Searches with top quarks in ATLAS

Vector-like quarks and resonances

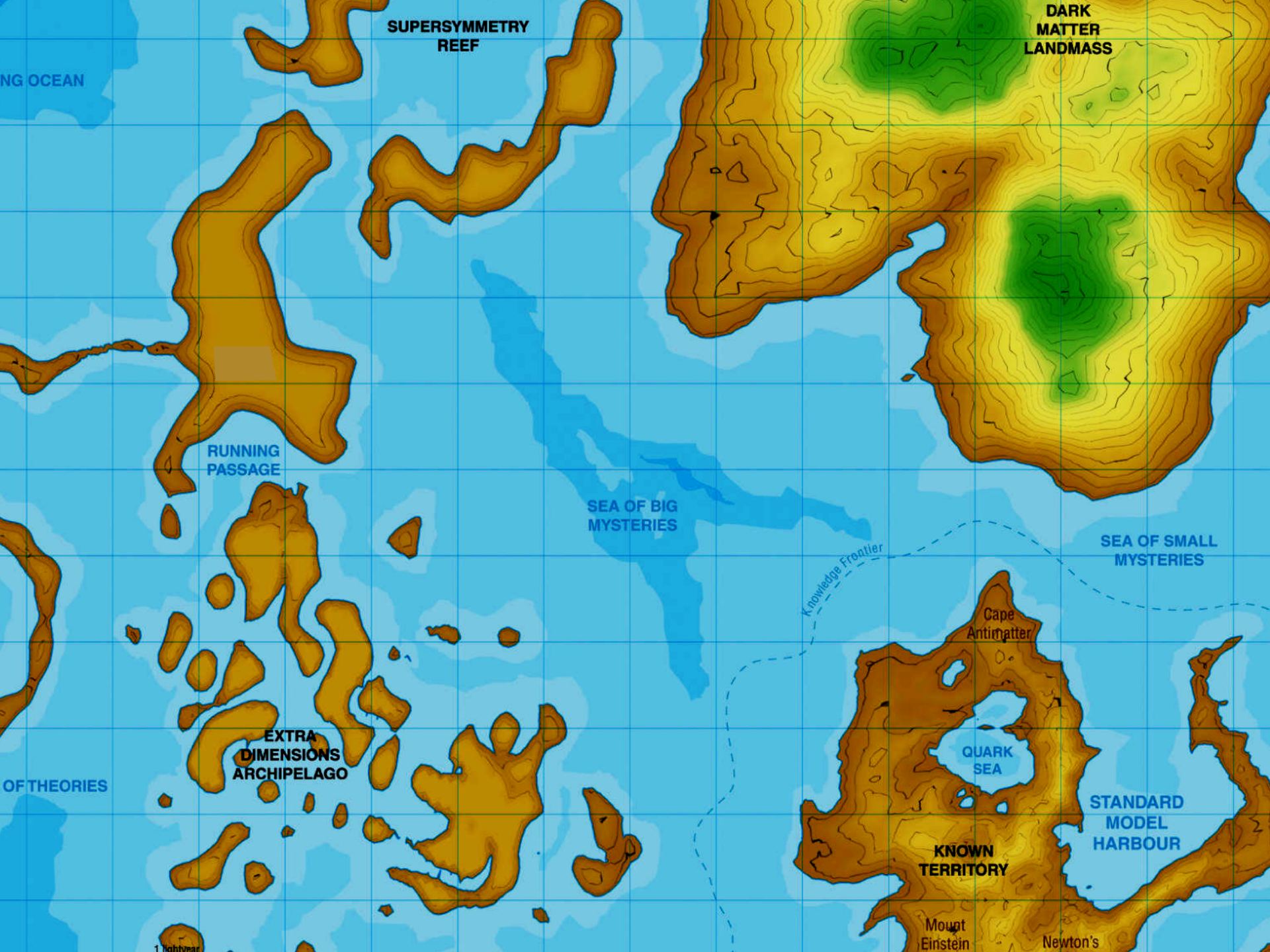
Loïc Valéry (DESY)
on behalf of the ATLAS Collaboration

CERN seminar — 18/09/2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ATLAS EXPERIMENT

DESY.


SUPERSYMMETRY REEF
DARK MATTER LANDMASS
NG OCEAN
RUNNING PASSAGE
SEA OF BIG MYSTERIES
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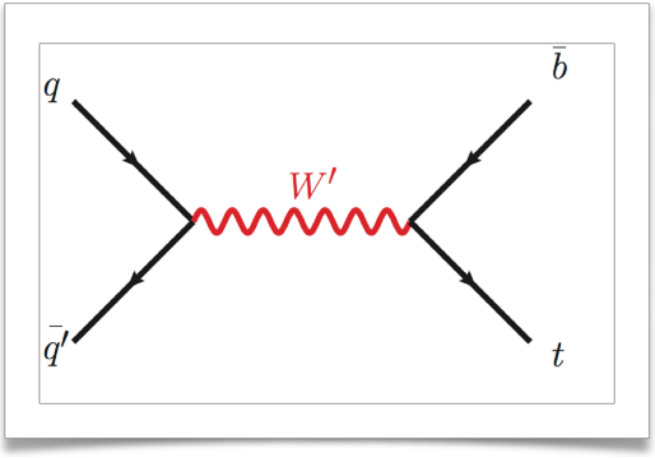
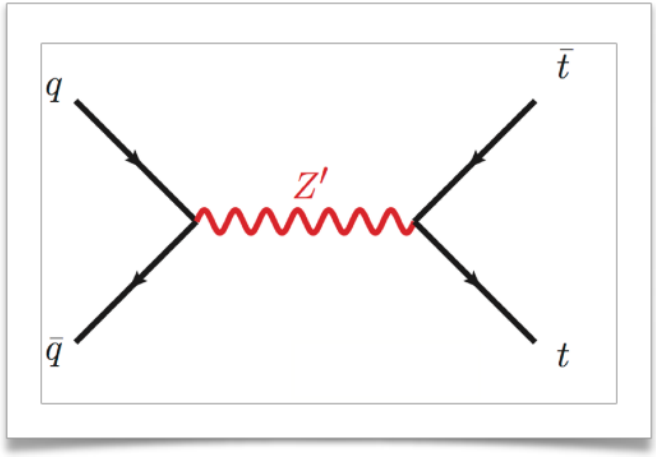
Knowledge Frontier
Cape Antimatter
QUARK SEA
STANDARD MODEL HARBOUR
KNOWN TERRITORY
EXTRA DIMENSIONS ARCHIPELAGO
OF THEORIES
Mount Einstein
Newton's

Beyond the Standard Model

Where we go …

- **Changing/adding symmetries**
  - SM low-energy effective theory ?
  - SM based on SU(3) x SU(2) x U(1) → Belong to a **larger symmetry group ?**
    - E6, SO(10), … (e.g. SSM, GUT theories)
  - Breaking ⇒ new symmetries remain ⇒ **additional gauge bosons predicted**
    - e.g. Z', W'

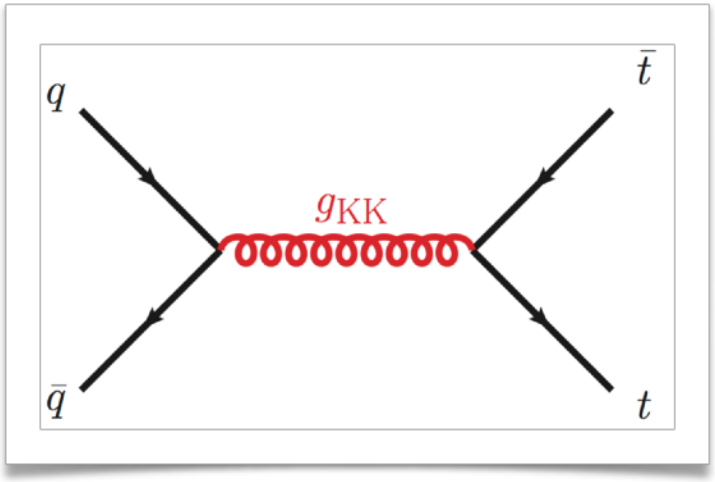




Beyond the Standard Model

Where we go …

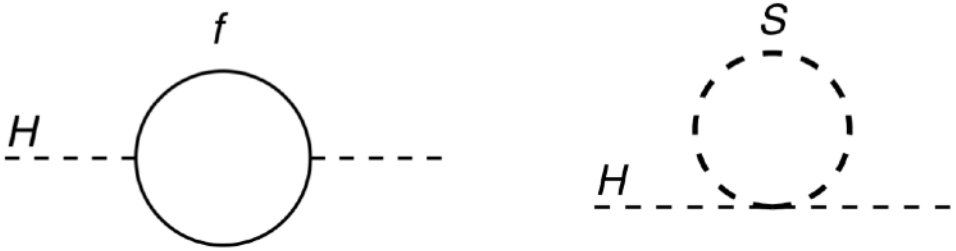
- **New dimensions**
  - Could explain e.g. **mass hierarchy**, scale hierarchy
  - Constraints ⇒ extra-dimensions **compactified**
    - e.g. warped extra-dimensions (Randall-Sundrum)
  - **Excitations of SM particles** ⇒ new particles
    - e.g. Kaluza-Klein gluons, gravitons, …

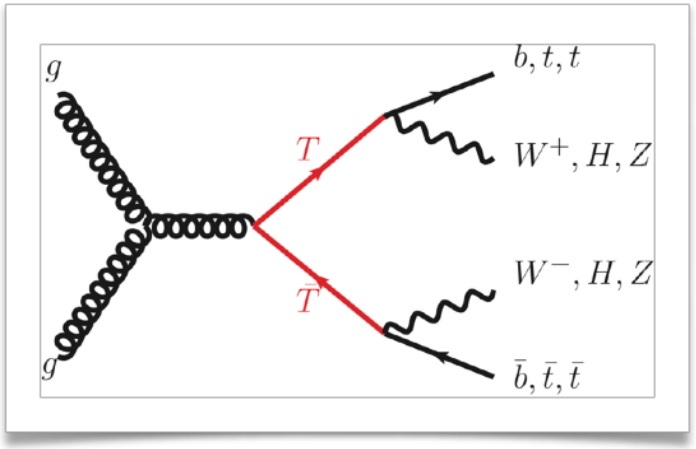


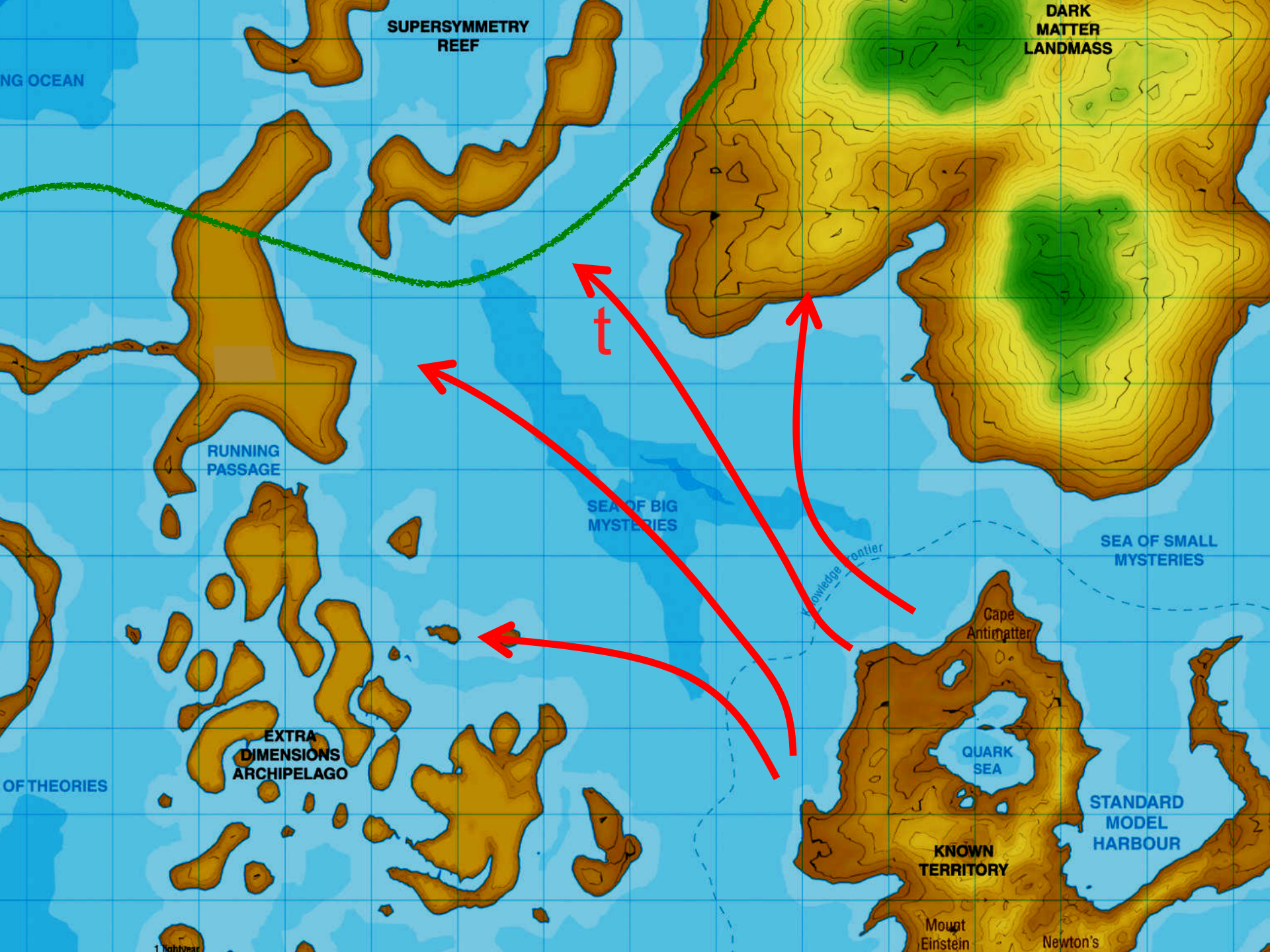
Beyond the Standard Model

Where we go …

- **Top quark partners**
  - New Physics at higher scale (Planck) ⇒ **could lead to large radiative corrections**
  - Reduction of these corrections: **top quark's partners**
    - superpartners (stops), **vector-like partners** (e.g. Higgs compositeness)



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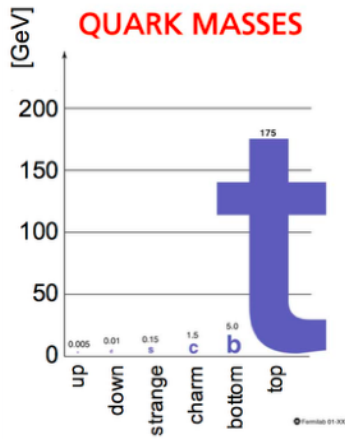
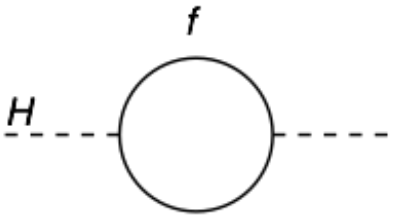
Top quark: probe for New Physics?

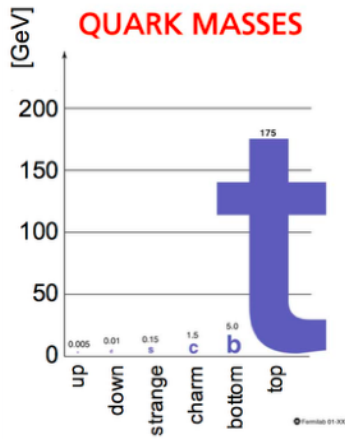


Distinctive **properties**
(mass, y_t, …)



Leading radiative corrections
to Higgs mass

Top quark: probe for New Physics?



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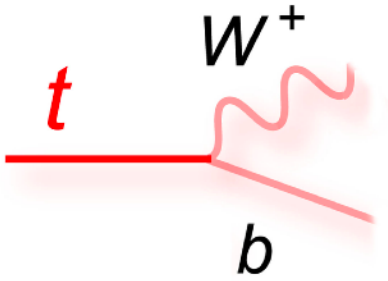
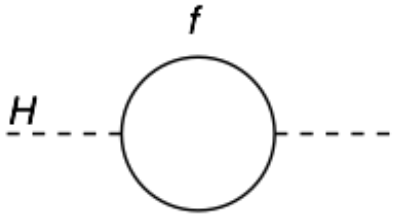


Unique **experimental signature**



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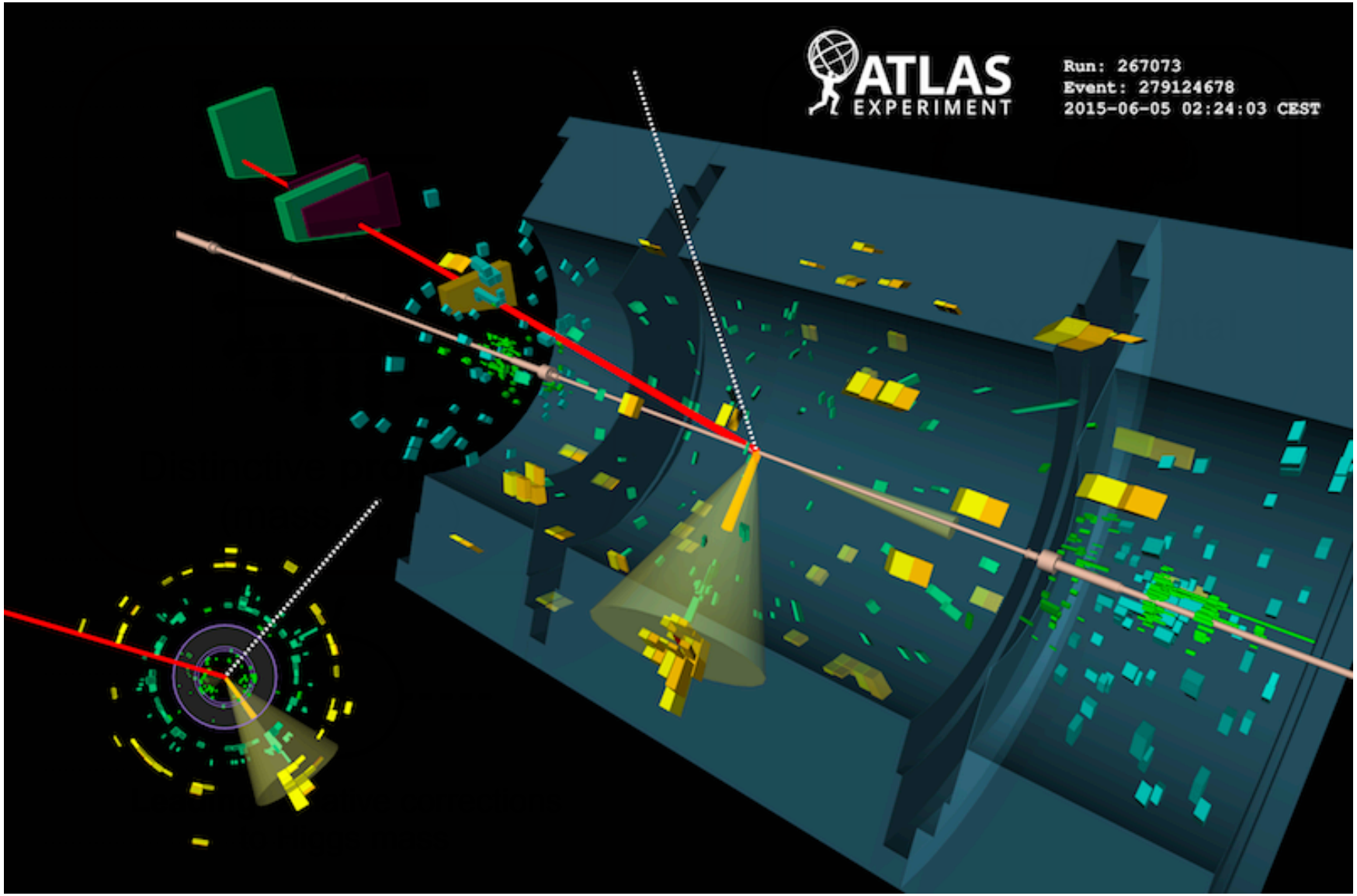
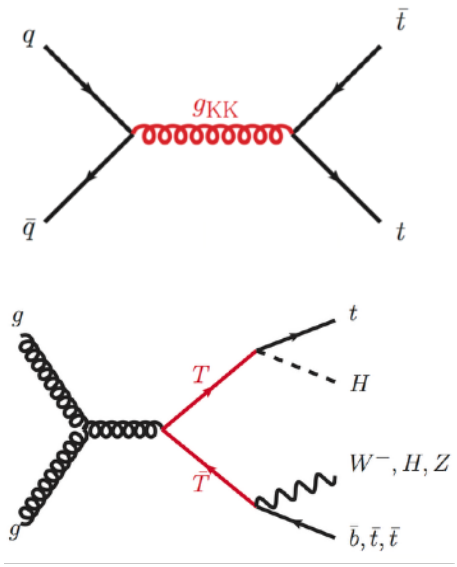
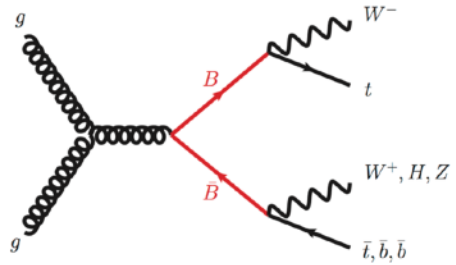
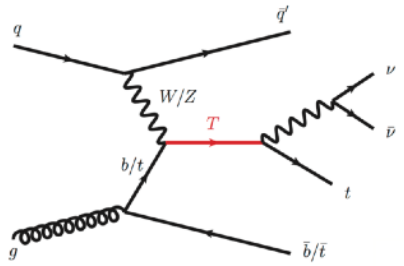


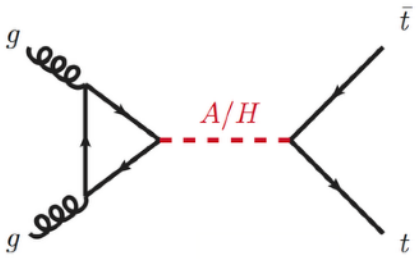
Top quark: probe for New Physics?

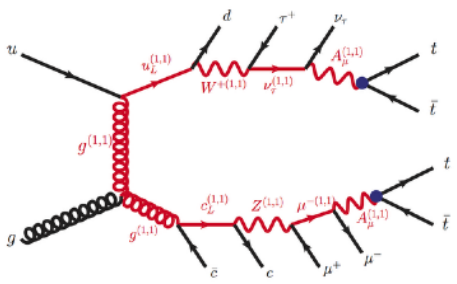
- **Large coupling** expected to BSM sector in several models

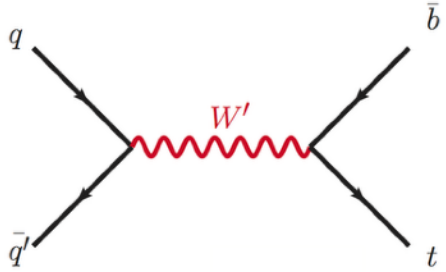


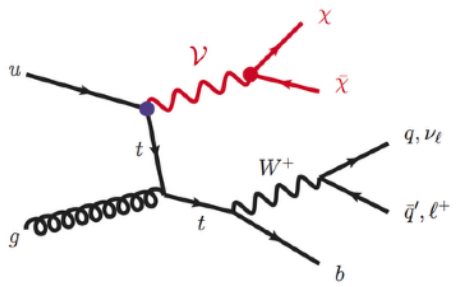


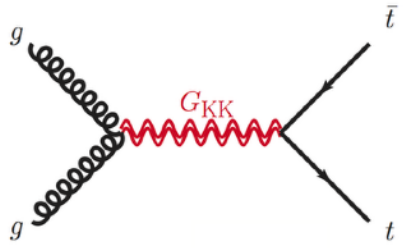








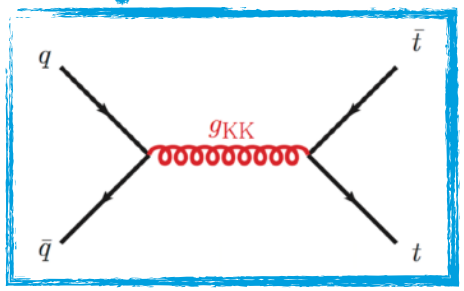


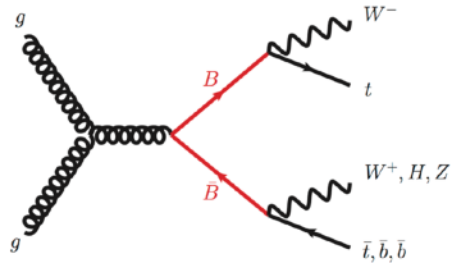


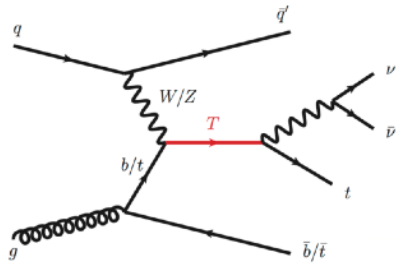
Top quark: probe for New Physics?

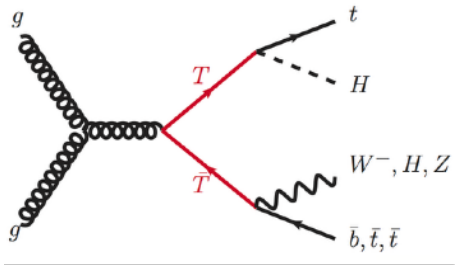
- **Large coupling** expected to BSM sector in several models

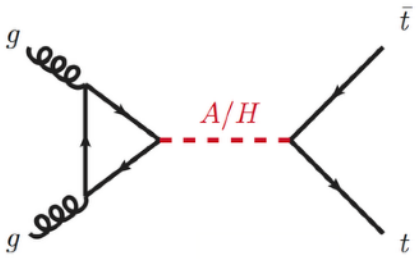
Heavy resonances

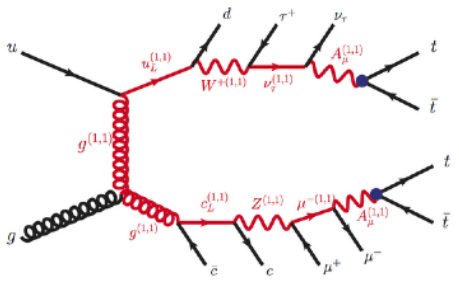


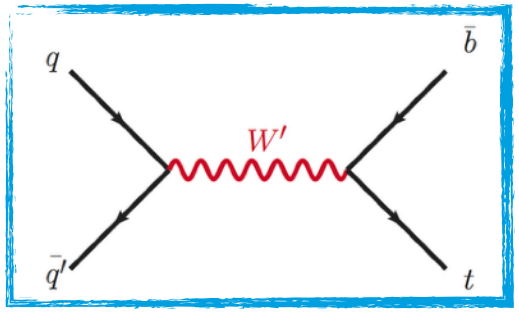


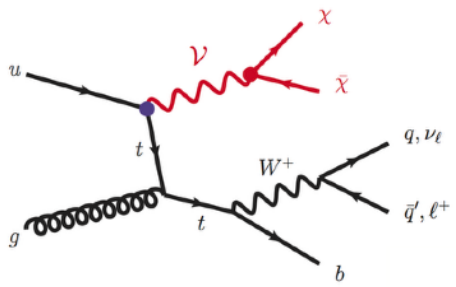


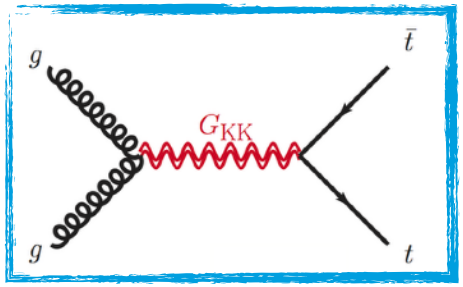












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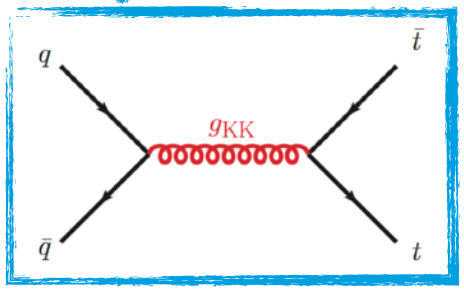
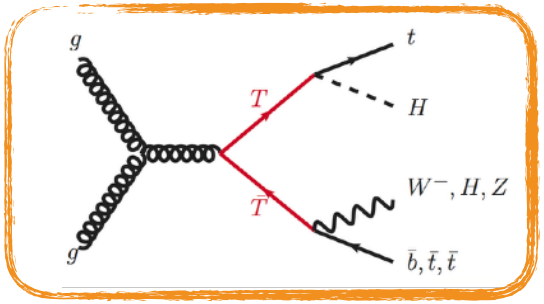
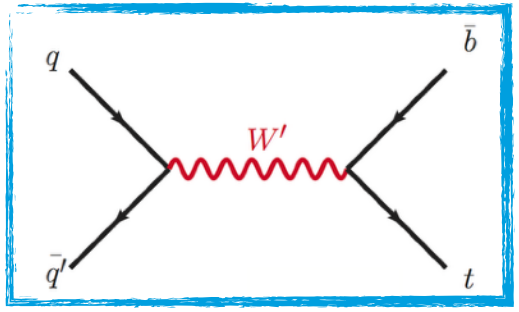
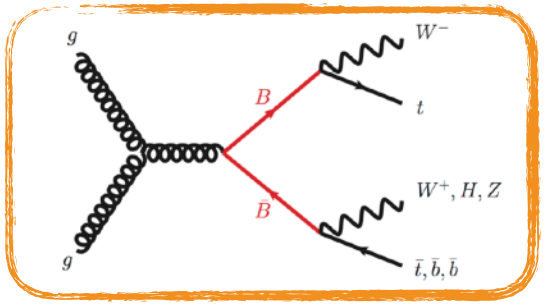
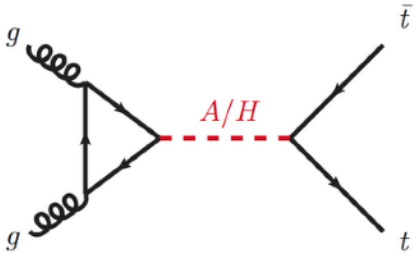
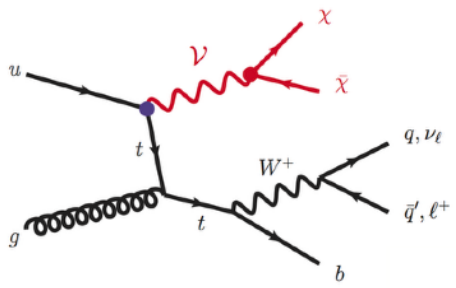




