# Highlights from the Search for New Physics

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# Non-Comprehensive / Incomplete Survey

# of the Search for New Physics

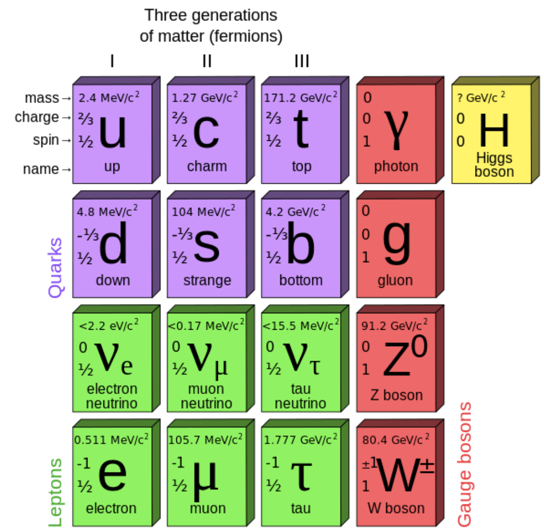
# Minimal Renormalizable Standard Model

Predictive

Incredibly Successful !!

Sectors:

Gauge
Yukawa
Higgs



# Minimal Renormalizable Standard Model

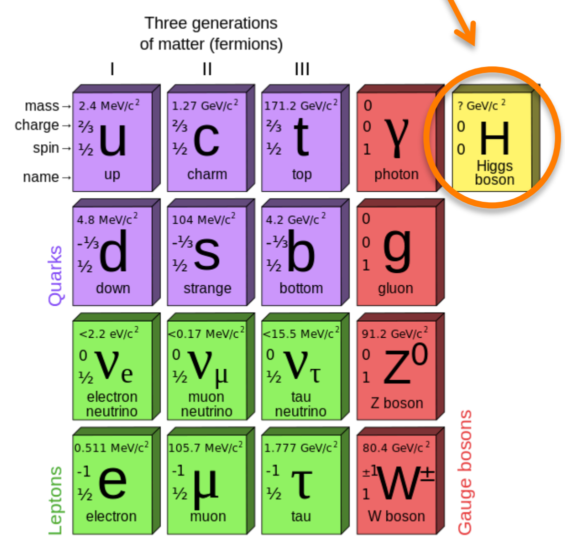
Success !!

Predictive

Incredibly Successful !!

Sectors:

- Gauge
- Yukawa
- Higgs



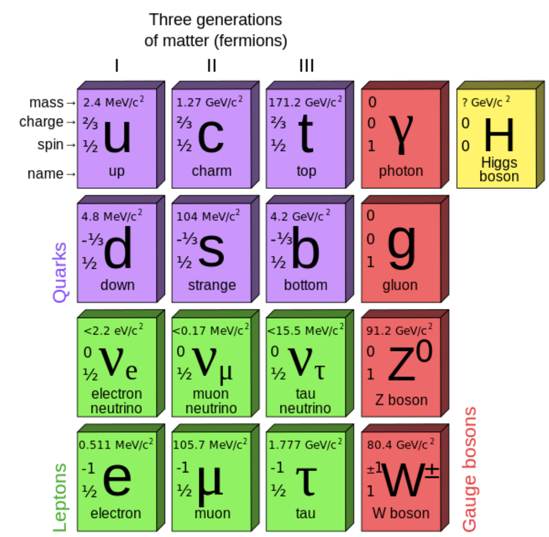
# Minimal Renormalizable Standard Model

Predictive

Incredibly Successful !!

Supplement by Non-Renormalizable Interactions

Gravity
Neutrino Mass Operators



# Search for New Physics at the Electroweak Scale

. Physics of ElectroWeak
Symmetry Breaking

. Quantum Space-Time Dimensions
(Super-Space)
. Identity of Dark Matter
. New Flavor Changing Interactions +
Origin of Flavor
. New Symmetries
. New Forces
. Origin of Cosmic Baryon Asymmetry
. Dark Hidden Sectors
…

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# Indirect Indications for Possible New Physics at the Electroweak Scale

Experimentally:

. Dark Matter
(ElectroWeak Scale WIMP)

. Super-Space
(Gauge Coupling Unification,
Top IR Quasi-Fixed Point, … )

. Experimental Anomalies …
(Easy to Find – Hard to Make Go Away)

Accompanying Theoretical Framework,
Connections …

# <u>Indirect</u> Indications for <u>Possible</u> New Physics at the Electroweak Scale

Theoretically:

. Quantum Stability of
ElectroWeak Scale
( EW Hierarchy Problem
LQFT- c.f. Vacuum Energy Problem )

Renormalizable Standard Model
Effective Theory – Breaks Down
"Just" Above the Electroweak Scale

New Interactions/States
Waiting to be Discovered "Just"
Above the Electroweak Scale

# <u>Indirect</u> Indications for <u>Possible</u> New Physics at the Electroweak Scale

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Doctrine of Naturalness

# <u>Indirect</u> Indications for <u>Possible</u> New Physics at the Electroweak Scale

Theoretically:

. Quantum Stability of
ElectroWeak Scale
( EW Hierarchy Problem
LQFT- c.f. Vacuum Energy Problem )

Doctrine of Naturalness

- Modify/Replace Doctrine …
  Multiverse Selection, ~~LQFT~~, …
- Retreat from "Just" Above
  ElectroWeak Scale
- Attempts to Re-evaluate Stability
  (within LQFT mis-guided)

# Indirect Indications for Possible New Physics at the Electroweak Scale

So Far:

. No Definitive Evidence for New States

. No Definitive Evidence for New Interactions
( Beyond Gravity + Neutrino Mass Op )

( Victims of Success of Minimal Standard Model )

# <u>Indirect</u> Indications for <u>Possible</u> New Physics at the Electroweak Scale

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( Victims of Success of
Minimal Standard Model )

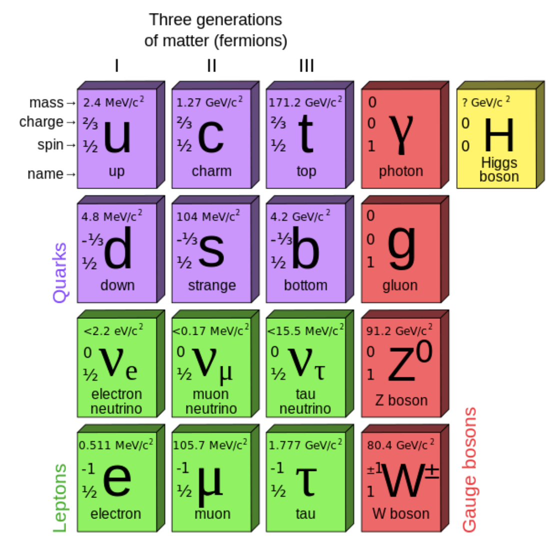
Strategy:


Search
Everywhere !!

# Search for New Physics at the Electroweak Scale

Approaches:

| | New Interactions | New States |
|---|---|---|
| Energy | ✓ | ✓ |
| Precision | ✓ | |
| Intensity | ✓ | ✓ |
| Cosmic | ✓ | ✓ |




+

New Interactions

New States

# Search for New Physics at the Electroweak Scale

Approaches:

| | New Interactions * | New States |
|---|---|---|
| Energy | ✓ | ✓ |
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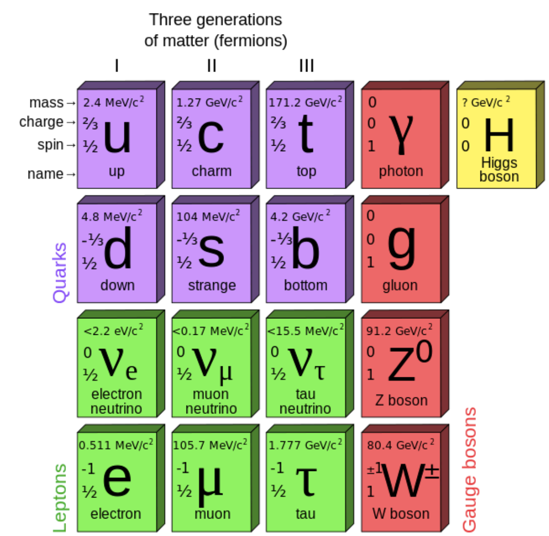
This Talk - Selected Topics

* New Flavor + CP Violating Interactions: See talks by Kagan + Artuso




\+

New Interactions

New States

# Search for New Interactions at the Electroweak Scale

Muon g-2 :

Chirality Violating Interaction –
Probes Interaction with Higgs Sector

Three Experimental Probes of Muon Interaction with Higgs Sector
(Unique Among SM Particles for Foreseeable Future)

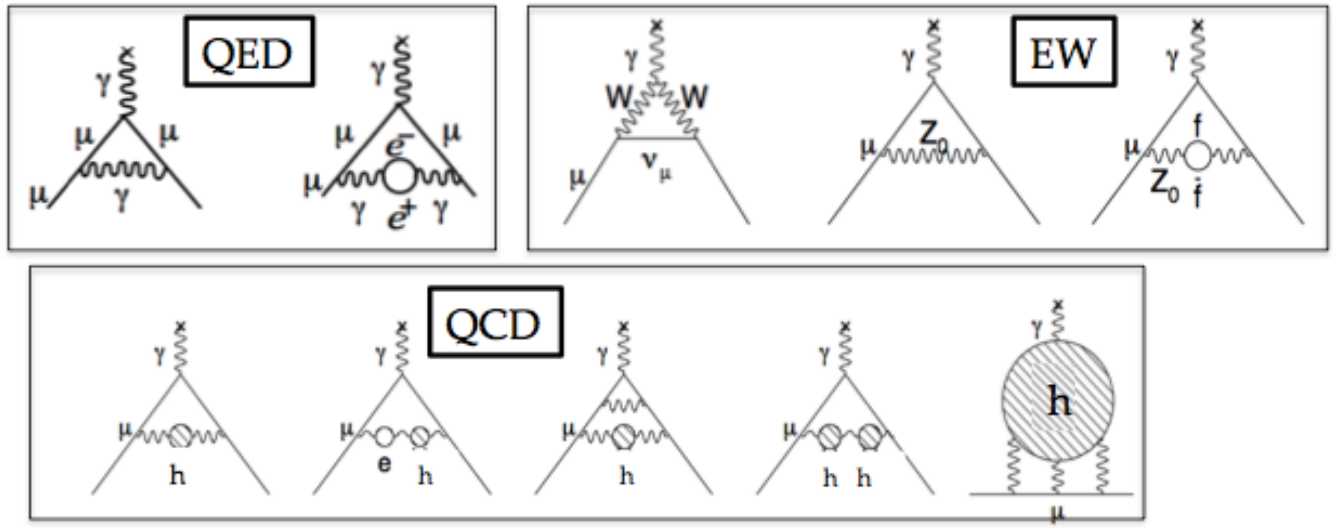
1. Muon Mass
2. Higgs -> $\mu$ $\mu$
3. Muon g-2

$$a_\mu^{Expt.} - a_\mu^{SM} = (260 \pm 78) \times 10^{-11} \quad (3.3\,\sigma)$$

Talks by Kiburg, Porter, Fukushima

# Search for New Interactions at the Electroweak Scale

Muon g-2 :




| Contribution | Result ($\times 10^{11}$) | | Error |
|---|---|---|---|
| QED (leptons) | 116 584 718 $\pm$ 0.14 | $\pm$ 0.04$_\alpha$ | 0.00 ppm |
| HVP(lo) [1] | 6 923 $\pm$ 42 | | 0.36 ppm |
| HVP(ho) | -98 $\pm$ 0.9$_{\text{exp}}$ | $\pm$ 0.3$_{\text{rad}}$ | 0.01 ppm |
| HLbL [2] | 105 $\pm$ 26 | | 0.22 ppm |
| EW | 154 $\pm$ 2 | $\pm$ 1 | 0.02 ppm |
| Total SM | 116 591 802 $\pm$ 49 | | 0.42 ppm |

