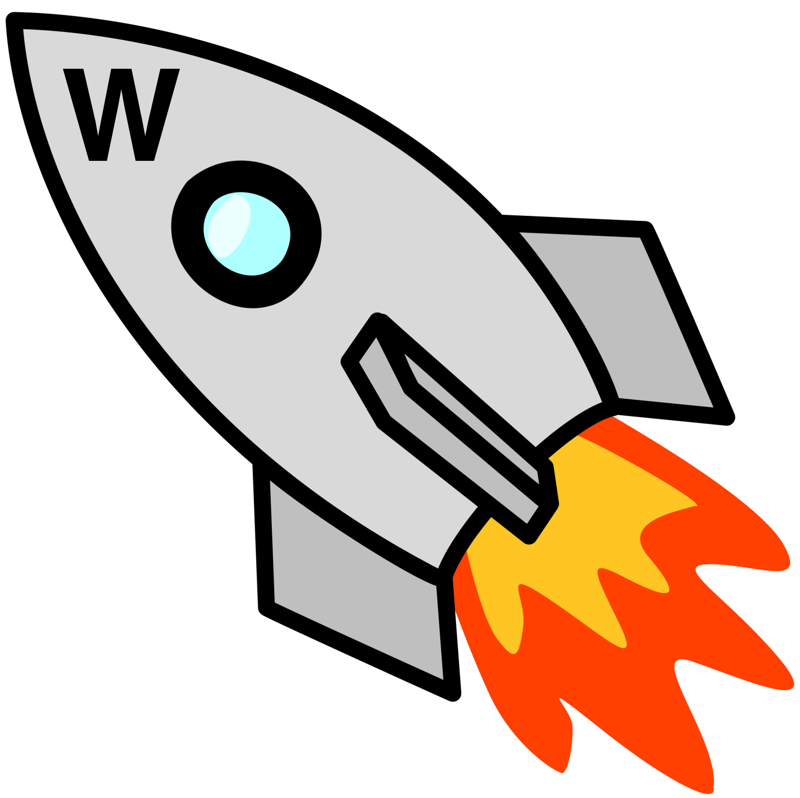
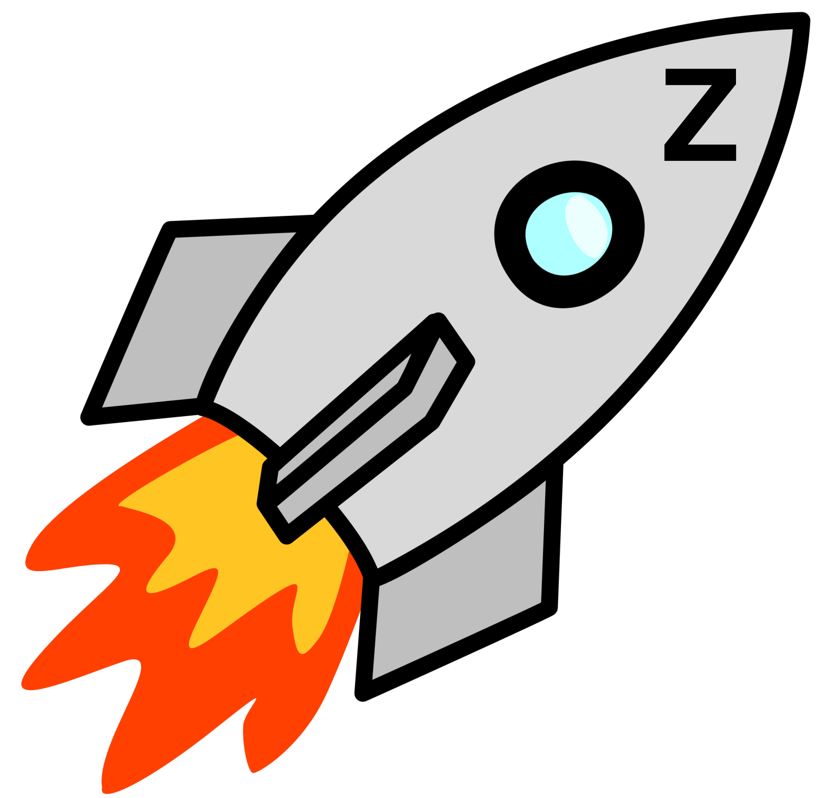
Discovery and Study of Resonances Decaying to Boosted Vector Bosons

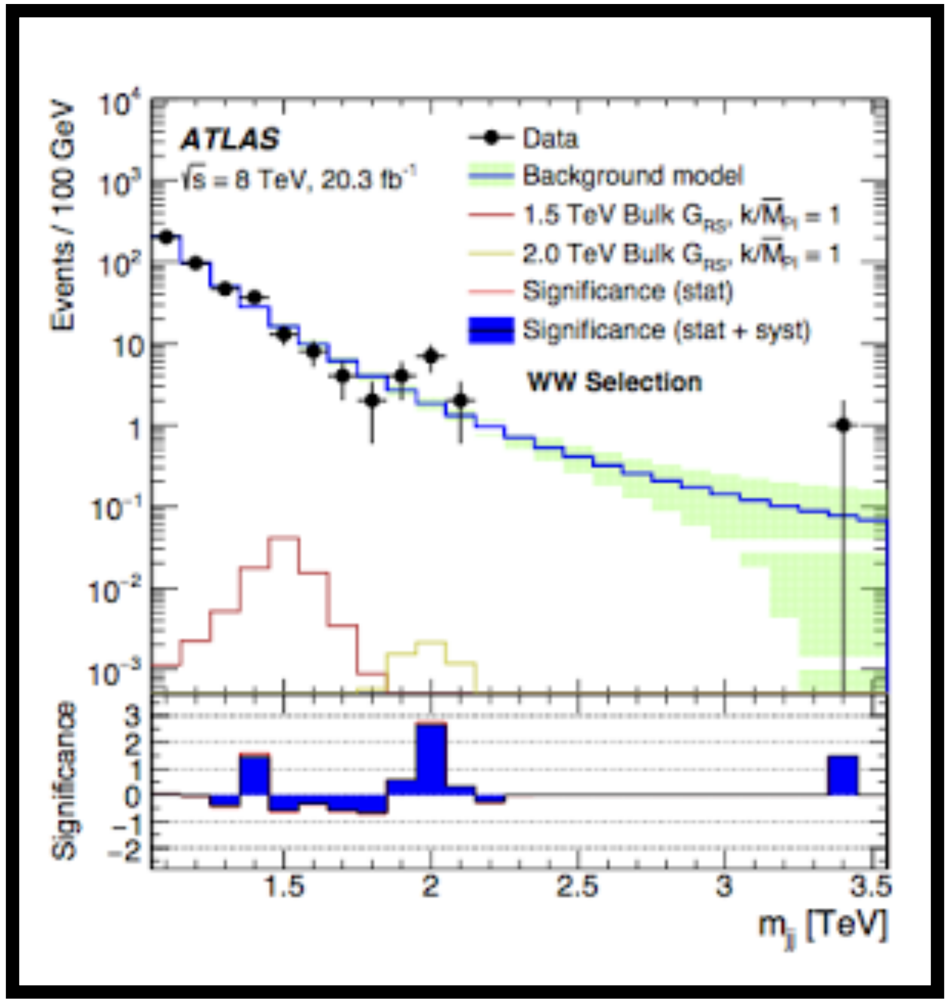




Jamie Gainer
University of Florida
BOOST 2015
August 11, 2015

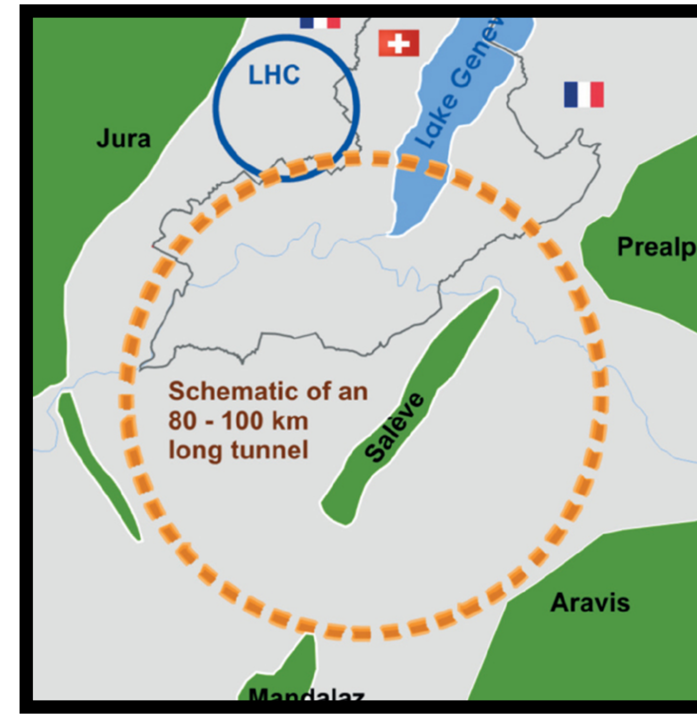
It Takes Two (Electroweak Gauge Bosons)

- Diboson final states (WW, WZ, ZZ) are fascinating
  - EWSB
  - Emissary of heavy new physics?
- Higgs
- Randall-Sundrum Gravitons
  (Agashe, Davoudiasl, Perez, Soni, 2007; etc.)
- Test of anomalous SM couplings
- A signature of unexpected new physics?



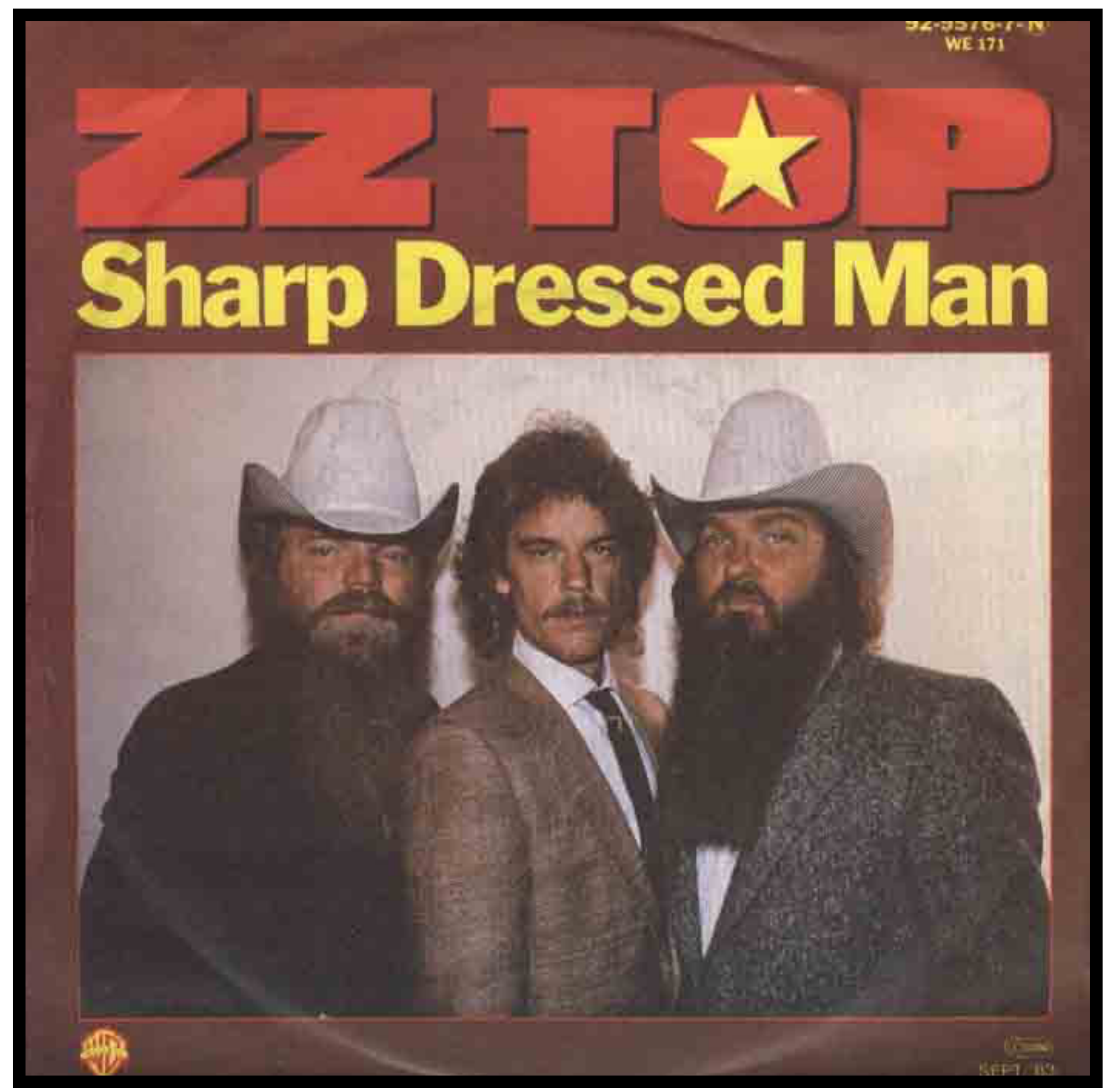
It Takes Two (Electroweak Gauge Bosons)

