INFN and University of Milano Bicocca [1]

Boosted Higgs boson identification

and

Matrix Element Methods in Higgs searches

Speaker: ***Raffaele Gerosa*** [1]

On behalf of ***CMS*** *and* ***ATLAS*** *collaborations*

HC15: Higgs Couplings 2015, 12-15 Oct 2015, IPPP, Durham (UK)

Boosted Higgs boson tagging

searches with boosted objects

- **New physics** at **high mass** might appear in topologies with heavy **SM** bosons (**$W^{\pm}$, Z, h**):
  - **Extra Dimensions : Bulk** or **RS** model → spin-2 **gravitons** and spin-0 **radions** → $M_X > 600$ GeV
  - **Higgs sector : 2HDM** and **(N)MSSM → H, A, $H^{\pm}$** → $M_X < 1$ TeV
  - **Composite Higgs : HVT** scenario → **spin-1 ($W^{\pm\prime}$, Z')** → decay mainly to W_L, Z_L, H
- **Multi-boson measurements**: **VBS** at high mass, **di-Higgs** production .. etc ..
- **Signatures: hadronic** or **semi-leptonic** final states to maximize **σ x BR**, despite higher backgrounds

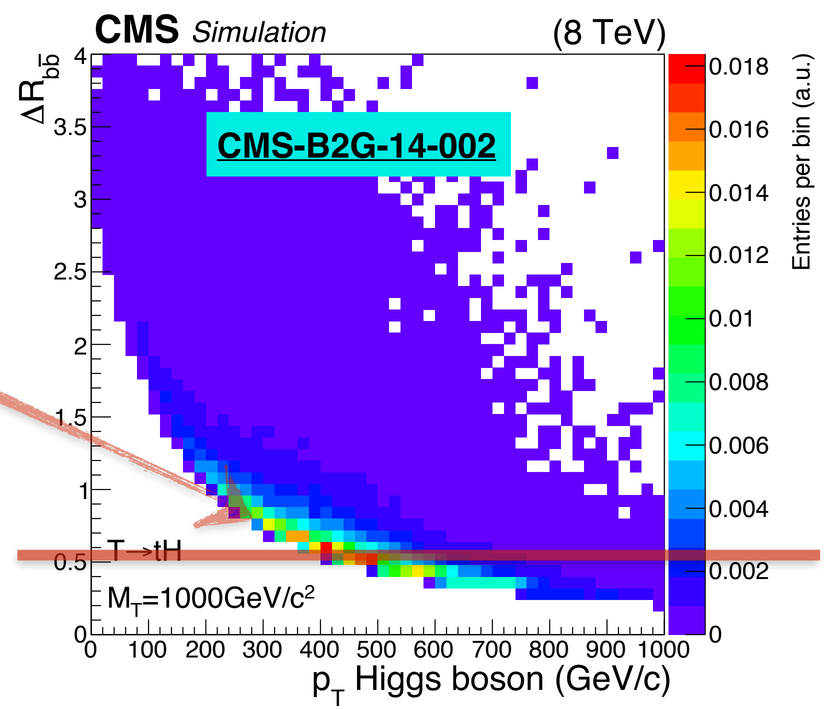
Heavy object (V) fragments into **two prongs** (p_1,p_2)

$$\Delta R(p_1 p_2) \sim 2m_V/p_T$$

m_h =125 GeV, p_T > 350 GeV → ΔR < 0.8

Resolving jets becomes **inefficient**

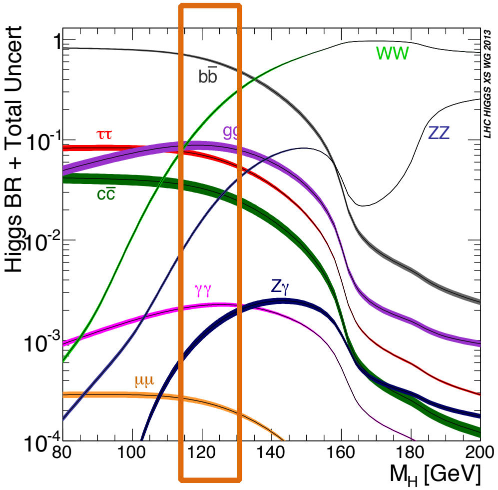
Boosted searches … jet **substructure**



boosted Higgs phenomenology

h

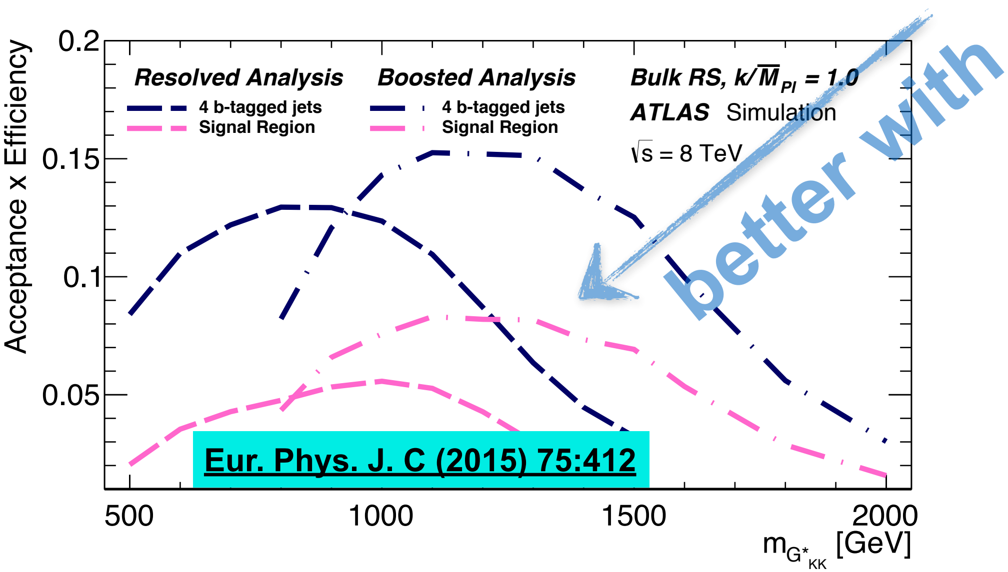
- **production** and **decay rates** consistent with **SM** predictions
- m_h = 125.09 ± 0.21 (stat.) ± 0.11 (syst.) GeV **Phys. Rev. Lett. 114, 191803 (2015)**
- $J^P = 0^+$



Branching fractions

- **$h \to b\bar{b}$ (57%)** → **b-tagging** and **substructure** to reduce **QCD bkg**
- **h → WW* (21.6%)** → fully hadronic decay, i.e. 4-prong substructure
- **$h \to \tau\tau$ (6.3%)** → boosted **τ-jet** reconstruction
- **$h \to \gamma\gamma$ (0.23%)** → excellent mass resolution but low BR

Boosted techniques increase analysis sensitivity at high mass



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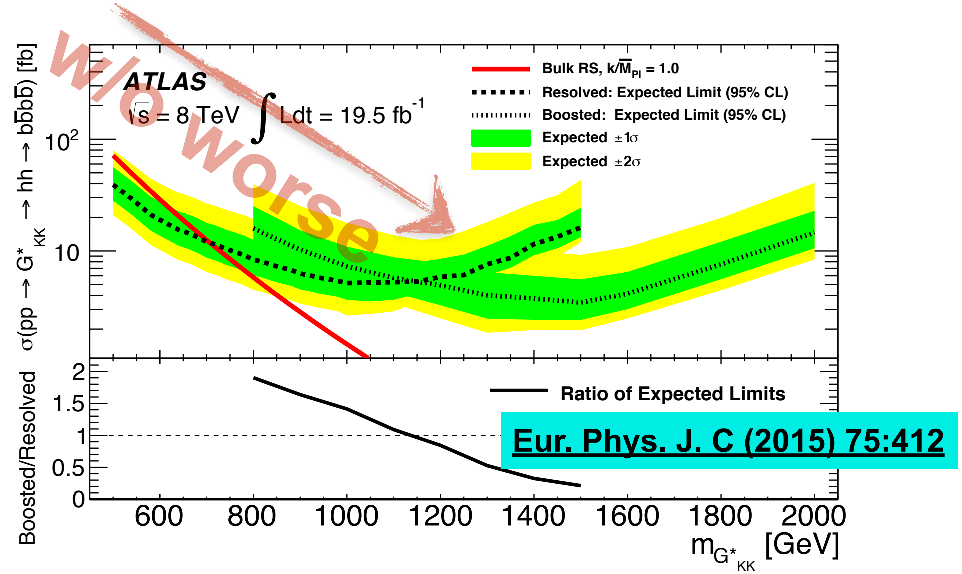

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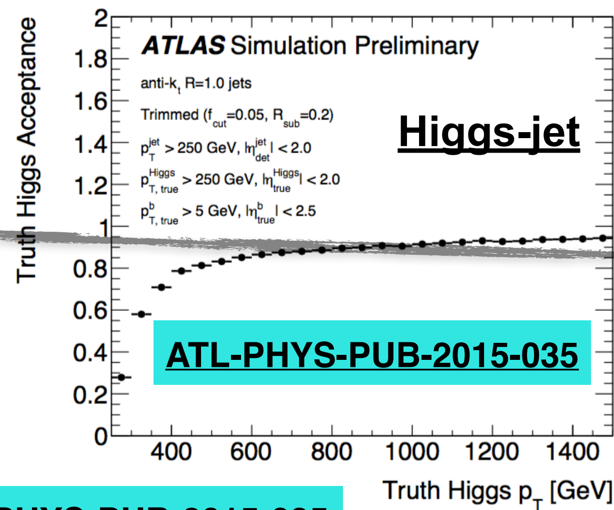
Higgs tagging: basic concepts

- To **identify hadronically** decaying heavy objects: $\mathbf{h \rightarrow b\bar{b}}$, $\mathbf{h \rightarrow WW^* \rightarrow qqqq}$, $\mathbf{W/Z \rightarrow qq}$

Cluster the **fragmentation** products within a **large cone jet** **anti-k$_t$** or **CA (R = 0.8, 1.0)**



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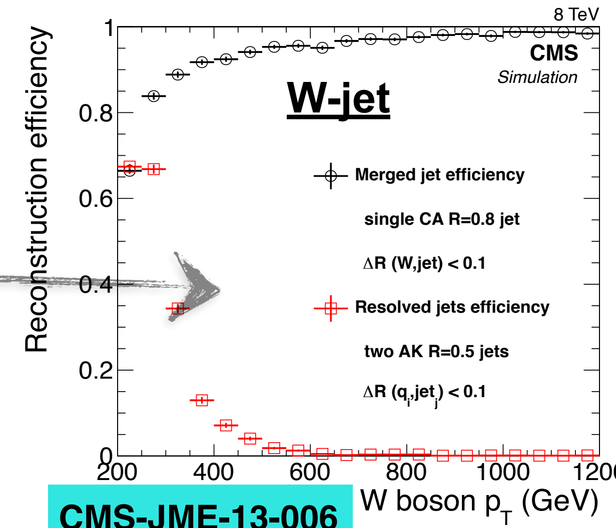

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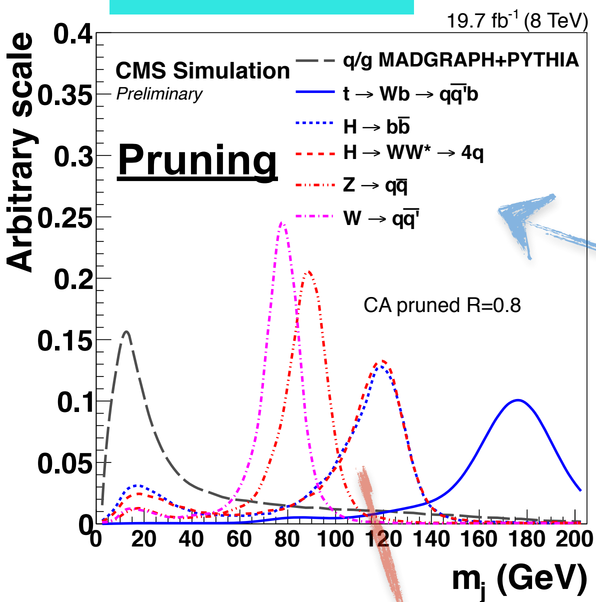

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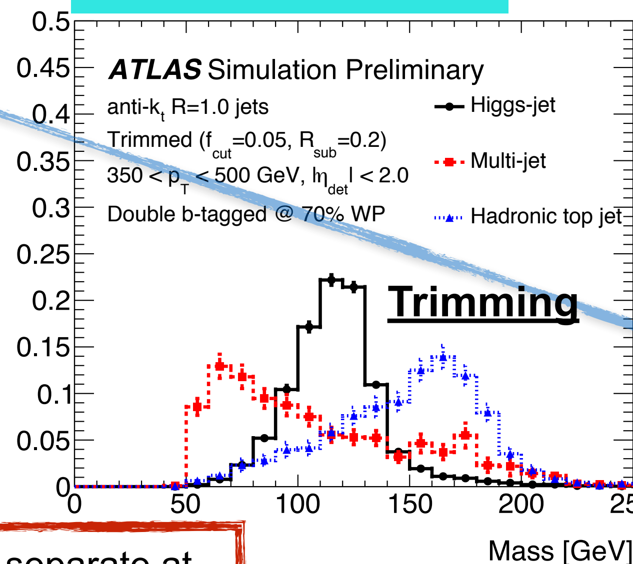


Jet mass is the **primary observable** to separate heavy bosons (W, Z or h) jets from q/g fragmentation

Strategies for **h-jet** similar to **W/Z-jet**

Grooming algorithms remove **pileup**, **soft** and **wide angle radiation**, **U.E**

Groomed mass scale and **resolution** calibrated with **W-jets** in semi-leptonic $\mathbf{t\bar{t}}$ events

Resolution not enough **alone** to separate at best **Higgs** from **W/Z, top, q/g jets**

substructure observables

- After applying a mass selection, **jet shapes** are used to **improve background rejection**

Measure the probability for a **jet** to be composed by **N substructures**

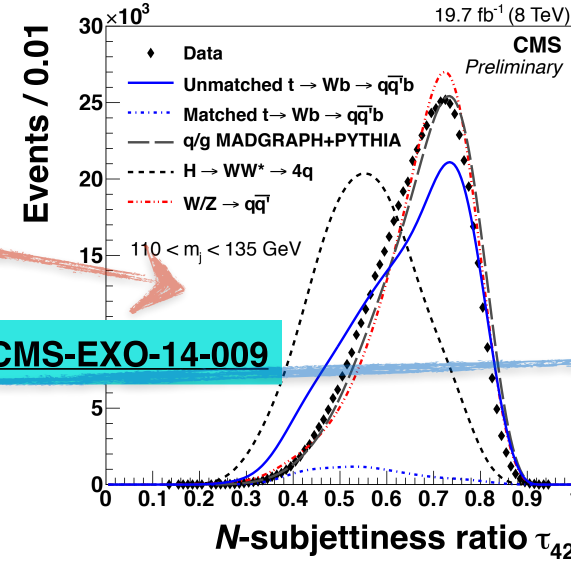
- **N-subjettiness**

  τ_{42} used in **CMS** to tag h → WW* → 4q

- **Energy Correlation Functions**

  $D_2(\beta=1)$ used in **ATLAS** for W-tagging

CMS-EXO-14-009



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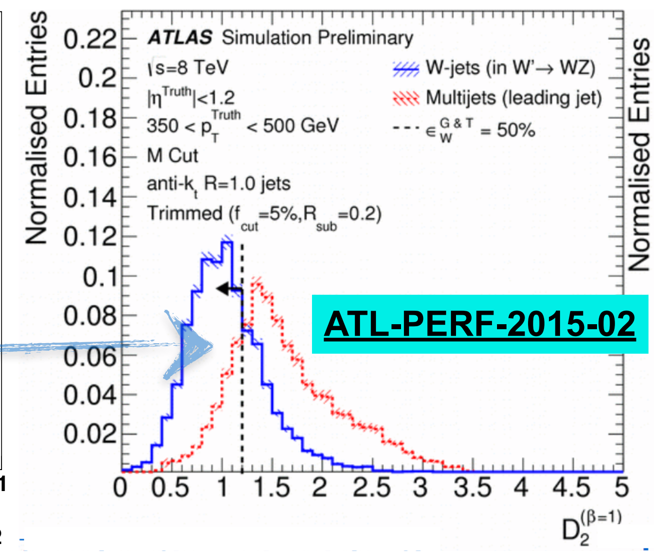
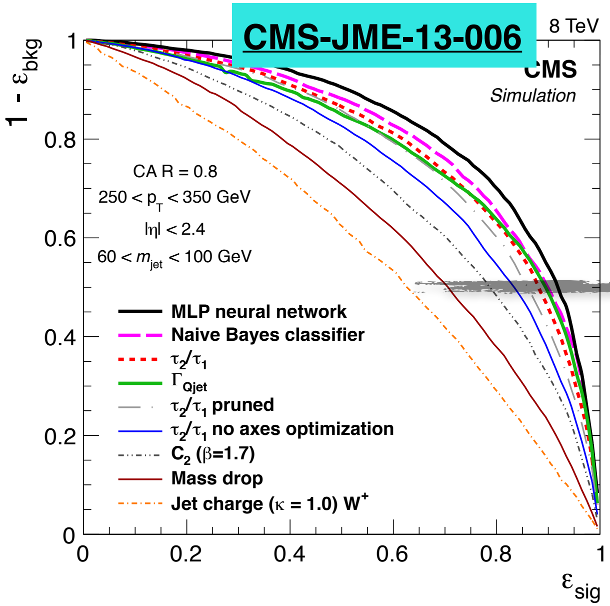
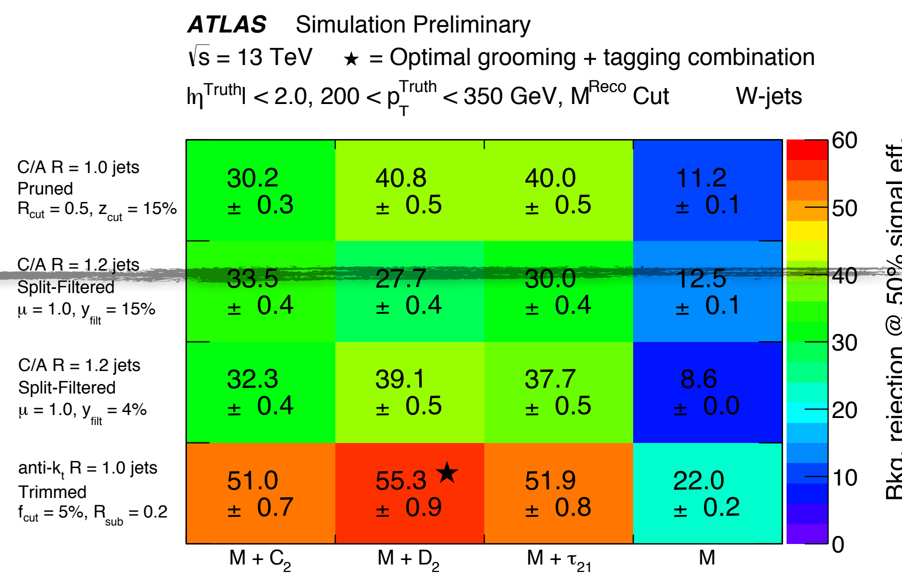


- **Optimize** a **combination** of **grooming techniques** and **substructure observables**

CMS-JME-13-006





Important gain exploiting additional variables to the **groomed jet mass**

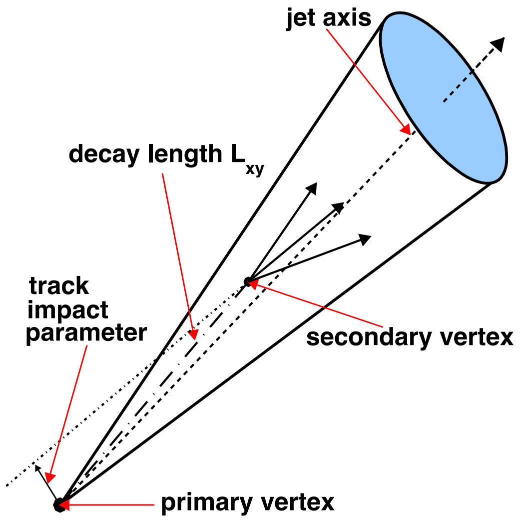
Higgs Tagging

golden channel for boosted h-jets is h→bb̄

b-tagging for **boosted jets** is **crucial**

b-tagging in a nutshell

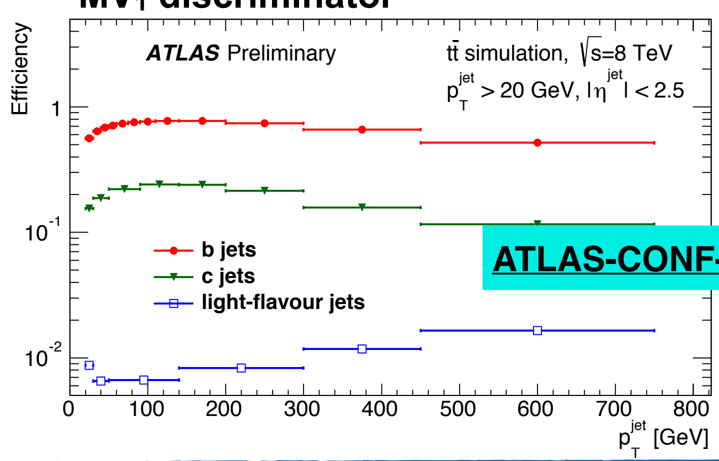
- **b-tagging** → identify jets from a **b-hadron** decays exploiting:
  - **Long lifetime:** $c\tau$ = 500 μm, $\beta\gamma c\tau$ ~ O(5-10 mm) @50-100 GeV
  - **Larger mass** and **higher track multiplicity** wrt light flavor or gluon jets
  - **Large semi-leptonic BR**
- **b-tagging techniques** are based on:
  - **Displaced track** information (IP significance)
  - **Secondary vertex** reconstruction and properties
  - **Soft leptons** (e,μ) inside jets



ATLAS Run-I

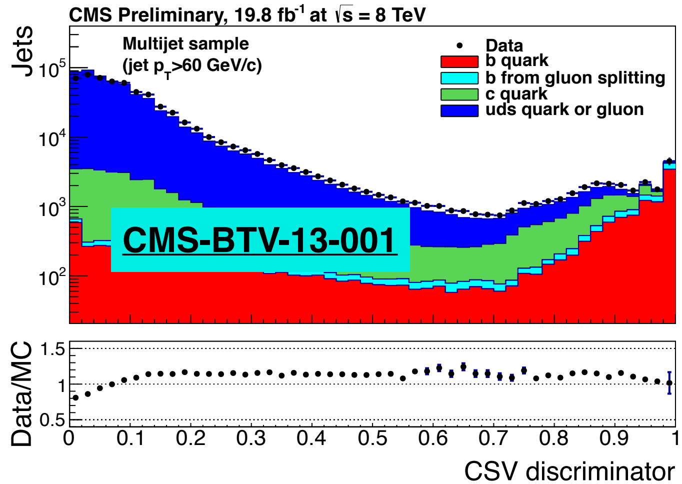
- Different algorithms: **IP3D, SV_1, jetFitter**
- Combination into a **MVA discriminator → MV_1**

MV_1 discriminator



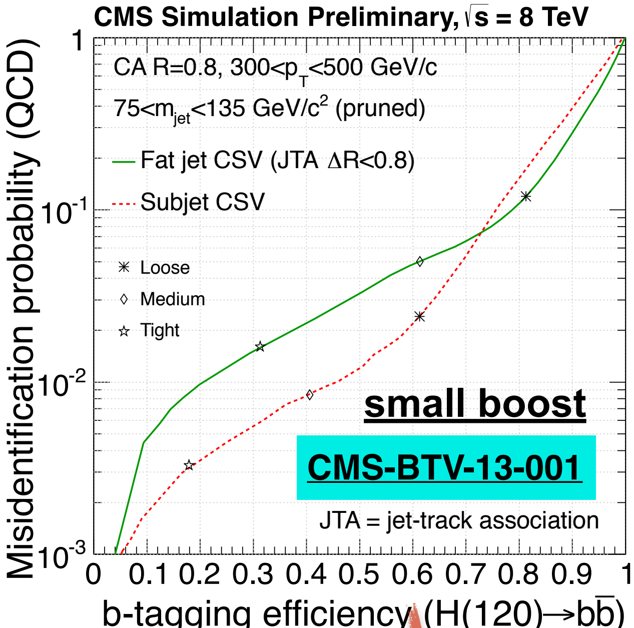
CMS Run-I

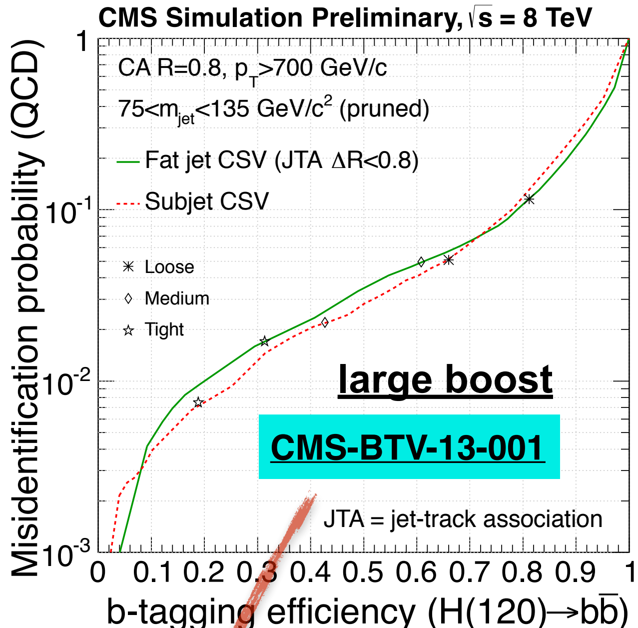
- **Secondary vertex** fitted from geometric jet-track association
- **CSV** → likelihood based on IP3D, SV, etc ..

