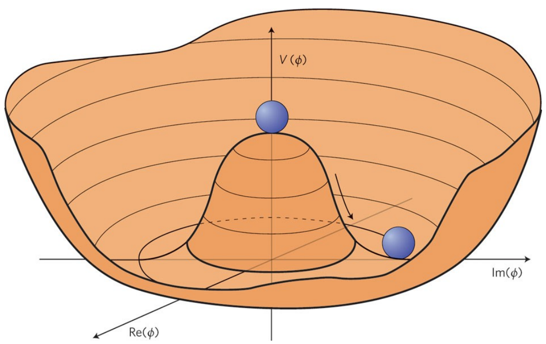
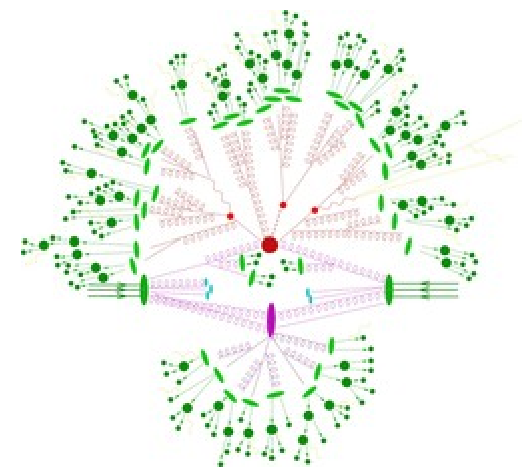
# Mass production at ATLAS

Thorsten Kuhl




Mass Generation
in Standard Model

Hamburg
February 18th, 2014



Generator event
production and tuning

HELMHOLTZ
GEMEINSCHAFT

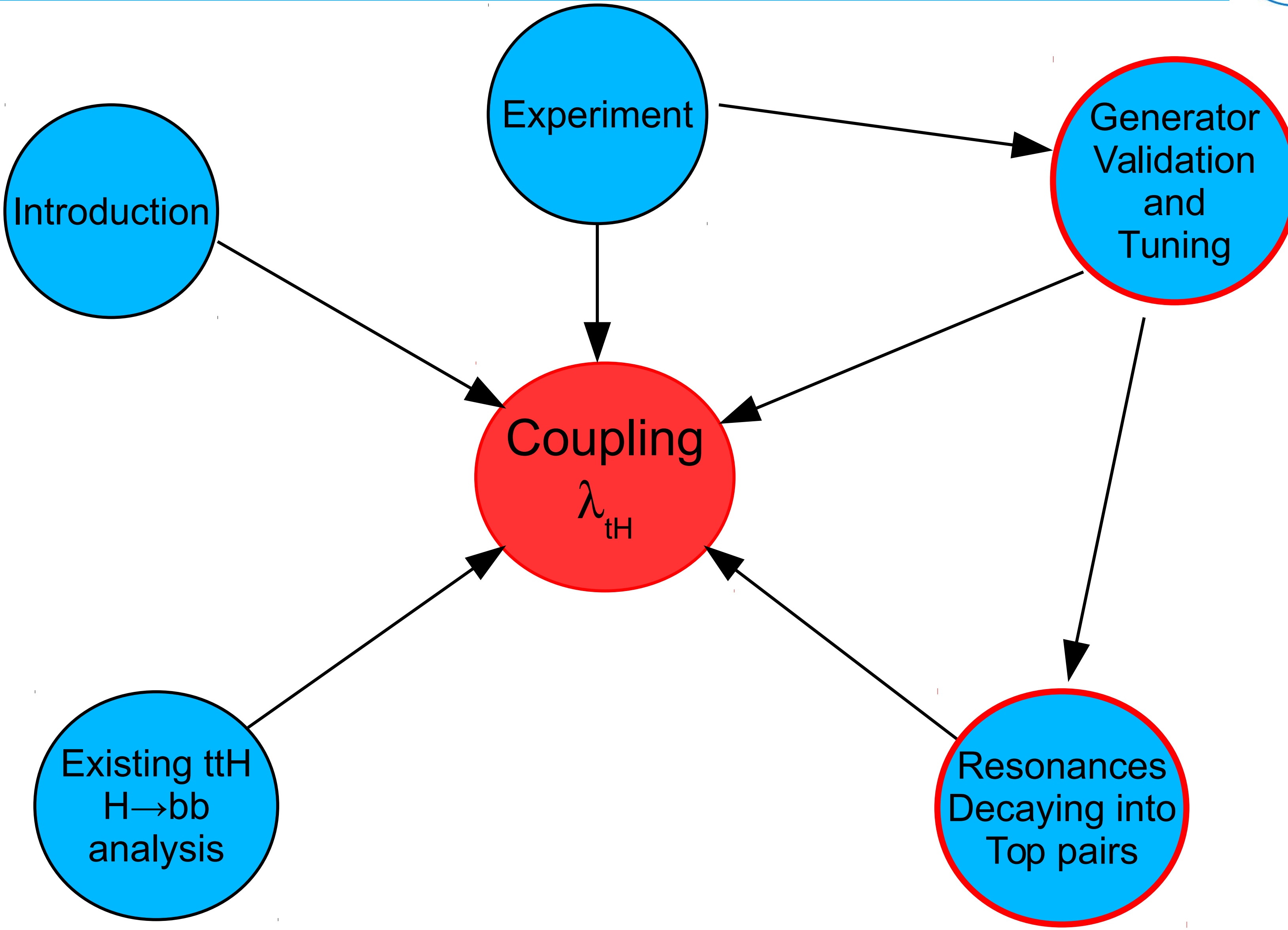
ATLAS

DESY

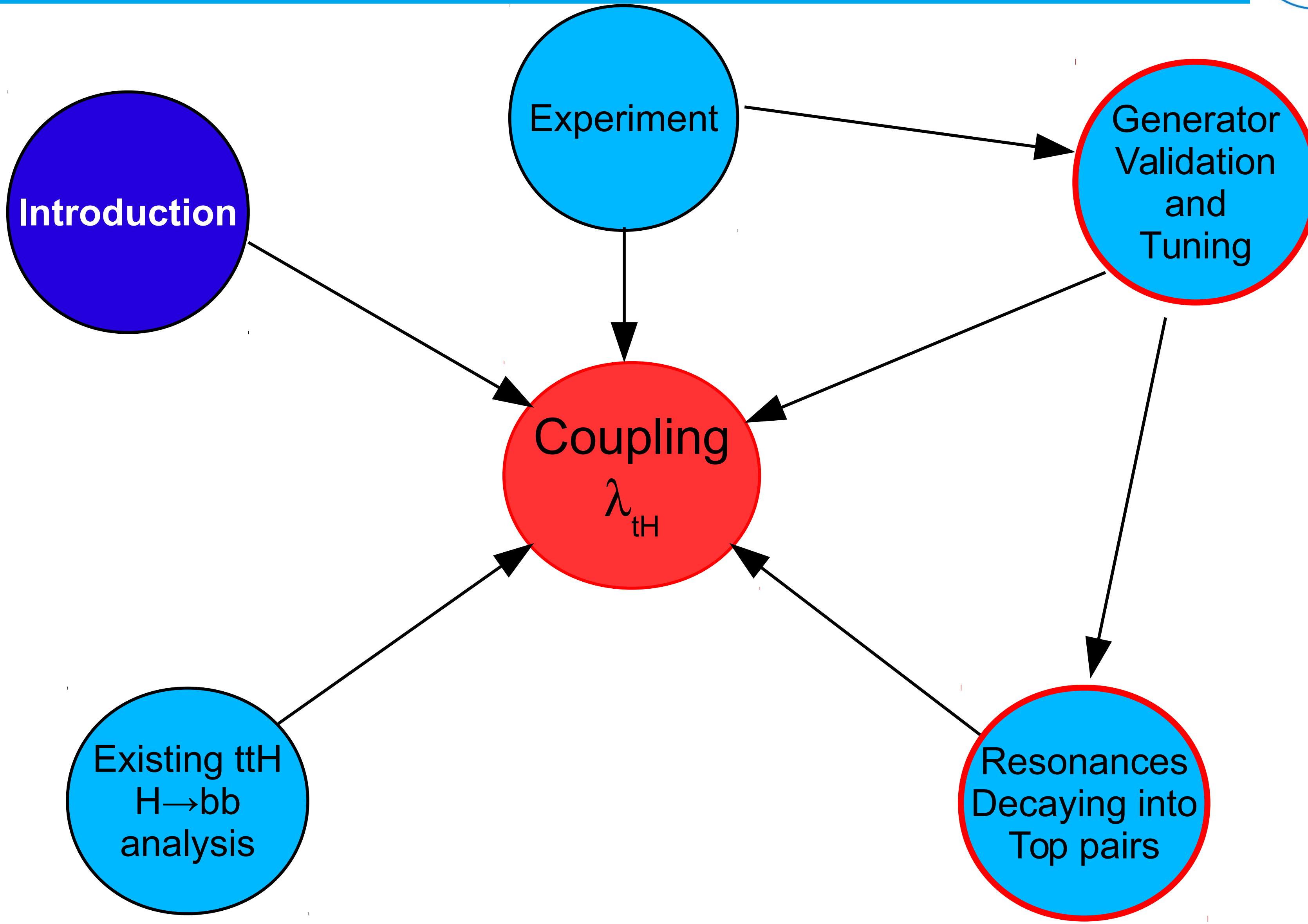
# Standard Model (of particle physics)

- Very successful "LEGO" which describes knowledge up to an accuracy of $O(10^{-6})$
- Higgs Boson, discovered 2012 at the LHC, was last missing ingredient
- Are we finished?
- Only bosonic couplings and coupling to $\lambda_{\tau H}$ are measured
- Biggest coupling $\lambda_{tH} \sim 1$ not measured

# Content


Experiment
Introduction
Generator Validation and Tuning
Coupling $\lambda_{tH}$
Existing ttH H→bb analysis
Resonances Decaying into Top pairs

# Content

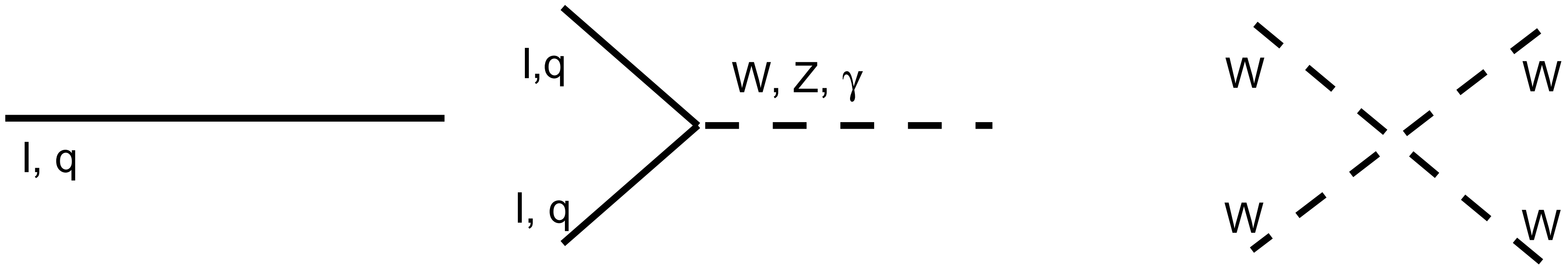

Experiment
Introduction
Generator Validation and Tuning
Coupling
$\lambda_{tH}$
Existing ttH
H→bb
analysis
Resonances Decaying into Top pairs

- Standard Model invariant under local gauge transformations:

$$\partial_\mu \longrightarrow D_\mu = \partial_\mu + i\frac{g}{2}\vec{\tau}\vec{W}_\mu + i\frac{g'}{2}YB_\mu$$

- Standard Model Lagrangian:

$$\mathcal{L} = \underbrace{\overline{\Psi}(x_\mu)i\gamma^\mu\partial_\mu\Psi(x_\mu)}_{\text{Free particle}} + \underbrace{\overline{\Psi}(x_\mu)(\frac{g}{2}\vec{\tau}\vec{W}_\mu + \frac{g'}{2}YB_\mu)\Psi(x_\mu)}_{\text{Interaction with gauge bosons}} - \underbrace{\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\text{Z/W self interactions}}$$

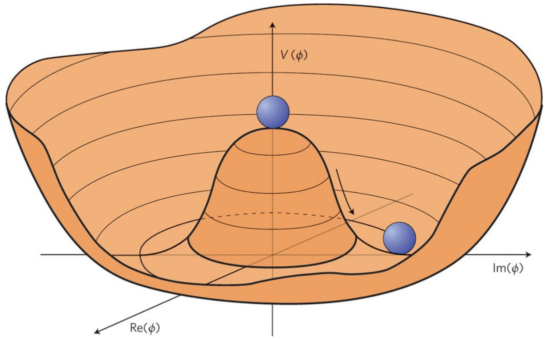



- This is a massless world:
  - terms like $\frac{1}{2}m_W^2 W_\mu^+ W^{+\mu}$ destroy the gauge symmetry

# Theory: The Higgs Potential and Boson

- Higgs Potential:

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$



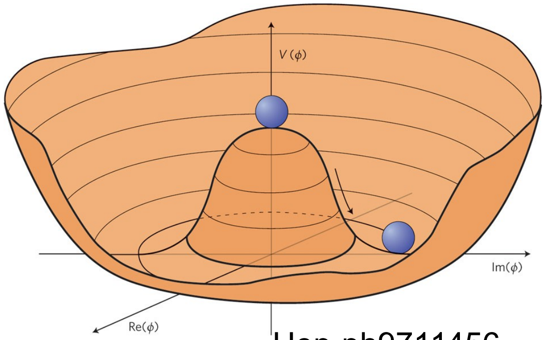

- One new neutral and massive scalar:
  - The SM Higgs Boson
- Unification of electromagnetic and weak force
- Electroweak gauge boson W/Z massive via Higgs mechanism, photon stays massless
- Fermion masses:

$$\mathcal{L}_{Yukawa} = \lambda_e \overline{e_L} \Phi e_R + \lambda_u \overline{u_L} \Phi u_R + \lambda_d \overline{d_L} \tilde{\Phi} d_R.$$

- Vector Boson scattering: not much heavier than 850 GeV

# Theoretical constraints

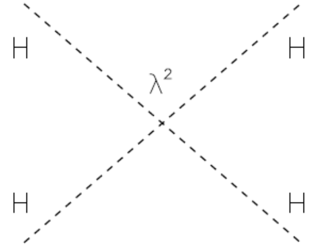
$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$



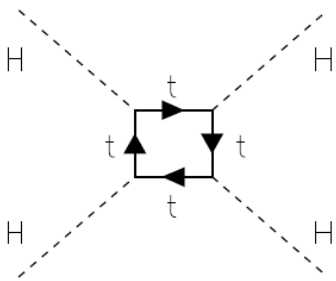
Hep-ph9711456

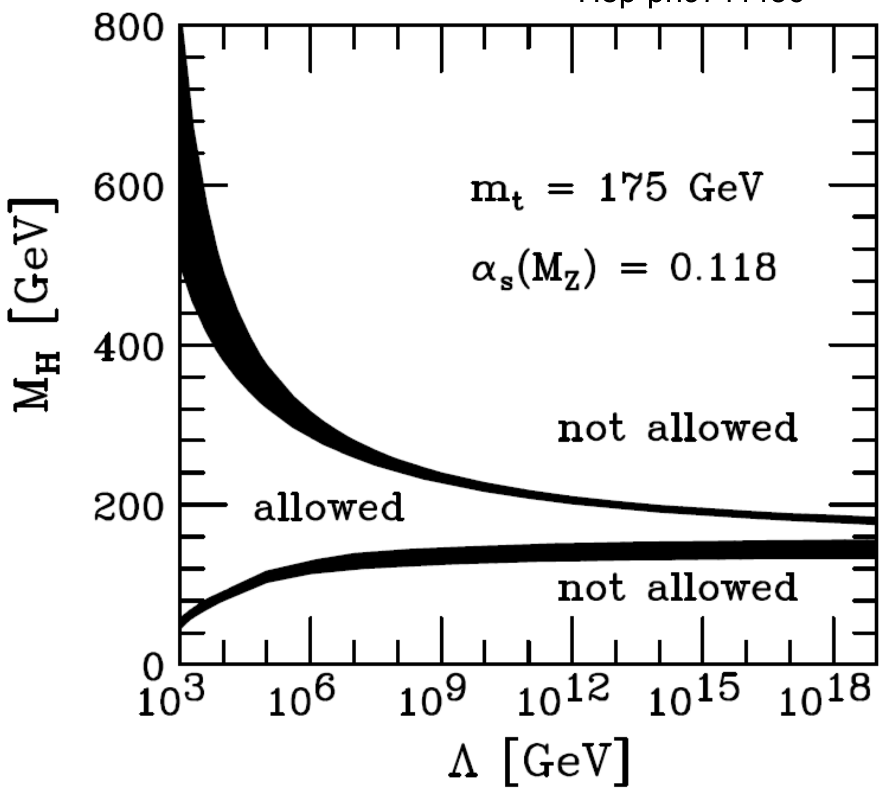
- Theoretical constraints:
  - Stability of the Higgs Potential up to a scale $\Lambda$

- Lower constraint:
  - Hat → Tube




- Higher constraint:
  - Value at (0,0) positive

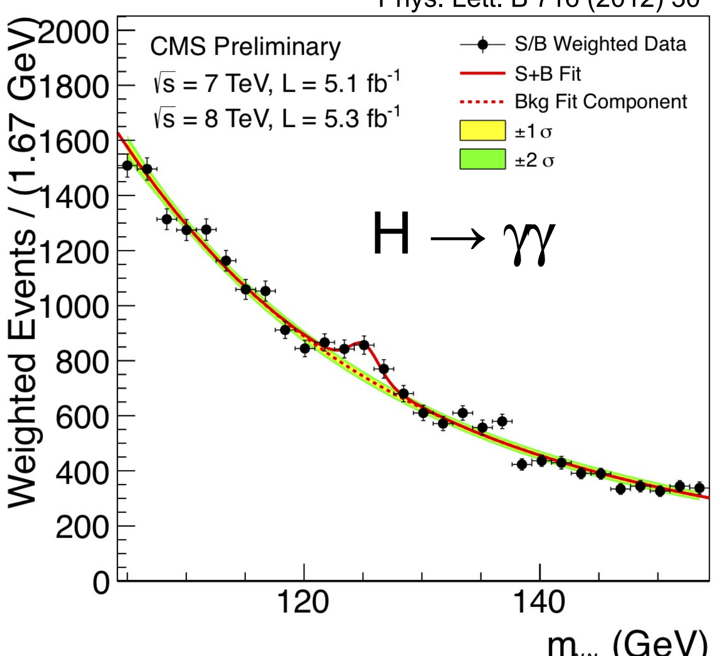


# Discovery and Nobelprize for Higgs Theory

- Discovery of the Higgs Boson in 2012 by ATLAS and CMS
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow 4Z \rightarrow 4l$
- Both experiments see in both channels a significant signal:


Phys. Lett. B 716 (2012) 30

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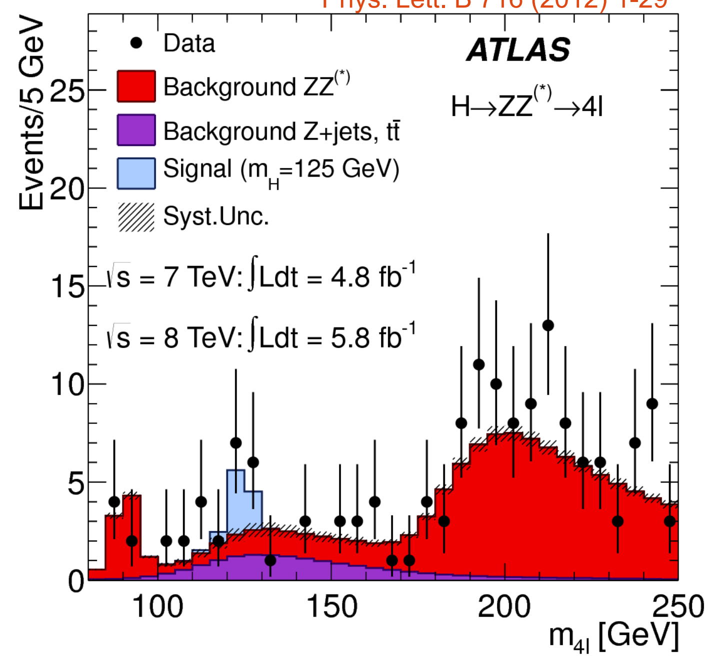
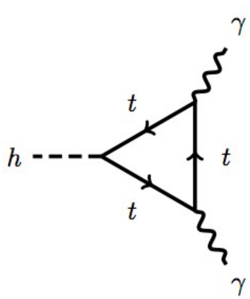
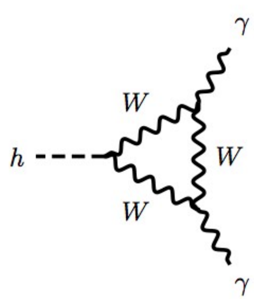
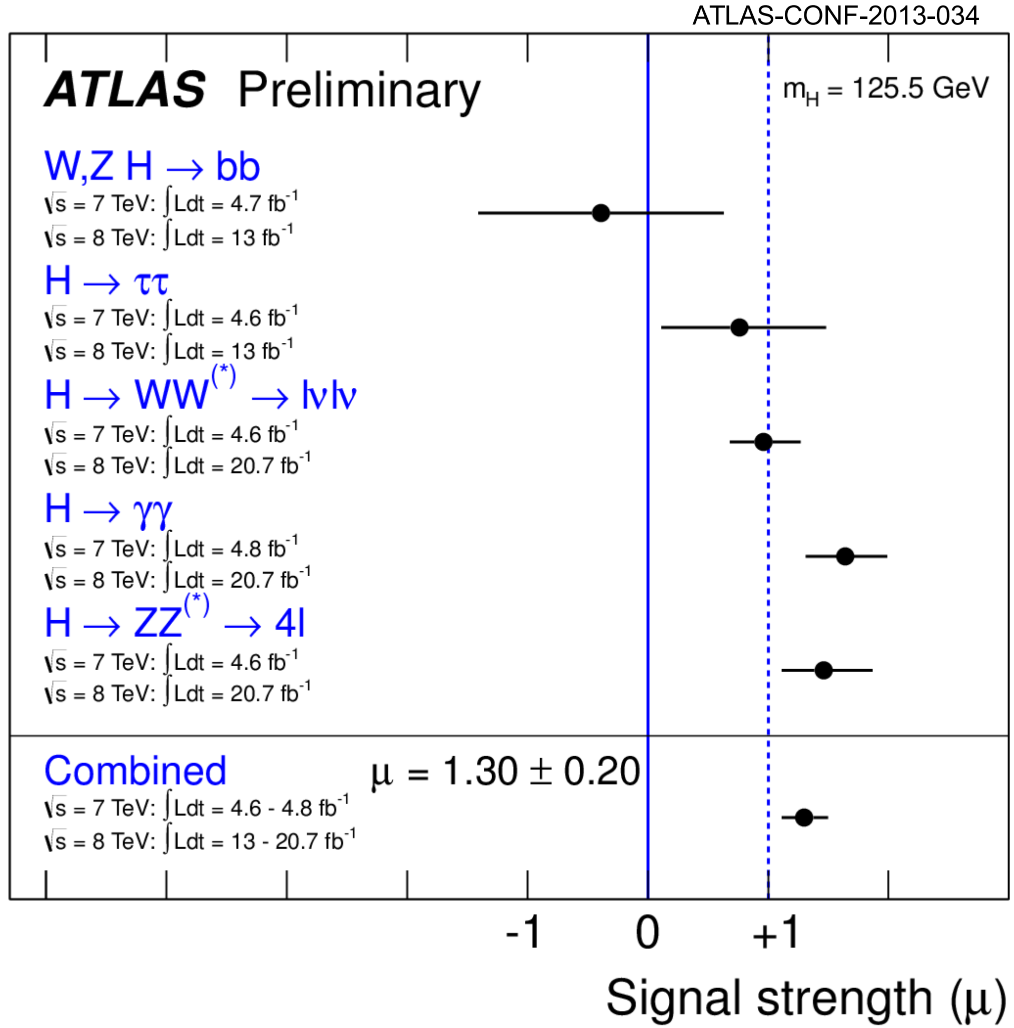


