Flavor and CP of the Higgs

Roni Harnik,
Fermilab

WG3 Meeting

* RH, Kopp, Zupan 1209.1397
* RH, Martin, Okui, Primulando, Yu 1308.1094
* Chen, RH, Vega-Morales 1404.1336, 1503.05855

Stating the Obvious:

* Why explore the flavor of Higgs couplings?
    - Duh! Its a new particle - explore it to death!
    - The Higgs couplings define flavor to begin with!
      → SM Higgs couples flavor diagonally by definition.
      → Discovery of FV is a discovery of BSM
    - The community has grown ver used to 2HDMs type X.
      Models that were constructed precisely to avoid FV.
      A generic 2HDM will violate flavor.

Higgs-fermion Couplings

It is simple to declare the Higgs boson

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

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

How do we generate these guys?

What are the constraints?

How can LHC probe them?

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.

See Fady's talk for specific examples.

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3. Re-diagonalize mass matrix.

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

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

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

$$Y_f \neq \frac{m_f}{v}$$

See Fady's talk for specific examples.

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$$\mathcal{L} = \lambda_{ij} H f_L^i f_R^j + \lambda'_{ij} \frac{H^3}{\Lambda^2} f_L^i f_R^j$$

$$m_f = (\lambda_{ij} + \frac{v^2}{\Lambda^2} \lambda'_{ij}) v$$

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

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

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

See Fady's talk for specific examples.

Here is a lighting review of FV Higgs couplings.

What are the constraints?
What are opportunities for LHC?

Leptonic Flavor Violation

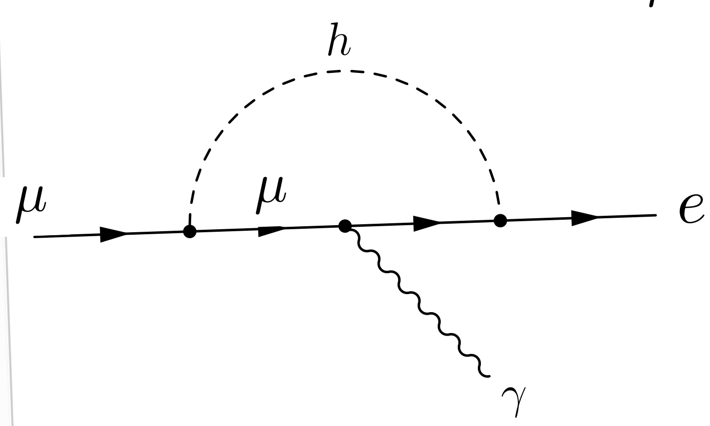
$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c..$$

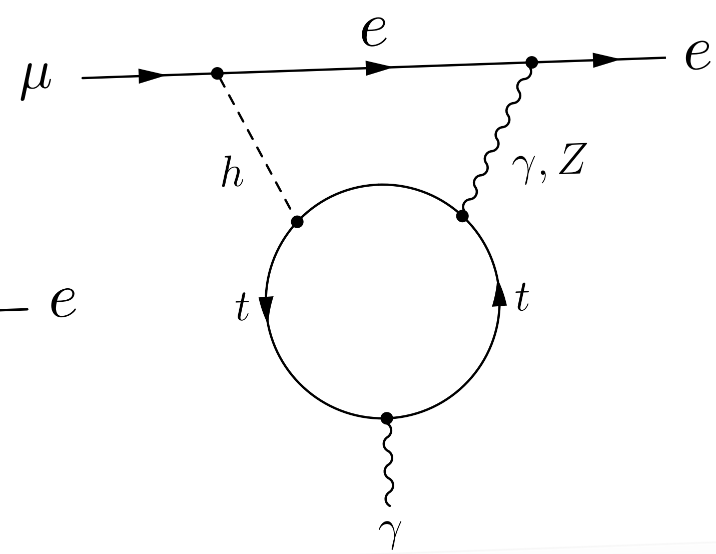
Which experiments constrain the Y_{ij}'s?

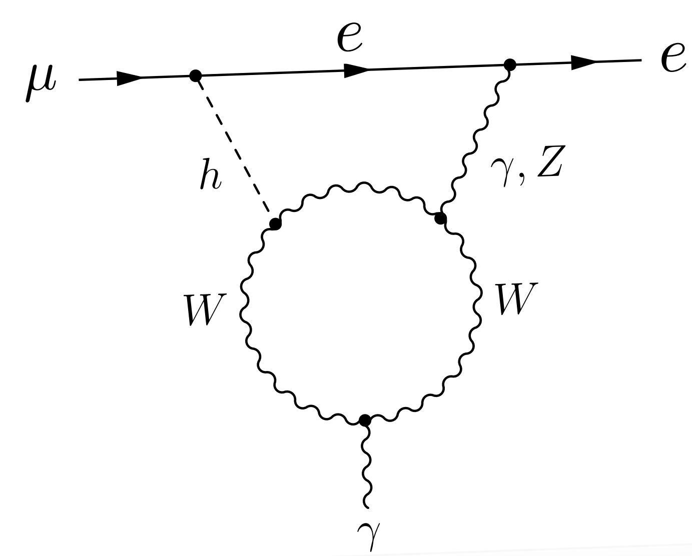
RH, Kopp, Zupan 1209.1397

FV Higgs constraints

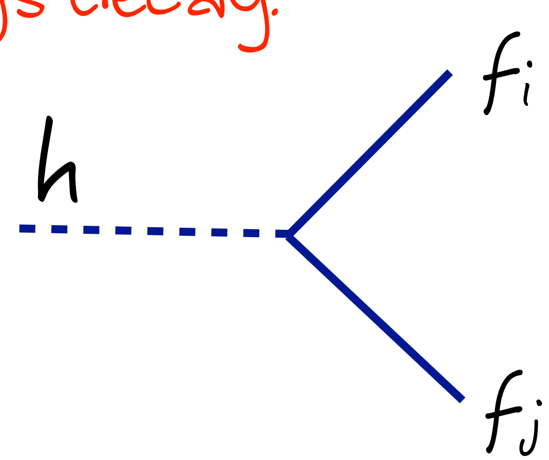
mu to e gamma & mu to 3e (at 1 and 2-loop):



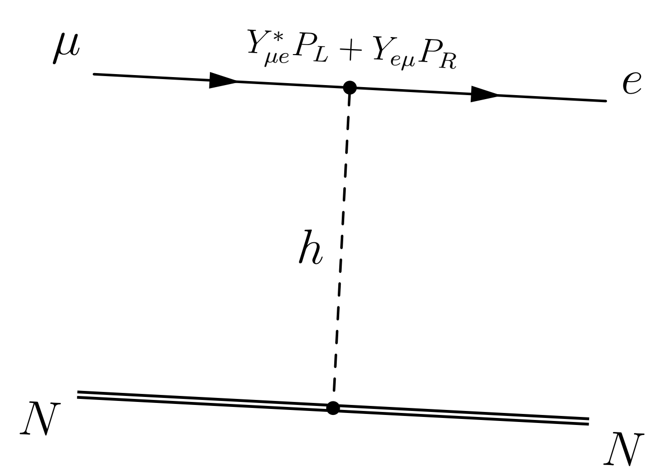




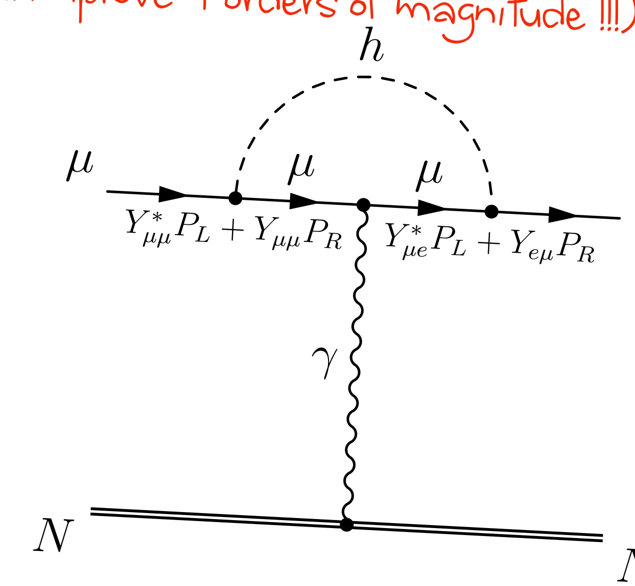
FV Higgs decay:



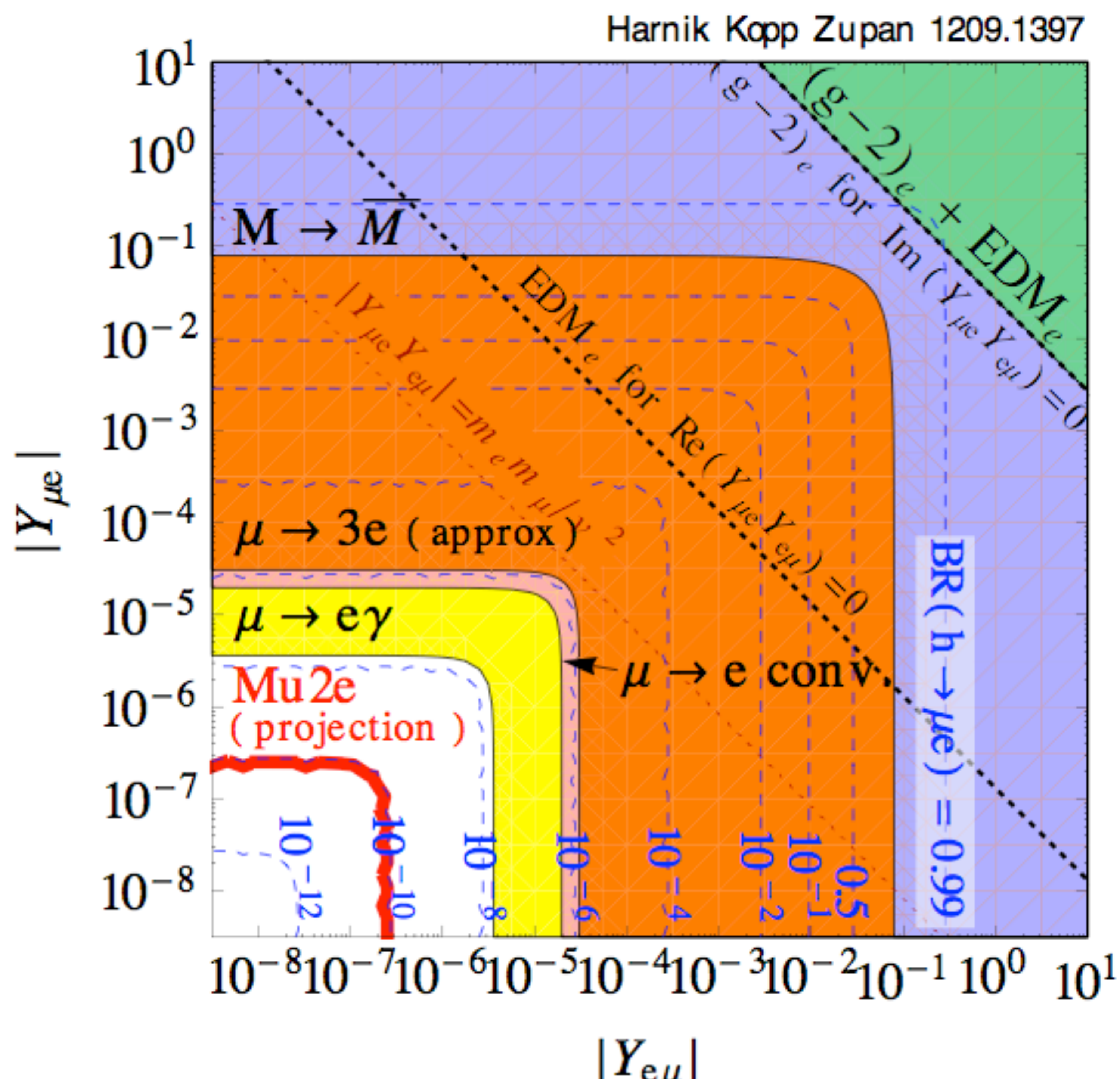
mu to e conversion (will improve 4 orders of magnitude !!!):