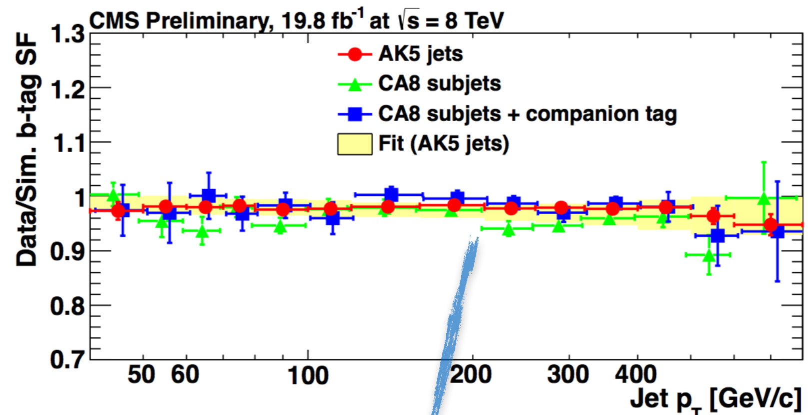


$h \to b\bar{b}$ tagging: CMS Run-I

- **Strategy: b-tagging optimized** for **small R-jets applied** on **large cone** ones
  b-tagging applied on **pruned sub-jets,** which are obtained undoing the last clustering stage
- Mainly **uncorrelated** wrt the other **substructure** observables → **improve separation**







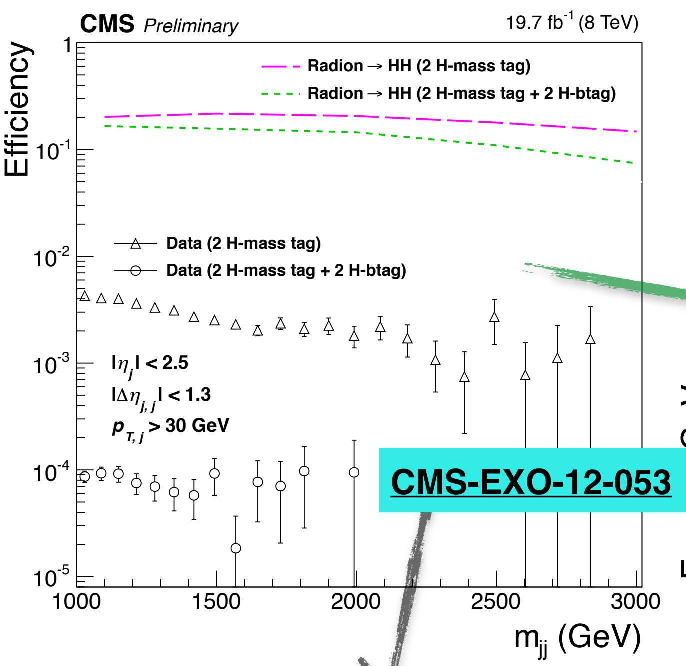
Validated with **data** in $g \to b\bar{b}$ and **light jet flavor** enriched **C.R.** **SFs** similar to AK5 jets

Double b-tagging on **subjets** performs better than **h-jet b-tag**
Worsening at **high p_T** due to track sharing between sub-jets

CMS: X → hh → $b\bar{b}b\bar{b}$

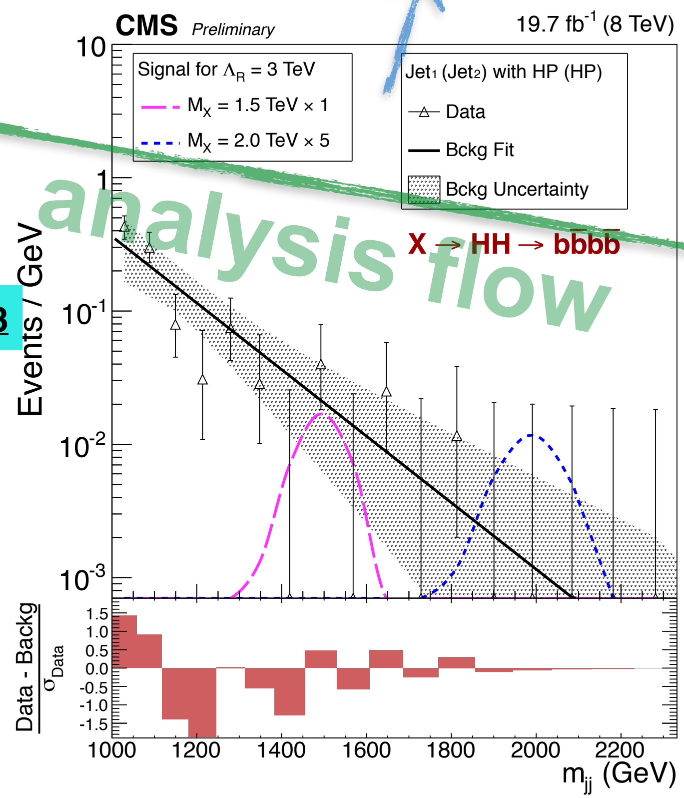
ATLAS X→hh→4b in backup

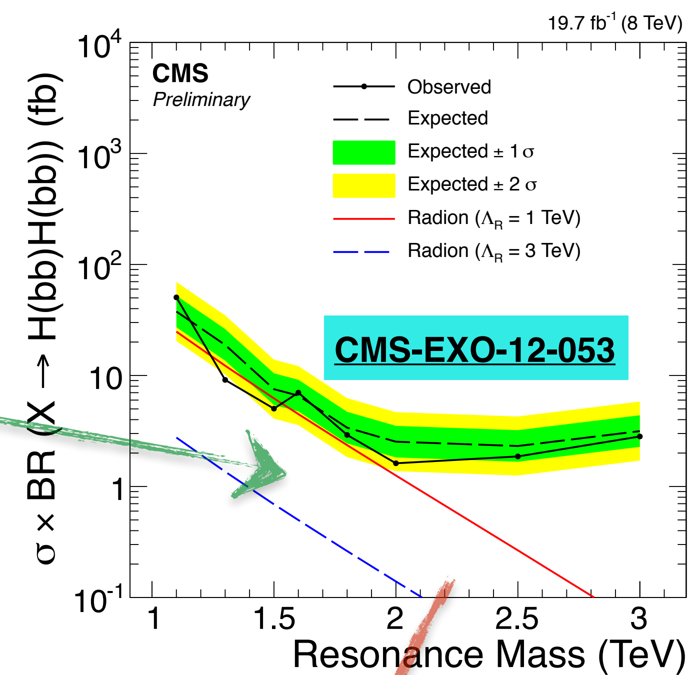
- **Selections:** two CA (R = 0.8) jets, $|\Delta\eta_{jj}| < 1.3$, $m_{jj} = m_{hh} > 1$ TeV
  - **Pruned mass selection:** $\mathbf{m_{jet}}$ in the range **110-135 GeV**
  - **N-subjettiness:** each higgs jet candidate should have $\tau_{21} < 0.5$
  - **b-tagging:** if $\Delta R(j_1,j_2) > 0.3$ b-tagging applied on the two **pruned sub-jets**, otherwise on the **CA8 jet**



- **signal efficiency** almost stable as a function of m_X
- **same** for **events** in the **data**

Fit to data in m_{jj} excluding the peak region

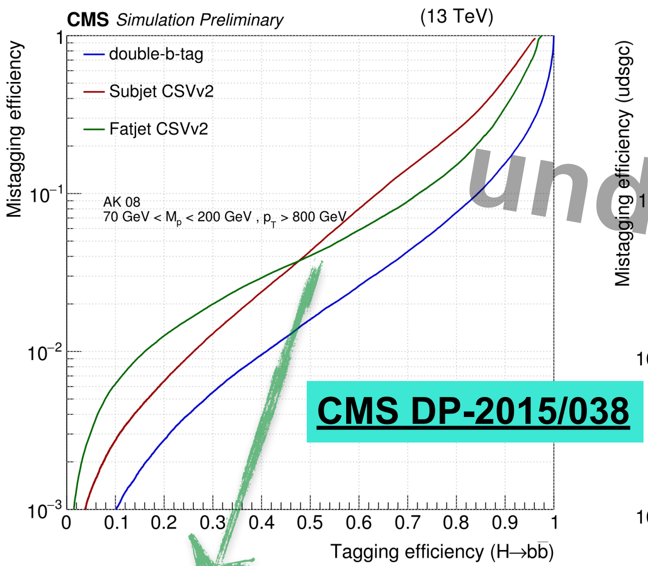


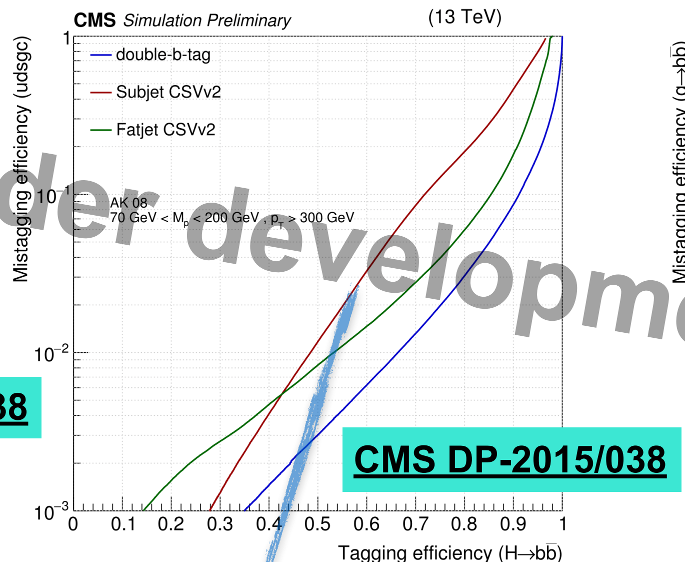


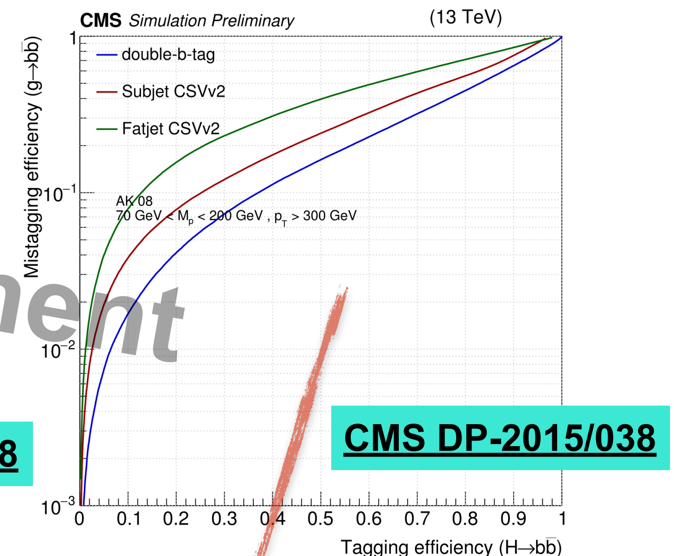
- **No excess** over B prediction
- **Upper bound** for **Radion** production

(*) comparison with Run-I in the backup

- **b-tagging** news for **Run-II (*)**
  - **Explicit jet-track association**: tracks linked to charged jet constituents → **no ambiguity**
  - **Inclusive Vertex Finder (IVF):** use all the tracks to fit secondary vertexes → independent from jet size
  - **Improved CSV algorithm**
- **Higgs b-tagging** news for **Run-II**
  - **Double b-tagging:** develop a specific **MVA** discriminator to identify h → b$\bar{b}$ jets
    Inputs: jet tracks, leading associated secondary vertex, leading soft lepton, sub-jet CSV values







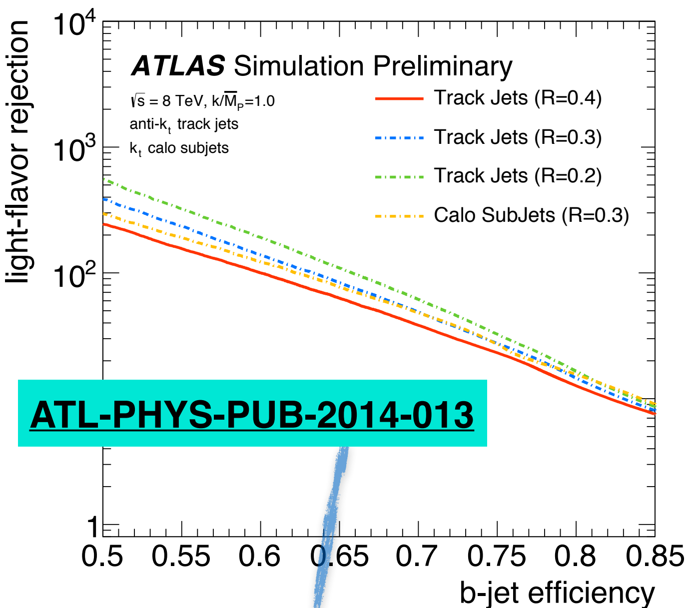
h→ b$\bar{b}$ against QCD multijet
Improvement with **double b-tag** by a **factor 3** even at high p_T

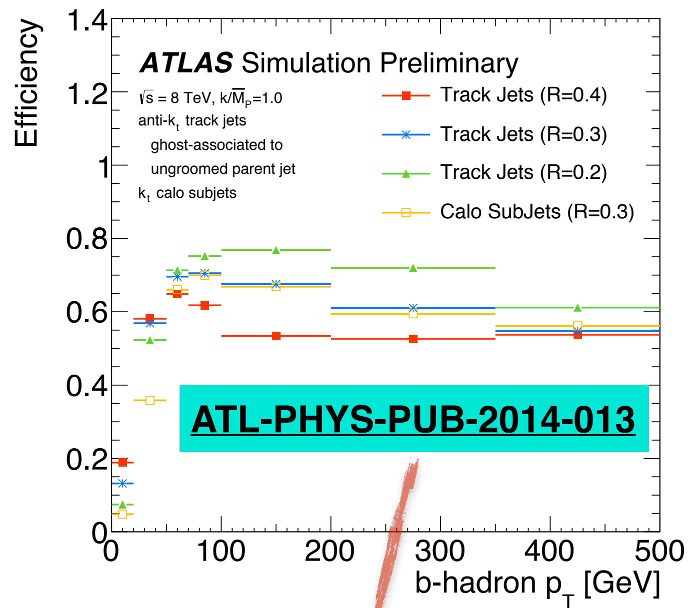
Discrimination vs **light flavor** jets

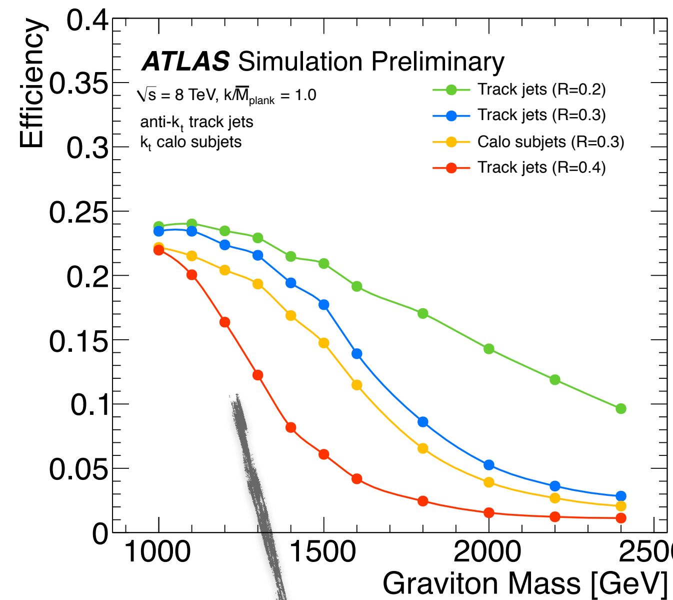
Gain also against **g→b$\bar{b}$**

$h \rightarrow b\bar{b}$ tagging: ATLAS Run-I

- **Calorimeter jets:** clustered from topo-clusters with anti-k_t R = 1.0
- **Track-jets:** clustered from tracks associated to the PV with anti-k_t R = {0.2,0.3,0.4}
- **Ghost-Association**: **track-jets 4V** added as **ghosts** before jet clustering → **un-ambiguous association**
- **b-tagging:** applied on both **associated track-jets** and **trimmed sub-jets** (R_{trim} = 0.3, p_T^{frac} = 5%)







Measure the separation between **b-jets** from **light flavor** ones inside a large cone jet in G_{RS} → **hh** → **$b\bar{b}b\bar{b}$** events

Efficiency for **b-hadrons** to be associated with a b-tagged jet **ε(association) x ε(single-b-tag)**

b-tagging applied on **small cone track-jets** performs at **best**

Efficiency to find **two b-tagged track-jets** or **trimmed sub-jets** in both **h-jet** candidates

$h \rightarrow b\bar{b}$ tagging: ATLAS Run-II

b-tagging news Run-II

- **New pixel** detector (IBL)
- **Improved** tracking for **high-p_T jets**

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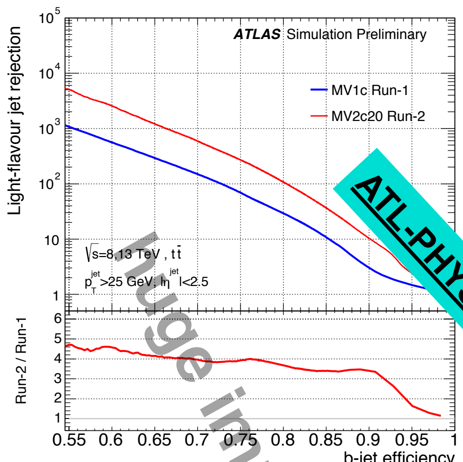
- **MV_2** discriminator based on a BDT



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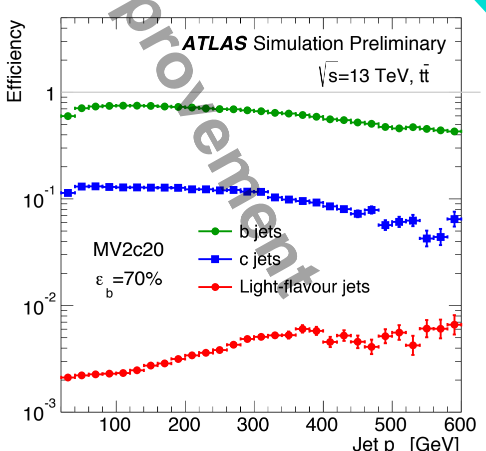
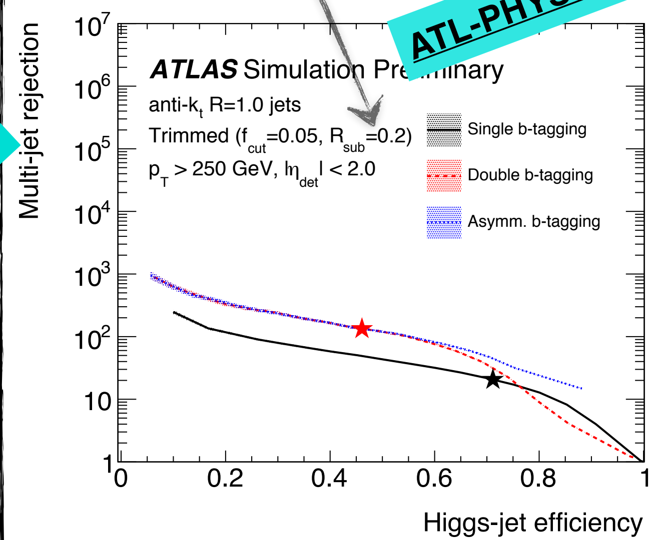
Huge improvement



