ATLAS Higgs Physics Prospects at the High Luminosity LHC

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on behalf of the **ATLAS Collaboration**

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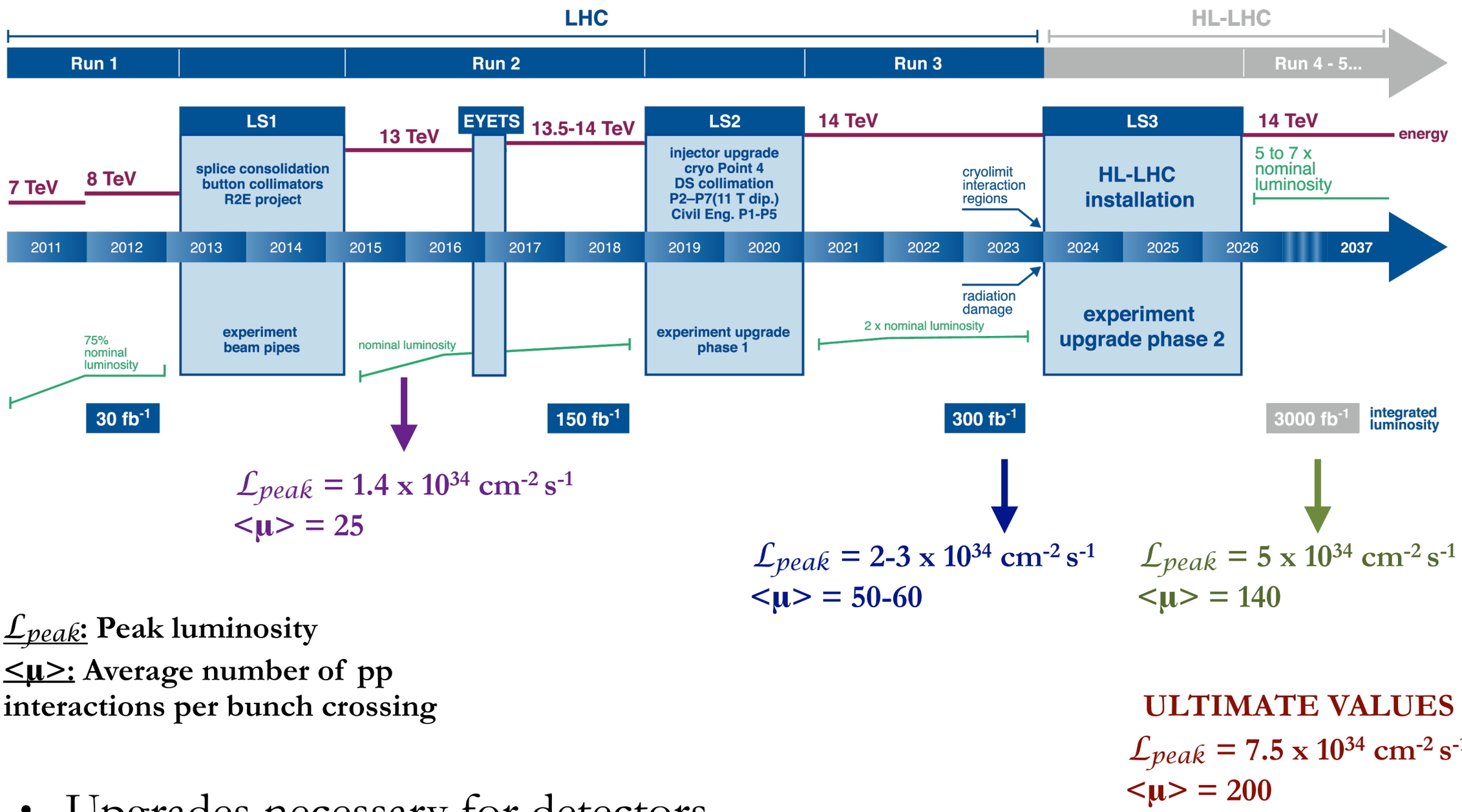
Outline

- High Luminosity LHC (HL-LHC)
- ATLAS detector upgrades
- ATLAS detector performances
- Higgs physics programme
  - SM Higgs coupling
  - BSM physics in Higgs coupling
  - Higgs production through vector boson fusion (VBF)
  - Higgs rare decays
  - Higgs pair production

HL-LHC



$\mathcal{L}_{peak}$ = 1.4 x 10^{34} cm^{-2} s^{-1}
<μ> = 25

$\mathcal{L}_{peak}$ = 2-3 x 10^{34} cm^{-2} s^{-1}
<μ> = 50-60

$\mathcal{L}_{peak}$ = 5 x 10^{34} cm^{-2} s^{-1}
<μ> = 140

$\mathcal{L}_{peak}$: Peak luminosity
<μ>: Average number of pp interactions per bunch crossing

ULTIMATE VALUES
$\mathcal{L}_{peak}$ = 7.5 x 10^{34} cm^{-2} s^{-1}
<μ> = 200

- Upgrades necessary for detectors
  - To maintain their performance in the higher luminosity environment
  - To mitigate the impact of radiation damage and detector aging

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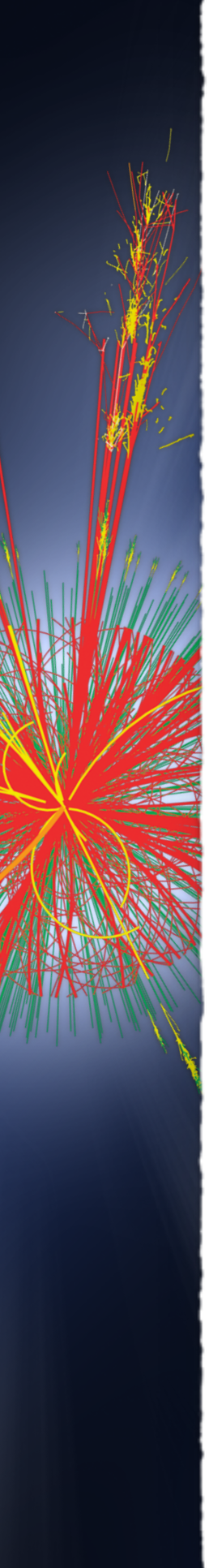
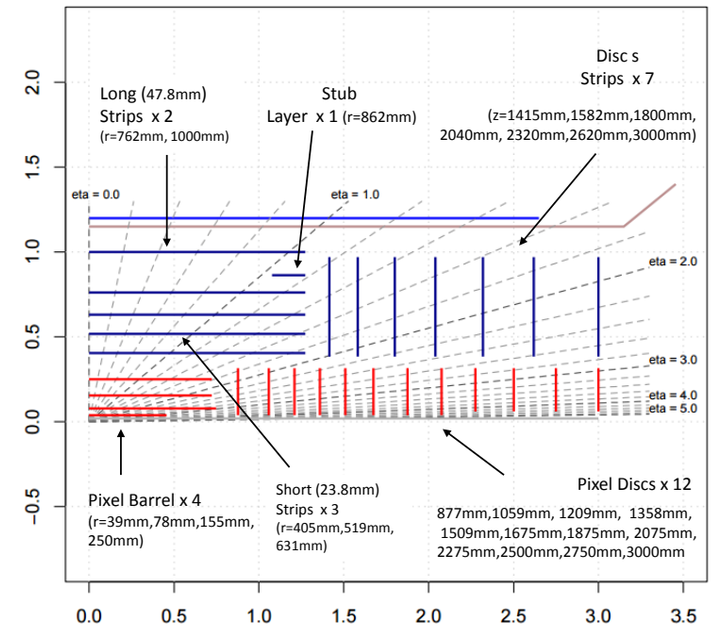
HL-LHC ATLAS Detector





- **Inner Detector**
  - Completely new, all silicon design
  - Extended coverage to $|\eta| < 4$
- **Calorimeters**
  - A new high granularity calorimeters in the forward regions to mitigate pile-up in the high pile-up HL-LHC environment
  - Readout electronics will be replaced to enable improved triggering
- **Muon Detectors**
  - Extended coverage for muon identification to $|\eta| < 4$
  - The use of precision tracking for early trigger decisions
  - Increase trigger acceptance by eliminating gaps

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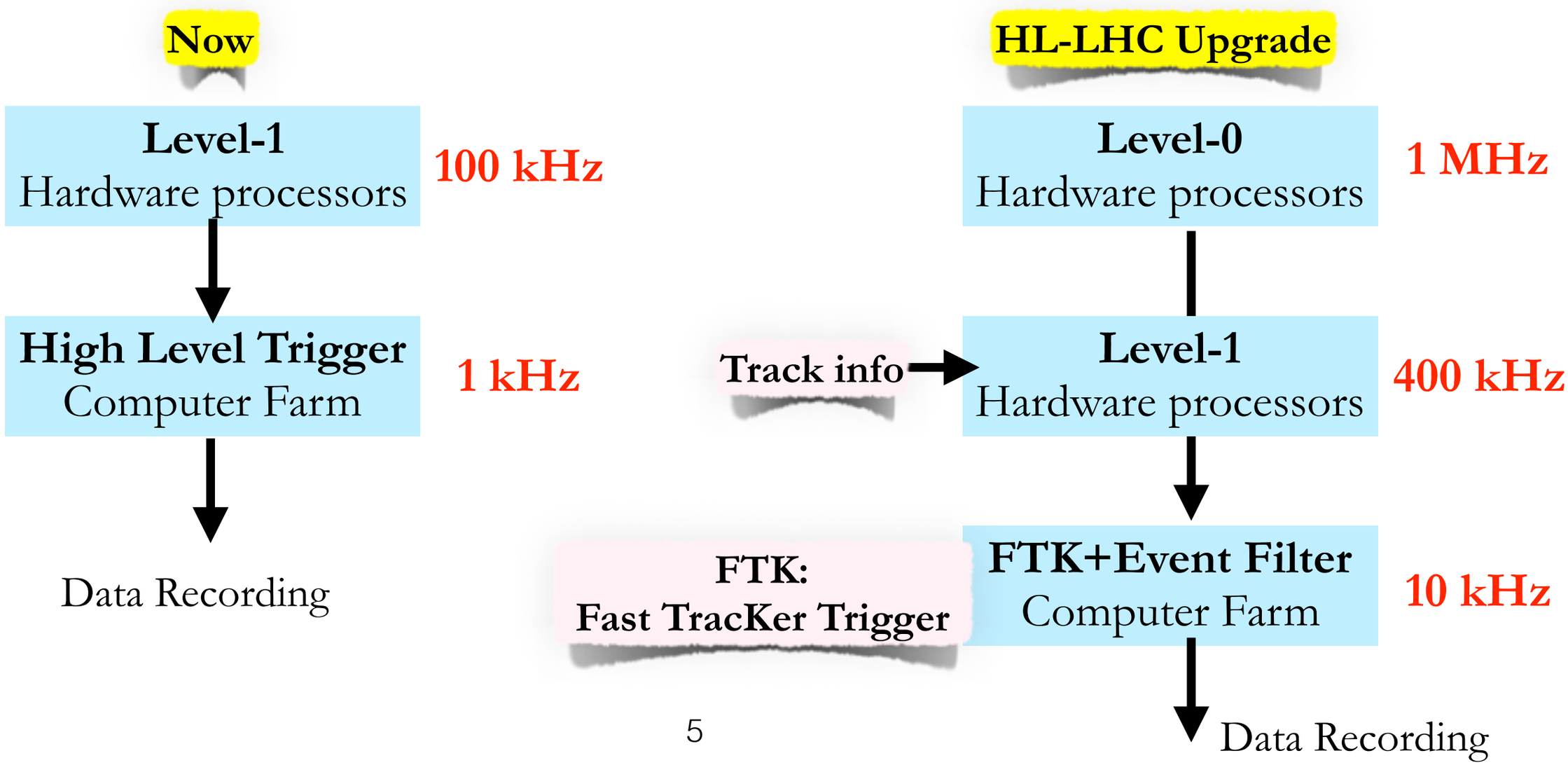
Trigger and Data Acquisition

- Improvements for preserving high signal acceptance in the high rate
- Using high granularity measurement and tracking information earlier in the trigger
- Based on two levels of "custom-hardware" trigger
- The input of 40 MHz at Level-0



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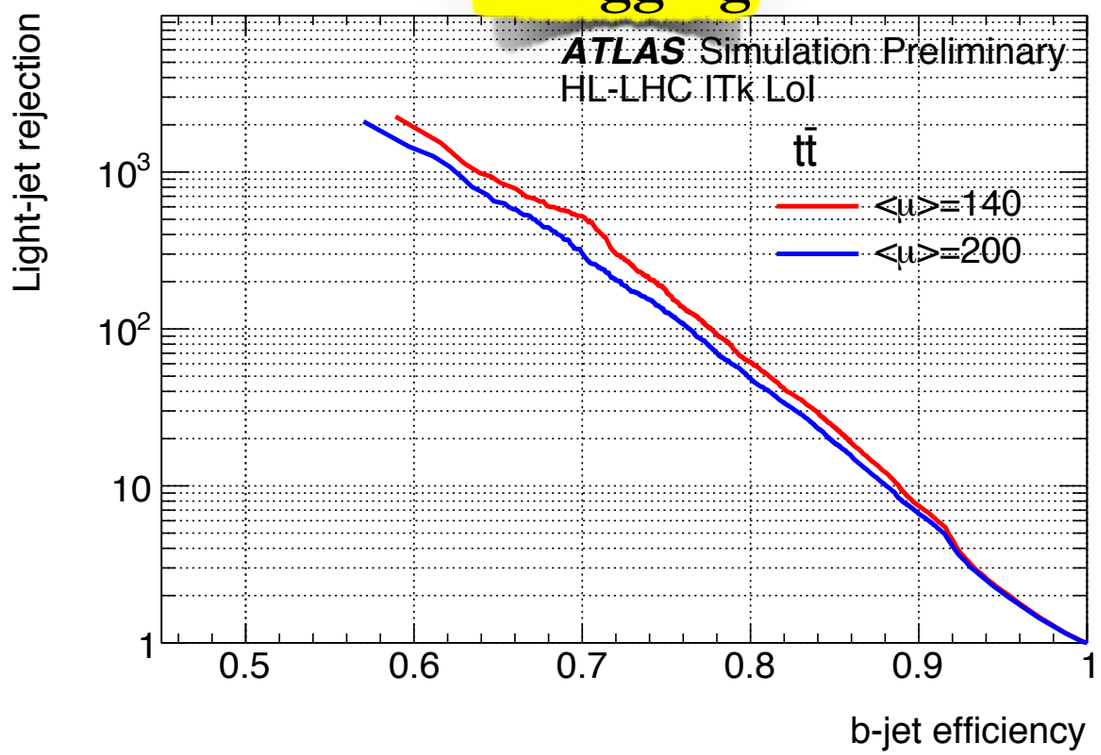
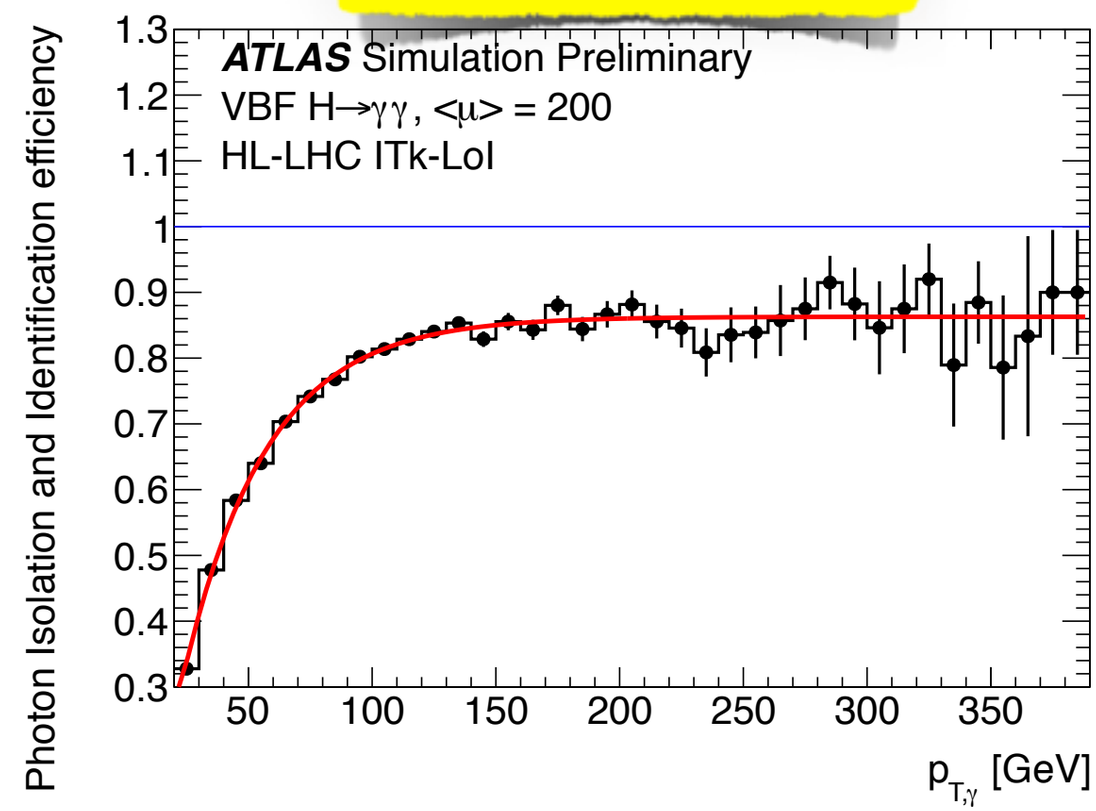
Detector Performances

b-Tagging



Photon Identification



At Run-2:

a light jet rejection of 380 at 70%
a light jet rejection of 33 at 85%

For <μ>=200:

a light jet rejection of ~300 at 70%
a light jet rejection of ~20 at 85%

The probability that a jet from the hard scatter interaction, mis-identified as a photon:
2.5×10^{-4}

