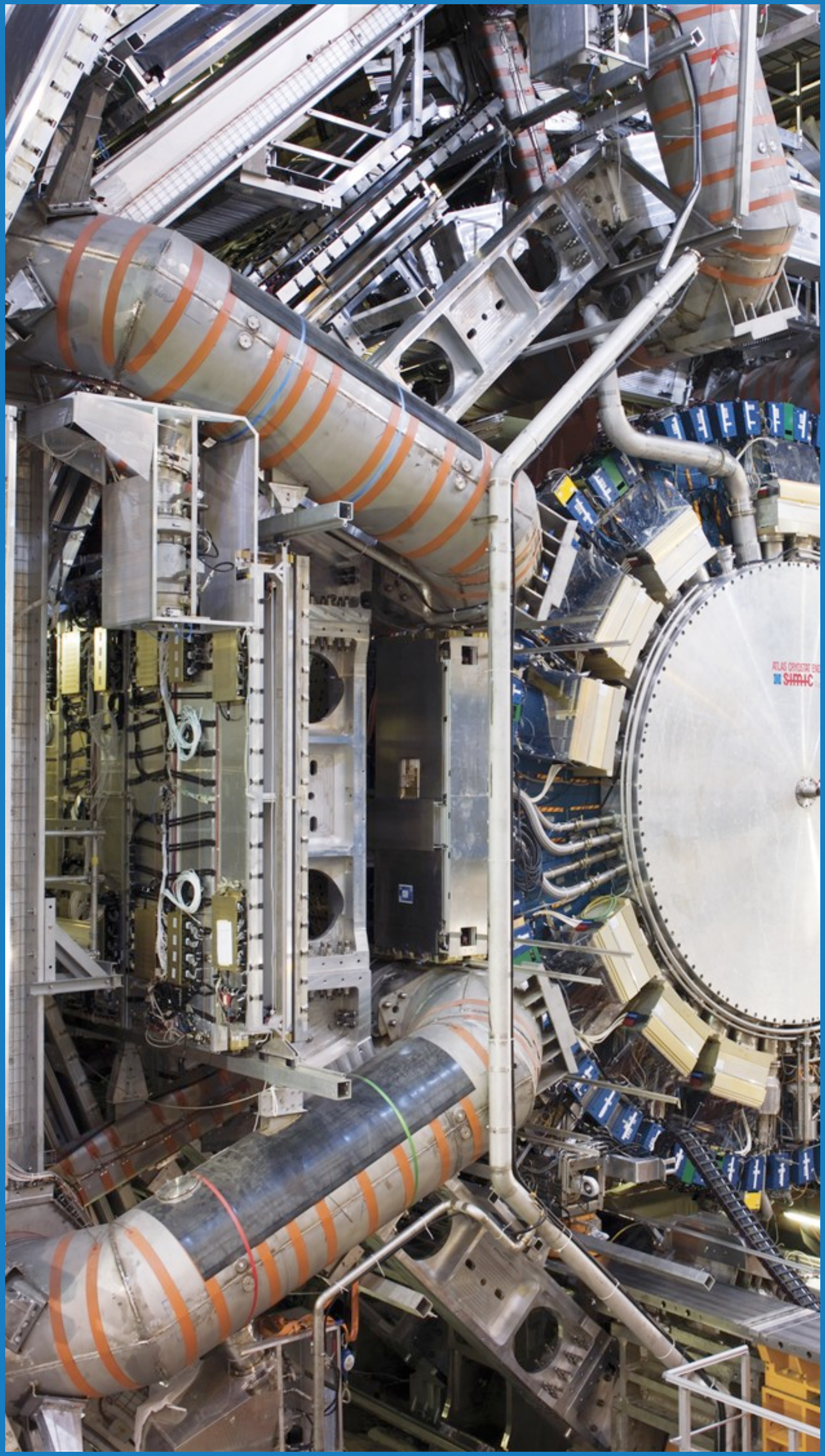
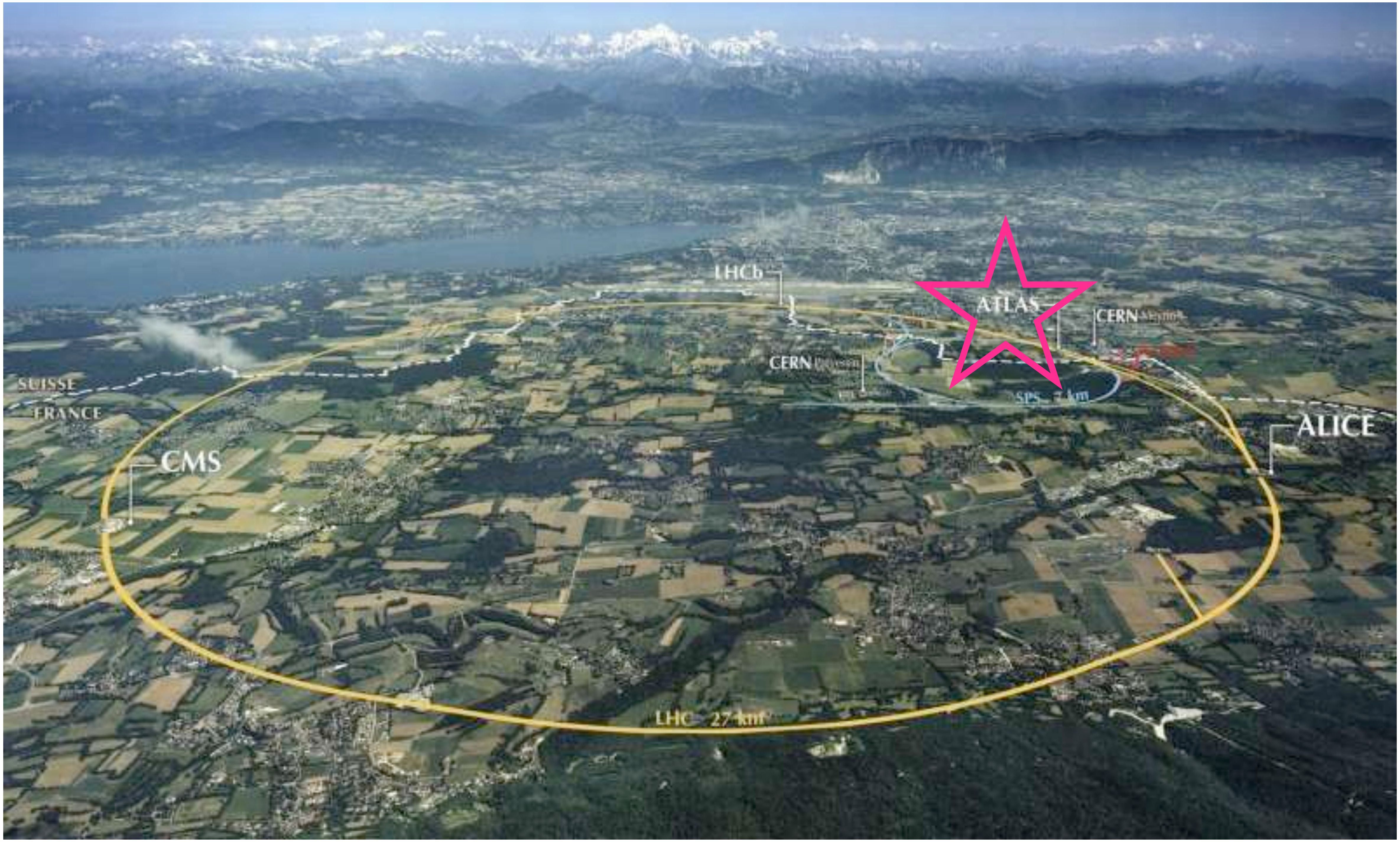


SEARCHING FOR DI-HIGGS PRODUCTION WITH THE ATLAS DETECTOR

Elizabeth Brost
Northern Illinois University

THE LHC


LHCb
ATLAS
CERN
CERN
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

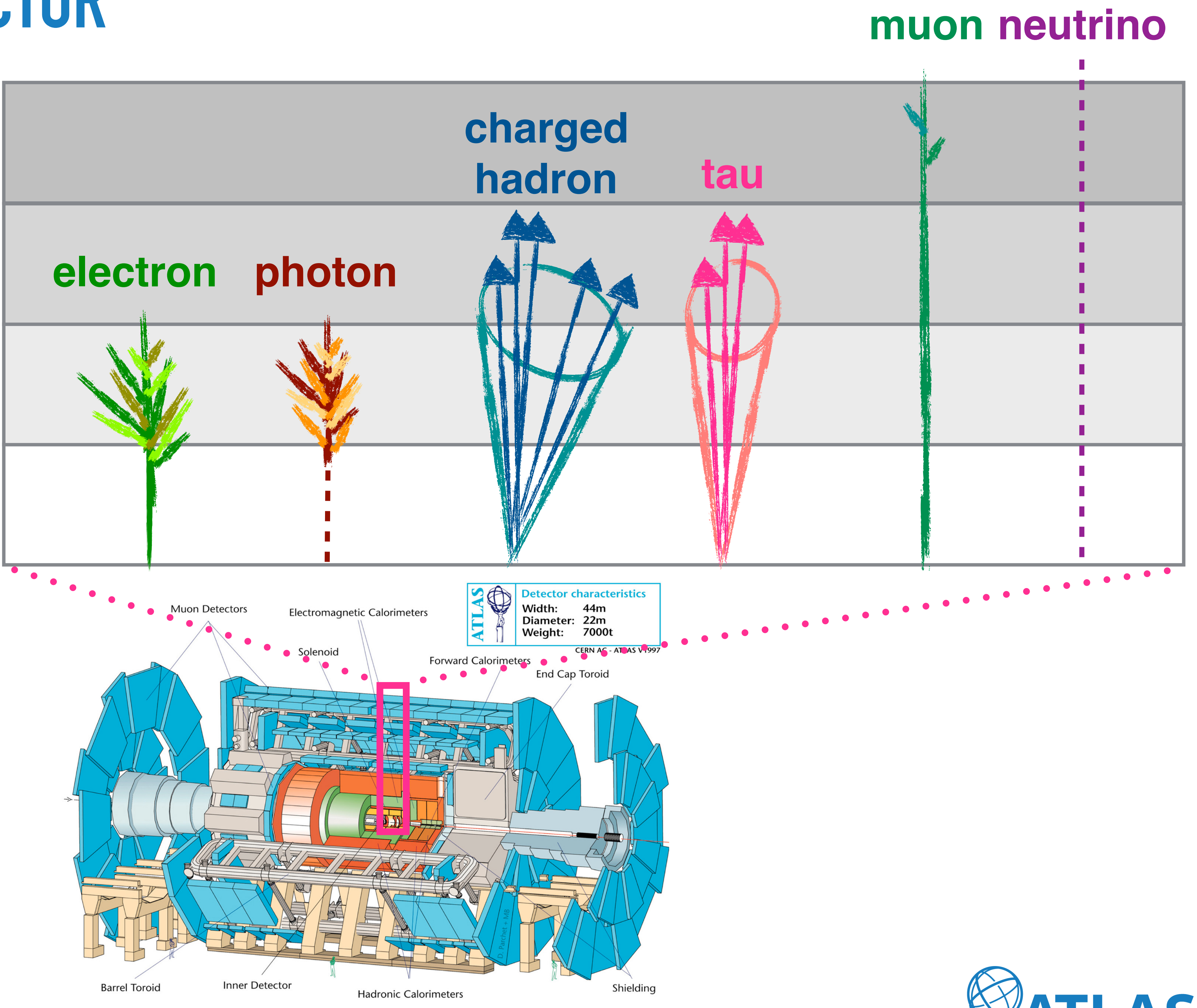
THE ATLAS DETECTOR

muon system

hadron calorimeter

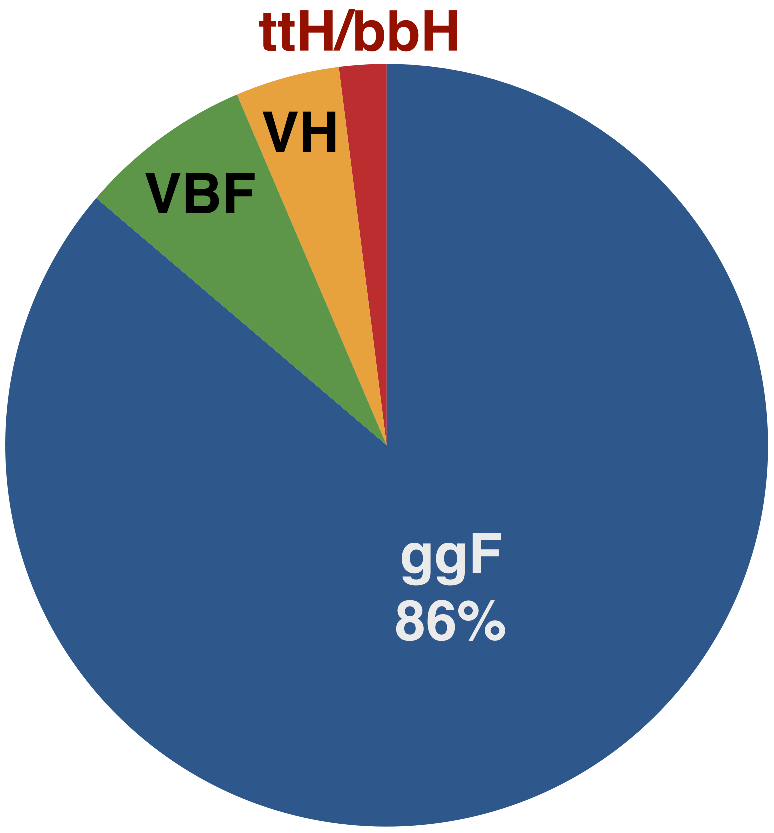
EM calorimeter

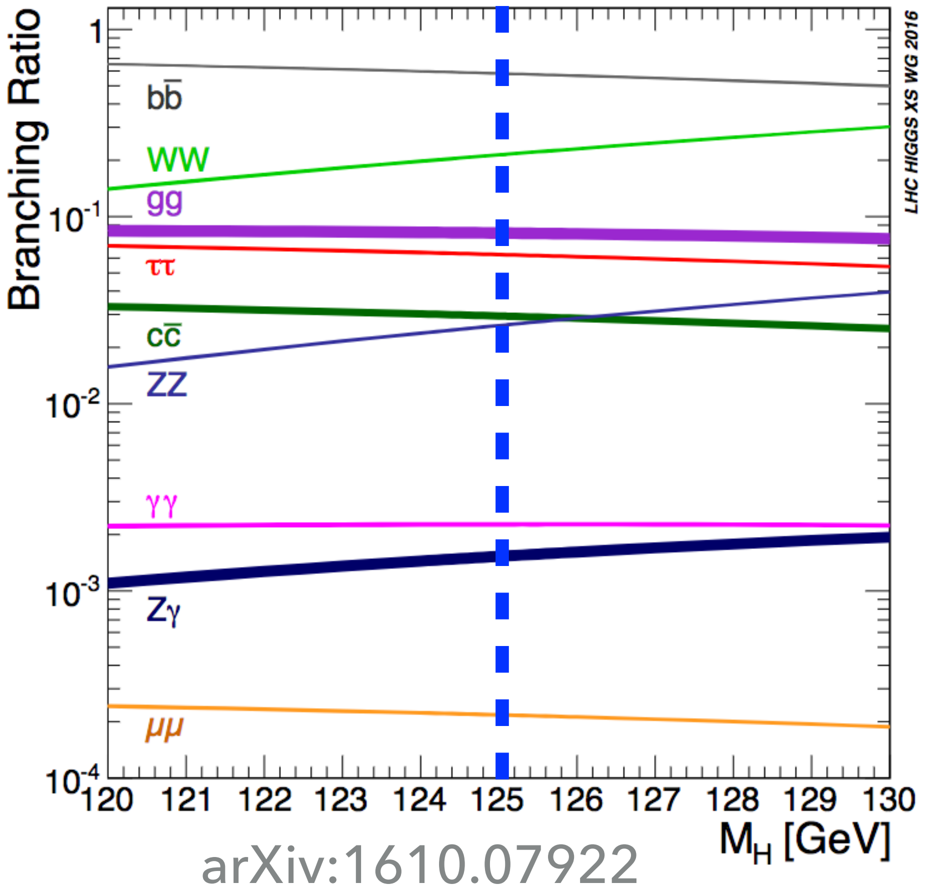
inner detector



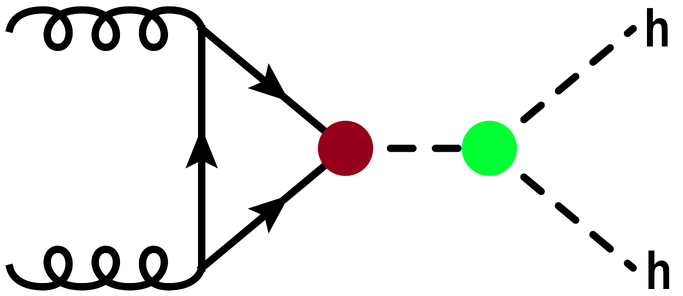
THE HIGGS BOSON

- Discovered in 2012 at the LHC – mass: 125.09 GeV – spin: 0
- Main production mode: gluon-gluon fusion
- Couples to itself – unique chance to probe electroweak symmetry-breaking (Higgs potential) – if we can observe it!



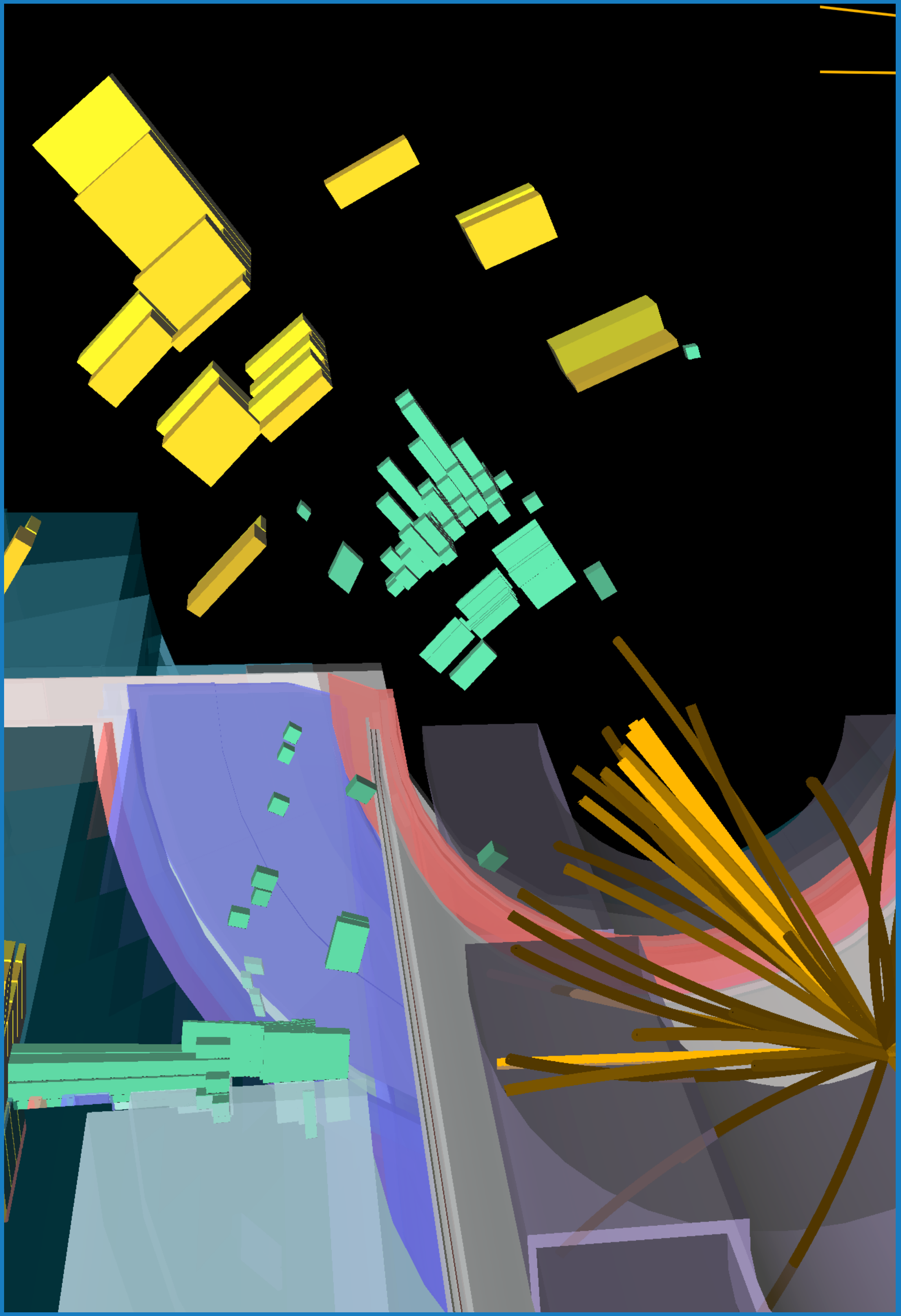


arXiv:1610.07922



OUTLINE

- Searching for di-Higgs production
- Data collection for di-Higgs searches
- Object and event selection
- Results of di-Higgs searches and combination
- Prospects for di-Higgs searches at the HL-LHC

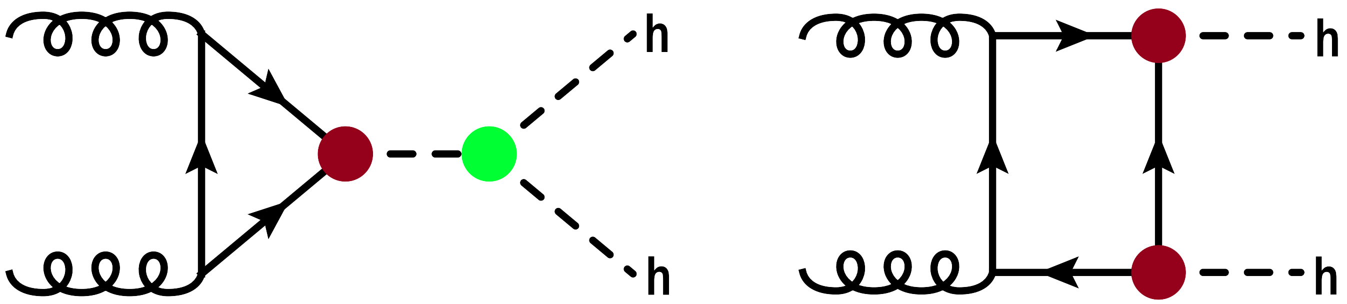


SEARCHING FOR DI-HIGGS PRODUCTION

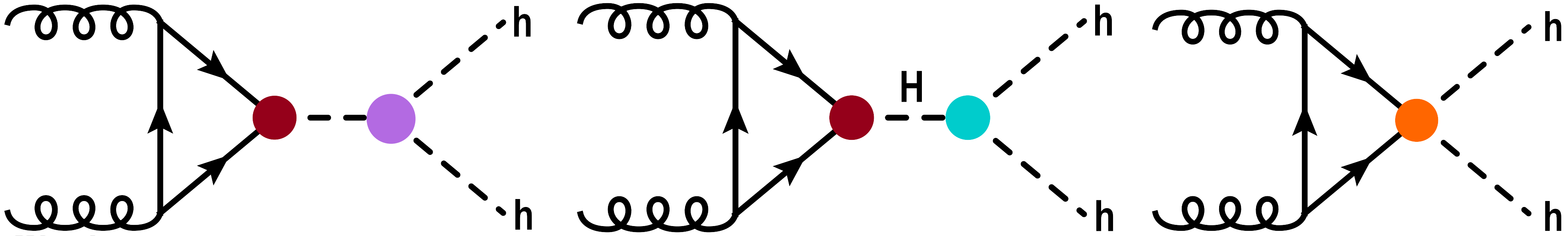
ATLAS EXPERIMENT

SM AND BSM DI-HIGGS PRODUCTION

- **Standard Model:** small! ggF σ(HH) = 33.41 fb @ 13 TeV
  - \+ destructive interference between processes involving Higgs self-coupling and box-diagram with two ttH vertices

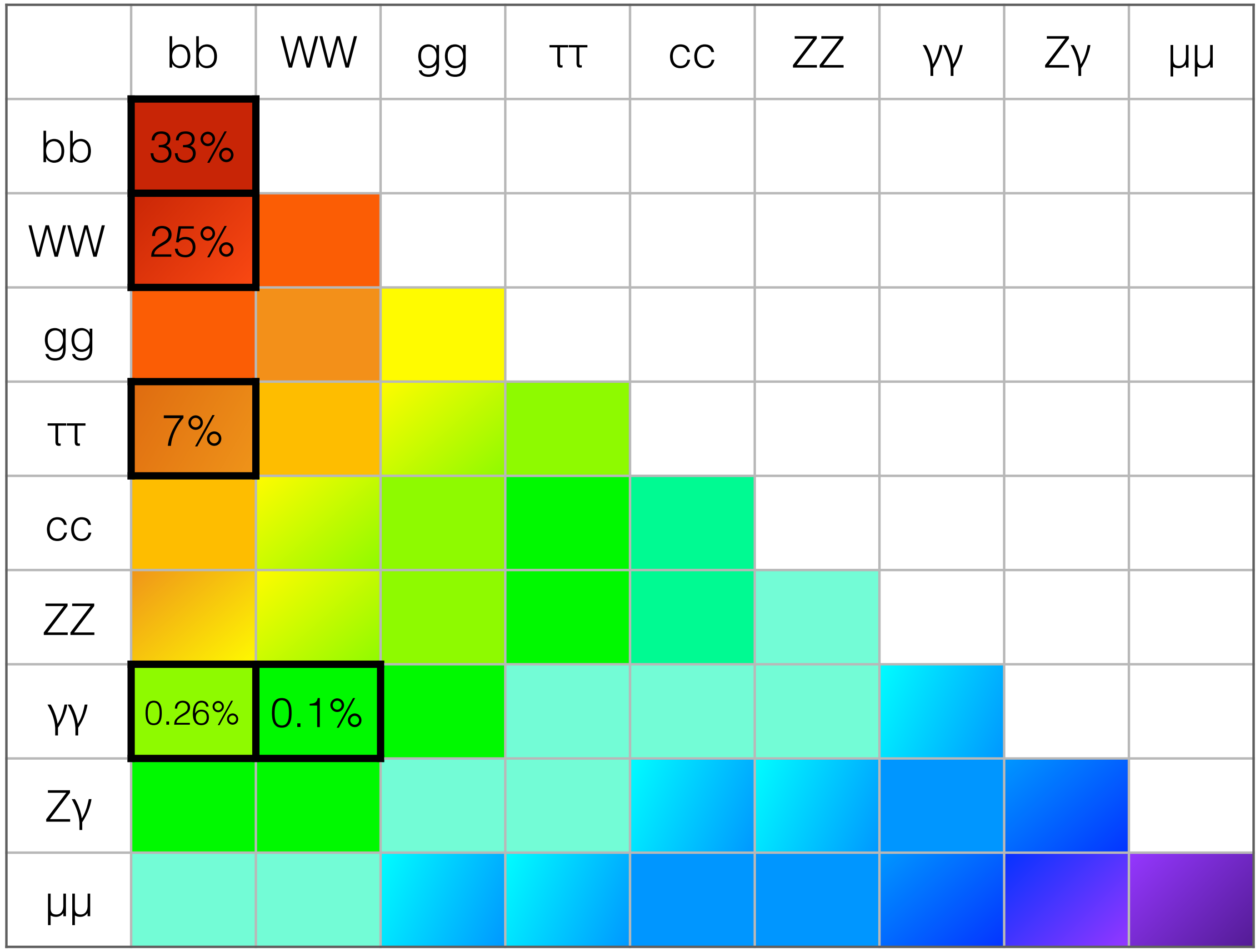


- **Beyond the Standard Model:** possible enhancements?
  - top quark Yukawa enhancements? enhanced self-coupling? resonant production via a heavy scalar? addition of a ttHH vertex?



HOW TO SEARCH FOR HH AT ATLAS

BR(HH → XXYY)

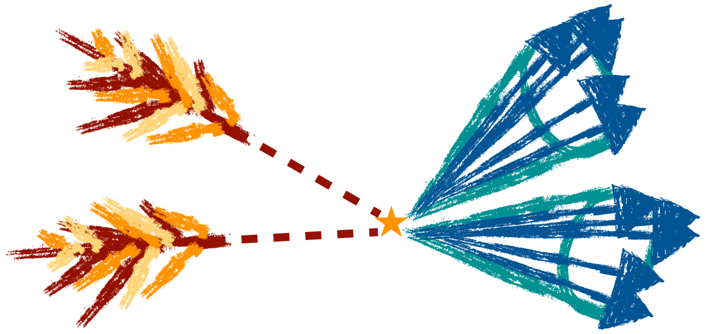


	bb	WW	gg	ττ	cc	ZZ	γγ	Zγ	μμ
bb	33%								
WW	25%								
gg									
ττ	7%								
cc									
ZZ									
γγ	0.26%	0.1%							
Zγ									
μμ									

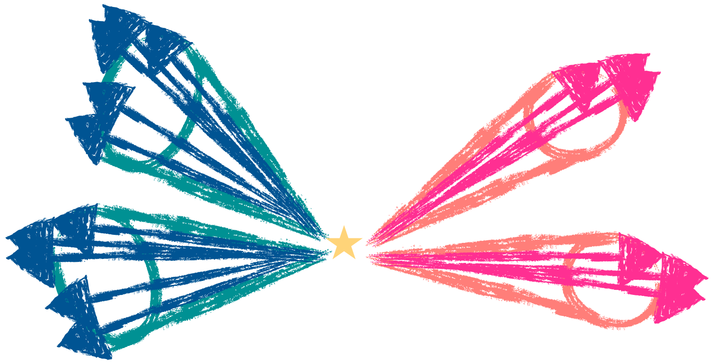
☐ = di-Higgs channel covered by ATLAS

in this talk, focus on:

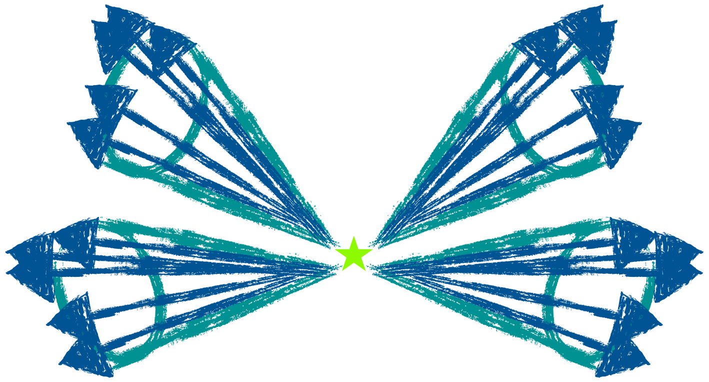
HH → γγbb



HH → bbττ



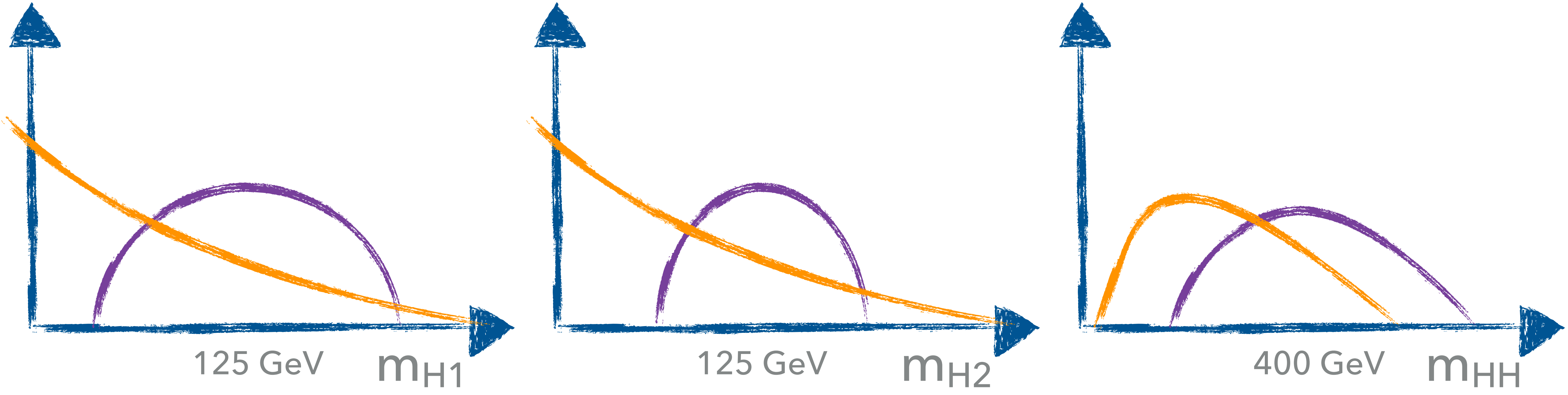
HH → bbbb



+ combination

DISCRIMINANT VARIABLES

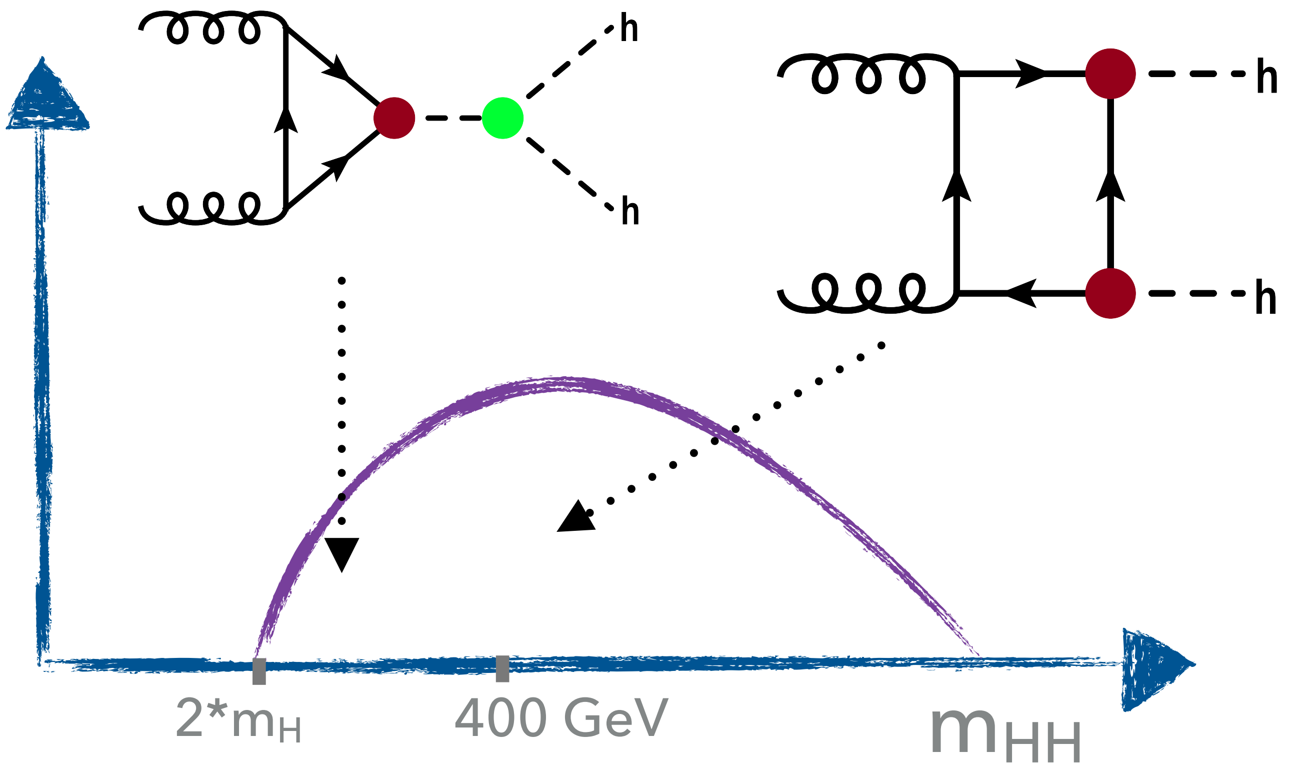
The Higgs masses, m_{H1} and m_{H2}, and the four-body mass, m_{HH} can be used to discriminate between signal and background:

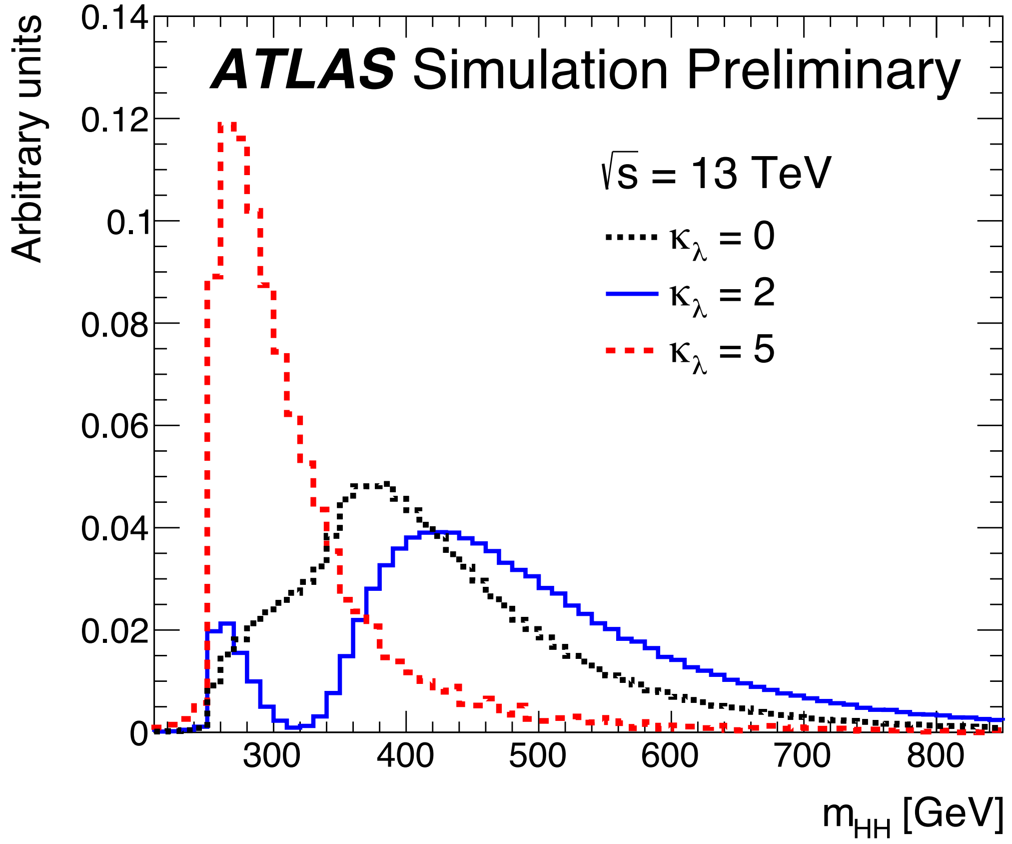


The resolution of the signal mass peak and the relative normalization of the signal and background vary greatly per channel

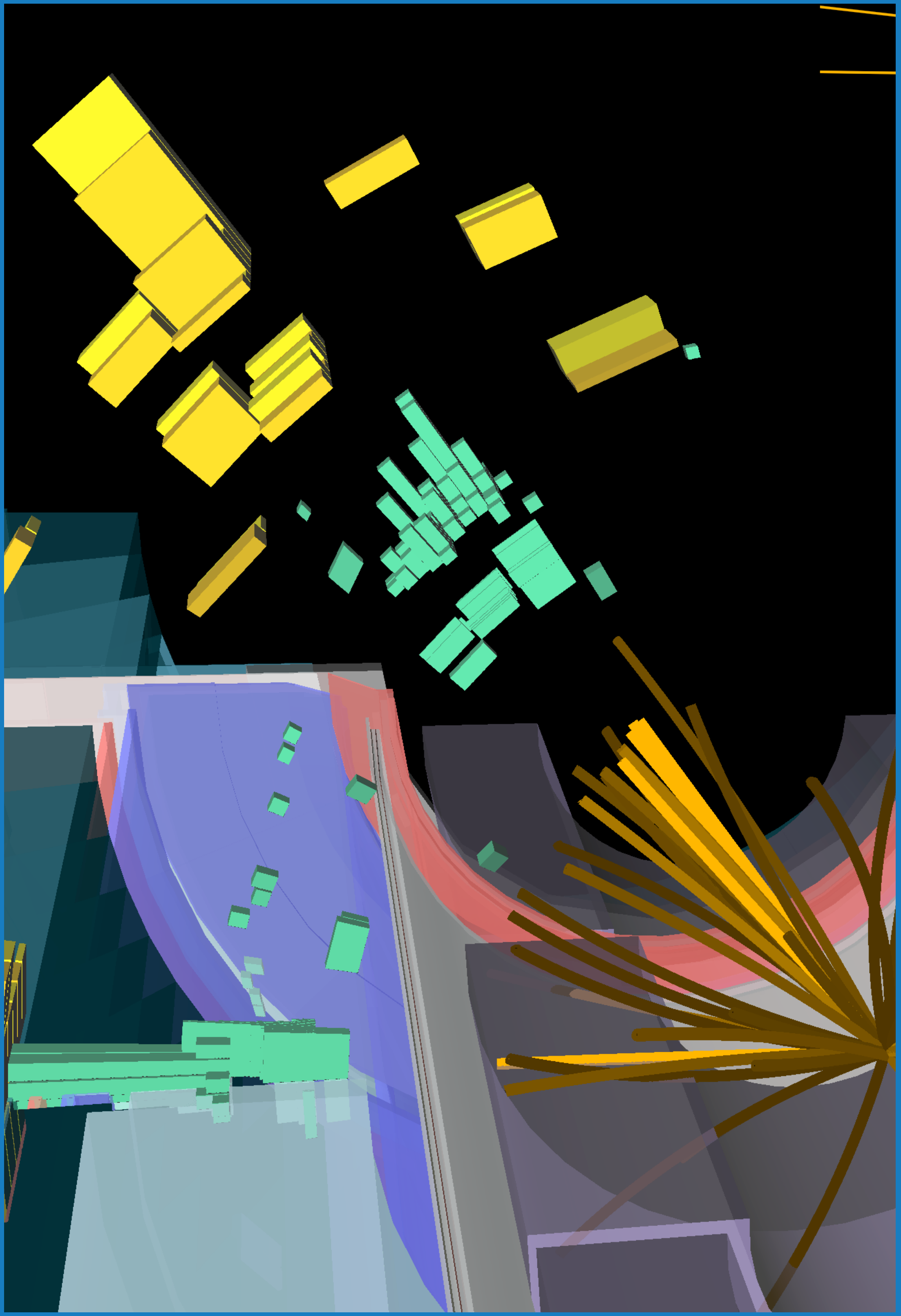
THE FOUR-BODY MASS

Different processes contribute to the m_{HH} spectrum at different masses:





- At $\kappa_\lambda \equiv \lambda_{HHH}/\lambda_{SM} = 0$, the only contributions are from the box diagram
- Maximal destructive interference at $\kappa_\lambda = 2$
- At $\kappa_\lambda >= 5$, the triangle diagram dominates

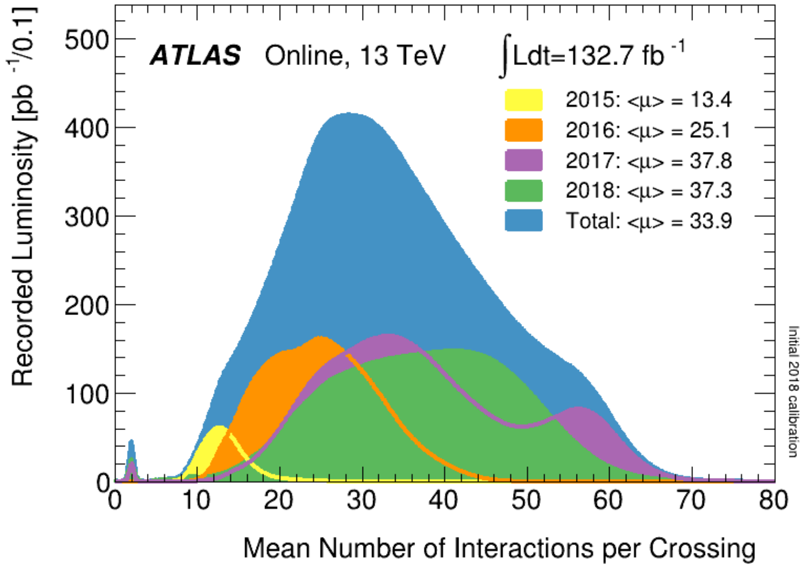


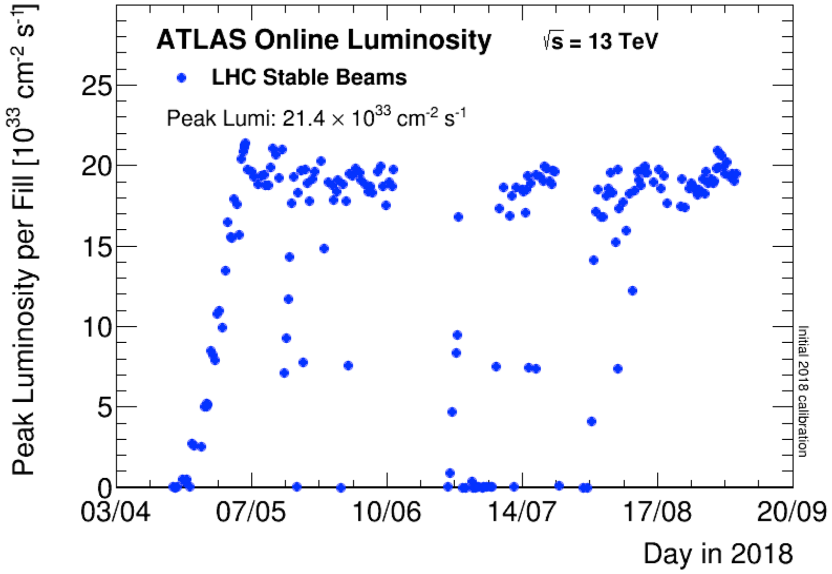
2015+2016
DATA

36.1/FB DATA COLLECTED BY THE ATLAS EXPERIMENT IN 2015 + 2016

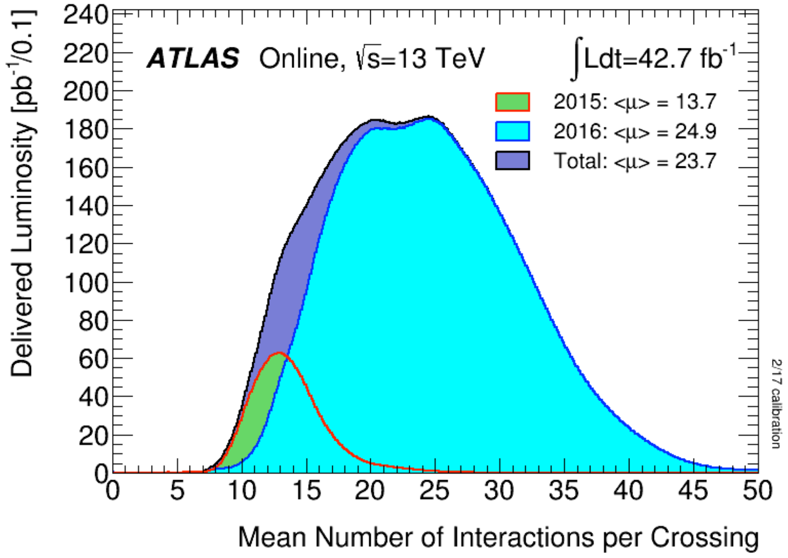
- Lower pileup in 2015/2016 (<μ> = 23.7 vs. 37.3 now)
- Lower instantaneous luminosity (13.8*10^{33}/cm^{2}s vs 21.4 now)

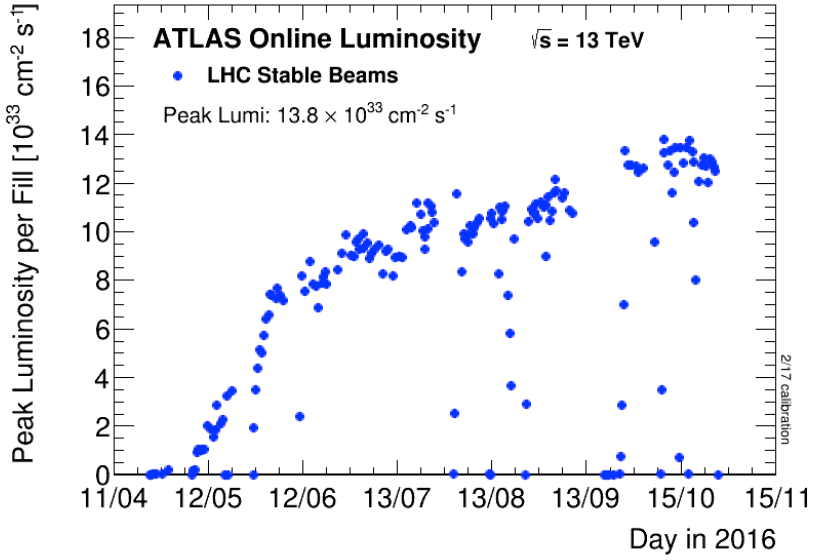
2018





2015-2016





Higher pileup already a small taste of our future challenges!