- Additionally, diboson signatures provide good benchmarks for for future colliders
- More complicated than Z’ signatures
- Complementary to SUSY benchmark approaches



The Higgs Boson

- The Higgs has relatively strong couplings to WW and ZZ, which are connected to the mass of these gauge bosons
- Diboson channels play a crucial role in Higgs studies

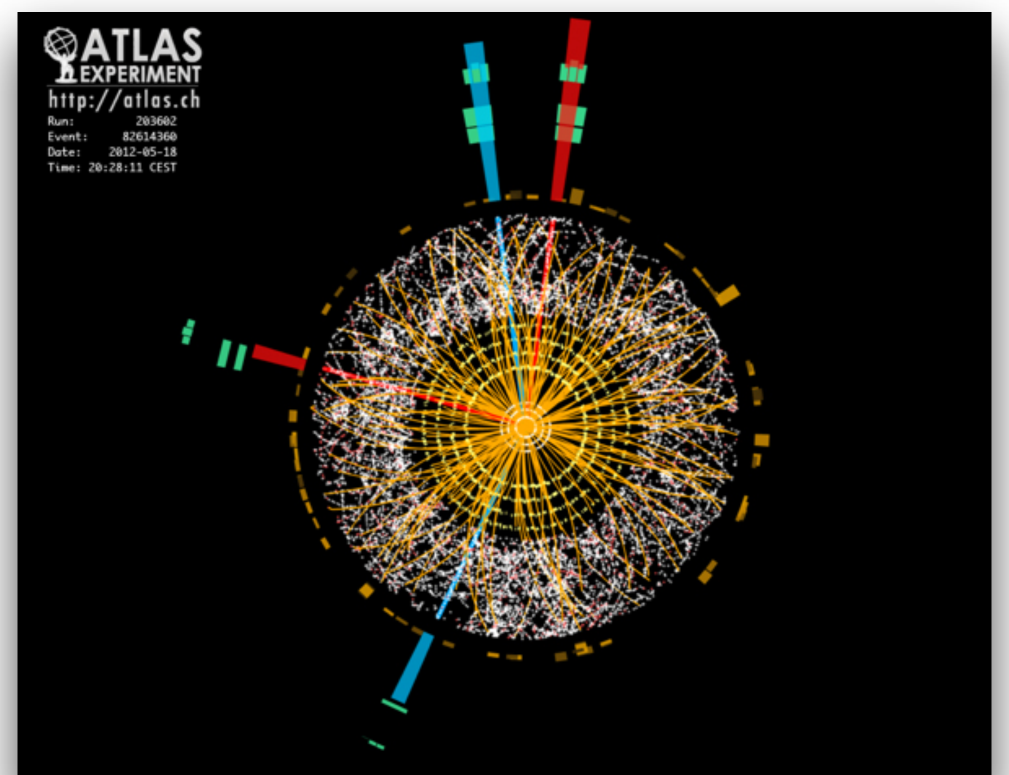


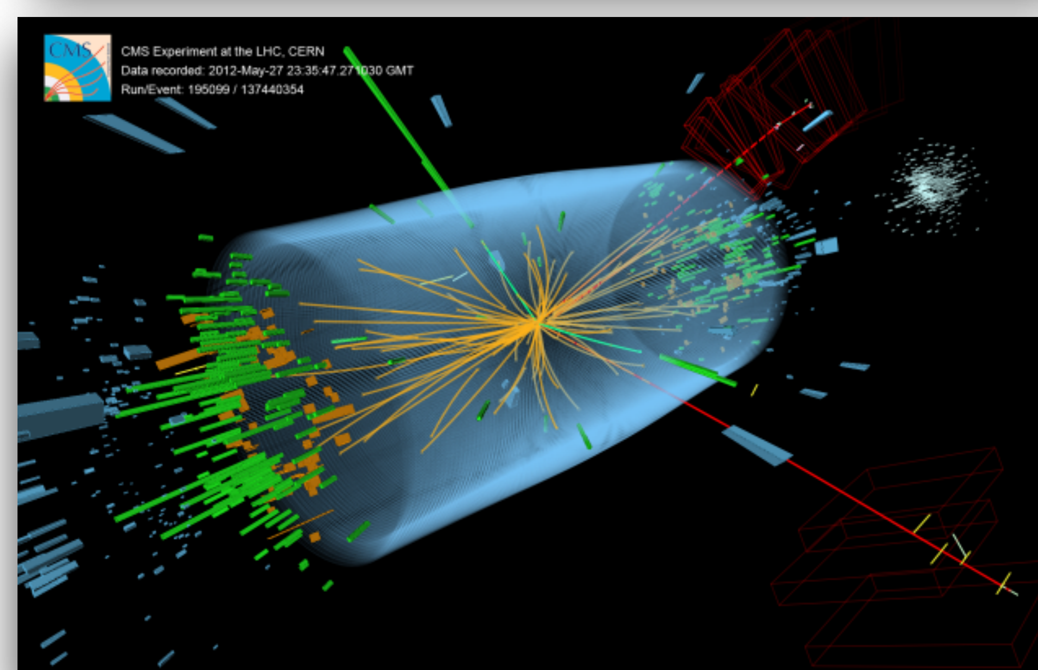
The Higgs Boson

- The Higgs has relatively strong couplings to WW and ZZ, which are connected to the mass of these gauge bosons
- Diboson channels play a crucial role in Higgs studies

Discovery

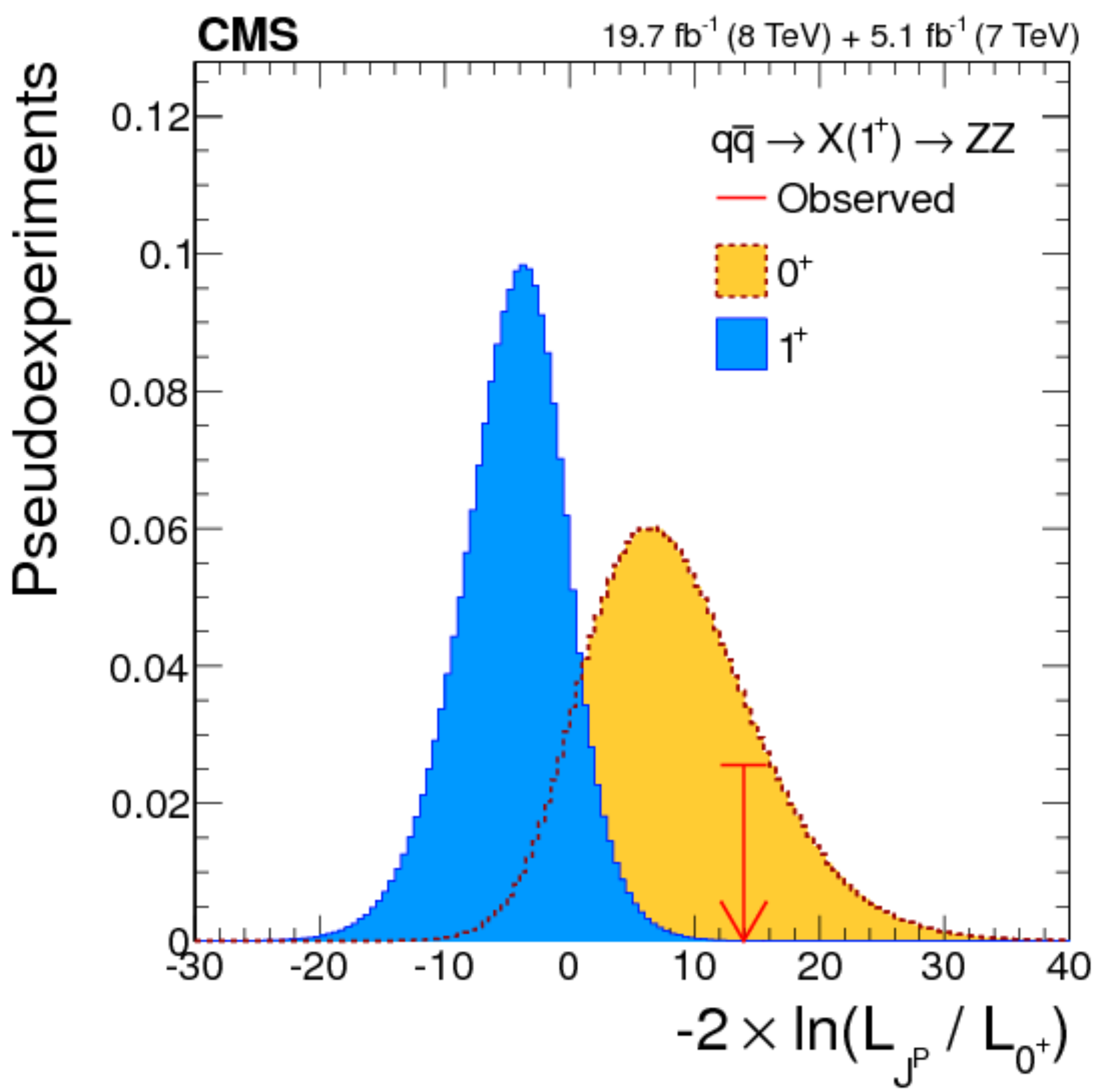
The Higgs to ZZ*
to four lepton channel
was one of the two main
discovery channels

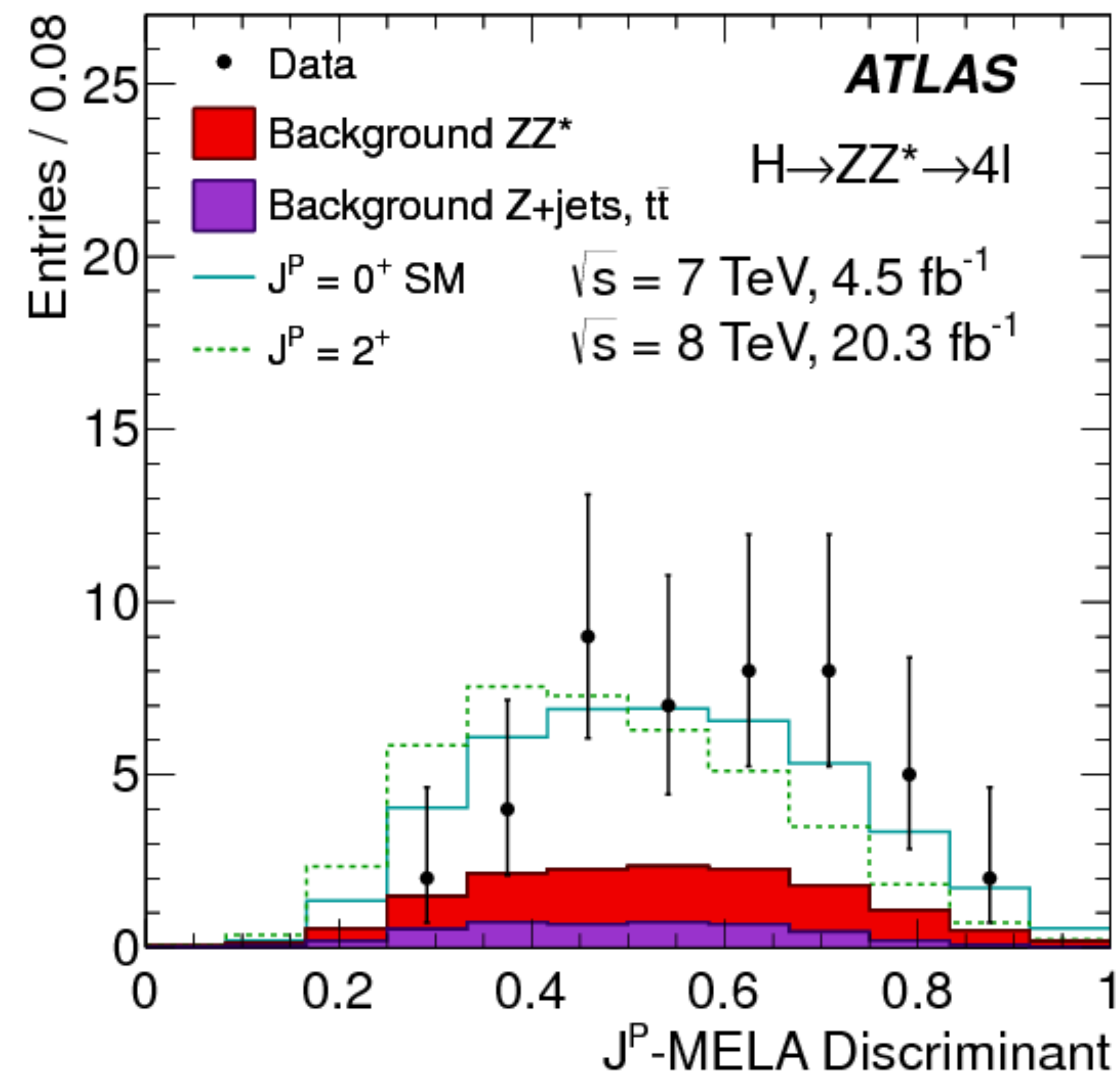




(The other major discovery channel, H $\rightarrow \gamma\gamma$, is also a diboson channel.)

