TH perspective on CPV in (fermionic) Higgs couplings

Adam Martin (amarti41@nd.edu)
University of Notre Dame

somewhat based on: Harnik, Martin, Okui, Primulando, Yu [1308.1094]

HE/HL-LHC workshop, FNAL, April 6th, 2018

Motivations

CPV in the Higgs sector is a clear signal of BSM physics

Theoretical motivations:

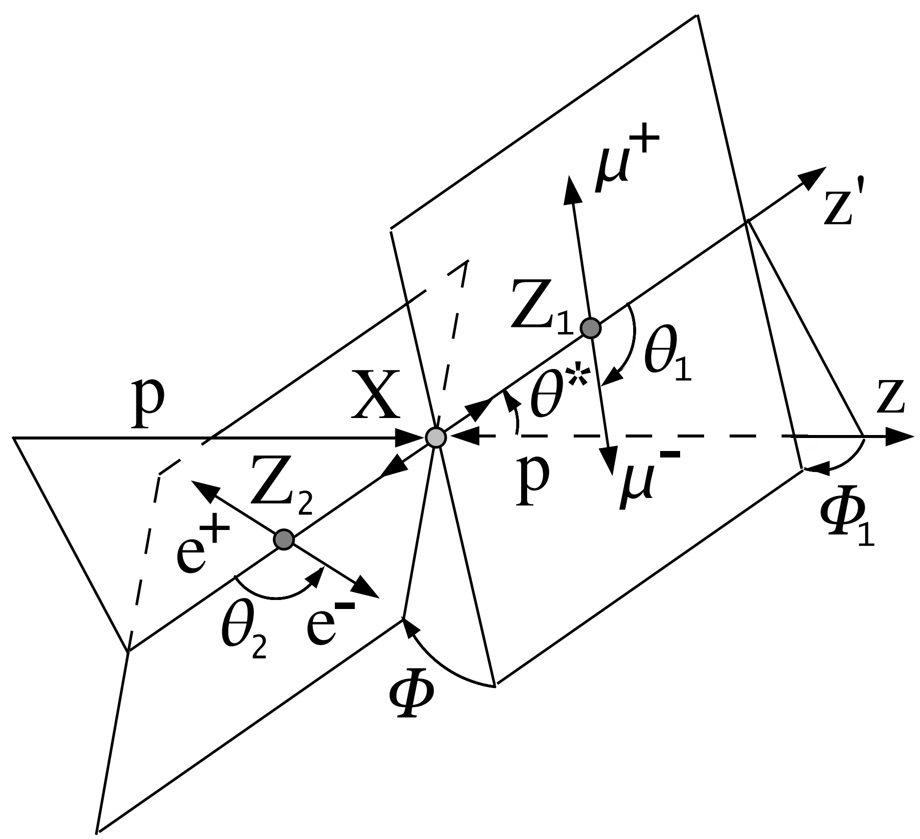
- matter/antimatter asymmetry requires CPV
- electroweak baryogengesis: SM insufficient
  $\therefore$ suggests new phases needed
- CP puzzles remain: $\theta_{QCD} < 10^{-10}$, phases of PMNS matrix
- many UV scenarios (i.e. 2HDM) involve extended Higgs sectors and the possibility of CPV Higgs

CPV in HVV couplings

$$\mathcal{L} \supset \frac{m_Z^2}{v}\, h\, Z^\mu Z_\mu + c_{ZZ}\frac{h}{\Lambda} Z^{\mu\nu} Z_{\mu\nu} + c_{Z\tilde{Z}}\frac{h}{\Lambda} Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

(+ analogous for W)

- CP nature tested extensively by h → ZZ^* to 4ℓ, acoplanarity of the Z decays



e.g. [Gao et al, 1001.3396]

- $c_{Z\tilde{Z}}$ operator dim-5, suppressed relative to m_Z^2/v term —
  hurts sensitivity to mixed CP

CPV in Hff couplings

$$\mathcal{L} \supset -m_f \bar{f} f - h\, \bar{f}(a + i\ b\,\gamma_5) f$$

$$\rightarrow f_L^\dagger f_R (a + i\, b) + f_R^\dagger f_L (a - i\, b)$$

Phase difference between $f_L^\dagger f_R$ and $f_R^\dagger f_L$

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leaves h$\bar{\tau}\tau$, h$\bar{t}$t as possibilities

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EFT approach: add dim-6 operator

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new phases, flavor indices..

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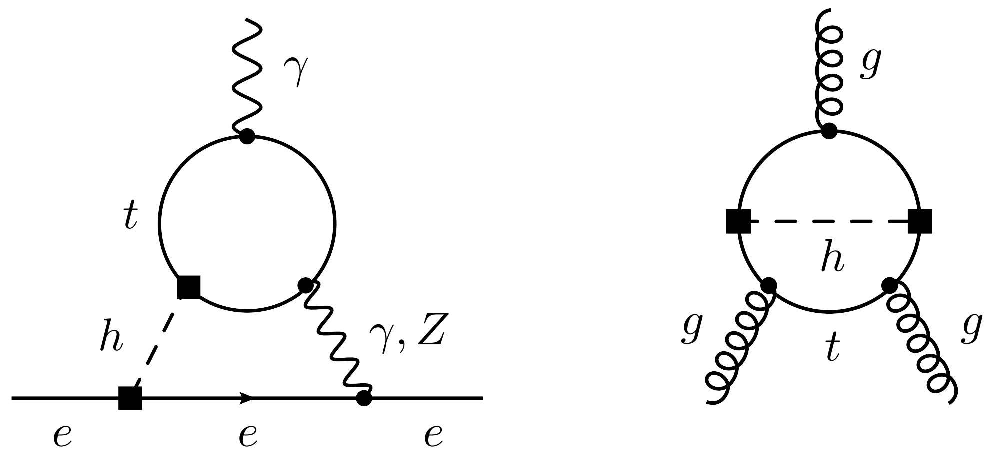
Indirect constraints of CPV Hff couplings: EDM and Higgs rates



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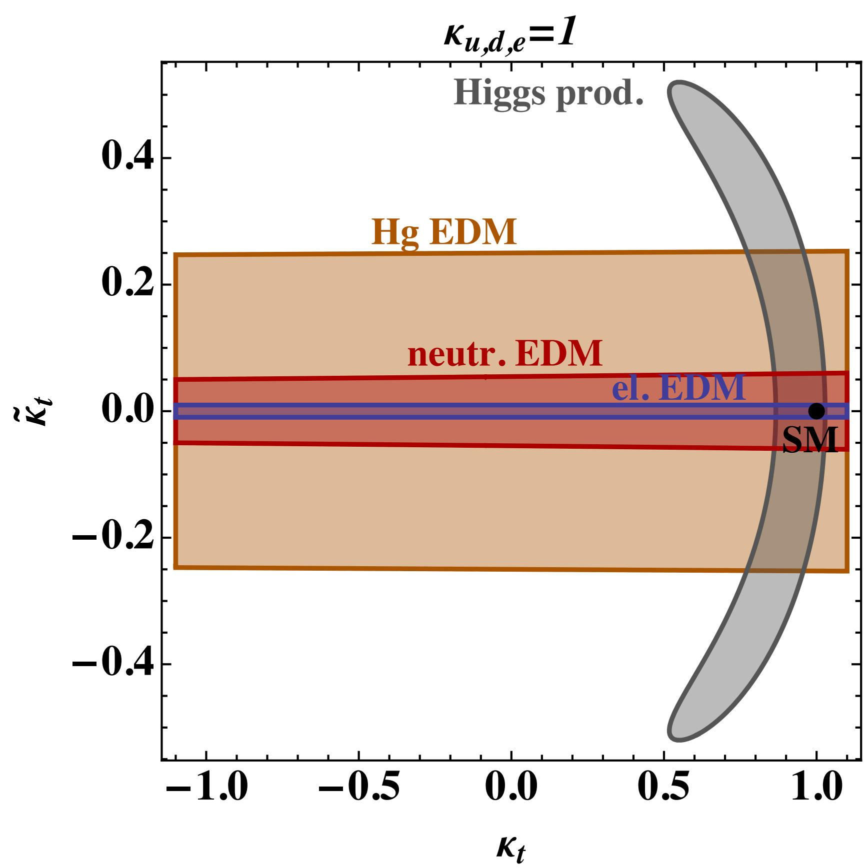

[Brod, Haisch, Zupan 1310.1385]

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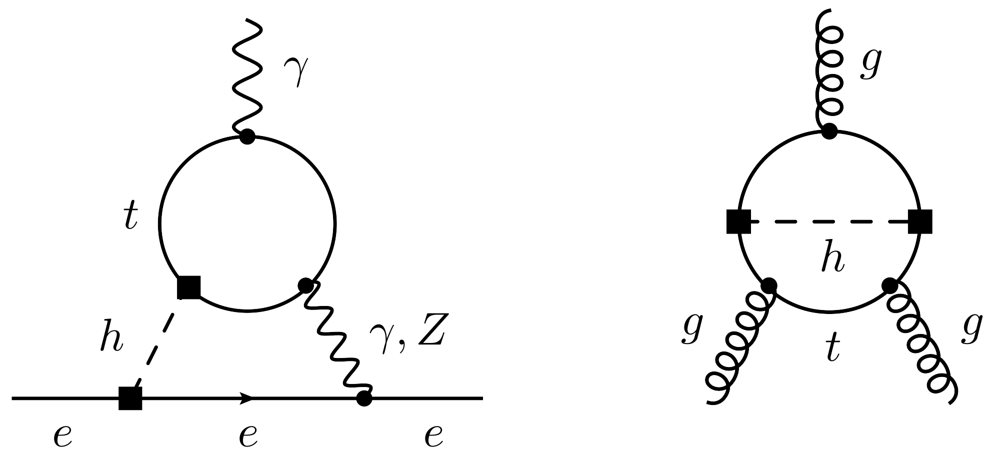

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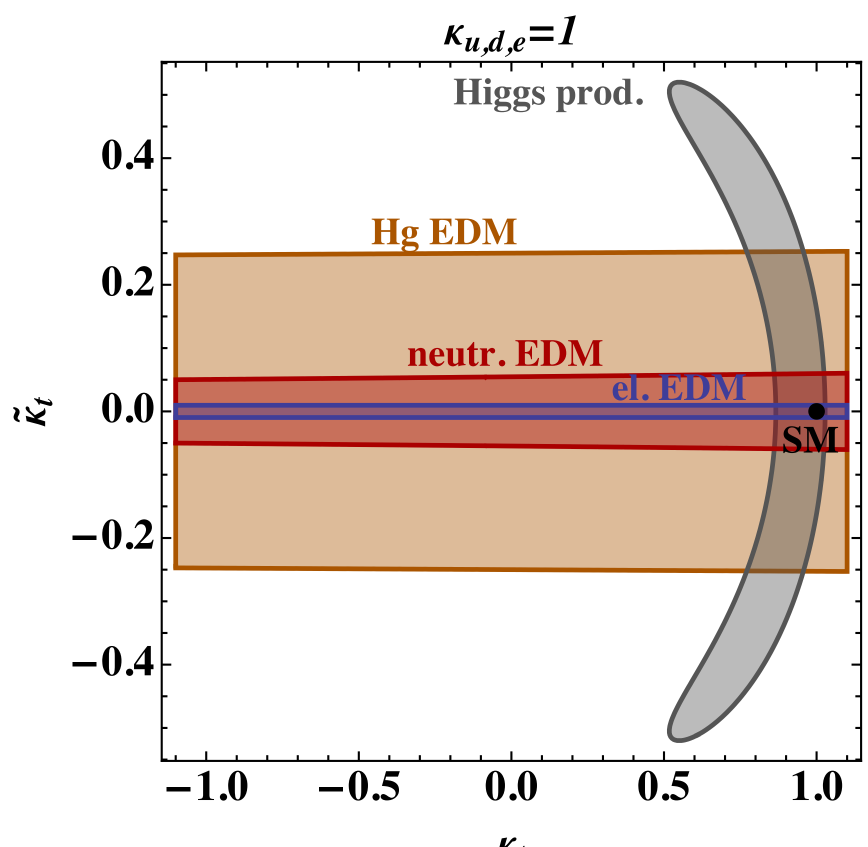

constraints can relax somewhat if light Yukawas, hWW not standard..

