Boosted hh→bbbb: a New Topology in Searches for TeV-Scale Resonances at the LHC

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Introduction

Higgs has been discovered with couplings consistent with the Standard Model

Many new physics models predict enhancement of Higgs pair production at high invariant mass

- New resonances
  - KK graviton
- Extended Higgs sectors
  - 2HDM
  - Single Higgs extensions
  - Composite Higgs models

Dominant Higgs decay is $H \rightarrow bb$ (Br ~ 57%)

Motivates searches in $X \rightarrow hh \rightarrow bbbb$

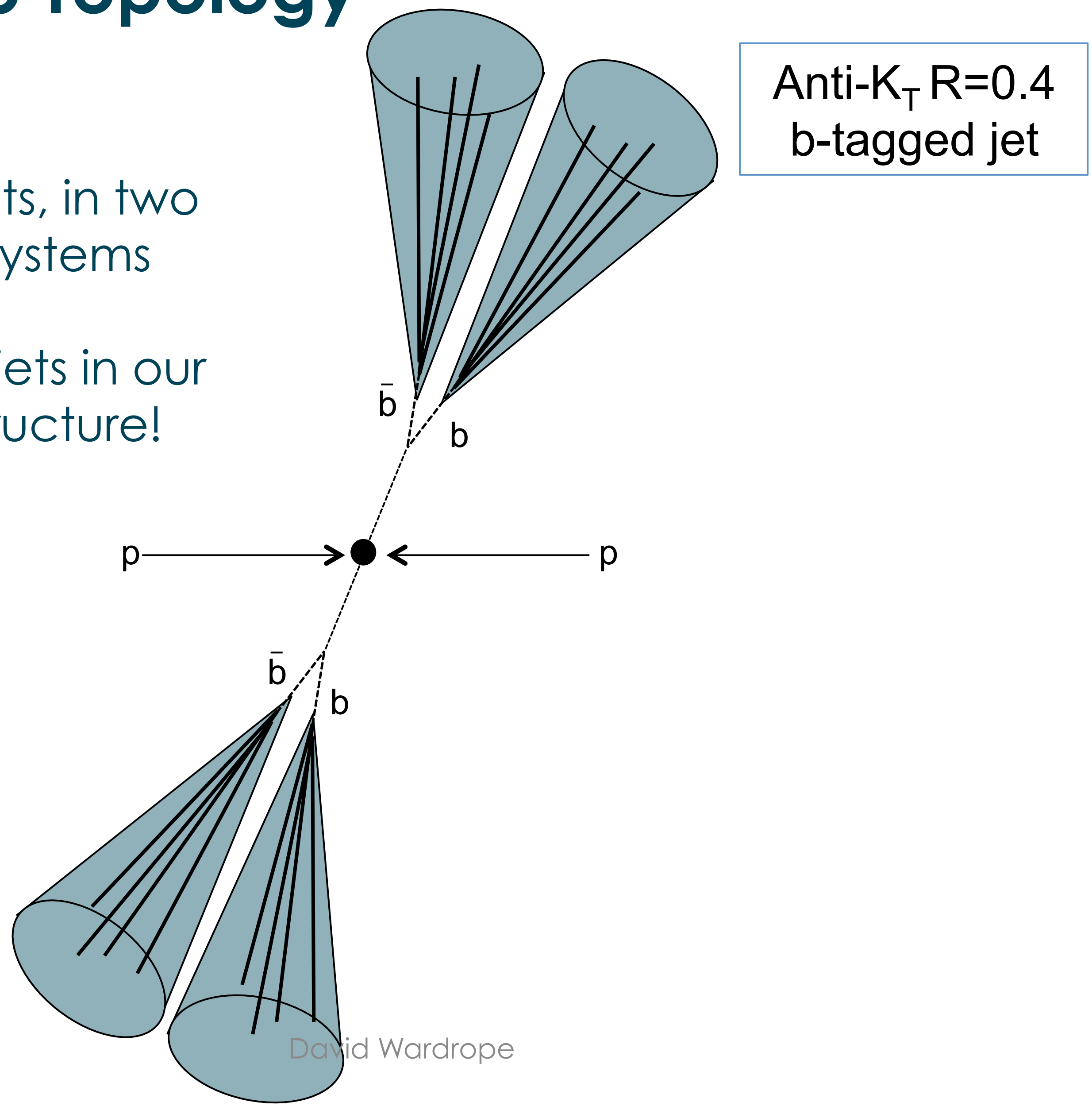
- As yet unexamined search topology
- But is it feasible?

Our short paper assesses the potential: arXiv:1307.0407

Boosted 4b Topology

Four b-tagged jets, in two boosted dijet systems

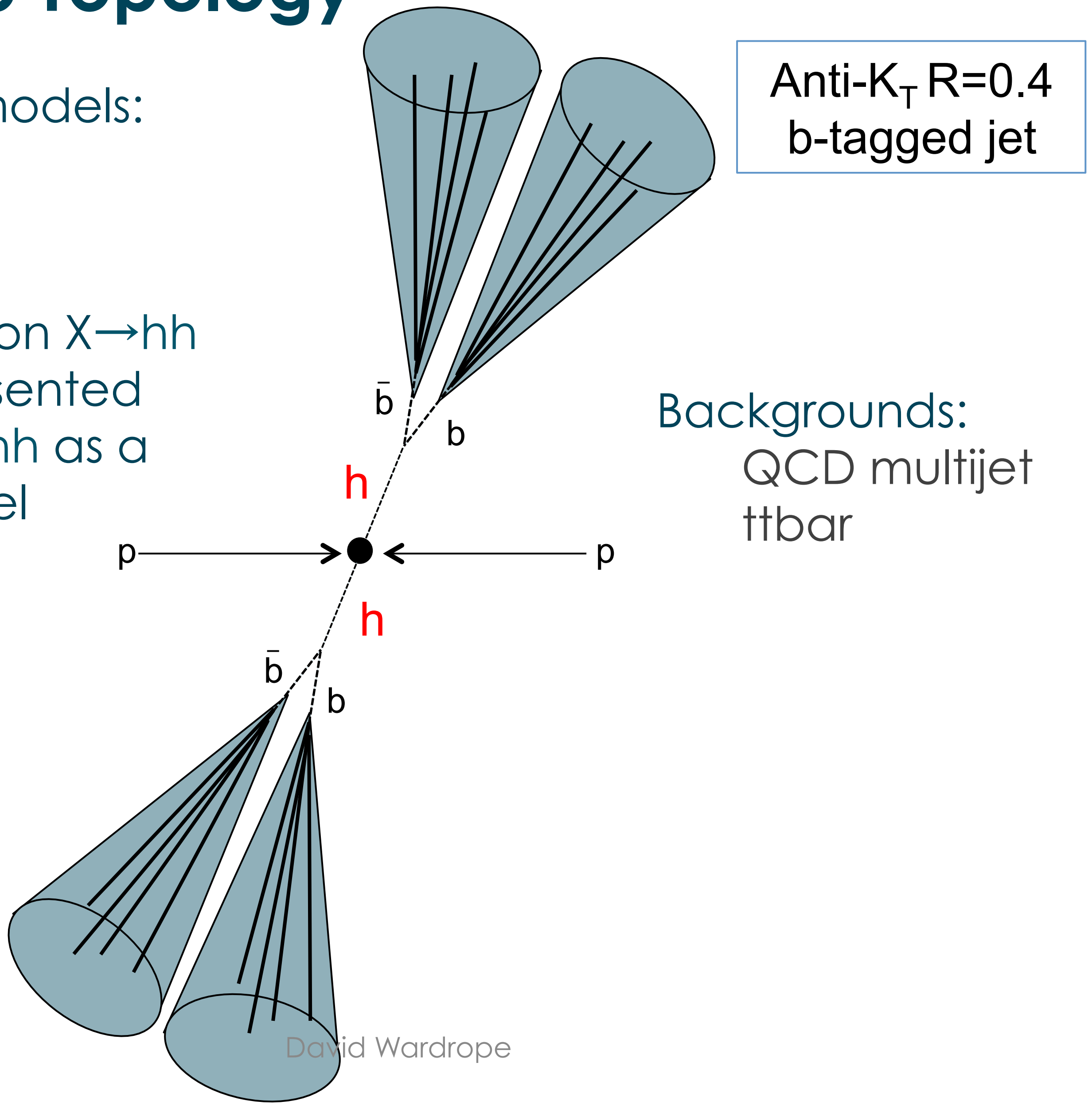
We use resolved jets in our study, no substructure!



Boosted 4b Topology

Potential Signal models:
- $G_{kk} \rightarrow hh$
- $H \rightarrow hh$
- $VV \rightarrow hh$

We concentrate on $X \rightarrow hh$ in the studies presented here, using $G_{kk} \rightarrow hh$ as a benchmark model



Backgrounds:
- QCD multijet
- ttbar

Boosted 4b Topology

The topology also allows for X→ZZ

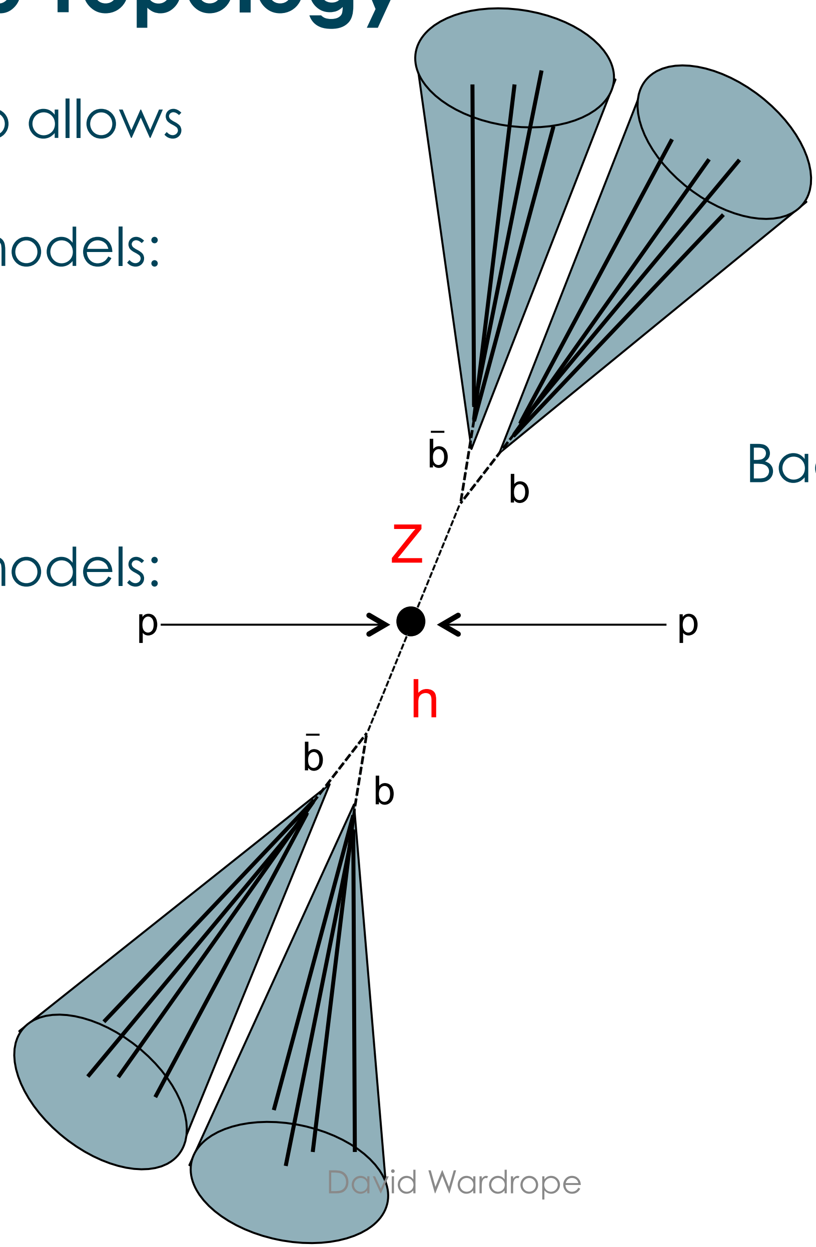
Potential signal models:

- G_{kk}→ZZ
- H→ZZ
- VV→ZZ

Or even X→hZ

Potential signal models:

- A→hZ



Anti-K_T R=0.4
b-tagged jet

Backgrounds:

- QCD multijet
- ttbar
- Z→bb + jets
- Diboson ZZ

Pros and Cons of Boosted 4b Channel

Advantages

- Double dijet topology is distinctive – reduces background
- Resonances with large Higgs couplings benefit from Br(h→bb)
  - This benefit is squared!
- Resonances with large Z couplings benefit from Br(Z→bb)
  - BR(ZZ→bbbb)/BR(ZZ→llll) ~ 5 (where l = e, μ)
- Multiple high p_T b-jets make efficient triggering possible
  - multijet triggers at first level
  - b-jet triggers at higher levels
- Boost removes ambiguity in assigning jets to parent