HOW TO TRIGGER ON HH EVENTS?

- Choose a trigger that is as efficient as possible, while keeping a low enough threshold to be able to reconstruct the Higgs mass
- **$HH \rightarrow \gamma\gamma bb$**: loose diphoton triggers, with 25/35 GeV photon p_T threshold
- **$HH \rightarrow bb\tau\tau$**: single- ($p_T >$ 80-160 GeV) and di-tau ($p_T >$ 25/35 GeV) triggers for $\tau_{had}\tau_{had}$, single lepton and lepton +tau triggers ($p_T >$ 24-26 GeV) for $\tau_{lep}\tau_{had}$
- **$HH \rightarrow bbbb$**: one or two jets passing online b-tagging (plus additional non-b-tagged jets)

HOW TO TRIGGER ON HH EVENTS?

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- H
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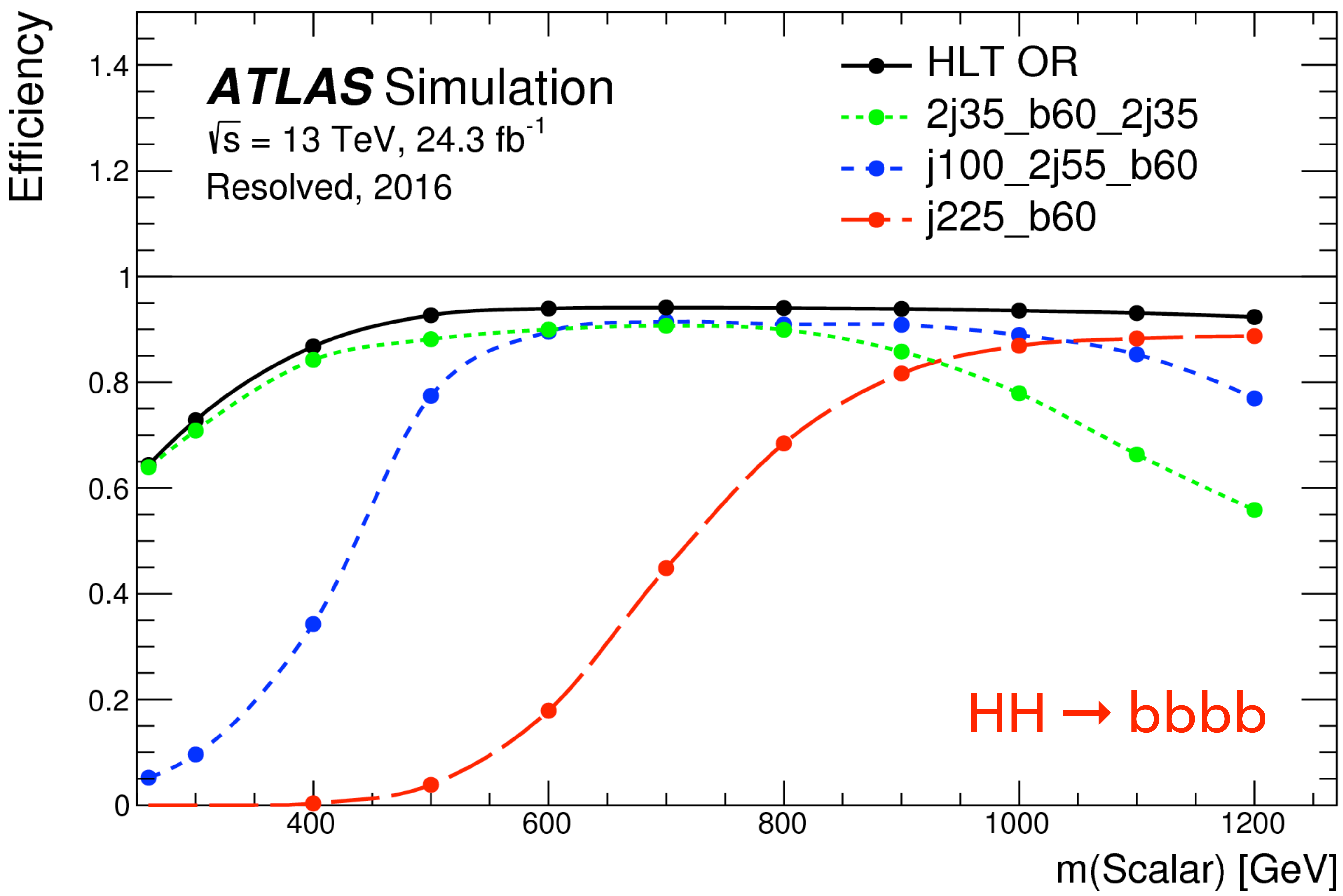
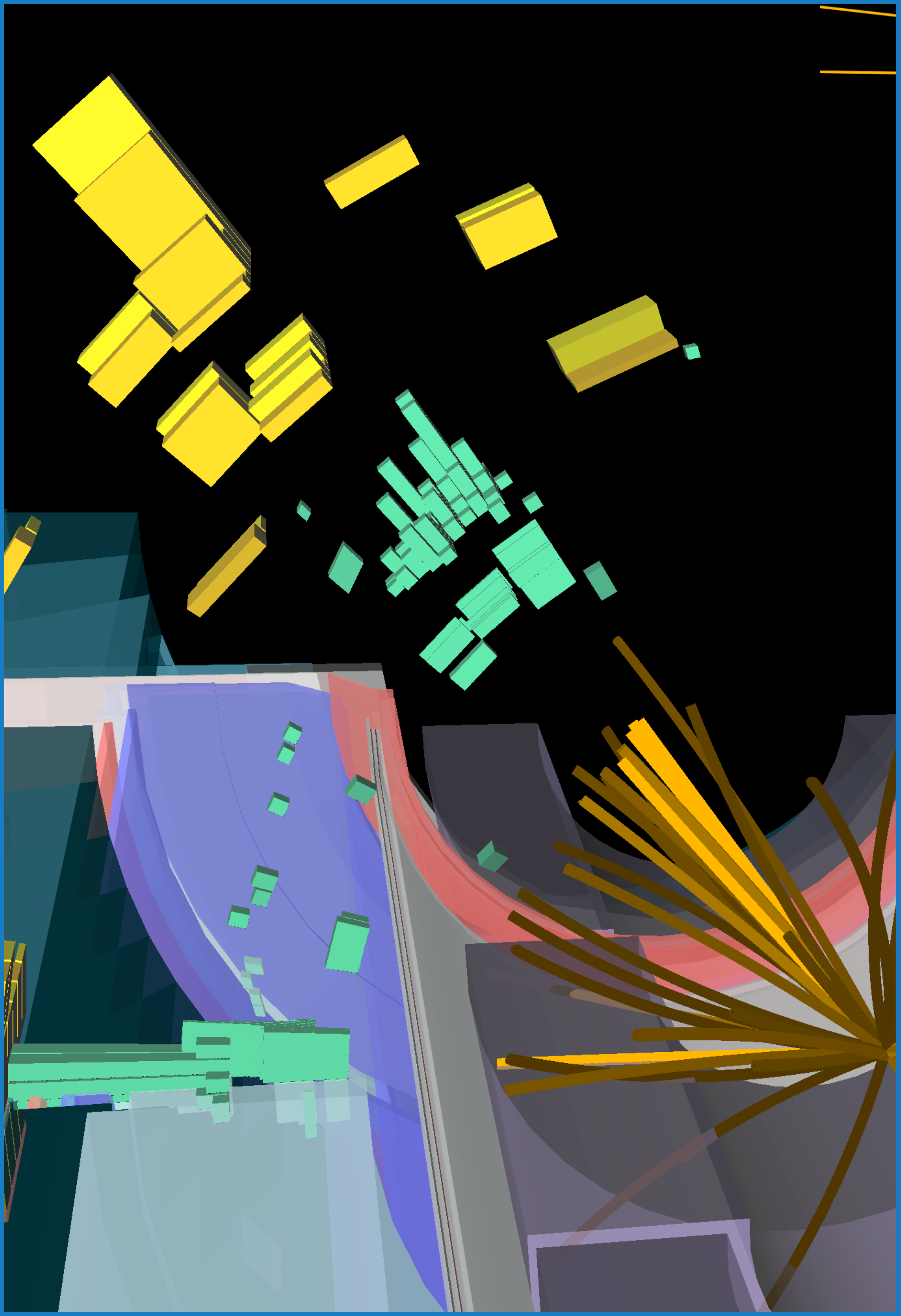
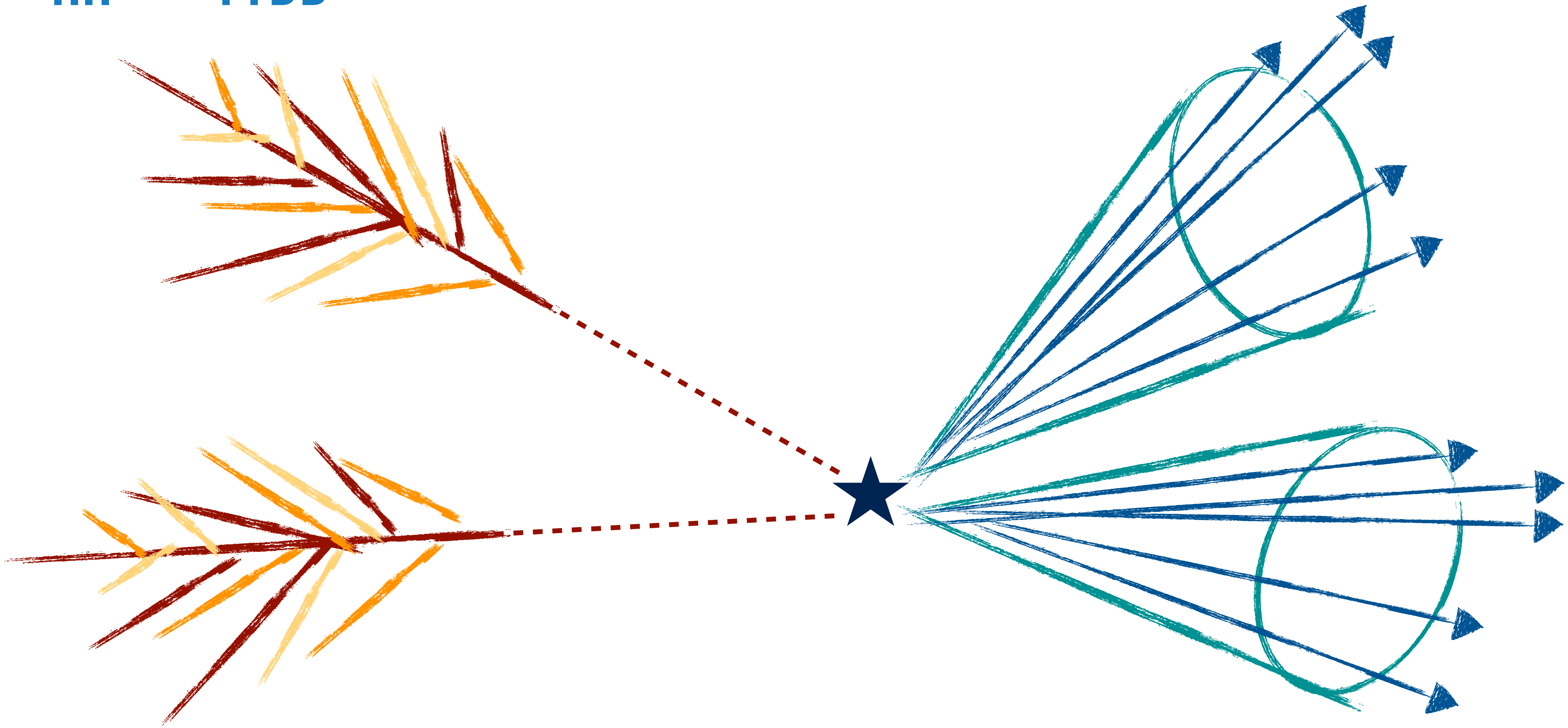
- H
  2 rs
  (p
- H lus
  ac





OBJECT AND EVENT SELECTION

HH → YYBB



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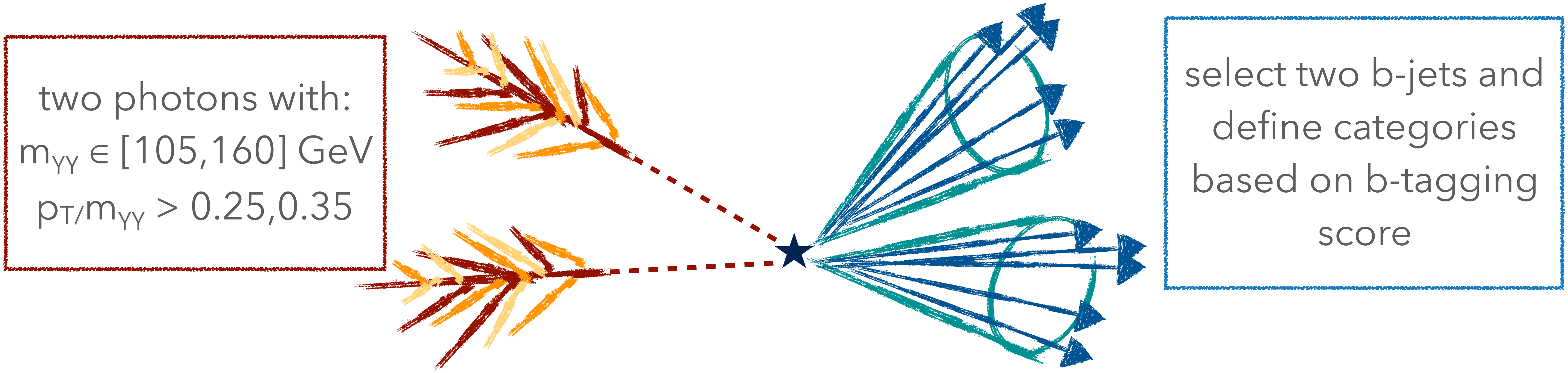
YYBB: OBJECT PRE-SELECTION

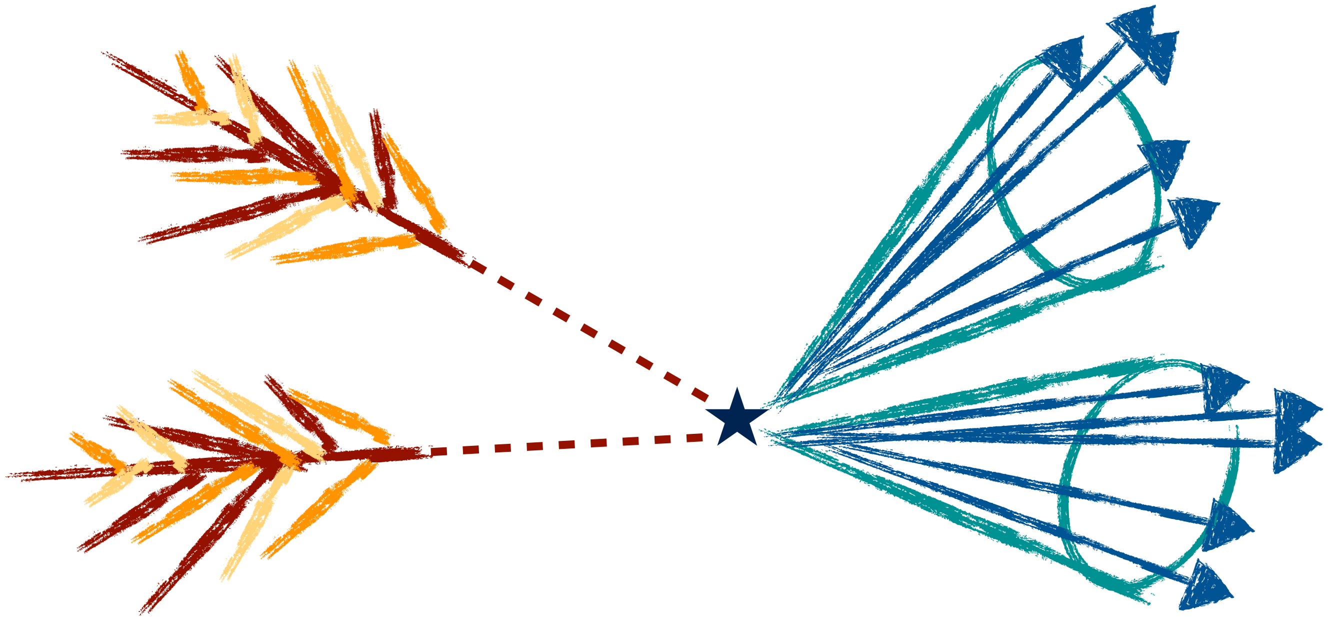


two photons with:
$m_{\gamma\gamma} \in [105,160]$ GeV
$p_{T}/m_{\gamma\gamma} > 0.25,0.35$

select two b-jets and define categories based on b-tagging score

- require two b-tagged jets, with $|\eta| < 2.5$, $p_T > 25$ GeV:
  - **if:** two jets pass 70% WP: 2 b-tag category (most senstive)
  - **else if:** one jet passes 60% WP: 1 b-tag category (use BDT to choose 2nd jet)
  - **else:** 0 b-tag control region

YYBB: 1 B-TAG BDT



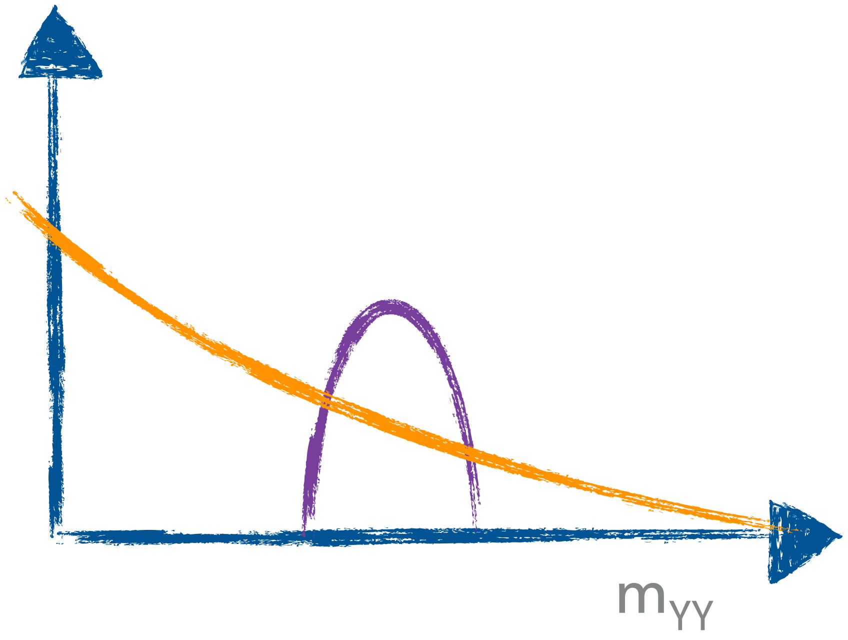
1st jet is b-tagged @ 60% WP → select 2nd jet

- Train BDT on correct and incorrect second jet selections, in signal and background MC (background has no correct choice!)
- Variables considered: jet p_T, di-jet p_T, di-jet mass, jet η, di-jet η, di-jet $\Delta\eta$, passes 77%/85% WP, ranking from best to worst in: p_T, best match to m_H, di-jet p_T

HOW DO WE SEARCH FOR HH → YYBB?

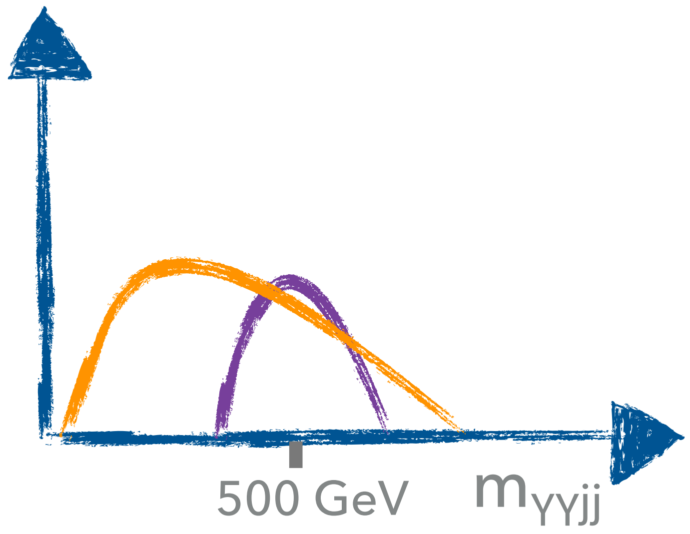
non-resonant search

- Excellent diphoton mass resolution!
- Cut on m_{bb}, fit the data in $m_{\gamma\gamma}$
  - signal: Double-sided Crystal Ball
  - background: exponential
- Set limits on di-Higgs cross section and varied Higgs self-coupling



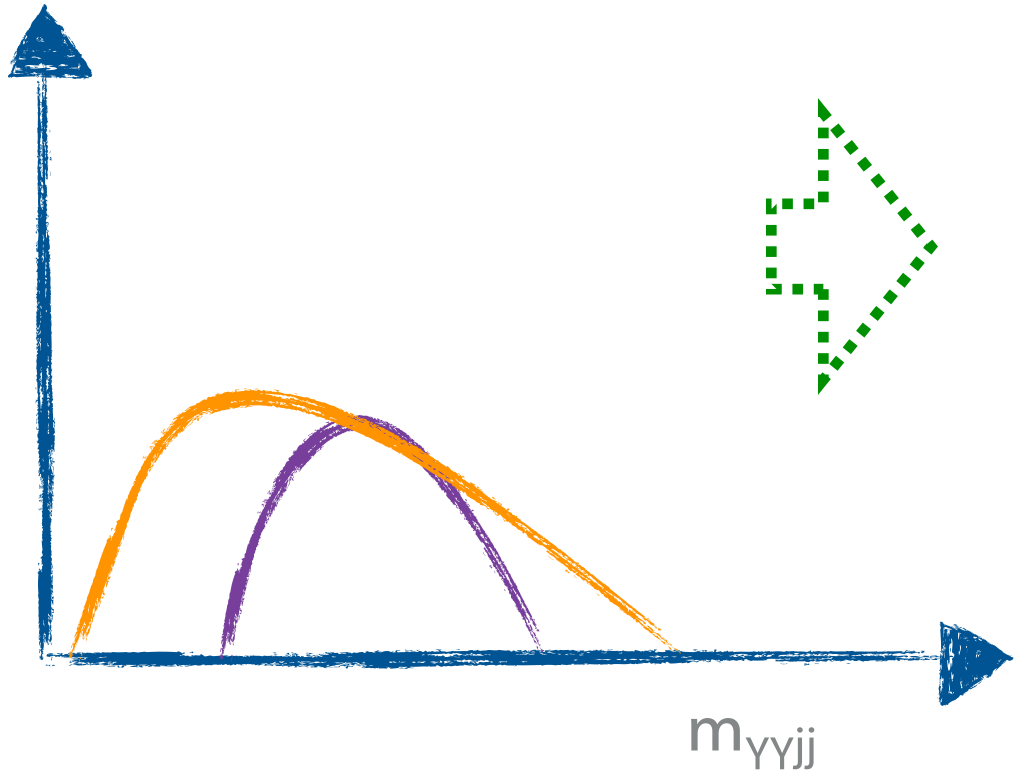
resonant search

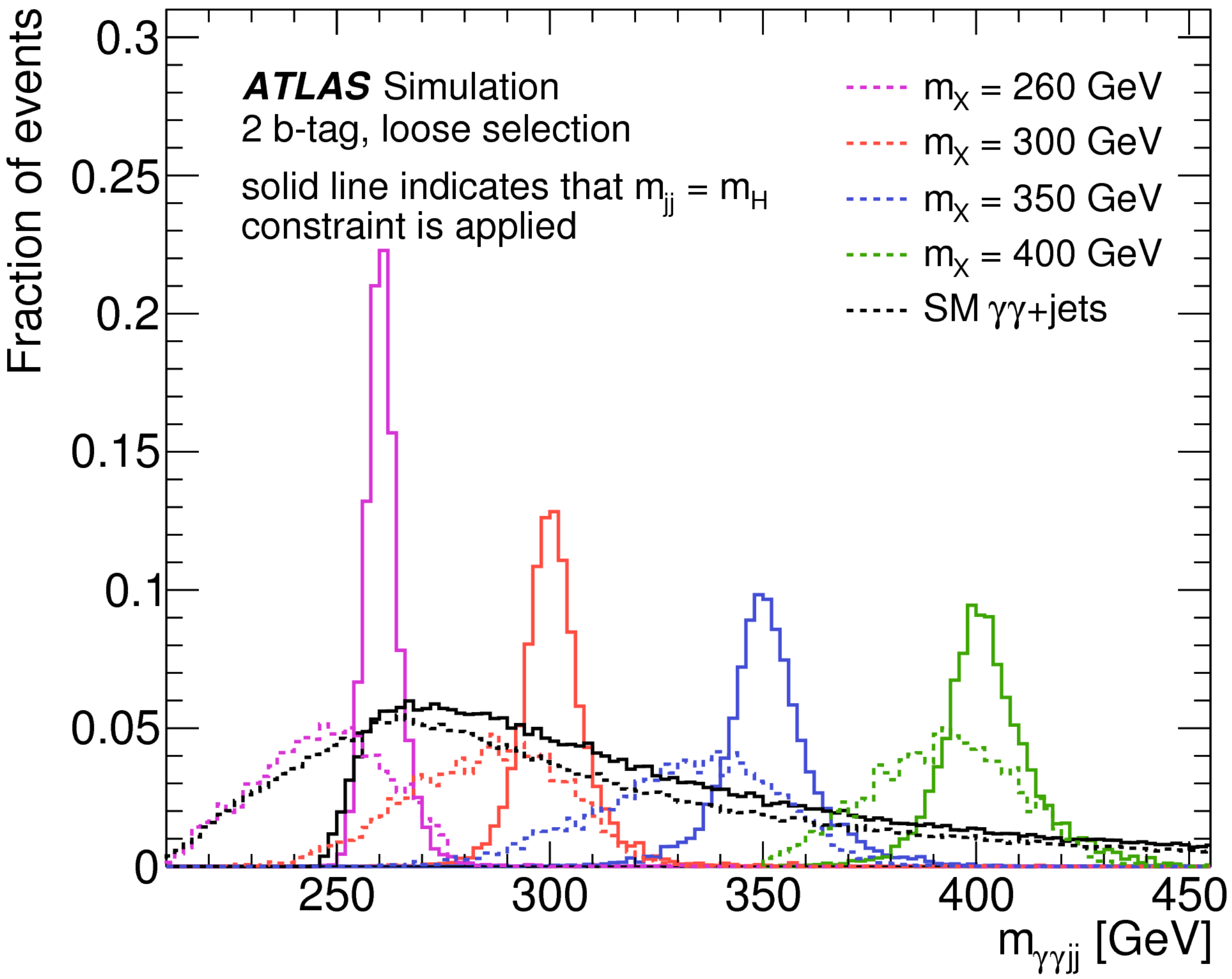
- Cut on m_{bb} and $m_{\gamma\gamma}$, fit the data in $m_{\gamma\gamma jj}$
  - signal: Gaussian with exponential tails
  - background: Novosibirsk for low masses (260-500 GeV), exponential for high masses (500-1000 GeV)
- Set limits on σ(X) → HH



YYBB: RESONANT MODELING

Scale the dijet mass to 125 GeV for both signal and background:





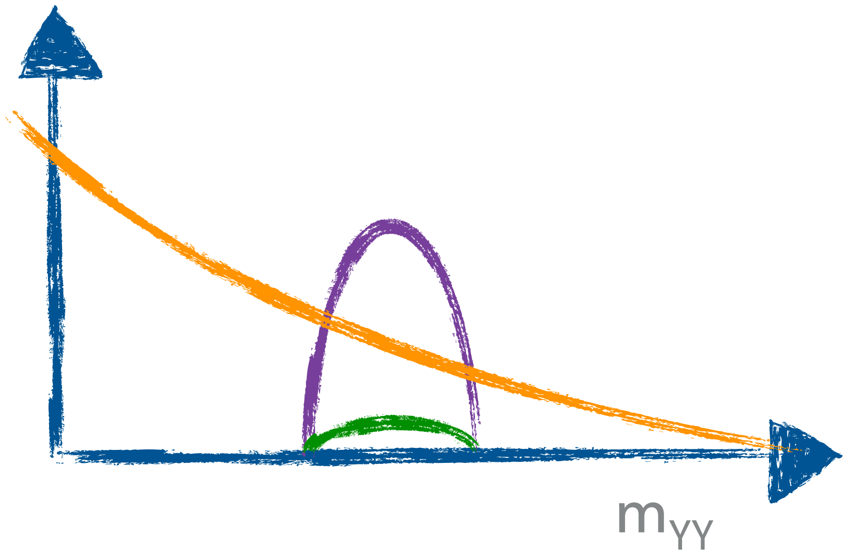
This improves the signal resolution and accuracy

HH ⟶ γγBB BACKGROUNDS

non-resonant search

main backgrounds:

- SM Higgs to diphotons
  - ggF, VBF, WH, ZH, ttH, bbH, tH
  - shape and normalization from MC
- γγ(+γj+jγ+jj) + jets
  - use MC model to choose a background fit function only



resonant search

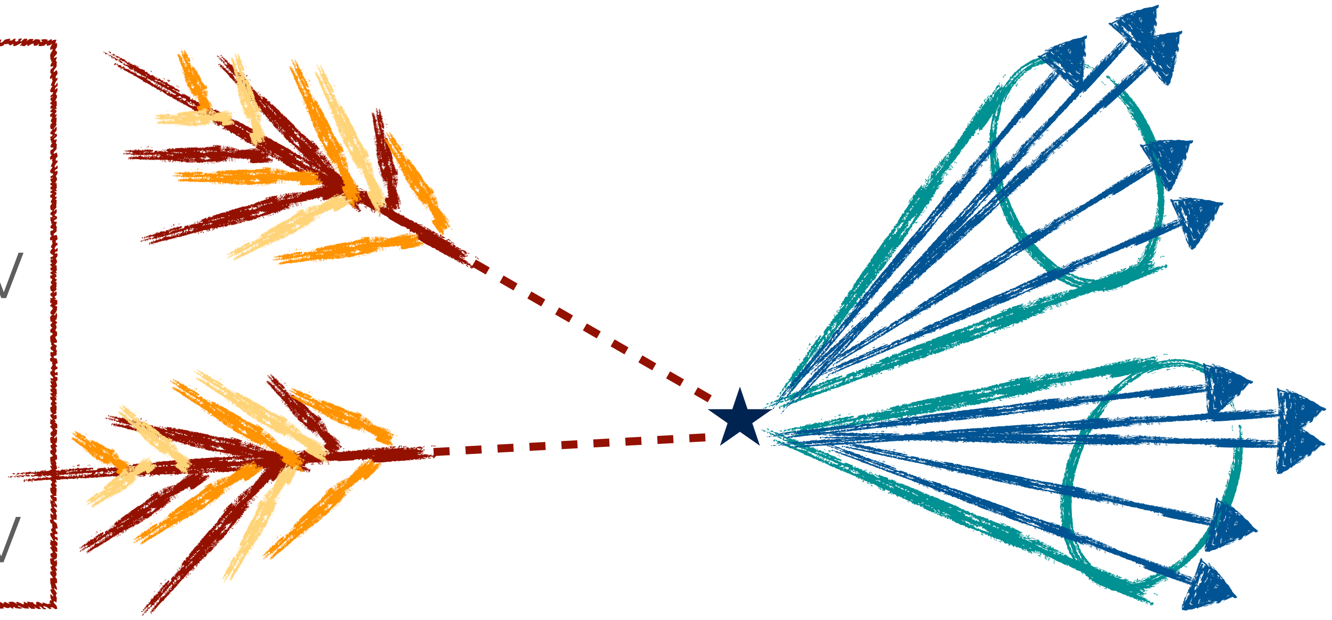
main backgrounds:

- SM Higgs to diphotons and SM di-Higgs to γγbb
  - shape and normalization from MC
- γγ + jets
  - use MC model to choose a background fit function only

YYBB: EVENT SELECTION

resonant only:
loose selection:
$|m_{\gamma\gamma} - m_H| < 4.7$ GeV

tight selection:
$|m_{\gamma\gamma} - m_H| < 4.3$ GeV



loose selection:
jet $p_T > 40\ (25)$ GeV
$m_{jj} \in [80,140]$ GeV

tight selection:
jet $p_T > 100\ (30)$ GeV
$m_{jj} \in [90,140]$ GeV

- define two non-orthogonal selections:
  - "loose" jet selection for $260 < m_X < 500$ GeV, and setting limit on self-coupling
  - "tight" jet selection for $500 < m_X < 1000$ GeV, and non-resonant search

YYBB: EVENT SELECTION

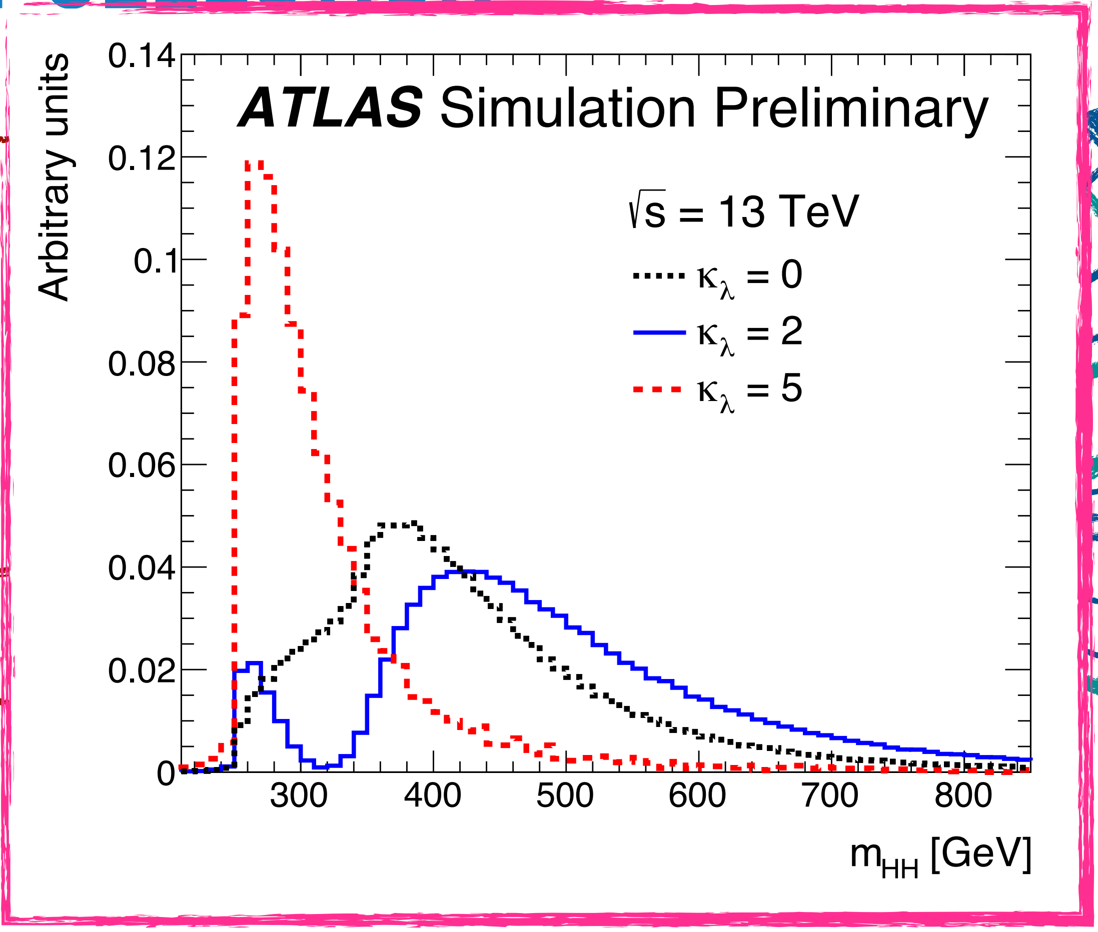
resonant only:

loose selection:

$|m_{\gamma\gamma} - m_H| < 4.7$ GeV

tight selection:

$|m_{\gamma\gamma} - m_H| < 4.3$ GeV



loose selection:

jet $p_T > 40$ (25) GeV

$m_{jj} \in [80,140]$ GeV

tight selection:

jet $p_T > 100$ (30) GeV

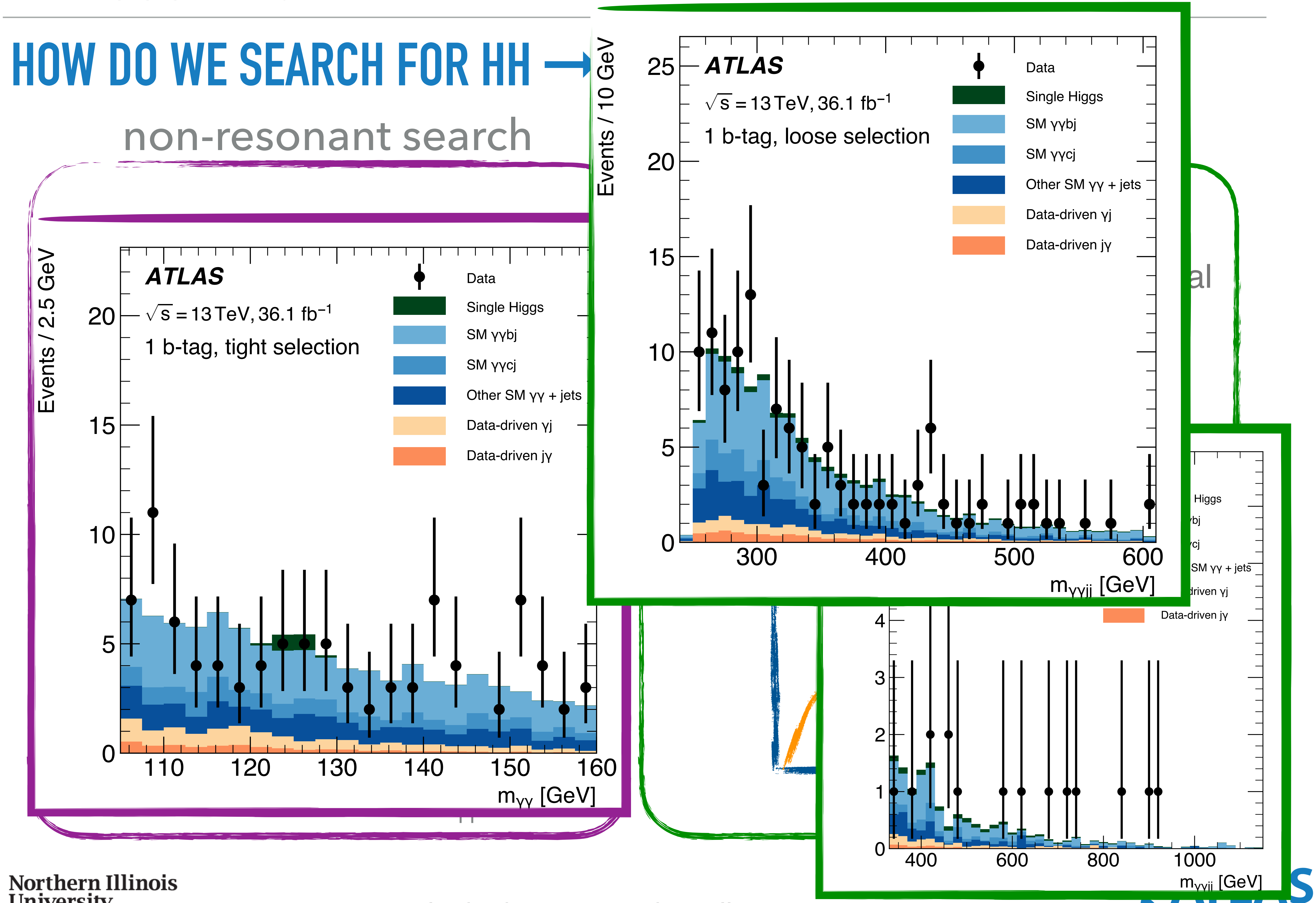
$m_{jj} \in [90,140]$ GeV

- define two
    - "loose" jet selection for $260 < m_X < 500$ GeV, and setting limit on **self-coupling**
    - "tight" jet selection for $500 < m_X < 1000$ GeV, and non-resonant search

HOW DO WE SEARCH FOR HH →

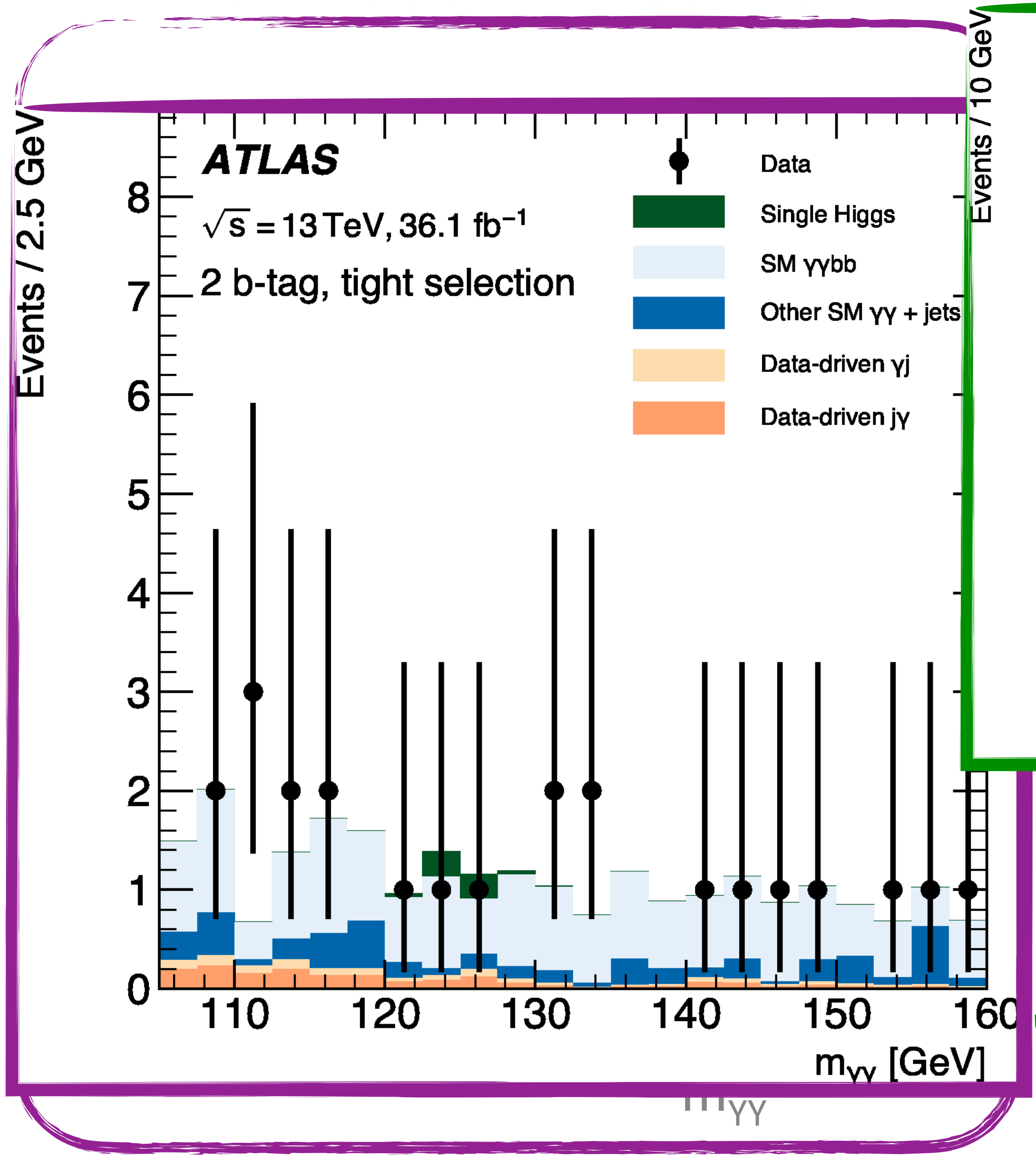
non-resonant search

al



HOW DO WE SEARCH FOR HH → YYBB?