# What do we know (I)?

- **Mass:** 125.5 ± 0.6 GeV
- **Spin:** 0+ (2+ excluded by 99.9% CL)
- **Couplings to bosons:**
  - $\mu=\sigma_{measured}/\sigma_{SM}$
- **Only one fermionic coupling:**
  - New: $\tau\tau$ (4$\sigma$ evidence)
  - Strong evidence (3$\sigma$) for $b\bar{b}$ at Tevatron and CMS
  - $\lambda_{tH}$: indirect access via $H \rightarrow \gamma\gamma$




$\mu=\sigma_{measured}/\sigma_{SM}$

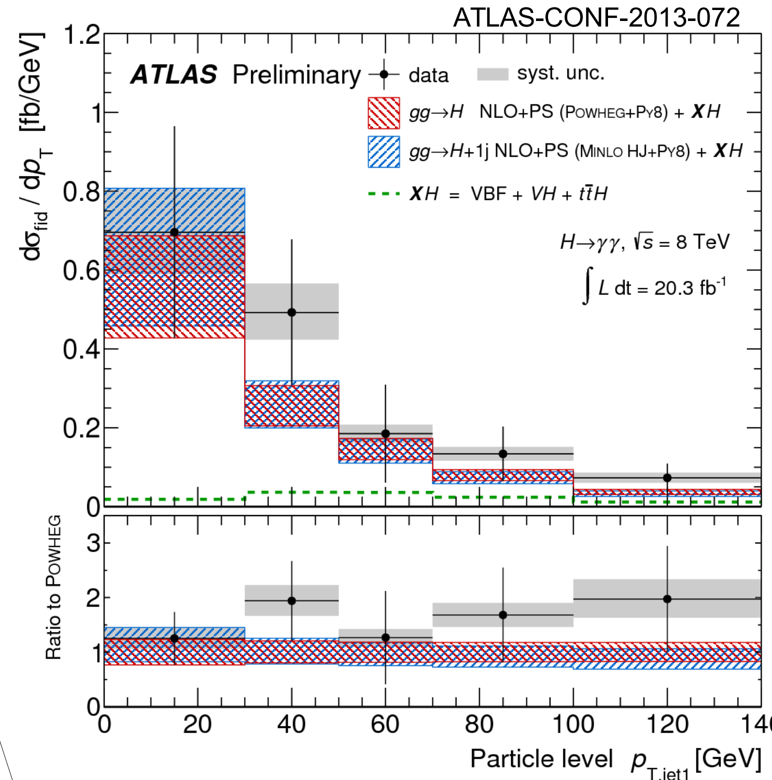
# What do we know (II)?

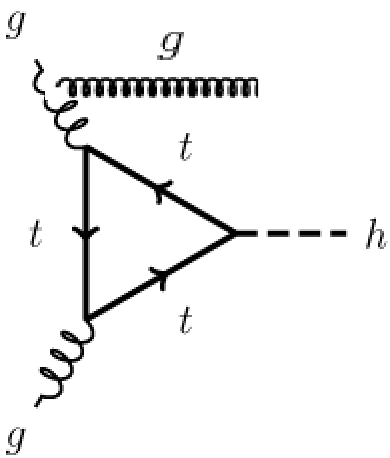
- Differential Higgs measurements:
  - First measurement of Higgs in QCD environment:

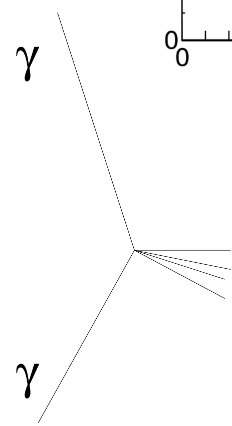
    H + jet→ γγ + jet

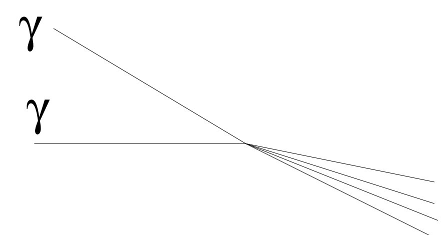
  - $p_T$ of the leading jet:

    Important for signal acceptance corrections → ingredient for high precision measurements



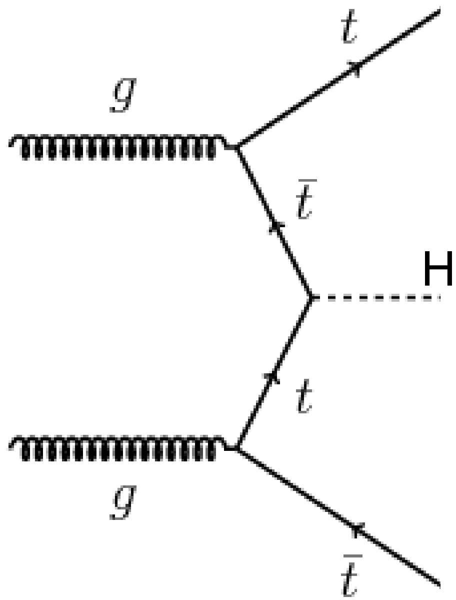



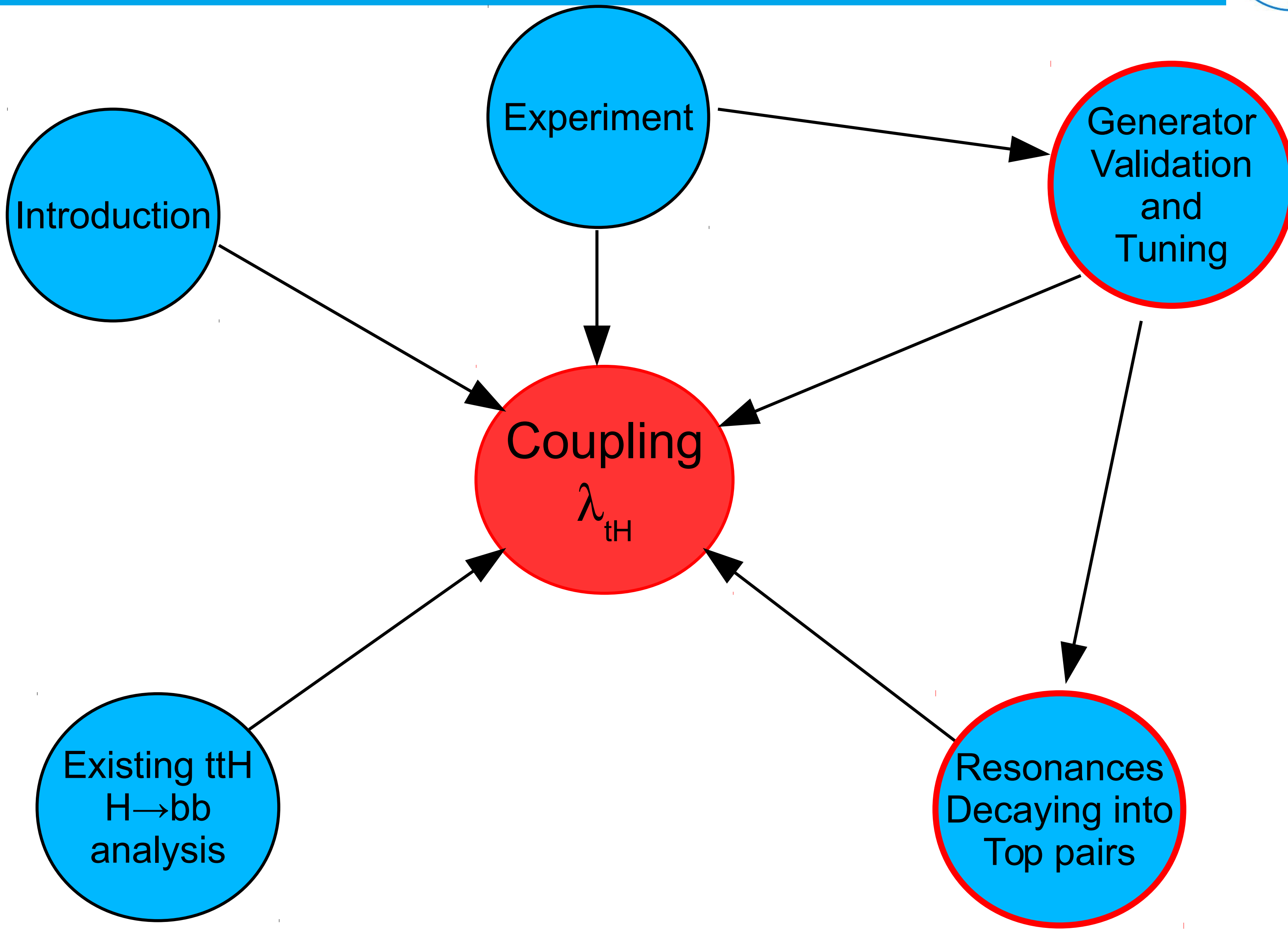

Low $p_T$ jet High $p_T$ jet

# What is not known?

- Only one fermionic coupling directly measured:
  $H \rightarrow \tau\tau$ (~ 4 $\sigma$)
  $\rightarrow \lambda_{bH}$ and $\lambda_{tH}$ missing to get a complete picture
- $\lambda_{tH}$ only huge coupling close to 1
  - Why is the difference in couplings that big?
  - Biggest sensitivity for new physics
- In SUSY expect different couplings than SM:
  - $b\bar{b}$ and $\tau\tau$ production bigger at high $\tan\beta$
- $H \rightarrow t\bar{t}$ is not possible because $m_H < 2\, m_{top}$
  - Measurement of $\lambda_{tH}$ in production via radiation from a top pair

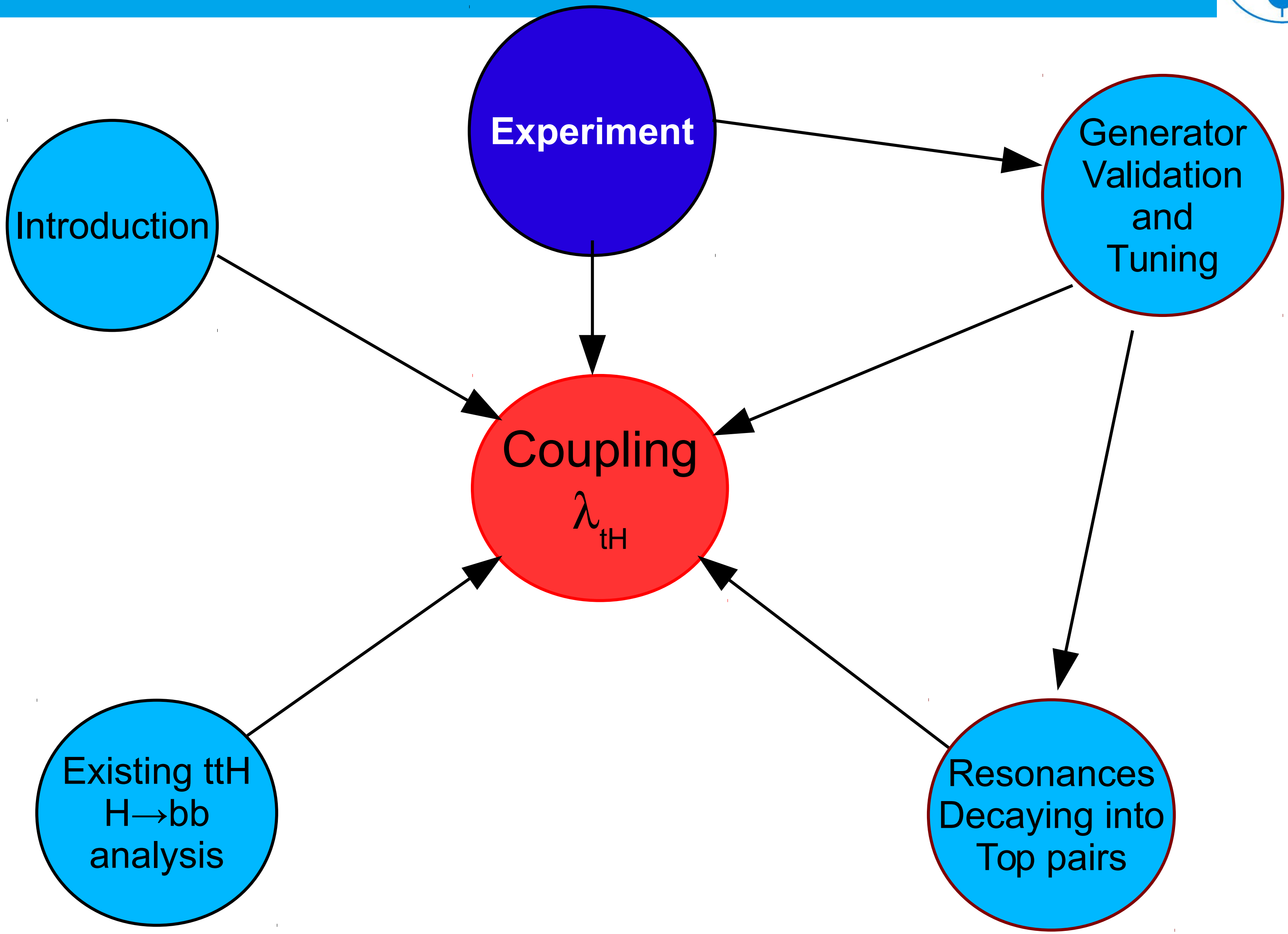


# Content



Experiment
Introduction
Generator Validation and Tuning
Coupling $\lambda_{tH}$
Existing ttH H→bb analysis
Resonances Decaying into Top pairs

# Content

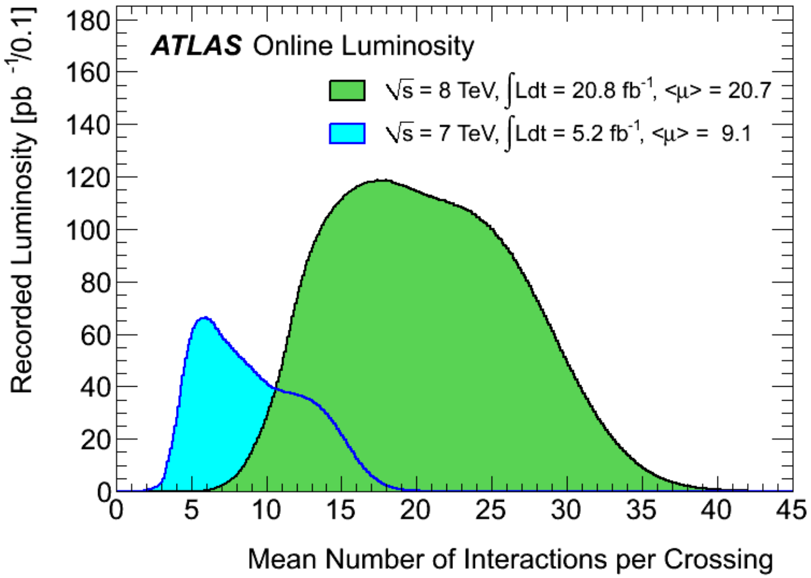

Experiment
Introduction
Generator Validation and Tuning
Coupling $\lambda_{tH}$
Existing ttH H→bb analysis
Resonances Decaying into Top pairs

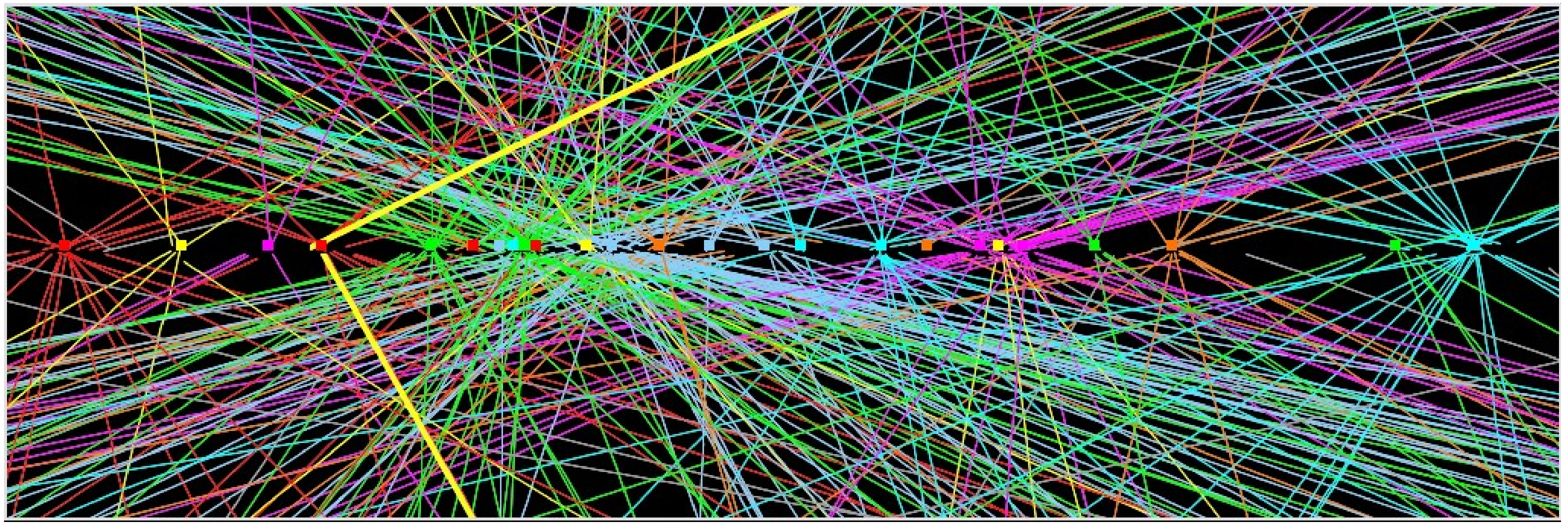
# Large Hadron Collider


- Proton-Proton Collider
- Center of mass Energy:
  - 2010-12: 7/8 TeV (achieved)
  - 2014+: 13/14 TeV (design)
- Instantaneous Luminosity:
  - $7 \cdot 10^{33}$ $fb^{-1}/s$ (achieved)
  - $2 \cdot 10^{34}$ $fb^{-1}/s$ (planned, 2015-17)
- Integrated Luminosities:
  - 2011 (7 TeV) : 5$fb^{-1}$
  - 2012 (8 TeV) : 20 $fb^{-1}$
  - 2015-17 : 100 $fb^{-1}$
  - ~2019-22 : 350 $fb^{-1}$
  - ~2024+ : 2500 $fb^{-1}$

