Searches for heavy resonances decaying to heavy-flavour quarks

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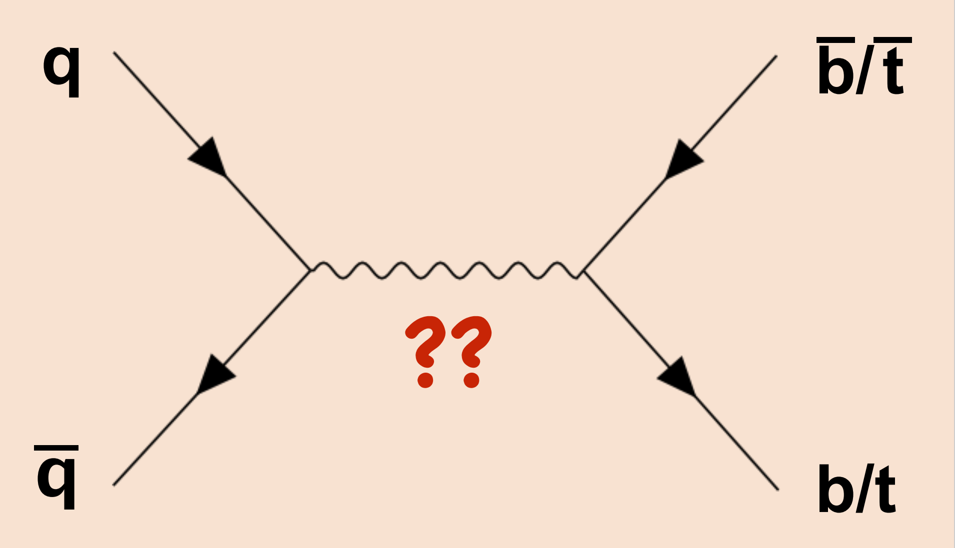
on behalf of the ATLAS collaboration

<u>*QFTHEP*</u>

27th June 2017

Heavy Quark Resonances Introduction

Many models of new physics couple to the heaviest family of quarks!!



p.s. slide # in top-left!!!

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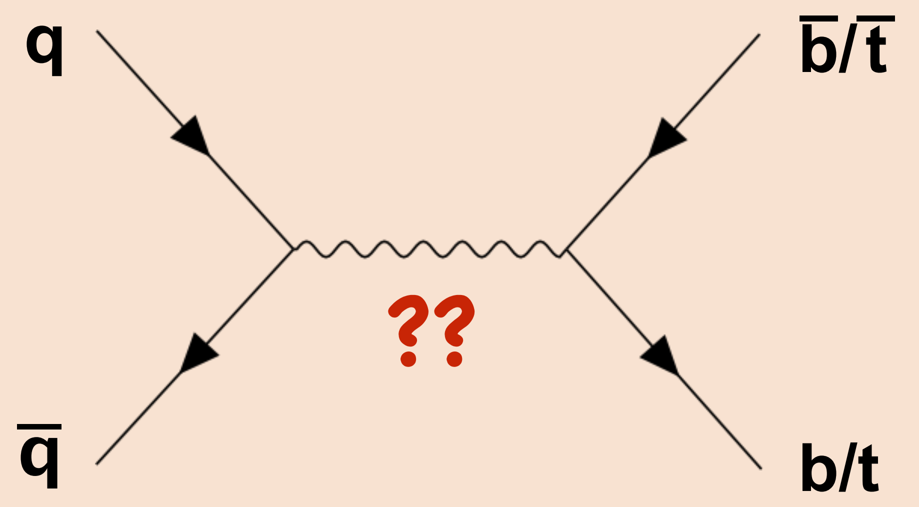
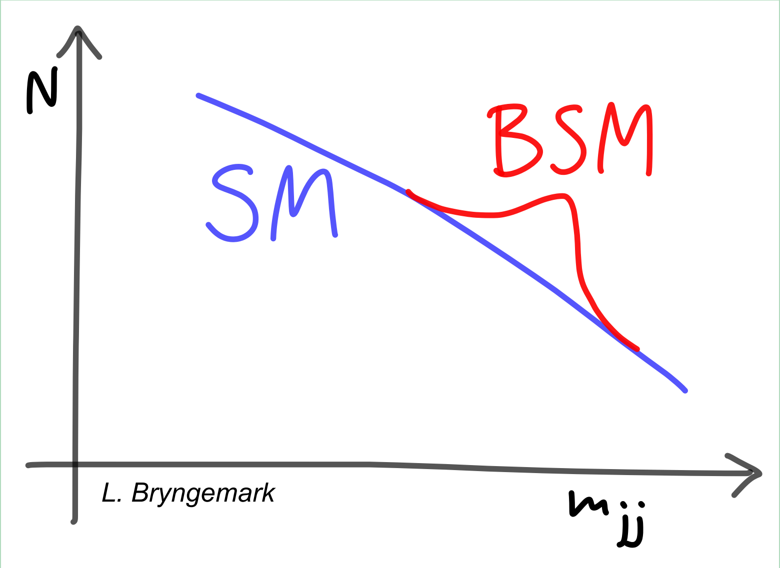


Observed as resonances



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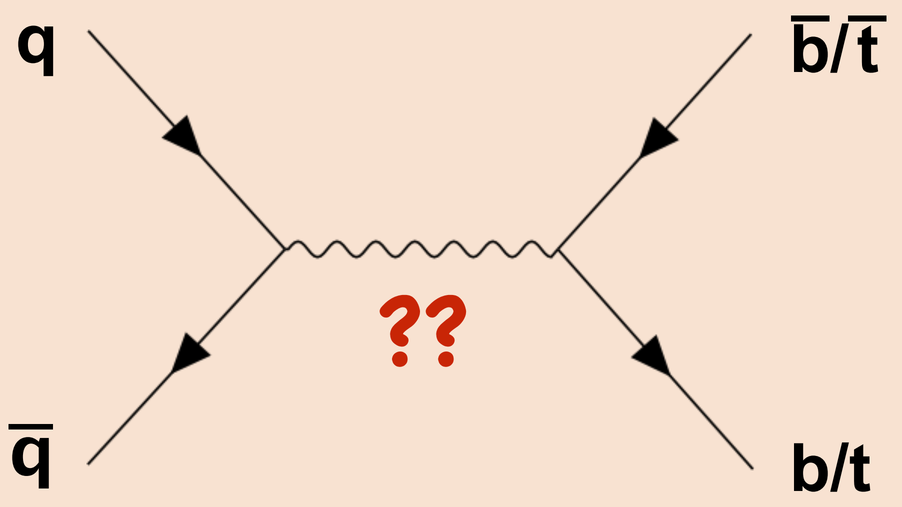

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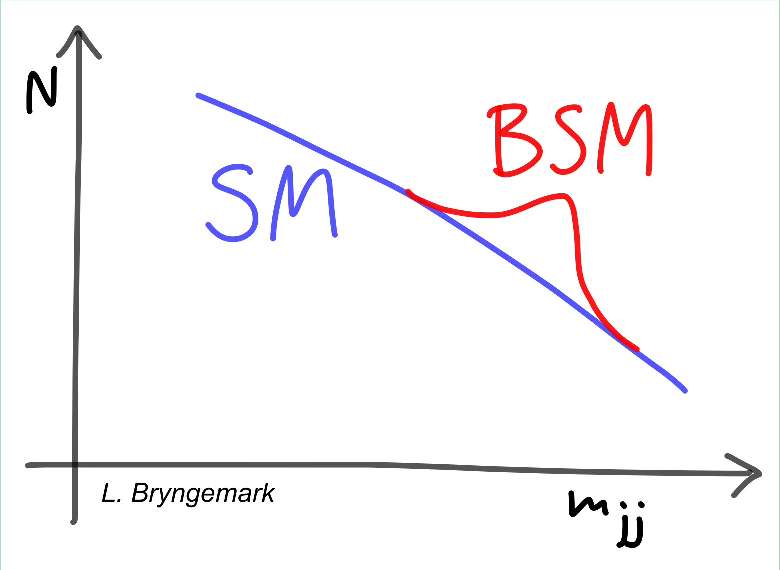

Two heavy quarks!
Two different analyses

1. ***b-quark analysis*** [1]
2. ***top quark analysis*** [2]

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2 Heavy Quark Resonances Introduction

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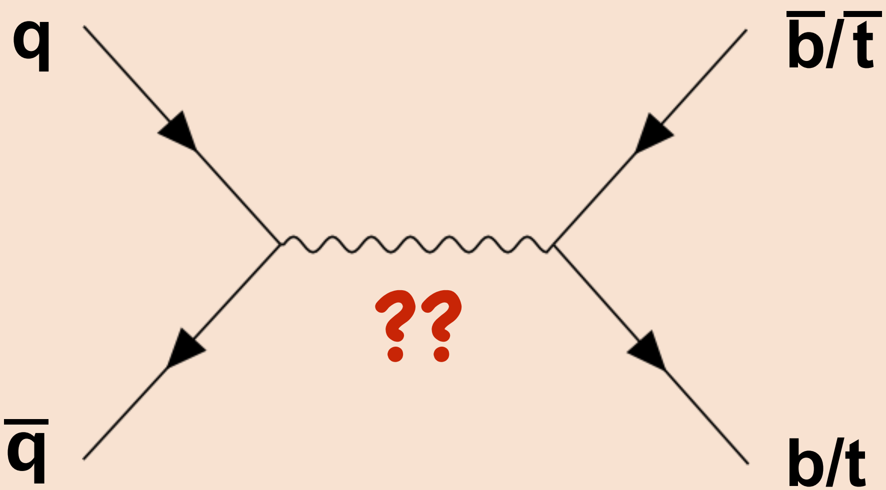

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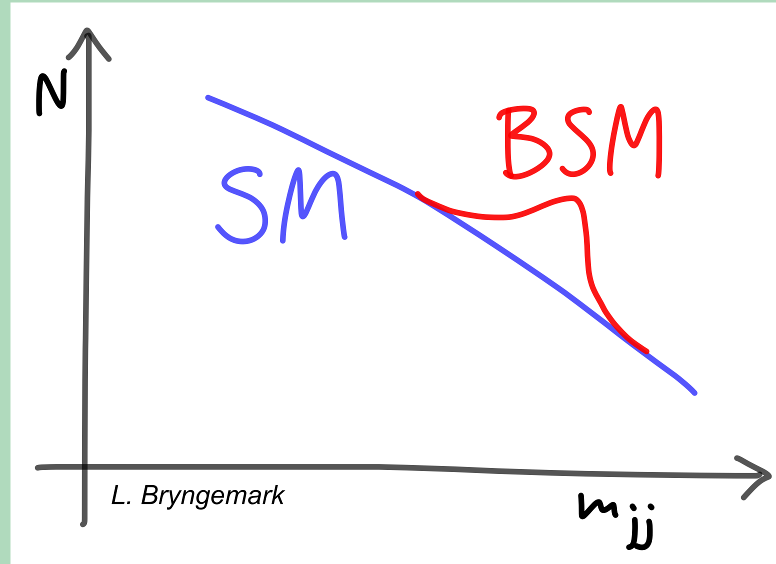


Two heavy quarks!
Two different analyses

1. ***b-quark analysis*** [1]
2. ***top quark analysis*** [2]

Heavy quarks are interesting because:

1. ***3rd generation is special!***
   ➡ *Could be a sign of new physics…*
2. ***Specialist reconstruction techniques***
3. ***Differing background modelling techniques employed***

p.s. slide # in top-left!!!

