LFV Higgs and Other Rare Decays

$(h \to 4\ell)$

Roni Harnik,
Fermilab

KEK-PH 2014

* RH, Kopp, Zupan 1209.1397
* Chen, RH, Vega-Morales 1404.1336
  and work in progress.
* RH, Martin, Okui, Primulando, Yu 1308.1094

Higgs - a new toy!

* We have discovered a Higgs! New particle!
* We're excited like kids that got a new toy.

What can it do?
How fast does it go?
Does it have wifi?
can I take it apart?
what else did you get me?
Lets take it for a ride!

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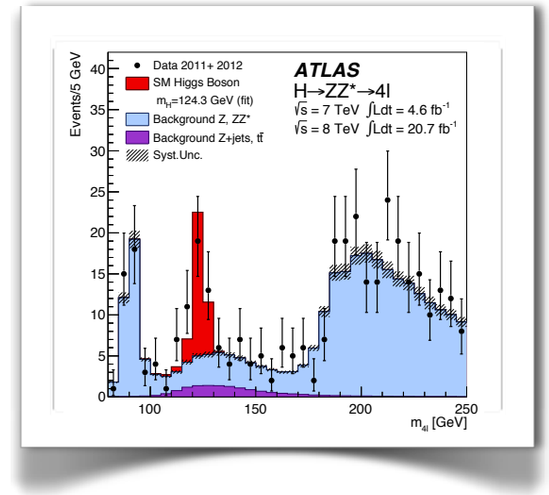

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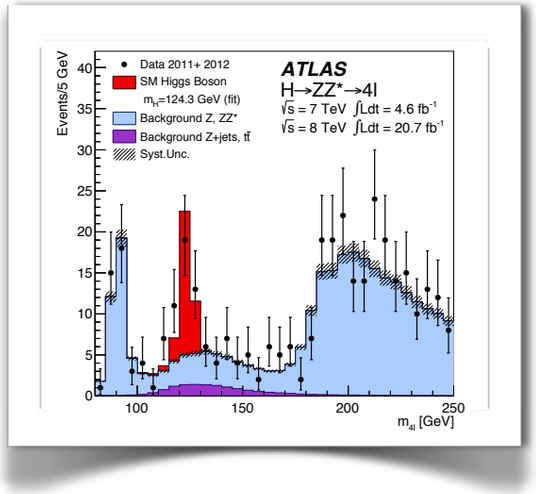

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This workshop:

Can we have another? pleaaase?!
Are its couplings SM-like?
Does it couple to DM?
Does it have flavor?
Does it Violate CP?
Lets take it for a ride!

Outline:

* Higgs Coupling to Gauge Bosons:
  - $h \to 4\ell$. (not $h \to ZZ^*$!)
  - Can it probe $h\gamma\gamma$? $h\gamma Z$?

A theory epilogue for talks by Xie and Whitbeck

* Higgs Couplings to Fermions: Flavor!
  - Higgs FV Theory
  - Limits
  - Colin's talk ($h \to \tau\mu$).

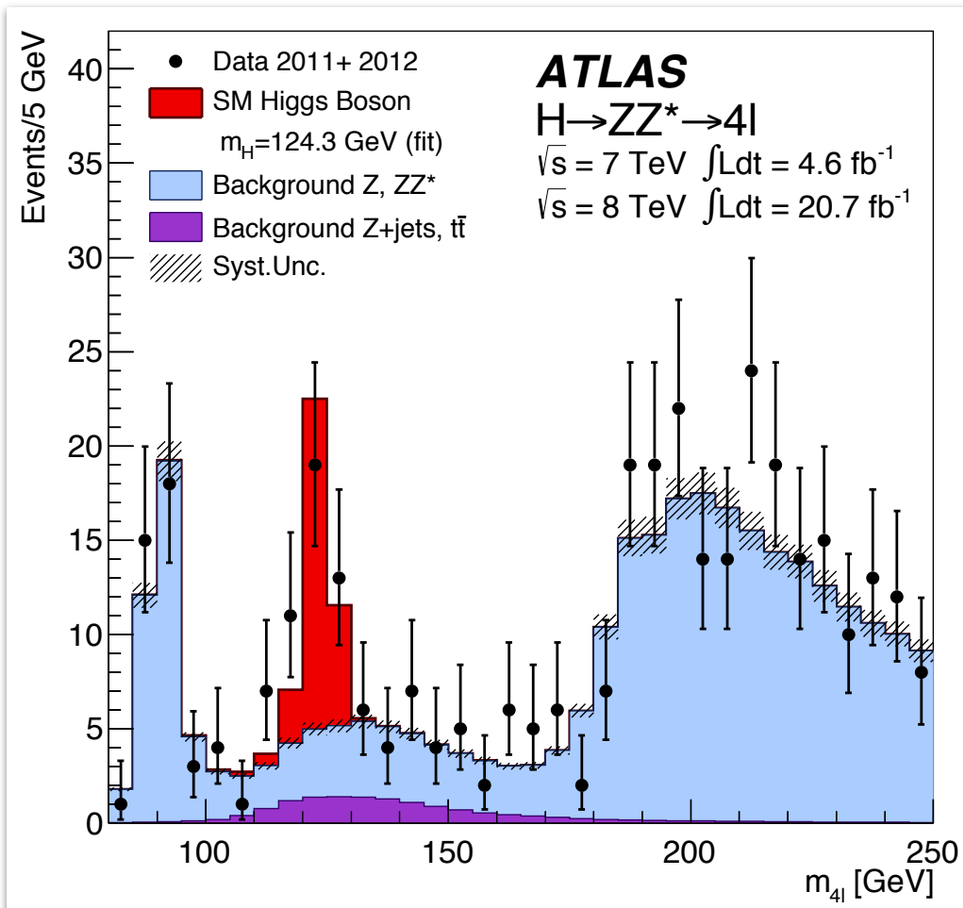
A theory introduction for the next talk.

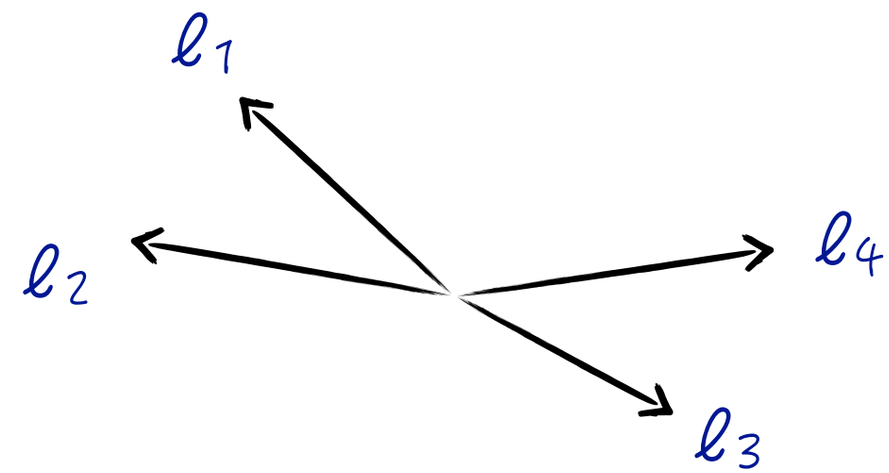
Higgs Couplings to Gauge Bosons:

Opportunities in $h \to 4\ell$.

$h \to 4\ell$

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

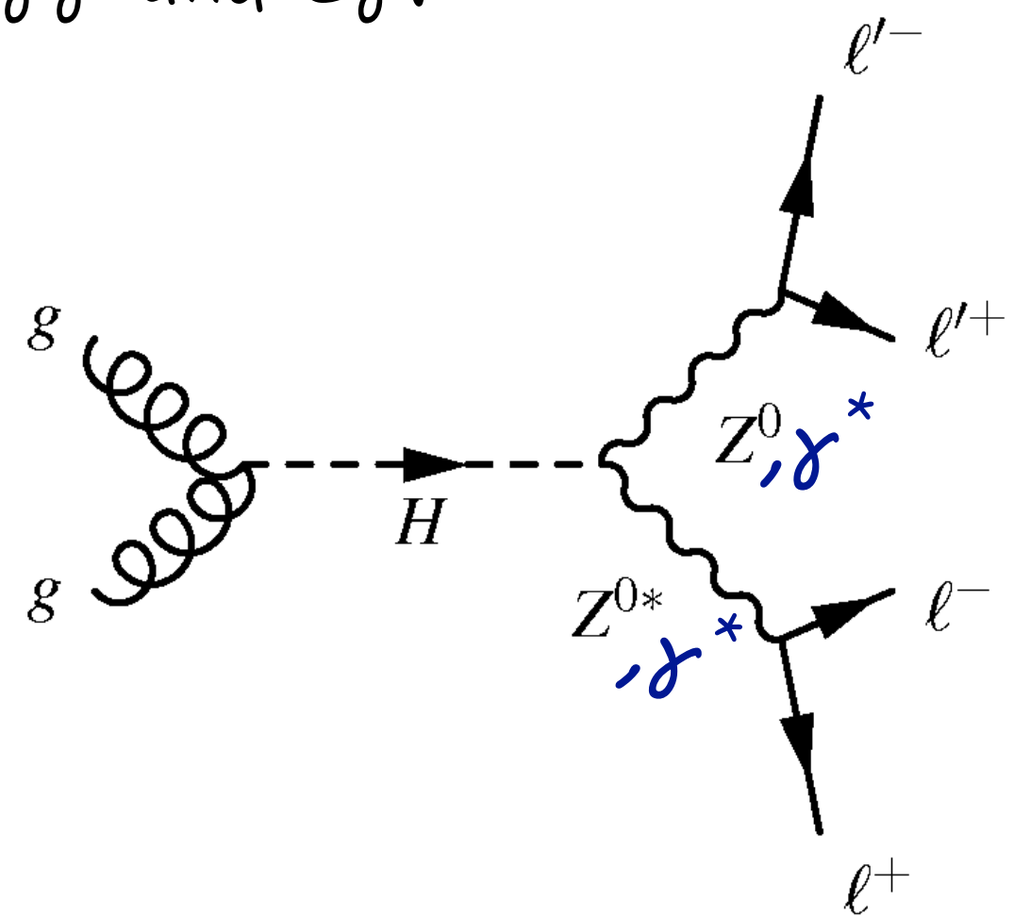




- Very clean.
- Many things to measure.
- What else can it do for us?

$h \to 4\ell$

* The search was optimized for discovery via ZZ^*.
* $h \to 4\ell$ is not only ZZ^*!
* I'm advocating: include $\gamma\gamma$ and $Z\gamma$.



Signal and Background

Our mindset in 2012:

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

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

too small...

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

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~~too small...~~

$$+ A_2^{\gamma}$$

Signal!

$$+2A_2^{Z}$$

Intuition:

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

Motivation

* Why look for $Z\gamma$ and $\gamma\gamma$ in four leptons?
  Isn't it clear we will loose to direct searches?

  - Yes, but **interference** = Sensitivity to **CPV** and signs.
  - Many observables = **discriminating power.**
  - **Interference** gives 4ℓ a head start.
    e.g., $A_2^{Z\gamma}$'s effect the rate like

$Z\gamma$:	$A_2 \times A_2 \sim \text{small}^2$
4ℓ:	$A_1 \times A_2 \sim \text{big} * \text{small}$

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.

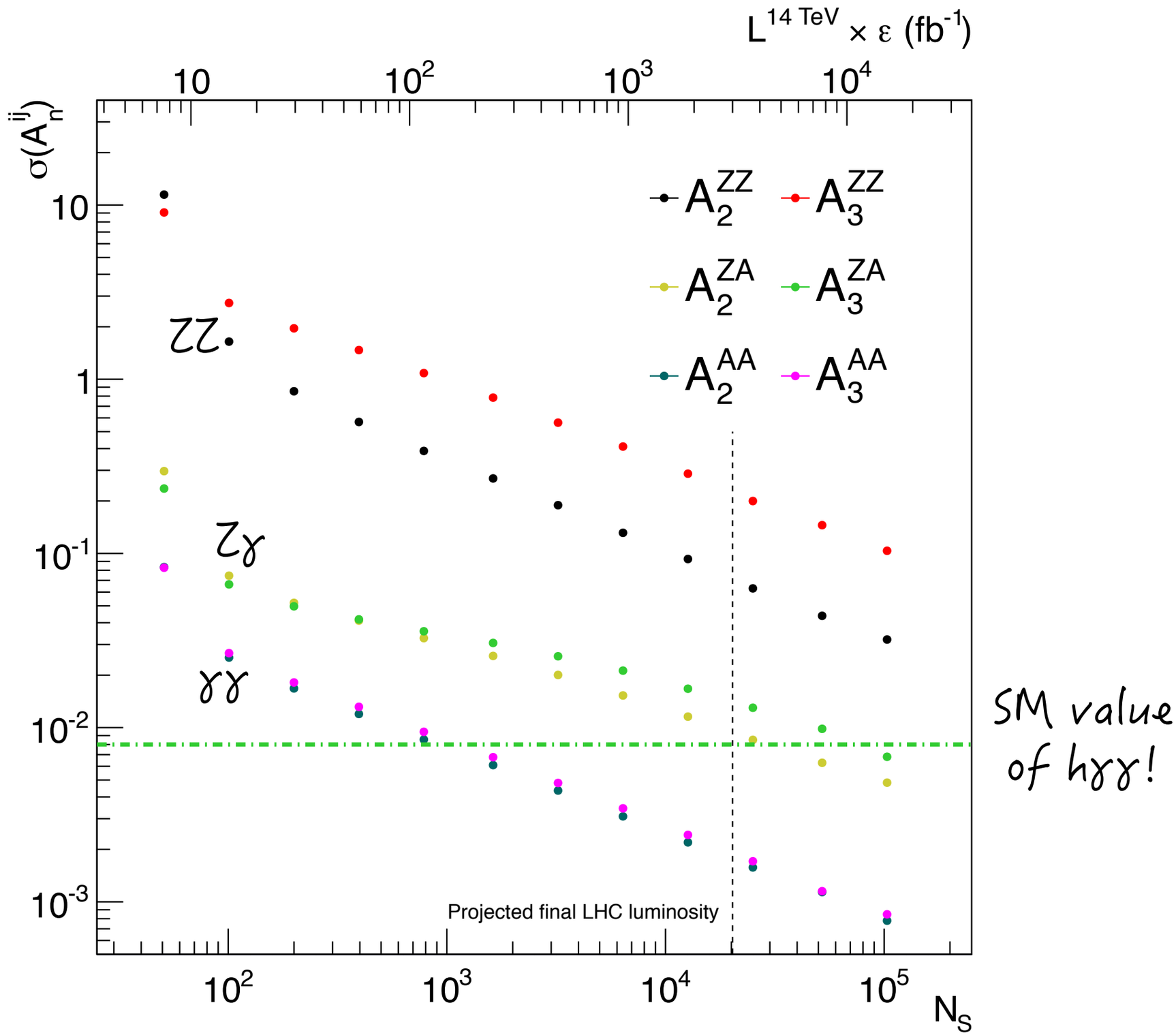
Method

a.k.a. method #1 in Xie's talk from monday.

* A simple procedure:
  - Calculate the fully differential cross section analytically*.
  - A big function of $(\overset{ZZ}{A_2}, \overset{ZZ}{A_3}, \overset{Z\gamma}{A_2}, \overset{Z\gamma}{A_3}, \overset{\gamma\gamma}{A_2}, \overset{\gamma\gamma}{A_3})$ & 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.

Results

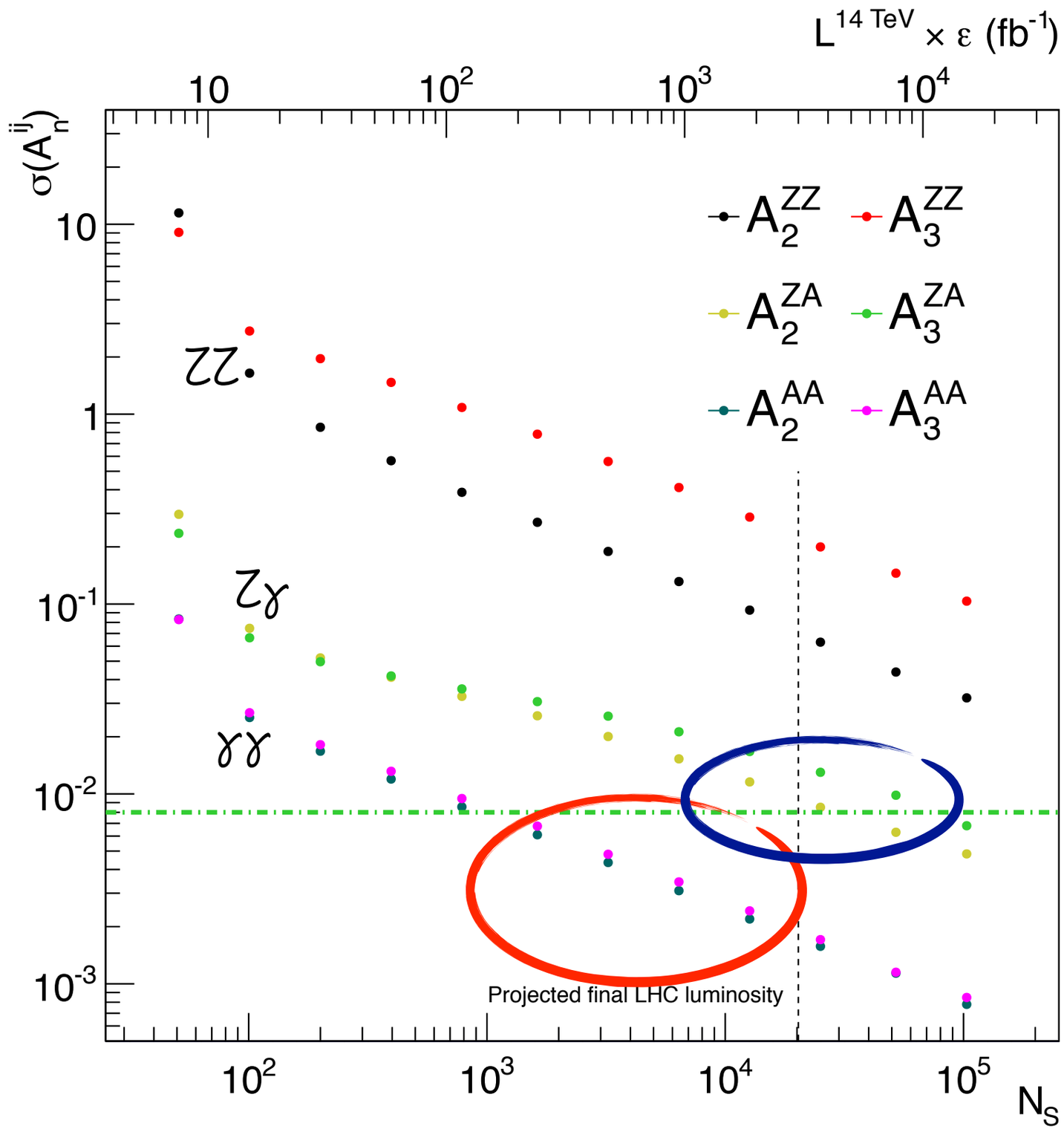


SM value of hγγ!

Results

We will be able to see hγγ at the SM value using h→ 4ℓ !!

Even Zγ is not too far!



