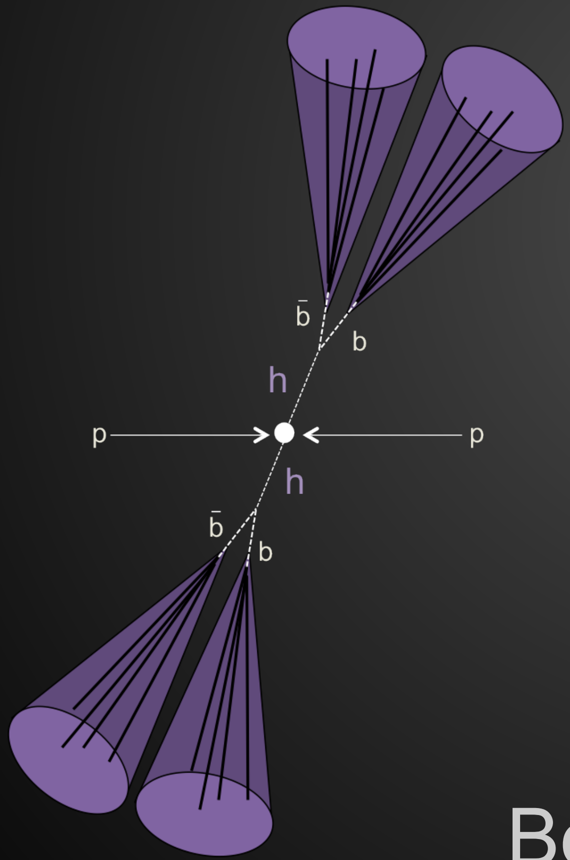
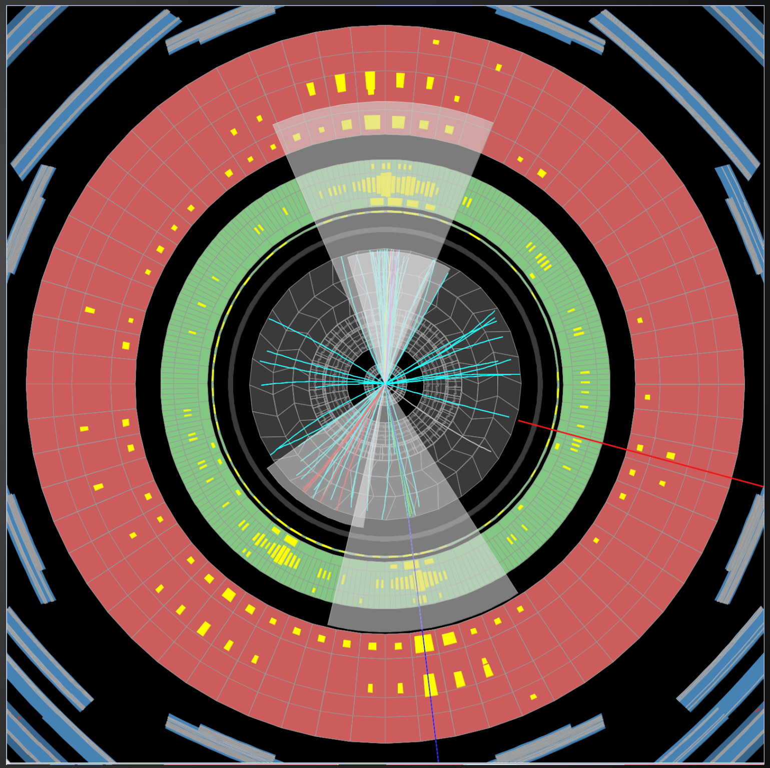
Searching for new physics with the hh→4b final state at the LHC



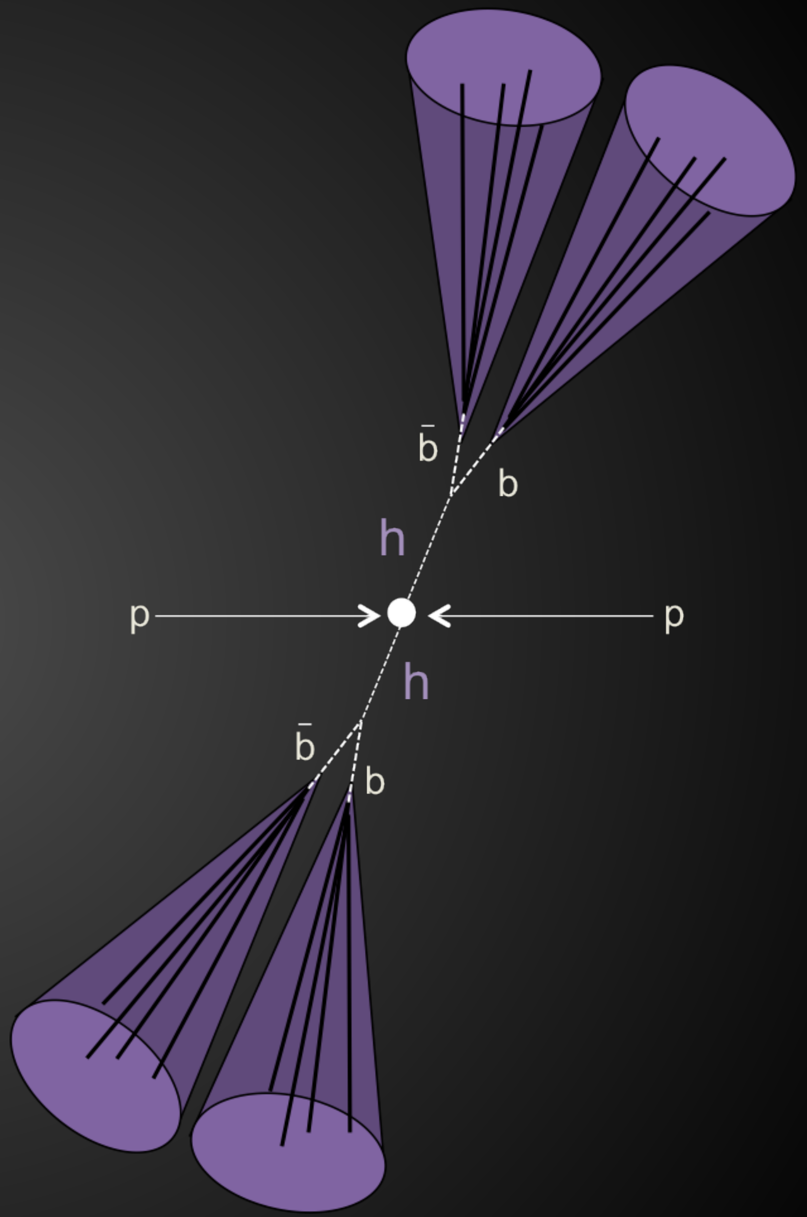


Ben Cooper & David Wardrope

Introduction

- In this talk:
  - Why this final state interesting.
  - How it is possible to study it at the LHC, and the results so far...
  - Where this might take us at the HL-LHC.

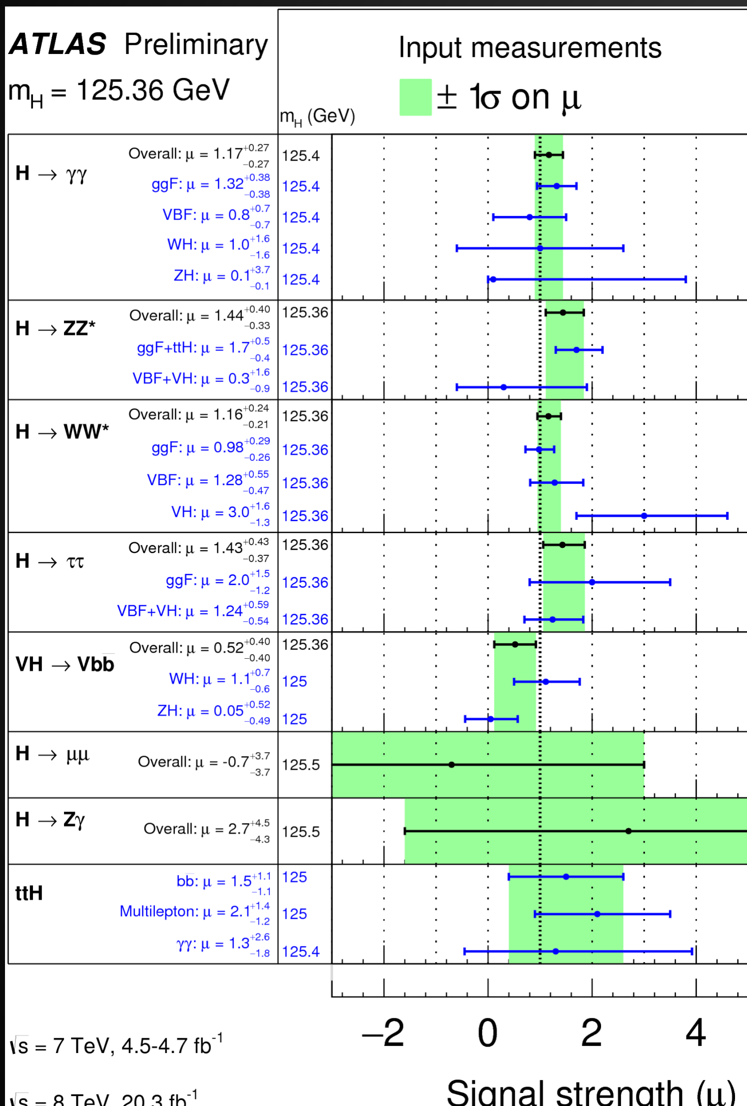
- The studies shown here are almost entirely UCL driven:
  - Nikos, Rebecca F, Luke L, Nurfikiri N, Eric J, BC, DW.

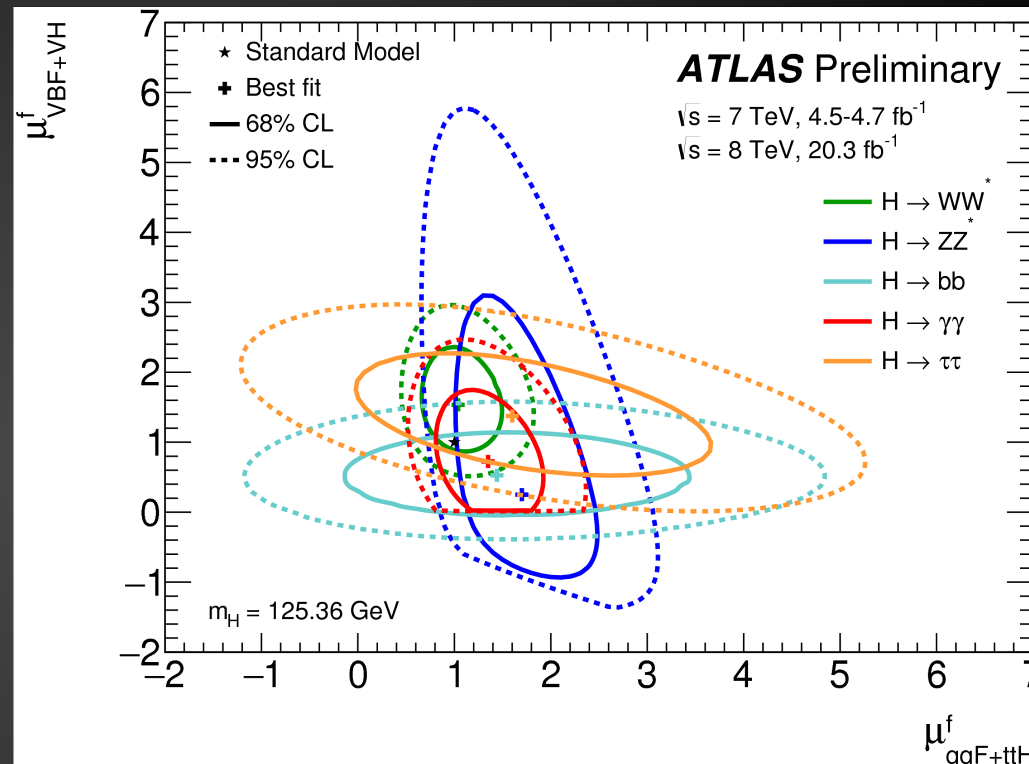


Motivation

Why is di-Higgs production interesting?
Wny look for it at the LHC?

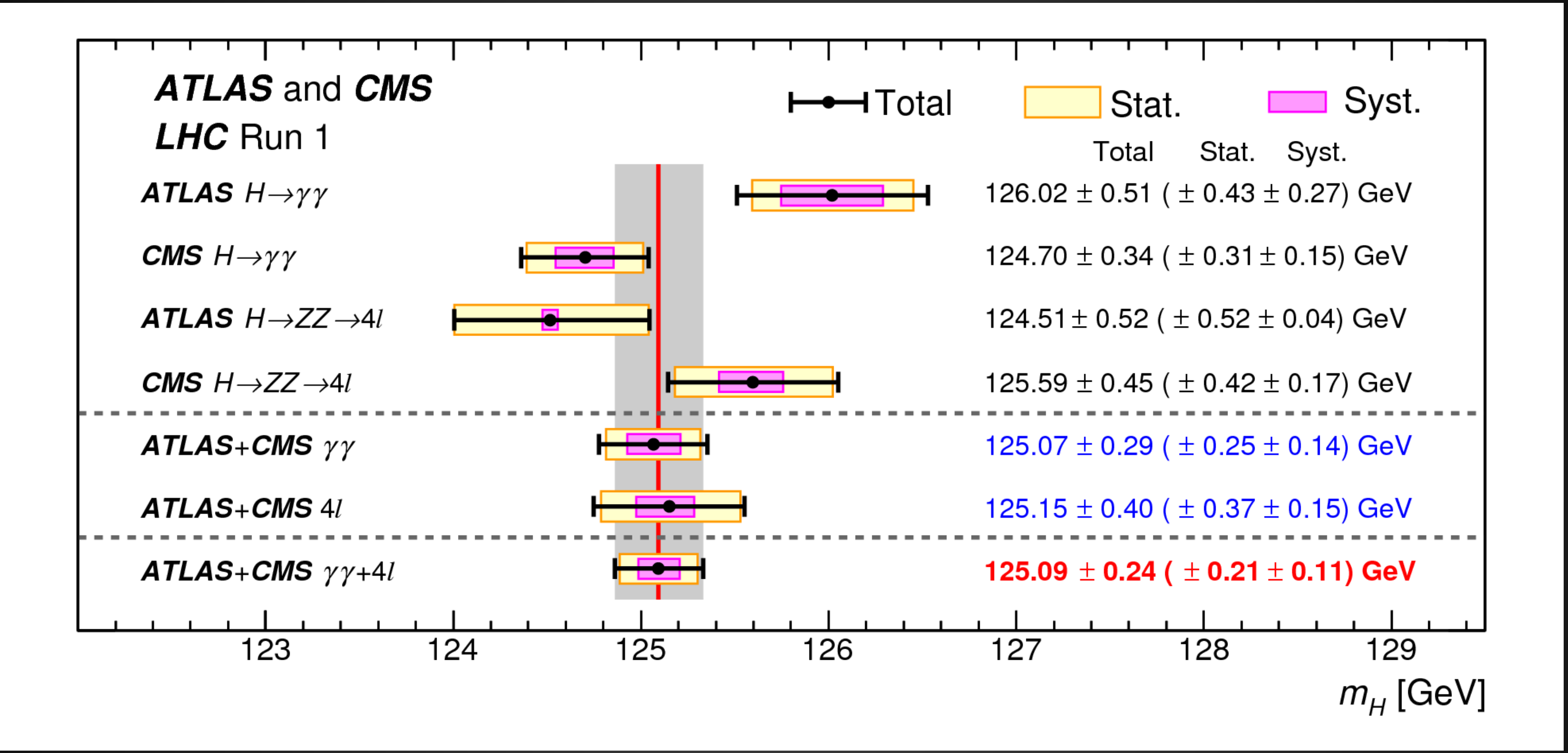
What we know about the Higgs...





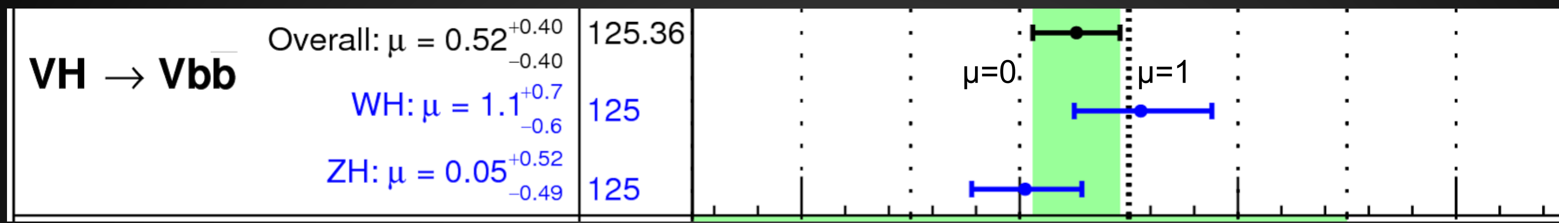
Consistent with the Standard Model in it’s couplings.

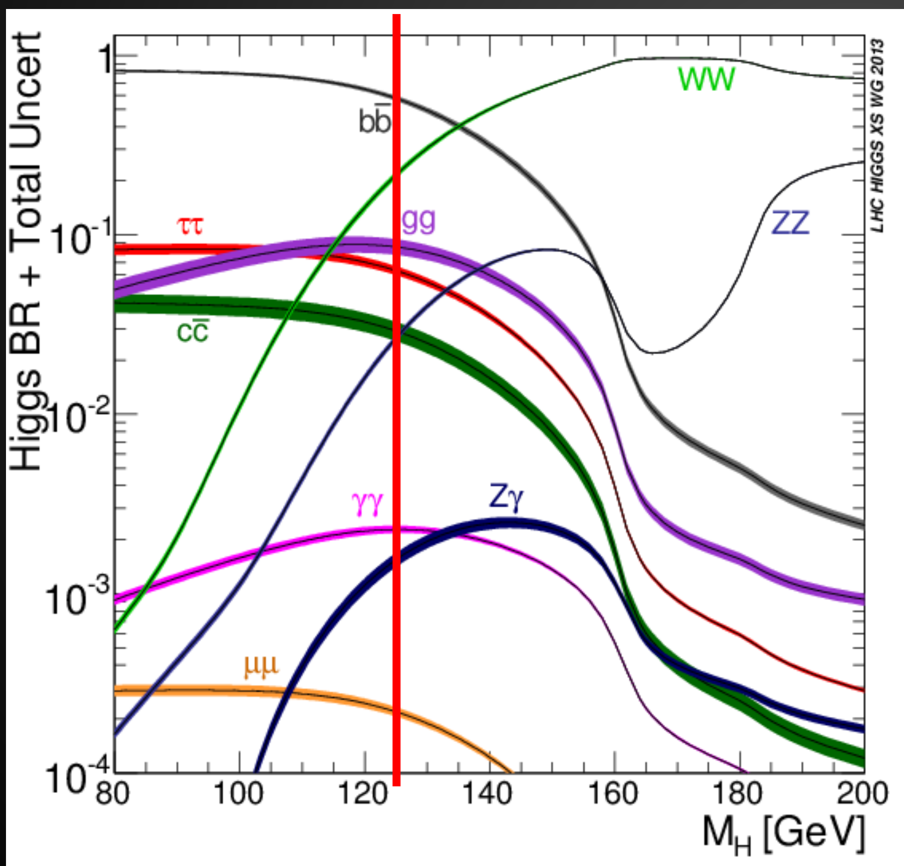
What we know about the Higgs...



Mass already known to 2 parts per mil precision!
Also have experimental handles on the spin, parity and total width properties.

...and what we don't know





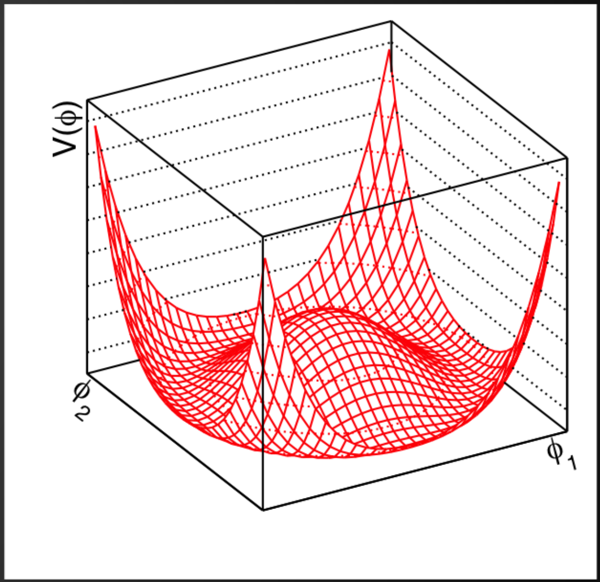
Have no solid observation of h→bb decay mode, despite this dominating the total width (BR 58%).

