Probing extended Higgs and Dark Sectors with *b*-jets at the LHC

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Matthias Saimpert (CERN)

Yukawa-like interactions in the Standard Model

Experimental signature at the LHC

b-jet identification in ATLAS

Application to Higgs and Dark Sectors

What is next?

Yukawa-like interactions in the Standard Model

Yukawa potential (1935)

$$V_{\text{Yukawa}}(r) = -g^2 \frac{e^{-\alpha m r}}{r},$$

$$\mathcal{L}_{\text{Yukawa}}(\phi, \psi) = -g\bar{\psi}\phi\psi\,, \quad \psi \ \text{ Dirac field}$$

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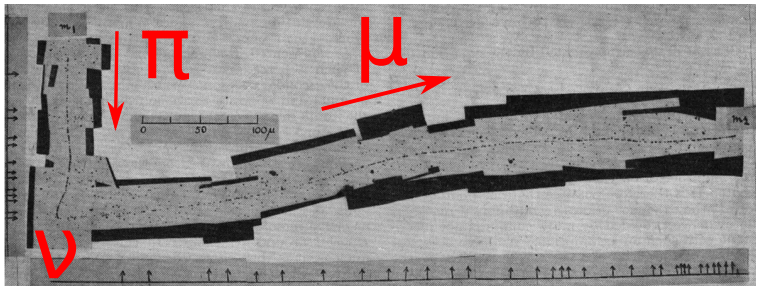
π meson discovery (1947)



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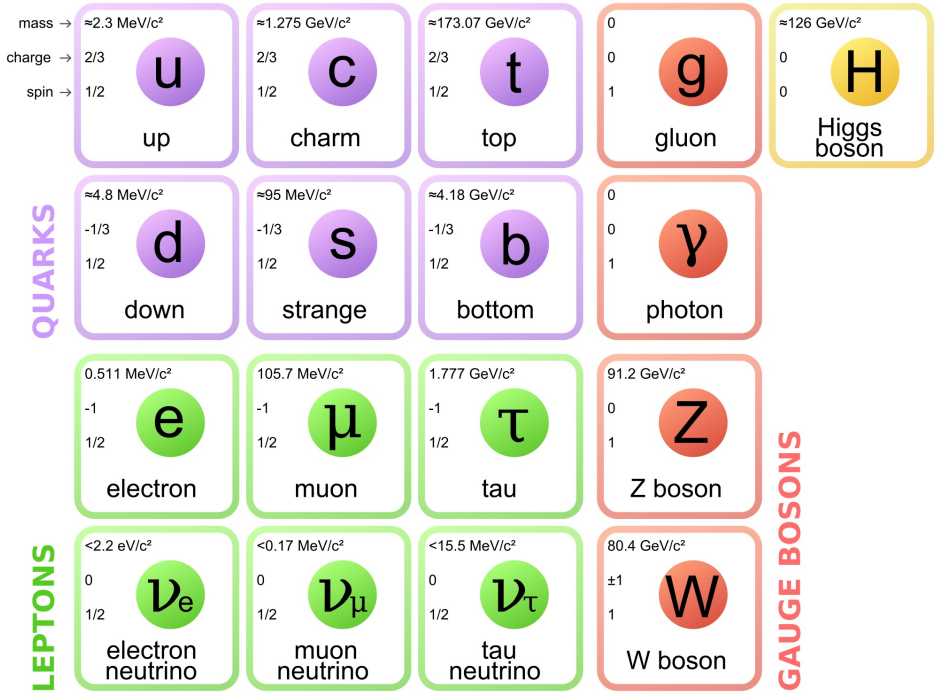

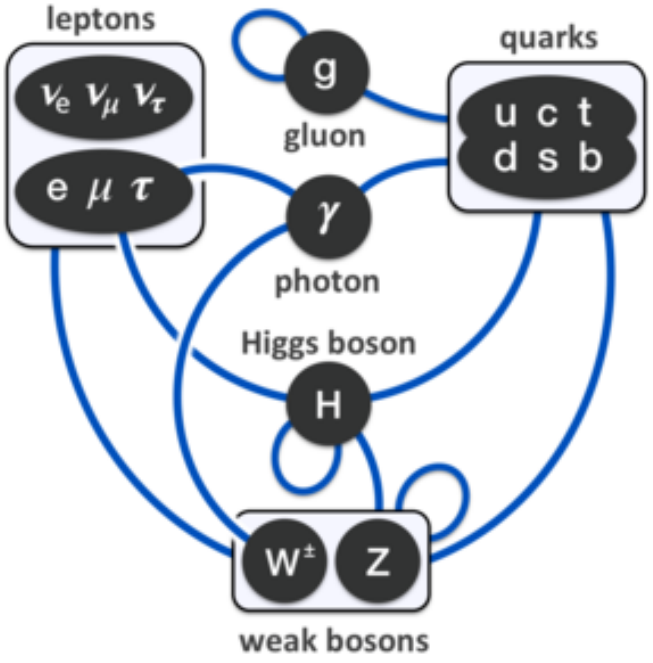

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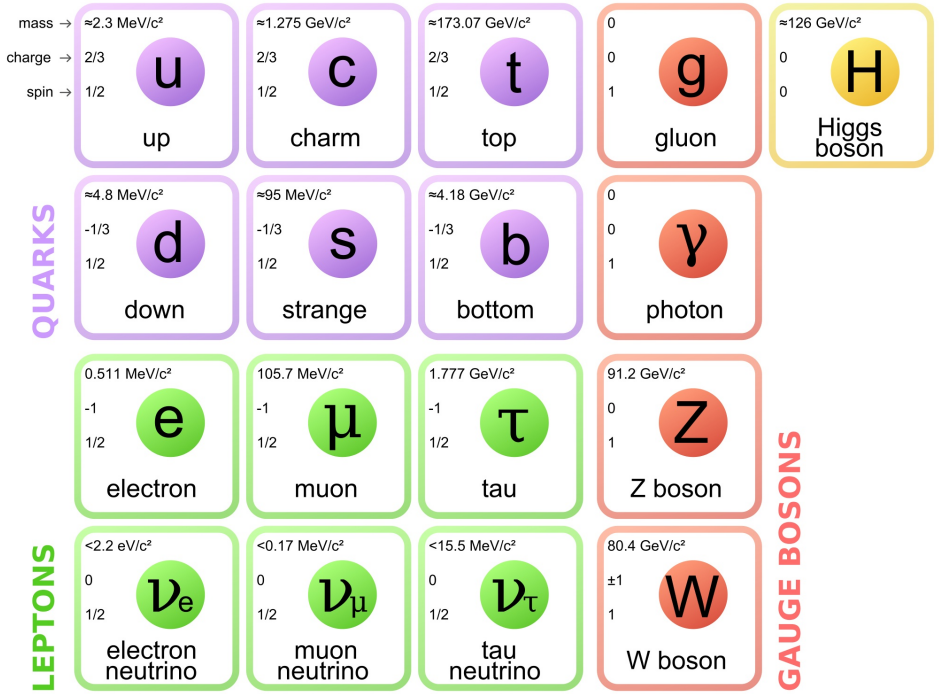

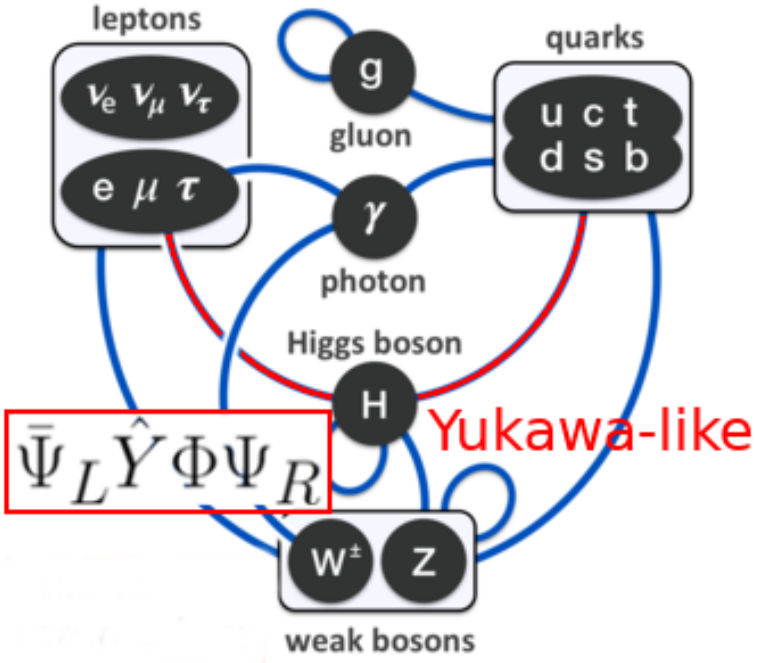

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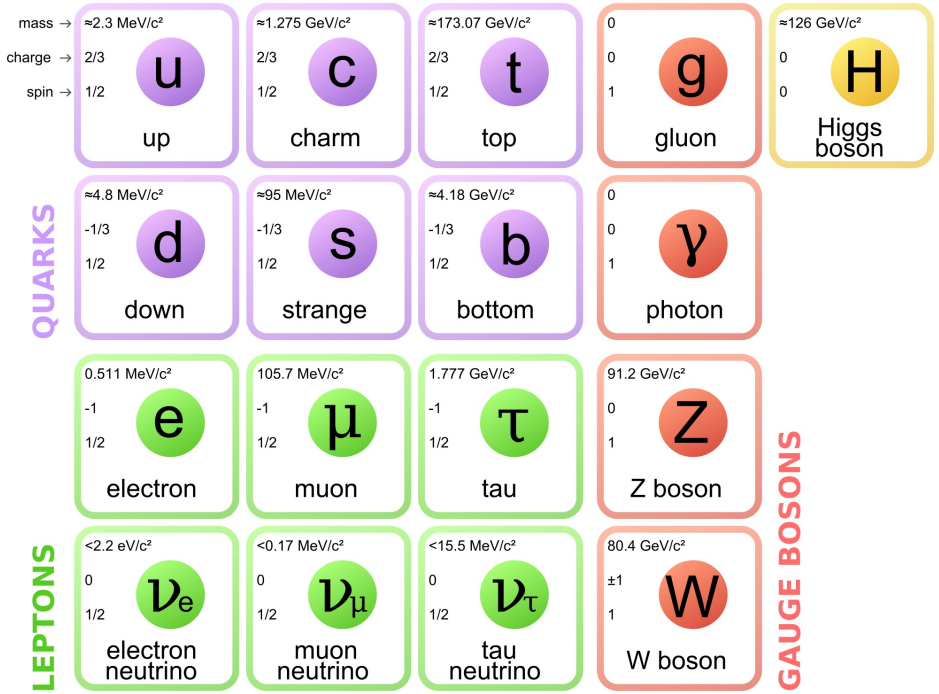

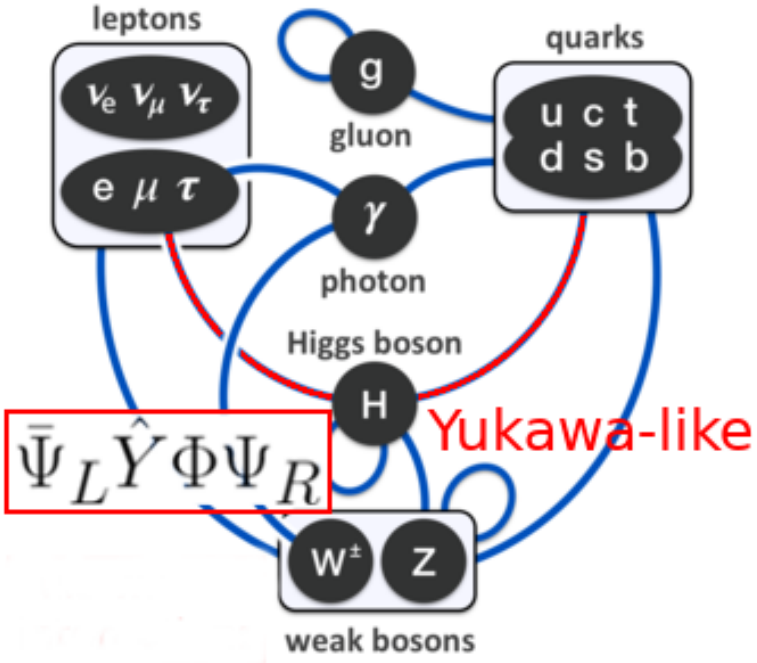

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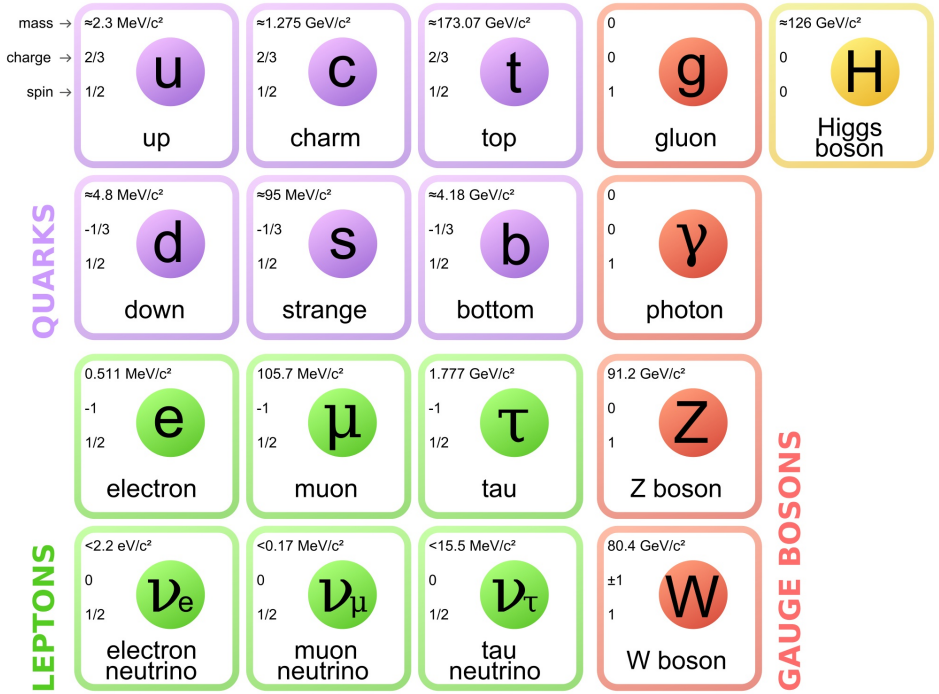

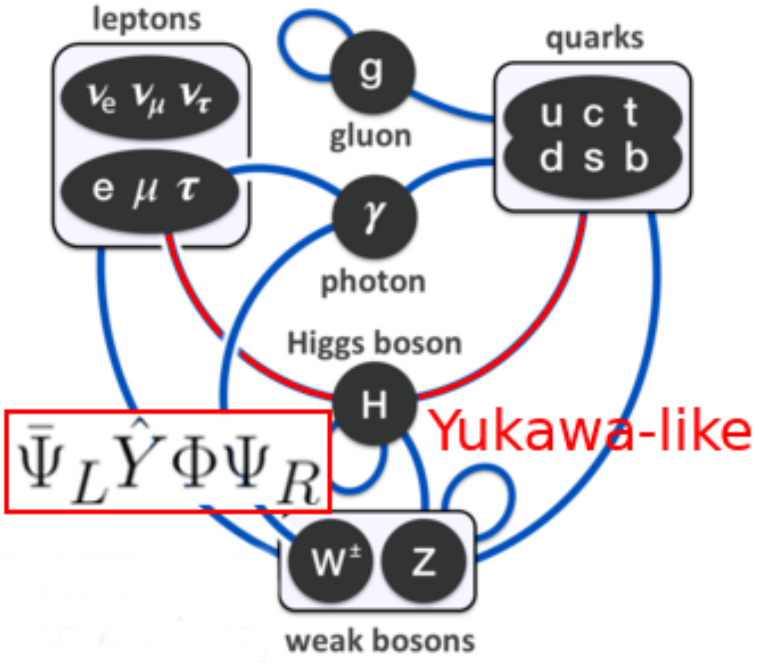

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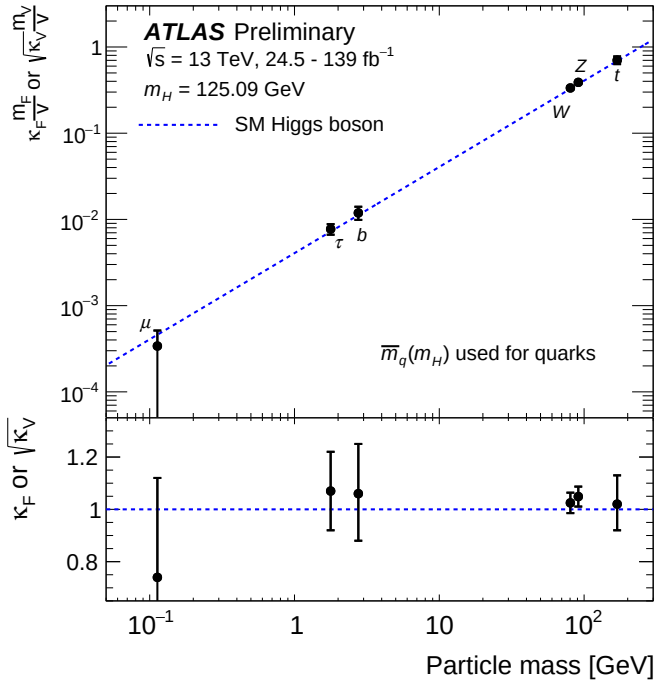
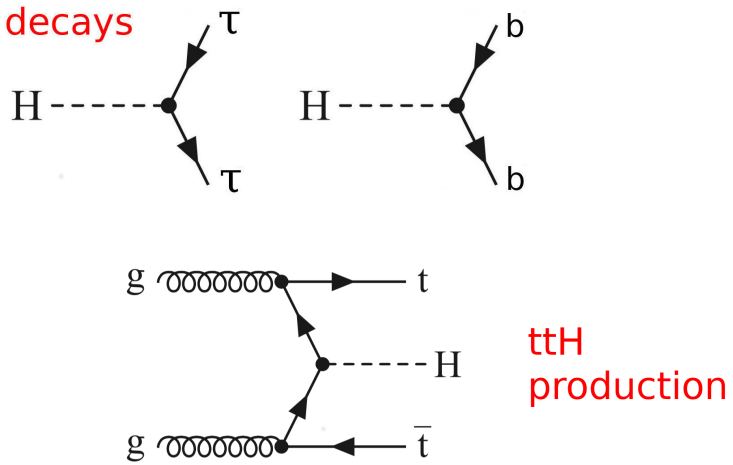
  - added "by hand" in SM lagrangian

Recently observed at the LHC!





- Observation of $H \to \tau\tau$ decays (2016) JHEP 08 (2016) 045
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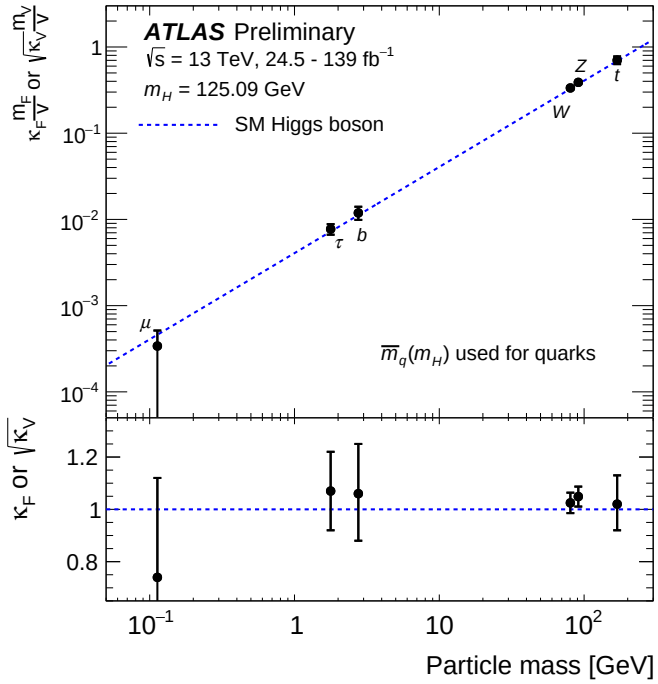

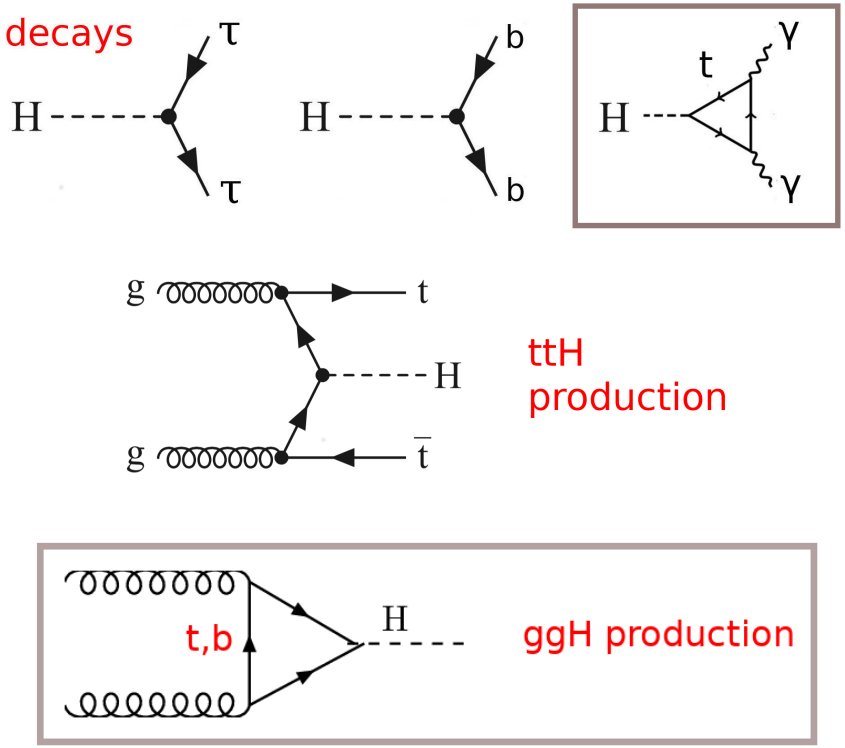

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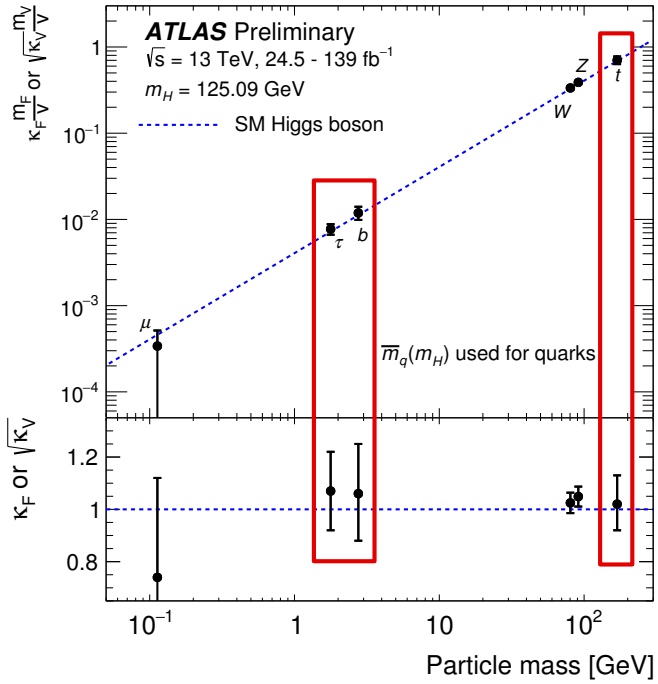

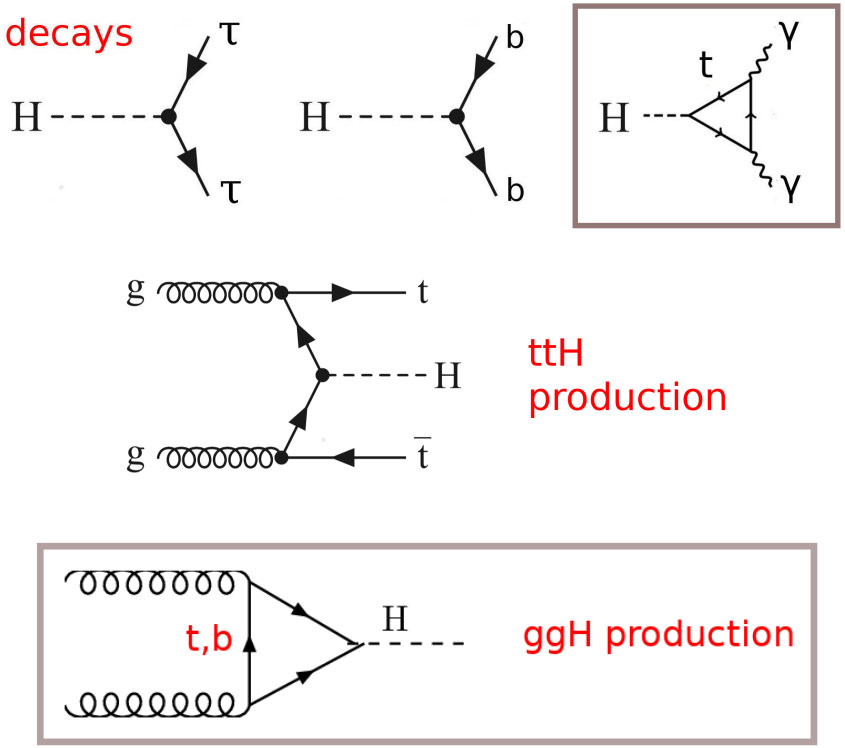

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  - t, b-H couplings probed via ggH prod. and $H \to \gamma\gamma$ decays since 2012
- Consistent with SM Yukawa-like couplings **but limited precision**

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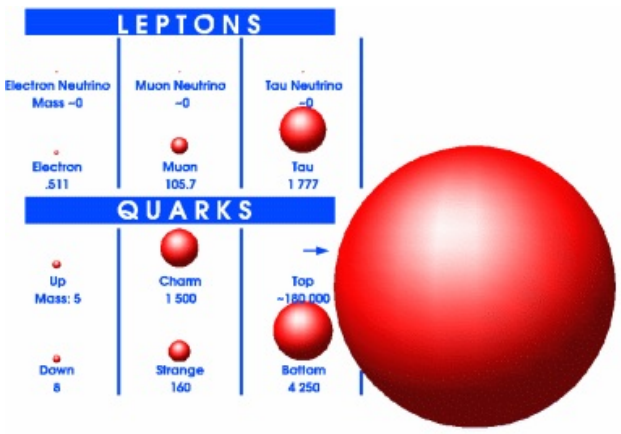
- SM Yukawa-like interactions are **special**
  - no underlying symmetry
  - no quantized charge
  - coupling over 6 orders of magnitude



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  - flavour structure of charged currents
  - nuclear physics ($m_n > m_p$)
  - connected to strong CP problem?
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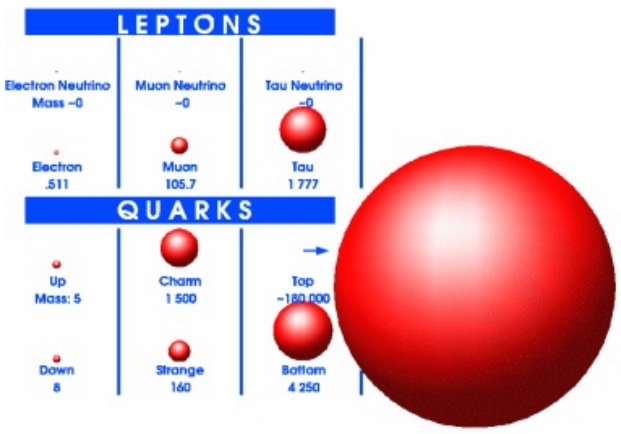