$h \rightarrow b\bar{b}$ performance

- **b-tagging applied** to the **leading two matched R = 0.2 track jets**
- **Asymmetric**: one tight b-tag, the other is scanned
- **Double b-tag better** for **high background rejection**



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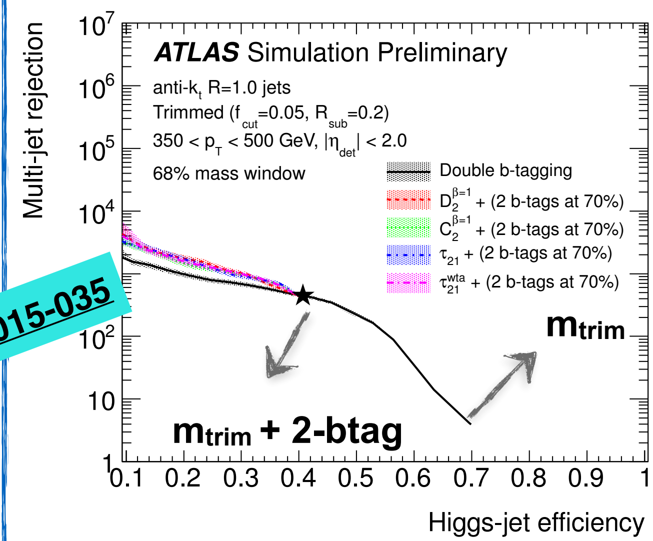
Adding substructure

- **Investigate** additional discrimination from substructure observables on top of **double b-tag + m_{trim}**



- **Good improvement** with **$D_2(\beta=1)$**
- **Higgs Tagging:**

  Trimmed Mass selection

  Double b-tag (w.p. 70% per leg)

  $D_2(\beta=1)$ selection

Matrix Element Method (MEM)

introduction to MEM

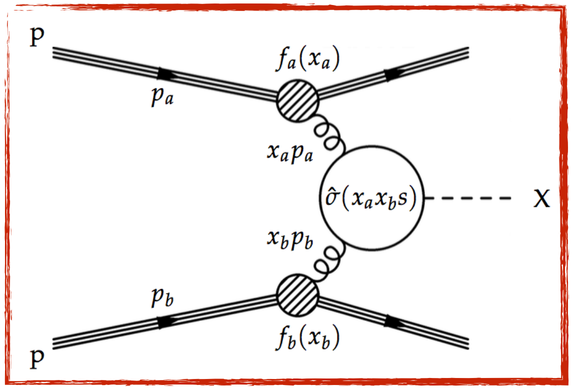
- Originally introduced for **top mass** measurement at Tevatron **Nature 429 (2004) 638–642**
- **Matrix Element Method (MEM)** uses theoretical calculation to compute per-event probabilities:
  - **Increase Signal** vs **Background** separation
  - **Analytic fits** to extract parameters of theoretical models or detector response
- **Goal:** estimate the **likelihood** for each **observed event** to be consistent with a physics process (**P**)

$$L_{\mathrm{evt}}(x_i;\, \vec{\alpha}, \vec{\beta}, \vec{f}) = \sum_{\mathrm{processes}\ P} f_P L_P(x_i;\, \vec{\alpha}, \vec{\beta})$$

$$\sum_P f_P = 1$$

- **P** is a process contributing to the final state
- **α, β** are the set of **theoretical** and **experimental parameters**

- The **likelihood** for **each process** is obtained from its **differential cross section** prediction



$$\mathrm{d}\sigma_P(a_1 a_2 \to y;\, \vec{\alpha}) = \frac{(2\pi)^4 |\mathscr{M}_P\,(a_1 a_2 \to y;\, \vec{\alpha})|^2}{\xi_1 \xi_2 s} \mathrm{d}\Phi_{n_f}$$

$$\mathrm{d}\sigma_P(p\bar{p} \to y;\, \vec{\alpha}) = \int_{\xi_1, \xi_2} \sum_{a_1, a_2} \mathrm{d}\xi_1 \mathrm{d}\xi_2\; f_{\mathrm{PDF}}^{a_1}(\xi_1)\; \bar{f}_{\mathrm{PDF}}^{a_2}(\xi_2)\; \mathrm{d}\sigma_P(a_1 a_2 \to y;\, \vec{\alpha})$$

- **dσ_P** is the **partonic** cross section
- **a_1, a_2** are the **incoming parton momenta** from **proton PDF**
- **y** is the **set** of the **n_f** final state particles **four vectors**

MEM: from partons to objects

- **Differential cross section** is then **convoluted** with a proper **transfer function**

$$\mathrm{d}\sigma_P(p\bar{p} \to x;\, \vec{\alpha}, \vec{\beta}) \;=\; \int_y \mathrm{d}\sigma_P(p\bar{p} \to y;\, \vec{\alpha})\; W(x, y;\, \vec{\beta})$$

assumptions →

- **factorized** for each type of particle
- **η** and **φ** well measured
- **jet energy transfer function** dependent on **flavor**

- To obtain a **probability**, **dσ$_P$ must be properly normalized**

$$\sigma_P^{\mathrm{obs}}(\vec{\alpha}, \vec{\beta}) = \int_{x,y} \mathrm{d}\sigma_P(p\bar{p} \to y;\, \vec{\alpha})\; W(x, y;\, \vec{\beta})\; f_{\mathrm{acc}}(x)\; \mathrm{d}x$$

→

$$L_P(x;\, \vec{\alpha}, \vec{\beta})\; \mathrm{d}x \;=\; \frac{\mathrm{d}\sigma_P(x;\, \vec{\alpha}, \vec{\beta})}{\sigma_P^{\mathrm{obs}}(\vec{\alpha}, \vec{\beta})}$$

- In final states with **multiple leptons** or **jets**, **one reco object** can be associated to **more** than one **parton**
  - The likelihood for each **possible permutation** has to be considered
- **Numerical multi-dimensional integration** is the "**bottleneck**" of the method:
  - Monte-Carlo integration with importance sampling usually adopted (**VEGAS**)
  - **Reduce** the **likelihood dimensionality**, the number of **process** and **sub-process** (diagrams)
- **Likelihoods Discriminators:**

$$D(x; \vec{\alpha}, \vec{\beta}) = \frac{L_{sig}(x; \vec{\alpha}, \vec{\beta})}{L_{sig}(x; \vec{\alpha}, \vec{\beta}) + \sum_i^{bkg} f_i \cdot L_{i,bkg}(x; \vec{\beta})}$$

MEM: Pro and Cons

- With respect to **Machine Learning:** **no overtraining** and **limitations** related to a small training sample
- **Embeds model parameters** that can be **fitted over a large phase space**
- **MEM** allows **best sensitivity** and **robustness**

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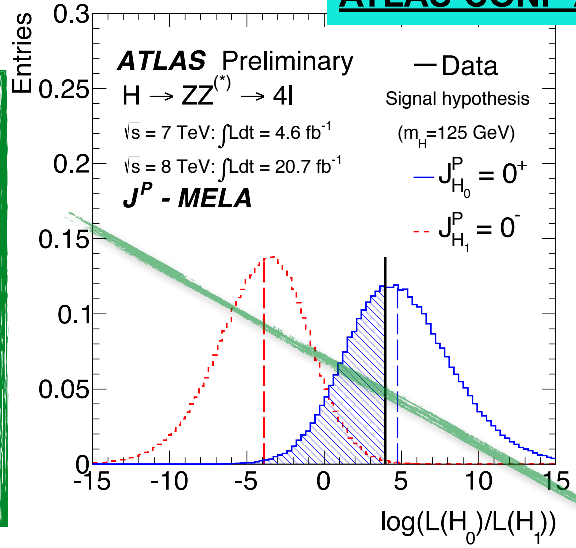

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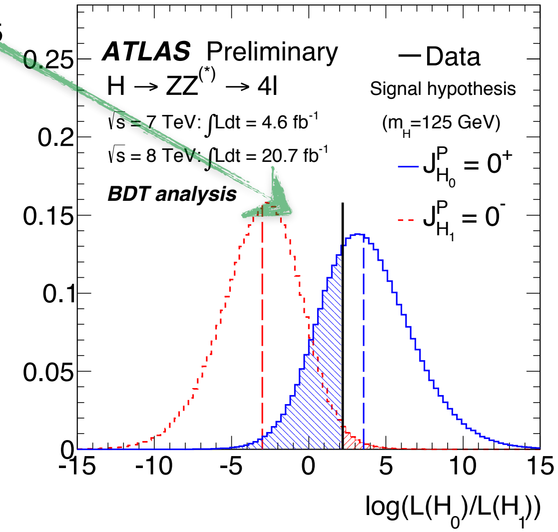


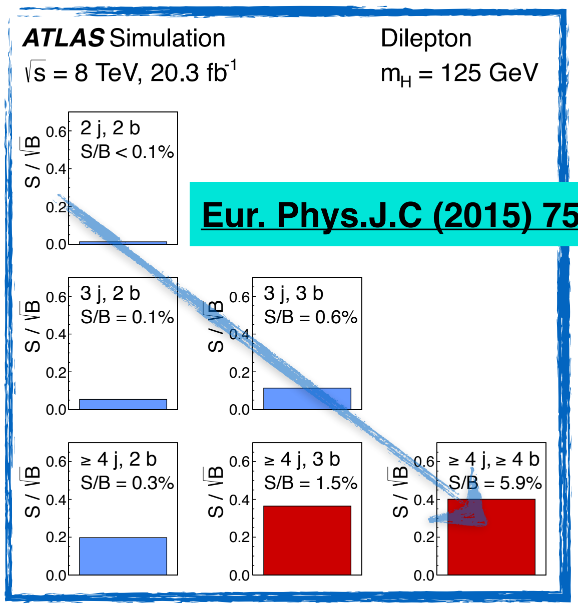
- **MEM** developed in **ATLAS** and **CMS** based on **LO matrix element**
- **ISR/FSR, hadronization** and **U.E. modeled** via the **transfer functions**
  - **ISR** important to **separate** process **initialized** by **gg** or **qq** → **ggF** vs **VBF**
  - **FSR** important for final state with jets and E_T^{miss}
- **Correlations** among **observables** only **reproduced** by **transfer functions**

- **Closure test** for **transfer functions**: compare **ME + transfer function** with **ME + PS + reconstruction**
- **Check data/MC** agreement applying the ME in control regions

ATLAS: tth h→$b\bar{b}$

CMS ttH→bb in backup

- **Signature:** one (two) isolated lepton, missing energy and at least 4 (2) reconstructed jets p_T > 25 GeV
- **Backgrounds** arise from mainly **$t\bar{t}$+$b\bar{b}$**, **$t\bar{t}$+$c\bar{c}$** and **$t\bar{t}$+light flavor**
- **Event Selection:** **S/B** ratio in **(N_{jets},N_{bjets})** bins is used to define **signal regions** and **control** ones



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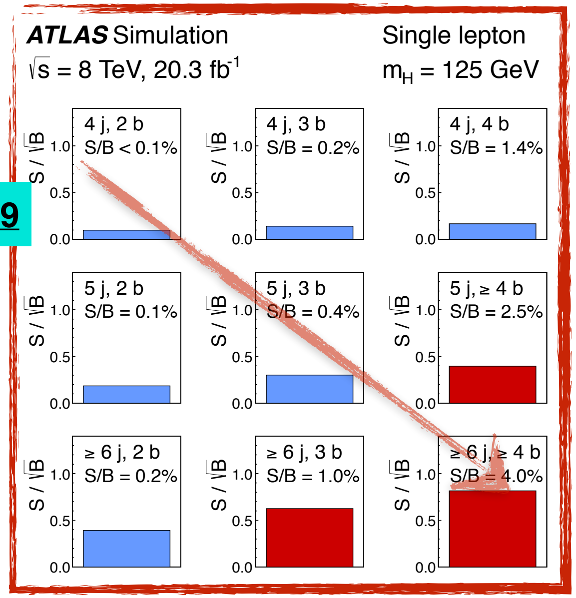

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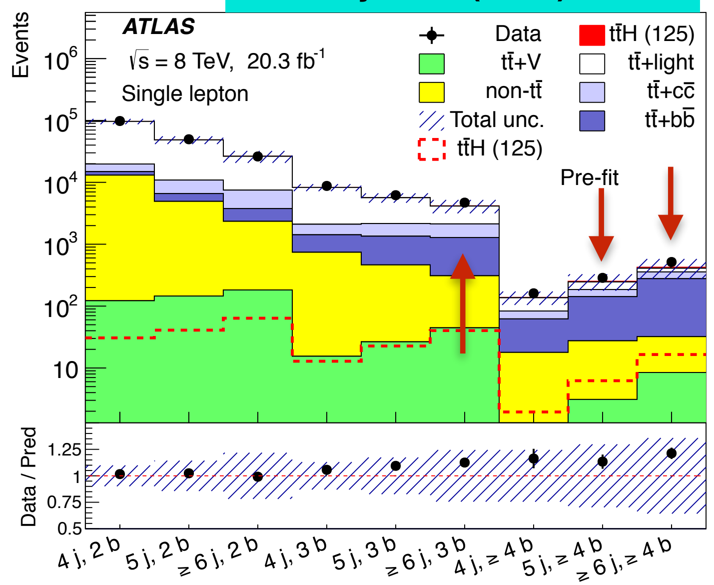


- **Simultaneous fit** of **signal** and **control** regions to **constraint background** shapes and normalizations
- **Signal vs Background discrimination** → based on a **Neural Network** in each signal region:
  - **Inputs:** b-jet kinematics, angular correlations between objects, number of jets, invariant masses .. etc
  - **Matrix Element Discriminator:** added as input to the NN in the **(6j,4b)** and **(6j,3b)** channels

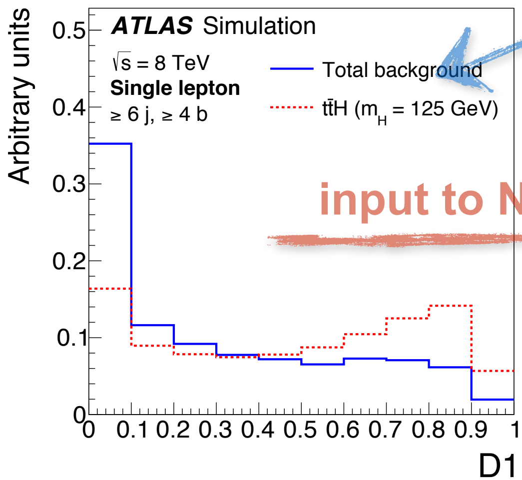
ATLAS: tth h→b$\bar{b}$

- **Complex event topology** → **ambiguities** in the **reco objects** to **parton** assignment for the ME
- **Probability** is calculated for each **permutation** of **jet** to **quark association**

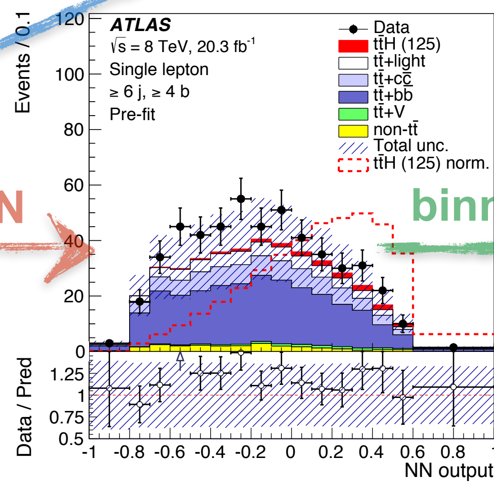
$$\mathcal{L}_i(\boldsymbol{x}|\boldsymbol{\alpha}) = \sum_{p=1}^{N_p} P_i^p(\boldsymbol{x}|\boldsymbol{\alpha})$$

$$r_{sig}(\boldsymbol{x}|\boldsymbol{\alpha}) = \frac{\mathcal{L}_{sig}(\boldsymbol{x}|\boldsymbol{\alpha})}{\sum_{bkg} f_{bkg}\mathcal{L}_{bkg}(\boldsymbol{x}|\boldsymbol{\alpha})}$$

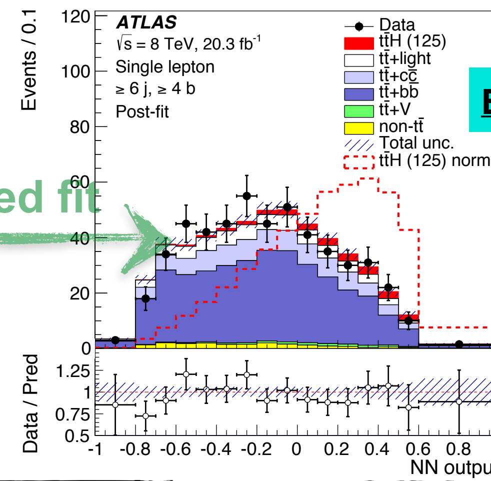
- **Weights** from **MadGraph LO tth** and **tt+b$\bar{b}$**
- **Observables** are the final state particles 4V
- **ME** is the most **discriminating** in **(6j,4b)**



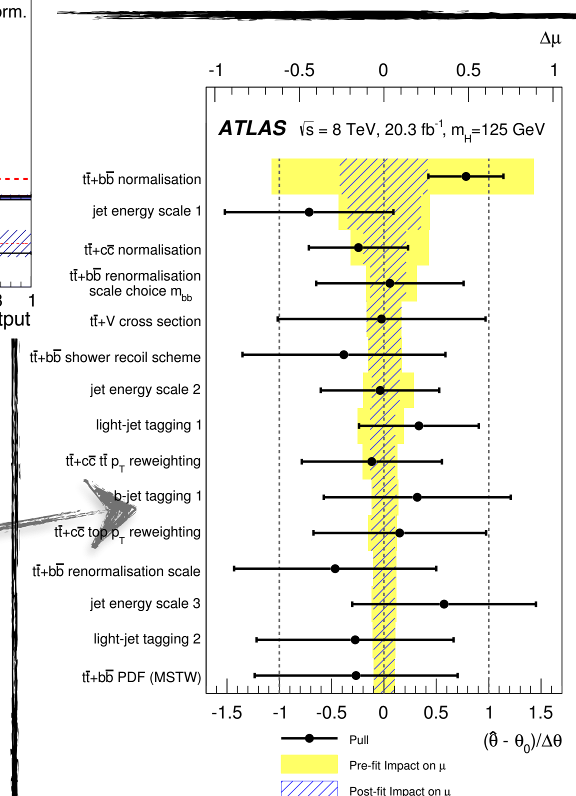
input to NN



binned fit



Eur. Phys.J.C (2015) 75:349



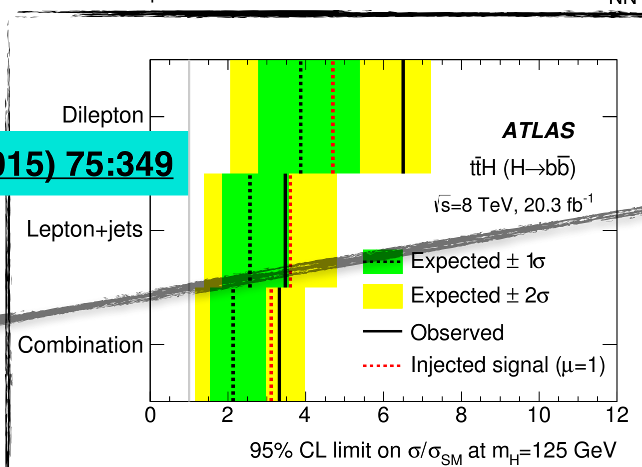
final result

Signal strength: μ = 1.5 ± 1.1

Significance: σ = 1.4 (1.1) obs (exp)

Observed limit 3.4 times **larger** than **SM** prediction at **95% CL**

Eur. Phys.J.C (2015) 75:349



conclusions

- Search for **new physics** in boosted topologies widely explored during Run-I by **ATLAS** and **CMS**
- Well **established techniques** have been developed to identify high p_T W/Z and $h \rightarrow b\bar{b}$ jets
- **Efforts ongoing** to enhance the background rejection through b-tagging for $h \rightarrow b\bar{b}$ jets
- **Investigation** of further gain via MVA-taggers: groomed masses, substructure, b-tagging inputs, q/g subjet
- **Different strategies** between the **ATLAS** and **CMS** related to the different detector characteristics

Run-II data : better sensitivity than Run-I expected after > 10 fb^{-1} for m_X > 1 TeV

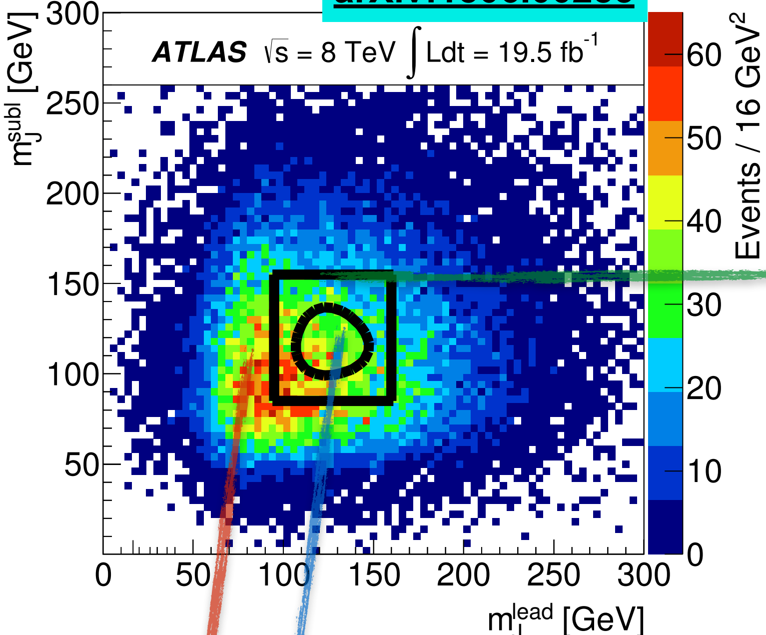
- **Matrix Element Methods** have been widely used: SM Higgs searches (J^p, hZZ, ttH), top quark physics …
- **MEM** allows to **enhance signal**-to-**background** discrimination → **alternative** to BDT, NN .. etc
- **MEM** limitations: so far only at **LO**, transfer functions embeds **ISR/FSR,** partial modeling of **correlations**
- **MEM** reaches ideal performances in final states not sensitive to QCD radiation or transverse boost (p_T^h)
- **Matrix Element Likelihood** discriminators can be used as input to MVA to increase sensitivity

