV/c^2, $tan\beta = 10$, $\mu = +$



- **CMS MC result:** 200 pb^{-1} with 10 TeV Center of Mass Energy

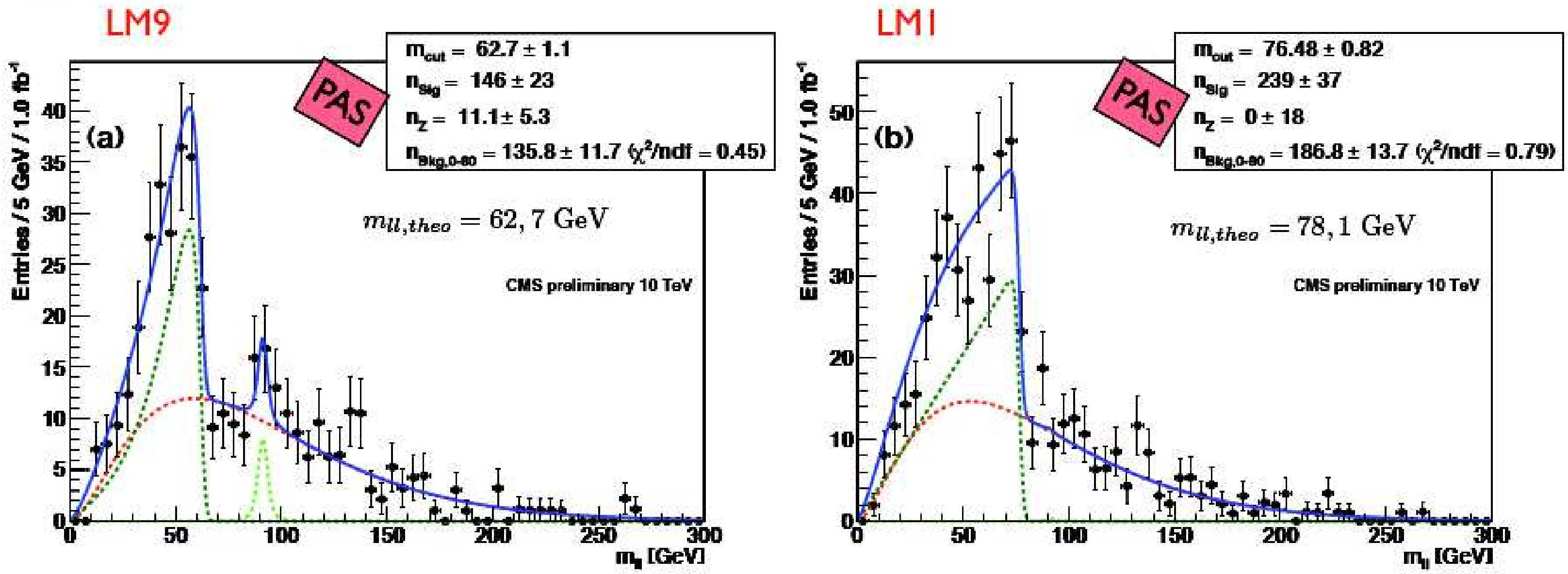
- $m_{\ell\ell}$ **distributions:** dilepton (left) and electron-muon (right)

- **CMS MC result:** (theoretical value = 52.7 GeV/c^2)

$$M_{\ell\ell}^{max} = 51.3 \pm 1.5_{stat} \pm 0.9_{syst} \text{ GeV}/c^2$$

CMS SUSY LM1 and LM9, 10 TeV CM

- **LM1:** $m_0 = 60$ GeV$/c^2$, $m_{1/2} = 250$ GeV$/c^2$, $A_0 = 0$, $tan\beta = 10$, $\mu = +$
- **LM9:** $m_0 = 1450$ GeV$/c^2$, $m_{1/2} = 175$ GeV$/c^2$, $A_0 = 0$, $tan\beta = 50$, $\mu = +$



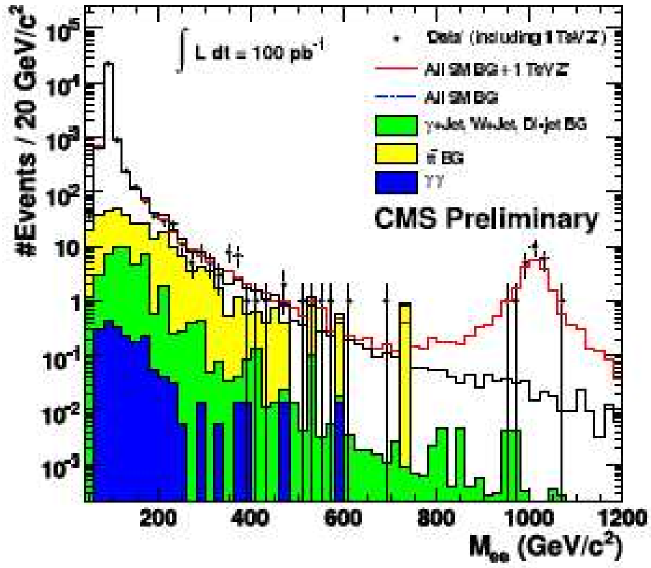
$m_{ll,max} = (62.8 \pm 1.4_{stat.} \pm 0.8_{syst.})$ GeV $\qquad$ $m_{ll,max} = (77.3 \pm 0.9_{stat.} \pm 0.9_{syst.})$ GeV

