Leptonic Flavour Models at Colliders

Jessica Turner
IPPP, Durham University

Bethe Forum: Discrete Symmetries

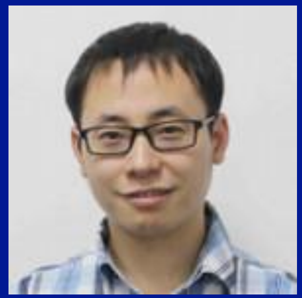
Work in collaboration with Ye-Ling Zhou and Holger Schulz

Science & Technology Facilities Council

Durham University


Warning
Coding in progress

Silvia Pascoli & Ye-Ling Zhou



(4 model parameters)

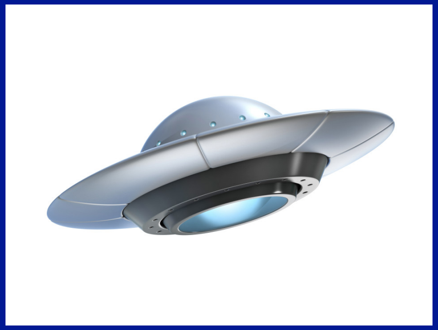
Flavour Model
A4

1607.05599 1604.00925

Lagrangian

FeynRules

UFO



MC Generator

Apply Higgs Width
and CLFV
Constraints
to your parameter
sampling

Measurement

ATLAS EXPERIMENT

1411.2921

Analysis Tool

Parametrisation Tool

Model Constraints
Multinest

The Flavour Model

Discrete Symmetries in the Lepton Sector

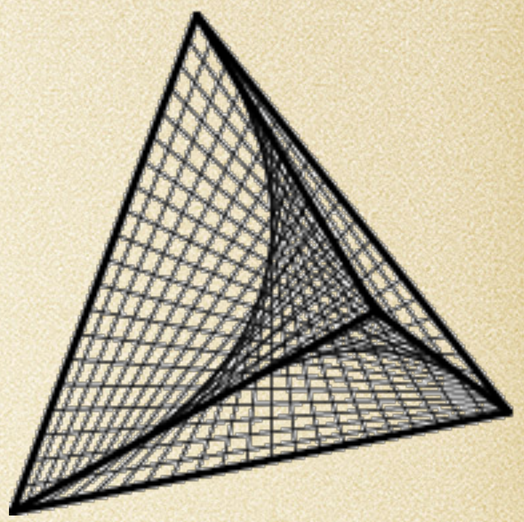
Harrison, Perkin, Scott
Xing

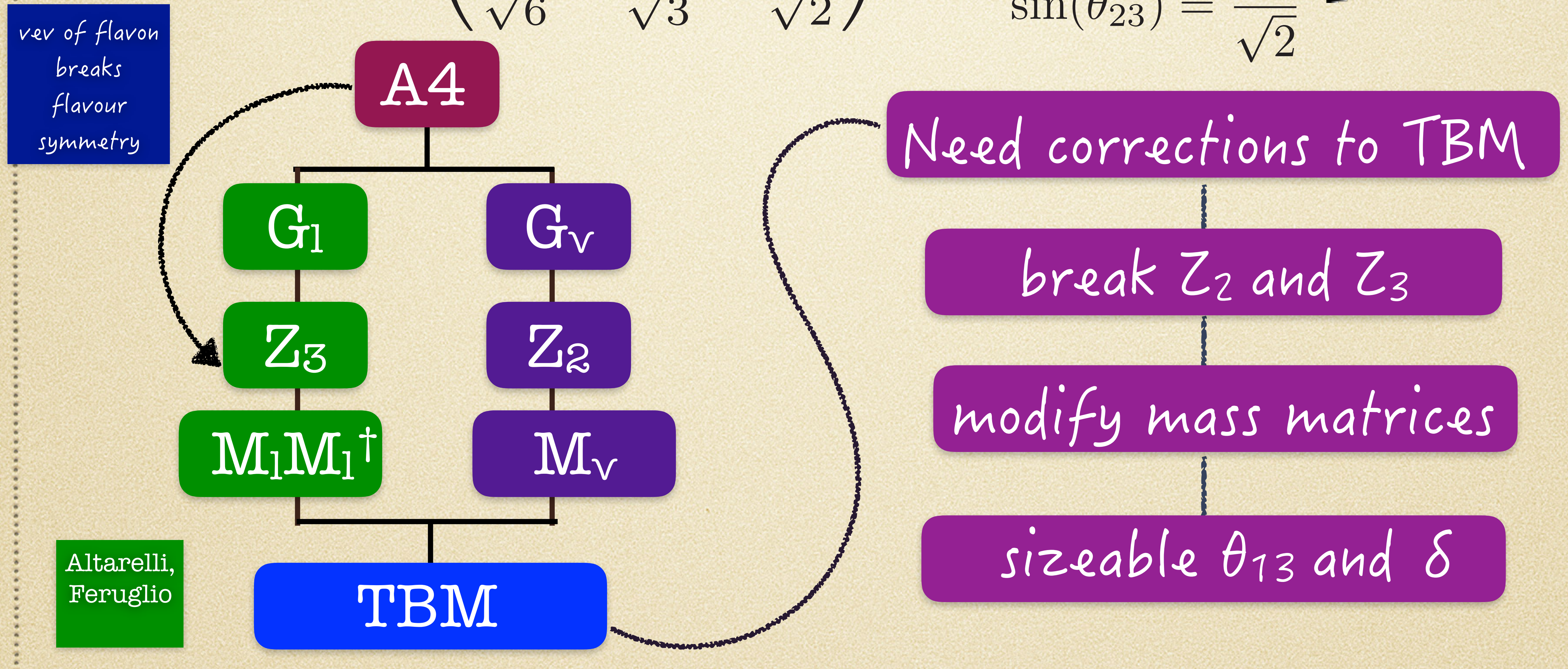
$$U_{TBM} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\sin(\theta_{13}) = 0$$

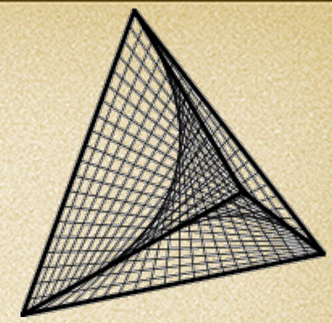
$$\sin(\theta_{12}) = \frac{1}{\sqrt{3}}$$

$$\sin(\theta_{23}) = \frac{1}{\sqrt{2}}$$





Vacuum Alignment Issue



Field Content

Talk by Tanimoto

$$\varphi = (\varphi_1, \varphi_2, \varphi_3)^T \sim 3, \quad \phi = (\phi_1, \phi_2, \phi_3)^T \sim 3,$$ flavon fields

$$\ell_L = (\ell_{eL}, \ell_{\mu L}, \ell_{\tau L})^T \sim 3, \quad e_R \sim 1, \quad \mu_R \sim 1'', \quad \tau_R \sim 1', \quad H \sim 1$$ SM fields

Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_\ell + \mathcal{L}_\nu + V(\phi) + V(\varphi) + V(\varphi, \phi)$$

extra dimension or SUSY models forbid cross coupling (Altarelli, Feruglio)

Vacuum Alignment

cross coupling will break residual symmetries

charged lepton sector: $T\langle\varphi\rangle = \langle\varphi\rangle$

neutrino sector: $S\langle\phi\rangle = \langle\phi\rangle$

$$T = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega^2 & 0 \\ 0 & 0 & \omega \end{pmatrix} \qquad S = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{pmatrix}$$

$$\omega = e^{\frac{2\pi i}{3}}$$

Basic Idea

- Allow for cross coupling which are small compared with self-couplings
- Small cross couplings tune the VEVS such that deviations from TBM are achieved and responsible for sizable θ_{13}

