Higgs, Flavor, CP @100 TeV

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IHEP 2015

Chen, RH, Vega-Morales - 1404.1336 and 1503.xxxxx.

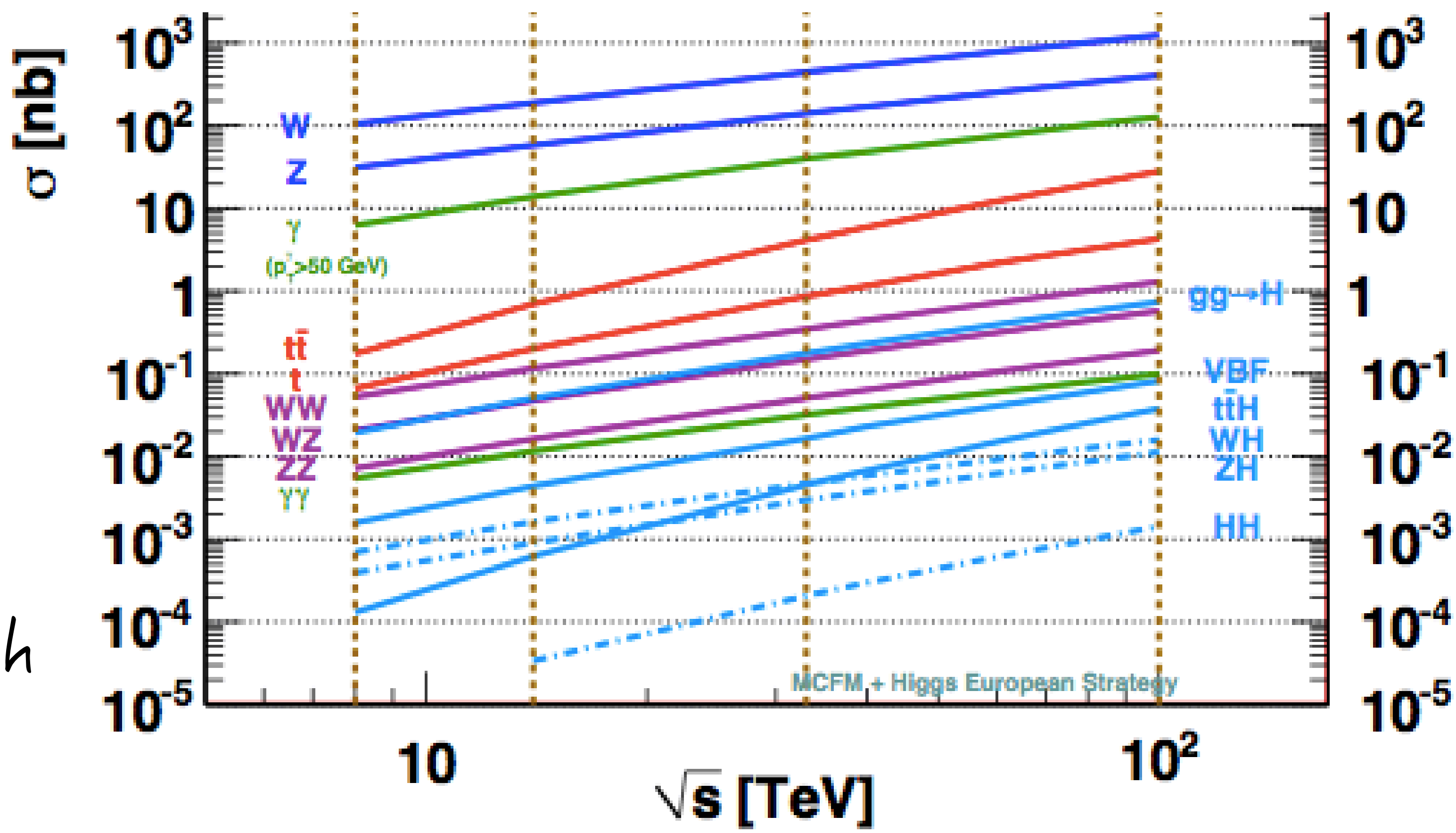
RH, Kopp, Zupan - 1209.1397

100 TeV

* For me, a Higgs factory + 100 TeV pp collider is the most exciting path for our field.
* **Exploration of the unknown, is the central physics case.**
* More specific opportunities certainly exist, see e.g. LianTao's talk.
* Here, I'll focus on exploring the Higgs boson and its connection to flavor and CP.

Higgs at 100 TeV

* Precision Higgs studies are often associated with e^+e^- "Higgs factories".
* However, a 100 TeV machine produces many more Higgs bosons.



taken from FCC-hh talk by Mangano

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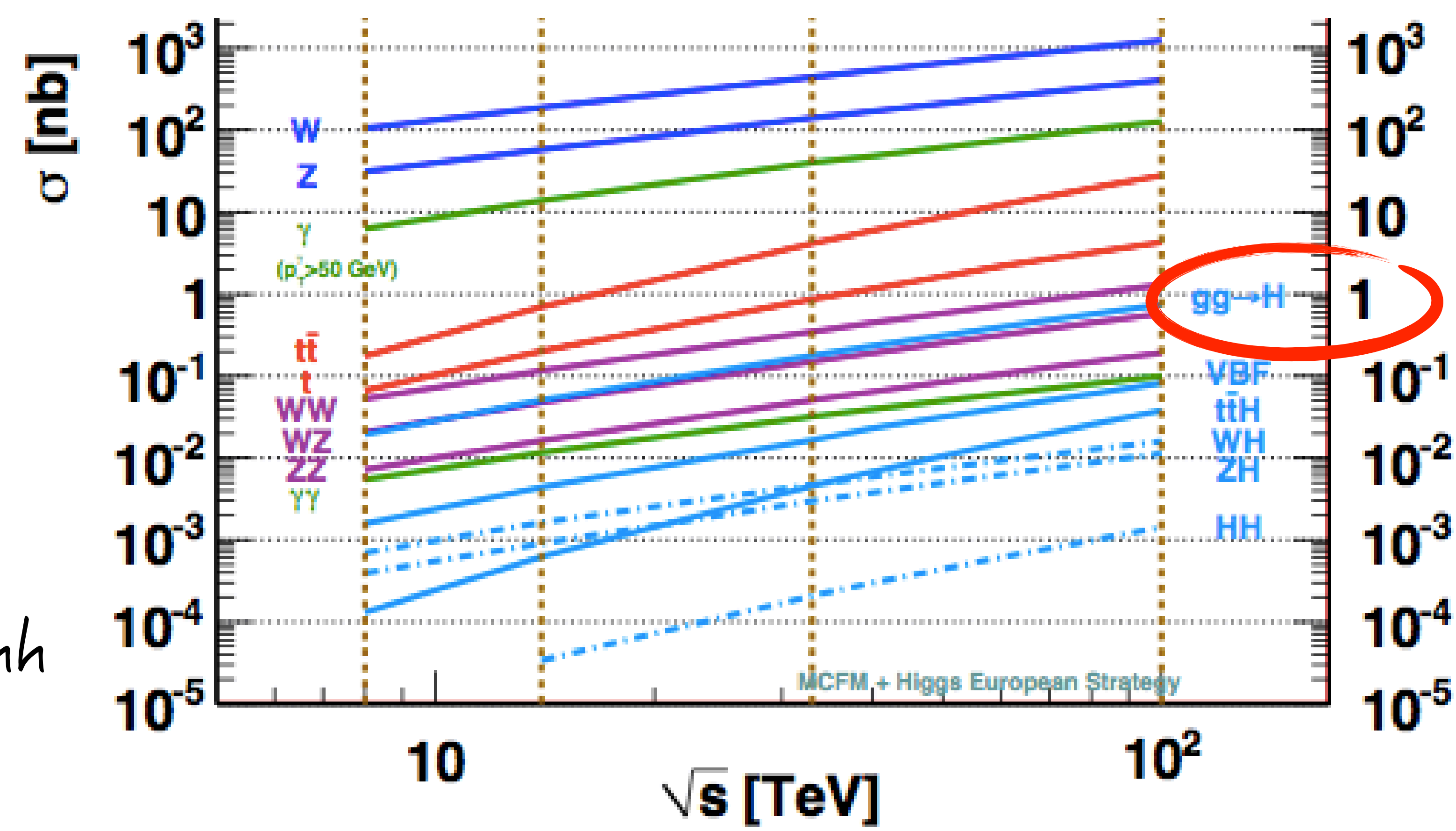

nanobarn!

taken from FCC-hh talk by Mangano

CepC

A Higgs "designer store"

Nice and clean.

SppC

A true factory

Dirtier,

but more productive.

10^9 Higges

* $(1\ \mathrm{nb} \times 1\ \mathrm{ab}^{-1}) \sim 10^9$ Higges!
* What can we do with 10^9 Higges?
  10^8 VBF Higgses?
  But in a messy hadronic environment...
* Obviously:
  Focus statistically limited channels.
* Example: Higgs trilinear (see LianTao's talk)

Higgs, Flavor, CP

* The Coupling of Higgs to Fermions has given us the flavor and CP structure of the SM.

* SM: Higgs couplings **conserve flavor and CP.**

$$\mathcal{L}_{SM} \supset \frac{m_Z^2}{v} h Z_\mu Z^\mu + \frac{m_W^2}{v} h W_\mu W^\mu$$

$$\frac{\alpha}{\pi v} h F_{\mu\nu} F^{\mu\nu} + \frac{2\alpha}{\pi v} h F_{\mu\nu} Z^{\mu\nu} + \frac{m_i}{v} h \bar{f}_i f_i$$

* BSM: Not Necessarily! NP can violate both.

hff Couplings

* With NP we can add CP or Flavor Violation:

$$\mathcal{L}_{FV} = m_i \bar{f}_i f_i + Y_{ij} h \bar{f}_i f_j$$

$$\mathcal{L}_{CPV} = \frac{m_i}{v} h \bar{f}_i (\cos\Delta + i \sin\Delta \gamma_5) f_i$$

Of course, we could add both.

hVV Couplings

* NP → Higgs interactions can be more general:

CP Even — CP odd

$$\mathcal{L}_{Z,\gamma} = \frac{h}{4v}\Big(2m_Z^2 A_1^{ZZ} Z_\mu Z^\mu$$

$$+ A_2^{ZZ} Z_{\mu\nu} Z^{\mu\nu} + A_3^{ZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

$$+ A_2^{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} + A_3^{\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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My homework for this talk:

what are the best opportunities
for Higgs flavor & CPV
at 100 TeV?

(Look for the statistically
dominated channels where we can
benefit from $10^9/ab^{-1}$)

Outline

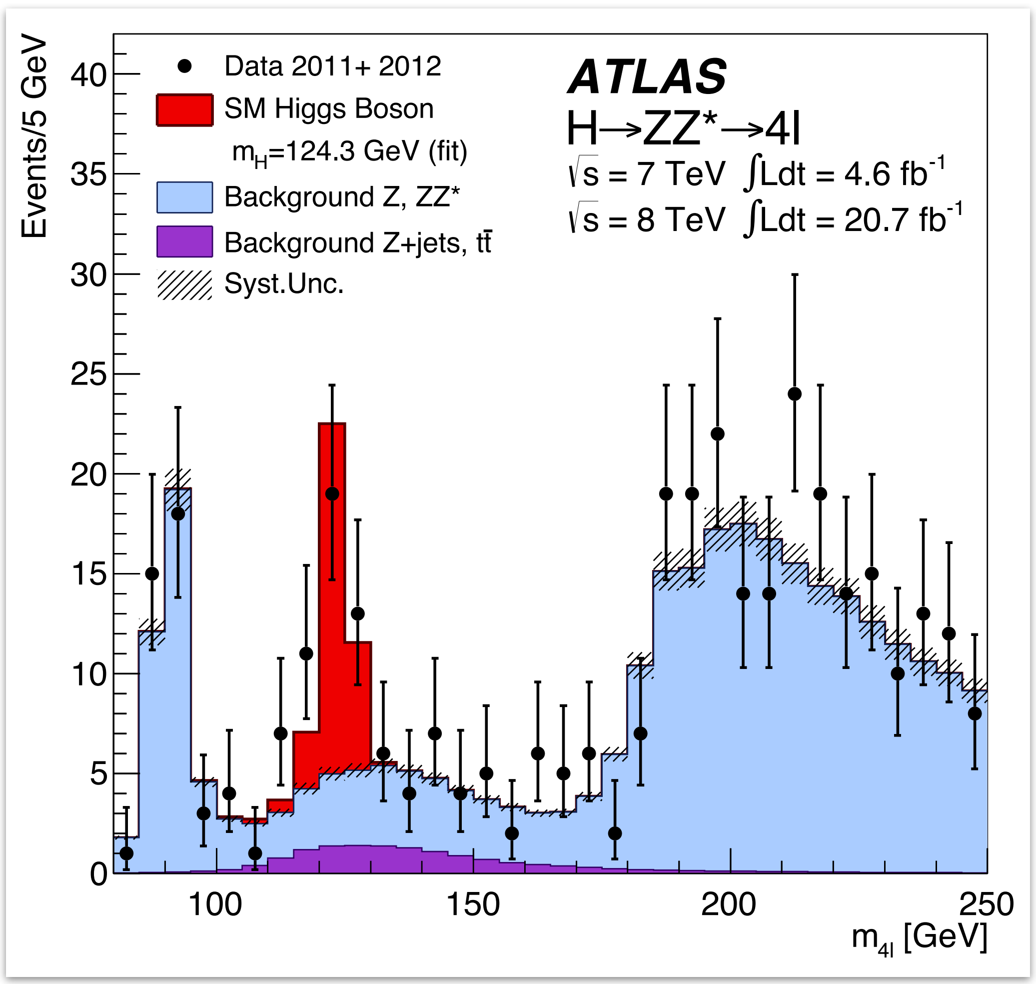
* Two parts:
    - Opportunities with $h \to 4\ell$.
    - Lepton Flavor violating Higgs decays

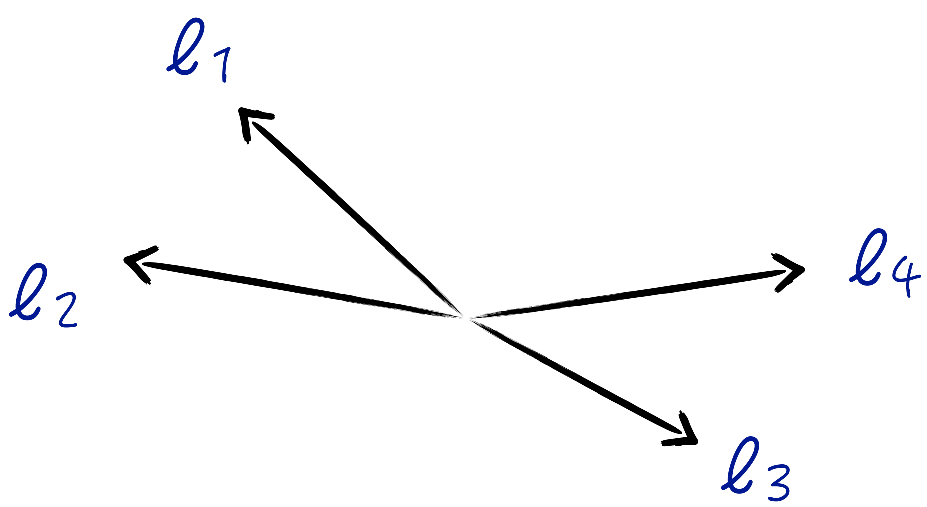
$h \to 4\ell$

Chen, RH, Vega-Morales - 1404.1336 and 1503.xxxxx.

$h \to 4\ell$

* The decay $h \to 4\ell$ was vitally important in discovering the Higgs. Determining its mass.

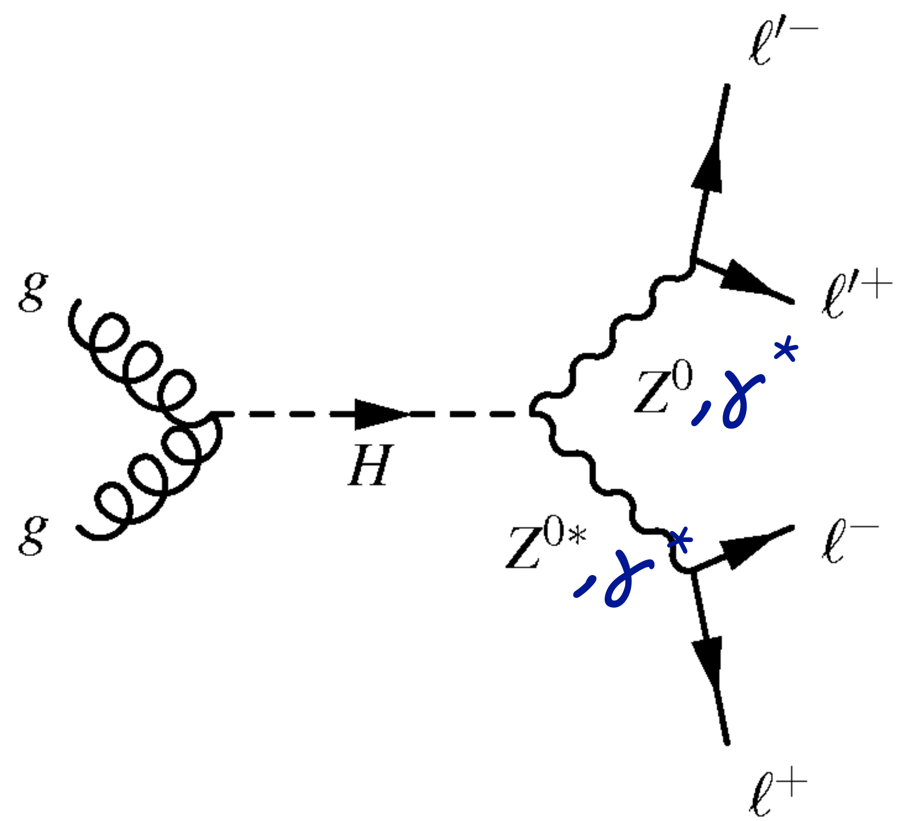




- Very clean.
- Many things to measure.
- Low background.
- Will remain statistic limited.

$h \to 4\ell$

- The search was optimized for discovery via ZZ^*.
- $h \to 4\ell$ is not only ZZ^*!



- Its time to optimize the search for new discoveries.

Signal and Background

* Amplitudes that contribute to $h \to 4\ell$ include-

$$\mathcal{L} = \frac{h}{4v}\Big(2m_Z^2 A_1^{ZZ} Z_\mu Z^\mu$$

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Background

$$+ A_2^{ZZ} Z_{\mu\nu} Z^{\mu\nu} + A_3^{ZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

Signal

$$+ A_2^{\gamma\gamma} F_{\mu \ldots}$$

$$+2A_2^{Z\gamma} Z_{\mu \ldots}$$

Lesson:

We expect to be most sensitive to the signal that is most different from BG.

Highest sensitivity is to $Z\gamma$ and $\gamma\gamma$.

hVV: Measurements

* There are many constraints on our signal operators, mainly from $h \to \gamma\gamma$ and EDM limits.
* It is worth emphasizing what we do **not** know:
  - Don't know the sign of the $h\gamma\gamma$ vertex.
  - Don't know its phase w/o assumptions
    (EDM constraint requires an assumption of e Yukawa).
  - Constraints on $Z\gamma$ and ZZ high-dim operators are very poor, and will remain so for a while.

Y. Chen, N. Tran, and R. Vega-Morales, 1211.1959
Y. Chen and R. Vega-Morales, 1310.2893
Earlier MEM work by Ian Low et al.