Benchmark Signal Models

UCL

Z' Boson

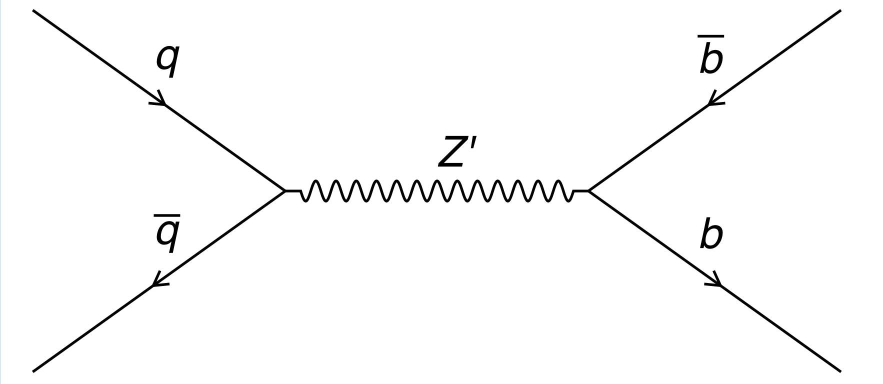
b quark*

Other models are also available…

Benchmark Signal Models

Z' Boson

Neutral spin-1 boson from additional U(1) symmetry to SM



- Can decay to pairs of heavy quarks
- Could act as dark matter mediator
  ➡ Links SM to DM sector
  ➡ Explain DM abundance

b* quark

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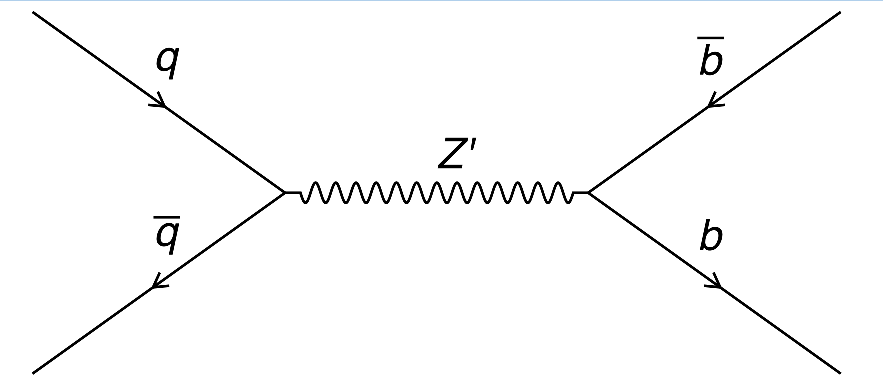

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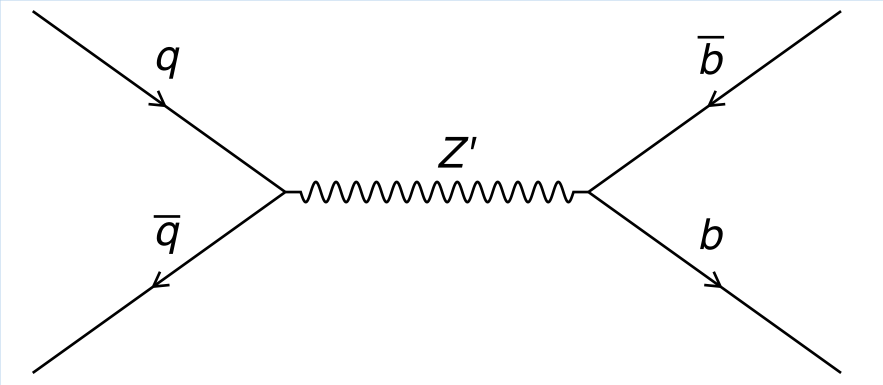
Two Models
- Leptophobic : No coupling to leptons — *b-quark analysis*
- Top-colour : Dynamic EWSB, Preferential decay to $t\bar{t}$ — *top quark analysis*

b* quark

Other models are also available…

3 Benchmark Signal Models

Z' Boson — *Neutral spin-1 boson from additional U(1) symmetry to SM*



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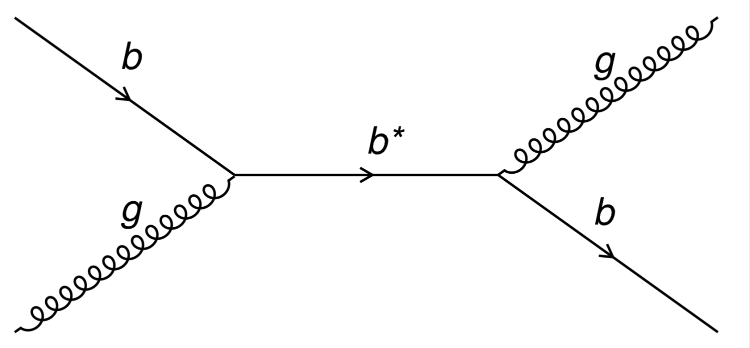
Two Models

- **Leptophobic : No coupling to leptons** — ***b-quark analysis***
- **Top-colour : Dynamic EWSB, Preferential decay to $t\bar{t}$** — ***top quark analysis***

b* quark — *Excited 3rd generation quark* — ***b-quark analysis***



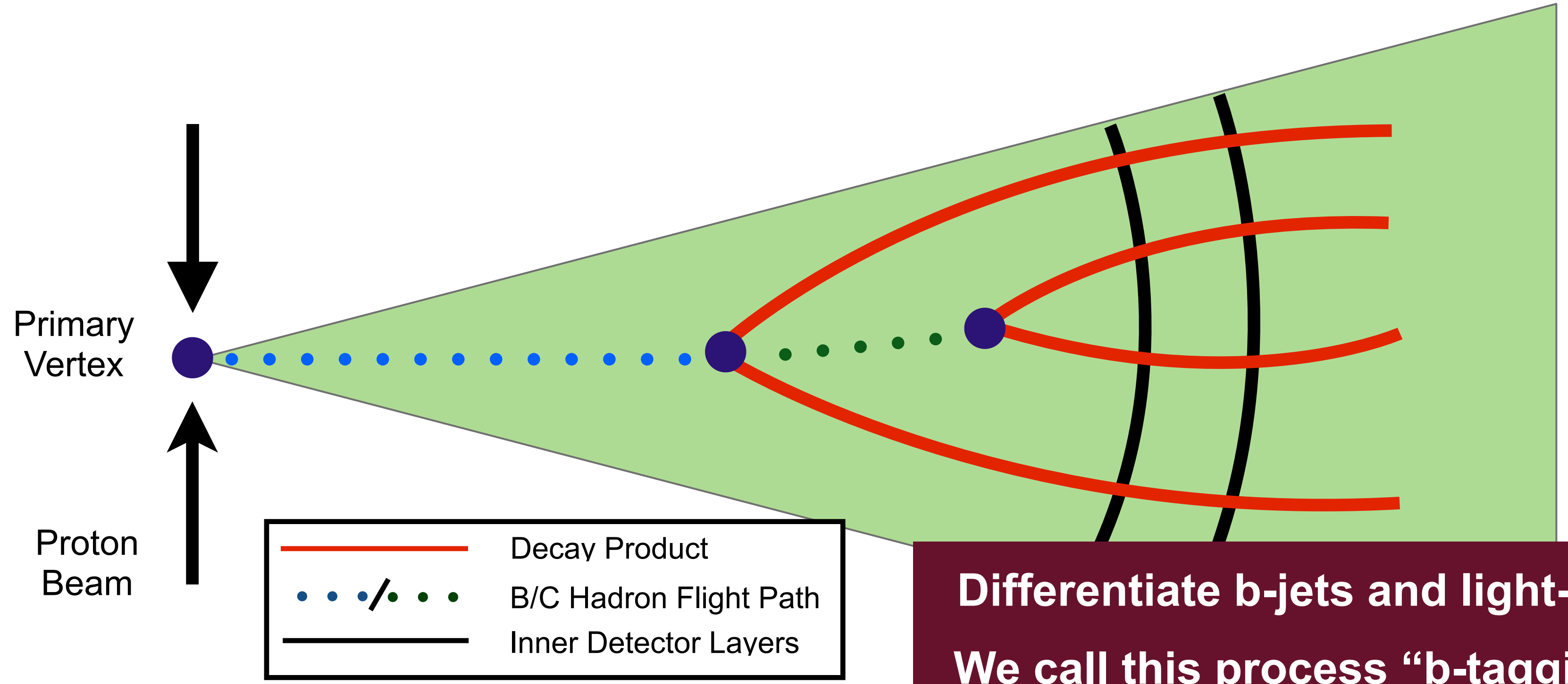
- **Quark compositeness models**
- **Could explain quark's**
  - ➡ **Generational structure**
  - ➡ **Mass hierarchy**

Other models are also available…

How to identify a b-quark?

b-quark analysis

top quark analysis



Differentiate b-jets and light-jets

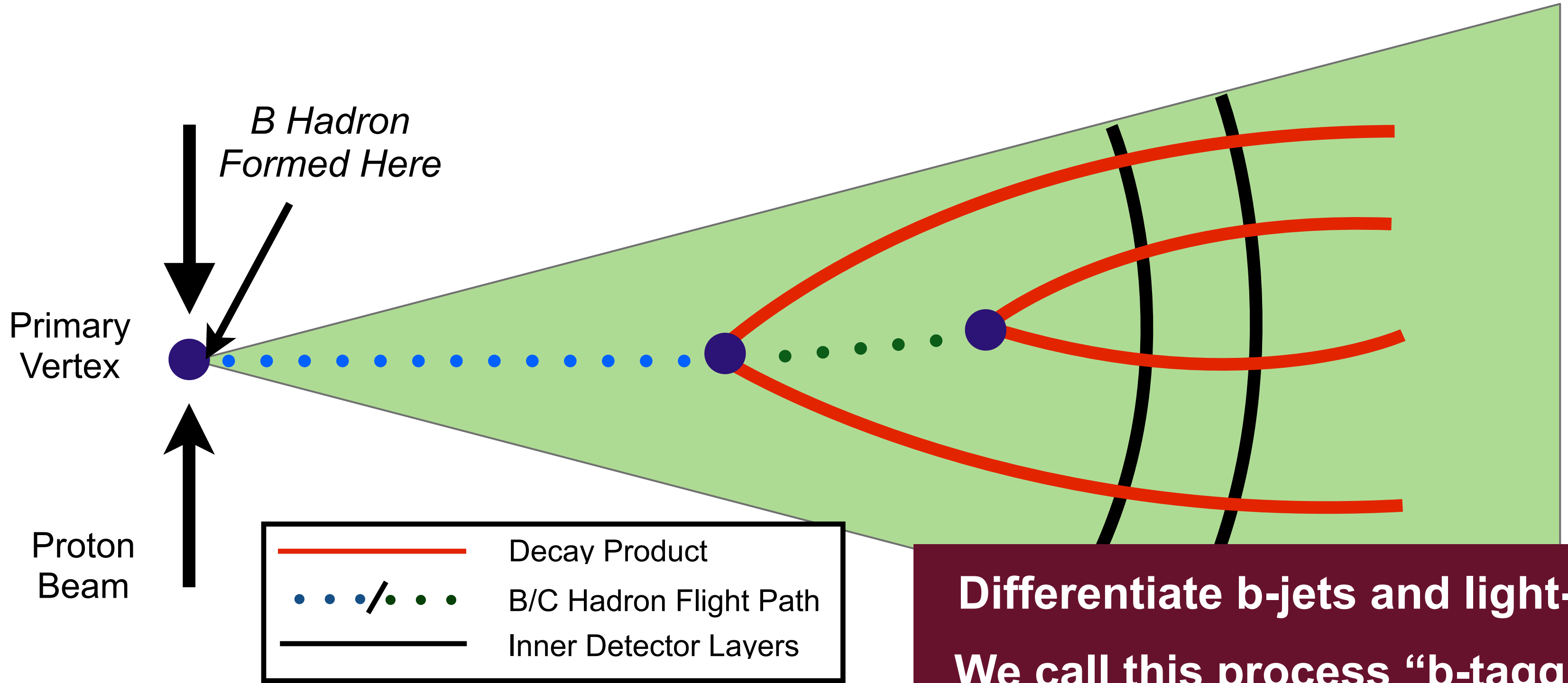
We call this process "b-tagging"

b-quark analysis

top quark analysis

How to identify a b-quark?

