Scale-invariant resonance tagging in multijet events and new physics in Higgs pair production

Juan Rojo
CERN, PH Division, TH Unit

Based on: M. Gouzevich, A. Oliveira, J. Rojo, R. Rosenfeld, G. Salam, V. Sanz
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Scale-Invariant Resonance Tagging

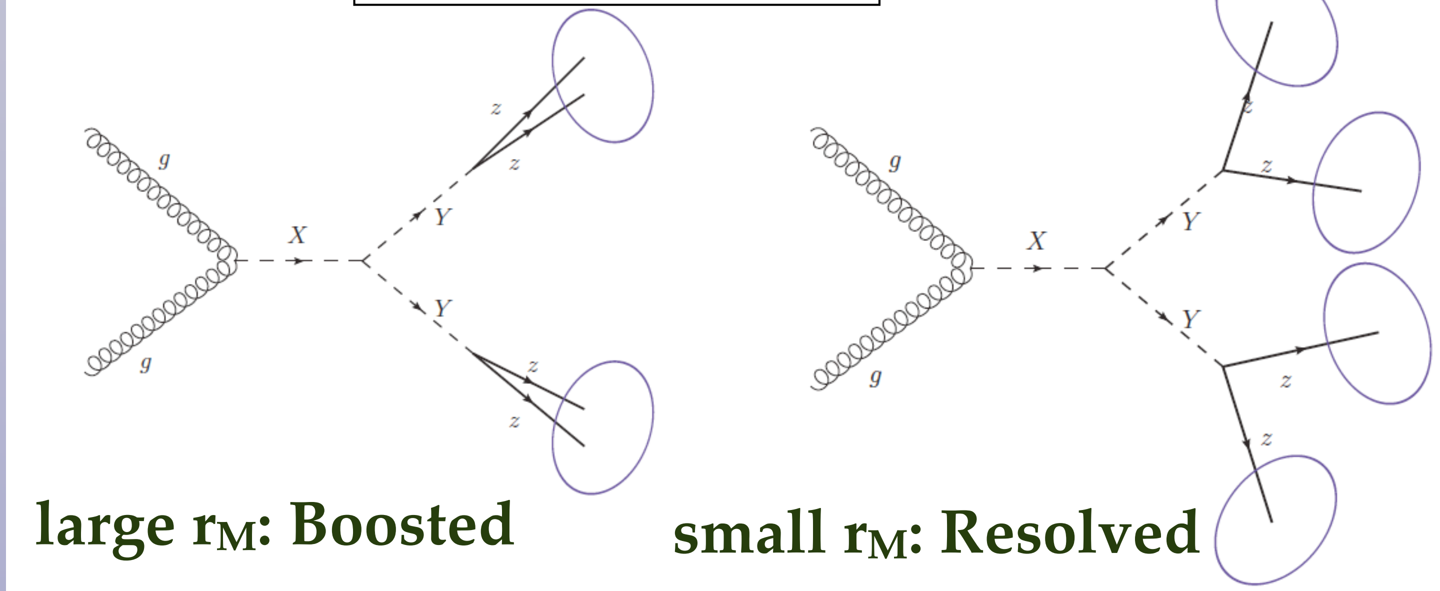
Motivation for scale-invariant tagging

- 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

$$pp \to X \to 2Y \to 4z$$

- Implemented in a **toy parton-level Monte Carlo** event generator. Hadron level with **Pyhtia8**
- Depending on the value of the mass ratio $\mathbf{r_M = M_X/2M_Y}$ different final state topologies
- 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**)

$$pp \to X \to 2Y \to 4z$$

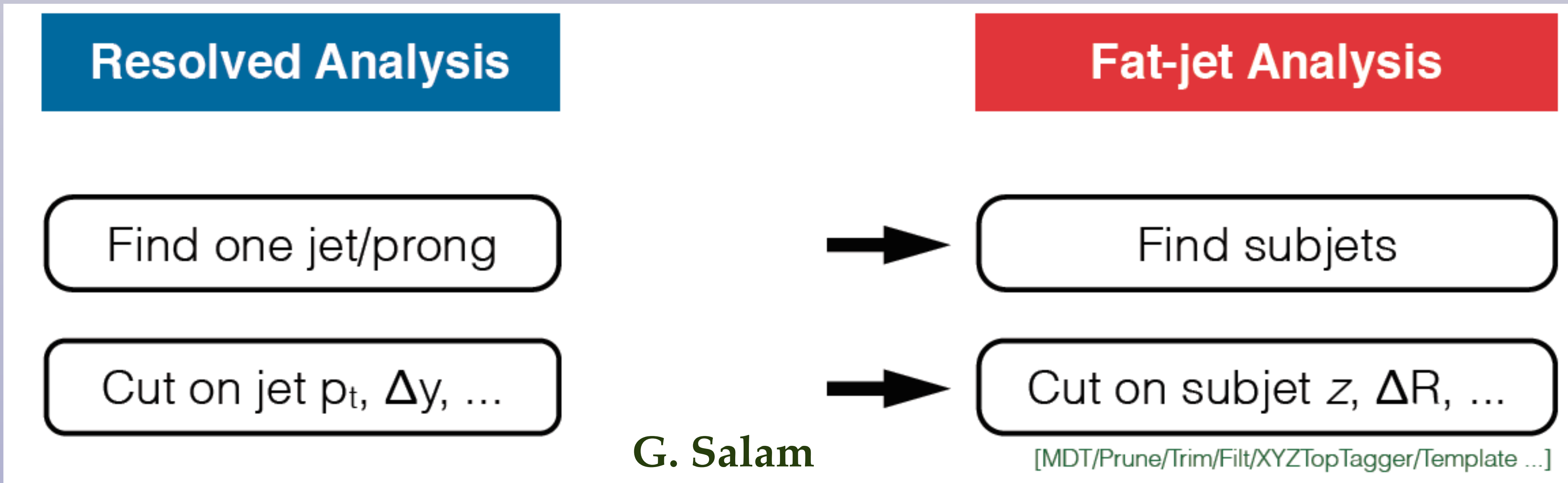


Motivation for scale-invariant tagging

- 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 **fat-jets with Mass-Drop Tagger**