+



Higgs couplings to μe

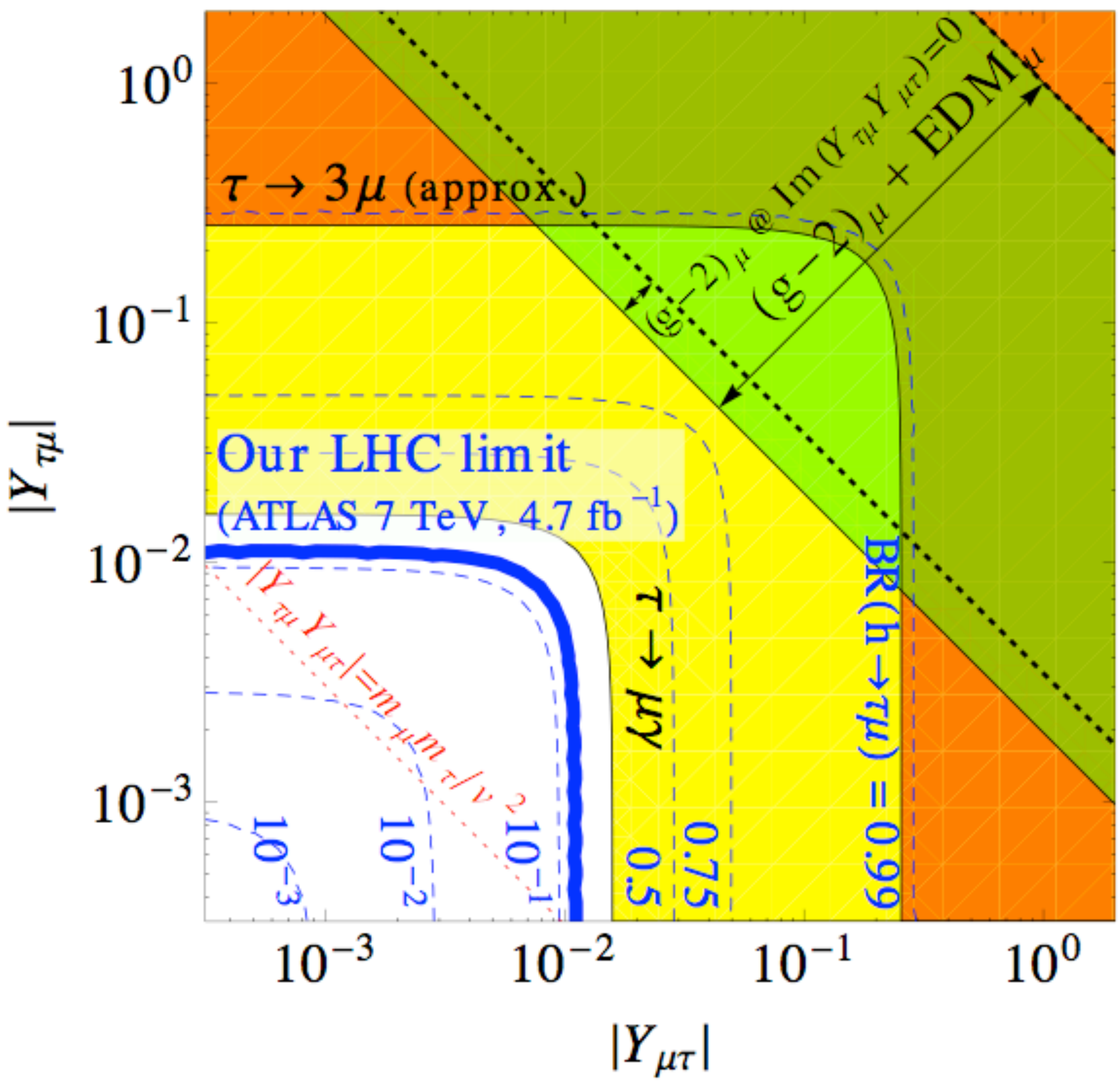


Outside of LHC reach.

Probing "natural" models.

Will be dominated by μ2e & COMET

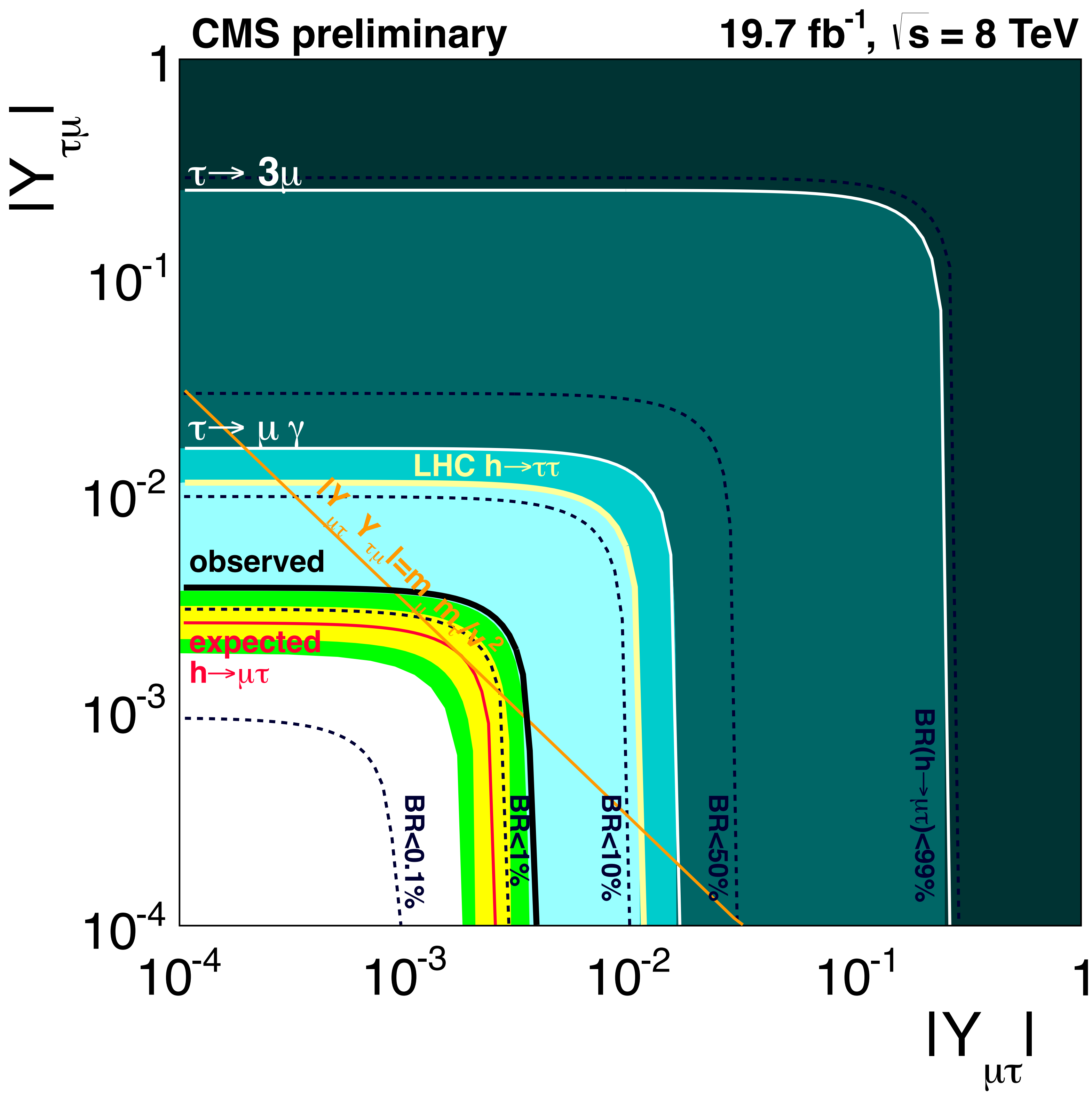
Higgs couplings to τμ



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

RH, Kopp, Zupan 1209.1397
& CMS

Higgs couplings to τμ



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

<u>CMS: A 2.5σ excess.</u>

(see next talk)

right around

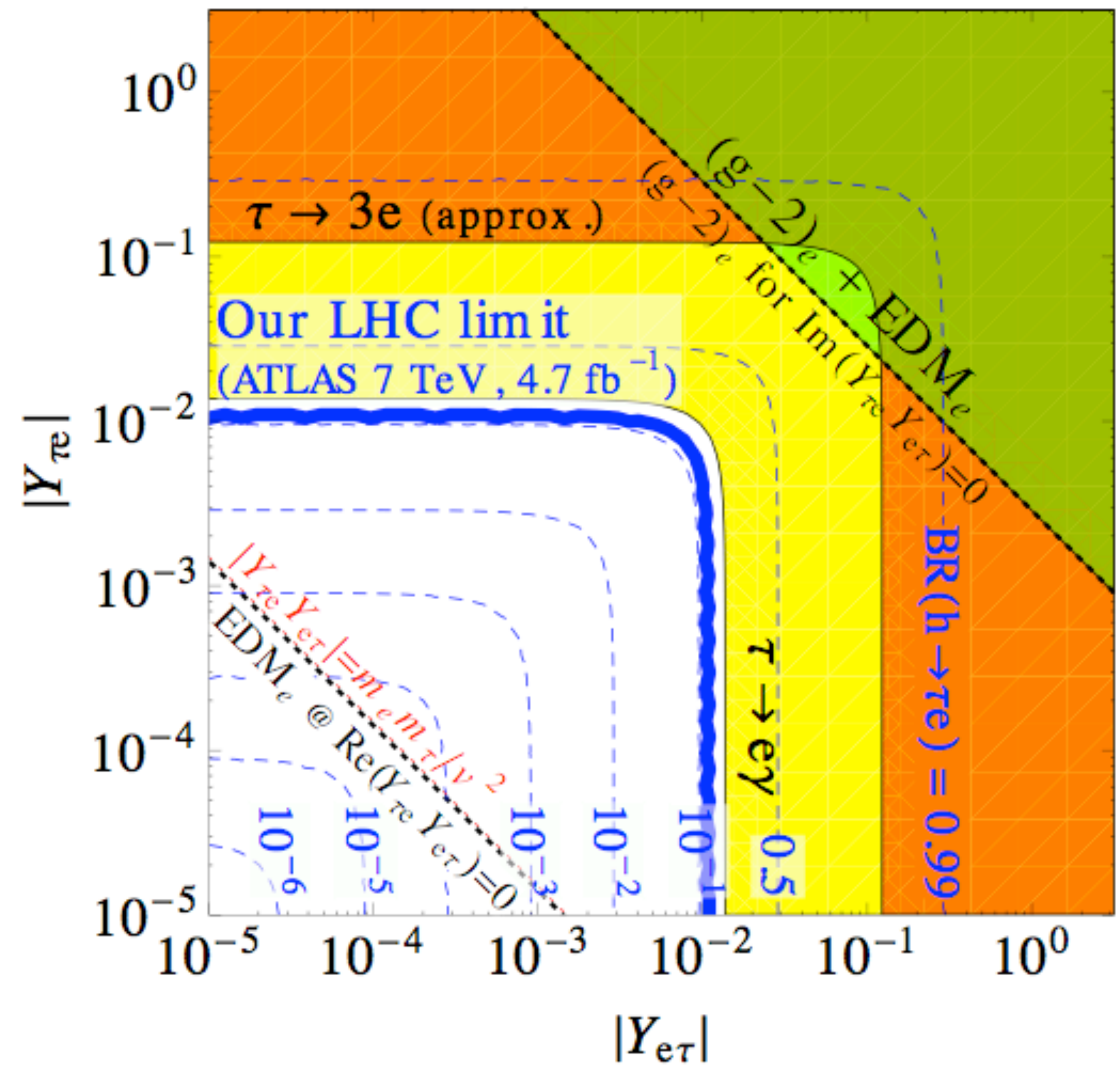
$y_{\tau\mu} \sim (y_\tau \cdot y_\mu)^{1/2}$

ATLAS analysis in the works.