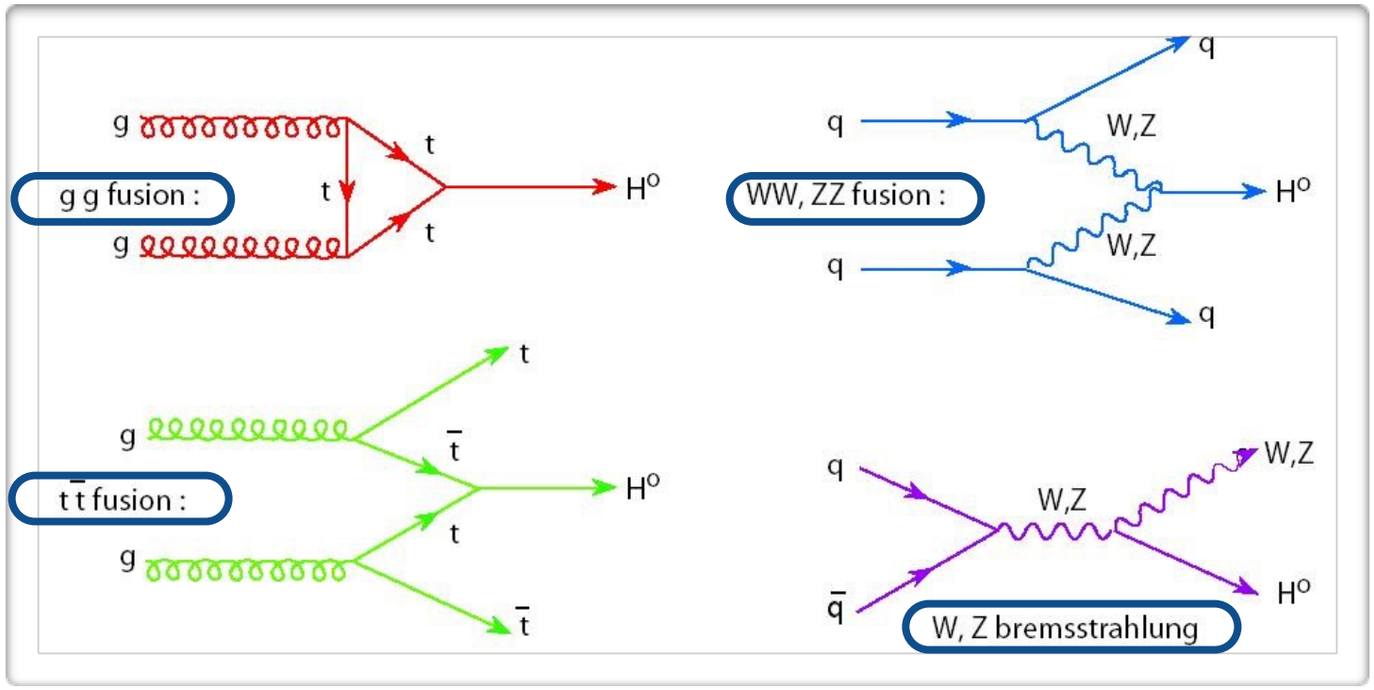
Detector Performance Implementation

Full simulations for all channels impractical

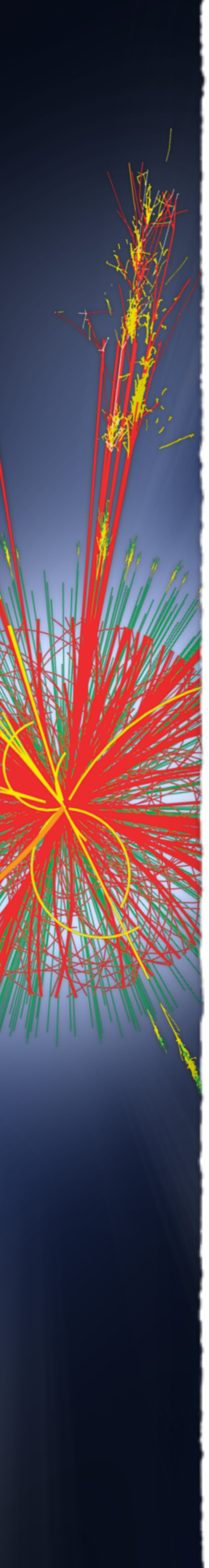
- **Parameterised Performance of the Upgraded Detector**
  - Parameterise object-level performance **based on full simulations**
  - Parameterisations (smearing functions) includes effects for
    - Resolution and reconstruction efficiencies for e,μ,τ,γ, E_T^{miss}
    - Jet energy smearing, b-tagging efficiency and pile-up
  - Apply **smearing functions** to **generator-level objects**

- **Extrapolation from Run-I/Run-II Analyses**
  - Assume **same detector performance** as Run-I/Run-II
  - **Scale** signal and background level **to higher luminosity and center of mass energy**

Higgs Physics at HL-LHC



- HL-LHC will be a **Higgs boson factory**
  - Over 100 million Higgs bosons with 3000 fb^{-1} of data (x10 more than end Run-III)
- Higher precision for properties already measured
- Access to rare decays, i.e $H \rightarrow Z\gamma$
- Access to second generation fermion couplings, $H \rightarrow \mu\mu$
- Possible access to di-Higgs production



SM Higgs Couplings

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Higgs Boson Signal Strengths

- Signal strengths from multiple decay channels can be combined to infer Higgs boson couplings to individual particles

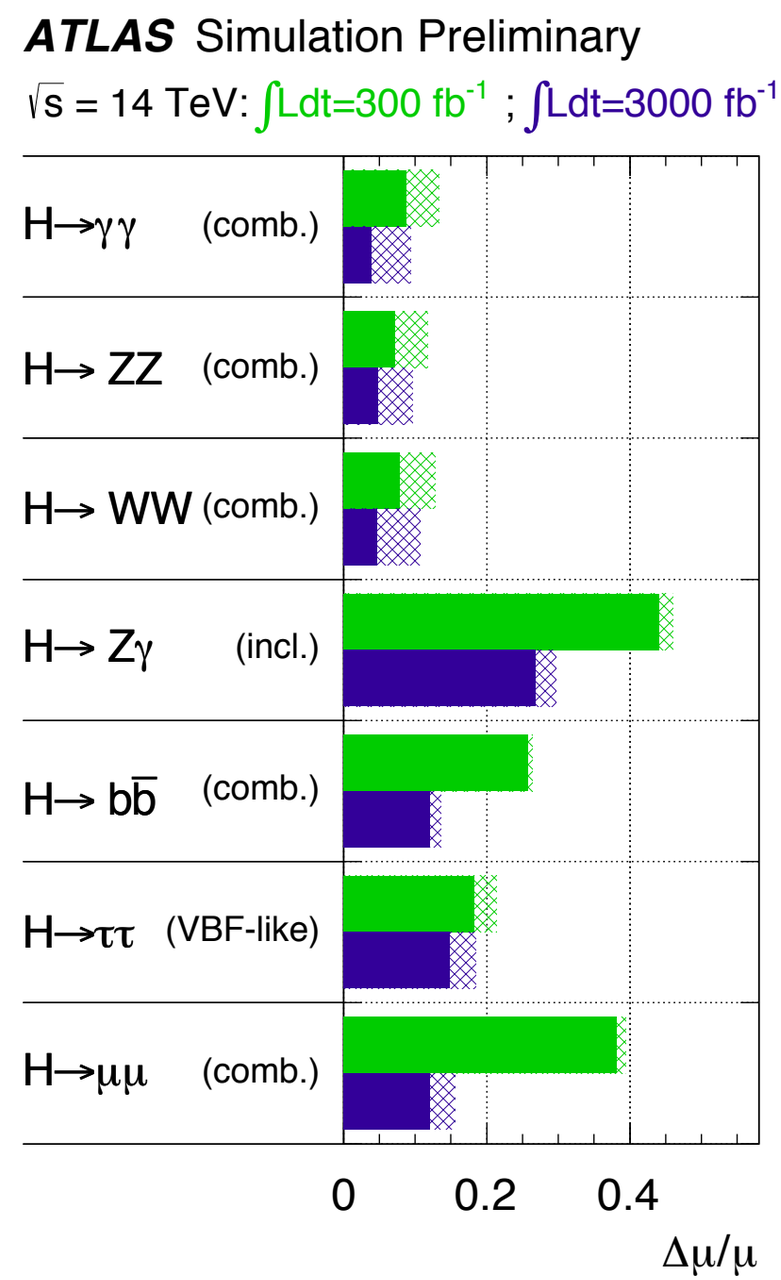
- **Input Channels:**
  - H → μμ
  - H → ττ
  - H → ZZ
  - H → WW
  - H → γγ
  - H → Zγ
  - VH/ttH → γγ
  - VH → bb

$$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$

Signal Strength

$$\frac{\Delta\mu}{\mu}$$

Expected Precision
(Relative uncertainty in the signal strength)



Higgs Boson Couplings Framework

- Define a framework in which to look for **deviations from the SM in the Higgs coupling sector**
  - **The leading-order** tree-level motivated **K-framework**

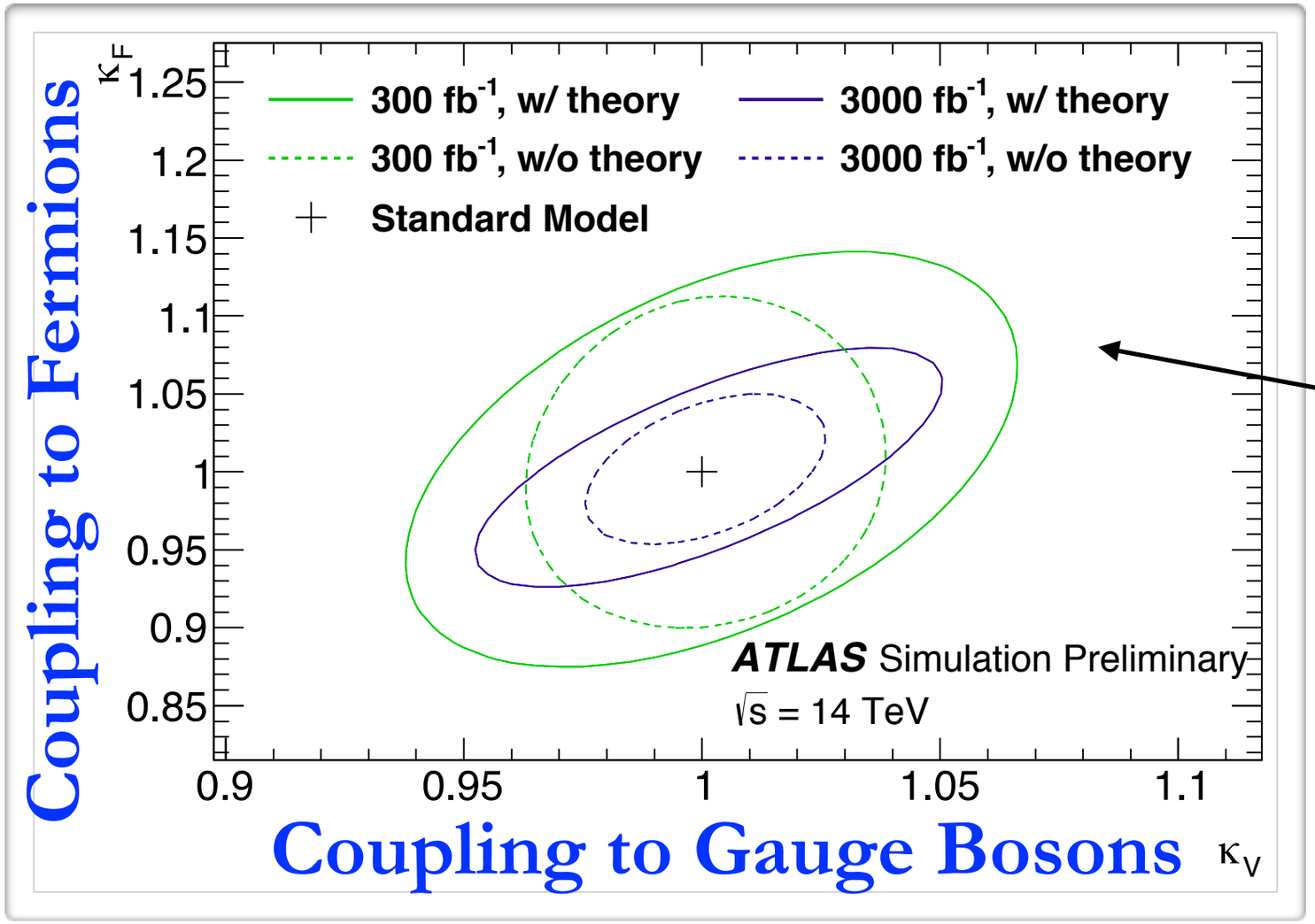
- **Assumptions made:**
  - Only **one signal resonance** ($m_H \sim 125$ GeV), no other signals
  - The **zero/narrow width** approximation $\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$
  - **Only modification of scalar coupling strength**, no change to production and decay kinematics of Higgs processes

- Introduce one scale factor K per SM particle $\sigma_i = \kappa_i^2 \cdot \sigma_i^{SM}$ $\Gamma_f = \kappa_f^2 \cdot \Gamma_f^{SM}$
- σ_i(ii→h) and Γ_i (h→ii) associated with the SM particle i, scale with K_i^2 compared to the SM prediction
- K_i^2 describe deviations from SM predictions $\frac{\sigma \cdot B\,(gg \to H \to \gamma\gamma)}{\sigma_{\rm SM}(gg \to H) \cdot B_{\rm SM}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$

Higgs Boson Couplings Framework

- The Higgs boson coupling scale factors are determined from a combined fit to all channels
- Some parameterisations make **no assumptions on the total width**
  - Allow **only measurements of ratios $\lambda_{ij} = \kappa_i / \kappa_j$** of coupling scale factors
- **<u>A minimal coupling fit:</u>**
  - One **universal coupling** to **vector bosons $\kappa_V = \kappa_Z = \kappa_W$**
  - One **universal coupling** to **fermions $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$**
  - Most sensitive to different deviations from the SM between the Higgs boson gauge- and Yukawa coupling sectors
- Uncertainties given with and without theory uncertainties

Experimental Precisions: 300 fb^{-1} vs 3000 fb^{-1}



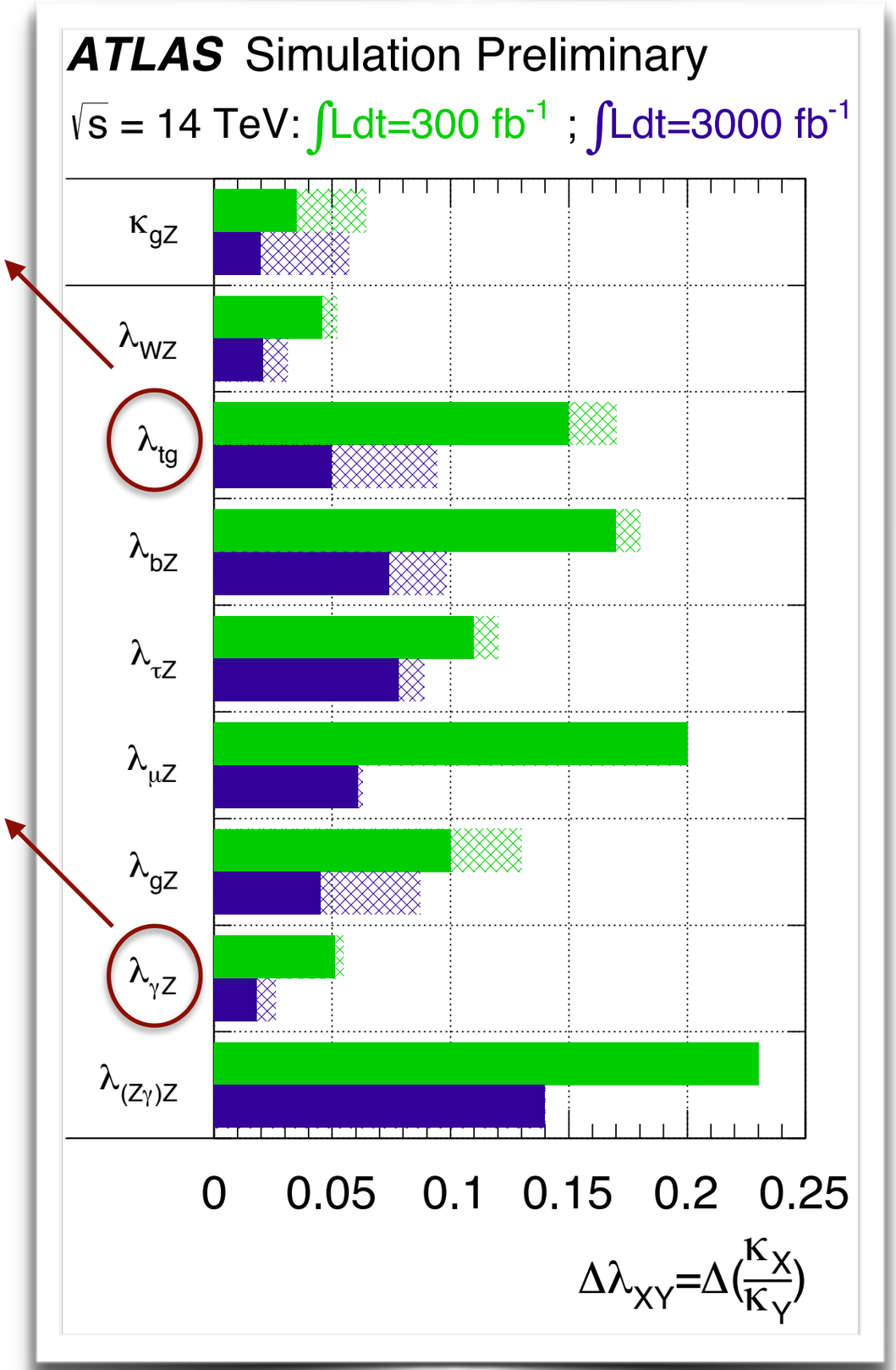
Minimal Coupling Fit

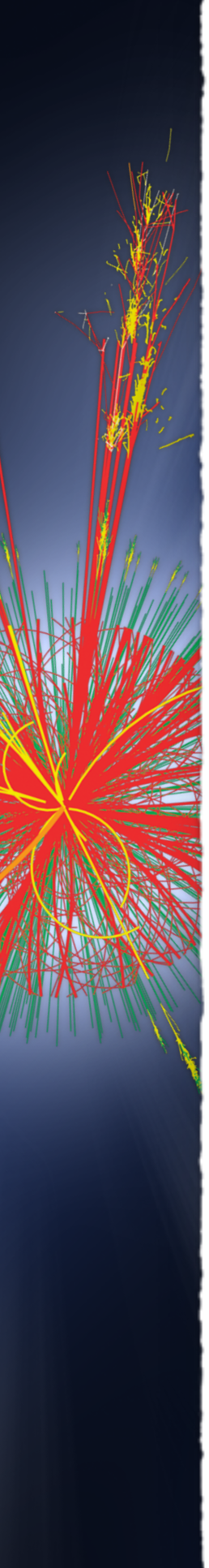
Coupling	Experimental Precision w/ Theory Uncertainties (w/o Theory Uncertainties)	
	300 fb^{-1}	3000 fb^{-1}
On K_V	2.5 (4.3)	1.7 (3.3)
On K_F	7.1 (8.8)	3.2 (5.1)

Higgs Boson Coupling Ratios

Crucial for **possible new colored particles** contributing through gluon fusion loop as compared to ttH

Important for indications of **new charged particles** contributing in the H→γγ loop in comparison to H→ZZ decays





BSM Physics in Higgs Couplings

ATL-PHYS-PUB-2014-017

BSM Coupling Sensitivity

- **BSM interpretation for following models:**
  - Higgs boson compositeness
  - Additional electroweak singlet
  - Additional electroweak doublet (2HDM)
  - Simplified MSSM
  - Higgs portal to dark matter
- **Input Channels:**
  - $h \rightarrow \gamma\gamma$, inclusive, 0-, 1-, 2-jet final states
  - $h \rightarrow ZZ^* \rightarrow 4l$, 0-, 1-, 2-jet final states
  - $h \rightarrow WW^* \rightarrow l\nu l\nu$, 0-, 1-, 2-jet final states
  - $h \rightarrow Z\gamma$, $Z \rightarrow ll$, inclusive and 2-jet final states
  - $h \rightarrow \tau^+\tau^-$, 2-jet final state
  - $h \rightarrow \mu\mu$, inclusive and in tth production
  - $h \rightarrow bb$ in Wh and Zh production