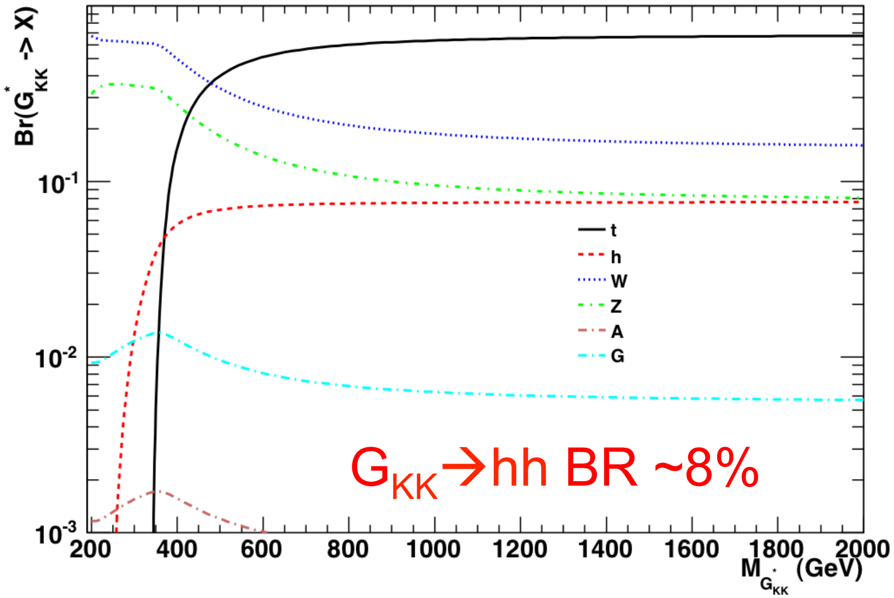
Disadvantages

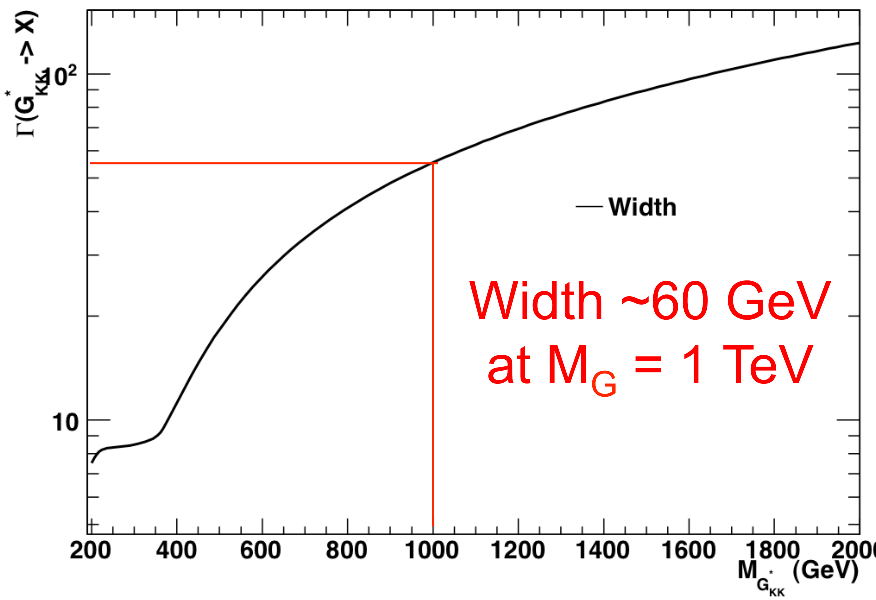
- QCD 4-jet production has a massive cross-section
- Signal efficiency reduced by ε_b^4

We have performed a particle-level study to ascertain whether advantages outweigh the disadvantages

Benchmark Signal Model

Taken from [3] with kind permission





- Randall-Sundrum Kaluza-Klein graviton (G_{kk}) in Agashe-Davoudiasl-Perez-Soni (ADPS) model with k/M_{Pl} = 1.0 [1,2]
  - G_{kk} production/decay to light fermions/photons highly suppressed.
  - Significant $G_{kk} \to hh$ branching ratio.
- Generated using Madgraph + Pythia 8.17 with CTEQ6L1, using the CP^3-Origins Madgraph implementation [3] of the ADPS model.
  - Only the $G_{kk} \to hh \to bbbb$ decay mode with m_h=125 GeV.

Particle-Level Study

Cluster final state particles into anti-K_T R=0.4 jets.
No detector smearing applied.

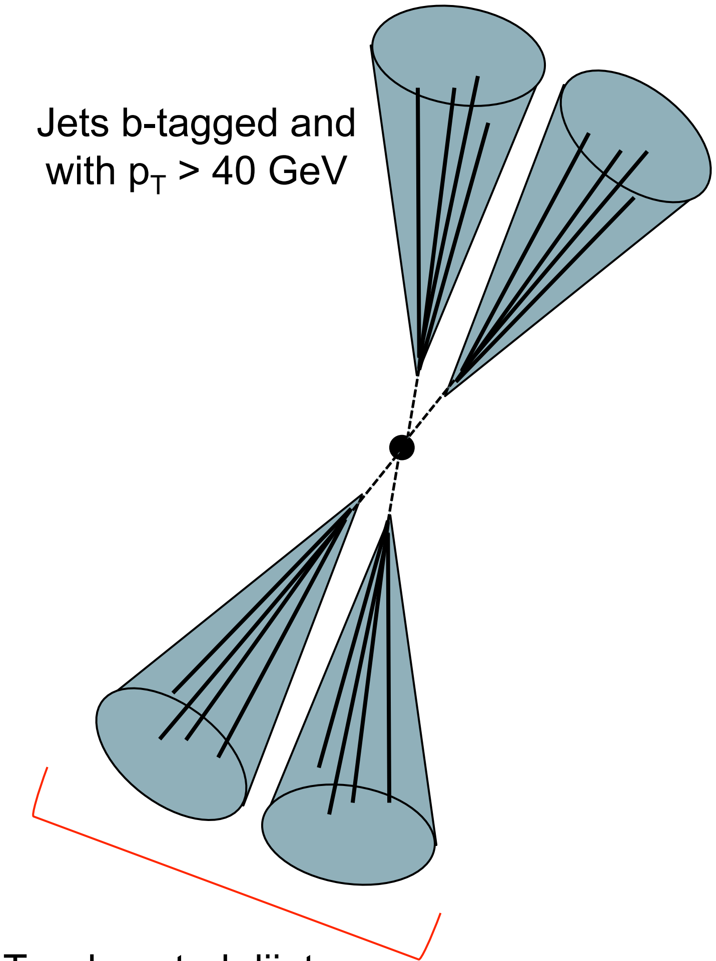
Require at least 4 b-tagged jets with p_T > 40 GeV and $|\eta| < 2.5$

"Truth" b-tagging using simple parameterisation of ATLAS/CMS b-tagging performance:
B-jet 70%
C-jet 20%
Light 1%

Require 2 dijets with p_T^{dijet} > 200 GeV and $\Delta R_{dijet} < 1.2$

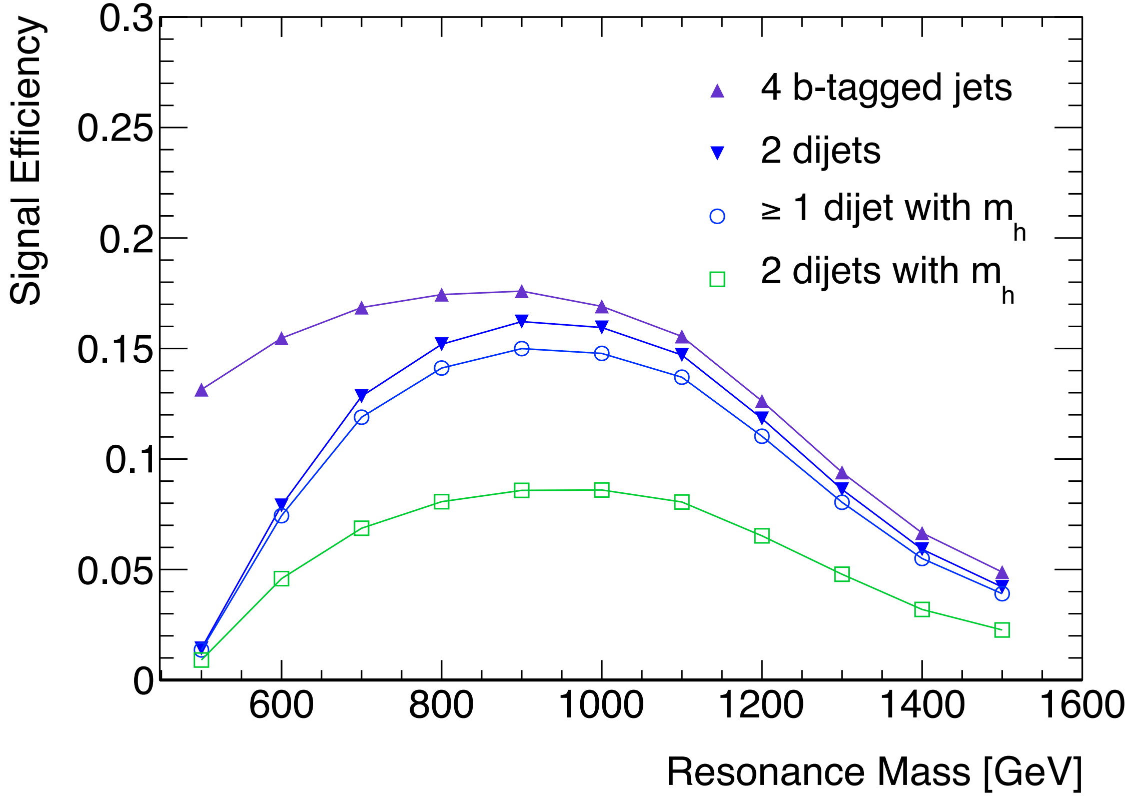
Require m_{dijet} consistent with m_h
$100 < M_{dijet} < 130$ GeV