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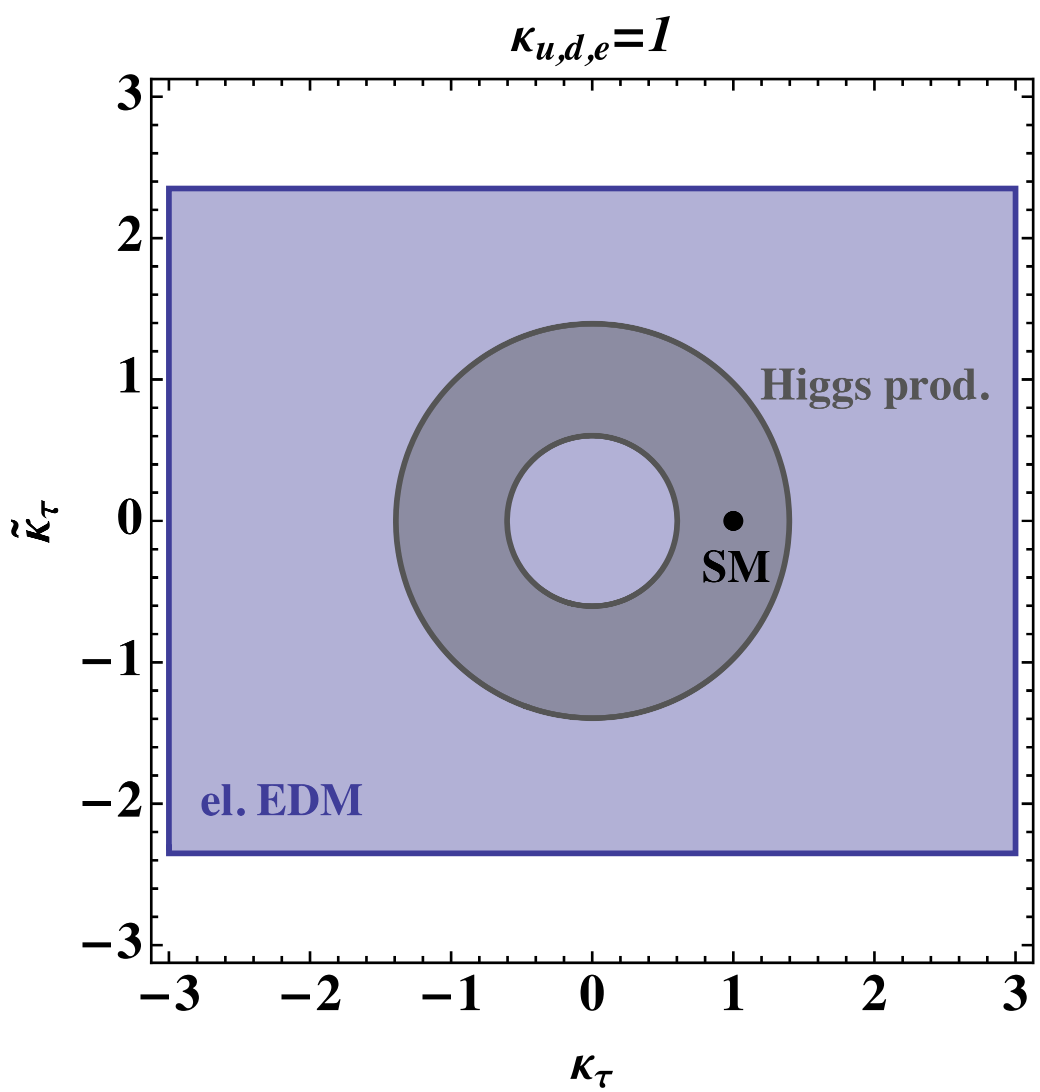

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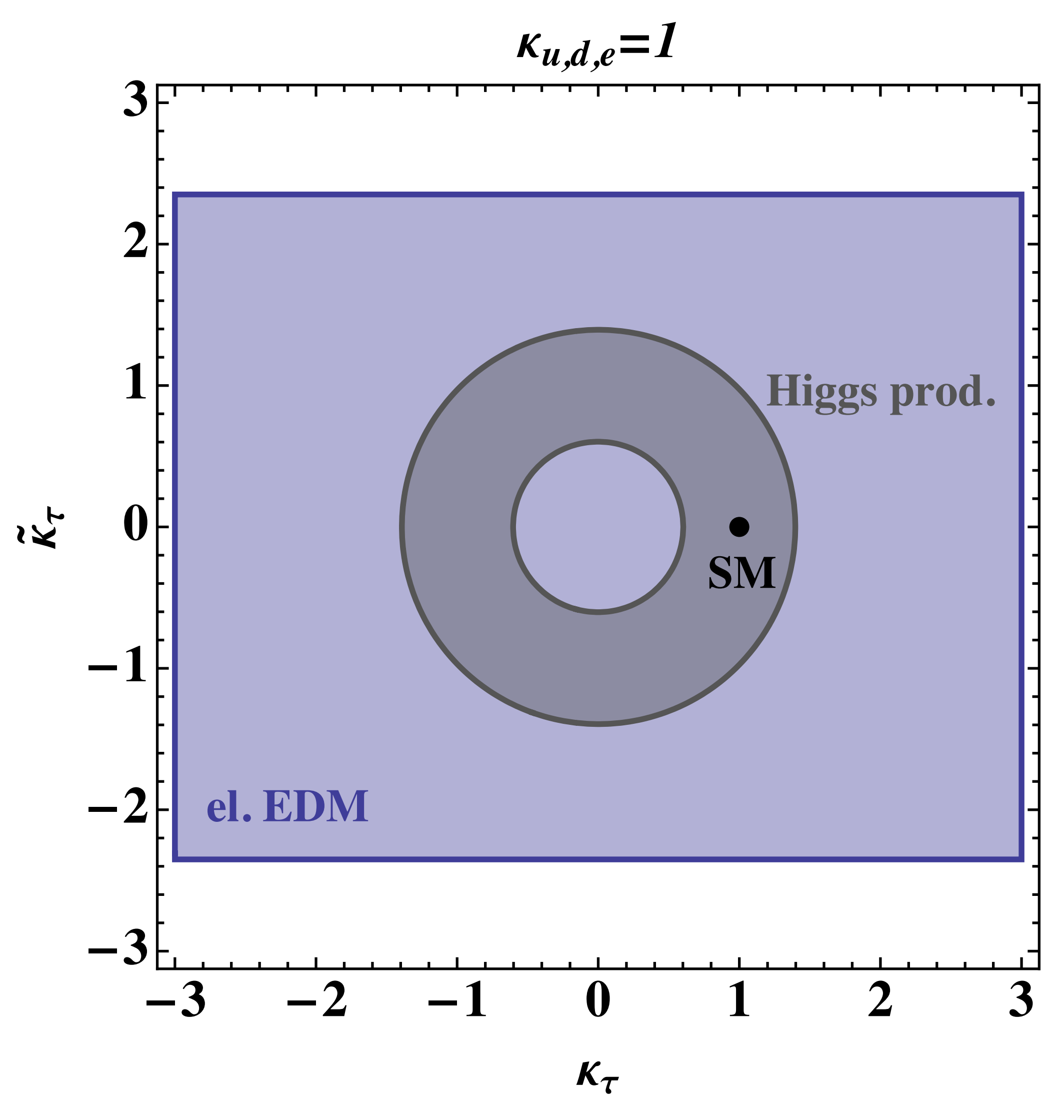

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Specifically, work with:

$a = y_{\tau,SM} \cos\Delta$

$b = y_{\tau,SM} \sin\Delta$

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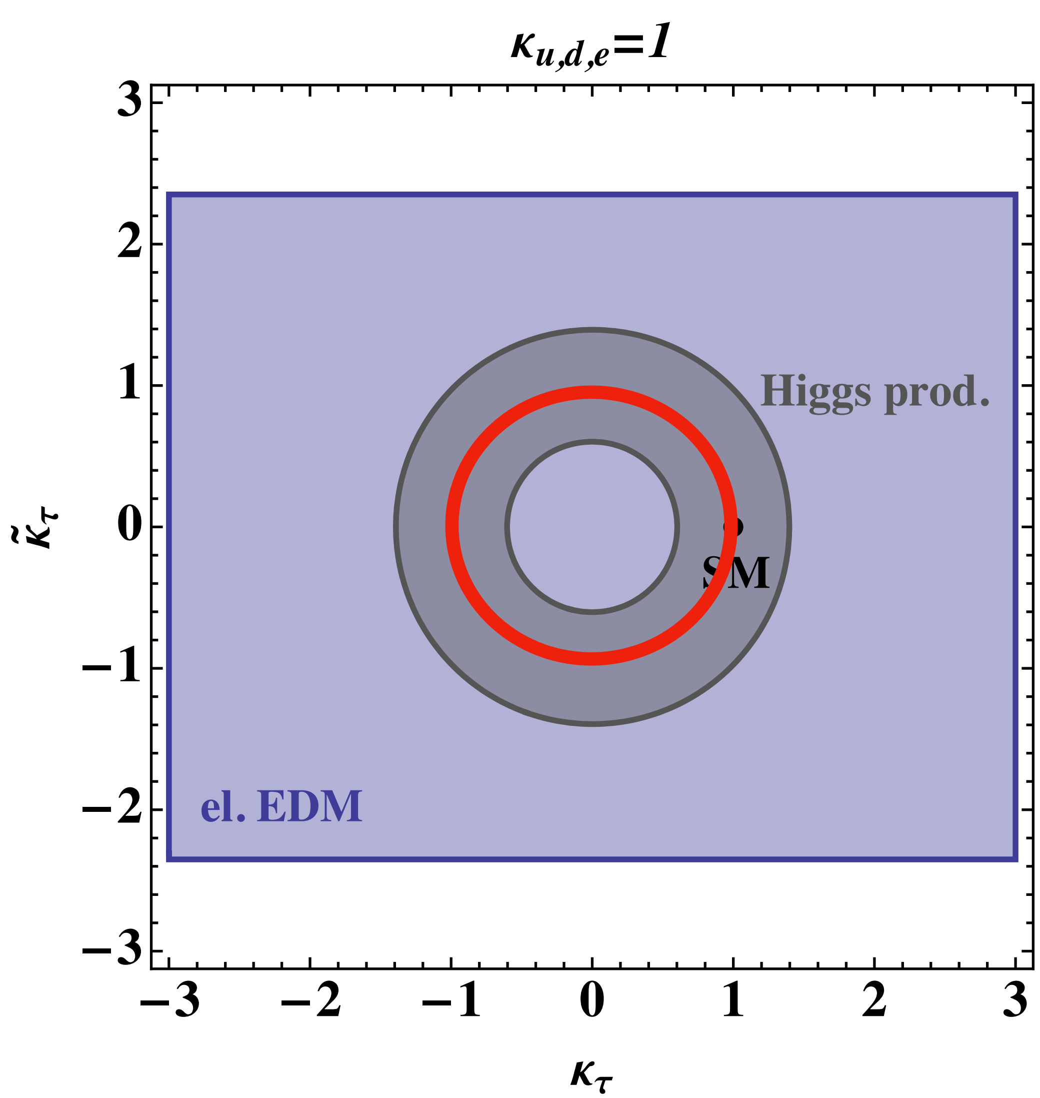