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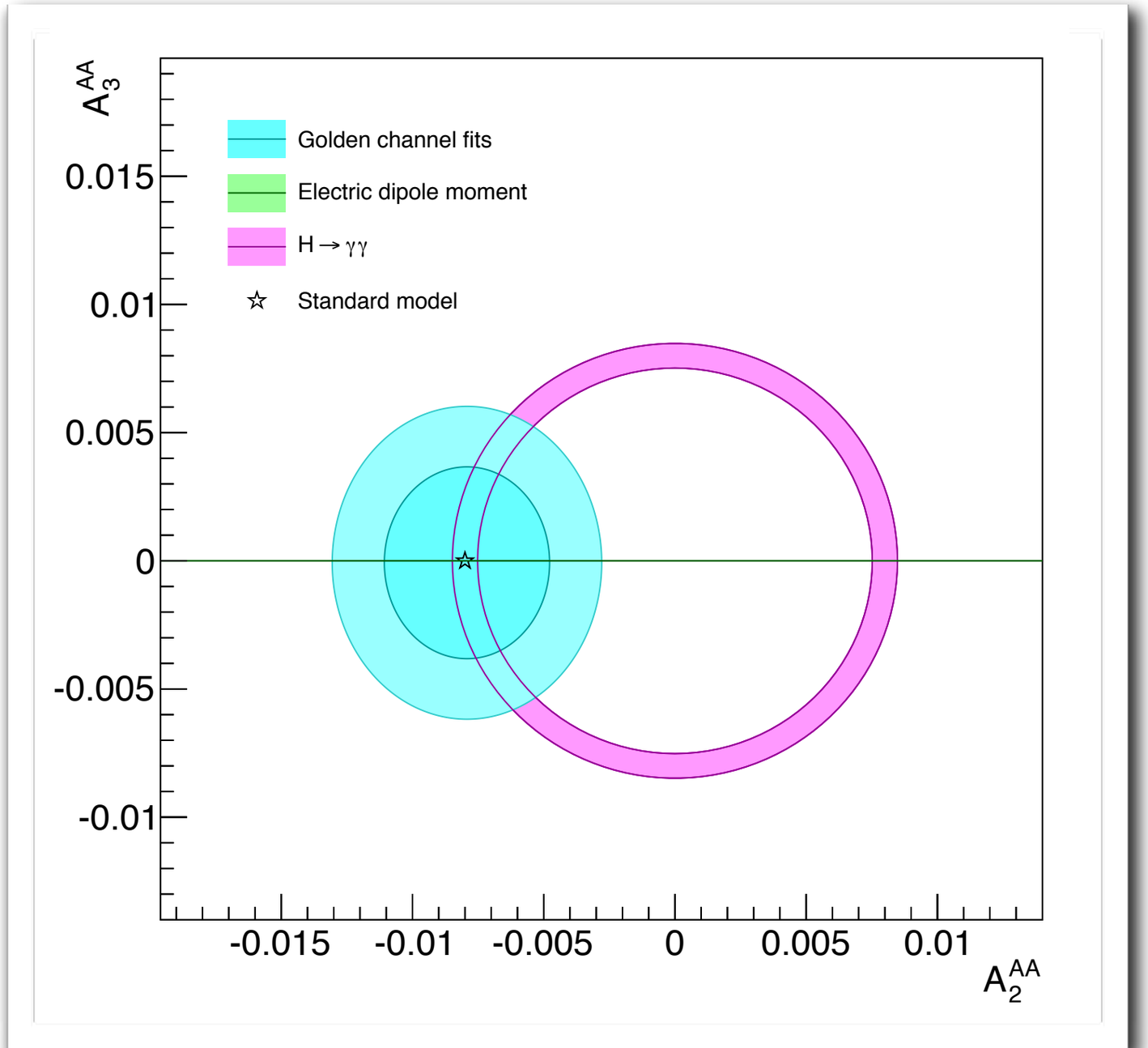
A_3^{AA}
Golden channel fits
Electric dipole moment
H → γγ
Standard model
0.015
0.01
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A_2^{AA}

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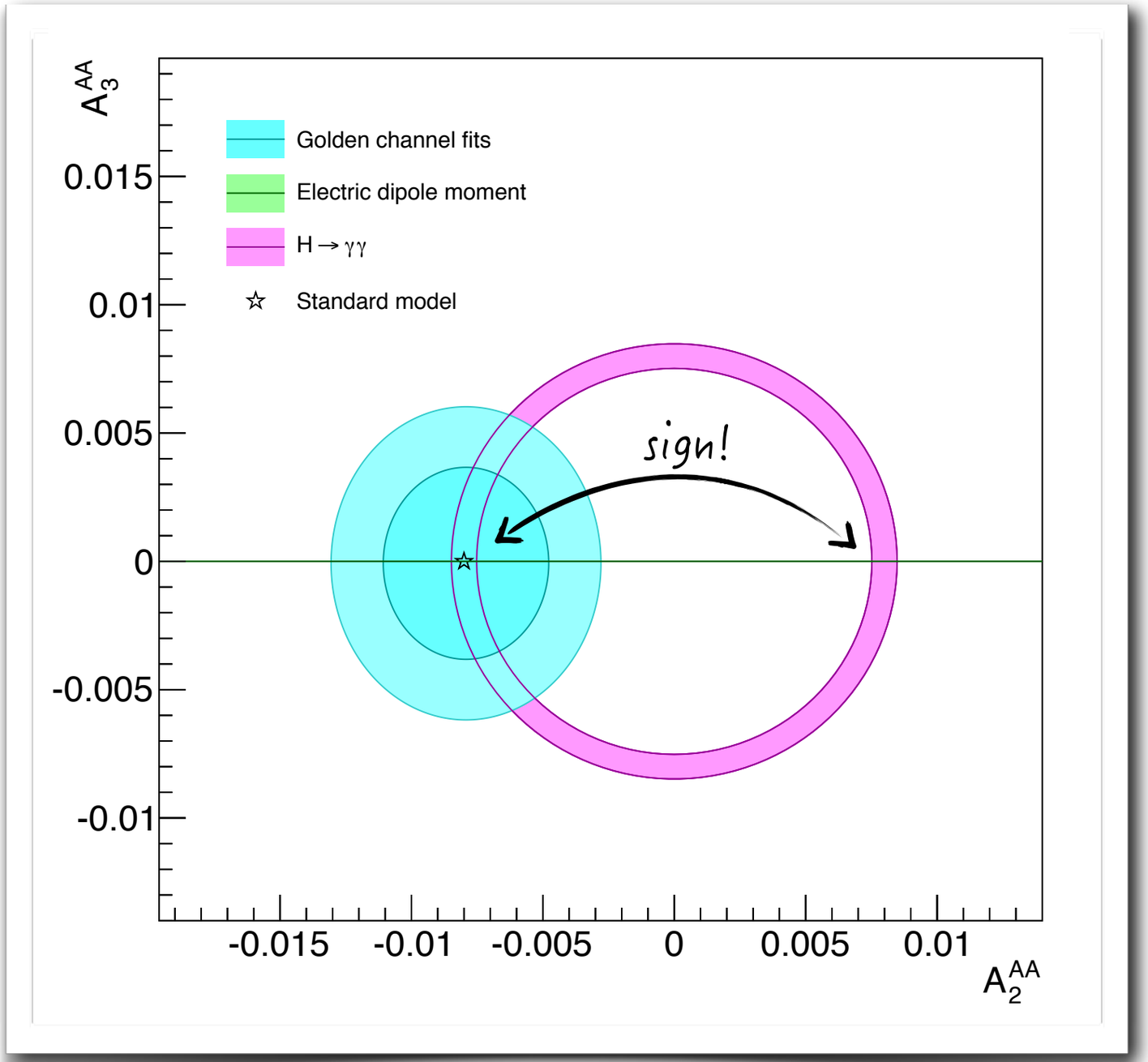
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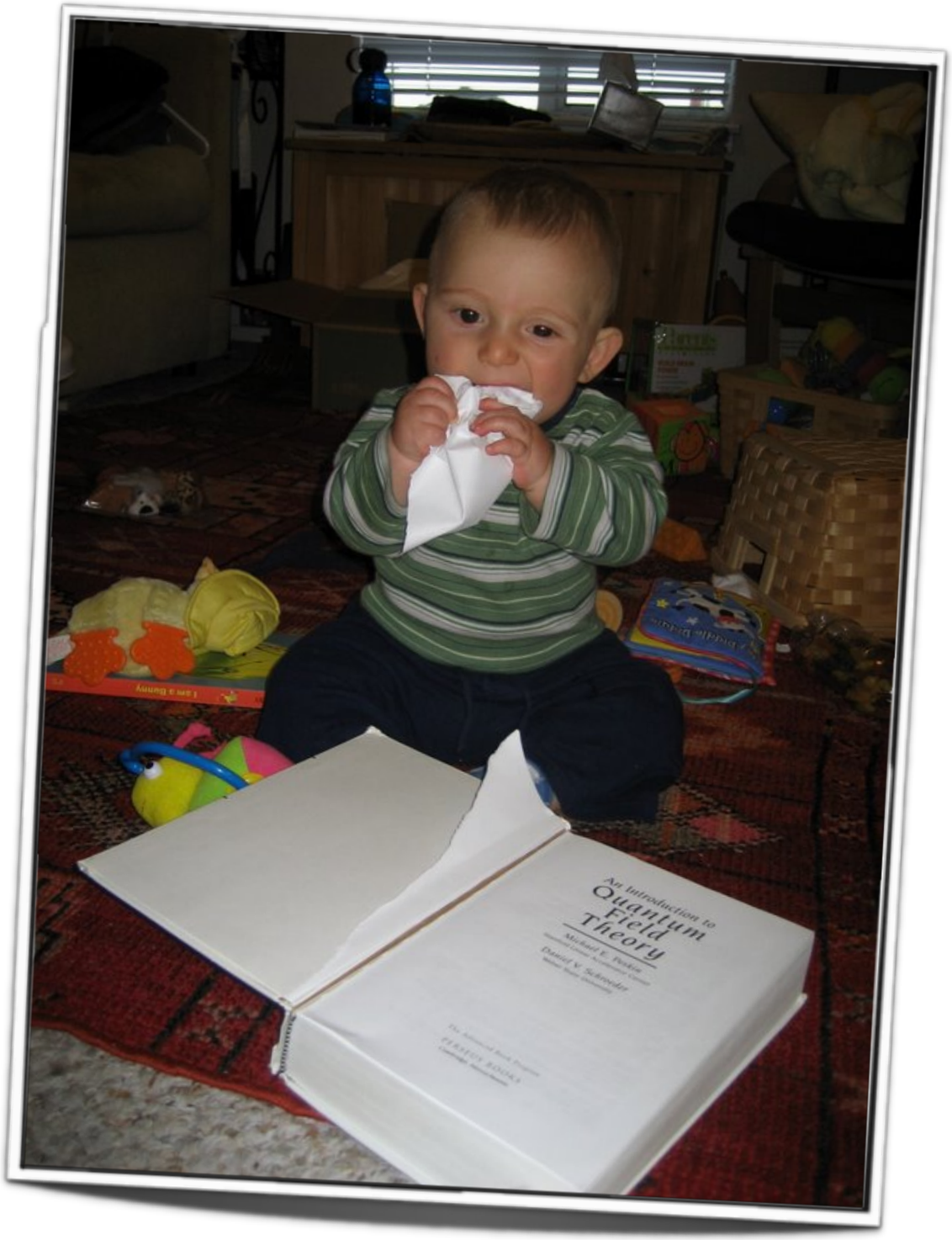
Part I: Summary

* $h \to 4\ell$ is powerful!
* Can do much more than discover the Higgs!
* Probe CPV and sign of $h\gamma\gamma$.
* Ongoing: we are optimizing the m_1-m_2 cuts.
  Preliminary: $hZ\gamma$ couplings are within reach!

Intermission:

My son, →
Testing both flavor and time reversal properties of QFT.



hff Couplings

* SM: the Higgs is the only source of mass.
  It **defines** the fermion mass basis.

  → Yukawa couplings are flavor diagonal.

* New physics can mean new sources of mass.
  In the presence of such NP we can have-

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

not-diagonal.

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

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

Leptonic Flavor Violation

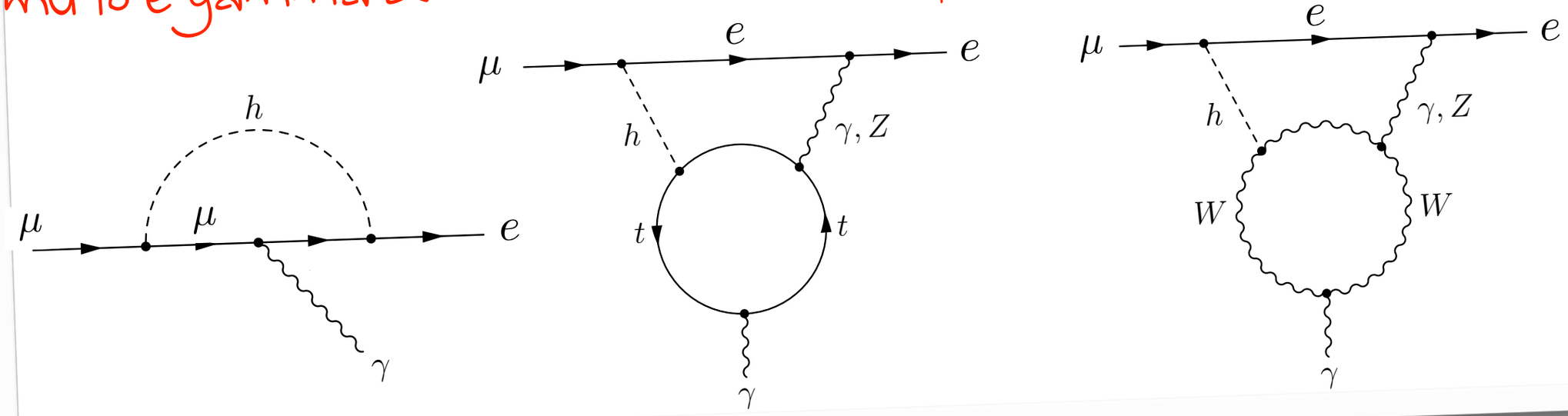
$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c..$$

Which experiments constrain the Y_{ij}'s?

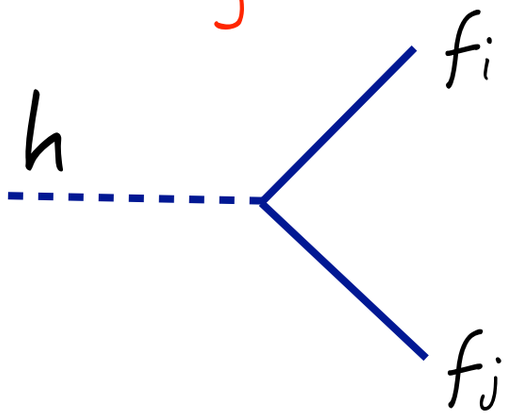
RH, Kopp, Zupan 1209.1397

FV Higgs constraints

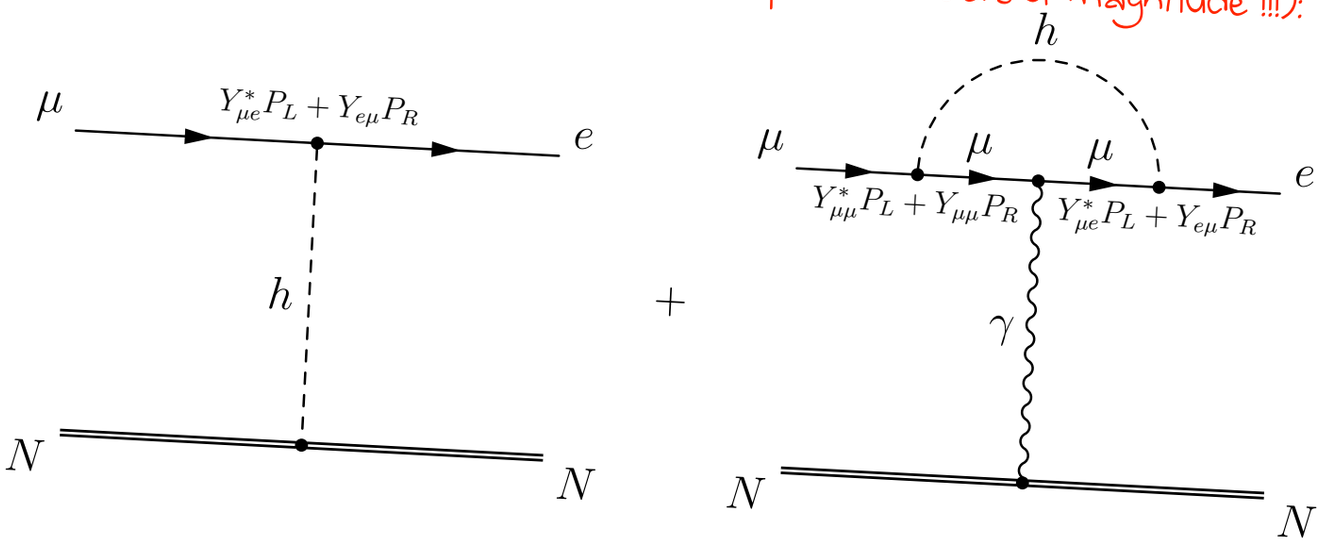
mu to e gamma & mu to 3e (at 1 and 2-loop):



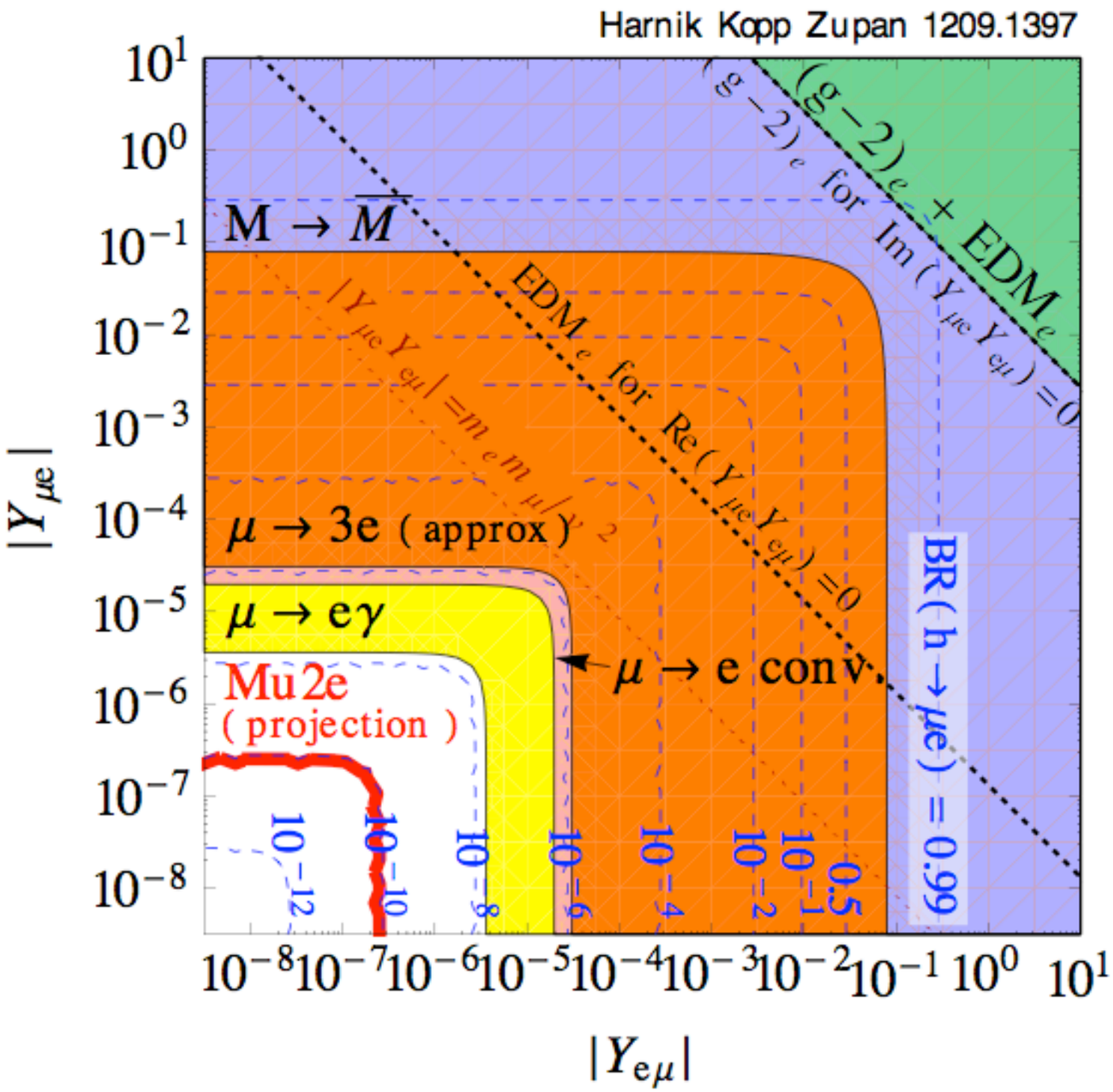
FV Higgs decay:



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



Higgs couplings to μe

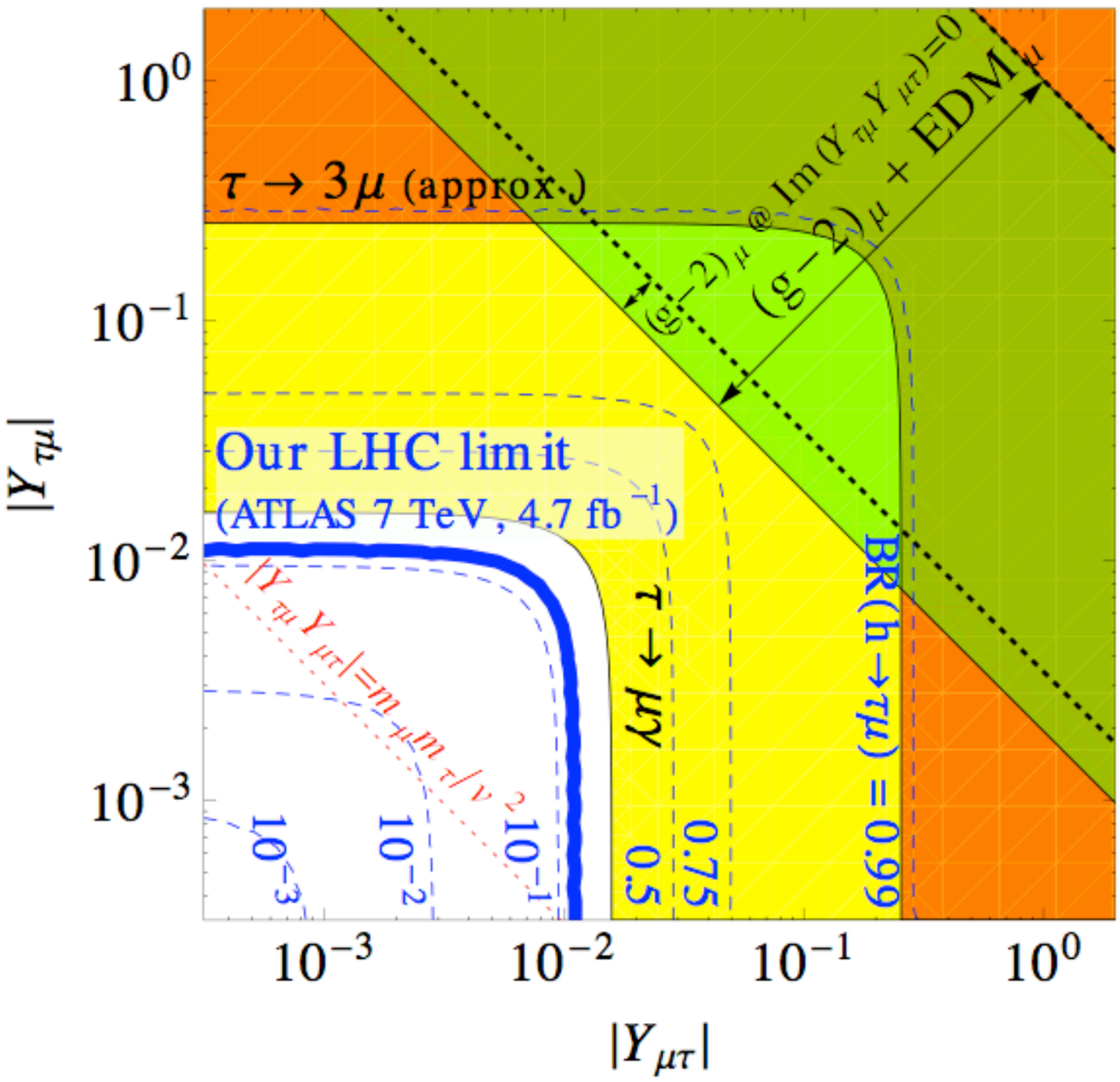


Outside of LHC reach.

Probing "natural" models.

Will be dominated by μ2e & COMET

Higgs couplings to μτ



LHC wins!

(see an update in the next talk!!)

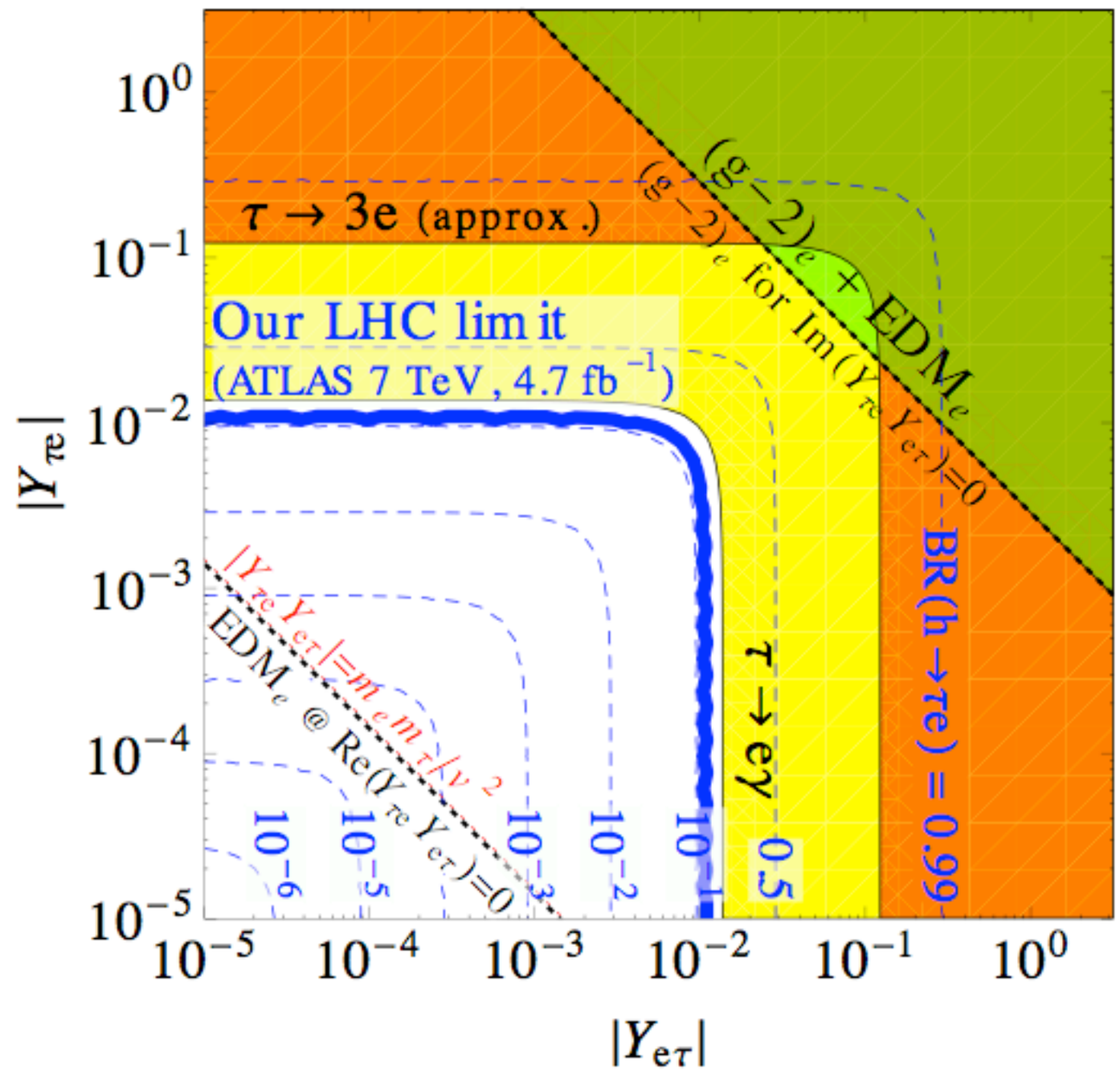
Theorist's lame re-interpretation of $h \to \tau\tau$ beats $\tau \to \mu\gamma$!

"natural models" are within reach.

RH, Kopp, Zupan 1209.1397

Higgs couplings to τe

* τe is similar to τμ, but without CMS bound and...



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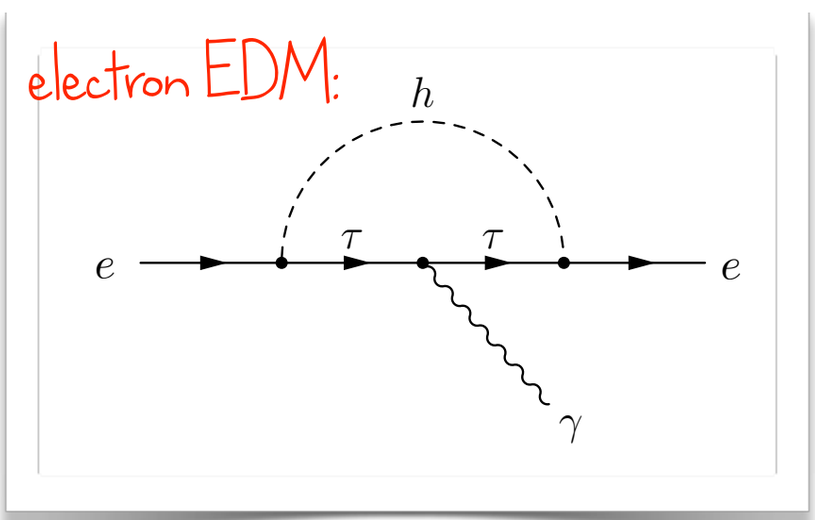
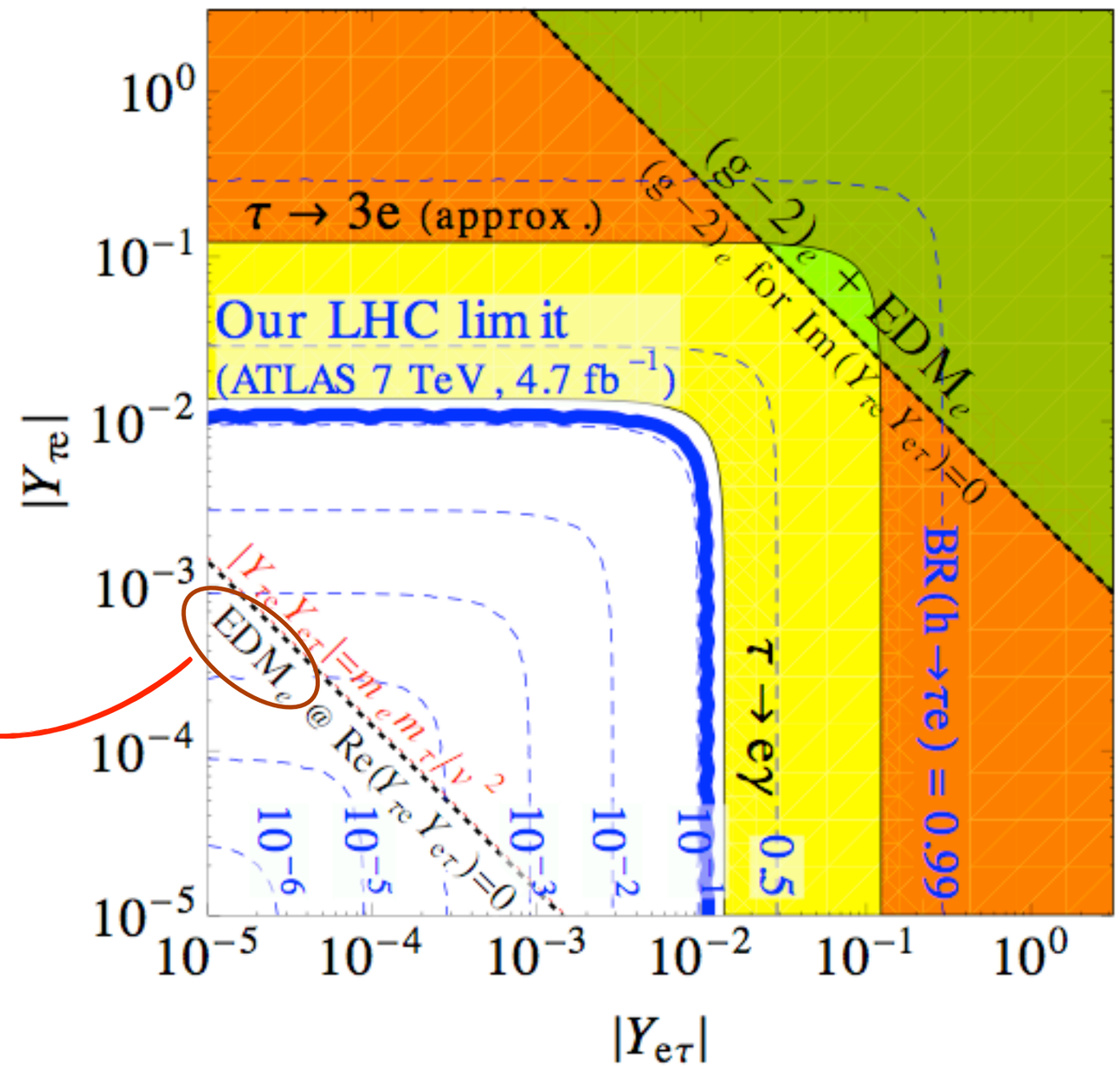
Electron EDM is interesting here!





Flavor and CP Probes:

Flavor violation:

✓=sensitive at the level of $Y_{ij} \lesssim \frac{\sqrt{m_i m_j}}{v}$.

Leptons	Probe
μ-e	muons ✓
τ-e	eEDM* ✓
τ-μ	LHC ✓

d-quarks	Probe
s-d	K-K ✓
b-d	B-B ✓
b-s	B_s-B_s ✓

u-quarks	Probe
c-u	D-D ✓
t-u	nEDM* ✓
t-c	LHC / D-D ✓?

*LHC, if CP is conserved.

CP violation:

Phase	Probe
e	e-EDM
u,d	nEDM
γ	eEDM

Phase	Probe
t	EDMs
τ	LHC / Higgs factory
W/Z	LHC

Multiple probes!
Many experiments!

Almost all channels are sensitive at well motivated levels!

Conclusion

* The Higgs is a new toy! Lets Explore it!
* Flavor conservation can't be taken for granted. Should be tested without theoretical prejudice.
* $h \to \tau\mu$ is a promising opportunity for LHC.
* $h \to 4\ell$ is more exciting than an iPhone!

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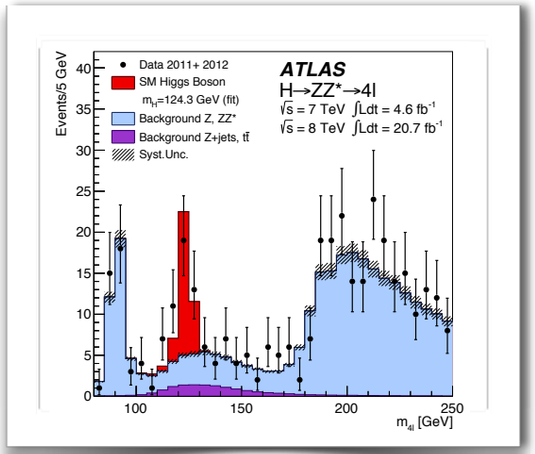
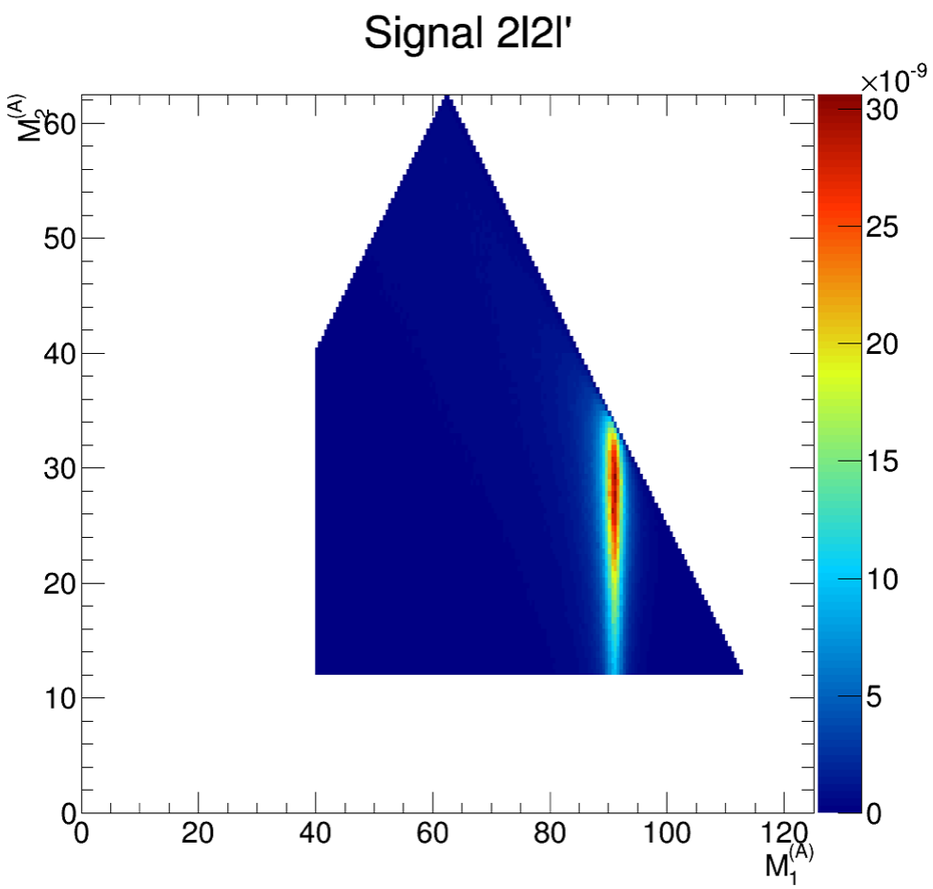
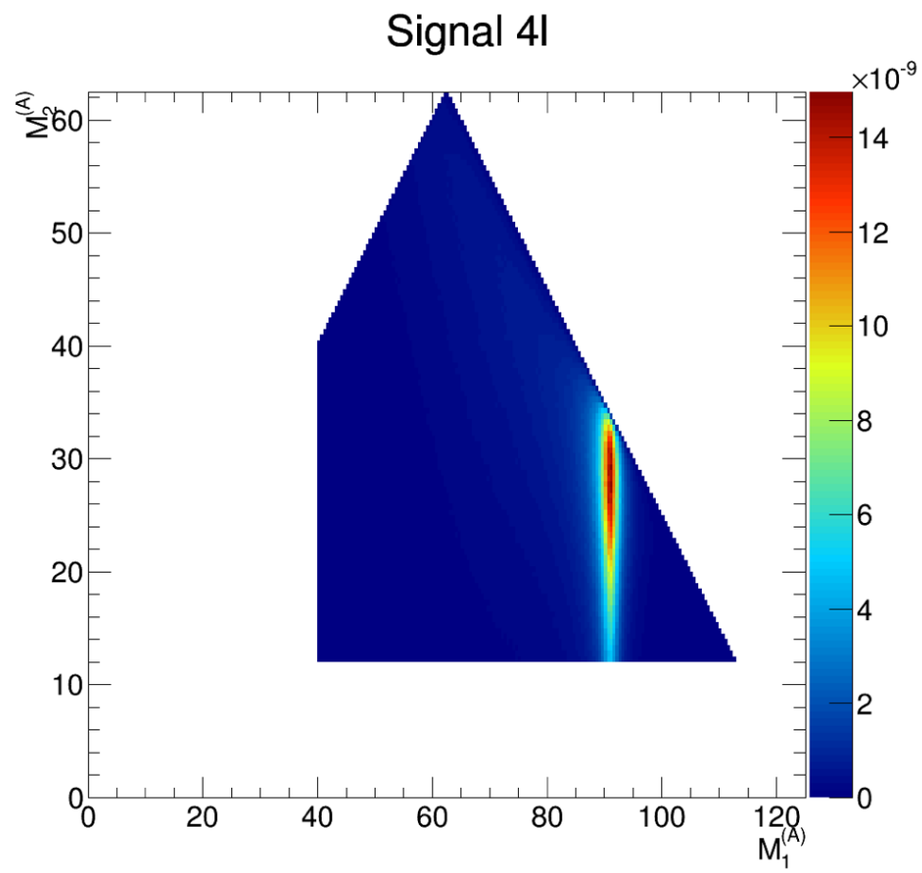