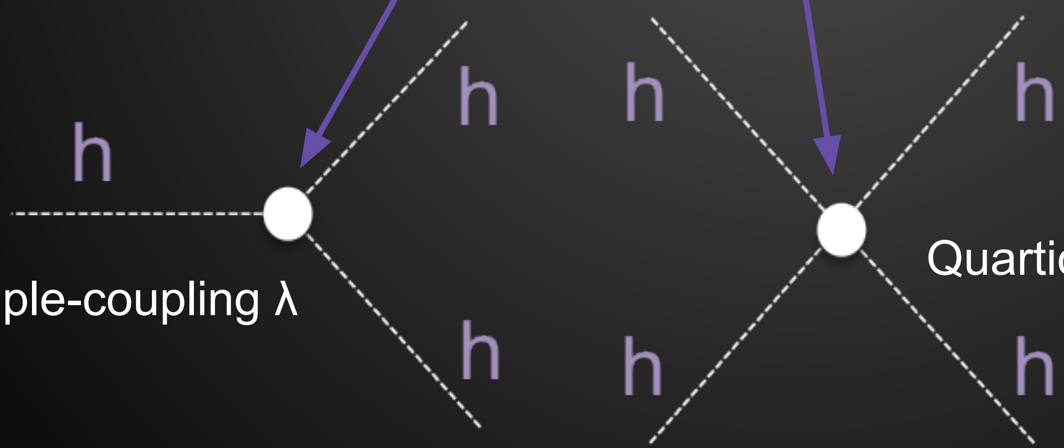
...and what we don't know

No measurement of Higgs "self-coupling"

Needed to understand structure of the symmetry breaking potential:

$$\mathcal{V} = \frac{1}{2} M_h^2 h^2 + \lambda v h^3 + \frac{\tilde{\lambda}}{4} h^4$$



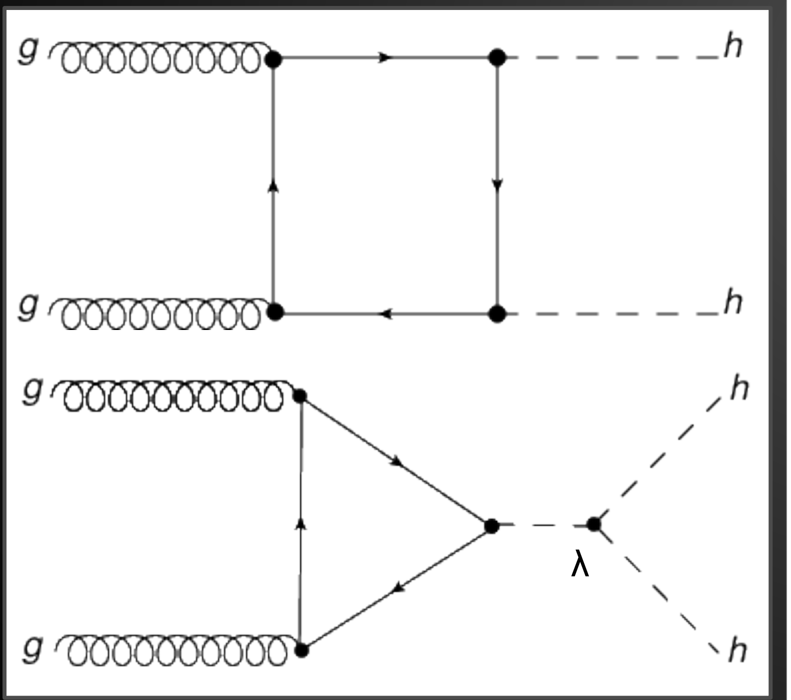


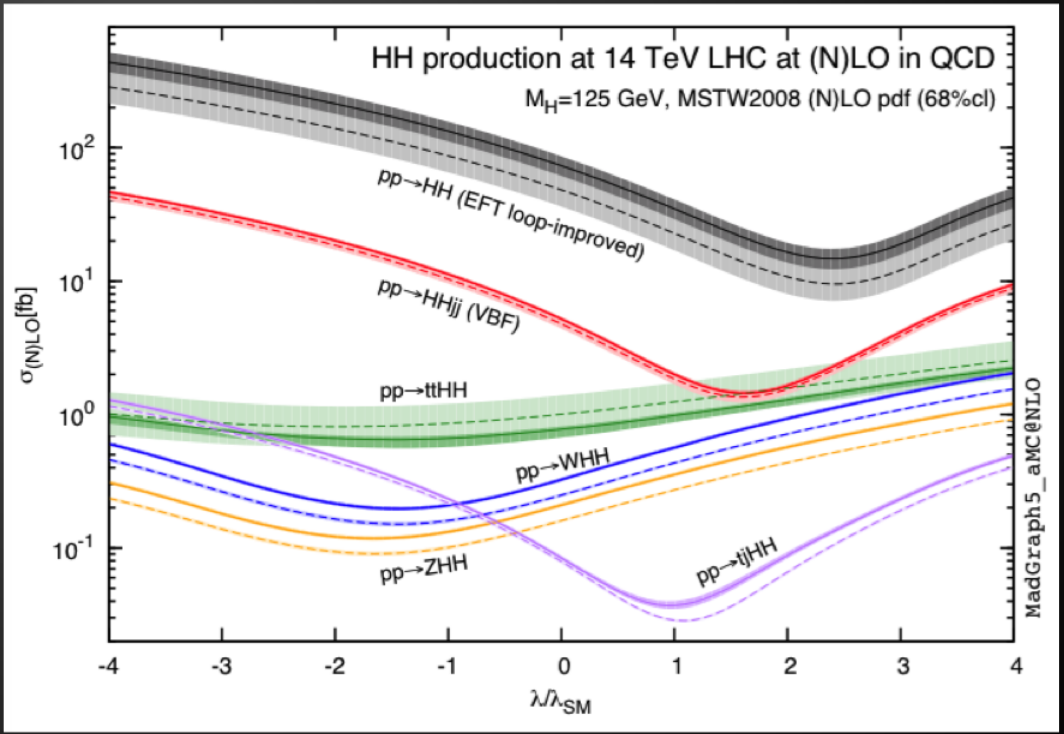
Triple-coupling λ

Quartic-coupling $\tilde{\lambda}$

...and what we don't know

- A measurement of di-Higgs production would give a handle on λ.
- Deviations of λ from Standard Model prediction would indicate new physics..but cross-sections are very small!



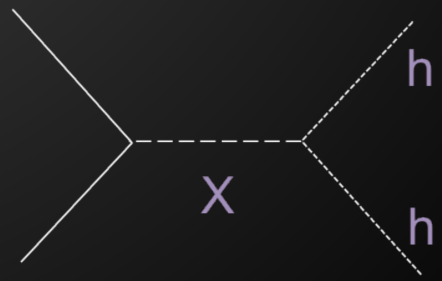


di-Higgs as a window to BSM Physics

Many models of new physics also predict resonant enhancements to di-Higgs production

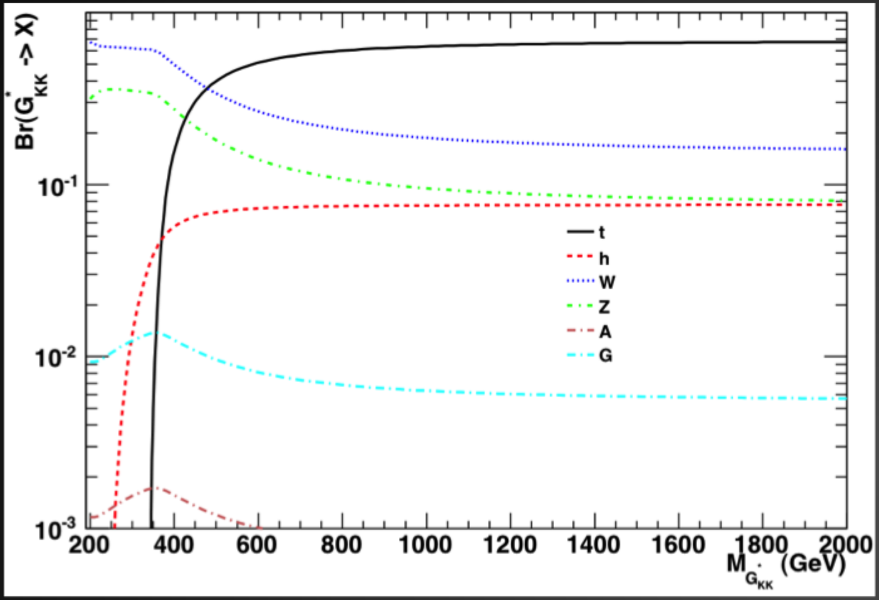
New physics model	Motivation	New particle with X→hh
Single Warped Extra Dimension[1,2]	Hierarchy problem Flavour problem	Kaluza-Klein Graviton, G_{KK} (Spin-2)
Additional Higgs Doublet[3] (2HDM)	MSSM Baryon asymmetry	Heavy neutral scalar, H
Additional Scalar Higgs[4] Singlet	Why not?	Heavy neutral scalar, H

1. Phys. Rev. Lett. 83 (1999) 3370-3373.
2. Phys. Rev. D76 (2007) 036006.
3. Phys. Rept. 516, (2012) 1.
4. arXiv:1303.1150



KK Gravitons at the LHC

http://cp3-origins.dk/content/uploads/2011/10/kkgrav.pdf



$\sqrt{s}$ = 8 TeV cross-sections and widths in ADPS Bulk Randall-Sundrum WED model with k/M_{Pl} = 1.0

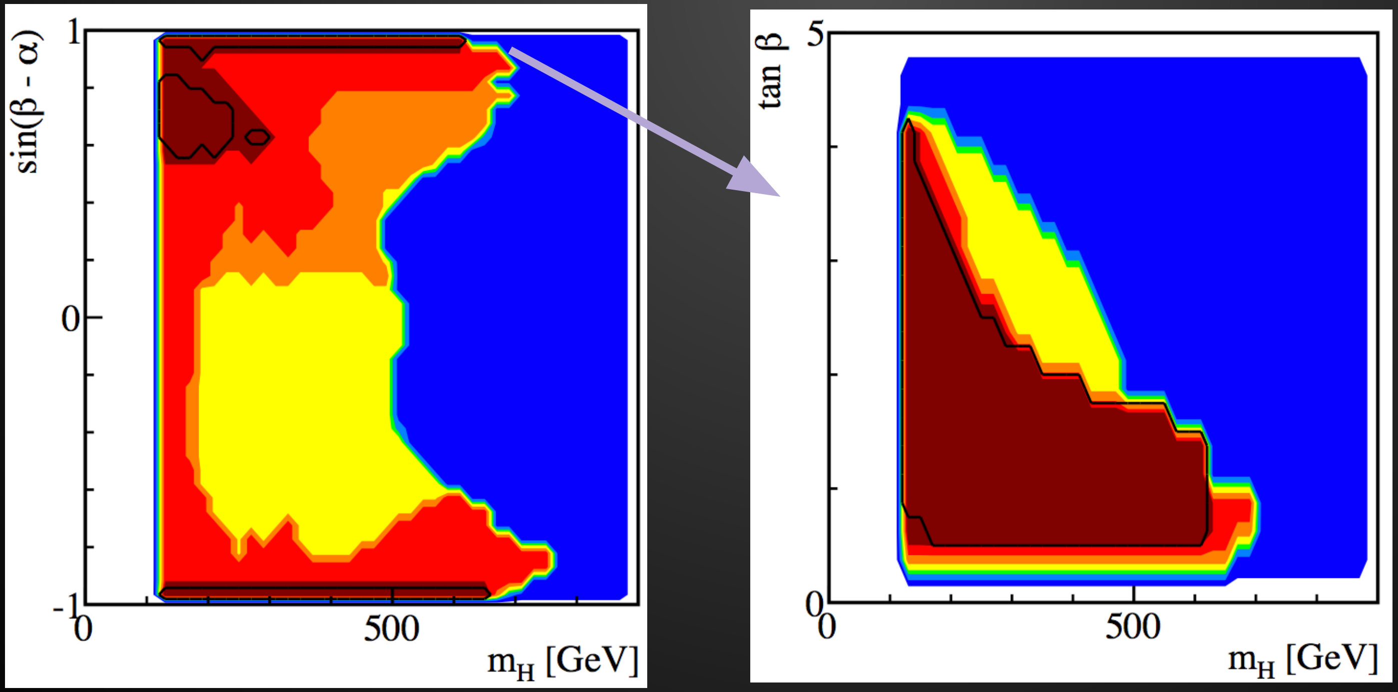
Graviton Mass [GeV]	$\sigma(pp \to G_{KK} \to hh \to b\bar{b}b\bar{b})$ [fb]	Γ [GeV]
500	70.9	18.6
700	12.44	33.9
900	2.83	48.6
1100	0.78	62.7
1300	0.25	76.5
1500	0.08	90.0

- Benchmark LHC model for resonant diboson production.
- Reasonably large BR to di-Higgs (6-7%).
- Narrow width resonance with cross-sections ~10’s fb at lower masses.
  - Accessible at LHC?

Two Higgs Doublet Models (2HDM)

- Enlarged scalar spectrum: h, H, H^+, H^-, A.
- Heavy Higgs can decay to pair of light Higgs: H→hh
- "Rich" structure with many parameters:
  - 5 masses: m_h, m_H, $m_{H+/-}$, m_A
  - Ratio of vevs of two Higgs fields: tan(β)
  - h-H mixing angle: cos(α)

arXiv:1305.0002



Assuming h is the SM Higgs, theoretical and experimental constraints make it difficult for m_H to be greater than ~500 GeV in 2HDM models.

How should we look for di-Higgs?

- Wide range of possible final states from fully hadronic to fully leptonic.

- The large BR of bbbb gives you plenty of signal to play with relative to the other channels...
- ...can this be used to control the large QCD backgrounds in this channel?

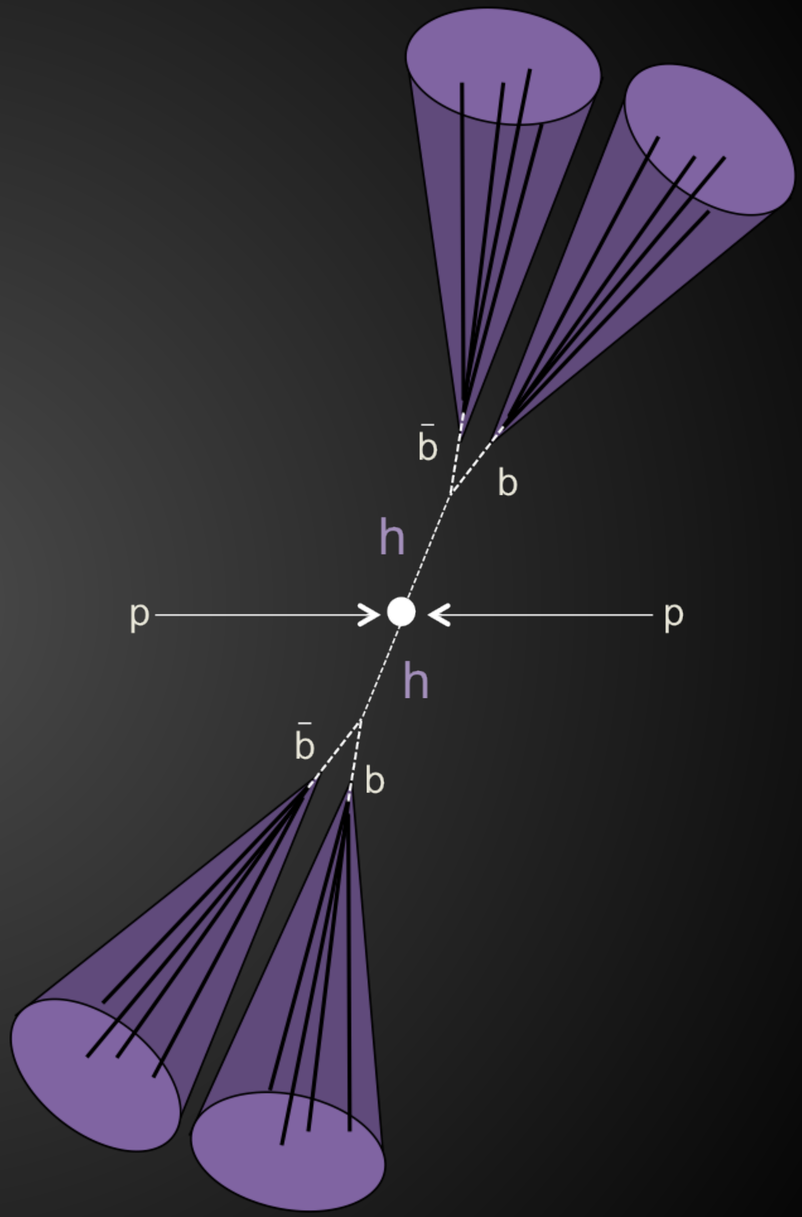
Channel	Branching ratio
bb bb	33.3%
bb $W^{had}W^{had}$	11.3%
bb tautau	7.3%
bb $W^{lep}W^{lep}$	1.2%
$W^{had}W^{had}$ $W^{had}W^{had}$	1.0%
tautau tautau	0.4%
bb γγ	0.3%
$W^{lep}W^{lep}$ $W^{had}W^{had}$	0.2%
$W^{lep}W^{lep}$ $W^{lep}W^{lep}$	0.01%
$W^{lep}W^{lep}$ γγ	0.005%
$Z^{lep}Z^{lep}$ $Z^{lep}Z^{lep}$	0.000002%

lep = electron or muon decay mode

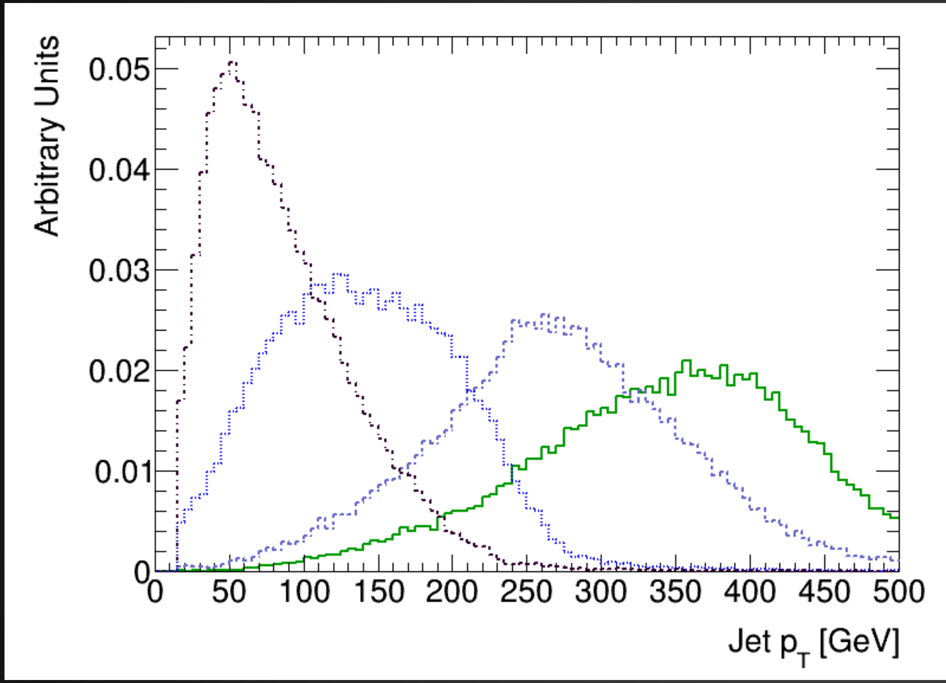
The Boosted 4b Topology

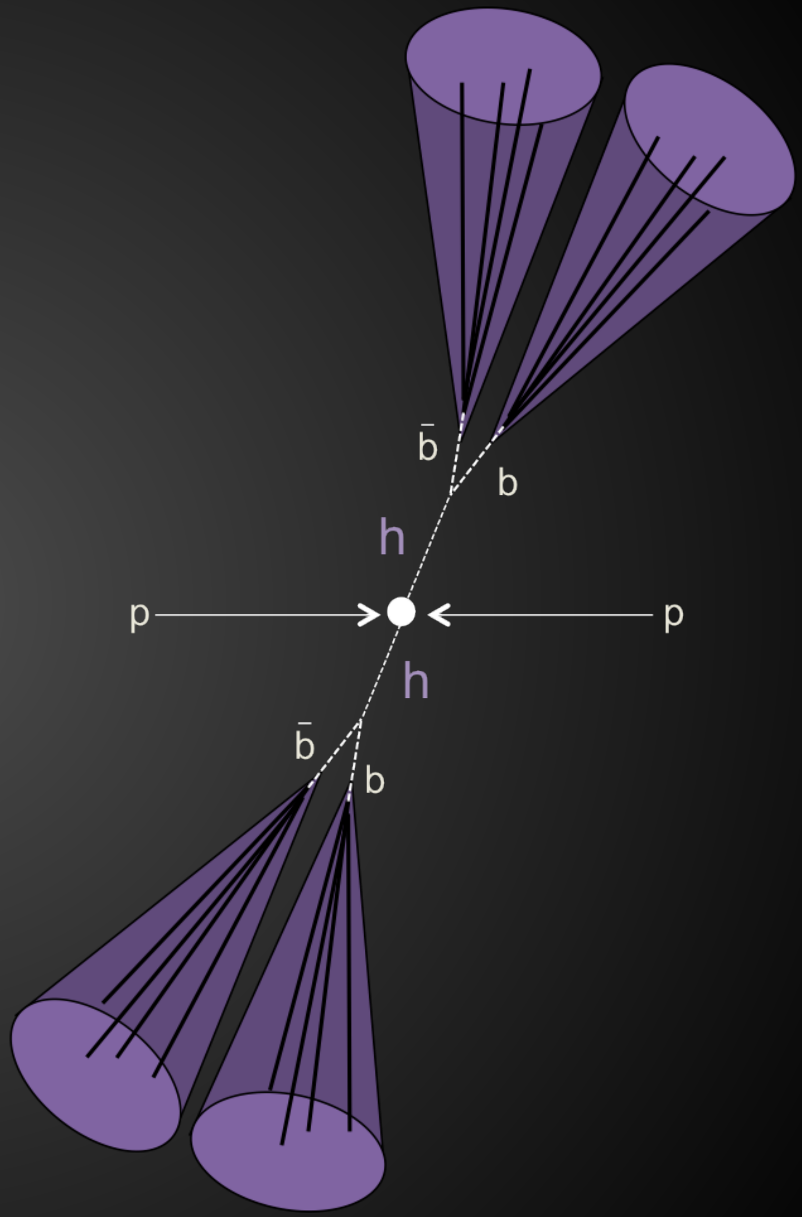
Boost it!

