Scale-invariant resonance tagging in multijet events

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Scale-Invariant Resonance Tagging

M. Gouzevich, A. Oliveira, J. Rojo, R. Rosenfeld, G. Salam, V. Sanz

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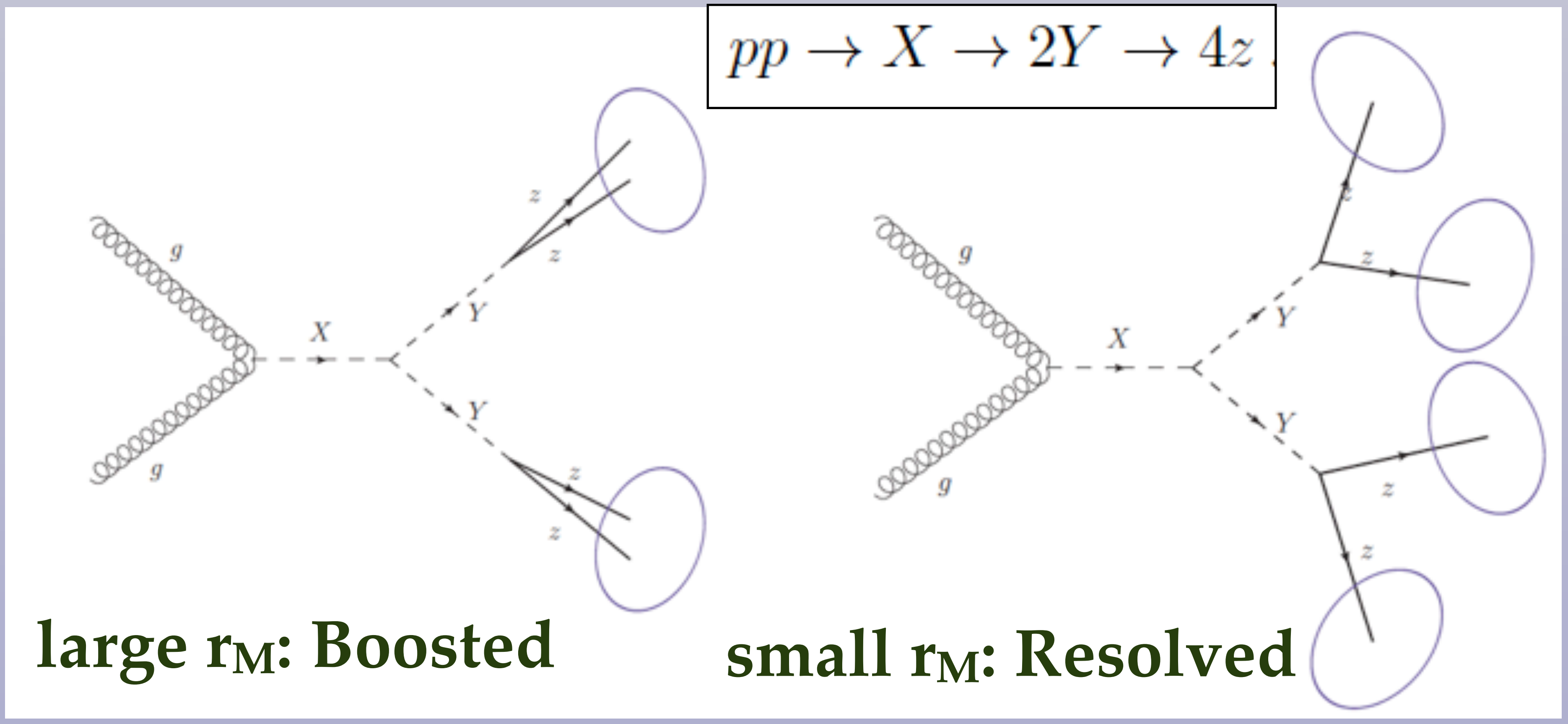
Motivation for scale-invariant tagging

- Many BSM scenarios involve **resonant pair production** of heavy (SM and BSM) particles
- In the spirit of **simplified models,** we assume that the underlying process is

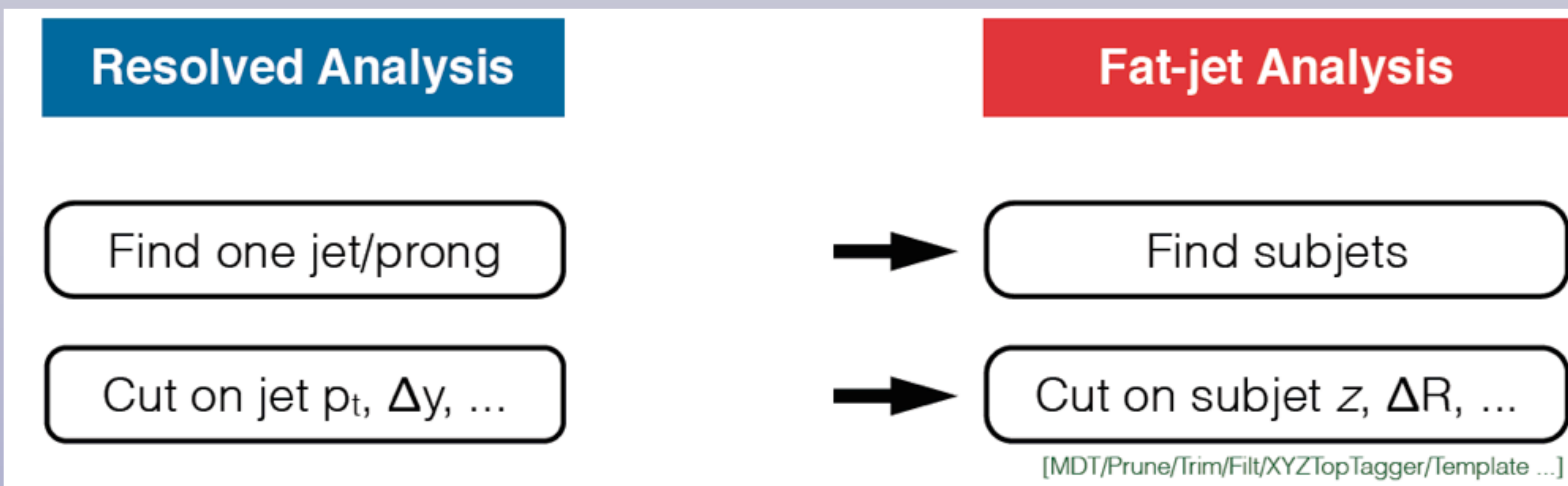
$$\boxed{pp \to X \to 2Y \to 4z}$$

- Depending on the value of the mass ratio $\mathbf{r_M=M_X/2M_Y}$ different final state topologies arise
- For large $\mathbf{r_M}$ the intermediate heavy particles Y will be **highly boosted,** and thus their decay products **z** will be close in the detector
- For small $\mathbf{r_M}$ the Y particles are produced close to rest, and the four decay particles **z** are well separated in the detector: **resolved regime**



Motivation for scale-invariant tagging

- In the resolved regime, **small r_M,** select two Y candidates by **dijet mass pairing**
- In the boosted regime, **large r_M,** select two Y candidates using **jet substructure**
- Can we design a **search strategy** that efficiently explores simultaneously **the whole r_M range,** and improves the overall efficiency by including the **intermediate mass** regime?
- To achieve a similar tagging efficiency, we want to apply the **similar selection cuts** in the **boosted and resolved regimes**

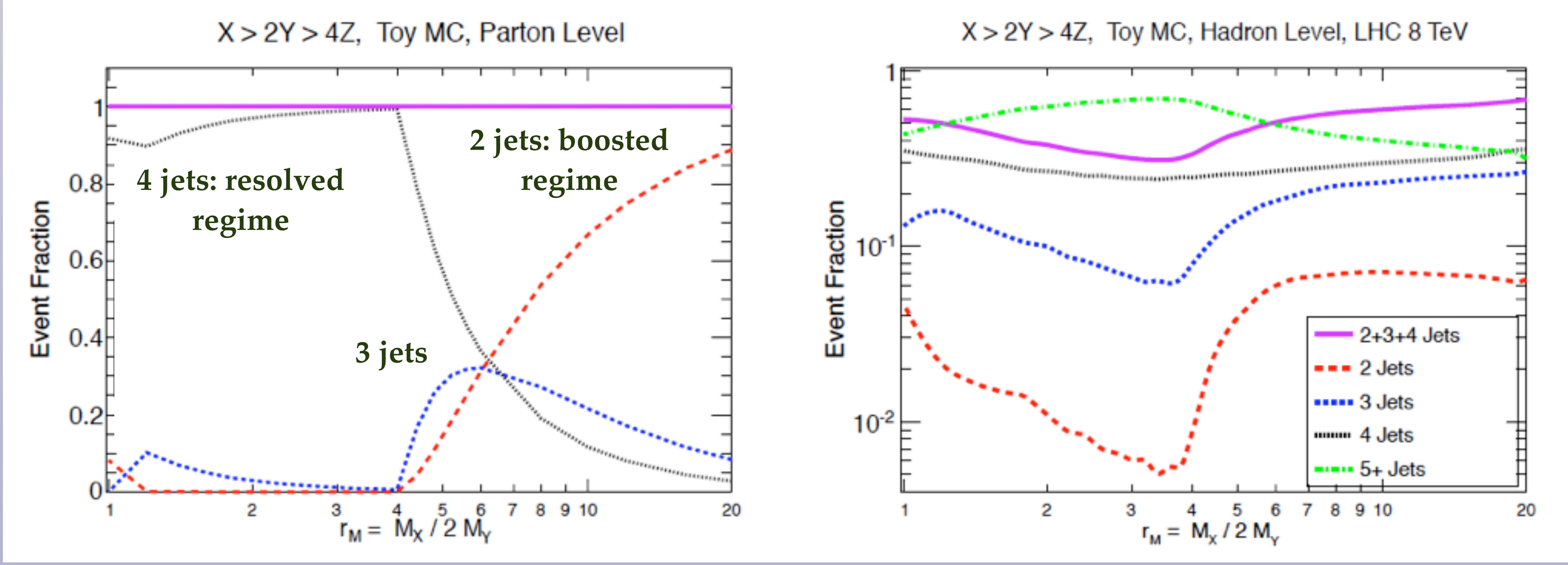


Event Classification

Generated events for **X > 2Y > 4z** with an **in-house toy MC**, interfaced to **Pythia8** for showering and hadronization