Deleted Scenes

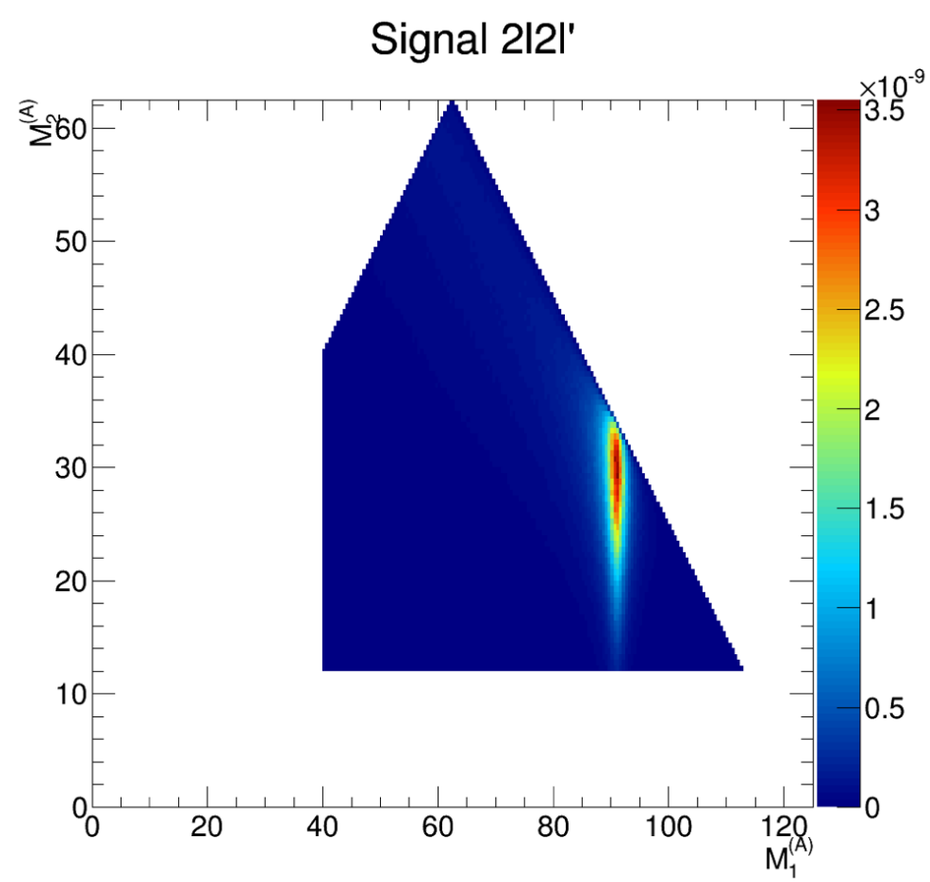
Shapes

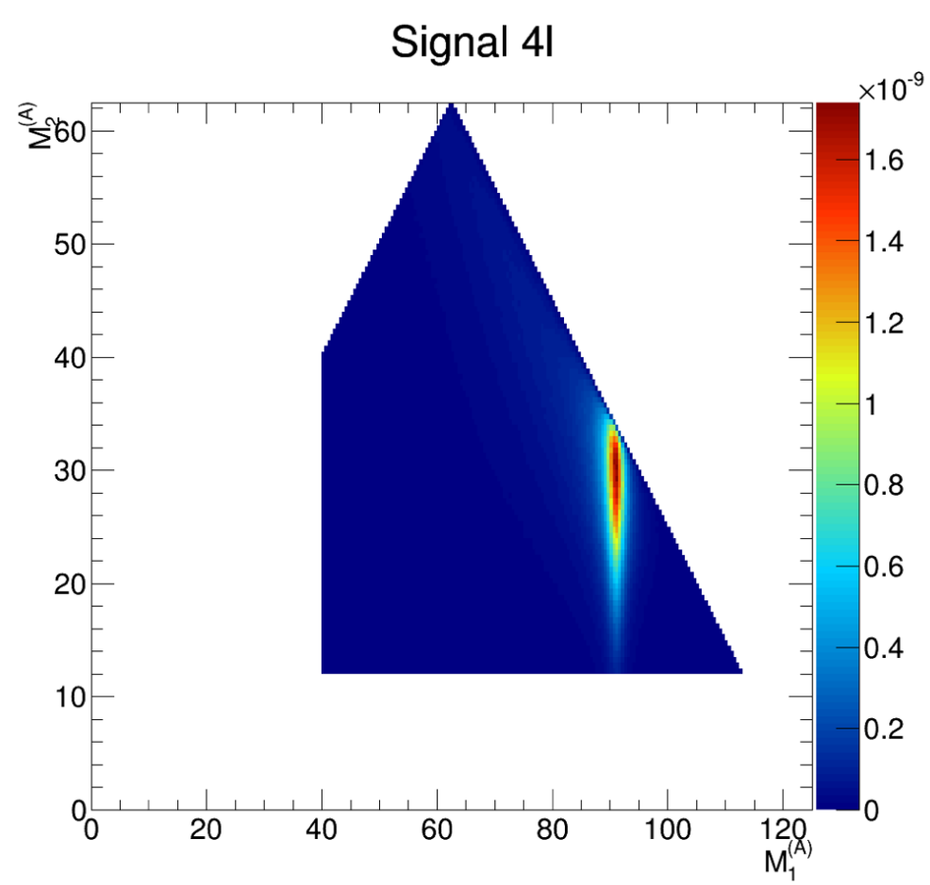
A_1^{ZZ} "background"





A_2^{ZZ}





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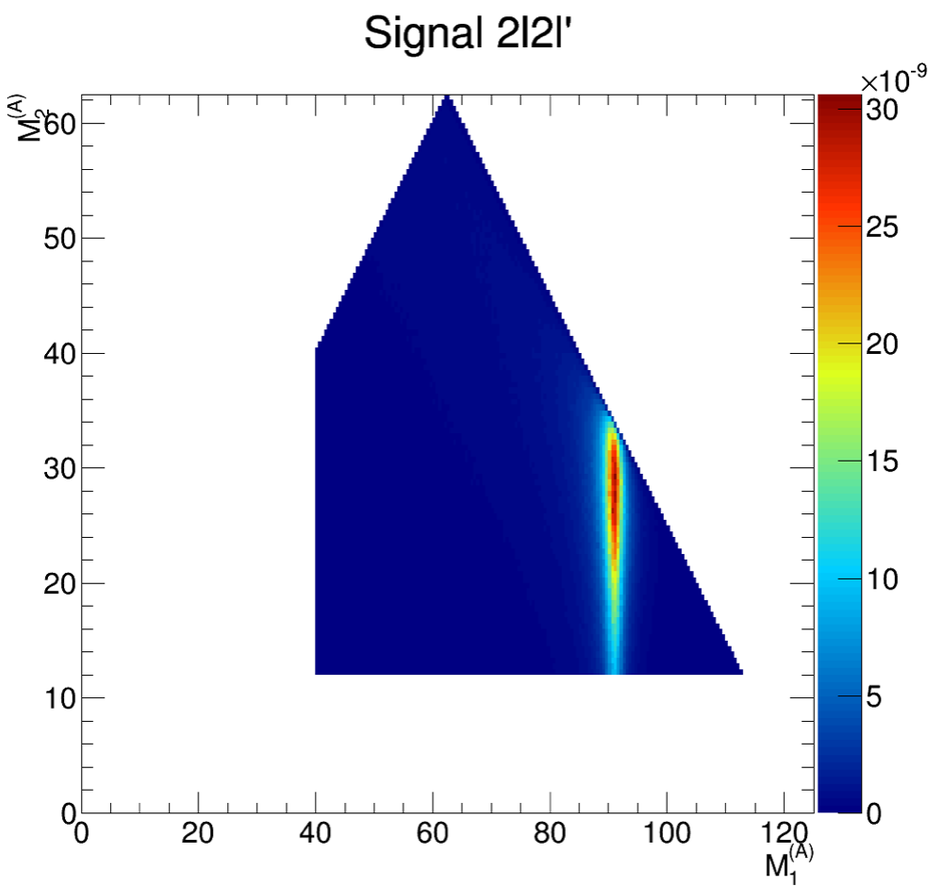
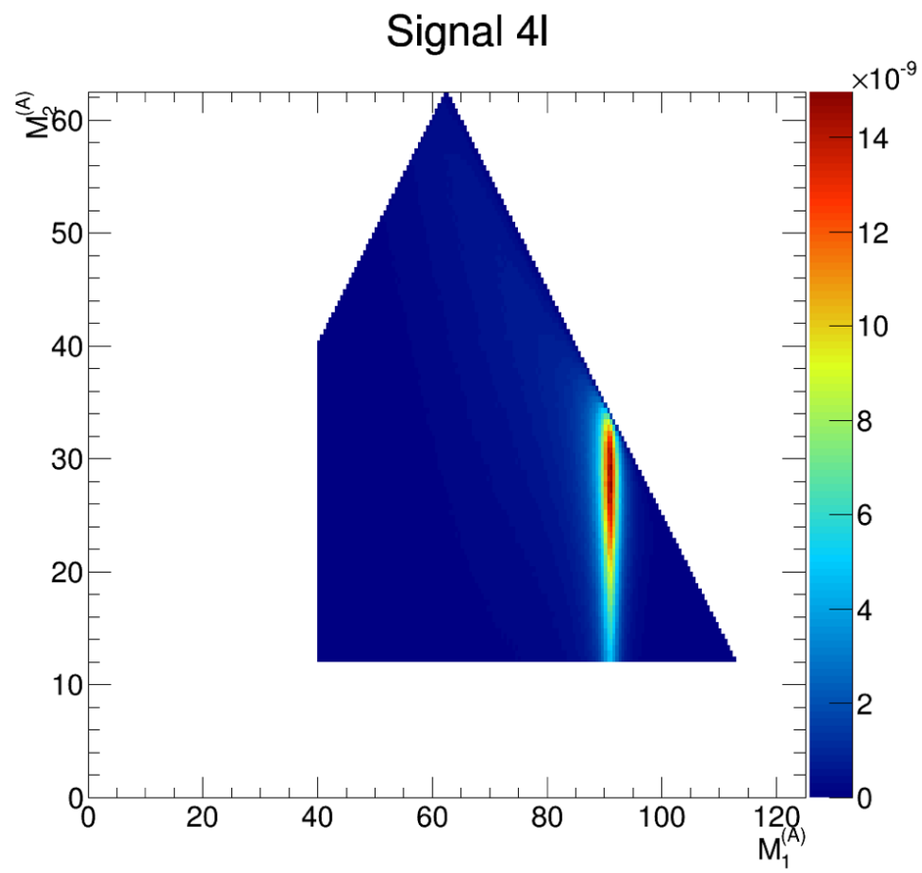
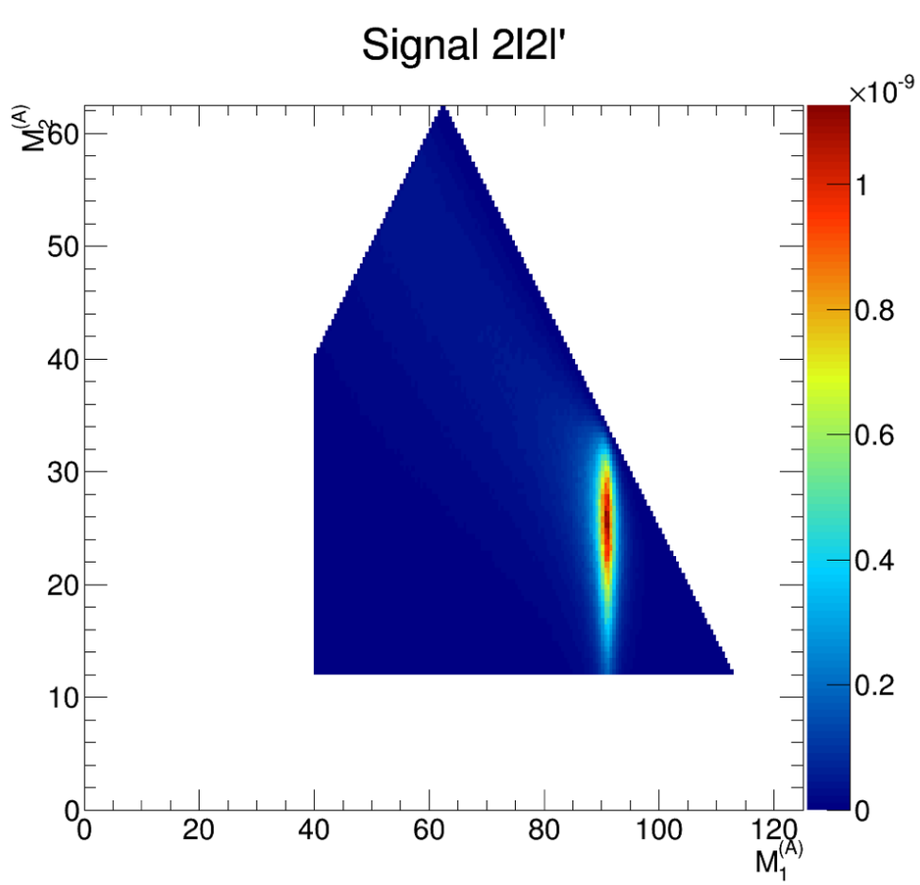
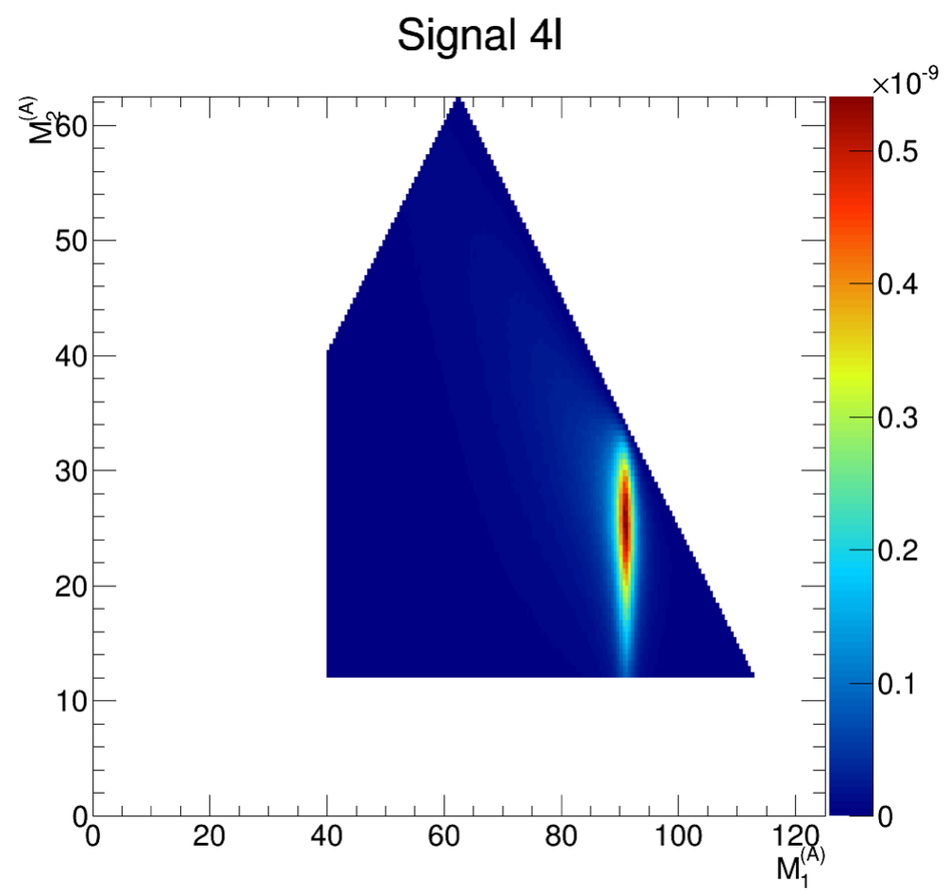