Method

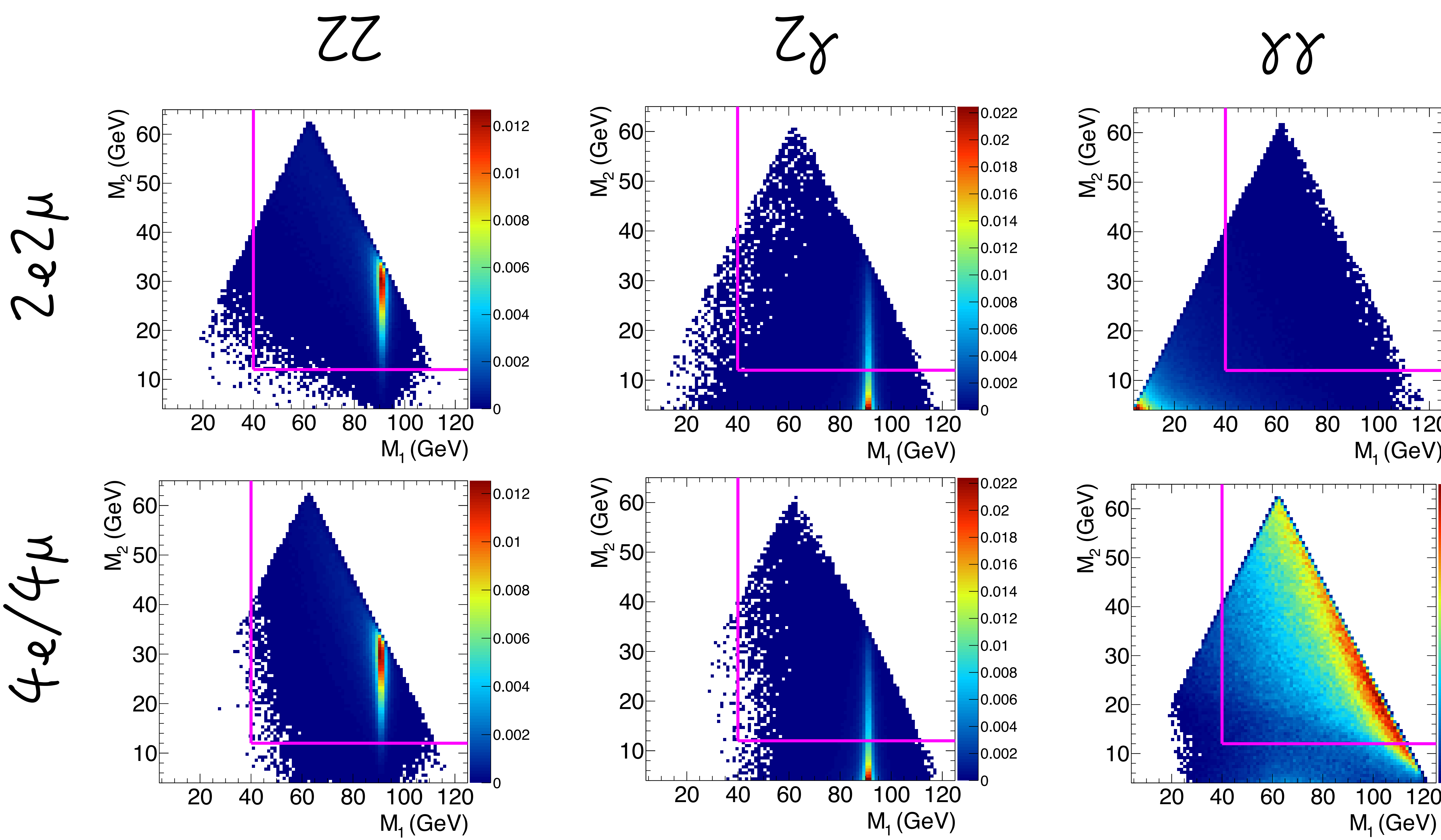
* A simple procedure:
  - Calculate the fully differential cross section analytically* for including interference.
  - A big function of $(A_2^{ZZ}, A_3^{ZZ}, A_2^{Z\gamma}, A_3^{Z\gamma}, A_2^{\gamma\gamma}, A_3^{\gamma\gamma})$ & phase space.
  - Include dominant backgrounds.
  - Fit to the data. Extract A's directly.

In flavor lingo: a double Dalitz analysis

* Keeps all operators simultaneously.
  No hypothesis testing, etc.

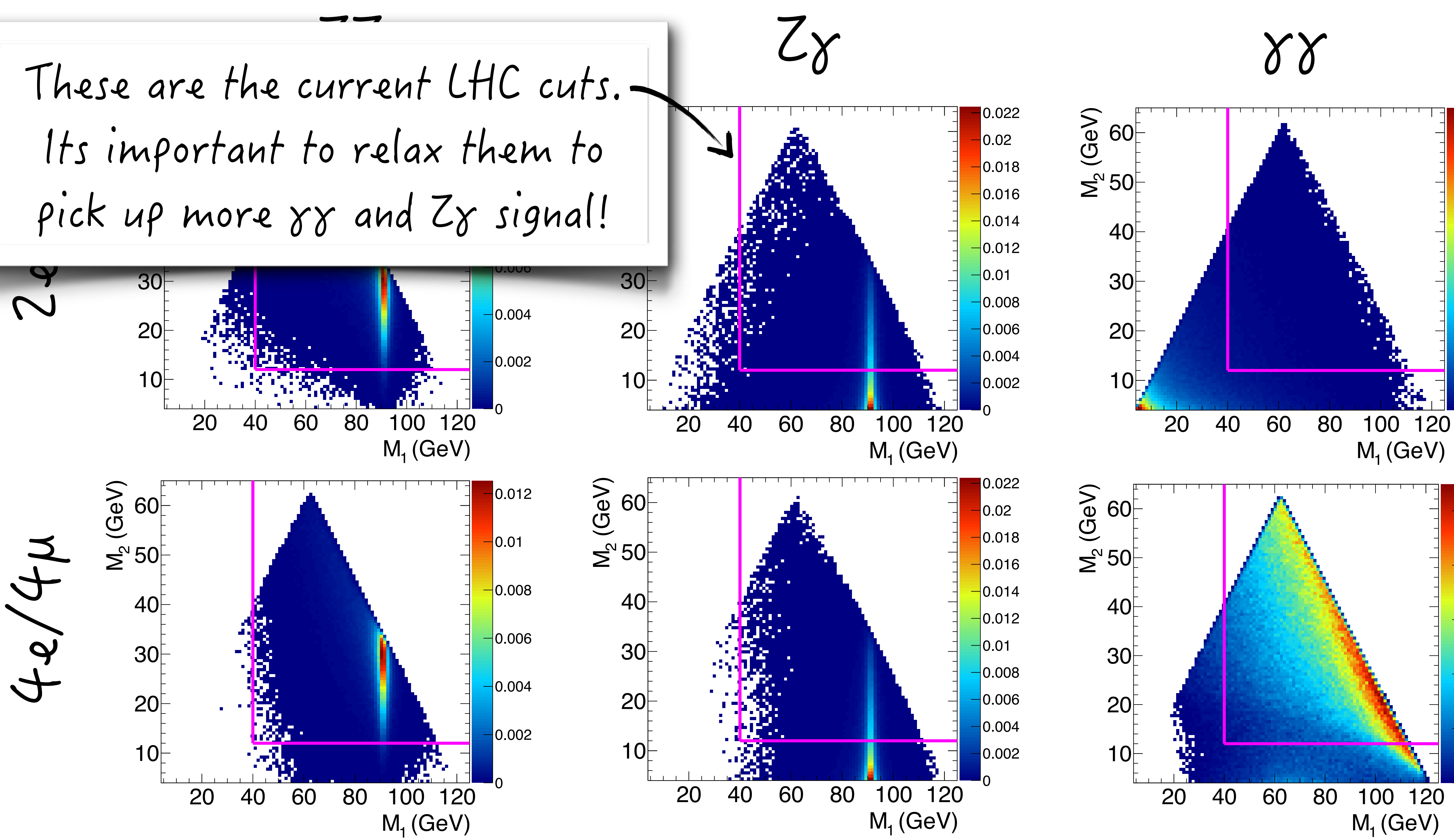
*Done in a **heroic** effort by youngsters Chen and Vega-Morales.

Distributions



Distributions

These are the current LHC cuts.
Its important to relax them to
pick up more γγ and Zγ signal!



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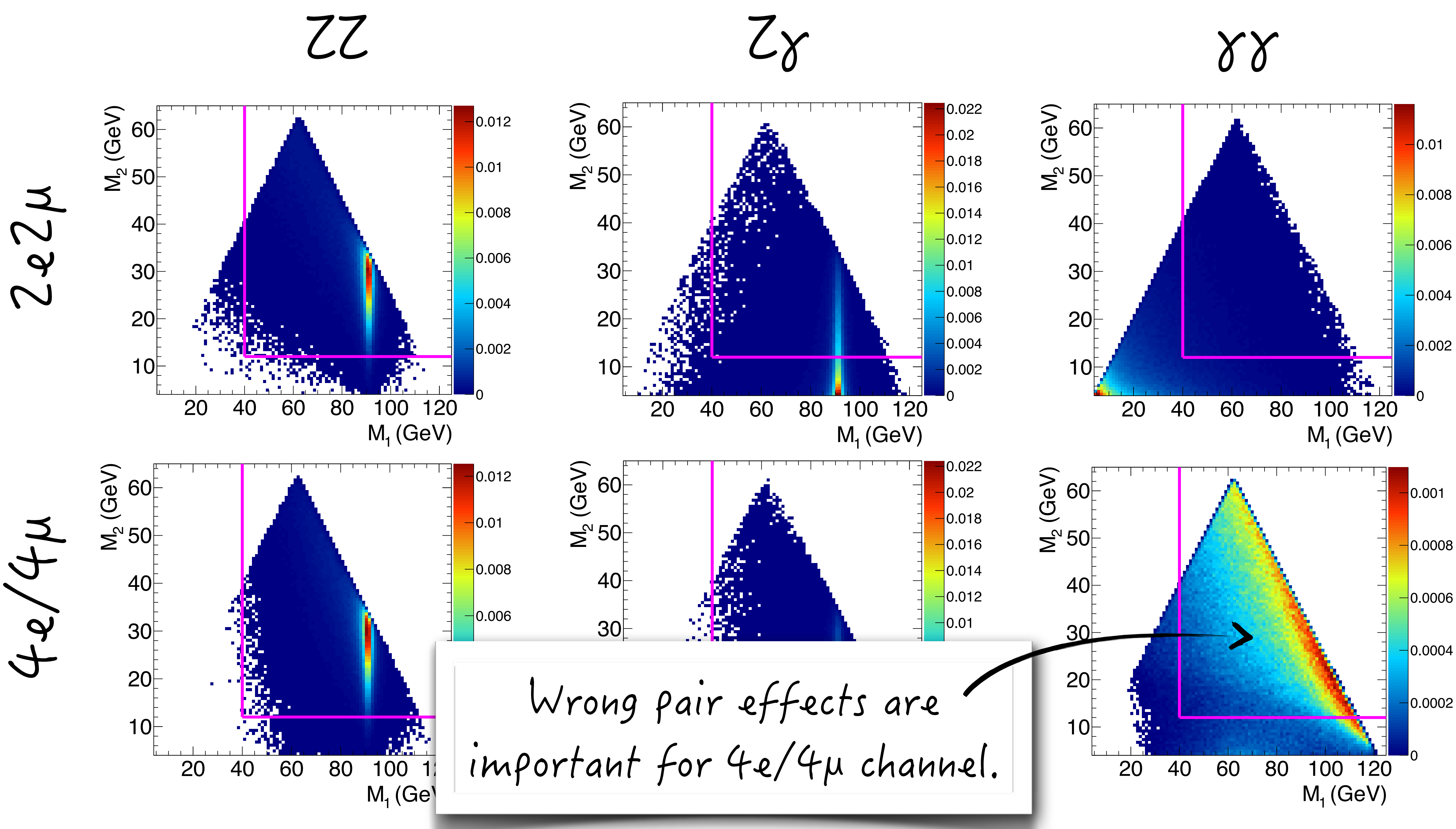
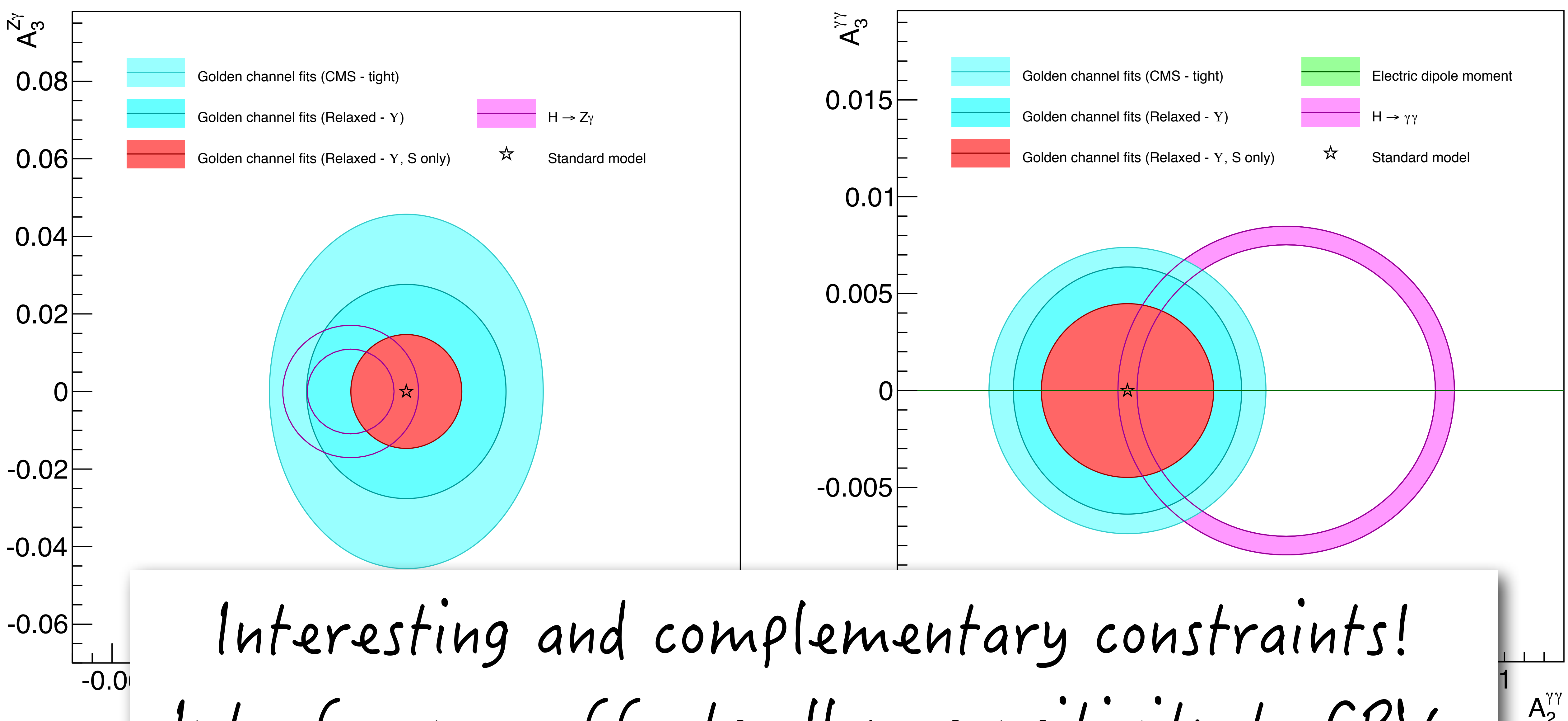


Wrong pair effects are important for 4e/4μ channel.

Results

* Estimate for HL-LHC (4000 h→4ell events):

γγ



Interesting and complementary constraints!
Interference effects allow sensitivity to CPV.

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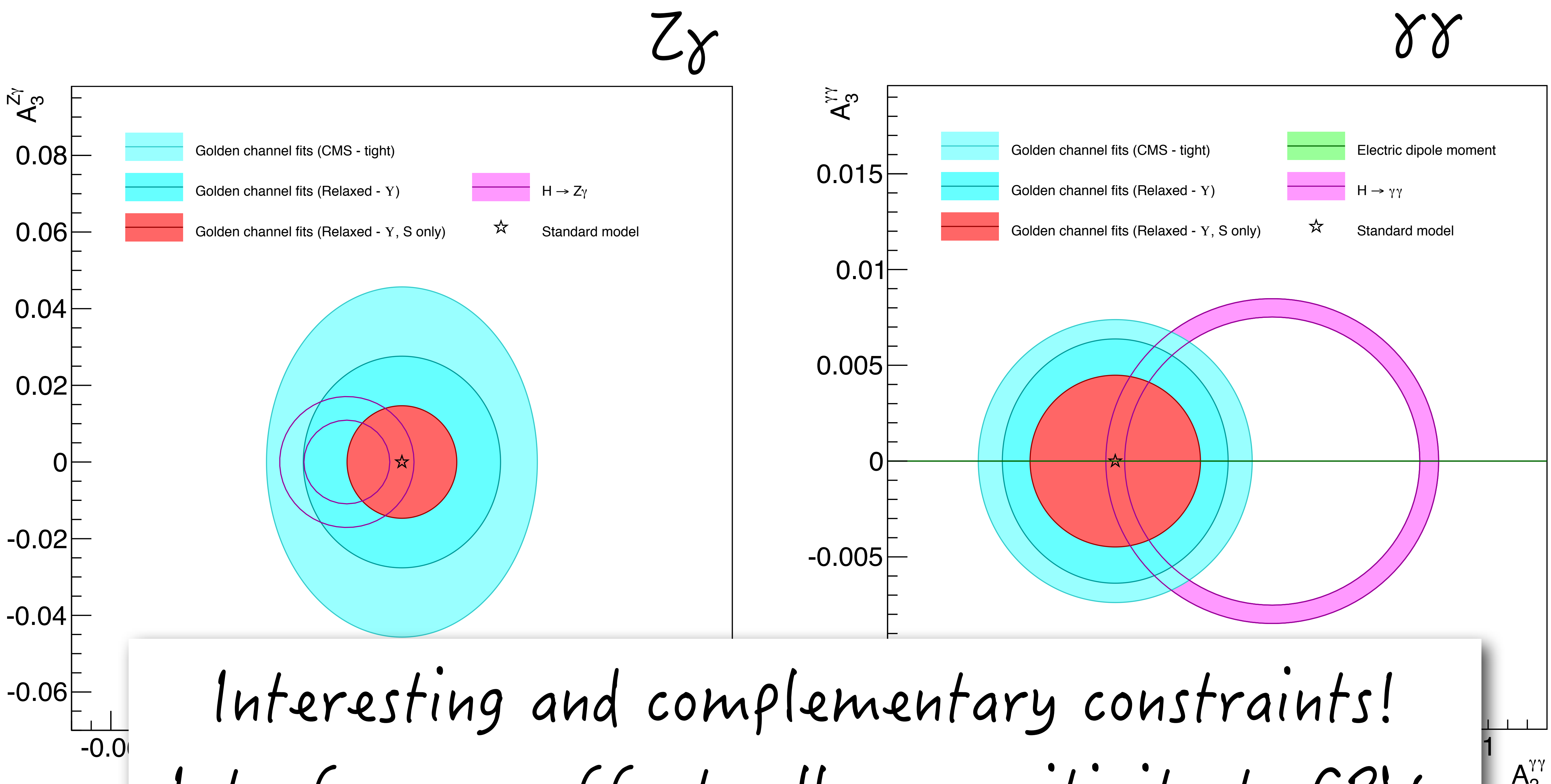


Interesting and complementary constraints!
Interference effects allow sensitivity to CPV.

