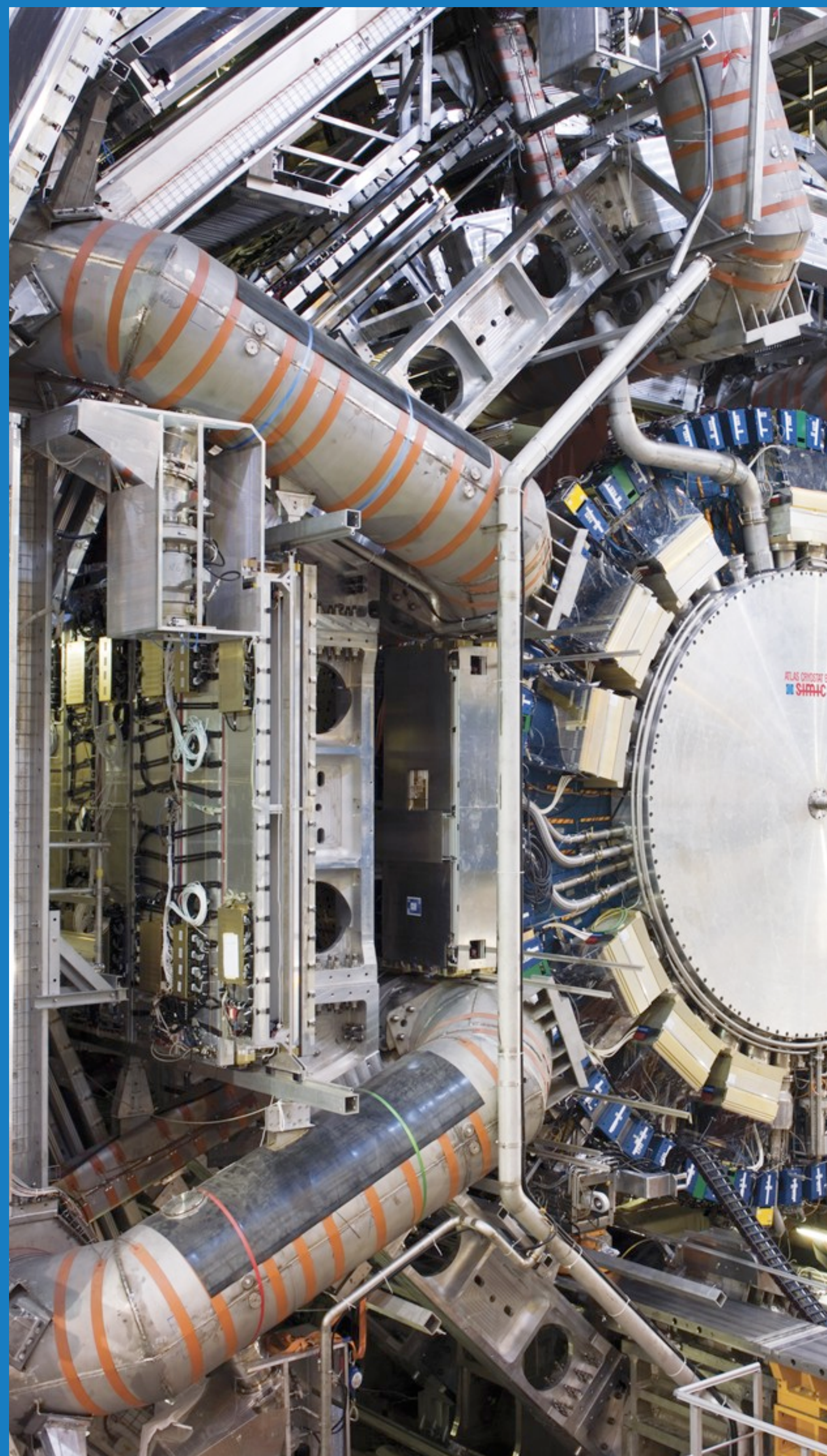


ATLAS HH → YYBB EXPERIMENTAL SUMMARY.

Elizabeth Brost

on behalf of the ATLAS Collaboration

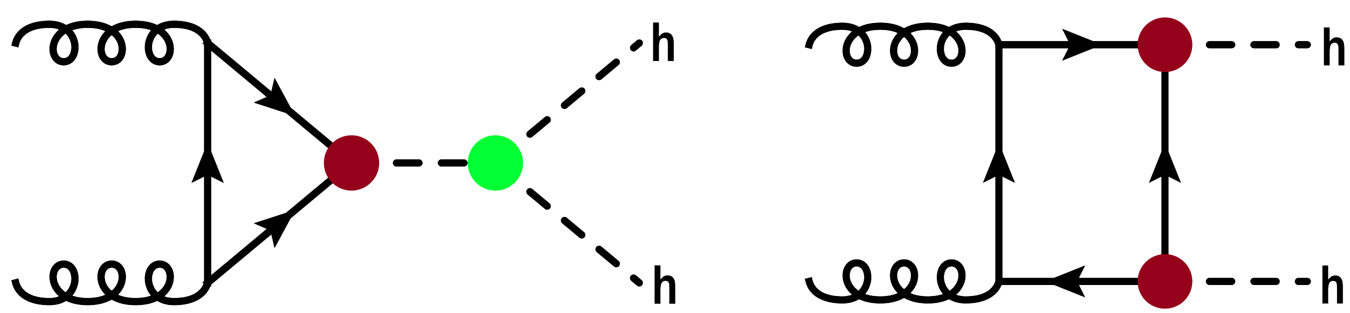
Northern Illinois University

NIU

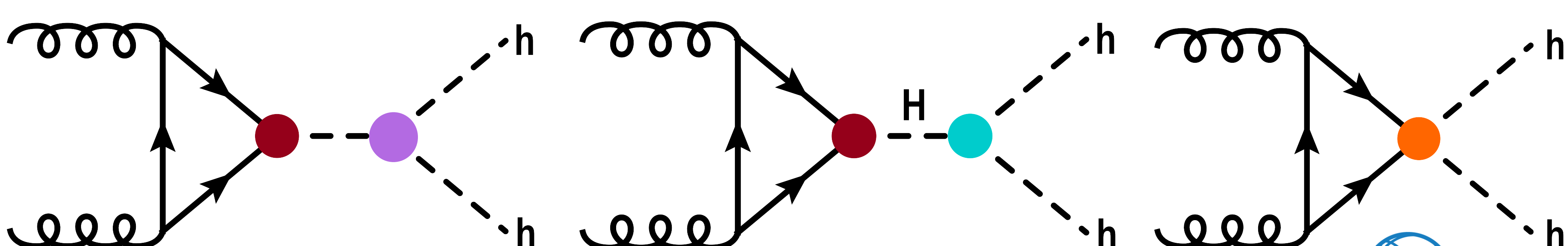
ATLAS EXPERIMENT

DI-HIGGS PRODUCTION

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



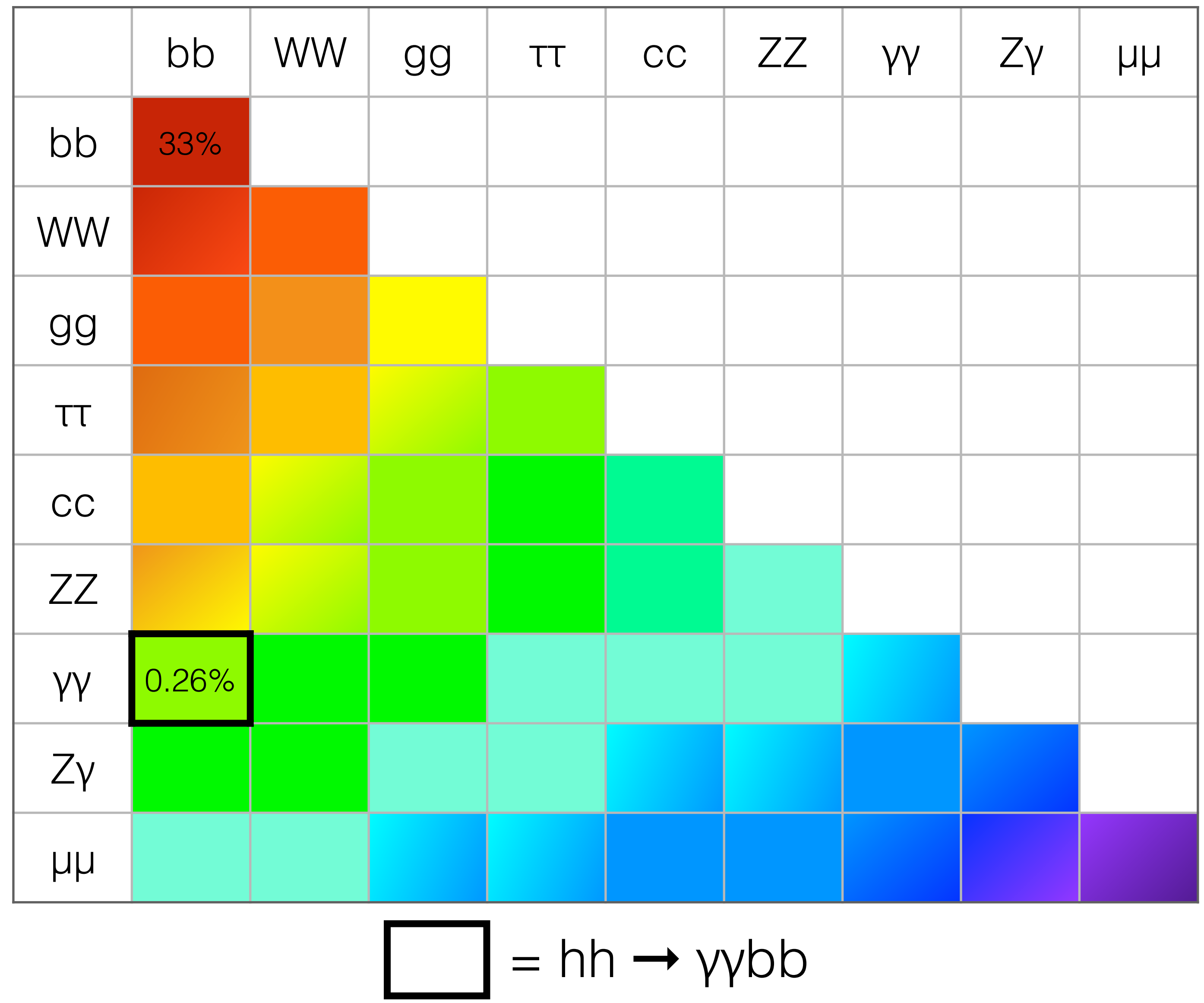
- **Beyond the Standard Model:** possible enhancements?
  - enhanced self-coupling? resonant production via a heavy scalar? addition of a ttHH vertex?



WHY SEARCH FOR HH → γγBB?

- large BR H → bb (0.57)
- great diphoton mass resolution
- excellent photon trigger and identification efficiency

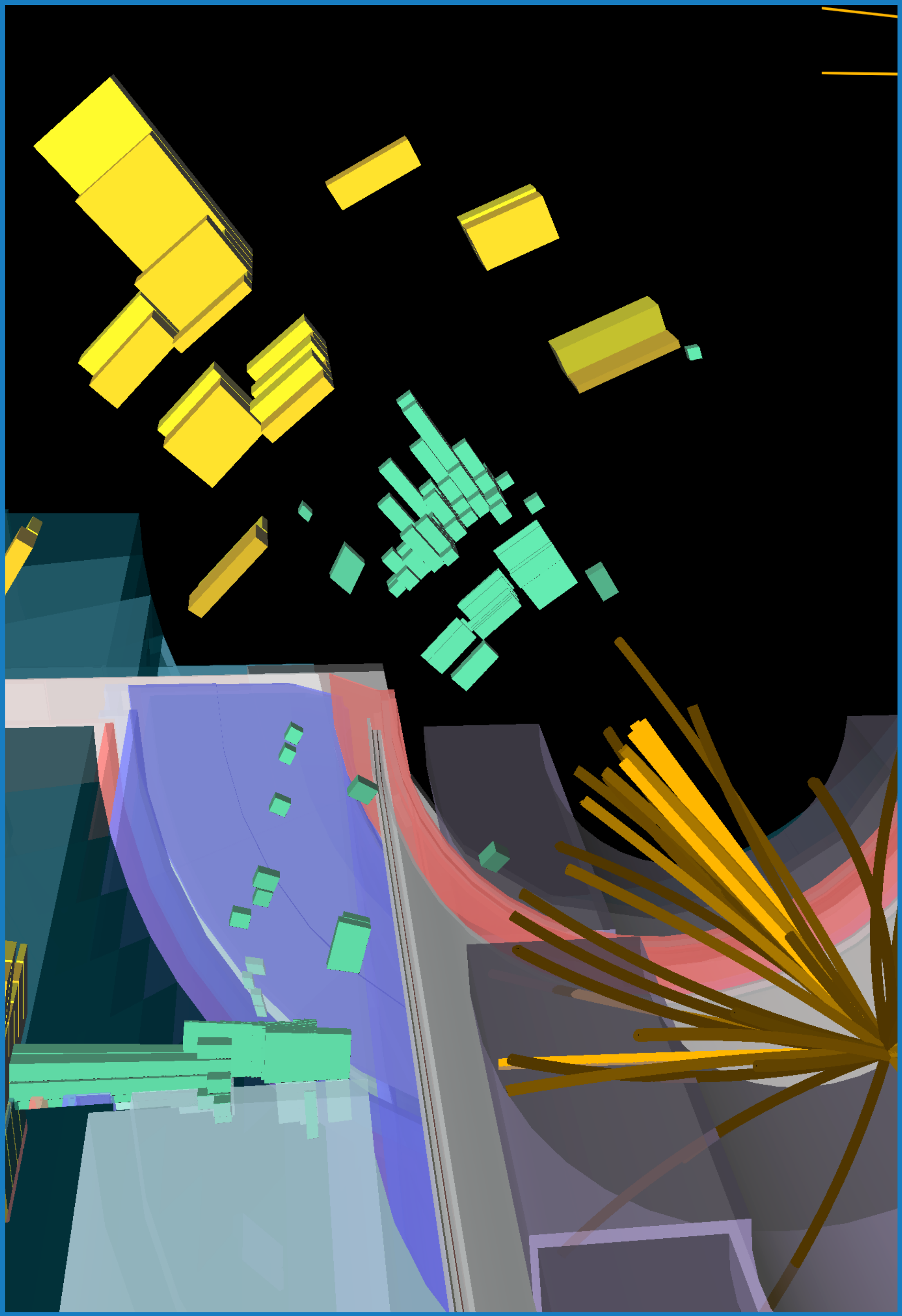
BR(HH → ??+??)