# Pile up

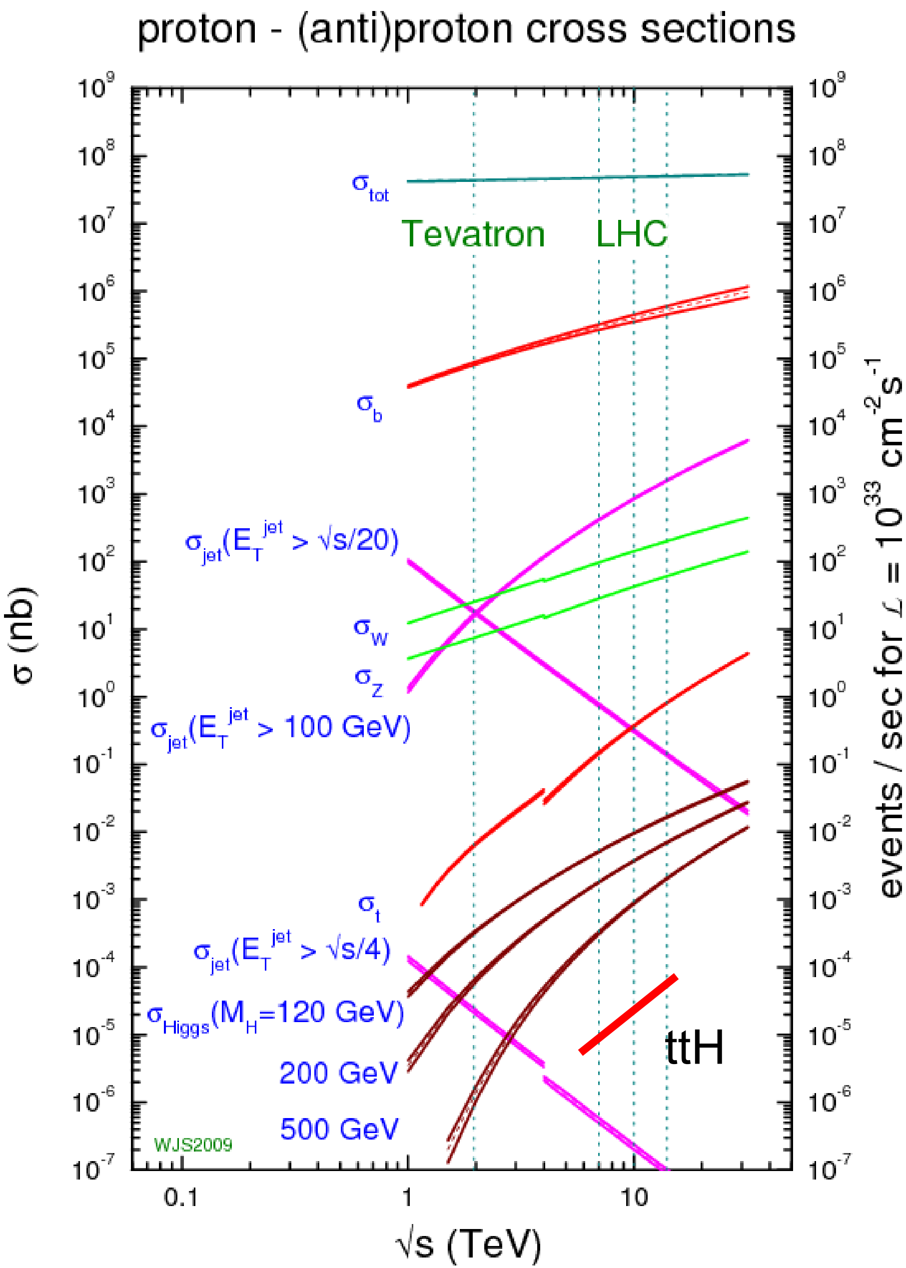
- $\sigma_{tot}$ = 100mb → Many Overlapping events in one bunch crossing
- Number of Pile up events:
  - 2011: up to 20 (average ~9)
  - 2012: up to 40 (average ~20)
  - 2015-17: average ~40 events



Z → μμ event with 25 vertices

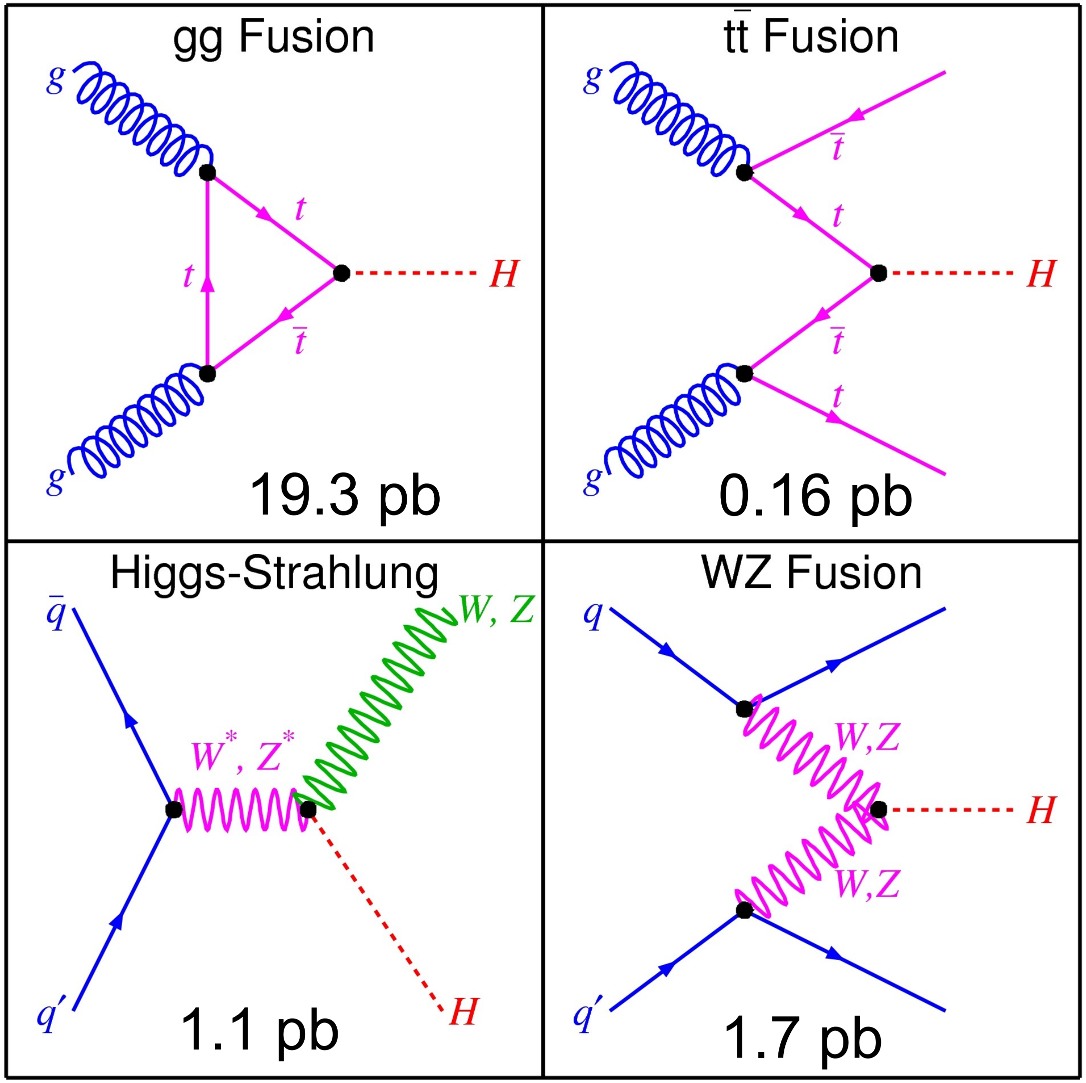
# Physics Processes at the LHC




- **Total cross section:** 100 mb
  - dominant QCD
- Other Standard Model processes $O(10^{6}\text{-}10^{9})$ smaller
- Higgs production: $O(10^{11}\text{-}10^{13})$ smaller
- $t\bar{t}H$ profit by increasing energy from 8 TeV to 14 TeV most:
  - W/Z → factor 2
  - Top → factor 3.8
  - ggH → factor 2.5
  - $t\bar{t}H$ → factor 4.5

# Higgs production at the LHC

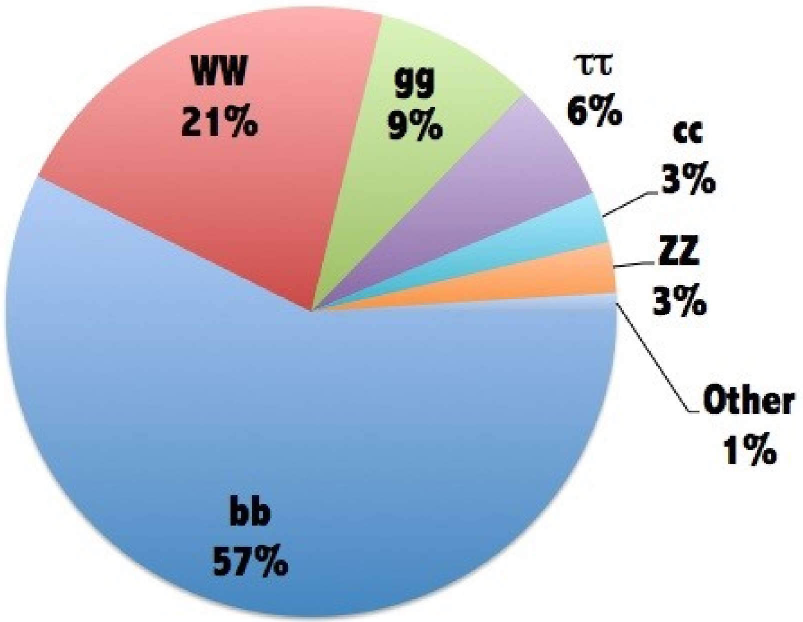
- Dominant: gg → H
- t$\bar{t}$H (t$\bar{t}$ fusion) is rare
  → factor 100 less than gg → H



# Higgs decay

- Pie chart of Higgs decays:
  - $H \rightarrow \gamma\gamma$: 0.2%

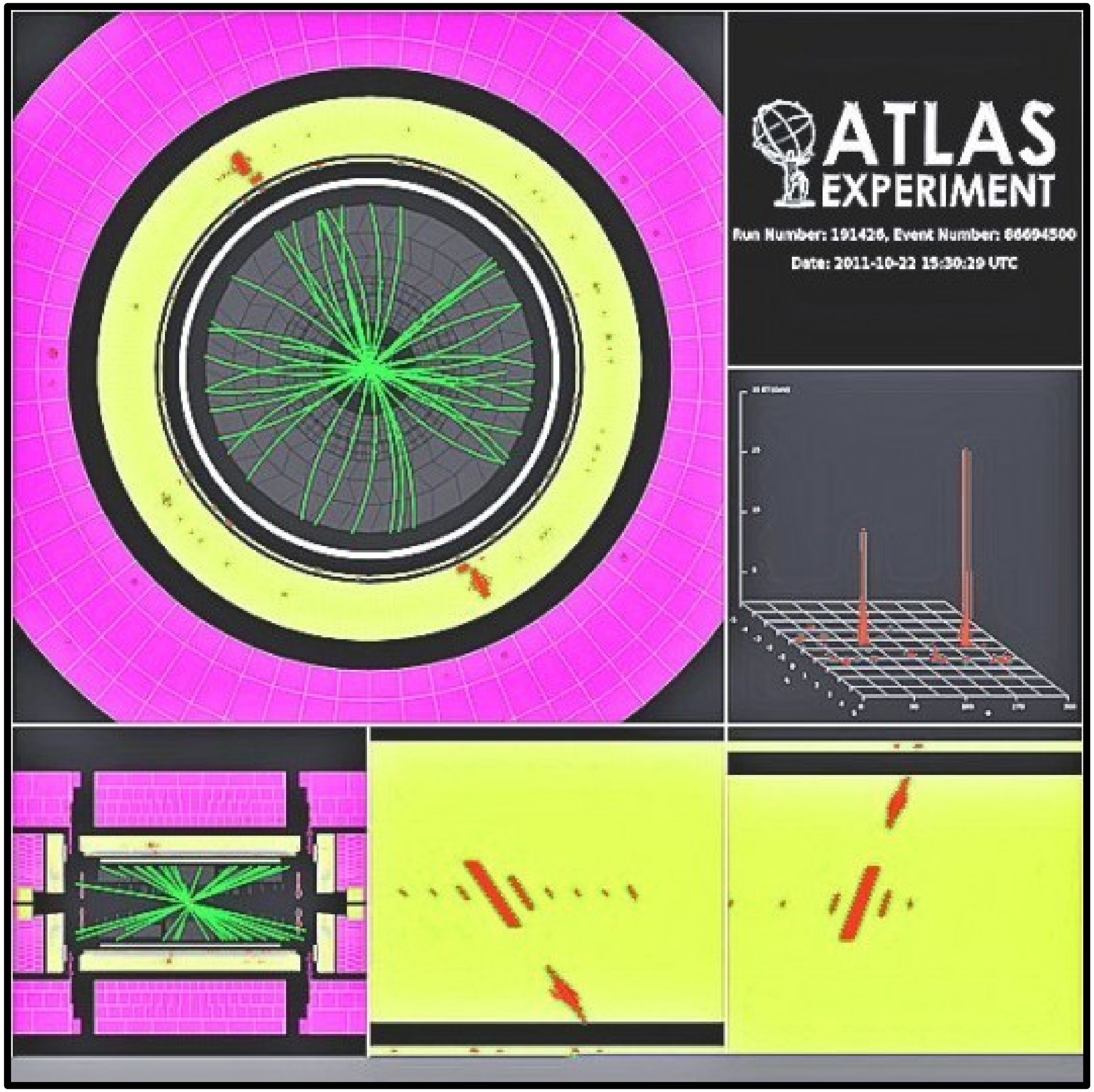
Higgs decays at $m_H$=125GeV




- Discovery channels are rare but easy to access with ATLAS detector:
  - Two photons
  - Four leptons
- Dominant process $b\bar{b}$ is difficult:
  - Huge background → Identification of b-Hadrons from b-quark hadronisation
- Z,W, τ decay further:
  - $Z \rightarrow ee$ or $\mu\mu$ : 6%
  - $W \rightarrow e\nu$ or $\mu\nu$ : 22%
  - $\tau \rightarrow e\nu\nu$ or $\mu\nu\nu$ : 36%

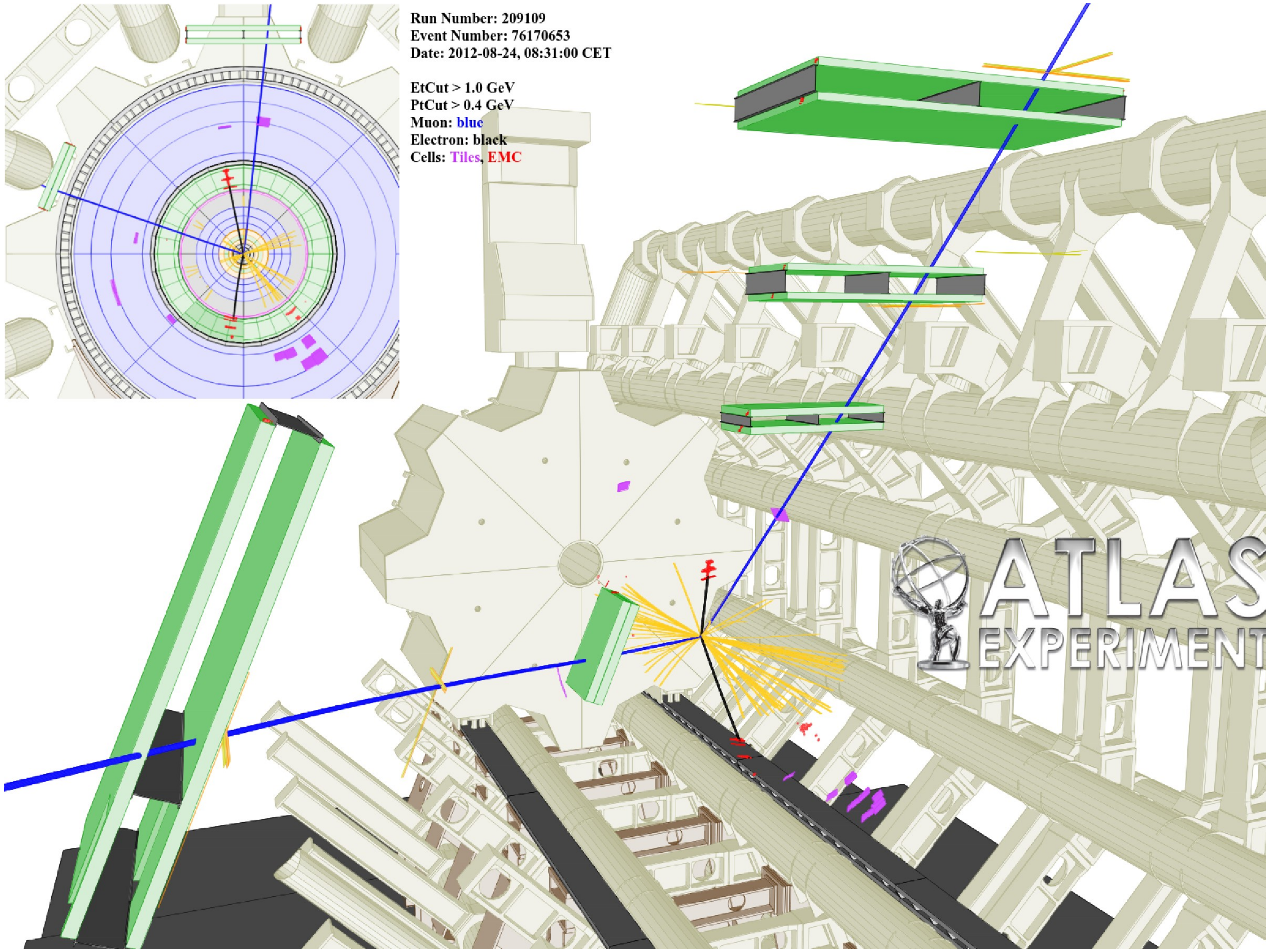
# Event display: Photons in H $\rightarrow \gamma\gamma$

- Signature:
  - Two isolated clusters in electromagnetic calorimeter
  - Calorimeter $|\eta|$ ~4.7



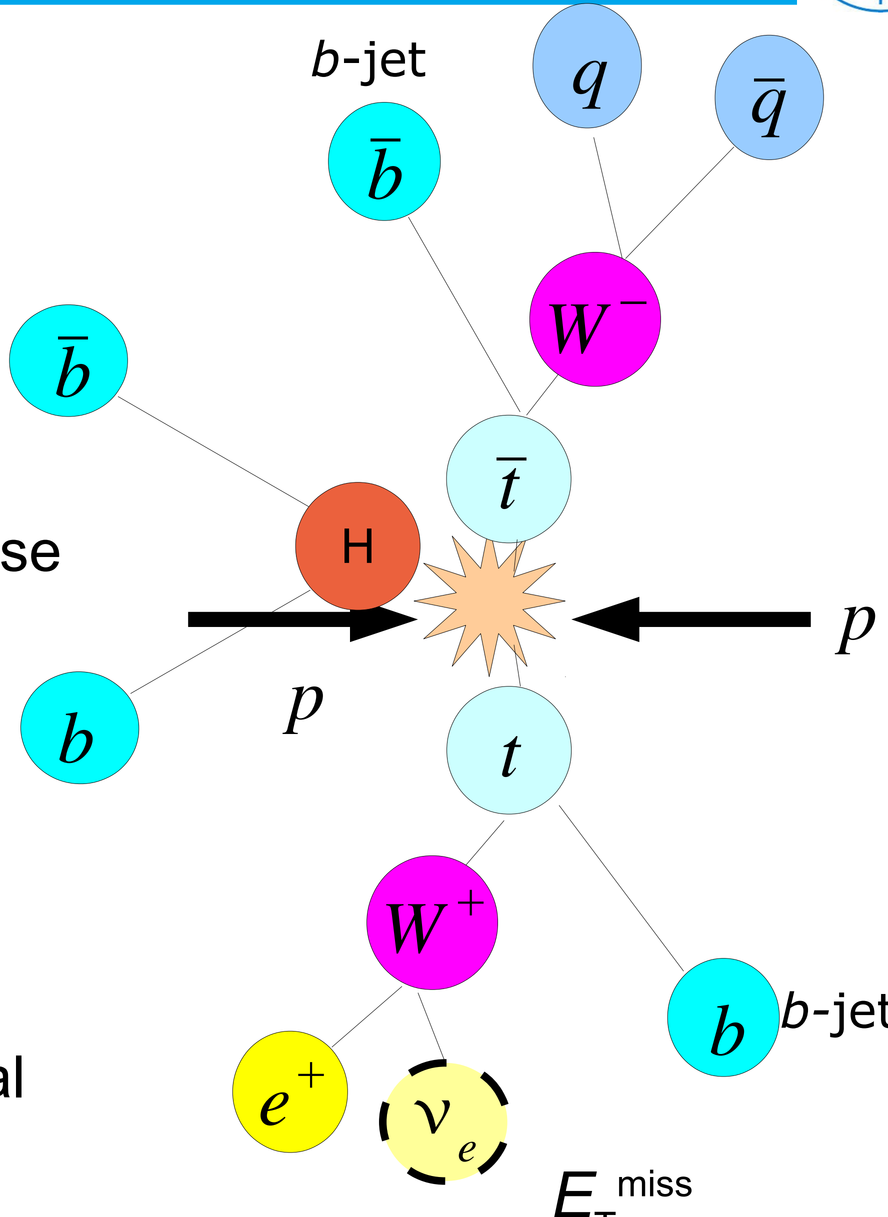
# Event display: Leptons in H → ZZ* → 4 leptons

- **Signature:**
  Four isolated leptons in the detector:
  - 2 electrons
  - 2 muons
- Large lepton acceptance up to $|\eta| \sim 2.5$