- Decay of a high mass resonance (~1 TeV) X→hh will naturally result in “boosted”, high momentum Higgs on opposite sides of the event.



Boost it!

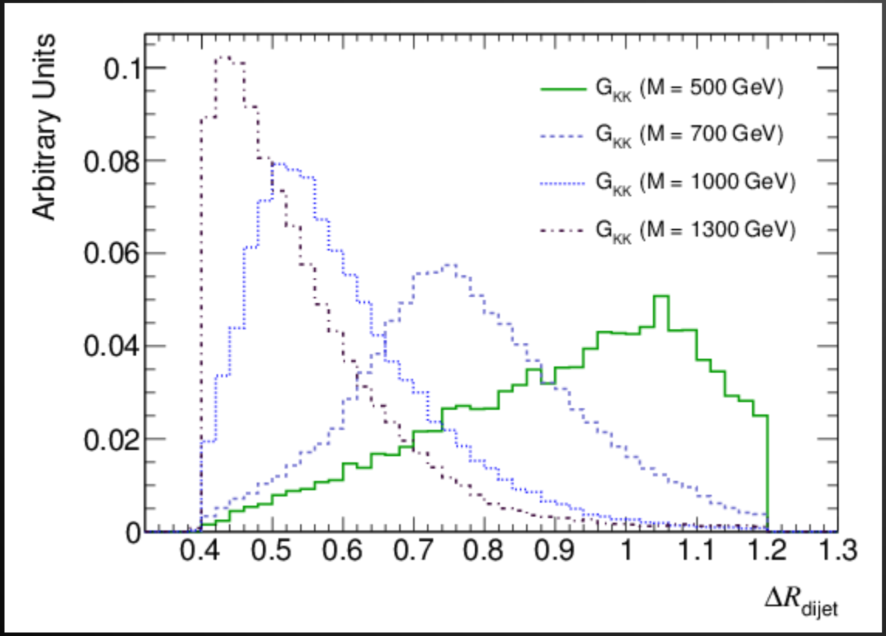


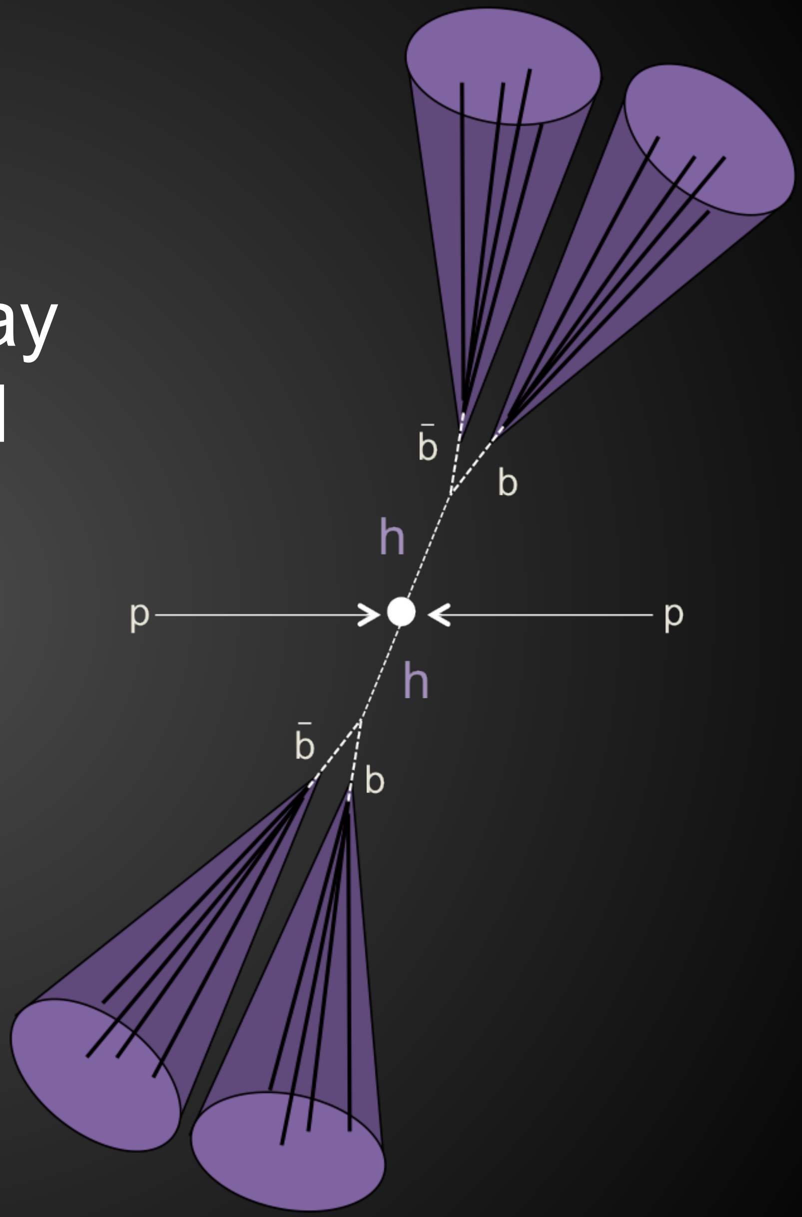


- Will tend to produce four “b-jets” of reasonable momentum.

Boost it!

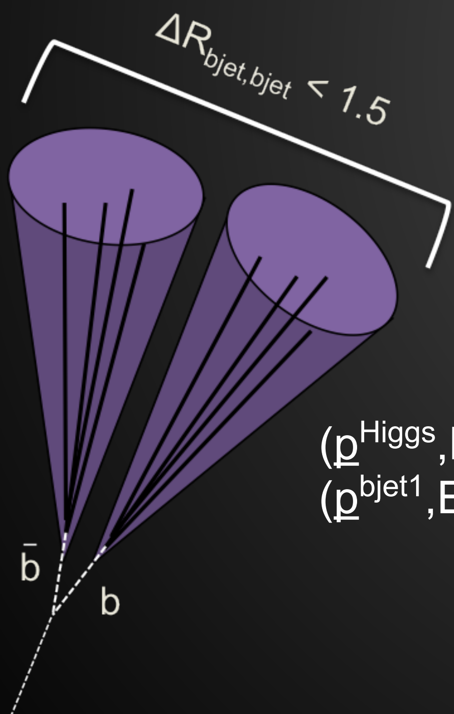
- The pair of b-jets from each boosted Higgs decay will be closely associated in angle.



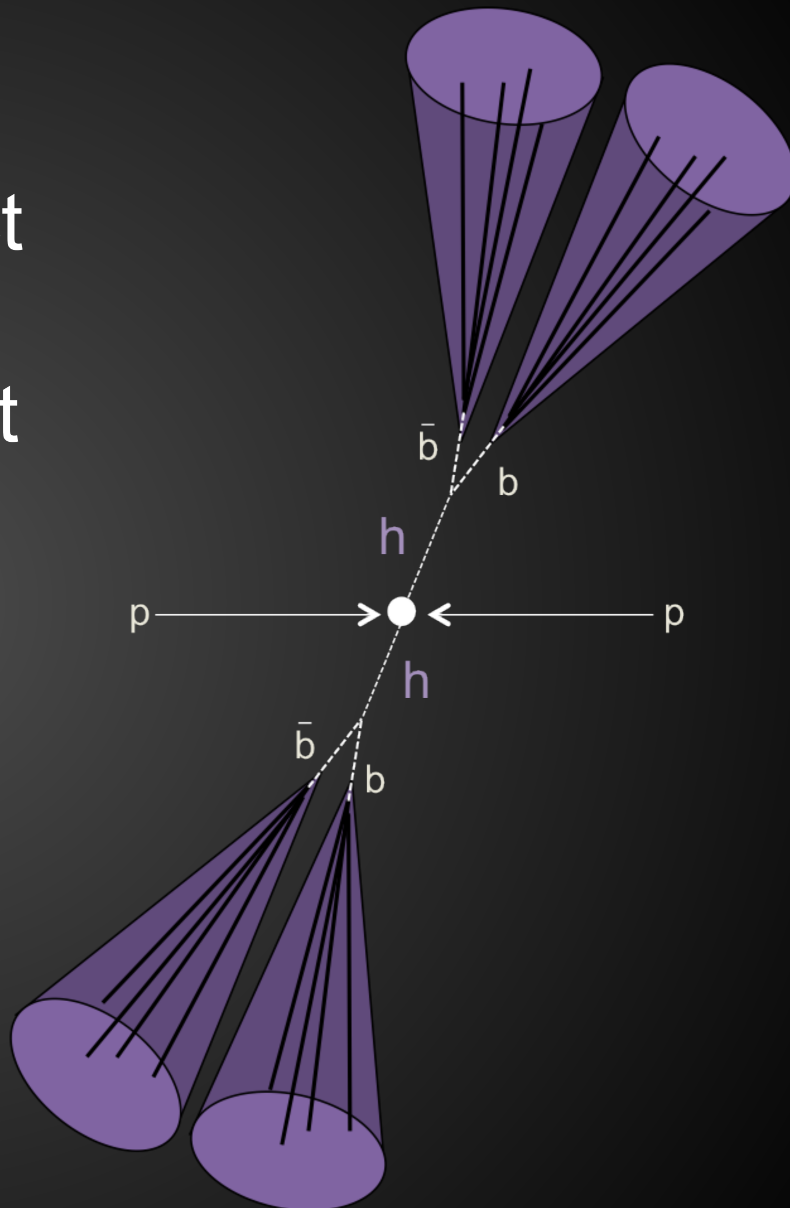


Boost it!

- Can therefore reconstruct the two Higgs as two boosted "dijets" per event



$$(\underline{p}^{Higgs}, E^{Higgs}) \approx (\underline{p}^{bjet1}, E^{bjet1}) + (\underline{p}^{bjet2}, E^{bjet2})$$



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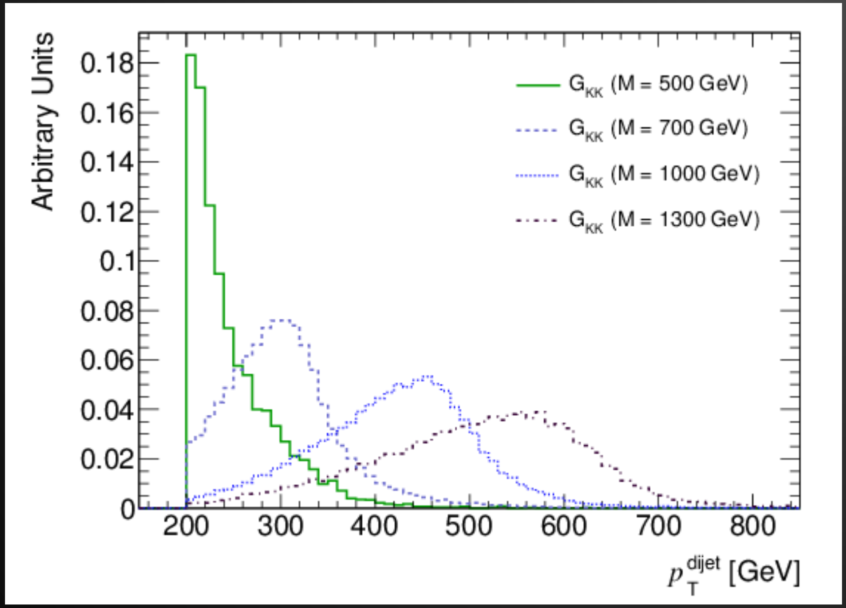
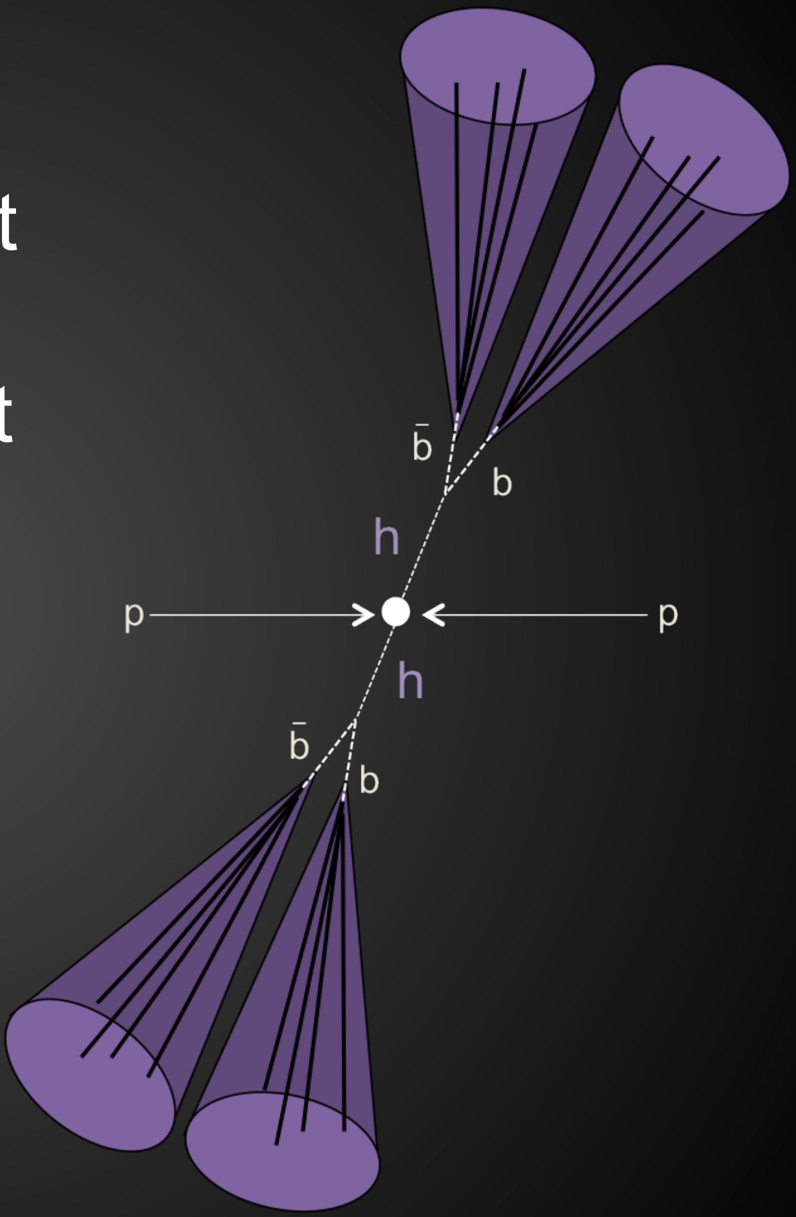




$X \to hh \to bbbb$ Particle-Level Studies

How large are the backgrounds?
Do we have sensitivity to new physics?

Phys. Rev. D 88:114005, 2013

X→hh→bbbb Particle-Level Studies

Basic Event Selection

- 4 b-tagged anti-k_T R=0.4 jets with p_T > 40 GeV and $|\eta| < 2.5$.
- B-tagging emulated using [b, c, light] [0.7, 0.2, 0.01] efficiencies.
- Two dijets with p_T > 200 GeV formed from the 4 b-tagged jets.

√s = 8 TeV Samples Used

- Signal:
  - RS G_{KK}→hh→bbbb
  - Madgraph + Pythia8
- QCD backgrounds:
  - pp→bbbb, pp→bbcc
  - Sherpa 1.4 (LO)
- Top pair background:
  - Pythia 8
  - LO scaled to LHC 8 TeV measurement.

QCD Doesn't Like This Topology

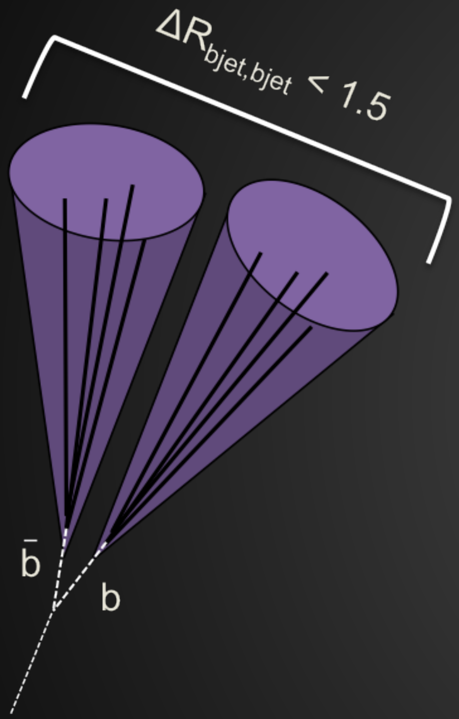
- Expected yields for $20 fb^{-1}$:

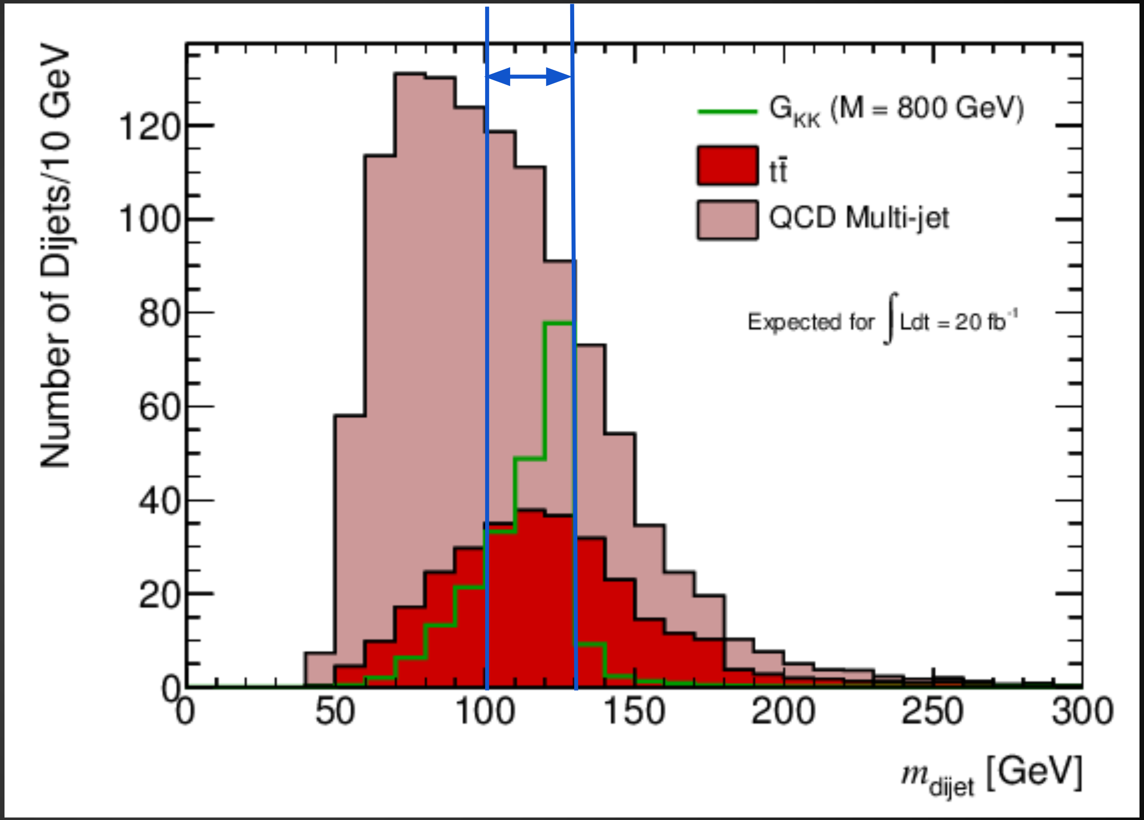
Requirement	$G_{KK}(M = 800\,GeV)$	QCD	$t\bar{t}$
4 b-tagged jets	126	19700	3590
2 dijets	109	414	151

- Dramatic reduction in backgrounds after boosted dijet requirements!
  - 98% reduction for QCD!!!

- Already looks very promising, can we do better?

Dijet Mass Windows





A requirement on the dijet mass can reduce the backgrounds further...