At **parton level**, without cuts, the classification of the event topology, *boosted*, *resolved* or *intermediate*, can be trivially obtained **based on the number of jets**

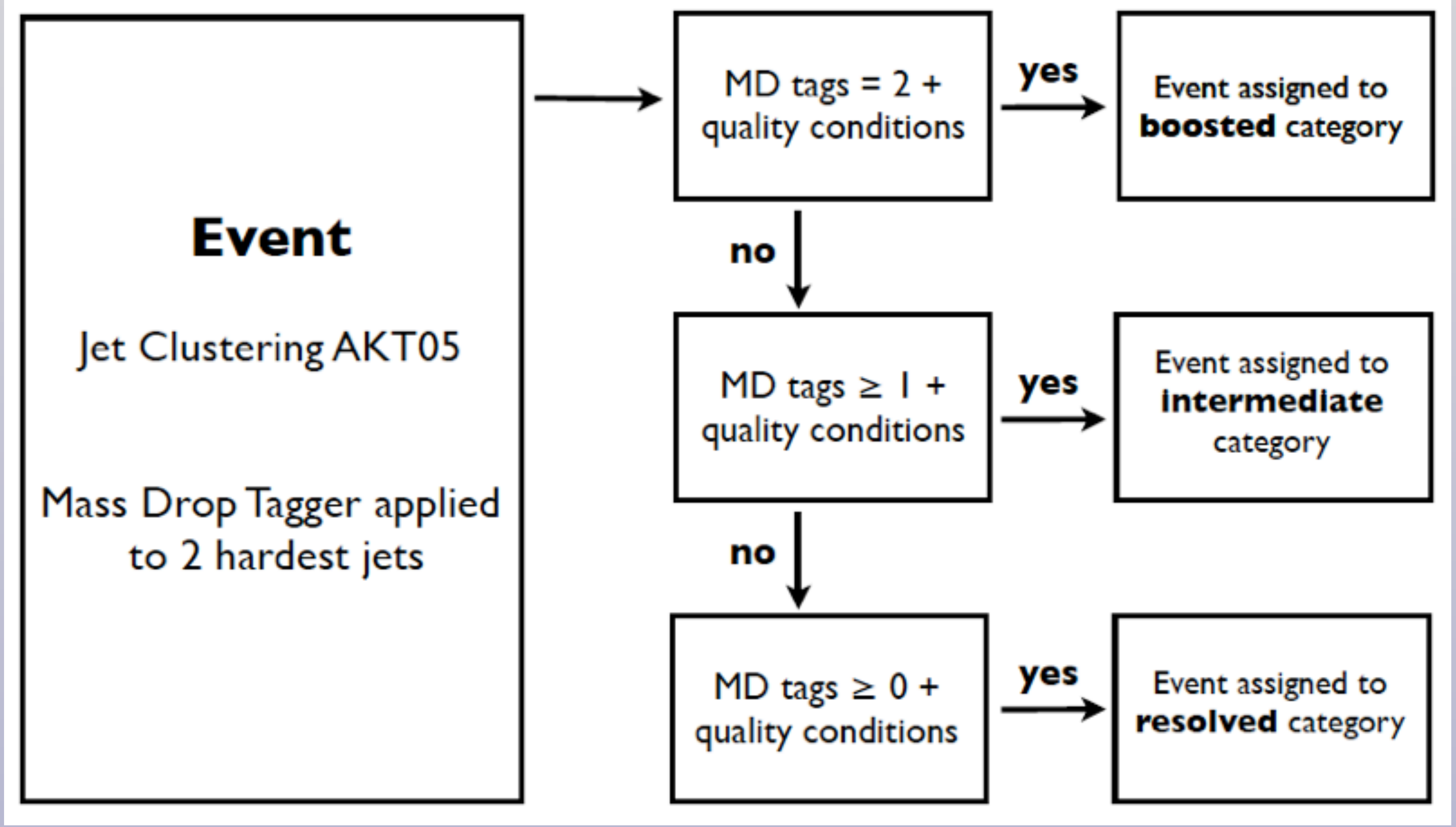
But at **hadron level** with **realistic cuts** such naive classification is not feasible



$|\eta| < 5$
$p_{t,jet} > 25$ GeV
$H_T > 100$ GeV

Event Classification

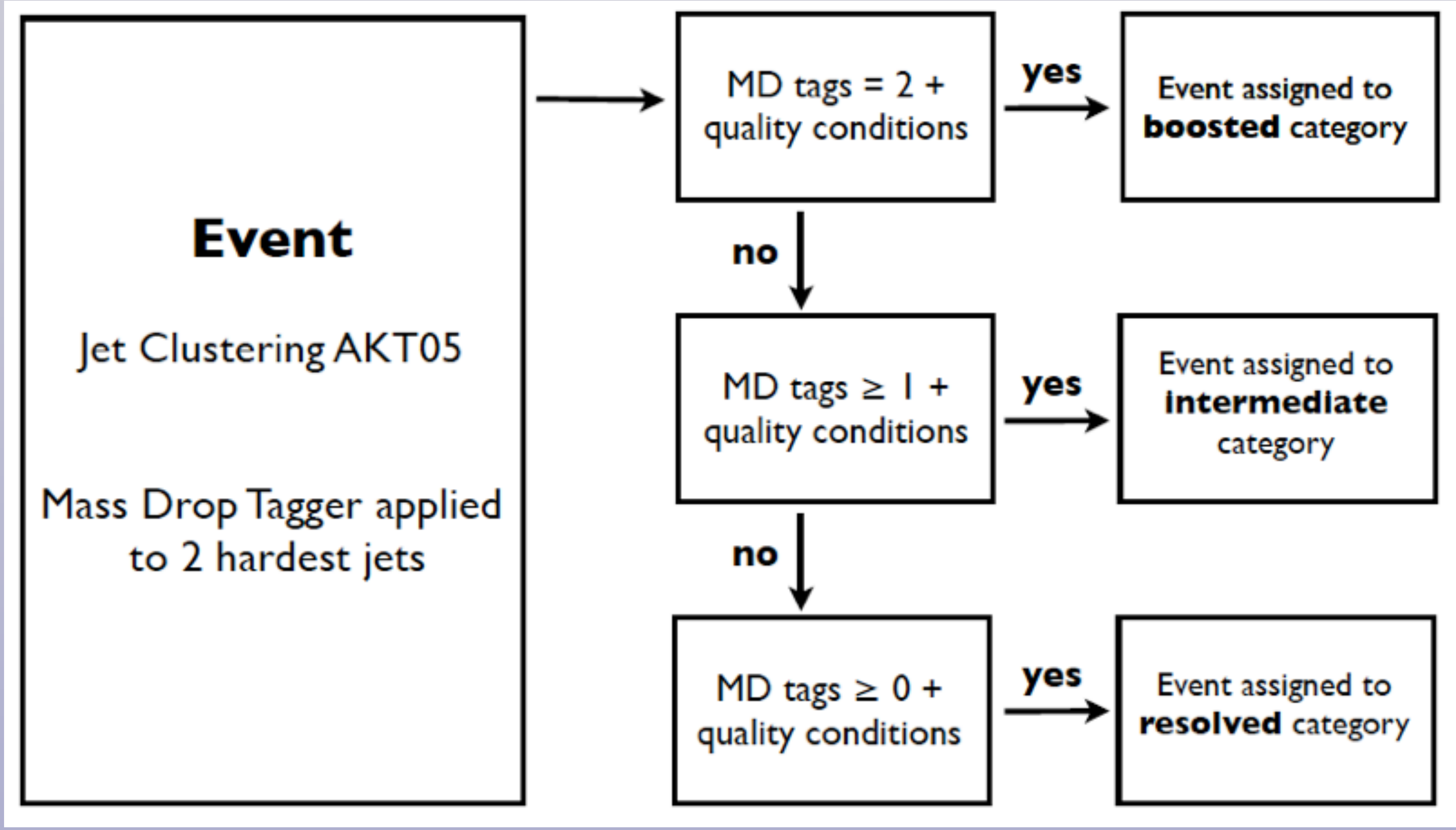
- Use **event classification** based on the number of **mass-drop substructure tags** of leading two jets



- **Boosted category:** each MD tagged jet assumed to be a Y resonance candidate
- **Intermediate category:** MD tagged jet first Y resonance, then pair the other two leading jets in event
- **Resolved category:** The two Y resonance candidates determined from dijet pairing that minimizes M_Y difference

Event Classification

- NB: this is really a **specific analysis** based on a **specific data sample ...**
- **...** but based on a **physical criterion, event-by-event**, to **apply the resonance analysis** that is specially **optimized for a given event topology**
- **Allows one to combine multiple analyses** into a common search, or at least, to **improve the efficiency of existing searches** thanks to the **smooth transition in the intermediate region**



Quality Conditions

To select events as arising from the **resonance X**, we require quality requirements, which are designed to lead to the same effects in the **boosted** and **resolved** regimes

Common cuts

$$\Delta y \equiv |y_{Y1} - y_{Y2}| \leq \Delta y_{\max}$$

(s-channel BSM production more central, t-channel QCD more forward)

$$\left| \frac{(m_{Y1} - m_{Y2})}{\langle m_Y \rangle} \right| \leq f_m$$

$$M_Y (1 - f_m) \leq m_{Y1}, m_{Y2} \leq M_Y (1 + f_m)$$

(Mass resolution & mass window)