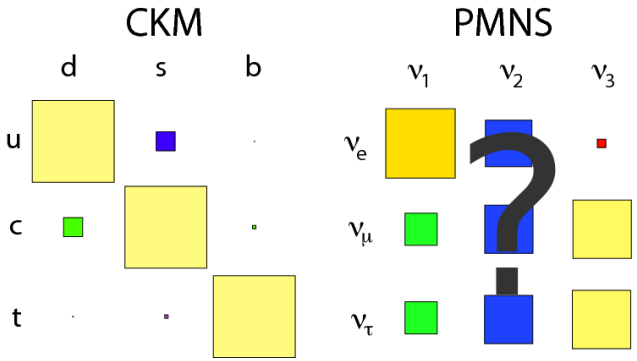

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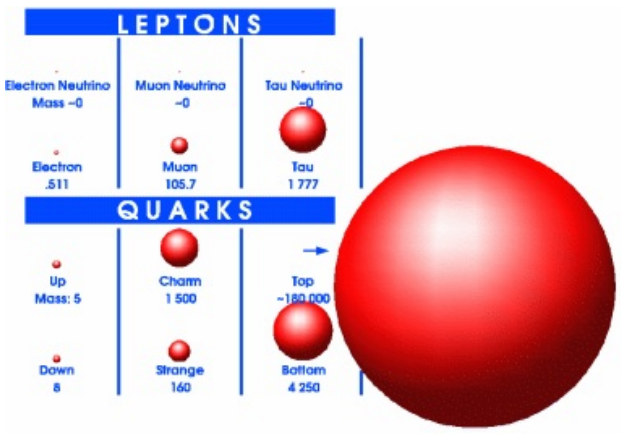

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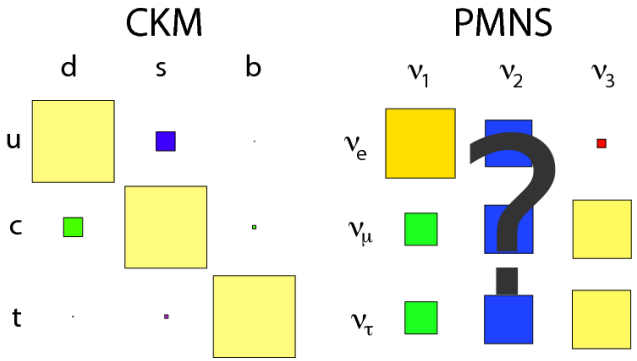
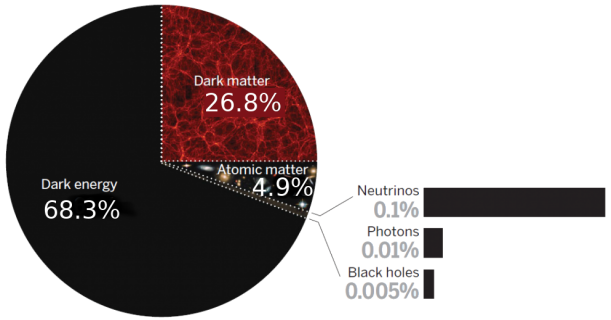
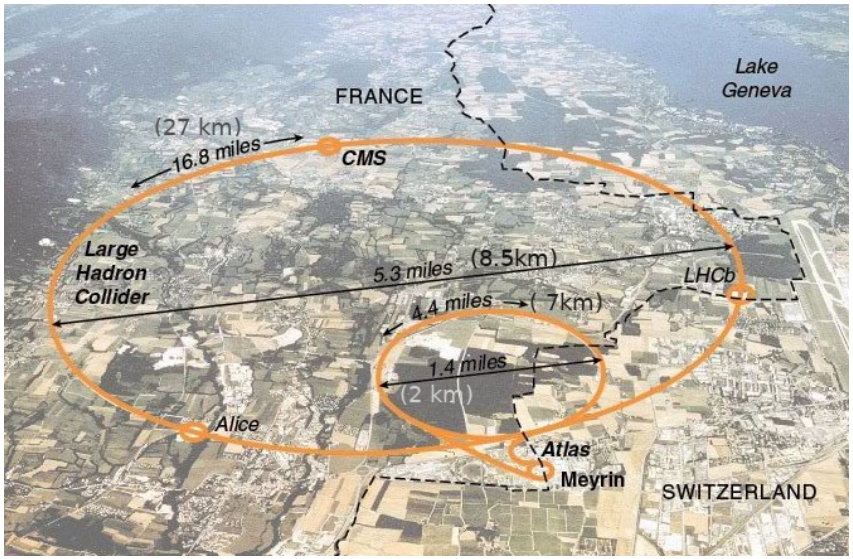


- True nature of SM Yukawa-like interactions?
  - fundamental or effective
  - *CP* invariant or *CP* violating
  - one or more mediator boson
  - portal to dark sector?



Experimental signature at the LHC

The Large Hadron Collider at CERN



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  - 2010-2012: $\sqrt{s} = 7, 8$ TeV
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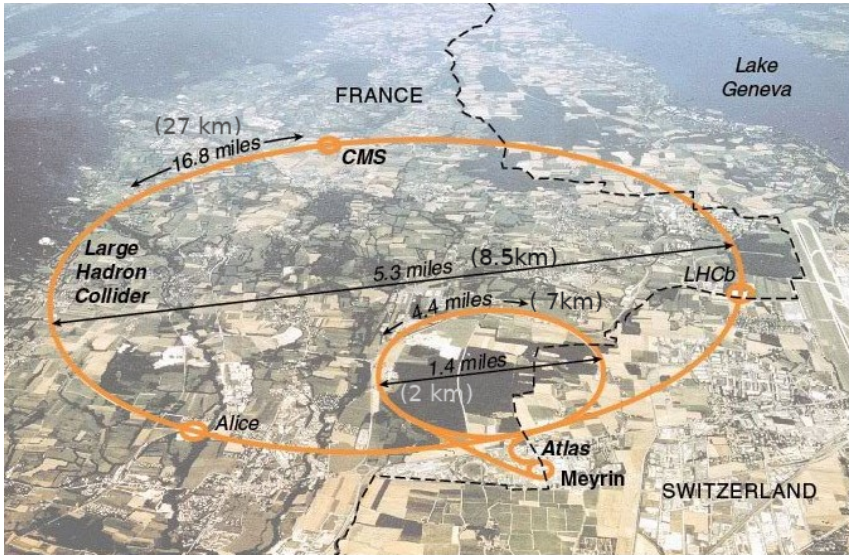
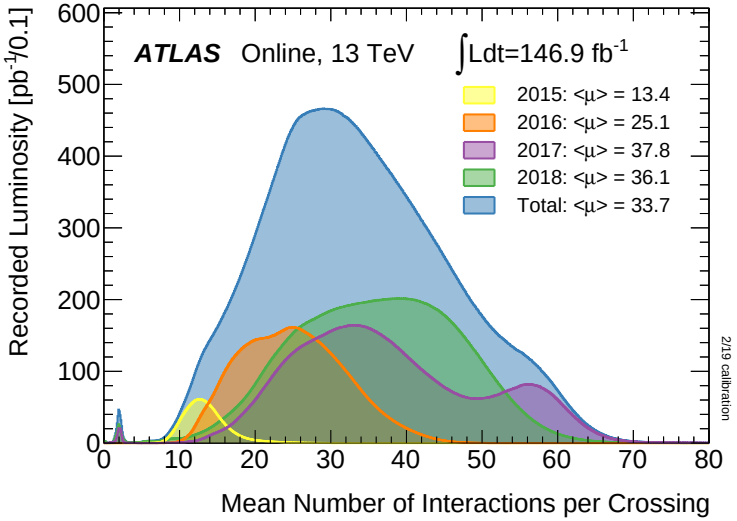


JINST 3 (2008) S08001 ATLAS Luminosity Public



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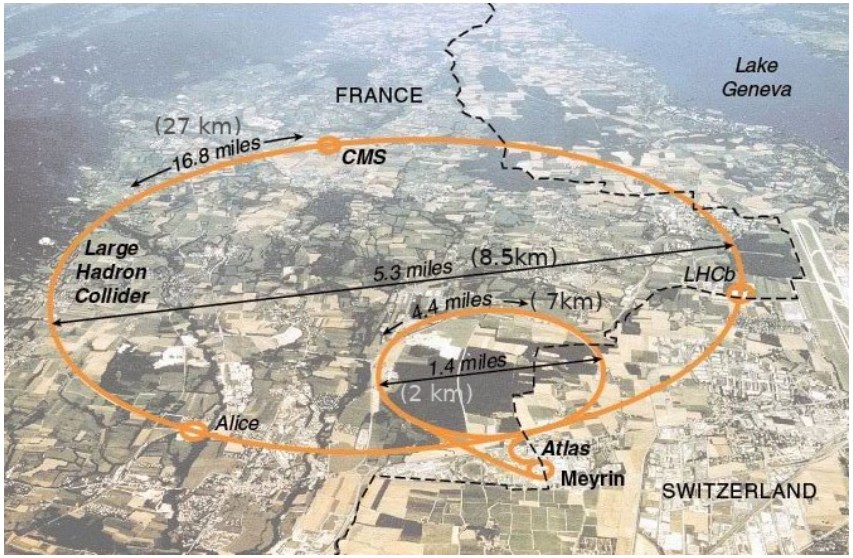

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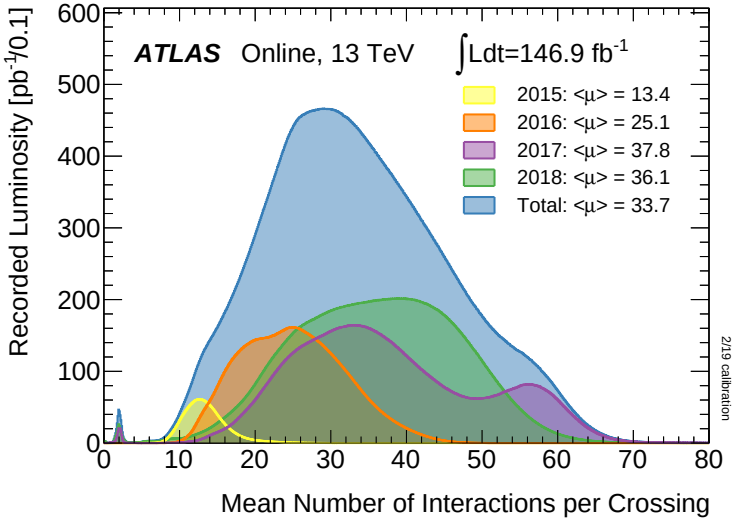

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- Long shutdown in 2019-2020
  - preparing for large luminosity increase

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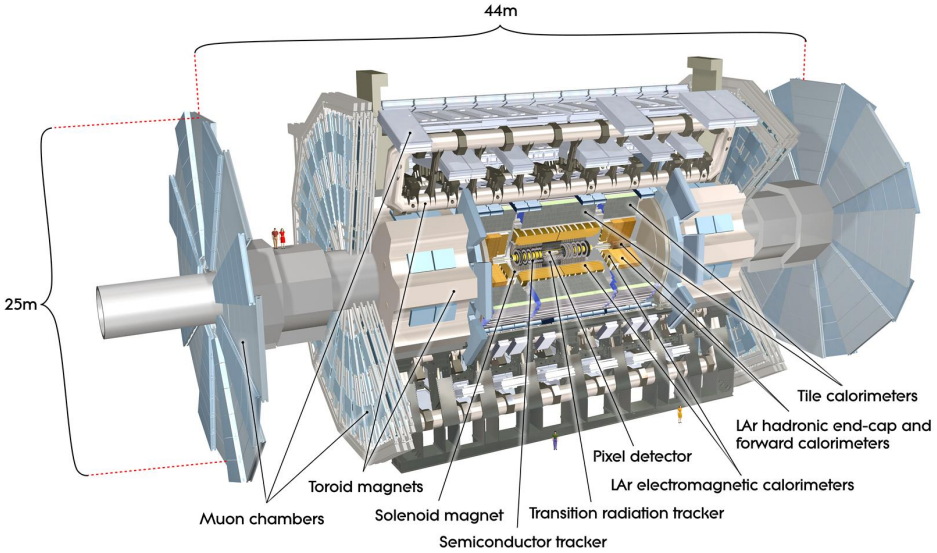
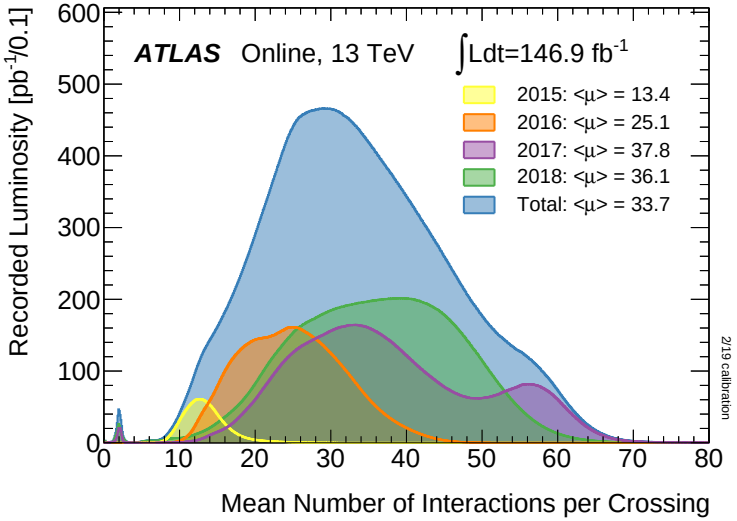


JINST 3 (2008) S08003 ATLAS Luminosity Public



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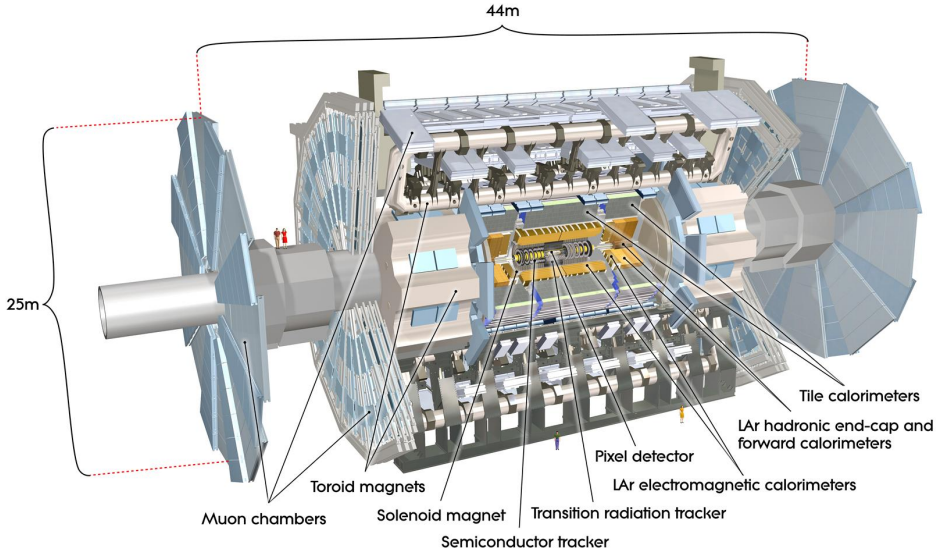

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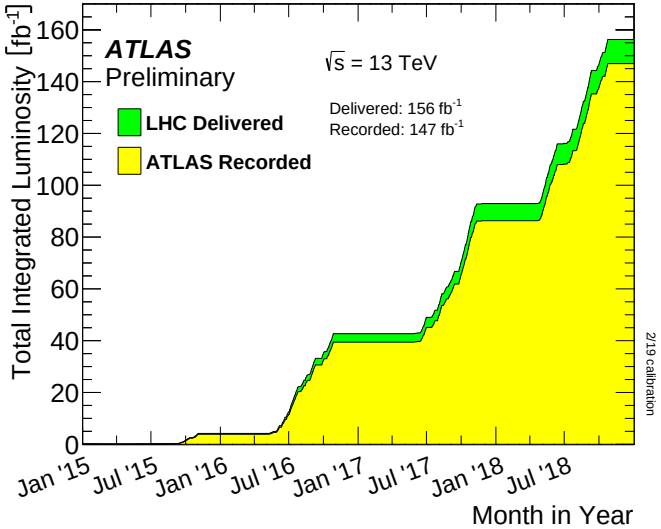

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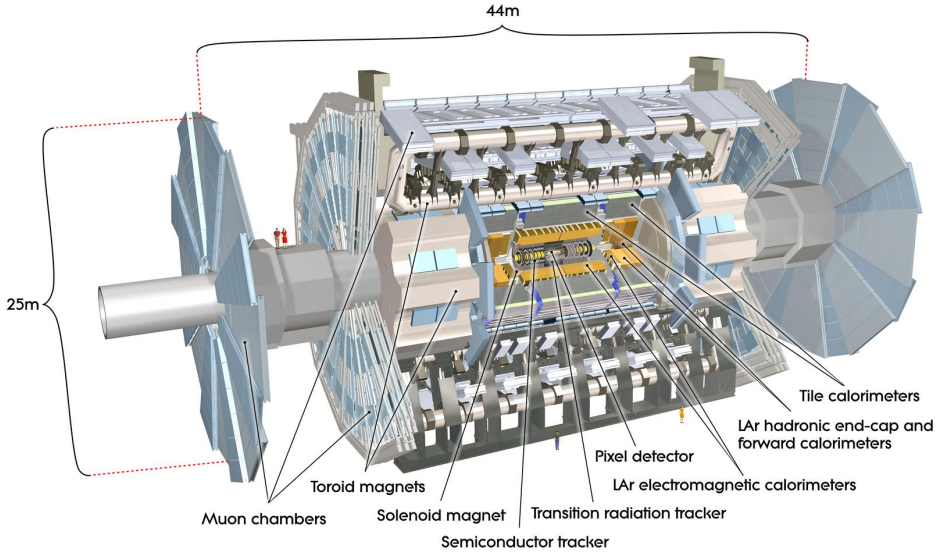

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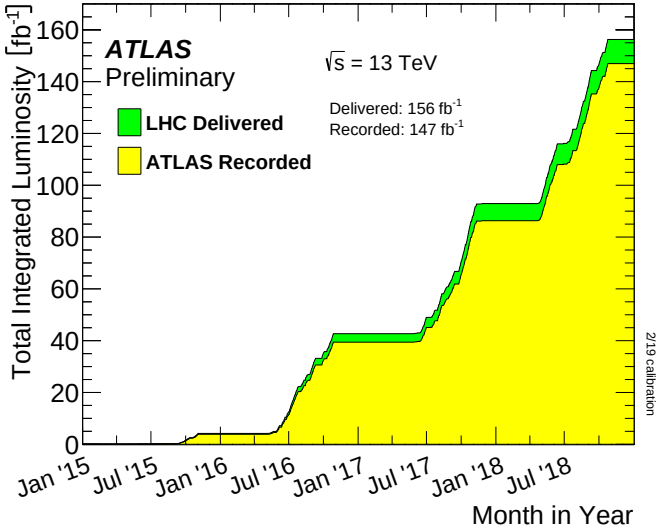

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- Focus on ATLAS results in the following
  - similar physics output from CMS

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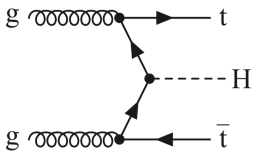

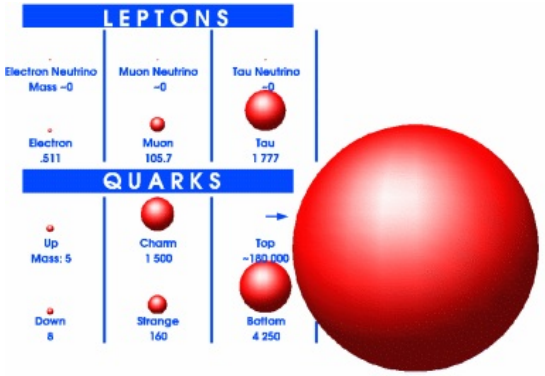

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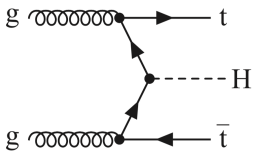

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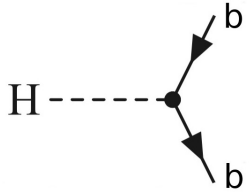

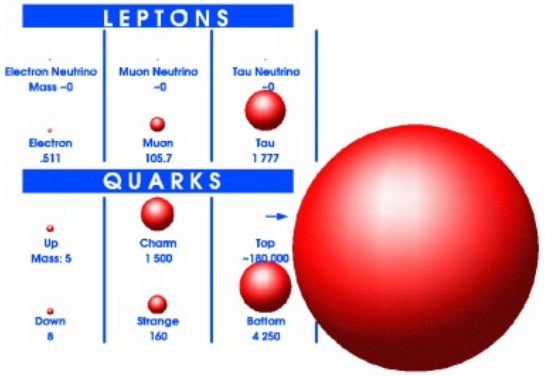

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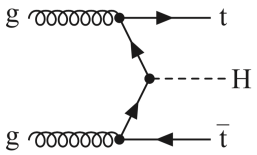

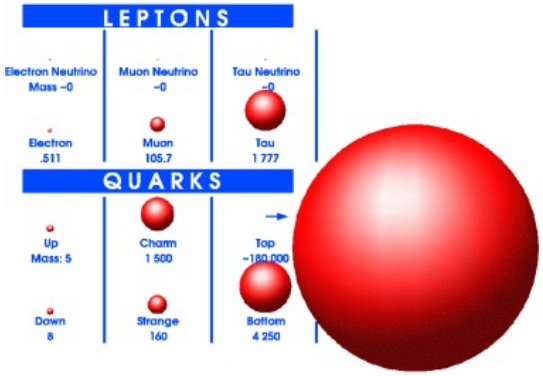

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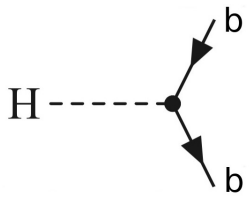
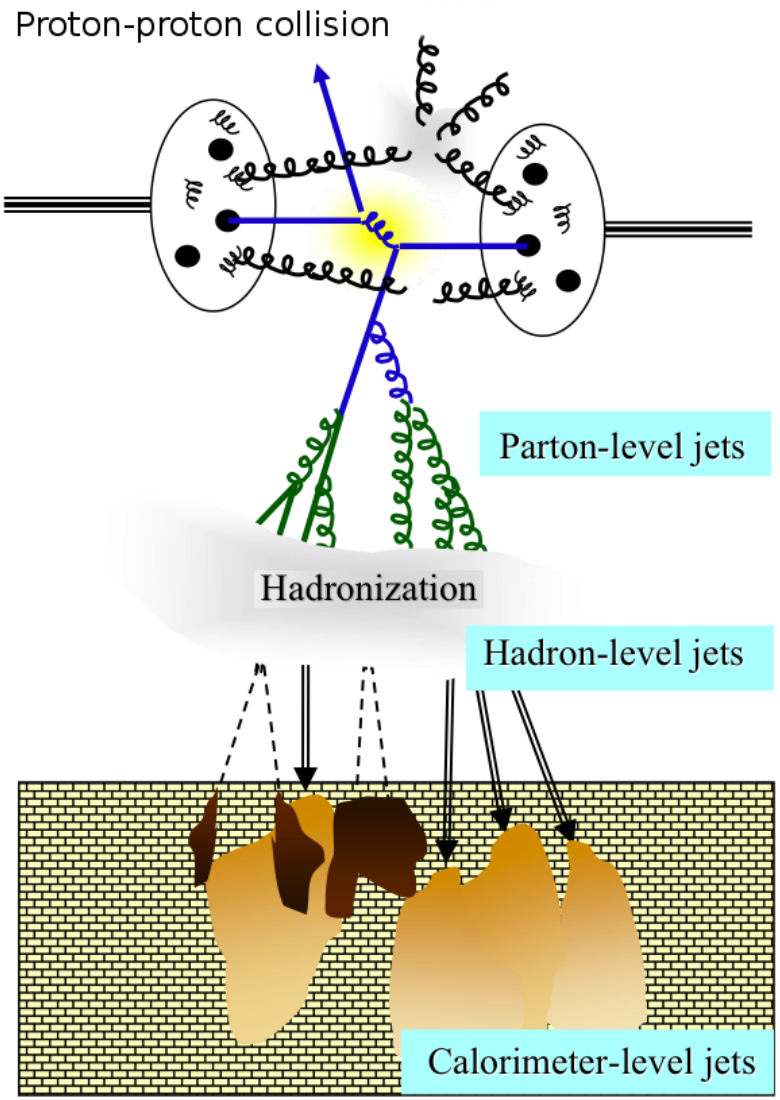


Identification of **jets originating from b quark (b-jet)** is key to study Yukawa-like interactions at the LHC

b-jet identification in ATLAS

What is a hadronic jet?