RH, Kopp, Zupan 1209.1397 & CMS

Higgs couplings to τe

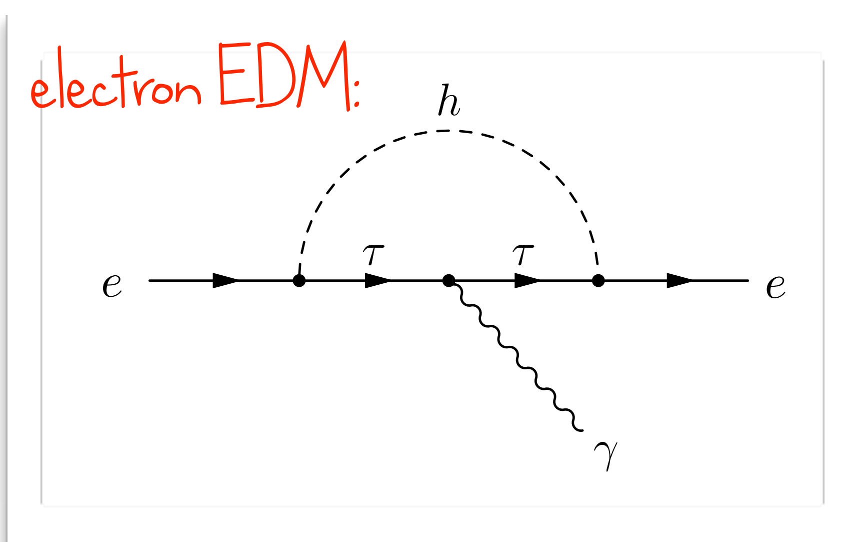
- τe is similar to τμ, but without CMS bound and...

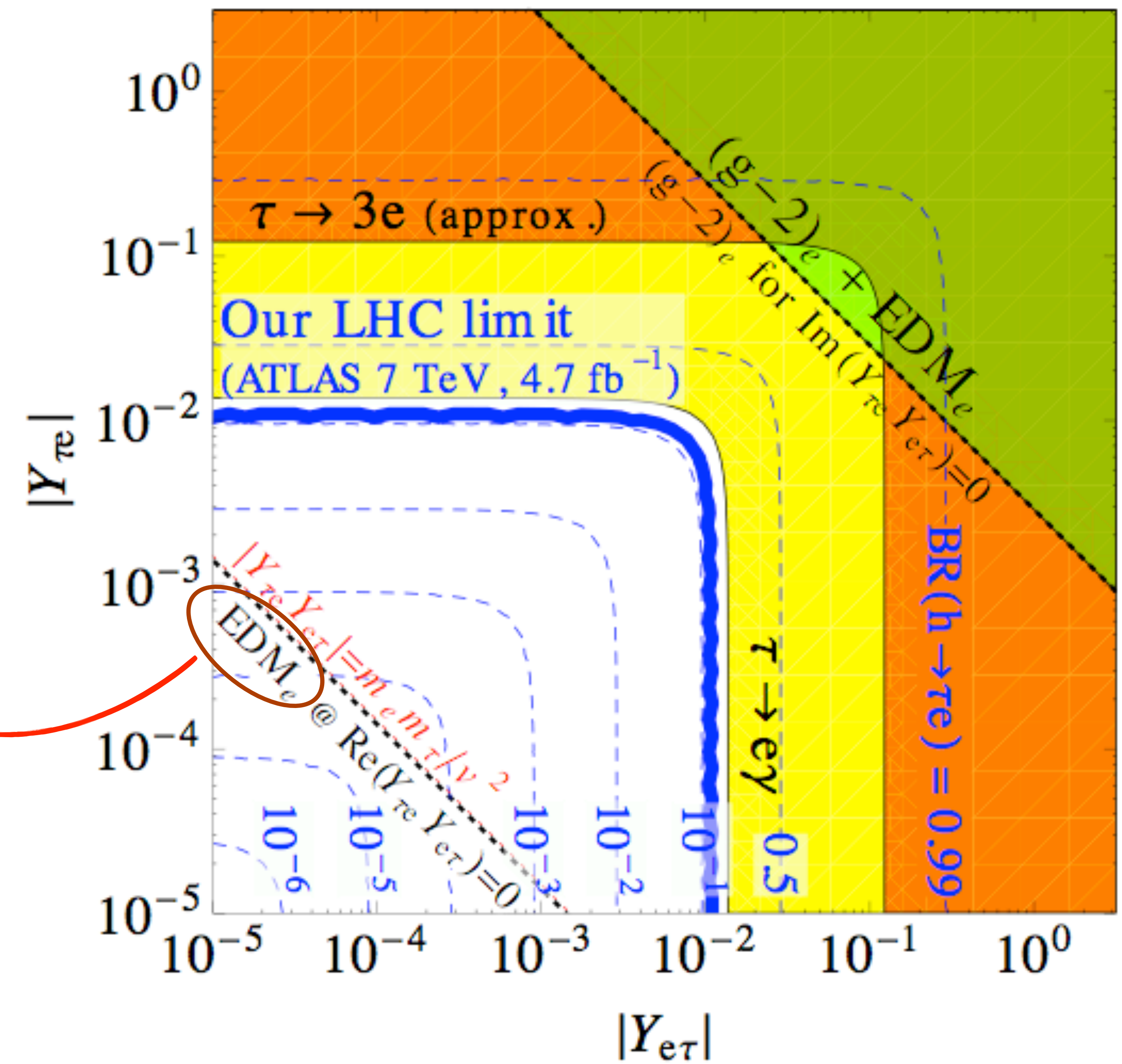


Higgs couplings to τe

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

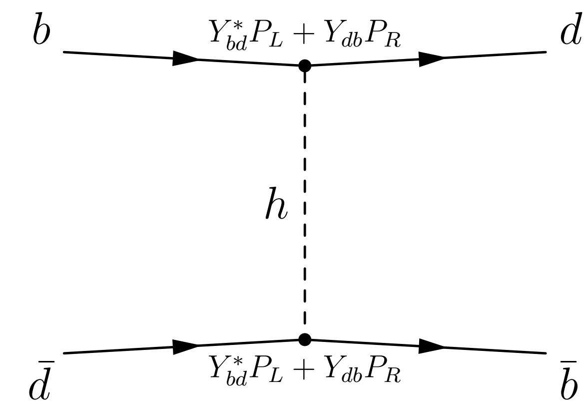
Electron EDM is interesting here!





Quark FV

Meson Mixing



* Meson mixing's powerful:

Technique	Coupling	Constraint	$m_i m_j / v^2$
D^0 oscillations [48]	$\|Y_{uc}\|^2$, $\|Y_{cu}\|^2$	$< 5.0 \times 10^{-9}$	5×10^{-8}
	$\|Y_{uc}Y_{cu}\|$	$< 7.5 \times 10^{-10}$	
B^0_d oscillations [48]	$\|Y_{db}\|^2$, $\|Y_{bd}\|^2$	$< 2.3 \times 10^{-8}$	3×10^{-7}
	$\|Y_{db}Y_{bd}\|$	$< 3.3 \times 10^{-9}$	
B^0_s oscillations [48]	$\|Y_{sb}\|^2$, $\|Y_{bs}\|^2$	$< 1.8 \times 10^{-6}$	7×10^{-6}
	$\|Y_{sb}Y_{bs}\|$	$< 2.5 \times 10^{-7}$	
K^0 oscillations [48]	$\mathrm{Re}(Y^2_{ds})$, $\mathrm{Re}(Y^2_{sd})$	$[-5.9 \ldots 5.6] \times 10^{-10}$	8×10^{-9}
	$\mathrm{Im}(Y^2_{ds})$, $\mathrm{Im}(Y^2_{sd})$	$[-2.9 \ldots 1.6] \times 10^{-12}$	
	$\mathrm{Re}(Y^*_{ds}Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$	
	$\mathrm{Im}(Y^*_{ds}Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$	

"Natural" models already constrained.

LHC cannot compete.

FV Couplings with top

* An opportunity for LHC (if CP is conserved):

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)

anything more recent?

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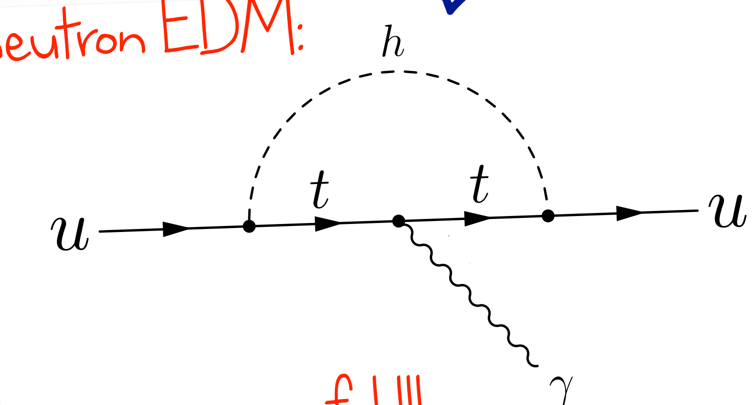

powerful !!!