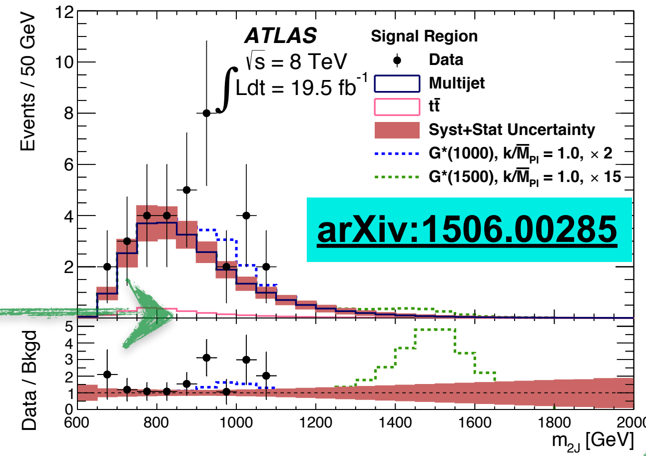
Backup slides

ATLAS: X → hh → $b\bar{b}b\bar{b}$

- **Selections:** two anti-k_t R = 1.0 jets, p_T > 250 GeV, $|\Delta\eta|$ < 1.7
  - **trimming:** jets re-clustered with k_t algorithm, R_{sub} = 0.3 rejecting sub-jets p_T^{sub} < 5% * p_T^{jet}
  - **b-tagging:** associate anti-k_t R = 0.3 **b-tagged track jets** to large cone calo-jets for each h-jet candidate
- **Event categorized** according to the number of b-jets: **2 or 3 b-jets** and **4 b-jets**

arXiv:1506.00285

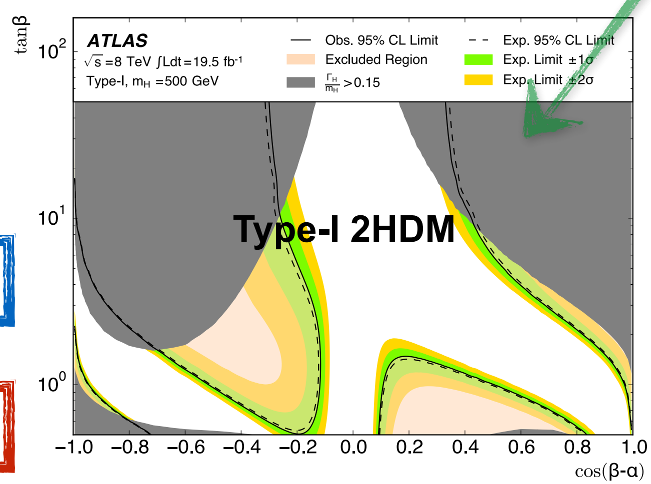




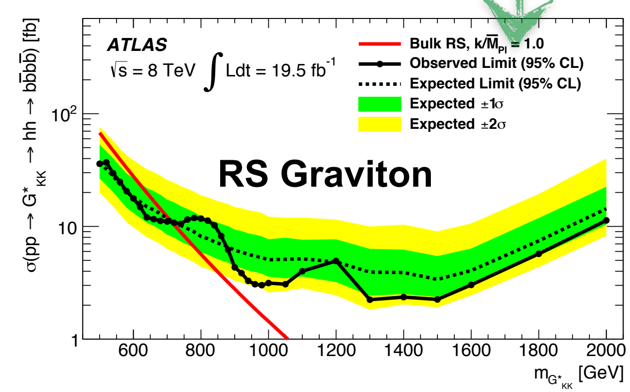
arXiv:1506.00285

Interpretations

- **H → hh production**
- **RS graviton** production
- **H in Type-I 2HDM**



arXiv:1506.00285



Signal Region: trimmed mass around m_h

Sideband to extract **multijet** bkg from data

CMS: spin-parity via hvv couplings

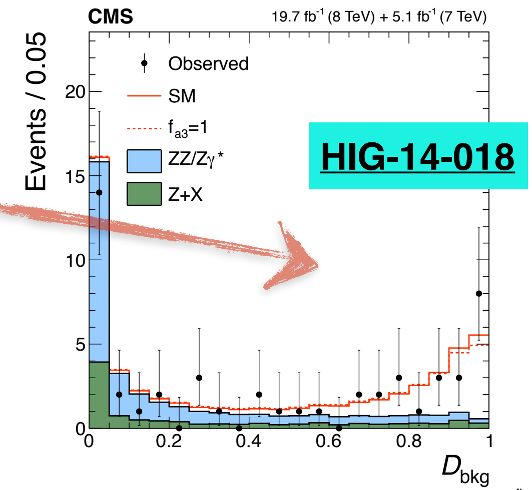
- **Goal:** deduce **Higgs spin-parity (J^P)** properties from CMS data → [more in **Marco Kovac** talk]
- **Alternative hypotheses** are separated looking at **angular correlations** among Higgs decay products
- Up to **eight observables** for $h \to ZZ^* \to 4\ell$ combined via a **Matrix Element Likelihood Analysis**

Probabilities

$$\mathcal{P}_{\rm SM} = \mathcal{P}^{\rm kin}_{\rm SM}(m_1, m_2, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm sig}(m_{4\ell}|m_{\rm H}),$$
$$\mathcal{P}_{\rm ggZZ} = \mathcal{P}^{\rm kin}_{\rm ggZZ}(m_1, m_2, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm ggZZ}(m_{4\ell}),$$
....

Discriminators

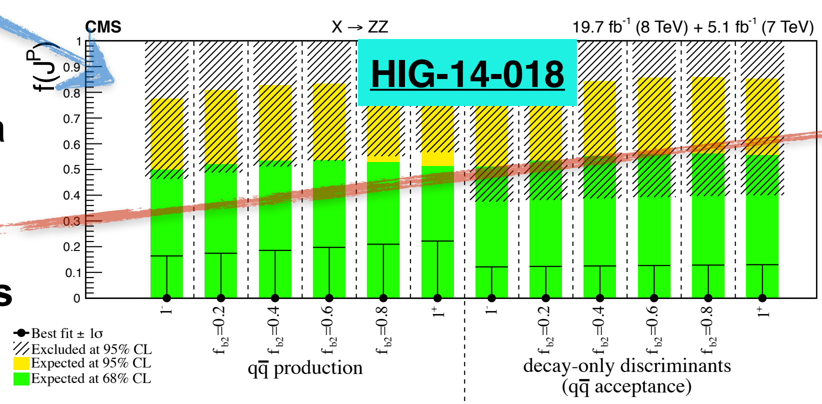
$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}^{\rm kin}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{\rm SM}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

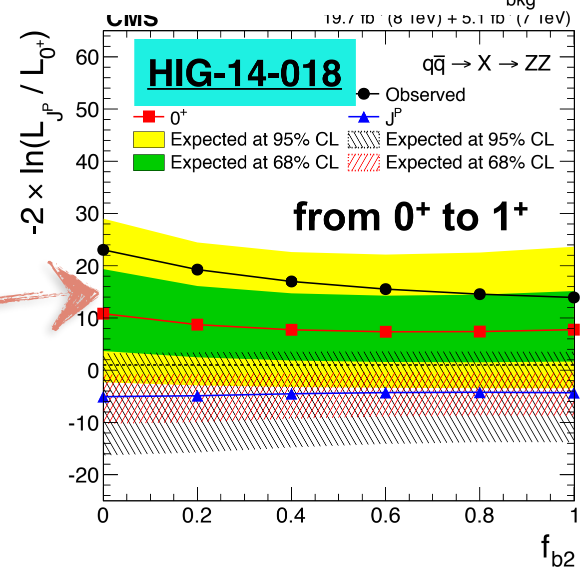


- **Template Likelihood Fit:** performed simultaneously on different discriminators

$$\mathcal{L} = \exp\left(-n_{\rm sig} - \sum_k n^k_{\rm bkg}\right) \prod_i^N \left(n_{\rm sig} \times \mathcal{P}_{\rm sig}(\vec{x}_i; \vec{\zeta}) + \sum_k n^k_{\rm bkg} \times \mathcal{P}^k_{\rm bkg}(\vec{x}_i)\right)$$

- **Maximize Likelihood** to extract **anomalous couplings** and **intervals** from **profile likelihood**
- **Spin hypotheses** are tested via a **likelihood ratio,** the **separation** between **test statistics** is converted in **standard deviations**

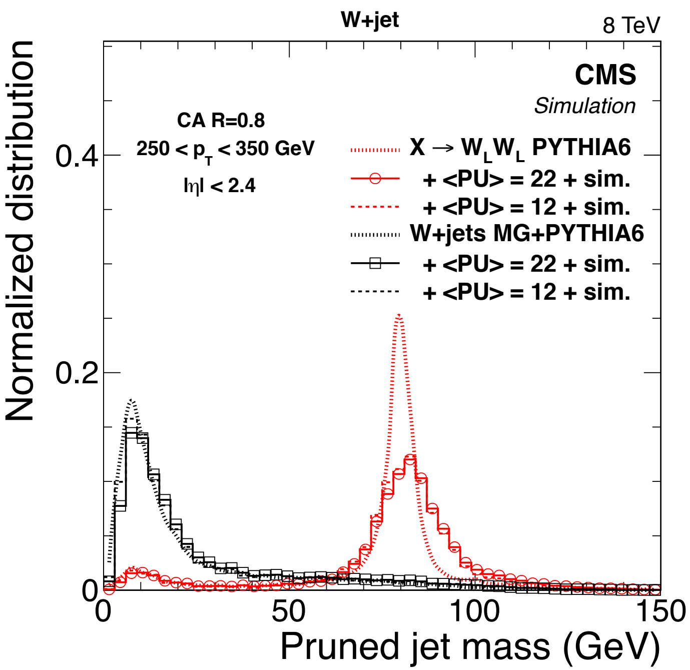


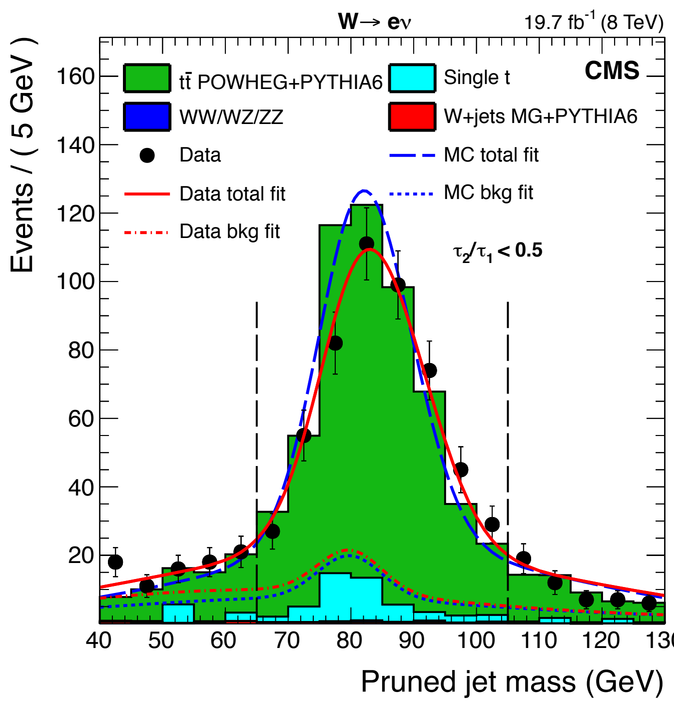


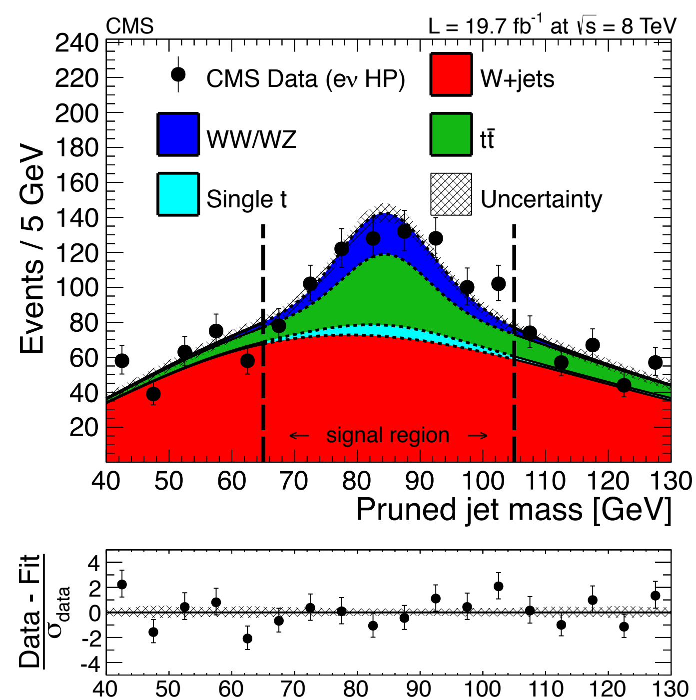
pruning

- **Improve jet mass resolution** by means of removing soft and large angle protojets along CA clustering
- **Strongly** reduce the mass of q/g jets, while preserving the one for W/Z or h-jets
- **Choosing** a **soft threshold Z_{cut}** and an **angular one ΔR,** skip protojets that:

$$z = \frac{\min(p_{T,j}, p_{T,i})}{p_T} < z_{cut} \qquad \Delta R_{ij} < \Delta R = \Delta R \times \frac{m_{jet}}{p_T}$$

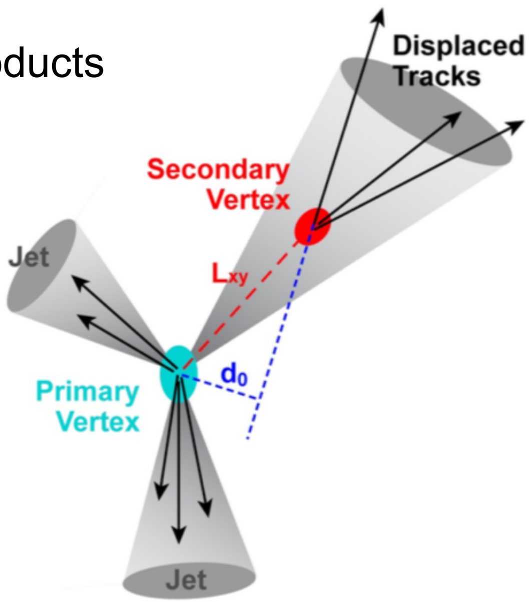




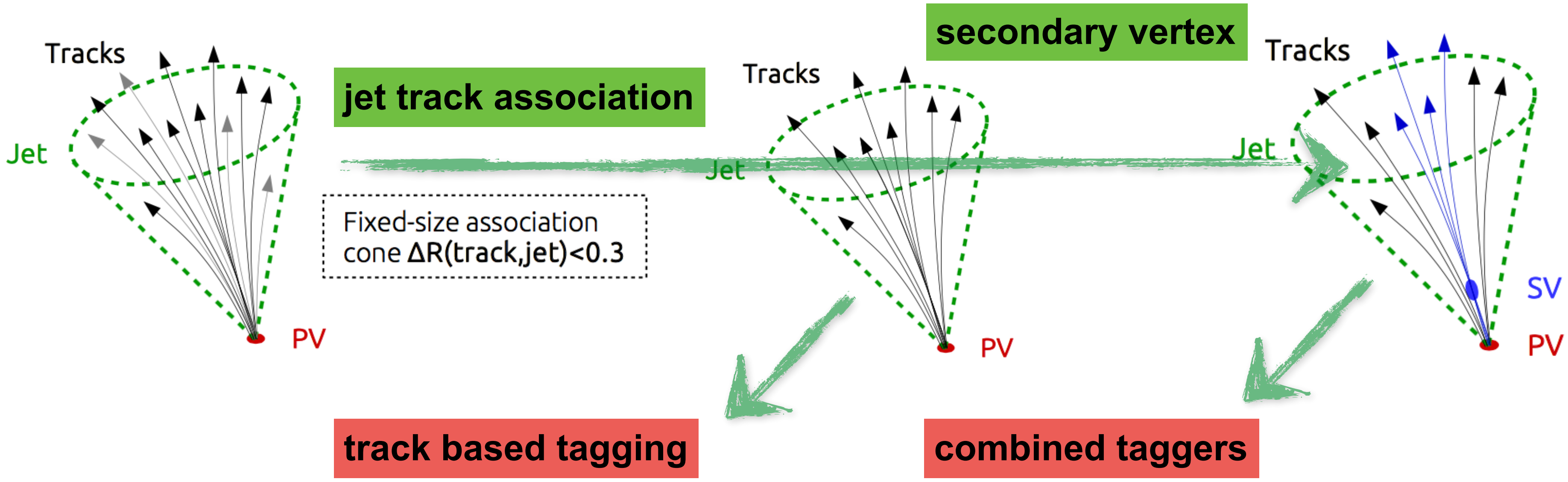


b-jets and b-tagging

- **Determine** if a reconstructed **jet** contains a **B-hadron** and its decay products
- **B-hadron properties:**
  - **Long lifetime:** $c\tau$ = 500 μm, $\beta\gamma c\tau$ ~ O(5-10 mm) @50-100 GeV
  - **Large mass + high track multiplicity**
  - **Large semi-leptonic BR**

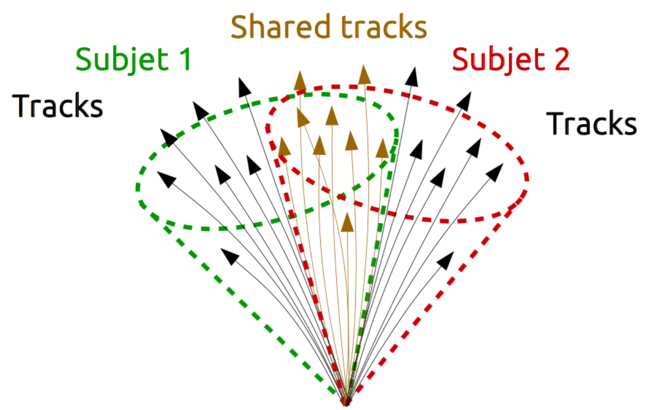


- **B-tagging is based on:**
  - **Displaced tracks information**
  - **Secondary vertex reconstruction**
  - **Soft lepton identification**

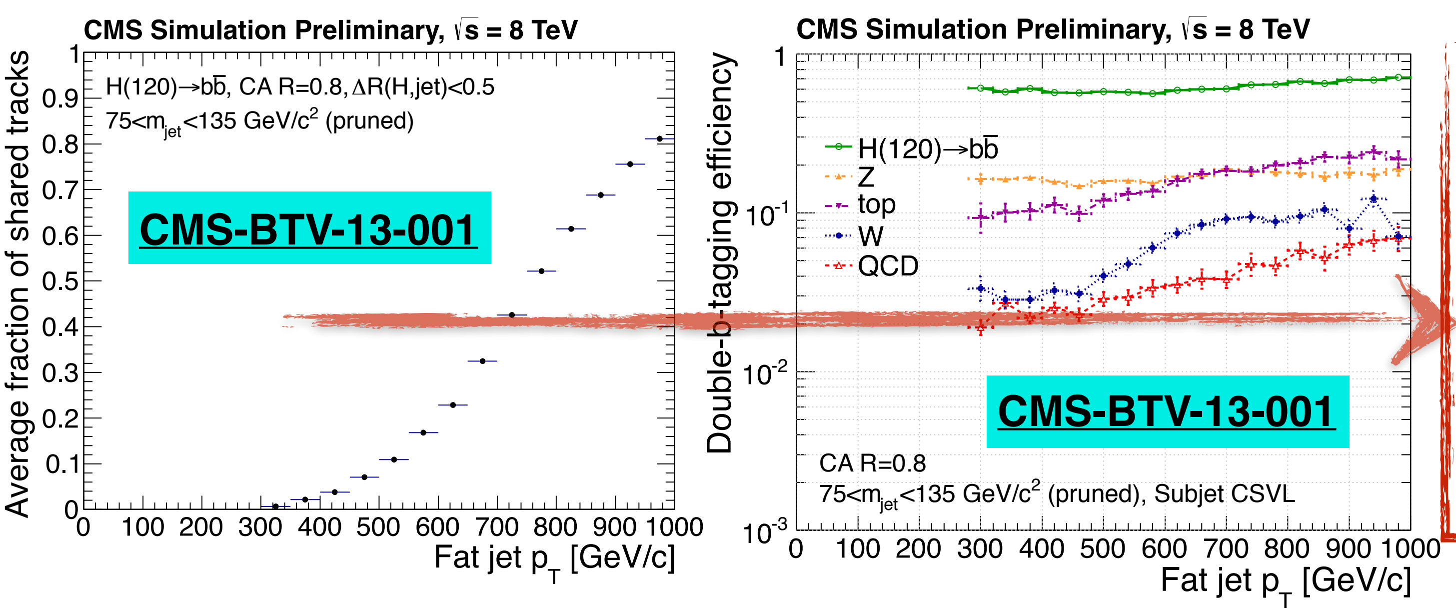


CMS: limitations H→b$\bar{b}$ Run-I

- **jet track association:**
  - Based on a fixed cone size leads to a **double counting at high p_T**
  - Problematic to apply **scale factors** measured on **single b-jets**



- **Jet flavor assignment**
  - based on a fixed cone, which can lead to ambiguities at sub-jet level
- **Secondary vertex fit**
  - Non optimal when there are shared tracks between two different B-hadrons fragmentation



Double b-tag loose WP

Flat efficiency vs p_T H(bb)

