A novel approach to $\tau \to \ell$ + invisible

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based on work in collaboration with

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Introduction & Motivation

Motivation

- *"invisible" = an escaping scalar (e.g. ALP)*
  or vector (e.g. hidden photon)

- *Such new (light) particles are well motivated*

- *New scalars in the MeV-GeV range w/ larger-than-weak couplings to 2nd or 3rd generation matter*
  fully compatible with present data

  see e.g. [Lanfranchi, Pospelov, Schuster, 2021]

- *No compelling reason why these particles should have flavour-diagonal couplings*

  see e.g. [Georgi, Kaplan, Randall, 1986]

Motivation

- *meson or lepton decays at colliders especially suited for such tests*

- *a common hypothesis allowing for minimal model-dependence is that the new particle escapes detection*

⇒ $\tau \to \ell$ + ALP : prototype example of such searches

$\tau \to \ell$ + ALP: status

- *performed at MARK-III* [Baltrusaitis *et al.* (MARK-III), 1985]
  and ARGUS [Albrecht *et al.* (ARGUS), 1995]

- *on-going at Belle-II* see e.g. [Tenchini at ICHEP 2020]

Strategy

- *pair-produced τ's*
- *total $\not{E}$ accurately measured*
- *Main bkg's: SM processes w/ undetected particles*

⇒ ***To separate signal from bkg's:***

Estimate the signal-tau momentum
using the visible momenta on the tag side

"ARGUS method"

Our approach

to the reconstruction

of the signal-τ momentum

Rationale

(i) *Signal and bkg's have identical topologies:*

τ *(→ visibles + invisibles) +* τ *(→ visibles + invisibles)*

Example

$$e^+e^- \to \underbrace{\tau(\to \ell\phi)}_{\text{signal}}\ \underbrace{\tau(\to 3\pi\nu)}_{\text{tag}} \quad \text{vs.} \quad e^+e^- \to \underbrace{\tau(\to \ell\nu\bar{\nu})\ \tau(\to 3\pi\nu)}_{\text{irreducible bkg.}}$$

For such pairwise topologies, there exists an arsenal of kinematic variables, e.g. the "stransverse mass"

(Think of searches of pair-produced SUSY particles)

☞ *Let us denote these variables collectively as* M_2

M_2-based strategies

have been widely used in high-p_T searches

We reappraise them

for low-energy pair-prod. leptons or mesons

M_2 101

- M_2 is the 2-decay-chain, Lorentz-invariant generalization of the M_T variable [Smith *et al.*; Barger *et al.*, 1983]

How to measure the W mass in $W \to \ell\nu$ ***(at a hadron collider)***

$$m_W^2 \;\geq\; m_\ell^2 + m_\nu^2 + 2(E_T^\ell E_T^\nu - \boldsymbol{p}_T^\ell \boldsymbol{p}_T^\nu) \;\equiv\; M_T^2$$

⇨ *the M_T endpoint allows to determine m_W*

If one has 2 parents decaying to visibles + invisibles

Would take: $\max\{M_T(\text{branch}_1), M_T(\text{branch}_2)\}$

However, the invisible momenta $\boldsymbol{k}_{1,2}$, for the 2 branches are not known separately

Only their sum is constrained: $\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} = \boldsymbol{P}_T^{\text{miss}}$

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⇨ *the M_T endpoint allows to determine m_W*

If one has 2 parents decaying to visibles + invisibles

$$M_{T2} = \min_{\boldsymbol{k}_{1T}, \boldsymbol{k}_{2T}} \left[\max\left\{ M_T(\boldsymbol{p}_{1T}, \boldsymbol{k}_{1T}),\, M_T(\boldsymbol{p}_{2T}, \boldsymbol{k}_{2T}) \right\} \right]$$
$$\text{subject to } \boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} = \boldsymbol{P}_T^{\text{miss}}$$

[Lester, Summers, *1999;* Barr, Lester, Stephens, *2003*]

M_2 101

- M_2 *is the 2-decay-chain, Lorentz-invariant generalization of the* M_T *variable* [Smith *et al.;* Barger *et al., 1983*]

At Belle II, we don't need the "T"