Jets b-tagged and with p_T > 40 GeV



Two boosted dijet systems p_T > 200 GeV and $m_{dijet} \sim m_h$

Signal Efficiency

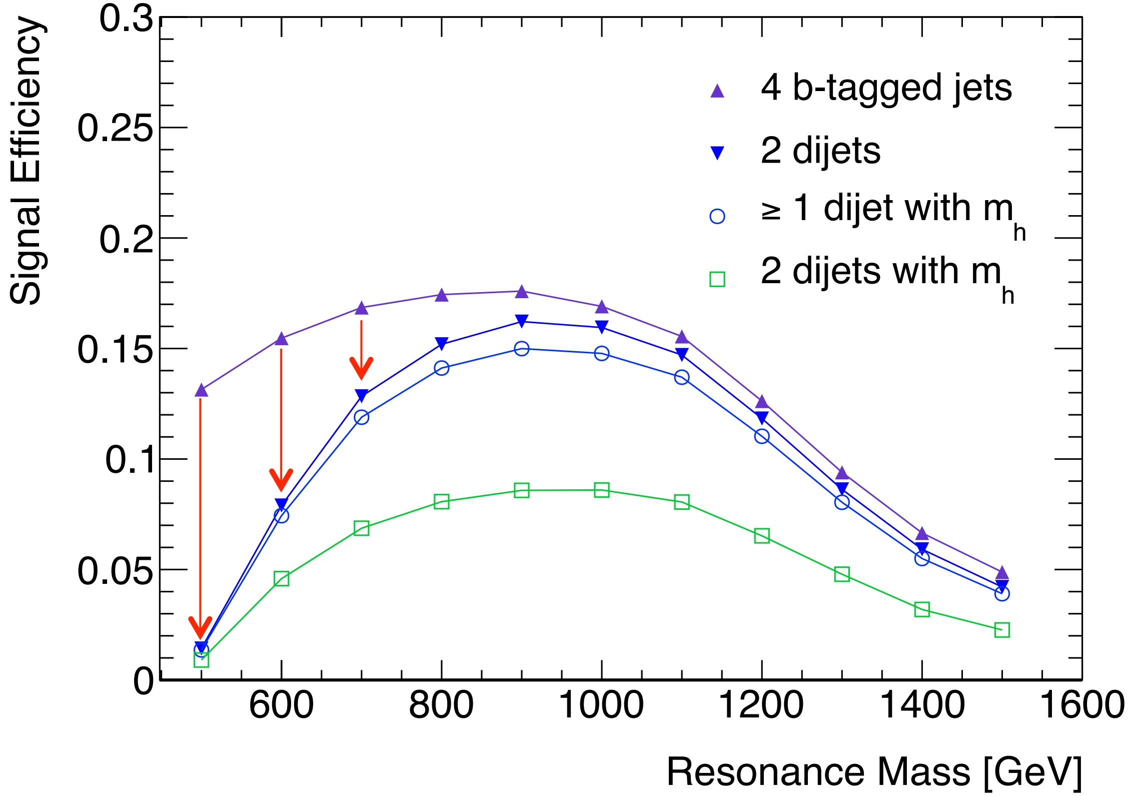


Efficiency peaks for masses between 0.7 and 1.2 TeV

b-tagging efficiency probably better than our assumption

- Most jets are central and have p_T, where ATLAS and CMS b-tagging perform best

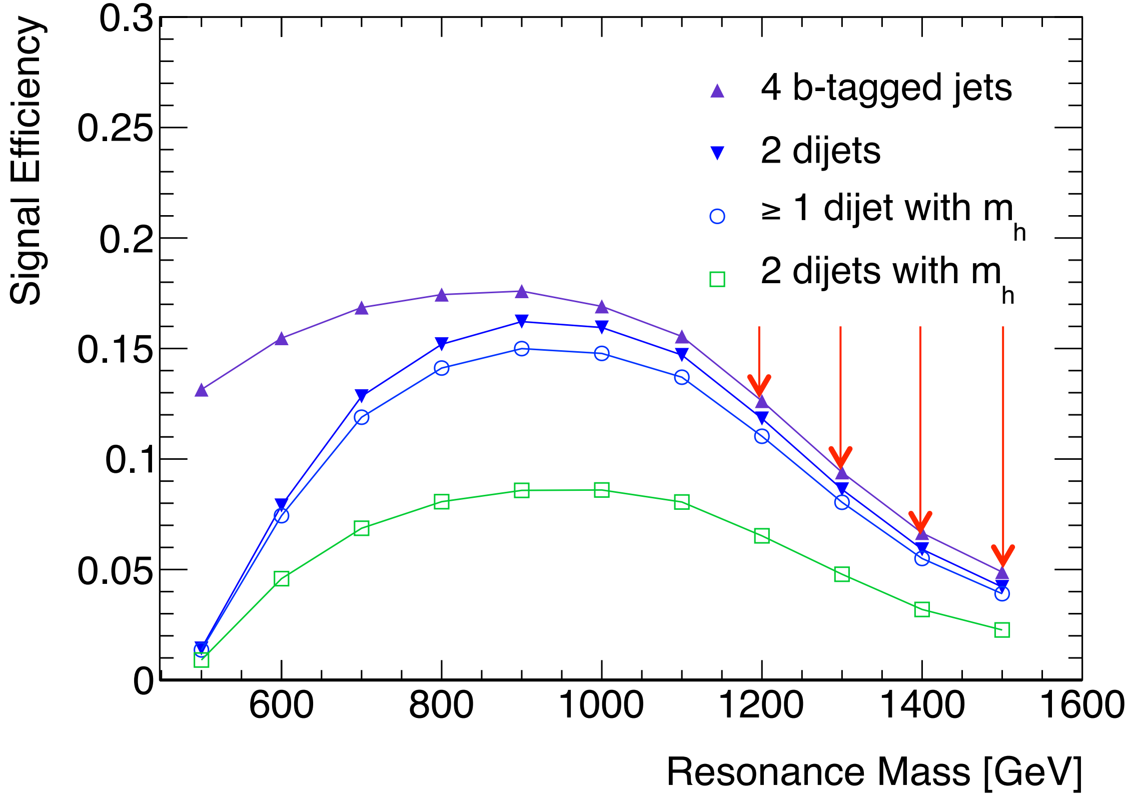
Signal Efficiency



Efficiency loss at low mass because of dijet p_T and ΔR requirements (and jet p_T)

requirements could be optimised to increase efficiency

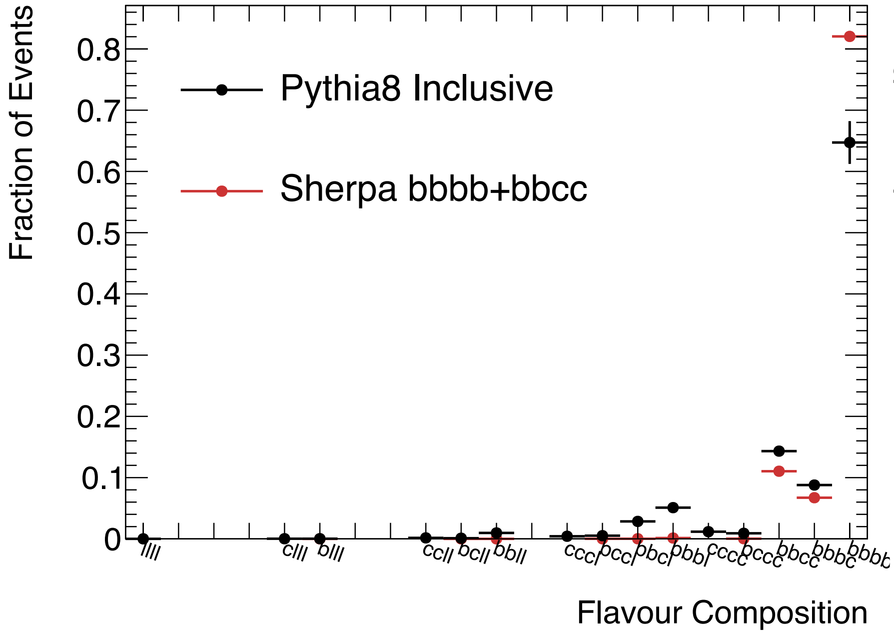
Signal Efficiency

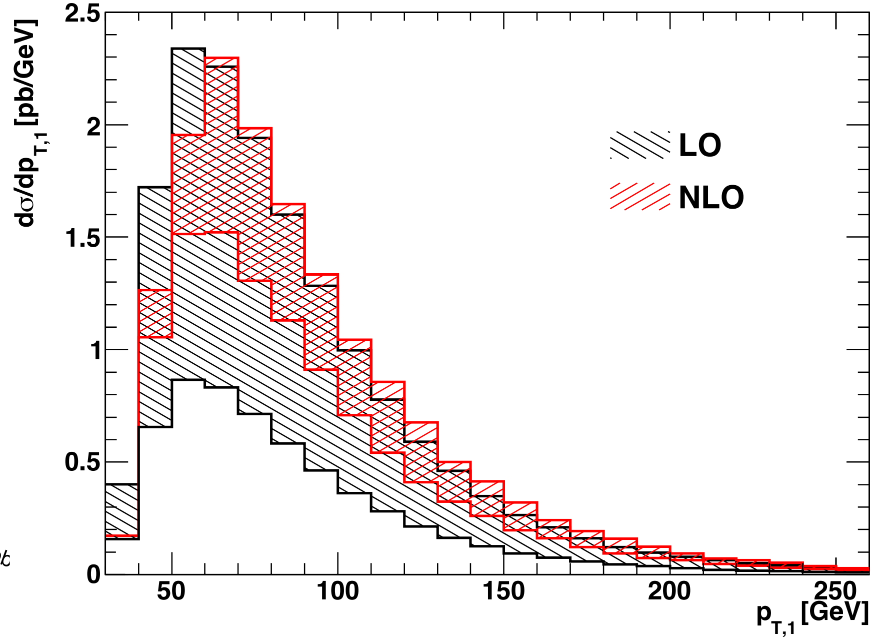


Efficiency loss at high mass because of jet merging

- substructure techniques could regain efficiency

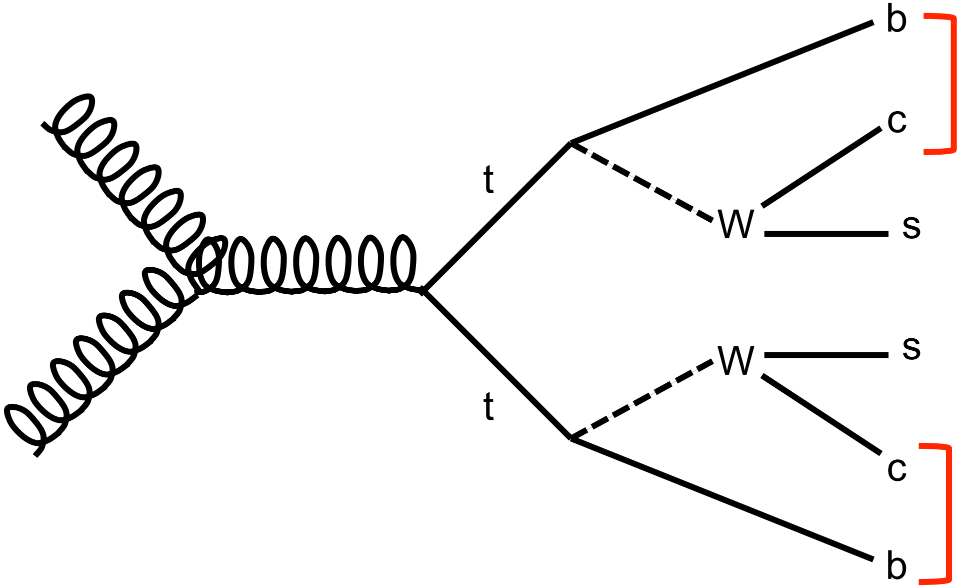
Background Estimation: QCD Multijet

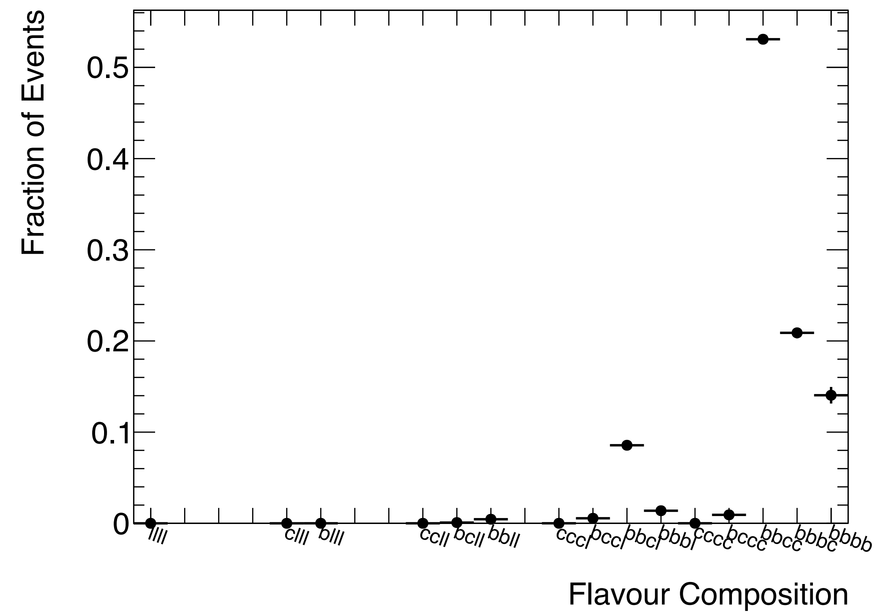




- Main component is the irreducible pp→bbbb.
  - Some contribution from mistagged charm and light jets
- Generated pp→bbbb and pp→bbcc using Sherpa 1.4.3
- We successfully reproduced the √s=14 TeV LO pp→bbbb prediction of [4] using Sherpa
- Use the same set-up for 8 TeV multijet background prediction
  - Confident that it is correct and scale variations covers NLO enhancement

Background Estimation: Top





Only significant top background is from all-hadronic ttbar

- c-jet from hadronic W decay fakes a b-jet, and forms dijet with true b-jet.

Generated using Pythia 8.17

Cross-section normalised to average ATLAS/CMS √s=8 TeV measurement (235pb) [6,7]

Measured uncertainties on ttbar cross-section are used

Background for 20 fb^{-1} at $\sqrt{s}$ = 8 TeV

Requirement	$G_{KK}(M = 800\,\mathrm{GeV})$	QCD	$t\bar{t}$
4 b-tagged jets	126	19700	3590
2 dijets	109	414	151
≥ 1 dijet with m_h	102	183	89
2 dijets with m_h	58	28^{+20}_{-11}	21 ± 3

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Backgrounds are dramatically suppressed when we require the b-tagged jets form two boosted dijets
~50× for QCD multijet and ~25× for ttbar

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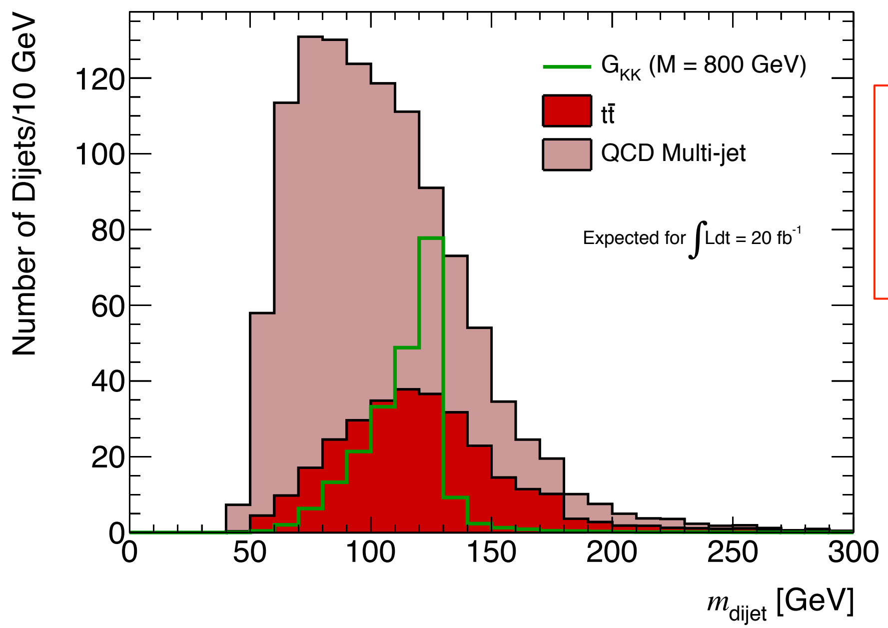

Dijet mass distribution after requirement of two dijets. S/B already 20%!