Boosted regime

(applied to subjets within fat jet)

$$m_{j1} \leq \mu \cdot m_j$$

$$\frac{\min(p_{t,j1}, p_{t,j2})^2}{m_j^2} \Delta R^2_{j1,j2} > y_{\rm cut}$$

Resolved regimes

(applied to resolved jets of a Y candidate)

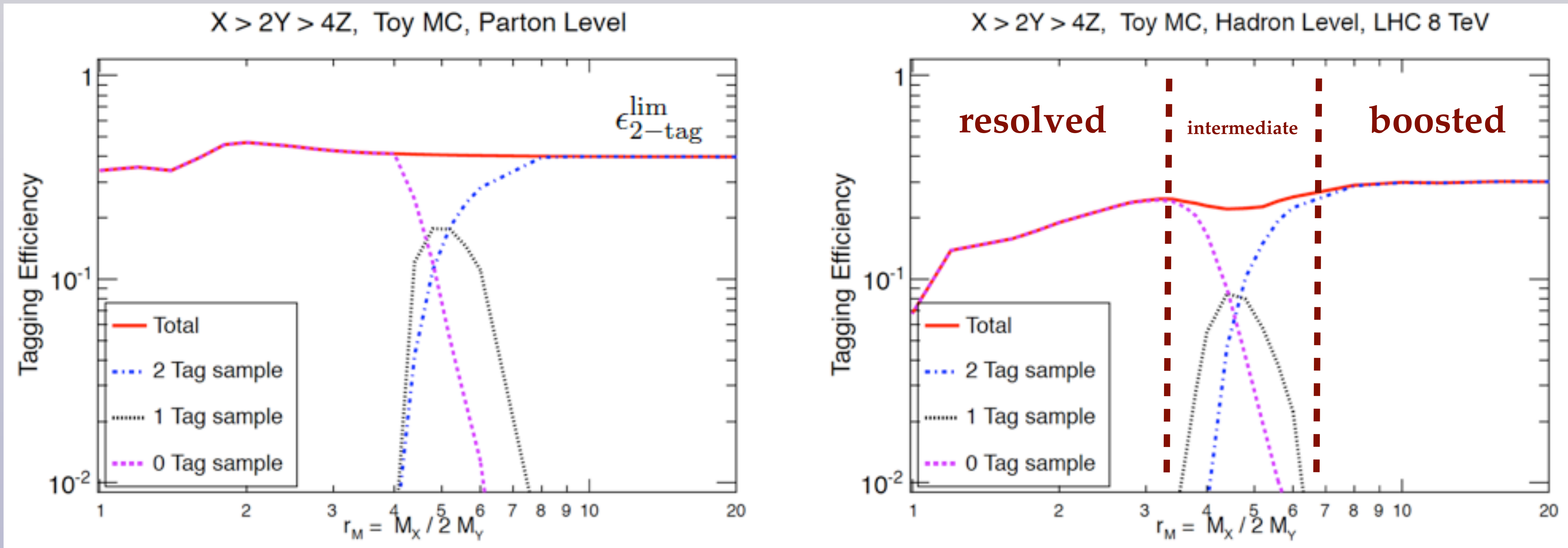
$$\max(m_{Yi,1}, m_{Yi,2}) \leq \mu \cdot m_{Yi}$$

$$p_T^{(2)} \geq y_{\rm cut} \cdot p_T^{(1)}$$

$$\Delta y \equiv |y_{Yi,1} - y_{Yi,2}| \leq \Delta y^{\rm res}_{\max}$$

Scale-invariant tagging

- Tagging efficiency **independent of the value of the mass ratio** (except hadron level small $\mathbf{r_M}$)
- **Smooth interpolation** between the boosted and resolved regimes



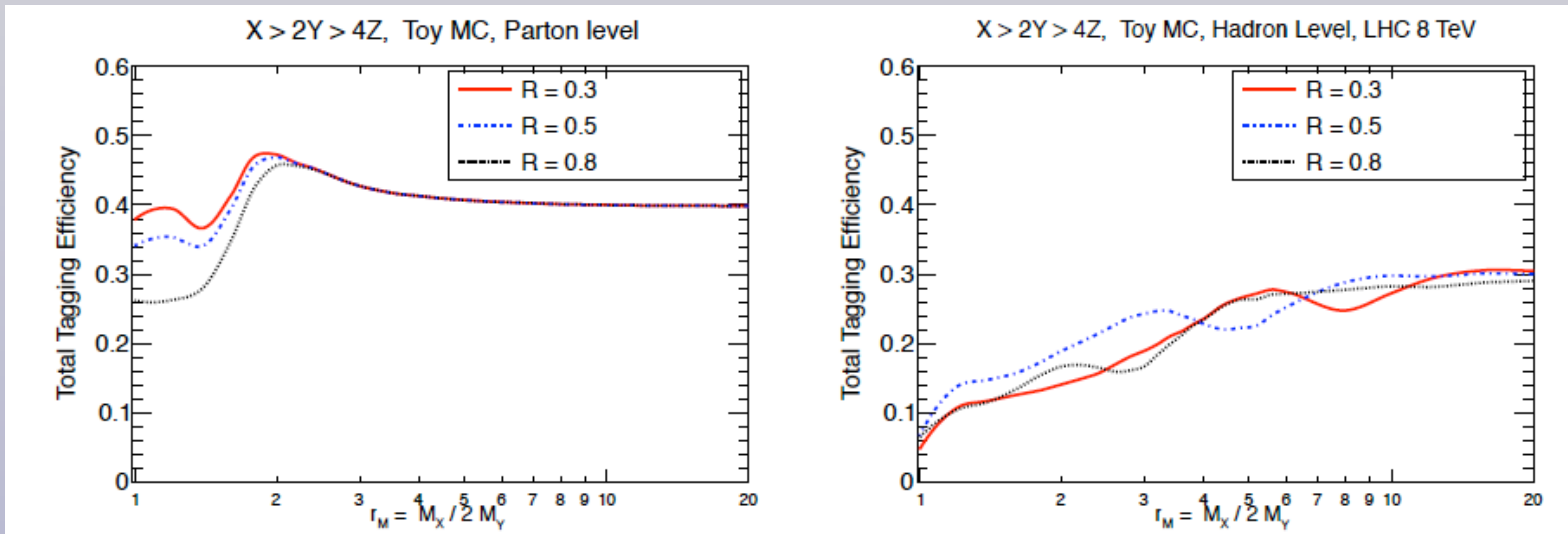
- At parton level the **tagging efficiency in the boosted limit** can be computed analytically

$$\epsilon_{2-\mathrm{tag}}^{\mathrm{lim}} \equiv \epsilon_{2-\mathrm{tag}}\left(r_M \gg 1\right) = \left(1 - \frac{2y_{\mathrm{cut}}}{1+y_{\mathrm{cut}}}\right)^2 \cdot \frac{\exp(\Delta y_{\mathrm{max}})-1}{\exp(\Delta y_{\mathrm{max}})+1} \sim 0.40$$

Scale-invariant tagging: with a **single analysis**, explore **simultaneously both the boosted and resolved regimes**, with a smooth interpolation for intermediate masses

Scale-invariant tagging

- Tagging efficiency is also **independent of the value of jet radius**
- **The relative classification of the events** in the **resolved**, **boosted** and **intermediate** categories depends on **R,** but the total tagging efficiency is reasonably **R-independent**



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Radius-independent tagging: Results are resilient against choice of **R**