Minimal Composite Higgs Model (MCHM)

- Higgs is a composite, pseudo-Nambu-Goldstone boson

MCHM4

$$\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$$

MCHM5

$$\kappa_V = \sqrt{1-\xi}$$

$$\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$

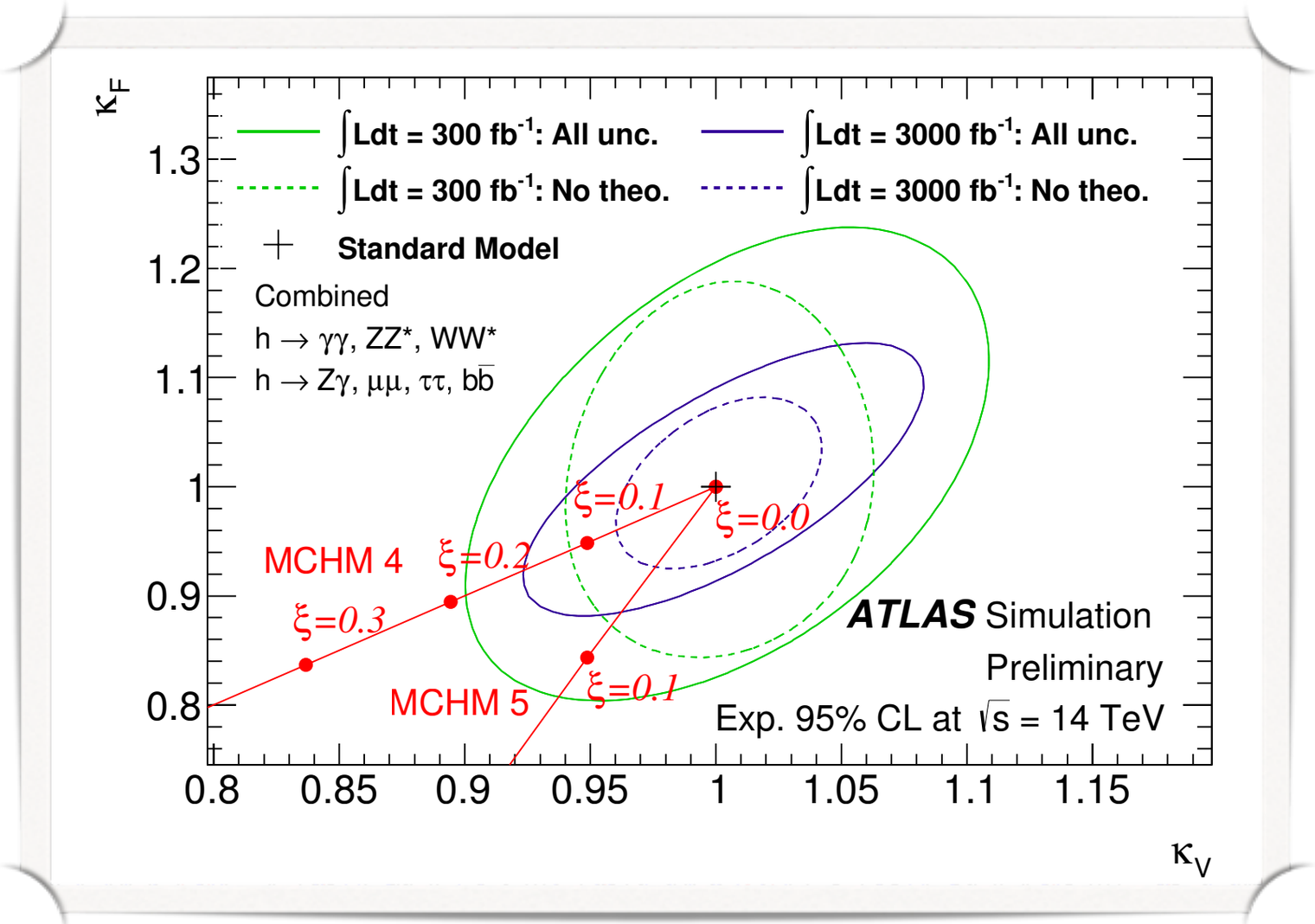
$$\xi = \frac{v^2}{f^2}$$

$v^2 \longrightarrow$ **vacuum expectation value**

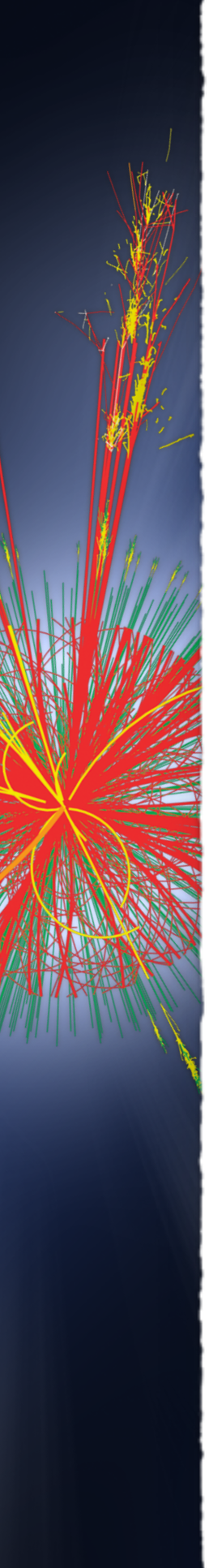
$f^2 \longrightarrow$ **the Higgs boson compositeness scale**

$\xi \to 0$ **is the SM**

Limits on the Higgs Compositeness Scale



Model	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
MCHM4	620 GeV	810 GeV	710 GeV	980 GeV
MCHM5	780 GeV	950 GeV	1.0 TeV	1.2 TeV



Vector Boson Fusion Higgs Production

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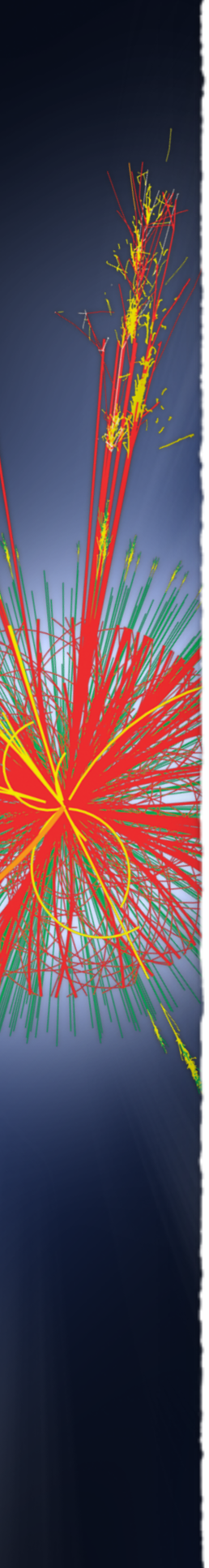
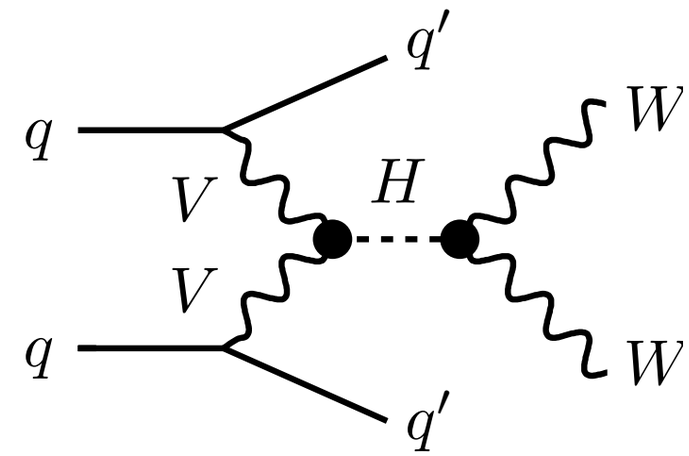
VBF H→WW*→eνμν

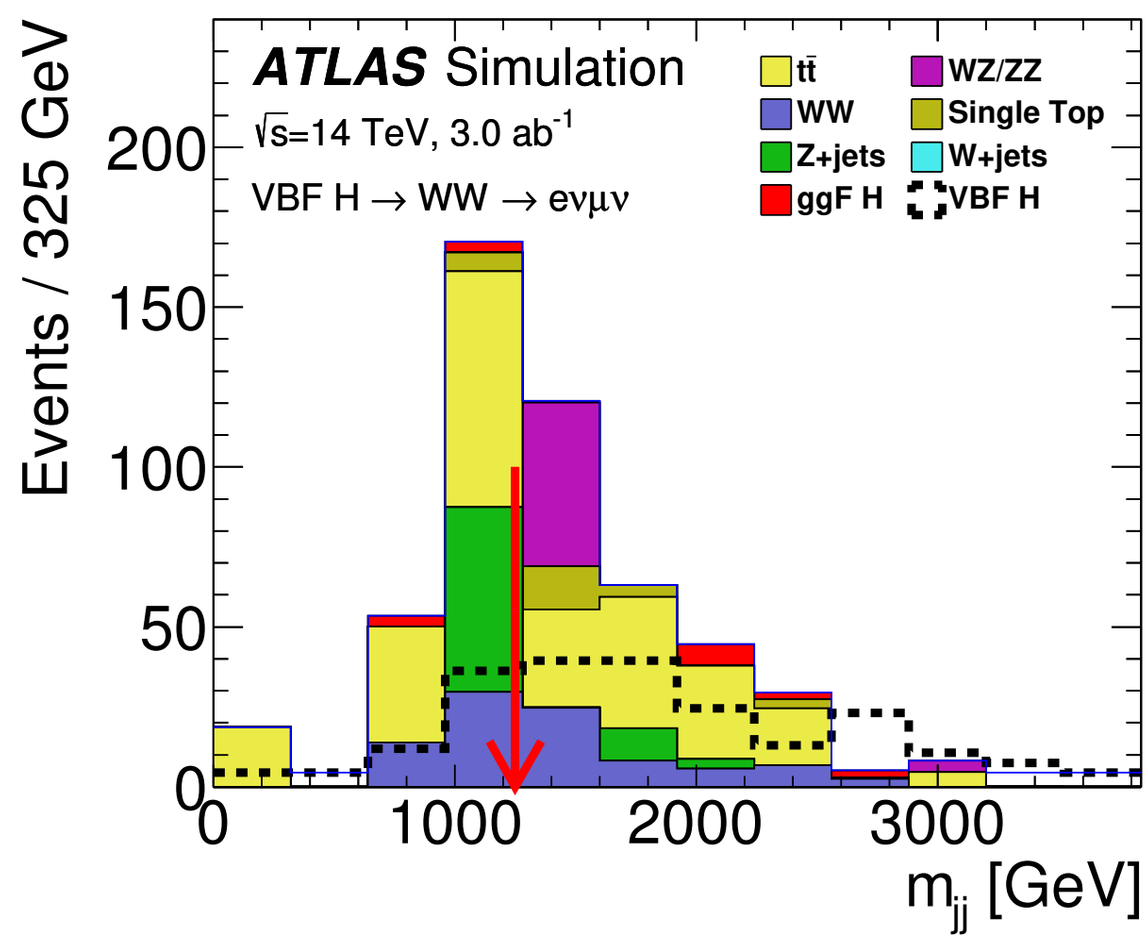


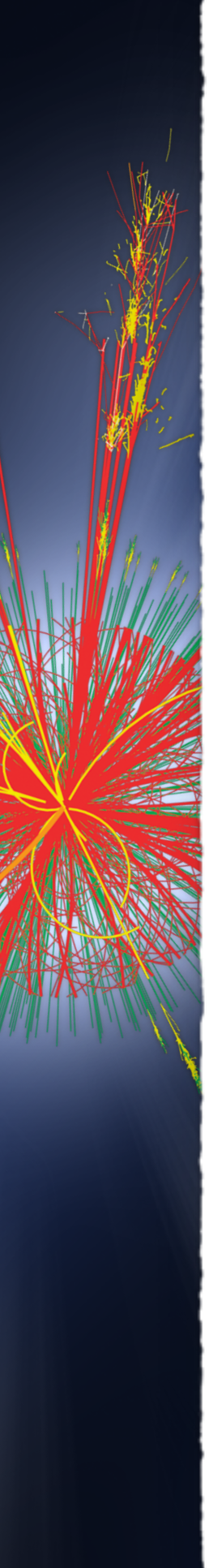
- Cut-based analysis:
  - <μ>=200
  - Two isolated leptons (one e and one μ) with opposite charge
  - Two forward jets in opposite hemispheres
  - E_T^{miss} > 20 GeV



- 200 signal events, 410 background events

Δ_μ			Significance (σ)		
Full	1/2	None	Full	1/2	None
0.20	0.16	0.14	5.7	7.1	8.0



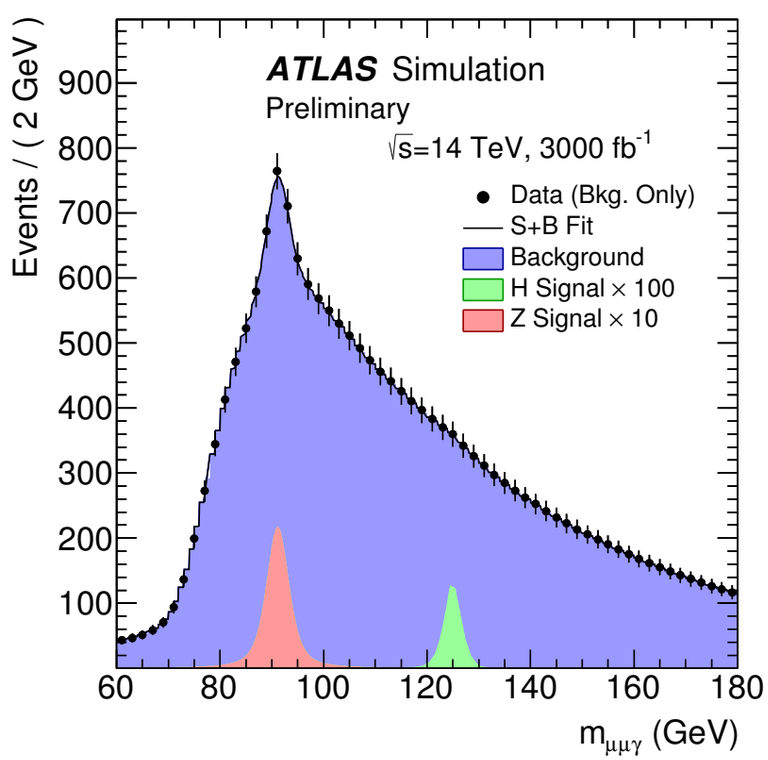


Higgs Boson Rare Decays

ATL-PHY-PUB-2015-043

$H \rightarrow J/\psi\ \gamma$ with $J/\psi \rightarrow \mu\mu$

- $\langle\mu\rangle = 140$
- Assume same detector performance as in Run-I
- Results provided for both
  - cut-based analysis
  - multivariate analysis (p_T^{γ}, $p_T^{\mu\mu}$, γ and $\mu\mu$ isolation)
    - 2.9 signal events, 1700 background events
- $m_{\mu\mu\gamma}$ and $p_T^{\mu\mu\gamma}$ are used as discriminating variables

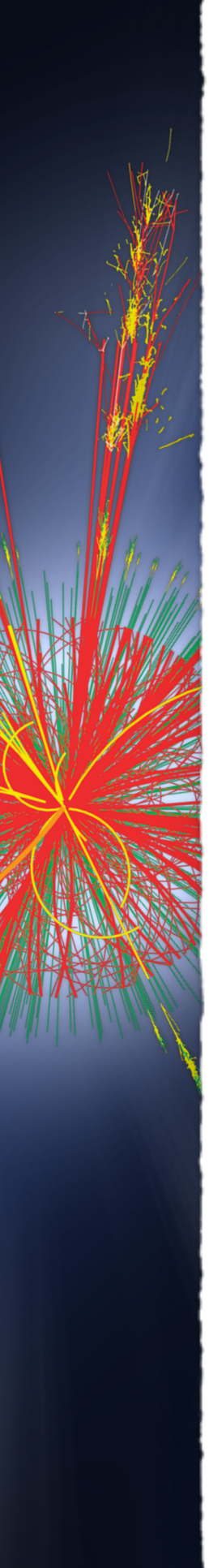


Expected branching ratio limit at 95% C.L

$BR(H \rightarrow J/\psi\ \gamma)$ [10^{-6}]

	Cut Based	Multivariate Analysis
300 fb^{-1}	185^{+81}_{-52}	153^{+69}_{-43}
3000 fb^{-1}	55^{+24}_{-15}	44^{+19}_{-12}

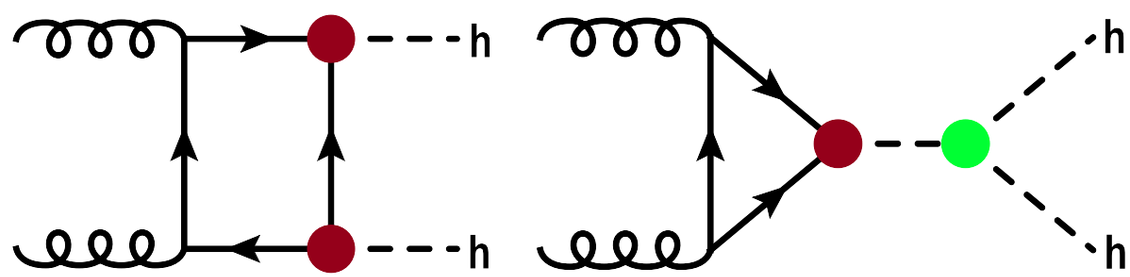
<u>SM expectation:</u> 2.9 ± 0.2



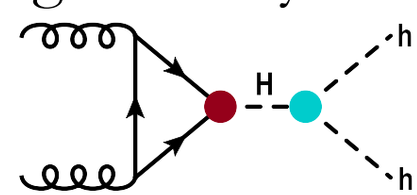
Higgs Pair Production

Higgs Pair Production

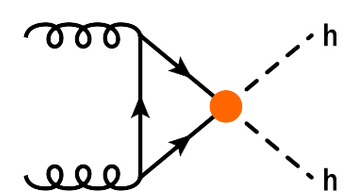
- **SM hh Production:**
  - Extremely small SM expectation due to destructive interference among diagrams
  - The dominant production at LHC is gluon fusion
    - $\sigma(hh)^{NNLO+NNLL} = 45.34$ fb (30 times smaller for other production modes)
  - Important for measuring the Higgs self-coupling



- **BSM hh Production** - hh production significantly enhanced in many BSM models



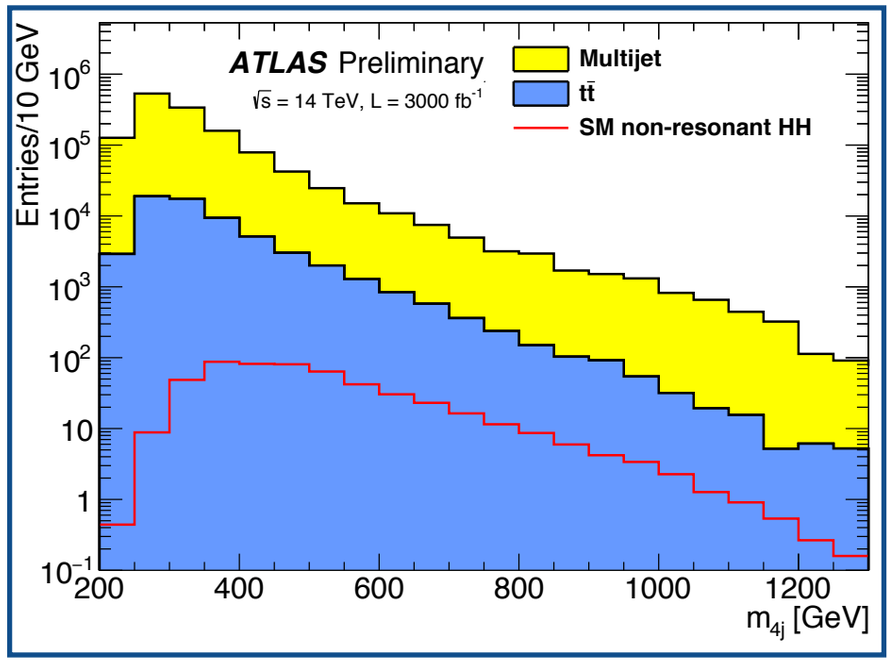
  - **Resonant enhancements**
    - KK-graviton G^*_{KK} predicted in the bulk Randall-Sundrum model
    - 2HDM (i.e: The heavy neutral scalar H of two-Higgs-doublet models)…
  - **Non-resonant enhancements**
    - Activating tthh vertex, altering λ_{hhh}, etc..