For more details see 1604.00925 and 1607.05599: Pascoli and Zhou

Lagrangian and Model Signatures

Z_3 Preserving Case ⇒ Deviation from TBM from Neutrino Sector

$$V(H,\varphi) = \frac{1}{2}\epsilon v_\varphi h^2 \varphi_1 + \frac{1}{2}\epsilon v_\varphi h \varphi_1^2 + \epsilon v_h h \varphi_2^* \varphi_2$$

flavon vev

Pseudo-real $\varphi_1 = {\varphi_1}^*, \varphi_3 = {\varphi_2}^*$

charged lepton flavour conserving

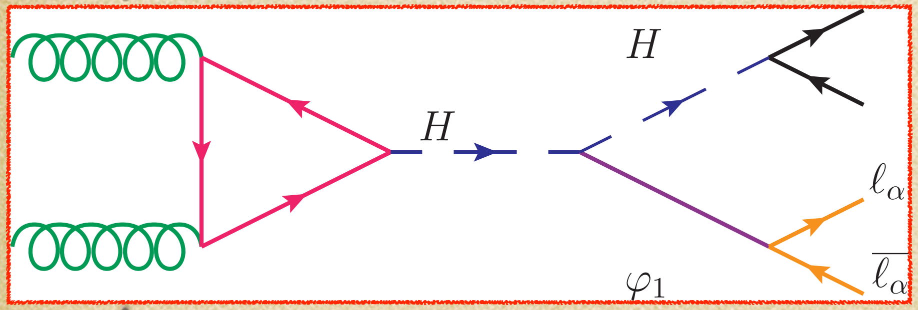
charged lepton flavour violating

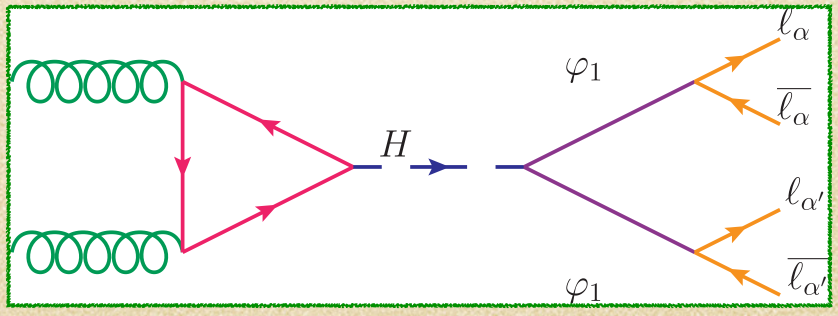
$$\mathcal{L}_\ell{}^{\text{eff}} = \frac{m_e}{v_\varphi}\left(\overline{e_L} e_R \varphi_1 + \overline{\mu_L} e_R \varphi_2 + \overline{\tau_L} e_R \varphi_2^*\right) + \frac{m_\mu}{v_\varphi}\left(\overline{\mu_L} \mu_R \varphi_1 + \overline{\tau_L} \mu_R \varphi_2 + \overline{e_L} \mu_R \varphi_2^*\right) + \frac{m_\tau}{v_\varphi}\left(\overline{\tau_L} \tau_R \varphi_1 + \overline{e_L} \tau_R \varphi_2 + \overline{\mu_L} \tau_R \varphi_2^*\right) + \text{h.c}$$

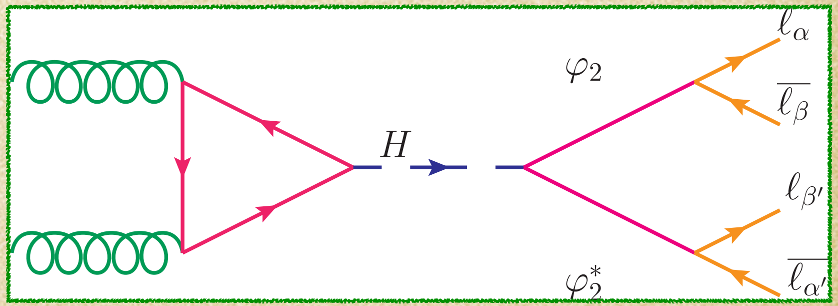
Final State tau dominated

Higgs radiating scalar

pair production of scalars







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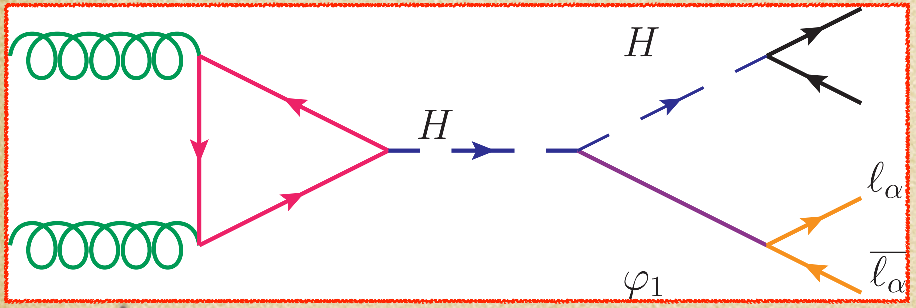
flavon vev

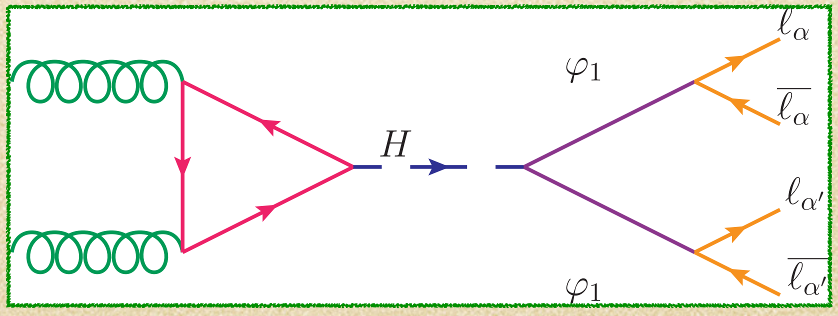
Need to constrain mixing with Higgs. Experimental limit (H-> scalar scalar) $\cos^2(\theta) > 0.96$ (1605.06834)

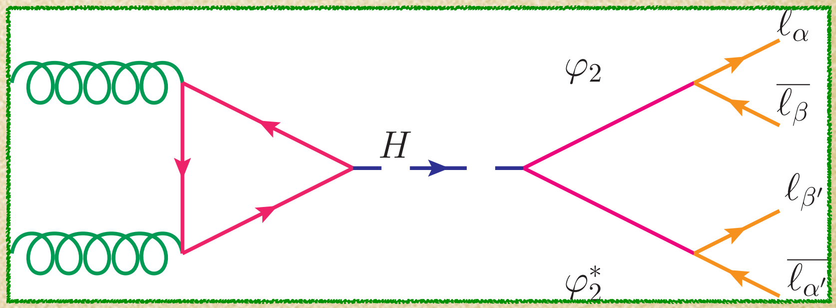
$$\frac{\epsilon v_H v_\varphi}{(m_H^2 - m_\varphi^2)} < 0.196$$

Higgs radiating scalar



pair production of scalars





Lagrangian and Model Signatures

Z_3 Preserving Case

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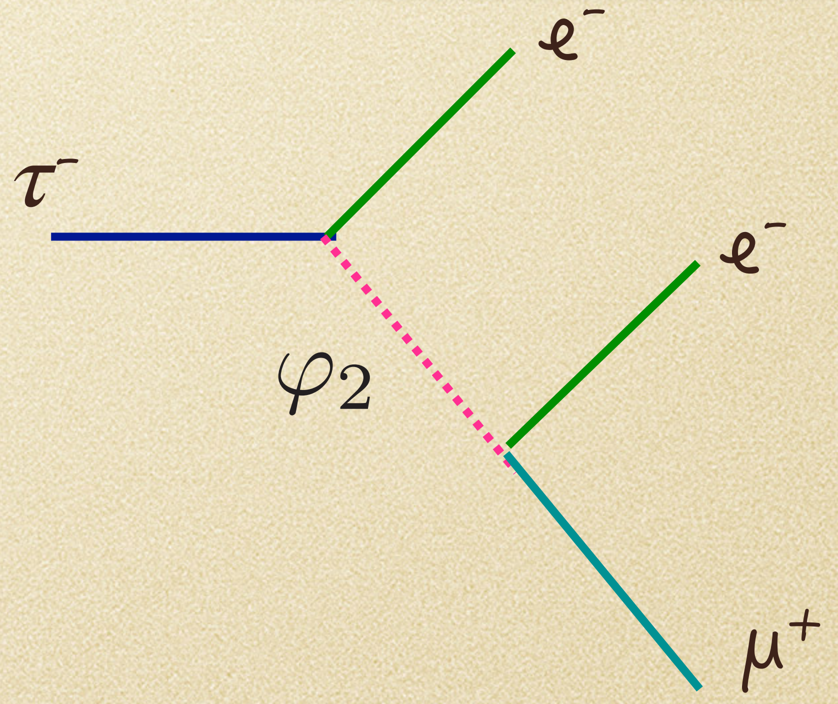
$$+ \frac{m_\mu}{v_\varphi}\left(\overline{\mu_L}\mu_R\varphi_1 + \overline{\tau_L}\mu_R\varphi_2 + \overline{e_L}\mu_R\varphi_2^*\right)$$
$$+ \frac{m_\tau}{v_\varphi}\left(\overline{\tau_L}\tau_R\varphi_1 + \overline{e_L}\tau_R\varphi_2 + \overline{\mu_L}\tau_R\varphi_2^*\right) + \text{h.c}$$