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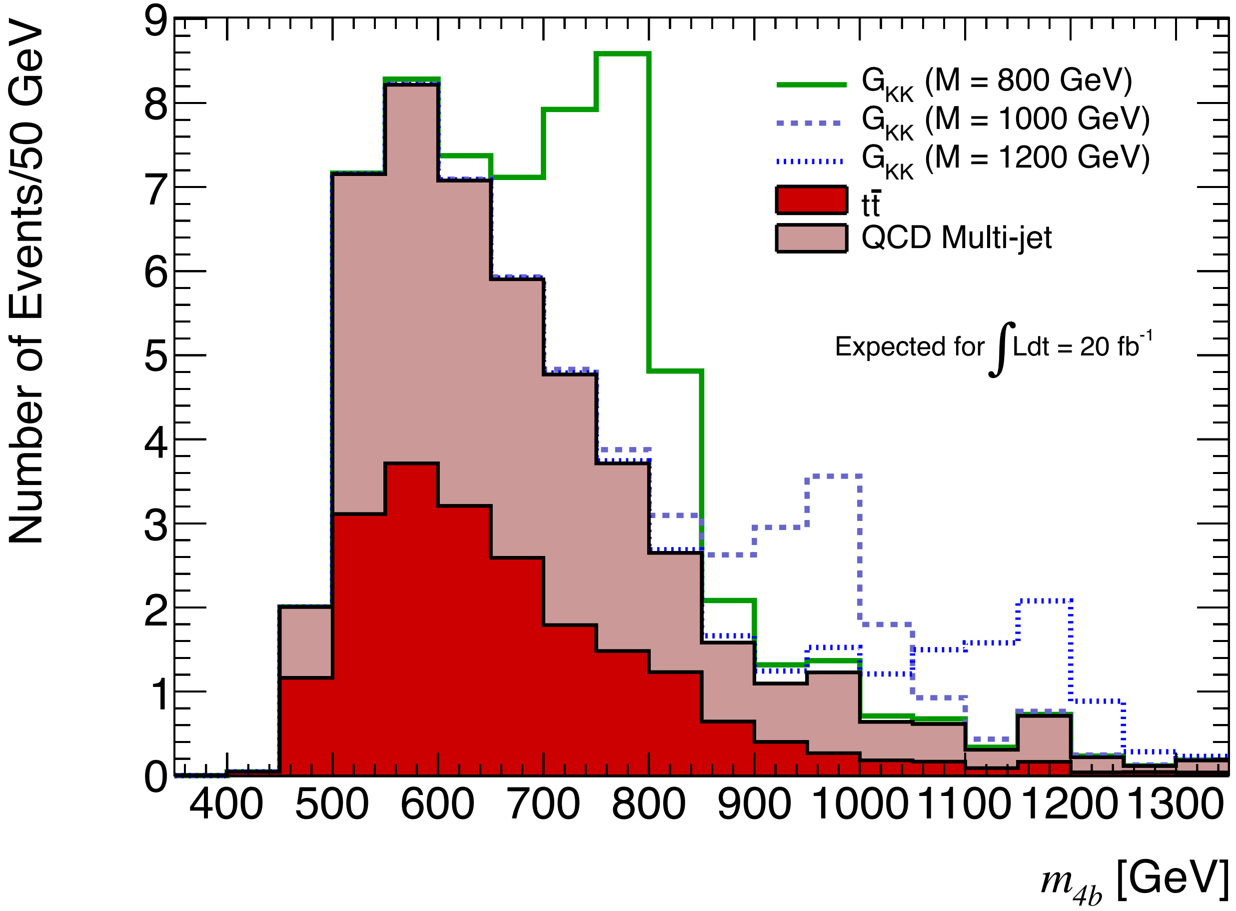
After requiring m_h, very little background remains

S/B ≈ 1, despite low signal cross-section σ = 36 fb

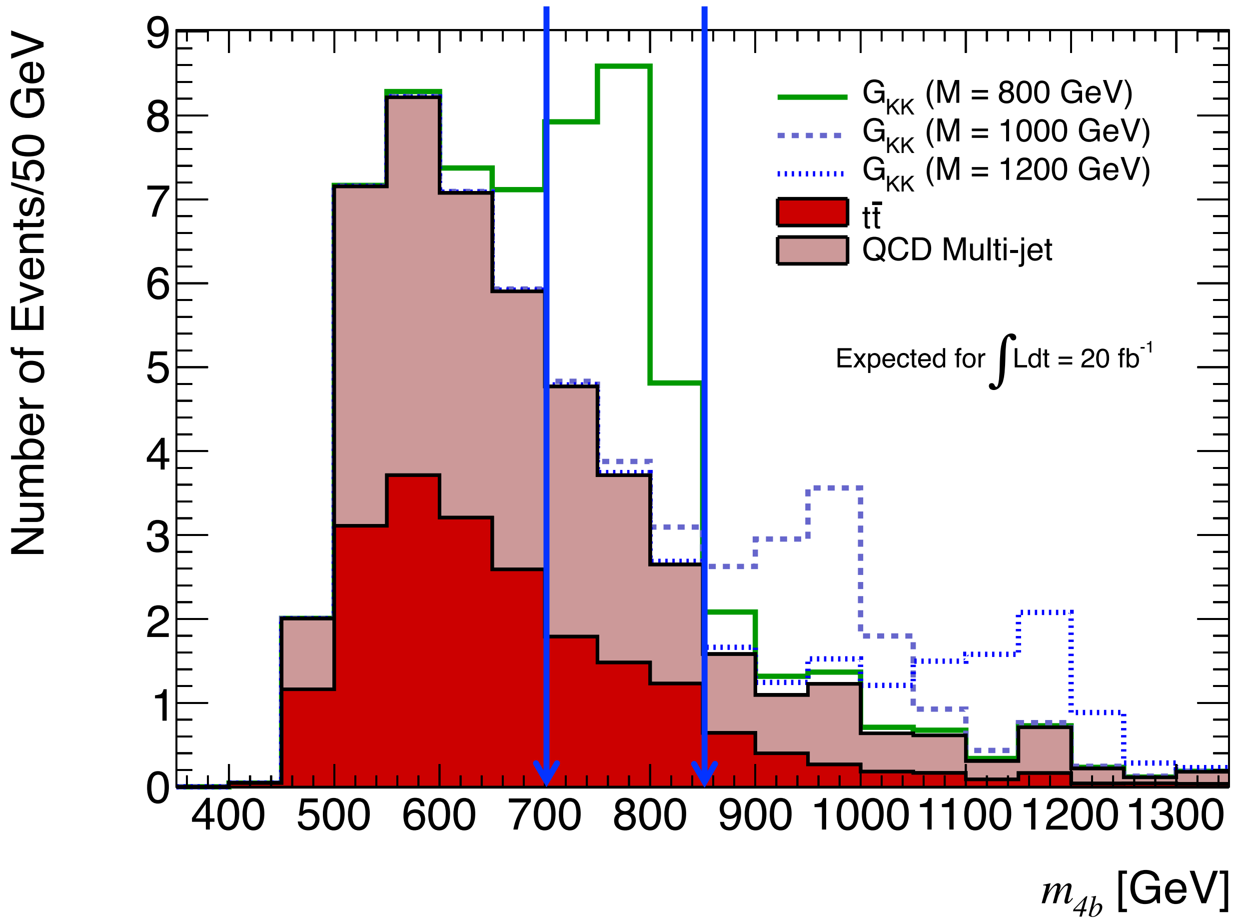
QCD and ttbar backgrounds of similar size