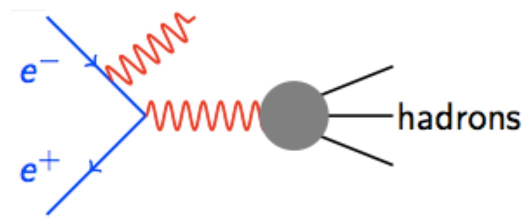
Program Requires

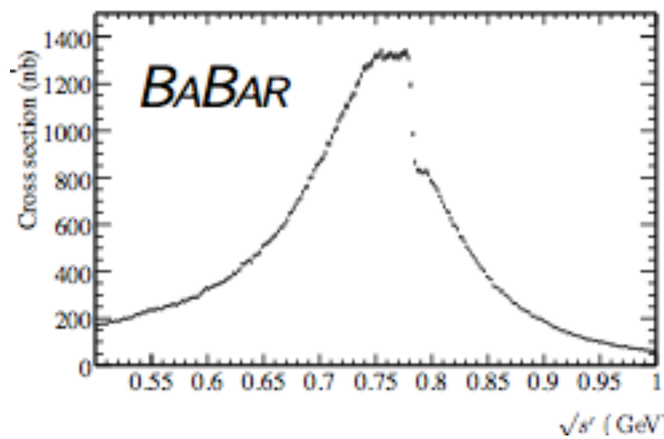
- g-2 Measurement
- $R_{had}$ Measurement
- Lattice hadronic $\gamma\gamma\gamma\gamma$ Interaction

# Search for New Interactions at the Electroweak Scale

Muon g-2 :

$R_{had}$ from Babar




$$a_\mu^{Expt.} - a_\mu^{SM} = (260 \pm 78) \times 10^{-11} \quad (3.3\ \sigma)$$

- New E989 experiment will reduce experimental uncertainty by a factor of 4 to $16 \times 10^{-11}$ (0.14 ppm)
- If current discrepancy remains this would yield $>5\sigma$
- Together with theory improvements could give $>8\sigma$

# Search for New Interactions at the Electroweak Scale

Pion Charged Current Decay:

$$R^{SM}_{e/\mu} = \frac{\Gamma(\pi \rightarrow e\nu + \pi \rightarrow e\nu\gamma)}{\Gamma(\pi \rightarrow \mu\nu + \pi \rightarrow \mu\nu\gamma)} = 1.2352(1)\,x\,10^{-4} \quad \sim (m_e / m_\mu)^2$$

Chirality Violating Interaction –
Probes Interaction with Higgs Sector

TRIUMF PIENU: aims at <0.1% in BR measurement

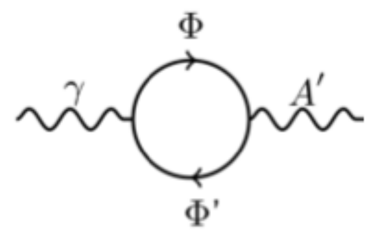
Talk by Sher

# Search for New Dark Hidden Sectors Below the Electroweak Scale

Dark Hidden Sector:

$m_D \sim O(\alpha_D / 4\pi)\ m_W$

Dark Gauge Boson <- Mix -> Photon

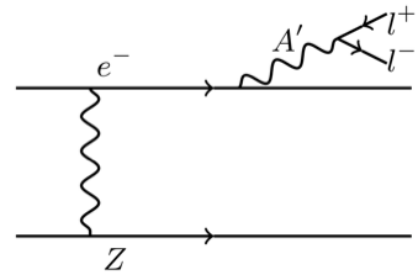


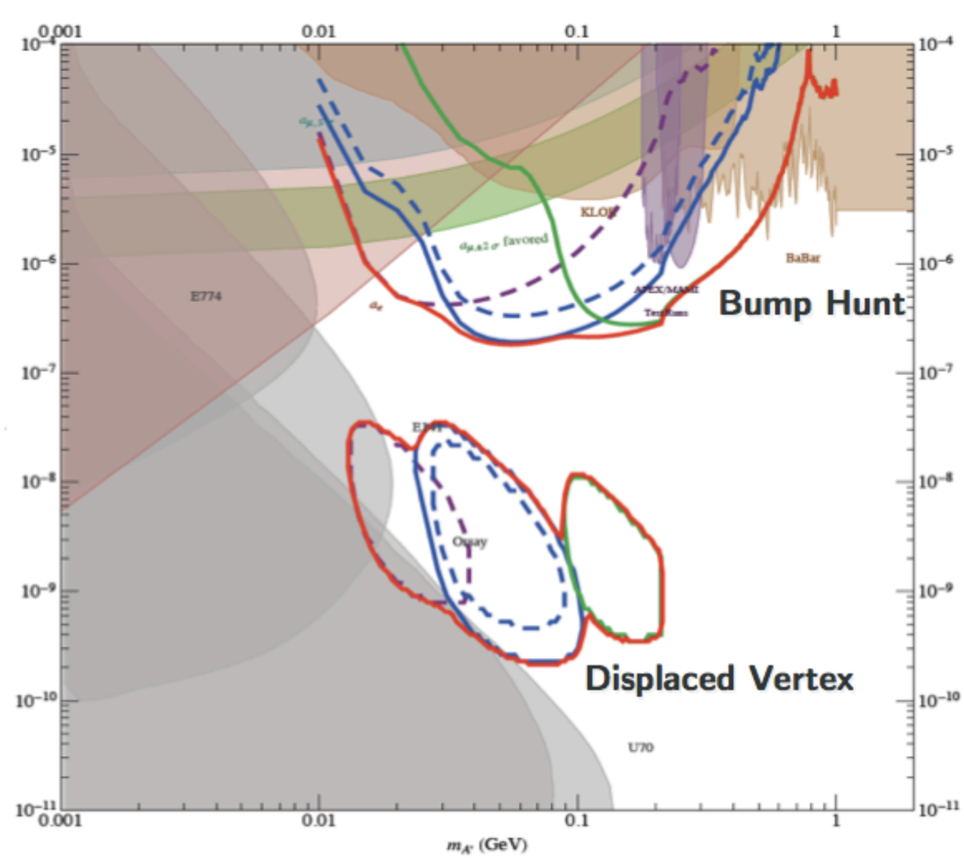

Talks by Moreno, Echenard

# Search for New Dark Hidden Sectors Below the Electroweak Scale

Dark Hidden Sector:

HPS Jefferson Lab



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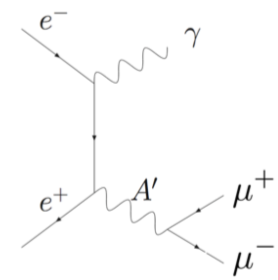
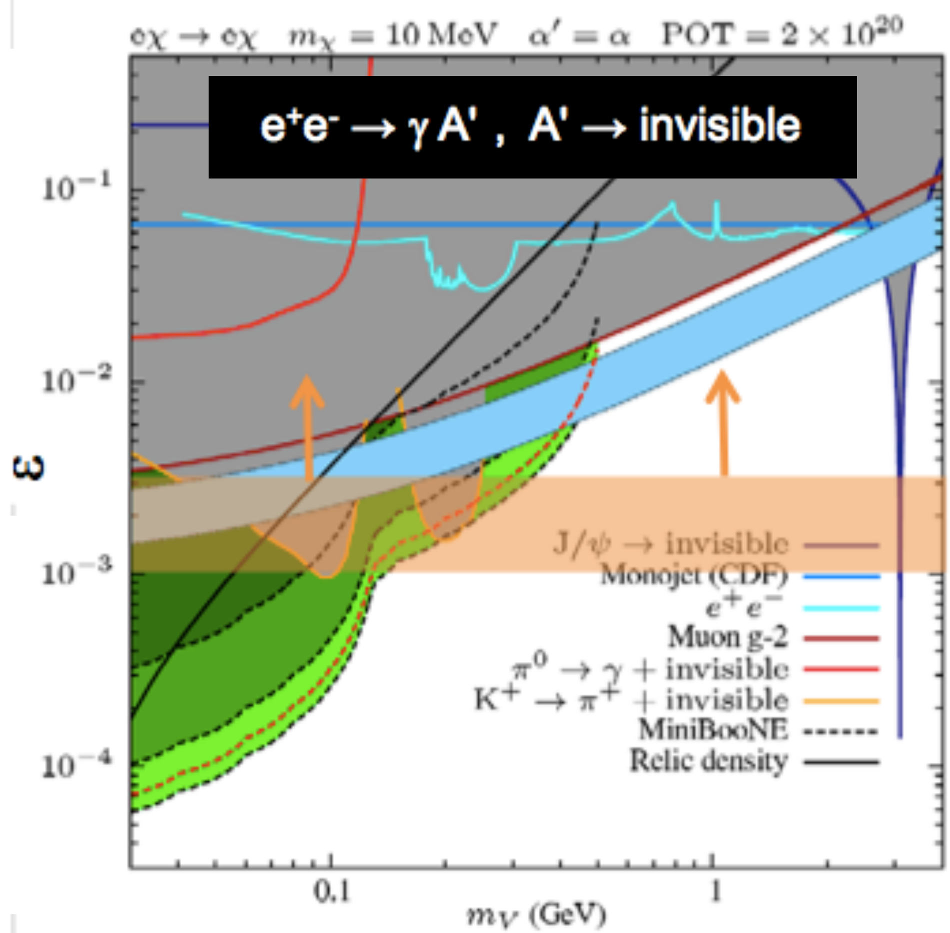
Dark Hidden Sector:




BaBar



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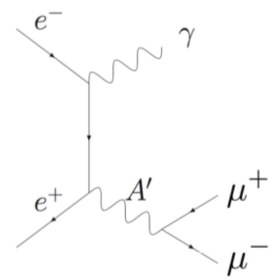
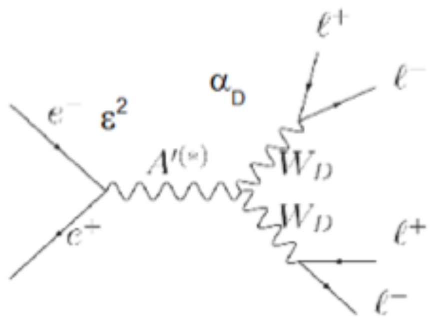
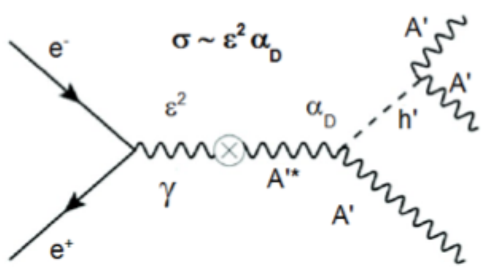



Dark Hidden Sector:

BaBar



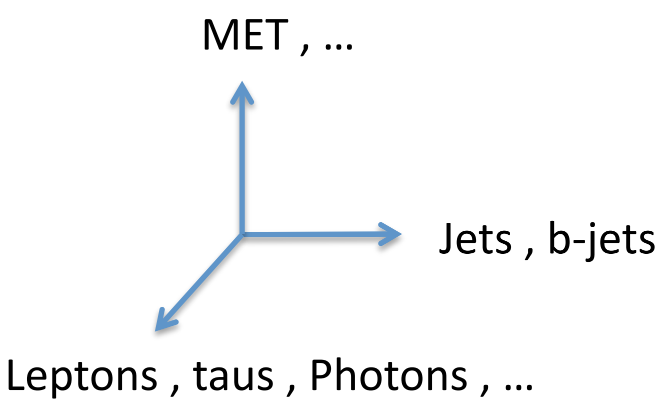
# Search for New States at the Electroweak Scale

Direct Production of New States :

High Energy Hadron Colliders

# Search for New States at the Electroweak Scale

Signature Space



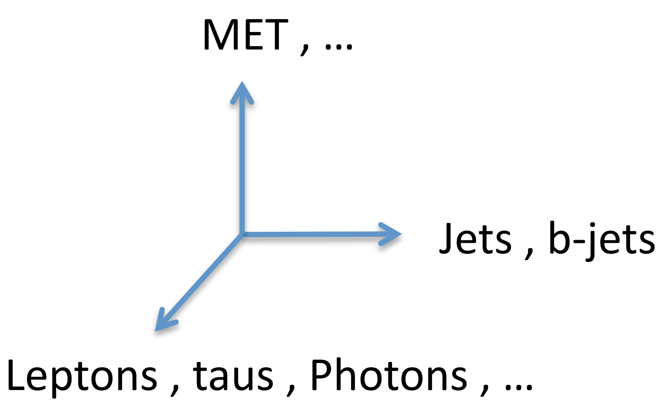

Searches are Built <u>Around</u> SM (+fake) Backgrounds –

Design Searches Away from "Origin" of Signature Space Along Some Axis or Axes

| | σ (fb) 7 TeV |
|---|---|
| W | 100,000,000 |
| Z | 30,000,000 |
| tt | 150,000 |
| WW | 40,000 |
| WZ | 17,000 |
| ZZ | 6,500 |
| h inclusive | 17,900 |
| ttW | 150 |
| ttZ | 100 |
| WWW | 60 |
| ttWW | 2 |
| $\tilde{w}\tilde{w}$ (400 GeV ) | 10 |
| $\tilde{g}\tilde{g}$ (1 TeV) | 10 |