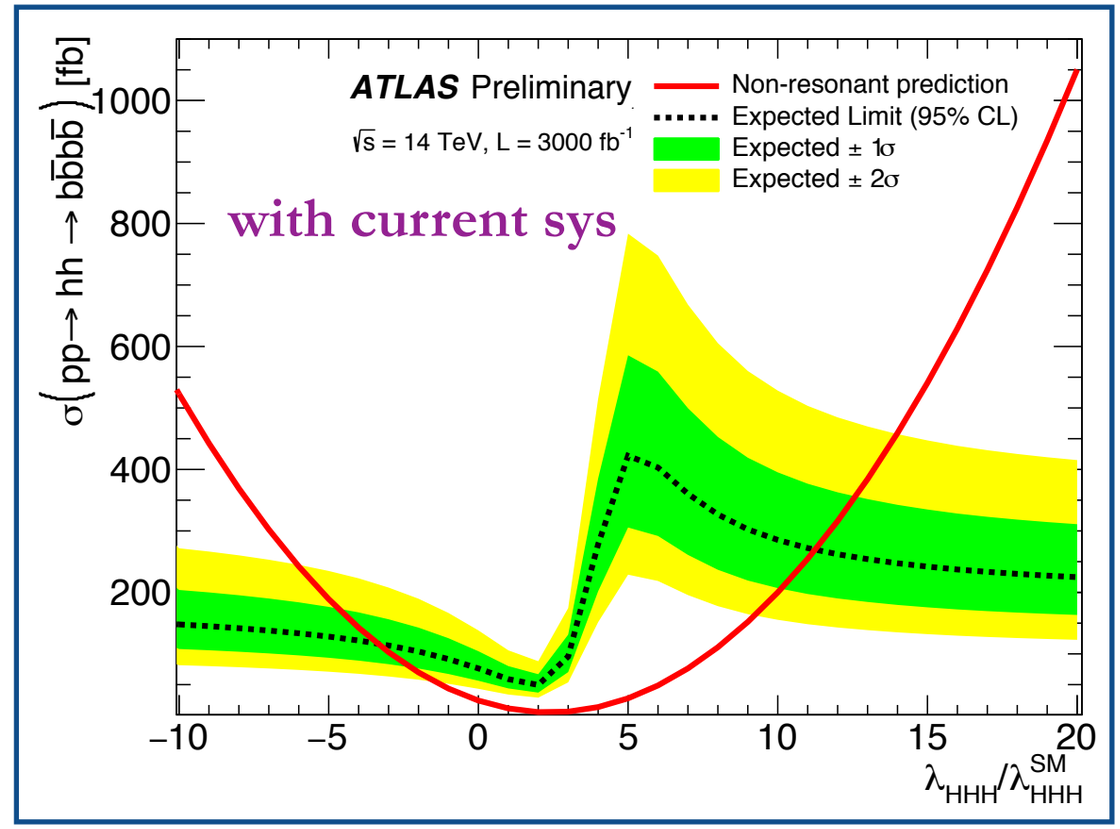


ATL-PHYS-PUB-2016-024

hh→bbbb

- Extrapolation from Run 2 analysis that was performed with 10.1 fb^{-1} of 2016 data
- Results from **"resolved analysis"** used
  - Reconstructs each b-quark from the Higgs boson decay as a distinct jet
  - Optimised for non-resonant or low-mass hh systems
- **The final analysis discriminant:** m_{4j}
- **Background:** 95% multijet, ~5% ttbar



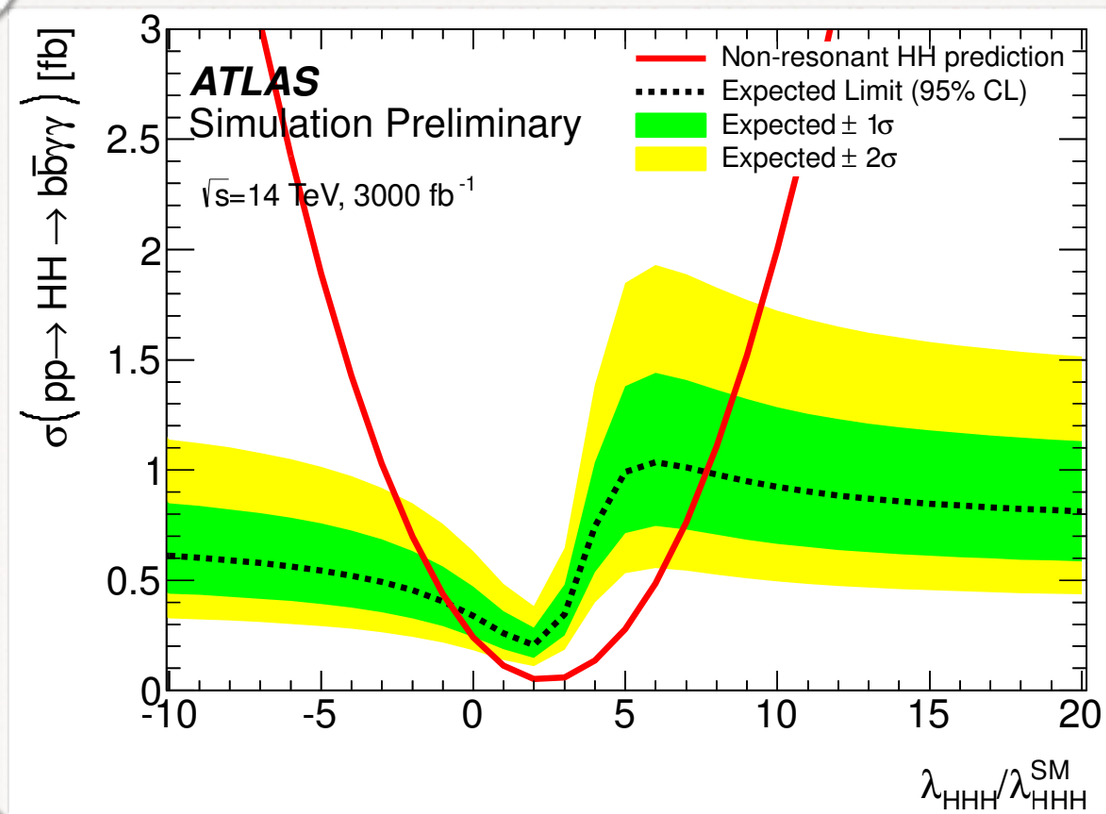


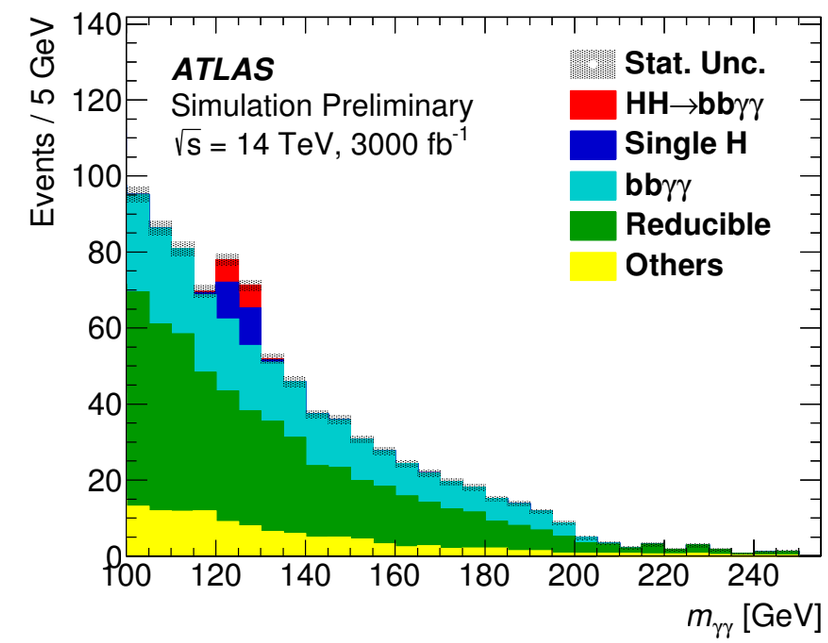
Jet Threshold [GeV]	Background Systematics	σ/σ_{SM} 95% Exclusion	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Lower Limit	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Upper Limit
30 GeV	Negligible	1.5	0.2	7
30 GeV	Current	5.2	-3.5	11
75 GeV	Negligible	2.0	-3.4	12
75 GeV	Current	11.5	-7.4	14

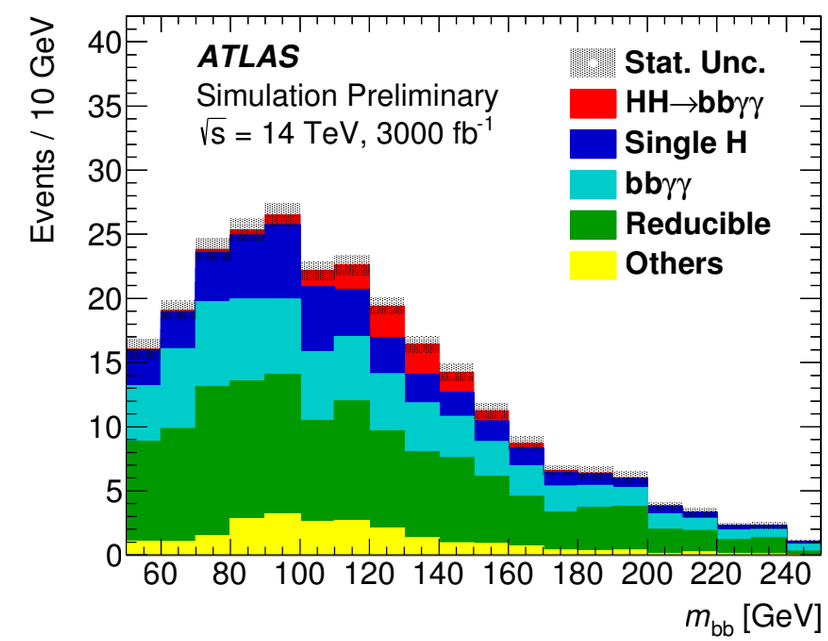
ATL-PHYS-PUB-2017-001

hh→bbγγ

- Excellent diphoton mass resolution
- Relatively small backgrounds
  - **Single-Higgs background**; ggH, ZH, ttH, bbH
  - **Continuum background**; bbγγ, ccγγ, jjγγ, bbjγ, ccjγ, bbjj
  - **Other contributions**; Z(bb)γγ, tt, ttγ







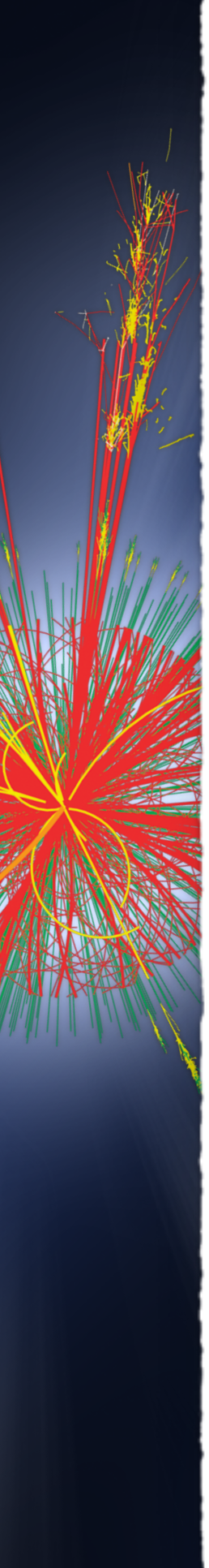
Signal	9.544 ± 0.029
Background	90.9 ± 2.0
S/√B	1.052 ± 0.026

95% C.L limits on λ

$0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$

Conclusion

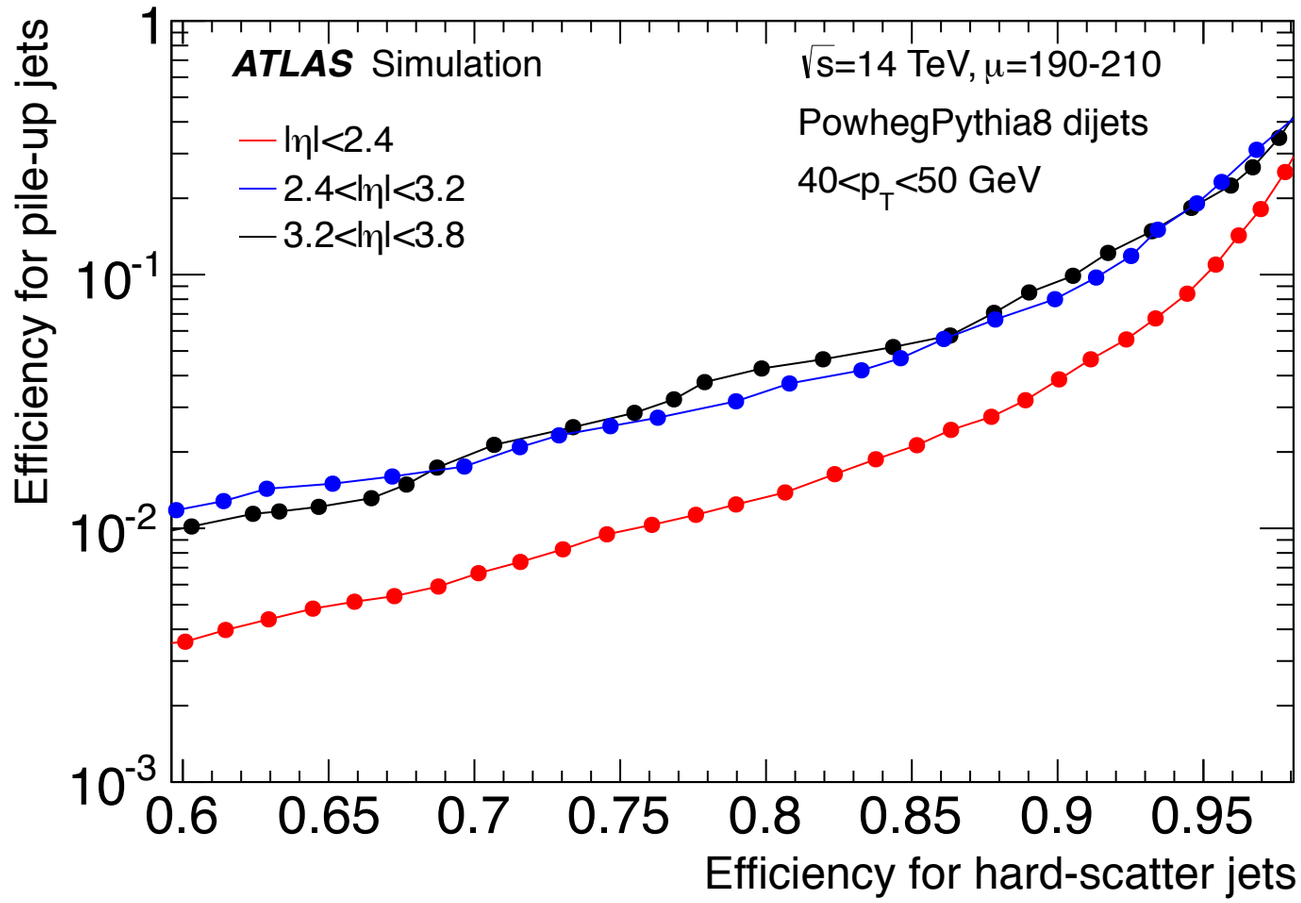
- HL-LHC opens possibilities for a rich physics program
  - Precise measurements of Higgs boson coupling
  - Search for rare Higgs boson decays
  - Direct searches for new physics
  - Higgs pair production
- Achieving the physics goals in the challenging HL-LHC environment requires major upgrades in ATLAS
- Exciting times ahead!