Spin and Parity…





(N.B. Higgs couplings studies go well beyond spin and parity…)

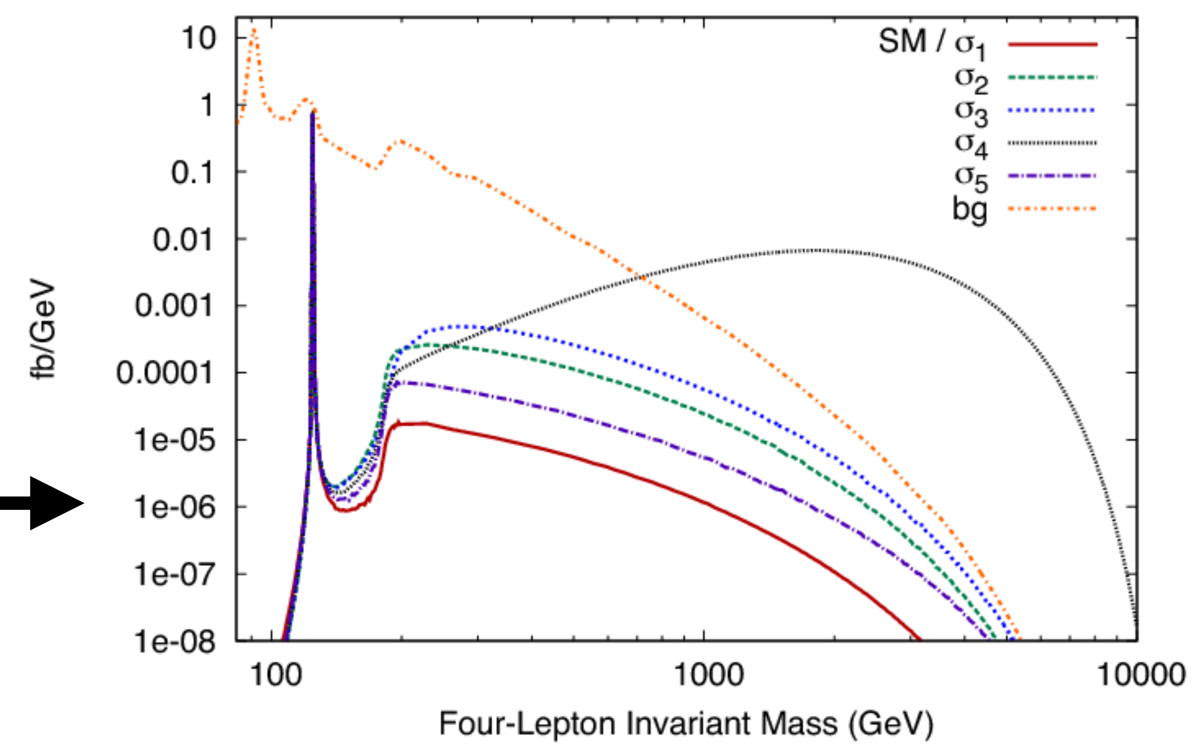
and Beyond

- Off-shell four-lepton events can be used to constrain/ discover an anomalous Higgs width

(Kauer and Passarino, 2012;
Caola and Melnikov, 2013;
Campbell, Ellis, Williams, 2013; etc.)

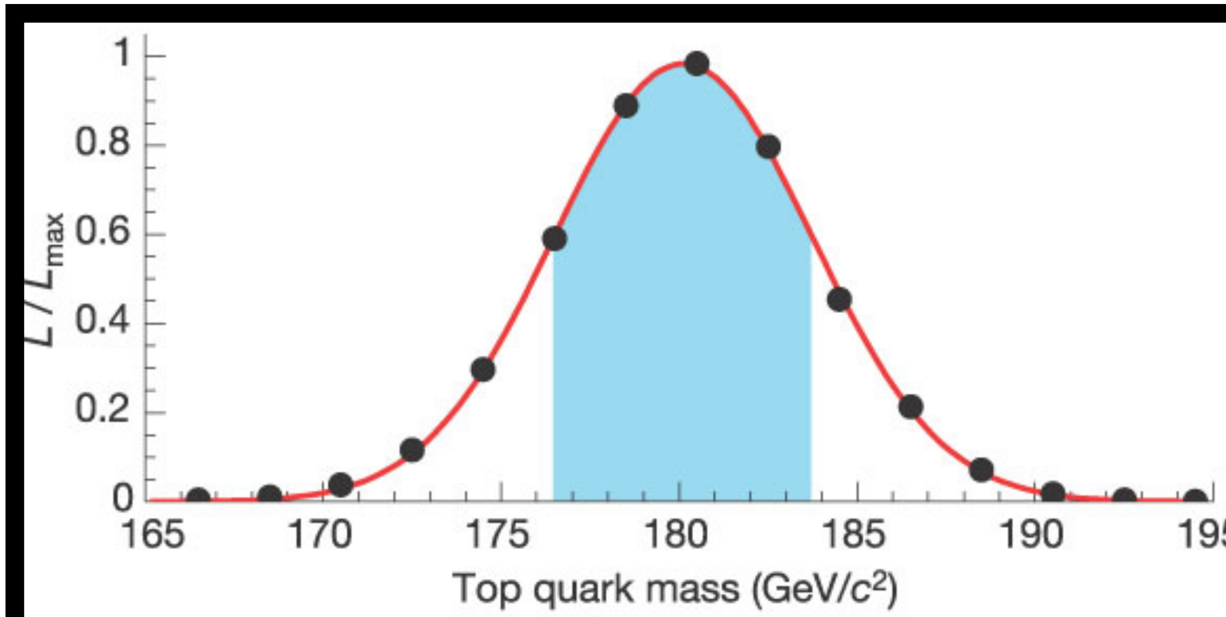
- or the effect of higher dimensional operators

(JSG, Lykken, Matchev, Mrenna, Park, 2014;
Englert and Spannowsky, 2014; etc.) →



The Matrix Element Method

- The **Matrix Element Method** (MEM) is the use of the analytically* calculated likelihood
  - **likelihood ~ normalized differential cross section**
- The **Neyman-Pearson Lemma** suggests that using the likelihood with respect to all possible variables should make the analysis optimal
- Early prominent use in top studies at the Tevatron



D0, 2004

Background: qq → $Z^{(*)}{}_{\lambda 1}\, Z^{(*)}{}_{\lambda 2}$ → 4 ℓ

$$\Delta\lambda = \pm 2: \quad \mathcal{A}^{\Delta\sigma}_{\pm\mp} = -\sqrt{2}(1+\beta_1\beta_2)\,,$$

$$\Delta\lambda = \pm 1: \quad \mathcal{A}^{\Delta\sigma}_{\pm 0} = \frac{1}{\gamma_2(1+x)}\left[(\Delta\sigma\Delta\lambda)\left(1+\frac{\beta_1^2+\beta_2^2}{2}\right) - 2\cos\Theta - (\Delta\sigma\Delta\lambda)(\beta_2^2-\beta_1^2)x - 2x\cos\Theta - (\Delta\sigma\Delta\lambda)\left(1-\frac{\beta_1^2+\beta_2^2}{2}\right)x^2\right]$$

$$: \quad \mathcal{A}^{\Delta\sigma}_{0\pm} = \frac{1}{\gamma_1(1-x)}\left[(\Delta\sigma\Delta\lambda)\left(1+\frac{\beta_1^2+\beta_2^2}{2}\right) - 2\cos\Theta - (\Delta\sigma\Delta\lambda)(\beta_2^2-\beta_1^2)x + 2x\cos\Theta - (\Delta\sigma\Delta\lambda)\left(1-\frac{\beta_1^2+\beta_2^2}{2}\right)x^2\right]$$

$$\Delta\lambda = 0: \quad \mathcal{A}^{\Delta\sigma}_{\pm\pm} = -(1-\beta_1\beta_2)\cos\Theta - \lambda_1\Delta\sigma(1+\beta_1\beta_2)x\,,$$

$$\Delta\lambda = 0: \quad \mathcal{A}^{\Delta\sigma}_{00} = 2\gamma_1\gamma_2\cos\Theta\left[((1-x)\beta_1+(1+x)\beta_2)\sqrt{\frac{\beta_1\beta_2}{1-x^2}} - (1+\beta_1^2\beta_2^2)\right].$$

(JSG, Kumar, Low, Vega-Morales, 2011)

Helicity amplitudes for arbitrarily off-shell Z bosons.

TABLE 8
Coefficients for the helicity amplitudes for the processes $e^+e^- \to ZZ$ and $e^+e^- \to Z\gamma$

$\Delta\lambda$	$(\lambda_1\lambda_2)$	$\mathscr{A}_{\lambda_1\lambda_2}$	$\mathscr{B}_{\lambda_1\lambda_2}$
± 2	$(\pm\mp)$	$-\sqrt{2}(1+\beta^2)$	$\sqrt{2}$
± 1	(± 0)	$\gamma^{-1}[\Delta\sigma\cdot\Delta\lambda(1+\beta^2)-2\cos\Theta]$	
± 1	$(0\pm)$	$\gamma^{-1}[\Delta\sigma\cdot\Delta\lambda(1+\beta^2)-2\cos\Theta]$	$2r(\cos\Theta+\Delta\sigma\cdot\lambda_2)$
0	$(\pm\pm)$	$-\gamma^{-2}\cos\Theta$	$r^2(\cos\Theta+\Delta\sigma\cdot\lambda_2)$
0	(00)	$-2\gamma^{-2}\cos\Theta$	

On-shell Z bosons

(Hagiwara, Hikasa, Peccei, Zeppenfeld, 1986)

$|\Delta\lambda| = 2$ amplitudes dominate for large invariant mass

Signal: $H \rightarrow Z^{(*)}_{\lambda 1}\, Z^{(*)}_{\lambda 2} \rightarrow 4\ \ell$

$$
\begin{aligned}
A_{00} &= -\frac{m_X^2}{v}\left(a_1\sqrt{1+x} + a_2\frac{m_1 m_2}{m_X^2}x\right)\,, \\
A_{++} &= \frac{m_X^2}{v}\left(a_1 + i a_3\frac{m_1 m_2}{m_X^2}\sqrt{x}\right)\,, \\
A_{--} &= \frac{m_X^2}{v}\left(a_1 - i a_3\frac{m_1 m_2}{m_X^2}\sqrt{x}\right)\,,
\end{aligned}
$$

(Bolognesi, Gao, Gritsan, Melnikov, Schulze, Tran, Whitbeck, 2012)