HOW DO WE SEARCH FOR HH → γγBB?

We're looking for **enhanced** HH → γγbb production:

- non-resonant production pp → HH
  - can be enhanced due to new particles in loops
  - can be enhanced if non-SM couplings exist (varied κ_λ)
  - S+B fit to $m_{\gamma\gamma}$ spectrum for events with $m_{bb} \approx m_H$
- resonant production pp → X → HH
  - can be enhanced if there exists a new heavy scalar, X
  - S+B fit to $m_{\gamma\gamma jj}$ spectrum for events with $m_{\gamma\gamma} \approx m_H$ and $m_{bb} \approx m_H$ in the range $260 < m_{\gamma\gamma jj} < 1000$ GeV

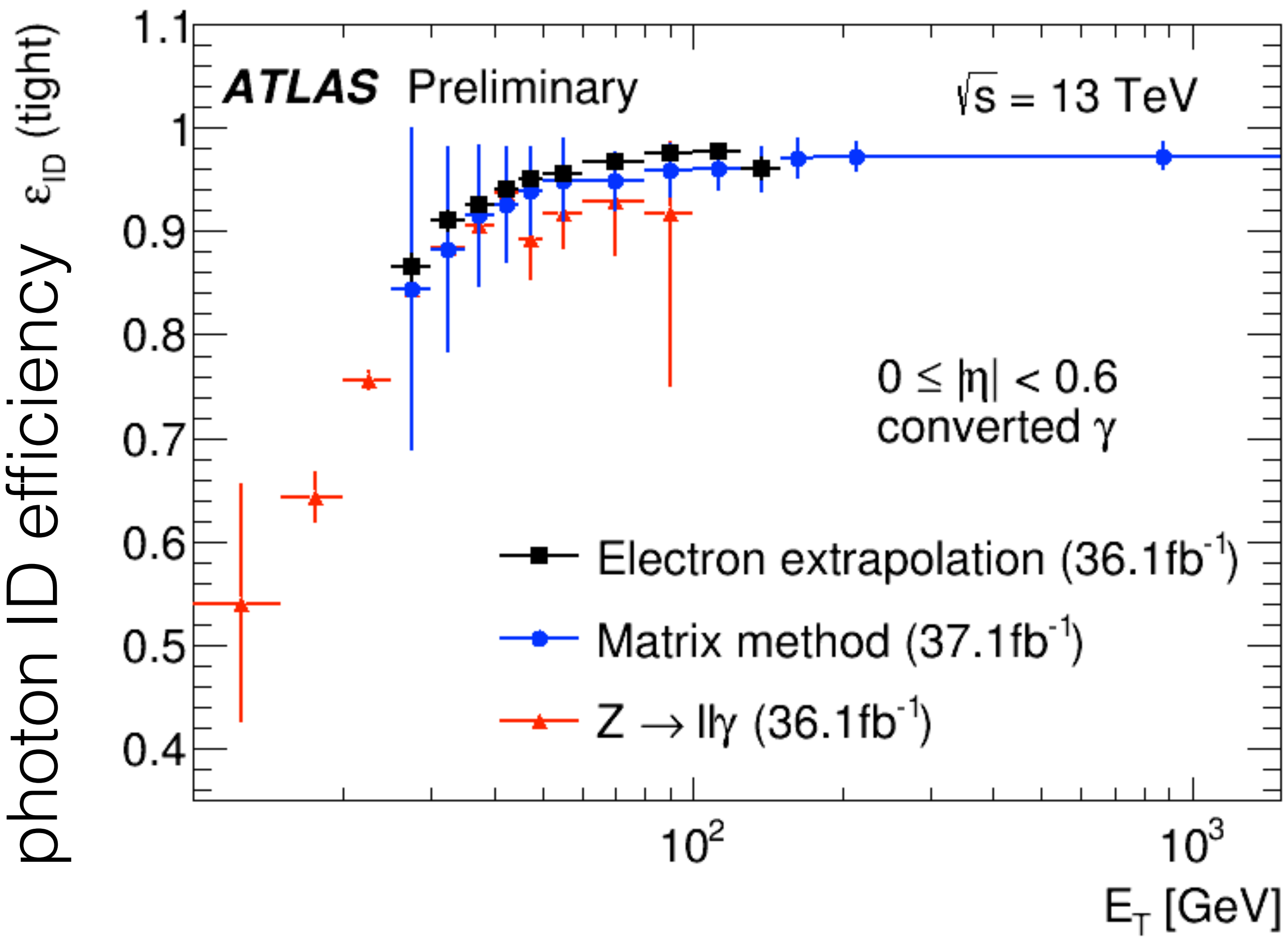


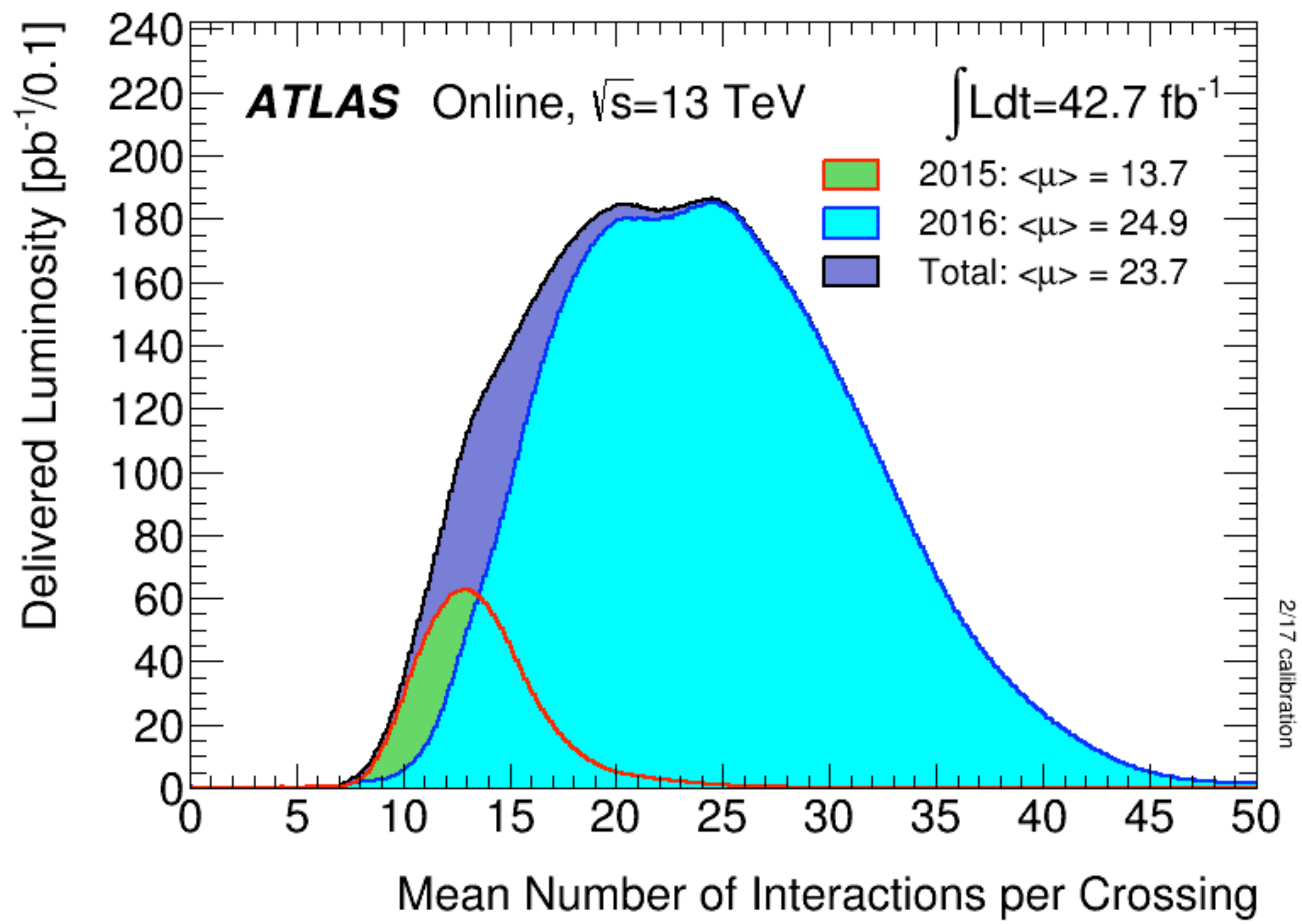
DATA AND MC SAMPLES

ATLAS EXPERIMENT

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

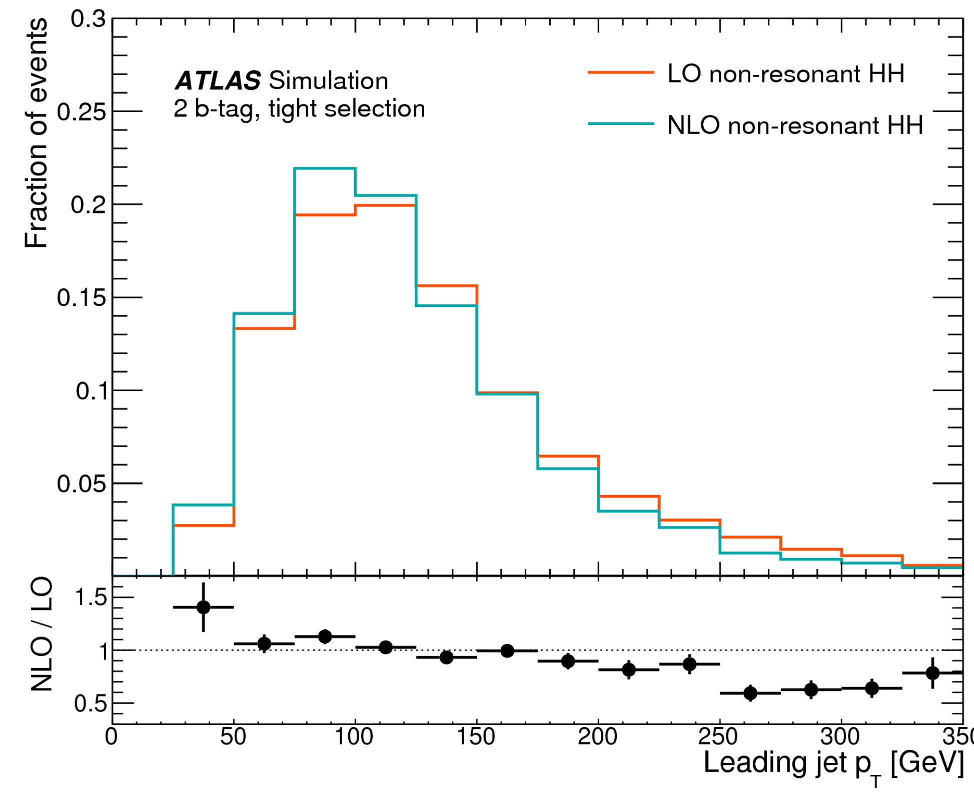
- analyze events selected by diphoton triggers
- 36.1/fb of data with <μ> = 23.7