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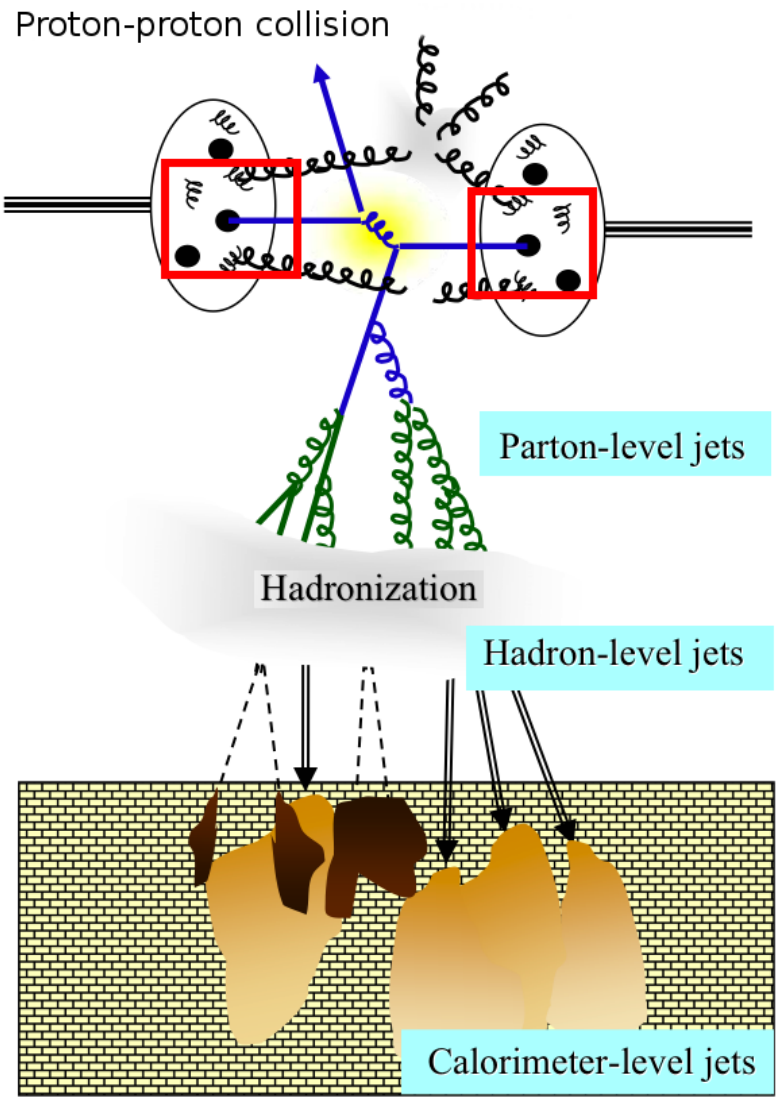

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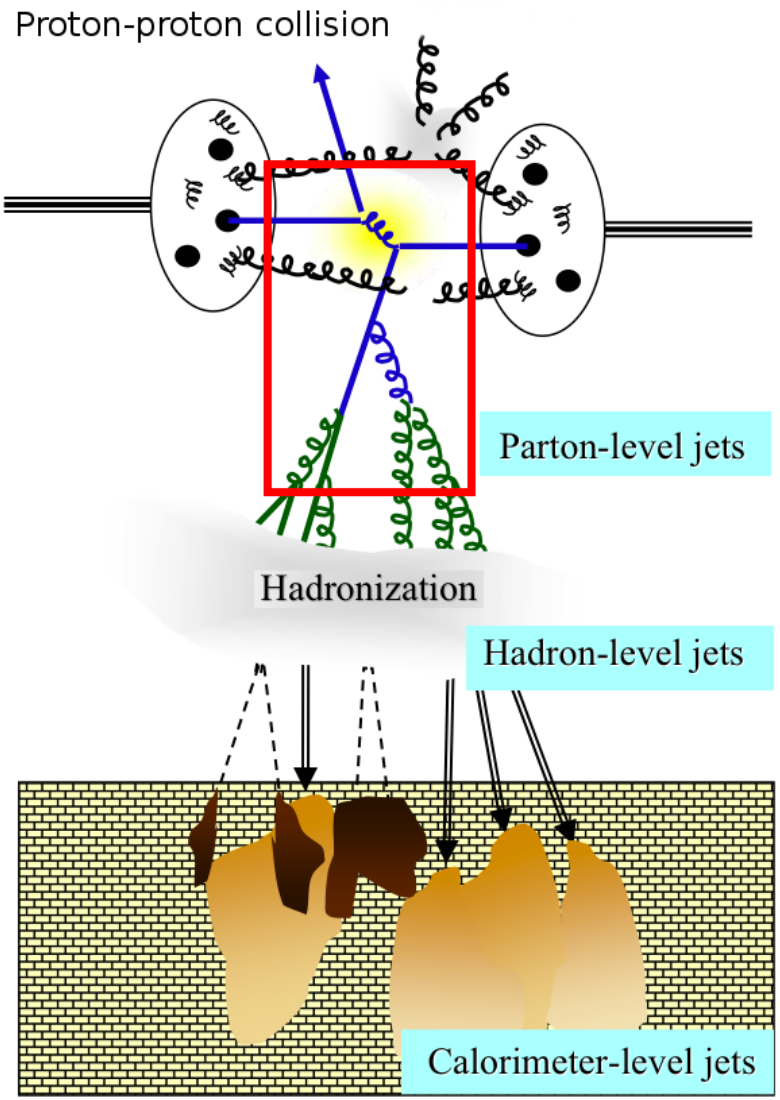

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- Partons ejected at high angles: collimated parton shower
  - in simulation: "parton-level" jets

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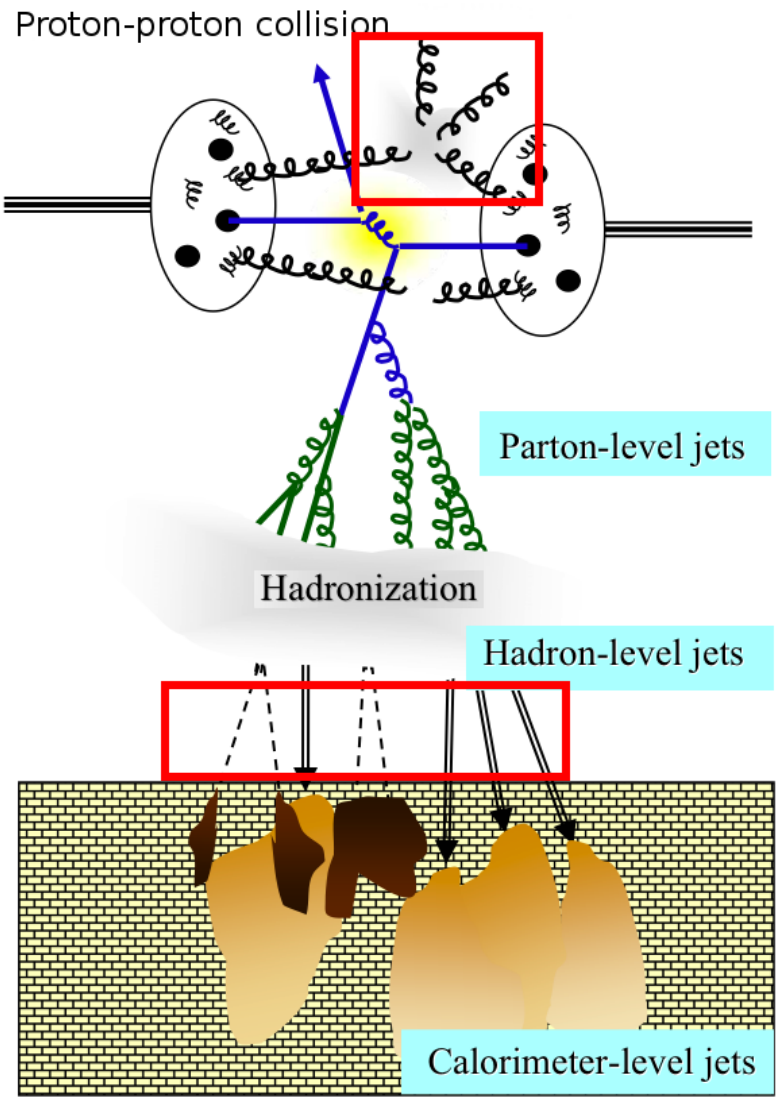

- High energy proton-proton collision $\rightarrow$ parton-parton scattering
- Partons ejected at high angles: collimated parton shower
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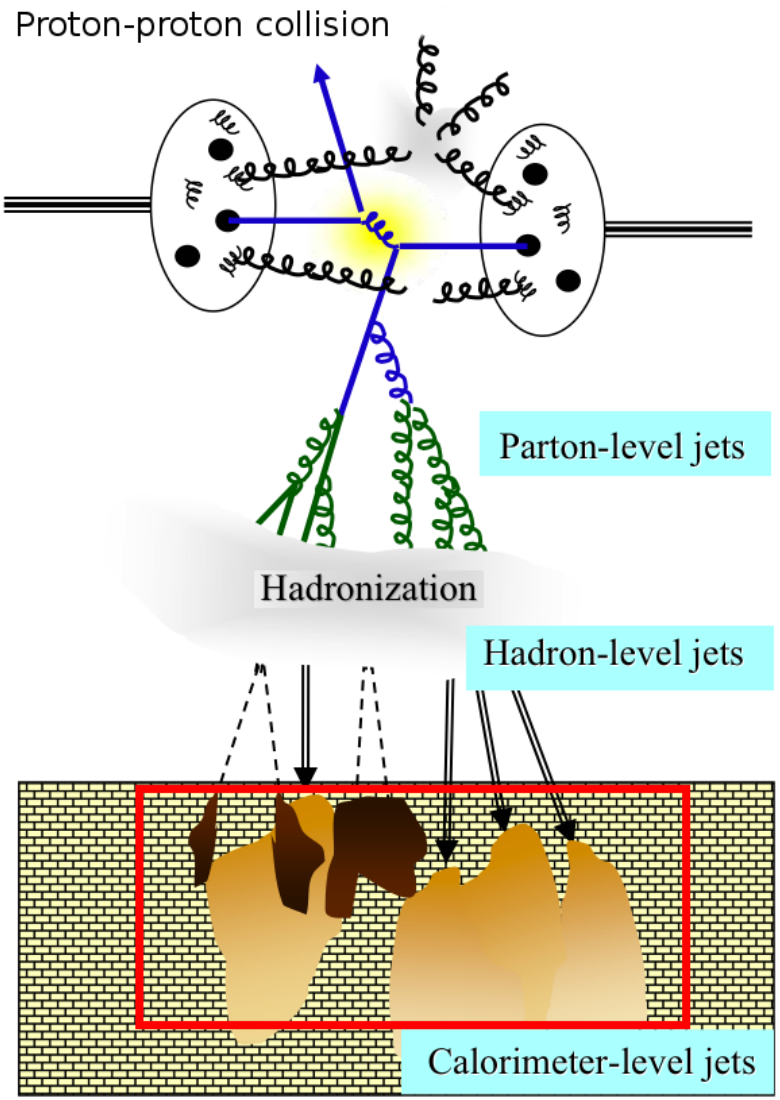

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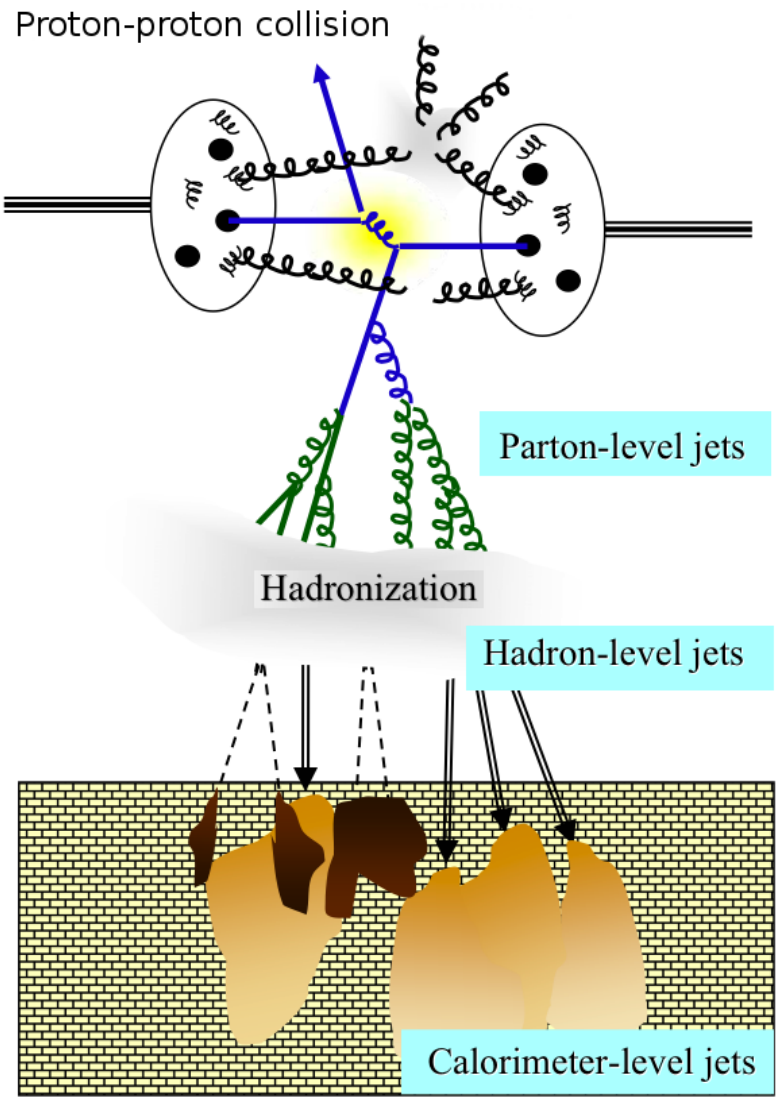
  - in simulation and in data: "calorimeter" or "track" jets

What is a hadronic b-jet?



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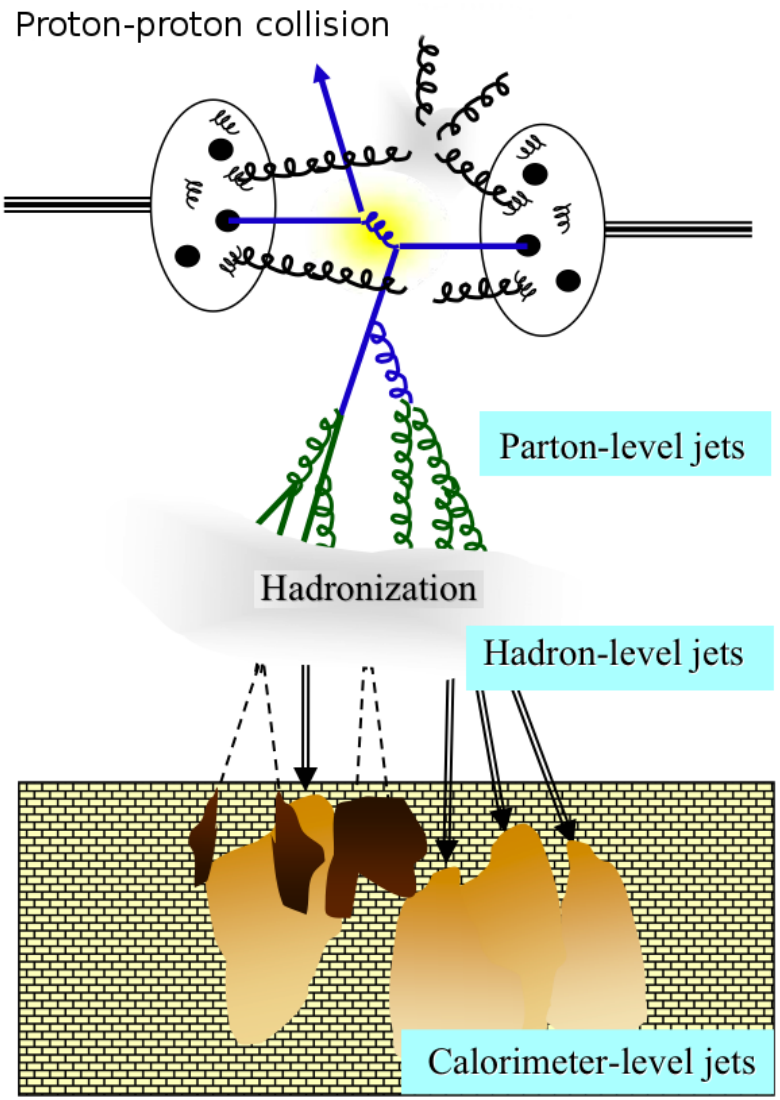

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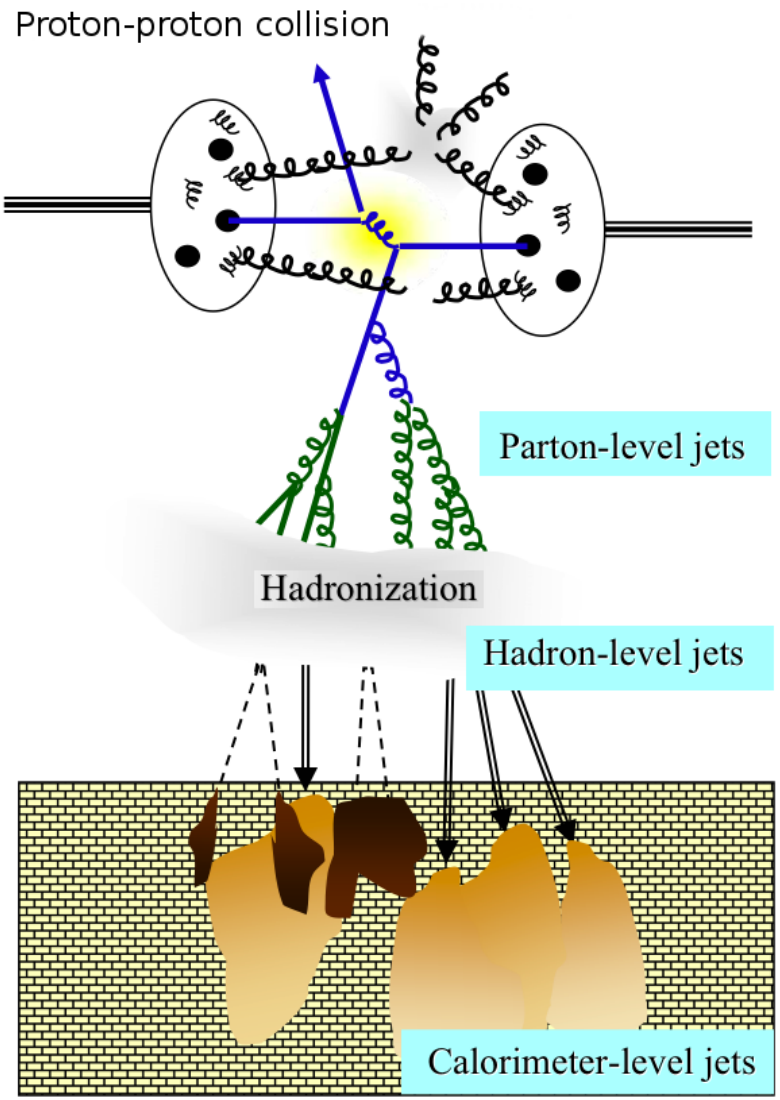
What is a hadronic c-jet?



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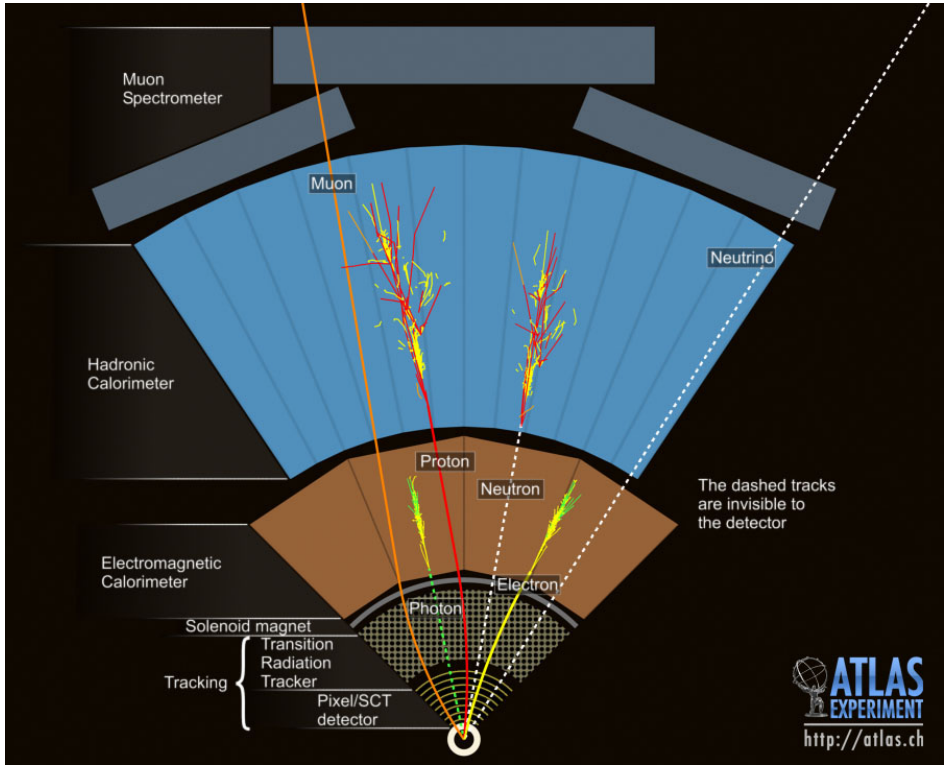
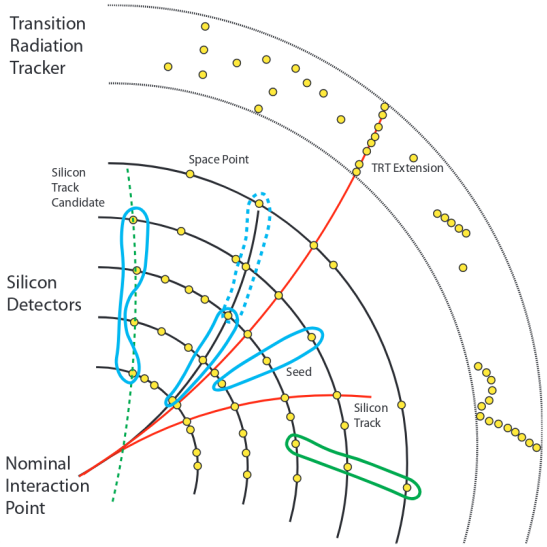
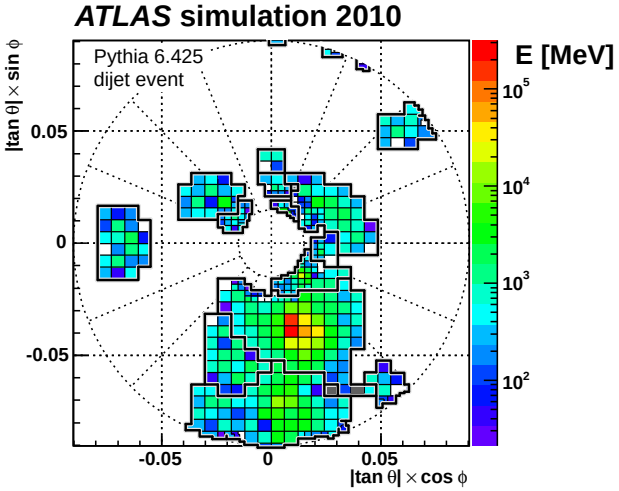
  - typical fake *b*-tagged jets

Jet and track reconstruction in ATLAS







- tracker reconstructs **trajectories** of charged particles ($\sim$ 600 per event!)
- calorimeters collects **energy deposits** of e/γ and hadrons $\rightarrow$ collimated jets

b-jet identification in ATLAS

- b-hadrons have: HFLAV website
  - **significant lifetime** (V_{cb} small)
    $c\tau \sim 450\ \mu$m
  - **large mass**
    $m \sim 5$ GeV
  - **high jet momentum fraction** (frag.)
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c-hadrons properties between b- and light hadrons

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  - more and higher energy tracks

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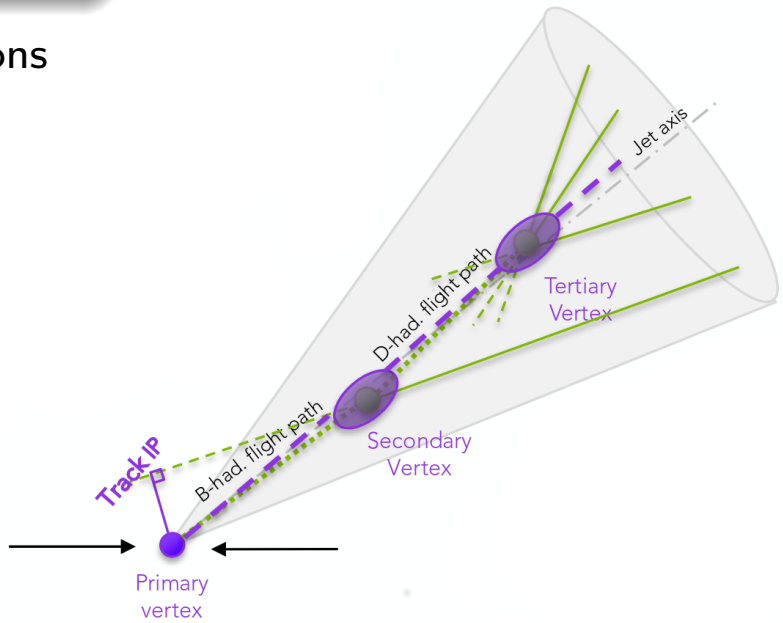

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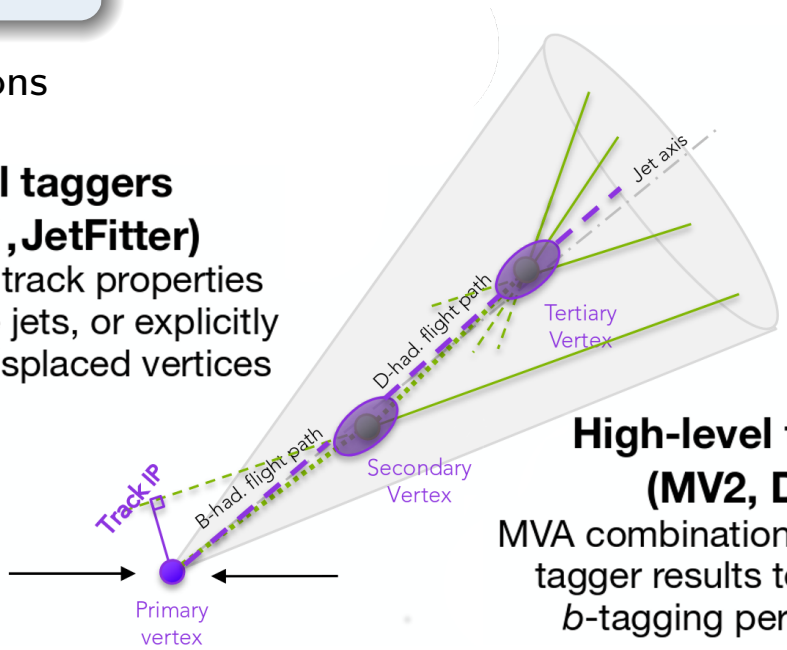
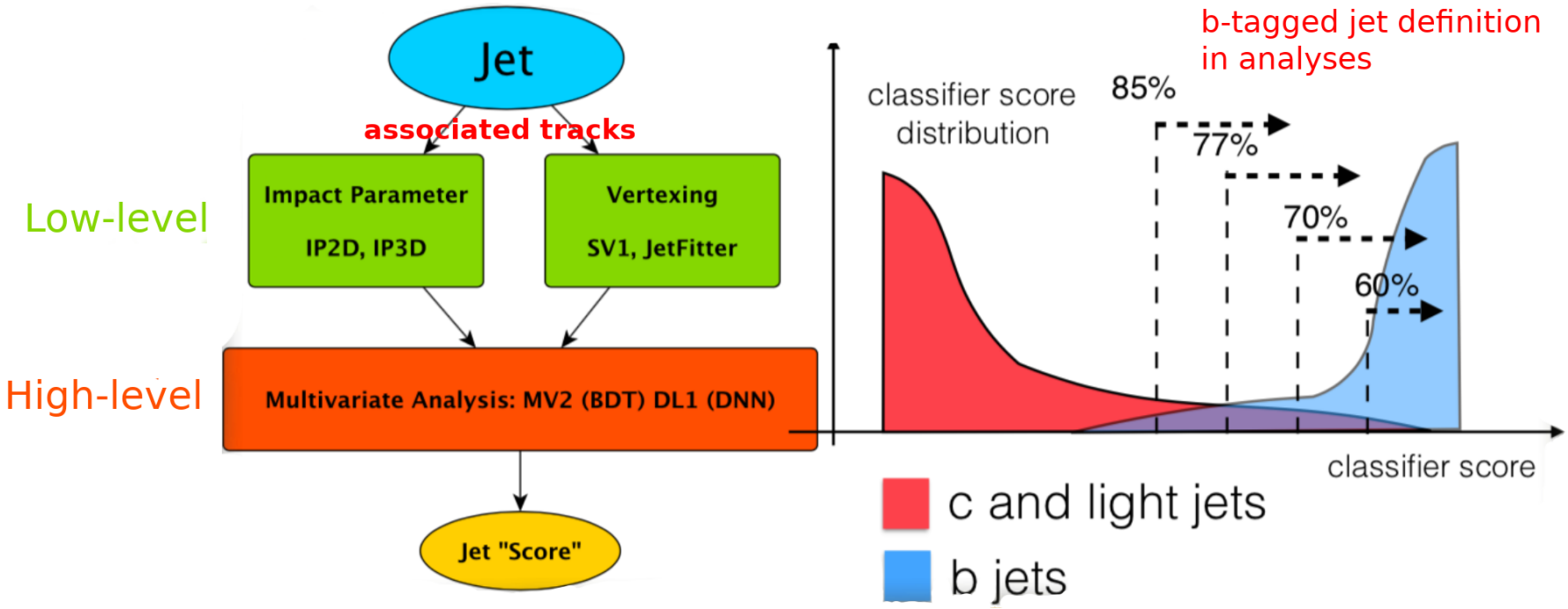
Low-level taggers
(IP3D,IP2D,SV1,JetFitter)
Using individual track properties associated to the jets, or explicitly reconstructing displaced vertices



High-level taggers
(MV2, DL1)
MVA combinations of low-level tagger results to maximise b-tagging performance

- in ATLAS, b-tagging in two-step approach

b-jet identification in ATLAS



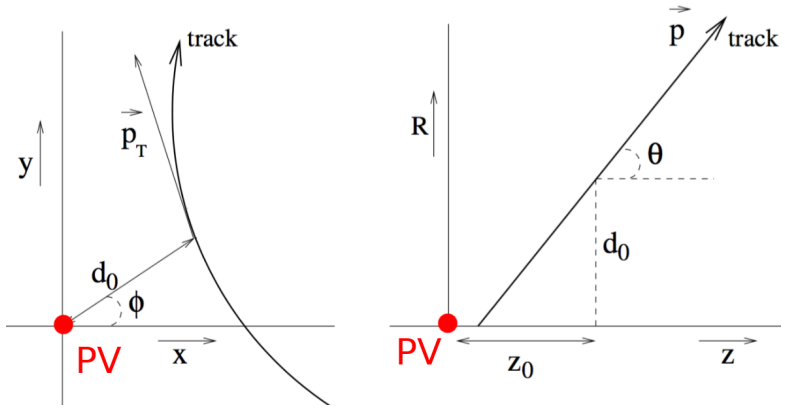
- Experimentally, *b*-tagged jets are jets with score $> X$