non-resonant search



resonant search

xponential

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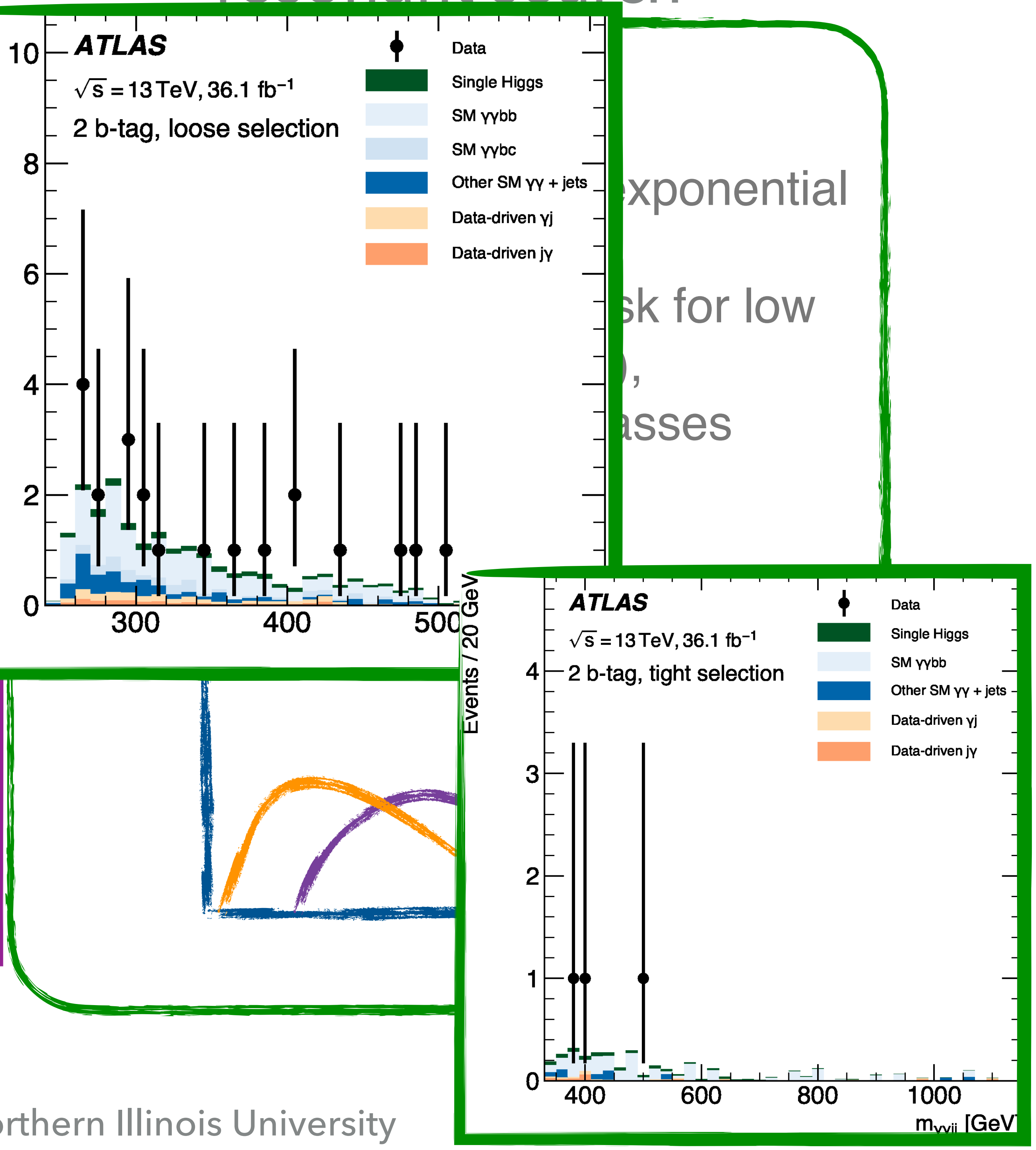
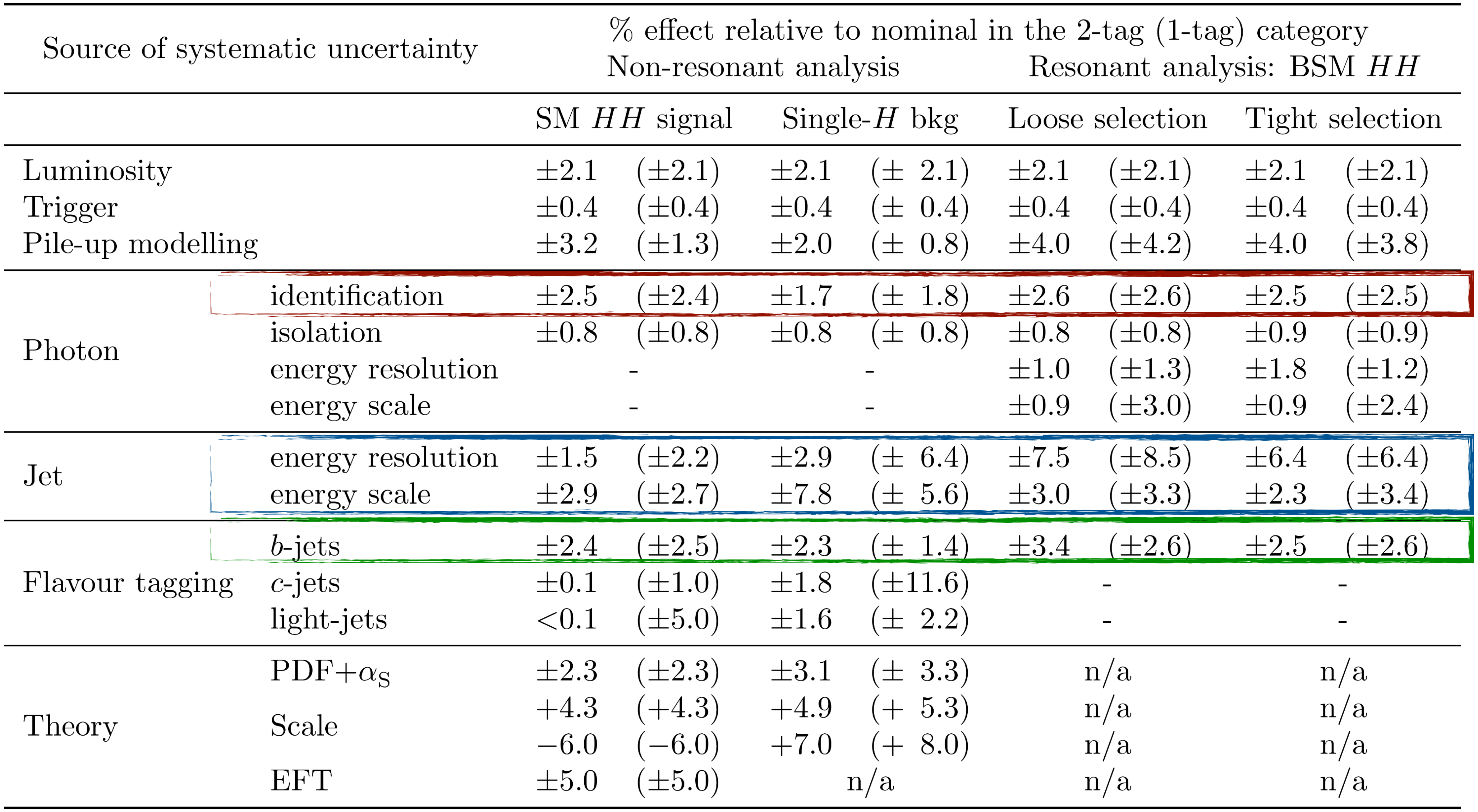
asses



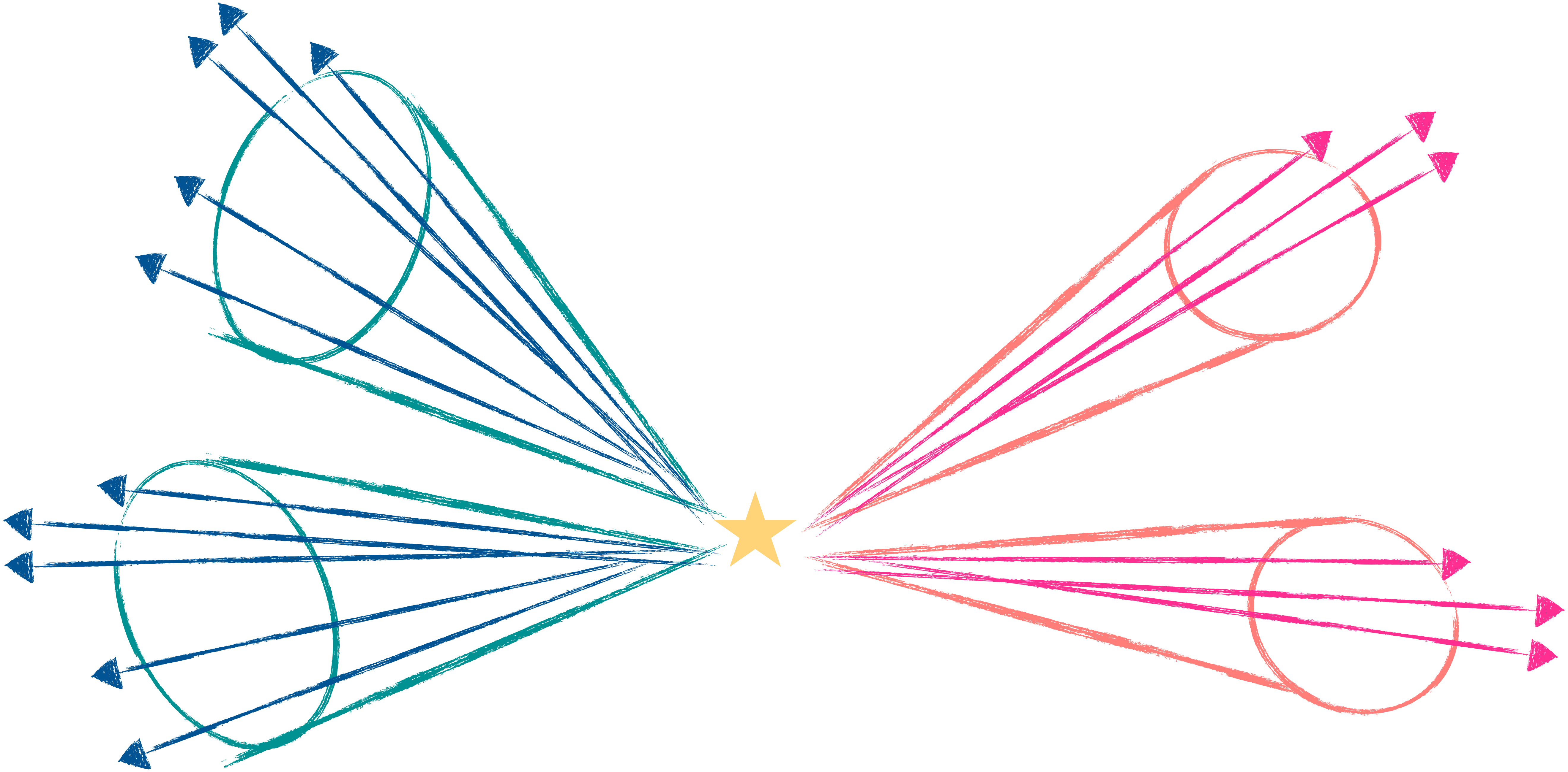
YYBB SEARCH IS STATS-LIMITED, BUT…

- largest systematic uncertainties from: photon ID, JES/JER, flavor-tagging



Source of systematic uncertainty		% effect relative to nominal in the 2-tag (1-tag) category Non-resonant analysis				Resonant analysis: BSM HH			
		SM HH signal		Single-H bkg		Loose selection		Tight selection	
Luminosity		±2.1	(±2.1)	±2.1	(± 2.1)	±2.1	(±2.1)	±2.1	(±2.1)
Trigger		±0.4	(±0.4)	±0.4	(± 0.4)	±0.4	(±0.4)	±0.4	(±0.4)
Pile-up modelling		±3.2	(±1.3)	±2.0	(± 0.8)	±4.0	(±4.2)	±4.0	(±3.8)
Photon	identification	±2.5	(±2.4)	±1.7	(± 1.8)	±2.6	(±2.6)	±2.5	(±2.5)
	isolation	±0.8	(±0.8)	±0.8	(± 0.8)	±0.8	(±0.8)	±0.9	(±0.9)
	energy resolution	-		-		±1.0	(±1.3)	±1.8	(±1.2)
	energy scale	-		-		±0.9	(±3.0)	±0.9	(±2.4)
Jet	energy resolution	±1.5	(±2.2)	±2.9	(± 6.4)	±7.5	(±8.5)	±6.4	(±6.4)
	energy scale	±2.9	(±2.7)	±7.8	(± 5.6)	±3.0	(±3.3)	±2.3	(±3.4)
Flavour tagging	b-jets	±2.4	(±2.5)	±2.3	(± 1.4)	±3.4	(±2.6)	±2.5	(±2.6)
	c-jets	±0.1	(±1.0)	±1.8	(±11.6)	-		-	
	light-jets	<0.1	(±5.0)	±1.6	(± 2.2)	-		-	
Theory	PDF+α_S	±2.3	(±2.3)	±3.1	(± 3.3)	n/a		n/a	
	Scale	+4.3	(+4.3)	+4.9	(+ 5.3)	n/a		n/a	
		−6.0	(−6.0)	+7.0	(+ 8.0)	n/a		n/a	
	EFT	±5.0	(±5.0)	n/a		n/a		n/a	

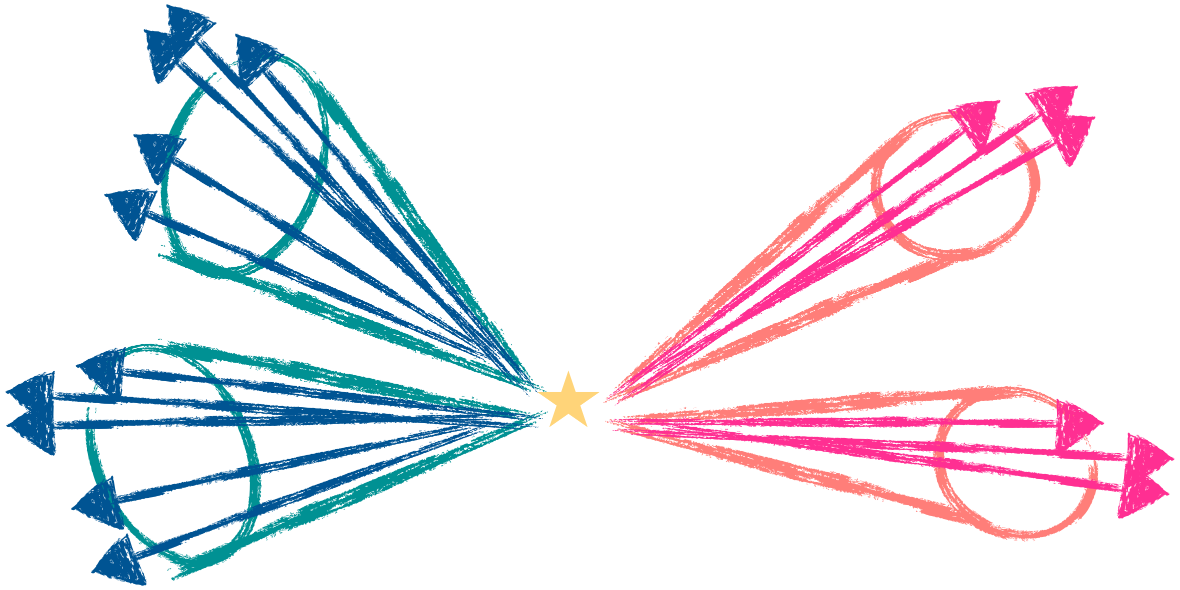
HH → BBTAUTAU



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-16/

BBTAUTAU: OBJECT SELECTION

two b-jets with:
70% WP,
p_T > 45,20 GeV



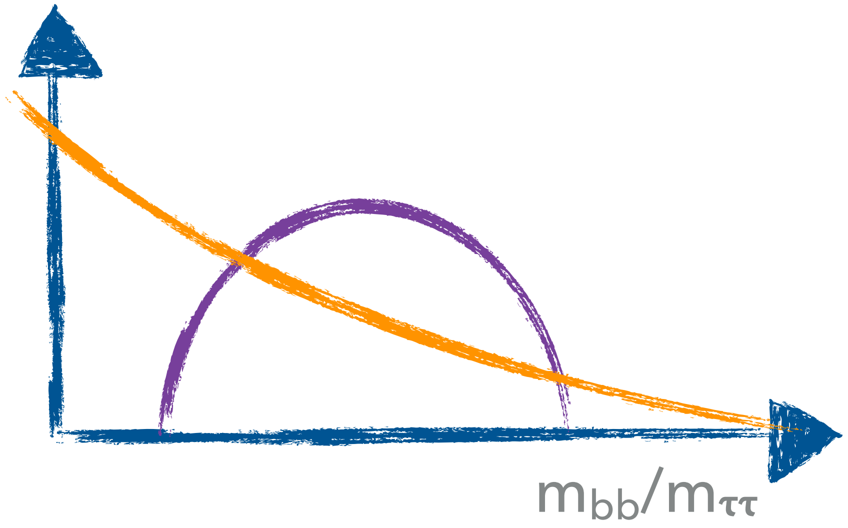
select two taus (or one light lepton and one tau) with opposite sign and $m_{\tau\tau}^{MMC} > 60$ GeV

- two selections: lep+had, had+had – based on the tau decays

HOW DO WE SEARCH FOR HH → BBTAUTAU?

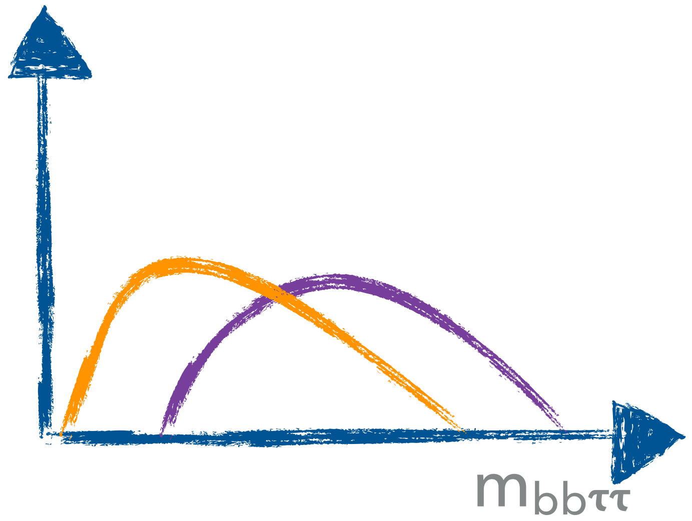
non-resonant search

- Train a BDT on SM HH signal, and on signal with varied self-coupling ($\kappa_\lambda = 20$)
  - Higgs and di-Higgs candidate masses used as input to the BDT
  - Scale m_{bb} and $m_{\tau\tau}$ to the Higgs mass when constructing $m_{bb\tau\tau}$
- Simultaneous fit of 3 BDT distributions (one had+had, two lep+had- based on the triggers used)



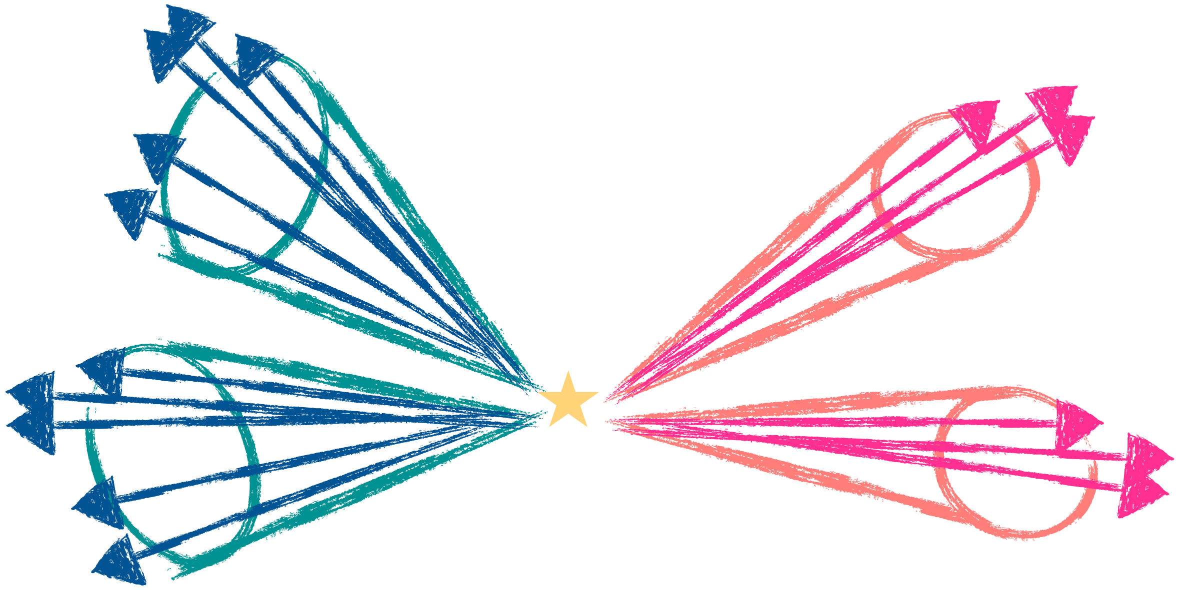
resonant search*

- Train a dedicated BDT for each mass point
  - Higgs and di-Higgs candidate masses used as input to the BDT
  - Scale m_{bb} and $m_{\tau\tau}$ to the Higgs mass when constructing $m_{bb\tau\tau}$
- Fit the 3 BDT results for each mass point



*also consider Randall-Sundrum graviton (RSG) model for spin 2, not covered in this talk

BBTAUTAU: BDT VARIABLES



- **lep+had** SLT resonant: m_{HH}, m_{bb}, $m_{\tau\tau}^{MMC}$, $\Delta R(\boldsymbol{\tau},\boldsymbol{\tau})$, $\Delta R(b,b)$, MET, MET centrality, transverse W mass, $\Delta\phi(H,H)$, $\Delta p_T(\ell, \boldsymbol{\tau}_{had\text{-}vis})$, subleading b-jet p_T
- **lep+had** SLT non-resonant, LTT: m_{HH}, m_{bb}, $m_{\tau\tau}^{MMC}$, $\Delta R(\boldsymbol{\tau},\boldsymbol{\tau})$, $\Delta R(b,b)$, transverse W mass
- **had+had:** m_{HH}, m_{bb}, $m_{\tau\tau}^{MMC}$, $\Delta R(\boldsymbol{\tau},\boldsymbol{\tau})$, $\Delta R(b,b)$, MET centrality

Northern Illinois University

ATLAS EXPERIMENT

HH ⟶ BBTAUTAU BACKGROUNDS

had+had channel

main backgrounds:

- ttbar (two real taus): 42%
- fake taus: 25% - estimated with data-driven ABCD* method
- Z+jets: 15%
- ttbar with fake taus: 15% - correct MC with fake rates from data
- other small backgrounds from MC

A: OS + 2 signal taus	B: SS + 2 signal taus
C: OS + >1 anti-ID taus	D: SS + >1 anti-ID taus

lep+had channel

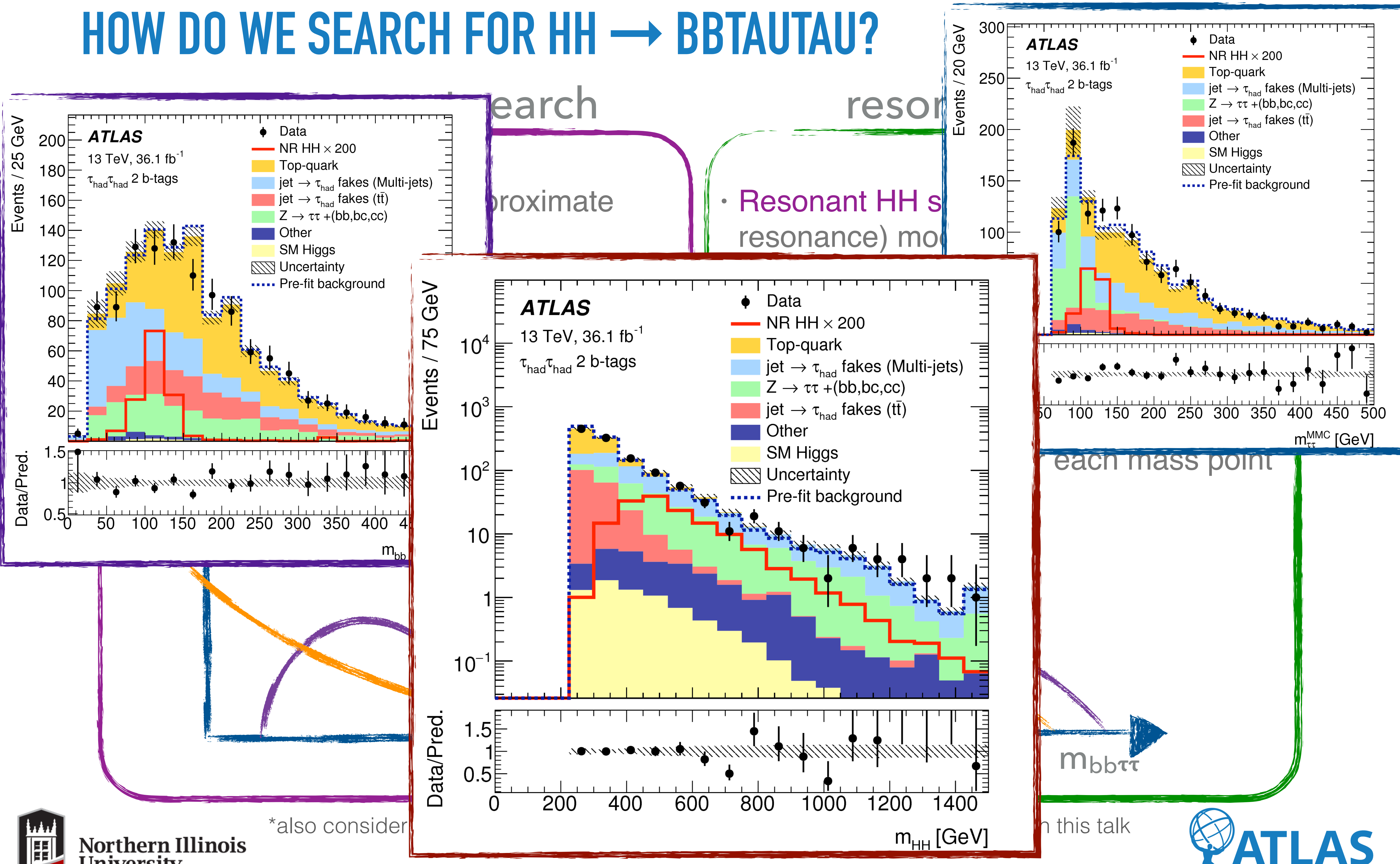
main backgrounds:

- ttbar (two real taus): 62%
- fake taus from ttbar, W+jets, QCD: 31% estimated with a combined fake factor* method
- other backgrounds (Z+jets, W+jets, single top, diboson) from MC: 7%

FF = #taus/#anti-taus

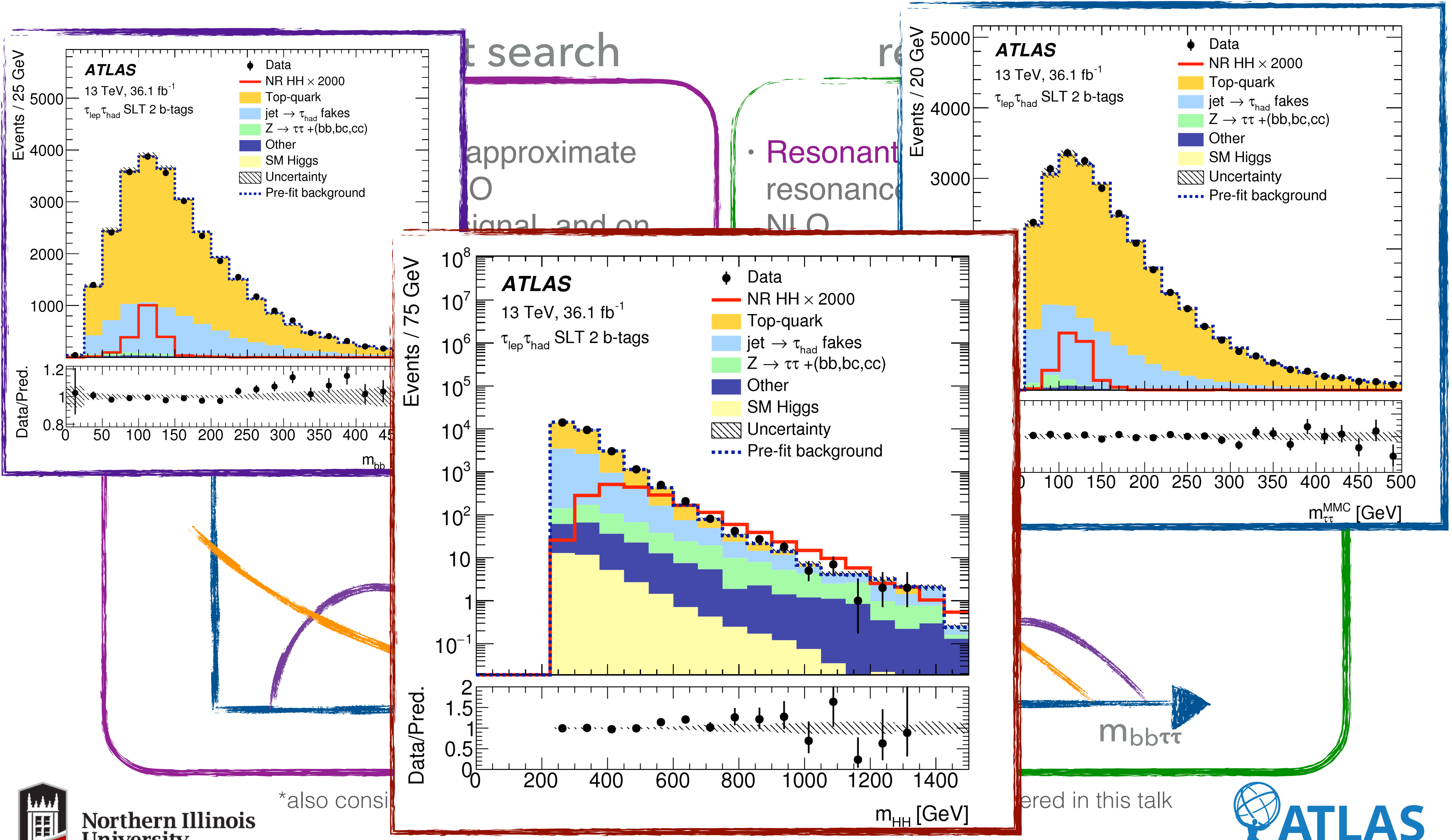
FF_{comb} = FF(QCD)*rQCD + FF(W/ttbar)*(1 - rQCD)

HOW DO WE SEARCH FOR HH → BBTAUTAU?



Elizabeth Brost - Northern Illinois University

HOW DO WE SEARCH FOR HH → BBTAUTAU?



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- Resonant
resonanc
NLO

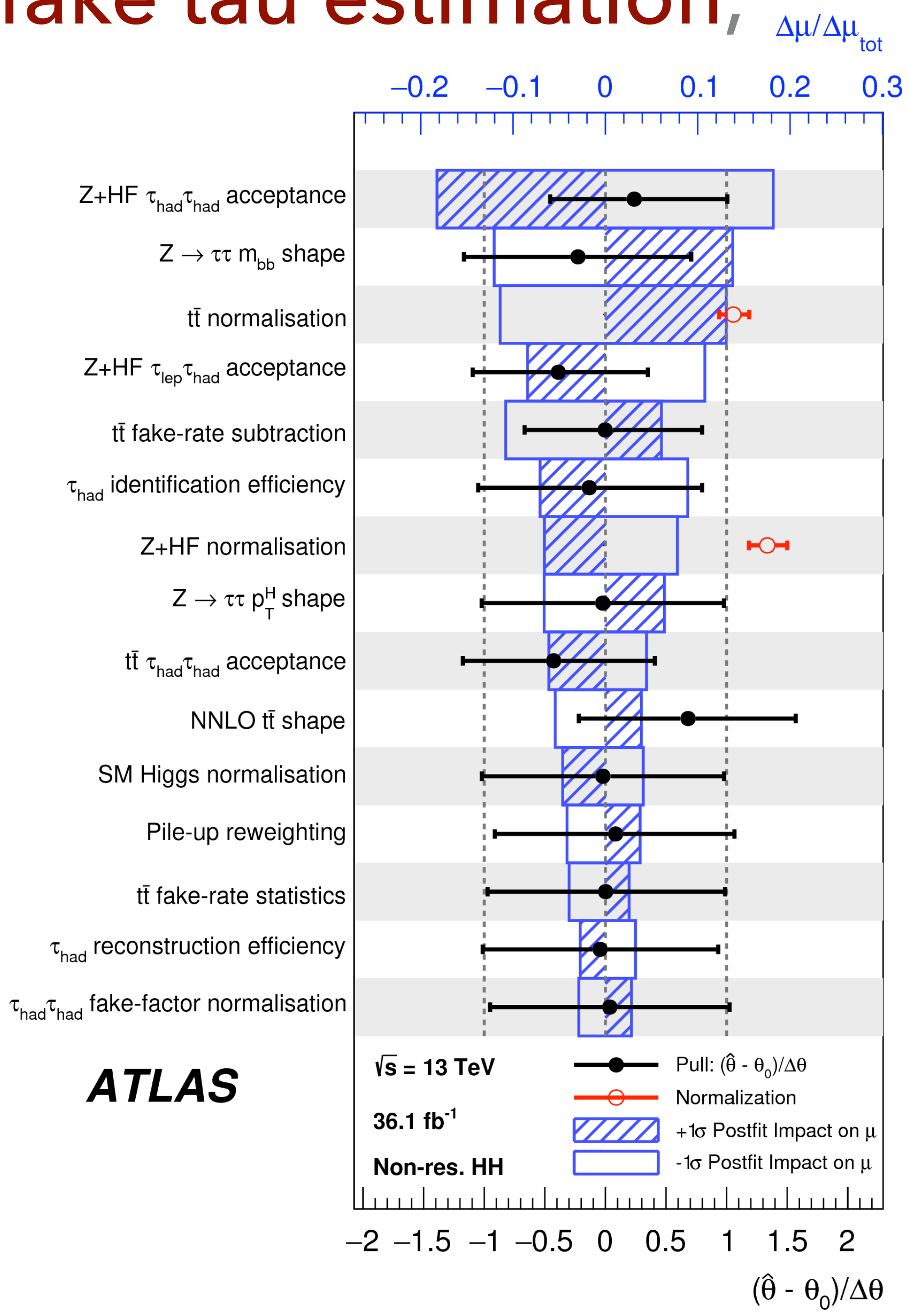
*also consi

ered in this talk

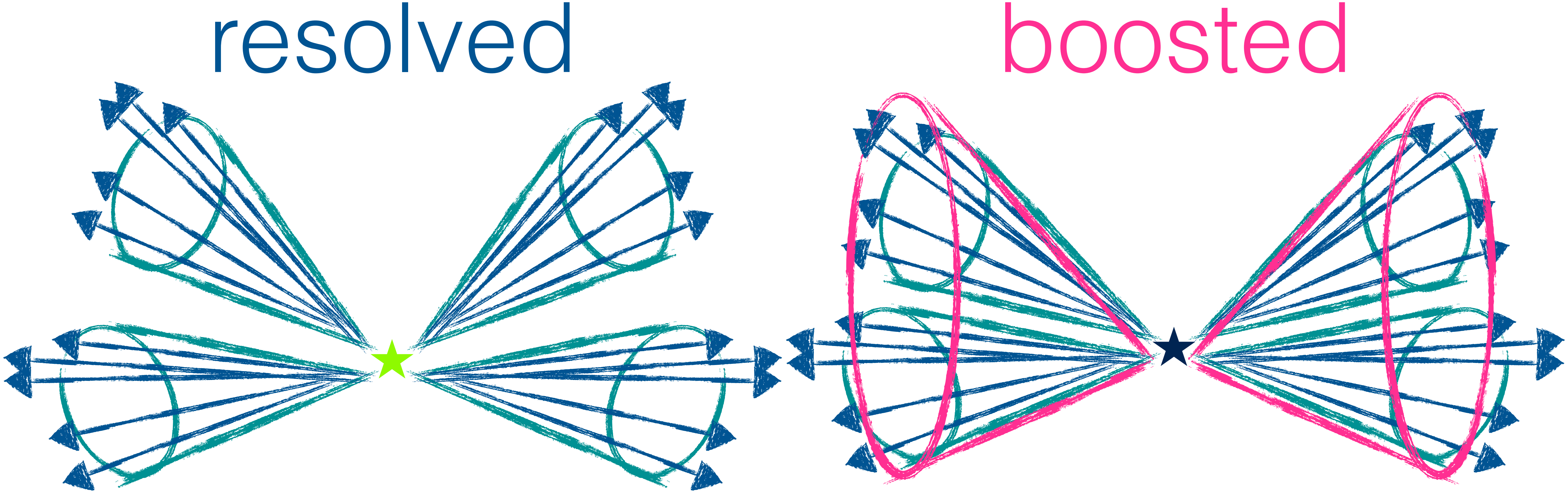
BBTAUTAU: SYSTEMATICS

- largest systematic uncertainties from: fake tau estimation, flavor-tagging, hadronic tau ID

Source	Uncertainty (%)
Total	± 54
Data statistics	± 44
Simulation statistics	± 16
Experimental Uncertainties	
Luminosity	± 2.4
Pileup reweighting	± 1.7
τ_{had}	± 16
Fake-τ estimation	± 8.4
b-tagging	± 8.3
Jets and $E_{\text{T}}^{\text{miss}}$	± 3.3
Electron and muon	± 0.5
Theoretical and Modeling Uncertainties	
Top	± 17
Signal	± 9.3
$Z \to \tau\tau$	± 6.8
SM Higgs	± 2.9
Other backgrounds	± 0.3

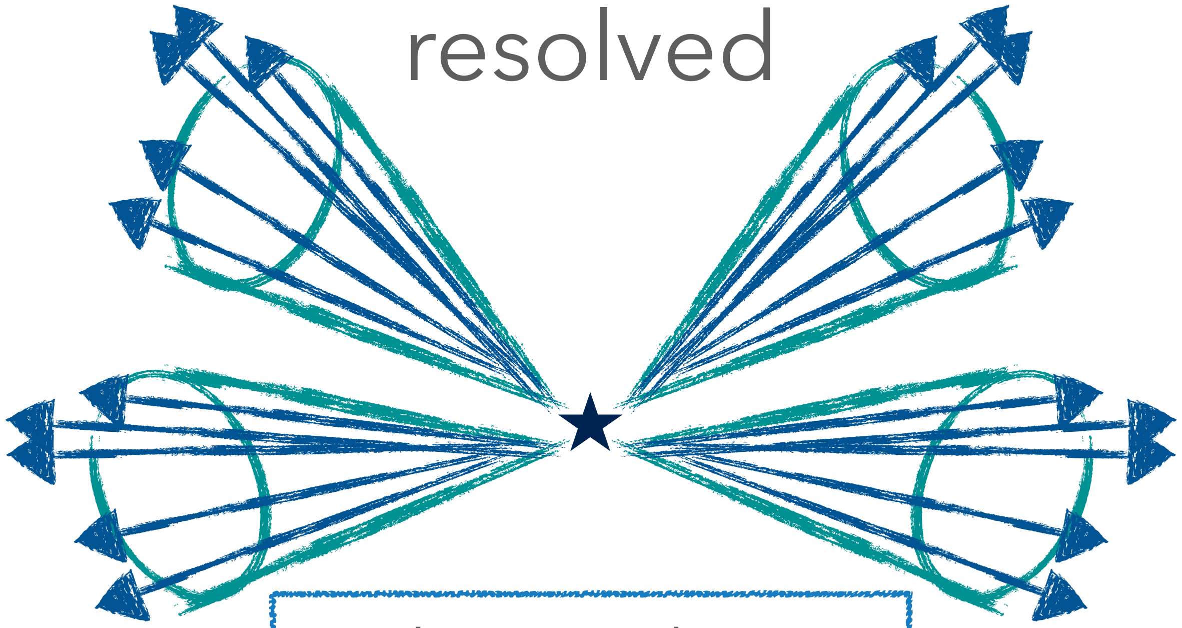


HH → BBBB

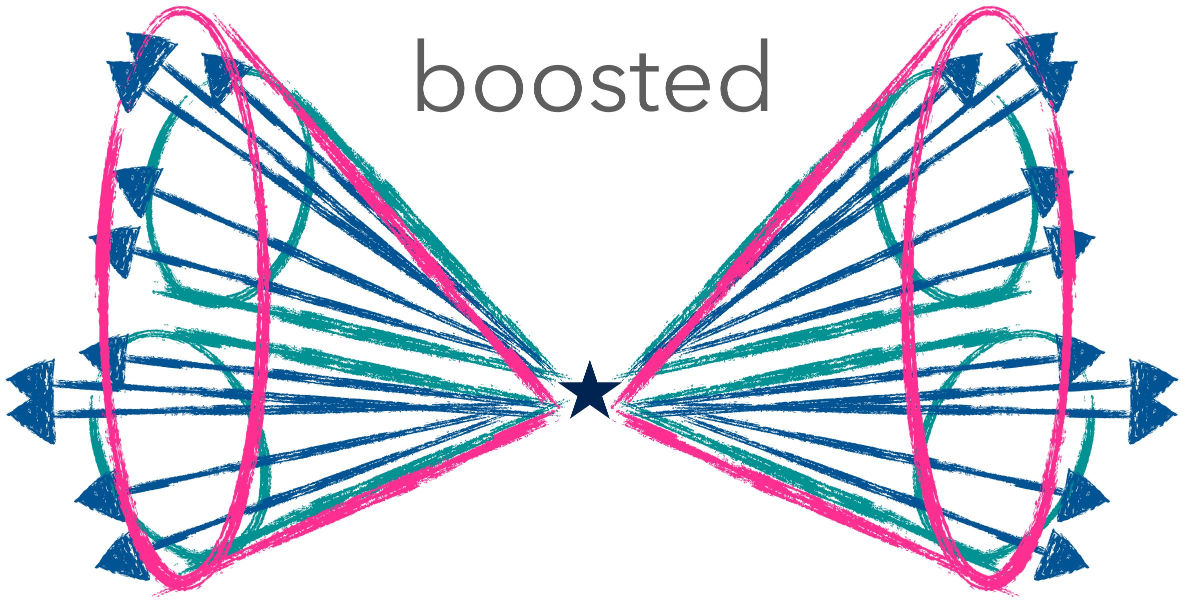


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-31/

BBBB: OBJECT SELECTION



≥4 b-tagged jets @
70% efficiency
p_T > 40 GeV



≥2 large-R (1.0) jets
(≥1 (R=0.2, 70% eff.)
b-tagged jet in each)

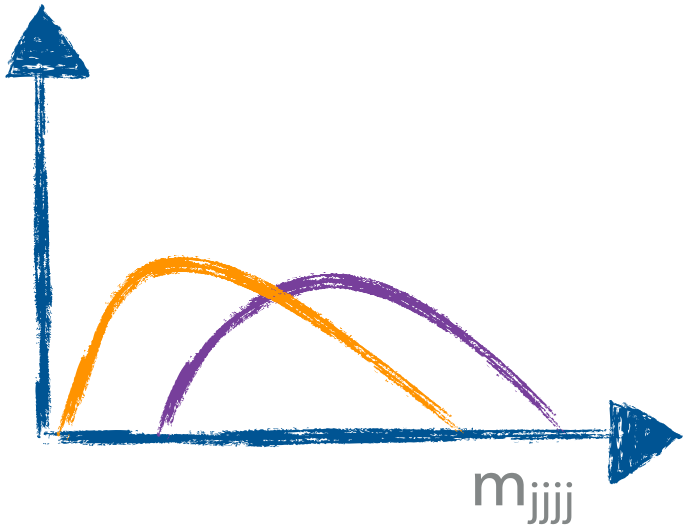
HOW DO WE SEARCH FOR HH → BBBB?

