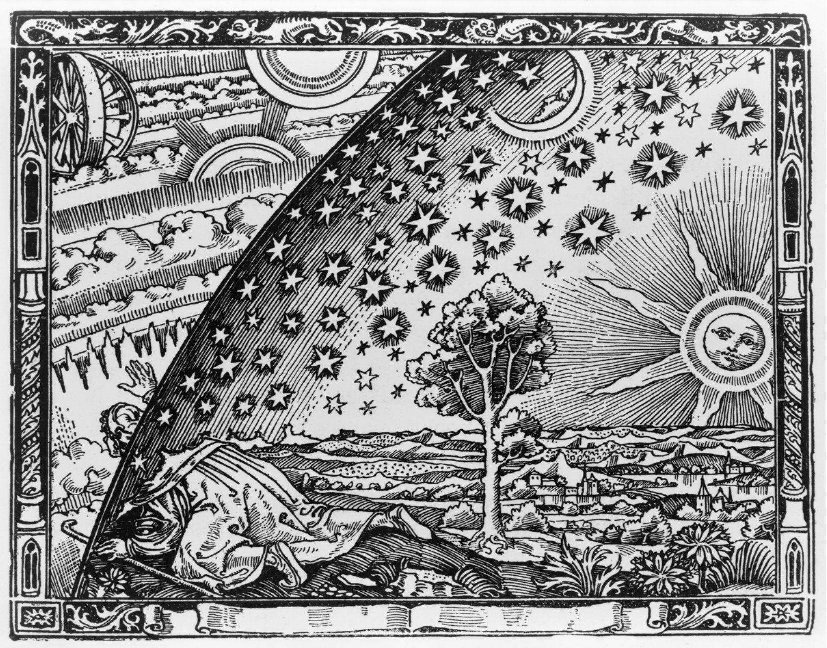
To the Higgs and beyond

Quantum Universe Days
17 – 19 February 2025



Katharina Behr

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ATLAS EXPERIMENT

DESY.

Outline

> **Part 1: The vacuum is not empty**

- The Higgs boson in the Standard Model
- Characterization of the Higgs boson since its discovery

h

> **Part 2: What is the fingerprint of the vacuum?**

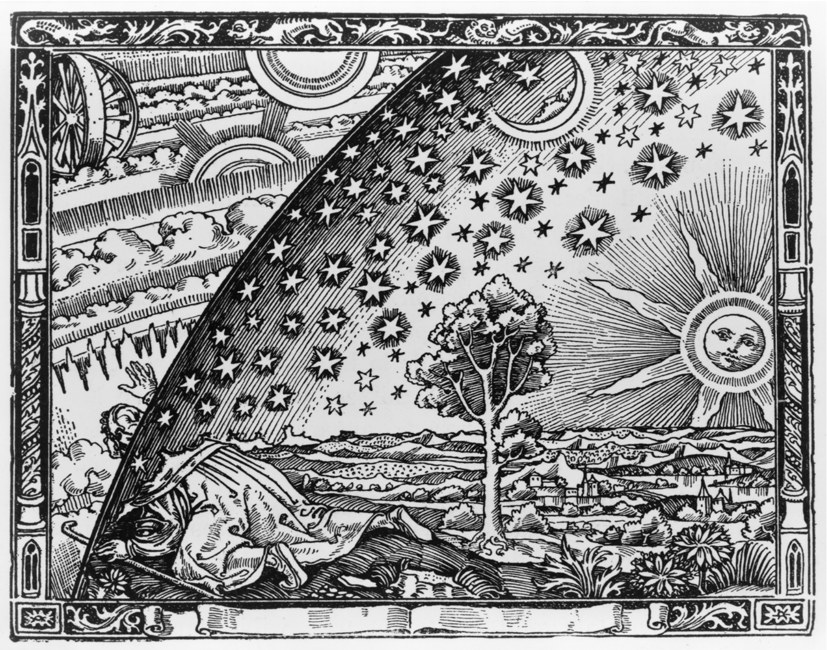
- Unravelling the Higgs potential
- Higgs boson pair production
- Extra: Triple Higgs production

h h

> **Part 3: Is there even more to the vacuum?**

- Extended Higgs sectors
- Extra: news from the ttbar threshold
- Outlook: the future of the LHC and beyond

h H A H^+ H^-



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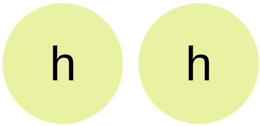
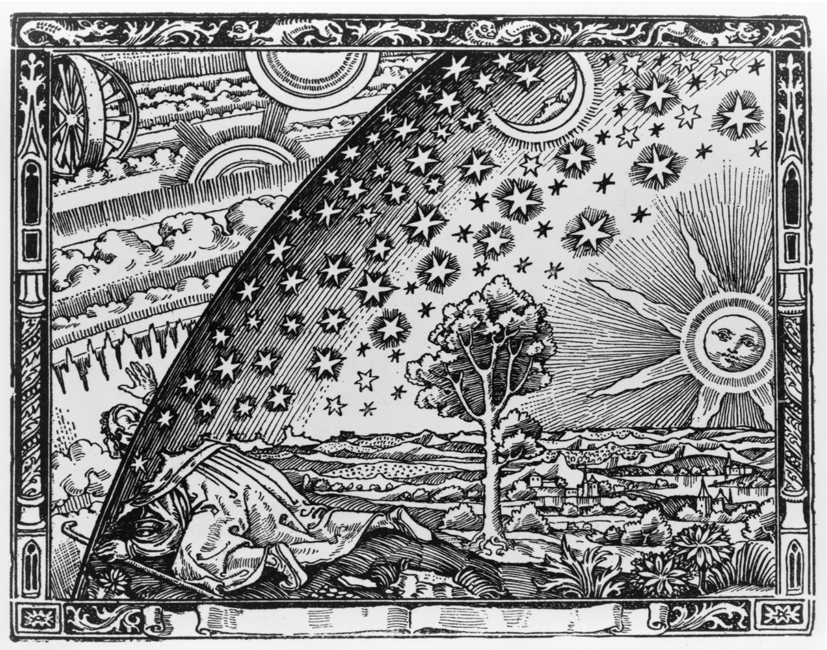
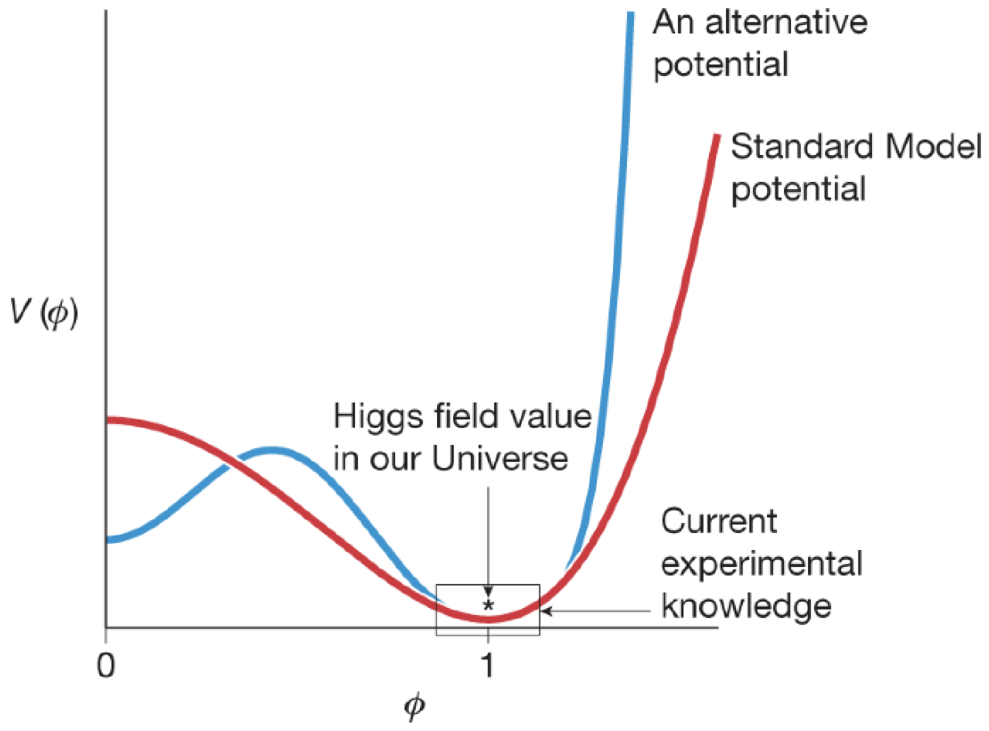




> **Part 3: Is there even more to the vacuum?**
  - Extended Higgs sectors
  - Extra: news from the ttbar threshold

A key piece of missing information

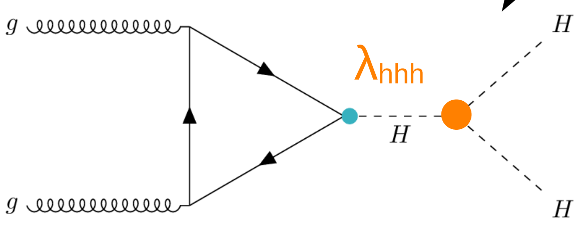
- Full shape of the Higgs potential
- Current measurements in single Higgs bosons only probe potential around minimum

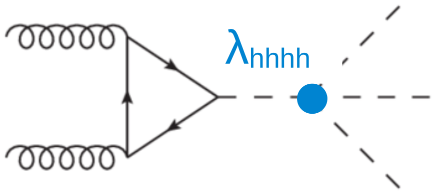


A key piece of missing information

- Full shape of the Higgs potential
- Current measurements in single Higgs bosons only probe potential around minimum
- SM prediction: Mexican hat potential

$$\boxed{V(h) = \frac{1}{2} m_h^2 h^2 + \frac{1}{3!}\lambda_3 h^3 + \frac{1}{4!}\lambda_4 h^4.}$$

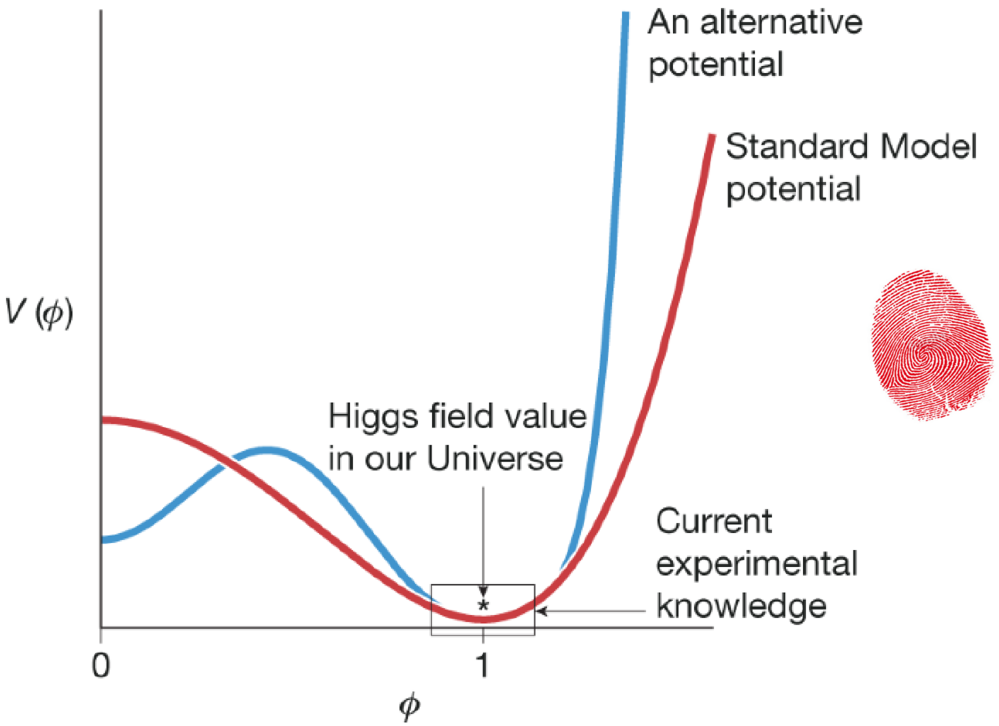




$m_h^2 = 2\lambda v^2$ (Higgs mass term),

$\lambda_3 = 3\lambda v = \frac{3m_h^2}{2v}$ (trilinear Higgs coupling),

$\lambda_4 = \lambda = \frac{m_h^2}{2v^2}$ (quartic Higgs coupling).



A key piece of missing information

- BSM: many different shapes possible
- E.g. extra scalar singlet

$$V(h,H) = V_{\rm SM}(h) + \frac{1}{2}m_H^2 H^2 + \frac{1}{2}\mu_{hH} hH + \frac{\lambda_{hH}}{2}h^2H^2 + \frac{\lambda_{3H}}{3!}H^3 + \frac{\lambda_{4H}}{4!}H^4$$

- Smoking-gun hints of extended Higgs sectors:
  - Deviation of self-coupling from SM value
    → This lecture!
  - Presence of extra Higgs bosons

    → Tomorrow's lecture

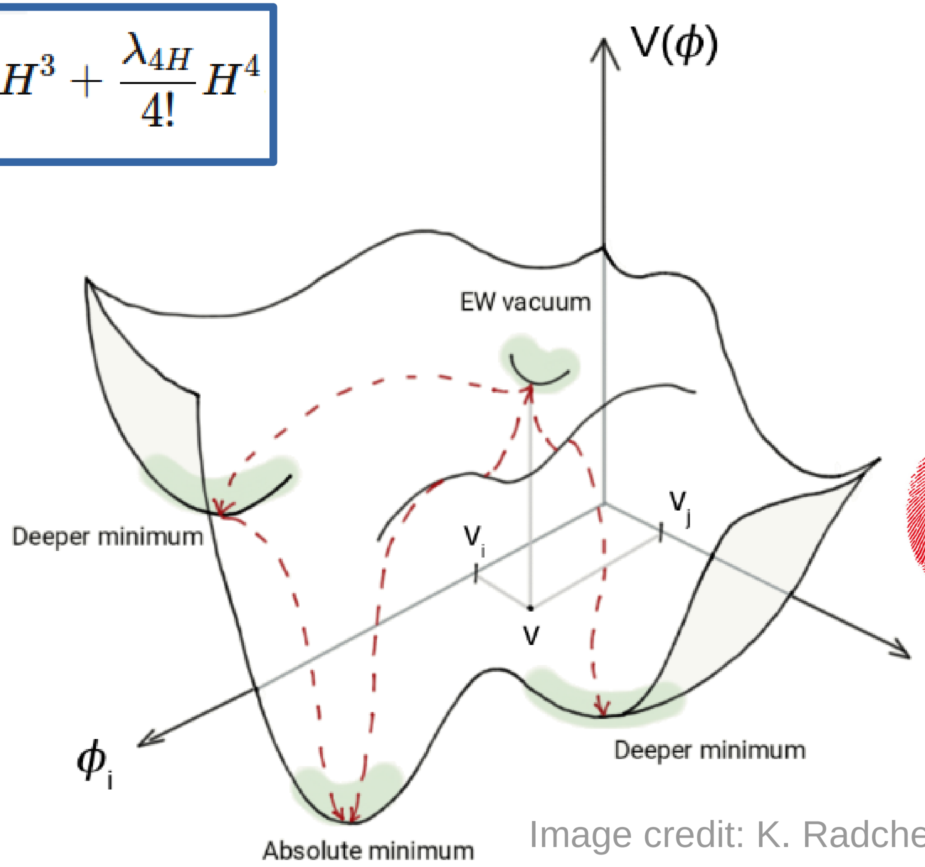
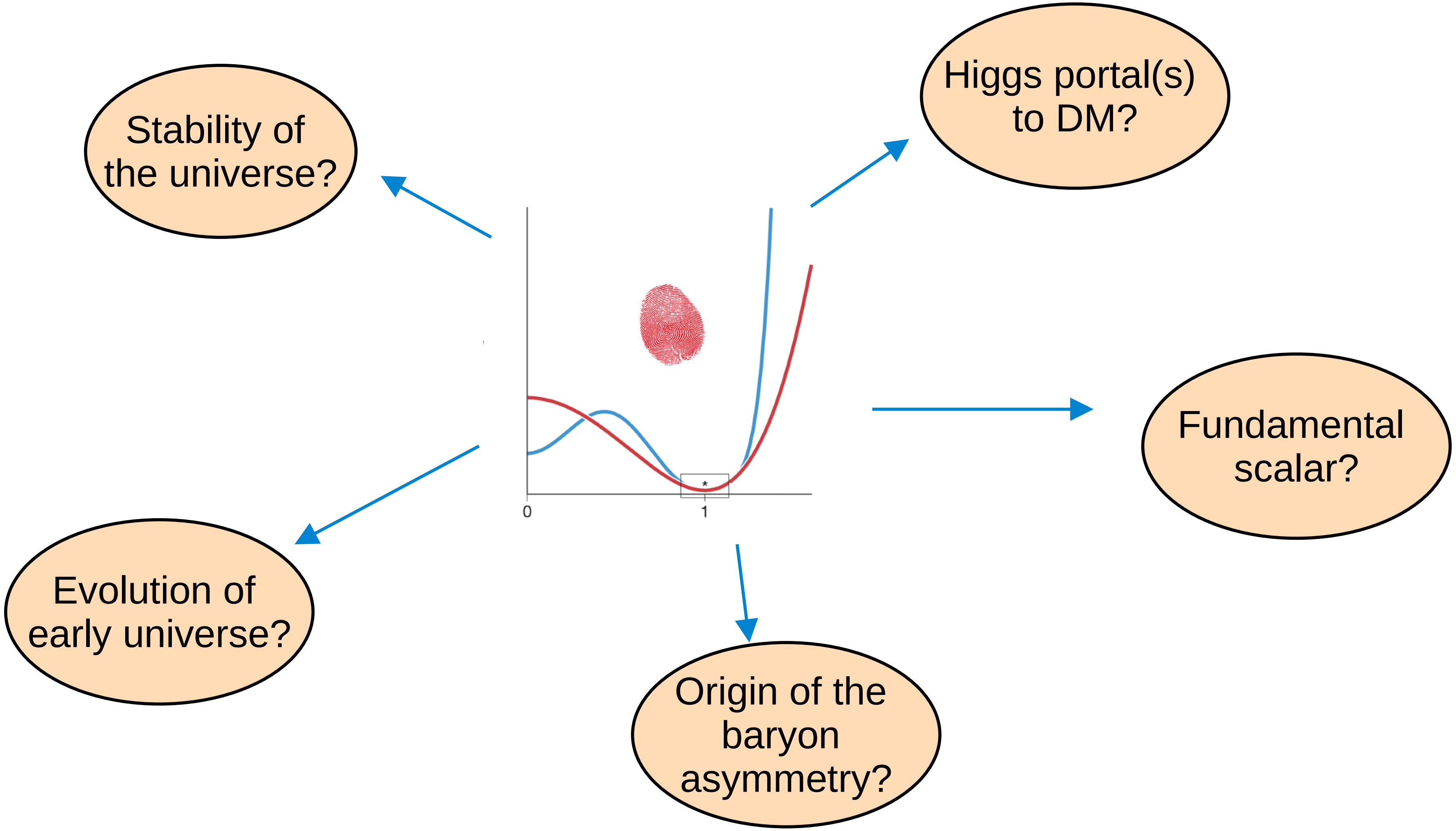


Image credit: K. Radchenko

Why care about the full potential?

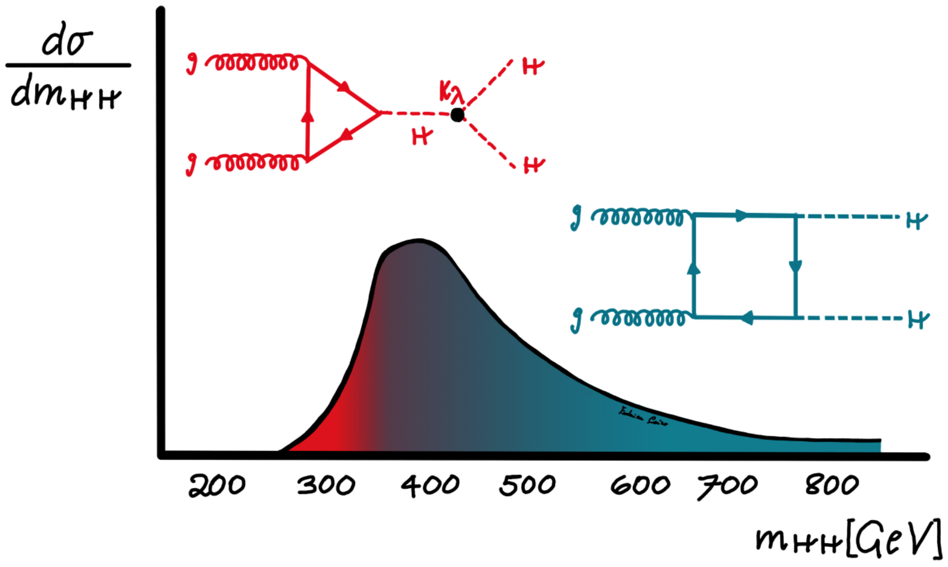
> Higgs potential may provide answers to many key open questions in particle physics



Higgs pair production at the LHC

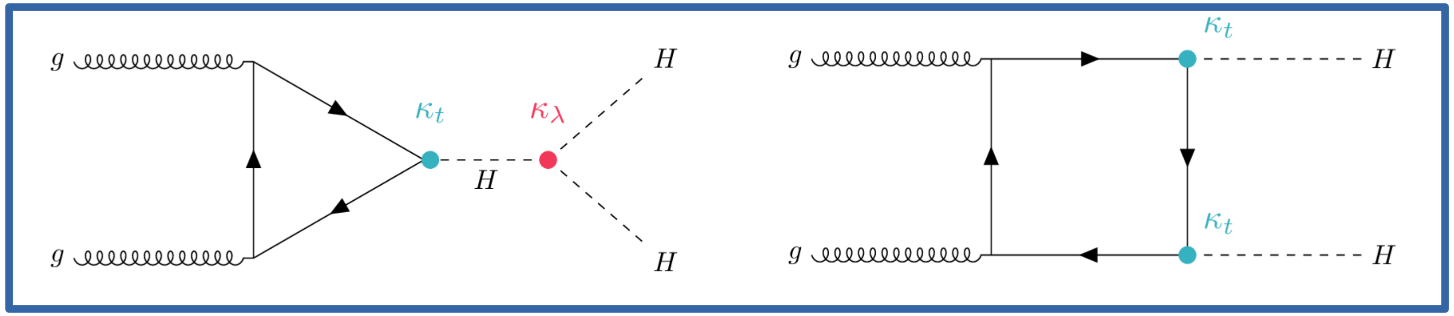
> Challenge: di-Higgs cross-section around 1800 times smaller than single Higgs cross-section

> ggF production (90.2%): leading sensitivity to trilinear coupling λ_{hhh}



$\kappa_\lambda = \lambda_3 / \lambda^{SM}_{hhh}$

$\kappa_{2V} = \lambda_{hhVV} / \lambda^{SM}_{hhh}$



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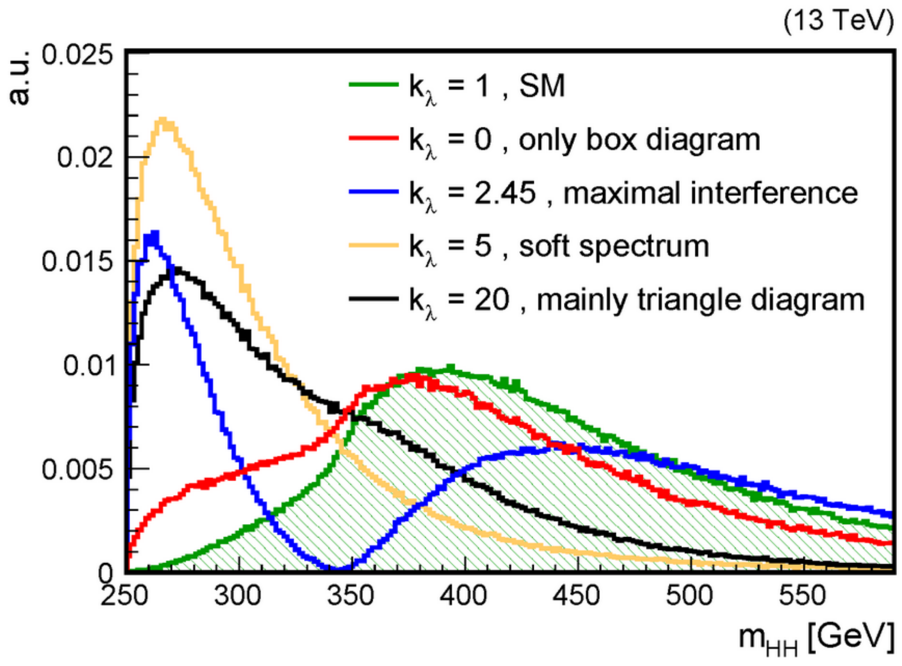
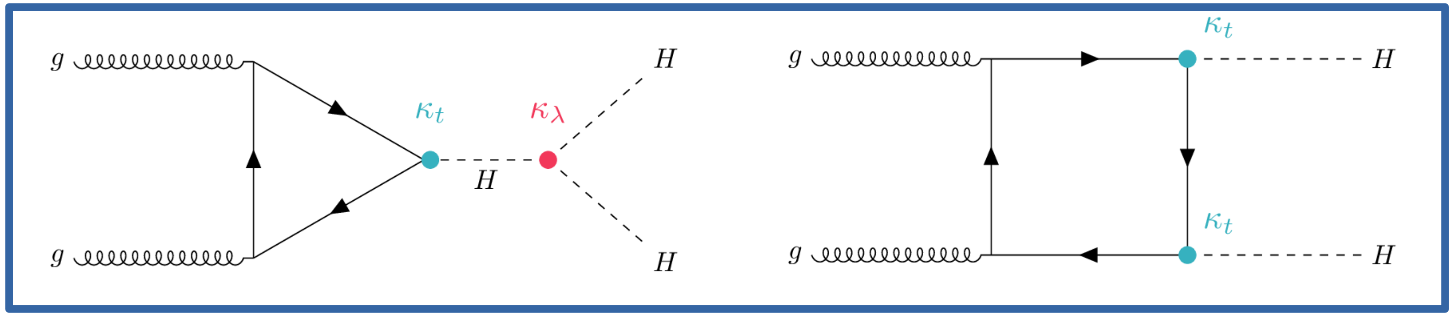
Softer spectrum away from SM value





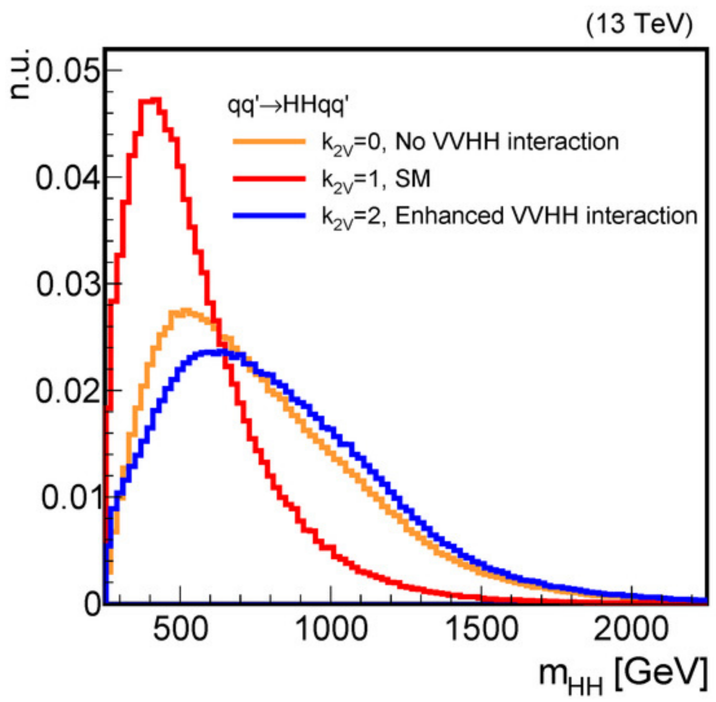
Higgs pair production at the LHC

> Challenge: di-Higgs cross-section around 1800 times smaller than single Higgs cross-section

> ggF production (90.2%): leading sensitivity to trilinear coupling λ_{hhh}

> VBF production (5%): unique access to di-Higgs-di-vector-boson coupling λ_{hhvv}

Harder spectrum away from SM value



$\kappa_\lambda = \lambda_3 / \lambda^{SM}_{hhh}$

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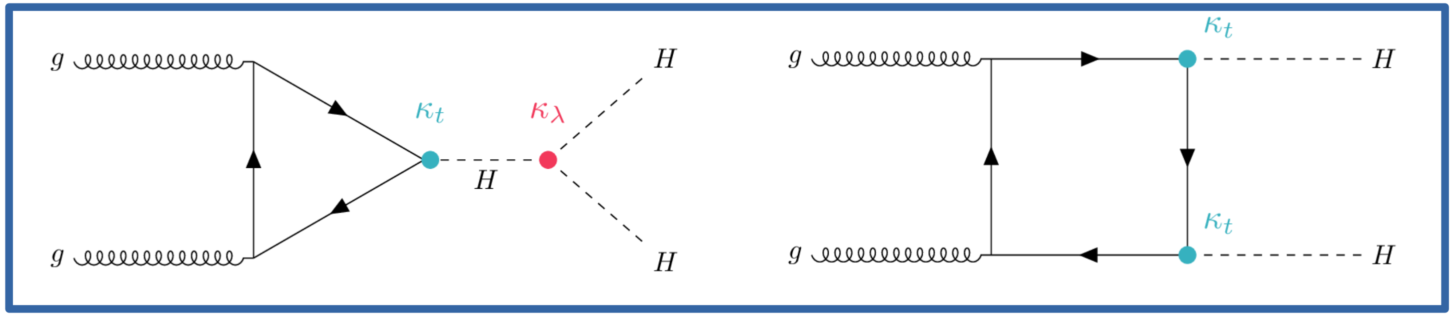
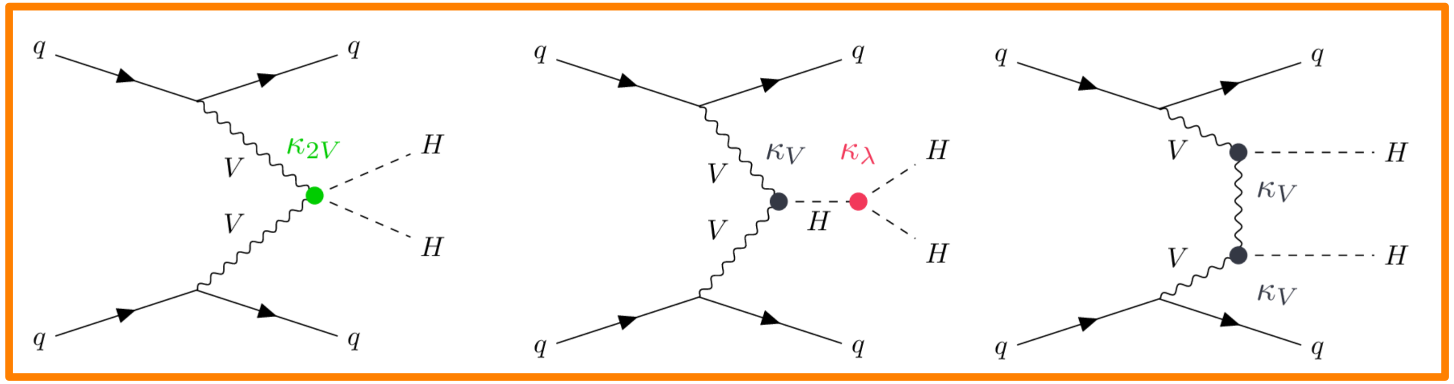
31.05 fb

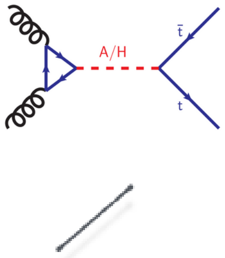




1.72 fb

How to find a needle in a haystack?

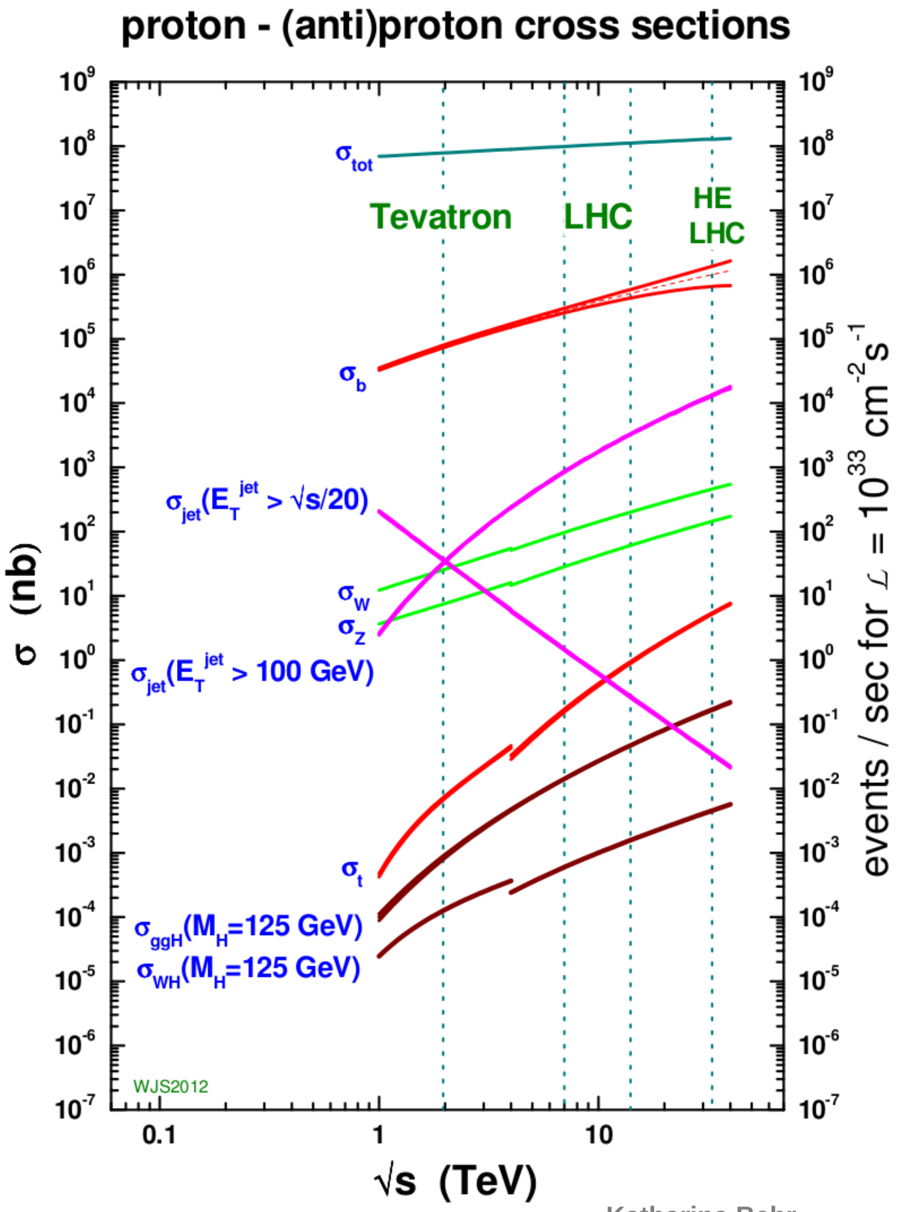
> Isolate small signal from huge dataset



Signal
(a.k.a. the needle)

Background
(a.k.a. the haystack)
(…it's meant to be a haystack)

T.G. McCarthy



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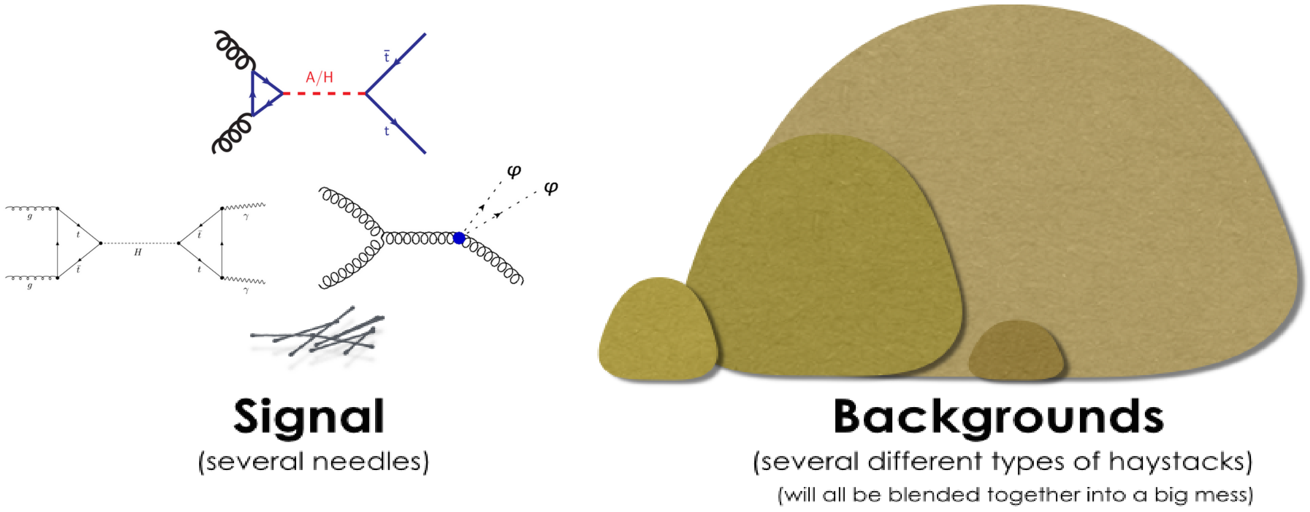

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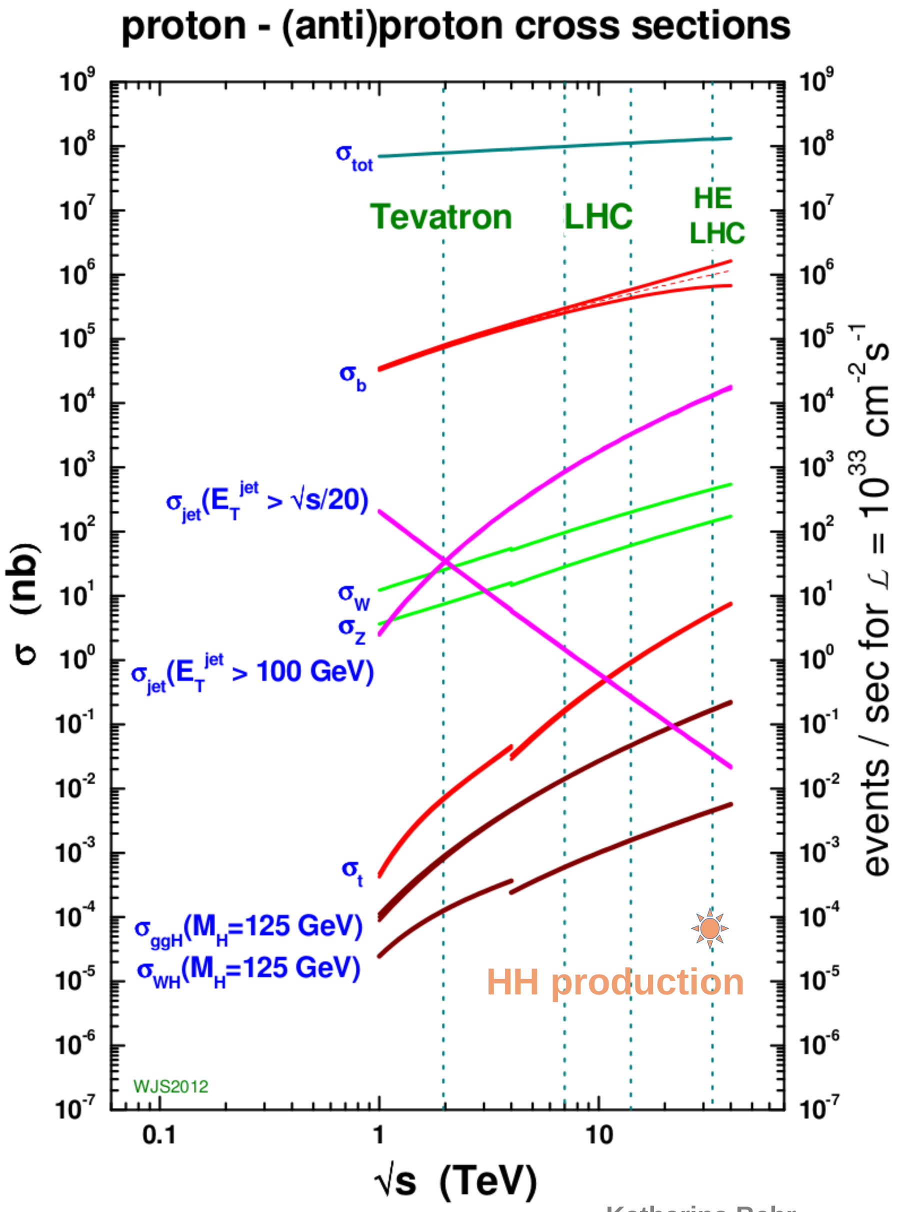
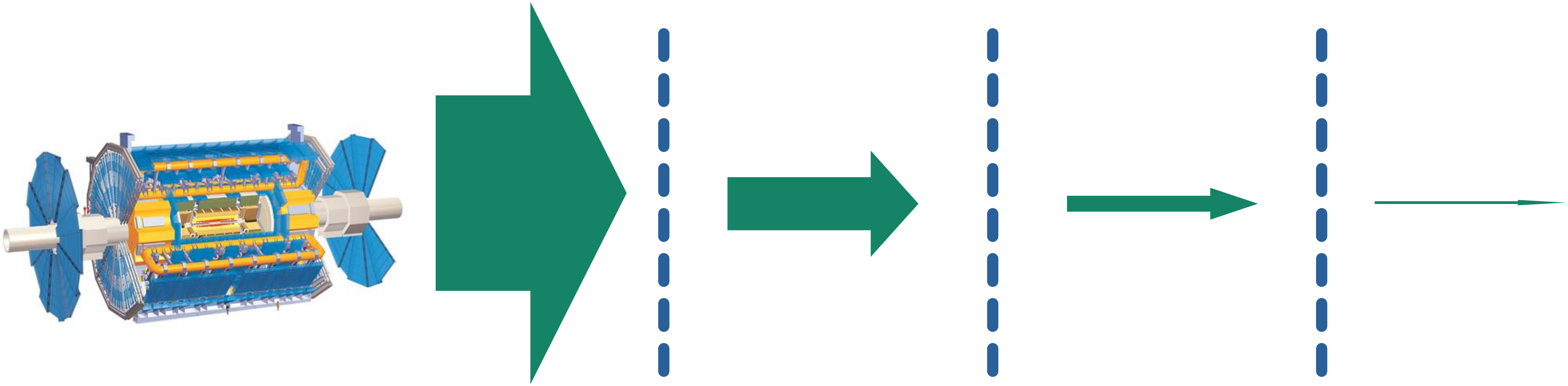


How to find a needle in a haystack?

- Define criteria that characterise chosen signal in detector
- Apply selection criteria to reduce background
- Signal-enriched region (signal region)



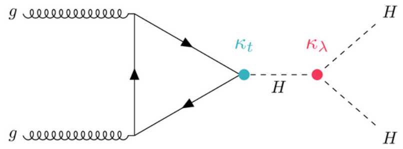
Trigger selection (online)

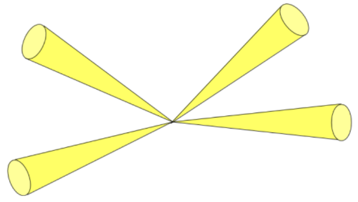
Coarse pre-selection (offline)

Tight signal region selection (offline)

Data analysis 101

> Pick and study a signal of interest (MC simulation)

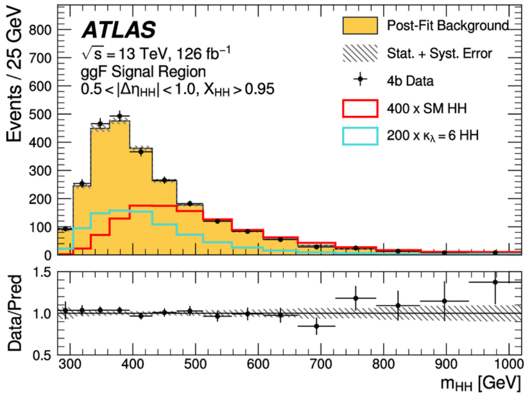




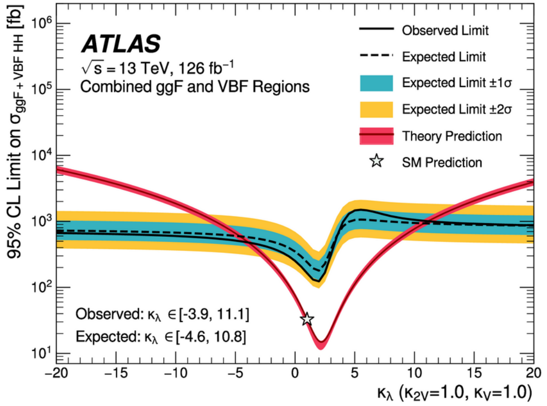
> Select subset of events enriched in signal (signal region)

> Estimate backgrounds and systematic uncertainties

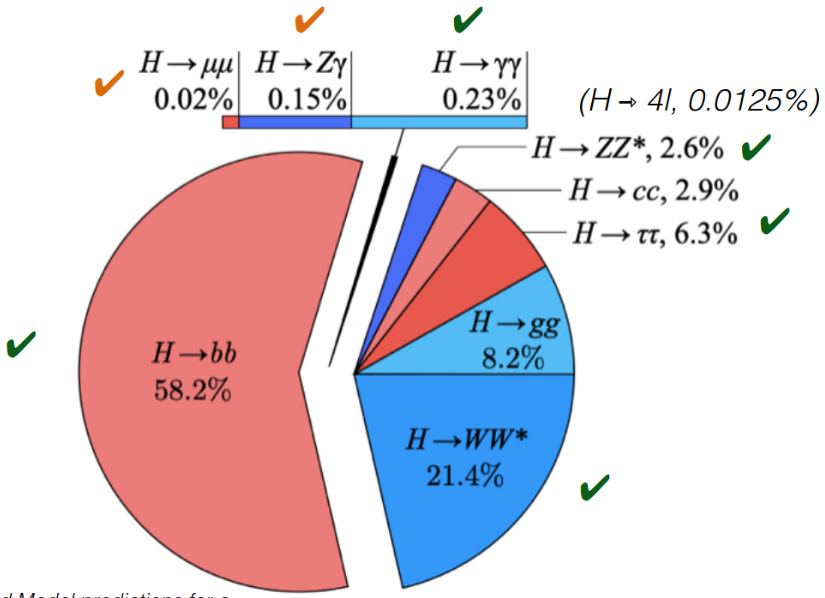
- Often via control regions enriched in background



> Test agreement between SM prediction and data (likelihood fits)



Signatures of di-Higgs production



(Standard Model predictions for a Higgs boson with mass 125 GeV)

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Signatures of di-Higgs production

> Three most sensitive channels:

- *bbbb*: largest BR (34%), large multi-*b*-jet background

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Event topologies in the *bbbb* channel

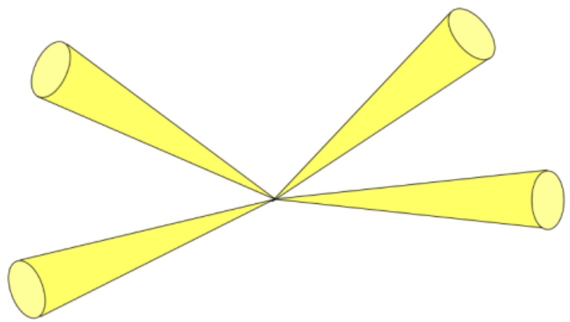
> Three possible topologies depending on Lorentz boost of the two Higgs bosons

> Identification of heavy flavour crucial:

- *b*-tagging for resolved decays
- $h \rightarrow bb$ tagging for merged decays

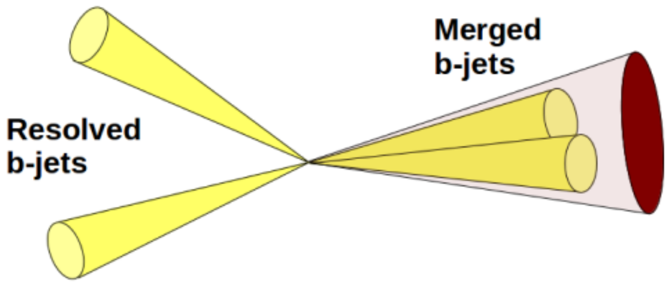
Resolved

$\varepsilon_{sig} \sim \varepsilon_b^{\,4}$



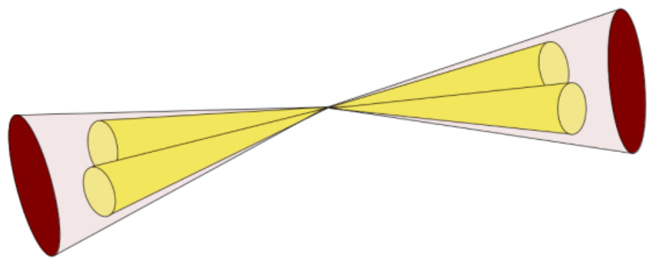
[Intermediate]

Less relevant for hh events ($p_{T,h1} \sim p_{T,h2}$), more relevant for scalar+h searches



Merged

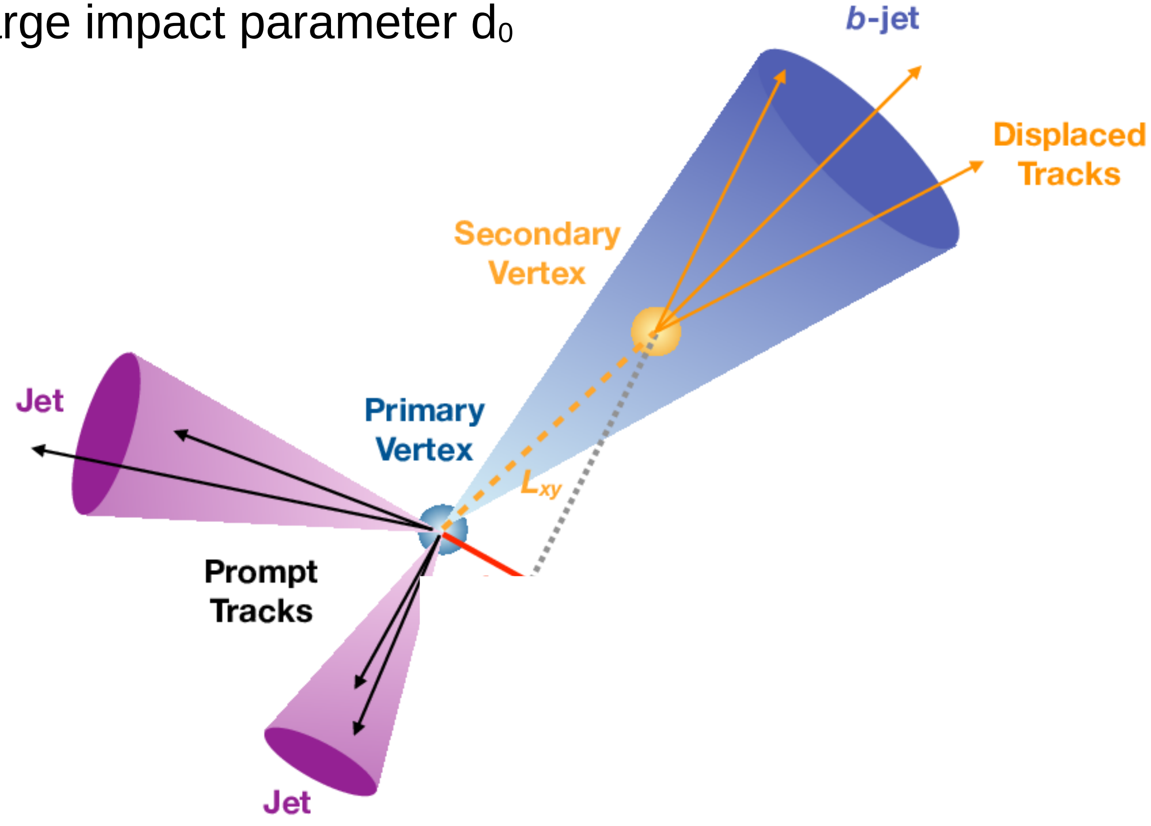
$\varepsilon_{sig} \sim \varepsilon_{Xbb}^{\,2}$



b-tagging

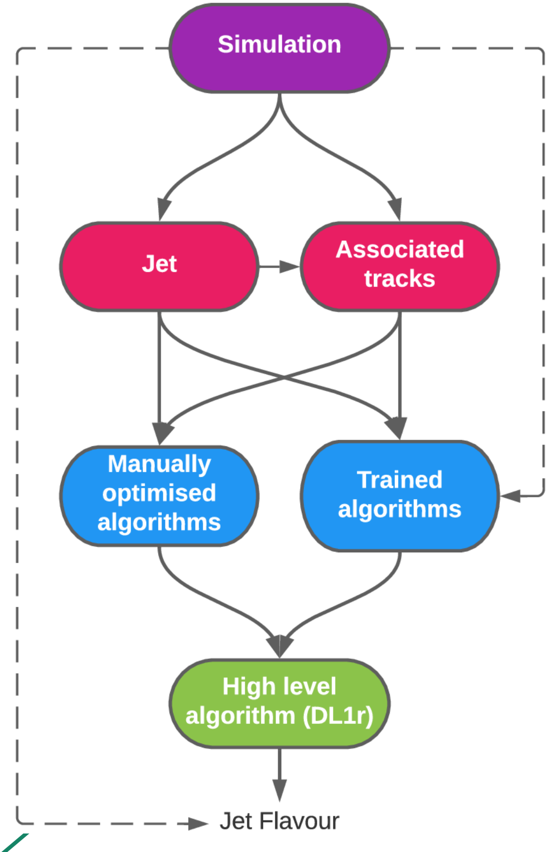
> Identification of jets initiated by *b*-quarks based on properties of resulting *B*-hadron

- Secondary decay vertex
- Significant decay length of O(mm – cm)
- Tracks not pointing back to primary vertex → large impact parameter d_0