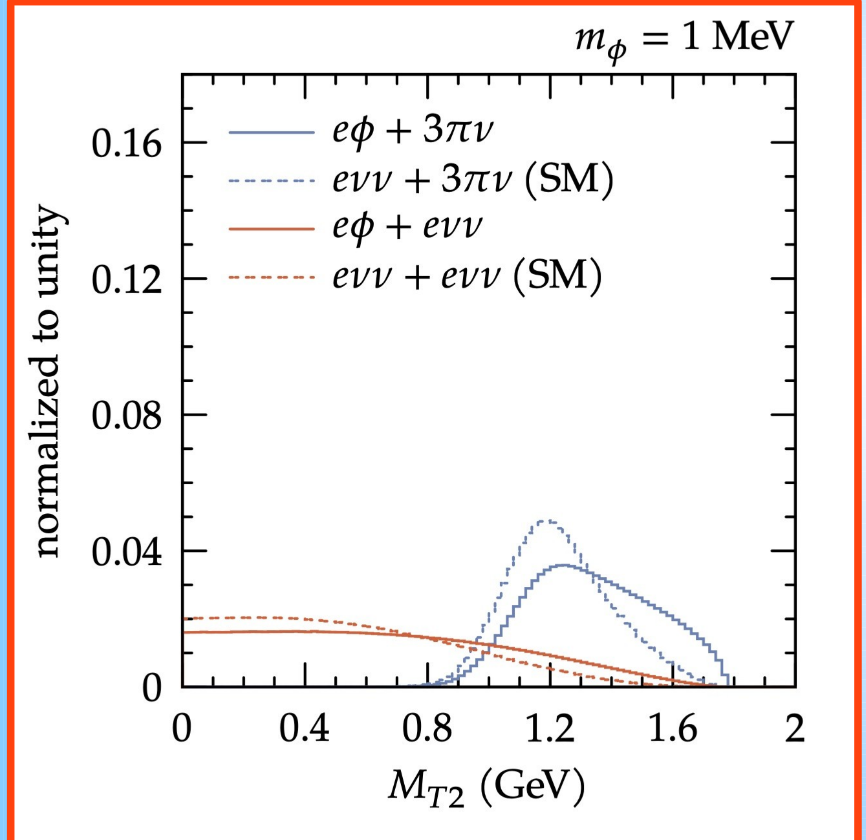
$$M_2 = \min_{\boldsymbol{k}_1, \boldsymbol{k}_2} \left[\max \left\{ M(p_1, k_1), M(p_2, k_2) \right\} \right]$$

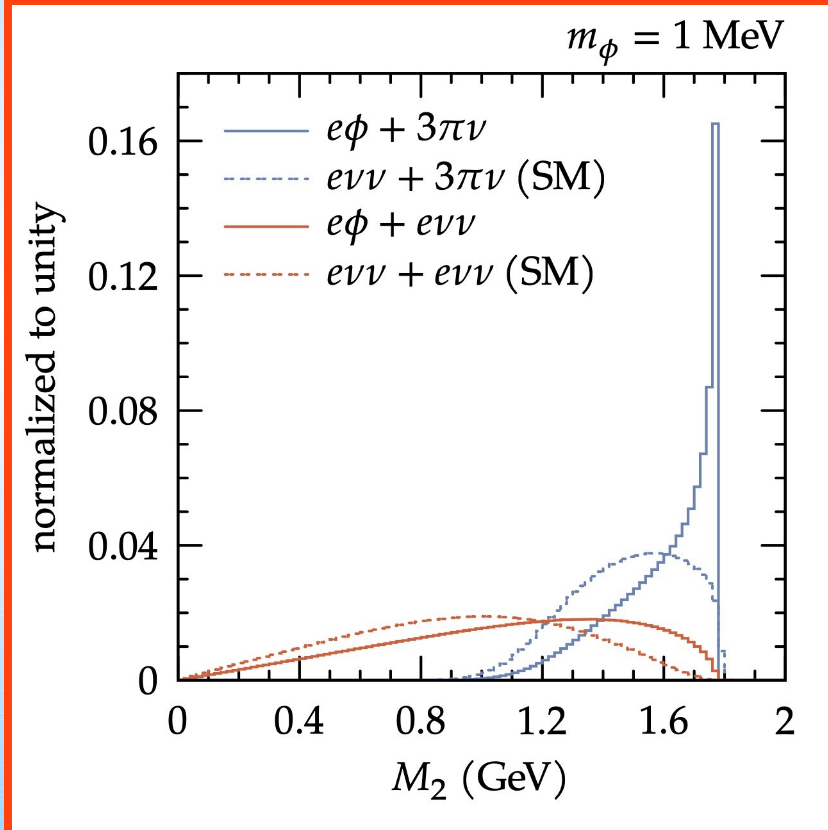
$$\text{subject to} \begin{cases} \boldsymbol{k}_1 + \boldsymbol{k}_2 = \boldsymbol{P}^{\text{miss}}, \\ (p_1 + p_2 + k_1 + k_2)^2 = s \end{cases}$$

[Barr *et al.,* 2011*;* see also Ross, Serna, *2007;* Cho *et al., 2014*]

M_2 shares most of the features that make M_{T2} very useful

E.g.: the smaller the number of invisibles, the more the distrib. is populated towards the upper edge





This makes these variables “invisible-savvy”

MAOS

$$M_2 = \min_{\boldsymbol{k}_1,\, \boldsymbol{k}_2} \left[\max \left\{ M(p_1,\, k_1),\, M(p_2,\, k_2) \right\} \right]$$

$$\text{subject to} \quad \begin{cases} \boldsymbol{k}_1 + \boldsymbol{k}_2 = \boldsymbol{P}^{\text{miss}}, \\ (p_1 + p_2 + k_1 + k_2)^2 = s \end{cases}$$

The solution to the minimization can be used as an estimator of the separate invisible momenta $\boldsymbol{k}_{1,2}$