BACK UP

CERN-LHCC-2015-020

Pile-up Jet Rejection



<μ>=200:

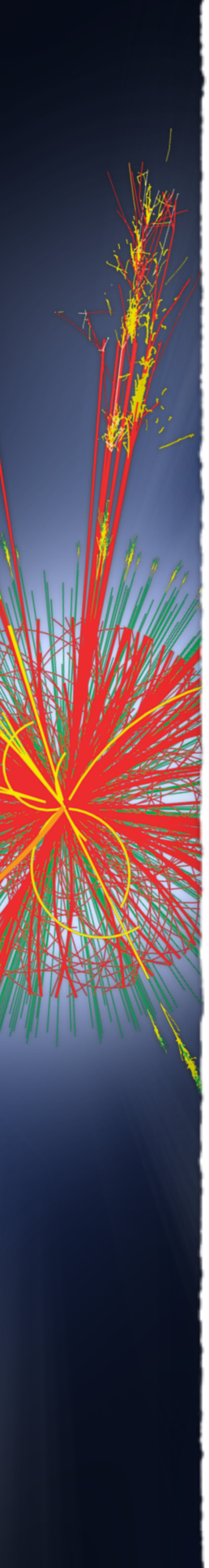
4.8 pile-up jets per event

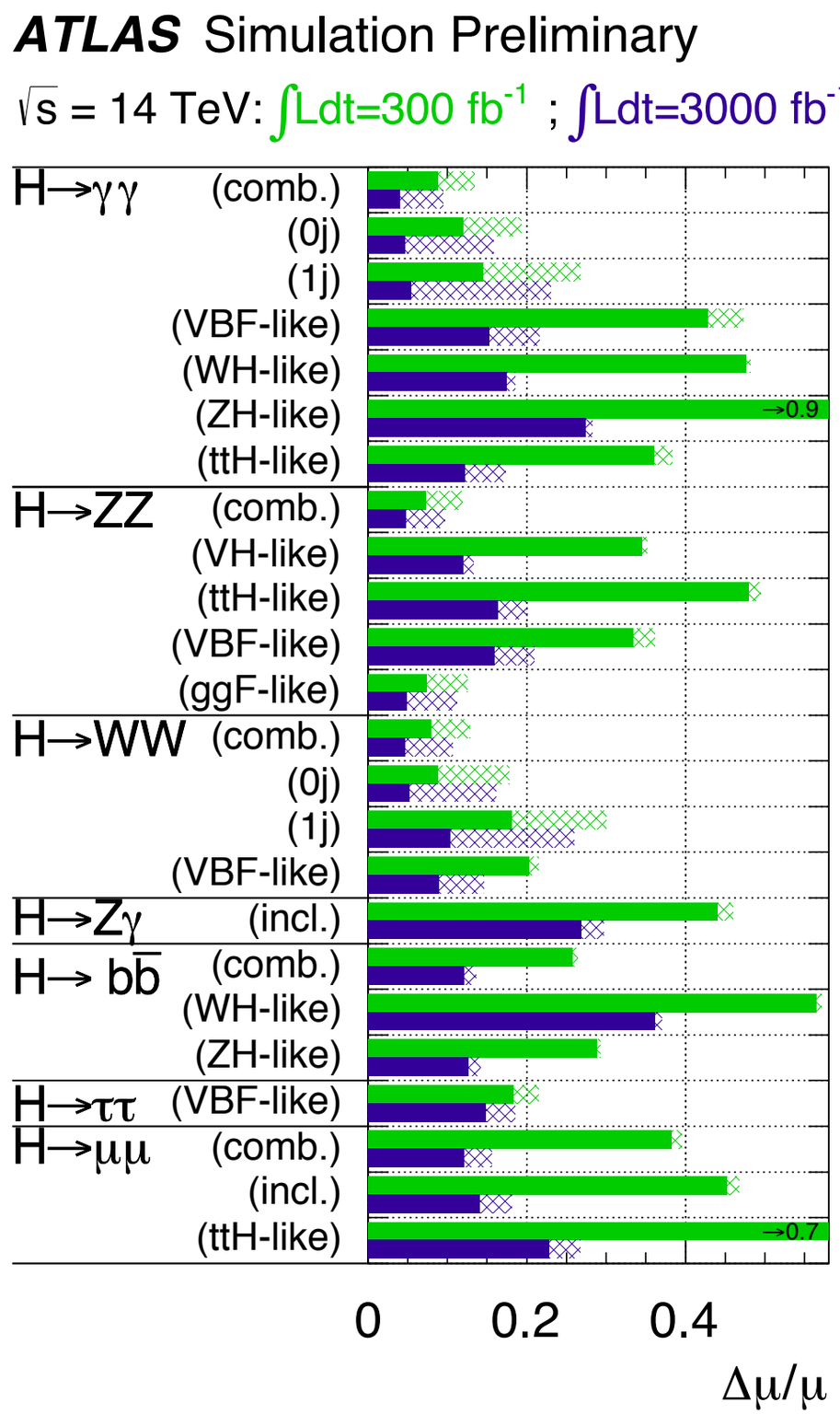
Pile-up jet rejection based on the track confirmation requirement

$$R_{pT} = \frac{\Sigma_i (p_{\mathrm{T}}^{\mathrm{track},i})}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

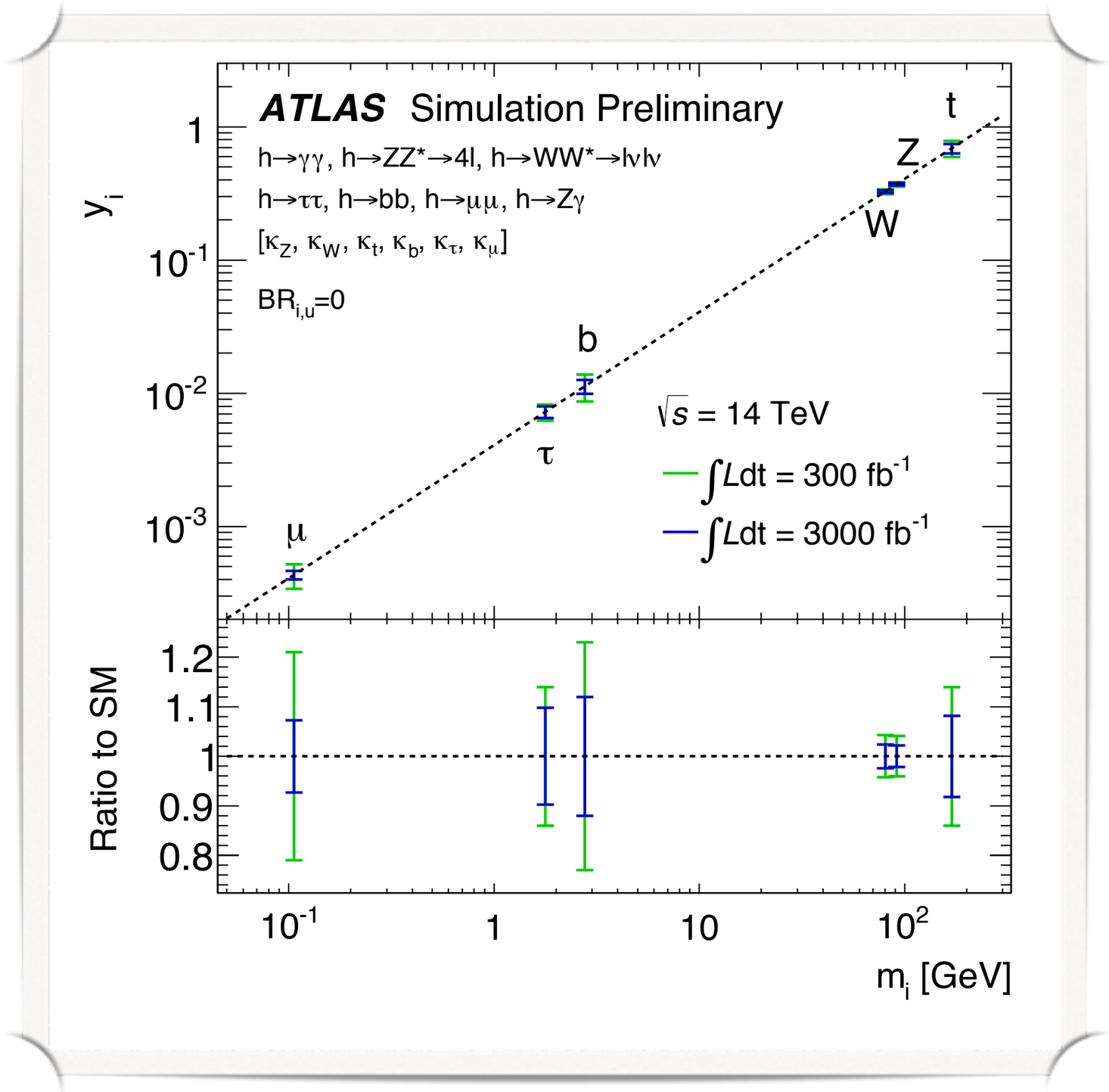
- **A typical rejection of 50 for pile-up jets**
  - ~0.1 pile-up jets per event survive
  - 85-70% efficiency on hard-scatter jets

Higgs Boson Signal Strengths





Testing Yukawa Interactions



For bosons

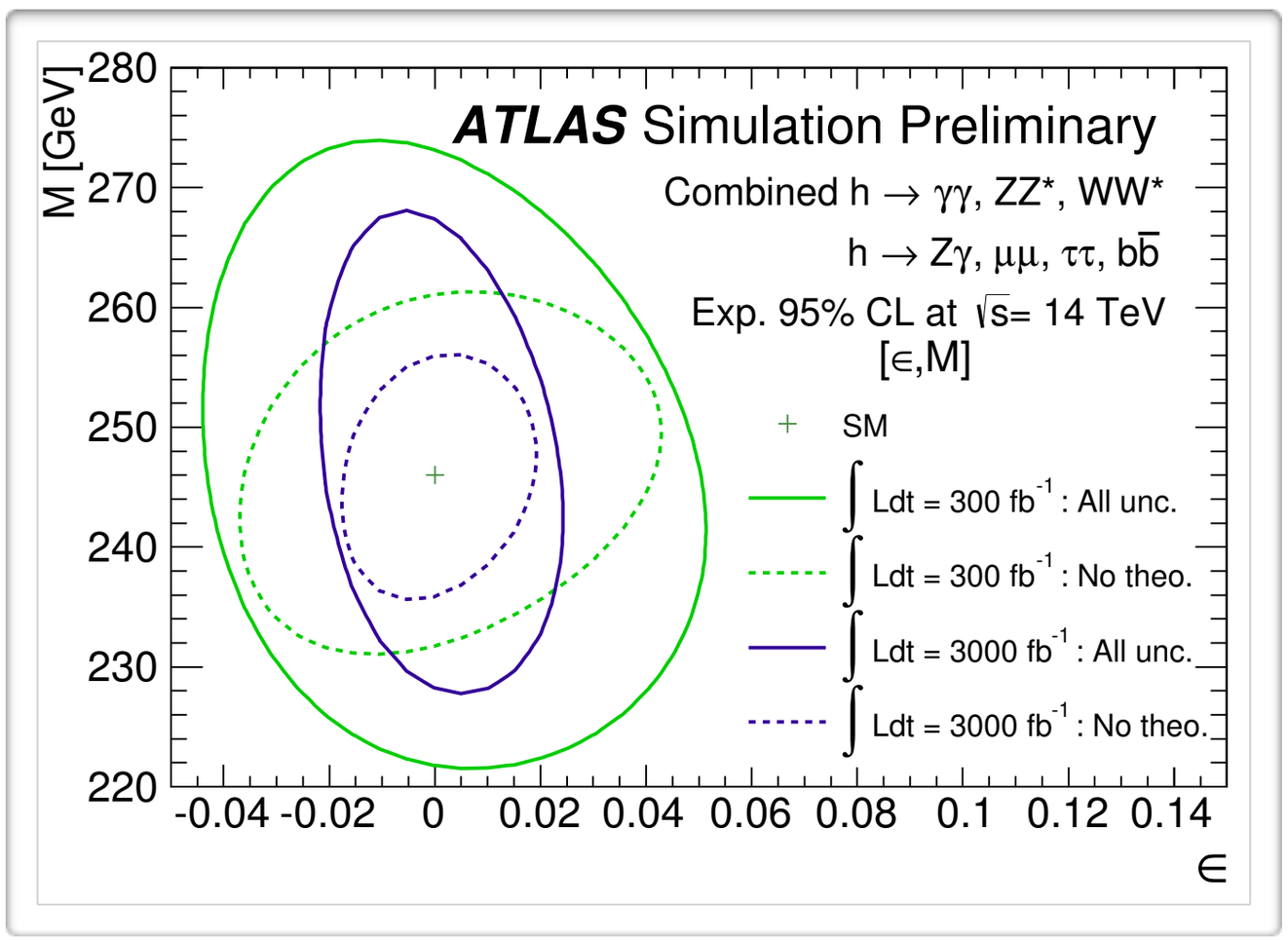
$$y_i = \sqrt{\kappa_i}\frac{m_i}{v}$$

For fermions

$$y_i = \kappa_i\frac{m_i}{v}$$

Mass Scaling of Couplings

- Determine the sensitivity to the mass scaling of the Higgs boson couplings to other particles
- The coupling scale factors are expressed in terms of **a mass scaling parameter ε** and a **vacuum expectation value parameter M**



$$\kappa_{f,i} = v\frac{m_{f,i}^{\epsilon}}{M^{1+\epsilon}}$$

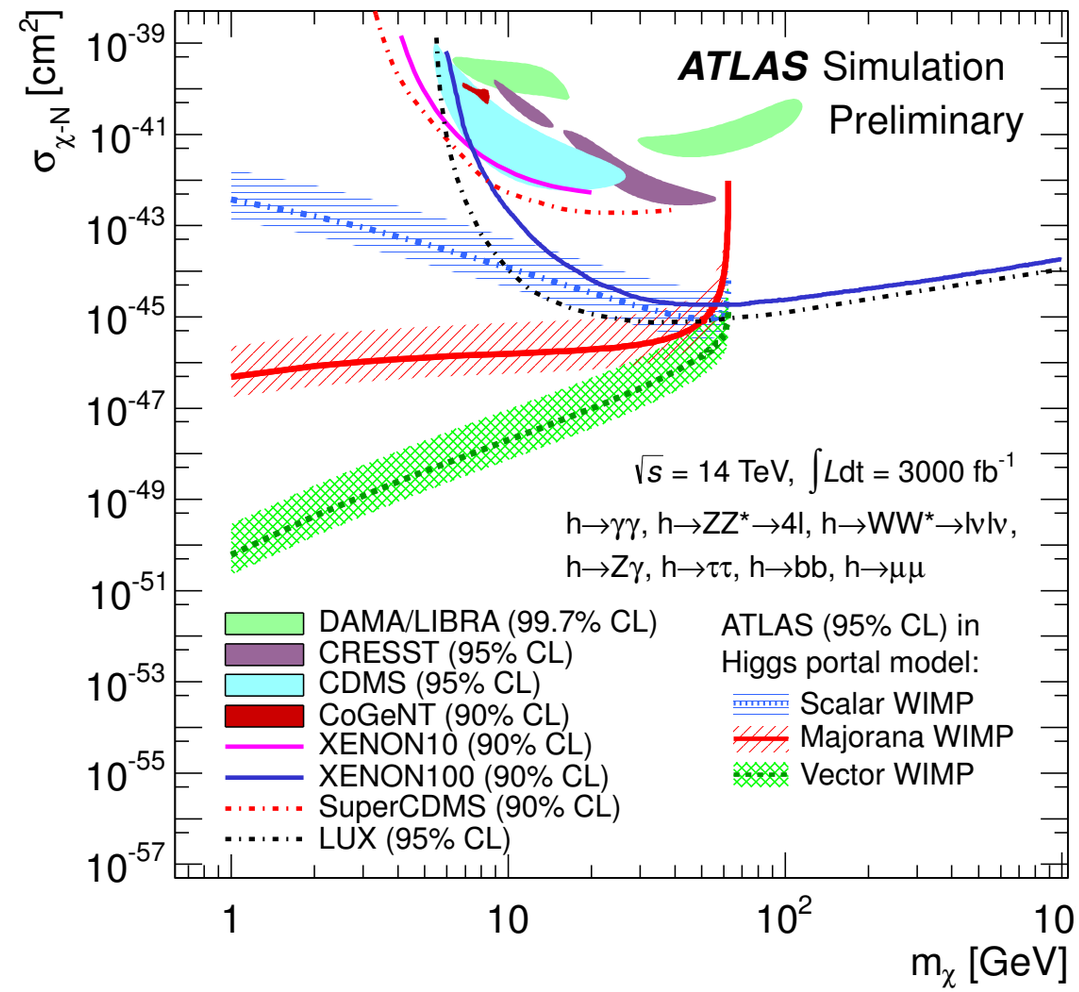
$$\kappa_{V,j} = v\frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}}$$

v = 246 GeV in SM

ε=0 and M=v in the SM

Higgs Portal to Dark Matter

- SM Higgs boson couples to all massive particles
  - Likely that h couples to DM as well, to WIMPs X
  - Look for h → invisible particles
  - Take coupling of X to h as a free parameter
  - BR(invisible) sets a limit on interactions of X with matter

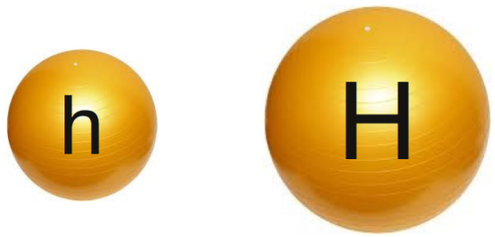


Coupling	The expected 95% CL upper limit on the BR(invisible)	
	300 fb^{-1}	3000 fb^{-1}
w/ theory unc.	0.22	0.13
w/o theory unc	0.19	0.09

Two Higgs Doublet Model

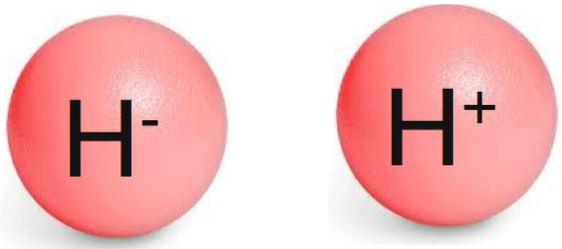
Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

$\cos(\beta-\alpha) \rightarrow 0$
if h is SM-like



CP-even neutral Higgses

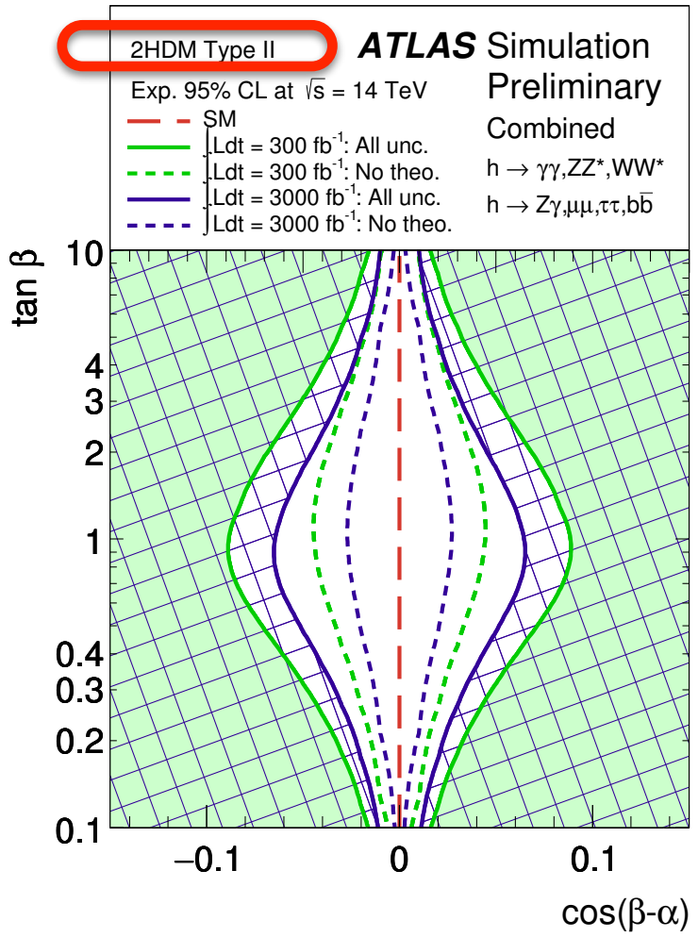
CP-odd neutral Higgs



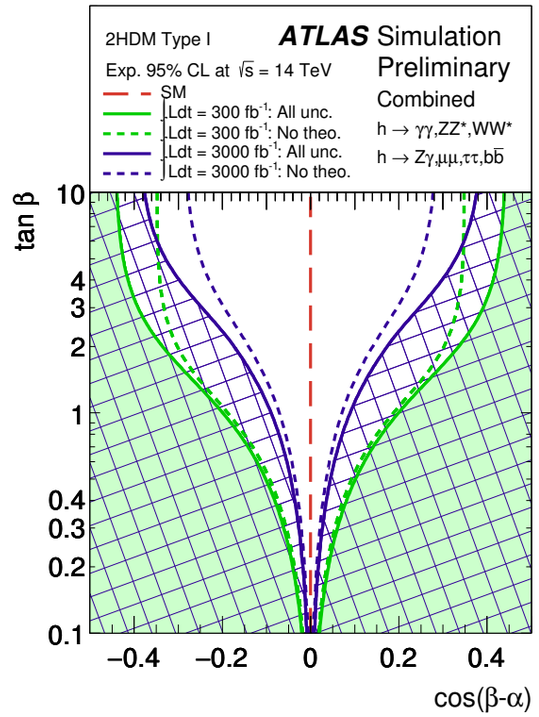
Charged Higgses

- The SM Higgs sector is extended by **an additional doublet**
  - 5 Higgs bosons
  - 6 parameters (4 Higgs boson masses $\mathbf{m_h}$, $\mathbf{m_H}$, $\mathbf{m_A}$, $\mathbf{m_{H^\pm}}$, **tanβ** and **α**)
  - **Type I, II, III, IV** (distinguishing them involve the branching ratios in Higgs decays)