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Accessing the CPV Hff phase in taus

$$\supset -m_\tau \bar{\tau}\tau - \frac{y_\tau}{\sqrt{2}} h\, \bar{\tau}(\cos\Delta + i\, \sin\Delta\, \gamma_5)\tau$$

Higgs rest frame:
$(m_H/2)\, \vec{p} \cdot (\vec{s}_1 \times \vec{s}_2)$

$$|\mathcal{M}(h \to \tau^+(p_1, s_1)\tau^-(p_2, s_2)|^2 \propto \sin 2\Delta\, \epsilon^{\mu\nu\rho\sigma} p_{1\mu} p_{2\nu} s_{1\rho} s_{2\sigma}$$

+ pieces independent of sinΔ

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Best candidate: $\tau^\pm \to \rho^\pm \nu, \rho^\pm \to \pi^\pm \pi^0,$ BR ~ 26%

A '1 prong' decay, see photons from $\pi^0 \to \gamma\gamma$

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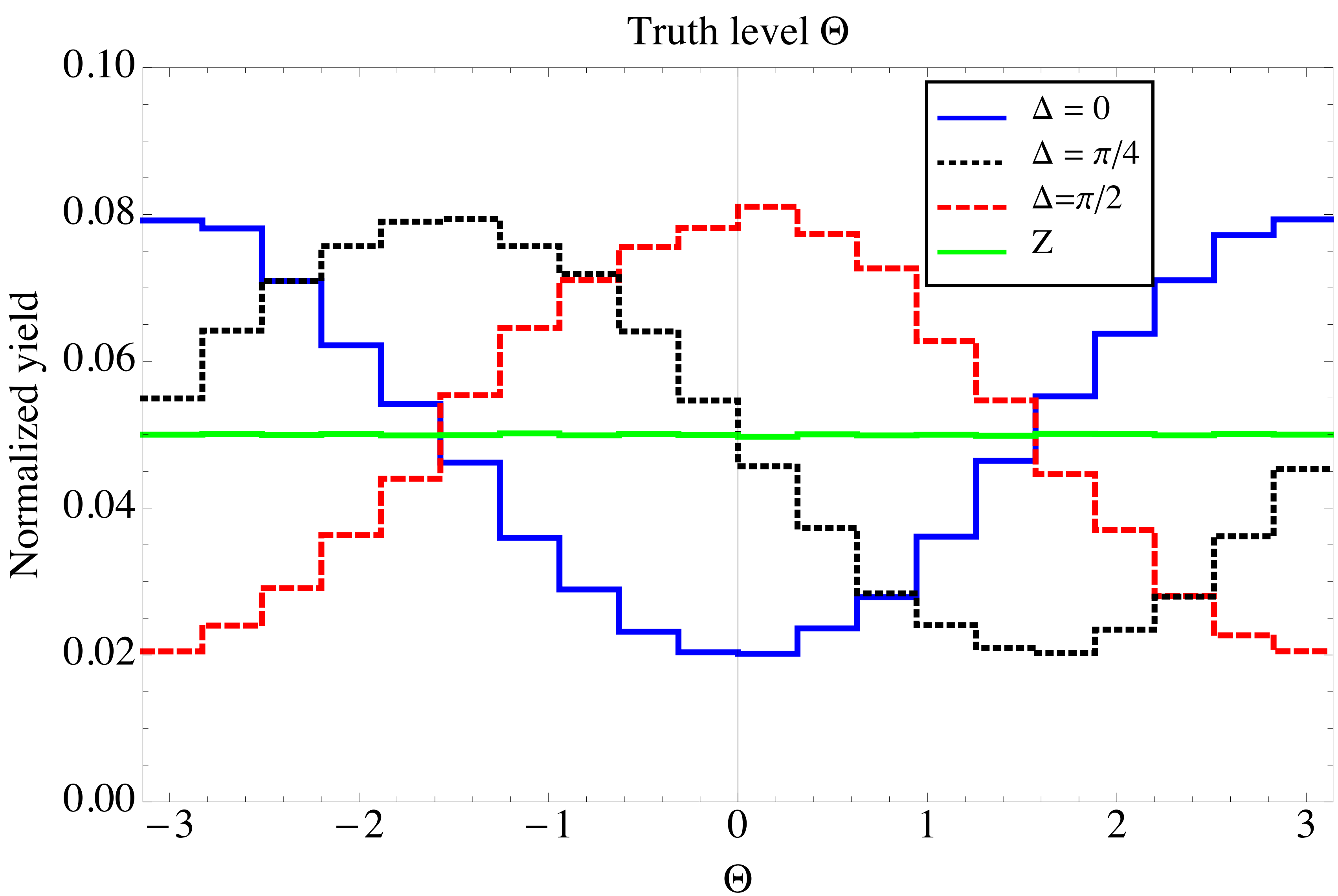
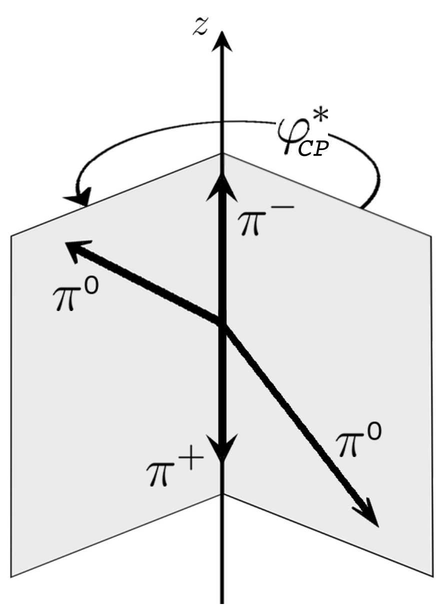
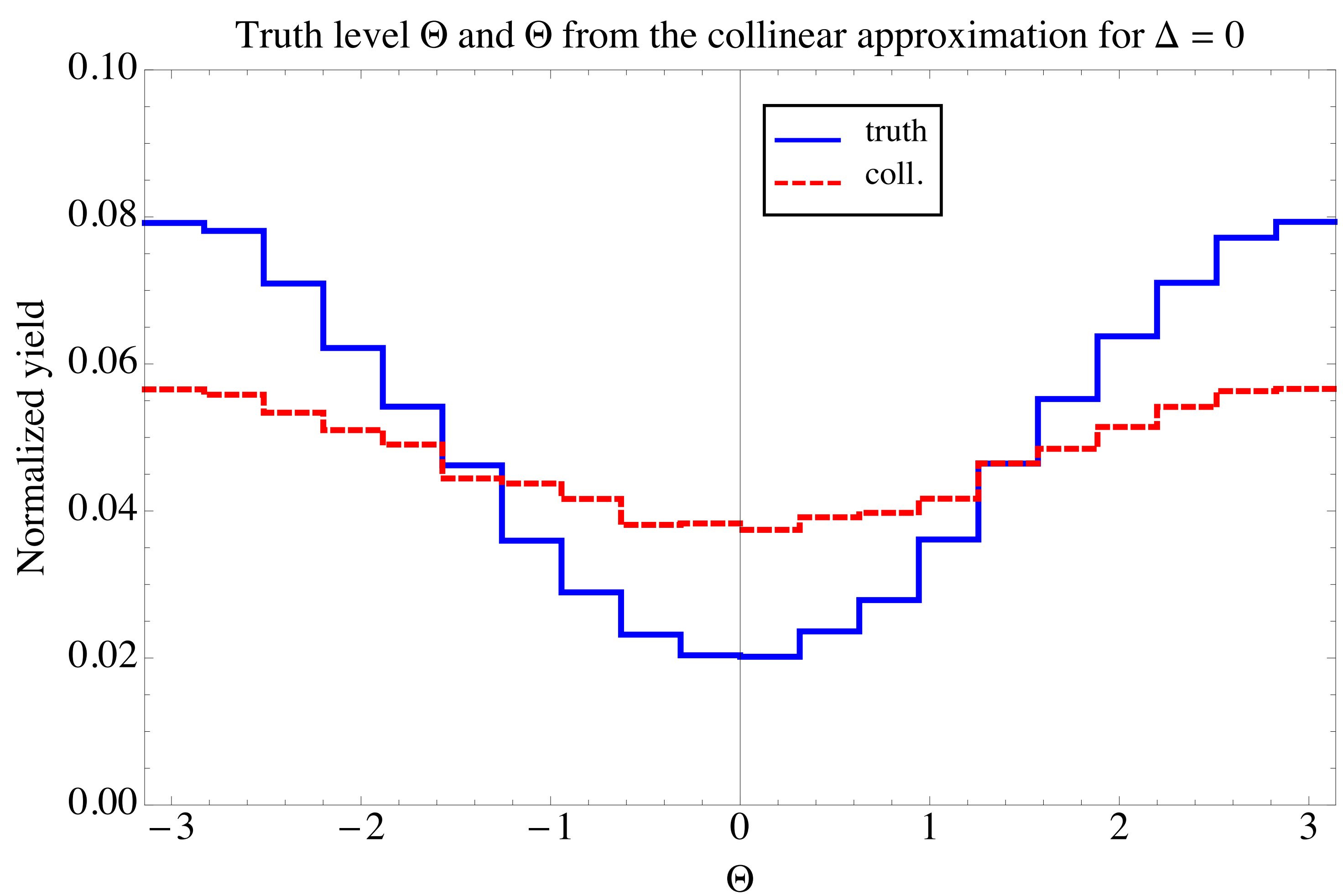


[Harnik, Martin, Okui, Primulando, Yu 1308.1094]

Accessing the CPV Hff phase in taus at the LHC

- At LHC, we can't measure p_ν...
- If we use the collinear approximation ($p_\nu \propto p_\rho$), can still form Θ but it reduces to the acoplanarity angle between $\rho^+\rho^-$ decay ex. [Bower et al 0204292, Worek 0305082]





Size of oscillation reduced by ~75%

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Proof of principle analysis: [Harnik, Martin, Okui, Primulando, Yu 1308.1094]

- signal: pp → h($\tau^+\tau^-$) + j, background Z + j
- require:

$$p_{T,j} > 140\,\mathrm{GeV}, |\eta_j| < 2.5$$

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} motivated by 8 TeV h(ττ) search in 1 jet bin

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For different tagging efficiencies, determine:

- $\mathscr{L}$ required to distinguish pure CP-even vs. CP-odd

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

- admixture sensitivity at 3 ab^{-1}

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[Askew, Jaiswal, Okui, Prosper, Sato 1501.03156]