M_2-Assisted On-Shell (MAOS) invisible momenta

[Cho *et al., 2008;* Park, *2011*]

With these tools

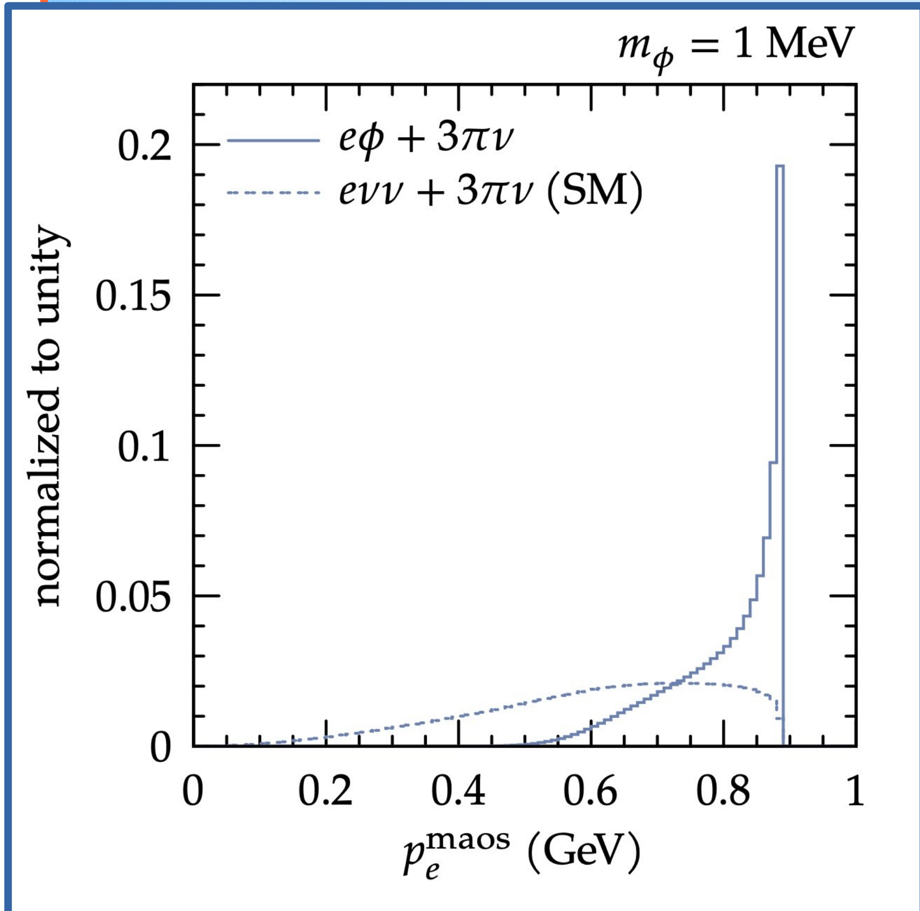
we then construct

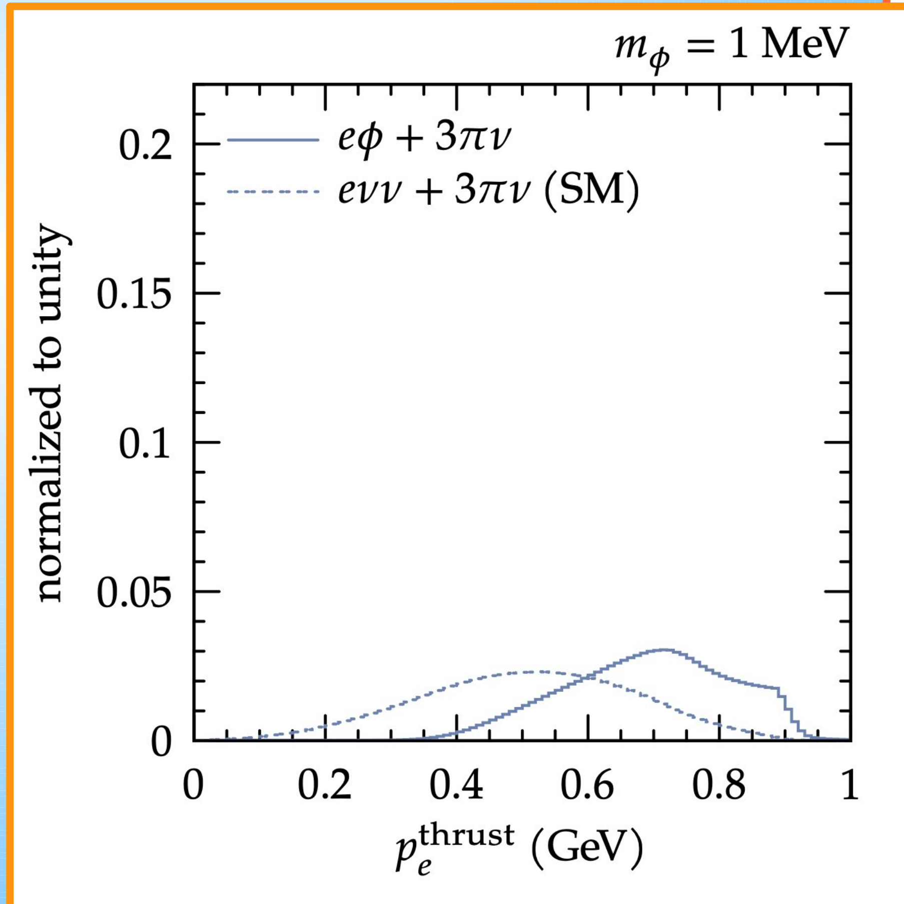
kinematic variables

for S / B discrimination

Example 1

- *With MAOS we can reconstruct $|\mathbf{p}_e|$ in the signal-τ rest frame (RF)*
- *The same variable can be defined within the "thrust method" (the current state-of-the-art, a generaliz. of the ARGUS method)*





Example 2

- *Using* $\boldsymbol{k}_{1,2}^{\rm maos}$ *we can construct the ratio*

$$\xi_k \equiv \frac{\min\{|\boldsymbol{k}_1|,\,|\boldsymbol{k}_2|\}}{\max\{|\boldsymbol{k}_1|,\,|\boldsymbol{k}_2|\}} \in [0,1]$$