Contamination from **QCD**, in particular g → bb **increase**

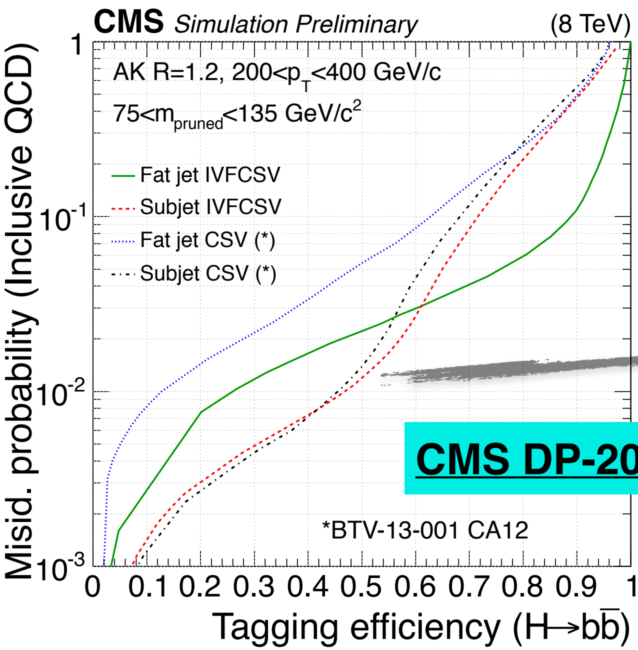
Mis-tag rate is stable vs NPV

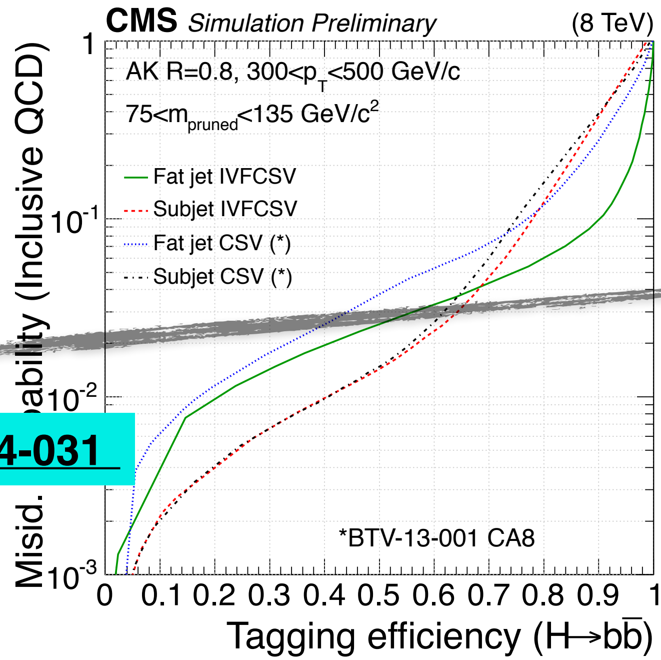
CMS: Inclusive Vertex Finder

- **IVF does not depend on jet clustering**
  - Starts from a list of **high IP tracks** taken as **seeds**
  - **Cluster the other tracks** wrt to a seed considering: 3D distance, angular separation
- **Vertex reconstruction/fitting** from for each **cluster** with **"adaptive vertex finder"**
- **Vertex Merging**
  - Check for shared tracks
  - **Merge vertexes** that have a **shared fraction > 0.7** and **distance significance < 2**
- **Track-vertex selection**
  - Trade off tracks between PVs and SVs based on their compatibility with each vertex
  - Re-fit SVs with the new track selection
- **Vertex Merging**
  - **Merge vertexes** that have a **shared fraction > 0.2** and **distance significance (χ^2) < 10**

arXiv:1102.3194

CMS: boosted b-jet Run-I vs Run-II



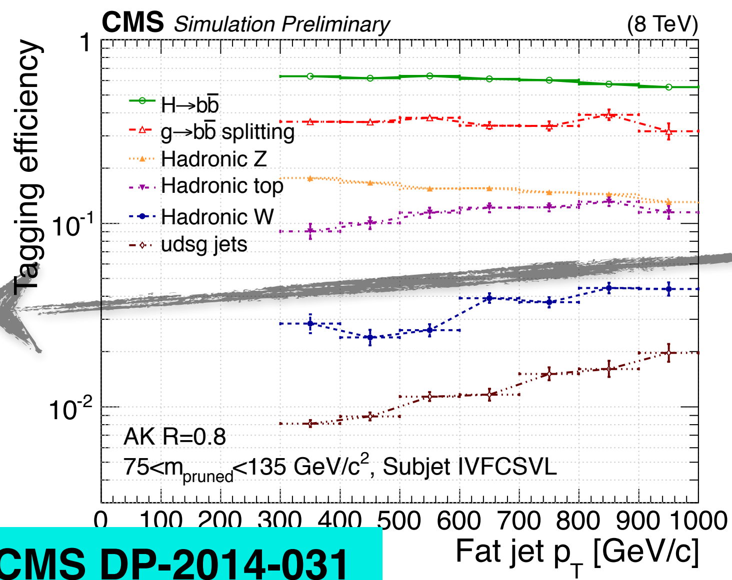


CMS DP-2014-031

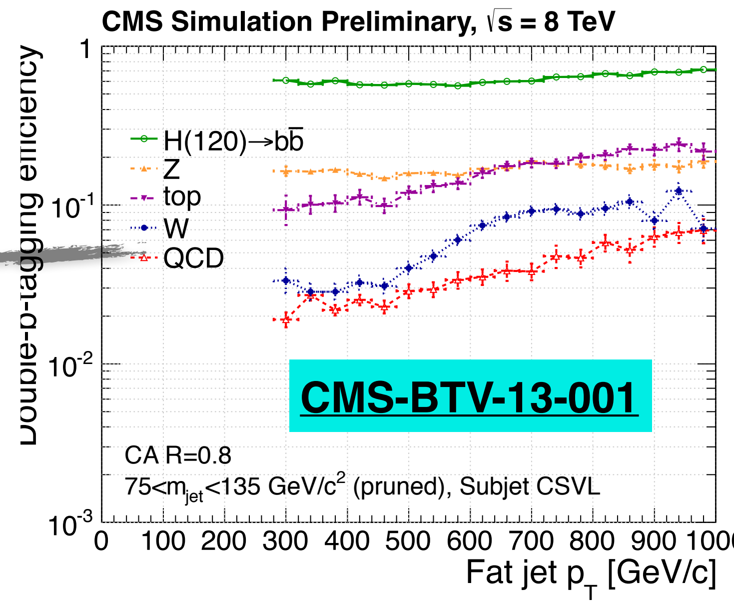
Improvement in both **fat-jet** and **subjet b-tagging** with **IVF** and **explicit jet-track association**

Good **improvement** in **background rejection**

Stable **signal** and **background efficiencies** vs **p_T**



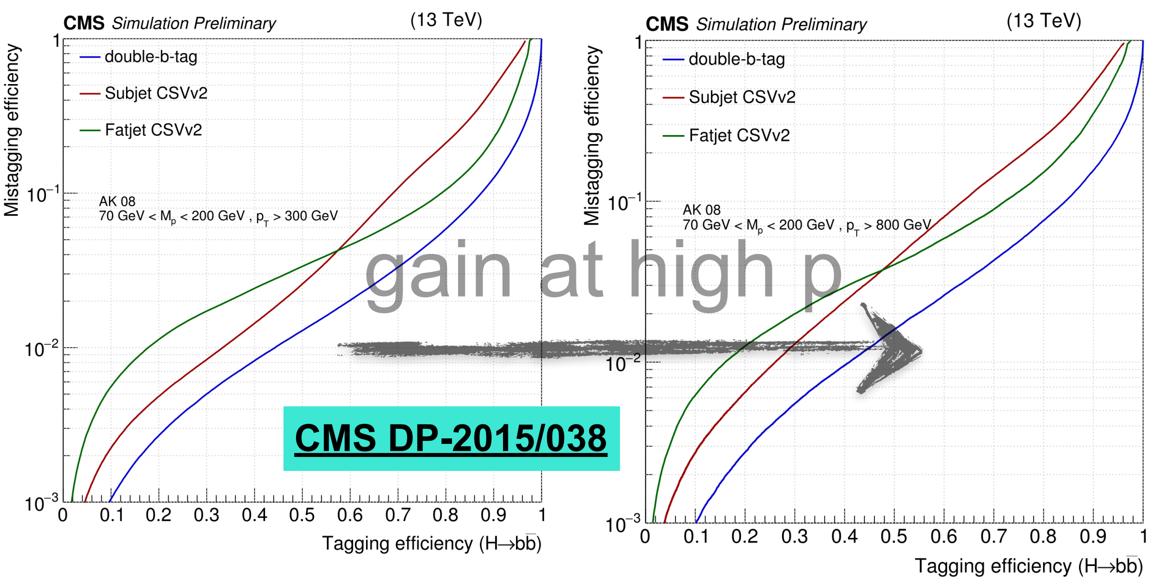
CMS DP-2014-031

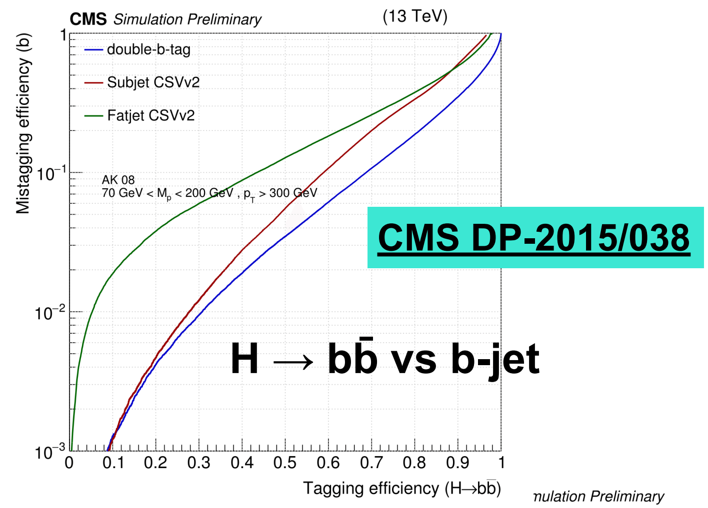


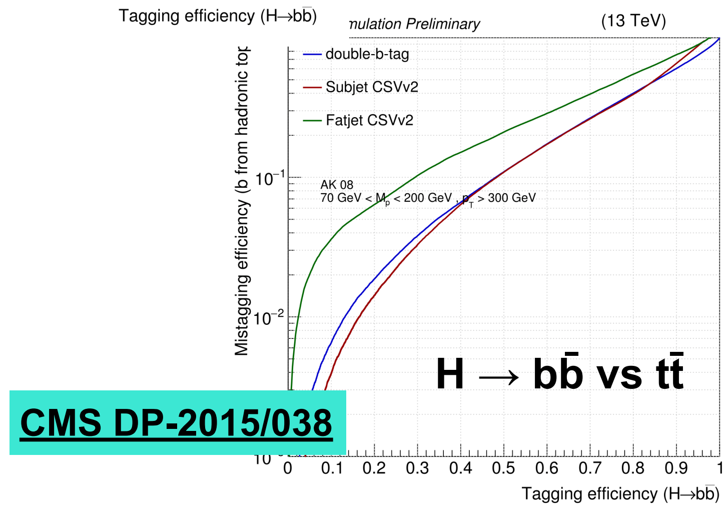
CMS-BTV-13-001

CMS: double b-tagging

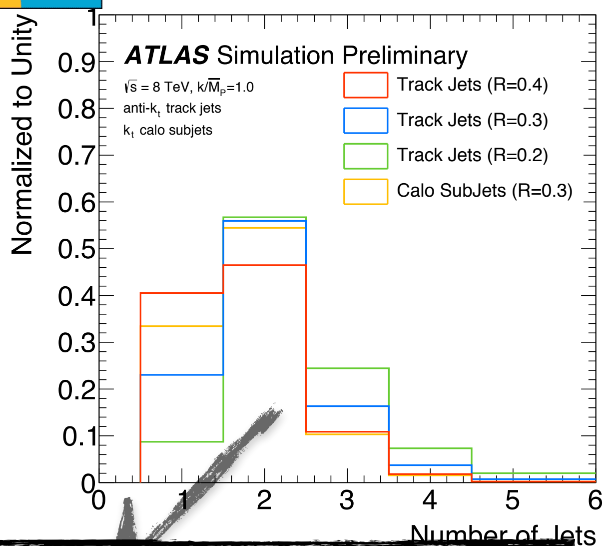
- **Tracks belonging to the jet**
  - N_{tracks}, 3D signed IP significance, angle wrt jet axis
- **Secondary Vertexes associated to the jet**
  - N_{tracks}, N_{vertex}, leading SV p_T over jet p_T, 2D flight distance significance, SV mass, ΔR
- **Soft leptons**
  - $N_{leptons}$, p_T leading leptons over jet p_T
- **Subjet b-tagging** value obtained with the new **$CSV_{(IVF)}$**



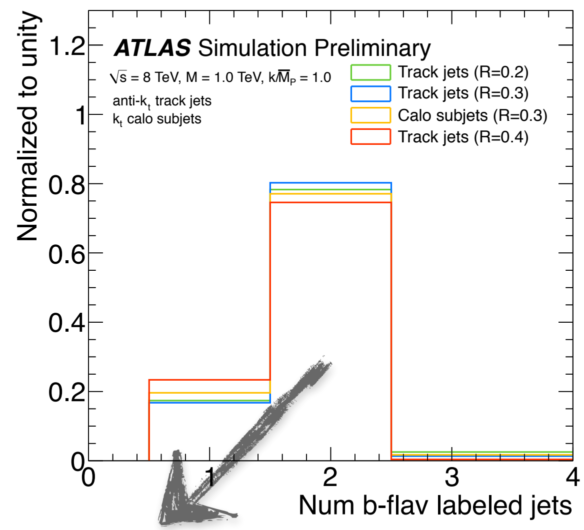




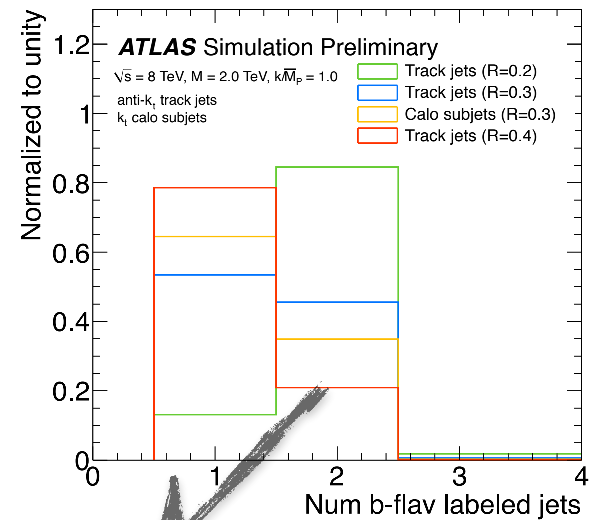
ATLAS: h→b$\bar{b}$ tagging



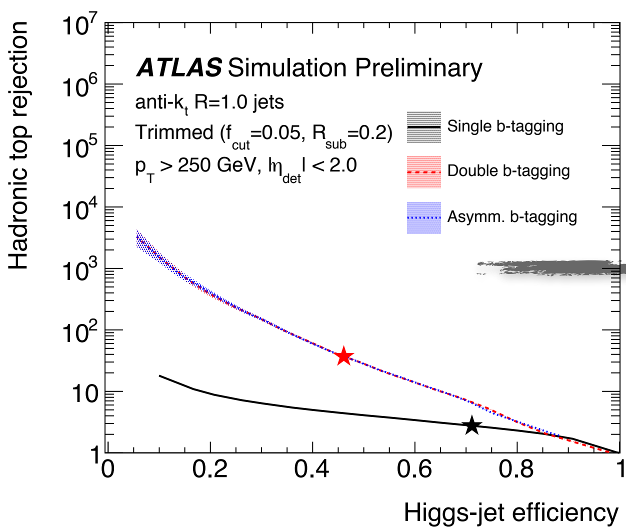
N_{track} jet matched to calo jets and number of trimmed sub-jets

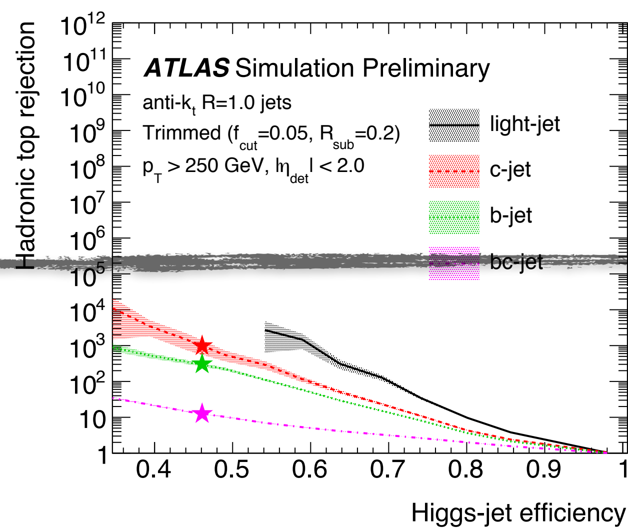


N_{bjets} when H-jets are produced by 1 TeV resonance



N_{bjets} when H-jets are produced by 2 TeV resonance .. **small R for track jets is suggested**

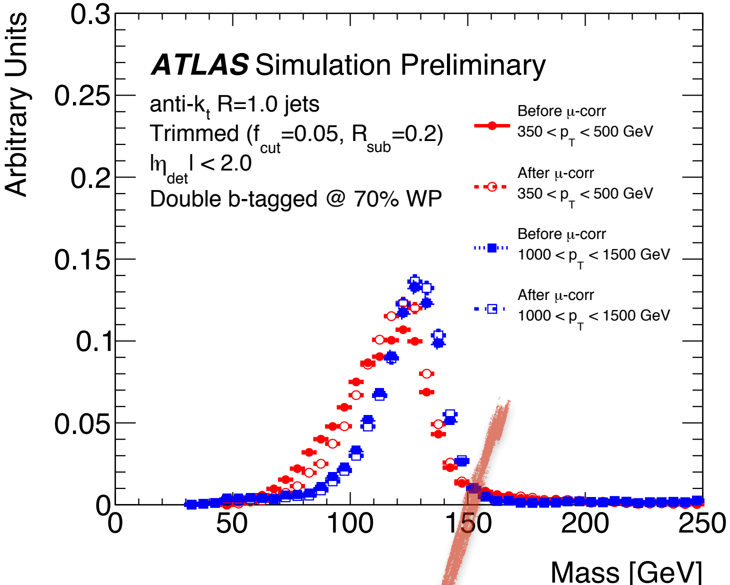


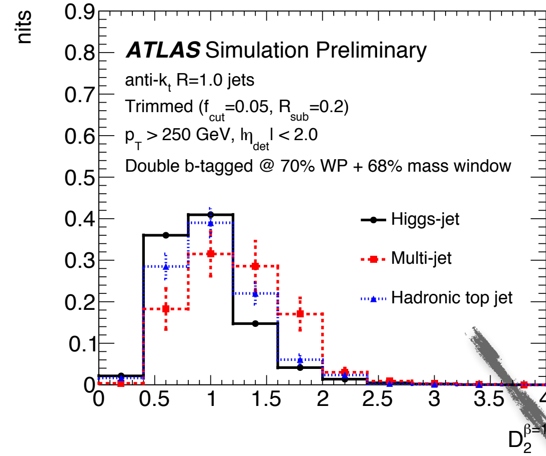


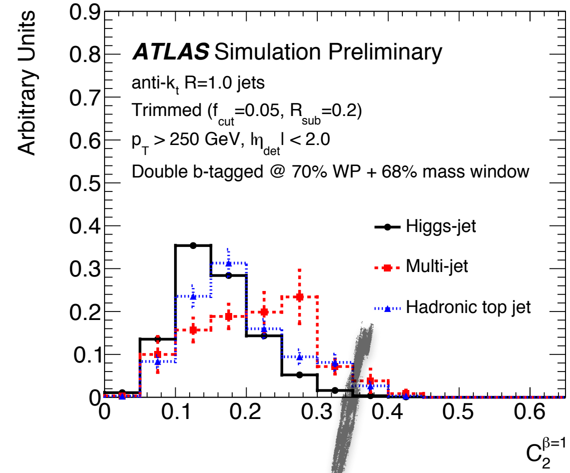
Hadronic top rejections through b-tagging of matched track jets

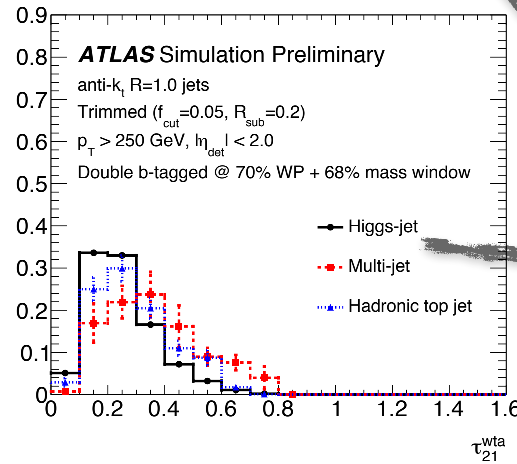
Single b-tag not enough since a hadronic top contains a b-jet

ATLAS: $h \to b\bar{b}$ tagging



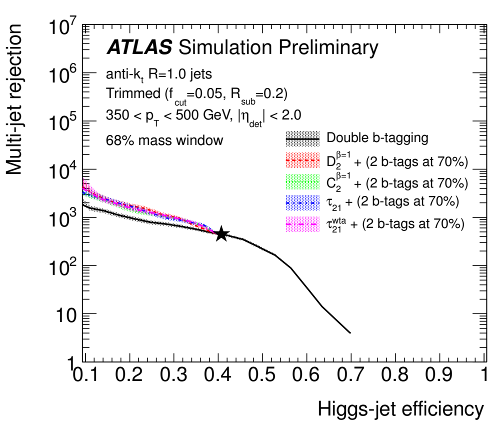


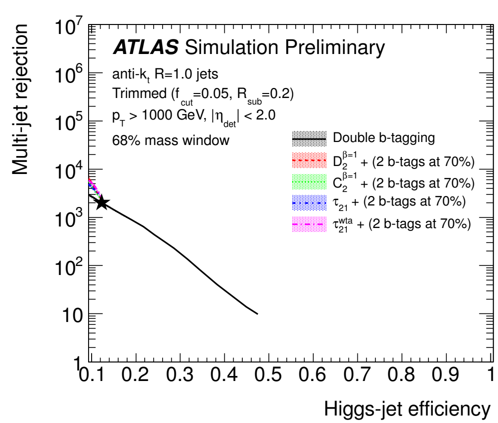


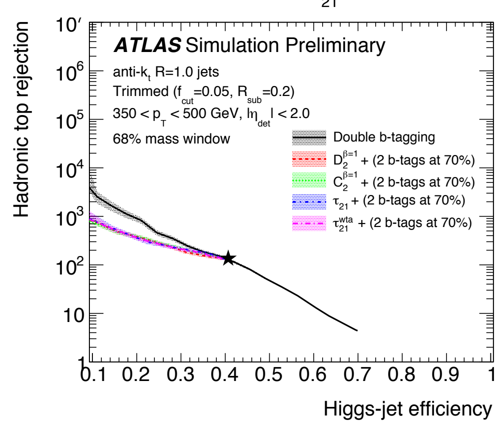


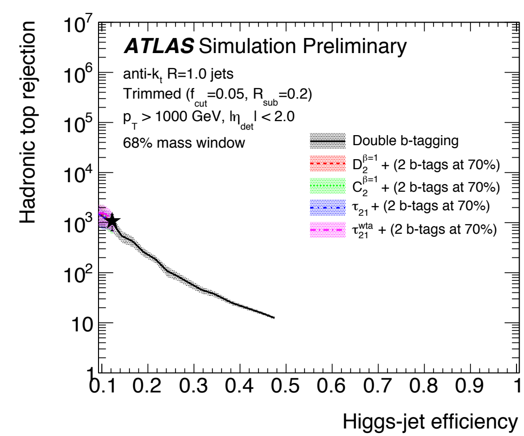
Additional discrimination power from substructure observables after trimmed mass selection and double b-tagging