Flavour Triality (Ma)

Pseudo-real $\varphi_1 = {\varphi_1}^*, \varphi_3 = {\varphi_2}^*$

$Br(\tau^- \to \mu^+ e^- e^-) \simeq Br(\tau^- \to e^+ \mu^- \mu^-)$

$$\sim \left(\frac{m_\mu m_\tau v^2}{m_{\varphi_2}^2 v_\varphi^2}\right)^2 < 10^{-8}$$



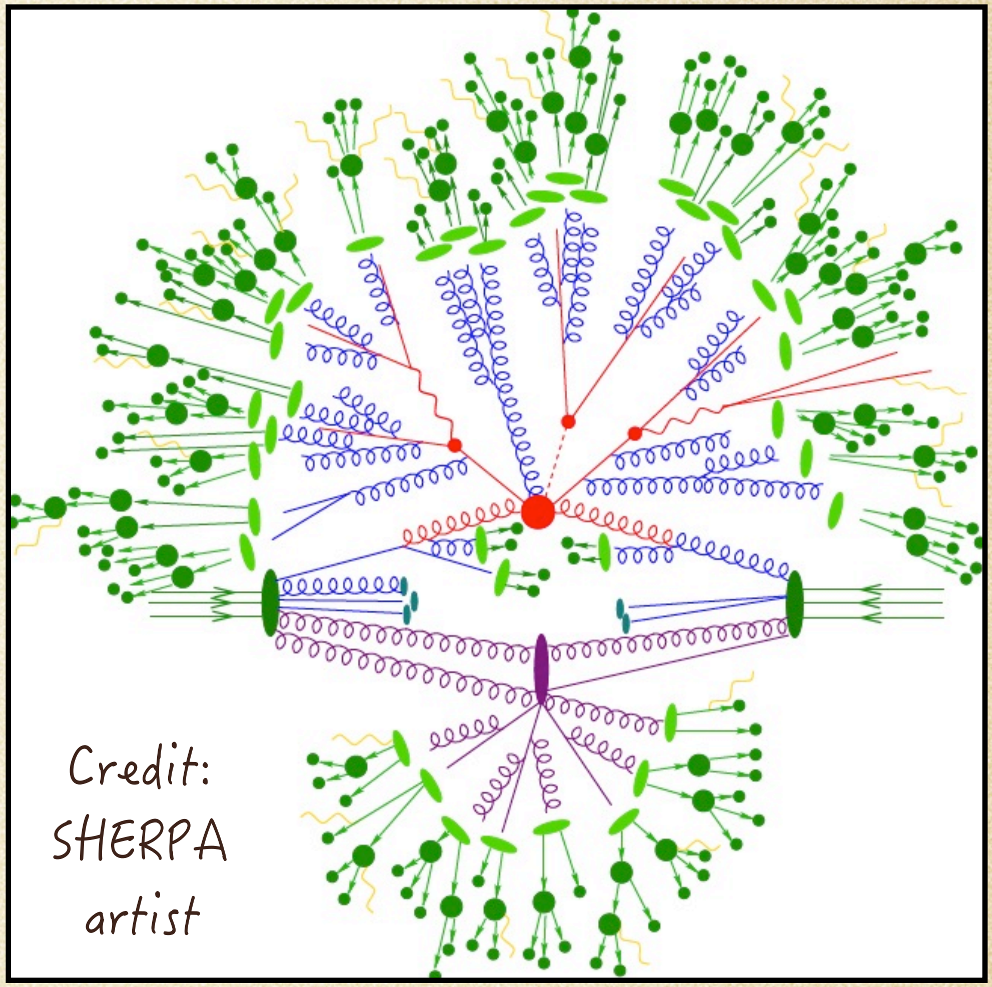
Confronting Model with Data

“Bottom-up physics is dirty business”

S. King

Sherpa

- Write Lagrangian in Feynrules ⇒UFO import to generator.
- Sherpa: in house MC generator that handles M.E + P.S + Hadronisation.
- Signal generated using Sherpa. BSM models available at LO. Apply a K-factor of 2.47, main correction from ggF.
- 4 parameters: $m_1, m_2, v_\varphi, \epsilon$



Sherpa handles on and off-shell decay of Higgs

```
}}(run)
(processes){{
  Process 21 21-> 9000007 -9000007
  End process;
  Process 21 21-> 9000006 9000006
  End process;
  Process 21 21-> 25 9000006
  End process;
}}(processes)
(selector){{
  # phase space cuts for matrix elements
  PT 9000007 20 E_CMS
#  PT 9000006 20 E_CMS
}}(selector)
(ufo){{
```