4b Invariant Mass After Selection



Signals are clearly visible over background

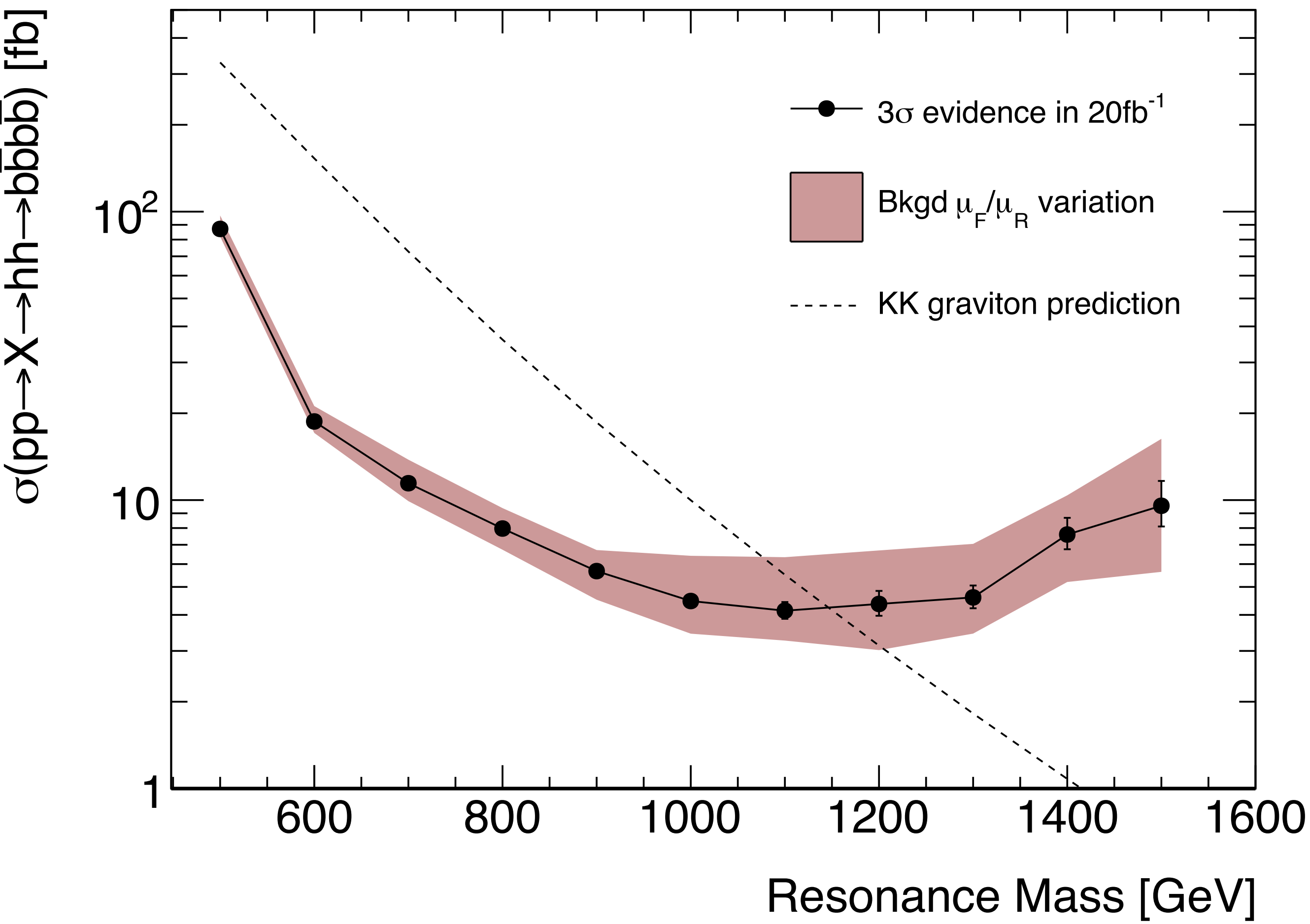
Sensitivity Estimation



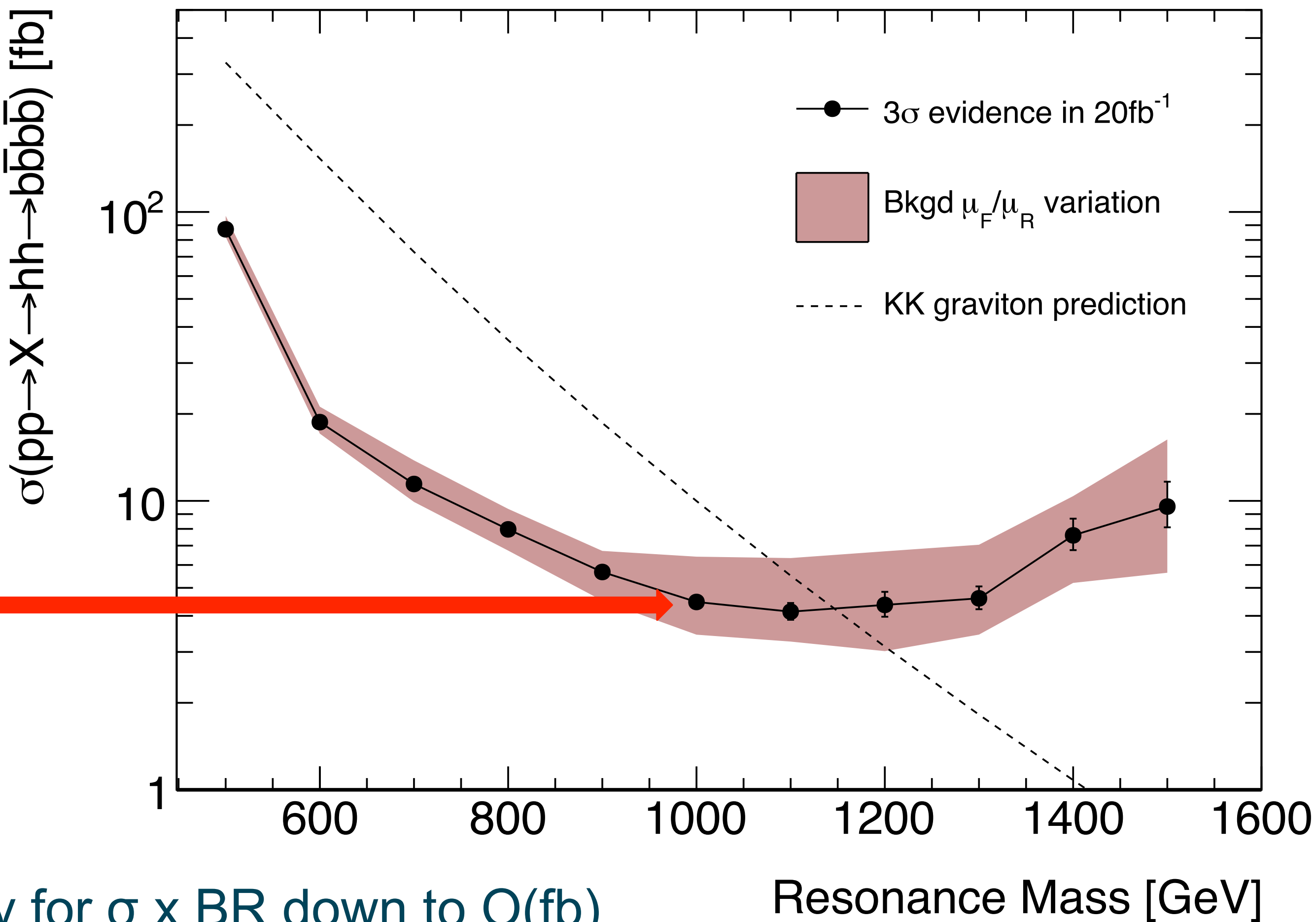
Count background in [-100,+50] GeV window around m_{Gkk}

Calculate signal cross-section needed for $s/\sqrt{b} = 3$ in $20fb^{-1}$

Cross-section for 3 σ Sensitivity

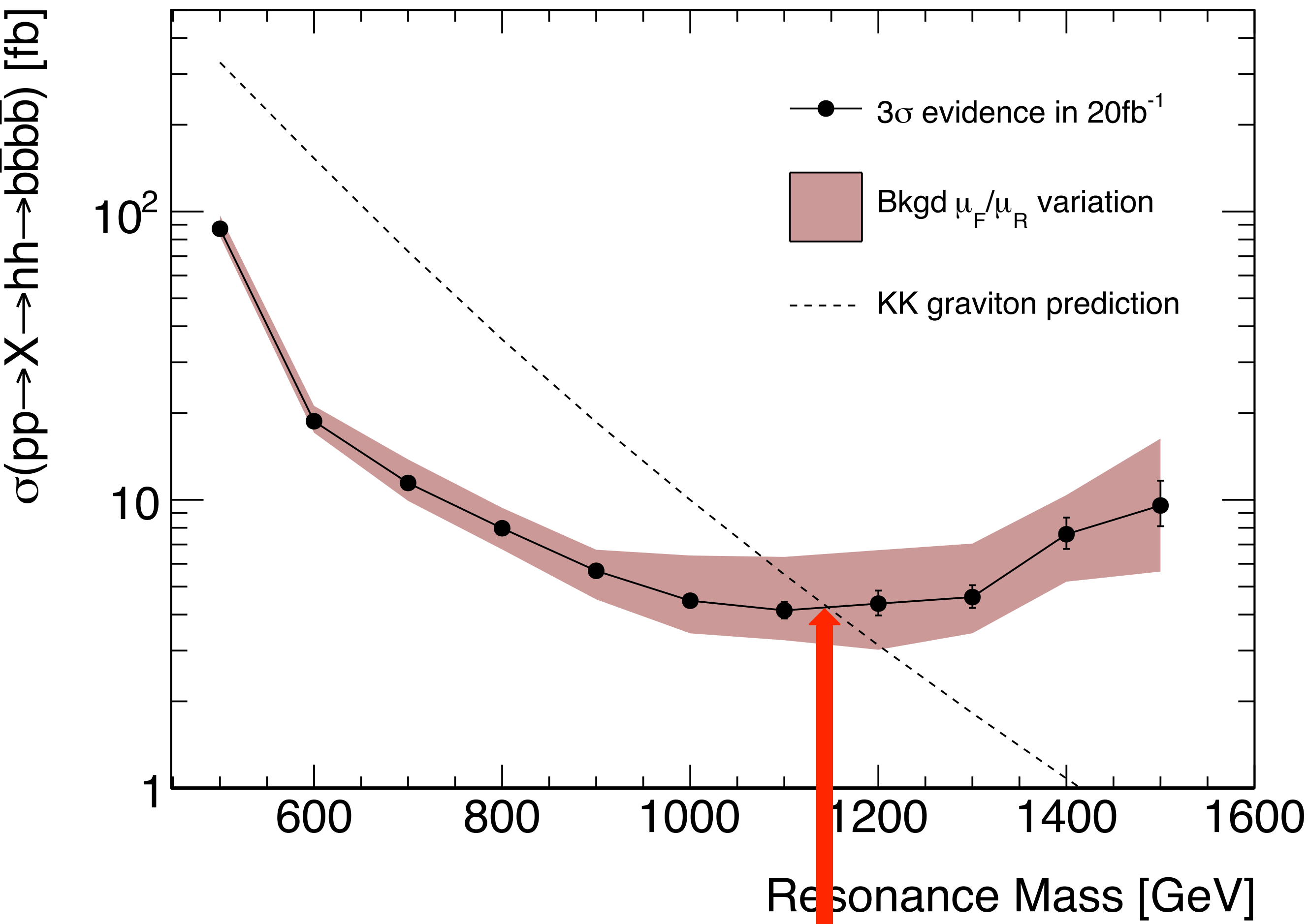


Cross-section for 3σ Sensitivity



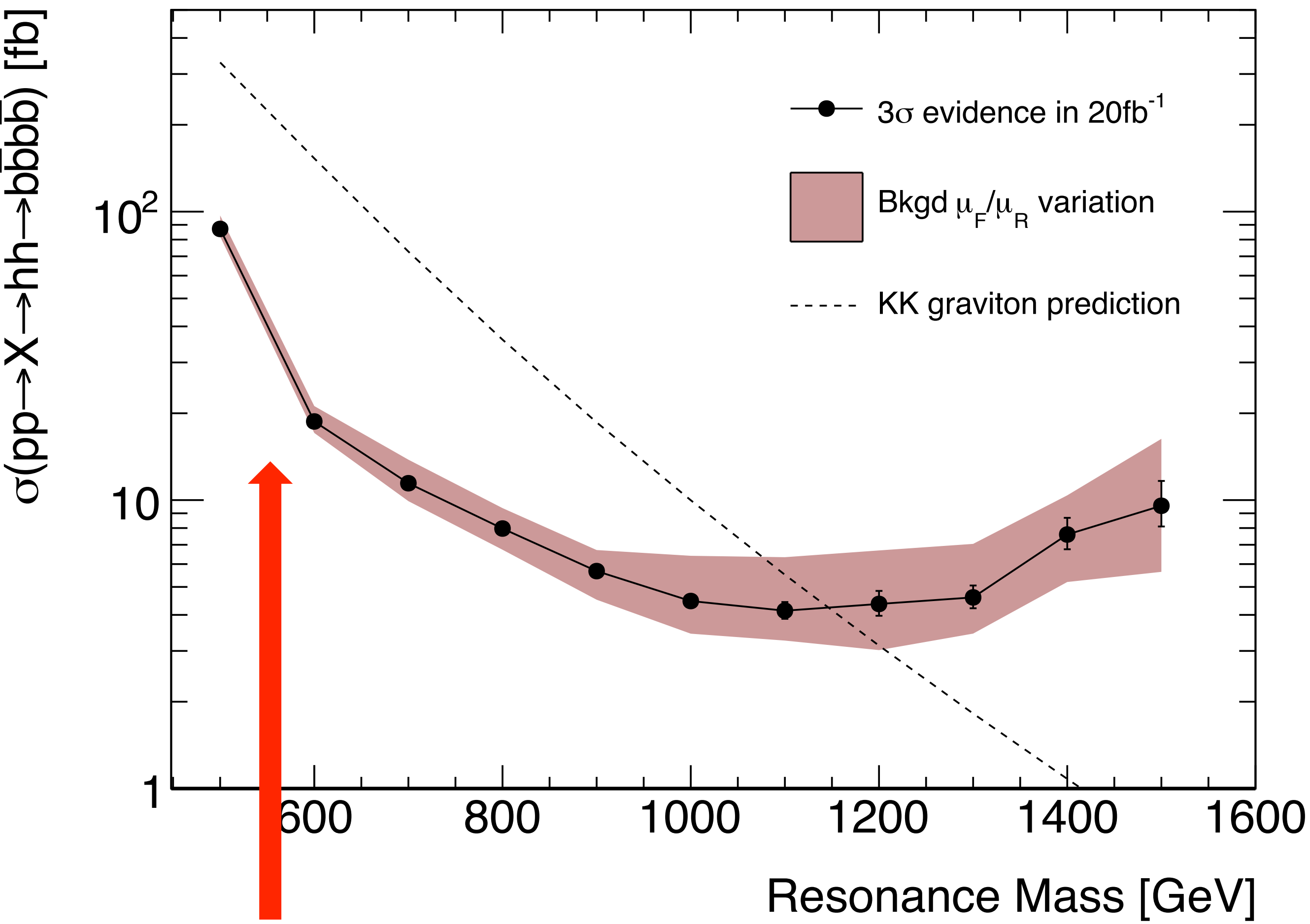
3σ sensitivity for σ x BR down to O(fb) for TeV resonances with existing LHC dataset of ∫Ldt = 20fb^{-1}!