non-resonant search

- use resolved selection only
- unlike the other di-Higgs searches, the discriminant variable in the non-resonant search is m_{jjjj}
  - scale m_{jj} to m_H when reconstructing the four-body mass
- main backgrounds:
  - QCD multijet (95%)
  - ttbar (5%)

resonant search

- resolved:
  - target m_X from 260-1400 GeV
- boosted:
  - target m_X from 800-3000 GeV
- the discriminant variable in the resonant search is m_{jjjj}
  - scale m_{jj} to m_H when reconstructing the four-body mass

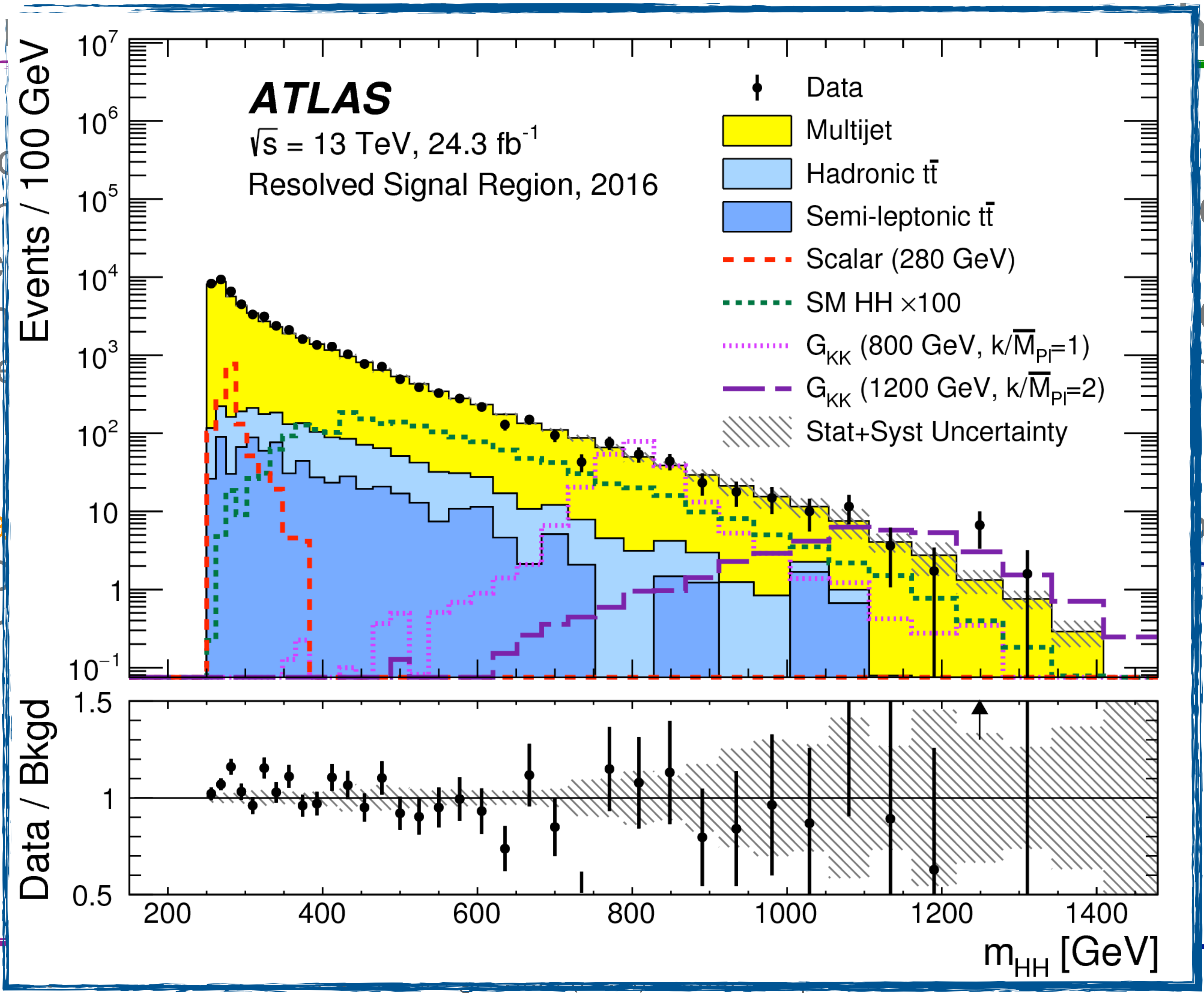


*also consider Randall-Sundrum graviton (RSG) model for spin 2, not covered in this talk

HOW DO WE SEARCH FOR HH → BBBB?

no

n



- use reso
- unlike th
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  resonan
  - scale
    reco
- main ba
  - QCD
  - ttbar

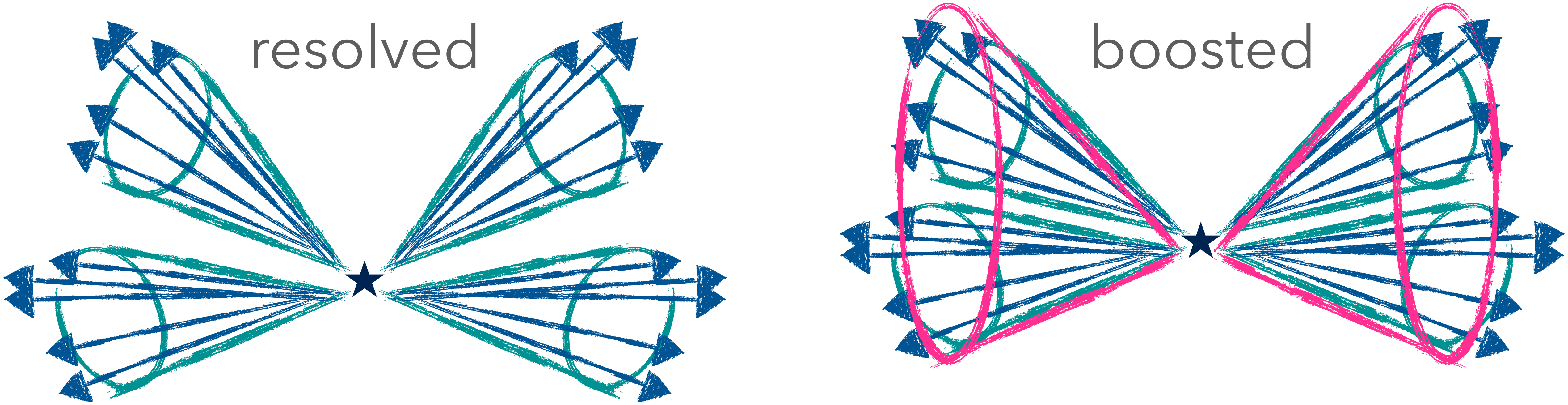
GeV

GeV

ne

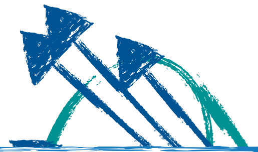
dy mass

BBBB: EVENT RECONSTRUCTION

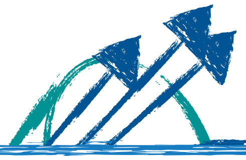


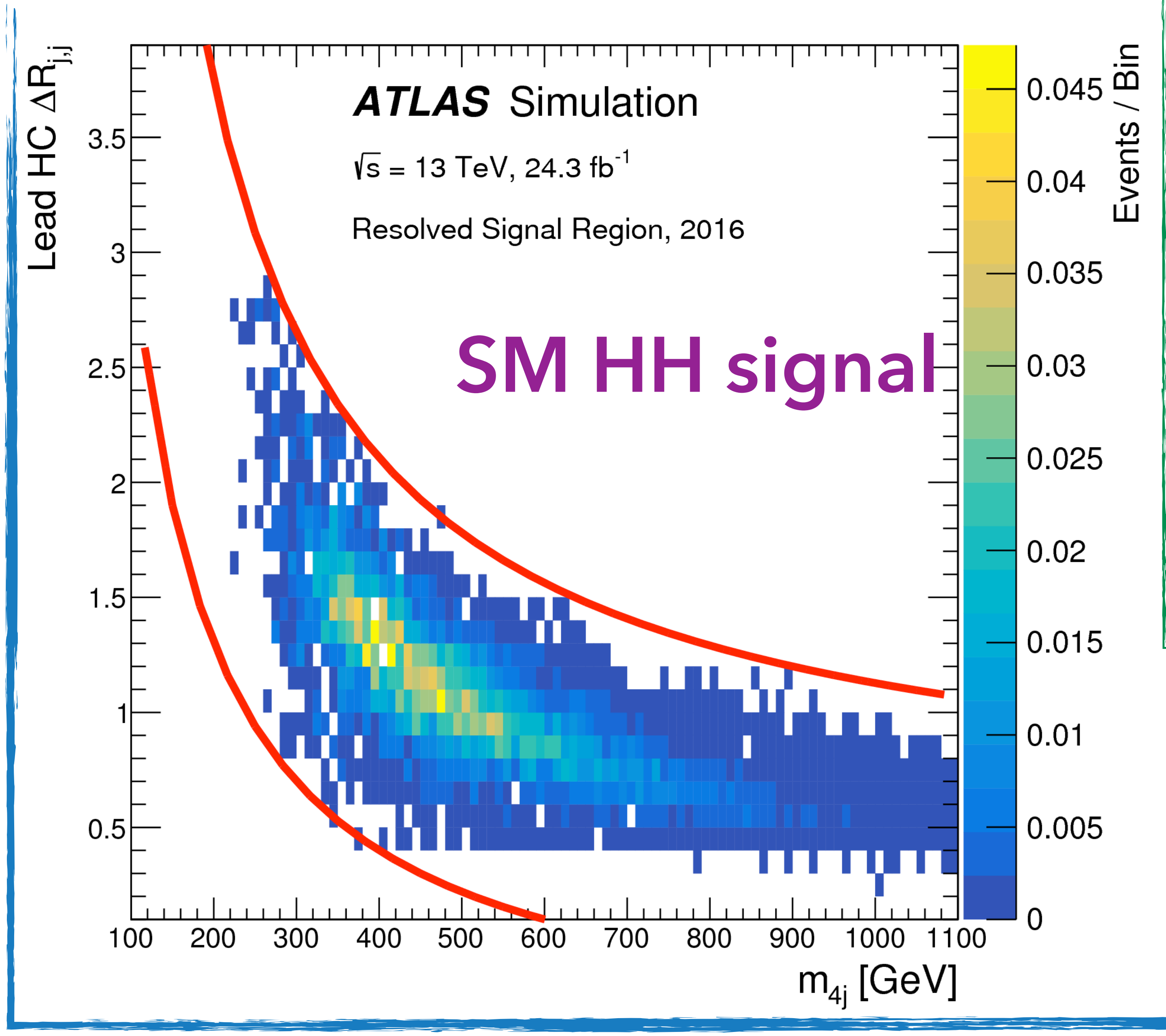
- resolved: angle between the two jets depends on the Lorentz boost, and thus the four-jet mass
    - four-jet-mass dependent cuts on ΔR(j,j) to reconstruct the two Higgs candidates
- boosted: signal eff. depends on four-jet mass (2b cat. most efficient at high mass)

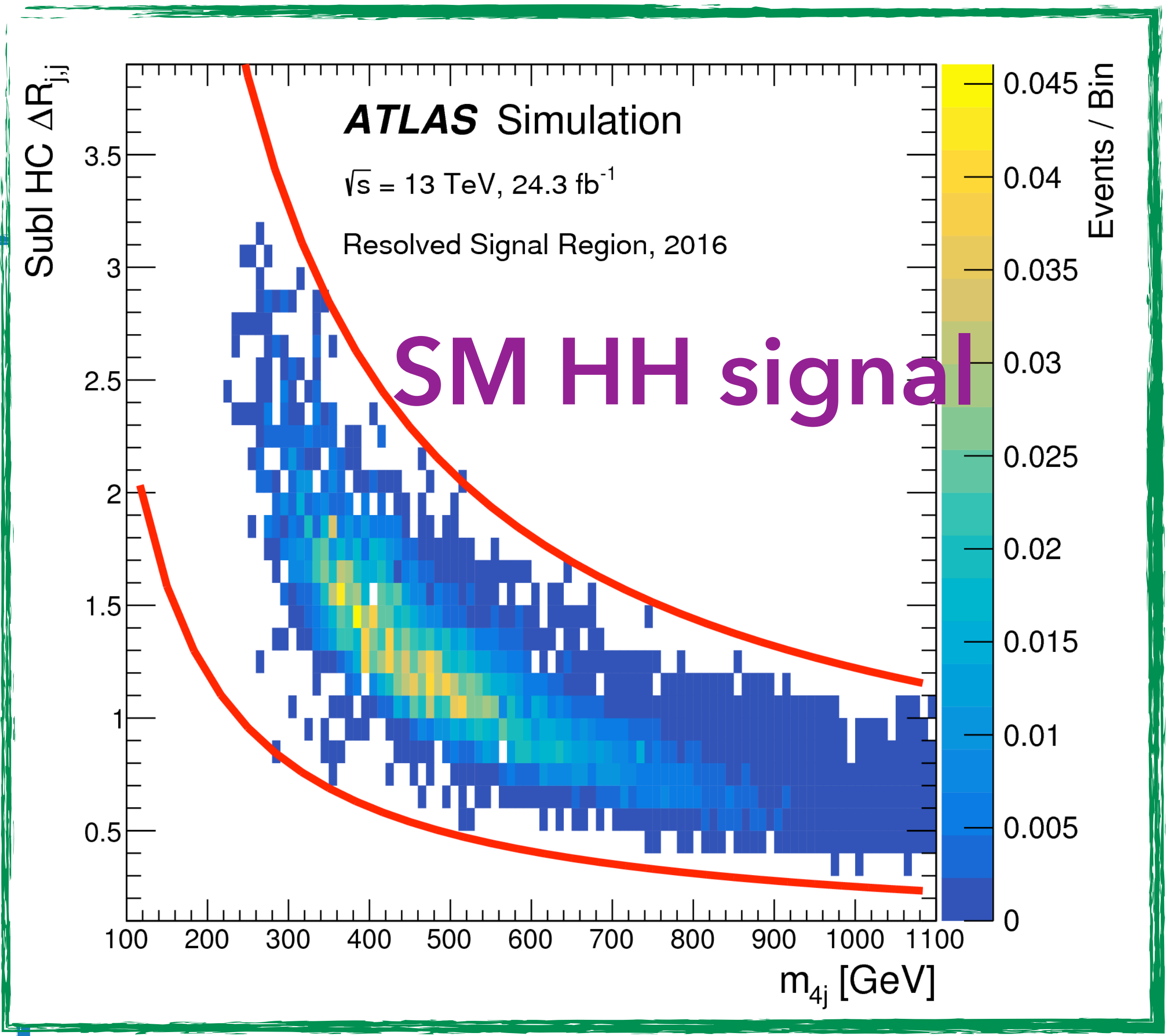
BBBB: EVENT RECONSTRUCTION



resolved





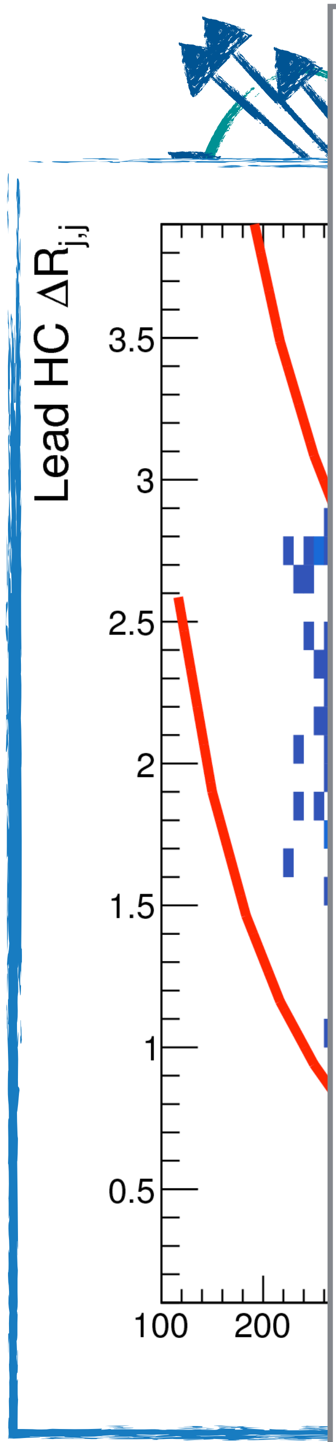


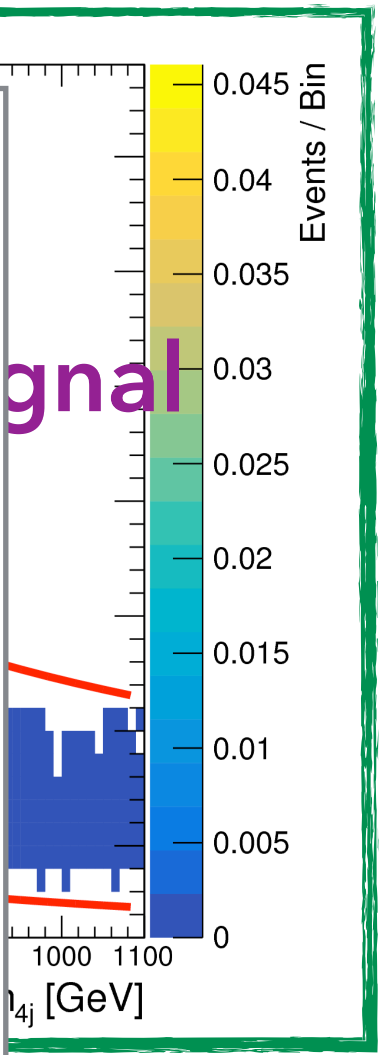
s on the Lorentz boost, and thus the

reconstruct the two Higgs

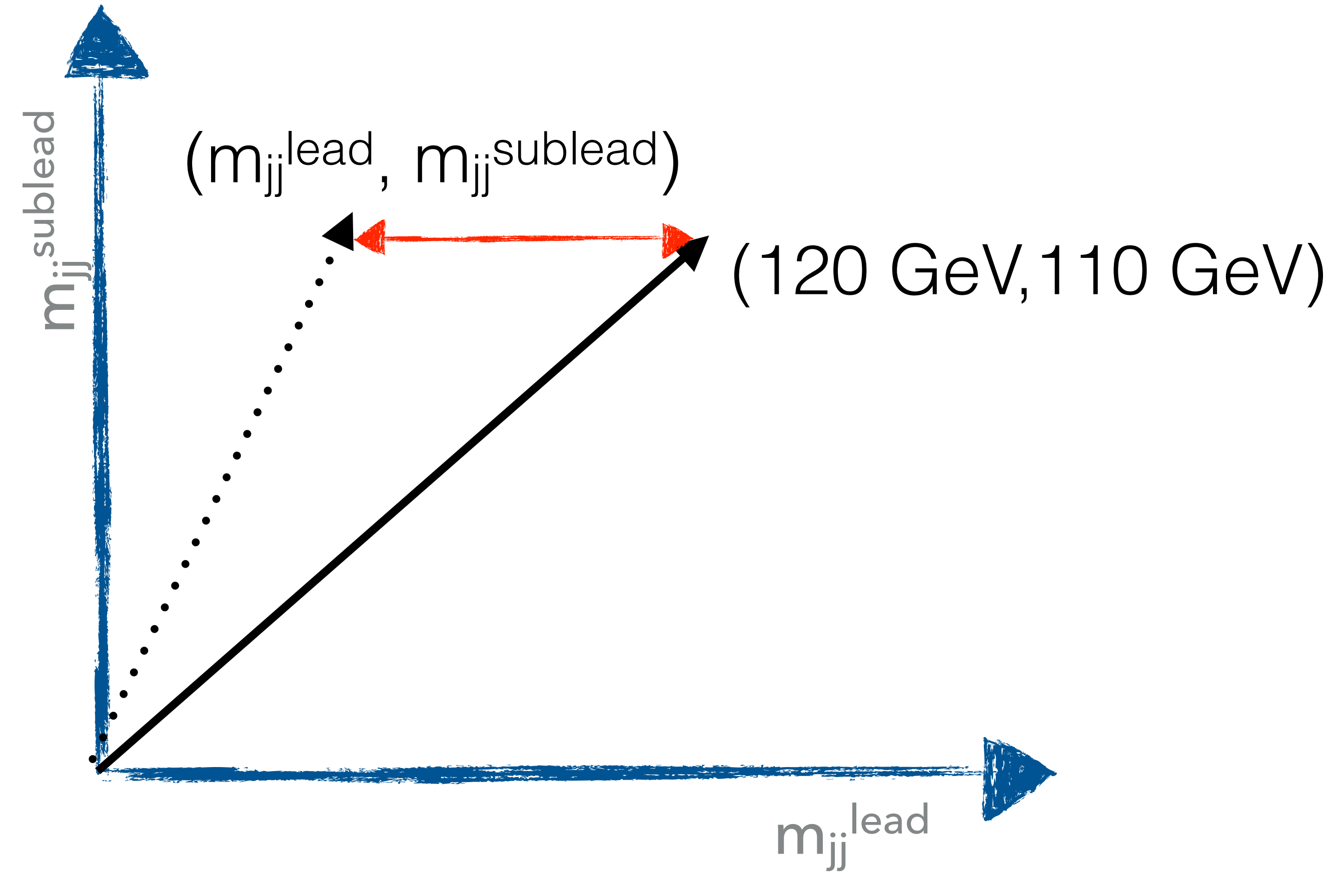
(2b cat. most efficient at high mass)

BBBB: EVENT RECONSTRUCTION





if there's still ambiguity in jet pairings (if more than two Higgs candidates can be reconstructed):

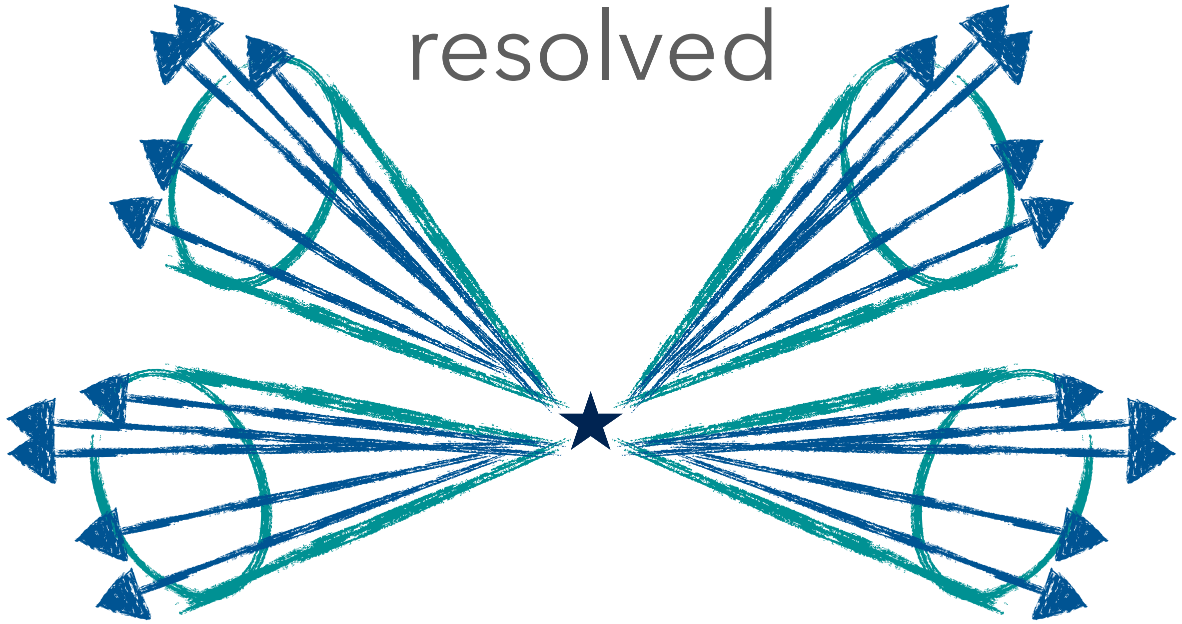


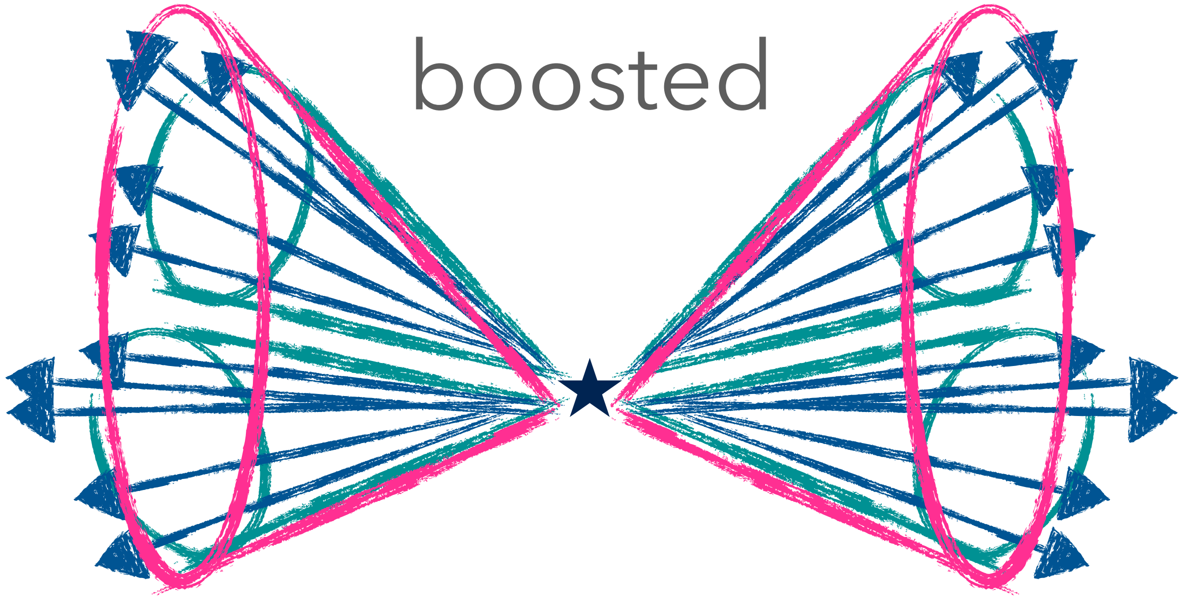
minimize distance **D_{HH}** between the Higgs candidates and the point (120 GeV, 110 GeV), determined from simulation

thus the

gh mass)

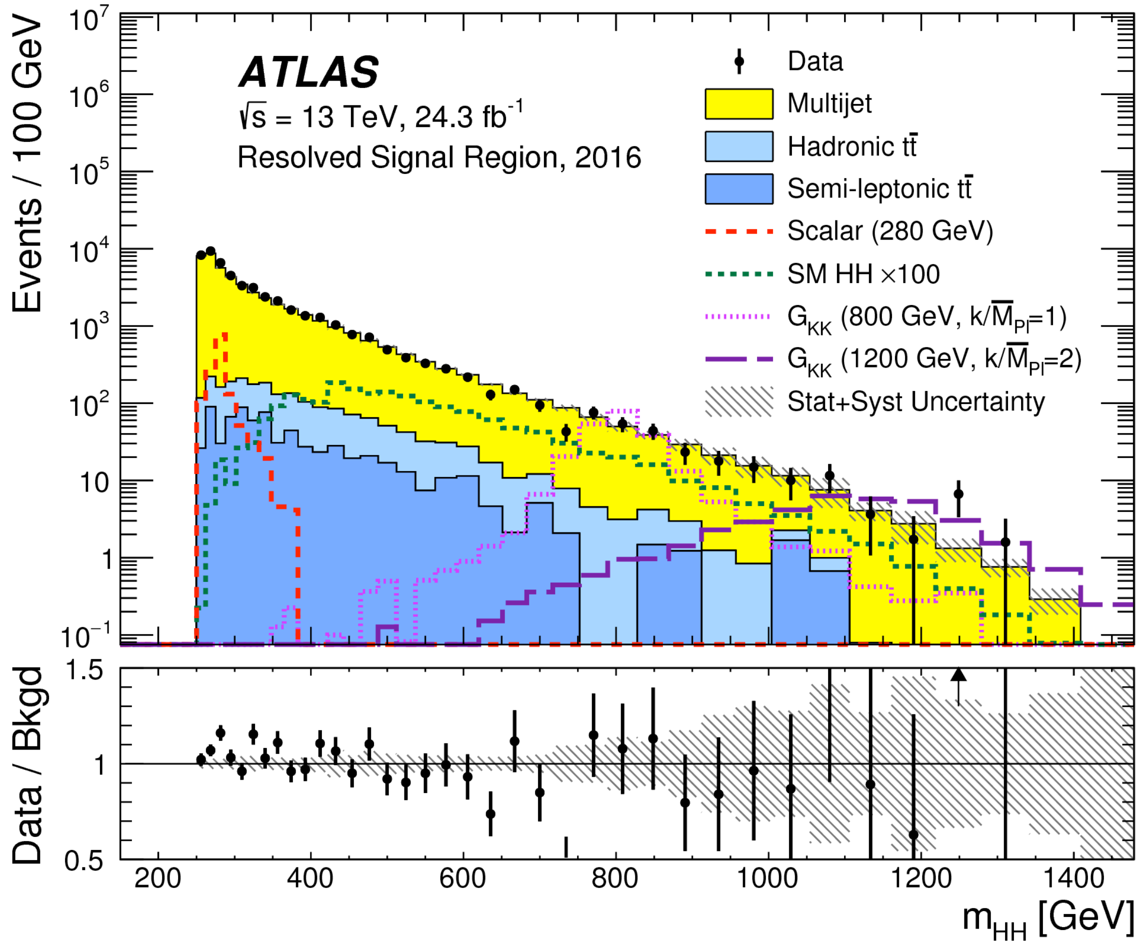
BBBB: EVENT SELECTION

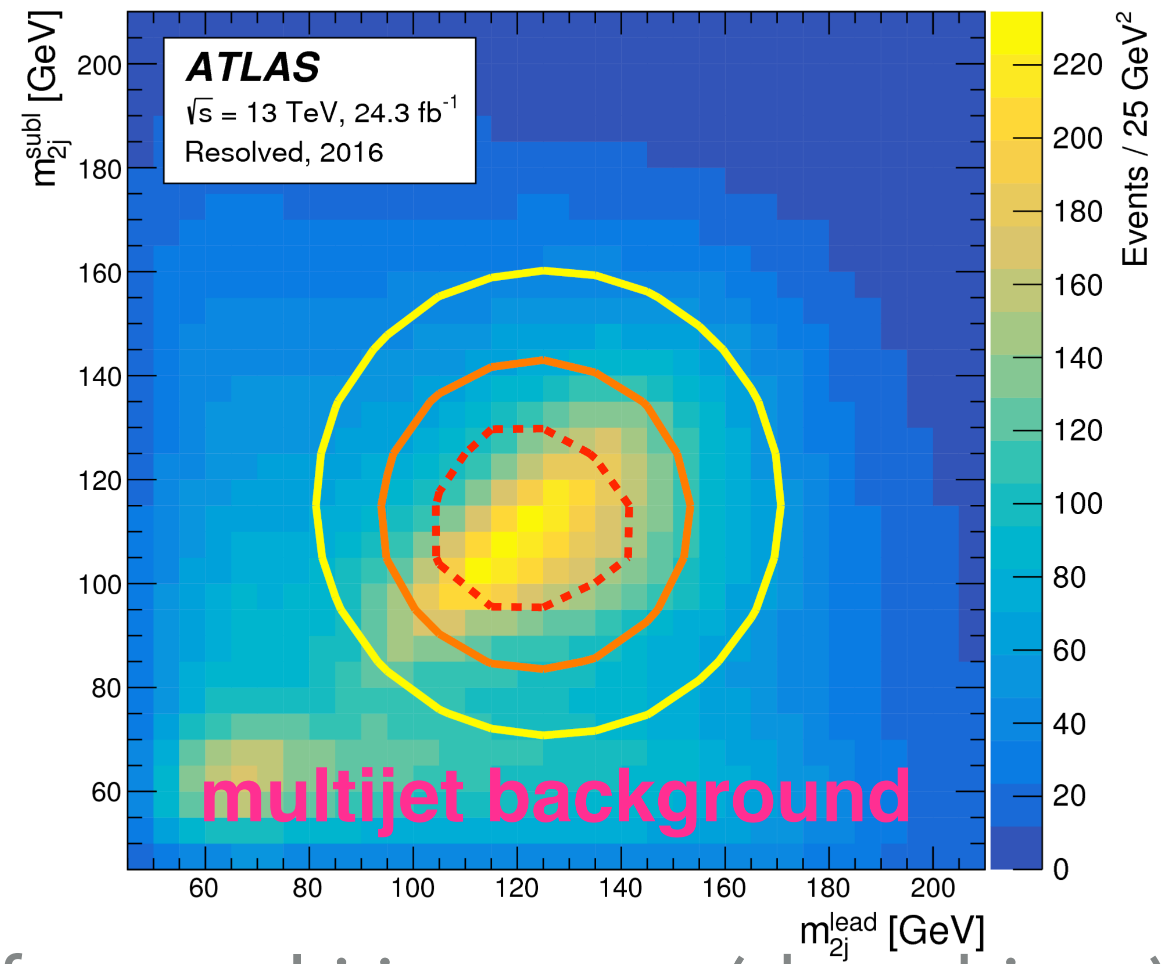




- Resolved: additional cuts on p_T of the Higgs candidates, $\Delta\eta$ between the Higgs candidates, and a top veto ($X_{Wt}=\sqrt{(m_W - 80\text{ GeV} / 0.1m_W)^2 + (m_t - 173\text{ GeV} / 0.1m_t)^2} > 1.5$)
- Resolved and boosted: Signal and control regions are defined in a ring around the Higgs mass in a 2D (m_{jj1},m_{jj2}) plane – background is data-driven, using control regions

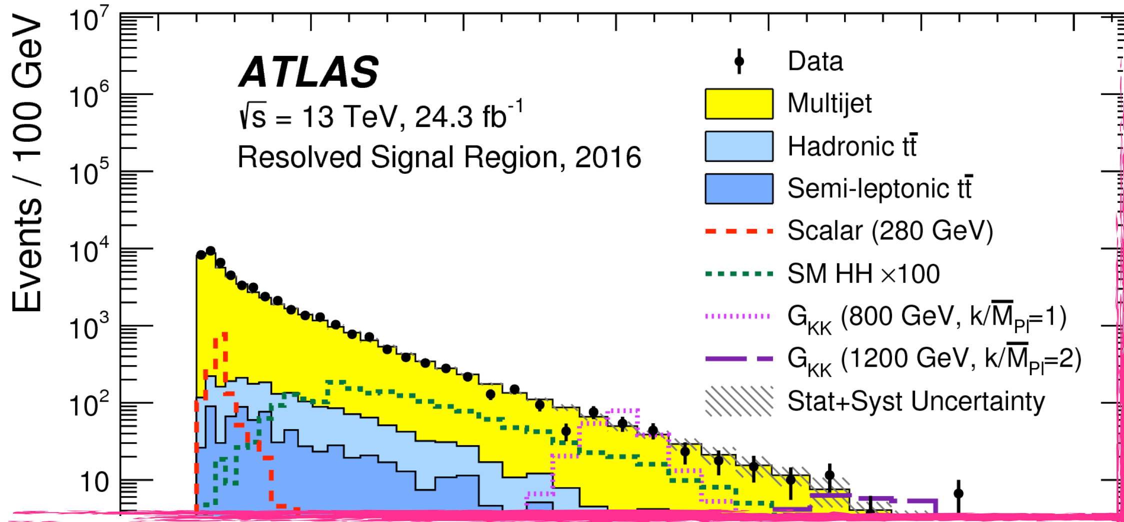
BBBB BACKGROUND MODELING

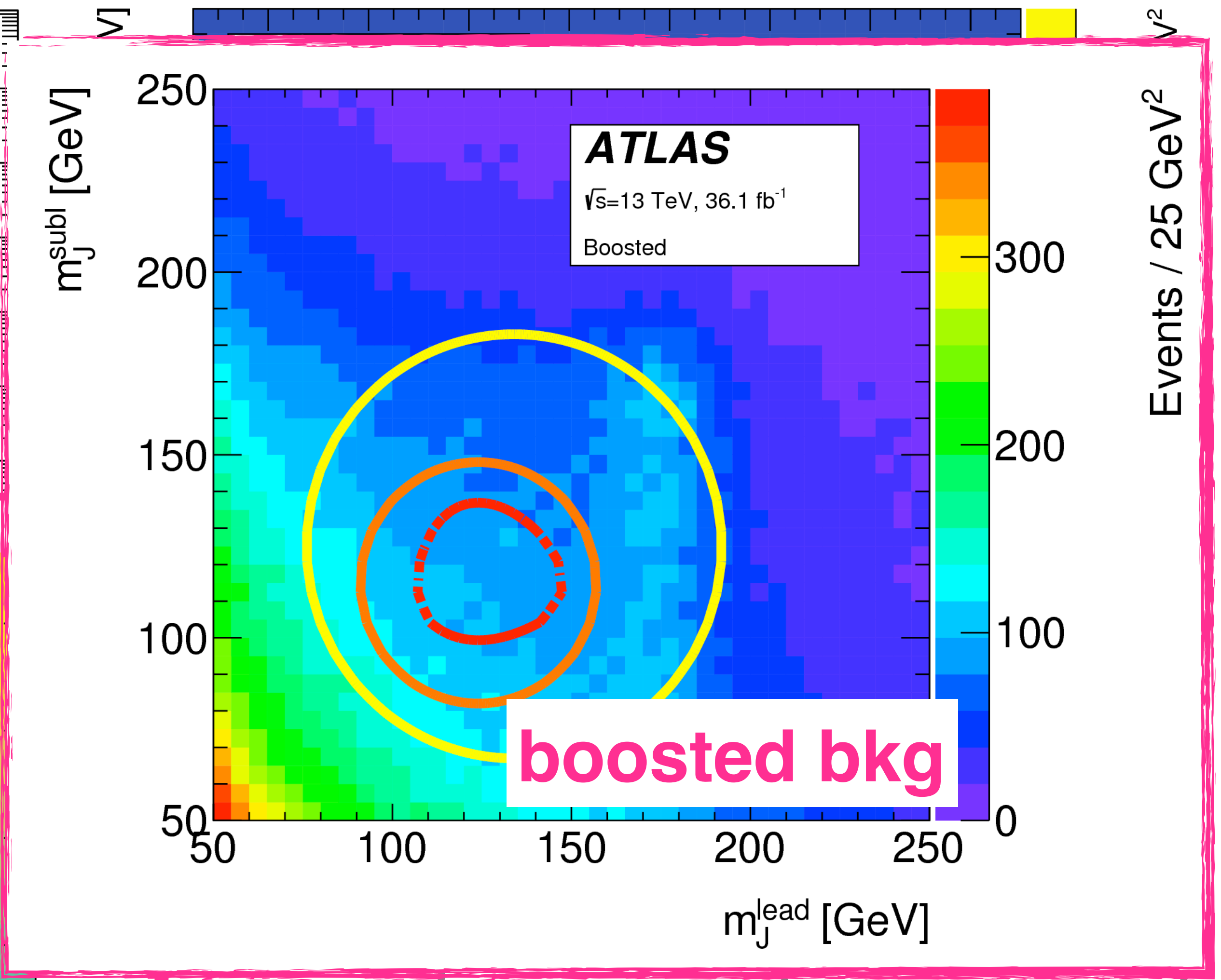


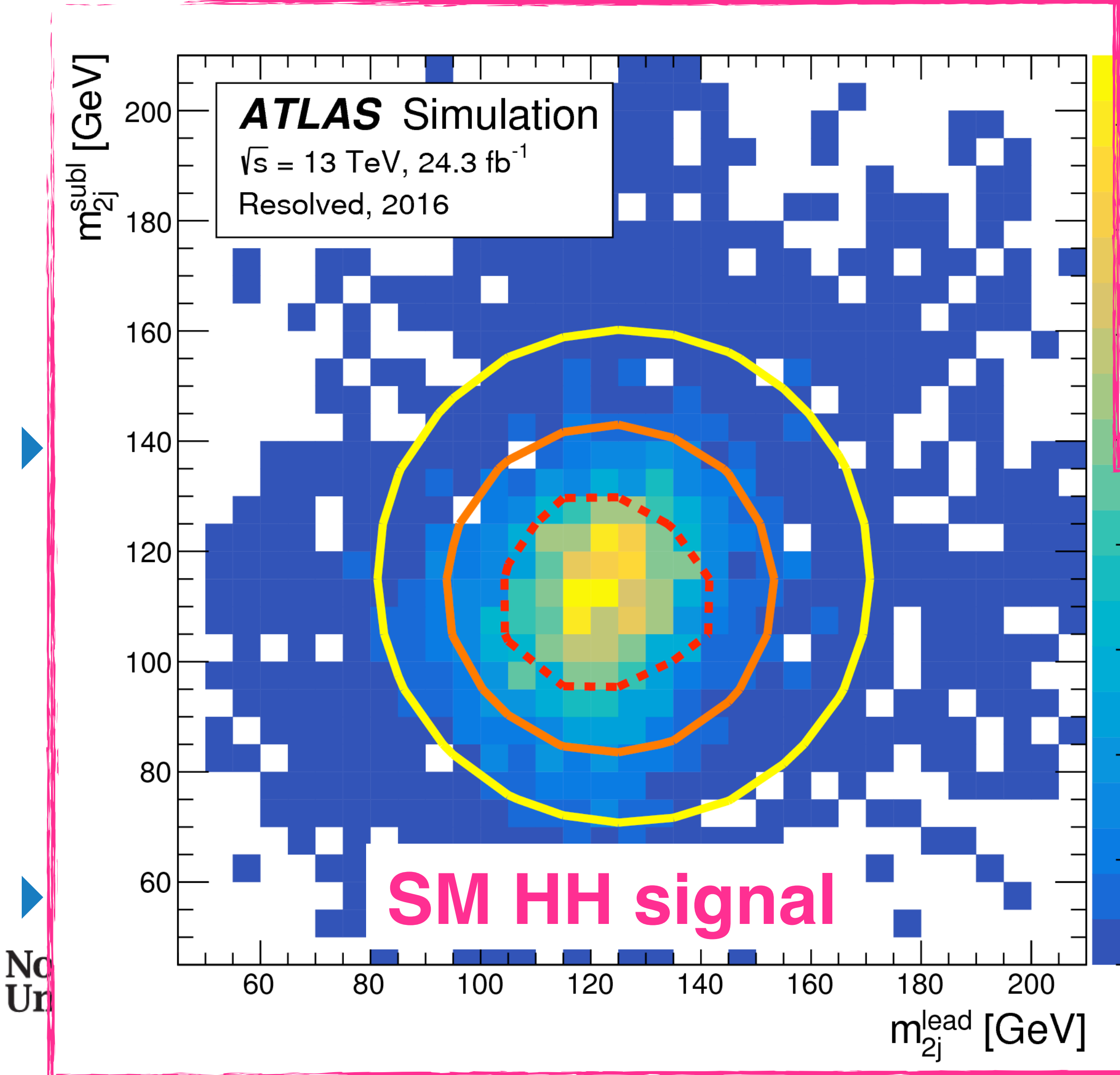


- resolved: ~95% of background is from multi-jet events (data-driven)
    - Define signal, control, and sideband regions in 2-tag selection
    - Multi-jet background is estimated in sidebands and reweighted to correct for differences between 2- and 4-tag selections
- Similar method in boosted analysis using N_{btags}