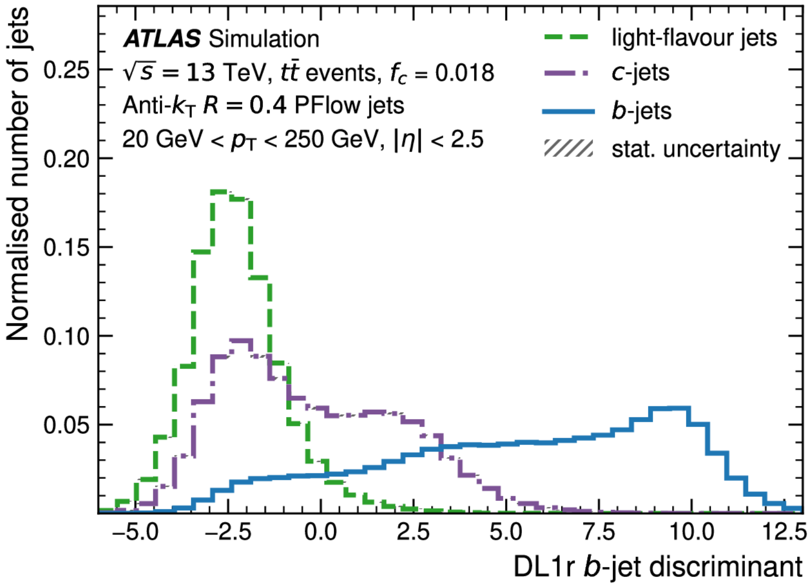


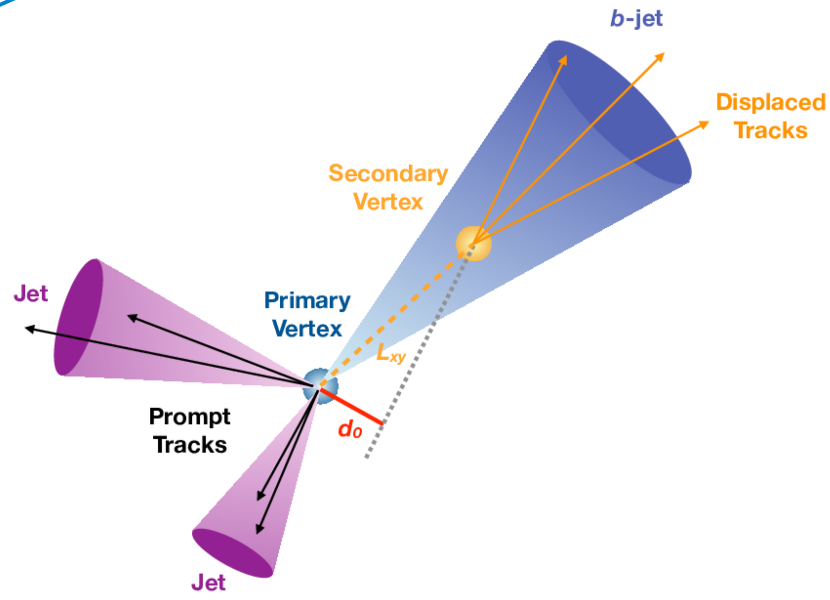
b-tagging (Run 2)

> Combine all information in high-level deep neural net discriminator



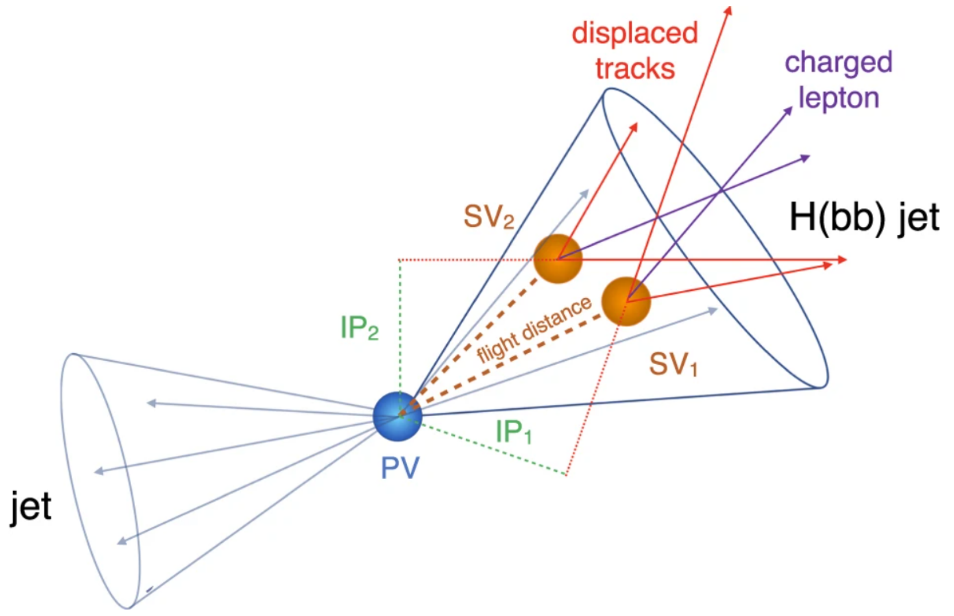
Secondary vertex based
Track IP (d_0) based

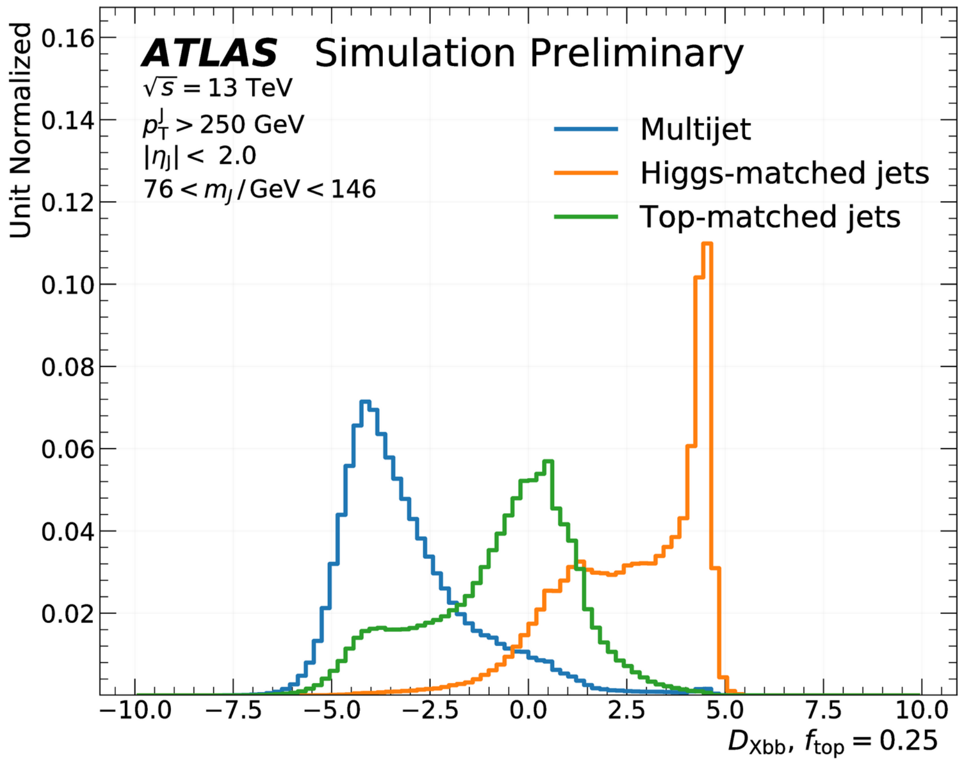




Higgs tagging (Run 2)

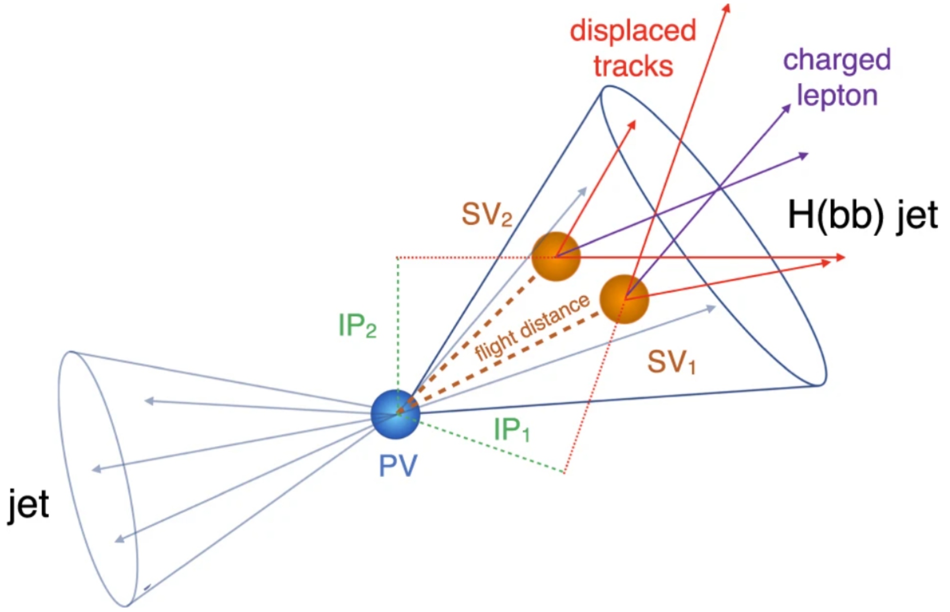
- Large calorimeter jet with fixed radius parameter *R*=1.0
- Identify small-radius subjets and check if they are *b*-tagged using standard *b*-tagging algorithm
- DNN classifier combining the following inputs:
  - DL1r scores of 2-3 sub-jets
  - Large-*R* jet kinematics





Next-generation taggers (Run 3) – transformers!

- Inputs: low-level objects (tracks, particle-flow objects)
- Significant performance improvements for analyses using *b*- and $h \rightarrow bb$ jets
  - x 2 better top and multijet rejection for 70% signal efficiency
- Need accurate tracks reconstruction!



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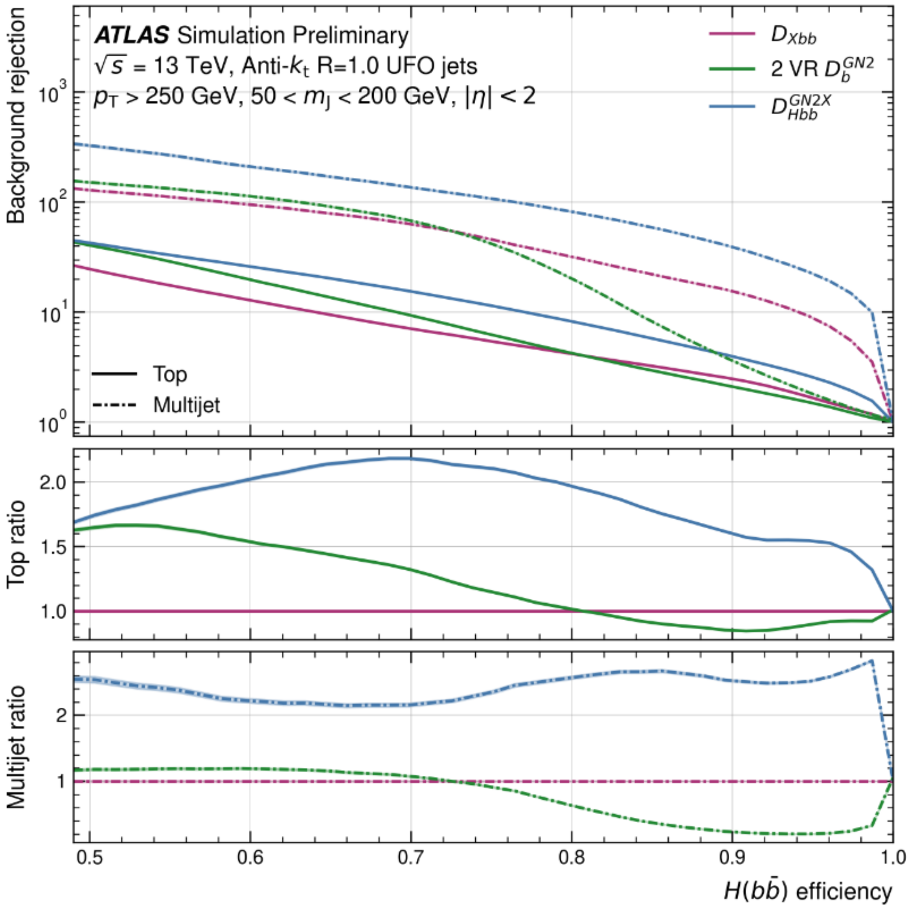
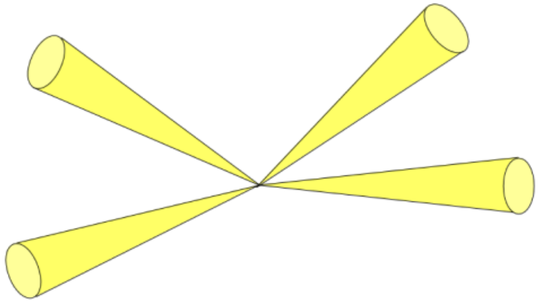


Analysis strategy for the *bbbb* channel

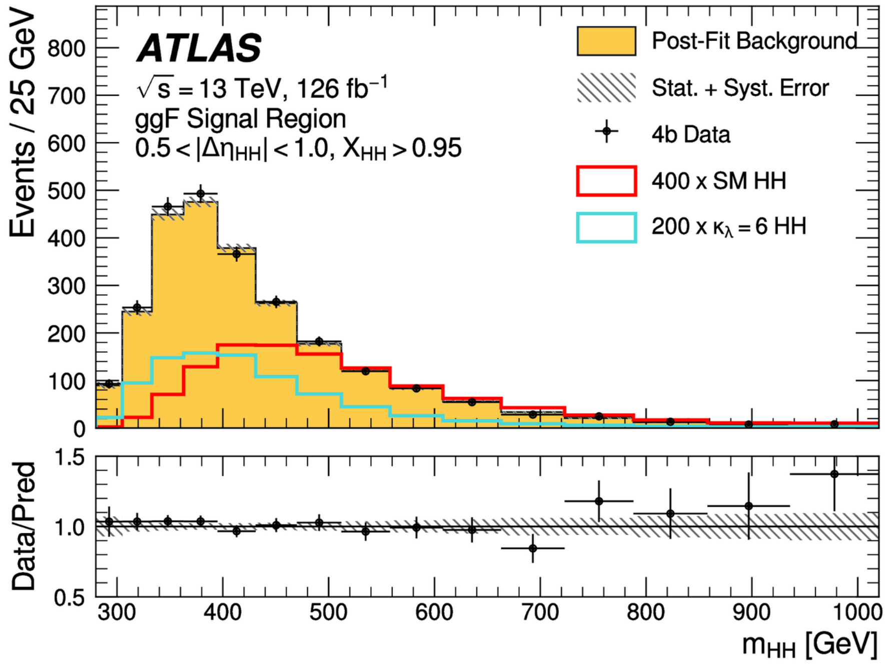
> Focus on resolved topologies here: ≥ 4 jets, ≥ 4 *b*-jets (signal region)

> Combinatorial problem: assign *b*-jets to the two Higgs decays

- Different possible approaches, based on m_{bb} or $\Delta R(b,b)$
- Focus on four leading *b*-jets → three possible combinations
- Choose configuration where Higgs candidate with the higher p_T has smallest $\Delta R(b,b)$



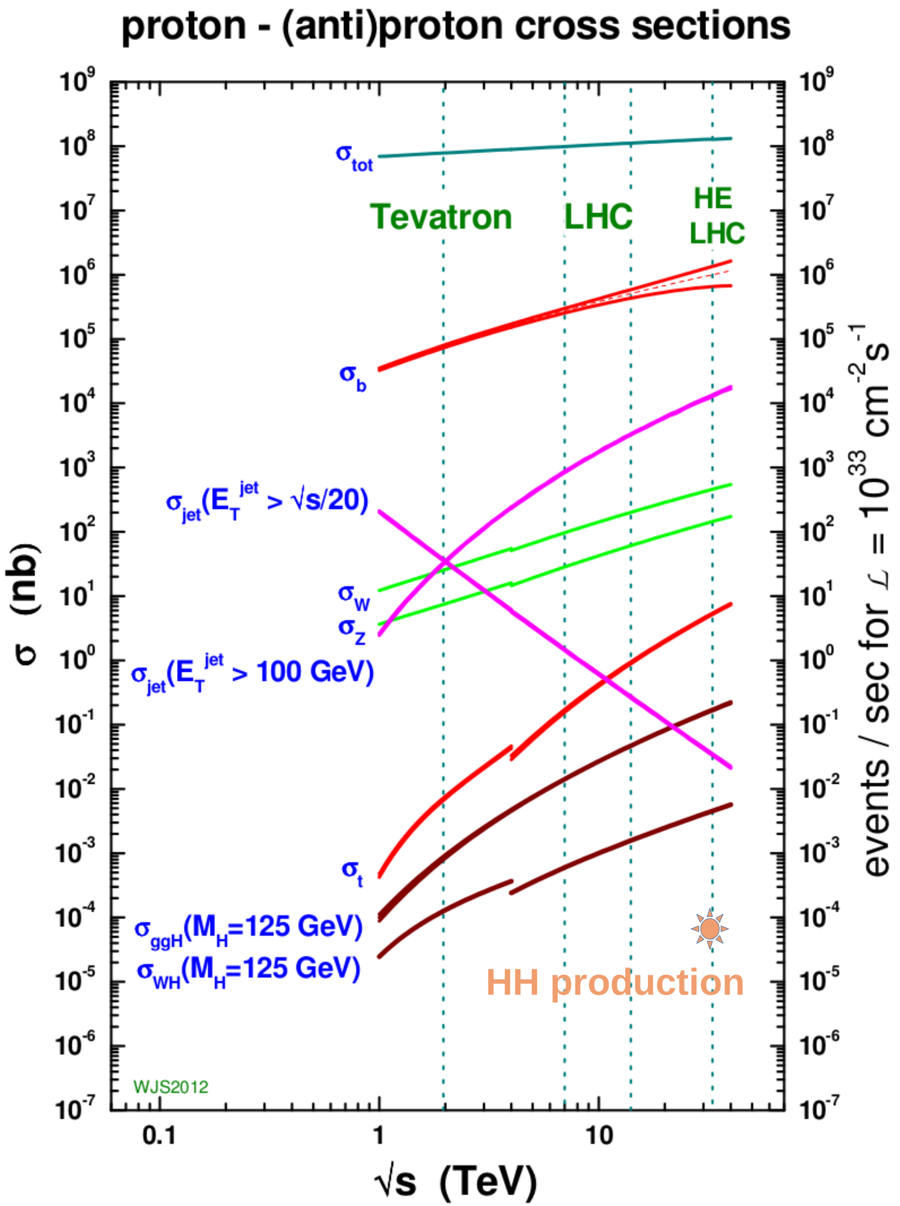
> Reconstruct m_{hh}



Background processes

> Background dominated by real *b*-jets and jets mis-identified as *b*-jets

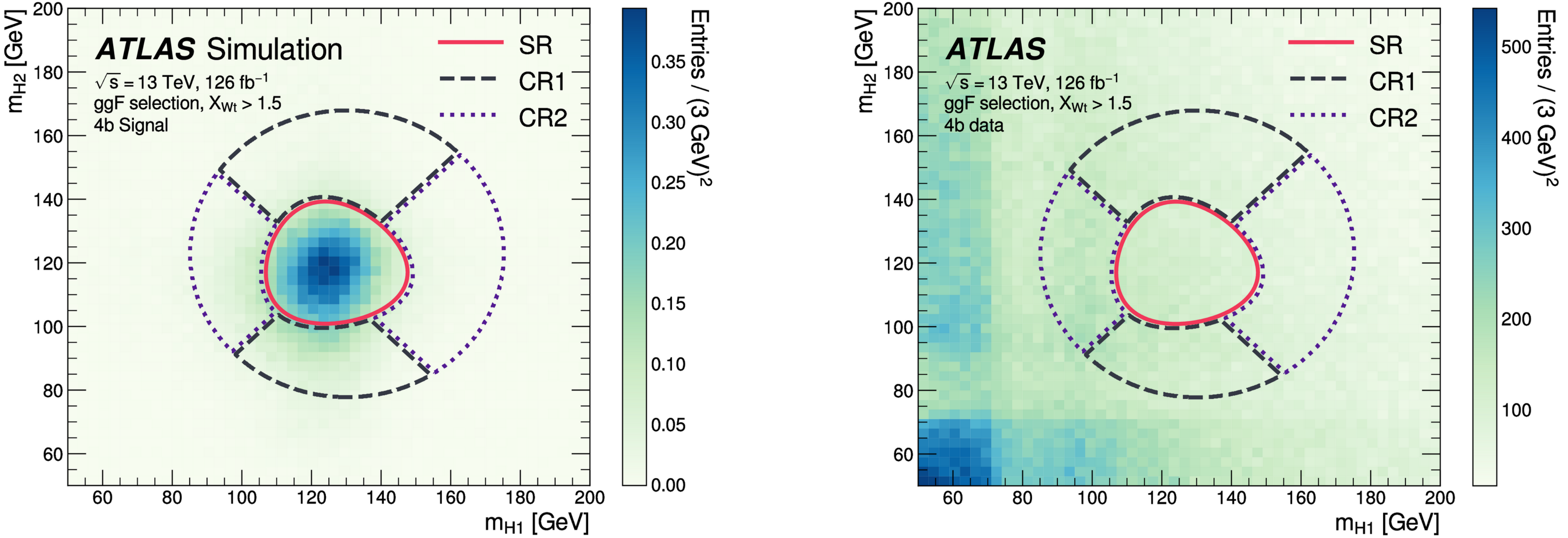
- Difficult to model in simulation due to relevance of detector effects



Analysis strategy for the *bbbb* channel

> Signal region: both Higgs candidates' masses close to 125 GeV

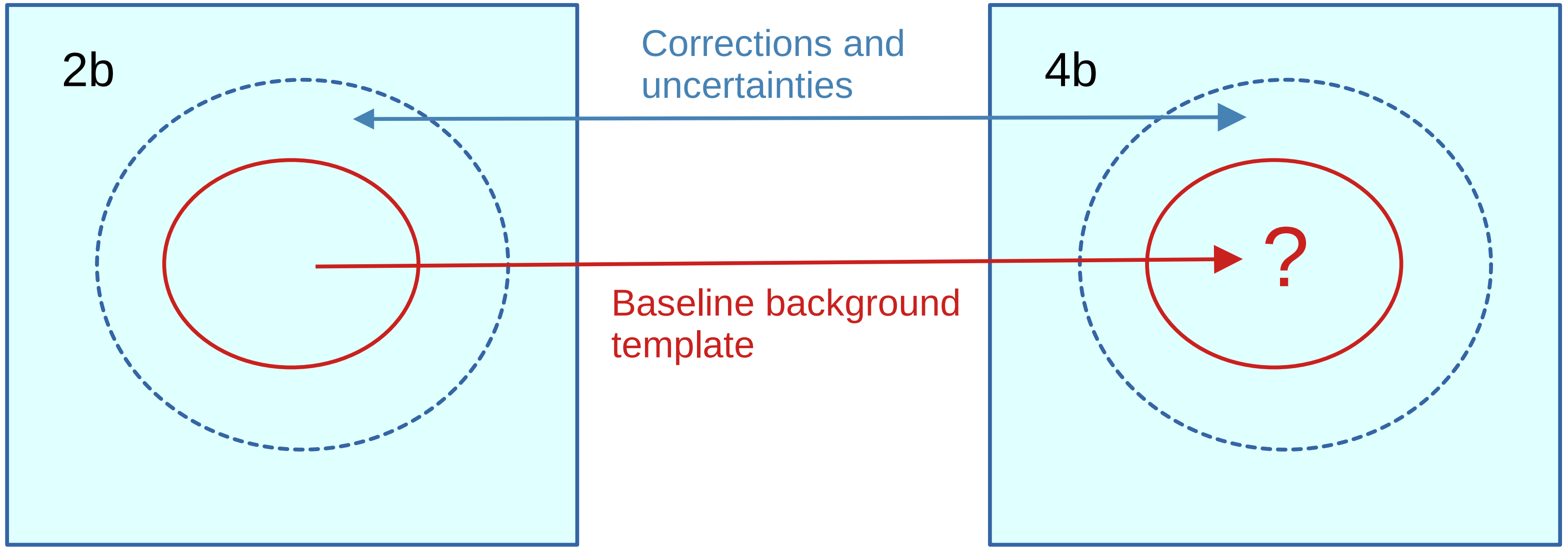
> Control regions used to estimate background from multi-jet production from data



Analysis strategy for the *bbbb* channel

> Background estimation:

- Define same regions in 2*b* data (background dominated)
- Baseline template from 2*b* “SR”
- Derive corrections and uncertainties by comparing 2*b* and 4*b* control regions



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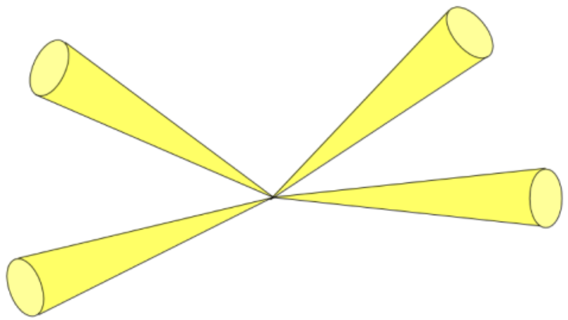
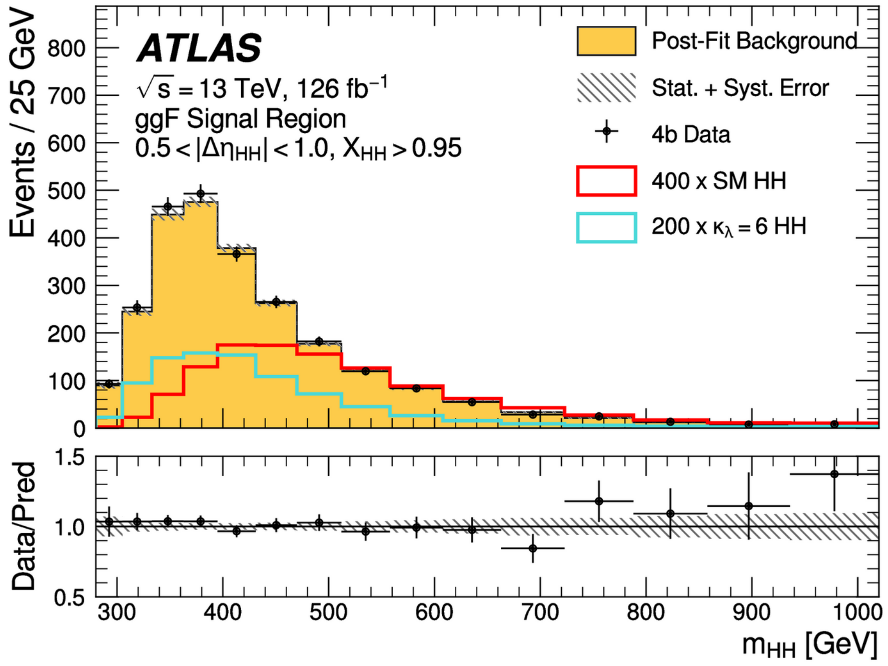


- Reconstruct m_{hh}
- Likelihood fit of predicted m_{hh} distribution to that in data
  - Prediction allowed to float within uncertainties



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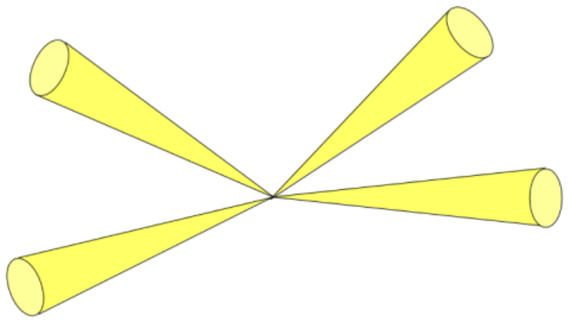

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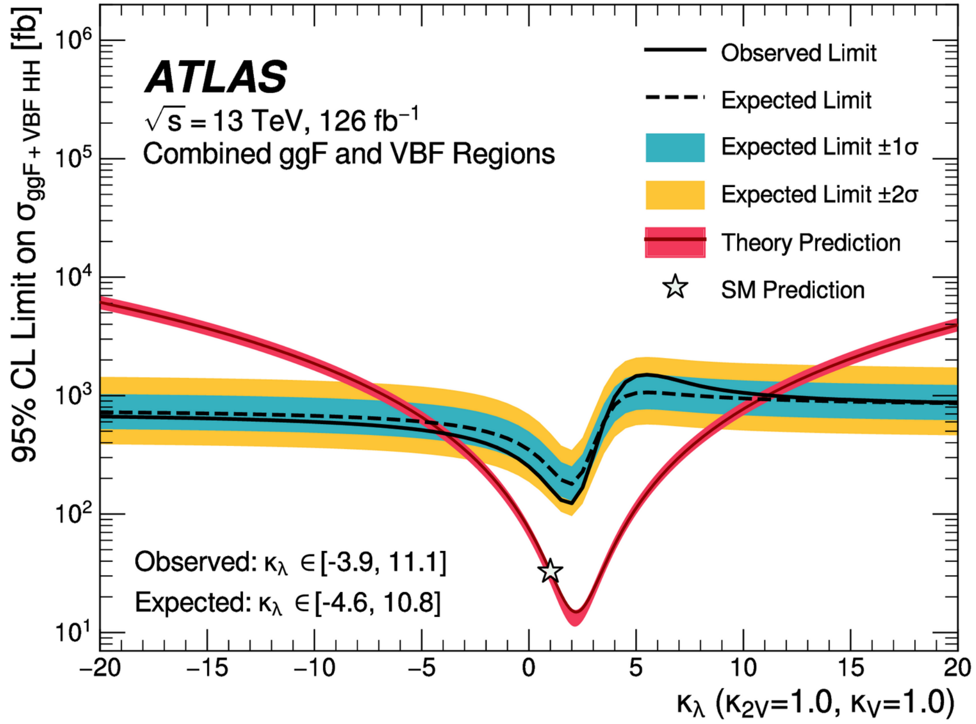
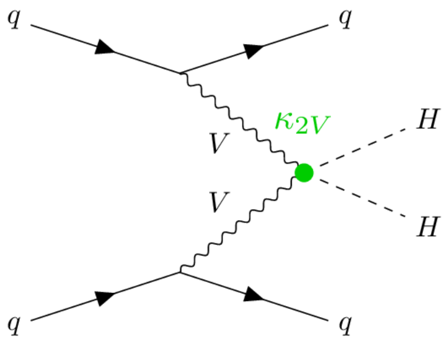
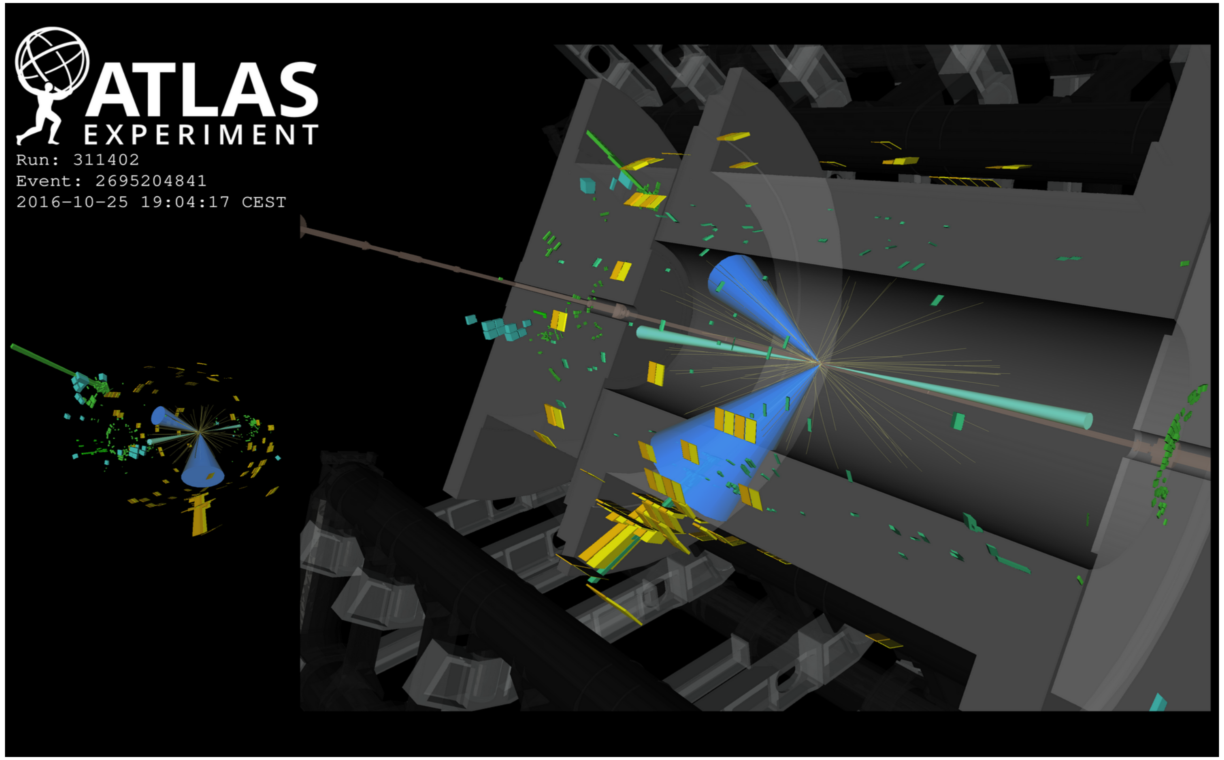
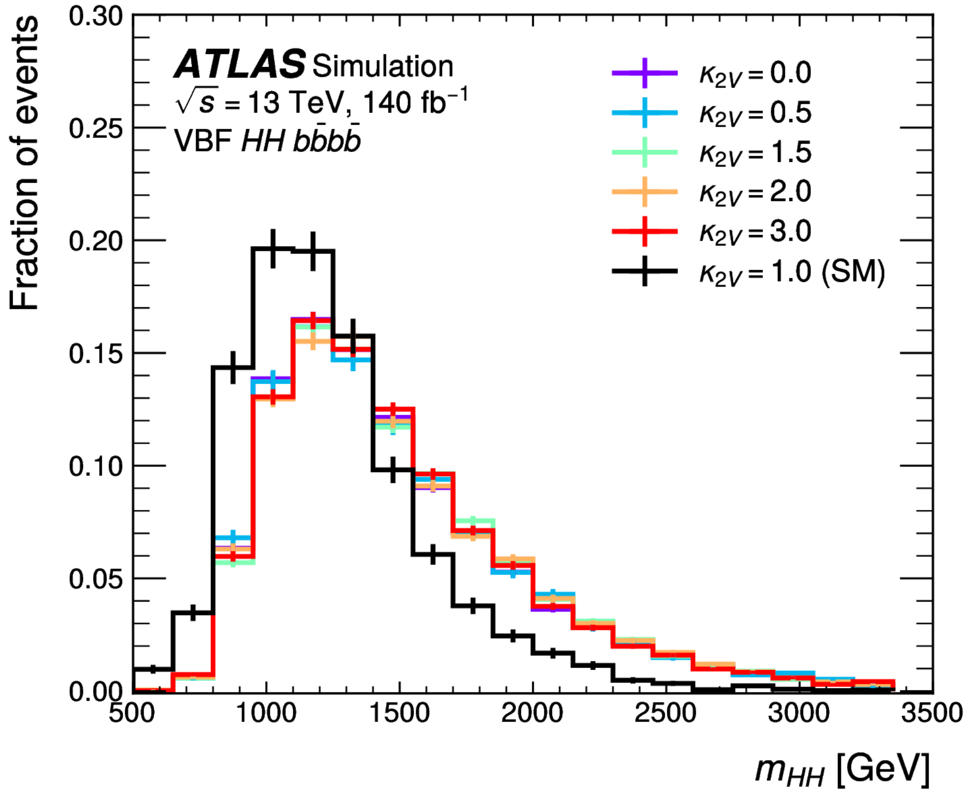


Constraining VVhh in vector-boson fusion

- Topologies with boosted Higgs boson particularly sensitive to non-SM values of k_{2V}
- Select events with two forward jets and two merged Higgs boson decays
- BDT trained on jet and event kinematics to separate signal and background
- Data-driven estimate of multi-jet background



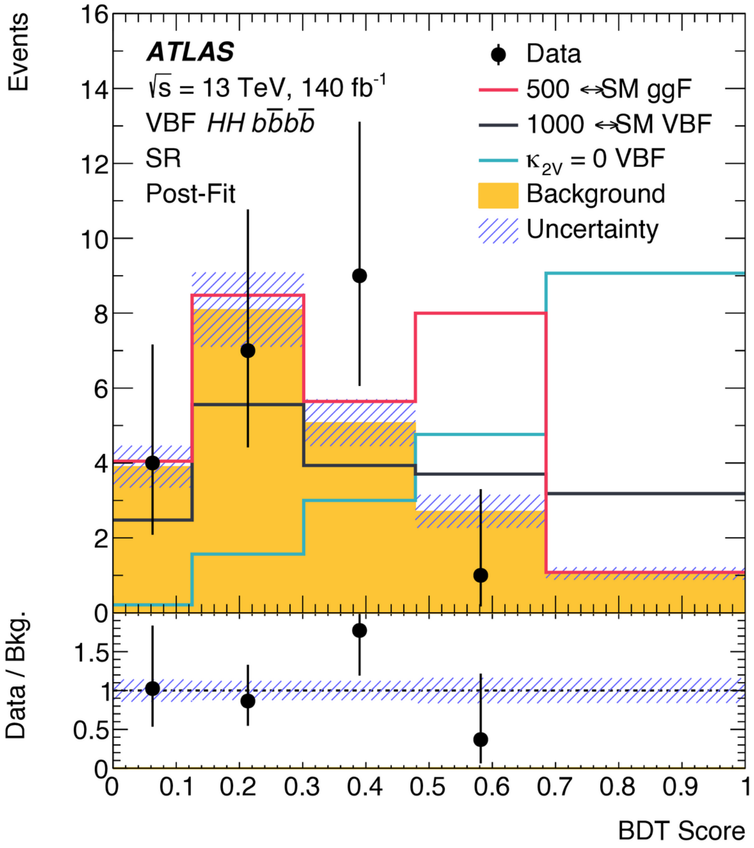


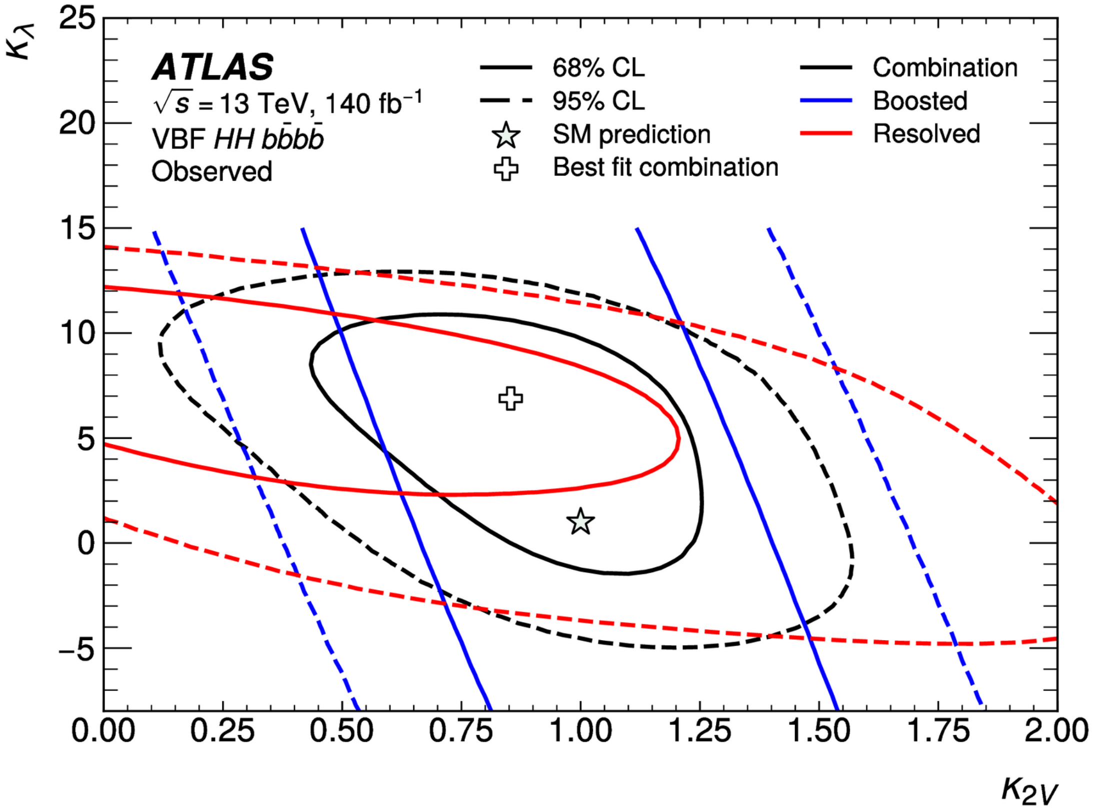


Constraining VVhh in vector-boson fusion

Phys. Lett. B 858 (2024) 139007

- Search primarily statistics-limited but Xbb tagging uncertainties also have a notable impact
- Interplay between boosted and resolved channels:
  - Resolved more sensitive to κ_λ, boosted more sensitive to κ_{2V}





Signatures of di-Higgs production

> Three most sensitive channels:

- *bbbb*: largest BR (34%), large multi-*b*-jet background
- *bbττ*: medium BR (7.3%), good signal purity

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Signature of the bbττ channel

> τ-leptons decay before interacting with the detector

> Leptonic decay: $\tau_{lep} \rightarrow e/\mu + 2\nu$

> Hadronic decays:

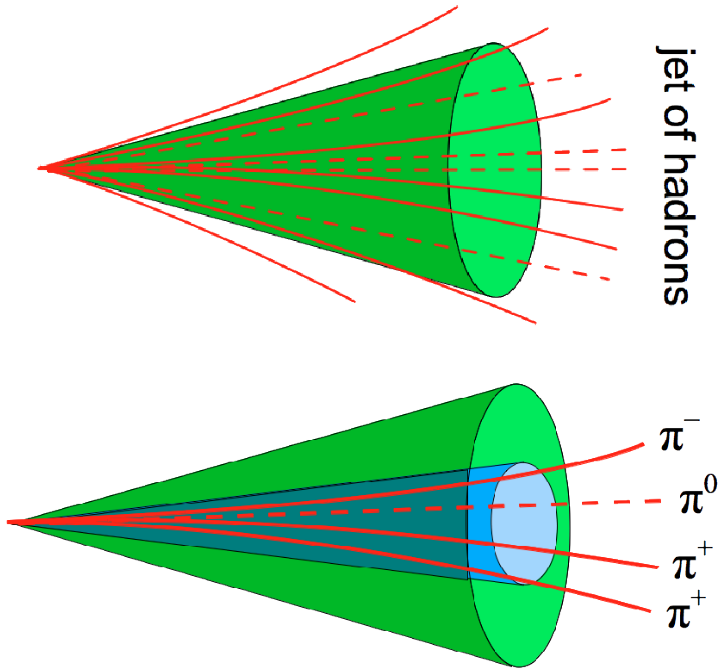
- $\tau_{had} \rightarrow 3\pi^{\pm} + X + \nu$ (3-prong)
- $\tau_{had} \rightarrow \pi^{\pm} + X + \nu$ (1-prong)

> τ-taggers to identify hadronic τ decays

- Run-2: BDTs
- Run-3: transformers (similar to *b*-taggers)

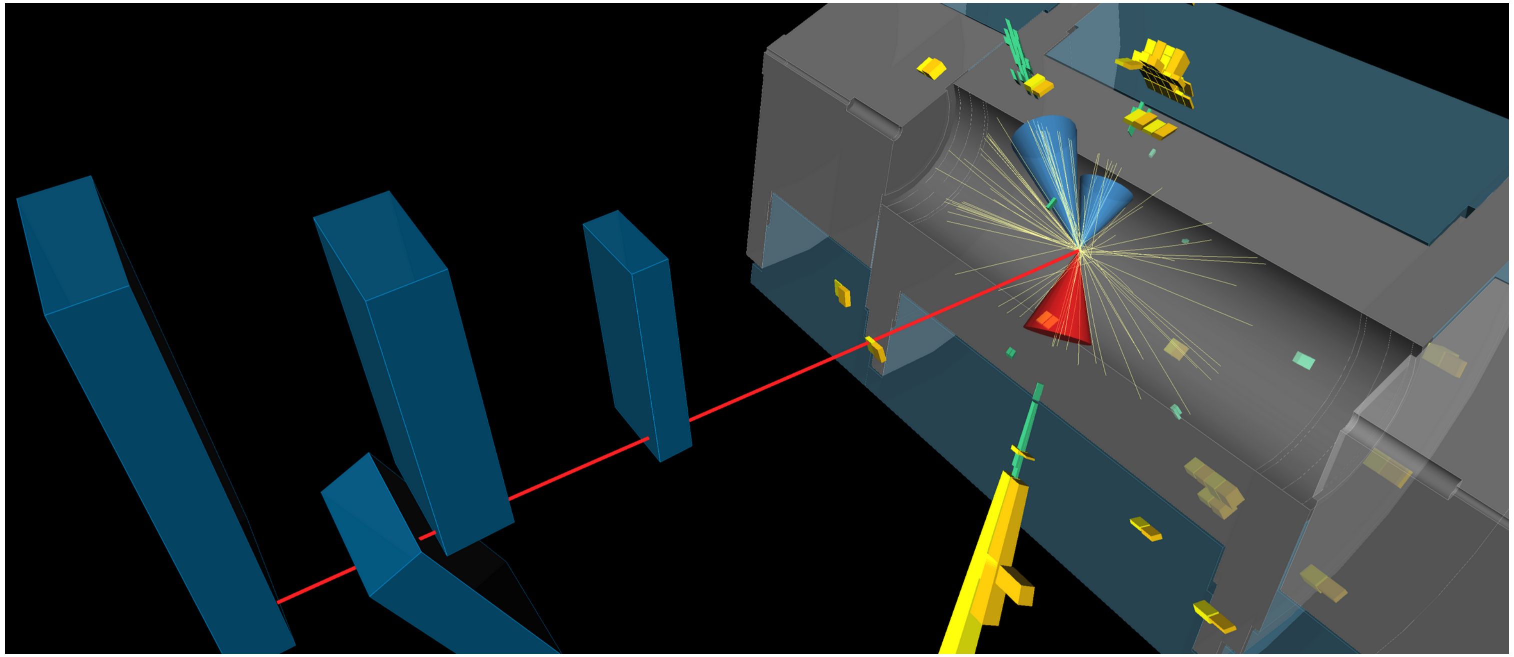
> Two orthogonal channels:

- LepHad: $\tau_{lep}\,\tau_{had}$
- HadHad: $\tau_{had}\,\tau_{had}$



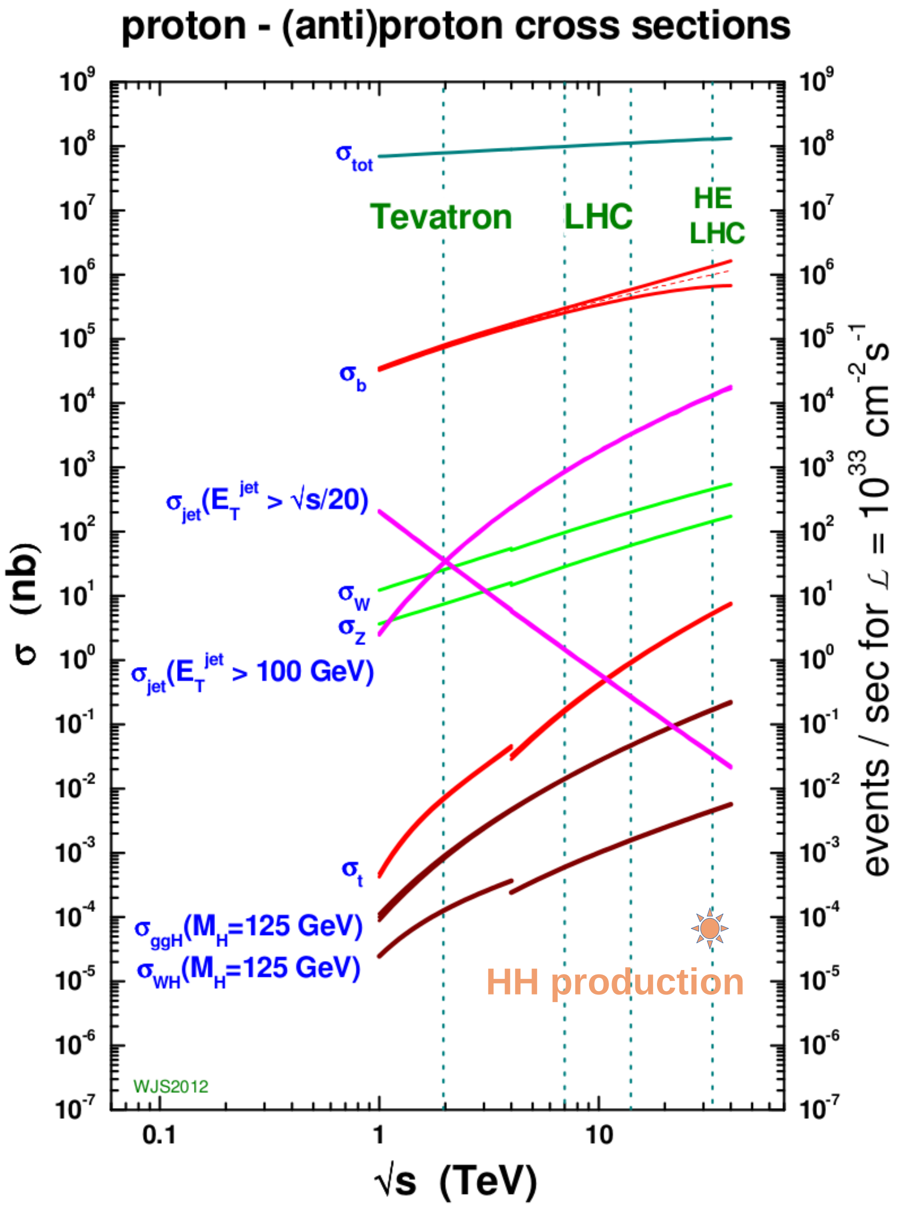
Background processes

Quiz question:
What SM processes can result in a *bbττ* final state?



Background processes

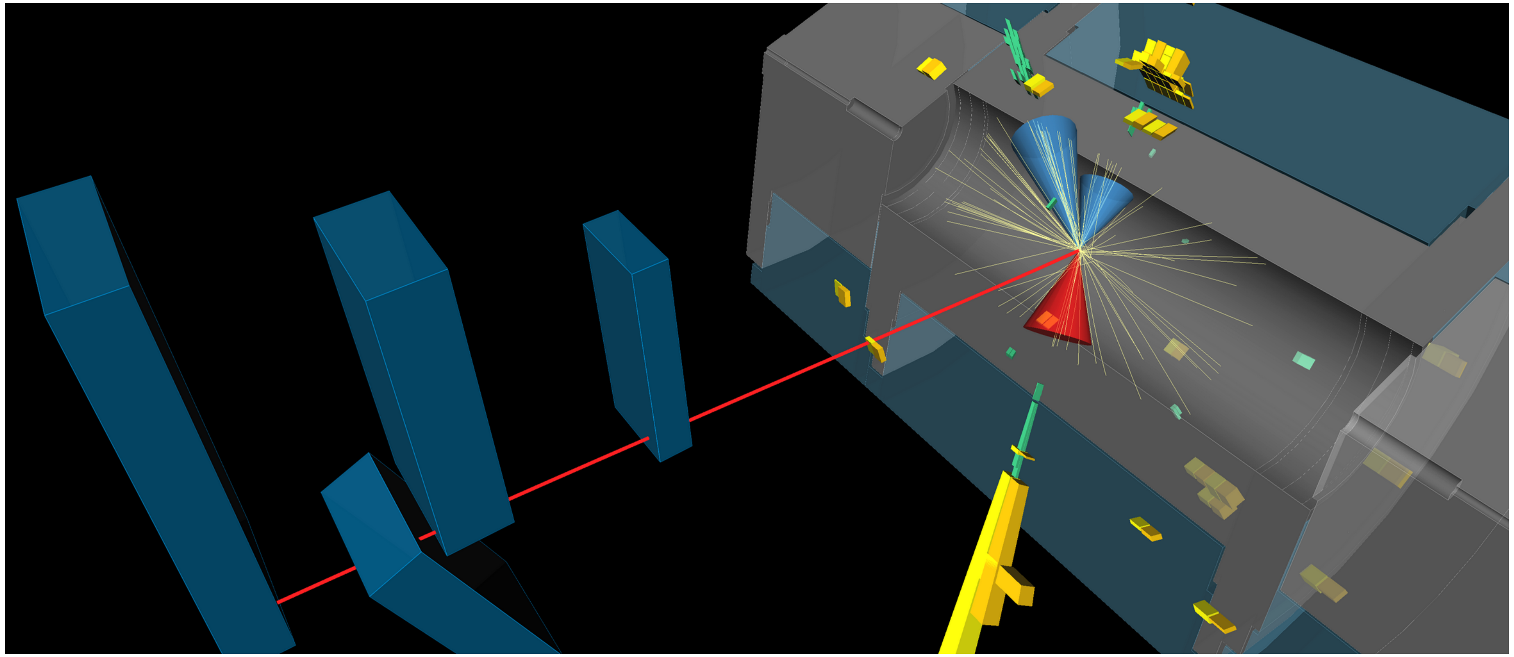
Quiz question:
What SM processes can result in a $bb\tau\tau$ final state?



