b-tagging and Higgs Associated Production with Top Quarks at ATLAS and CMS

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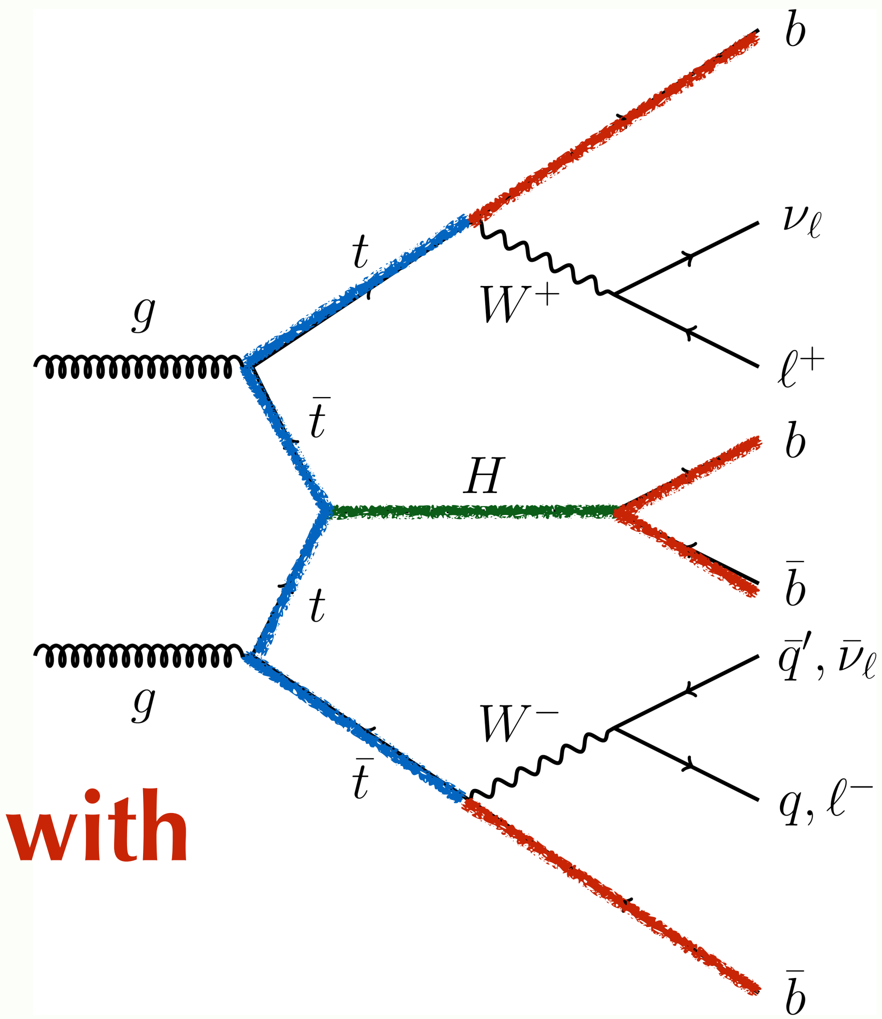
Outline

- **b-tagging**
  - Algorithms
  - Performance
  - Upgrade studies



- **Higgs associated production with top quarks**
  - Single top associated production
  - Top quark pair associated production
  - Search for FCNH

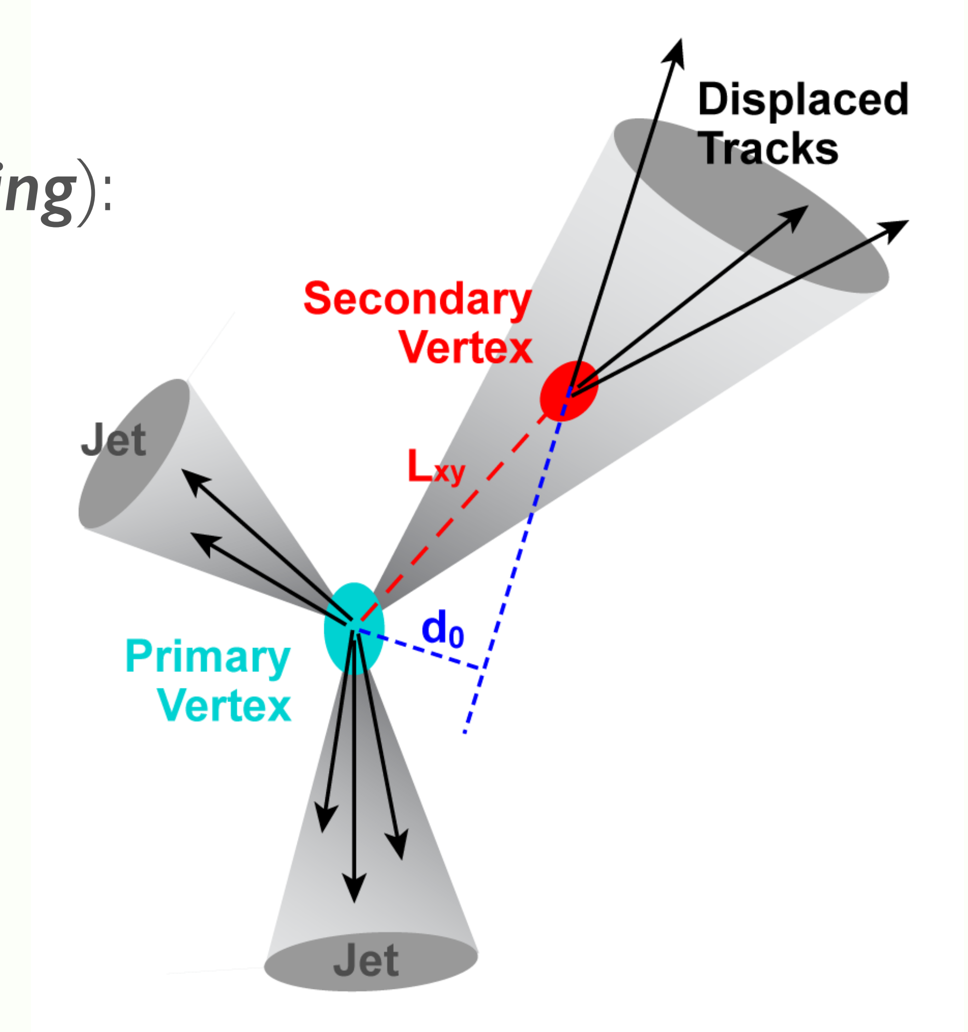
- b-quarks are present in top quark decays, **Br(t→Wb) ≈100%**
- **Br(H→bb) = 57.7%** is the dominant Higgs decay mode

b-tagging

Introduction to b-tagging

- **b-jets** = jets that arise from the process of hadronization of b-quarks
- Many physics analyses (Top, Higgs, Exotics) rely on efficient identification of b-jets

- Use **B-hadron properties** to identify b-jets (***b-tagging***):
  - Relatively large mass [5-10 GeV]
  - Long lifetime [$c\tau \approx 450\ \mu m$]
    E = 70 GeV gives $\beta\gamma c\tau \approx 5$ mm
  - Daughter particle multiplicity
    ≈ five charged tracks per decay
  - Possible presence of semileptonic decays
    $b \rightarrow \mu\nu X$ [Br ≈ 11%], $b \rightarrow c \rightarrow \mu\nu X$ [Br ≈ 10%]
  - Tertiary vertex
    (B-meson decay to a charmed hadron), $c\tau \approx 120$-$310\ \mu m$



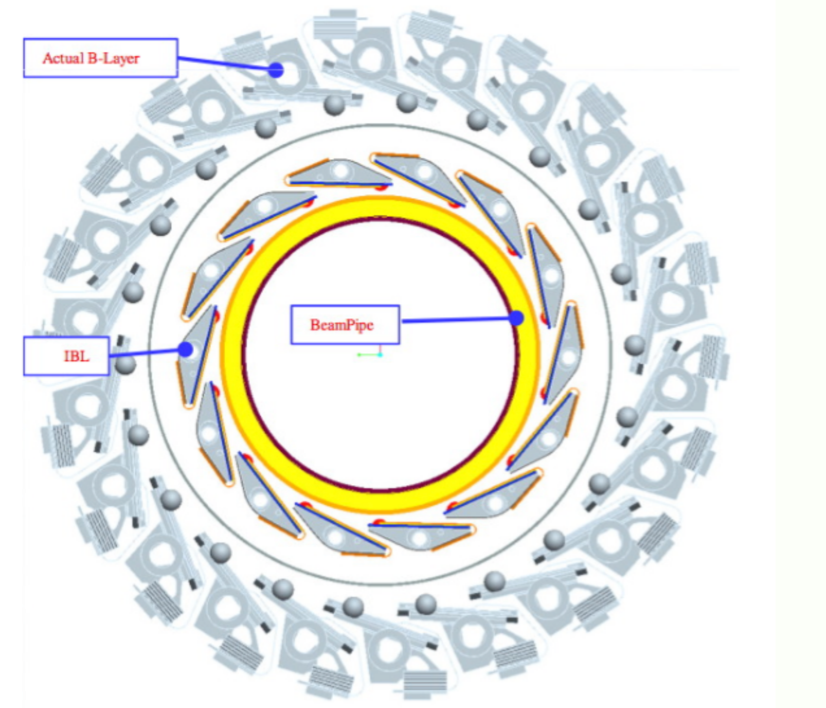
Challenges in Run 2

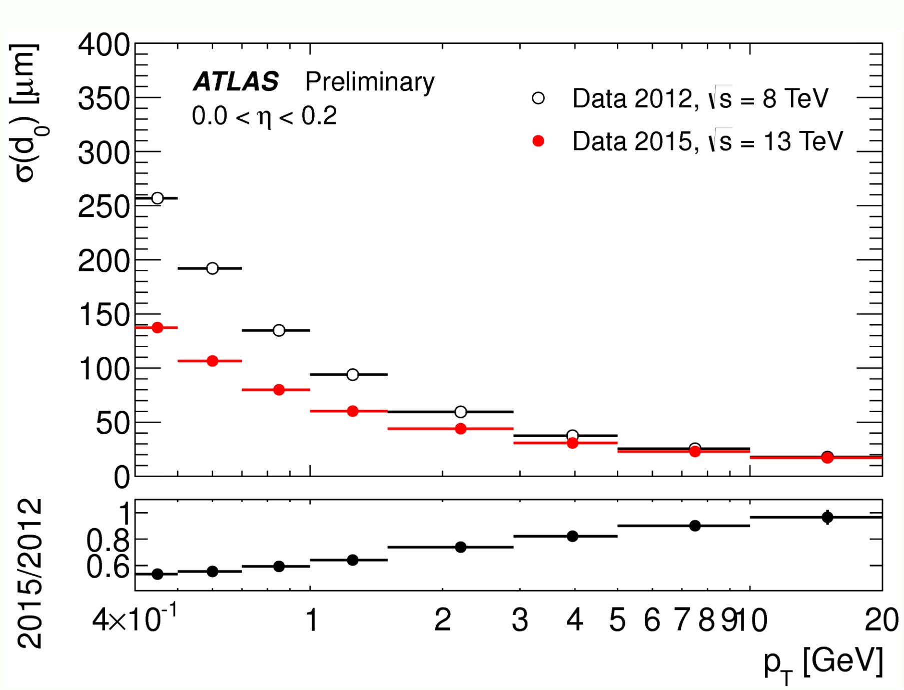
- **LHC beam collisions** setup during **Run 2** includes:
  - Higher center-of-mass energy of 13 TeV (was 8 TeV)
  - Higher instantaneous luminosity of 1.3×10^{34} cm^{-2} s^{-1} (was 7×10^{33})
  - Smaller bunch spacing of 25 ns (was 50 ns)