See also (Gao, Gritsan, Guo, Melnikov, Schulze, Tran, 2010; De Rujula, Lykken, Pierini, Rogan, Spiropulu, 2010; Avery, Bourilkov, Chen, Cheng, Drozdetskiy, JSG, Korytov, Matchev, Milenovic, Mitselmakher, Park, Rinkevicius, Snowball, 2012; etc.)

$$
x = \left(\frac{m_X^2 - m_1^2 - m_2^2}{2 m_1 m_2}\right)^2 - 1.
$$

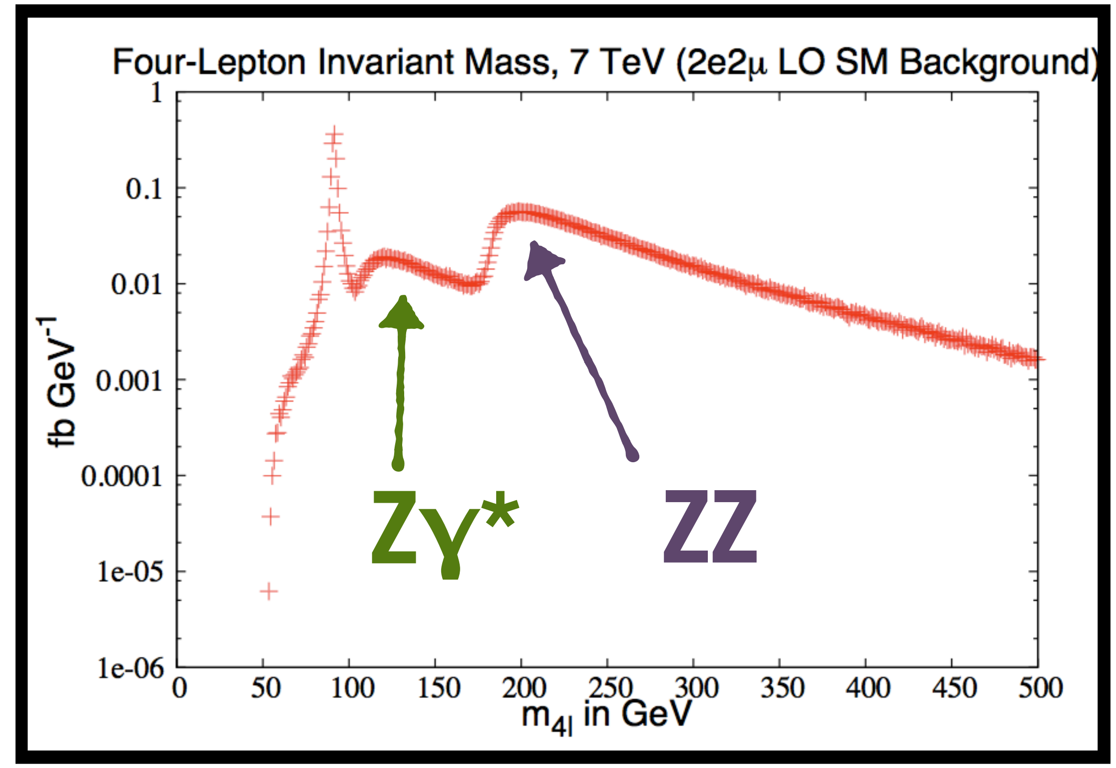
Spin-Zero

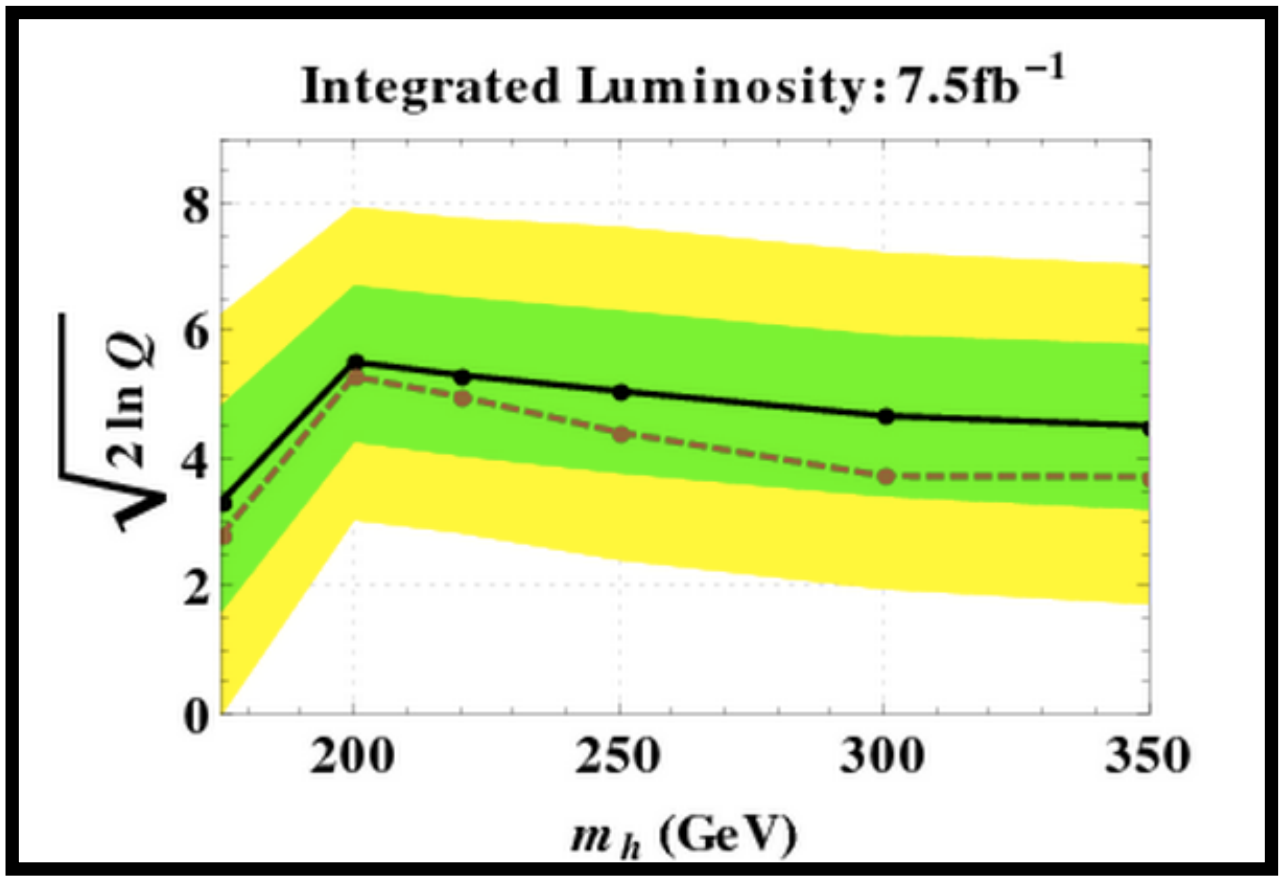
Only $|\Delta\lambda| = 0$ amplitudes non-vanishing

CP odd (a_3): $A_{++} = - A_{--}$

CP-even (a_1, a_2), $A_{++} = A_{--}$

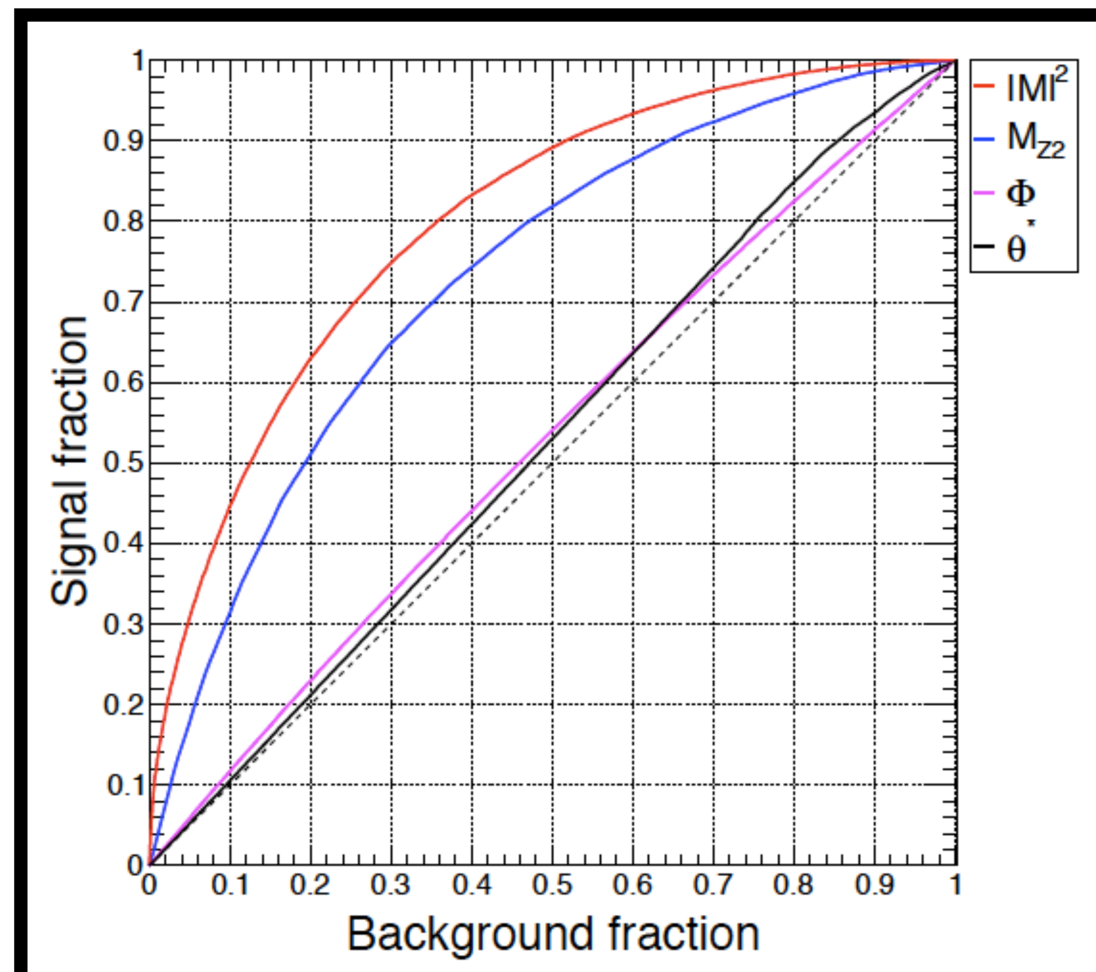
For light Higgs, **dominant** contribution to sensitivity is from different propagators for signal and background





(JSG, Kumar, Low, Vega-Morales, 2011)

For heavy Higgs*, different helicity structure of H→ZZ amplitudes drives sensitivity



(Avery, Bourilkov, Chen, Cheng, Drozdetskiy, JSG, Korytov, Matchev, Milenovic, Mitselmakher, Park, Rinkevicius, Snowball, 2012)