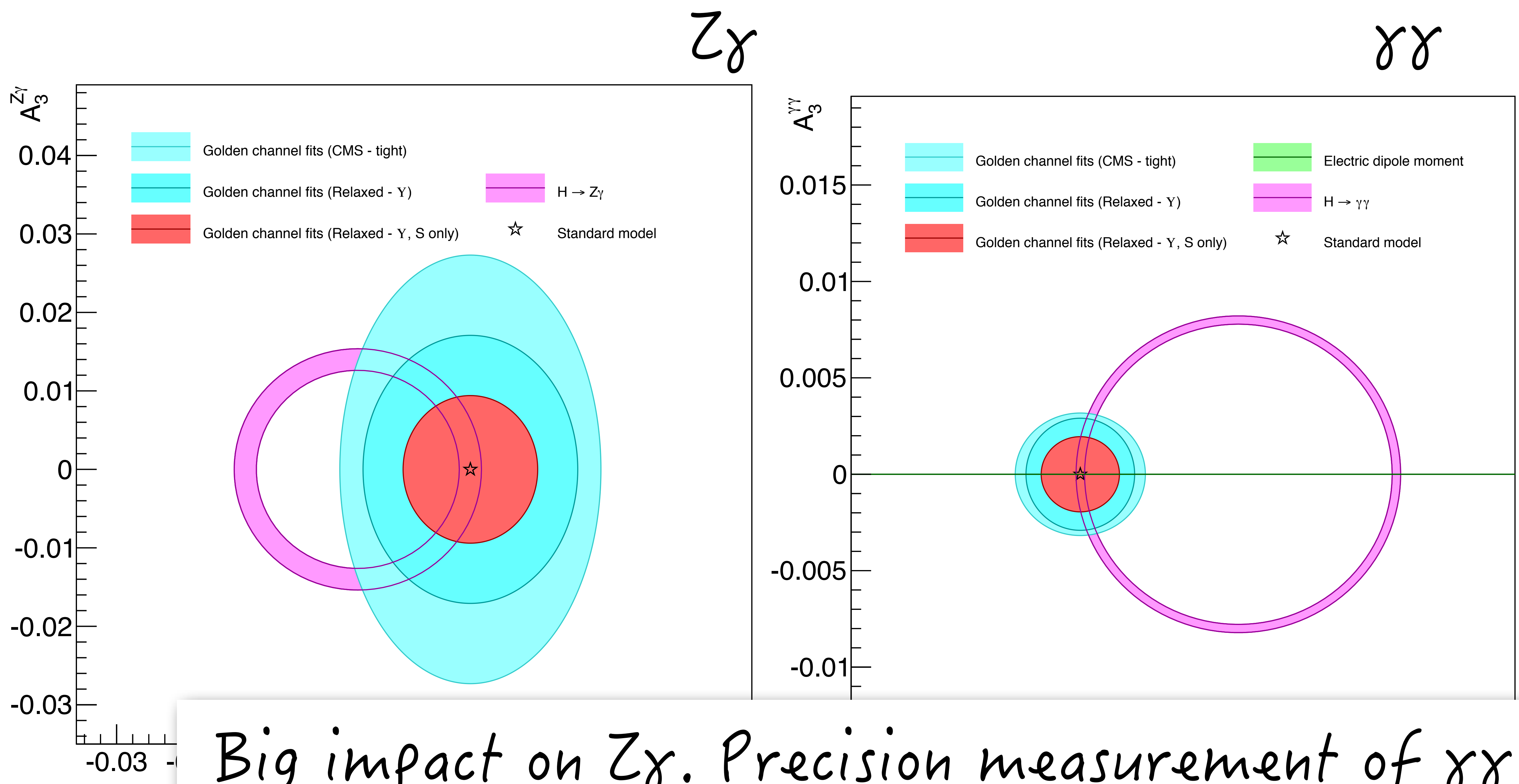
How about 100 TeV?
The dominant effect is an increase in statistics.

What happens if we take HL-LHC x 5?
(that's 20,000 4ℓ events)

(different kinematic distributions and acceptance
may also make a difference. Future work)

Results

* Five times LHC statistics:



Big impact on Zγ. Precision measurement of γγ.

Thoughts on Higgs and Flavor @ 100 TeV

$$\mathcal{L}_{FV} = m_i \bar{f}_i f_i + Y_{ij} h \bar{f}_i f_i$$

How do we generate these interaction?

What are the constraints?

What are opportunities for SppC?

Flavor Violating Higgs

* Recipe: CPV/FV Higgs

1. Rip a page from a paper that modifies Higgs couplings.

2. Sprinkle flavor indices and phases all over the place.

3. Re-diagonalize mass matrix.

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$$\mathcal{L} = \lambda \, H f_L f_R + \lambda' \frac{H^3}{\Lambda^2} f_L f_R$$

$$m_f = \left(\lambda + \frac{v^2}{\Lambda^2}\lambda'\right) v$$

$$Y_f = \lambda + 3\frac{v^2}{\Lambda^2}\lambda'$$

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$Y_f \neq \frac{m_f}{v}$ and not diagonal.

$Y_{ij} \lesssim (m_i m_j)^{1/2}$ is natural.

Leptonic Flavor Violation

$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c..$$

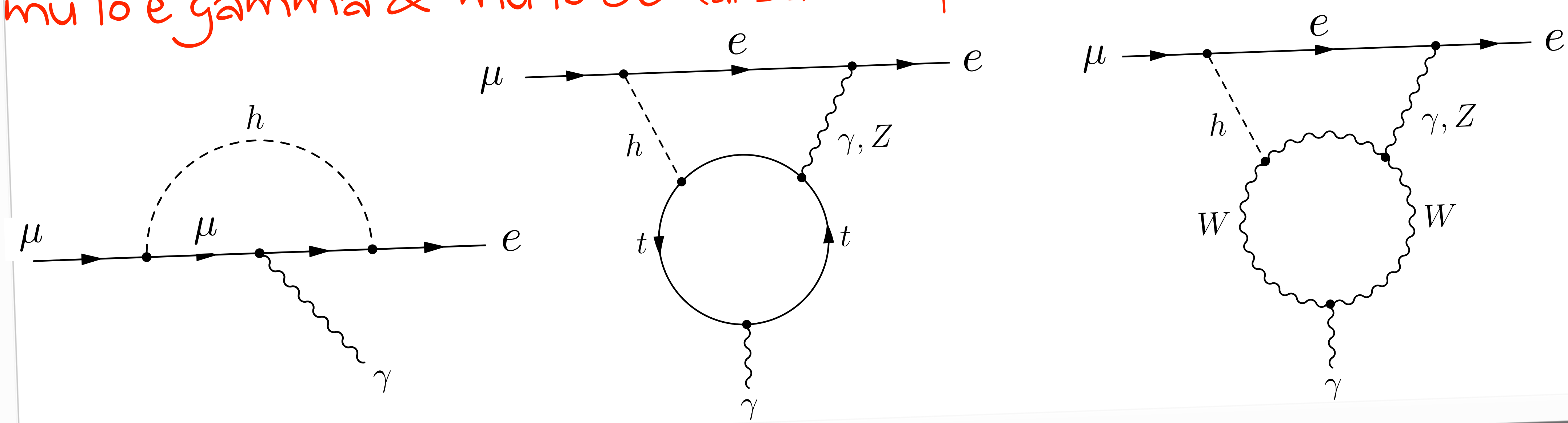
Which experiments constrain the Y_{ij}'s?

RH, Kopp, Zupan - 1209.1397

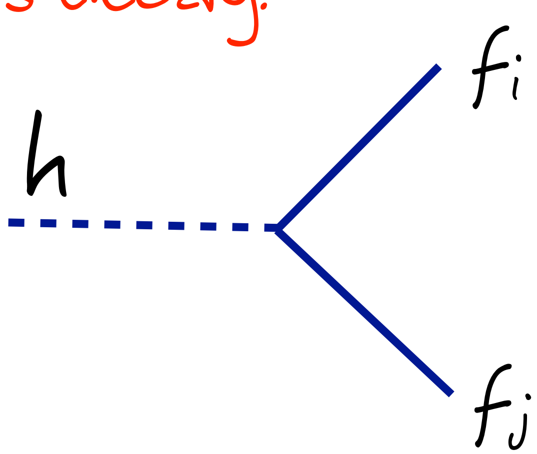
RH, Kopp, Zupan 1209.1397

FV Higgs constraints

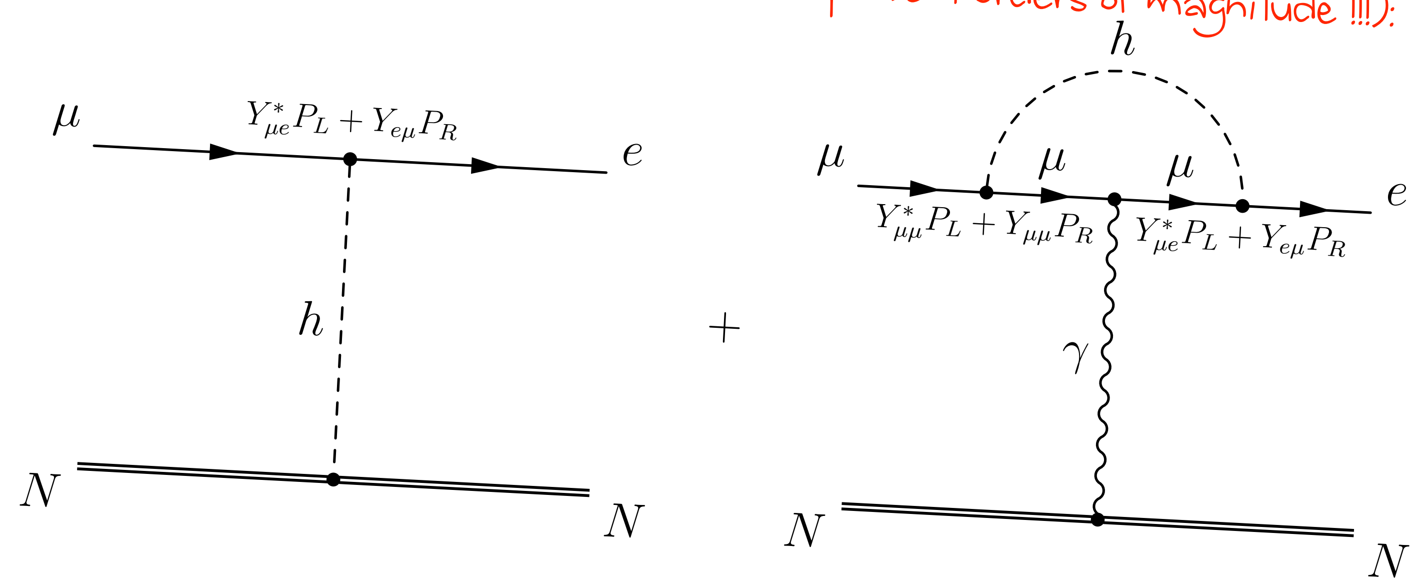
mu to e gamma & mu to 3e (at 1 and 2-loop):



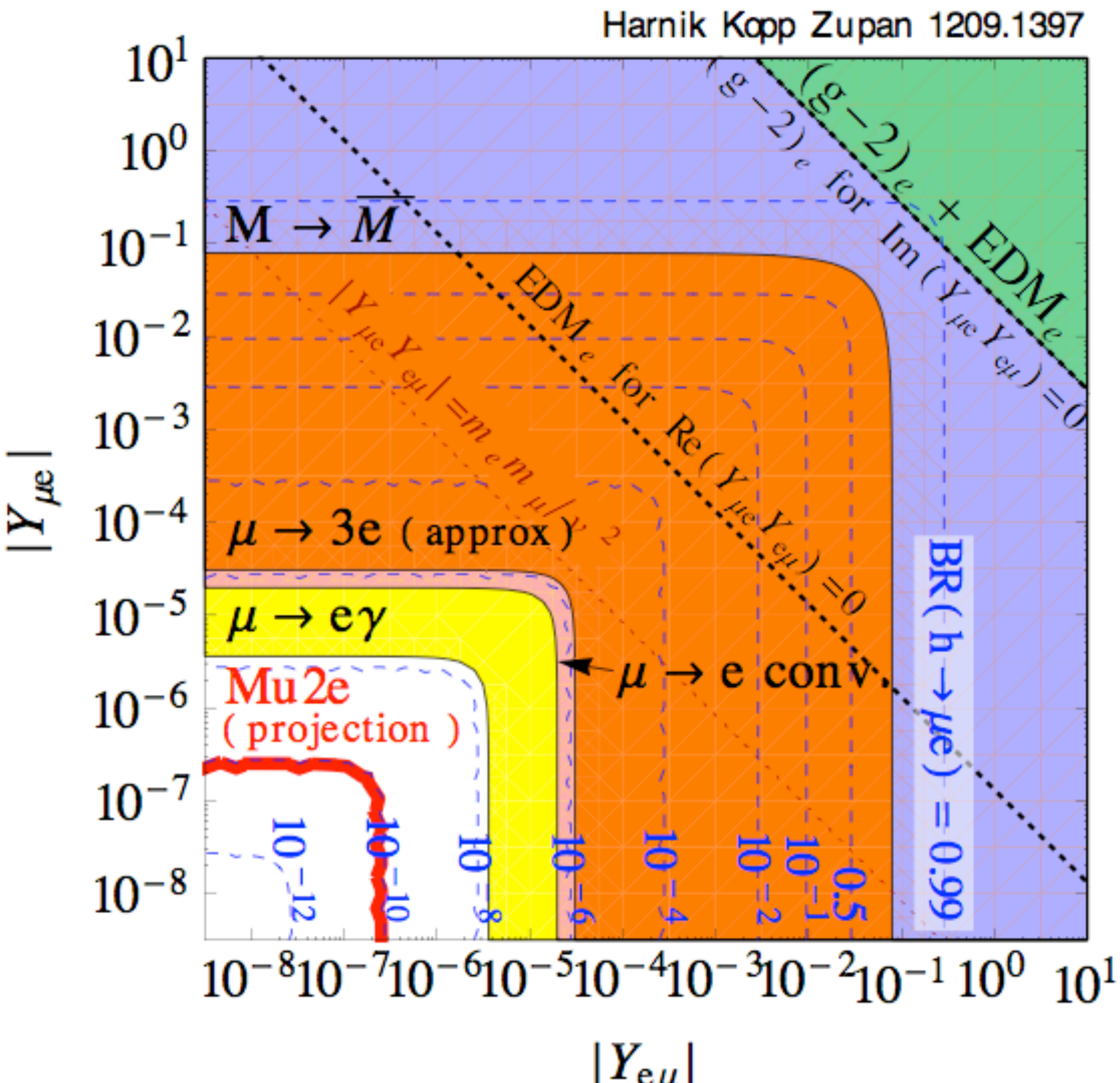
FV Higgs decay:



mu to e conversion (will improve 4 orders of magnitude !!!):



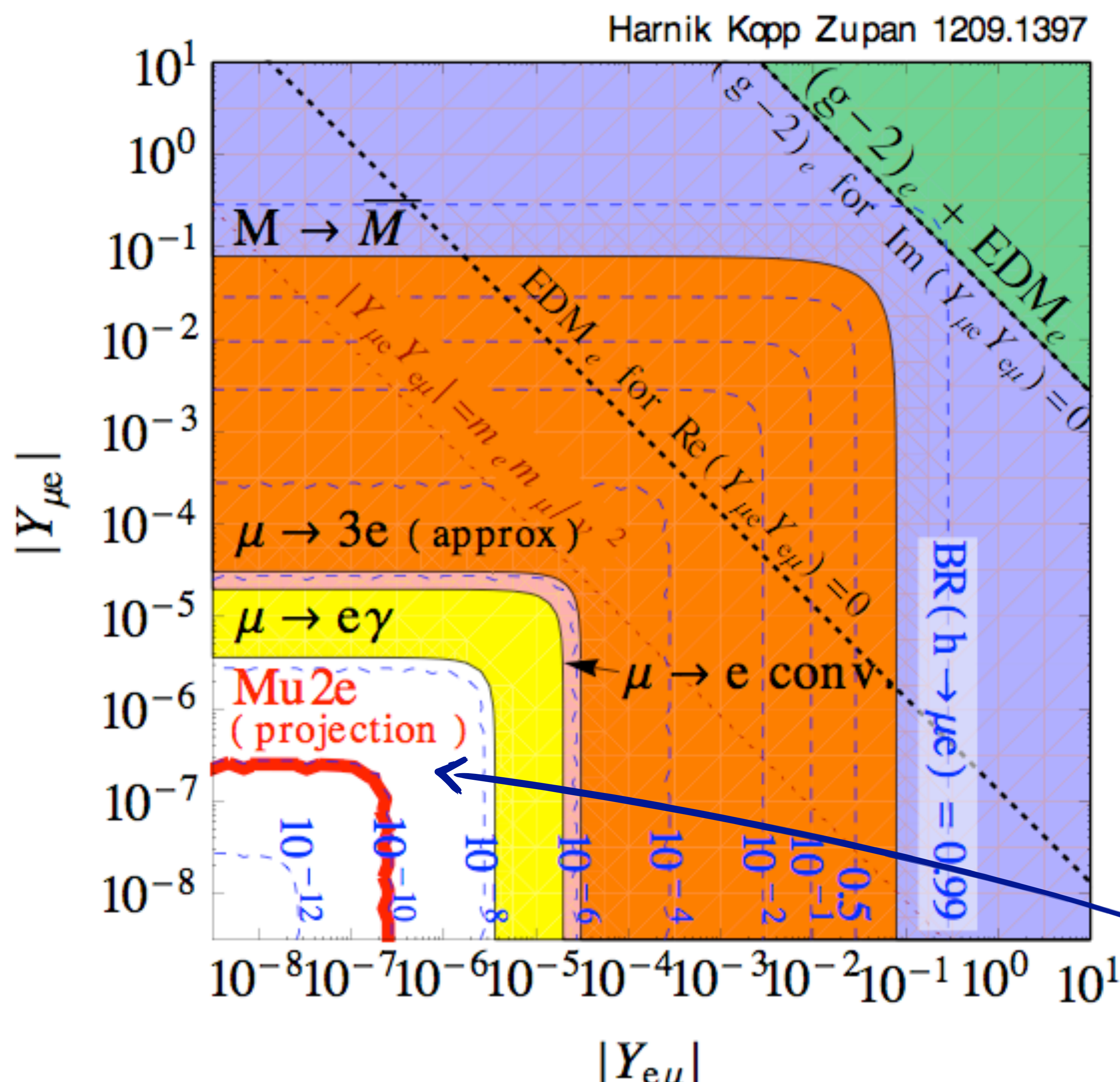
Higgs couplings to μe



$\mu \to e\gamma$ wins.
Will be dominated by μ2e.

Probably outside of LHC reach.

Higgs couplings to μe



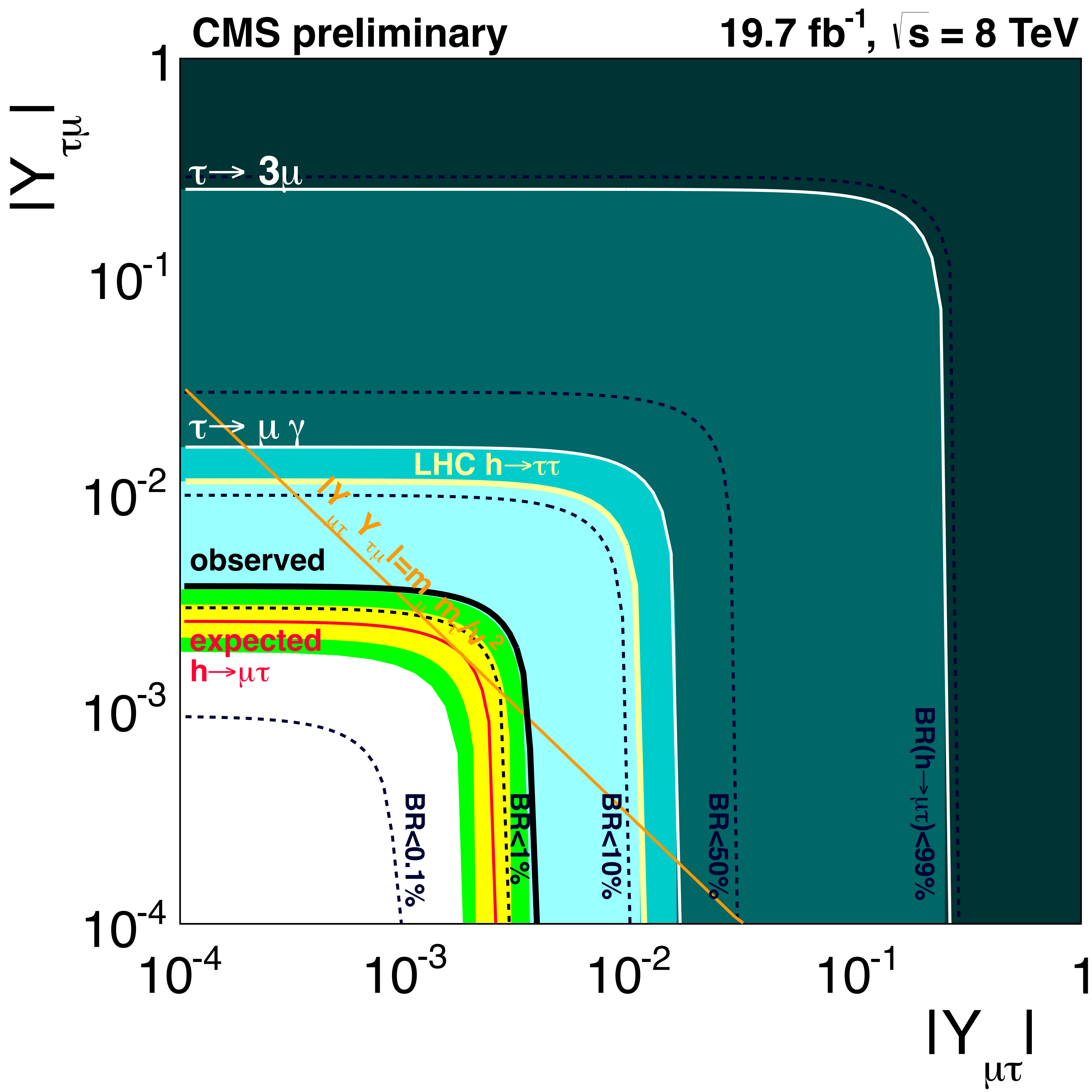
μ→eγ wins.
Will be dominated by μ2e.