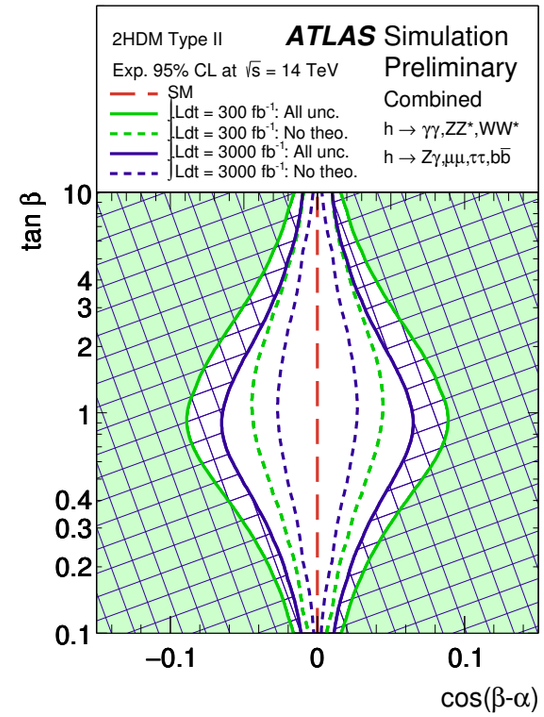
- **tanβ:** Ratio of vevs of Higgs doublets (v_2/v_1)
- **α:** The mixing angle of the two neutral, CP-even Higgs states



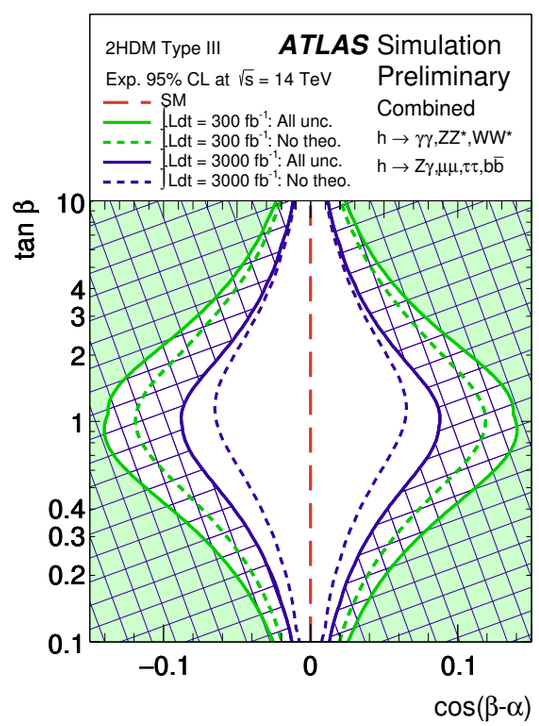
Two Higgs Doublet Model



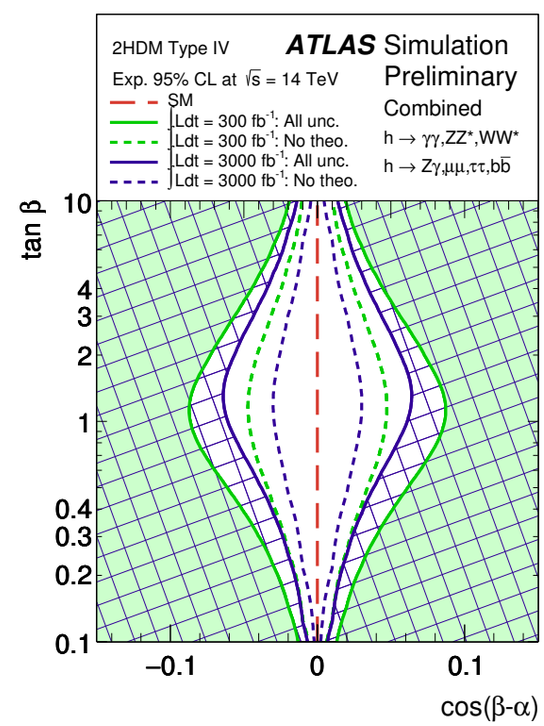
(a) Type I



(b) Type II



(c) Type III

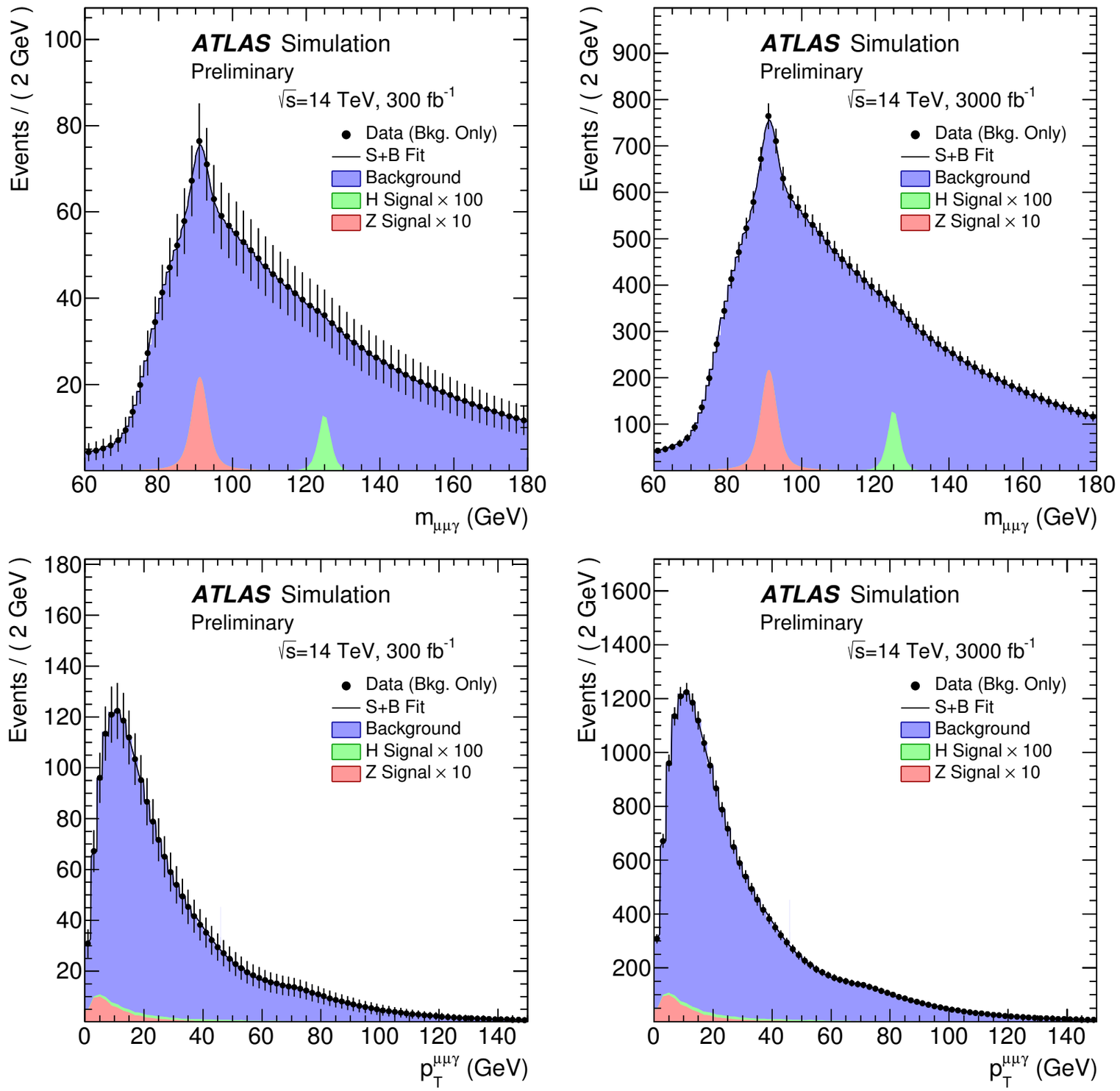


(d) Type IV

VBF H→WW*→eνμν

Category	$N_{\text{jet}} \geq 2$
Pre-selection	Two isolated leptons (one e and one μ) with opposite charge Leptons with $p_{\text{T}}^{\text{lead}} > 25$–$28$ GeV and $p_{\text{T}}^{\text{sublead}} > 15$ GeV $m_{\ell\ell} > 10$ GeV
Jet-corrected-track-$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 20$ GeV
General selection	$p_T^{\text{jet}} > 70$ (60) GeV lead (sublead) $N_{\text{b-jet}} = 0$ (before pile-up jet removal) $p_{\text{T}}^{\text{tot}} < 20$ GeV $Z/\gamma^* \to \tau\tau$ veto (Collinear approx. $m_{\tau\tau} < 50$ GeV)
VBF topology	$m_{\text{jj}} > 1250$ GeV and $\lvert\eta_j\rvert > 2.0$, opposite hemisphere No jets ($p_{\text{T}} > 30$ GeV) in rapidity gap (CJV) Require both ℓ in rapidity gap
$H \to WW^* \to e\nu\mu\nu$ topology	$m_{\ell\ell} < 60$ GeV $\Delta\phi_{\ell\ell} < 1.8$ $m_{\text{T}} < 1.07 \times m_H$

H→J/ψ γ with J/ψ→μμ



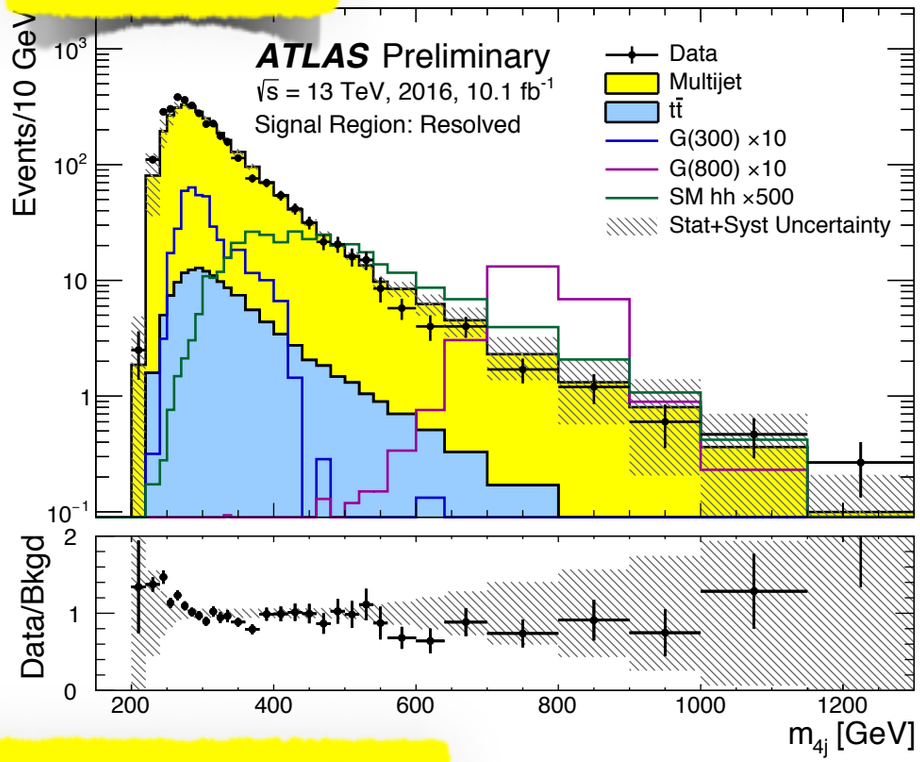
Higgs Pair Production

- Assuming 3000 fb^{-1} at $\sqrt{s} = 14$ TeV

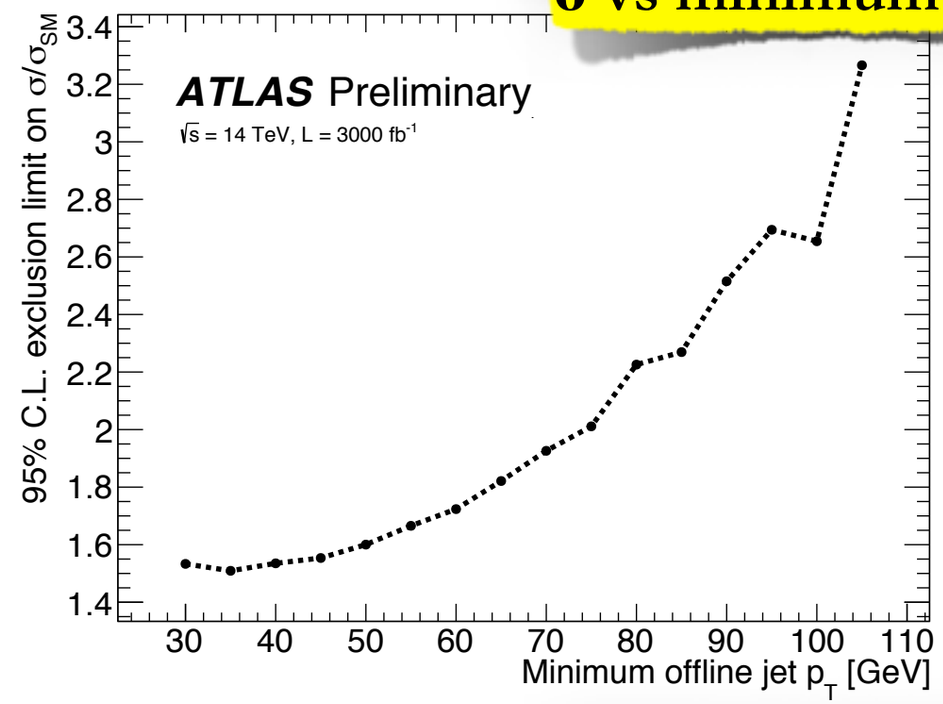
Decay channel	Branching Ratio (%)	Event Yield
$hh \rightarrow bbbb$	33	41000
$hh \rightarrow bbWW$	25	31000
$hh \rightarrow bb\tau\tau$	7.4	9000
$hh \rightarrow WW\tau\tau$	5.4	6600
$hh \rightarrow bbZZ$	3.1	3800
$hh \rightarrow WWZZ$	1.2	1400
$hh \rightarrow bb\gamma\gamma$	0.3	330
$hh \rightarrow WW\gamma\gamma$	0.1	100
$hh \rightarrow \gamma\gamma\gamma\gamma$	0.0010	1

hh→bbbb

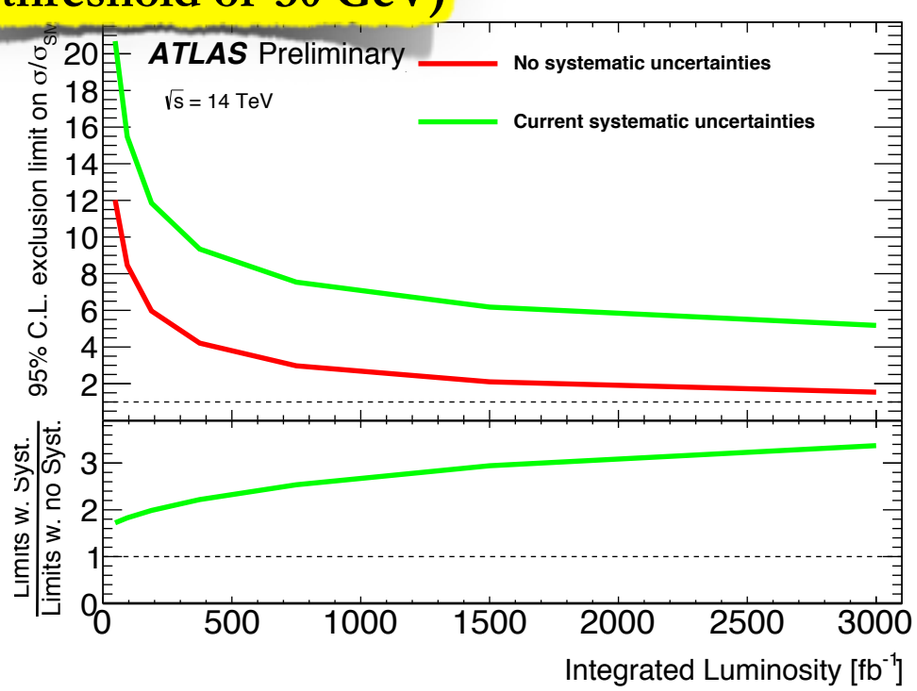
2016 Results



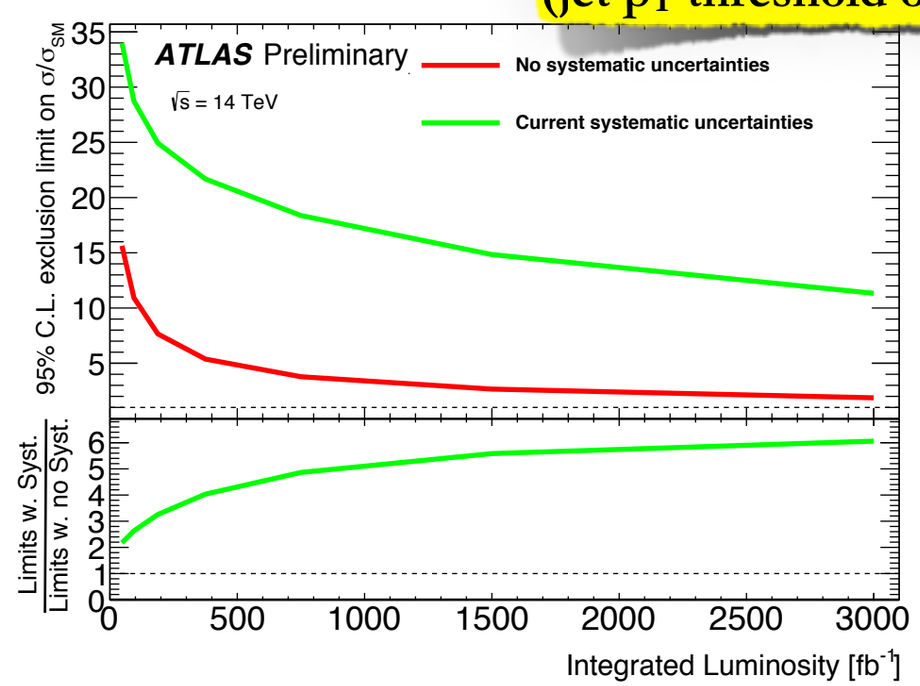
Limits on σ vs minimum jet p_T



Limits on σ vs $\mathcal{L}_{int}$ (jet p_T threshold of 30 GeV)