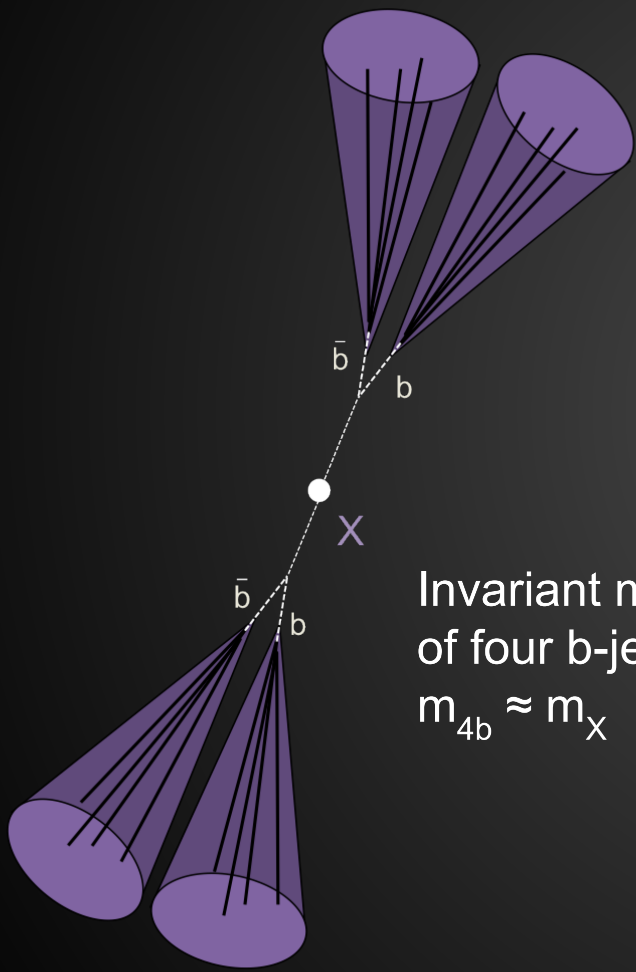
Dijet Mass Windows

- Expected yields for $20 fb^{-1}$:

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

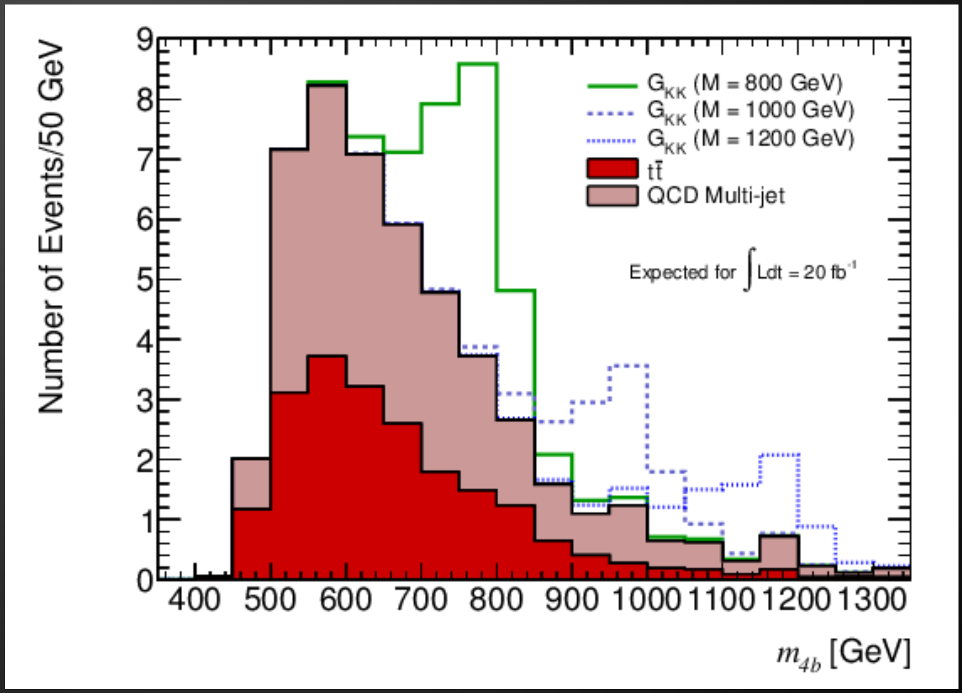
- Making dijet requirement on both sides gives big improvement in s/b.

Use 4b Mass Information



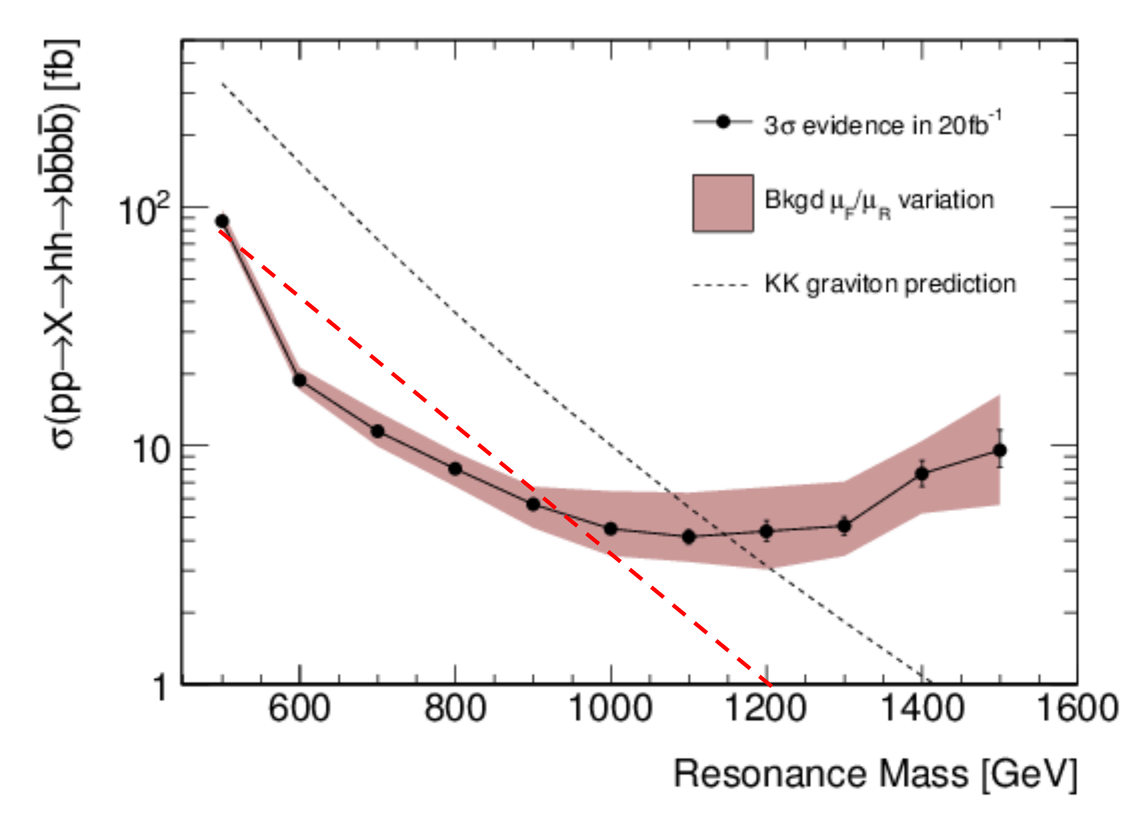
Can improve s/b further by searching for a resonance of a mass m_X only in a particular m_{4b} window.

Invariant mass of four b-jets = $m_{4b} \approx m_X$



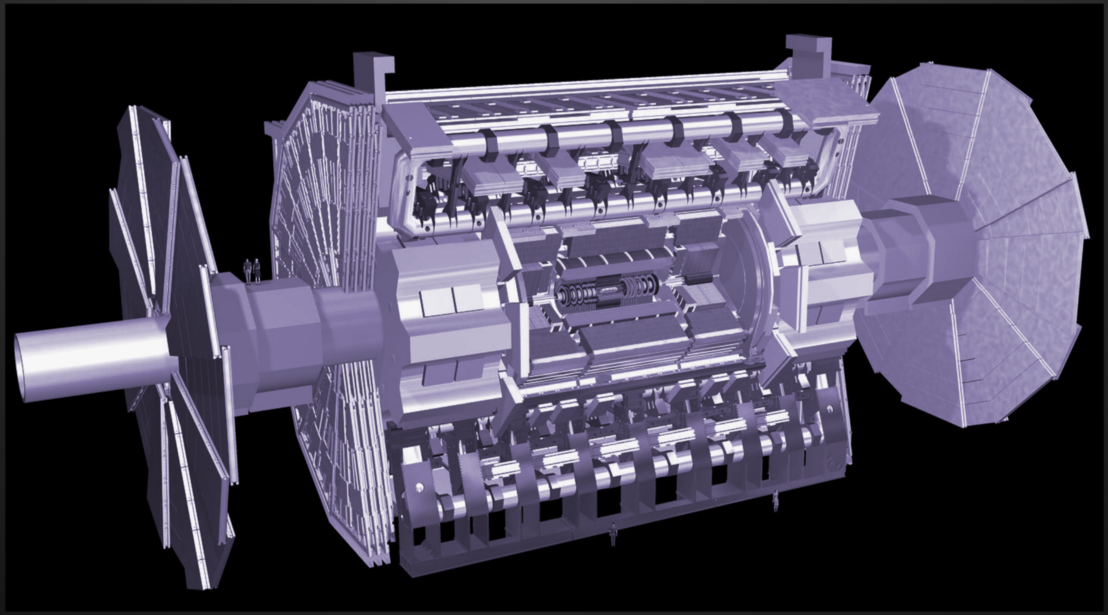
Sensitivity for 3σ observation

- Use [m_X-100, m_X+50] GeV m_{4b} windows, count background and plot signal cross-section such that signal yield = 3 x √bkg.
- Estimate sensitivity down to 4fb!
  - ~1 TeV graviton should be within reach!



Caveat: G_{KK} prediction here is a factor 4 too large (generator bug that is now fixed).

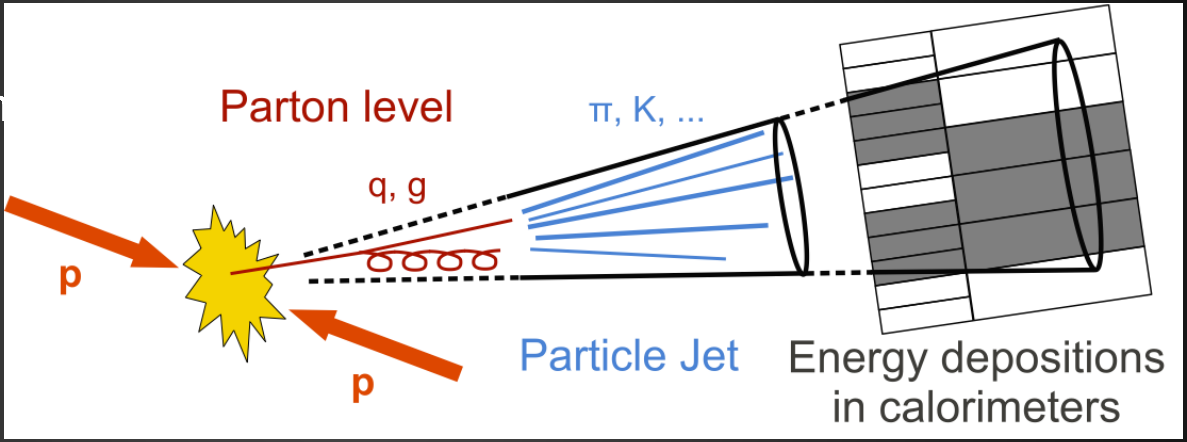
Jets and b-tagging at ATLAS



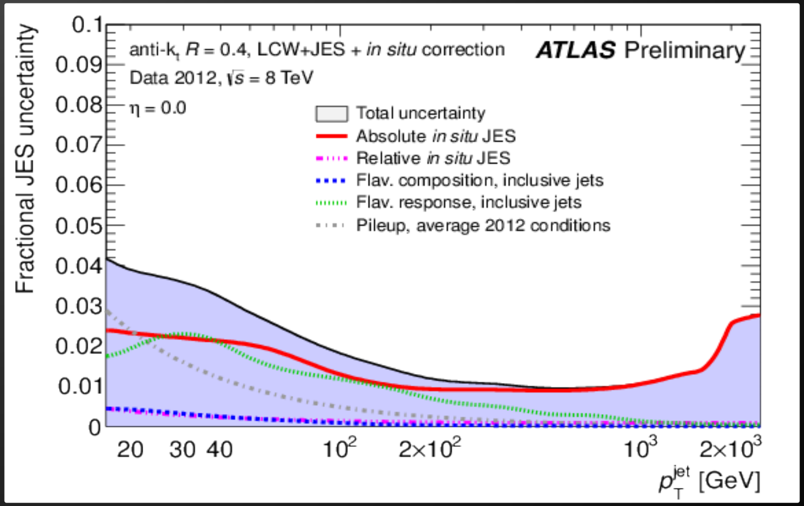
Jets and b-tagging at ATLAS

Success of 4b analysis depends crucially on performance of jet reconstruction and b-tagging.

Jets reconstructed from calorimeter energy clusters using Anti-k_T algorithm with R=0.4.



This analysis benefits from excellent understanding of the jet energy scale (< 3%) and resolution (~10%).



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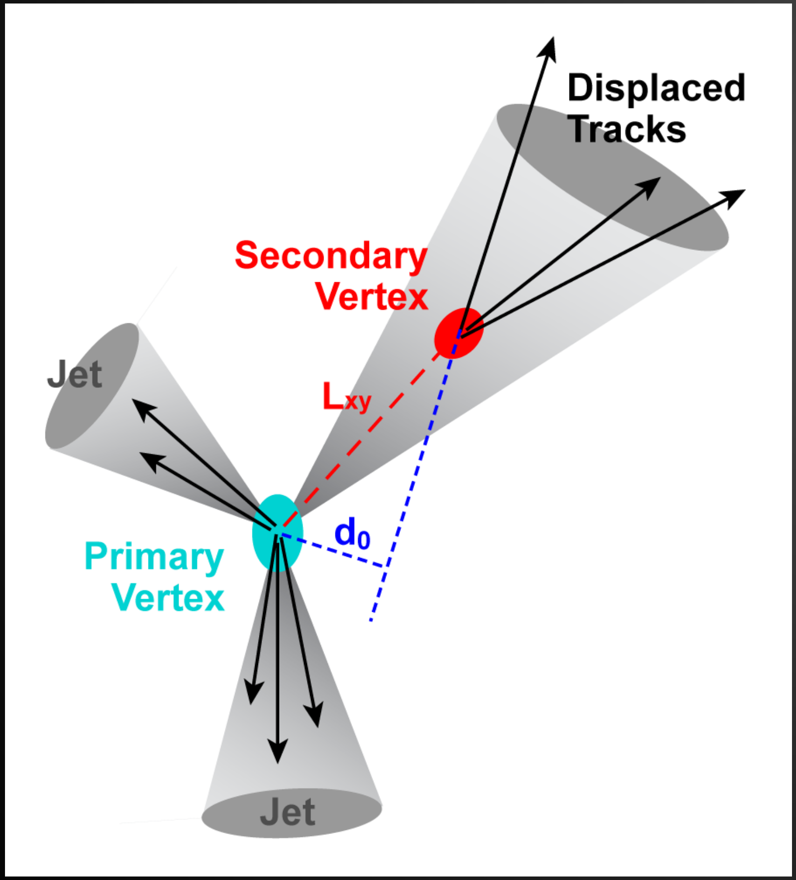
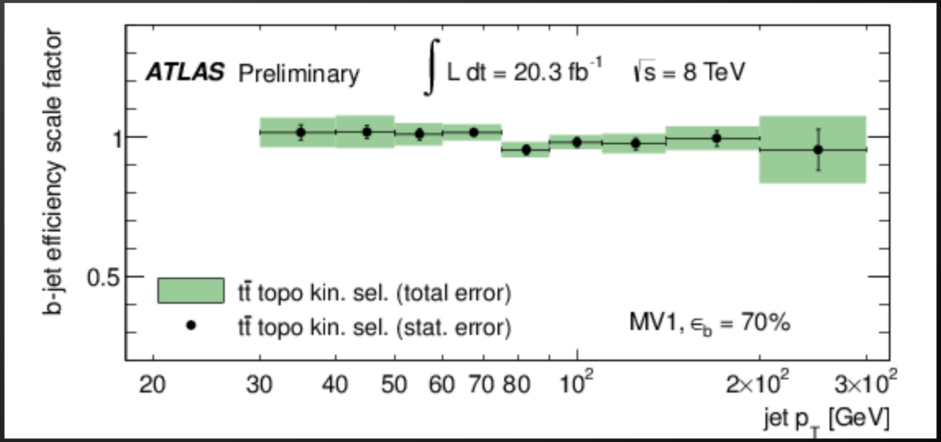


Jets "b-tagged" using information from the tracks associated to the jet to infer the presence of a long-lived B hadron.

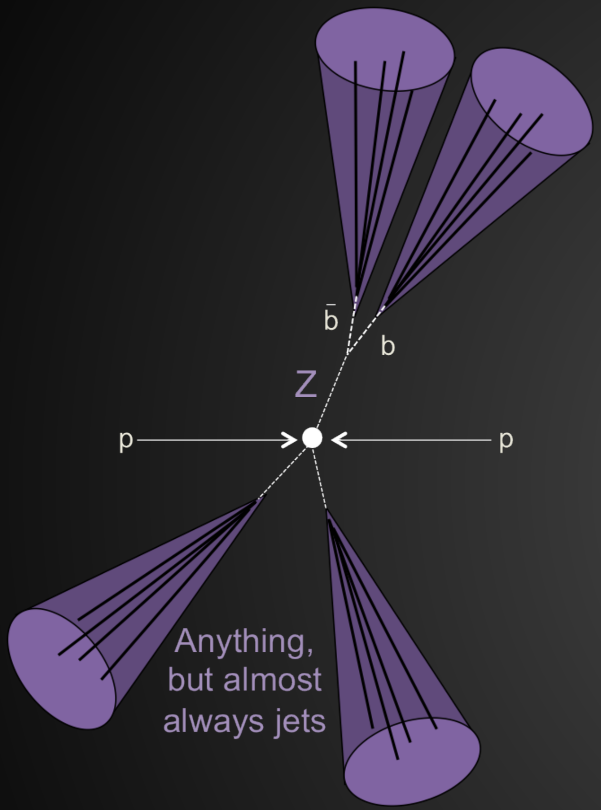
Analysis benefits from excellent separation of b-jets from "light" jets (70% vs 1%), and understanding of b-tag rate (5-10%).



ATLAS Boosted Z→bb Measurement

Physics Letters B 738 (2014) 25-43

Measurement of boosted Z→bb



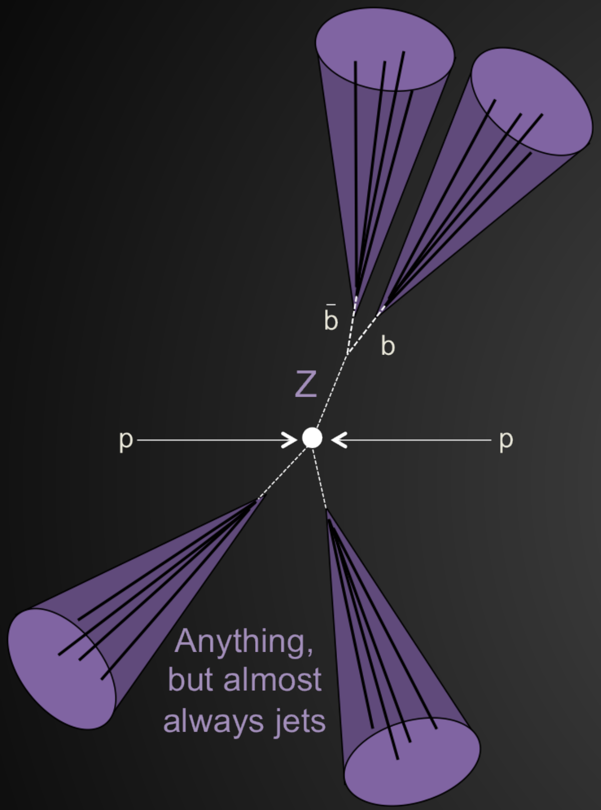
$$\sigma^{\text{fid}}_{Z\to b\bar{b}} = 2.02 \pm 0.20\ (\text{stat.})\ \pm 0.25\ (\text{syst.}) \pm 0.06\ (\text{lumi.})\ \text{pb}$$

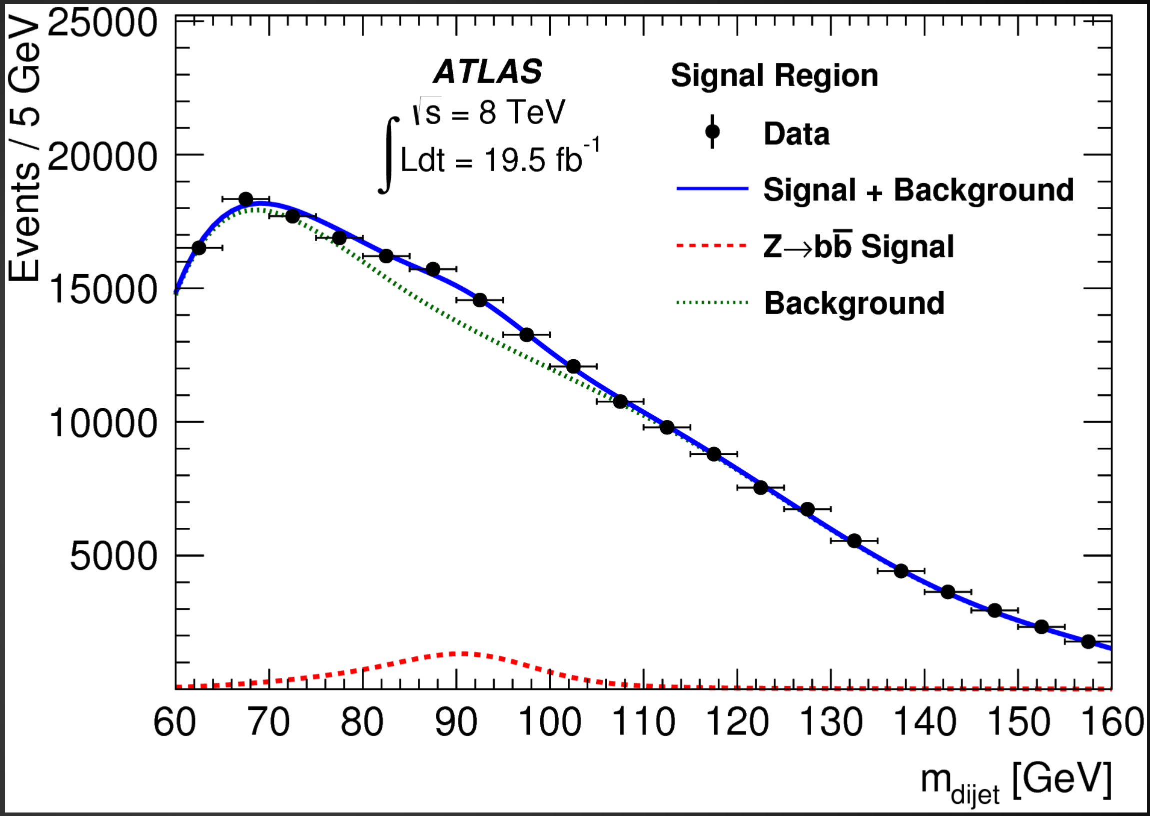
$$\text{POWHEG}: \quad \sigma^{\text{fid}}_{Z\to b\bar{b}} = 2.02\ ^{+0.25}_{-0.19}(\text{scales})\ ^{+0.03}_{-0.04}(\text{PDF})\ \text{pb}$$

$$\text{aMC@NLO}: \quad \sigma^{\text{fid}}_{Z\to b\bar{b}} = 1.98\ ^{+0.16}_{-0.08}(\text{scales}) \pm 0.03(\text{PDF})\ \text{pb}$$

- Used b-tagged dijet approach to measure boosted Z→bb cross-section to ~15%!
- A world first at a hadron collider!