Probably outside of LHC reach.

A very clean channel! can we get here with ~10^{10} Higgs bosons?

(an open question)

Higgs couplings to τμ



LHC $h \to \tau\mu$ gives dominant bound.

<u>CMS: A 2.5σ excess.</u>

right around

$y_{\tau\mu} \sim (y_\tau \cdot y_\mu)^{1/2}$

Waiting for ATLAS...

RH, Kopp, Zupan 1209.1397
& CMS

μ-e asymmetry

* $h \to \tau\mu$ is statistically limited in some channels. How about after 10^9 Higges plus BG's?

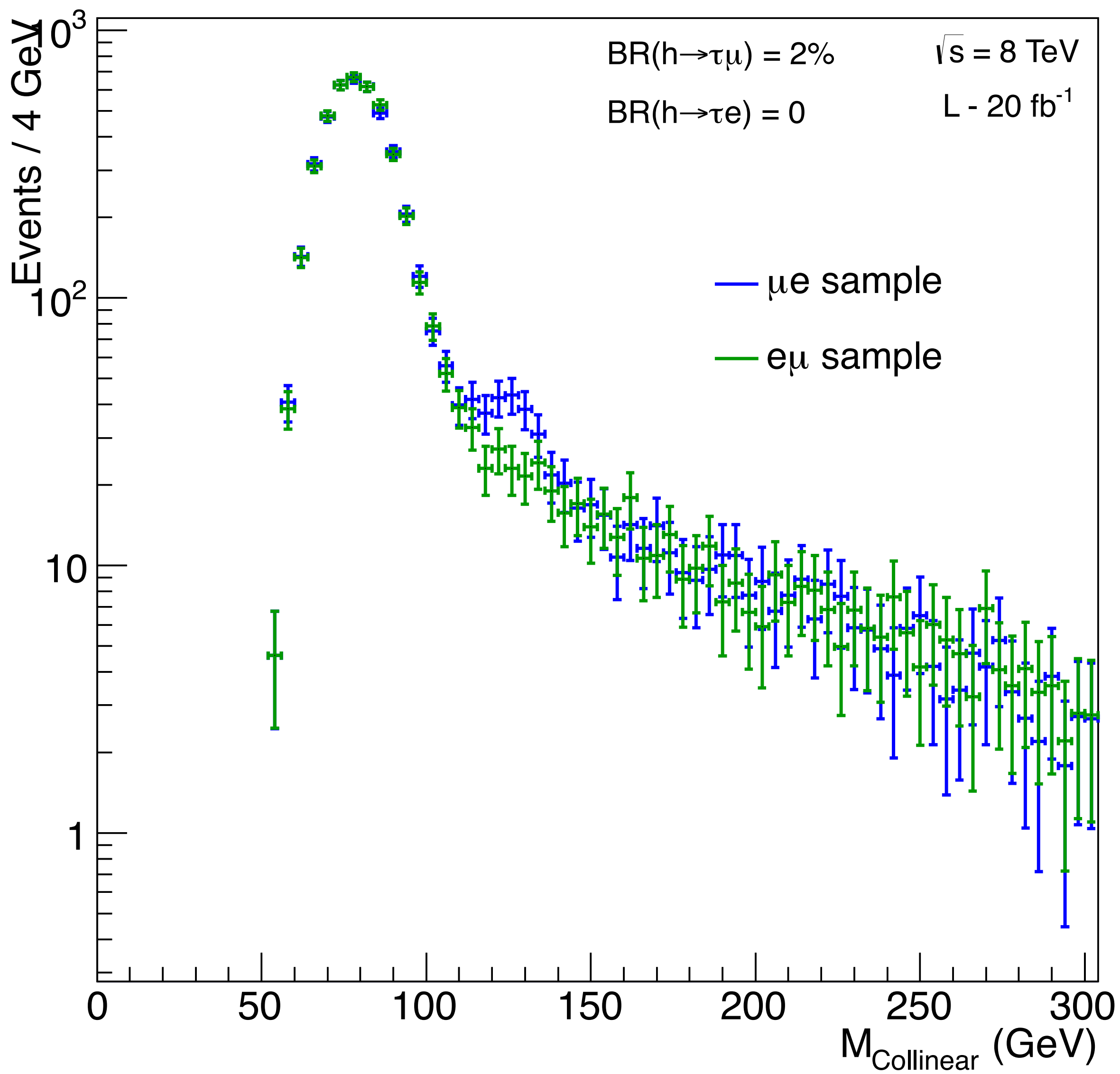
* For the future:
  A novel technique for reducing systematics in the fully leptonic channel: **μ-e asymmetry**

  - Backgrounds are symmetric under $\mu \leftrightarrow e$.
  - $h \to \tau\mu$ violates this.

see Bressler, Dery, Efrati (1405.4545).

μ-e asymmetry

* Use this to measure BG in a data driven way. Expected to be statistic dominated for a long time.



A promising approach for a future hadron machine.

Still, may be hard to beat CepC/ILC/FCC-ep.

see Bressler, Dery, Efrati (1405.4545).

Conclusion

* Massive Higgs production rate at 100 TeV. An opportunity for clean, low rate channels.
* Examples of statistically limited searches:
    - Double Higgs production.
    - $h \to 4\ell$ for hVV couplings and CP properties.
    - Leptonic Flavor violating Higgs decays.
    - Top FCNC's (e.g. $top \to hc$).
    - ...?

Deleted Scenes

hVV: Measurements

- We already have some searches for our signal:

$$\mathcal{L} = \frac{h}{4v}\Big(2m_Z^2 A_1^{ZZ} Z_\mu Z^\mu$$

$$+ A_2^{ZZ} Z_{\mu\nu} Z^{\mu\nu} + A_3^{ZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

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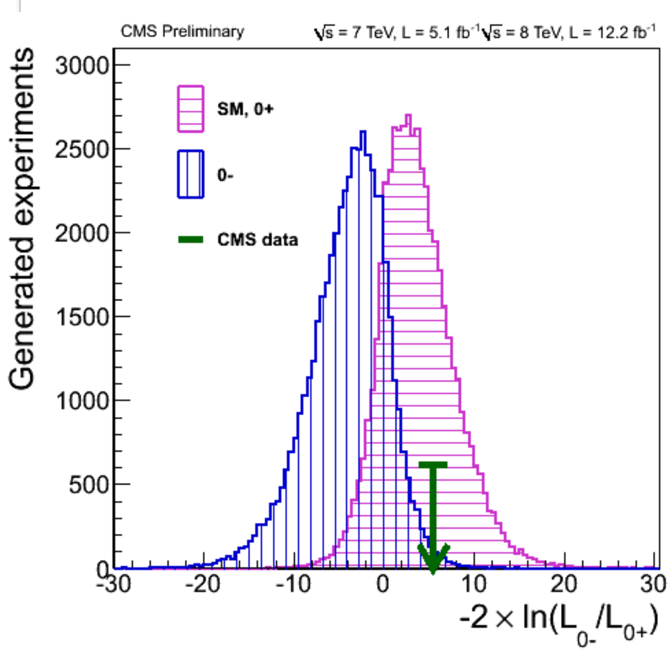
$h \rightarrow 4\ell$:

or

scalar vs. pseudoscalar.

(Hypothesis test).



Scalar preferred @ 3σ

A good first step, but this is not the way to go forward with this search.

(CMS already started this change)

hVV: Measurements

* We have some measurements of A's:

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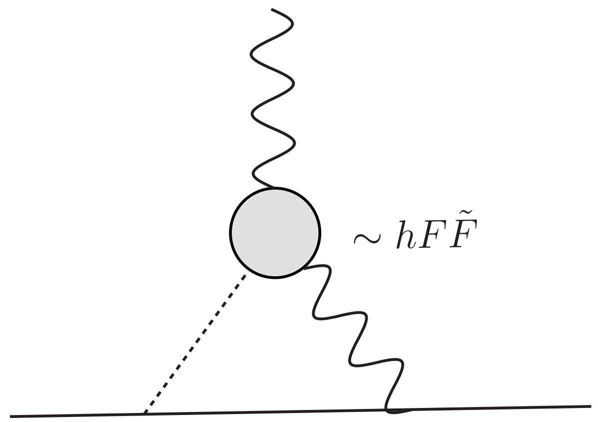


If Higgs couples to electron - EDM!

$A_2 \gg A_3$

McKeen, Pospelov, Ritz

$$+ A_2^{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} + A_3^{\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

LHC $h \to \gamma\gamma$ rate (assuming standard production):

$$|A_2^{\gamma\gamma}|^2 + |A_3^{\gamma\gamma}|^2 \sim \text{SM value}$$

Motivation

* Why look for $Z\gamma$ and $\gamma\gamma$ in four leptons?
  Isn't it clear we will loose to direct searches?
  - Yes, but backgrounds are also smaller.
  - Interference = Sensitivity to CP violation.
  - Many observables = **discriminating power.**
  - **Interference** also gives 4ℓ a head start.
    e.g., $A_2^{Z\gamma}$'s effect the rate like -

$Z\gamma$:	$A_2 x A_2 \sim small^2$
4ℓ:	$A_1 x A_2 \sim big^* small$

Setup

Y. Chen, N. Tran, and R. Vega-Morales, 1211.1959
Y. Chen and R. Vega-Morales, 1310.2893
Earlier MEM work by Ian Low et al.

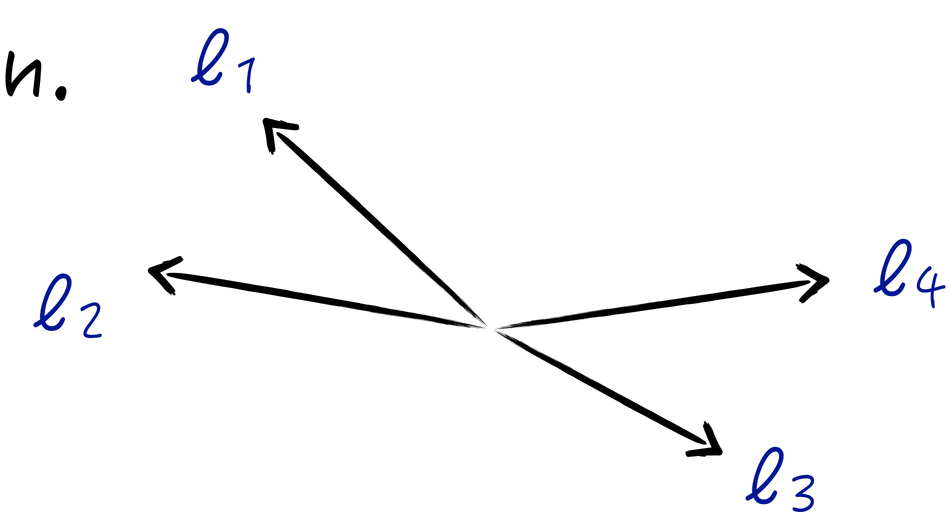
Method

* A simple procedure:
  - Calculate the fully differential cross section analytically*.
  - A big function of $(A_2^{ZZ}, A_3^{ZZ}, A_2^{Z\gamma}, A_3^{Z\gamma}, A_2^{\gamma\gamma}, A_3^{\gamma\gamma})$ & phase space.
  - Fit to the data. Extract A's directly.
* Keeps all operators simultaneously.
  No hypothesis testing, etc.

*Done in a **heroic** effort by youngsters Chen and Vega-Morales.

Phase Space

* The relevant phase space for $h \to 4\ell$ can be written as:
    - two invariant masses of lepton pairs, m1 and m2.
    - two opening angles.
    - a relative azimuthal angle.
* All other variables are the boost to the Higgs rest frame, and overall rotation.



m_1 & m_2

* We dopt the CMS/ATLAS convention for picking m_1 and m_2:
  - Same flavor pairs.
  - Always pick $m_1 > m_2$
  - For $4e$ and 4μ: pick m_1 to be closest to the Z mass.

Note: These choices have ZZ^* in mind.

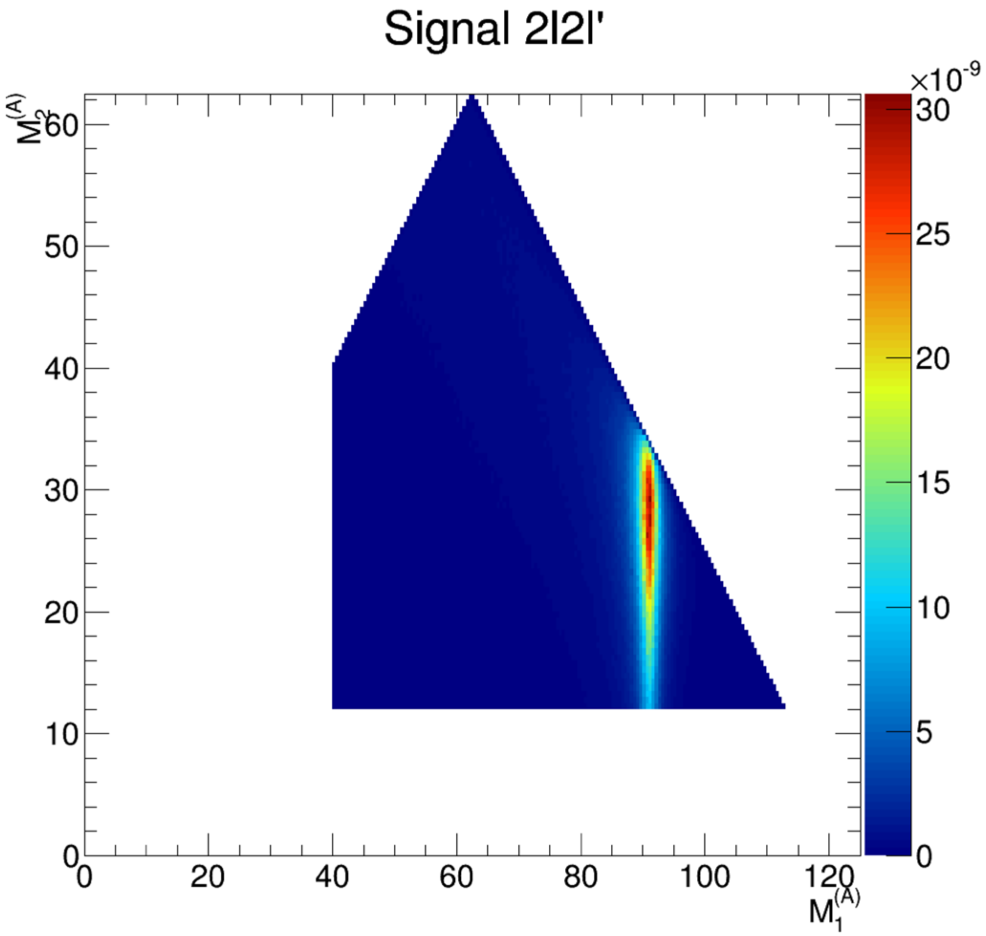
* We also employ CMS-like cuts:

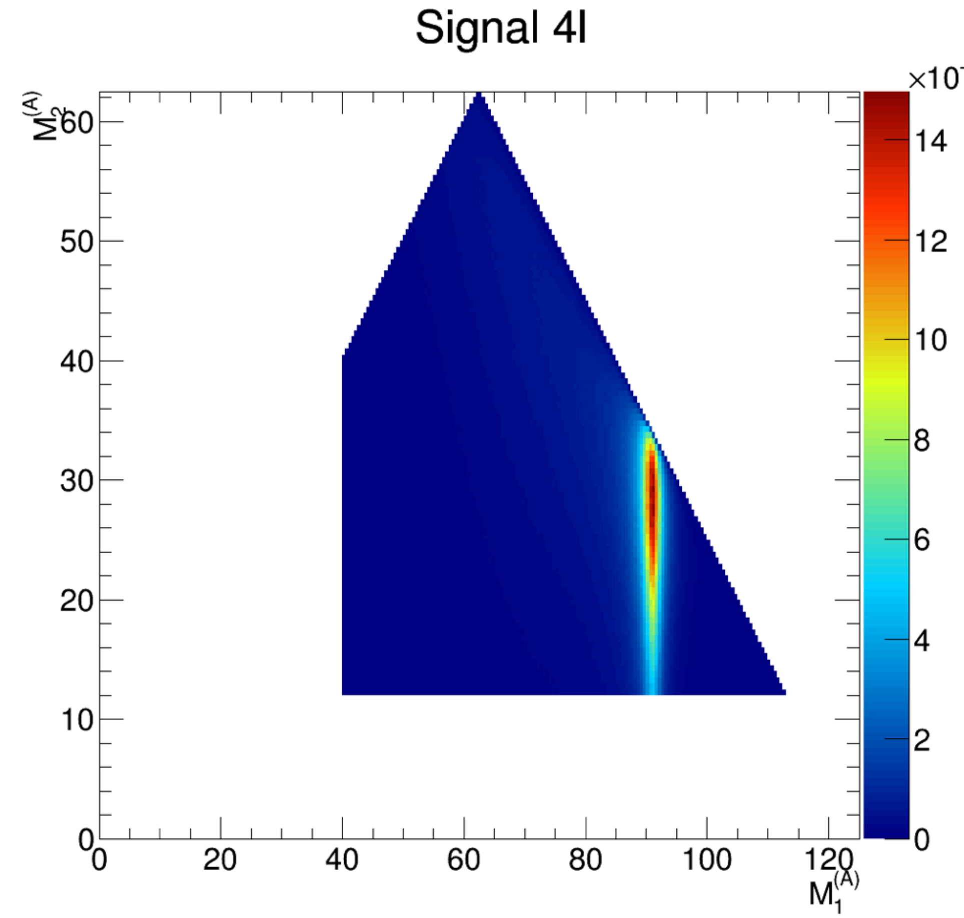
- $p_{T\ell} > 20, 10, 7, 7$ GeV for lepton p_T ordering,
- $|\eta_\ell| < 2.4$ for the lepton rapidity,
- $40 \text{ GeV} \leq M_1$ and $12 \text{ GeV} \leq M_2$.