Sherpa

- Write Lagrangian in Feynrules ⇒UFO import to generator.
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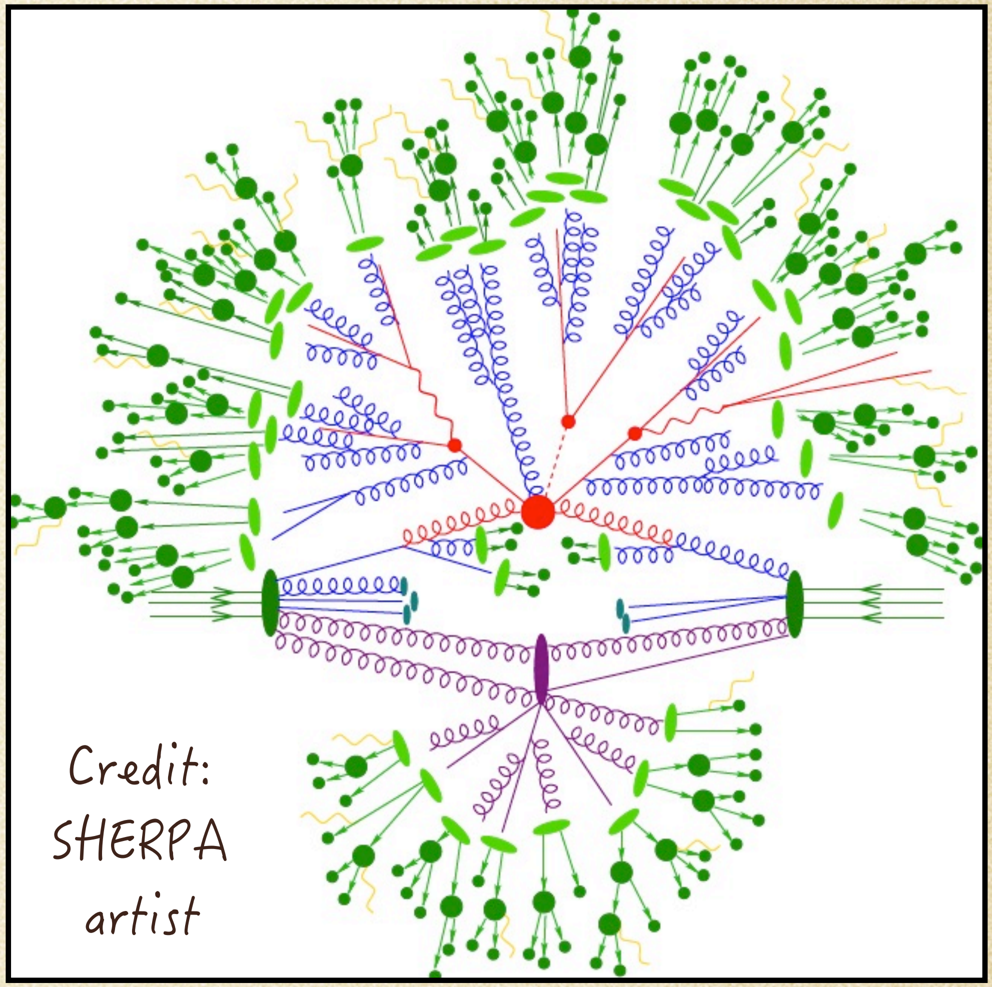
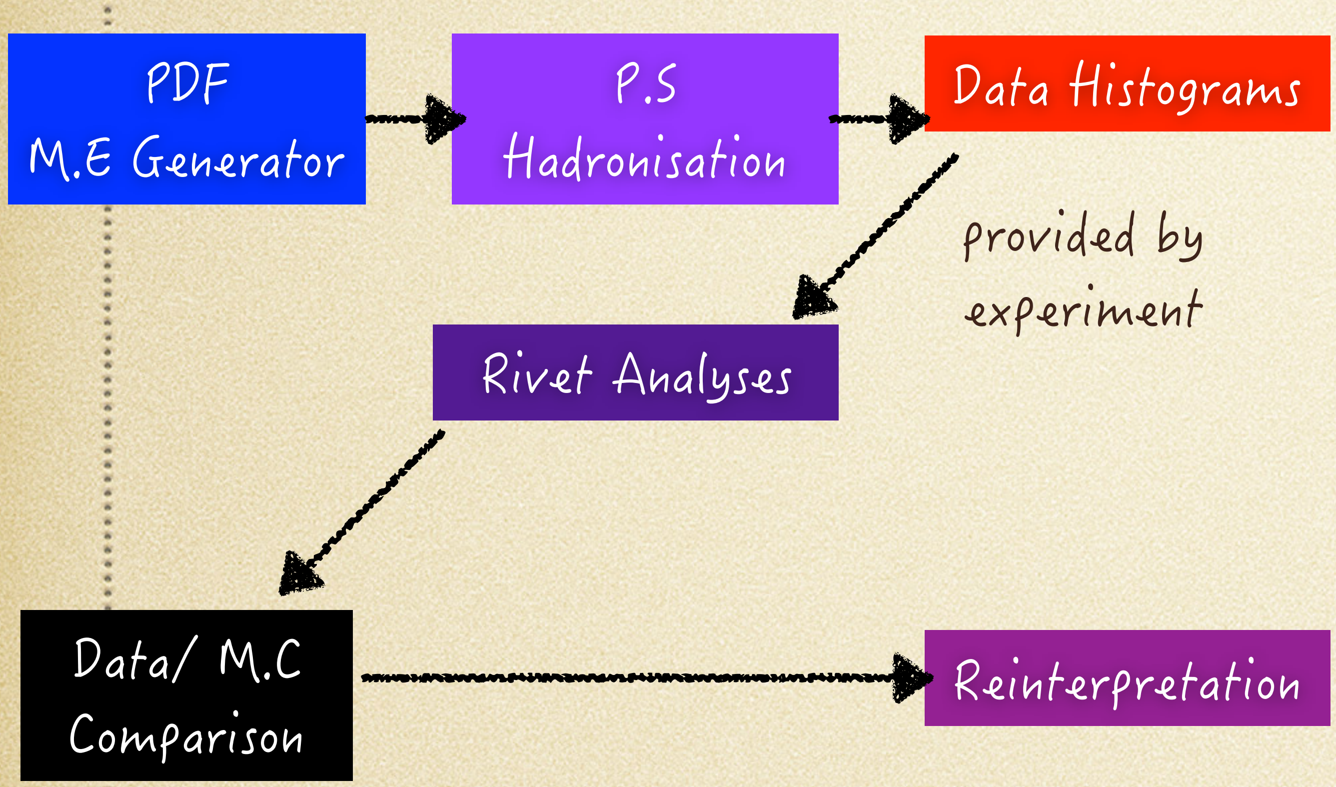



```
block frblock
      1       {VP2}        # vp2
      2       0.1          # ep
decay         23      2.4952       # WZ
decay         24      2.085        # WW
decay         6       1.50833649   # WT
decay         25      0.00407      # WH
decay         9000005 0.00407      # Wh1
decay         9000006 {WSC1}         # Wsc1
decay         9000007 {WSC2}         # Wsc2
}
 }(ufo)
(analysis) {
 {
BEGIN_RIVET {
 {
-a ATLAS_2014_I1327229
}
} END_RIVET
}
 }(analysis)
```

Sherpa can be linked directly to Rivet: no need to stored huge hepMC files!

Rivet

- Rivet is generator agnostic analysis tool for MC events, with lots of analyses!



Rivet analyses reference

+250 Analysis available and validated

Contents

init(): book his declare histograms and declare projections

```
    /// Book histograms and initialise projections before the run
  void init() {
        // Basic final state
        FinalState fs(-5,5);

        // Electron Final State
        FinalState es(Cuts::abspid == PID::ELECTRON && Cuts::abseta < 2.5);
        declare(es, "TruthElectrons");
        declare(SmearedParticles(es, ELECTRON_EFF_CMS_RUN2, ELECTRON_SMEAR_CMS_RUN2), "Electrons");

        // Muon Final States
        FinalState mus(Cuts::abspid == PID::MUON && Cuts::abseta < 2.4);
        declare(mus, "TruthMuons");
        declare(SmearedParticles(mus, MUON_EFF_CMS_RUN2, MUON_SMEAR_CMS_RUN2), "Muons");

    //Charged Final States
        ChargedFinalState cfs(Cuts::abseta < 2.5);
        declare(cfs, "TruthCharged");
        declare(SmearedParticles(cfs,TRK_EFF_ATLAS_RUN2),"Charged");

         //Neutral Final State
         NeutralFinalState nfs(Cuts::abseta < 2.5);
         declare(nfs, "Neutrals");

         //Photon Final State
         IdentifiedFinalState photons(fs);
         photons.acceptId(PID::PHOTON);
         declare(photons, "Photons");

         // Jet Final State
         FastJets fj(fs, FastJets::ANTIKT, 0.5);
         declare(fj, "TruthJets");
     declare(SmearedJets(fj, JET_SMEAR_ATLAS_RUN2), "Jets");

     // Missing Momentum Final State
     MissingMomentum mm(fs);
     declare(mm, "TruthMET");
     declare(SmearedMET(mm, MET_SMEAR_ATLAS_RUN2), "MET");

        // Book histograms
                  //_h_m_emu_truth = bookHisto1D("m_emu_truth", 25, 79, 103);
        _h_m_emu       = bookHisto1D("m_emu", 25, 60, 120);
    _h_pT_jet      = bookHisto1D("m_emu_JV", 40, 0, 200);
    _h_pT_e        = bookHisto1D("pT_e", 40, 0, 100);
        _h_pT_mu       = bookHisto1D("pT_mu", 40, 0, 100);
```