Algorithms based on displaced IP

- ATLAS Impact Parameter (IP)-based algorithms: IP2D/IP3D

- jet flavour probability from tracks
  $\mathbf{IP_{r\phi}} = |d_0|$ and $\mathbf{IP_z} = |z_0 \sin\theta|$
  - log-likelihood ratios (b, c, light)

ATL-PHYS-PUB-2017-013



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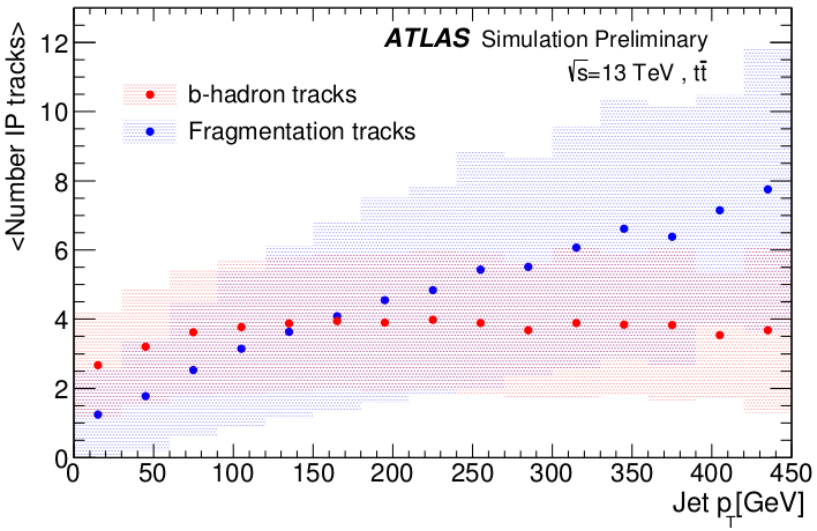
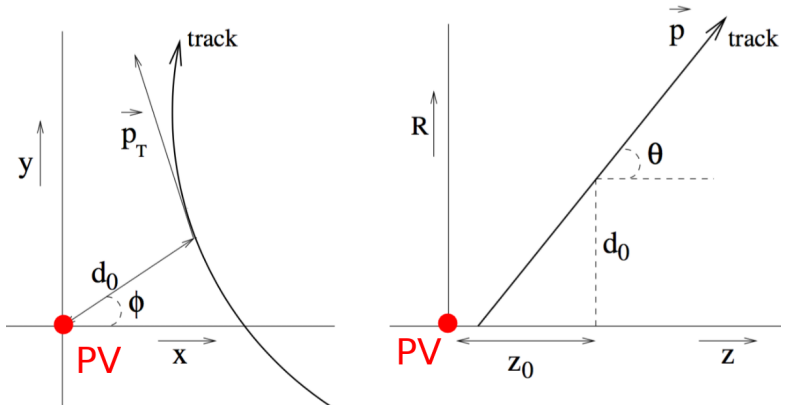
- **Strengths:** very inclusive, simple





- **Weaknesses:**
  - sensitive to IP resolution and non-Gaussian tails
  - lower performance at high $p_{\mathrm{T}}^{\mathrm{jet}}$ (higher track multiplicity)

Algorithms based on displaced vertices

- Inclusive secondary vertex algorithm: SV1
- Decay chain multi-vertex reconstruction: JetFitter

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ATL-PHYS-PUB-2017-011 ATL-PHYS-PUB-2018-025

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ATL-PHYS-PUB-2017-011 ATL-PHYS-PUB-2018-025

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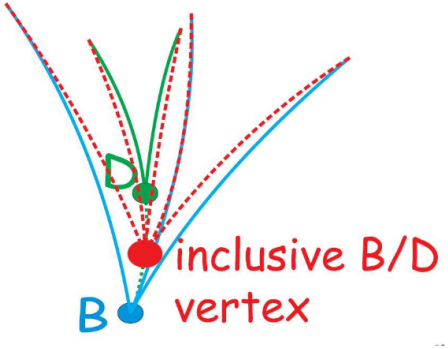

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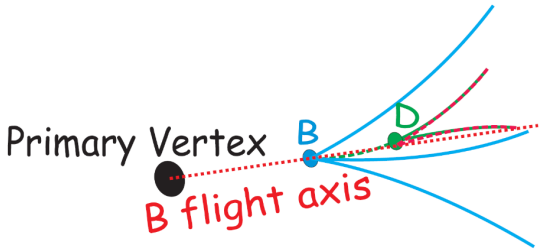

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- Less inclusive but complementary w.r.t IP-based algorithms

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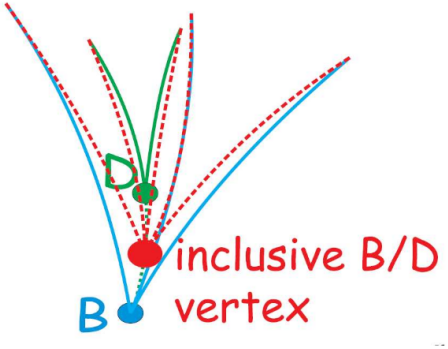

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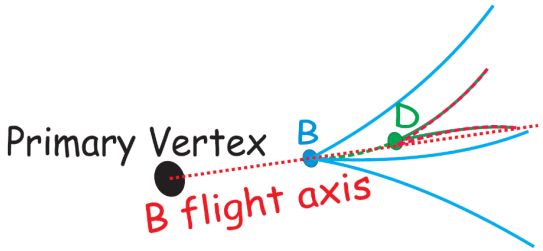

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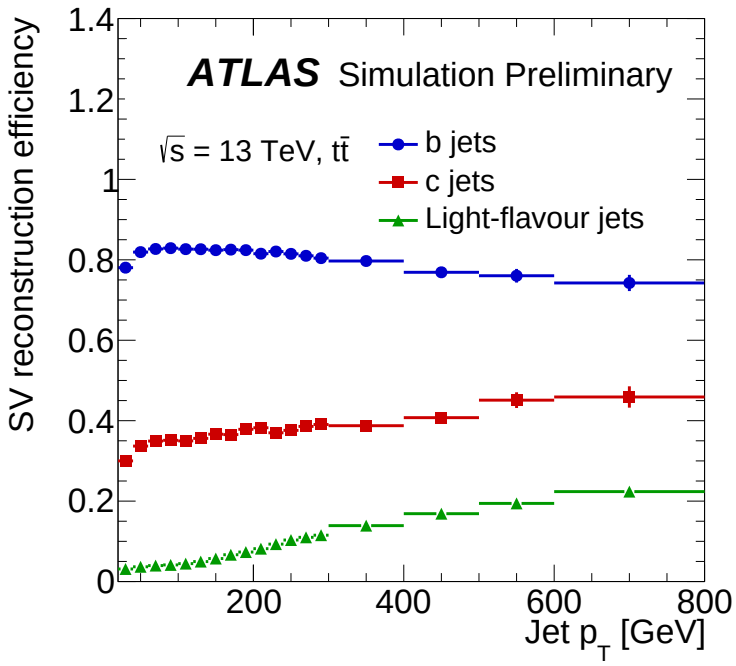

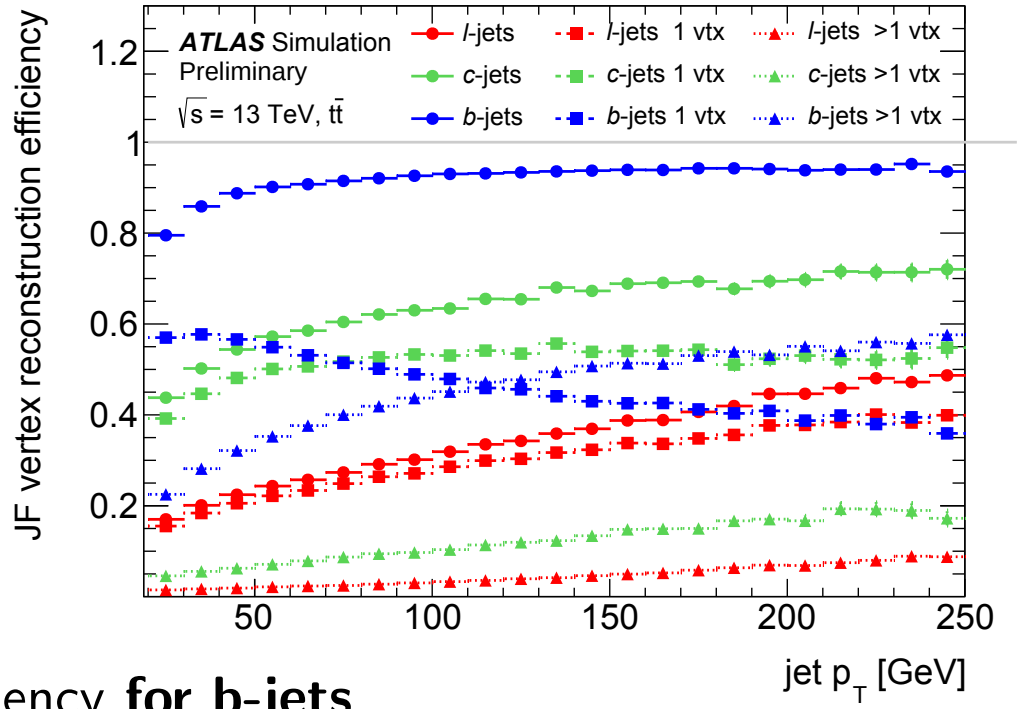

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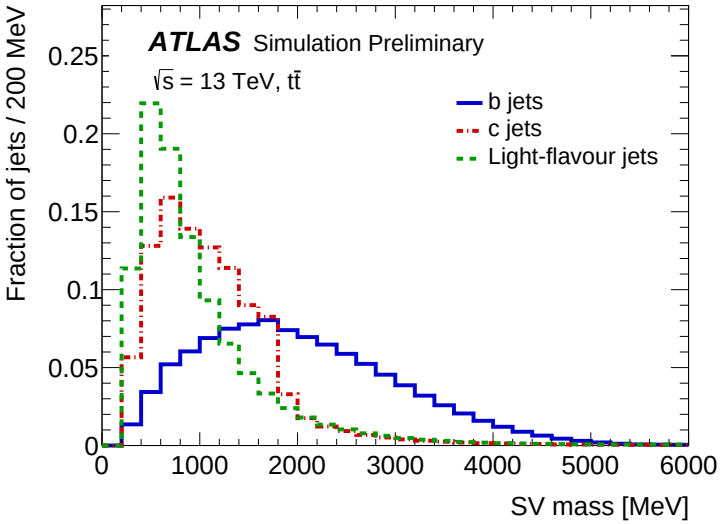

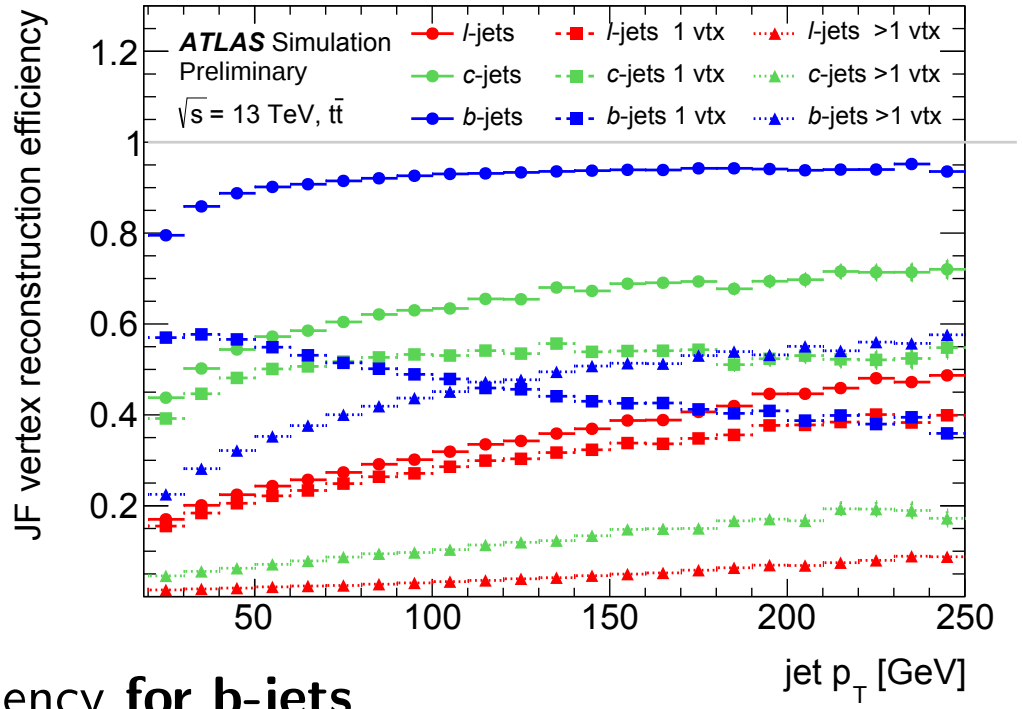

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- **Properties** of SV1 and JetFitter vertices provide discriminations
  - ex: invariant mass of tracks fitted to vertex

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- machine learning algorithms with $\sim$ 25 input discriminating variables

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- Algorithm trained to **identify b-jets**
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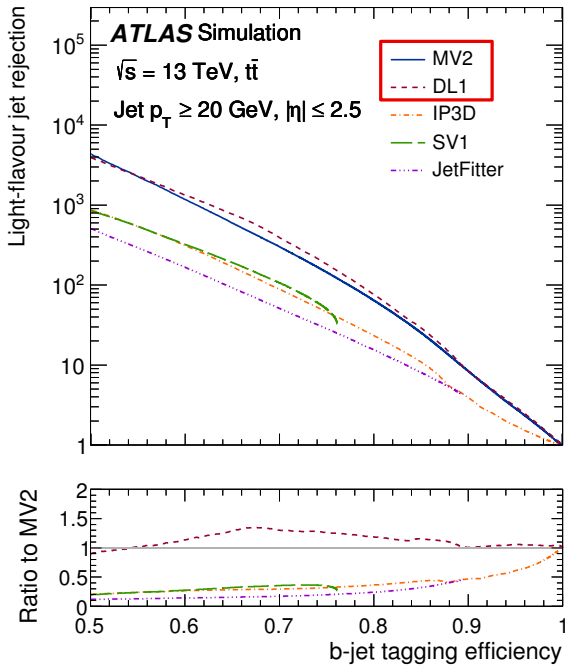

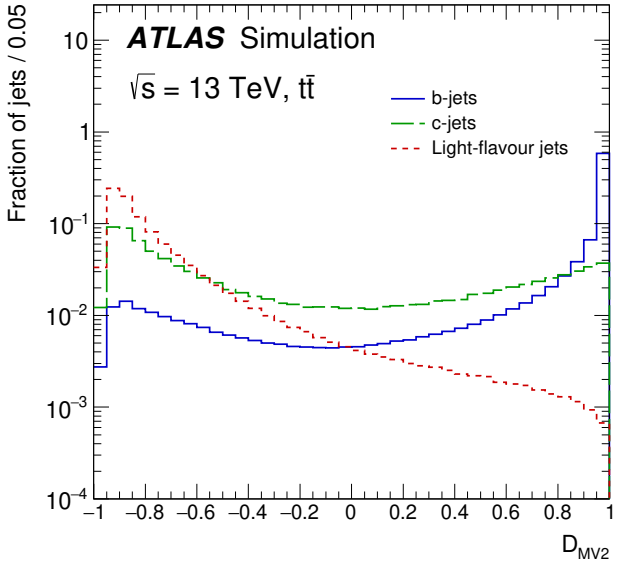

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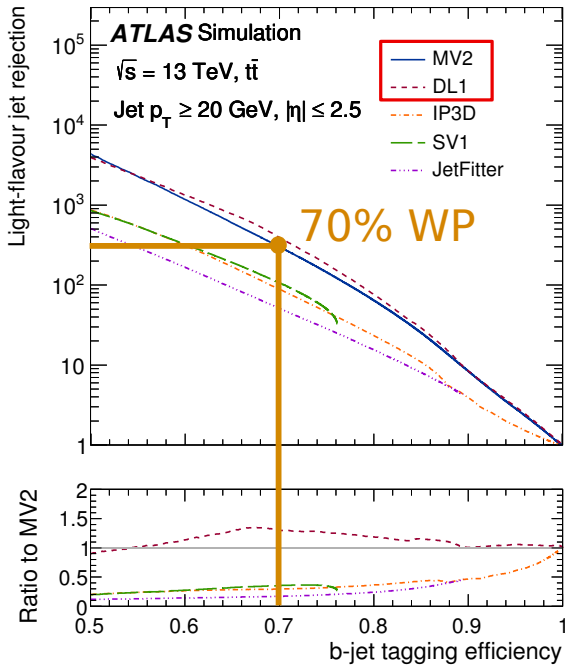

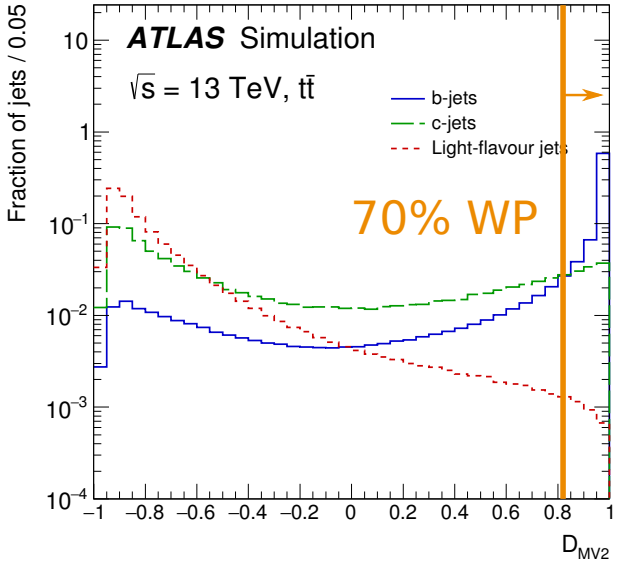

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Efficiency measurement in data

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  - precision measurement **in collision data** required
  - select pure sample of b-jets from $t\bar{t}$ events: $\boxed{e\mu \ + \ \text{exactly 2 jets}}$

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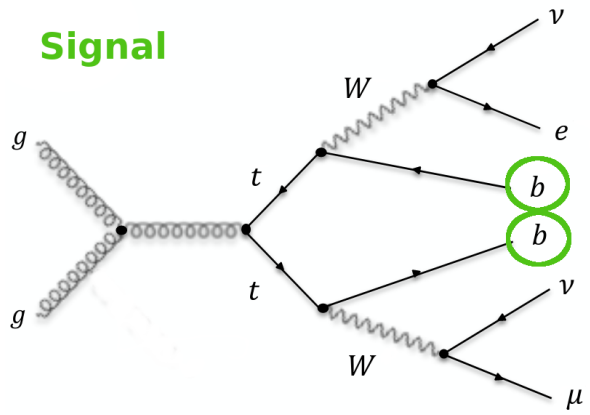

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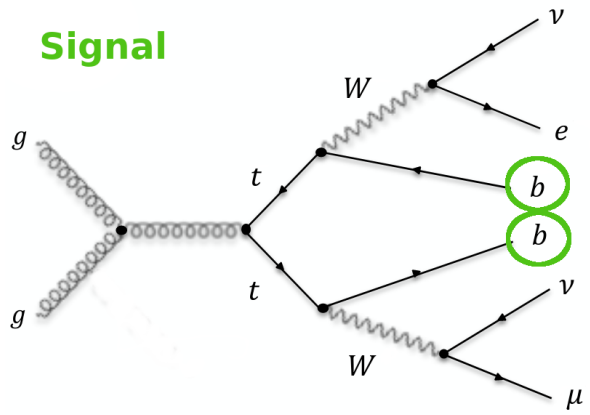

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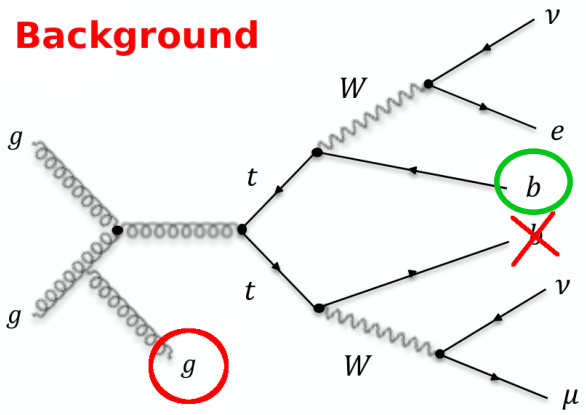

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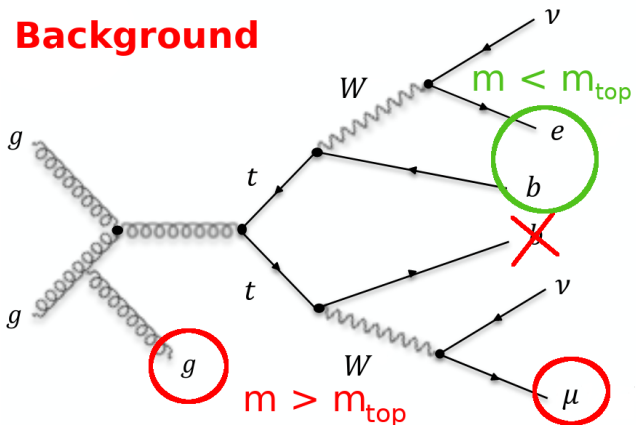
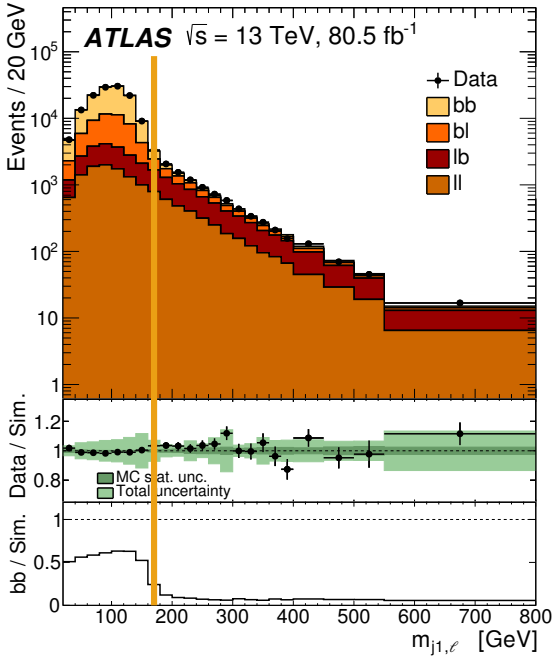
- **Improvement:** lepton-jet invariant mass for signal/control regions
  - **strong constraints on background level**





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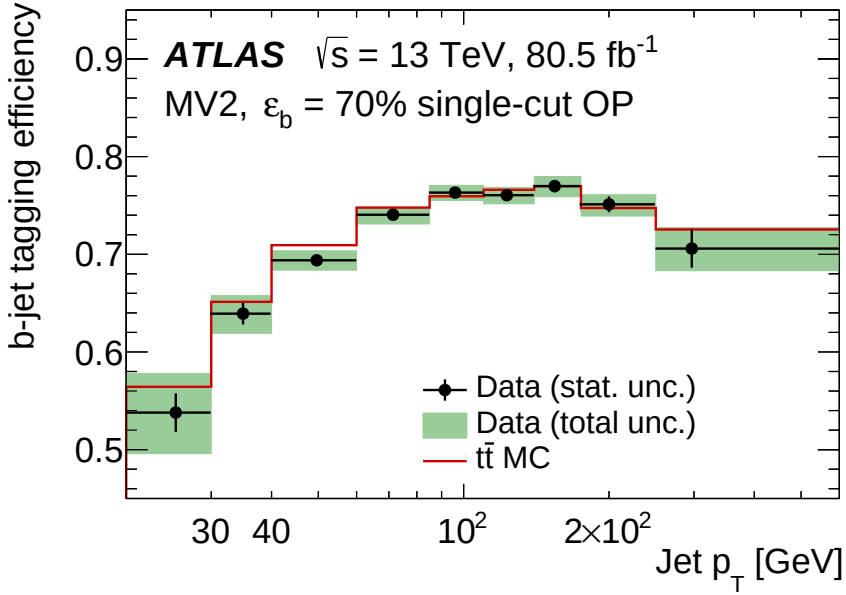

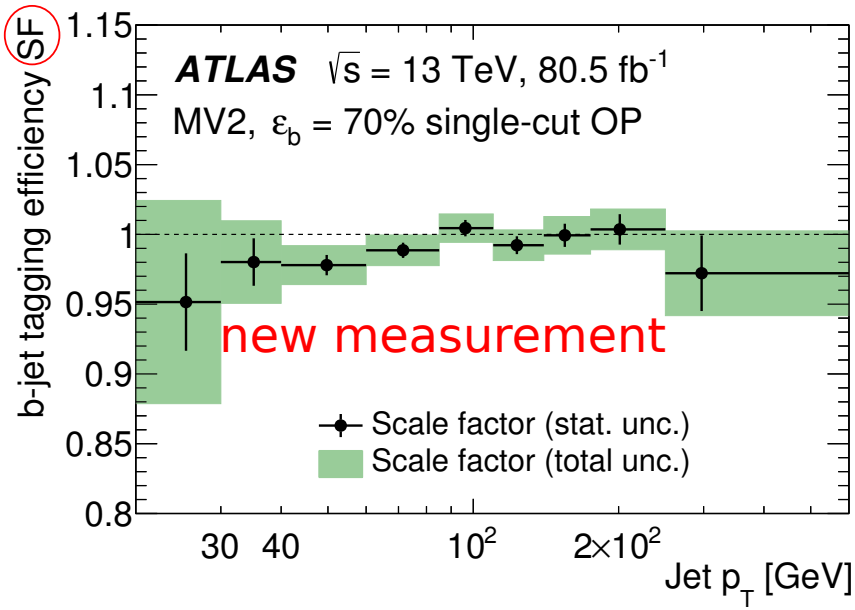

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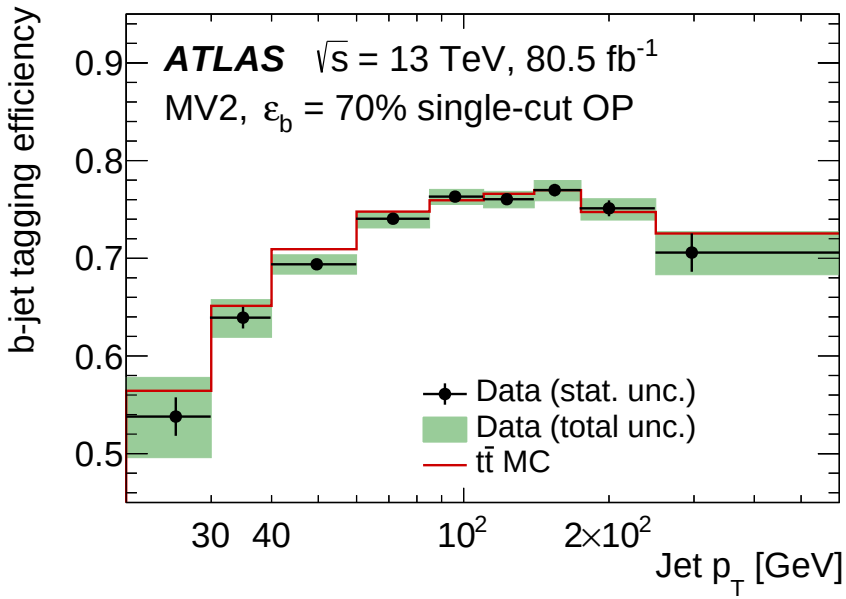