Shapes

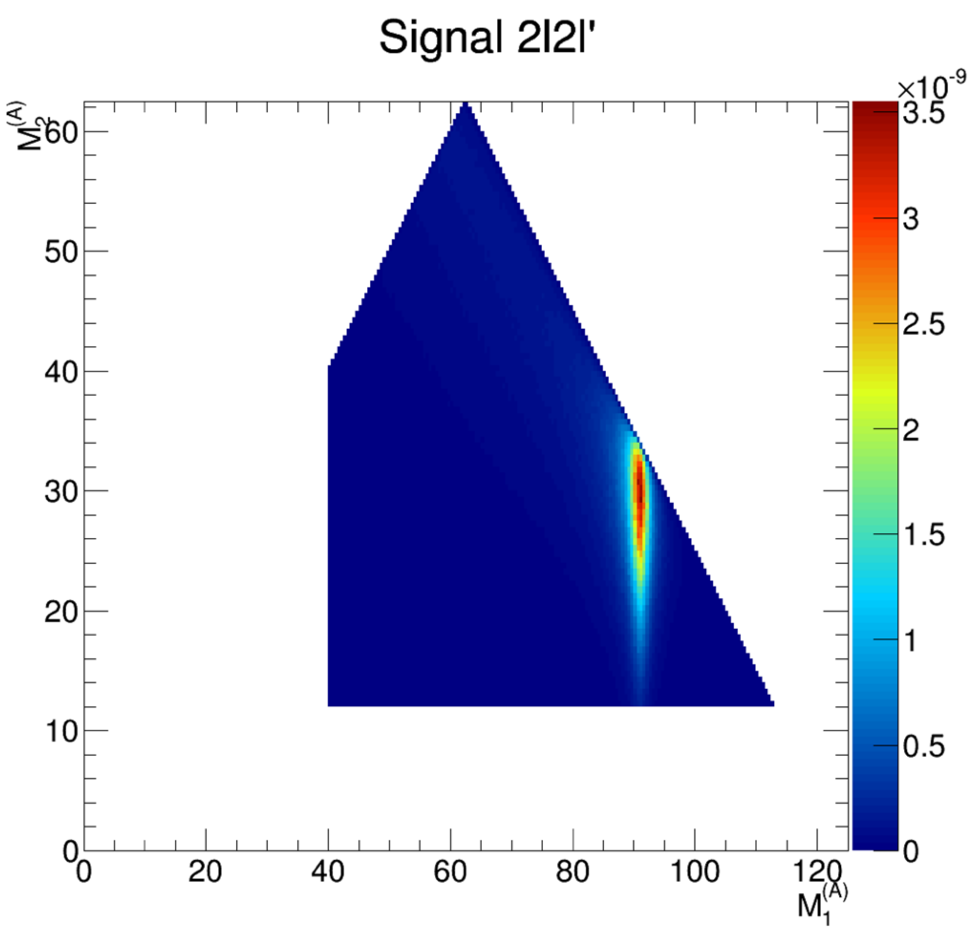
A_1^{ZZ}

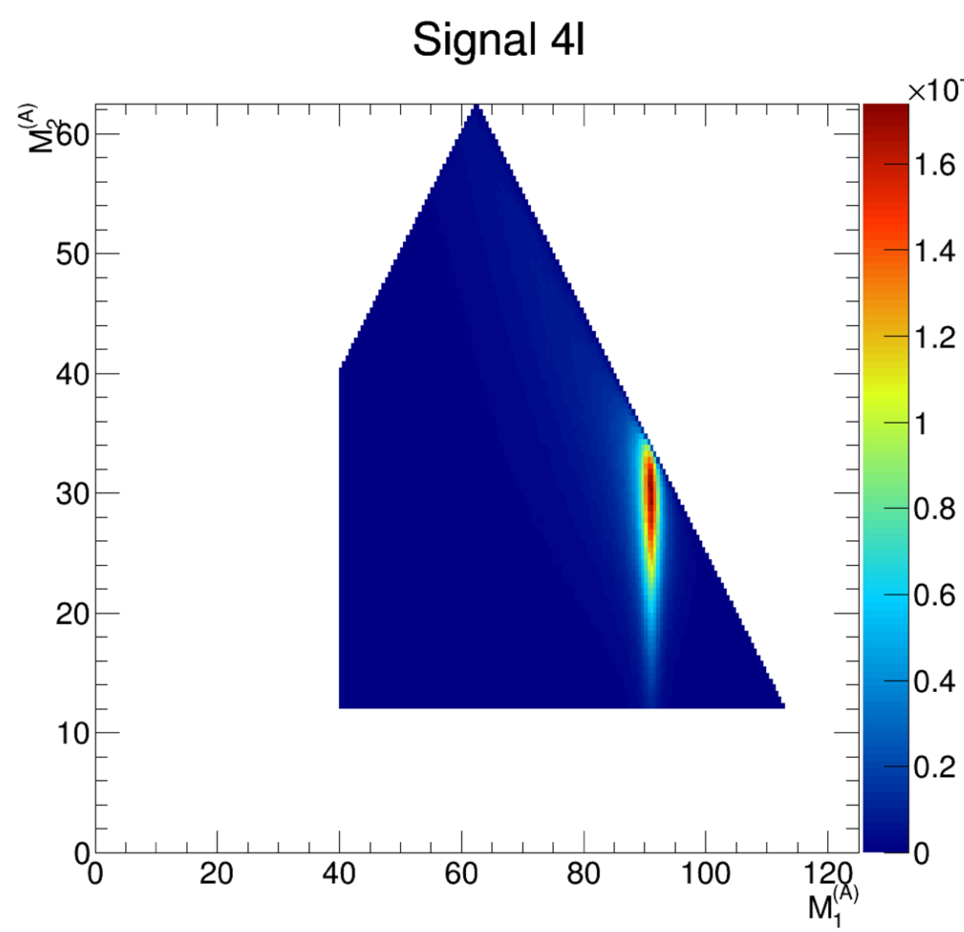
"background"





A_2^{ZZ}

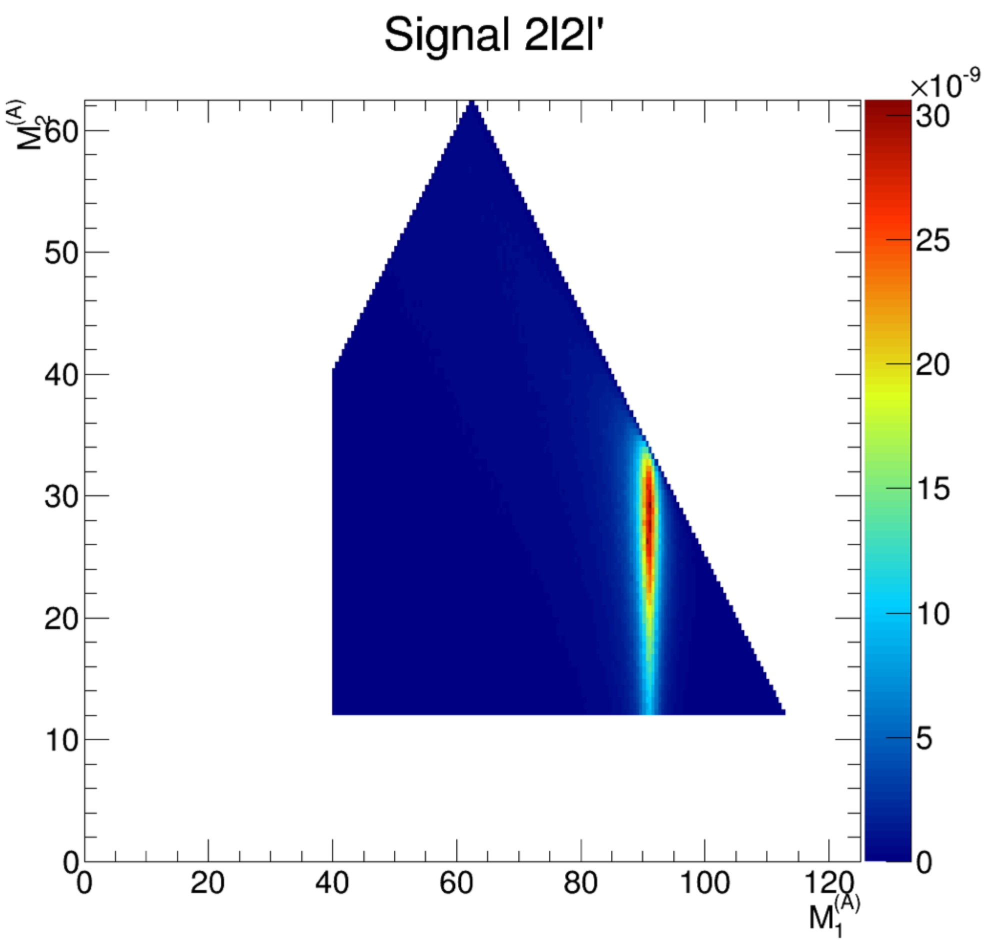


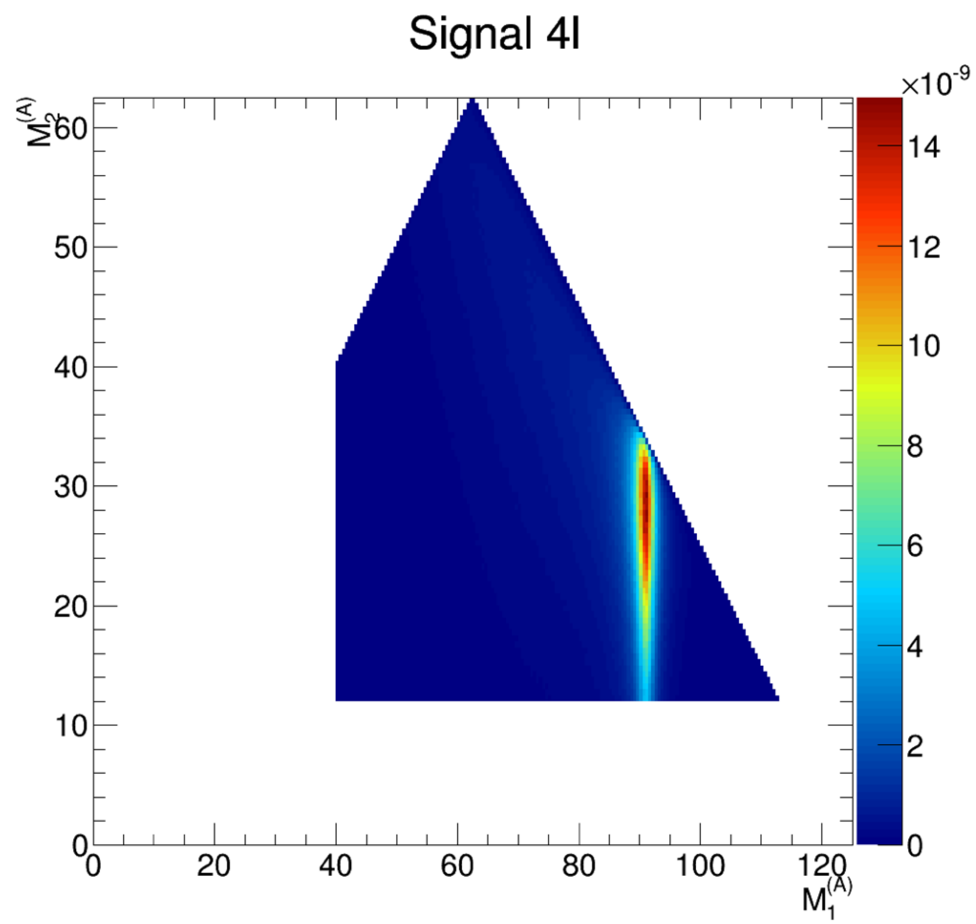


Shapes

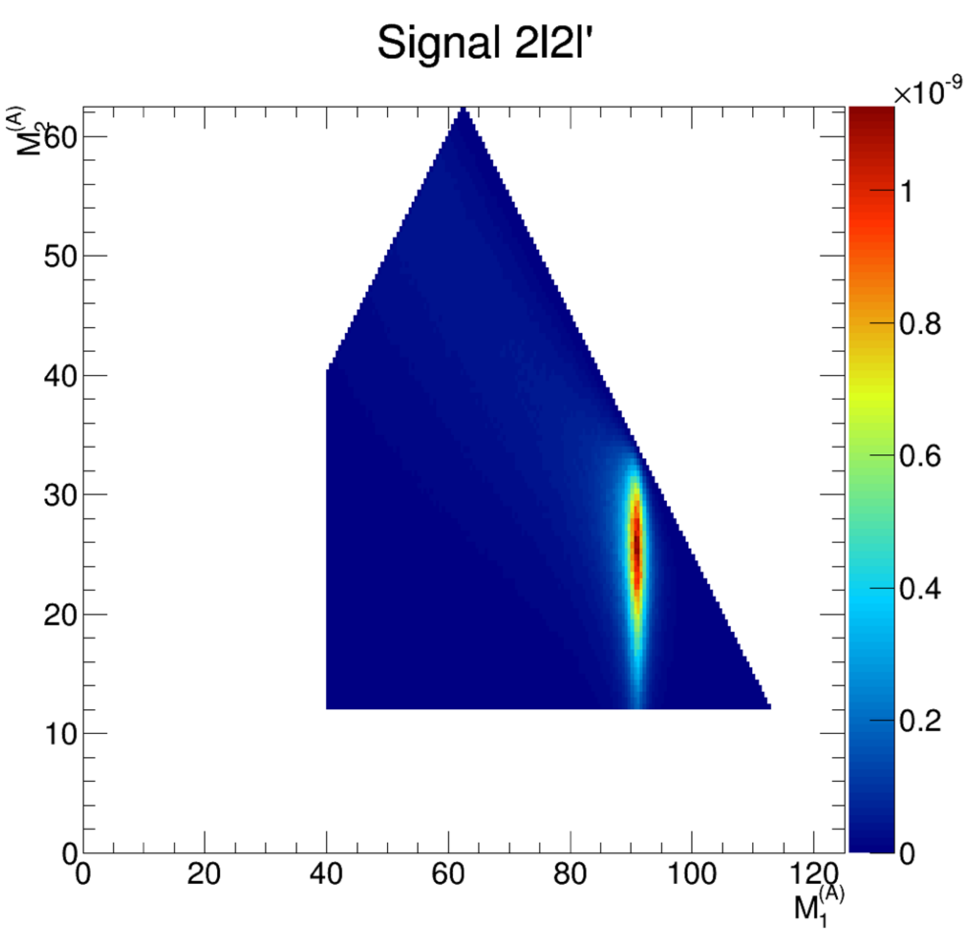
A_1^{ZZ}

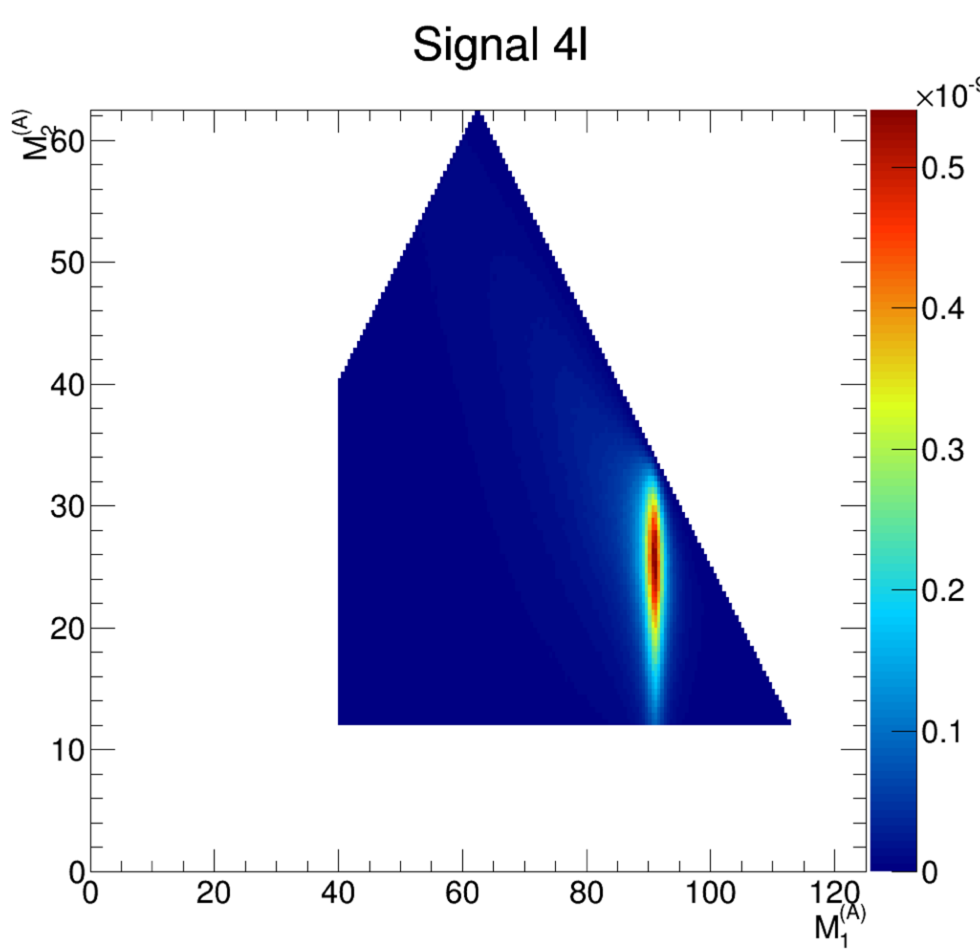
"background"





