Boosted hh→bbbb: a new topology in searches for TeV-scale resonances at the LHC

BOOST13

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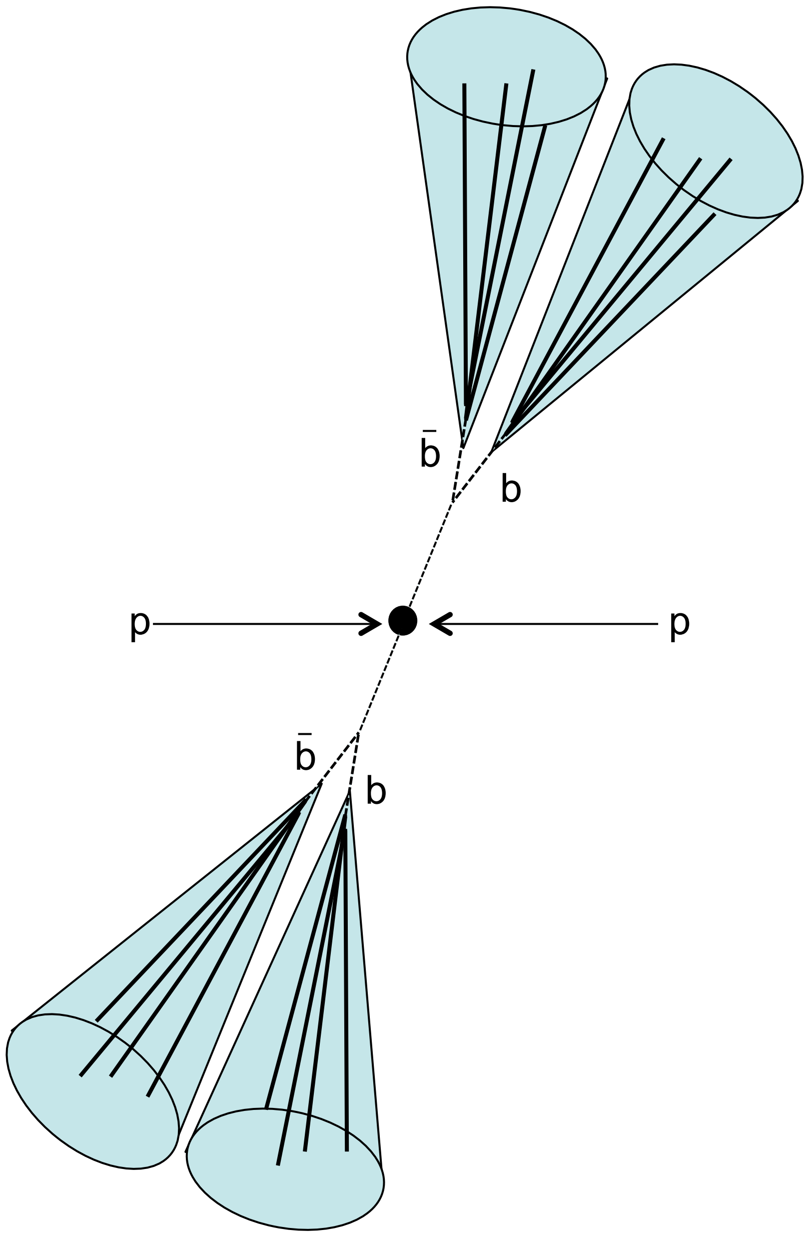
Introduction

- Many NP models predict enhancement of Higgs pair production at high invariant mass:
  - New physics resonances:
    - KK Graviton: $pp \rightarrow G_{KK} \rightarrow hh$
  - Extended Higgs sectors:
    - 2HDM: $pp \rightarrow H \rightarrow hh$
    - Singlet Higgs extensions: $pp \rightarrow H \rightarrow hh$
    - Composite Higgs models: $VV \rightarrow hh$
- A Higgs with SM-like couplings appears to have been discovered!
  - $h \rightarrow bb$ decay dominant at m_h~125 GeV (BR~57%).
- Motivates us to study $X \rightarrow hh \rightarrow bbbb$
  - This is a new region of phase space not yet covered by searches!
  - But is it feasible?

- See our short paper on archive for more details arXiv:1307.0407

4b Topology



Anti-K_T R=0.4
b-tagged jet

Four b-tagged jets, in two boosted dijet systems.

We use resolved jets here, no substructure!

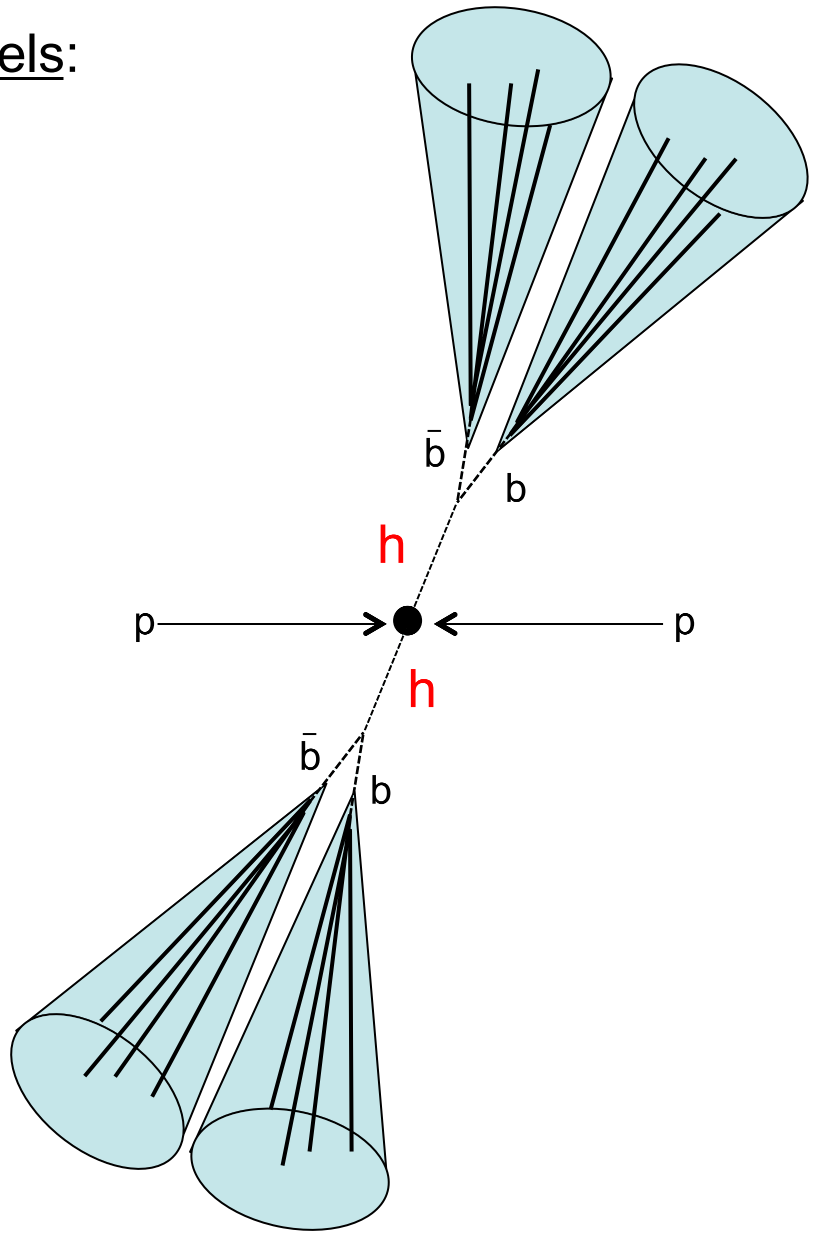
4b Topology

<u>Signal models</u>:

$G_{kk} \rightarrow hh$

$H \rightarrow hh$

$VV \rightarrow hh$



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

<u>Backgrounds</u>:

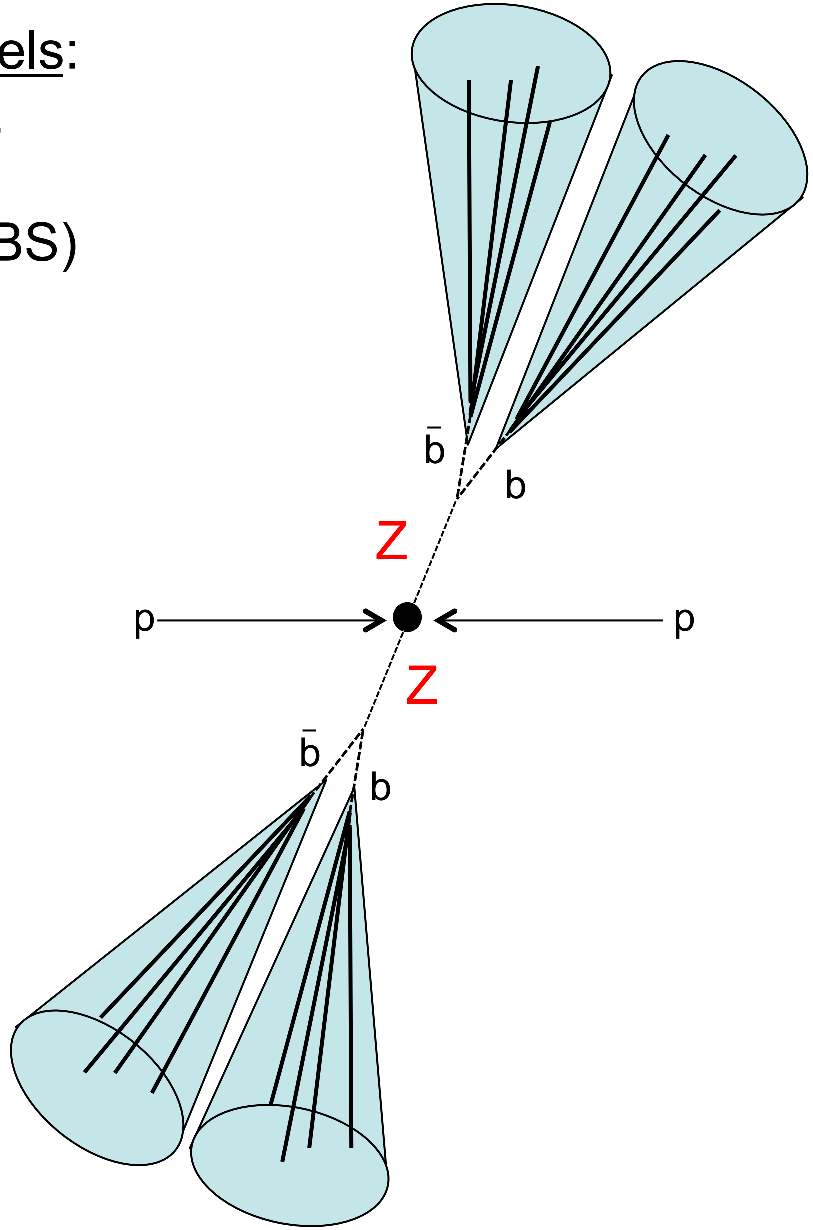
QCD

ttbar

4b Topology

<u>Signal models</u>:

G_{kk}→ZZ
H→ZZ
VV→ZZ (VBS)



But clearly the topology also allows for X→ZZ…and VBS of ZZ.

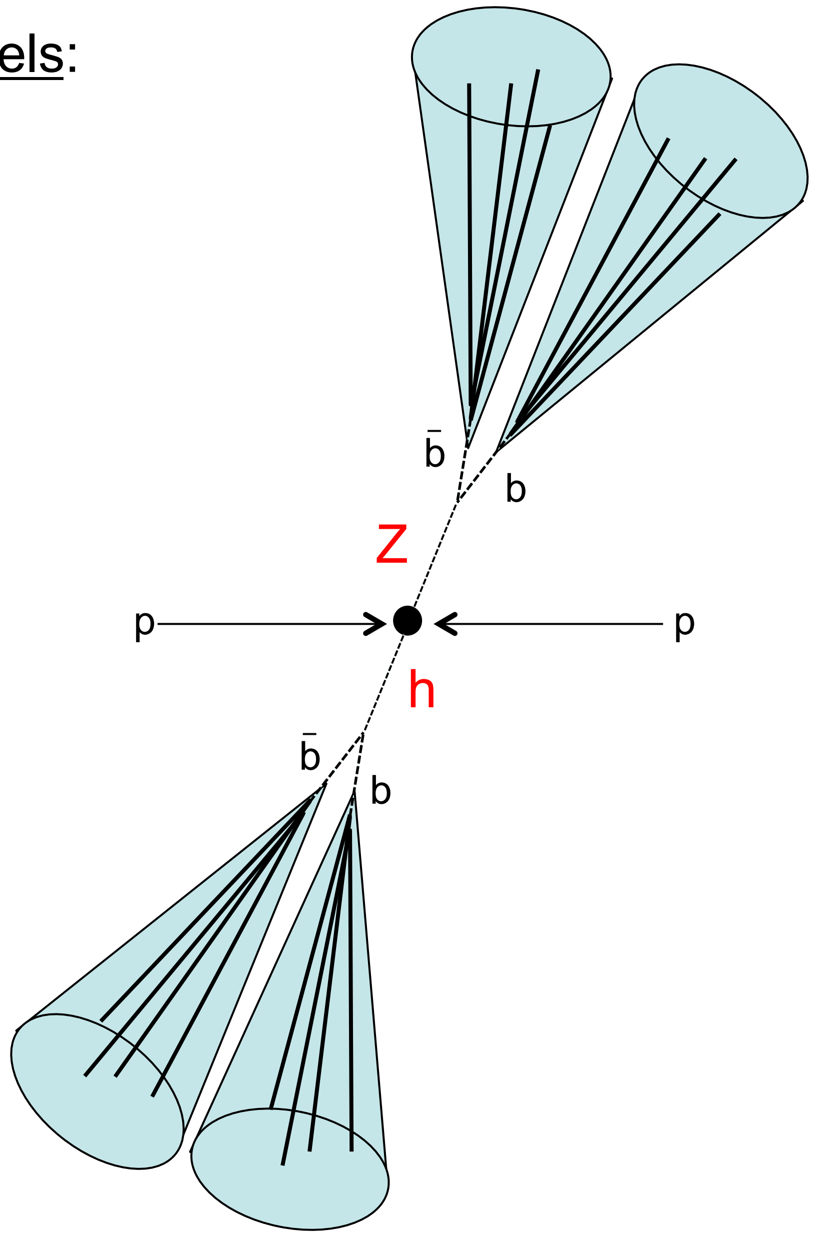
<u>Backgrounds</u>:

QCD
ttbar
Z→bb + jets
Diboson ZZ→bbbb

4b Topology

Signal models:

A→Zh



Even X→Zh!