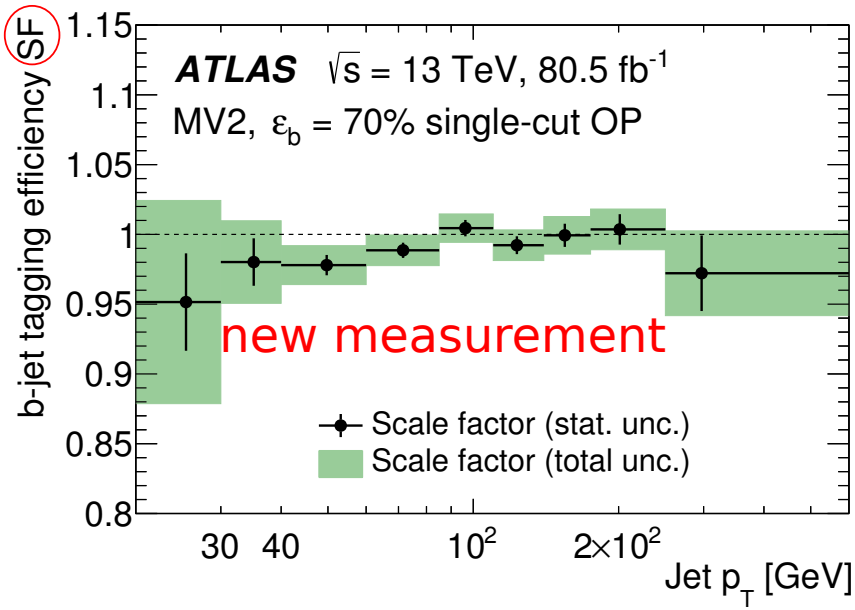

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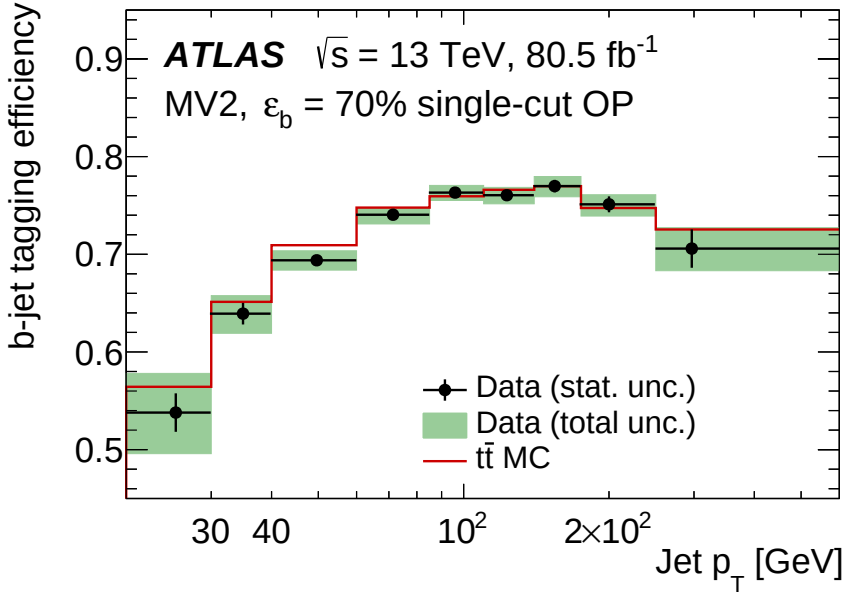

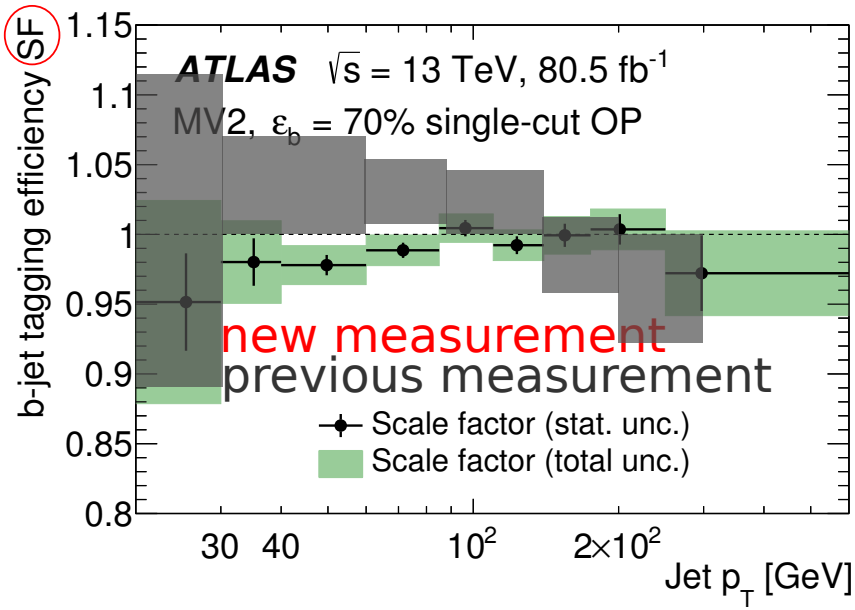

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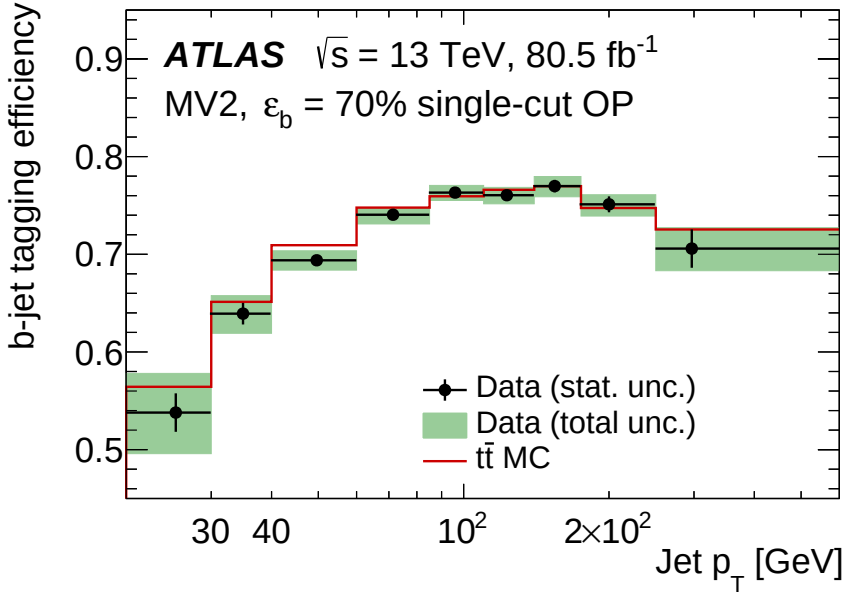
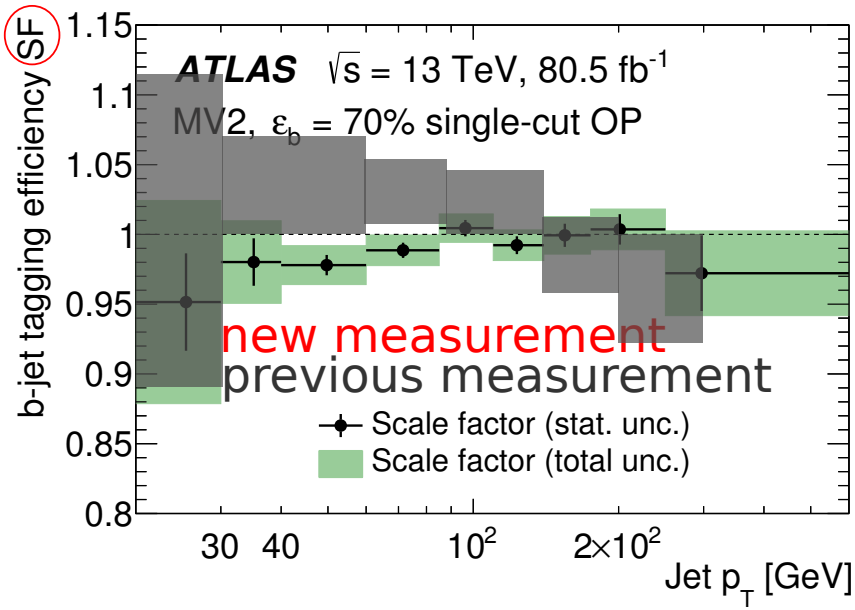
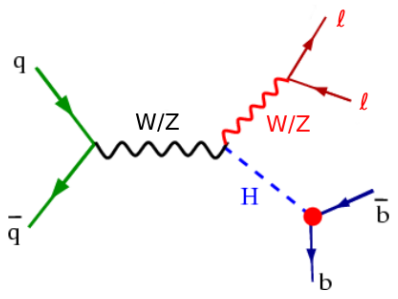


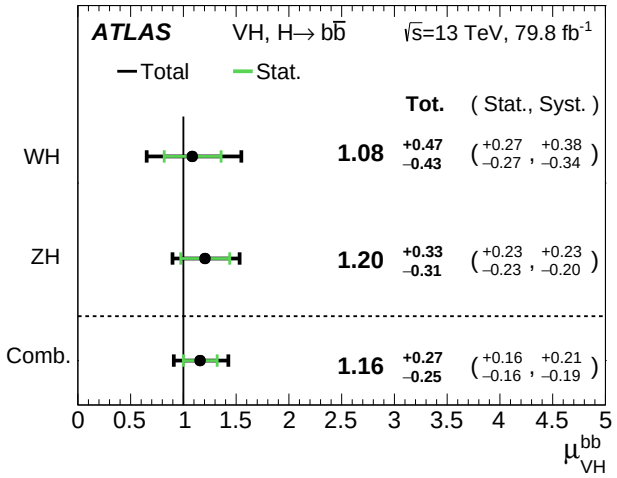


Application to Higgs and Dark Sectors

$H \to bb$ measurement (b-H)

Phys. Lett. B 786 (2018) 59 ATLAS-CONF-2020-006





Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

- **Dominant Higgs decays** ($\sim$ 60%) but large background from multi-jet events
  - most sensitive channel: VH with leptons
- b-tagging crucial to reject **V + jets events**
  - leading experimental uncertainty
  - 30% reduction for b-jets in latest result

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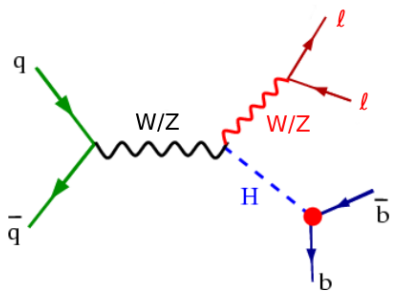
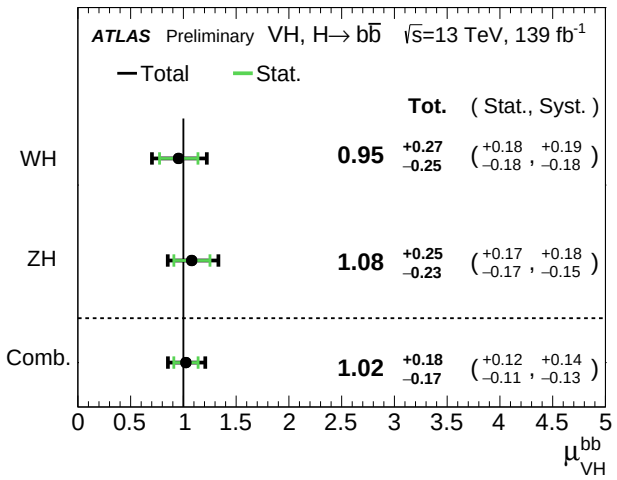
Phys. Lett. B 786 (2018) 59 **ATLAS-CONF-2020-006**





Source of uncertainty		σ_μ
Total		0.177
Statistical		0.115
Systematic		0.134
Statistical uncertainties		
Data statistical		0.108
$t\bar{t}$ $e\mu$ control region		0.014
Floating normalisations		0.034
Experimental uncertainties		
Jets		0.043
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.015
Leptons		0.004
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	c-jets	0.035
	light-flavour jets	0.009
Pile-up		0.003
Luminosity		0.016
Theoretical and modelling uncertainties		
Signal		0.052
Z + jets		0.032
W + jets		0.040
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Multi-jet		0.005
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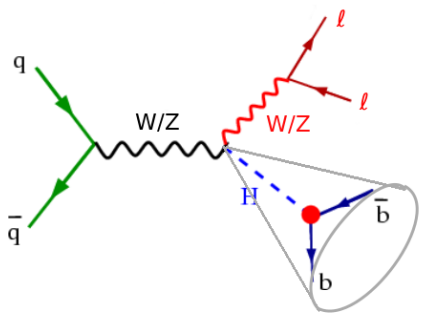
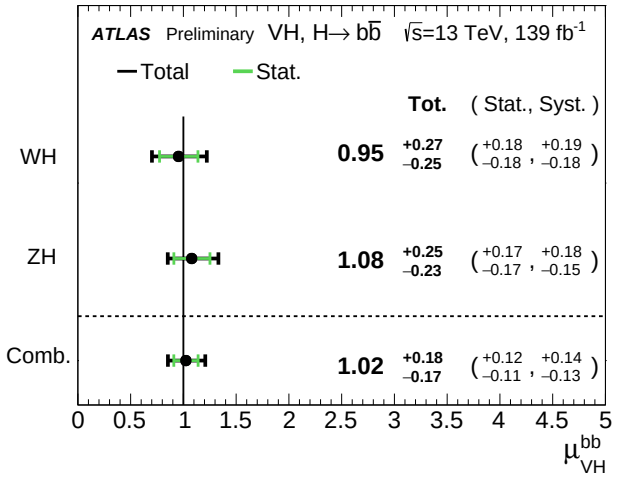
Phys. Lett. B 786 (2018) 59 **ATLAS-CONF-2020-006**





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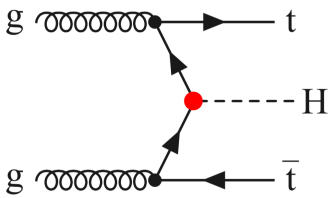
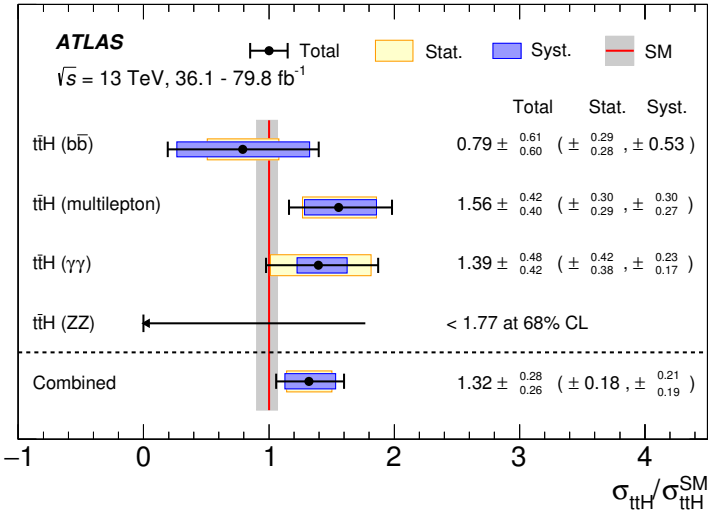
  - most sensitive channel: VH with leptons
- b-tagging crucial to reject **V + jets events**
  - leading experimental uncertainty
  - 30% reduction for b-jets in latest result
- **Extra challenge:** boosted $H \to bb$ tagging (high $p_{\mathrm{T}}^{\mathrm{H}}$)
  - see ATLAS-CONF-2020-007

ttH measurement (top-H)

Phys. Lett. B 784 (2018) 173 full Run 2 analyses in progress





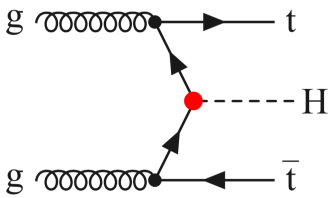
- $H \to bb$ channel has largest cross section but ...
  - large background from $\mathbf{t\bar{t} + g(\to b\bar{b})}$
  - $H \to \gamma\gamma$ leading sensitivity in ATLAS so far
- On-going work to improve $t\bar{t} + g(\to b\bar{b})$ modeling

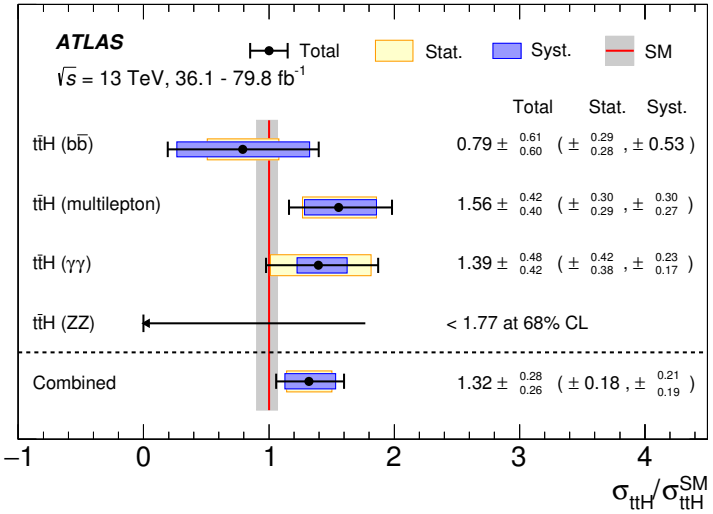
$ttH(\to bb)$ uncertainties

Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	$+0.46$	-0.46
Background-model stat. unc.	$+0.29$	-0.31
b-tagging efficiency and mis-tag rates	$+0.16$	-0.16
Jet energy scale and resolution	$+0.14$	-0.14
$t\bar{t}H$ modeling	$+0.22$	-0.05
$t\bar{t} + \geq 1c$ modeling	$+0.09$	-0.11
JVT, pileup modeling	$+0.03$	-0.05
Other background modeling	$+0.08$	-0.08
$t\bar{t}$ + light modeling	$+0.06$	-0.03
Luminosity	$+0.03$	-0.02
Light lepton (e, μ) id., isolation, trigger	$+0.03$	-0.04
Total systematic uncertainty	$+0.57$	-0.54
$t\bar{t} + \geq 1b$ normalization	$+0.09$	-0.10
$t\bar{t} + \geq 1c$ normalization	$+0.02$	-0.03
Intrinsic statistical uncertainty	$+0.21$	-0.20
Total statistical uncertainty	$+0.29$	-0.29
Total uncertainty	$+0.64$	-0.61

ttH measurement (top-H)

Phys. Lett. B 784 (2018) 173 full Run 2 analyses in progress





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  - large background from $\mathbf{t\bar{t} + g(\to b\bar{b})}$
  - $H \to \gamma\gamma$ leading sensitivity in ATLAS so far
- On-going work to improve $t\bar{t} + g(\to b\bar{b})$ modeling
- **Challenge: b-tagging at high multiplicity**
  - going beyond simple cut on b-tagging score

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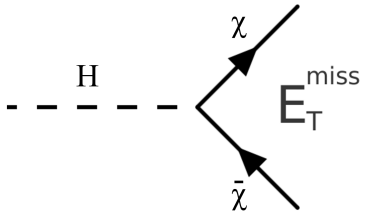
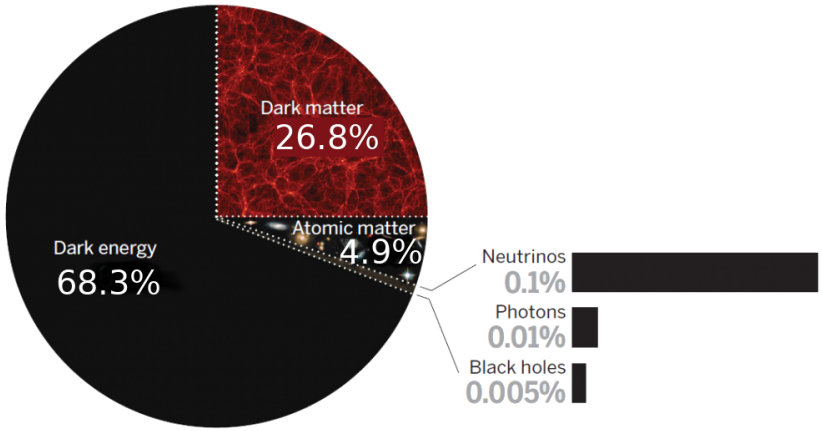
$ttH(\rightarrow$ inv.) search (DM-H)

CMS-PAS-HIG-18-008 (2018)
Phys. Lett. B 793 (2019) 520
Phys. Rev. Lett. 122 (2019) 231801
ATLAS-CONF-2020-008





- Many observational evidence for **Dark Matter (DM)**
  - weakly-interacting (e.g. only Yukawa-like) massive particles?
- $H \rightarrow$ invisible decays in SM $\sim$ **0.1%**
  - any deviation is hint for the dark sector
  - missing transverse energy signatures (E_T^{miss})
- On-going effort to probe lowest possible branching ratio

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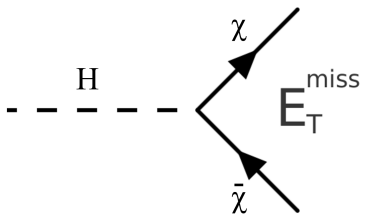
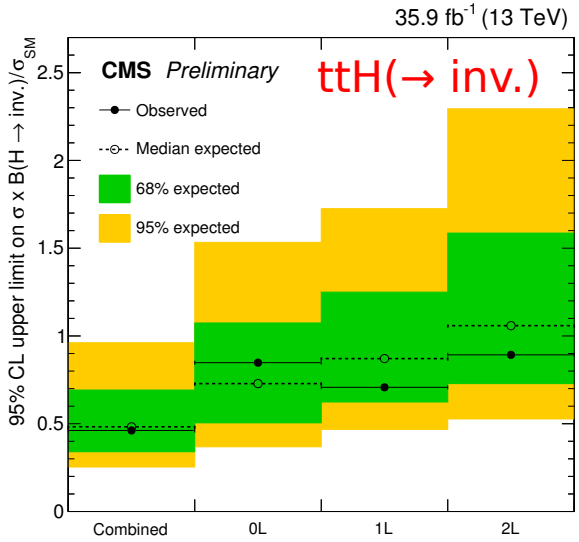
CMS-PAS-HIG-18-008 (2018)

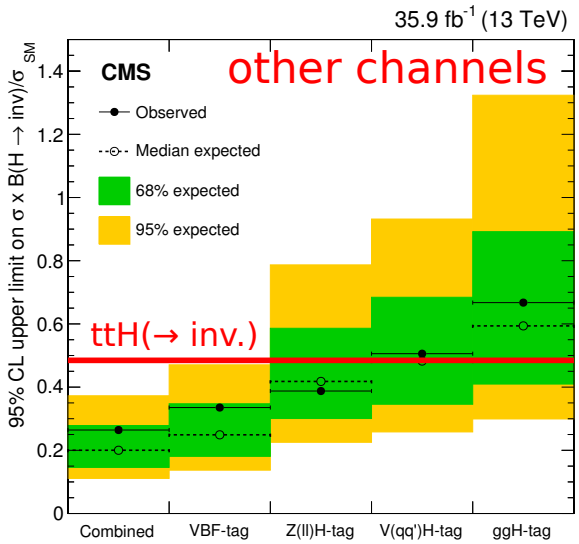
Phys. Lett. B 793 (2019) 520

Phys. Rev. Lett. 122 (2019) 231801

ATLAS-CONF-2020-008







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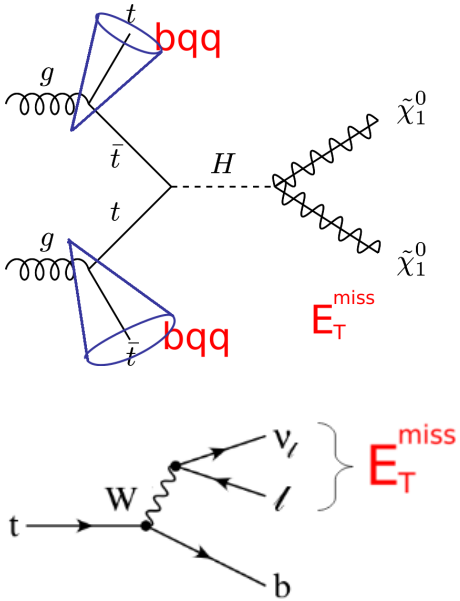
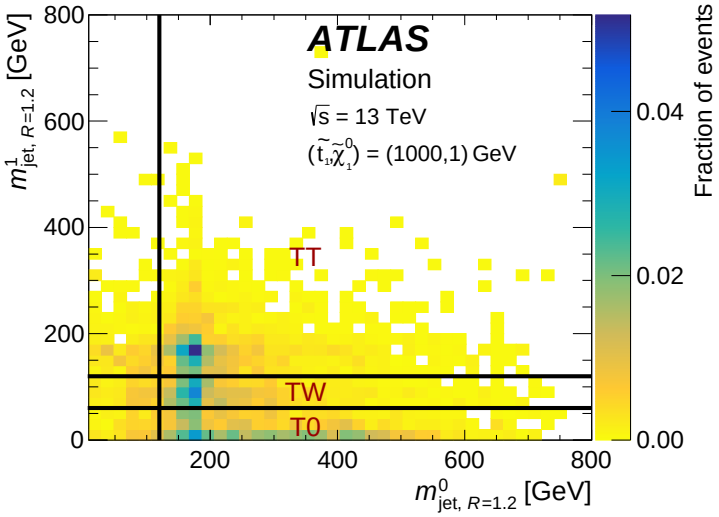
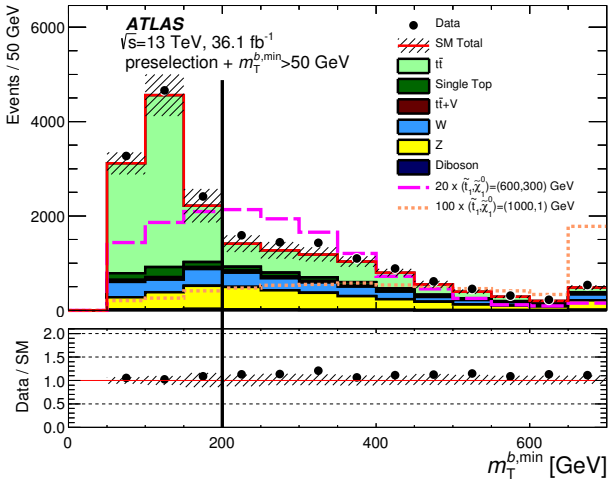
  - **ttH(→inv.) sensitive channel:** $t\bar{t} + E_T^{miss}$ search

Main backgrounds (0-lepton channel)

JHEP 12 (2017) 085 arXiv:2004.14060 (2020)





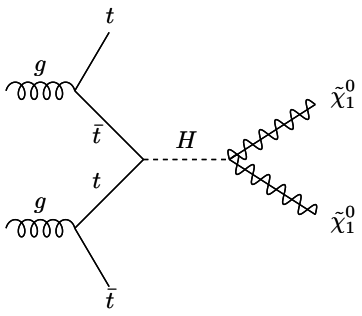


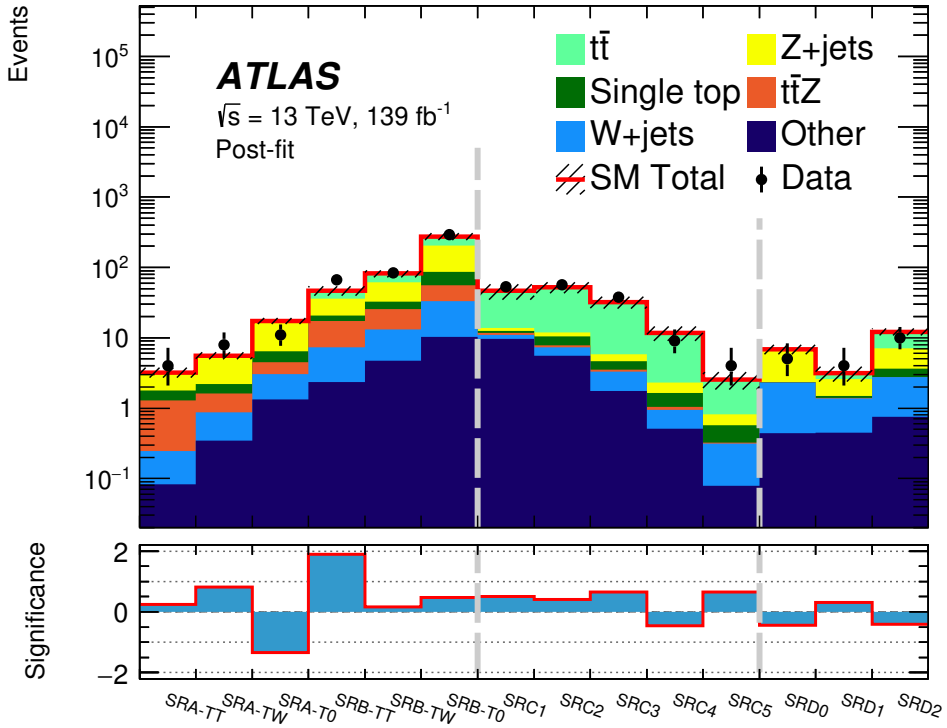
- Selection: $e/\mu/\tau$ veto, ≥ 4 jets, ≥ 2 b-jets, large $\mathrm{E_T^{miss}}$
- Main background: $Z(\rightarrow \nu\nu)$ + jets, $t\bar{t}$ with missing lepton
  - rejected by b-jets + top reconstruction, $\mathbf{m_T(E_T^{miss}, b) > m_{top}}$
- "Irreducible" background: ttZ, usually subleading