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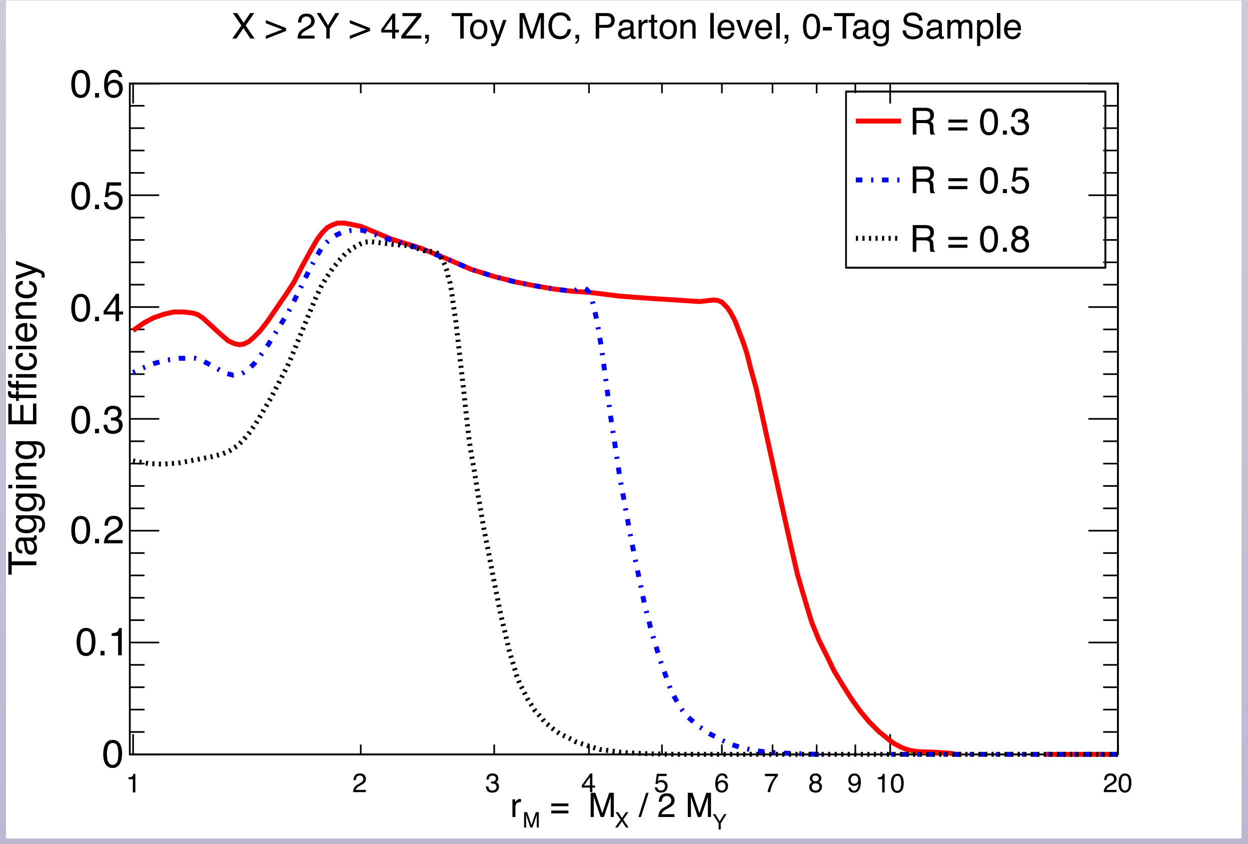
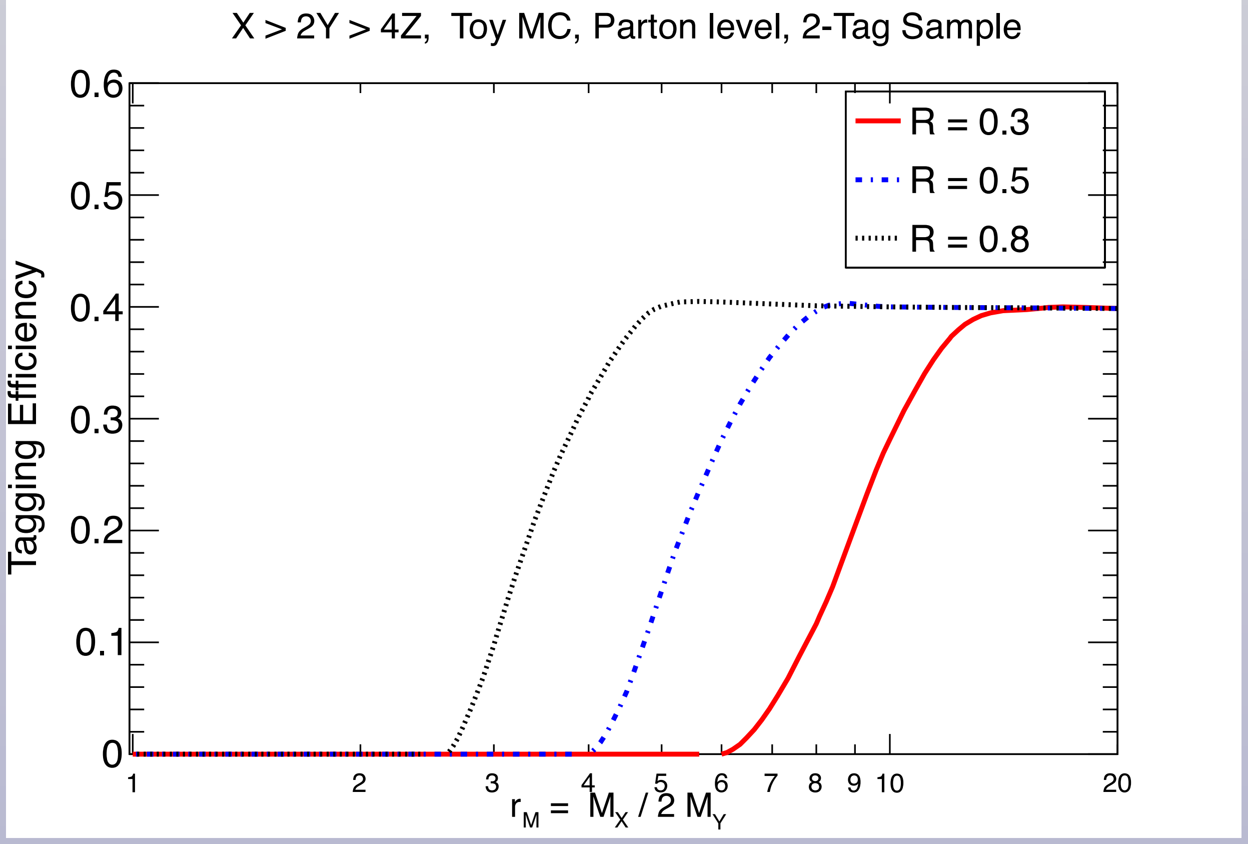
Resolved



Boosted



Scale-invariant tagging: with a **single analysis**, explore **simultaneously both the boosted and resolved regimes**, with a smooth interpolation for intermediate masses

Radius-independent tagging: Results are resilient against choice of **R**

Application to Searches for Enhanced Higgs Pair production in the 4b Final State

M. Gouzevich, A. Oliveira, J. Rojo, R. Rosenfeld, G. Salam, V. Sanz

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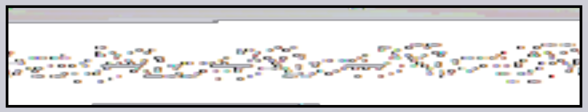
See also **Ben's talk** and **arXiv:1307.0407**

New physics in Higgs pair production

- As a first application of the general scale-invariant strategy, we study **resonant Higgs pair production** in the **4b final state**



$$pp \to X \to 2H \to 4b$$

General kinematics

Specific application

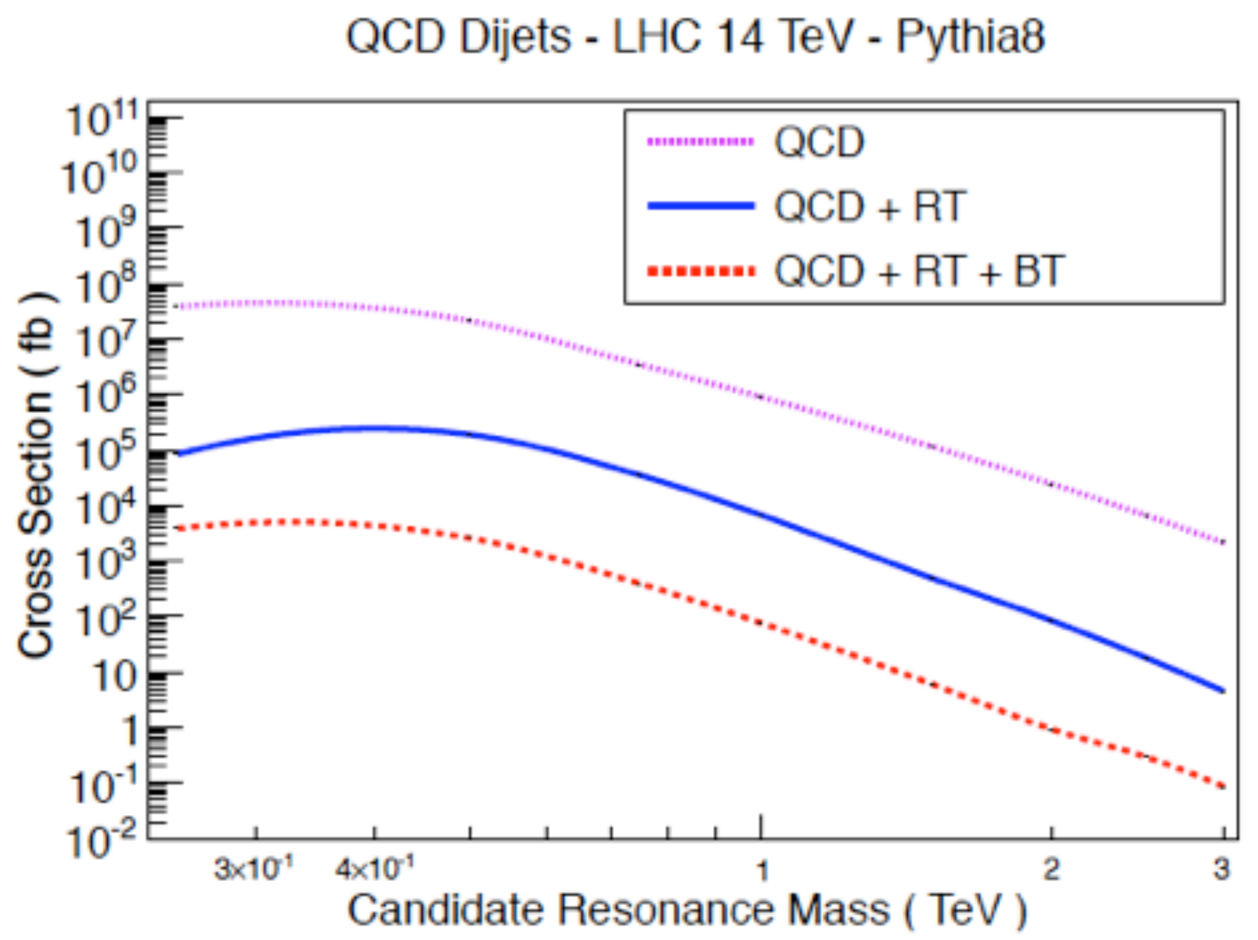
- Enhancement of Higgs pair production is a generic feature of many BSM scenarios
- Here we provide first a **model-independent analysis**, and then interpret the results in the context of **radion and graviton production** in warped extra dimension models