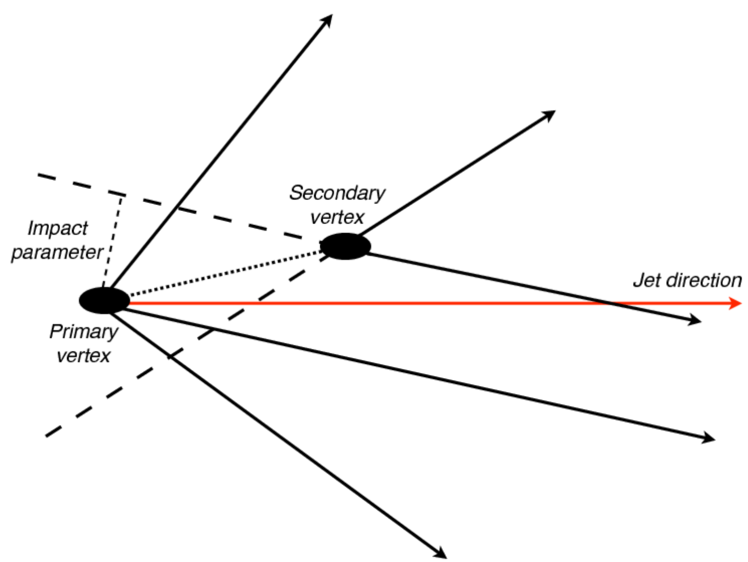
# $t\bar{t}H$: Signature

- **Signal Signature:**
  - 6 jets ($p_T$>25 GeV)
  - 4 b-tagged jets
  - 1 lepton ($p_T$>25 GeV)
  - $E_t^{miss}$ (Energy imbalance because off not measured neutrino)
- **Requirements:**
  - Good lepton identification
  - Good jet resolution
  - Heavy flavour identification
  - Complex final state: good generator simulation of the final state



# ATLAS Detector: Heavy flavor identification

- B-Hadrons have significant life time and high mass:
  - Decay vertex a few mm away from primary vertex
- B-identification combines information in neural network:
  - separate vertex, flight length, vertex mass
  - tracks with impact parameter

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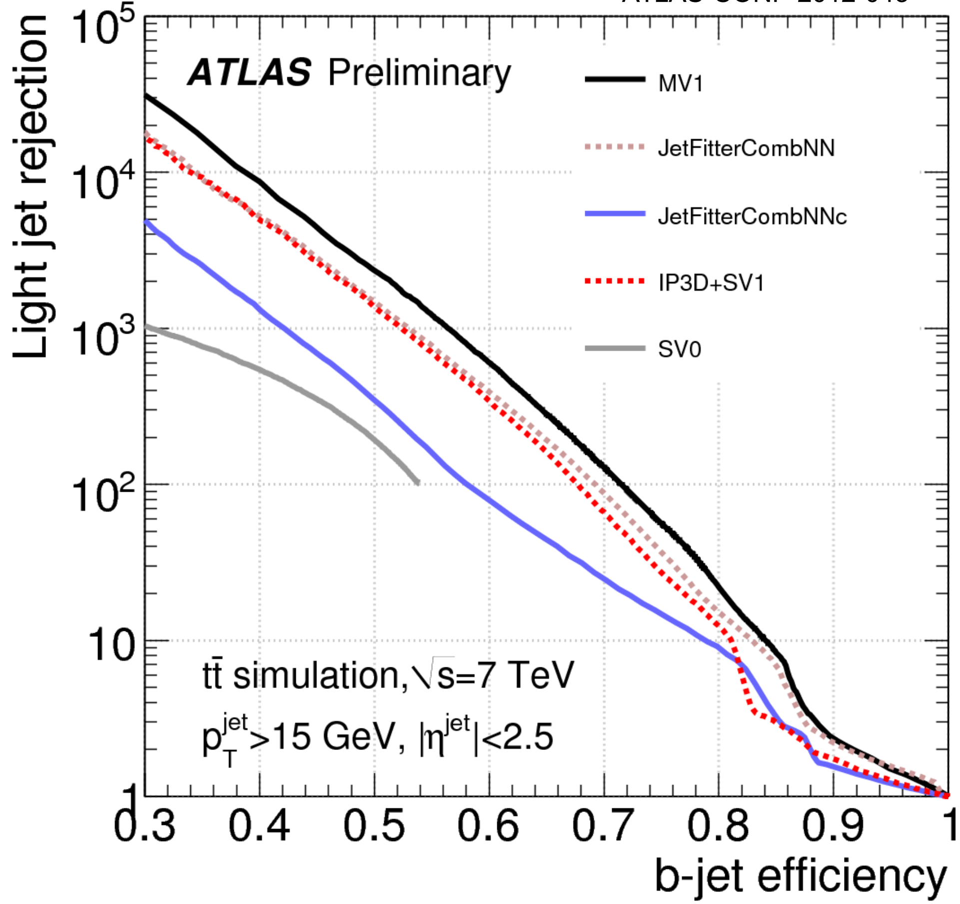
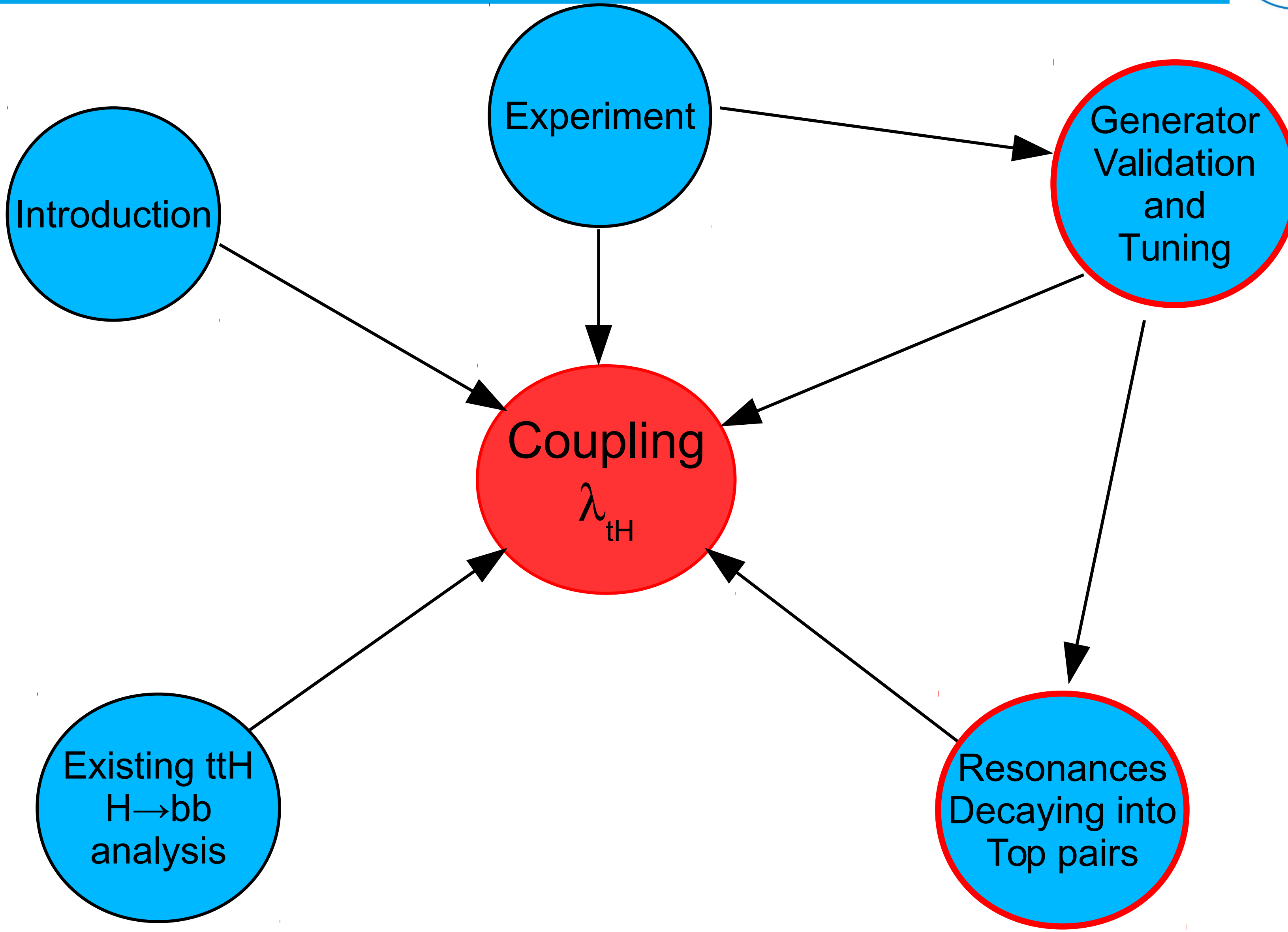
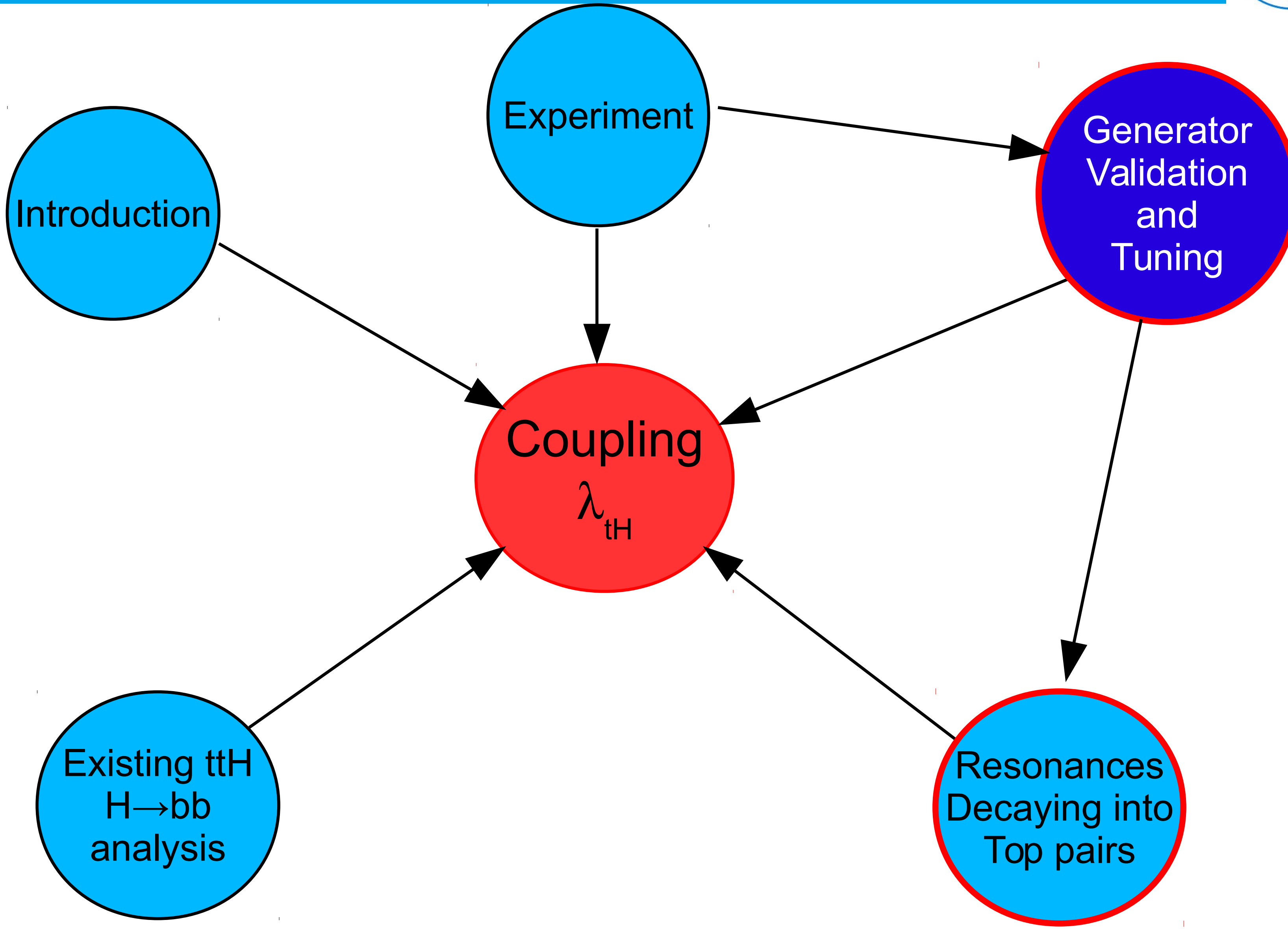



2014+: Additional innermost pixel layer → light flavor suppression improves by 50%

# Content


Experiment
Introduction
Generator Validation and Tuning
Coupling
$\lambda_{tH}$
Existing ttH H→bb analysis
Resonances Decaying into Top pairs

# Content



Experiment
Introduction
Generator Validation and Tuning
Coupling $\lambda_{tH}$
Existing ttH H→bb analysis
Resonances Decaying into Top pairs

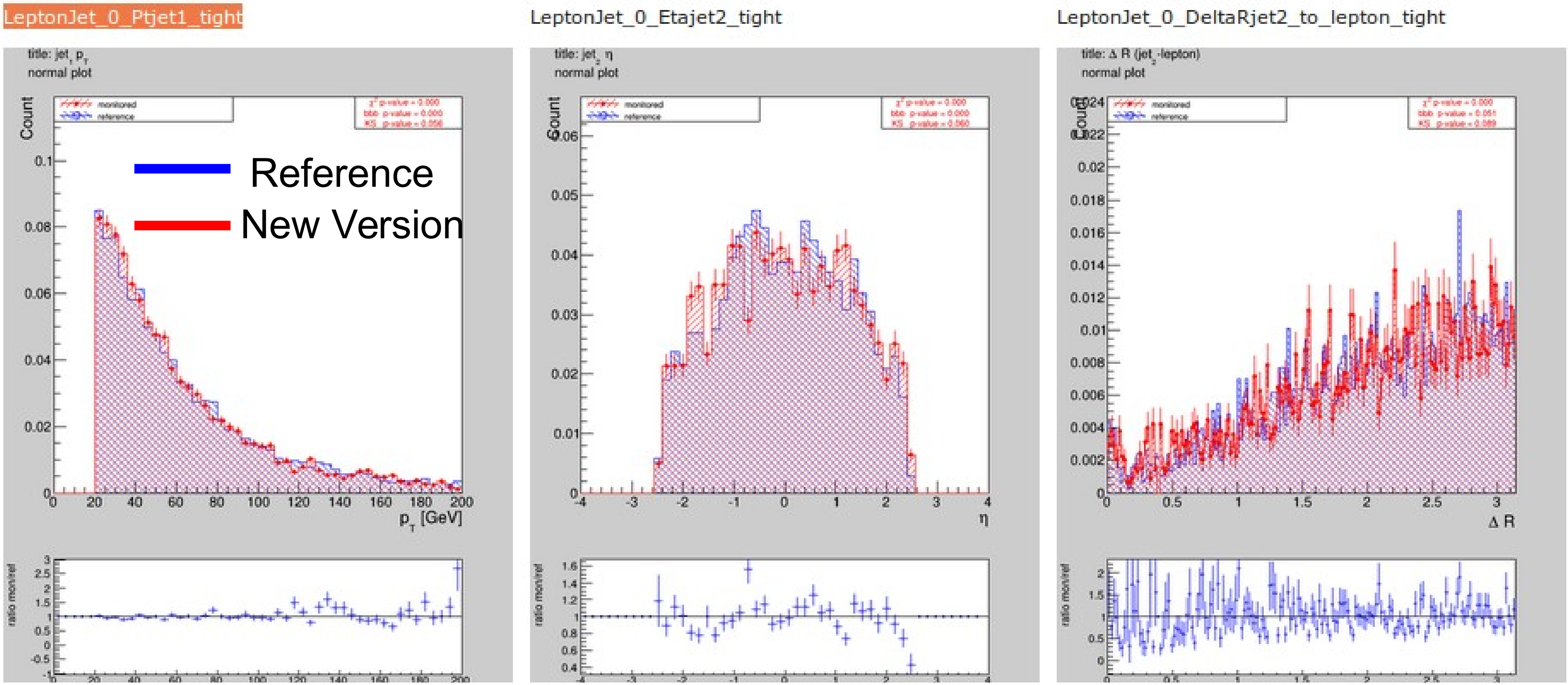
# Generator group in ATLAS

- Atlas Simulation chain:
  - Generator → Detector Simulation → Digitization → Reconstruction
- Implements new generators and infrastructure in the ATLAS software
  - ~ 50 generators (Matrix Element+shower combination)
  - Automatization and validation for generators
- Use ATLAS measurements to improve performance of generators:
  - Soft QCD tuning (→ air shower generators (EPOS))
  - New: Created three task forces for hard processes:
    W/Z+jet, Top, Heavy flavour handling
- Samples definition of commonly used samples in ATLAS
- Smallest ATLAS physics group:
  - ~ 30 generator experts; software, production, validation managers
  - ~ 12 authorship qualifiers supervised by conveners or experts

# Automatization and validation of Generators

- $t\bar{t}H$: Complex analysis → depend heavily on Monte Carlo simulation
  - Huge background reduction → huge simulation samples: 1-2 billion events for typical analysis
  - 7/8 TeV MC sample: each 5-7 billion events in total
- Move generator event production into the Monte Carlo production system (“on-the-fly”):
  - Automatic running after set up
  - Automatic validation (e.g. new generator version)
  - Monte Carlo validation manager

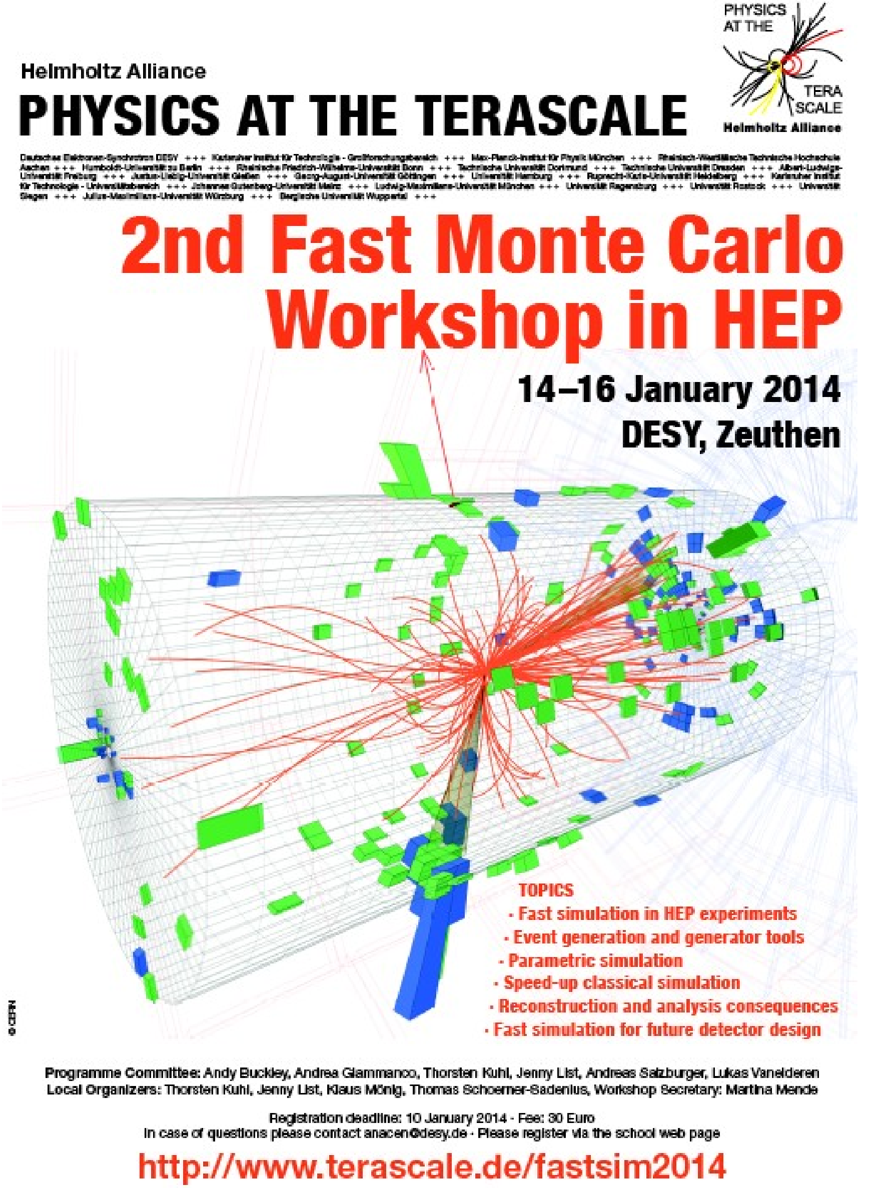
# Generator validation web page



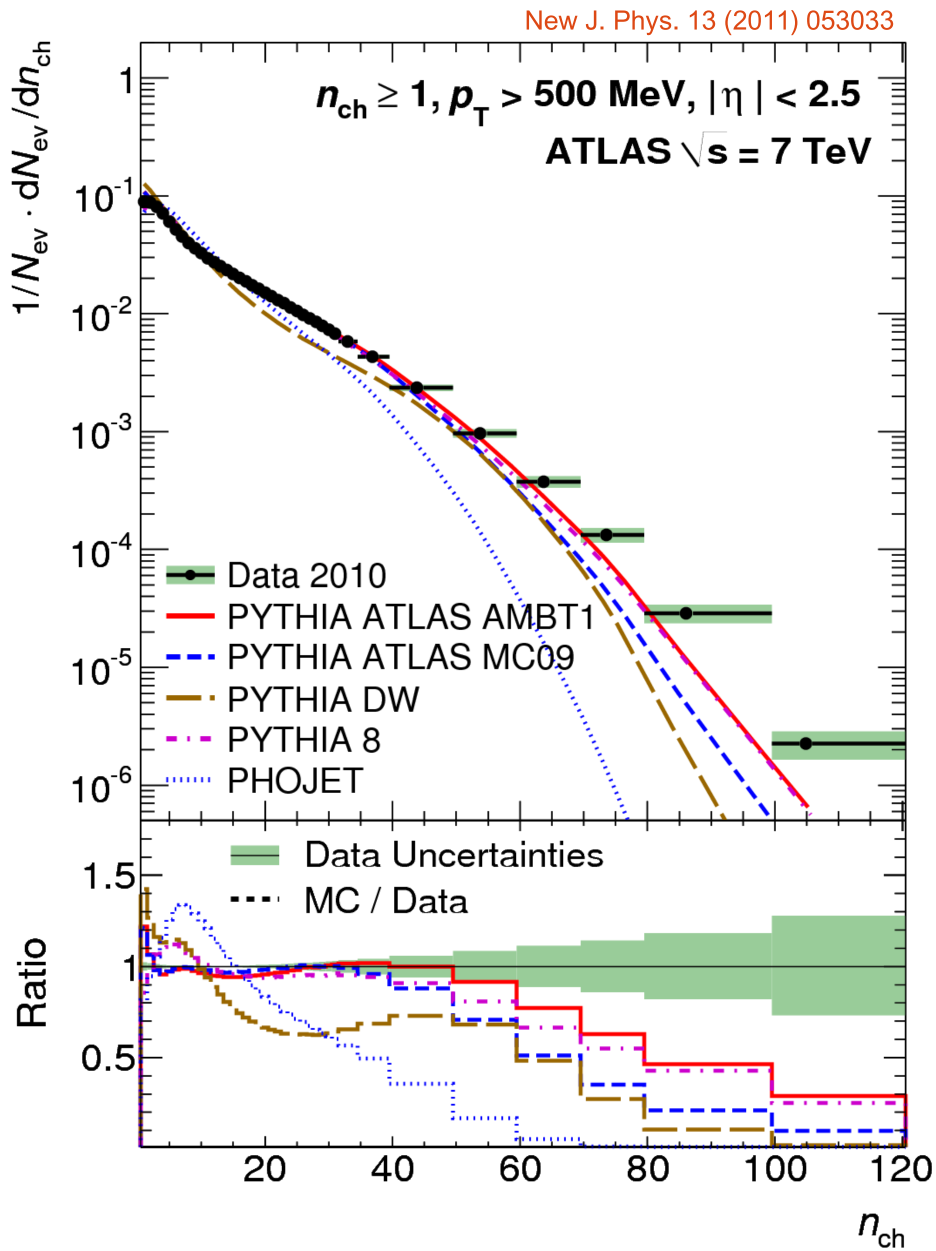

- Validation of new generator version:
  - compare ~12 representative processes with reference
  - Every time ~ 300 histograms filled (ME, jets, leptons, b-hadrons)
- Automatic detection of problematic distributions by statistical test: worse get displayed