Latest results

arXiv:2004.14060 (2020)

$ttH(\rightarrow \text{inv.})$

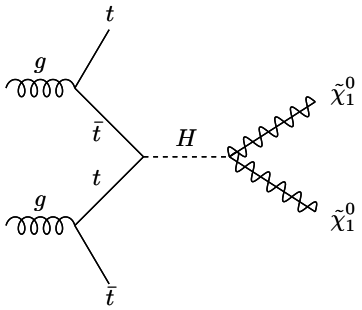




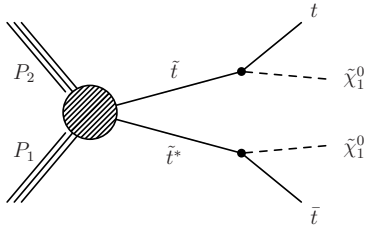
- No significant data excess over SM predictions so far $\rightarrow$ limits

Latest results

$ttH(\rightarrow \text{inv.})$



direct stop pair



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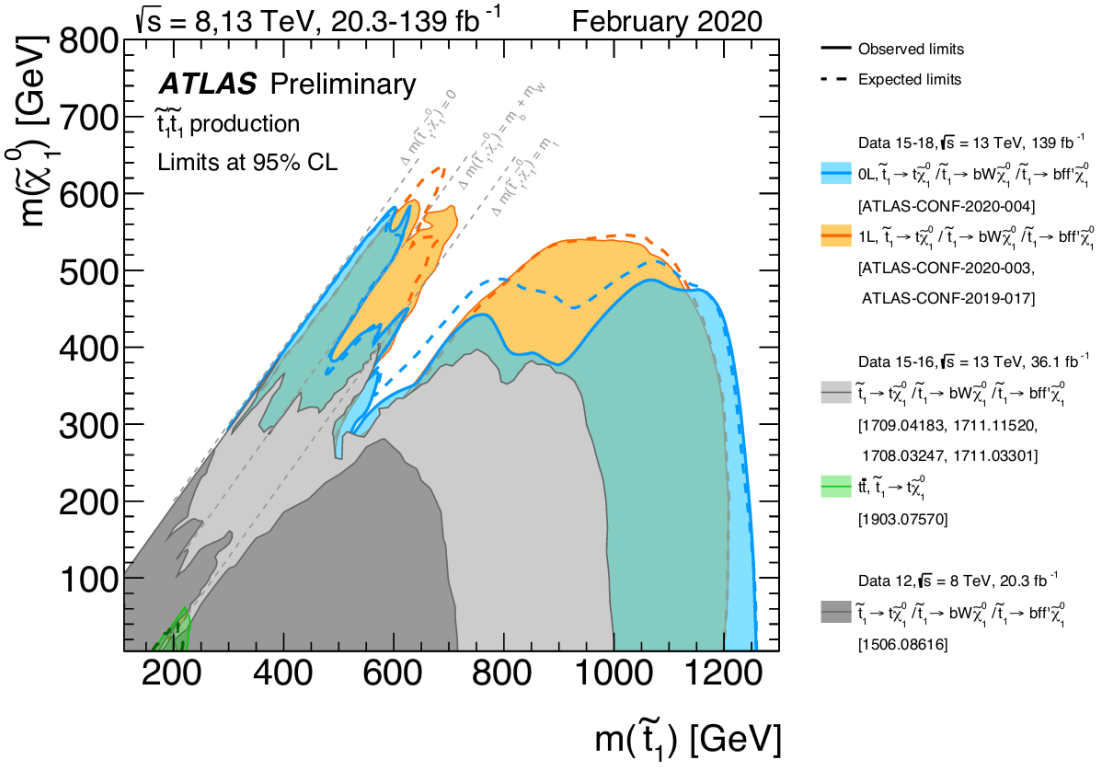
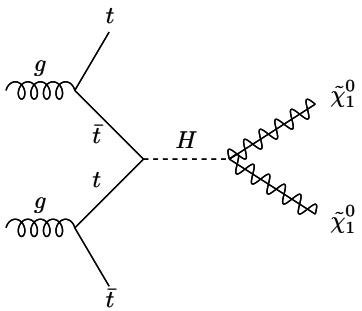


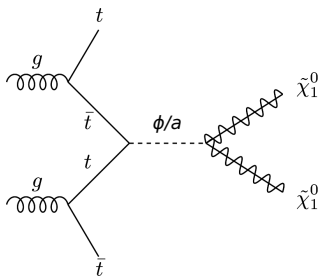
- No significant data excess over SM predictions so far $\rightarrow$ limits
- Typically interpreted in supersymmetric $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ plane

Constraints on Dark Matter

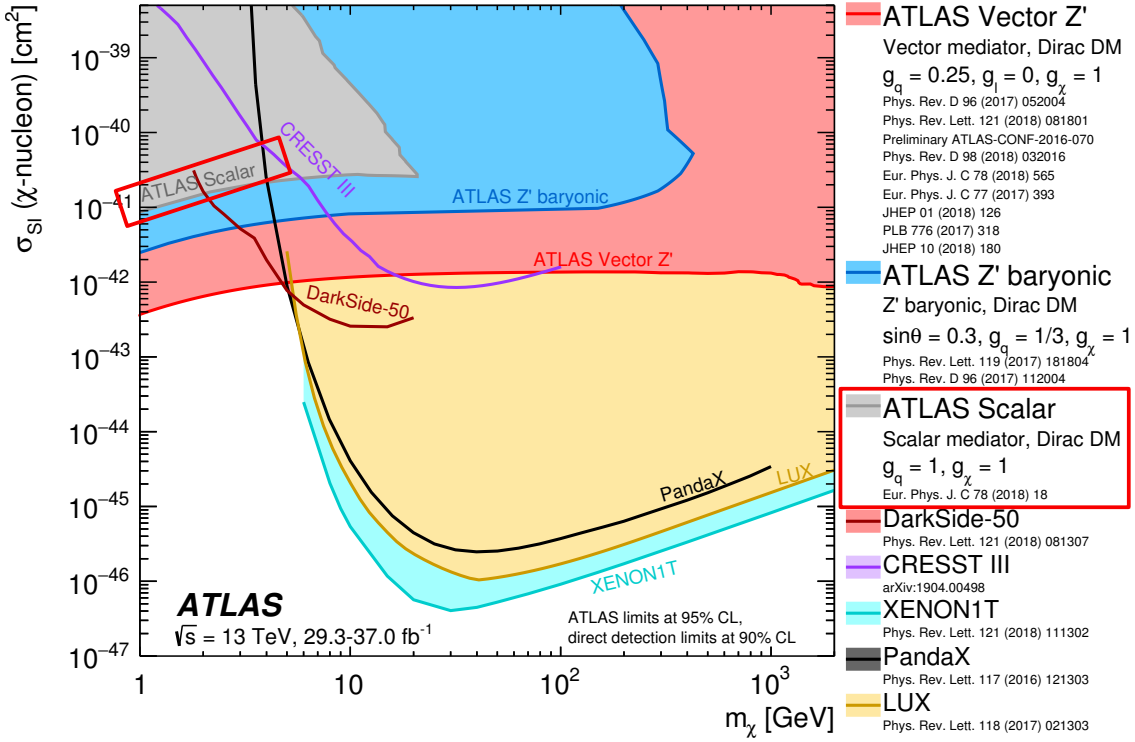
$ttH(\rightarrow \text{inv.})$



simplified DM



JHEP 05 (2019) 142 full Run 2 analyses in progress

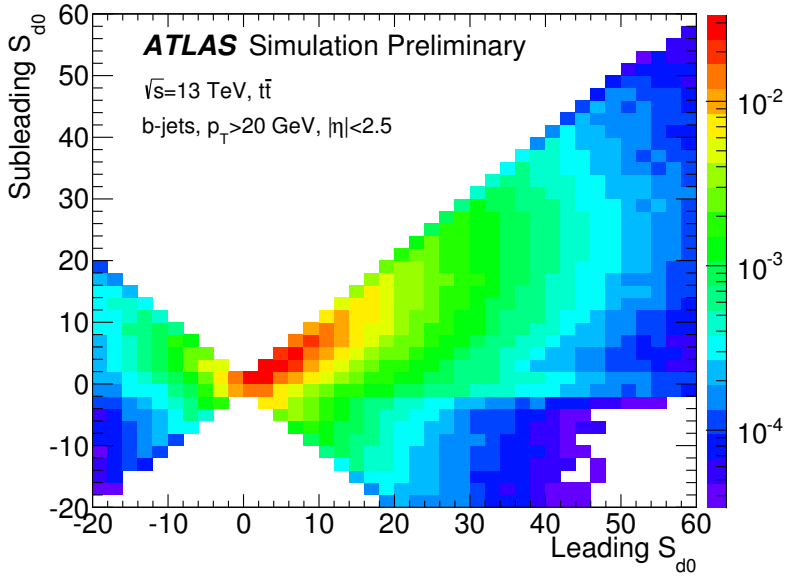


- No significant data excess over SM predictions so far $\rightarrow$ limits
- DM interpretation with simplified model in progress
  - $H(\rightarrow \text{inv.}) \sim$ scalar mediator with $m = m_H$
  - more complex models also considered

What is next?

Recent improvements in b-tagging

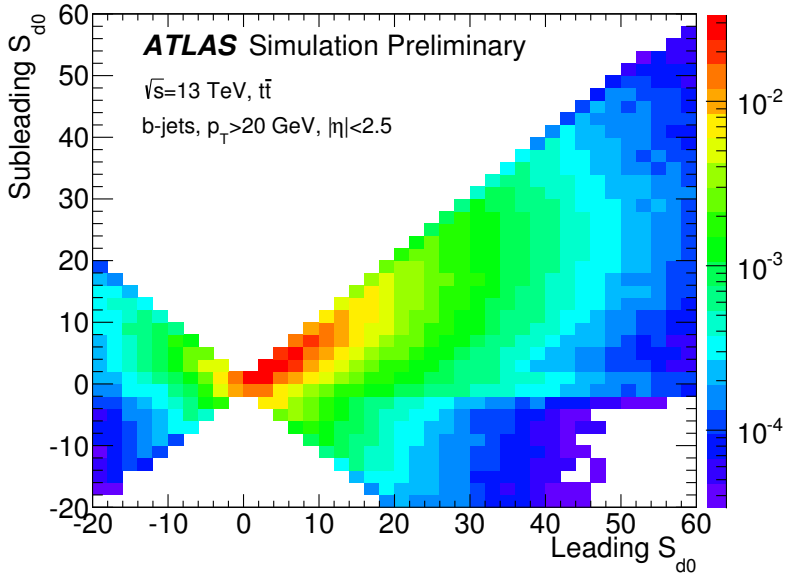
track IP correlation in b-jets
ATL-PHYS-PUB-2017-003



- Current algorithms assume track IP uncorrelated
- New algorithm **learns correlations** via recurrent neural network

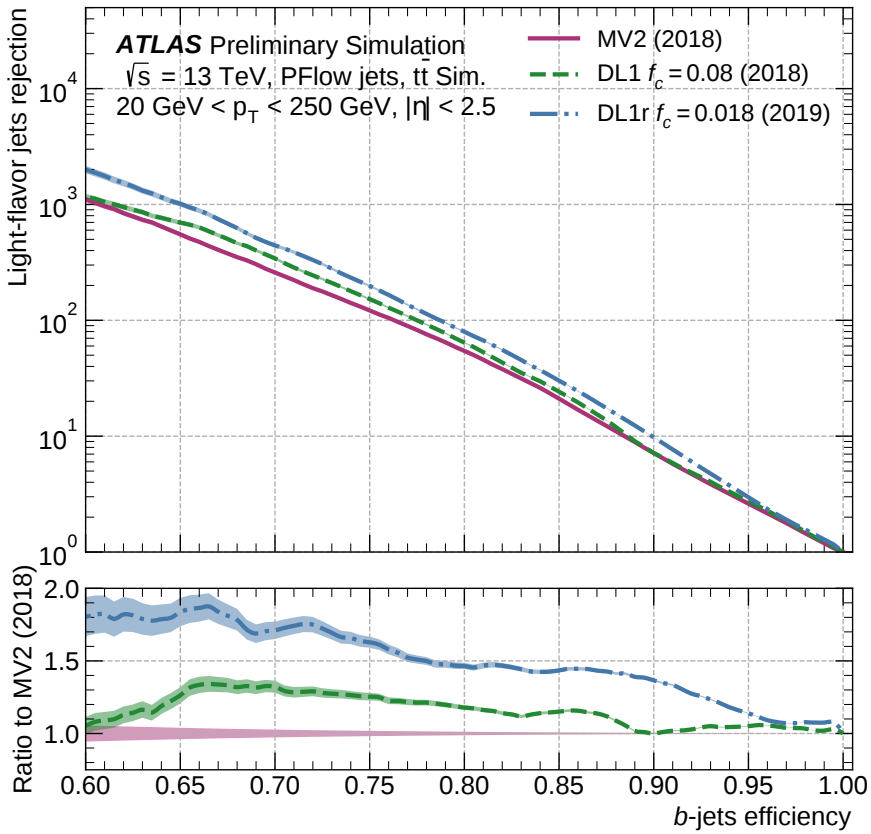
Recent improvements in b-tagging

track IP correlation in b-jets
ATL-PHYS-PUB-2017-003



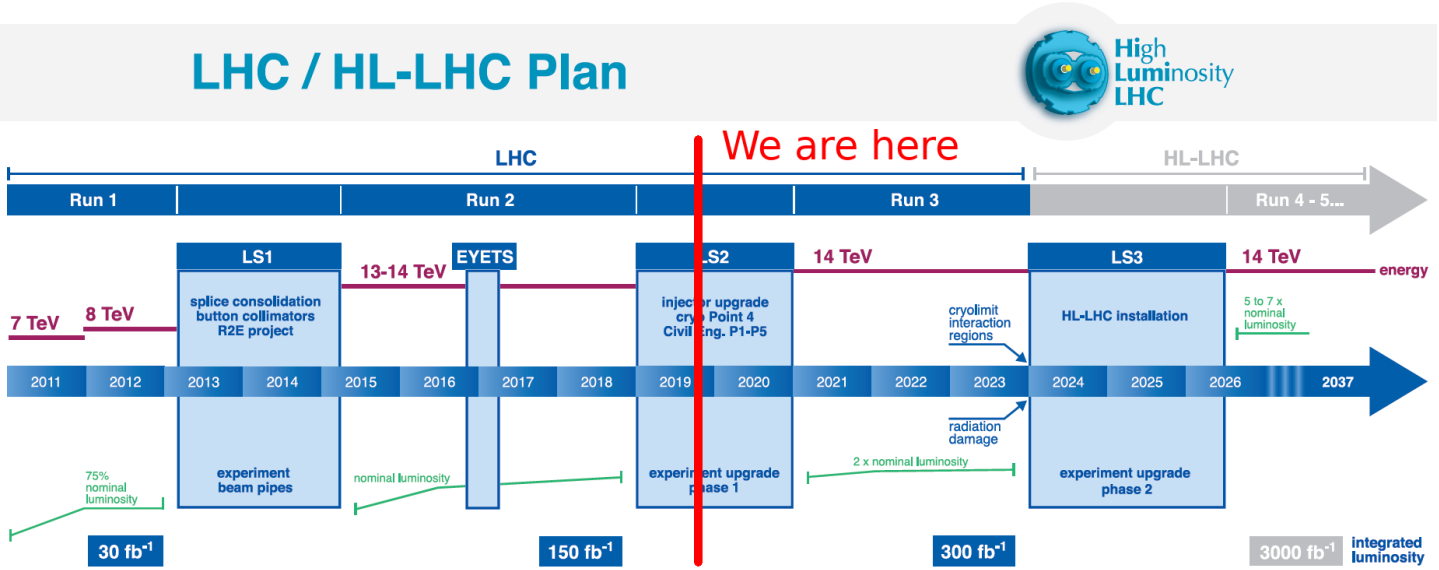
- Current algorithms assume track IP uncorrelated
- New algorithm **learns correlations** via recurrent neural network
- Improves high-level performance (DL1r vs DL1)

Performance of latest high-level taggers
FTAG-2019-005

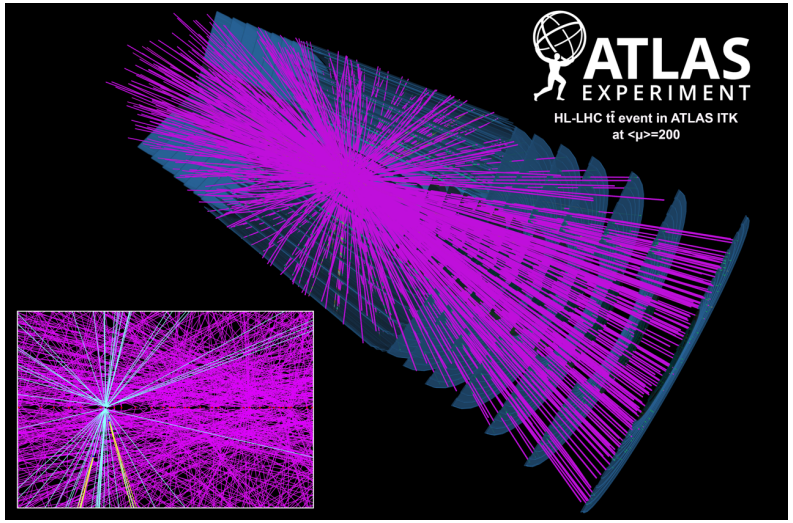


- confirmed in collision data
  FTAG-2020-001

The high luminosity LHC (HL-LHC)

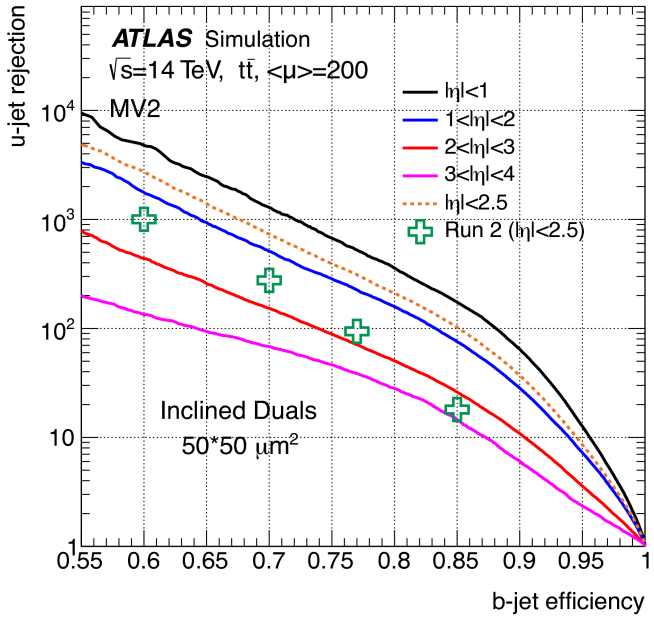


- large luminosity increase planned
  - $\times 20$ current dataset
- major upgrades required
- **tracking and b-tagging in very busy environment** ($\mu = 200$!)

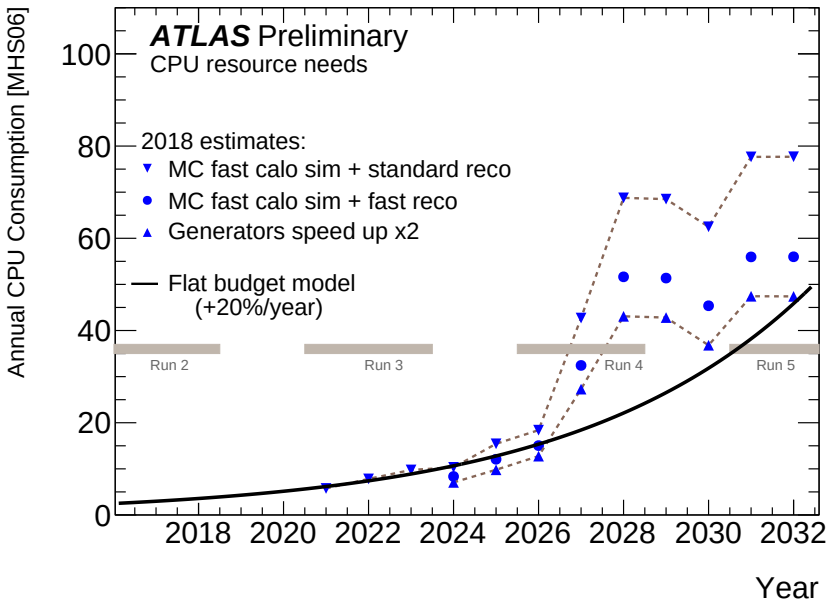


HL: performance and ressources

ATL-PHYS-PUB-2019-005



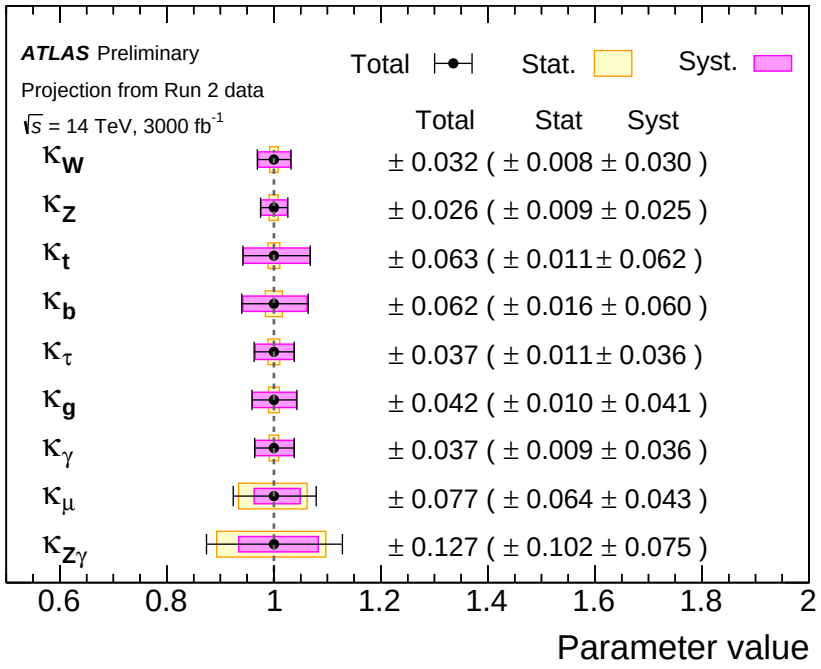
ATL-PHYS-PUB-2019-041



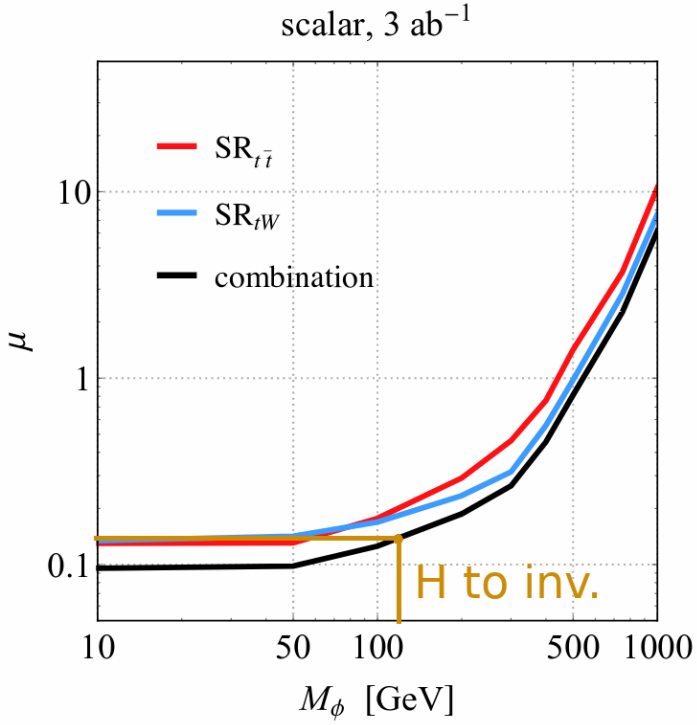
- ATLAS Inner Tracker (ITk) upgrade should **improve and extend** ($|\eta| < 2.4 \rightarrow 4$) b-tagging performance
- **But huge rise in CPU needs**
  - improvements in offline event reconstruction required
  - tracking typically biggest consumer $\rightarrow$ choices will have to be made

HL-LHC sensitivity

ATL-PHYS-PUB-2018-054



JHEP 02 (2019) 029



- **observation of y_μ** expected (but not y_c)
- $\sigma(y_{t,b}) \sim 5\%$, dominated by systematics
- limits on $H(\to \text{inv.})$ BR: $< 0.05 - 0.1$ (VBF channel),
  $ttH + tWH$ (2-lepton channel only) < 0.2!