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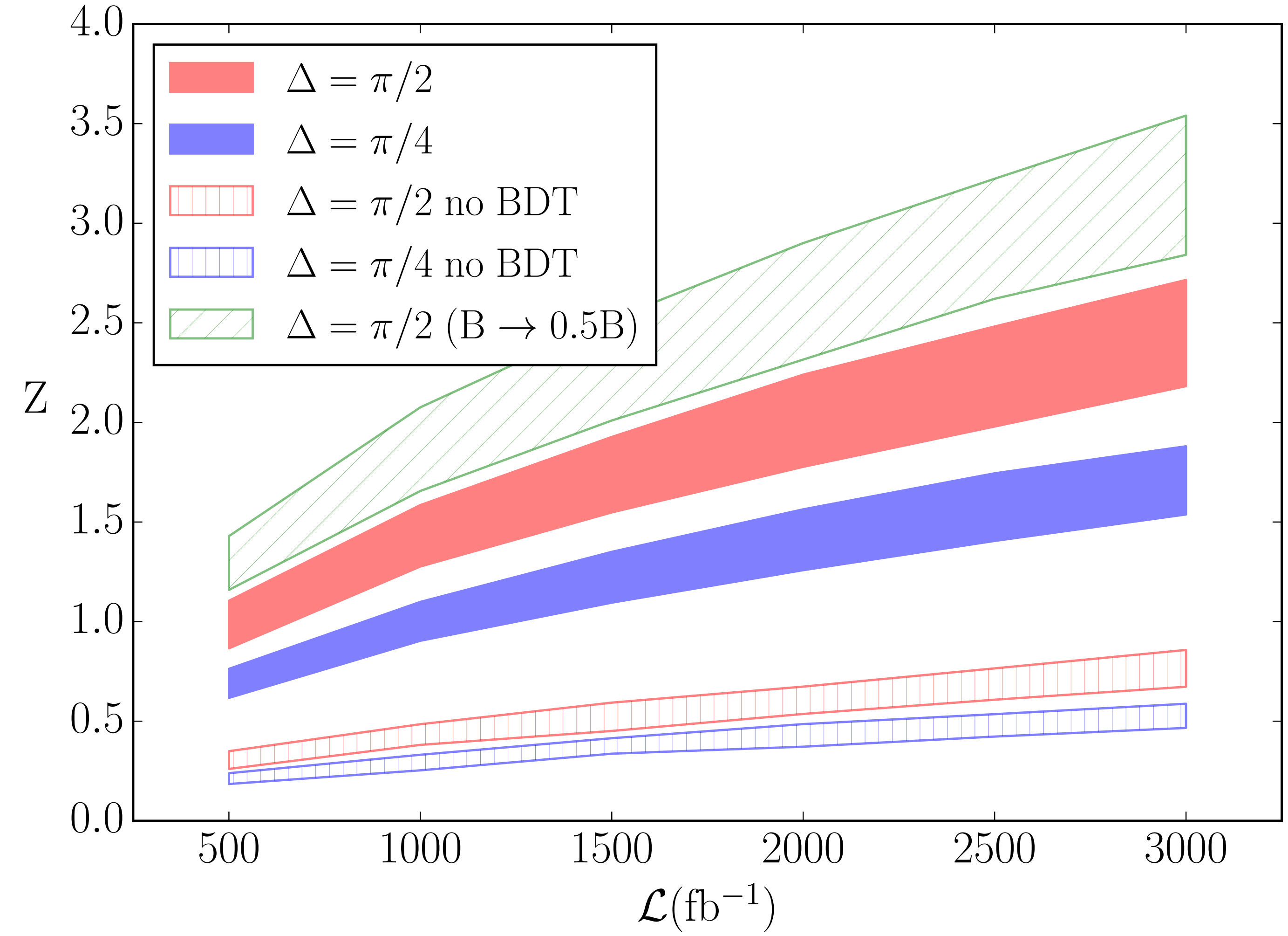

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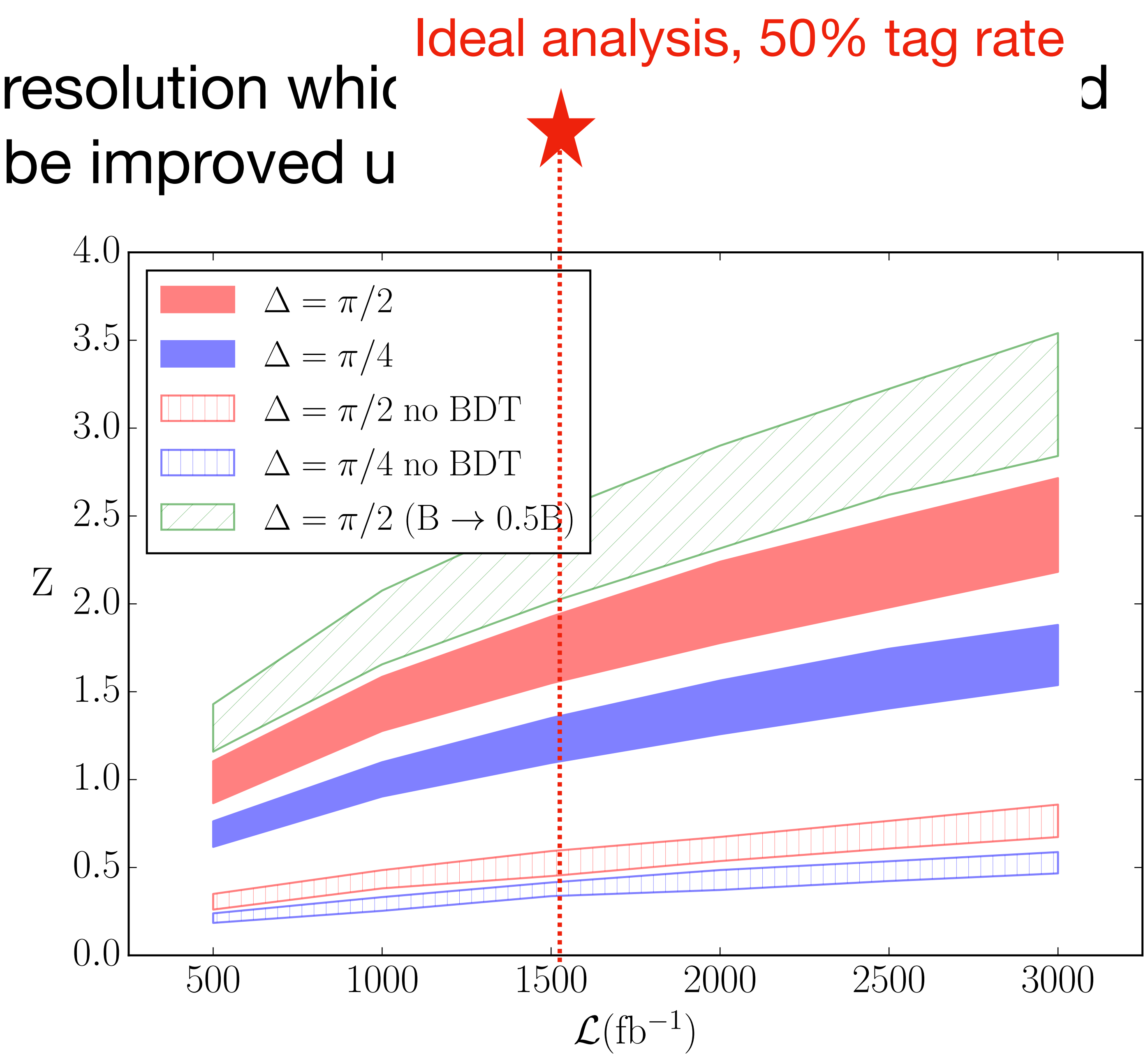

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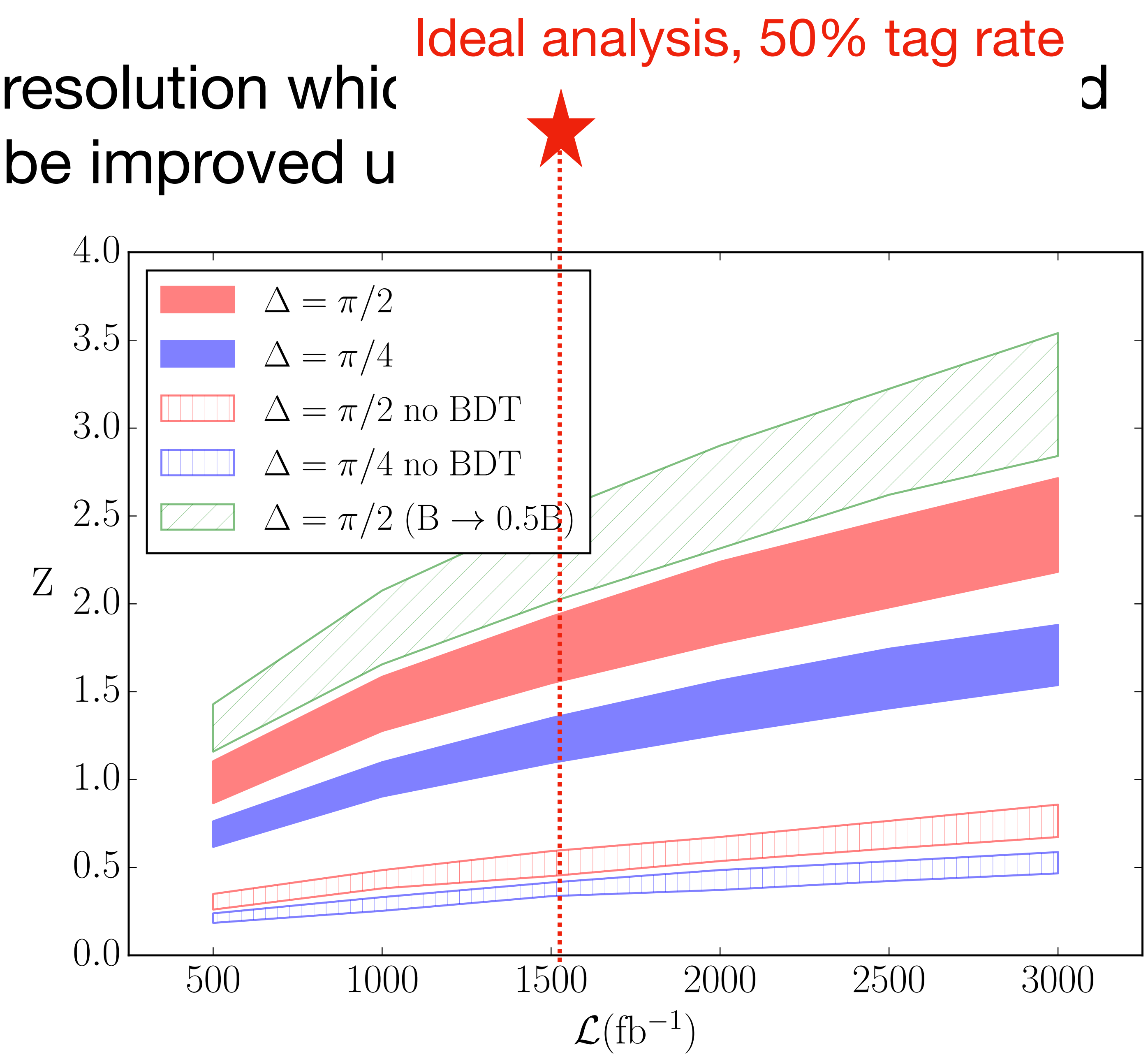