- **b-quark will hadronise to form a B-hadron**



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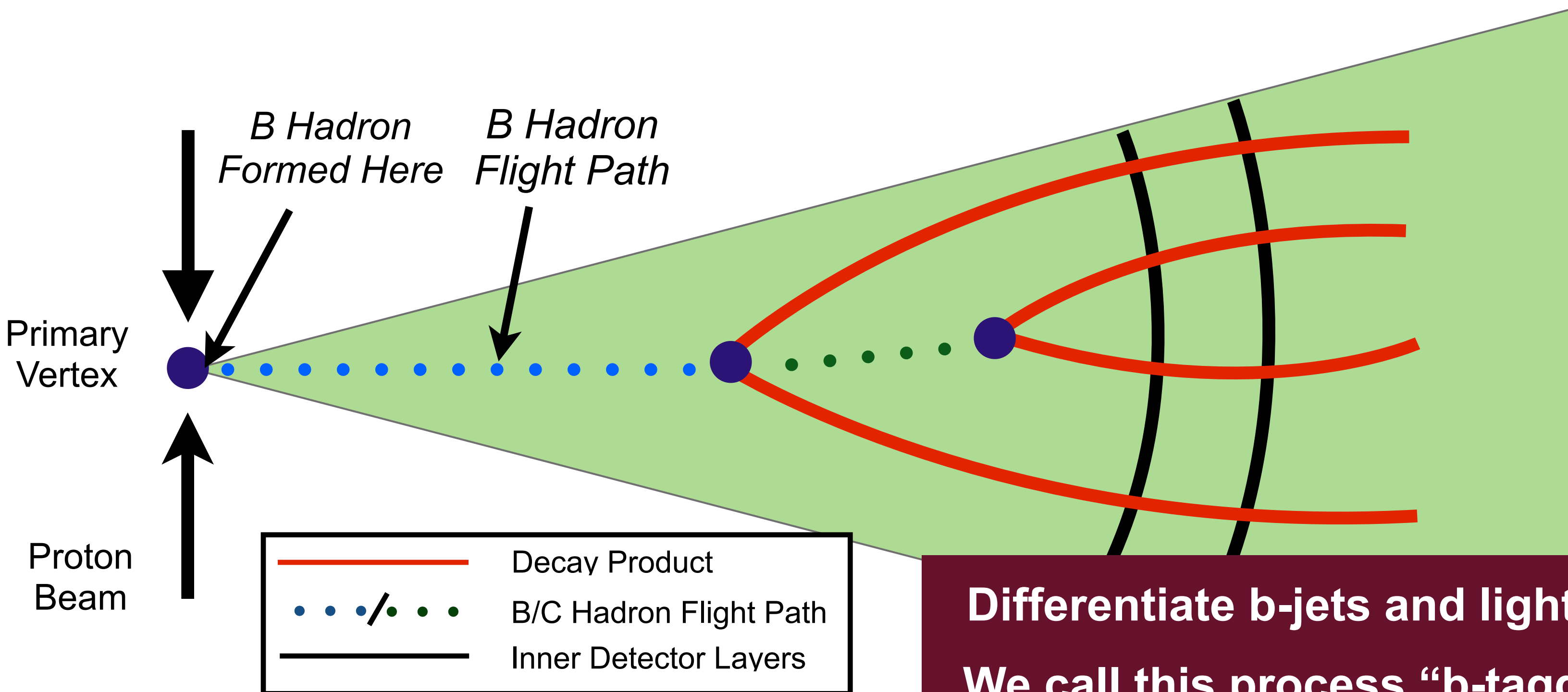
  - *For pT = 200 GeV => d = 20 mm*



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UCL

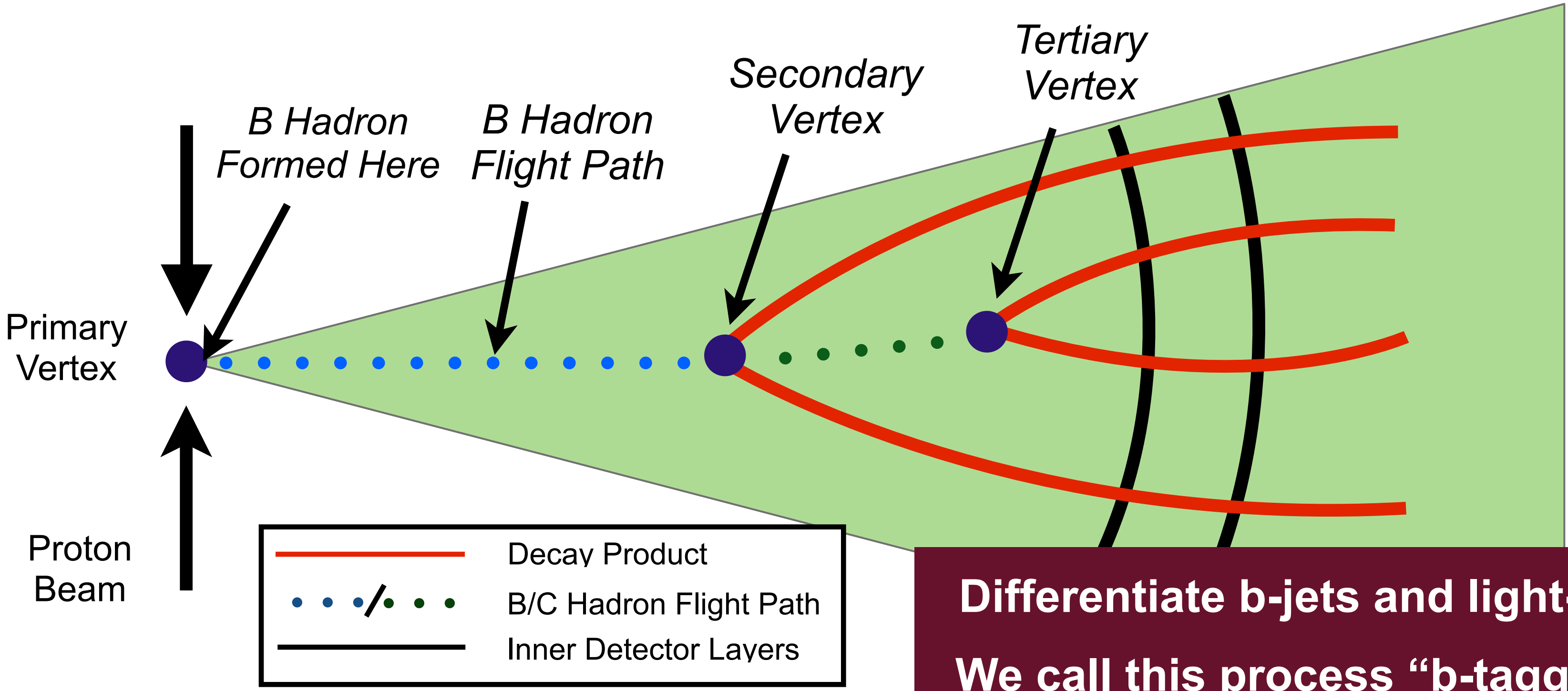
b-quark analysis

top quark analysis

How to identify a b-quark?

- **b-quark will hadronise to form a B-hadron**
- **B-hadrons travel a finite distance before decaying**
  - *For pT = 200 GeV => d = 20 mm*
- **Search for:** ***1) Displaced crossing of tracks*** = *(Secondary vertex)*
  2) Tracks not pointing to primary vertex = *(Impact parameter)*
  3) Tertiary vertex from C-hadron decay = *(Jet Fitter)*

➡ **Combine these variables in a multi-variate algorithm**



Differentiate b-jets and light-jets

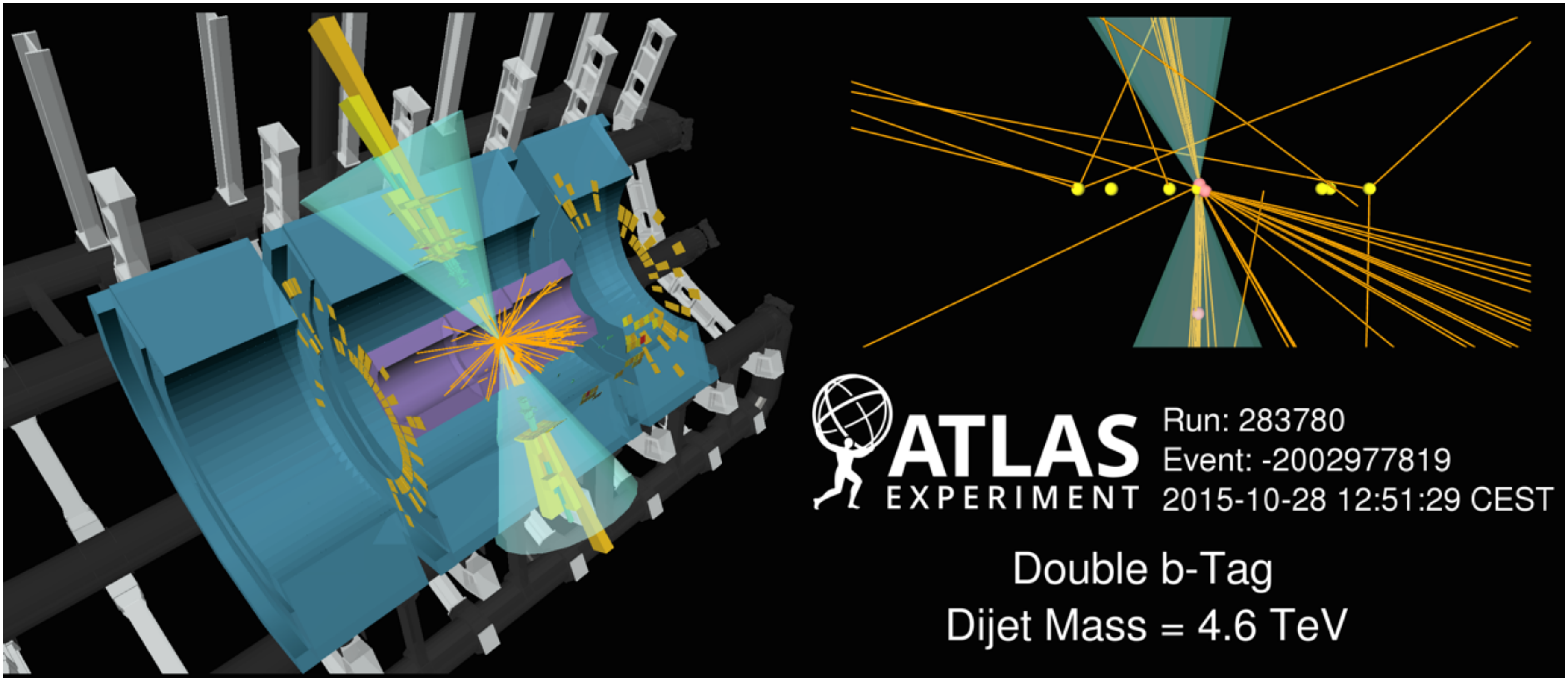
We call this process "b-tagging"

Event Selection : b-quarks

[1]

b-quark analysis

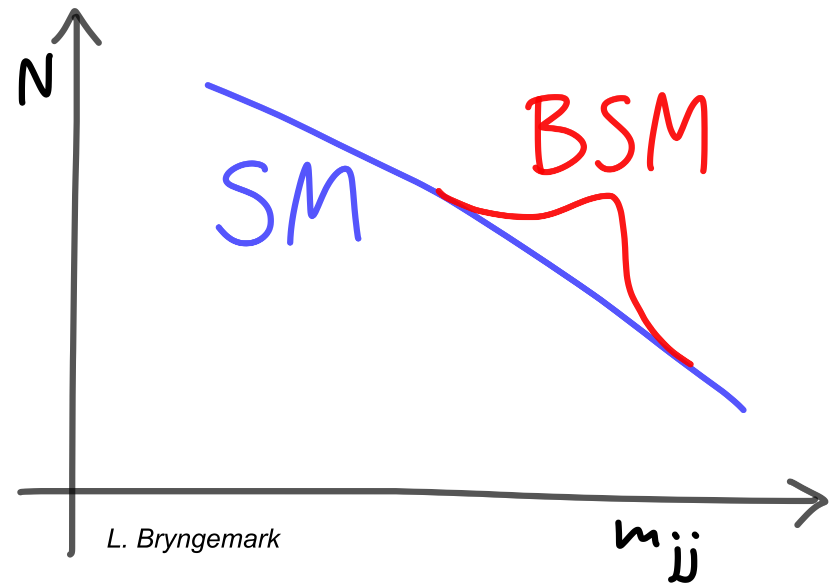
- **2015 and 2016 Data Combined**
  - 13 fb^{-1} of 13 TeV pp collision data
- **Select Dijet Events**
  - Require two high-p_T jets
  - m_{jj} > 1.4 TeV
- **b-Tagging to identify b-jets:**
  - **Two categories:**
    - >= 1 b-tag cat. *(for b*)*
    - == 2 b-tag cat. *(for Z')*



Full list of events selection in backup

EXOT-2015-22

- **Background is totally dominated by multi-jet background**
- **Use data-driven method**
  - Avoid large modelling uncertainties



Two Step strategy:

- **Fit to smooth background**
  - **Use smoothly falling function:**

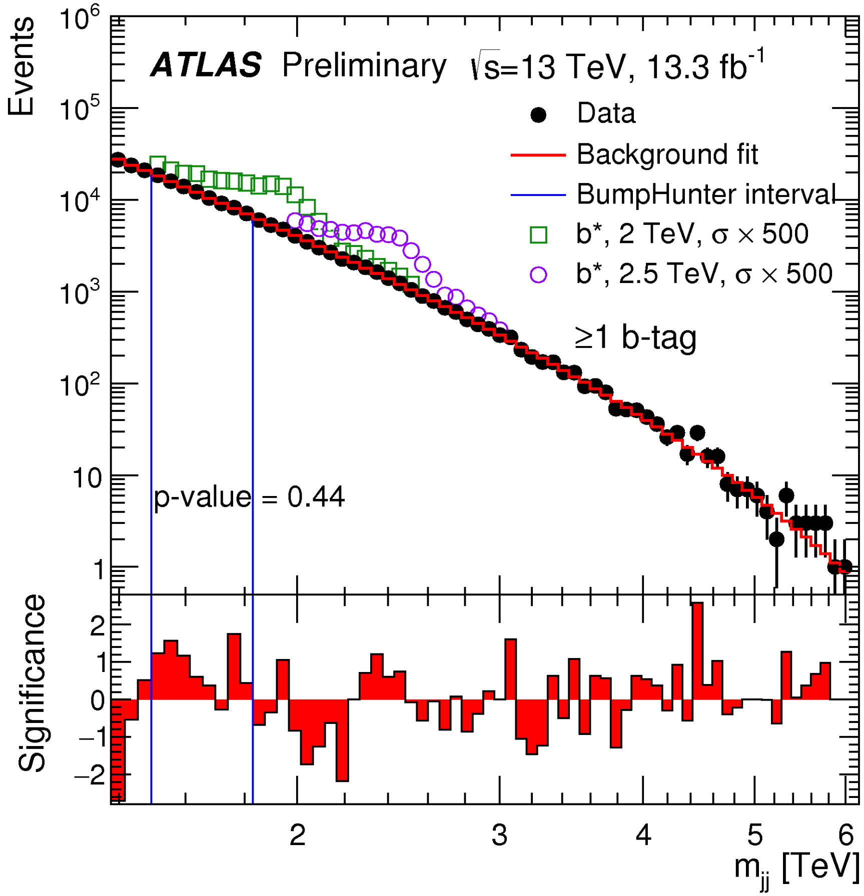
$$f(z) = p_1 (1 - z)^{p_2} (z)^{p_3}$$

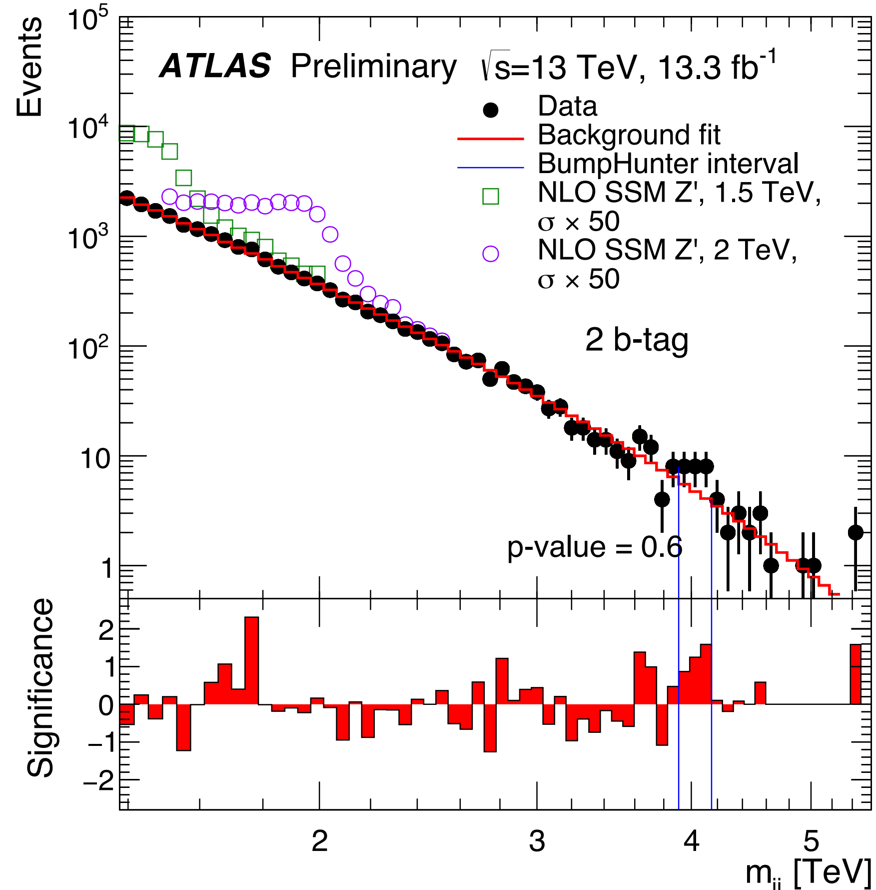
where, $z = m/\sqrt{s}$

- **Search for discrepancies from fit**
  - **BumpHunter algorithm is used**
  - Finds most discrepant excess.
  - p-Value from pseudo-experiments
  - Accounts for look-elsewhere effect
  - If significant excess is found, bkgd fit is repeated ignoring this excess.

- **Search Strategy**
  - Fit to smoothly falling background
  - Find resonances using bumpHunter

b-quark analysis





No Significant Deviation	***>= 1 b-tag BH p-value = 0.44***	***2 b-tag BH p-value = 0.60***

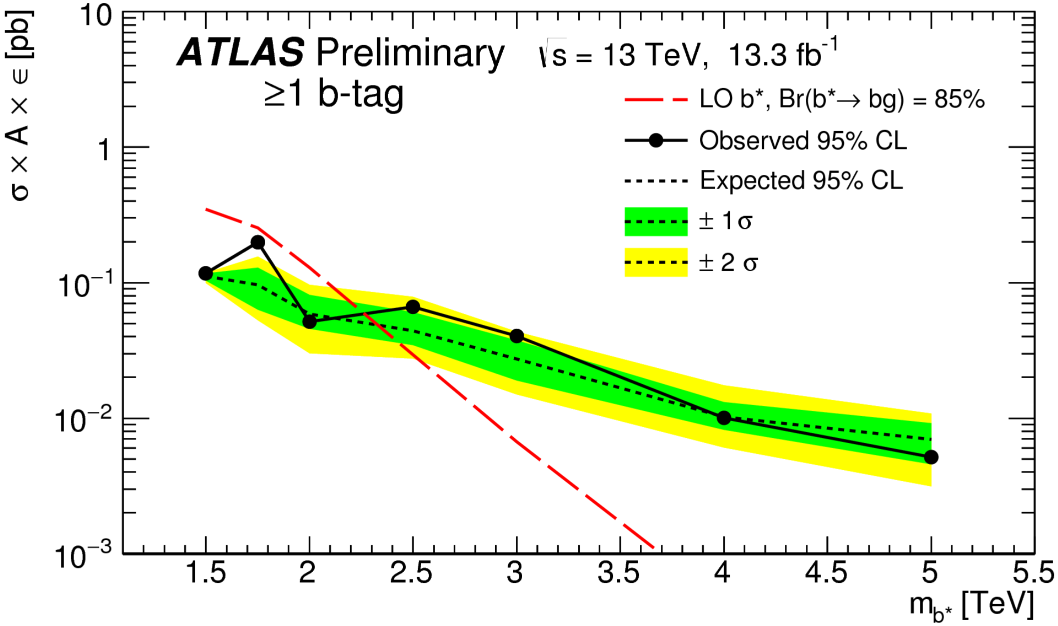
b-quark analysis [1]

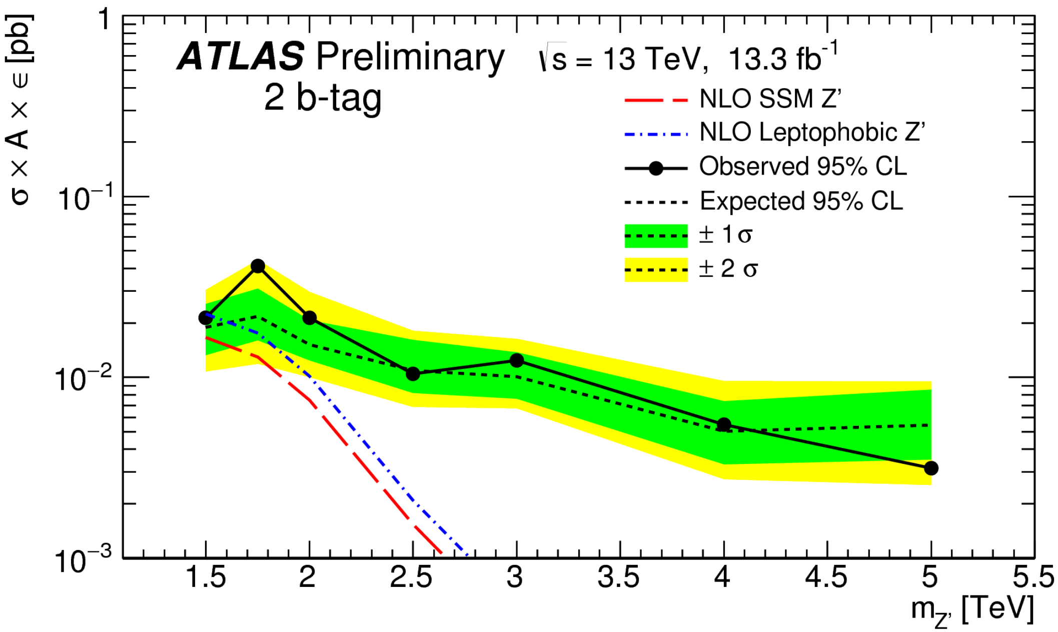
UCL

Limits Set on Benchmark Models

b* excited quark
1.5 < m_{b^*} < 2.3 TeV

Leptophobic
Z' boson
$m_{Z'}$ = 1.5 TeV





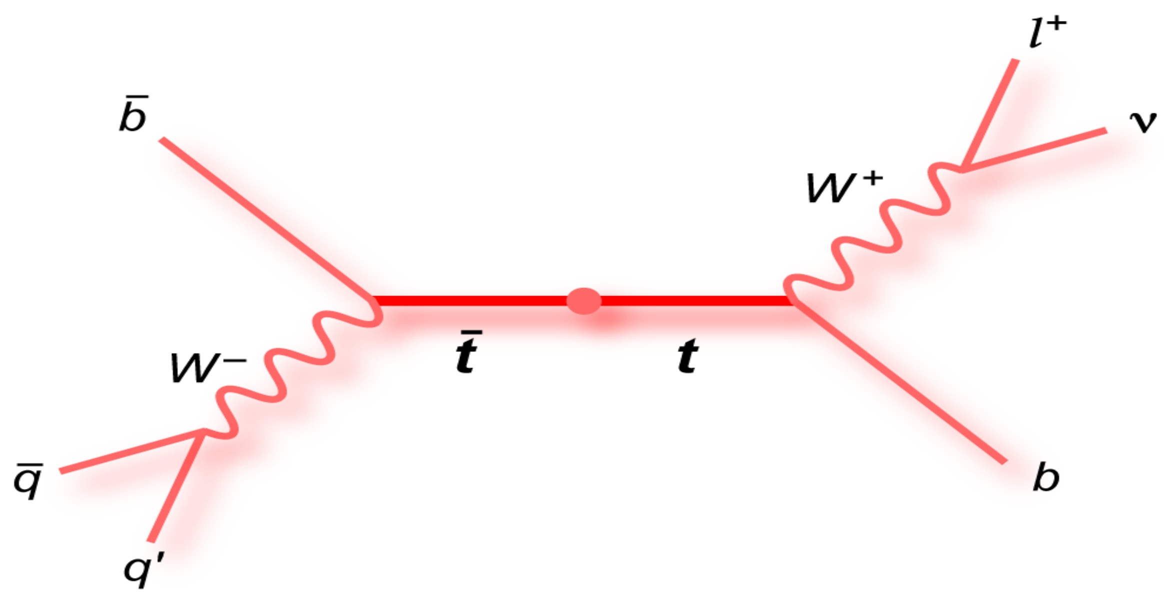
Model	b* quark	Z' Boson
ATLAS *13 TeV, 13.3 ifb*	2.3 TeV	1.5 TeV *(Leptophobic)*
CMS *8 TeV, 19.6 ifb* [3]	1.54 TeV	1.68 TeV *(Sequential SM)*

Event Selection : Top quark

[2]

top quark analysis

- **2015 data set** - ***3.2 fb^{-1}*** *13 TeV pp data*
- **Single lepton $t\bar{t}$** *(electron or muon)*
  - Good Branching Ratio: 28% events
  - Lepton makes for easier reconstruction and identification