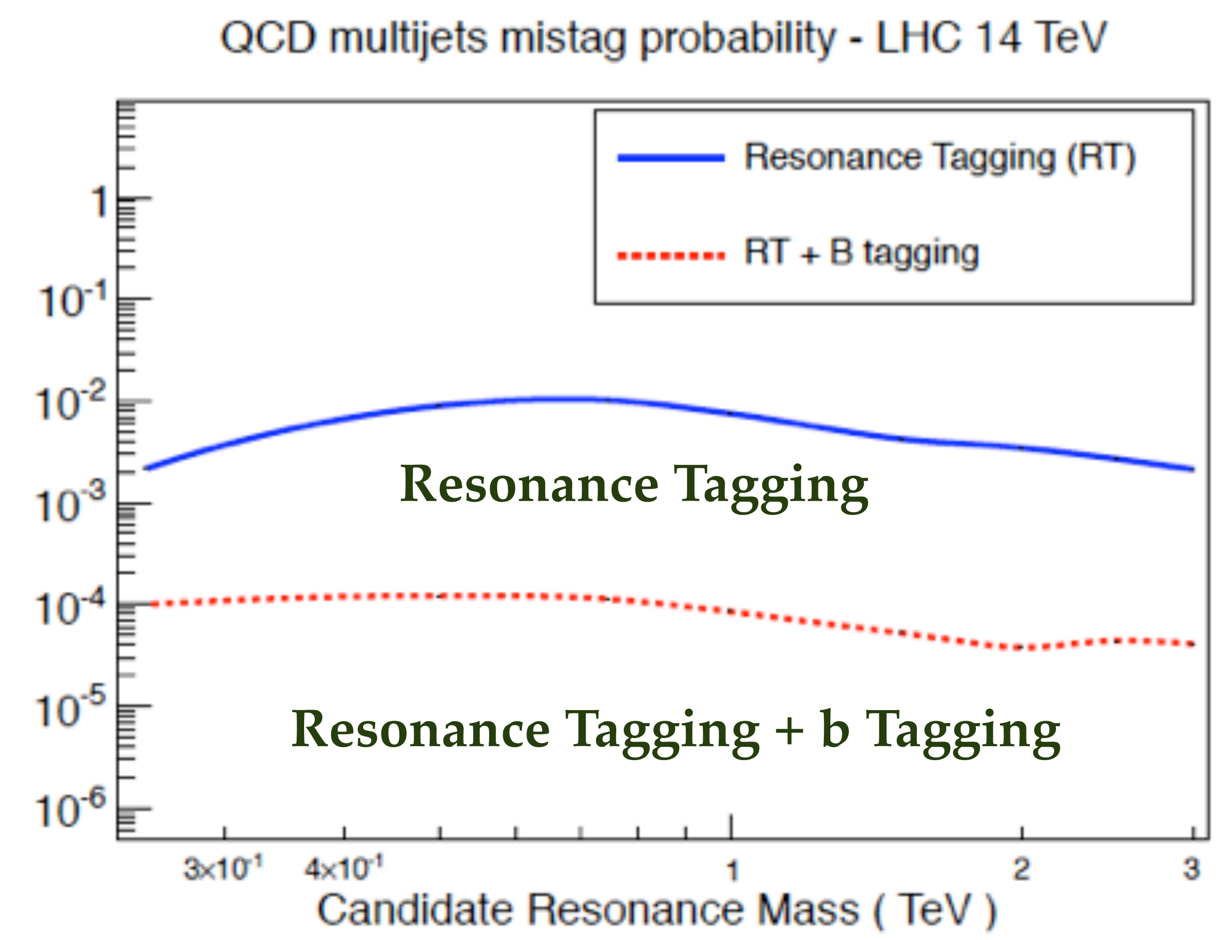
- The dominant background to the **4b** final state comes from **QCD multijet production,** estimated with **Pythia8** dijets
- For any value of the **heavy resonance X mass M_X,** define **QCD dijet cross section** as the number of events where invariant mass of the leading two jets is in a window around M_X
- A Higgs candidate is considered as ***b*-tagged** if it contains at least one *b* quark.

  The *b*-tagging efficiency is $f_b = 0.75$, and mistag rates are $f_c = 0.10$ and $f_{light} = 0.03$ for $p_T > 10$ GeV

Background rejection rates

- Like the tagging efficiency, the **background rejection rate is scale invariant**: 10^{-4} for all masses
- The flat background rejection rate arises from a **non-trivial combination** of the contributions from the *boosted, resolved* and *intermediate* **jet tagging categories**





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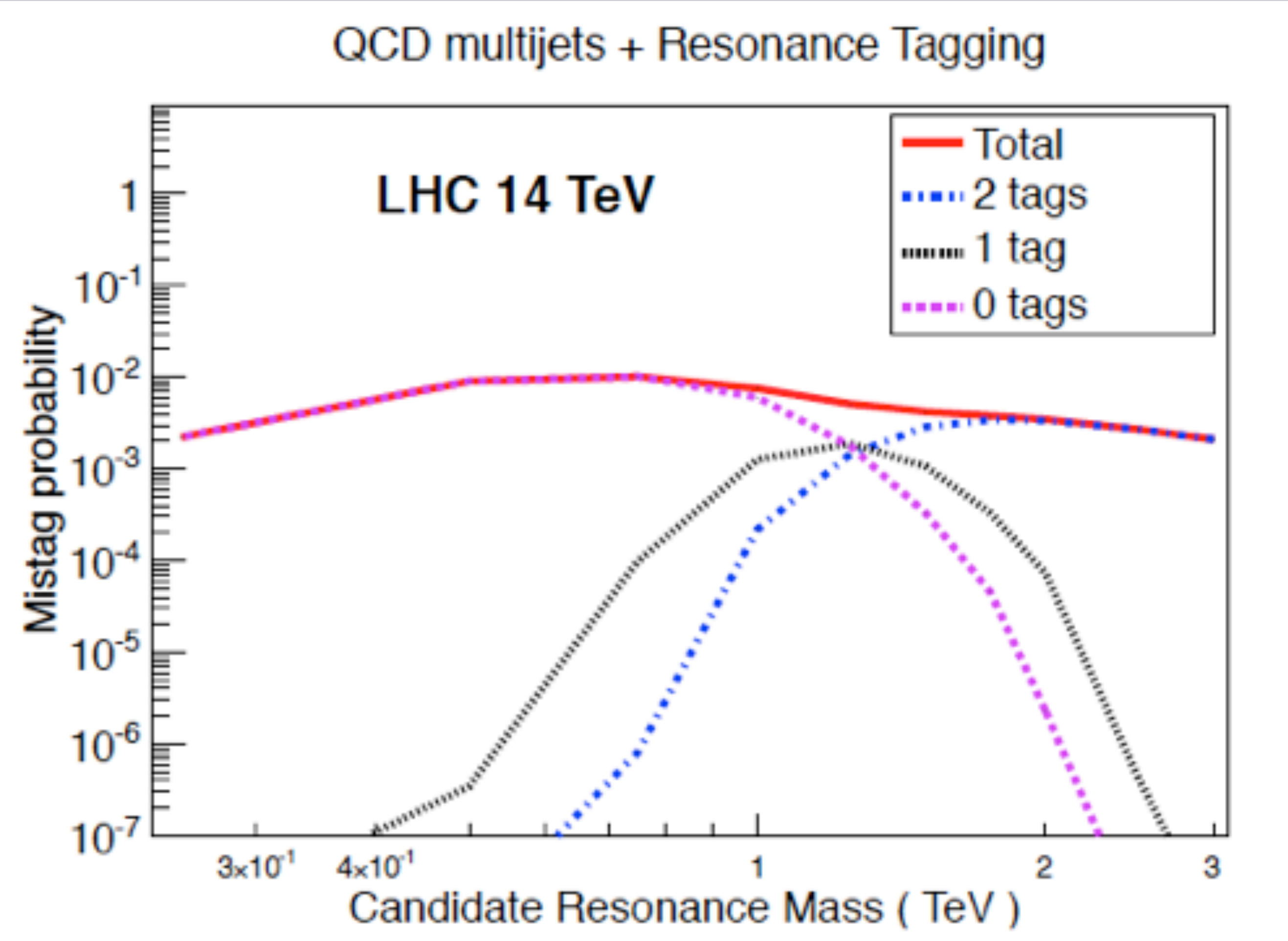
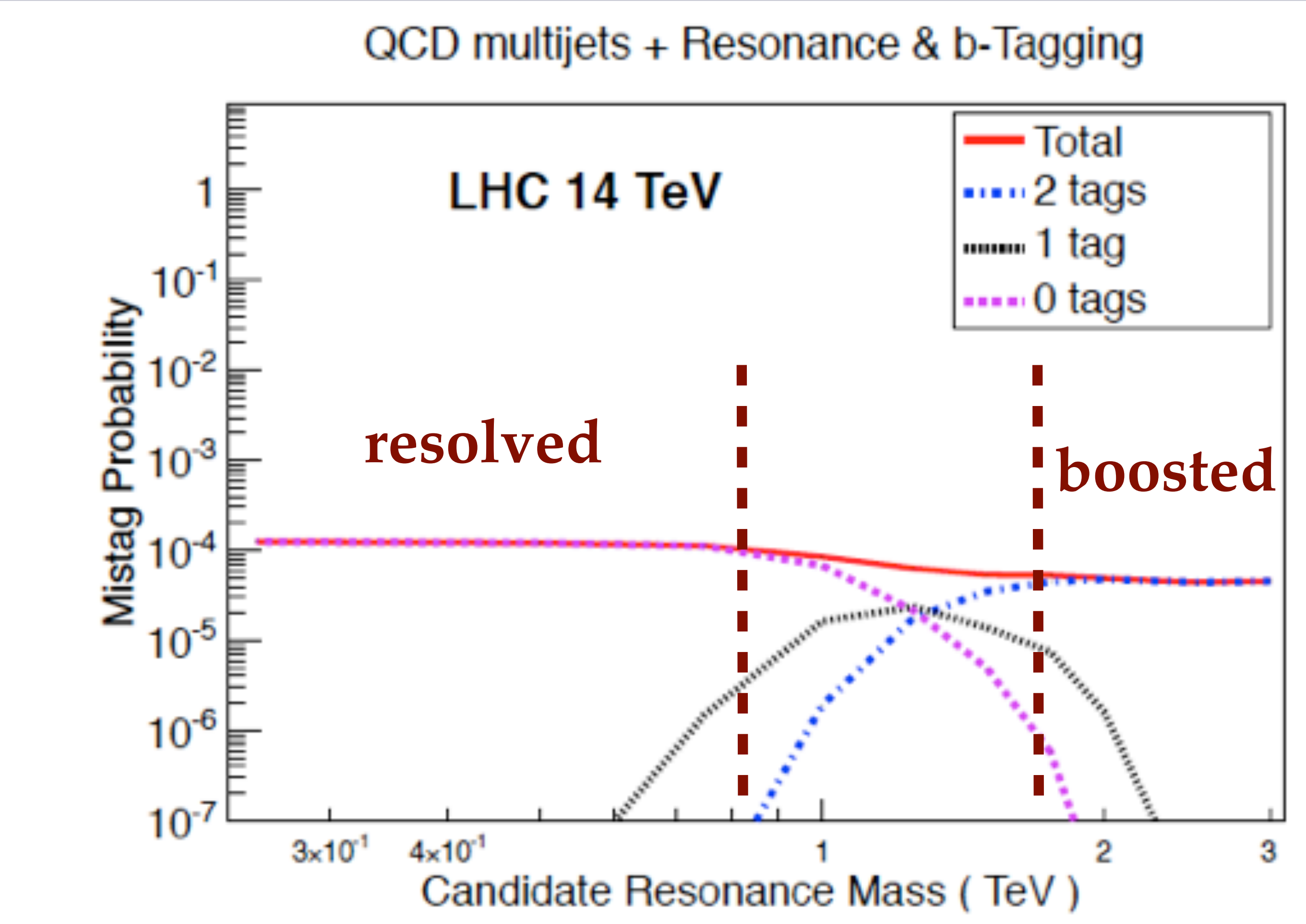
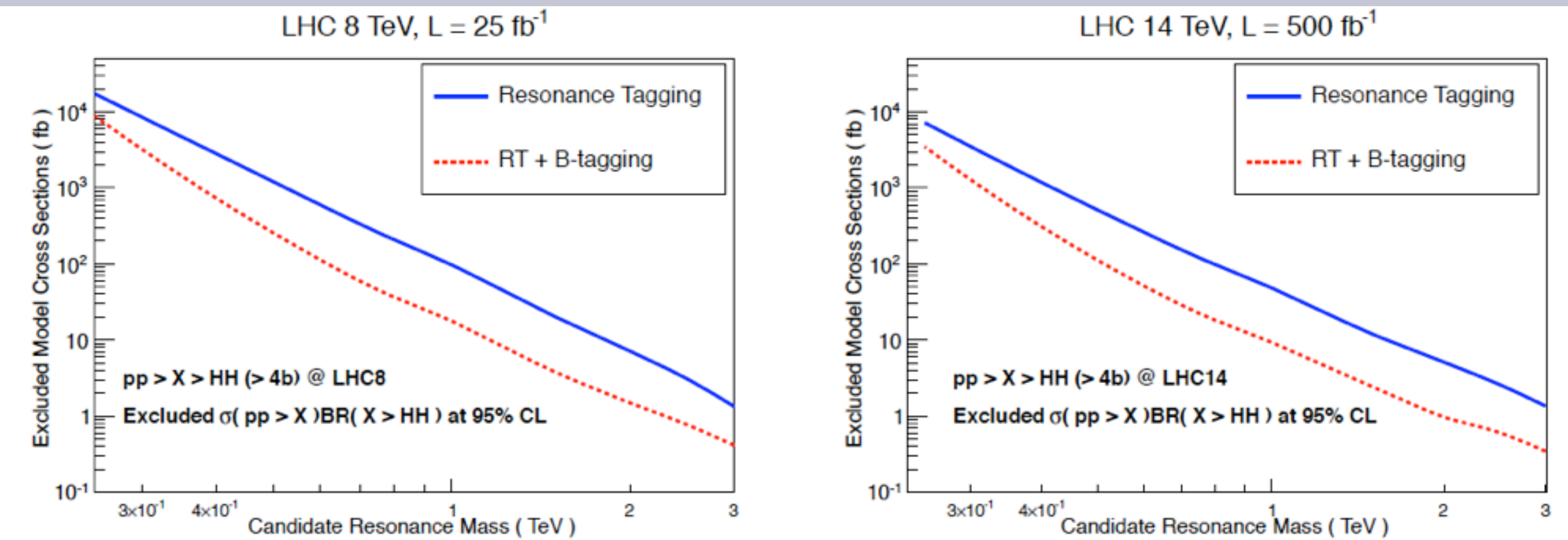