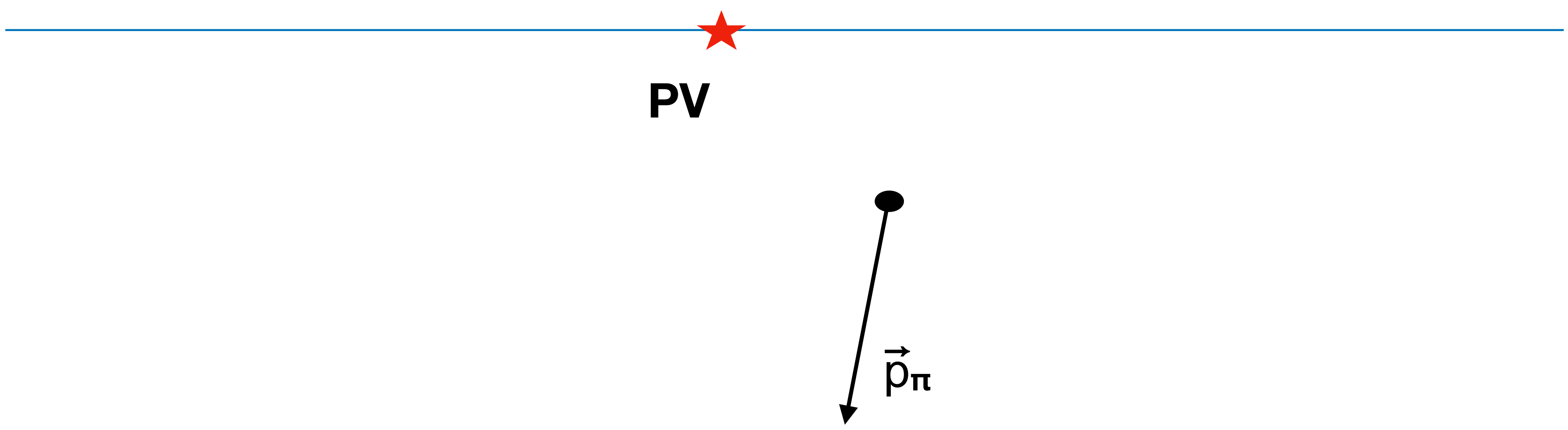
- studied collinear approx.,find it's likely the limit at LHC
- pileup effects not studied

Some help by including other modes: $c\tau_\tau \sim 90\ \mu m$

- for τ with displaced vertices, a second triple product can be defined

[Berge, Bernreuther 0812.1910]

Ex: $\tau^\pm \to \pi^\pm + \nu$



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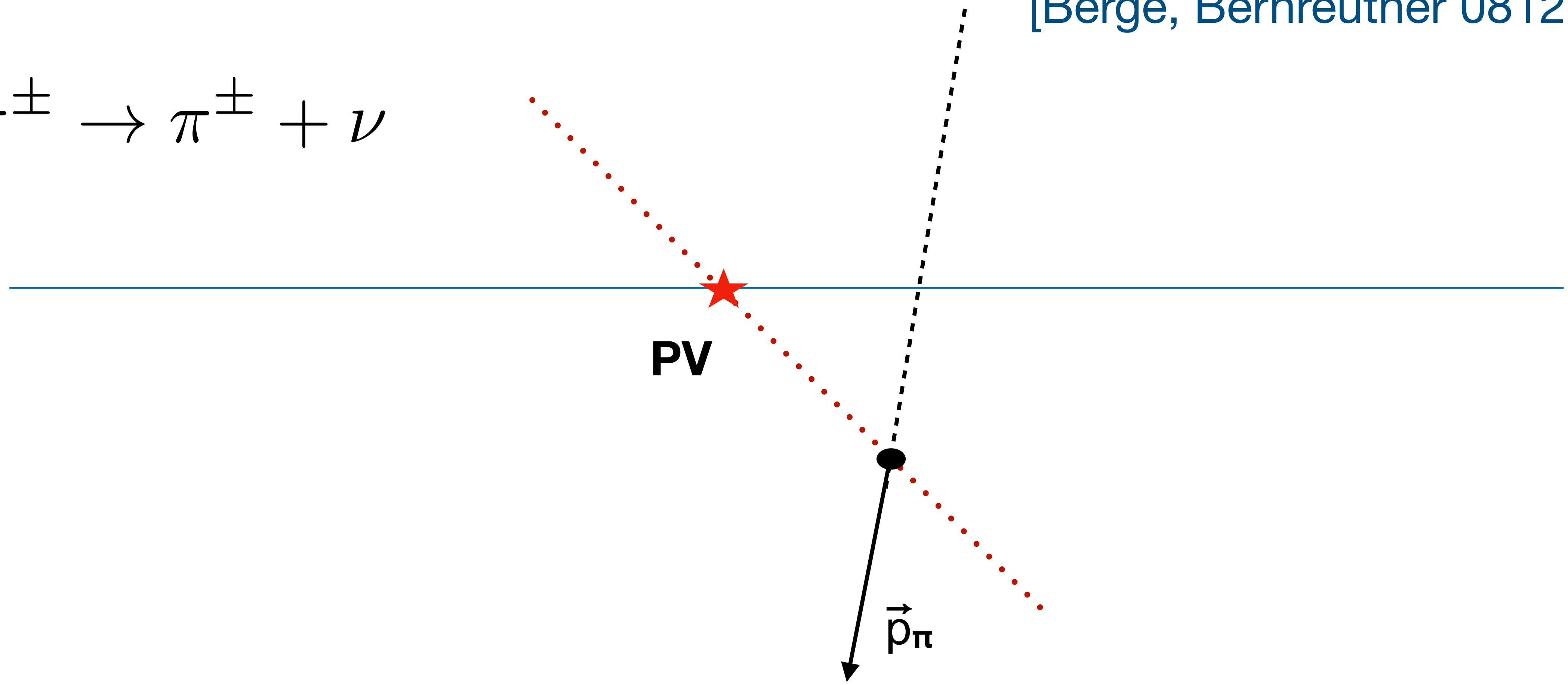

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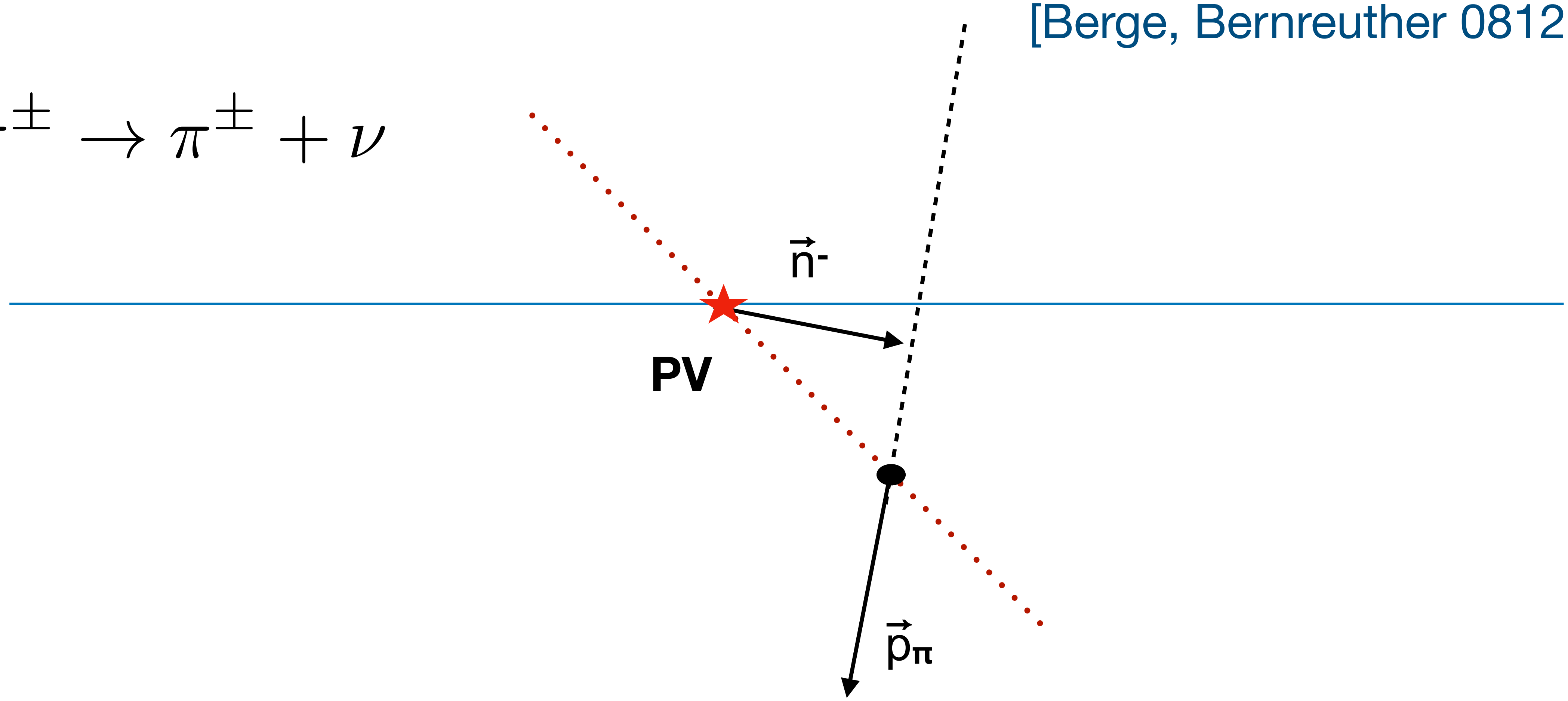

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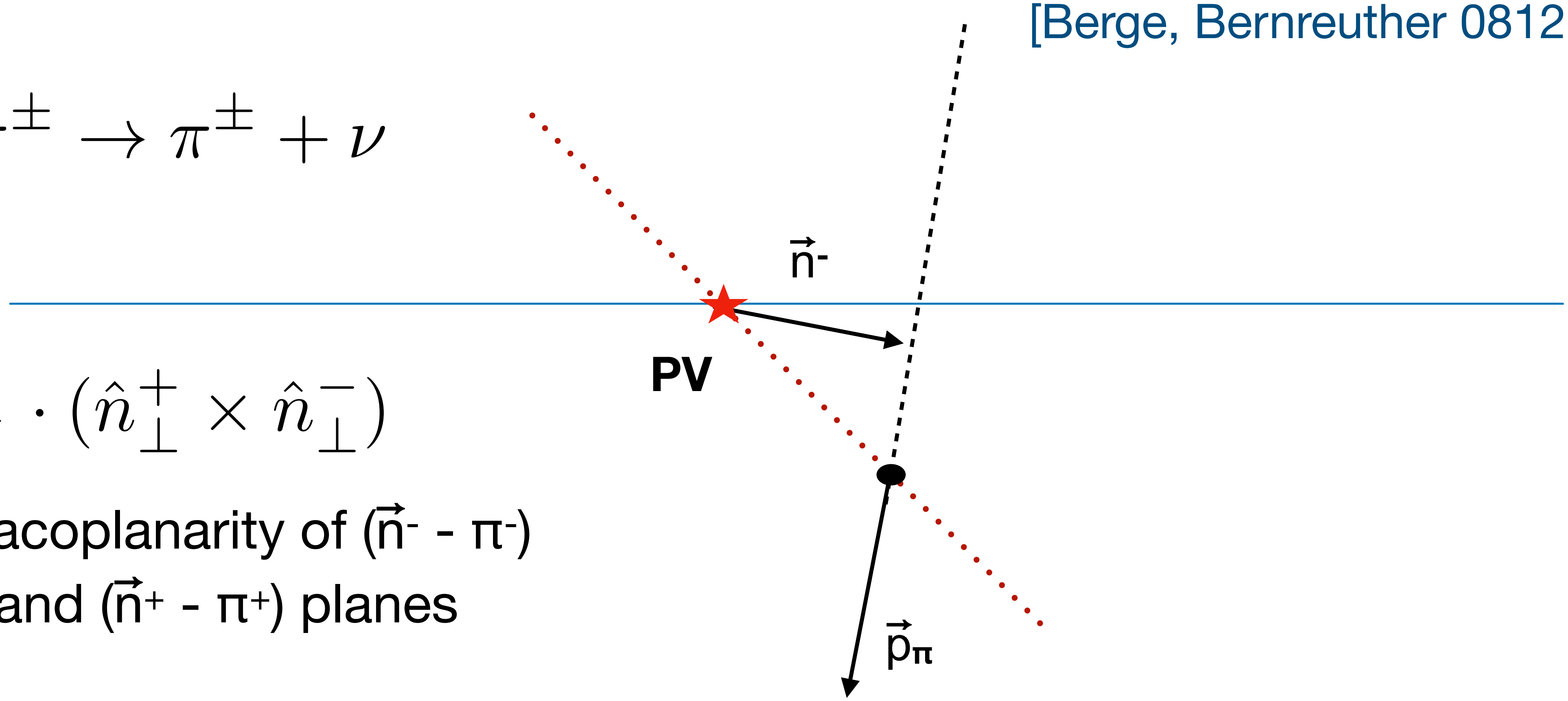