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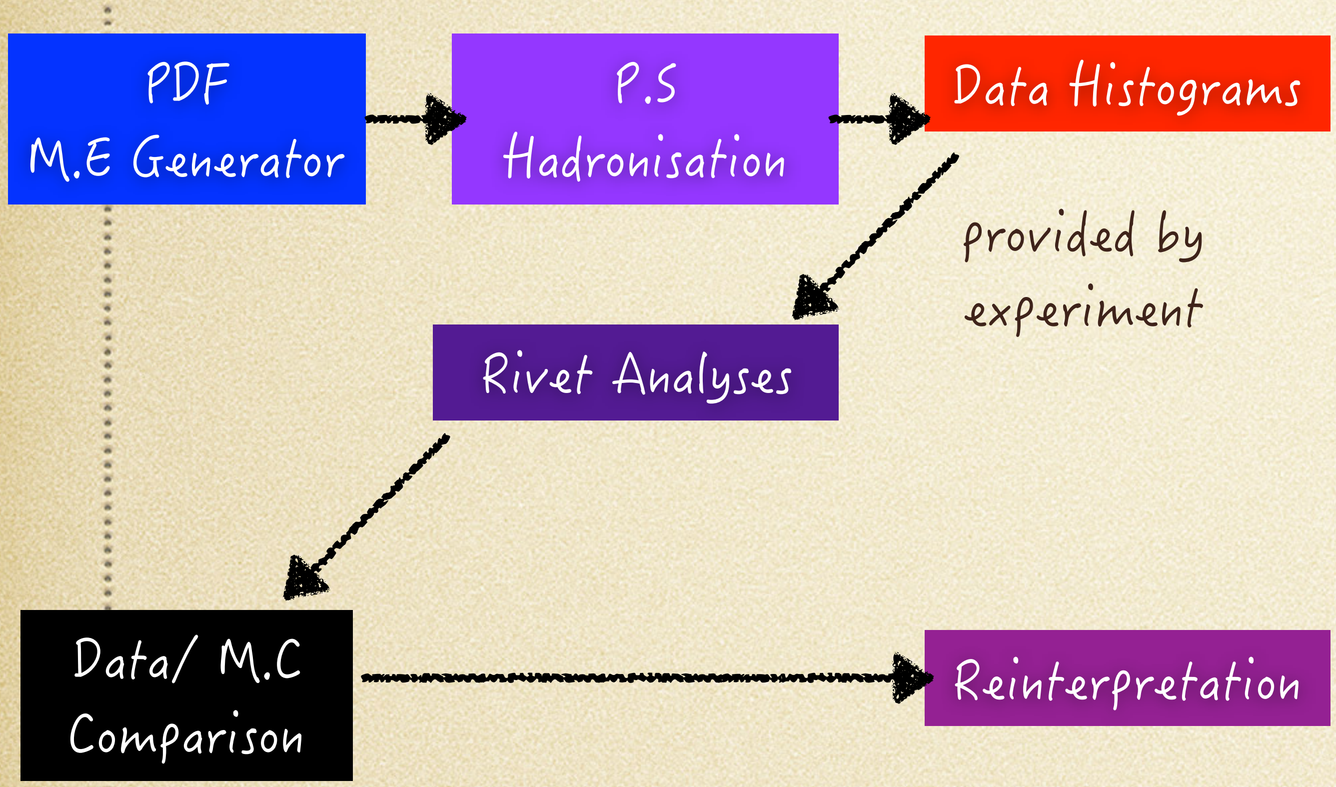

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- ATLAS_2010_S8919674 – W + jets jet multiplicities and $p_\perp$

+250 Analysis available and validated

analyze(): holds projections of interesting quantities, event selection, and histogram filling.

```
void analyze(const Event& event) {

        // Get the event weight
    double weight = event.weight();

        // Get electrons & muons
        Particles elecs         = apply<ParticleFinder>(event,"Electrons").particlesByPt(Cuts::pT>10*GeV);
        Particles muons         = apply<ParticleFinder>(event,"Muons").particlesByPt(Cuts::pT>10*GeV);

        Particles truth_elecs   = apply<ParticleFinder>(event, "TruthElectrons").particlesByPt(Cuts::pT>10*GeV);
        Particles truth_muons   = apply<ParticleFinder>(event,     "TruthMuons").particlesByPt(Cuts::pT>10*GeV);

        //Get jet
        Jets jets = apply<JetAlg>(event, "Jets").jetsByPt(Cuts::pT>20*GeV);

        // Use existing invariant mass calculation infrastructure --- no chaching
        InvMassFinalState invfs({ {PID::ELECTRON, PID::ANTIMUON}, {PID::MUON, PID::POSITRON} }, 60*GeV, 120*GeV);

    // Lepton Isolation
    Particles sigelecs = filter_select(elecs,Cuts::abseta < 2.5);
    Particles sigmuons = filter_select(muons,Cuts::abseta < 2.4);

    const Particles charged = apply<ParticleFinder>(event, "Charged").particles();
    const Particles neutral = apply<ParticleFinder>(event, "Neutrals").particles();
    const Particles photon = apply<ParticleFinder>(event, "Photons").particles();

    // Muon isolation: have I included the muon in sum pT? If so this should not be, this is double counting

    ifilter_discard(sigmuons, [&](const Particle& mu){
        double muPt = mu.pT()/GeV;

        double sumPtCharged = 0.0;
        for (const Particle& c:charged)
          if (deltaR(c,mu) < 0.4) sumPtCharged += c.pT()/GeV;
                sumPtCharged -= muPt;

       double sumEtNeutral = 0.0;
        for (const Particle& n:neutral)
          if (deltaR(n,mu) < 0.4) sumEtNeutral += n.Et()/GeV;

        double sumEtPhoton = 0.0;
        for (const Particle& p:photon)
          if (deltaR(p,mu) < 0.4) sumEtPhoton += p.Et()/GeV;

        double sumPtChargedHadron = 0.0;
        for (const Particle& ch:charged)
          if ( PID::isHadron(ch.pid()) && deltaR(ch,mu) < 0.4 && ch.origin().mod() > 0) sumPtChargedHadron += ch.pT();

        const double I = (sumPtCharged + max(sumEtNeutral + sumEtPhoton -0.5*sumPtChargedHadron, 0.0))/muPt;
        return I > 0.12;
                  });

    // Electron isolation
      ifilter_discard(sigelecs, [&](const Particle& e){
          double ePt= e.pT()/GeV;

        double sumPtCharged = 0.0;
        for (const Particle& c:charged)
```

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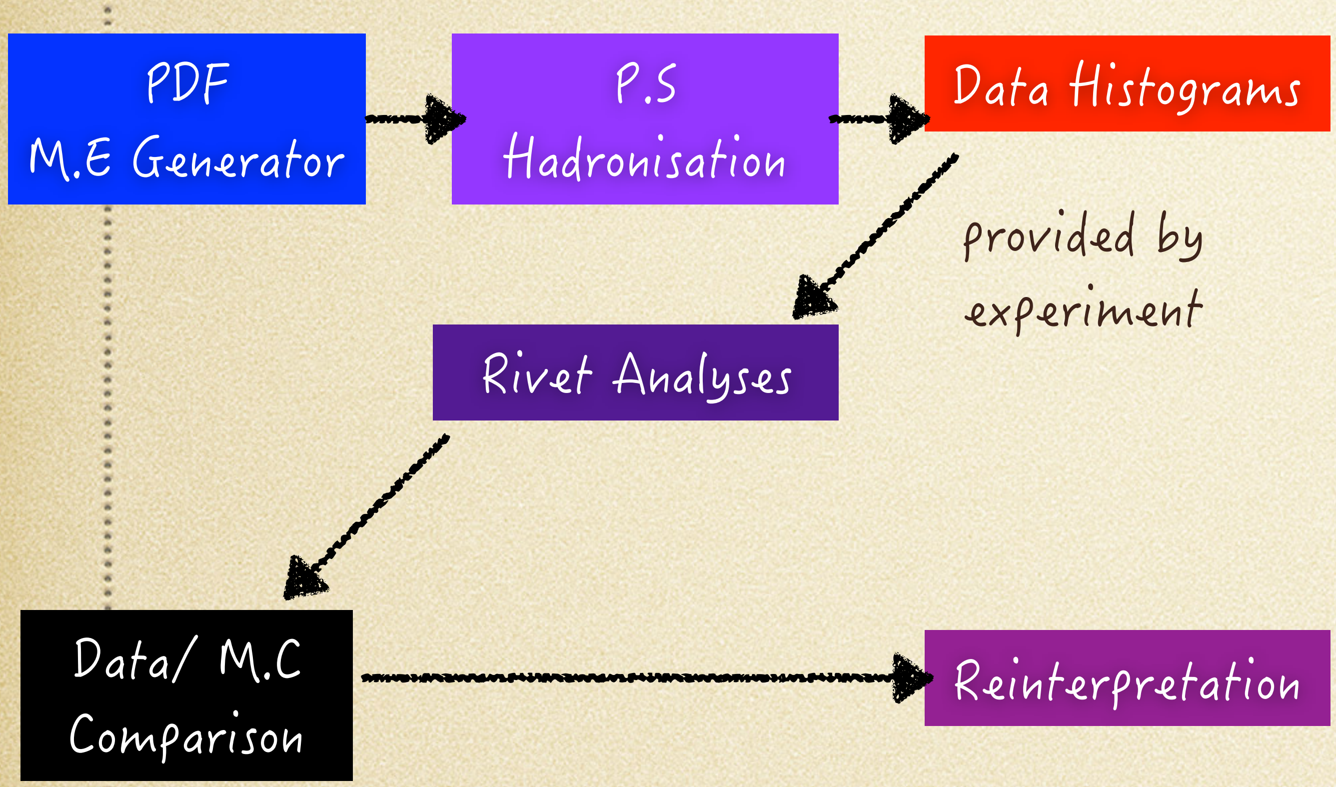