Same Method, Different Physics

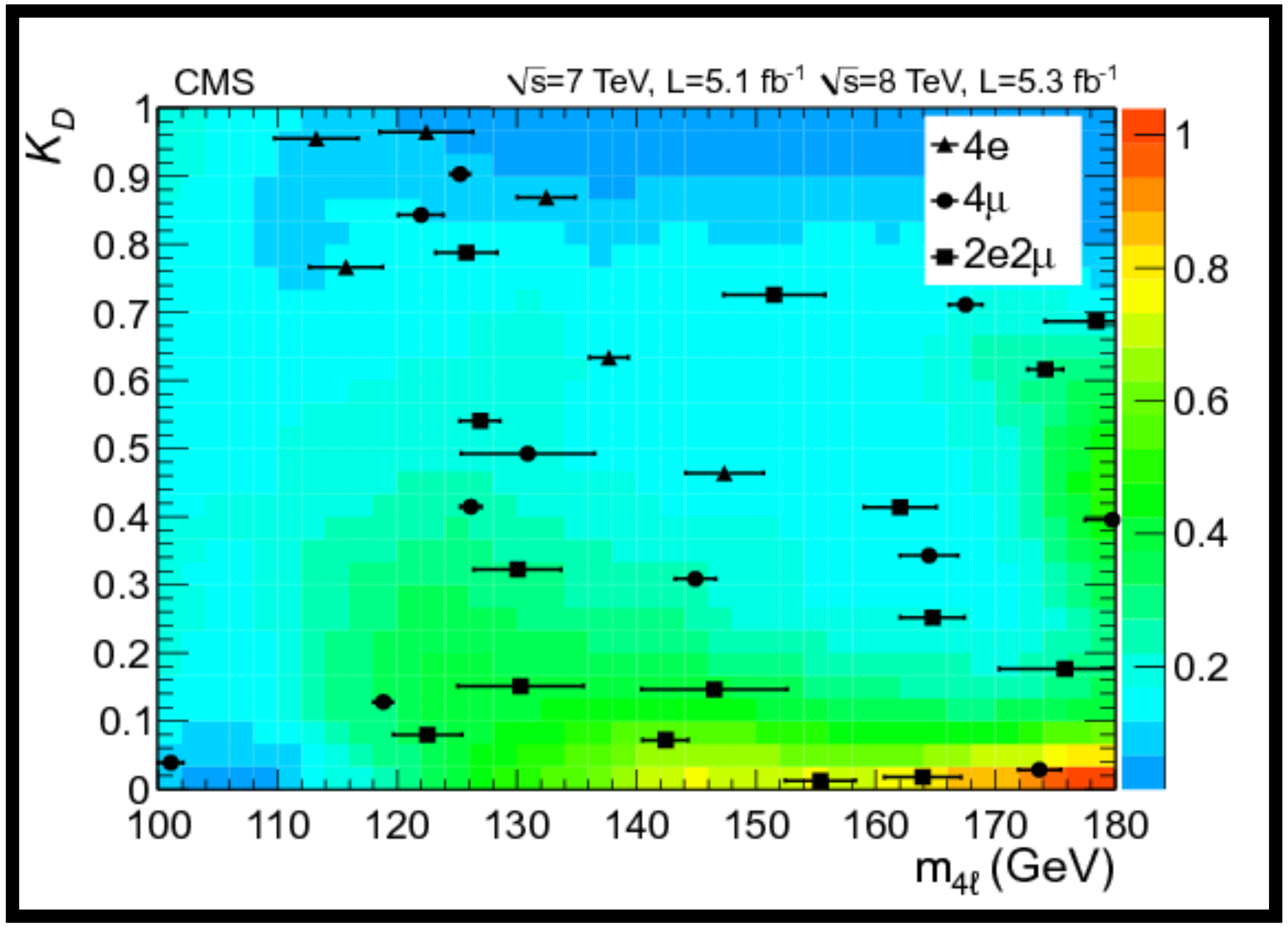
- The Matrix Element Method works well both a heavy Higgs and for the 125 GeV Higgs
- **Heavy Higgs**: Sensitivity Driven by Differences in Helicity Amplitudes, which reflect spin, CP properties of Higgs
- **125 GeV Higgs**: Sensitivity from different propagator structure, ultimately because signal involves the HZZ vertex predicted by the Higgs mechanism

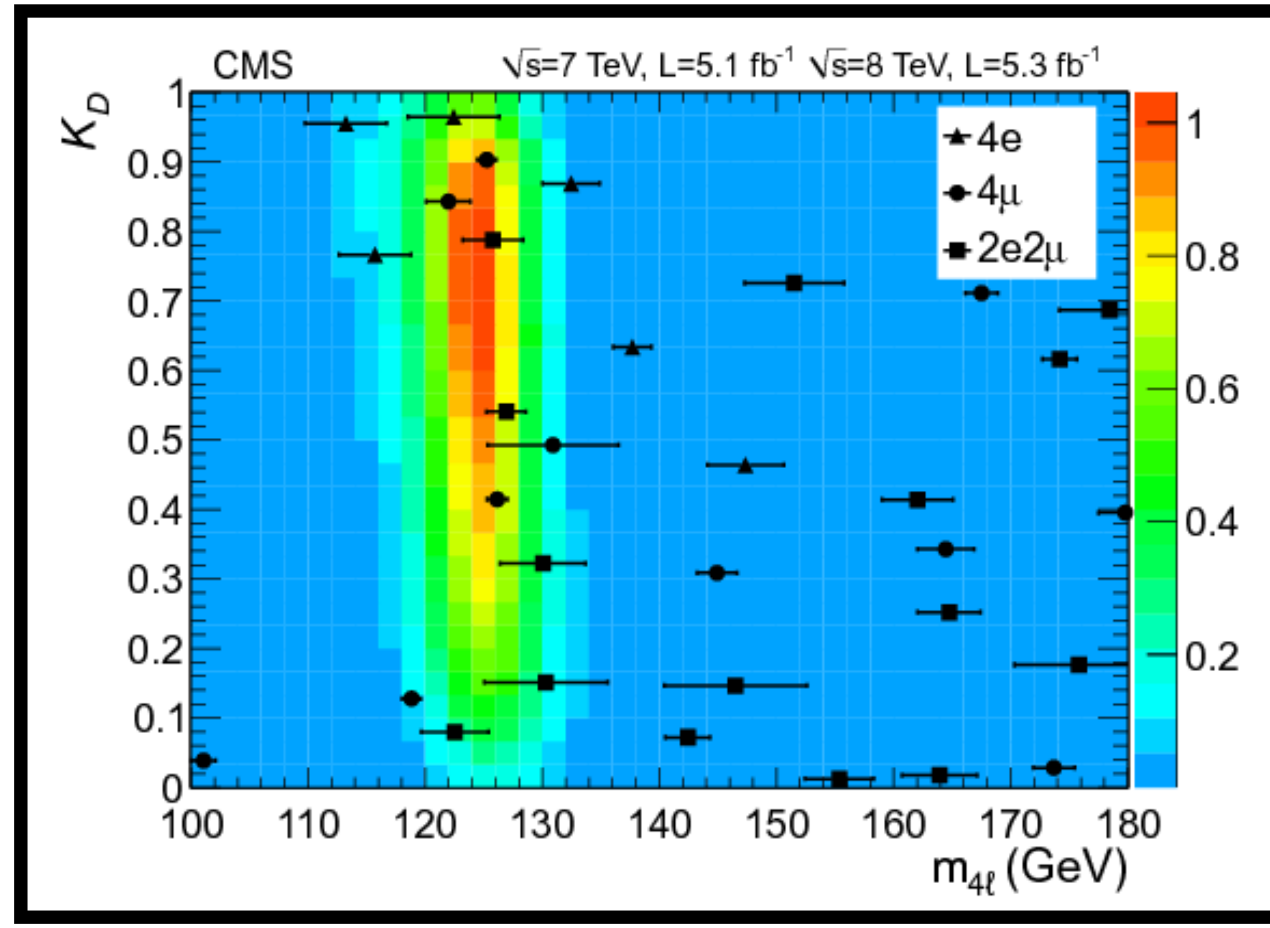
Physics reasons for ability to discriminate signal and background

Straightforward to connect with the (MEM) analysis

"Pheno-iest" of the MVAs

Not just a theoretically nice analysis framework





CMS Phys.Lett. B716 (2012) 30-61

Actually used in Higgs discovery (MELA) CMS

Crucial for subsequent studies of properties by both experiments (MELA, MEKD, etc.)

So what lessons have we learned for the future?

and what does any of this have to do with boost (or BOOST)?

More ZZ Resonances?

- Heavy Higgs*
- Randall Sundrum Gravitons**
- A signature of unexpected new physics? (Stay tuned!)
- A signature whose time has come?

In all of these cases the MEM will add to search sensitivity and help us figure out what we're looking at

Hadronic Channels

- Z to leptons is a small branching fraction (about 1/16 for e^+e^- and $\mu^+\mu^-$ **combined**)
- Semi-leptonic decays and totally hadronic decays of ZZ resonances have much larger rates

Can’t ignore jets!

Hadronic Channels

- Often the MEM treatment of jets is to use a Gaussian(-ish) “transfer function” to parametrize the probability of measuring a jet with observed momentum given some parton-level colored object

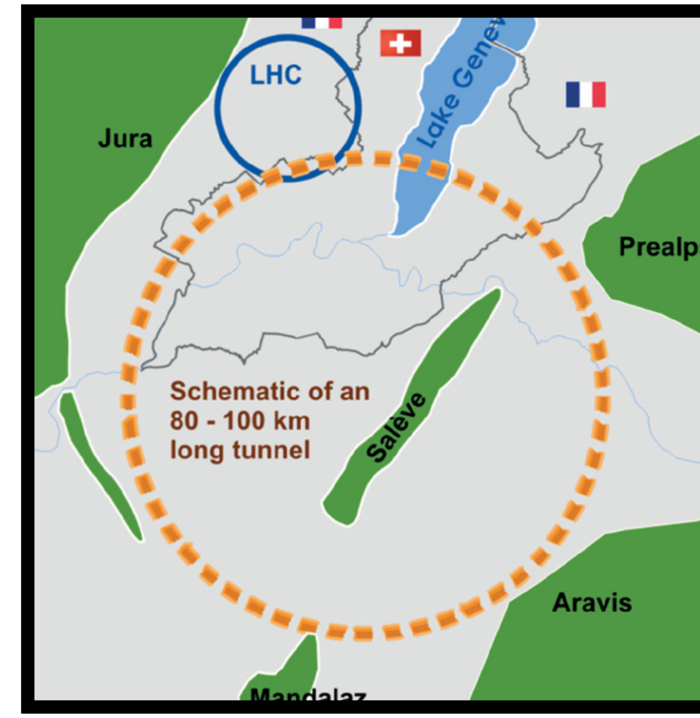
- Obviously we know much more about jet physics than is taken into account in this transfer function
(**cf. 90% of the talks here!**)

- Going forward, it is important to incorporate our growing understanding of jet physics in MEM-like analyses to optimize sensitivity.

- Shower deconstruction (Soper and Spannowsky, 2011; etc.) is a big step in this direction, but much more work to be done

The Future

- At future hadron colliders Zs and Ws from resonance decays (or relevant backgrounds) will be **even more highly boosted**



- Even for purely leptonic channels it's important to understand the drivers of sensitivity and how they depend on detector resolution, etc.

- **Help determine necessary detector parameters**

Step One…

Increasing RS Graviton Discovery Sensitivity with the MEM in 4ℓ Final States

with Doojin Kim

Introduction

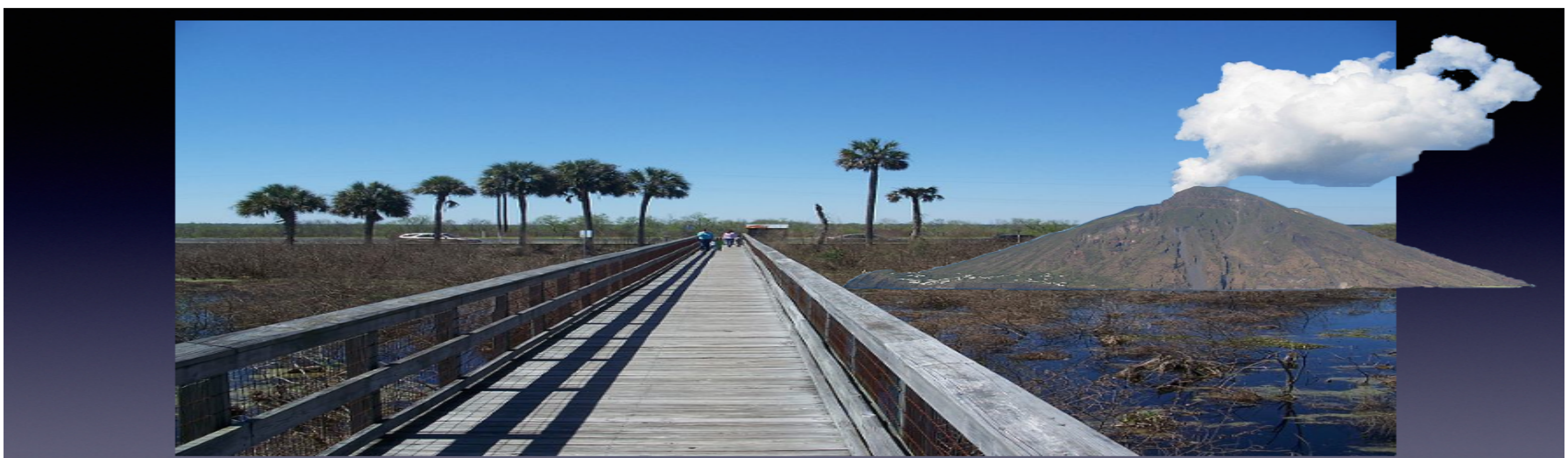
- Determine the extent to which the MEM, etc. improves sensitivity over standard analyses when searching for RS Gravitons via decay to ZZ to 4ℓ
- Understand the drivers of this sensitivity…
- and how they are affected by detector resolution, etc., especially when going to future collider energies (where the Zs are more boosted)
- Ultimately include other channels
- What I'll show today: sensitivity plots for a benchmark point (Graviton mass 2 TeV, width ~ 32 GeV (c = 0.5))