Trimmed jet mass correction for soft muons produced in the b-quark decay by adding muon 4V matched the identified jet



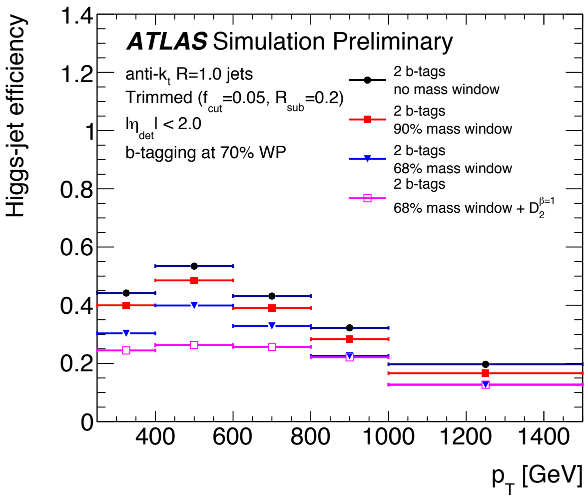


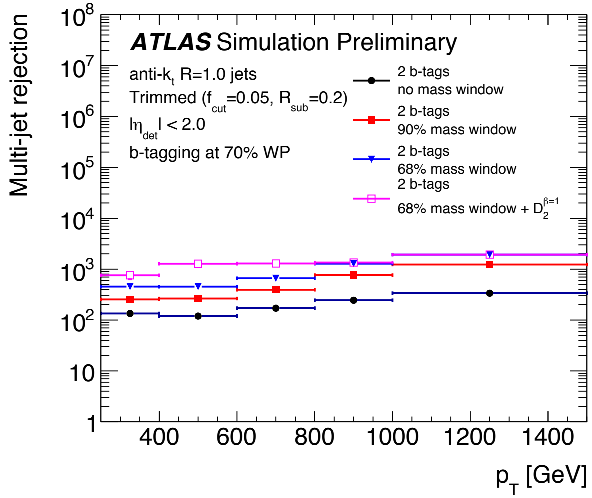


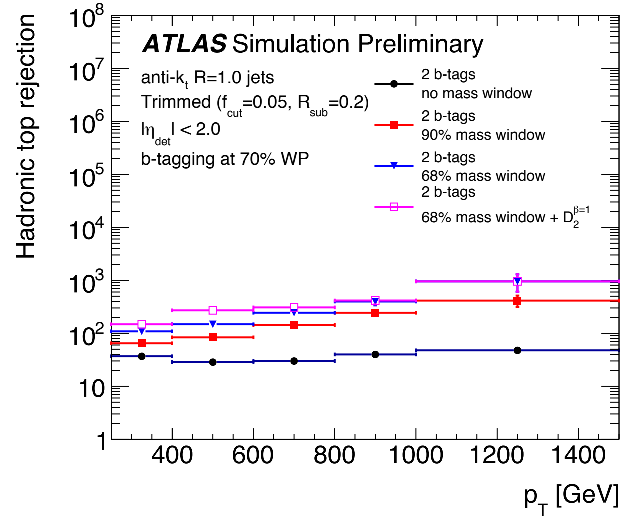


ATLAS: h→b$\bar{b}$ tagging

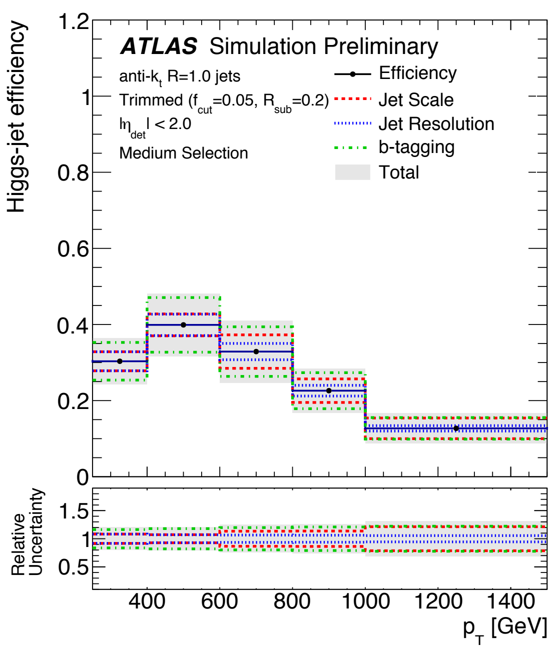
- Performance in terms of signal efficiency and background rejection vs p_T

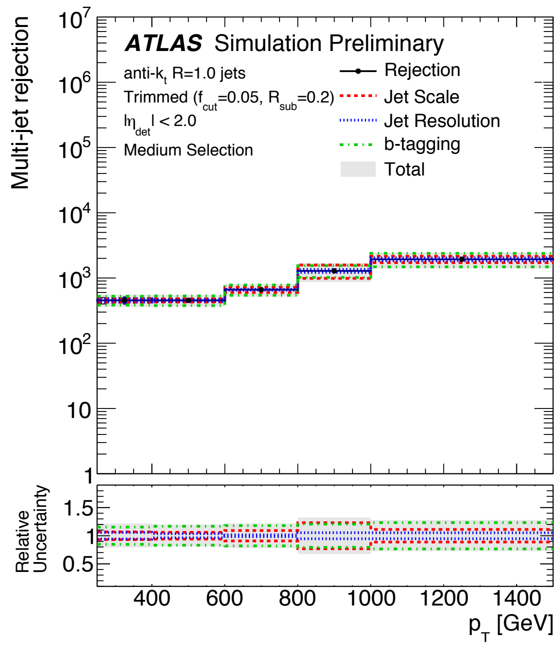


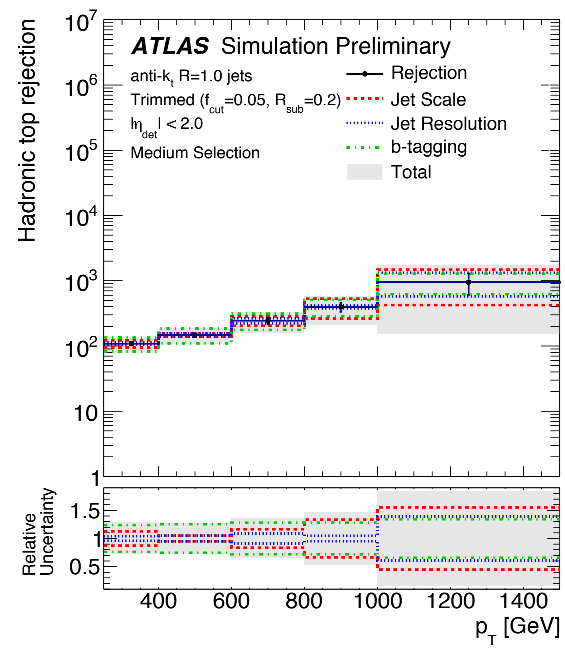




- Systematic uncertainties on the efficiency for a medium w.p.

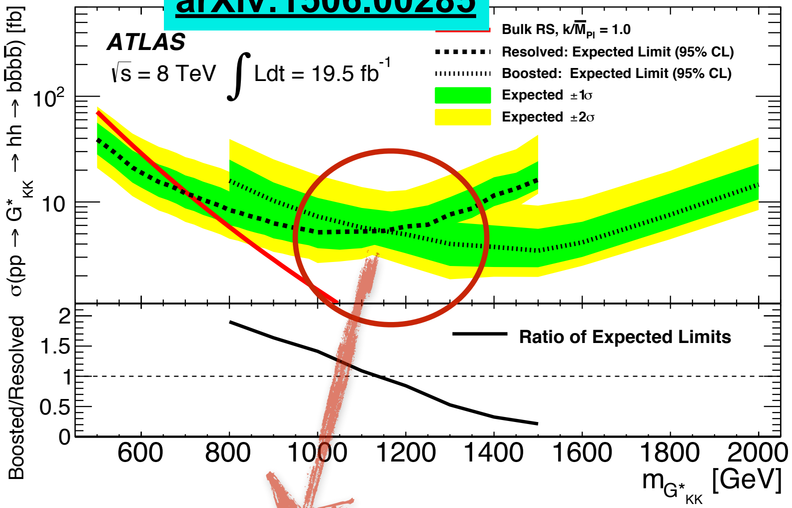




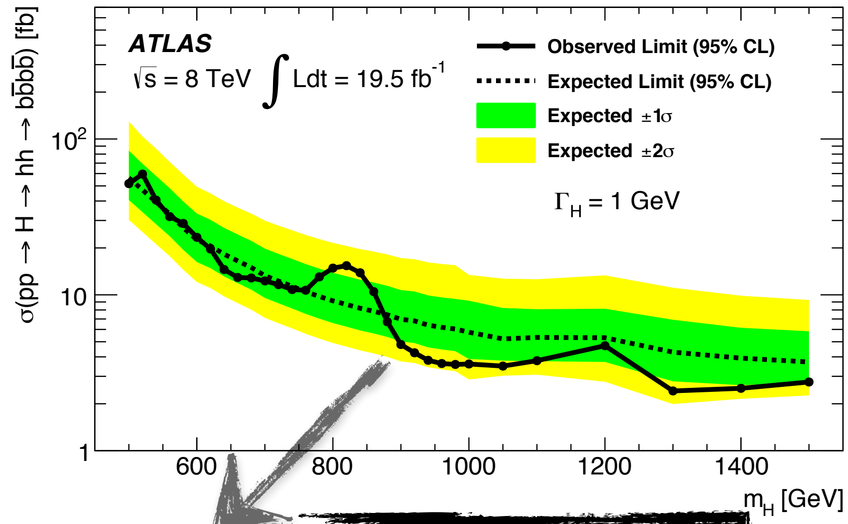


ATLAS: X → HH → $b\bar{b}b\bar{b}$

arXiv:1506.00285



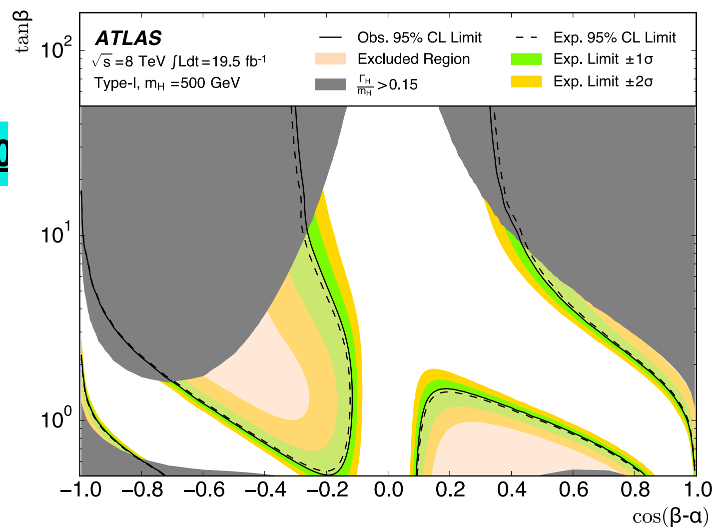
Boosted analysis performs better



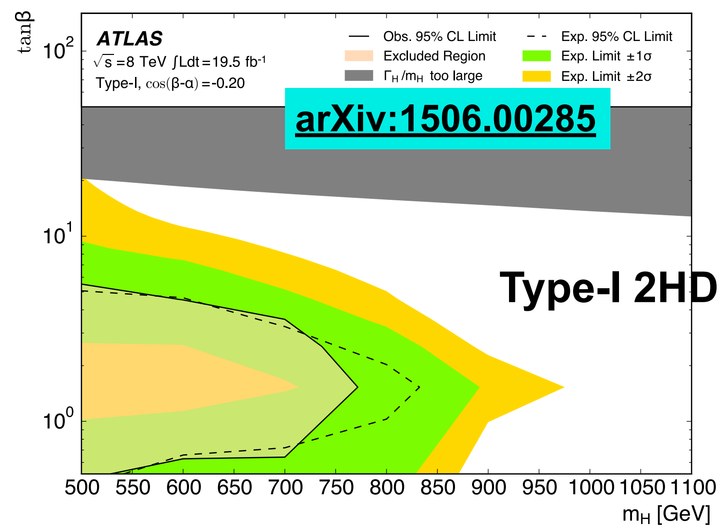
di-Higgs production

- **2HDM** limits as a function of $\mathbf{m_H}$ and $\mathbf{\Gamma_H}$, assuming that the **acceptance** is **independent** from $\mathbf{\Gamma_H}$

arXiv:150



arXiv:1506.00285



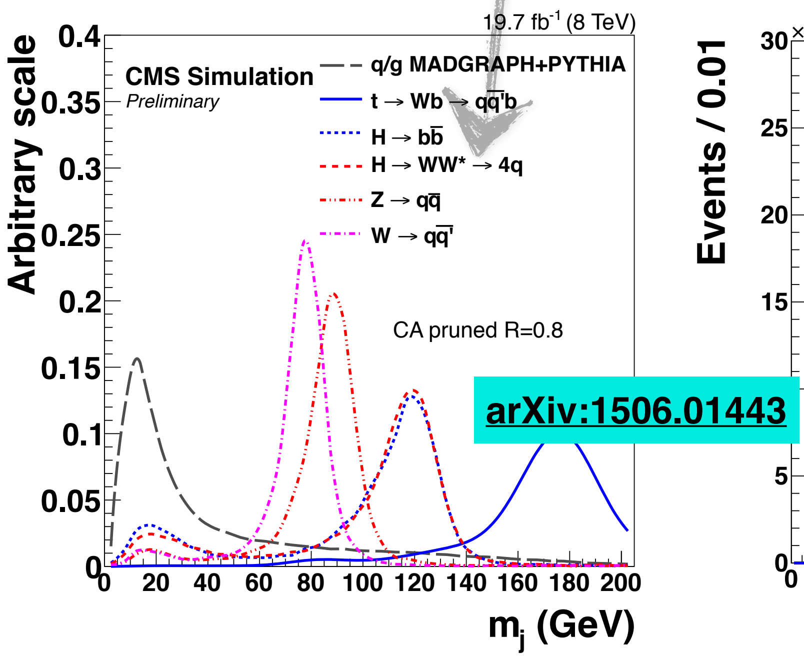
Type-I 2HDM

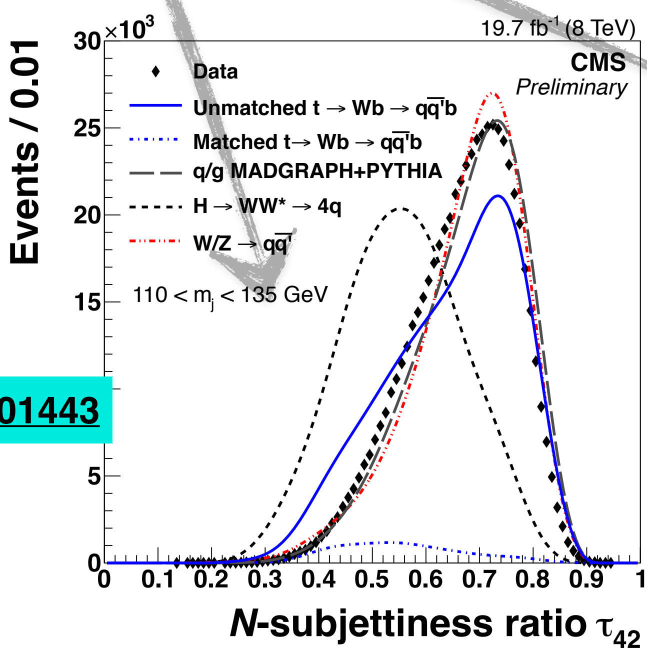
CMS: X → WH/ZH → $qqb\bar{b}$ or qqqq

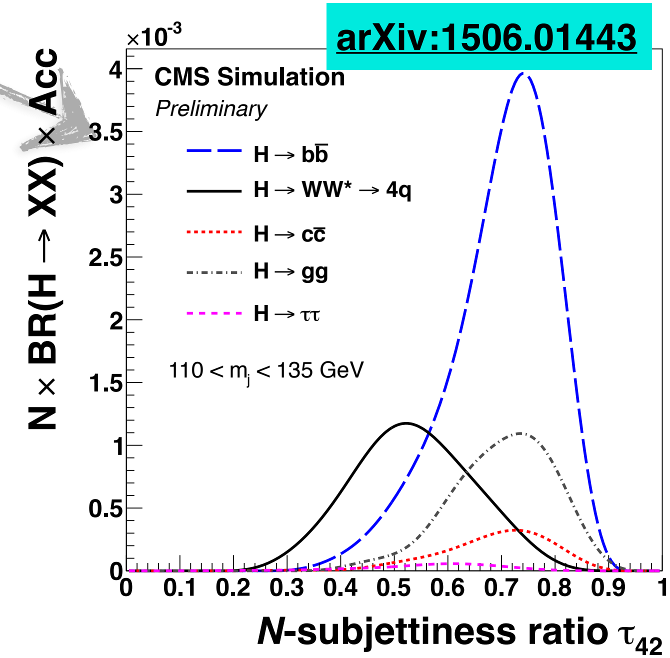
- **Signatures:** W or Z into hadrons, **$H \to b\bar{b}$** or **$H \to WW^* \to qqqq$**
- **Selections:** two Cambridge-Aachen R=0.8 jets $p_T > 200$ GeV, $|\Delta\eta| < 1.3$ and $m_{JJ} > 890$ GeV
  - **Pruning** removes soft and large angle protojets in CA8 jets → ±15 GeV around M_W M_Z or M_h
  - **B-tag:** apply **CSV** tagger to pruned sub-jets if $\Delta R_{jj} < 0.3$, otherwise to the CA8 jet
  - **N-subjettiness:** look at **jet shape** to separate **H(WW*→qqqq)** from **$H(b\bar{b})$**

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}),$$

W/Z → qq tagged with τ_{21}
H → WW* → qqqq with τ_{42}
H → bb with **b-tagging**

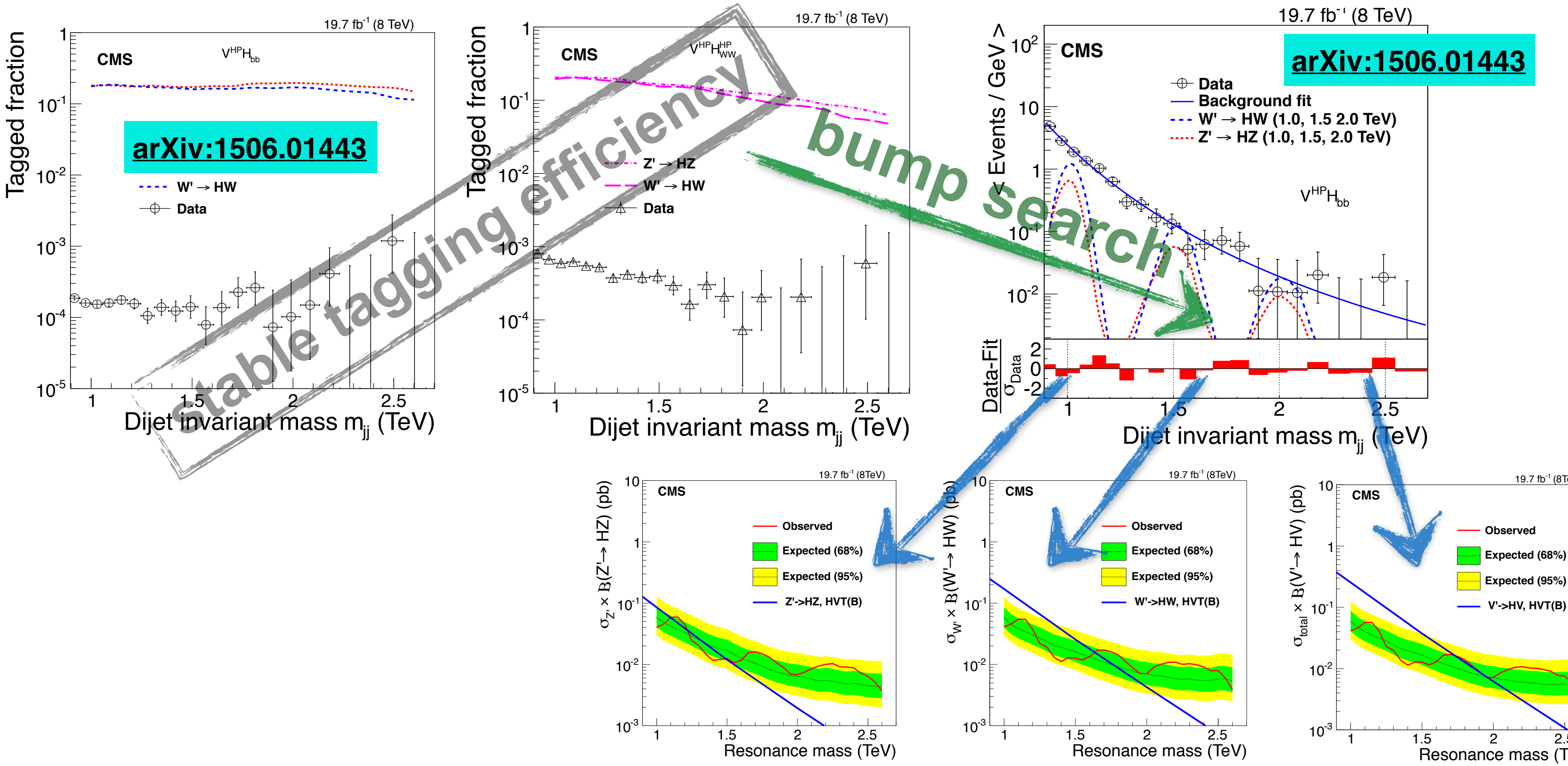






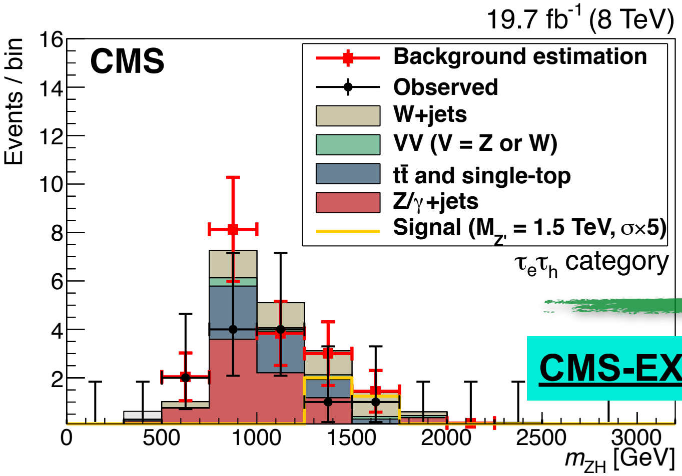
CMS: $X \rightarrow WH/ZH \rightarrow qqb\bar{b}$ or qqqq