$$\hat{p}_{\pi^-} \cdot (\hat{n}_\perp^+ \times \hat{n}_\perp^-)$$

i.e acoplanarity of ($\vec{n}^-$ - π^-) and ($\vec{n}^+$ - π^+) planes

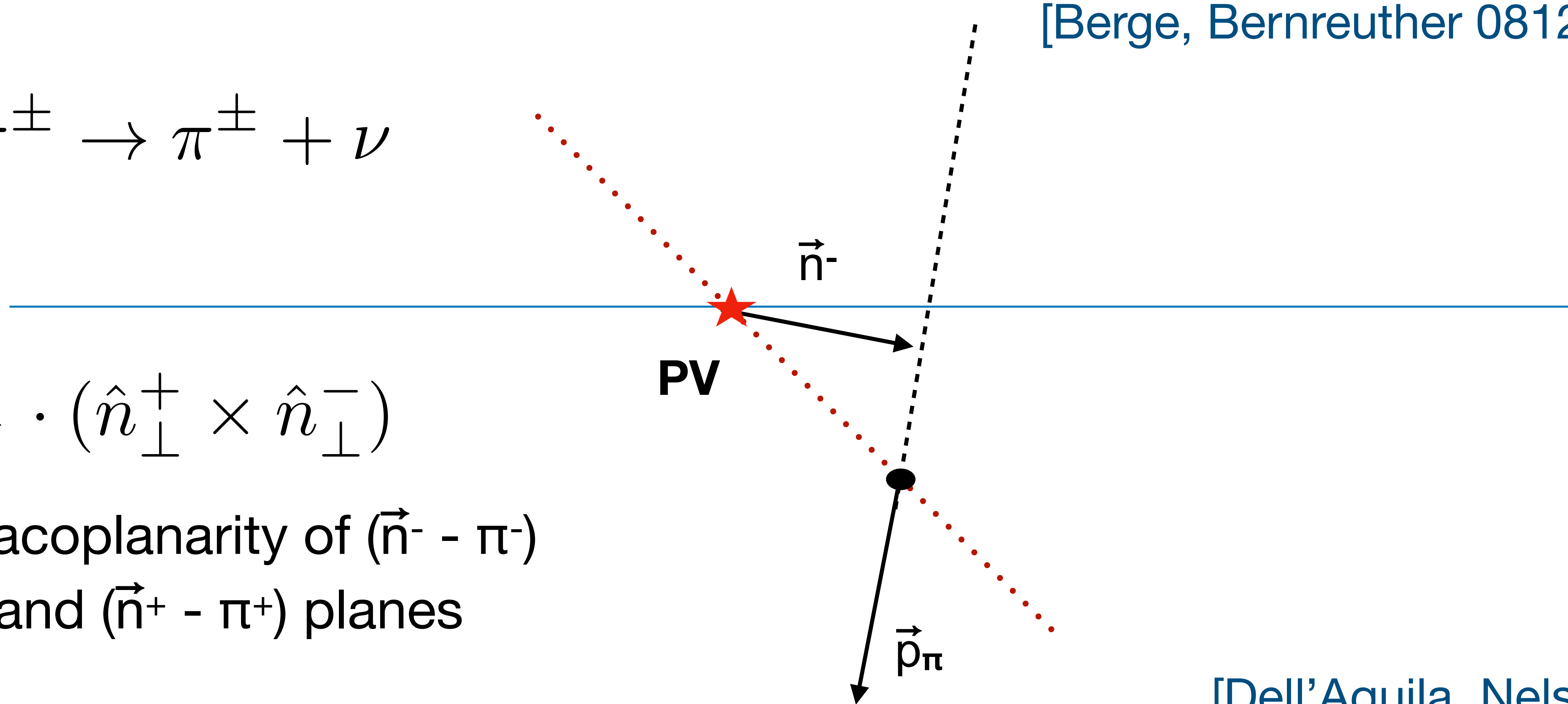
Accessing the CPV Hff phase in taus at the LHC

Some help by including other modes: $c\tau_\tau \sim 90\ \mu m$

- for τ with displaced vertices, a second triple product can be defined

[Berge, Bernreuther 0812.1910]

Ex: $\tau^\pm \to \pi^\pm + \nu$



$$\hat{p}_{\pi^-} \cdot (\hat{n}^+_\perp \times \hat{n}^-_\perp)$$

i.e acoplanarity of ($\vec{n}^-$ - π^-) and ($\vec{n}^+$ - π^+) planes

[Dell'Aquila, Nelson '89]

- approximates τ decay plane orientation, which is sensitive to CP mix
- can be formed in either lab frame or π^+-π^- zero momentum frame
- works for any τ decay mode, can be mixed with previous method

Accessing the CPV Hff phase in taus at the LHC

Combining all modes & methods: [Berge, Bernreuther, Kirchner 1510.03850]

- $gg \to h \to \tau^+ \tau^-$ vs. Drell-Yan background
- $m_{\tau\tau} > 100$ GeV, pT > 20 GeV $|\eta| < 2.5$ for all charged objects, Gaussian smearing

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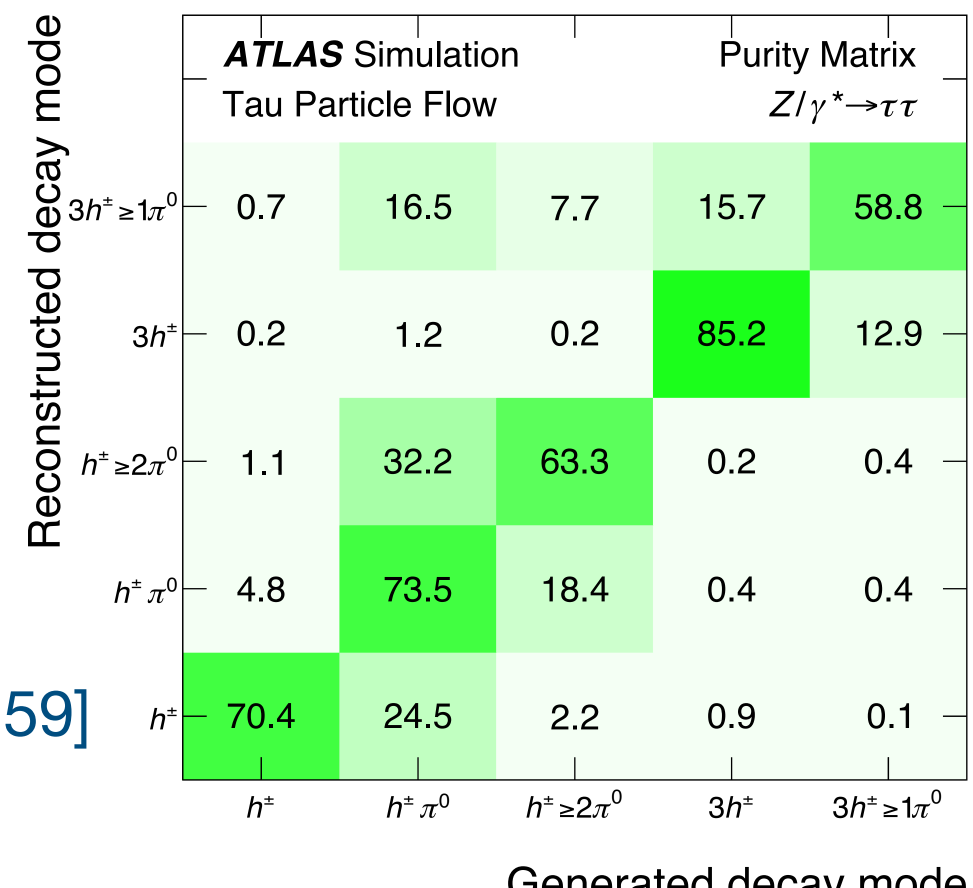
Would be great to know how these sensitivities hold up in more realistic studies

- τ reconstruction obviously crucial

[see talk by Demers]

[Zanzi 1703.10259]



Accessing the CPV Hff phase in taus at the HE- LHC: first thoughts

HE-LHC: h + j rate increases by roughly a factor of 3.5 for the ‘proof of principle’ cuts: faster increase than Z+j

p_T cut (GeV) on h+j for	NLO cross section for 27 TeV pp collider (MCFM 8.0)	Signal enhancement compared to 14 TeV, p_T > 140 GeV
100	12.1 pb	6.05×
140	6.96 pb	3.48× [Our original working point]
150	6.12 pb	3.06×
200	3.43 pb	1.72×
250	2.08 pb	1.04×

[F. Yu, 2017 HE/HE-LHC workshop]

Much higher rate of boosted Higgses:

- **pros:** can apply jet substructure technology, perhaps provide new insight into τ CP variables; more/better instrumented displaced τ’s?
- **cons:** everything boosted means everything overlapping

What about CPV Hff phase in tops?