Underlying rationale

ξ_k distrib. will be populated around 1 for symm. decay chains

This is the case for the $e\nu\bar{\nu} + e\nu\bar{\nu}$ background

Note

- *Earlier literature proposes max / min.* [Agashe *et al., 2010*]
  Advantage of min / max : compact domain.
- *ξ_k could be defined in the lab or CMS (or yet another) frame.*
  We use the CMS frame:

  ⇨ *slope differences are magnified*

Example 2

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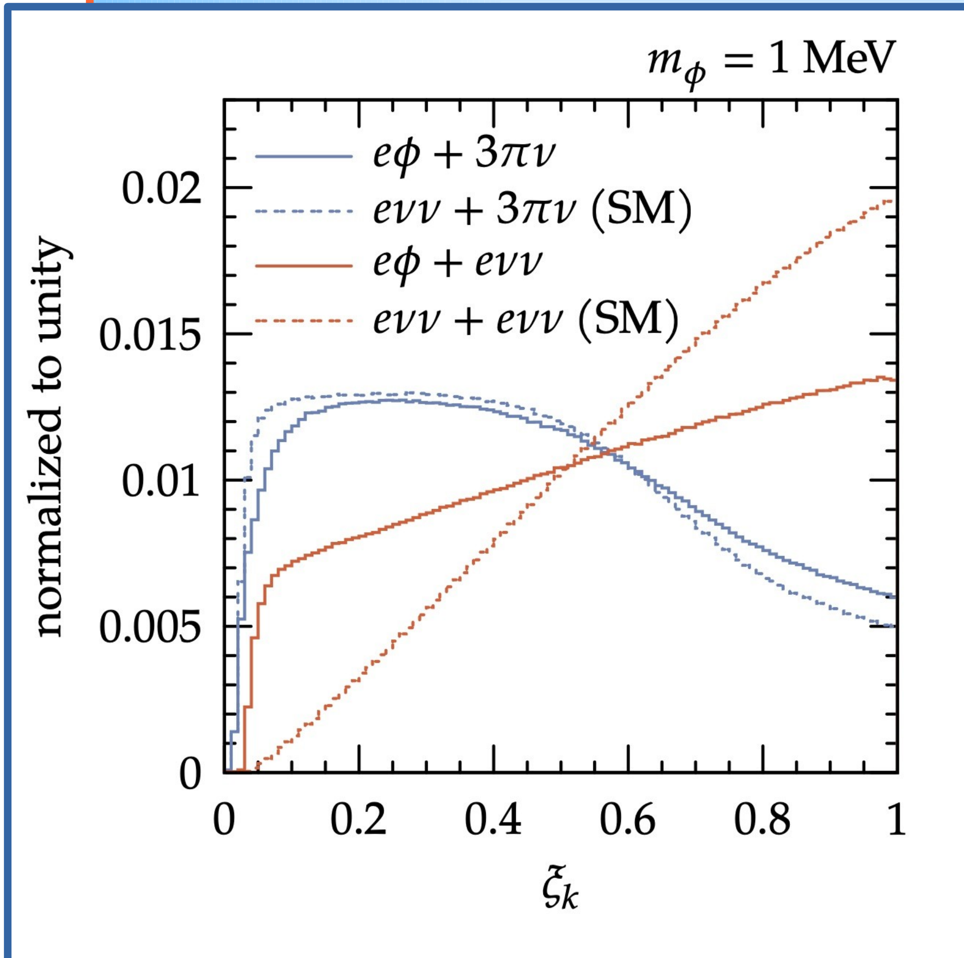
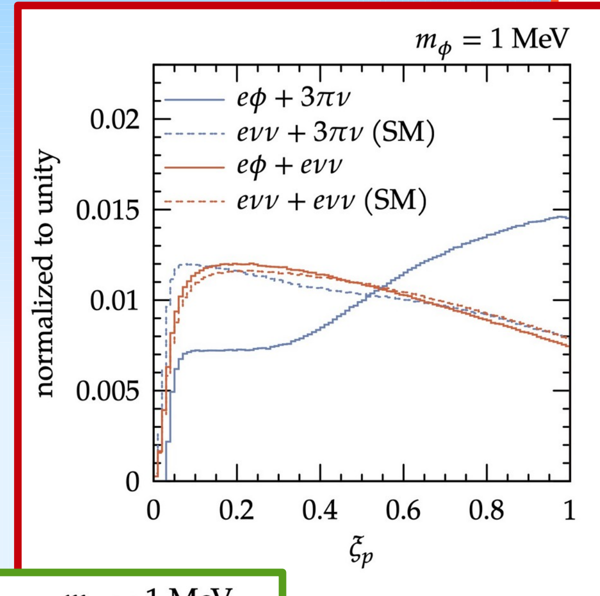
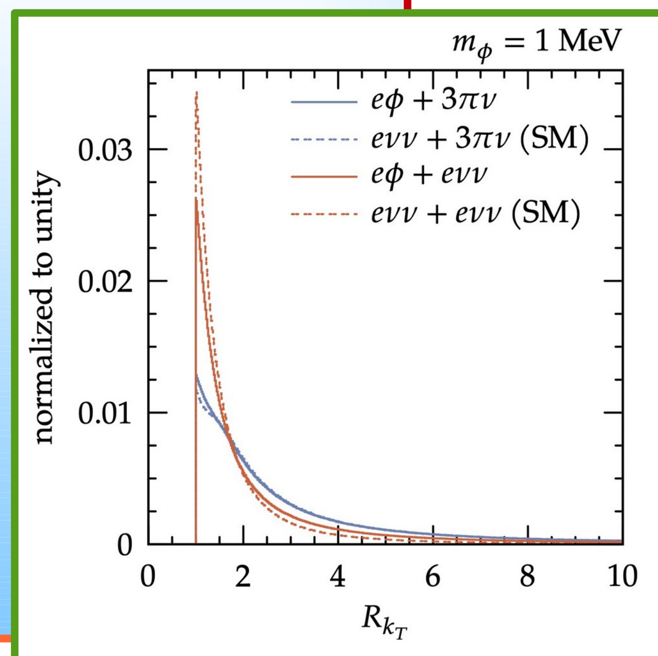