FV Couplings with top

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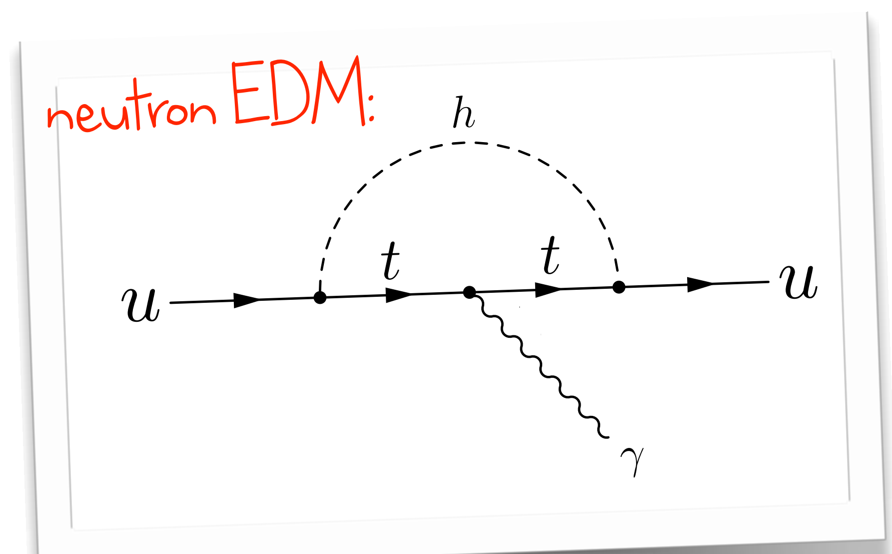
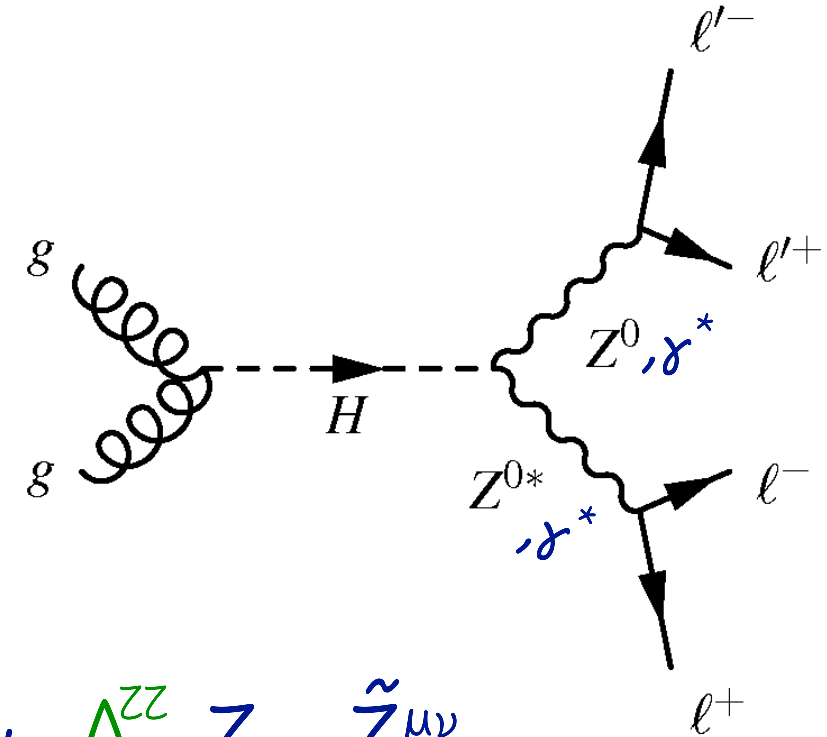
The neutron EDM is powerful!

(Probing "natural" models).



What about CP violation? Any opportunities?

Strongest opportunity is in $h \to 4\ell$:



$$\mathcal{L}_{Z,\gamma} = \frac{h}{4v} \Big(2m_Z^2 A_1^{ZZ} Z_\mu Z^\mu + A_2^{ZZ} Z_{\mu\nu} Z^{\mu\nu} + A_3^{ZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + A_2^{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} + A_3^{\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} + 2A_2^{Z\gamma} Z_{\mu\nu} F^{\mu\nu} + 2A_3^{Z\gamma} Z_{\mu\nu} \tilde{F}^{\mu\nu} \Big)$$

But current analysis is sub-optimal!

Signal and Background

* Our mindset in 2012:

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

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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~~Signal~~ Background

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~~Too small..~~ Signal!

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Relaxed cuts

* The cuts in $h \to 4\ell$ analyses were set with 2012 mindset. We can do better!

* We found that **relaxing cuts** on m_1 and m_2 improves sensitivity to higher dim operators and to CPV.
(currently $m_1>40$, $m_2>12$ GeV. We lowered both down to the j/ψ)

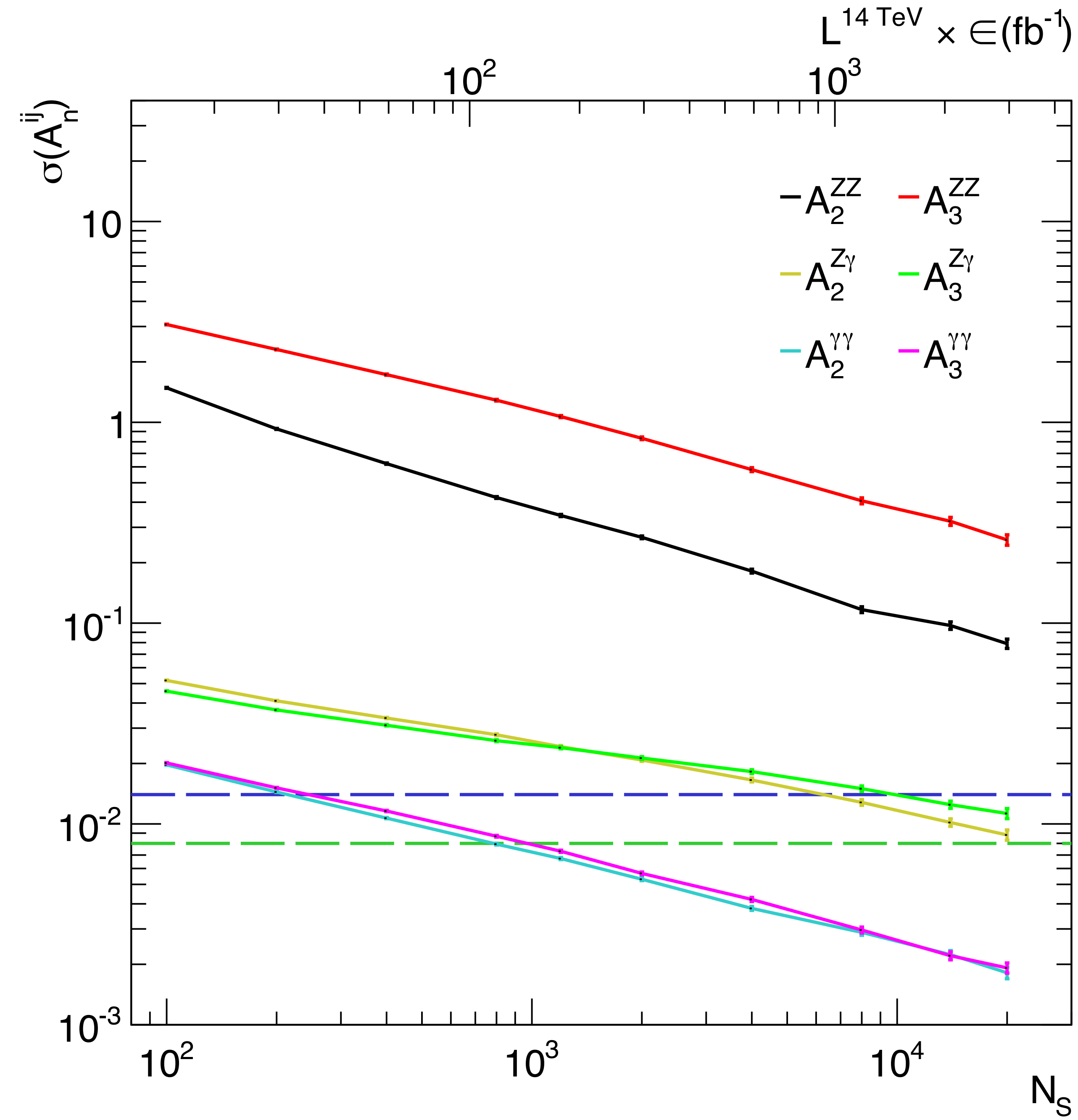
* Expect similar behavior for $h \to$ dark photons...

Reach

* $h\to 4\ell$ estimated reach:

Can reach SM values of $h\gamma\gamma$ during run 2.

Can almost reach SM values of $hZ\gamma$ with HL-LHC.



What about CP violation with Fermions?

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

For most fermions Δ
is constrained by EDMs.

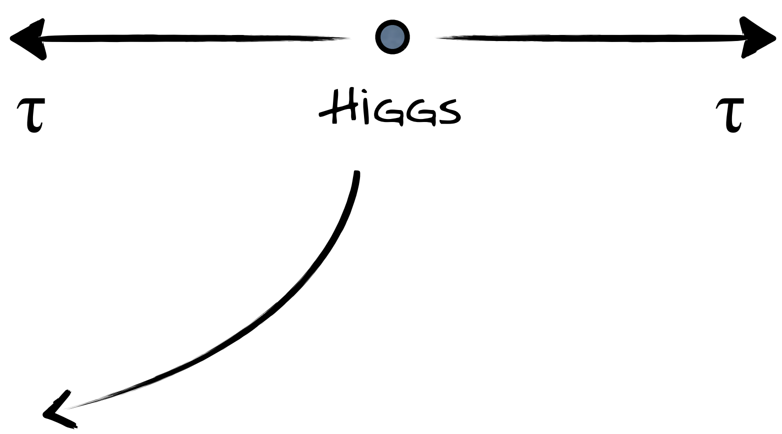
But, for τ's the phase Δ is un-constrained!

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

RH, Martin, Okui, Primulando, Yu 1308.1094

τ Polarizers

* $h \to \tau\tau$:



ττ final state(helicity basis):

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

RH, Martin, Okui, Primulando, Yu 1308.1094

τ Polarizers

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

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Linear polarizers:

$$|\phi\rangle = e^{+i\phi}|+\rangle + e^{-i\phi}|-\rangle$$

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Linear polarizers:

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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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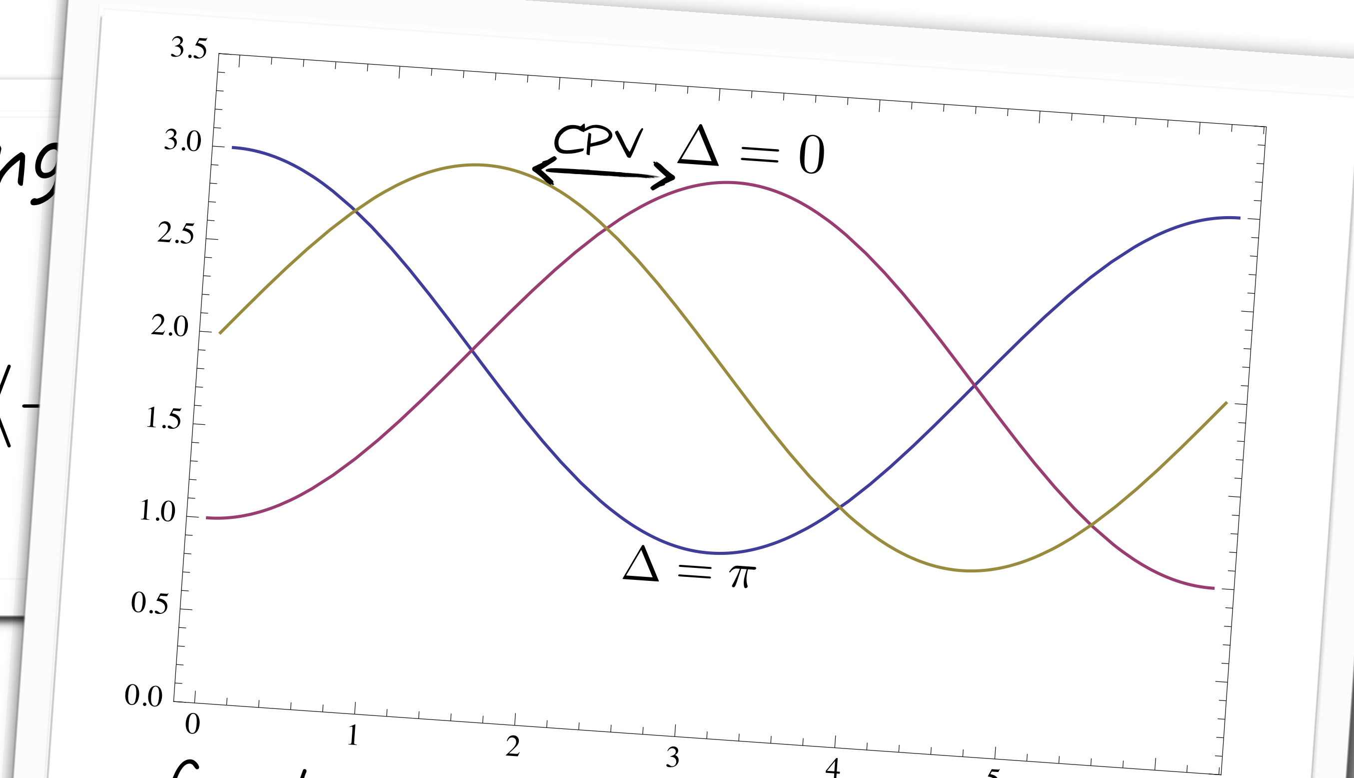
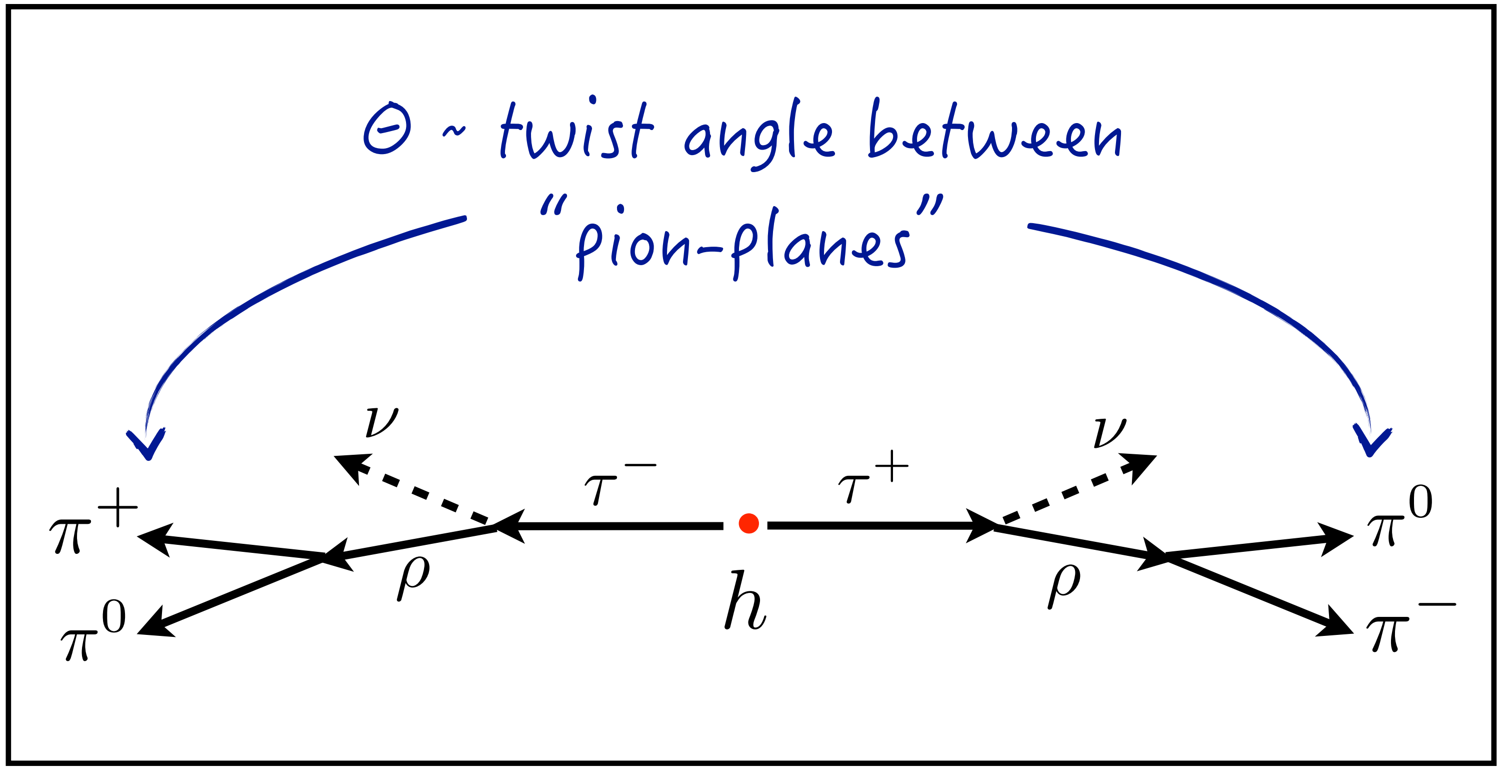


Counts vs relative polarization angle, ϕ

RH, Martin, Okui, Primulando, Yu 1308.1094

τ Polarizers

* "τ substructure":



Limited by MET resolution. see 1501.03156
(by FSU group - Askew, Jaiswal, Okui, Prosper, Sato)

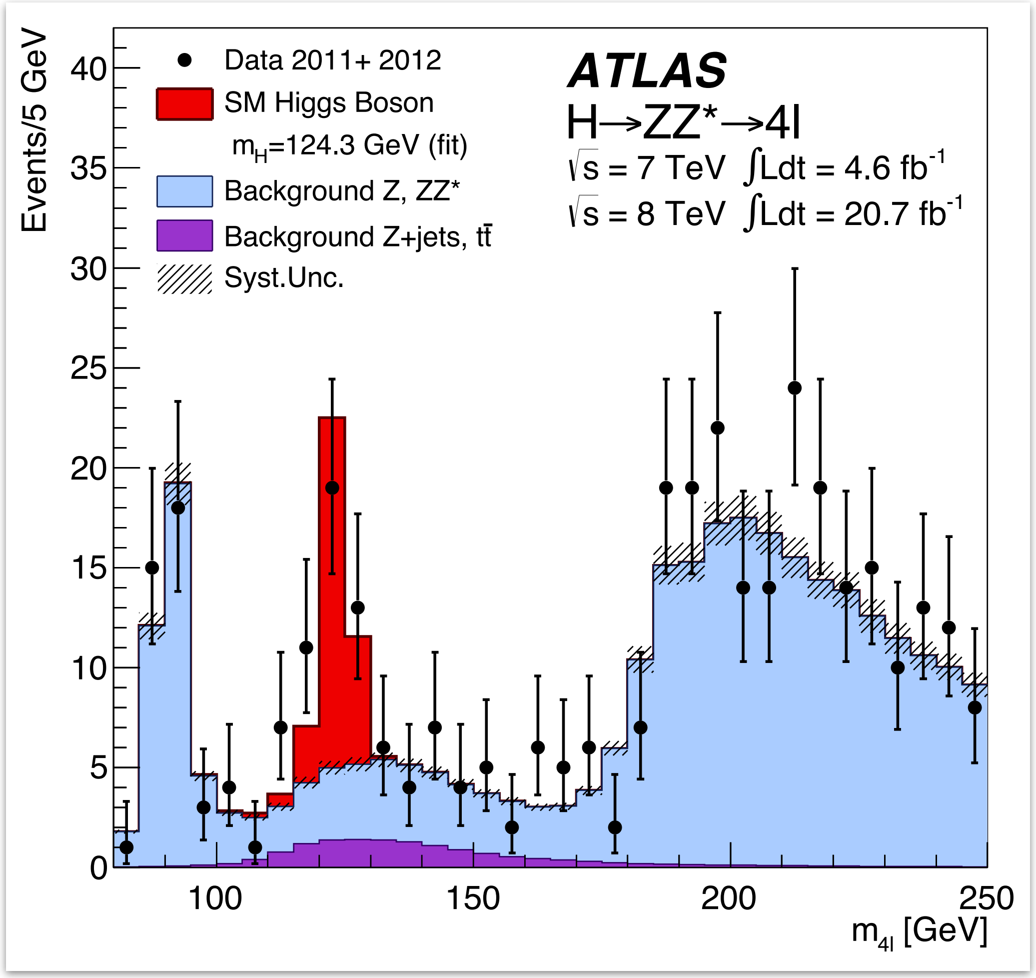
Conclusions

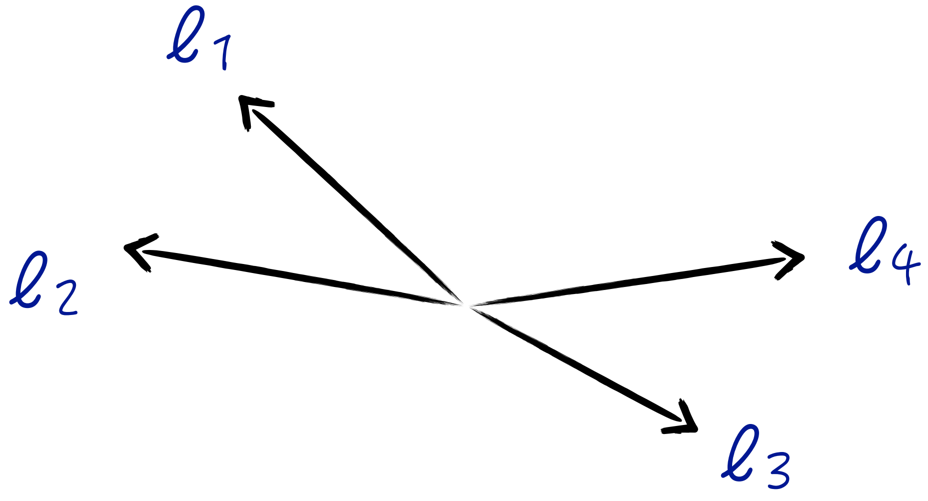
* We are motivated flavor and CP structure of Higgs couplings.
* Opportunities:
  - $h \to \tau\mu, \tau e$.
  - $t \to hc, hu$.
  - CPV in $h \to 4\ell$
  - CPV in $h \to \tau\tau$