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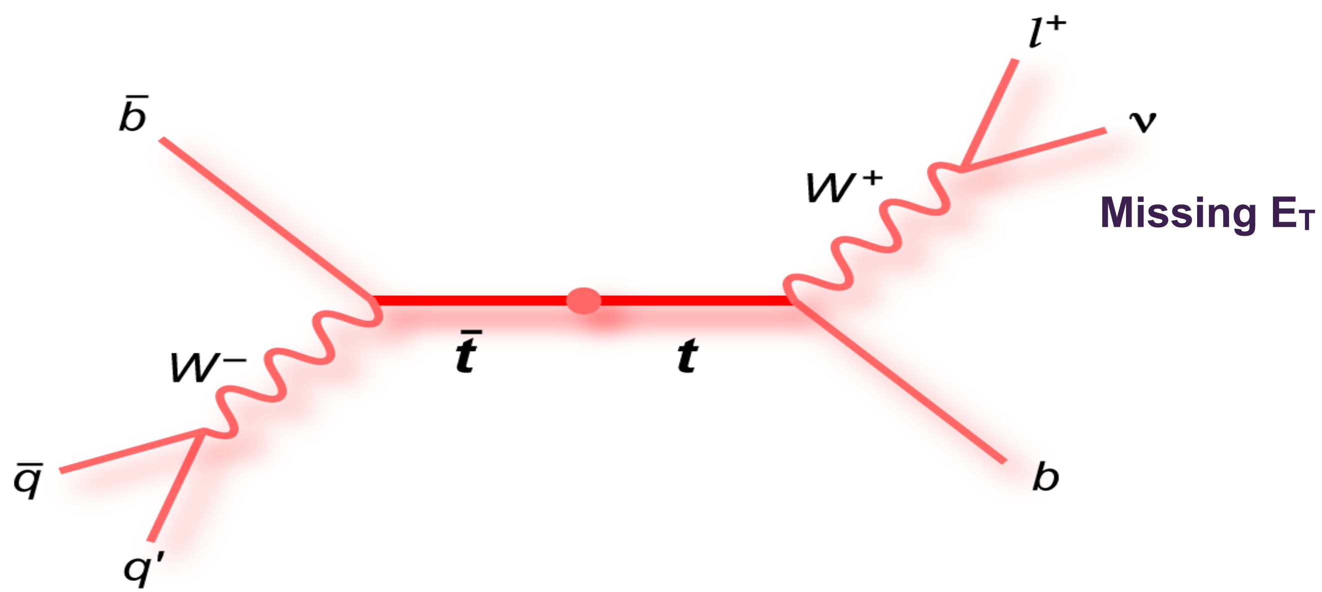
Exactly 1 electron or muon



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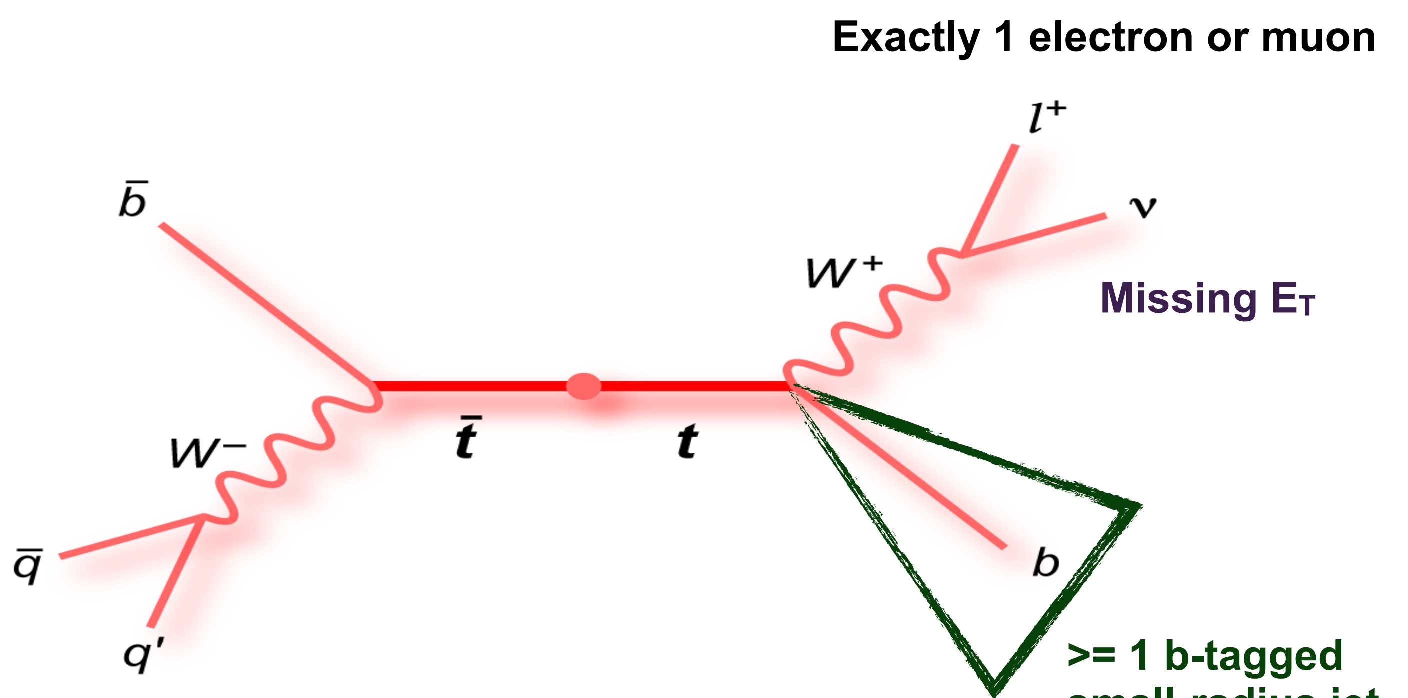

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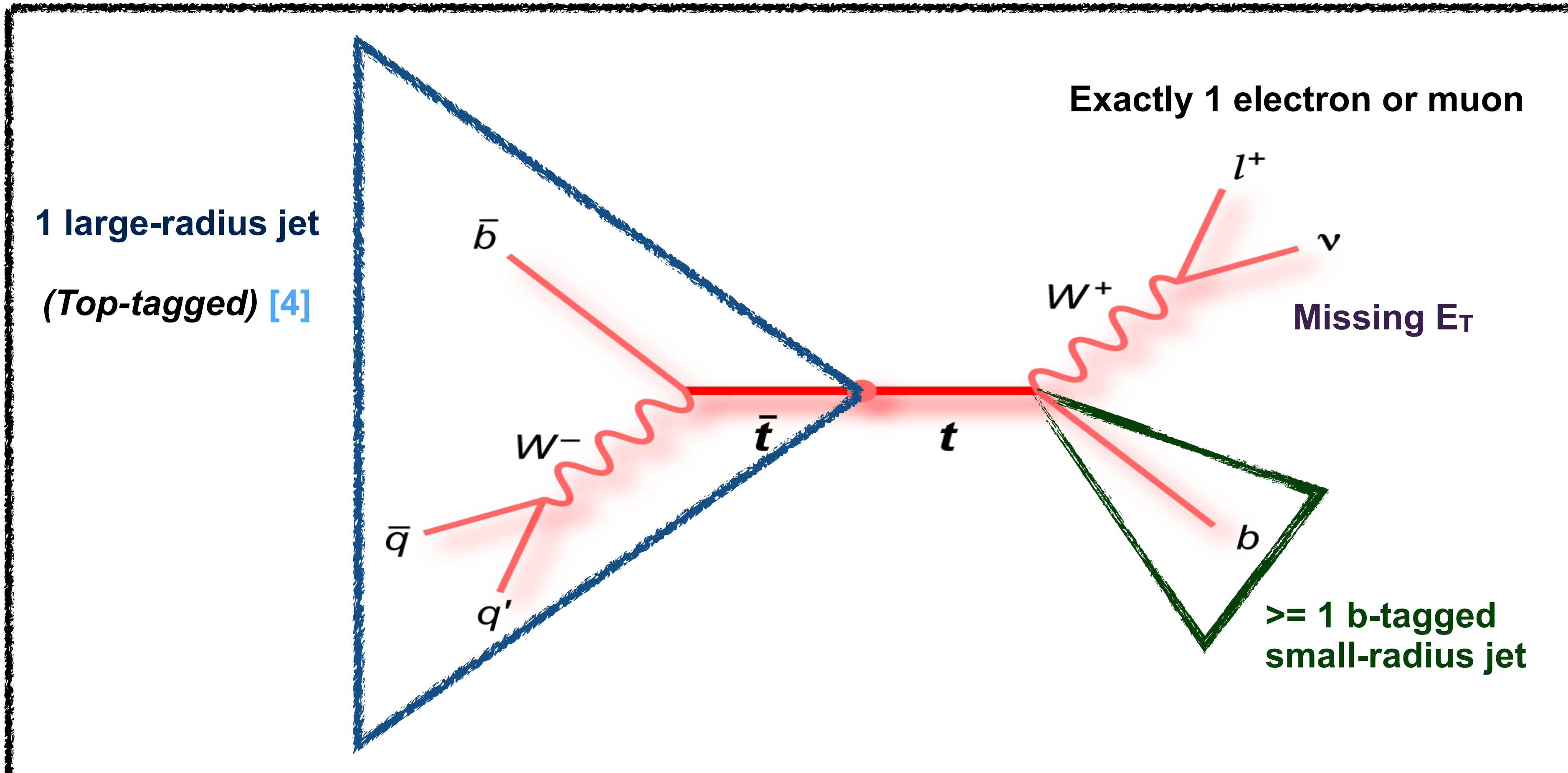

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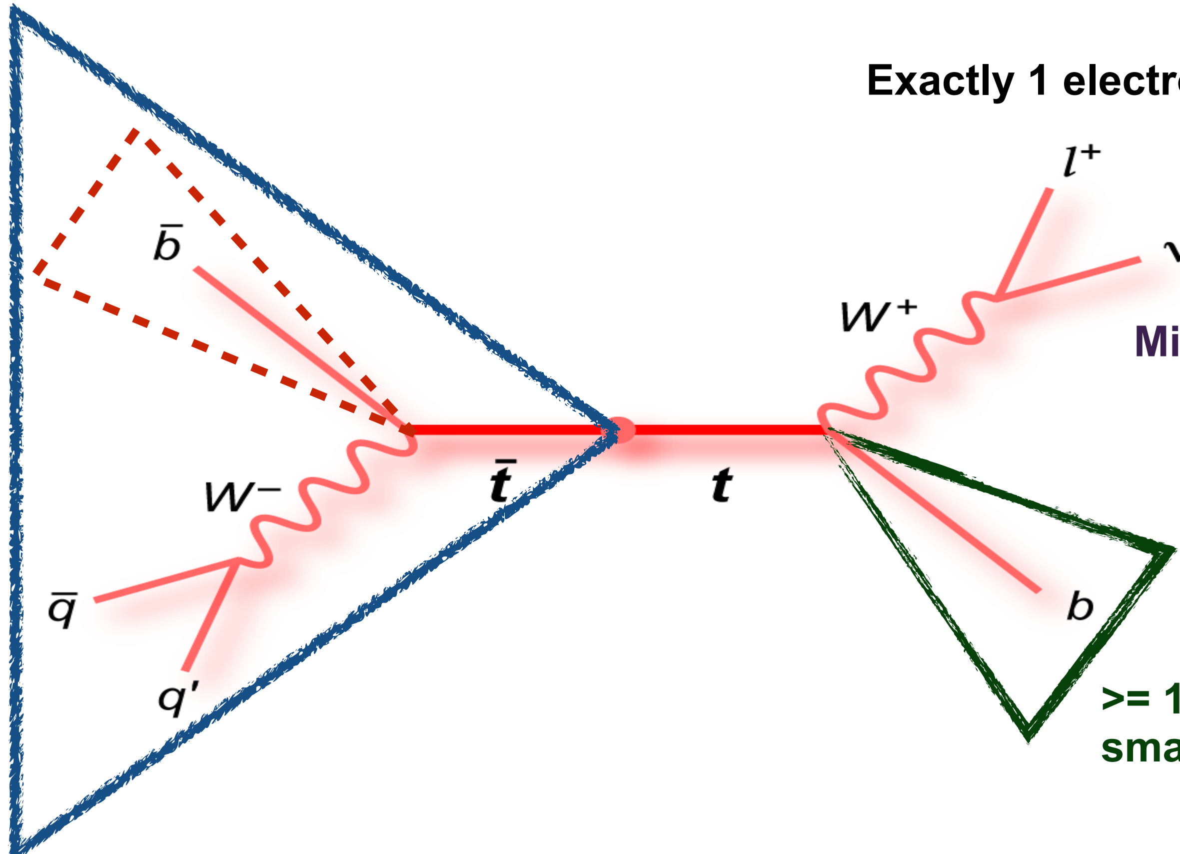
1 large-radius jet

