

Probing MeV-Range Scalar Bosons and TeV Range Vectorlike Fermions Associated with $U(1)_{T3R}$ at the LHC

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Outline:

- $U(1)_{T3R}$ + vectorlike quarks model.
- Experimental considerations and previous bounds.
- “ $\chi_t - t$ ” fusion interaction topology.
- Samples and simulations.
- Boosted top tagging & boosted W tagging.
- ϕ decay length efficiency and reconstruction considerations.
- Signal optimization.
- Signal significance and exclusion bounds.
- Discussion & summary.

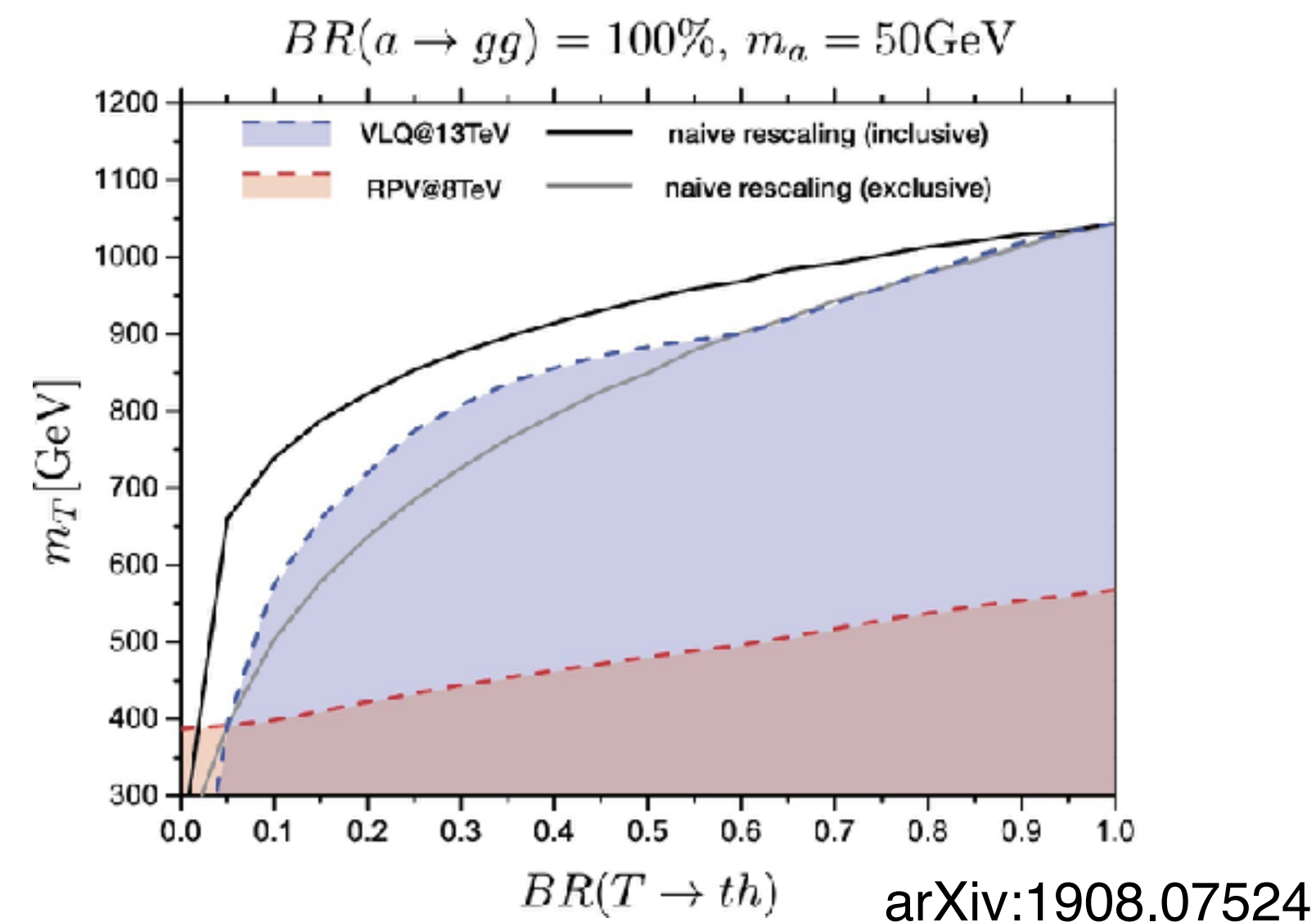
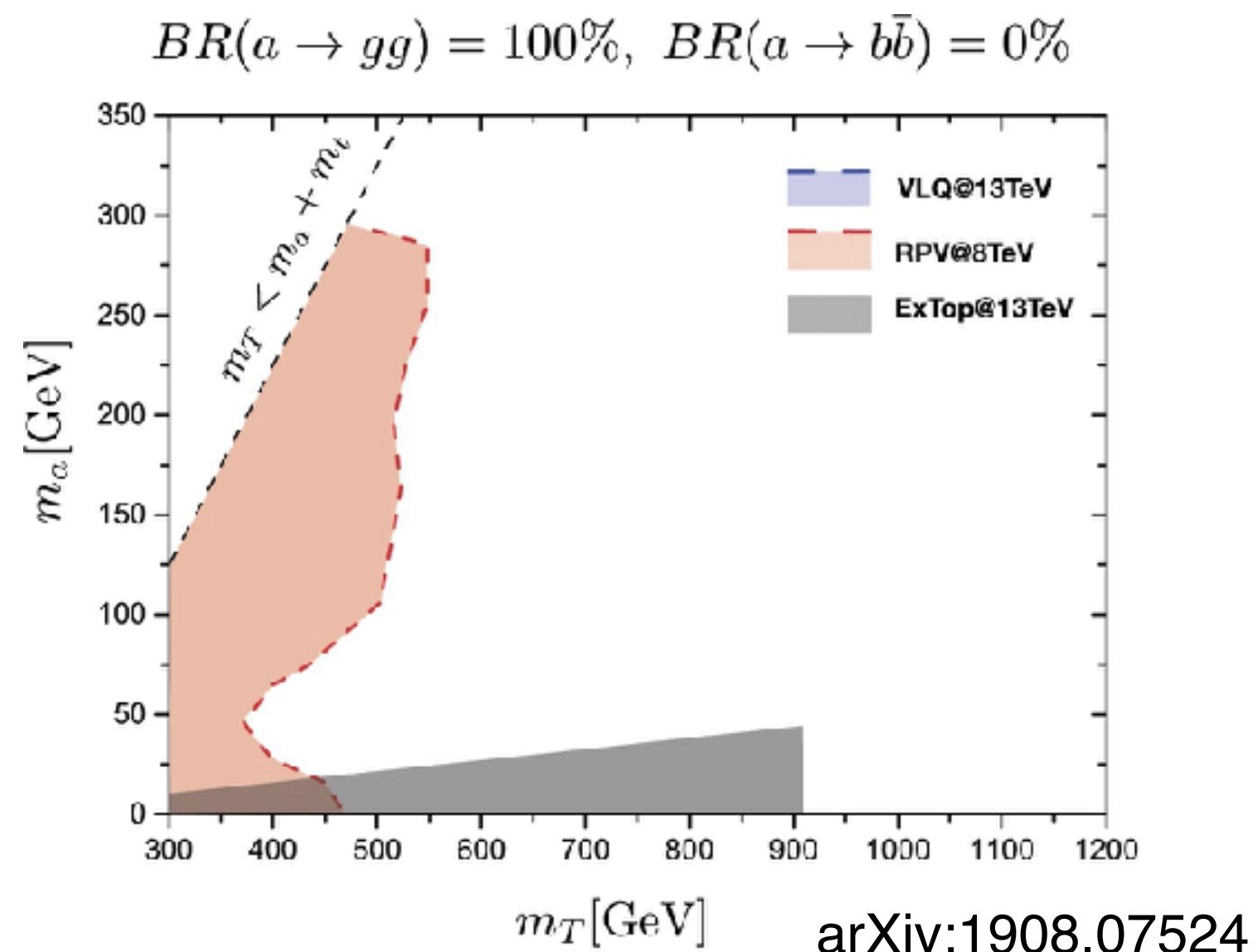
$U(1)_{T3R}$ + Vectorlike Quarks Model:

- Recently, there has been interest in beyond-the-Standard Model (BSM) physics involving new low-mass matter and mediator particles.
- For this model, we consider:
 - A new $U(1)_{T3R}$ gauge group that couples exclusively to a set of right-handed Standard Model (SM) fermions.
 - A set of new vectorlike fermions ($\chi_t, \chi_b, \chi_\ell, \chi_\nu$).
 - A dark Higgs boson (ϕ) (whose vev spontaneously breaks the $U(1)_{T3R}$ symmetry at a low symmetry breaking scale).
 - A resultant massive dark photon.
- The new vectorlike fermions add the following interaction terms to the Lagrangian:

$$\mathcal{L} = \dots - \tilde{m}_{\chi_f} \tilde{\chi}_f \tilde{\chi}_f - \lambda_{fL} H (\tilde{\chi}_f P_L \tilde{f}_L) - \lambda_{fR} \phi^* (\tilde{\chi}_f P_R \tilde{f}_R) - \lambda_{WL} W (\tilde{\chi}_f P_L \tilde{f}_L) - \dots$$

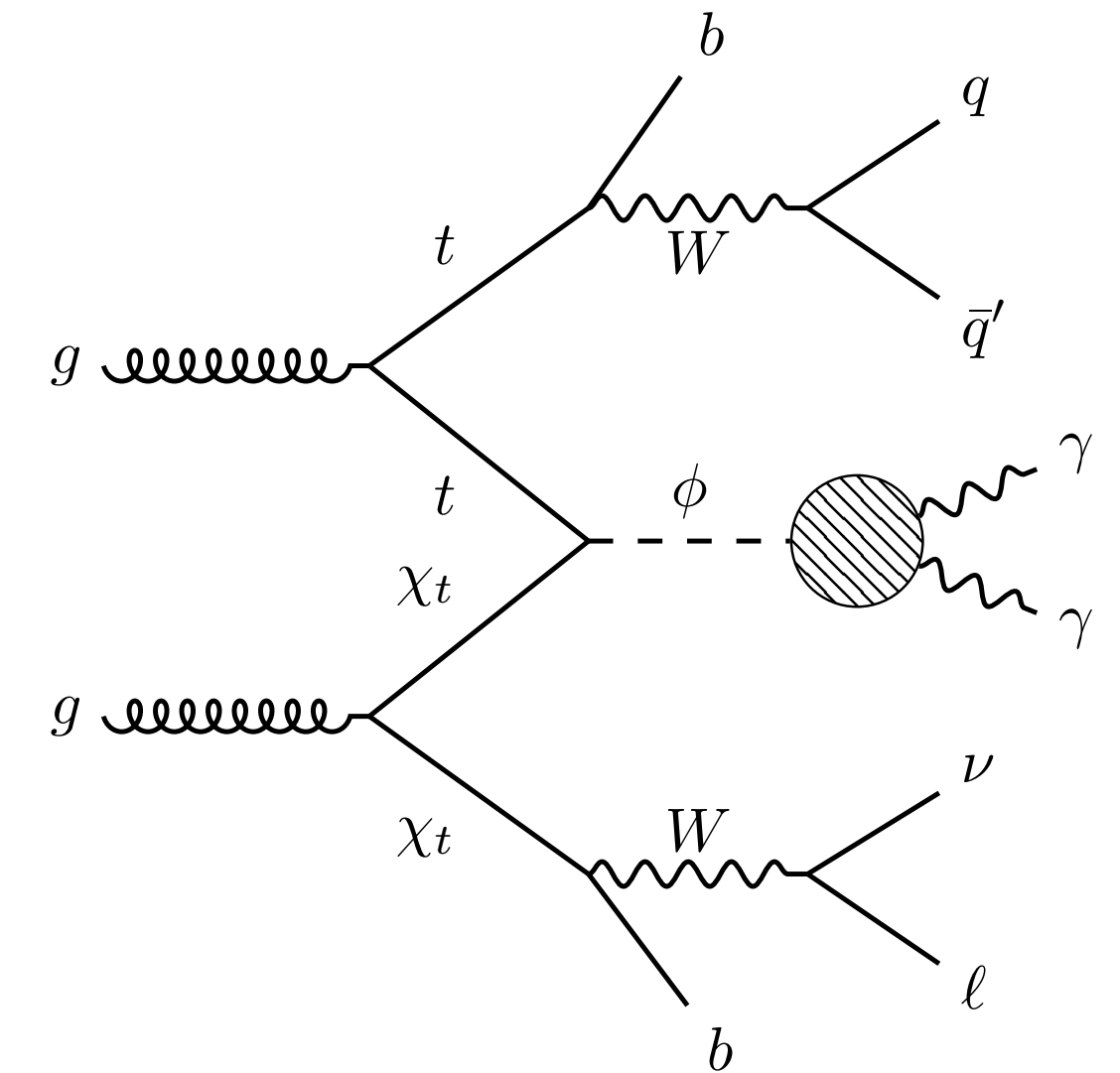
Experimental Considerations & Previous Bounds:

- ϕ can be extremely light, including $\mathcal{O}(\text{MeV}) - \mathcal{O}(\text{GeV})$:
 - Mass scales of this range have traditionally been difficult to probe at the Large Hadron Collider (LHC).
 - SM backgrounds tend to dominate the phase space and are difficult to distinguish from signal.
- ATLAS and CMS Collaborations have excluded χ_t (or T) with masses $m(\chi_T) < 1.3 \text{ TeV}$, for the assumption $\text{Br}(T \rightarrow Ht) + \text{Br}(T \rightarrow Zt) + \text{Br}(T \rightarrow Wb) = 1$.
- For models which also introduce accompanying light scalar bosons, these limits may change depending on the T/χ_t branching fraction and ϕ mass.
- In our model, typical branching fractions are $\text{Br}(T \rightarrow Wb) = 0.5$, and we assume $\text{Br}(\phi \rightarrow \gamma\gamma) = 1$.

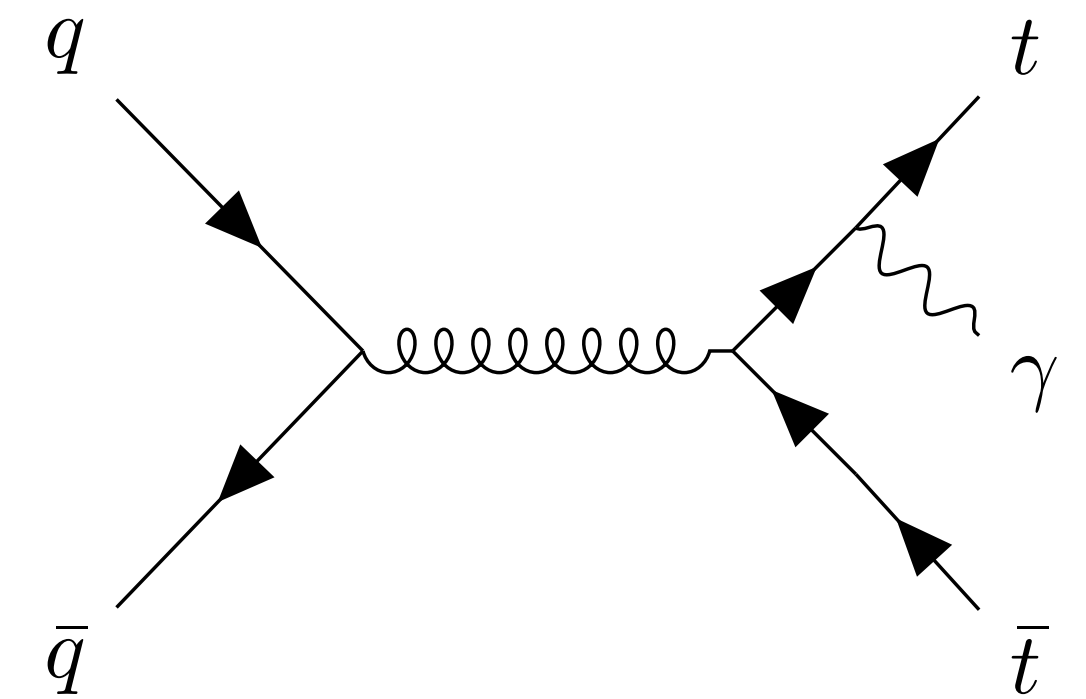


“ $\chi_t - t$ ” Fusion Interaction Topology:

- Sensitivity to $\mathcal{O}(\text{MeV})$ scalars requires production mechanisms which create boosted topologies.
- For this study, we target a “ $\chi_t - t$ fusion” interaction in which:
 - $\phi \rightarrow \gamma\gamma$ (highly collimated!)
 - $t \rightarrow b + jj$
 - $\chi_t \rightarrow b + \ell + \nu$ (see Feynman diagram)
- The final state will contain:
 - a boosted top system which decays hadronically.
 - b-tagged jets.
 - a high p_T lepton + large MET system (due to the χ_t mass scale).
 - a single (highly energetic) photon.
- χ_t mass can be probed via the invariant mass of the b-jet + ℓ + MET system.
- We considered various SM backgrounds such as:
 - W + Jets, Z + jets, γ + jets, $\gamma\gamma$ + jets, QCD multijet, $t\bar{t} + \gamma\gamma$ (higgs & non-higgs), and $t\bar{t} + \gamma$.
 - $t\bar{t} + \gamma$ is the dominant SM background.