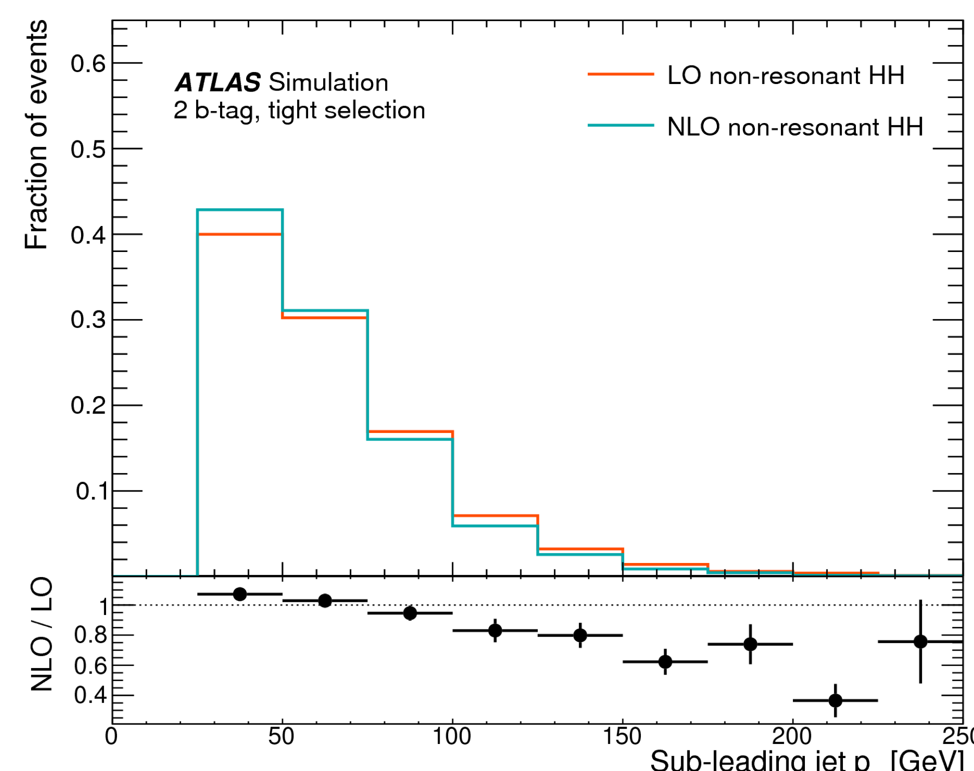




SIGNAL MONTE CARLO SAMPLES

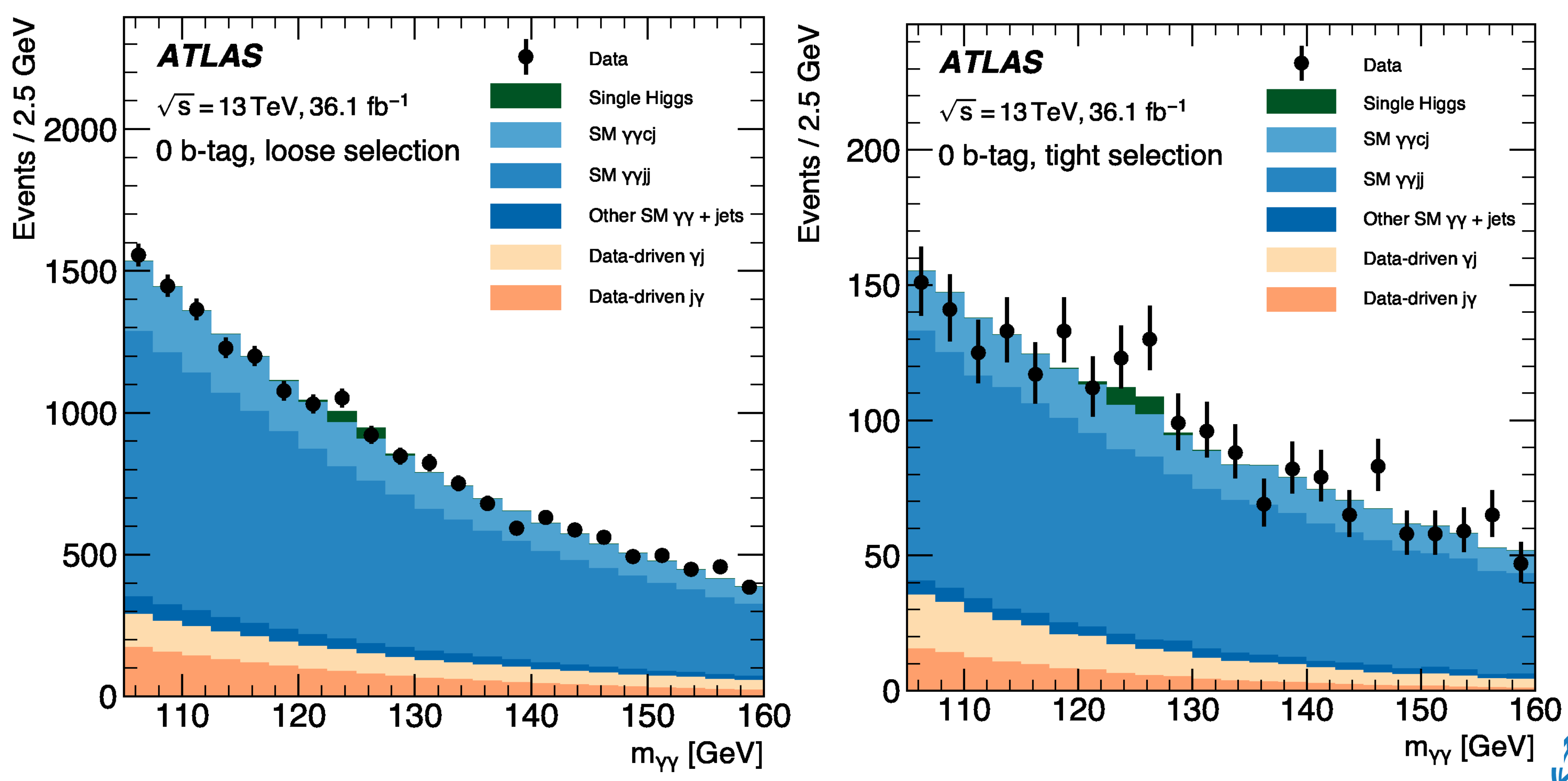
- non-resonant signal
  - pp → HH → γγbb: ≈ NLO Madgraph+Herwig, reweighted to full NLO
  - pp → HH → γγbb (varied κ_λ): LO Madgraph+Pythia
- resonant signal
  - pp → X → HH → γγbb: ≈NLO Madgraph+Herwig
  - m_X = 260, 275, 300, 325, 350, 400, 450, 500, 750, 1000 GeV





BACKGROUND MONTE CARLO SAMPLES

- single-Higgs background: take prediction entirely from MC
  - consider **ggF**, VBF, WH, **ZH**, **ttH**, bbH, tH processes
- reweight Sherpa γγ+jets MC to data in 0-tag control region – used to choose background fit function only



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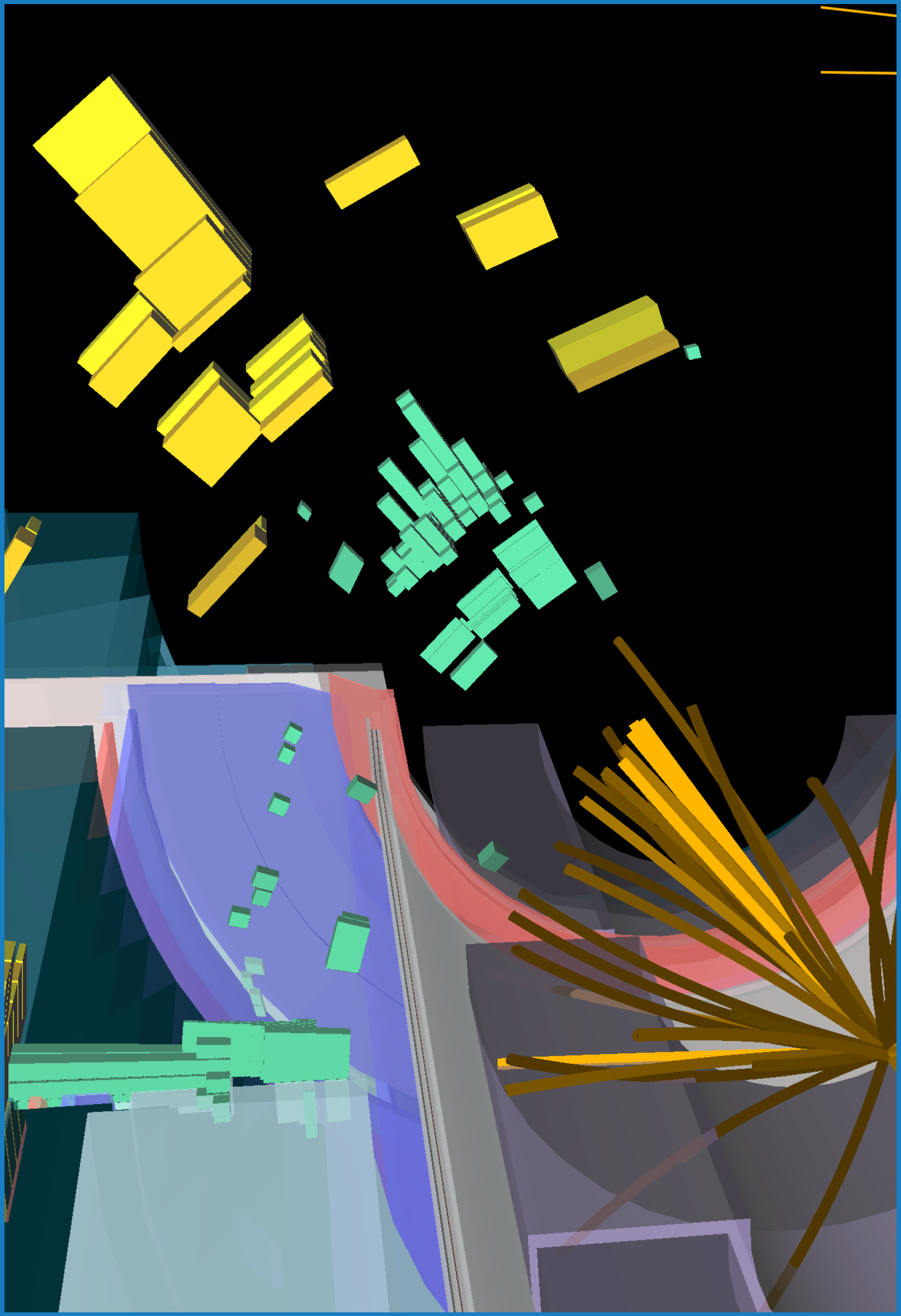
ATLAS EXPERIMENT