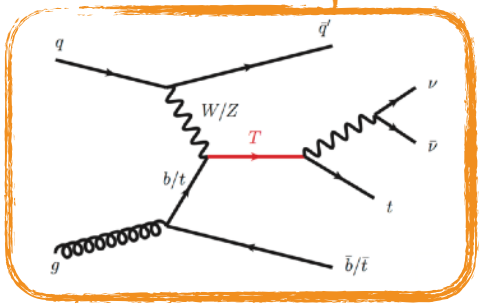


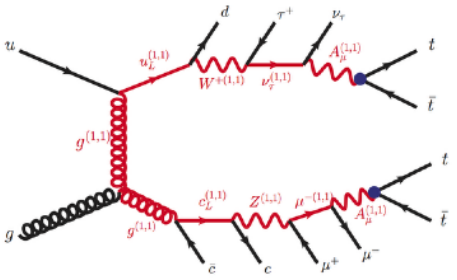


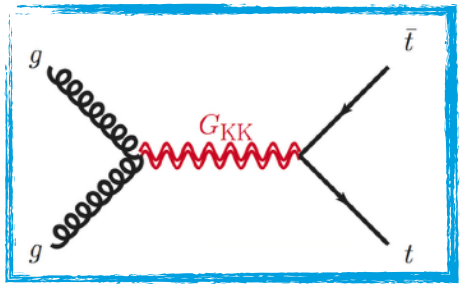




Vector-like quarks

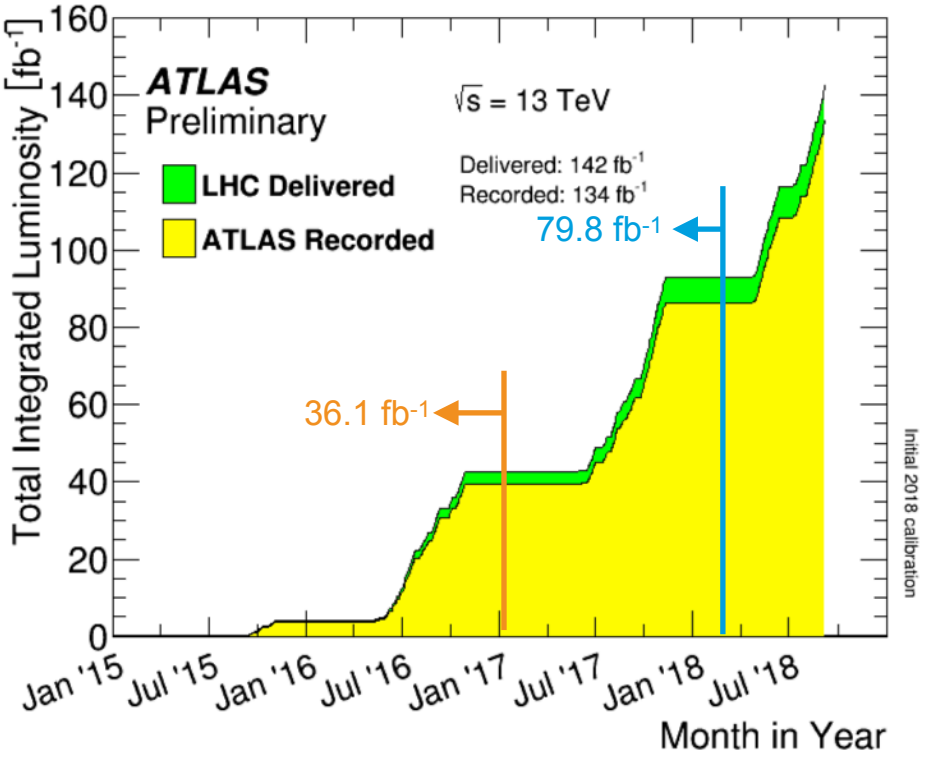






LHC and luminosity

- New Physics events: **rare** and at **high energy**
- Searches using **Run 2 LHC data**
  - Centre-of-mass energy: $\sqrt{s}$ = 13 TeV
  - Luminosity: 36.1 fb^{-1} or 79.8 fb^{-1}

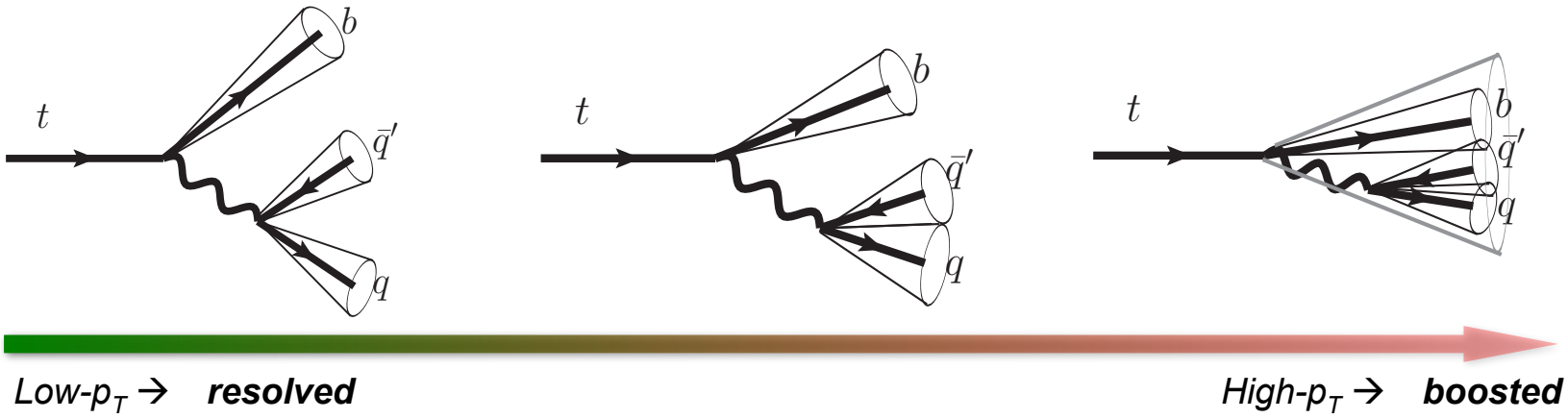


Looking for new physics with top quarks

Key features

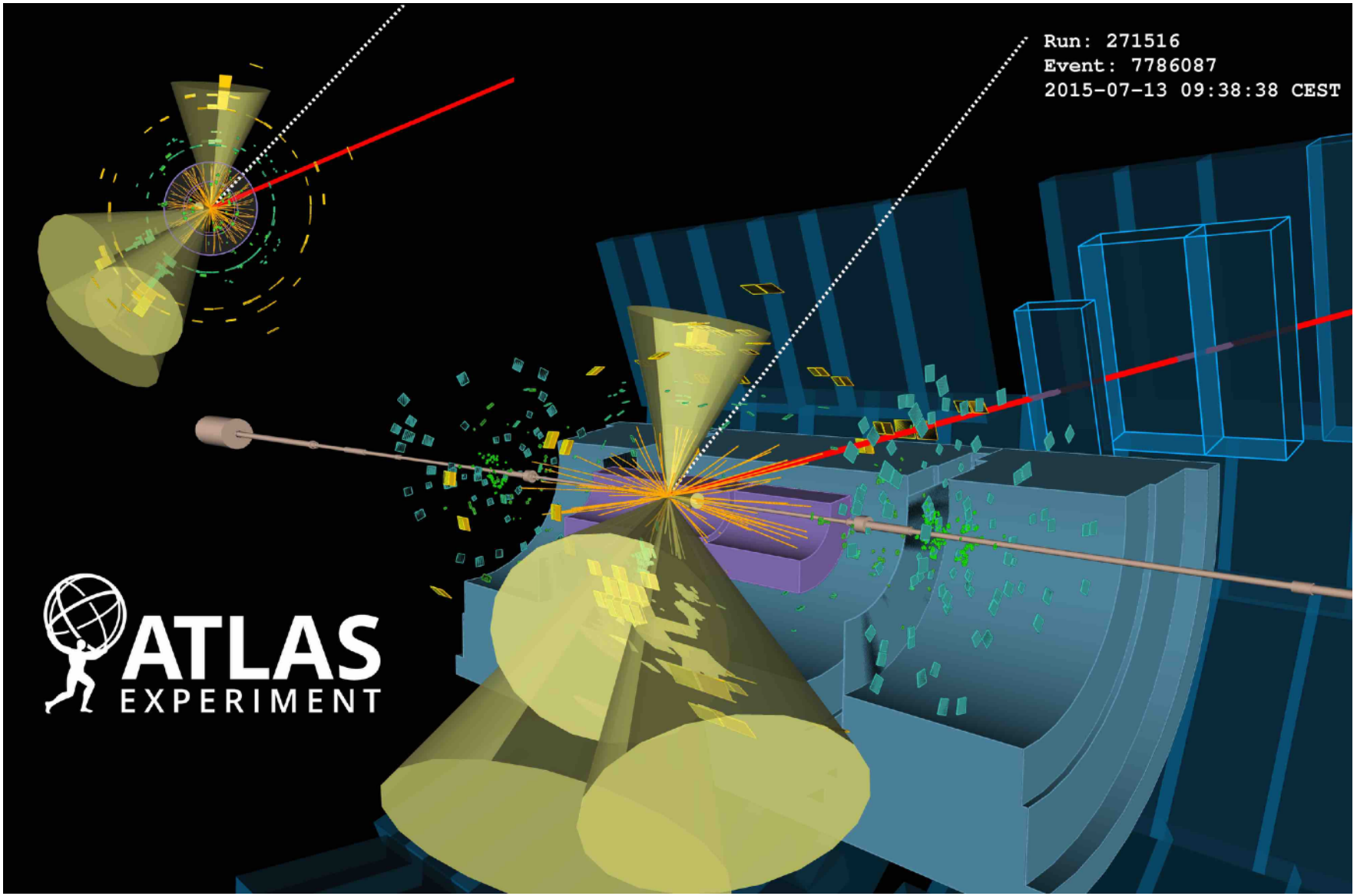
Event reconstruction

- New **heavy particles**: **high-p_T hadronically-decaying objects**



Low-p_T → ***resolved*** ***boosted*** ← *High-p_T*

Event reconstruction



Event reconstruction

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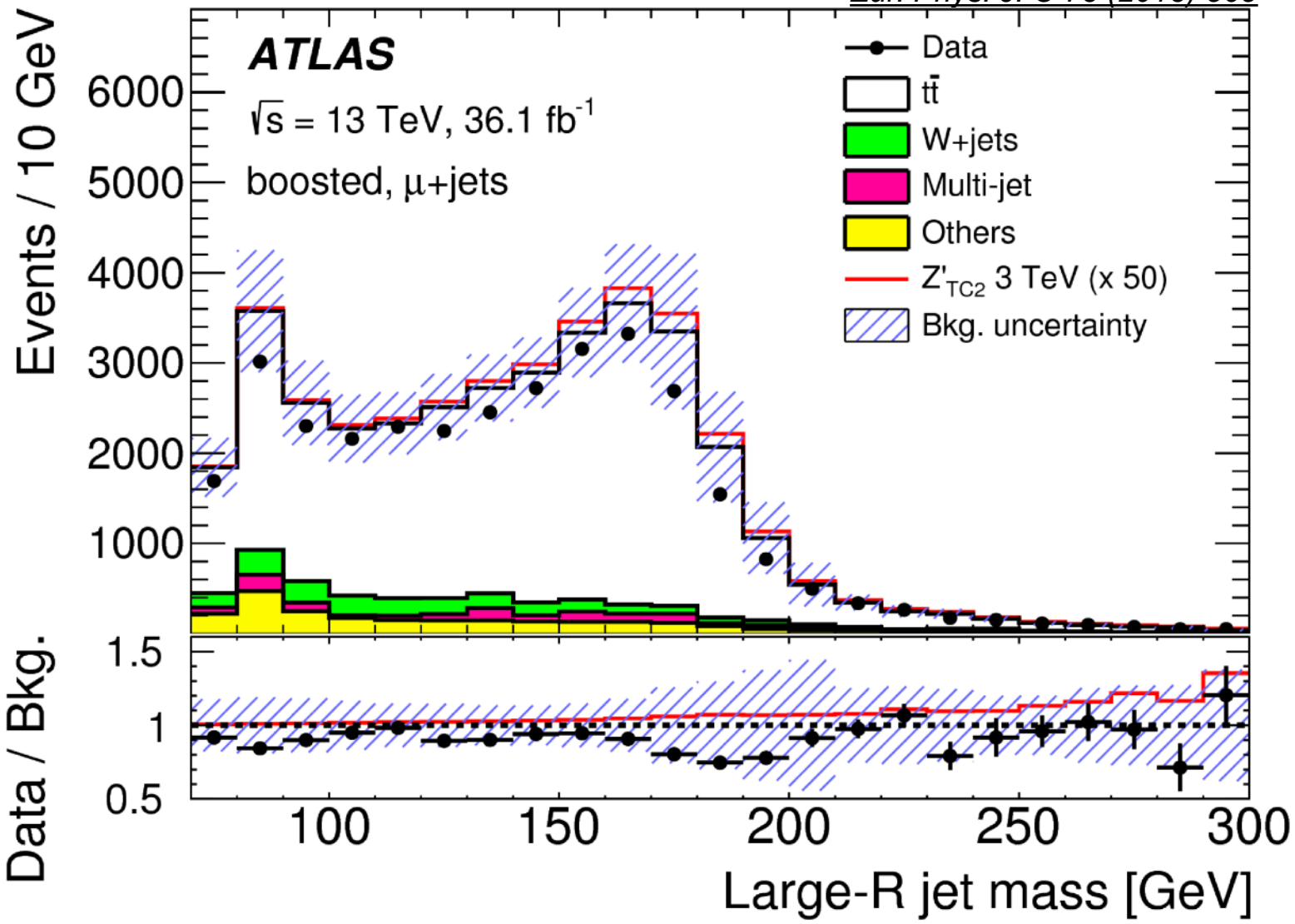
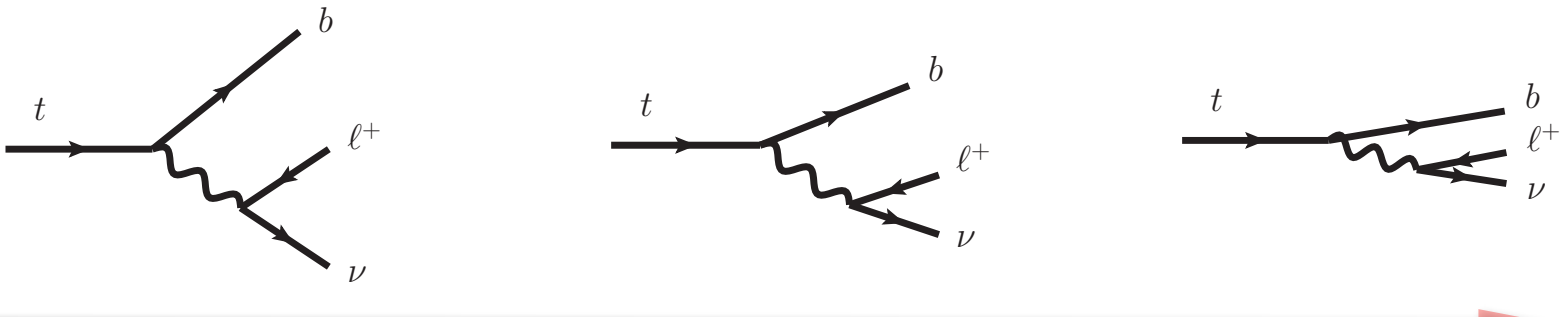


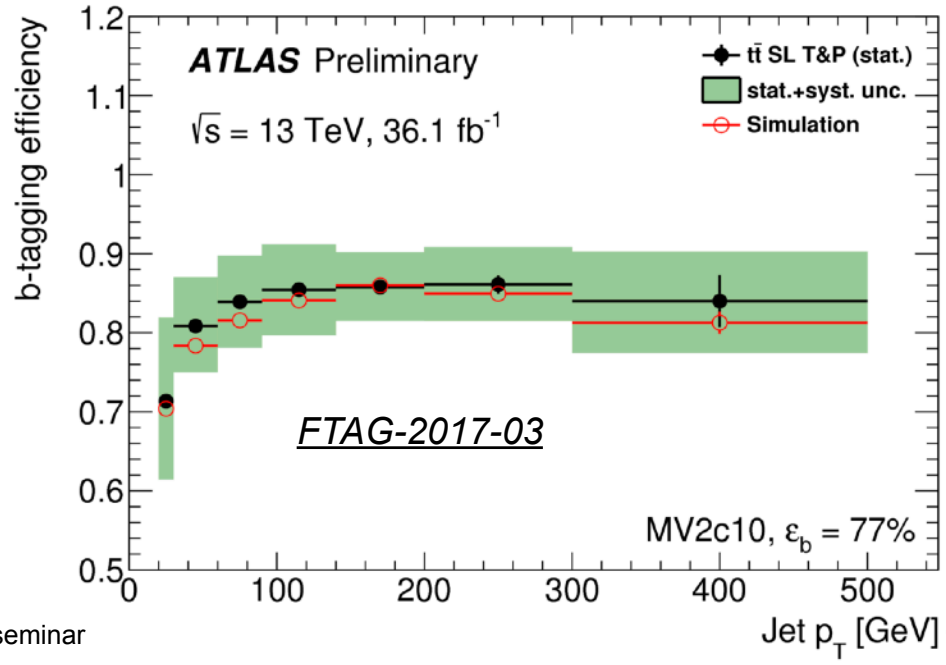
Event reconstruction

- New **heavy particles**: **high-p_T semi-leptonically-decaying objects**

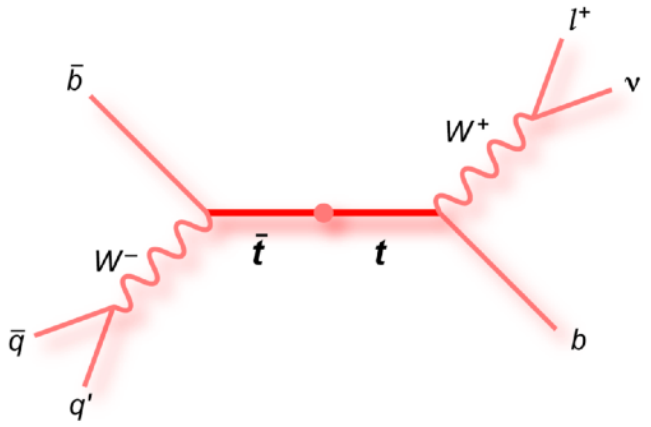


Low-p_T → ***resolved*** *High-p_T* → ***boosted***

- **Key aspects**
  - Lepton **isolation**
  - Impact of **overlapping b-jet**
  - **b-jets** tagging at **high-p_T**



$t\bar{t}$+jets background



- **$t\bar{t}$ + jets** process: often largest background source in top-enriched BSM searches

- Different types probed in searches:
  - many additional jets, b-jets
  - high-p_T top quarks
  - high-p_T top-antitop system

Background estimation strategy adapted to each phase space and observable

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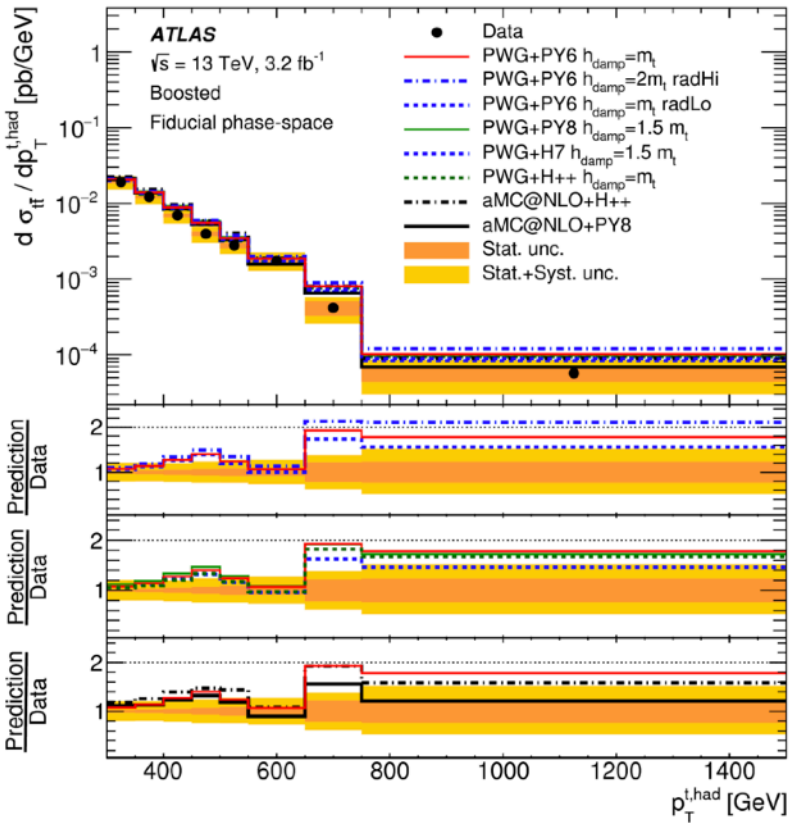

Resonance searches

Resonances

- **New heavy leptophobic gauge bosons** (Z', W', g_{KK}, …)
  - Several models probed (e.g. extra-dimension, SSM, Dark Matter)
  - Charge conservation: decays to $t\bar{t}$ or $t\bar{b}$

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  - Several models probed (e.g. extra-dimension, SSM, Dark Matter)
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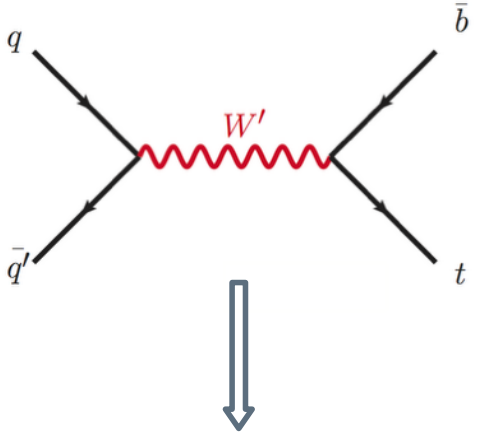
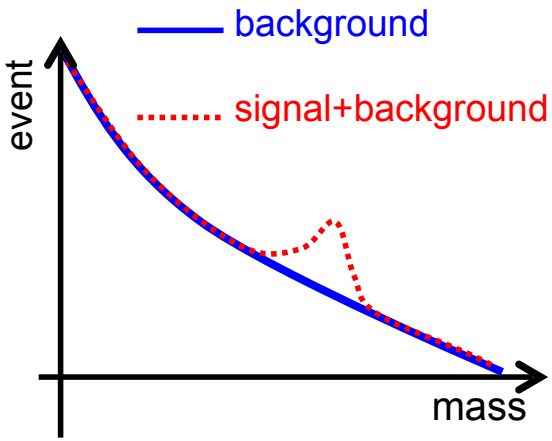
- **Strategy**
  - Continuously falling background
  - New Physics → **bump on invariant mass spectrum**





- **Key aspects**
  - Identification of boosted objects (e.g. boosted top quarks)
  - **Reconstruction** of invariant mass
  - **Background shape** modelling

$t\bar{t}$ resonances

1-lepton channel

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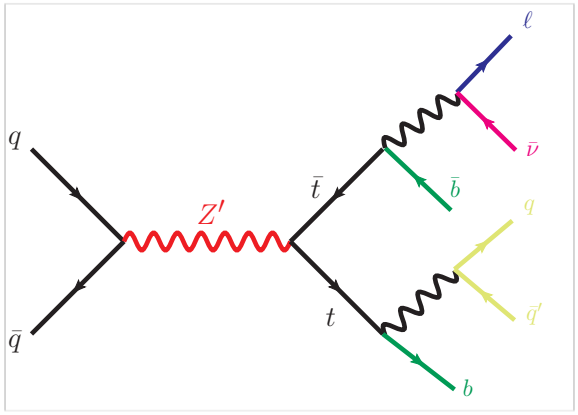

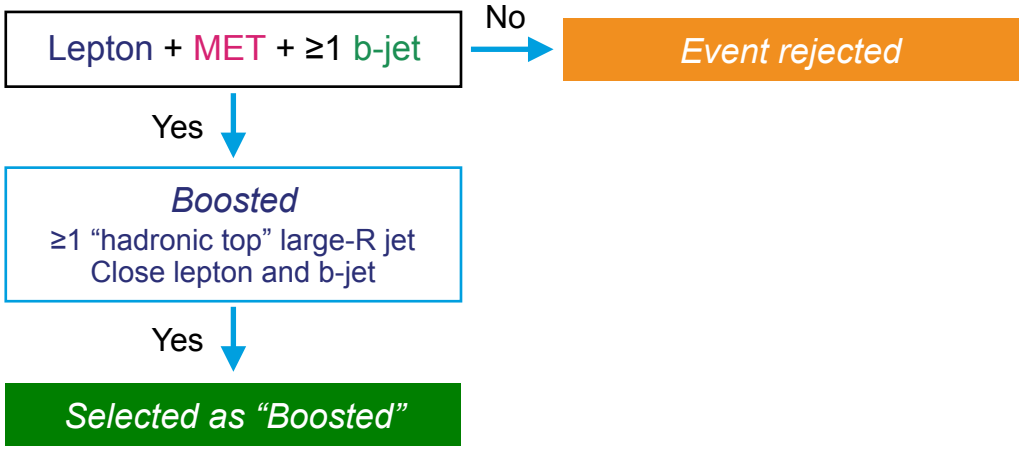

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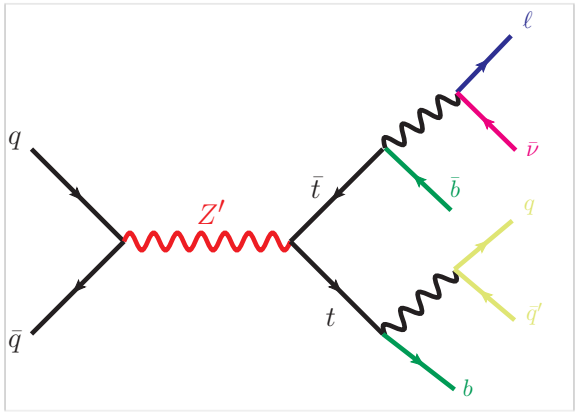
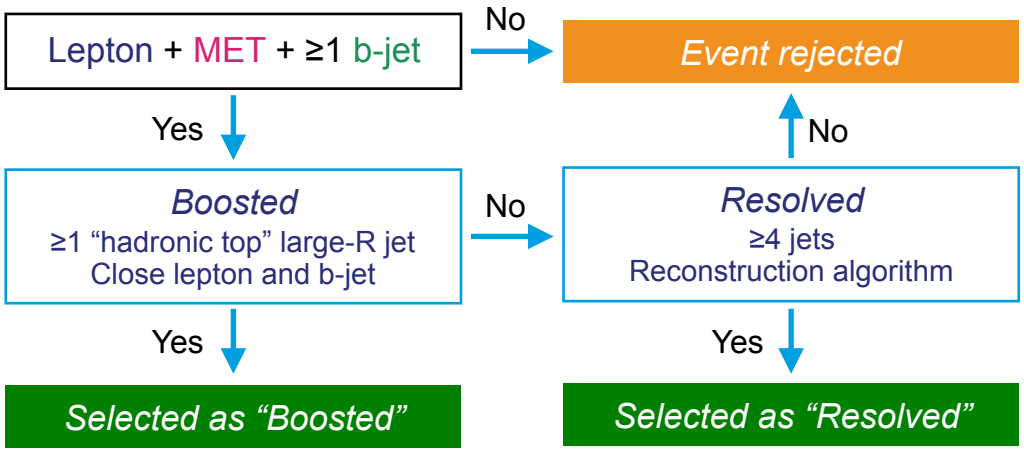
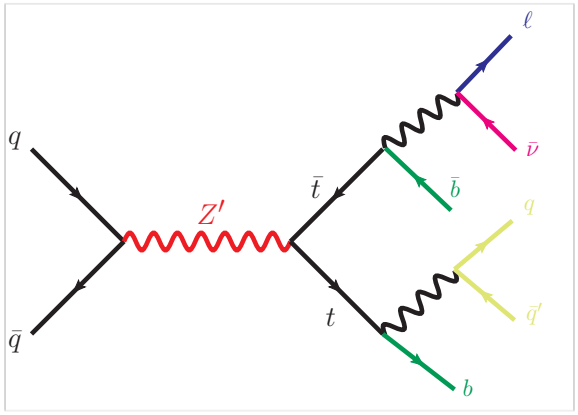