Conclusion

- **Yukawa-like interactions** in the Standard Model are puzzling
  - "ad hoc" in lagrangian, no quantized charge, wide range of coupling

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- To study them at the LHC, **one needs to identify b-jets**
  - some leading measurements already dominated by systematic uncertainties
  - $t\bar{t} + \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$, one of the leading channel to search for dark sector

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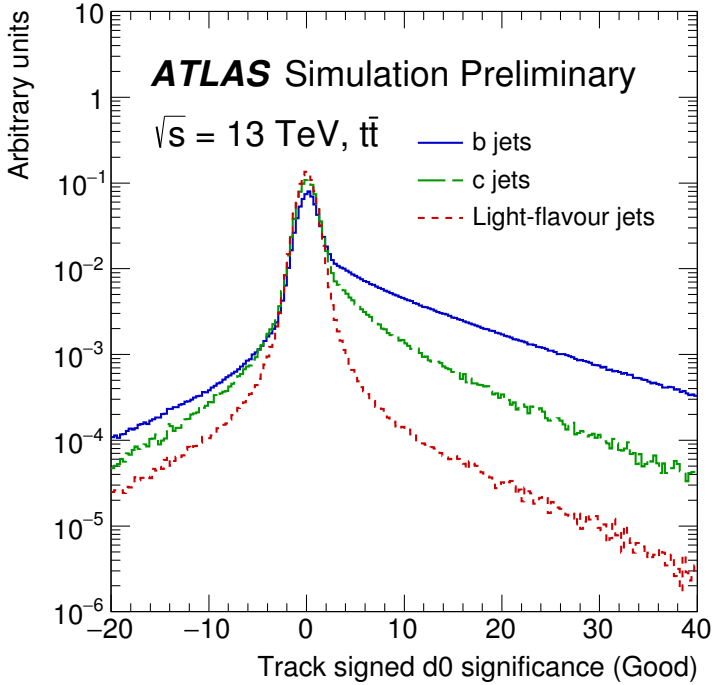
  - some leading measurements already dominated by systematic uncertainties
  - $t\bar{t} + \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$, one of the leading channel to search for dark sector
- **Continuous improvement** of *b*-tagging performance
  - advanced machine learning, improved efficiency measurements
  - benefit to results with full Run 2 dataset and beyond

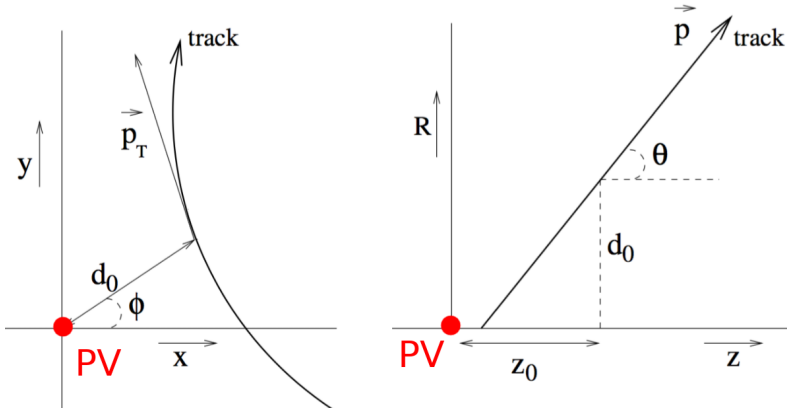
Conclusion

- **Yukawa-like interactions** in the Standard Model are puzzling
  - "ad hoc" in lagrangian, no quantized charge, wide range of coupling
- To study them at the LHC, **one needs to identify b-jets**
  - some leading measurements already dominated by systematic uncertainties
  - $t\bar{t} + \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$, one of the leading channel to search for dark sector
- **Continuous improvement** of *b*-tagging performance
  - advanced machine learning, improved efficiency measurements
  - benefit to results with full Run 2 dataset and beyond
- The HL-LHC opens up **new possibilities,** brings **new challenges**
  - extended tracking in extremely busy environment
  - probing of Yukawa-like couplings with unprecedented precision

Additional material

Algorithms based on displaced IP

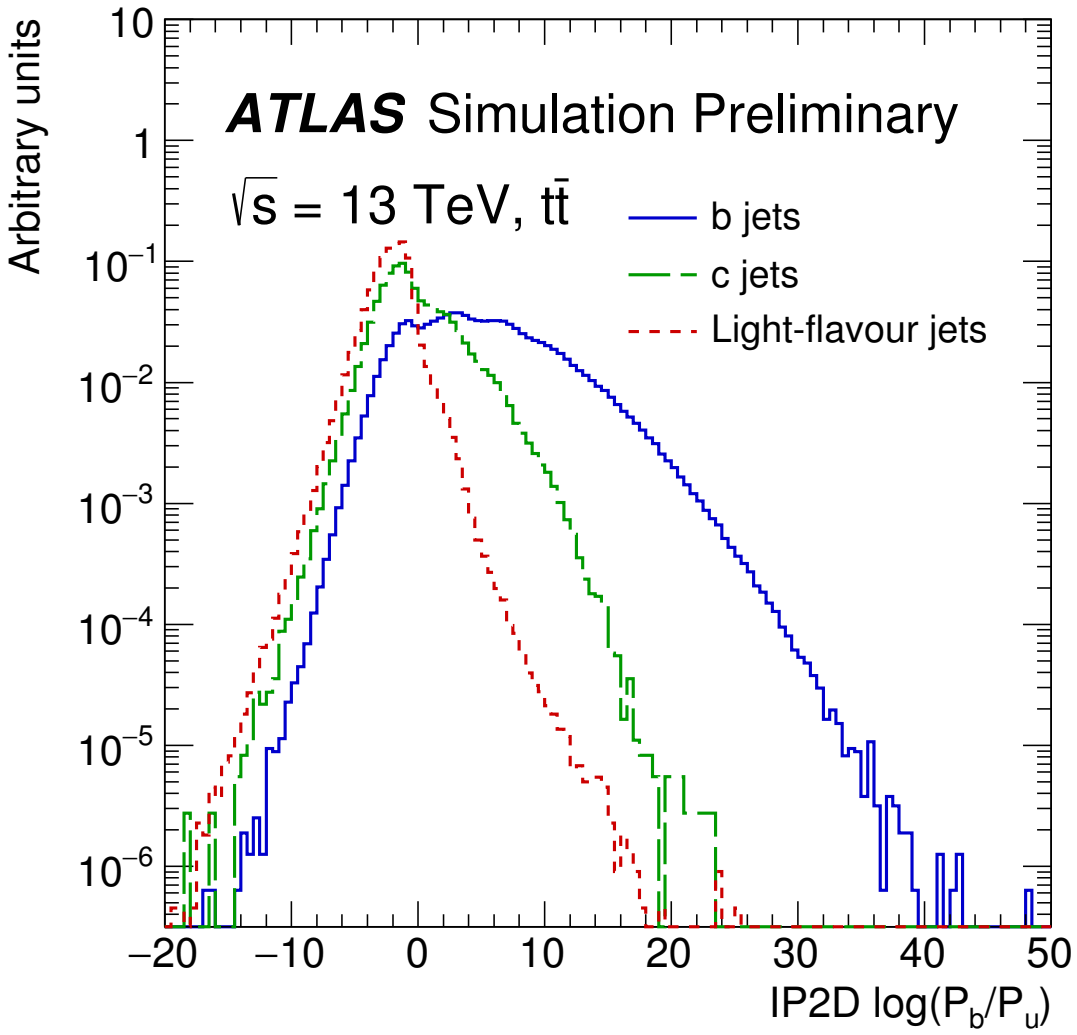




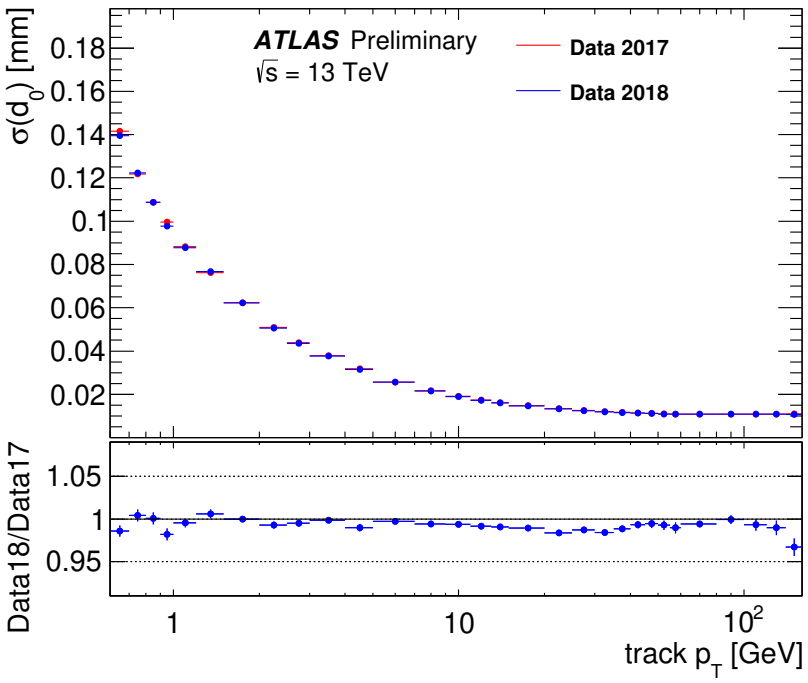
- **per-jet log-likelihood ratios** for "b vs l", "b vs c", "c vs l"

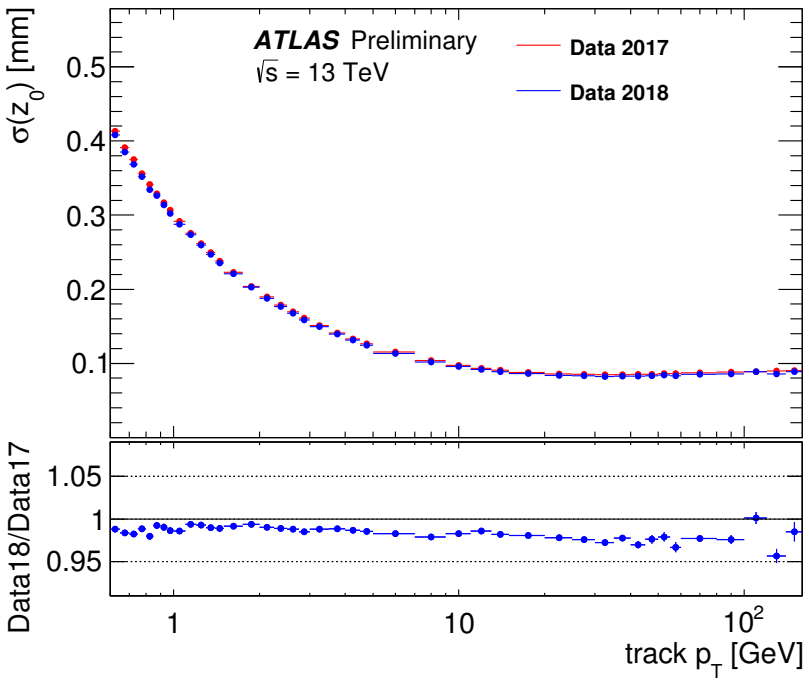
$$D_{IP} = \sum_{i=1}^{N^{trk}} \log(p_b/p_l)$$

IP2D "b vs light" discriminant

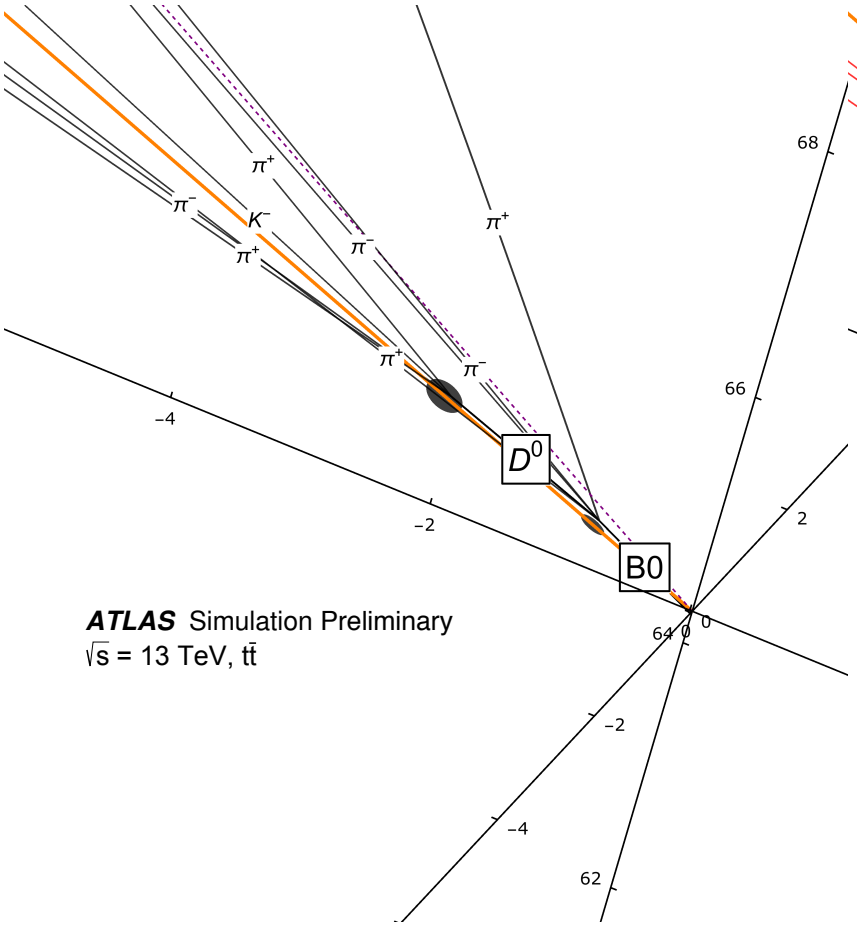


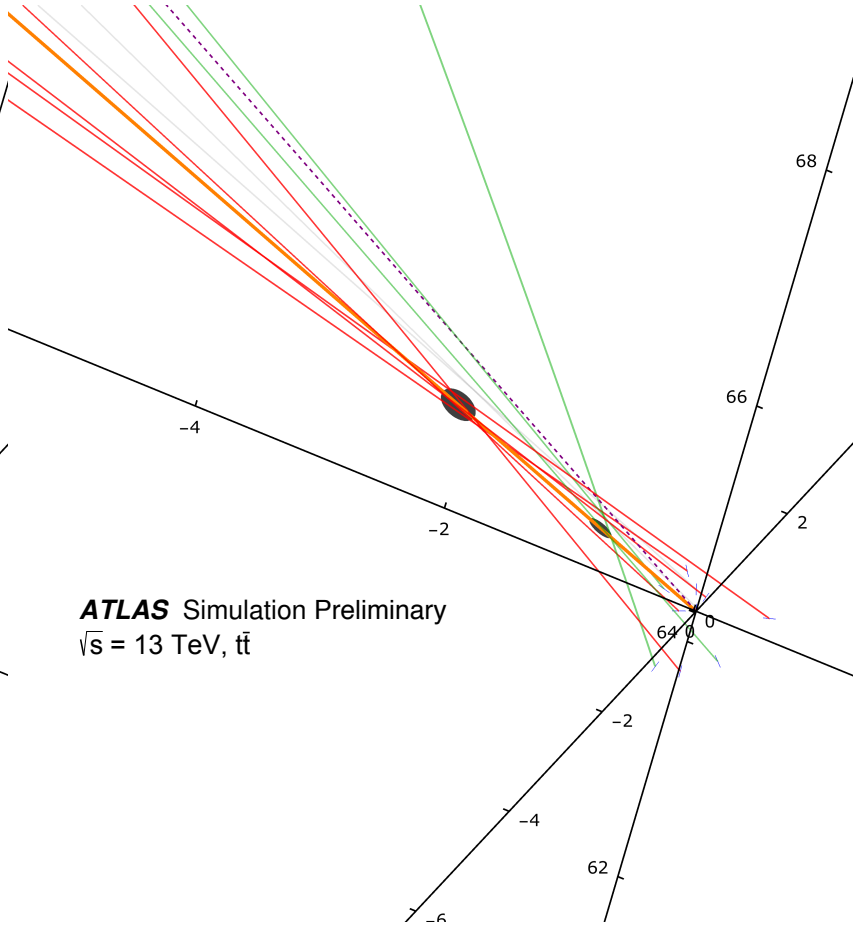
IP resolution measurements





JetFitter reconstruction

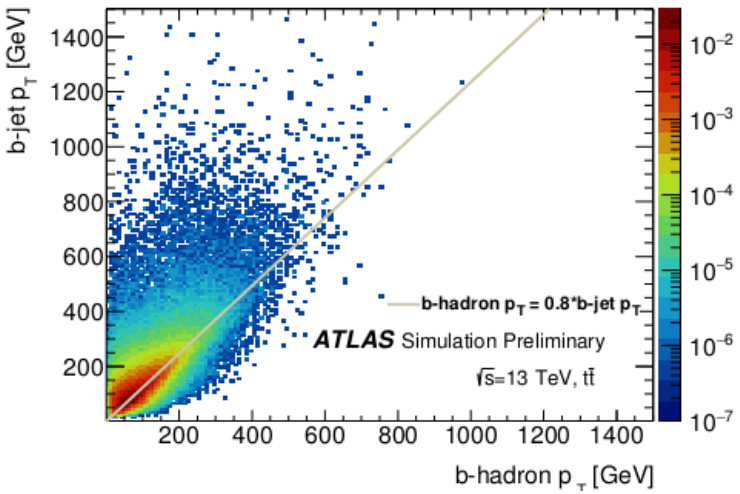




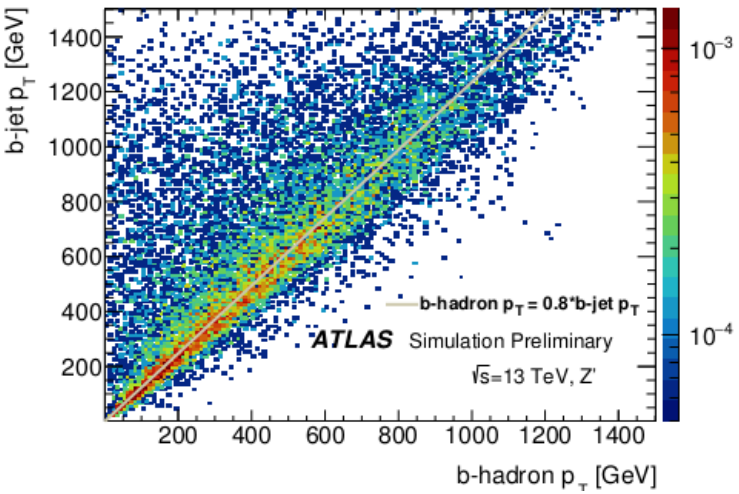
Hybrid training sample

- b-hadron p_T spectrum in $t\bar{t}$ intrinsically limited by $m_t \sim 175$ GeV
- for $p_T^{jet} > m_t$, jet clusters nearby hadronic activity, uncorrelated to the b-hadron (e.g. final state radiation) → $t\bar{t}$-based training may not be optimal
- Use of an hybrid sample: $t\bar{t}$ (b-hadron $p_T < 250$ GeV) and Z' (> 250 GeV)

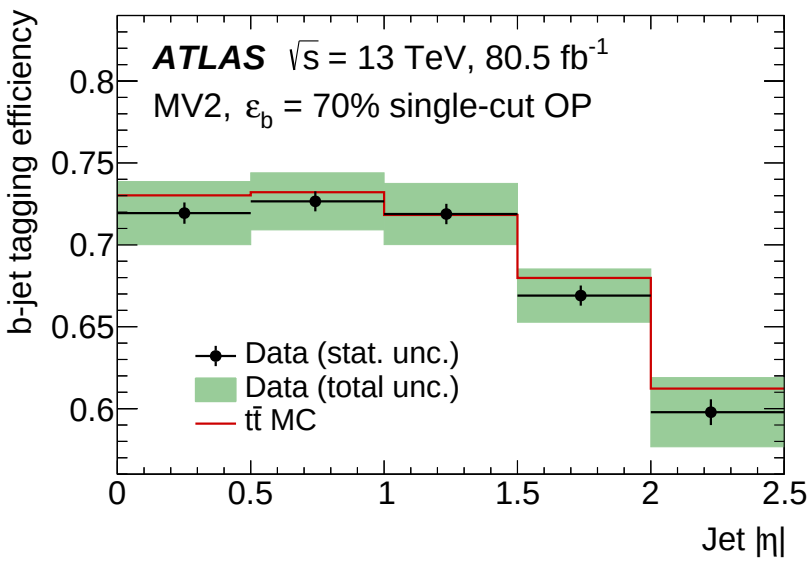
$t\bar{t}$ simulated sample

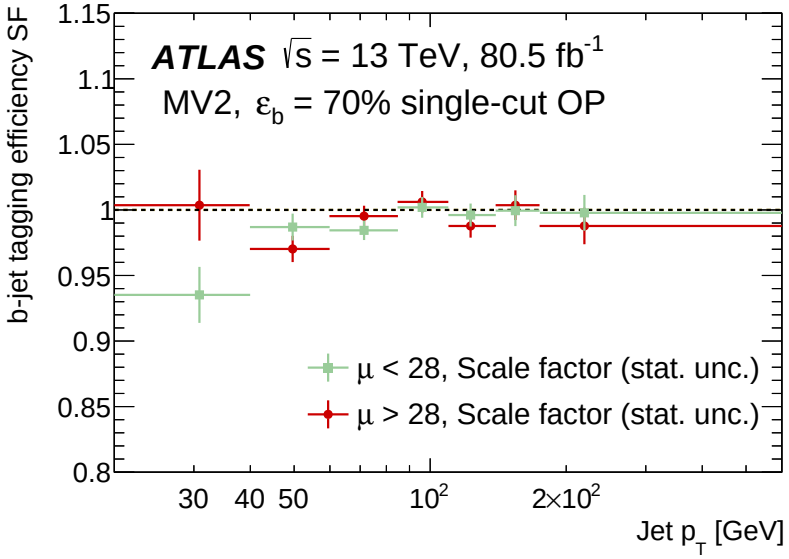


Z′ simulated sample

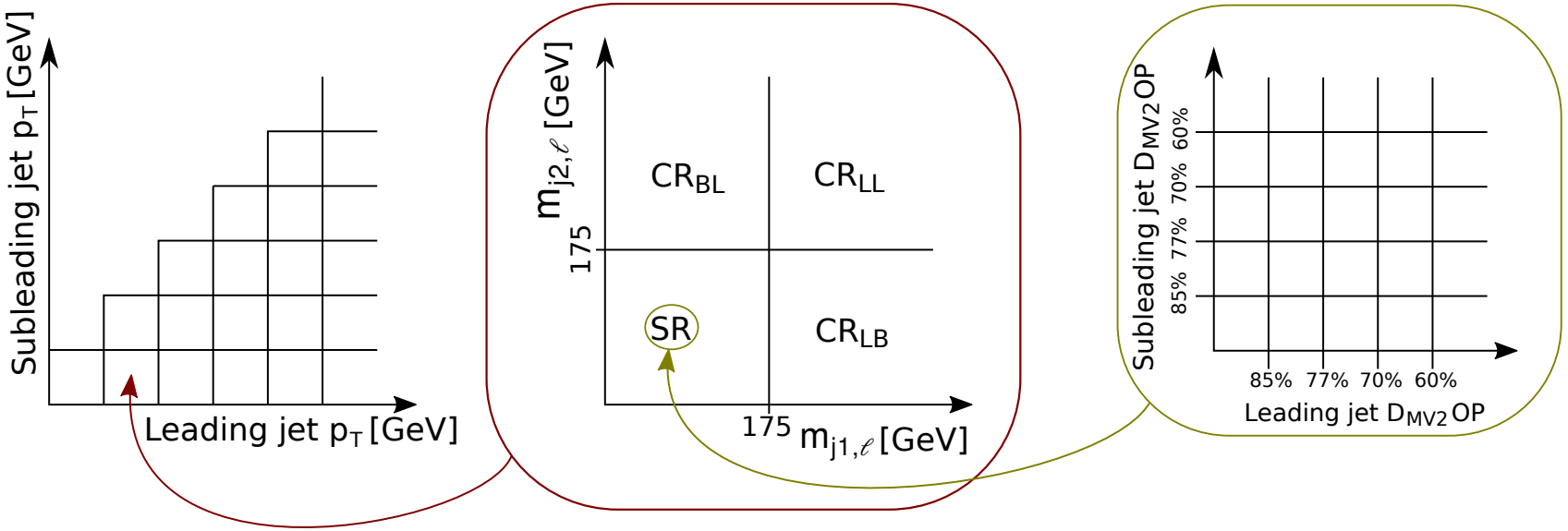


Performance vs η and μ





Efficiency measurement in data



c-jet mistag rate measurement in data (1/2)

- use of $t\bar{t}$ semi-leptonic decays, i.e. one W$\rightarrow l\nu$ and one W$\rightarrow cs$
- selection: 1 lepton, 4 jets (incl. 2 b-jets), kinematic fit to reduce background
- 2 jets attributed to W decay used in final fit
- uncertainty 5-20 %, dominated by $t\bar{t}$ modeling

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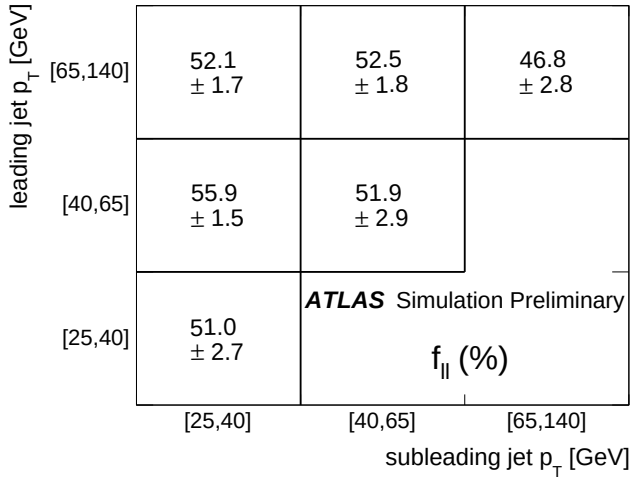
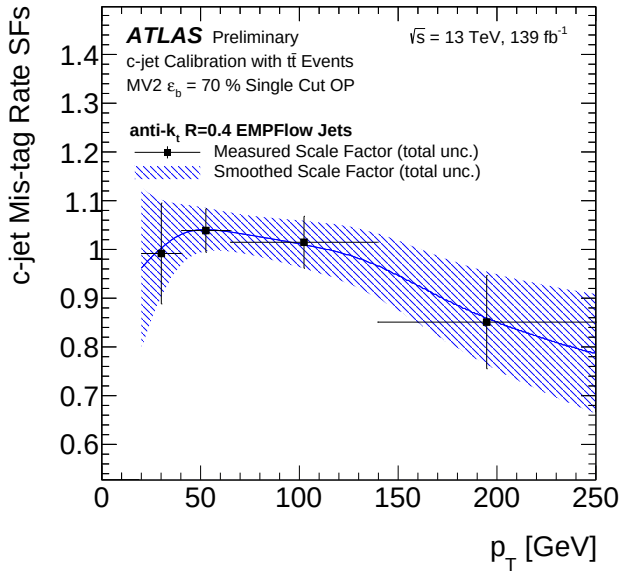
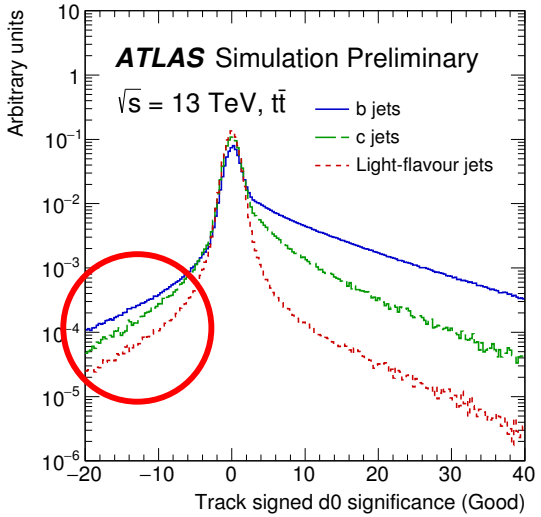


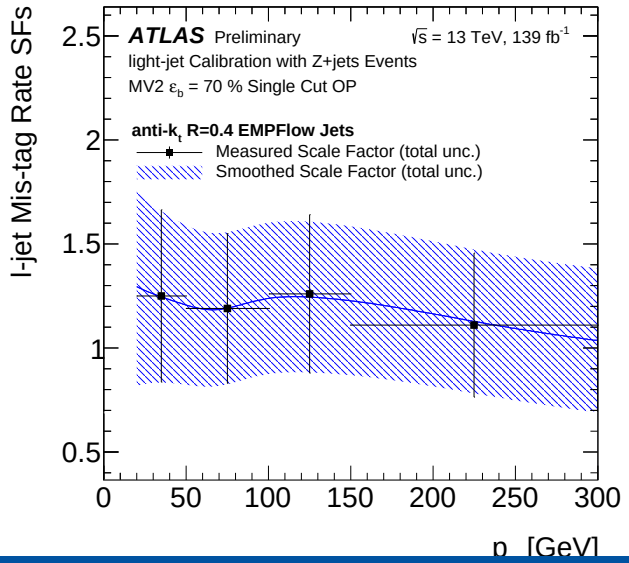


l-jet mistag rate measurement in data (2/2)

- sample of true light-jet **before and after** *b*-tagging required
- not achievable by regular di-jet selection: $\sim$ 2% (5%) b-(c-)jet bef tag ... x10 after.
- use of a "flipped" tagger to calibrate **fakes from track resolution effects**
- tag jets with negative attributes
  $\rightarrow$ **similar mistag rate for light** (resolution function symmetric)
  $\rightarrow$ **much lower rate for b and c**