Measurement of boosted Z→bb





- This demonstrated that:
  - We could trigger on a hadronic boosted bb final state.
  - B-tagging of boosted bb systems was working well.
  - Large QCD backgrounds could be controlled.

ATLAS Run-1 hh $\rightarrow$ 4b

Strategy

Based on the phenomenology paper

- Select two boosted, b-tagged dijets
- Scan m_{4j} to search for resonances

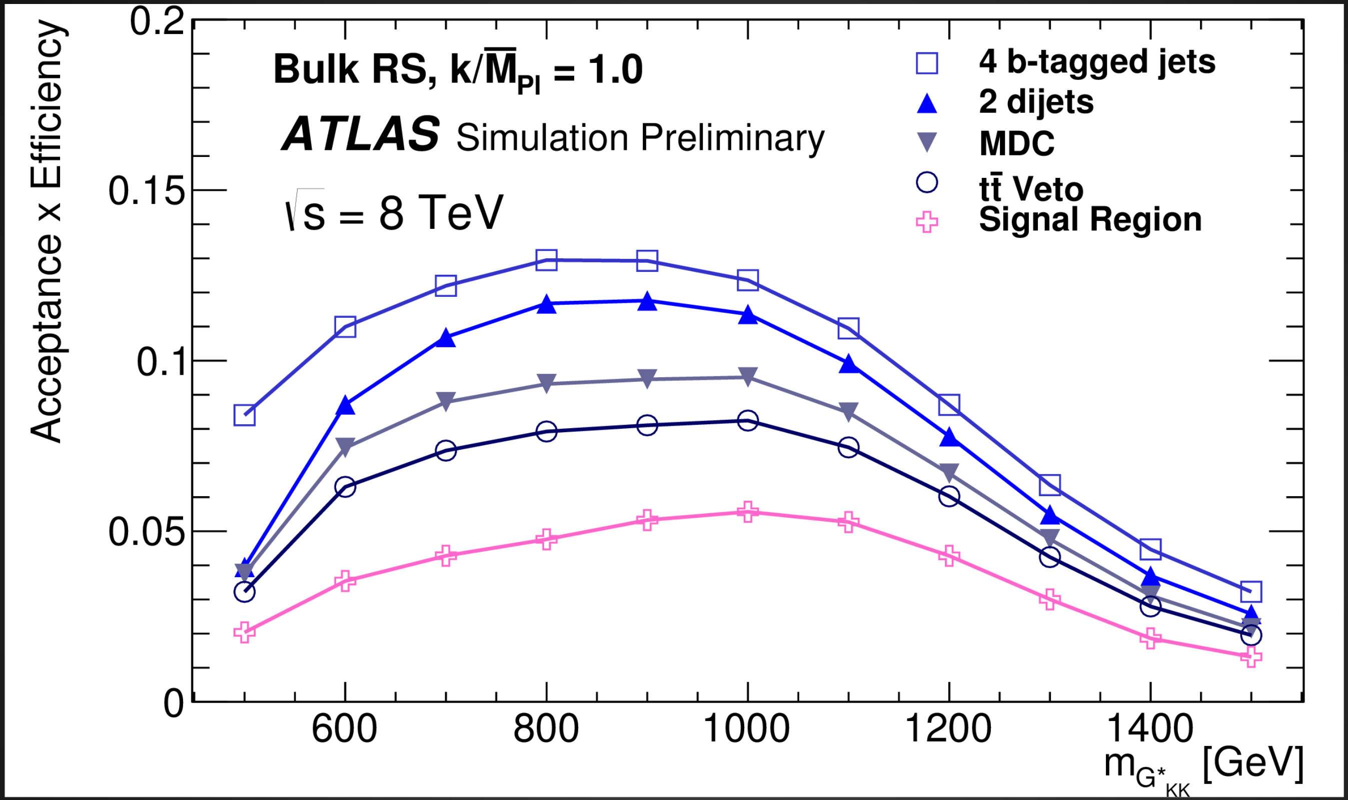
Extensions to the search

- Non-resonant hh search using event counting
- large-R jets to reconstruct heaviest resonances

Improvements to increase sensitivity

- Mass dependent cuts

Signal Acceptance



Acceptance for high mass resonances limited by jet R parameter (anti-k_T R = 0.4 jets used)

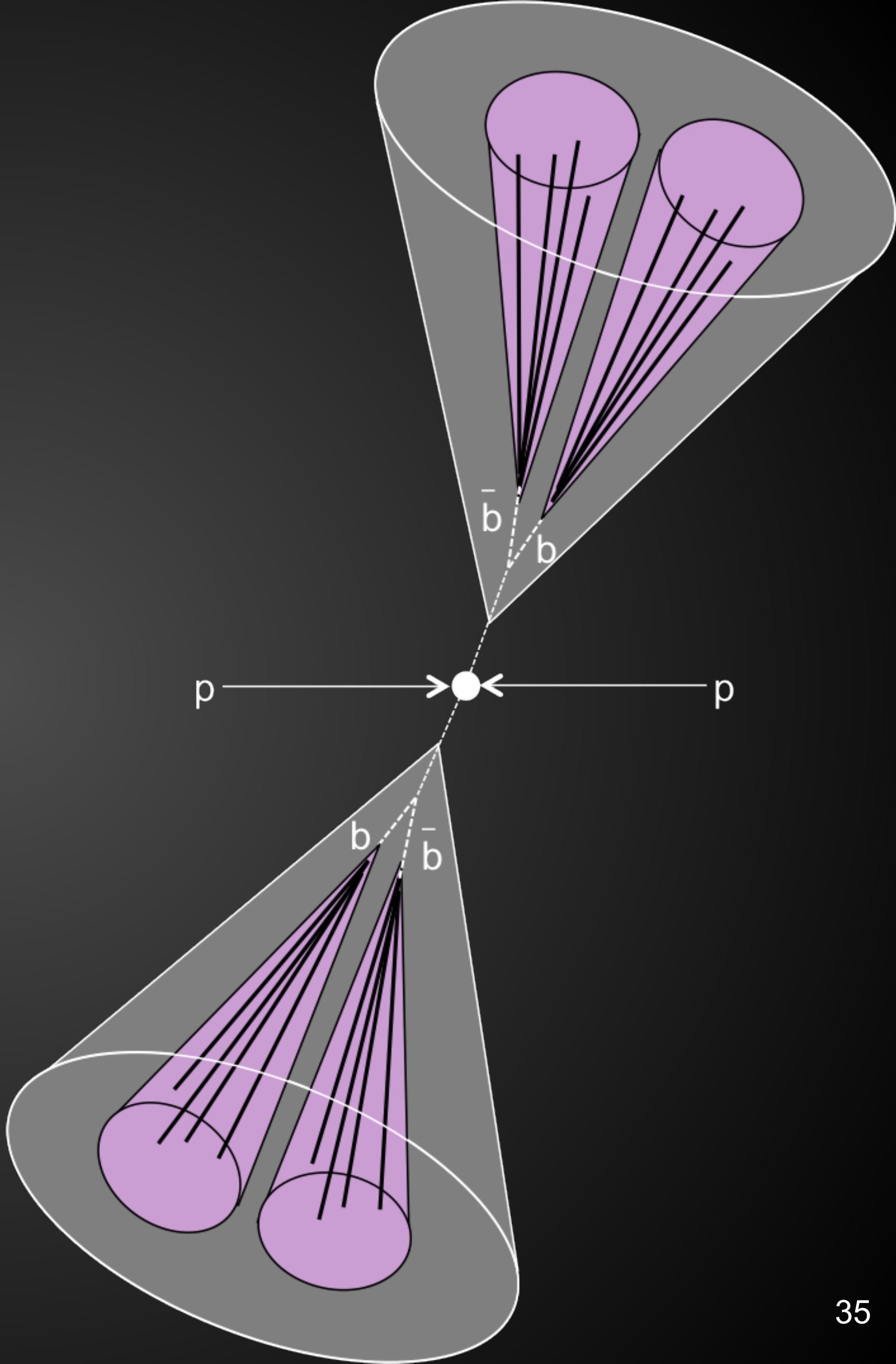
Jets overlap because of Higgs boson boost

Boosted Analysis

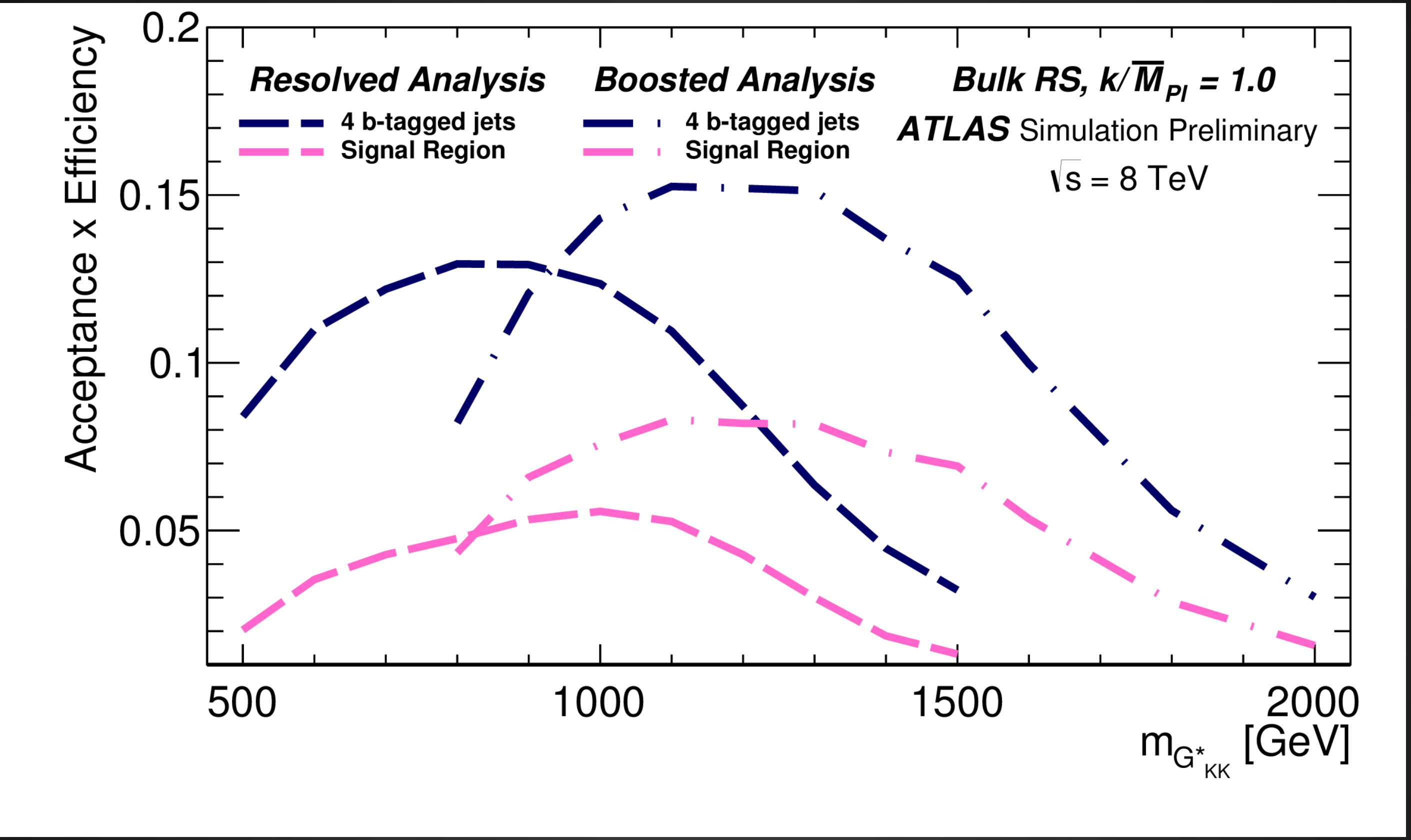
Reconstruct high p_T Higgs candidate as single large-radius jet

Use two smaller radius track-jets to identify b-hadrons

→ Extends acceptance to higher masses



Selection Efficiency



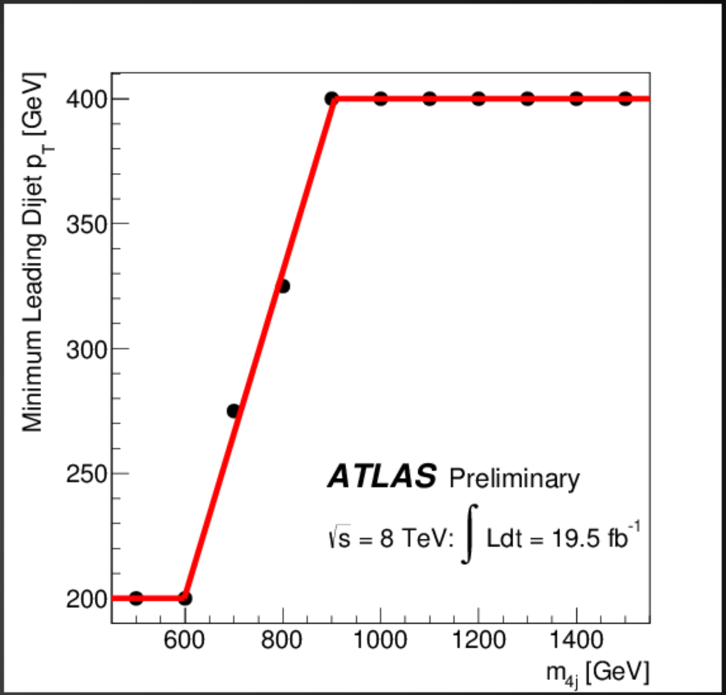
Complementary resolved and boosted analyses offer sensitivity $500 \leq m_X \leq 2000$ GeV

Mass-Dependent Cuts

Search for a wide range of resonance masses

Optimal selection for low mass not optimal for high mass

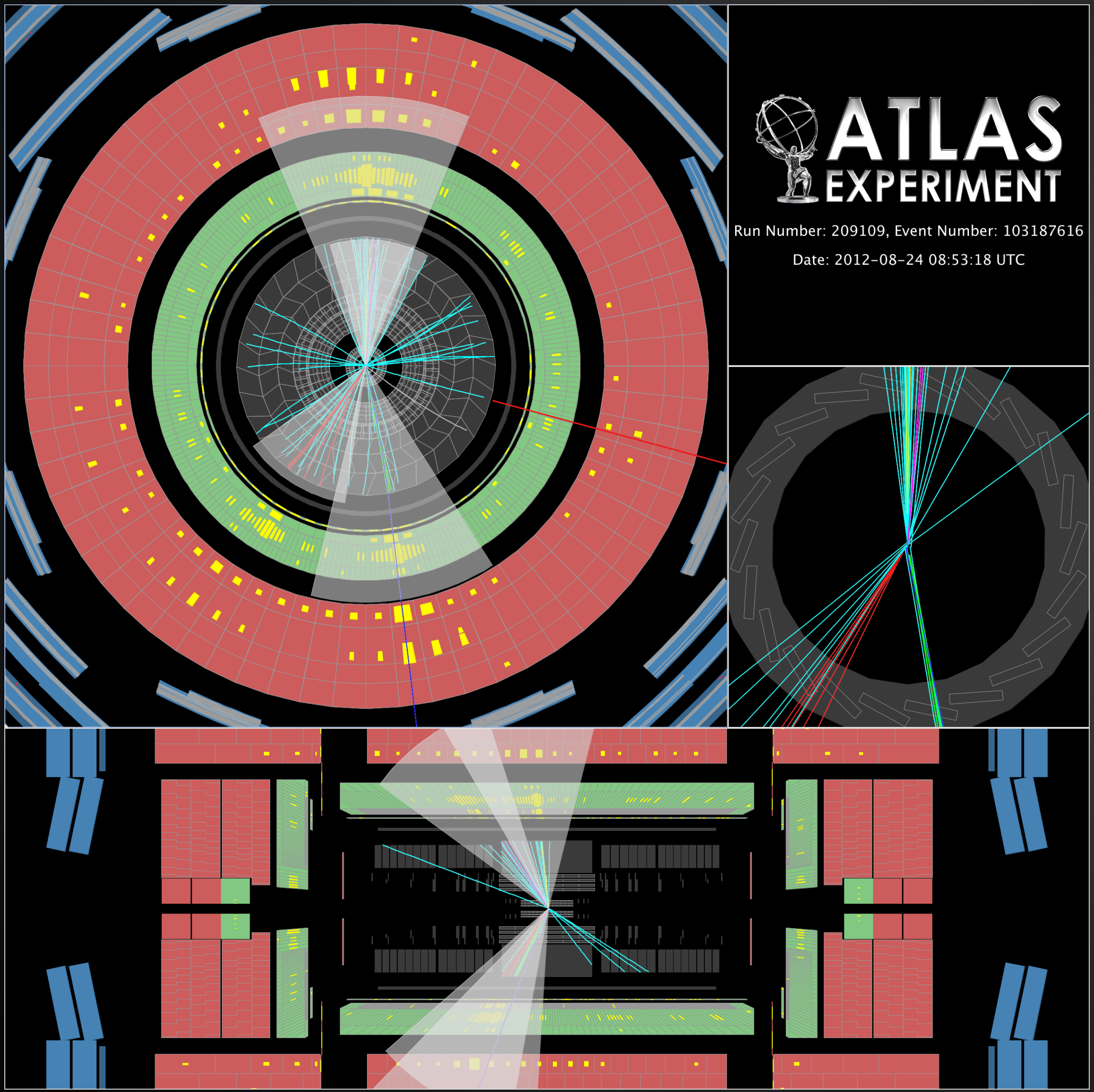
⇒Mass-dependent cuts on p_T^{lead}, p_T^{subl} and $|\eta_{dijets}|$



Best cuts found by 3D scan of possible values

Use best expected limit as the objective function

A Selected Event



m_{2j}^{lead} = 114 GeV

m_{2j}^{subl} = 123 GeV

m_{4j} = 809 GeV

Is this event signal or background?