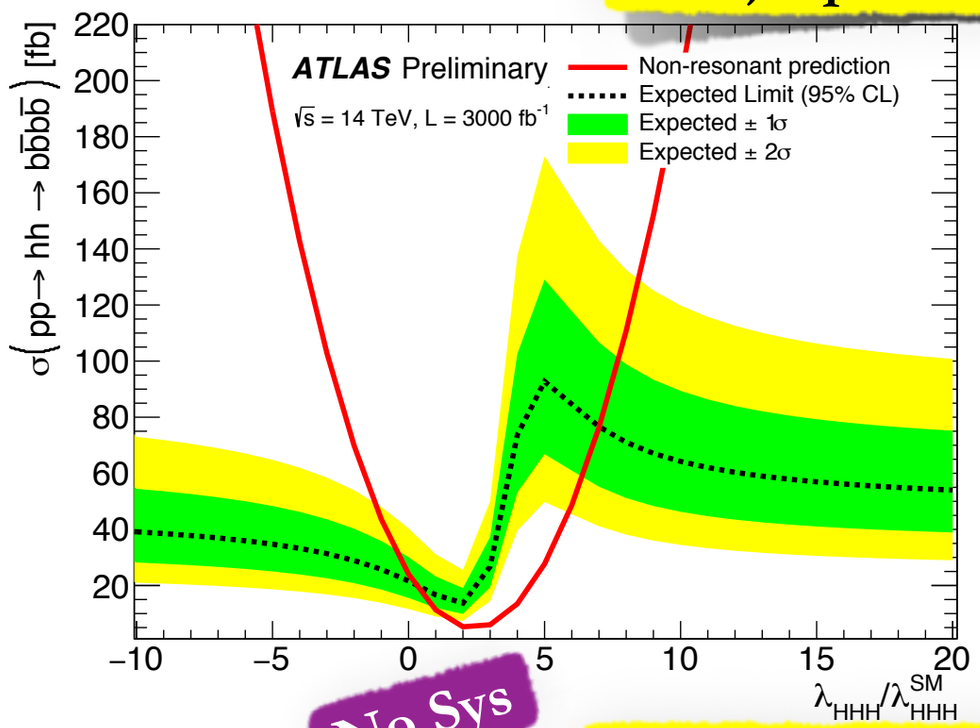


Limits on σ vs $\mathcal{L}_{int}$ (jet p_T threshold of 75 GeV)

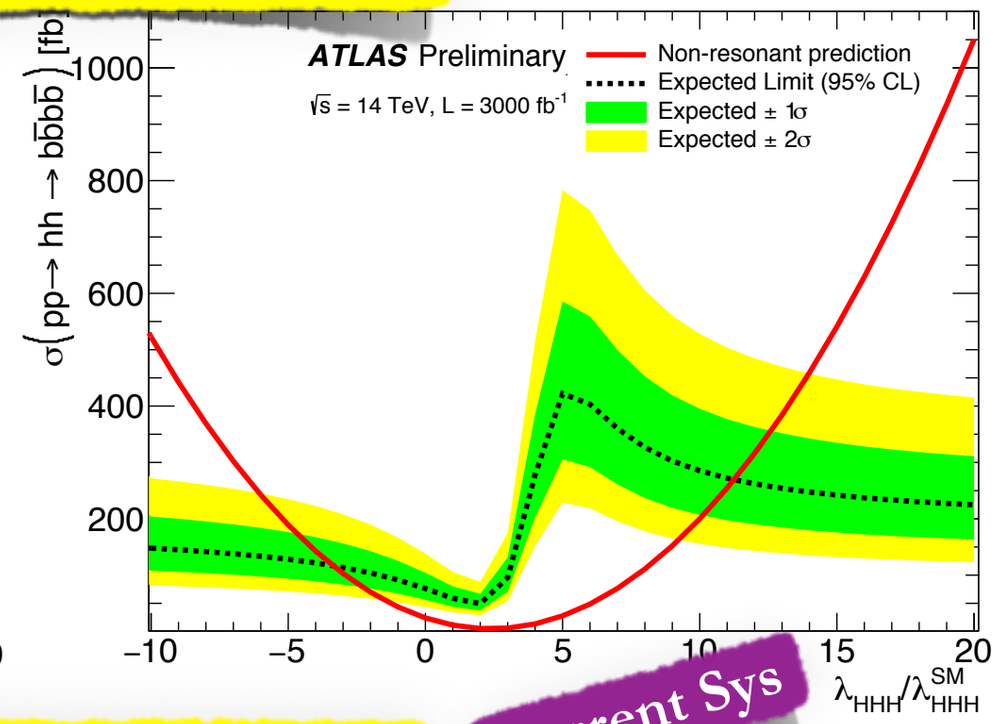


hh→bbbb

With jet p_T threshold of 30 GeV

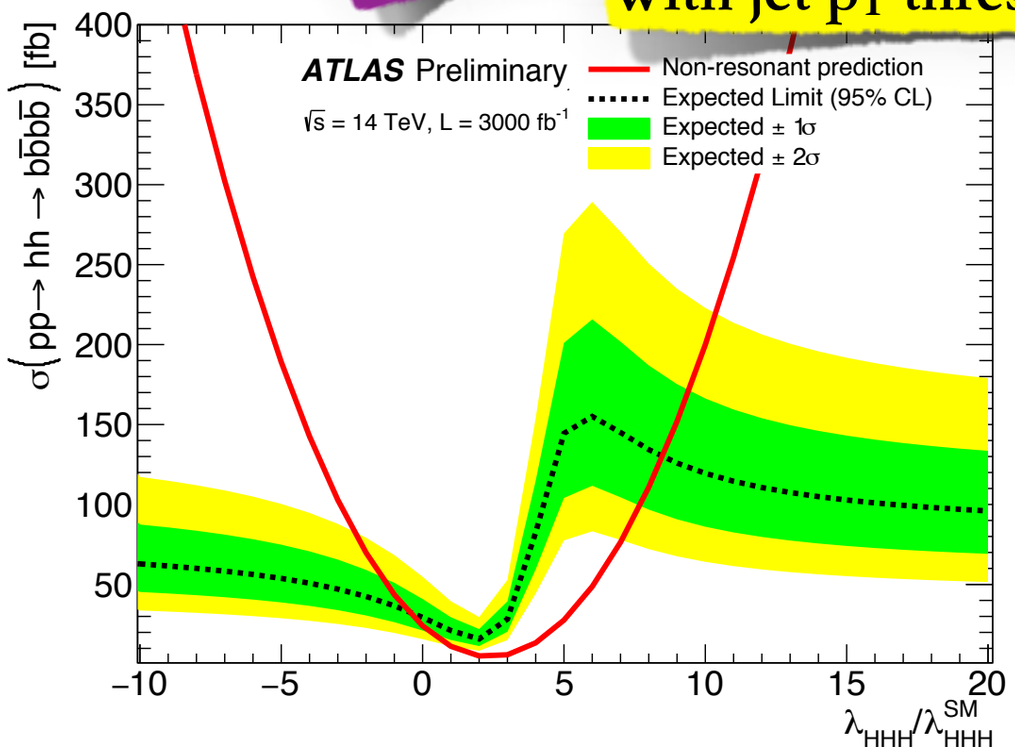


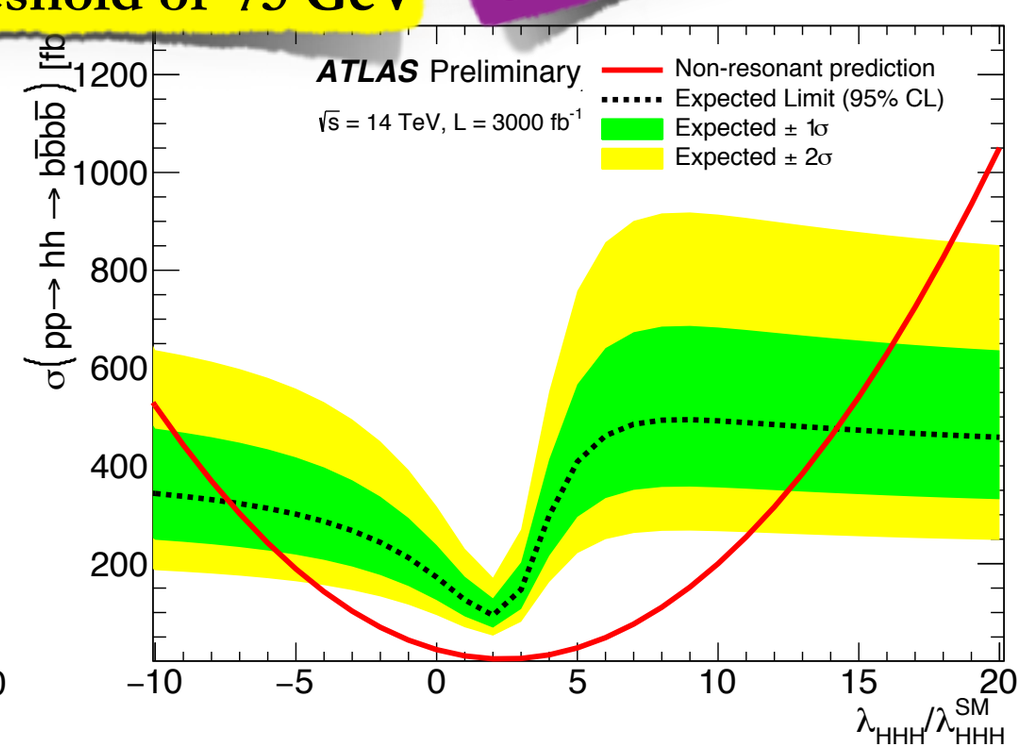
No Sys



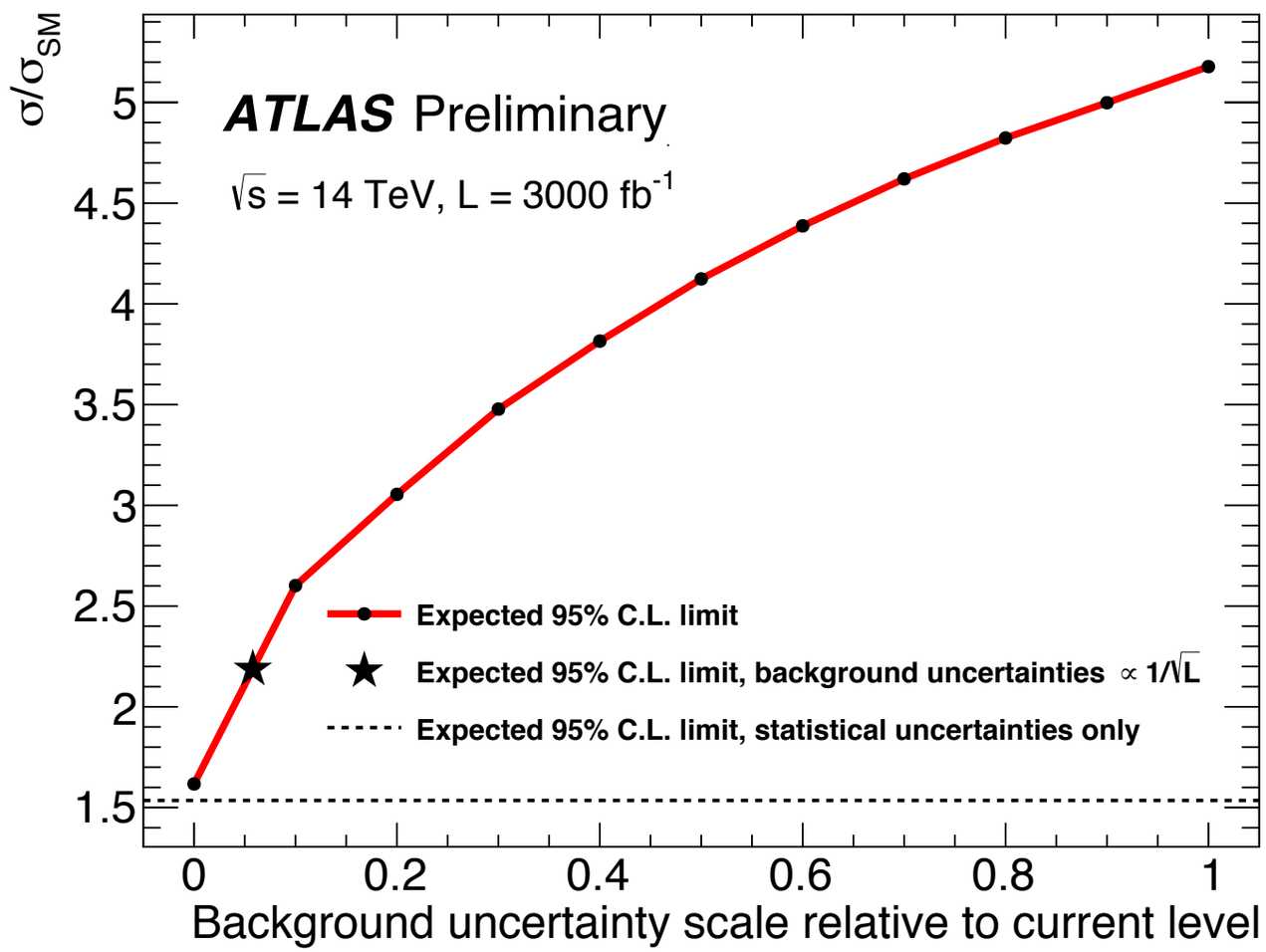
Current Sys

With jet p_T threshold of 75 GeV





hh→bbbb

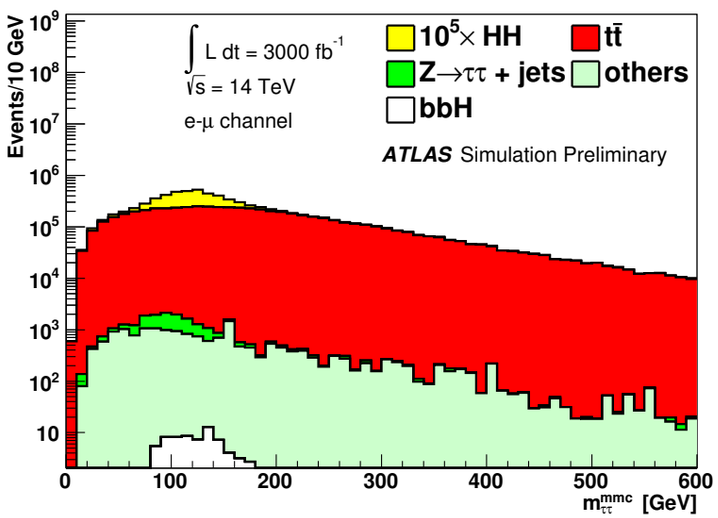


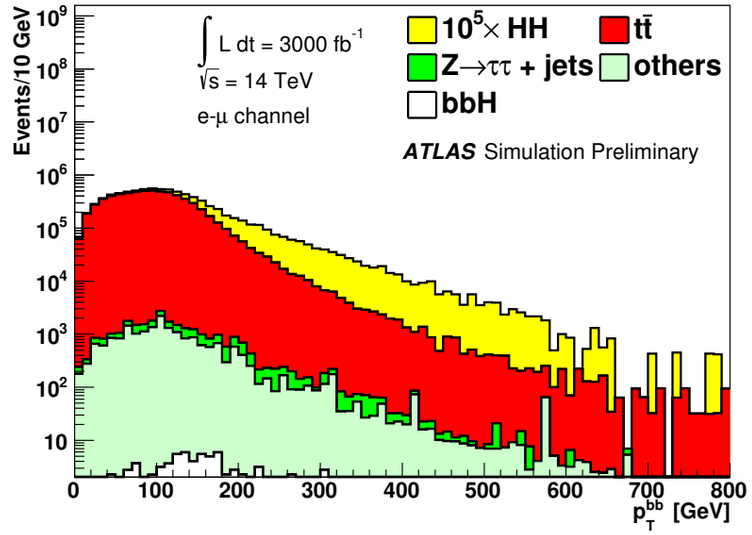
Source	$\Delta\mu$
Luminosity	0.05
Jet Energy	0.09
b-tagging	0.34
Theoretical	0.10
Multijet	1.85
$t\bar{t}$	2.83

ATL-PHYS-PUB-2015-046

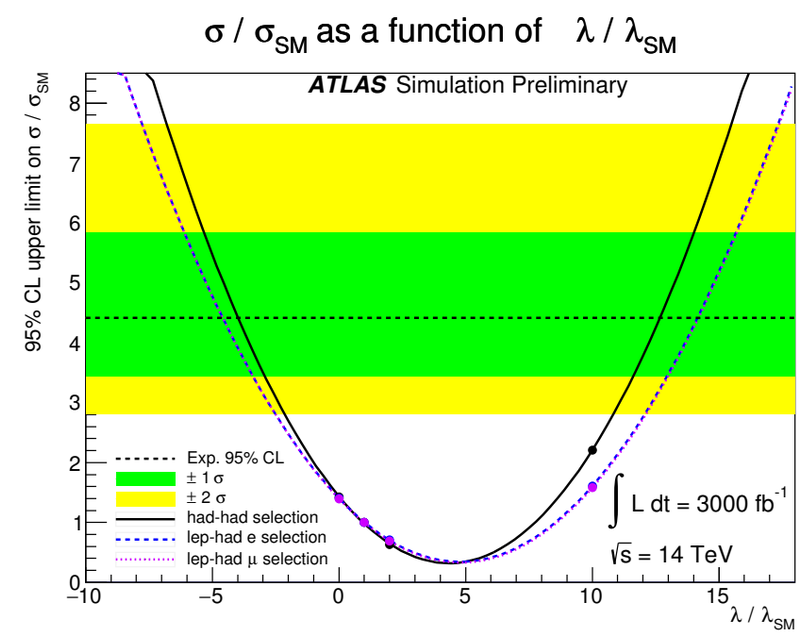
$hh \rightarrow bb\tau\tau$

- **Three sub-channels:** $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$ with different trigger requirements and slightly different event selections
  - Fully leptonic final state does not contribute to final results
- Significant background from tt and $Z(\tau\tau)$+jets processes
- Pile up level of $<\mu>$ =140, worsening ET_{miss} resolution





Channel	Significance	Combined in channel	Total combined
e + jets	0.31	0.43	0.60
μ+jets	0.30		
$\tau_{had}\tau_{had}$	0.41	0.41	