Model independent limits

- We can define **model-independent limits** for BSM excluded cross sections for **pp->X->HH->4b** at the 95% CL
- At the LHC 14 TeV, cross sections as small as 10 (1) fb can be excluded for **M_X = 1 (2) TeV**
- The **tagged 2b jet cross section** is thus a potentially relevant channel for enhanced Higgs pair production searches



Radion and Graviton production

- A particular example of **pp->X->HH->4b** appears when **X** is a **radion φ** or a **graviton G** in the context of **warped extra dimensions** scenarios

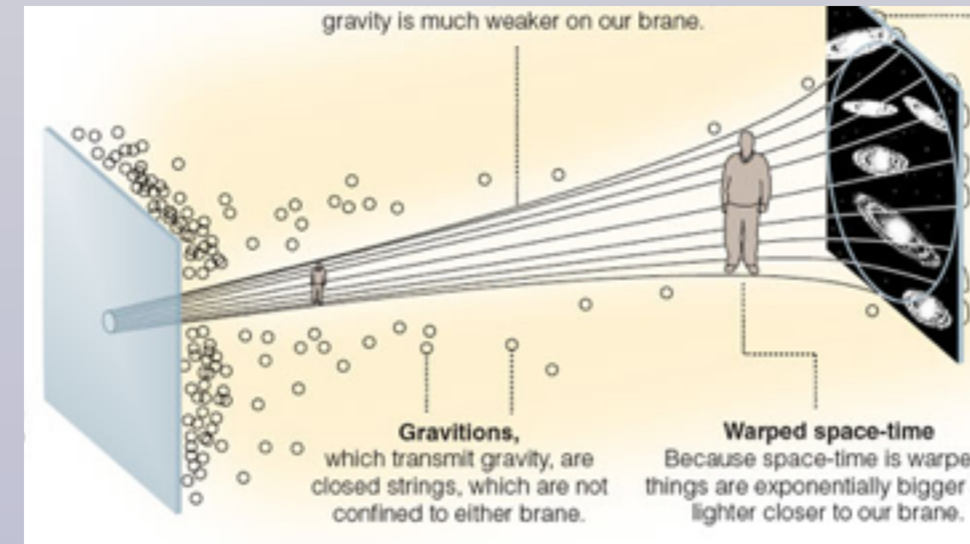
$$g_{\mu\nu} = e^{-2ky}\eta_{\mu\nu} \rightarrow e^{-2(ky+F(x,y))}\left(\eta_{\mu\nu} + G_{\mu\nu}(x,y)\right)$$

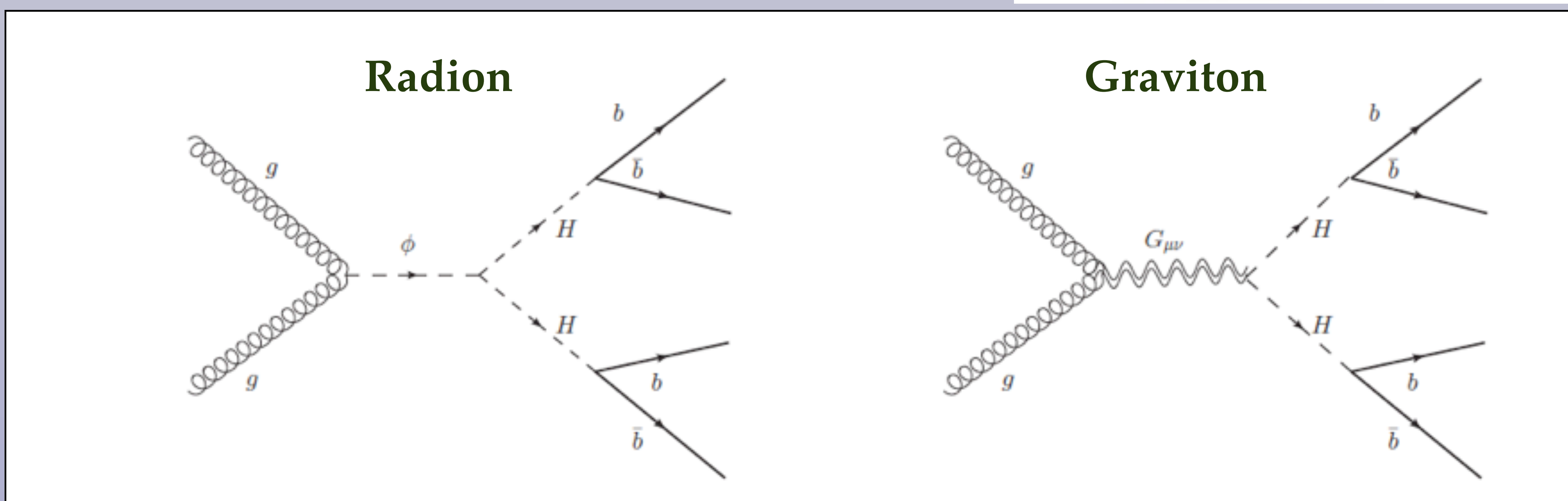
$$F(x,y) \propto e^{2ky}\,\phi(x)$$

4D Radion

$$G^{(1)}_{\mu\nu}(x,y) \propto e^{2ky}\,J_2\left(e^{2ky}\frac{m_G}{k}\right)\,G^{(1)}_{\mu\nu}(x).$$