Background processes

> Z+bb
- With Z → ττ
- Also: Z → ee, μμ with additional missing energy from mis-measurements

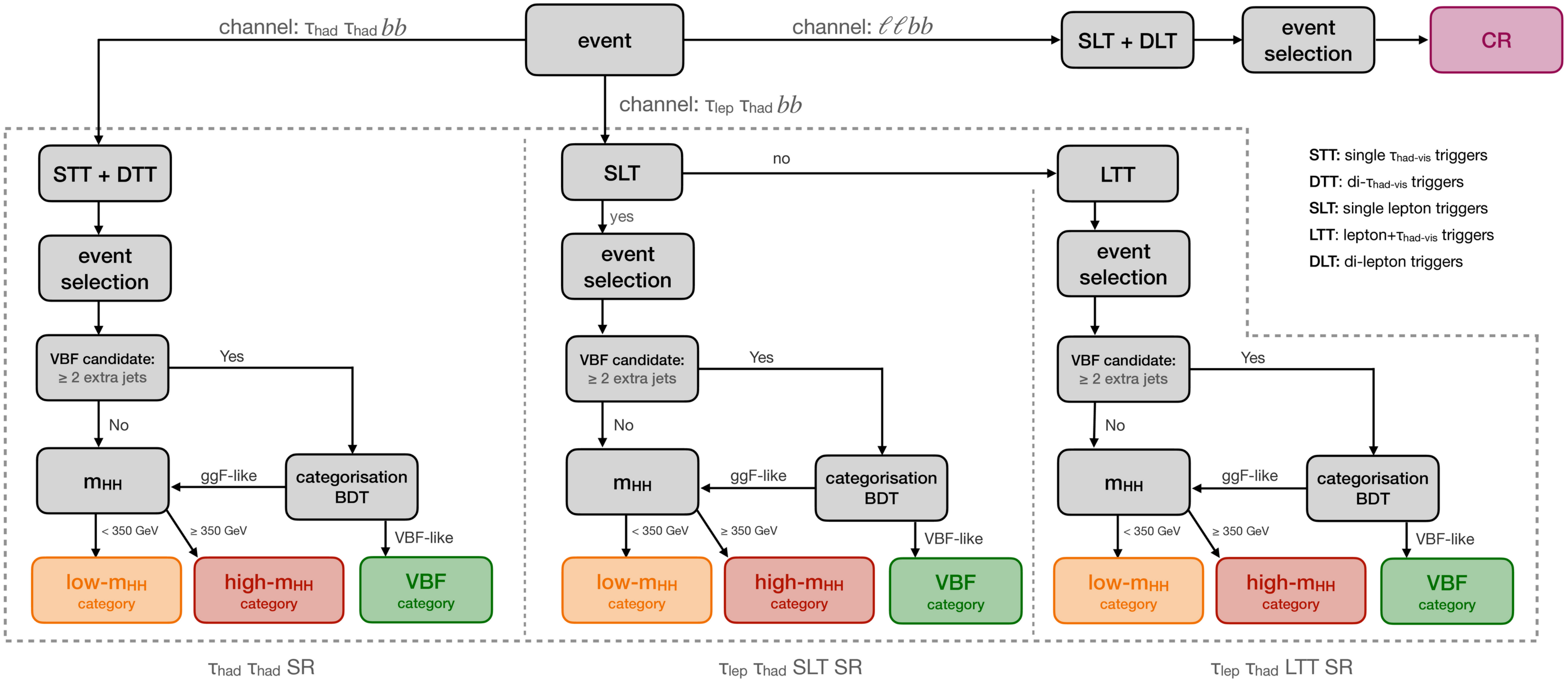
> tt → (Wb)(Wb)
- With (Wb)(Wb) → (τν)b(τν)b
- Also (Wb)(Wb) → (eνb)(μνb) ...



Complex analysis strategy for the *bbττ* channel

> Loose pre-selection of events based on different triggers

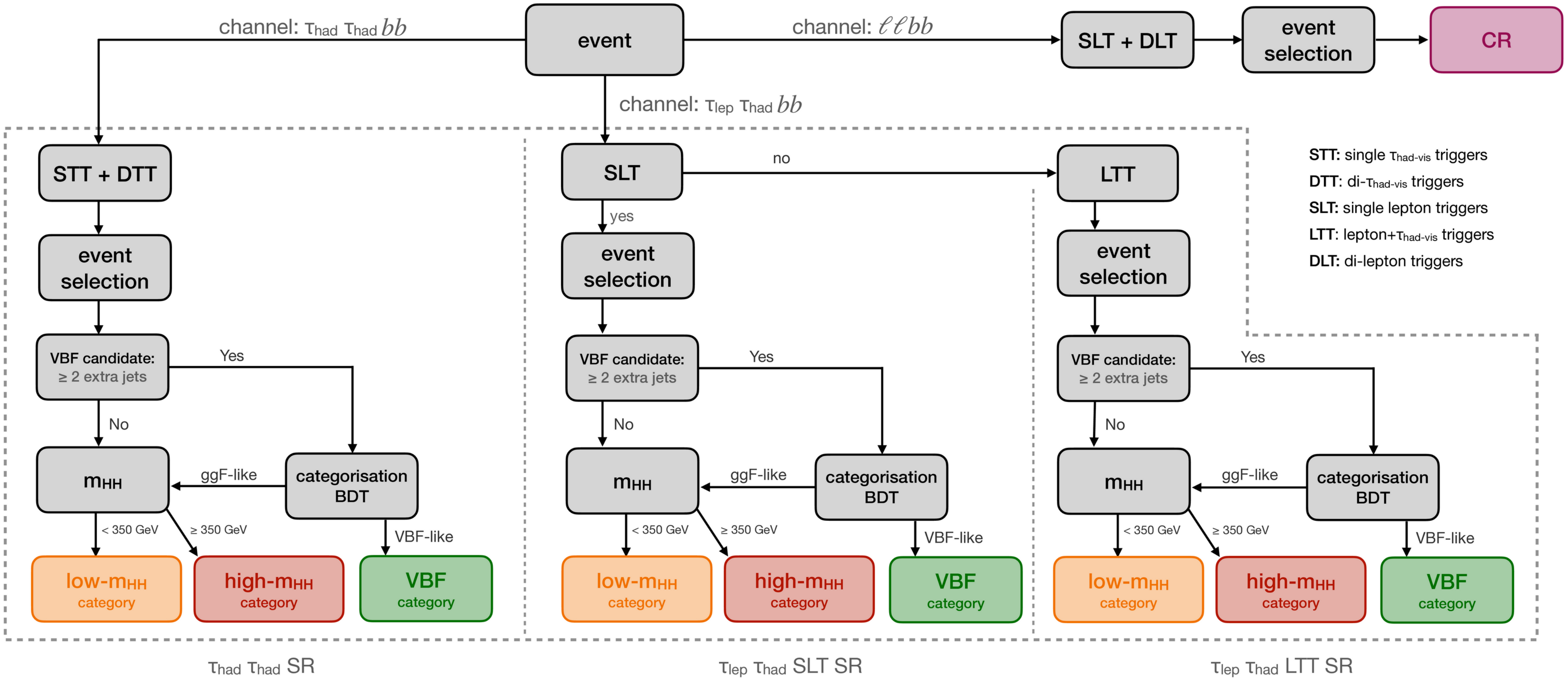
- Triggers requiring one or two τ_{had} candidates vs triggers requiring one or two e/μ



STT: single $\tau_{had\text{-}vis}$ triggers
DTT: di-$\tau_{had\text{-}vis}$ triggers
SLT: single lepton triggers
LTT: lepton+$\tau_{had\text{-}vis}$ triggers
DLT: di-lepton triggers

Complex analysis strategy for the *bbττ* channel

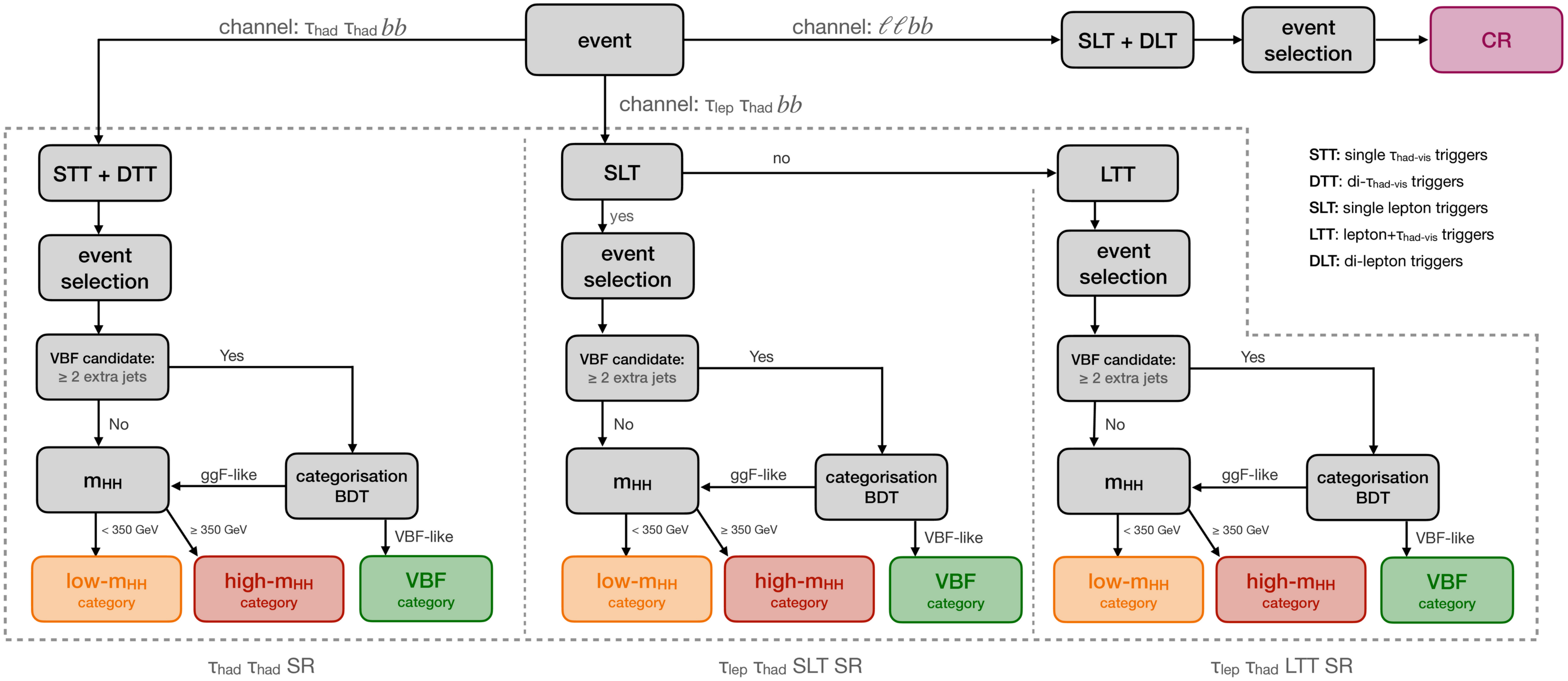
> Control regions to estimate main backgrounds from Z+jets and ttbar production



STT: single $\tau_{had\text{-}vis}$ triggers
DTT: di-$\tau_{had\text{-}vis}$ triggers
SLT: single lepton triggers
LTT: lepton+$\tau_{had\text{-}vis}$ triggers
DLT: di-lepton triggers

Complex analysis strategy for the *bbττ* channel

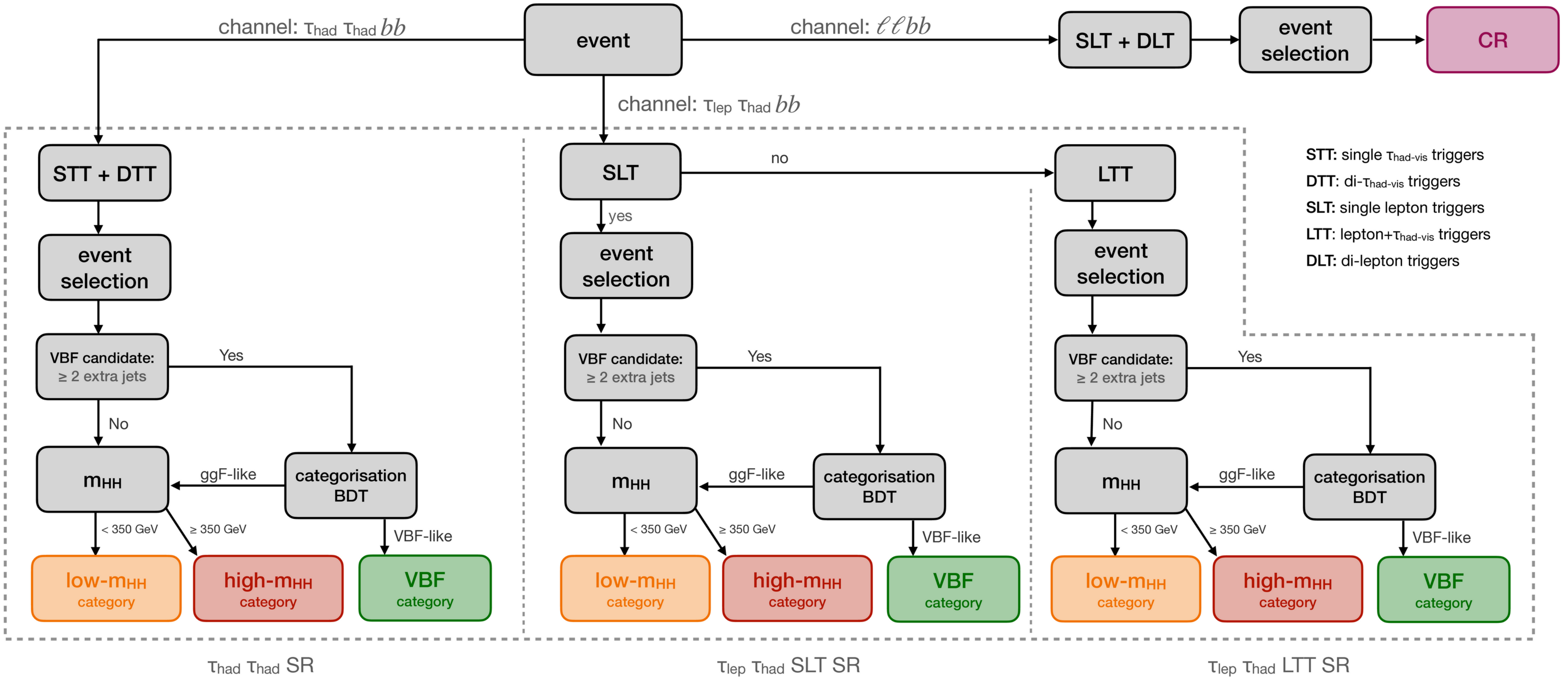
> Multivariate classifier in each to distinguish between ggF and VBF production



Complex analysis strategy for the *bbττ* channel

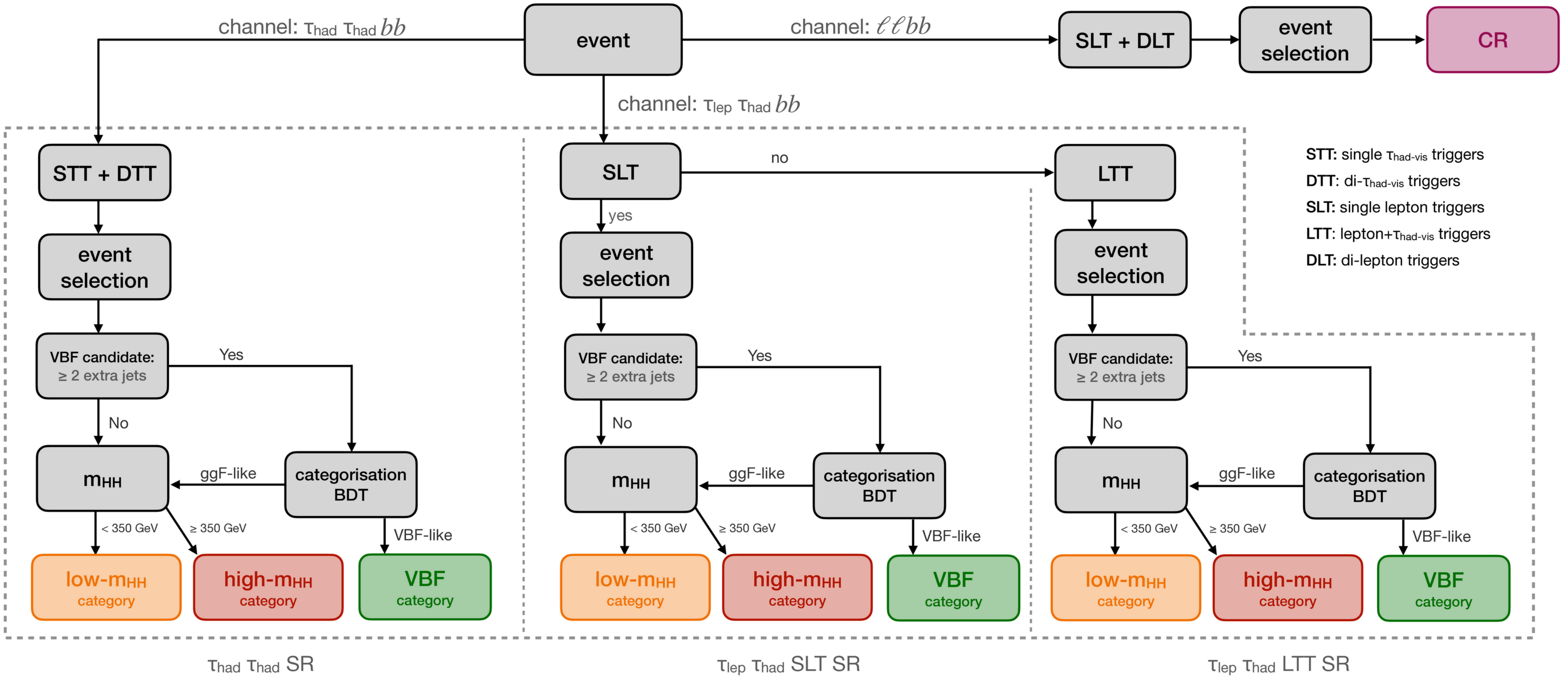
> Multivariate classifier in each to distinguish between ggF and VBF production

> Additional categorisation based on m_{hh}



Complex analysis strategy for the *bbττ* channel

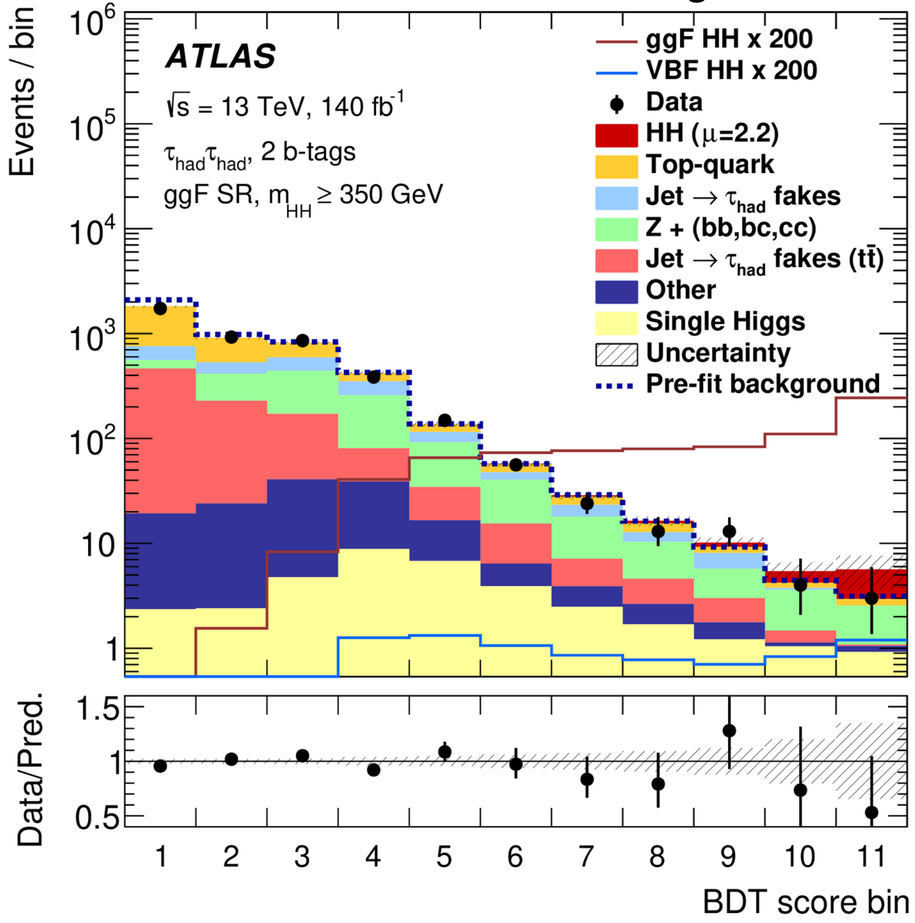
> Multivariate classifier to distinguish signal from background in each sub-category



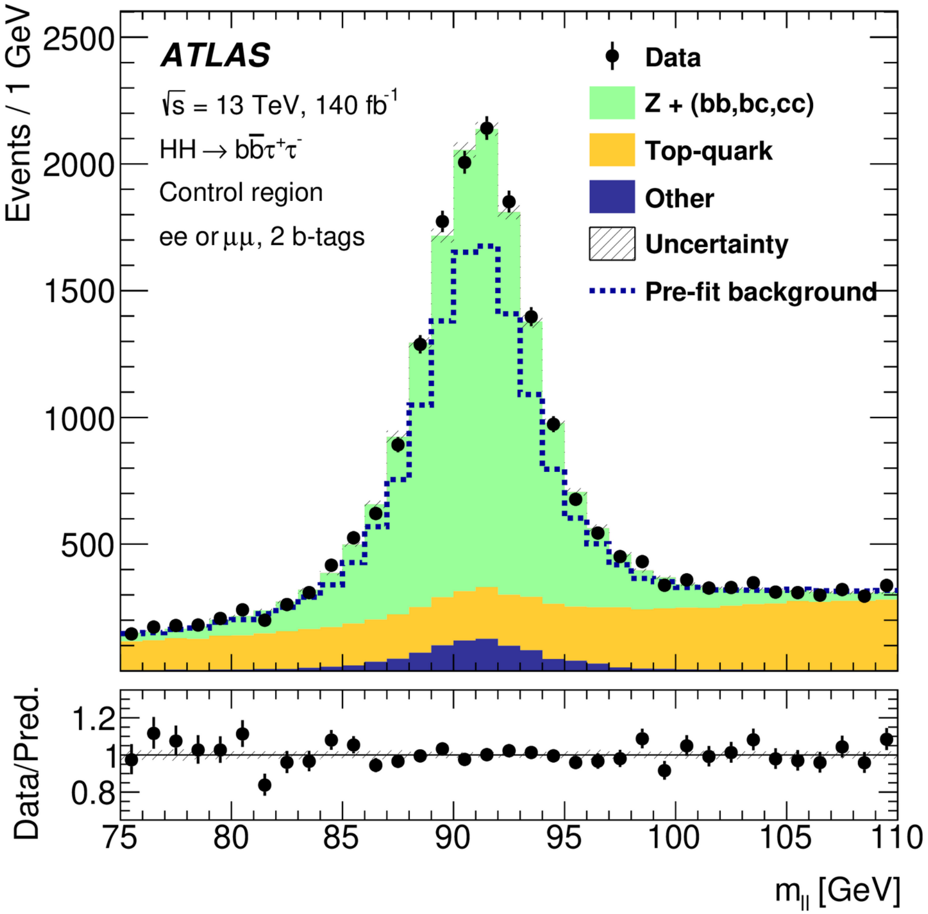
Complex analysis strategy for the *bbττ* channel

- Backgrounds estimated from simulation and corrected using data in control regions
- Simultaneous fit of predictions to data: BDT scores in each signal region + distributions in control regions

BDT score in $\tau_{had}\tau_{had}$ region

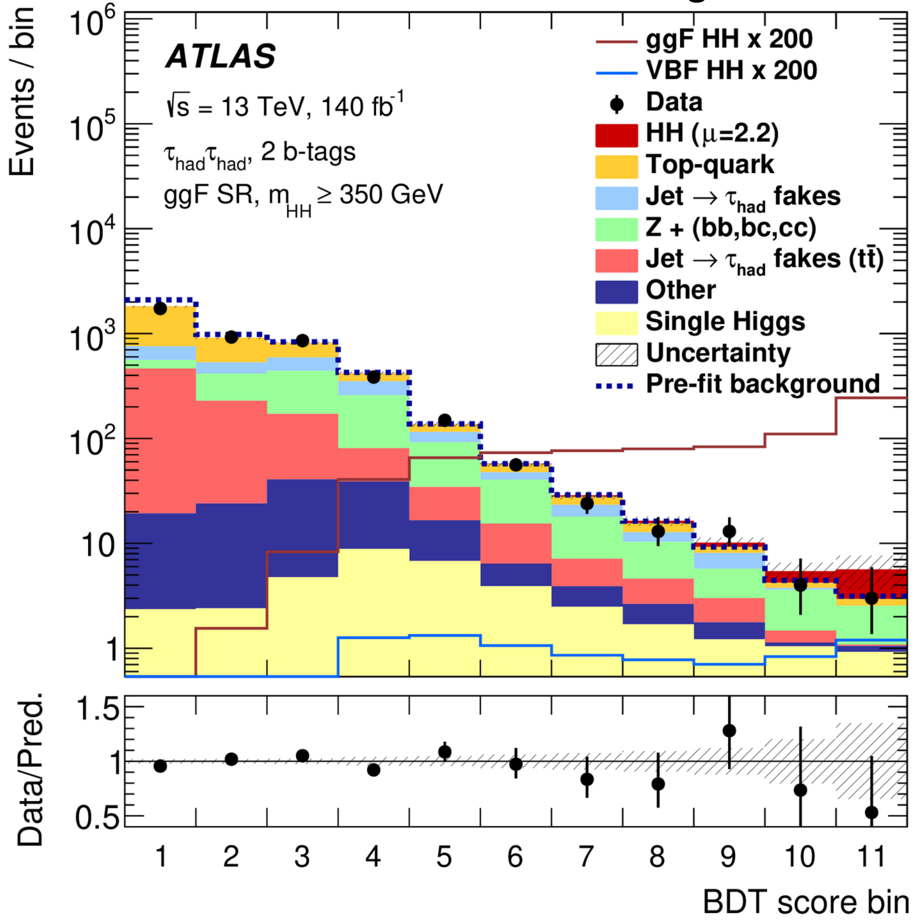


Z+jets control region

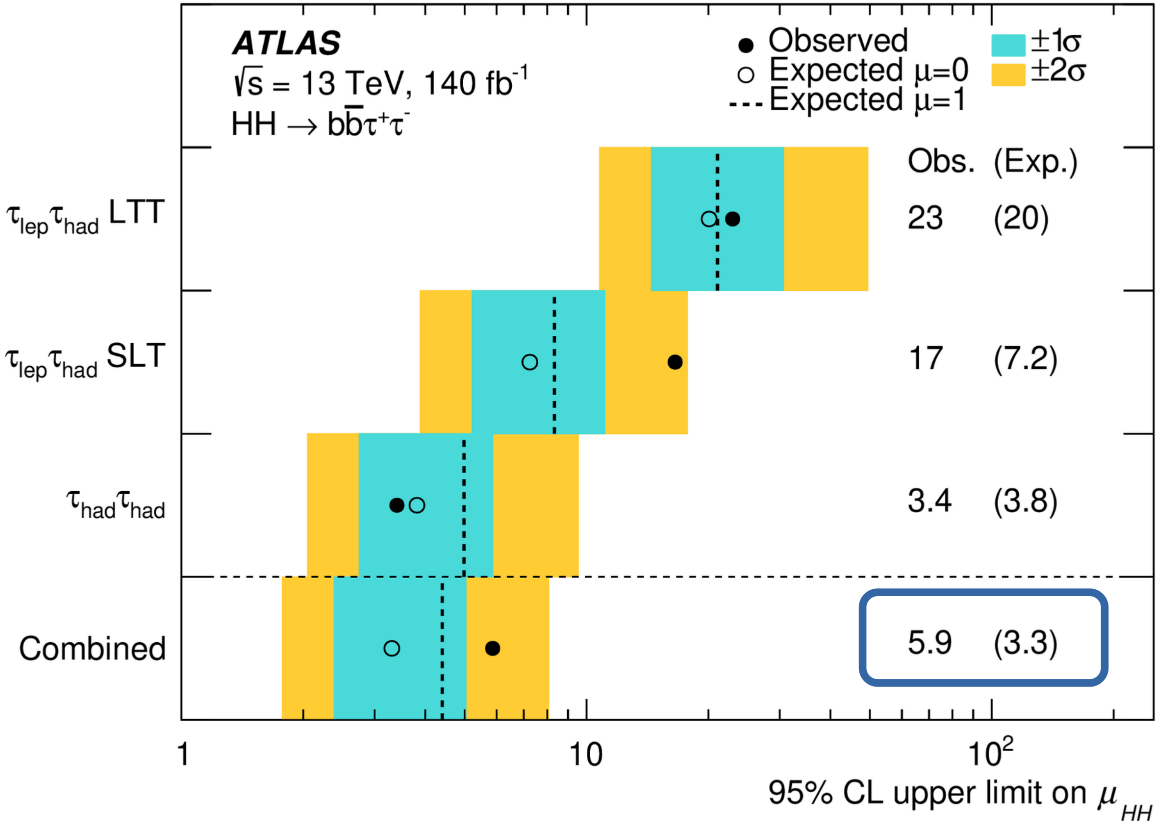


> Simultaneous fit of predictions to data: BDT scores in each signal region + distributions in control regions

BDT score in $\tau_{had}\tau_{had}$ region



μ_{hh} = measured xsec / SM xsec



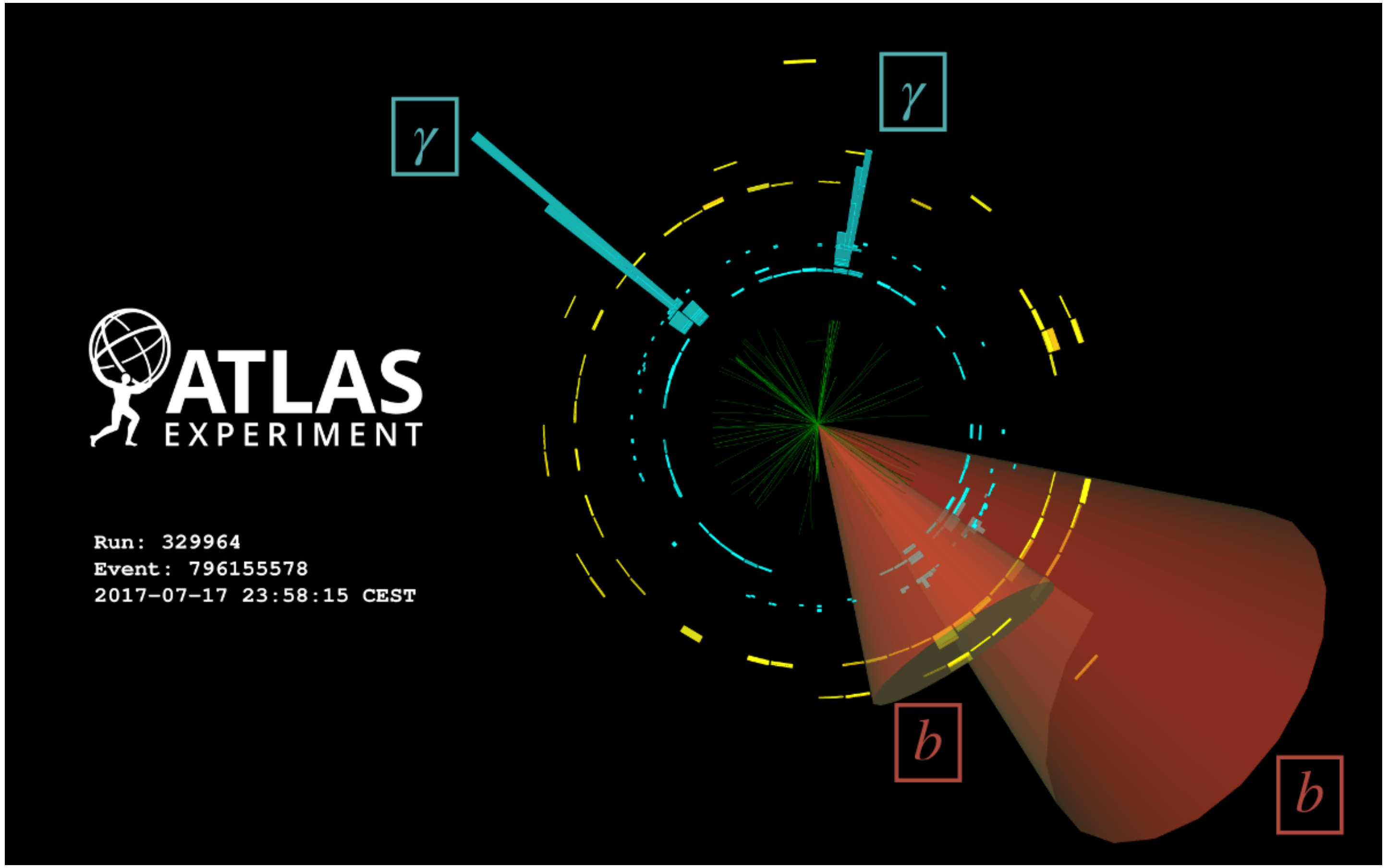
Signatures of di-Higgs production

> Three most sensitive channels:
  - *bbbb*: largest BR (34%), large multi-*b*-jet background
  - *bbττ*: medium BR (7.3%), good signal purity
  - *bbγγ*: clean channel, but low BR (0.26%)

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Signature of the *bbyy* channel

- Photons can be efficiently and precisely with the electromagnetic calorimeters
- Require events with two photons and at least two b-tagged jets
- Straightforward reconstruction of two Higgs candidates

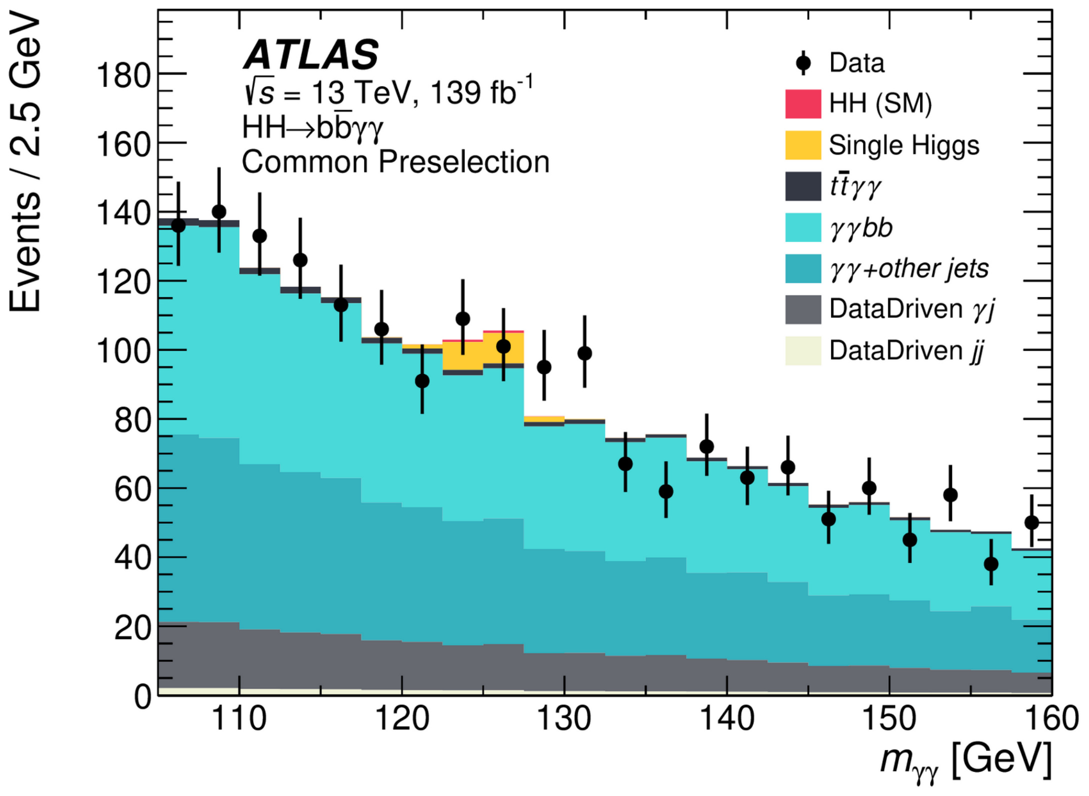


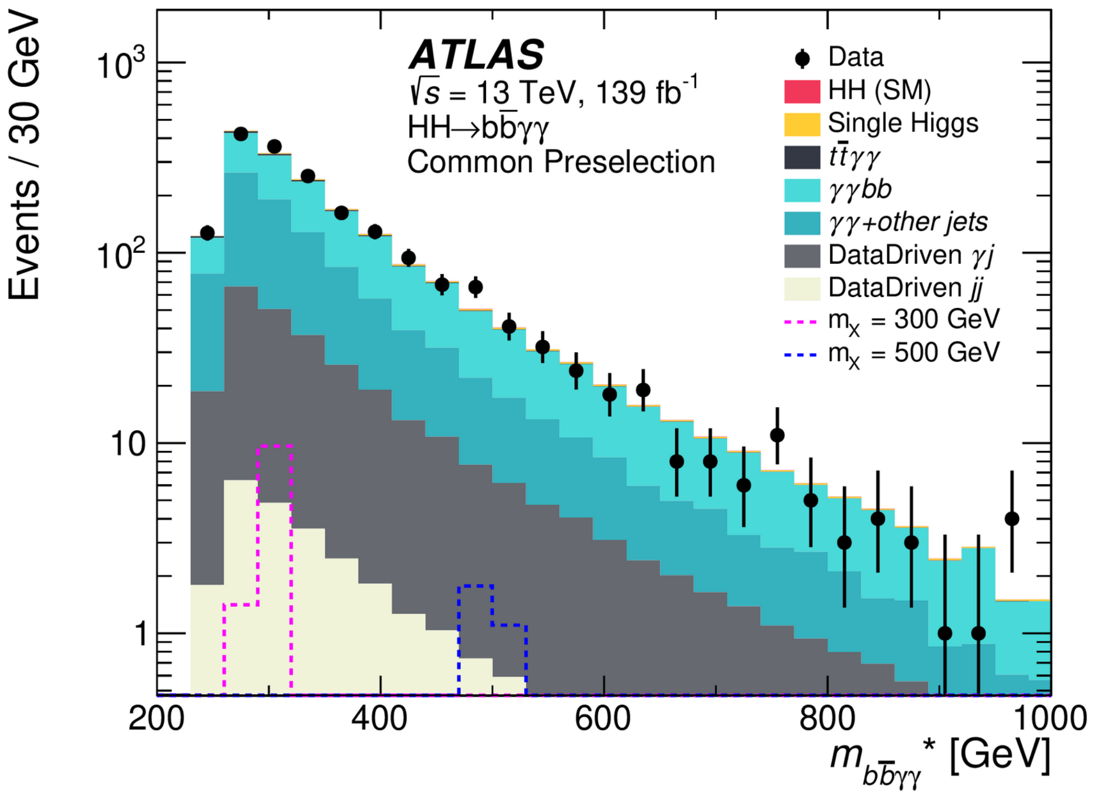
Analysis strategy of the *bbyy* channel

> Mass resolution of Higgs candidate from *yy* much better than *bb*

- Use m_{yy} as discriminating variable instead of m_{yybb}

> Main backgrounds from real photons produced in association with jets → taken from simulation

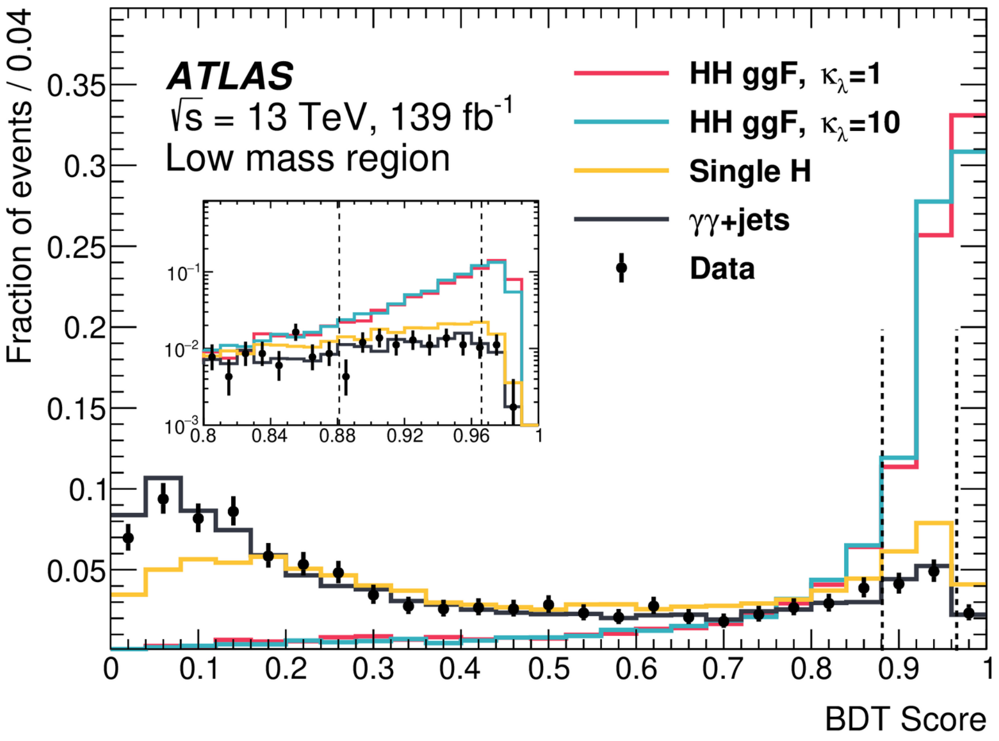


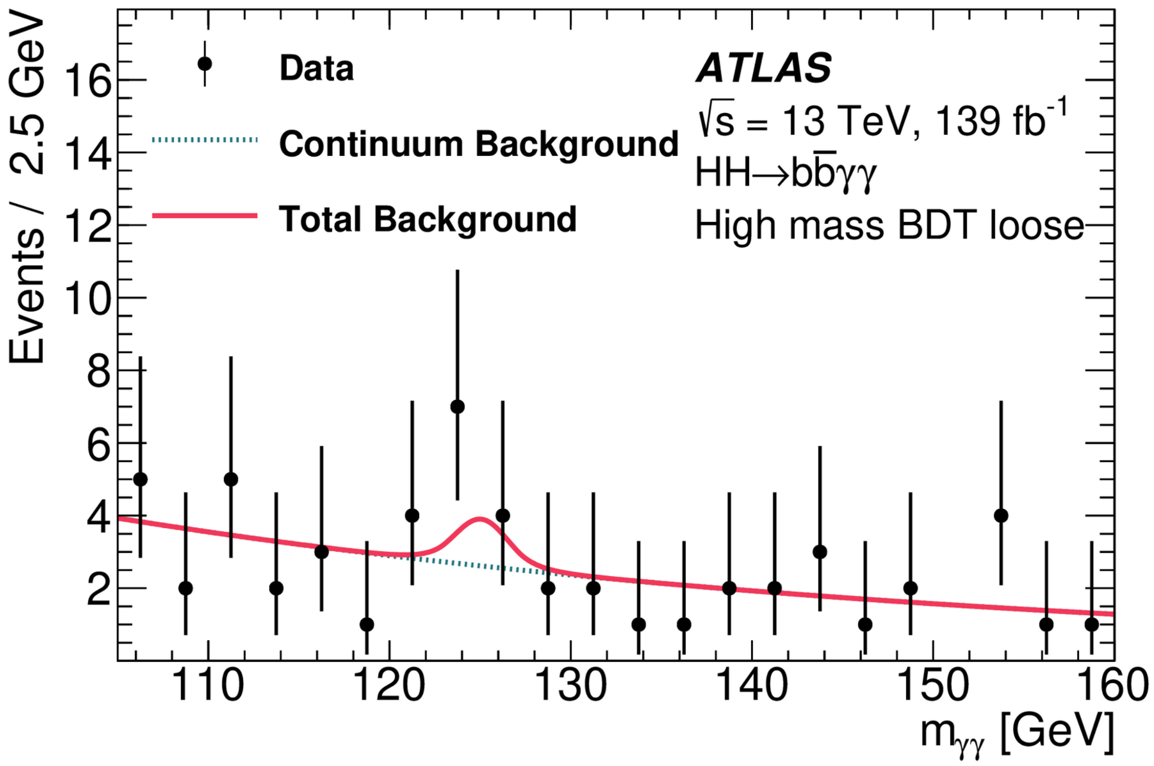


Analysis strategy of the *bbyy* channel

> Multivariate methods to improve signal-background discrimination
  - Trained separately in different m_{bbyy} regions for better sensitivity

> Fit analytic function for signal+background hypothesis to data in each signal region
  - Similar to Higgs-boson discovery and measurements in *yy* decay channel





Combination of hh searches (ATLAS, Run 2)

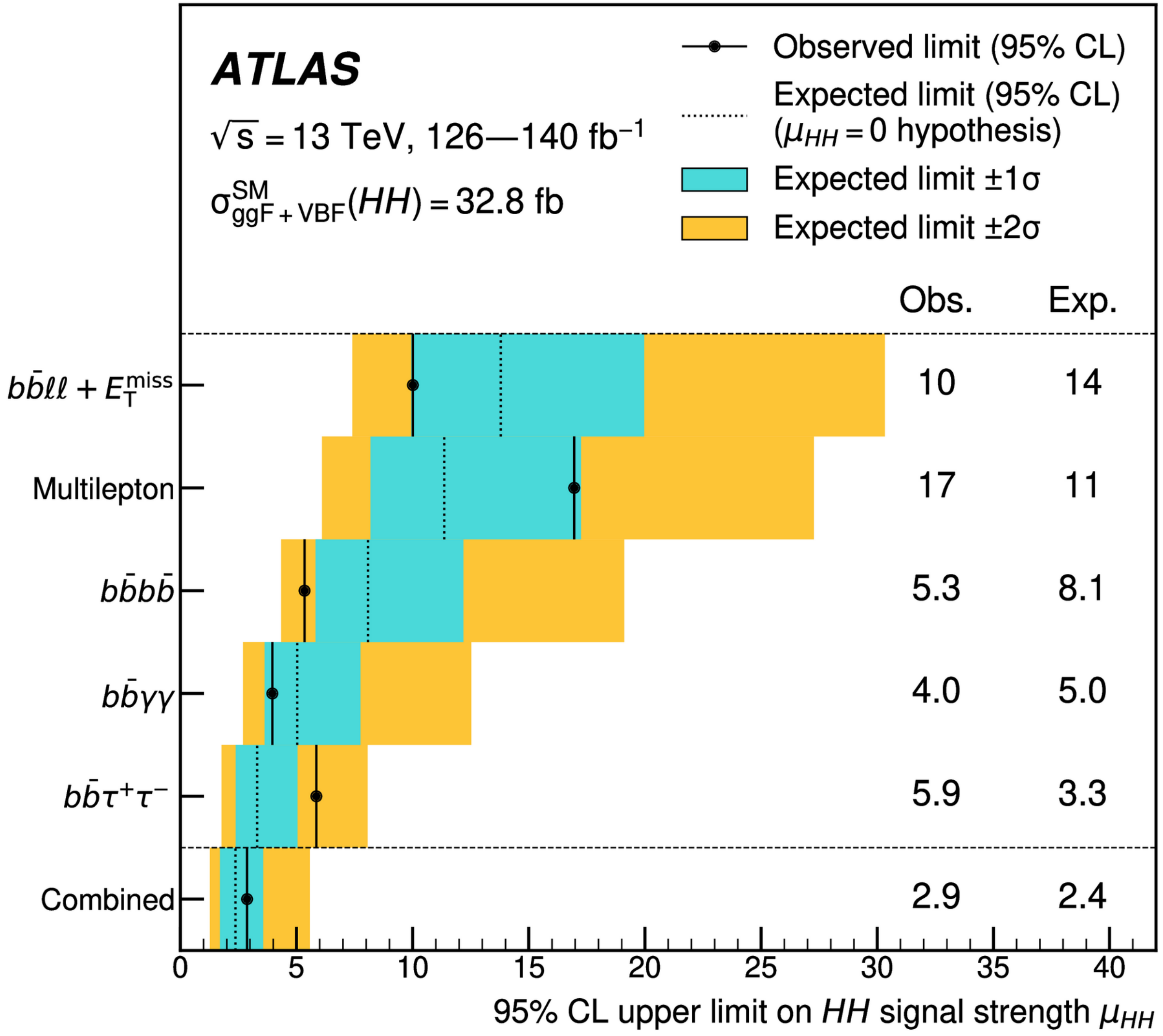
Phys. Rev. Lett. 133 (2024) 101801

> Statistical combination of three leading channels + sub-dominant channels

> Current best constraints on Higgs pair production

$\mu_{hh} < 2.9$ (2.4 exp.)