Backgrounds:

QCD

ttbar

Z→bb + jets

Diboson ZZ→bbbb?

4b Topology

- Advantages:
  - Resonances with large BR to hh benefit from dominant h→bb BR.
    - Take a big (double) hit in BR with any other Higgs decay channel.
  - Resonances with large BR to ZZ benefit from the larger Z→bb BR.
    - BR(ZZ→bbbb)/BR(ZZ→llll) ~ 5 (where l = e,μ)
  - High boost/multijets means efficient triggering possible:
    - Can use multijet triggers at first level.
    - Online b-tagging can be used at higher levels.
  - High boost means negligible ambiguity in correct pairing to reconstruct h→bb decays.

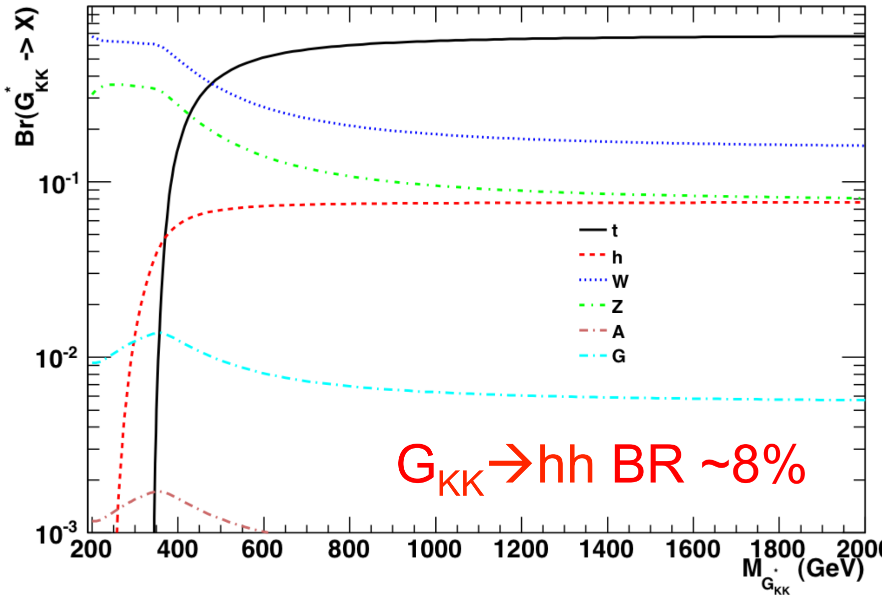
- Disadvantages:
  - The QCD background is huge, right?
  - Signal efficiency is poor?

Test with a particle-level study for 20fb^{-1} at 8 TeV

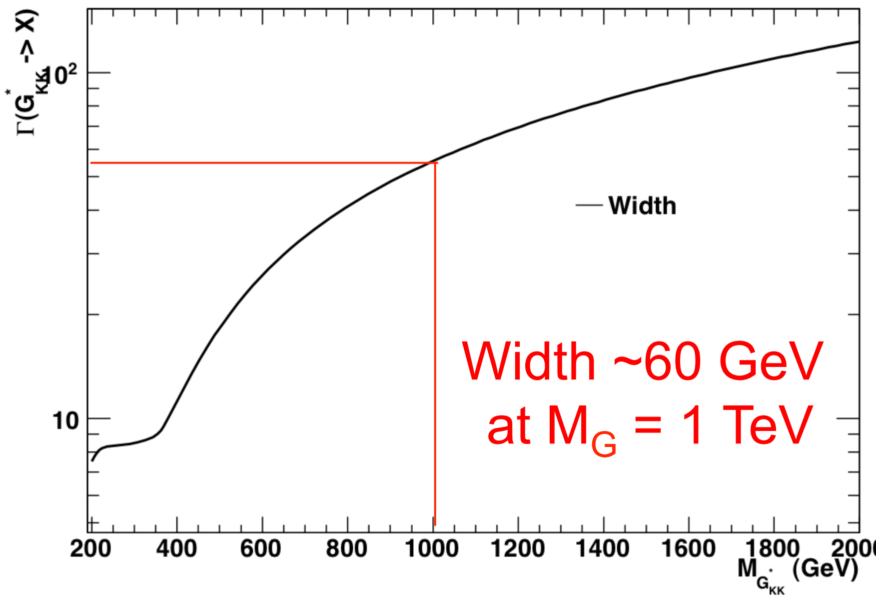
Particle-Level Study

Benchmark Signal Model

Taken from [3] with kind permission



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 $G_{kk} \rightarrow hh$ branching ratio.
- Generated using Madgraph + Pythia8.17 with CTEQ6L1, using the CP³-Origins Madgraph implementation [3] of the ADPS model.
  - Only the $G_{kk} \rightarrow hh \rightarrow bbbb$ decay mode with m_h=125 GeV.

Particle-Level Study

Fastjet used to cluster final state particles into anti-K_T R=0.4 jets.
No detector smearing applied.

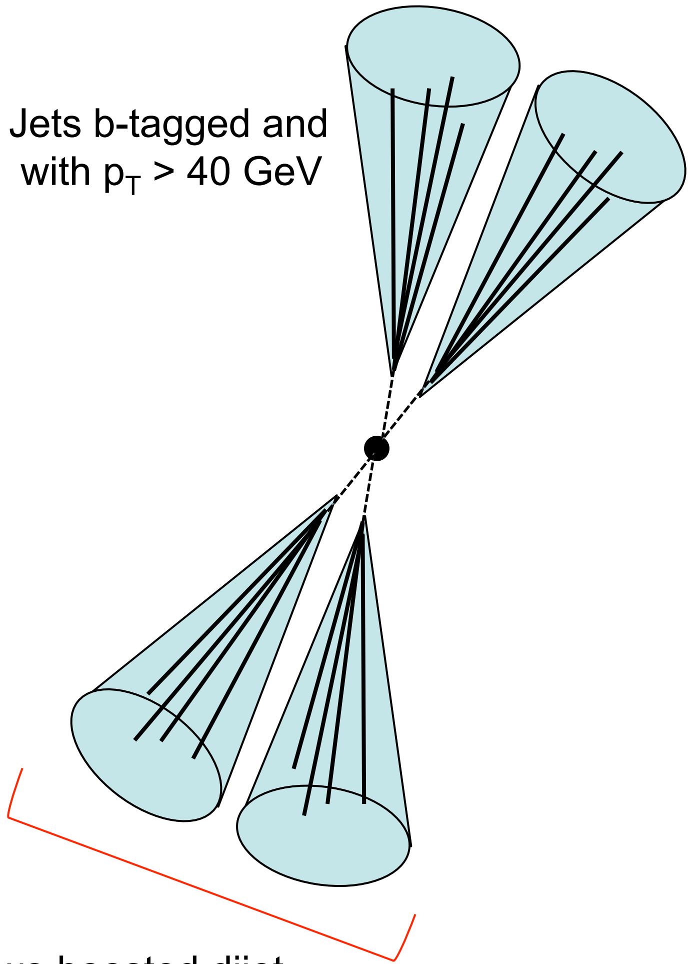
Require at least 4 b-tagged jets with p_T > 40 GeV and $|\eta|$ < 2.5

"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 and ΔR_{dijet} < 1.2

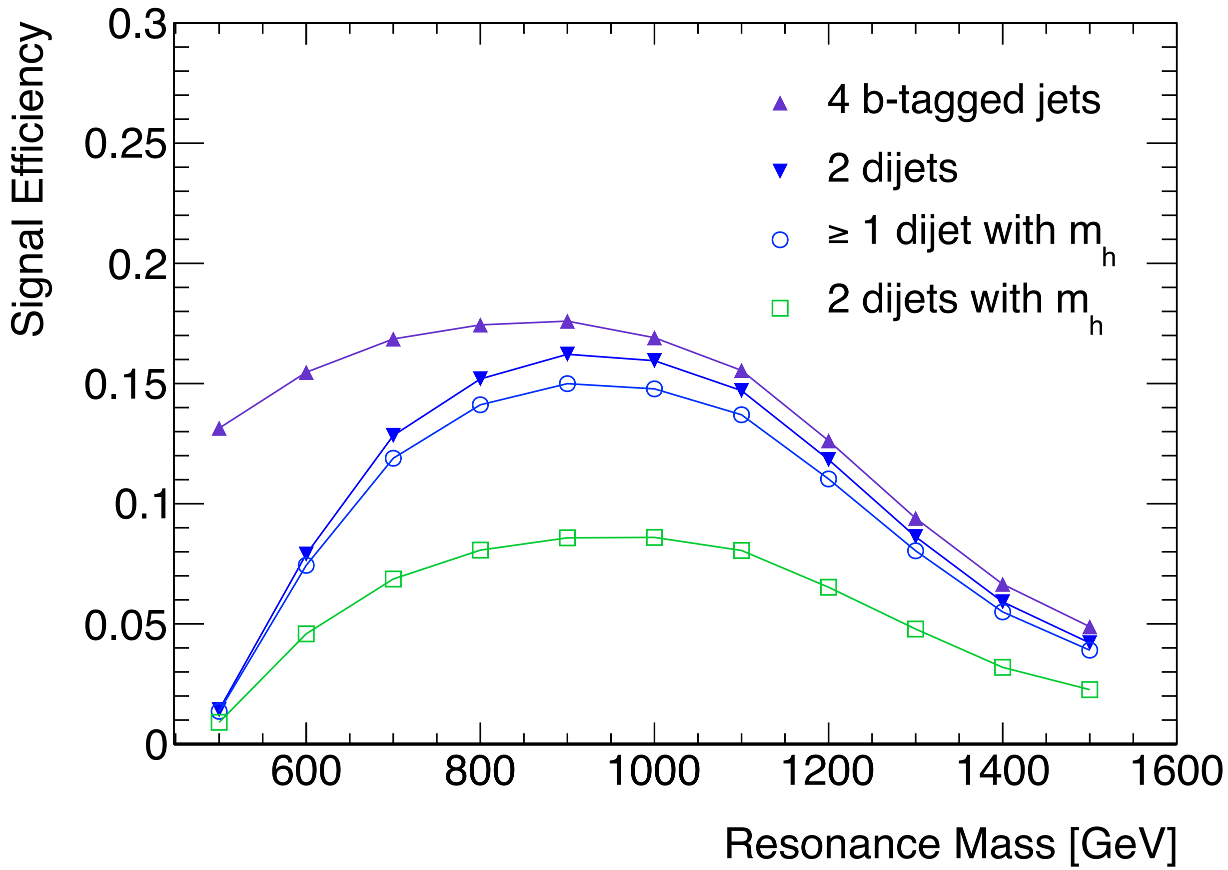
Require m_{dijet} consistent with m_h
100 < M_{dijet} < 130 GeV

Jets b-tagged and with p_T > 40 GeV



Two boosted dijet systems p_T > 200 GeV and m_{dijet}~m_h

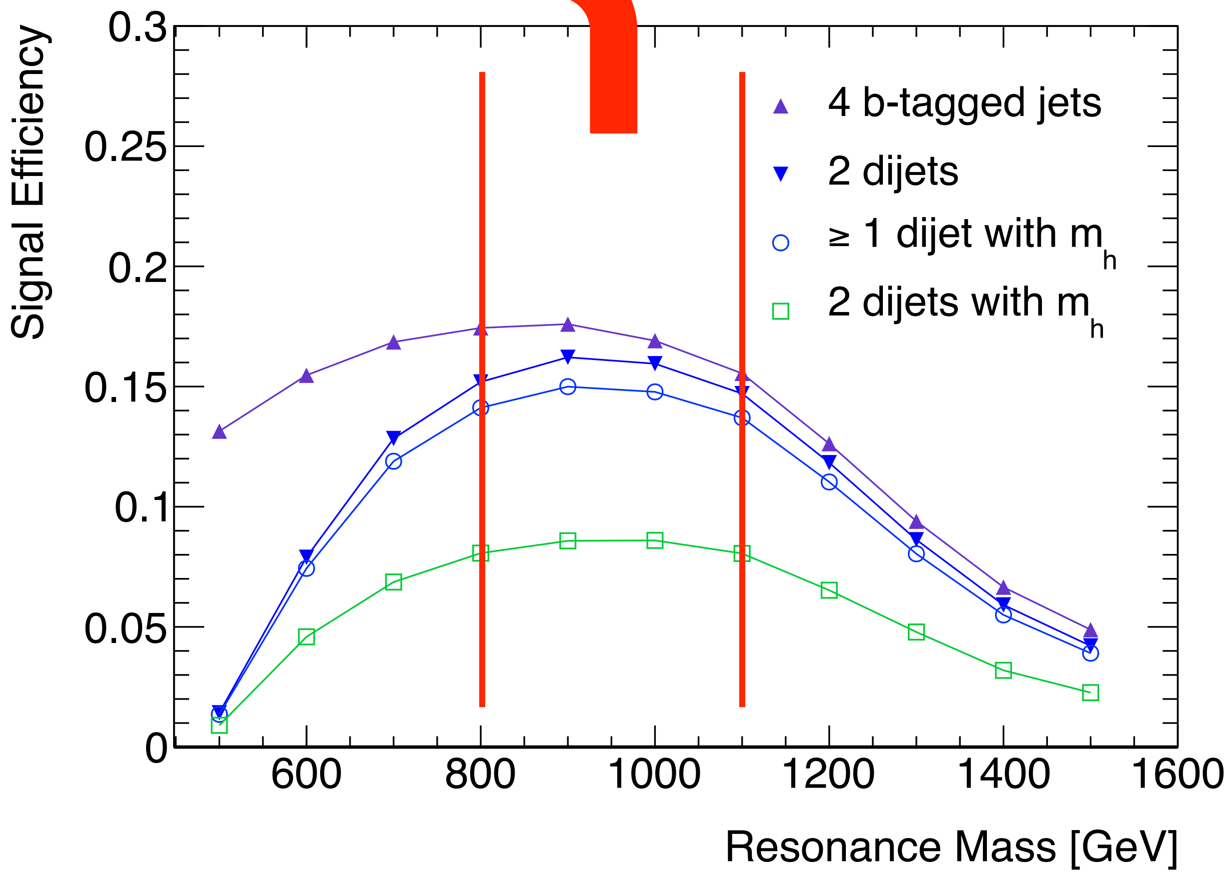
Signal Efficiency



- Approximately constant signal efficiency ~8% between 800-1100 GeV.