BBBB BACKGROUND MODELING







j

nd regions in 2-tag selection

in sidebands and reweighted

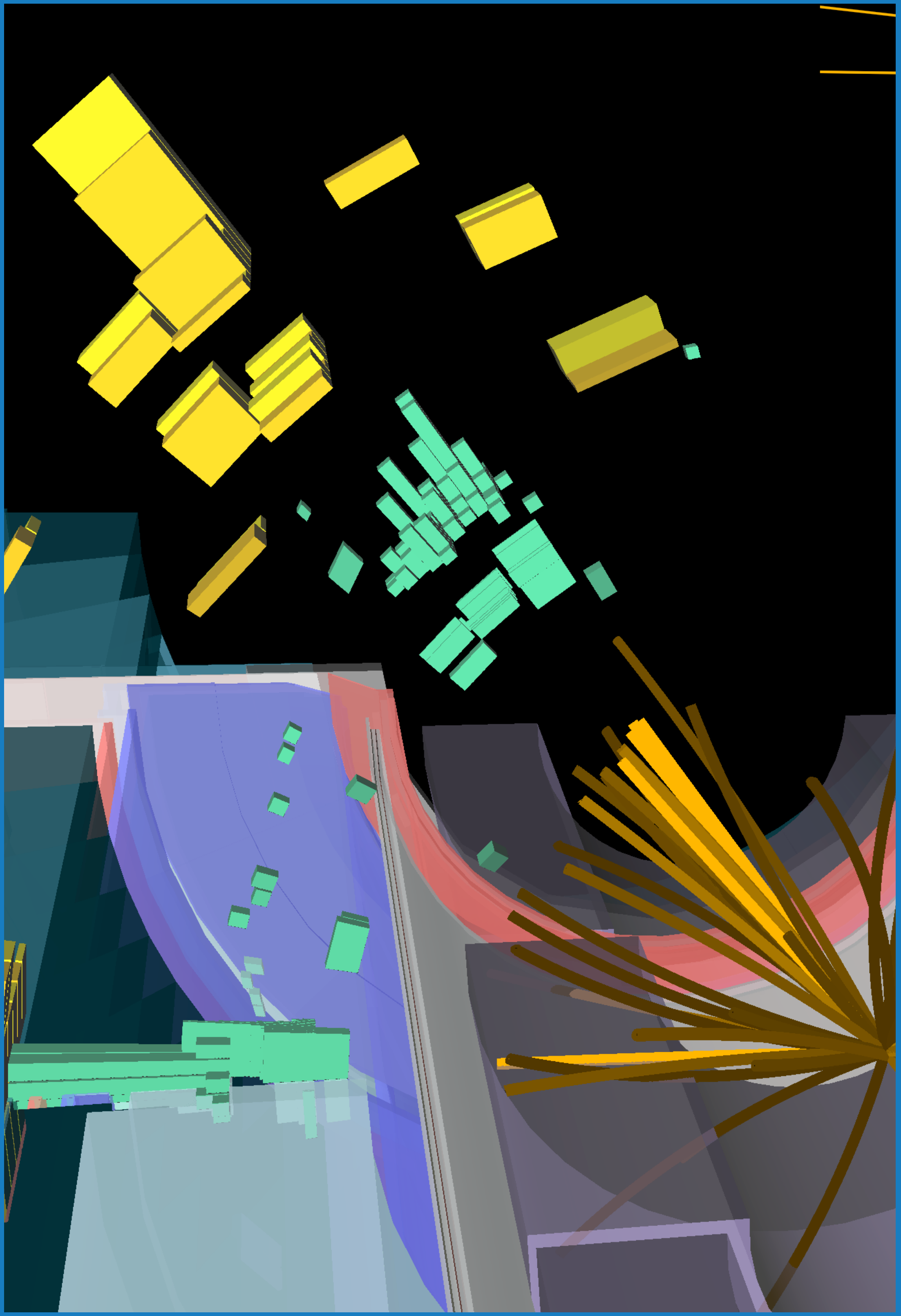
2- and 4-tag selections

sing N_{btags}

BBBB: RESOLVED SYSTEMATICS

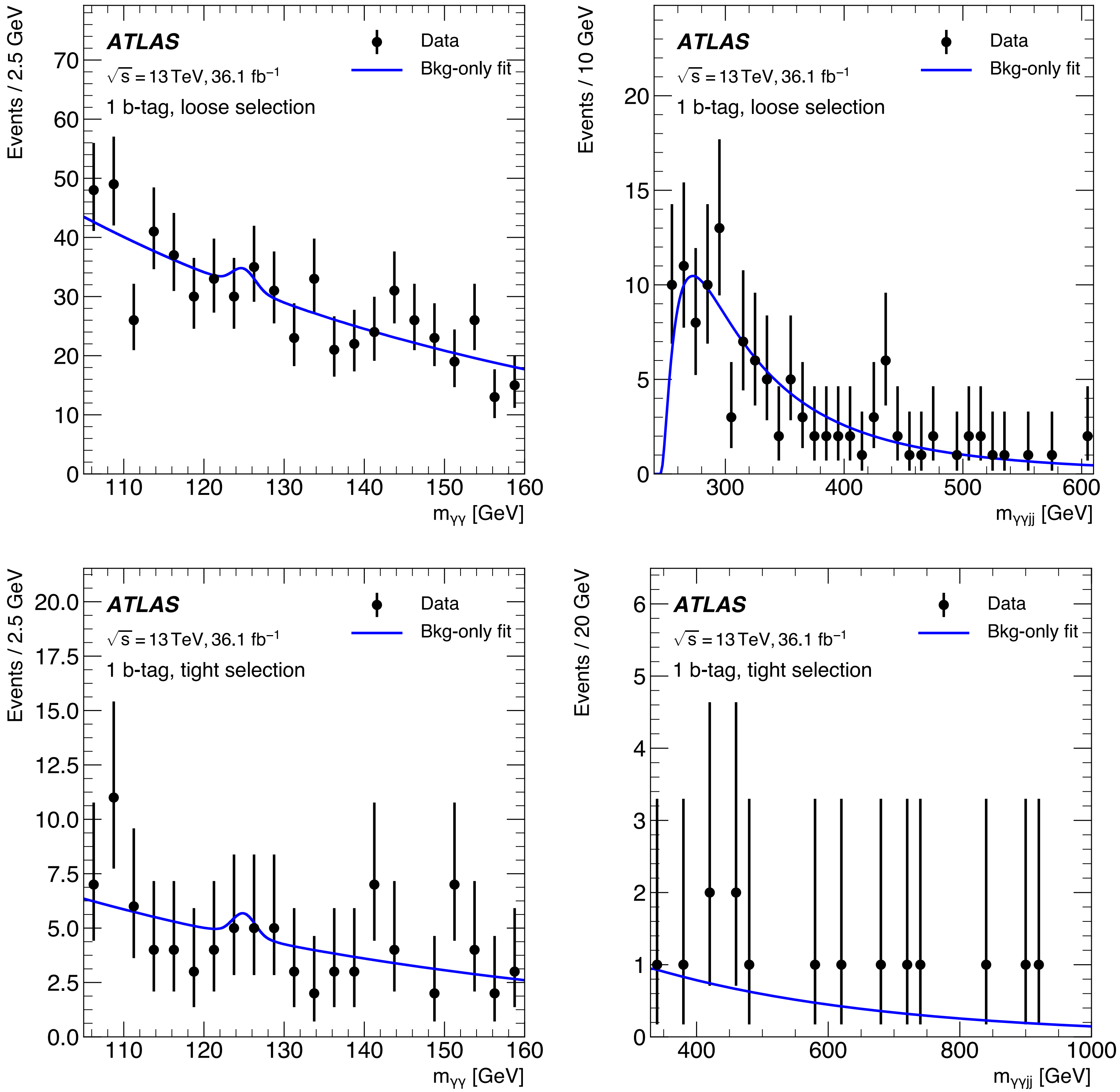
- largest systematic uncertainties from: JES, flavor-tagging

	2015				2016			
Source	Background	Scalar	SM HH	G_{KK}	Background	Scalar	SM HH	G_{KK}
Luminosity	–	2.1	2.1	2.1	–	2.2	2.2	2.2
Jet energy	–	17	7.1	3.7	–	17	6.4	3.7
b-tagging	–	13	12	14	–	13	12	14
b-trigger	–	4.0	2.3	1.3	–	2.6	2.5	2.5
Theoretical	–	23	7.2	0.6	–	23	7.2	0.6
Multijet stat	4.2	–	–	–	1.5	–	–	–
Multijet syst	6.1	–	–	–	1.8	–	–	–
$t\bar{t}$ stat	2.1	–	–	–	0.8	–	–	–
$t\bar{t}$ syst	3.5	–	–	–	0.3	–	–	–
Total	7.5	31	16	15	1.8	31	16	15



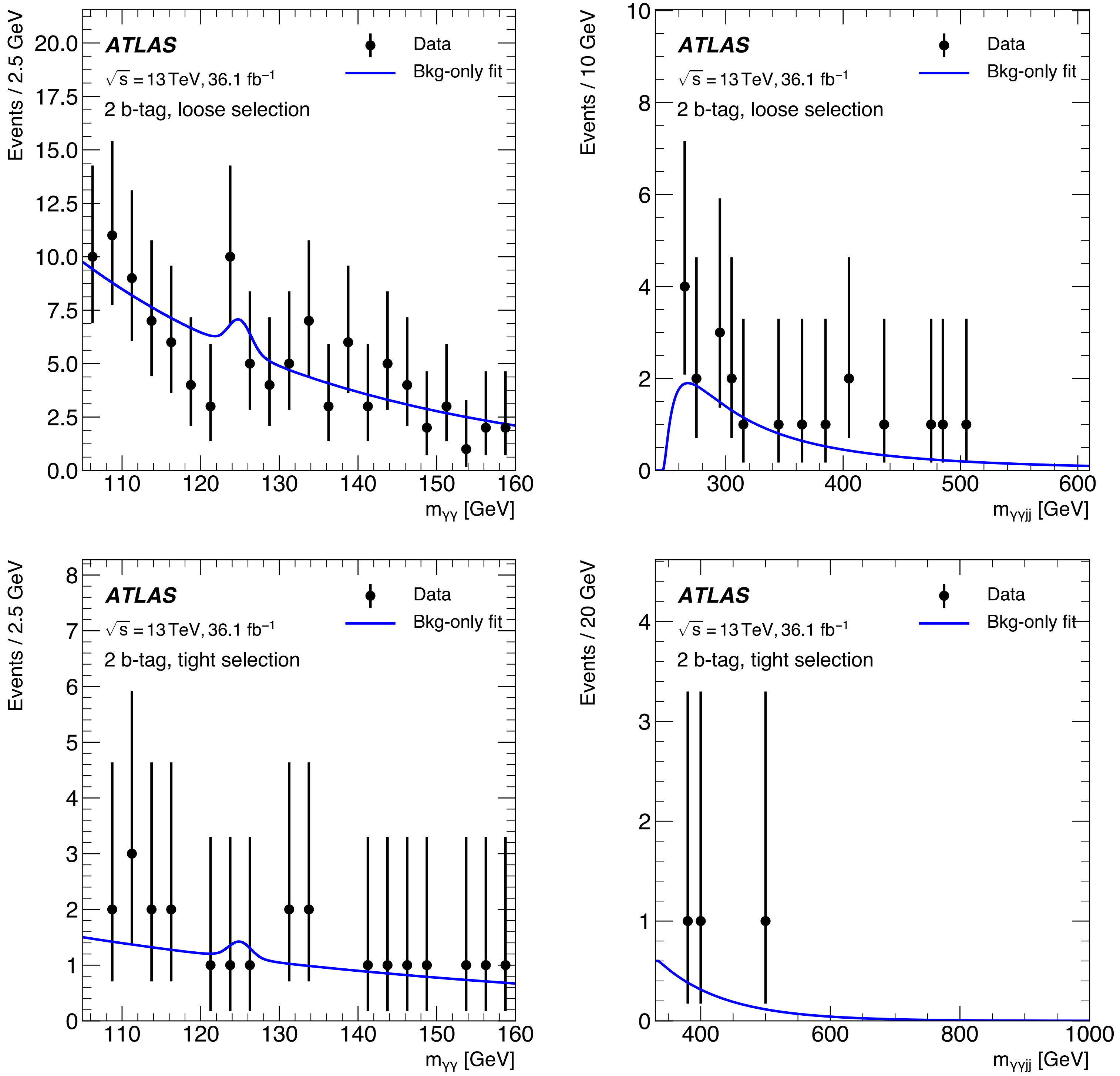
RESULTS + COMBINATION

YYBB: COMPARISON OF DATA TO BACKGROUND-ONLY FIT



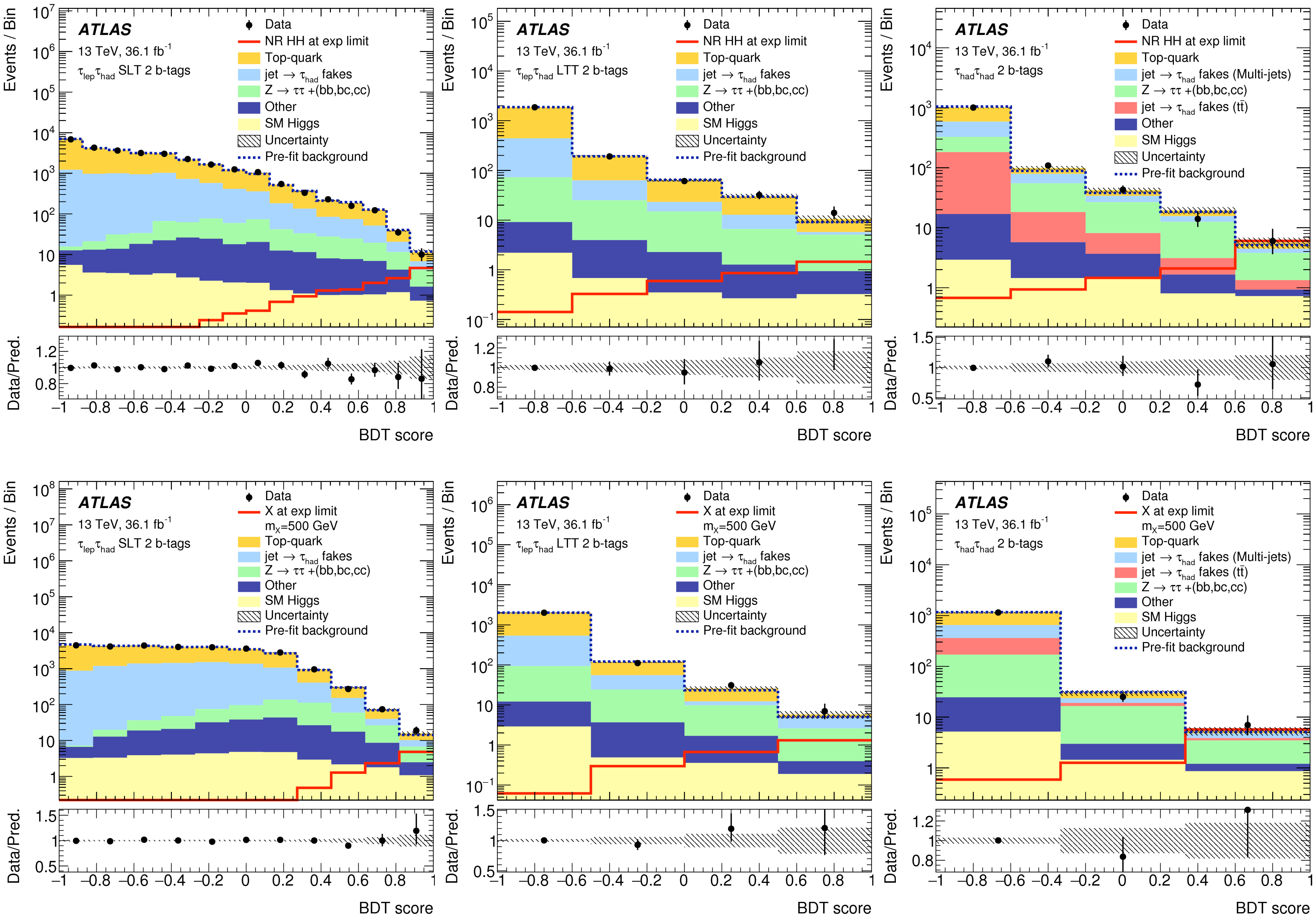
- Fit 1- and 2 b-tag categories in data simultaneously
- Best fit non-resonant signal: 0.04 pb (–0.21 pb) for loose (tight) selection
- Best-fit resonant signal: at 480 GeV (local significance of 1.2σ)
- No significant excess observed → set limits

YYBB: COMPARISON OF DATA TO BACKGROUND-ONLY FIT



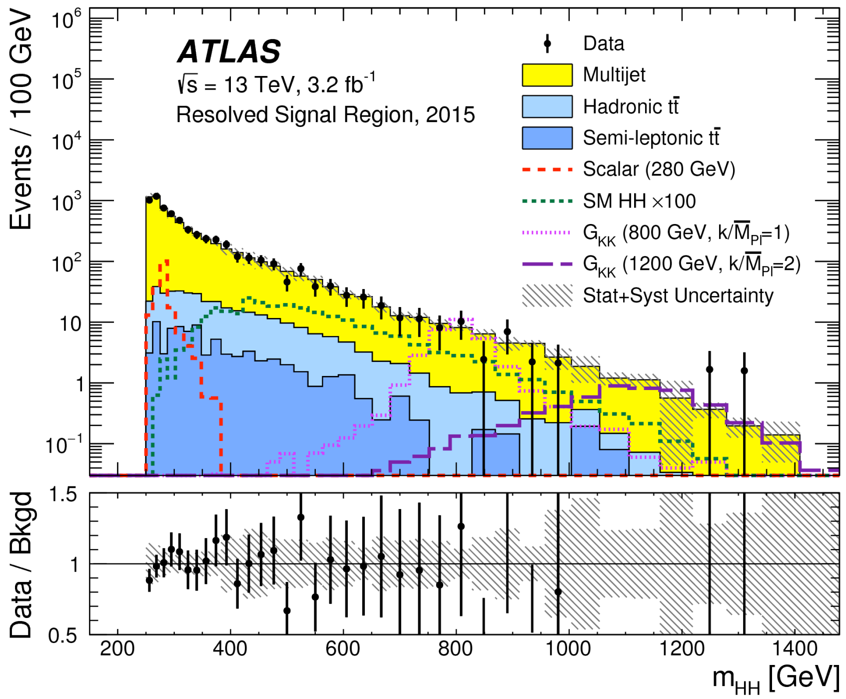
- Fit 1- and **2 b-tag** categories in data simultaneously
- Best fit non-resonant signal: 0.04 pb (-0.21 pb) for loose (tight) selection
- Best-fit resonant signal: at 480 GeV (local significance of 1.2σ)
- No significant excess observed → set limits

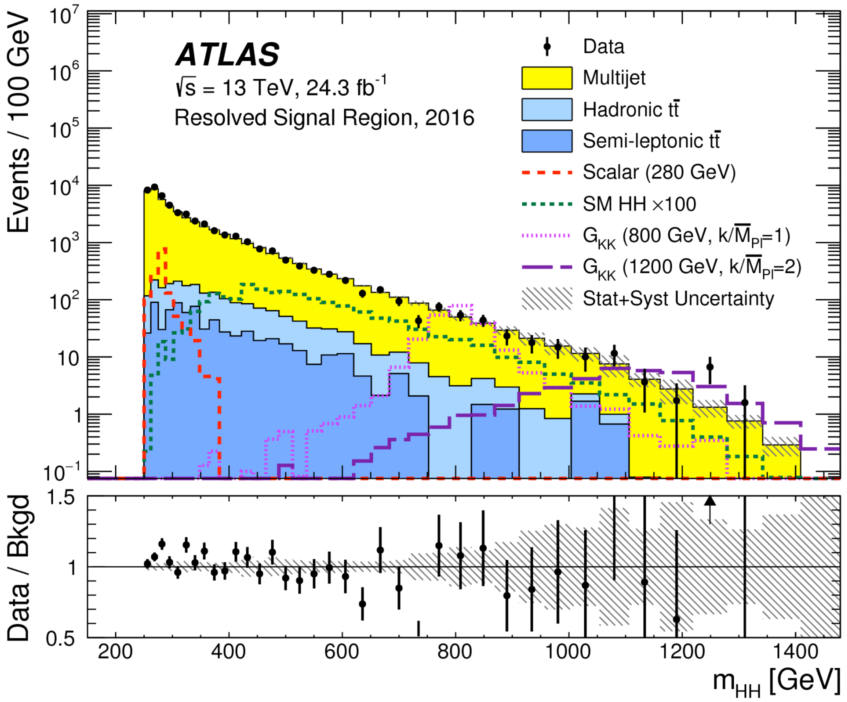
BBTAUTAU: COMPARISON OF DATA TO BDT OUTPUT

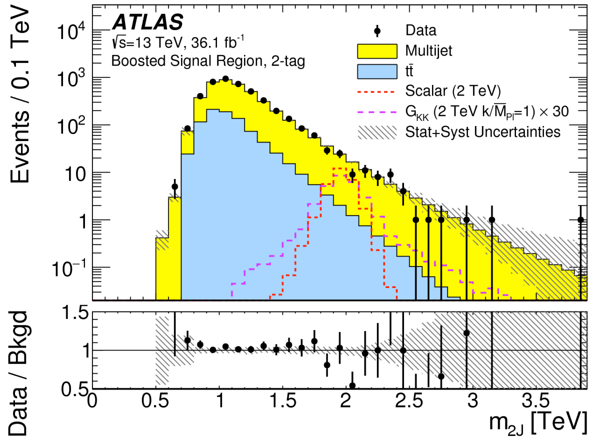


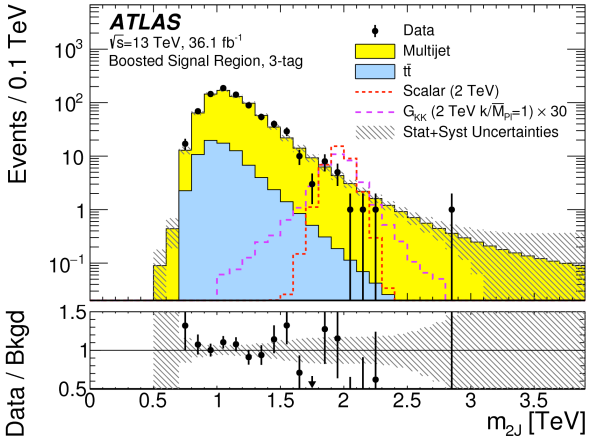
- Simultaneous fit of three categories (lep+had SLT, LTT and had+had)
- Z+HF normalization from control region
- ttbar normalization from the low BDT score region of lep+had SLT
- No significant excess observed → set limits

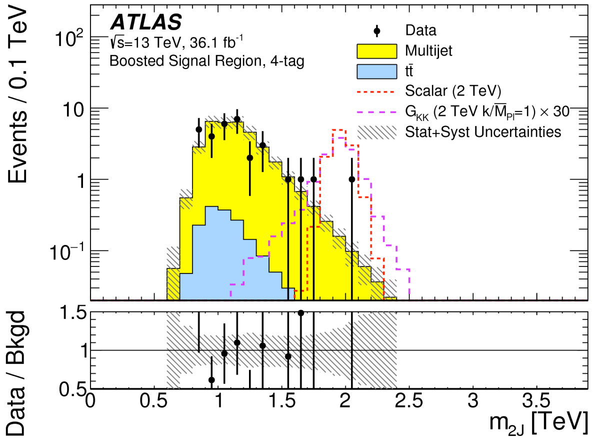
BBBB: COMPARISON OF DATA TO BACKGROUND MODEL







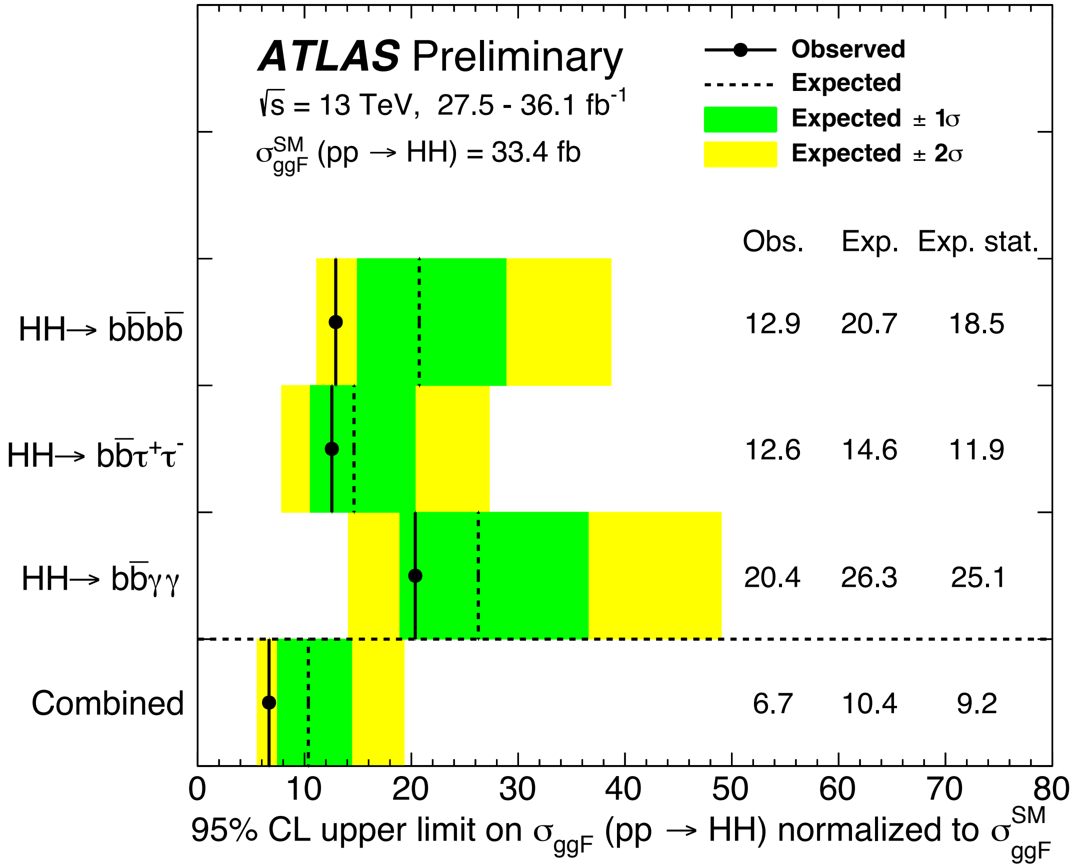




- Profile likelihood fit to 2015+2016 data simultaneously (resolved) and 2-, 3-, and 4-tag signal regions (boosted)
- The largest deviation from the background-only hypothesis is at 280 GeV (2.3σ global significance)
- no significant excess observed → set limits

NON-RESONANT LIMITS: HH CROSS SECTION

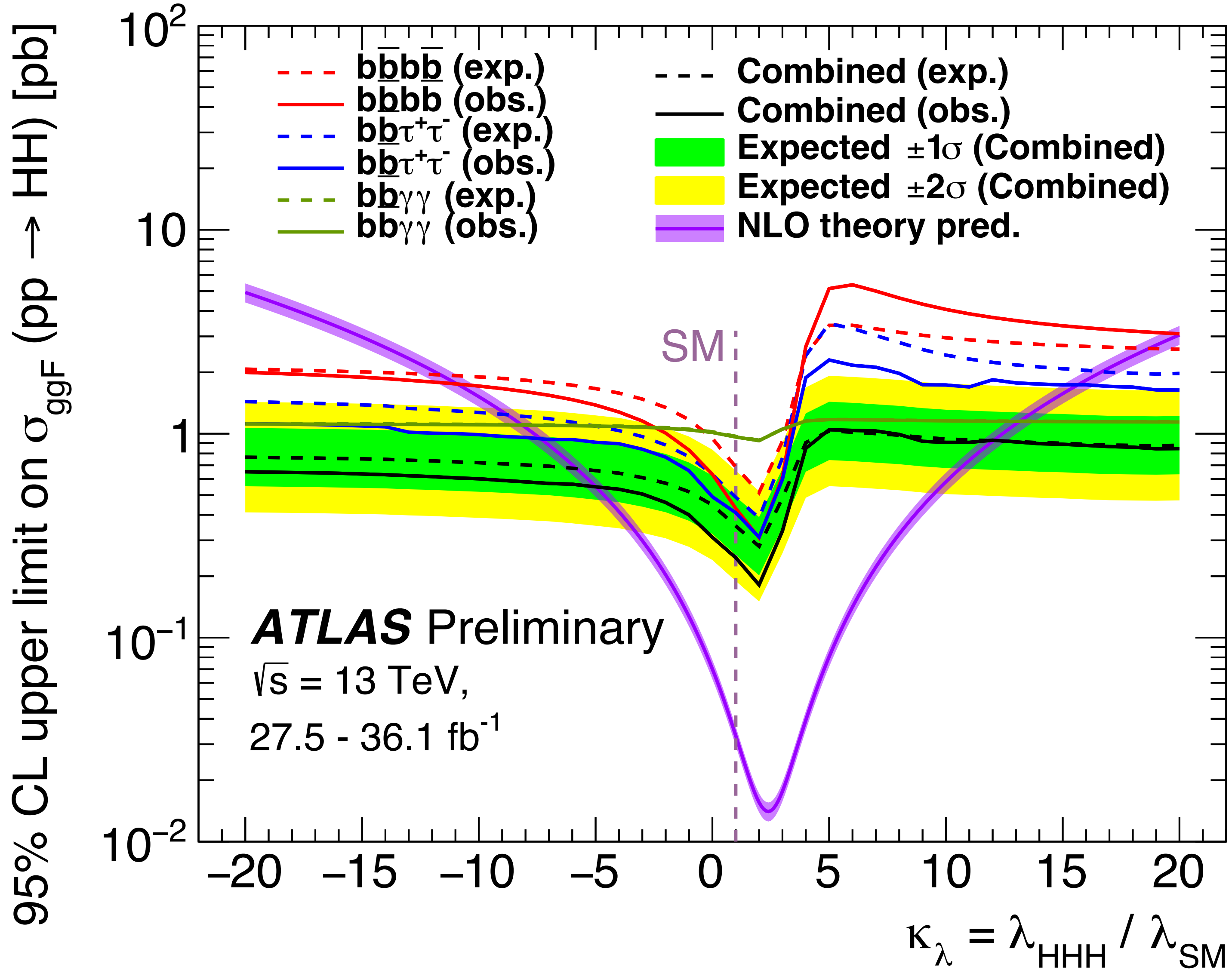
brand new!



	observed	expected
HH → γγbb	20.4*σ_{SM}	26.3*σ_{SM}
HH → bb**ττ**	12.6*σ_{SM}	14.6*σ_{SM}
HH → bbbb	12.9*σ_{SM}	20.7*σ_{SM}
combination	6.7*σ_{SM}	10.4*σ_{SM}

n.b. these are slightly different than the published γγbb limits, since this analysis uses asymptotics

NON-RESONANT LIMITS: HIGGS SELF-COUPLING



HH → bbbb

HH → bbττ

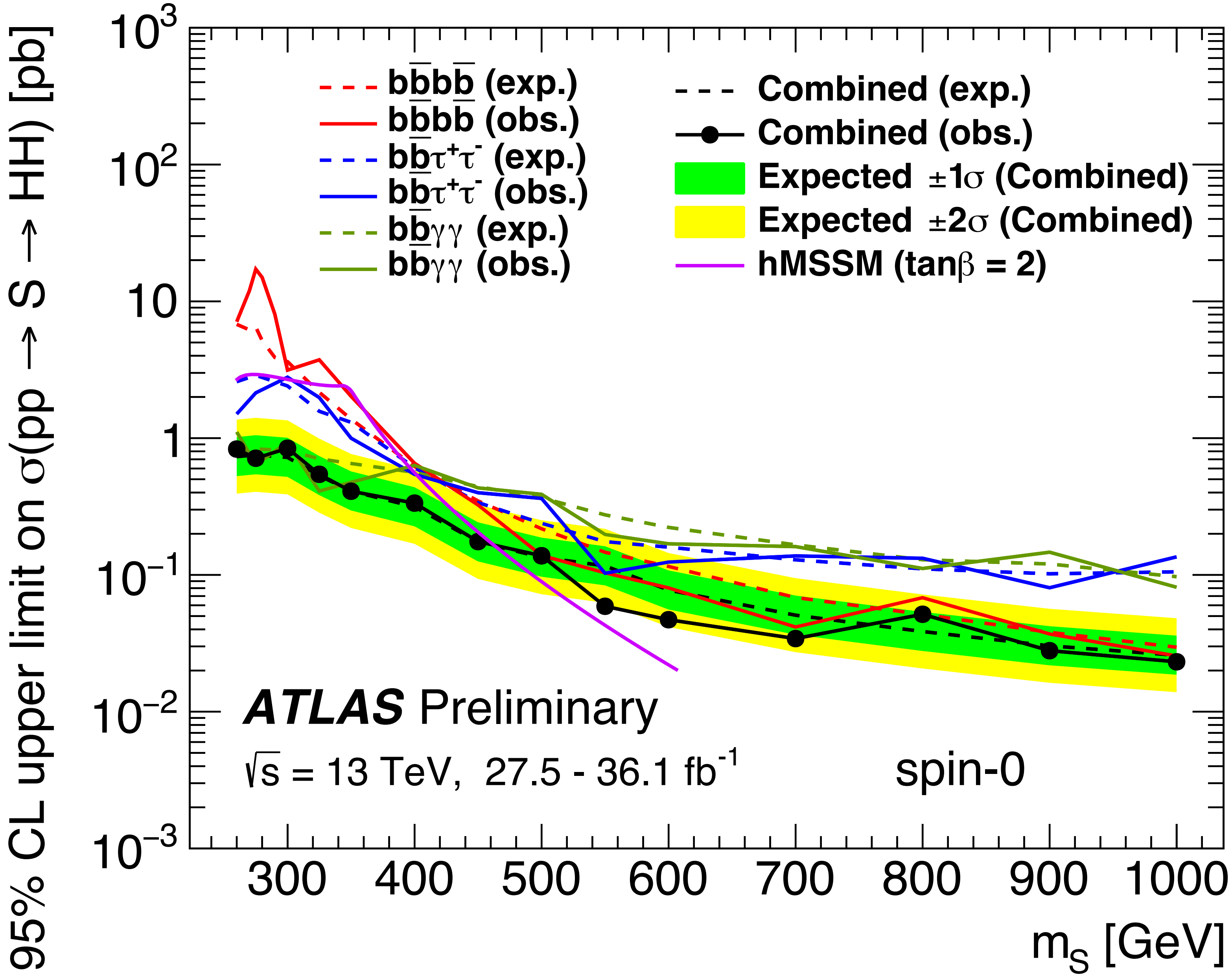
HH → γγbb

dashed: expected

solid: observed

observed (expected) limits: $-5.0 < \kappa_\lambda \equiv \lambda_{HHH}/\lambda_{SM} < 12.1$ ($-5.8 < \kappa_\lambda < 12.0$)

RESONANT LIMITS: XS(X)*BR(X → HH)



HH → bbbb

HH → bbττ

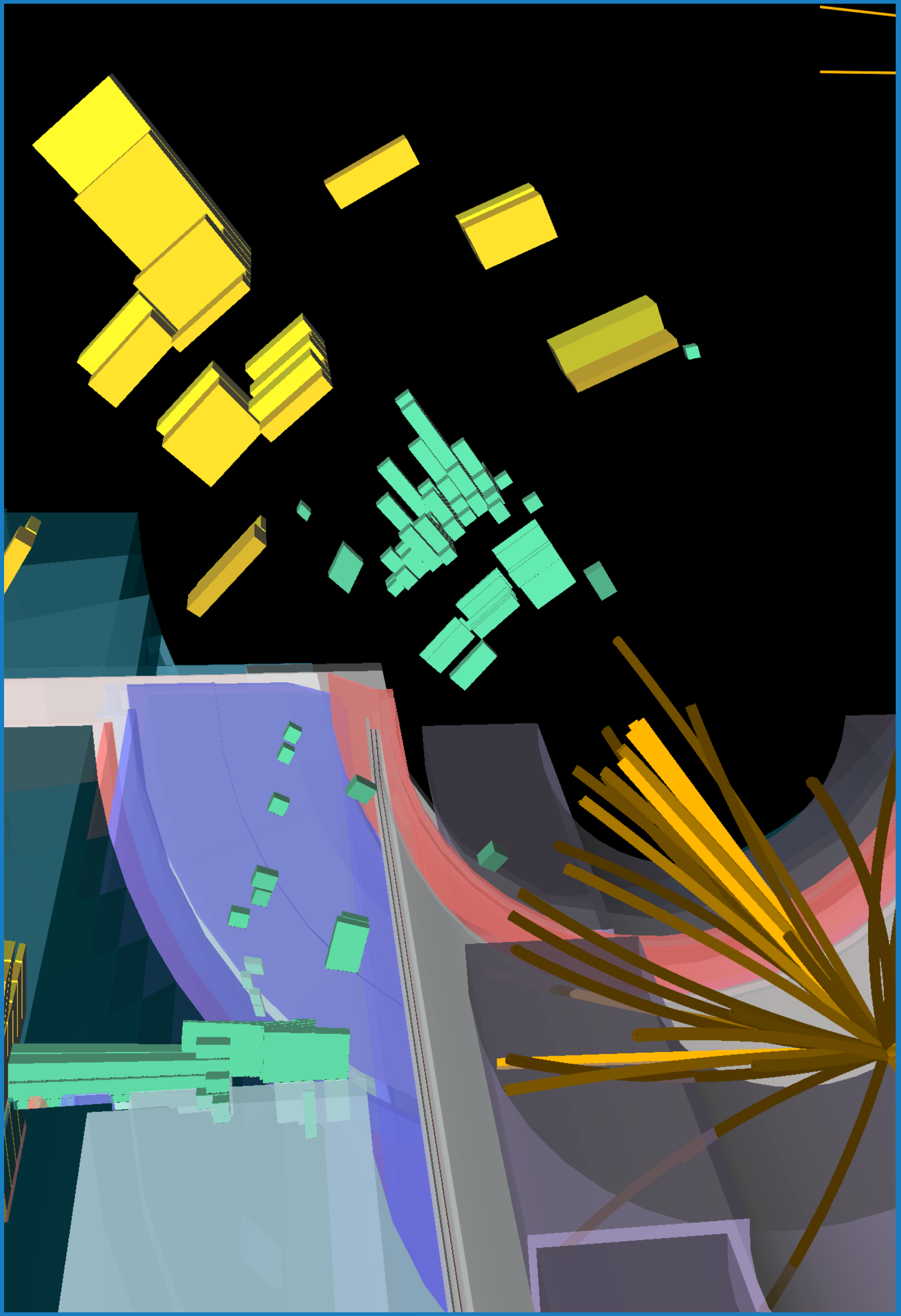
HH → γγbb

dashed: expected

solid: observed

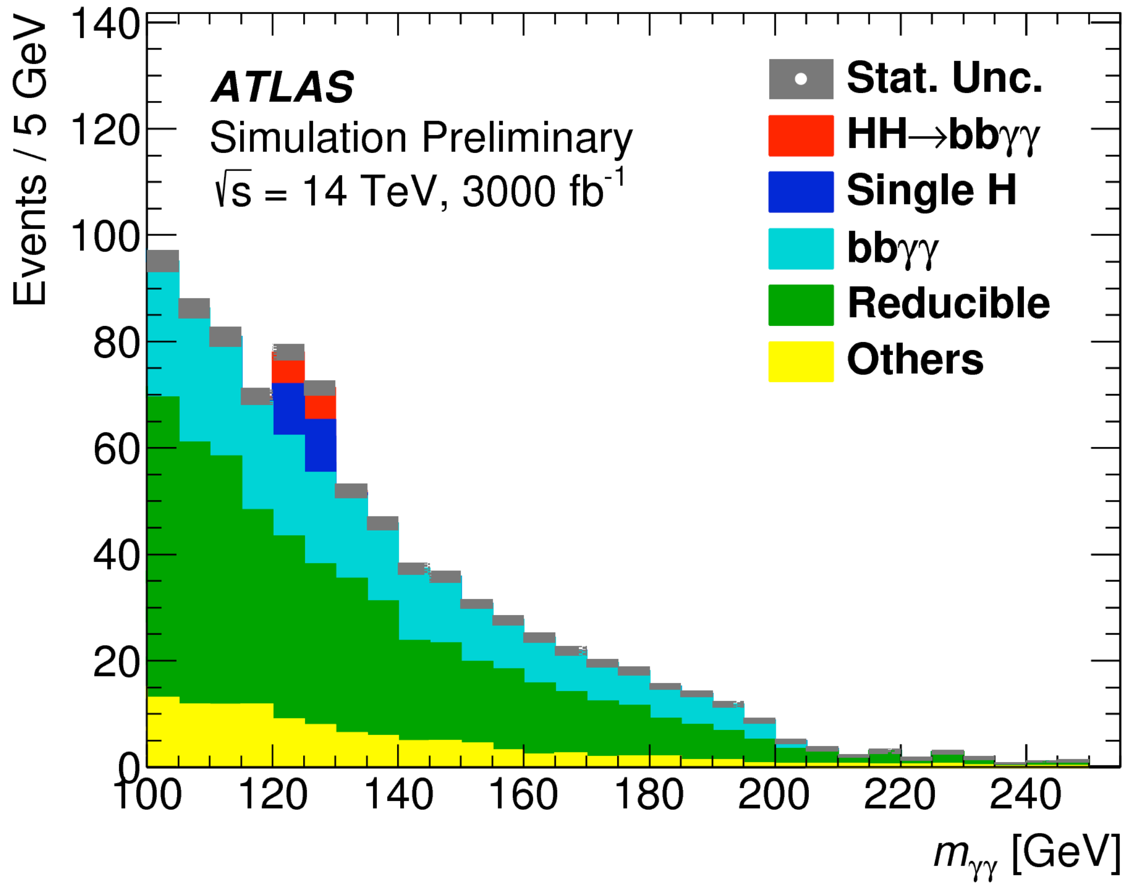
FUTURE: HOW TO IMPROVE?