Background Model

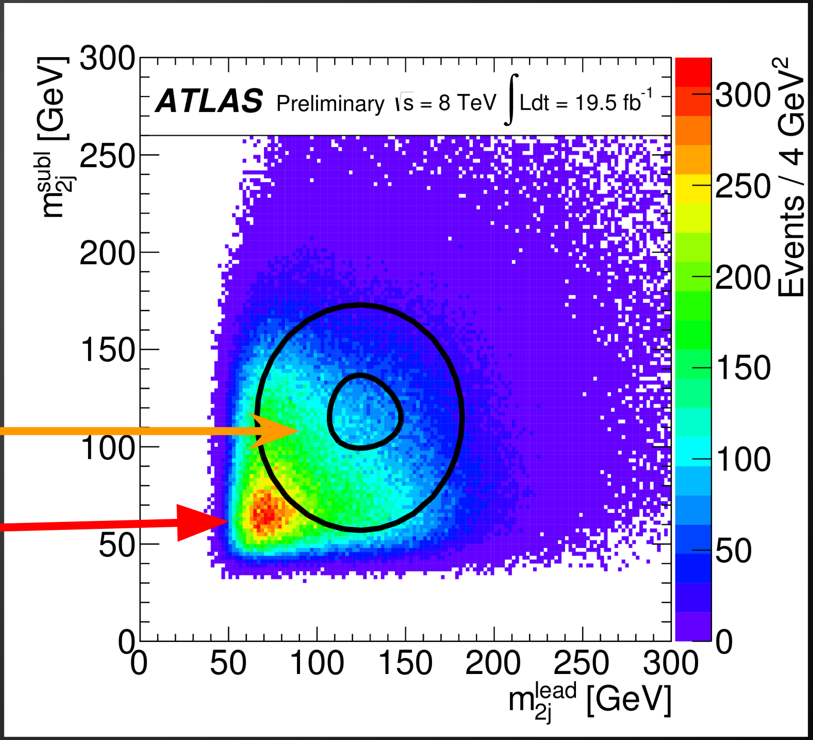
Boosted 4 b-tagged jet background difficult to simulate accurately and precisely

→ Use data to model the background

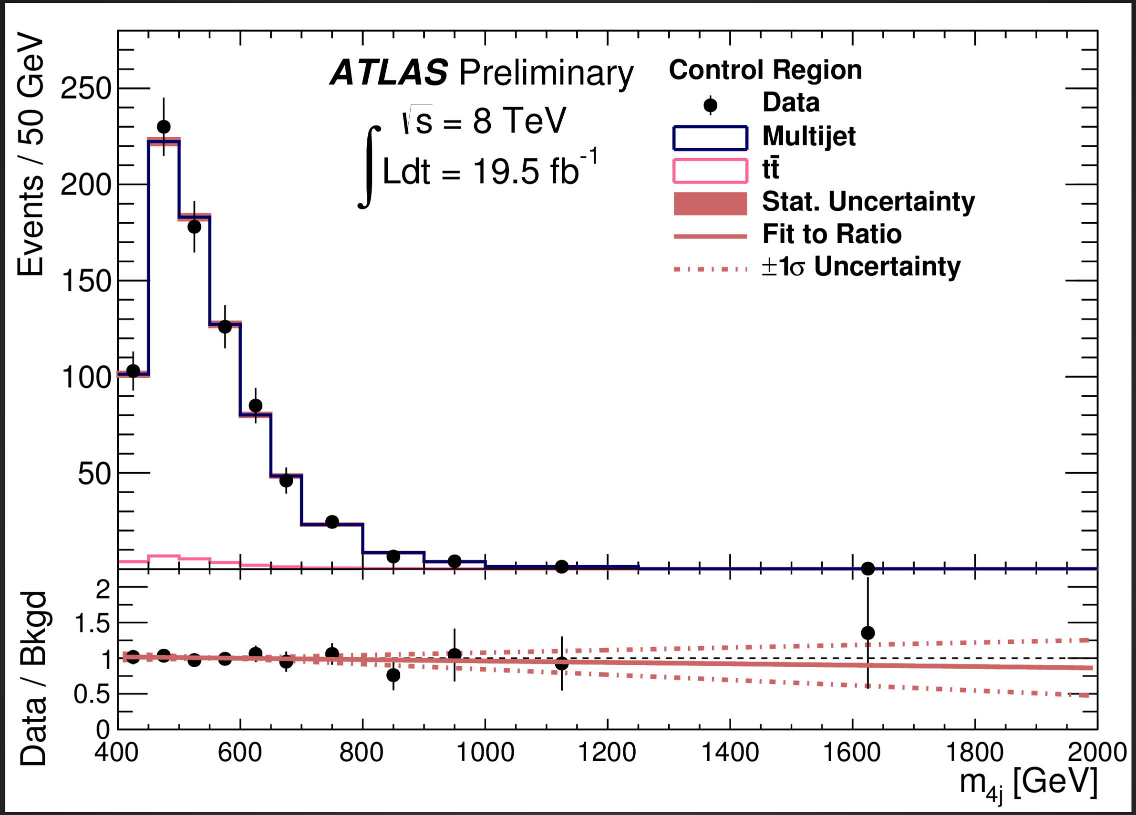
Background events selected using standard requirements **except** only one b-tagged dijet is required

Normalisation and kinematic corrections derived in sideband region

Description validated in control region



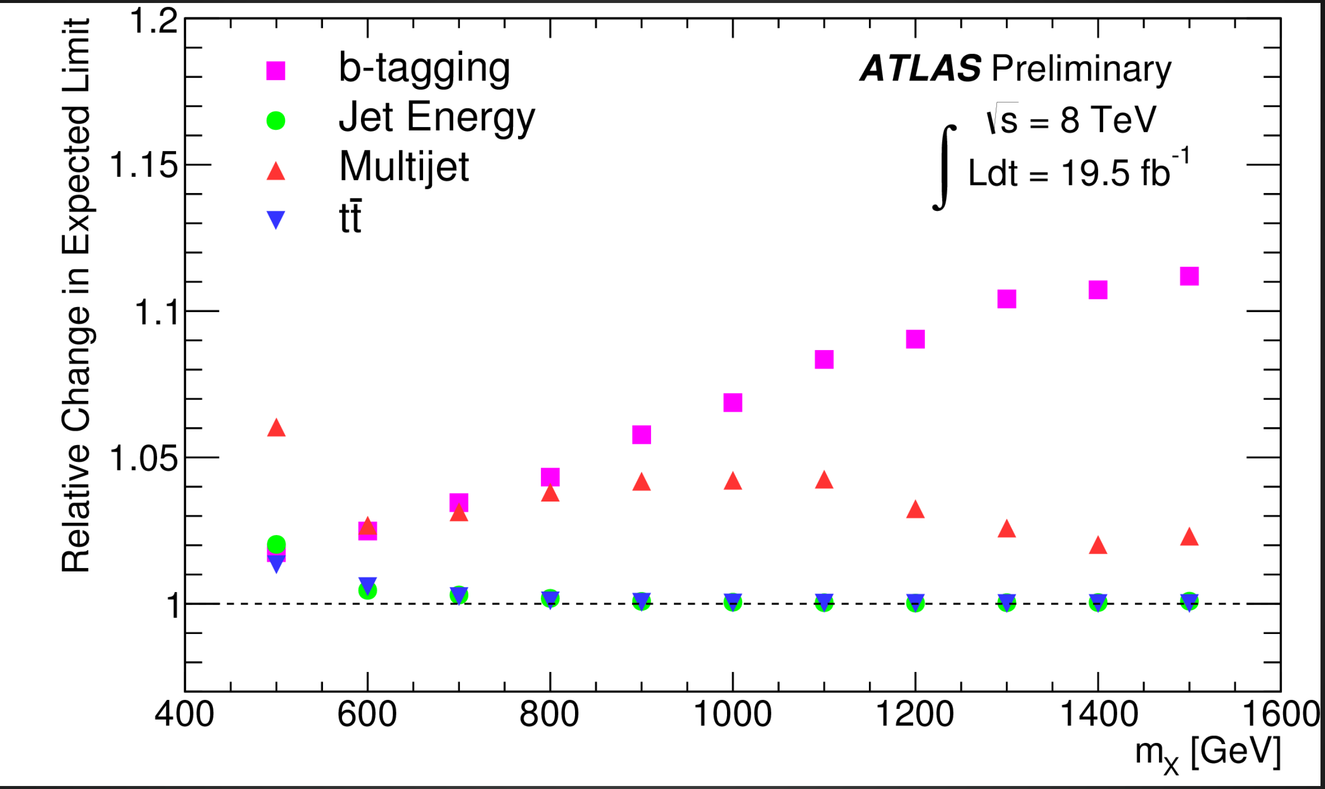
Control Region Validation



Extremely good description of background

Uncertainties set based on comparisons like this

Systematic Uncertainties



Large b-tagging uncertainties for high p_T jets

Calibration performed using ttbar events, with limited statistical precision at high jet p_T

Non-Resonant Results

Sample	Signal Region Yield
Multijet	81.4 ± 4.9
$t\bar{t}$	5.2 ± 2.6
Z+jets	0.4 ± 0.2
Total	87.0 ± 5.6
Data	87
SM hh	0.34 ± 0.01
G^*_{KK} (500 GeV), $k/\bar{M}_{\mathrm{Pl}} = 1$	27 ± 0.8

No excess seen:

SM wins again!

Place 95% C.L. limit on non-resonant Higgs pair production:

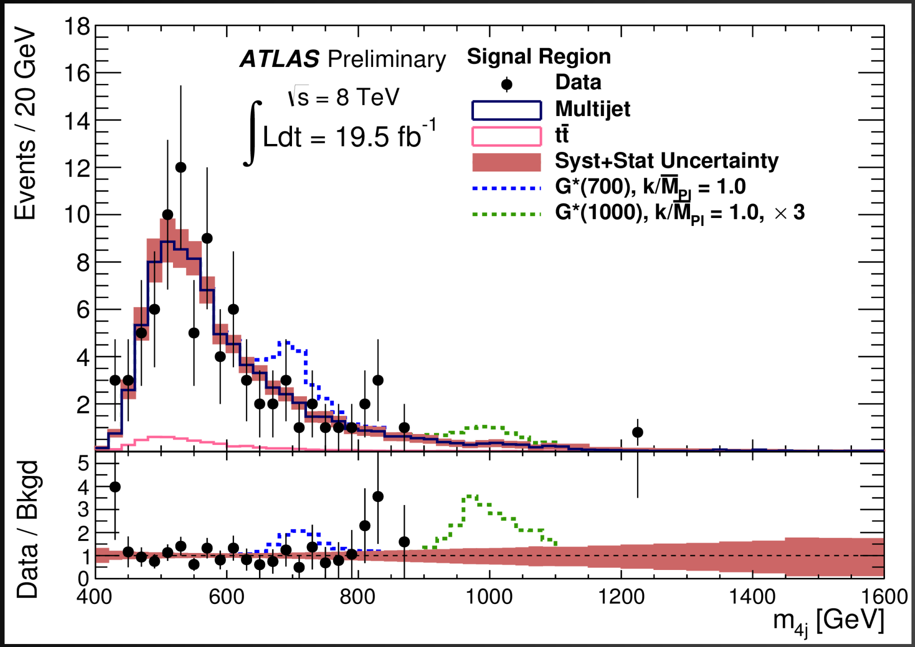
$\sigma(pp \to hh \to bbbb) = 202$ fb

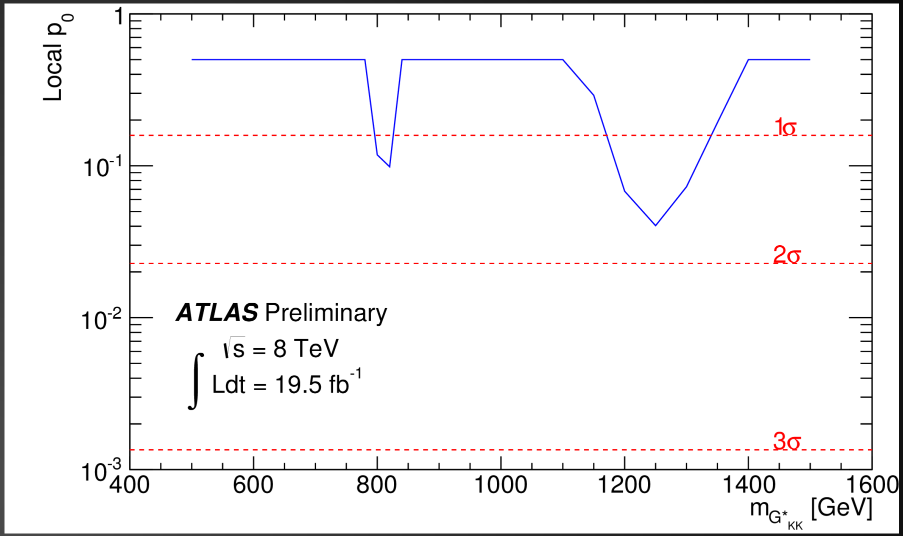
$\mu = \sigma/\sigma_{SM} = 202/(3.6 \pm 0.5) = 57 \pm 8$

World's best limit on non-resonant Higgs pair production!

Only other limit is ATLAS $pp \to hh \to bb\gamma\gamma$: $\mu = 205$

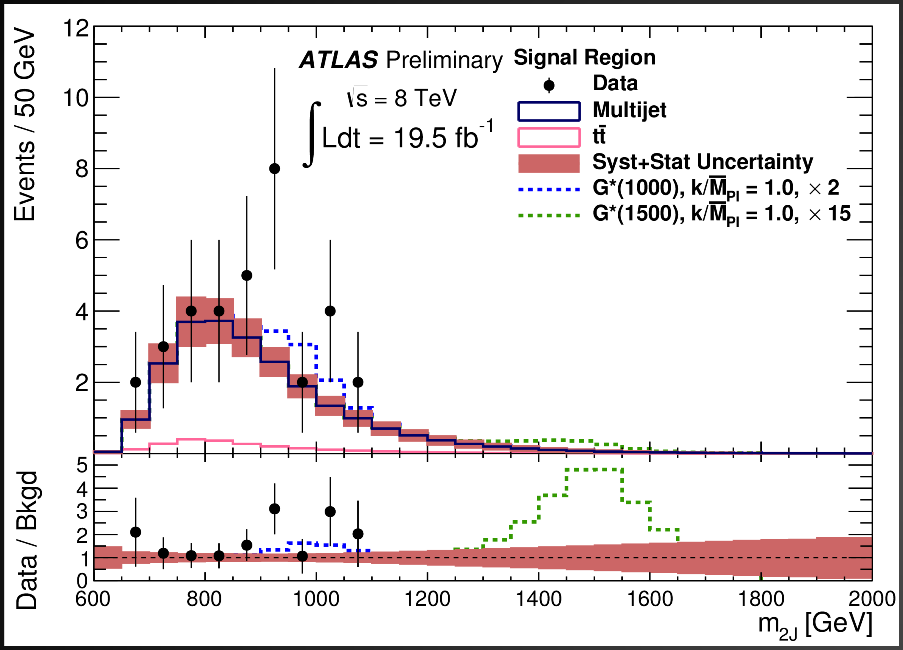
Resonant Results: Resolved

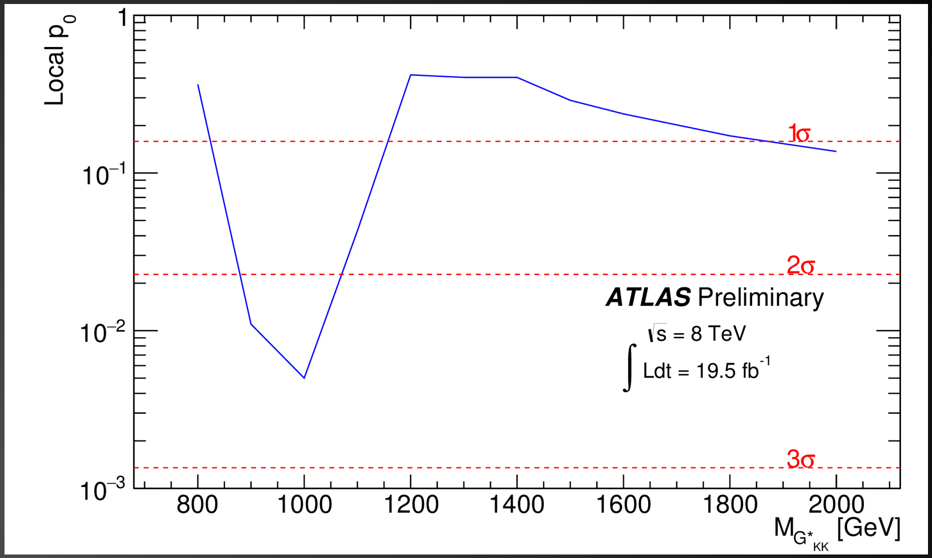




No significant excesses observed

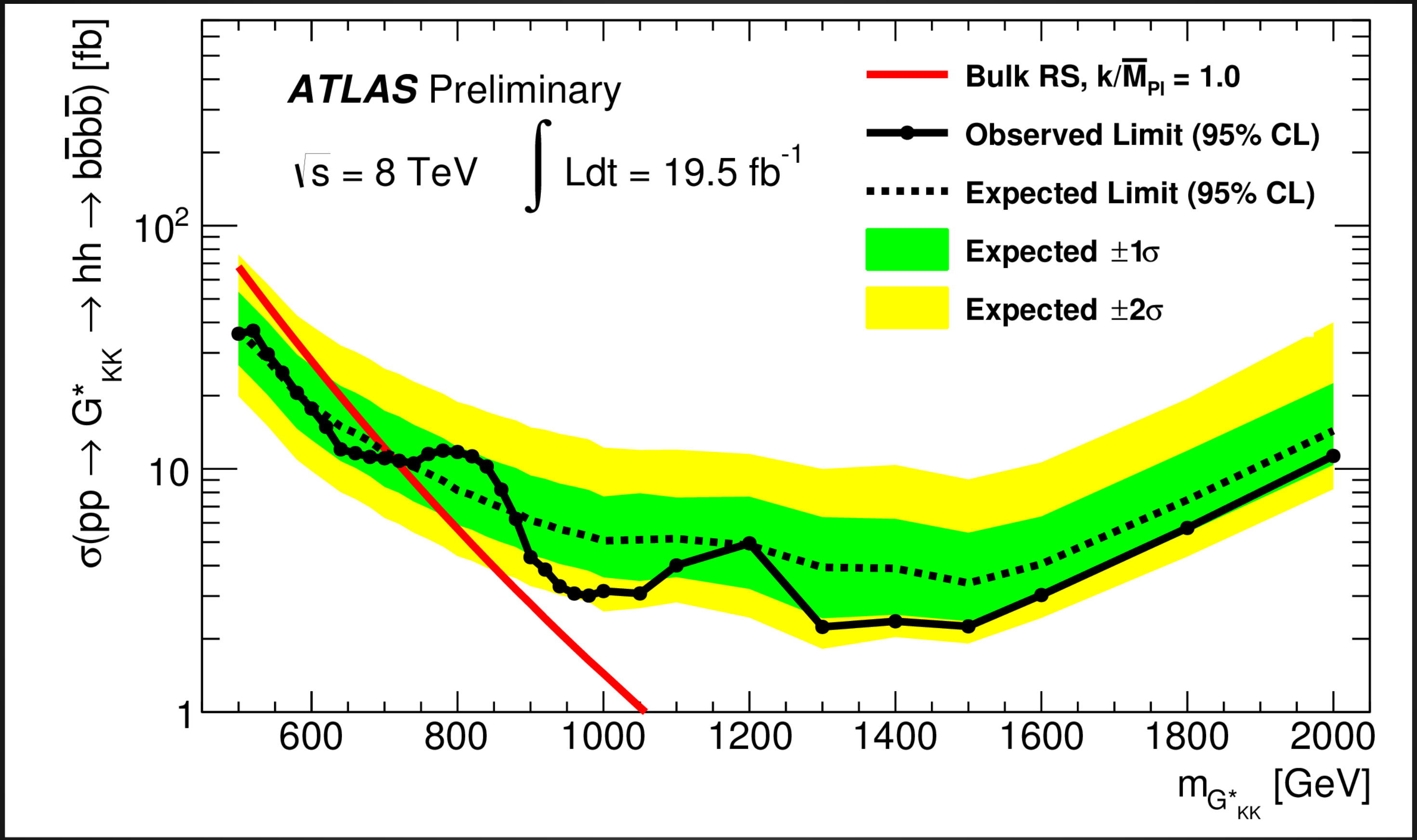
Resonant Results: Boosted





No significant excesses observed here either!