Other variables

- *We also included variables that do not require MAOS momenta*
  (and show negligible correlation with them)

M_{recoil} = *invariant mass of the full invisible system*

⇒ *bkg's have more invisibles than the signal*

'typically'
$M_{recoil}(bkg) > M_{recoil}(sig)$

$E_{miss} = |\mathbf{P}_{miss}|$

the more symmetric the 2 decay chains (as in $e\nu\nu\ e\nu\nu$ bkg)

the more the invisible momenta tend to cancel

⇒ *the smaller E_{miss}*

- *In short, we define a number of kin. variables, whose distrib's are sensitive to the # of invisibles in the decay*
- *These variables can be applied to any search channel with the mentioned decay topology*

***In particular** it can be applied to*

"1 $\times$ 3 channel"

signal + tag	irred. bckgr.
$e\phi \; + \; 3\pi\nu$	$e\nu\bar{\nu} \; + \; 3\pi\nu$

for which we can compare with the ARGUS method

but also to

"1 $\times$ 1 channel"

signal + tag	irred. bckgr.
$e\phi \; + \; e\nu\bar{\nu}$	$e\nu\bar{\nu} \; + \; e\nu\bar{\nu}$

for which the ARGUS method is not available

Analysis

and

Results

Analysis Structure

- *We collectively denote our kin. variables (M_2 , $\xi_{k,p}$, E_{miss} , M_{recoil}) as 'invisible-savvy'* ⇨ 'ISy' classifier