finalize: Any post-processing of outgoing information (e.g. histograms)

```
void finalize() {

      const double sf = crossSection()/femtobarn/sumOfWeights();
   scale(_h_pT_jet, sf);       // norm to cross-section
   scale(_h_pT_e, sf); // norm to cross-section
   scale(_h_pT_mu, sf); // norm to cross-section
   scale(_h_m_emu, sf);
   scale(_h_mu_mT, sf);
 }

      Histo1DPtr   _h_pT_jet;
      Histo1DPtr   _h_pT_e;
      Histo1DPtr   _h_pT_mu;
      Histo1DPtr   _h_m_emu;
      Histo1DPtr   _h_mu_mT;
};
 // The hook for the plugin system
      DECLARE_RIVET_PLUGIN(ZMUE);
```

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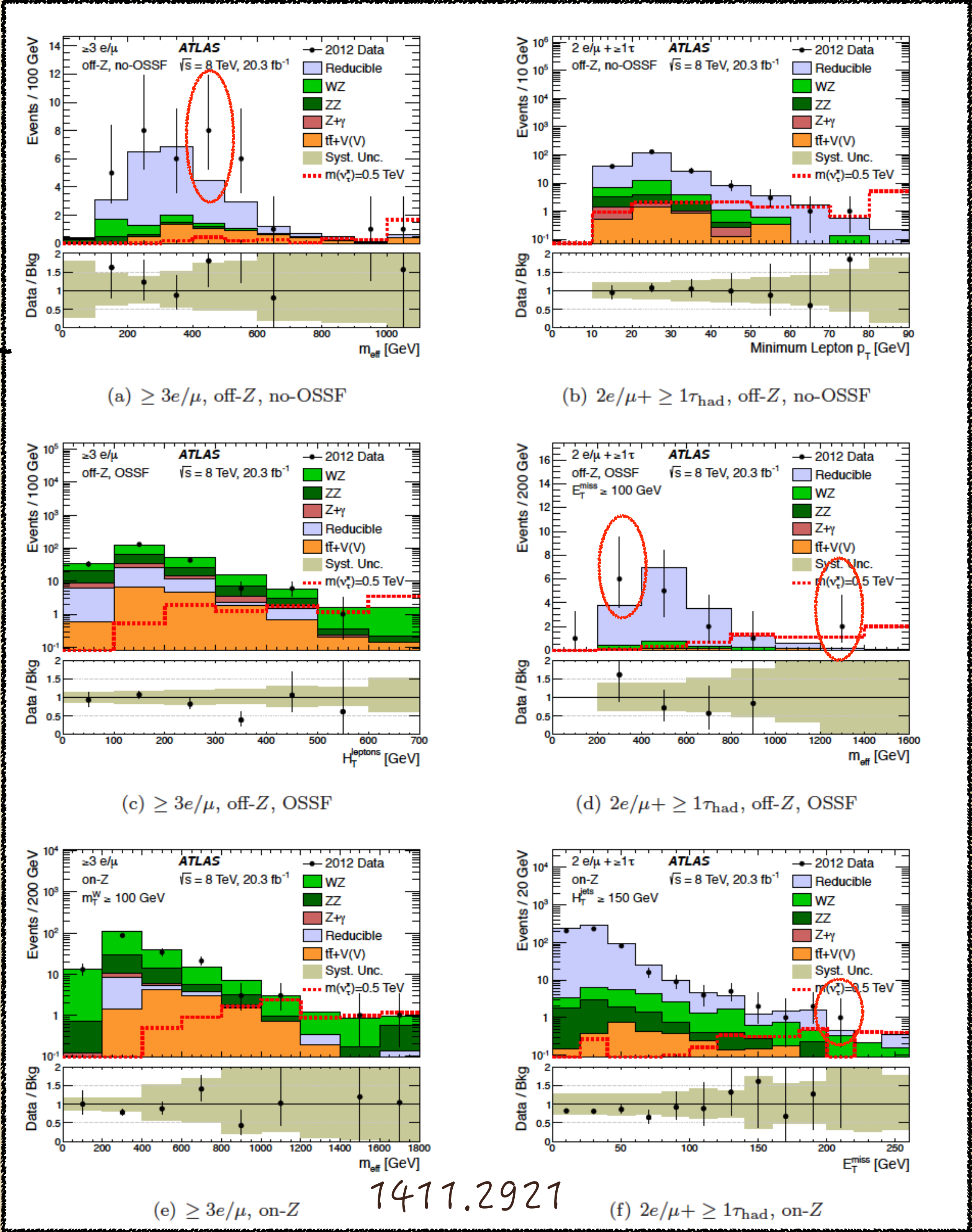
The ATLAS Measurement

Search for new phenomena in events with three or more charged leptons in pp collisions at $\sqrt{s} = 8$ TeV with ATLAS detector

Event Selection

weighted events need MC to be smeared

- c.o.m 8 TeV and 20 fb^{-1} integrated luminosity
- 2 channels: $\geq$ 3 e/μ and 2 $e/\mu + \geq 1\tau$
- $|\eta|_e < 2.47$, $|\eta|_\mu < 2.47$
- $p_T\, e > 10$ GeV, $p_T\, \mu > 10$ GeV
- p_T jet > 30 GeV, $|\eta| < 4.9$.
- Only select hadronically decaying τ
- Ensure good separation between leptons and jets (see analysis for more details)



(a) $\geq 3e/\mu$, off-Z, no-OSSF
(b) $2e/\mu + \geq 1\tau_{\rm had}$, off-$Z$, no-OSSF
(c) $\geq 3e/\mu$, off-Z, OSSF
(d) $2e/\mu + \geq 1\tau_{\rm had}$, off-$Z$, OSSF
(e) $\geq 3e/\mu$, on-Z
(f) $2e/\mu + \geq 1\tau_{\rm had}$, on-$Z$