4D Graviton





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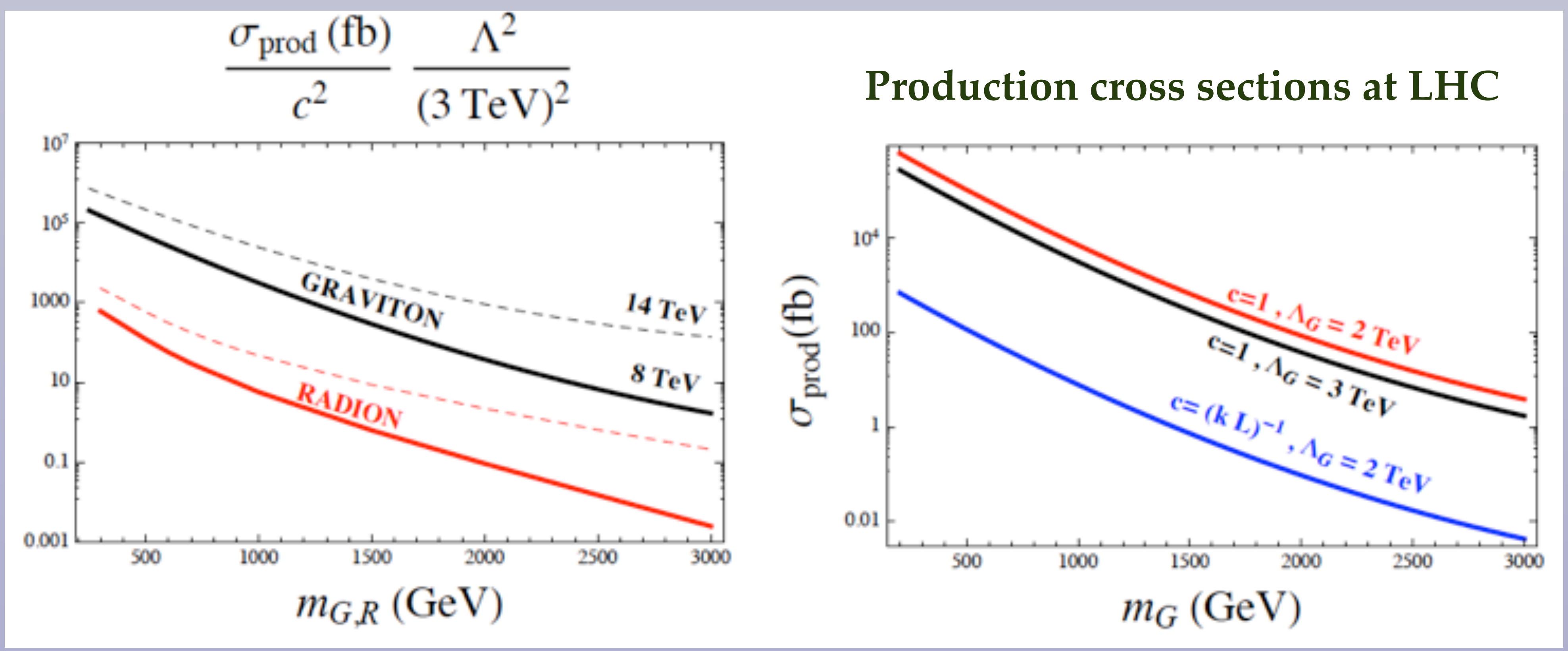
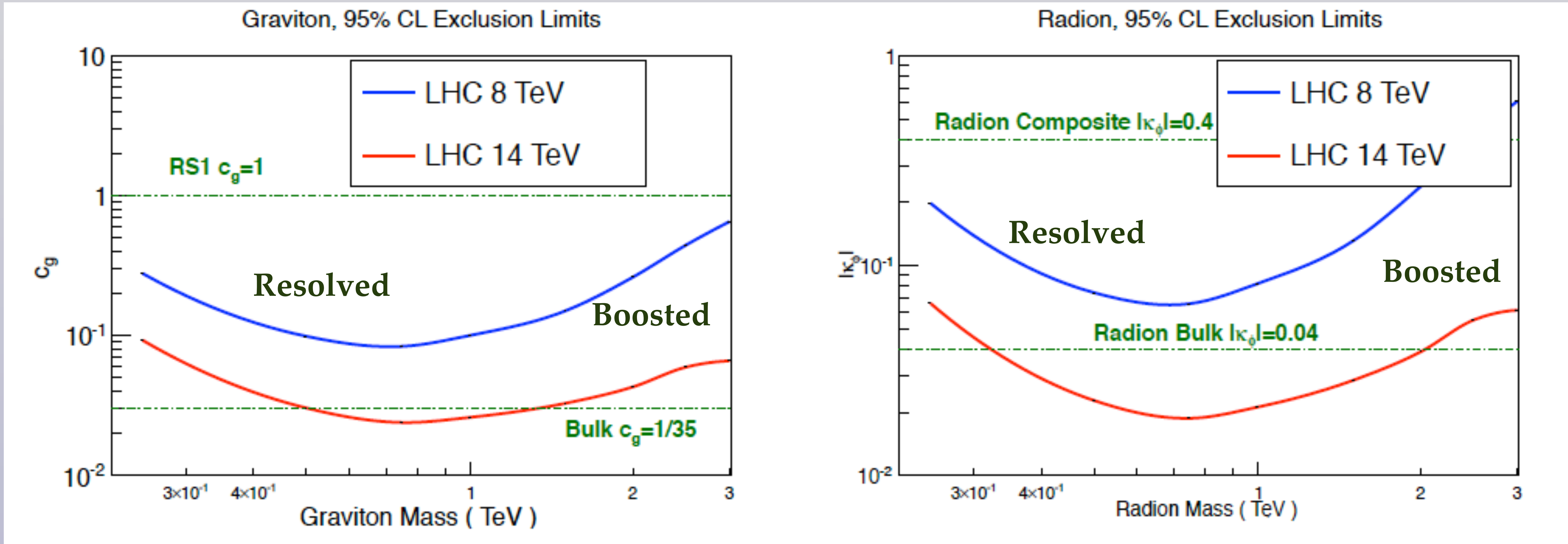
- Cross sections scale quadratically with the **coupling to gluons c_g** and with the **UV scale Λ**
- We assume production via **gluon fusion**, and a branching ratio of 25% into Higgs pairs

$$\sigma_G\left(M_G,\Lambda_G,c_g\right)=\left(\frac{c_g}{\Lambda_G}\right)^2\left(\frac{\tilde{\Lambda}_G}{\tilde{c}_g}\right)^2\sigma_G\left(M_G,\tilde{\Lambda}_G,\tilde{c}_g\right)$$



Exclusion limits

We can perform exclusion scans for **specific model parameters**



- The **4b** channel for graviton is competitive at 8 TeV with other experimental signatures
- At 14 TeV, the **whole parameter space of radion and graviton** production accessible
- The **boosted** and **resolved** regimes are being explored simultaneously
- The dependence of the exclusion limits with the mass arise from the **different shapes of the signal and background** events (gg vs qq initiated at high mass)