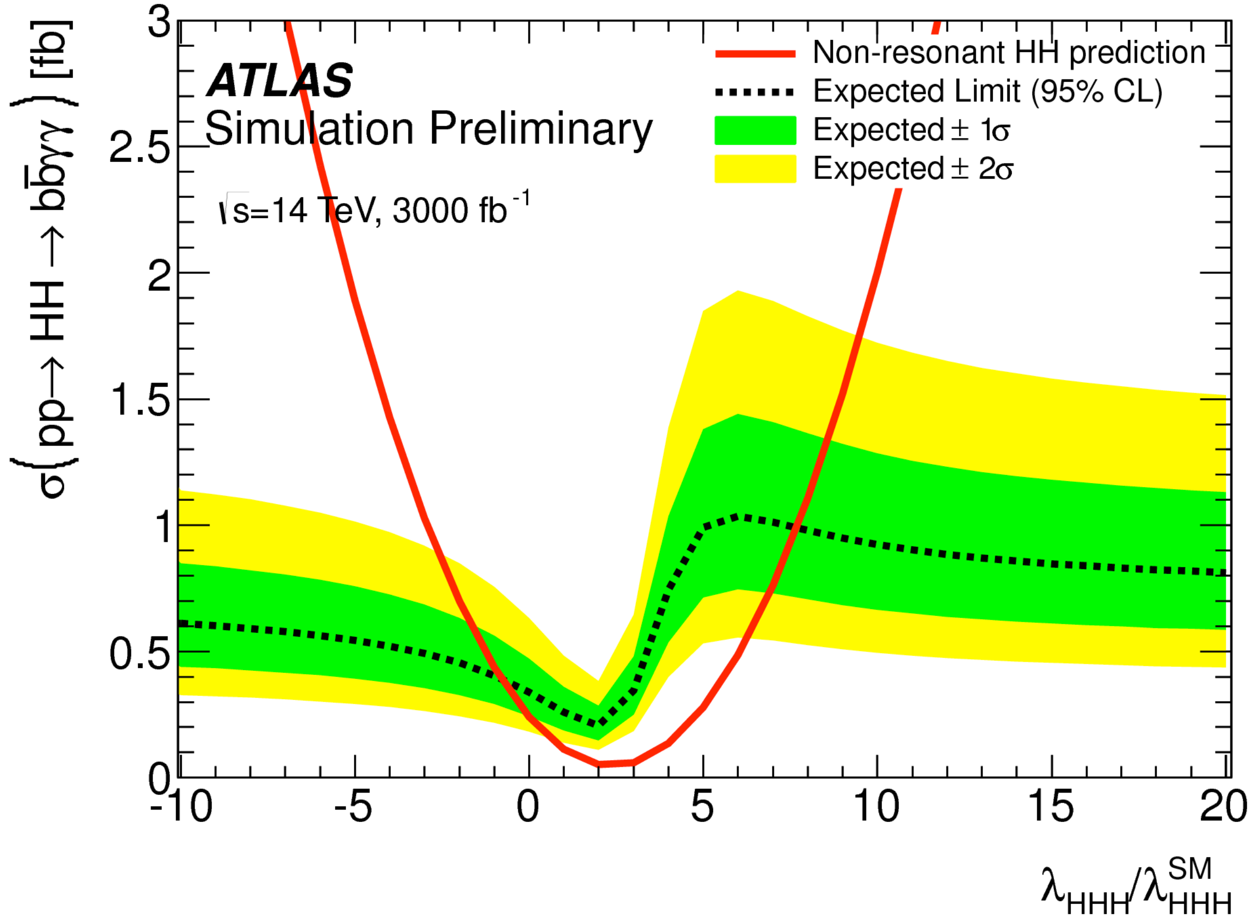
- Searches are still stats-limited, so the full Run 2 dataset (150/fb, which we will have in hand in less than a month) will improve our reach
- Studying the use of more complex analysis strategies, such as multivariate algorithms (bb$\tau\tau$ already uses a BDT to discriminate between signal and background)
- Current analyses only consider the ggF production mode – VBF production is 7% of the Higgs cross section, and we can make use of the unique event topology to improve S/B
- Keep efficient trigger strategies, even with more difficult machine conditions



PROSPECTS FOR THE HL-LHC

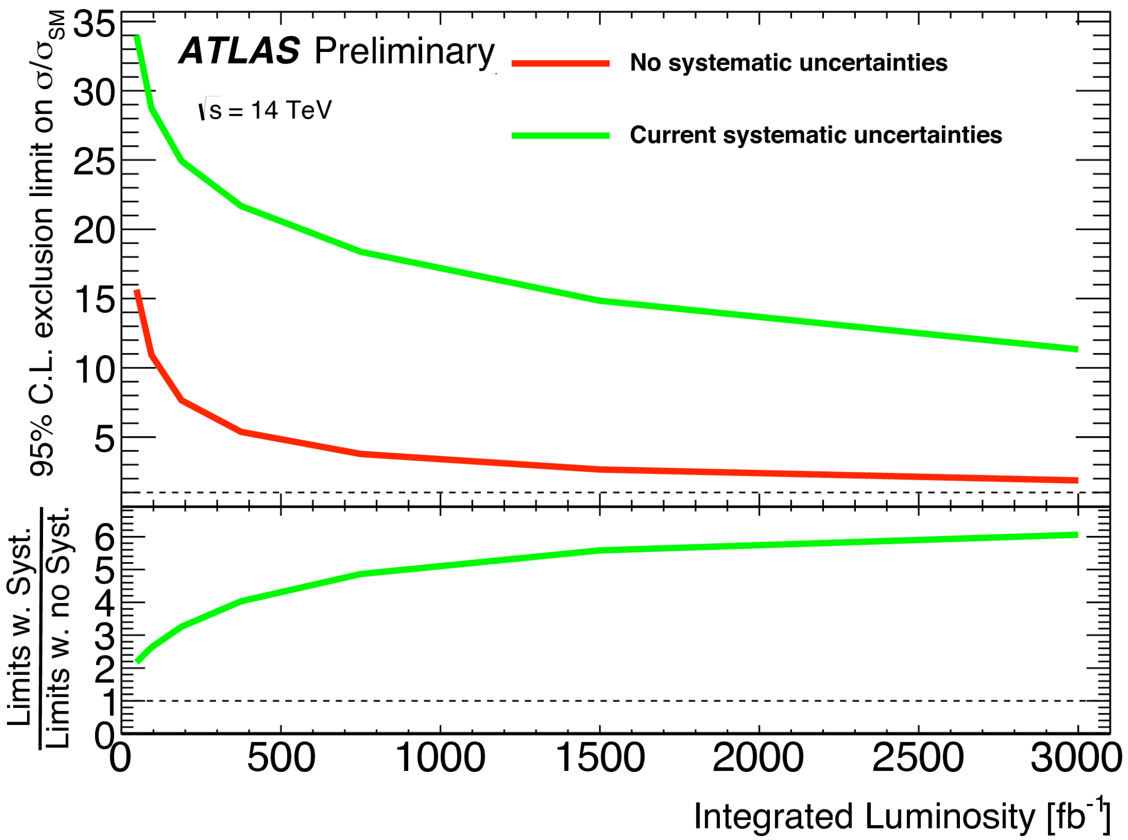
HH → γγbb @ HL-LHC (ATL-PHYS-PUB-2017-001)

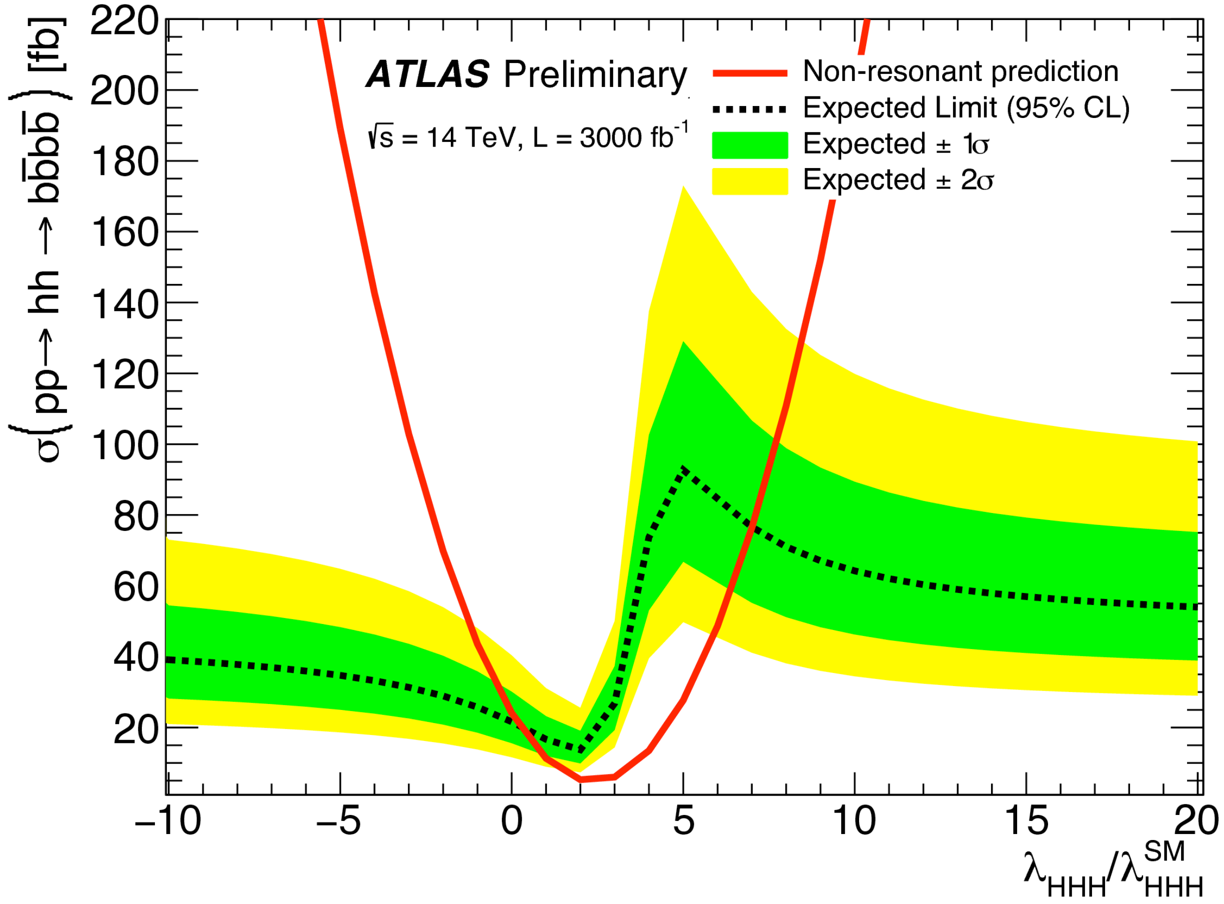




- set expected limits using truth-level MC for $\sqrt{s}$ = 14 TeV, $\int L$ = 3000 fb^{-1}
  - The truth-level objects are smeared according to predicted detector resolution at <μ> = 200
- expected significance for non-resonant SM hh → γγbb: 1.05σ
- limits on Higgs self-coupling: $-0.8 < \lambda/\lambda_{SM} < 7.7$

HH ⟶ BBBB @ HL-LHC (ATL-PHYS-PUB-2016-024)

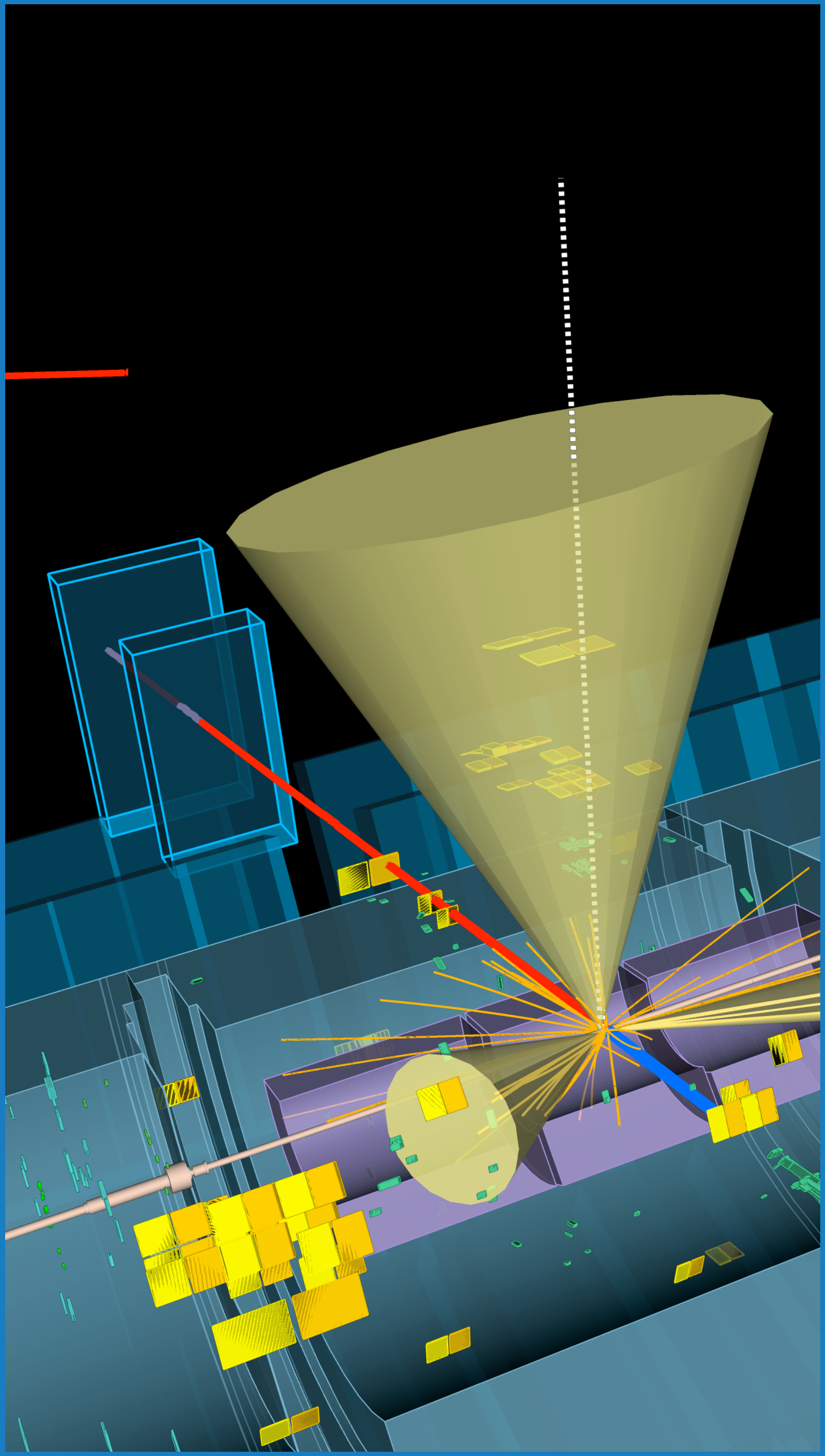




- extrapolate (ICHEP 2016) Run 2 results to $\sqrt{s}$ = 14 TeV, $\int L$ = 3000 fb^{-1}
- expected limit on non-resonant SM hh ➞ bbbb: 1.5*σ_{SM}
    - with current systematic uncertainties: 5.2*σ_{SM}
- limits on Higgs self-coupling: $0.2 < \lambda/\lambda_{SM} < 7.0$ ($-3.5 < \lambda/\lambda_{SM} < 11$ syst)

DI-HIGGS AND THE FUTURE

- Studying electroweak symmetry breaking is one of the long-term goals of the LHC
- Measuring the Higgs self-coupling is one of the final open points in our suite of measurements of the properties of the Higgs boson– and it is nearly within our reach (at the HL-LHC?)
- Keeping up with our current rate of progress will require novel experimental techniques and data-collection methods!

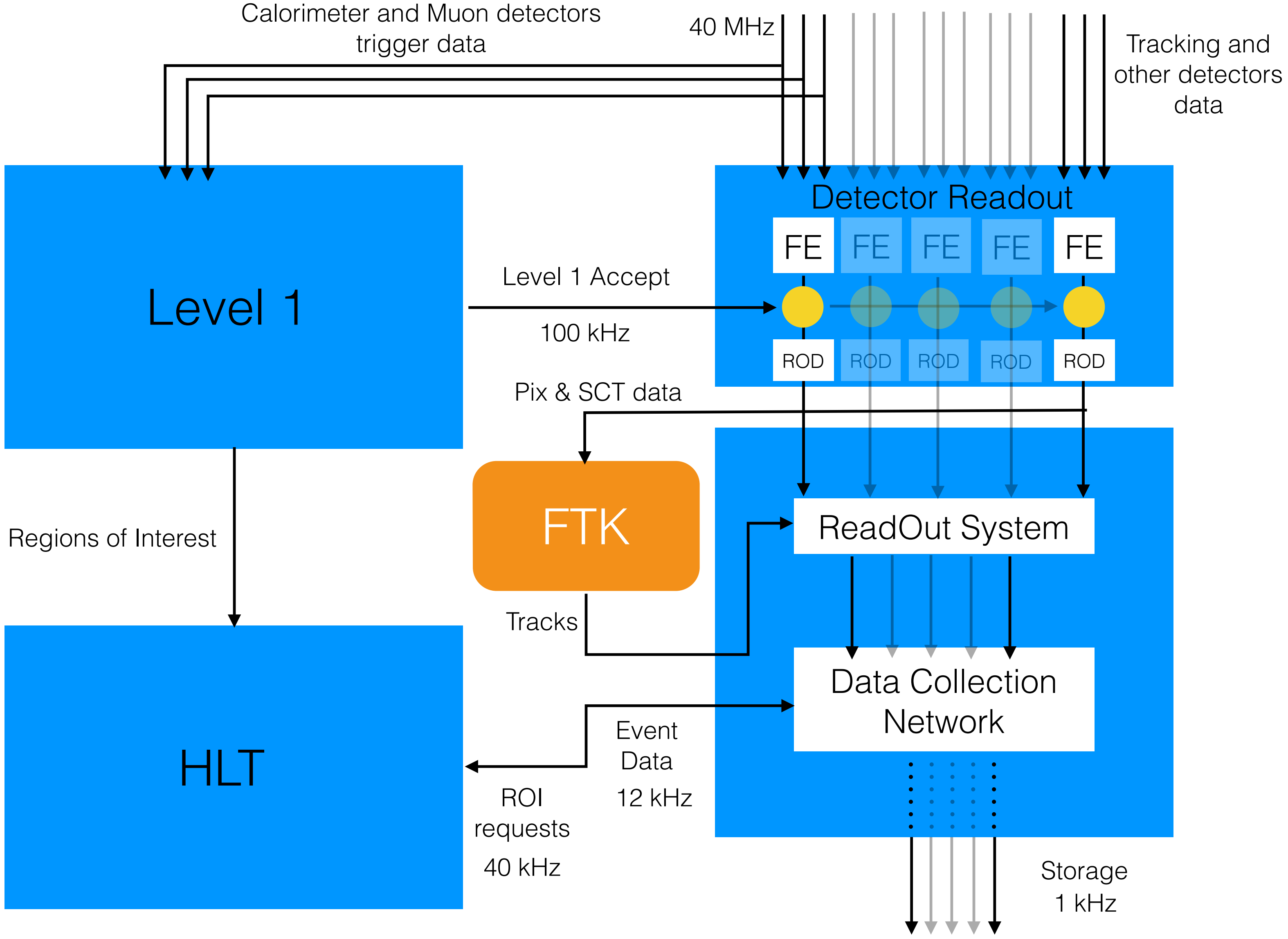


BACKUP SLIDES

ATLAS
EXPERIMENT

THE ATLAS TRIGGER SYSTEM

Reduce from 40 MHz bunch crossing rate to 1 kHz (which is sent to storage), while choosing interesting events



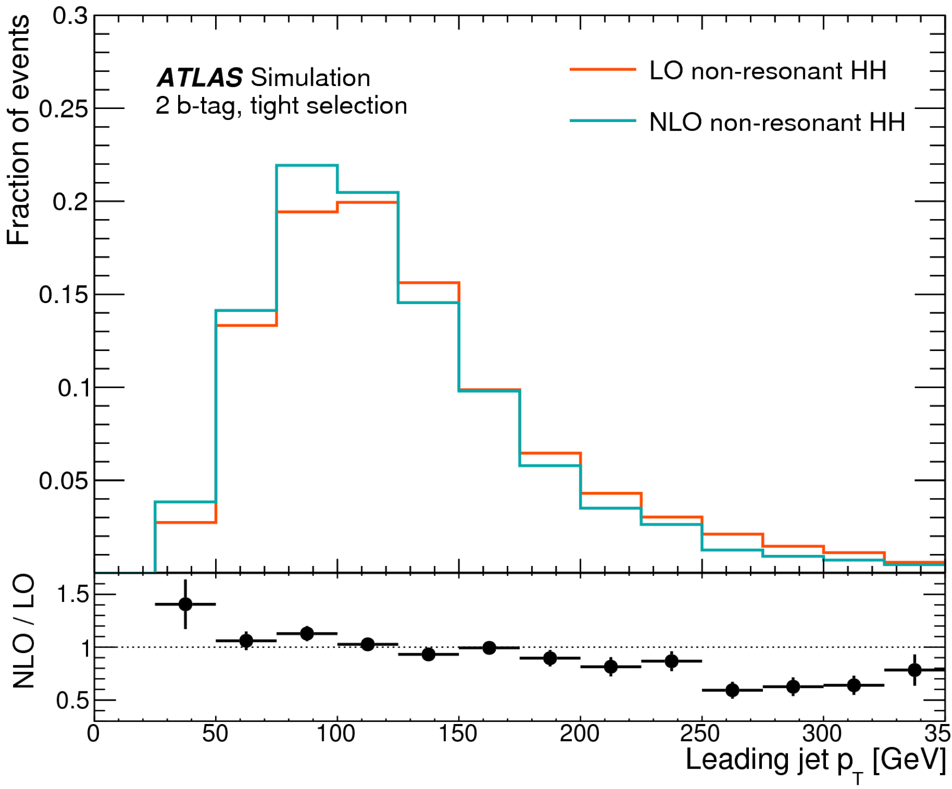
YYBB: DETAILS ON MONTE CARLO SAMPLES

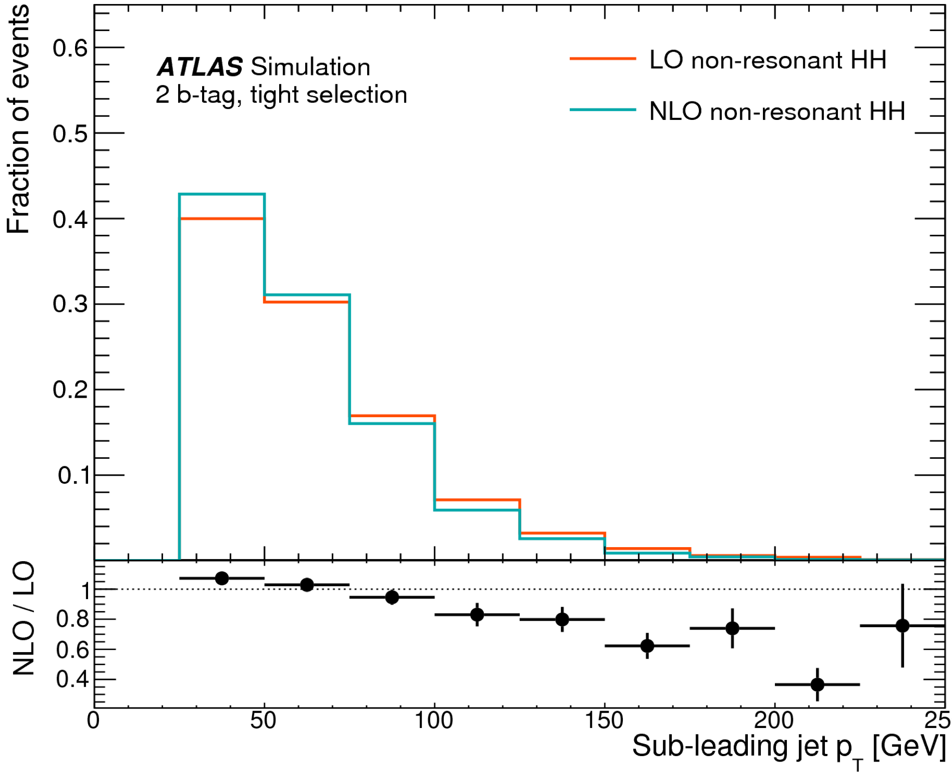
- generators, PDF sets, cross sections for signal and background MC:

Process	Generator	Showering	PDF set	σ [fb]	Order of calculation of σ	Simulation
Non-resonant SM HH	MadGraph5_aMC@NLO	Herwig++	CT10 NLO	33.41	NNLO+NNLL	Fast
Non-resonant BSM HH	MadGraph5_aMC@NLO	Pythia 8	NNPDF 2.3 LO	-	LO	Fast
Resonant BSM HH	MadGraph5_aMC@NLO	Herwig++	CT10 NLO	-	NLO	Fast
$\gamma\gamma$ plus jets	Sherpa	Sherpa	CT10 NLO	-	LO	Fast
ggH	Powheg-Box NNLOPS (r3080) [60]	Pythia 8	PDF4LHC15	48520	N^{3}LO(QCD)+NLO(EW)	Full
VBF	Powheg-Box (r3052) [61]	Pythia	PDF4LHC15	3780	NNLO(QCD)+NLO(EW)	Full
WH	Powheg-Box (r3133) [62]	Pythia	PDF4LHC15	1370	NNLO(QCD)+NLO(EW)	Full
$q\bar{q} \to ZH$	Powheg-Box (r3133) [62]	Pythia 8	PDF4LHC15	760	NNLO(QCD)+NLO(EW	Full
$t\bar{t}H$	MadGraph5_aMC@NLO	Pythia 8	NNPDF3.0	510	NLO(QCD)+NLO(EW)	Full
$gg \to ZH$	Powheg-Box (r3133)	Pythia 8	PDF4LHC15	120	NLO+NLL(QCD)	Full
$b\bar{b}H$	MadGraph5_aMC@NLO	Pythia	CT10 NLO	490	NNLO(5FS)+NLO(4FS)	Full
t-channel tH	MadGraph5_aMC@NLO	Pythia 8	CT10 NLO	70	LO(4FS)	Full
W-associated tH	MadGraph5_aMC@NLO	Herwig++	CT10 NLO	20	NLO(5FS)	Full

ΓΓBB SIGNAL MONTE CARLO

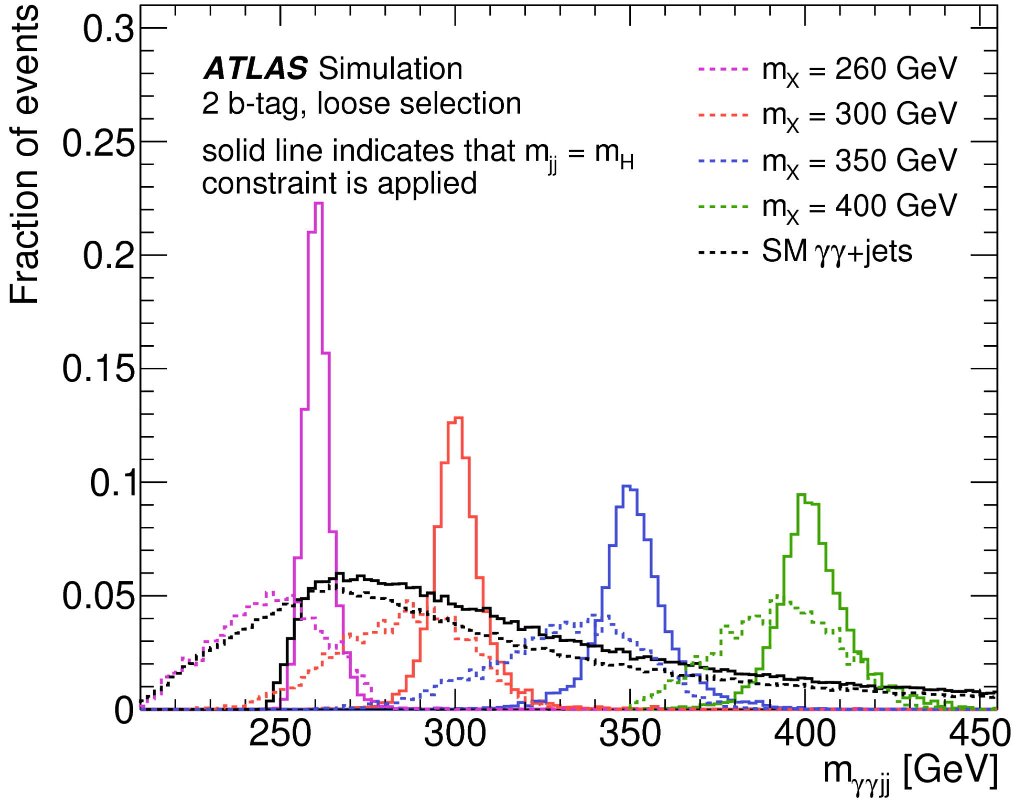
- non-resonant signal
    - pp → HH → γγbb: ≈ NLO Madgraph+Herwig, reweighted to full NLO
    - pp → HH → γγbb (varied κ_λ): LO Madgraph+Pythia
- resonant signal
    - pp → X → HH → γγbb: ≈NLO Madgraph+Herwig
    - m_X = 260, 275, 300, 325, 350, 400, 450, 500, 750, 1000 GeV

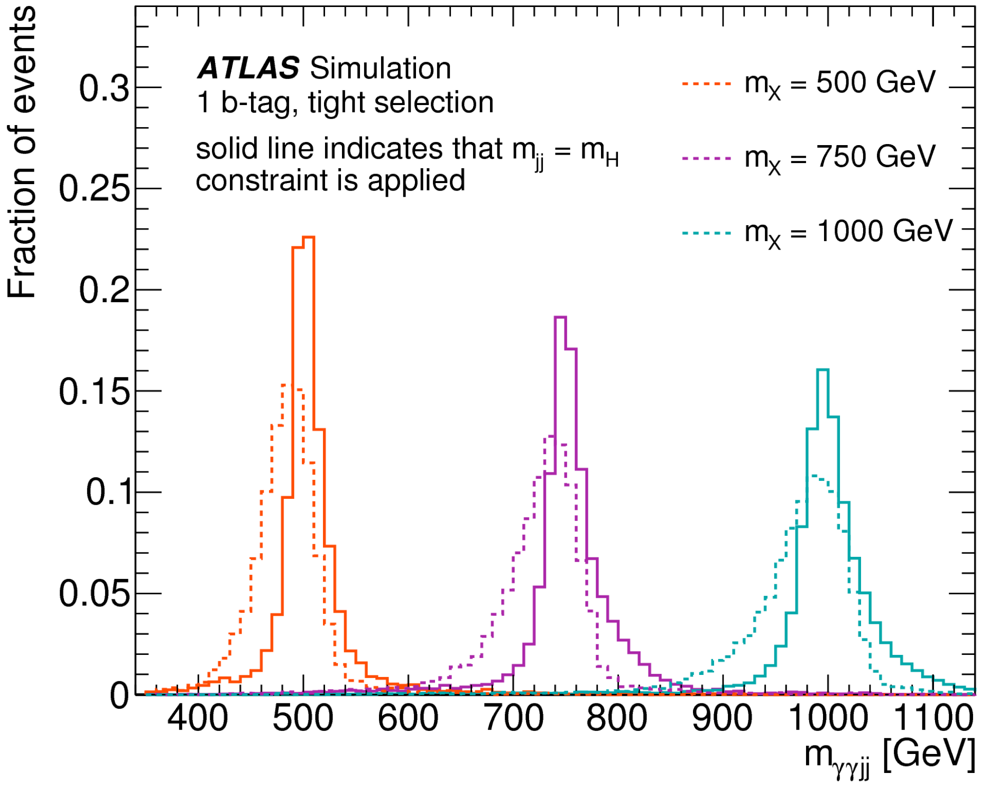




YYBB: RESONANT SIGNAL MODELING

loose selection

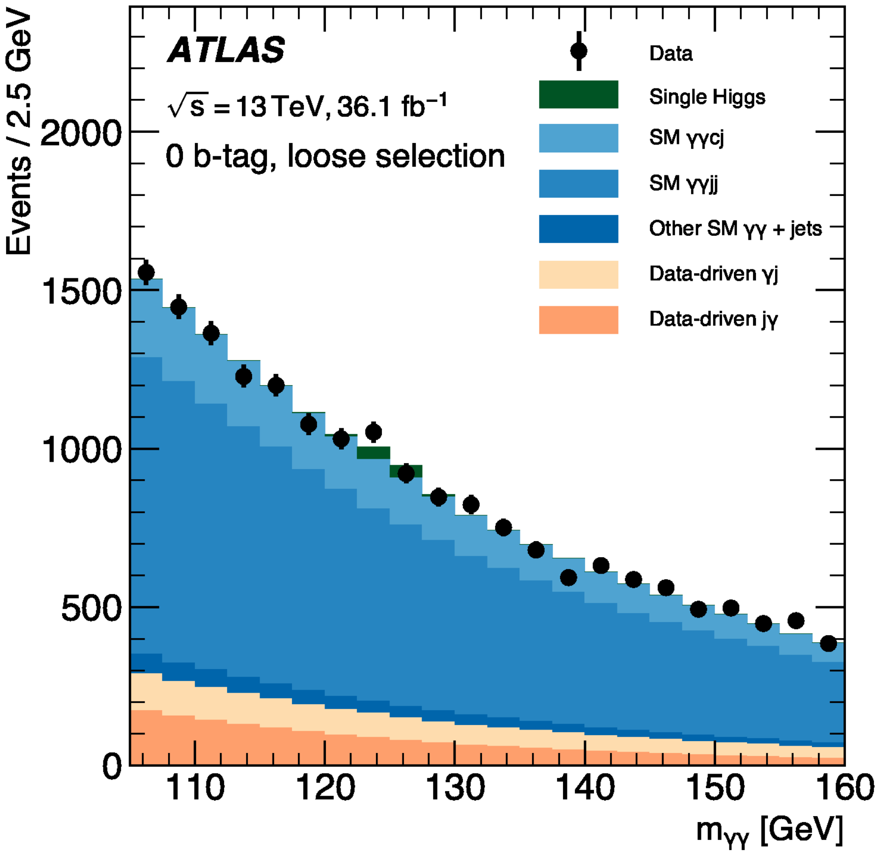


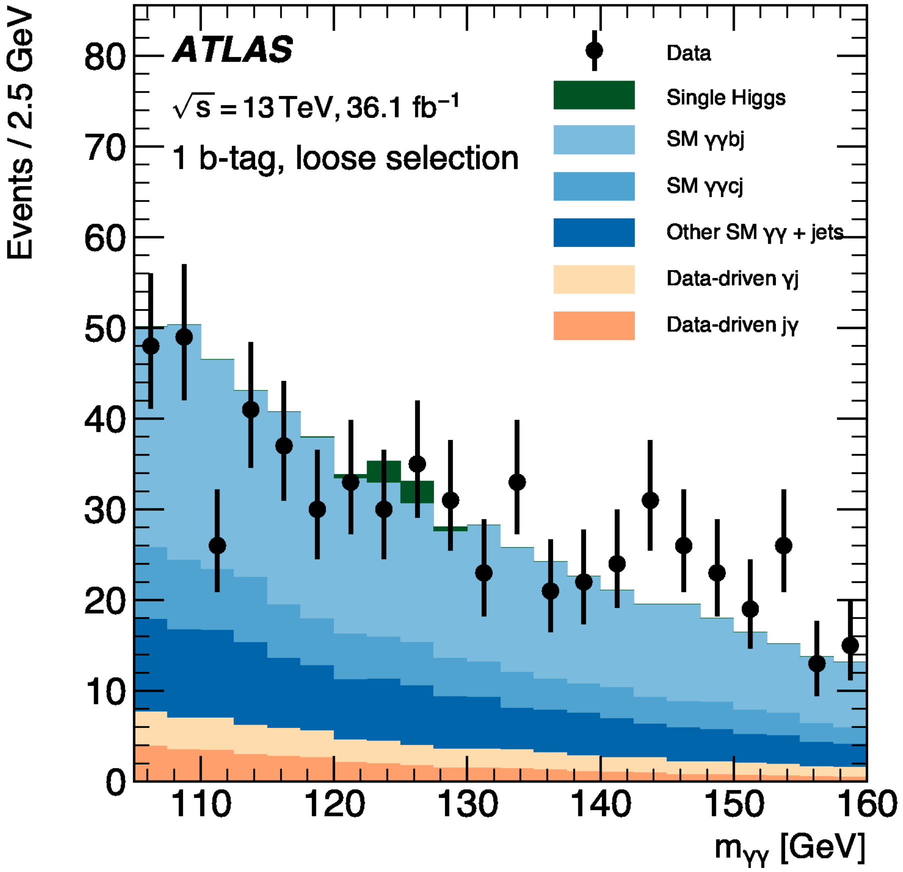


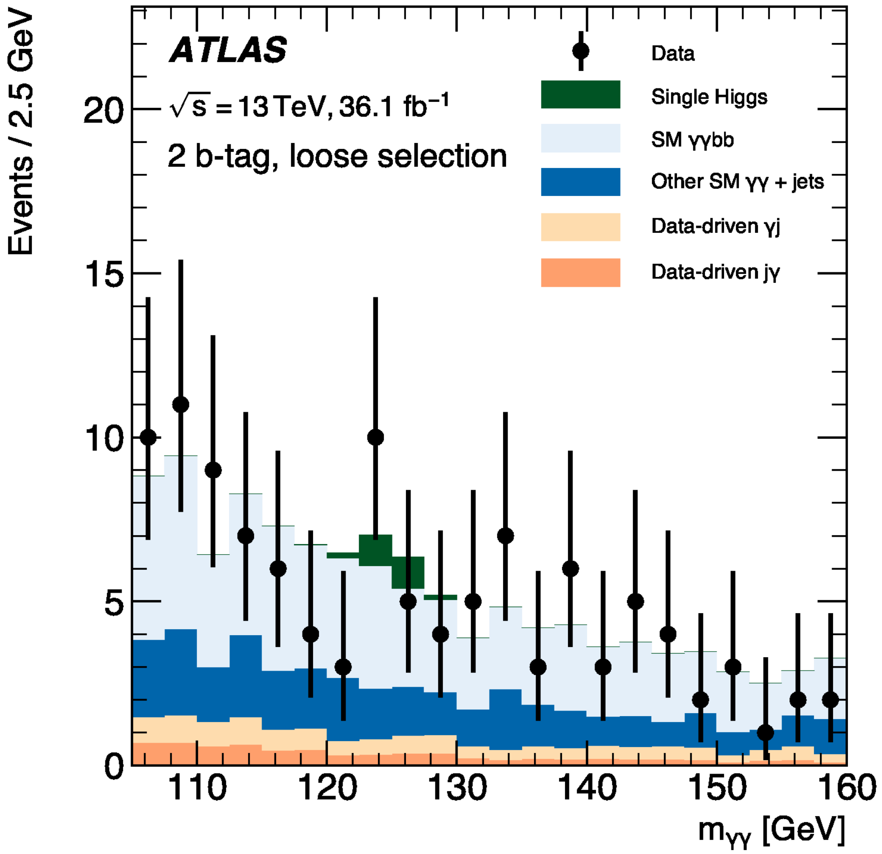
tight selection

- resonant signal is modeled with a Gaussian with exponential tails - simultaneous fit to all mass points
- constrain $m_{jj} = m_H$ in the resonant search, to improve four-body mass resolution

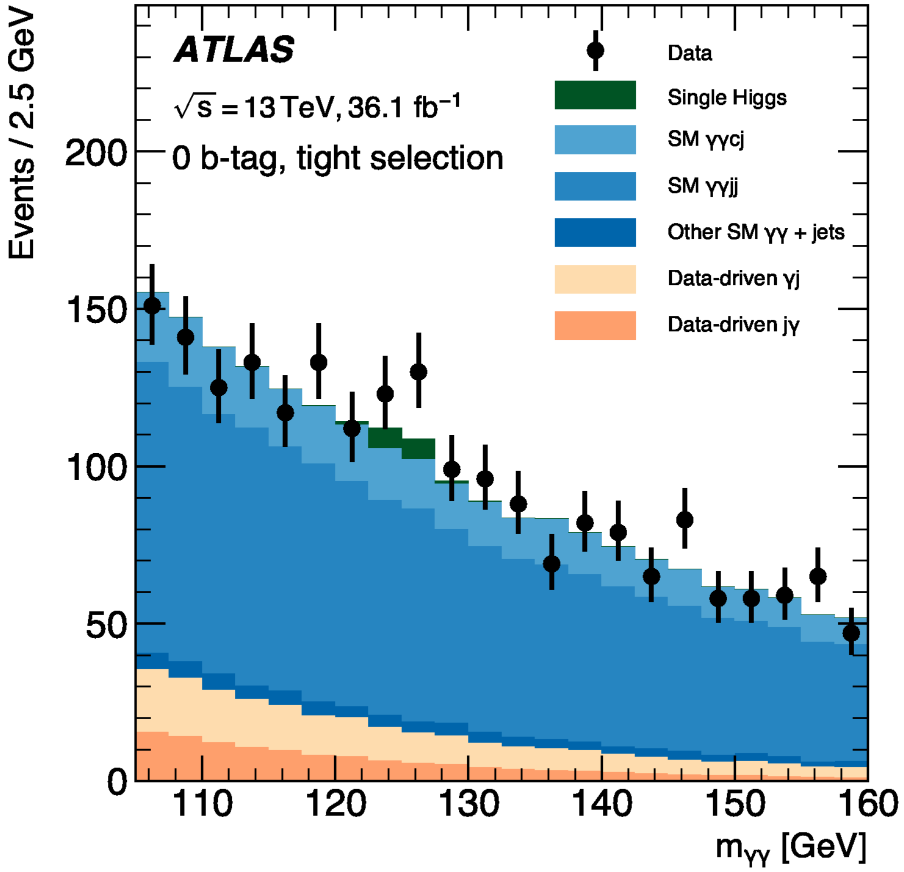
YYBB: CONTINUUM BACKGROUND MODELING, NON-RESONANT SEARCH

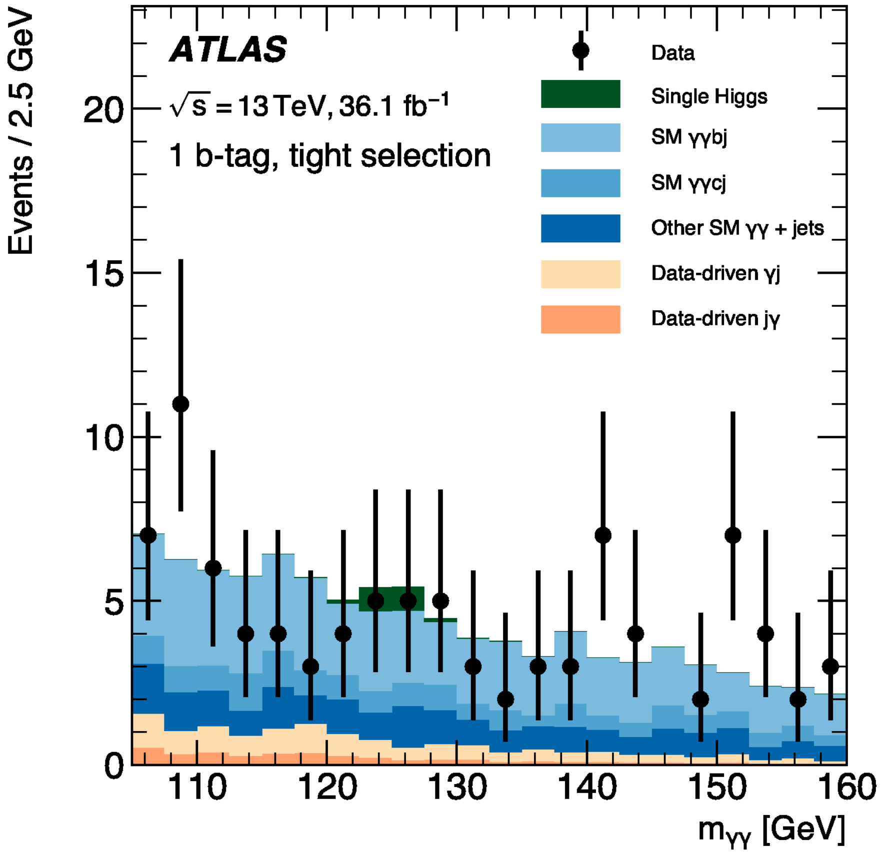


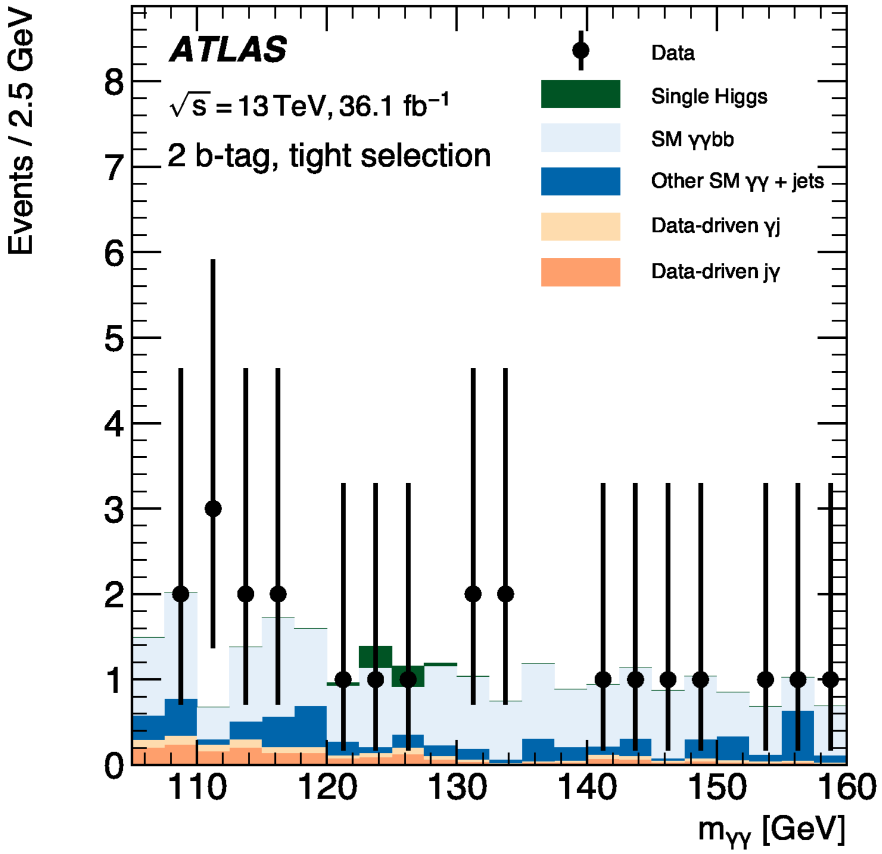




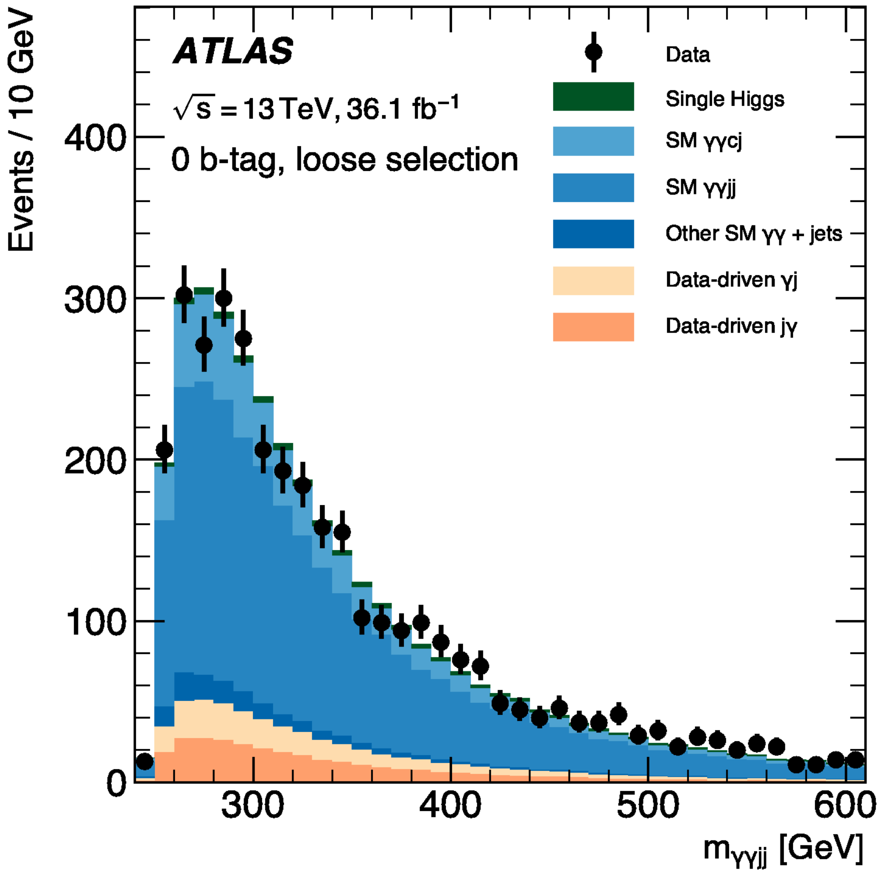
YYBB: CONTINUUM BACKGROUND MODELING, NON-RESONANT SEARCH