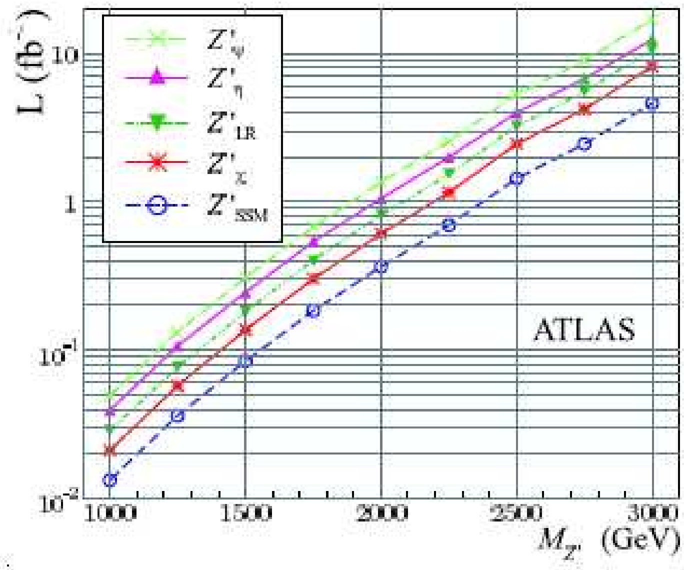
- **CMS MC results:** $1\ fb^{-1}$ with 10 TeV Center of Mass Energy

LM9: $M_{\ell\ell}^{max} = 62.8 \pm 1.4_{stat} \pm 0.8_{syst}$ GeV$/c^2$

ML1: $M_{\ell\ell}^{max} = 77.3 \pm 0.9_{stat.} \pm 0.9_{syst}$ GeV$/c^2$

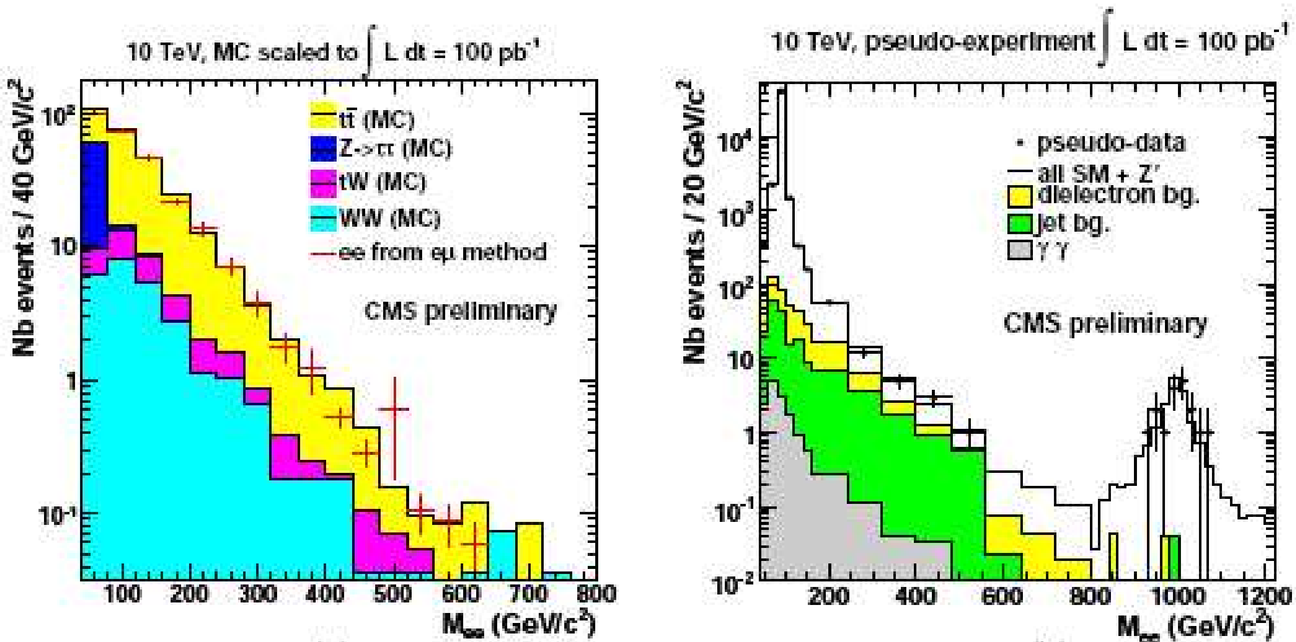
Other BSM Background, 14 TeV CM





- ☐ **CMS:** (left) $Z' \rightarrow e^+e^-$ @ 1 TeV/c^2 (5σ discovery), σ = 30 GeV/c^2
  - MC sample: 100 pb^{-1} with 14 TeV Center of Mass Energy
  - SM bkg (blue-dash): Drell-Yan process, $t\bar{t}$, W+jet, dijets, γ+jet, and $\gamma\gamma$
- ☐ **ATLAS:** (right) $Z' \rightarrow e^+e^-$ (5σ discovery) as a function of Z' mass
- ☐ Only statistical uncertainties are included

Other BSM Background, 10 TeV CM



(a) (b)

- **CMS MC sample:** 100 pb^{-1} with $=$ 10 TeV Center of Mass Energy
- Electron selection $E_T^e > 25$ GeV
- Same bkg as 14 TeV: Drell-Yan process, $t\bar{t}$, W+jet, dijets, γ+jet, and $\gamma\gamma$
- (left) Sum of the dielectron backgrounds: $40 < M_{ee} < 800$ GeV/c^2
- (right) $Z' \rightarrow e^+e^-$ @ 1 TeV/c^2 (5σ discovery)

Summary

- CATFISH produces consistent results compared to other BH generators
- CATFISH includes different final BH decays and remnant formation
- Missing momentum transverse is a good tool to discriminate between BH and BSM including SUSY
- The Opposite-sign, Same-Flavor (OSSF) dilepton provides a powerful discriminator between BH and BSM
- We understand the BH backgrounds including BSM events

Expected new result on BH using dilepton channel $\longrightarrow$ Stay tune!