Cross-section for 3 σ Sensitivity



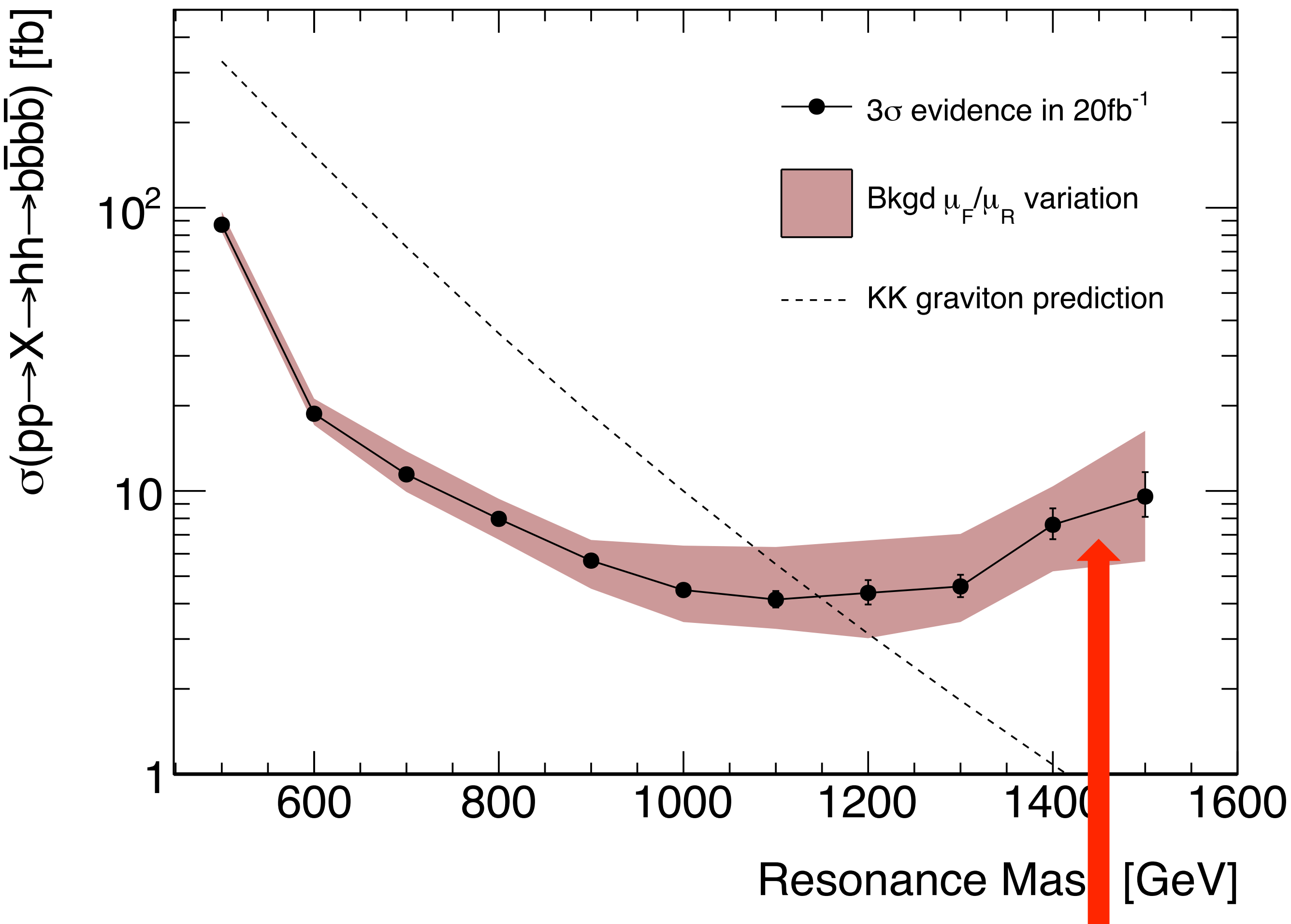
Have discovery sensitivity to KK gravitons up to 1.15 TeV

Cross-section for 3σ Sensitivity



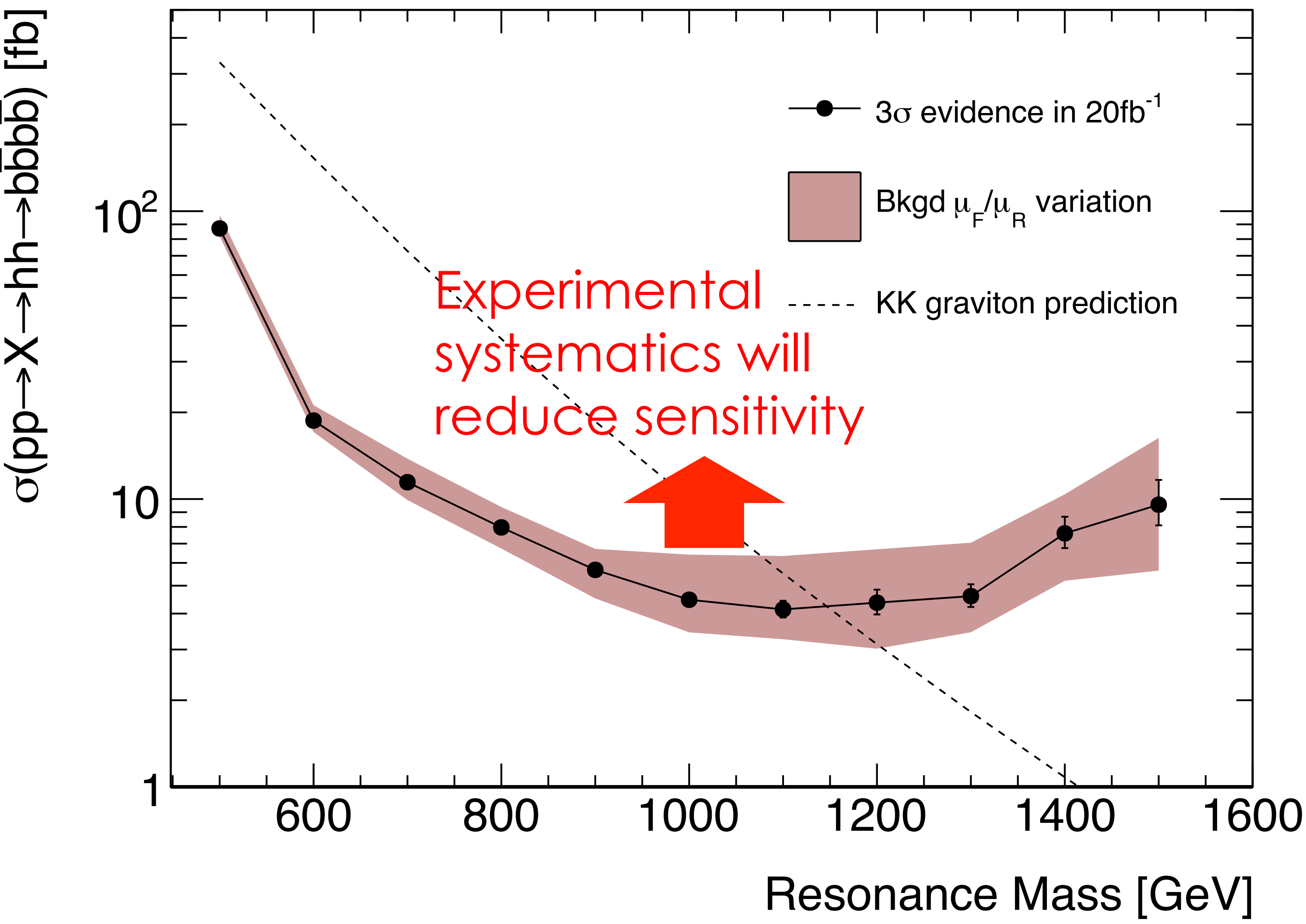
Sensitivity worse at lower mass due to lower signal efficiency and higher background

Cross-section for 3σ Sensitivity

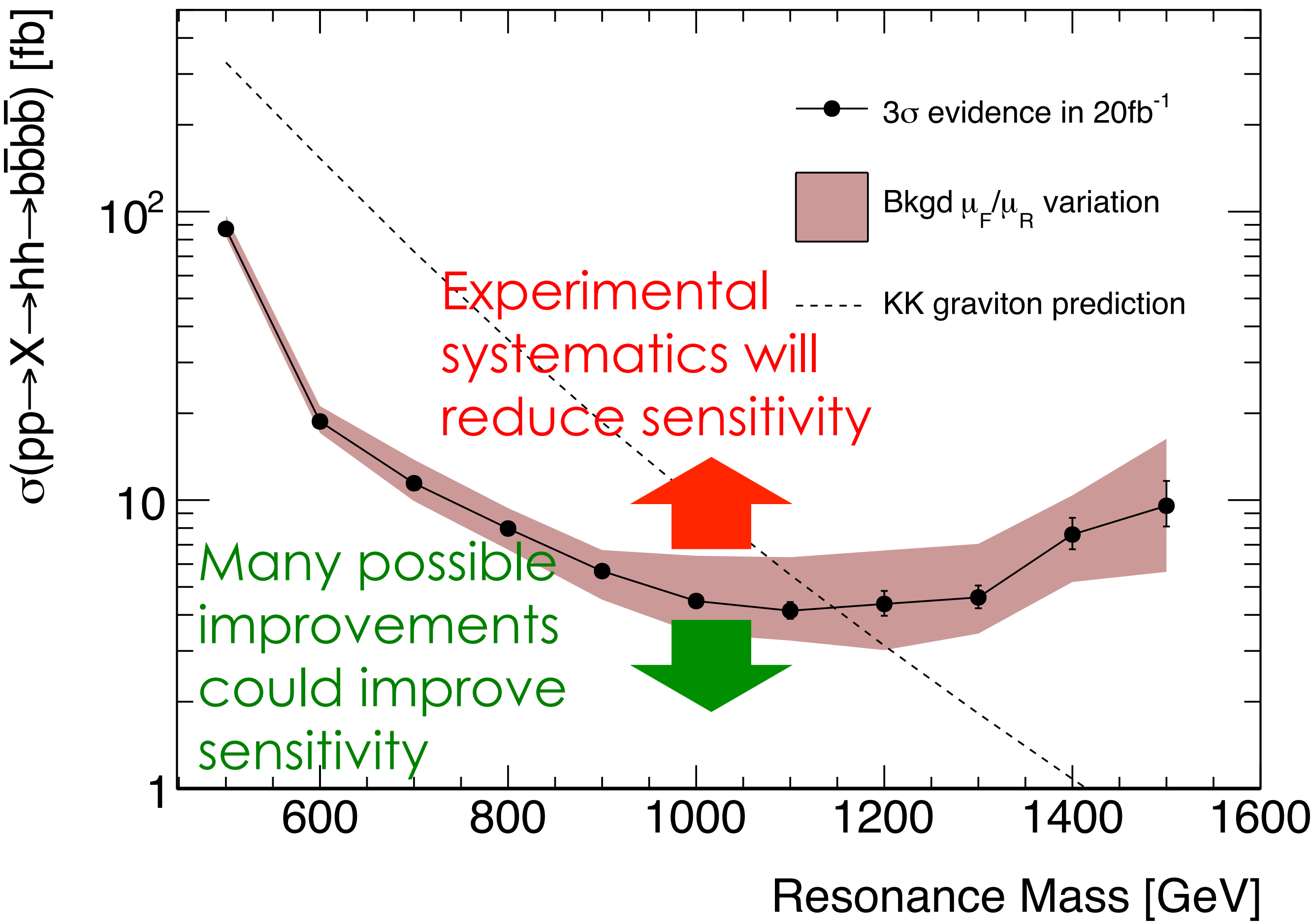


Sensitivity decreases at high mass due to lower signal efficiency
Counteracted by very low background at these resonance masses