# Search for New States at the Electroweak Scale

## Signature Space




### New States – Decays

. Prompt
. Quasi-Stable
. Stable
  - Interacting
  - Non-Interacting

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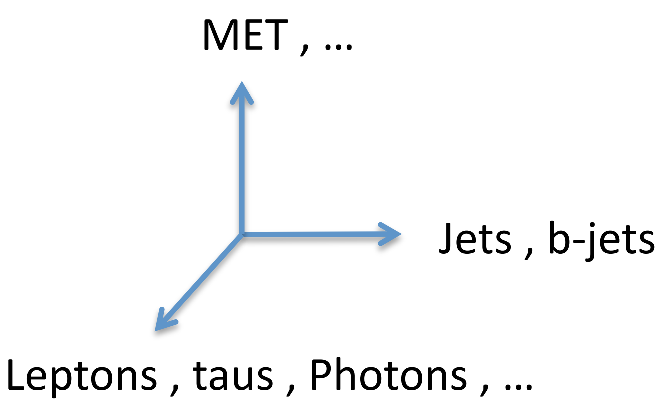


### New States – Decays

This Talk

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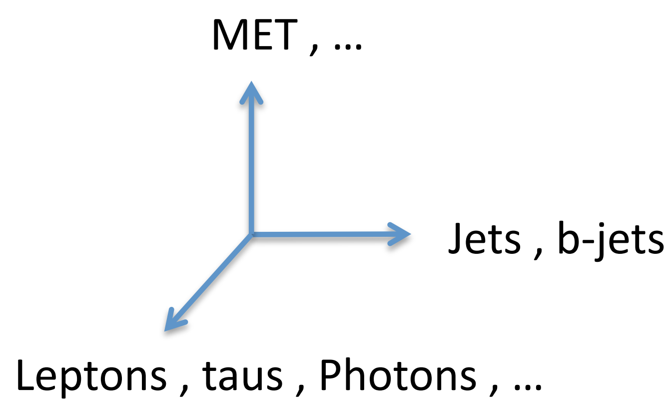


Kinematic Discriminants in Signature Space

- Blunt
- Refined
- Focused

| | $\sigma$ (fb) 7 TeV |
|---|---|
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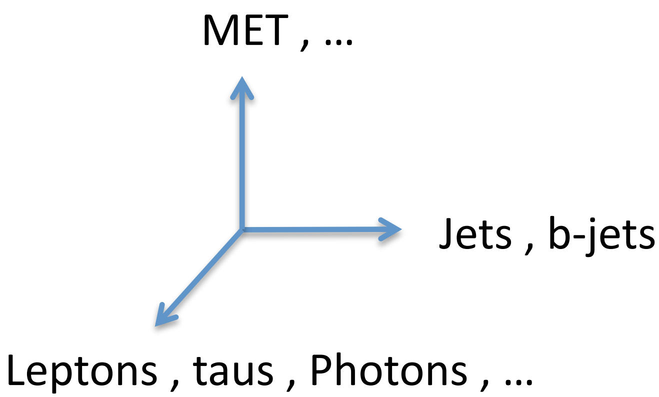
# Search for New States at the Electroweak Scale

## Signature Space



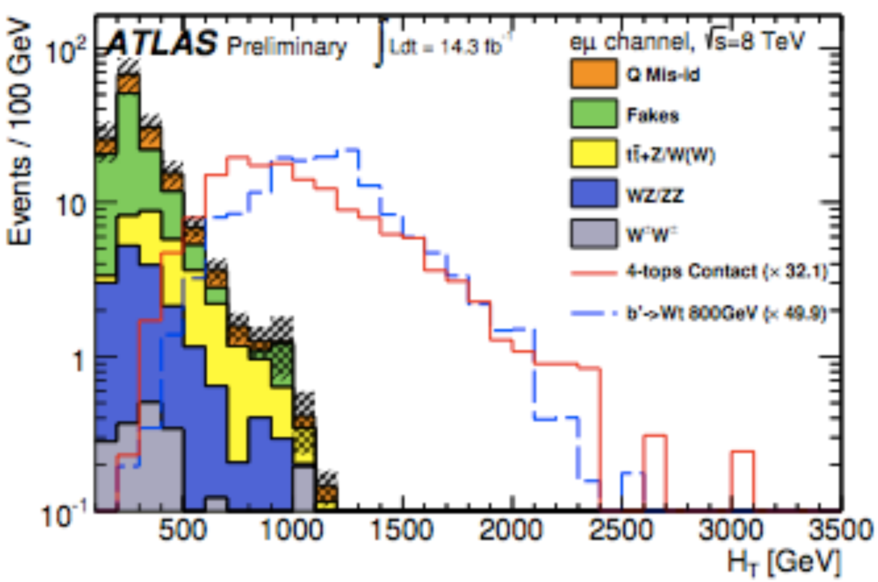

Kinematic Discriminants in
Signature Space

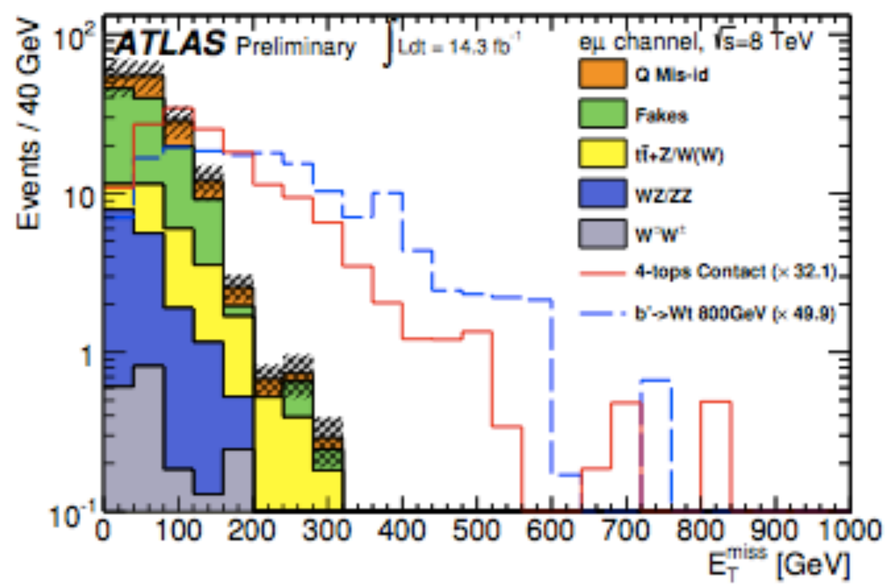
. Blunt — Signature Space Well Covered
. Refined — Parts of Signature Space Pretty Well Covered
. Focused — Isolated Regions of Signature Space Covered

# Search for New States at the Electroweak Scale

Blunt

Same Sign Di-Leptons + b-jets + MET : ATLAS




Talk by Lei

# Search for New States at the Electroweak Scale

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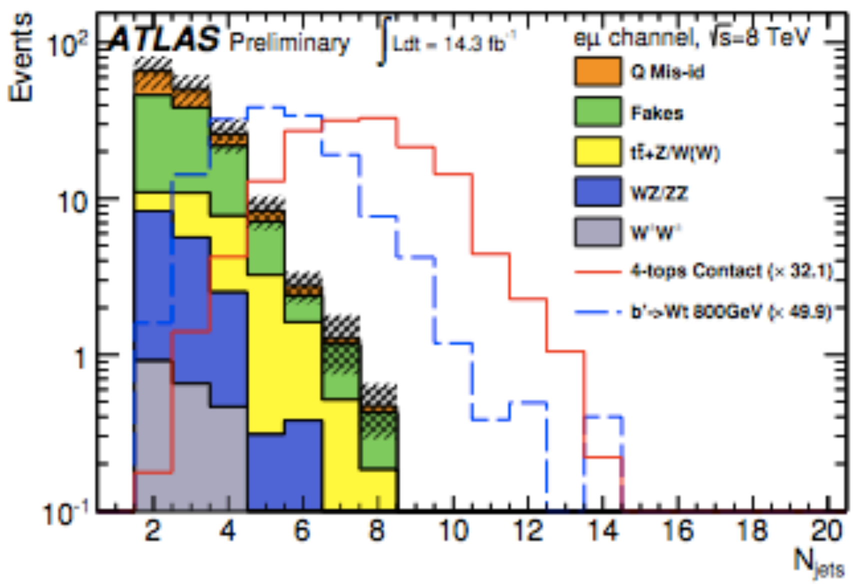
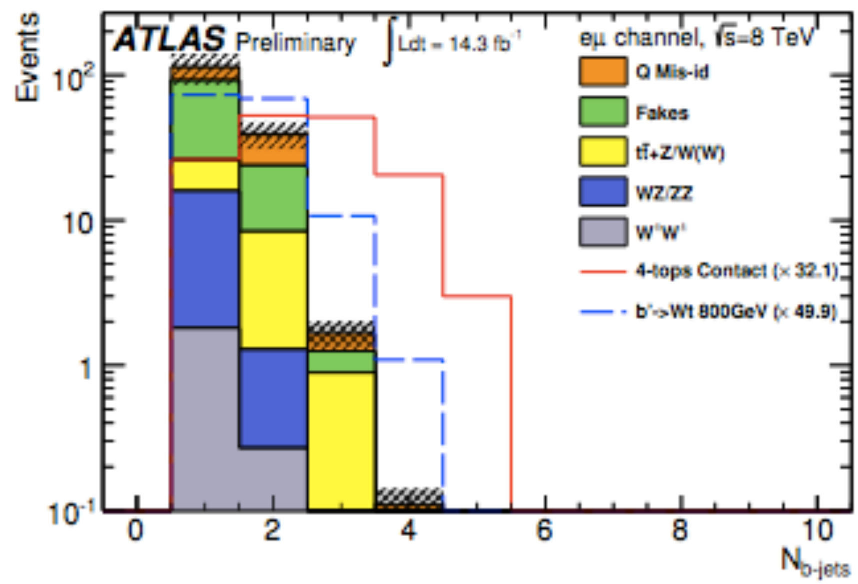



Talk by Lei

# Search for New States at the Electroweak Scale

Blunt +

Multi-Leptons: ATLAS

O(100) Channels

| Variable | Meaning |
|---|---|
| $H_T$ | $\Sigma p_T$ of all jets in the event |
| $m_T^W$ | Transverse mass of $W$-boson candidate (on-$Z$ events only) |

| Variable | Meaning | Lower Bounds [GeV] | | | | Additional Requirements |
|---|---|---|---|---|---|---|
| $H_T^{\text{leptons}}$ | $\Sigma p_T$ of leading three leptons | 0 | 200 | 500 | 800 | |
| Min. $p_T^\ell$ | $p_T$ of softest (third) lepton | 0 | 50 | 100 | 150 | |
| $E_T^{\text{miss}}$ | MET_RefFinal | 0 | 100 | 200 | 300 | $H_T < 150$ GeV |
| $E_T^{\text{miss}}$ | | 0 | 100 | 200 | 300 | $H_T \geq 150$ GeV |
| $m_{\text{eff}}$ | | 0 | 600 | 1000 | 1500 | |
| $m_{\text{eff}}$ | $E_T^{\text{miss}}+H_T+H_T^{\text{leptons}}$ | 0 | 600 | 1200 | | $E_T^{\text{miss}} \geq 100$ GeV |
| $m_{\text{eff}}$ | | 0 | 600 | 1200 | | $m_T^W \geq 100$ GeV, on-$Z$ |

| Variable | Meaning | Lower Bounds | | |
|---|---|---|---|---|
| $b$-tags | Number of $b$-tagged jets | 0 | 1 | 2 |