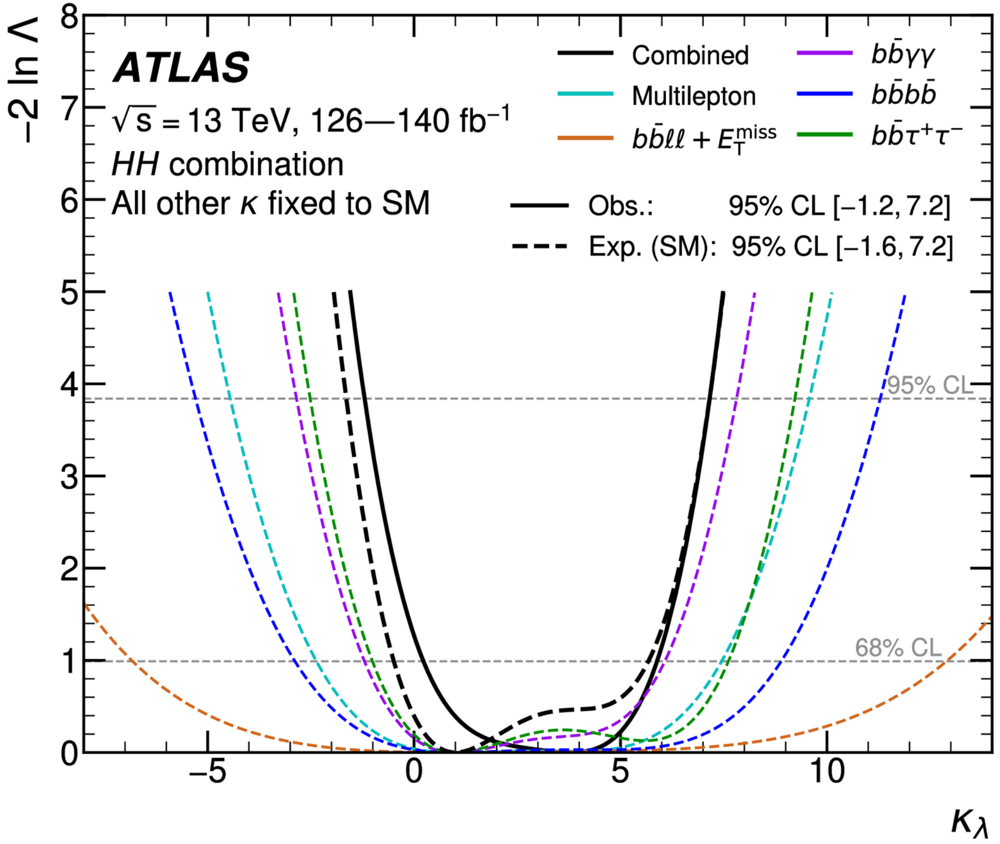
μ_{hh} = measured xsec / SM xsec



> Significant improvement in expected sensitivity on κ_λ

Observed: $\kappa_\lambda \in [-1.2, 7.2]$
Expected: $\kappa_\lambda \in [-1.6, 7.2]$

Dominated by *bbττ* and *bbγγ*
(photon and lepton triggers powerful at low m_{hh})



Combination of hh searches (ATLAS, Run 2)

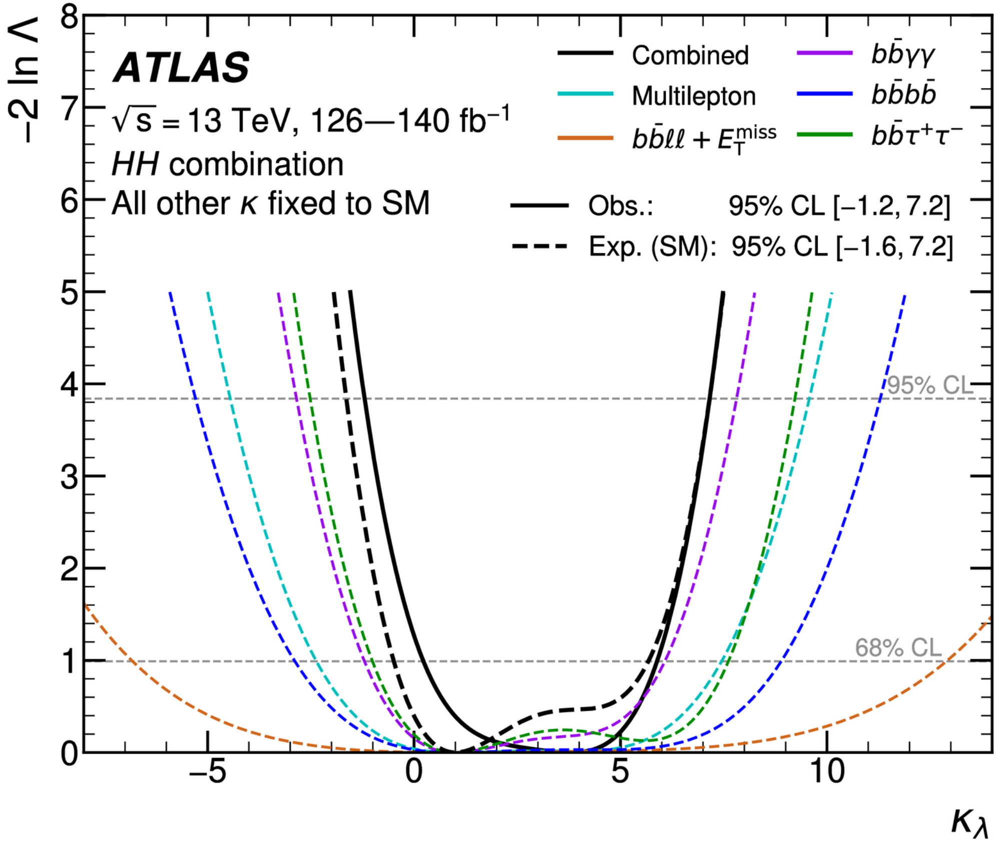
Phys. Rev. Lett. 133 (2024) 101801

> Significant improvement in expected sensitivity on κ_λ

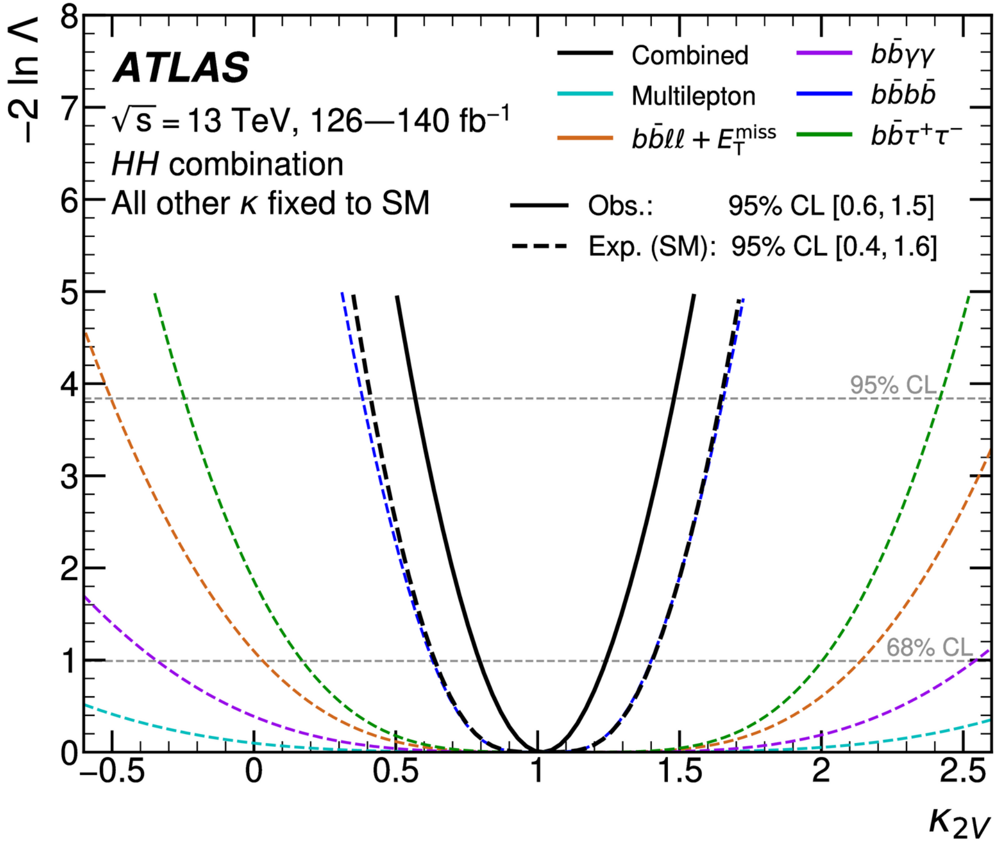
Observed: $\kappa_\lambda \in [-1.2, 7.2]$
Expected: $\kappa_\lambda \in [-1.6, 7.2]$

Observed: $\kappa_{2V} \in [-0.6, 1.5]$
Expected: $\kappa_{2V} \in [-0.4, 1.6]$

Dominated by *bbττ* and *bbγγ*
(photon and lepton triggers powerful at low m_{hh})



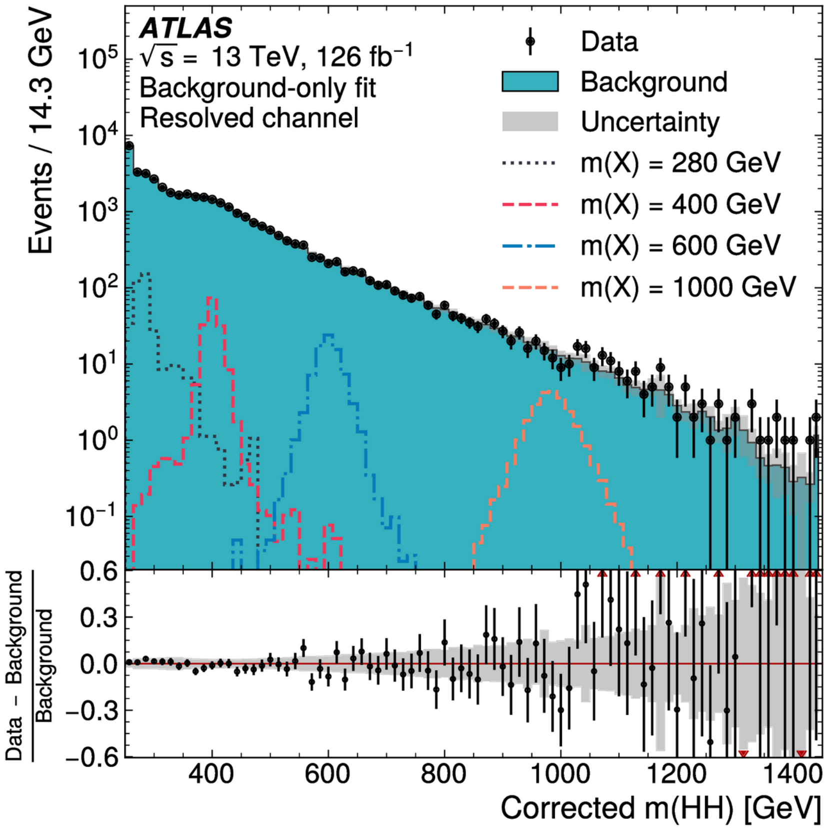
Dominated by boosted VBF *bbbb*
(boosted *bbbb* signatures powerful at high m_{hh})

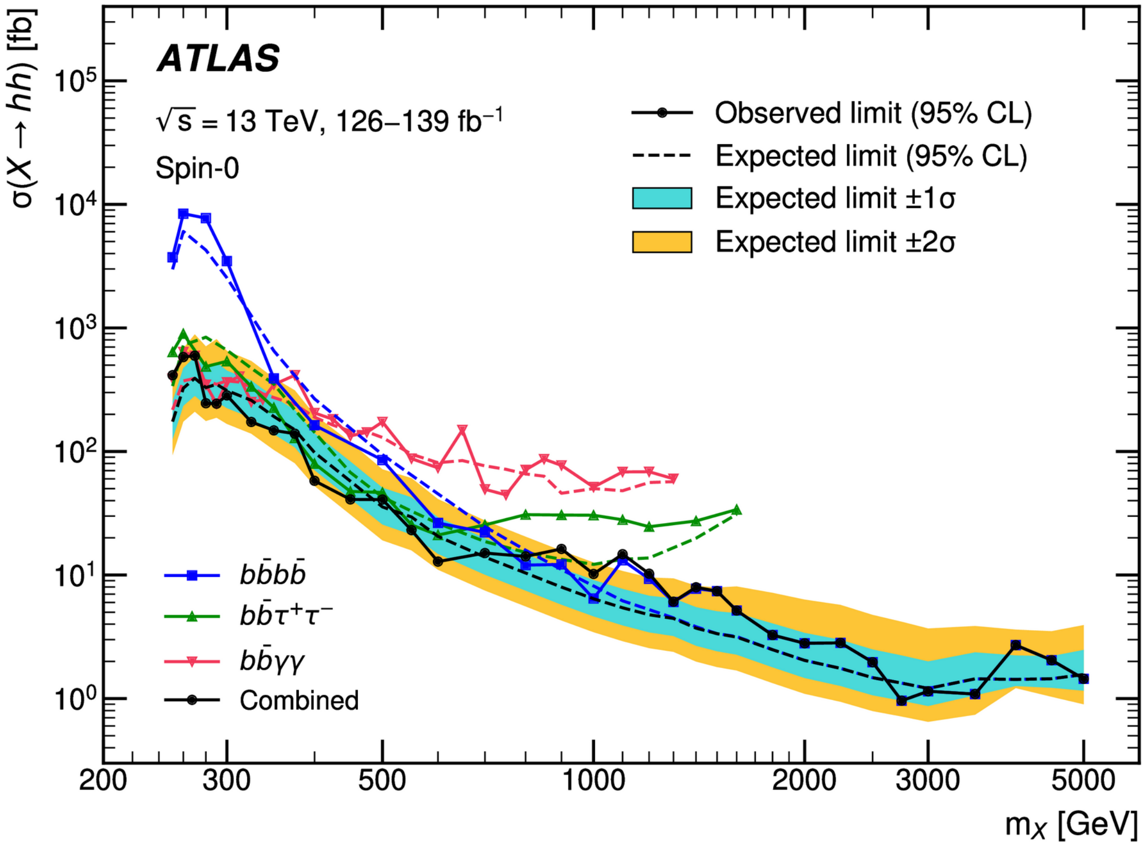


Resonant Higgs pair production

- BSM theories predict extra heavy states that can decay into a pair of Higgs bosons: $pp \to X \to hh$
  - More details tomorrow
- Search for local "bump" in hh invariant mass spectrum (similar to 2012 Higgs discovery)

Example: *bbbb* channel





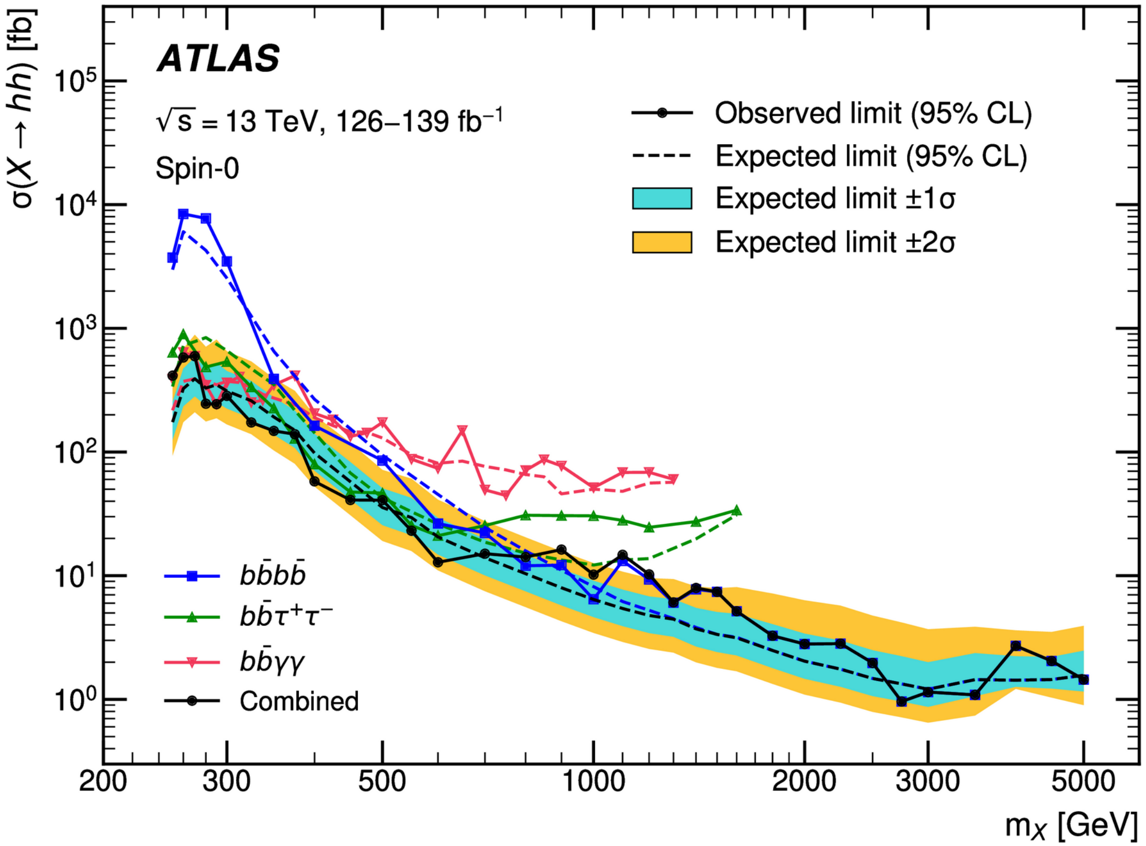
Resonant Higgs pair production

> BSM theories predict extra heavy states that can decay into a pair of Higgs bosons: $pp \rightarrow X \rightarrow hh$

- More details tomorrow

> Search for local "bump" in hh invariant mass spectrum (similar to 2012 Higgs discovery)

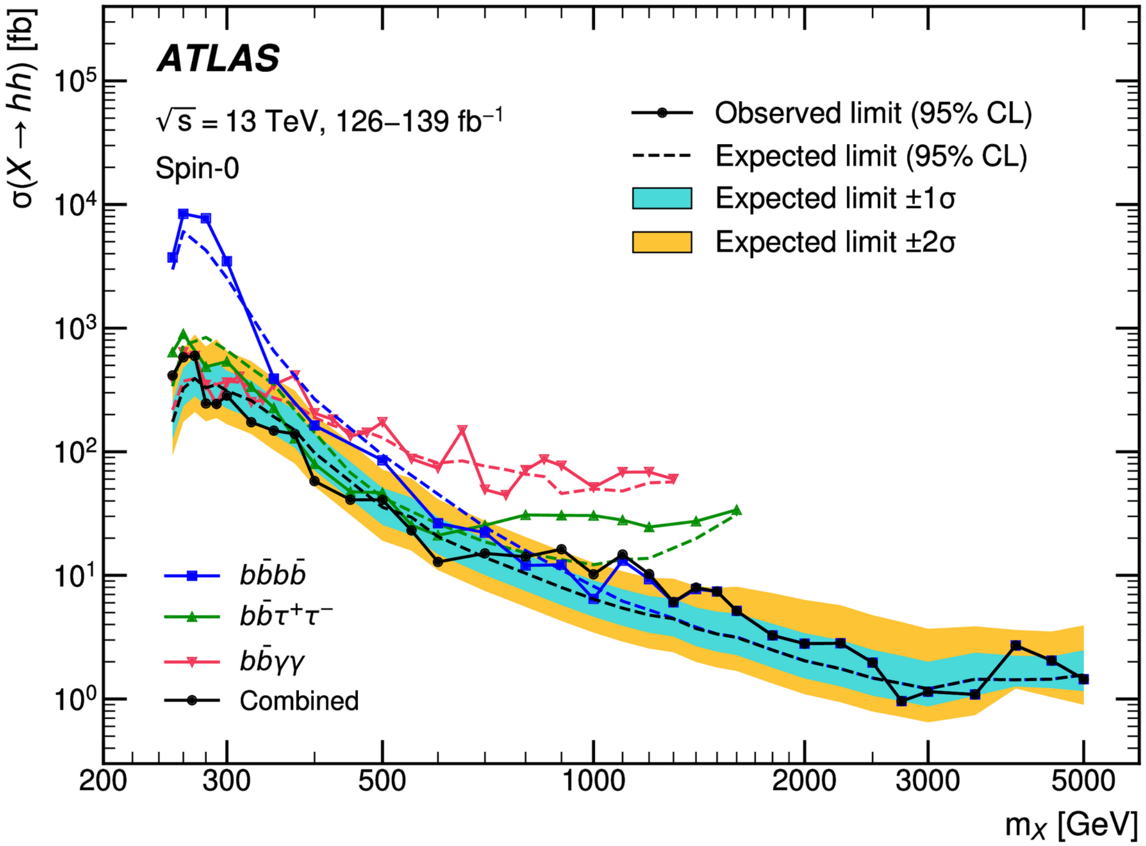
Quiz question:
Why does the bbyy channel dominate at low m_X and the bbbb channel at high m_X?



Resonant Higgs pair production

- BSM theories predict extra heavy states that can decay into a pair of Higgs bosons: $pp \to X \to hh$
  - More details tomorrow
- Search for local "bump" in hh invariant mass spectrum (similar to 2012 Higgs discovery)

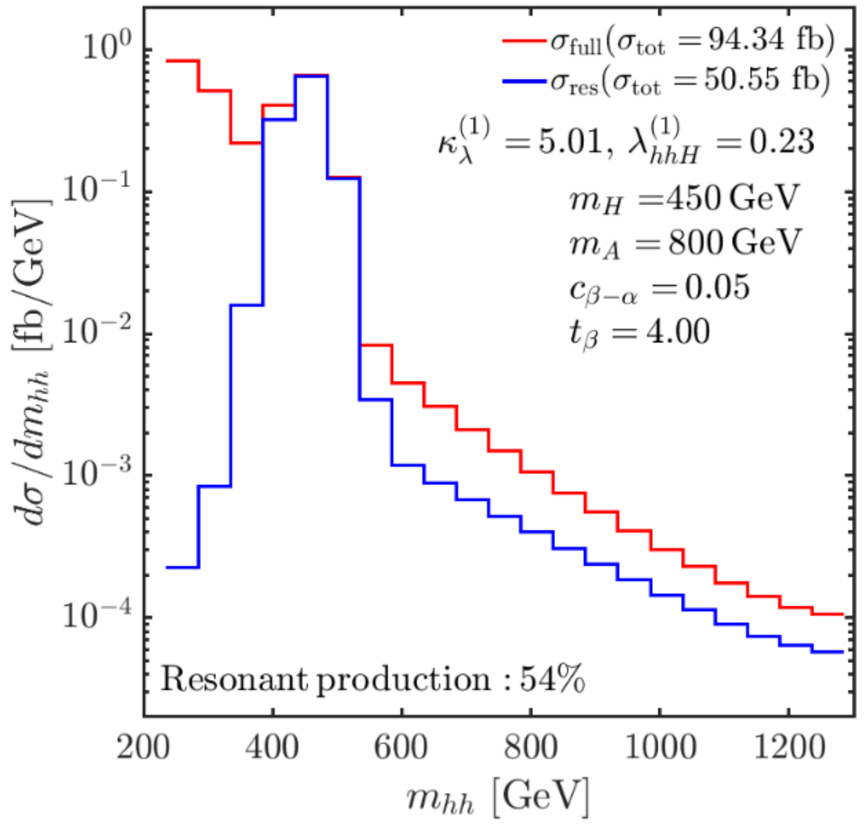
- *bbyy*: clean channel, most competitive in low m_X region where QCD multijet background dominates
- *bbbb:* dominates in high-mass region where sensitivity is limited by signal statistics
- *bbττ*: dominant in medium region

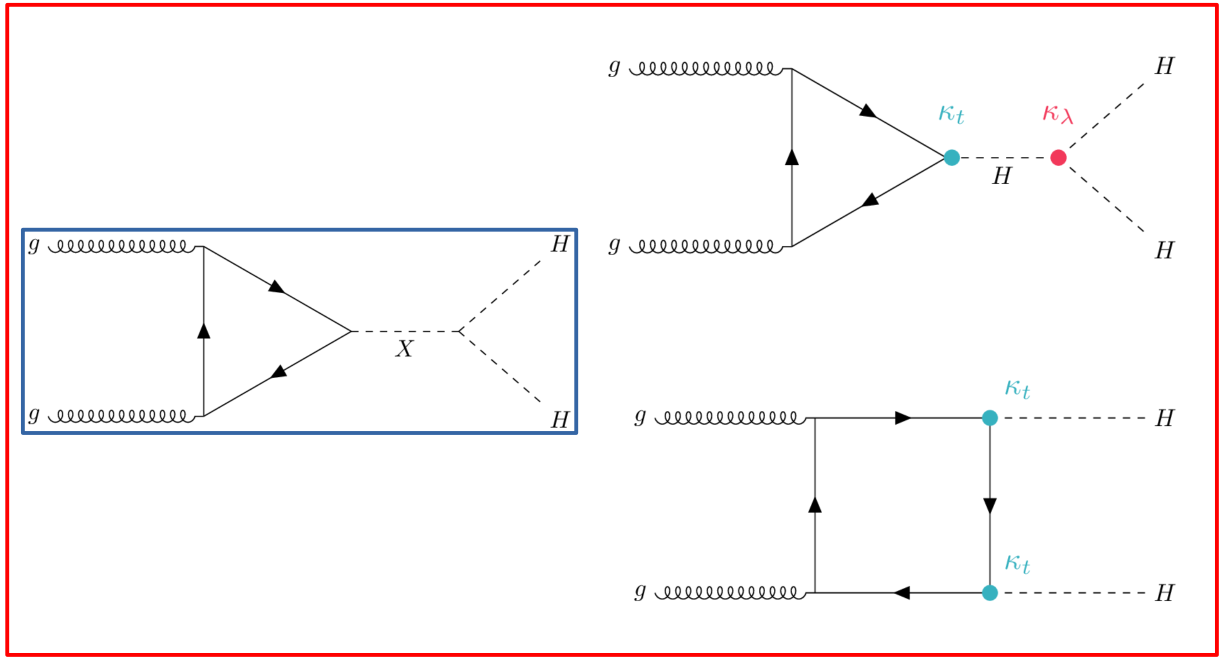


Aside: Interference

- Current resonant $X \rightarrow hh$ searches do not consider interference with non-resonant production (or higher-order effects)
- Reduced sensitivity for some benchmarks that may be falsely excluded by resonant searches

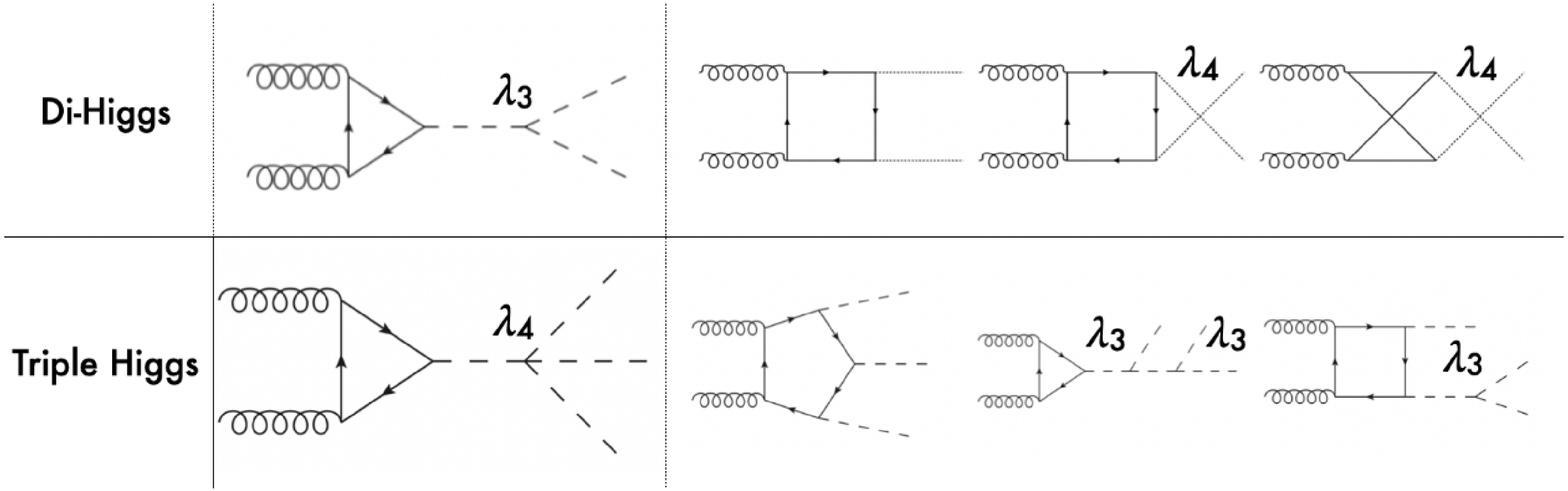
K. Rachenko, G. Weiglein et al. arXiv:2403.14776





Not twins … but triplets!

- Recent effort to search for triple Higgs production at the LHC
- Most direct access to quartic Higgs coupling with modifier κ_4
- Process ~400 times rare than Higgs pair production!
  - Expect around 10 events for *hhh* production in full LHC Run-2 dataset (across all decay modes)



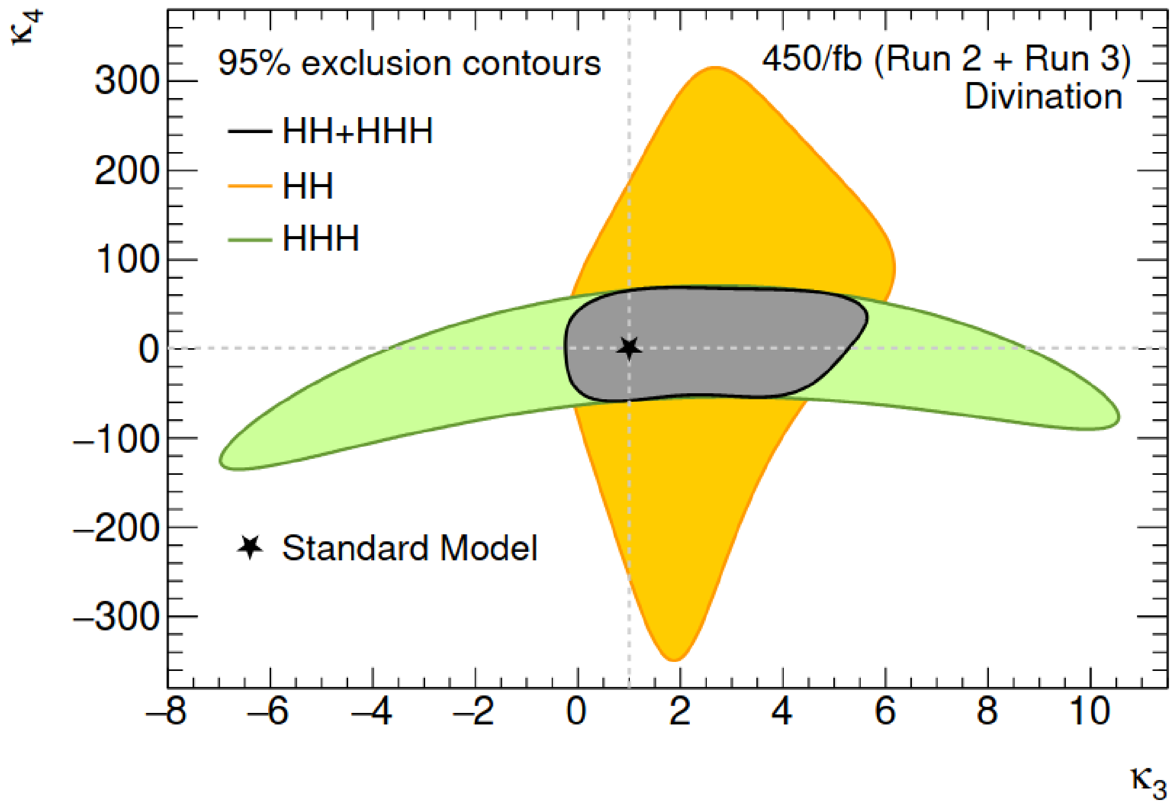
31 fb

0.08 fb

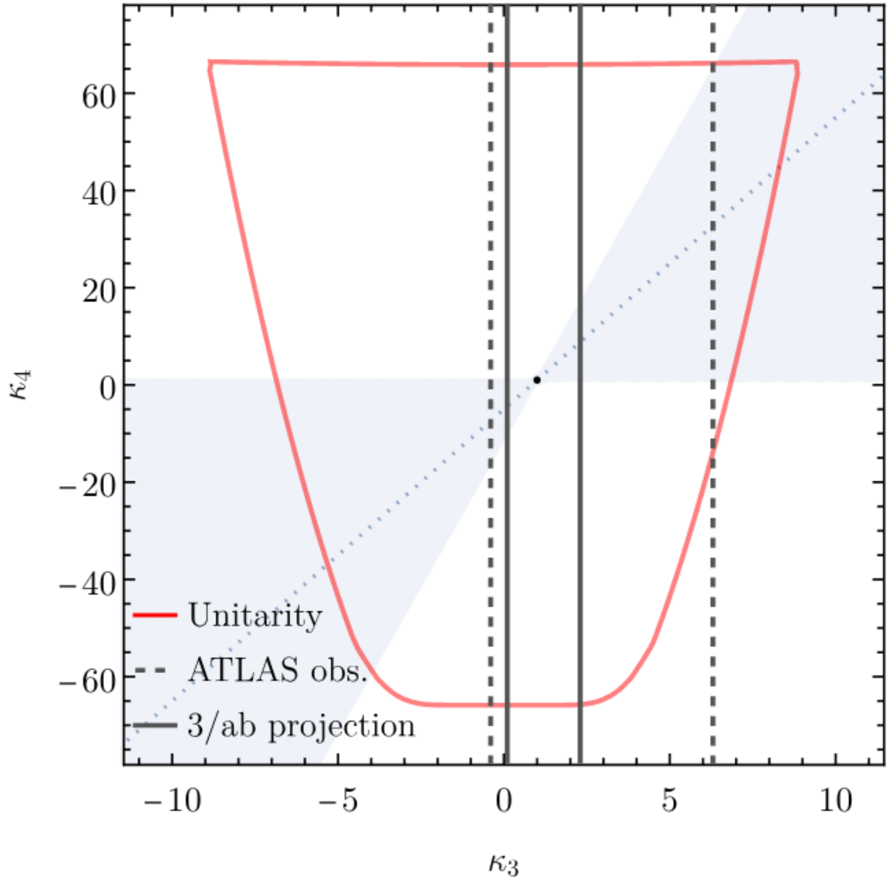
Complementarity between *hh* and *hhh* searches

- Searches for Higgs triplets expected to provide better constraints on κ_4
- Current best constraints from theoretical considerations (unitarity)

Projection for Run 2 + 3



P. Stylianou, G. Weiglein
[Eur.Phys.J.C 84 (2024) 4, 366]

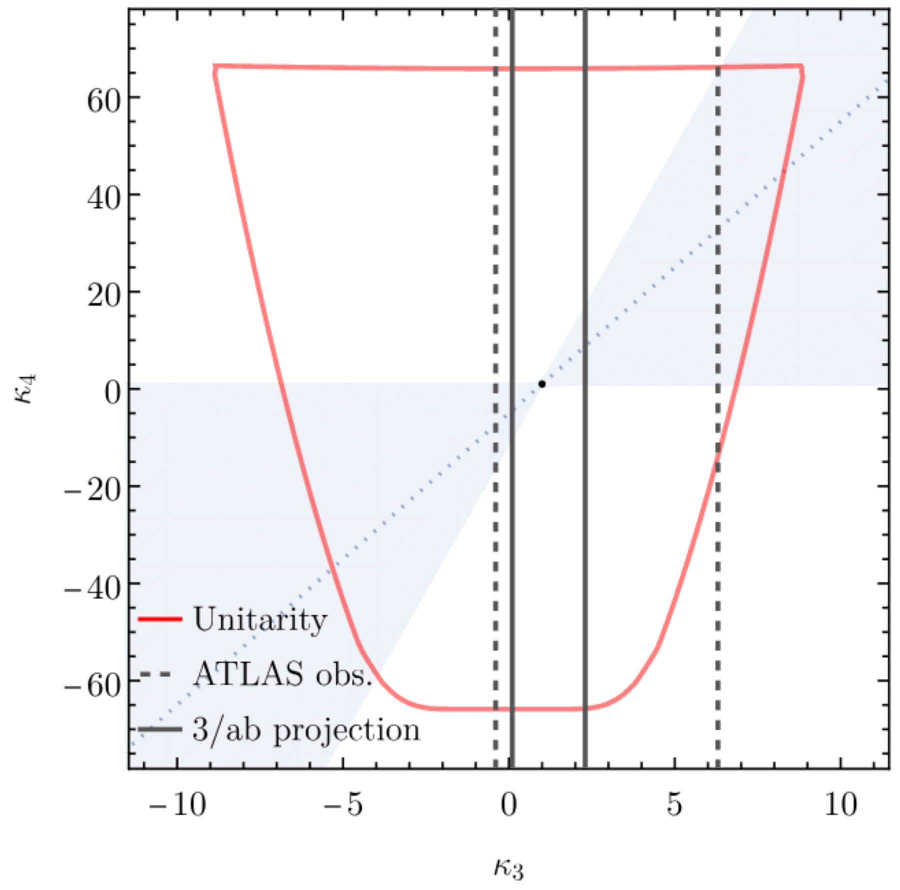


Relevance?

- Constraints on κ_4 seem loose by comparison
- Little explored probe of BSM physics
  - BSM effects could affect κ_4 much more than κ_3
  - Resonant enhancement in extended Higgs sectors

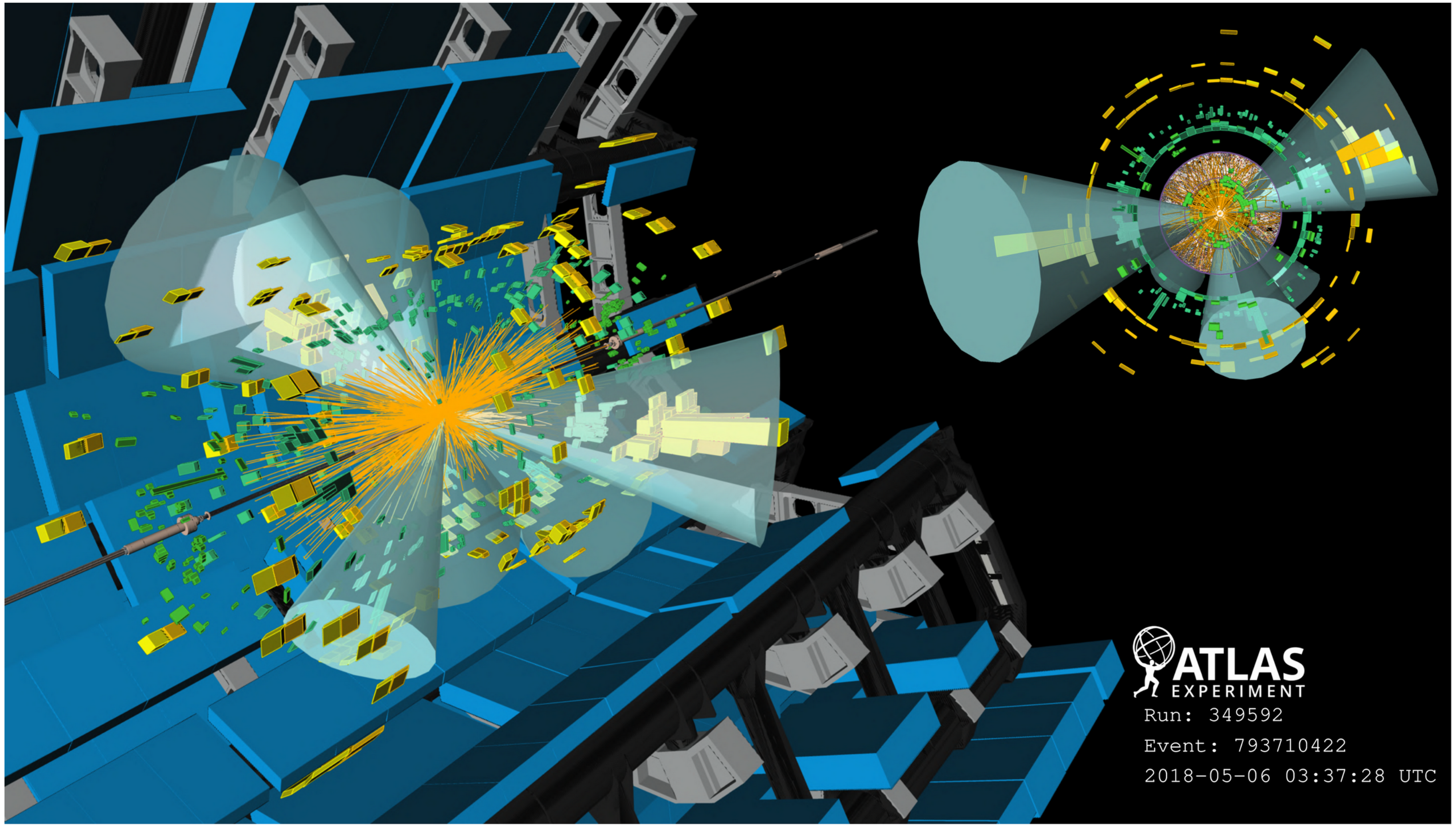
$$\boxed{\begin{aligned}(\kappa_3 - 1) &= \boxed{\frac{C_6 v^2}{\lambda\Lambda^2}}\,, \\ (\kappa_4 - 1) &= \boxed{\frac{6C_6 v^2}{\lambda\Lambda^2}} + \frac{4C_8 v^4}{\lambda\Lambda^4} \\ &\simeq 6(\kappa_3 - 1) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)\end{aligned}}$$

P. Stylianou, G. Weiglein
[Eur.Phys.J.C 84 (2024) 4, 366]



First search for triple Higgs production

- Final states with six b-quarks: largest branching ratio, large background from multijet production

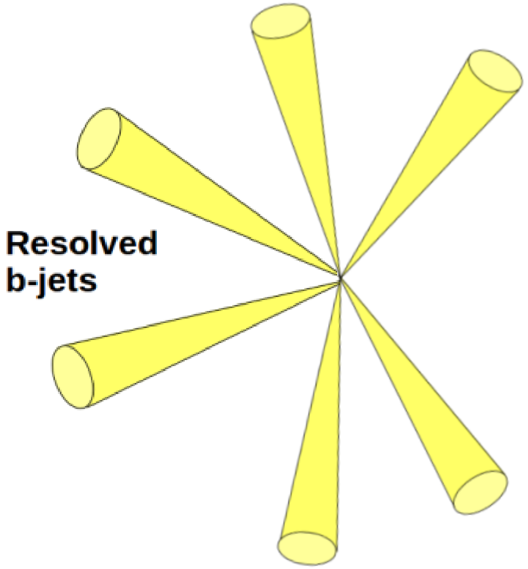


First search for triple Higgs production

- Signal regions: events with at least 6 *b*-tagged jets
- Control & validation regions: events with ==5 and ==4 *b*-tagged jets
- Higgs reconstruction: three *b*-jet pairs that minimises

  $|m_{h1} - 120\ \text{GeV}| + |m_{h2} - 115\ \text{GeV}| + |m_{h3} - 110\ \text{GeV}|$

  where $p_{T,h1} > p_{T,h2} > p_{T,h3}$
- DNNs to discriminate between signal and background

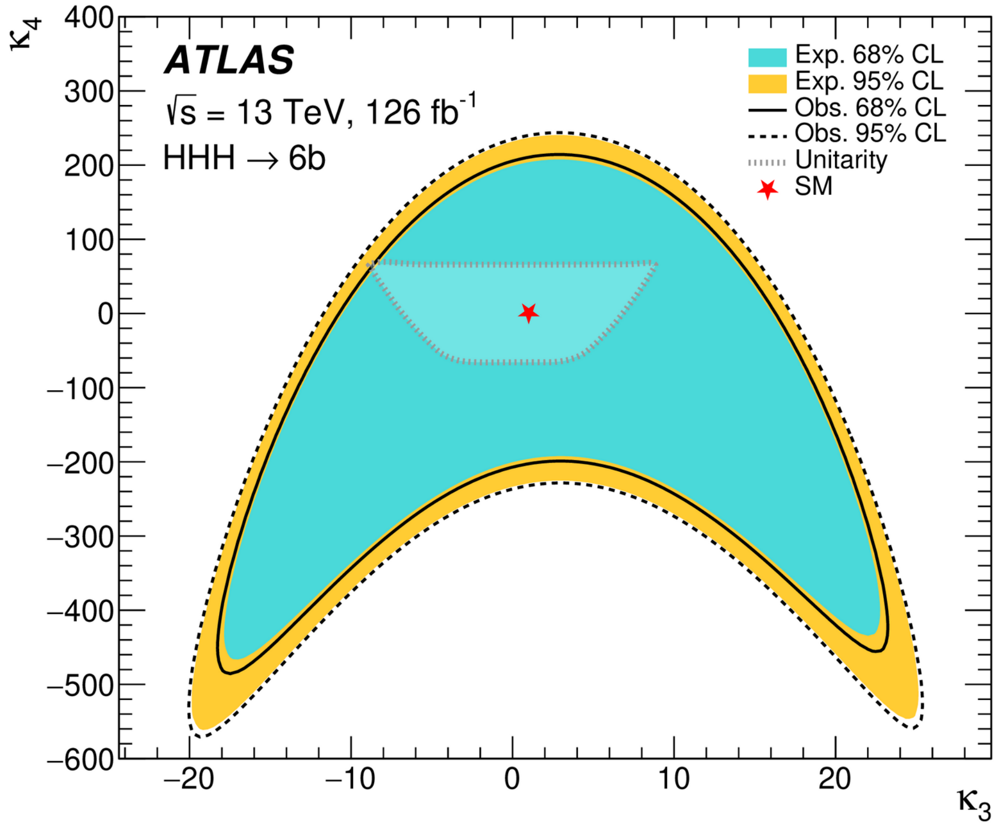


Results

> First experimental constraints on κ_4, first constraints beyond unitarity constraints!

> Limited by available data statistics and achievable signal-background ratio

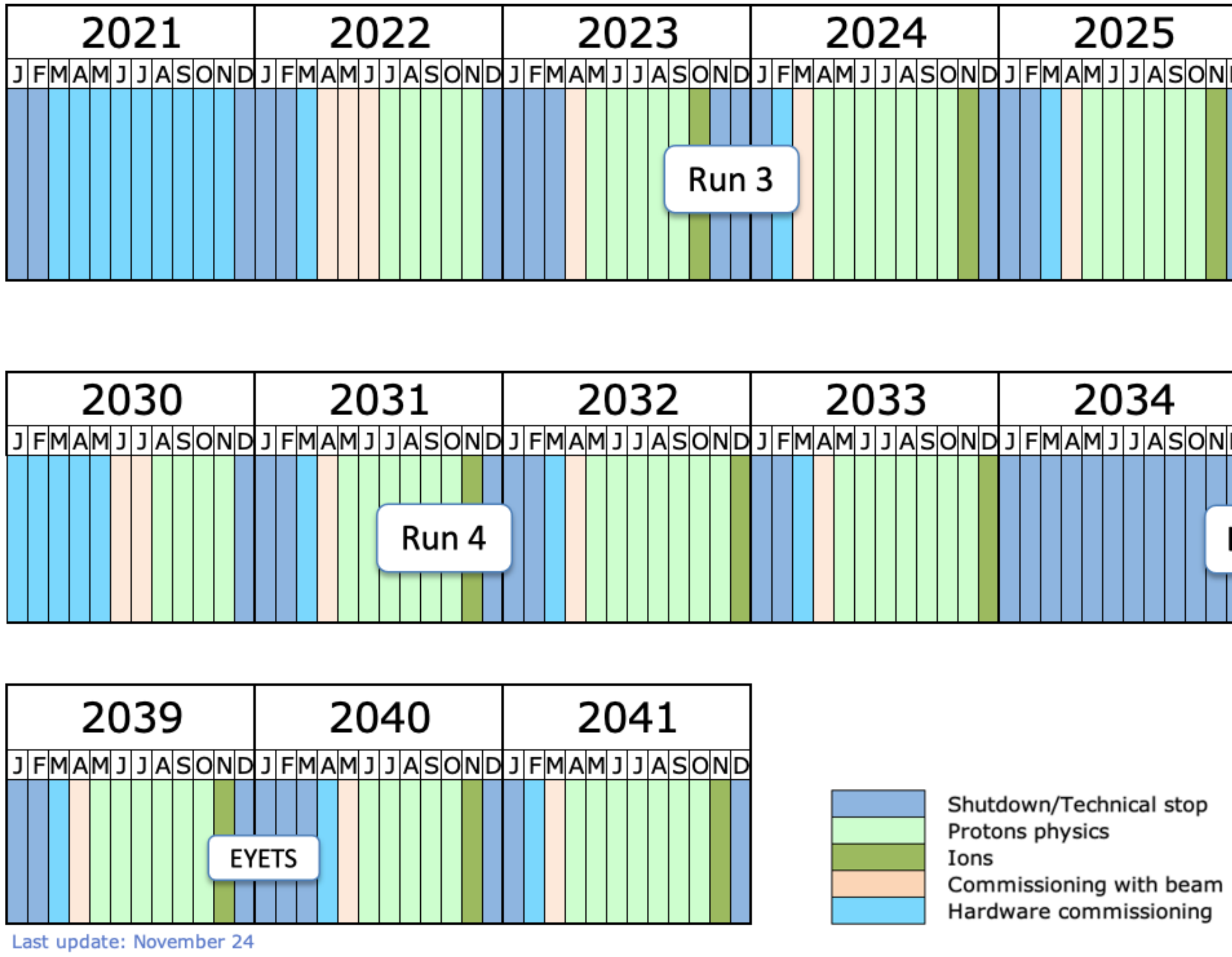
> Significant improvement expected at HL-LHC (studies on-going)



> Searches in cleaner channels have started:

- Most promising: 4b2τ

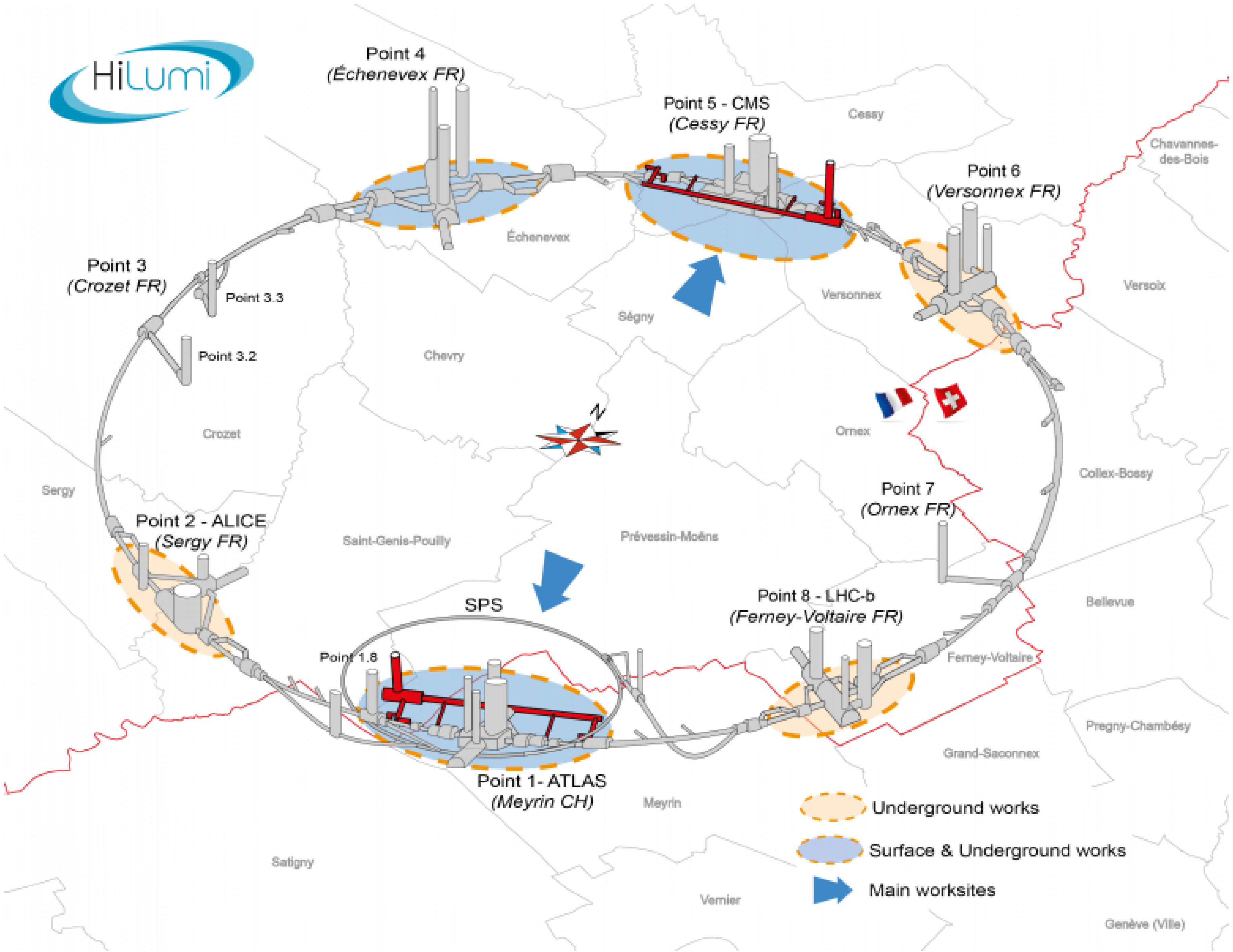
Where do we go from here?



High-Luminosity LHC (2030 - 2041)

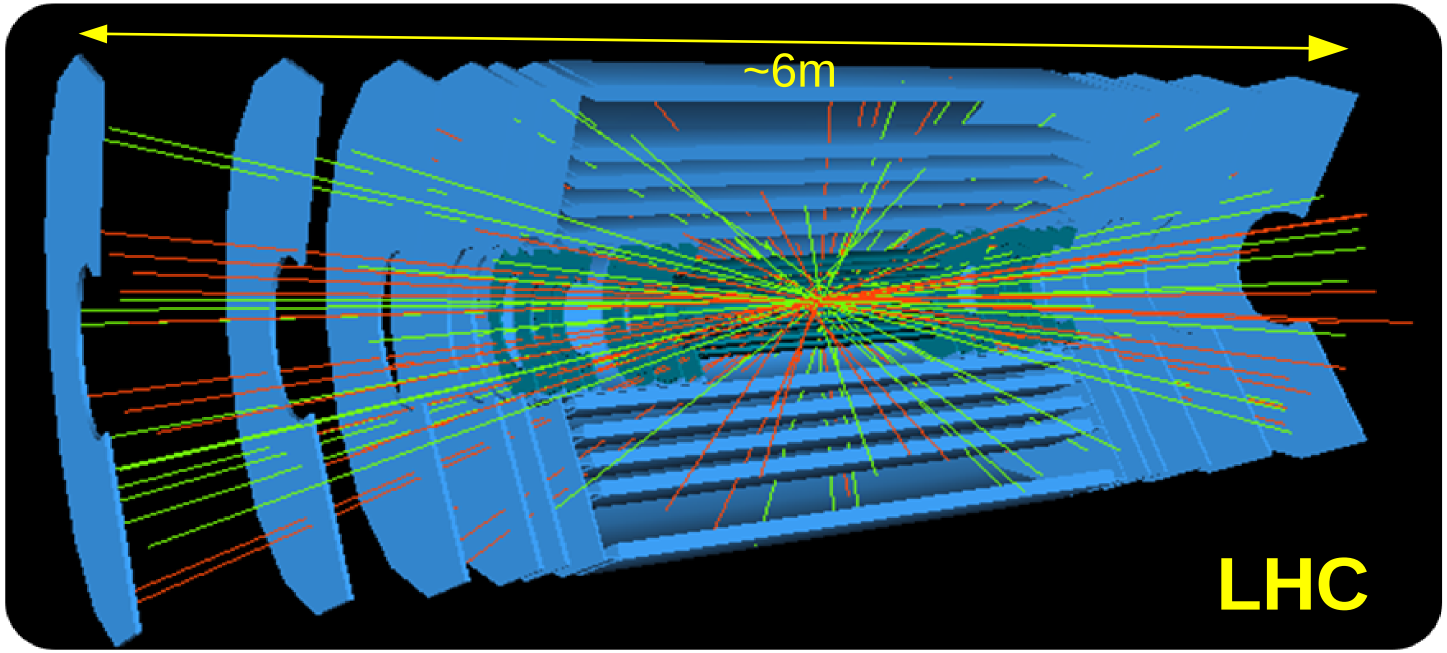
> Final dataset goal: 3000 fb^{-1}

> Compared to >300 fb^{-1} for Run 2+3



Challenges

> Significant increase in number of interactions per bunch crossing and particle flux

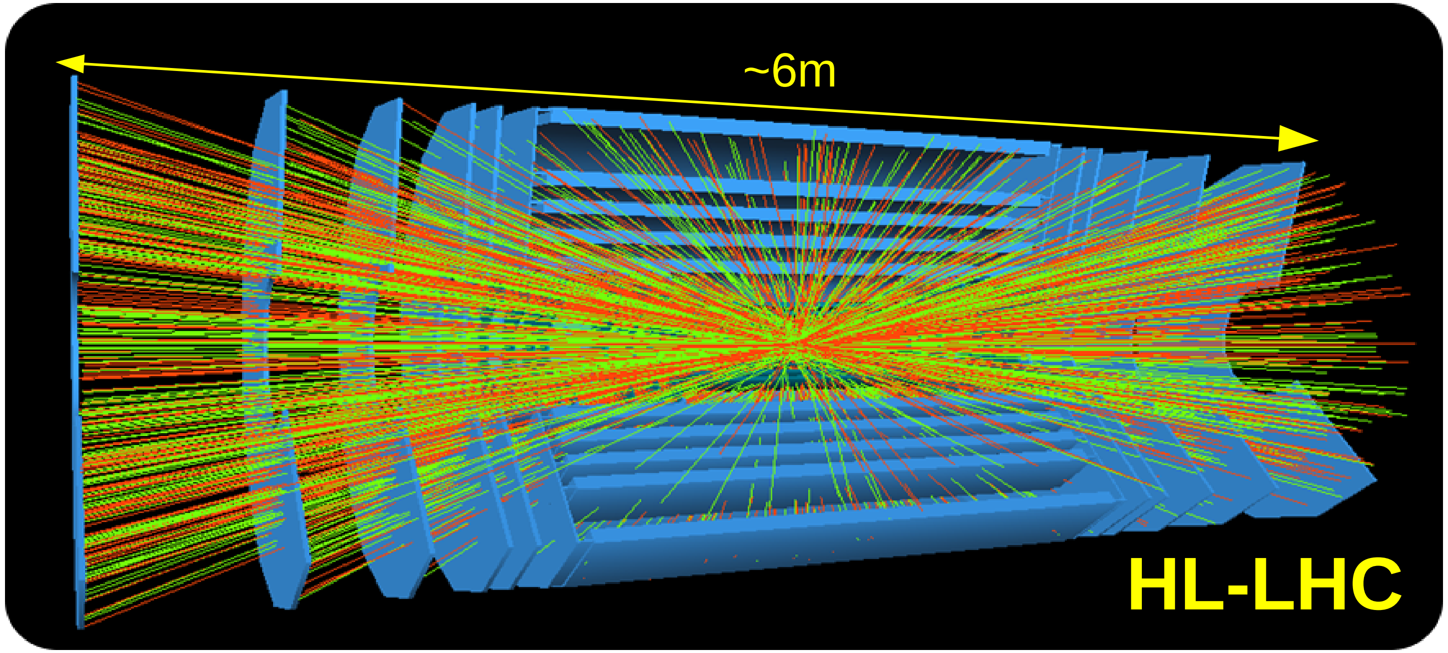


25 interactions (Run 1)

New ATLAS Inner Tracker

Challenges

> Significant increase in number of interactions per bunch crossing and particle flux

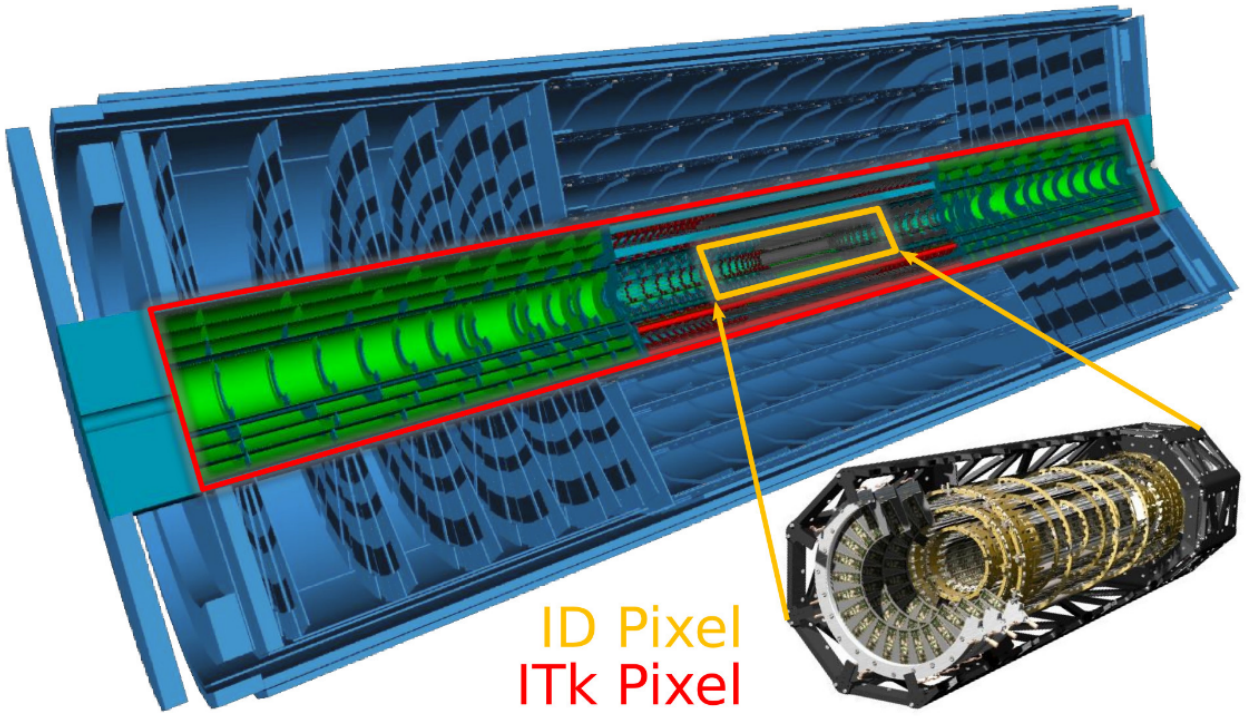


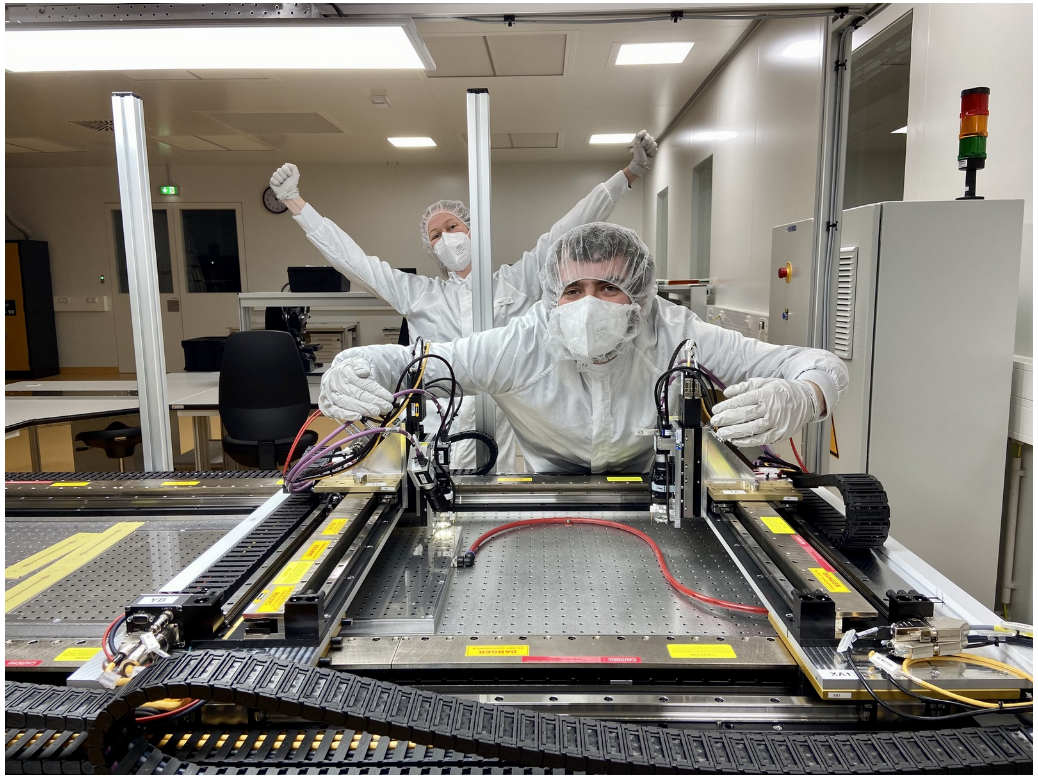
New ATLAS Inner Tracker

200 interactions

Major LHC detector upgrades

- For example brand-new all-silicon tracking detector for ATLAS (Inner Tracker, ITk)
- Up to 4 times higher granularity in innermost pixel layers



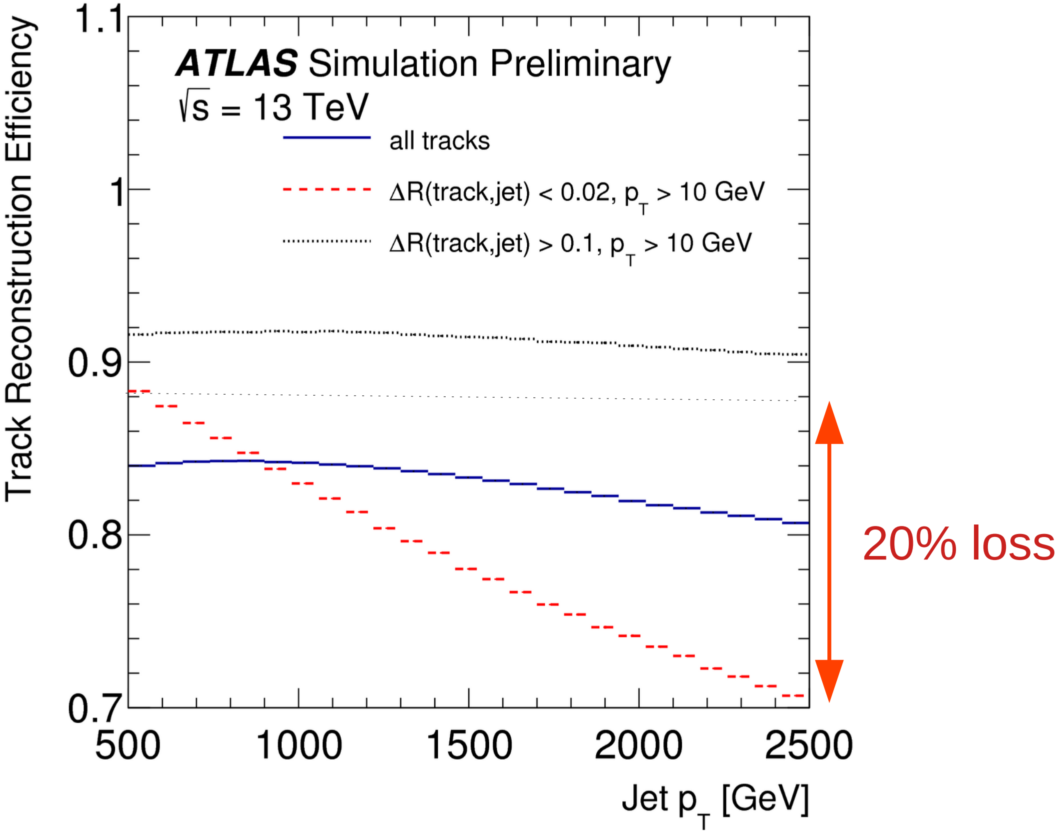


Partially constructed at DESY!