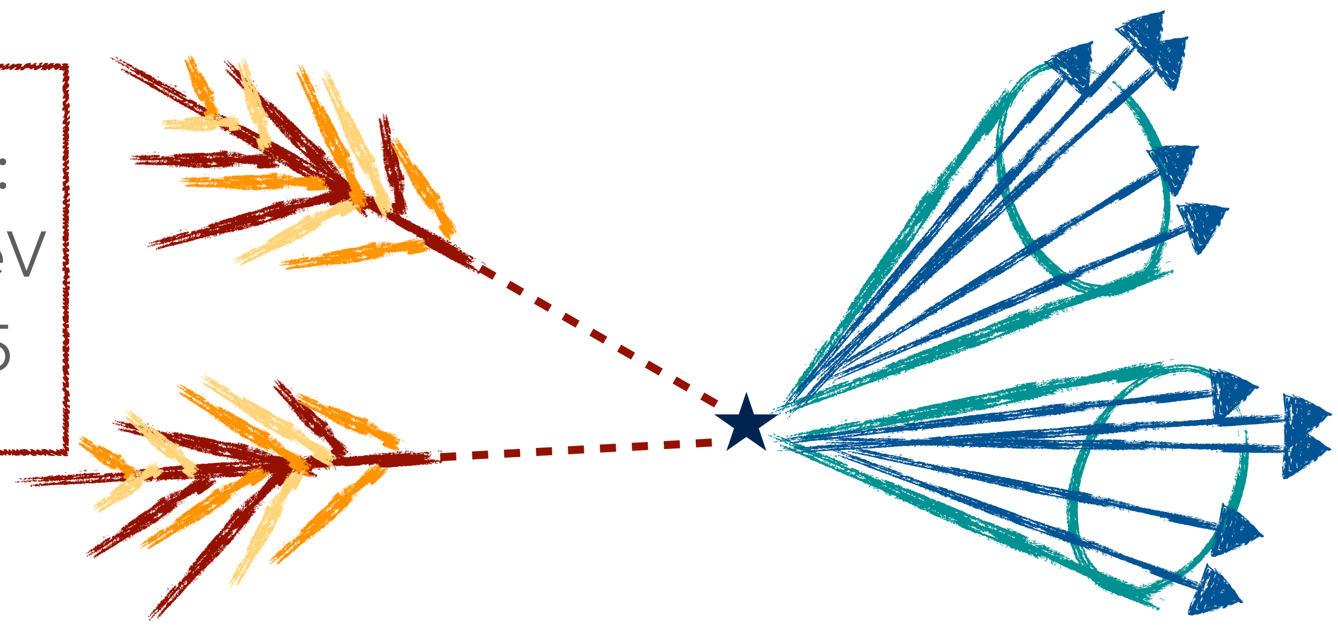


OBJECT AND EVENT SELECTION

ATLAS EXPERIMENT

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

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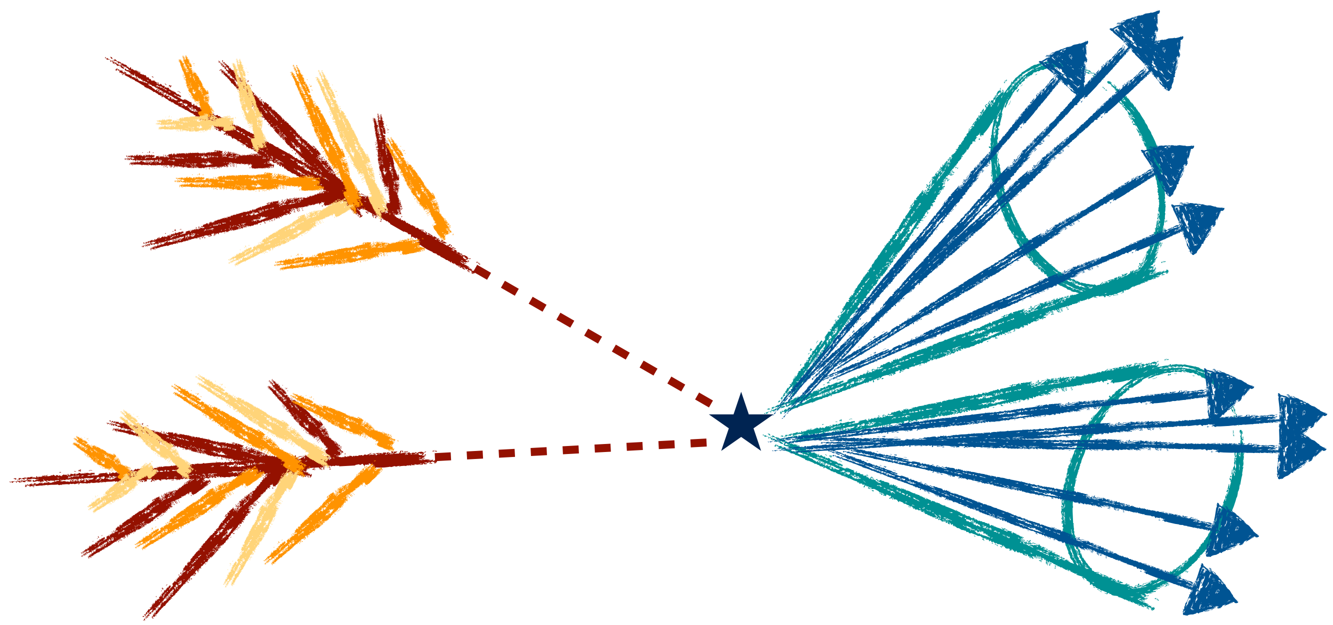
ATLAS EXPERIMENT

1 B-TAG BDT



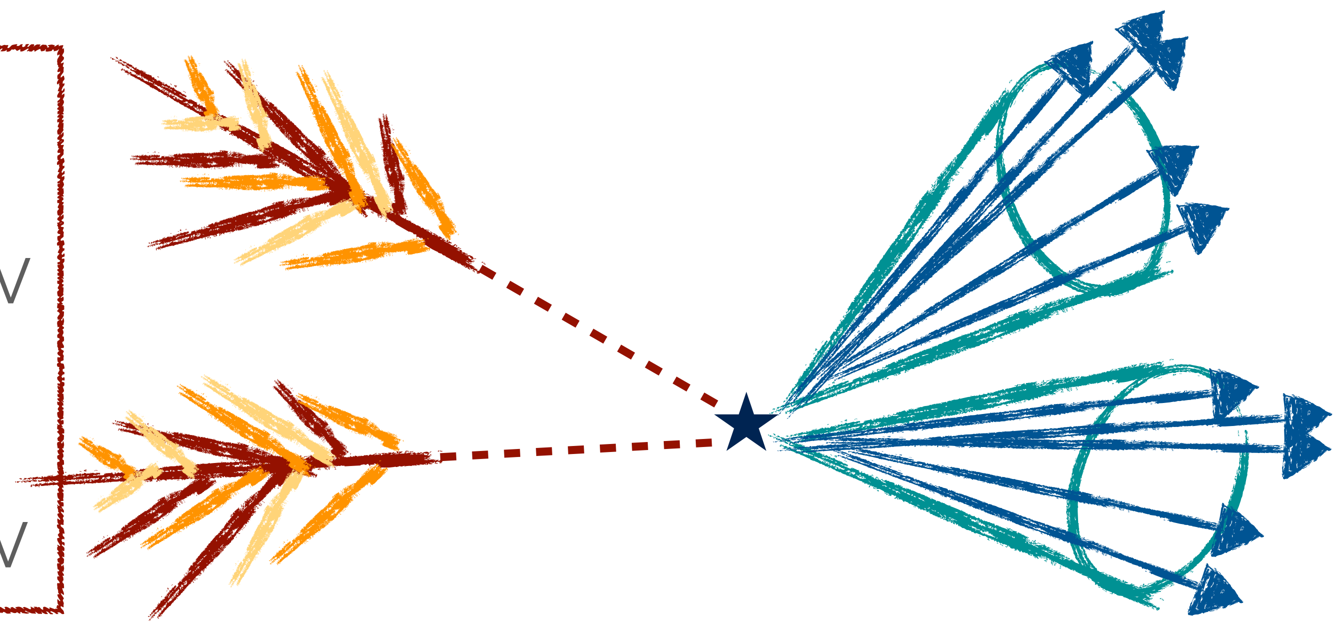
1st jet is b-tagged @ 60% WP → select 2nd jet

- 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

EVENT SELECTION

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

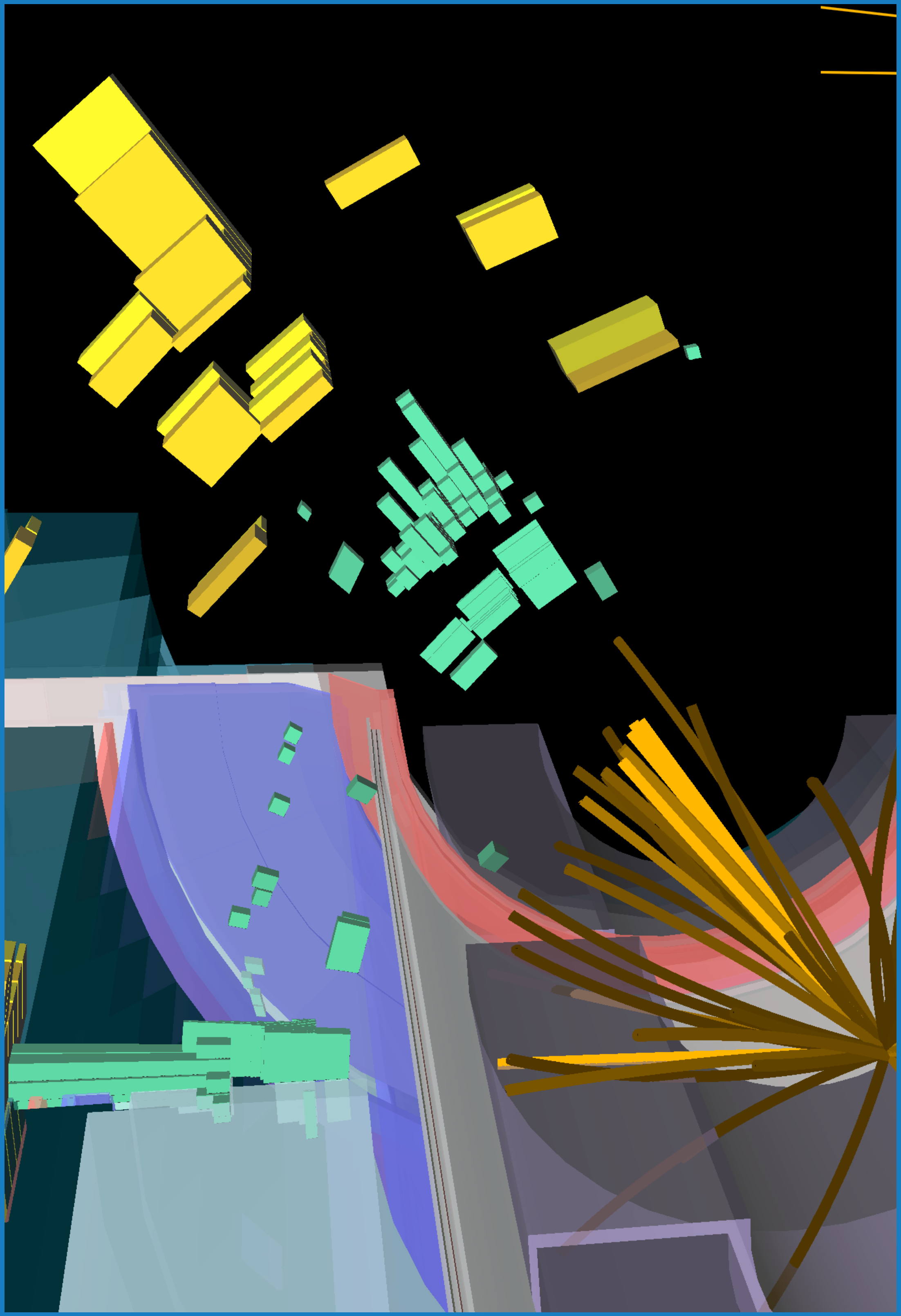
tight selection:
$|m_{\gamma\gamma} - m_H| < 4.3$ GeV



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

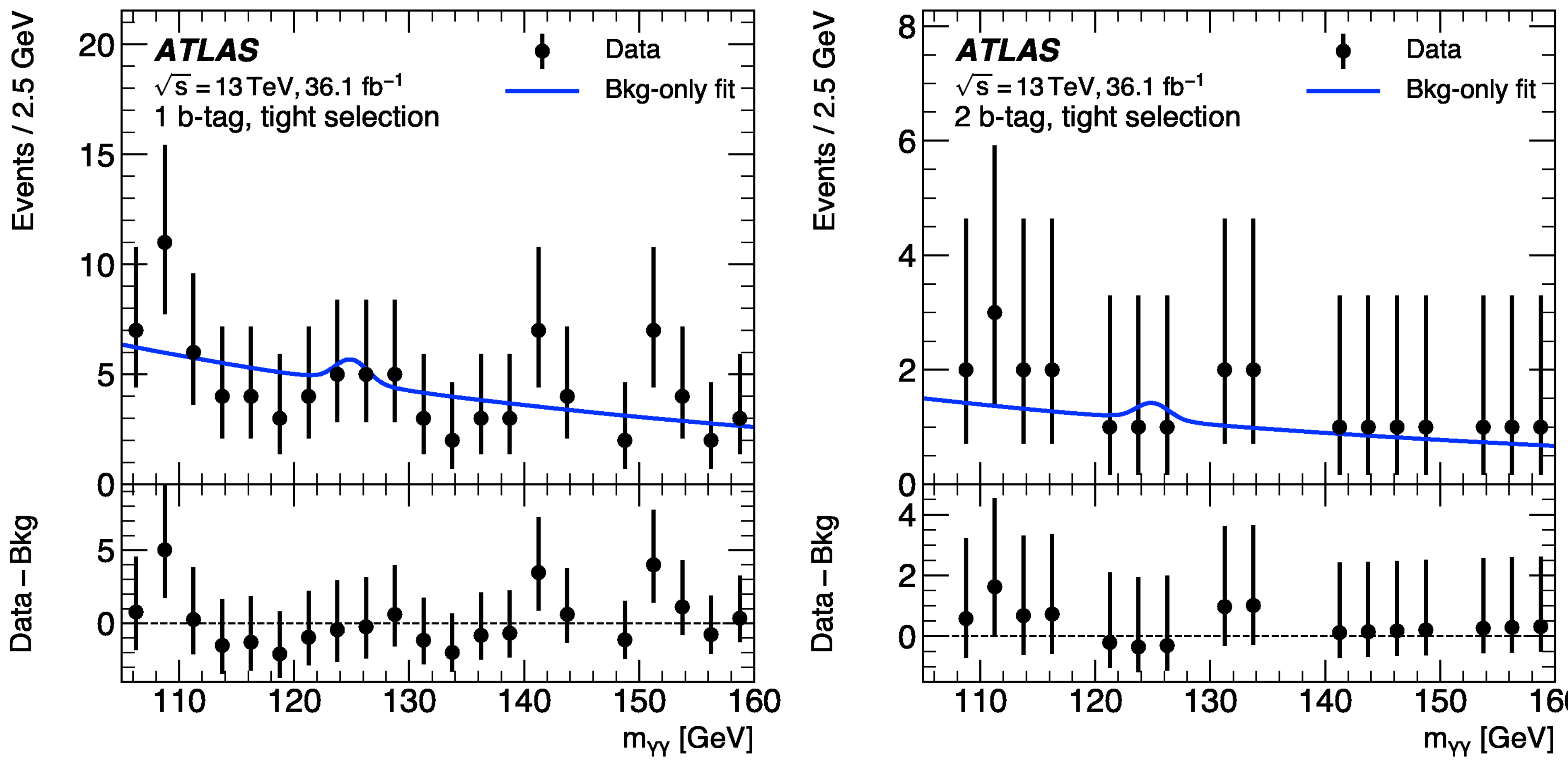
tight selection:
jet $p_T > 100$ (30) GeV
$m_{jj} \in [90, 140]$ GeV