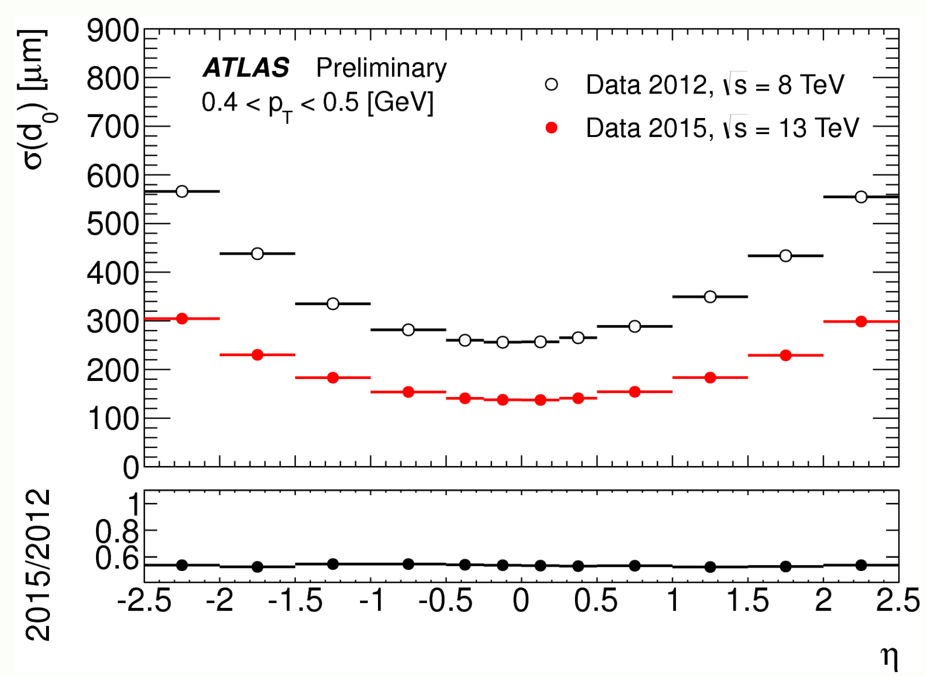
- **ATLAS and CMS detectors** are facing **new challenges**:
  - Larger number of pileup interactions
    Not yet in 2015 but expected to be up to ≈ 40 by LS2
    Affects track and vertex reconstruction, dynamic inefficiency, increased occupancy
  - Increased trigger rates
  - Higher probability of boosted objects imposes requirements on tracking performance

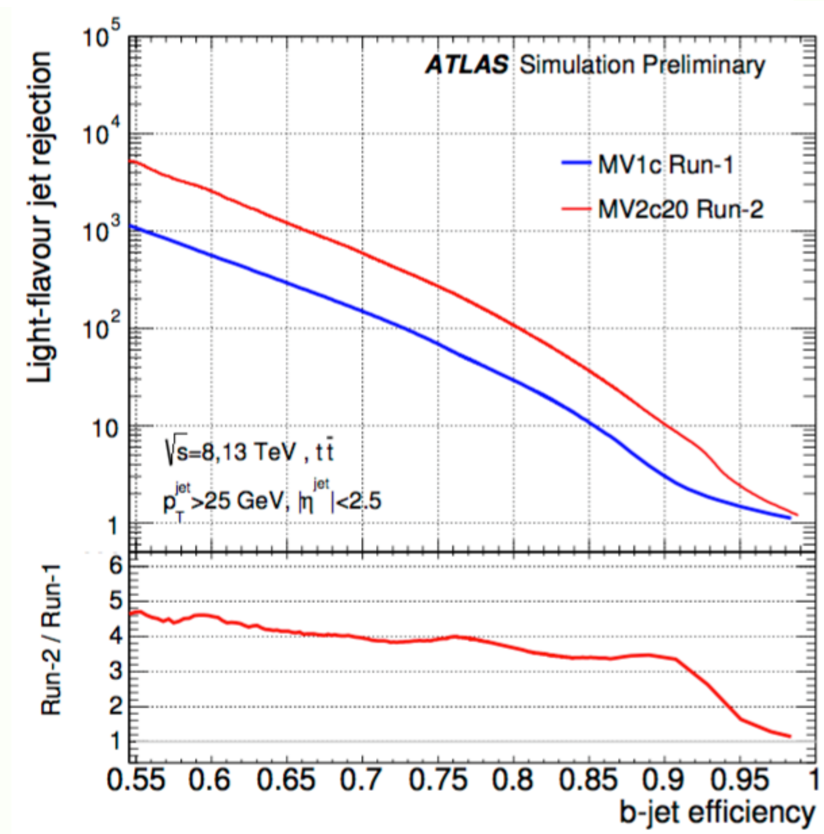
ATLAS Phase 0 upgrade for Run 2

- A new beam pipe and addition of **Insertable-B-Layer (IBL)** in the PIXEL detector
- Distance to the beam pipe reduced from 5 cm to 3.3 cm
- Finer granularity of IBL (50 μm x 250 μm) with respect to other PIXEL layers (50 μm x 400 μm)
- **Improved impact parameter resolution** - very important impact on b-tagging performance - ***4x more light-jet rejection***









InDetTrackingPerformanceApprovedPlots#Run_2 ATLAS-TDR-019, ATL-PHYS-PUB-2015-022

Algorithms

b-tagging algorithms

Algorithm	ATLAS	CMS
Impact parameter based	IP2D, IP3D, TrackCounting, JetProb	IP2D, IP3D, TCHP, TCHE, JP
Secondary vertex based	SV0, SV1, SV	SSVHP, SSVHE
Decay chain multi-vertex	JetFitter	[Part of CSVv2]
Soft lepton	SMT, p_TRel	Soft Muon Tagger, p_TRel
Multivariate	JetFitterCombNN, MV1c, **MV2c00**, **MV2c20**	CSV, **CSVv2**

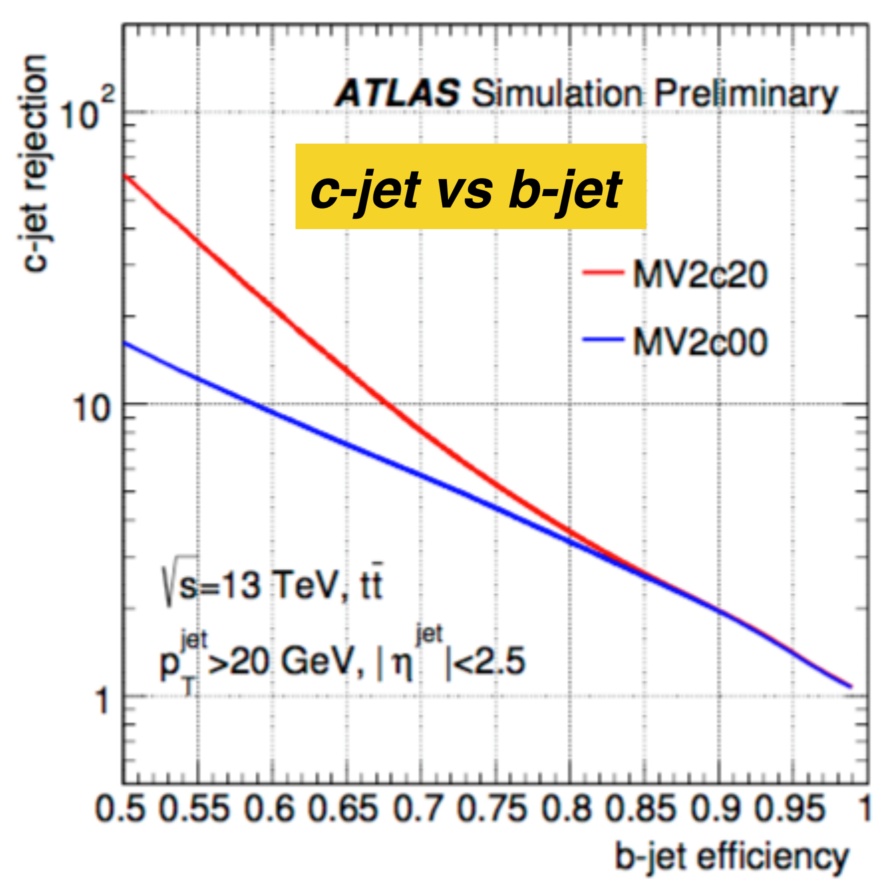
Operating points either based on b-tagging or mis-tagging efficiencies:

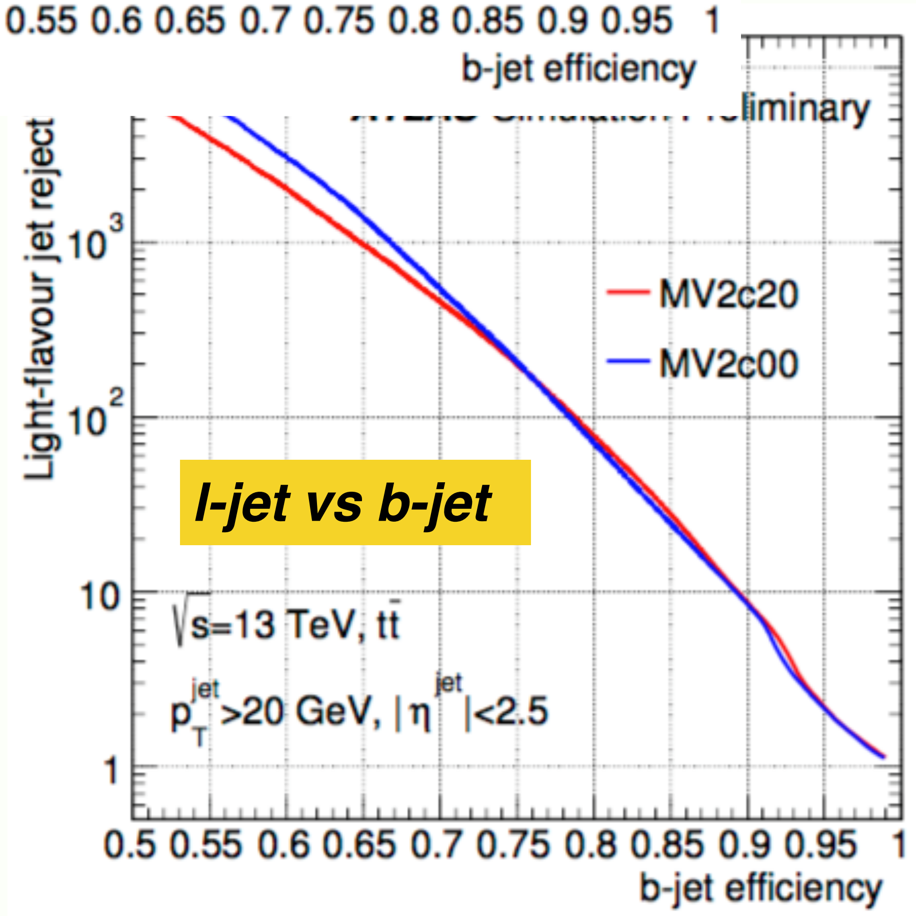
b-tag: 60%, 70%, 77%, 85% (ATLAS)
mis-tag: 0.1%, 1%, 10% (CMS)