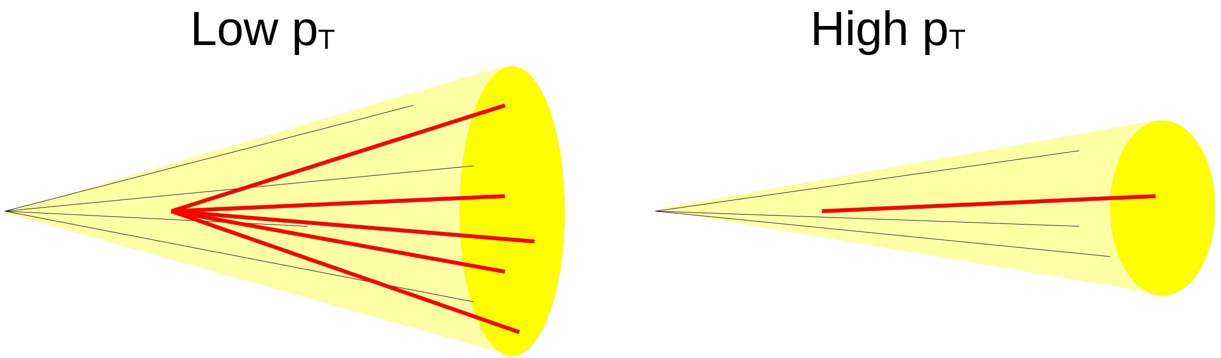
Major improvements in track reconstruction

- Example: reconstructing tracks in cores of high-p_T jets (dense environments)

Current detector

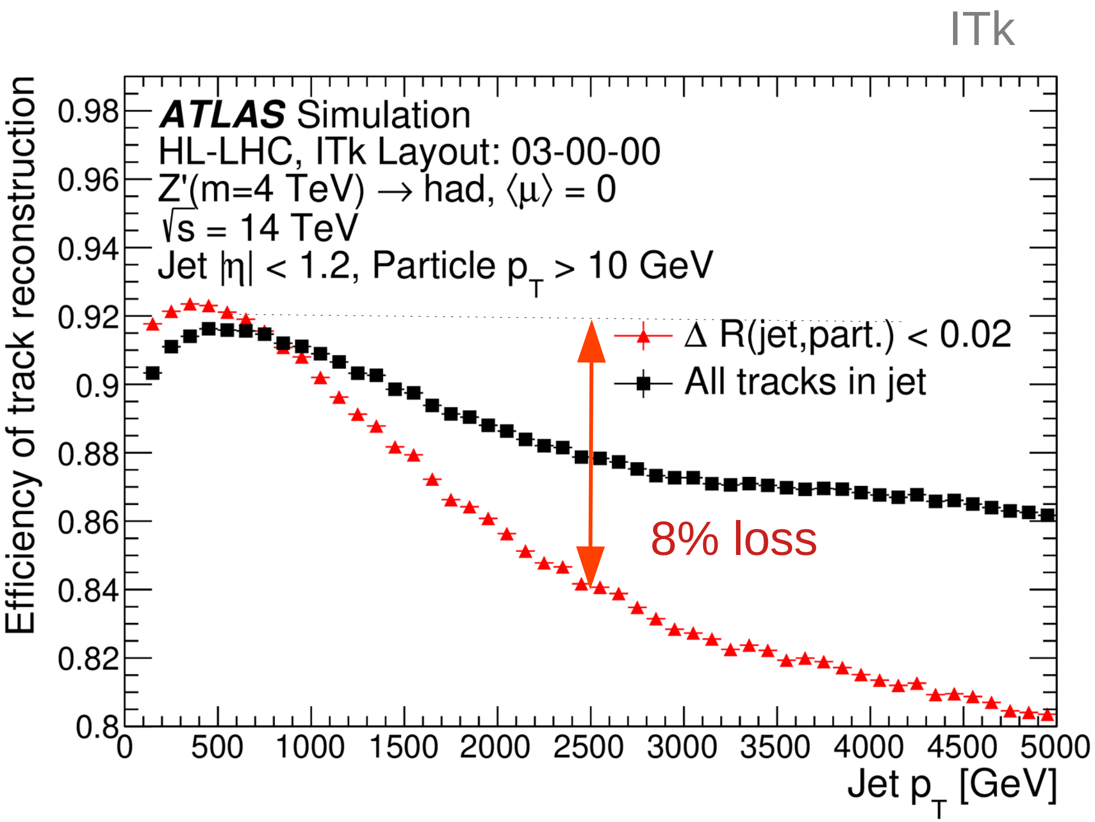


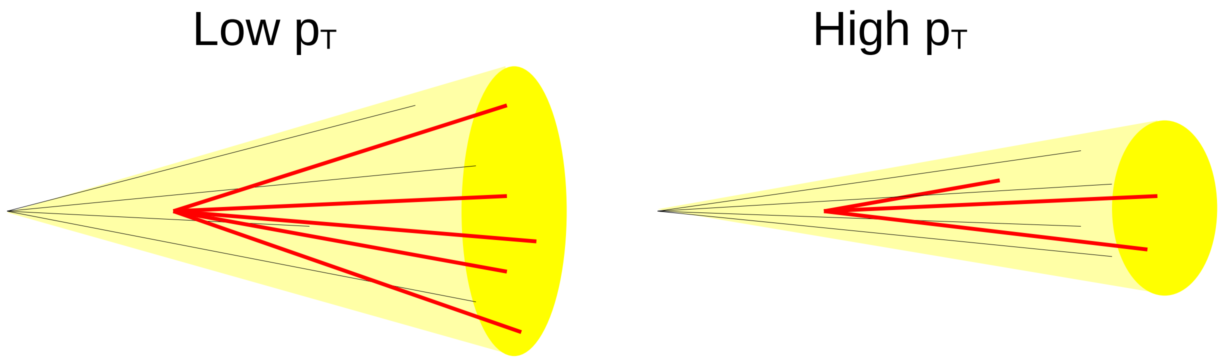
b-jets with p_T = 1 TeV:
30% contain ≤ 1 track from *b*-hadron decay
(4-5 expected)



Major improvements in track reconstruction

- Example: reconstructing tracks in cores of high-p_T jets (dense environments)
- Tracking efficiency significantly improved in jet cores → better inputs for *b*-tagging

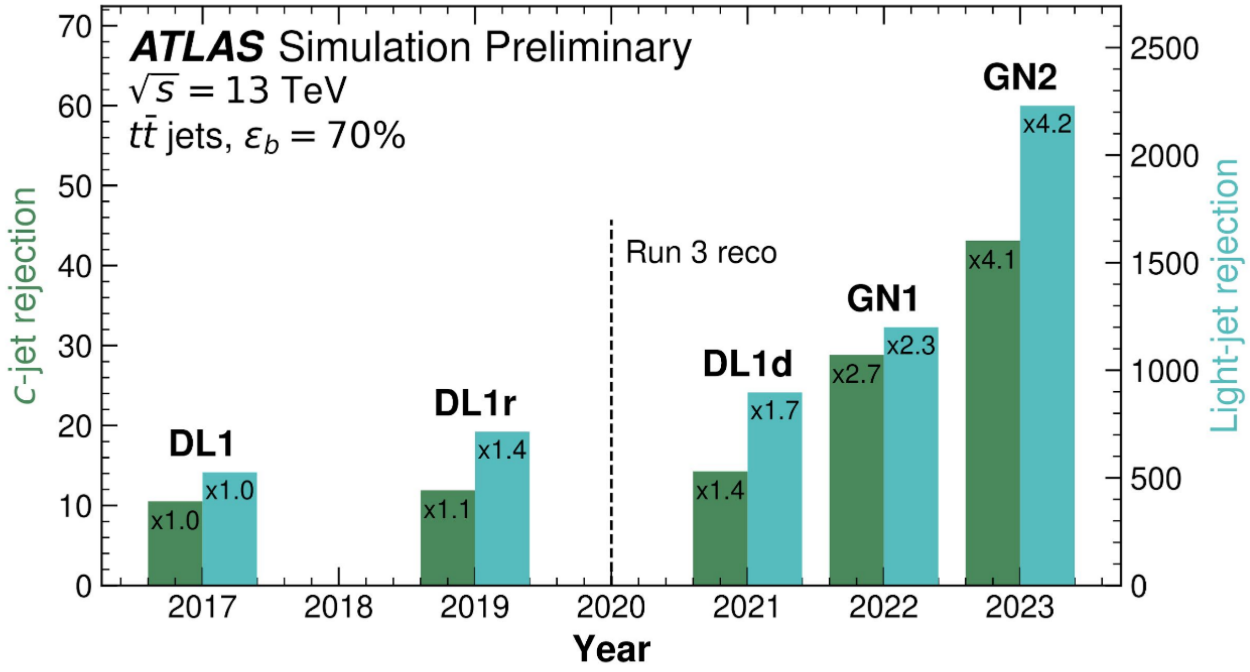


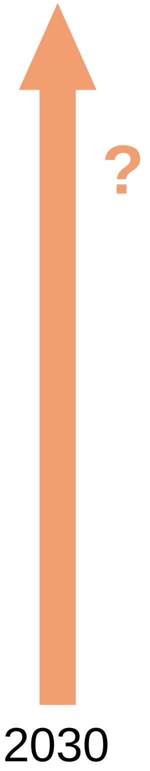


Algorithmic improvements for the HL-LHC

> Improvements in *b*-tagging crucial for (di-)Higgs analyses

- Better inputs due to more efficient and accurate tracking and vertexing
- More performant algorithms (e.g. transformers)

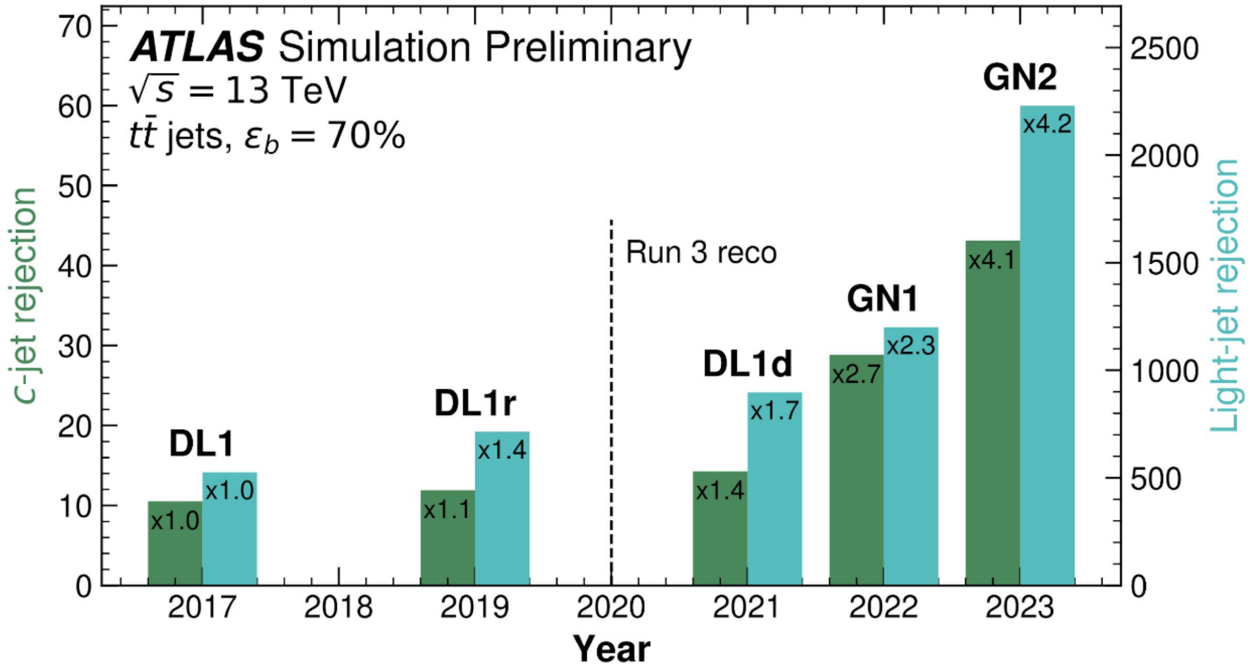


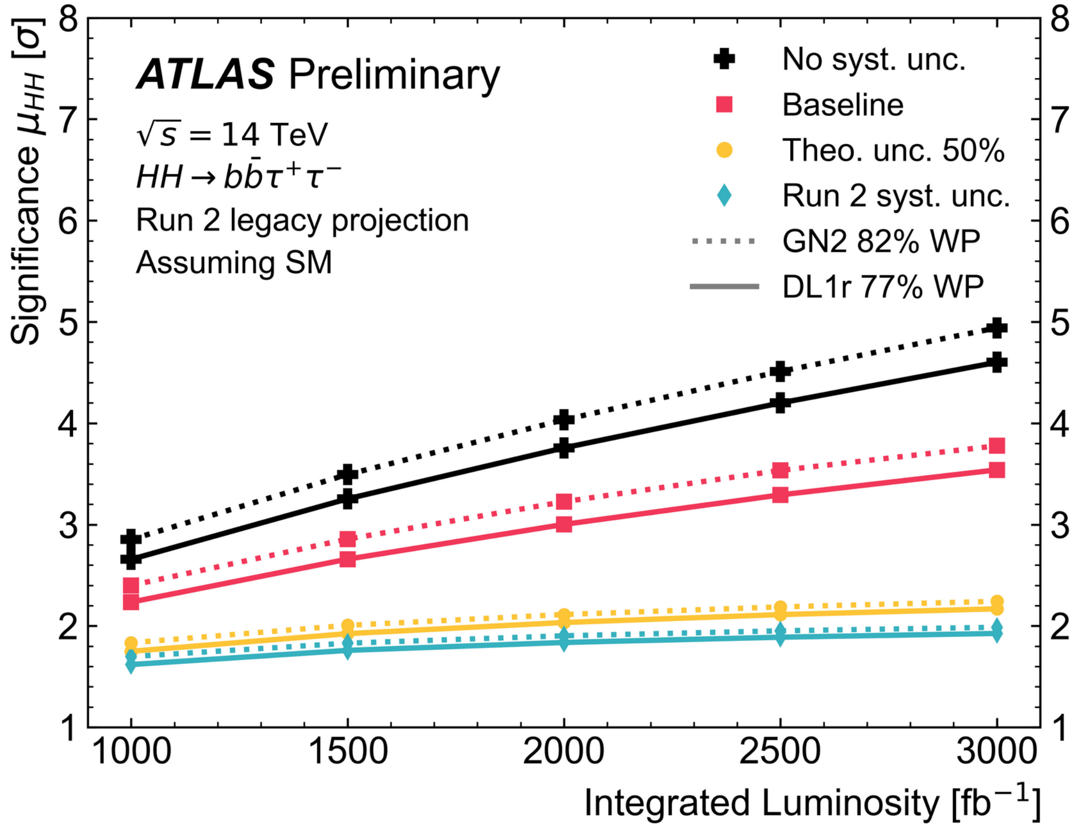


Discovery potential for Higgs pair production at HL-LHC

- Example: projection in $bb\tau\tau$ channel
- Largest leverage: experimental improvements
  - Especially *b*-tagging performance
  - Reduction of systematic uncertainties

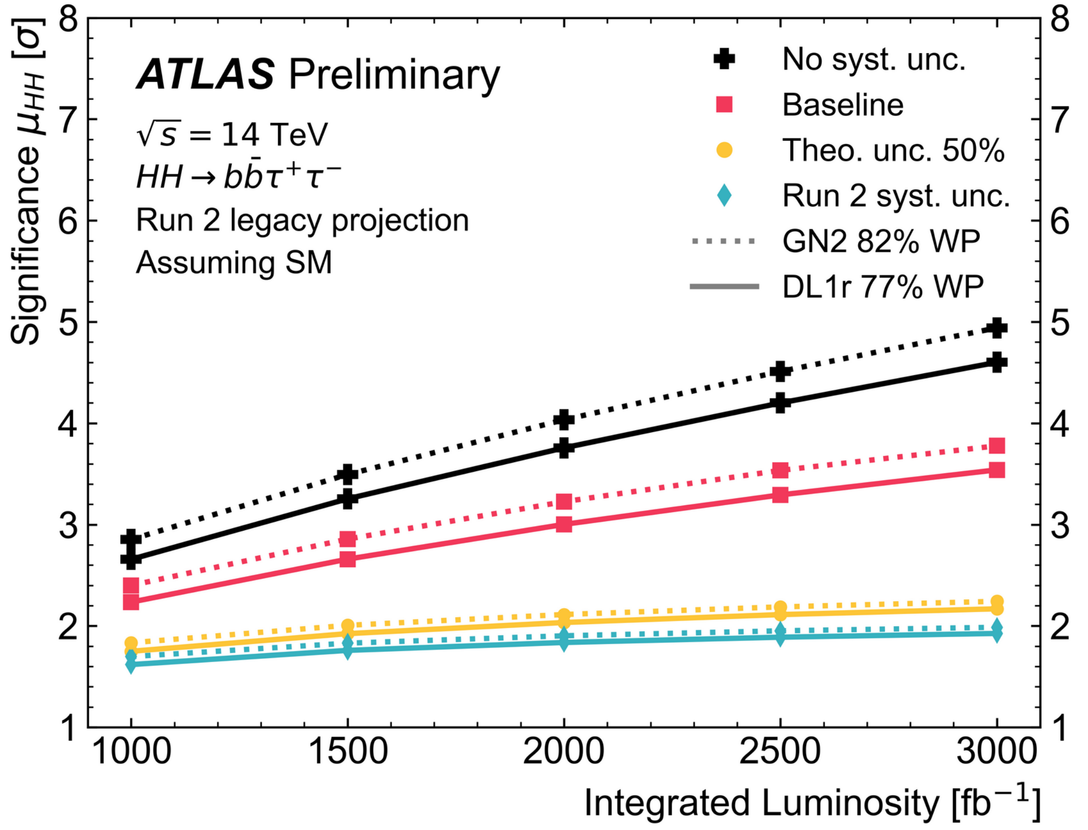
Baseline: halve theory uncertainties, reduce selected experimental uncertainties with lumi





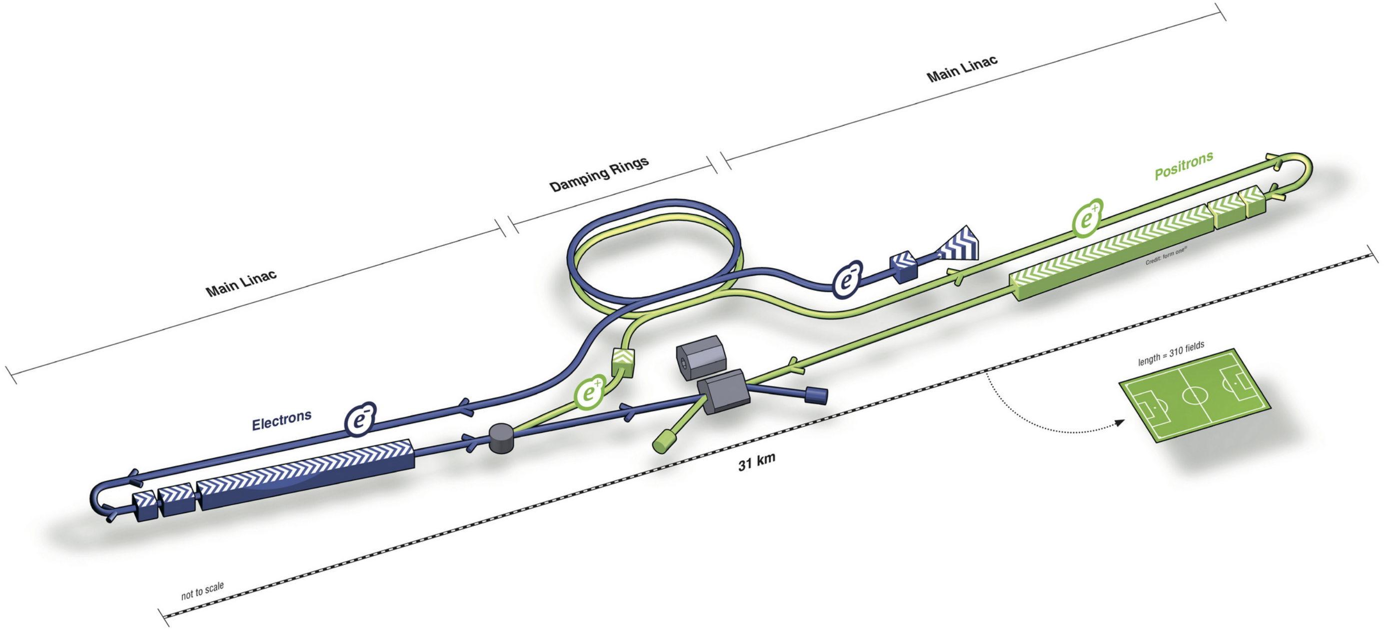
Discovery potential for Higgs pair production at HL-LHC

- Expect to see evidence (≥ 3σ) in *bbττ* alone before end of HL-LHC
- Similar projections currently under way for European Strategy for Particle Physics Update
- Good prospects for discovery by combining several ch
- Further experimental improvements can further boost sensitivity!

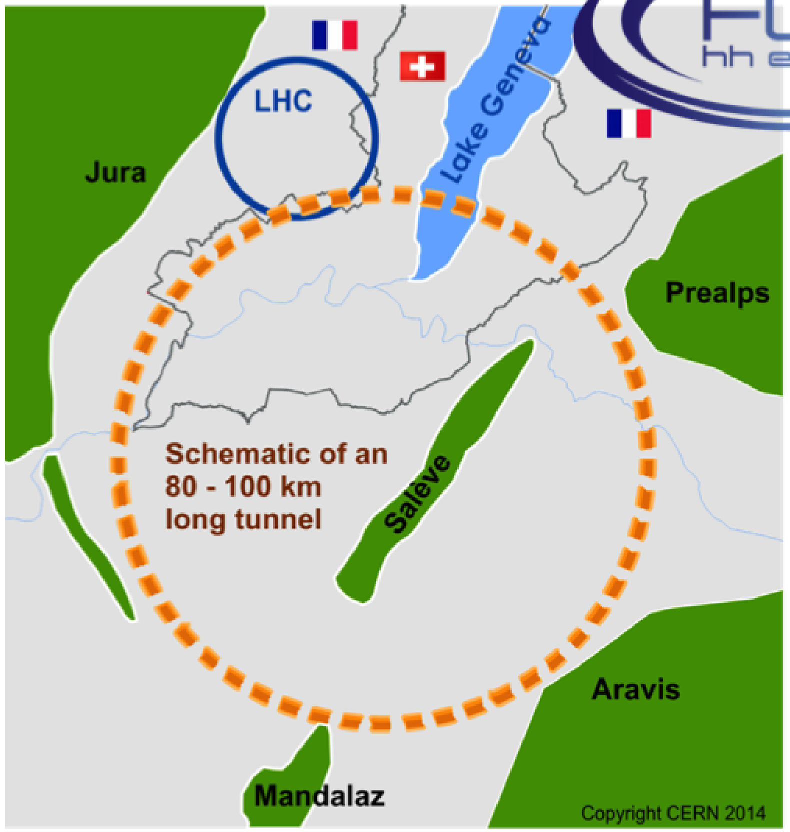


Future Collider Plans

- Higgs factories for precision measurements
- BSM searches also possible



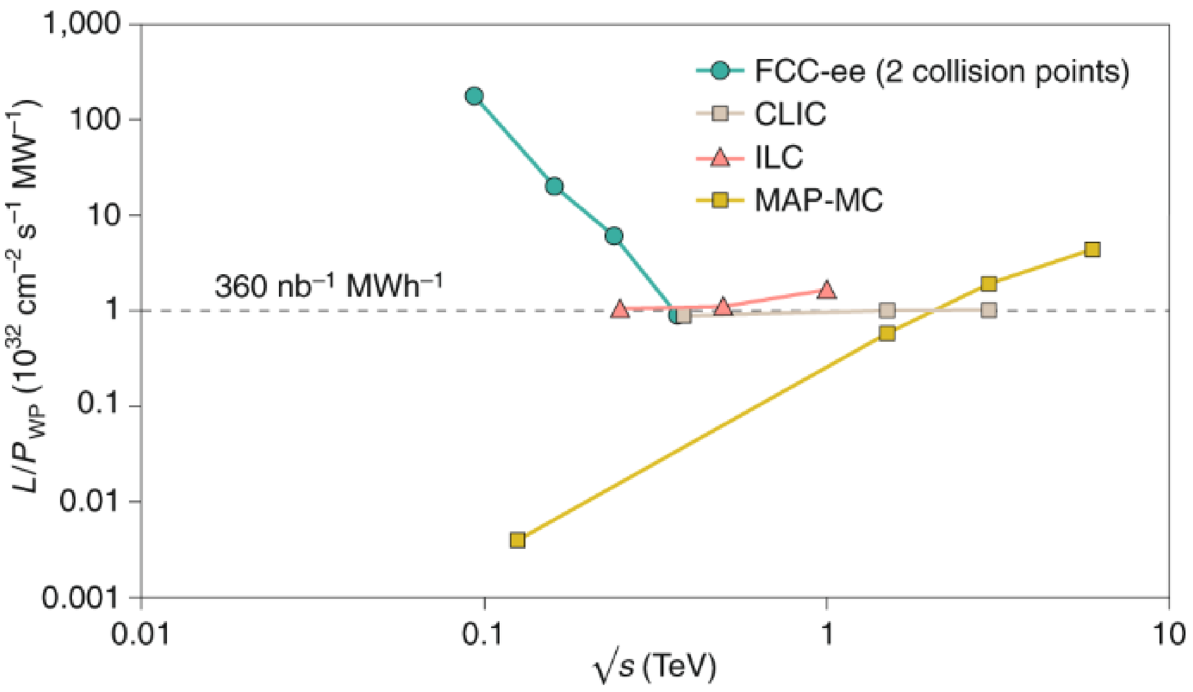
International Linear Collider



Future Circular Collider

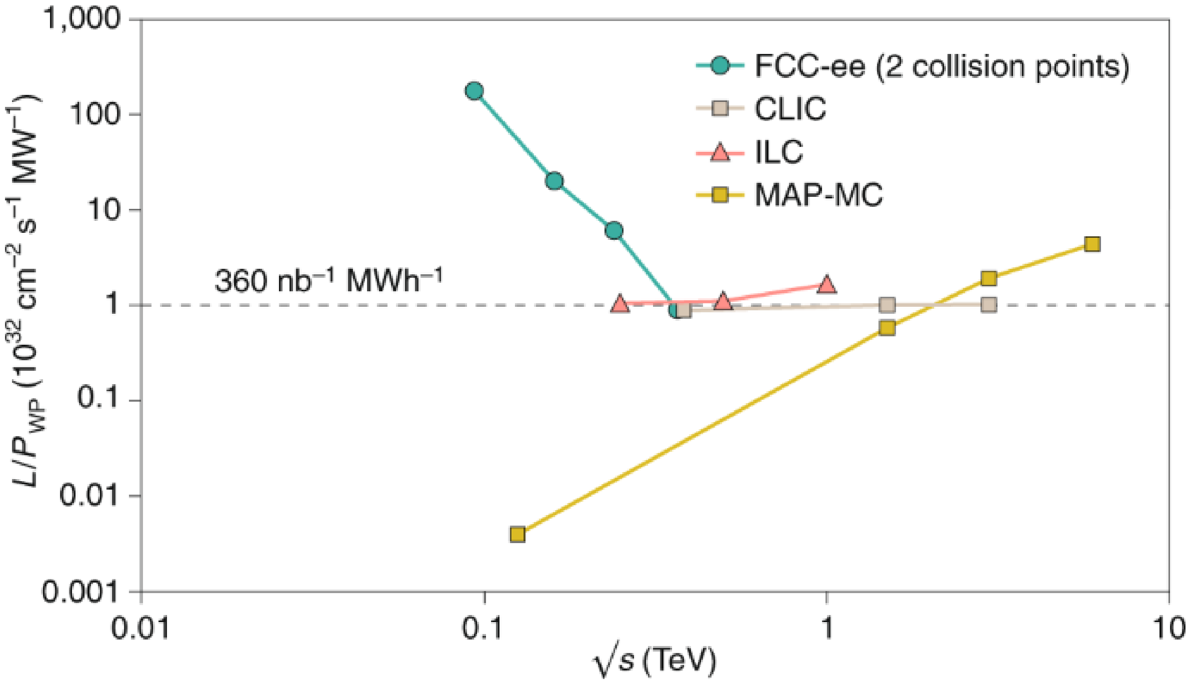
Linear vs circular – it depends on the energy!

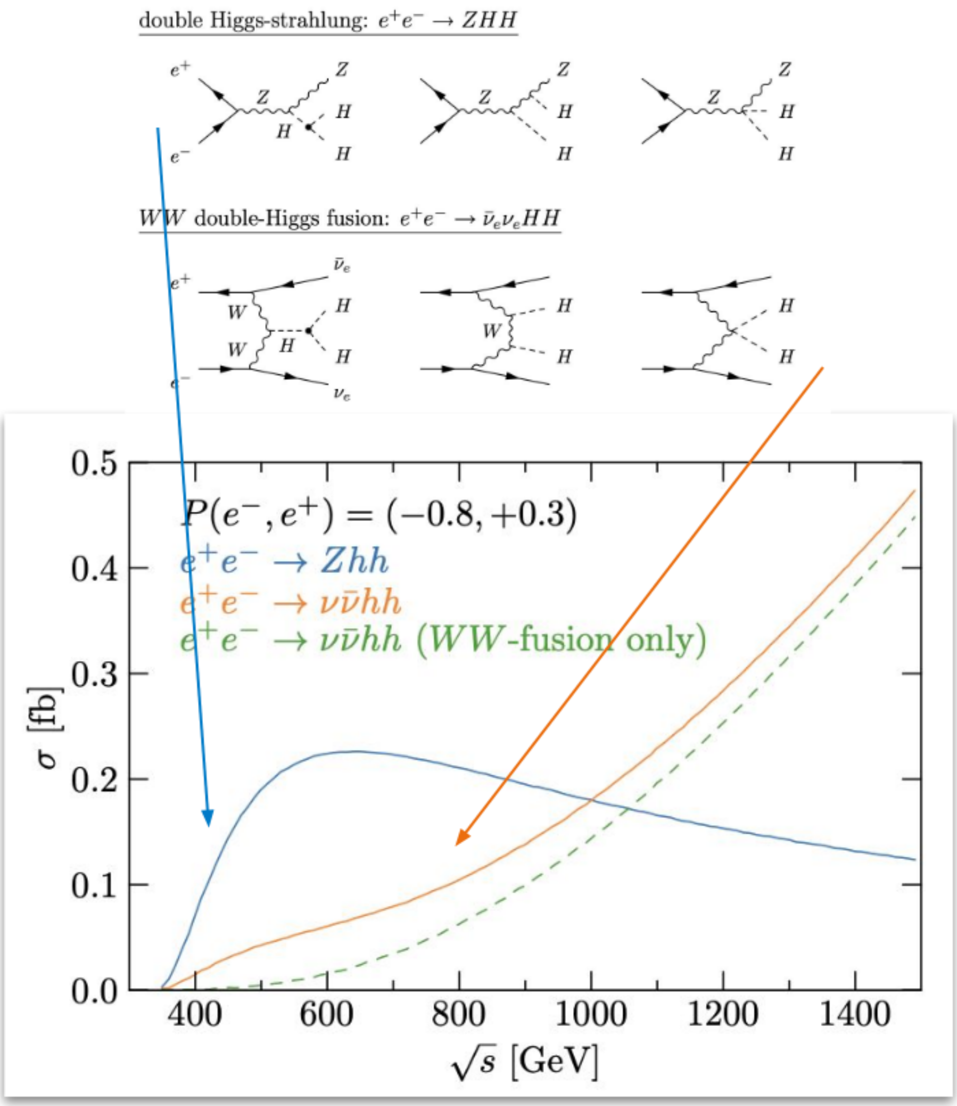
- Circular colliders more competitive at lower collision energies (higher instantaneous luminosity)
- Linear colliders more competitive at higher collision energies (no losses from synchrotron radiation)



Linear vs circular – it depends on the energy!

> Direct access to trilinear coupling only for √s > 400 GeV
→ linear collider!

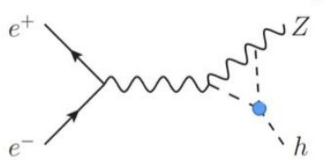


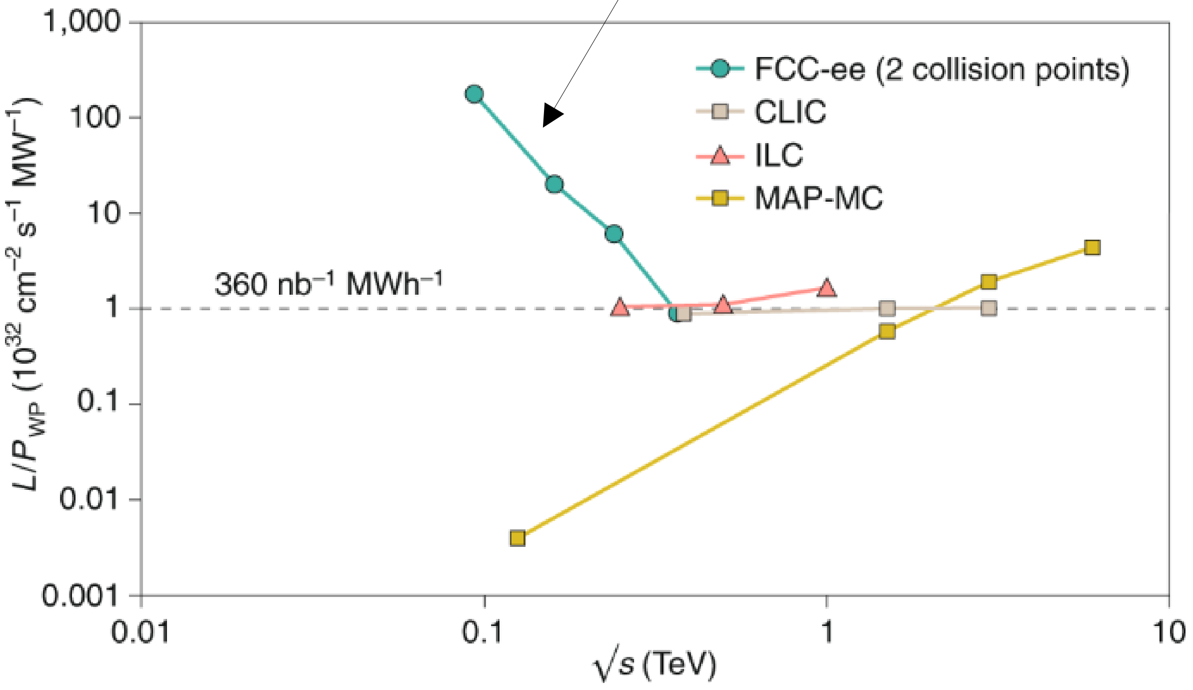


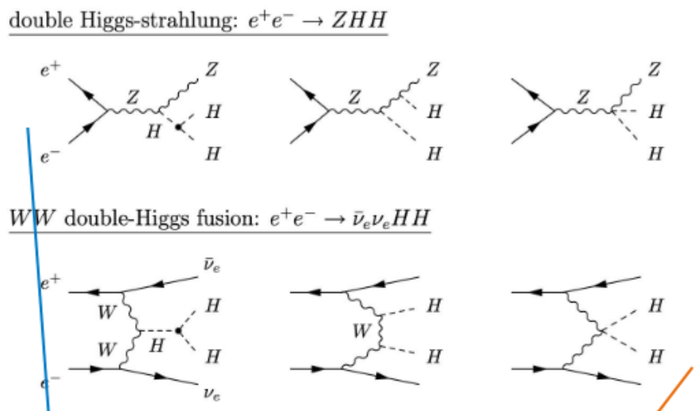
Linear vs circular – it depends on the energy!

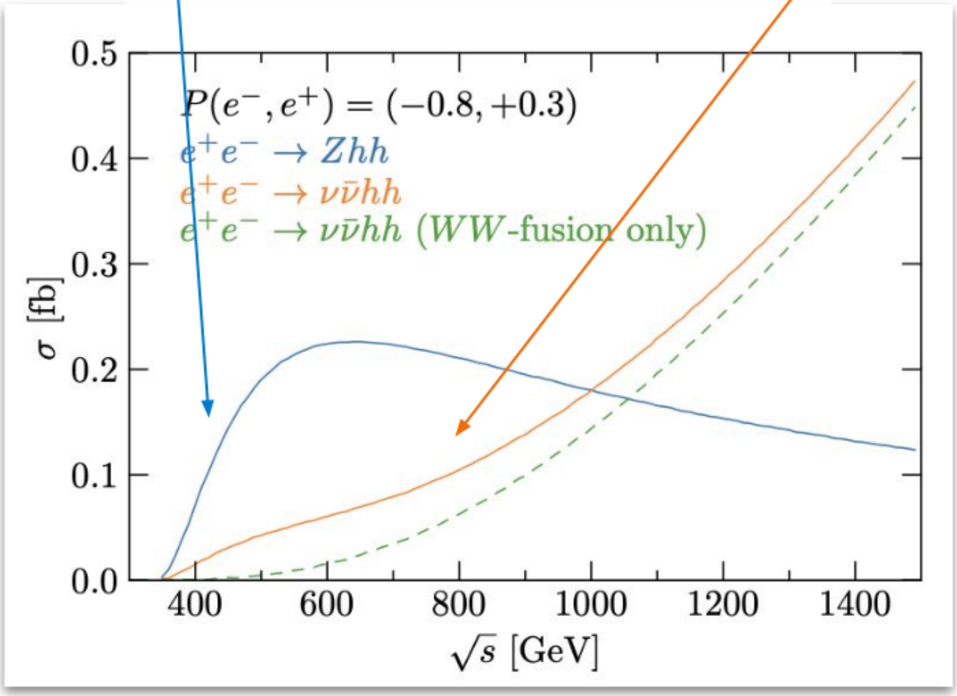
> Direct access to trilinear coupling only for √s > 400 GeV
> → linear collider!

> Indirect access via single-Higgs production at lower energies
> (model dependence!)

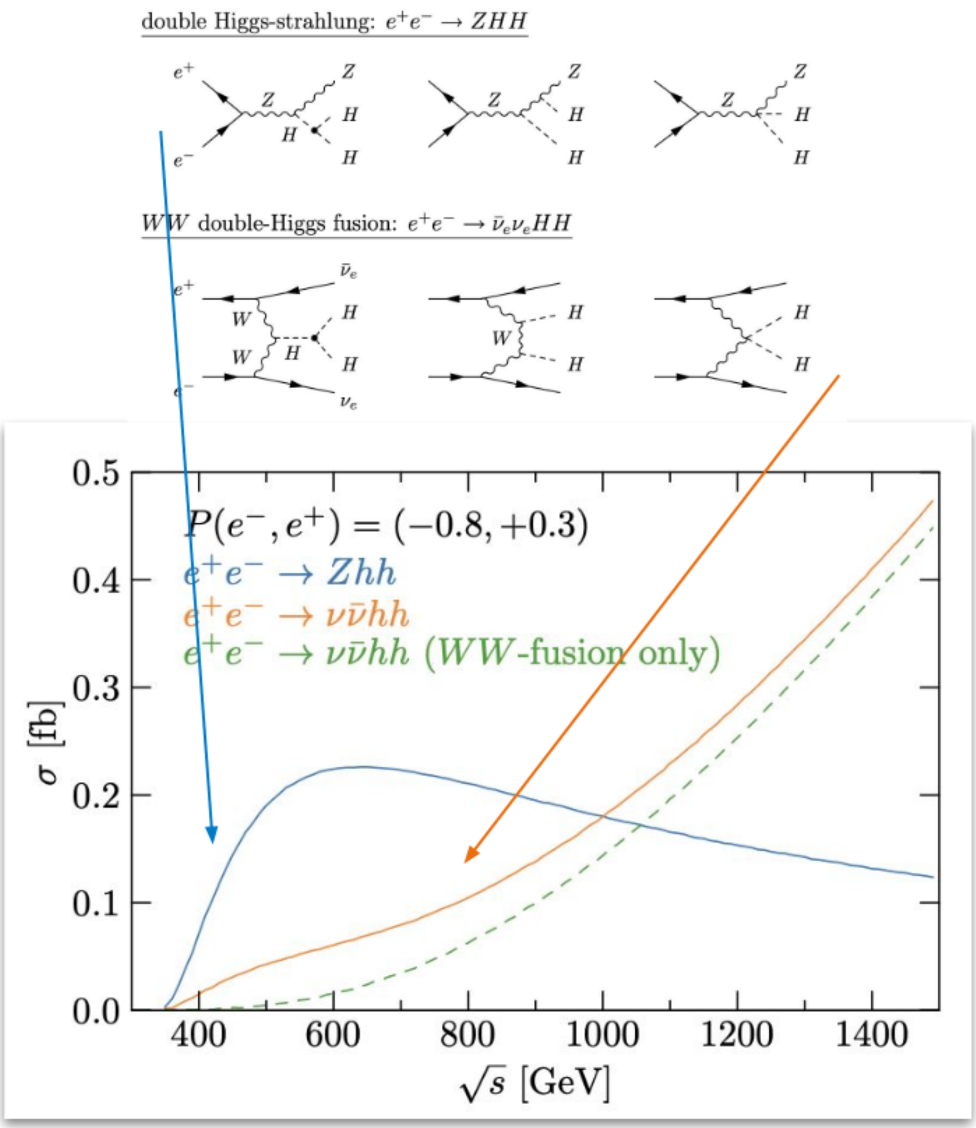




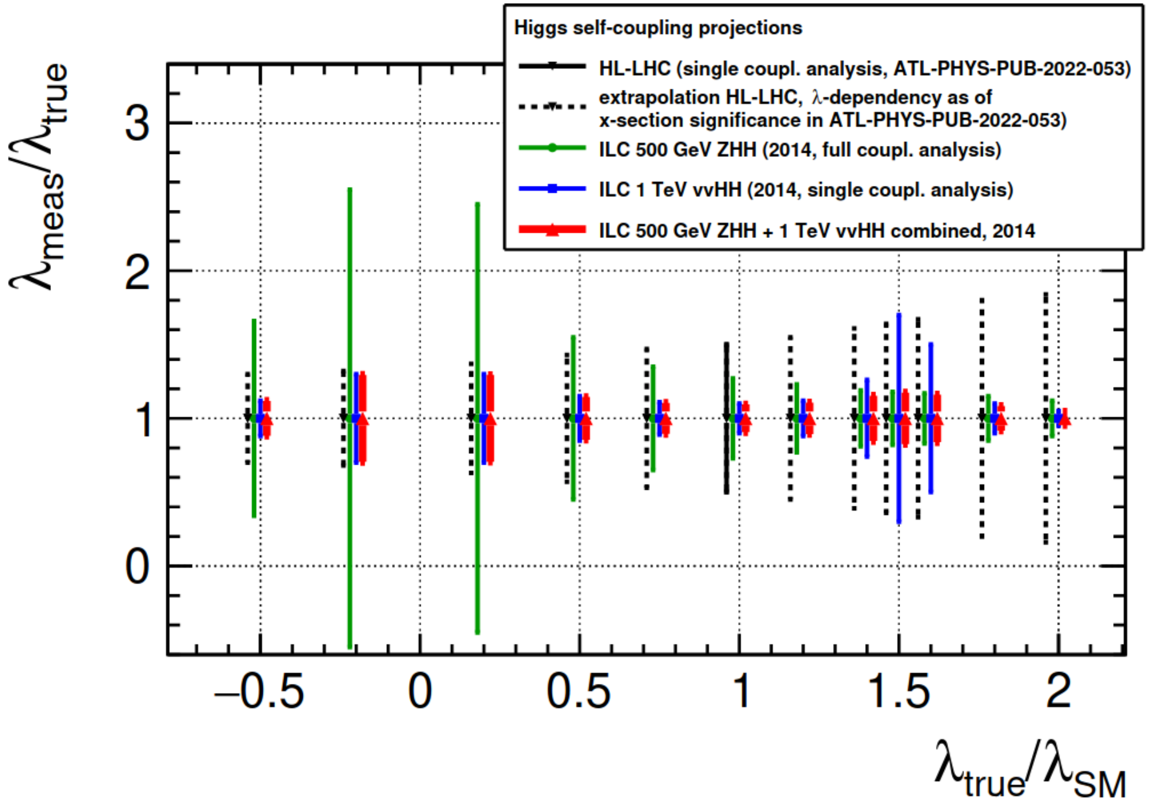




Trilinear coupling at the ILC



- ILC (0.5 TeV): ~20% precision achievable on λ_3
- ILC (1 TeV): ~10% precision (adding WW production)
- CLIC (3 TeV): ~ 8% precision



Summary: Part 2

> Full shape of the Higgs potential could provide hints at BSM physics.

> Best access via Higgs boson pair production at the LHC.

- About 1800 times less abundant than single-Higgs production.

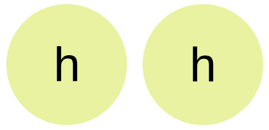
> Stringent constraints derived by searches on the LHC Run-2 dataset.