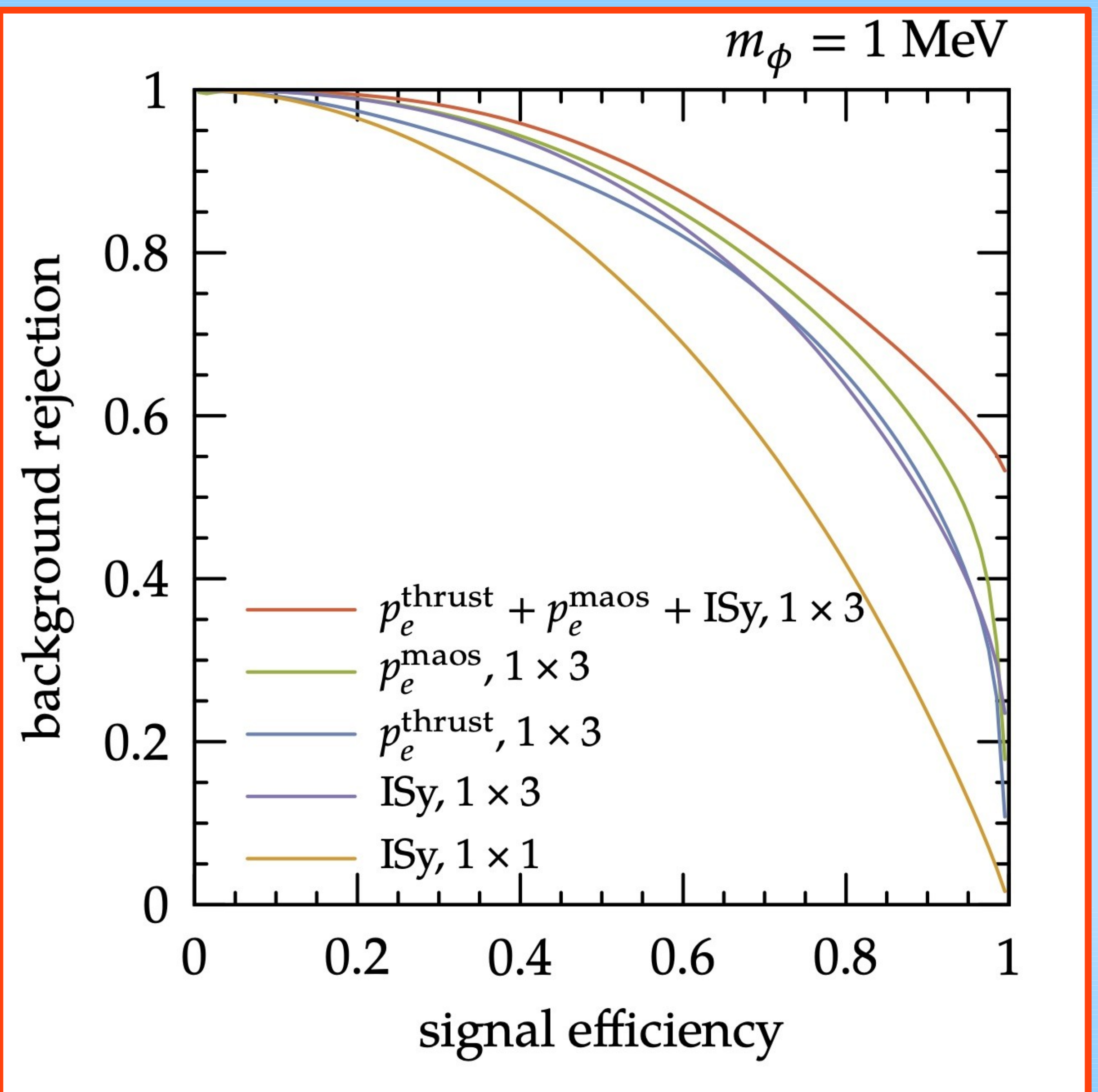
Note: p_e^{maos} *is considered separately (i.e. it's not part of* ISy*)*

to allow for a direct comparison with p_e^{thrust}

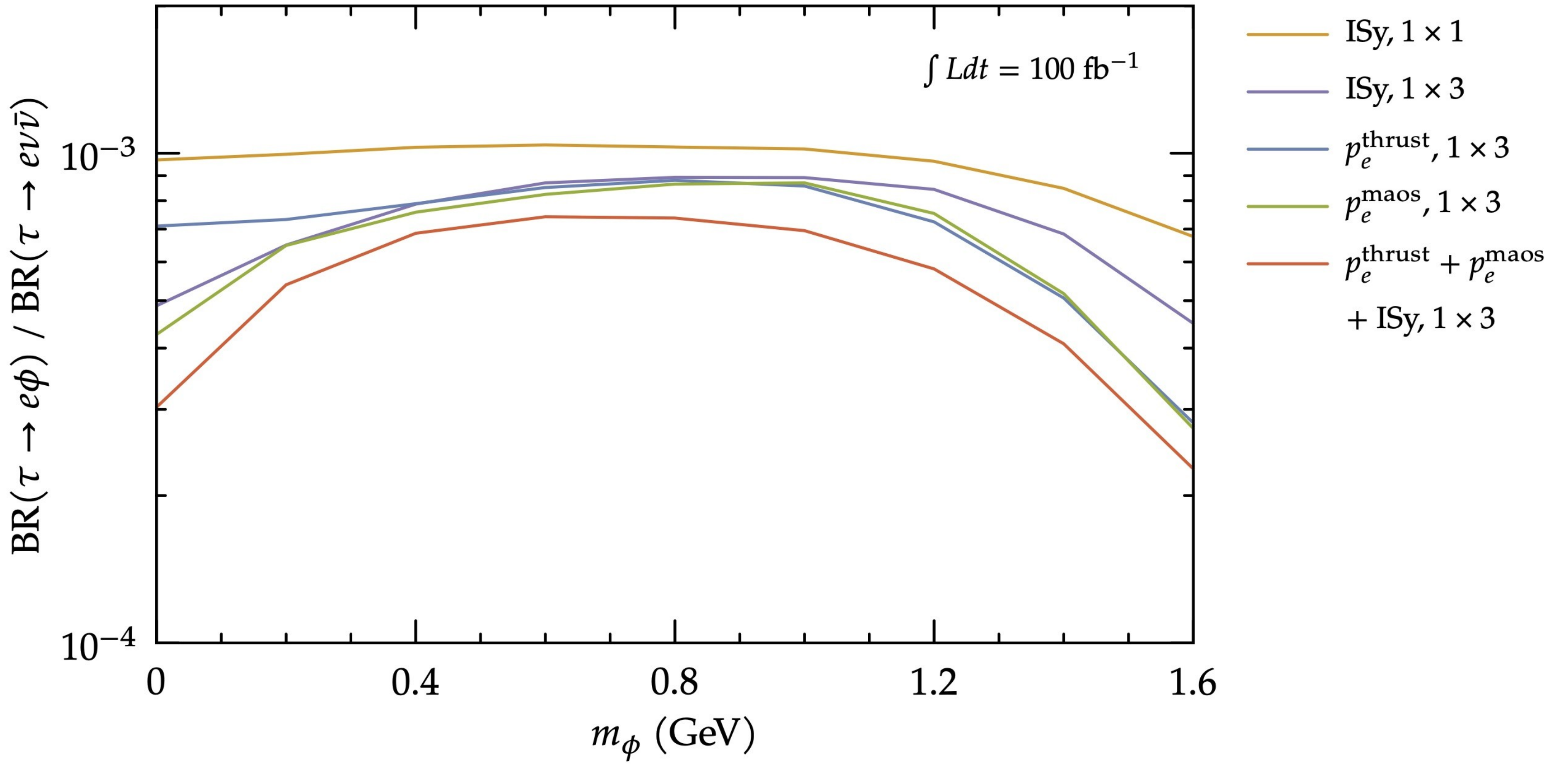
- *We then consider the following cases*