Not an exhaustive list of taggers

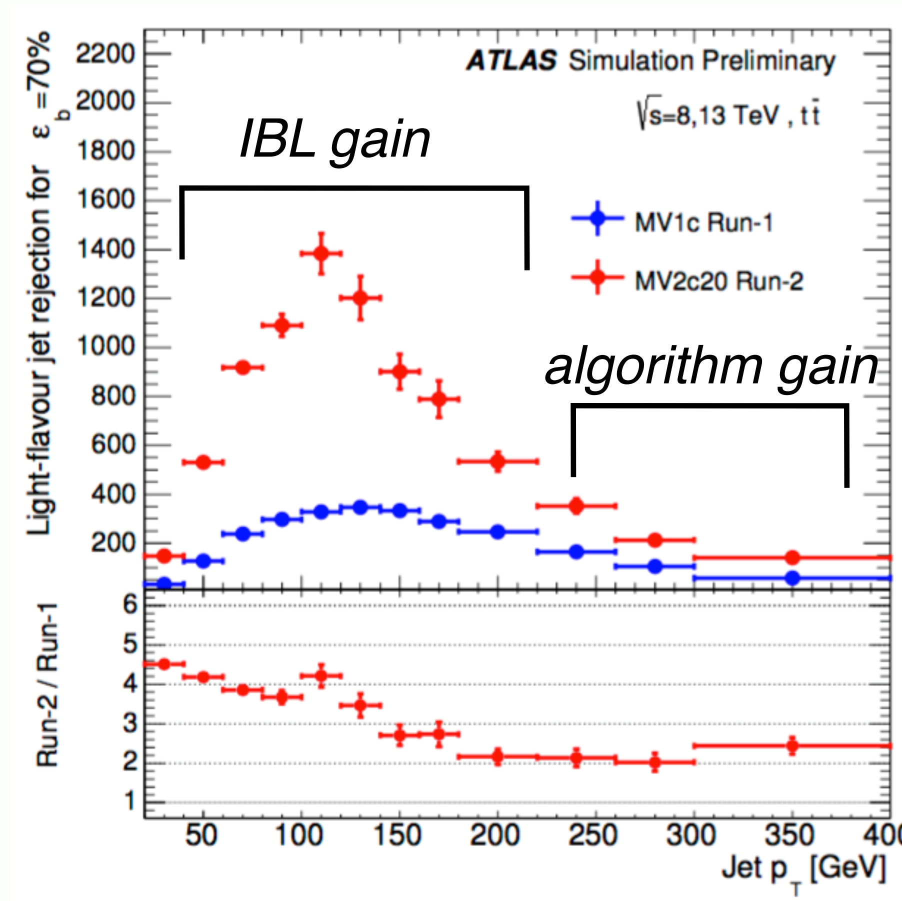
Current **flagman** taggers for Run 2 (more updates expected later in 2016)

ATLAS multivariate b-tagging algorithm

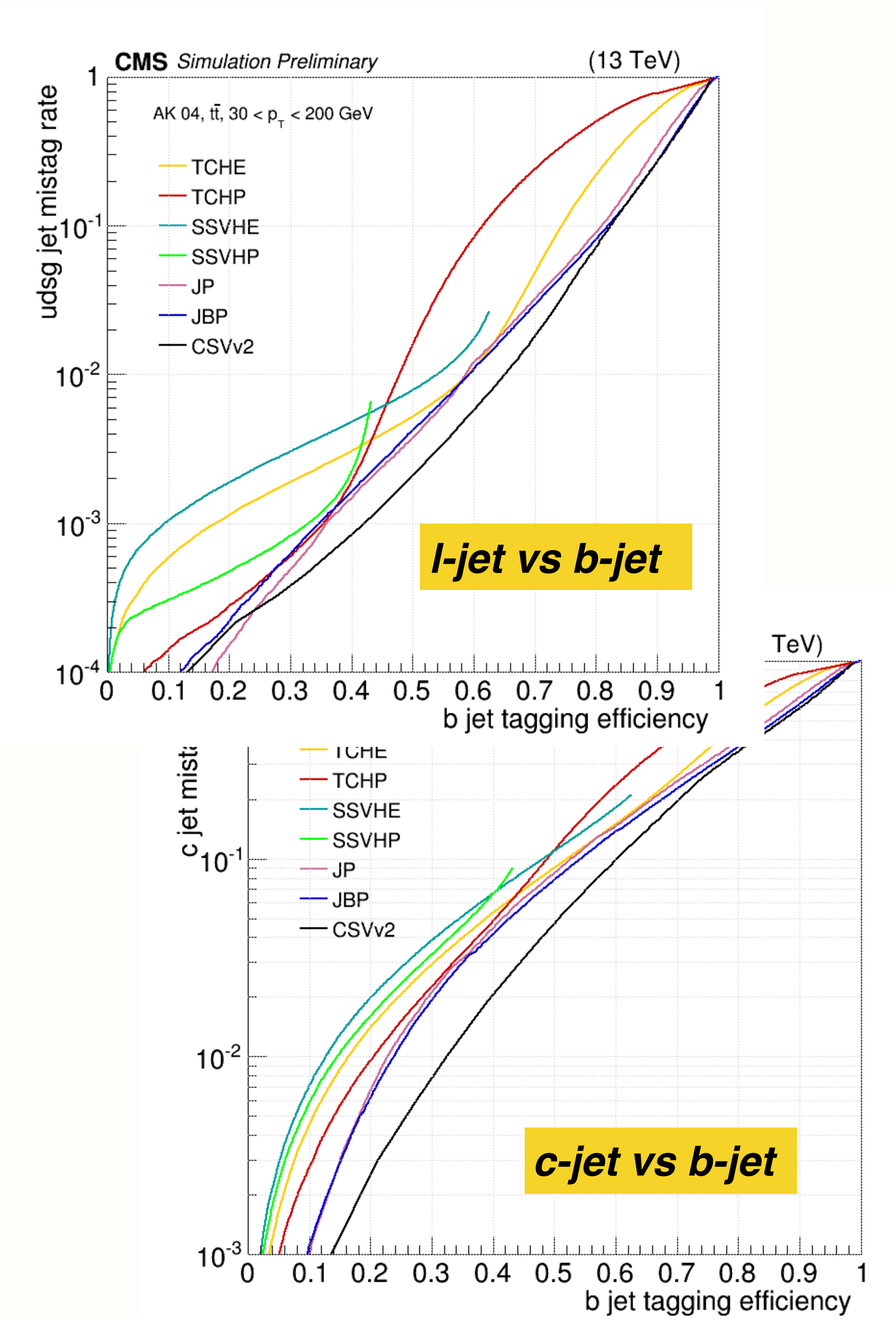




- **MV2** outperforms the previous version MV1
- Trained with different background composition:
  - MV2c00 (100% light jets)
  - MV2c20 (80% light and 20% c-jets)
- **Combines** variables from single basic algorithms using BDT:
  - Jet p_T and η
  - IP2D, IP3D
  - SV
  - Jet Fitter



CMS multivariate b-tagging algorithm



- **CSVv2** outperforms the previous version CSV
- Now uses the **Inclusive Vertex Finder** algorithm
- MLP-based discriminator **combines** track and vertex information:
  - Track 2D and 3D IP significances
  - Track multiplicity
  - Vertex mass
  - 2D flight distance significance
  - etc.
- Training is done in three SV categories
  - RecoVertex
  - PseudoVertex (SV from tracks with large SIP)
  - NoVertex (no SV)

Calibration

Calibration of b-tagging performance

Calibration of b-tagging efficiencies in data and MC is usually done in:

- **QCD multijet** events with b-jets containing muons
- **ttbar** events with inclusive jets

Sample	ATLAS	CMS
QCD	p_TRel, System8	p_TRel/IP3D, System8, Lifetime Tag (LT)
ttbar	Tag counting, Kinematic selection, Kinematic fit, Combinatorial likelihood	Flavour tag consistency, bSample, Flavour tag matching, LT, KIN

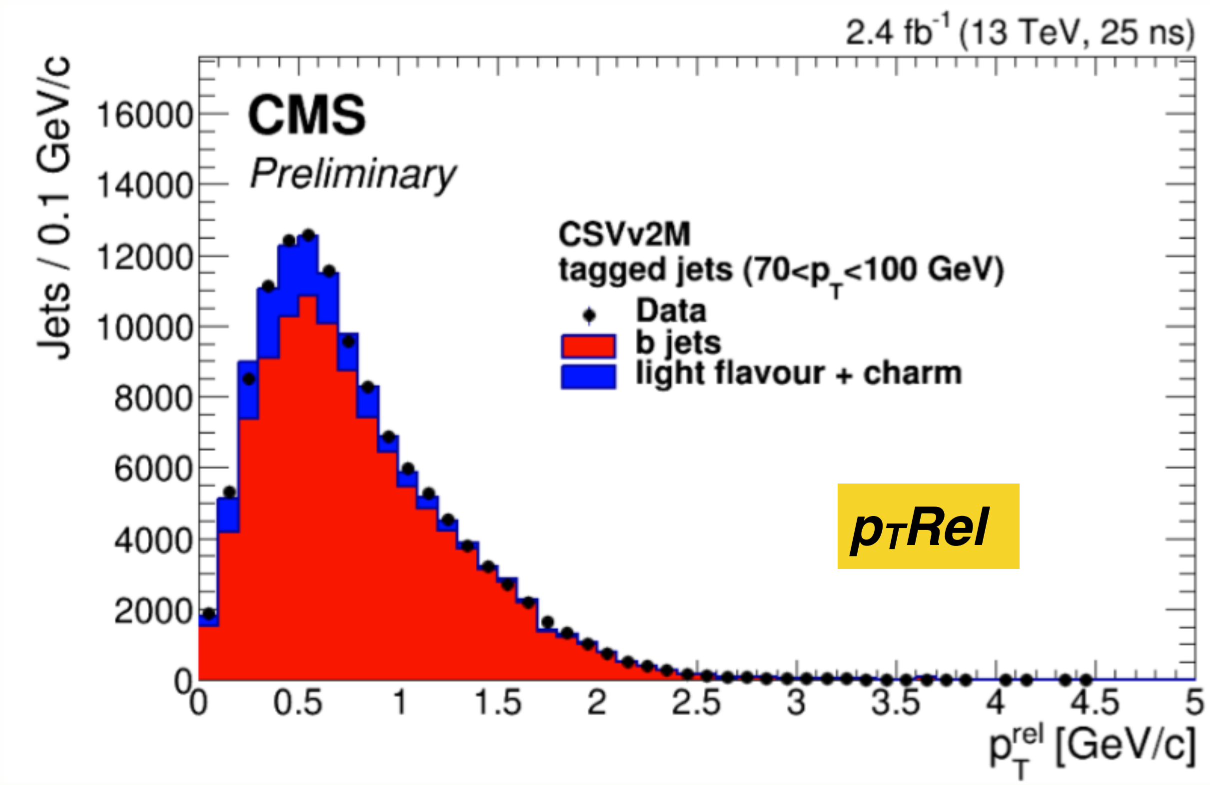
Eventually, a **combination** of the measured data/MC b-tag SFs from different methods is performed