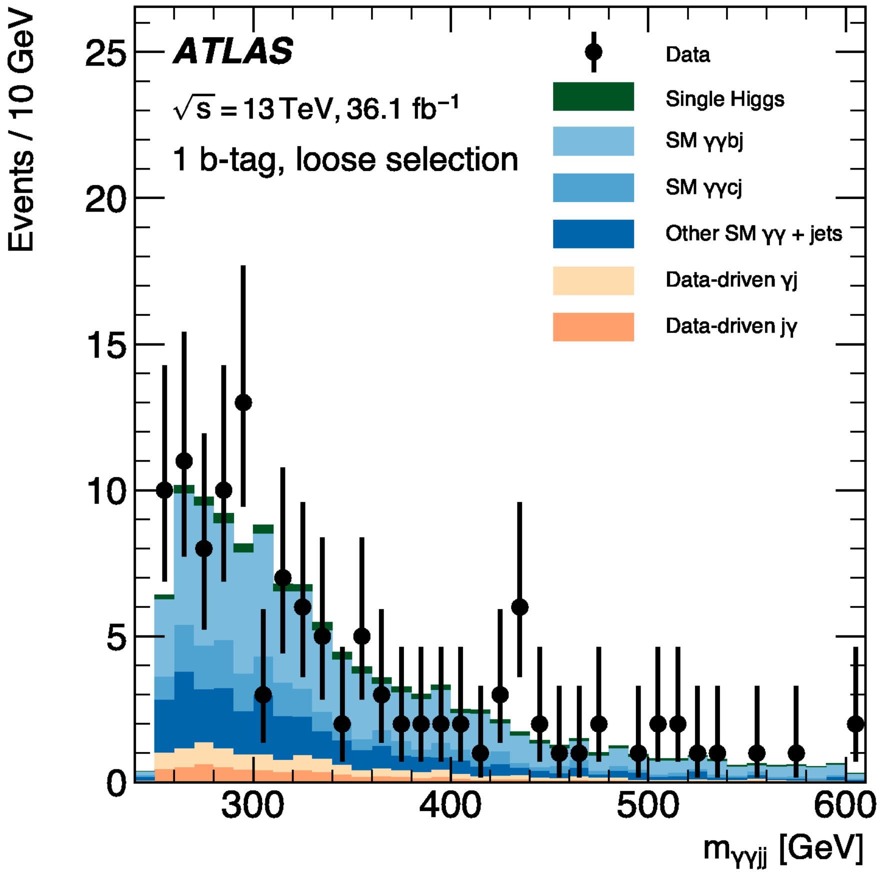


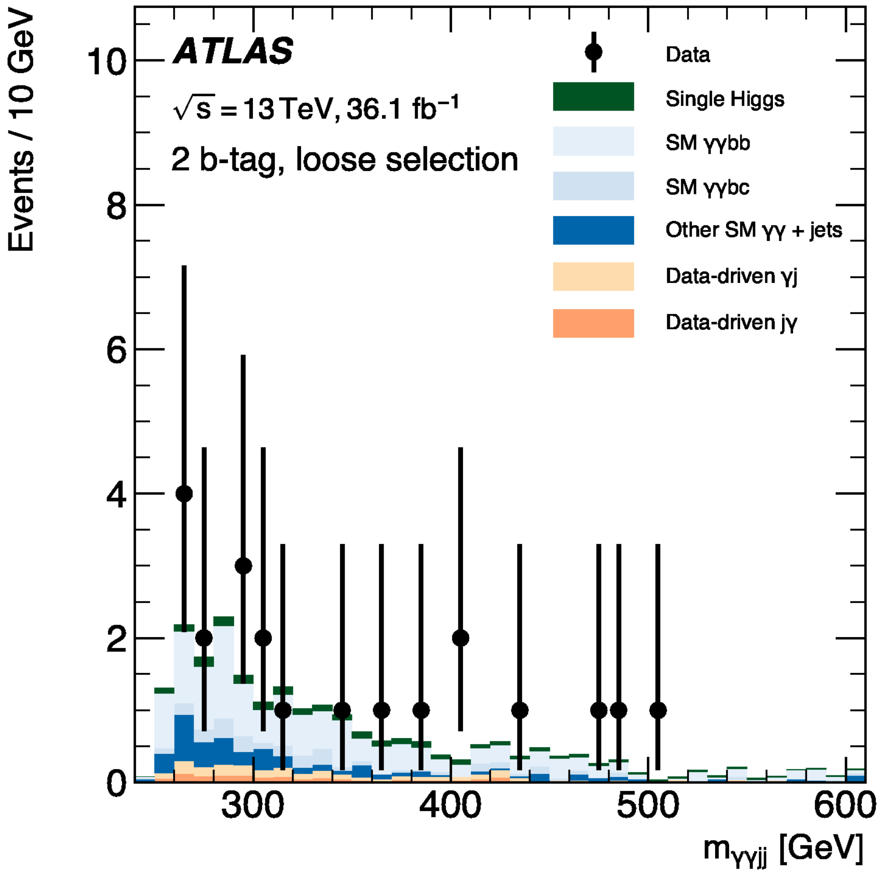




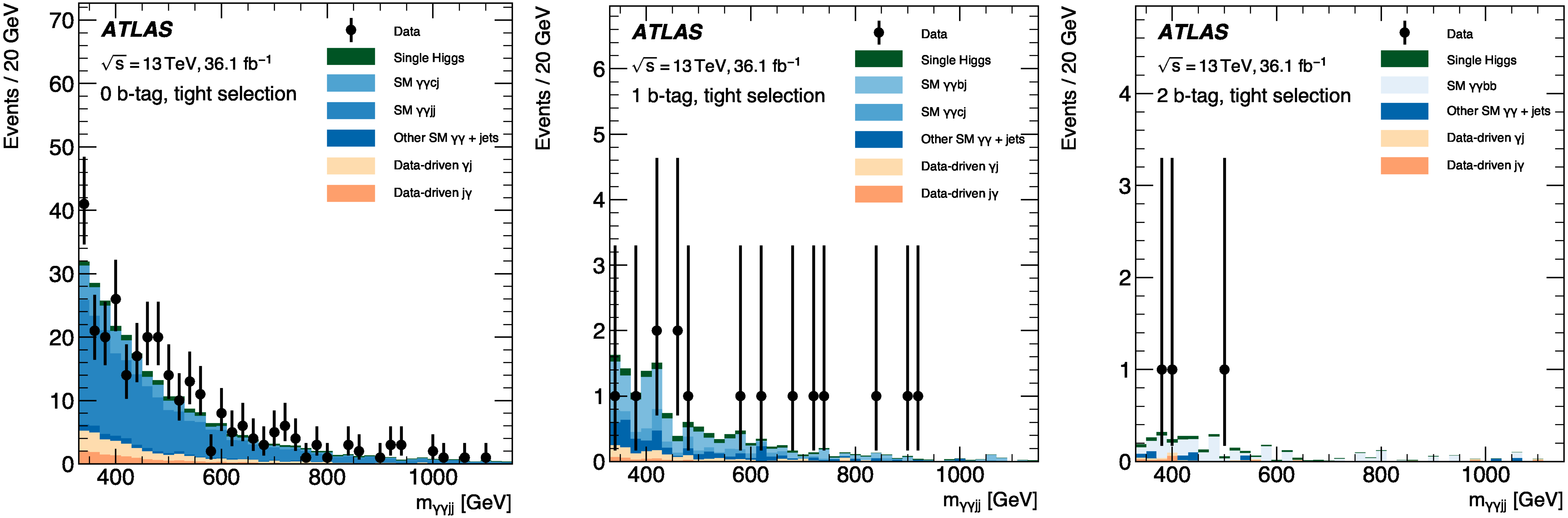
YYBB: CONTINUUM BACKGROUND MODELING, RESONANT SEARCH







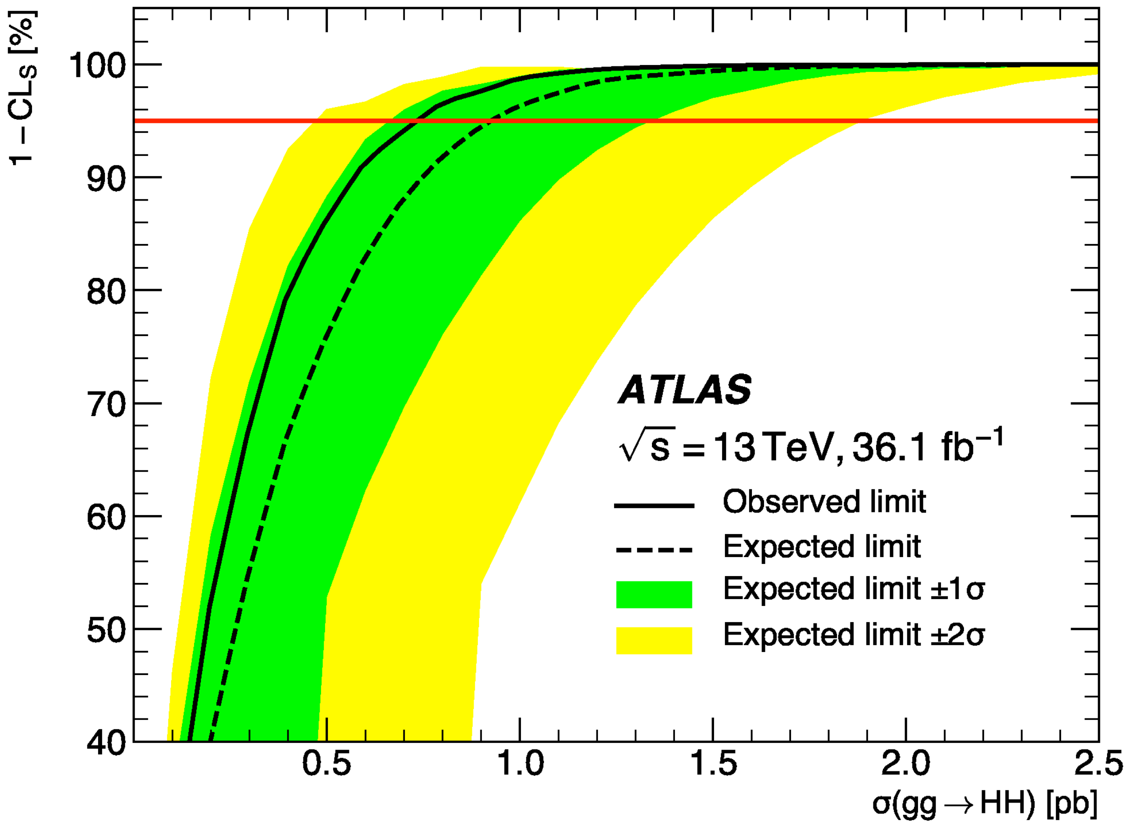
YYBB: CONTINUUM BACKGROUND MODELING, RESONANT SEARCH



YYBB: FINAL EVENT YIELDS

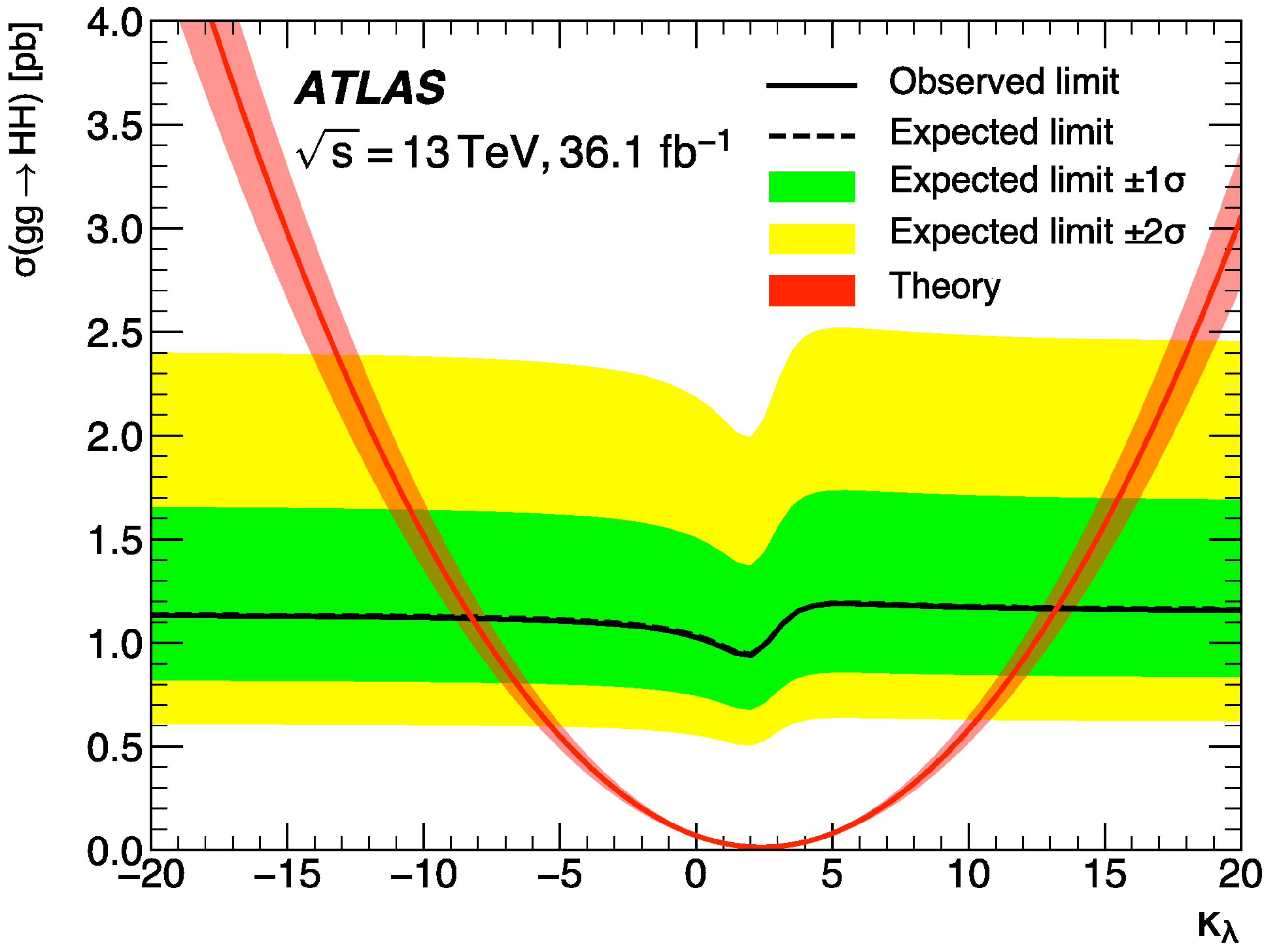
	1-tag		2-tag	
	Loose selection	Tight selection	Loose selection	Tight selection
Continuum background	117.5 ±4.7	15.7 ± 1.6	21.0 ± 2.0	3.74 ± 0.78
SM single-Higgs-boson background	5.51 ±0.10	2.20 ± 0.05	1.63 ± 0.04	0.56 ± 0.02
Total background	123.0 ±4.7	17.9 ± 1.6	22.6 ± 2.0	4.30 ± 0.79
SM Higgs boson pair signal	0.219±0.006	0.120± 0.004	0.305± 0.007	0.175± 0.005
Data	125	19	21	3

NON-RESONANT LIMITS: HH CROSS SECTION



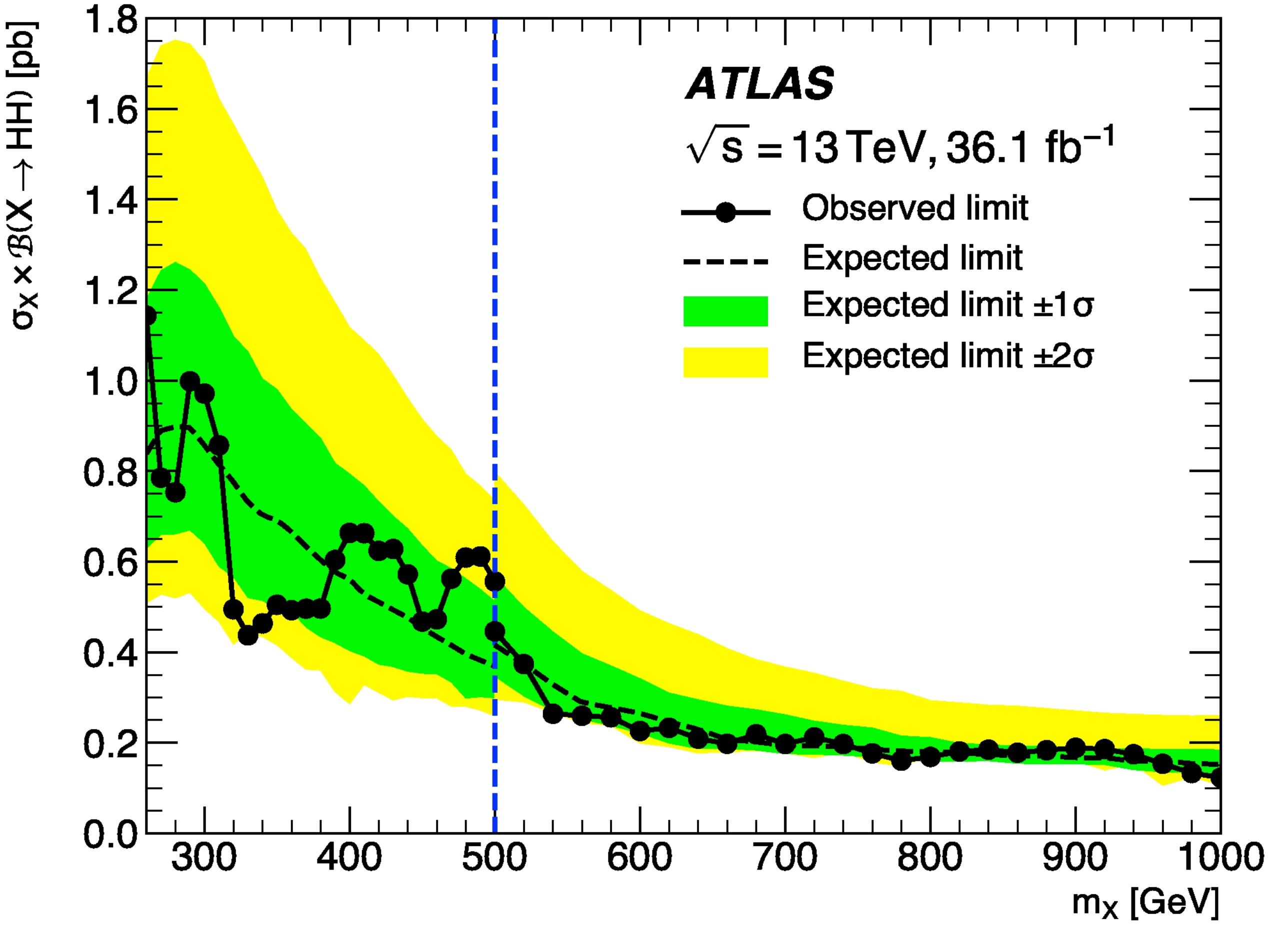
	Observed	Expected	-1σ	$+1\sigma$
$\sigma_{gg\to HH}$ [pb]	0.73	0.93	0.66	1.4
As a multiple of σ_{SM}	22	28	20	40

NON-RESONANT LIMITS: HIGGS SELF-COUPLING



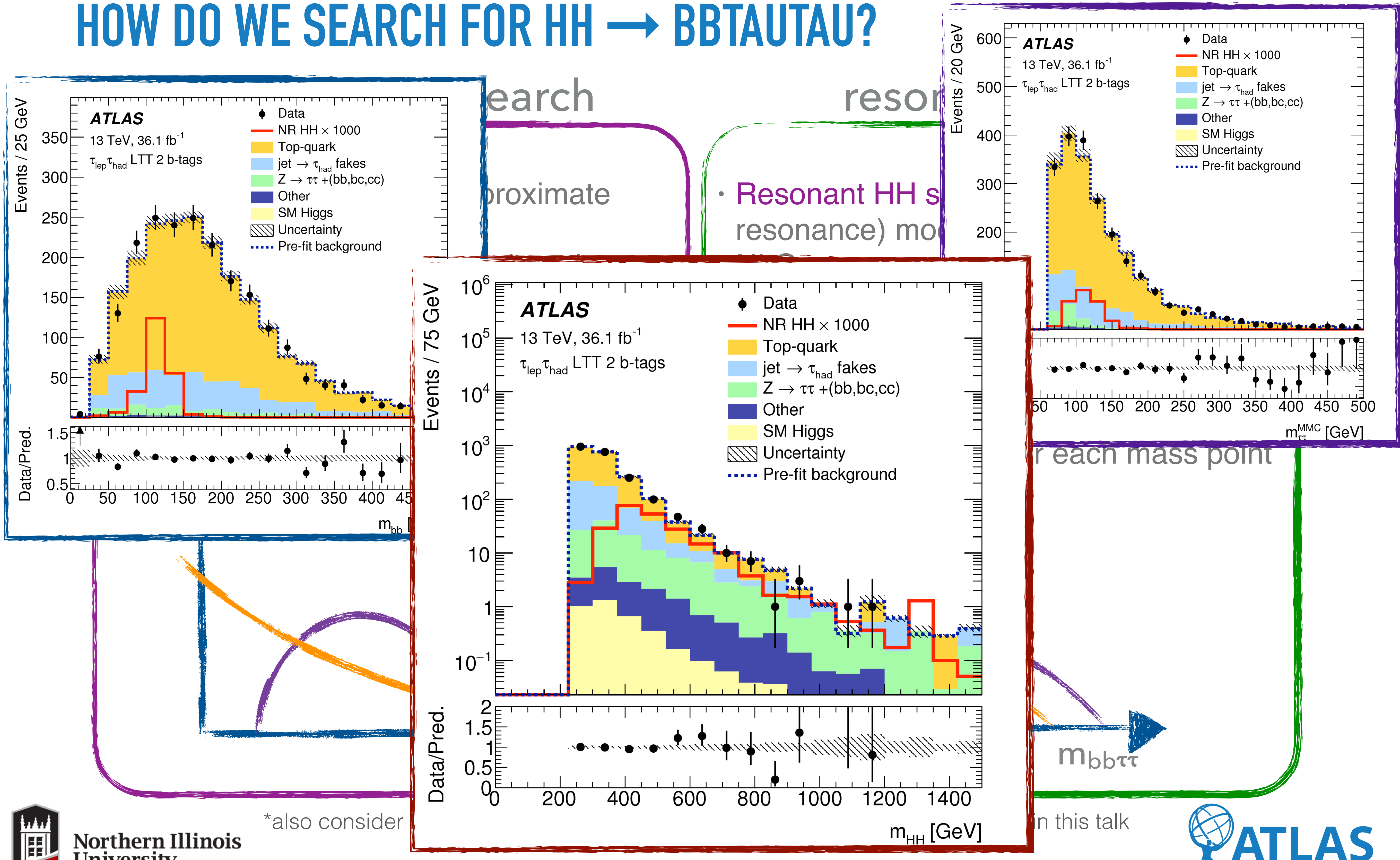
- Parameterize the acceptance*efficiency as a function of κ_λ
- Theory cross section shown for illustration
- Set limits on the Higgs self-coupling: $-8.2 < \kappa_\lambda < 13.2$

RESONANT LIMITS



- Blue line separates loose and tight selections
- Largest deviation from background-only hypothesis is at 480 GeV (local significance of 1.2σ) → No significant excess observed
- Maximum observed (expected) limit : 1.1 pb (0.9 pb) at 260 GeV
- Minimum observed (expected) limit: 0.12 pb (0.15 pb) at 1000 GeV

HOW DO WE SEARCH FOR HH → BBTAUTAU?



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resor

proximate

- Resonant HH s resonance) mo

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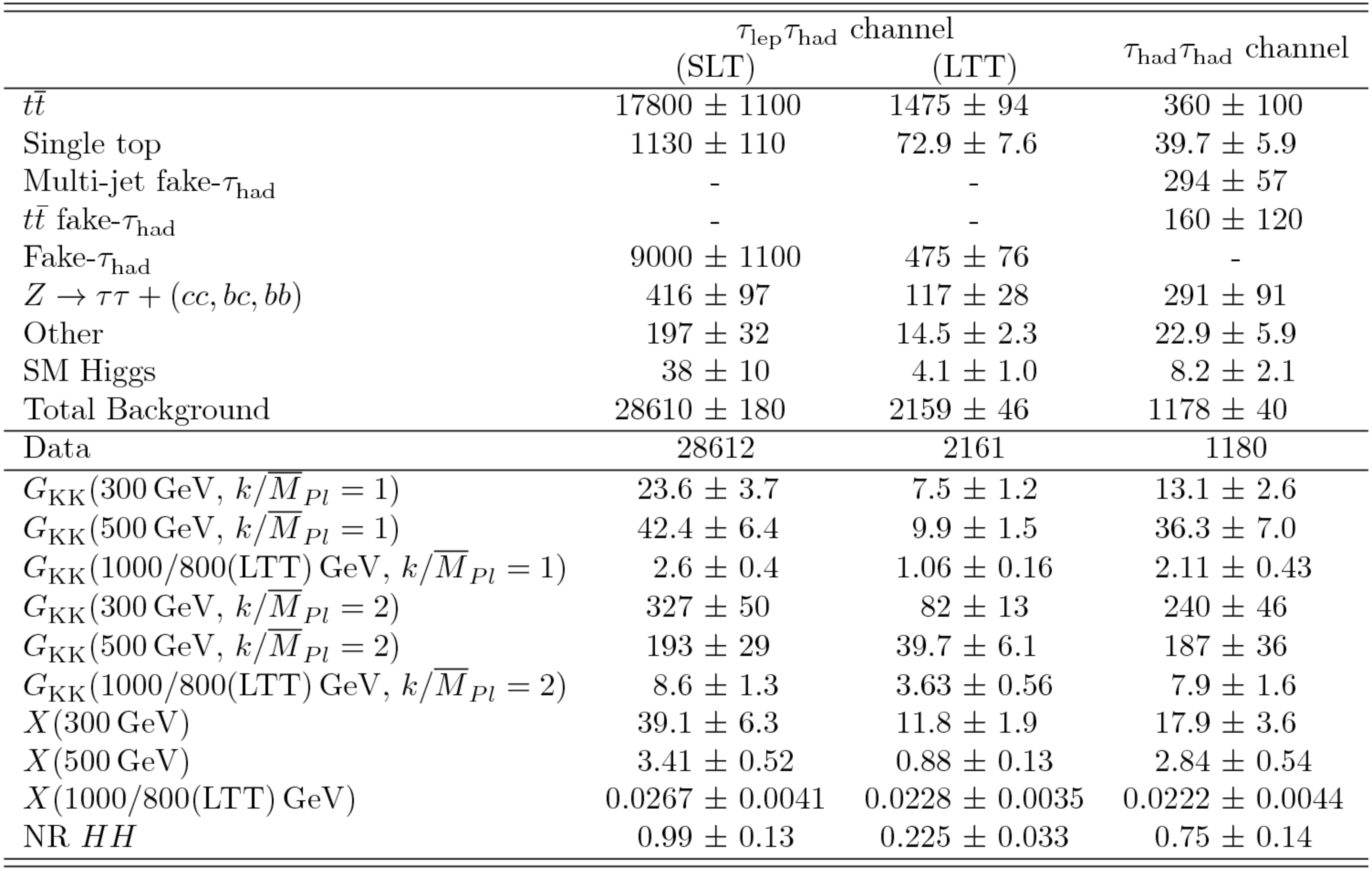
$m_{bb\tau\tau}$

*also consider

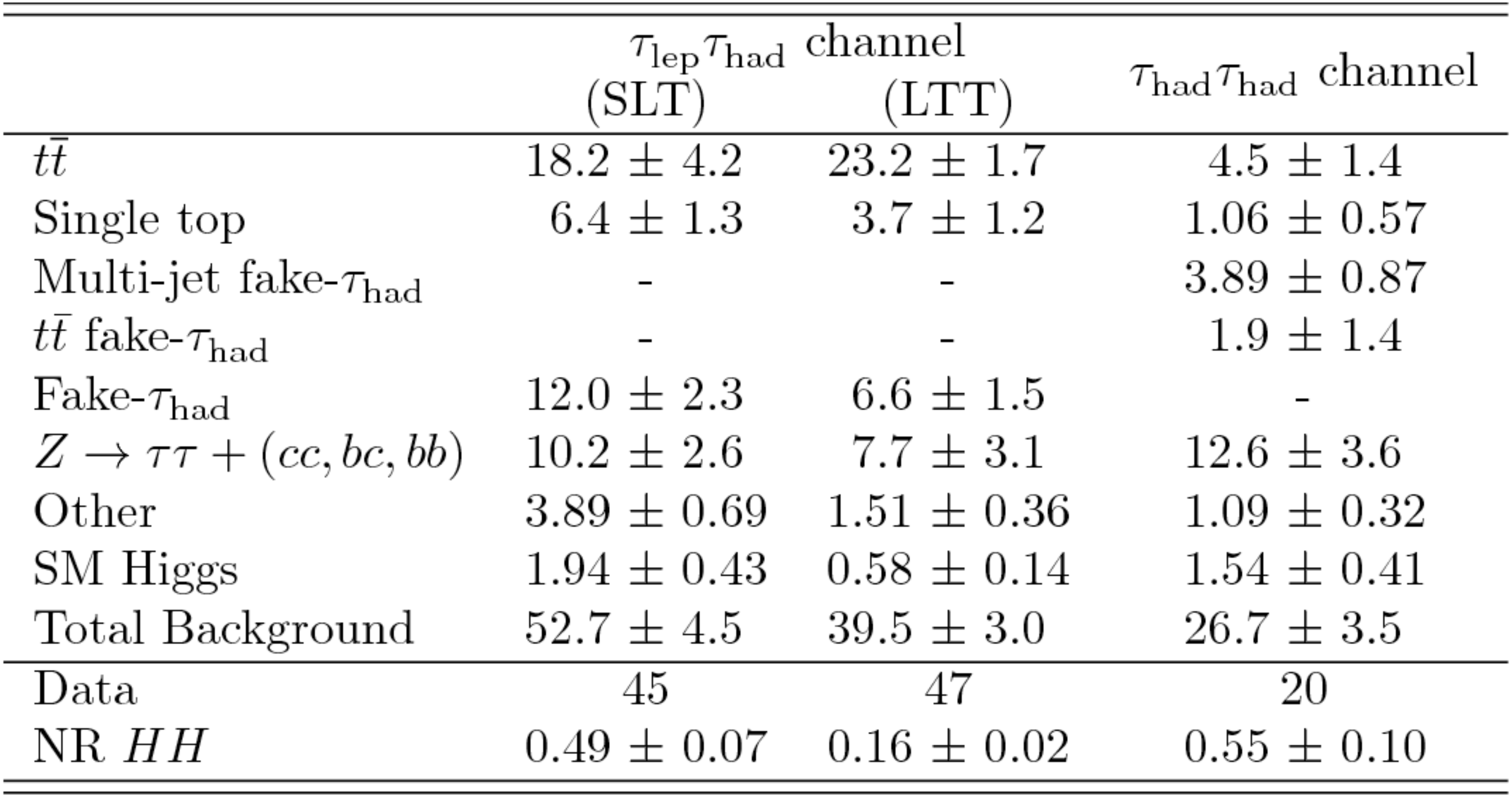
n this talk

BBTAUTAU: EVENT YIELDS BEFORE BDT CUTS



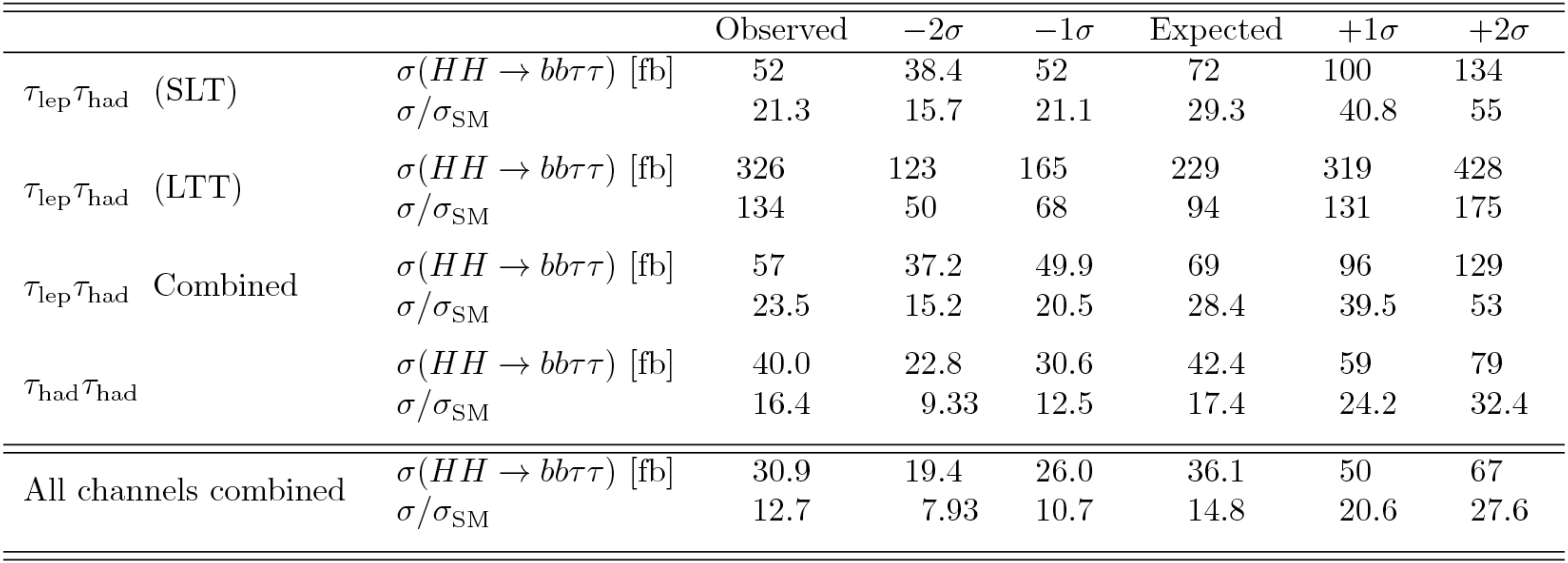
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel		$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel
	(SLT)	(LTT)	
$t\bar{t}$	17800 ± 1100	1475 ± 94	360 ± 100
Single top	1130 ± 110	72.9 ± 7.6	39.7 ± 5.9
Multi-jet fake-τ_{had}	-	-	294 ± 57
$t\bar{t}$ fake-τ_{had}	-	-	160 ± 120
Fake-τ_{had}	9000 ± 1100	475 ± 76	-
$Z \to \tau\tau + (cc, bc, bb)$	416 ± 97	117 ± 28	291 ± 91
Other	197 ± 32	14.5 ± 2.3	22.9 ± 5.9
SM Higgs	38 ± 10	4.1 ± 1.0	8.2 ± 2.1
Total Background	28610 ± 180	2159 ± 46	1178 ± 40
Data	28612	2161	1180
$G_{\mathrm{KK}}(300\,\mathrm{GeV},\ k/\overline{M}_{Pl} = 1)$	23.6 ± 3.7	7.5 ± 1.2	13.1 ± 2.6
$G_{\mathrm{KK}}(500\,\mathrm{GeV},\ k/\overline{M}_{Pl} = 1)$	42.4 ± 6.4	9.9 ± 1.5	36.3 ± 7.0
$G_{\mathrm{KK}}(1000/800(\mathrm{LTT})\,\mathrm{GeV},\ k/\overline{M}_{Pl} = 1)$	2.6 ± 0.4	1.06 ± 0.16	2.11 ± 0.43
$G_{\mathrm{KK}}(300\,\mathrm{GeV},\ k/\overline{M}_{Pl} = 2)$	327 ± 50	82 ± 13	240 ± 46
$G_{\mathrm{KK}}(500\,\mathrm{GeV},\ k/\overline{M}_{Pl} = 2)$	193 ± 29	39.7 ± 6.1	187 ± 36
$G_{\mathrm{KK}}(1000/800(\mathrm{LTT})\,\mathrm{GeV},\ k/\overline{M}_{Pl} = 2)$	8.6 ± 1.3	3.63 ± 0.56	7.9 ± 1.6
$X(300\,\mathrm{GeV})$	39.1 ± 6.3	11.8 ± 1.9	17.9 ± 3.6
$X(500\,\mathrm{GeV})$	3.41 ± 0.52	0.88 ± 0.13	2.84 ± 0.54
$X(1000/800(\mathrm{LTT})\,\mathrm{GeV})$	0.0267 ± 0.0041	0.0228 ± 0.0035	0.0222 ± 0.0044
NR HH	0.99 ± 0.13	0.225 ± 0.033	0.75 ± 0.14

BBTAUTAU: EVENT YIELDS AFTER BDT CUTS



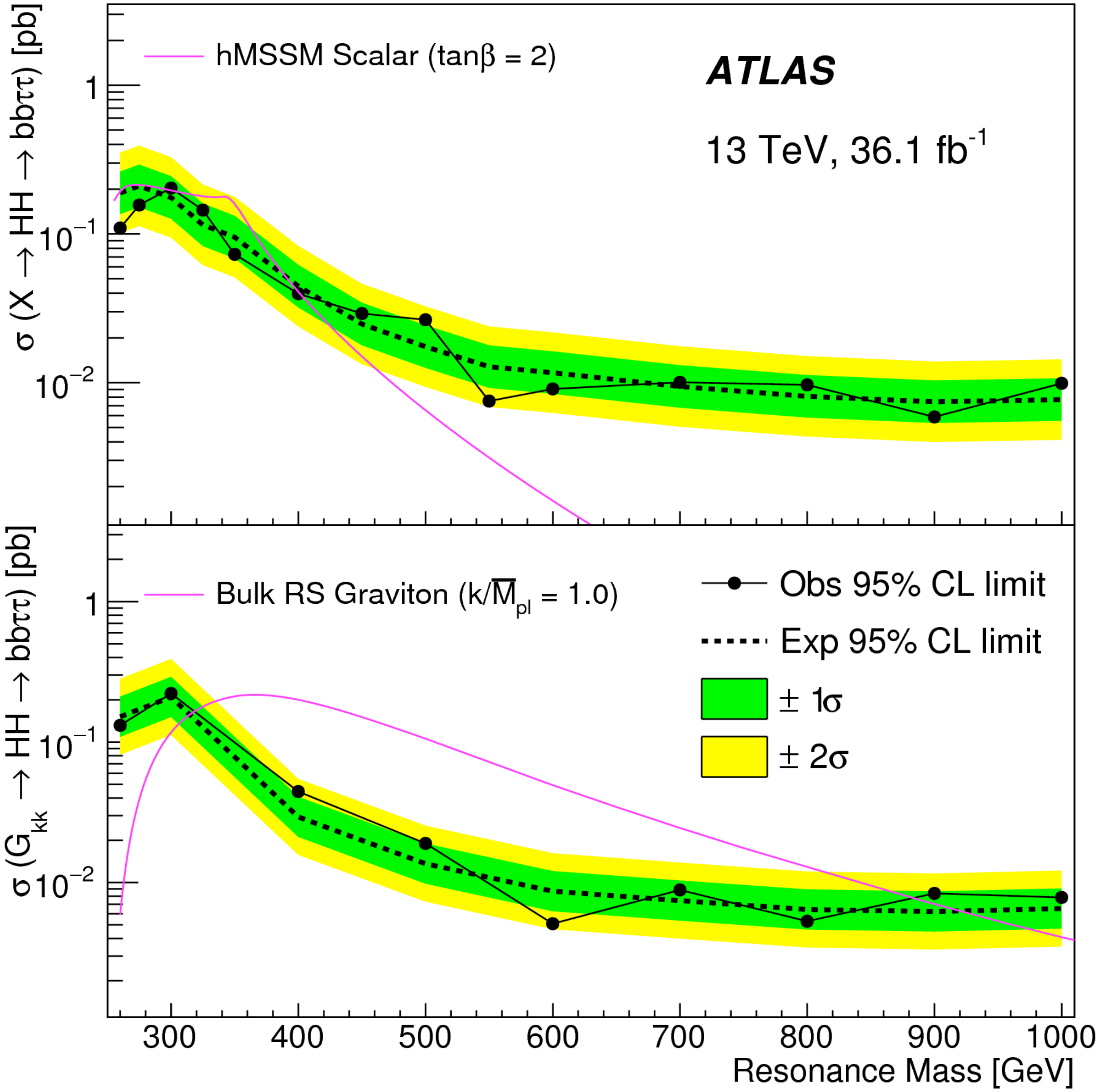
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel		$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel
	(SLT)	(LTT)	
$t\bar{t}$	18.2 ± 4.2	23.2 ± 1.7	4.5 ± 1.4
Single top	6.4 ± 1.3	3.7 ± 1.2	1.06 ± 0.57
Multi-jet fake-τ_{had}	-	-	3.89 ± 0.87
$t\bar{t}$ fake-τ_{had}	-	-	1.9 ± 1.4
Fake-τ_{had}	12.0 ± 2.3	6.6 ± 1.5	-
$Z \rightarrow \tau\tau + (cc, bc, bb)$	10.2 ± 2.6	7.7 ± 3.1	12.6 ± 3.6
Other	3.89 ± 0.69	1.51 ± 0.36	1.09 ± 0.32
SM Higgs	1.94 ± 0.43	0.58 ± 0.14	1.54 ± 0.41
Total Background	52.7 ± 4.5	39.5 ± 3.0	26.7 ± 3.5
Data	45	47	20
NR HH	0.49 ± 0.07	0.16 ± 0.02	0.55 ± 0.10

BBTAUTAU: NON-RESONANT LIMITS

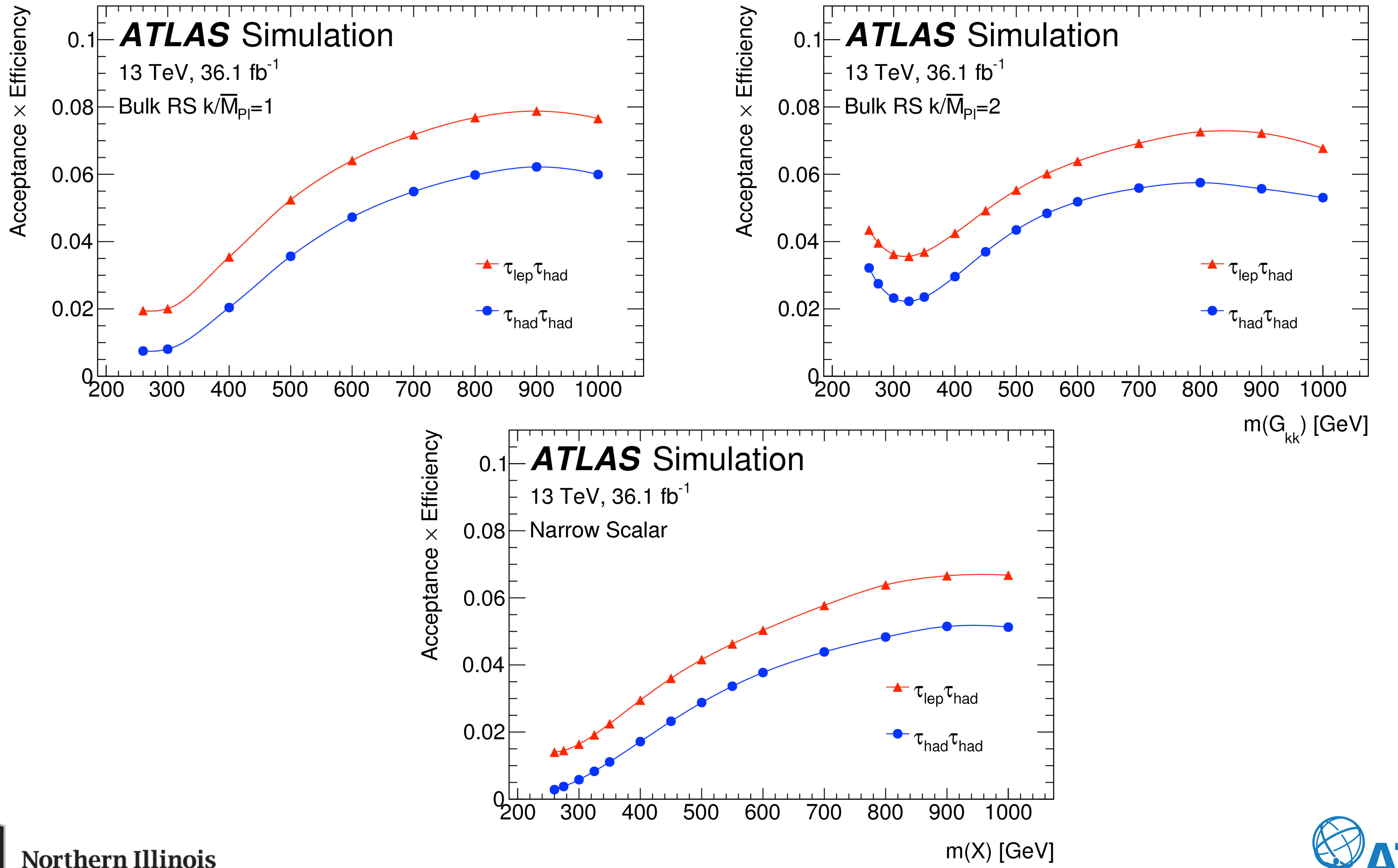


		Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
$\tau_{\text{lep}}\tau_{\text{had}}$ (SLT)	$\sigma(HH \to bb\tau\tau)$ [fb]	52	38.4	52	72	100	134
	$\sigma/\sigma_{\text{SM}}$	21.3	15.7	21.1	29.3	40.8	55
$\tau_{\text{lep}}\tau_{\text{had}}$ (LTT)	$\sigma(HH \to bb\tau\tau)$ [fb]	326	123	165	229	319	428
	$\sigma/\sigma_{\text{SM}}$	134	50	68	94	131	175
$\tau_{\text{lep}}\tau_{\text{had}}$ Combined	$\sigma(HH \to bb\tau\tau)$ [fb]	57	37.2	49.9	69	96	129
	$\sigma/\sigma_{\text{SM}}$	23.5	15.2	20.5	28.4	39.5	53
$\tau_{\text{had}}\tau_{\text{had}}$	$\sigma(HH \to bb\tau\tau)$ [fb]	40.0	22.8	30.6	42.4	59	79
	$\sigma/\sigma_{\text{SM}}$	16.4	9.33	12.5	17.4	24.2	32.4
All channels combined	$\sigma(HH \to bb\tau\tau)$ [fb]	30.9	19.4	26.0	36.1	50	67
	$\sigma/\sigma_{\text{SM}}$	12.7	7.93	10.7	14.8	20.6	27.6