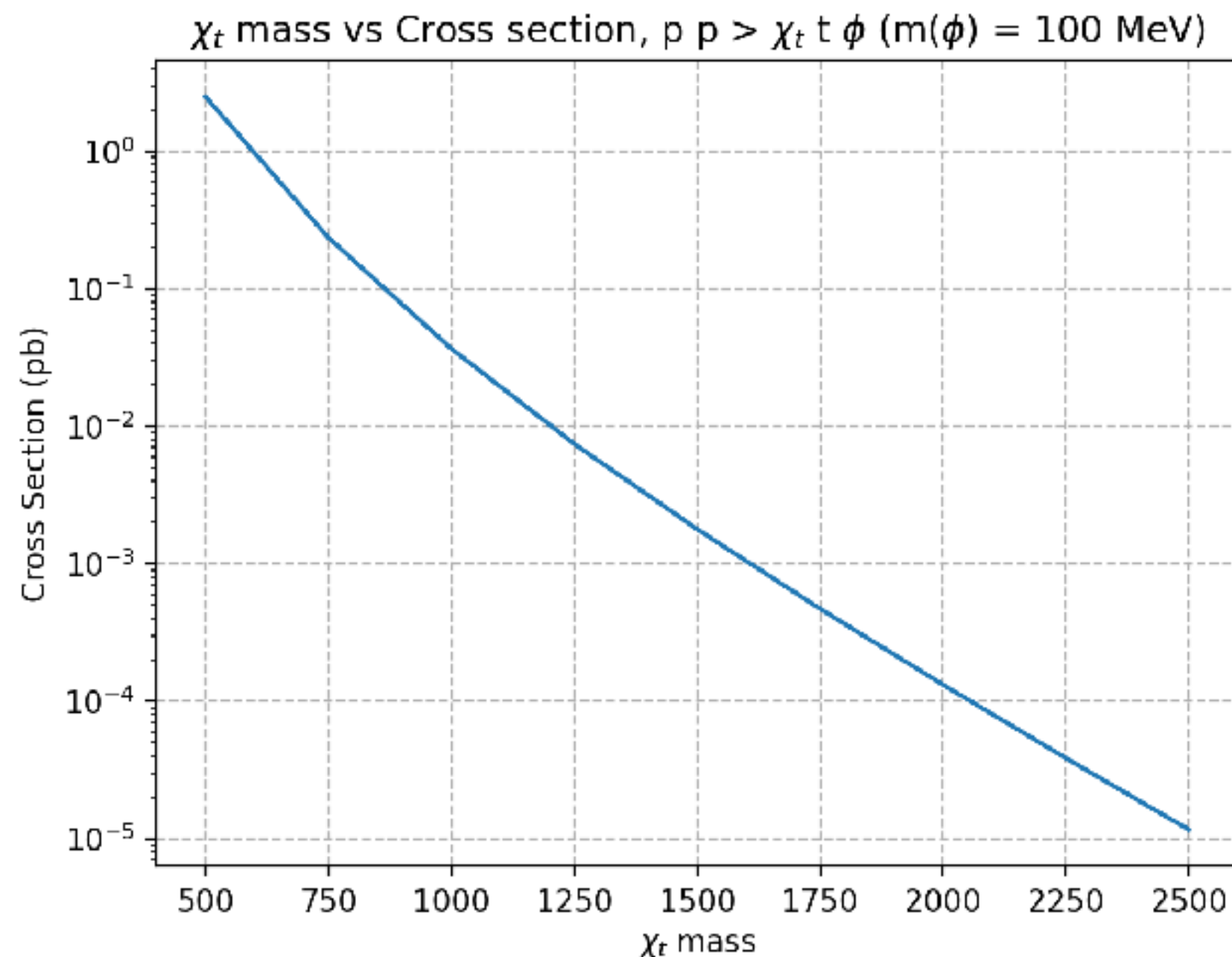
$\chi_t - t$ fusion Feynman diagram.



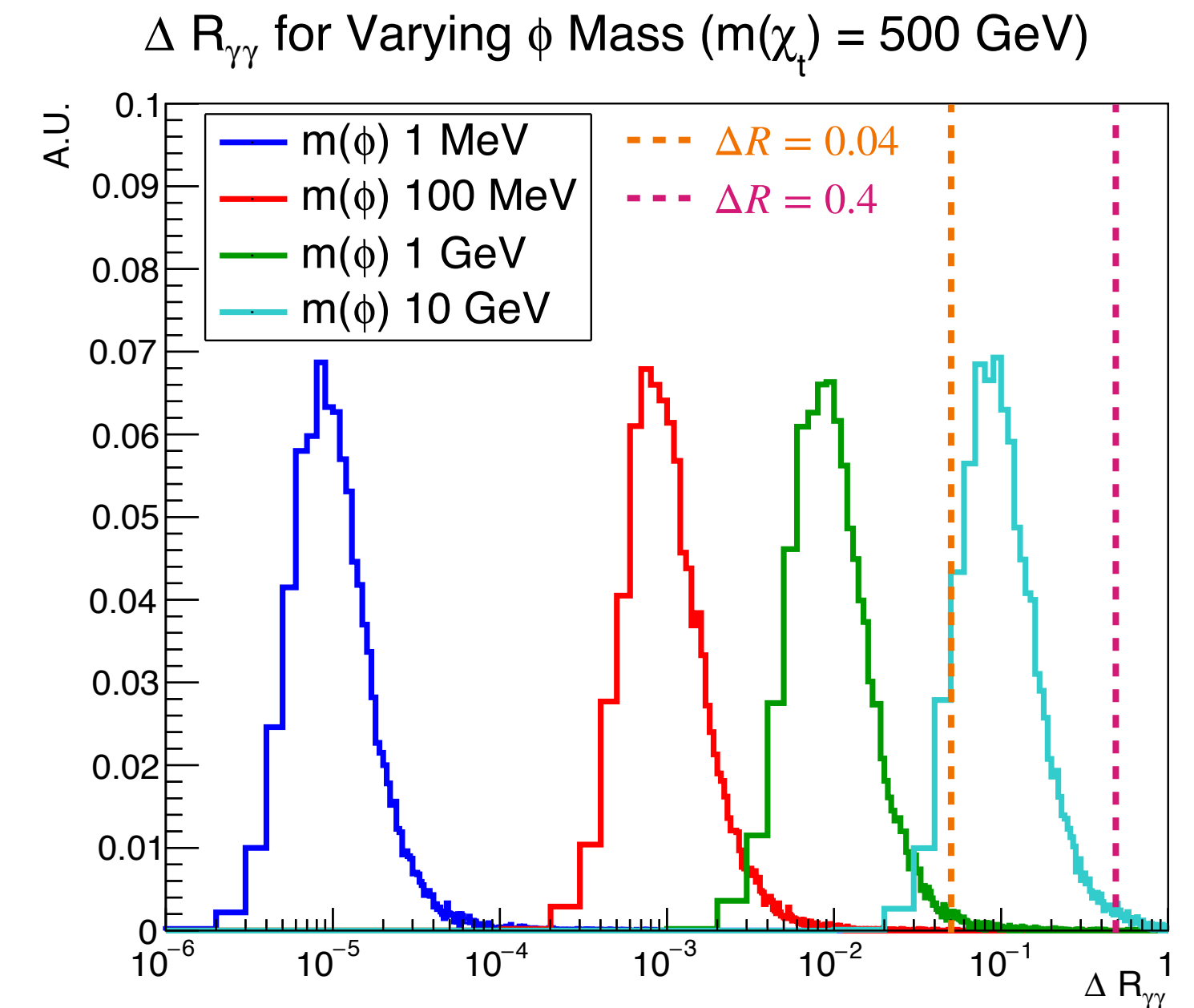
$t\bar{t} + \gamma$ Feynman diagram.