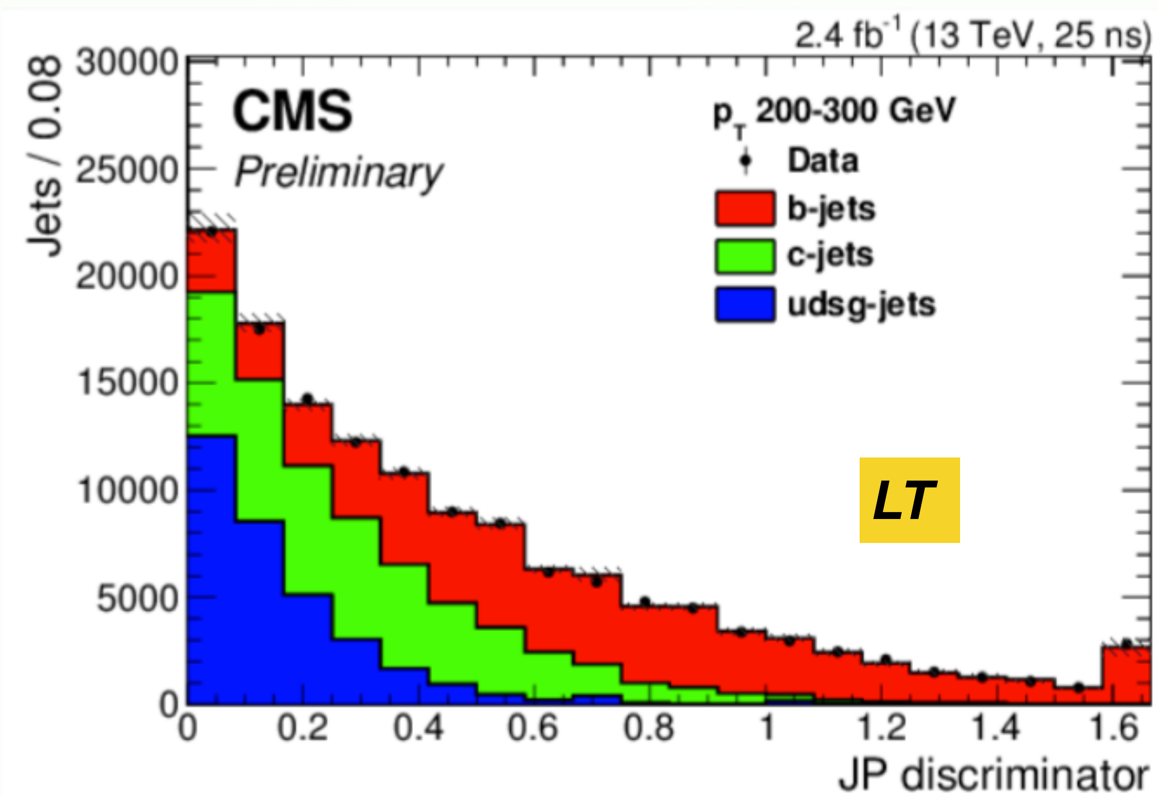
b-tag calibration in QCD events

- **Template fit methods** based on ***p_TRel*** and Jet Probability (JP) discriminant (***LT***)
  - **p_TRel** - momentum of muon transverse to muon+jet axis
  - **JP** - compatibility of a set of tracks from a jet to originate from a primary vertex:

$$P_{tr}(S) = sign(S) \int_{|S|}^{\infty} R(x)dx$$

Resolution function built with negative IP tracks

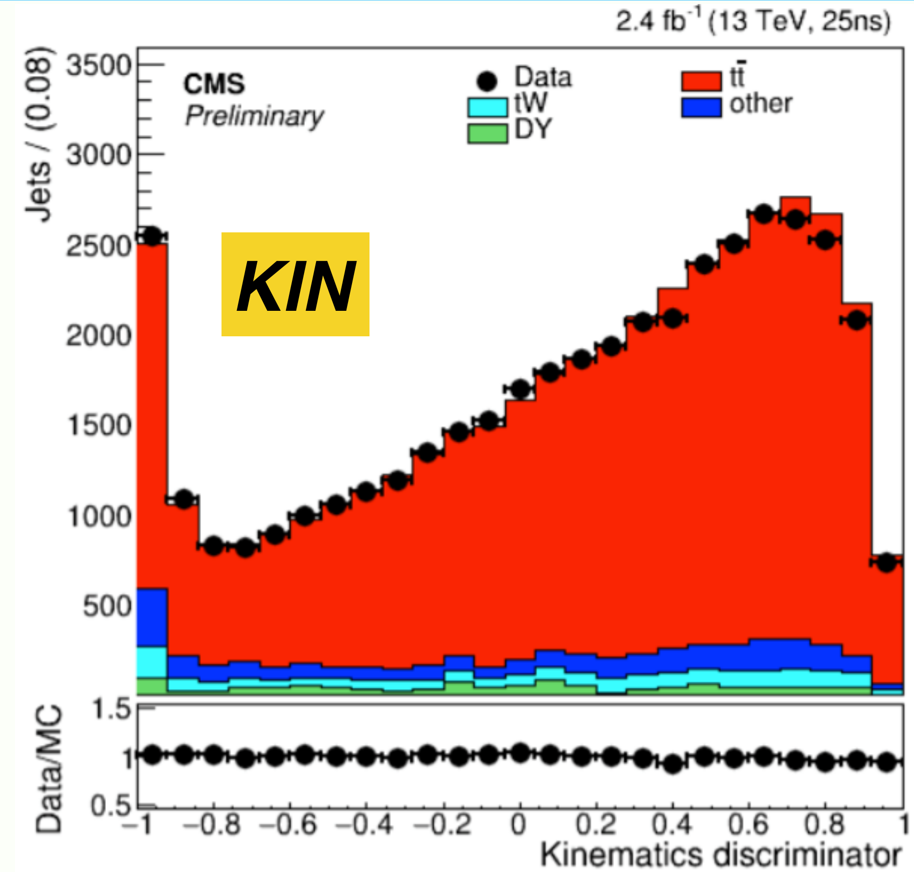


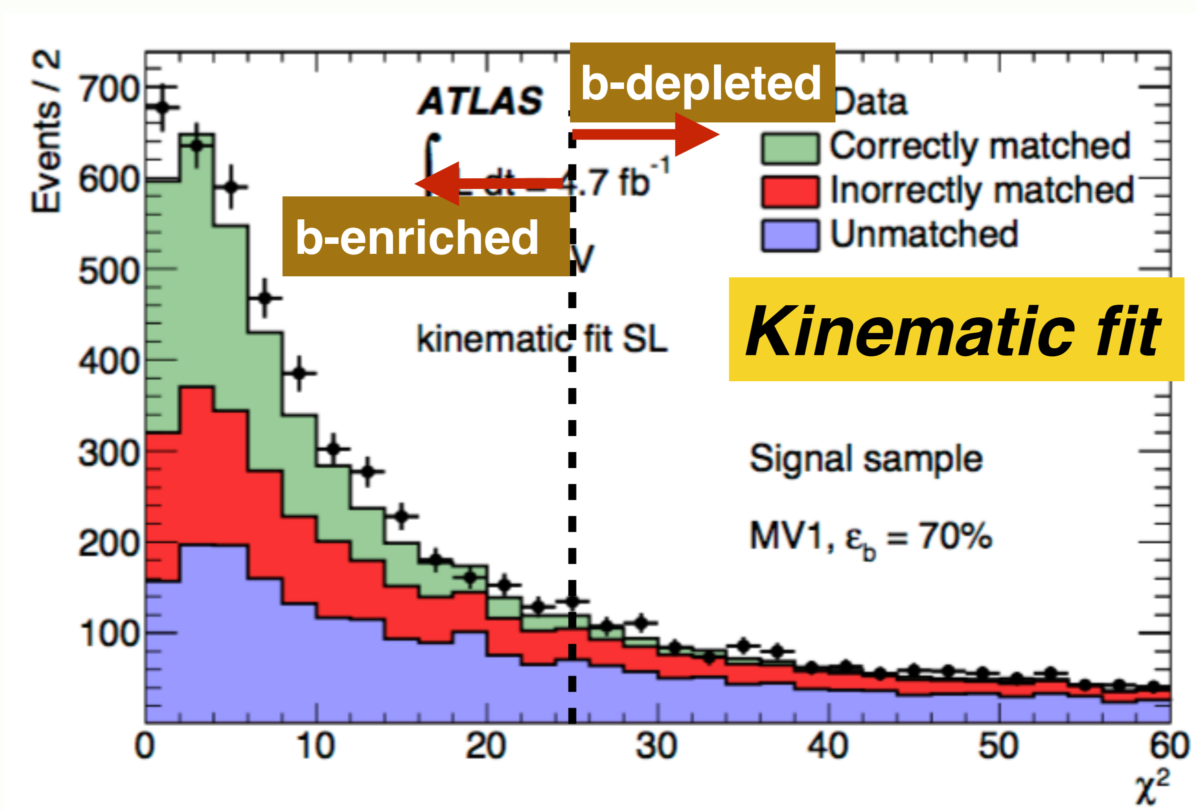


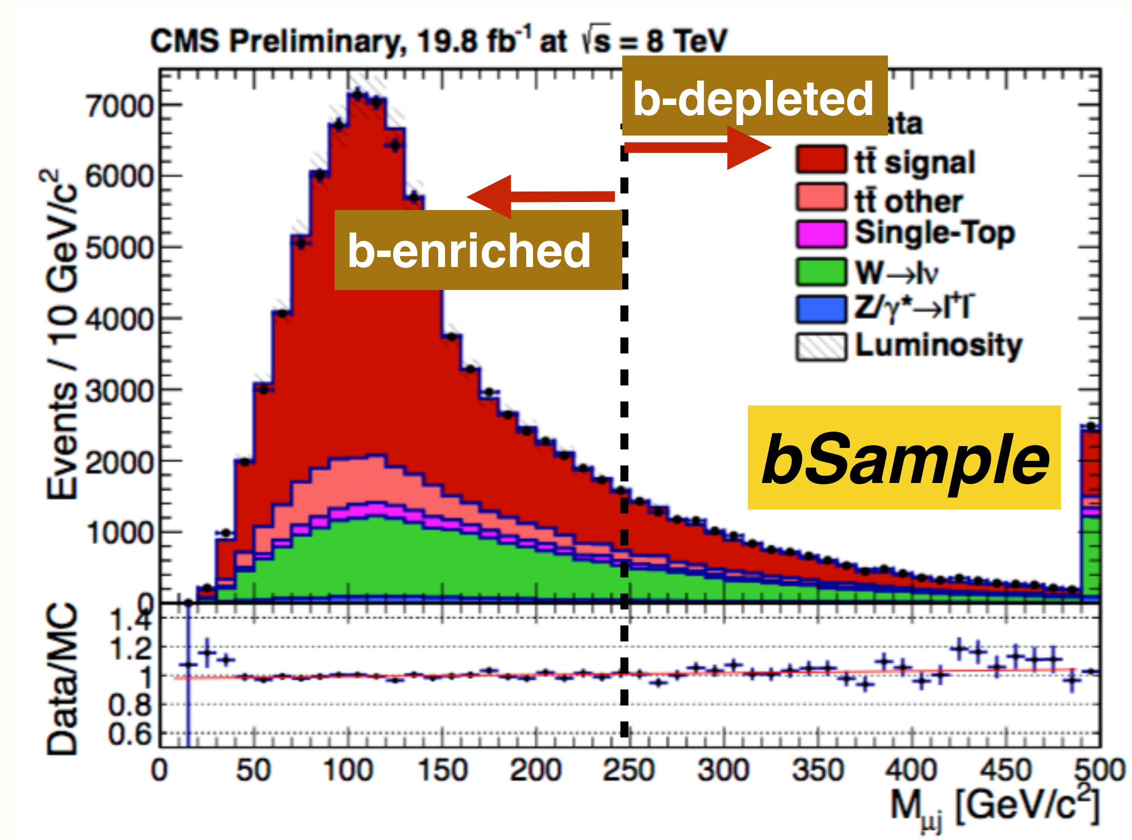
- Fits are done before (or for jets failing b-tagging) and after b-tagging requirement to measure the efficiency

b-tag calibration in ttbar events

- **Kinematic fit methods** exploit kinematic variables from ttbar reconstruction
  - Allows continuous calibration of b-tag weight
  - ATLAS ***kinematic fit*** and CMS ***bSample*** methods use b-enriched region
  - CMS ***KIN*** method is based on template fit to MVA kinematics discriminator

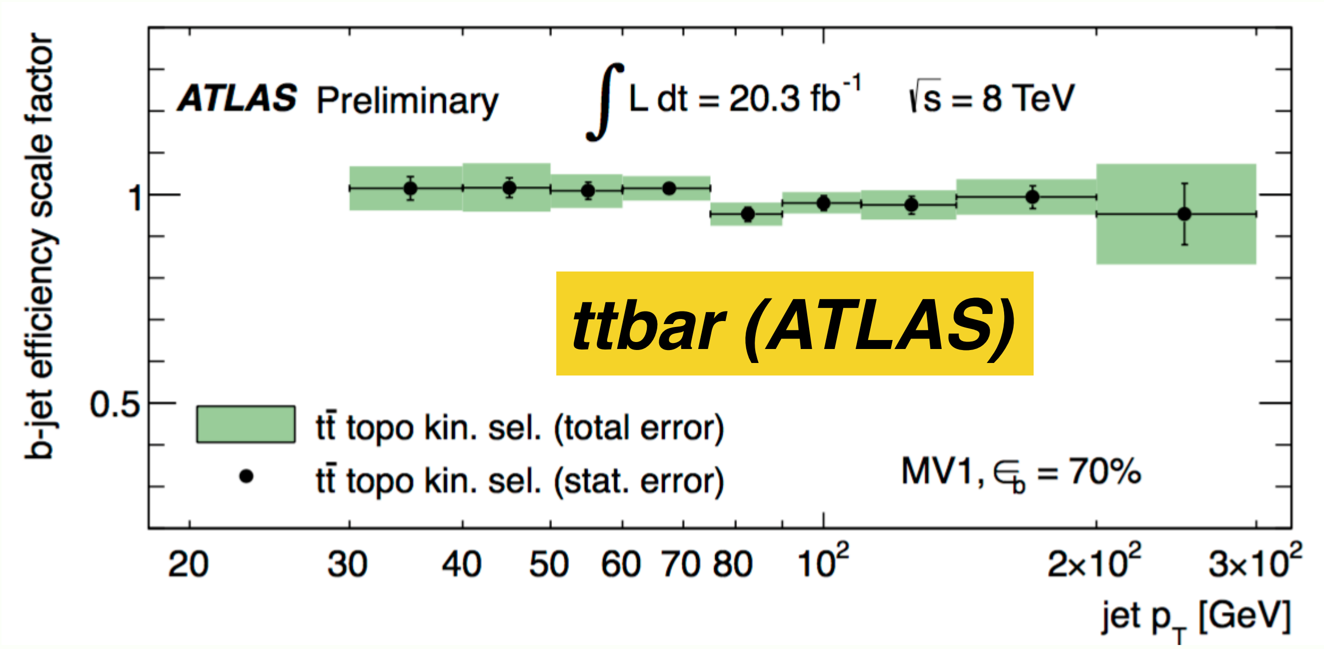




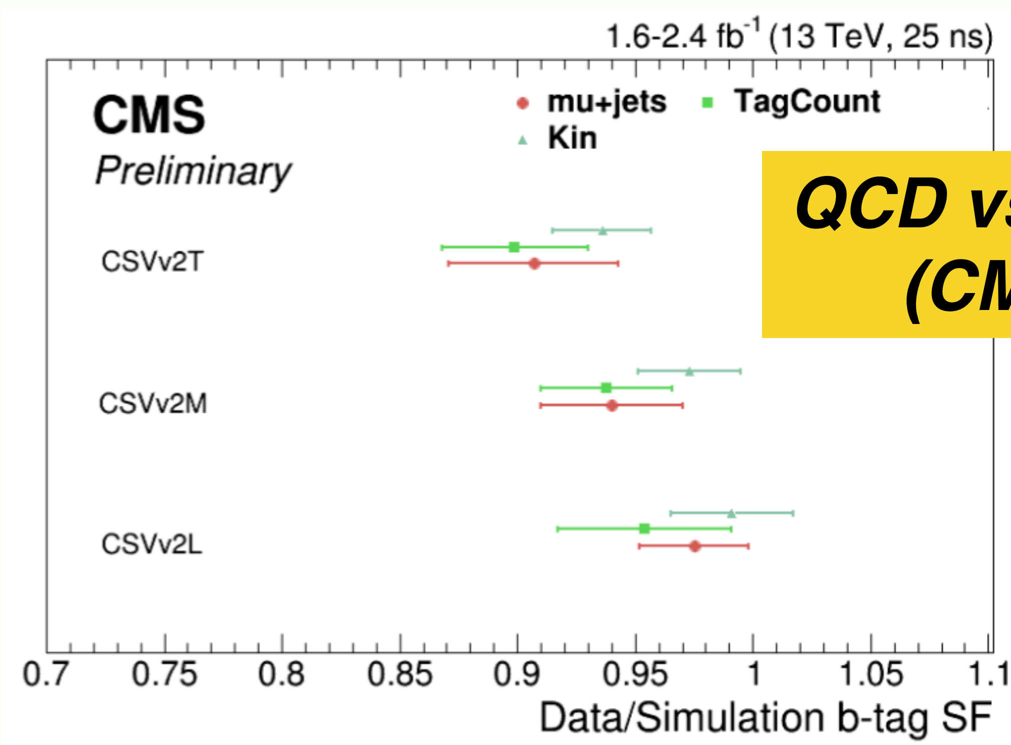


Scale factors for b-tagging

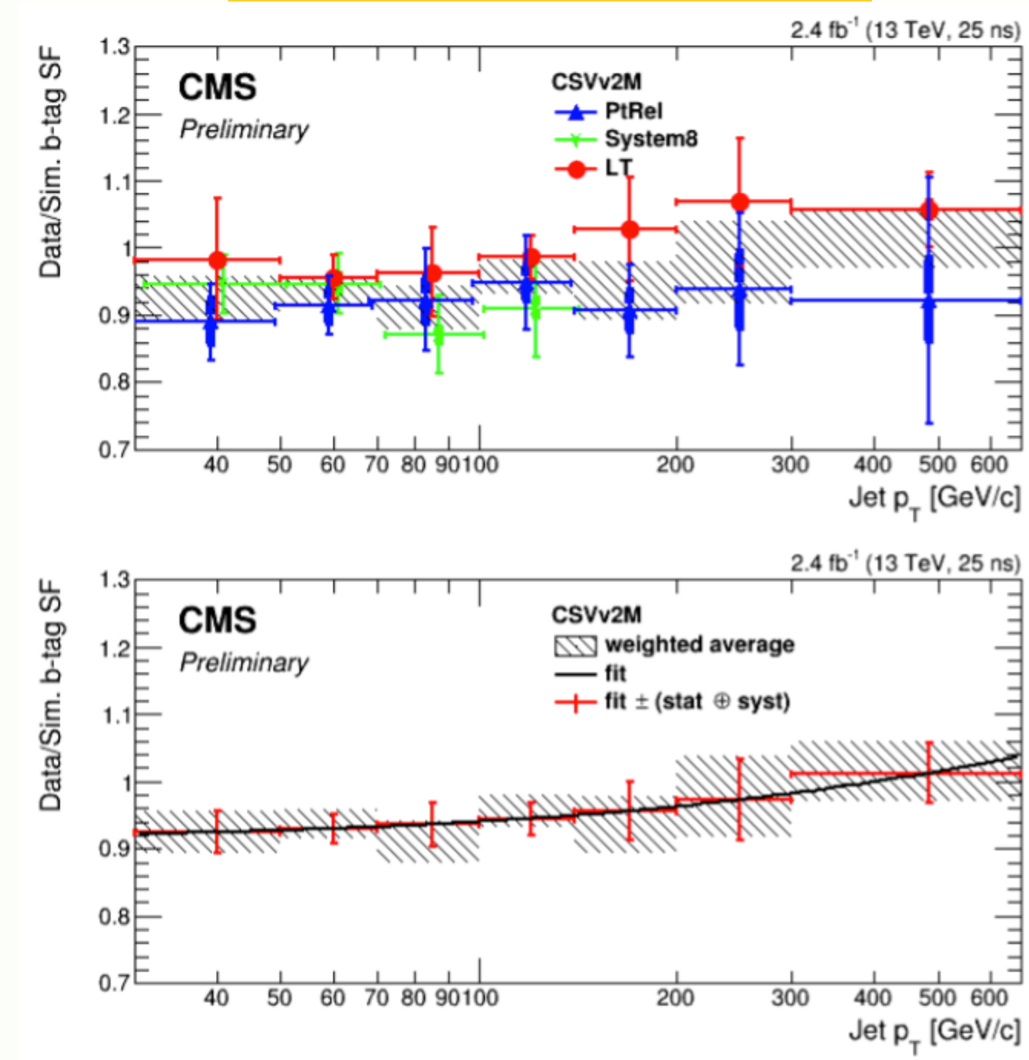
ttbar (ATLAS)



QCD vs ttbar (CMS)



QCD combination (CMS)