Signal Efficiency

Sweet spot for this resolved analysis where this is little efficiency loss from the dijet requirement



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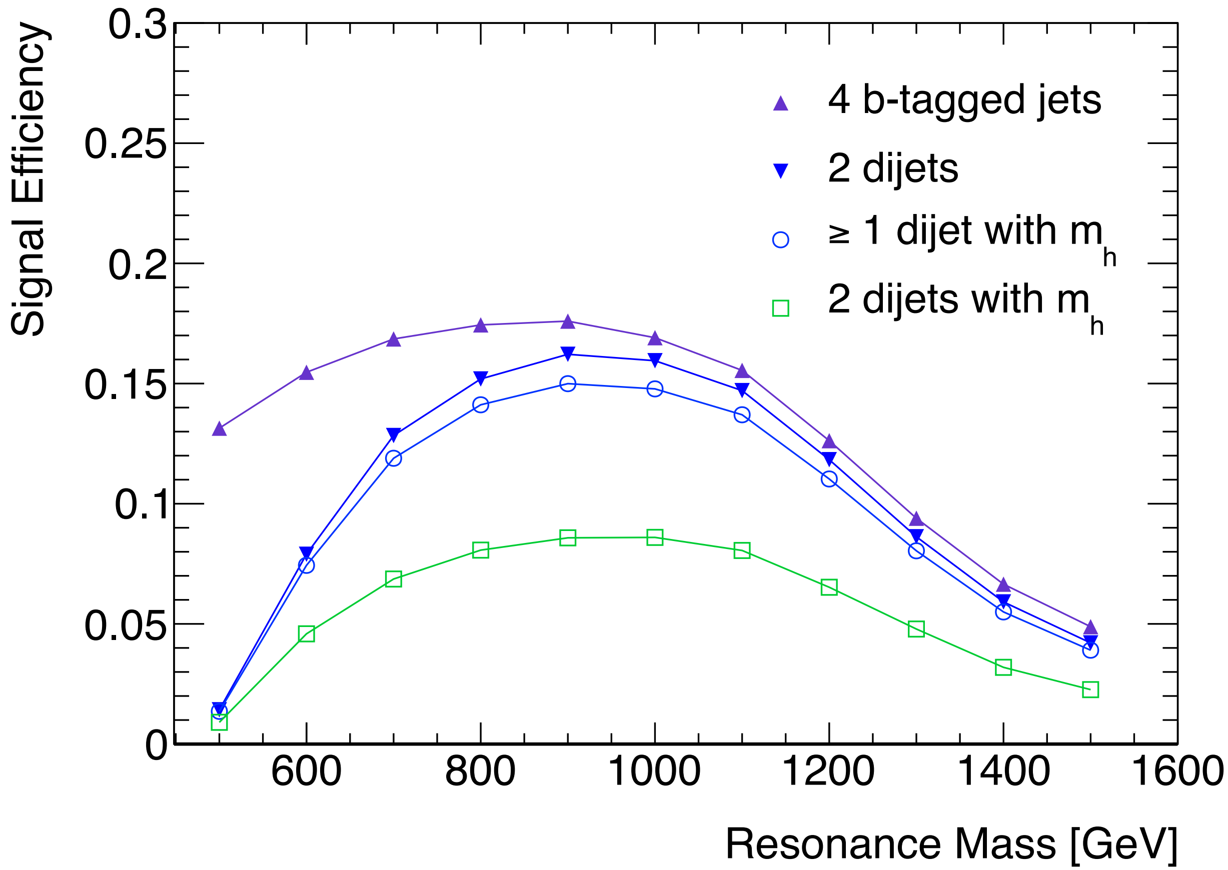
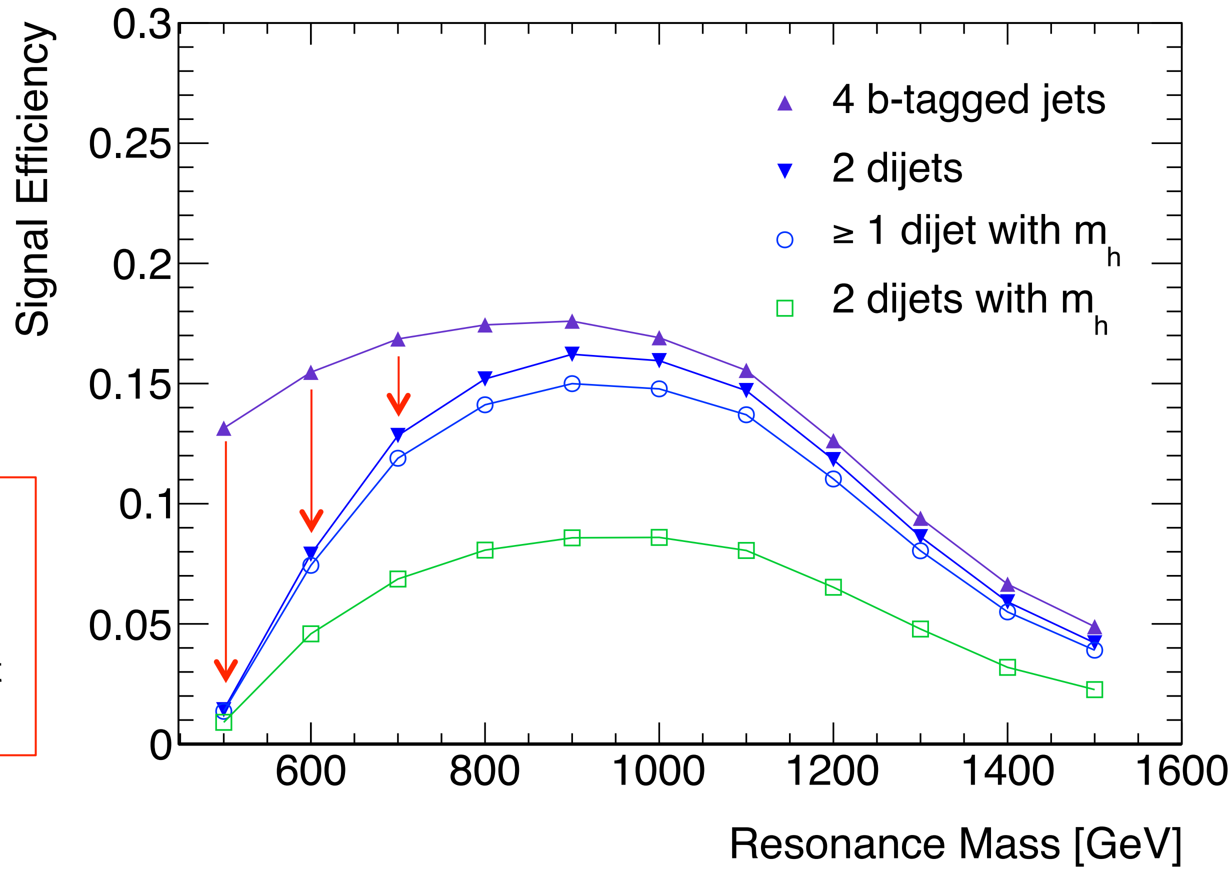
Signal Efficiency



- Approximately constant signal efficiency ~8% between 800-1100 GeV.
- At higher and lower masses we have some efficiency loss.

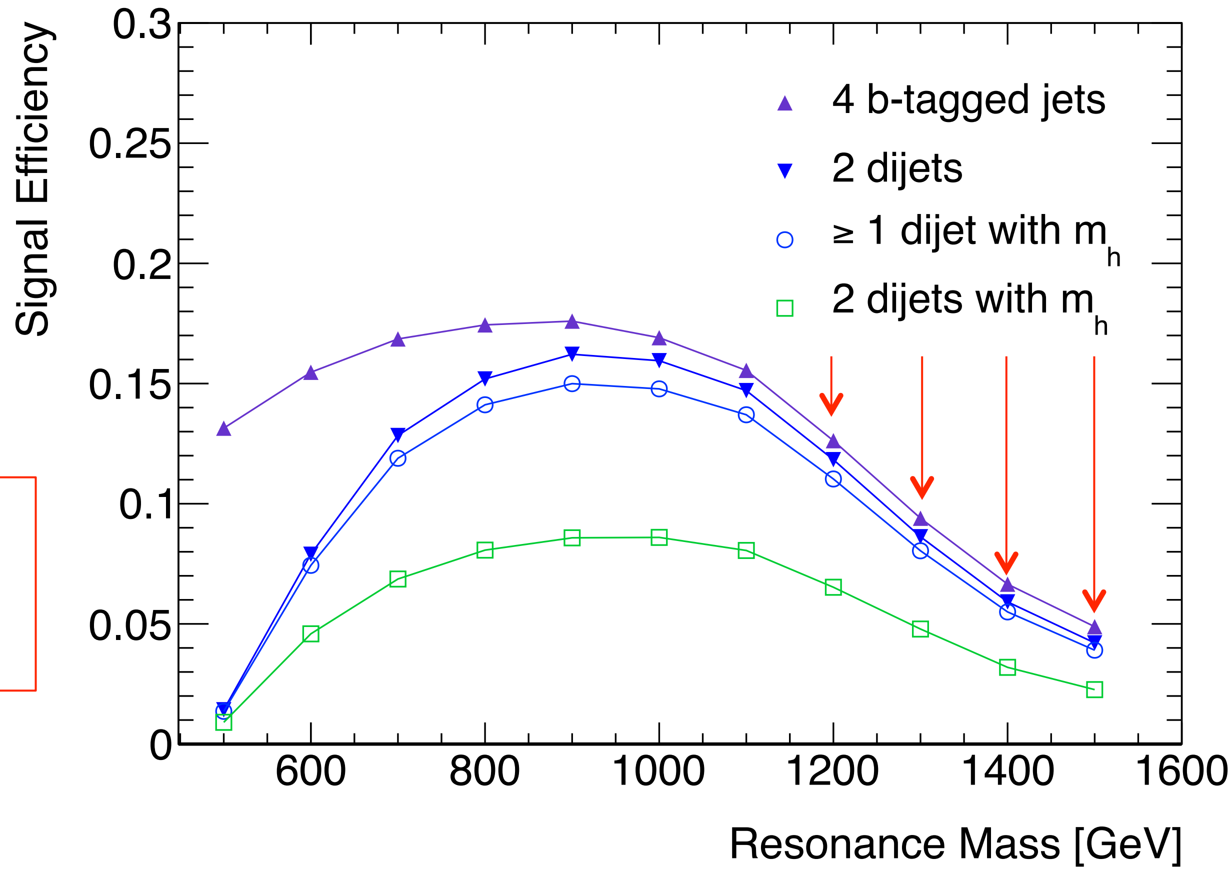
Signal Efficiency



Loss of efficiency at lower masses due to p_T^{jet}, p_T^{dijet} and ΔR_{dijet} cuts.

- Approximately constant signal efficiency ~8% between 800-1100 GeV.
- At higher and lower masses we have some efficiency loss.

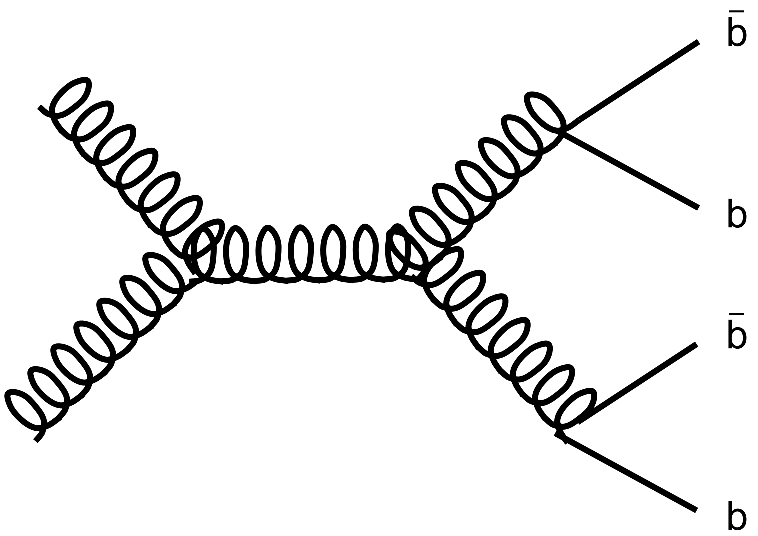
Signal Efficiency

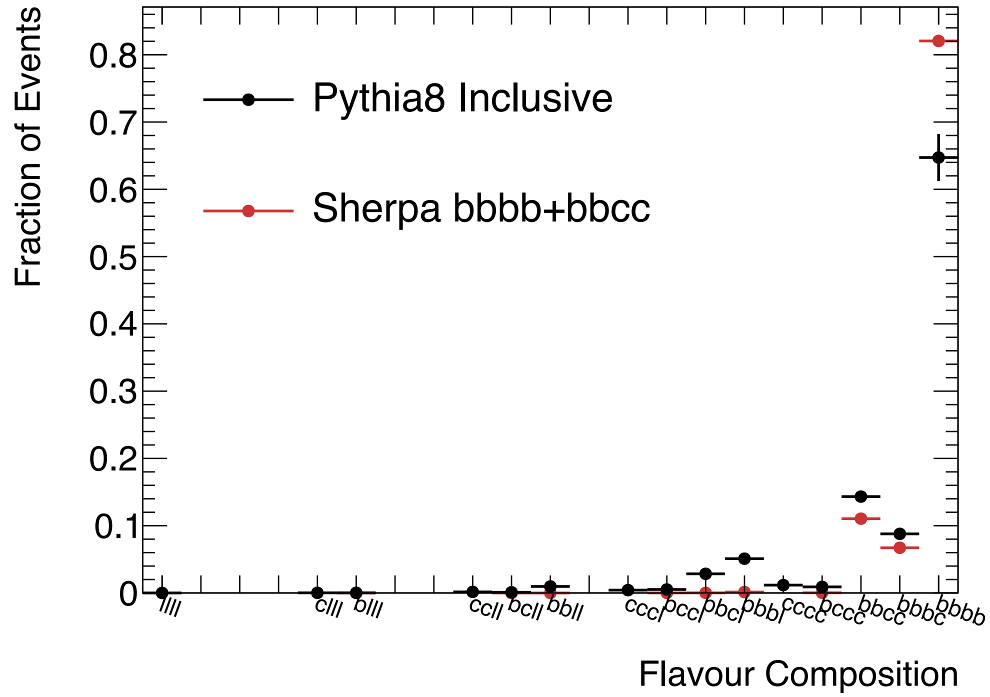


Loss of efficiency at higher masses due to jet merging.

- Approximately constant signal efficiency ~8% between 800-1100 GeV.
- At higher and lower masses we have some efficiency loss.