- 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



SIGNAL AND BACKGROUND MODELING

NON-RESONANT MODELING

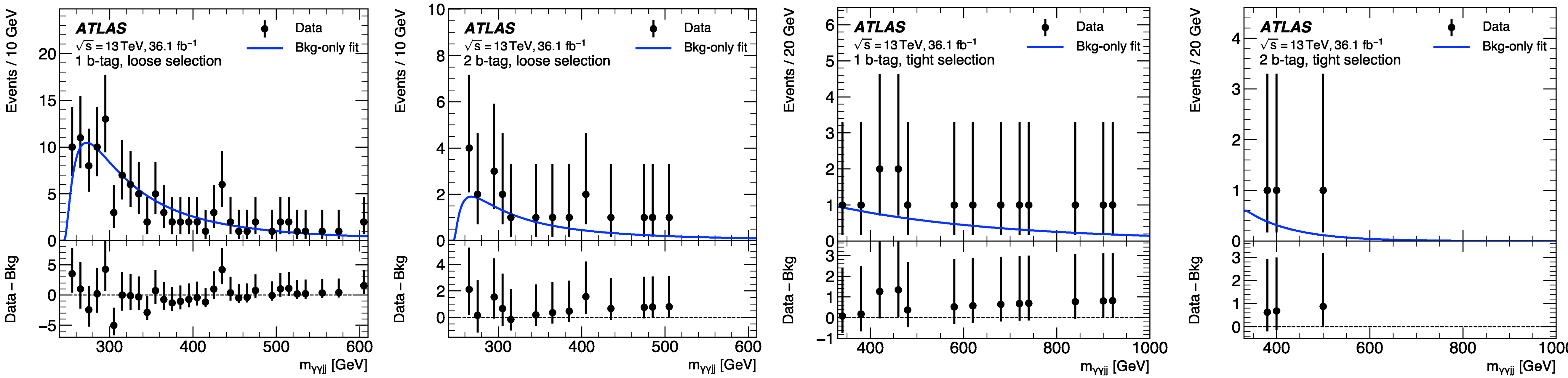


- **background modeling**: exponential + DSCB for single-Higgs components (fit the data directly)
- **signal modeling**: Double-sided Crystal Ball (DSCB)

RESONANT BACKGROUND MODELING

Novosibirsk function

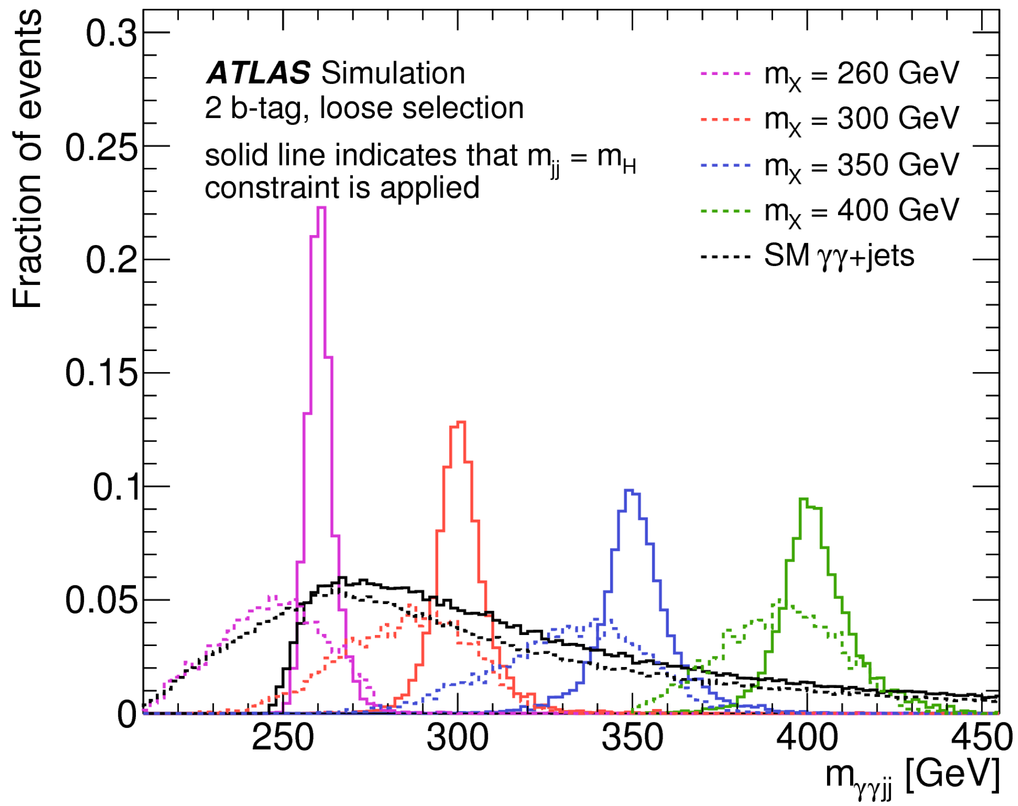
exponential function

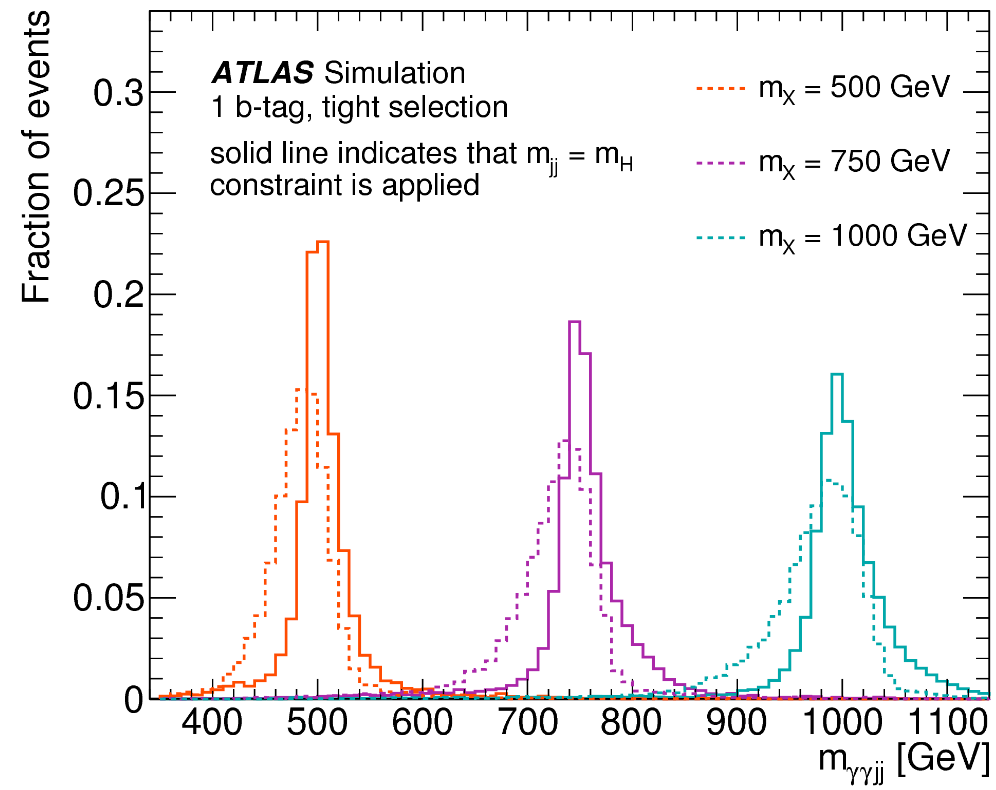


- **"loose" selection** (260-500 GeV): $m_{\gamma\gamma jj}$ is modeled with a Novosibirsk function
- **"tight" selection** (500-1000 GeV): $m_{\gamma\gamma jj}$ is modeled with an exponential function