# Fast Monte Carlo Workshop

- Geant 4 simulated event in ATLAS needs ~8 minutes
- More data → need Fast Simulation and Reconstruction:
  - Simplification
  - Parametrisation
- Second time workshop in Zeuthen
- Participants:
  - Atlas
  - CMS
  - Belle II
  - Alice
  - ILC
  - Theory



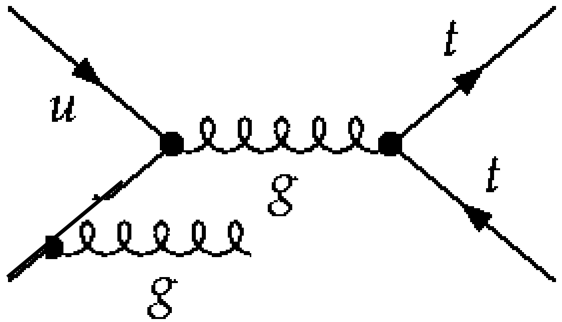
# Improving Monte Carlo: Pile up description




- Pile up disturbed energy resolution of detector
- "Minimum bias selection": single pile up events in detector
  - Counting tracks in detector
  - Used for tune pile up
- Comparison shows improvement including more and more data:
  - Pythia6 DW (red dashed) → AMBT1 (full red line)
  - Phojet: hard part missing
- Now using Pythia8 improved tunes

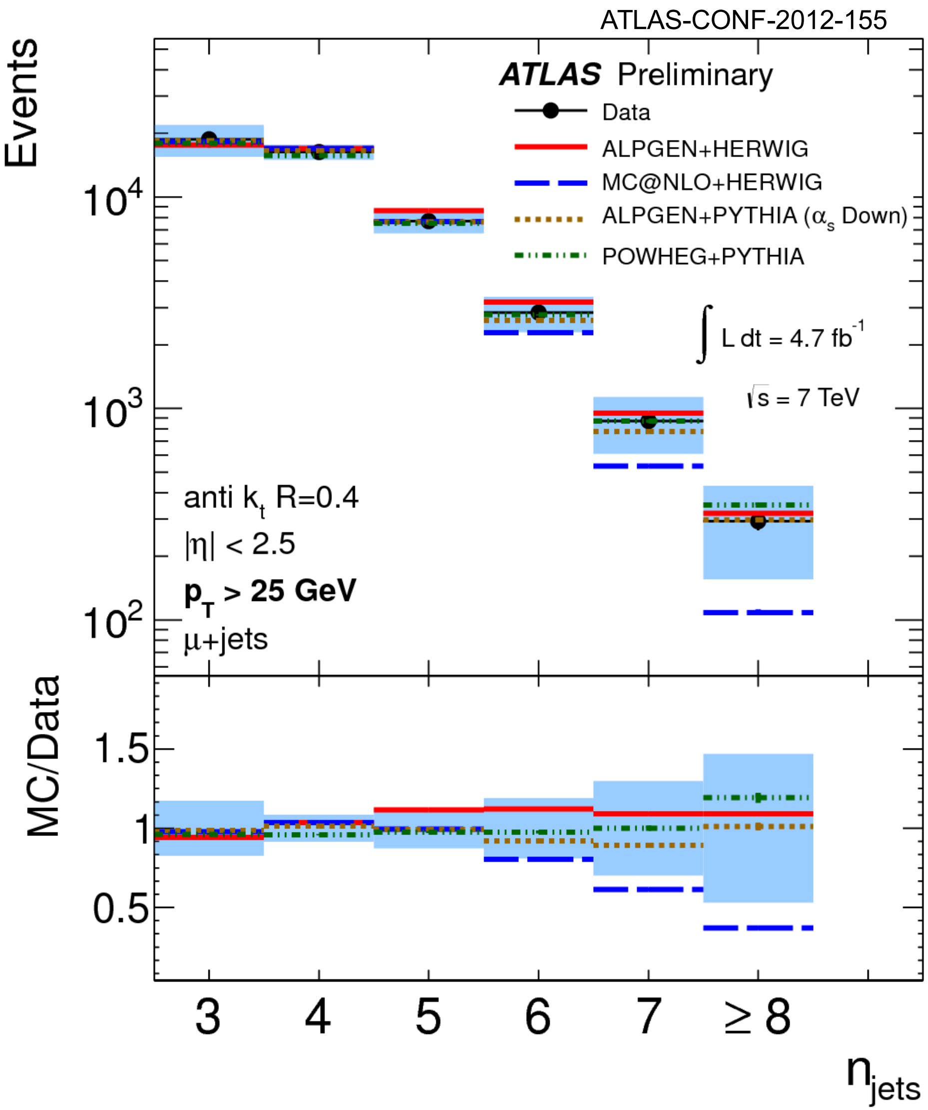
# Top pair modelling task force

- $t\bar{t}H$: needs good modelling of top pairs
- Measurement of jet distribution in top events
  - How many 4,5,6 jet events in top pairs?




- Use measurements like these to tune generators to data and constrain systematics

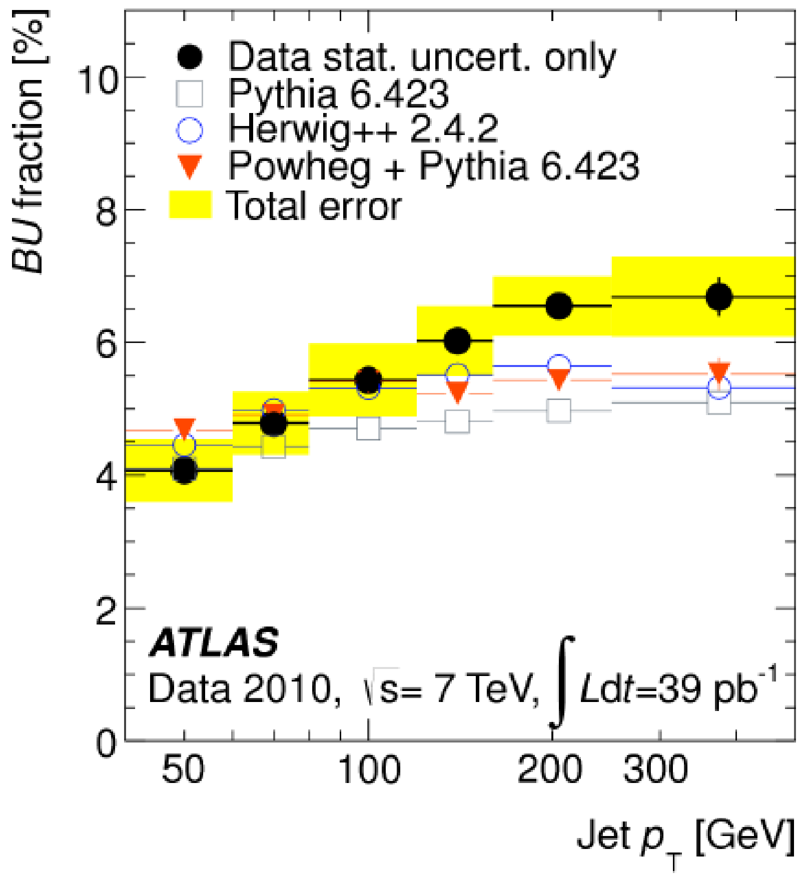
Blue band: measurement error



# Heavy flavor modeling task force

- Heavy flavour modelling is very important for searches in 2015-17
- Modelling Task force include:
  - Unifications of branching fractions, life time
  - Hard process
  - Heavy flavour production in shower
    - not well known
    - huge differences in generators
  - Heavy flavour matching: hard interaction (Matrix Element) versus soft interaction (shower)

Eur. Phys. J. C (2013) 73:2301



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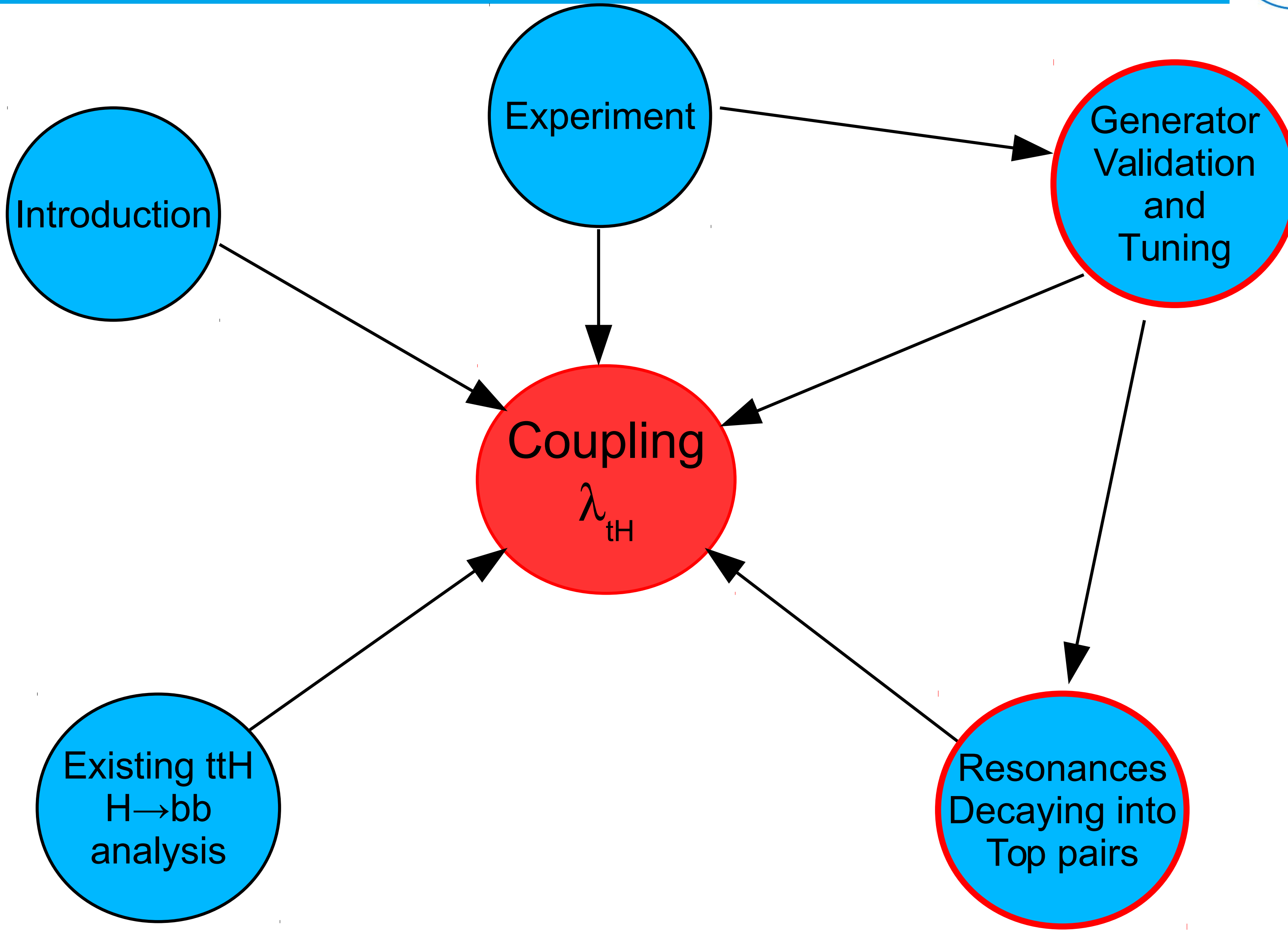
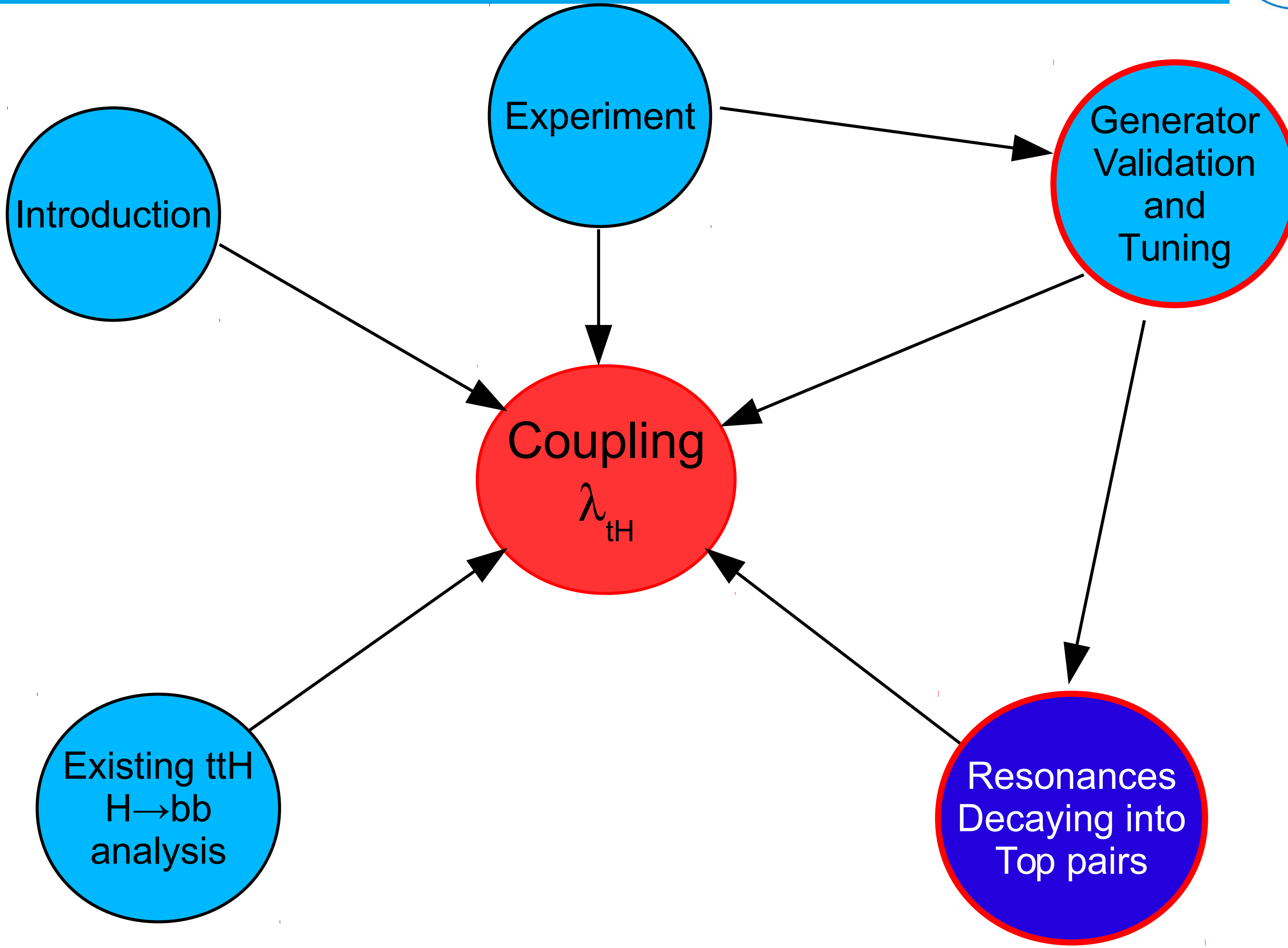

Experiment
Introduction
Generator Validation and Tuning
Coupling $\lambda_{tH}$
Existing ttH H→bb analysis
Resonances Decaying into Top pairs

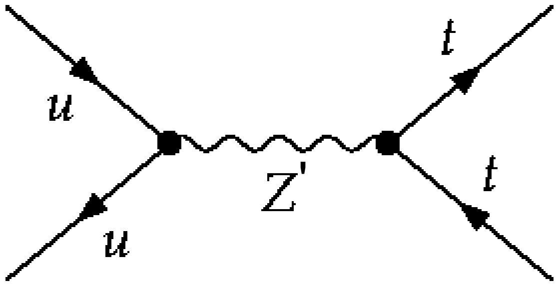
# Content



Experiment
Introduction
Generator Validation and Tuning
Coupling $\lambda_{tH}$
Existing ttH H→bb analysis
Resonances Decaying into Top pairs

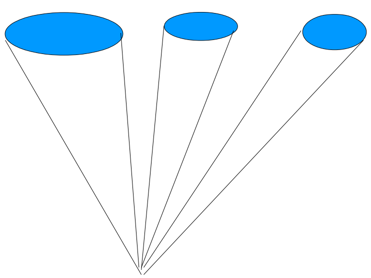
# Resonances decaying into top pairs

- Signature for new physics beyond SM (and SUSY)
  - Kaluza-Klein-Gluons in Randall-Sundrum-Model
  - Leptophobic Z' in Topcolor Models: Heavy Z-like particle which gives particles mass
  - Heavy neutral Higgs bosons in 2HDM
- Benchmark models accessible with O($fb^{-1}$) of data → nice signature to search for new physics in early running of LHC

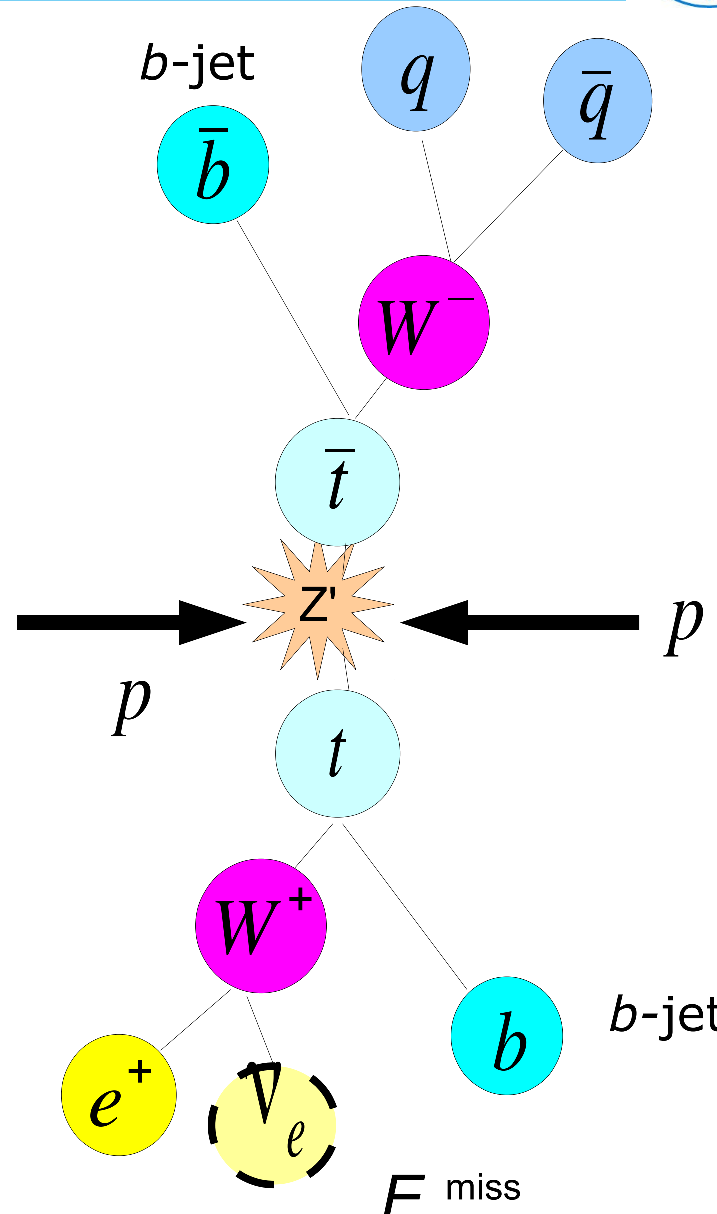


# Resonances decaying into top pairs

- Lower part:
  - 1 isolated lepton, 1 b-jet
    Missing transversal energy
- Upper part:

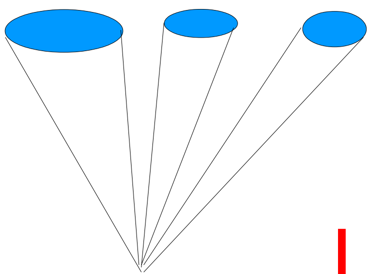


**Normal (resolved)**:
3 jets, $p_T$>25 GeV



> **Lower part:**
- 1 isolated lepton, 1 b-jet, Missing transversal energy

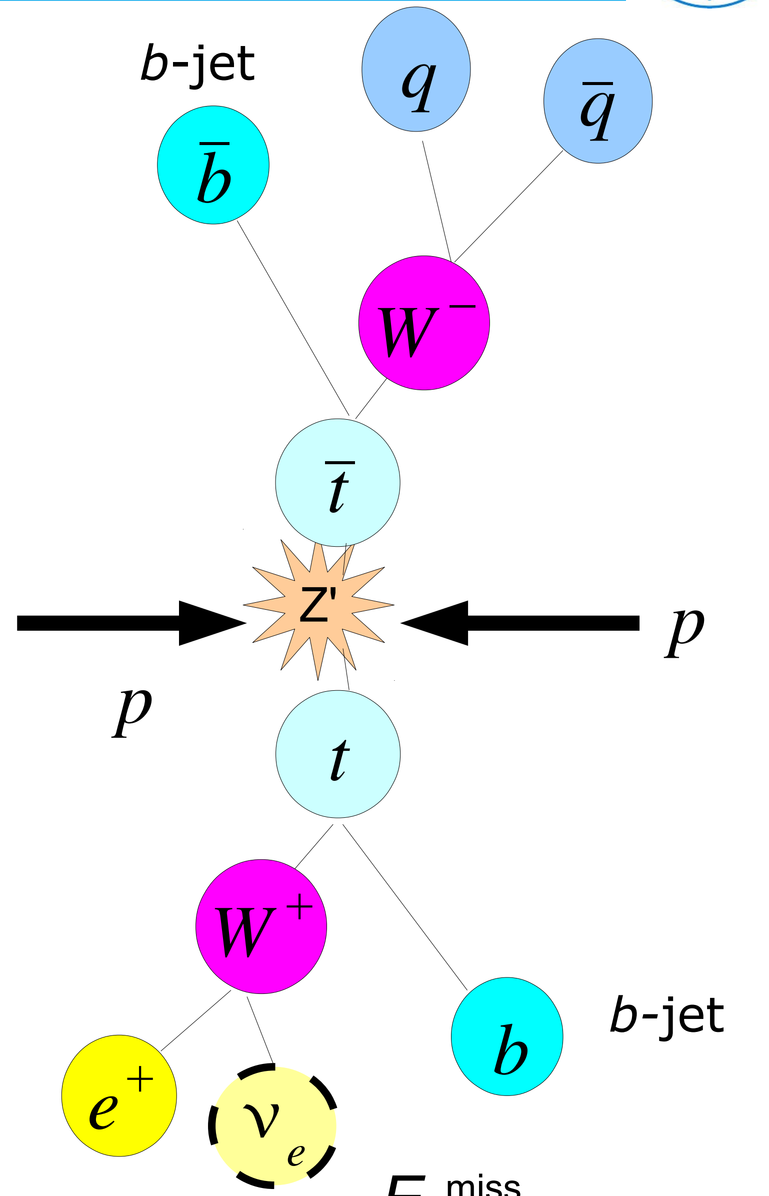
> **Upper part:**



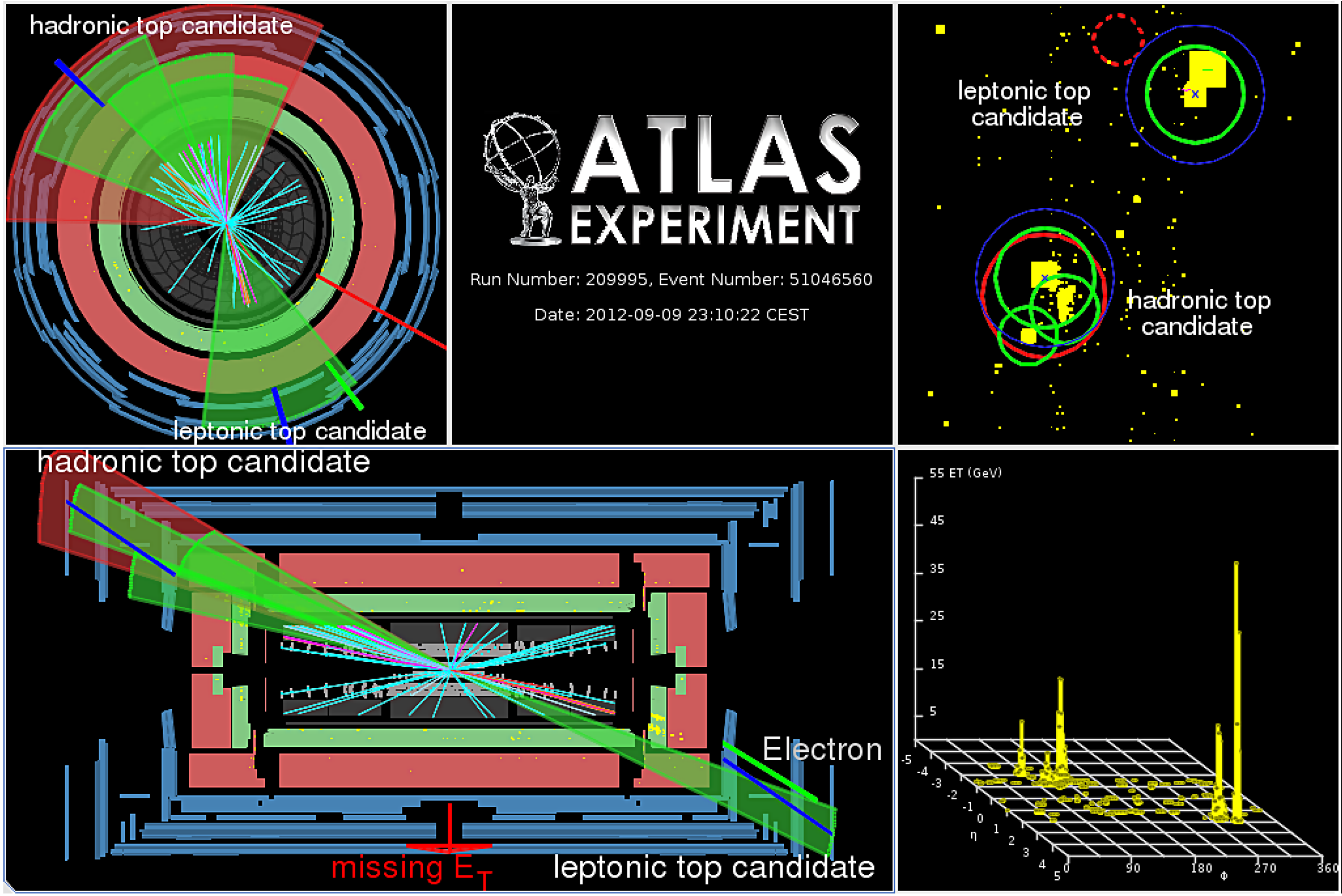
**Normal (resolved)**:
3 jets, $p_T$>25 GeV

Higher top energy
(bigger boost)

**Boosted**
Only one fat jet ($p_T$>250 GeV)
with high jet mass (m>100 GeV)
→ jet has substructure



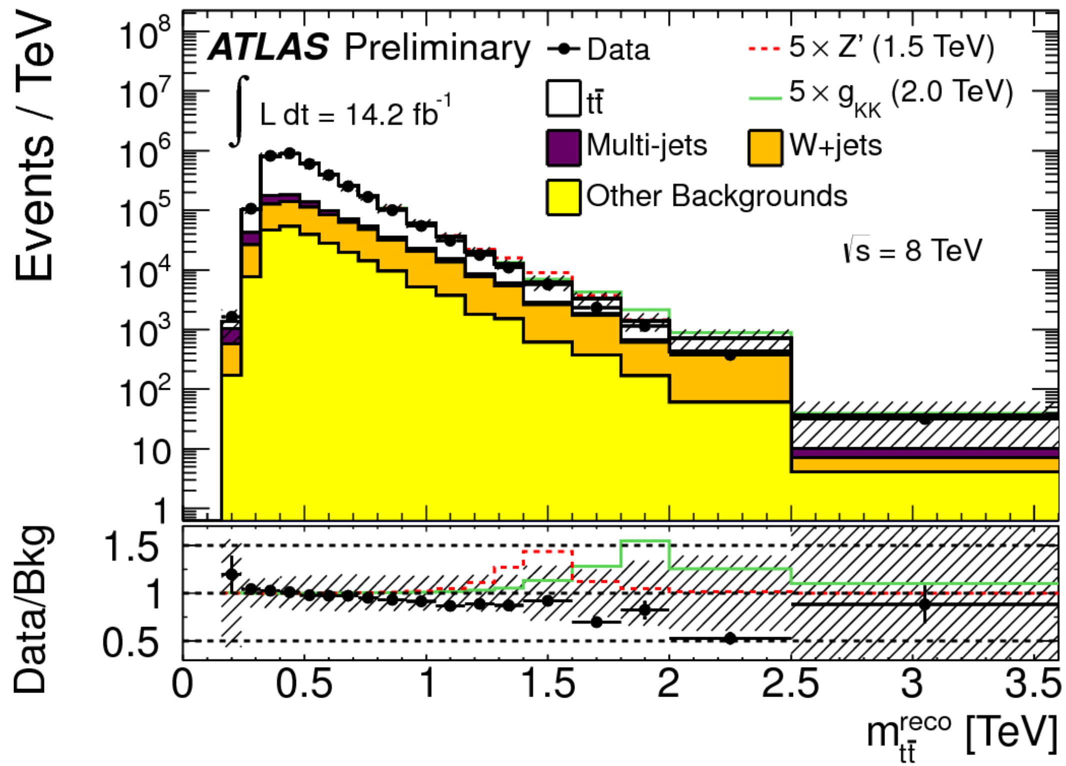
# Resonances decaying into top pairs



# Resonances into top pairs

- All data combined:
  - Resolved: 4 jets, lepton, neutrino (Missing $E_T$)
  - Boosted: fat-jet, b-jet, lepton, neutrino
    → Calculate invariant mass from all objects
- Huge systematic uncertainties (dashed area) and slope versus data
- No signal observed:

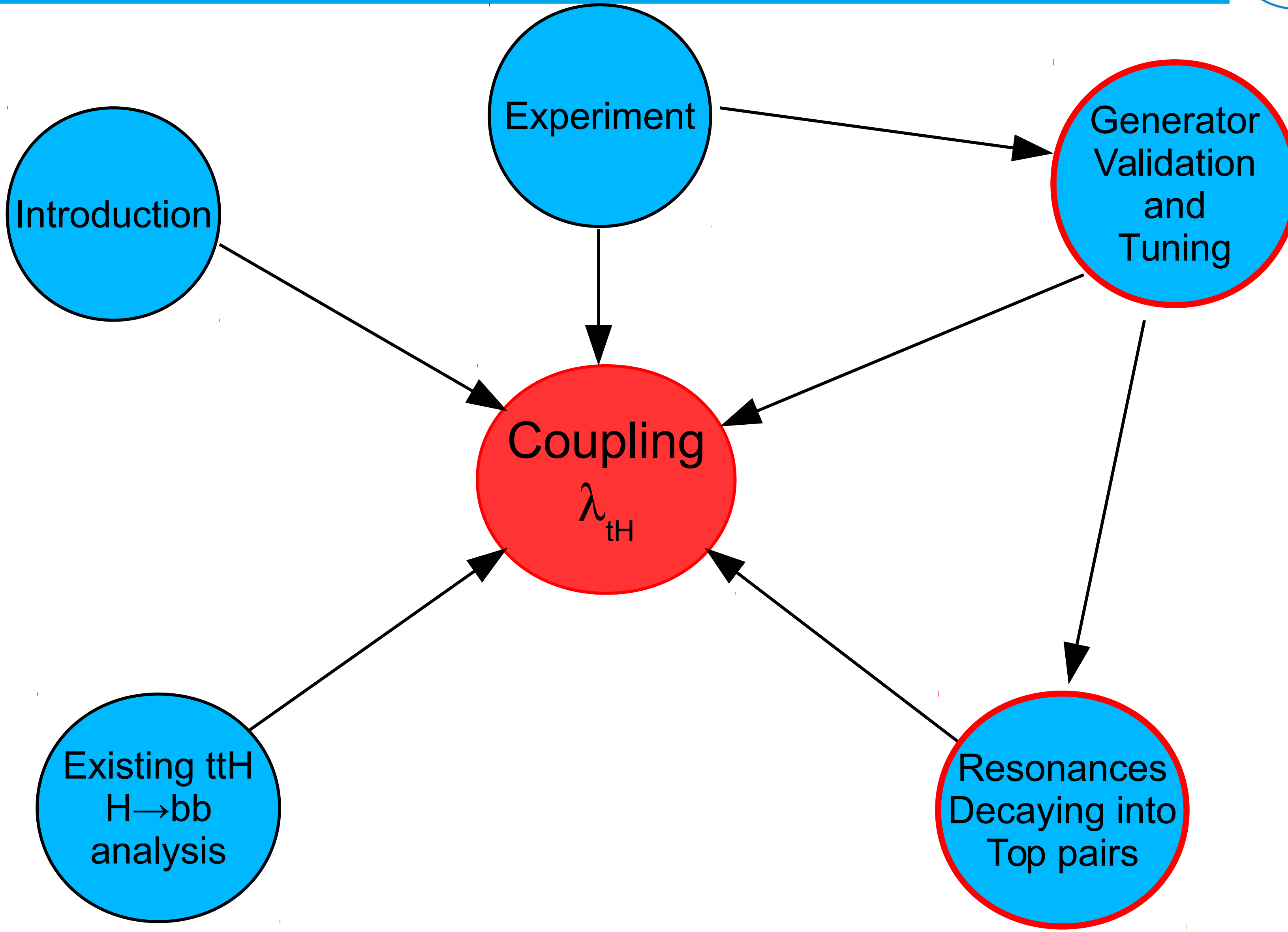
ATLAS-CONF-2013-052



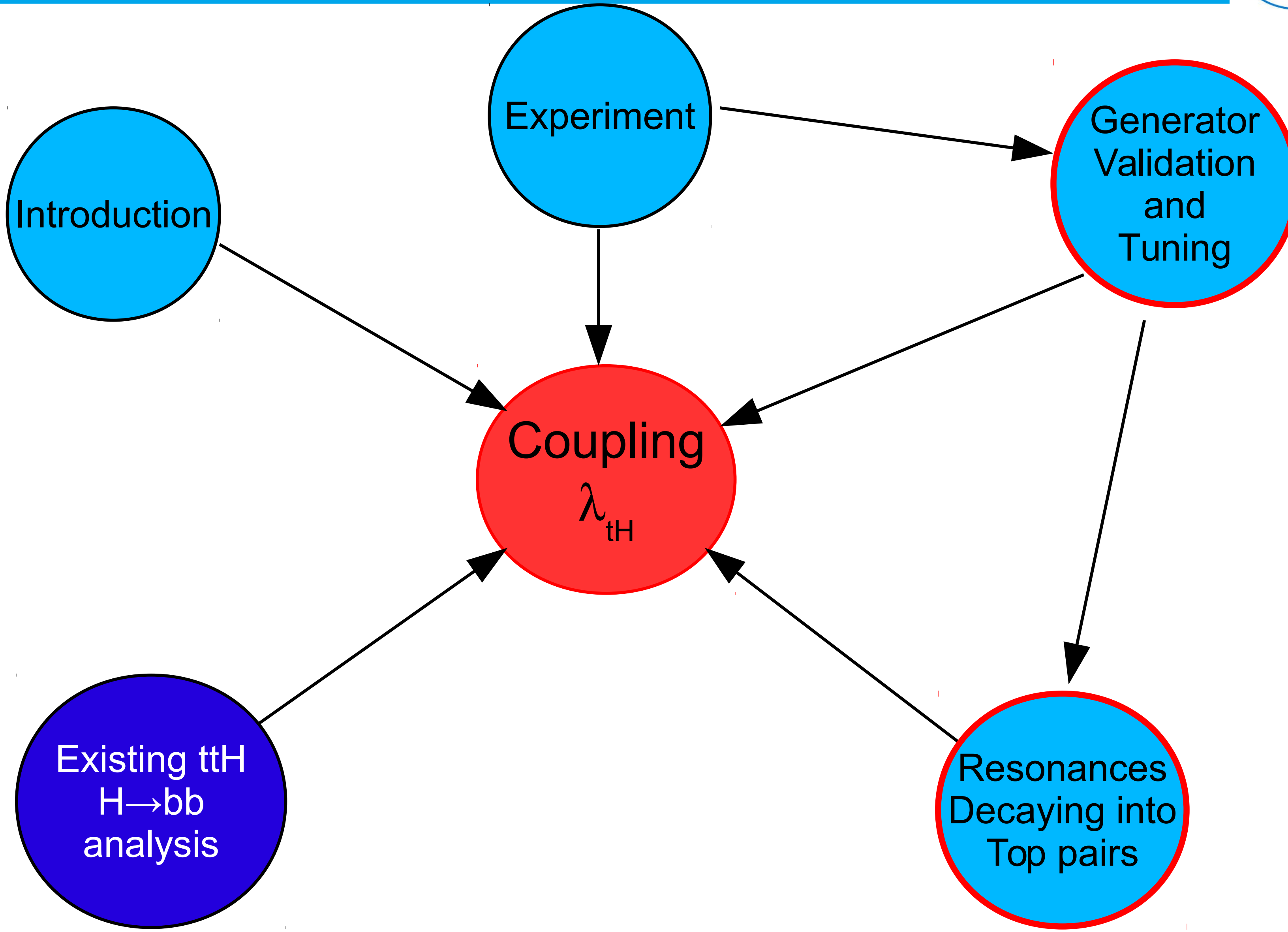

Exclusion Limits on the mass of new particles:

Z' (Leptophobic Topcolor) : M > 1.8 TeV
Kaluza-Klein-Gluons : M > 2.47 TeV

# Content

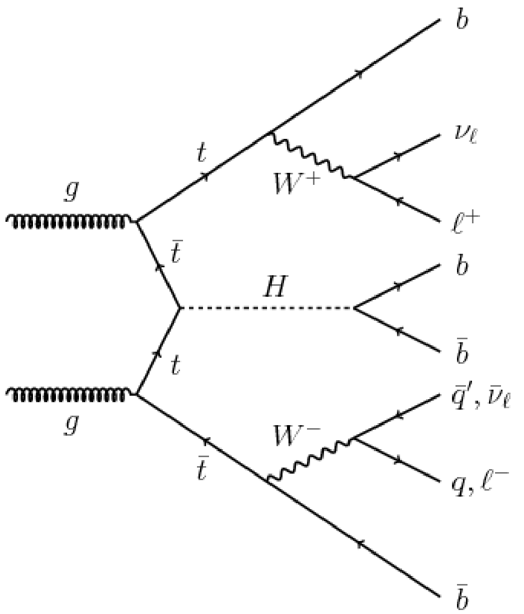

Experiment
Introduction
Generator Validation and Tuning
Coupling
λ tH
Existing ttH H→bb analysis
Resonances Decaying into Top pairs

# Content


Experiment
Introduction
Generator Validation and Tuning
Coupling $\lambda_{tH}$
Existing ttH H→bb analysis
Resonances Decaying into Top pairs

# $t\bar{t}H$: Effective (topological) cross section

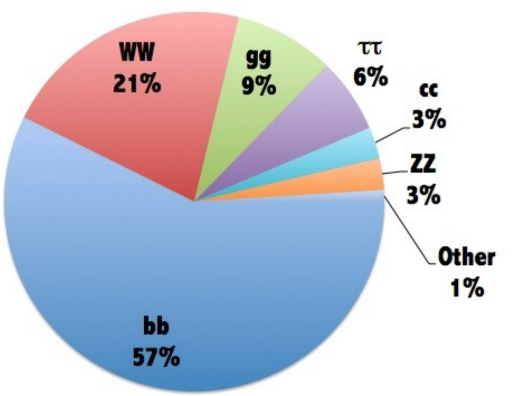
- Top decays:
  - 45% full hadronic (6 jets)
  - 45% one lepton (+ four jets)
  - 10% two leptons (+ two b-jets)




Search Topologies:

- $H \to b\bar{b}$:
  - 1 lepton plus 6 jets (4 b-jets) 18%
  - 2 leptons plus 4 b-jets 4%
- $H \to WW/ZZ$:
  - Many (3+) leptons+jets 2-3%
- $H \to \gamma\gamma$:
  - 2 tops plus 2 photons ~0.2%
  - ATLAS analysis with full 8TeV data: Limit: $\sigma/\sigma_{SM} < 5.3$ (90% CL)