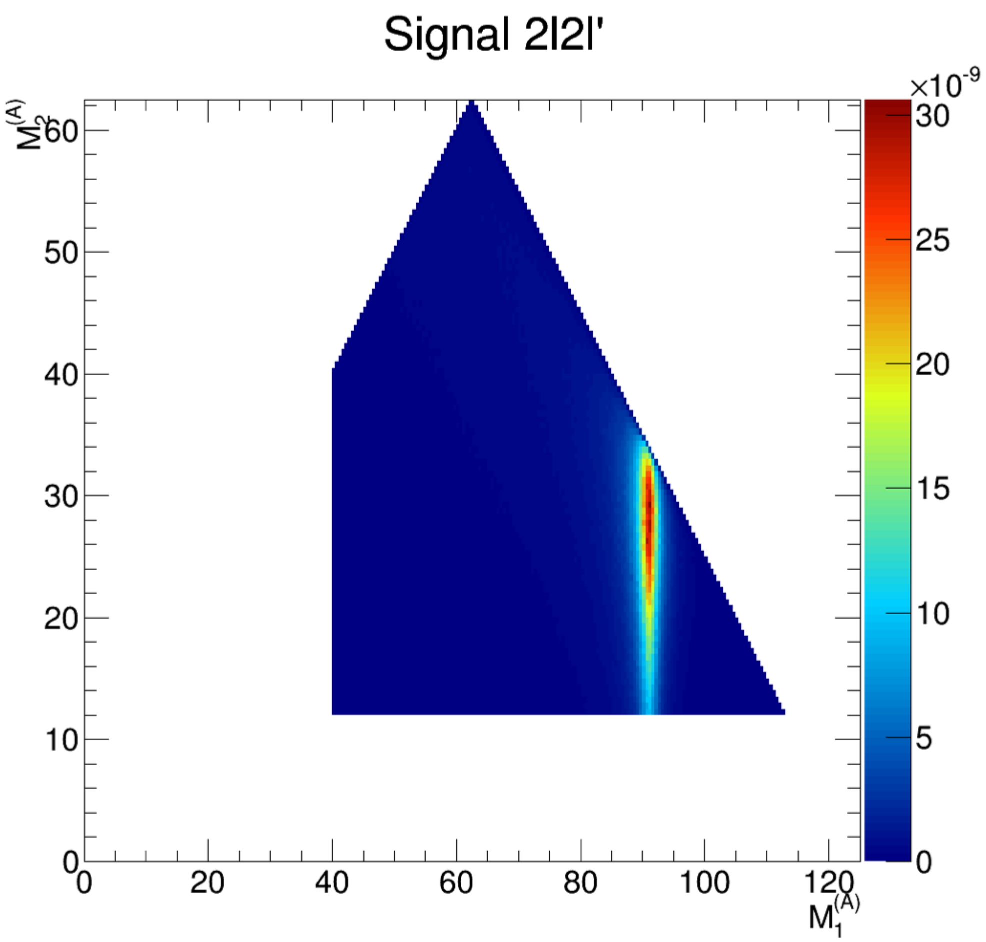
A_3^{ZZ}

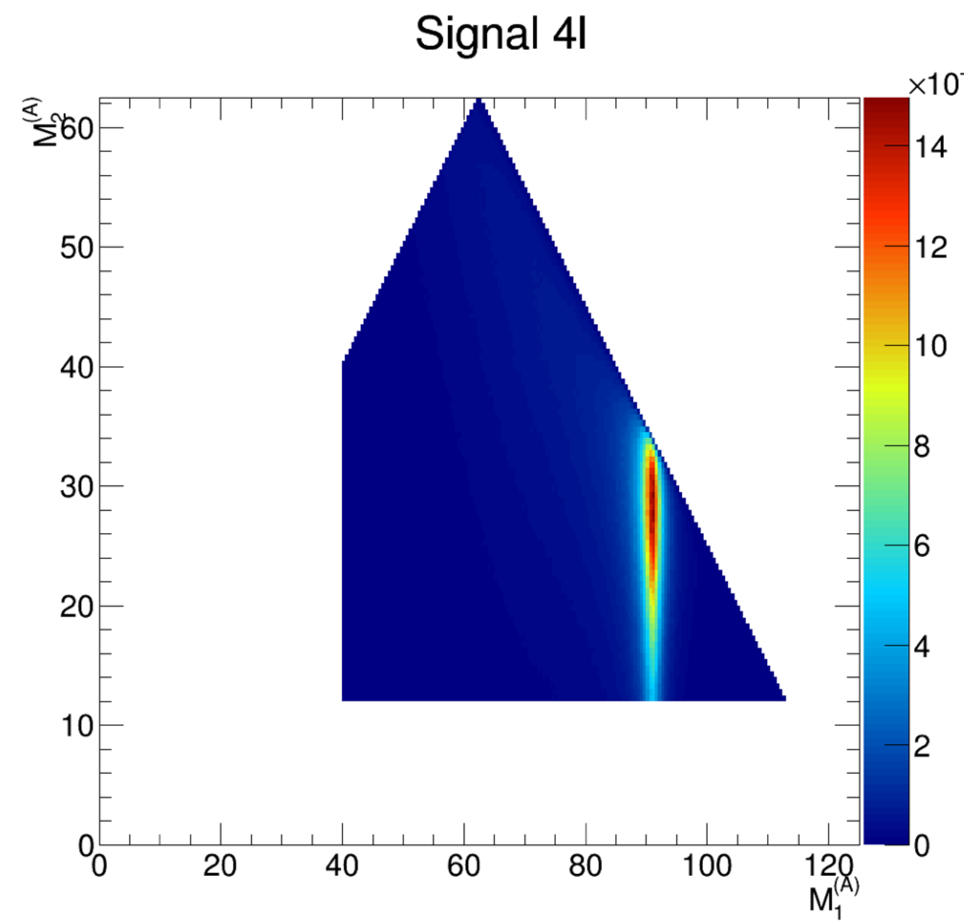




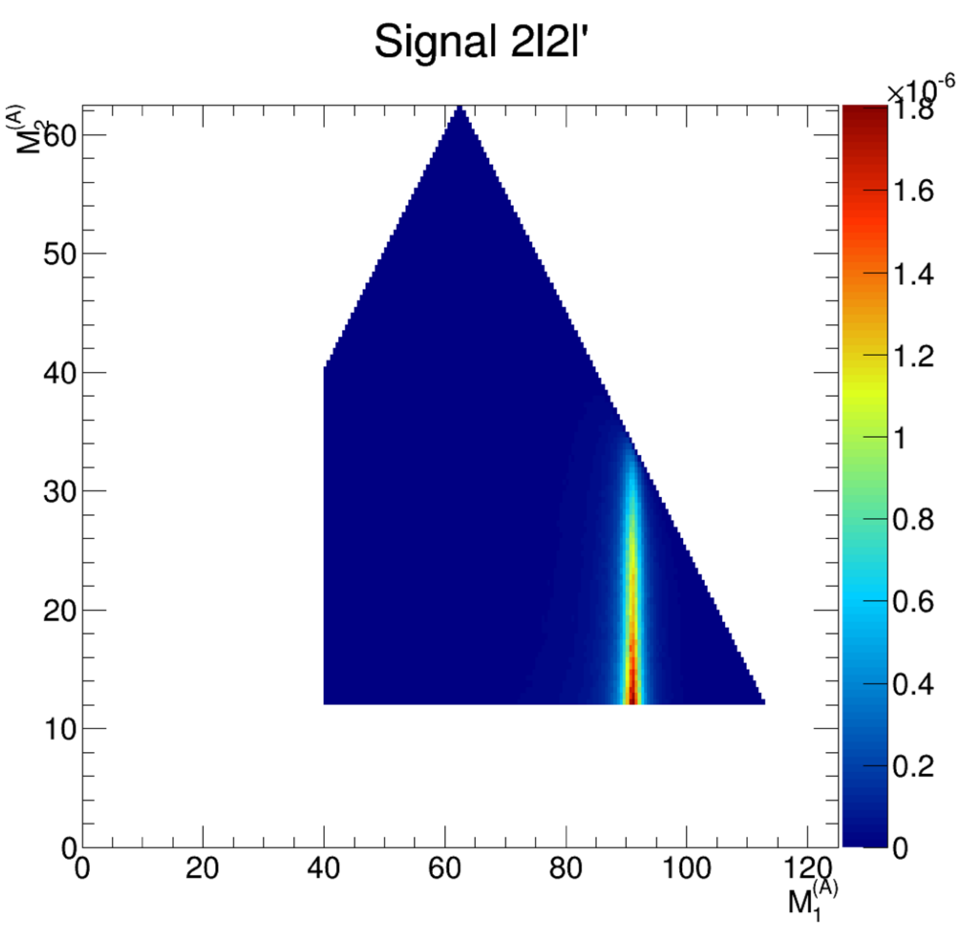
Shapes

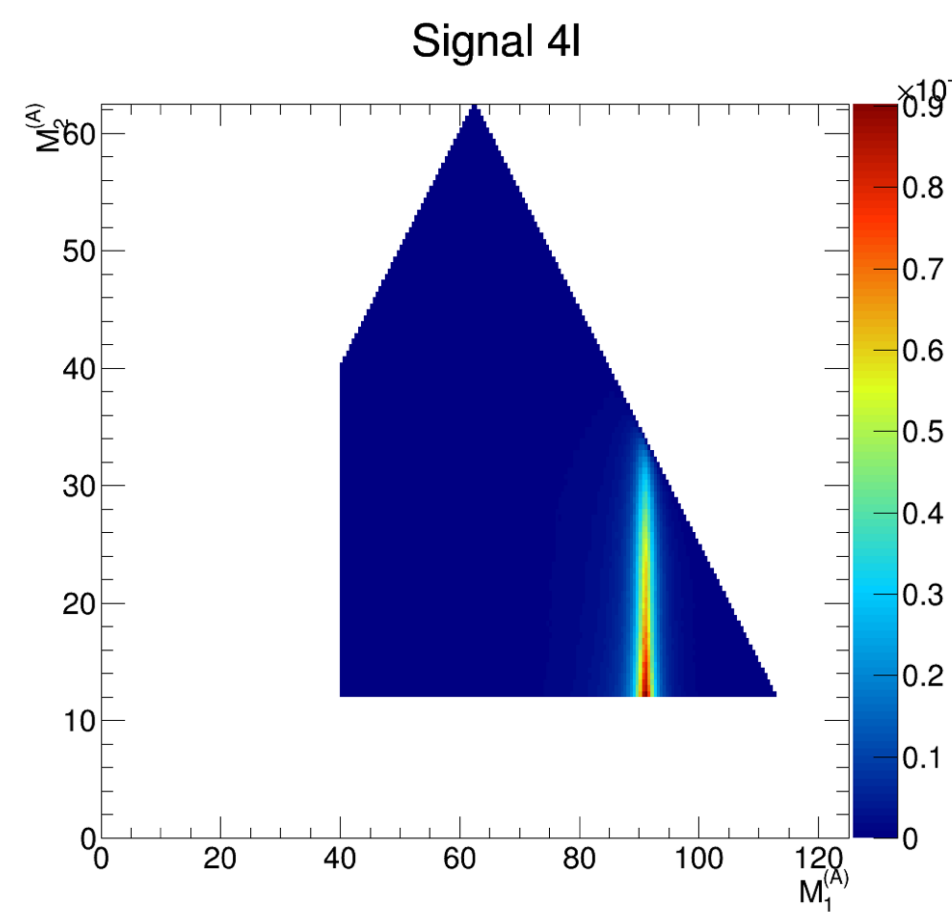
A_1^{ZZ} "background"





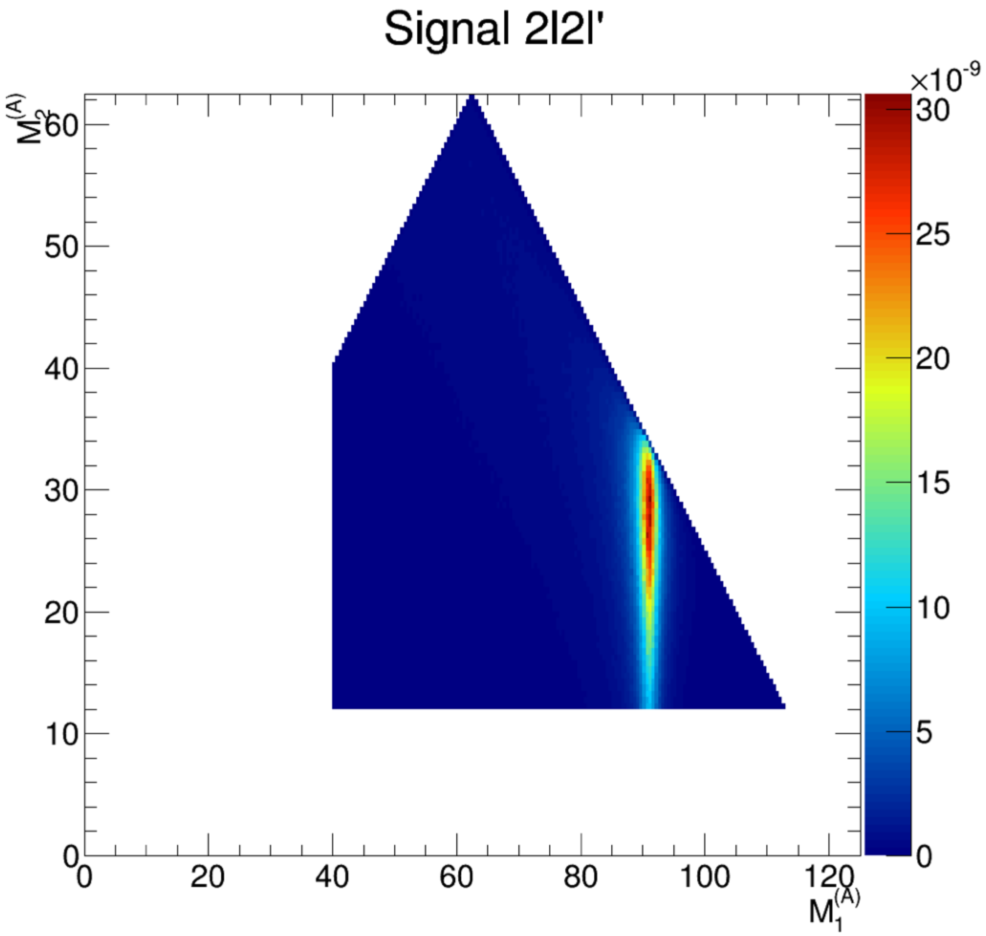
A_2^{ZA}

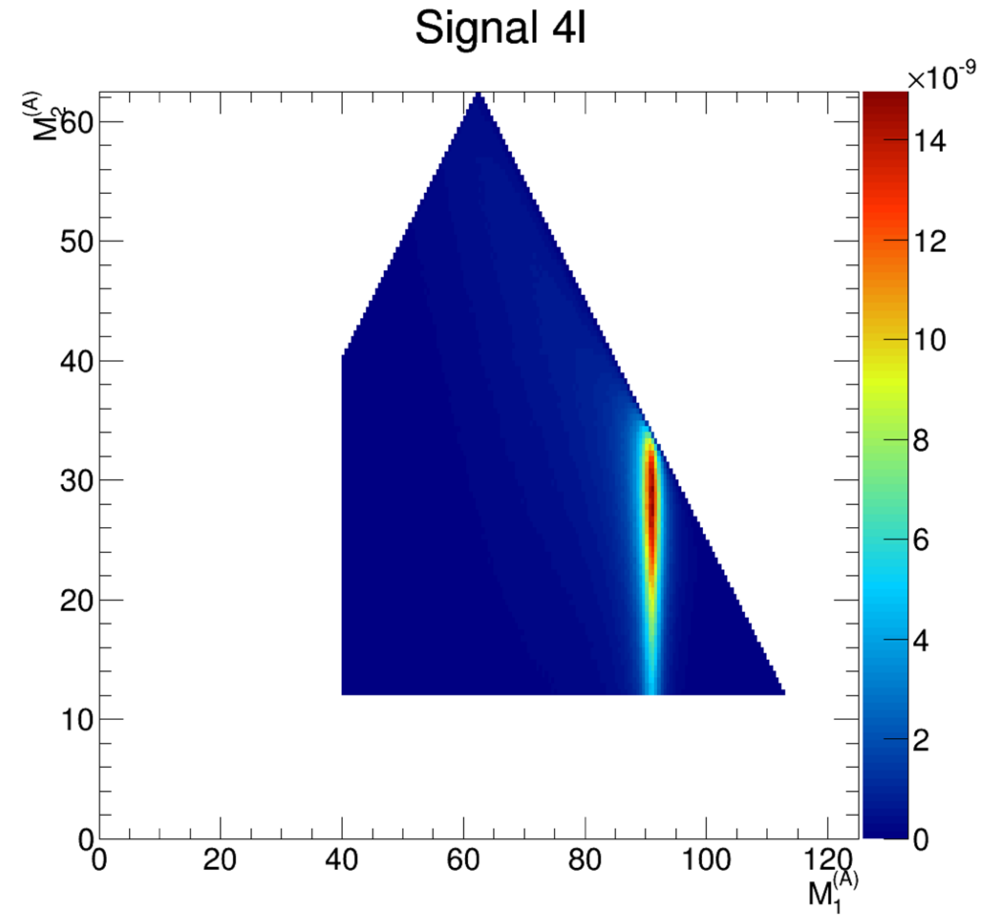




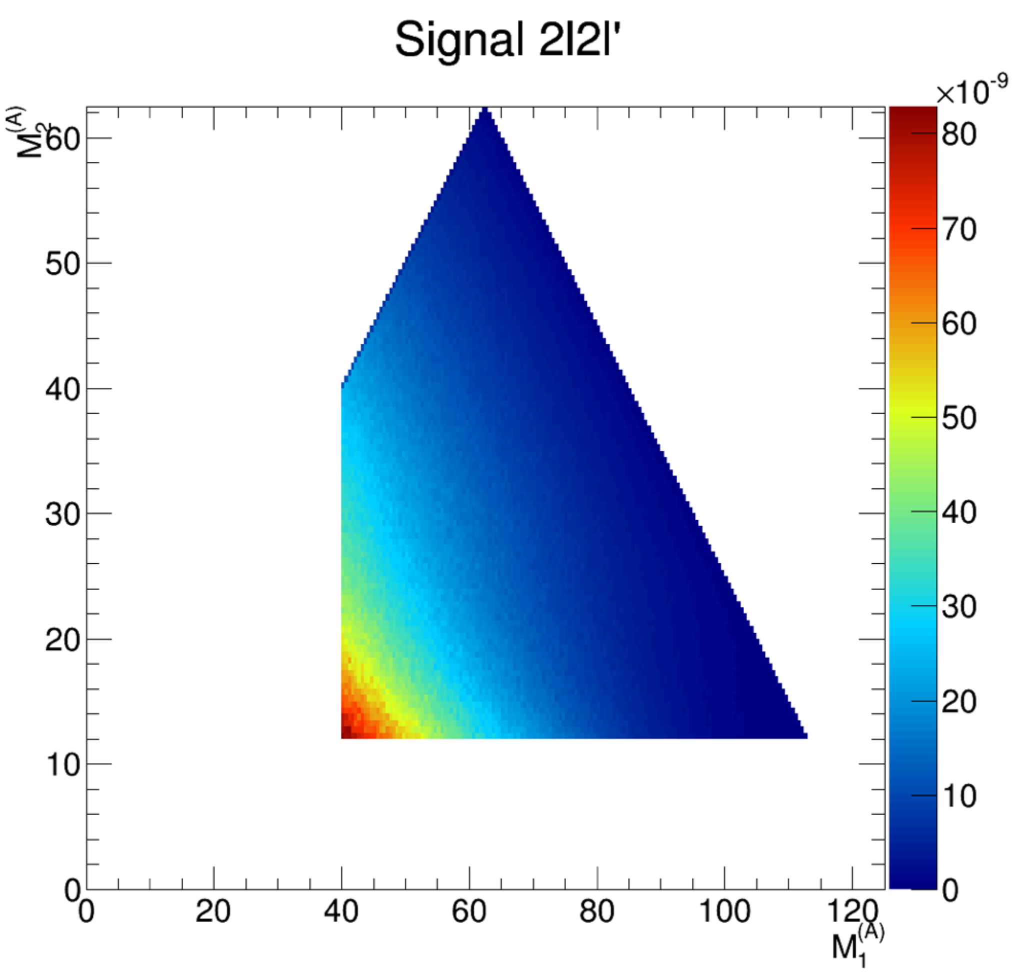
Shapes

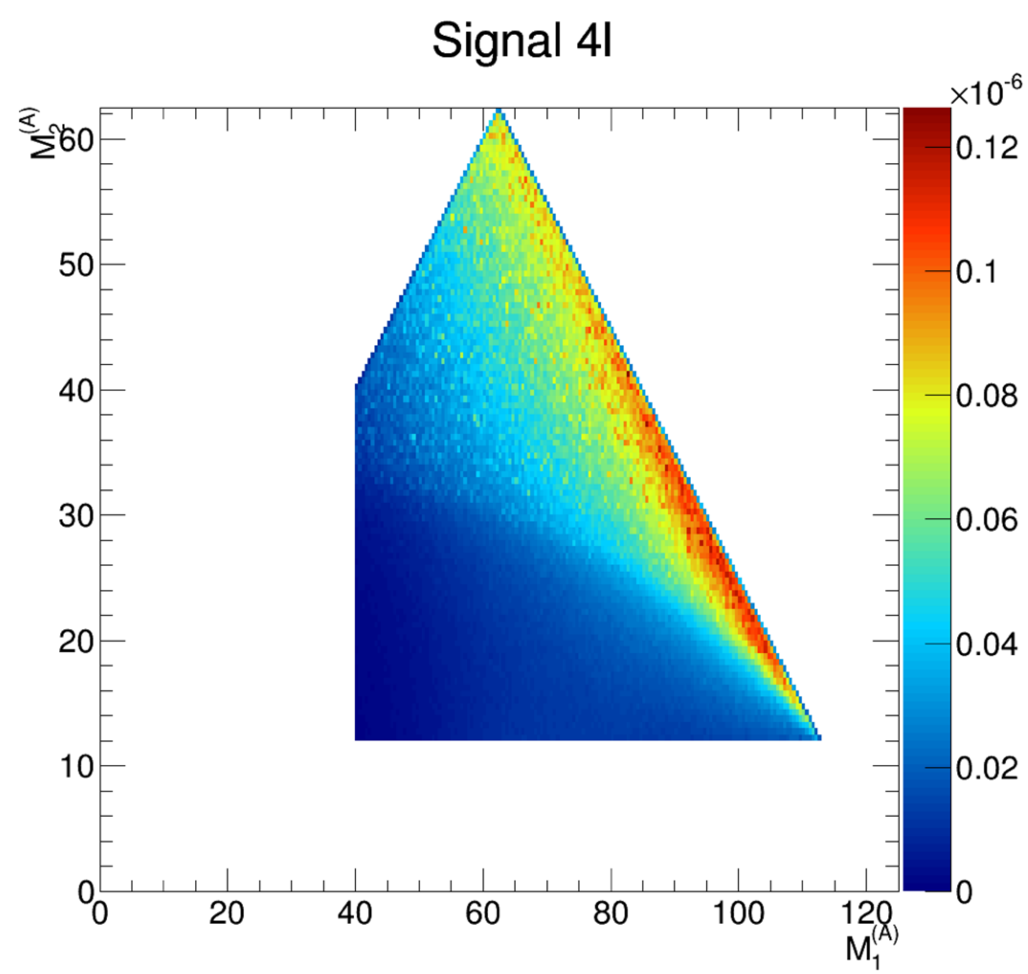
A_1^{ZZ} "background"