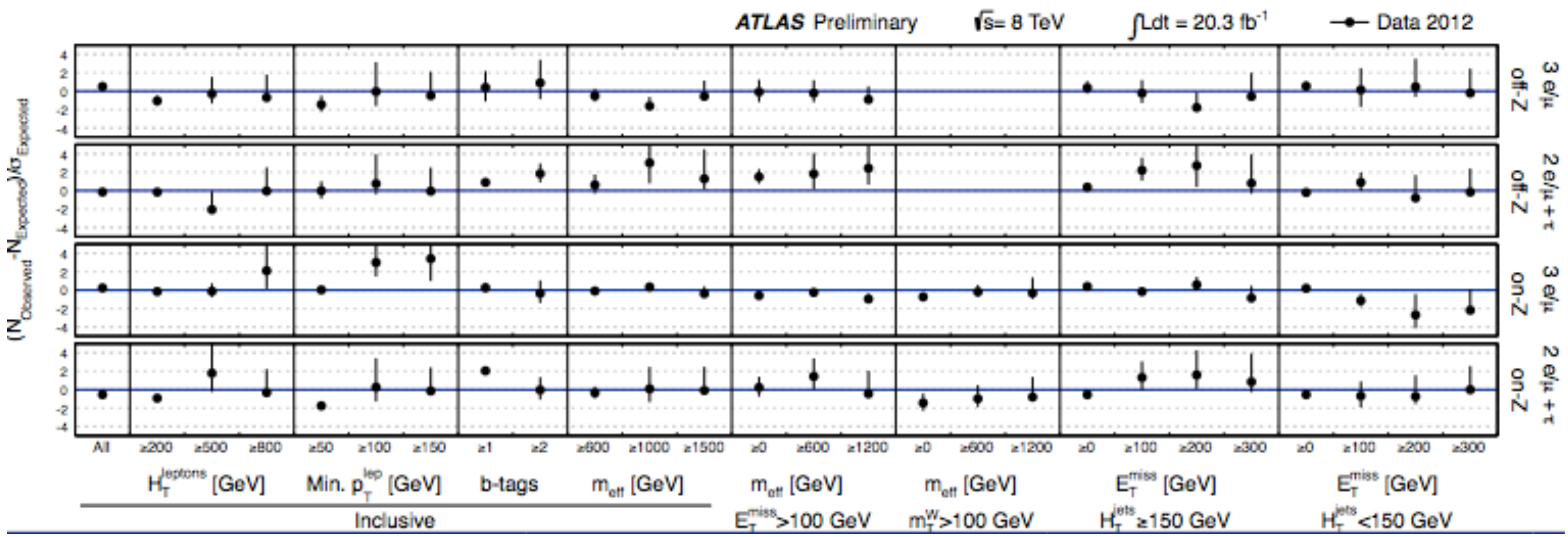
Talk by Hance

# Search for New States at the Electroweak Scale

Blunt +

Multi-Leptons: ATLAS

O(100) Channels




Talk by Hance

# Search for New States at the Electroweak Scale

Blunt +

Multi-Leptons: ATLAS

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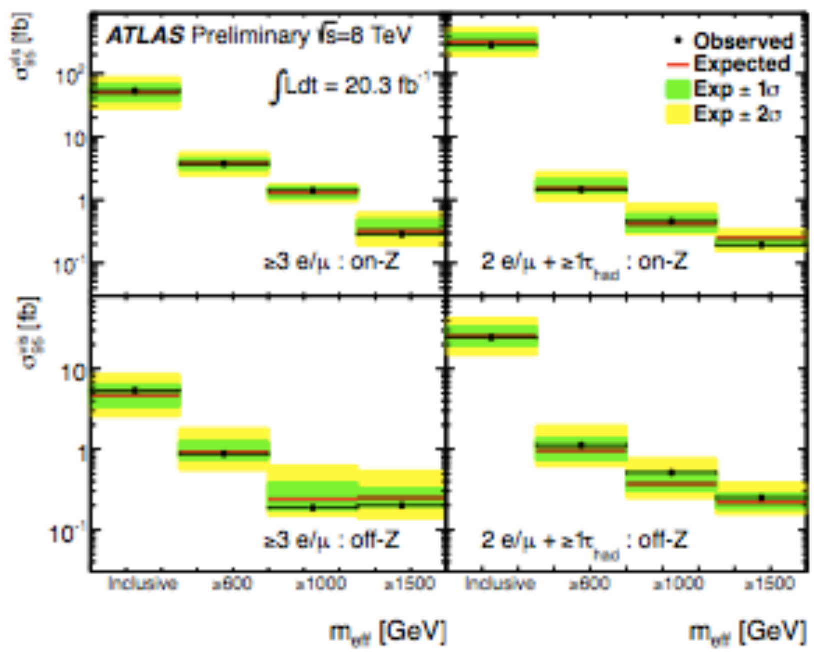
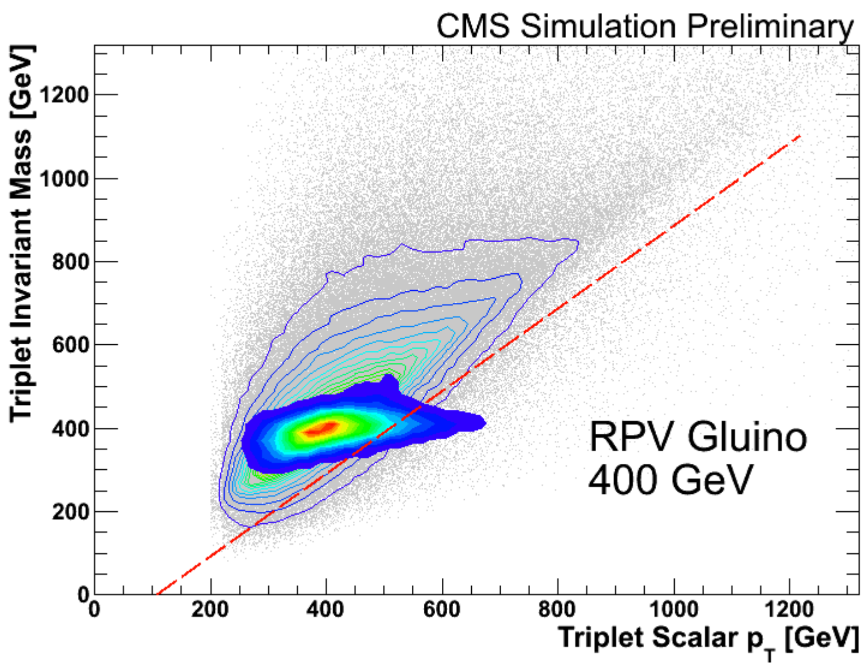



Talk by Hance

# Search for New States at the Electroweak Scale

Refined

Boosted 3-Jet Resonances: CMS




Ensemble of
6 choose 3 = 20
Jet Triplets

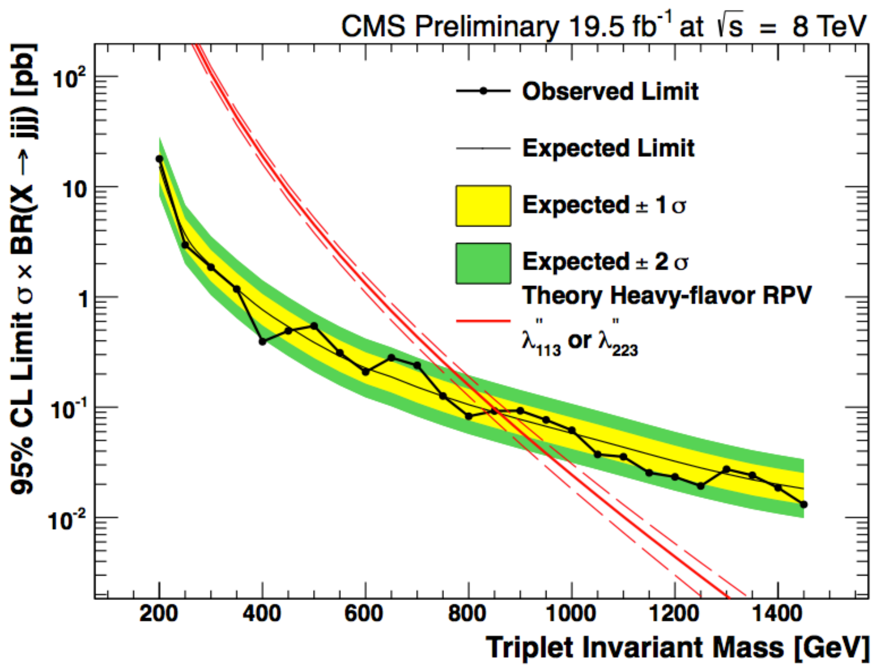
(No MET)

Talk by Seitz

# Search for New States at the Electroweak Scale

Refined

Boosted 3-Jet Resonances: CMS




Ensemble of
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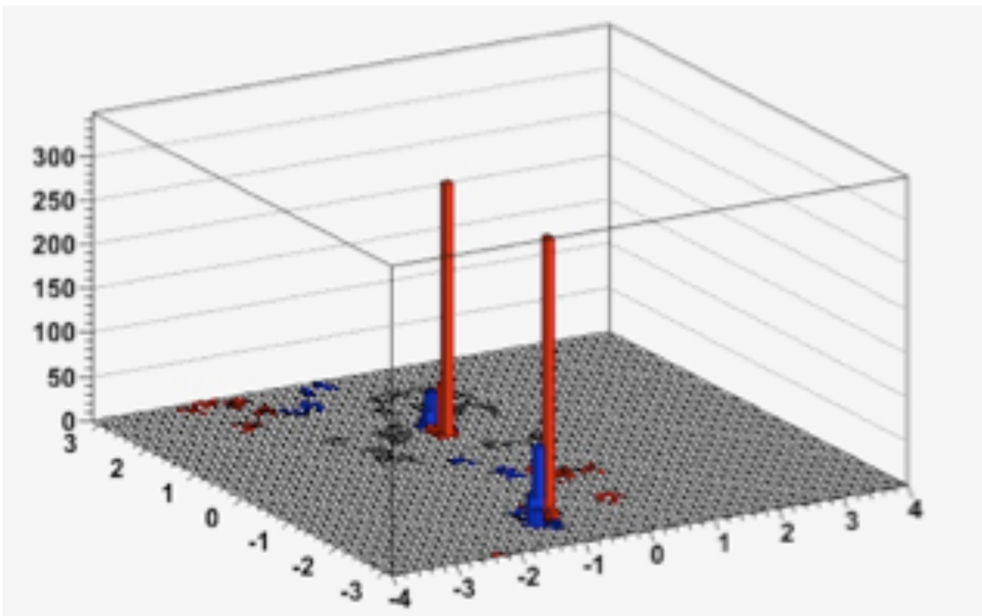
Talk by Seitz

# Search for New States at the Electroweak Scale

Focused

Paired Di-Jet Resonances:




Fat-Jet
Sub-Jets

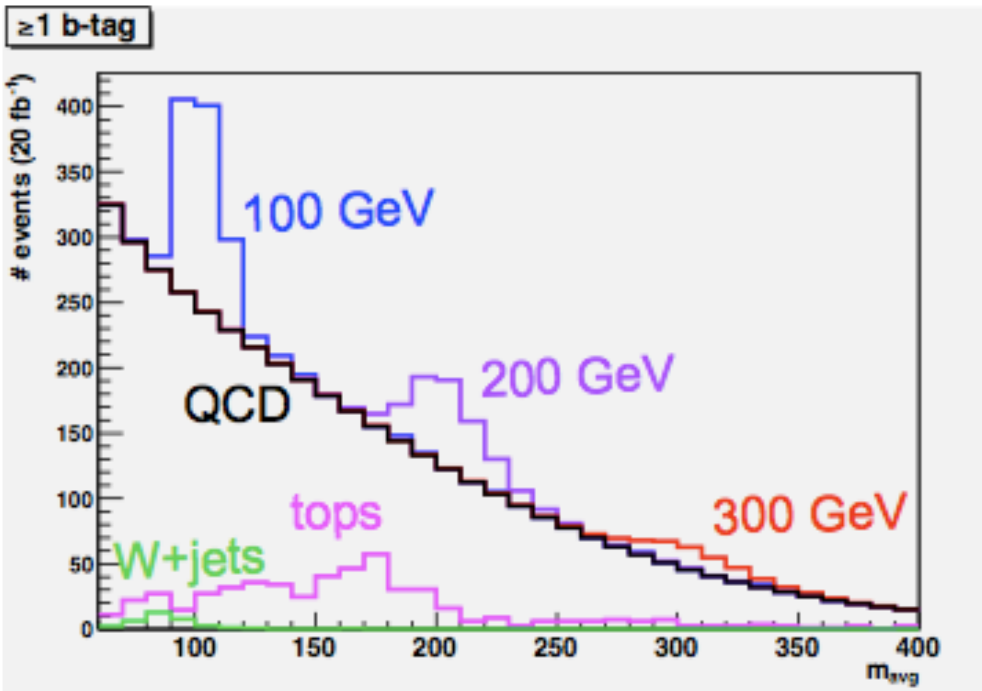
(No MET)