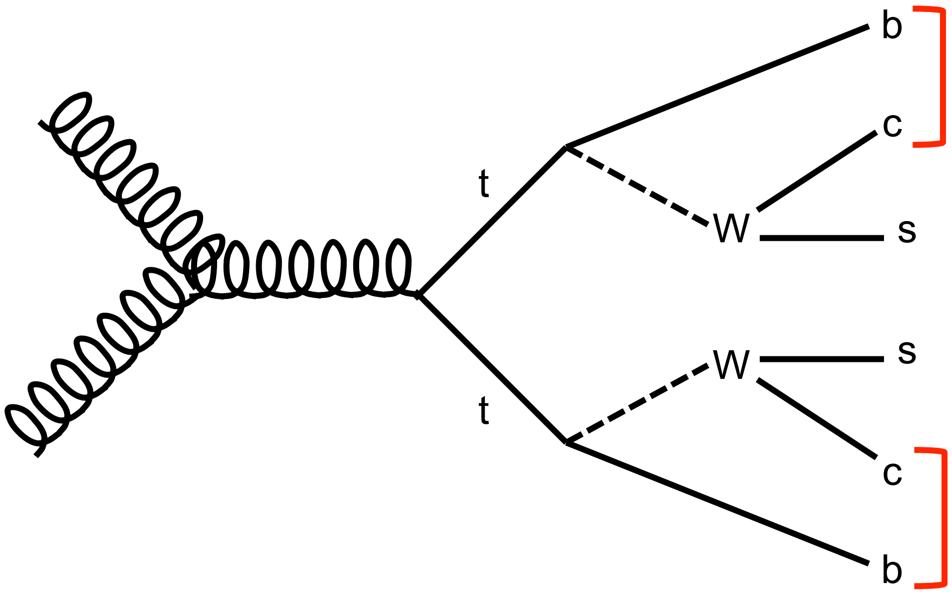
QCD Backgrounds

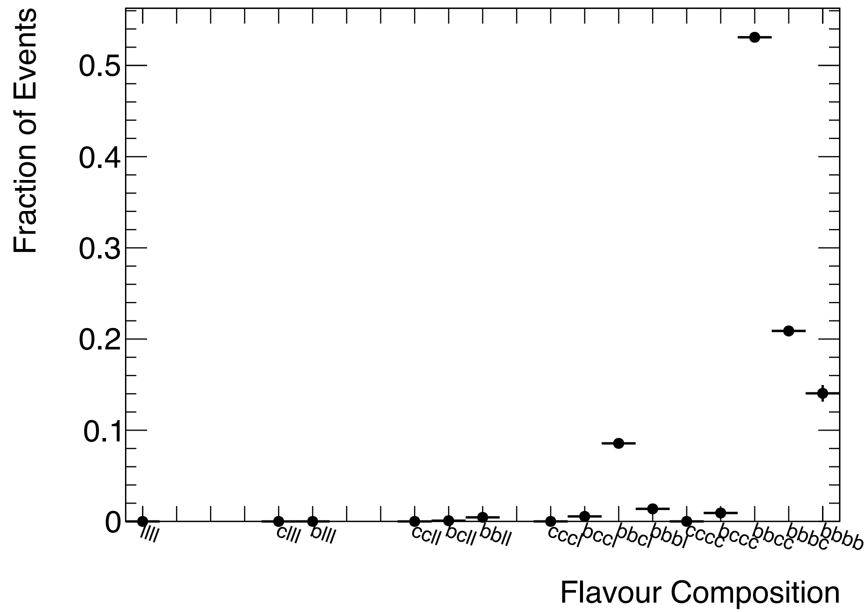




- Main component of QCD background is the irreducible pp→bbbb.
  - But also some contribution from mistagged pp→bbcc.
- QCD Backgrounds generated using Sherpa 1.4.3
  - Using bbbb and bbcc matrix elements.
  - No k-factor applied…
  - …but scale factor variations should cover NLO corrections [4].

$t\bar{t}$ Background





- ttbar background arises from all hadronic channel, where c-jet from hadronic W decay fakes a b-jet, and forms dijet with true b-jet.
- Generated using Pythia 8.17.
- Rate normalised to average ATLAS/CMS √s=8 TeV ttbar measurement (235pb) [6,7].
- Uncertainty on ttbar background rate from uncertainty on measurements.

Background for 20fb^{-1} @ 8 TeV

Requirement	$G_{KK}(M = 800\,GeV)$	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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Dramatic ~50 times reduction in QCD and ttbar backgrounds when we require the b-tagged jets form two boosted dijets

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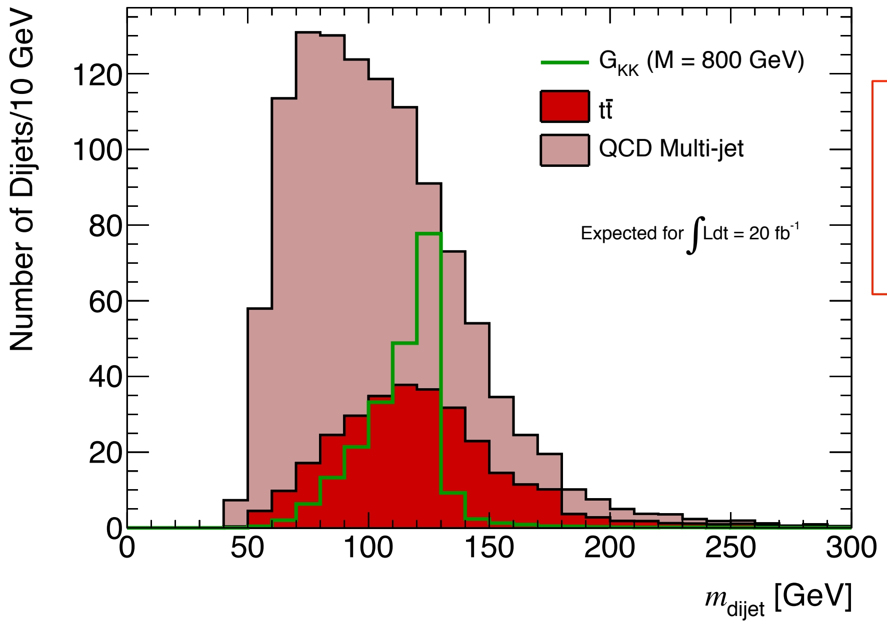


Dijet mass distribution after requirement of two dijets. s/b already 20%!

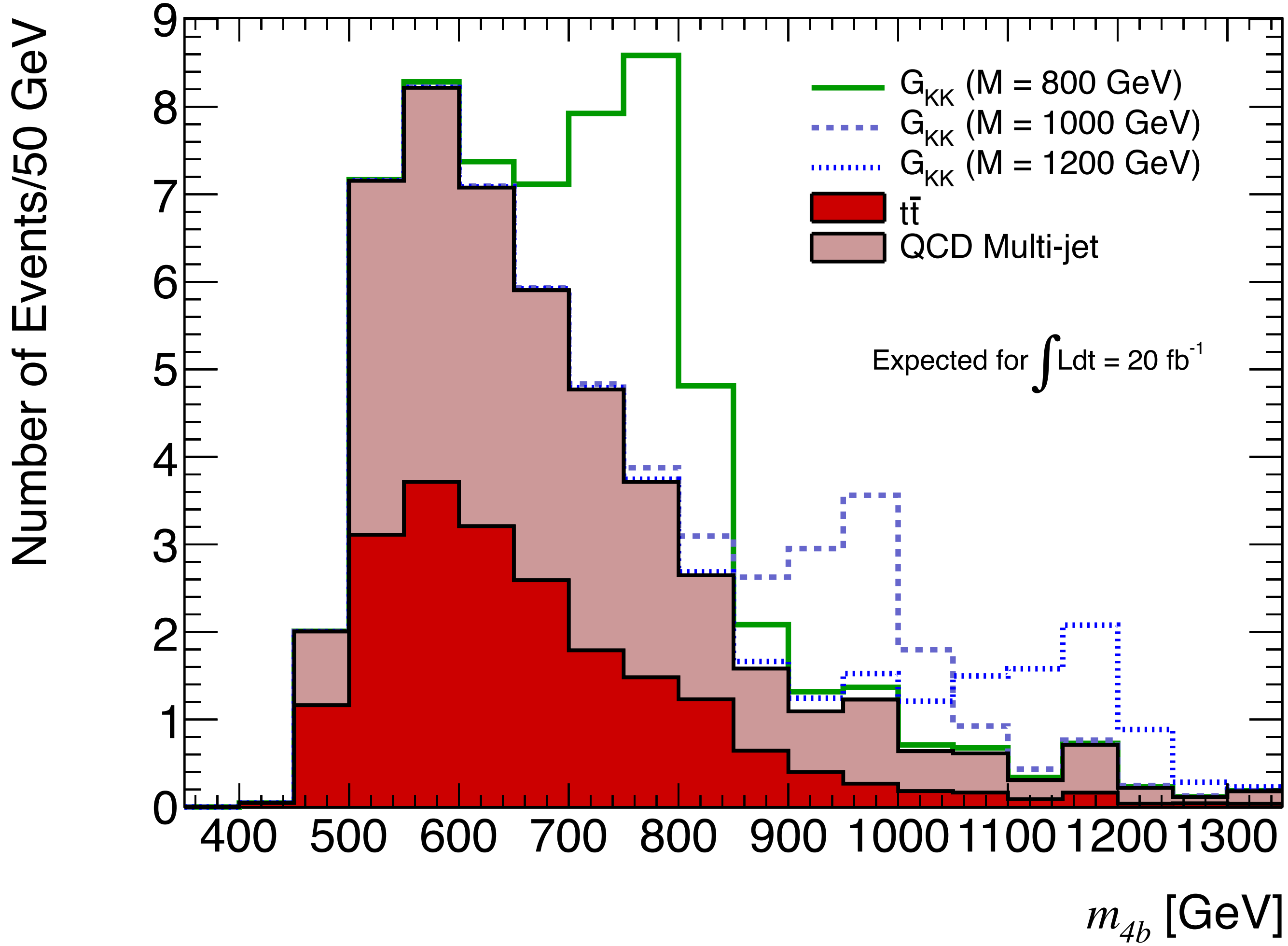
Background for $20fb^{-1}$ @ 8 TeV

Requirement	$G_{KK}(M = 800\,GeV)$	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

- After m_h dijet mass requirement get s/b~1!
- This for a signal with cross-section of only 36fb!
- Backgrounds are very small!

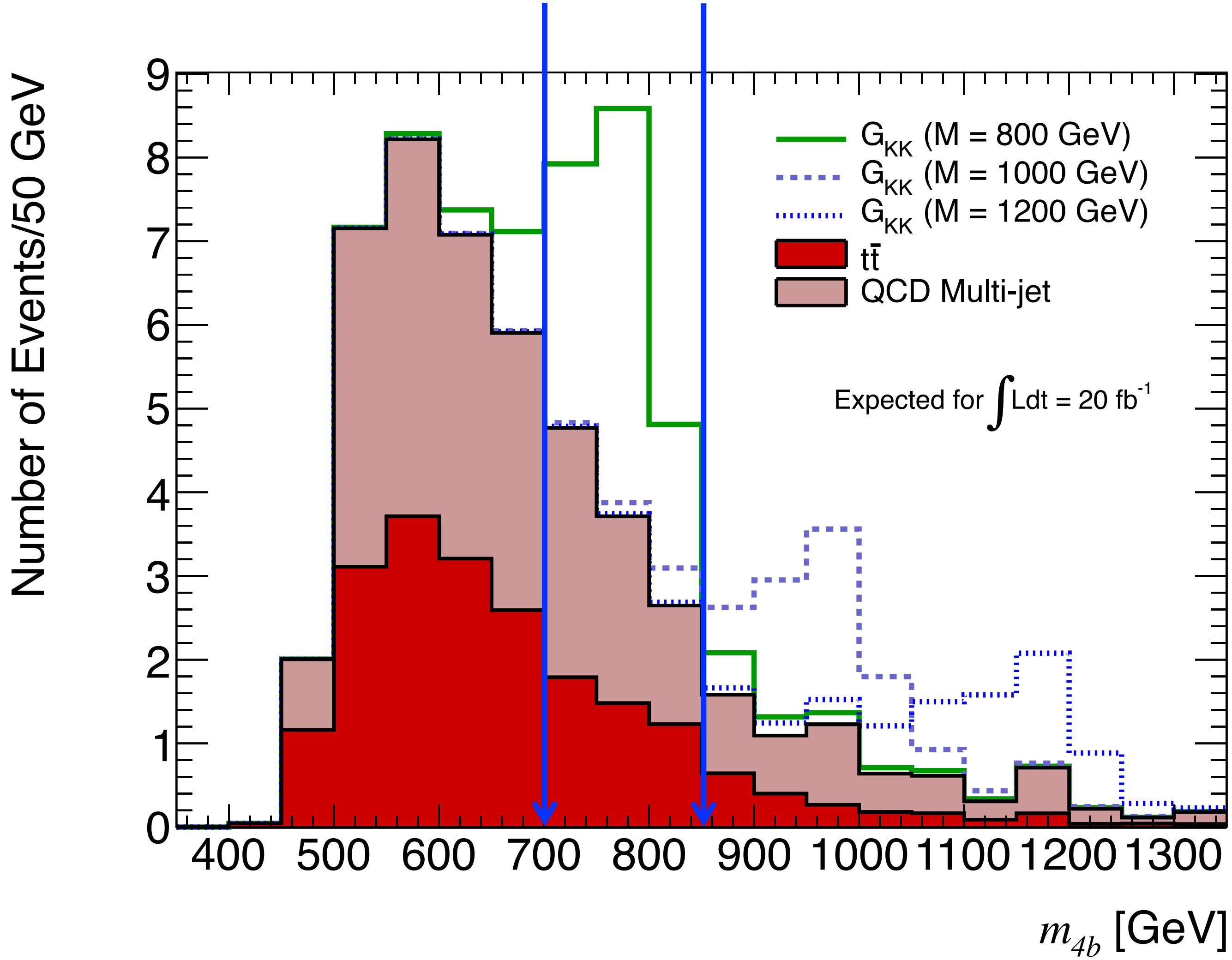
- QCD and ttbar backgrounds of similar size.