A_3^{ZZ}





Shapes

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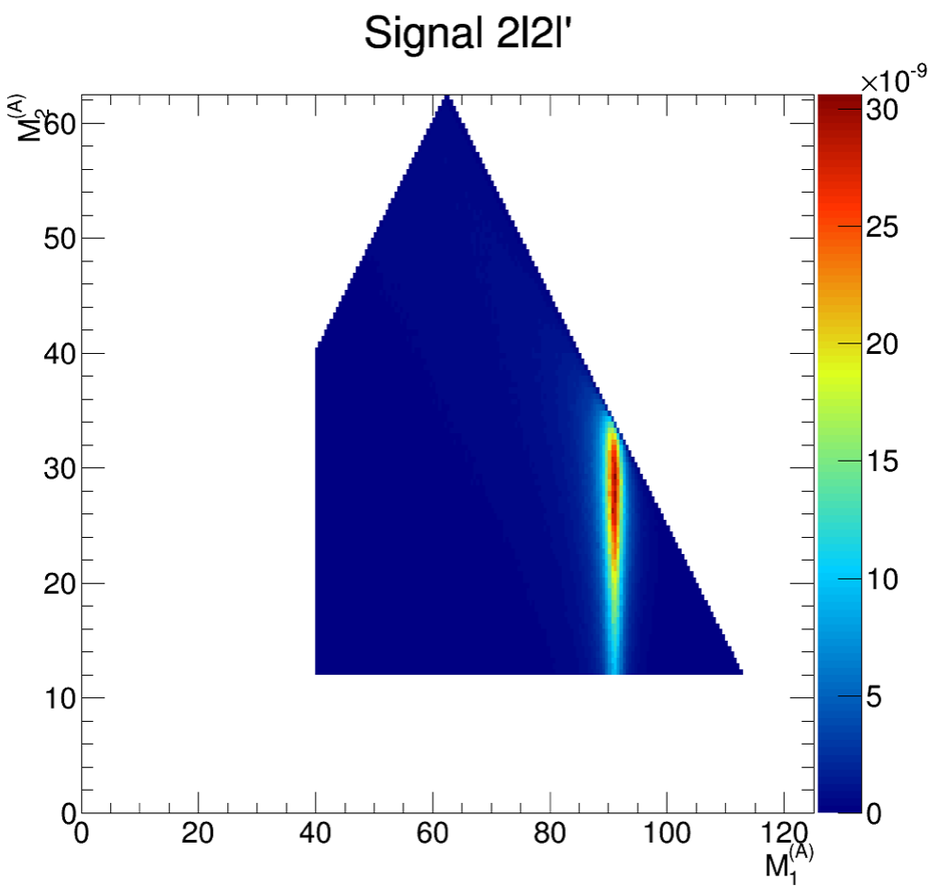
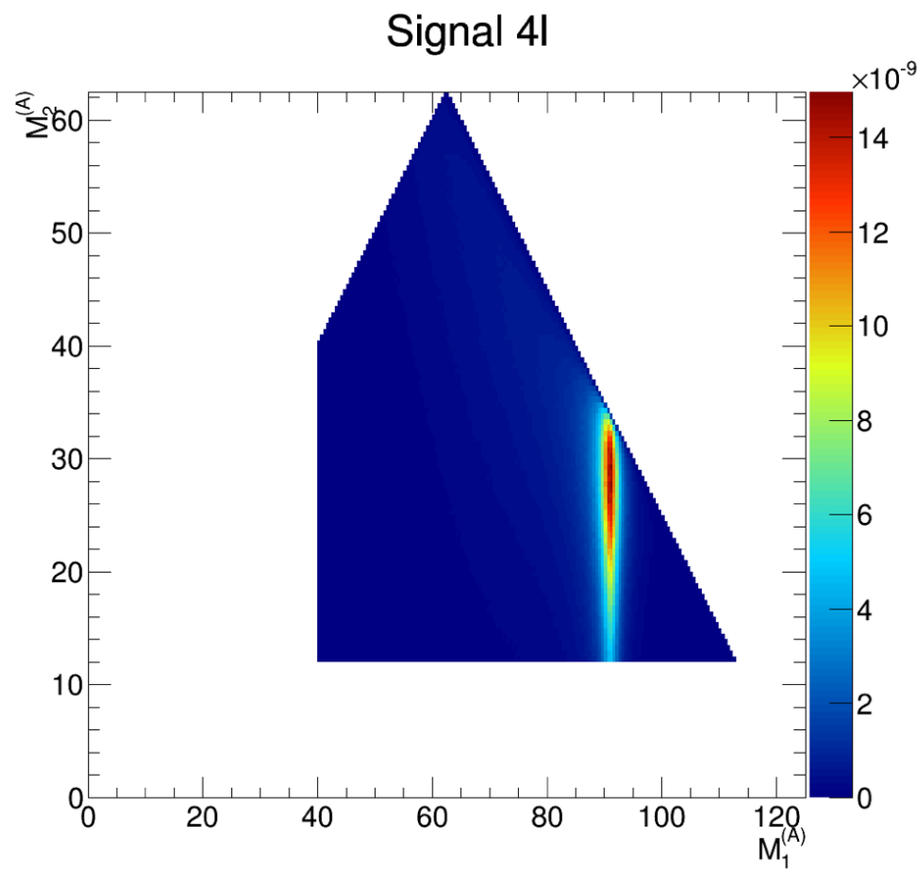
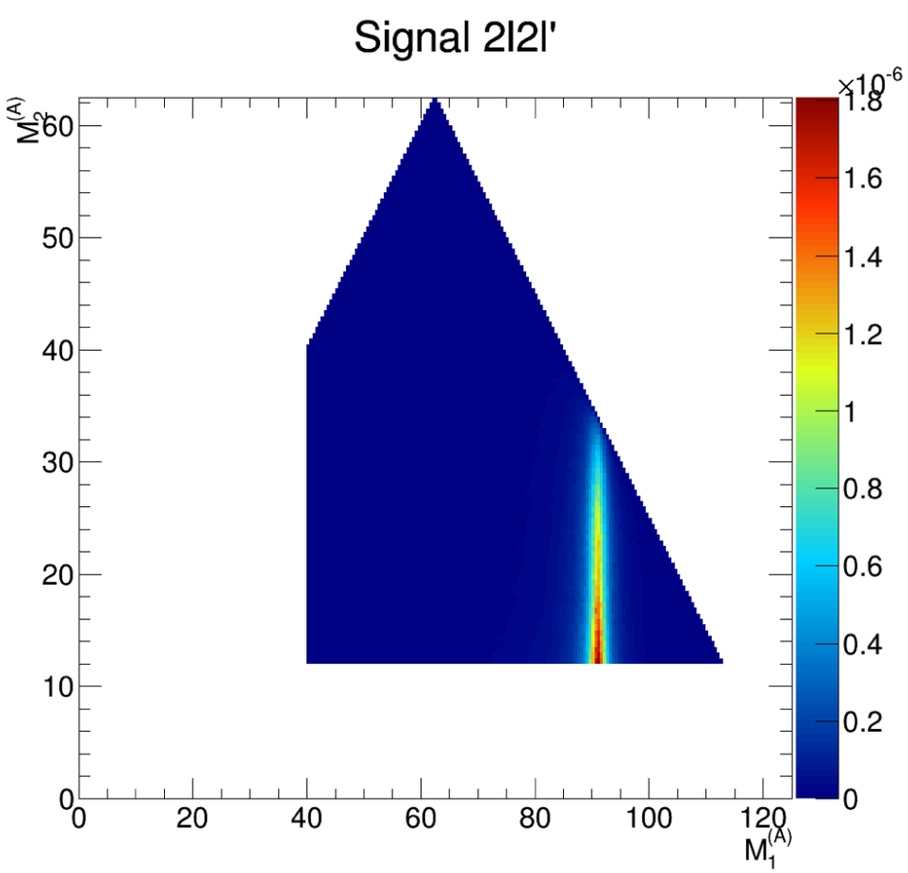
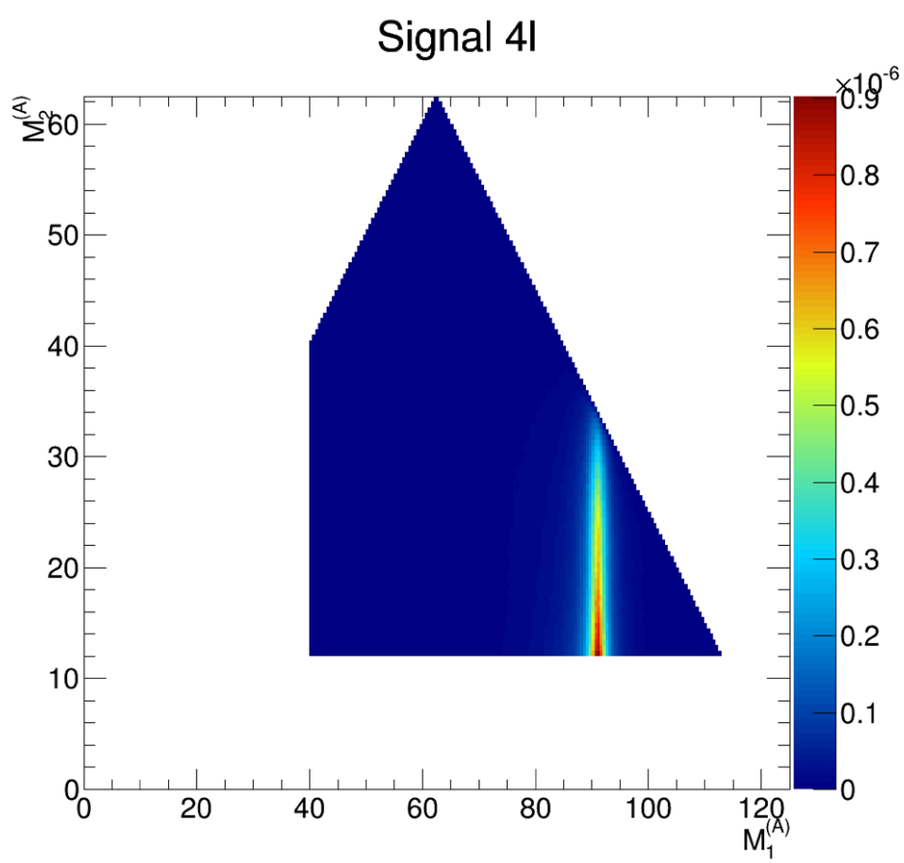




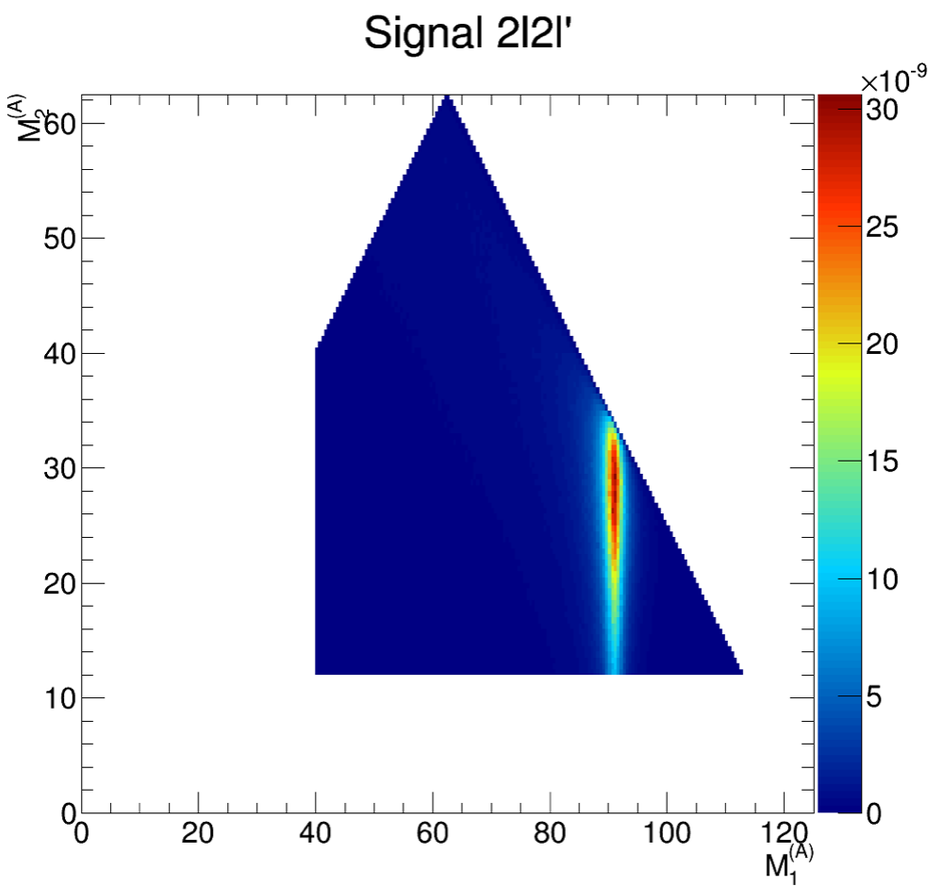
A_2^{ZA}

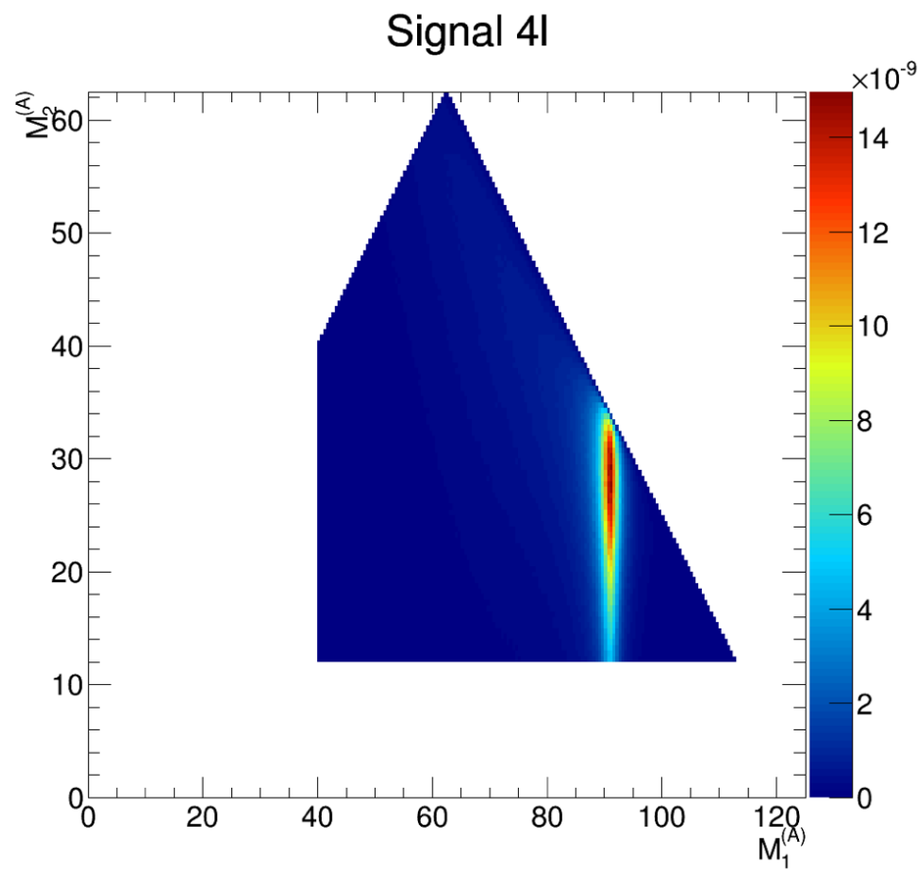




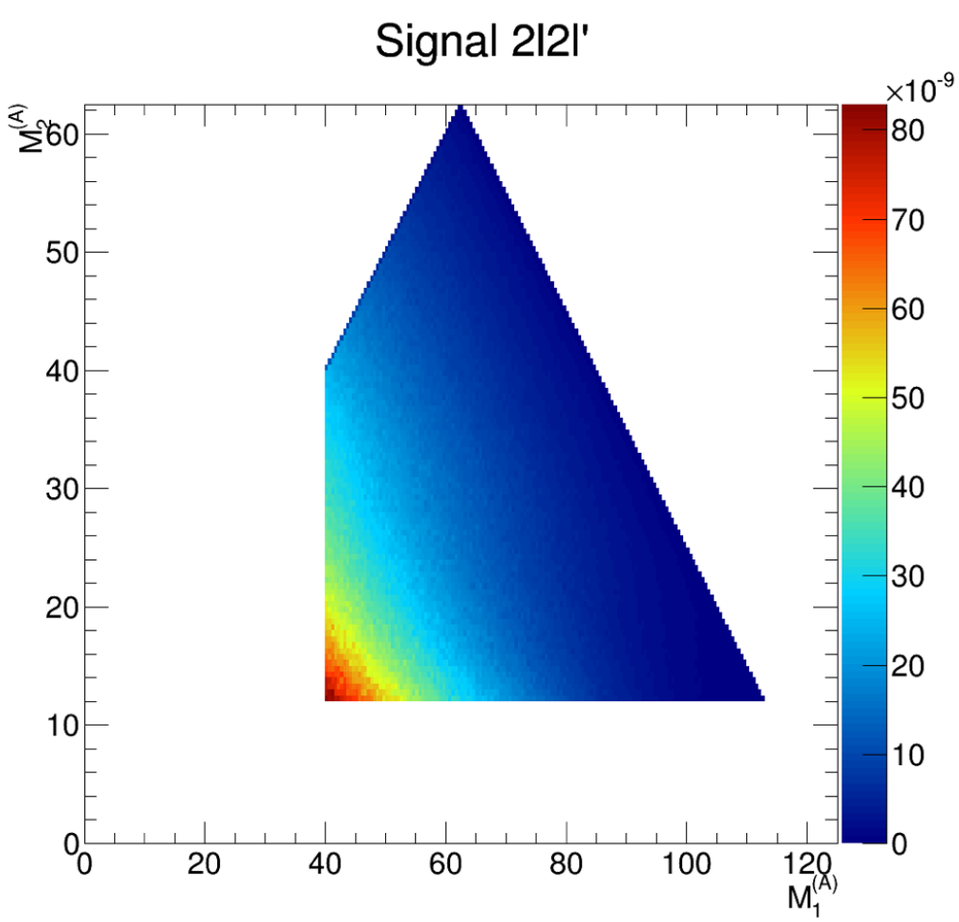
Shapes

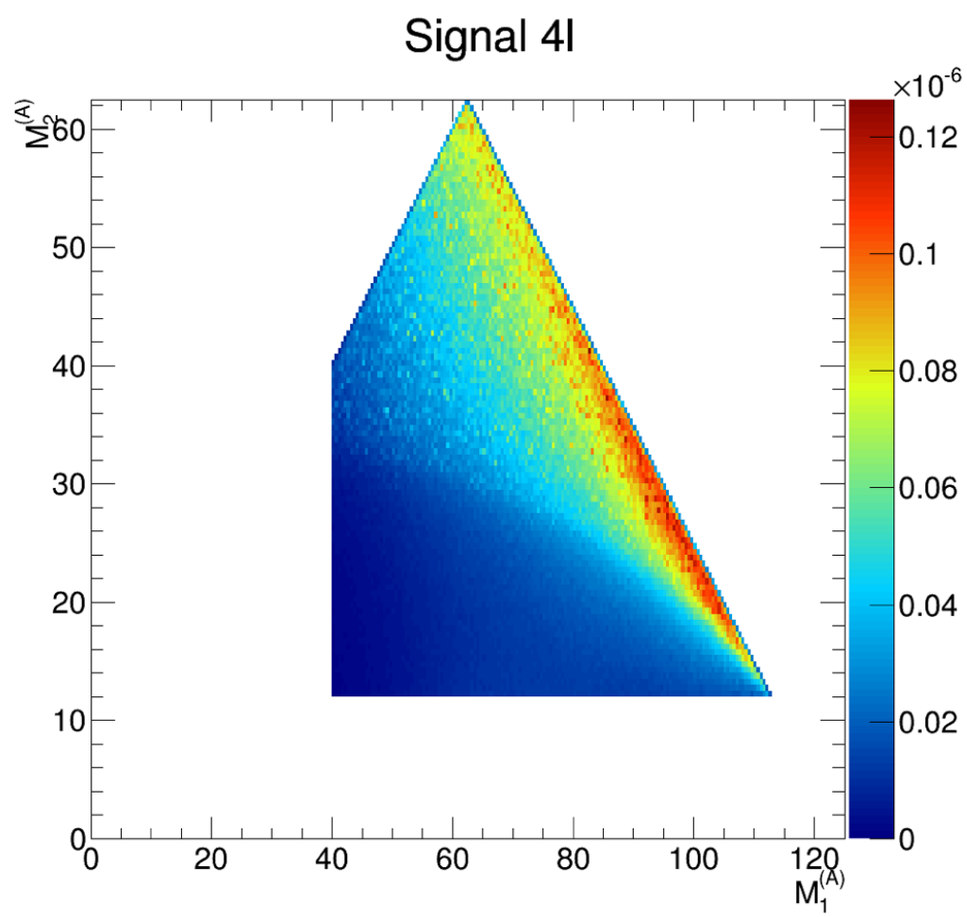
A_1^{ZZ} "background"





A_2^{AA}





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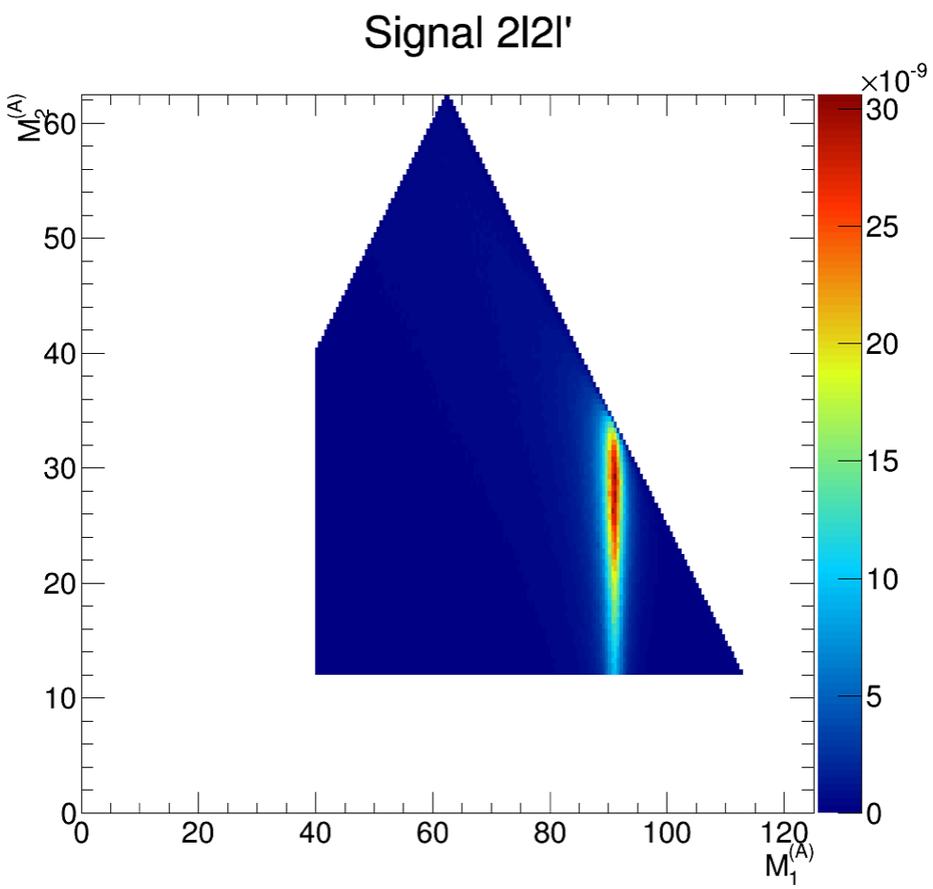