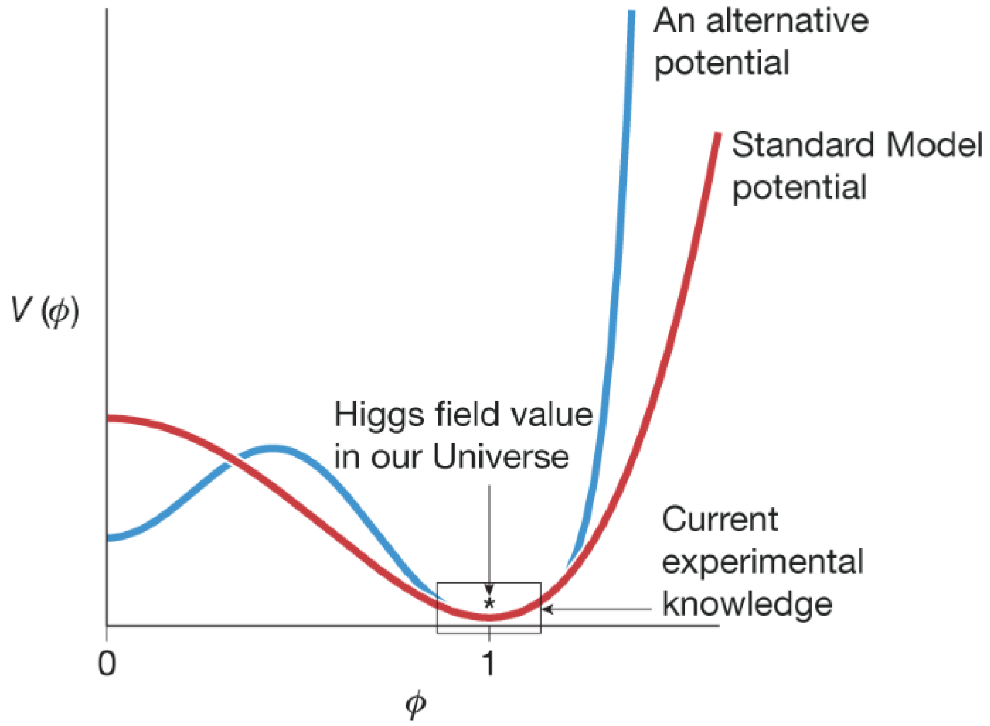
- Main decay channels: *bbbb*, *bbττ*, *bbγγ*

> Observation expected to be possible at HL-LHC

> Precision measurements possible at future Higgs factories

- Require collision energies > 500 GeV for model-independent measurements





BONUS SLIDES

Triple Higgs 6b search

> Use DNNs to discriminate between signal and background

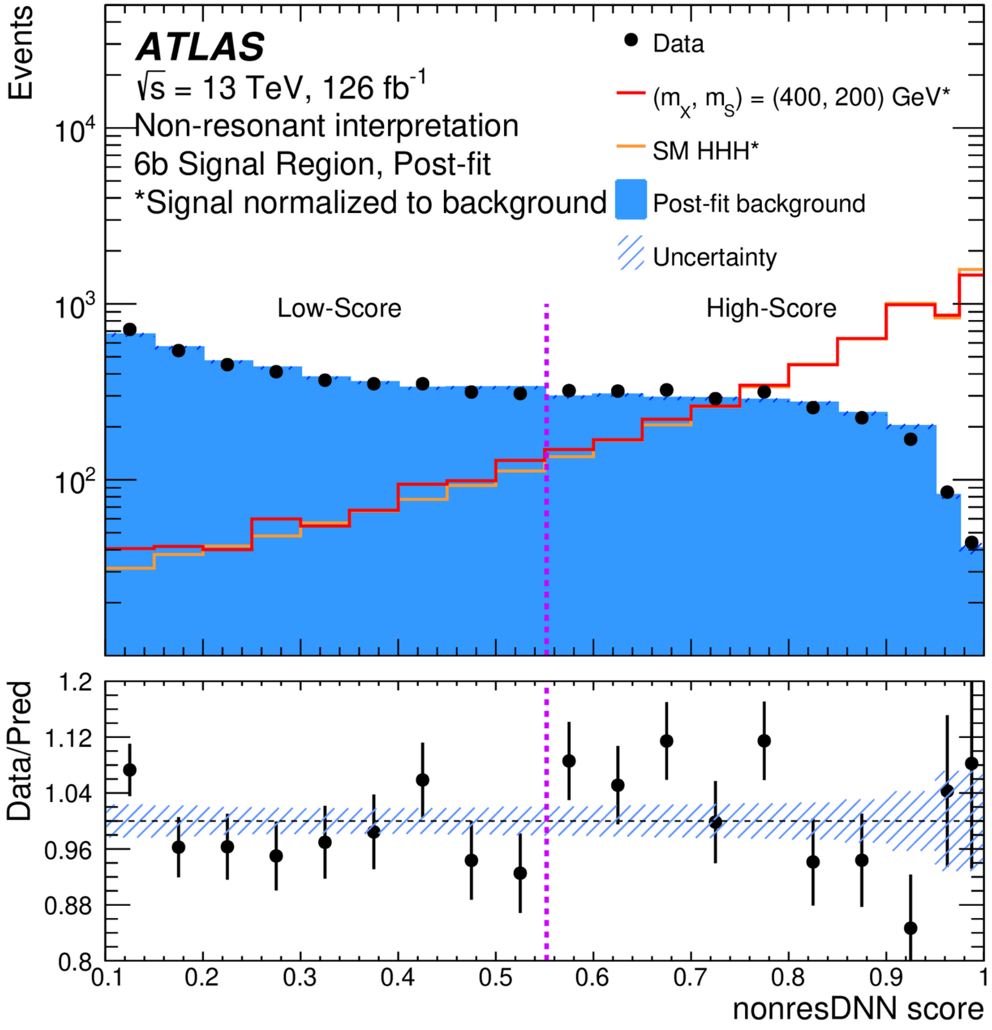
> Distribution of DNN score as discriminating variable

> High-score region:

- Signal enriched
- Used to define signal region

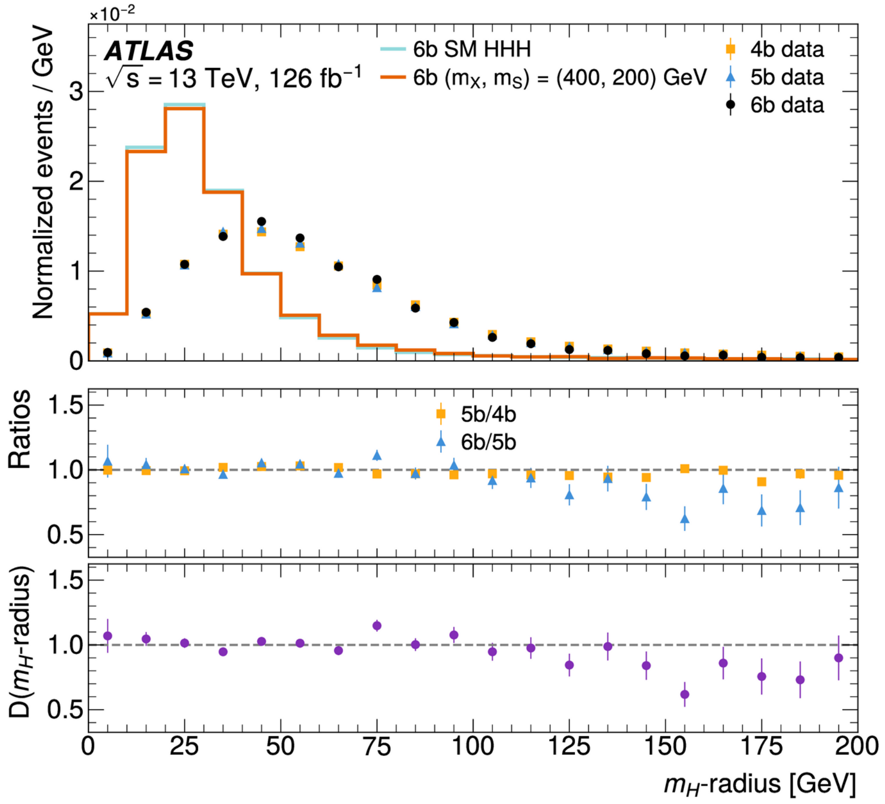
> Low-score region:

- Signal depleted
- Used to improve background estimate in signal region



Triple Higgs 6b search

- Use DNNs to discriminate between signal and background
- Separate DNNs for non-resonant (varying κ_3 and κ_4) and resonant (BSM) production
- Trained on high-level variables describing the triple Higgs system



Data-driven background estimate

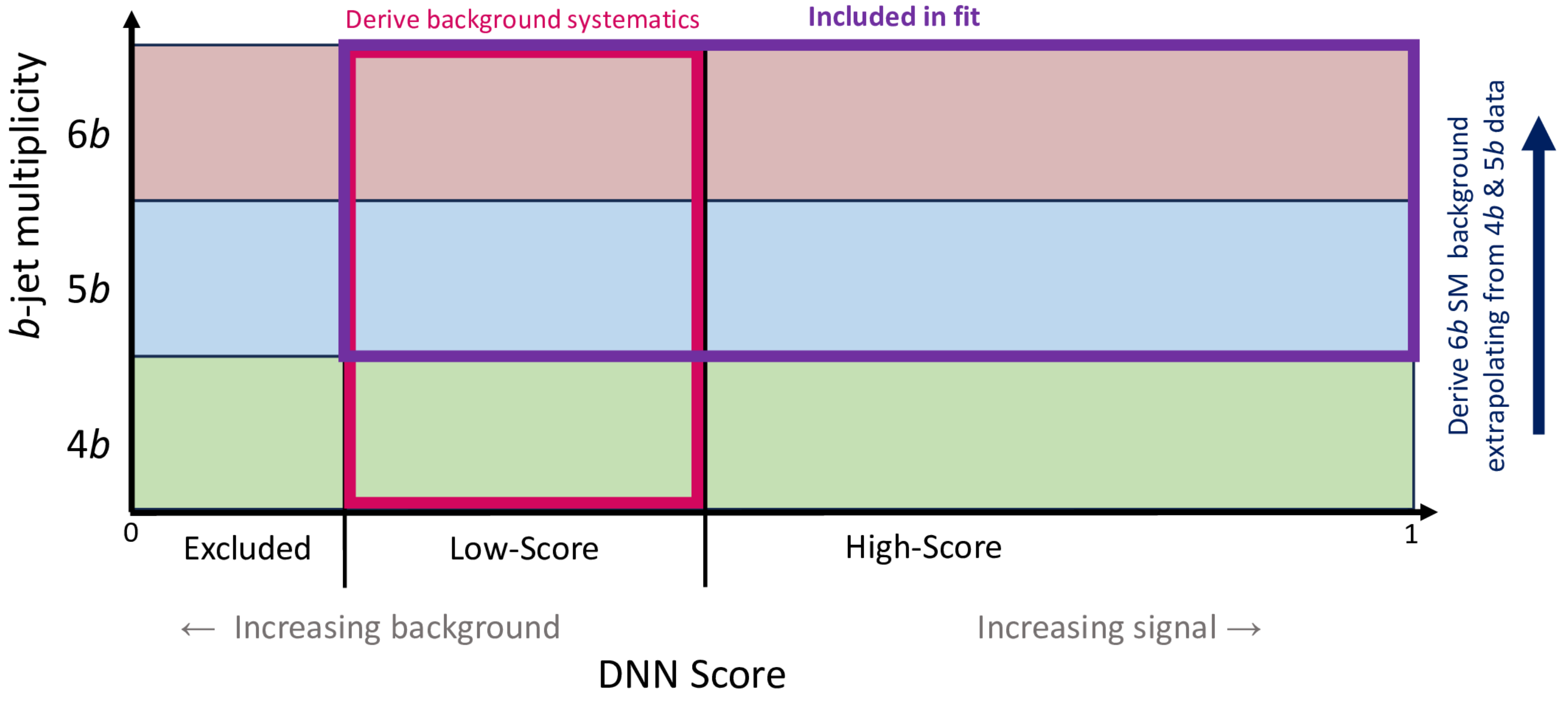
> Key assumption 1: background kinematics do not change significantly with *b*-jet multiplicity

→ Background **shape** in signal region taken from 5*b* region

> Key assumption 2: yield ratio N_{5b} / N_{4b} = yield ratio N_{6b} / N_{5b}

→ Background **normalisation** by extrapolating yields from 4*b* and 5*b* regions

> Validate assumptions in low-score regions and derive systematic uncertainties

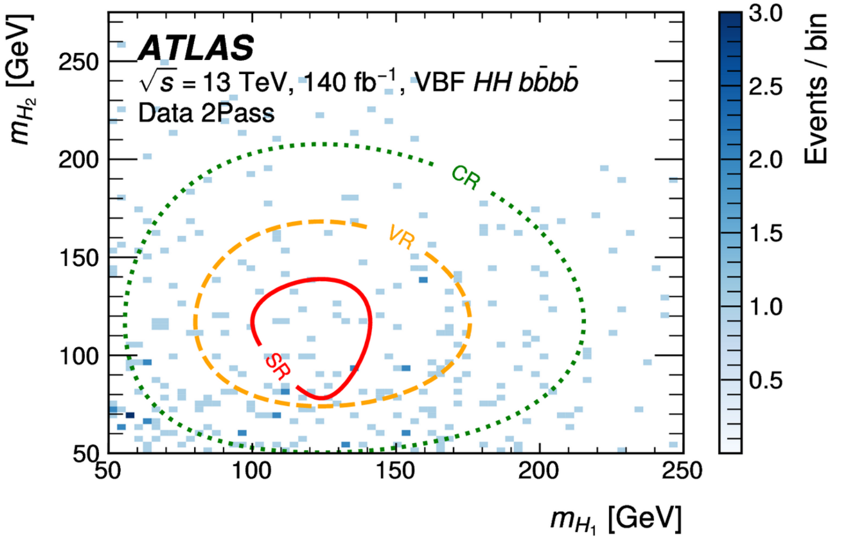


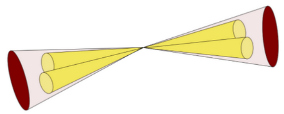
Search for VBF production in boosted *bbbb* events

> Main background from QCD multi-jet production estimated from data
  - Both multi-*b*-final states and events with mis-identified *b*-jets (10% ttbar events in total)

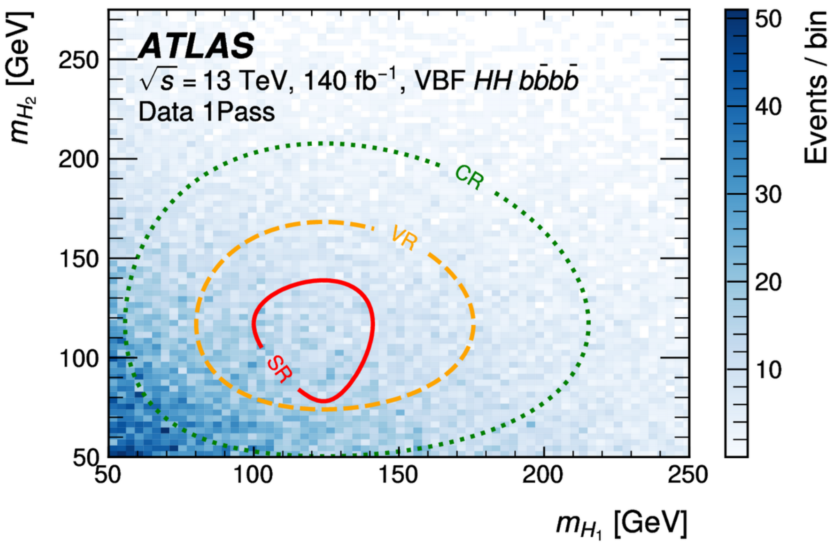
> Normalisation factor calculated as event ratio between 2Pass and 1Pass CR
  - $w = 0.0081 \pm 0.0010$
  - Signal contamination in 1Pass CR is <8% in highest BDT bin (below stats uncertainty)

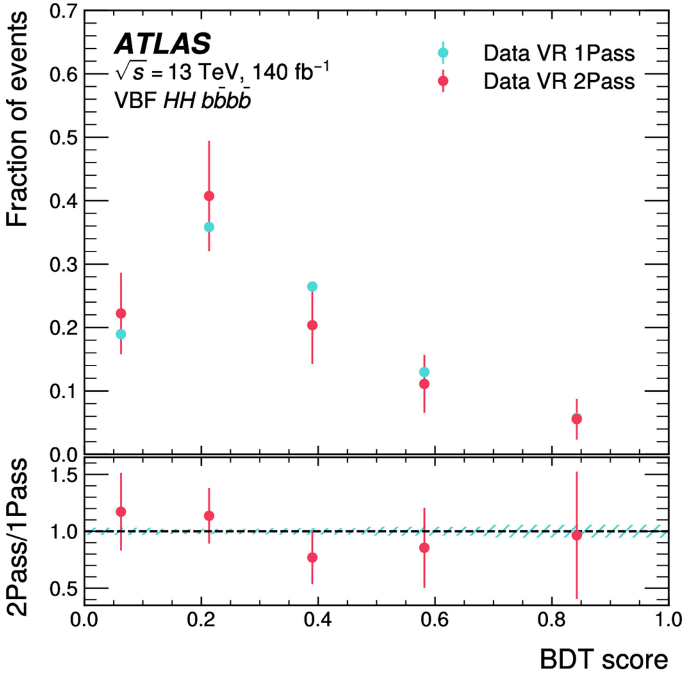
2Pass





1Pass





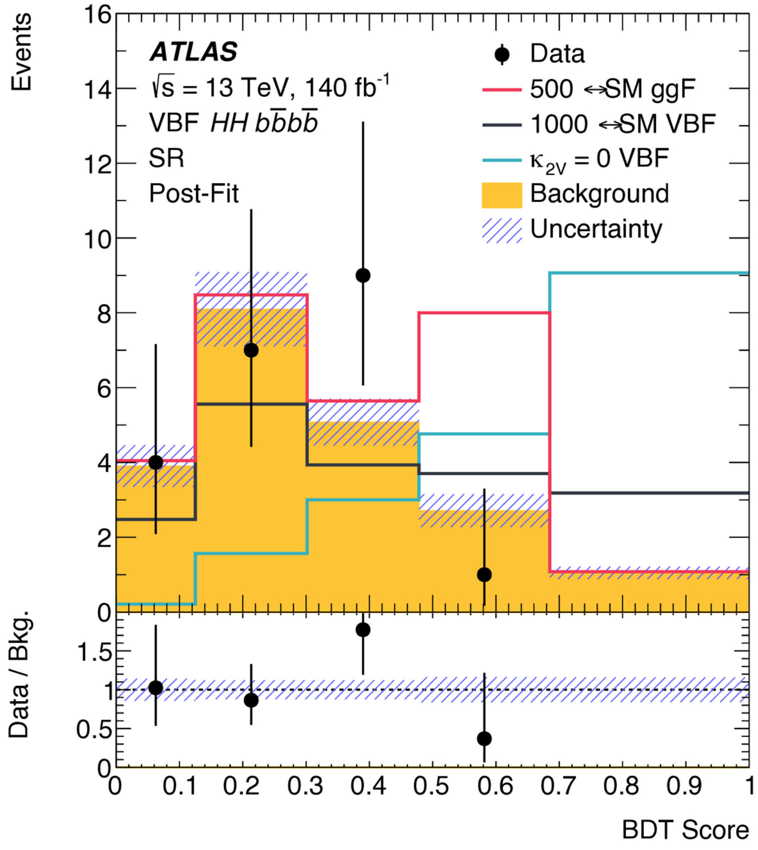
Search for VBF production in boosted *bbbb* events

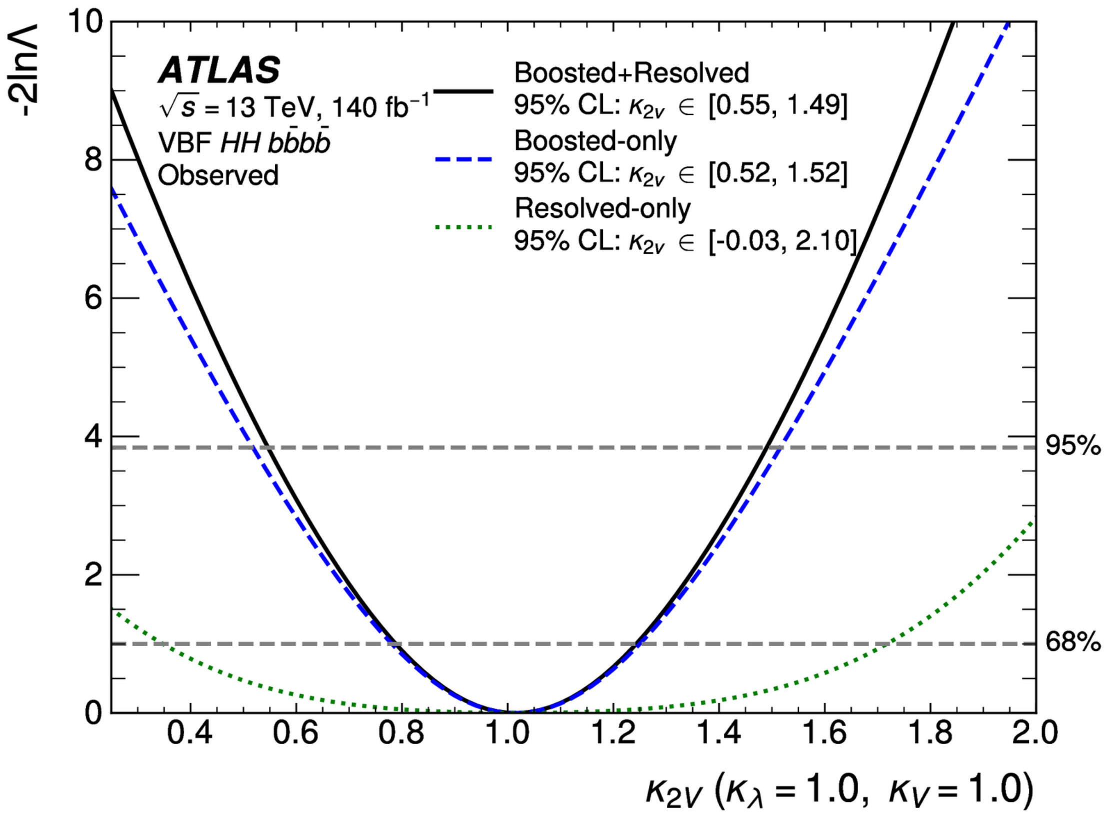
Phys. Lett. B 858 (2024) 139007

> Search primarily statistics-limited but Xbb tagging uncertainties also have a notable impact

> Interplay between boosted and resolved channels:

- Resolved more sensitive to κ_λ, boosted more sensitive to κ_{2V}



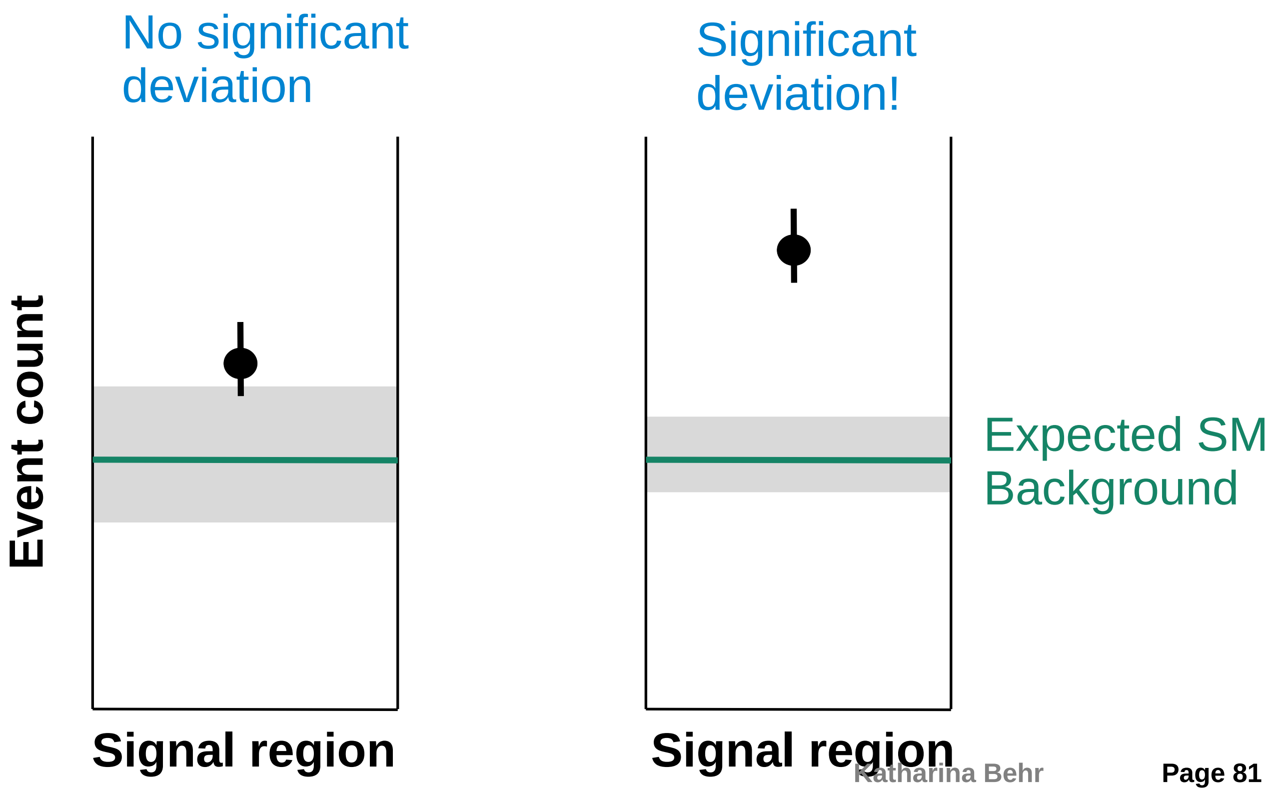


Cut-and-count method

> Select (**cut**) events that you expect to be consistent with signal (signal region)

> **Count** data events in signal region and compare with number of expected SM events

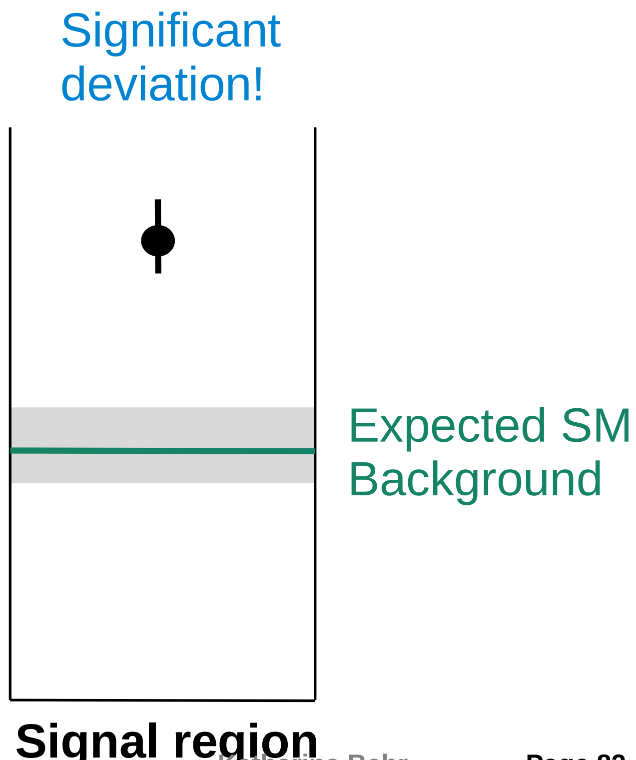
> Calculate significance of deviation from SM prediction (accounting for uncertainties)



Cut-and-count method

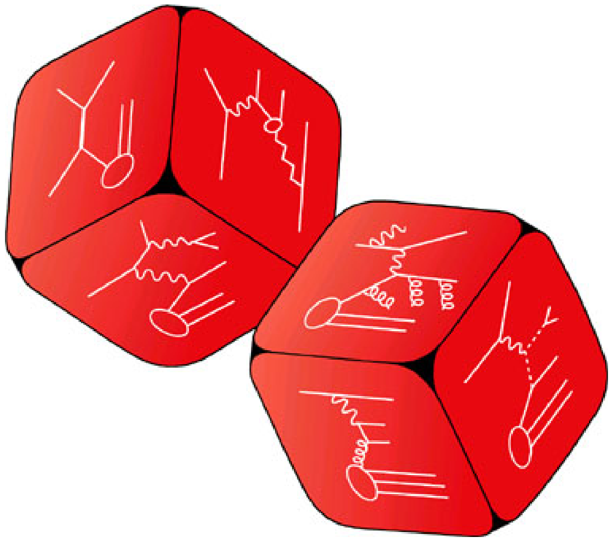
- Select (**cut**) events that you expect to be consistent with signal (signal region)
- **Count** data events in signal region and compare with number of expected SM events
- Calculate significance of deviation from SM prediction (accounting for uncertainties)

- **Advantage**: suited for low-stat regions, model agnostic
- **Disadvantage**: single bin → vulnerable to fluctuations → less sensitive



Monte Carlo event generators in a nutshell

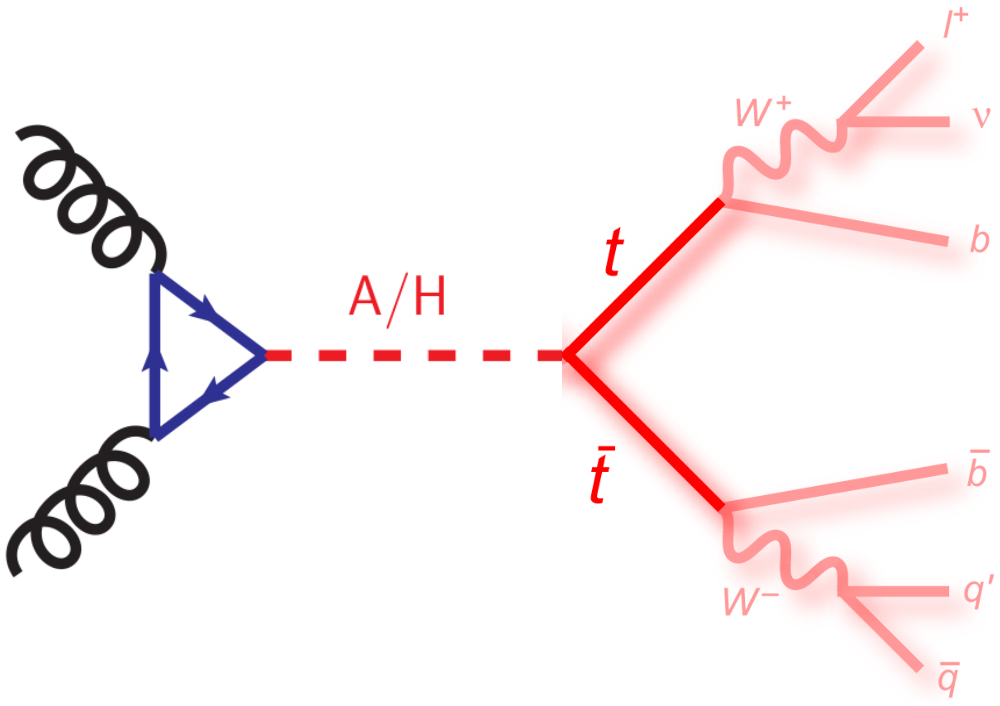
- Quantum nature of elementary particle interactions: non-deterministic
  - Given initial state can lead to different final states with different probabilities
- **Idea:**
  - Calculate probability distribution for a given process (or sub-processes)
  - Random sampling to generate events with particle kinematics according to these distributions



Experimental Techniques

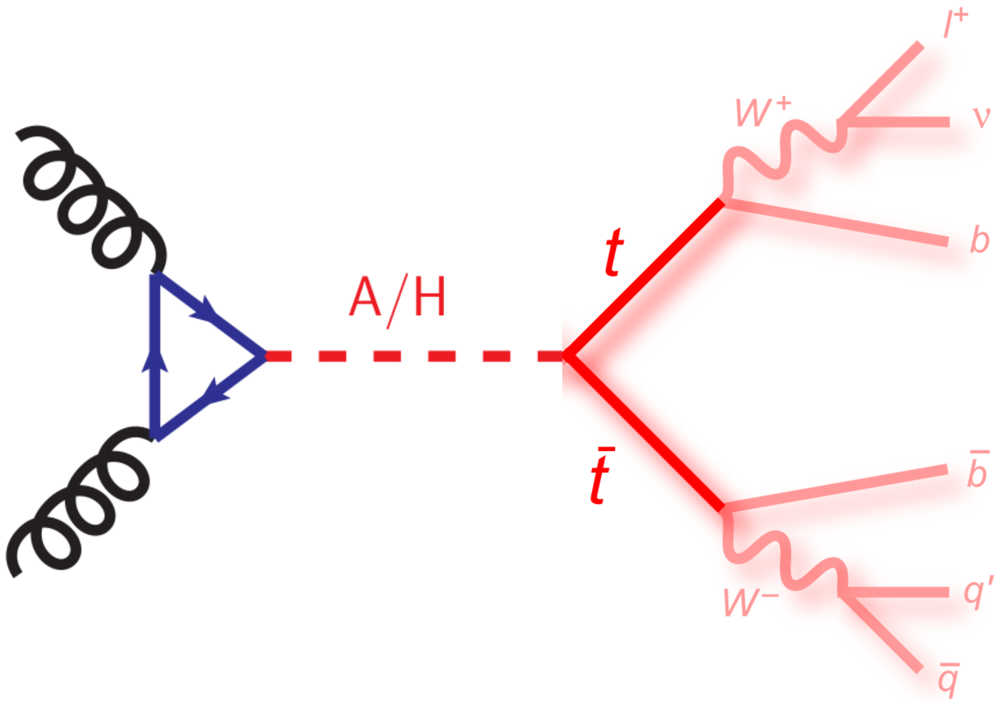
Exercise

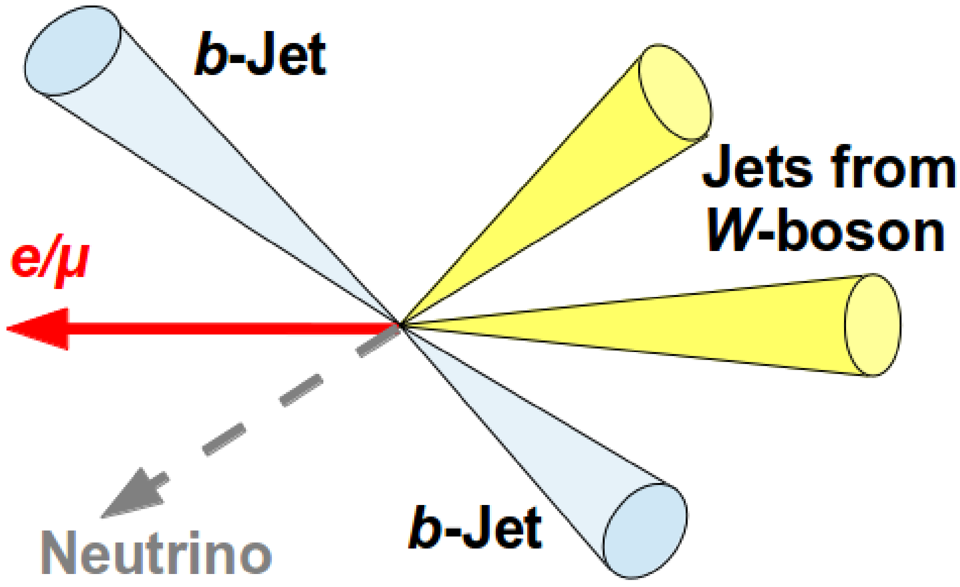
- Define a signal region for semi-leptonic ttbar decay
- For simplicity assume that charged lepton is an electron or muon



Exercise

> Define a signal region for semi-leptonic ttbar decay



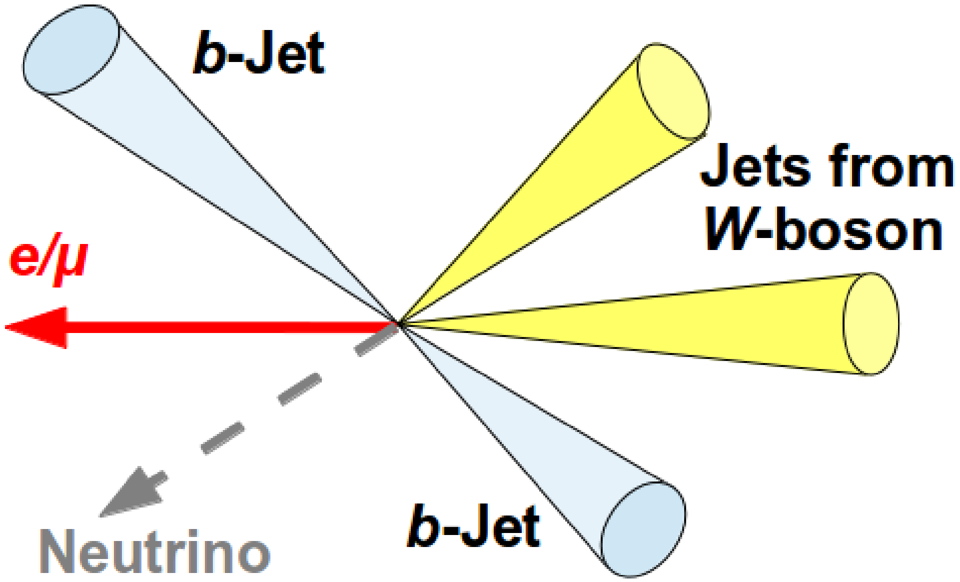


Exercise: Solution

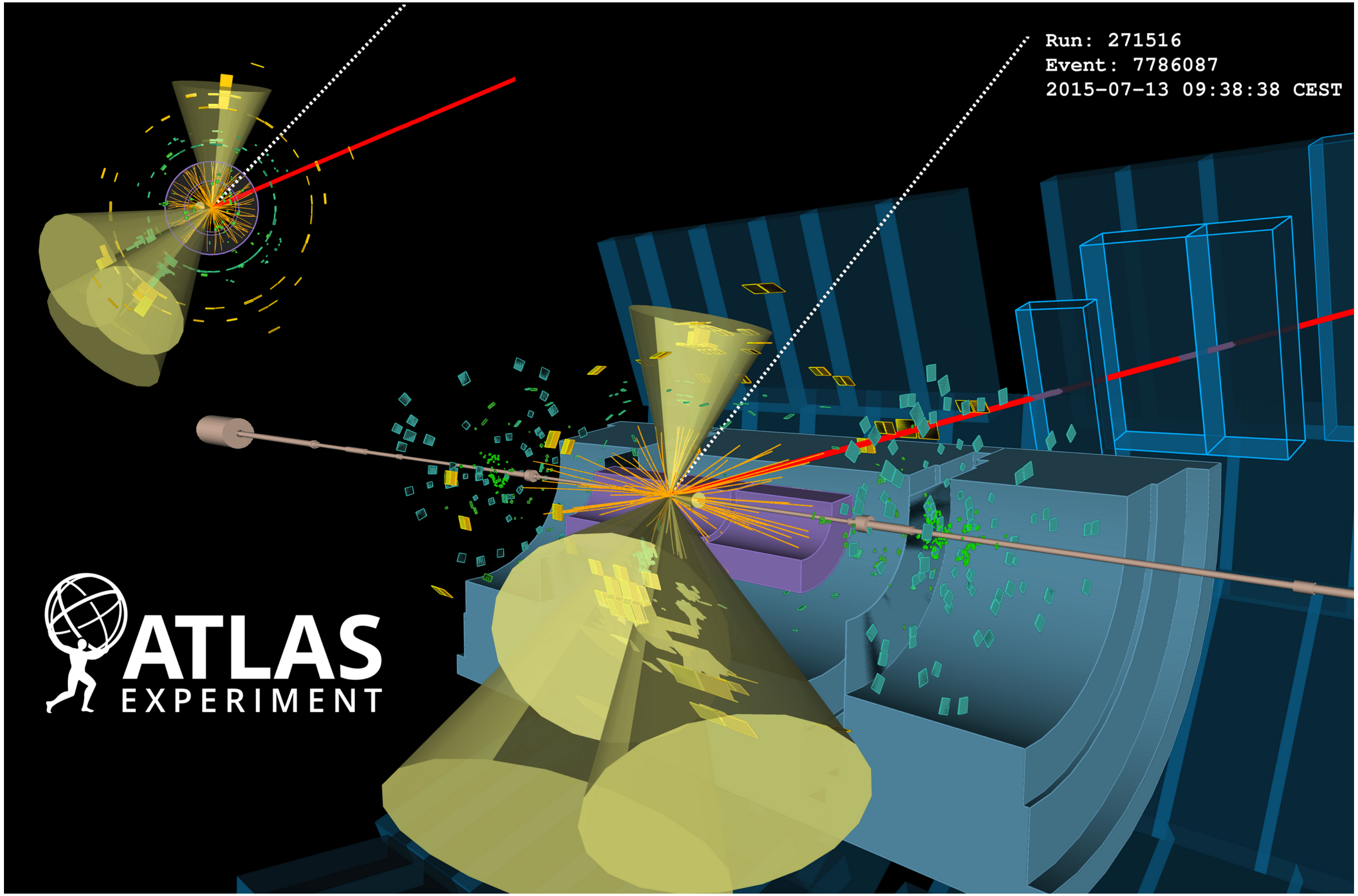
- Exactly 1 electron or muon
- Missing energy (from the neutrino)
- At least 4 jets

- Bonus 1: 2 jets identified as b-jets

- Bonus 2:
  - Combined mass of 2 jets = W mass
  - Combined mass of 3 jets = top mass

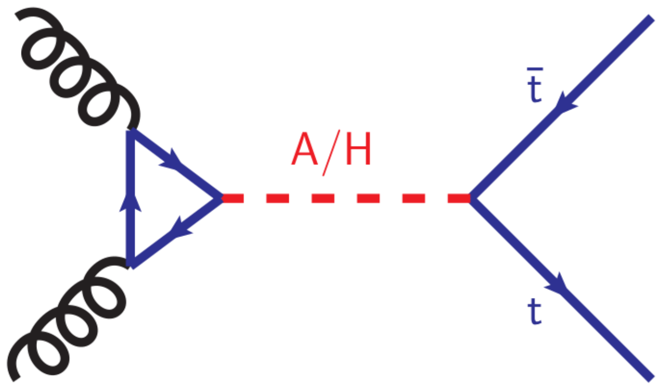


Exercise: Solution

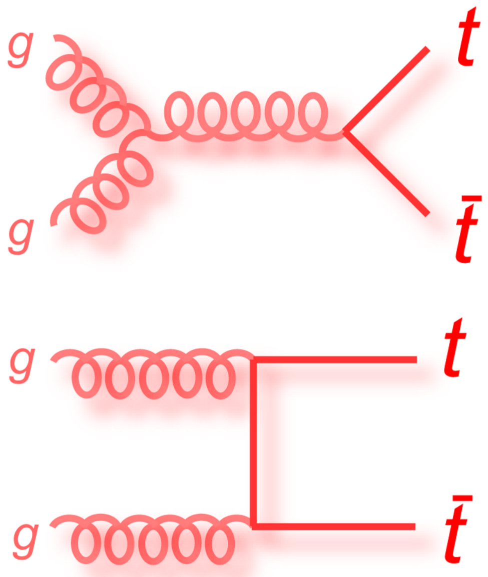


Signal vs backgrounds

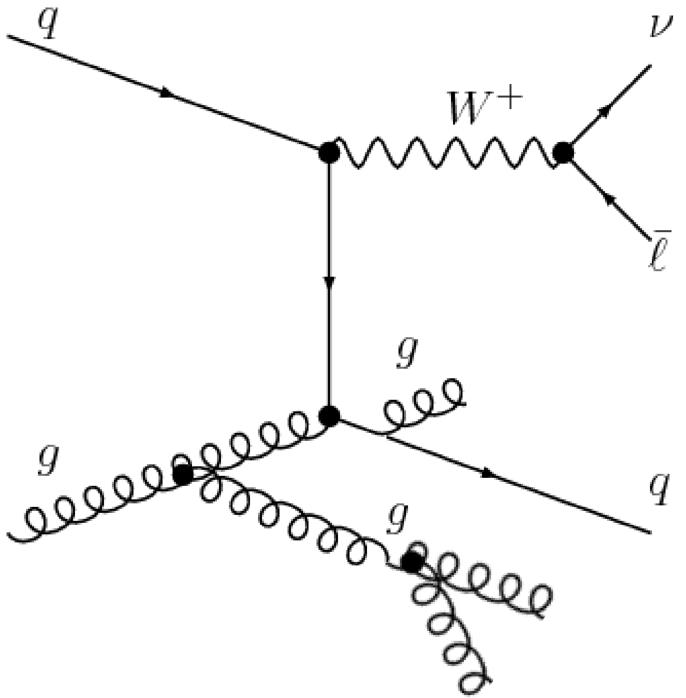
Signal



SM ttbar production
Irreducible background

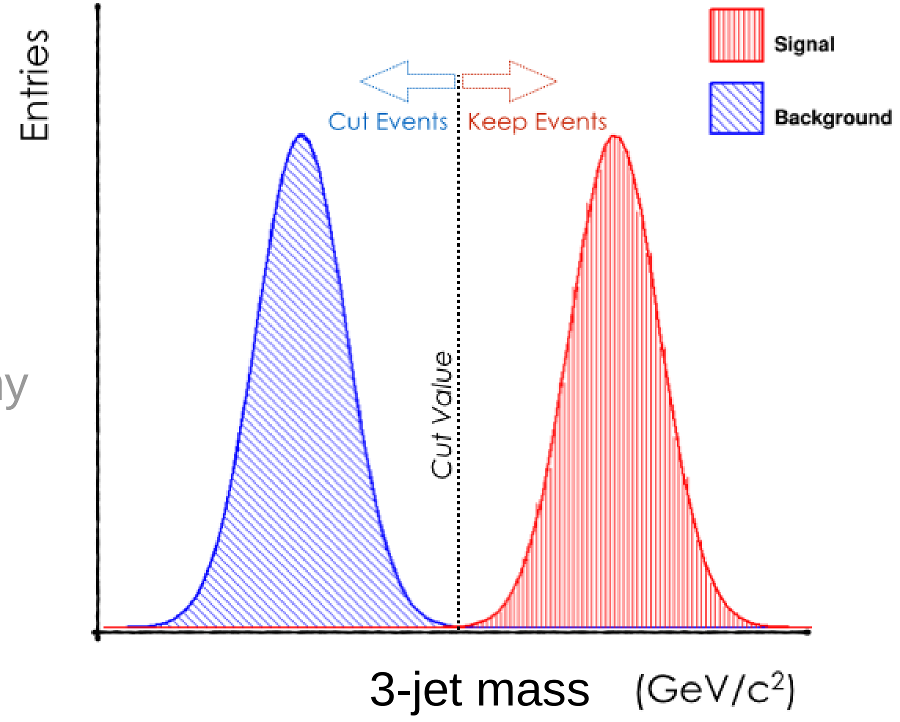


SM W+jets production
Reducible background



Signal region definition

- Apply selection criteria (cuts) to reduce background
- Signal-enriched region (signal region)
- Additional cuts based on differences in kinematic distributions



T.G. McCarthy

Signal region definition

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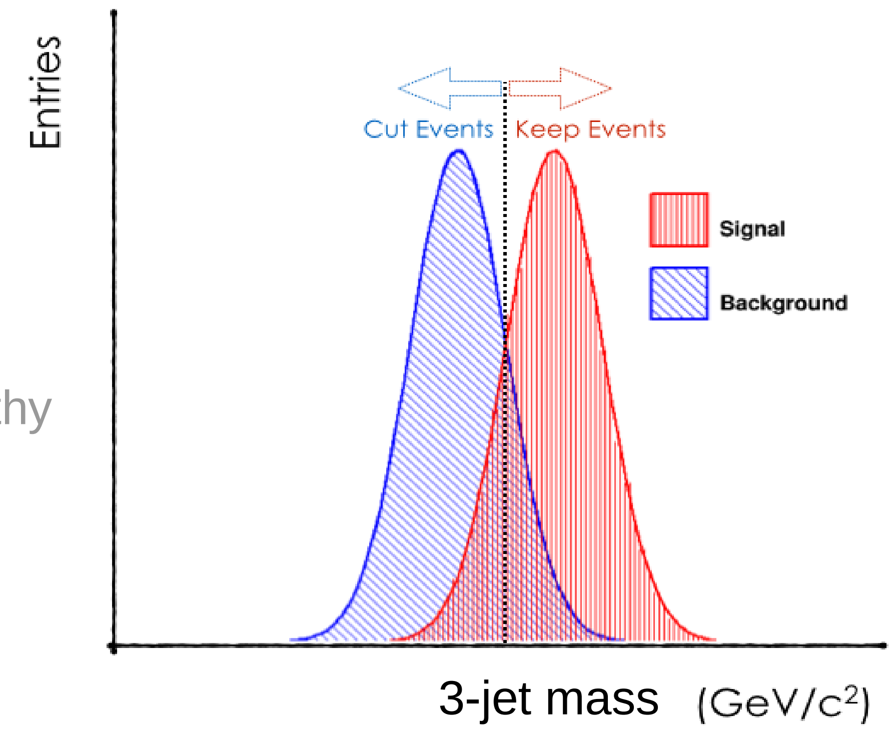

T.G. McCarthy

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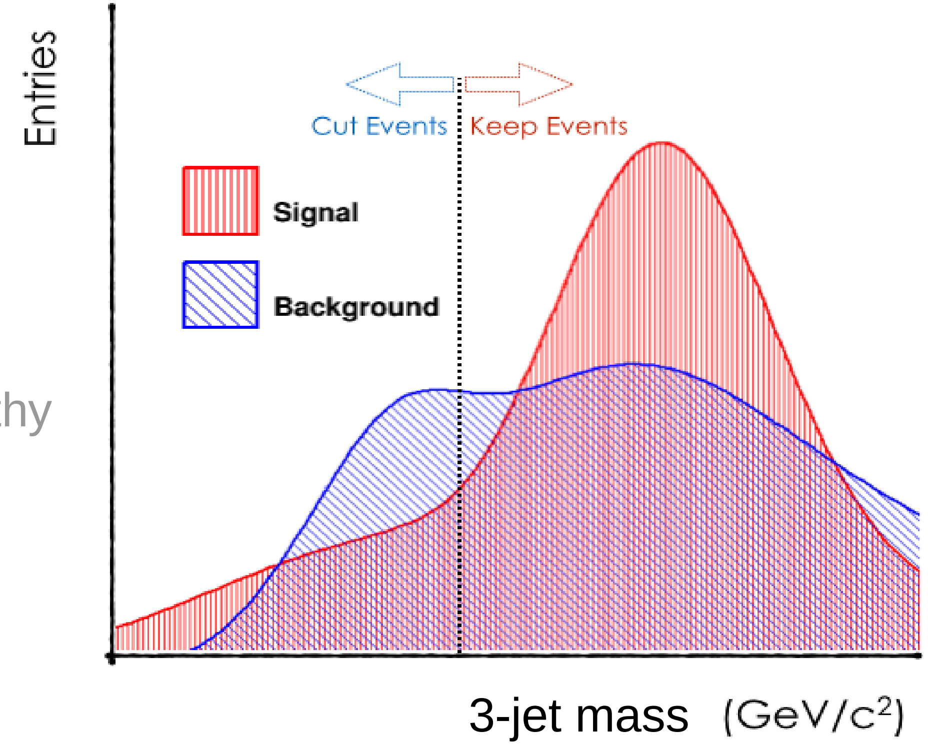
T.G. McCarthy



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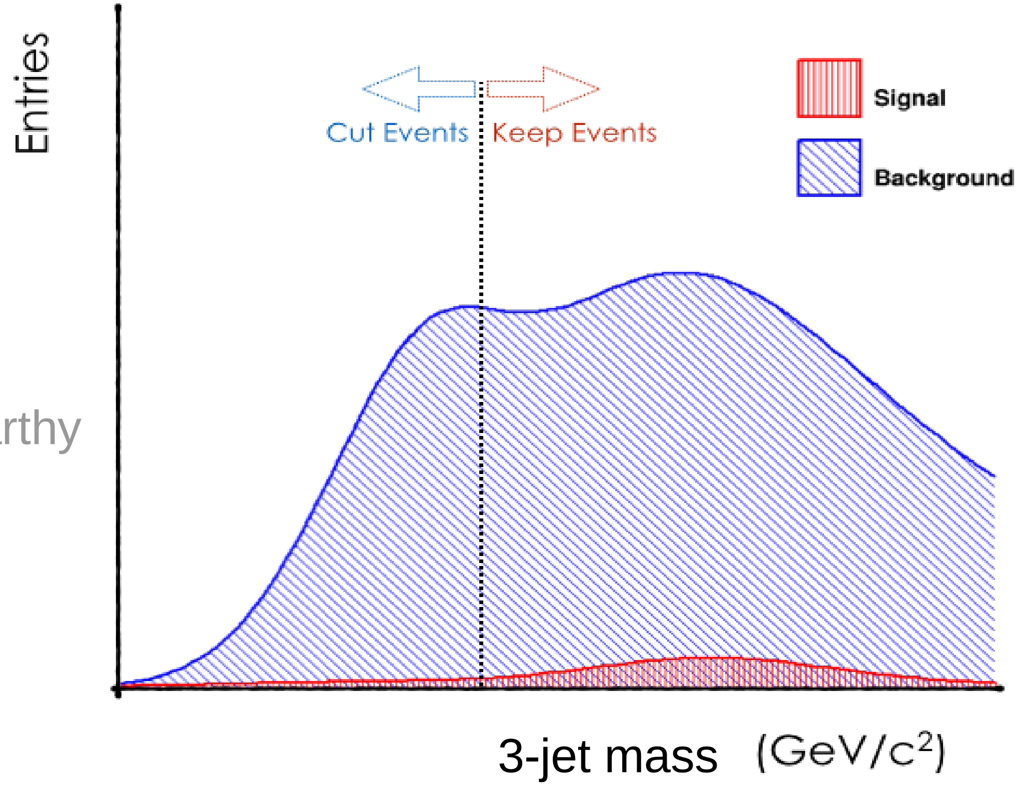
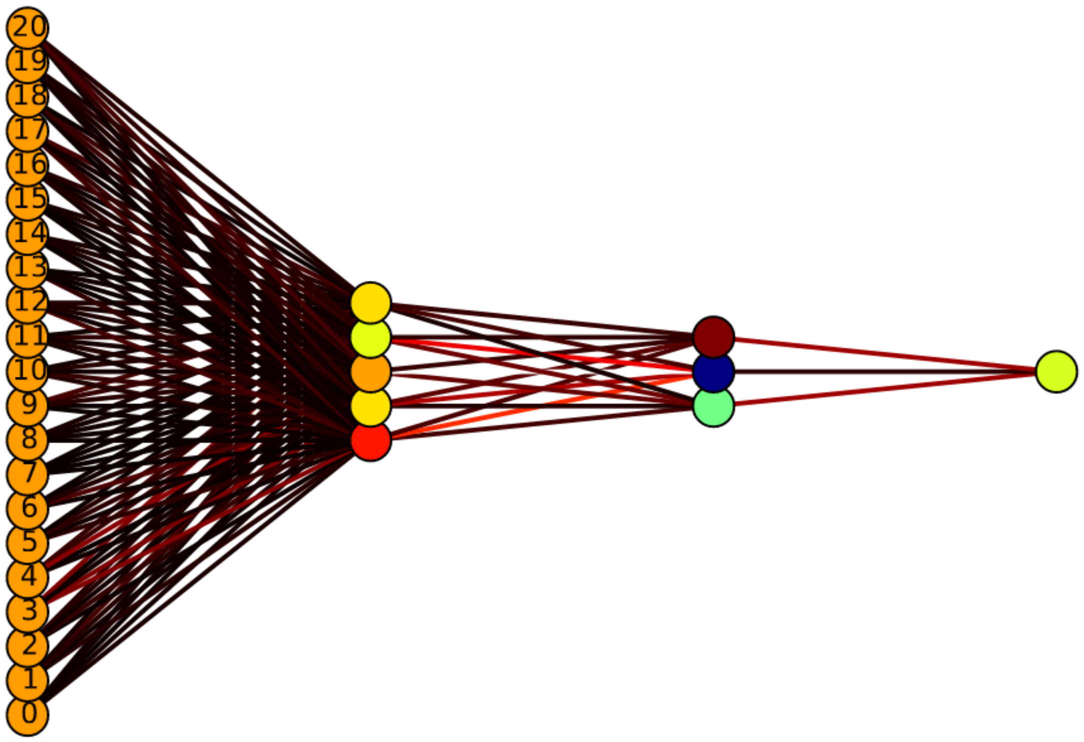
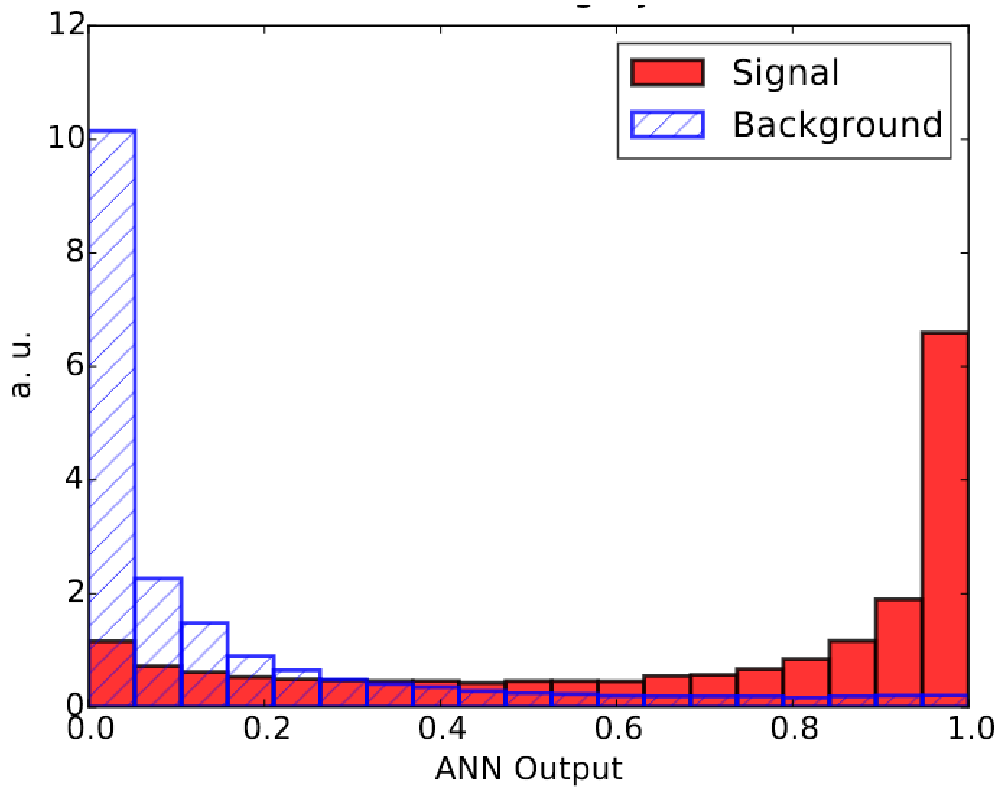