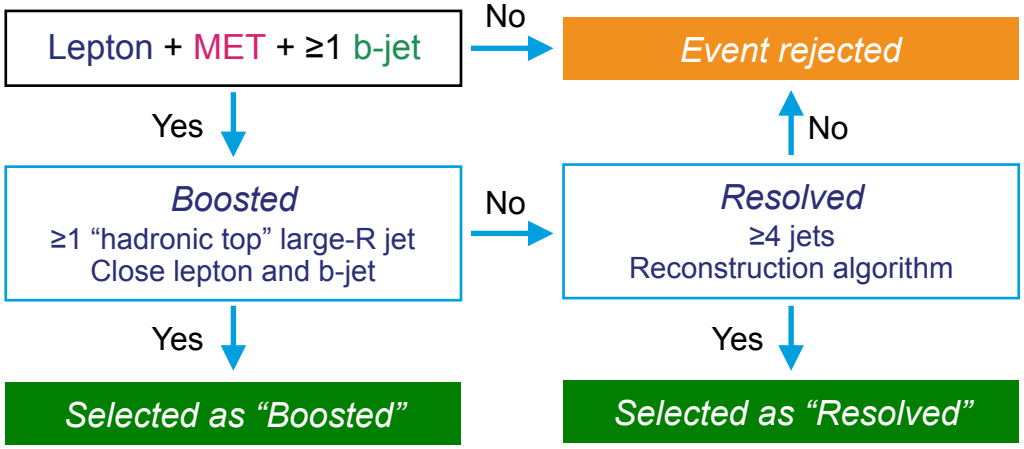


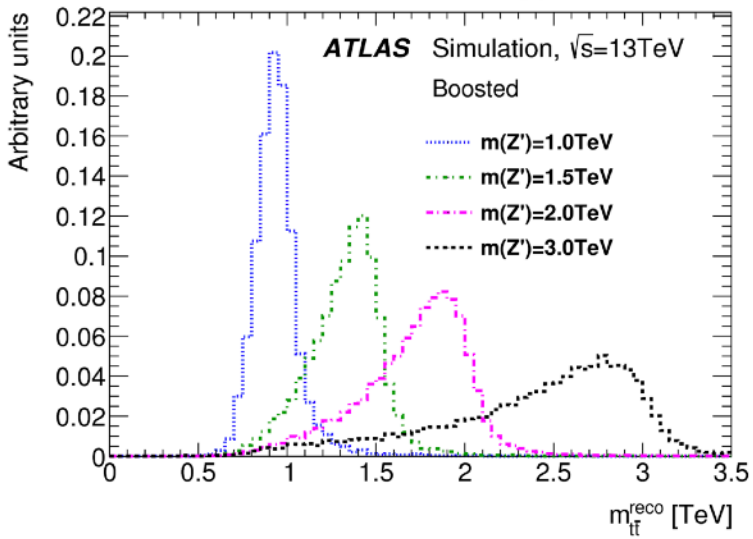
$t\bar{t}$ resonances

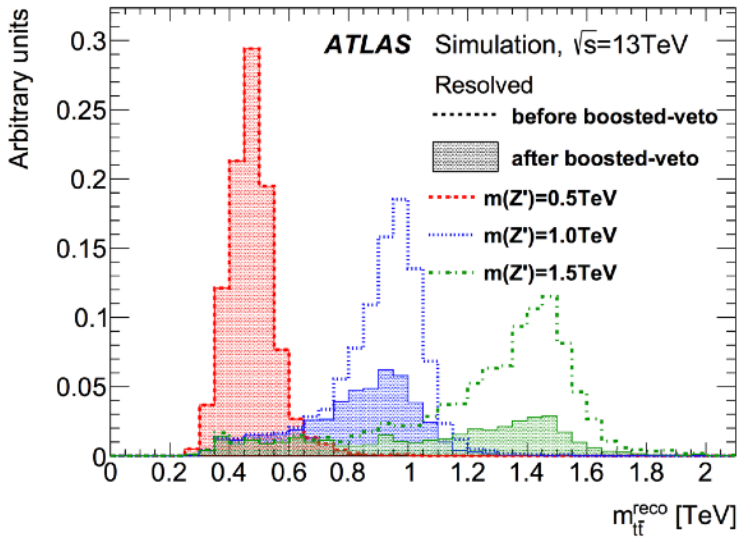
1-lepton channel

Eur. Phys. J. C 78 (2018) 565







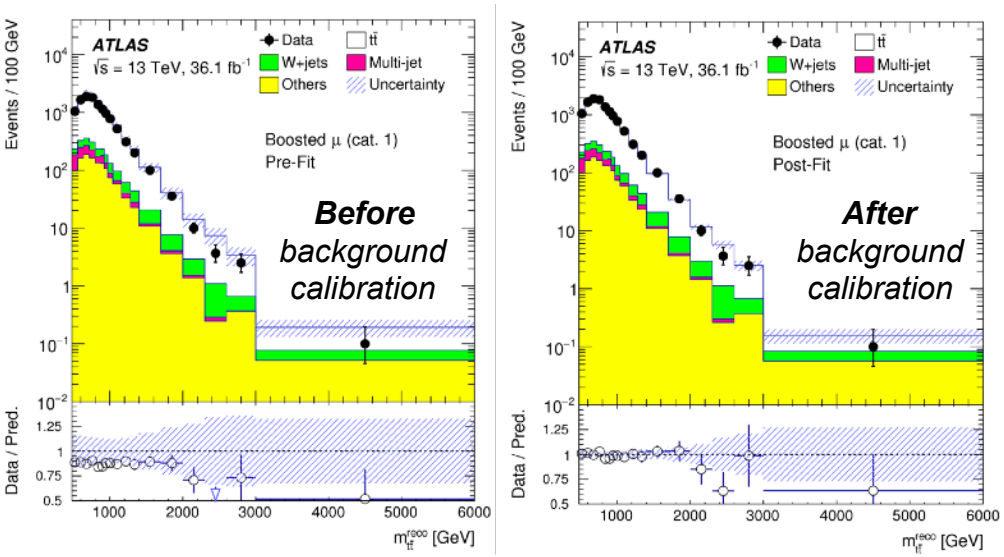


$t\bar{t}$ resonances

1-lepton channel

Eur. Phys. J. C 78 (2018) 565

- $m_{t\bar{t}}$ spectrum compared between data and background prediction
  - Data/prediction agreement can be improved → **background calibration**
    - simultaneous profile likelihood fit in all channels with all nuisance parameters

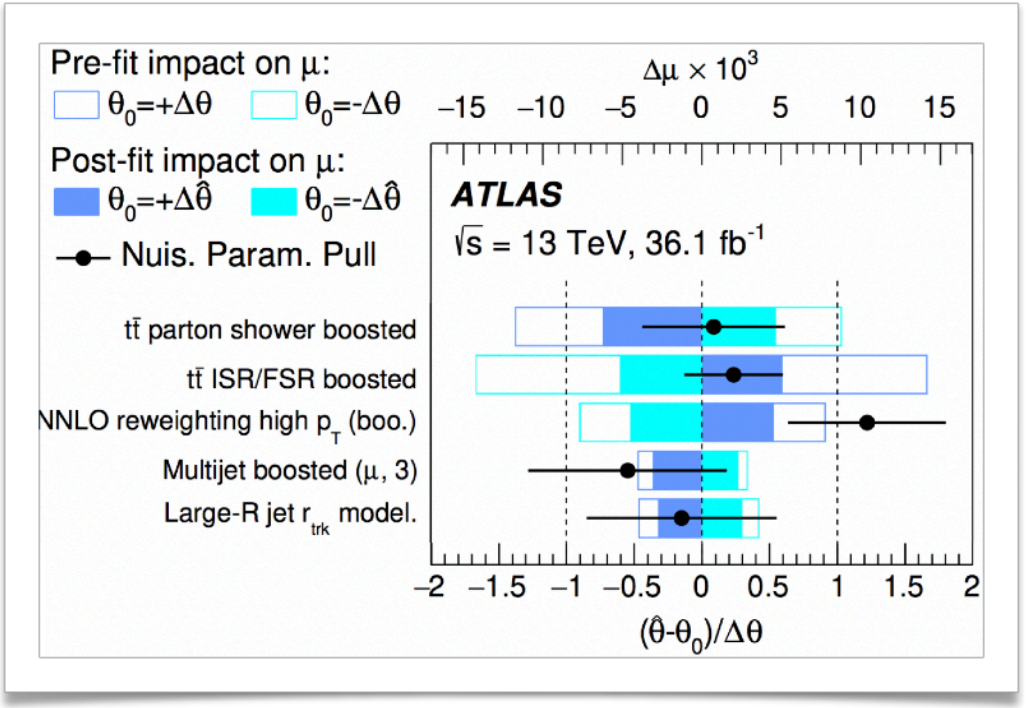


$t\bar{t}$ resonances

1-lepton channel

Eur. Phys. J. C 78 (2018) 565

- Background estimate **parameters**
  - Background **normalisation**
  - MC generator **settings**
  - **Alternative** generators
- Background calibration
  - **Background model fit to data**



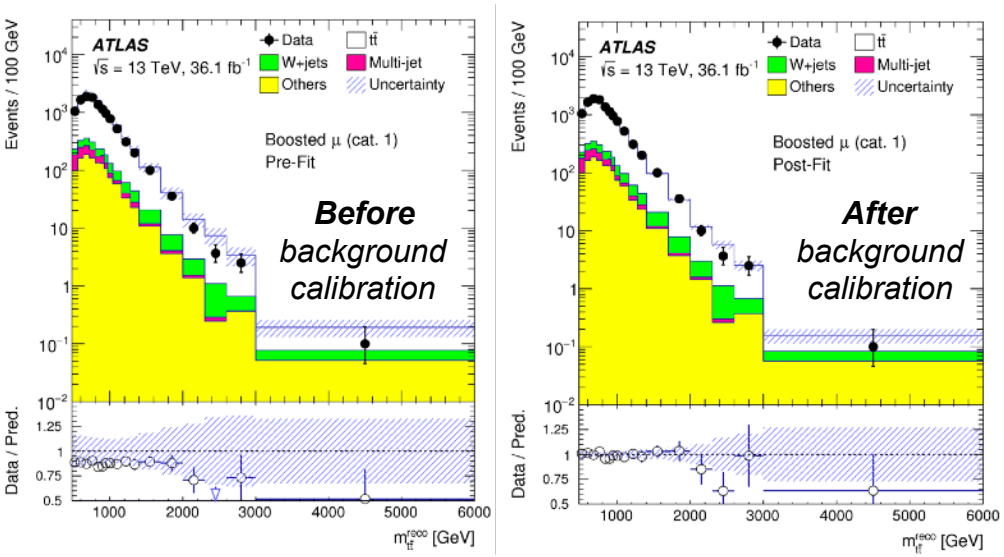
Extracted from Eur. Phys. J. C 78 (2018) 565

$t\bar{t}$ resonances

1-lepton channel

Eur. Phys. J. C 78 (2018) 565

- $m_{t\bar{t}}$ spectrum compared between data and background prediction
  - Data/prediction agreement can be improved → **background calibration**
    - simultaneous profile likelihood fit in all channels with all nuisance parameters
  - After fit, **very good agreement with prediction**

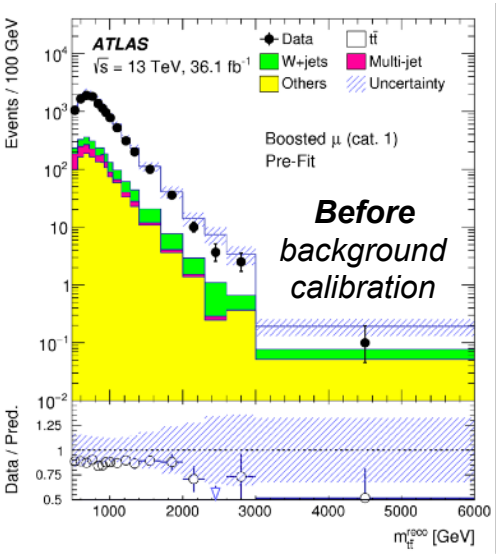


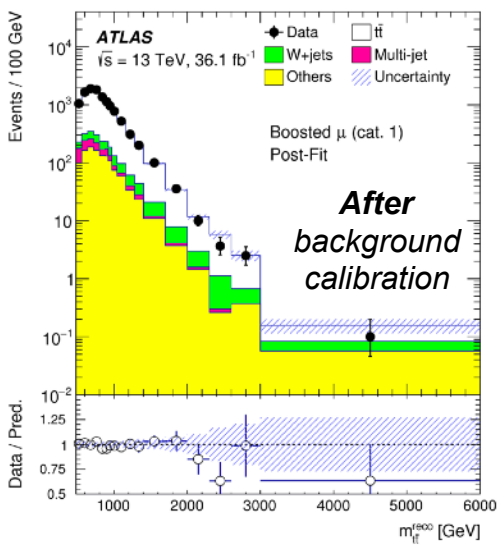
$t\bar{t}$ resonances

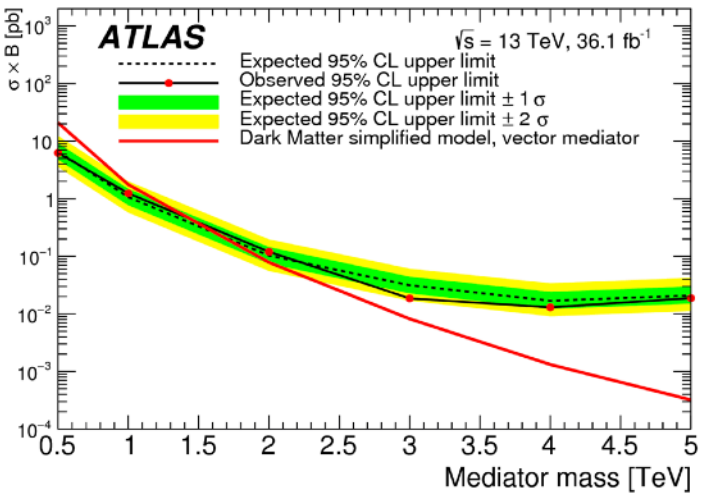
1-lepton channel

Eur. Phys. J. C 78 (2018) 565

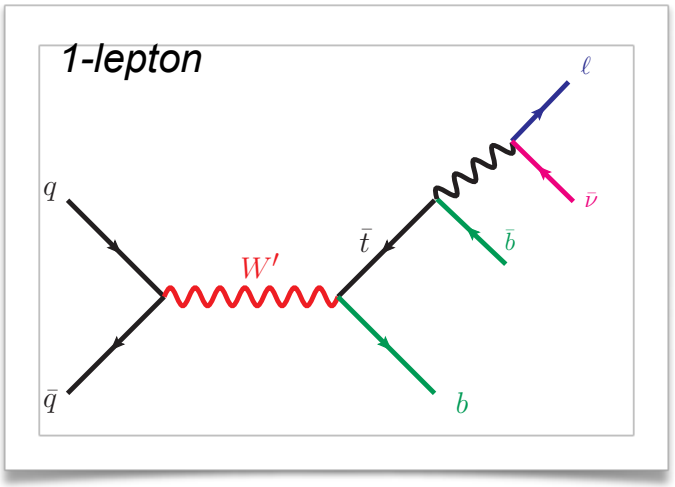
- $m_{t\bar{t}}$ spectrum compared between data and background prediction
  - Data/prediction agreement can be improved → **background calibration**
    - simultaneous profile likelihood fit in all channels with all nuisance parameters
  - After fit, **very good agreement with prediction**
- Bumps searched for in all channels → **no significant bump observed**
- CL_s limits set at 95% CL for various **models**, **masses** and **widths**

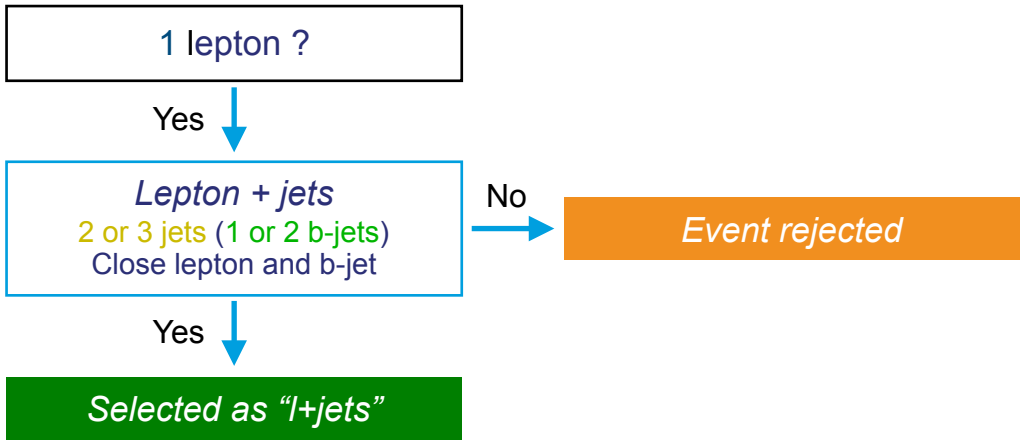




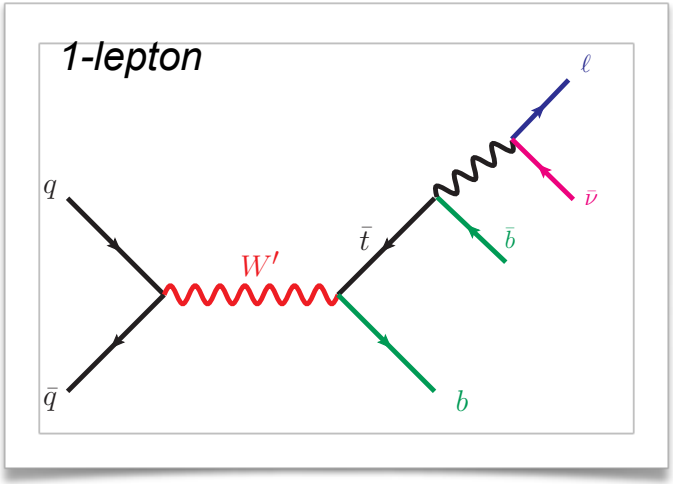


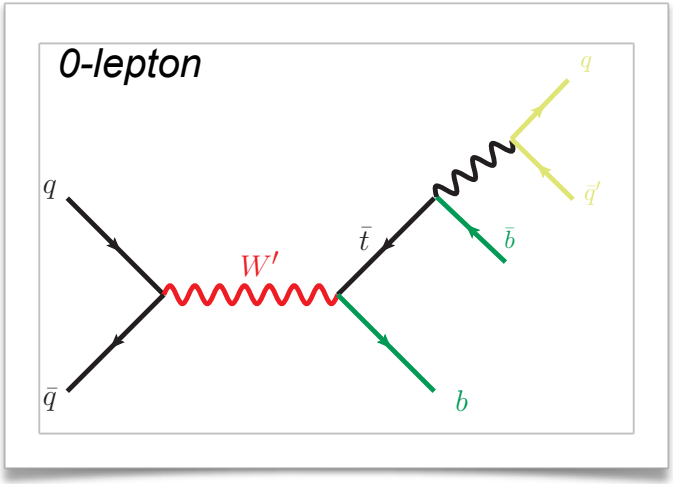
$t\bar{b}$ resonances

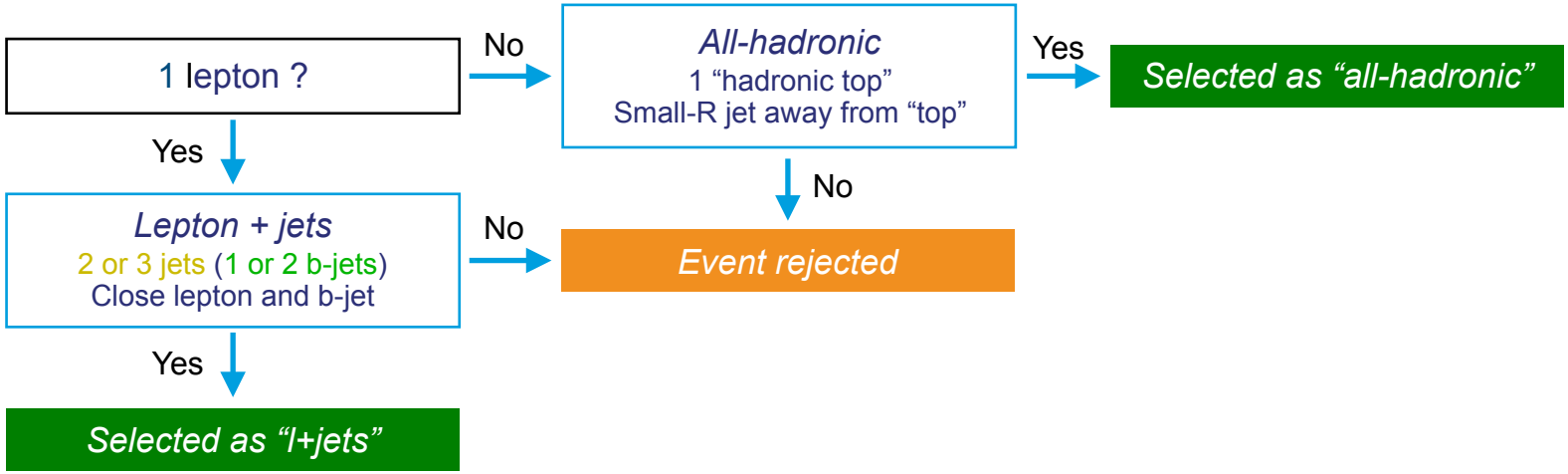




$t\bar{b}$ resonances



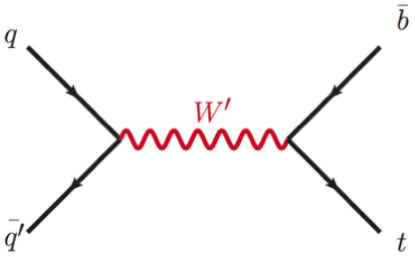




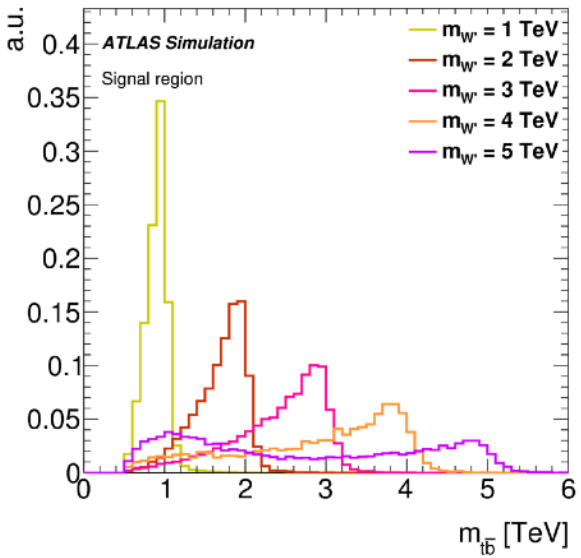
$t\bar{b}$ resonances

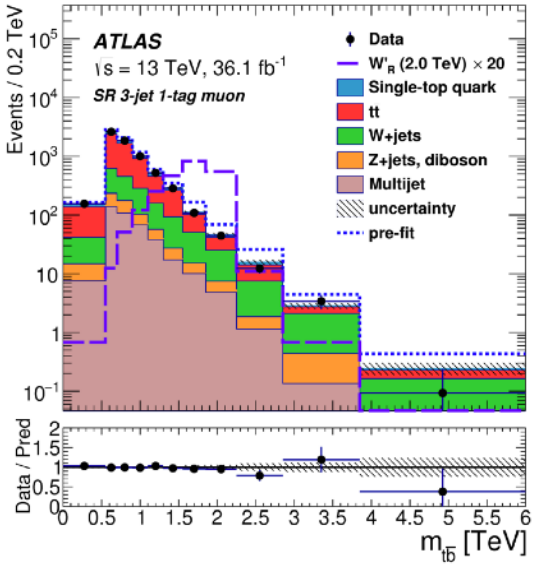
1-lepton search

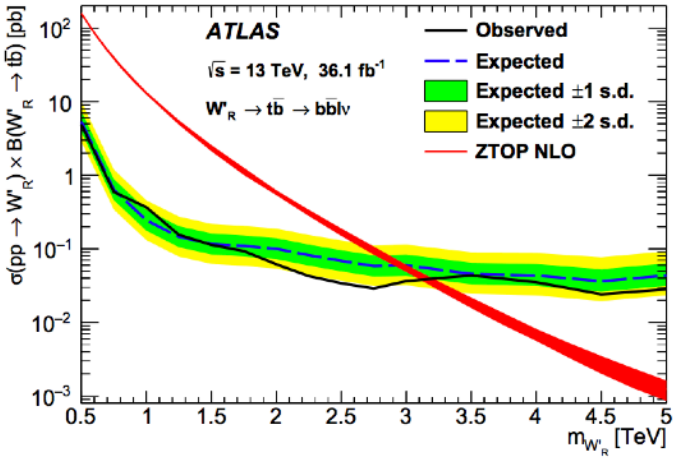
arXiv:1807.10473



- Event **reconstruction**
  - W' candidate: combination of lepton, MET and b-jet candidate
  - Resolution effects: combinatorics and PDF
- After fit, background prediction in good agreement with data
- Limits on **m(W') ~ 3 TeV**



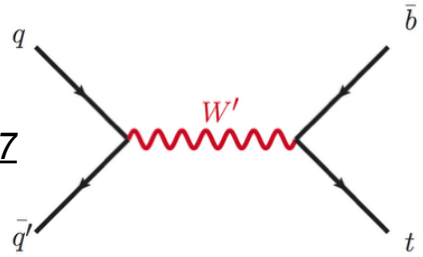




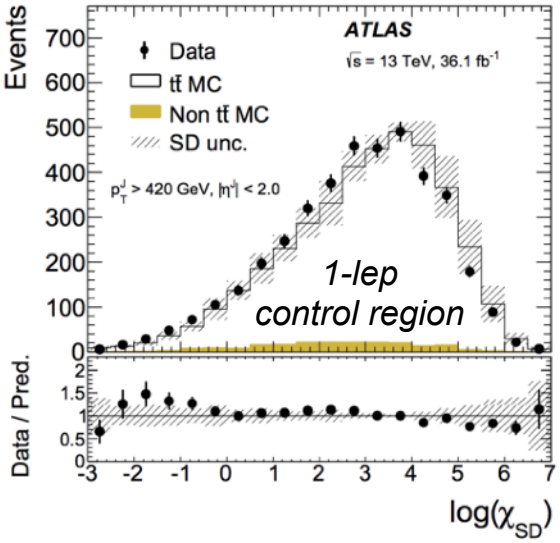
$t\bar{b}$ resonances

0-lepton search

Phys. Lett. B 781 (2018) 327



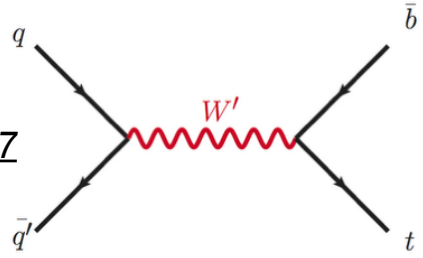
- **Top-tagging** algorithm
  - Using **shower deconstruction** (SD) algorithm on large-R jets *[Phys. Rev. D 84, 074002]*
    - consider all possible shower histories leading to subjet configuration
    - **variable of interest** (likelihood ratio): χ_{SD}



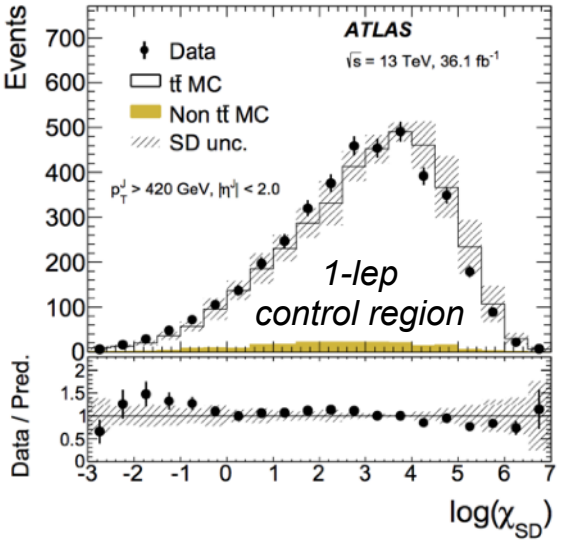
$t\bar{b}$ resonances

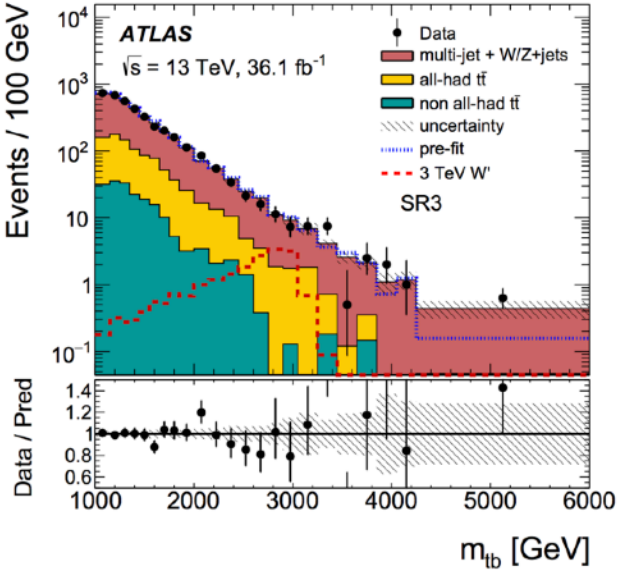
0-lepton search

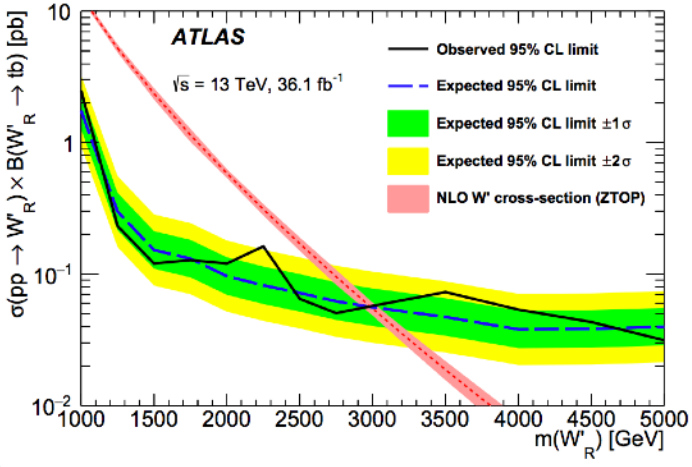
Phys. Lett. B 781 (2018) 327



- **Top-tagging** algorithm
  - Using **shower deconstruction** (SD) algorithm on large-R jets *[Phys. Rev. D 84, 074002]*
    - consider all possible shower histories leading to subjet configuration
    - **variable of interest** (likelihood ratio): χ_{SD}
- Data-driven **multijet background** estimation
- **Very good data/prediction agreement** across all bins and regions



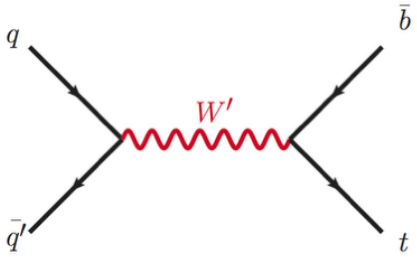




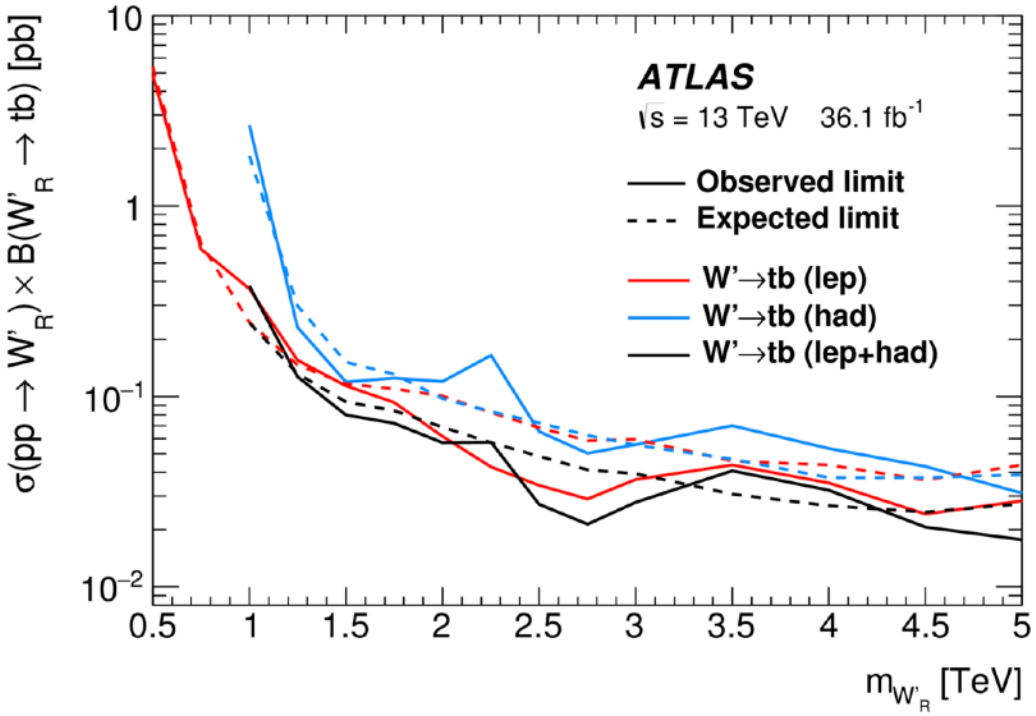
$t\bar{b}$ resonances

Combination

arXiv:1807.10473

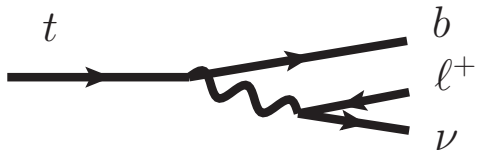


- 1- and 0-lepton searches: **similar sensitivity**
- **Different** dominating **background sources**
- Combination: **expected sensitivity improved by factor ~2**

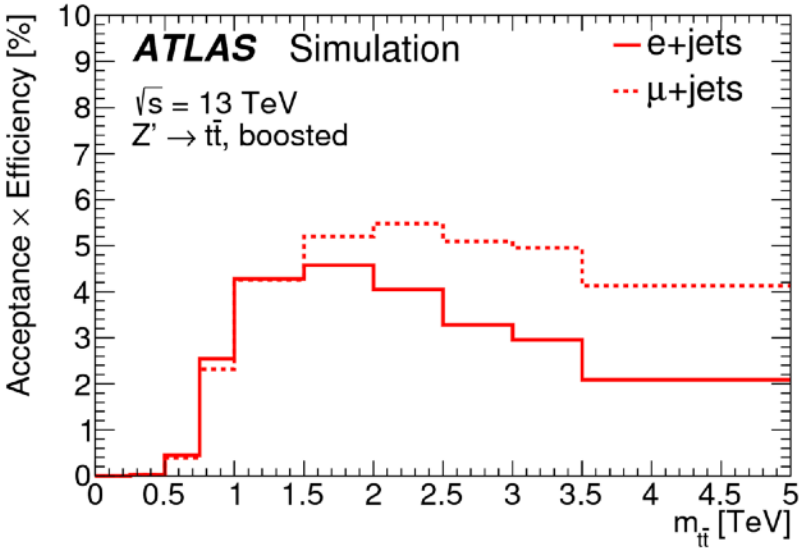


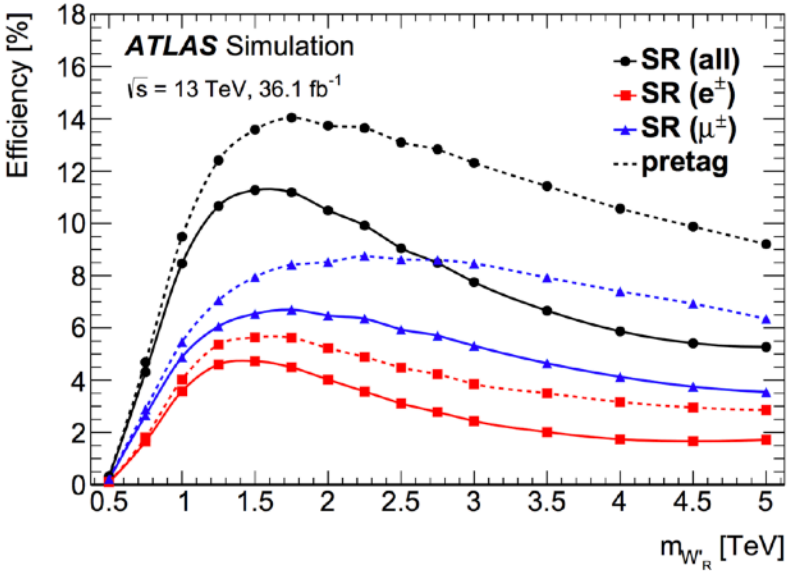
Resonances: a few lessons learnt ?