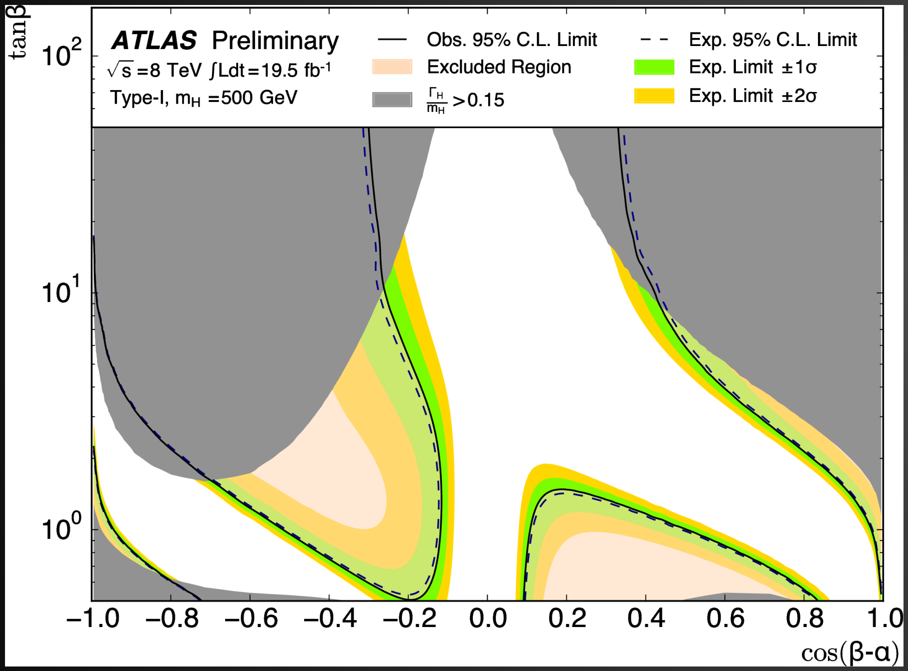
Limits on Bulk RS G_{KK} Models

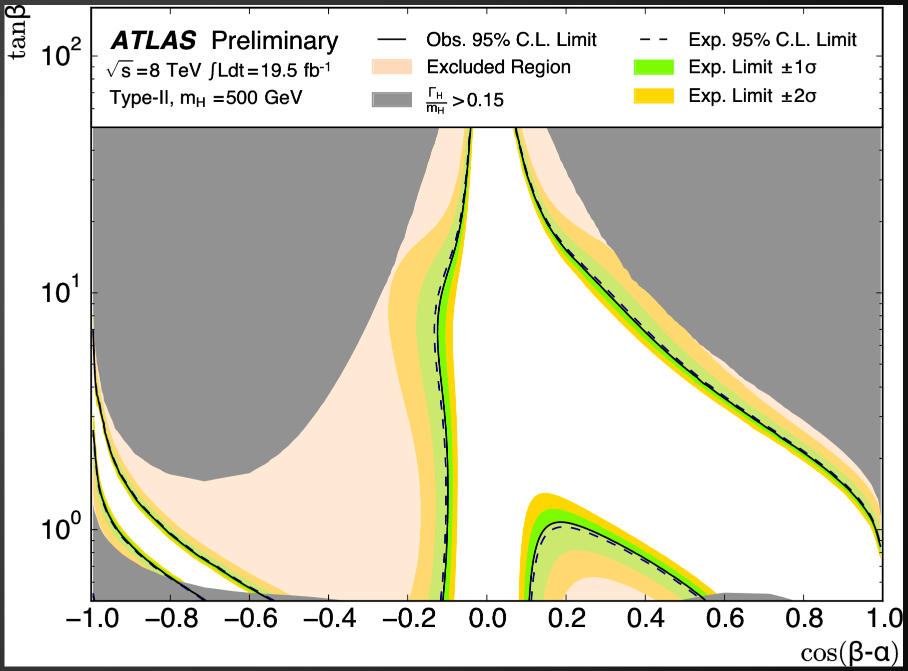


Exclude σ(pp → X → hh → bbbb) ~ 3 fb at m = 1 TeV

Limits on 2HDM

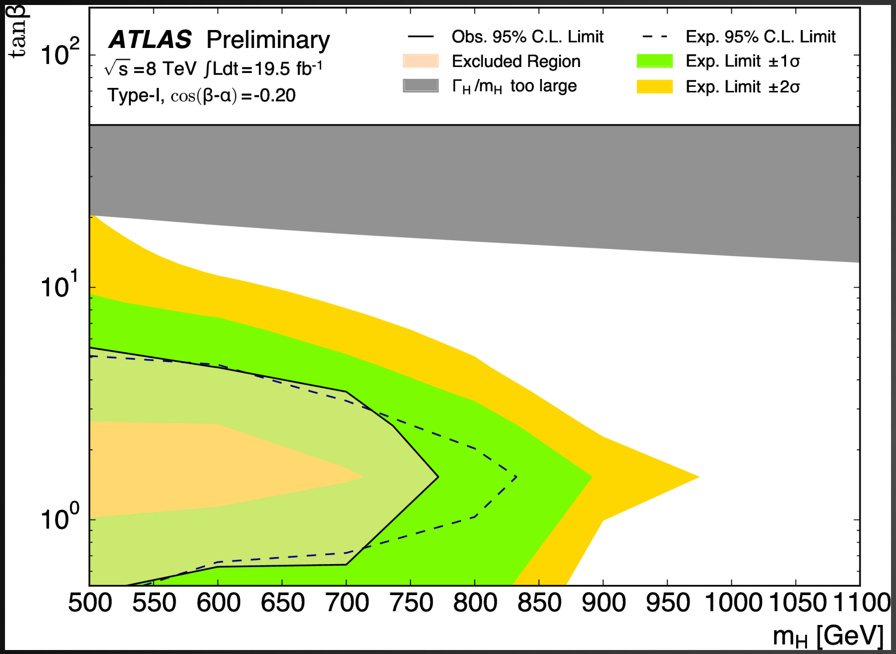
σ(pp → X → hh → bbbb) and Γ_H depend on 2HDM parameters

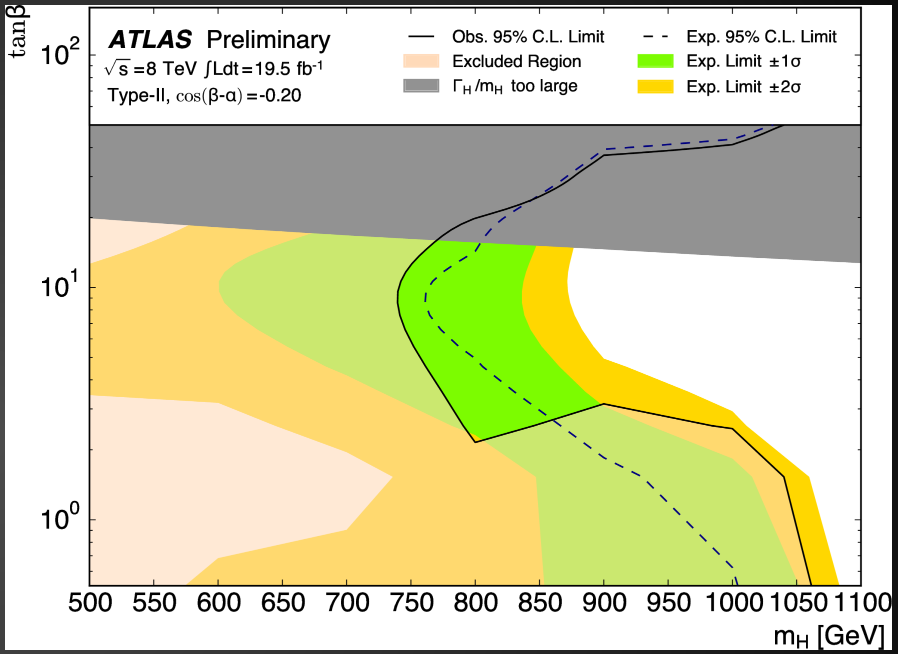




Complementary to other direct searches and Higgs coupling-based exclusions

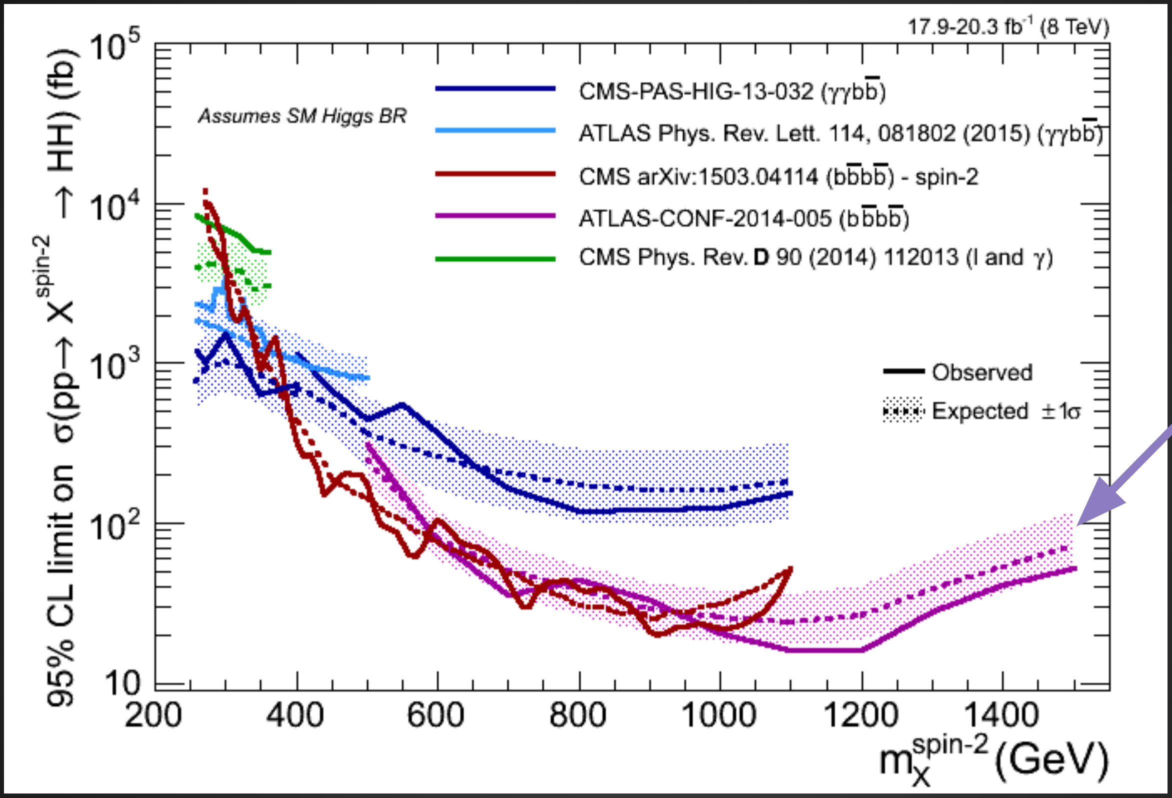
Limits on 2HDM





Exclusions span 500 GeV ≤ m_H ≤ 1000 GeV

Other Di-Higgs Channels Comparison



Credit: Alexandra Carvalho
https://indico.cern.ch/event/302395/session/12/contribution/24/material/slides/0.pdf

This is the old ATLAS CONF result. Limit from paper is significantly better than this!

- Only other di-Higgs channels with public results is γγbb and multileptons (+ photons).
  - Worse than bbbb everywhere except lowest masses.
- Other channels (bbττ and WWγγ) currently being explored.

Expectations for LHC Run-2

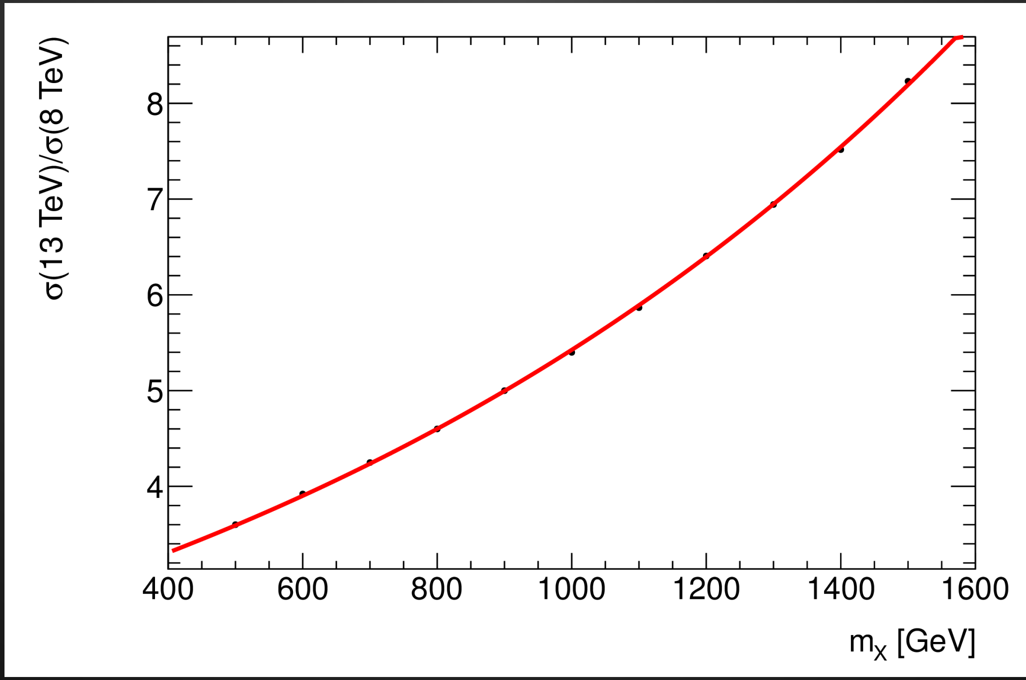
LHC Run-2

LHC will run 2015-2018 at $\sqrt{s}$ = 13 TeV

- Should accumulate $\int L dt$ = 100 fb^{-1}

Cross-sections enhanced due to $\sqrt{s}$ increase

- Unfortunately for both background and signal



Extrapolation for Run-2

Assume signal and backgrounds scale by same f (m_X)

- Close to truth, since both dominated by g-g initial state

Dominant systematic uncertainties are statistically limited

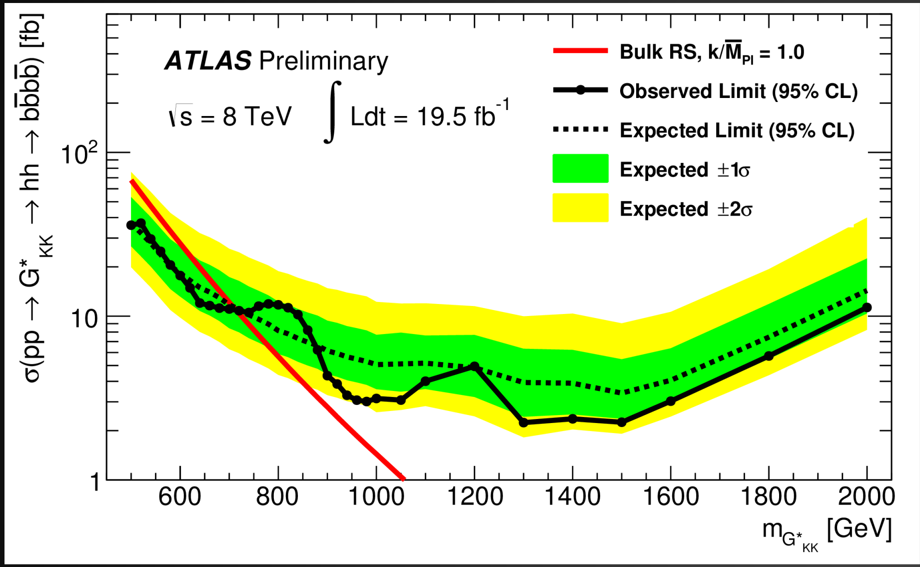
- ⇒scale with luminosity

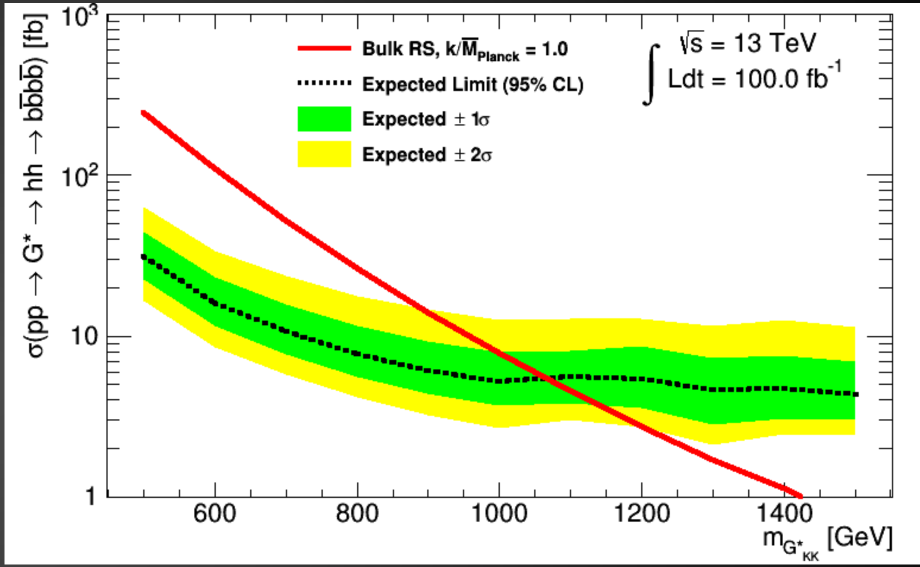
Assume same analysis performance as in Run-1

Conservative, since:

- b-tagging will be improved by new inner tracking layer
- several analysis improvements are foreseen

Run-2 vs Run-1





Extrapolated Run-2 non-resonant limit is

$\mu = \sigma/\sigma_{SM} = 17 \pm 6$

(Run-1 limit was $\mu = 57 \pm 8$)

HL-LHC Studies

Eur. Phys. J. C 75 219, 2015

Non-resonant HH at HL-LHC

High-luminosity upgrade of LHC

- Will run 2025-2035 with 10x higher luminosity
- Will accumulate dataset of $\int Ldt = 3000\ fb^{-1}$

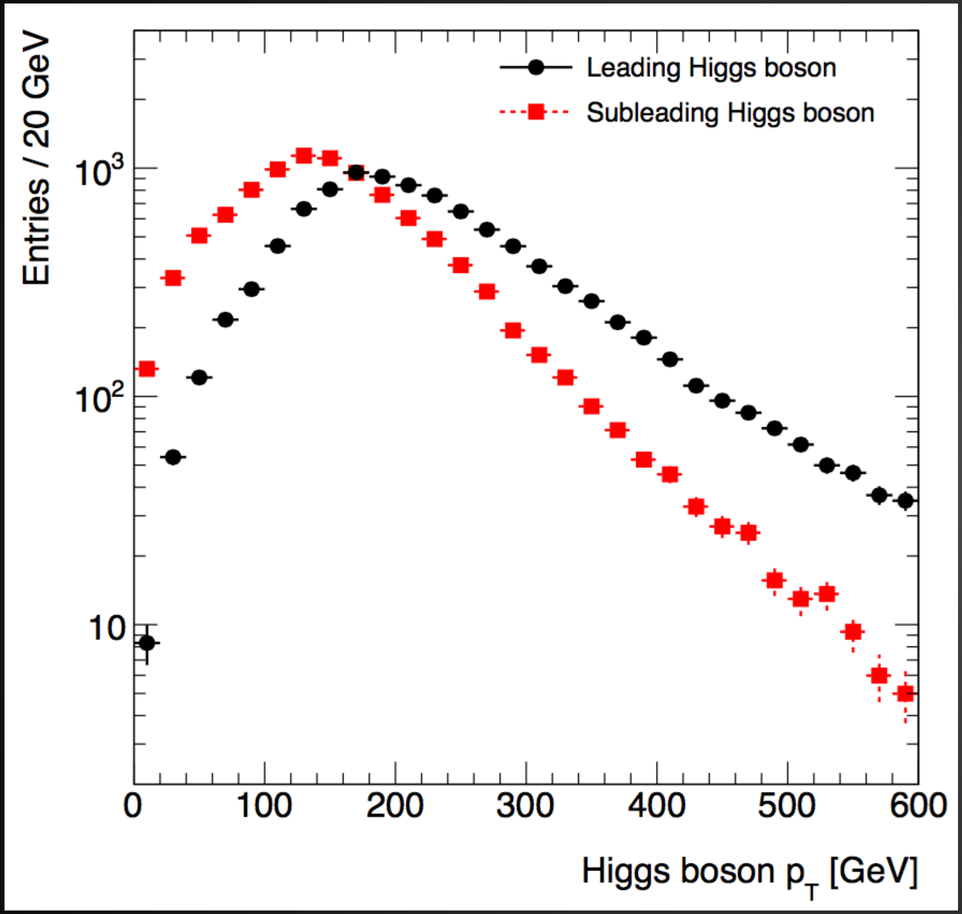
Large dataset needed to observe rare processes

- Like non-resonant Higgs pair production!

Will HL-LHC dataset be enough?