Deleted Scenes

$h \to 4\ell$

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

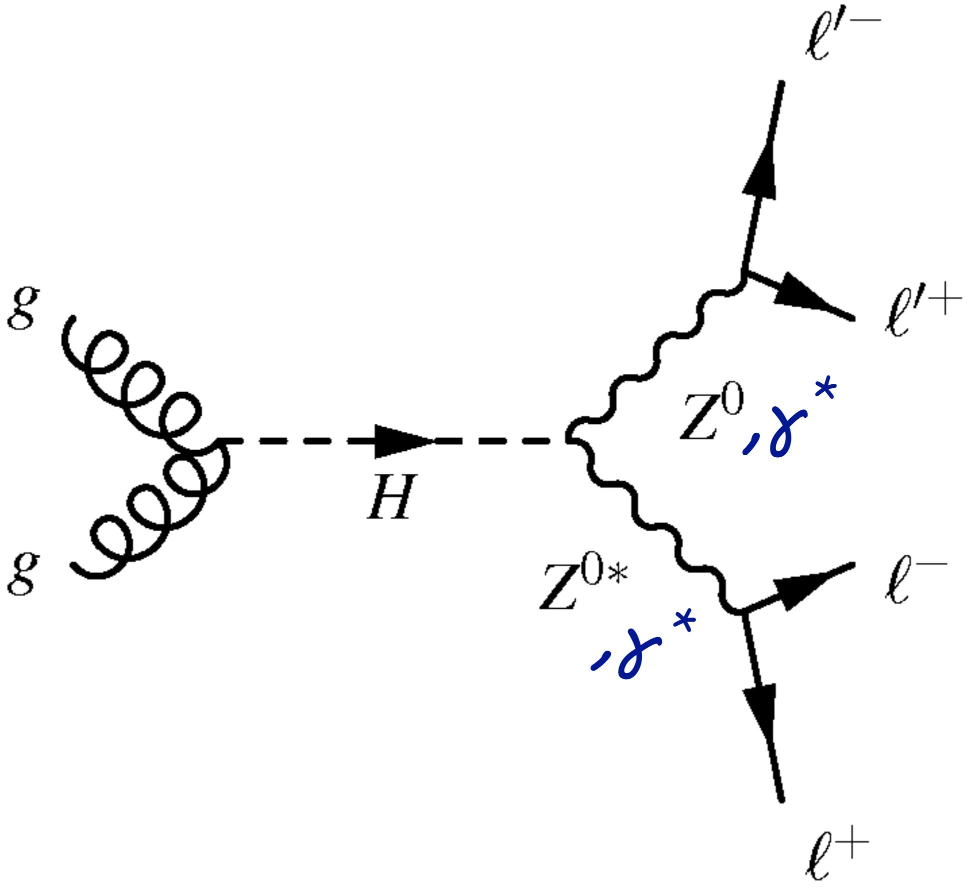




- Very clean.
- Many things to measure.
- What else can it do for us?
- CP violation?

$h \to 4\ell$

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



hVV: Measurements

* We have some measurements of A's:

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

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

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hVV: Measurements

* We have some measurements of A's:

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

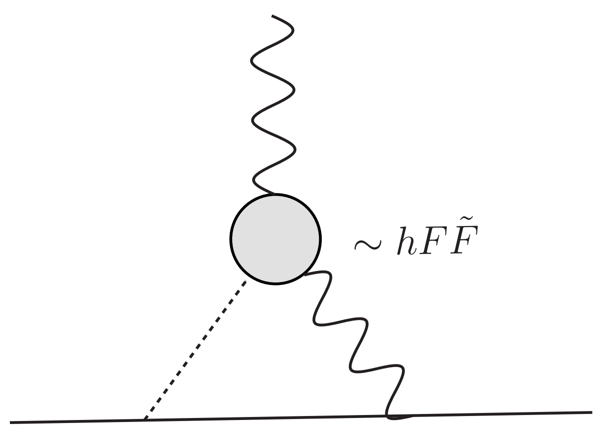
$$+ A_2^{ZZ} Z_{\mu\nu} Z^{\mu\nu} + A_3^{ZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

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

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

hVV: Measurements

* We have some measurements of A's:



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):

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

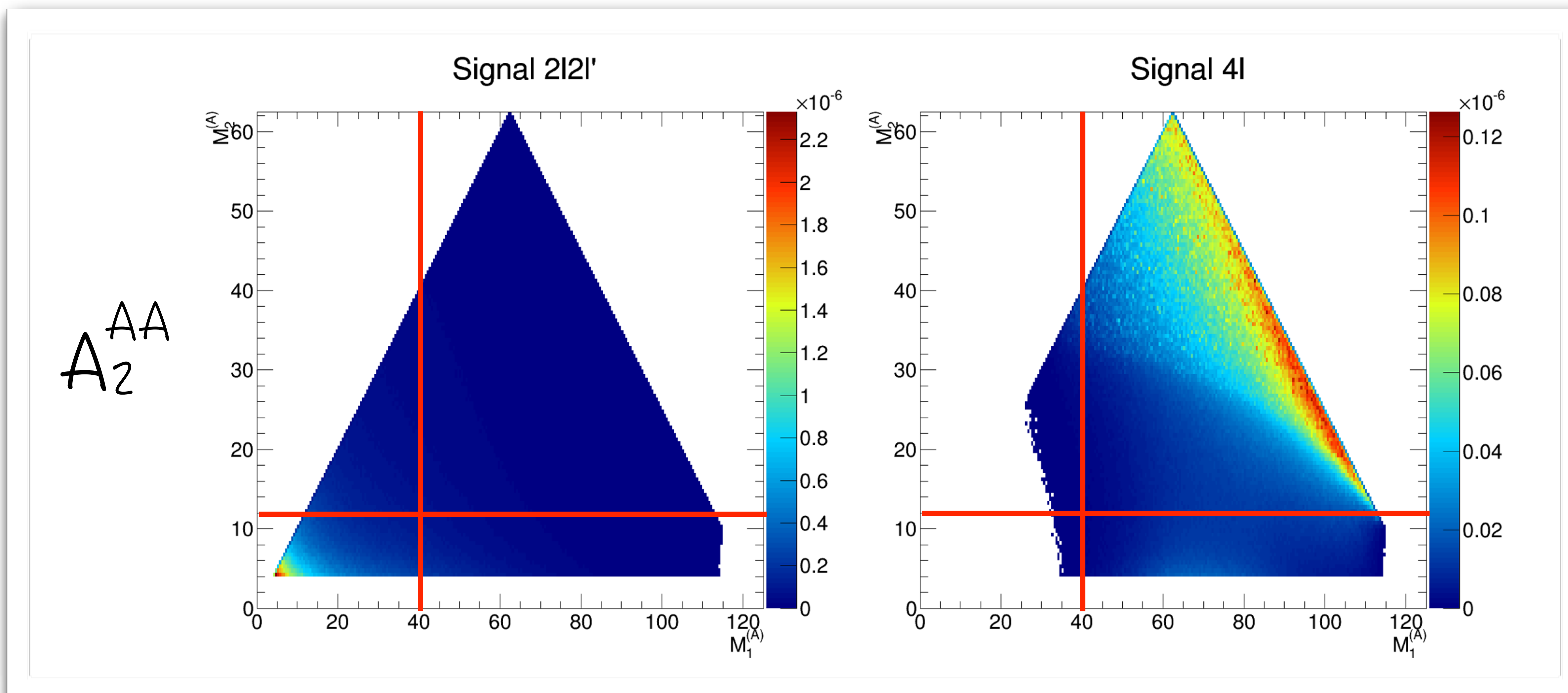
hVV: Measurements

* 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?

Optimization

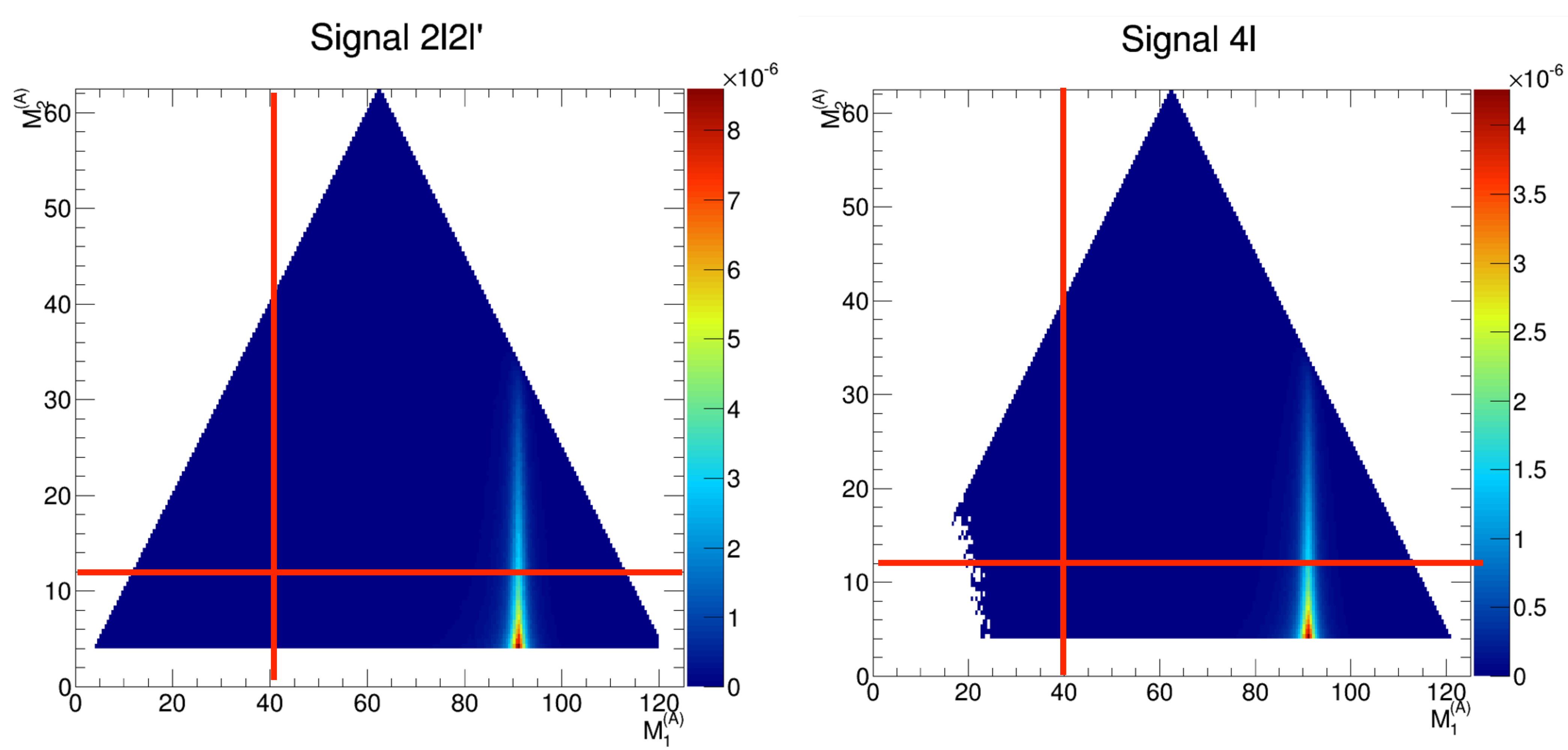
* The cuts on m_1 and m_2 had ZZ^* in mind.
* We can relax them!
  (or pick "wrong pairings" on purpose..)