(Top-tagged) [4]

which contains

1 b-tagged track-jet



Exactly 1 electron or muon

Missing E_T

>= 1 b-tagged small-radius jet

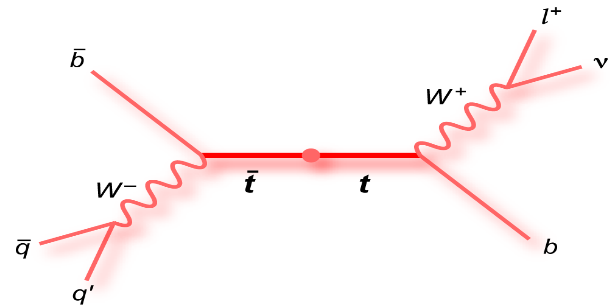
Full list of event selection in backup

Background Modelling : top-quark

[2]

top quark analysis

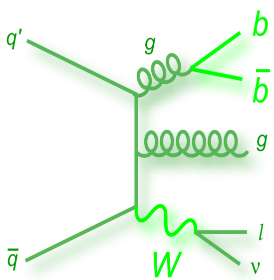
Backgrounds



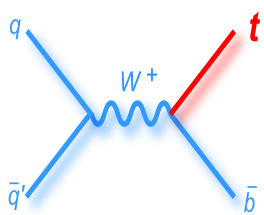
SM $t\bar{t}$

- Largest

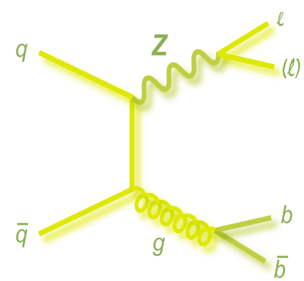
- Irreducible



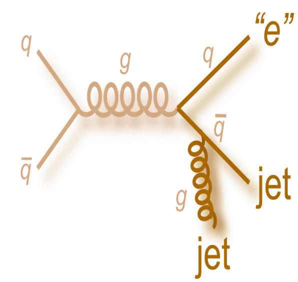
W + Jets



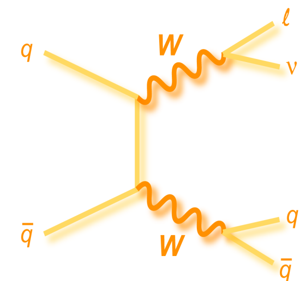
Single Top



Z + Jets



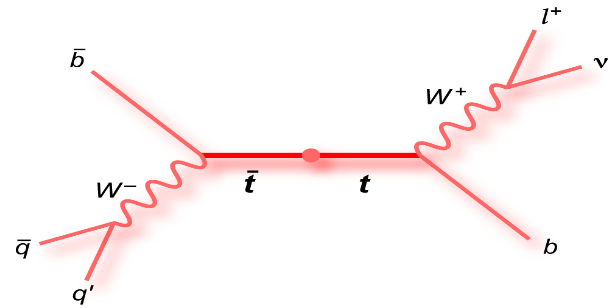
Multi-jet



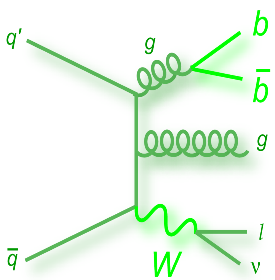
Diboson

top quark analysis

Backgrounds



SM $t\bar{t}$
- *Largest*
- *Irreducible*



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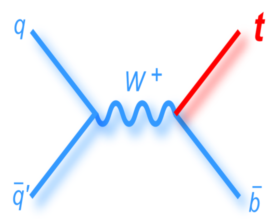

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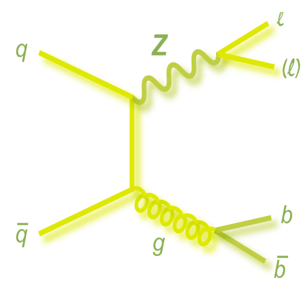

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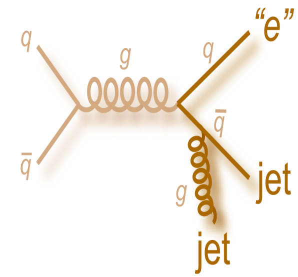
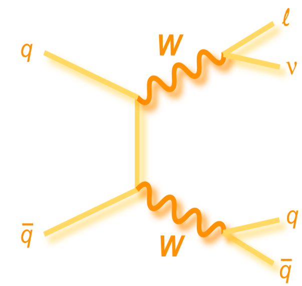


Multi-jet

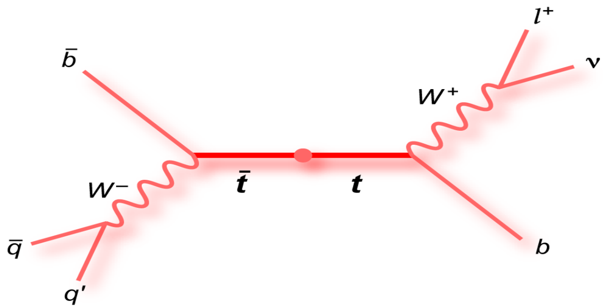


Diboson

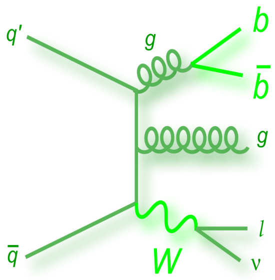
Background Estimations

- **Monte-Carlo Simulation is used for most backgrounds** top quark analysis

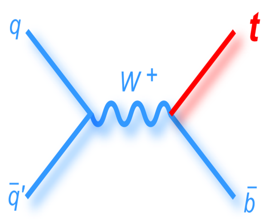
Backgrounds



SM tt̄
- Largest
- Irreducible



W + Jets



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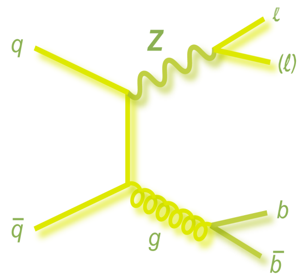
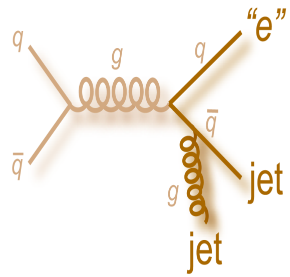
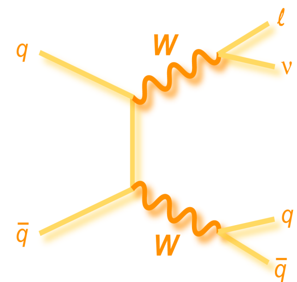


Z + Jets



Multi-jet



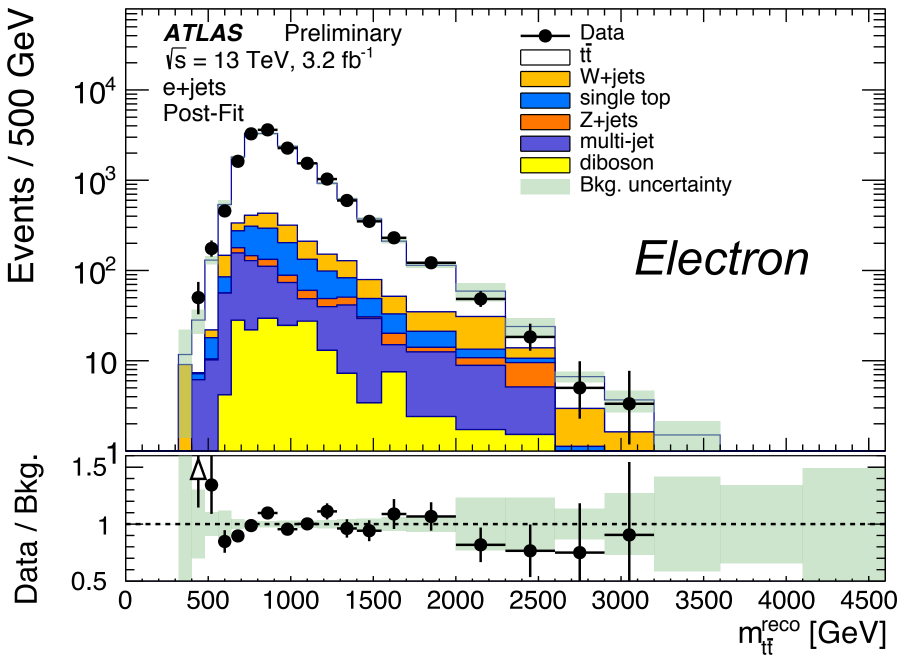
Diboson

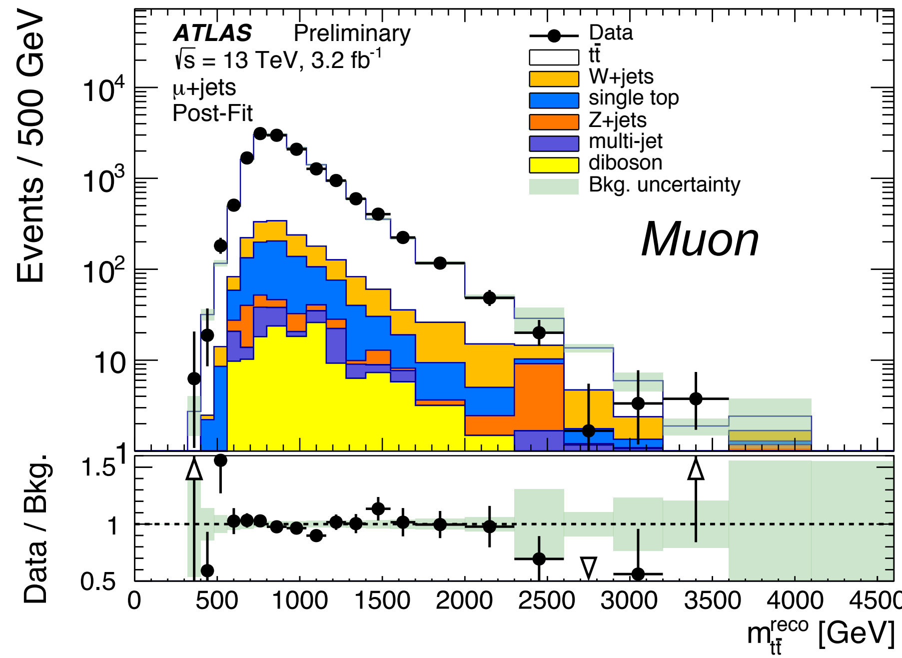
Background Estimations

- **Monte-Carlo Simulation is used for most backgrounds**
- **Data-Driven**
  - ➡ **W+Jets** - Use well predicted W^+/W^- charge asymmetry to correct simulation normalisation
  - ➡ **Multi-jet** - Estimate using a "loose" lepton selection control region, which is multi-jet dominated

- **Search Strategy**
  - Compare data to background estimates
  - Find excesses using BumpHunter

top quark analysis

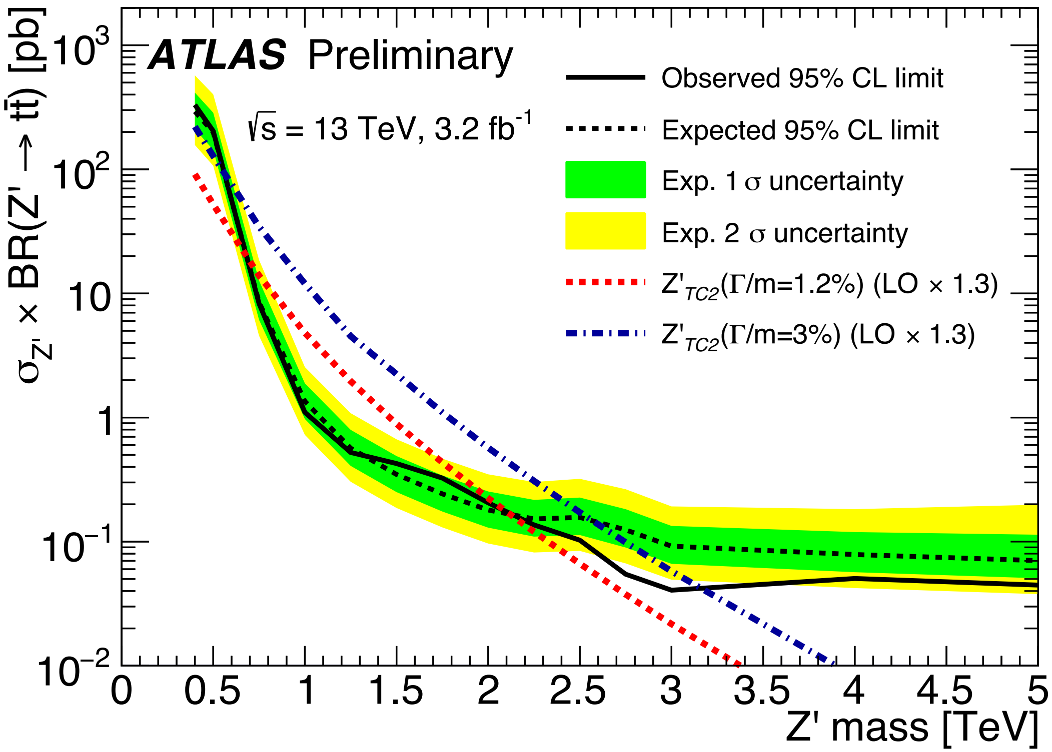




No Significant Deviation Found

Most significant excess:
M = 1.75 TeV
Sig = 0.9 σ

top quark analysis [2]