Samples and Simulation:

- Signal and background samples were produced using:
 - **MadGraph5_aMC (v2_7_3)** for event generation.
 - **Pythia8** for parton showering and hadronization.
 - **Delphes** for detector effects.
- To simulate collimated photon reconstruction, photons with $\Delta R_{\gamma\gamma} < 0.04$ were merged into one single object.

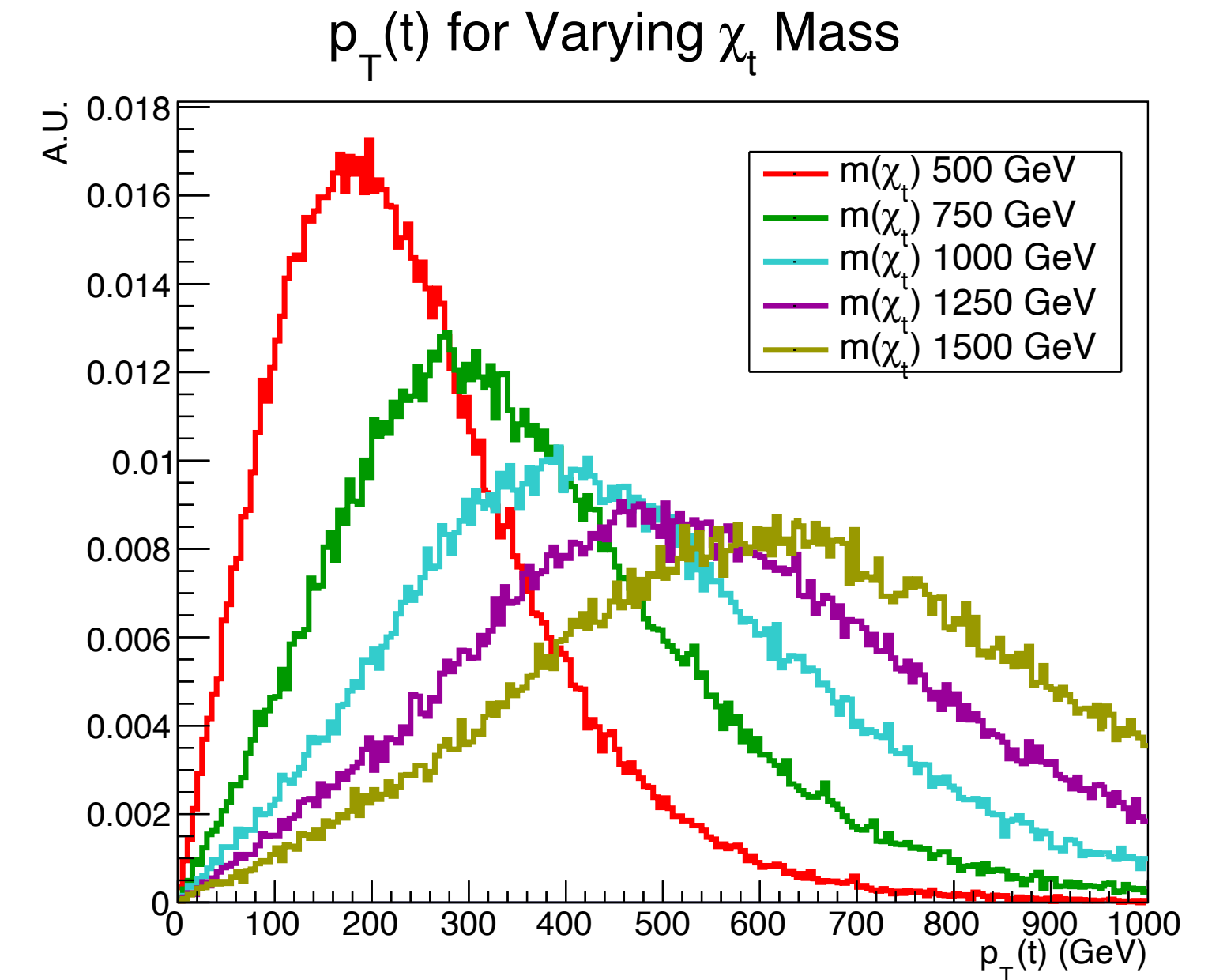
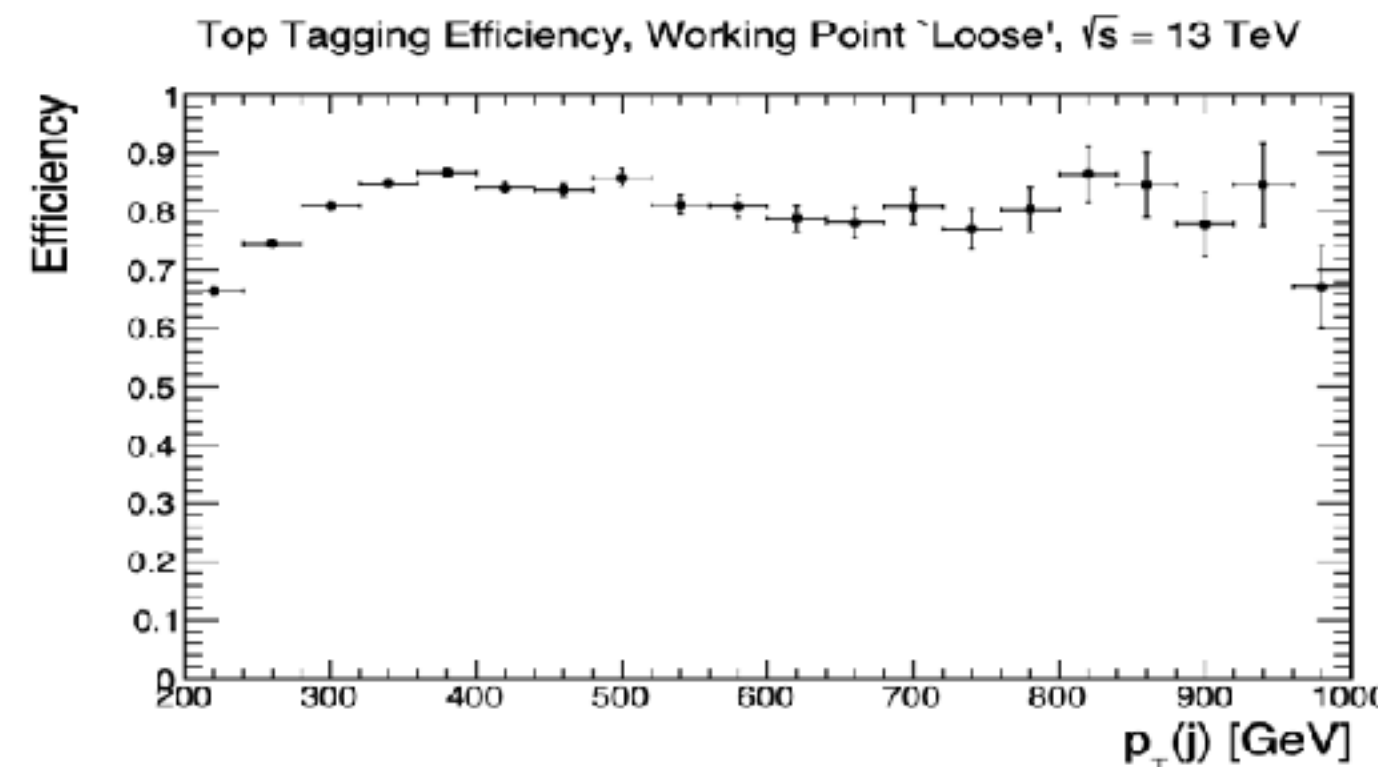
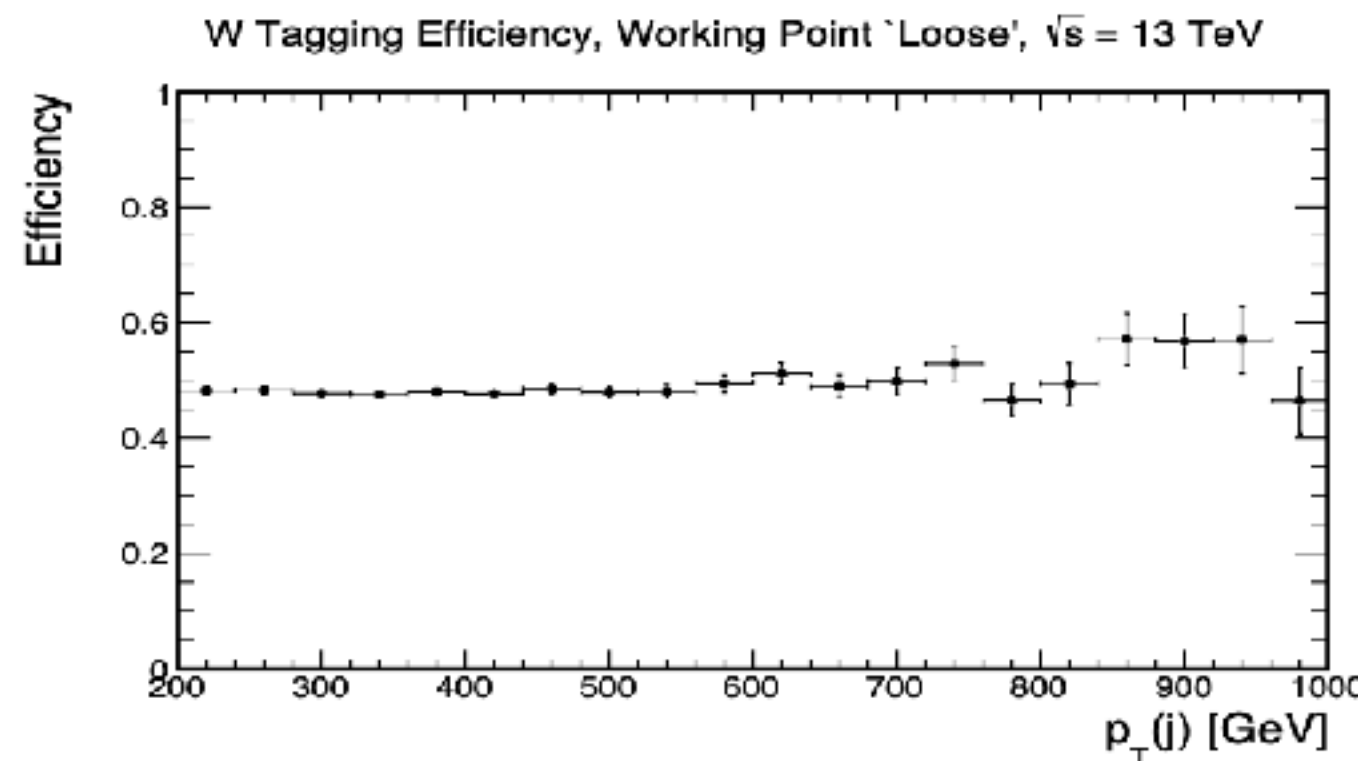
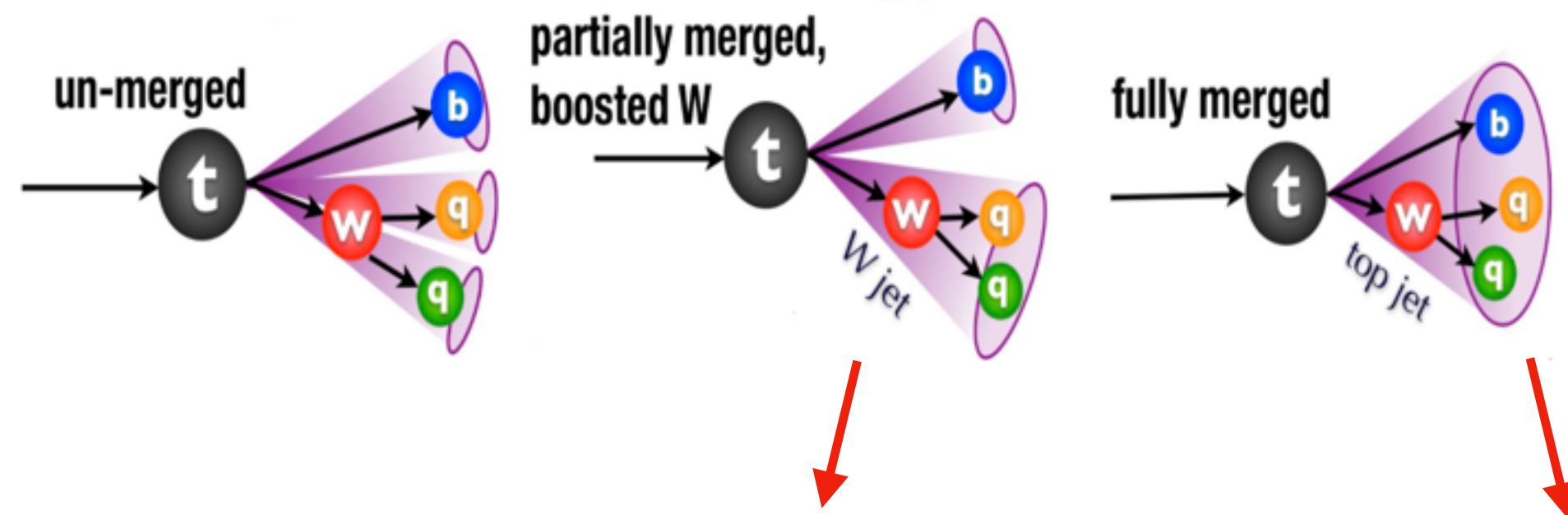