Background for 20fb^{-1} @ 8 TeV

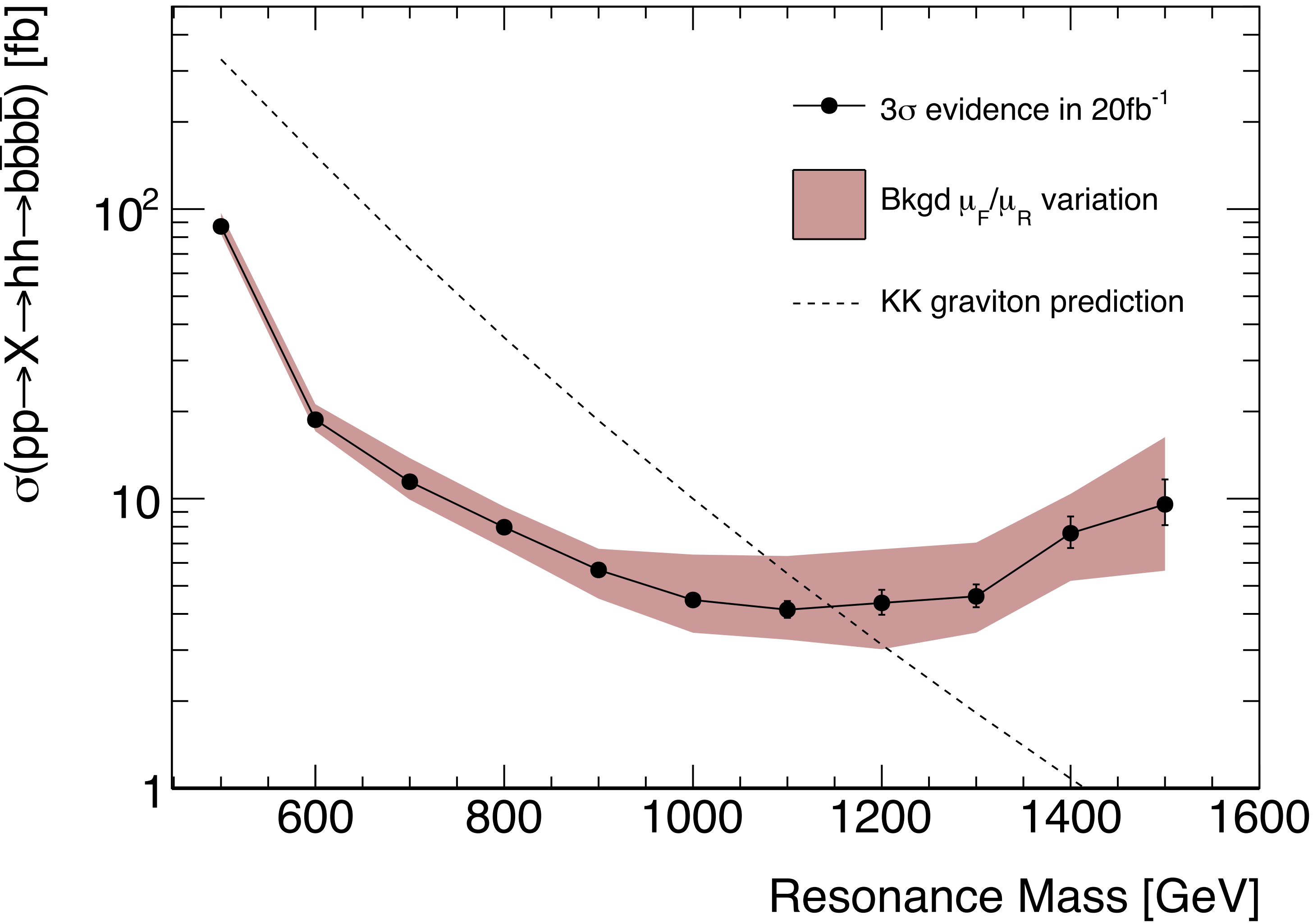


Estimate Sensitivity

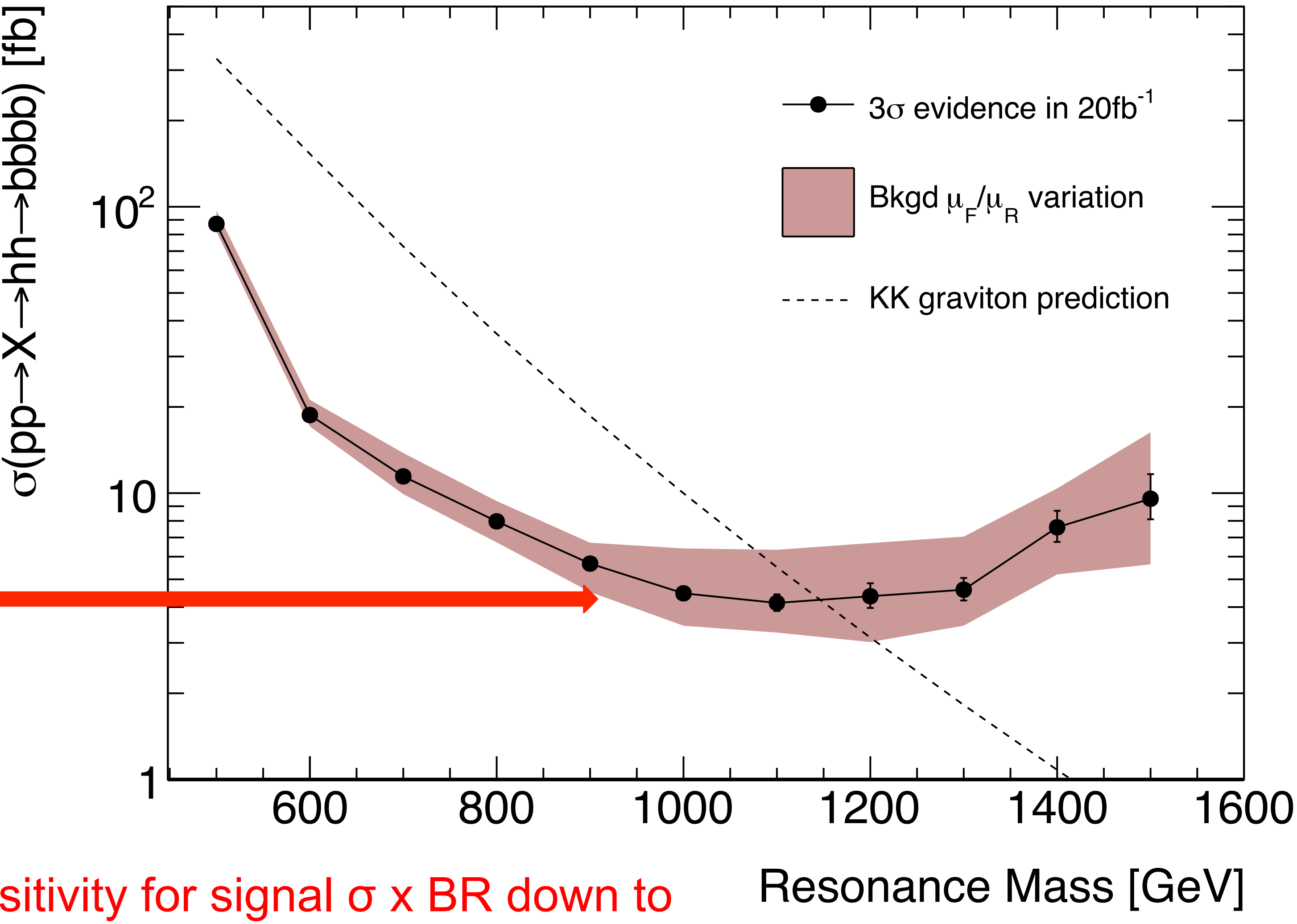
Count background events in [-100,+50] GeV window around m_{Gkk}. Use known signal efficiency to calculate signal cross-section for $s/\sqrt{b} = 3$ in $20 fb^{-1}$



Cross-section for 3σ Sensitivity

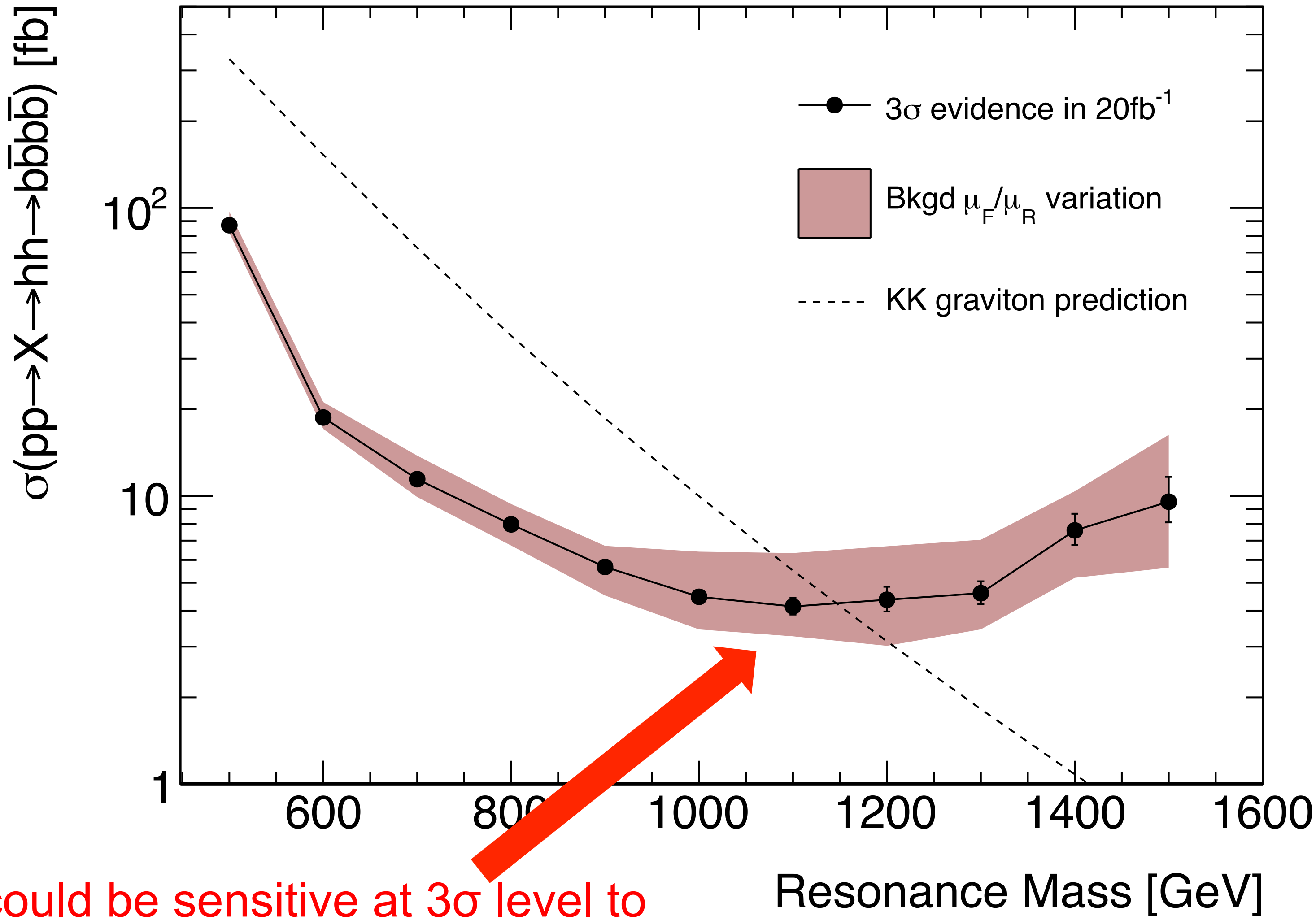


Cross-section for 3σ Sensitivity



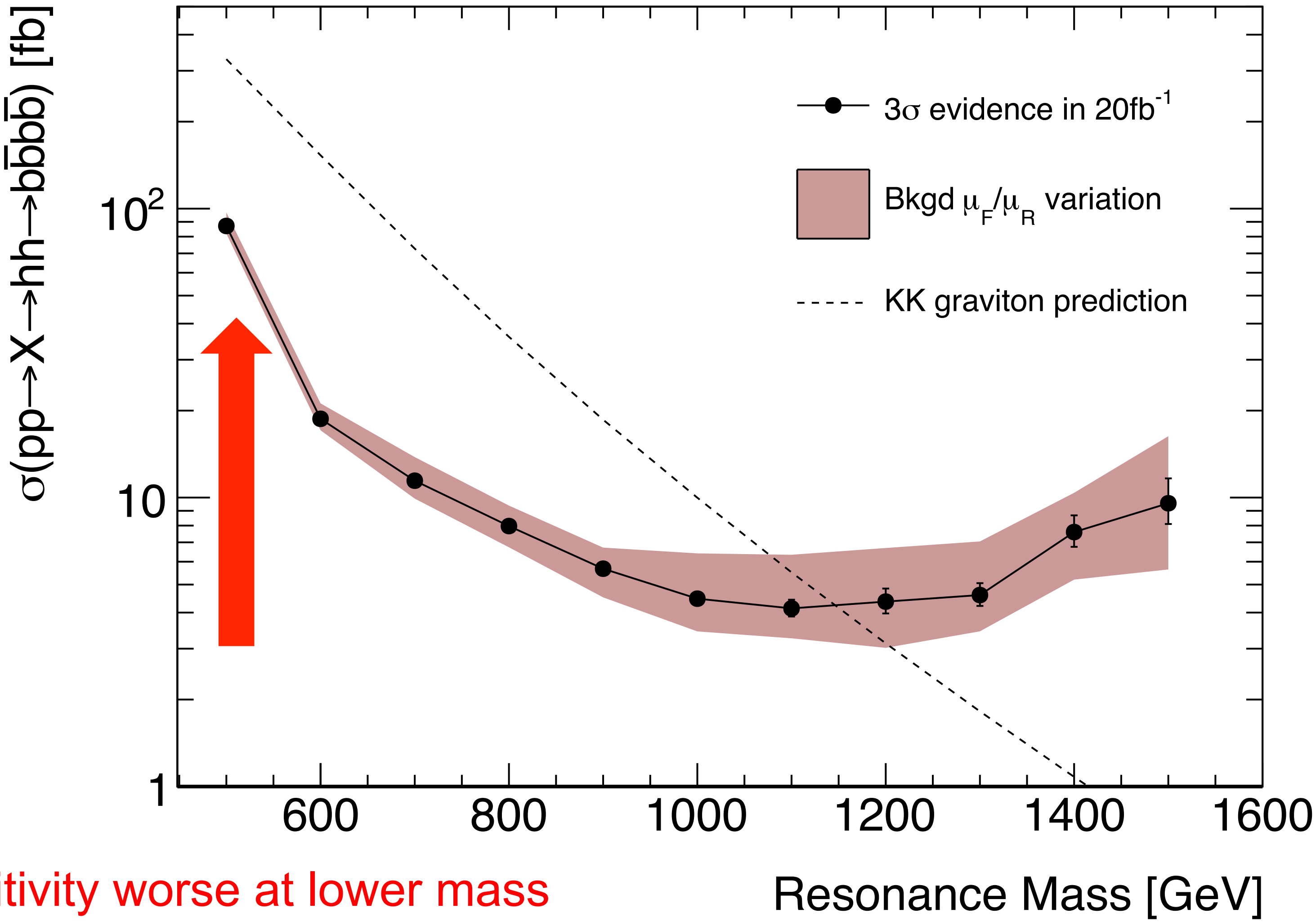
3σ sensitivity for signal σ x BR down to few fb at 1 TeV with $20fb^{-1}$!