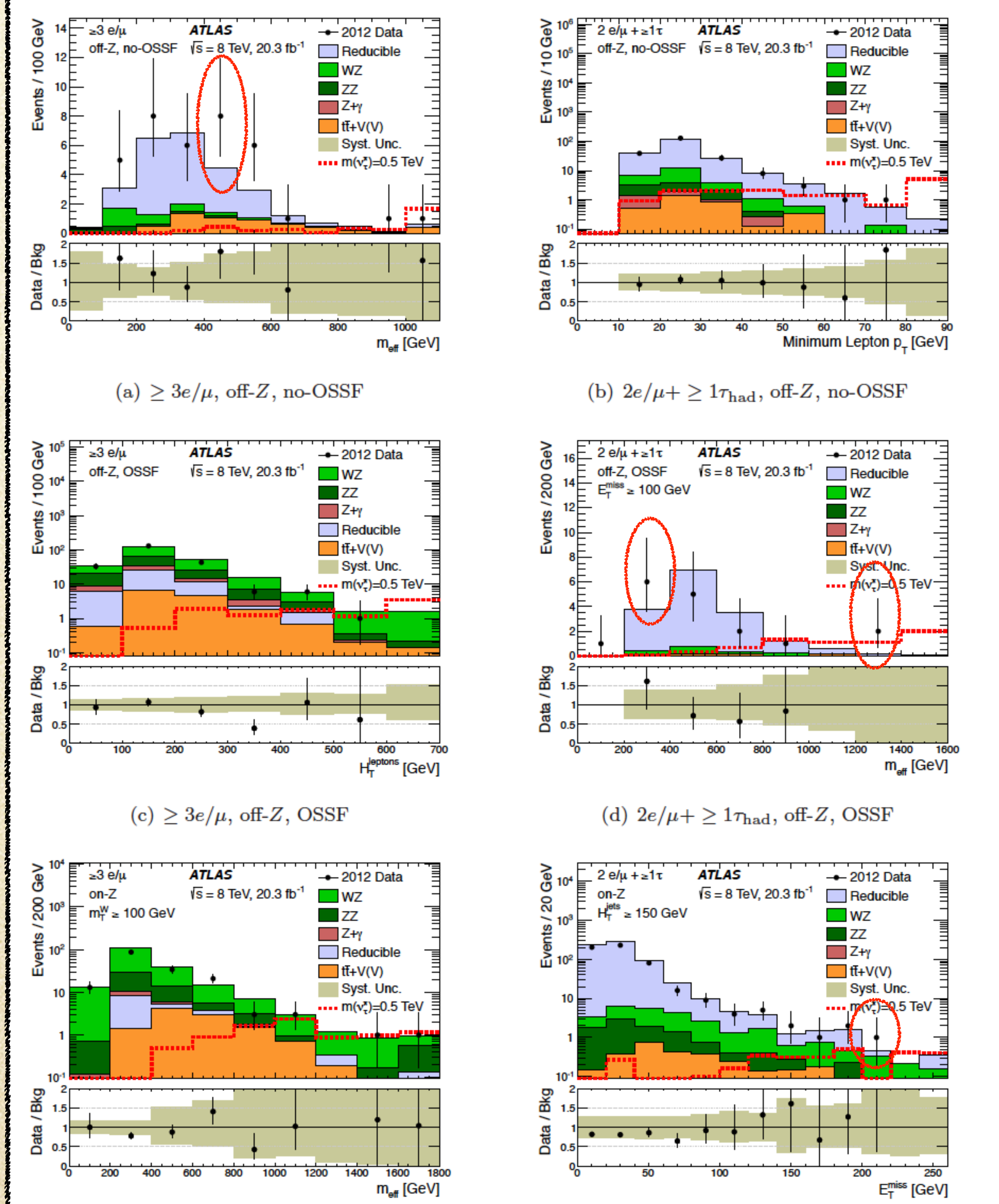
1411.2921

The ATLAS Measurement

Search for new phenomena in events with three or more charged leptons in pp collisions at $\sqrt{s} = 8$ TeV with ATLAS detector

Signal Regions

- Several kinematic variables used to characterise events
- Minimum lepton p_T : of 3 leptons used to characterise event
- $H^{leptons}$: scalar sum of pT
- m_{eff} : scalar sum of missing E_T + p_T jets and pT leptons



(a) $\geq 3e/\mu$, off-Z, no-OSSF

(b) $2e/\mu + \geq 1\tau_{\text{had}}$, off-$Z$, no-OSSF

(c) $\geq 3e/\mu$, off-Z, OSSF

(d) $2e/\mu + \geq 1\tau_{\text{had}}$, off-$Z$, OSSF

(e) $\geq 3e/\mu$, on-Z

(f) $2e/\mu + \geq 1\tau_{\text{had}}$, on-$Z$

1411.2921

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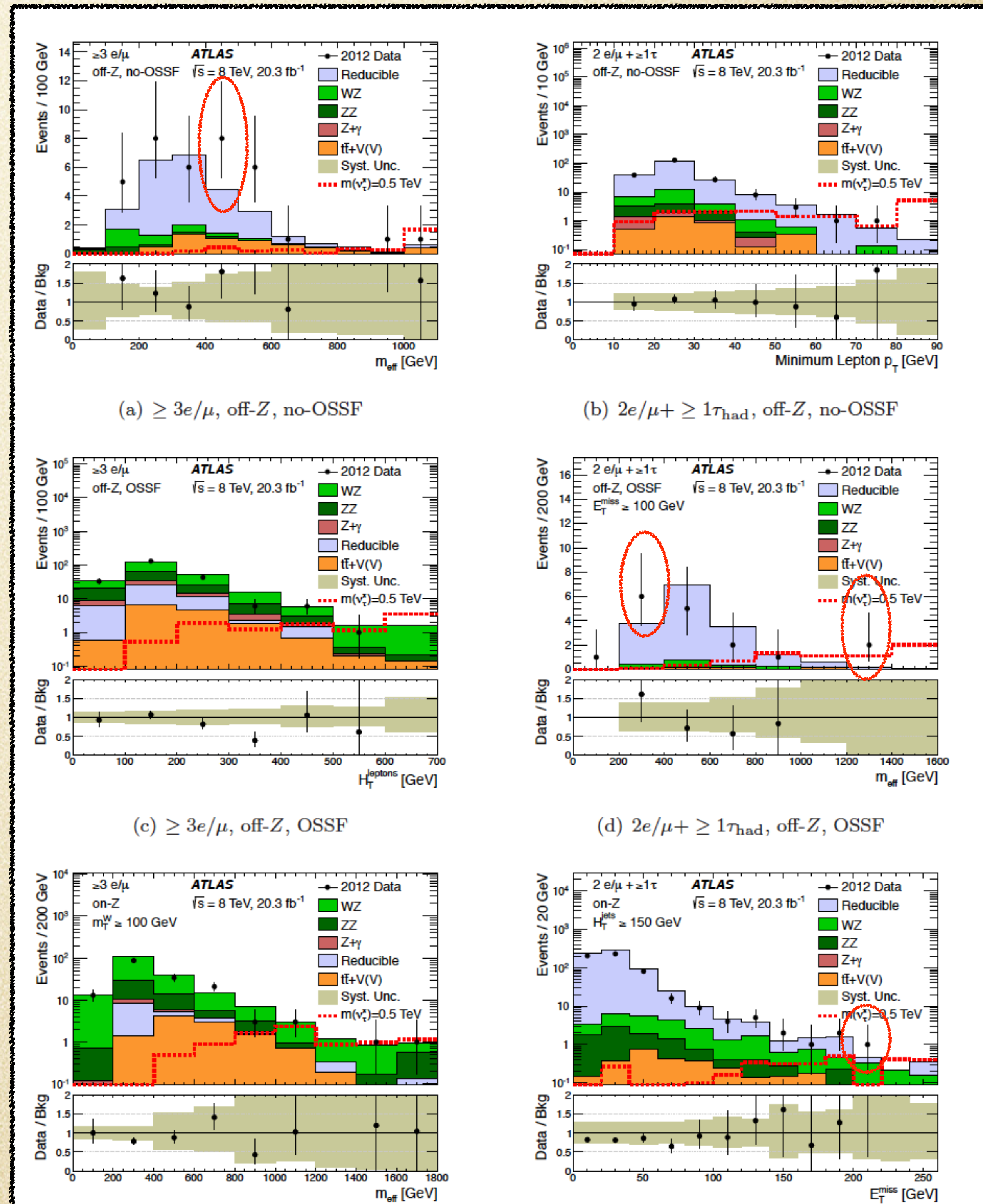
Backgrounds

- Main backgrounds: WZ, ZZ, Zγ, ttbar + W/Z
- Search is not very efficient: most of our events get thrown away 😕
- Also backgrounds are **quite** consistent with data. Either insensitive or very constraining! 😫
- Keep calm and try anyways 🤞
- In our results, we account for BG uncertainties and we checked with ATLAS the BGs are not correlated [1].