- Bottom quark identification:
 - b-tagged jet closest in ΔR to the dijet pair is labeled the "hadronic bottom" (b_h).
 - b-tagged jet furthest is labeled the "leptonic bottom" (b_ℓ).
 - This identification scheme resembles what is possible experimentally.
- Total event yields are parameterized as $N = \sigma \times \mathcal{L} \times \epsilon$:
 σ - total cross section, \mathcal{L} - luminosity, ϵ - efficiencies (reconstruction, detector effects, signal cuts, etc.)



Boosted Top tagging & Boosted W Tagging:

- A significant portion of tops created will be boosted enough that reconstructing individual decay products becomes difficult:
 - For $p_T(W) > 200$ GeV, ability to resolve two jets decreases quickly.
 - For $250 \text{ GeV} < p_T(t) < 400$ GeV, hadronic decay is partially merged
 - For $p_T(t) > 400$ GeV, top jet is fully merged. [arXiv:1808.07858]



Unmerged - Only the efficiency of b tagging (85%).

Partially merged - b tagging efficiency (85%), Boosted W tagging (50%).

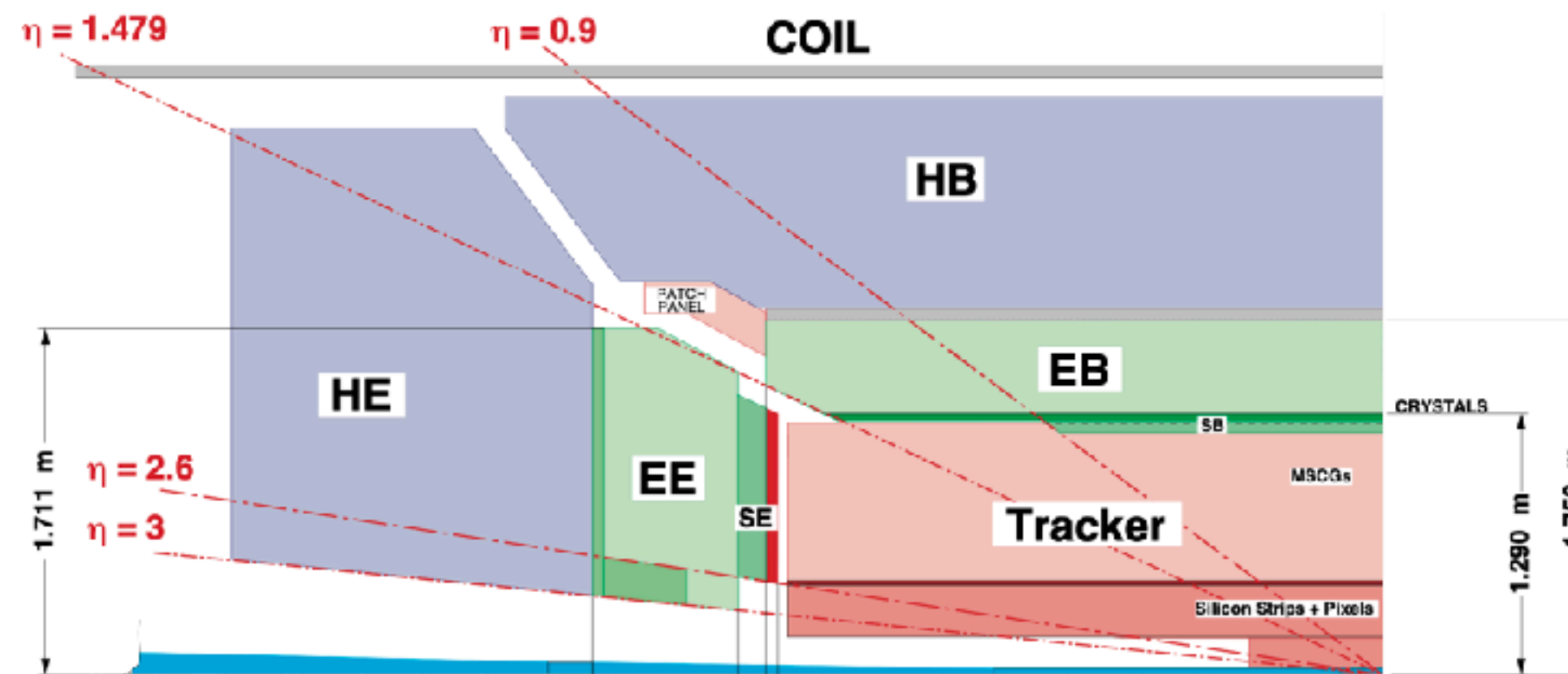
Totally merged - top tagging efficiency (80%).

ϕ Decay Length Efficiency:

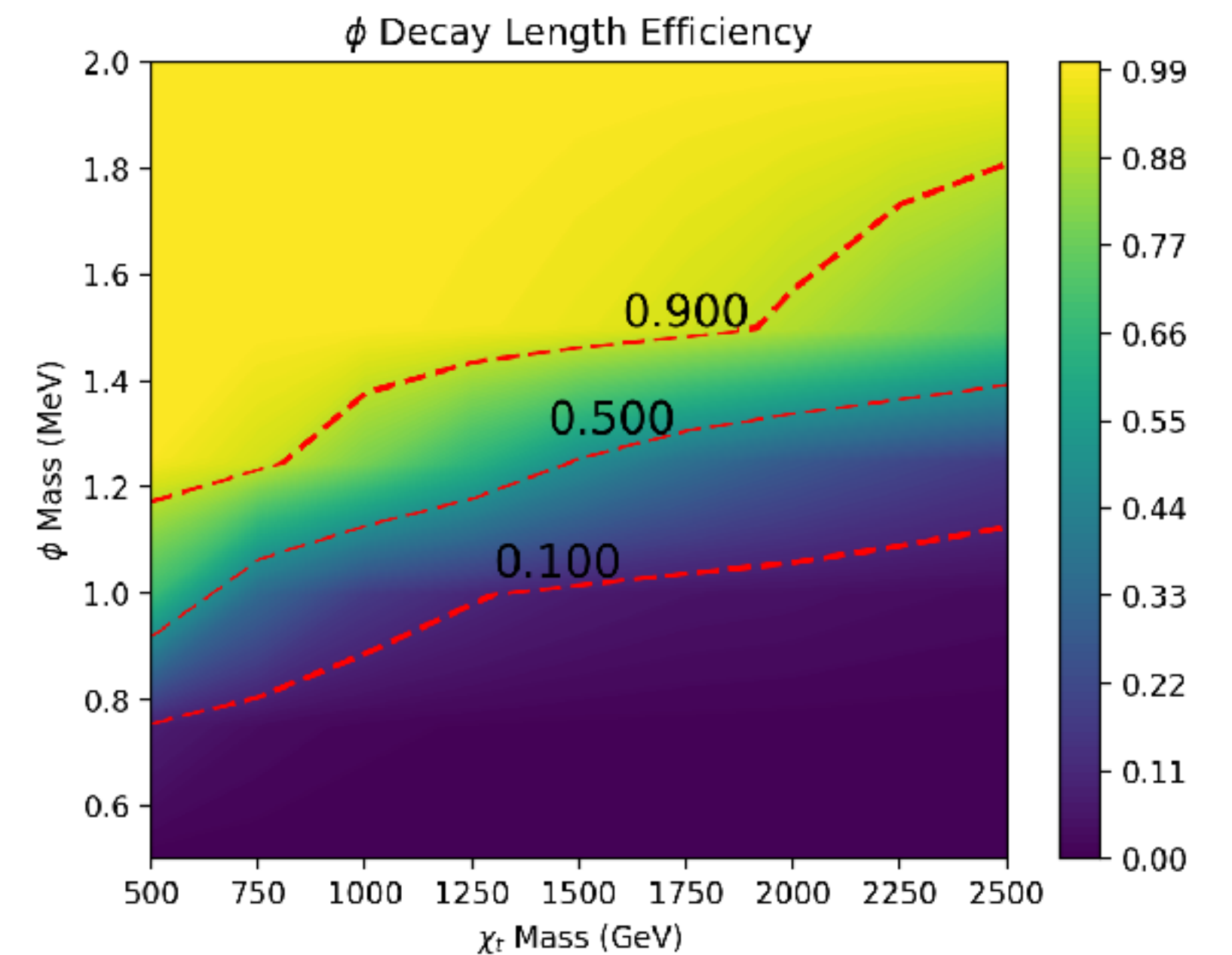
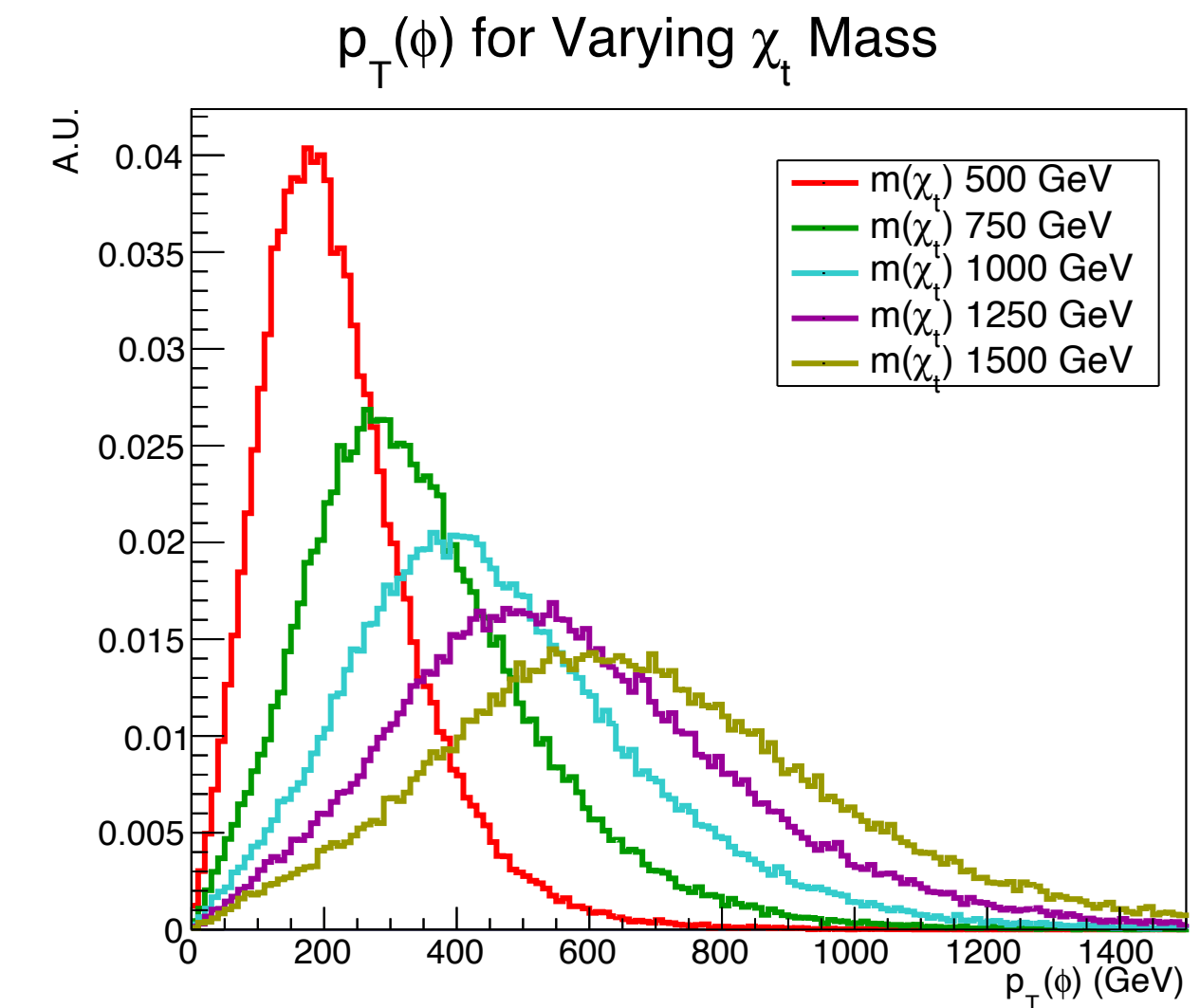
- For sufficiently light ϕ mass, ϕ will decay outside the detector:
 - The final state topology in this case changes (added MET).
 - This represents a lower bound of ϕ mass which can be probed by this search channel.