Limits Set On Benchmark Models

Top-colour Z' boson

0.7 < $m_{Z'}$ < 2.0 TeV, (1.2% width)

0.7 < $m_{Z'}$ < 3.2TeV (3% width)

Model	ATLAS *13 TeV, 3.2 ifb*	CMS [5] 13 TeV, 2.6 ifb	ATLAS *14 TeV, 300 ifb*	ATLAS [6] *14 TeV, 3000 ifb*
Top-colour Z' Boson	**0.7 - 2.0 TeV** *(Width = 1.2%)*	**0.6 - 2.3 TeV** *(Semi-leptonic, Width = 1%)* ***0.6 - 2.5 TeV*** *(Combined with hadronic)*	**3.0 TeV** *(Resolved + Boosted)* *Projected*	**4.0 TeV** *(Resolved + Boosted)* *Projected*

Future Plans For Analysis

b-quark analysis

- **Use trigger level b-tagging to reach new mass ranges**
  - ***m_{jj} > 1.4 TeV*** *: Using single jet-level trigger as presented*
  - ***0.5 < m_{jj} < 1.5 TeV*** *: Using trigger level b-tagging*
  - Such a search performed in 2015 data-set **[7]**

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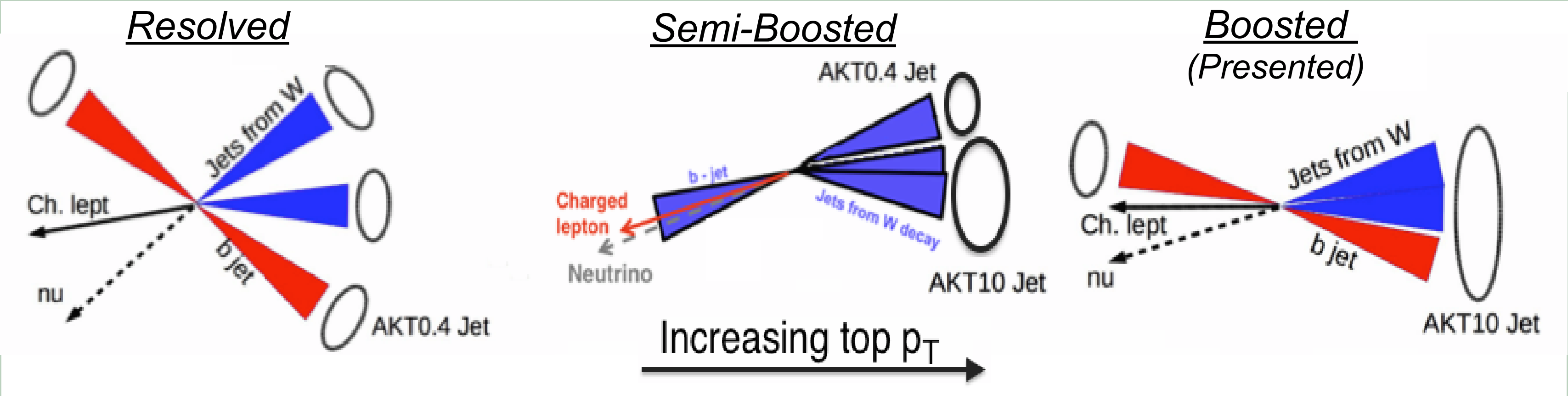
top quark analysis

- **Different topologies for differing top-quark momentums**



- **All hadronic $t\bar{t}$ channel**

Future Plans For Analysis

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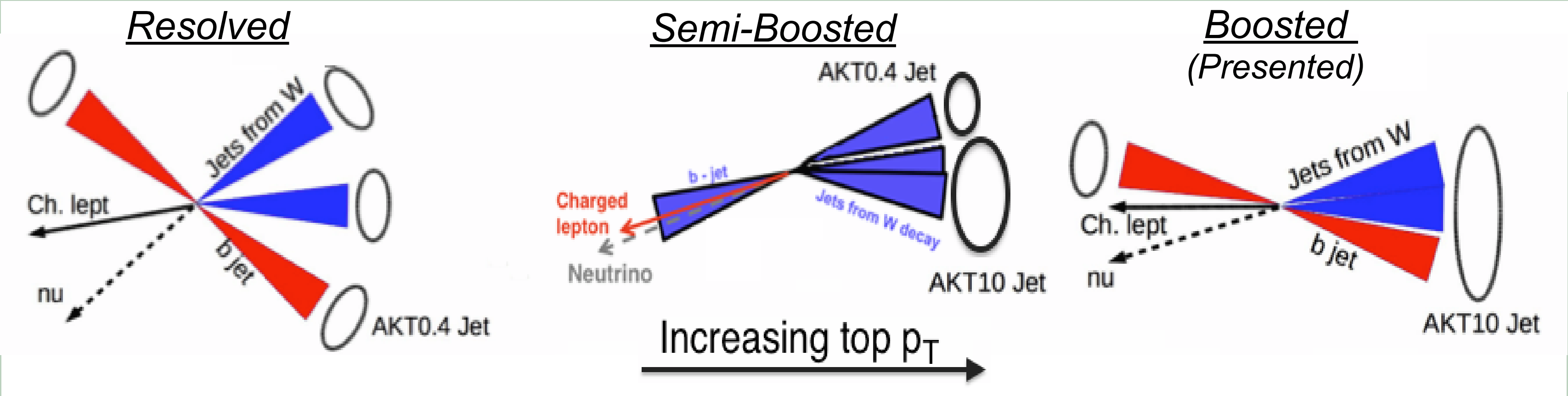
top quark analysis

- **Different topologies for differing top-quark momentums**



- **All hadronic $t\bar{t}$ channel**

both analyses

- *2015 + 2016 data-set :* **~ 36.1 fb^{-1}** *of data*
- **Both analyses expect updates with more data…**

Conclusions

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  - ***b* heavy quark*** *: model could explain quark hierarchy*

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- **Updates expected with full 2015 + 2016 data-set, so stay tuned!**

References and Acknowlegements

[1] : **ATLAS-CONF-2016-060:** **b-quark analysis**
Search for resonances in the mass distribution of jet pairs with one or two jets identified as b-jets with the ATLAS detector with 2015 and 2016 data

[2] : **ATLAS-CONF-2016-014:** **top quark analysis**
Search for heavy particles decaying to pairs of highly-boosted top quarks using lepton-plus-jet events in proton-proton collisions at sqrt(s) = 13 TeV with the ATLAS detector

[3] : **CMS PAS EXO-12-023** *(CMS di-b-jet, 8 TeV)*

[4] : **ATL-PHYS-PUB-2015-053** *(Top-tagger)*

[5] : **arXiv:1704.03366** *(CMS $t\bar{t}$ resonance, 13 TeV)*

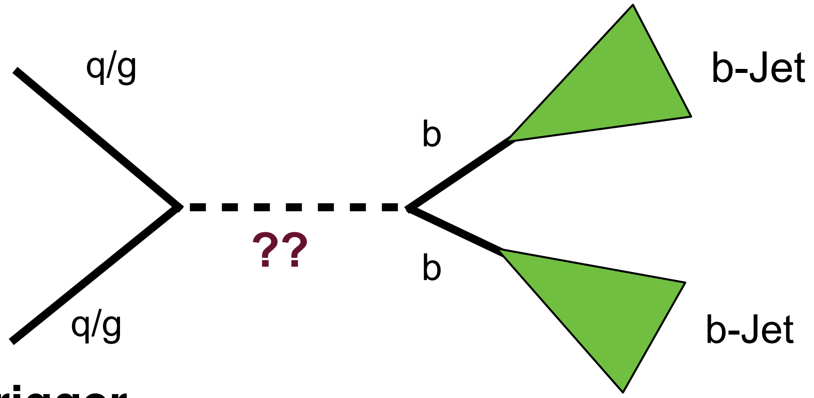
[6] : **ATL-PHYS-PUB-2017-002** *(High-lumi prospects $t\bar{t}$ ATLAS)*

[7] : **ATLAS-CONF-2016-031** *(Low-mass di-b-jet)*

Thanks to:

- Anna Duncan: for overview slides and sourcing cartoons for $t\bar{t}$ analysis
- Andreas Korn: for some figures and slides on Z' as DM mediator
- Lene Bryngemark: for the dijet resonance cartoon

Backup



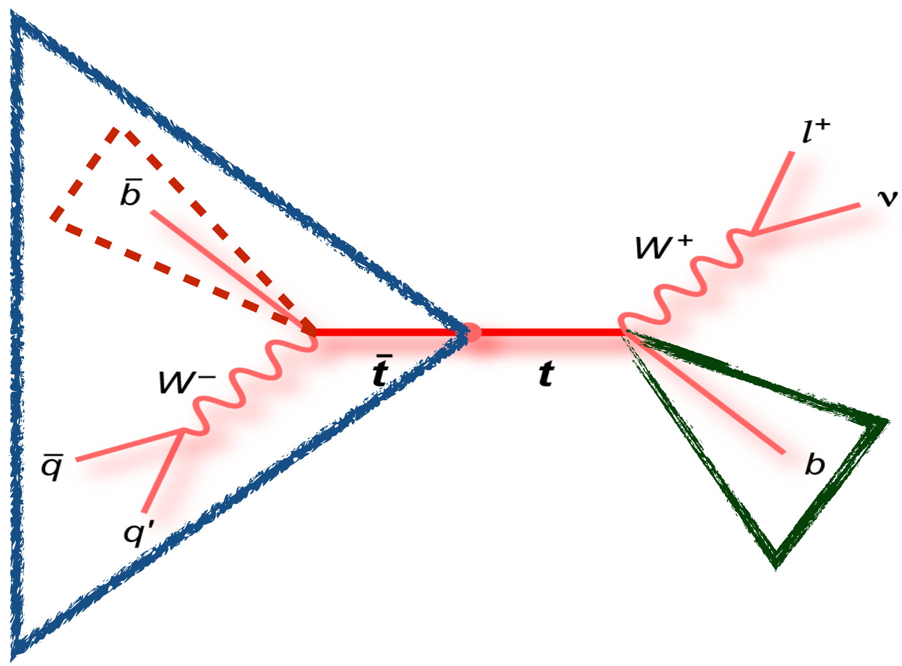
- **Data Used**
  - **Comined 2015 + 2016 Data Set 13.3 ifb**
  - **GRL - IBL-on data only**
- **Trigger**
  - **HLT_j380, lowest unprescaled single jet trigger**
- **Event Selection**
  - Reject events with problematic calo. reconstruction (LAr, Tile and Core Errors)
  - **At least two jets.**
  - **Leading-jet $p_T > 440$ GeV, Subleading jet $p_T > 60$ GeV**
  - **$m_{jj} > 1340$ GeV, such that we are on the trigger plateau.**
  - **$|y^*| < 0.6$, where $y^*=0.5*(y_1 - y_2)$, central region more sensitive**
  - **$|\eta| < 2.4$, in tracking geometry for b-tagging**
  - **2 b-Tagged jets:** fixed 85% efficiency WP
- **Jet Selection**
  - Standard jet calibration (with JES correction applied)
  - 2016 loose jet quality cuts applied.