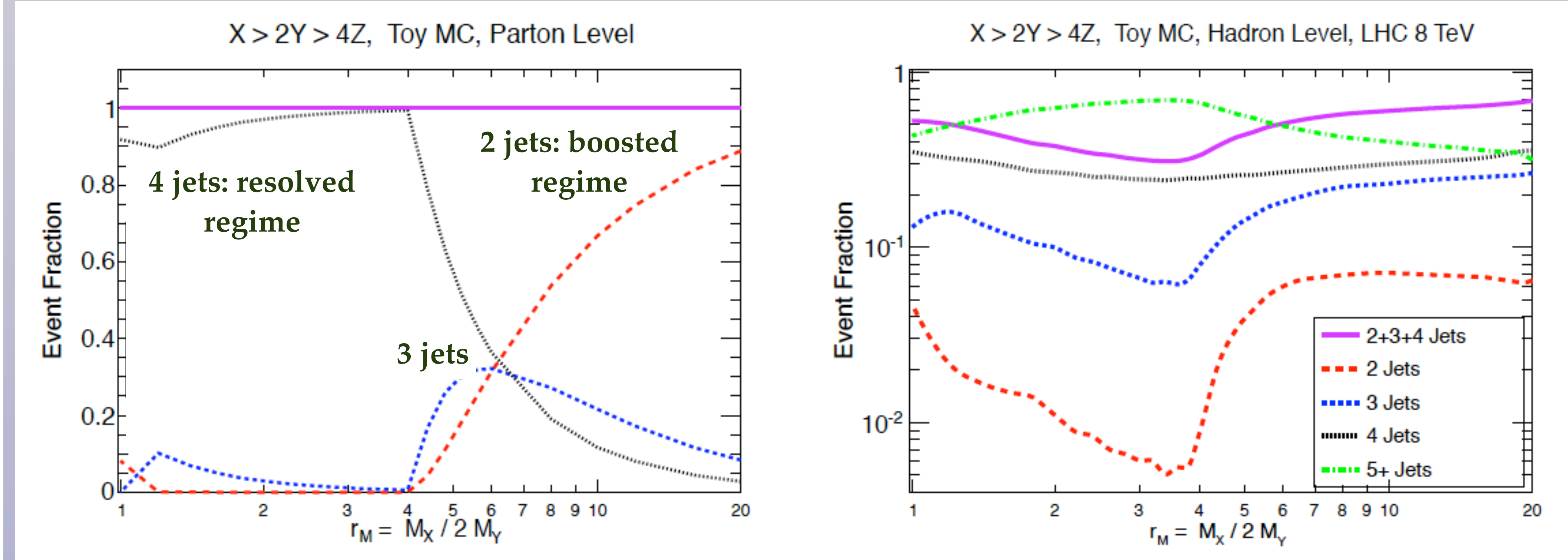
$$m_{j1} \leq \mu \cdot m_j \qquad \frac{\min(p_{t,j1}, p_{t,j2})^2}{m_j^2} \Delta R^2_{j1,j2} > y_{\rm cut}$$

- Can we design a search strategy that efficiently explores **the whole mass range**?
- To achieve a similar tagging efficiency, we want to apply the **same selection cuts** in the **boosted and resolved regimes**



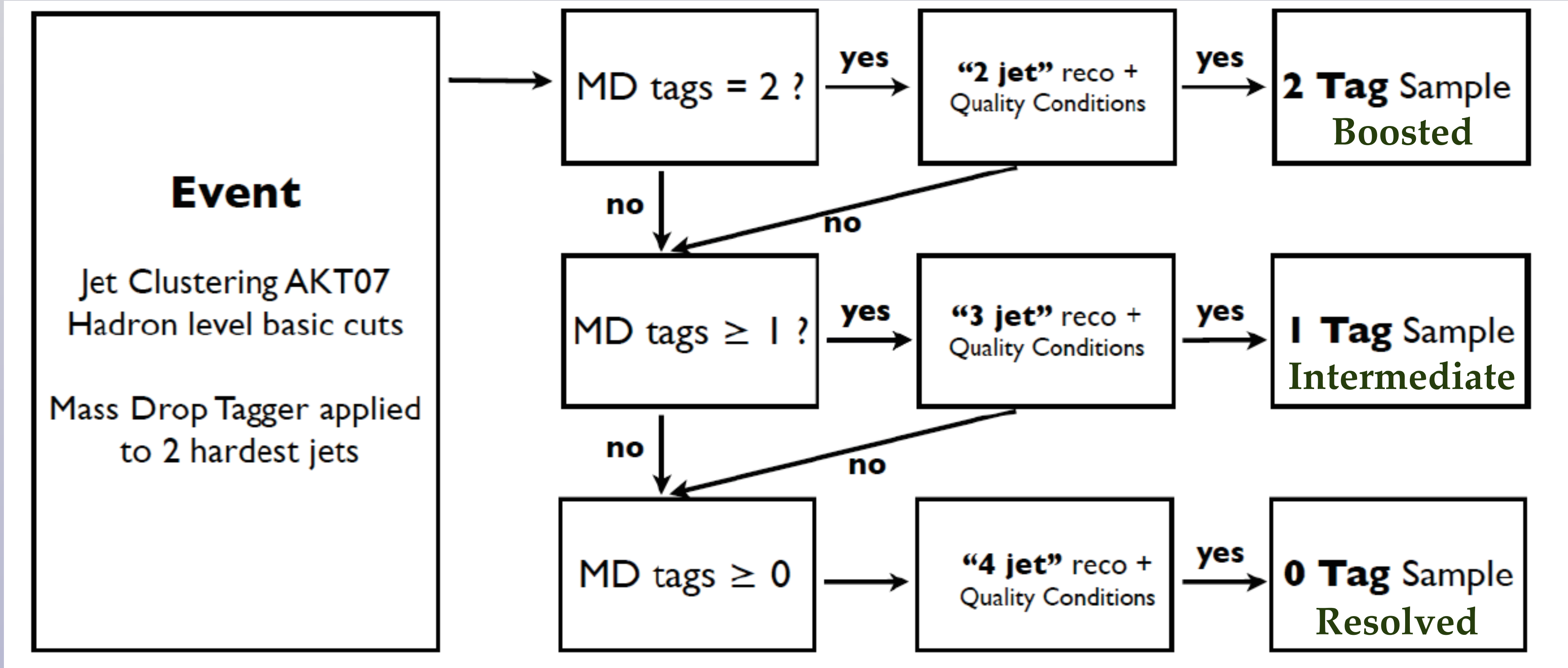
Event Classification

- At **parton level**, without cuts, the classification of the event topology (boosted, resolved or intermediate) is trivial **based on the number of jets**
- But at **hadron level** with **realistic cuts** such naive classification is not feasible
- A more robust event classification achieved based on the number of **jet substructure tags**



Event Classification

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



- First we look for two mass-drop tags. if quality conditions are satisfied, **tag the event as arising from a heavy resonance X** and classify it in the **2 Tag sample**

- If any of the above fails, require a mass-drop tag and pair the fat jet with the remaining two hardest jets. If quality conditions are satisfied, **tag the event as arising from a heavy resonance X** and classify it in the **1 Tag sample**