Trigger

b-jet trigger in Run 2

- ***L1*** is a ***hardware***-based trigger [output rate ≈**100 kHz**]
- ***HLT*** (L2+EF for ATLAS) is a ***software***-implemented trigger executed on a multi-processor farm [output rate ≈**1 kHz**]
  - Many analyses that rely on b-jet identification (VBF H(bb), Z(νν)H(bb), HH(4b), etc.) ***suffer from very high trigger rates*** due to QCD multi-jet production
- ***Implement b-tagging selection at trigger level*** to significantly reduce the rate
- b-jet triggers already extensively used during Run 1 with several important upgrades for Run 2

New Fast TracKer hardware-based (in 2016) + HLT ATLAS EXPERIMENT

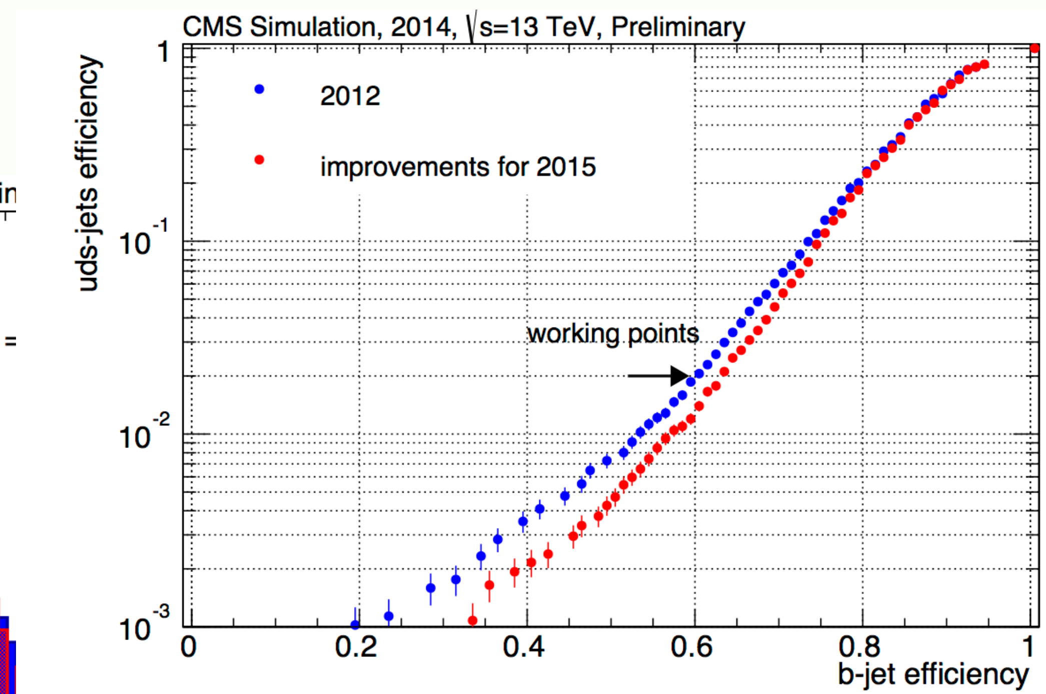
HLT-based trigger CMS

b-tagging sequence at HLT in CMS

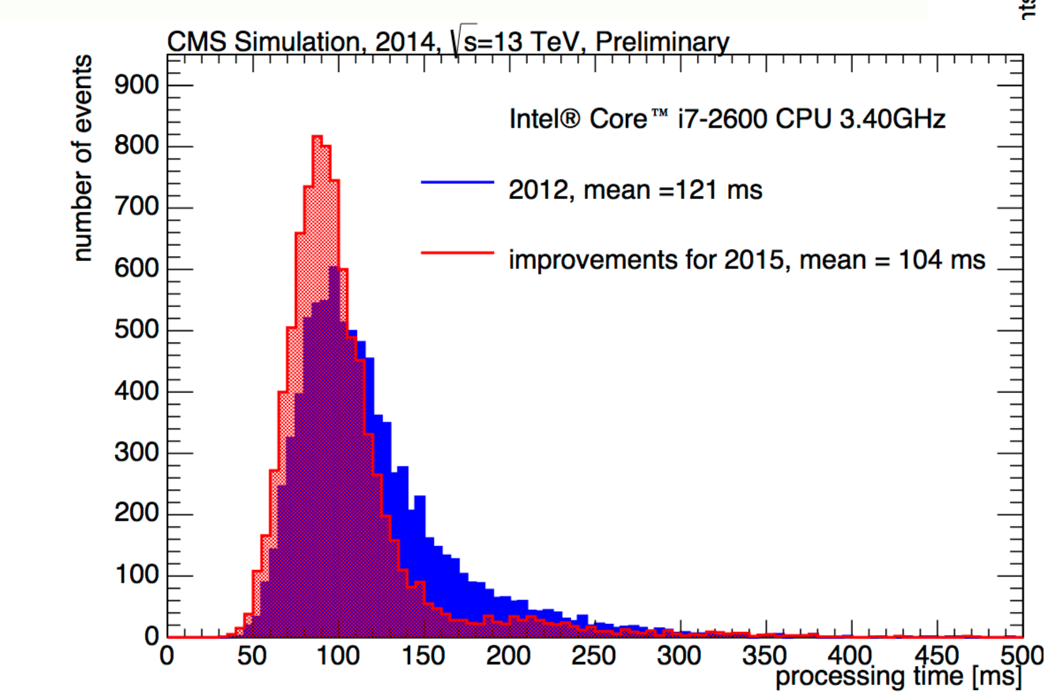
- ***Regional*** reconstruction of **pixel clusters** compatible with L1 calo jets
- Fast Primary Vertex (FastPV) reconstruction using only pixel information [$\sigma_z \approx 2$ mm]
- ***Regional*** **pixel track** reconstruction
- **Primary vertex** from pixel tracks [$\sigma \approx 100$ μm]
- Pixel+Strips **full track** reconstruction using ***iterative tracking*** [$\sigma \approx 20$-30 μm]
- Apply CSVv2 ***b-tagging*** algorithm

Also: L1 stage-2 trigger added in 2016 (topological selection at L1)