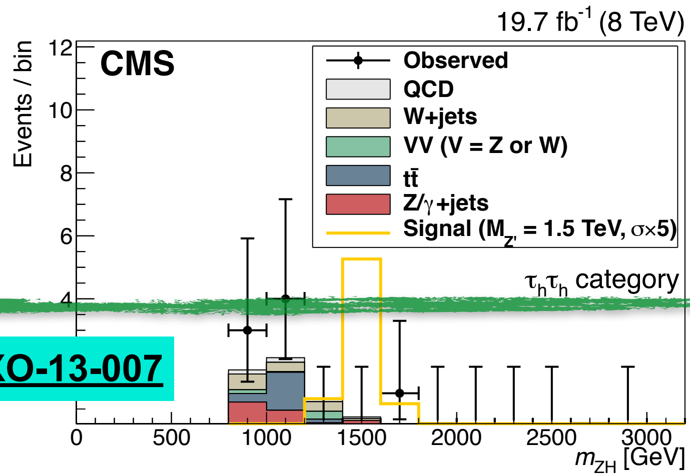
- **Event classification:**
  - Require **4-btag (H_{bb}),** τ_{21} on the W/Z jet split event into two purity categories
  - Events **failing b-tag**, classified according to τ_{42} to have **exclusive categories**
- **Benchmarks:** HVT model, in which B(W’ → WH) ~ B(W’ → WZ) and B(Z’ → ZH) ~ B(Z’ → WW)



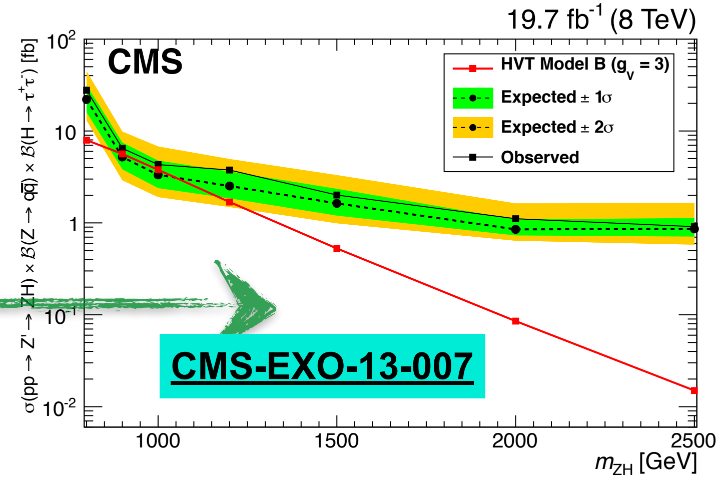
CMS: X → ZH → $qq\tau\tau$

- **Signature:** **one boosted Z-jet** and a **boosted Higgs : $\{\tau_e\tau_e, \tau_\mu\tau_\mu, \tau_\mu\tau_e\}$ $\{\tau_h\tau_\mu, \tau_h\tau_e\}$ $\{\tau_h\tau_h\}$**
- **Z-boson tagging:** standard V-tagging based on **pruned mass** and **τ_{21}**
- **τ-tagging:**
  - **high p_T leptons** from Higgs small ΔR separation → **tune dedicated identification** and **isolation**
  - **hadronic τ-leptons:** cluster the event with CA (R = 0.8)
    the last two sub-jets should have: p_T > 10 GeV, $m_{leading}$ < 2/3 m_{CA8}
    then the two sub-jets are reconstructed via **HPS** algorithm
- **Data driven** extraction for the total **background** in the different **categories:**
  - **m_{pruned}** sideband extraction in $\tau_\ell\tau_\ell$ and $\tau_\ell\tau_h$
  - **ABCD** m_{pruned}, $m_{\tau\tau}$ in $\tau_h\tau_h$





CMS-EXO-13-007



CMS-EXO-13-007

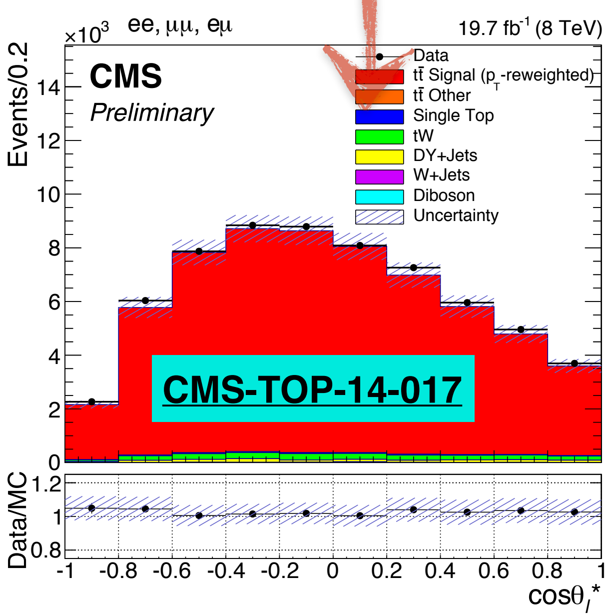
CMS: W-boson helicity in $t\bar{t}$

- **Measure W-boson helicity fractions** in **fully leptonic $t\bar{t}$** via **angular distributions** of the decay products
- **W-boson** and **top-quark mass constraints** determine a set of solutions for neutrino kinematics
- **The best one** is selected via an **Analytical Matrix Weighting**
  - **Smear** jet, lepton and E_T^{miss} momentum by a **Gaussian resolution N_{times}** for each event
  - **Assign to each configuration a weight**

$$w(\vec{X}|m_t) = \{ \sum_{\text{Initial partons}} F(x_1)F(x_2) \} \, p(E^*_{\ell^+}|m_t) \, p(E^*_{\ell^-}|m_t)$$

$$p(E|m_t) = \frac{4m_t E(m_t^2 - m_b^2) - 2m_t E}{(m_t^2 - m_b^2)^2 + m_W^2(m_t^2 - m_b^2) - 2m_W^4}$$

Top quark momentum is determined **by averaging** the **best solution** over the different randomizations



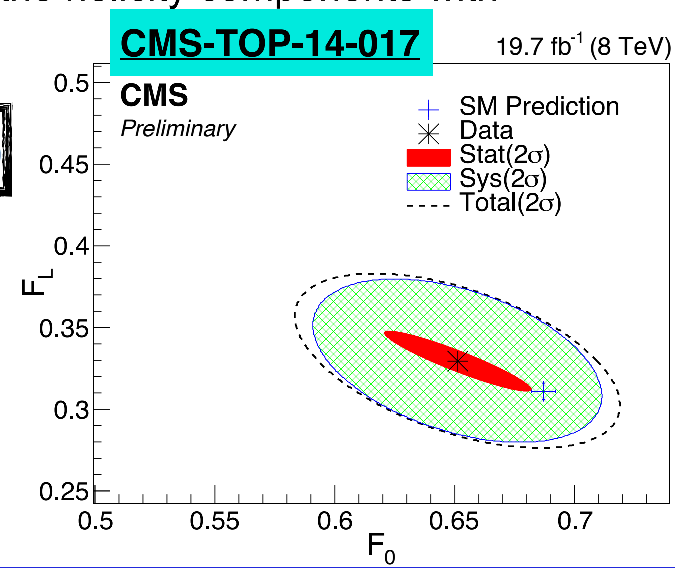
- **ϑ^* angle** between **leading lepton** and the **reconstructed W-boson**
- **Binned Likelihood** fit as a function of the helicity components with the constraint $f_L + f_R + f_0 = 1$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*_\ell} = \frac{3}{8}(1-\cos\theta^*_\ell)^2 F_L + \frac{3}{8}(1+\cos\theta^*_\ell)^2 F_R + \frac{3}{4}\sin^2\theta^*_\ell F_0$$

$$\mathcal{L}(\vec{F}) = \prod_{i \in bins} \frac{N_{MC}(i;\vec{F})^{N_{data}(i)}}{N_{data}(i)!} \times e^{-N_{MC}(i;\vec{F})}$$

$$N_{MC}(i;\vec{F}) = N_{BKG}(i) + N_{t\bar{t}}(i;\vec{F}),$$

$$N_{t\bar{t}}(i;\vec{F}) = \mathcal{F}_{t\bar{t}}[\sum_{t\bar{t}\text{ events,bin i}} W_{\ell^+\ell^-}(\cos\theta^*_{gen};\vec{F})],$$



CMS: ttH, H→b$\bar{b}$

- **Signature:** one/two isolated lepton, missing energy at least 6 (4) reconstructed jets p_T > 30 GeV
- **Likelihood** is used to combine **jet b-tag values** to **discriminate** between **tt+b$\bar{b}$** and **tt+q$\bar{q}$ hypotheses**
- **Matrix Element Likelihood** used since power of m_{bb} suffers from combinatorial bkg in multijet environment
  - **MEM** probabilities calculated at **LO** considering only **gg → ttH** contribution for both signal and background
  - **Single (light flavor) or double-Gaussian (b-jets) resolution function for jets**
- **Event classification:**
  - **Semi-leptonic** : [**>=6** jets,4 with higher b-tags are b-quarks, the other W → q$\bar{q}$] and [**=5** jets, partial reco of W → q$\bar{q}$]
  - **Fully-leptonic** : [**=4** jets, jets are considered b-tagged jets and associated to b-quarks]

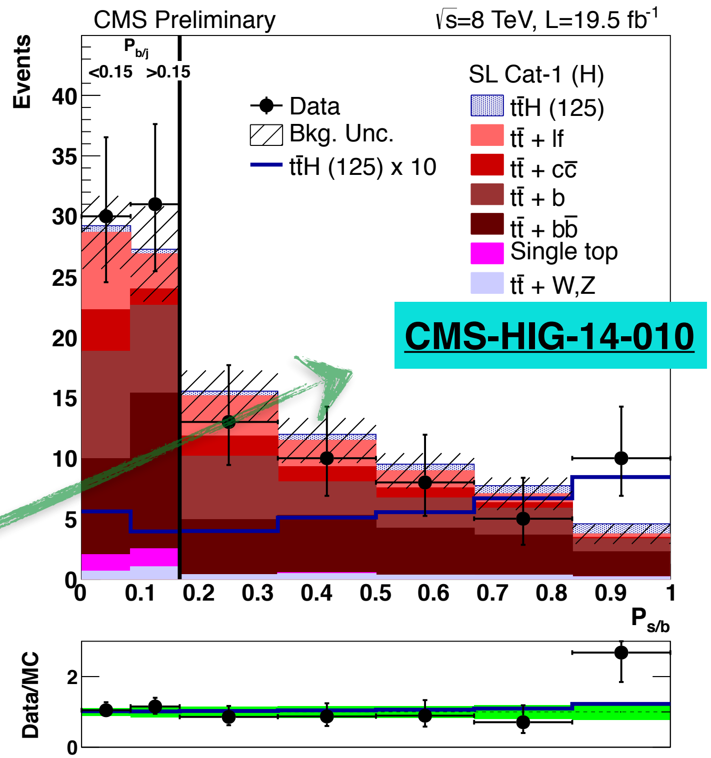
$$P_{s/b} = \frac{w(\vec{y}|t\bar{t}H)}{w(\vec{y}|t\bar{t}H) + k_{s/b}\, w(\vec{y}|t\bar{t}+b\bar{b})}$$

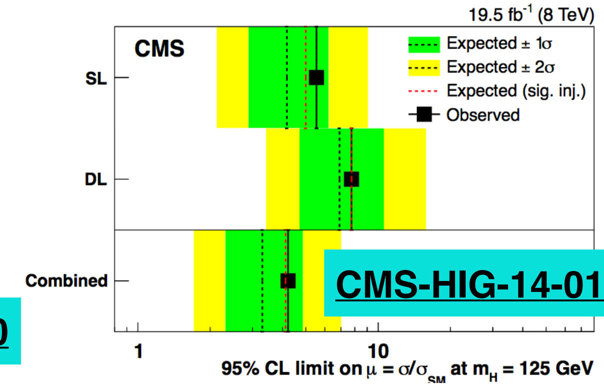
Probability from **MEM** method

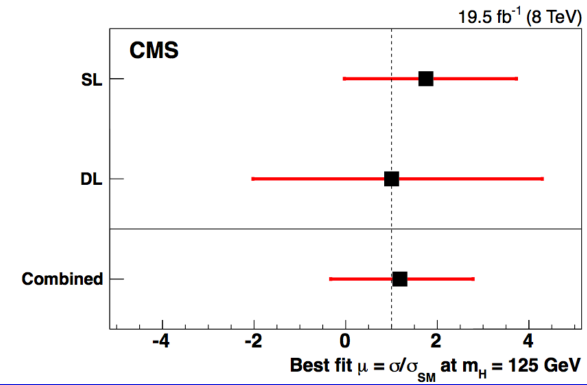
$$P_{h/l} = \frac{f(\vec{\xi}|t\bar{t}+hf)}{f(\vec{\xi}|t\bar{t}+hf) + k_{h/l}\, f(\vec{\xi}|t\bar{t}+lf)}$$

Likelihood from **b** and **non-b jet PDF**

2D Binned Likelihood fit for the ultimate **statistical interpretation**







CMS: ttH, H→$b\bar{b}$

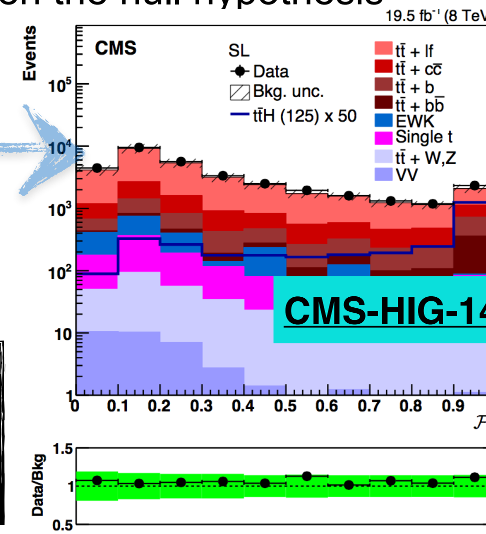
- **Likelihood** is used to combine **jet b-tag values** to **discriminate** between **tt+$b\bar{b}$** and **tt+$q\bar{q}$ hypotheses**
  - Only 6 (4) jets with highest b-tag value in the event are considered

$$f(\vec{\xi}|t\bar{t}+\mathrm{hf}) = \sum_{i_1}\sum_{i_2\neq i_1}\cdots\sum_{i_6\neq i_1,\ldots,i_5}\left\{\prod_{k\in\{i_1,i_2,i_3,i_4\}} f_{\mathrm{hf}}(\xi_k)\prod_{m\in\{i_5,i_6\}} f_{\mathrm{lf}}(\xi_m)\right\},$$

  - **F_{hf} and F_{lf} are** the **PDF** for the jet to originate from a heavy flavor or light flavor quark
  - Trying all the possibile dispositions of N jets in 4-bjets and N-4 non b-jets when the null hypothesis is the heavy flavor one

- **Likelihood discriminator**

$$\mathcal{F}(\vec{\xi}) = \frac{f(\vec{\xi}|t\bar{t}+\mathrm{hf})}{f(\vec{\xi}|t\bar{t}+\mathrm{hf}) + f(\vec{\xi}|t\bar{t}+\mathrm{lf})}$$



CMS-HIG-14-010

- **Event weight given hypothesis H and y observables**

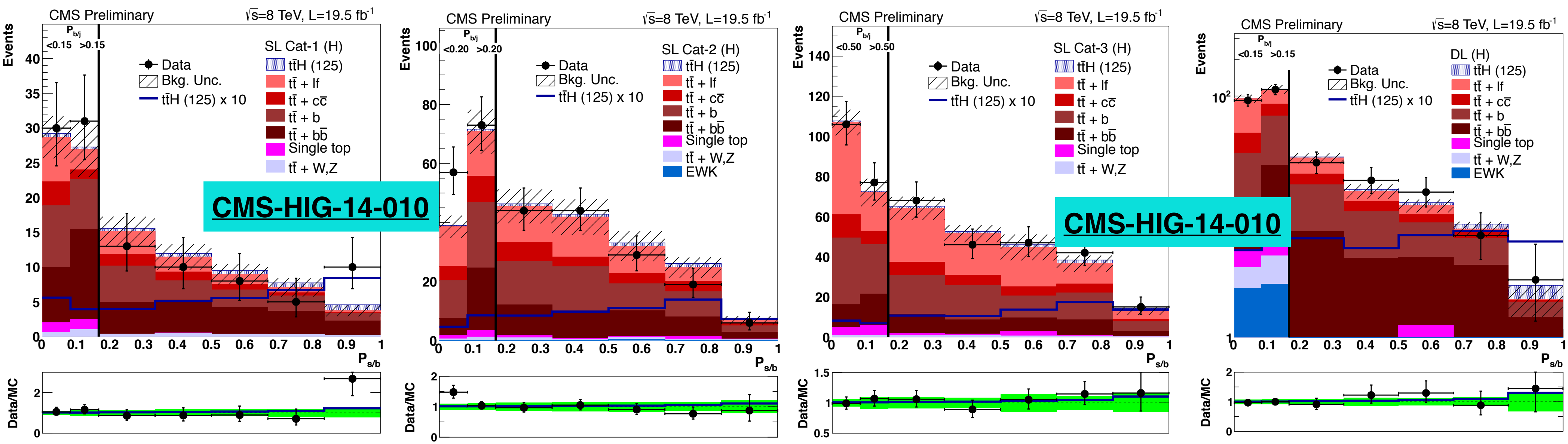
$$w(\vec{y}|\mathcal{H}) = \sum_{i=1}^{N_a}\int\frac{dx_a dx_b}{2x_a x_b s}\int\prod_{k=1}^{8}\left(\frac{d^3\vec{p}_k}{(2\pi)^3 2E_k}\right)(2\pi)^4\delta^{(E,z)}\left(p_a+p_b-\sum_{k=1}^{8}p_k\right)\mathcal{R}^{(x,y)}\left(\vec{\rho}_T,\sum_{k=1}^{8}p_k\right)\times g(x_a,\mu_F)g(x_b,\mu_F)|\mathcal{M}_{\mathcal{H}}(p_a,p_b,p_1,\ldots,p_8)|^2 W(\vec{y},\vec{p}),$$

gluon PDF and amplitude at LO

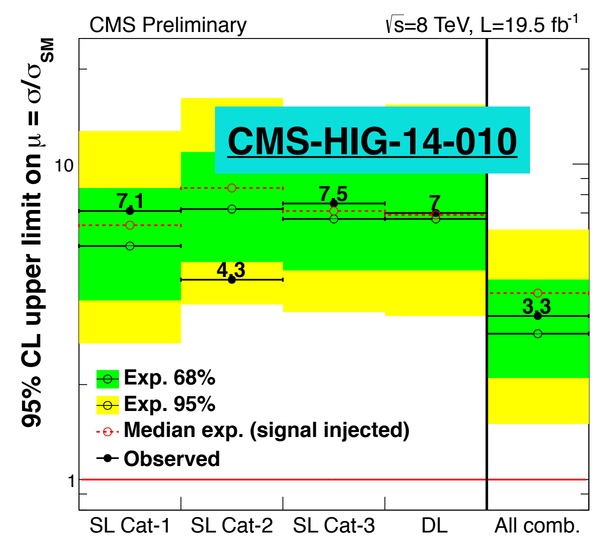
Transfert functions from quarks to jets

Take into account **final/initial** state radiation which alterate the **conservation** in the **delta function**

CMS: ttH, H→b$\bar{b}$

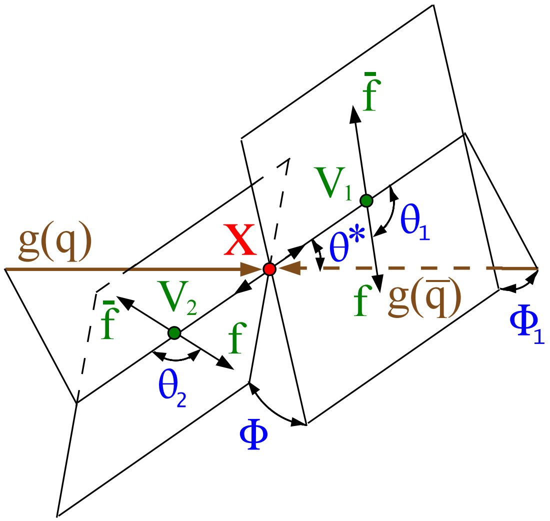


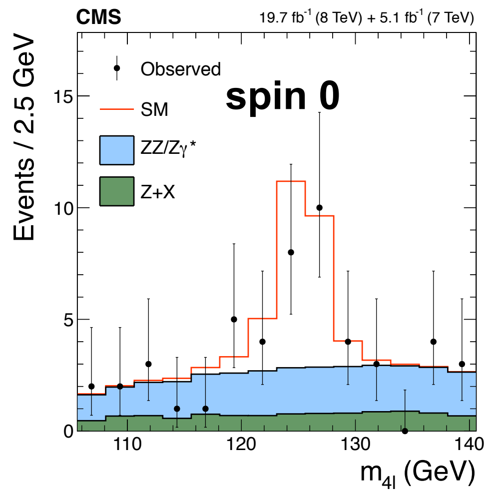
Source	Rate uncertainty	Shape	Process: tt̄H	Process: tt̄+jets	Process: Others
Experimental uncertainties					
Integrated luminosity	2.6%	No	✓	✓	✓
Trigger and lepton identification	2–4%	No	✓	✓	✓
JES	4–13%	Yes	✓	✓	✓
JER	0.5–2%	Yes	✓	✓	✓
b tagging	2–17%	Yes	✓	✓	✓
Theoretical uncertainties					
Top p_T modelling	3–8%	Yes		✓	
μ_R/μ_F variations	2–25%	Yes		✓	
tt̄+bb̄ normalisation	50%	No		✓	
tt̄+b normalisation	50%	No		✓	
tt̄+cc̄ normalisation	50%	No		✓	
Signal cross section	7%	No	✓		
Background cross sections	2–20%	No		✓	✓
PDF	3–9%	No	✓	✓	✓
Statistical uncertainty (bin-by-bin)	4–30%	Yes	✓	✓	✓