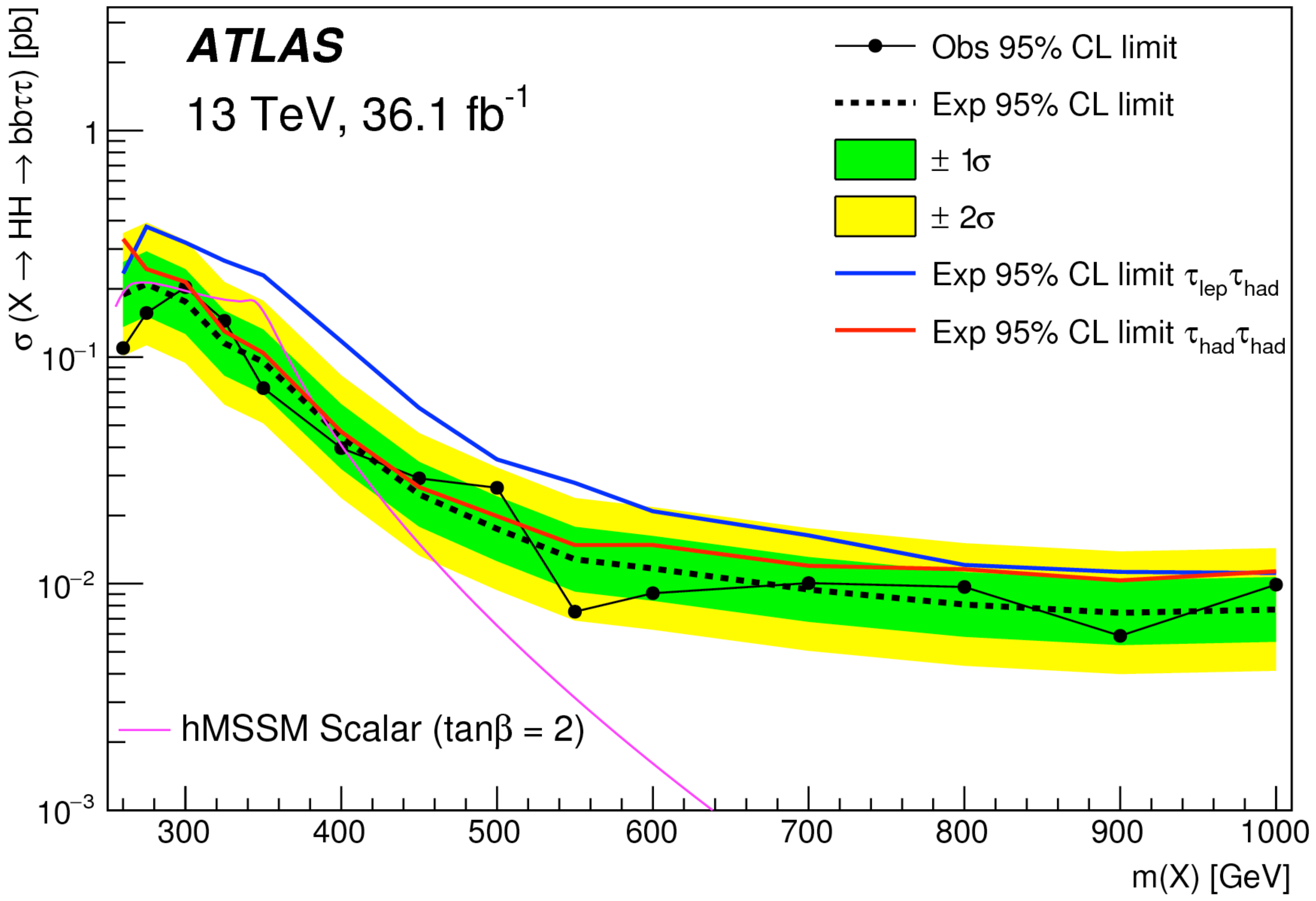
RESONANT LIMITS



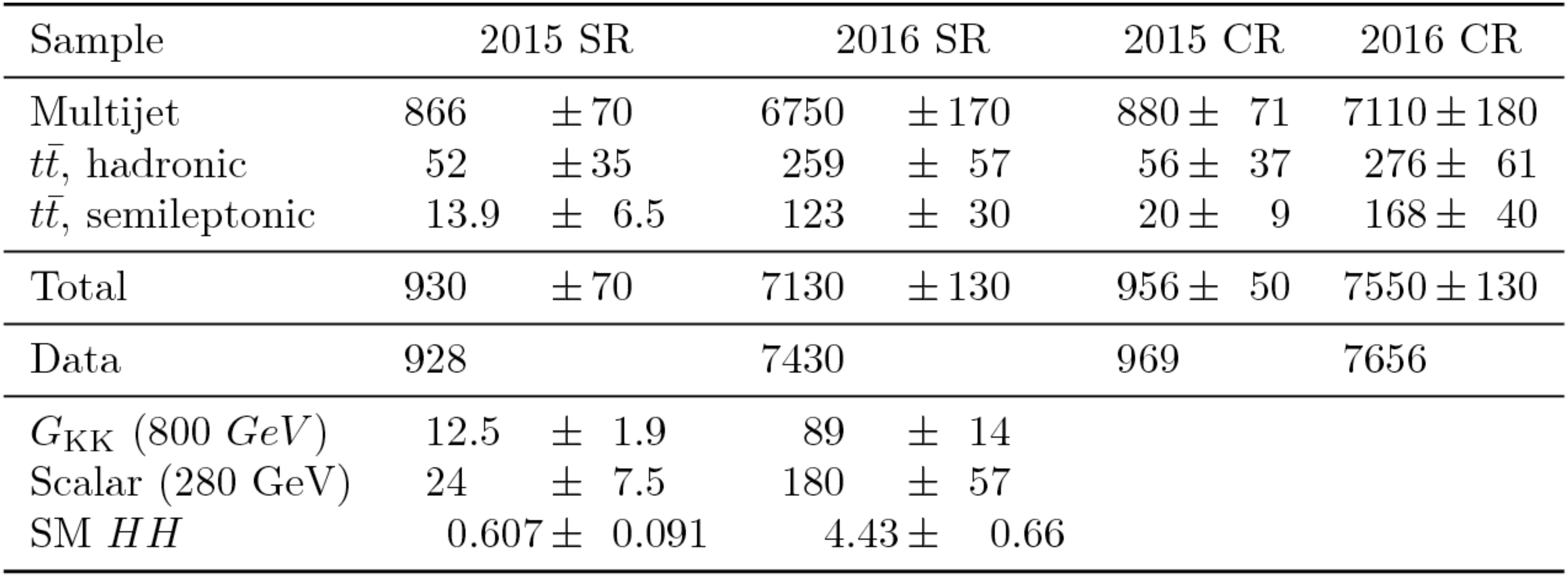
ACC*EFF


ATLAS Simulation
13 TeV, 36.1 fb^{-1}
Bulk RS $k/\overline{M}_{Pl}$=1
Acceptance × Efficiency
0.1
0.08
0.06
0.04
0.02
0
200 300 400 500 600 700 800 900 1000
$\tau_{lep}\tau_{had}$
$\tau_{had}\tau_{had}$
ATLAS Simulation
13 TeV, 36.1 fb^{-1}
Bulk RS $k/\overline{M}_{Pl}$=2
Acceptance × Efficiency
0.1
0.08
0.06
0.04
0.02
0
200 300 400 500 600 700 800 900 1000
$\tau_{lep}\tau_{had}$
$\tau_{had}\tau_{had}$
$m(G_{kk})$ [GeV]
ATLAS Simulation
13 TeV, 36.1 fb^{-1}
Narrow Scalar
Acceptance × Efficiency
0.1
0.08
0.06
0.04
0.02
0
200 300 400 500 600 700 800 900 1000
$\tau_{lep}\tau_{had}$
$\tau_{had}\tau_{had}$
m(X) [GeV]

RESONANT LIMITS

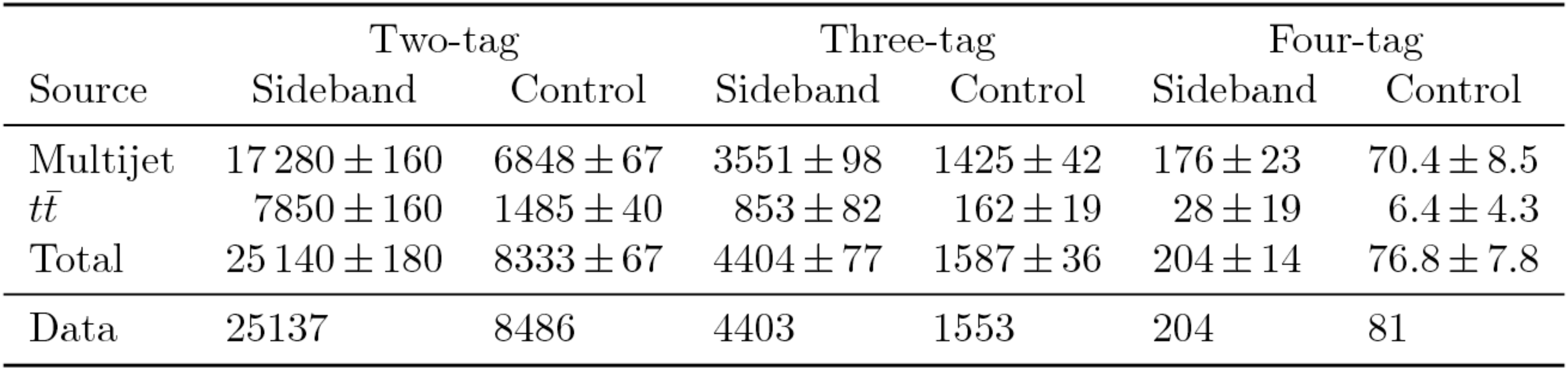


BBBB: RESOLVED EVENT YIELDS

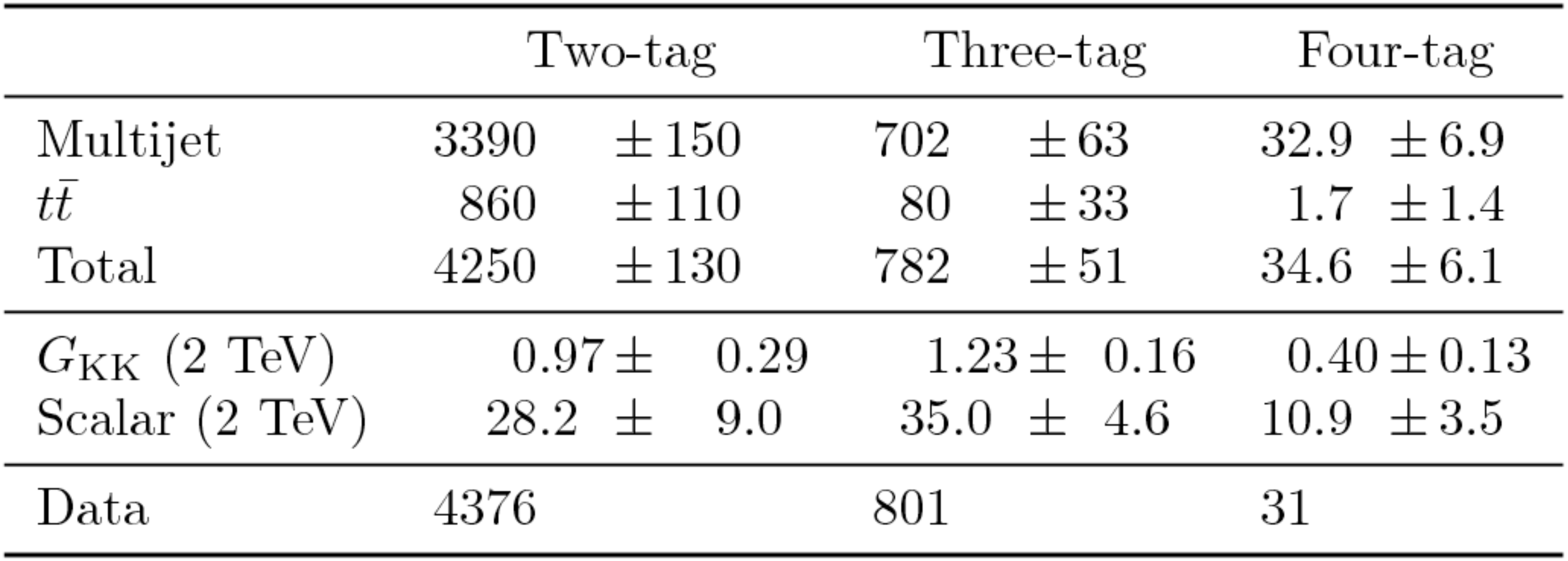


Sample	2015 SR	2016 SR	2015 CR	2016 CR
Multijet	866 ± 70	6750 ± 170	880 ± 71	7110 ± 180
$t\bar{t}$, hadronic	52 ± 35	259 ± 57	56 ± 37	276 ± 61
$t\bar{t}$, semileptonic	13.9 ± 6.5	123 ± 30	20 ± 9	168 ± 40
Total	930 ± 70	7130 ± 130	956 ± 50	7550 ± 130
Data	928	7430	969	7656
G_{KK} (800 GeV)	12.5 ± 1.9	89 ± 14		
Scalar (280 GeV)	24 ± 7.5	180 ± 57		
SM HH	0.607 ± 0.091	4.43 ± 0.66		

BBBB: BOOSTED EVENT YIELDS



Source	Two-tag Sideband	Two-tag Control	Three-tag Sideband	Three-tag Control	Four-tag Sideband	Four-tag Control
Multijet	17 280 ± 160	6848 ± 67	3551 ± 98	1425 ± 42	176 ± 23	70.4 ± 8.5
$t\bar{t}$	7850 ± 160	1485 ± 40	853 ± 82	162 ± 19	28 ± 19	6.4 ± 4.3
Total	25 140 ± 180	8333 ± 67	4404 ± 77	1587 ± 36	204 ± 14	76.8 ± 7.8
Data	25137	8486	4403	1553	204	81

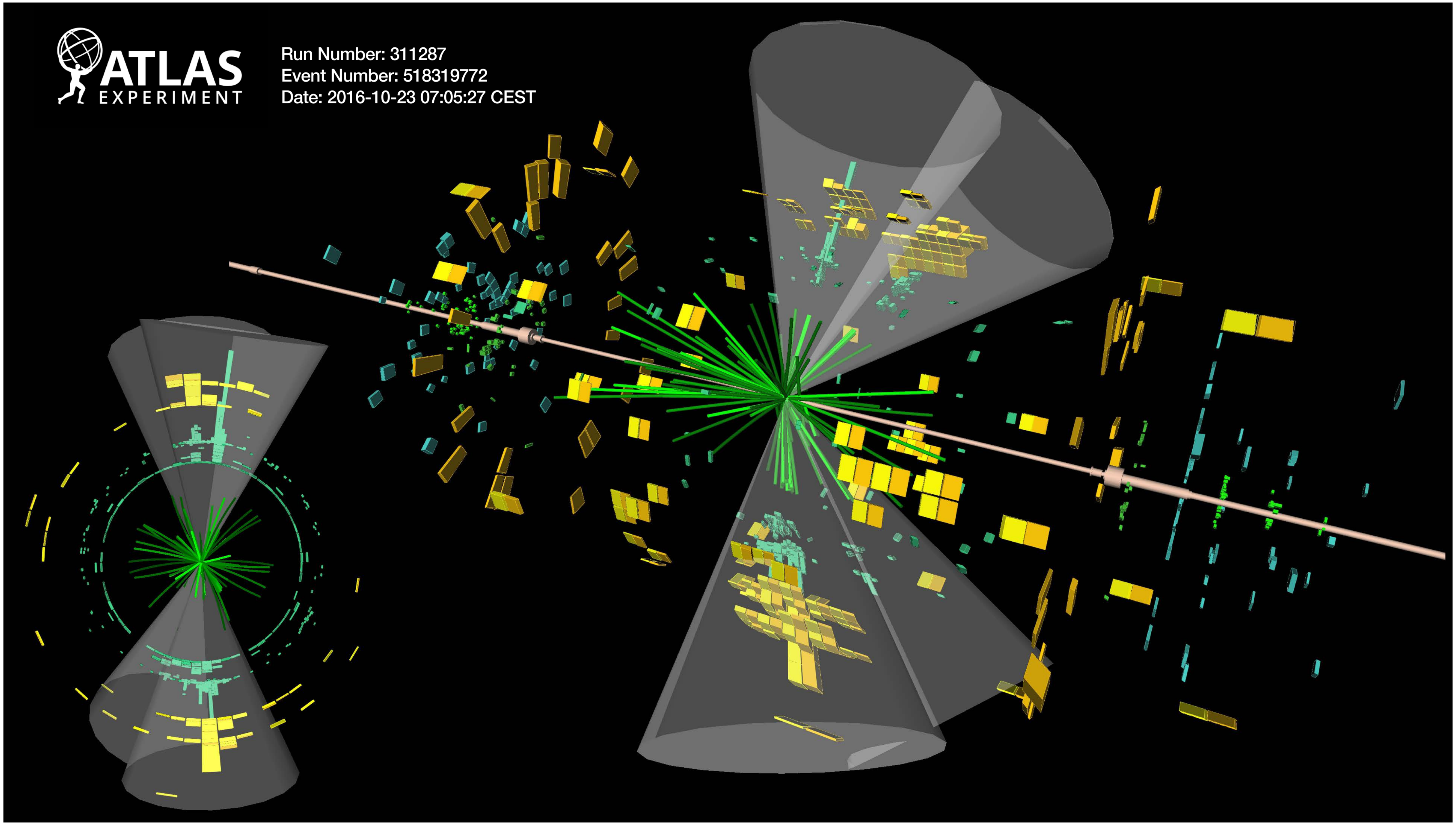


	Two-tag	Three-tag	Four-tag
Multijet	3390 ± 150	702 ± 63	32.9 ± 6.9
$t\bar{t}$	860 ± 110	80 ± 33	1.7 ± 1.4
Total	4250 ± 130	782 ± 51	34.6 ± 6.1
G_{KK} (2 TeV)	0.97 ± 0.29	1.23 ± 0.16	0.40 ± 0.13
Scalar (2 TeV)	28.2 ± 9.0	35.0 ± 4.6	10.9 ± 3.5
Data	4376	801	31

BBBB: BOOSTED SYSTEMATICS

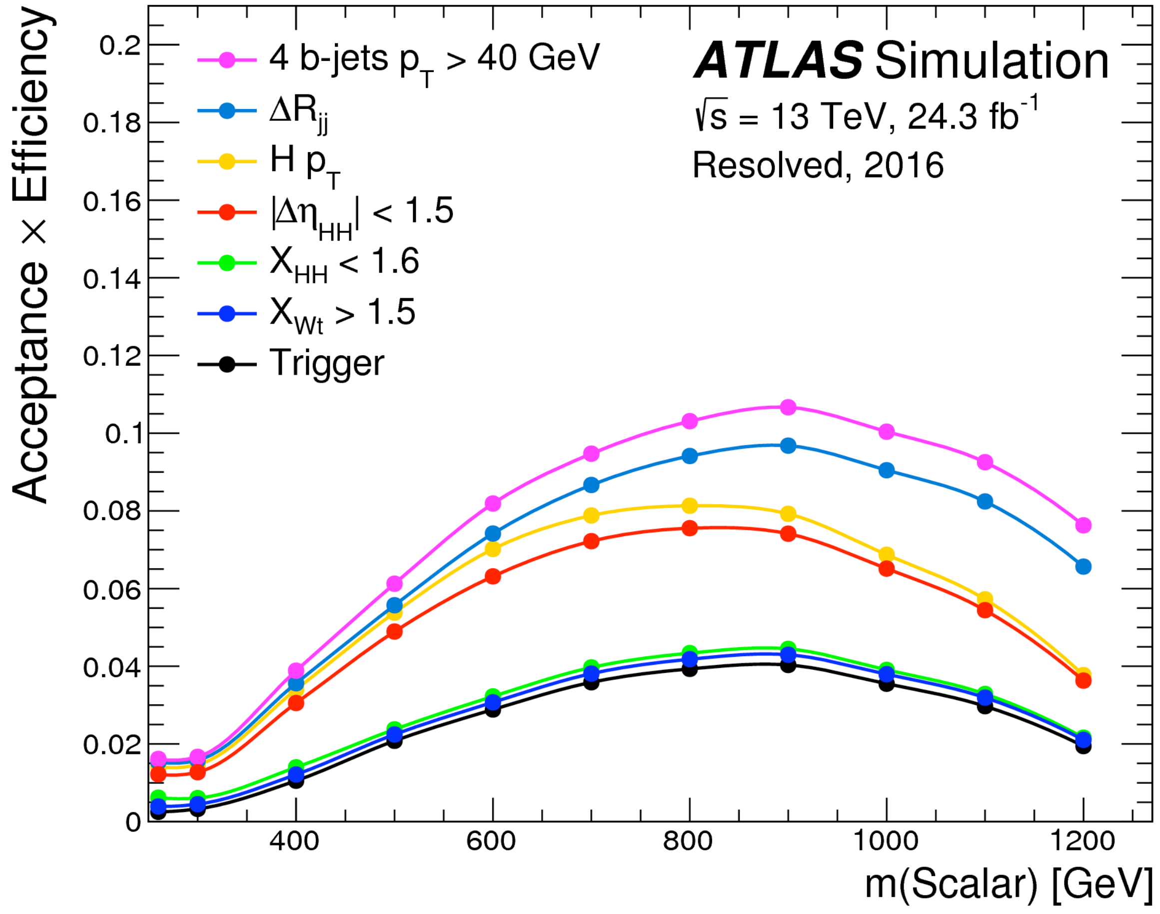
	Two-tag			Three-tag			Four-tag		
Source	Background	G_{KK}	Scalar	Background	G_{KK}	Scalar	Background	G_{KK}	Scalar
Luminosity	-	2.1	2.1	-	2.1	2.1	-	2.1	2.1
JER	0.25	0.74	1	1.4	0.93	0.93	0.45	1.1	1.5
JMR	0.52	12	12	1.4	12	13	7.9	13	14
JES/JMS	0.43	1.7	2.1	2.0	1.9	2.2	1.3	3.7	5.7
b-tagging	0.83	27	29	0.48	2	2.9	1.1	28	28
Bkgd estimate	2.8	-	-	5.8	-	-	16	-	-
Statistical	0.6	1.2	1.3	1.3	1.0	1.1	3.1	1.6	1.9
Total Syst	3.1	30	32	6.6	13	14	18	31	32

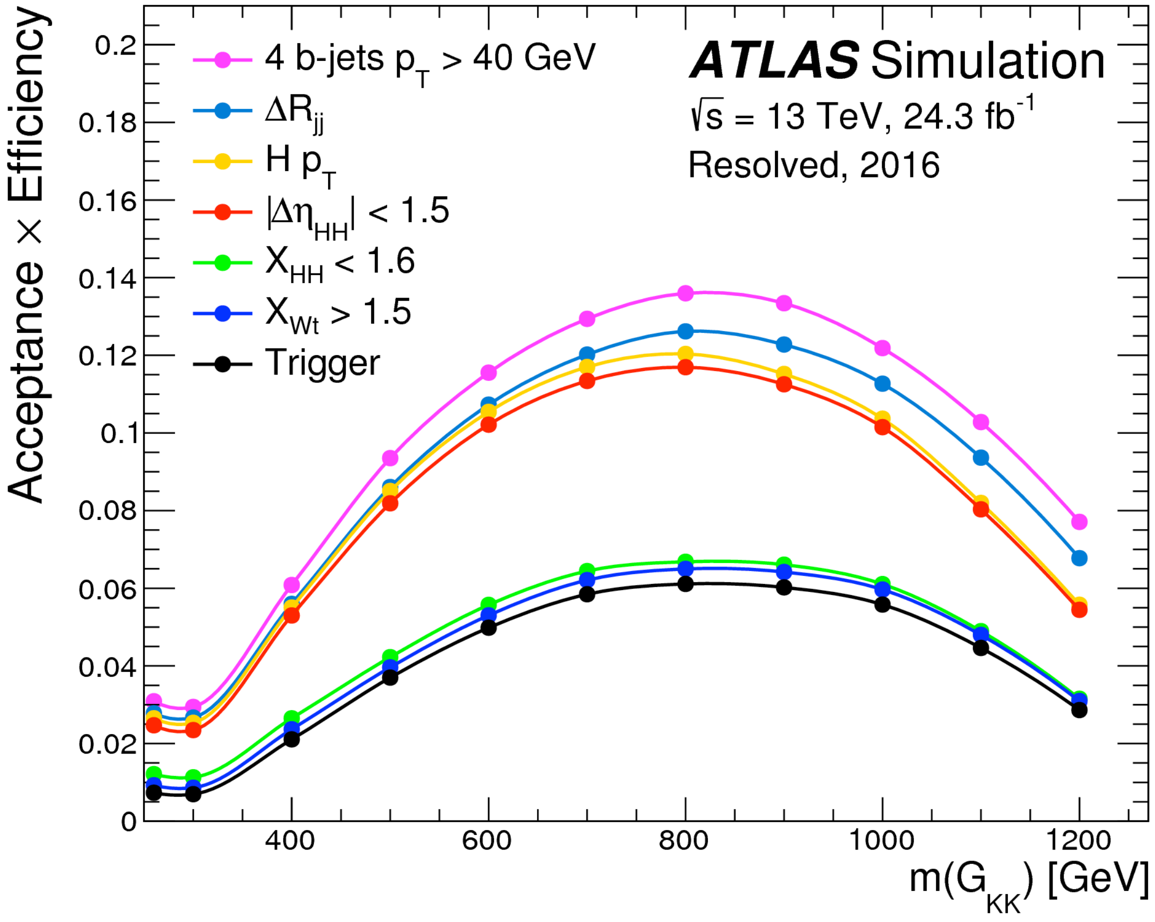
4B EVENT DISPLAY: RESOLVED SELECTION



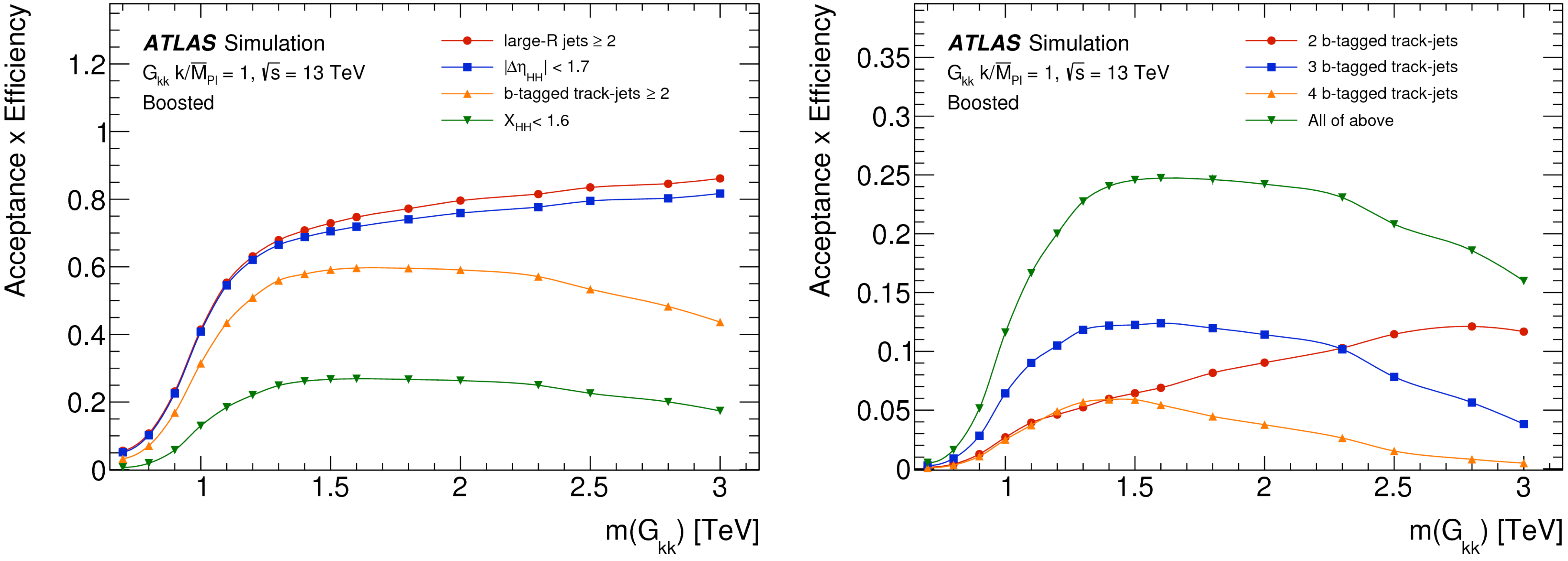
Run Number: 311287
Event Number: 518319772
Date: 2016-10-23 07:05:27 CEST

ACC*EFF RESOLVED

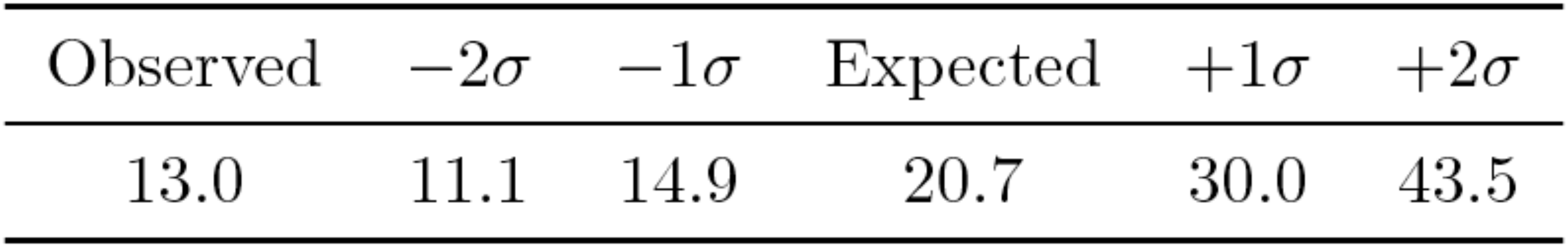




ACC*EFF BOOSTED

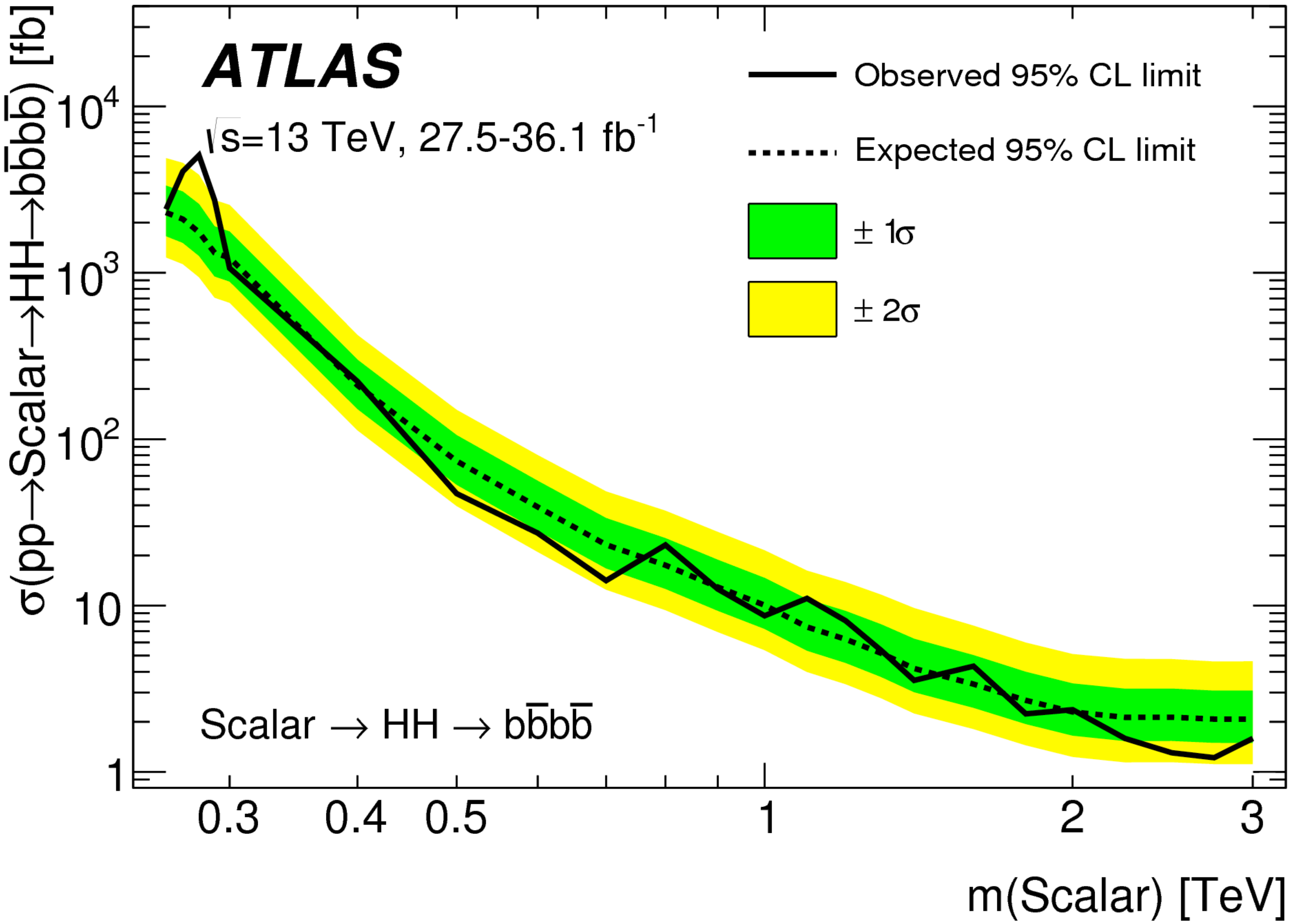


NON- RESONANT LIMITS

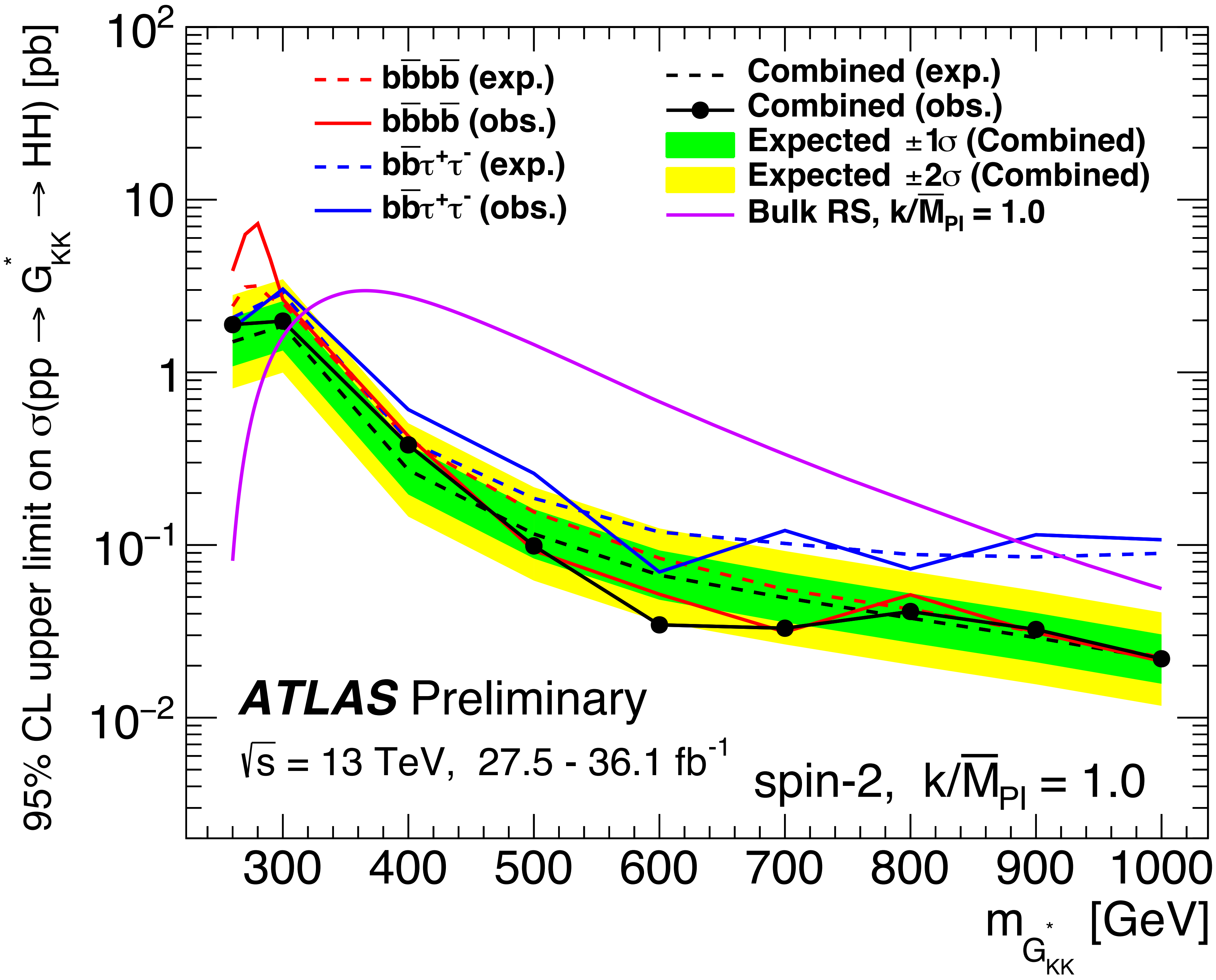


Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
13.0	11.1	14.9	20.7	30.0	43.5

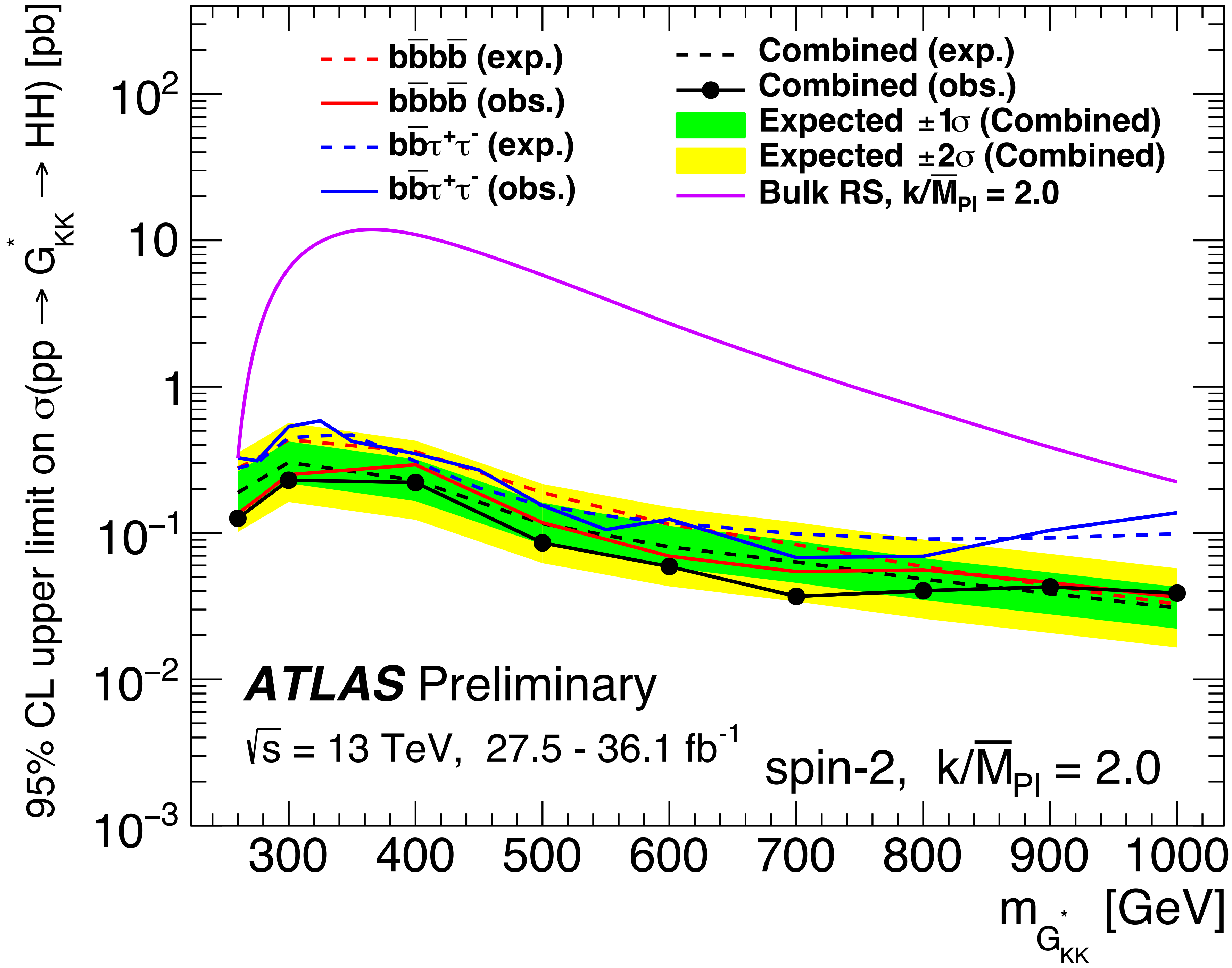
SPIN 0 RESONANT LIMITS



SPIN 2 RESONANT LIMITS

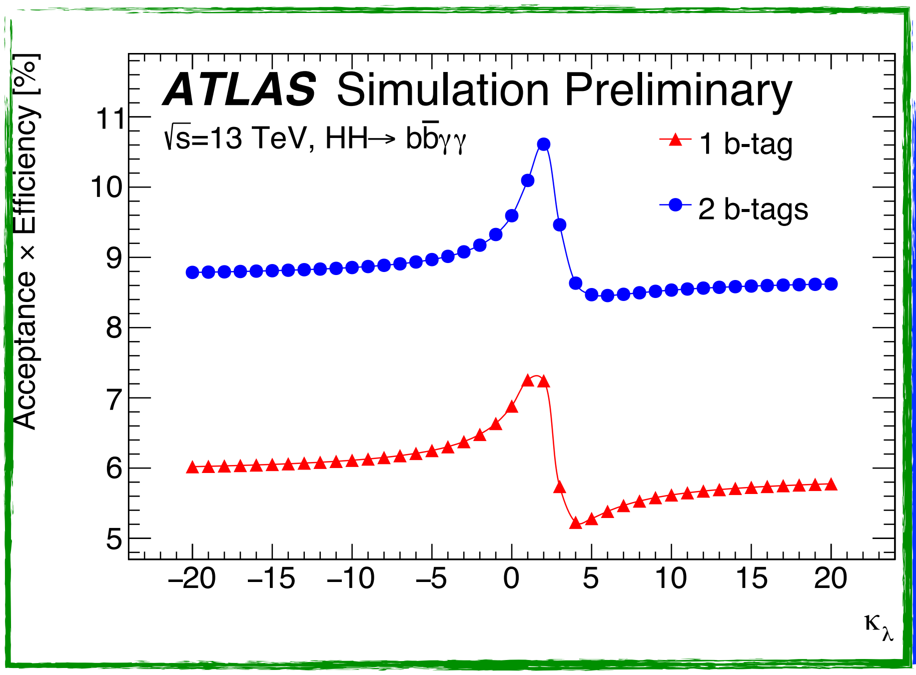


SPIN 2 RESONANT LIMITS

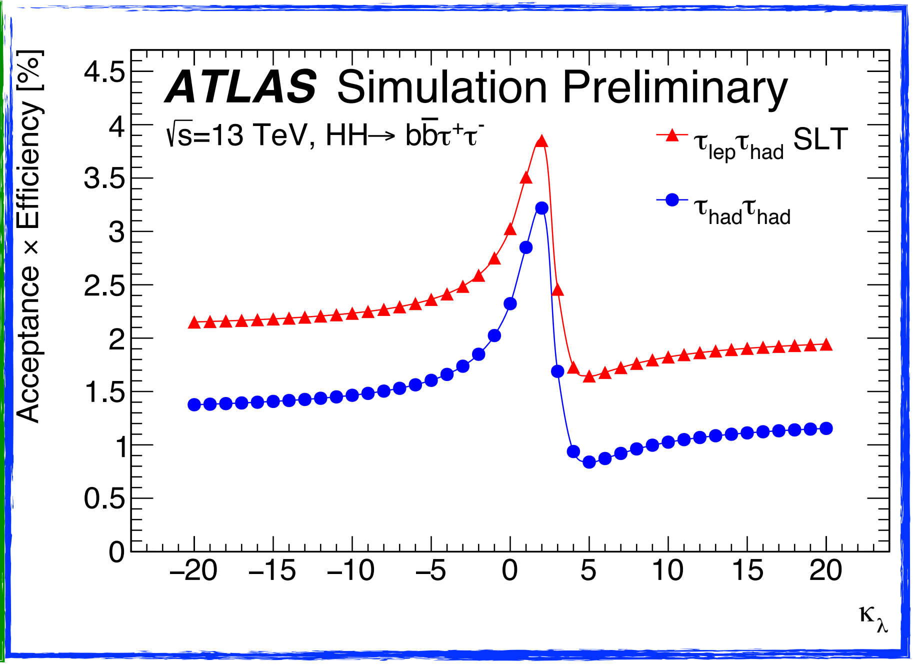


NON-RESONANT LIMITS: HIGGS SELF-COUPLING

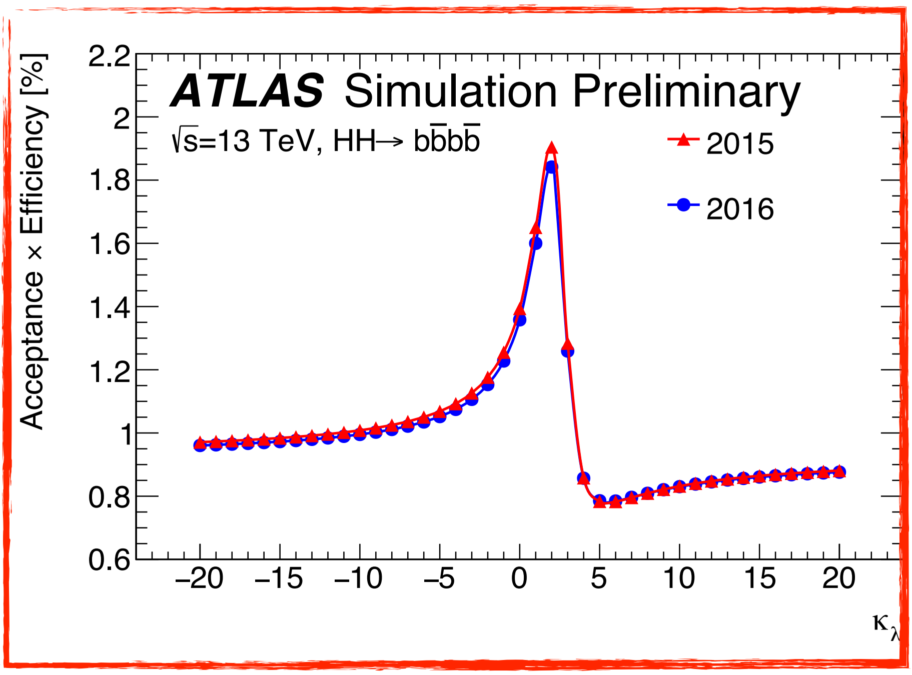
acceptance*efficiency curves for each channel



HH → γγbb



HH → bbττ



HH → bbbb