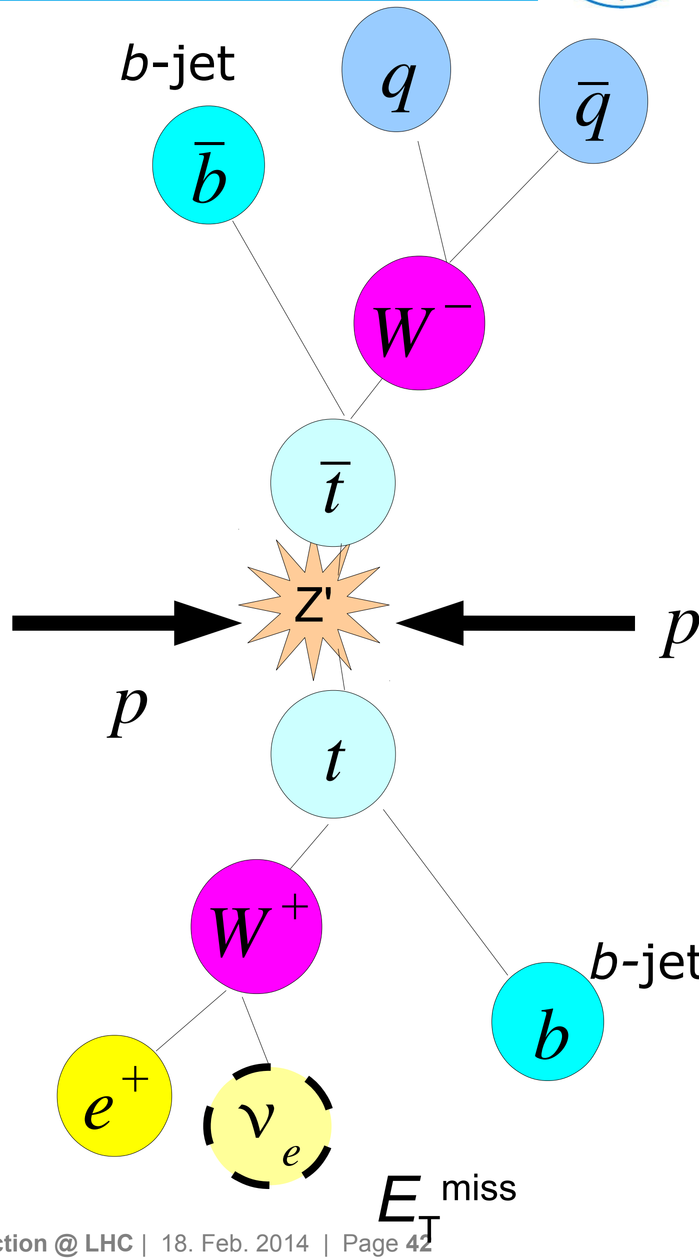
Higgs decays at $m_H$=125GeV




ATLAS-CONF-2013-080

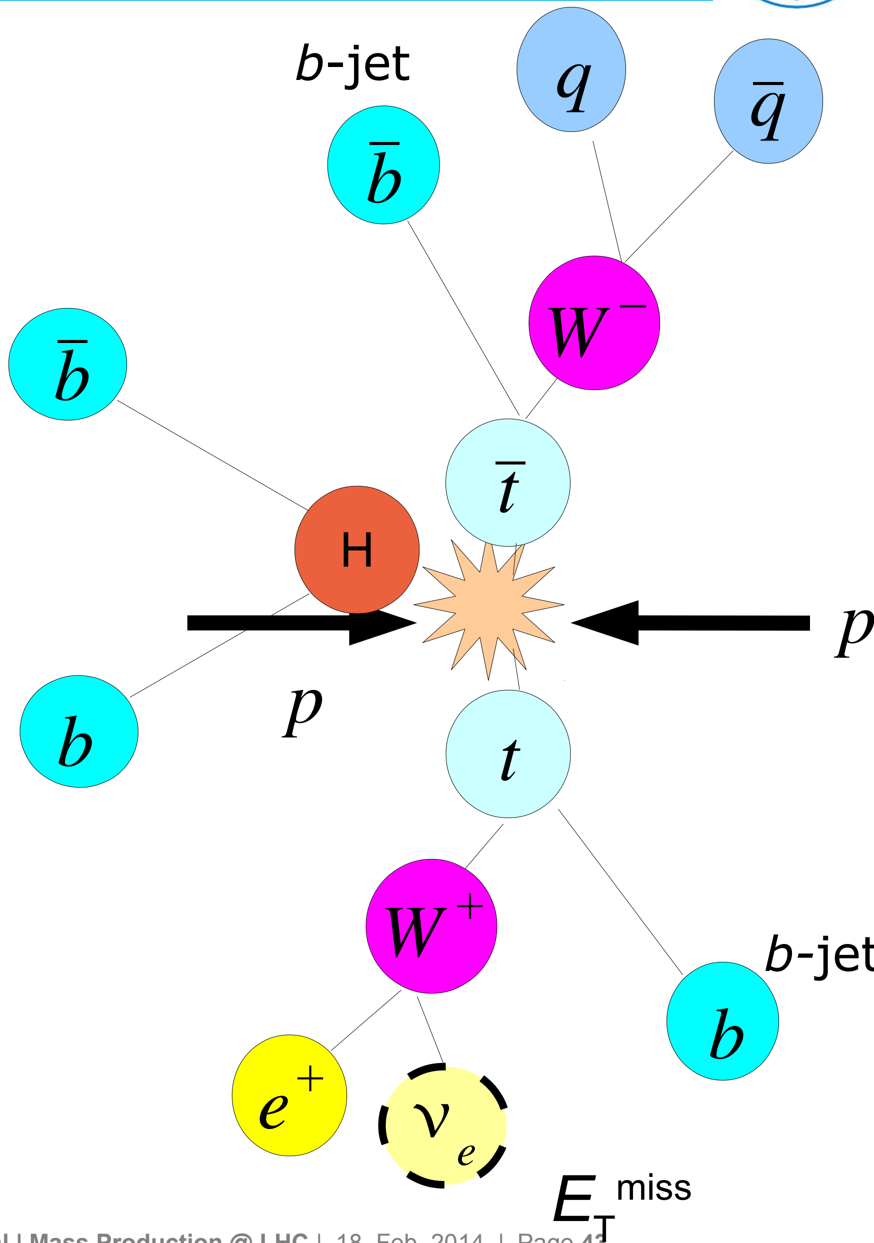
# From $t\bar{t}$ resonances to $t\bar{t}H$

- **Resonance** production of two top quarks



# From $t\bar{t}$ resonances to $t\bar{t}H$

- Resonance production of two top quarks
- $t\bar{t}H$: a Higgs produced together with a top pair



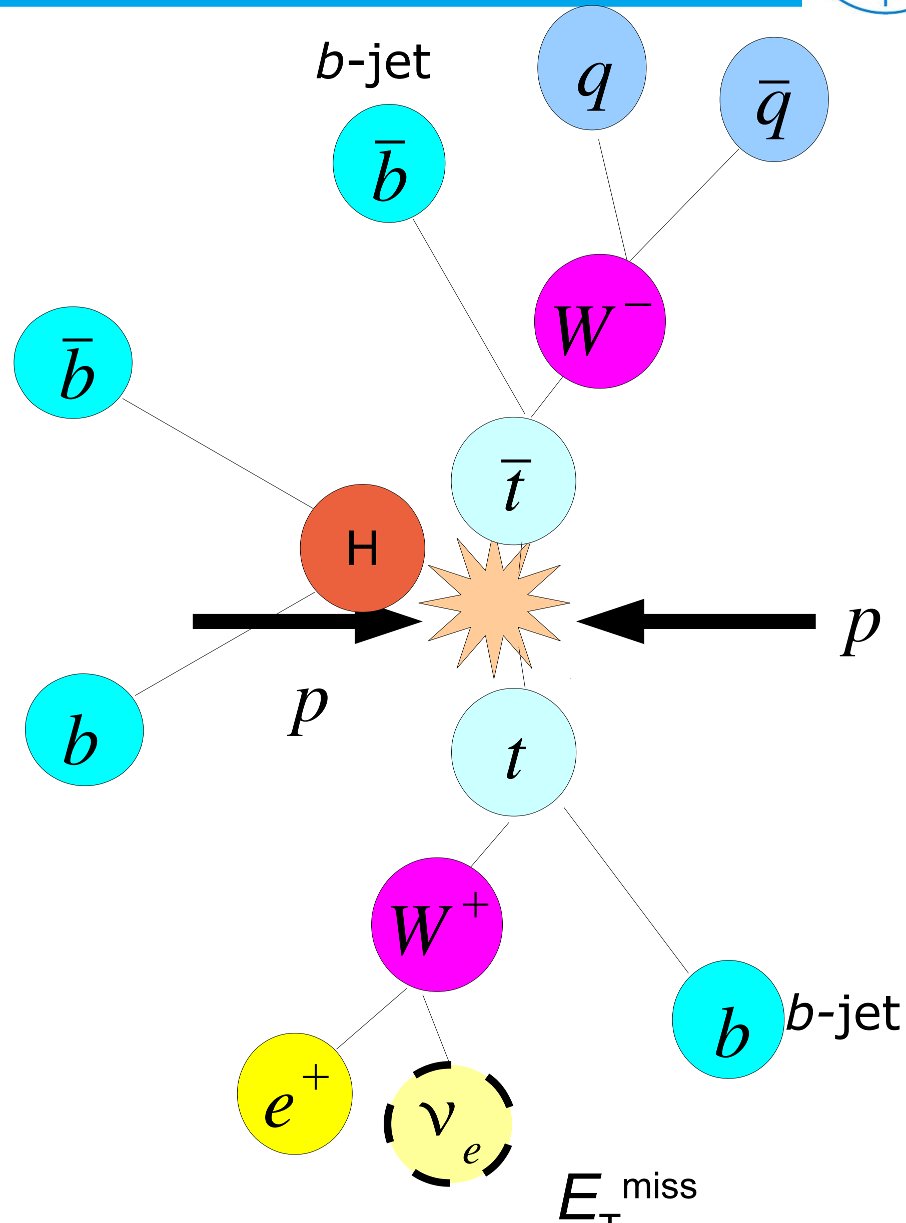

## Common:

- Two top quarks in final state
- Main background:
  - Standard Model top pairs
- b-hadron identification essential
- Final states are very complex:
  - Acceptance and background estimation relies heavily on simulation

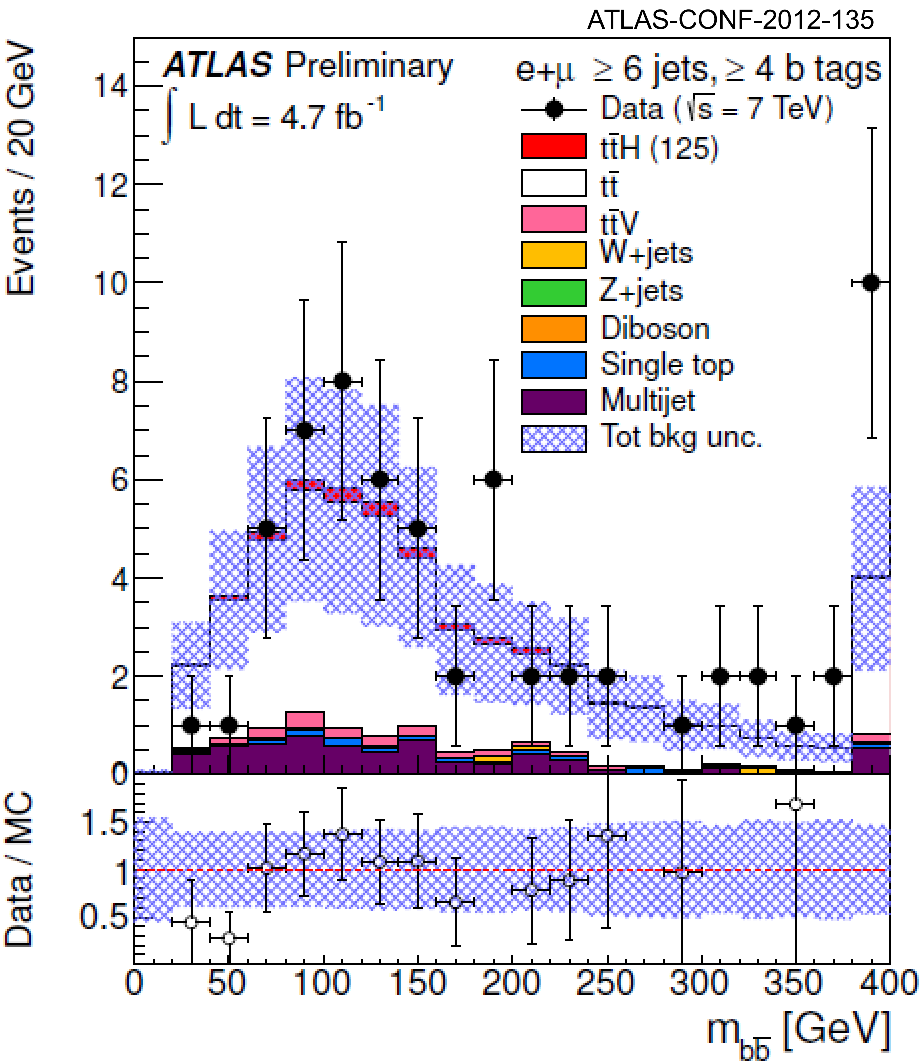
# $t\bar{t}H$: H → $b\bar{b}$ selection

## Signal Signature:

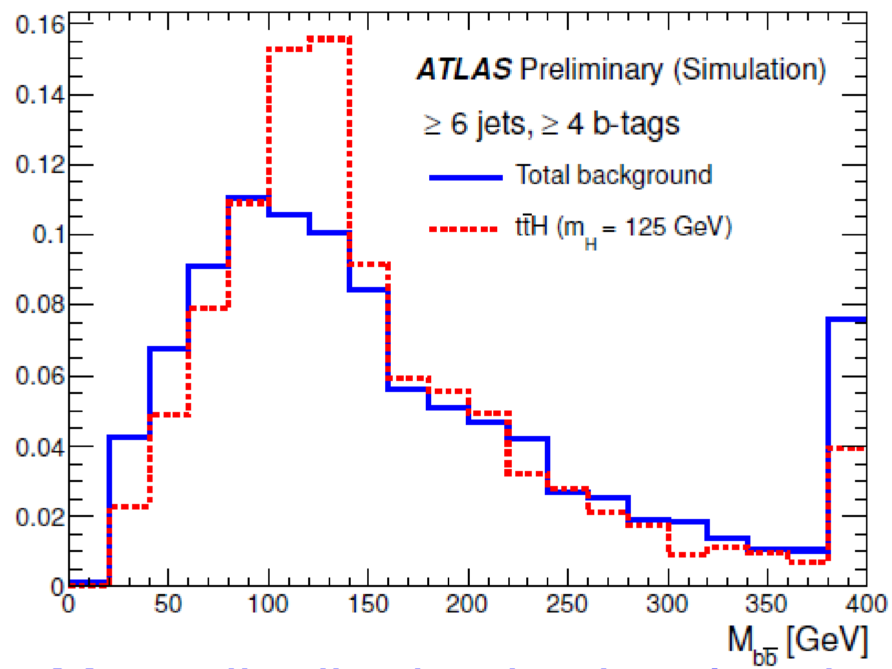
- 6 jets ($p_T$>25 GeV)
- 4 b-tagged jets
- 1 lepton ($p_T$>25 GeV)
- Missing $E_T$



# 6 jets + 4 btag: fully reconstructed signal



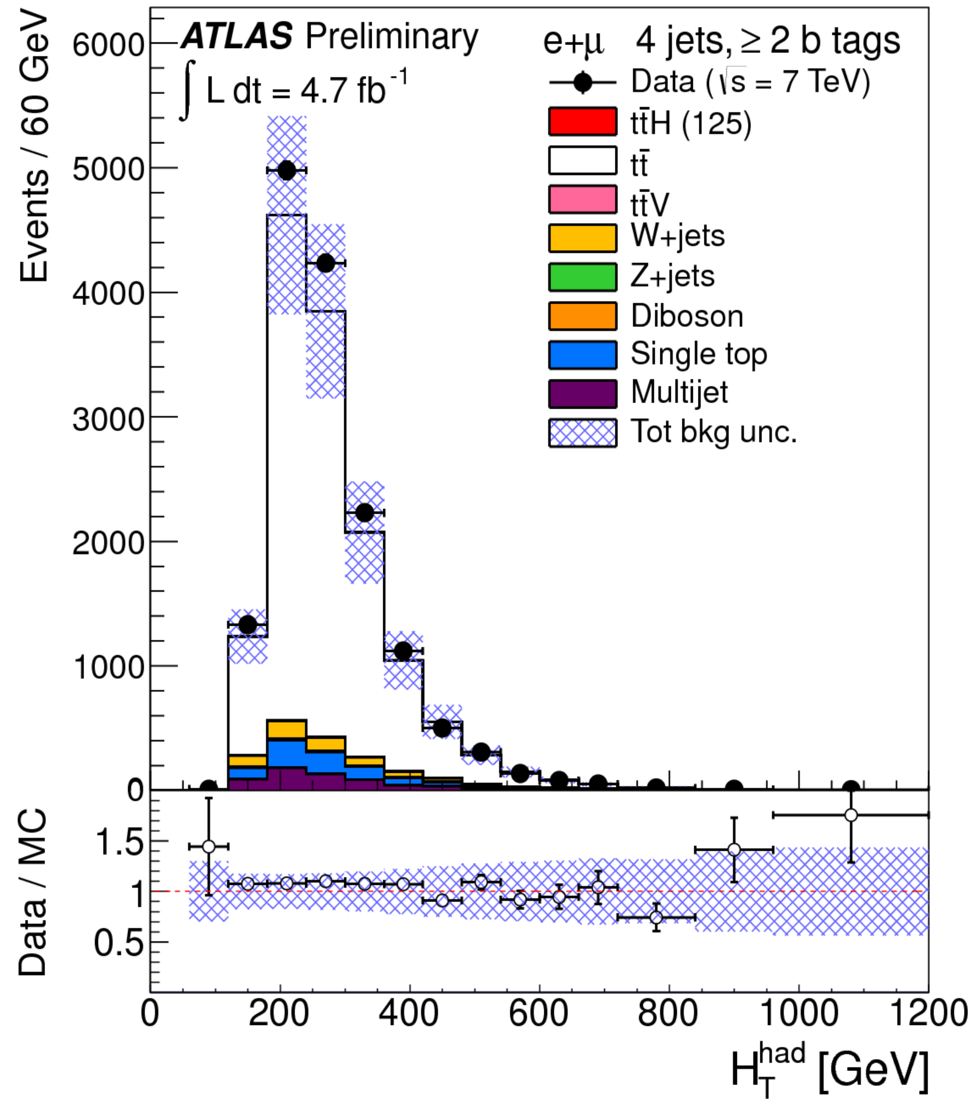

Invariant mass of two Higgs Boson candidate jets




- Mass distribution in signal region
- Large systematic errors on background expectation → need sophisticated methods to extract signal
- Some separation in mass distribution

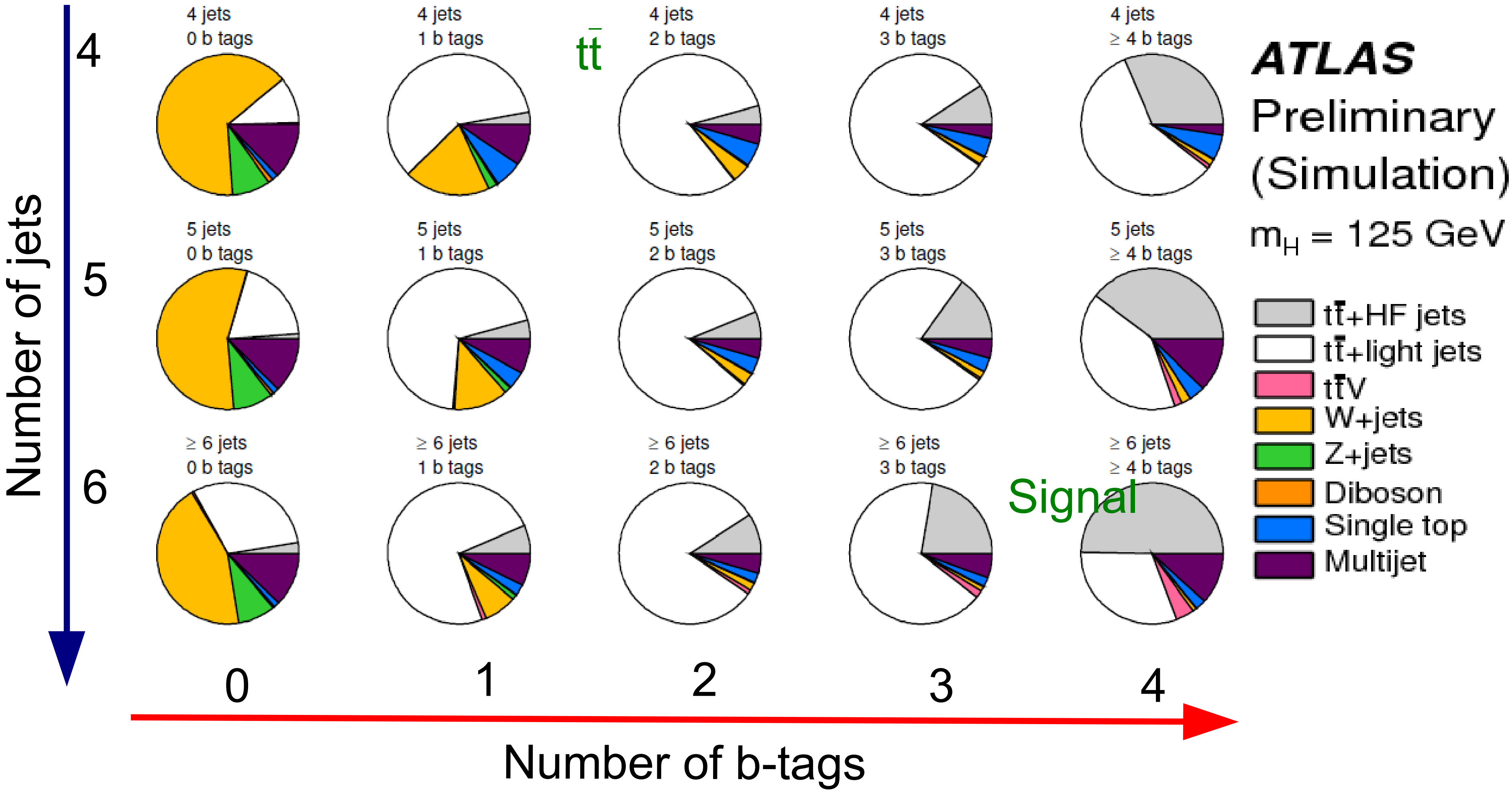
# 4Jet + 2 b-tag: top pair background

- Top pair selection: 4 jets + 2 b-tags:
  - Perfectly reconstructed top pairs
  - Little signal expected
  - Can be used to constrain top pairs cross section