Quantile Bin Plots

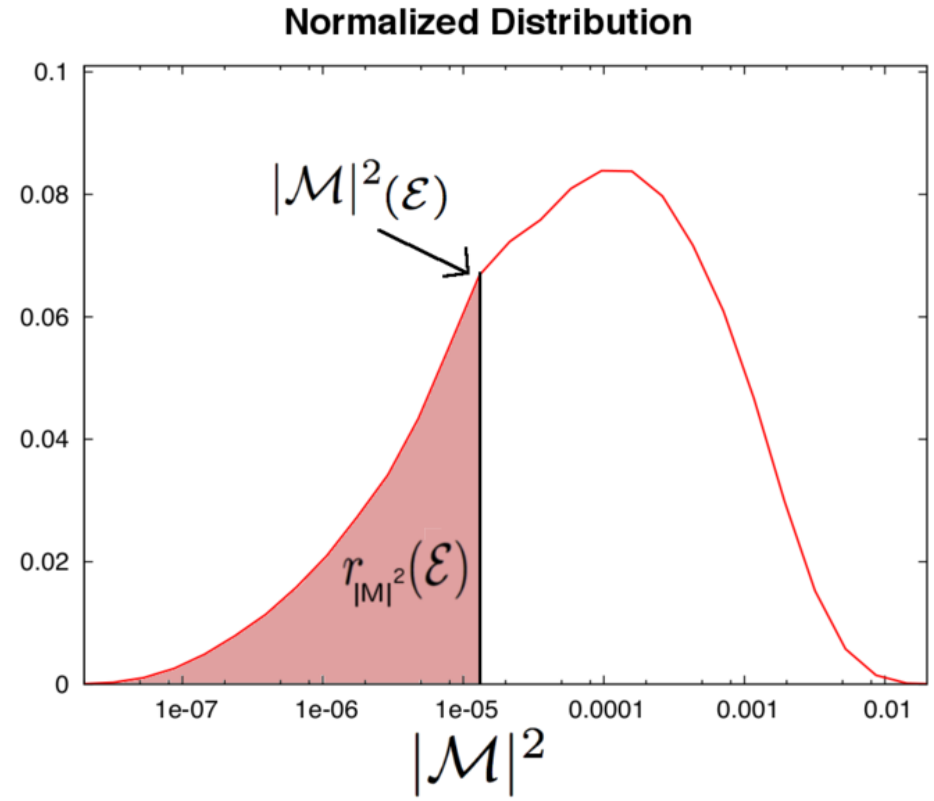
- Inspired by experimental procedure, we will make a “template” or binned likelihood distribution in two variables
    - Invariant mass of the four-lepton system
    - Additional variable (MEKD value, angle, …)
- We use “quantile bins”: each bin will have the same background cross section
- The differing signal cross section shows how the sensitivity sausage is made

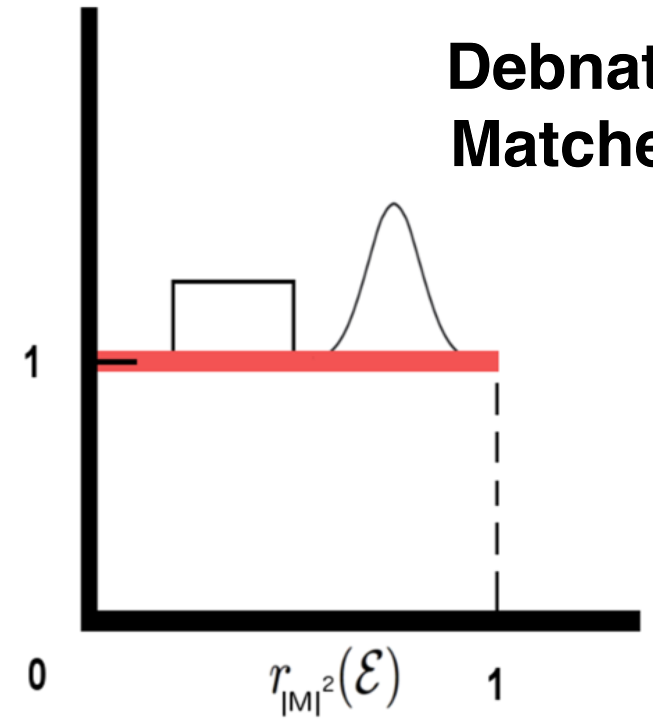
Ranking and Flattening Backgrounds for Model-Independent Discoveries

based on Physics Letters B743 (2015) 1-5
(Debnath, JSG, Matchev, 2014)



Model-Independent Searches





Debnath, JSG, Matchev, 2014

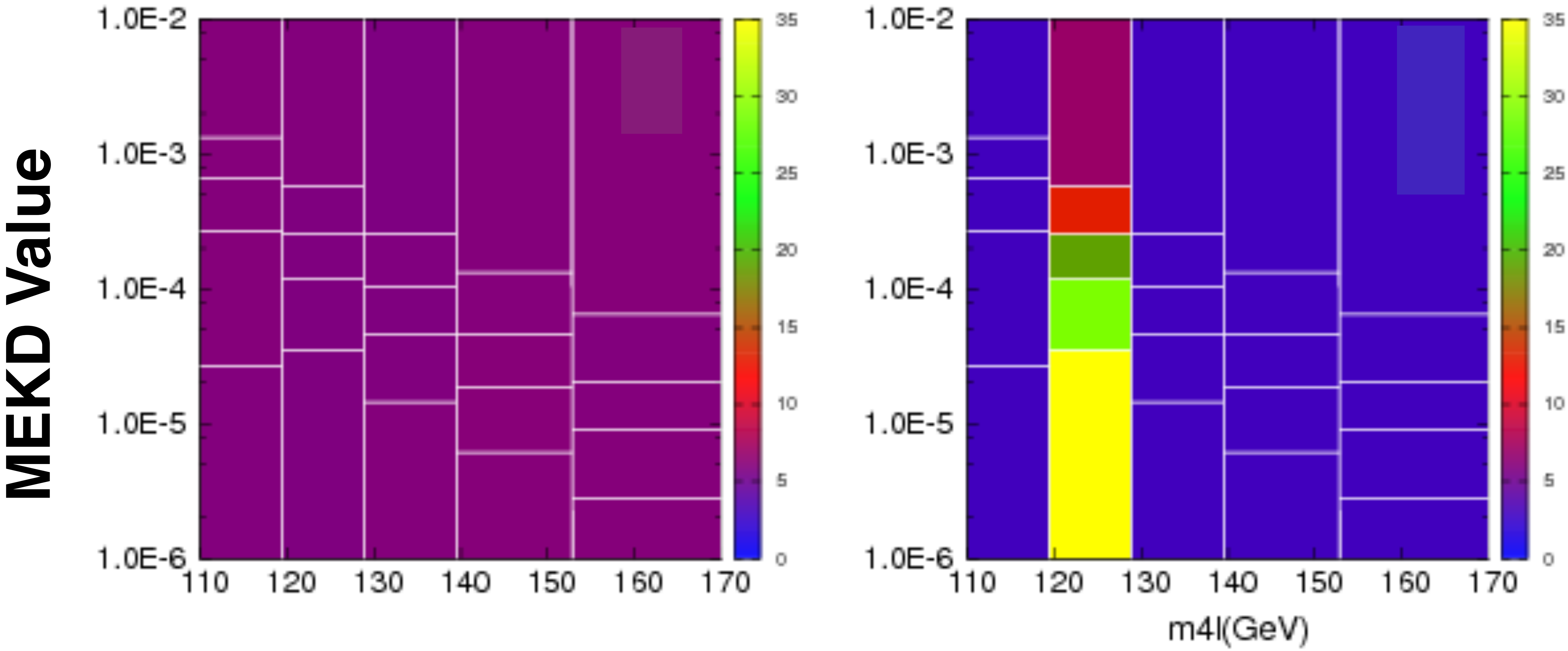
- Potential approach to finding new physics in a model-independent way
  and displaying the results:

  "**Flatten**" (take the cdf) of a powerful variable, then look for deviations from flatness in the data.

- New physics shows up as excesses or deficits.

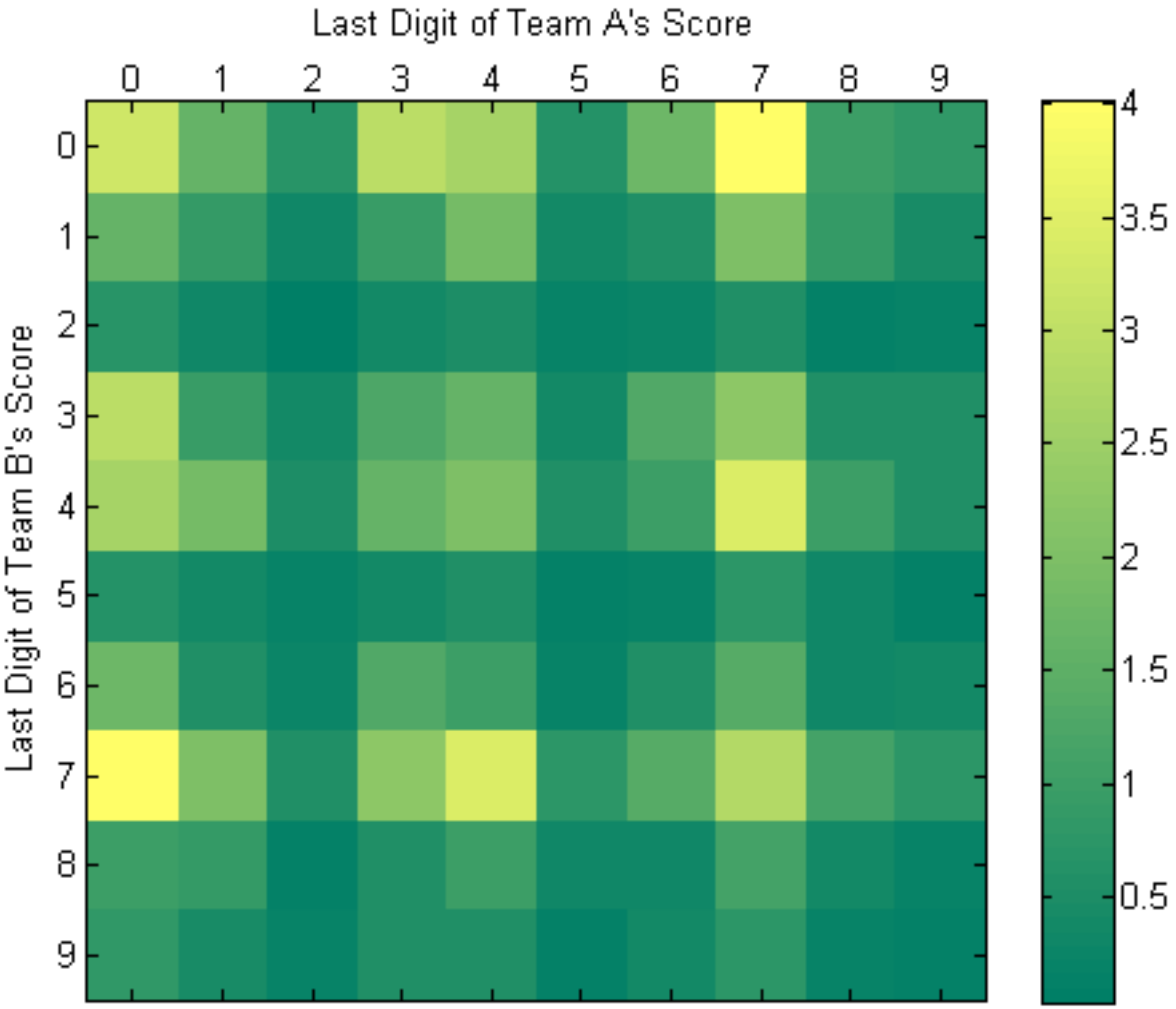
Model-Independent Searches: Quantile Bins