Cross-section for 3σ Sensitivity



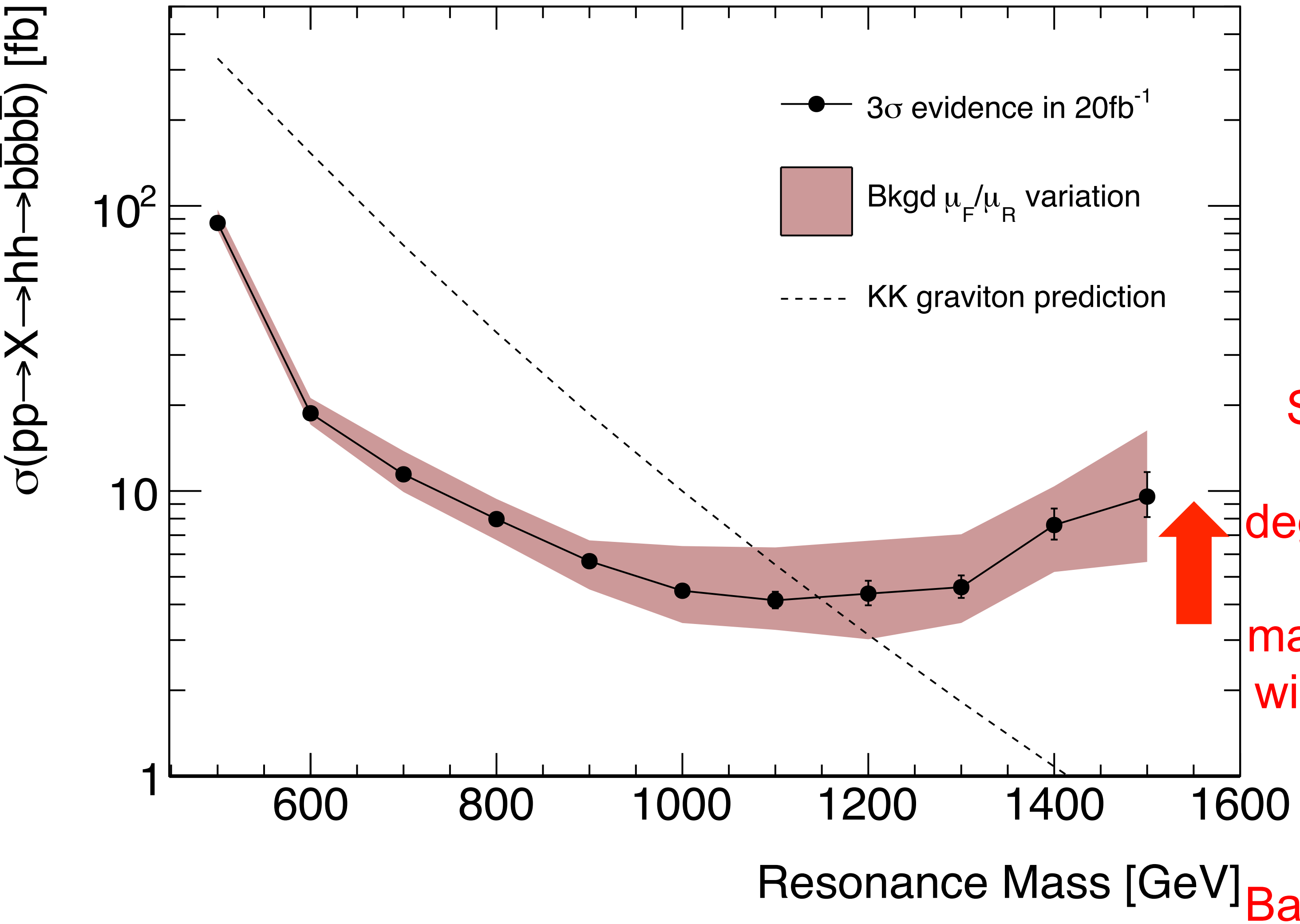
We could be sensitive at 3σ level to ADPS KK gravition masses up to ~1 TeV

Cross-section for 3σ Sensitivity



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

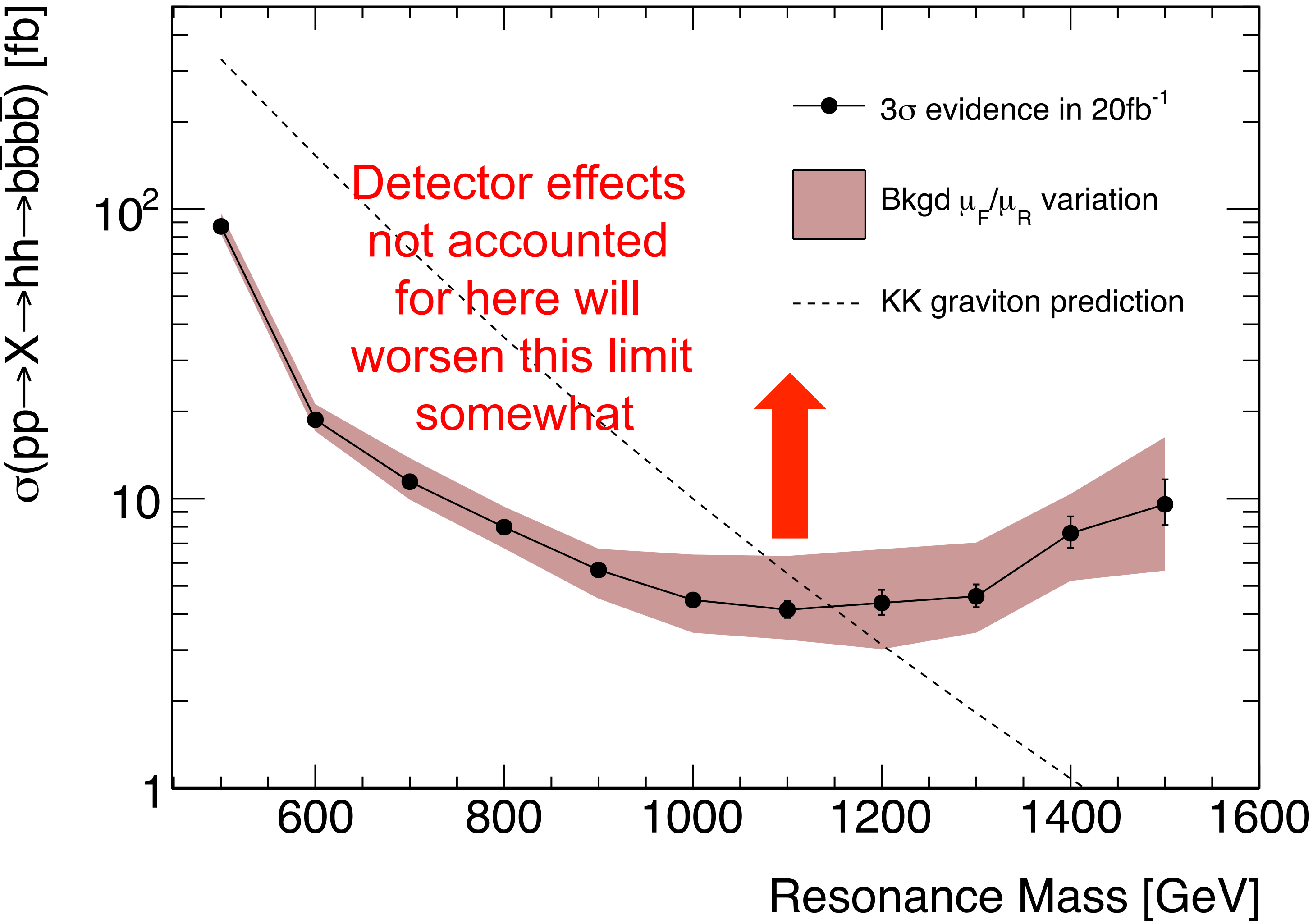
Cross-section for 3σ Sensitivity



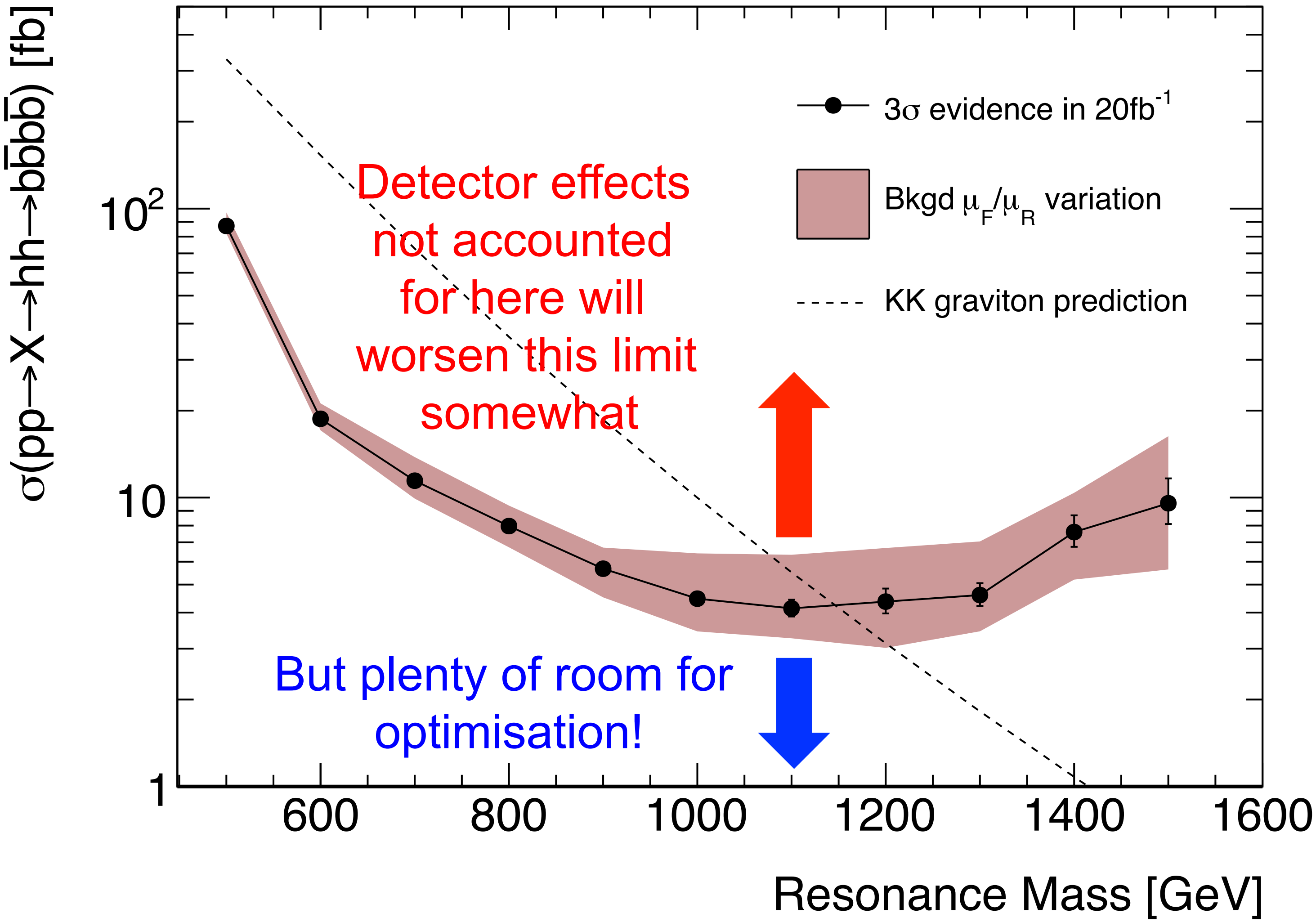
Sensitivity does not degrade much at higher masses, even with resolved analysis.

Background is very low out here!