  $\rightarrow$ **obtention of a purer sample after tag**





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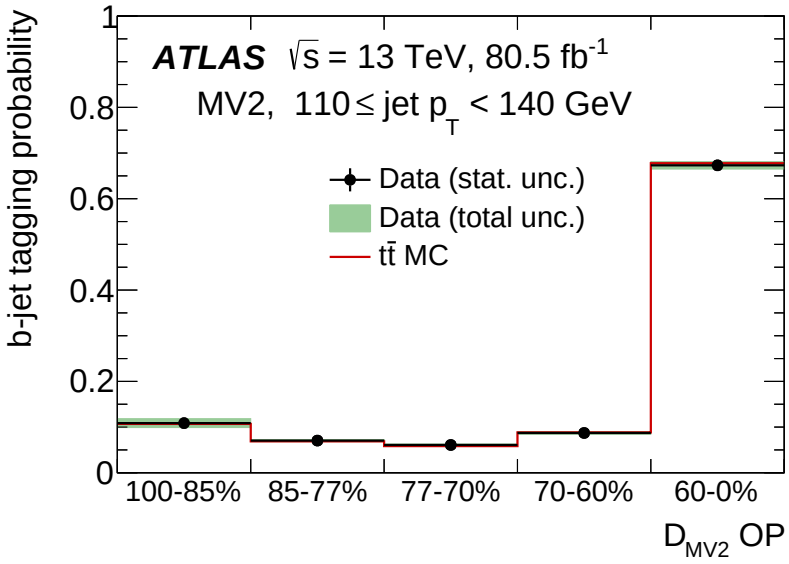
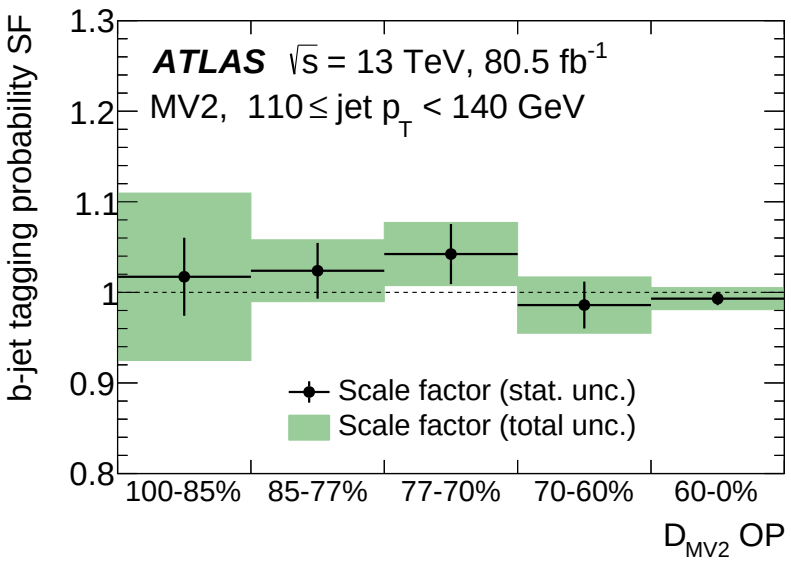
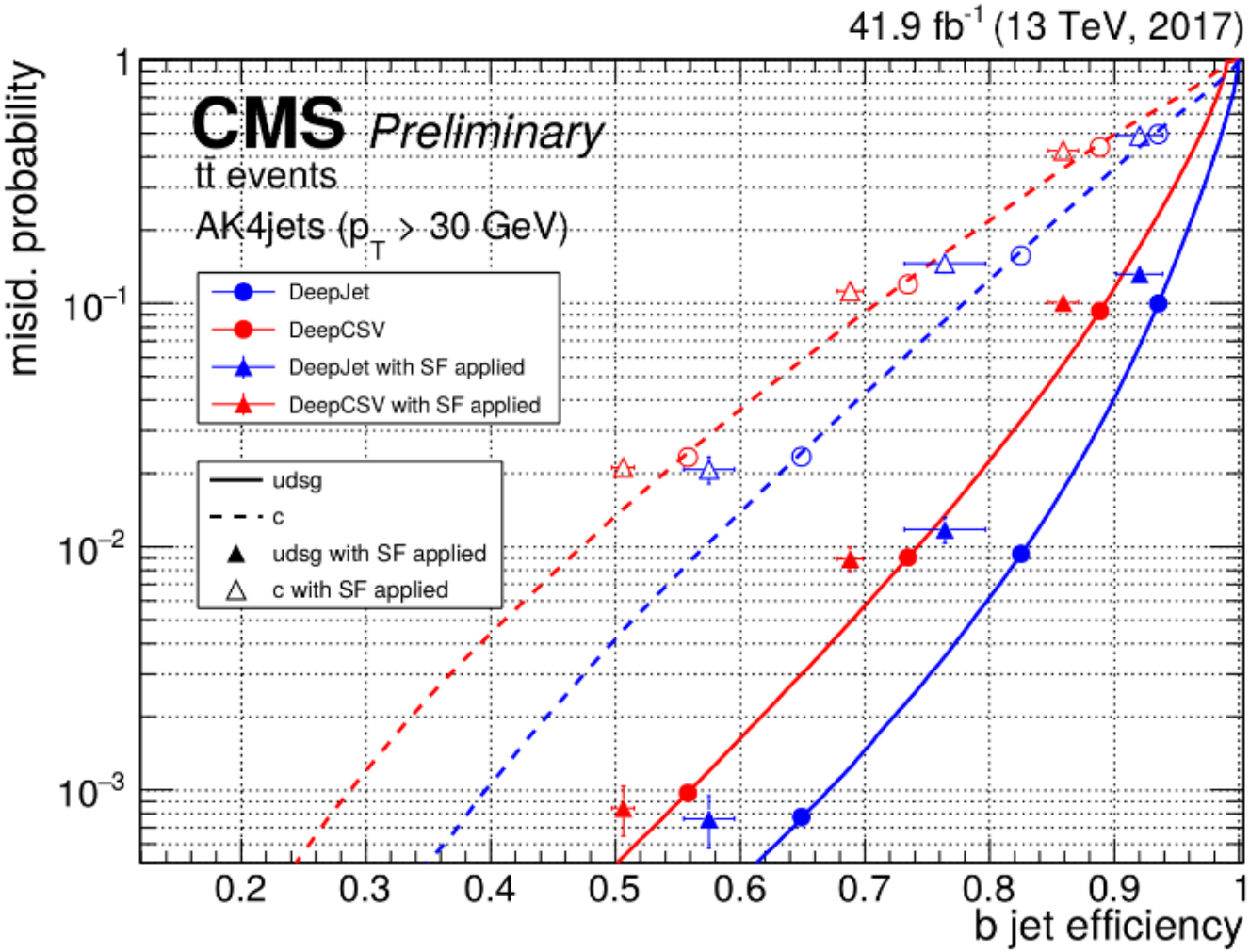
Pseudo-continuous *b*-tagging

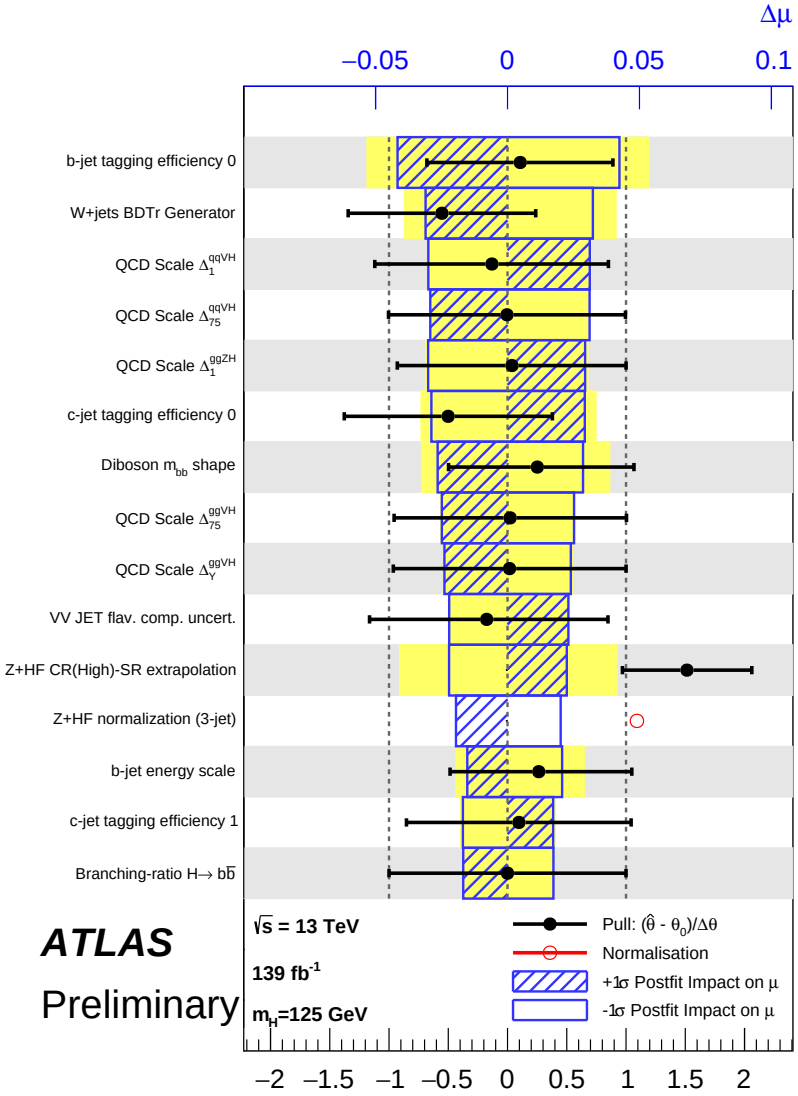


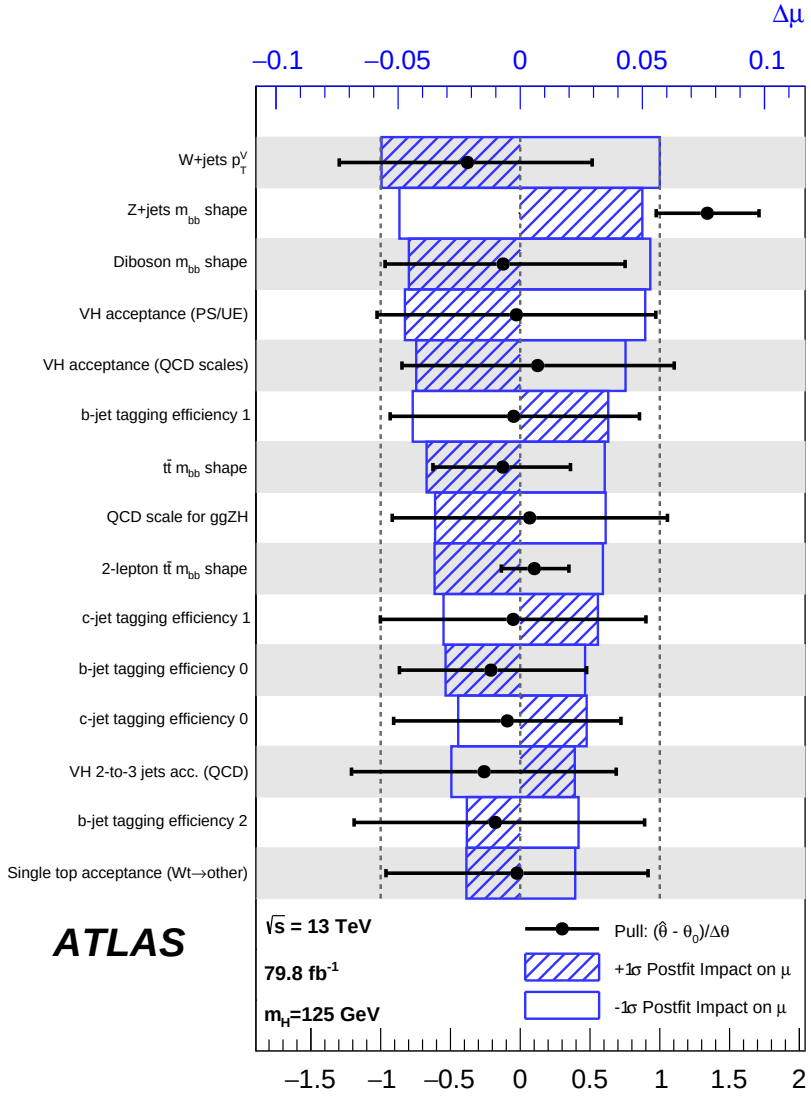


CMS performance

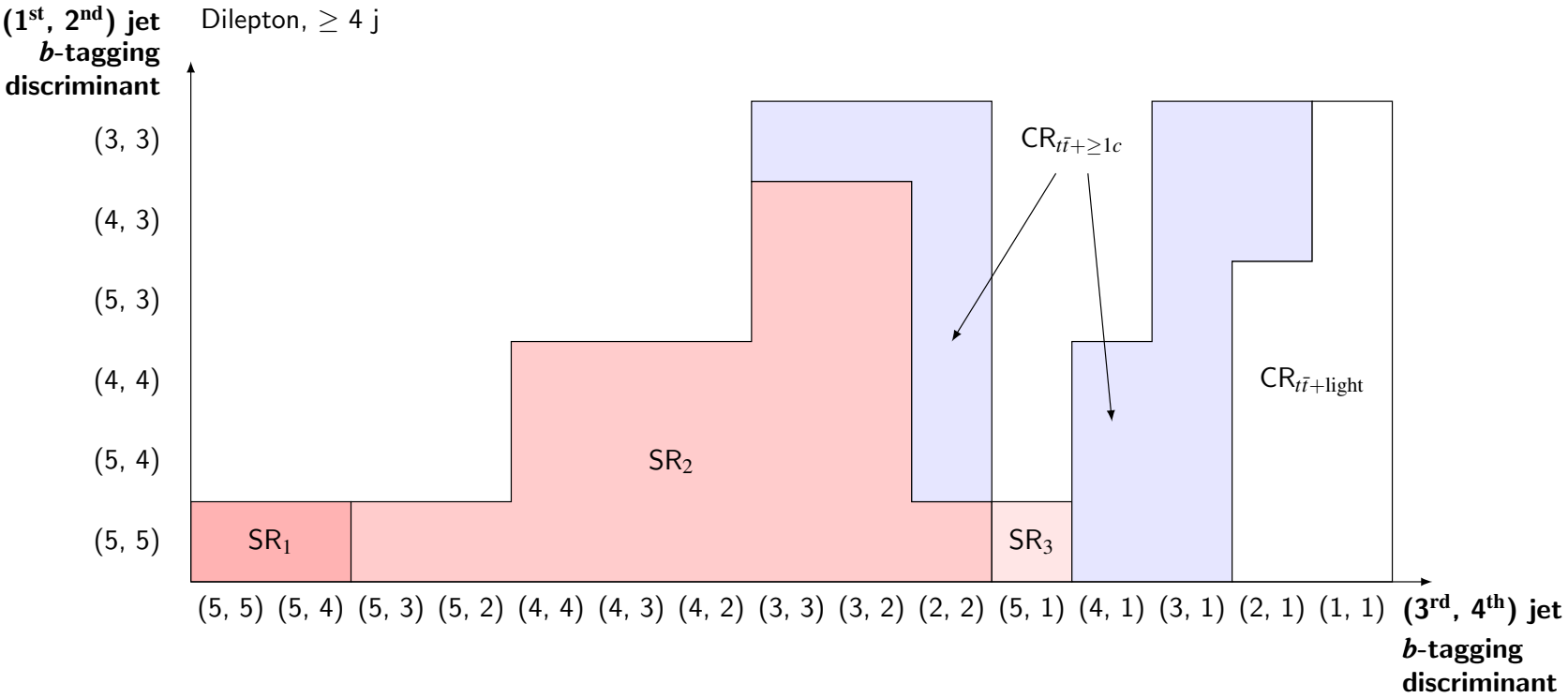


$VH(\rightarrow bb)$ systematic ranking plot





$ttH(\rightarrow bb)$ categorization



$X \to bb$ tagging

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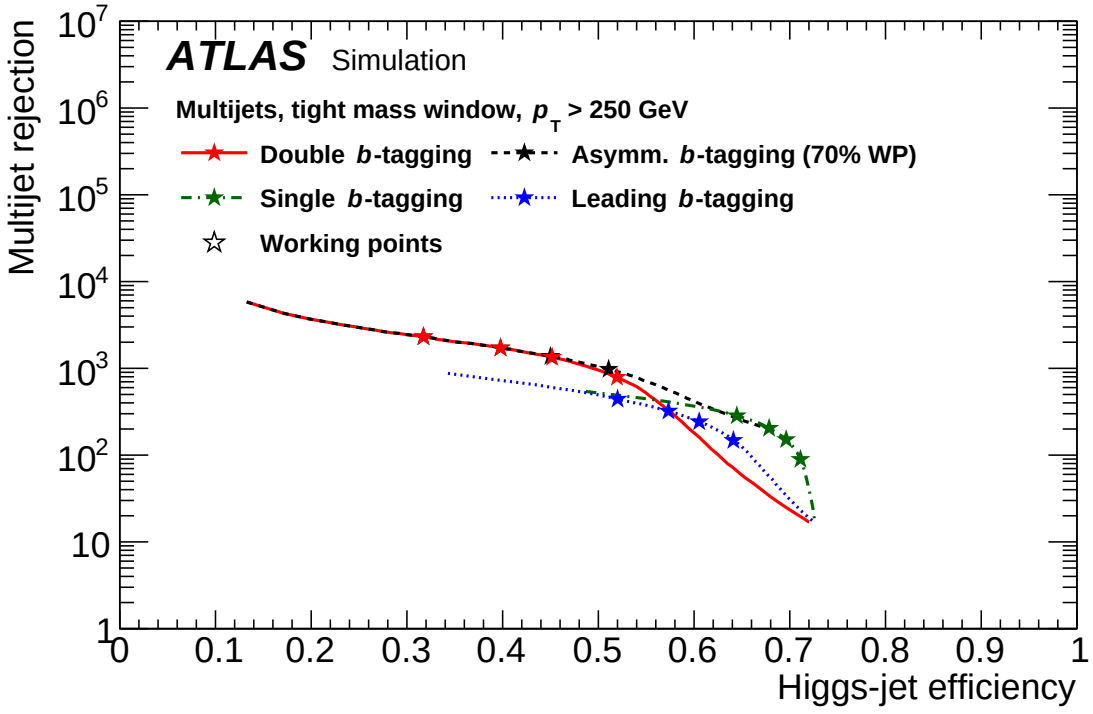

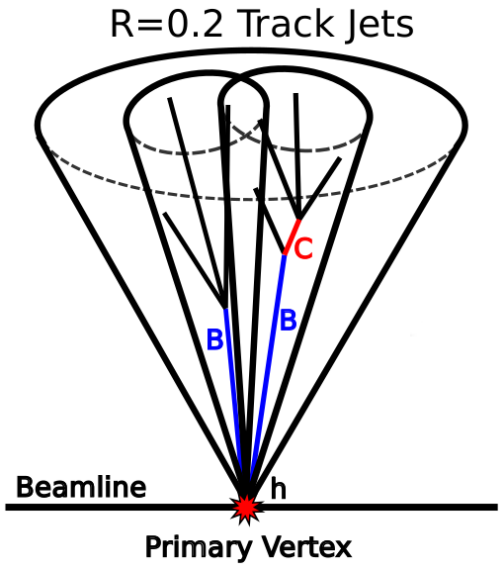

Top tagging

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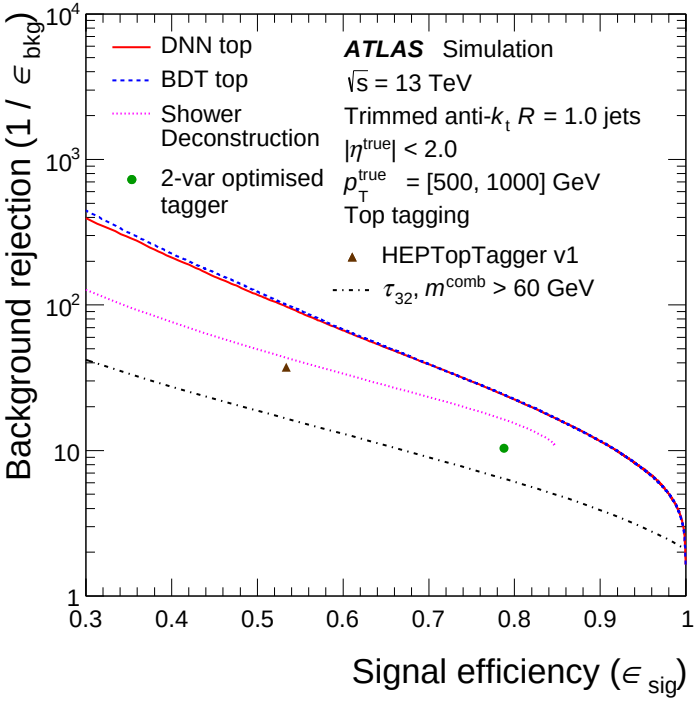
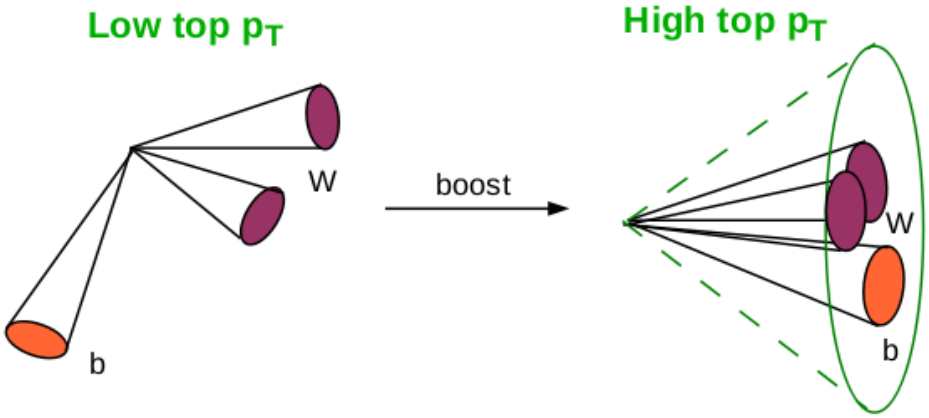
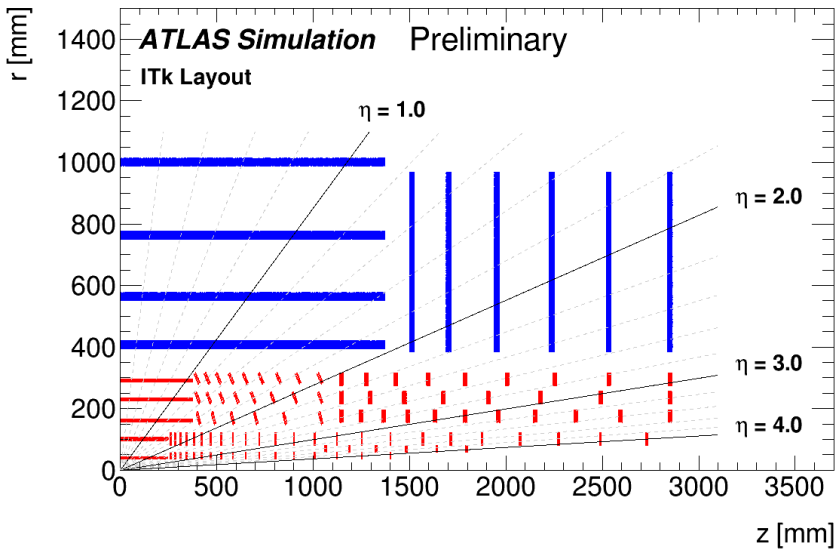
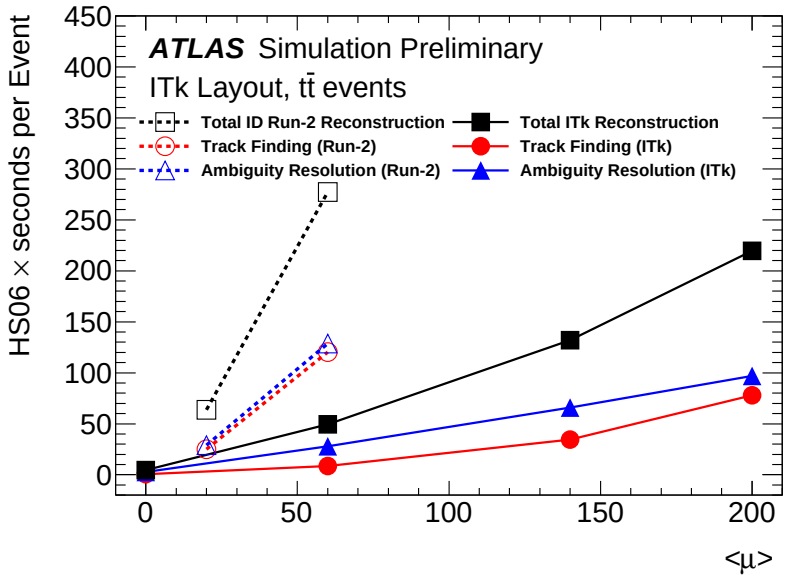


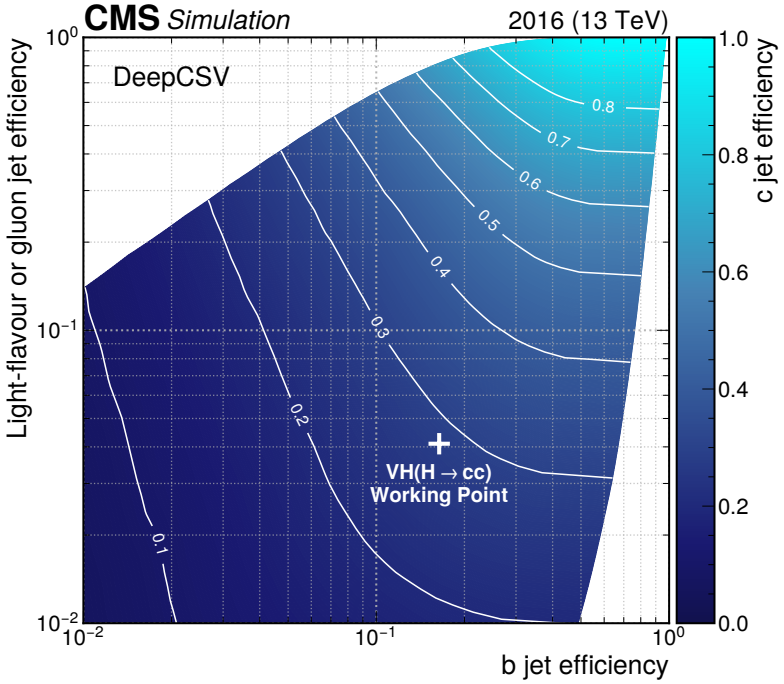


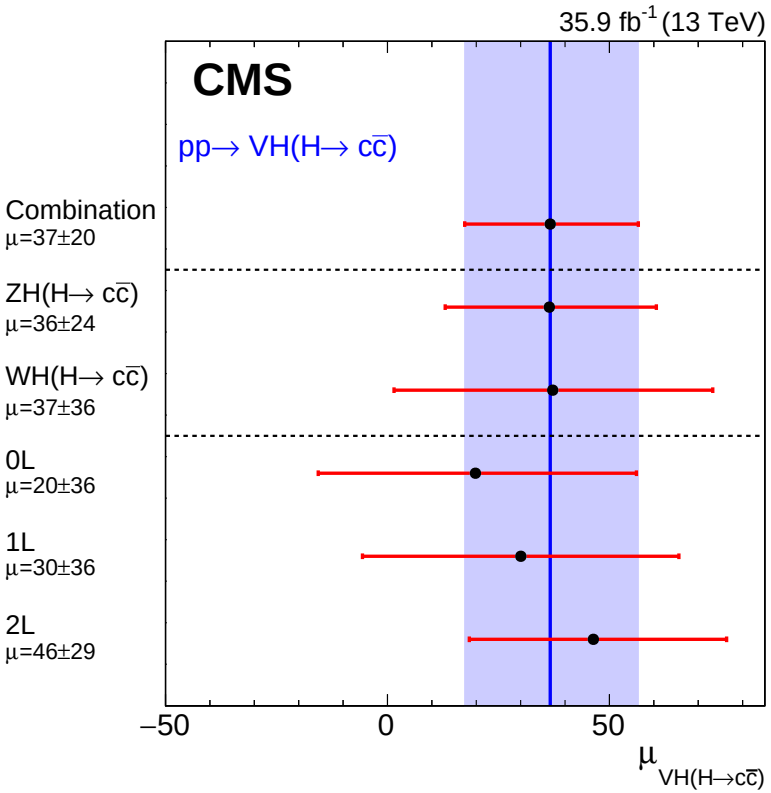
Tracking at HL-LHC





$c - H$ Yukawa-like coupling





HL-LHC projections: $\mu < 6.3$ times the SM