RESONANT SIGNAL MODELING

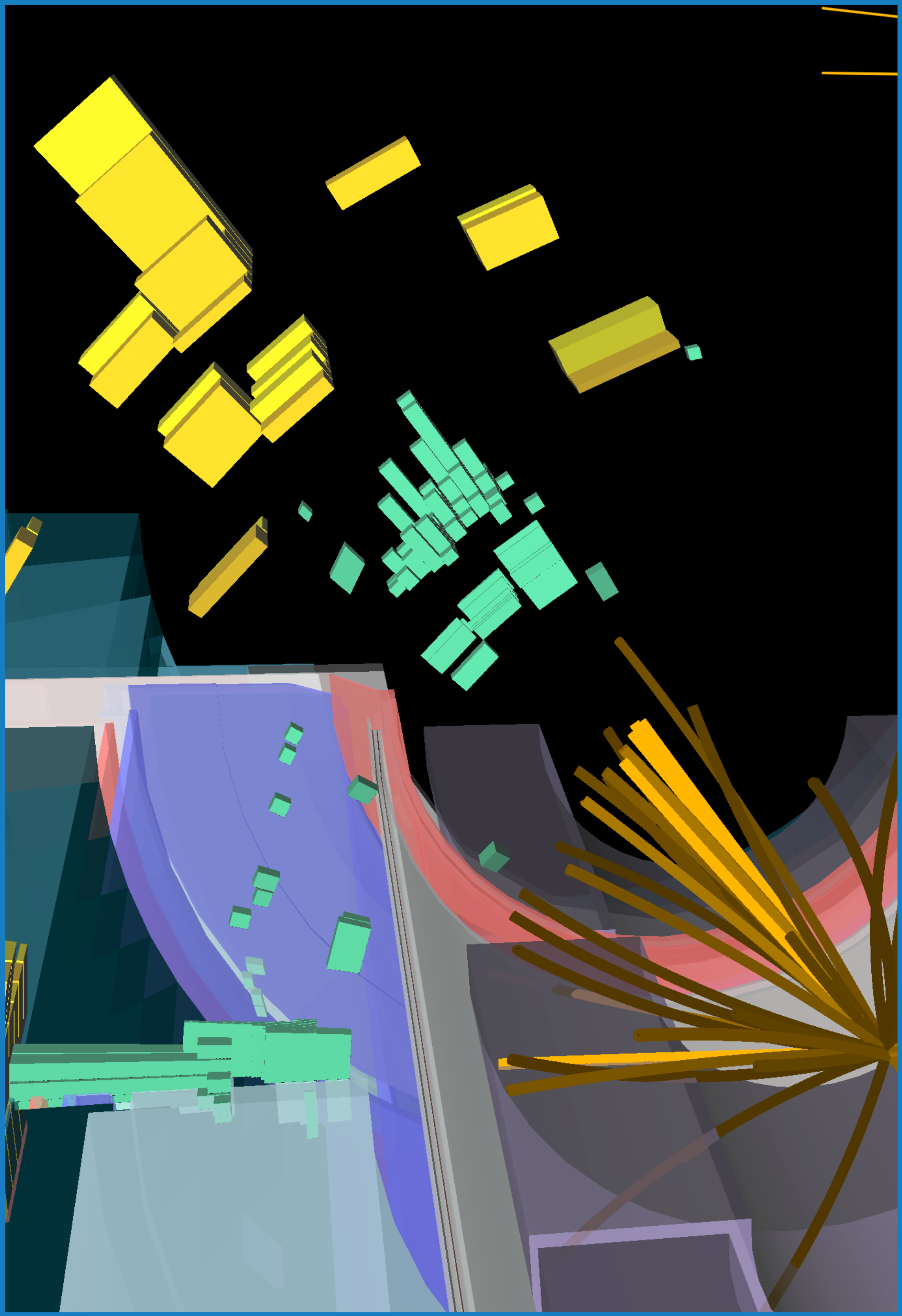
loose selection





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



EVALUATING SYSTEMATIC UNCERTAINTIES

ATLAS EXPERIMENT

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

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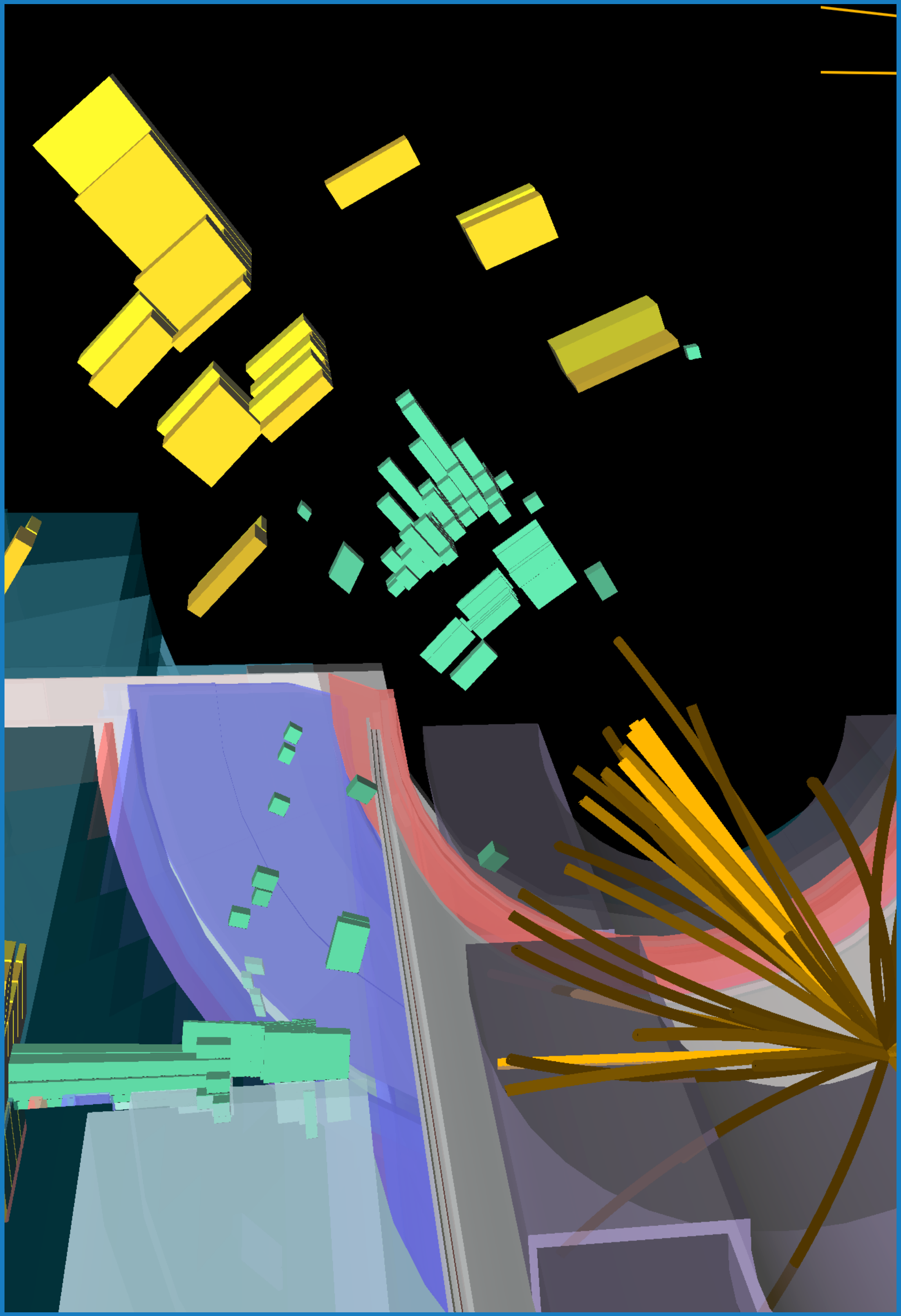
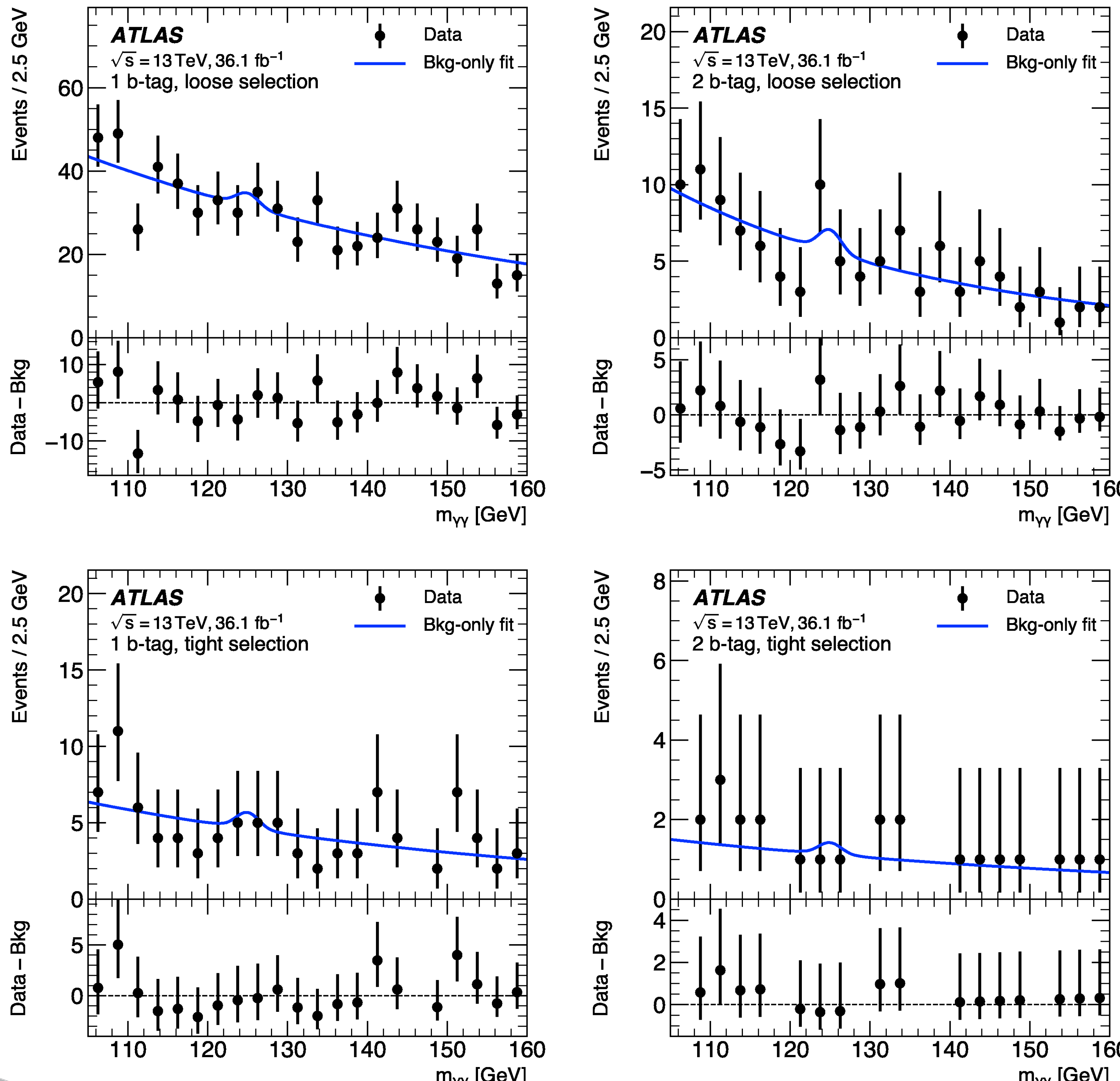
ATLAS EXPERIMENT



RESULTS

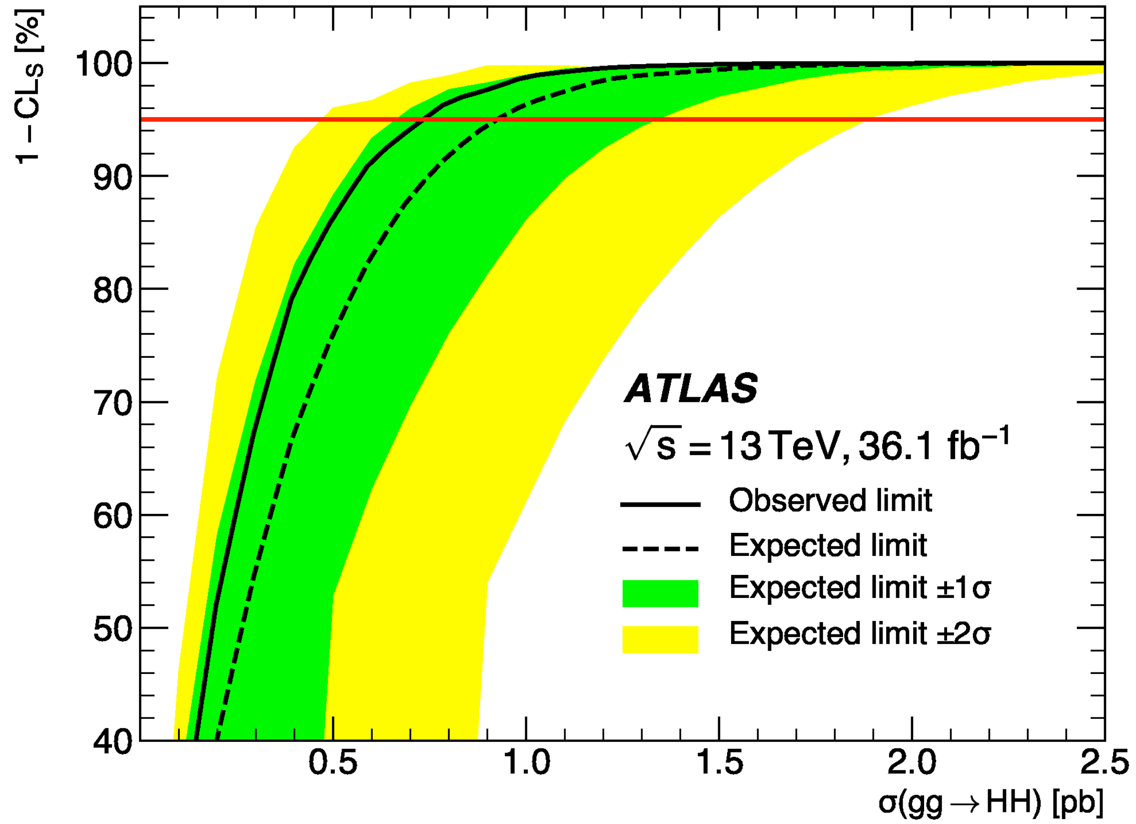
ATLAS EXPERIMENT

COMPARISON OF DATA TO BACKGROUND-ONLY FIT



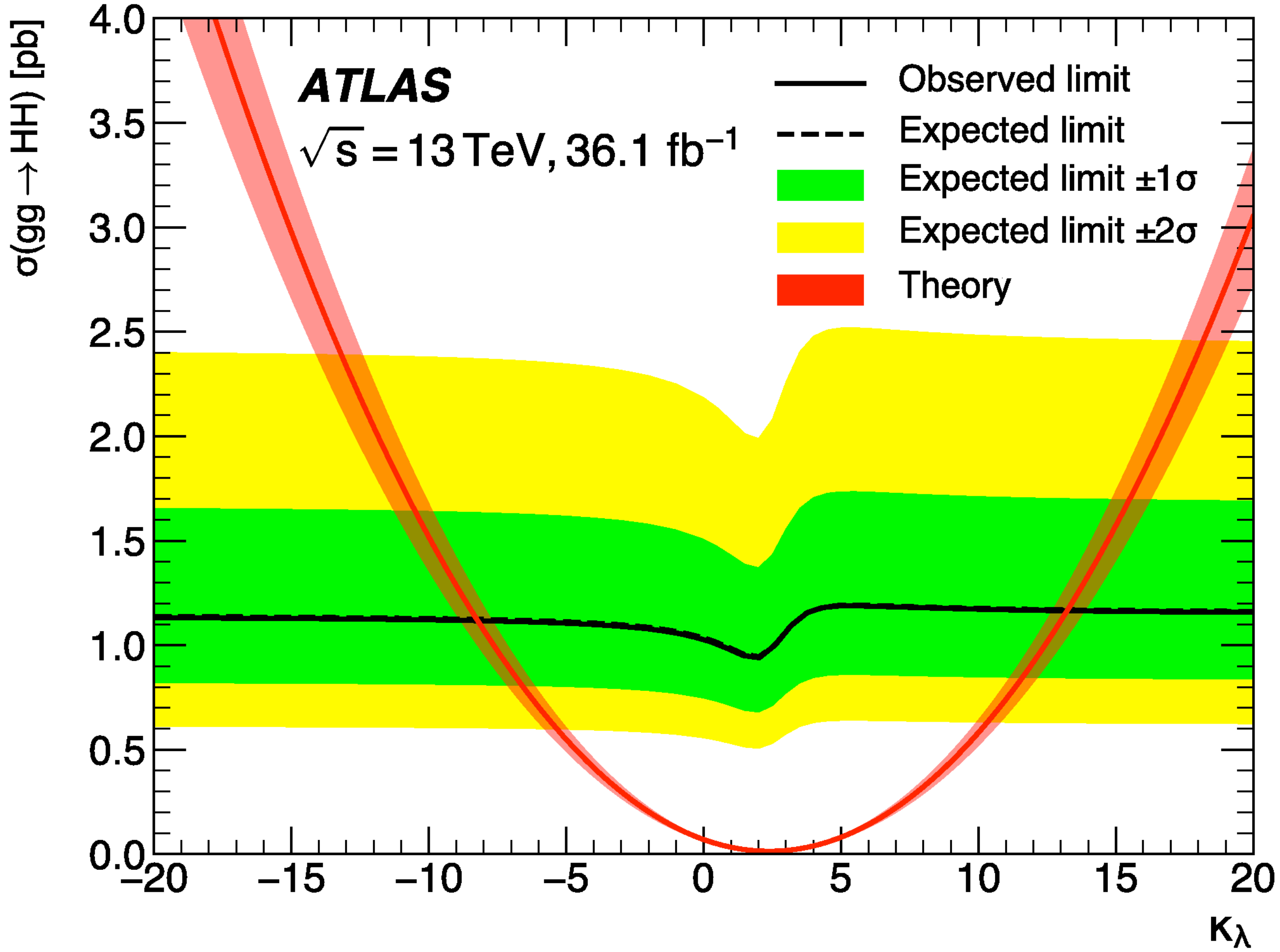
- fit 1- and 2-tag categories simultaneously
- best fit signal: 0.04 pb (–0.21 pb) for loose (tight) selection
- no significant excess observed