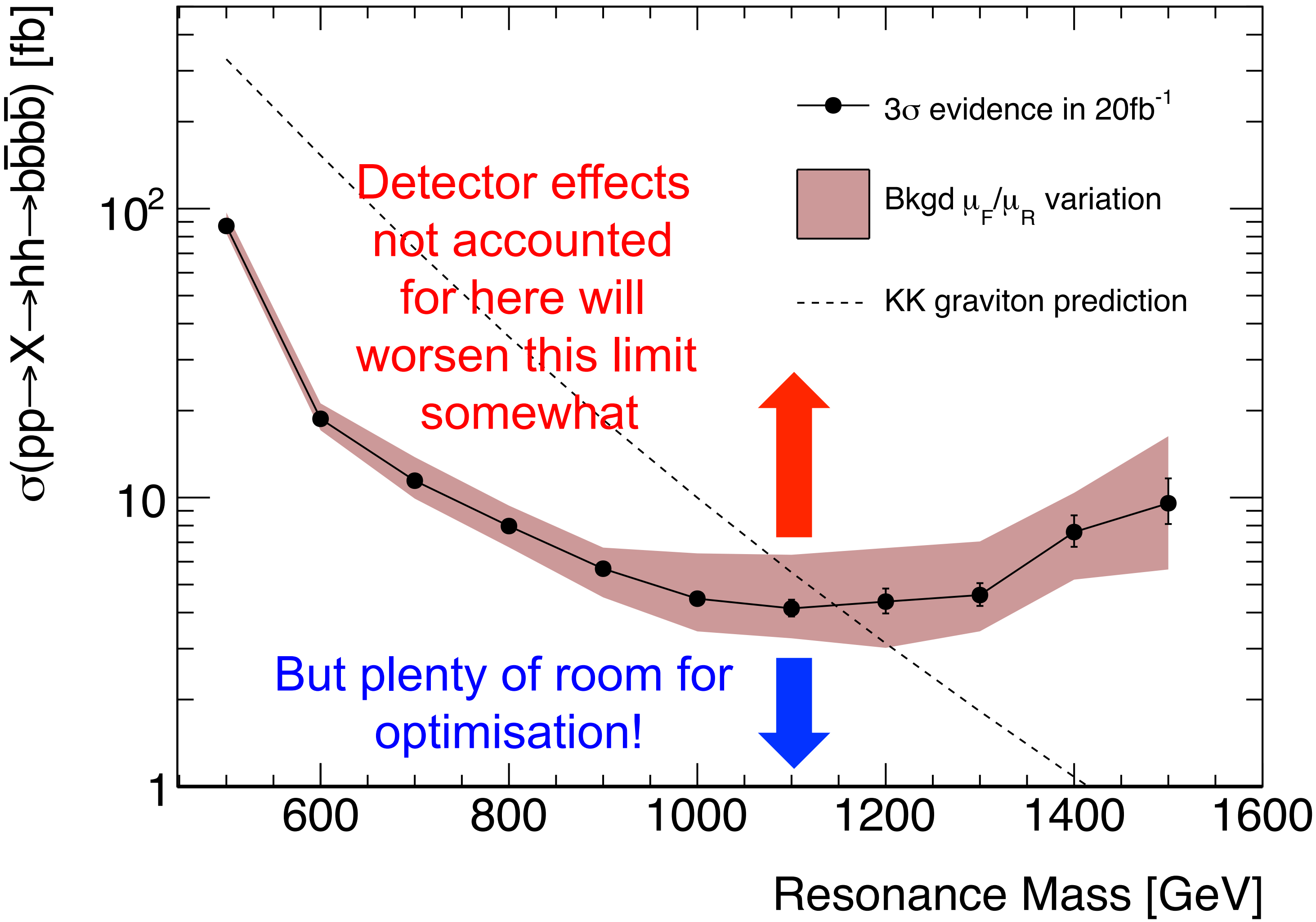
Cross-section for 3σ Sensitivity



Cross-section for 3σ Sensitivity



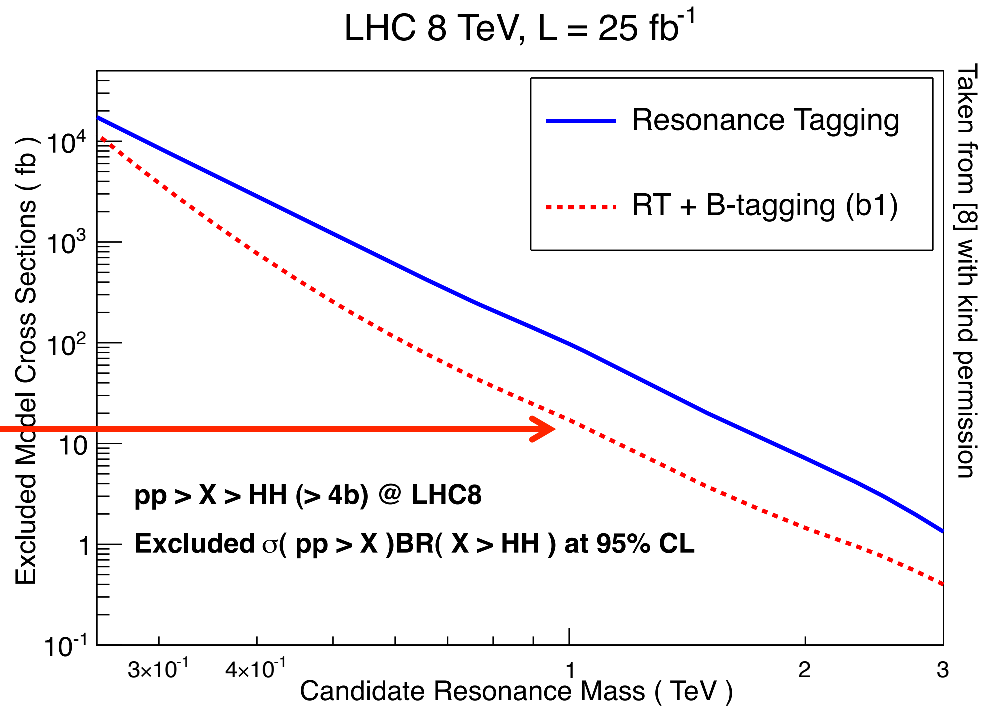
Cross-section for 3σ Sensitivity



Appears to be potential for great sensitivity to new physics in this 4b final state!

Different Study, Same Conclusion

95% CL limit at ~10fb for 1TeV G_{KK} mass with $25fb^{-1}$ @ 8 TeV



- An independent study also shows the great potential of the X→hh→bbbb final state [8].
- Different approach:
  - Use substructure techniques to "tag" Higgs resonance.
  - Only one b-tag per Higgs.

Outlook

Optimisation

- Purpose of this simple study is to flag X→hh→bbbb as a very promising final state for new physics searches.
  - We leave the optimisation for the experiments!
- But clearly a lot of options 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
  - Use single jet masses for Higgs reconstruction in merged region (G_{KK} mass > 1.1 TeV).
    - Use trimming, pruning? Double b-tagging of single jets?
  - Use substructure “Higgs tagging”?
    - Requirement of 4 b-tags has already decimated the bkgds.
    - Some mixture of b-tagging and resonance tagging optimal?
  - Reduction of ttbar background.
  - Kinematic fit: taking advantage of known m_h to improve m_{4b} resolution.

Summary

- There is huge background reduction power in the boosted bb-bb final state.
- Opens up searches for new physics resonances in X→hh and X→Zh channels.
  - This is unchartered territory, with many models testable!

- But also can extend current searches in X→ZZ channel:
  - Potential to be very competitive versus current ZZ→lljj and ZZ→jjjj searches.
  - Can be combined with these to improve limit further.
- Intriguing possibility of measuring ZZ VBS in bb-bb final state.
- In addition ZZ→llbb or ZZ→ττbb must also be worthy of investigation…

- Also VLQ BB→bbbbbb searches!

Backups

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.

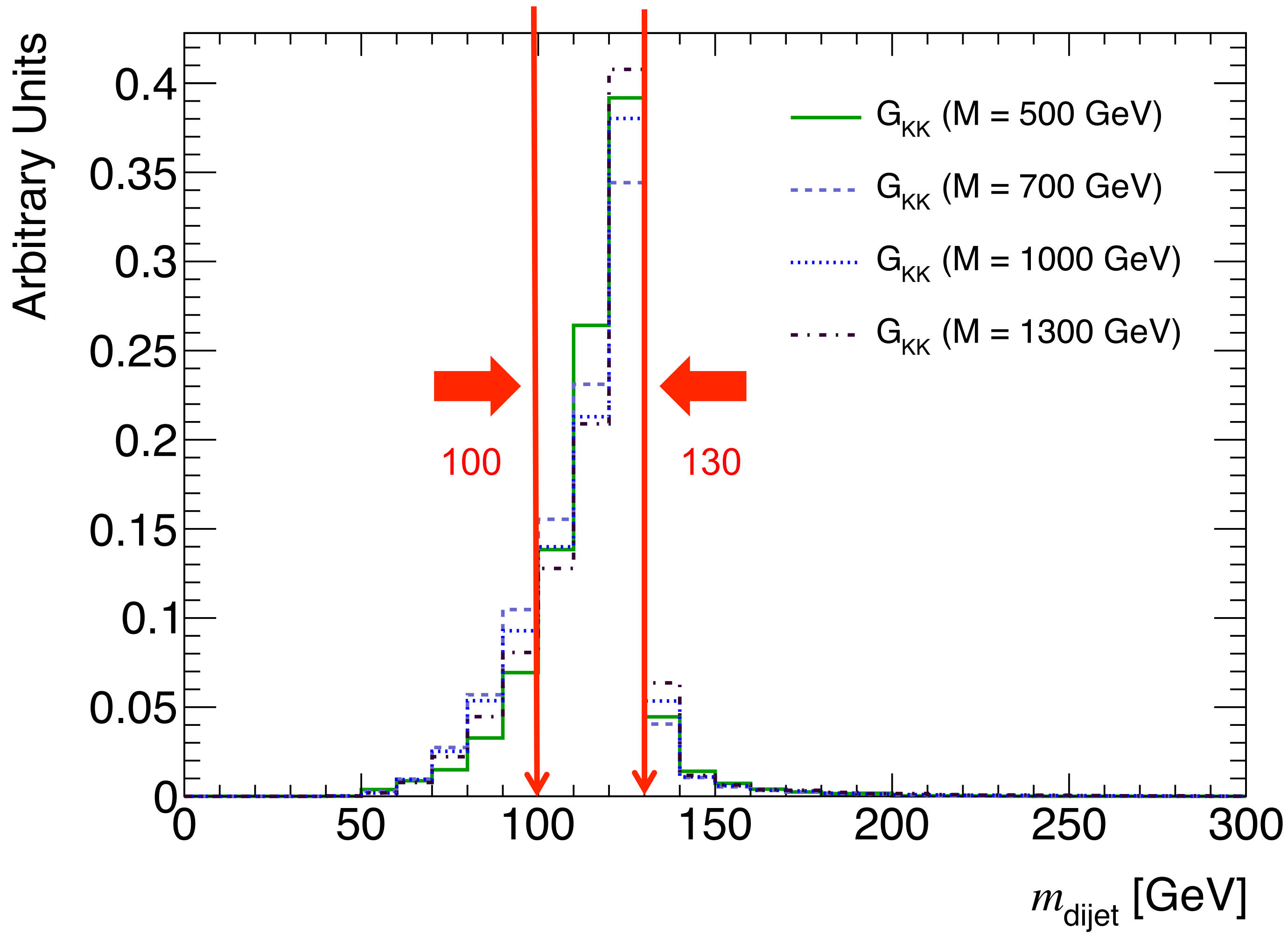
[5] G. Bevilacqua et al arXiv:1304.6860 [hep-ph].

[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



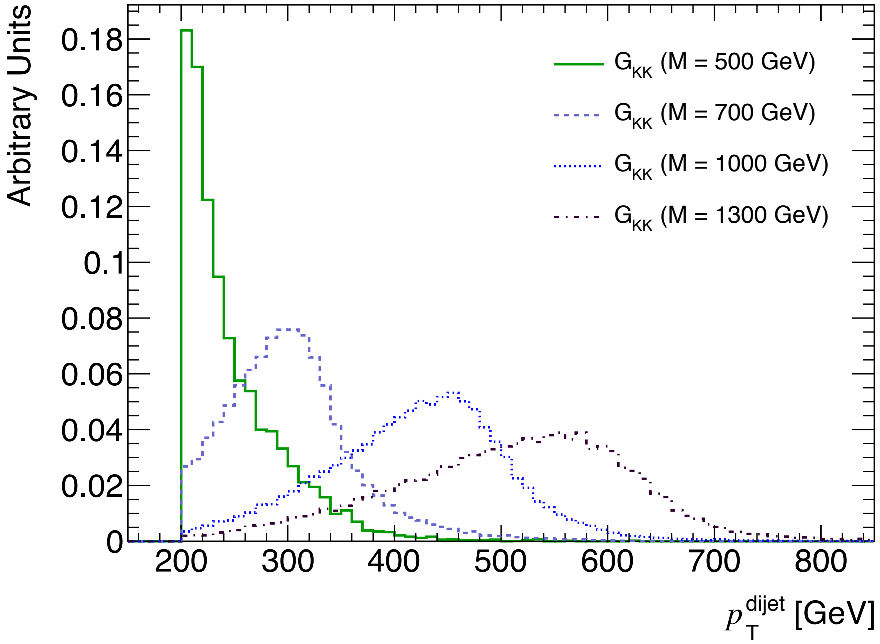
- Jets do not include muons or neutrinos, and not corrected for out-of-cone.
- Asymmetric cut around m_h=125 GeV is appropriate.

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

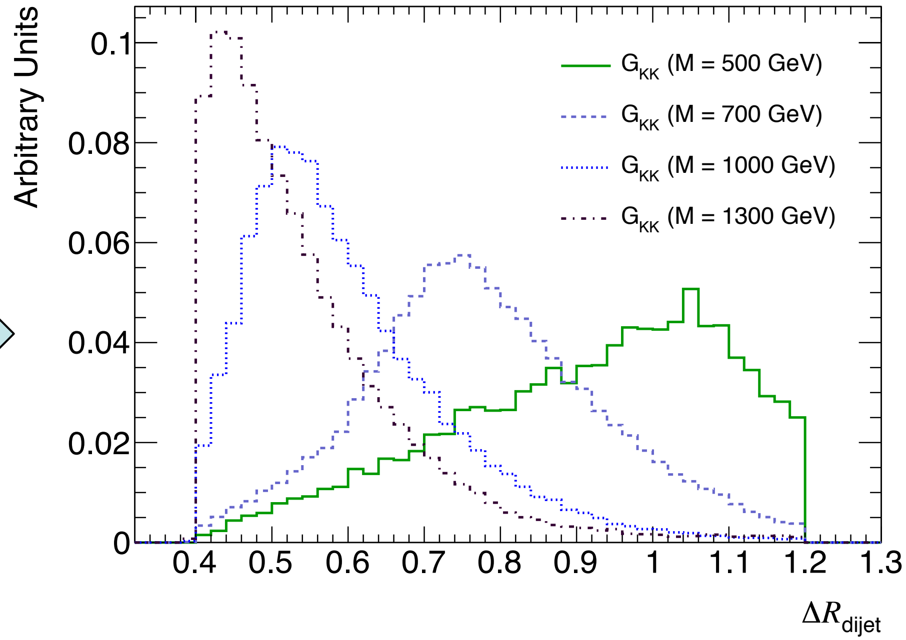
- Cross-sections and widths for pp→G_{KK}→hh→bbbb at 8 TeV.

Signal Kinematics

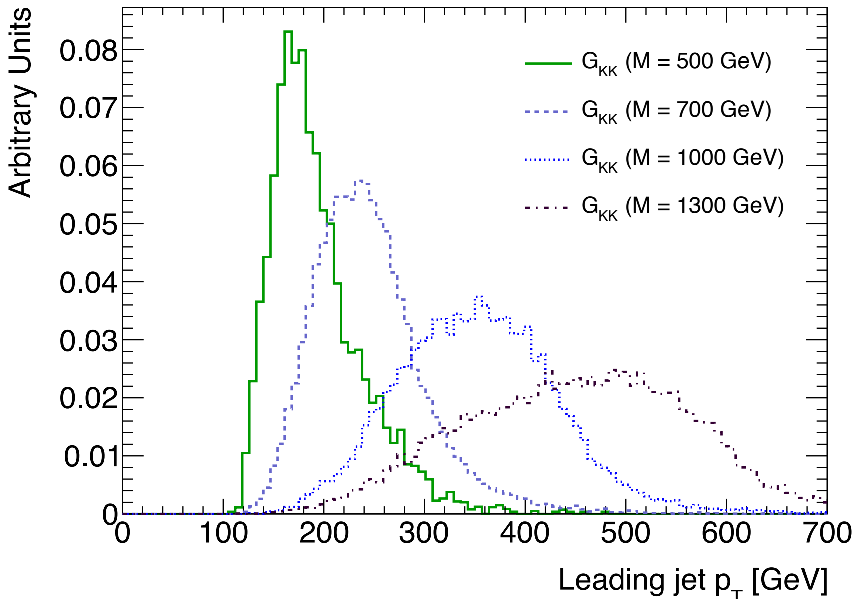


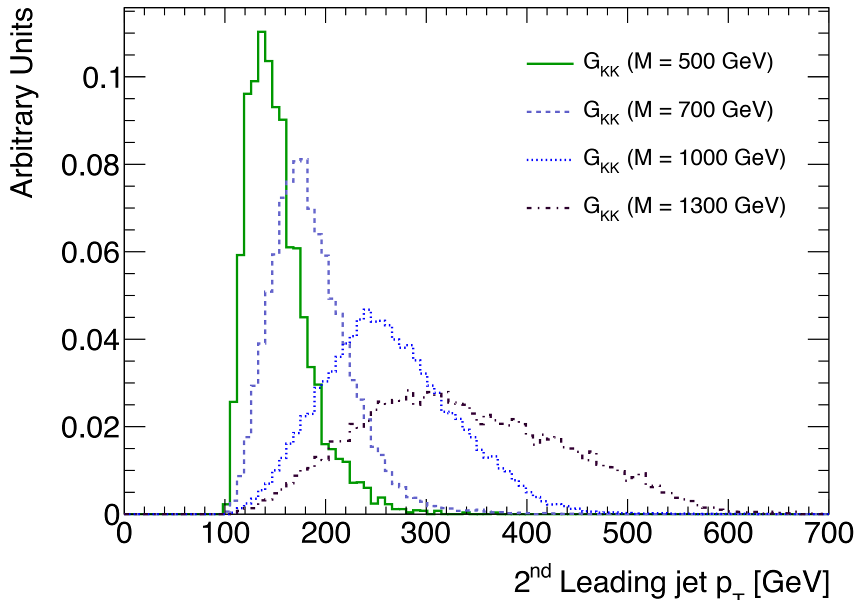
- Clear efficiency loss at low G_{KK} masses from dijet p_T requirement.
- Optimal dijet p_T cut likely to be higher for higher masses.