Outlook:
Application to hadronic and semi-leptonic top quark pair decays

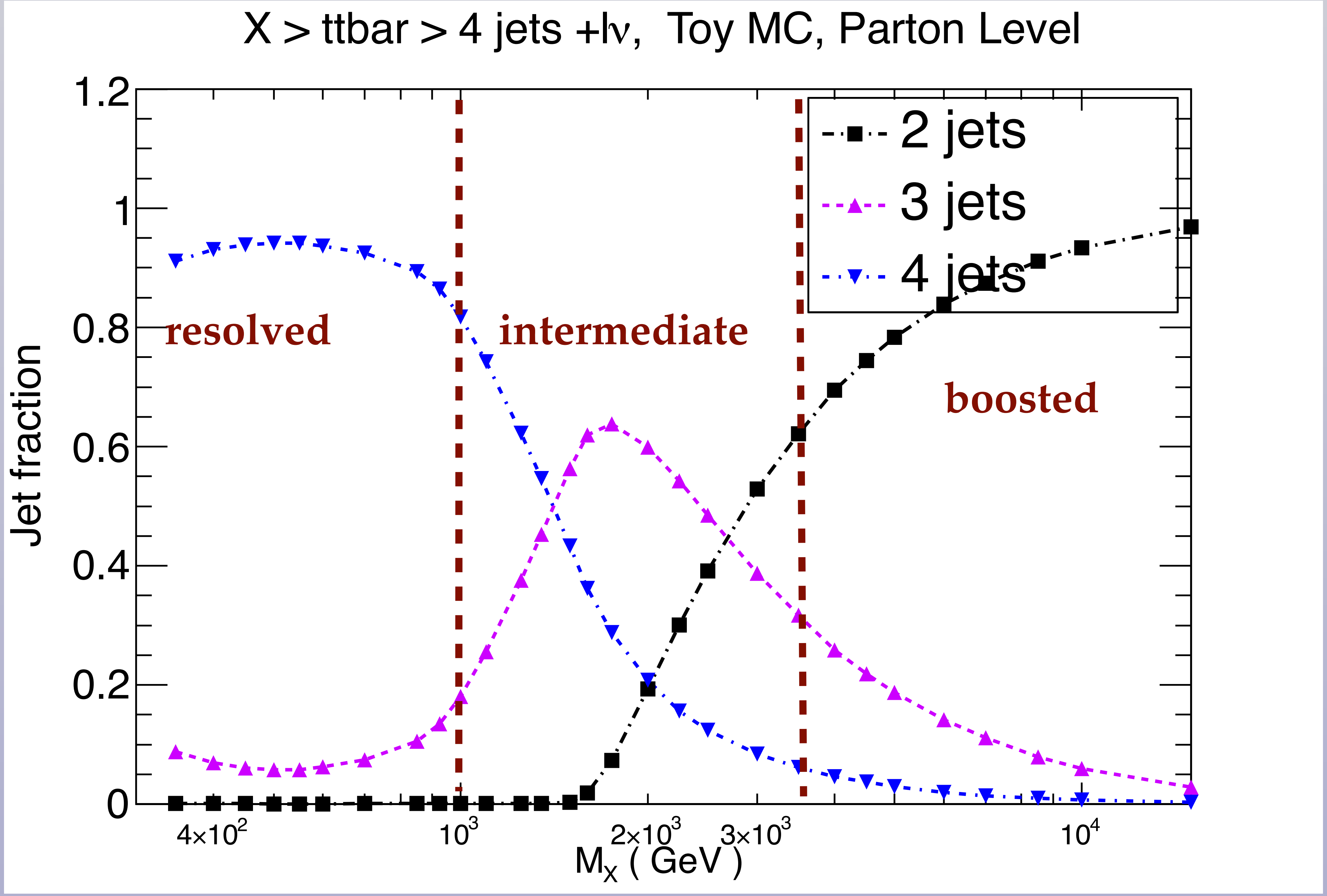
J. Rojo, G. Salam, work in progress

Merging threshold and boosted regimes in ttbar

- **Top quark pair production** is widely used in BSM searches
- Typically searches are separated into the **boosted** and **fully resolved** regimes
- It would be desirable to **merge the two regimes** into a common analysis, while improving the overall efficiency by including the **intermediate regime** as well

Toy MC for heavy resonance X decaying to ttbar

Semileptonic decays



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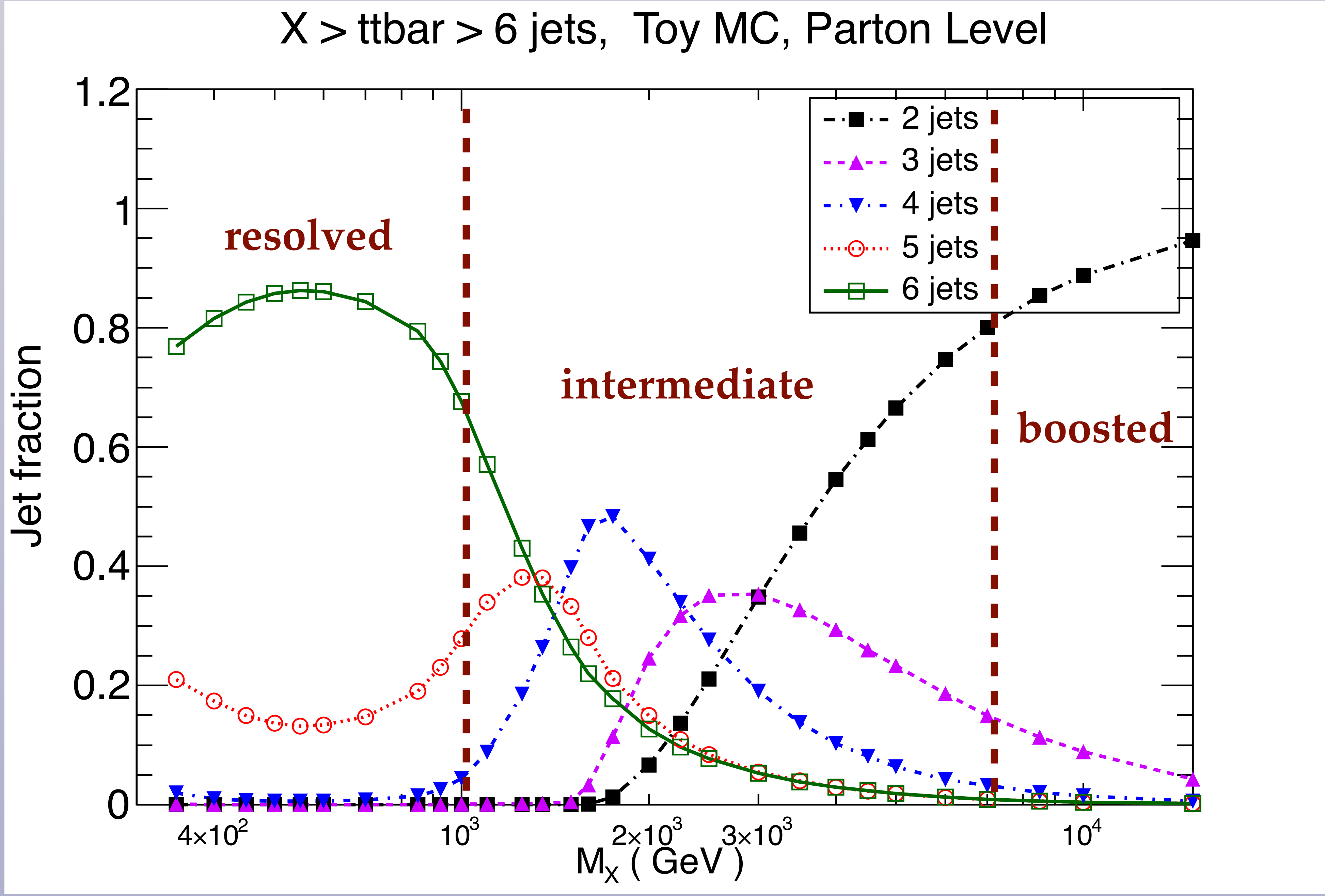
Toy MC for heavy resonance X decaying to ttbar

Fully hadronic decays



Summary and outlook

- **Scale-invariant resonance tagging** is a new theoretical development which aims to **efficiently combine separate searches** (resolved vs boosted) into a **common analysis,** and improving the overall efficiency by including the **intermediate** regime as well
- The generic method has been applied to the **4b final state,** showing that it is competitive with other final states for searches of **enhanced Higgs pair production**, a generic feature of many BSM scenarios
- Similar ideas could be applied to **top pair production**, to combine the **boosted** and **threshold** regimes into a common search

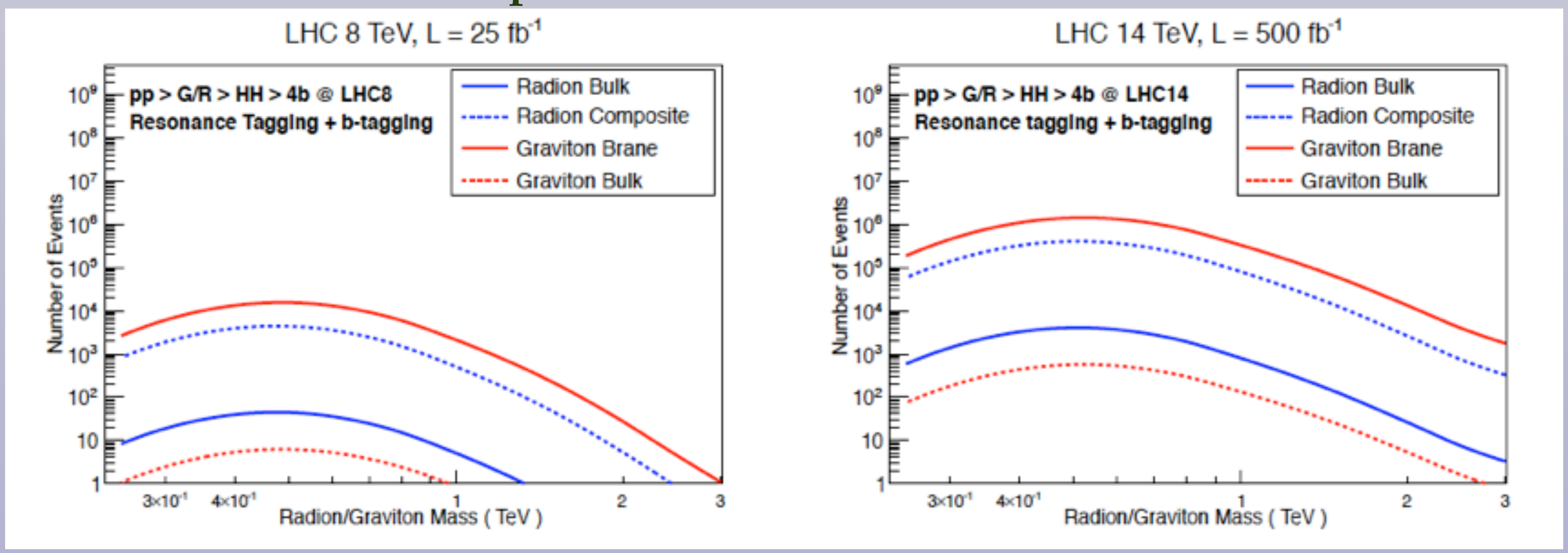
Extra Material

Radion and Graviton production

Benchmark scenarios

radion Production			
Scenario	$\lvert\kappa_g^\phi\rvert$	Λ_ϕ	$\mathrm{BR}(\phi \to 2H)$
radion Bulk (R-Bulk)	$\lvert -\alpha_s b_3/8\pi - 1/4kL\rvert \sim 0.04$	2 TeV	1/4
radion Composite (R-Comp)	0.4	2 TeV	1/4
graviton Production			
Scenario	c_g	Λ_G	$\mathrm{BR}(G \to 2H)$
graviton RS1 (G-Brane)	1	2 TeV	1/4
graviton Bulk (G-Bulk)	$1/kL = 1/35$	2 TeV	1/4

Expected number of events



Few radion events at 8 TeV, unless coupling to gluons enhanced (composite models)
The whole graviton/radion parameter space accessible at 14 TeV