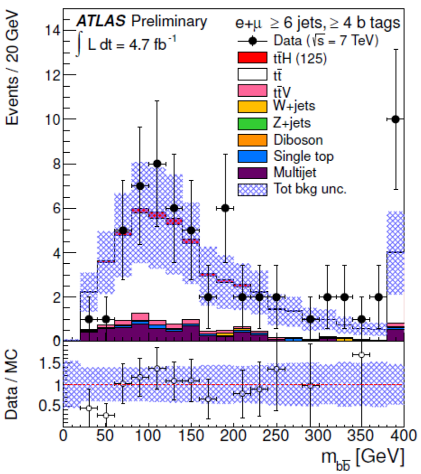

Transversal Energy of all jets in detector

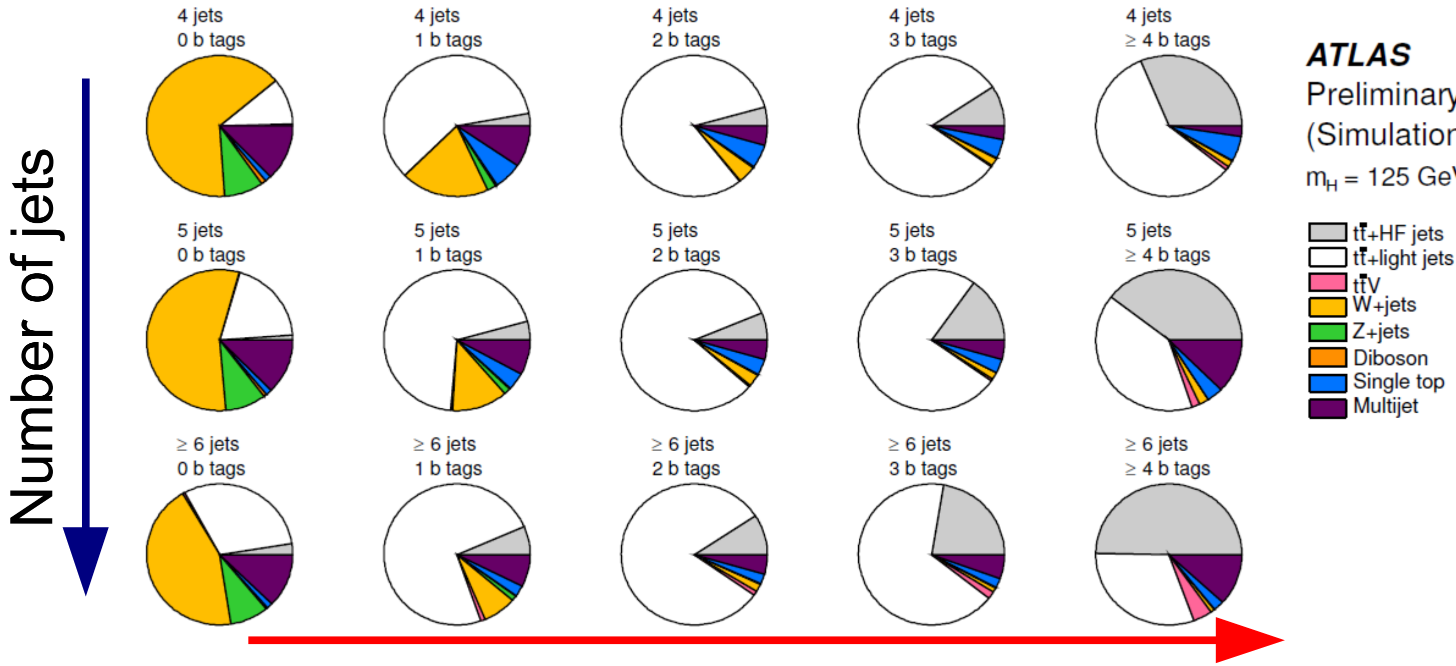
# ttH: Background composition




> Topological analysis of the background: different background composition for different number of jets and b-tag

# Systematics



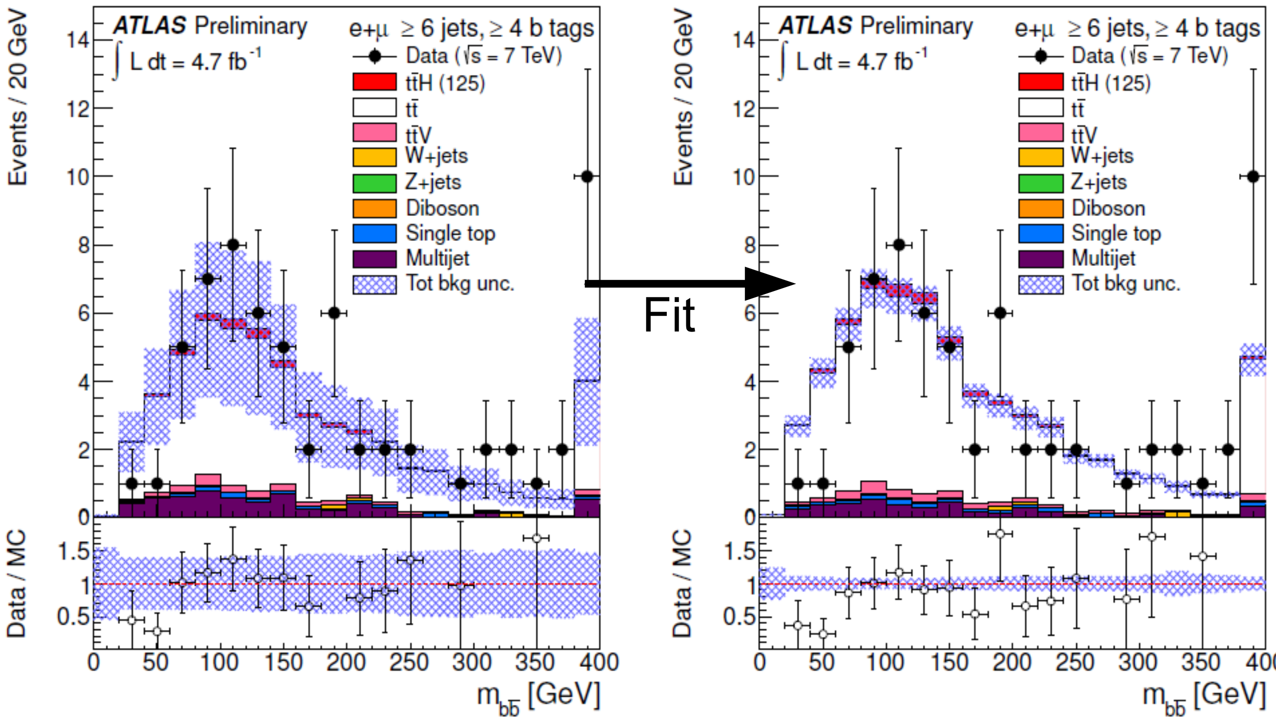




Number of b-tags

- Normalization
- Systematics changing number of jets:
  - Experimental: Jet energy scale; Theory: radiation of additional jets ($\alpha_s$)
- Systematics changing b-tagging:
  - Experimental: b-tagging efficiency, fake rate

    Theory: b-production in ME, b-production in shower (gluon-splitting)
- Simultaneous fit of Monte Carlo templates in number of jets and b-tags including systematics to the data

# Signal extraction




- Systematics get reduced by huge amount using combined fit (profiling)
  - Sensitivity for signal increases
- Cost: statistical error of signal strength gets bigger
  - Better to reduce systematic errors before analysis
- Result: $E_{CM}$=7 TeV; Luminosity: 4.7 $fb^{-1}$; $m_H$=125 GeV
  - Observed limit: $\sigma < 10.5\ \sigma_{SM}$

# How to improve in future

- Use full existing data set: add 20 $fb^{-1}$ at $E_{CM}$ = 8 TeV
- 2015-17:
  - 13/14 TeV with a luminosity of 100 $fb^{-1}$: 18 times more signal events
  - additional innermost pixel layer → better b-tagging capability
  - Expectation: $\Delta\lambda_{tH}/\lambda_{tH}$ ~ 30% with 300 $fb^{-1}$ for $H \to \gamma\gamma$ and $H \to ZZ^*$

    need $H \to b\bar{b}$ to get evidence already with 100 $fb^{-1}$ (2015-17)

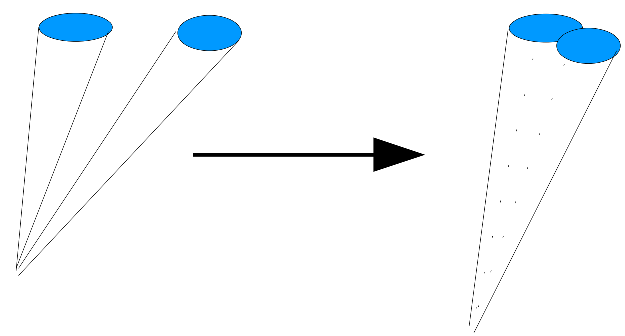
Possible improvement in addition:

- Add more phase space:

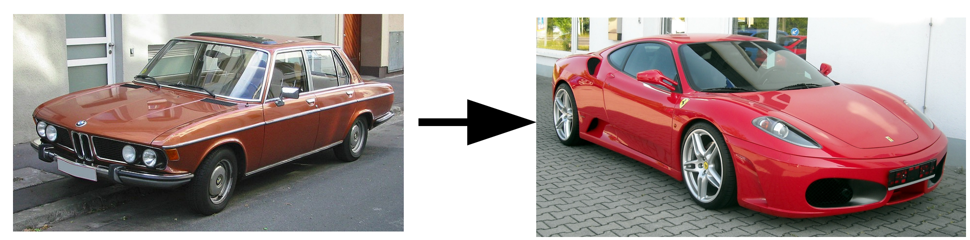
  → boosted $t\bar{t}H$

  - less background

  - two b-tags in one fat jet



- New generator developments:
  - Constrain generators using measurements
  - Use modern generator from active theory groups



# Summary

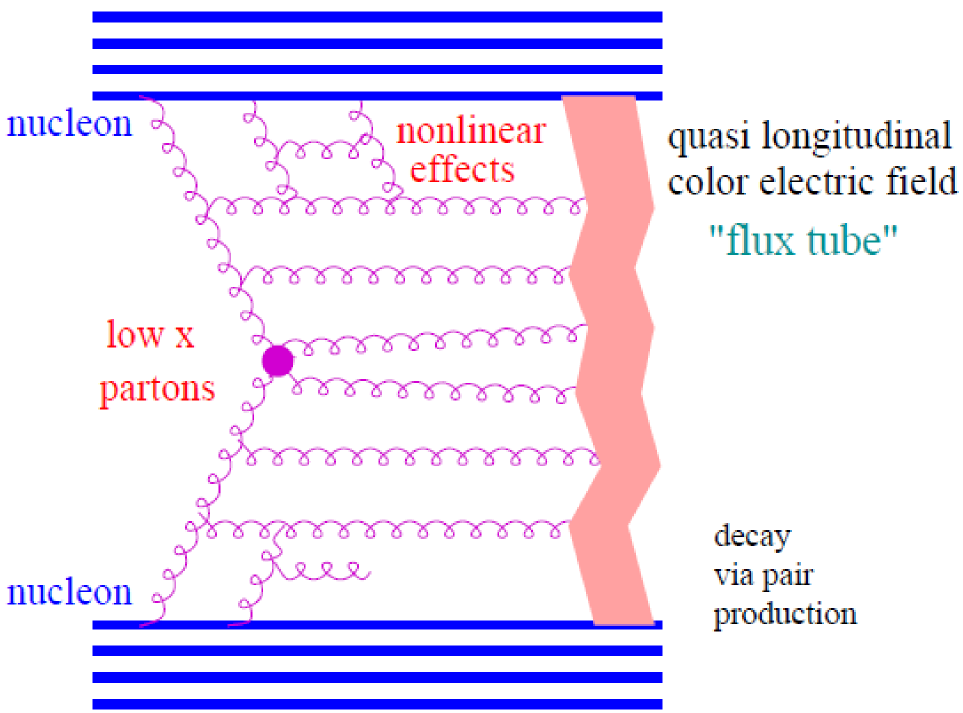
- $\lambda_{tH}$: crucial measurement establishing the Standard Model Higgs Boson:
  - The only coupling close to 1 → understanding of the origin of mass
  - Big lever arm for new physics
  - Need to combine many channels to get evidence with 100 $fb^{-1}$
- Resonances decaying into top quarks:
  - Nice possibility to look for new physics beyond the SM on the TeV scale
  - Similar final state like $t\bar{t}H$ → similar problems
- (Good) Monte Carlo Simulation is important:
  - Huge statistic need automation and validation
  - Task forces using early measurements to improve generator description of main background processes

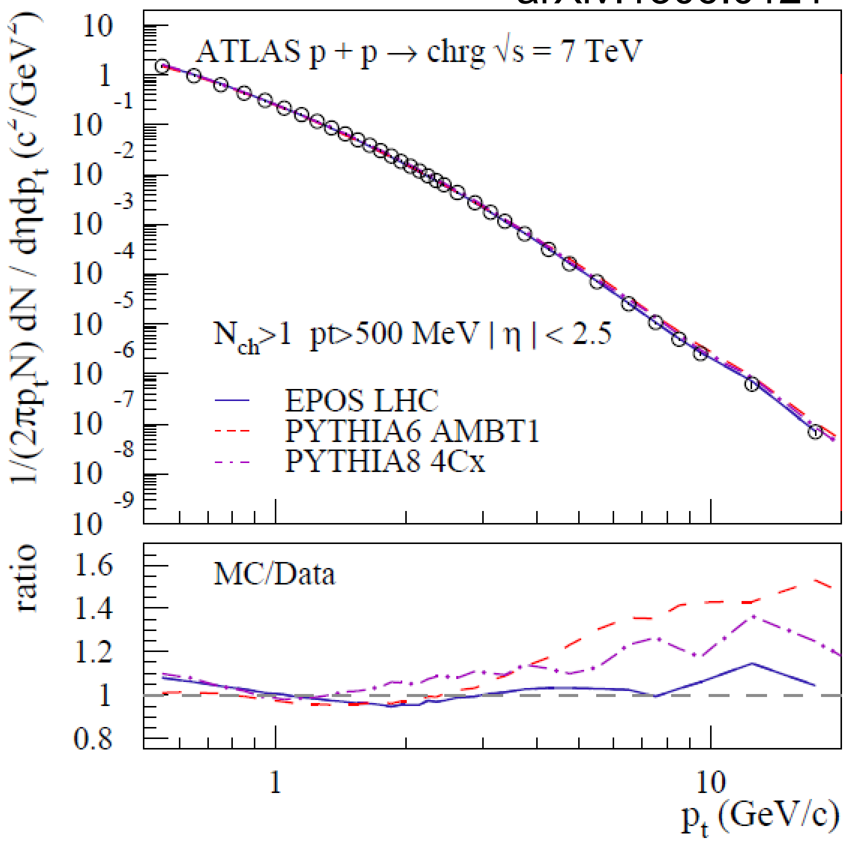
# End of talk

Back up

# Improving Monte Carlo: EPOS

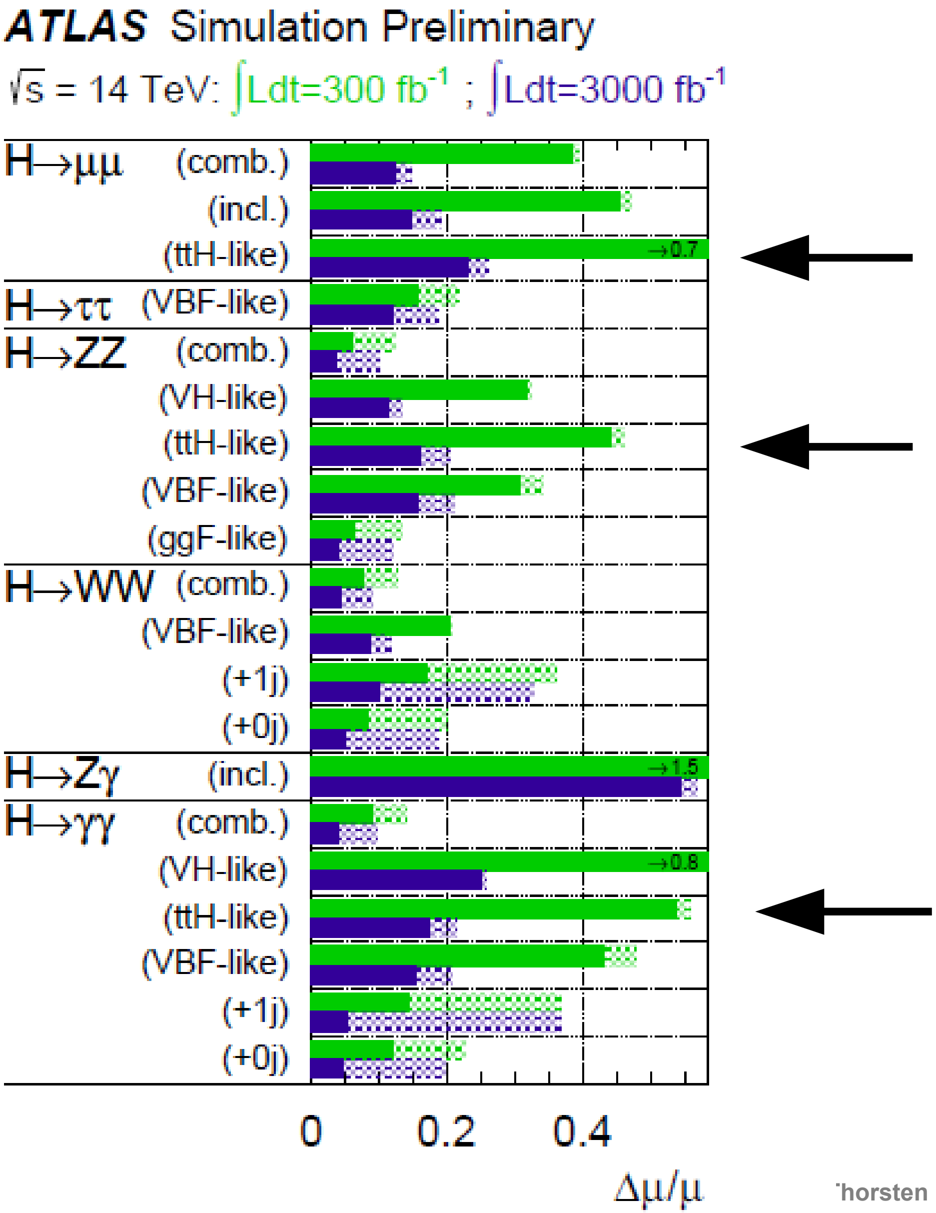
arXiv:1306.0121

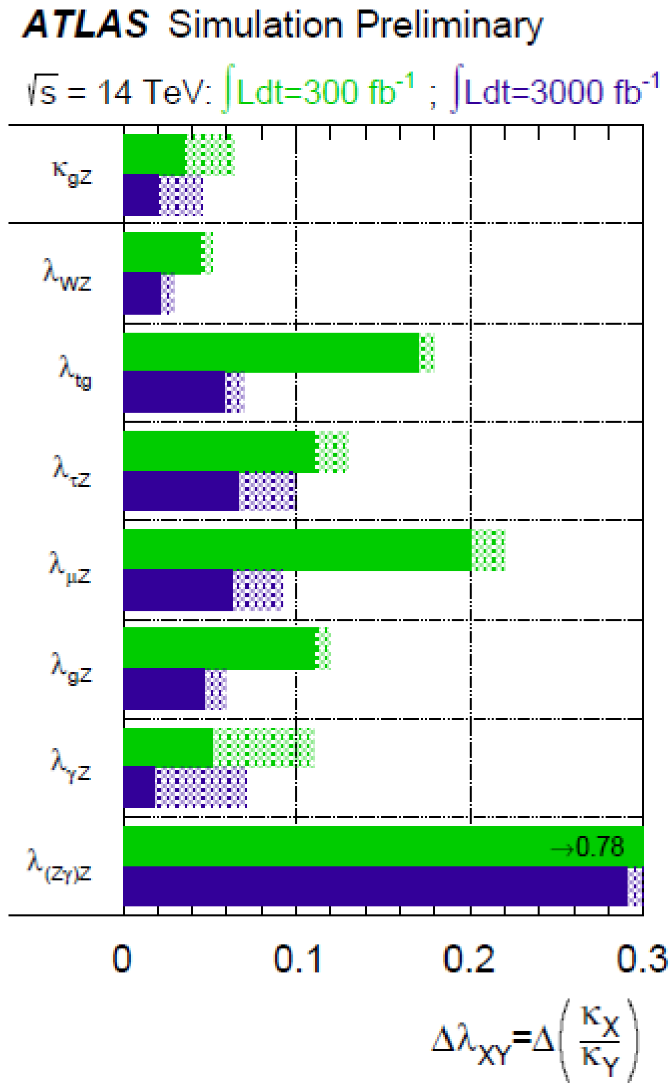



- Improvement of Pile up simulation
- EPOS: Generator used in air shower and in heavy ion physics
- Best generator in forward direction and low multiplicity events
- Little drawback: no jets, try to combine with multijet generator

# Atlas Higgs Projections



# End of talk

End