Data and Event/Jet Selection

top quark analysis

UCL

- **Data Used**
  - 2015 Dataset - 3.2 ifb - (GRL - IBL-on)
- **Trigger**
  - e trigger: *HLT_e24_lhmedium_L1EM18VH OR HLT_e60_lhmedium OR HLT_e120_lhloose.*
  - •μ trigger: *HLT_mu20 _loose_L1MU15 OR HLT_mu50*
- **Event pre-selection**
  - Exactly one lepton (electron or muon)
    - Veto on the 2nd lepton at pT > 25 GeV.
  - $E_T^{Miss} > 20$ GeV
  - $E_T^{Miss} + m_T^W > 60$ GeV
- **Jets**
  - **≥ 1 b-tagged track jet**
  - **≥ 1 R = 0.4 jet (small-R jet)**
    - ΔR(small-R jet,l) < 1.5.
  - **≥ 1 large-R jet (large-R jet)**
    - Δφ(l,large-R jet) > 2.3
    - ΔR(large-R jet, small-R jet) > 1.5.



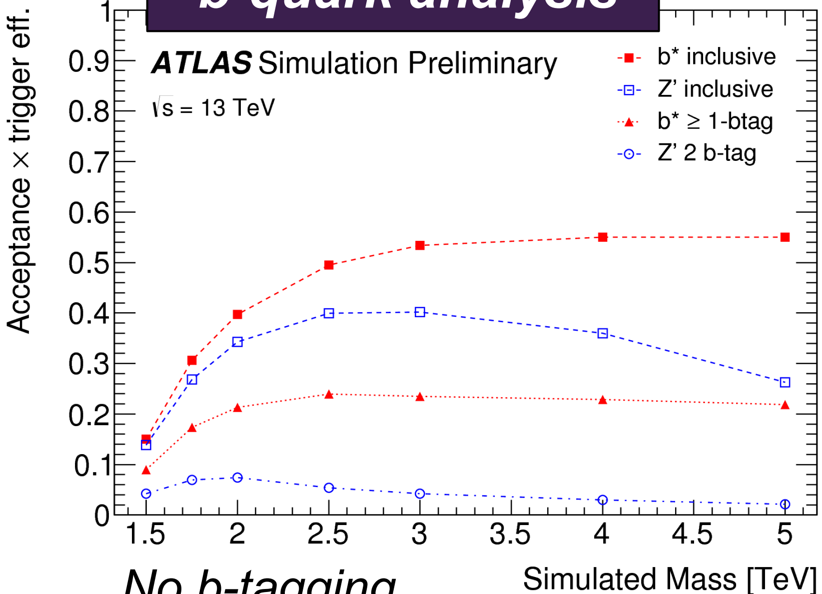
Lepton/Jet Overlap Removal

- **Muons**
  - If $\Delta R(\text{muon, jet}) < (0.04 + 10\text{GeV}/p_{\mu T})$:
    - If the jet has at least 3 tracks originating from the primary vertex, remove the muon
    - Else, remove the overlapping jet

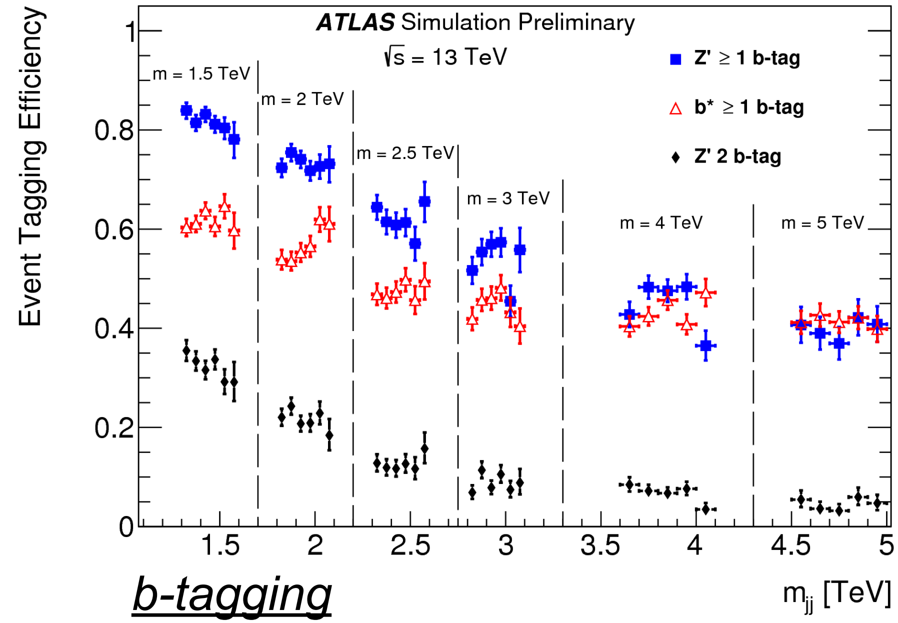
- **Electrons**
  - Reject small-R jets with $\Delta R(\text{electron, jet}) < 0.2$
    (assume it's an electron energy deposit)
  - Then, reject electrons that have $\Delta R(\text{electron, jet}) < 0.4$
  - (assume it's a b-jet decay).

Signal Acceptance

b-quark analysis



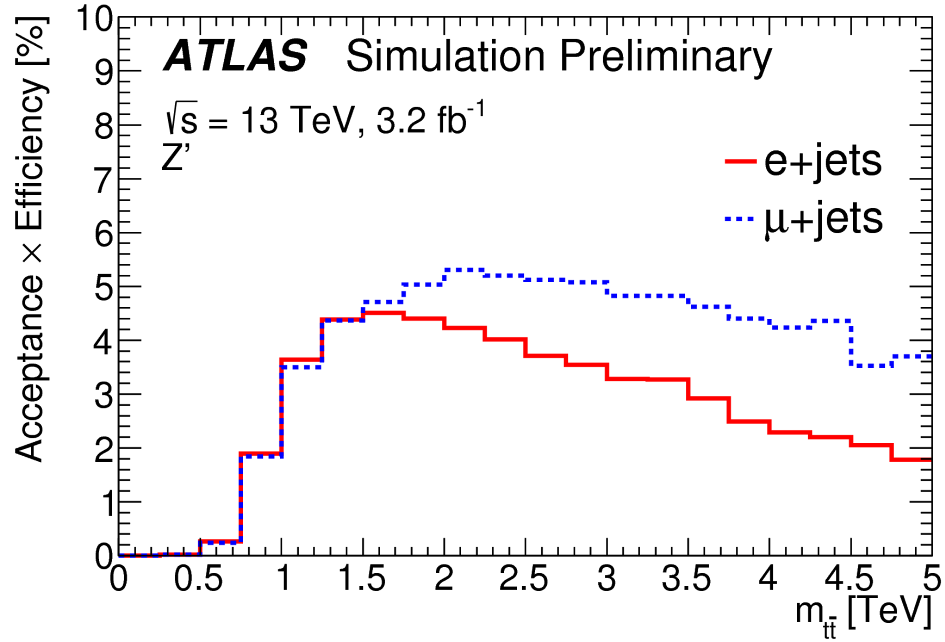
No b-tagging



b-tagging

[1]

top quark analysis



[2]

Background Function Choice

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b-quark analysis

- Fit to background using smoothly falling

$$f(x) = p_1(1-x)^{p_2}(x)^{p_3+p_4\ln x+p_5\ln x^2} \quad \text{where,} \quad x = m_{jj}/\sqrt{s}$$

- This comes in 3, 4 and 5 parameter functions for 3 and 4 parameter set $p_4 = p_5 = 0$ or $p_5 = 0$ respectively

- Use Wilks' statistic for nested function
  - Compares to a higher-order function
  - Follows chi2 distribution
  - Hence, can calculate a p-value from it

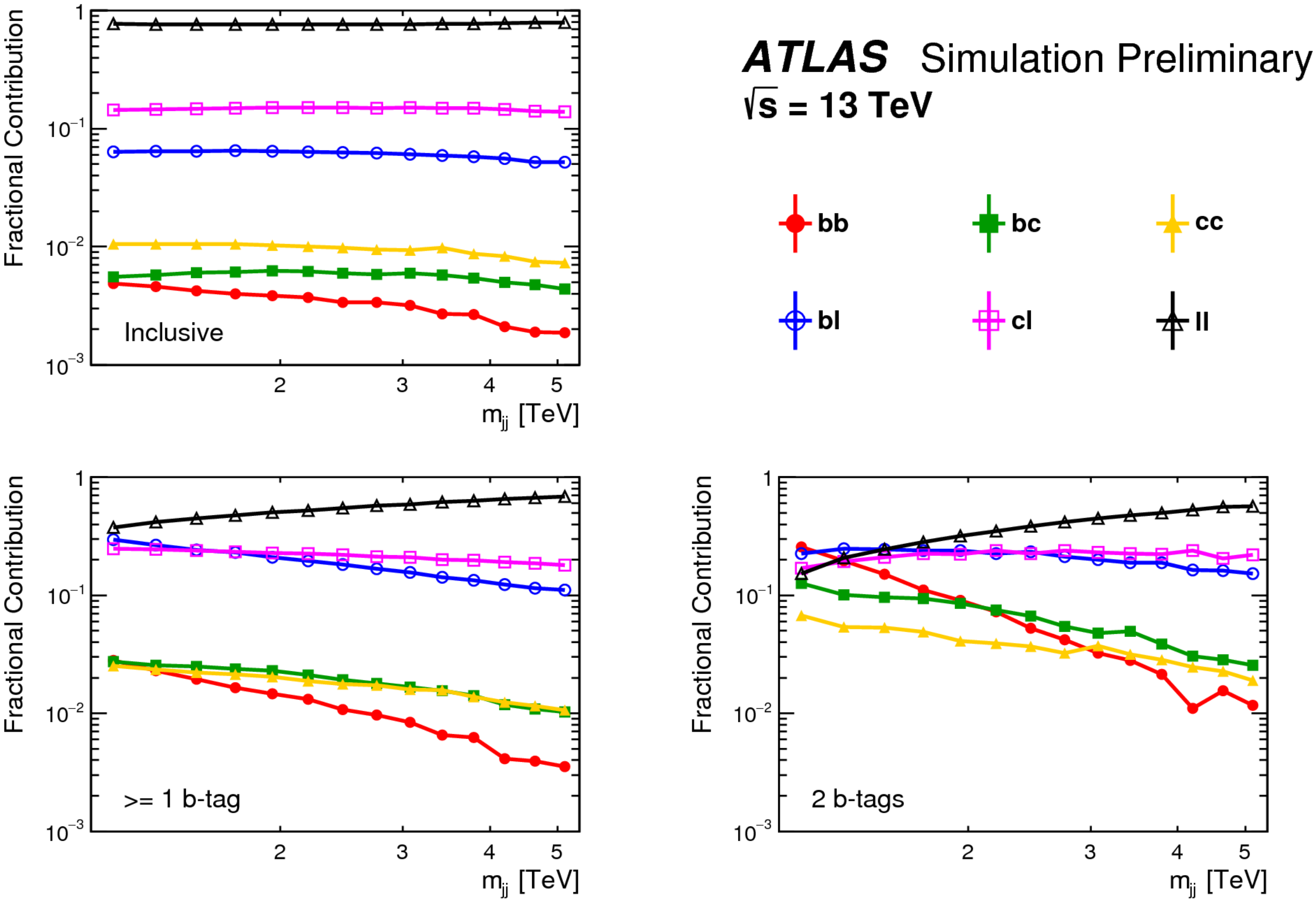
$$-2log(\Lambda) = -2log\left(\frac{L(H_0|x)}{L(H_1|x)}\right)$$

- Use Wilks' p-value to choose fit function
  - Default option is 3 parameter fit function
  - Compare to higher order function (4 parameter)
  - If p-value drops below 0.05:
    - Indicates that the higher-order function required.
    - Adopt higher order function and then test against 5-parameter

Background Flavour Composition

b-quark analysis

[1]



1. **Background from sources of non-prompt leptons (predominantly QCD multijet).**
    - Very large uncertainties in Monte Carlo modelling
    - Choose region with many leptons of low reconstruction quality (larger contribution from QCD multijet events).
    - Matrix method separated prompt from non-prompt leptons.
    - loose→tight efficiency ε and fake rate f derived from (or validated with) data.
    - Select signal events except with loose lepton criteria. The number selected will be Nprompt + NQCD
    - Ntight =ε×Nprompt +f ×NQCD
    - Solve for f × NQCD (using anti-tight leptons)
    - Shape: Weights to account for f and ε dependency on variables.

2. **W+jets background normalisation.**
    - Data driven scale factors
    - Select events with signal selection, except ≥ 1 b-tag cut.
    - W+jets charge asymmetry well predicted.