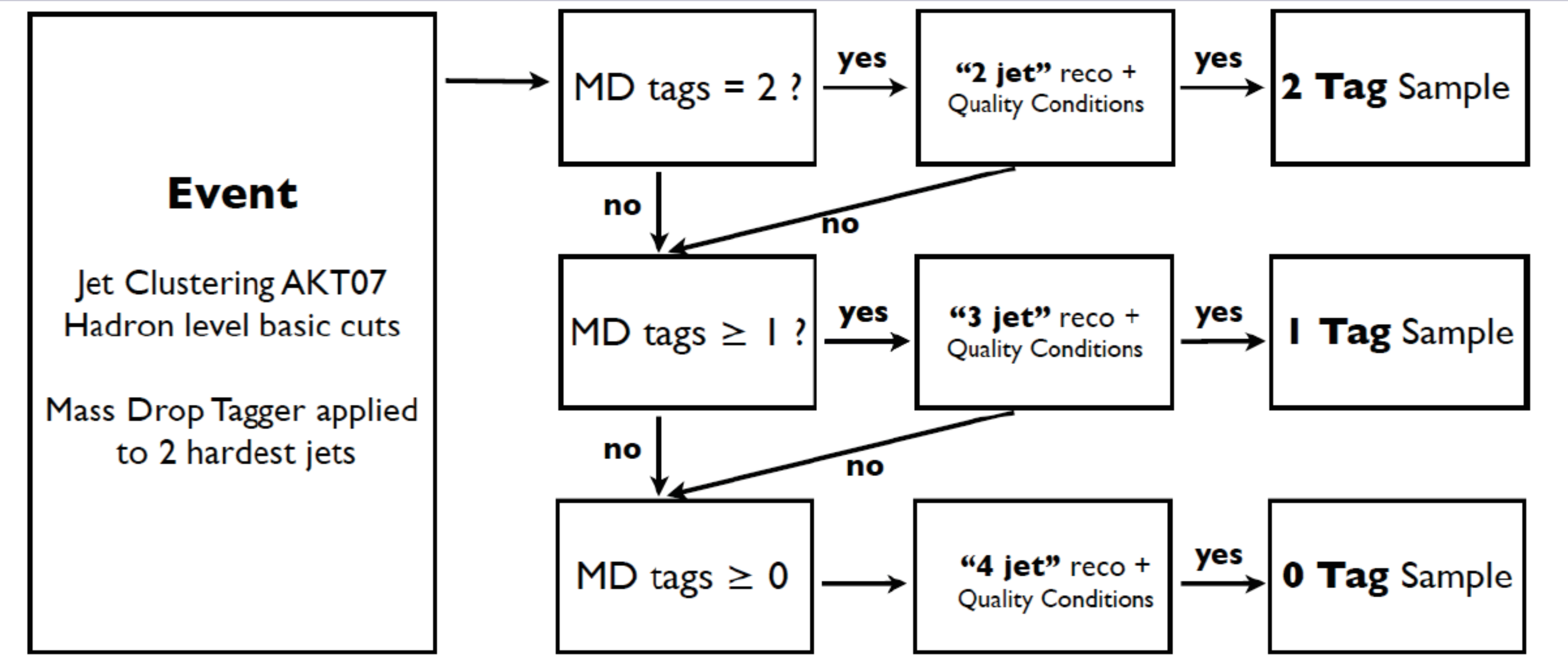
- If any of the above fails, and the event has at least four jets, apply the dijet mass pairing. If quality conditions are satisfied, **tag the event as arising from a heavy resonance X** and classify it in the **0 Tag sample**

Event Classification

- NB: this is really a **unique analysis** based on a **unique 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 to combine multiple analysis** into a common search, or at least, to **improve the efficiency of existing searches** thanks to the **smooth transition in the intermediate region**



Quality Requirements

- 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)

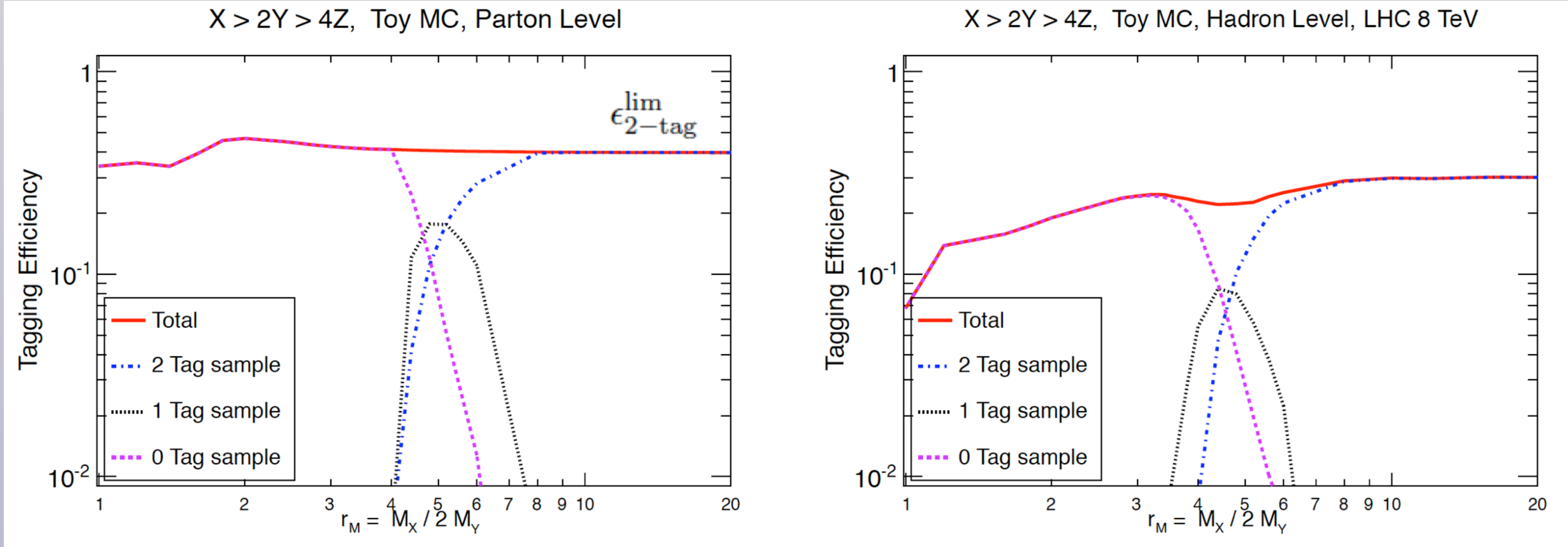
$$\max\left(m_{Yi,1}, m_{Yi,2}\right) \leq \mu \cdot m_{Yi}$$