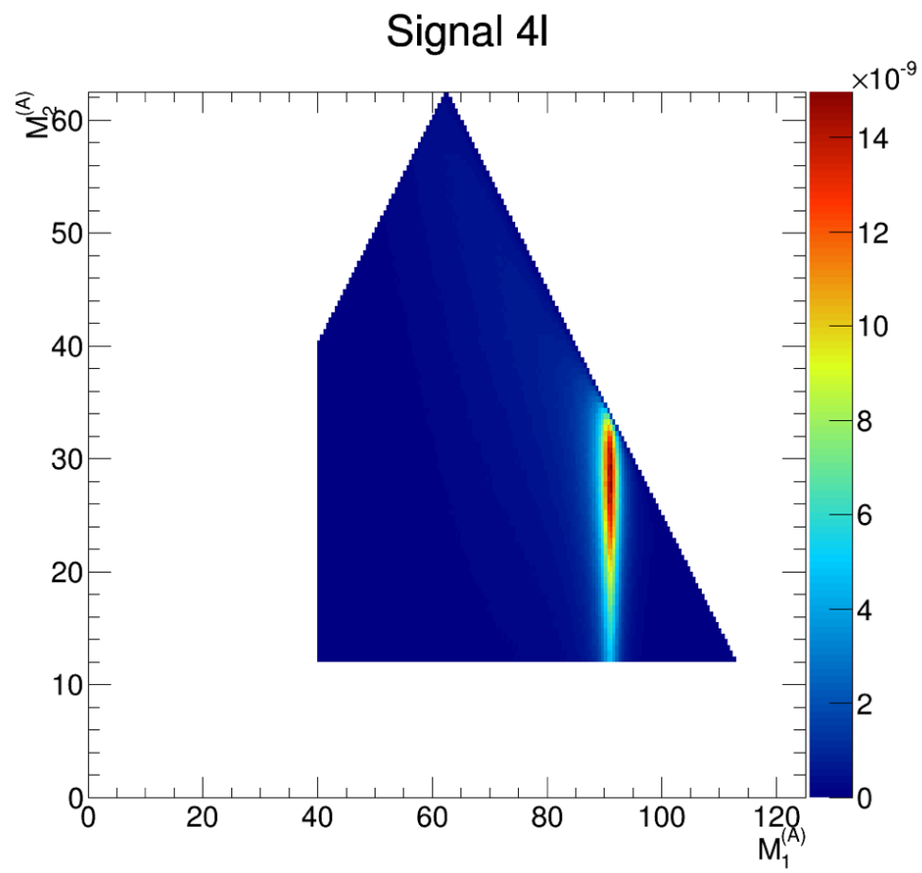

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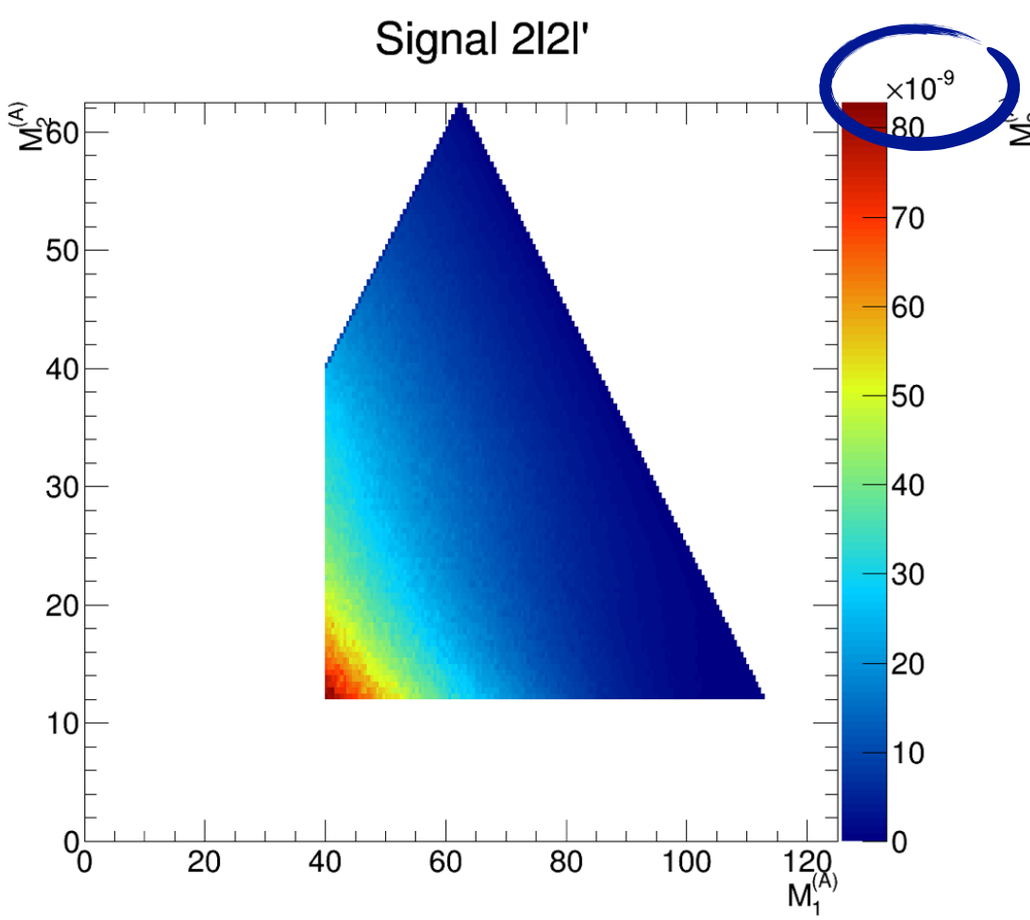
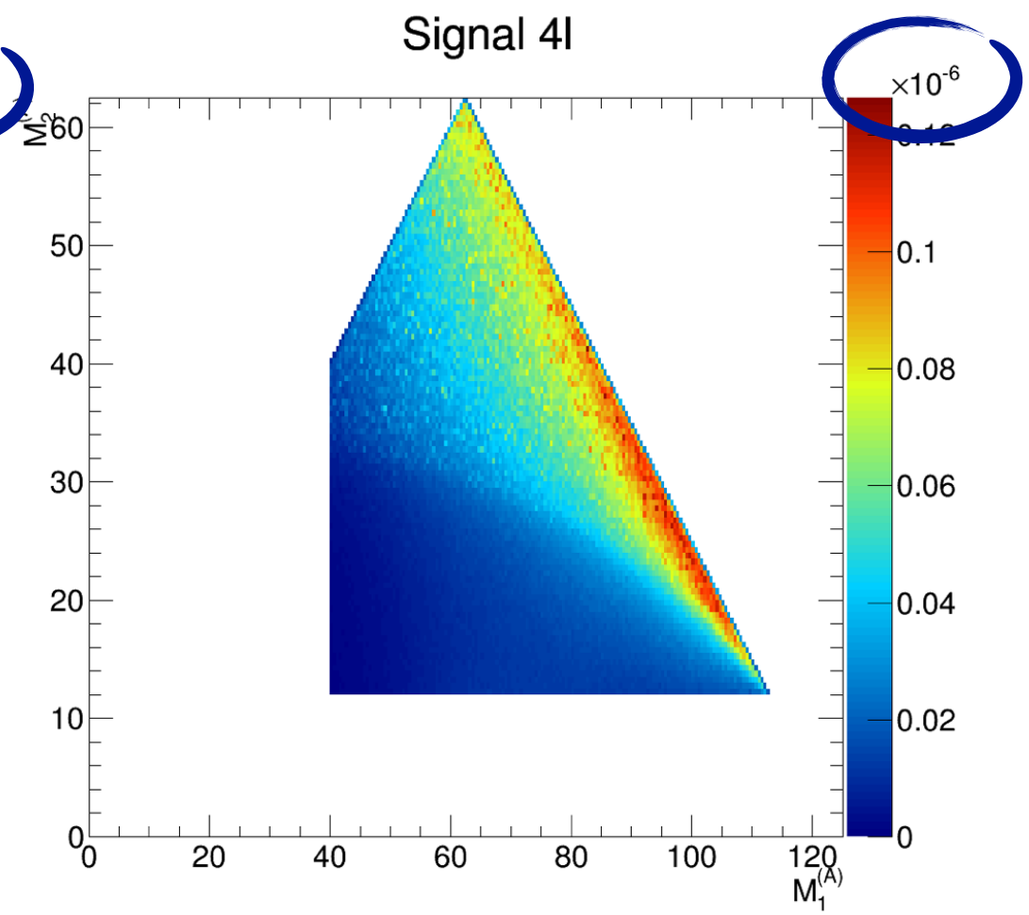
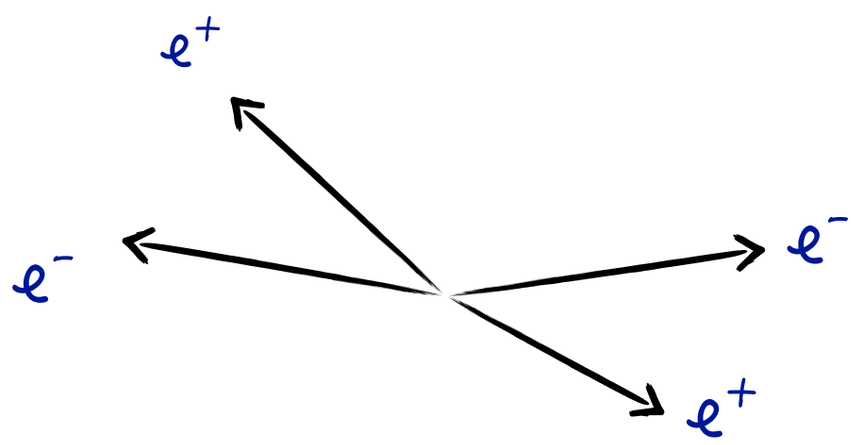




"Wrong Pair"

* 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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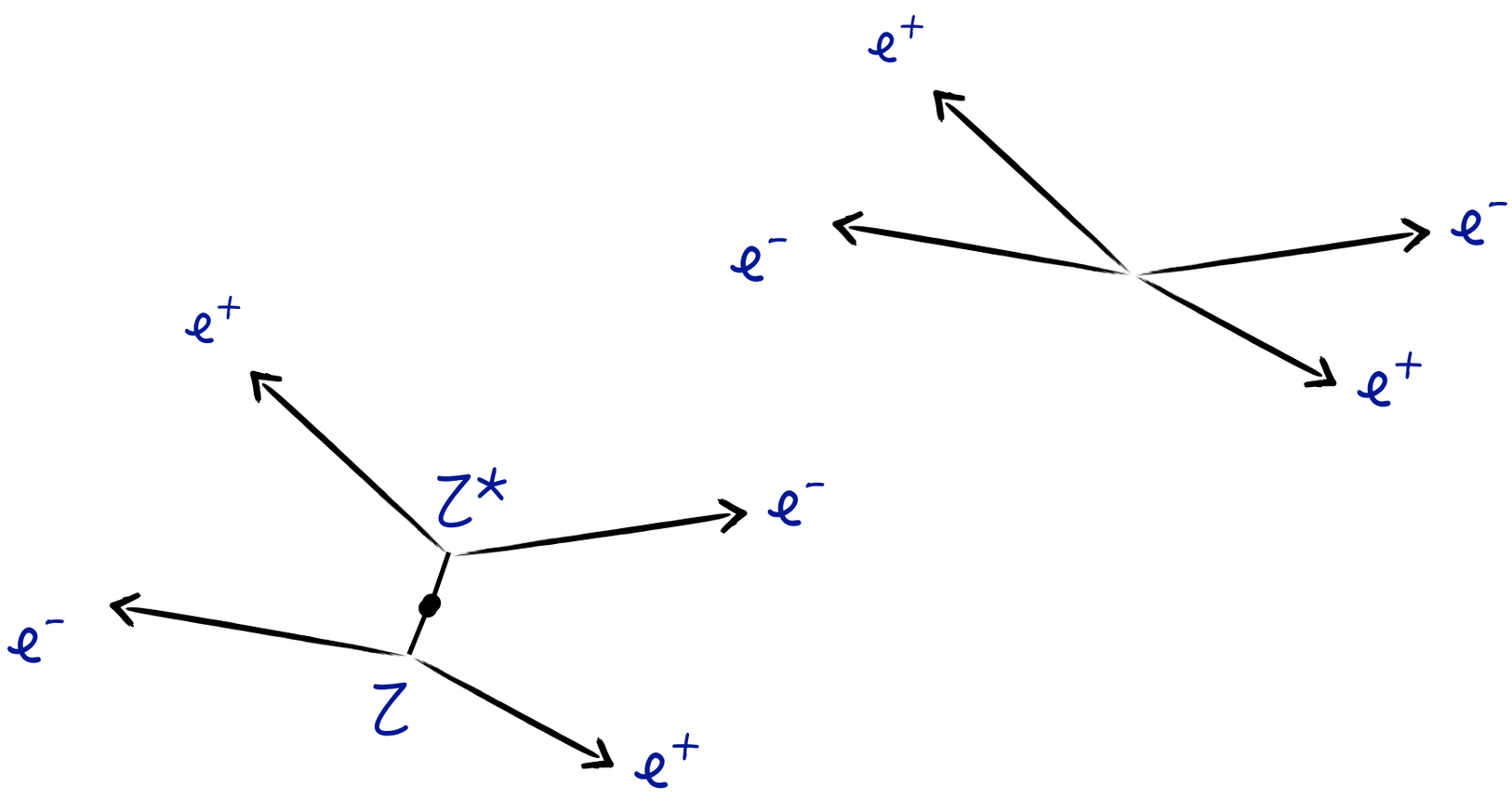

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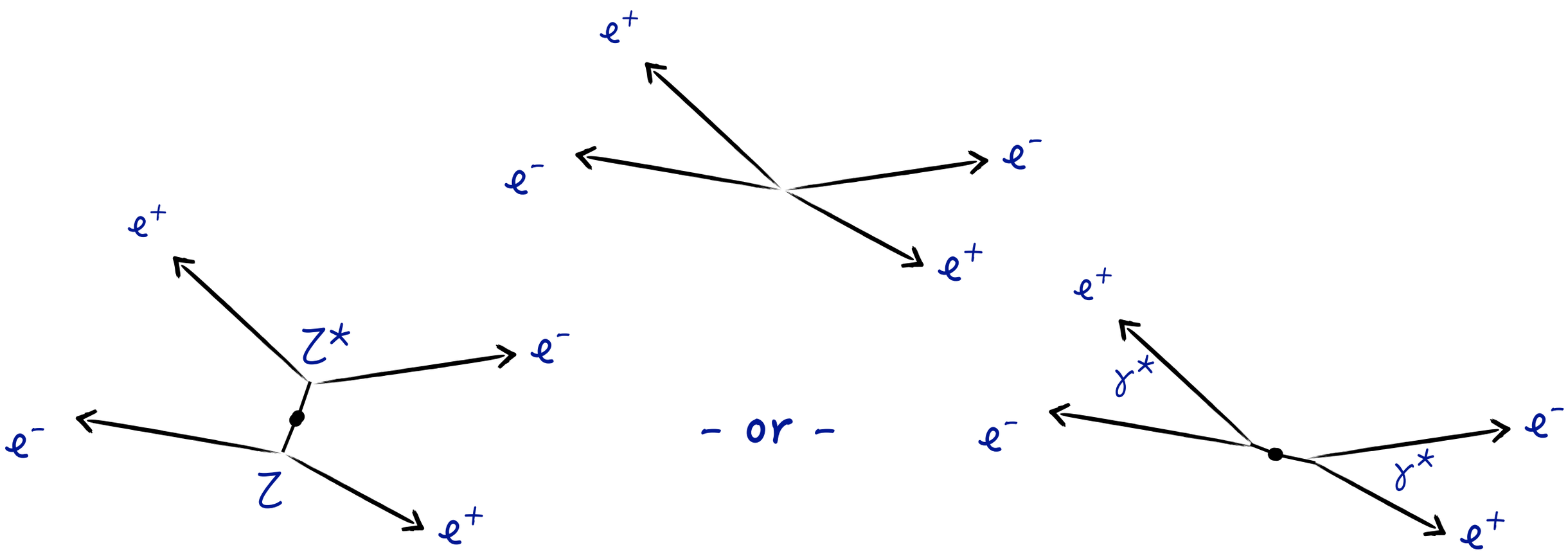

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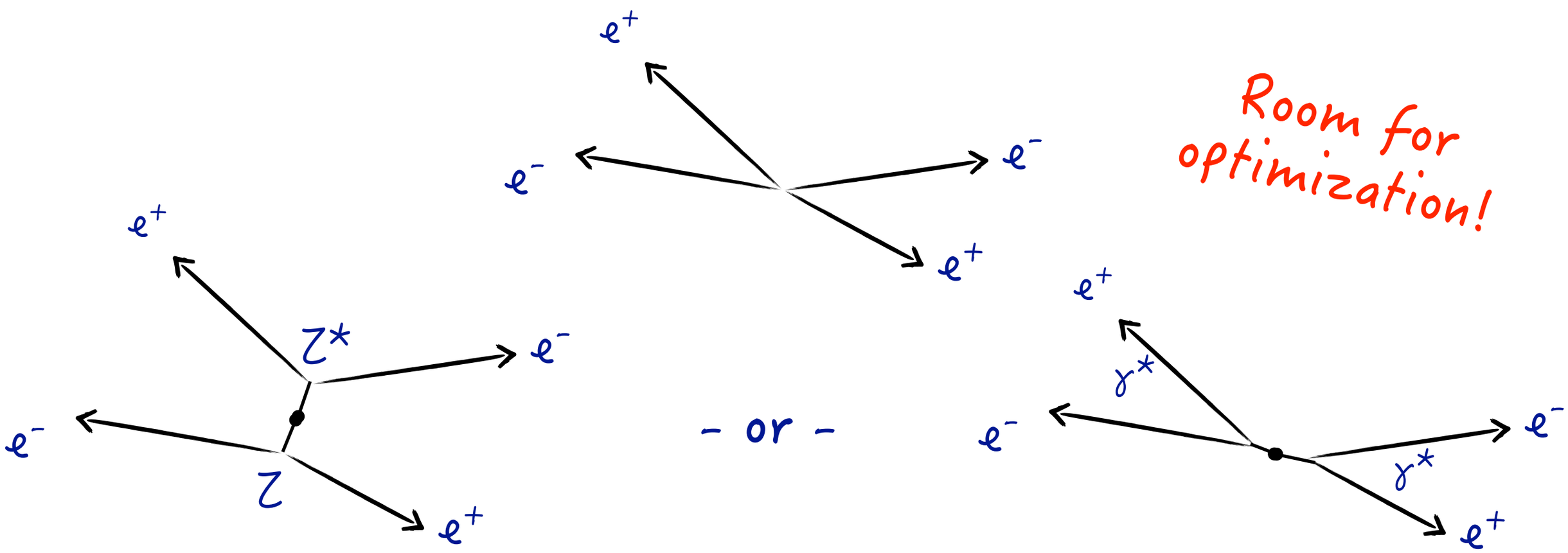
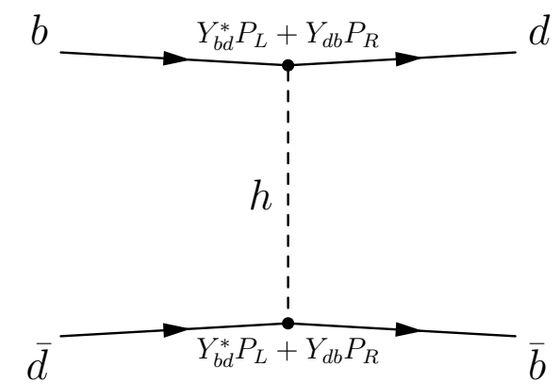


For completeness:

Meson Mixing



* Meson mixing's powerful:

Technique	Coupling	Constraint	$m_i m_j / v^2$
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$	5×10^{-8}
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$	
B^0_d oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$	3×10^{-7}
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$	
B^0_s oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$	7×10^{-6}
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$	
K^0 oscillations [48]	$\mathrm{Re}(Y^2_{ds})$, $\mathrm{Re}(Y^2_{sd})$	$[-5.9\ldots5.6] \times 10^{-10}$	8×10^{-9}
	$\mathrm{Im}(Y^2_{ds})$, $\mathrm{Im}(Y^2_{sd})$	$[-2.9\ldots1.6] \times 10^{-12}$	
	$\mathrm{Re}(Y^*_{ds}Y_{sd})$	$[-5.6\ldots5.6] \times 10^{-11}$	
	$\mathrm{Im}(Y^*_{ds}Y_{sd})$	$[-1.4\ldots2.8] \times 10^{-13}$	

"Natural" models are constrained!