Talk by Tweedie

# Search for New States at the Electroweak Scale

Focused

Paired Di-Jet Resonances:




Fat-Jet
Sub-Jets

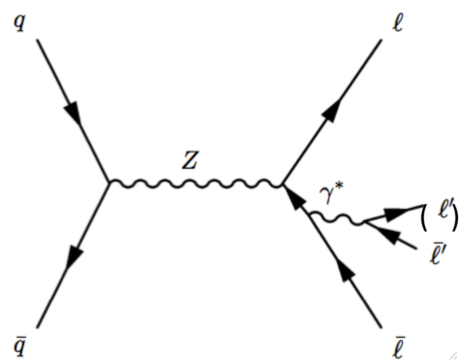
(No MET)

Talk by Tweedie

# Discovery of an Un-Anticipated High $p_T$ (Standard Model) Process

## Asymmetric Internal Conversion

Largest Source:
$Z \to l\, l\, \gamma^* \to l\, l\, l\, (l)$
(Others)



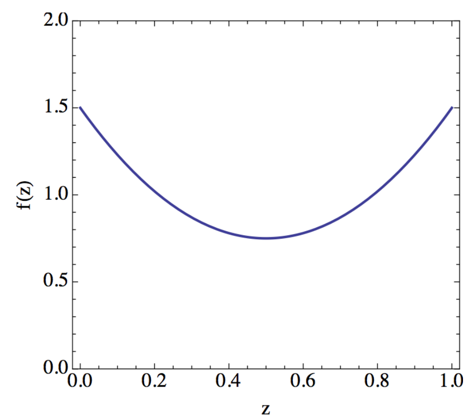

Asymmetric Internal Conversion
$\gamma^* \to e(e)$ , $\mu(\mu)$

Compare External Conversion in Material $\gamma \to e(e)$

Standard MC's Don't Capture IR Singular Region of Phase Space

$$m_{\ell\ell} \frac{d\mathcal{P}(\gamma^* \to \ell\ell)}{dm_{\ell\ell}} = \frac{2}{3}\frac{\alpha}{\pi}\left(1 - \frac{4m_\ell^2}{m_{\ell\ell}^2}\right)^{1/2}\left(1 + \frac{2m_\ell^2}{m_{\ell\ell}^2}\right)$$

Momentum Fraction Distribution



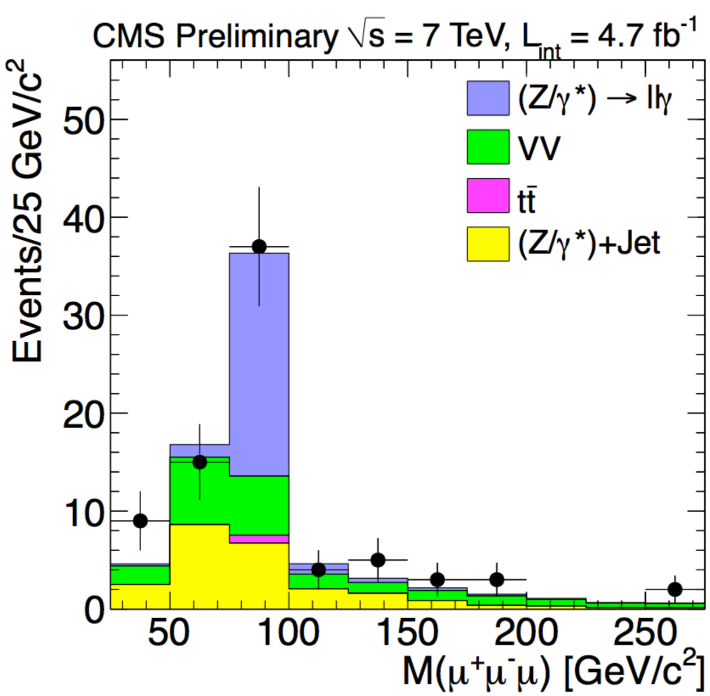
# Discovery of an Un-Anticipated High $p_T$ (Standard Model) Process

## Asymmetric Internal Conversion

Largest Source:

$Z \to l\,l\,\gamma^* \to l\,l\,l\,(l)$

(Others)




Asymmetric Internal Conversion
$\gamma^* \to e(e)$ , $\mu(\mu)$

Compare External Conversion
in Material $\gamma \to e(e)$

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Developed Special Purpose AIC MG MC

First Observed in Multi-Dimensional
Dalitz Distribution O(few) Events

First Observation of $Z \to lll(l)$

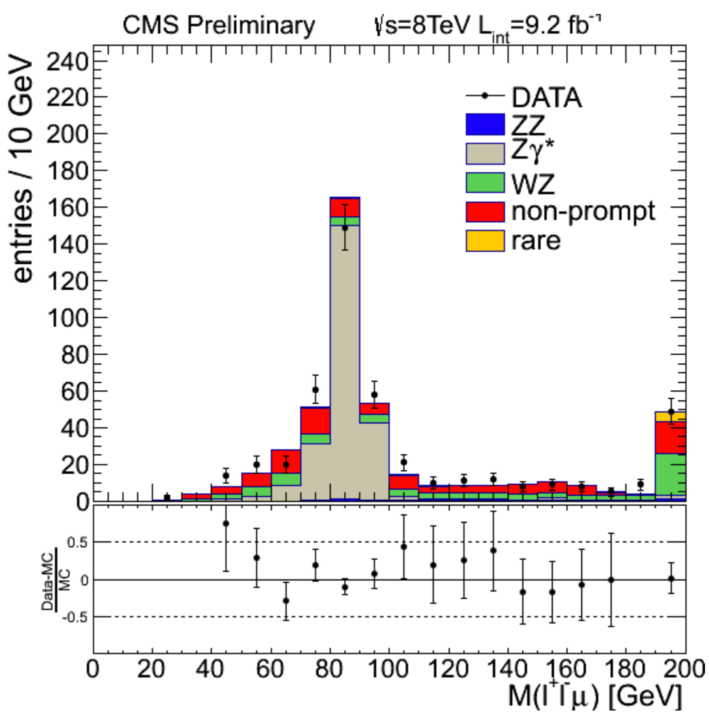
# Discovery of an Un-Anticipated High $p_T$ (Standard Model) Process

## Asymmetric Internal Conversion

Largest Source:

Z -> l l $\gamma$* -> l l l (l)

(Others)




Asymmetric Internal Conversion
$\gamma$* -> e(e) , $\mu(\mu)$

Compare External Conversion
in Material $\gamma$ -> e(e)

Standard MC's Don't Capture IR Singular Region of Phase Space

$$m_{\ell\ell}\frac{d\mathcal{P}(\gamma^*\to\ell\ell)}{dm_{\ell\ell}}=\frac{2}{3}\frac{\alpha}{\pi}\left(1-\frac{4m_\ell^2}{m_{\ell\ell}^2}\right)^{1/2}\left(1+\frac{2m_\ell^2}{m_{\ell\ell}^2}\right)$$

Developed Special Purpose AIC MG MC

First Observed in Multi-Dimensional Dalitz Distribution O(few) Events

First Observation of Z -> lll(l)

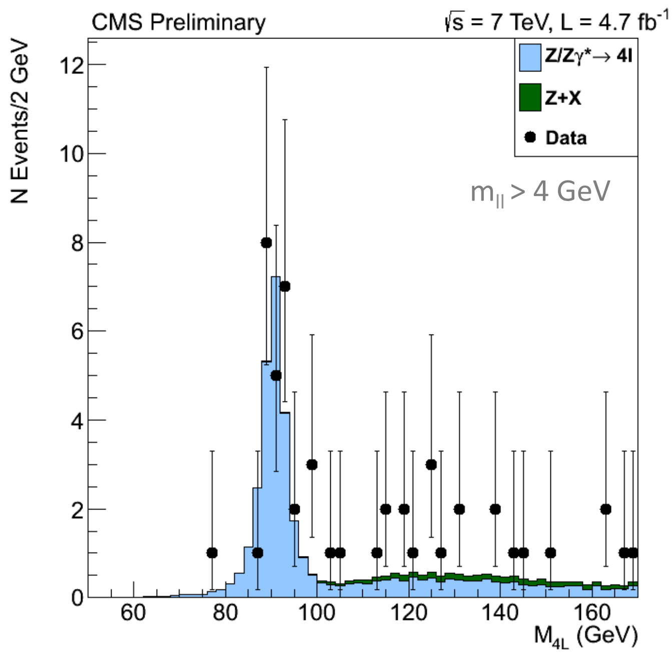
# Discovery of an Un-Anticipated High $p_T$ (Standard Model) Process

## Asymmetric Internal Conversion

Largest Source:

$Z \to l\, l\, \gamma^* \to l\, l\, l\, (l)$

(Others)




Asymmetric Internal Conversion
$\gamma^* \to e(e)\ ,\ \mu(\mu)$

Compare External Conversion in Material $\gamma \to e(e)$

Standard MC's Don't Capture IR Singular Region of Phase Space

$$m_{\ell\ell}\frac{d\mathcal{P}(\gamma^*\to\ell\ell)}{dm_{\ell\ell}} = \frac{2}{3}\frac{\alpha}{\pi}\left(1-\frac{4m_\ell^2}{m_{\ell\ell}^2}\right)^{1/2}\left(1+\frac{2m_\ell^2}{m_{\ell\ell}^2}\right)$$

Developed Special Purpose AIC MG MC

First Observed in Multi-Dimensional Dalitz Distribution O(few) Events

First Observation of Z -> lll(l) , llll

# Discovery of an Un-Anticipated High $p_T$ (Standard Model) Process

## Asymmetric Internal Conversion

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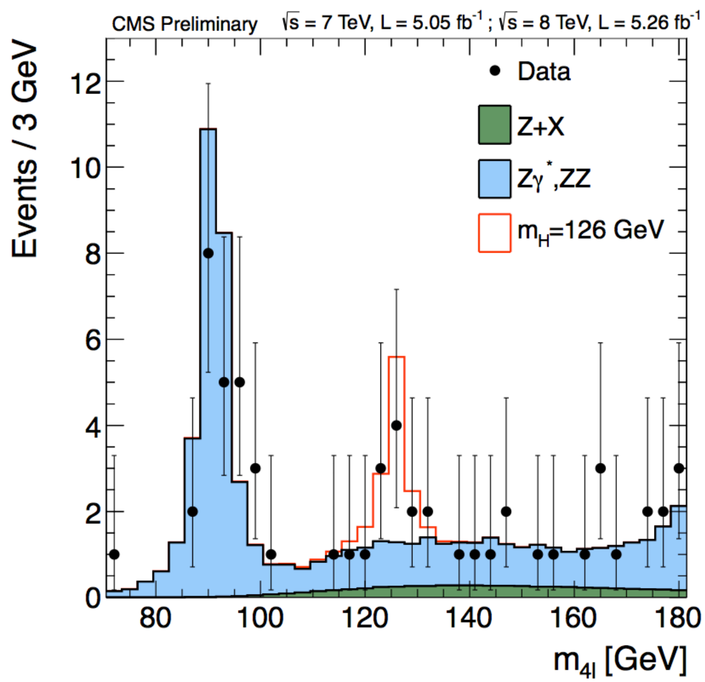


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Used in Higgs -> llll as "calibration"