Phi mass	Phi decay width	Phi lifetime (s)	Distance* (m)
1MeV	3.979e-011 GeV	1.654E-14	0.99
100 MeV	3.979e-05 GeV	1.654E-20	9.9E-09
1 GeV	0.03979 GeV	1.65E-23	9.9E-13

Table 1: Phi parameters (for $p_T(\phi) = 200$ GeV)



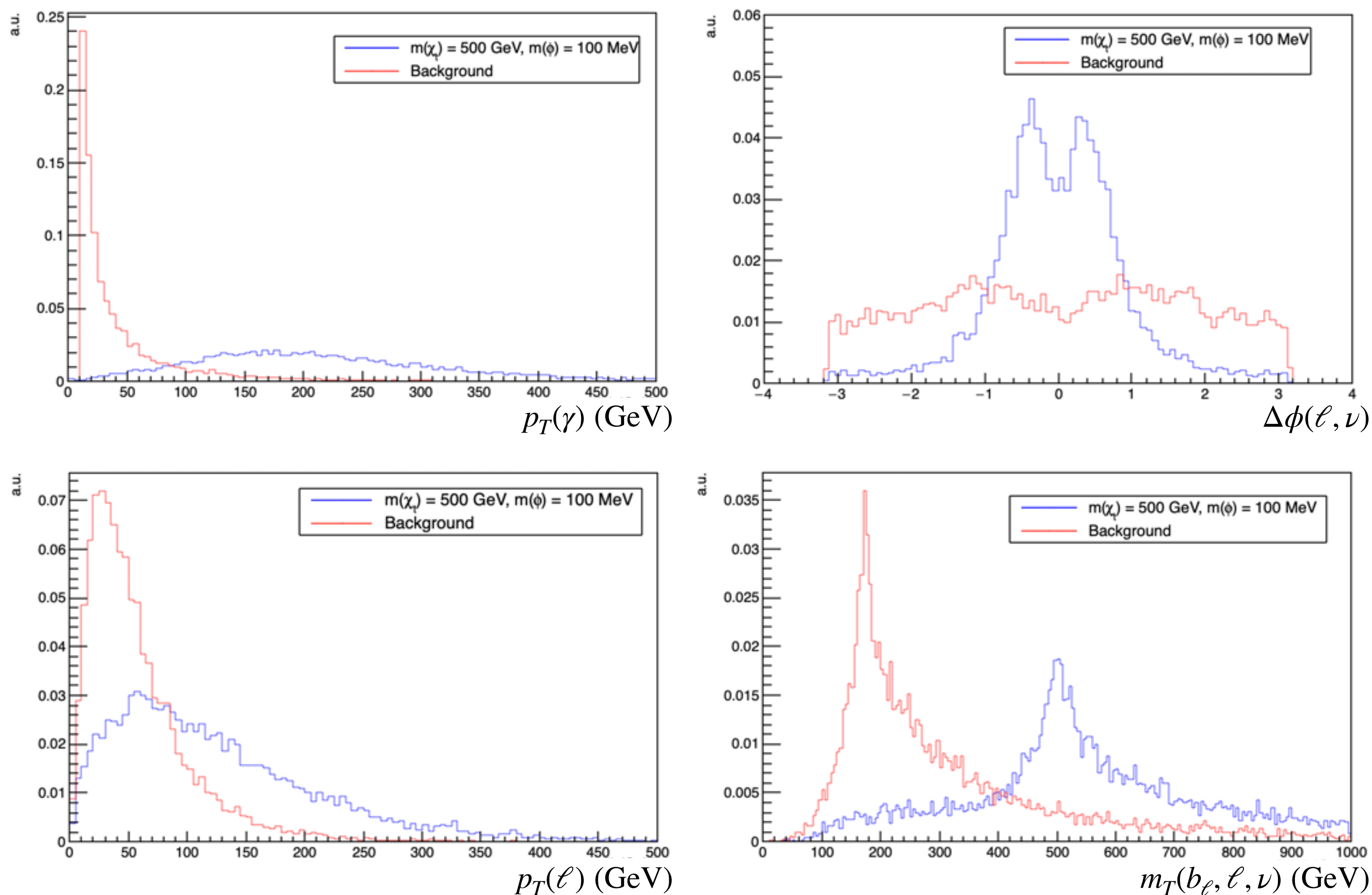
CMS cross section showing transition from Tracker to ECAL.



Signal Optimization:

- Signal optimization was performed sequentially (as shown in Table 2). Selections which showed the greatest contrast between signal and background were optimized first.

Pre-Selection Kinematic Plots:



- Cut values were derived to optimize signal significance:

$$\frac{S}{\sqrt{S + B + (0.25 \cdot (S + B))^2}}$$

S - Event yield in signal, B - event yield in background

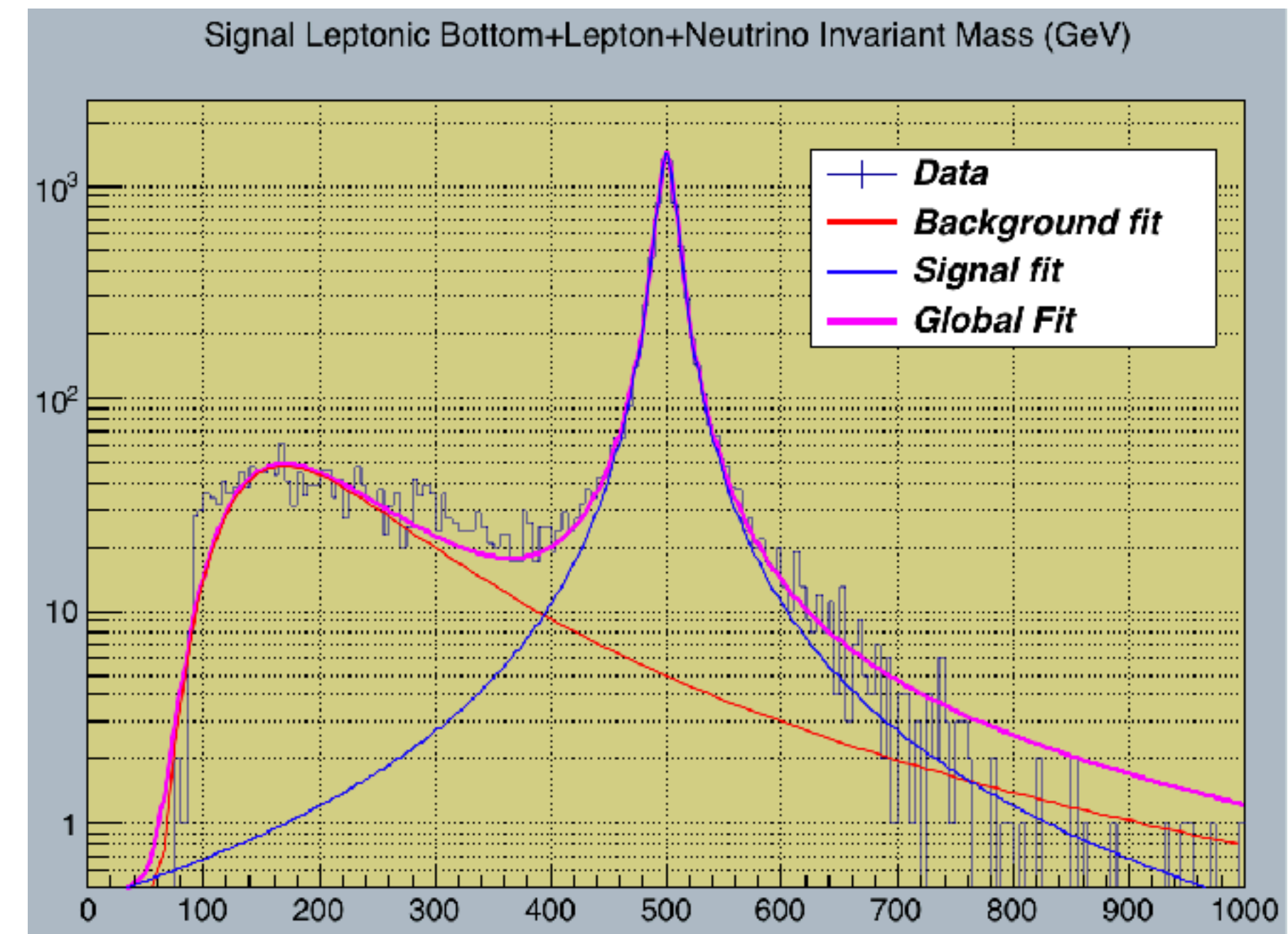
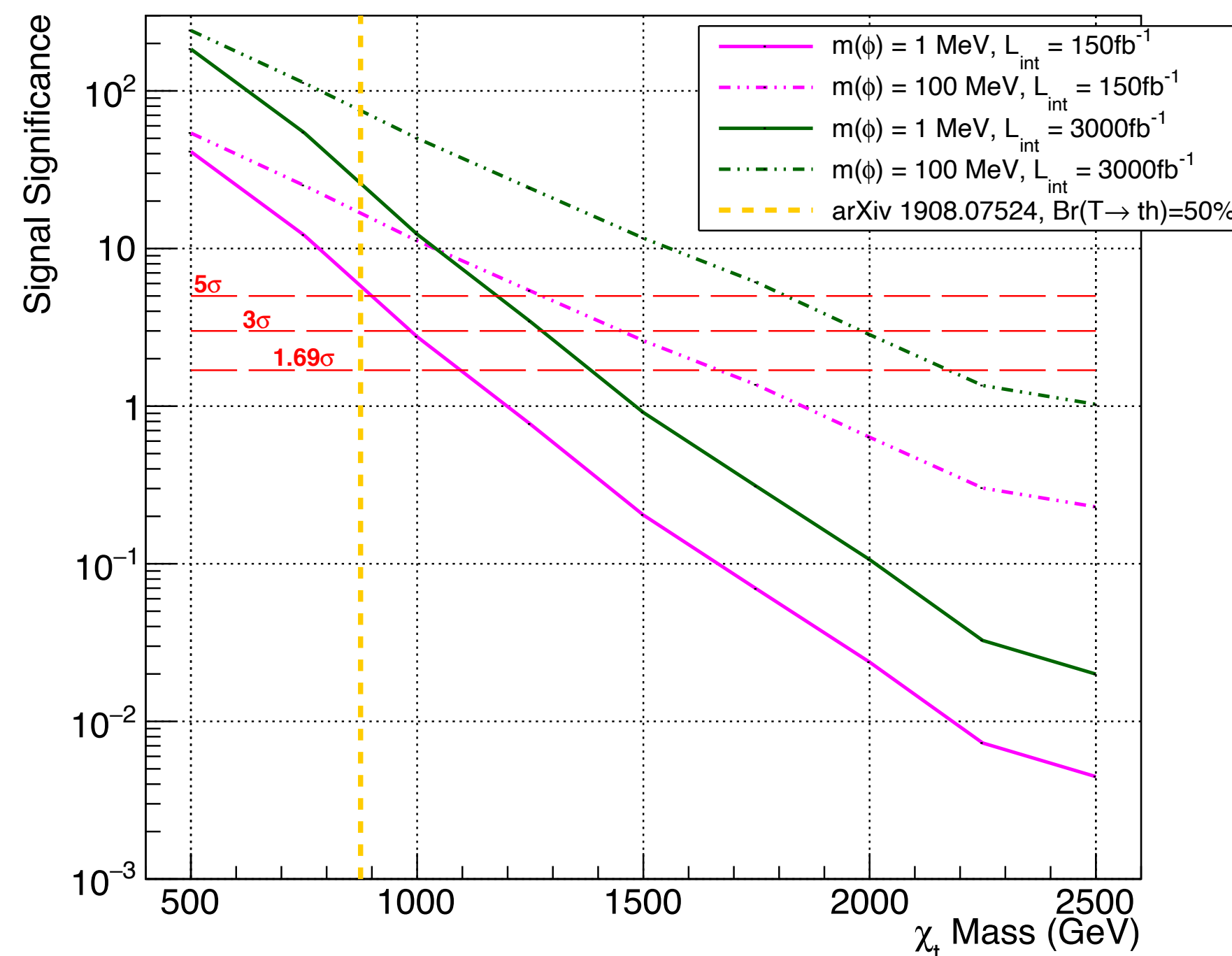
Selection	Value
$p_T(\gamma)$	≥ 160 GeV
$\Delta\phi(\ell, \cancel{E}_T)$	≤ 1
$p_T(\ell)$	≥ 50 GeV
$\eta(\ell)$	≤ 2.5
$p_T(b_\ell)$	≥ 140 GeV
$\eta(b_\ell)$	≤ 2.4
\cancel{E}_T	≥ 20 GeV
$m(b, jj)$	$[120, 220]$ GeV

Table 2: Event selection parameters and values.

Signal Significance & Exclusion Bounds:

- 5σ (95% CL exclusion) signal sensitivity achievable for χ_t masses up to 1.8 (2.2) TeV, for $m(\phi) = 100$ MeV and $L_{int} = 3000 \text{ fb}^{-1}$.
- For lighter ϕ masses, χ_t masses can still be probed up to ~ 1.4 TeV.
- The lower bounds of ϕ mass are heavily dependent on the decay width of ϕ (as this directly affects the decay length efficiency). For larger decay widths, even lower ϕ mass can be probed.
- χ_t mass and width can be measured via the invariant mass of the b-jet + ℓ + MET system.

Signal Significance



Discussion & Summary:

- A new model is proposed that includes: a (broken) $U(1)_{T3R}$ gauge group, a set of vectorlike fermions, & a light scalar boson ϕ (with masses $\mathcal{O}(\text{MeV})$), and a massive dark photon .
- A “ $\chi_t - t$ fusion” interaction is targeted that has a final state consisting of: a top-tagged jet, a bottom tagged jet, a single highly energetic photon, a single lepton + MET.
- The upper bounds of χ_t which can be probed is limited by low cross section. The lower bounds for ϕ which can be probed is limited by ϕ decays outside the detector (these could be probed with a different final state).
- Signal sensitivity can be achieved for χ_t masses up to 2.2 TeV (assuming $m(\phi) = 100 \text{ MeV}$ and $L_{int} = 3000 \text{ fb}^{-1}$).
- Signal sensitivity can be achieved for ϕ masses down to 1 MeV (for $m(\chi_t) = 1.2 \text{ TeV}$ and $L_{int} = 3000 \text{ fb}^{-1}$).

Thank you! Questions?