- High mass regime: statistics is limiting



- **Event selection**
  - *Electrons close to jets*: electron channel less powerful
  - *High-p_T jets b-tagging:* efficiency loss at high p_T (more likely to miss high-p_T b-jets)





- **Improvements** ongoing for next generation (e.g. ATL-PHYS-PUB-2017-013)

Vector-like quark searches

Vector-like quarks

- **Heavy quarks** for which **left-** and **right-handed** chirality components transform the same under SU(2)
  - Predicted in **many theories** (extra-dimensions, Higgs compositeness, …)
  - Gauge invariant mass term

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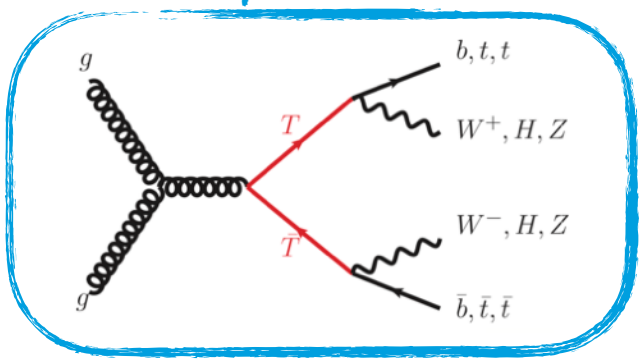
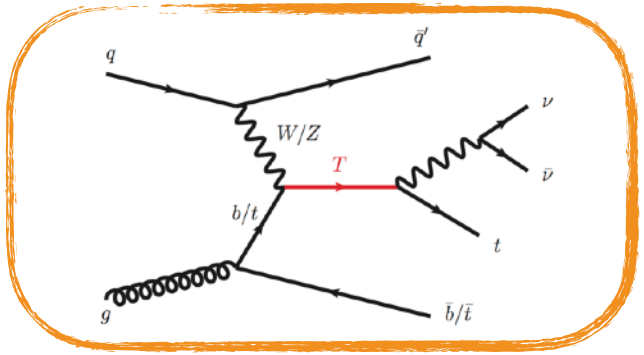
Pair-production



- Production ~independent on coupling to SM partners
- Dominant for low masses

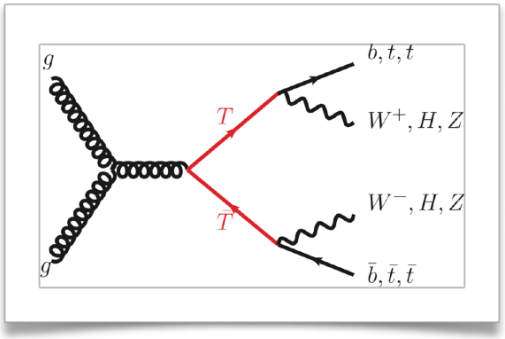
Single-production

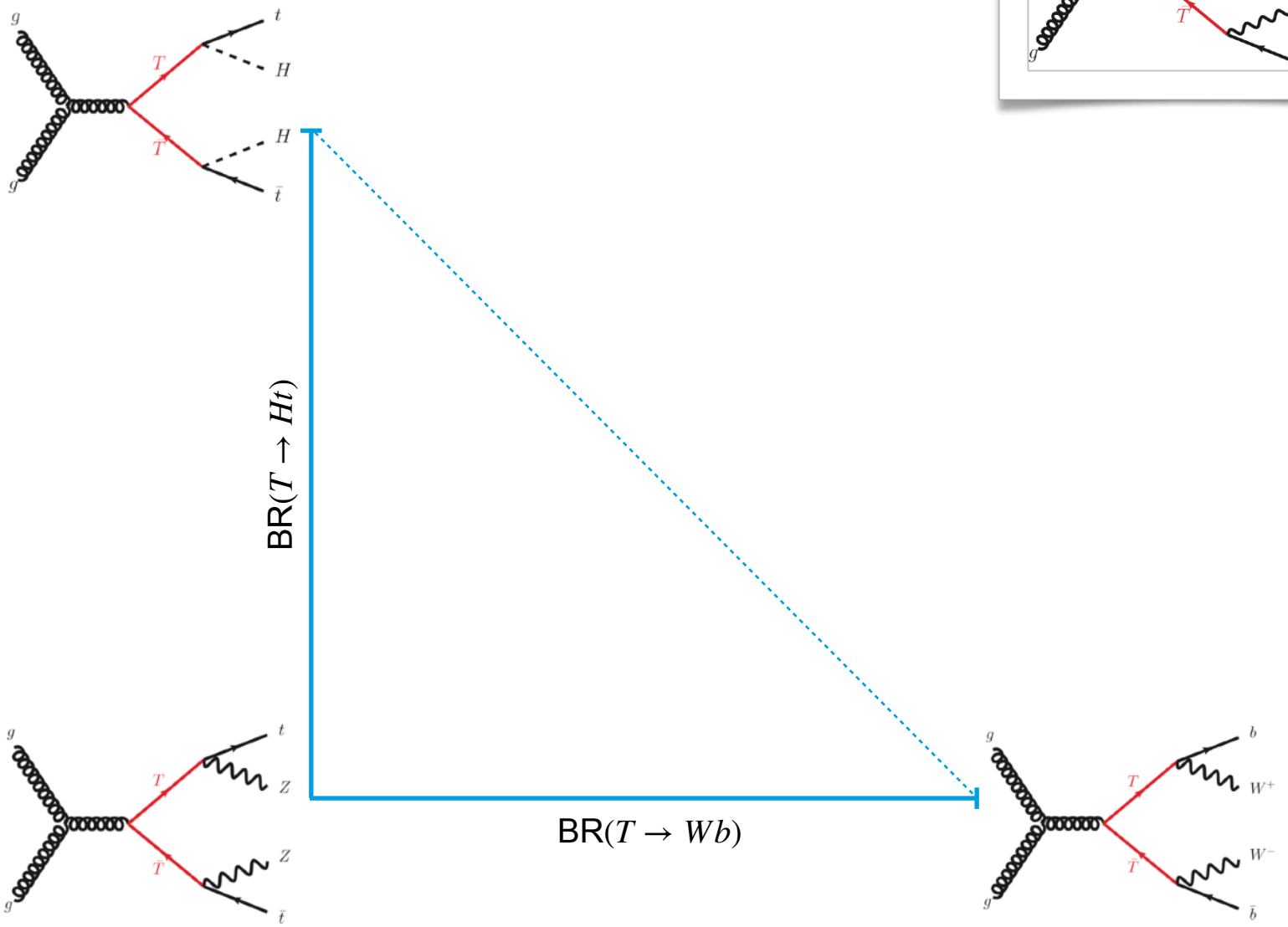


- Cross-section depends on coupling assumptions
- Can be dominant for high masses

Pair-production searches

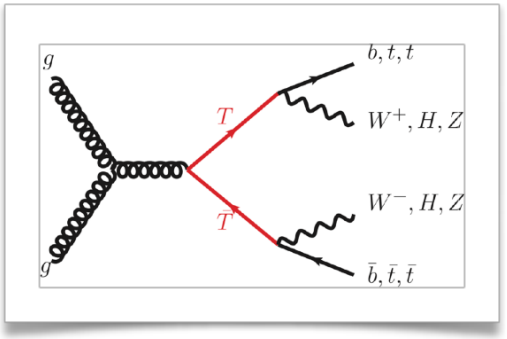
Decay configurations

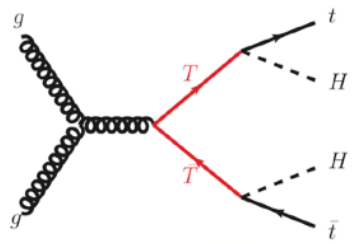




Pair-production searches

Decay configurations

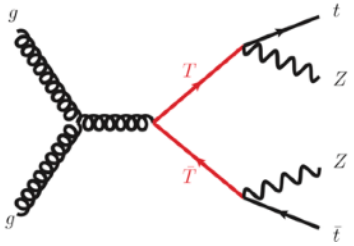


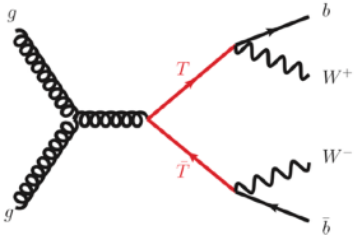


(Boosted) top quark(s)

BR($T \to Ht$)

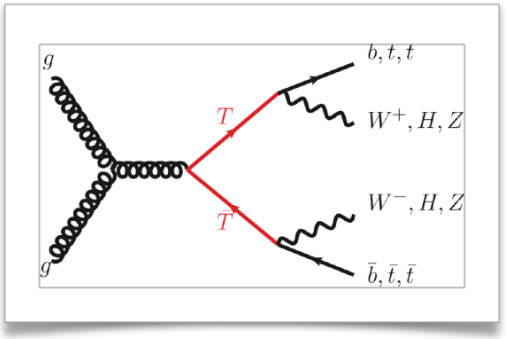
BR($T \to Wb$)

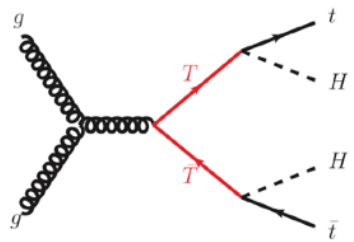




Pair-production searches

Decay configurations





(Boosted) top quark(s)

High-p_T b-jet(s)

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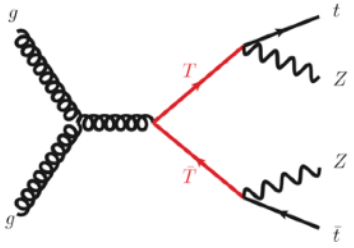
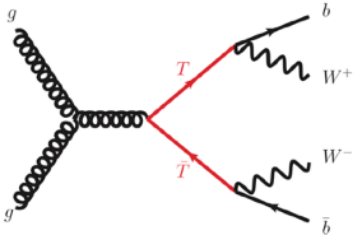
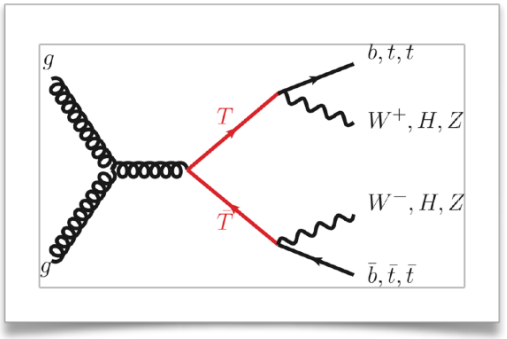
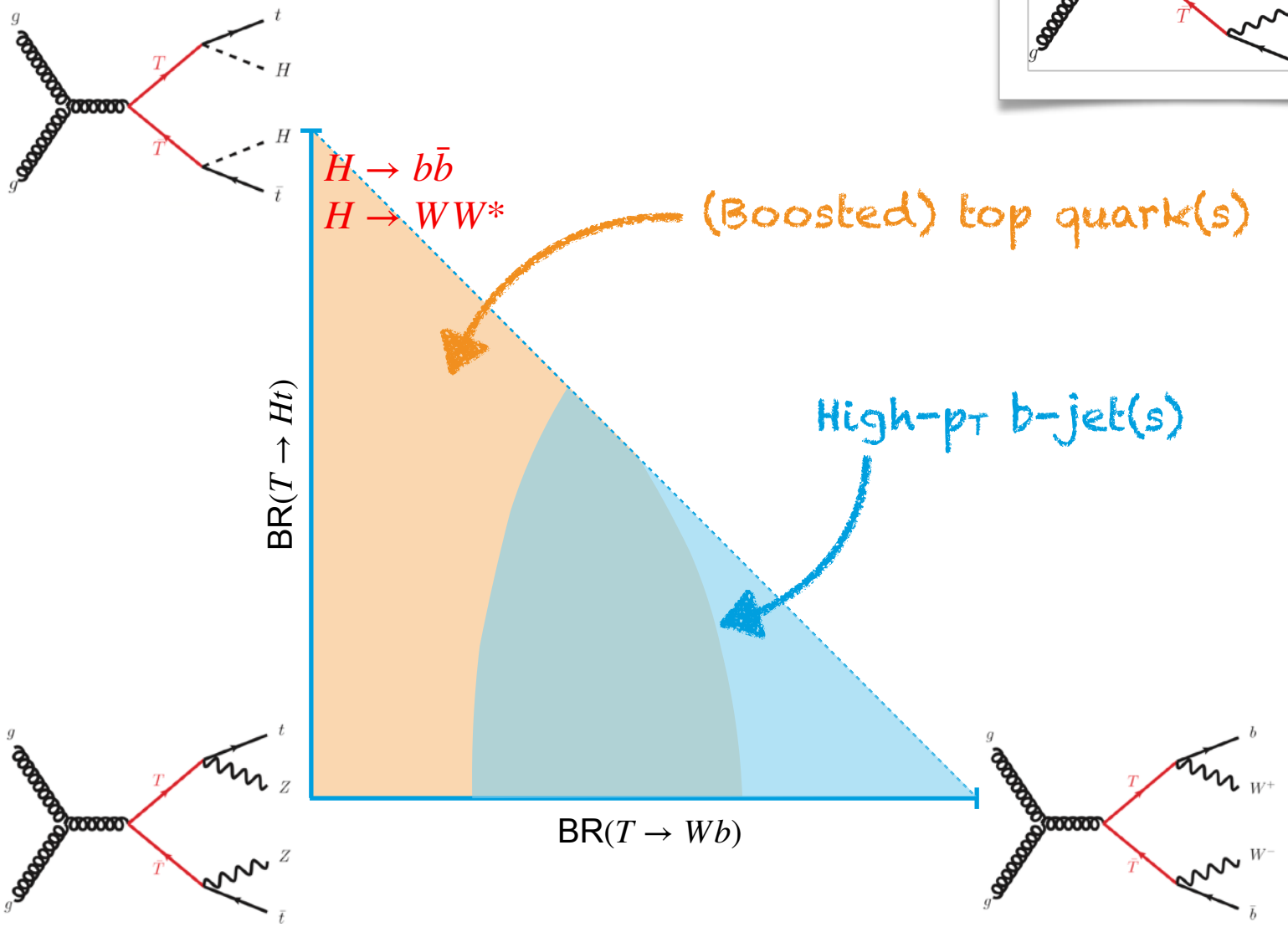




Pair-production searches

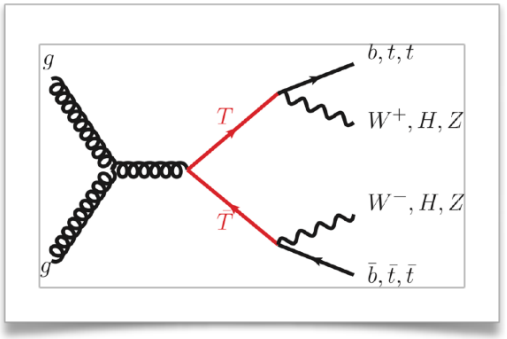
Decay configurations

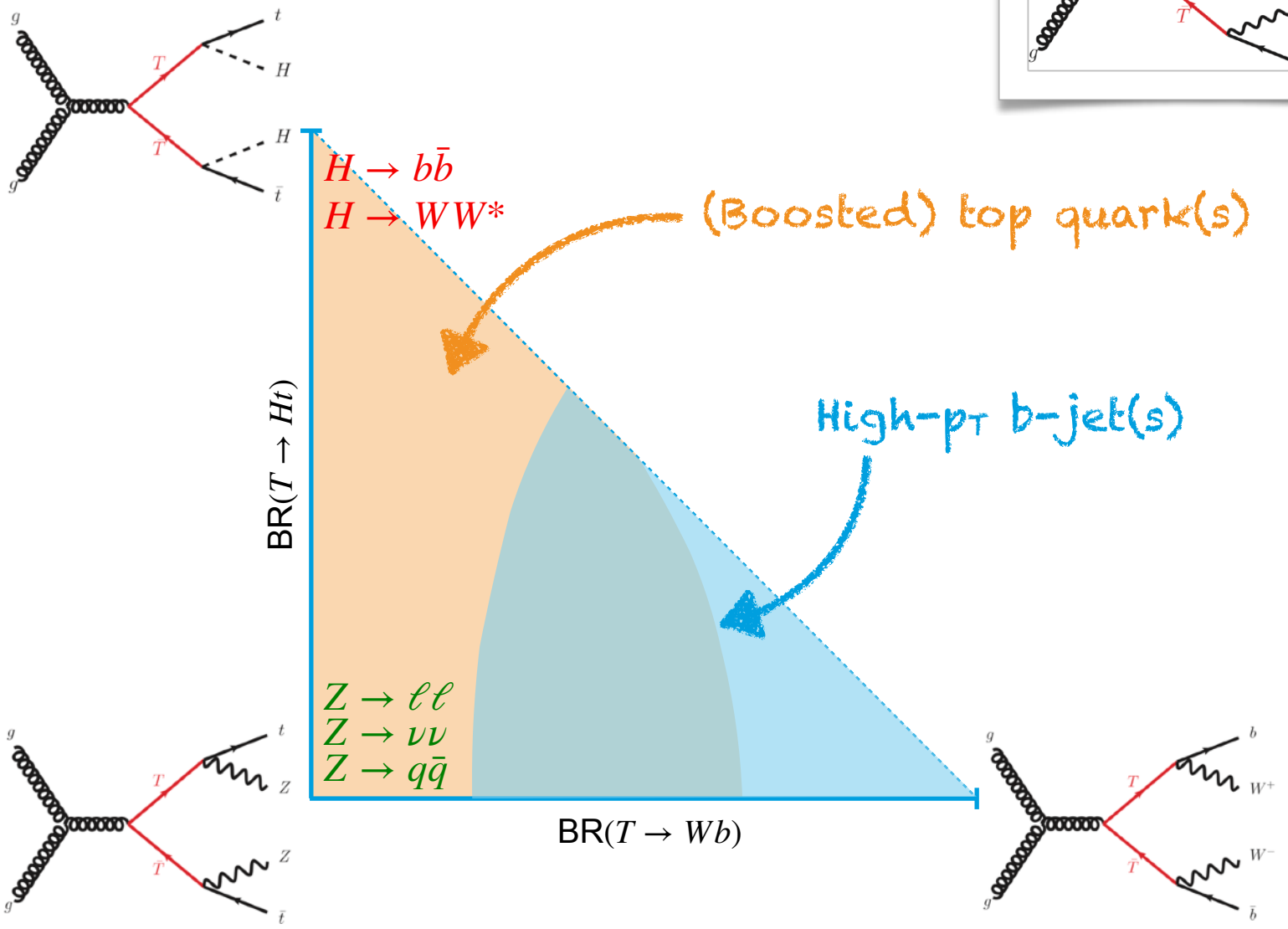




Pair-production searches

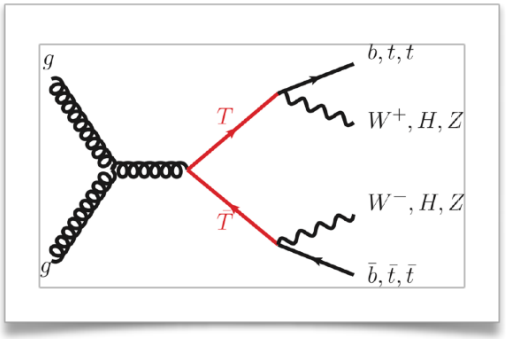
Decay configurations

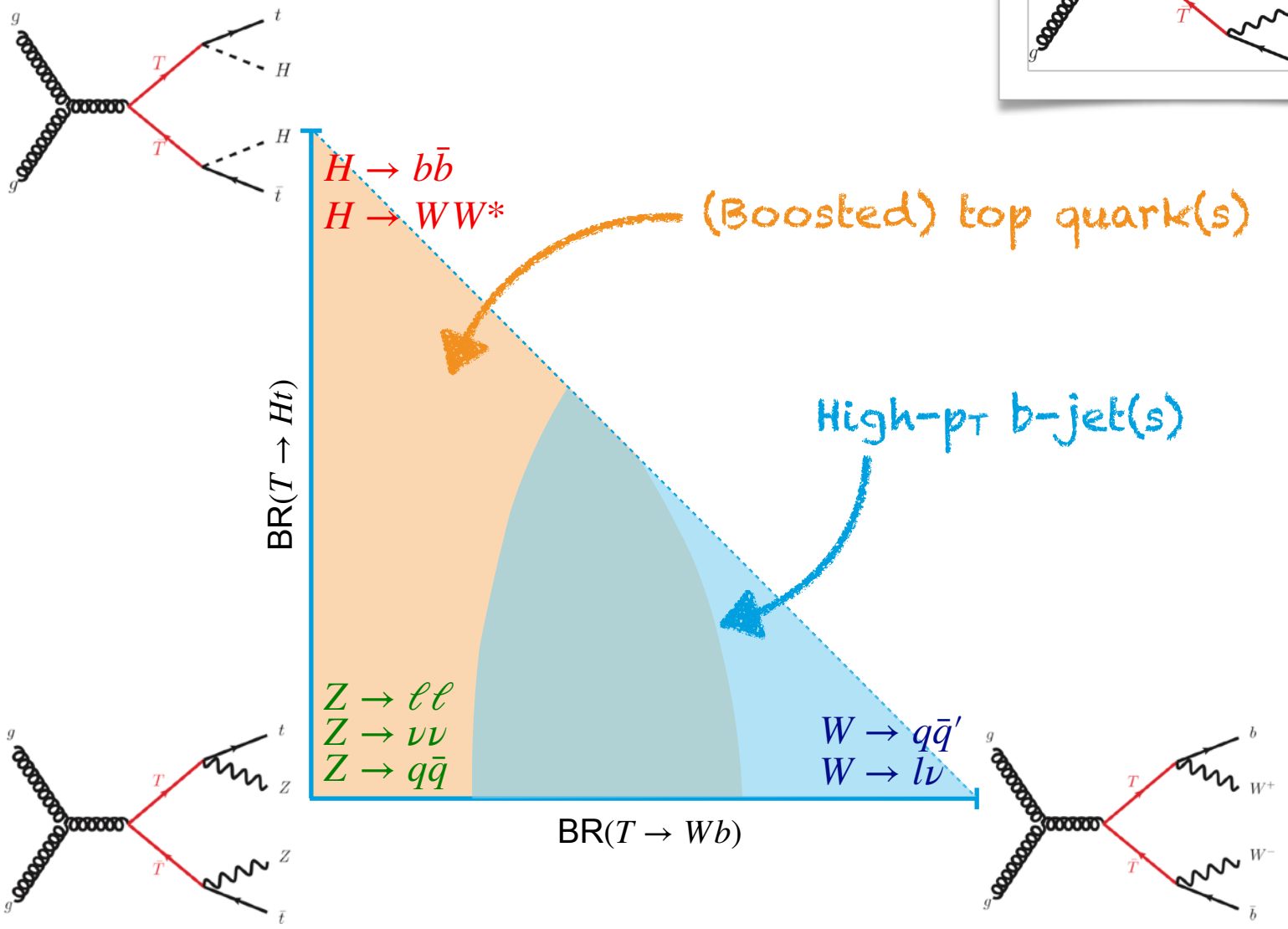




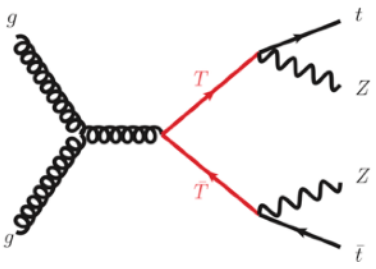
Pair-production searches

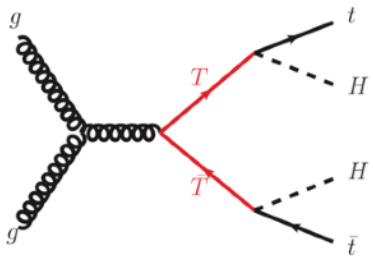
Decay configurations

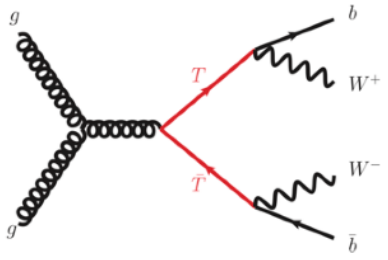




Pair-production searches





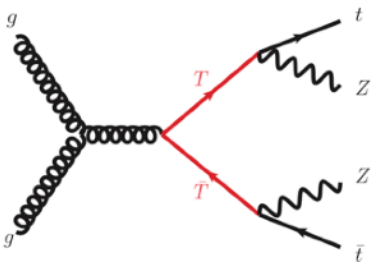


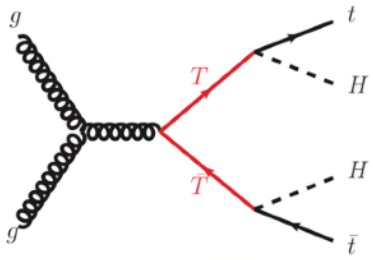
≥ 2 leptons ?

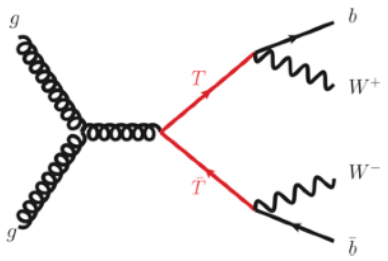
= 1 lepton ?

= 0 lepton

Pair-production searches







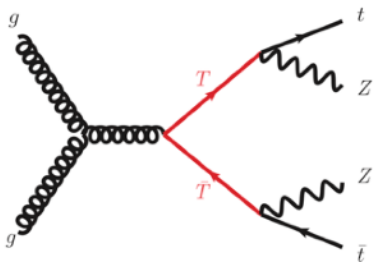
≥ 2 leptons ? → Yes → OS lepton pair coming from a $Z \to \ell\ell$? → Yes → *"Z(ll)t/b+X"*

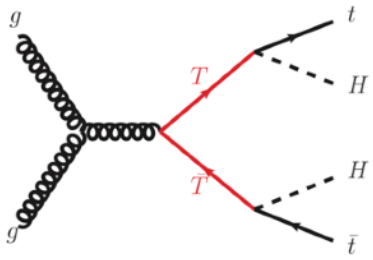
No

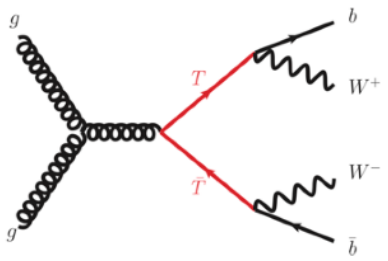
= 1 lepton ?