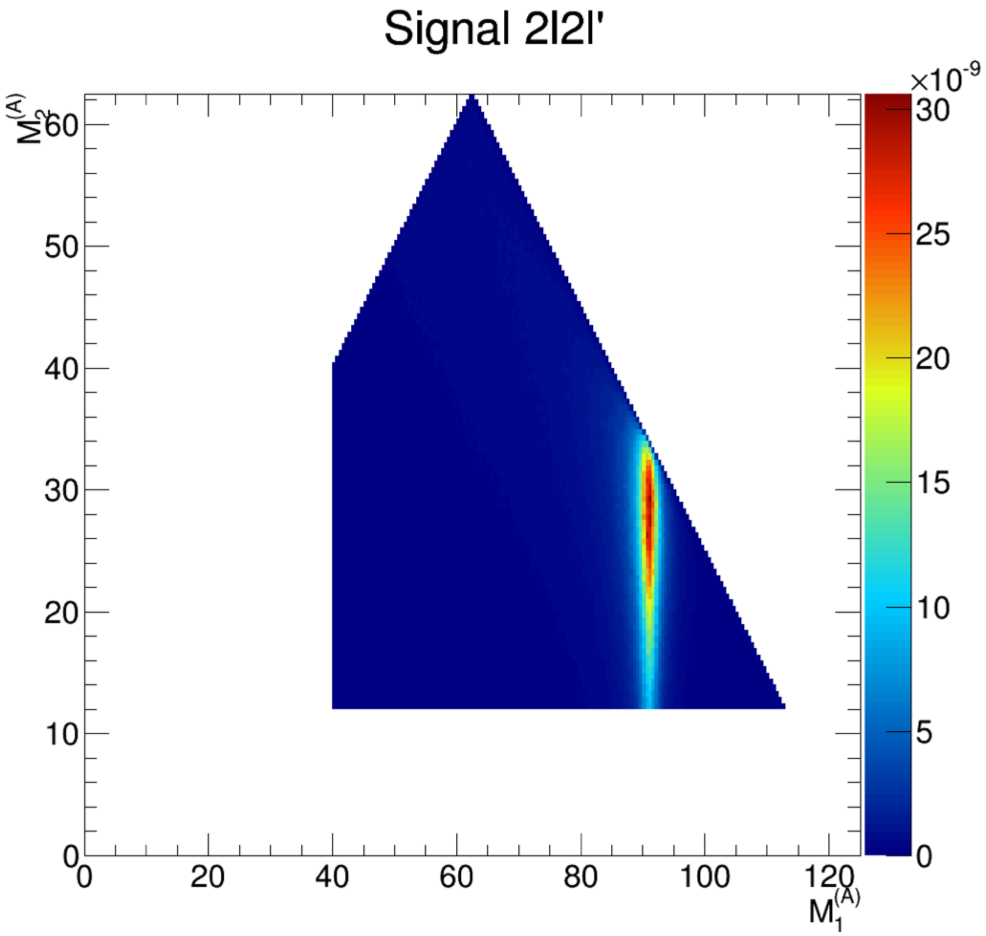
A_2^{AA}

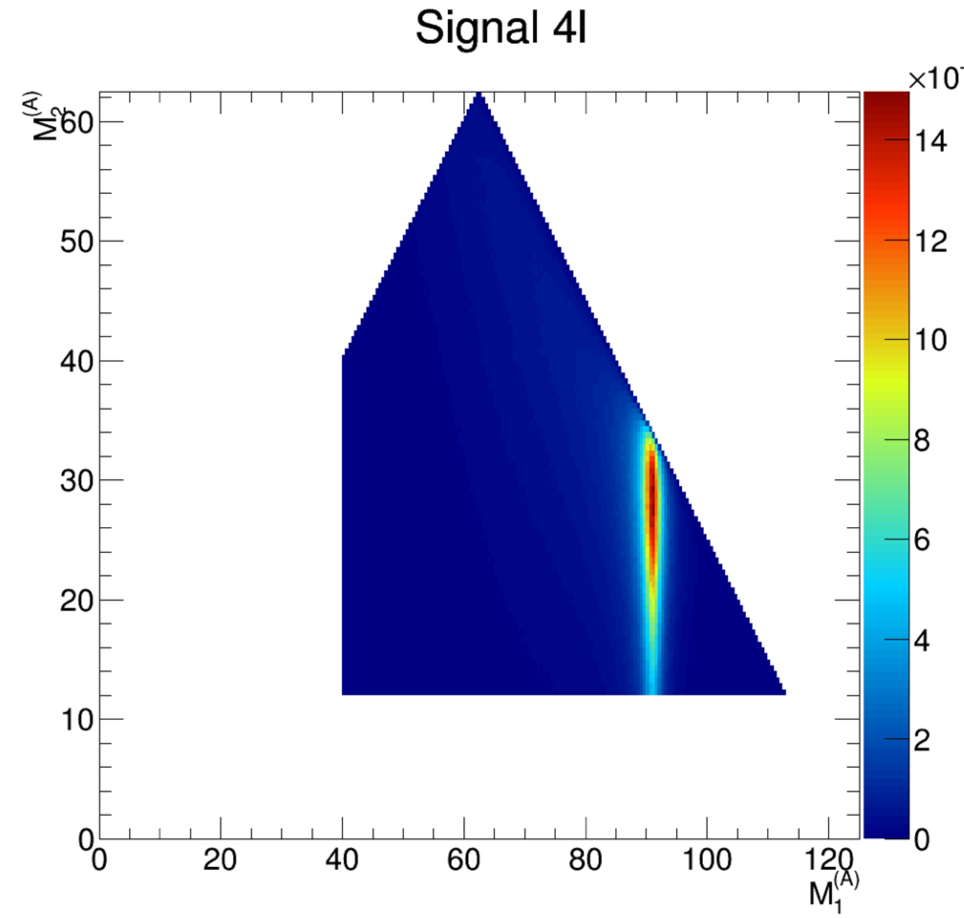




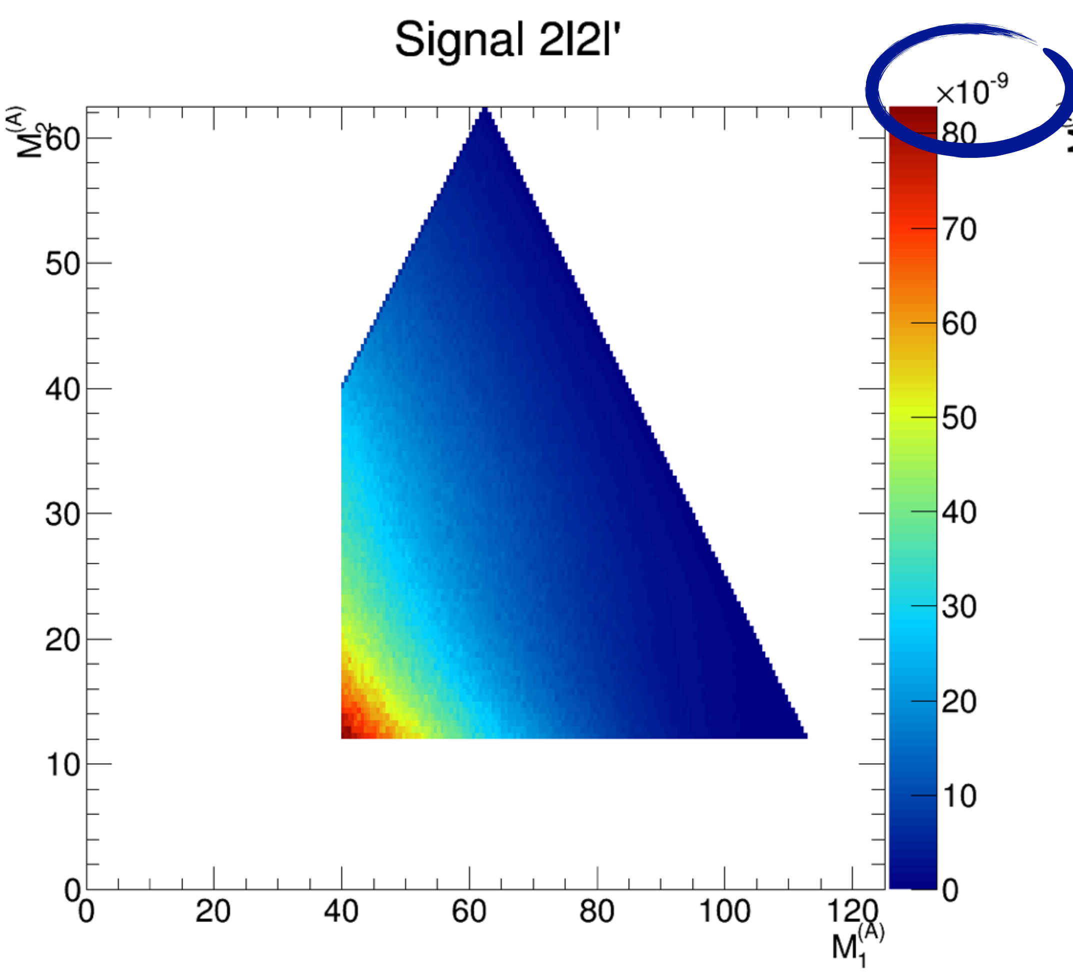
Shapes

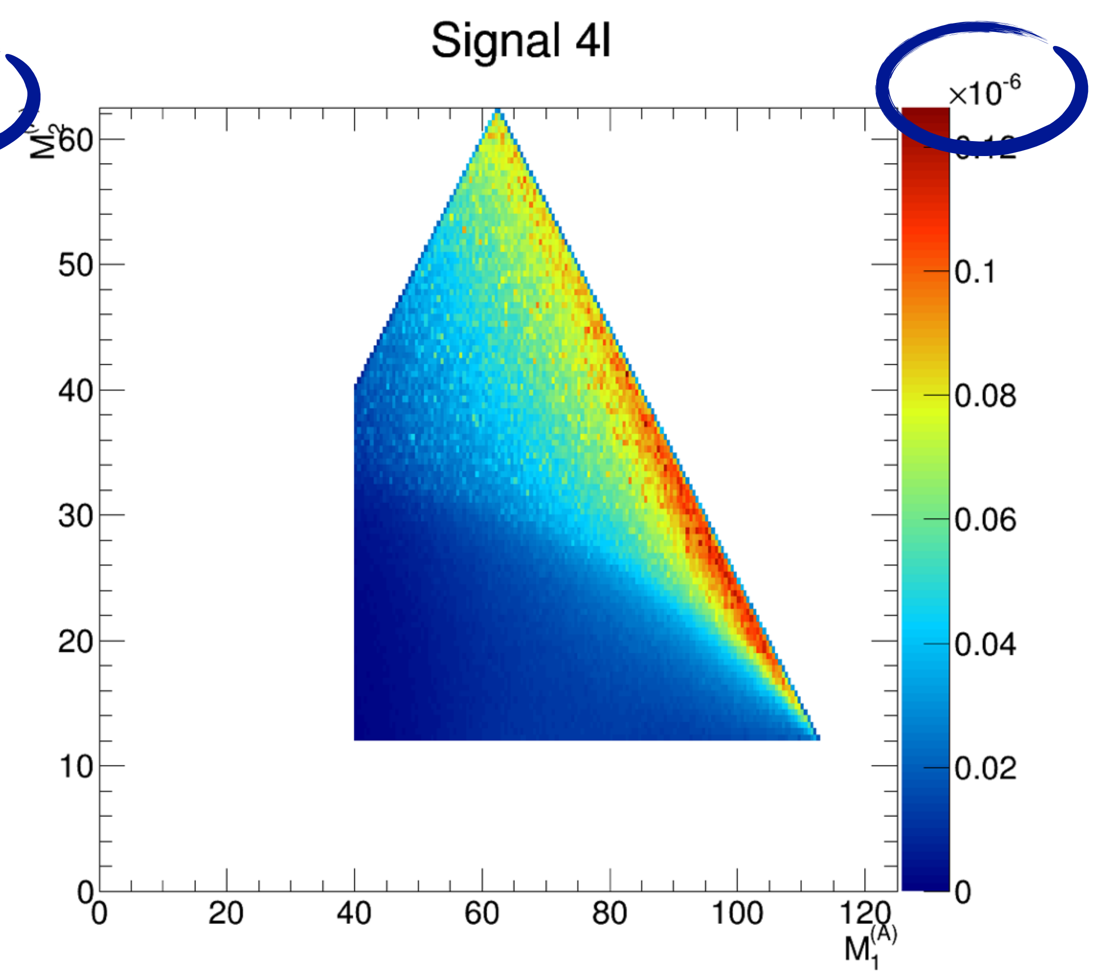
A_1^{ZZ} "background"





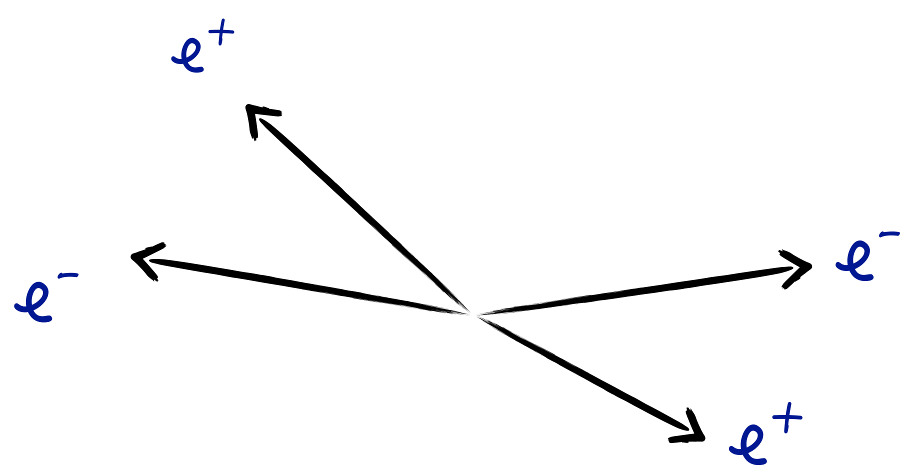
A_2^{AA}





"Wrong Pair"

* These cuts were optimized to discover the Higgs. Motivated by ZZ^*.
* But accidentally, they have good efficiency for $\gamma^*\gamma^*$ in the $4e$ and 4μ channel! :-)



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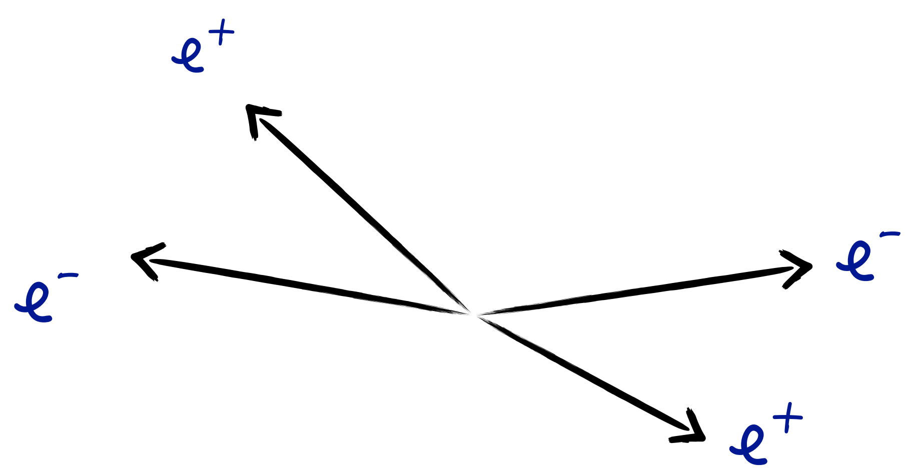

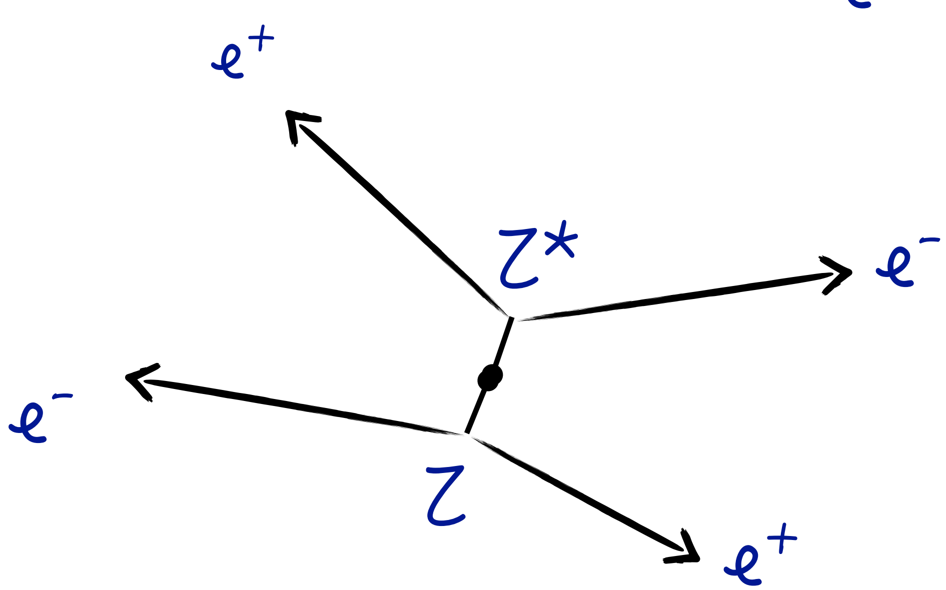

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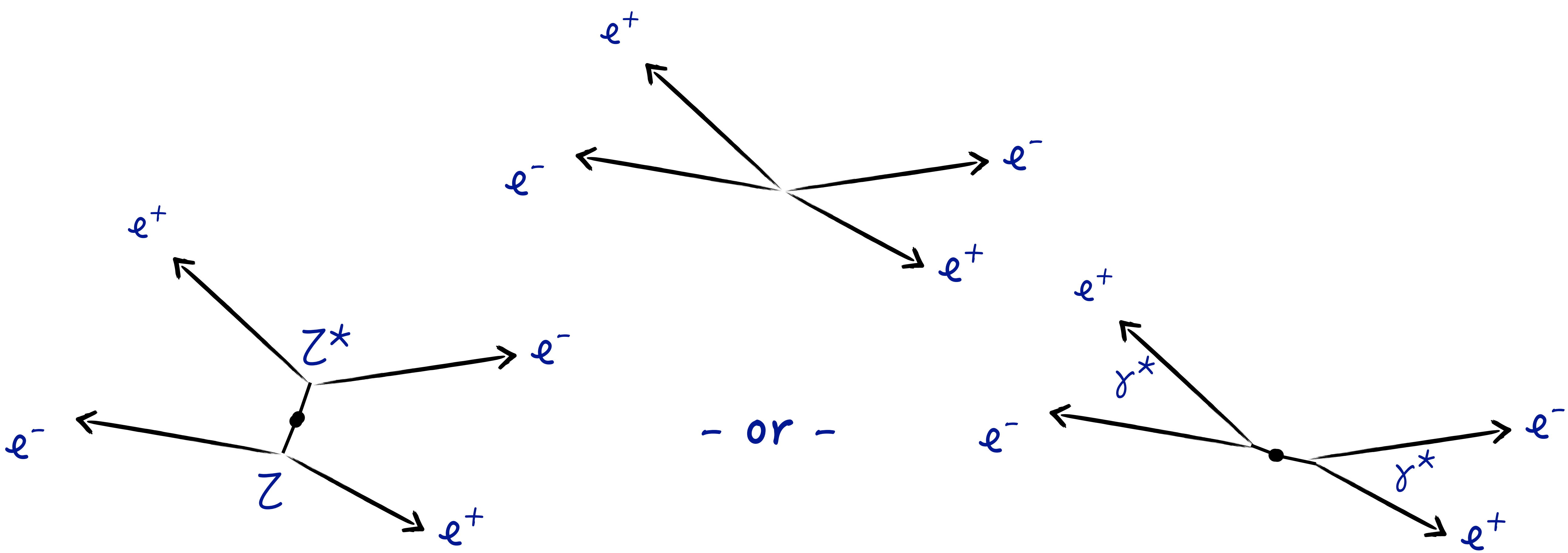