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

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

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



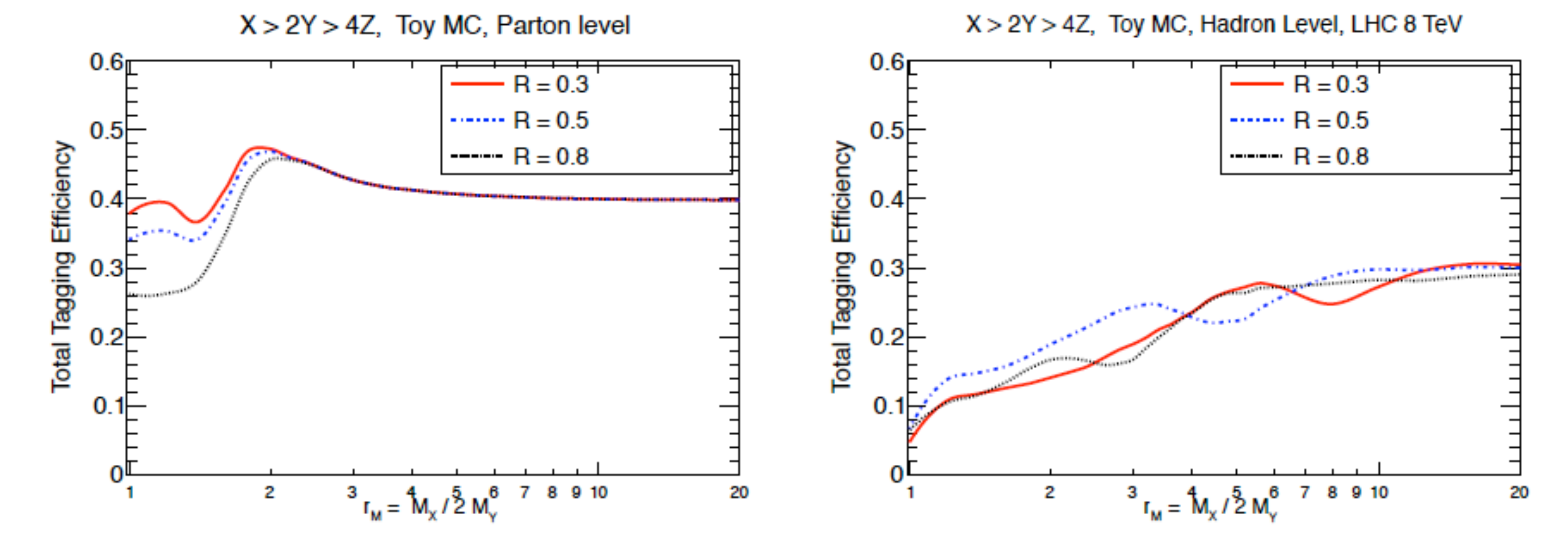
- At parton level the **tagging efficiency in the boosted limit** can be computed analytically

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

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 0-tag, 1-tag and 2-tag 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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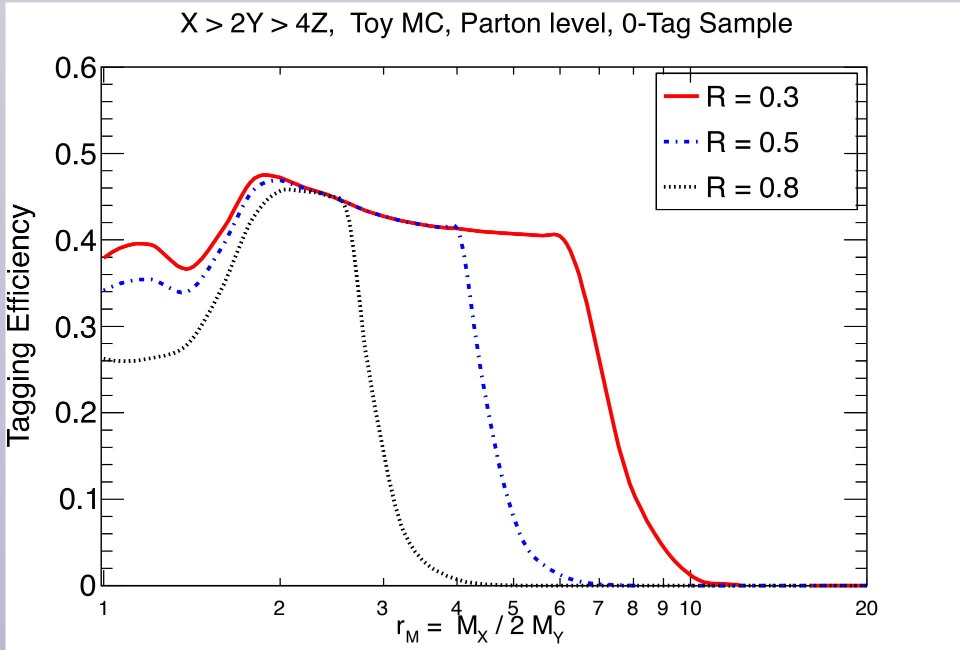
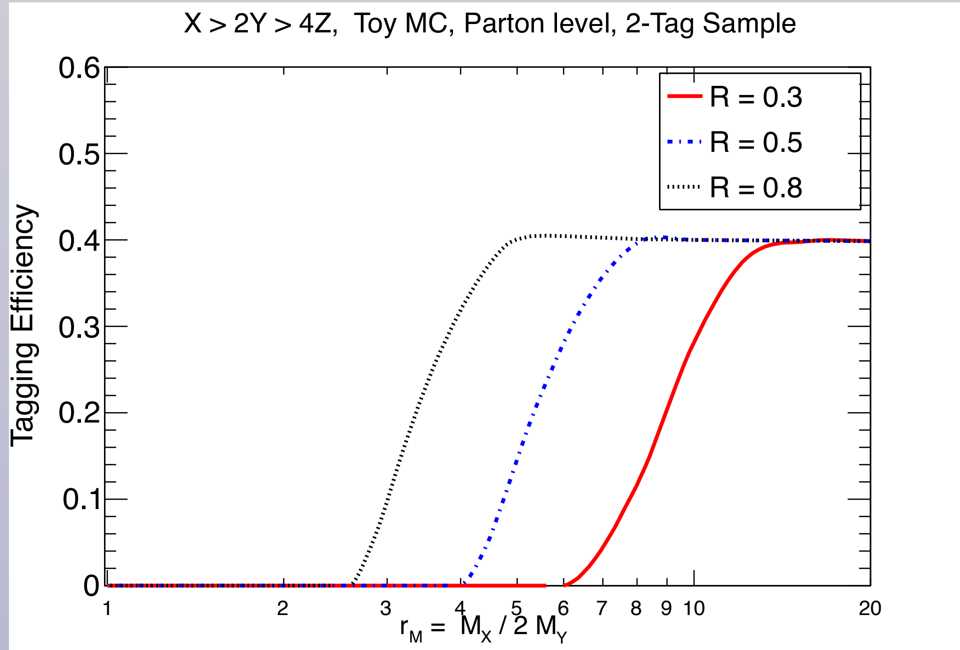
Resolved