- Evaluate using particle-level study

Higgs Boson p_T



Higgs bosons have sizeable p_T in non-resonant production

36.6% of SM events have both Higgs with p_T > 150 GeV

Dijet Selection

Demand four anti-k_T $R = 0.4$ jets, $p_T > 40$ GeV

Weight events to replicate b-tagging

$\varepsilon_b = 0.7$, $\varepsilon_c = \varepsilon_\tau = 0.2$, $\varepsilon_l = 0.01$

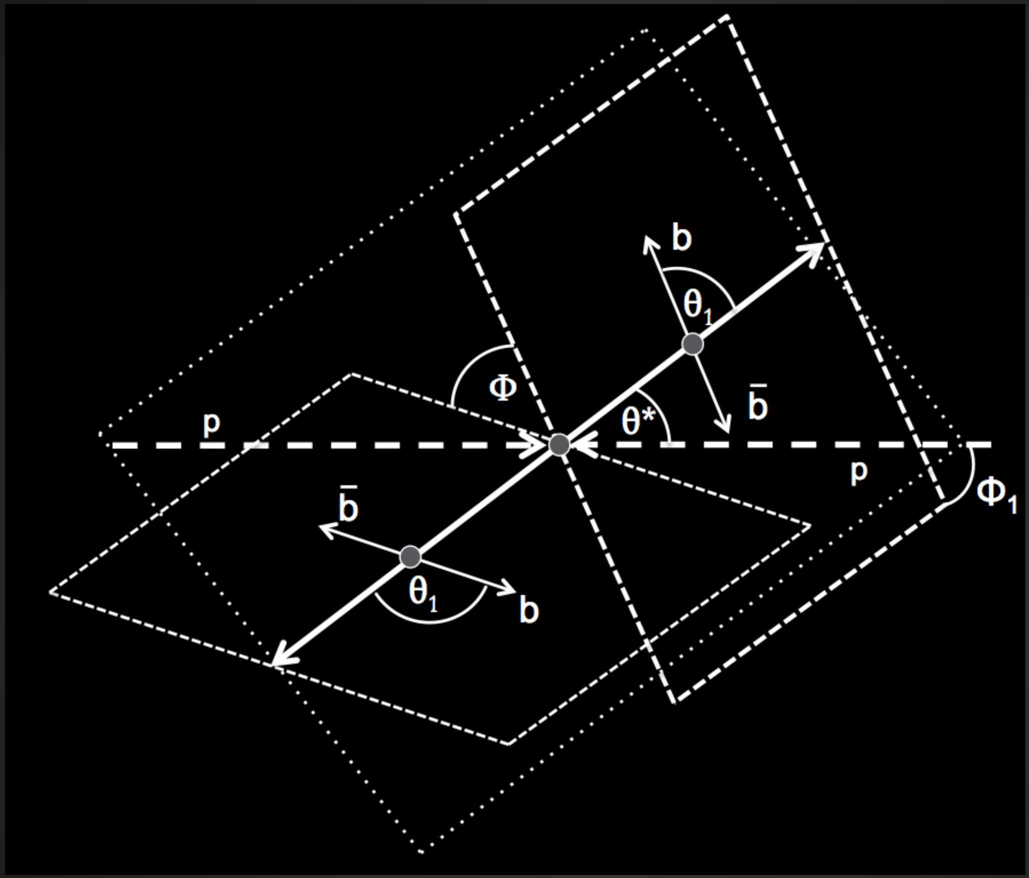
Demand two dijets with $p_T > 150$ GeV and $\Delta R(\text{jet, jet}) < 1.5$

- leading dijet: $100 < m_{lead} < 140$ GeV
- subleading dijet: $85 < m_{subl} < 130$ GeV

Requirement	HH [fb]	$b\bar{b}b\bar{b}$ [fb]	$b\bar{b}c\bar{c}$ [fb]	$t\bar{t}$ [fb]	single-H [fb]	s/b	$s/\sqrt{b}$ (for 3 ab^{-1})
Two dijets	0.30	513	122	290	2.53	3.2×10^{-4}	0.5
m_H windows	0.21	74	17	73	0.65	1.3×10^{-3}	0.9

No chance of observation at this stage of analysis

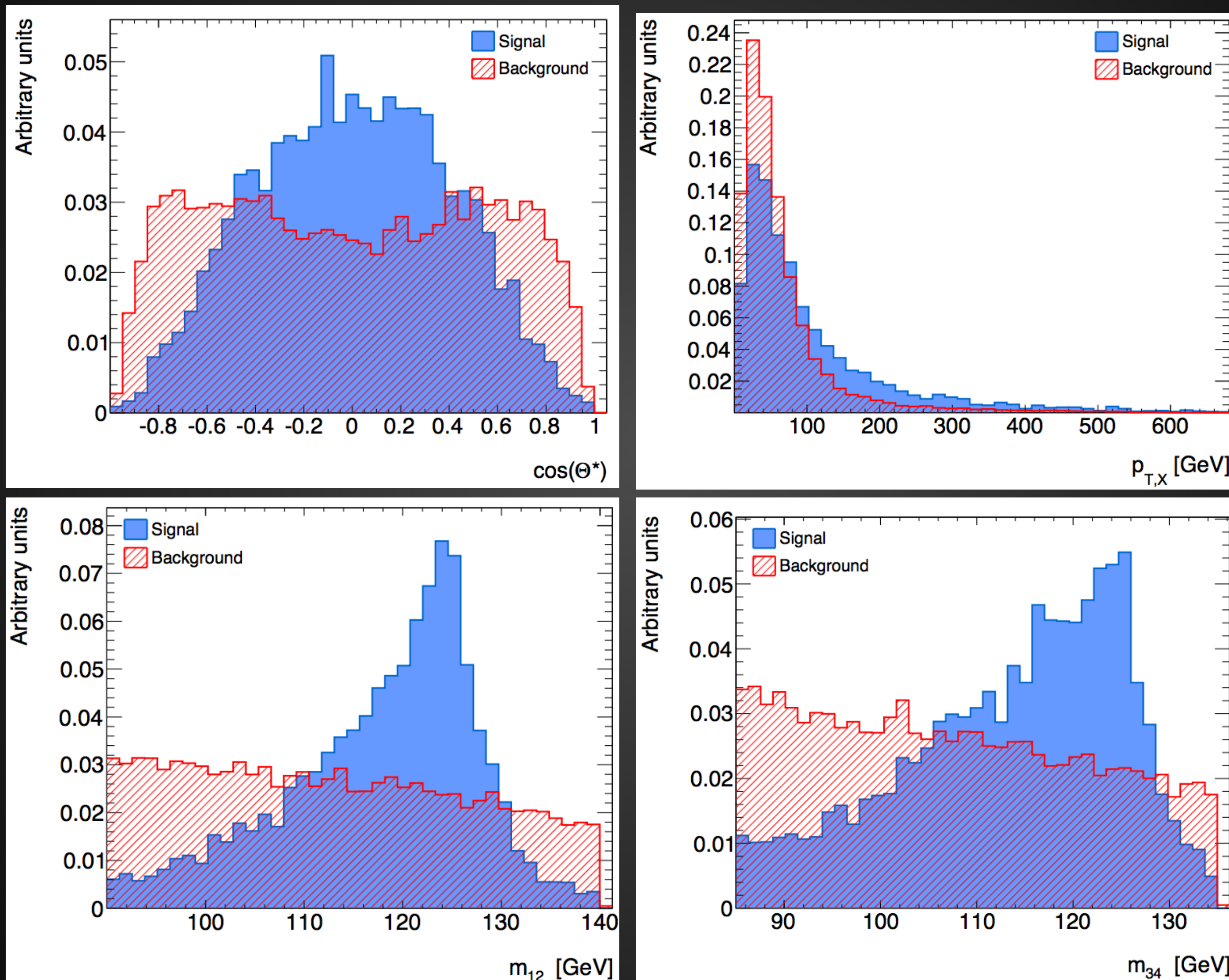
Decay Kinematic Variables



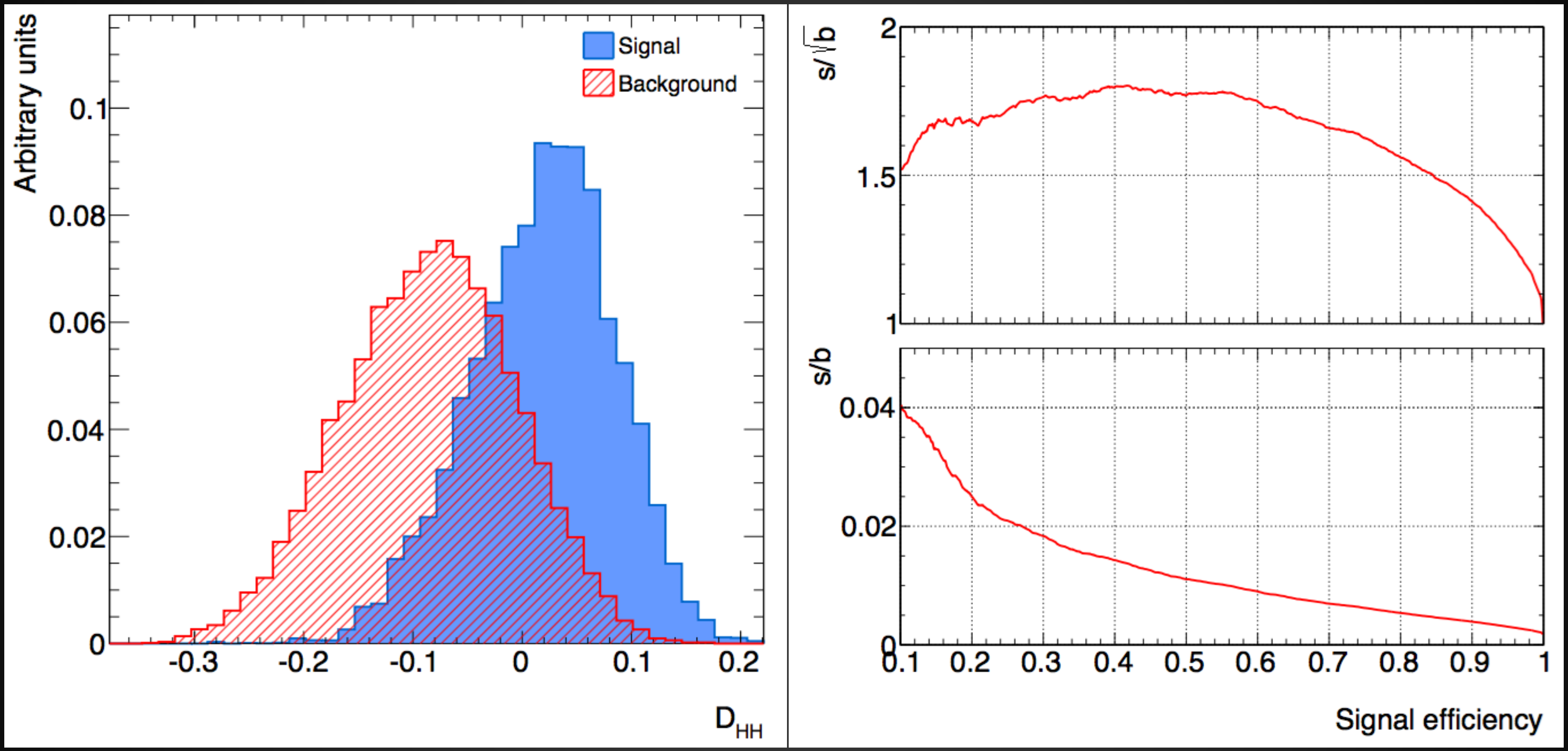
5 angles + 3 masses describe kinematics in rest-frame

Add p_T and y of “resonance” to fully specify system

Best Discriminating Variables



Combined BDT Discriminant



Results

Requirement	HH [fb]	$b\bar{b}b\bar{b}$ [fb]	$b\bar{b}c\bar{c}$ [fb]	$t\bar{t}$ [fb]	single-H [fb]	s/b	$s/\sqrt{b}$ (for 3 ab^{-1})
Two dijets	0.30	513	122	290	2.53	3.2×10^{-4}	0.5
m_H windows	0.21	74	17	73	0.65	1.3×10^{-3}	0.9
Top veto	0.19	67	15	29	0.33	1.7×10^{-3}	1.0
$\mathcal{D}_{HH}$	0.08	2.8	0.6	2.6	0.05	1.3×10^{-2}	1.8
$\epsilon^{b}_{c/\tau-\text{jet}} = 10\%$	0.06	1.5	0.1	1.0	0.04	2.4×10^{-2}	2.1
BDRS analysis	0.06	11.8	1.4	6.8	0.06	3.0×10^{-3}	0.7

Reach a significance of 1.8σ with full dataset

- Could have 3σ evidence if combined with other hh channels!
- Could combine with CMS searches too
- Potential to improve 4b sensitivity further

We should observe SM non-resonant Higgs pair production at HL-LHC

- Investigate VBF production for information on coupling

Conclusions

Keep looking and keep pushing!

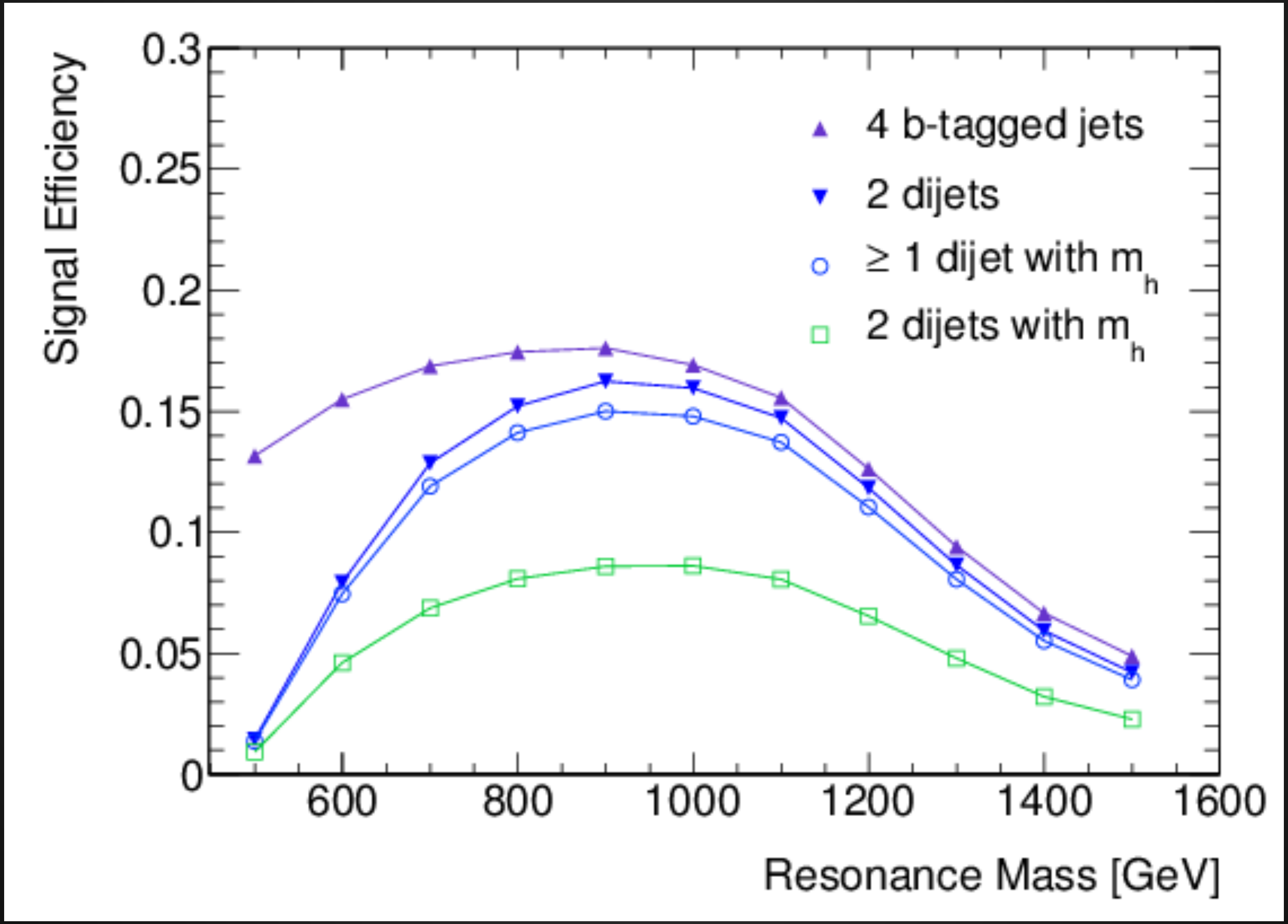
- Higgs boson pair production is interesting!
  - Many new physics models predict enhanced rates.
  - Even if there’s no new physics, it exists in the SM.
  - Can answer whether SM has a vanilla Higgs sector or something more complicated.

- Our hh→4b analysis was the first ever search for resonant di-Higgs production in the ~1 TeV range.
  - We have shown that this is the channel to search for new di-Higgs resonances above ~500 GeV (and even lower?)
  - Nothing there yet, but will push this further in Run-2...

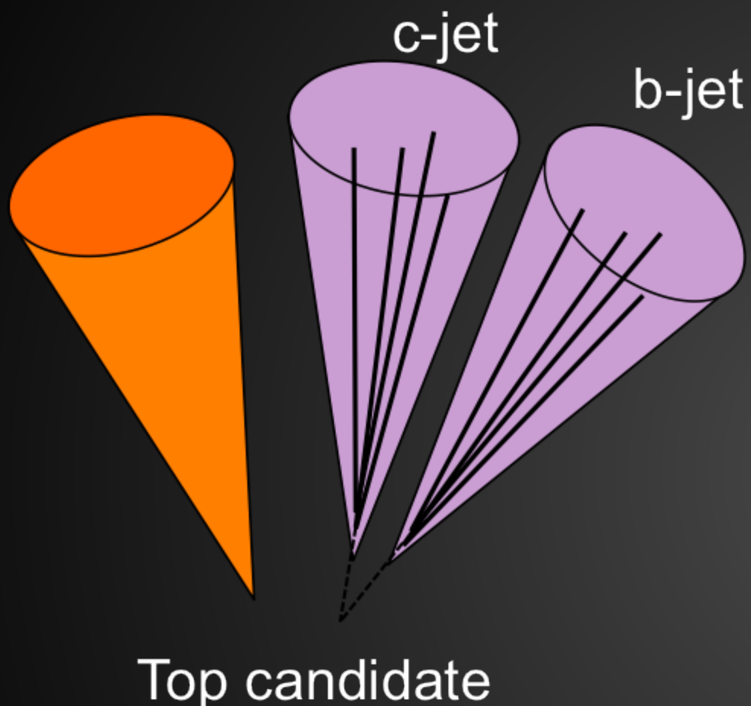
- Can significantly improve the chances of observing non-resonant SM production
  - Could be a real game changer for the physics reach of the HL-LHC!

Additional Slides

Signal Efficiency in Resonant Pheno



Top Veto



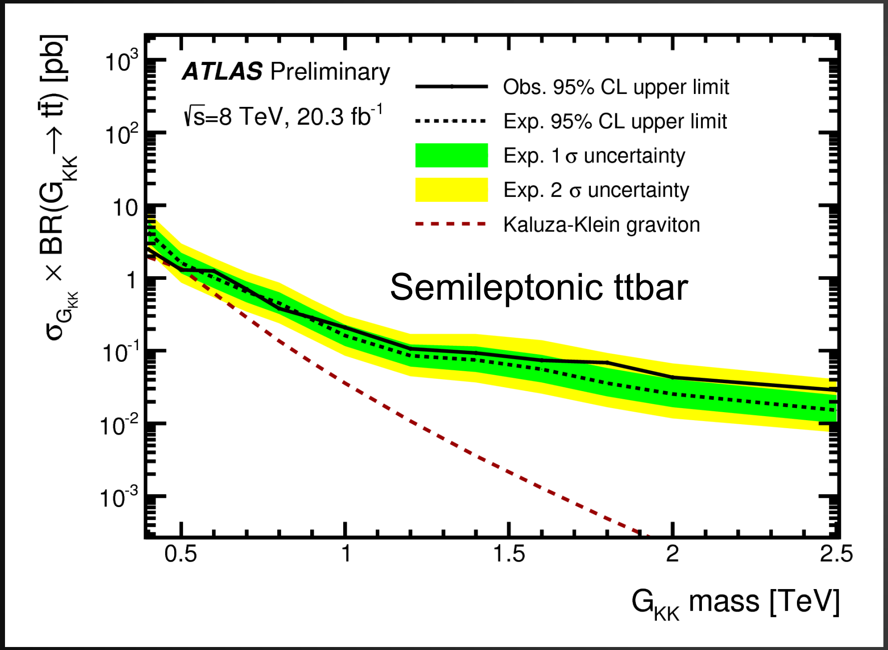
Top events ~ 10% of total background

Reject events if top candidate can be formed:

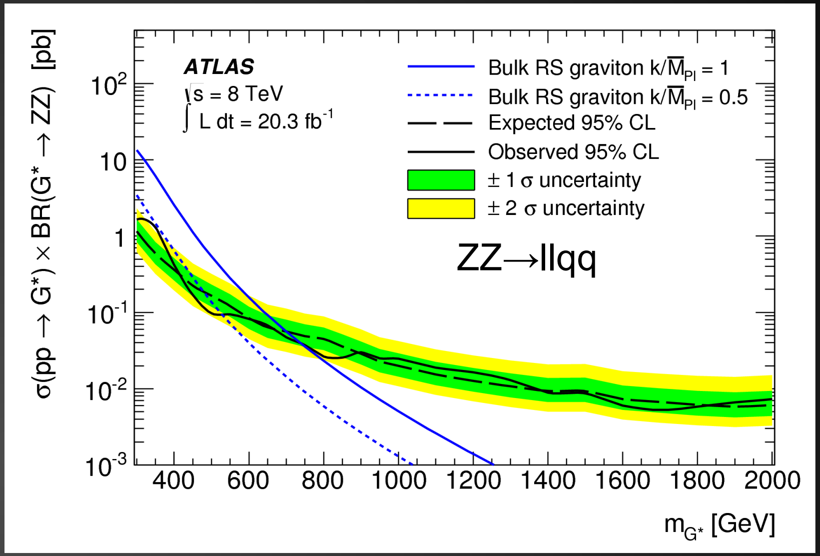
1. Combine dijets with "extra jets"
2. Reject if $m_{3j} \sim m_t$ and m ("c-jet", extra) $\sim m_W$

Other Run-1 Searches for G_{KK}

ATLAS-CONF-2015-009



EPJC 2015 75:69



EPJC 2015 75:209