Optimization

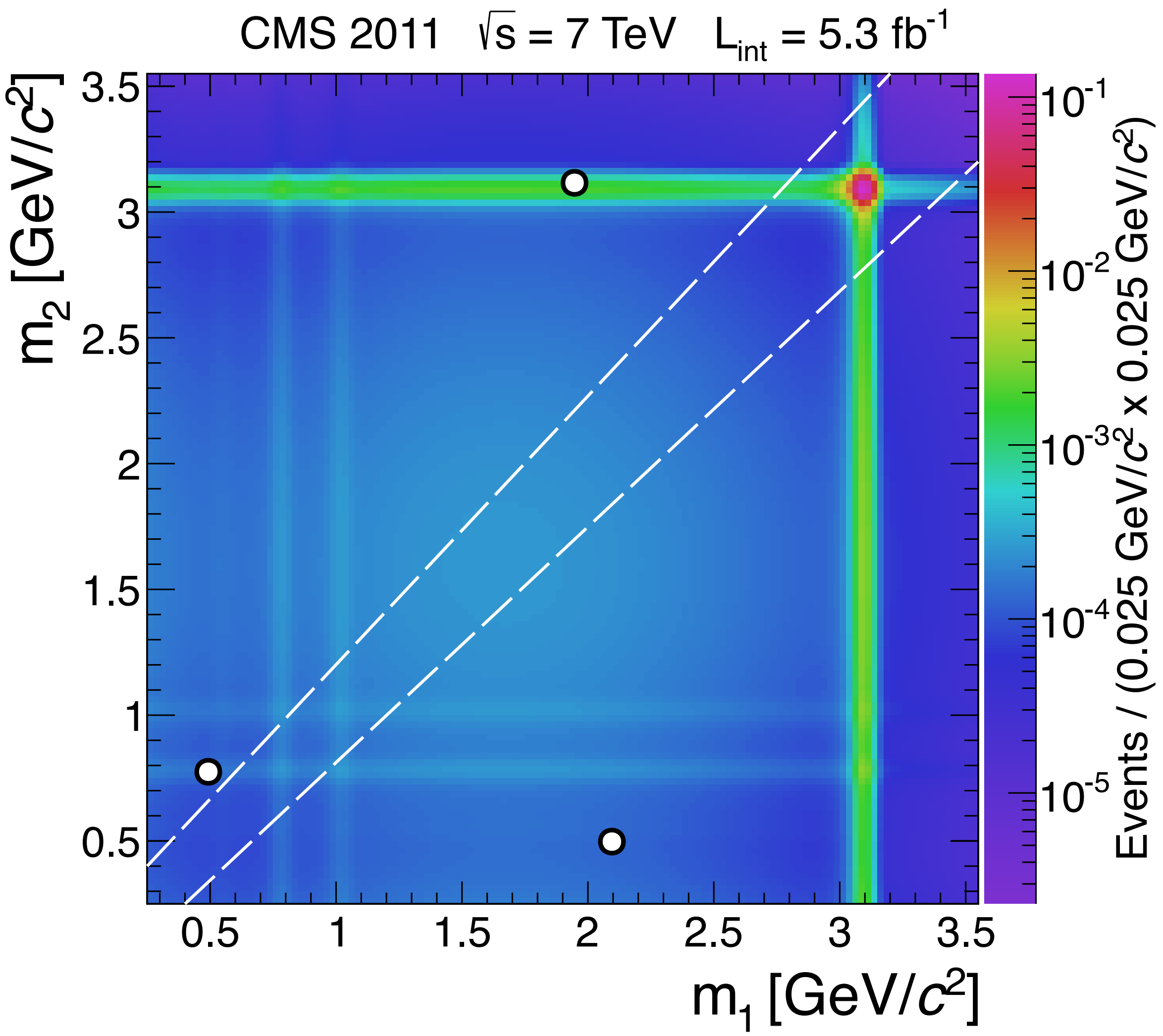
* The cuts on m_1 and m_2 had ZZ^* in mind.
* We can relax them!
  (or pick "wrong pairings" on purpose..)

A_2^{ZA}

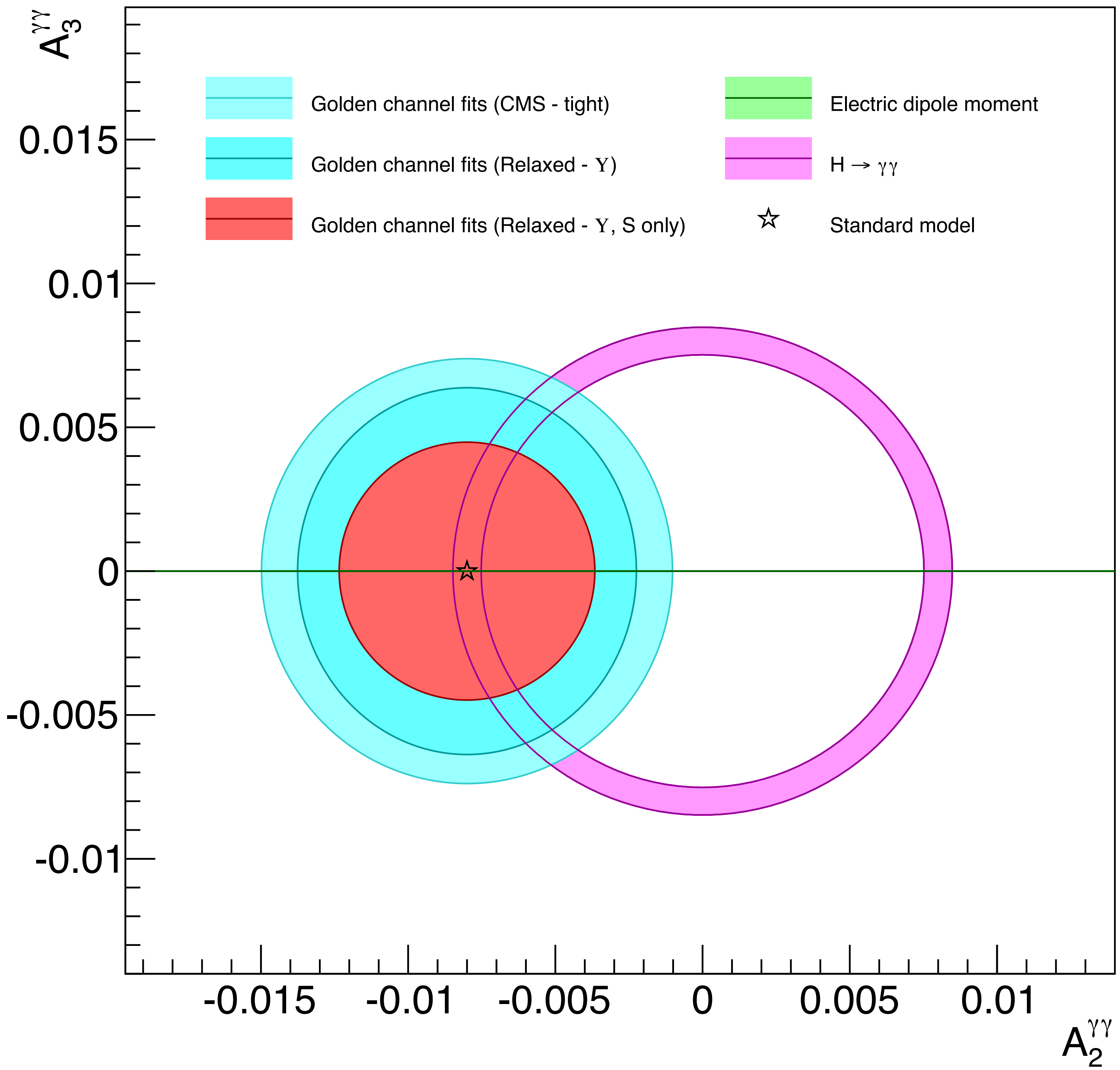


Optimization

* Going low in m1 and m2 is doable.

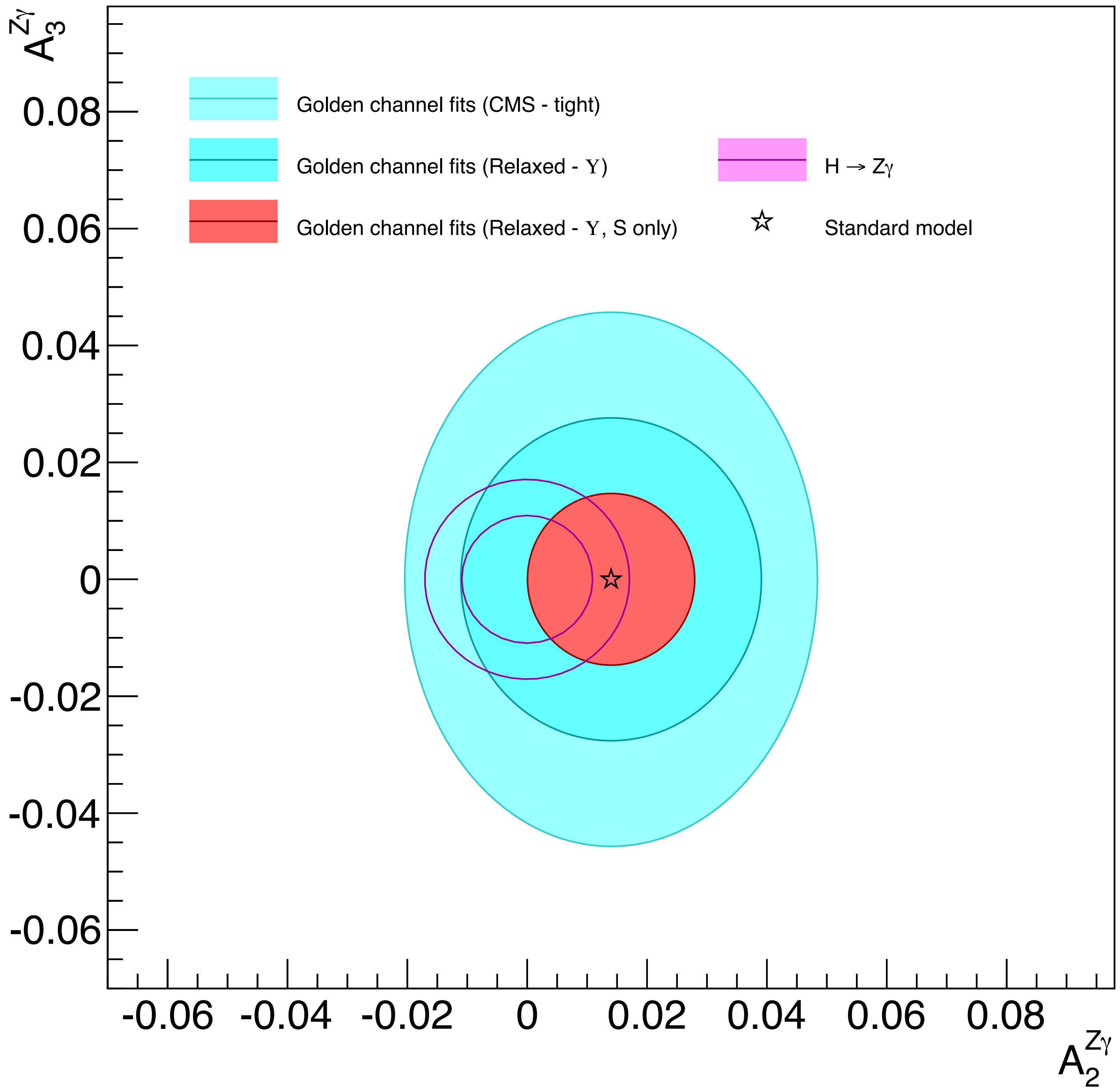


Reach



Golden channel fits (CMS - tight)
Golden channel fits (Relaxed - Υ)
Golden channel fits (Relaxed - Υ, S only)
Electric dipole moment
H → γγ
Standard model
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.01
-0.005
0
0.005
0.01
$A_3^{\gamma\gamma}$
$A_2^{\gamma\gamma}$