Debnath, JSG, Matchev, 2014



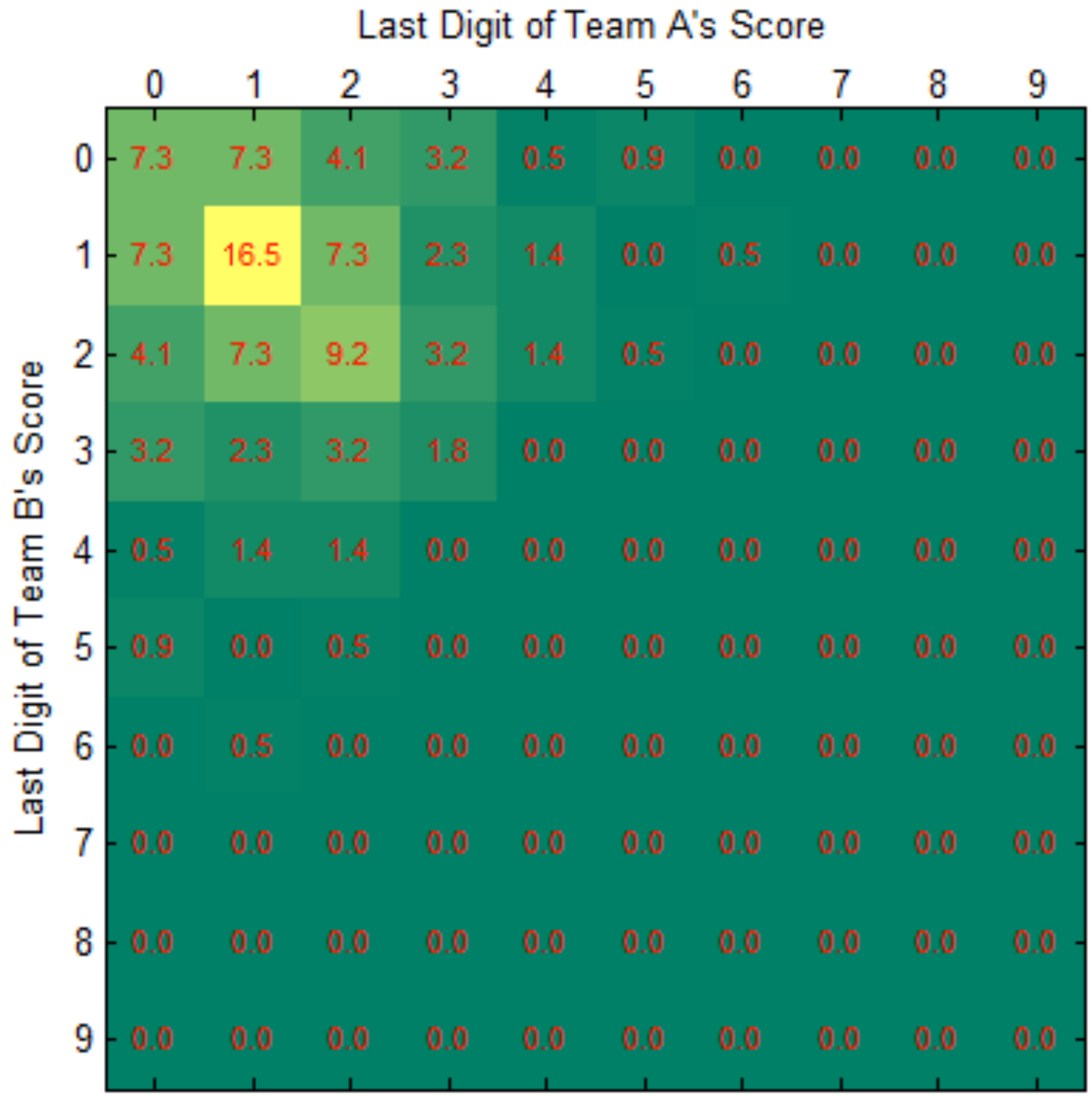
Four-lepton events, Higgs signal and irreducible background

Quantile Bins



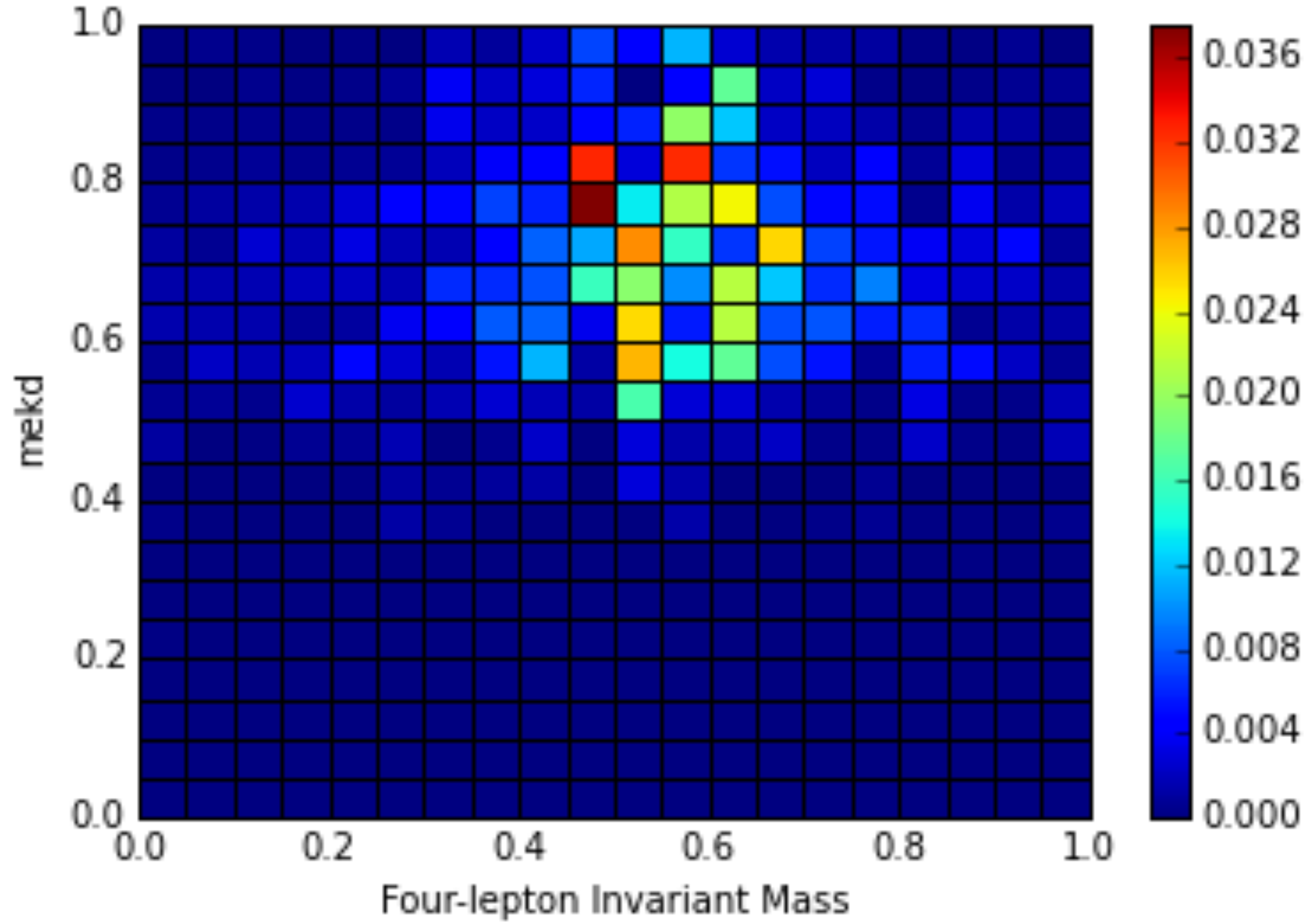
http://blogs.mathworks.com/community/2013/01/07/football-squares-with-matlab/

Quantile Bins



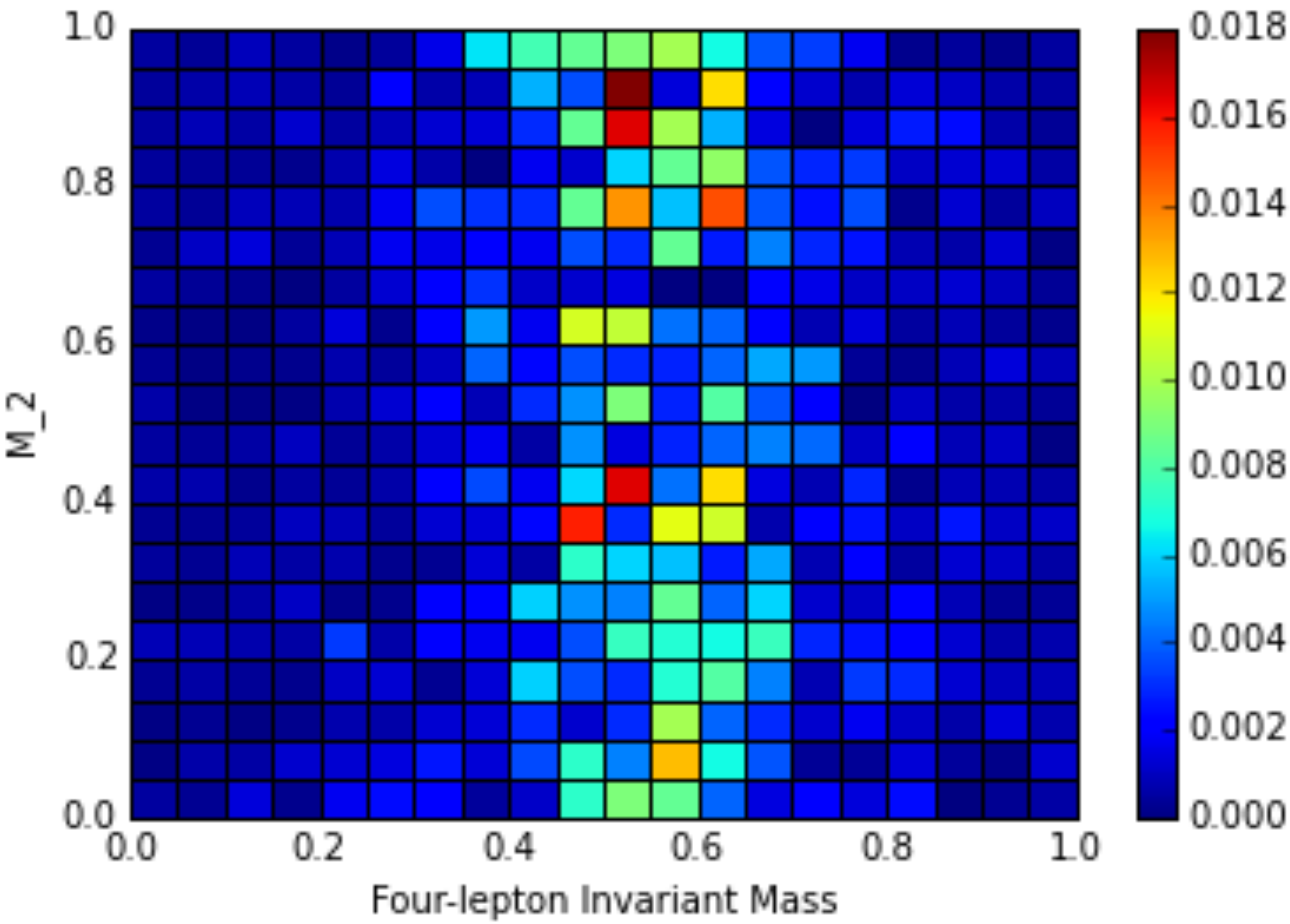
http://blogs.mathworks.com/community/2013/01/07/football-squares-with-matlab/