NON-RESONANT LIMITS: HH CROSS SECTION



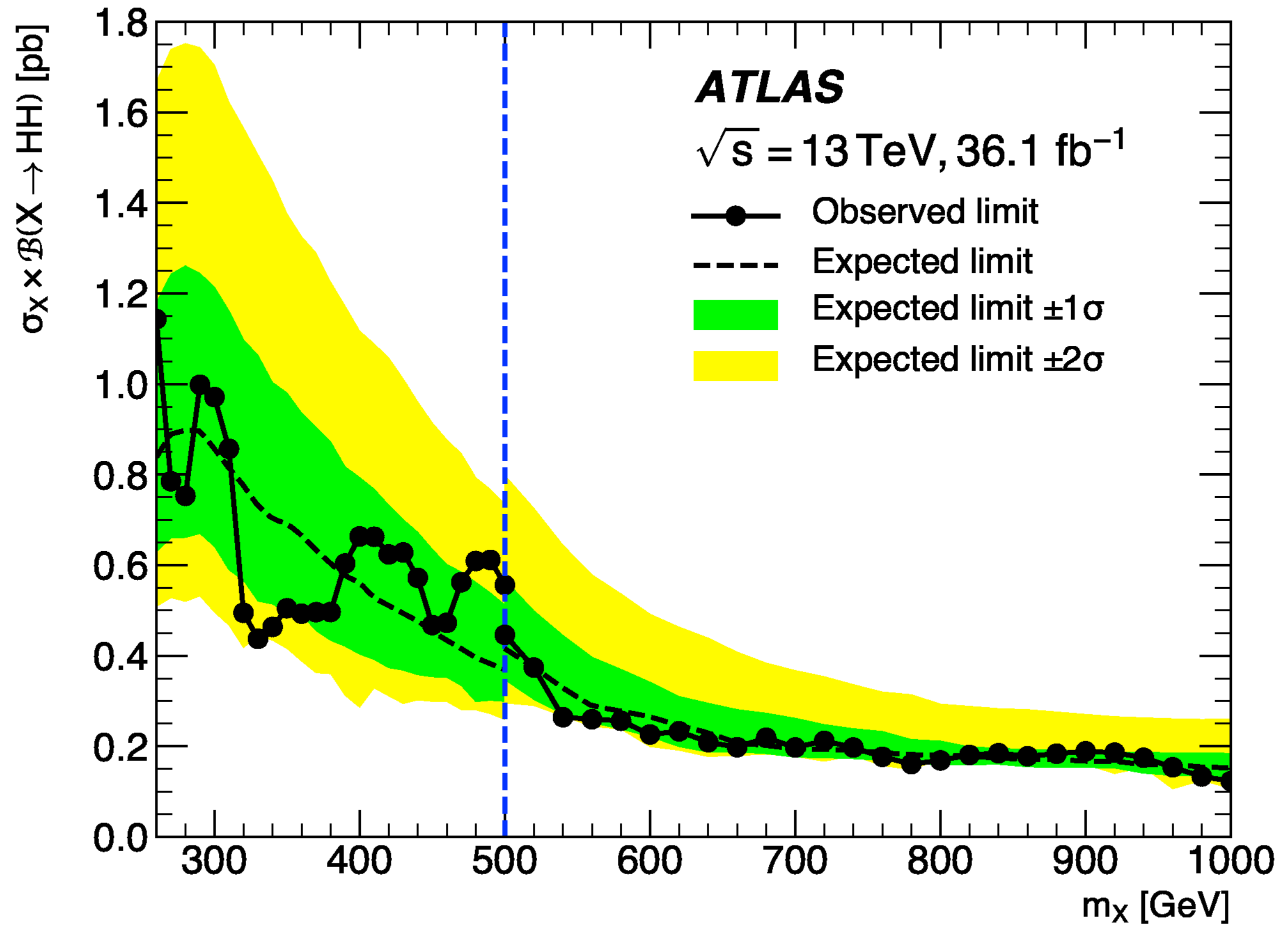
	Observed	Expected	-1σ	$+1\sigma$
$\sigma_{gg\to HH}$ [pb]	0.73	0.93	0.66	1.4
As a multiple of σ_{SM}	22	28	20	40

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

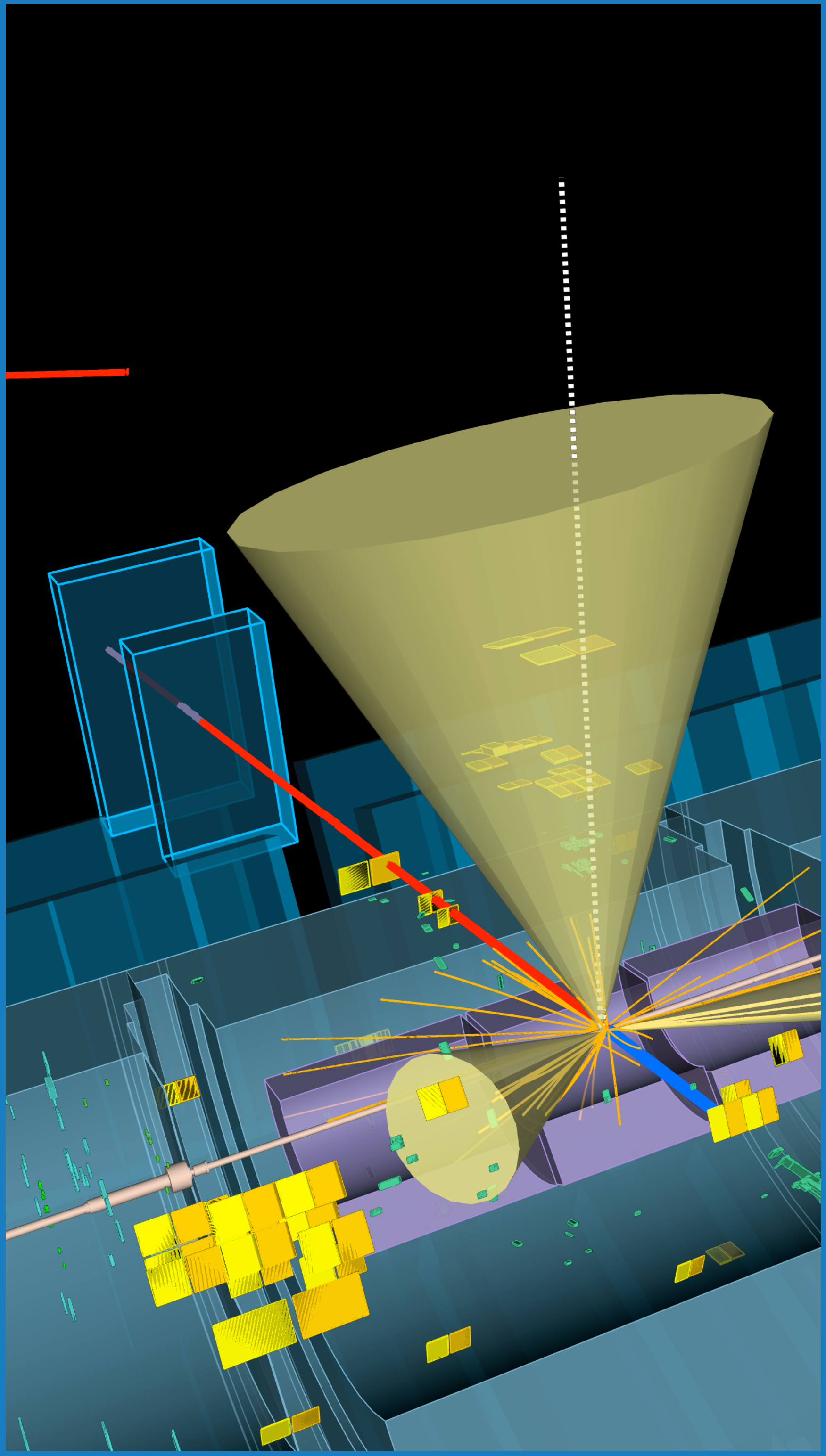


- Blue line separates loose and tight selections
- Largest deviation from background-only hypothesis is at 480 GeV (local significance of 1.2σ) → No significant excess observed
- Maximum observed (expected) limit : 1.1 pb (0.9 pb) at 260 GeV
- Minimum observed (expected) limit: 0.12 pb (0.15 pb) at 1000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

SEARCH FOR NON-RESONANT AND RESONANT HH → YYBB

- Searched for di-Higgs production in the di-photon plus di-b-jet channel in 36.1/fb of data from the ATLAS experiment
- No significant excess observed in the non-resonant or resonant searches
- Set a limit on σ(HH) of $22*\sigma_{SM}$
- Set limits on the Higgs self-coupling: $-8.2 < \kappa_\lambda < 13.2$
- Set limits on resonant di-Higgs production from 1.1 pb to 0.12 pb for $260 < m_X < 1000$ GeV

HTTPS://ATLAS.WEB.CERN.CH/ATLAS/GROUPS/PHYSICS/PAPERS/HIGG-2016-15/



BACKUP SLIDES

ATLAS EXPERIMENT

DETAILS ON MONTE CARLO SAMPLES

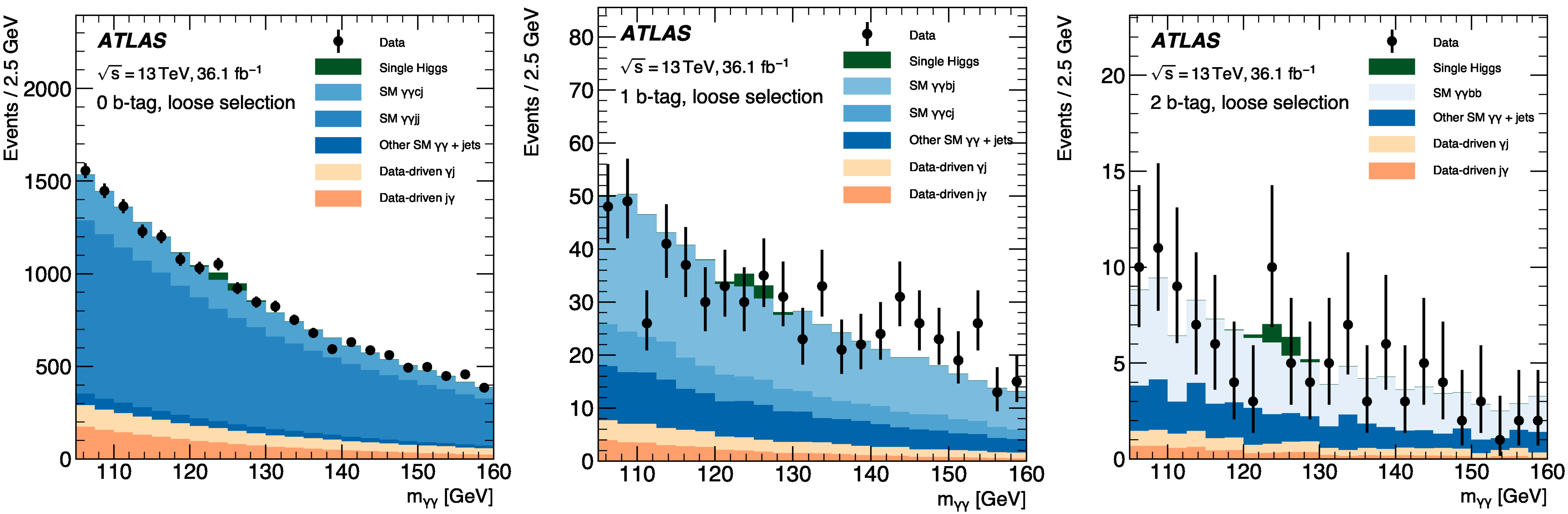
- generators, PDF sets, cross sections for signal and background MC:

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

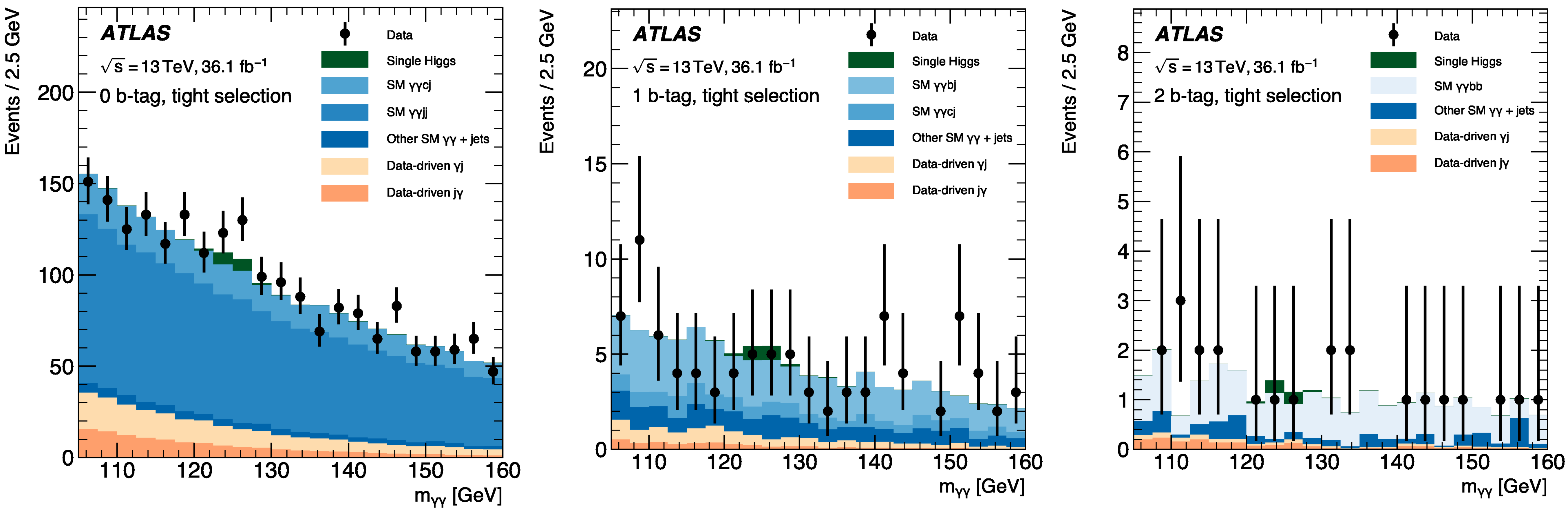
EVENT SELECTION SUMMARY

	Non-resonant				Resonant			
	1-tag		2-tag		1-tag		2-tag	
	Loose	Tight	Loose	Tight	Loose	Tight	Loose	Tight
$m_{\gamma\gamma}$ range [GeV]	105–160	105–160	105–160	105–160	120.39–129.79	120.79–129.39	120.39–129.79	120.79–129.39
Jet b-tagging WPs used	60% + BDT	60% + BDT	70%	70%	60% + BDT	60% + BDT	70%	70%
Leading jet p_{T} [GeV]	>40	>100	>40	>100	>40	>100	>40	>100
Subleading jet p_{T} [GeV]	>25	>105	>25	>30	>25	>30	>25	>30
m_{jj} range [GeV]	80–140	90–140	80–140	90–140	80–140	90–140	80–140	90–140

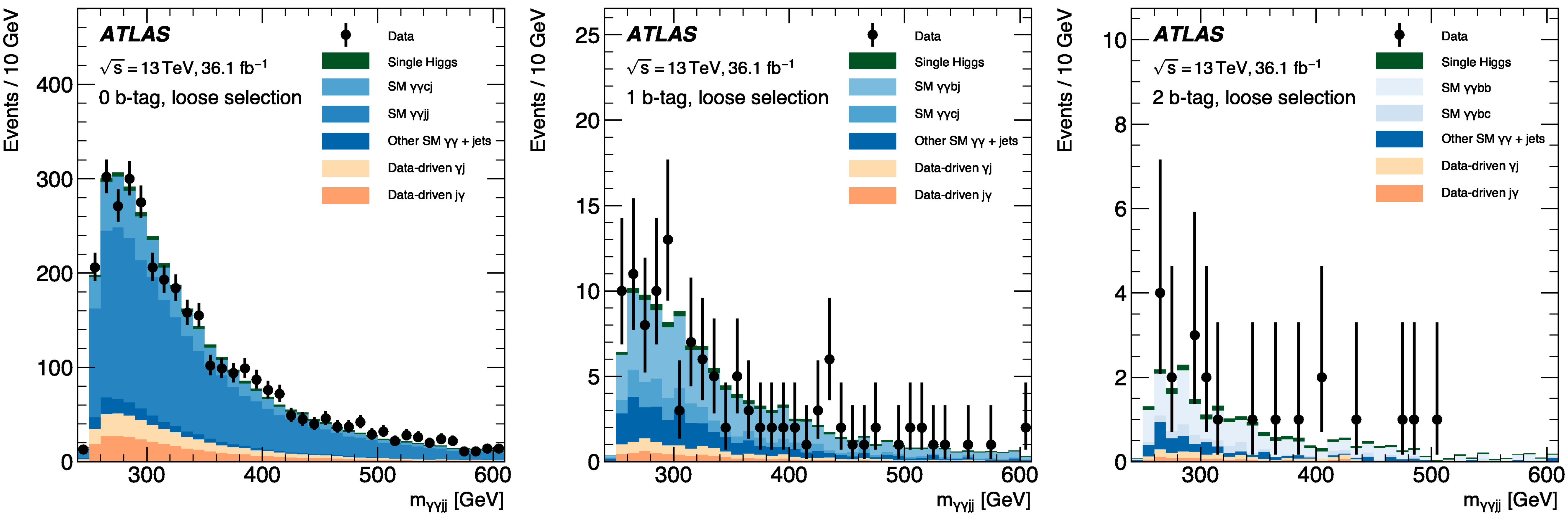
CONTINUUM BACKGROUND MODELING, NON-RESONANT SEARCH



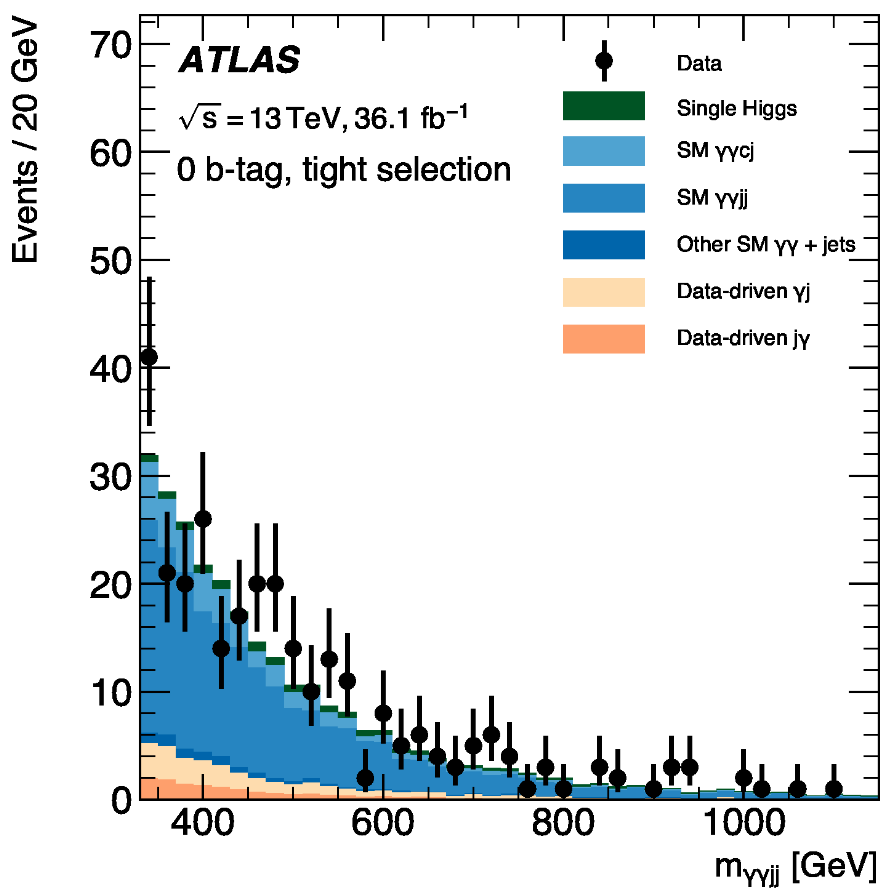
CONTINUUM BACKGROUND MODELING, NON-RESONANT SEARCH

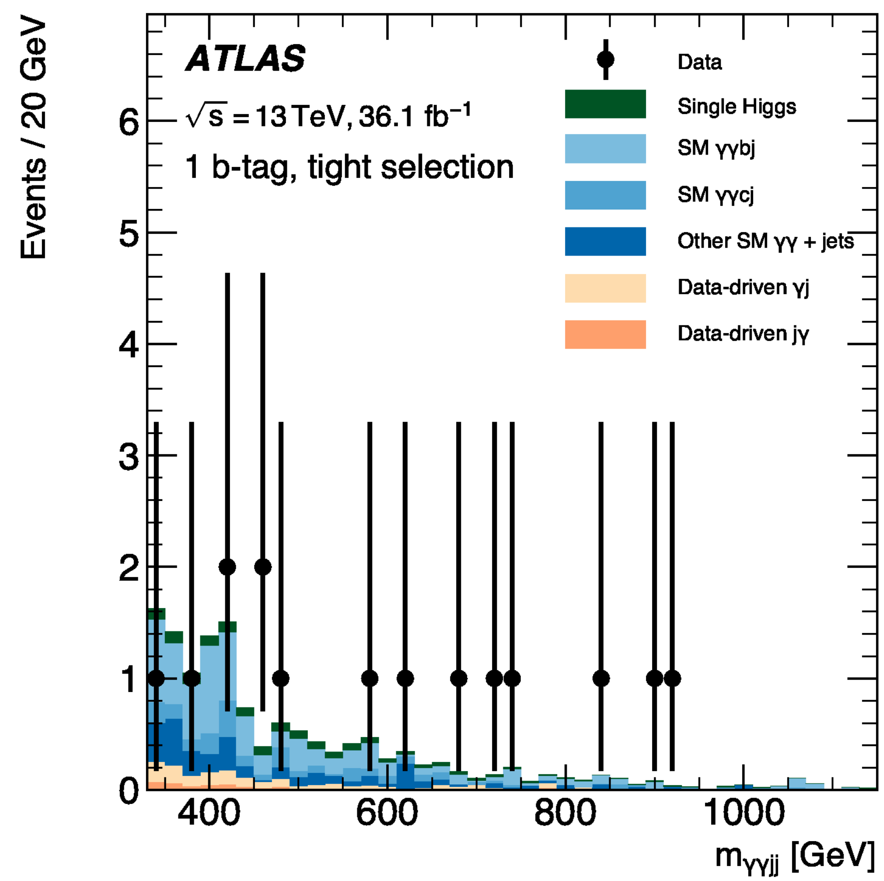


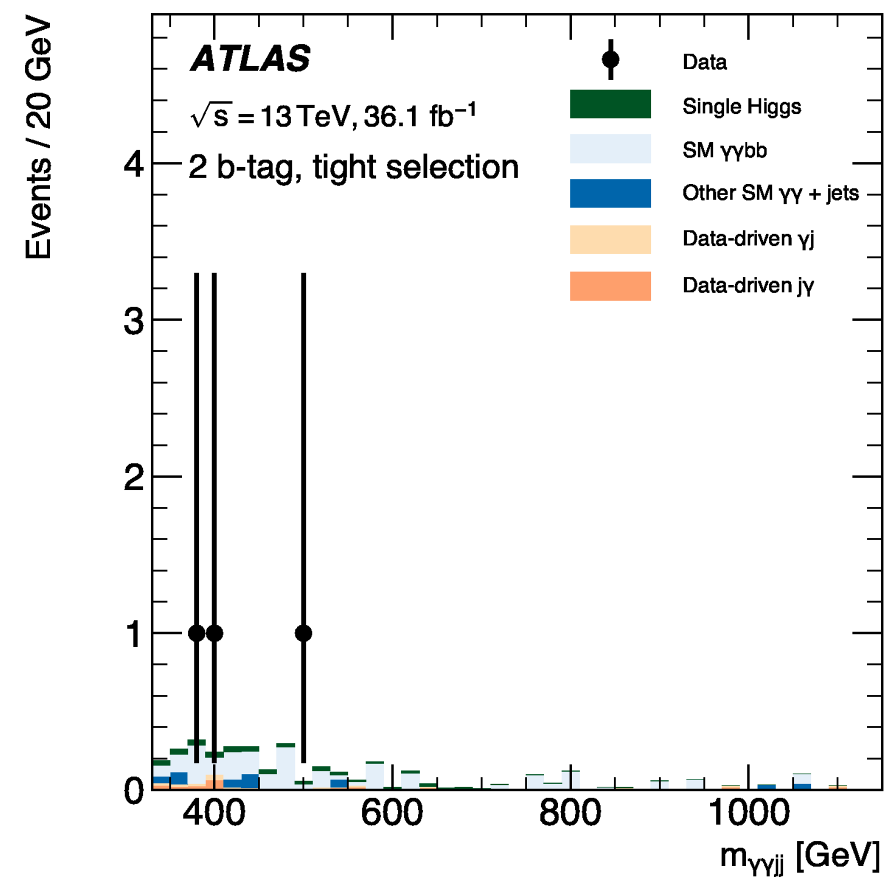
CONTINUUM BACKGROUND MODELING, RESONANT SEARCH



CONTINUUM BACKGROUND MODELING, RESONANT SEARCH







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ATLAS EXPERIMENT

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

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