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

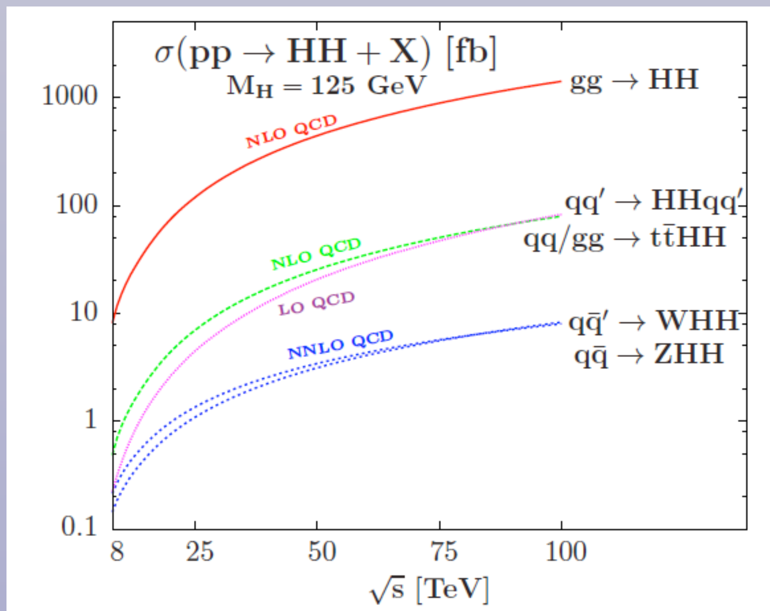
New physics in Higgs pair production

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

$$pp \to X \to 2Y \to 4z$$ **General kinematics**

$$pp \to X \to 2H \to 4b$$ **Specific application**

- Higgs pair production is **small in SM**, but **enhanced** in 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



HH production in SM
200 events at 8 TeV
Feasible only at 14 TeV

b-tagging

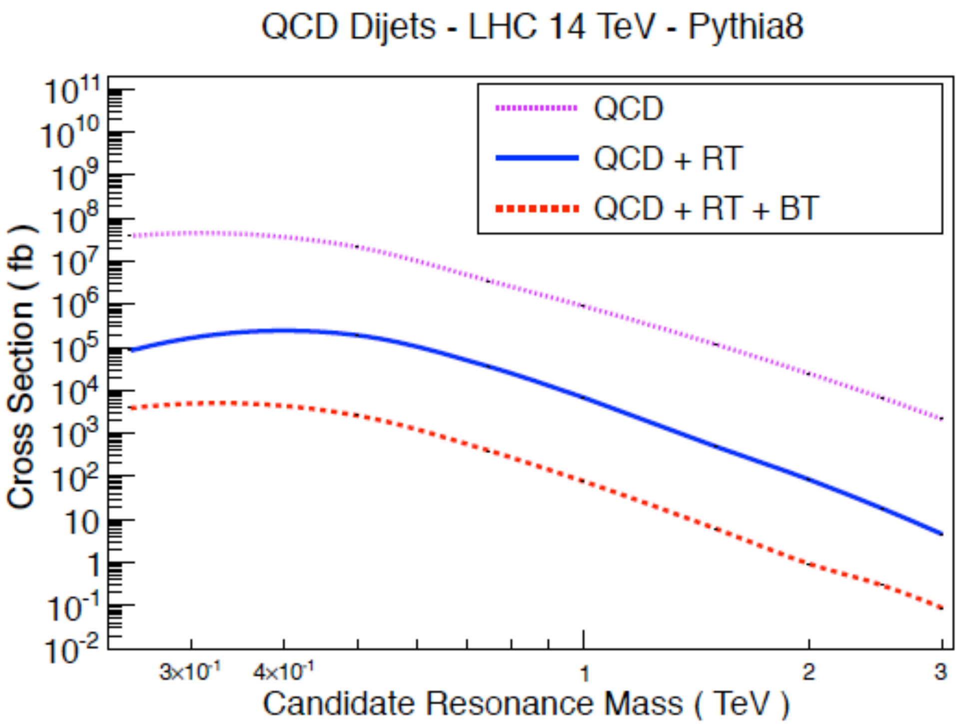
- The dominant background to the **4b** final state comes from **QCD multijet production**
- In order to reduce it we need to perform **b-tagging**

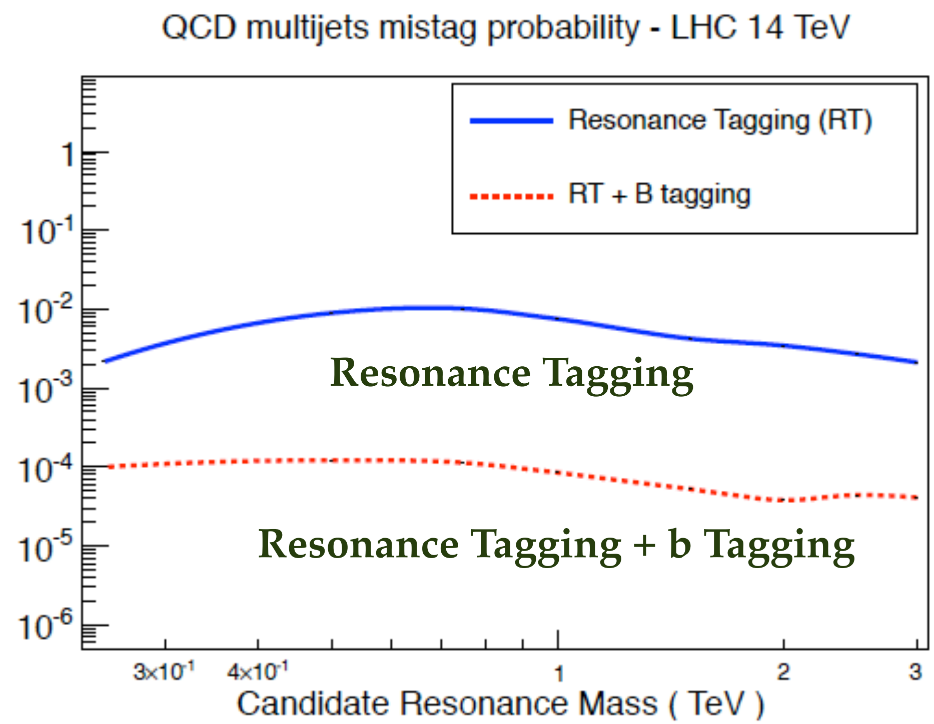
- Determine the number of b-quarks within each of the two Higgs candidates' jets. Such candidate jets can be a single anti-k_T jet with radius R (in the boosted regime) or a jet composed by the sum of two different anti-k_T jets (in the resolved limit).
- A Higgs candidate jet is considered to be b-tagged if it contains at least one b quark with $p_{T,b} \geq p_{T,b}^{\min} = 10$ GeV. The b-tag efficiency is denoted by f_b. **$f_b = 0.75$**
- A Higgs candidate jet which does not fulfill the previous condition, but contains at least one c quark with $p_{T,c} \geq p_{T,b}^{\min}$, will be b-tagged with a mistag probability f_c. **$f_c = 0.10$**
- A Higgs candidate jet which contains only light quarks and gluons will be b-tagged with a mistag probability f_l.[12] **$f_l = 0.03$**
- b-tagged events are those for which the two Higgs candidates' jets have been both b-tagged.