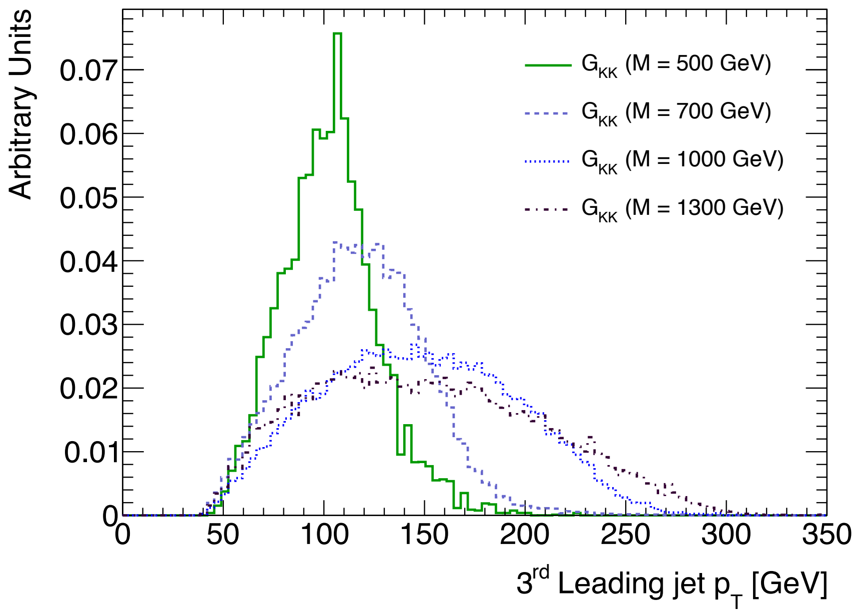
- Loss of efficiency from jet merging at high G_{KK} masses in this resolved analysis.
- For lowest masses the ΔR_{dijet} cut could be optimised.

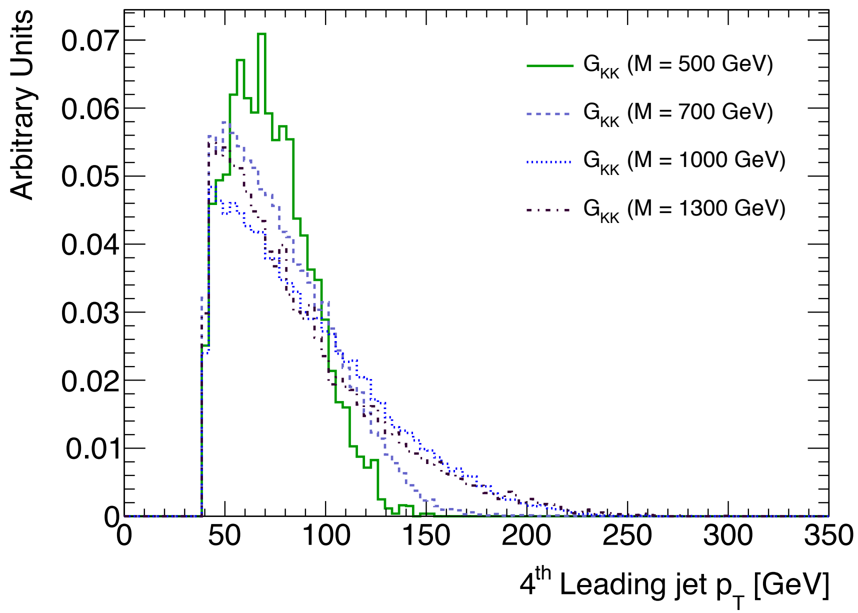


Signal Jet Kinematics





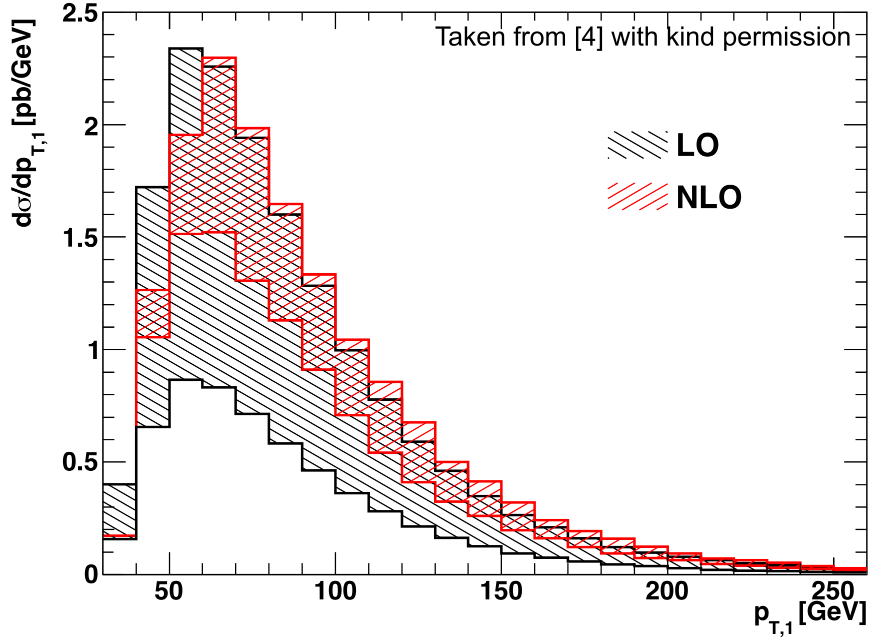




QCD Backgrounds

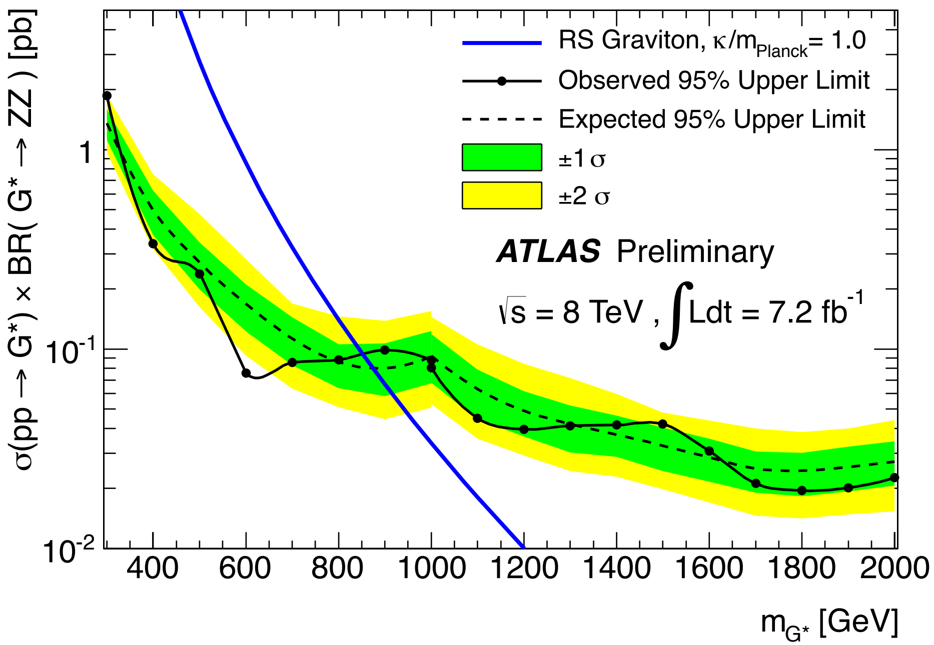
- Define uncertainty on our Sherpa background prediction as variation in renormalisation/factorisation scale choice μ_0 by factor ½ and 2:

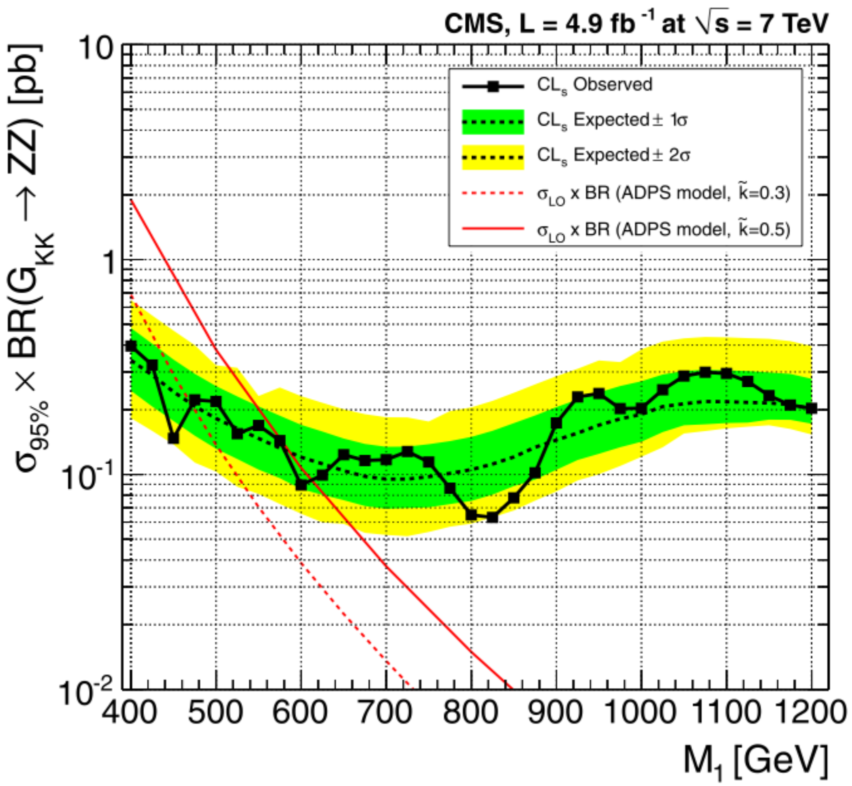
$$\mu_0 = \mu_F = \mu_R = \frac{1}{4}\sqrt{\sum_i p_{T,i}^2}$$



- NLO corrections to LO pp→bbbb + X 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.

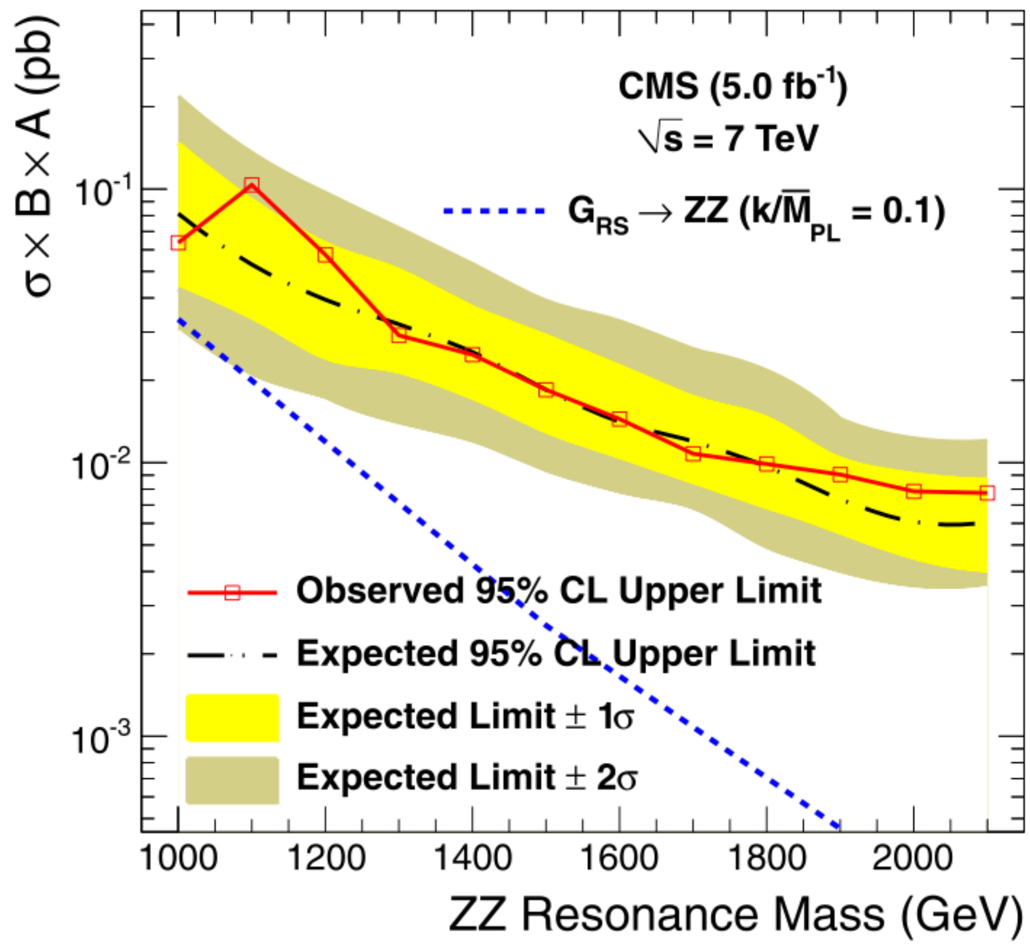
ZZ→lljj Limits on G_{KK}





- 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_{KK}



- 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.