T.G. McCarthy

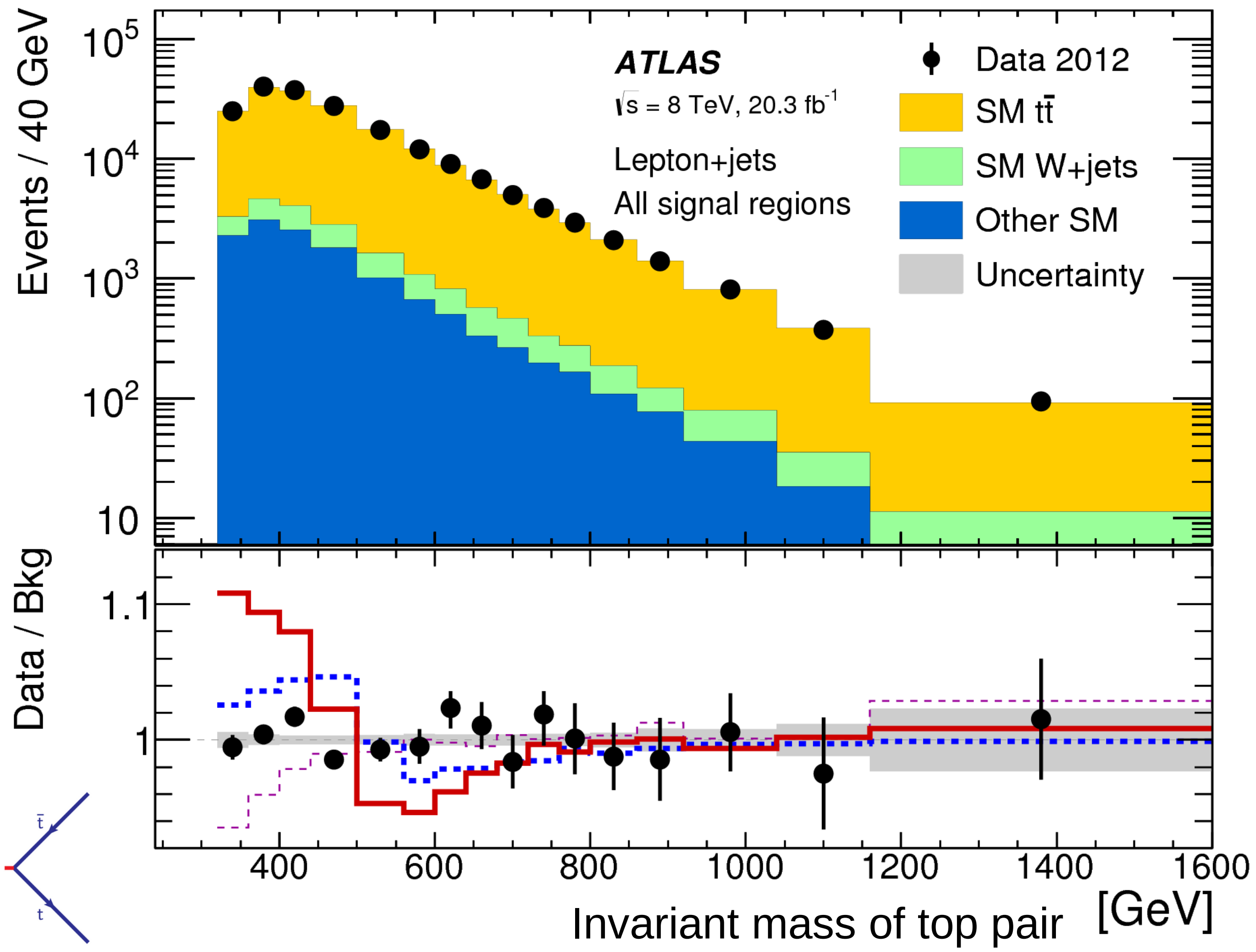
Signal region definition

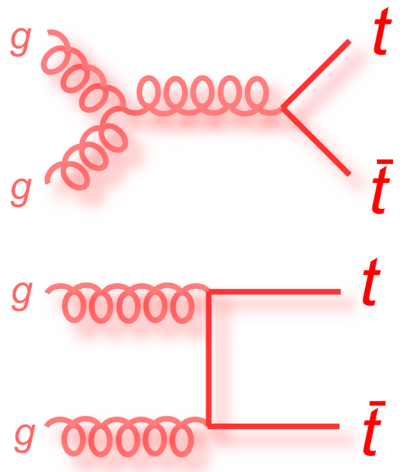
> Can refine signal regions using machine-learning algorithms
  - Exploit small differences in various kinematic variables
  - Exploit correlations

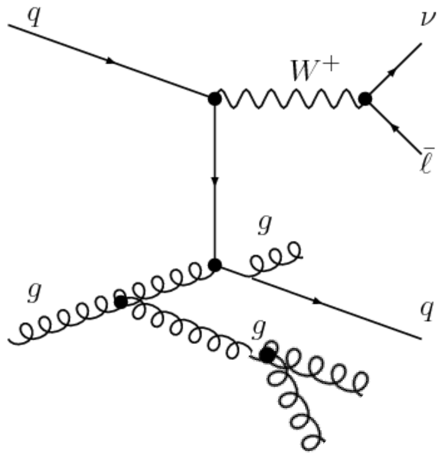


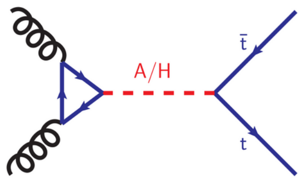


A final signal region









Event simulation

> Simulate possible signals based on theoretical models
  - Optimise sensitivity of searches

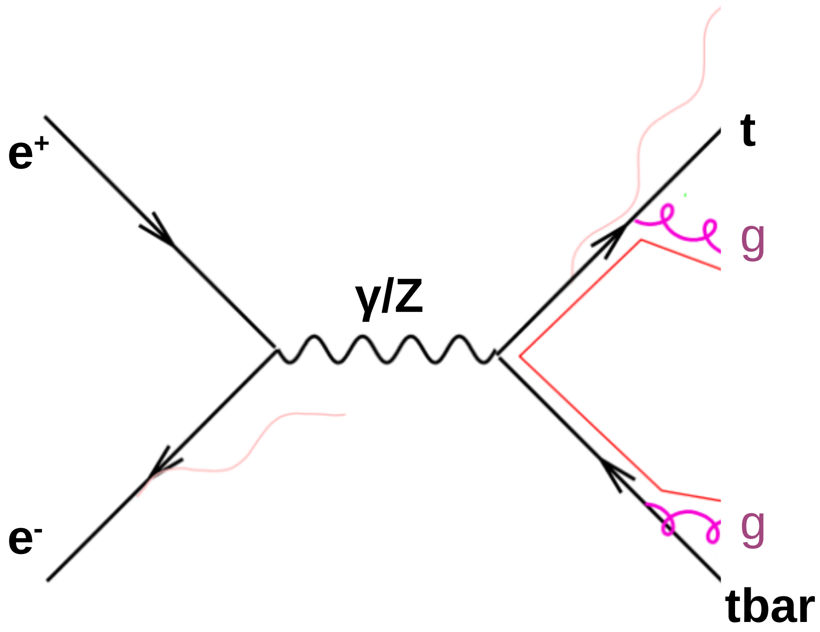
> Simulate background processes
  - Compare predictions to data and look for deviations
  - Some background processes can be simulated very accurately…
  - … others not (see data-driven estimates later)

> Estimate systematic uncertainties
  - Create different background predictions within experimental uncertainties
  - E.g. top mass known with ±1 GeV uncertainty
    - → Simulate top quark pair production for m_{top}(central) and m_{top}(central)±1 GeV

Simulation step by step

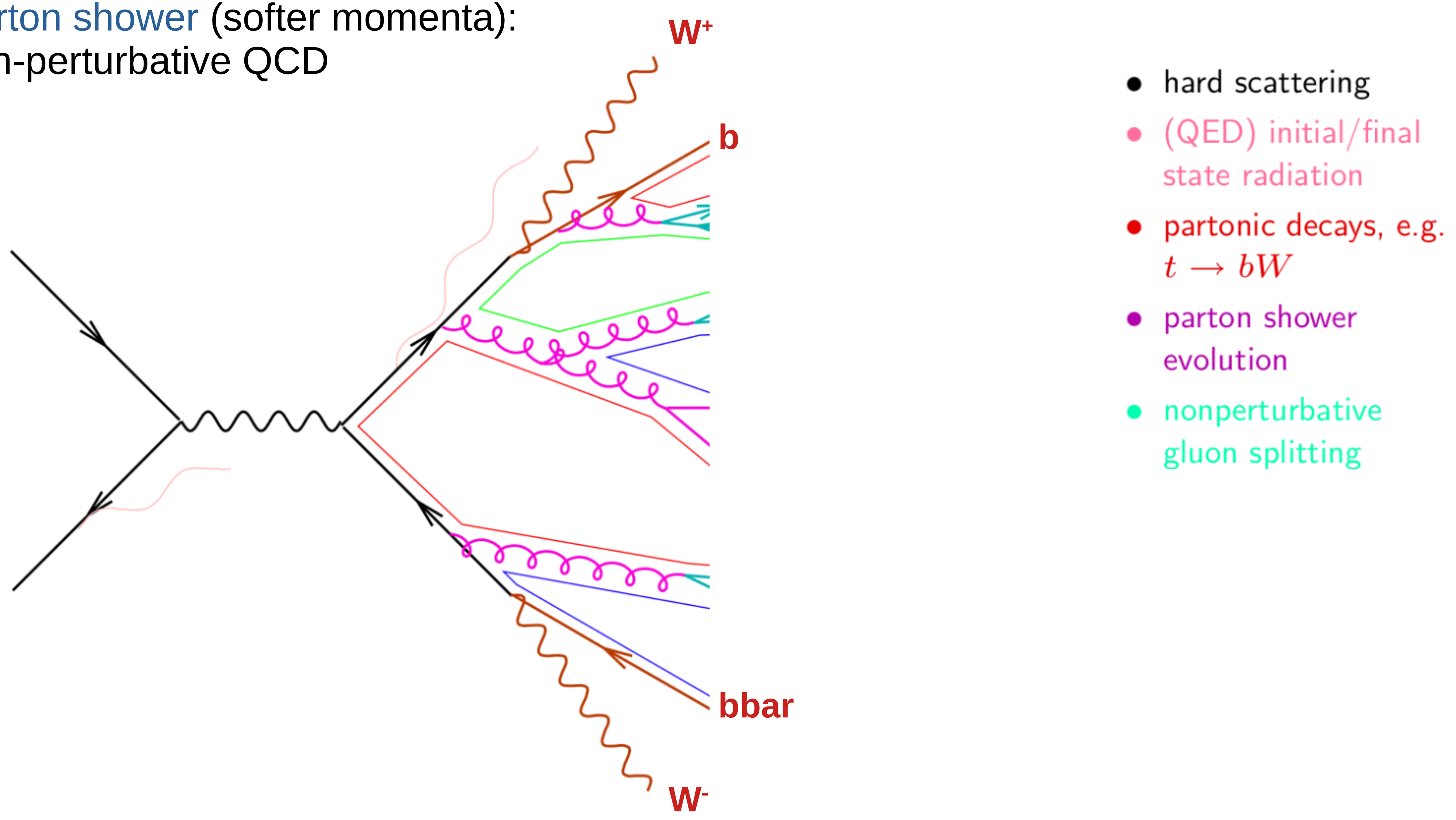
> Hard processes (large momentum transfers): perturbative QCD

- hard scattering
- (QED) initial/final state radiation



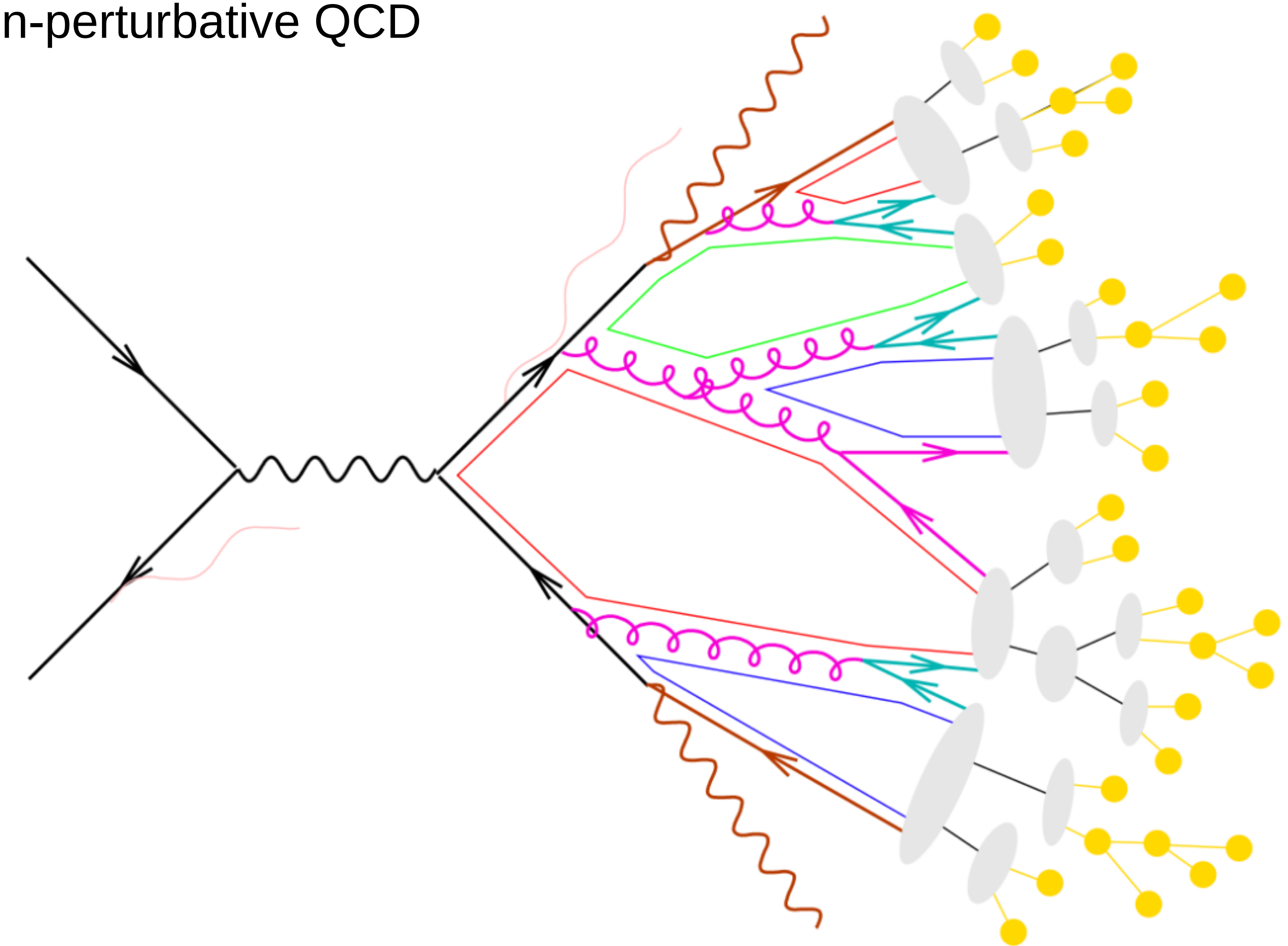
Simulation step by step

> Parton shower (softer momenta): non-perturbative QCD



Simulation step by step

> Hadronisation (soft, low energy):
> non-perturbative QCD



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays

Think outside the (black)box!

- Many different event generators available for HEP/LHC
  - Choice depends on process, required precision, …
    - E.g. matrix-element generators: MadGraph, Powheg
    - E.g. matrix-element + parton-shower generators: Pythia, Herwig
  - Important to understand differences and subtleties to not treat them as blackboxes!

Think outside the (black)box!

*“[…] remember that the programs **do not represent a dead collection of established truths**, but rather one of many possible approaches to the problem of multiparticle production in high-energy physics, at the frontline of current research. **Be critical!**”*

From the manual of the Pythia5 MC generator

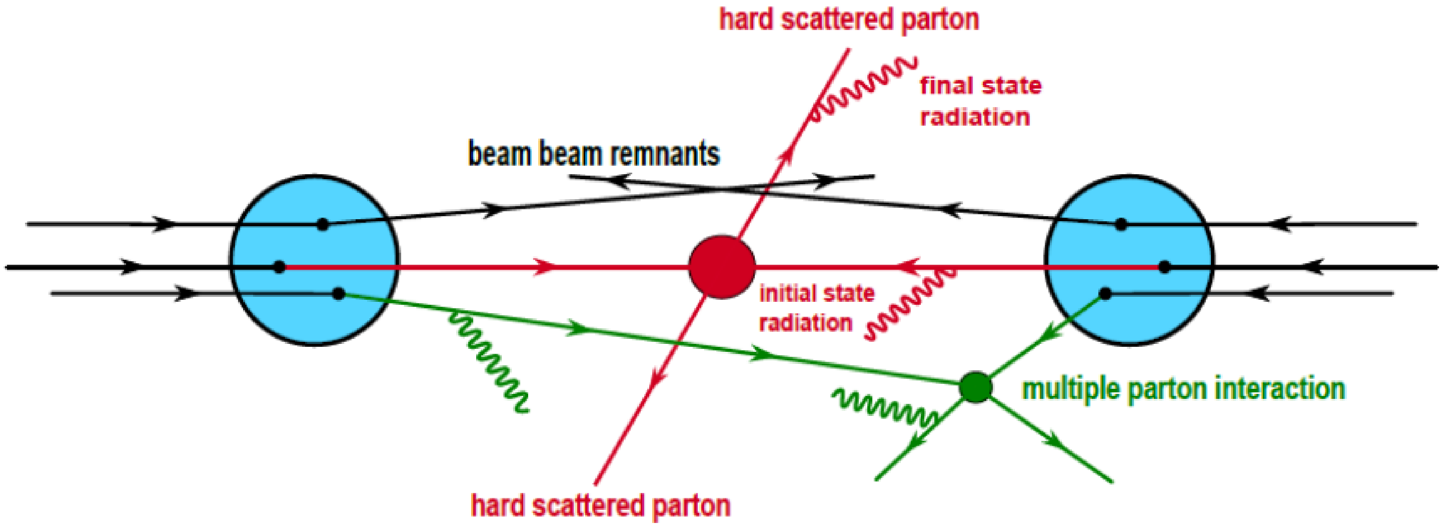
Further aspects

> Simulate interactions of (collider) stable particle with detector material

  - Geant4, Delphes, ...

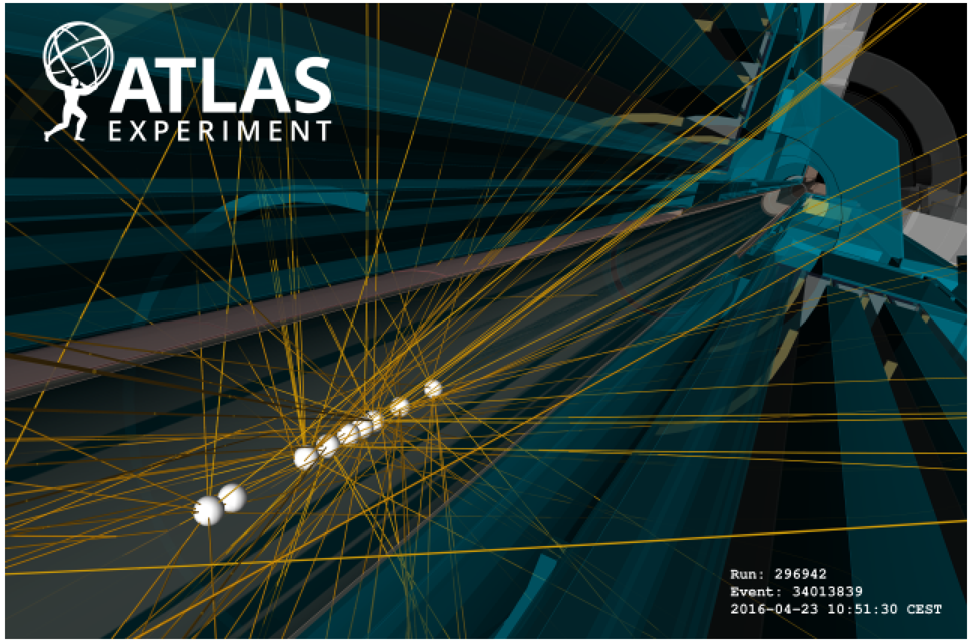
Further aspects

- Simulate interactions of (collider) stable particle with detector material
  - Geant4, Delphes, …
- Specifically for hadron colliders (LHC, Tevatron, …):
  - **Underlying Event**: simulate interactions of additional partons within same two protons



Further aspects

- Simulate interactions of (collider) stable particle with detector material
  - Geant4, Delphes, …
- Specifically for hadron colliders (LHC, Tevatron, …):
  - **Underlying Event**: simulate interactions of additional partons within same two protons
  - **Pile-up**: simulate interactions of additional protons in the same bunch crossing



- Further reading:

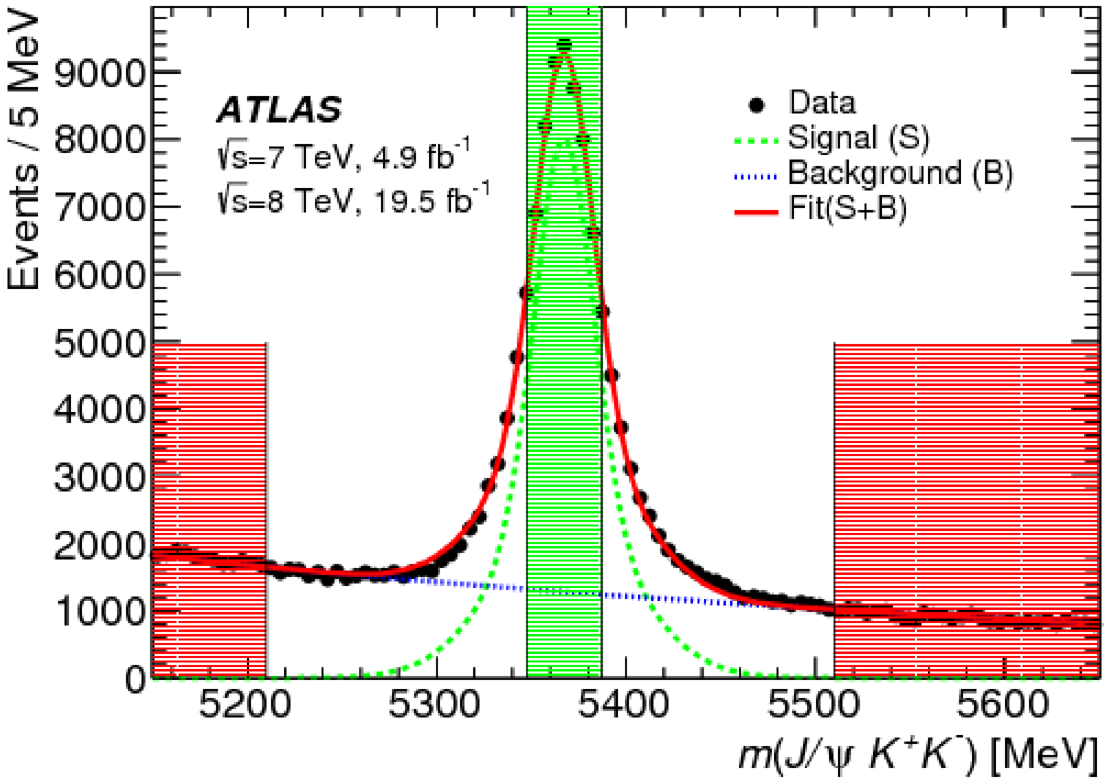
  lecture by M. Seymour and M. Marx [link]

Estimating background processes from data

- Simulation not always feasible for estimating background processes
  - Instrumental backgrounds (related to detector effects)
    - Jets with high EM component faking electrons
    - Backgrounds from detector noise
    - …
  - Processes with large cross-section that would require large MC statistics
    - Mostly multijets at the LHC
  - Known modeling limitations
    - Missing higher-order processes
    - …
- Use fully data-driven estimates or data-driven corrections

Sidebands

- Assume known signal region (= location in the spectrum)
- Fit background in sidebands (= adjoining parts of the spectrum, signal depleted)
- Extrapolate to signal region

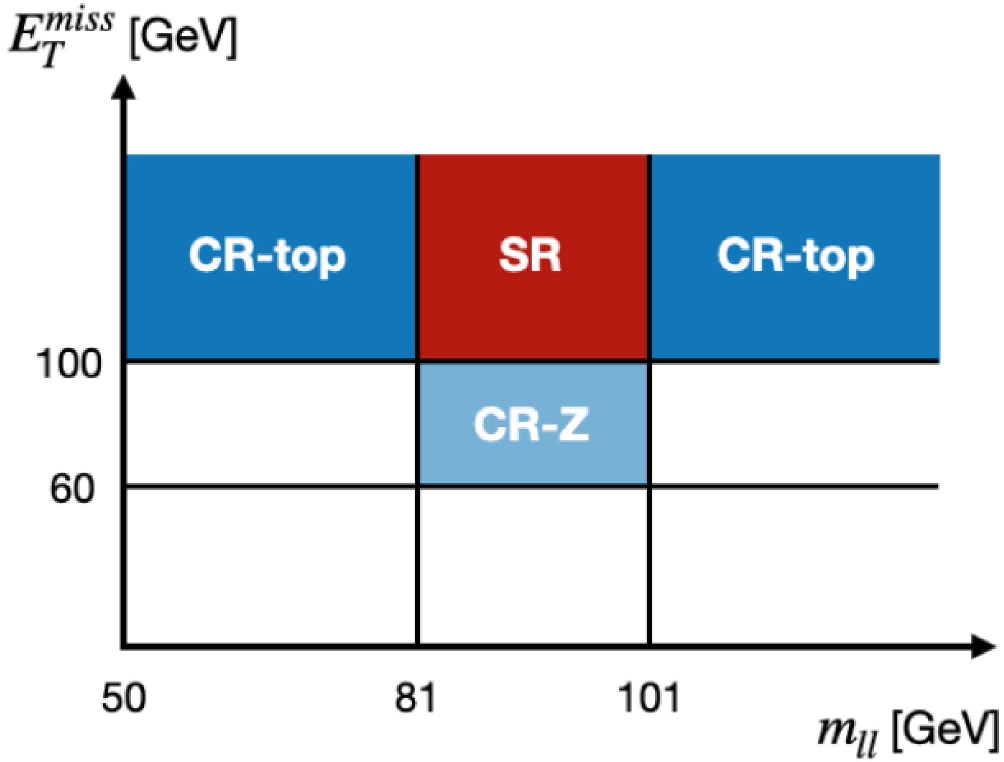


Control Regions

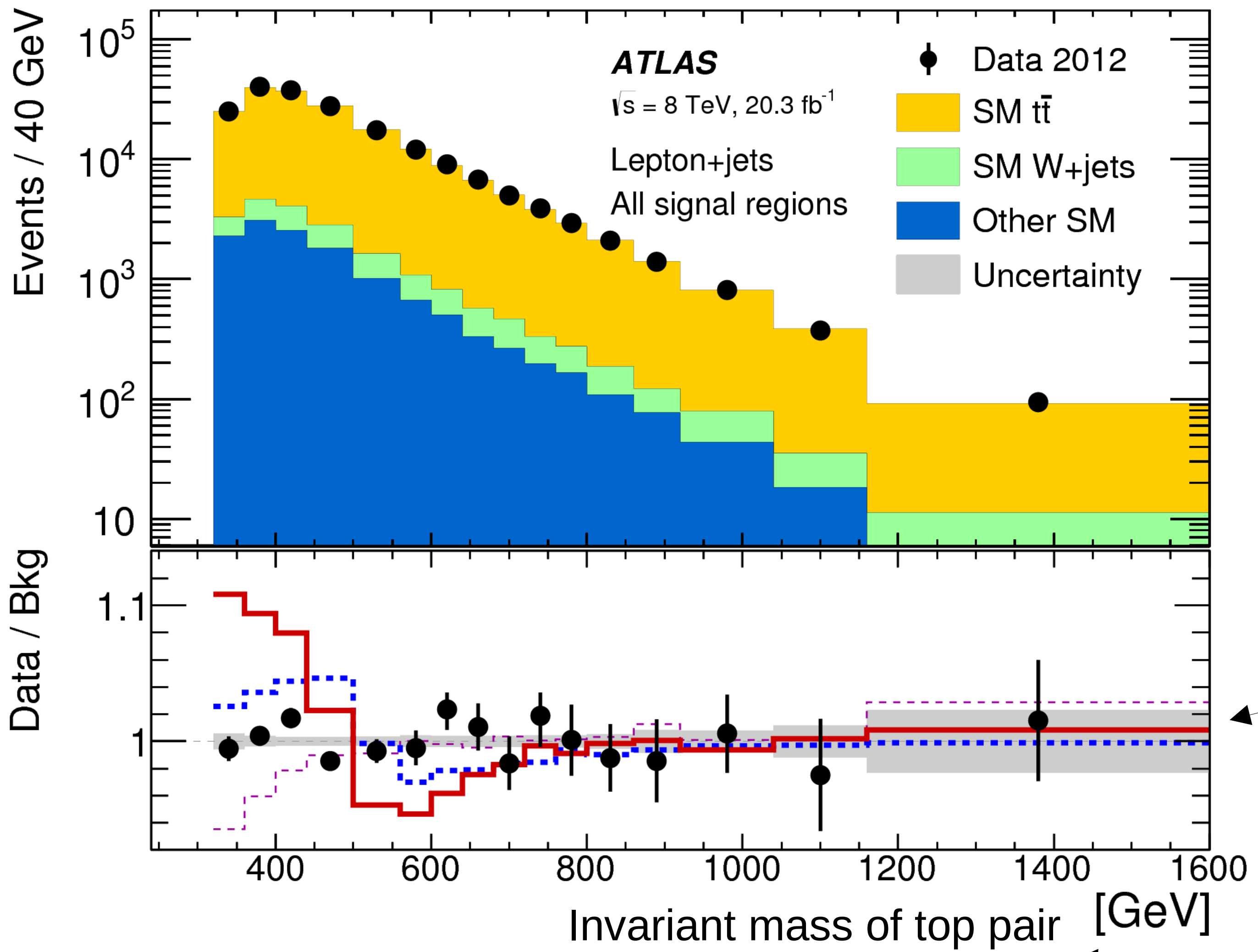
> Same idea as with sidebands but using a modified selection to define a control region
  - Orthogonal to signal region, signal depleted

Signal signature: $Z(\rightarrow ll) + E_T^{miss}$ + bbar

> Must be carefully designed to
  - Be signal depleted
  - Be enriched in background of interest
  - Close enough to SR to avoid biases
  - ...



A final signal region

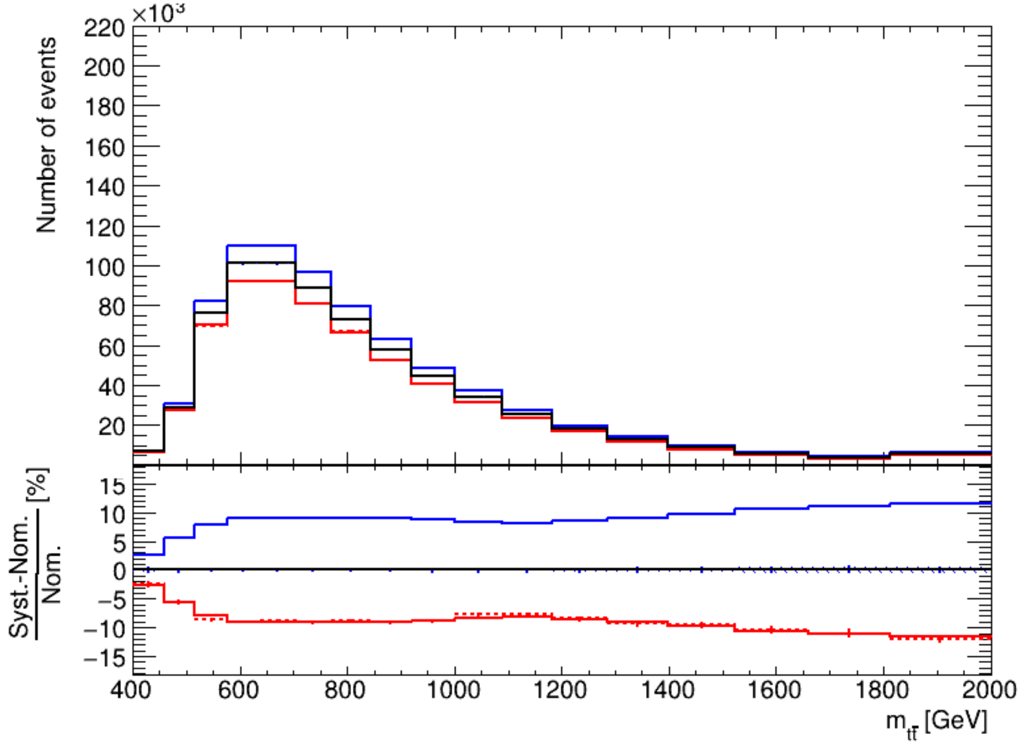


Systematic and statistical uncertainties

Variable of interest

Systematic uncertainties

- Various different sources:
  - Modeling uncertainties, e.g. unknown higher-order corrections
  - Experimental uncertainties, e.g. uncertainties on electron energy measurement
- Propagate to final spectrum
- Uncertainties degrade sensitivity to signal



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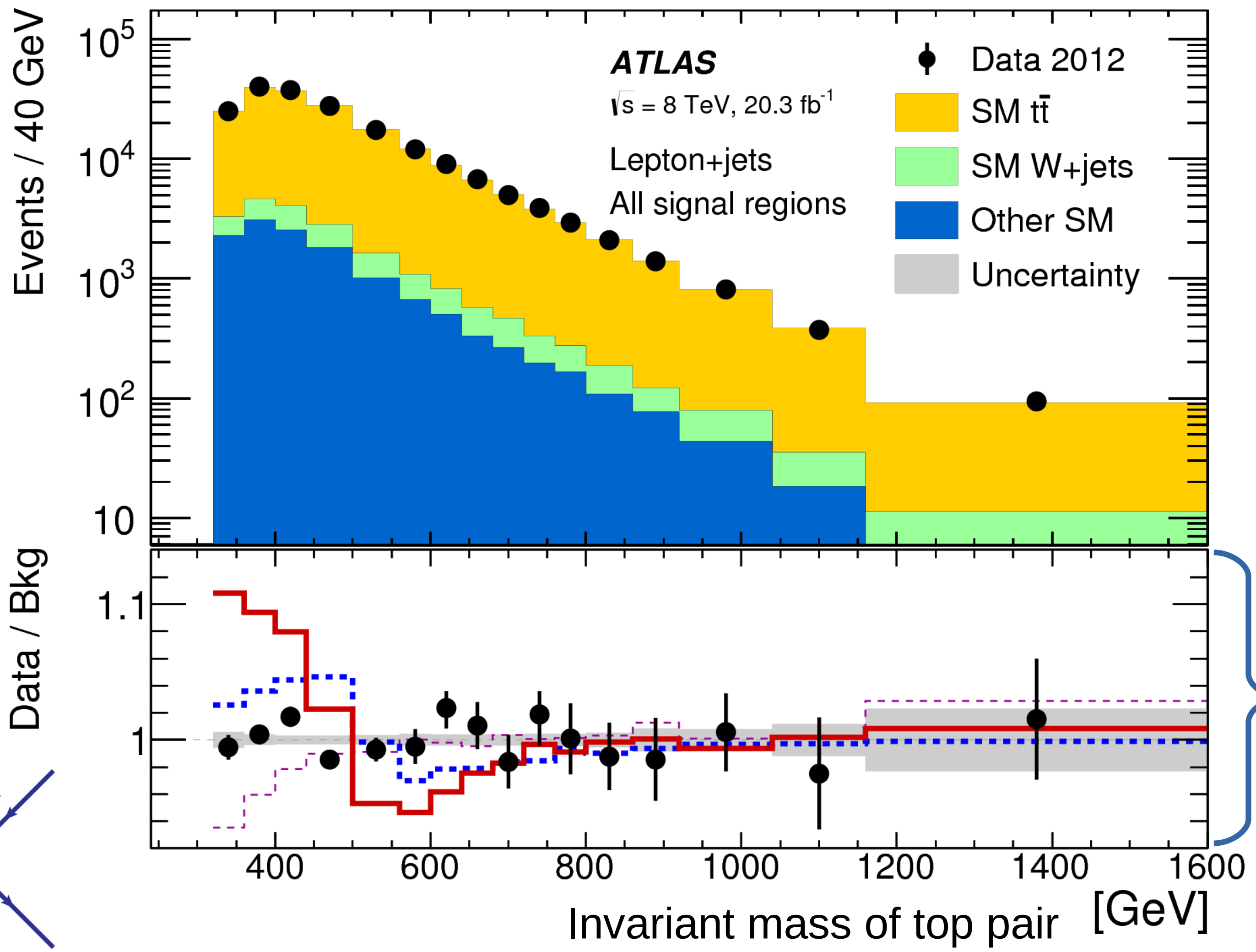
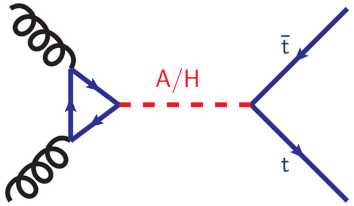
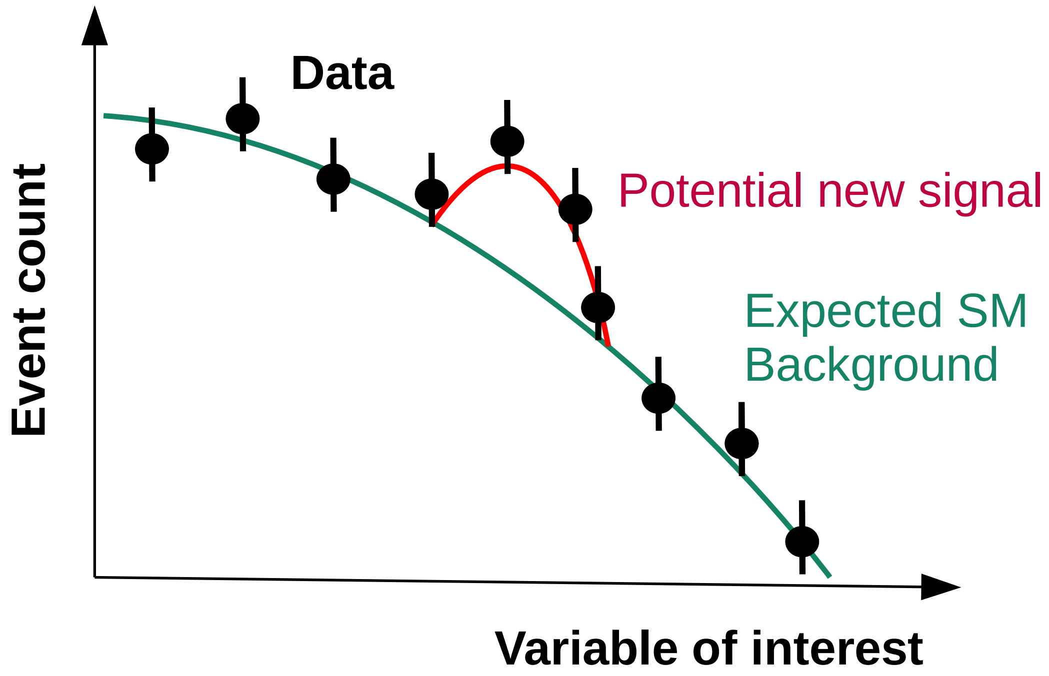




What type of deviation are we looking for?

What are we looking for?

> Most generally put: we search for a significant deviation from the SM prediction

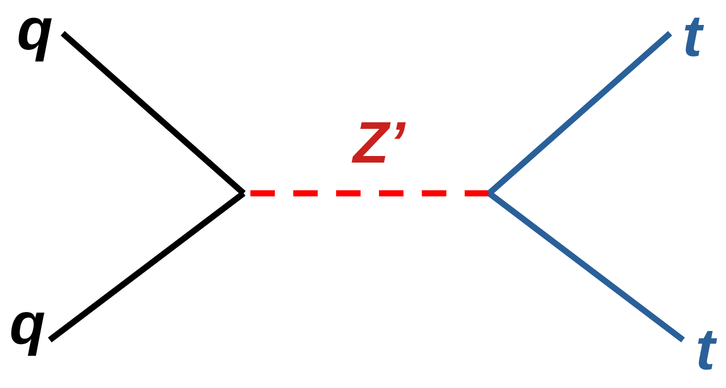


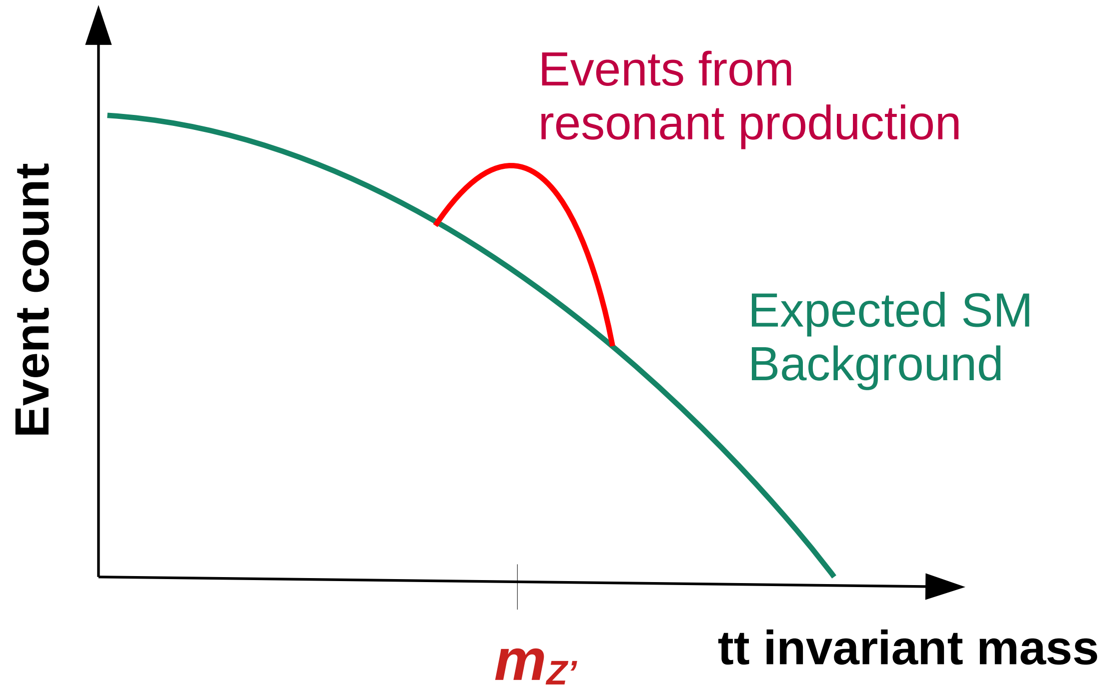
> Different search strategies
  - Cut-and-count method
  - Bump hunt
  - Tail hunt
  - ...

> Each comes with its own set of advantages/disadvantages!

Bump Hunting

- Search for a localised deviation in the distribution of a variable of interest
  - Typically: invariant mass

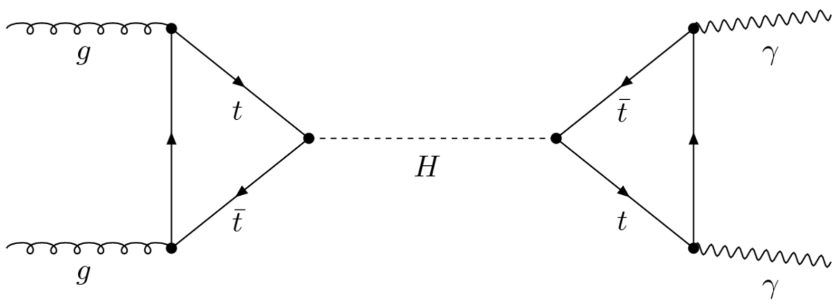


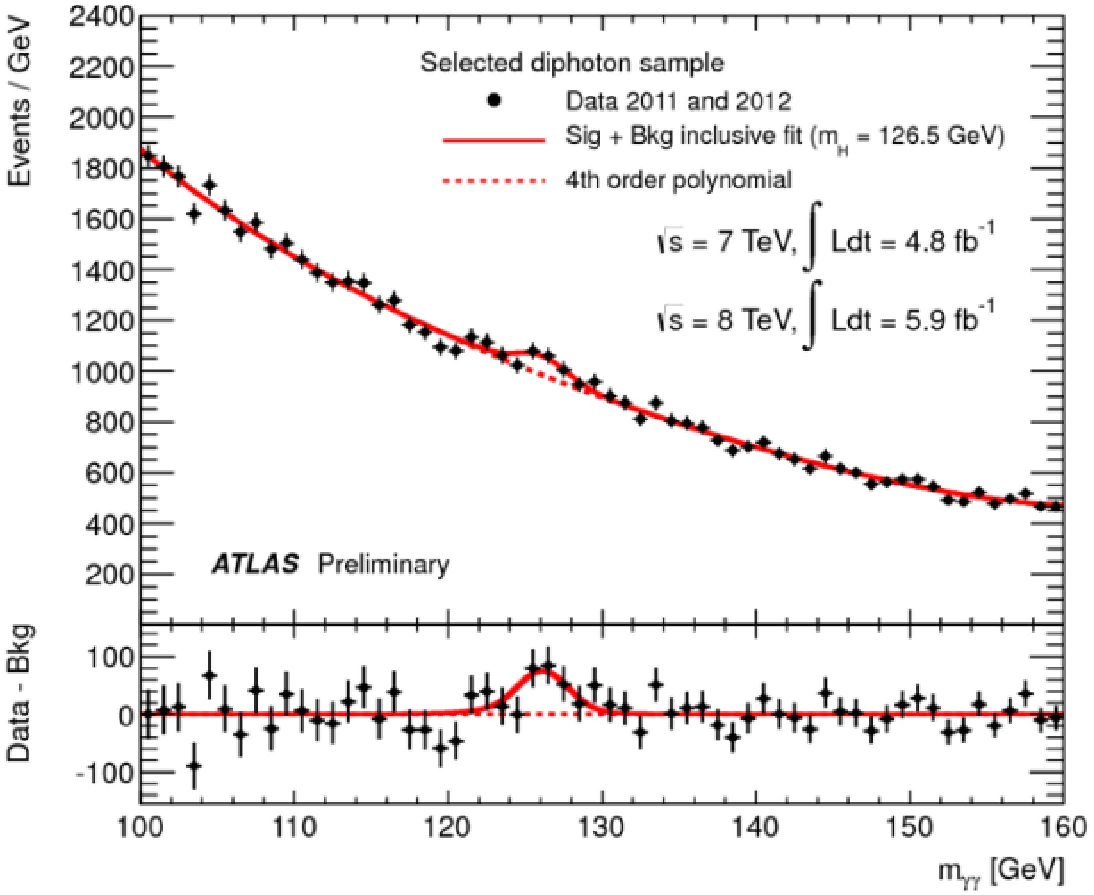


Bump Hunting

> Search for a localised deviation in the distribution of a variable of interest
  – Typically: invariant mass

> Most recent successful example:
  – Higgs boson discovery (2012, CERN)



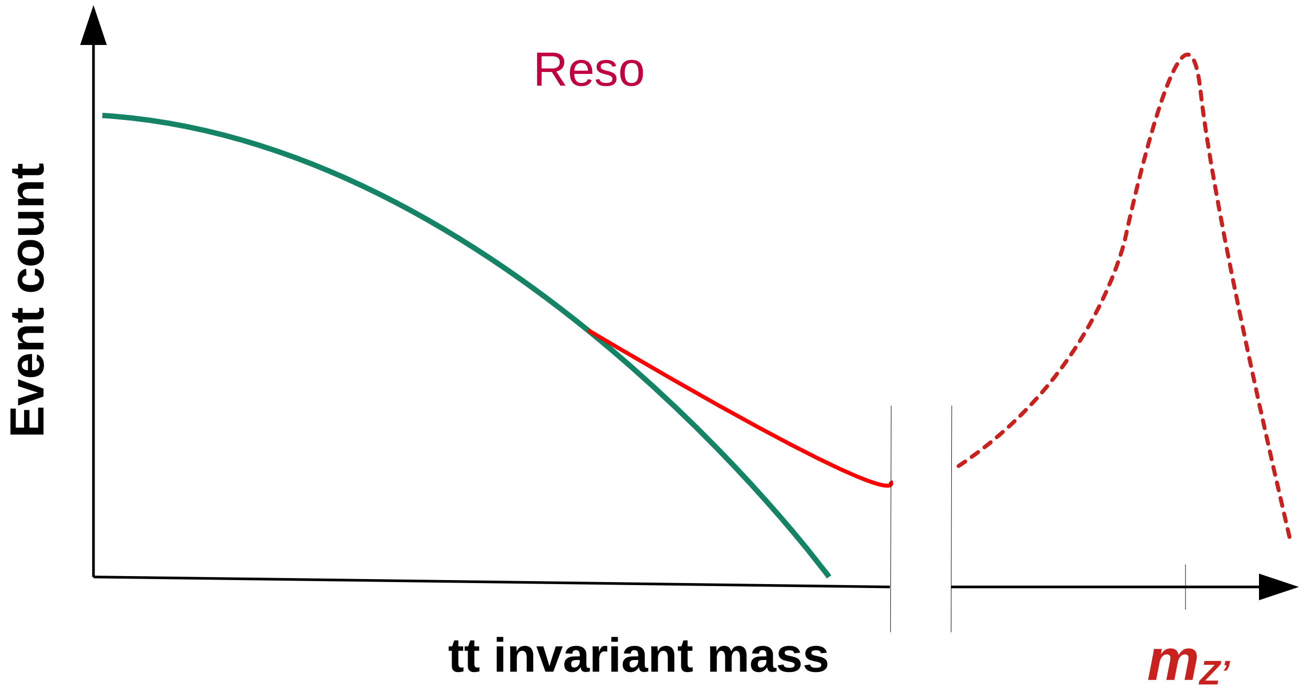


Tail Hunting

> Search for a tail enhancement in the distribution of a variable of interest

> Typical examples:

- Resonances beyond reach of the LHC

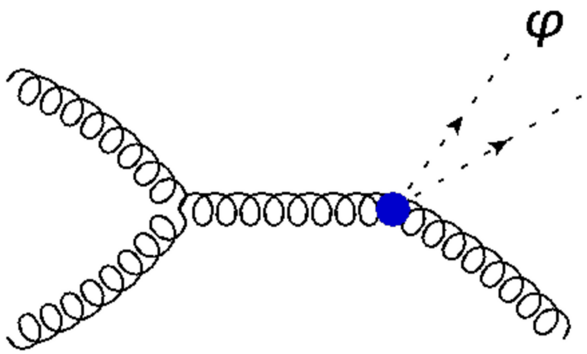


Tail Hunting

> Search for a tail enhancement in the distribution of a variable of interest

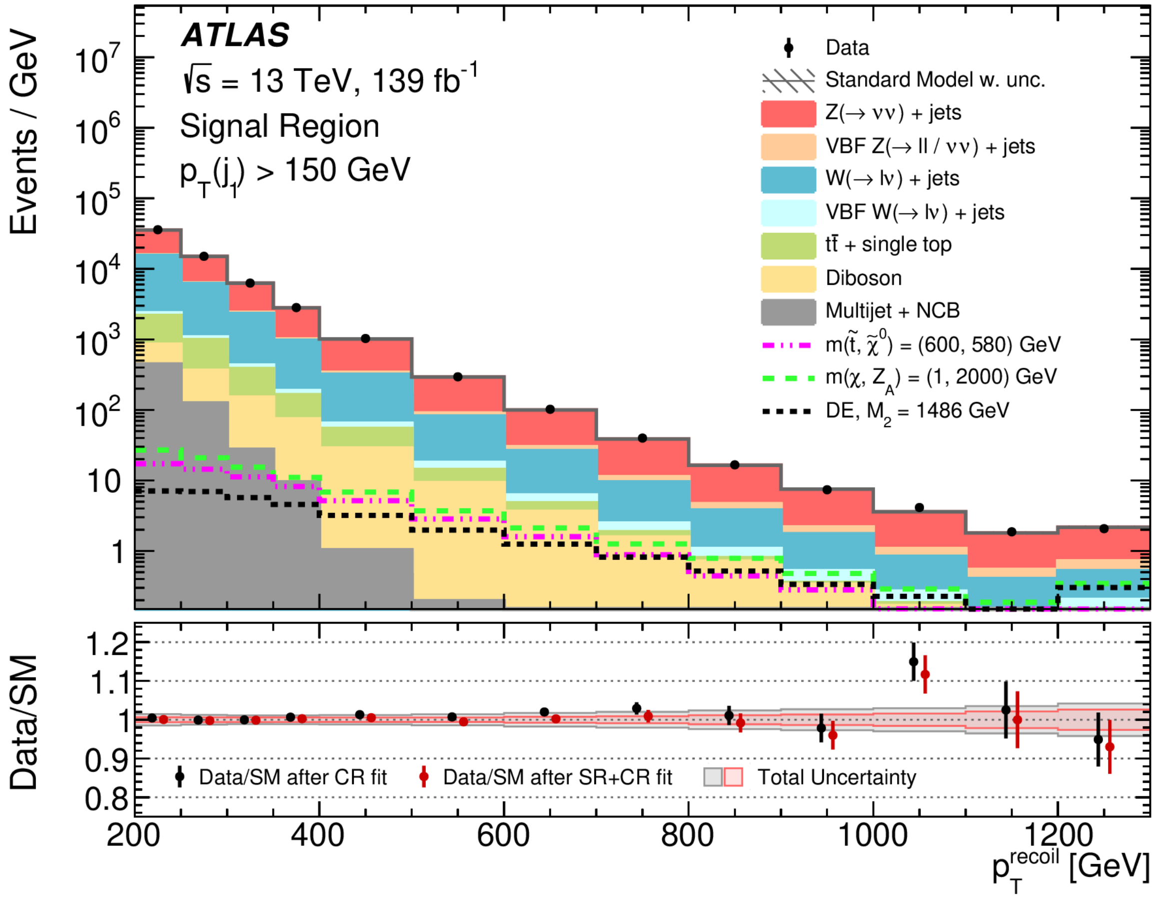
> Typical examples:

  – Resonances beyond reach of the LHC
  – Non-resonant production of new particles
    • E.g. dark matter or dark energy



Non-interacting scalar dark energy particles, → missing energy

Recoiling gluon, leading to single visible jet



Tail Hunting

> Search for a tail enhancement in the distribution of a variable of interest

> Typical examples:

– Resonances beyond reach of the LHC

– Non-resonant production of new particles

> **Advantages**:

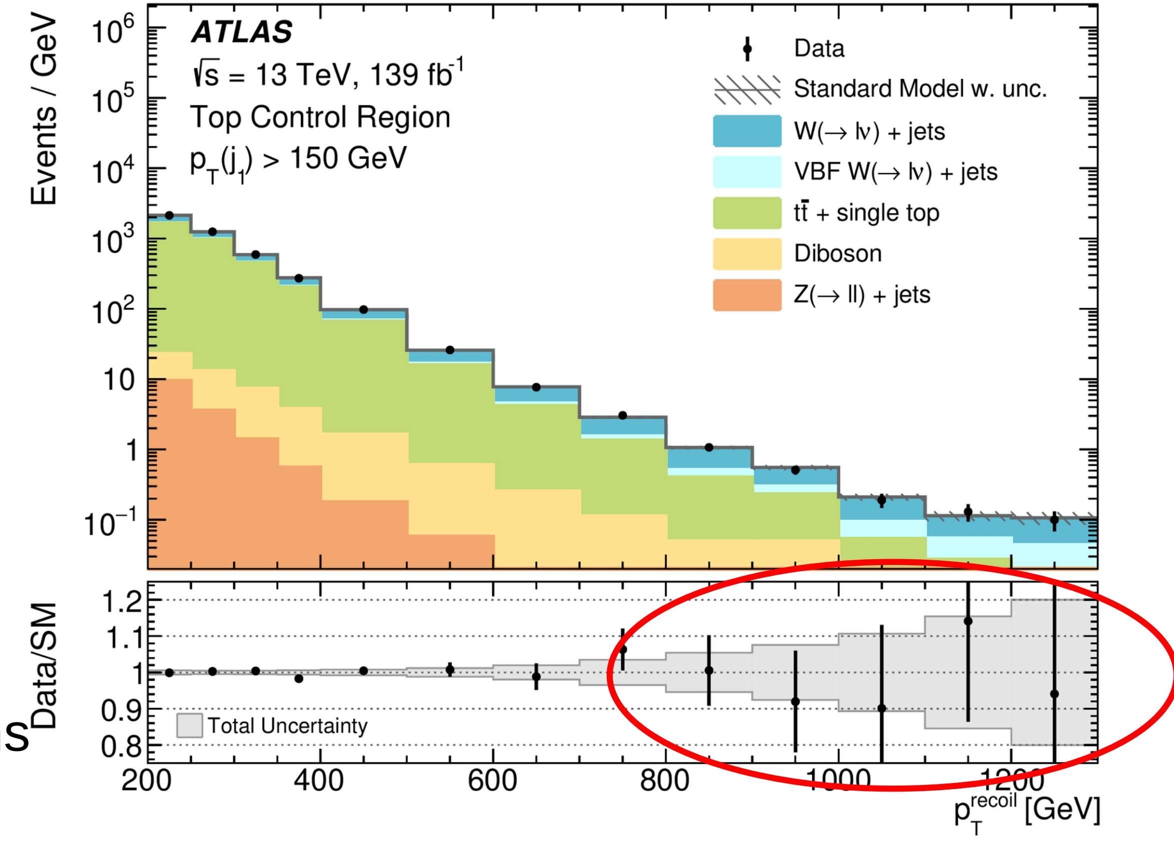
– Sensitive to processes that cannot be identified by bump hunts

> **Disadvantages**:

– Tails of distributions suffer from low statistics

– Often sizeable systematic uncertainties

• E.g. due to missing higher-order calculations



What if new particles are less obvious to spot?