= 0 lepton

Pair-production searches







≥ 2 leptons ? — Yes → OS lepton pair coming from a $Z \to \ell\ell$? — Yes → *"Z(ll)t/b+X"*

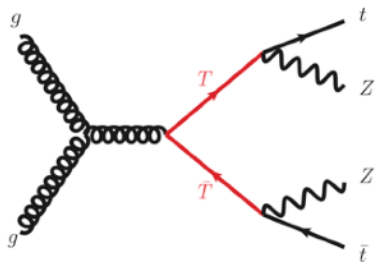
No

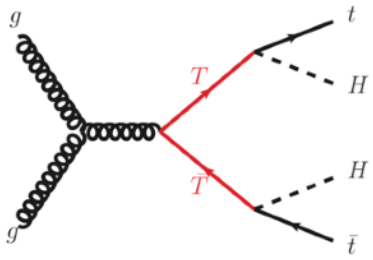
OS lepton pair coming from a $Z \to \ell\ell$? — No → 3 leptons or 2 same-charge leptons — Yes → *"trilepton/same-sign dilepton"*

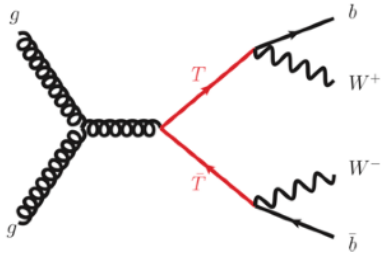
= 1 lepton ?

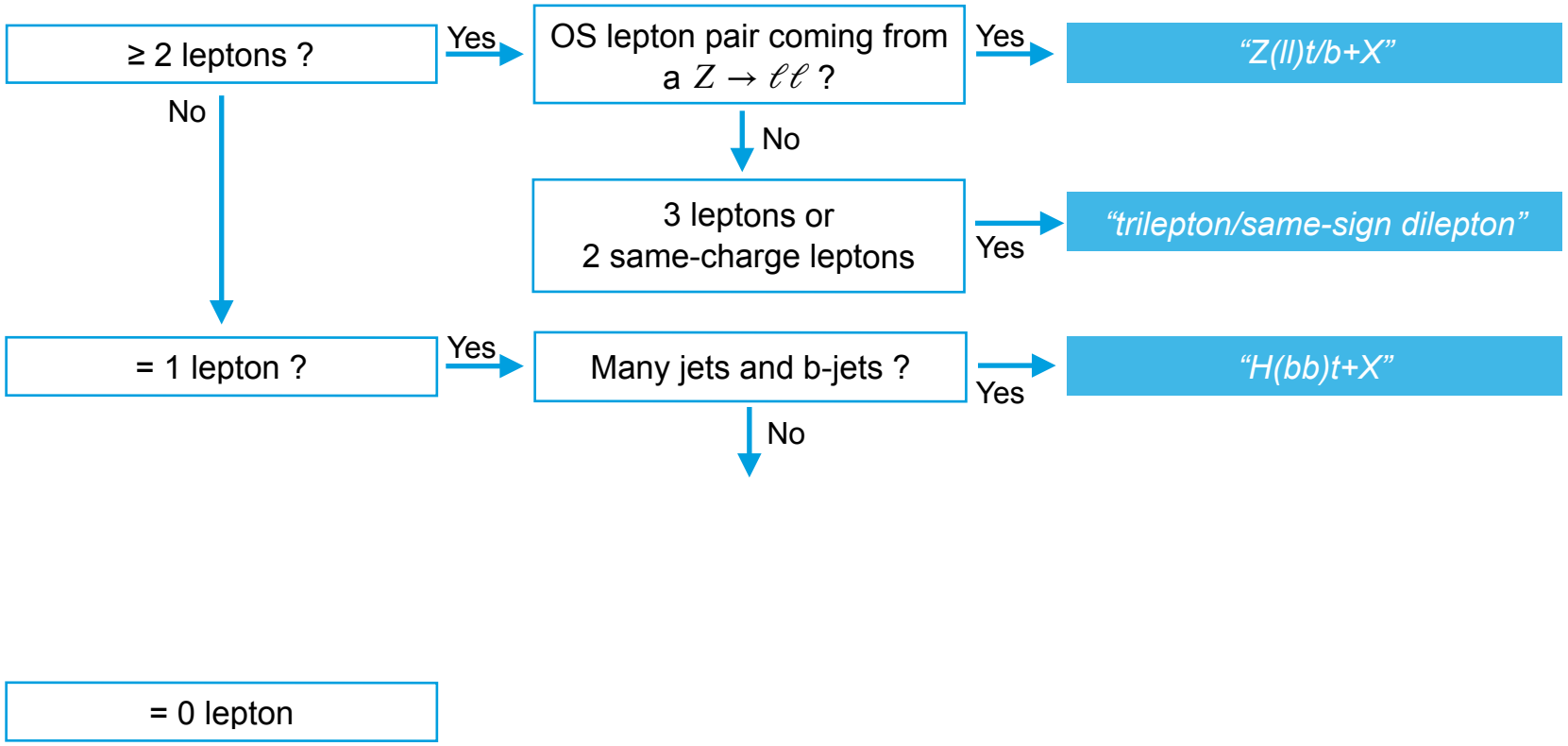
= 0 lepton

Pair-production searches

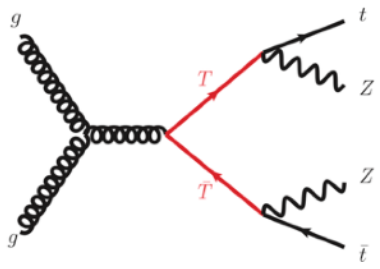


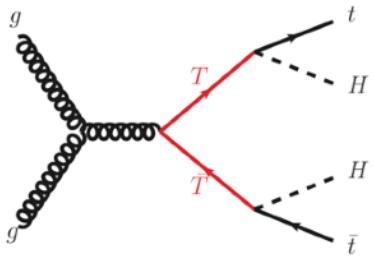


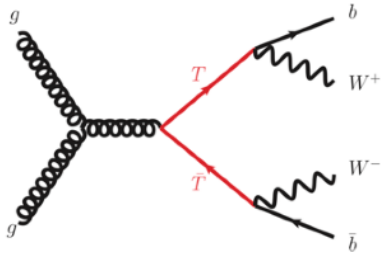


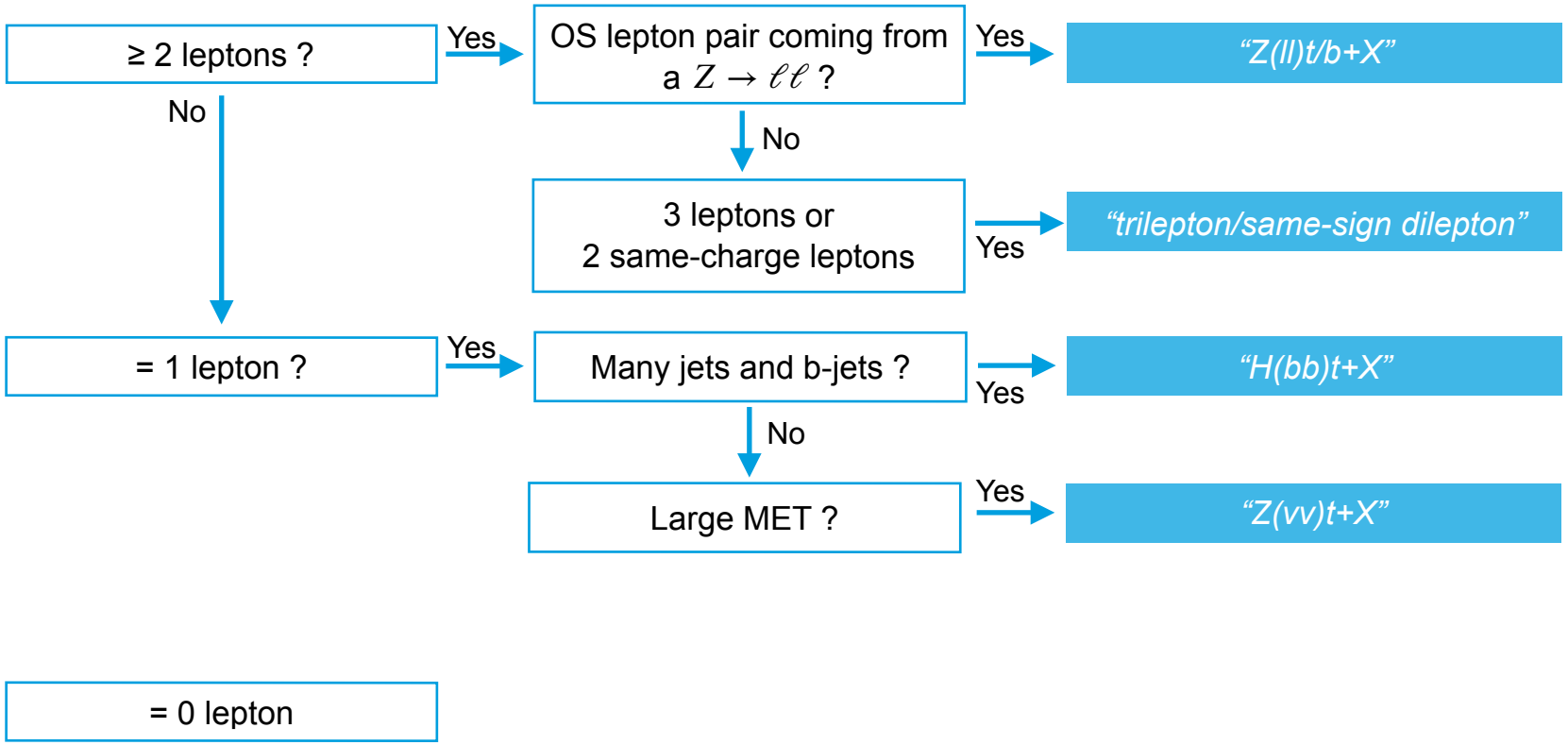


Pair-production searches

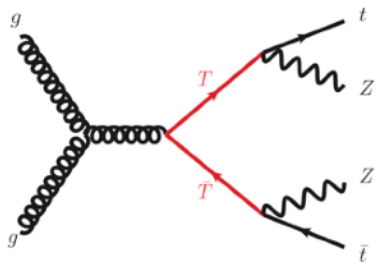


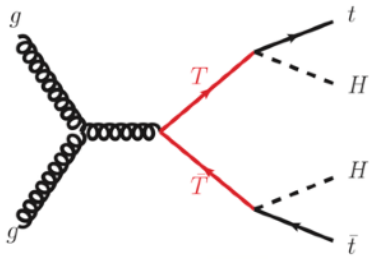


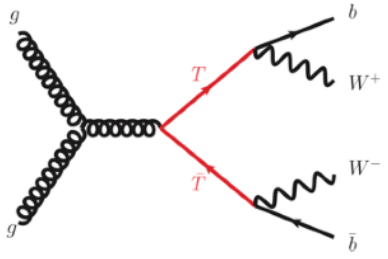


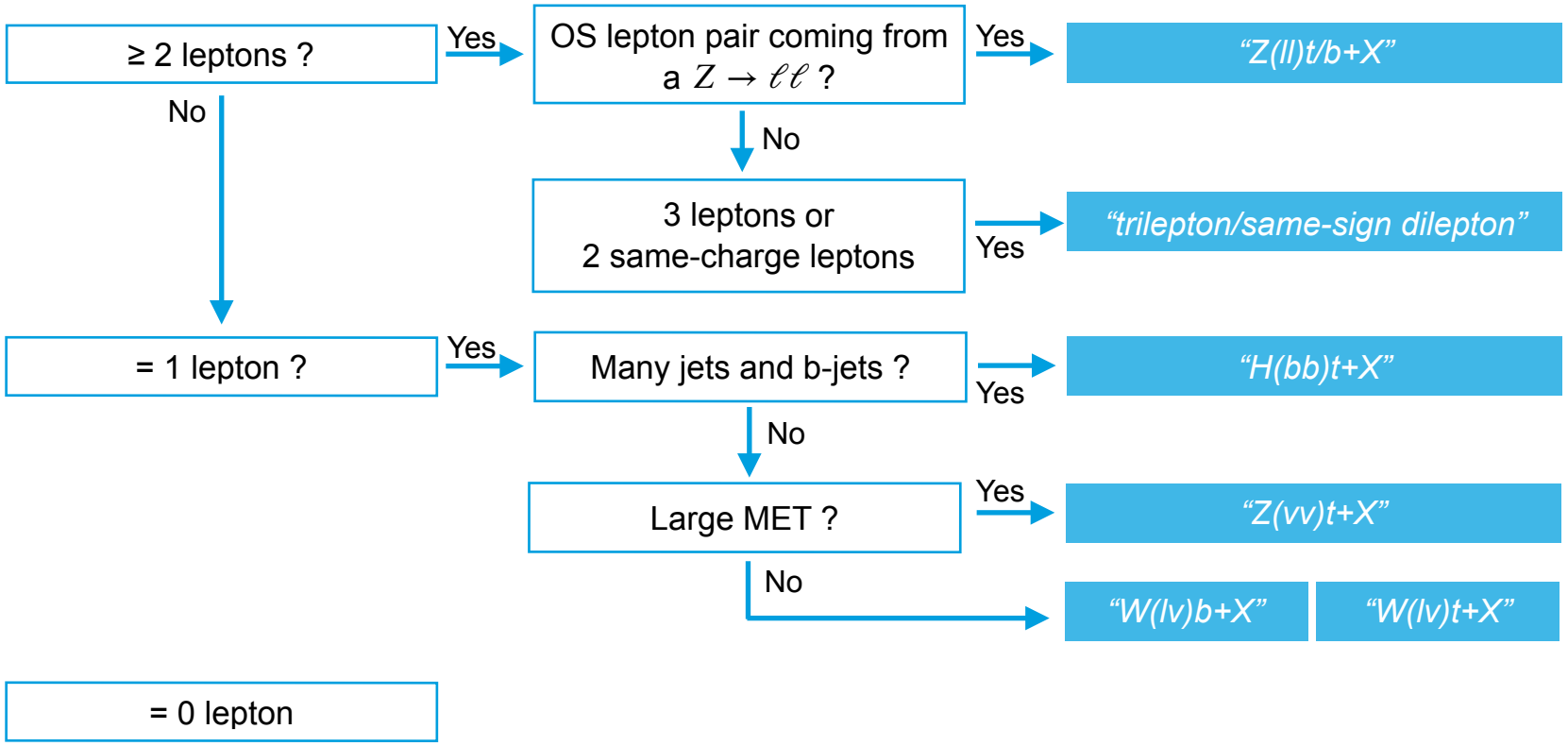


Pair-production searches

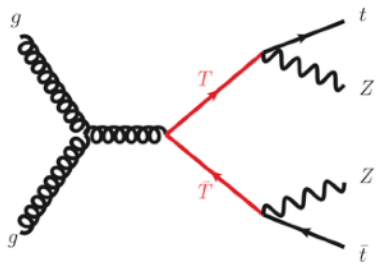


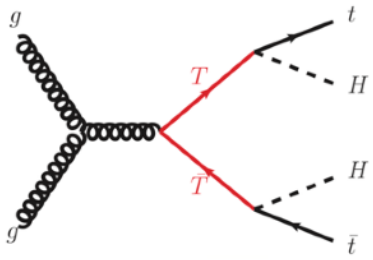


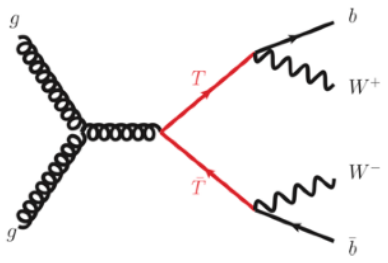


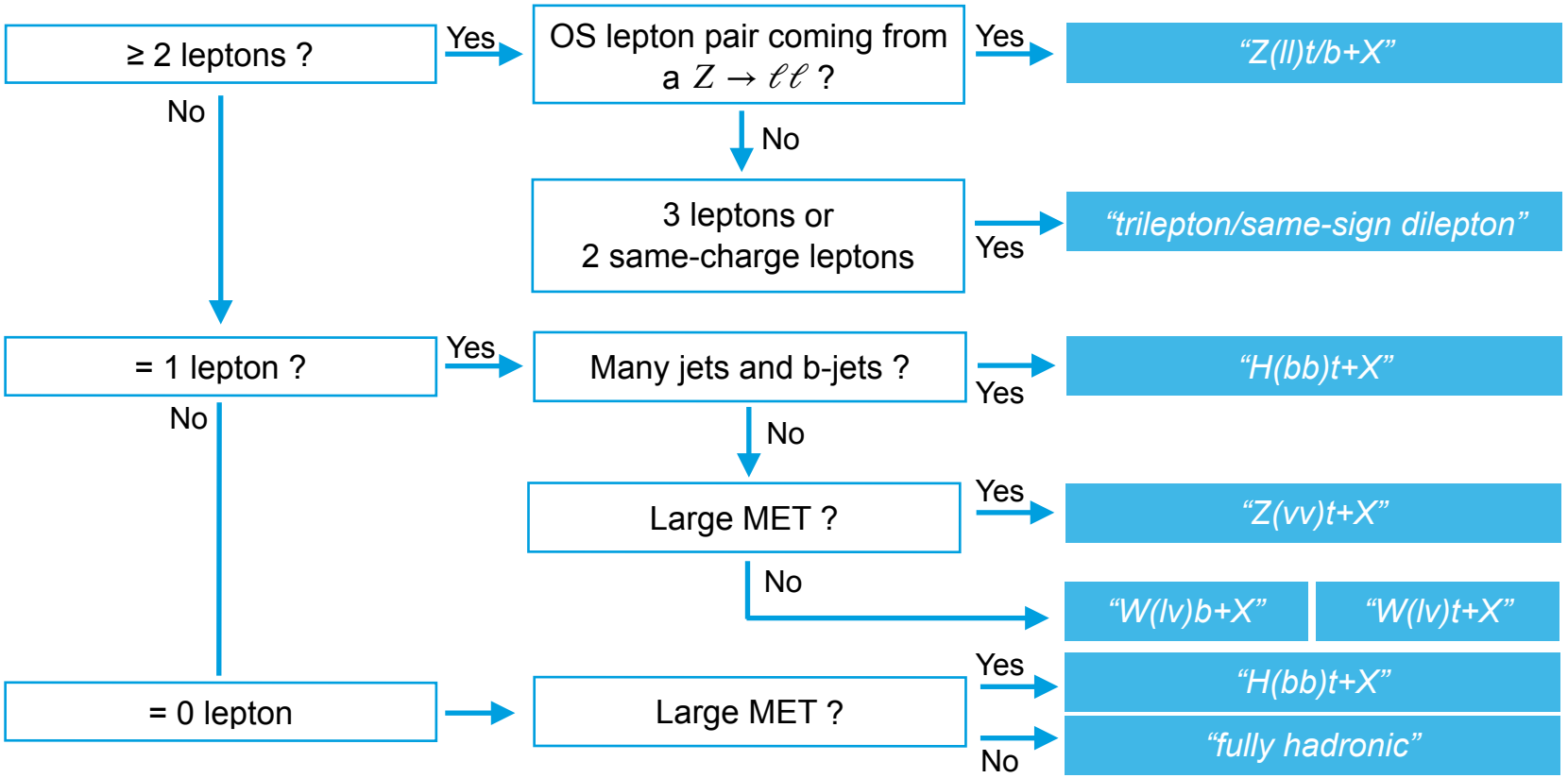


Pair-production searches





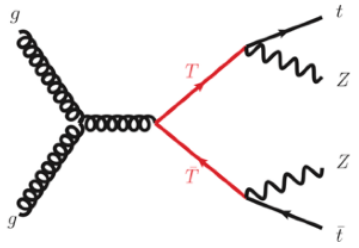




Pair-production searches

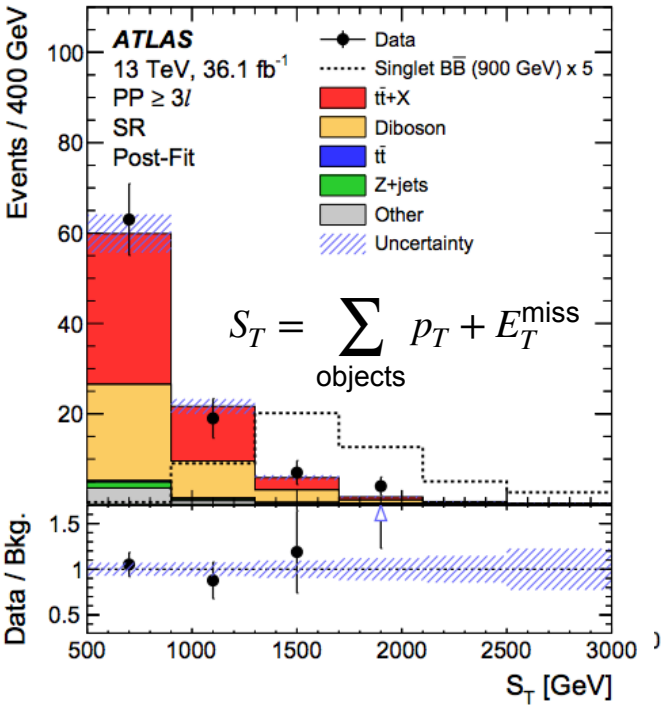
Zt/b+X

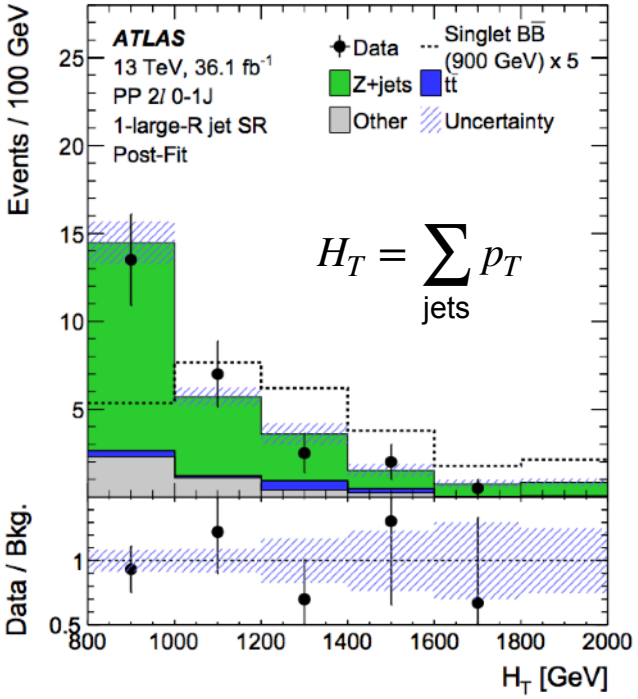
arXiv:1806.10555



- Selects **high-p_T** $Z \to \ell\ell$ events in dilepton / trilepton events
  - sub-channels depending on $N_{leptons}$ and $N_{boosted\ tops}$ (4 signal regions)
  - 3-lepton channel: **most sensitive**
- **Main backgrounds**: $t\bar{t}$+V, diboson, depending on SR (calibrated in data)

Highest purity channel

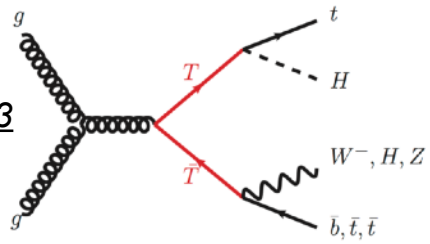




Pair-production searches

Same-sign leptons

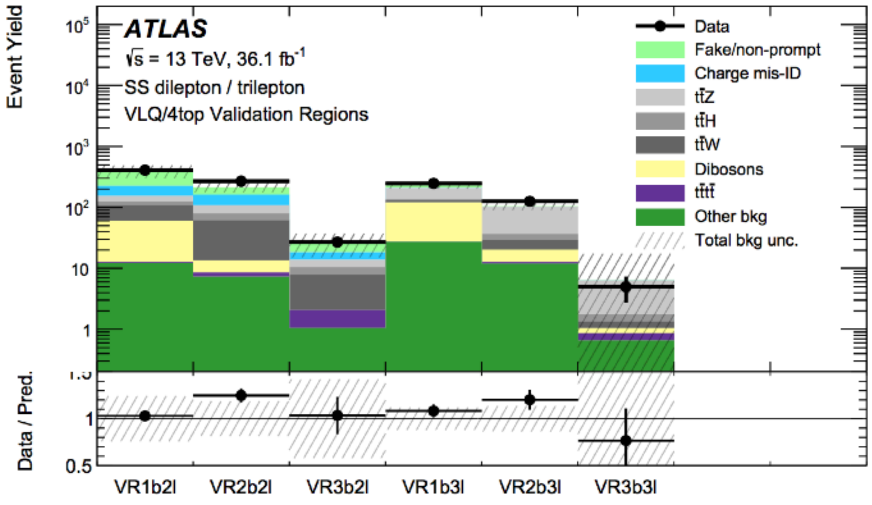
arXiv:1807.11883

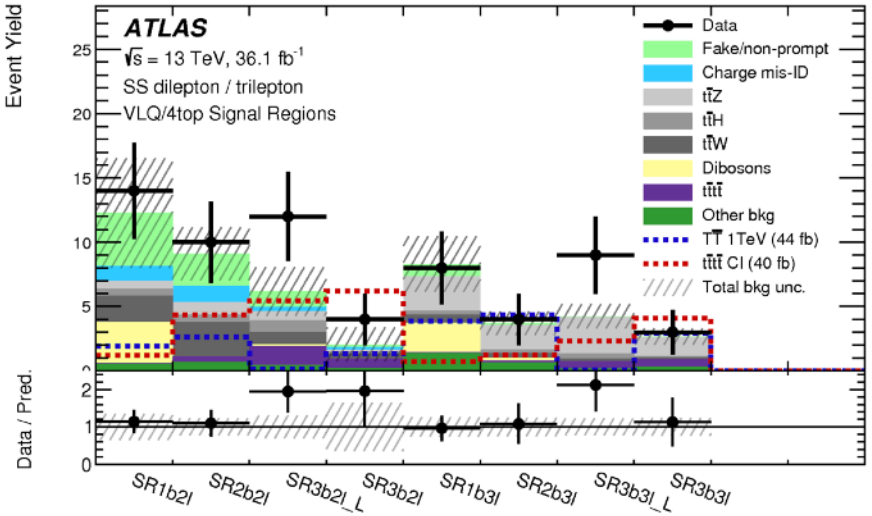


- Selects **same-sign dilepton** and non-Z **trilepton** events
  - typically from $T \to Ht \to WW^{*}\, t$ or $BB \to WtWt$ decays
  - signal regions: depending on $N_{leptons}$, $N_{b\text{-}jets}$, kinematic cuts

Background estimation

- **Main backgrounds**: fake/non-prompt leptons, charge mis-measurement, $t\bar{t}$+V
  - validated in dedicated regions





Pair-production searches

Z(νν)t+X

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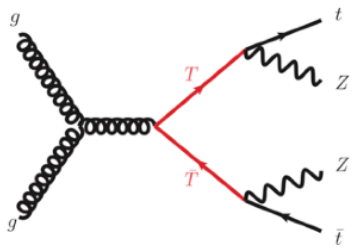
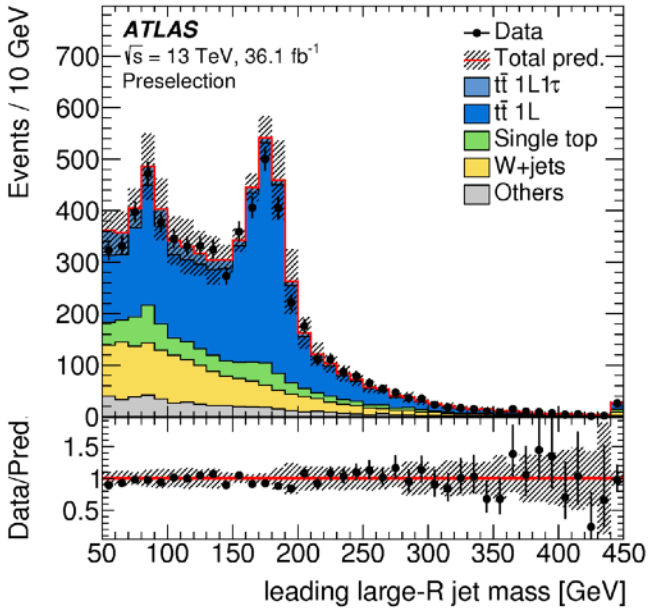
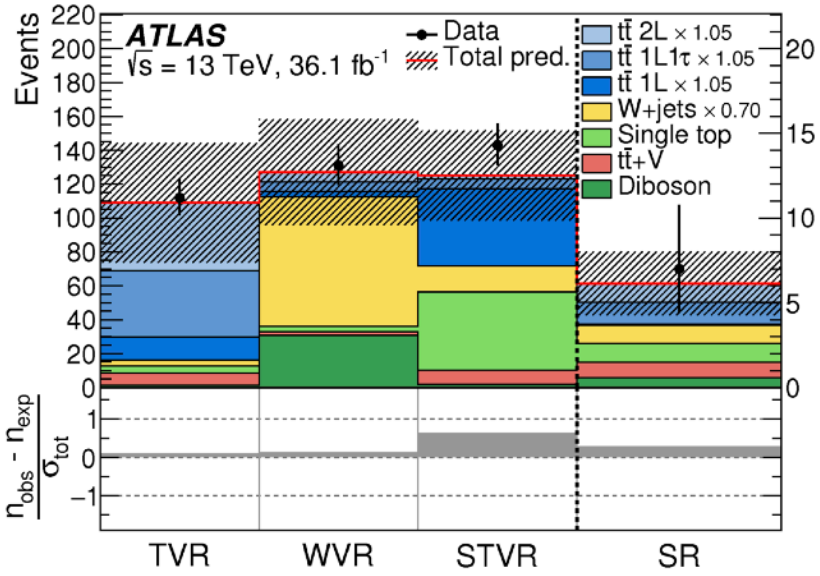


- Selects 1-lepton events with **large MET**
  - Selecting $T \to Z(\nu\nu)t$ events
  - **Jet-reclustering** to identify boosted top quarks

Hadronic top identification

- **Main backgrounds**: top background and W+jets (calibrated in data)