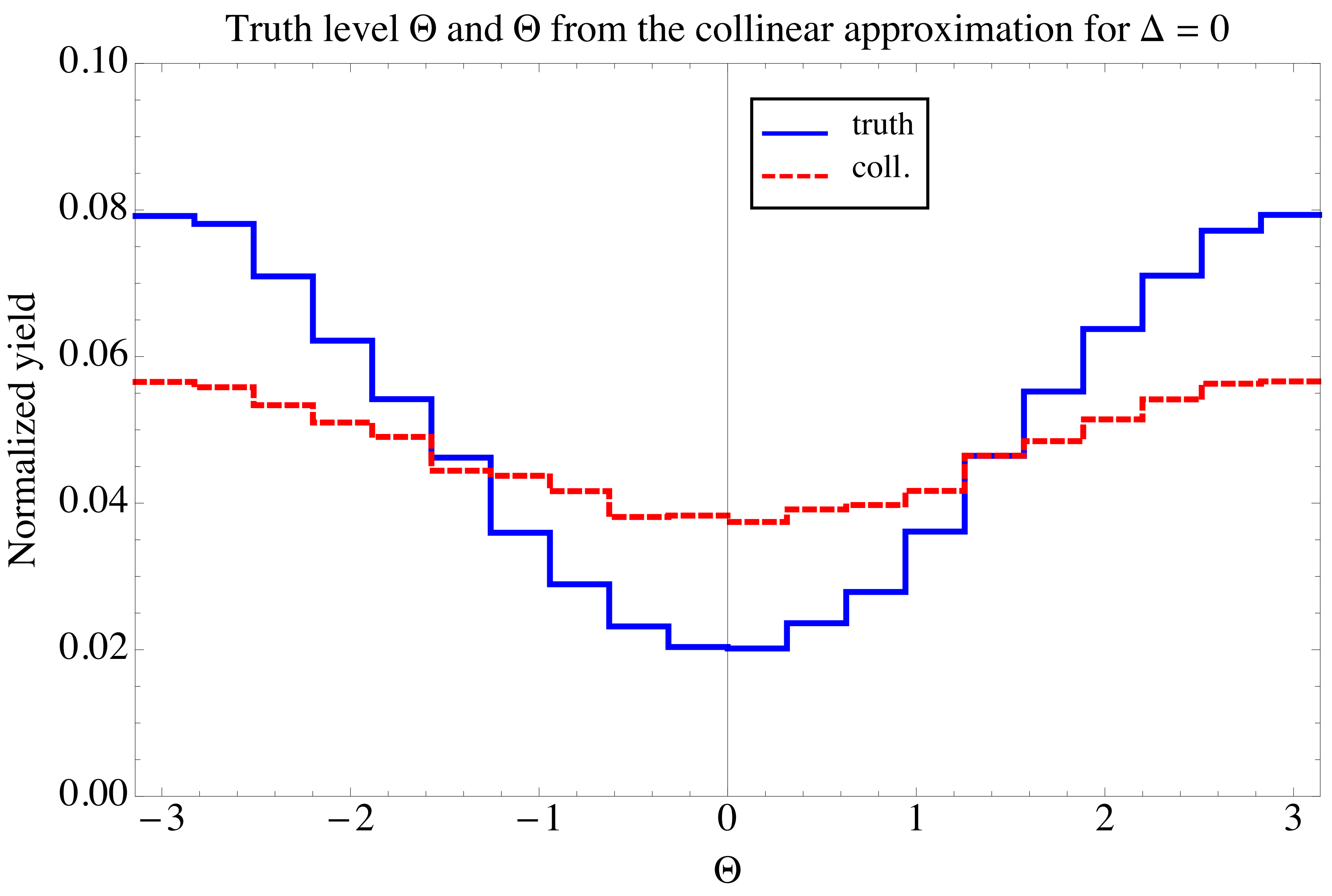
Reach



$A_3^{Z\gamma}$
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
Golden channel fits (CMS - tight)
Golden channel fits (Relaxed - Υ)
Golden channel fits (Relaxed - Υ, S only)
H → Zγ
Standard model
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
$A_2^{Z\gamma}$

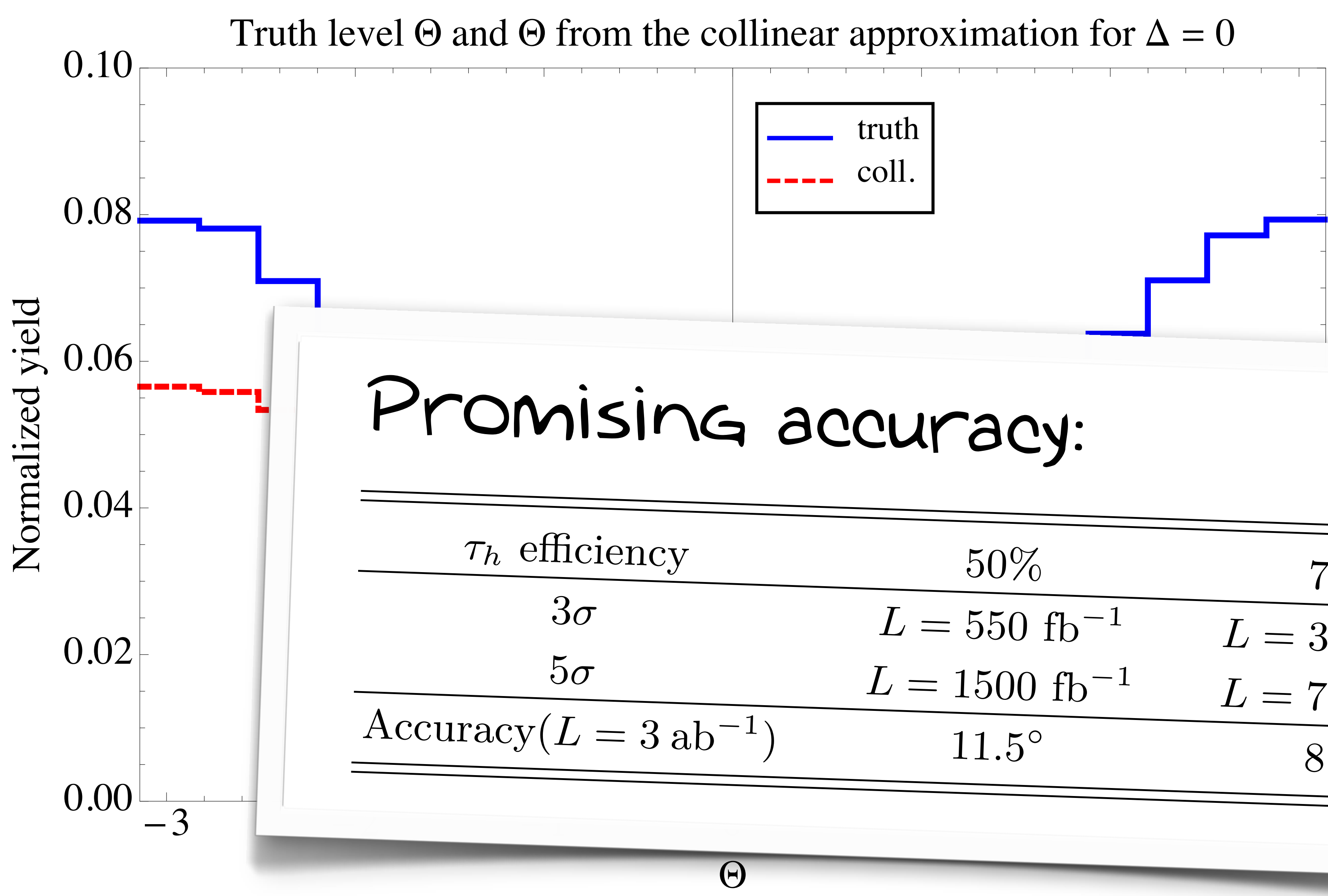
LHC

* Using collinear approximation, we form an LHC observable:



LHC

* Using collinear approximation, we form an LHC observable:

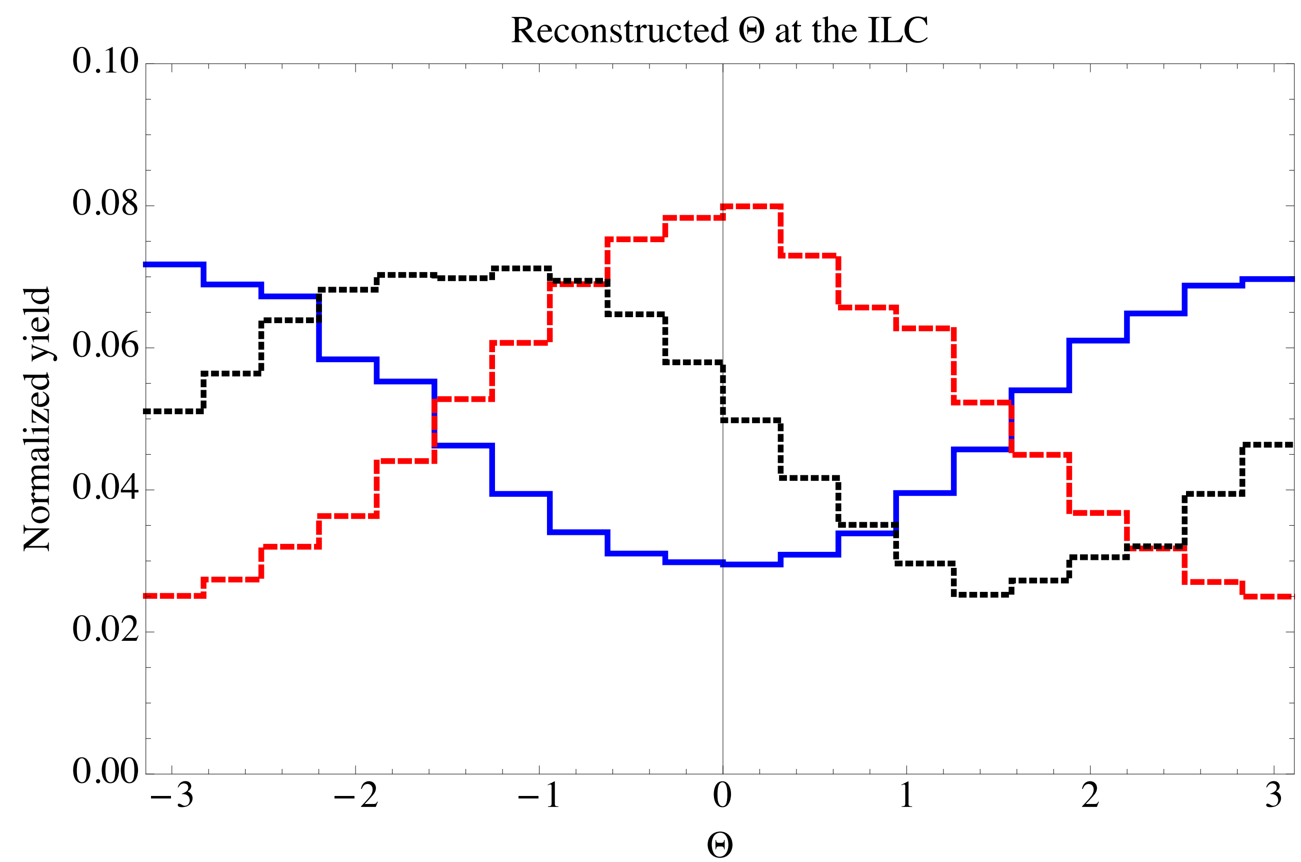


Promising accuracy:

τ_h efficiency	50%	70%
3σ	$L = 550\ \text{fb}^{-1}$	$L = 300\ \text{fb}^{-1}$
5σ	$L = 1500\ \text{fb}^{-1}$	$L = 700\ \text{fb}^{-1}$
Accuracy($L = 3\ \text{ab}^{-1}$)	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%
$\mathrm{N}_{\text{events}}$	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.