var's, channel	aim
(a) $p_e^{\text{thrust}}, 1 \times 3$	*reproduce the on-going Belle-II analysis, and validate our setup*
(b) $p_e^{\text{maos}}, 1 \times 3$	*compare MAOS with thrust 'directly' i.e. on a single, common variable*
(c) $\text{ISy}, 1 \times 3$	*compare* ISy *with cases (a) and (b)*
(d) $\text{ISy}, 1 \times 1$	*apply* ISy *to the* 1×1 *channel and check its performance compared to* 1×3
(abc) $p_e^{\text{thrust}} + p_e^{\text{maos}} + \text{ISy}, 1 \times 3$	

S efficiency vs. B rejection

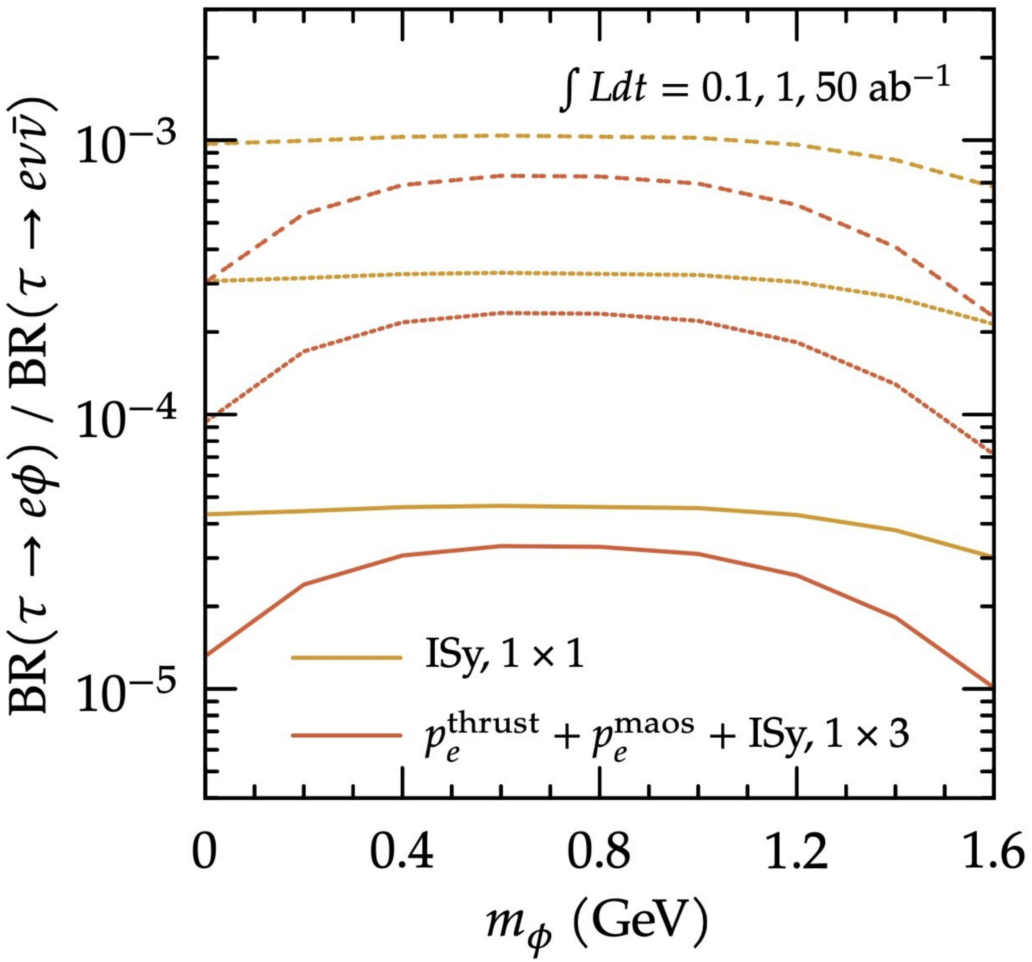


Upper Limit on BR($\tau \to e\phi$)



Our method has a clear edge at the two mass endpoints

Upper Limit on BR($\tau \to e\phi$)



With 3 benchmark
Belle-II luminosities we get

BR($\tau \to e\phi$) ≤

$5.4 \cdot 10^{-5}$ ($\int L\ dt = 0.1/\mathrm{ab}$)

$1.7 \cdot 10^{-5}$ ($\int L\ dt = 1.0/\mathrm{ab}$)

$2.4 \cdot 10^{-6}$ ($\int L\ dt = 50/\mathrm{ab}$)

for m_ϕ = 1 MeV

Our method improves by
a factor 3x the limits obtained
with the current strategy

WIP

$B \to K \tau\mu$

at Belle / Belle II

Motivation

- *B anomalies suggest NP dominantly coupled to the 3rd gen of down-type fermions* [Glashow *et al.*, 2015]

  (and w/ hierarchically smaller couplings to the lighter gen's)

- *Flavour mixing*

  ⇒ *Dominant (flavoured) effects in $b \to s$ & final states w/ τ, including LFV ones*

- *Above obs. made $SU(2)_L$- compliant in* [Bhattacharya *et al.*, 1412.7164]

  thus paving the way for joint explanations of $b \to s$ and $b \to c$

  see also intro of [Greljo *et al.*, 1506.01705]

- *Limitations imposed by data on the above picture discussed in* [Buttazzo *et al.*, 1706.07808]

  A viable avenue: minimally broken $SU(3)^5$ [Barbieri *et al.*, 2011-'12]

$B \to K\,\tau\mu$ at Belle

(only correlated charges shown)

signal: $B^+_{\rm sig} \to K^+_{\rm sig} \tau \ell_{\rm sig}$