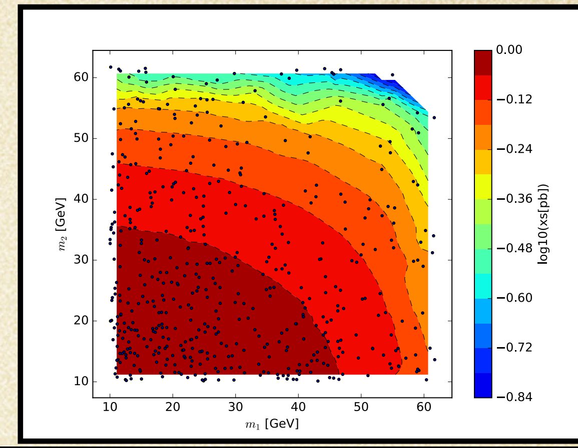


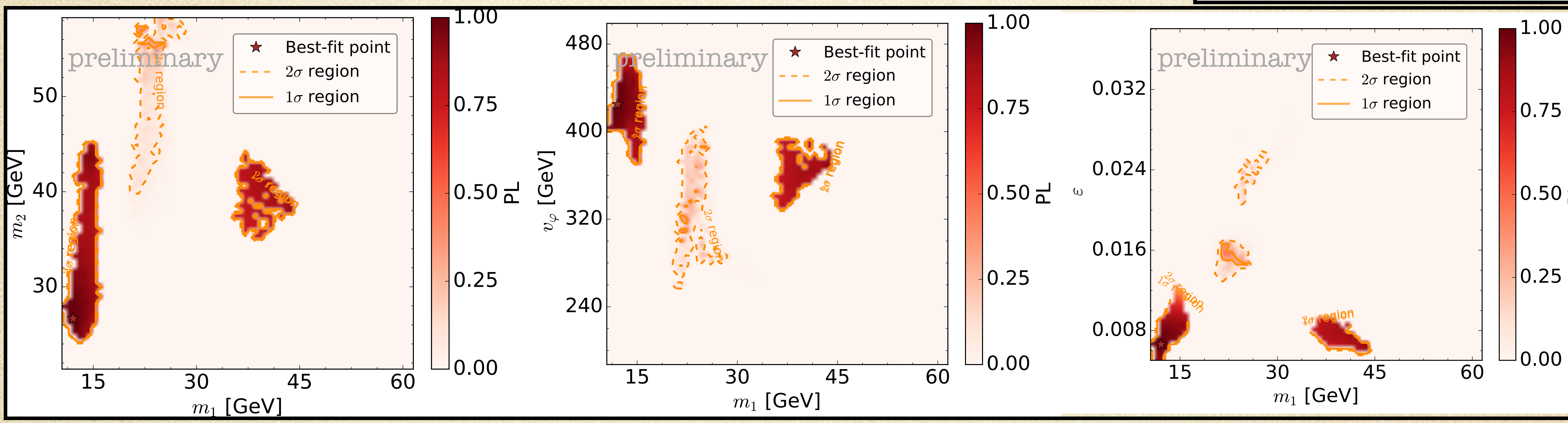
(a) $\geq 3e/\mu$, off-Z, no-OSSF
(b) $2e/\mu + \geq 1\tau_{\rm had}$, off-$Z$, no-OSSF
(c) $\geq 3e/\mu$, off-Z, OSSF
(d) $2e/\mu + \geq 1\tau_{\rm had}$, off-$Z$, OSSF
(e) $\geq 3e/\mu$, on-Z
(f) $2e/\mu + \geq 1\tau_{\rm had}$, on-$Z$

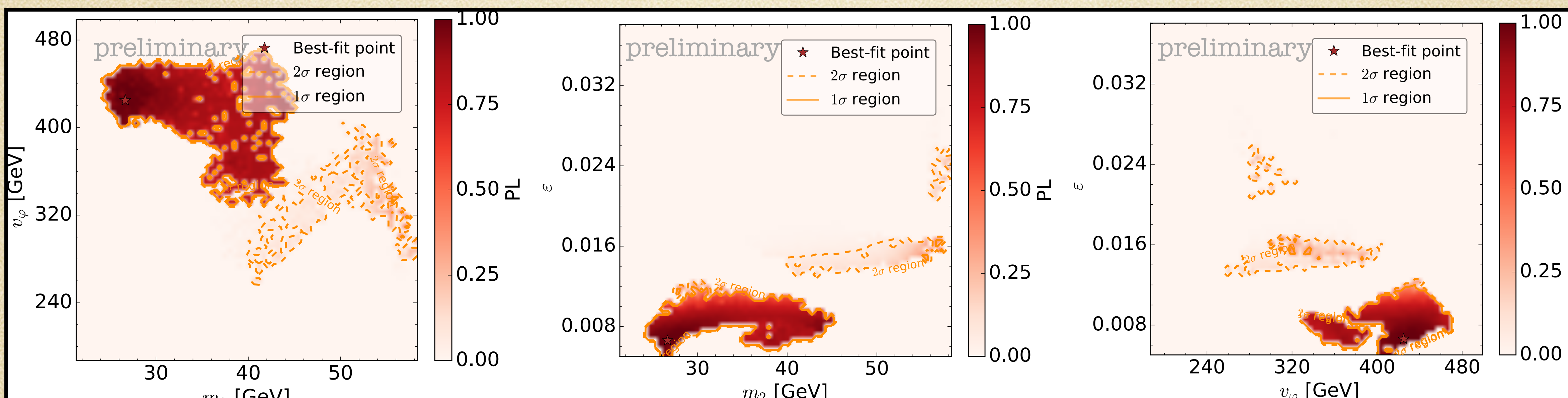
1. Thanks to Beate Heinemann and Mike Hance

Very Preliminary Results

- Cross Section looks consistent
- High flavour breaking scale, small mixing as expected







Comments

- A Priori it is not clear the flavour breaking scale is very high
- Given the wealth of data collected by LHC (I think) it is worth looking
- We have established a robust and efficient tool chain to do so
- What's Next? Scalar masses heavier than mH/2. However current search may not be sensitive.
- Z3-breaking: additional channel H-> H sc2.
- 13 TeV Searches
- Suggestions or Models you would like to constrain?
- If all of this sounds like a painful process, ATLAS may provide a framework to do it for you: RECAST (Kyle Cranmer & Lukas Heinrich)

https://arxiv.org/abs/1010.2506

Back Up Slides: Rivet and Sherpa Docker Images

Download Docker Image for Rivet and run Z tau tau events

https://rivet.hepforge.org/trac/wiki/Docker

Download Docker Image for Sherpa

https://sherpa.hepforge.org/trac/wiki/Docker

Follow a Rivet Tutorial

https://www.hepforge.org/archive/rivet/Talk.pdf

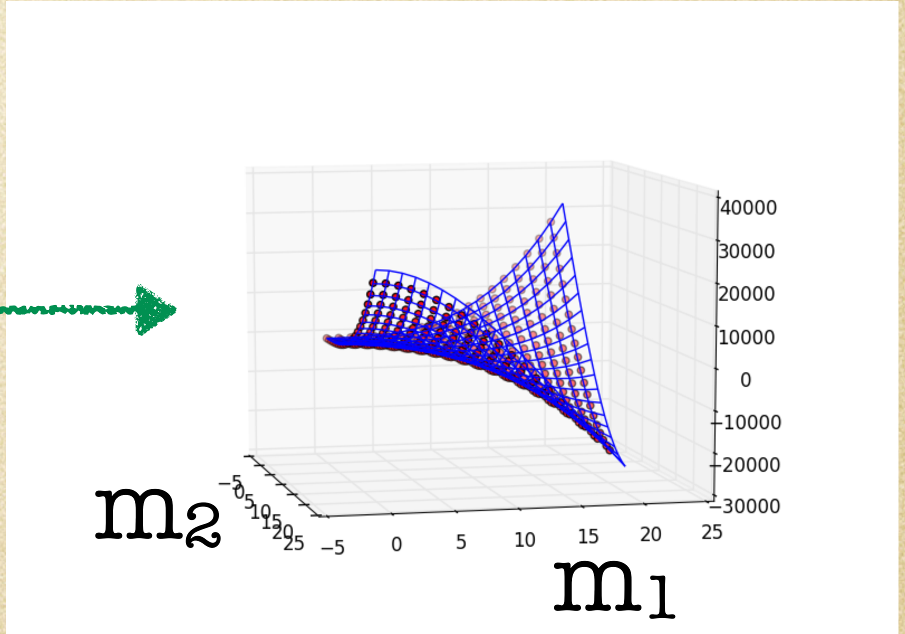
Back Up Slides: Professor

Idea: Professor parametrises (per bin) the signal as a polynomial of the model parameters

MultiNest: Evaluates Likelihood for specific point in model parameter space and then cleverly moves to next point in model parameter space where likelihood is higher.

Rather than rerun generator for this point, Professor provides the signal from the polynomial parametrisation.

Points in model parameter space
Professor provides a "surface"
over such points.



https://arxiv.org/pdf/0907.2973.pdf