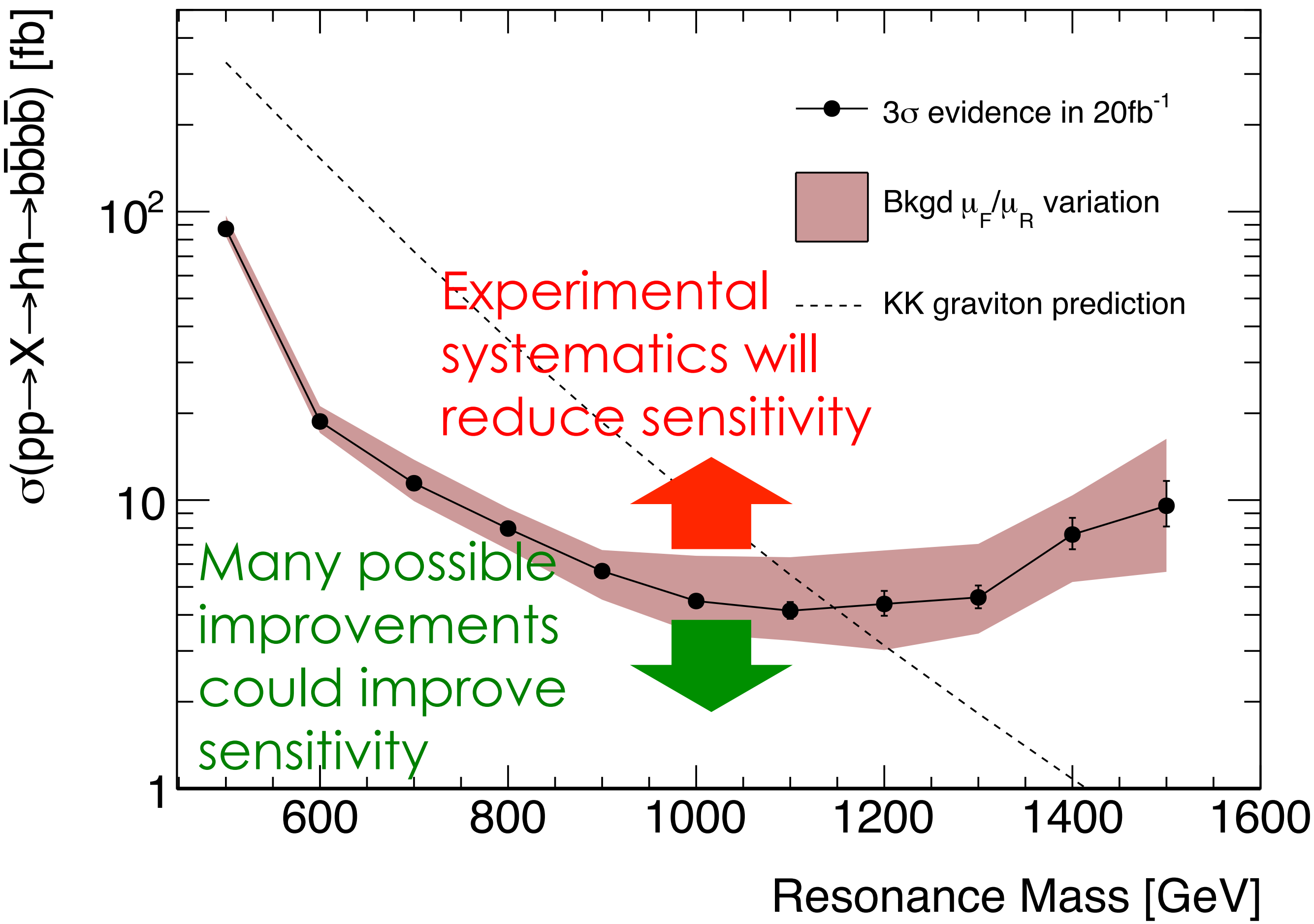
Cross-section for 3σ Sensitivity



Cross-section for 3σ Sensitivity



Cross-section for 3 σ Sensitivity



We conclude there is great potential for searches in the boosted 4b final state

Potential for Optimisation

- Purpose of this simple study is to flag $X \rightarrow hh \rightarrow bbbb$ as a very promising final state for new physics searches
  - We leave the optimisation for the experiments!
- A few suggestions for extracting best possible sensitivity:
  - Tuning of basic cuts versus mass in the resolved analysis
    - p_T^{jet}, p_T^{dijet}, ΔR_{dijet}, m_H window
  - Incorporate large-R jets and substructure into analysis for resonance masses > 1.2 TeV
  - Additional cuts to reduce ttbar background
    - e.g. optimised b-tagging, n_{jets} requirements
  - Improve m_{4b} resolution using a kinematic fit
    - take advantage of known m_h

Summary

The boosted bb-bb final state is extremely promising

Powerful background rejection of the boosted dijet topology enables sensitive searches for X→hh

- despite final state being fully-hadronic

Should work for X→hZ and to complement X→ZZ

- And for ZZ VBS in bb-bb final state
- ZZ→llbb
- hZ→ $\tau\ \tau$ bb
- could even extend to VLQ BB→bbbbbb
- Many more we haven't thought of

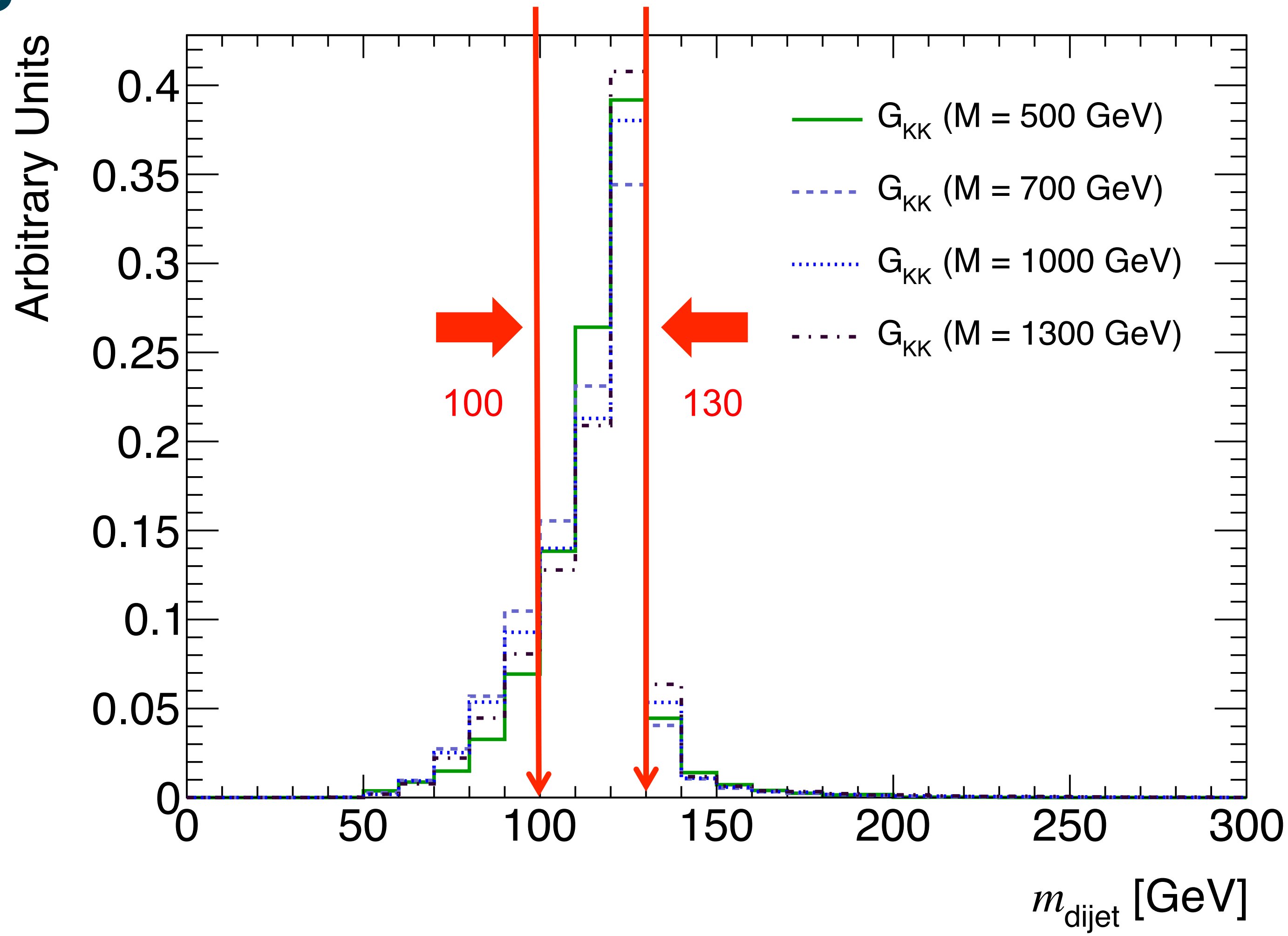
This is uncharted territory!

ADDITIONAL SLIDES

References

[1] K. Agashe et al Phys.Rev. D76 (2007) 036006.
[2] L. Fitzpatrick et al, JHEP 2007 (2007) 013.
[3] http://cp3-origins.dk/content/uploads/2011/10/kkgrav.pdf
[4] N. Greiner et al, Phys. Rev. Lett. 107 (Sep, 2011) 102002.
[5] G. Bevilacqua et al arXiv:1304.6860 [hep-ph].
[6] ATLAS Collaboration, ATLAS-CONF-2012-149.
[7] CMS Collaboration, CMS-PAS-TOP-12-027.
[8] M. Gouzevitch et al, JHEP 1307 (2013) 148.

Higgs Mass Window

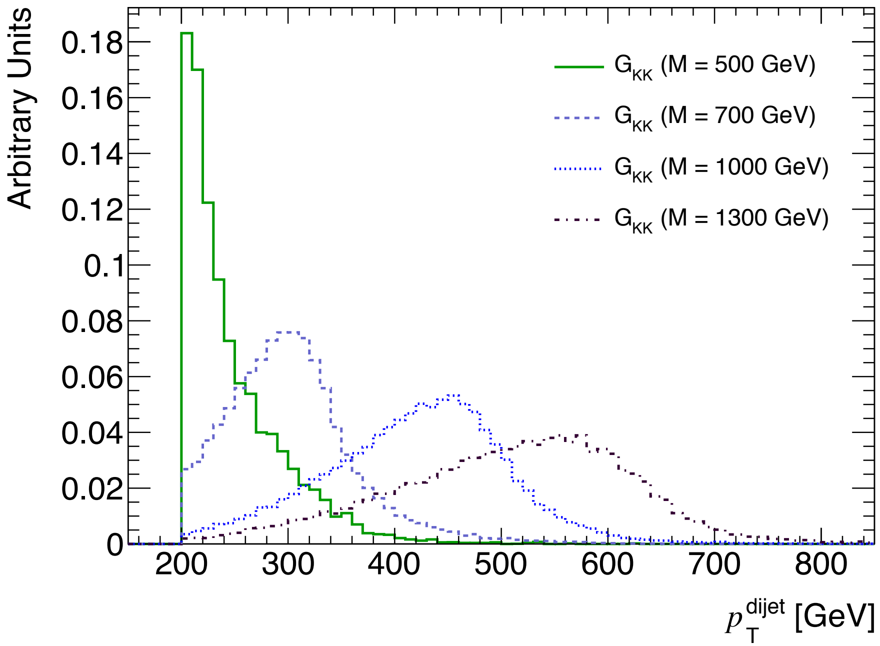


Jets do not include muons or neutrinos, and not corrected for out-of-cone.
Asymmetric cut around m_h=125 GeV is appropriate.

Benchmark Signal Model

Graviton Mass [GeV]	$\sigma(pp \to G_{\mathrm{KK}} \to hh \to b\bar{b}b\bar{b})$ [fb]	Γ [GeV]
500	329	18.6
700	72.7	33.9
900	18.6	48.6
1100	5.51	62.7
1300	1.82	76.5
1500	0.65	90.0