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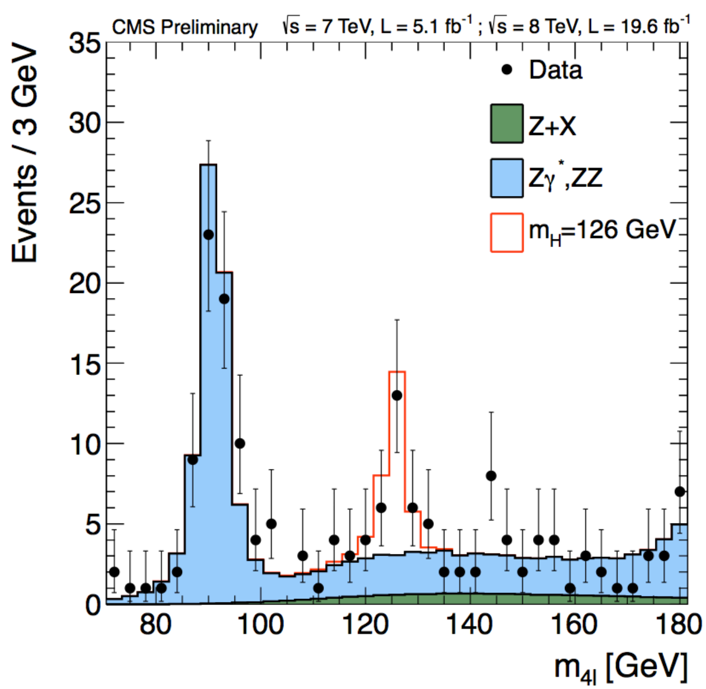


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# Higgs -> WW: Asymmetric Internal Conversion

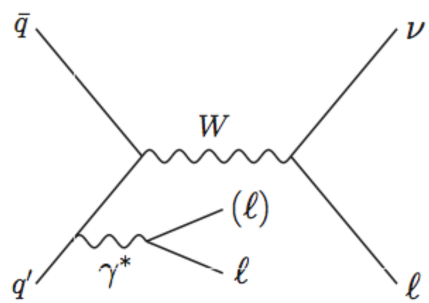
H -> WW -> l ν l ν

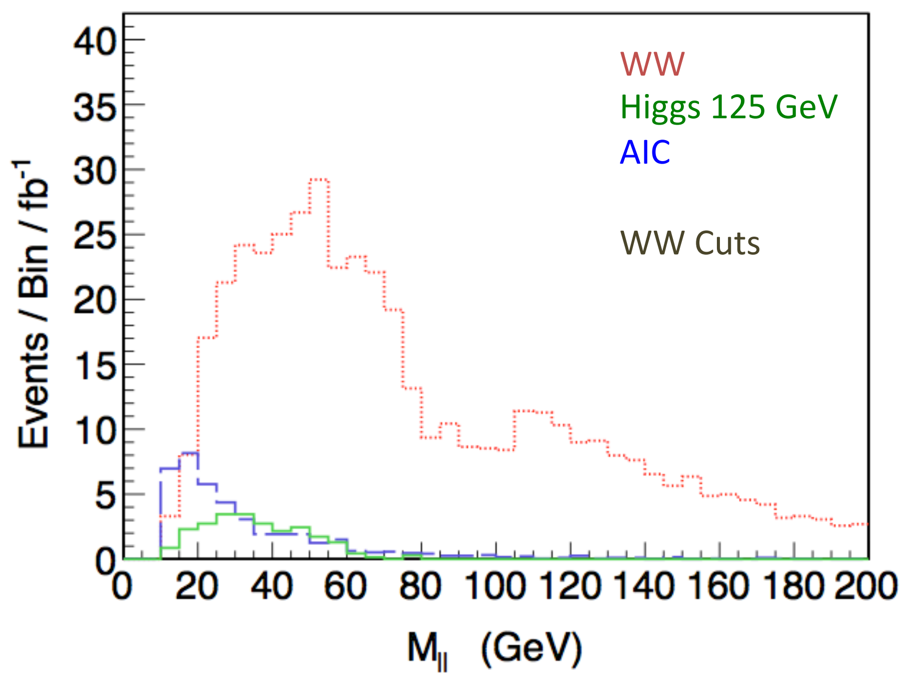
(Gray, Kilic, Park, Somalwar, ST)

Un-Anticipated Process – “Fake” Lepton Background

W γ* -> l ν l (l)   + …

(Comparable to Higgs Signal)



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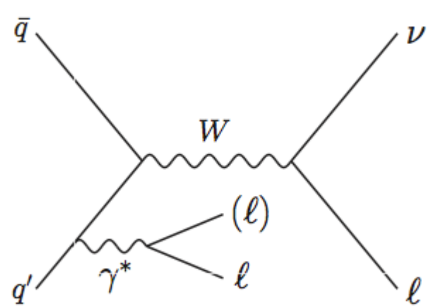


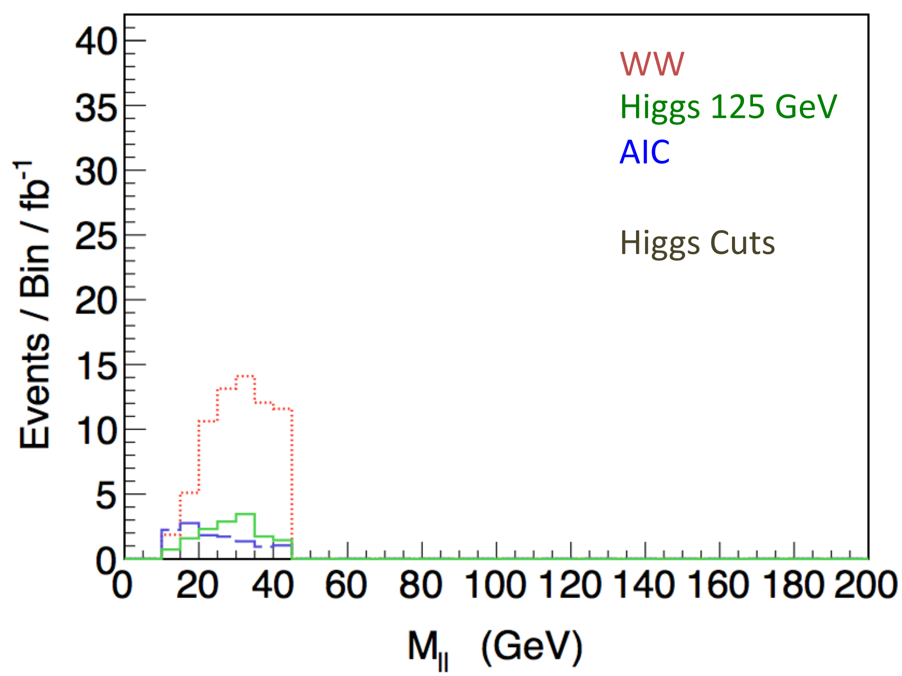

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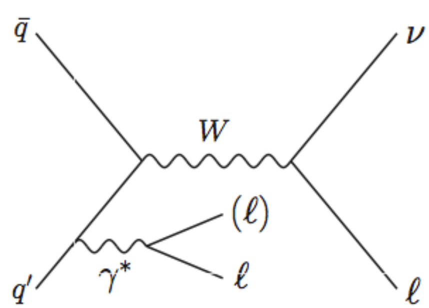
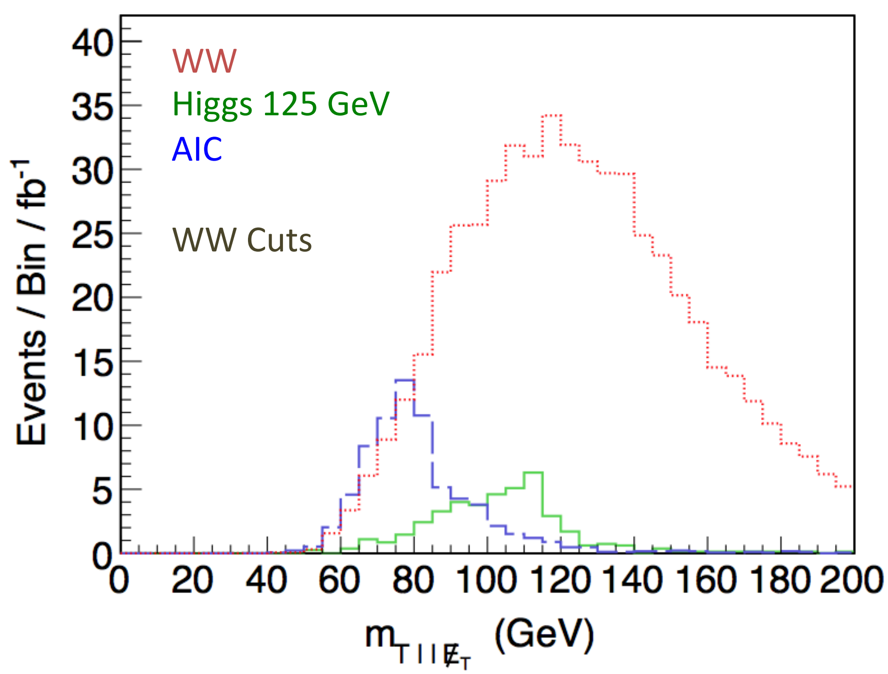


# Search for the Physics of Electroweak Symmetry Breaking

New Physics at Electroweak Scale Associated with Higgs Sector

- Higgs Rate Measurements        This Talk

- Search for Additional States in the Higgs Sector

- Searching for New Physics Produced
  in Association with Higgs (Calibrated Source)

- Precision Higgs Measurements to Search for
  New Physics

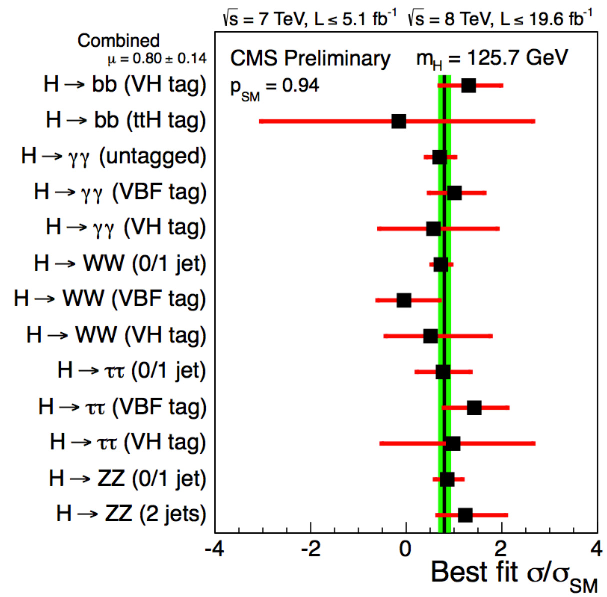
Still Possible to Discover New Physics at Electroweak
Scale in Existing Data

# Search for New Physics in Higgs Boson Rate Measurements

## Number of Channels Observed + Measured

## Many Many More Eventually ...

| | Inclusive | VBF | Vh | tth |
|---|---|---|---|---|
| $\gamma\gamma$ | X | X | X | X |
| ZZ* | X | X | X | X |
| WW* | X | X | X | X |
| $\tau\tau$ | X | X | X | X |
| bb | | | X | X |
| Z $\gamma$ | X | X | X | |
| $\mu\mu$ | X | X | X | X |



# Search for New Physics in Higgs Boson Rate Measurements

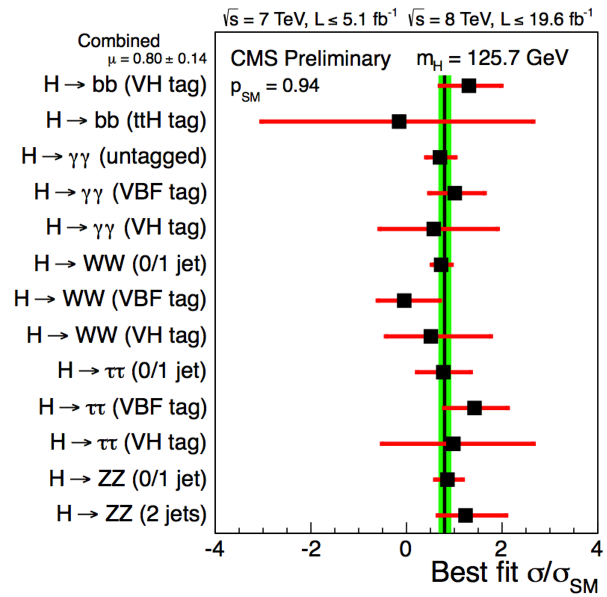
## Signals of New Physics in SM Higgs Rate Measurements