95% C.L limits on λ

$\lambda_{HHH}/\lambda_{SM} \leq -4$ and $\lambda_{HHH}/\lambda_{SM} \geq 12$

95% C.L limits on σ

4.3 x $\sigma(HH \rightarrow bb\tau\tau)$

hh→bbγγ

Process	Generator	$\sigma \cdot BR$ [fb]	Order QCD	Equivalent Lumi. [fb^{-1}]
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 1$	MadGraph5/Pythia 8	0.11	NNLO	5.5×10^6
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 0$	MadGraph5/Pythia 8	0.23	NNLO	1.3×10^6
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 2$	MadGraph5/Pythia 8	0.05	NNLO	6.1×10^6
$H(b\bar{b})H(\gamma\gamma), \lambda/\lambda^{SM} = 10$	MadGraph5/Pythia 8	1.81	NNLO	0.2×10^6
$ggF(\gamma\gamma)$	Powheg-Box/Pythia 6	1.2×10^2	NNNLO	8.1×10^3
$t\bar{t}H(\gamma\gamma)$	Pythia 8	1.40	NLO	7.1×10^4
$ZH(\gamma\gamma)$	Pythia 8	2.24	NLO	4.4×10^4
$b\bar{b}H(\gamma\gamma)$	Pythia 8	1.26	NLO	4.2×10^6
$b\bar{b}\gamma\gamma$	MadGraph5/Pythia 8	1.4×10^2	LO	1.8×10^4
$c\bar{c}\gamma\gamma$	MadGraph5/Pythia 8	1.1×10^3	LO	3070
$jj\gamma\gamma$	MadGraph5/Pythia 8	1.6×10^4	LO	2460
$b\bar{b}j\gamma$	MadGraph5/Pythia 8	3.8×10^5	LO	130
$c\bar{c}j\gamma$	MadGraph5/Pythia 8	1.1×10^6	LO	36
$b\bar{b}jj$	MadGraph5/Pythia 8	4.6×10^8	LO	0.005
$Z(\rightarrow b\bar{b})\gamma\gamma$	MadGraph5/Pythia 8	5.07	LO	2.0×10^4
$t\bar{t}(\geq 1\text{lepton})$	Powheg-Box/Pythia 6	5.3×10^5	NNLO	5.7×10^2
$t\bar{t}\gamma(\geq 1\text{lepton})$	MadGraph5/Pythia 8	5.0×10^3	NLO	2×10^3

Event Selection Criteria
≥ 2 isolated photons, with $p_T > 30$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$
≥ 2 jets identified as b-jets with leading/subleading $p_T > 40/30$ GeV, $\lvert\eta\rvert<2.4$
< 6 jets with $p_T > 30$ GeV, $\lvert\eta\rvert < 2.5$
No isolated leptons with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
$0.4 < \Delta R_{b\bar{b}} < 2.0, 0.4 < \Delta R_{\gamma\gamma} < 2.0, 0.4 < \Delta R_{\gamma jet}$
$122 < m_{\gamma\gamma} < 128$ GeV, $100 < m_{b\bar{b}} < 150$ GeV
$p_T^{\gamma\gamma}, p_T^{b\bar{b}} > 80$ GeV

Selection requirement	Efficiency (%)
trigger + ≥ 2 tight photons with $p_T > 25$ GeV	32.0
≥ 2 photon candidates with $p_T > 30$ GeV	27.4
≥ 2 jet candidates	21.7
≥ 2 b-jet candidates	7.73
< 6 jet candidates	7.46
isolated lepton veto	6.96
$0.4 < \Delta R_{b\bar{b}} < 2.0, \Delta R_{\gamma\gamma} < 2.0$	5.25
$122 < m_{\gamma\gamma} < 128$ GeV	3.95
$100 < m_{b\bar{b}} < 150$ GeV	2.90
H candidates $p_T > 80$ GeV	2.89

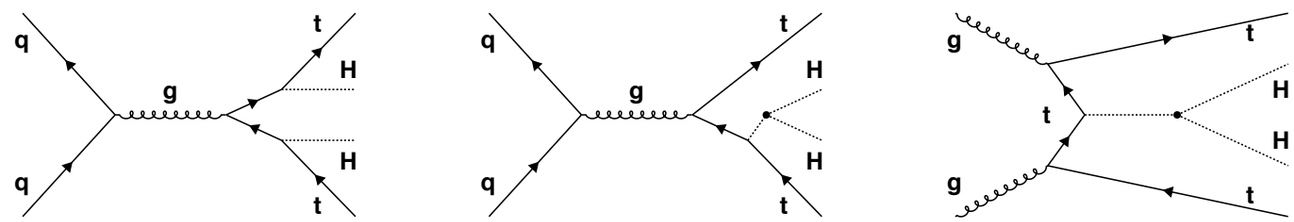
hh→bbγγ

Categorisation	Barrel-barrel	Other
$H(\to b\bar{b})H(\to\gamma\gamma), \lambda/\lambda^{SM} = 1$	7.309 ± 0.025	2.235 ± 0.016
$t\bar{t}H(\to\gamma\gamma)$	5.89 ± 0.13	1.98 ± 0.08
$ZH(\to\gamma\gamma)$	3.42 ± 0.17	1.56 ± 0.06
$b\bar{b}H(\to\gamma\gamma)$	0.106 ± 0.011	0.042 ± 0.005
$ggH(\to\gamma\gamma)$	1.96 ± 0.29	0.78 ± 0.19
$b\bar{b}\gamma\gamma$	12.4 ± 0.4	9.4 ± 0.5
$c\bar{c}\gamma\gamma$	5.70 ± 0.31	2.77 ± 0.34
$jj\gamma\gamma$	2.2 ± 0.5	1.84 ± 0.32
$b\bar{b}j\gamma$	11.8 ± 0.8	10.8 ± 0.8
$c\bar{c}j\gamma$	2.5 ± 0.7	0.7 ± 0.4
$b\bar{b}jj$	3.3 ± 0.7	2.05 ± 0.33
$Z(\to b\bar{b})\gamma\gamma$	1.21 ± 0.10	0.85 ± 0.10
$t\bar{t}\gamma(\geq 1\text{lepton})$	3.80 ± 0.34	1.36 ± 0.14
$t\bar{t}(\geq 1\text{lepton})$	0.80 ± 0.28	1.6 ± 0.4
Total background	55.1 ± 1.6	35.7 ± 1.3
Significance	0.984 ± 0.018	0.373 ± 0.017
Combined significance	1.052 ± 0.026	

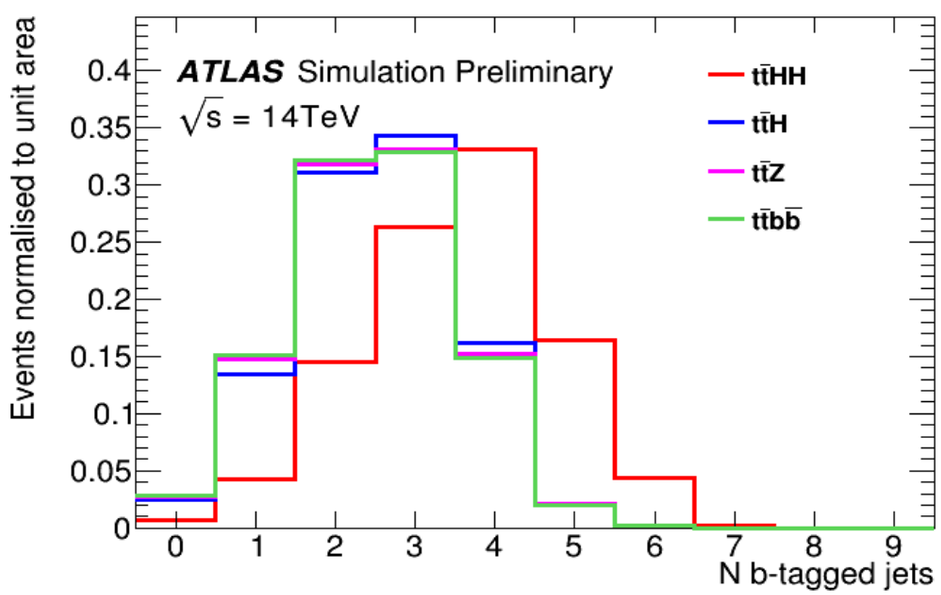
ATL-PHYS-PUB-2016-023

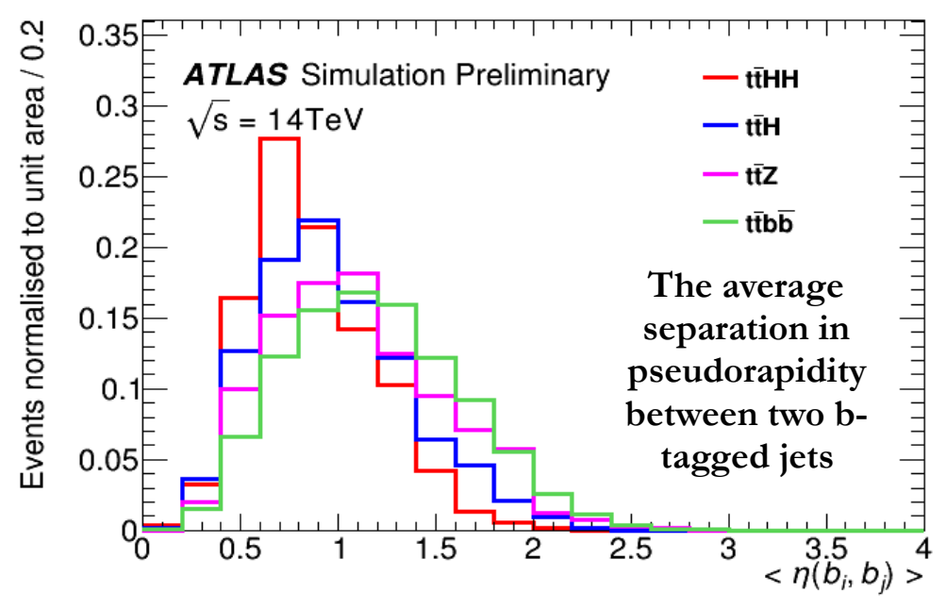
tthh, hh→bbbb

- ttHH cross-section is more than an order of magnitude smaller than hh in gluon-gluon fusion
  - The presence of top quark pair reduces the backgrounds
  - Not suffer from destructive interference in the cross section
- A cut-based analysis
- Semi-leptonic final state of tt

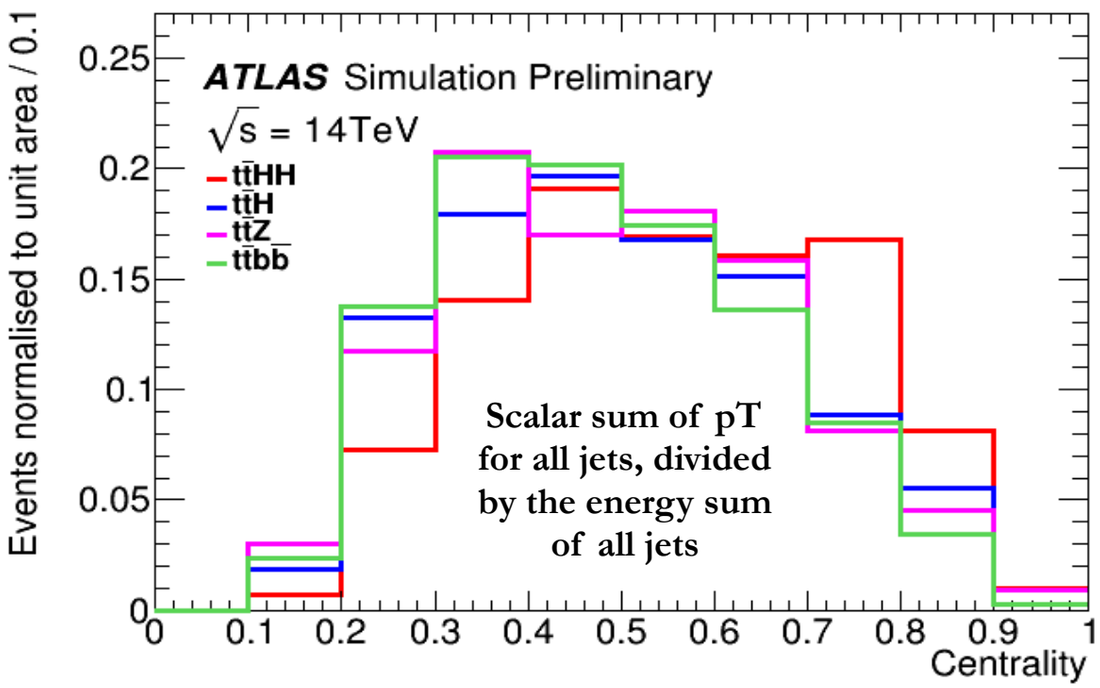


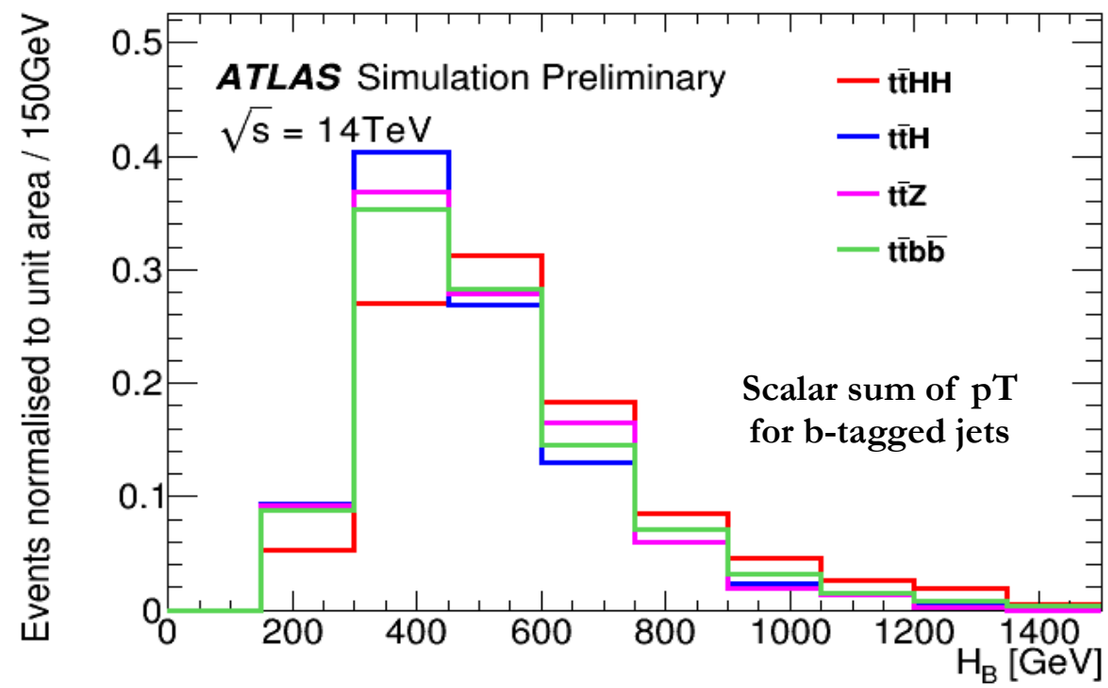
- **Backgrounds: ttbb+jets**, ttZ(Z→bb)+jets, ttH(H→bb)+jets
- **Final State:** 1 e or μ, 2 light jets, 6 b-jets, E_T^{miss} **Significance: 0.35σ (No sys errors)**
- **For the ≥ 5 b-tag selection:** 25 signal events, 7100 background events
- Combining significances from exactly 5 b-tag and ≥ 6 b-tag selection region

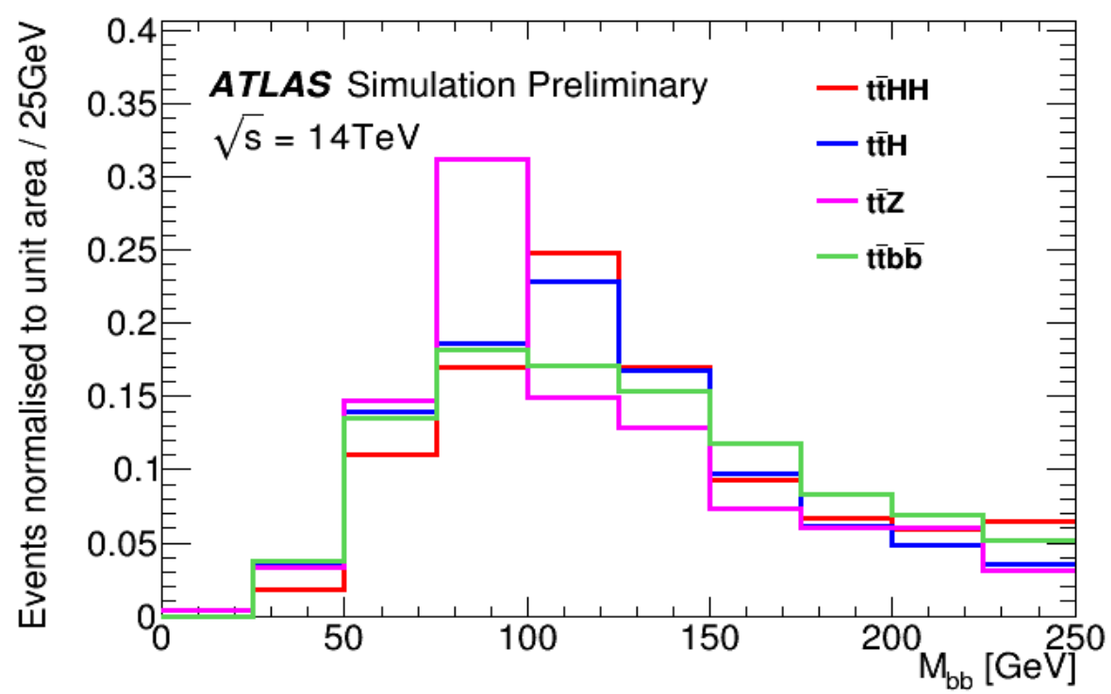




tthh, hh→bbbb


ATLAS Simulation Preliminary
√s = 14TeV
tt̄HH
tt̄H
tt̄Z
tt̄bb̄
Scalar sum of pT
for all jets, divided
by the energy sum
of all jets
Events normalised to unit area / 0.1
Centrality


ATLAS Simulation Preliminary
√s = 14TeV
tt̄HH
tt̄H
tt̄Z
tt̄bb̄
Scalar sum of pT
for b-tagged jets
Events normalised to unit area / 150GeV
H_B [GeV]


ATLAS Simulation Preliminary
√s = 14TeV
tt̄HH
tt̄H
tt̄Z
tt̄bb̄
Events normalised to unit area / 25GeV
M_bb [GeV]

tthh, hh→bbbb

Event Selection for Signal and Background

Sample	No cuts	Trigger	One lepton	≥7 jets	≥5 b-tags	$\eta(b_i, b_j)$	≥6 b-tags
$t\bar{t}HH(HH \to b\bar{b}b\bar{b})$	990	513	253	139	29	25	6
$t\bar{t}H(H \to b\bar{b})$ + jets	610,000	500,000	290,000	69,000	1,580	1,200	90
$t\bar{t}Z(Z \to b\bar{b})$ + jets	270,000	220,000	125,000	26,000	600	390	30
$t\bar{t}b\bar{b}$ + jets	5,900,000	4,800,000	2,800,000	460,000	9,700	5,500	400
total background	6,800,000	5,500,000	3,200,000	550,000	11,900	7,100	520

For the ≥ 5 b-tag Selection

Background uncertainty	95% CL limit on $\sigma(t\bar{t}HH)/\sigma_{\mathrm{SM}}$
0	6.8
5%	20
10%	32

For the ≥ 6 b-tag Selection

Background uncertainty	95% CL limit on $\sigma(t\bar{t}HH)/\sigma_{\mathrm{SM}}$
0	8.0
5%	10
10%	16