tag: *(example)* $B^-_{\rm tag} \to D^0(\to K^-_{\rm tag}\pi^+)\pi^-$ fully reconstructed

- *Search usefully reduced to a "bump hunt" in the τ_{sig} decay products*

$$M^2_{\rm recoil} \equiv (p^*_{e^+e^-} - p^*_{B_{\rm tag}} - p^*_{K_{\rm sig}\ell_{\rm sig}})^2$$
$$= m^2_{B_{\rm tag}} + m^2_{K_{\rm sig}\ell_{\rm sig}} - 2(E^*_{B_{\rm tag}} E^*_{K_{\rm sig}\ell_{\rm sig}} + |\boldsymbol{p}^*_{B_{\rm tag}}||\boldsymbol{p}^*_{K_{\rm sig}\ell_{\rm sig}}|\cos\theta)$$

- *Search could also use semi-lep. tag decays. But then B_{tag} momentum not known, and likewise cos θ*

⇨ Enter M_2 ...

Conclusions

- The M_{T2} variable and its generalizations were conceived for high-p_T events such as pair production of SUSY particles.

  We port these ideas to low-energy processes

- We devise a novel search strategy, that we apply to pair production of tau leptons, with one decaying as

  $\tau \to \ell + \phi$ with ϕ a new, elusive particle

- Our strategy improves the decay-rate sensitivity by 3x compared to the state-of-the-art method.

  (This holds for small m_ϕ, which is the most interesting case.)

- Our strategy has a vast domain of applicability. To B decays as well!

How we get from S / B to the BR limit

- Let N_s (N_b) be the # of generated signal (bkg.) events

  ⇨ the bkg. weight is $w_b = B / N_b$

- By def., B is also given by

$$B = \sigma_{\tau\tau} \times \mathrm{BR}(\tau\tau \to bkg) \times \int \mathrm{L}dt$$

- The 95% CL stat. significance $\sigma(w_s)$ is given by

$$\sigma(w_s) \simeq S / \sqrt{S + B} = w_s N_s / \sqrt{w_s N_s + w_b N_b} = 1.96$$

  ⇨ we can invert in terms of w_s

- Using $S = w_s N_s$ we finally have

$$\mathbf{BR(\tau \to e\, \phi) / BR(\tau \to bkg) = S / B}$$

Note:

The Belle-II analysis determines the BR limit through a template fit instead.

The two procedures are thus independent