FV Couplings with top

* A variety of techniques:

Technique	Coupling	Constraint	$m_i m_j / v^2$
$t \to hj$ [Craig et al. 1207.6794]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.34	3×10^{-3}
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.34	7×10^{-6}
D^0 oscillations	$\lvert Y_{ut}Y_{ct}\rvert,\ \lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$	
	$\lvert Y_{tu}Y_{ct}\rvert,\ \lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$	2×10^{-4}
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$	
neutron EDM	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$	7×10^{-6}

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* Improvements:

  $t + (h \to \gamma\gamma)$: $Y_{tj} < 0.17$ (!)

  (ATLAS-CONF-2013-081)

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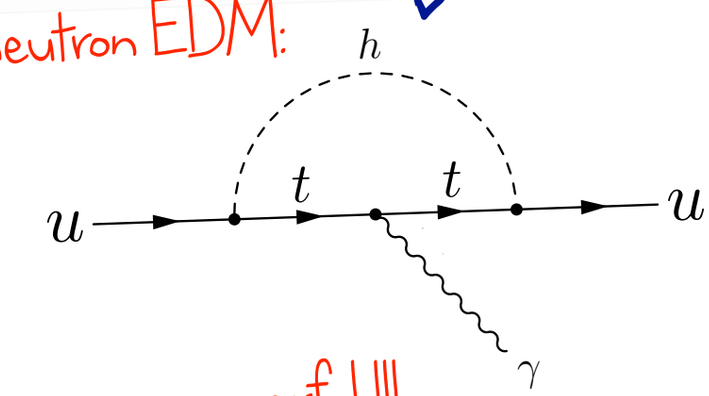
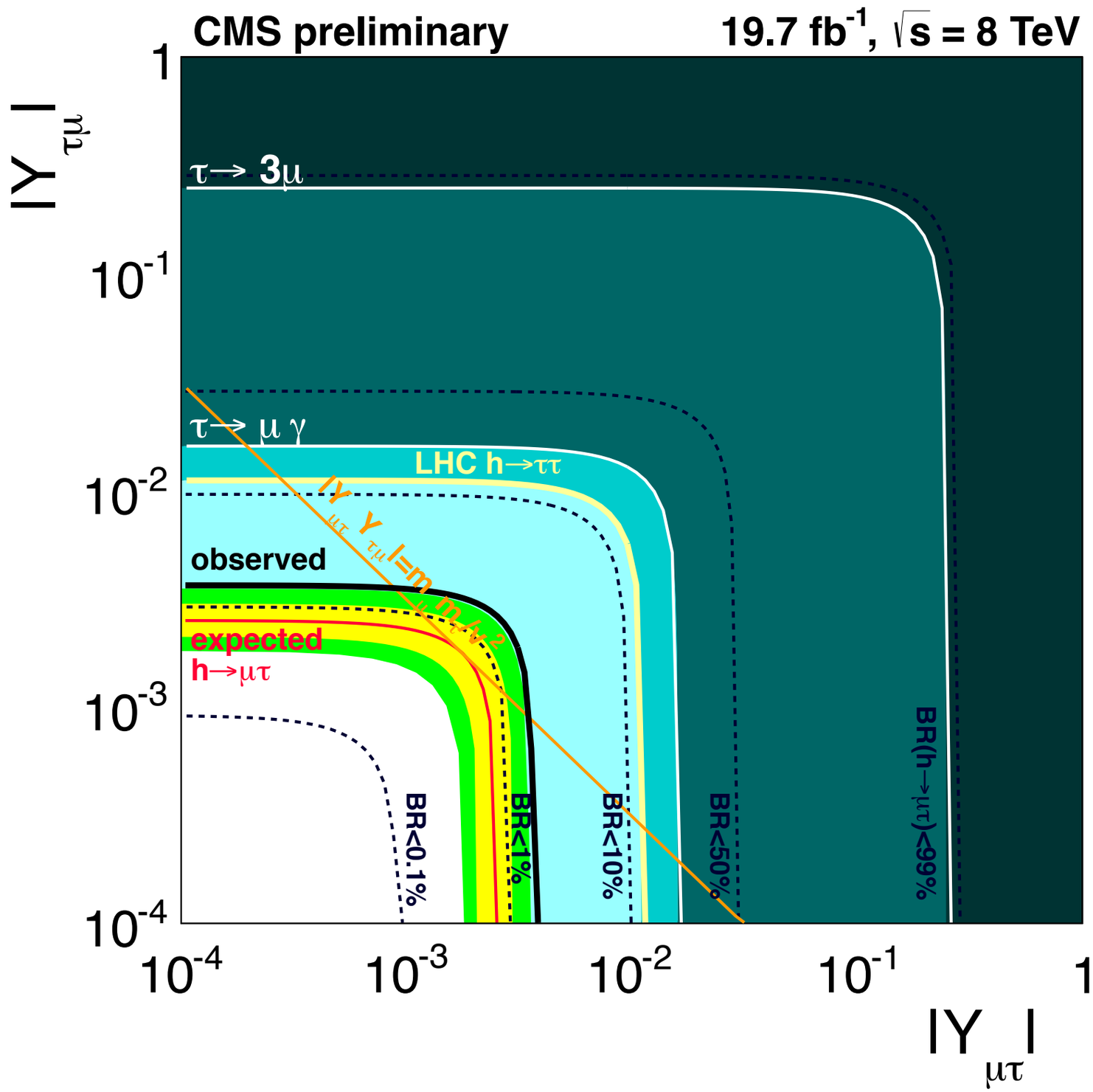
neutron EDM:



powerful !!!

Higgs couplings to τμ



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

CMS: A 2.5σ excess.

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

Waiting for ATLAS...

RH, Kopp, Zupan 1209.1397
& CMS

hVV: Measurements

* We already have some searches for our signal:

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

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

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

$$+ 2A_2^{Z\gamma} Z_{\mu\nu} F^{\mu\nu} + 2A_3^{Z\gamma} Z_{\mu\nu} \tilde{F}^{\mu\nu}\Big)$$

hVV: Measurements

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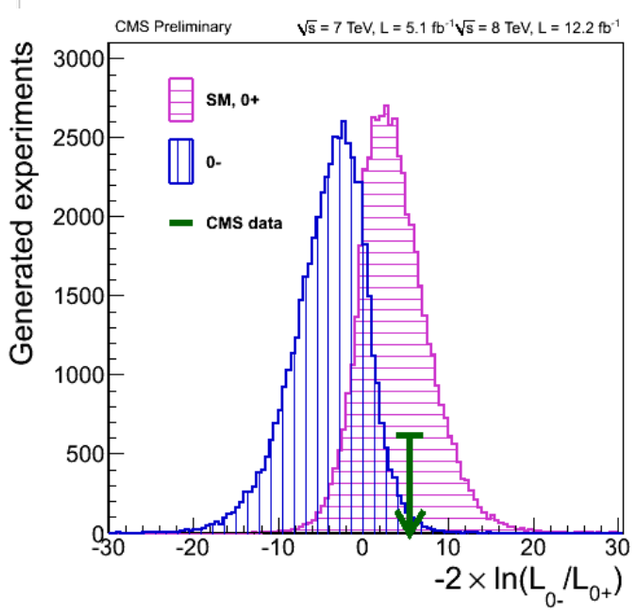
$h \to 4\ell$: scalar vs. pseudoscalar. (Hypothesis test).

or



Scalar preferred @ 3σ

This is <u>not</u> 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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$$+ A_2^{ZZ} Z_{\mu\nu} Z^{\mu\nu} + A_3^{ZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

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

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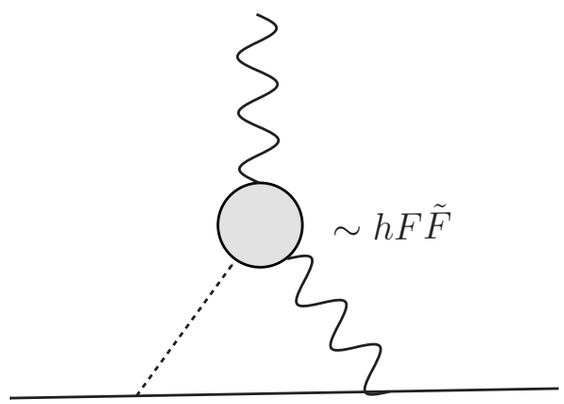


If Higgs couples to electron - EDM!

$A_2 >> A_3$

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):

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

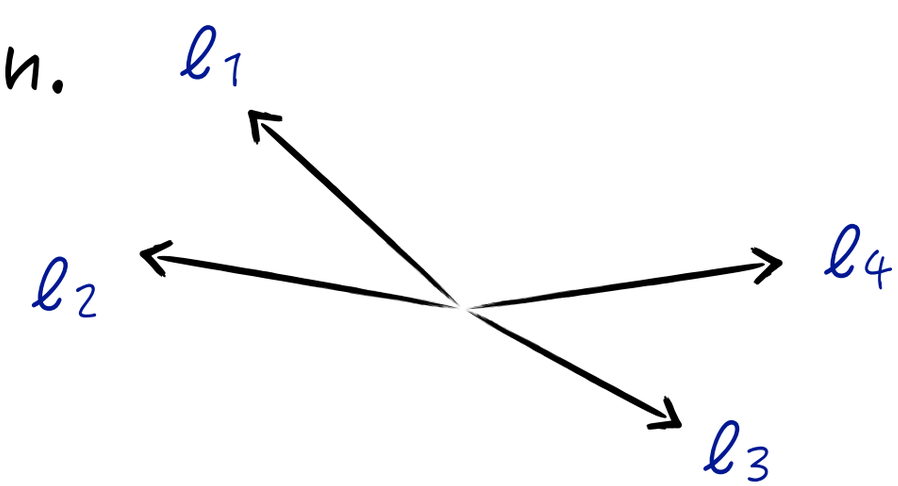
hVV: Measurements

* The SM-like rate to 4ℓ + "scalar evidence" imply that the Higgs is SM-like.
* 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.
  - Constraints on $Z\gamma$ and ZZ high-dim operators are very poor, and will remain so for a while.

Can the golden channel shed light on the small dim-5 operators? which ones?

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 and m_2

* For now, we adopt the CMS 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.
* 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 GeV $\leq M_1$ and 12 GeV $\leq M_2$.

Lesson from Shapes

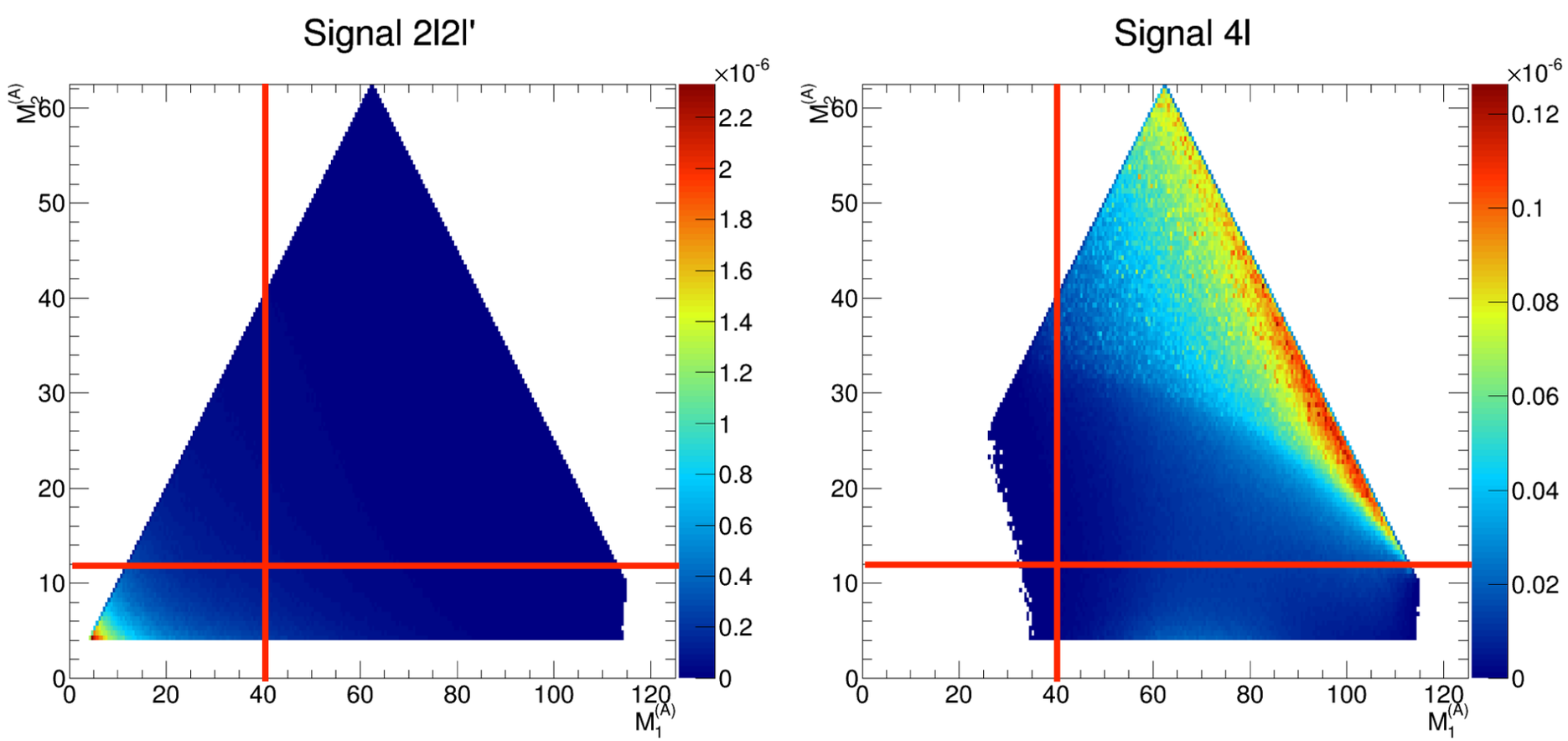
* Not surprisingly: the $\gamma\gamma$ shapes are most different from background (recall: BG= A_1).
* $Z\gamma$ is next.
* Interesting pair selection effects in $\gamma\gamma$ $4e/4\mu$. There is room for optimization! (more later)

Optimization

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}



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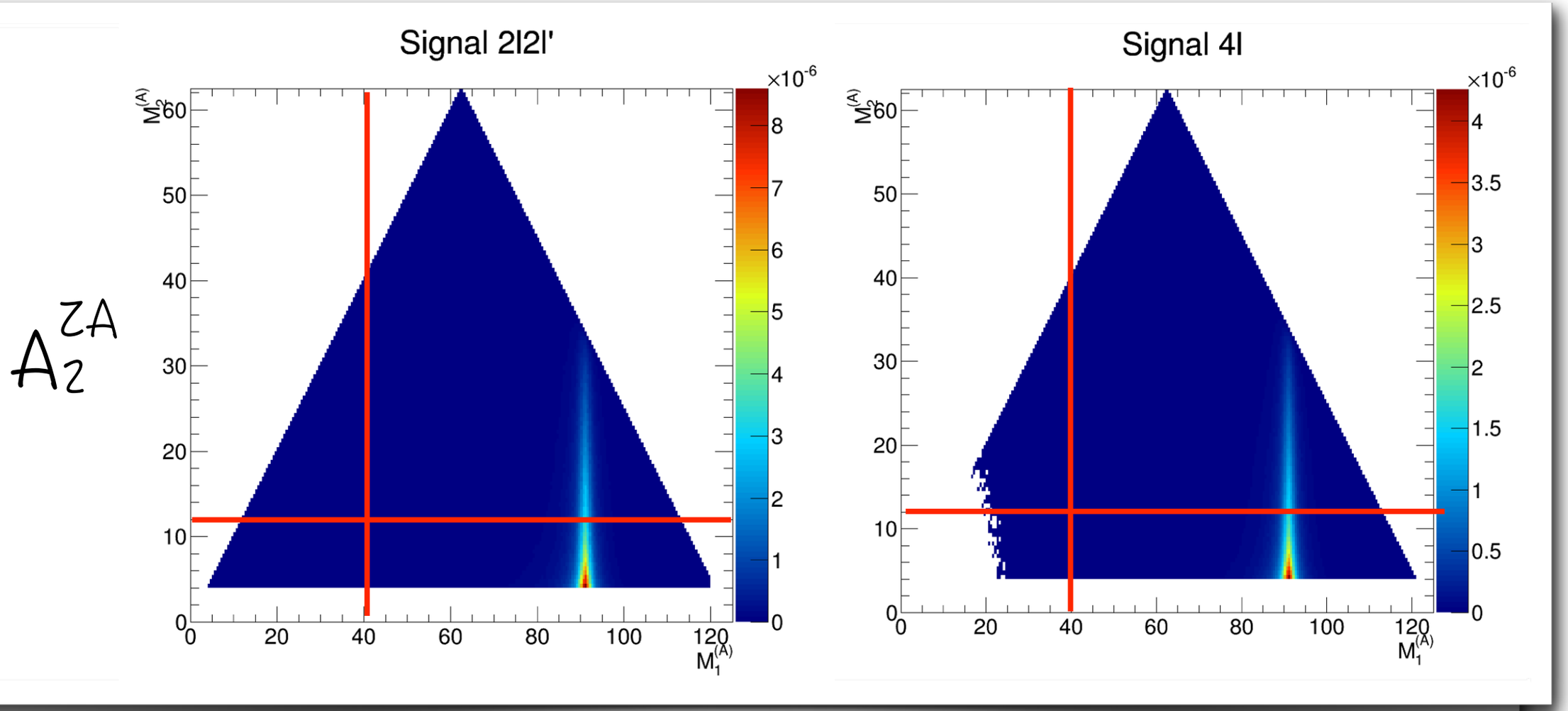

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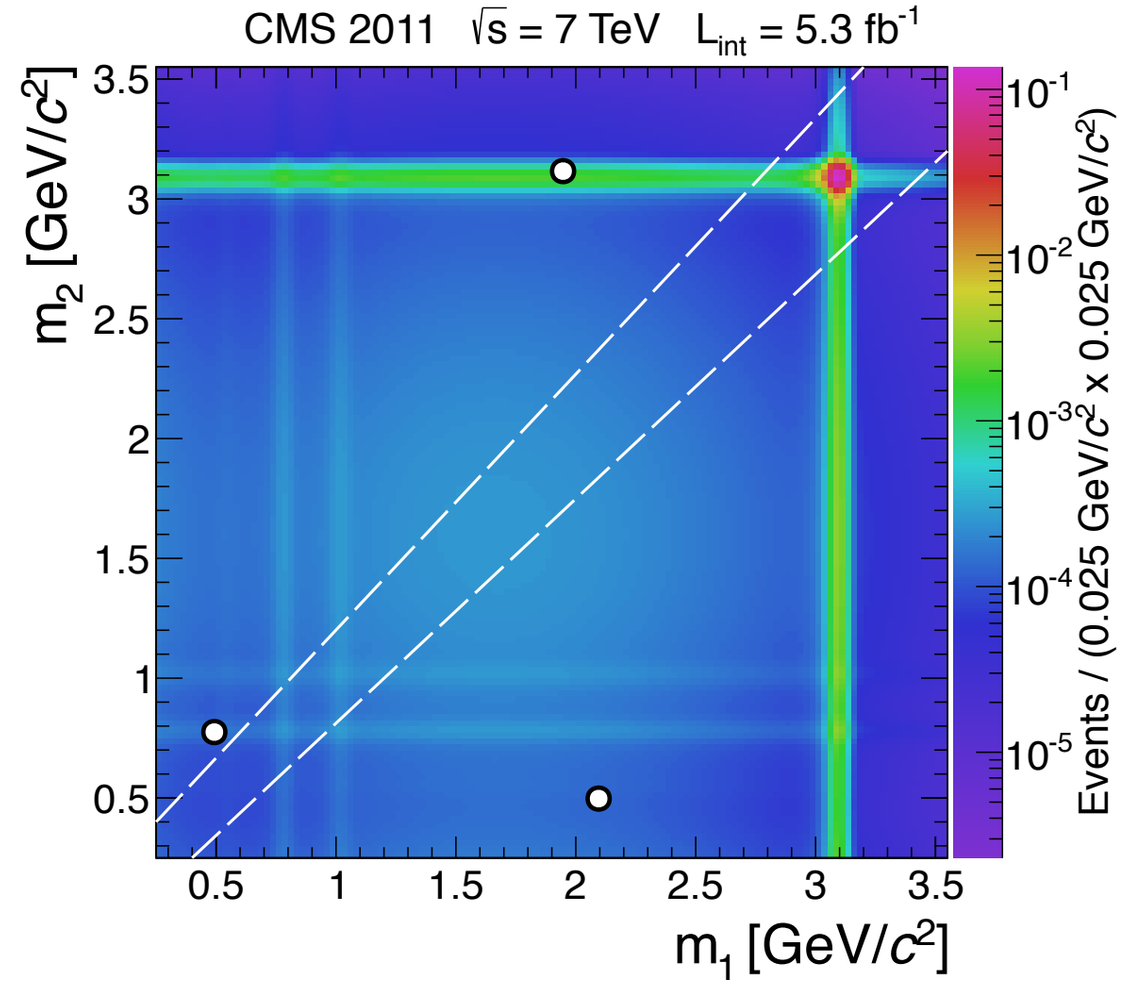

* Going low in m1 and m2 is doable.