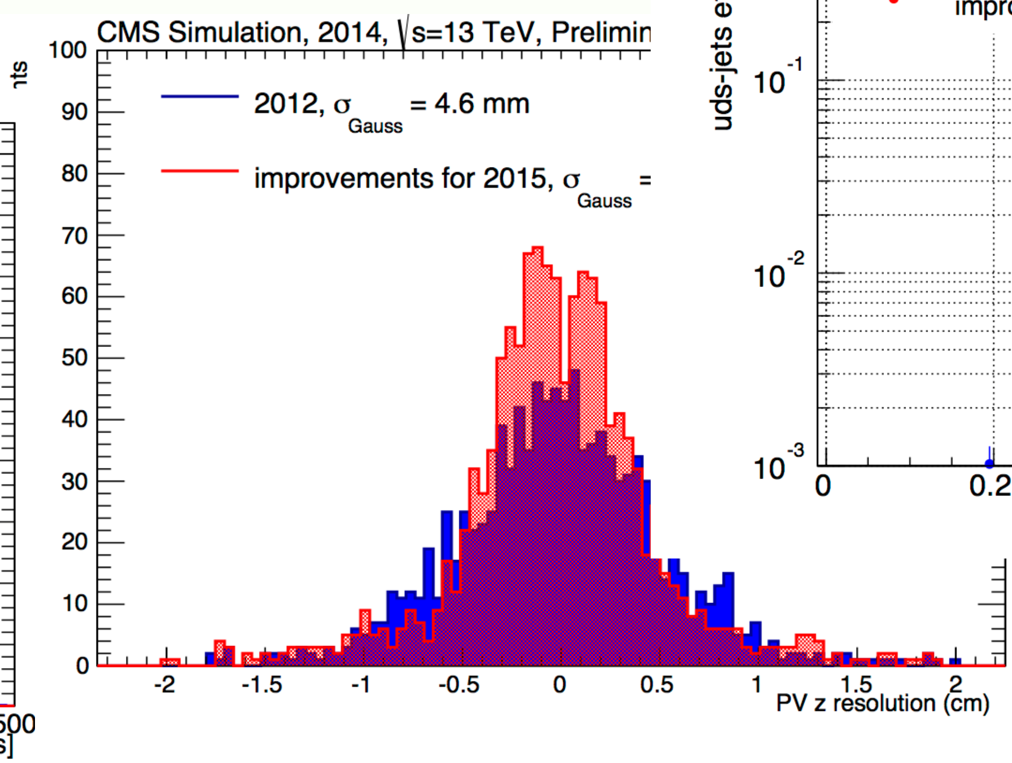
b-tagging performance at HLT



Timing performance for Z(vv)H(bb) trigger path



FastPV resolution

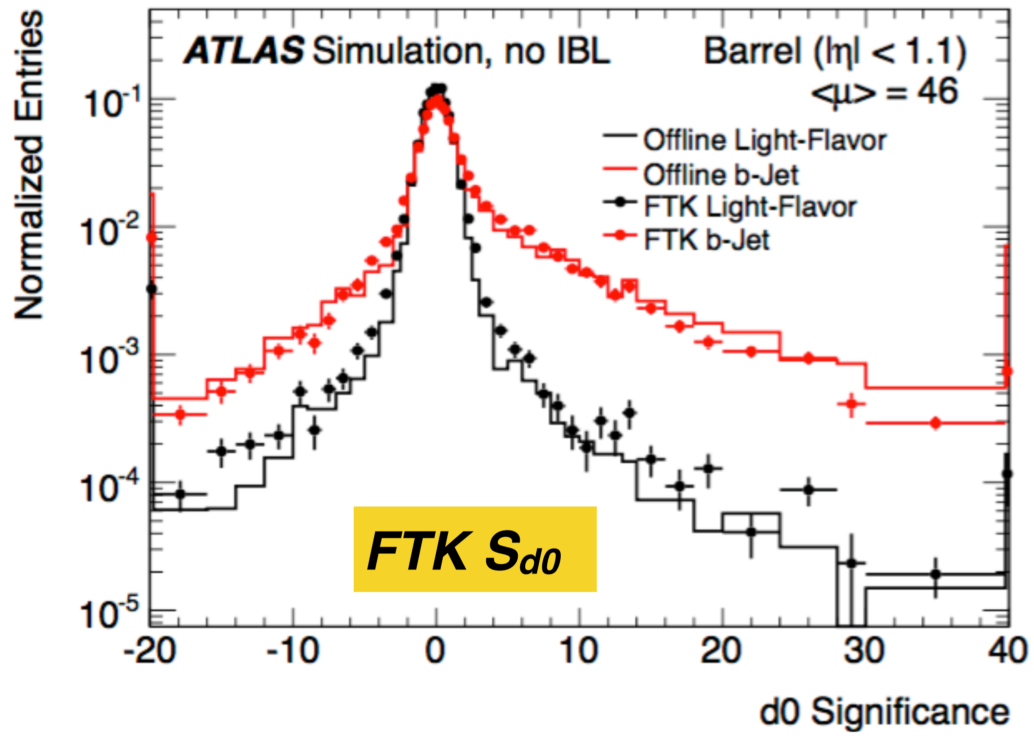


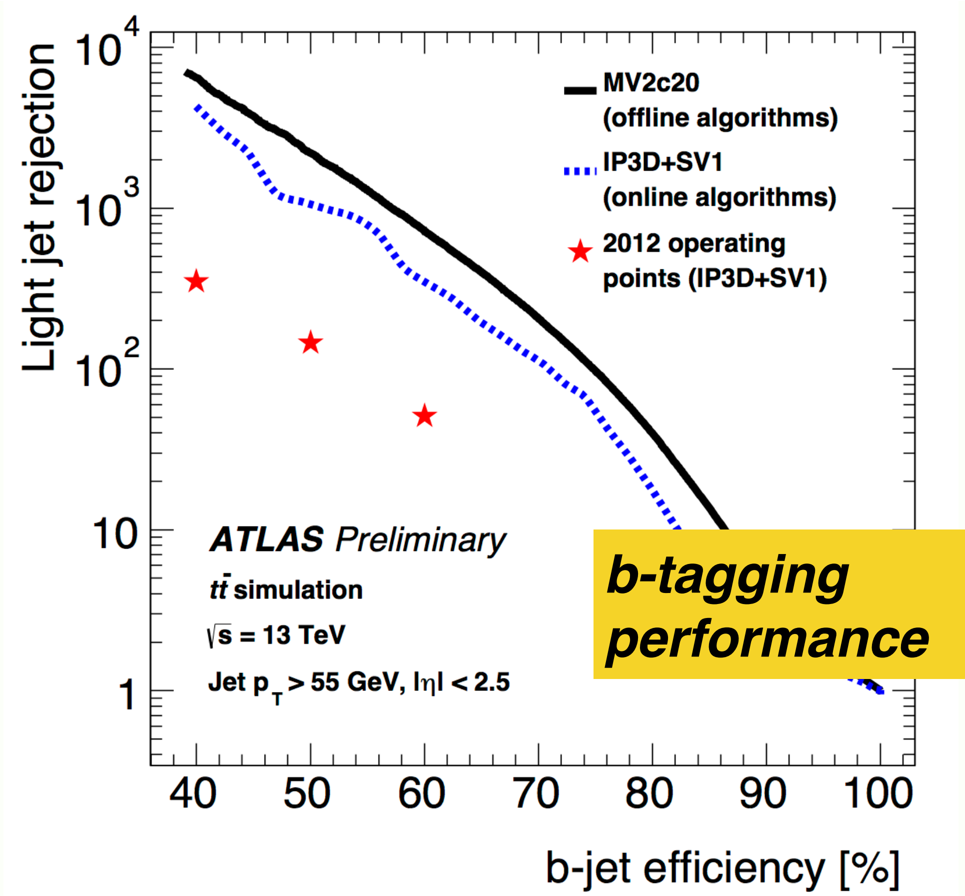
Trigger updates in ATLAS for Run 2

- ***L1 Topological triggers (L1Topo)***
  - **Hardware-based**
  - Real-time event selection based on kinematic properties of trigger objects
  - Muon-jet association at L1

- ***Fast TracKer (FTK) - Spring 2016***
  - **Hardware-based** in-between L1 and L2
  - Use Pixel, SCT and IBL data
  - Reconstruction of charged track candidates (p_T > 1 GeV) with pattern recognition and primary vertex [$\sigma_z \approx 56$ μm, $\sigma \approx 20$ μm]
  - **Tracking information for the whole detector without HLT processing**
  - Track-jets, track-based isolation, etc. after L1

ATLAS-TDR-021 FTKPublicResults





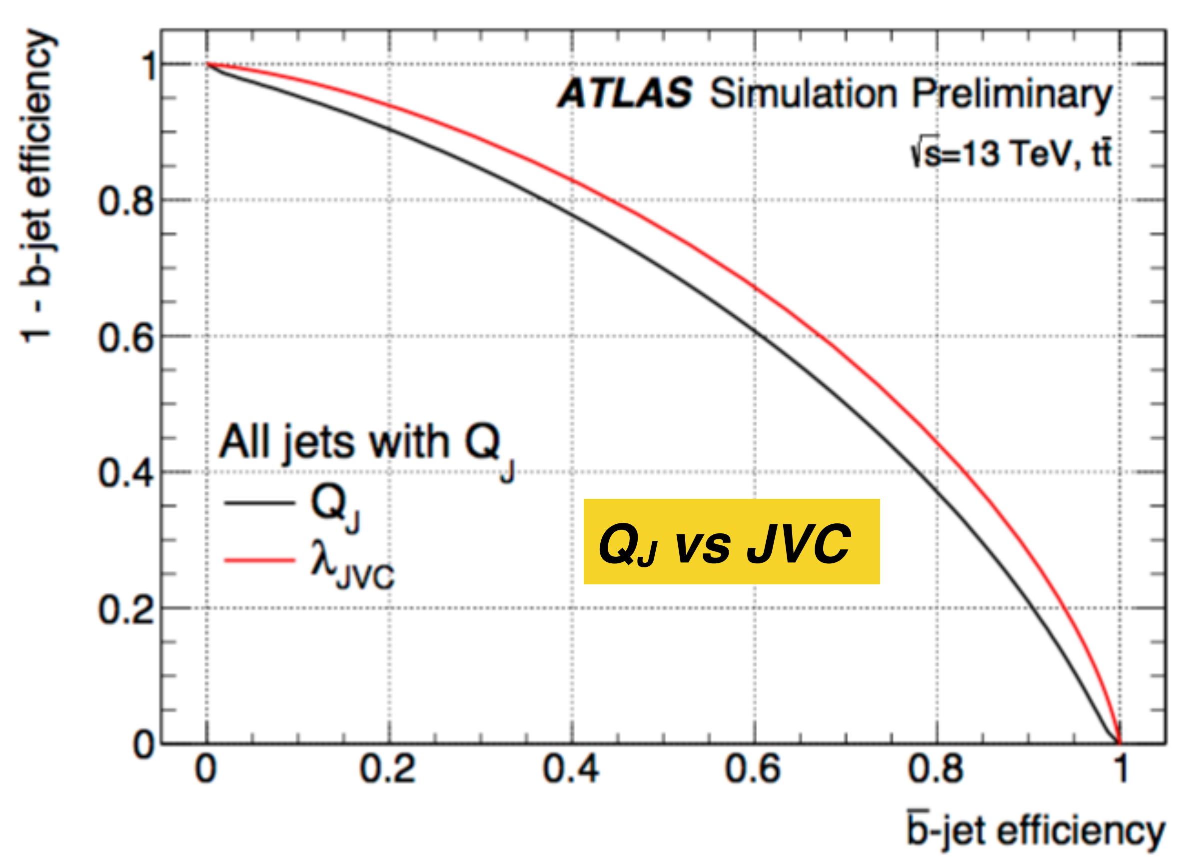
New developments

Tagging of b- and anti-b jets

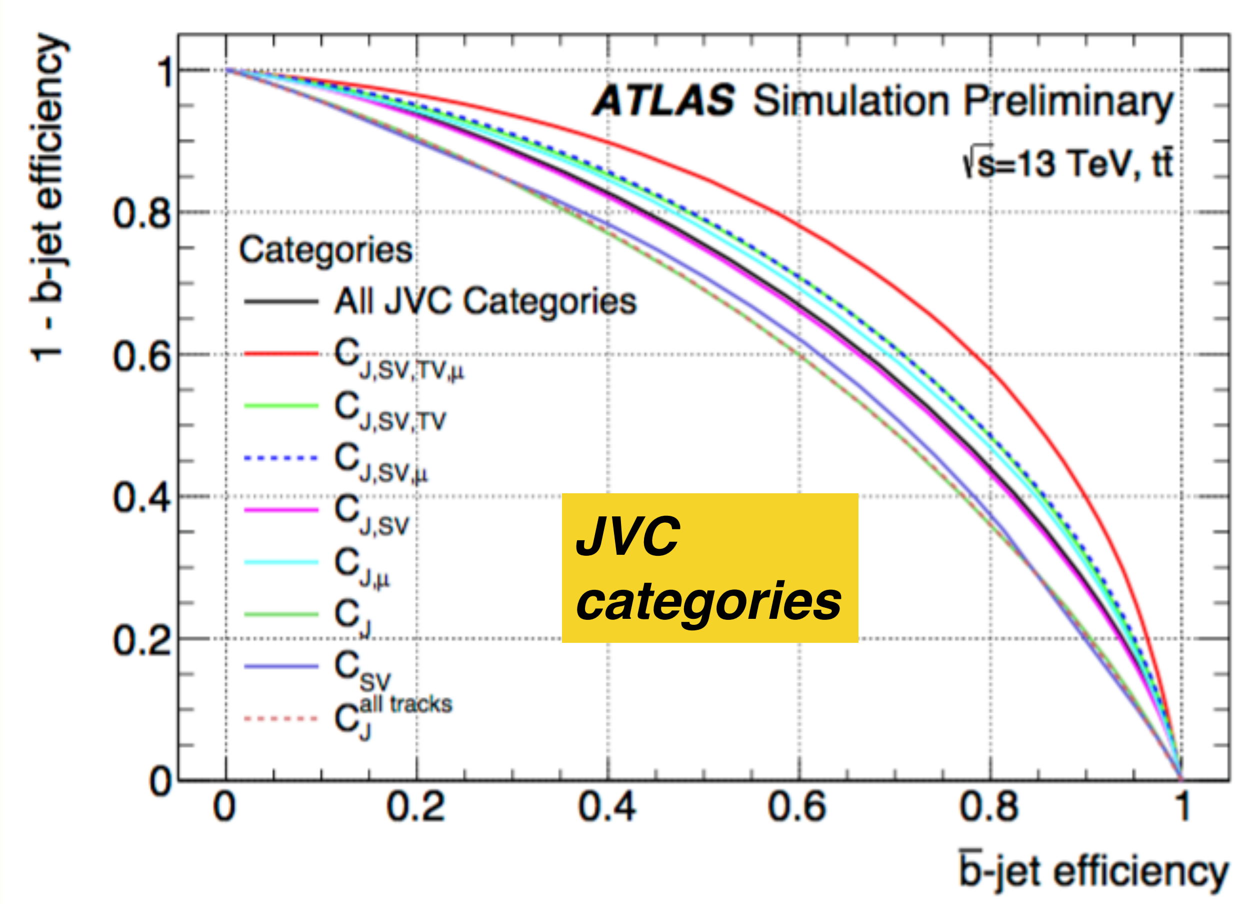
- b-quark hadronizes before its charge could be measured

- **Previous method Q_J** to tag the b-charge based on the **sum of jet track charges weighted by p_T**

- Useful to reduce combinatorial background



$$Q_{\text{jet}} = \frac{\sum_{i \in \text{Trk}} q_i \cdot {p_T}_i^{\kappa}}{\sum_{j \in \text{Trk}} {p_T}_j^{\kappa}}$$