- if light Yukawa are $\ll$ SM values, can loosen EDM constraints
- loosening Higgs rate constraints requires non-SM hWW or other BSM
- directly probe $\sin\Delta_t$ in $t\bar{t}H$ production (or $t/\bar{t}H$)

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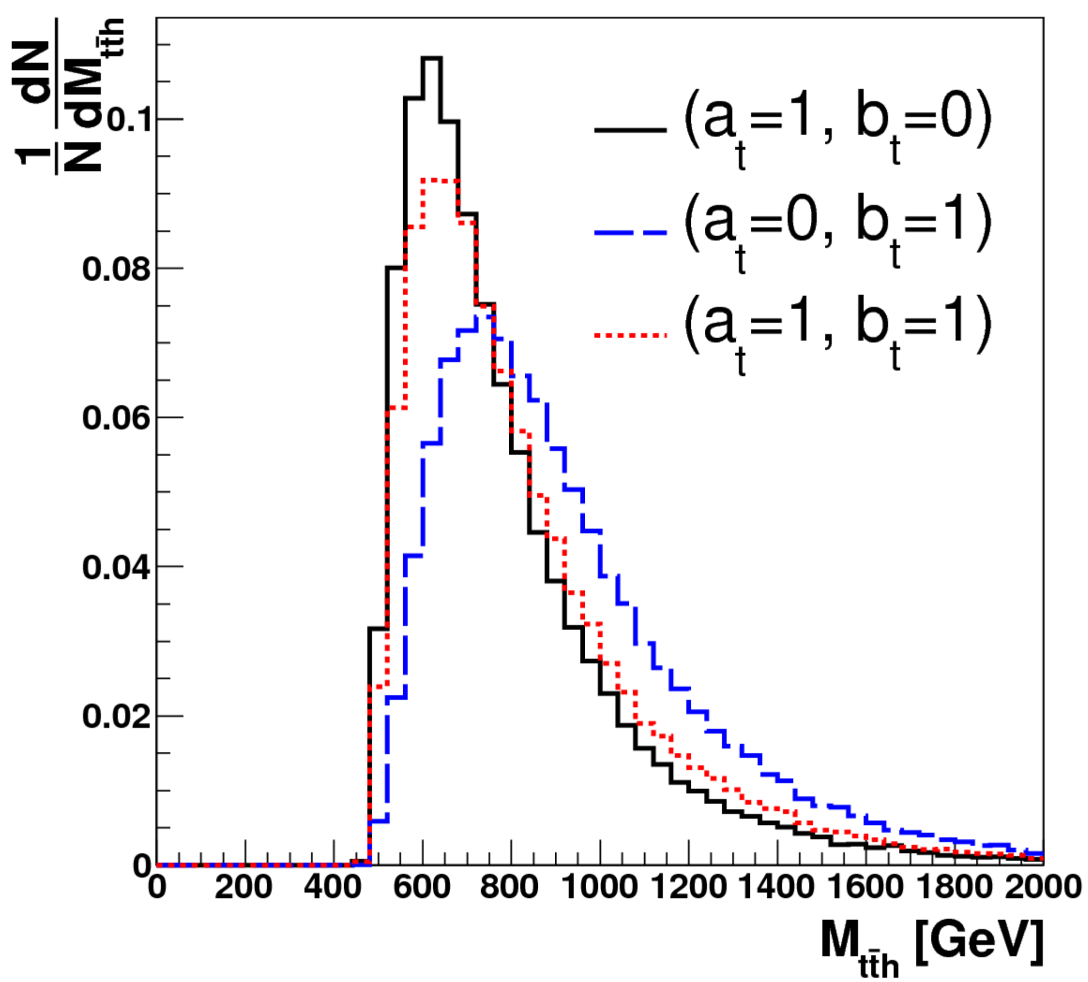

[Boudjema et al 1501.03157]

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Some recent $\bar{t}th$ observables that don't require complete event reconstruction:

$$\Delta\phi_{\ell^+\ell^-}\big|_{p_{T,h}>200\,\mathrm{GeV}}$$

[Buckley, Goncalves 1507.07926]

$$\cos(\Delta\theta_h(\ell^+,\ell^-)) = (\hat{p}_h \times \hat{p}_{\ell^+}) \cdot (\hat{p}_h \times \hat{p}_{\ell^-})$$

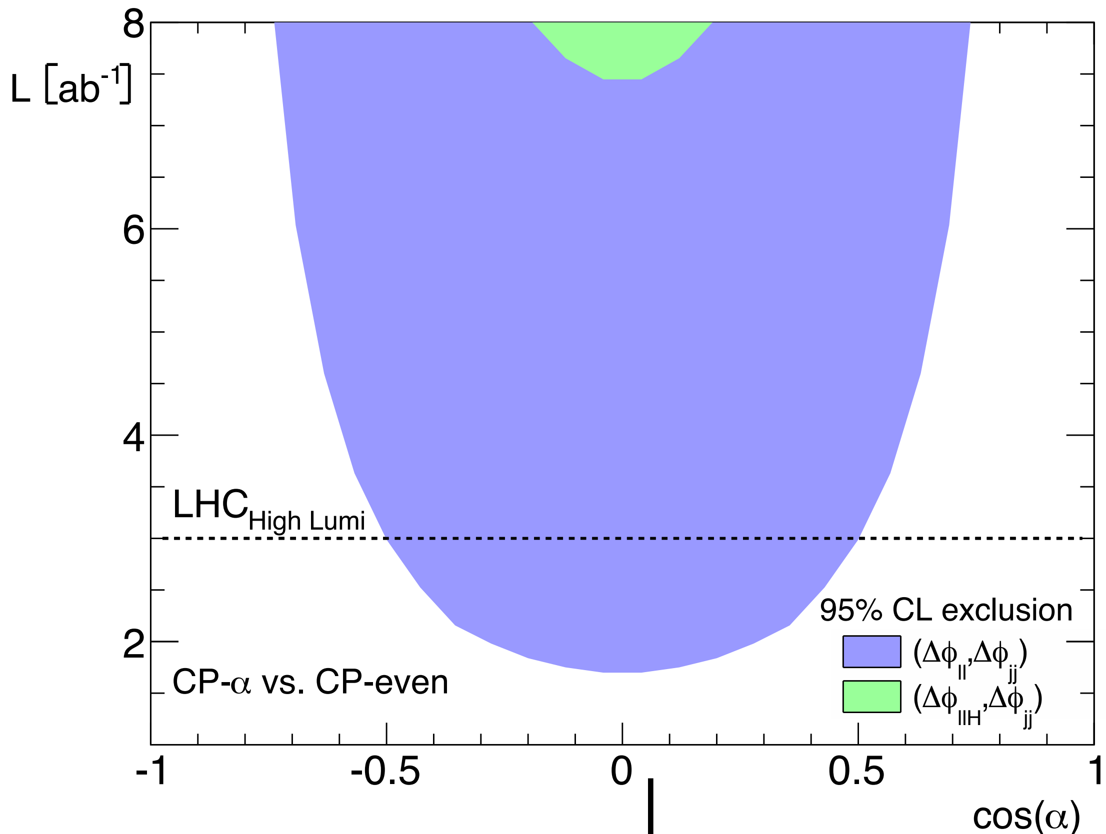
[Boudjema et al 1501.03157]

inspired by $\Delta\phi_{\ell^+\ell^-}$ sensitivity to spin correlations in $pp \to \bar{t}t$

[Mahlon, Parke 9512264,1001.3422]

What about CPV Hff phase in tops?

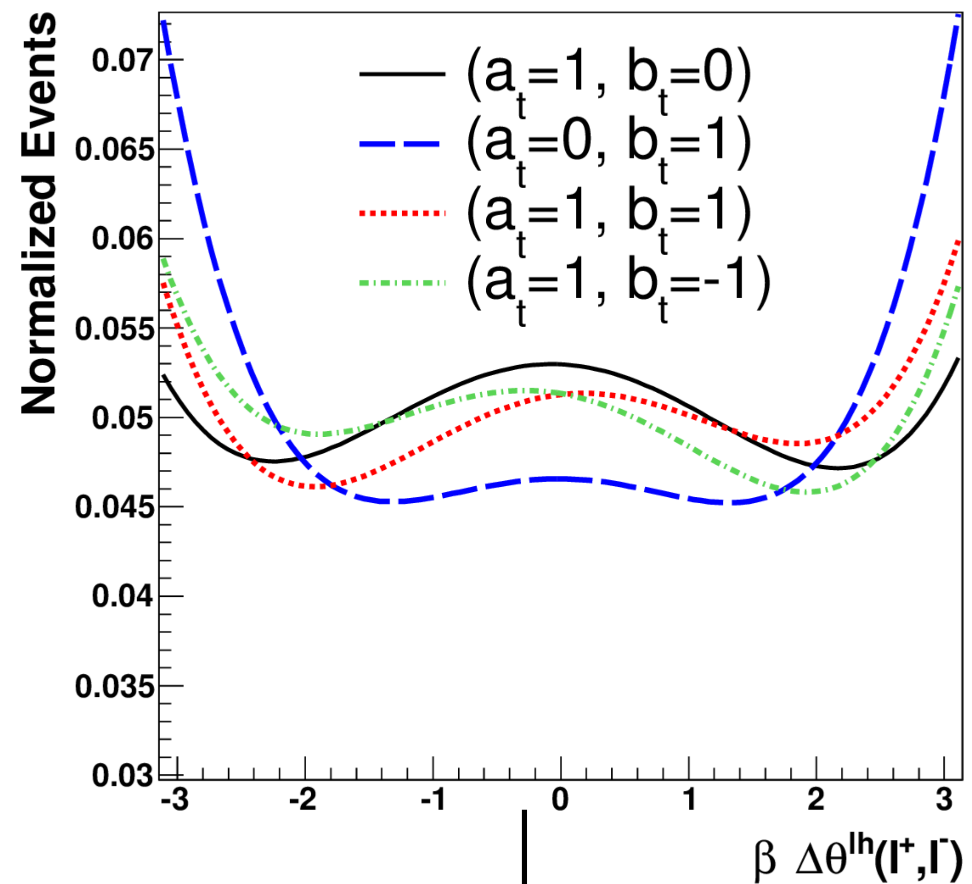
[Buckley, Goncalves 1507.07926]



sensitivity at large Higgs boost, good for HE-LHC…

[see talk by Goncalves]

[Boudjema et al 1501.03157]



sensitive to sign of Δ_t

Conclusions

CPV $H\bar{f}f$ couplings: sure sign of new physics, present in simple UV completions and desired for EW baryogengesis

@LHC: collider environment limits study to **$h\bar{\tau}\tau$**, **$h\bar{t}t$**

easy to arrange for relatively large BSM

tightly constrained (indirectly) by EDM, nEDM, though ∃ caveats

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Spin correlation information communicated to f decay products (prompt or displaced), picked out through differential distributions → lots of statistics needed → HL-LHC arena