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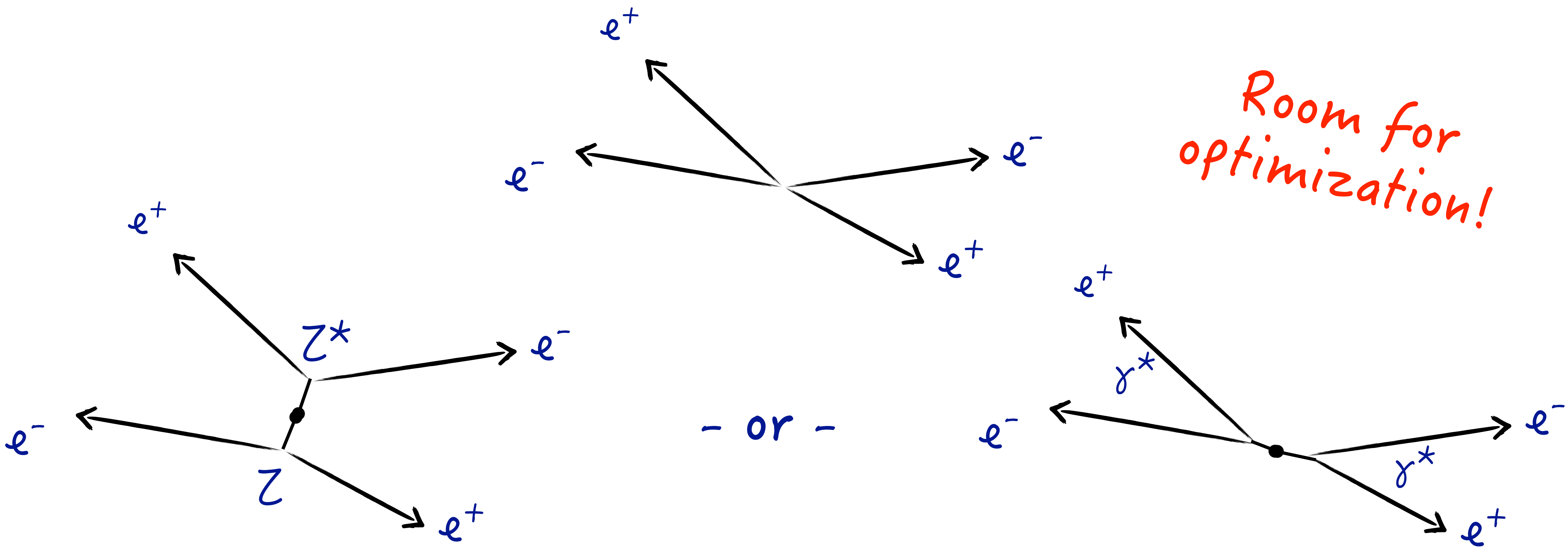


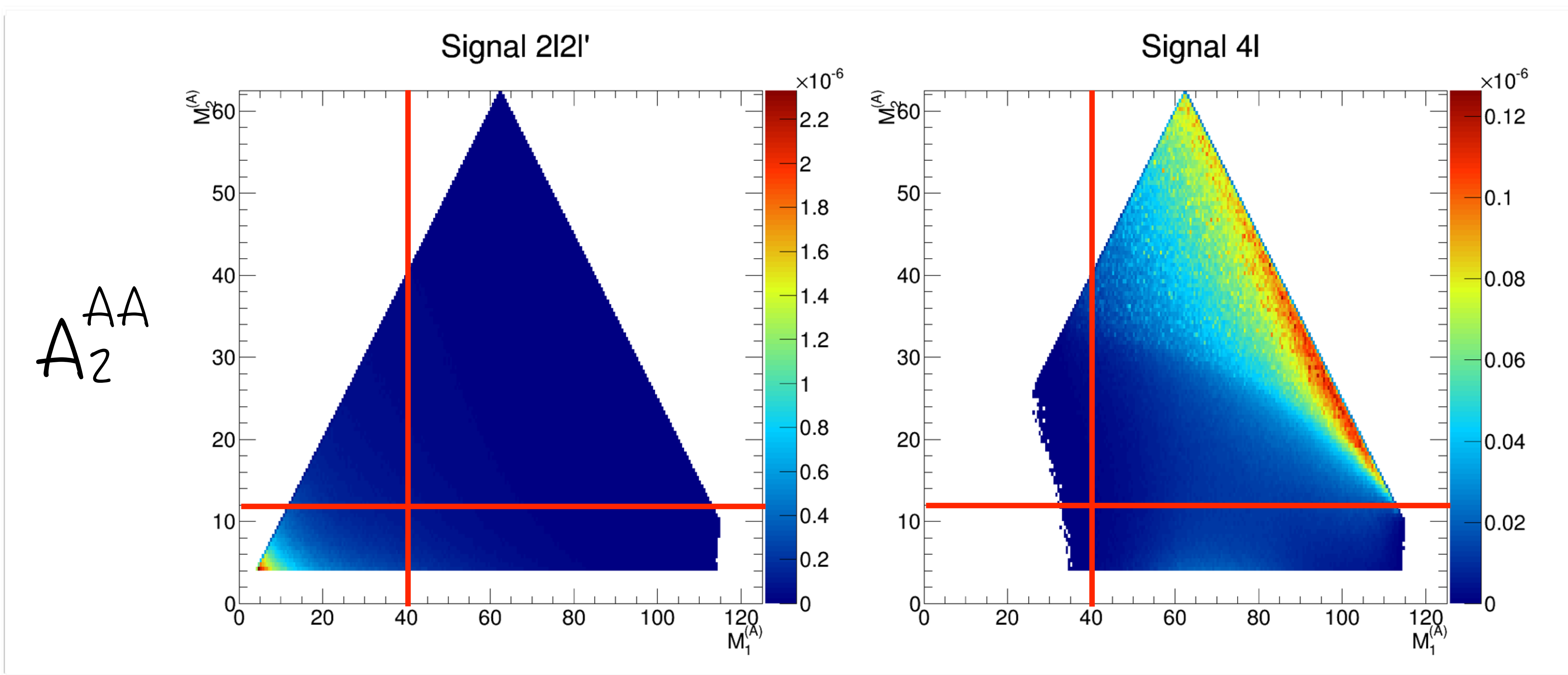
Lesson from Shapes

* Not surprisingly: the $\gamma\gamma$ shapes are most different from background (recall: BG= A_1).
* $Z\gamma$ is next.
* Interesting pair selection effects in $\gamma\gamma$ 4e/4μ. There is room for optimization! (more later)

Optimization

* The cuts on m_1 and m_2 had ZZ^* in mind.
* We can relax them!
  (or pick "wrong pairings" on purpose..)

A_2^{AA}



Optimization

* The cuts on m_1 and m_2 had ZZ^* in mind.
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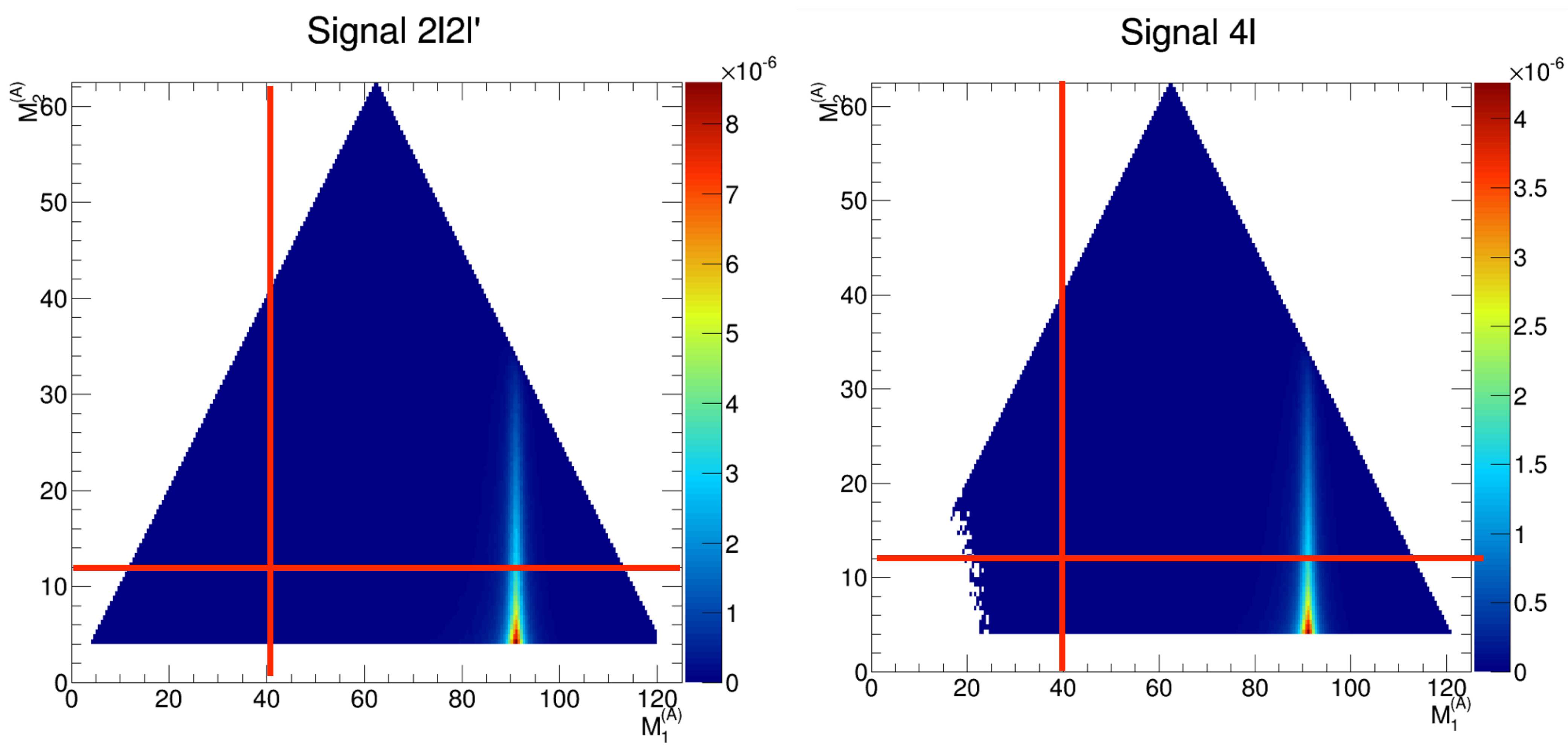
(or pick "wrong pairings" on purpose..)

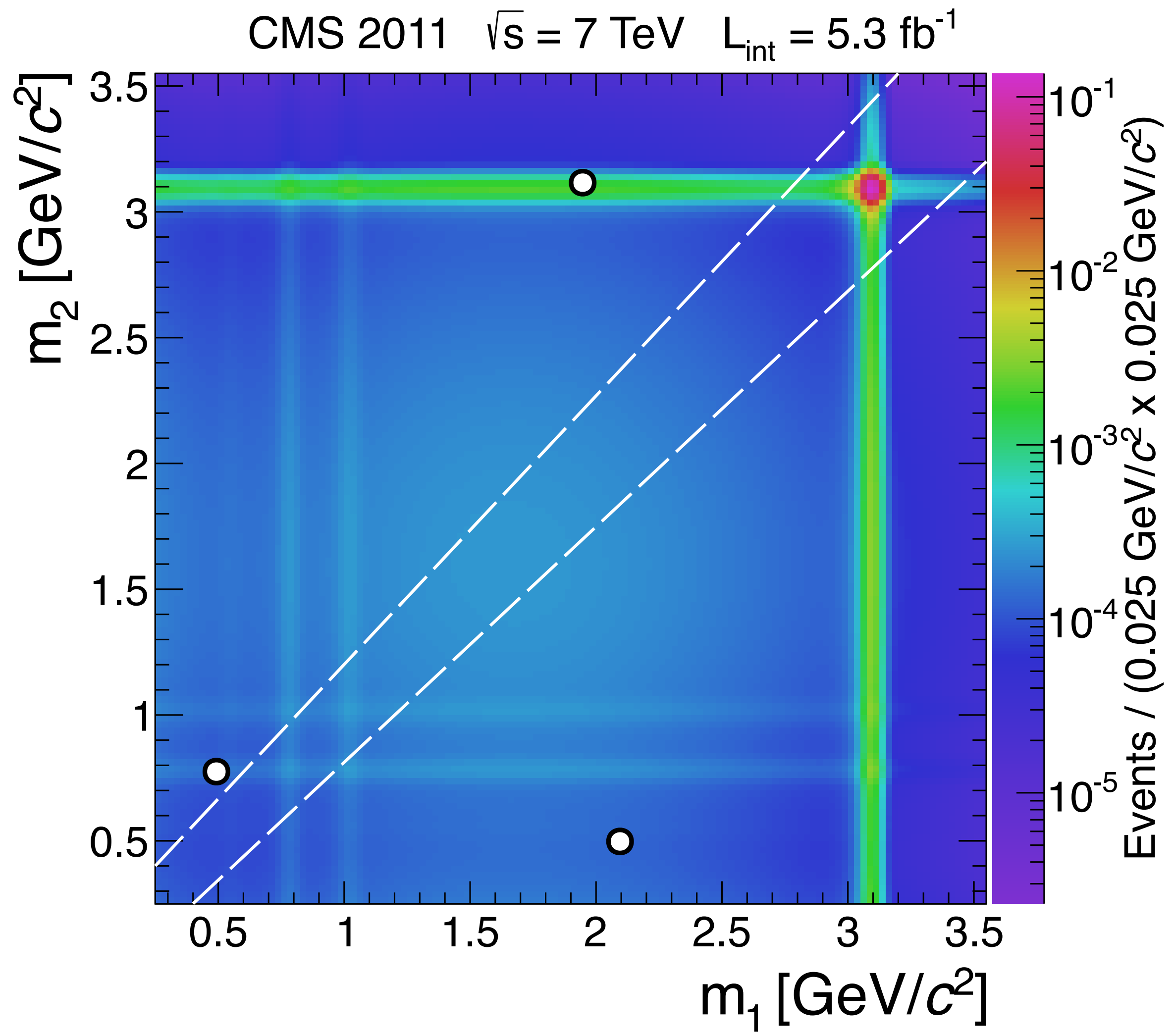
A_2^{ZA}



Optimization

* Going low in m1 and m2 is doable:

CMS search for $h \to A'A' \to 4\mu$



* Success hinges on what happens when we include non-Higgs background (in progress).

Non-Higgs Background

* We include the leading backgrounds, $q\bar{q} \to VV \to 4\ell$ in our analytic framework (including interference).

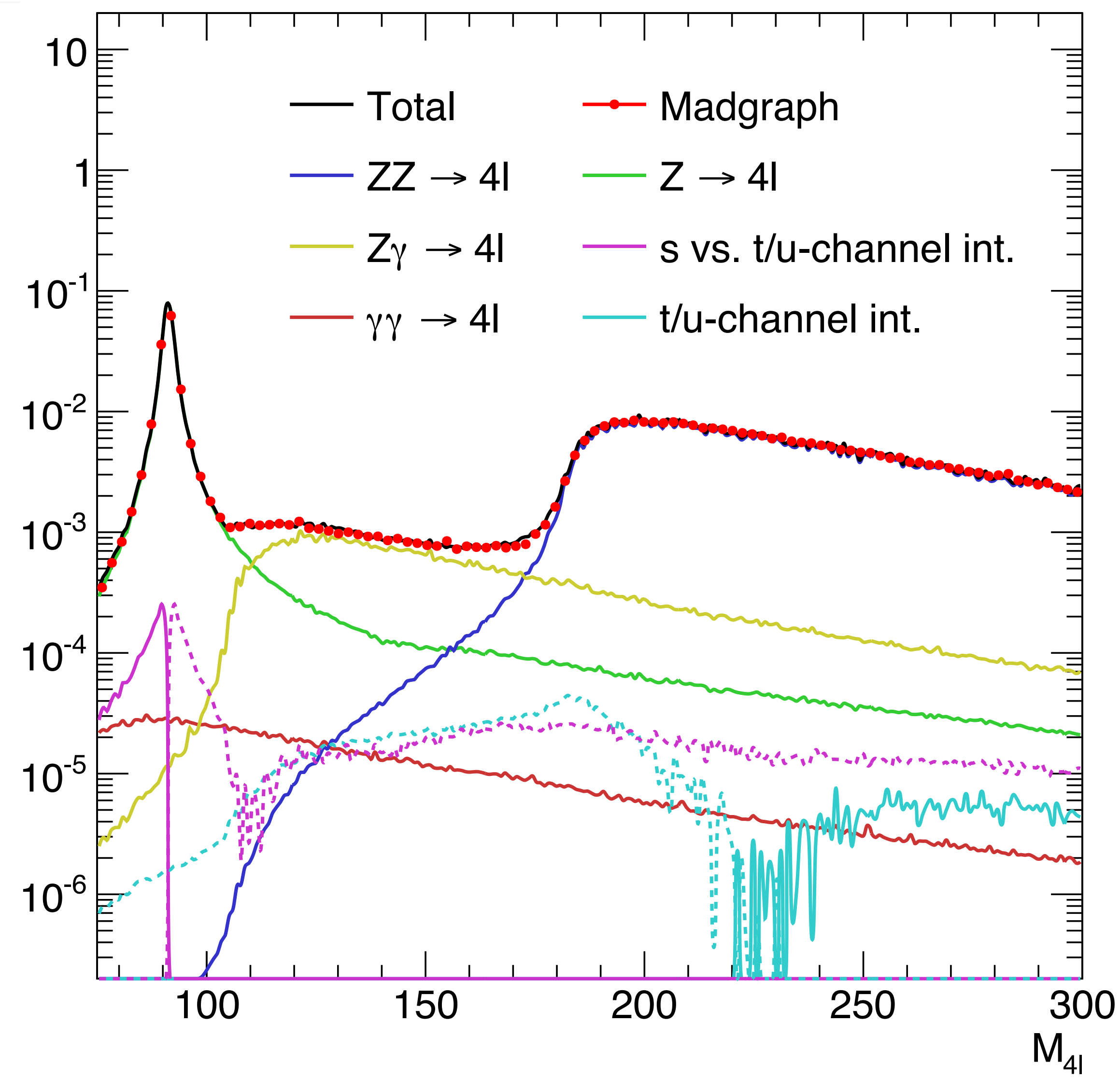
* $m_{4\ell}$ is a good Higgs vs non-Higgs discriminant. We smear the Higgs $m_{4\ell}$ by 2 GeV.

* Include the Higgs to non-Higgs ratio as a parameter in our fit.

Non-Higgs Background

* We include the leading backgrounds, $q\bar{q} \to VV \to 4\ell$ in our analytic framework

Dominant BG at 125 GeV is $q\bar{q} \to Z\gamma \to 4\ell$.



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