* <u>Preliminary results:</u>
  - We can reach SM values of $h\gamma\gamma$ by the end of run2 !
  - We can reach SM values for $Z\gamma$!
    Perhaps compete with on-shell $h \rightarrow Z\gamma$....

* Everything hinges on what happens when we include non-Higgs background.

What about CP violation?

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

For τ's, the phase Δ is un-constrained!

How can LHC probe CPV in $h \to \tau\tau$?

RH, Martin, Okui, Primulando, Yu 1308.1094

Polarizers

* $h \to \tau\tau$:

$\tau\tau$ final state(helicity basis):

$$\left(e^{+i\Delta}|++\rangle + e^{-i\Delta}|--\rangle\right)$$

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Counts vs relative polarization angle, ϕ:

$$\left|\left(\langle+| + \langle-|\right)_1 \otimes \left(e^{-i\phi}\langle+| + e^{+i\phi}\langle-|\right)_2 \left(e^{+i\Delta}|++\rangle + e^{-i\Delta}|--\rangle\right)\right|^2$$

RH, Martin, Okui, Primulando, Yu 1308.1094

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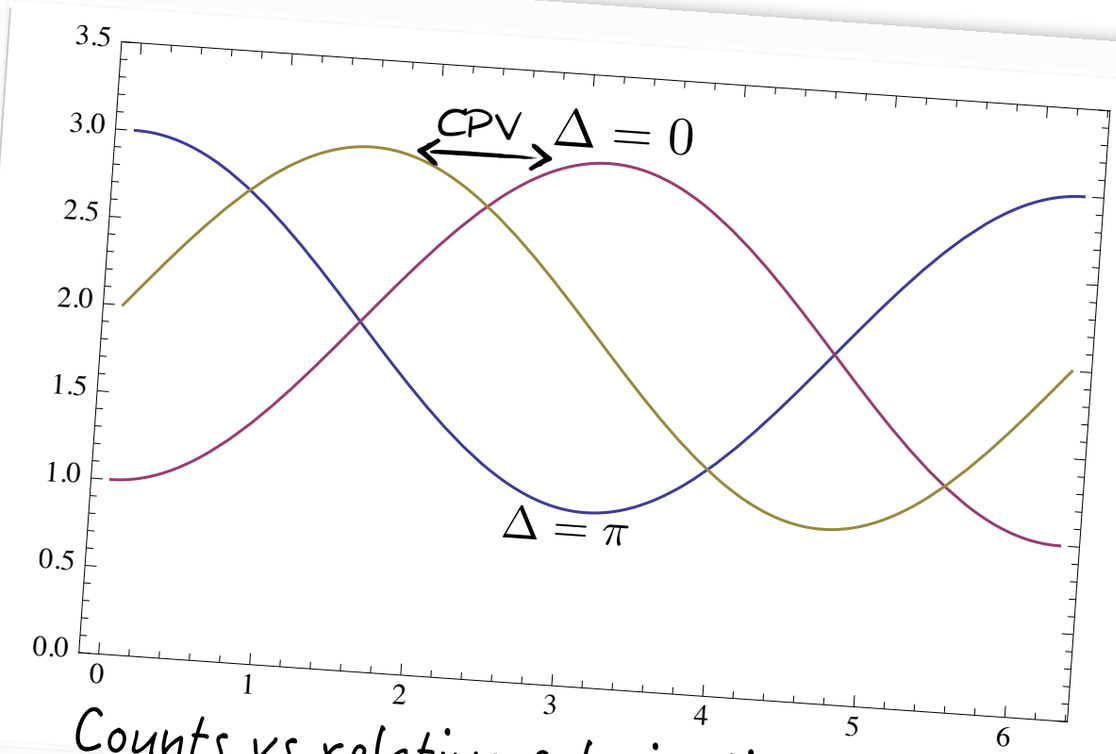


Counts vs relative polarization angle, ϕ

RH, Martin, Okui, Primulando, Yu 1308.1094

Summary

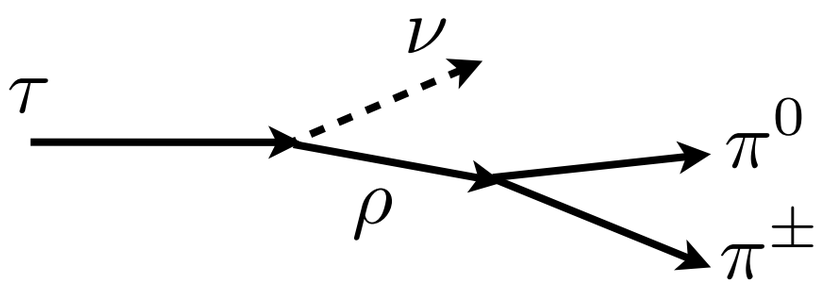
* Its time to probe the Higgs beyond rates. Today's examples:
  - Flavor violating Higgs decay. 2.5 σ excess in $h \to \tau\mu$.
  - CP violation in $h \to \tau\tau$. Polarization measurements.
  - CP properties of $h\gamma\gamma$. Golden channel!
* The decay $h \to 4\ell$ can be a complementary probe of the $hZ\gamma$ coupling.

} in progress.

Deleted Scenes

Real World

* Unfortunately we don't have polarizers for τ's.
  But they decay!



"pion-plane" correlated with τ polarization.

* An optimized "polarizer" (using ν knowledge):

$$\frac{m_h}{2}\left[(y_\pm - r)\,\vec{p}_{\pi^\pm}\big|_0 - (y_\pm + r)\,\vec{p}_{\pi^{0\pm}}\big|_0\right]^\perp$$

with
$$\begin{cases} q_\pm \equiv p_{\pi^\pm} - p_{\pi^{0\pm}} \\ y_\pm \equiv \dfrac{2q_\pm \cdot p_{\tau^\pm}}{m_\tau^2 + m_\rho^2} = \dfrac{q_\pm \cdot p_{\tau^\pm}}{p_{\rho^\pm} \cdot p_{\tau^\pm}}\,, \\ r \equiv \dfrac{m_\rho^2 - 4m_\pi^2}{m_\tau^2 + m_\rho^2} \approx 0.14\,. \end{cases}$$

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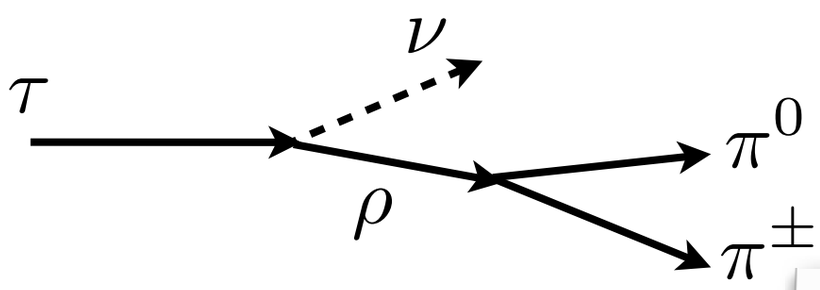

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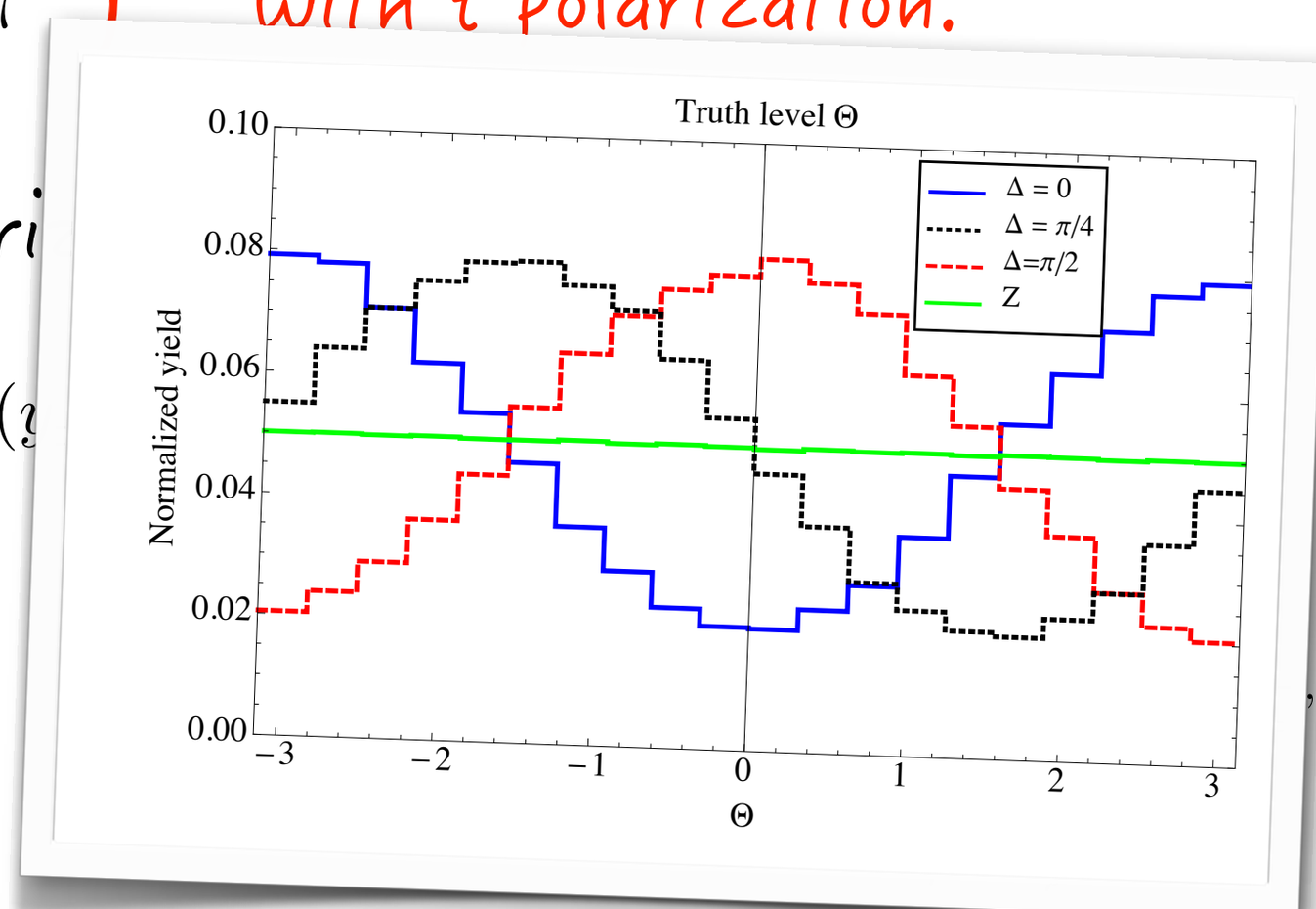
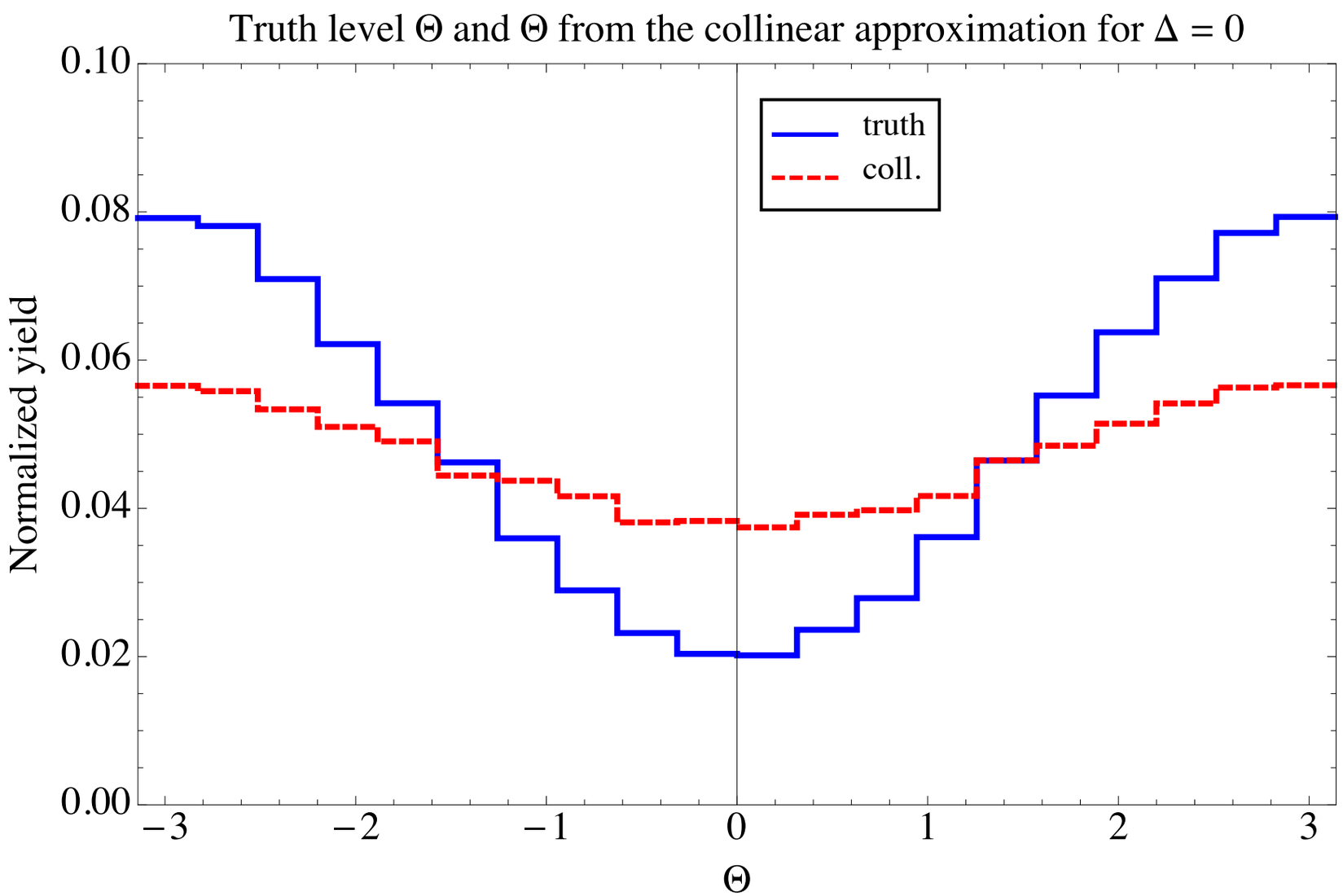


LHC

* Using collinear approximation, we form an LHC observable:



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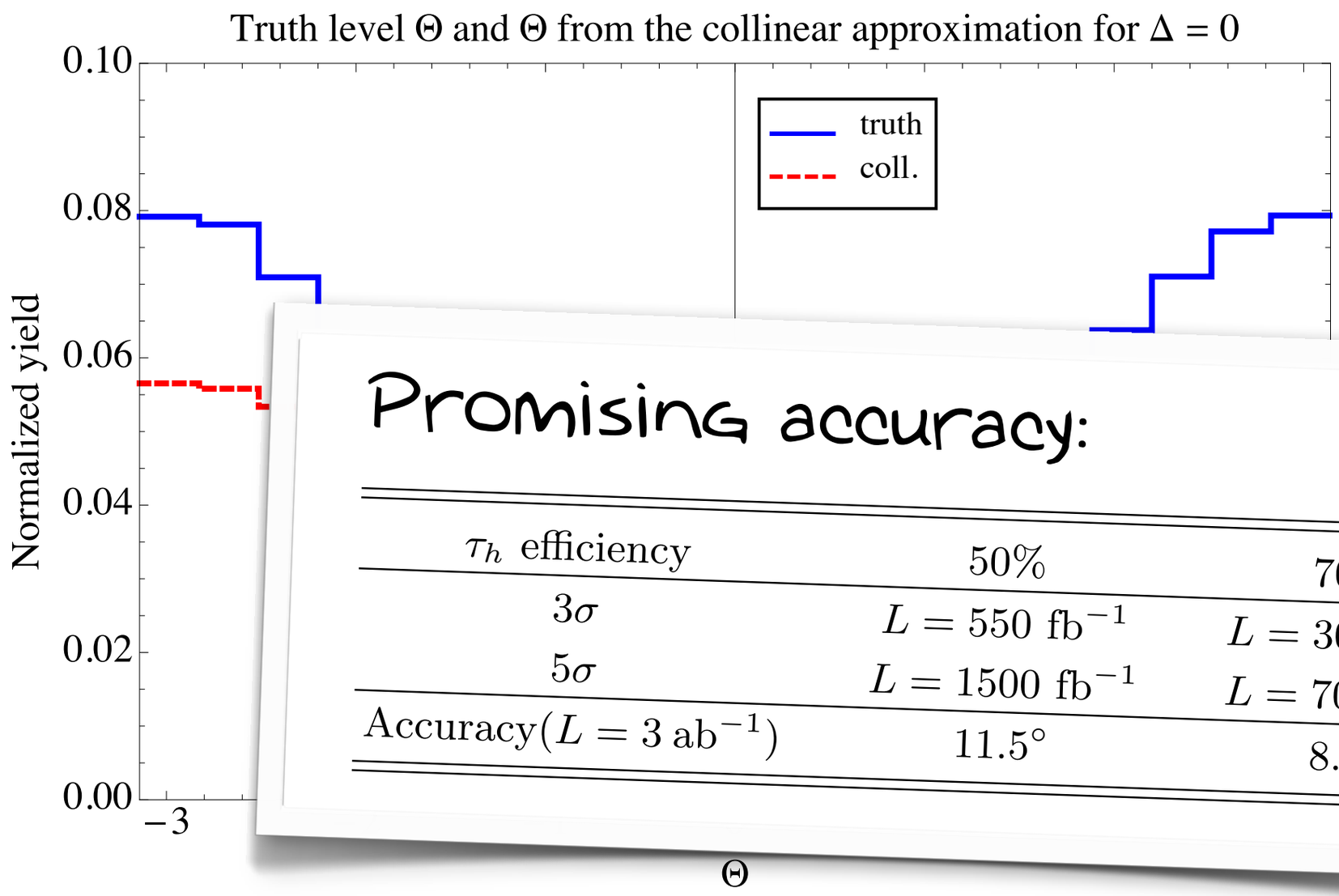

Promising accuracy:

τ_h efficiency	50%	70%
3σ	$L = 550$ fb^{-1}	$L = 300$ fb^{-1}
5σ	$L = 1500$ fb^{-1}	$L = 700$ fb^{-1}
Accuracy($L = 3$ ab^{-1})	11.5°	8.0°

Higgs Factory

* In a Higgs factory we can reconstruct the whole event (up to a two-fold ambiguity).

$\sigma_{e^+e^-\to hZ}$	0.30 pb
$\mathrm{Br}(h \to \tau^+\tau^-)$	6.1%
$\mathrm{Br}(\tau^- \to \pi^-\pi^0\nu)$	26%
$\mathrm{Br}(Z \to \text{visibles})$	80%
$\mathrm{N}_{\mathrm{events}}$	990
Accuracy	4.4°

TABLE I: Cross section, branching fractions, expected number of signal events, and accuracy for measuring Δ for the ILC with $\sqrt{s} = 250$ GeV and 1 ab^{-1} integrated luminosity.