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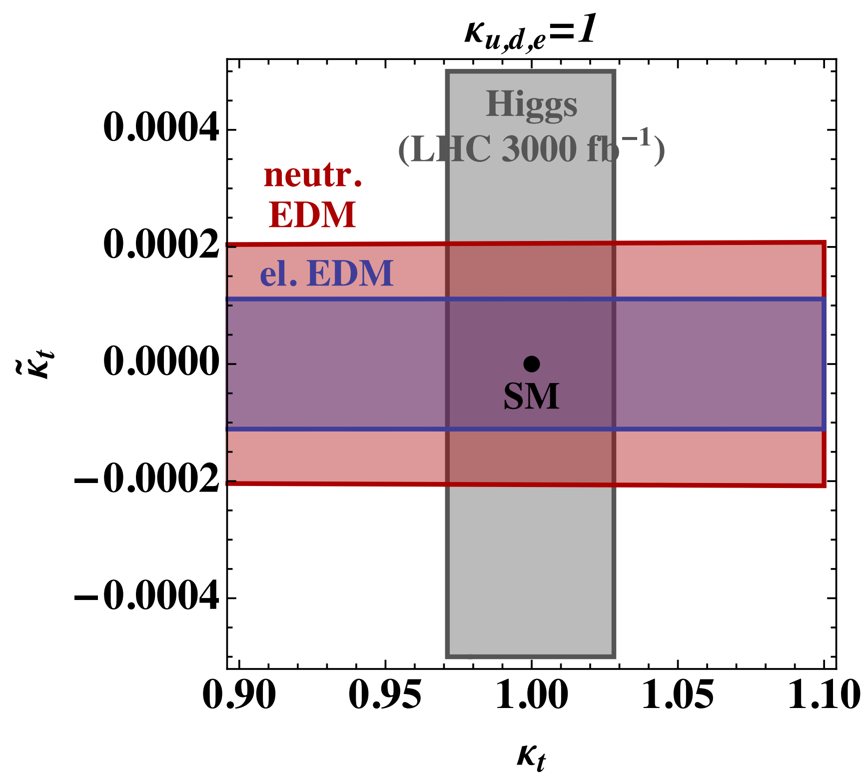
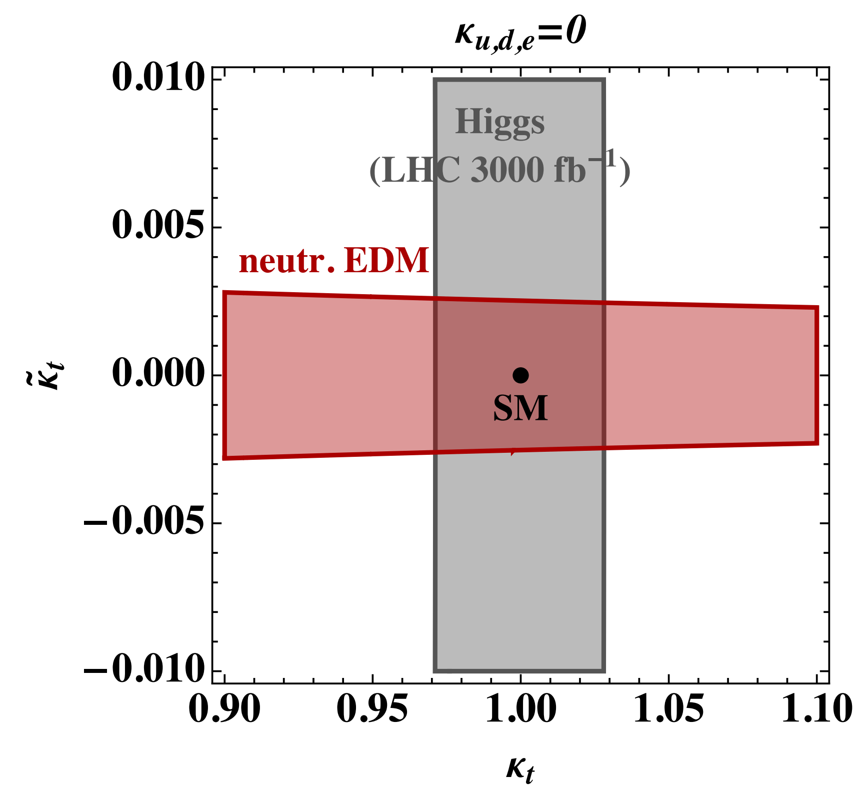
Some preliminary studies, but plenty of room for dedicated studies (pileup effects, tagging techniques + substructure, etc.) at LHC and beyond

HL/HE - LHC complementarity with future EDM experiments

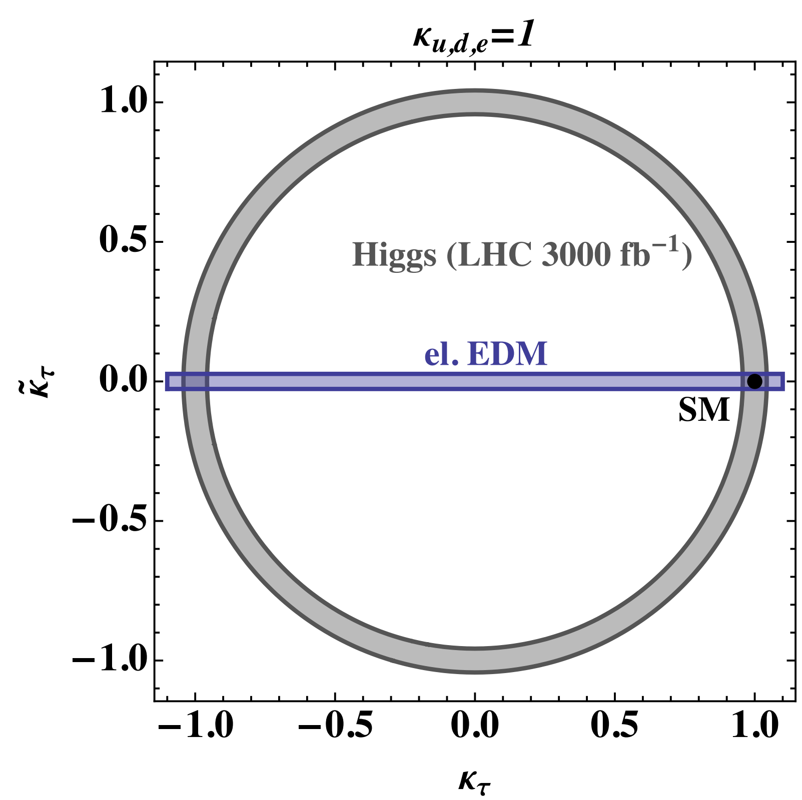


Range of CPV Hff couplings after future EDM/ nEDM projected bounds (factor of 300 improvement)

h$\bar{t}$t



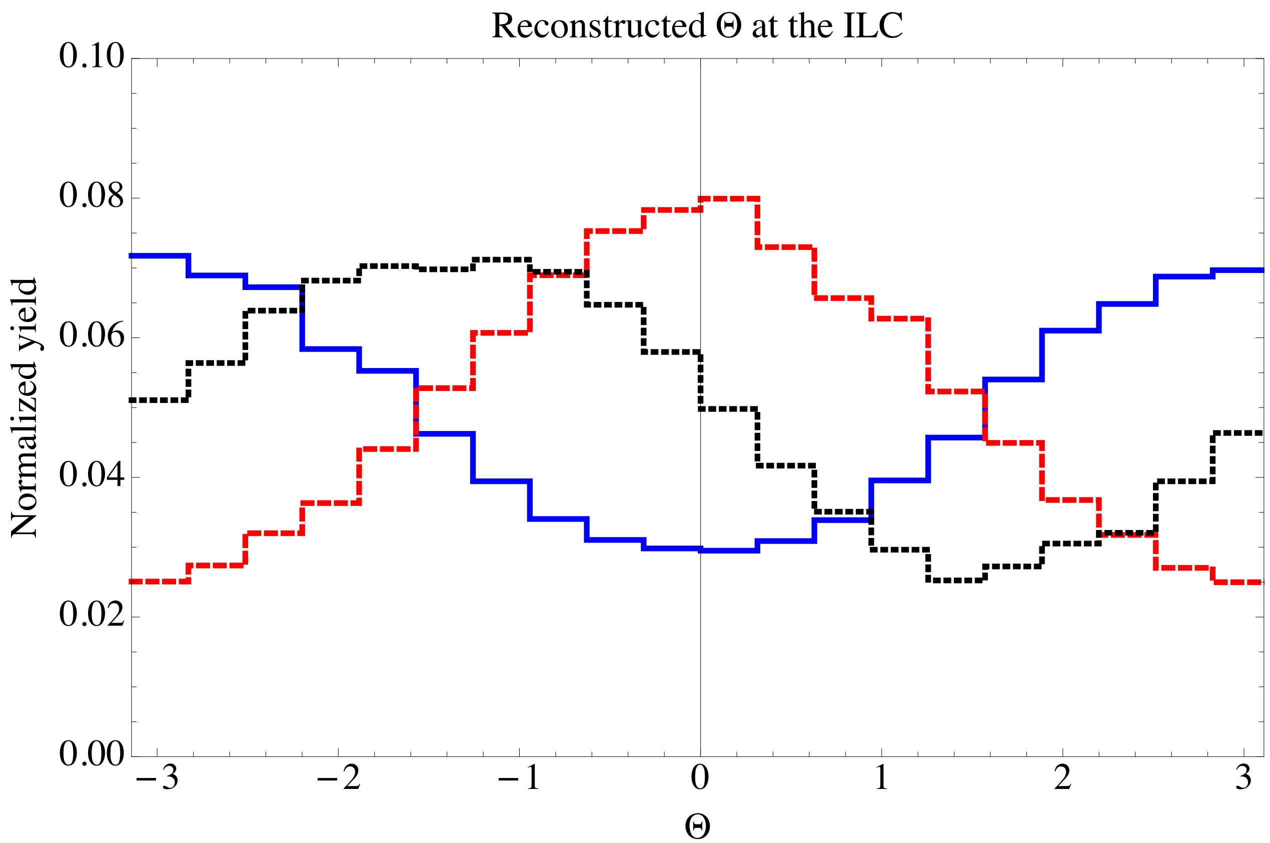
h$\bar{t}$t, just 3rd gen couplings



h$\bar{\tau}\tau$

[Brod, Haisch, Zupan 1310.1385]

At a Higgs factory



- Here we can reconstruct the entire event (up to 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.

Another way to understand cos(Θ-2Δ)

Can rewrite CPV hττ as $$e^{i\,\Delta}|++\rangle + e^{-i\,\Delta}|--\rangle$$

If we measure polarization along momenta

$$\langle ++| \quad \textbf{Or} \quad \langle --|$$

τ^+ τ^-

$$P_{\pm\pm} \propto \left| \begin{matrix} \langle ++| \\ \text{or} \\ \langle --| \end{matrix} \quad \left(e^{+i\Delta}|++\rangle + e^{-i\Delta}|--\rangle\right) \right|^2$$

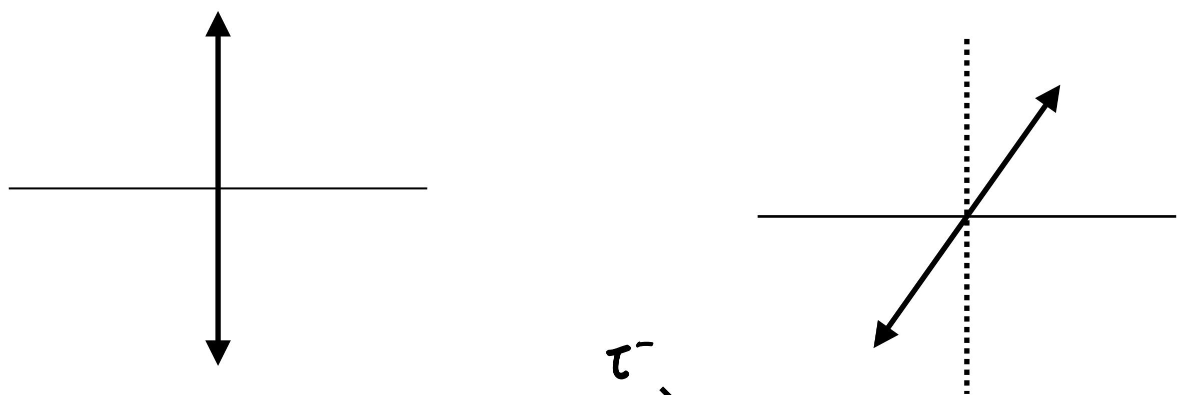
Not sensitive to Δ

(explanation thanks to R. Harnik)

Another way to understand cos(Θ-2Δ)

Can rewrite CPV hττ as $e^{i\,\Delta}|++\rangle + e^{-i\,\Delta}|--\rangle$

If we instead polarization ⊥ momenta, with angle Θ between polarization planes of τ+ and τ-:



τ^-

$$\left|\frac{1}{\sqrt{2}}(\langle+| + \langle-|)\,\frac{1}{\sqrt{2}}(e^{-i\Theta/2}\langle+| + e^{+i\Theta/2}\langle-|)\,\Big|\,e^{i\,\Delta}|++\rangle + e^{-i\,\Delta}|--\rangle\right|^2$$

τ^+

$$\propto A + B\cos(\Theta - 2\,\Delta)$$

(explanation thanks to R. Harnik)