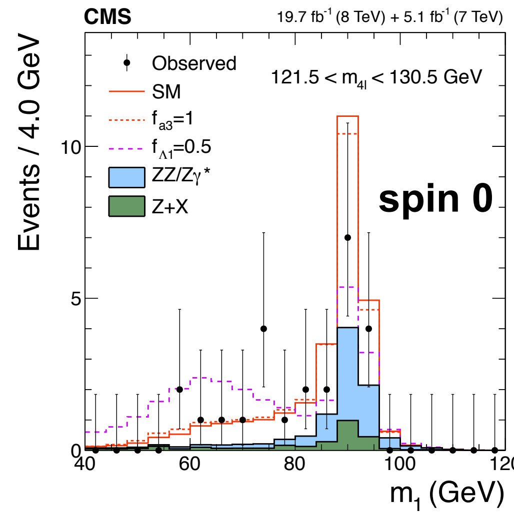


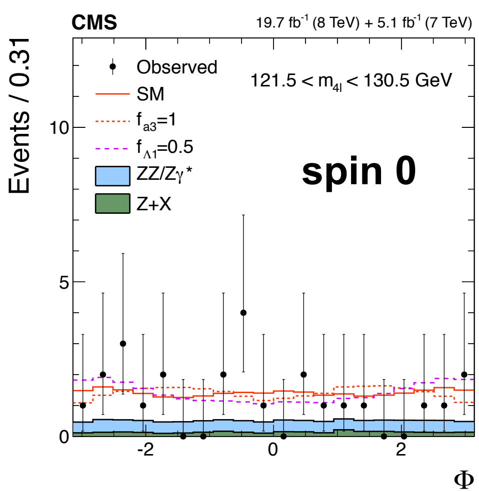
CMS: spin-parity via hVV couplings

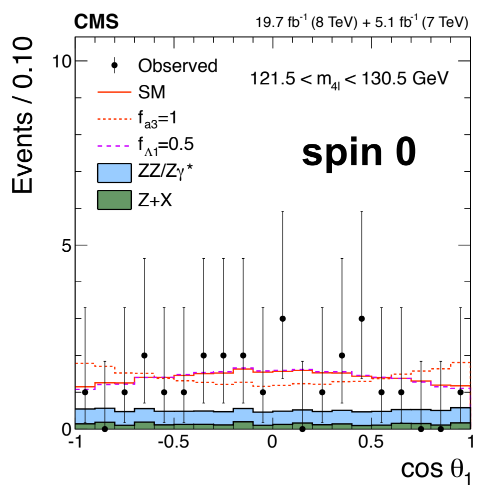
- **Best fit value** from **h→WW** and **h→ZZ** channel used: $\mathbf{m_H = 125.6}$ **GeV**
- **H → ZZ → 4ℓ 8 d.o.f. :** 16 components - constraints (4 from m_ℓ, m_Z, m_H, momentum conservation)
- **Chosen to be:** 5 decay angles in the Higgs rest frame, invariant mass of di-leptons, Higgs invariant mass
- Don't use $\mathbf{p_T^H}$ or **kinematics** of additional **jets** since are **production** dependent even if **sensitive to spin**

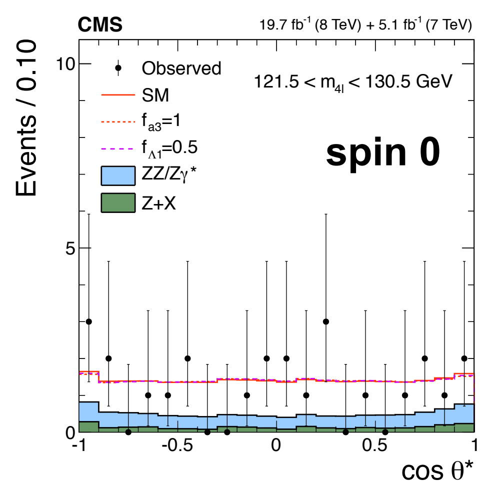


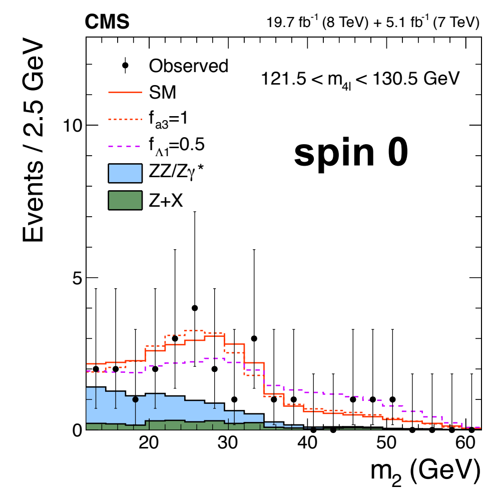












CMS: spin-parity via hvv couplings

- **JHUGen LO ME** for signal **(ggH, qqH)**, **MCFM LO** for **ZZ background (qqZZ, ggZZ)**
- **No specific matrix elements** to discriminate different **spin hypotheses** (only one **j^P = spin 0**)

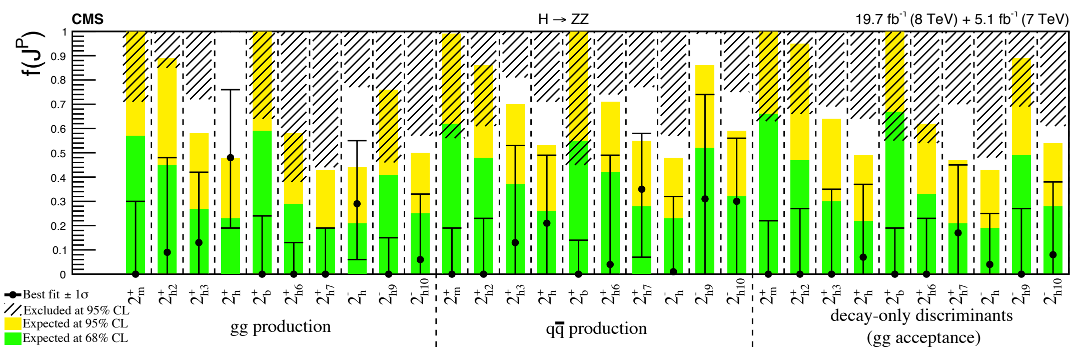
$$\mathcal{D}^{\rm dec}_{\rm bkg} = \left[1 + c(m_{4\ell}) \times \frac{\frac{1}{4\pi}\int d\Phi_1 d\cos\theta^* \mathcal{P}^{\rm kin}_{q\bar{q}ZZ}(m_1, m_2, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{q\bar{q}ZZ}(m_{4\ell})}{\mathcal{P}^{\rm kin}_{\rm SM}(m_1, m_2, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm sig}(m_{4\ell}|m_{\rm H})}\right]^{-1},$$

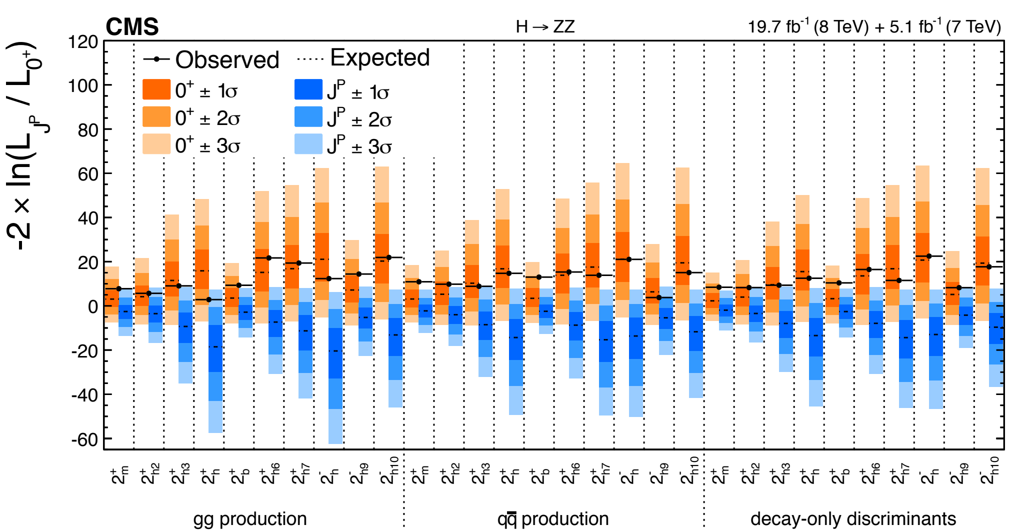
$$\mathcal{D}^{\rm dec}_{J^P} = \left[1 + \frac{\frac{1}{4\pi}\int d\Phi_1 d\cos\theta^* \mathcal{P}^{\rm kin}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{\rm SM}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}.$$

marginalize over two angles sensitive to spin

- **Final fit model for spin-0:**

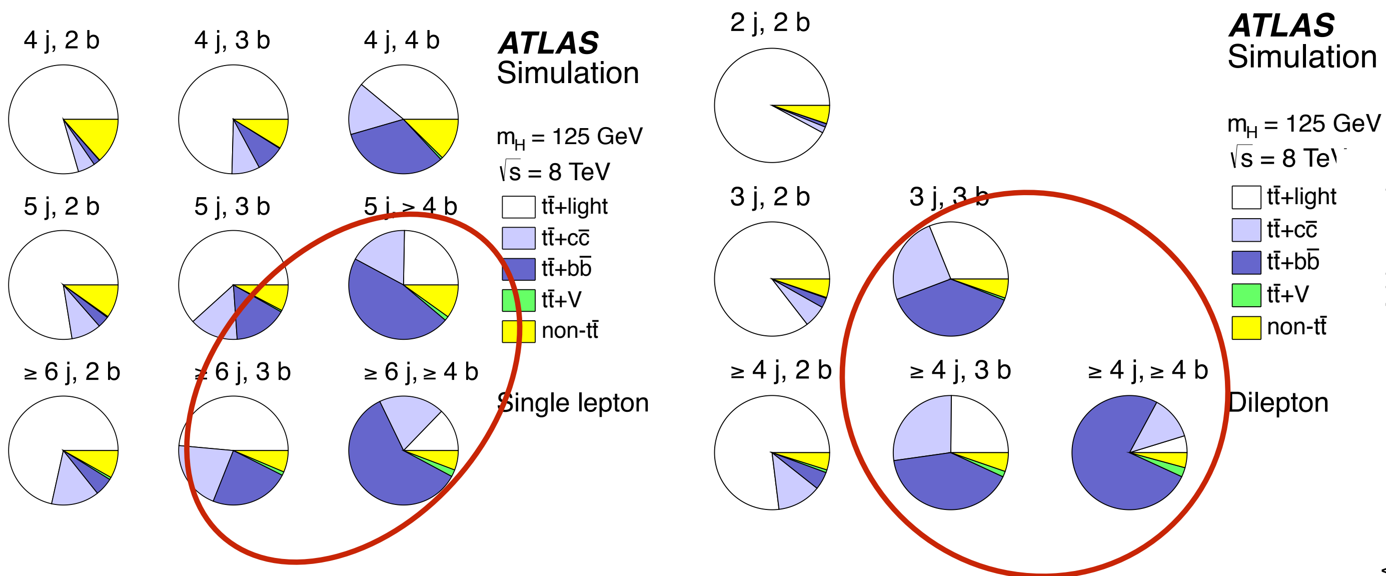
$$\mathcal{P}_{\rm sig}\left(\vec{x}; \vec{\zeta} = \{f_{ai}, \phi_{ai}\}\right) = \left(1 - \sum_{ai} f_{ai}\right) \mathcal{P}_{0^+}(\vec{x}) + \sum_{ai} f_{ai} \mathcal{P}_{ai}(\vec{x})$$
$$+ \sum_{ai} \sqrt{f_{ai}\left(1 - \sum_{aj} f_{aj}\right)}\, \mathcal{P}^{\rm int}_{ai,0^+}(\vec{x}; \phi_{ai})$$
$$+ \sum_{ai<aj} \sqrt{f_{ai} f_{aj}}\, \mathcal{P}^{\rm int}_{ai,aj}(\vec{x}; \phi_{ai} - \phi_{aj})$$

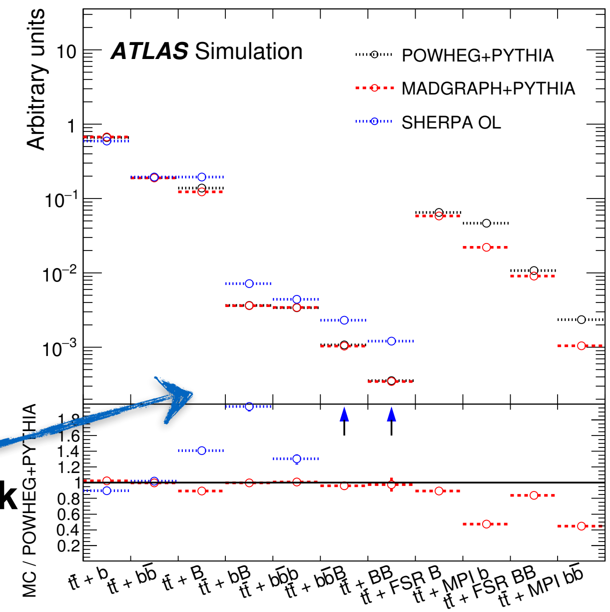




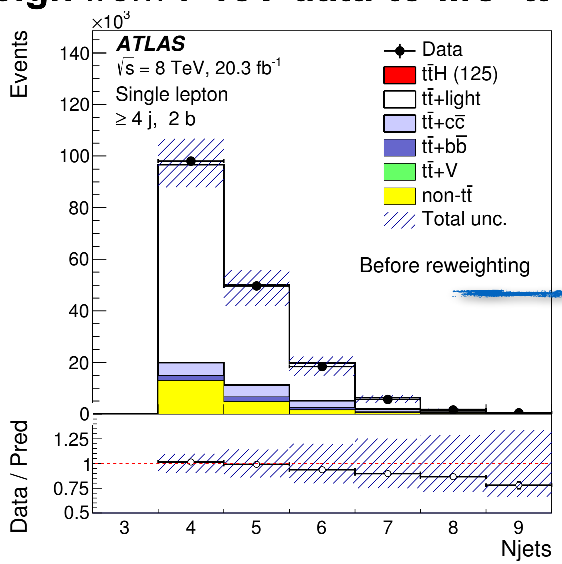
ATLAS: ttH H→b$\bar{b}$

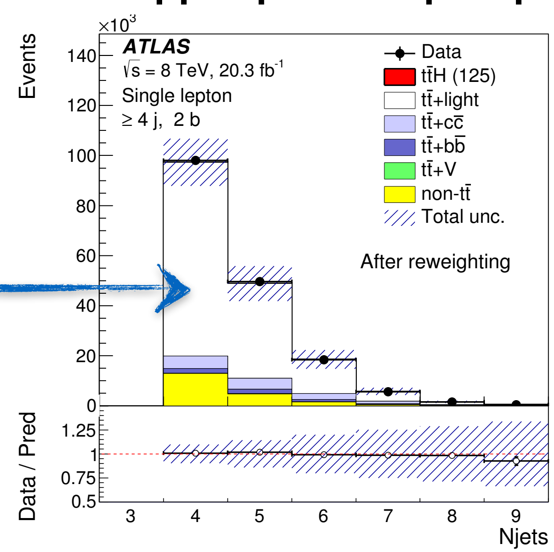
- **Background contamination** in the different **(N_{jet}, N_{bjet}) categories**





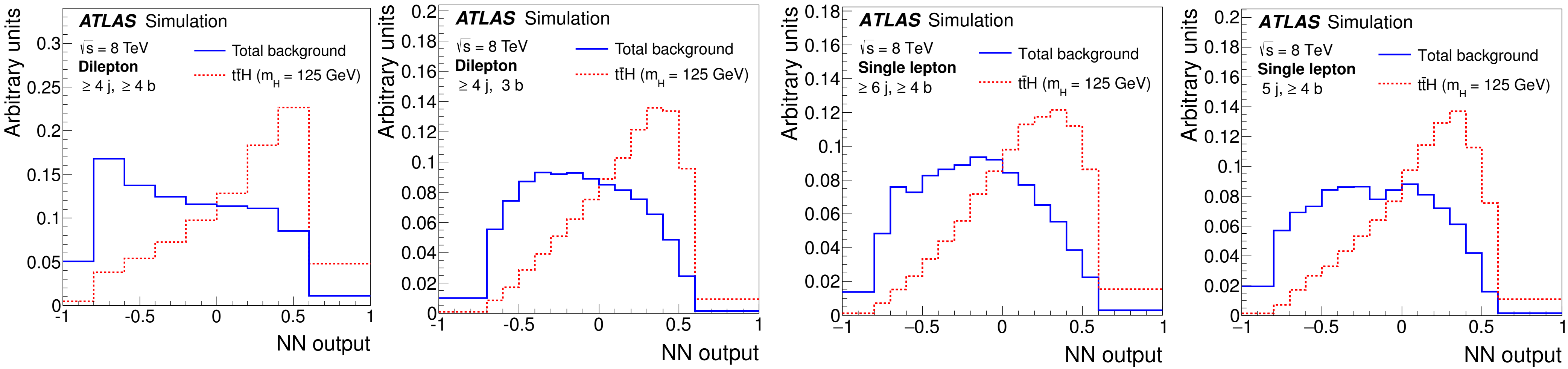
- **Validation** of **tt+ heavy flavor jet simulation** among different **generators**
- **Re-weigh** from **7 TeV data-to-MC tt+c$\bar{c}$** and **tt+qq** on **p_T t$\bar{t}$** and **p_T top quark**



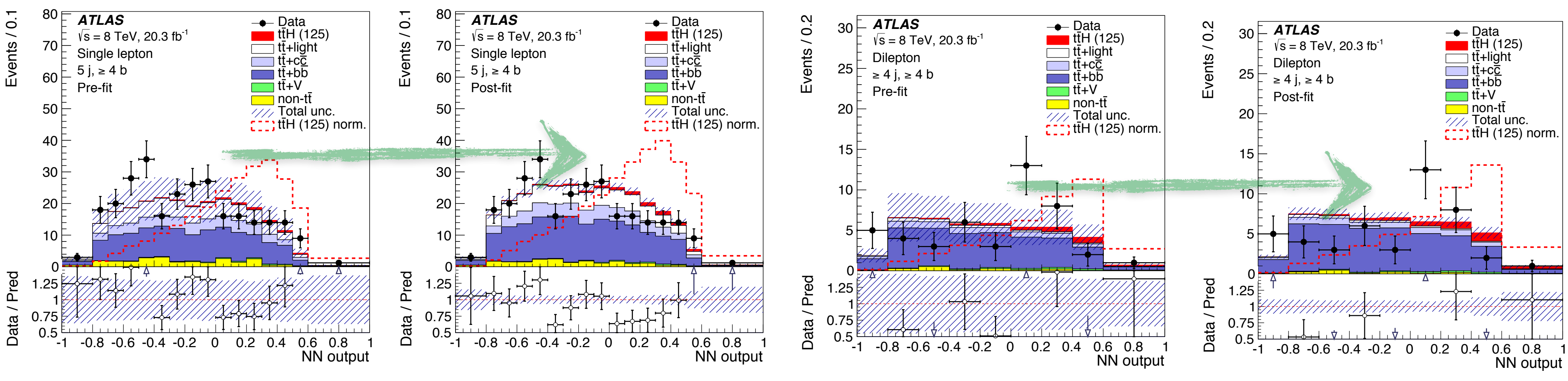


ATLAS: ttH H→$b\bar{b}$

- **Single Lepton** and **Double Lepton** **Neural Networks**



- **Pre-fit vs post-fit in the signal regions**



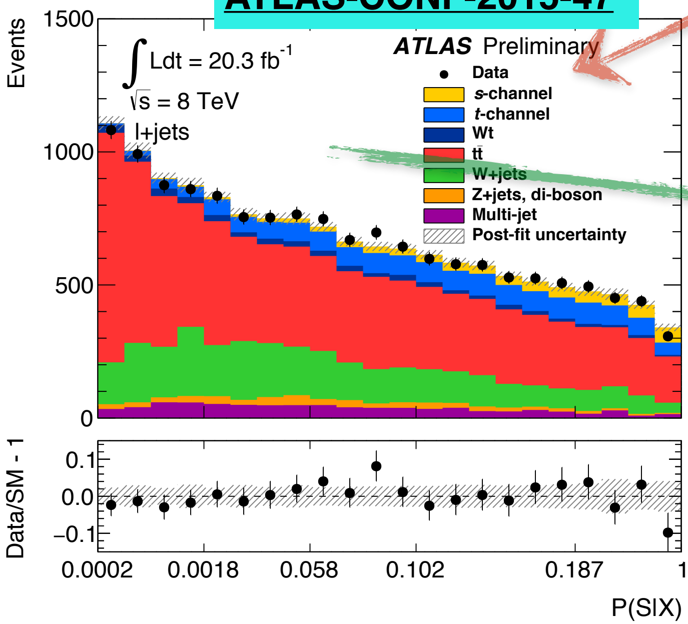
ATLAS: single top s-channel

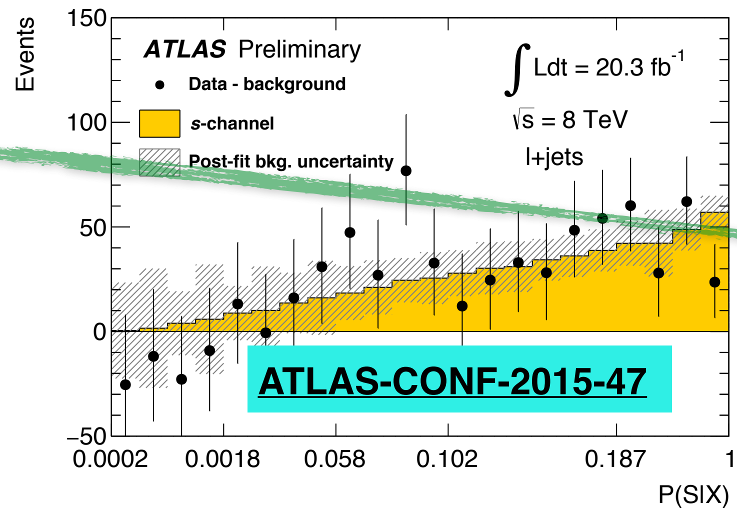
- First result for **s-channel single top** @8 TeV: **σ = 5.0 ± 4.3 pb**, observed signal **significance** of **1.3σ**
- **Signature:** one lepton + 2 b-jets + E_T^{miss}
- **Backgrounds**: $t\bar{t}$ reduced by vetoing additional leptons or jet, jet veto useful also for W+jets
- **Analysis improvements:** better selections optimization, updated calibration, use **Matrix Element** wrt BDT
  - **8 processes**: s-channel, t-channel, semi and fully leptonic $t\bar{t}$, W+2b, W+2q, W+qc

$$P(S|X) = \frac{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i)}{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i) + \sum_j \alpha_{B_j} \mathcal{P}(X|B_j)}$$

Binned Shape Analysis on the ME discriminator

ATLAS-CONF-2015-47





ATLAS-CONF-2015-47

Signal strength $0.86^{+0.44}_{-0.40}$

Observed significance 3.2σ

σ=4.8 ± 1.1(stat)± 2.2(sys) pb

Improvement with respect to the previous **public result**