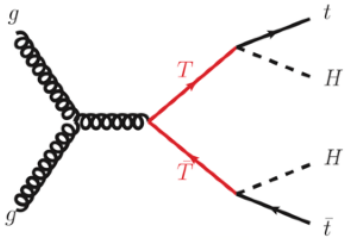




Pair-production searches

Ht+X

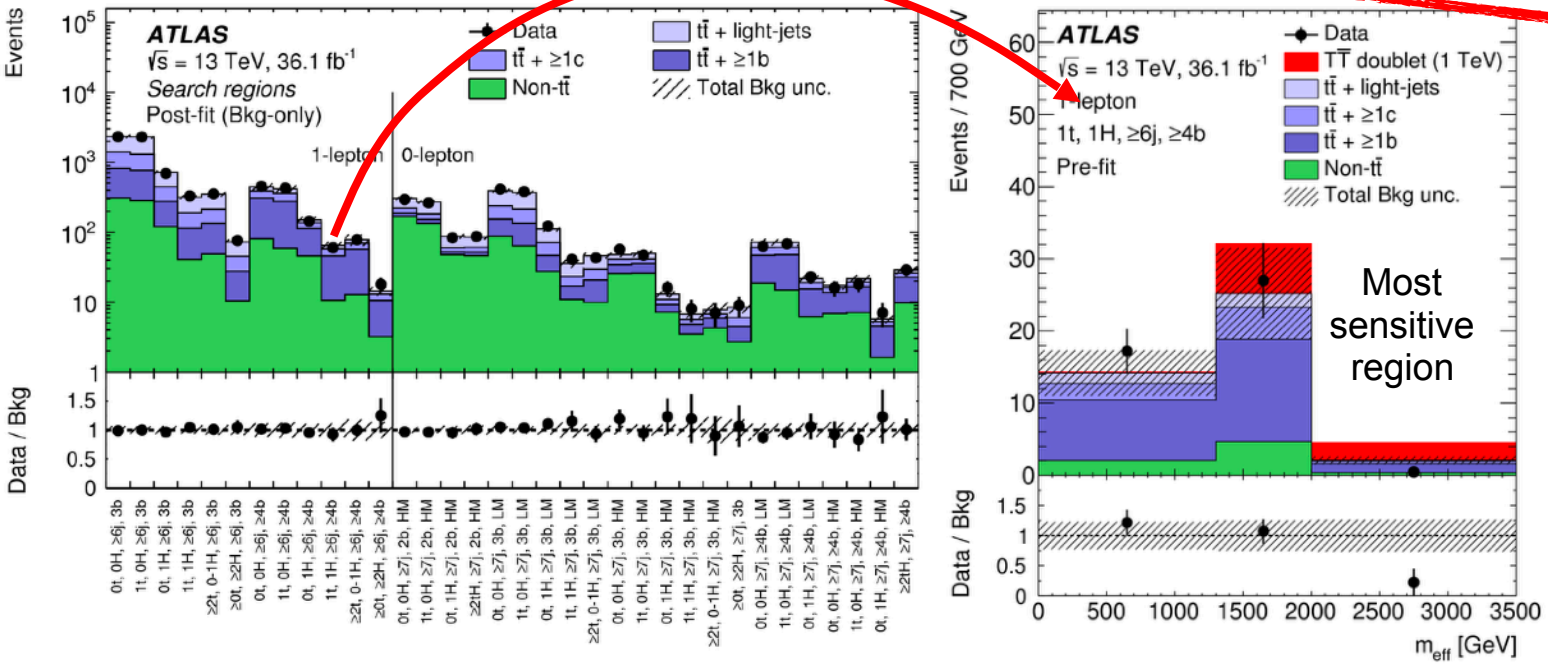
JHEP 07 (2018) 089



- Selects **high-p_T top quarks / Higgs bosons** in 1-lepton/0-lepton (high-MET) events
  - sub-channels depending on $N_{leptons}$, N_{tops}, N_{Higgs}, $N_{b\text{-}jets}$ (34 signal regions)

- **Main background:** $t\bar{t}$ + ≥1b (calibrated in data)

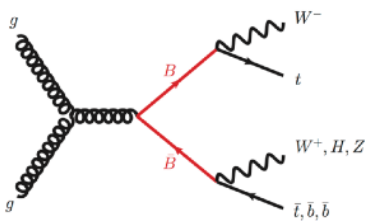
Background estimation



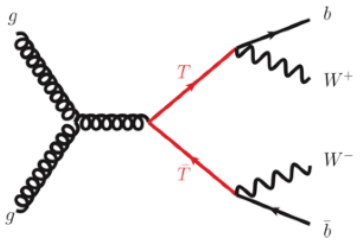
$$m_{\text{eff}} = \sum_{\text{objects}} p_T + E_T^{\text{miss}}$$

Pair-production searches

Wb/t+X



JHEP 08 (2018) 048



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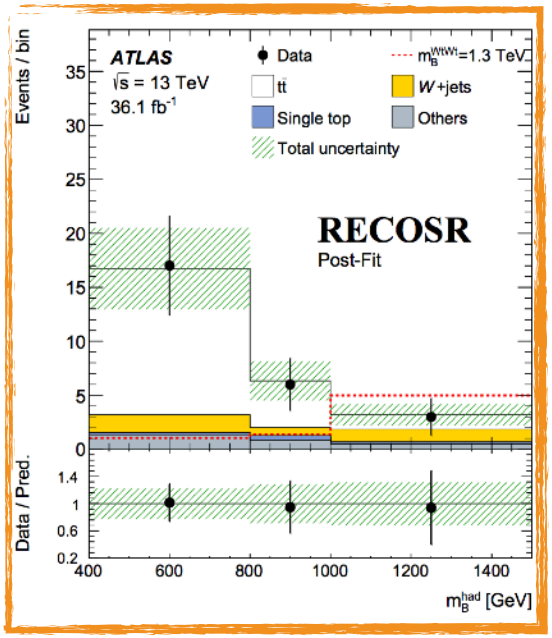
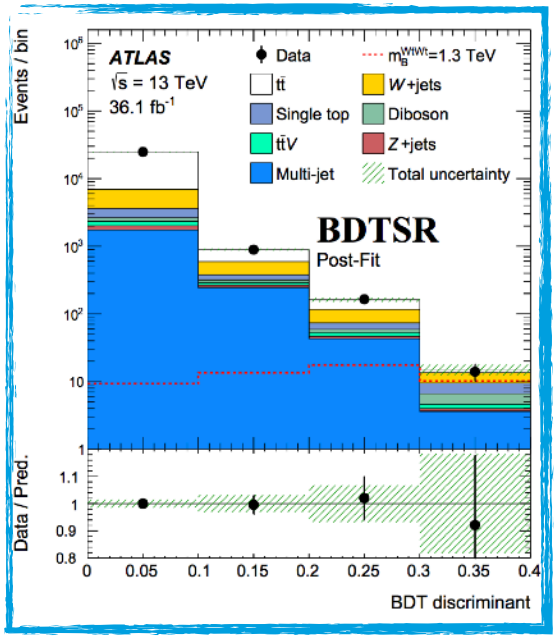
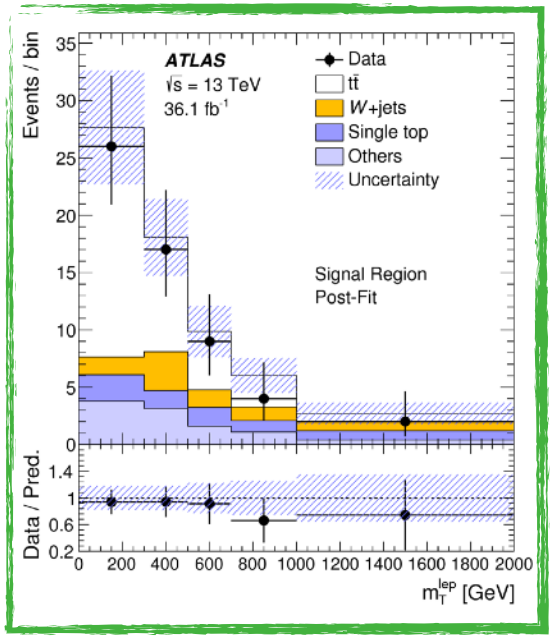
- Select 1-lepton events with **high-p_T hadronic W bosons**
  - BB → Wt+X: complex final state → **full reconstruction** otherwise **MVA strategy**
  - TT → Wb+X: reconstruct $T \to Wb \to l\nu b$ mass
- **Main background**: $t\bar{t}$ (calibrated in data)

Event reconstruction



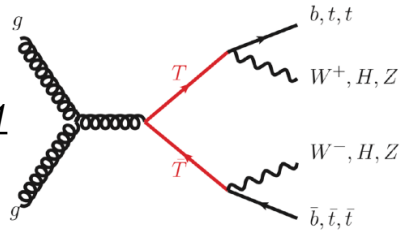




Pair-production searches

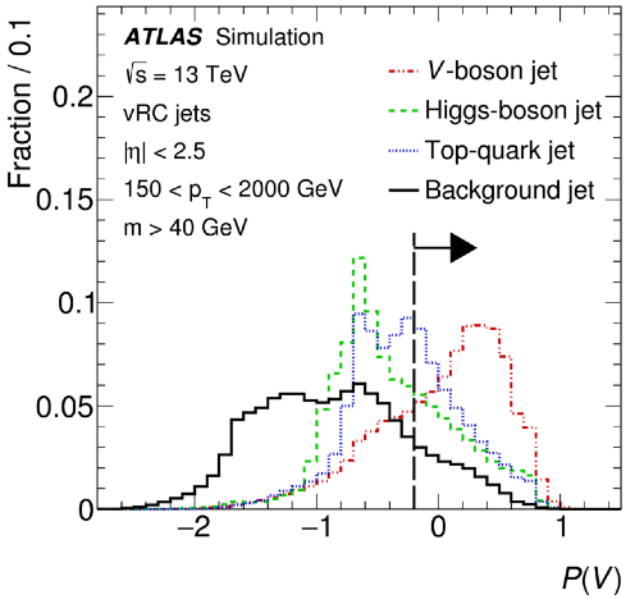
Fully-hadronic

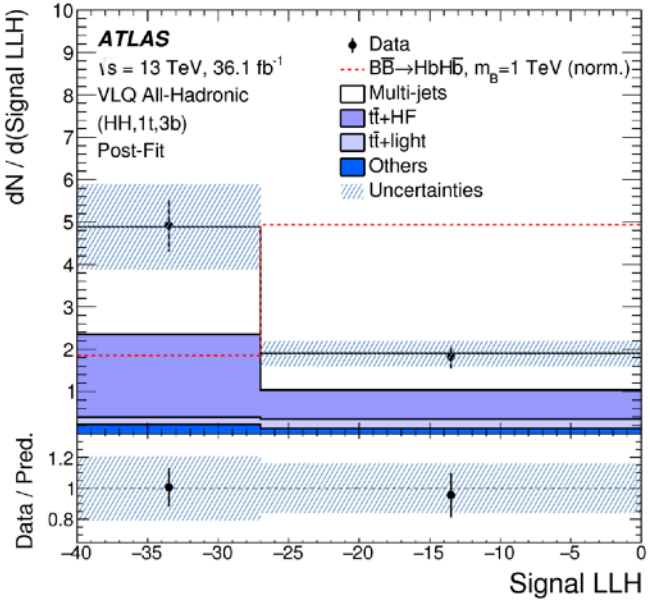
arXiv:1808.01771



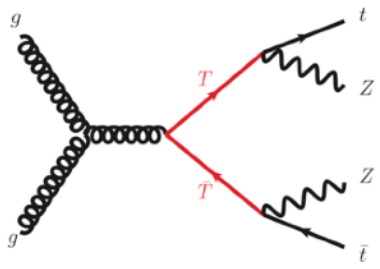
- Selects **0-lepton events** with **high-p_T** top quarks or V/H bosons
  - sub-channels depending on boosted object content (12 channels)
- **Main background**: multi-jet (data-driven)
- Boosted object tagging: **multi-class DNN classifier** on vRC jets
  - using of jet and subjet kinematic properties
- Final discriminant: **Matrix Element Method**

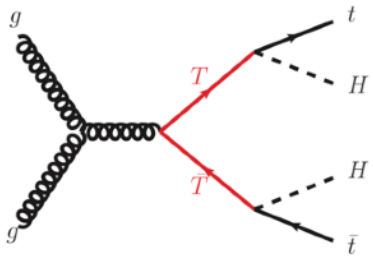
Background suppression

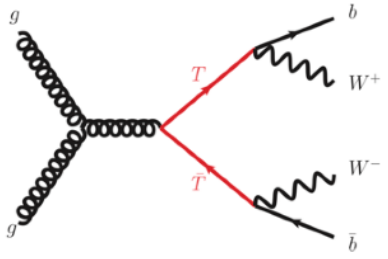


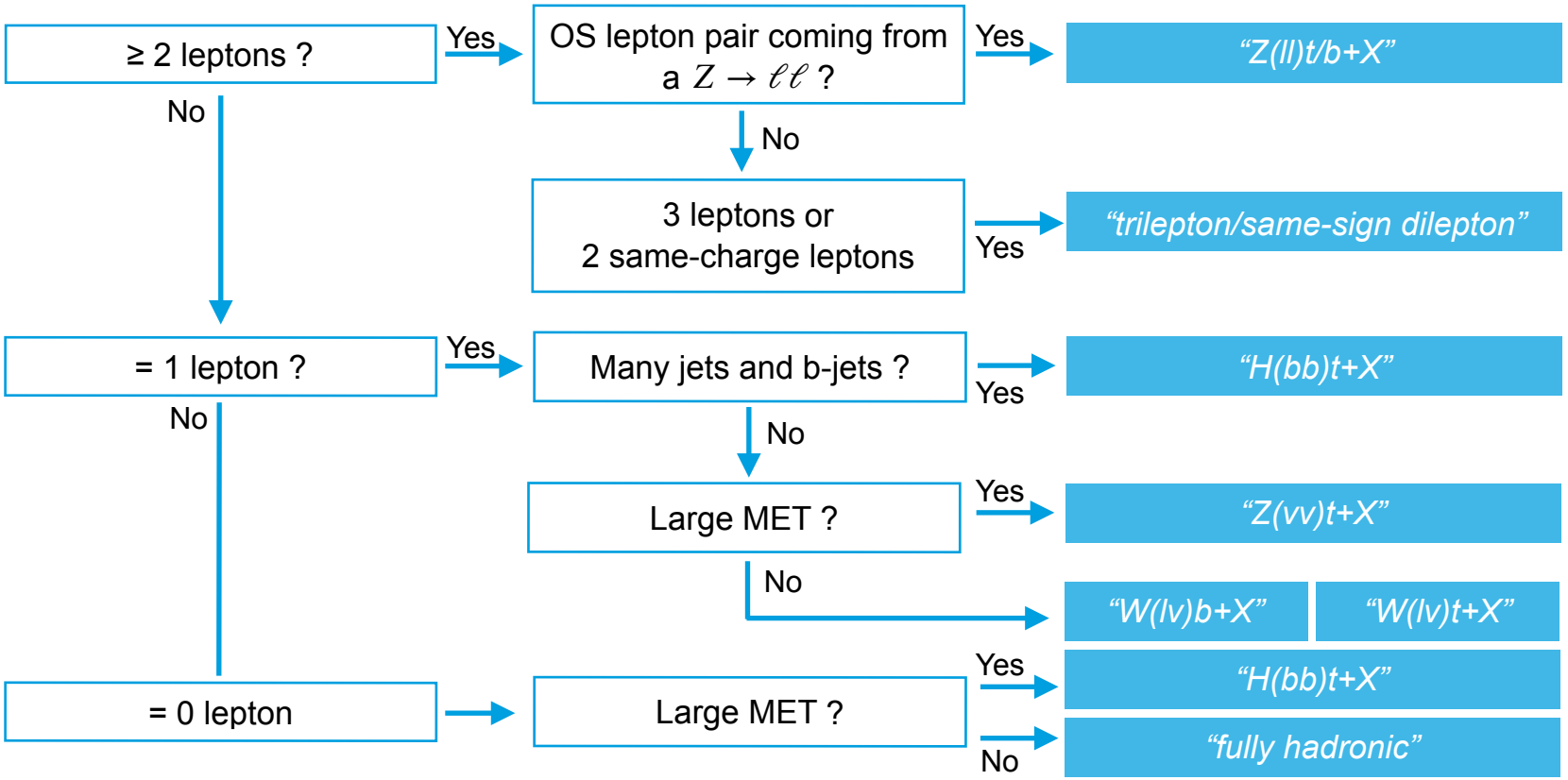


Pair-production searches





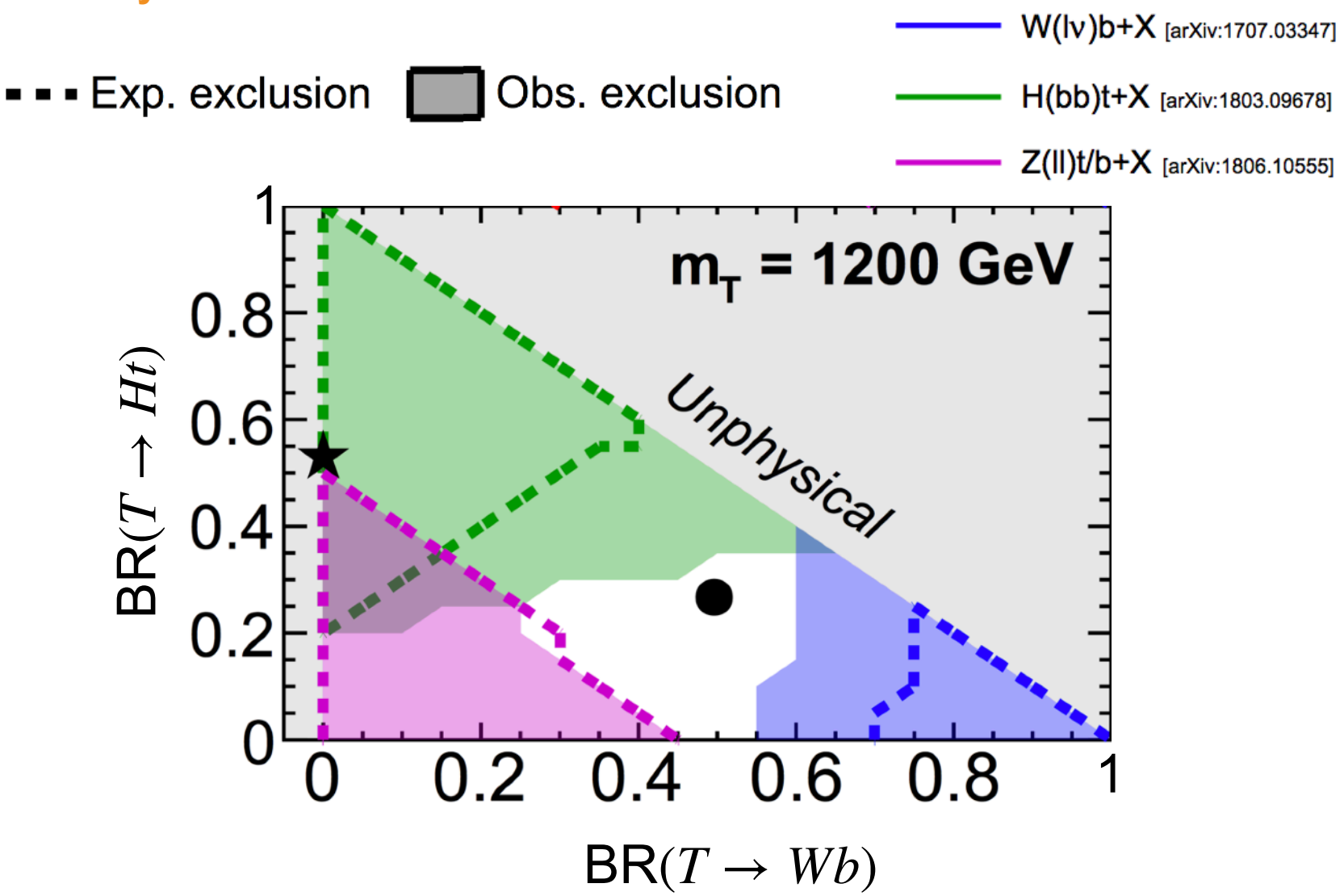




Pair-production searches

Sensitivity

arXiv:1808.02343

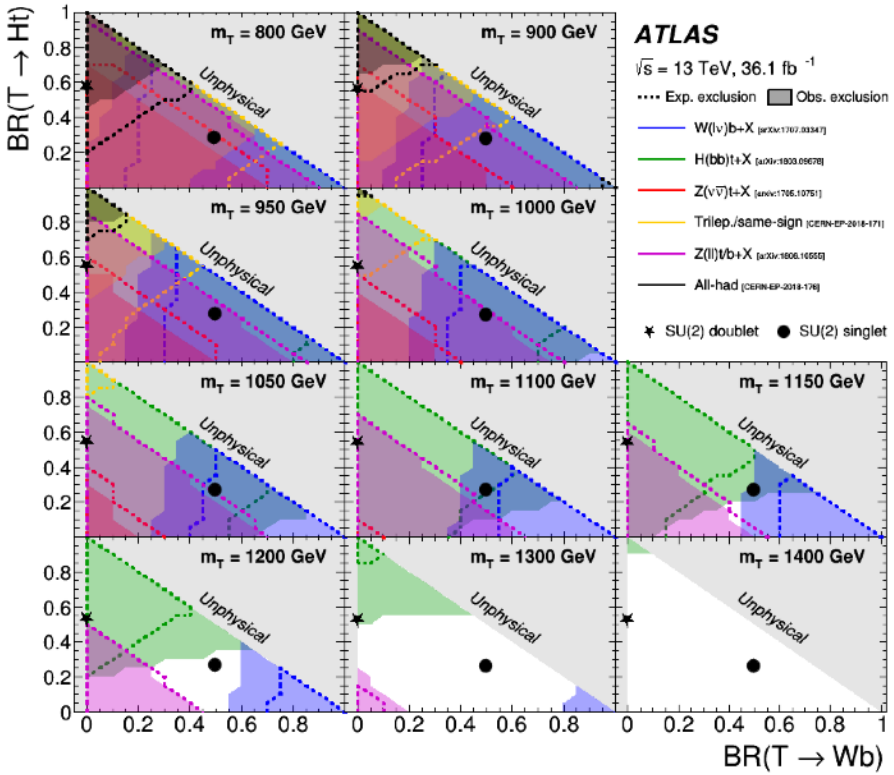


Pair-production searches

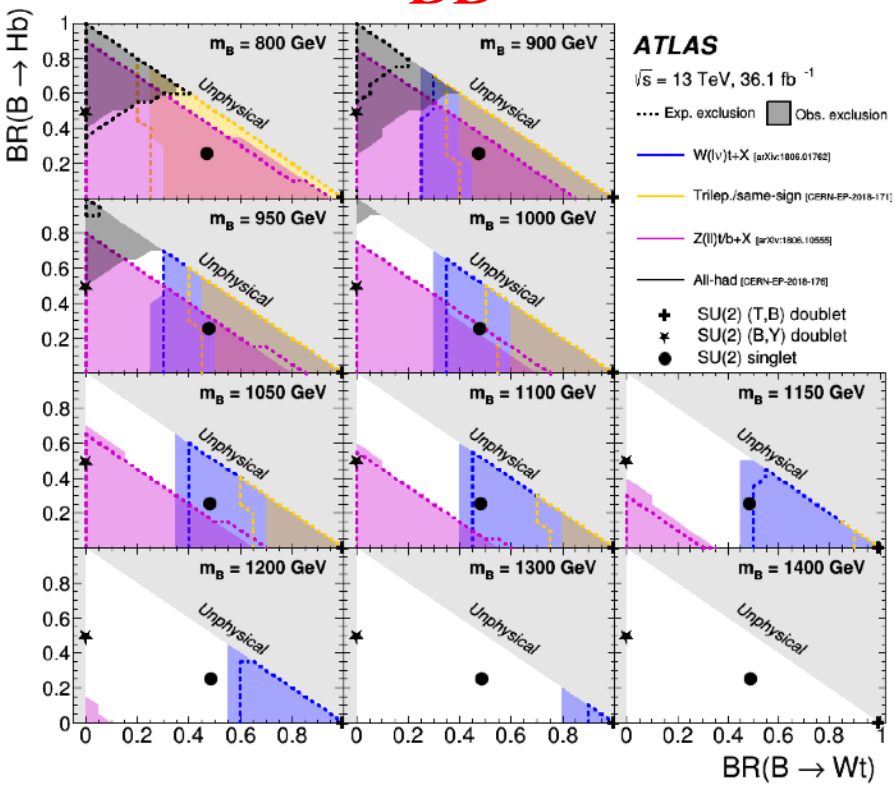
arXiv:1808.02343

Summary plots

$T\bar{T}$



$B\bar{B}$



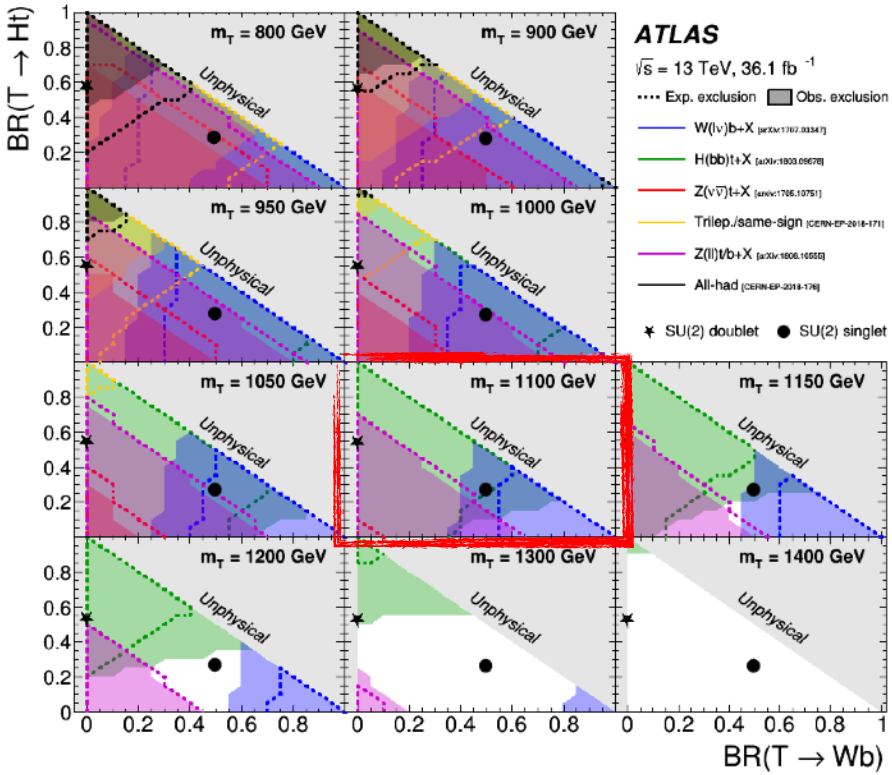
- **Excellent complementarity** between analyses: most parameter space “covered”
- Non-overlapping analyses ➔ **combined interpretation**

Pair-production searches

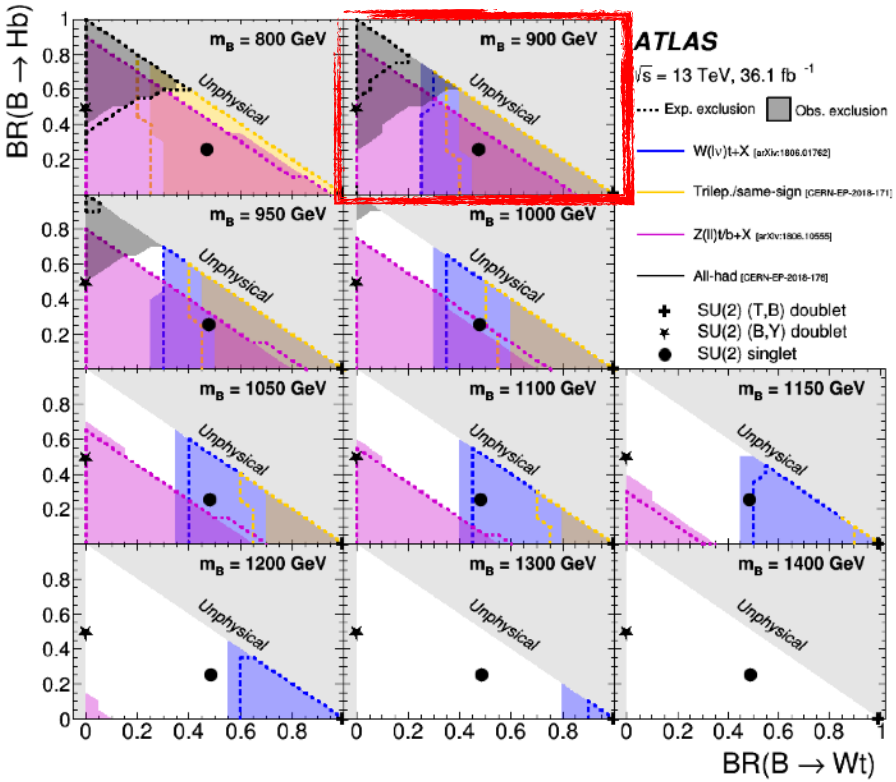
arXiv:1808.02343

Summary plots

$T\bar{T}$



$B\bar{B}$



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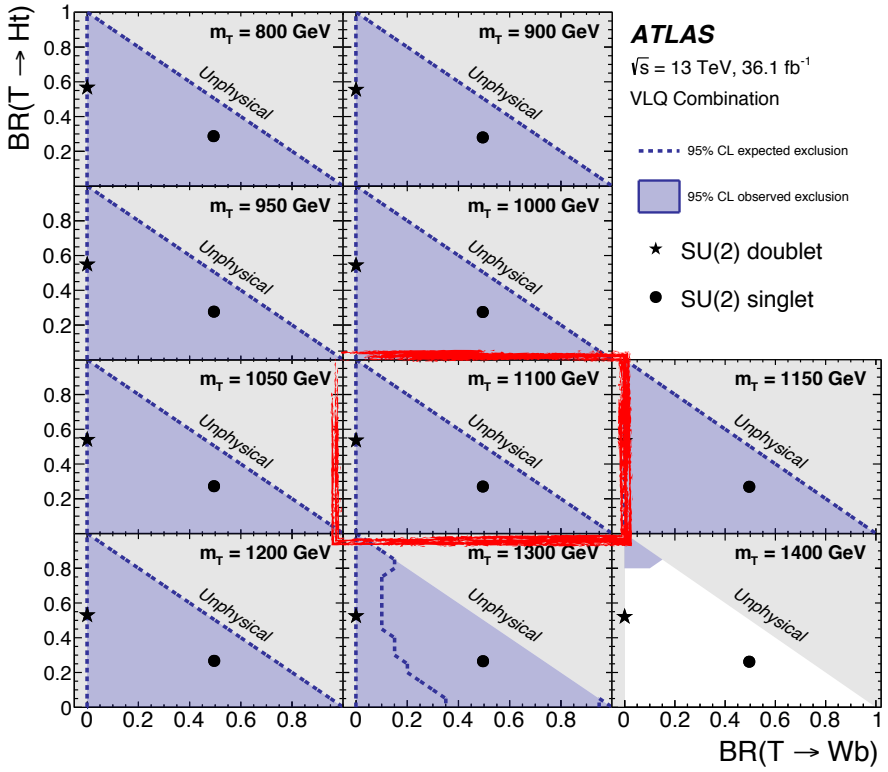
- Non-overlapping analyses ➔ **combined interpretation**