Signal Kinematics

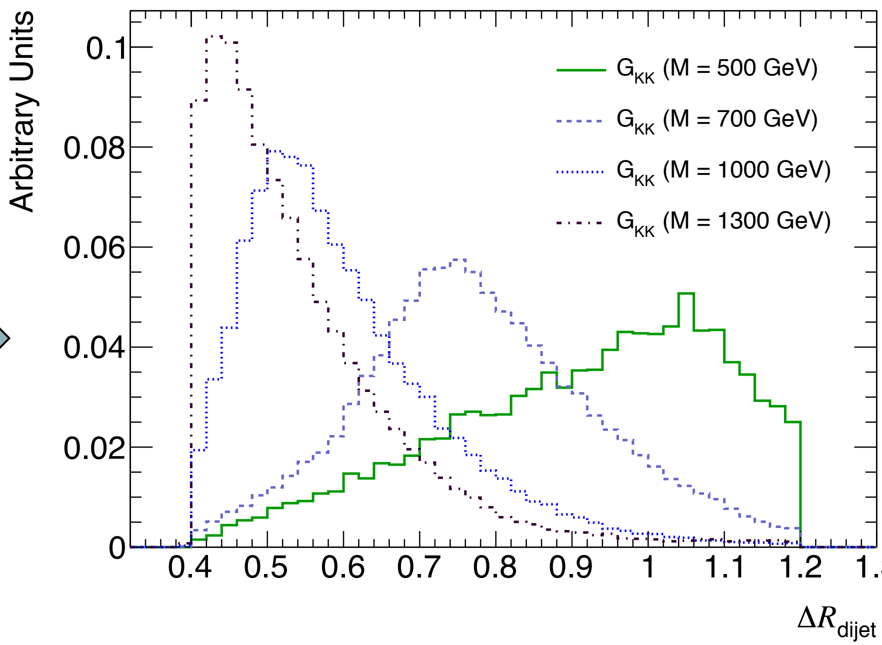


Clear efficiency loss at low G_{KK} masses from dijet p_T requirement

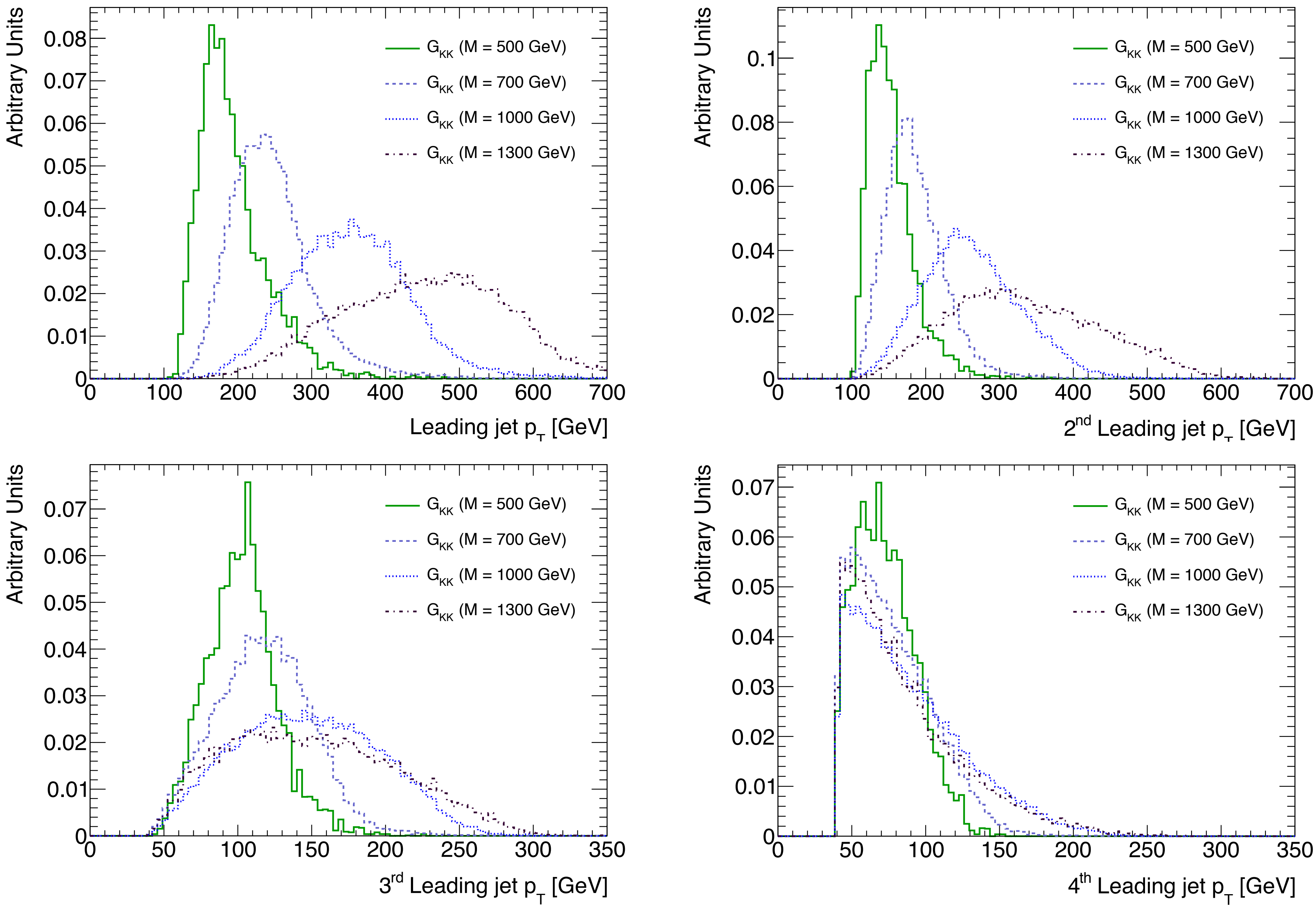
Optimal dijet p_T cut likely to be higher for higher masses

Loss of efficiency from jet merging at high G_{KK} masses in this resolved analysis

For lowest masses the ΔR_{dijet} cut could be optimised



Signal Jet Kinematics



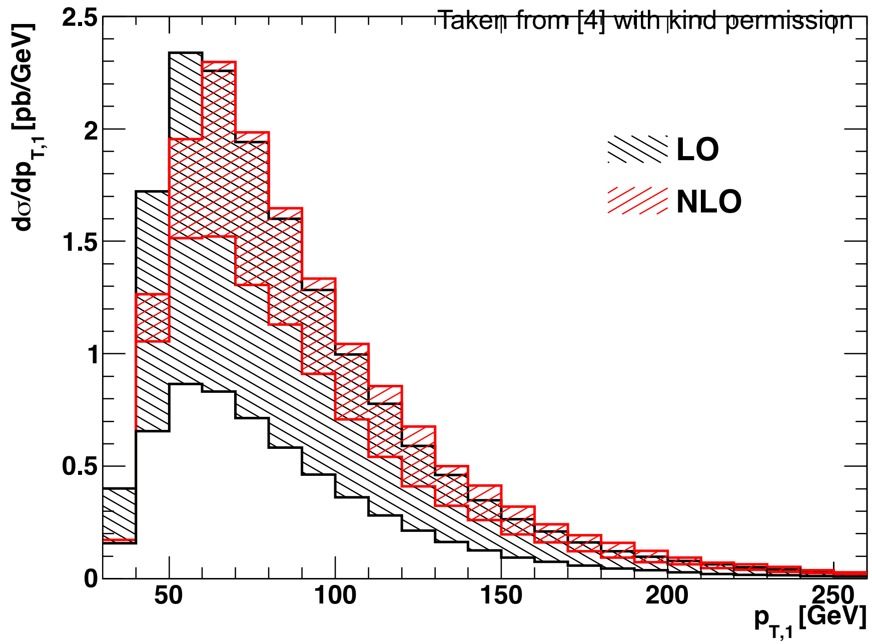
QCD Backgrounds

Define uncertainty on our Sherpa background prediction as variation in renormalisation/factorisation scale choice μ_0 by factor ½ and 2:

$$\mu_0 = \mu_F = \mu_R = \frac{1}{4}\sqrt{\sum_i p_{T,i}^2}$$

NLO corrections to LO pp→bbbb at √s=14 TeV recently calculated in [4] and [5]

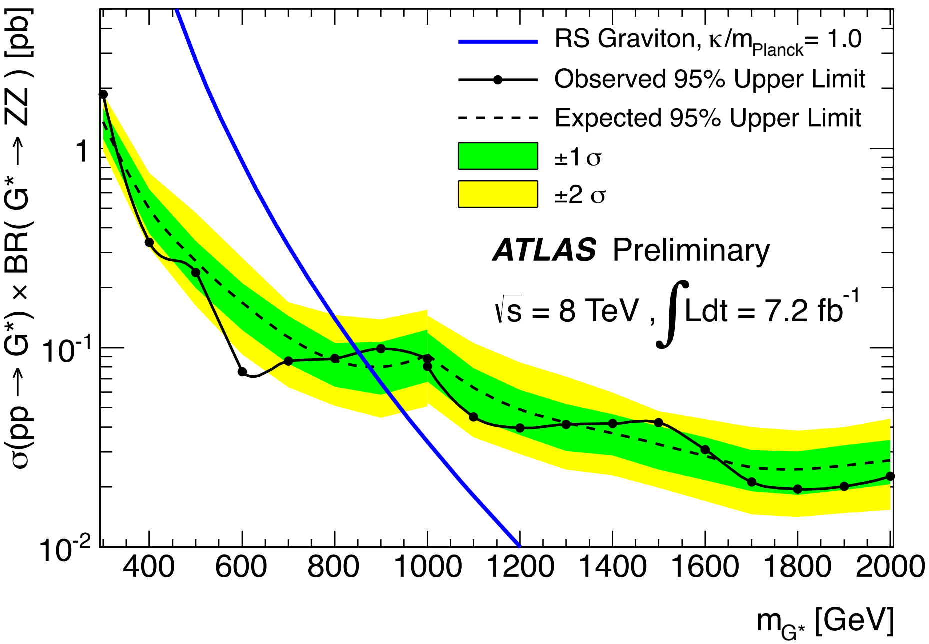
- NLO/LO corrections are large ~50%
- But renormalisation/factorisation scale variations of LO cover the variation at NLO

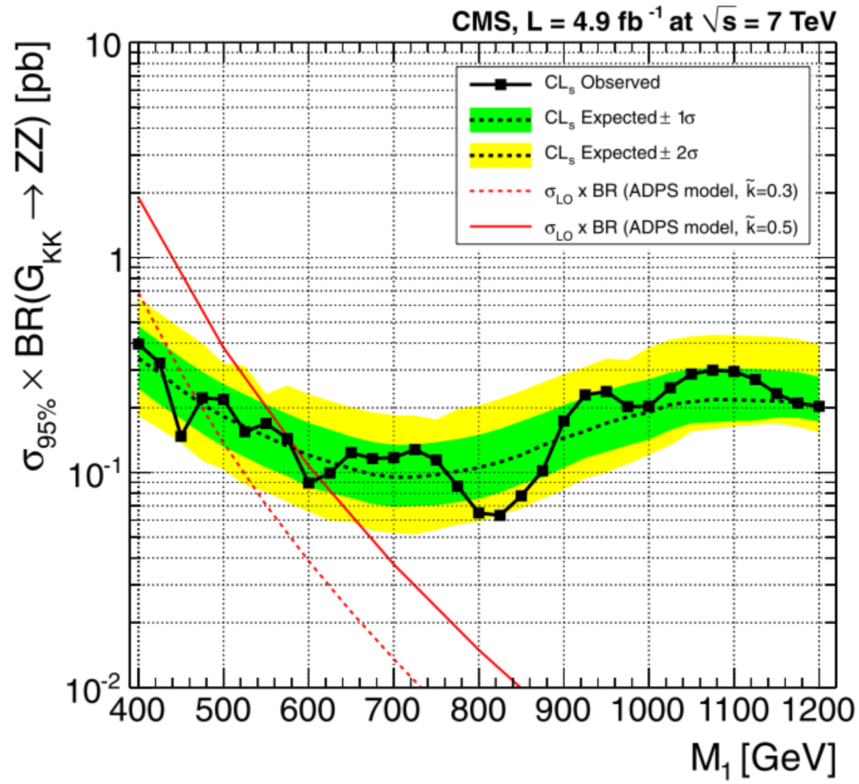


We successfully reproduced the LO prediction of [4] using Sherpa bbbb at √s=14 TeV with the same scale choice μ_0

Hence we have some confidence that our scale variations of Sherpa cover NLO corrections

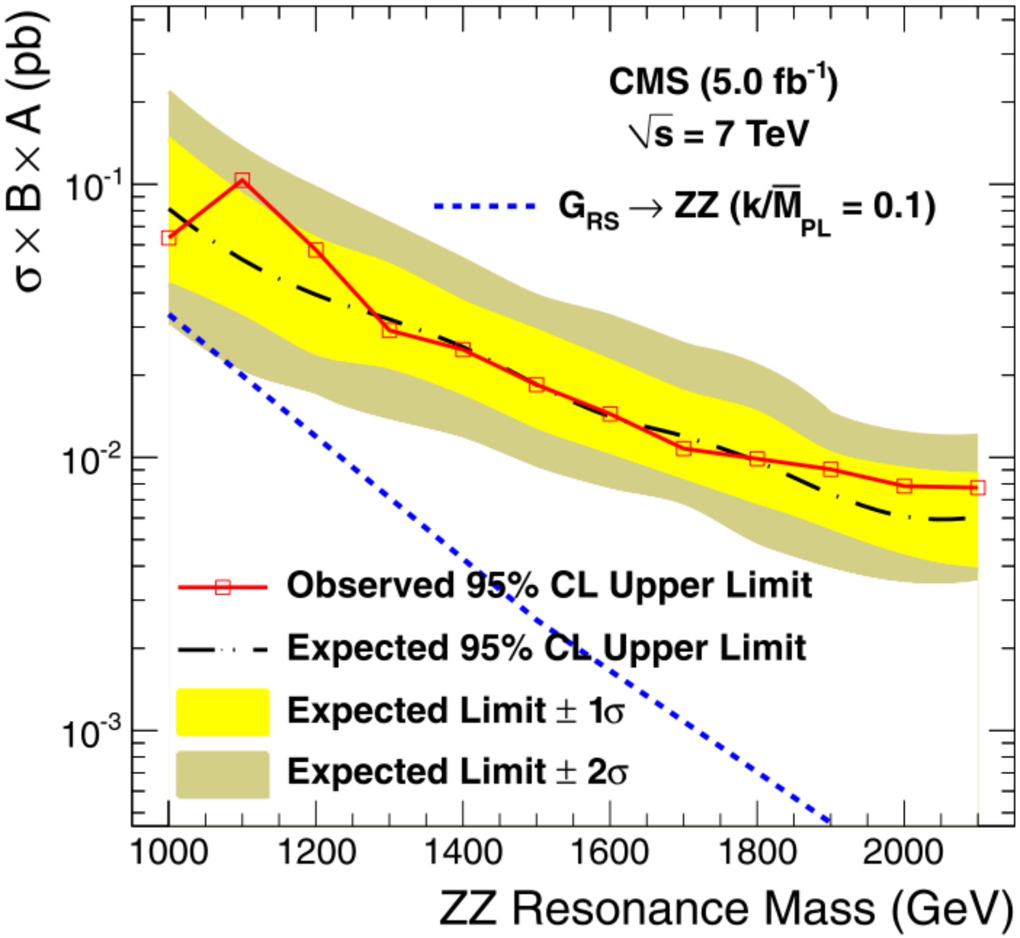
ZZ→lljj Limits on G





95% C.L. upper limits of ~100fb at 1 TeV.
Exclusion up to mG_{KK} ~ 900 GeV for k/M_{Pl} = 1.0.

ZZ→jjjj Limits on G



Don't use ADPS model explicitly.
95% C.L. upper limits of ~90fb at 1 TeV.
Uses dijet mass of fat-jets with pruning and MDT.