Deviations in SM Higgs Couplings

- Fit to SM Couplings
- Effective Operator Analysis
- Specific Underlying Theoretical Framework

  Extended Higgs Sector
  Supersymmetry
  …

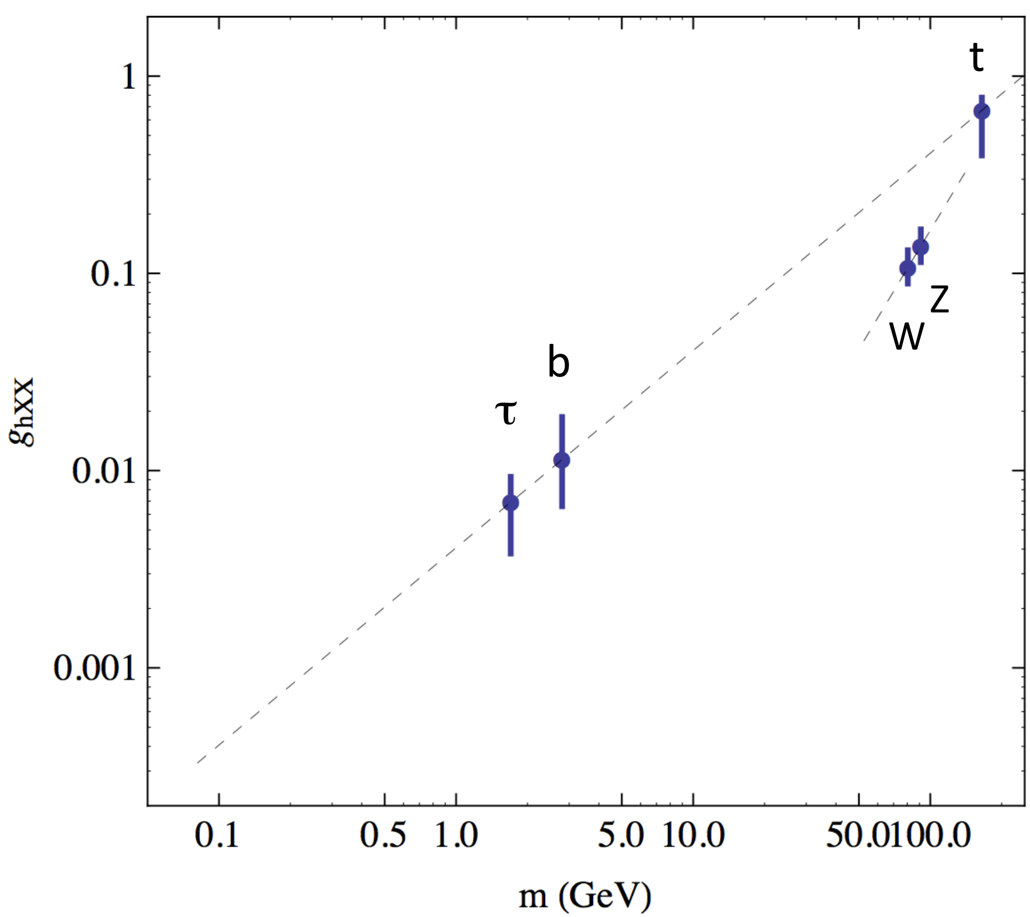
This Talk




Any Deviations at Discovery Level are by Definition Large …

# Search for New Physics in Higgs Boson Rate Measurements

It's the Higgs Boson !!




CMS Global Fits
(Pre-Moriond 2013)

Re-interpreted Loop Couplings in terms of W and top Couplings

$g_{hXX} = (m_X/v)^n$

n = 1 Fermion
n = 2 Boson

# Precision Probes of New Physics

## Electroweak Observables

$G_F$, $m_W$, $m_Z$, $\Gamma_Z$, $A_{Z\text{-}FB}$, ...

Renormalizable SM +
D=6 Operators

H = <H>

$$\frac{\xi_T}{M^2}\,(H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2}\; H^\dagger W_{\mu\nu} H\; B^{\mu\nu}$$

PDG

S = 0.01 +- 0.10

T = 0.03 +- 0.11

Systematics: $m_t$, $\ln(m_h)$, $\alpha_S$ , ....

# Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

- $\sigma$ . Br ( Initial -> h -> Final )

# Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

$\sigma$ . Br ( Initial -> h -> Final )

Best Channels:

$\sigma$ . Br ( Inclusive -> h ->
Resonant Final )

# Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

$\sigma$ . Br ( Initial -> h -> Final )

$$\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)}$$

Best Channels: (Ratios)

$\sigma$ . Br ( Inclusive -> h -> Resonant Final )

# Precision Physics Through the Higgs

(Craig, ST)

## Higgs Observables

σ . Br ( Initial -> h -> Final )

$$\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)} \simeq \left.\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)}\right|_{\mathrm{SM}} \left[1 + \mathcal{O}\left(\frac{\alpha}{4\pi v^2}\frac{M^2}{\xi}\right)\right]$$

**Best Channels:** (Ratios)

σ . Br ( Inclusive -> h -> Resonant Final )

Renormalizable SM + D=6 Operators

H = ‹H› + h

$$\frac{\xi_T}{M^2}\,(H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2}\;H^\dagger W_{\mu\nu} H\;B^{\mu\nu}$$

$$\frac{g_1^2 \xi_{S_{11}}}{2M^2}\;H^\dagger H\;B_{\mu\nu}B^{\mu\nu}$$

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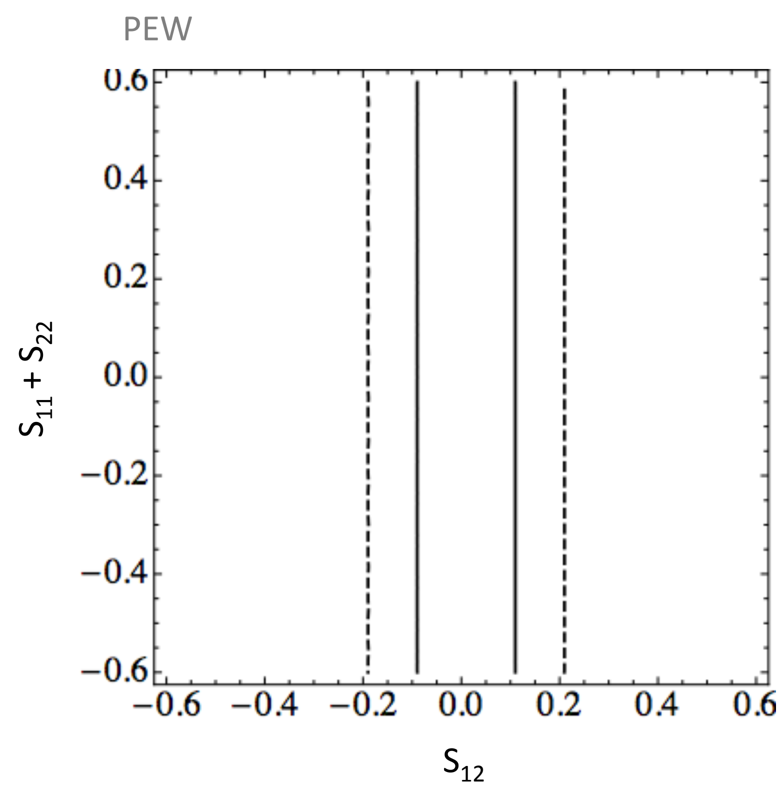

# Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables
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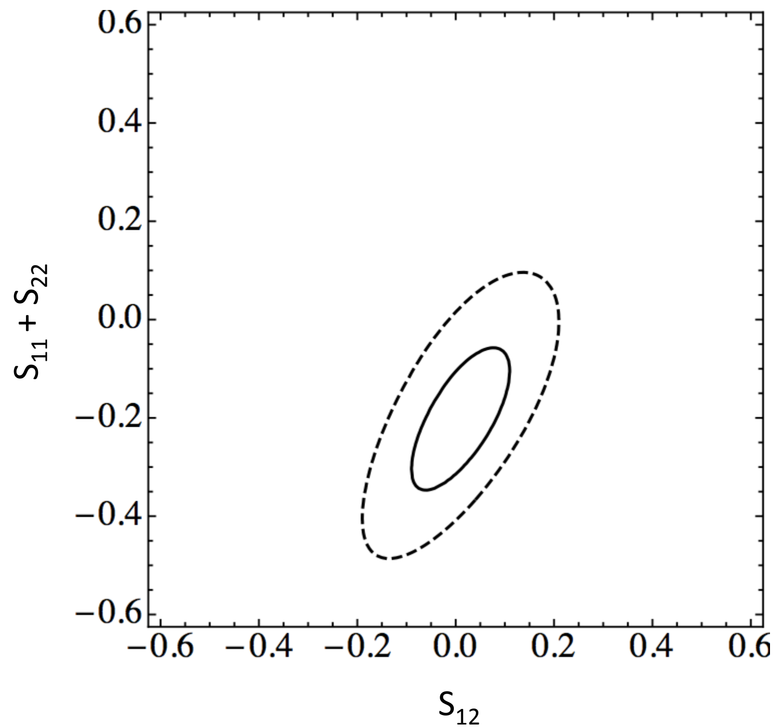
PEW + CMS 5 + 12(5) fb$^{-1}$ 7 + 8 TeV




Systematics: Statistics, Resonant-Continuum Separation + Interference, …

# Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

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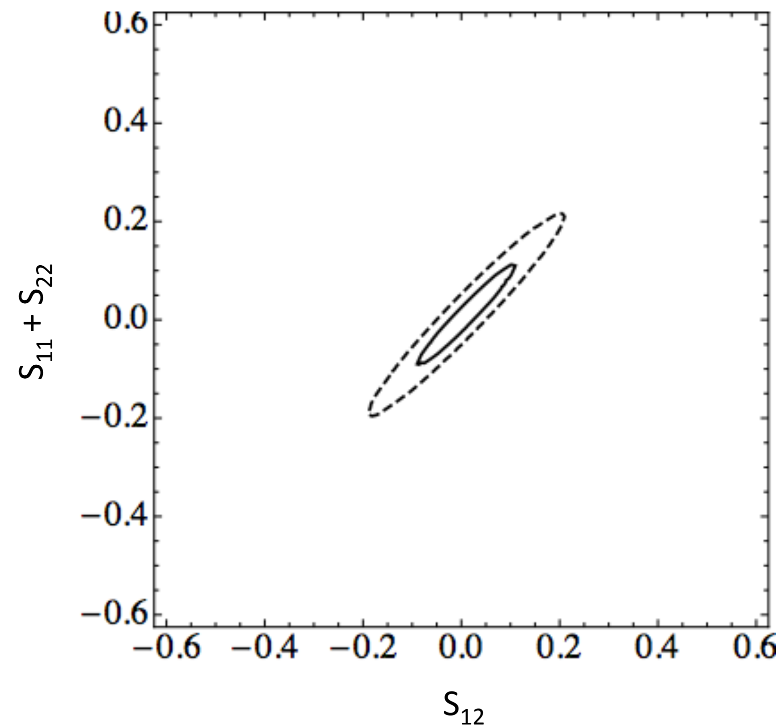
Best Channels: (Ratios)

σ . Br ( Inclusive -> h -> Resonant Final )

PEW + 5% Uncertainty Br(h->γγ)/Br(h->ZZ)




Renormalizable SM + D=6 Operators

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Systematics: Statistics, Resonant-Continuum Separation + Interference, …

# Implications of the Higgs Mass

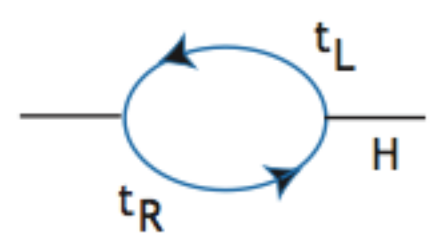
Higgs Self Coupling is Small

$m_h \sim m_Z \qquad \lambda \sim g$

Renormalizable Standard Model Remains Perturbative to Very High Scale

ElectroWeak Scale can be Stabilized by Partner Particles – Cancel Quadratic Divergence in Low Energy Theory