Pair-production searches

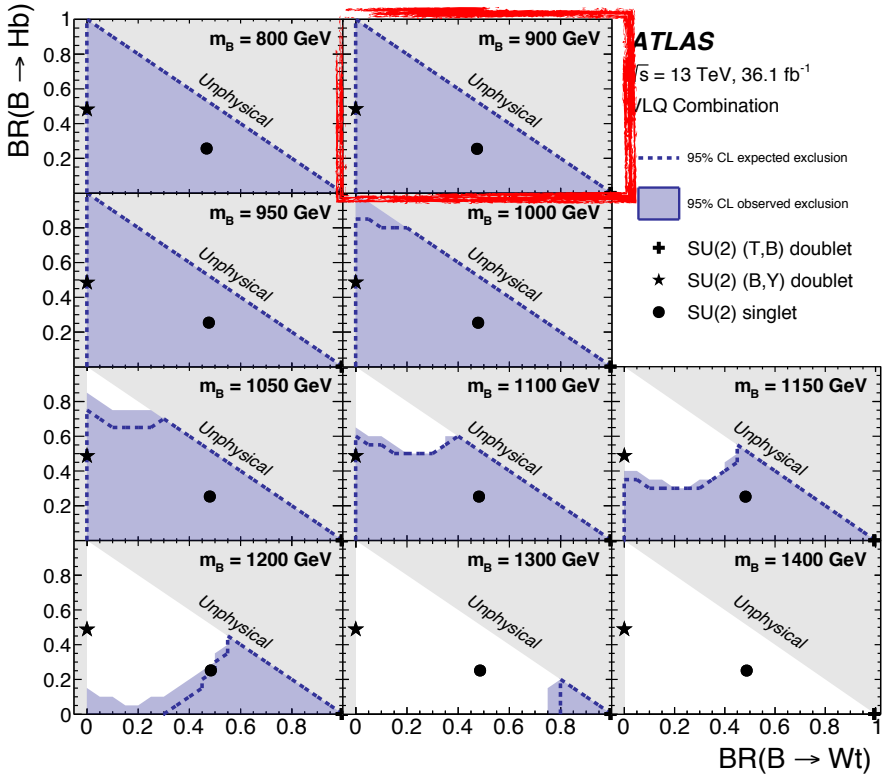
arXiv:1808.02343

Combination

$T\bar{T}$



$B\bar{B}$

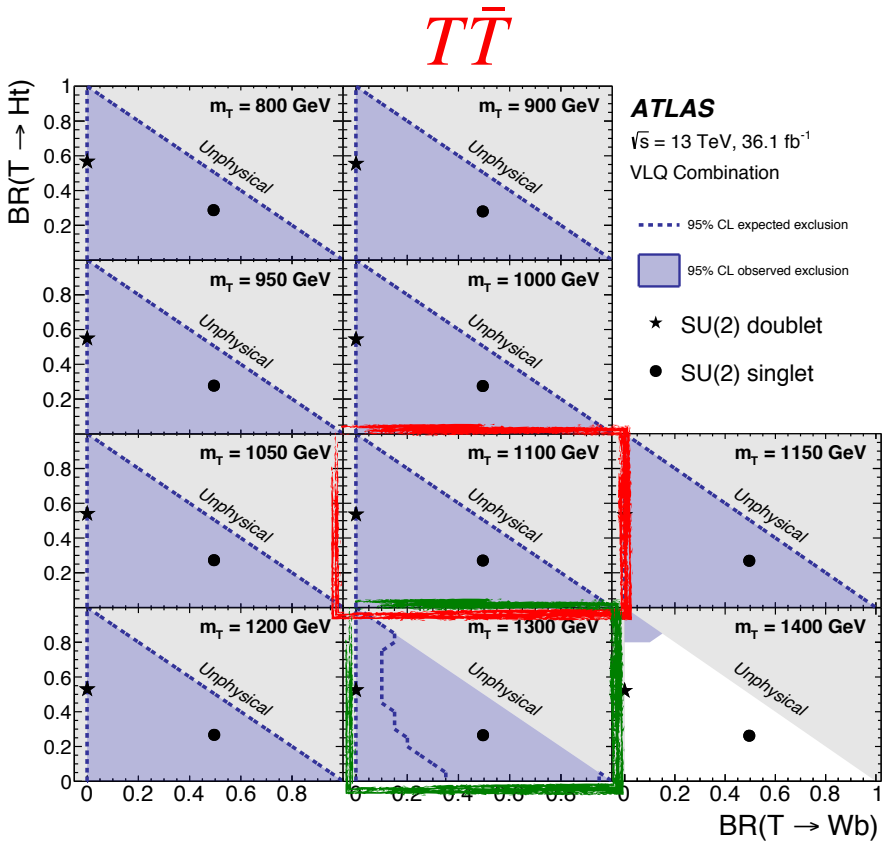


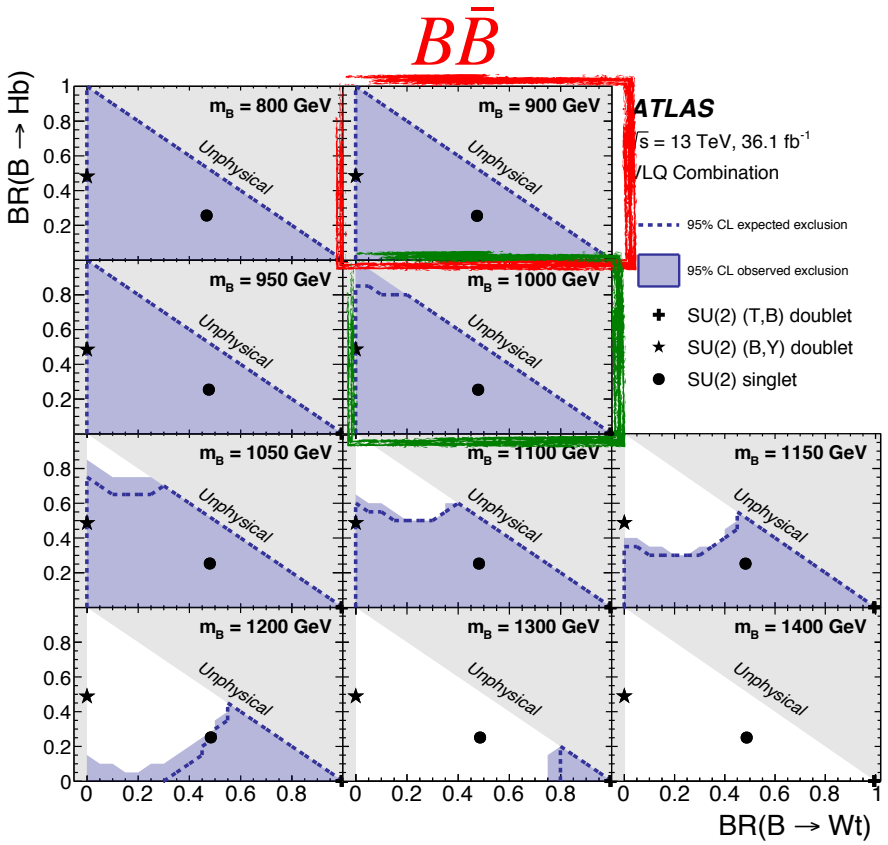
- **Strong sensitivity gain !**
- **No signs of low-mass VLQs** → check high-mass → use of **single production**

Pair-production searches

arXiv:1808.02343

Combination



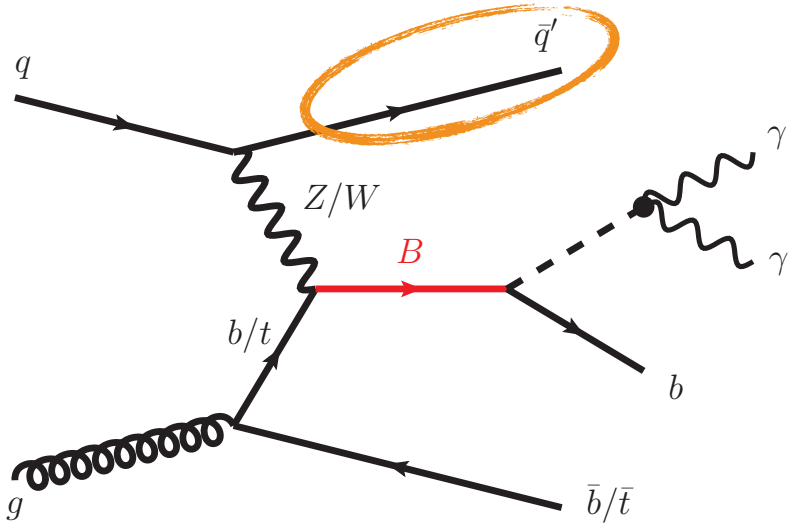


- **Strong sensitivity gain !**
- **No signs of low-mass VLQs** → check high-mass → use of **single production**

Single-production searches

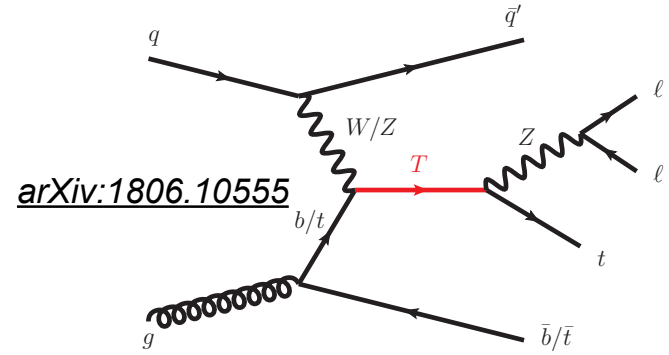
Topologies

- **Event properties** different from pair-production
  - Less busy final state
  - Presence of a **forward jet**
- Interpretation depends on **coupling to SM particles**
  - **Couplings varied** to provide more “model independent” constraints
  - Set of **couplings fixed**



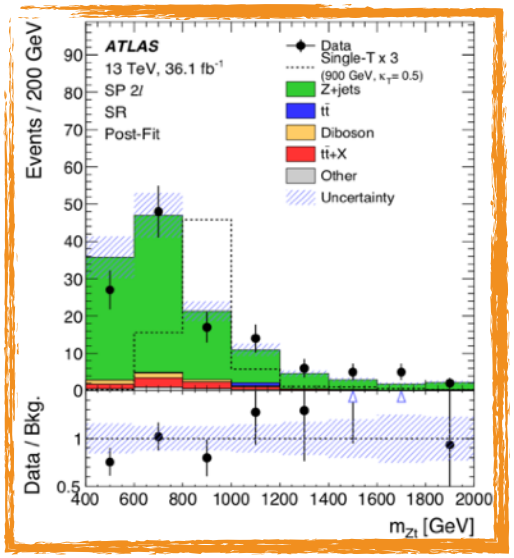
Single-production searches

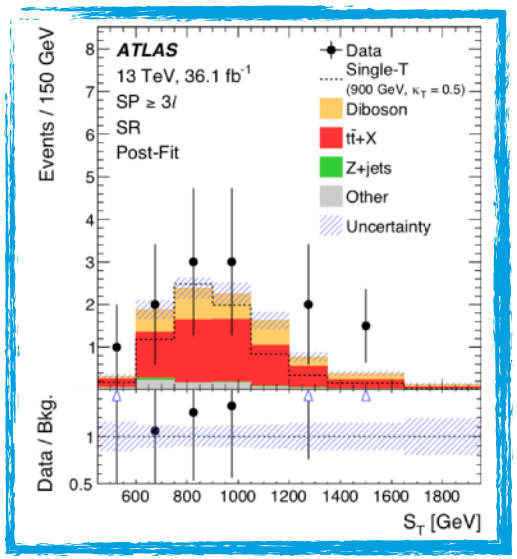
Single $T/B \to Z(\ell\ell)t/b$



arXiv:1806.10555

- Selects **high-p_T** $Z \to \ell\ell$ events
  - *dilepton*: presence of a **top-tagged jet** → **full VLQ reconstruction**
  - *trilepton*: ambiguity in reconstruction → **use kinematic variable**
- Main background: Z+jets or $t\bar{t}$+V

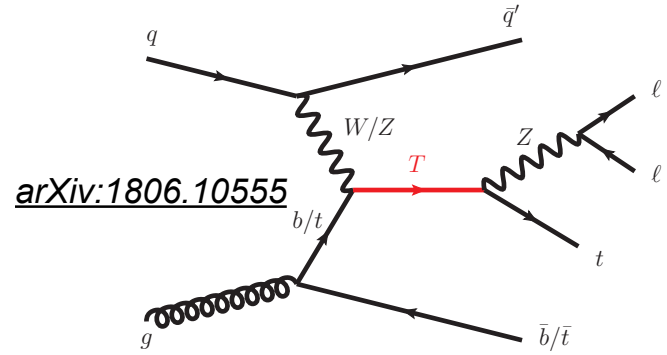




$$S_T = \sum_{\text{objects}} p_T + E_T^{\text{miss}}$$

Single-production searches

Single $T/B \to Z(\ell\ell)t/b$



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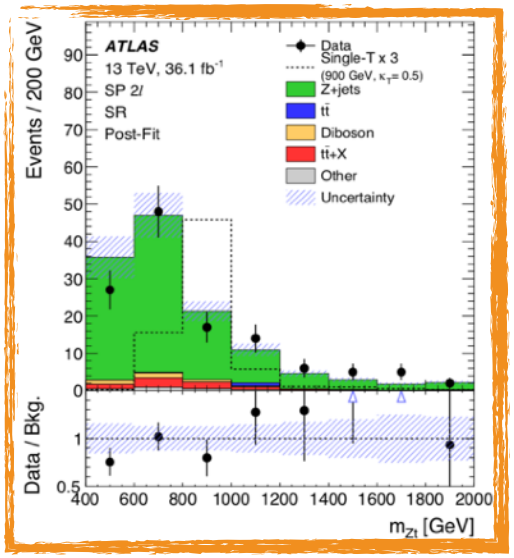
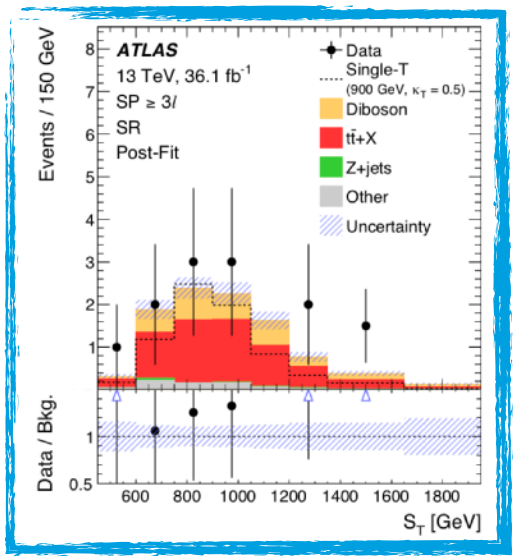
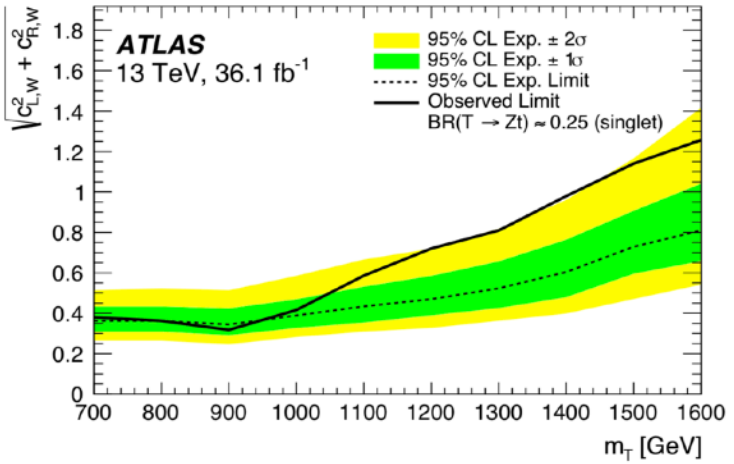
- Main background: Z+jets or $t\bar{t}$+V
- Limits set for variable coupling assumptions → **model-independent interpretation**



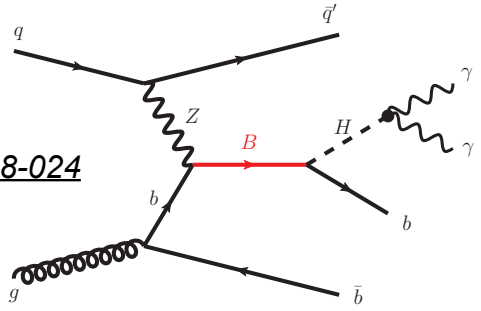




$$S_T = \sum_{\text{objects}} p_T + E_T^{\text{miss}}$$

Single-production searches

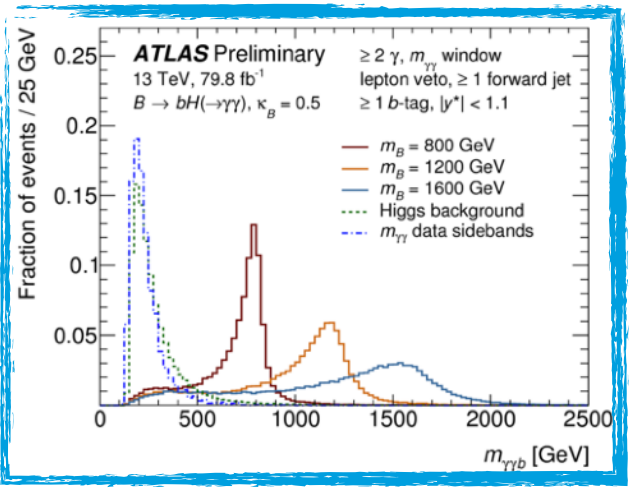
Single $B \to Hb \to \gamma\gamma b$

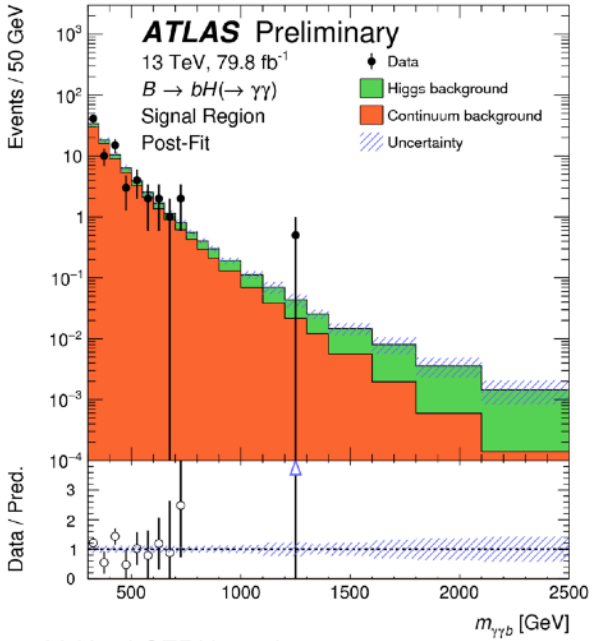


ATLAS-CONF-2018-024

- Selects **events with two photons** originating from Higgs + **b-jet**
  - Use $m_{\gamma\gamma b}$ to **reconstruct vector-like B mass**
- Main background: continuum $\gamma\gamma$ + jets (estimated from data in sidebands)

With 2017 data!

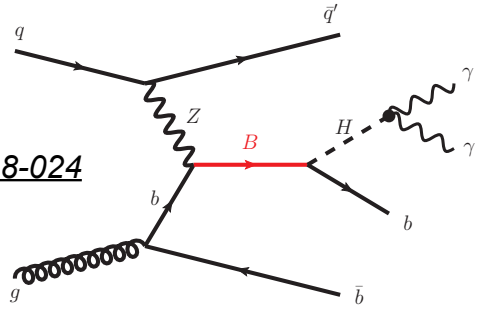




Single-production searches

Single $B \to Hb \to \gamma\gamma b$

ATLAS-CONF-2018-024



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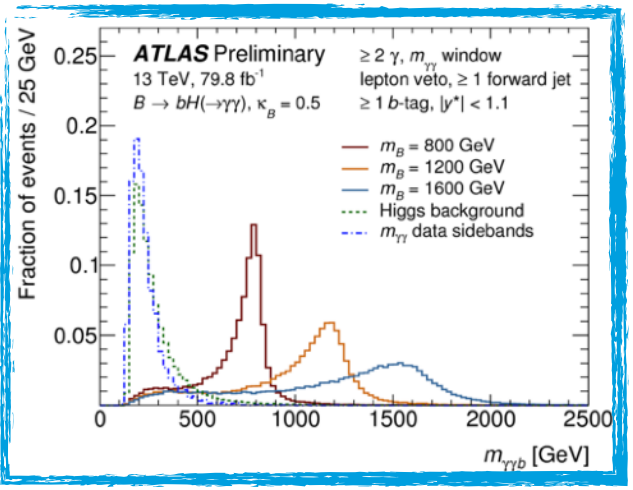
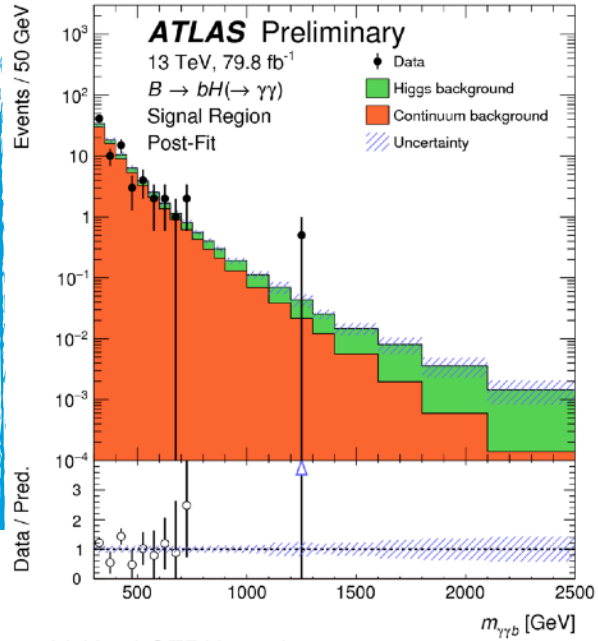
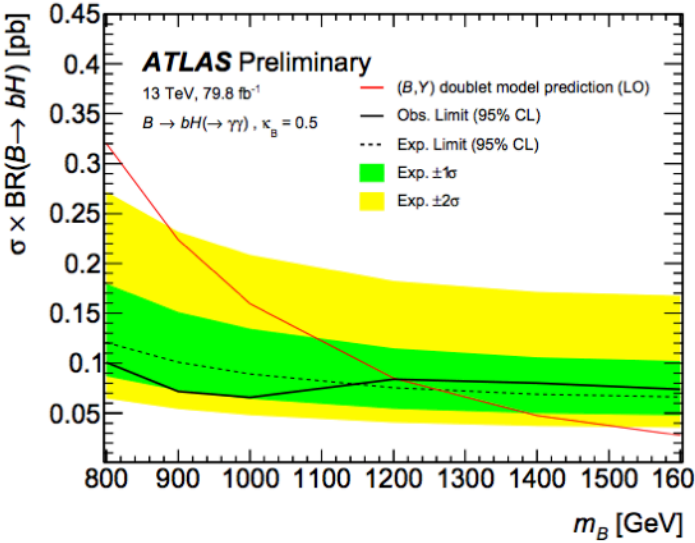
- Main background: continuum $\gamma\gamma$ + jets (estimated from data in sidebands)
- Limits set with **fixed coupling**

With 2017 data!





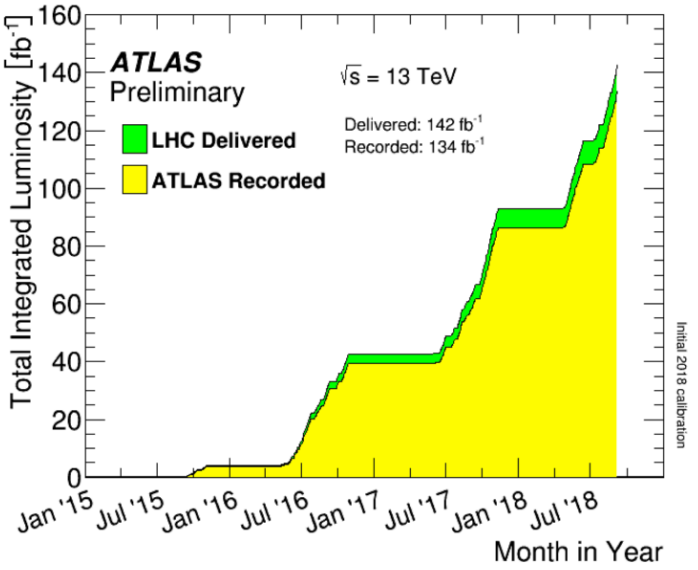


VLQ searches: next steps ?

- For all VLQ searches: sensitivity **limited by statistics**
- Excellent coverage in **pair-production** ➔ low-mass VLQs strongly constrained
  - Combination significantly extends sensitivity !
- Single-production **more and more relevant**: several studies underway !
  - Quite challenging to interpret in a “model-independent” manner
- More complete models ? Exotics decays ?

Summary

- Top quark: ideal to **probe several new theories extending Standard Model**
- **Heavy resonances** decaying to top quarks and **vector-like quarks**
  - Thoroughly searched for by ATLAS in several (new) channels
  - Challenging experimental final states
  - No signs of new particles (yet) → strong **constraints** on many BSM theories
- Sensitivity mostly **limited by statistics**
  - Will benefit from new data coming from LHC …
  - … and increase of signal acceptance !
- **Stay tuned for full Run 2 results !**



Thank you

Contact

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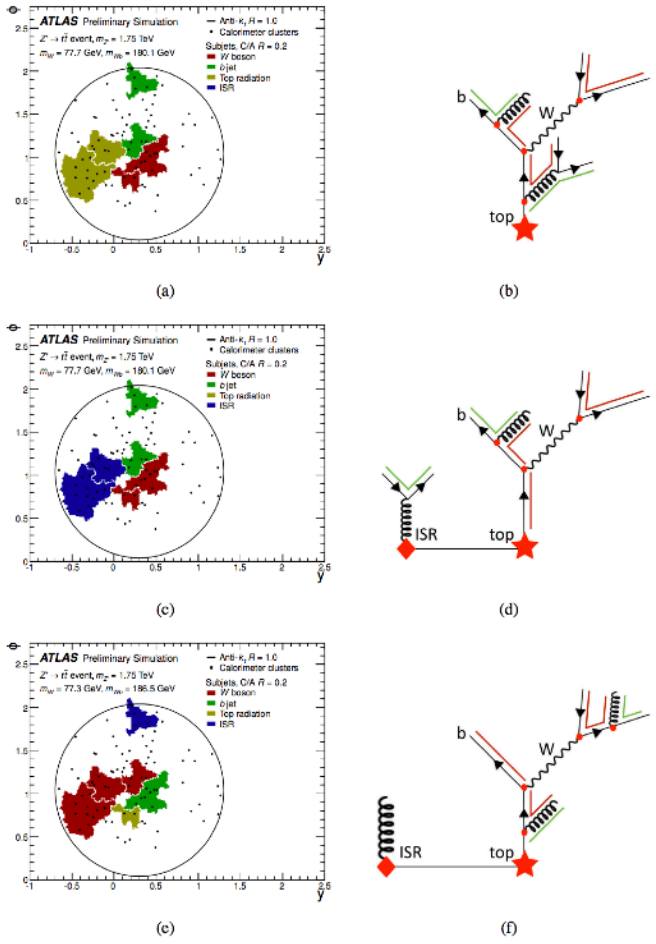
Backup

Shower deconstruction algorithm

A bit more information

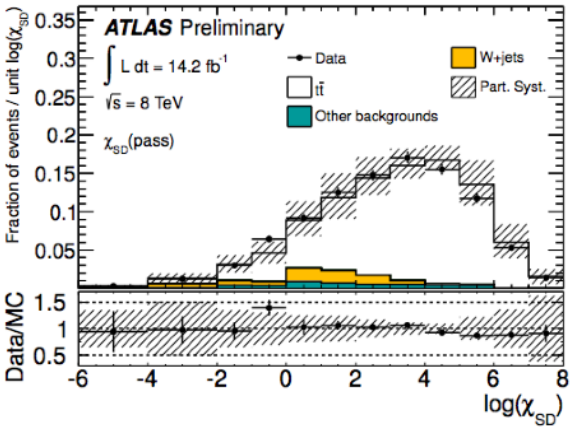
- Taken from https://cds.cern.ch/record/1648661



- Subjets used as proxies to parton
- All parton shower history leading to this parton configuration are used: **each has a probability**

sum over signal-hypotheses PS histories

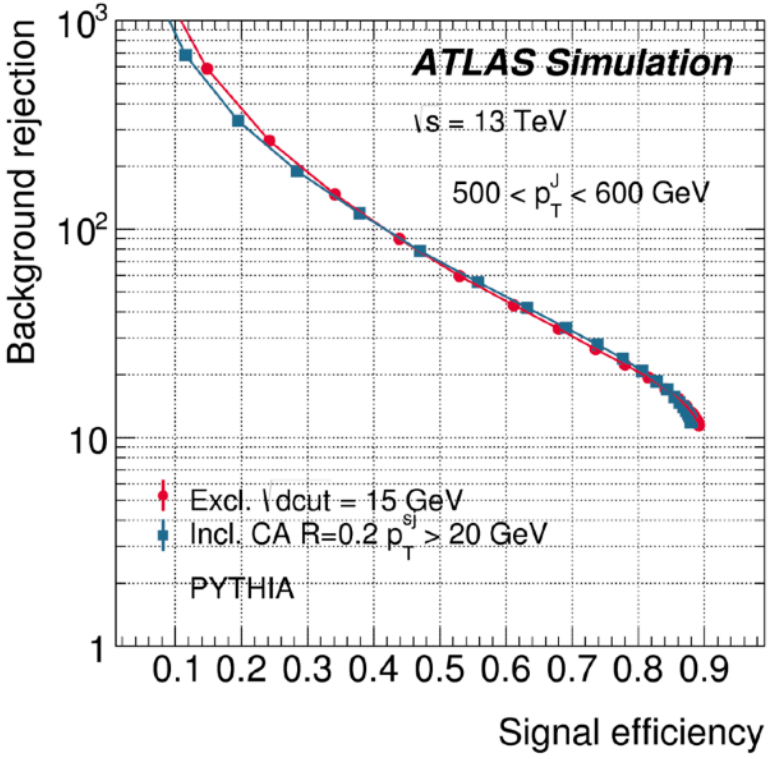
$$\chi_{SD}(\{p\}_N) = \frac{P(\{p\}_N|S)}{P(\{p\}_N|B)} = \frac{\sum_{\text{histories}} P(\{p, c^J\}_N|S)}{\sum_{\text{histories}} P(\{p, c^J\}_N|B)}$$

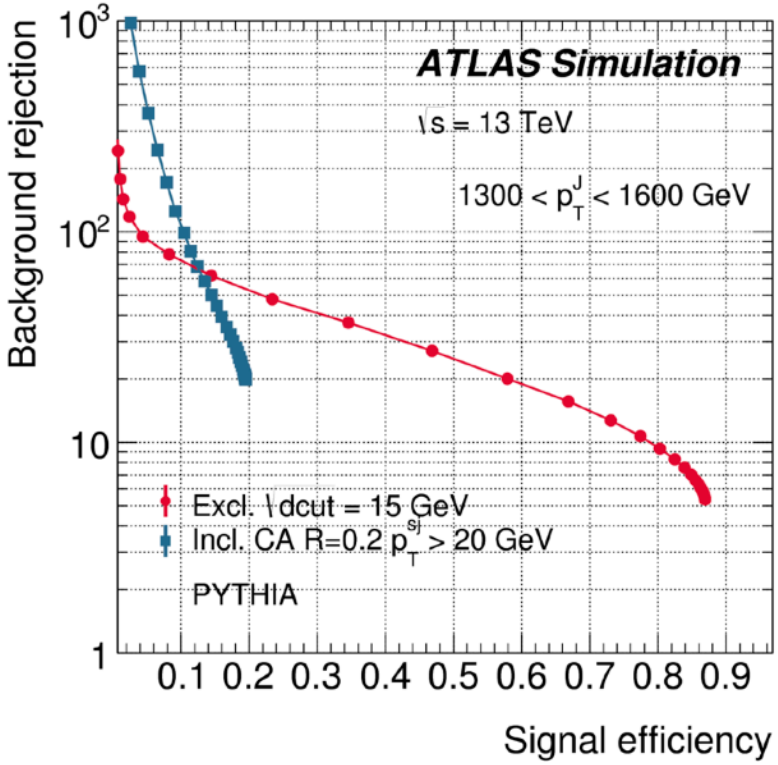


sum over background-hypotheses PS histories

Shower deconstruction performance

A bit more information



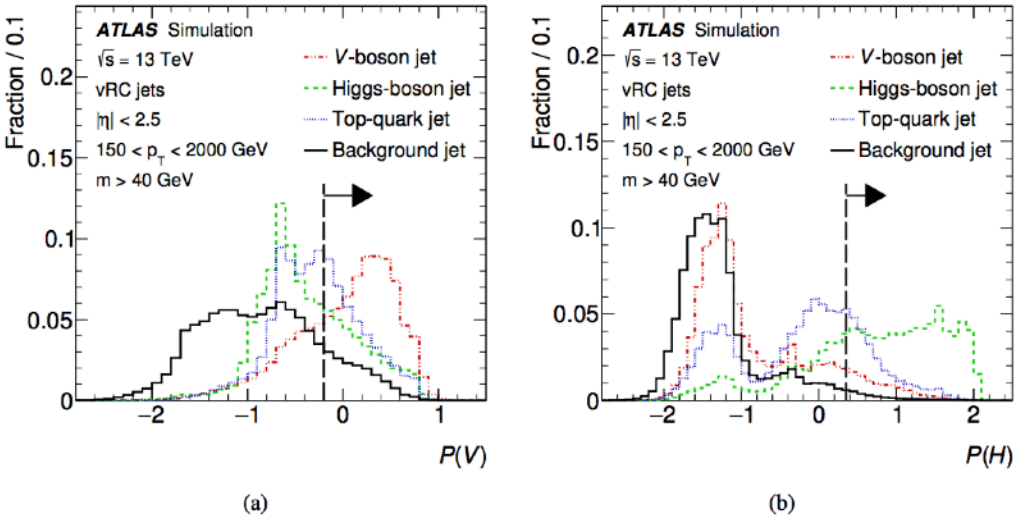


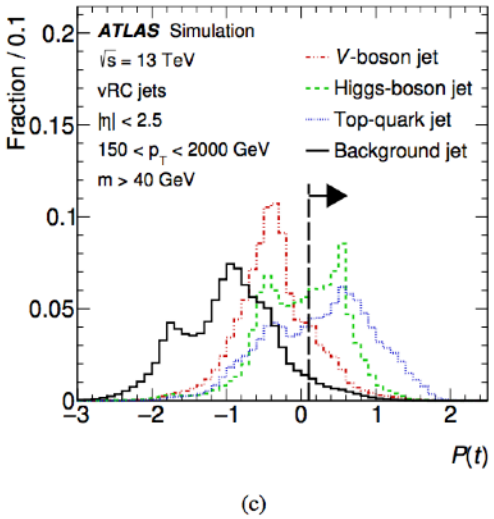
- Use of **exclusive subjets** => better performance for very-highly-boosted top quarks.