> Bump hunt assumes "signal sitting on top of background": **S + B** $= |s|^2 + |b|^2$

What if new particles are less obvious to spot?

- Bump hunt assumes "signal sitting on top of background": **S** **+** **B** = $|s|^2 + |b|^2$
- Quantum mechanics: two processes with same initial and same final state will interfere!
  - $|s + b|^2 = |s|^2 + 2\,\mathrm{Re}(s\,b) + |b|^2$ = **S** **+** **I** **+** **B** → **Interference!!**

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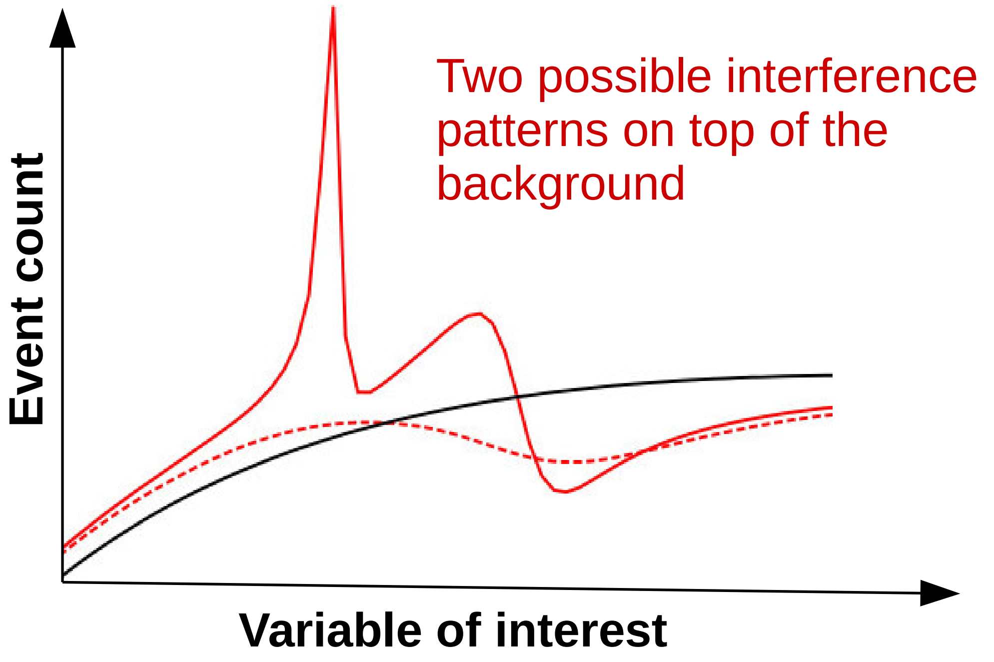
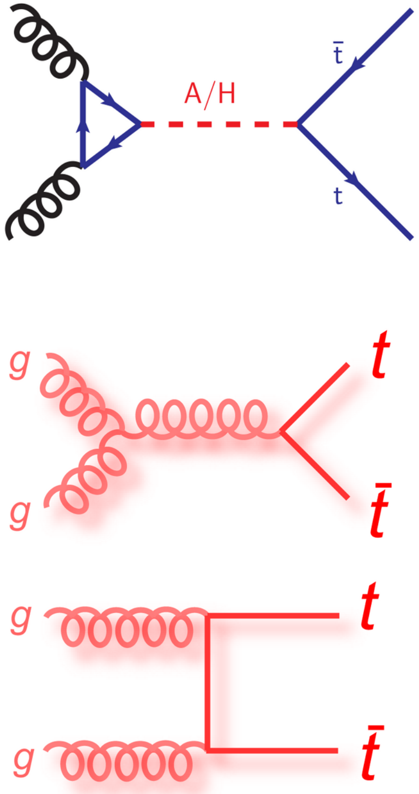
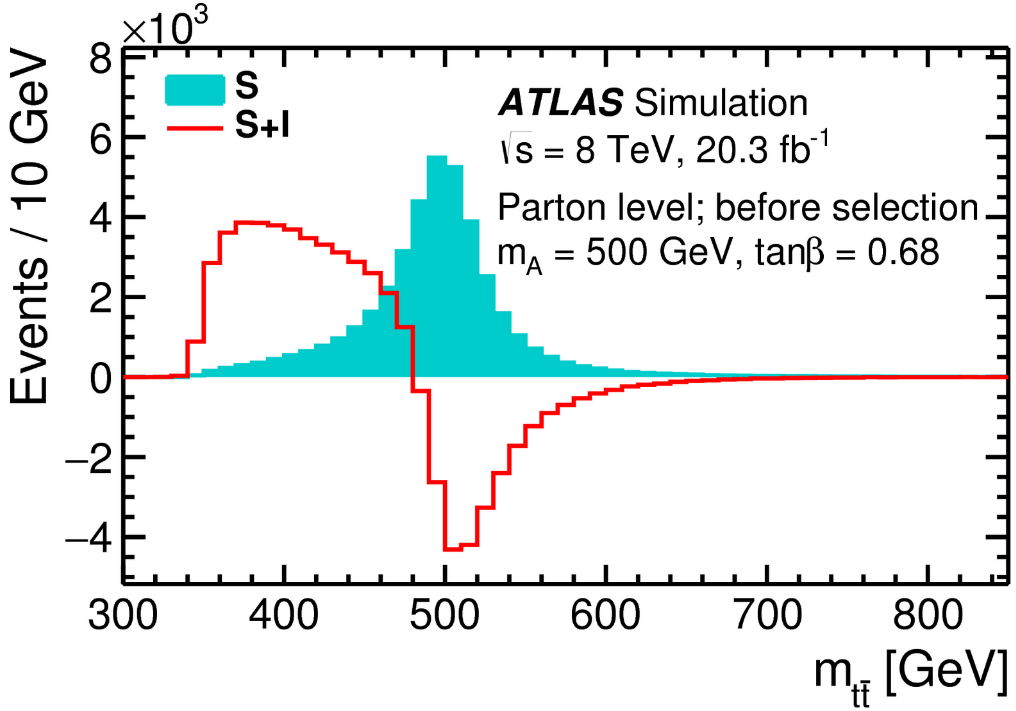


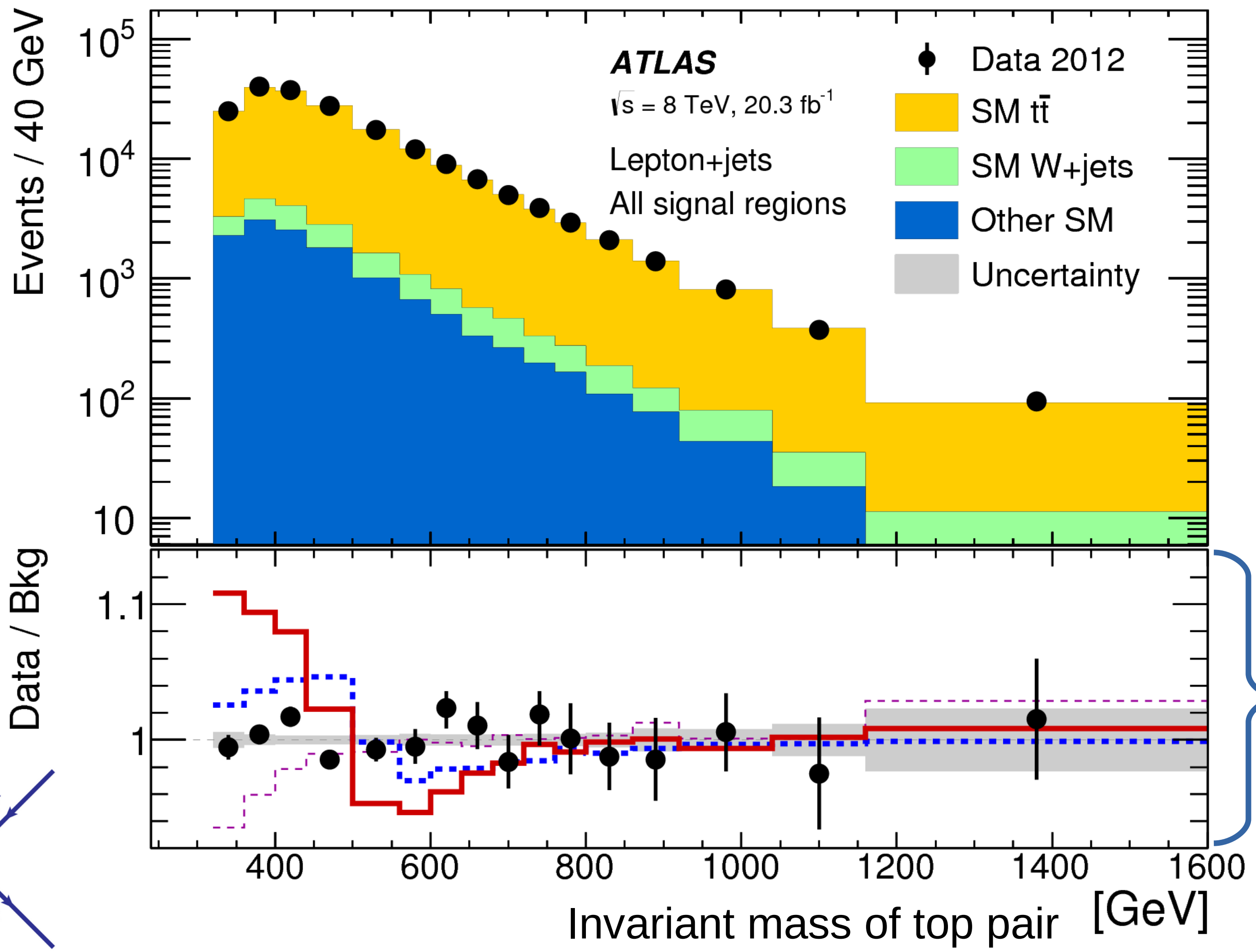
Beyond Bump Hunts

- Prominent example: decay of a heavy Higgs boson A/H to a top-antitop quark pair
- Need cutting edge methods → on-going research @ DESY

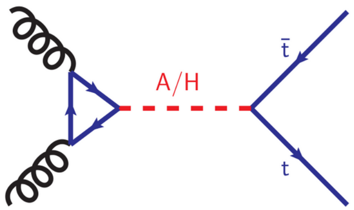




A final signal region



Need to quantify agreement between data and SM prediction

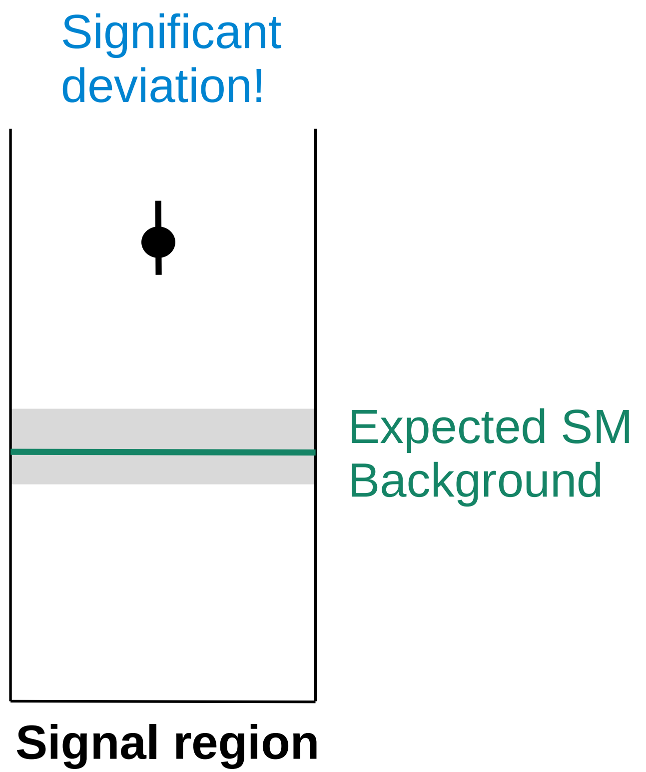


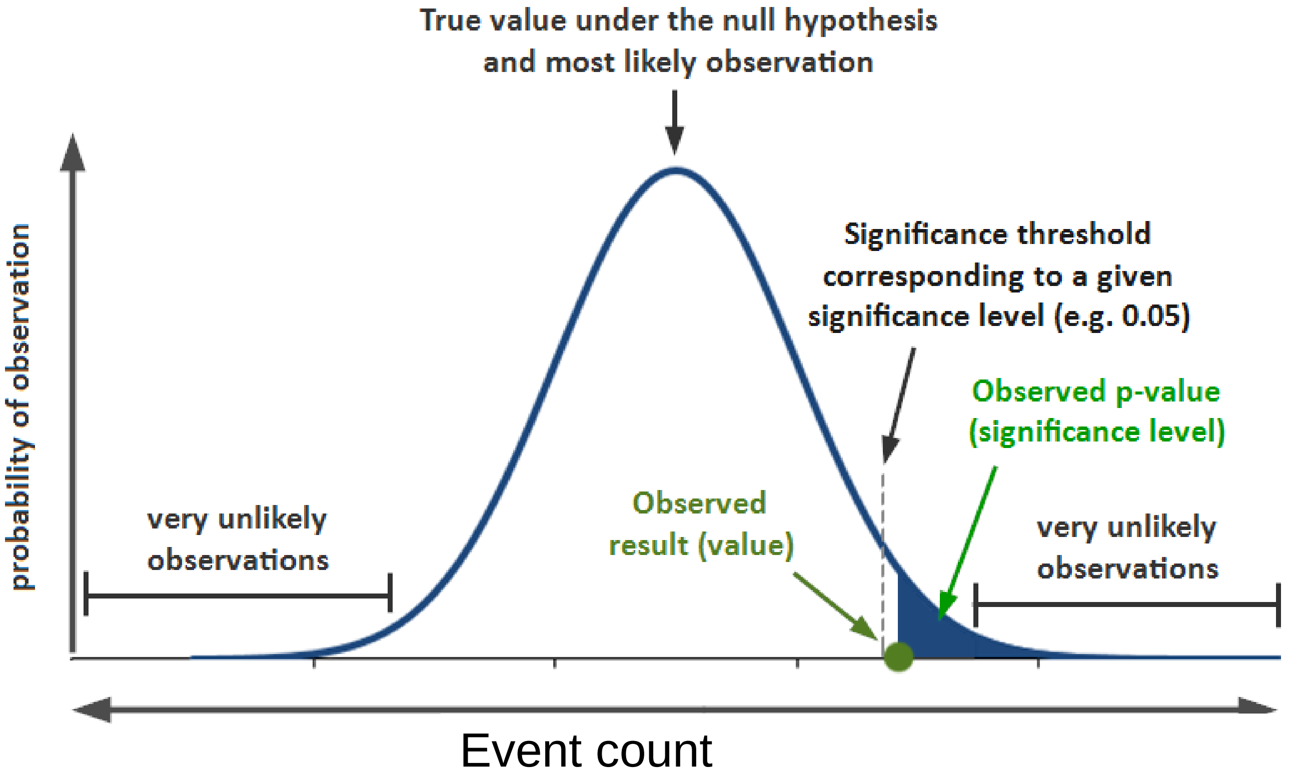
Statistical analysis

- Two statistical analysis stages in BSM searches:
  - Quantify agreement between data and SM prediction (*“Any interesting deviation?”*)
  - Quantify (dis)agreement between data and BSM hypothesis (*“limit setting”*)

Step 1: quantify agreement with SM prediction

- Null hypothesis H_0: SM only, no BSM
- **p-value**: probability that H_0 produces deviation at least as extreme as the one observed
- Simple example: cut-and-count



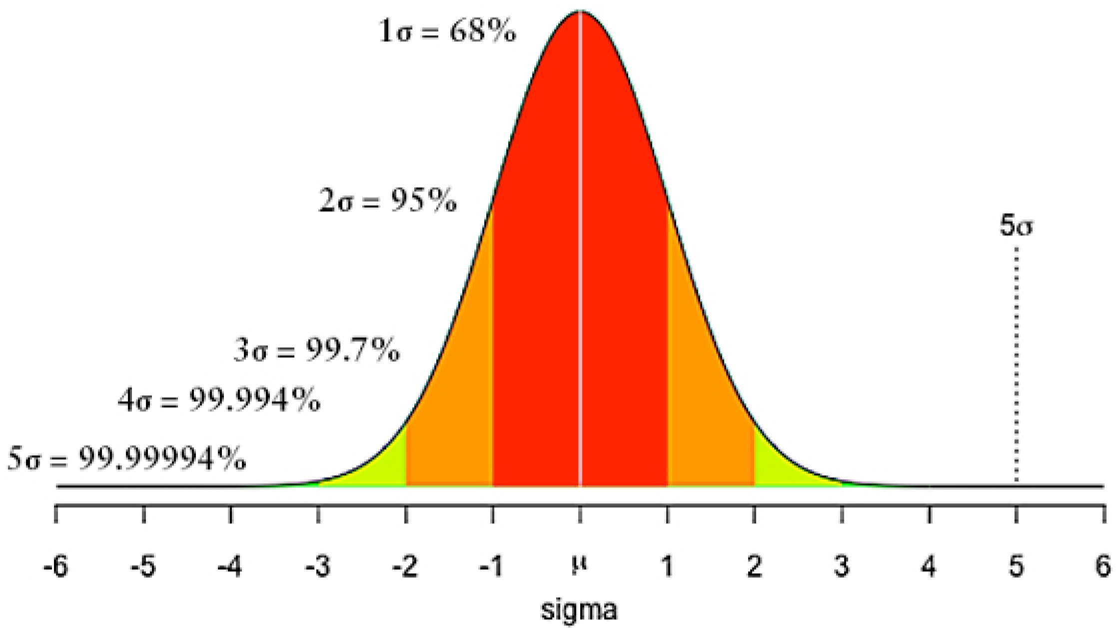


Step 1: quantify agreement with SM prediction

- Null hypothesis H_0: SM only, no BSM
- **p-value**: probability that H_0 produces deviation at least as extreme as the one observed
- Or quote **significance** instead:

$$\boxed{Z = \Phi^{-1}(1-p),}$$

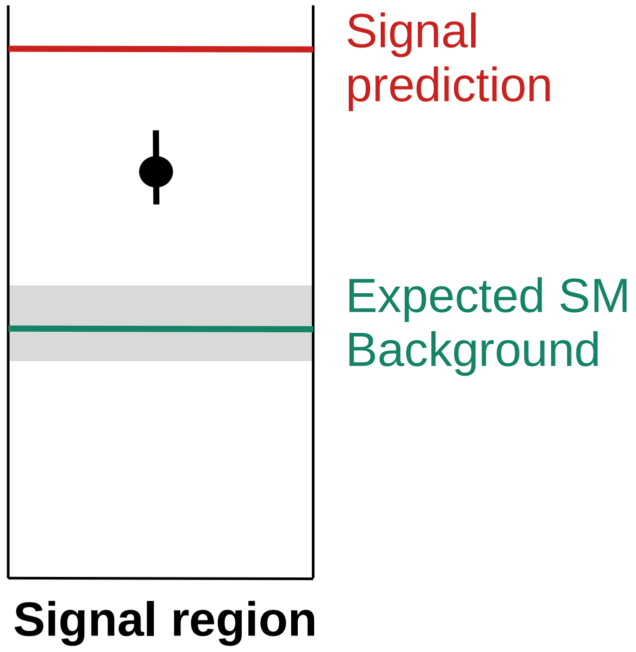
- where Φ^{-1} is inverse of cumulative Gaussian

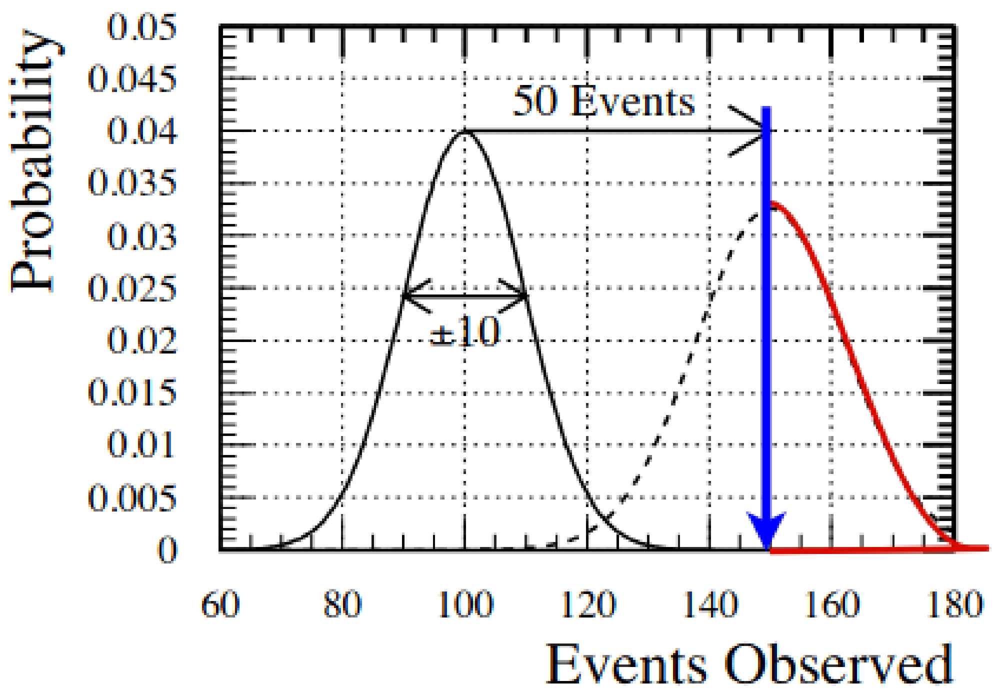


Step 2: Quantify agreement with BSM hypothesis H_1

> If excess was found: test agreement with BSM … and open the champagne ;)

> If no excess was found: test degree to which H_1 is excluded by data (limit setting)



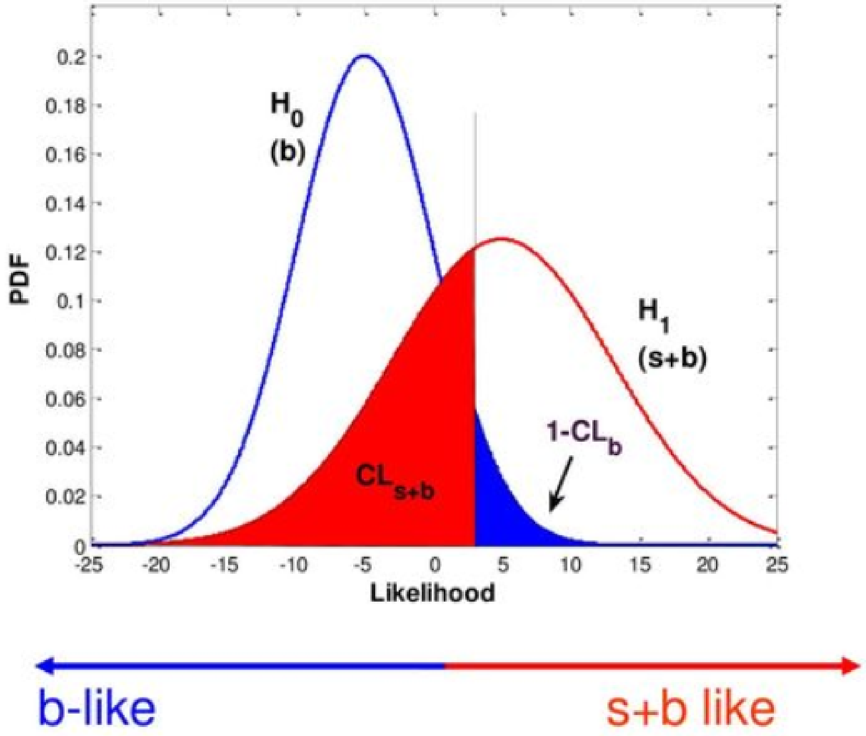


Step 2: Quantify agreement with BSM hypothesis H_1

> Usually, setup is more complicated: many bins, many signal regions

> Construct a likelihood function that quantifies data/MC agreement in all bins

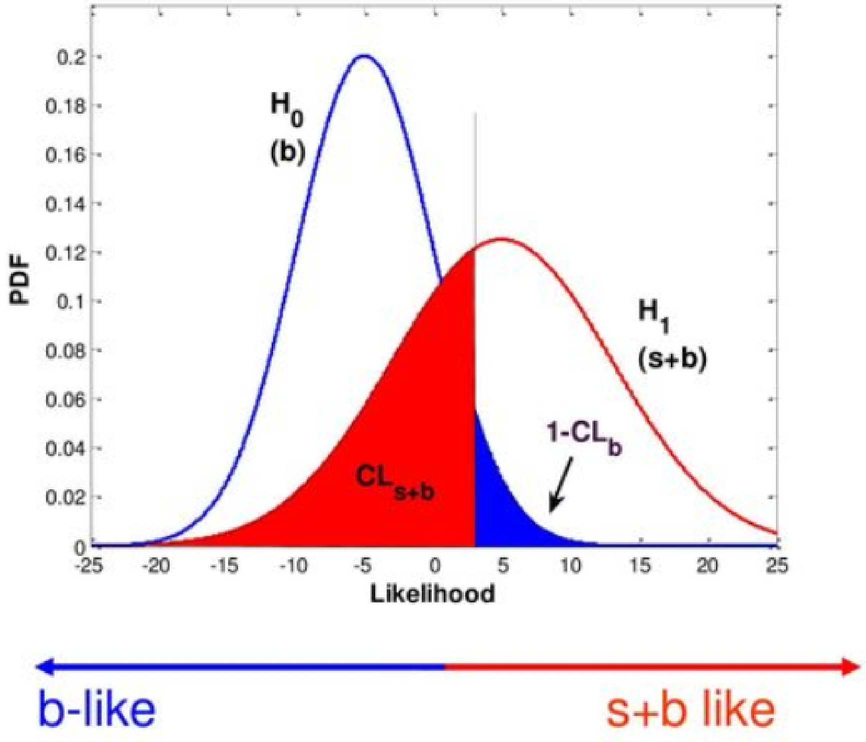
$$\boxed{L(D|\mu,\boldsymbol{\theta}) = \underbrace{\prod_{j=1}^{M}\prod_{i=1}^{N}\mathrm{Pois}(n_{i,j}|\mu,\boldsymbol{\theta})}_{\text{Poisson terms}} \cdot \underbrace{\prod_{\mathrm{NP}} f(\theta^{(\mathrm{NP})})}_{\text{Constraint terms}}}$$



Further reading:
Lecture by G. Cowan [link]

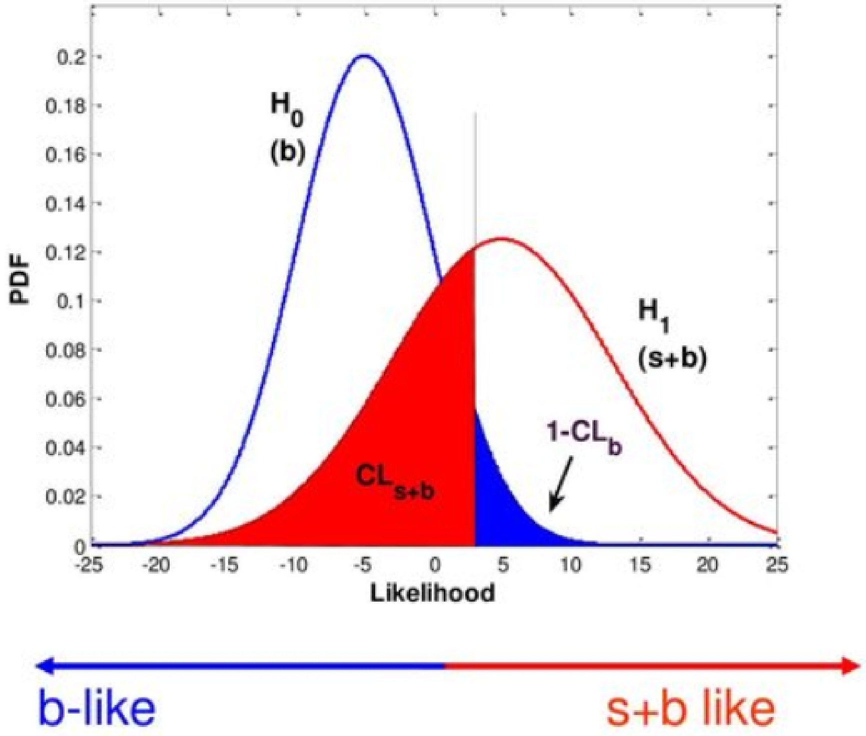
Step 2: Quantify agreement with BSM hypothesis H_1

- CL(s+b) – probability to falsely reject signal because it is too similar to background
- Confidence level
  - H_1 excluded at 95% CL if CL(s+b) < 0.05



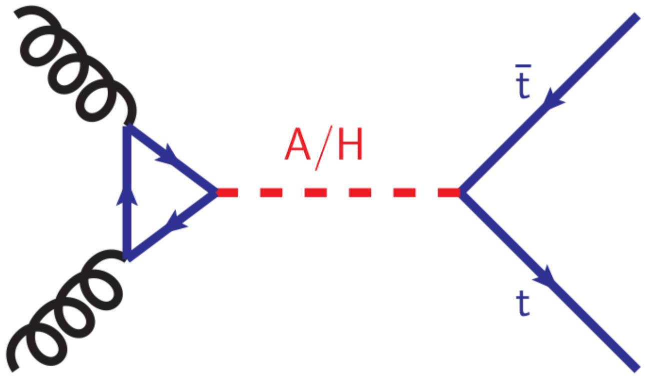
Step 2: Quantify agreement with BSM hypothesis H_1

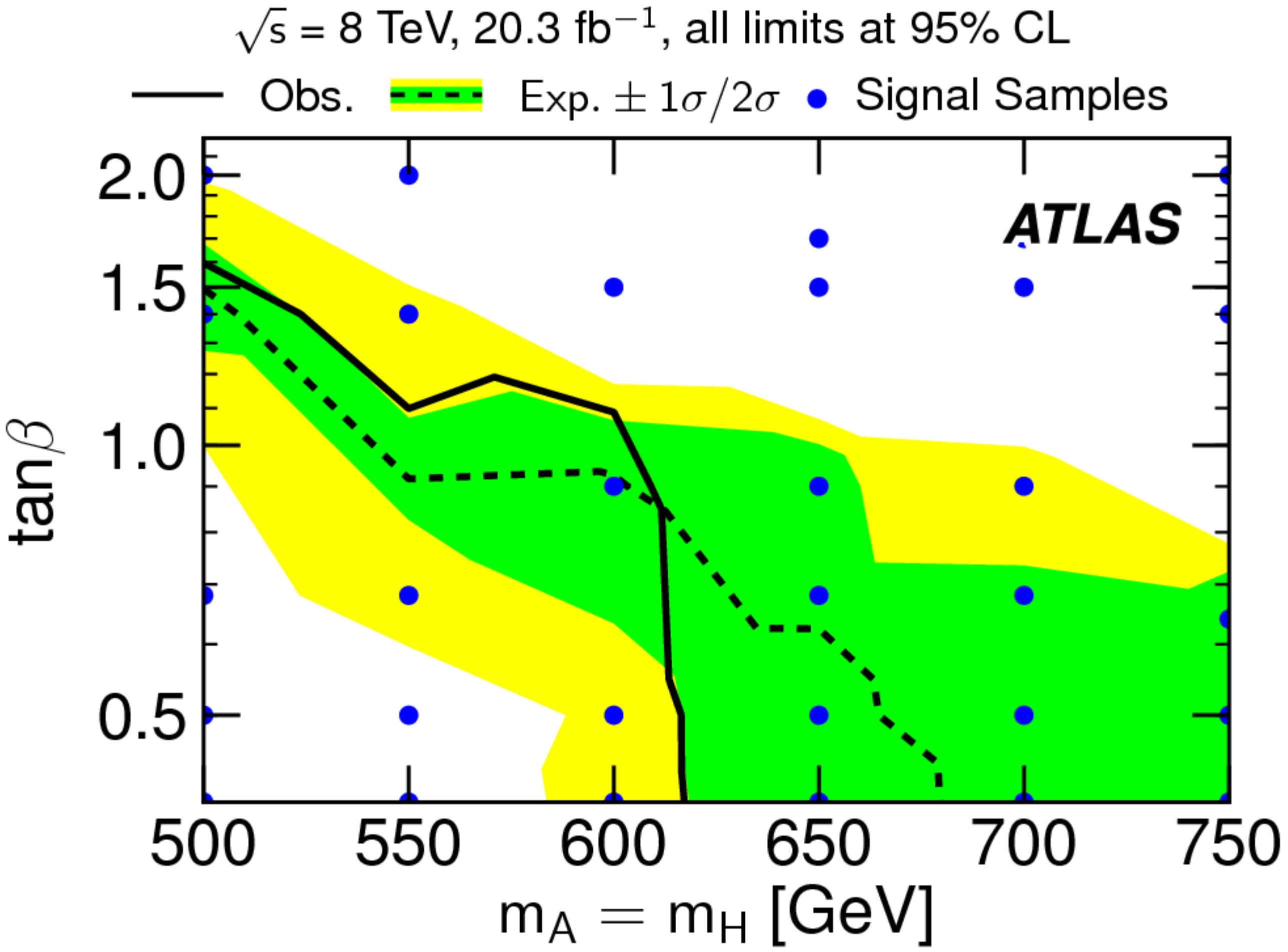
- Problem:
  - Danger to falsely reject H_1 even if separation between H_1 and H_0 is poor, i.e. sensitivity to H_1 is low
- Solution:
  - $CL(s) = CL(s+b)/[1-CL(b)]$
- Confidence level
  - H_1 excluded at 95% CL if $CL(s) < 0.05$



A final result

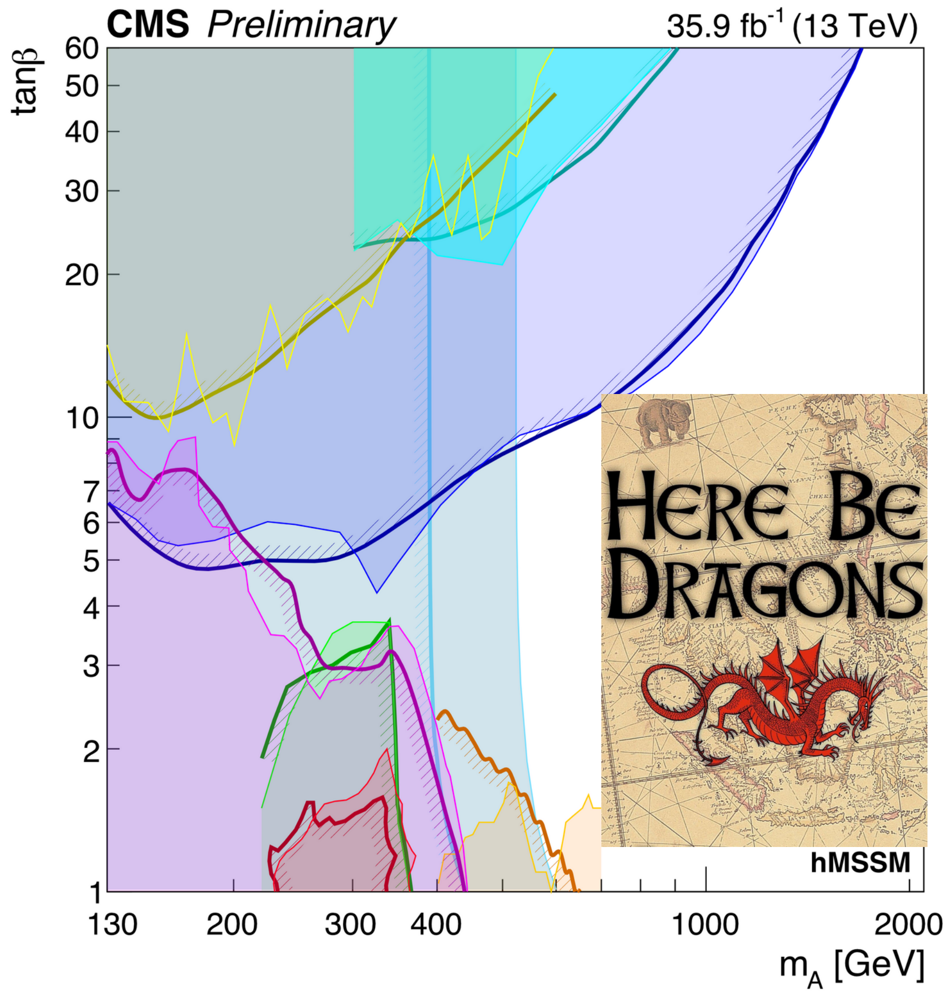
- The famous “Brazilian” plot, showing observed and expected exclusion limits with error bands





Where do we stand?

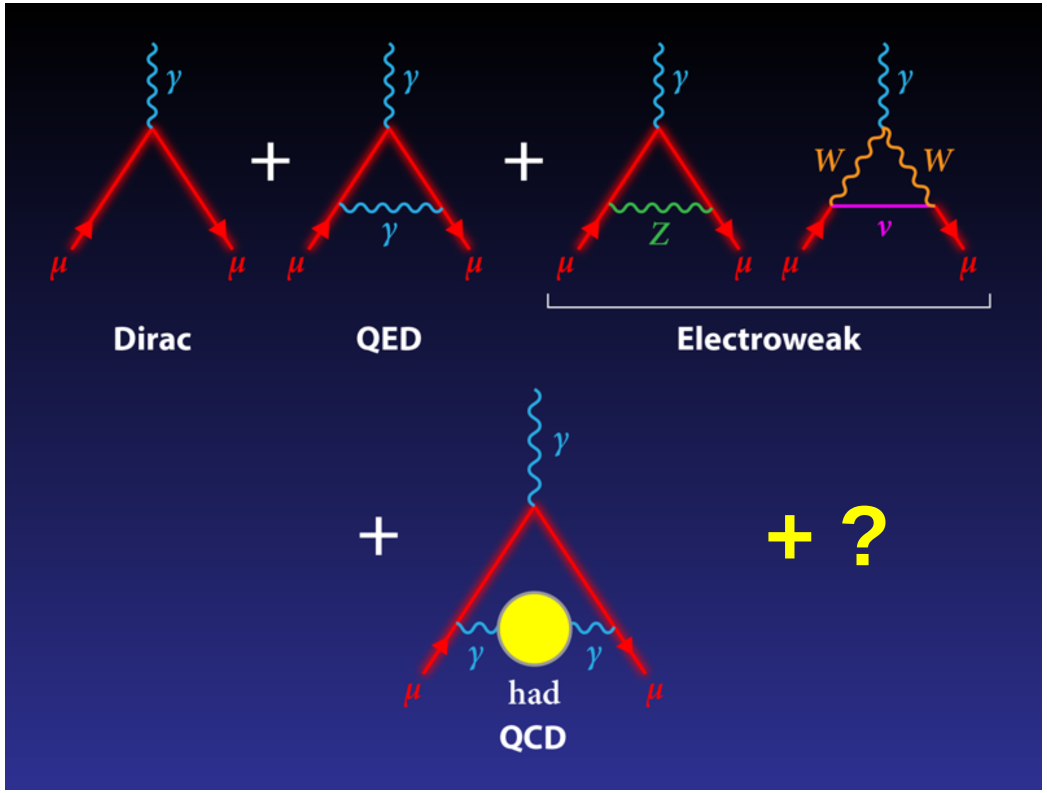
- No significant (5σ) deviation from the SM observed so far.
- Results constrain BSM models…
- … and point to uncharted territory!



Muon g-2 (1)

> Anomalous magnetic moment of the muon in analogy to that of the electron

$$\boxed{\vec{\mu} = g\,\frac{q}{2m}\,\vec{S}}$$



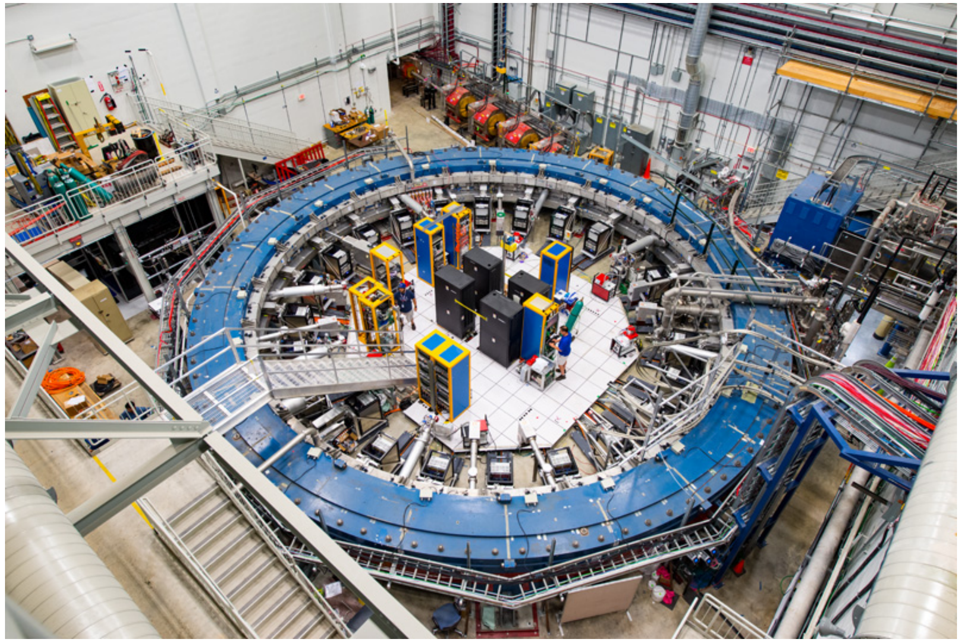
> Loop quantum corrections: $g \neq 2$

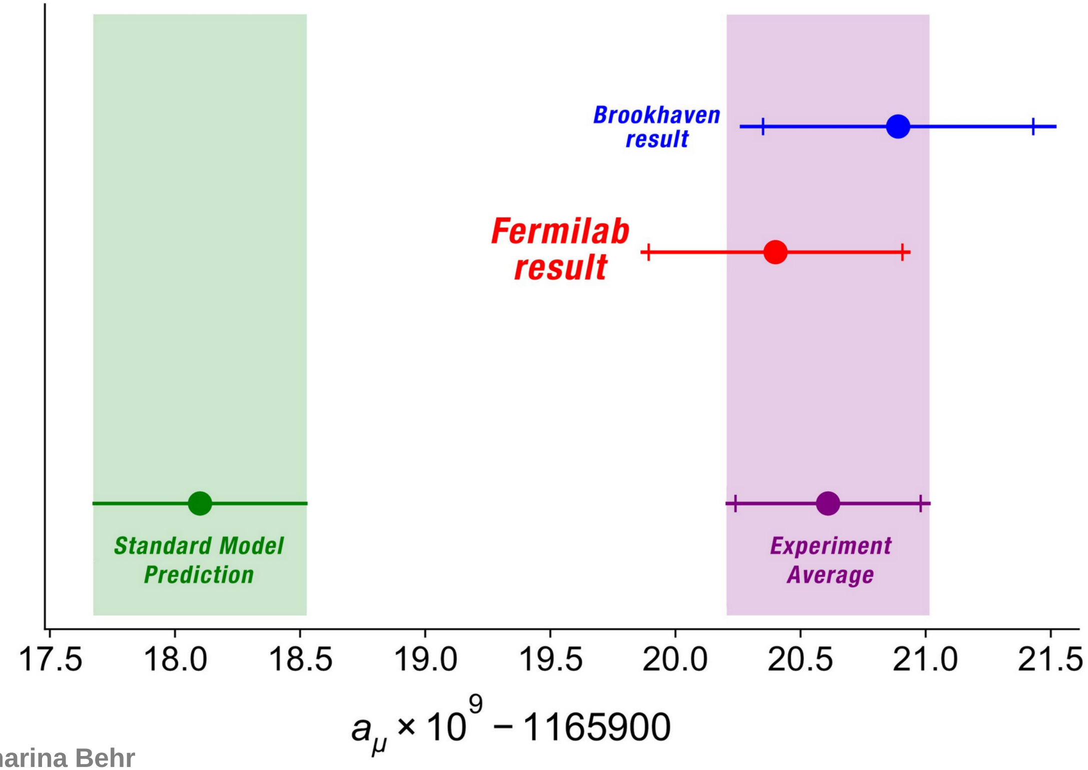
> Anomalous magnetic moment: $a = (g-2)/2$

> Sensitive to large range of possible quantum corrections, including possible BSM contributions

Muon g-2 (2)

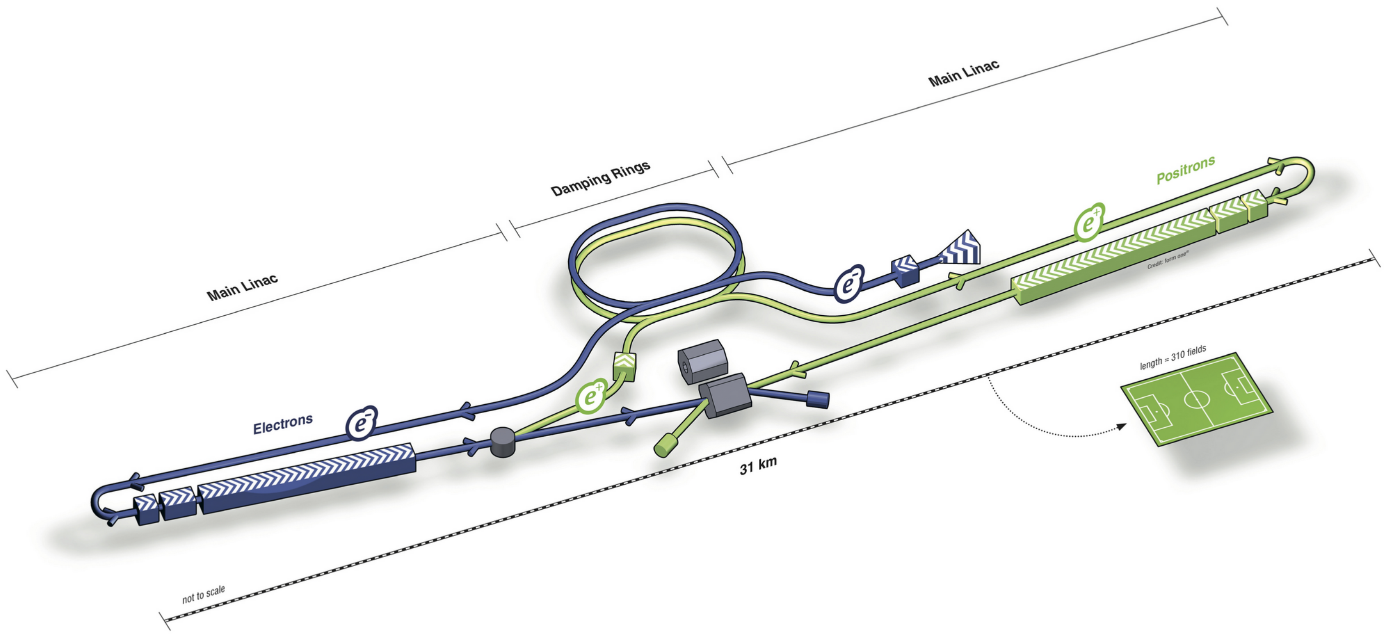
- Storage ring with polarised muons in magnetic field → measure precession frequency
- Measurements at BNL (2004) first revealed tension with SM of 2.6σ significance
- Confirmed by new Fermilab measurement (2021) at 4.2σ combined significance
  - More data is being taken and analysed

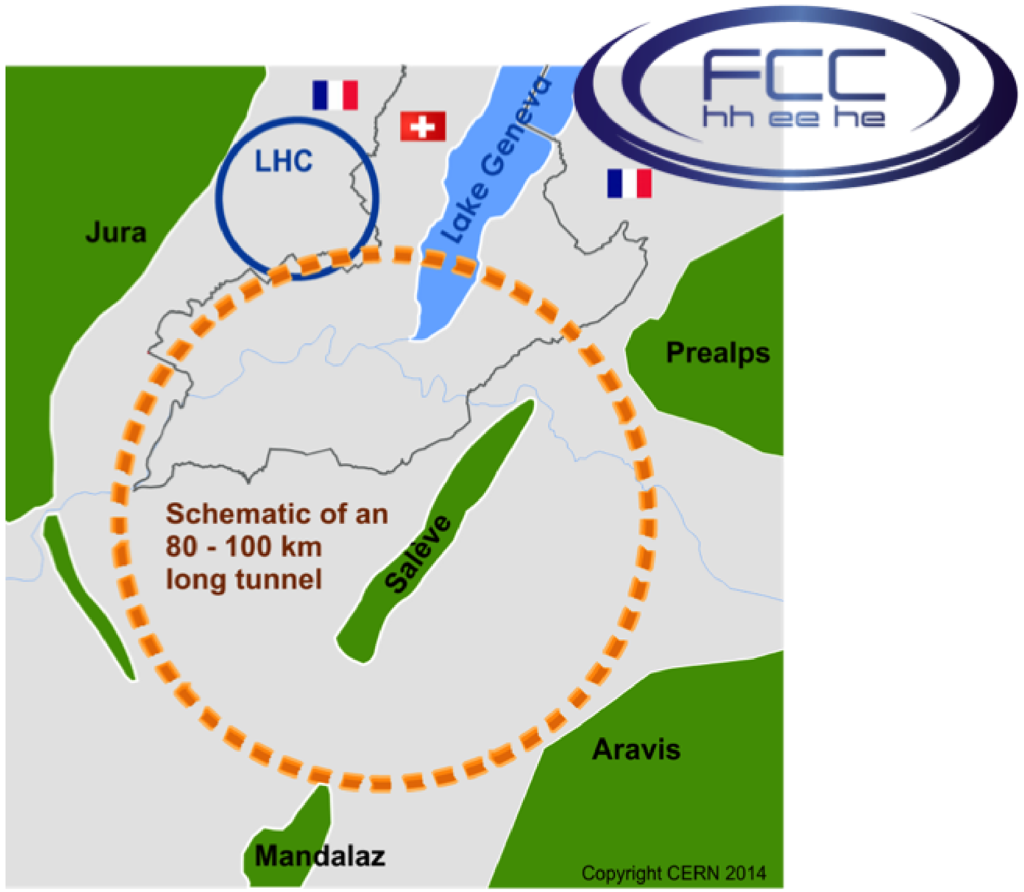




Future Collider Plans

- Higgs factories for precision measurements
- BSM searches also possible





International Linear Collider

Future Circular Collider