Preliminary Results



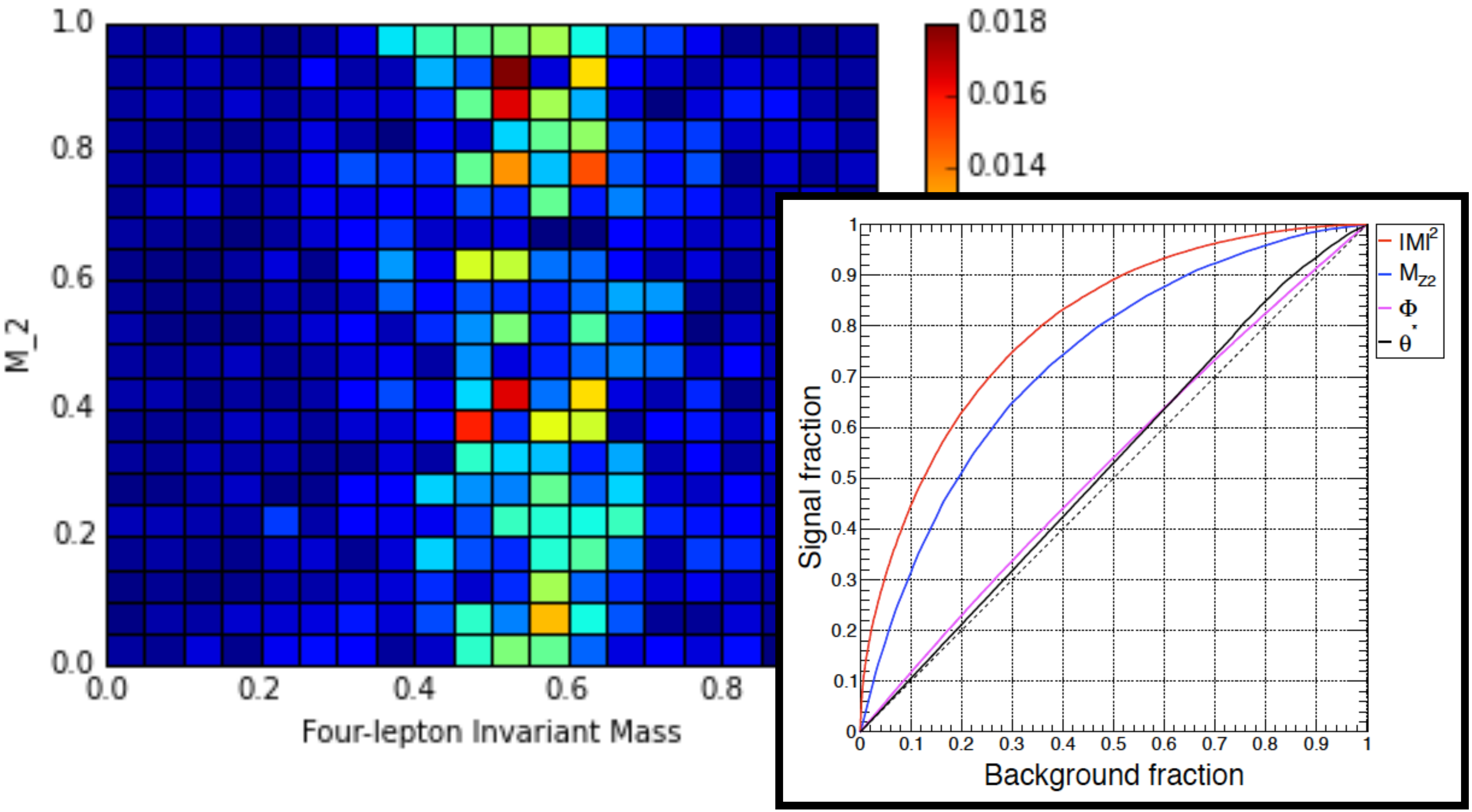
Signal is narrow 2 TeV RS Graviton

Preliminary Results

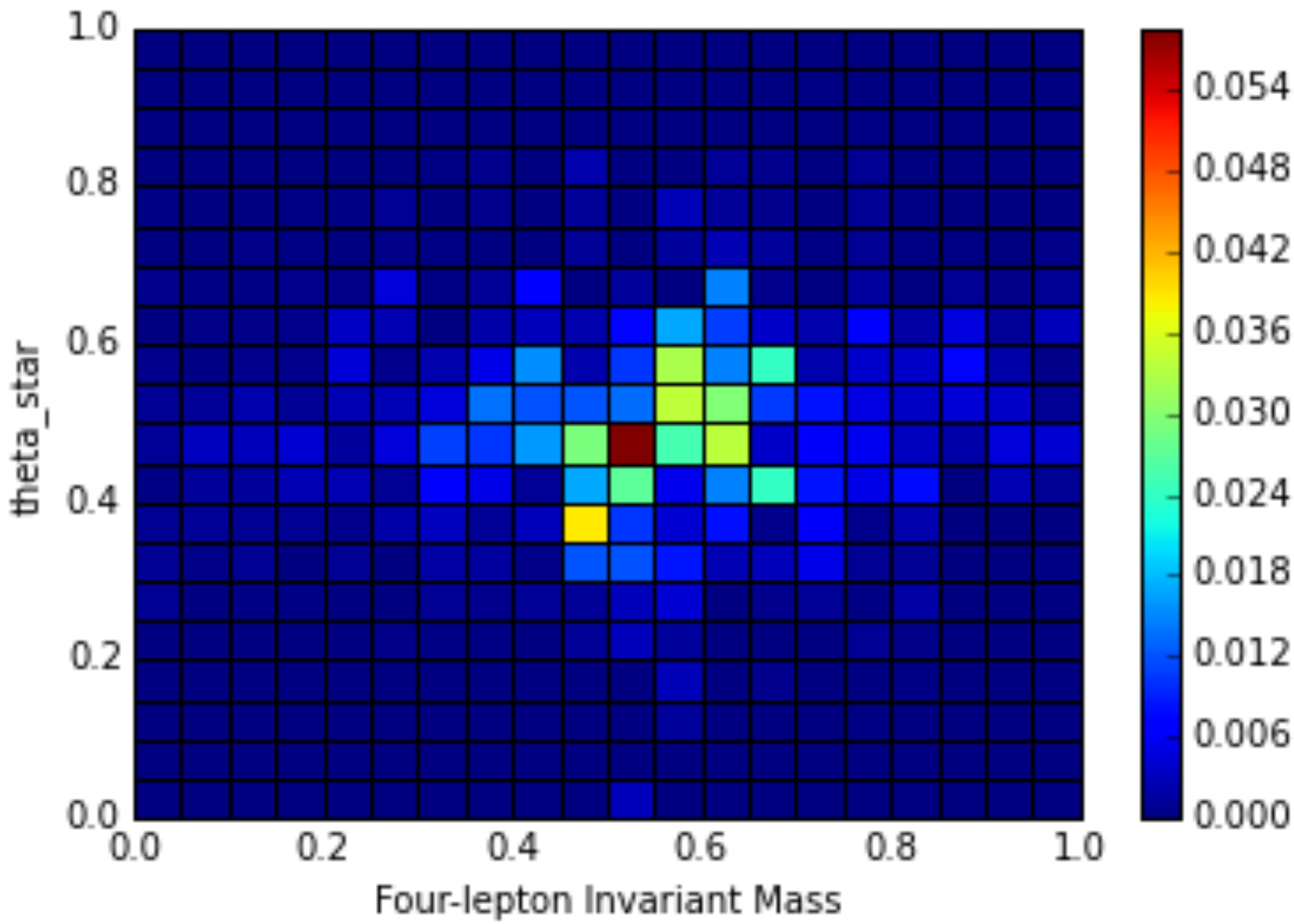


Signal is narrow 2 TeV RS Graviton

Preliminary Results

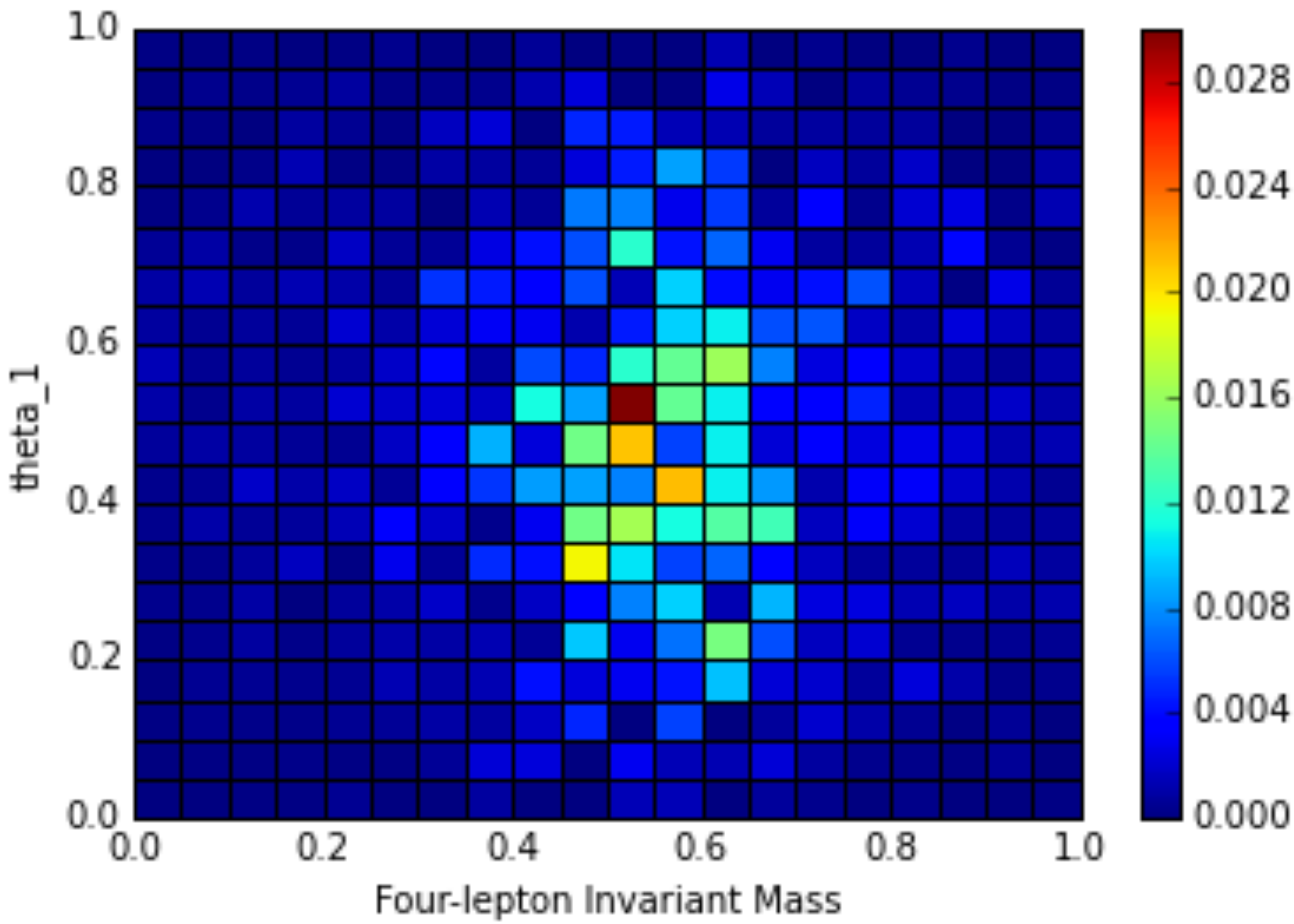


Preliminary Results



Signal is narrow 2 TeV RS Graviton

Preliminary Results



Signal is narrow 2 TeV RS Graviton

Preliminary Conclusions

- θ* seems to be the primary driver of signal/ background separation
- Not a big surprise: background peaks when the Zs are forward/ backward
- This variable should be more robust to boosting than the angles which parametrize the Z decay to leptons in the Z rest frame
- Those angles will be more important for measuring the graviton-ZZ couplings

Conclusions

- Diboson final states have taught us much about the Higgs and will continue to do so.
- They may also teach us about new Higgs-related physics, RS gravitons, or something completely unexpected!
- Studying models with boosted diboson resonances will help us understand detector requirements at future colliders.
- and provide an important laboratory for developing improved MEM-like techniques for the LHC and beyond!

$m_{(W/Z)(W/Z)}$?