DNN tagger

A bit more information

https://arxiv.org/pdf/1808.01771.pdf





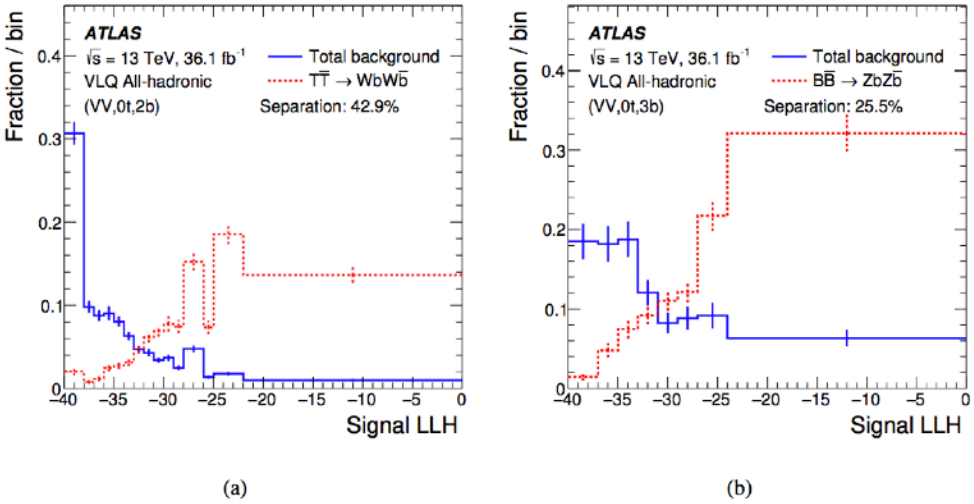
$$P(V) = \log_{10}\left(\frac{D^{V}_{\mathrm{DNN}}}{0.9 \cdot D^{\mathrm{background}}_{\mathrm{DNN}} + 0.05 \cdot D^{t}_{\mathrm{DNN}} + 0.05 \cdot D^{H}_{\mathrm{DNN}}}\right),$$

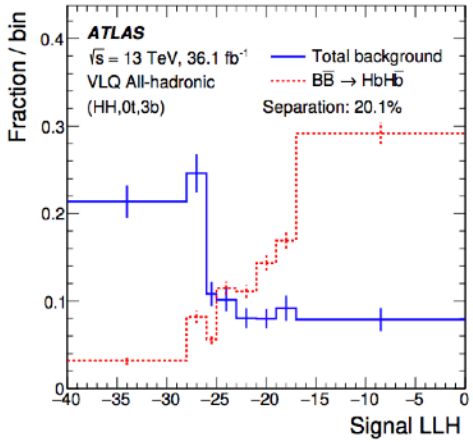
$$P(H) = \log_{10}\left(\frac{D^{H}_{\mathrm{DNN}}}{0.9 \cdot D^{\mathrm{background}}_{\mathrm{DNN}} + 0.05 \cdot D^{V}_{\mathrm{DNN}} + 0.05 \cdot D^{t}_{\mathrm{DNN}}}\right) \text{ and}$$

$$P(t) = \log_{10}\left(\frac{D^{t}_{\mathrm{DNN}}}{0.9 \cdot D^{\mathrm{background}}_{\mathrm{DNN}} + 0.05 \cdot D^{H}_{\mathrm{DNN}} + 0.05 \cdot D^{V}_{\mathrm{DNN}}}\right),$$

Matrix element method

A bit more information





Truth-reco transfer function

Phase space element

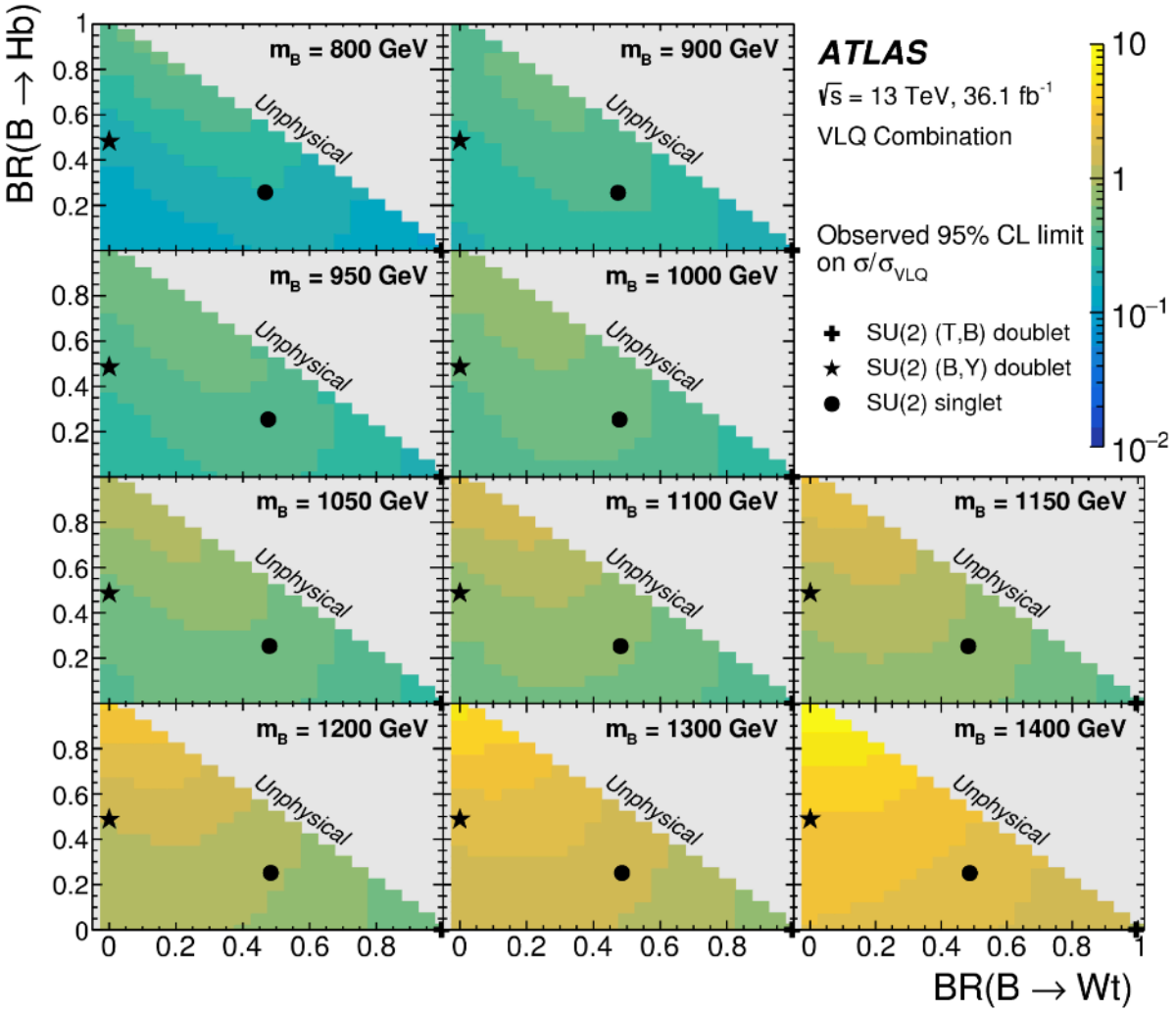
$$P_i(\boldsymbol{x}|\boldsymbol{\alpha}) = \frac{(2\pi)^4}{\sigma_i^{\text{eff}}(\boldsymbol{\alpha})} \int d\Phi_N(\boldsymbol{y}) f(p_A) f(p_B) \frac{|\mathcal{M}_i(\boldsymbol{y}|\boldsymbol{\alpha})|^2}{\mathcal{F}} W(\boldsymbol{y}|\boldsymbol{x})$$

PDF

Transition matrix element of the process

VLQ searches: next steps ?

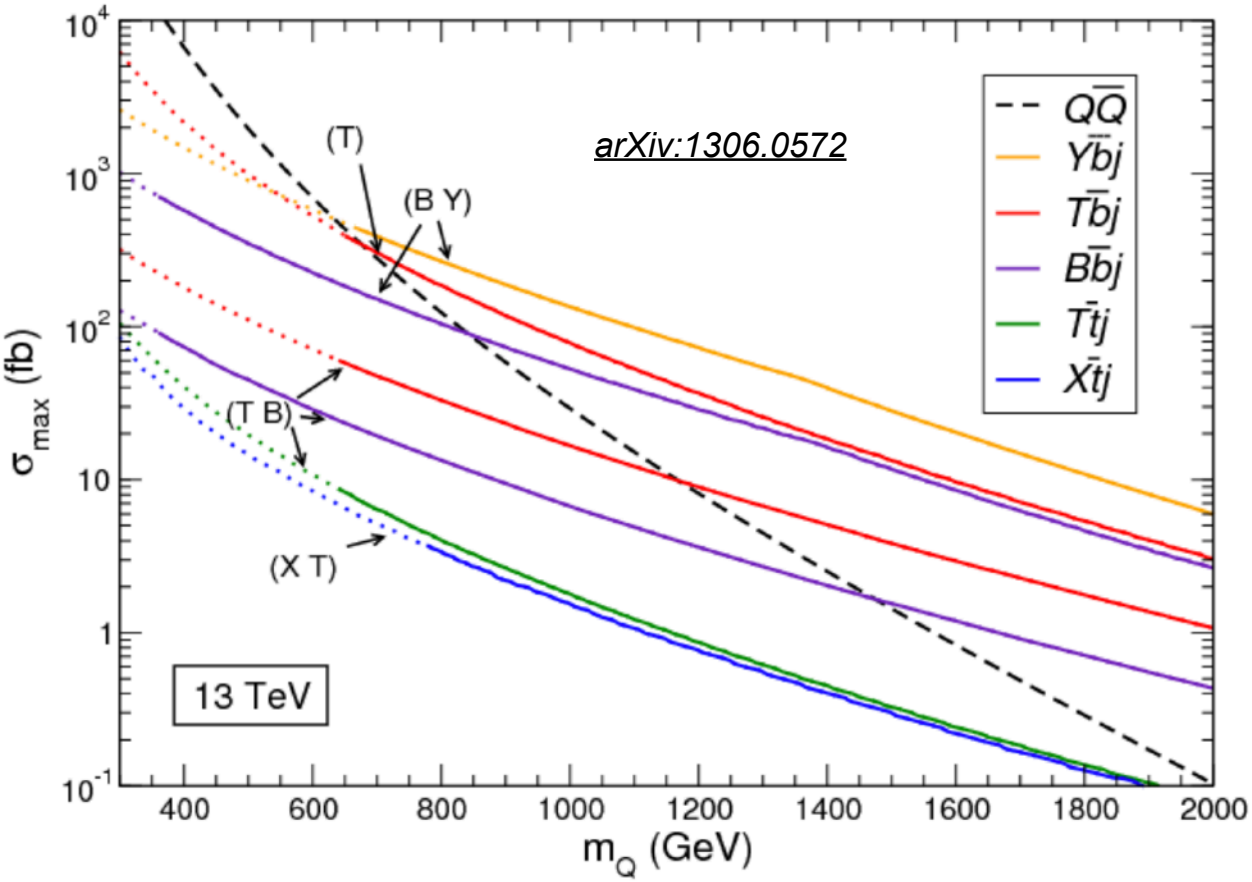
arXiv:1808.02343



Single VLQ production

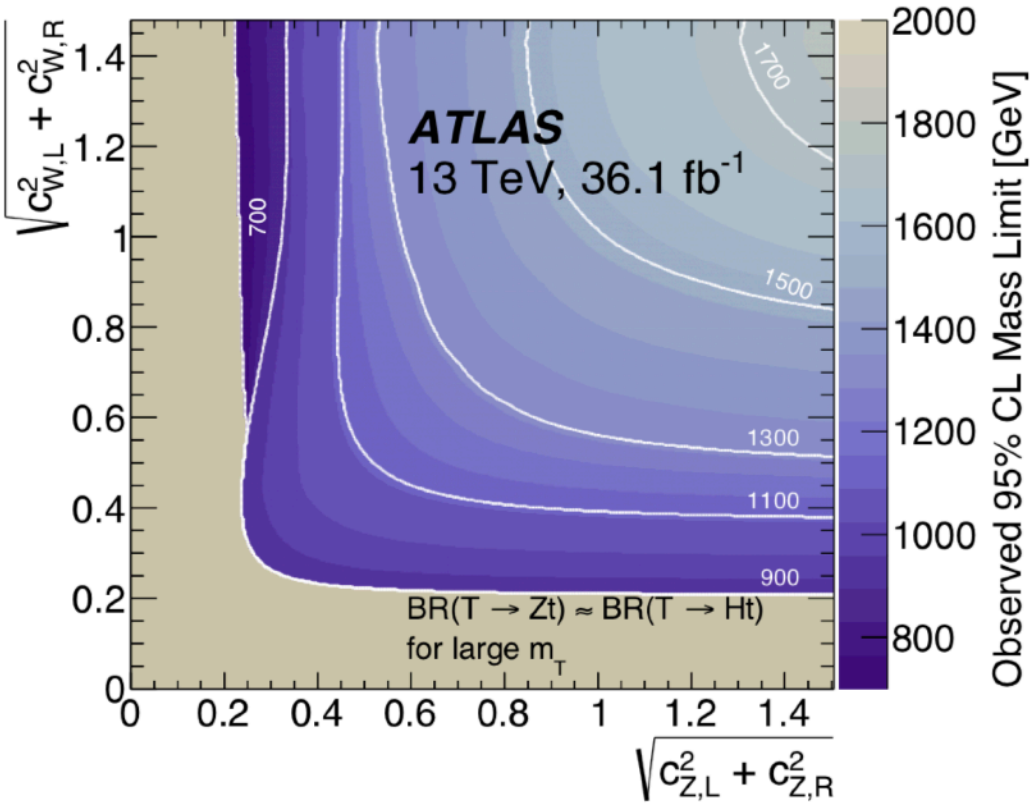
A bit more information

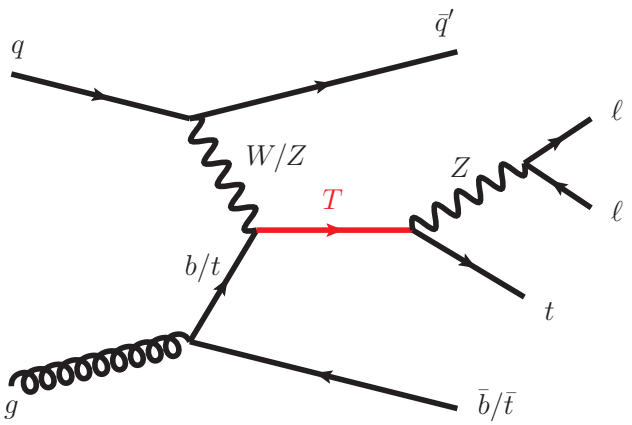
- Single production production cross-section **depends on coupling** between quarks and vector-like partners.



Single VLQ interpretation

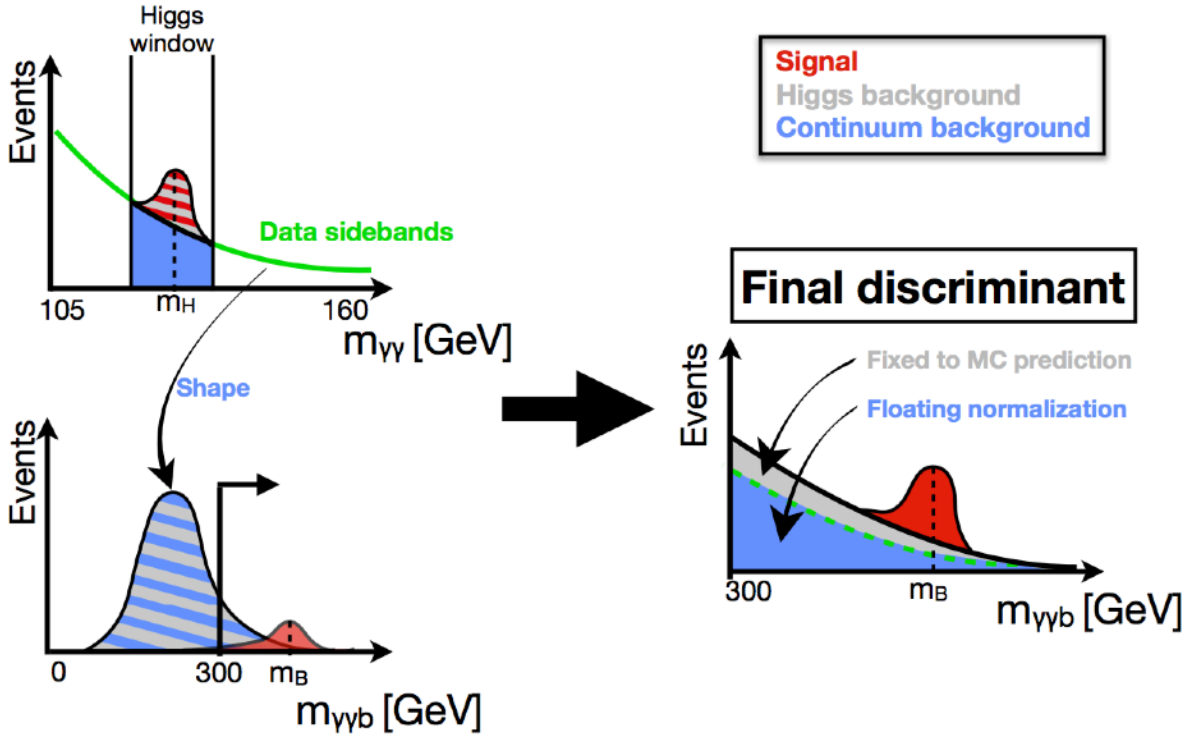
A bit more information





B —> H —> yyb

Some more information

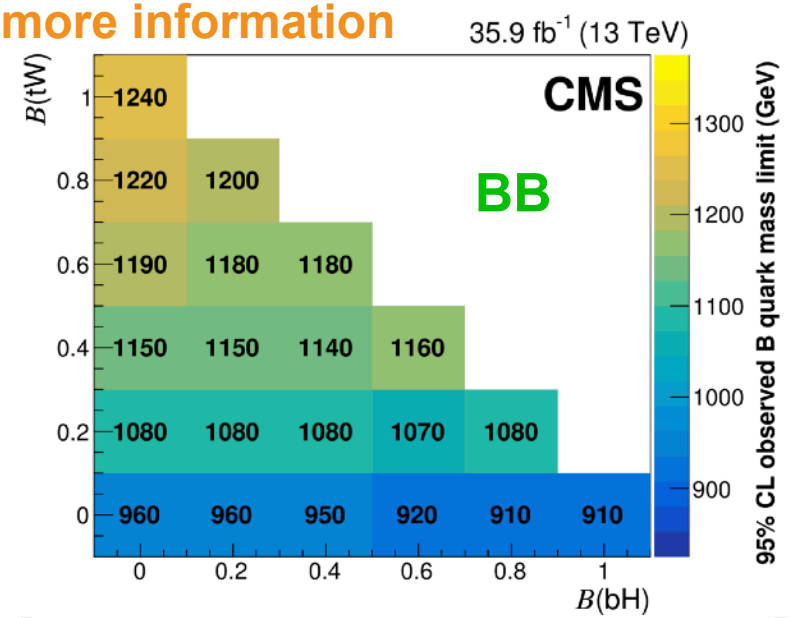


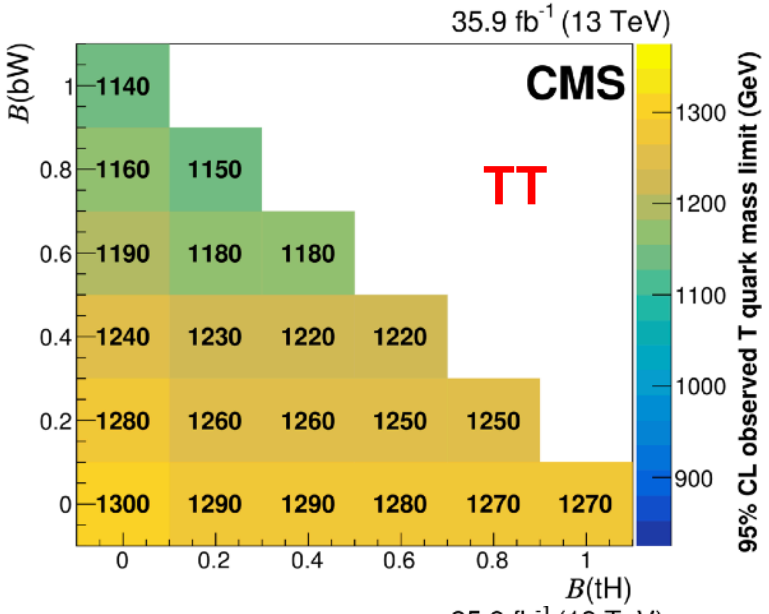
CMS results

A bit more information

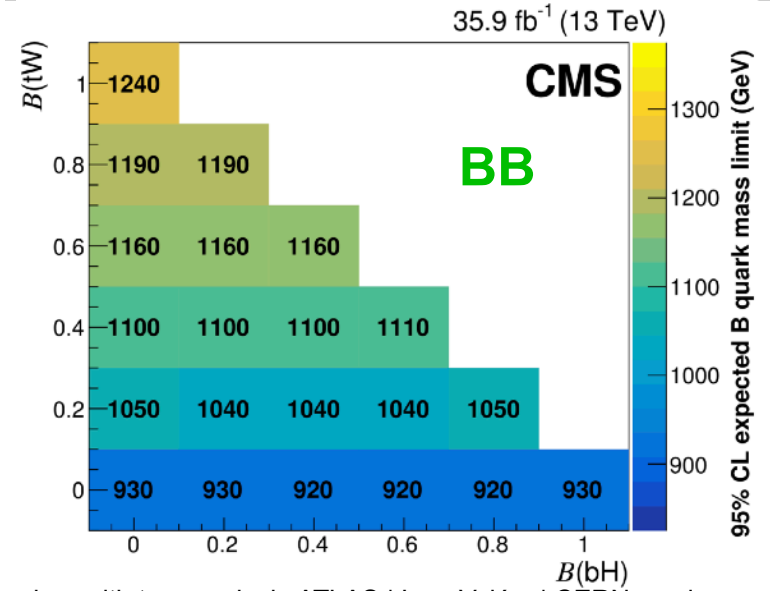
arXiv:1805.04758 (Accepted by JHEP)

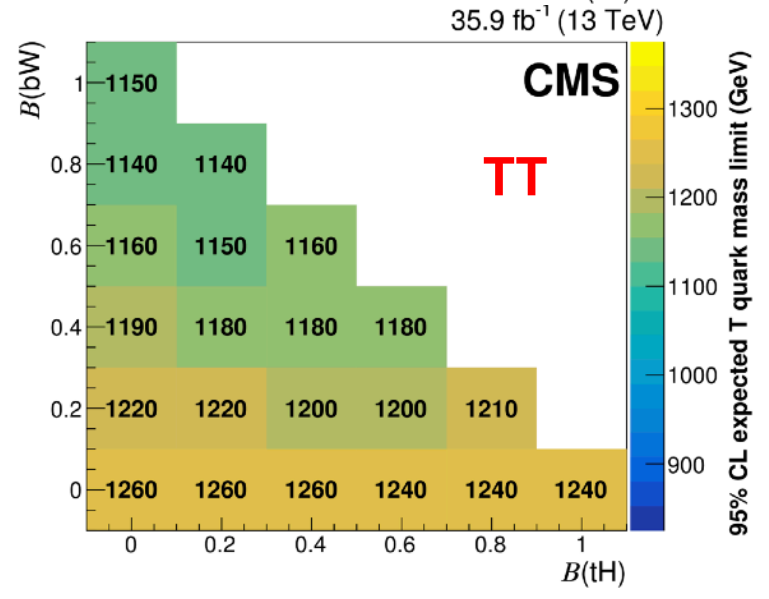
Observed





Expected



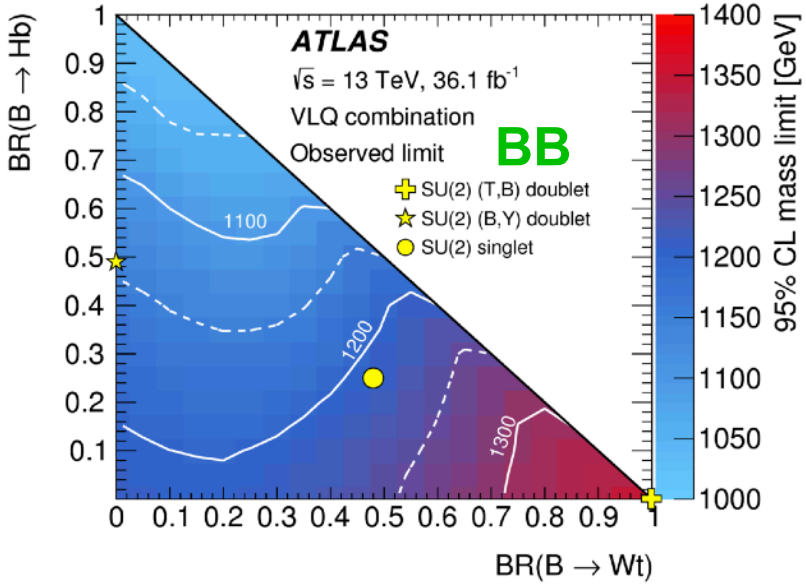


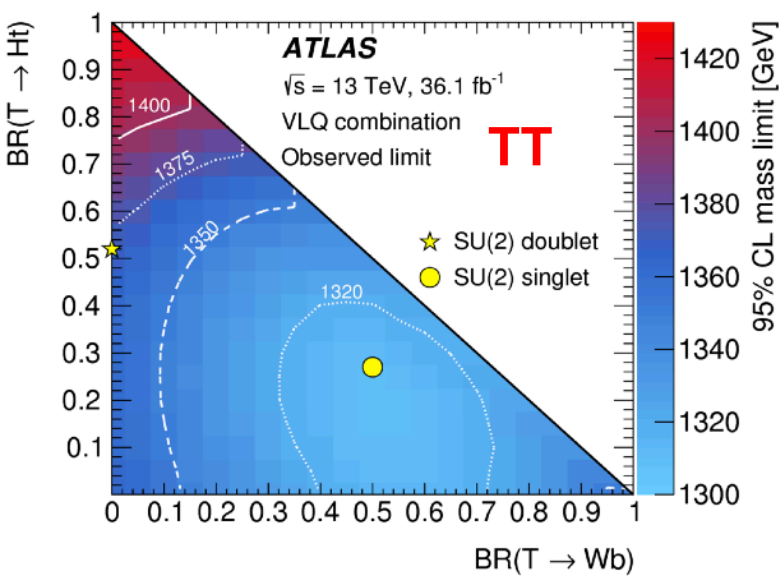
ATLAS results

arXiv:1808.02343 (Submitted to PRL)

A bit more information

Observed





Expected