- A single **b-quark** in each **Higgs candidate** enough to consider event as tagged
- Also explored **double b-tagging,** with two tags per Higgs. Challenging in the **boosted limit**

Background rejection rates

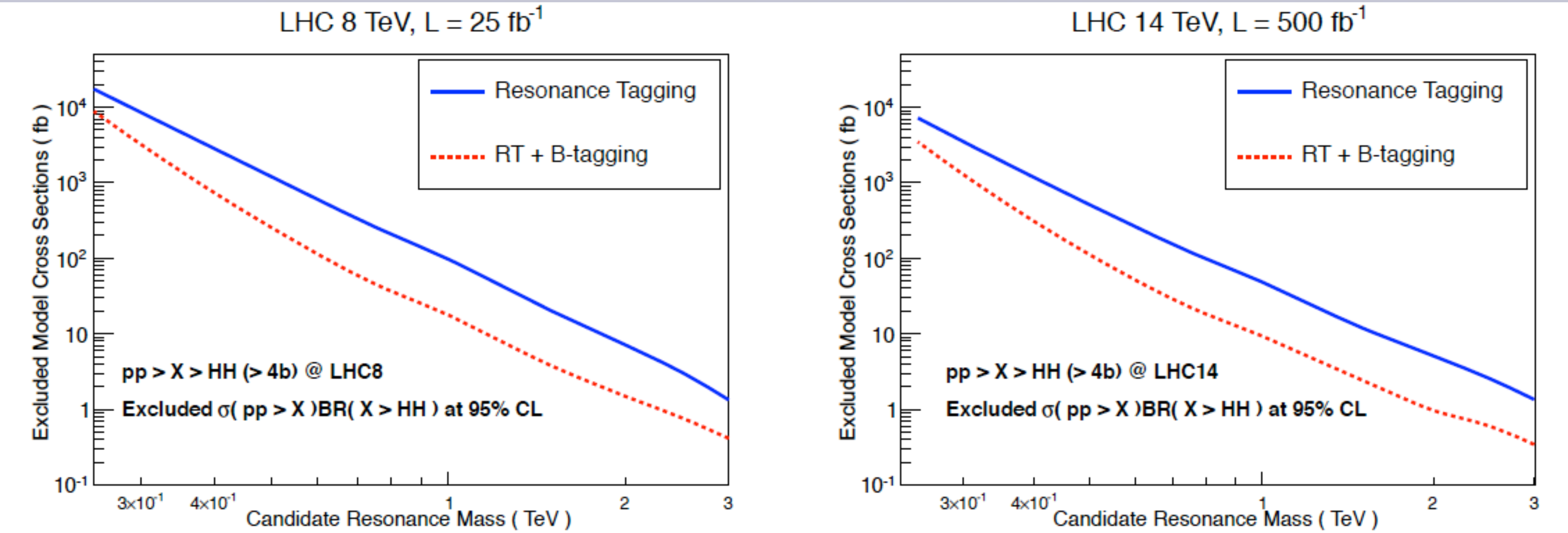
- The dominant background to the **4b** final state comes from **QCD multijet production,** estimated with **Pythia8** dijets
- For any value of the **heavy resonance X mass M_X,** define **QCD dijet cross section** as the number of events where invariant mass of the leading two jets is in a window of 15% around M_X
- As the tagging efficiency, the **background rejection rate is scale invariant: 10^{-4} for all masses.** Substantial background rejection!
- The **2b dijet tagged cross section** is below 1 fb above 2 TeV at LHC14





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**
- **SM Higgs-pair production** (non-resonant) has a cross section of 20 fb at LHC 14 TeV
- The **tagged 2b jet cross section** is thus a potentially relevant channel for BSM 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

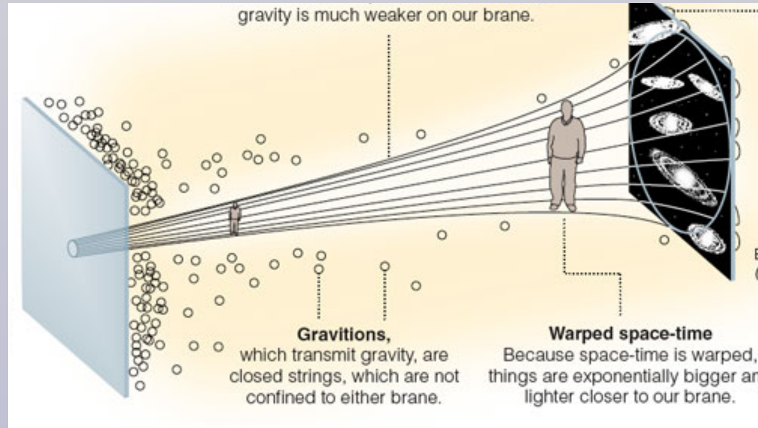
$$g_{\mu\nu} = e^{-2ky}\eta_{\mu\nu} \rightarrow e^{-2(ky+F(x,y))}\left(\eta_{\mu\nu} + G_{\mu\nu}(x,y)\right)$$