Doctrine of Naturalness Suggests Partner Particles <u>Below</u> TeV Scale



# Doctrine of Naturalness

Quantum Stability of K-K mixing
Against Changes in UV Physics

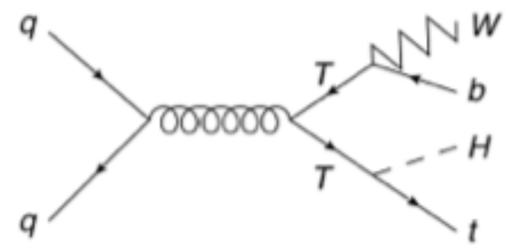
Charm Quark Cancels Quadratic
Divergence of ΔS=2 Amplitude
in Low Energy Theory

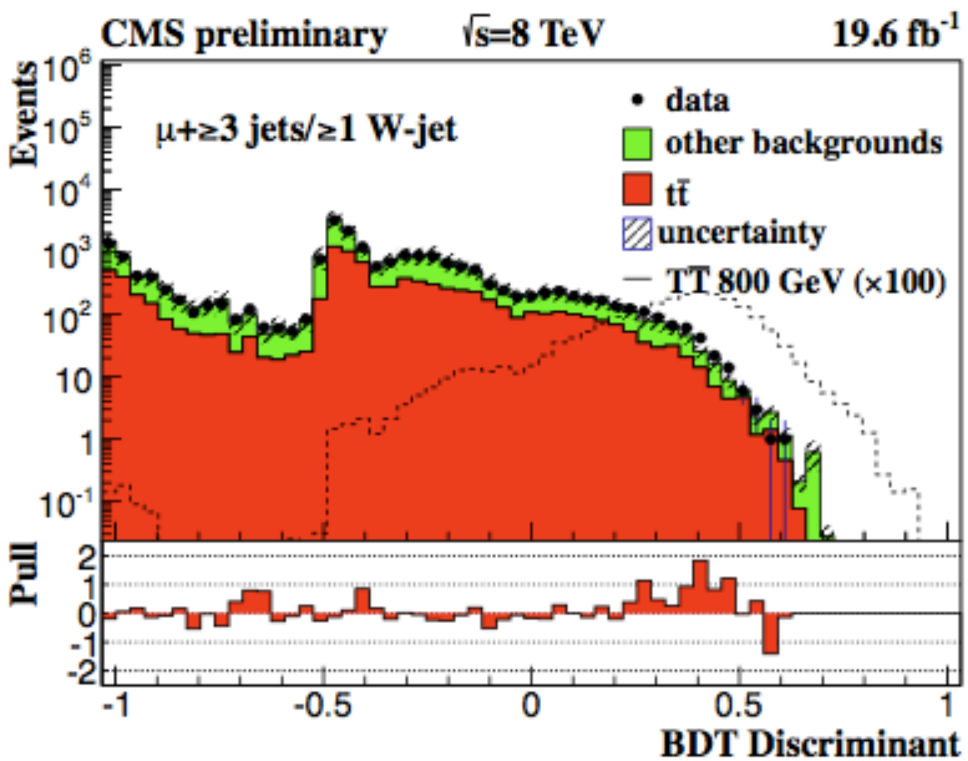
(Successful) Prediction of Charm Mass !

# Search for Partner Particles

Focused

Top Partner: CMS




Multi-Variate Analysis

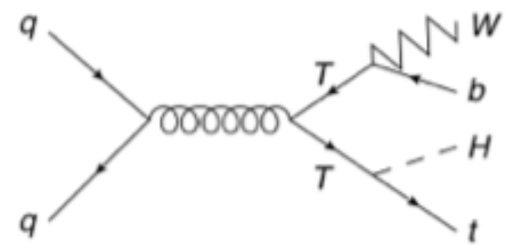
Blunt Variables +
W- and Top Tagging
Jet Substructure

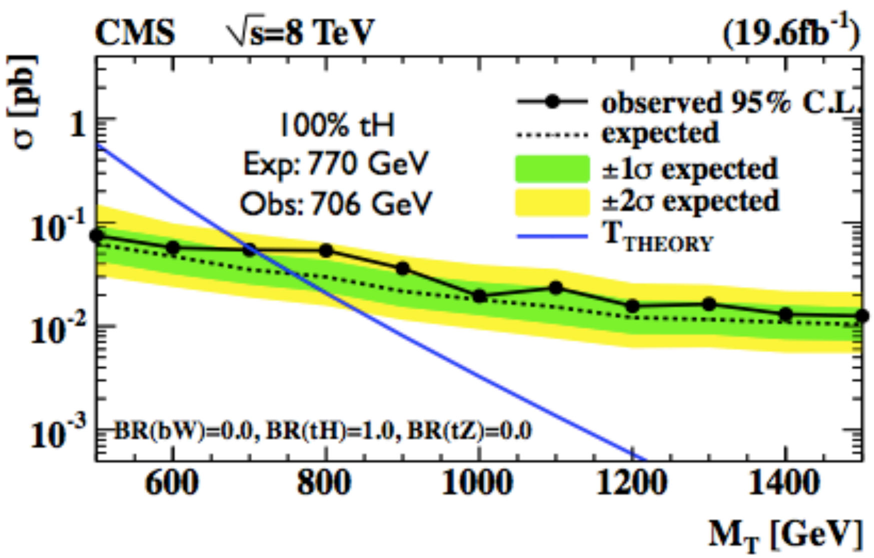
Talk by Lei

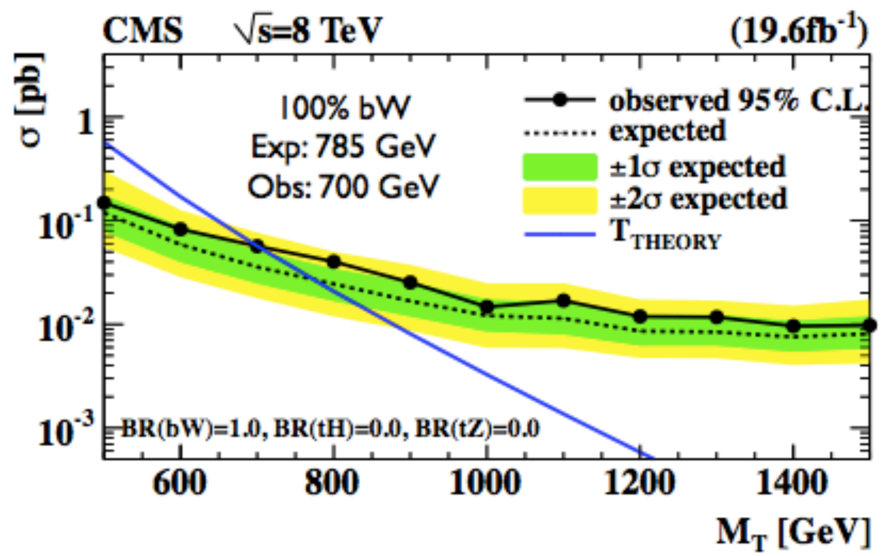
# Search for Partner Particles

Focused

Top Partner: CMS



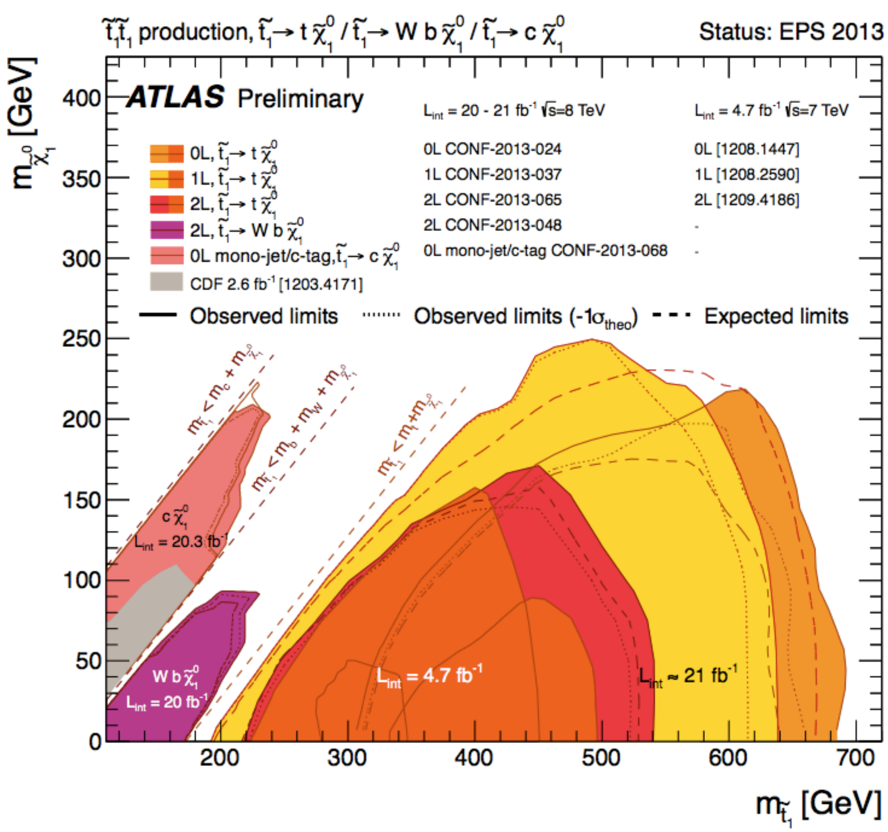



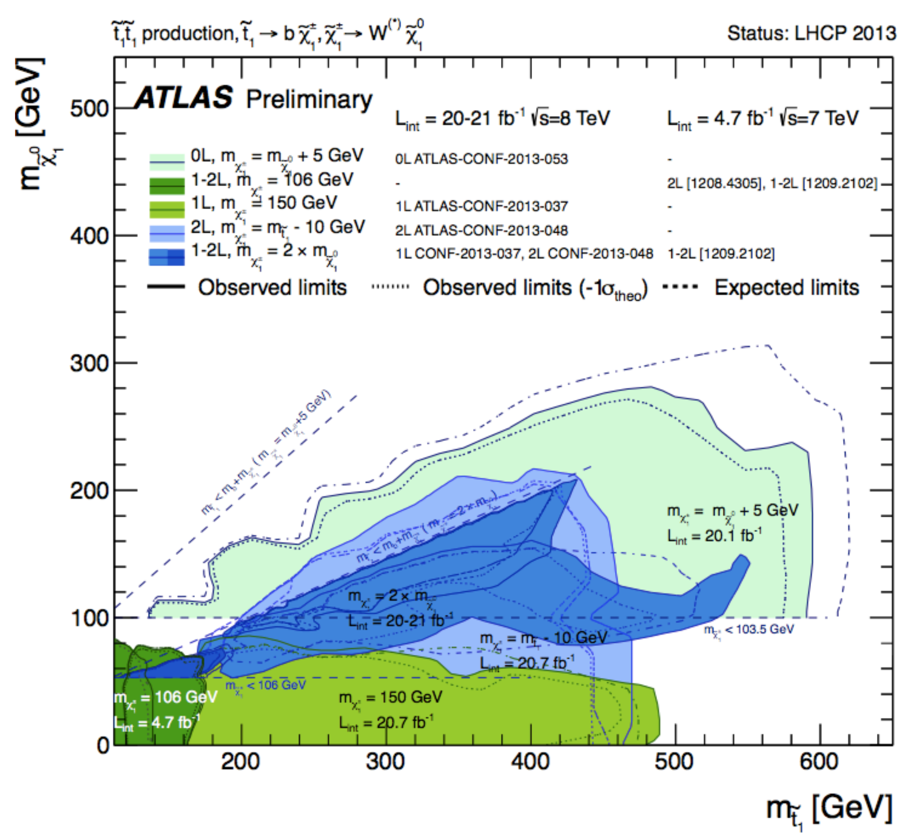

Talk by Lei

# Search for Partner Particles

Refined + Focused

## Top Spartner Super-Space: ATLAS



# Search for Electroweak States at the Electroweak Scale

Higgs Sector

Mass Scale O(100-200) GeV

$SU(2)_L$ $U(1)_Y$ Interactions

$\sigma$(pp -> Resonant Higgs Sector)$_{LHC}$ = O(10 pb)
$\sigma$(pp -> Pair Production Higgs Sector)$_{LHC}$ = O(1 pb)

Higgs Identified/Calibrated Object
(New Opportunities for Searches)

LHC Sensitivity to New Electroweak Physics at Electroweak Scale and in Higgs Sector Just Beginning ...

## Search for New Physics

A lot of Territory has Been Mowed Down

A Lot of Territory Remains Uncut
Including in Current LHC Data

Stay Tuned !