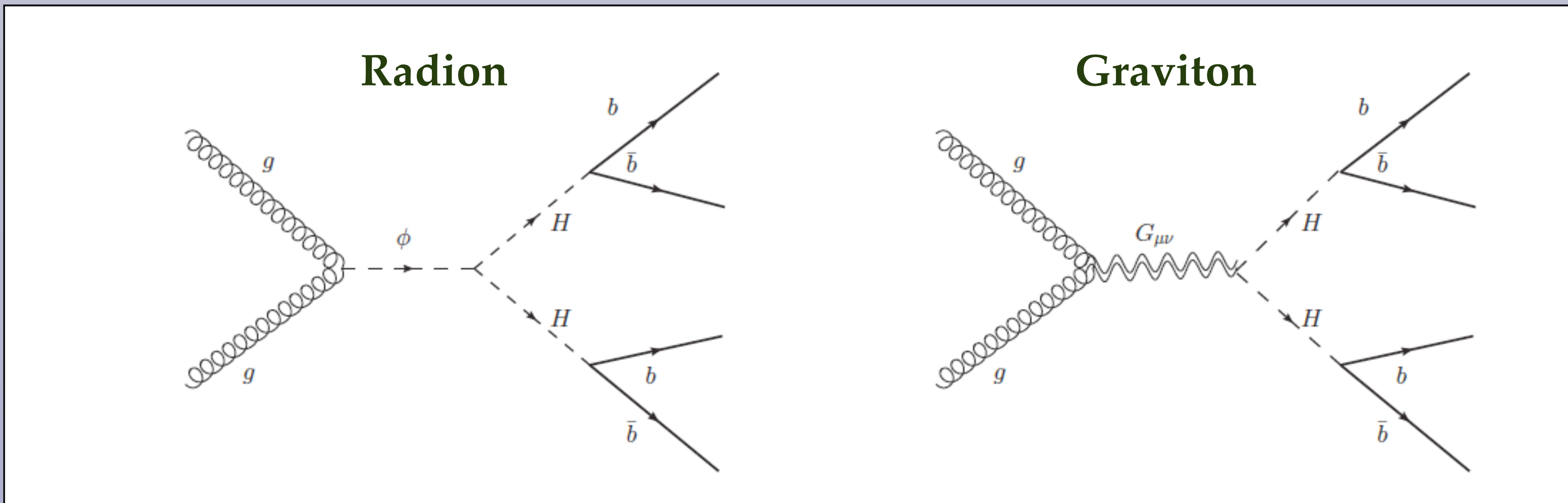
$$F(x,y) \propto e^{2ky}\,\phi(x)$$

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

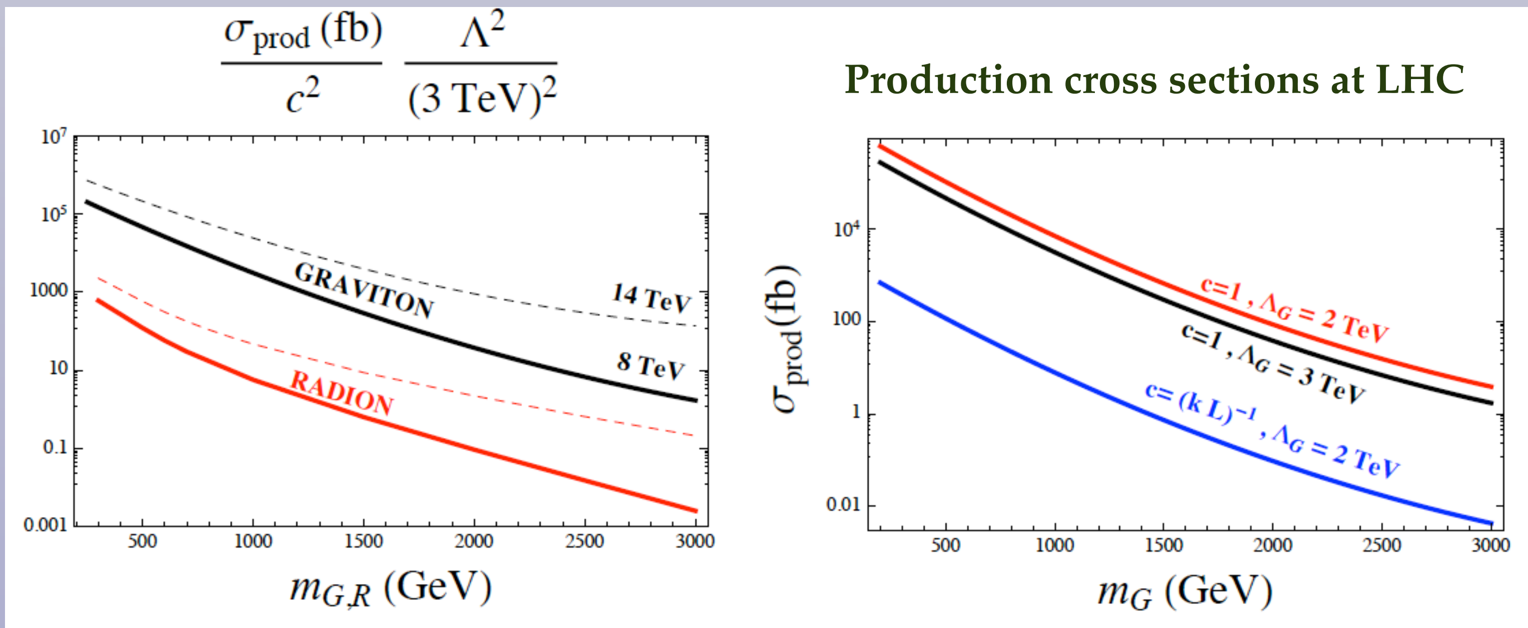




Radion and Graviton production

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

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

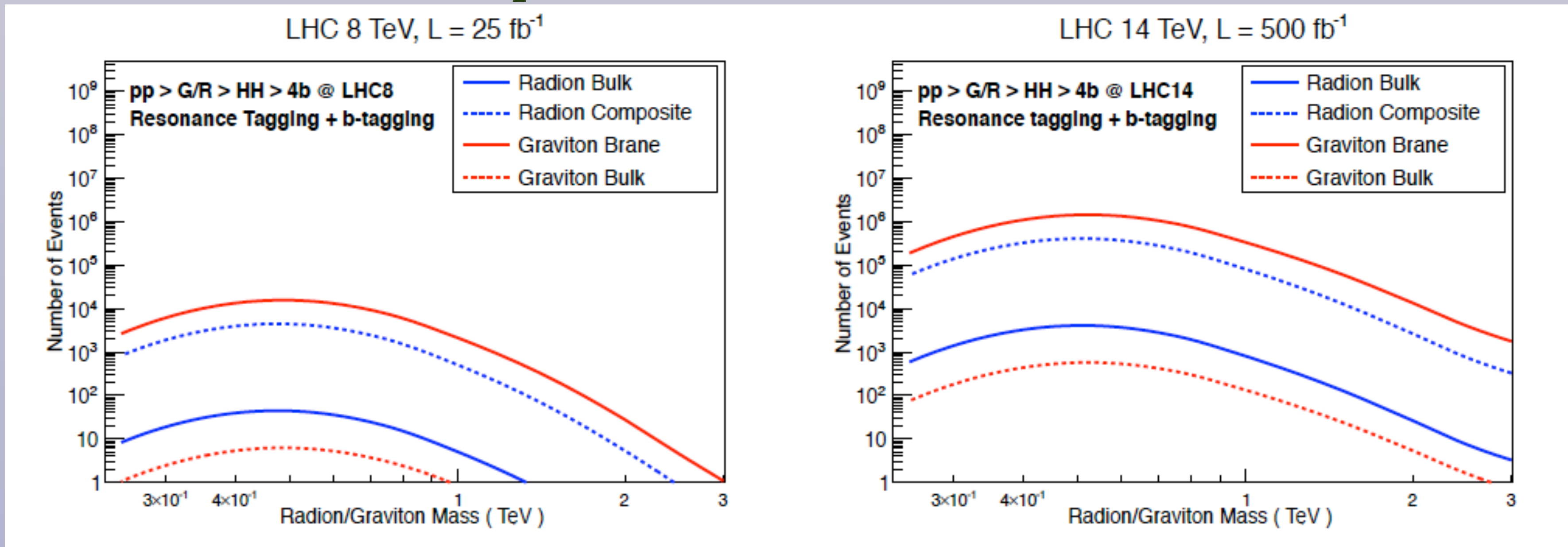


Radion and Graviton production

Benchmark scenarios

radion Production			
Scenario	$\lvert\kappa_g^\phi\rvert$	Λ_ϕ	$BR(\phi \to 2H)$
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	$BR(G \to 2H)$
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

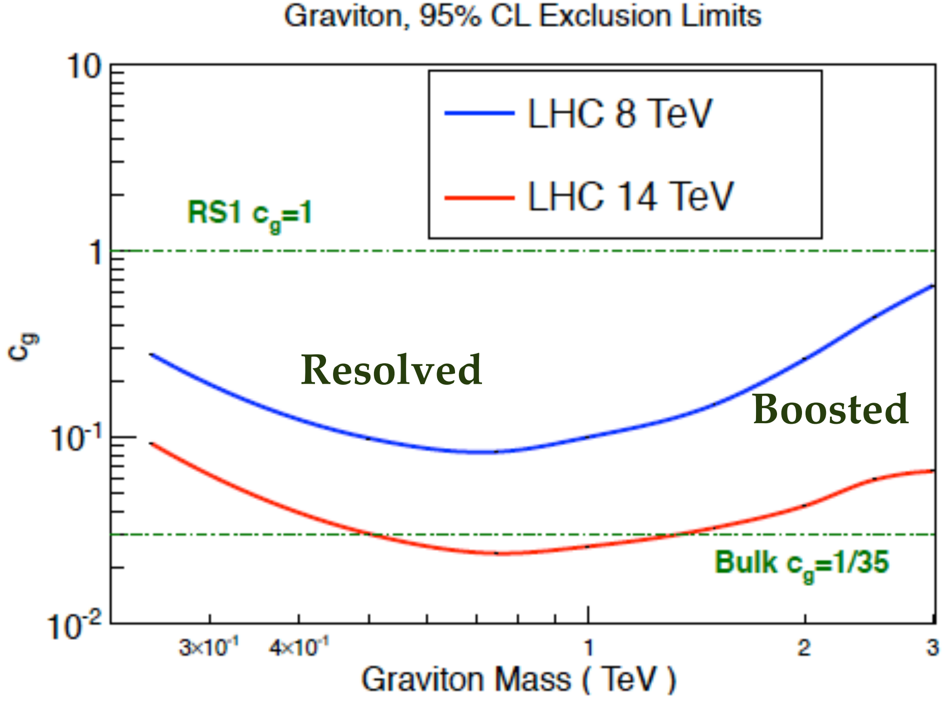


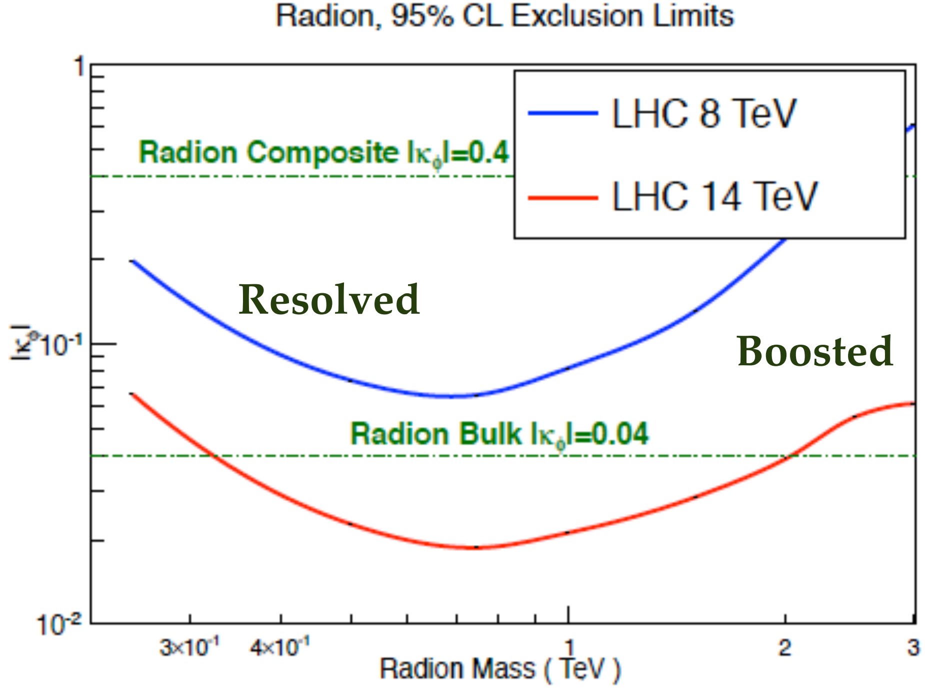
Few radion events at 8 TeV, unless coupling to gluons enhanced (composite models)

The whole graviton/radion parameter space accessible at 14 TeV

Exclusion limits

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





- At 8 TeV, we can exclude a ratio with couplings a factor 2 the default value
- The **4b** channel for graviton is competitive at 8 TeV with other experimental signatures
- At 14 TeV, the **whole parameter space of ration and graviton** production accessible
- The **boosted** and **resolved** regimes are being explored simultaneously

Summary and outlook

- **Scale-invariant resonance tagging** is a new theoretical development in jet physics which allows to **efficiently combine separate searches** (resolved vs boosted) into a **common analysis**
- Using these methods, **4b final state** is competitive for searches of **enhanced Higgs pair production**, a generic feature of many BSM scenarios
- In the context of **radion and graviton models,** a substantial fraction of parameter space can be excluded
- Now extending the feasibility analysis for the **bb $\gamma\gamma$ final state**
- Similar ideas can be applied to **top pair production**, to combine the boosted and resolved regimes in a common BSM searches