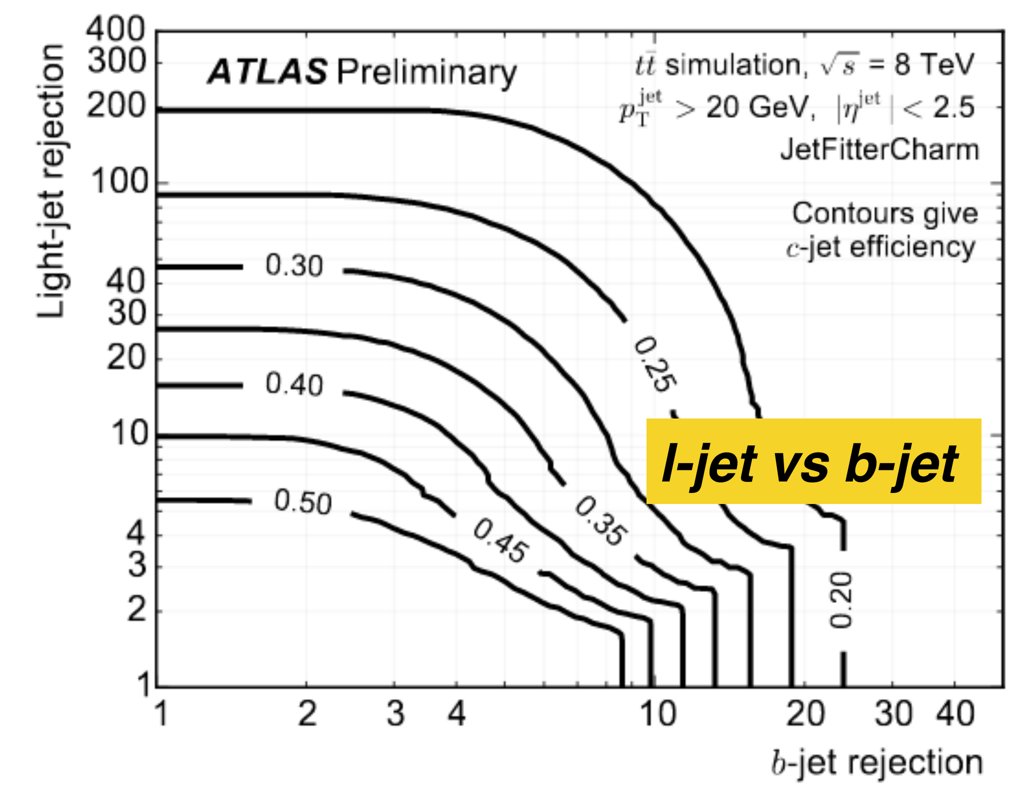


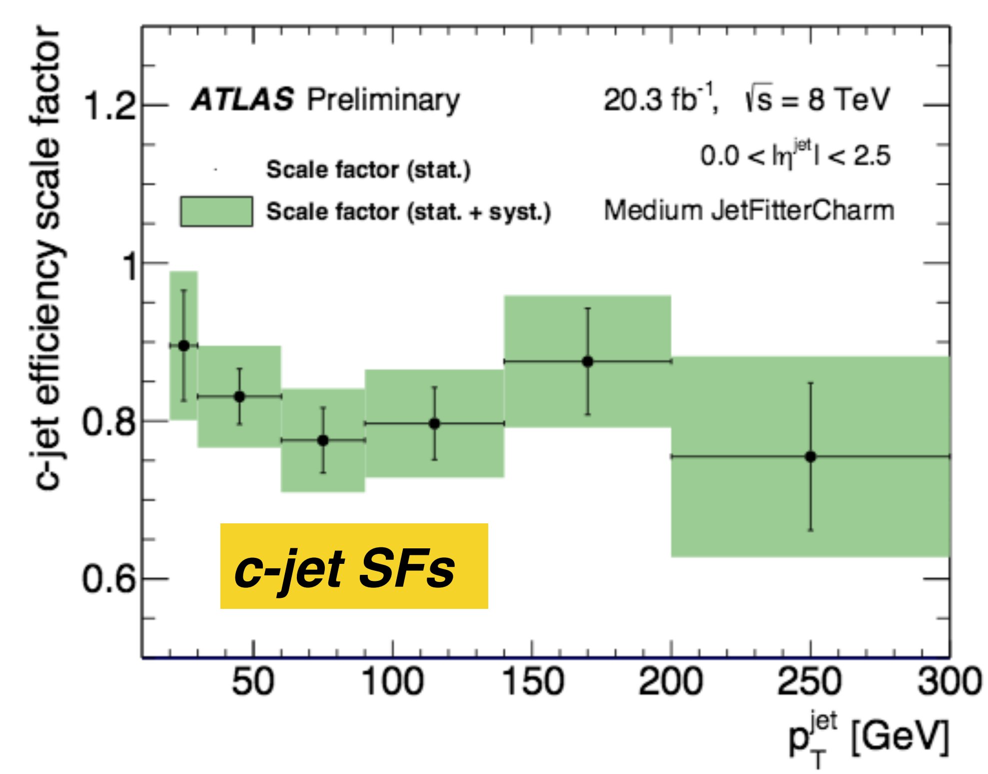
- The **new method *Jet Vertex Charge (JVC)* MVA-based** to add displaced vertices information to distinguish between b and anti-b jets
  - Several jet charge categories based on all associated, all selected, SV, TV and muon tracks

ATL-PHYS-PUB-2015-040

c-tagger

- A broad range of analyses benefit from **c-jet identification** (SUSY, FCNC, etc.)
- Discrimination of **charm** from light and b flavours is **challenging**:
  - Smaller decay vertex displacement for c-hadrons relative to b-hadrons, smaller impact parameters
  - b-hadrons can decay via c-hadrons
- ATLAS developed ***JetFitterCharm tagger***
  - Improved version of ***JetFitterCombNN*** trained to select charm with ***an addition of***:
    - Transverse displacement of secondary and tertiary vertices
    - Min and max track rapidity along jet axis
  - ***Calibration***
    - **b-jets**: Combinatorial Likelihood in ttbar
    - **c-jets**: multijet D* mesons
    - **l-jets**: negative tag in QCD multijet



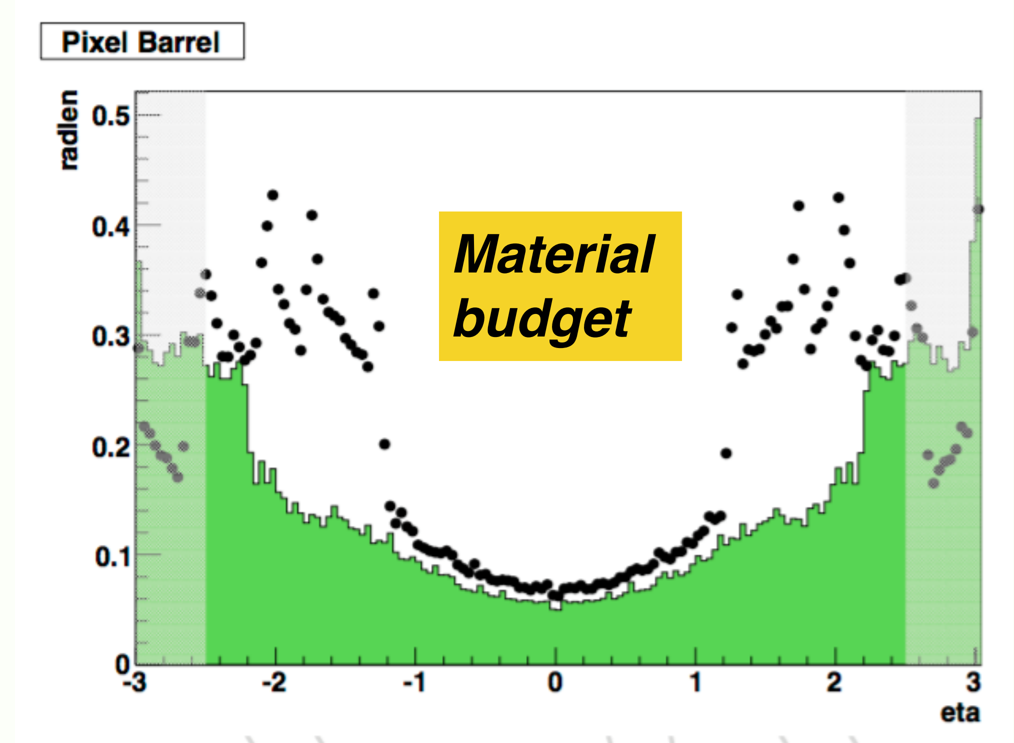


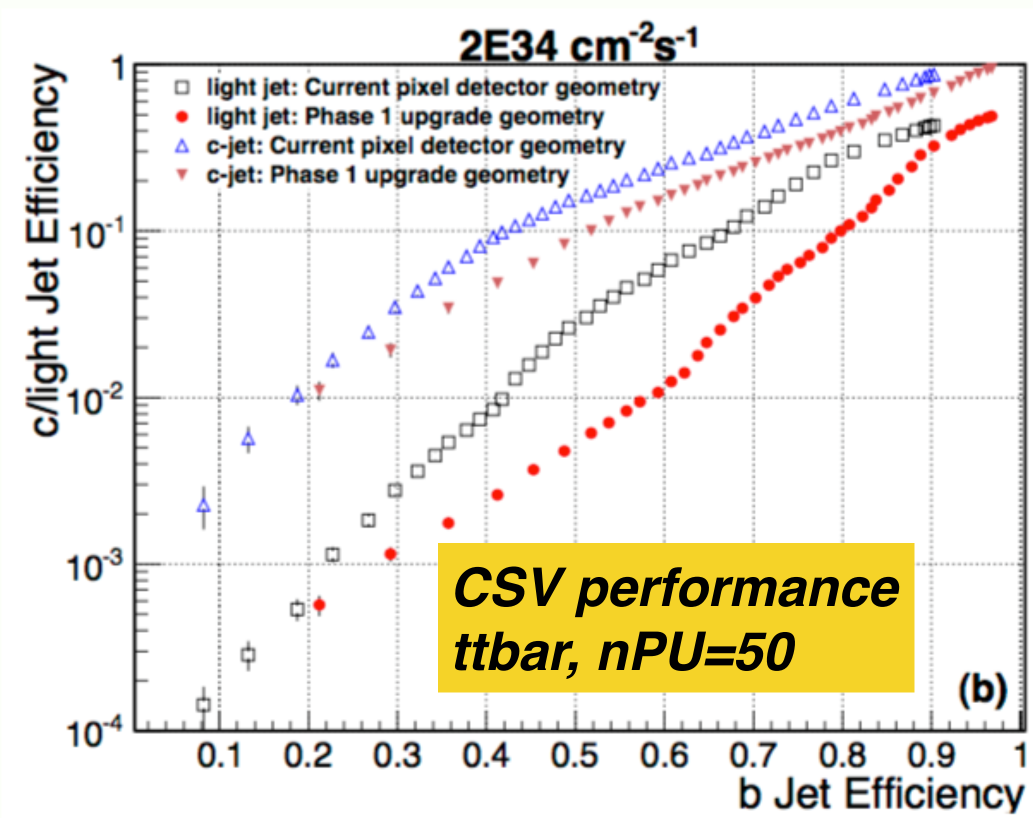
ATL-PHYS-PUB-2015-001

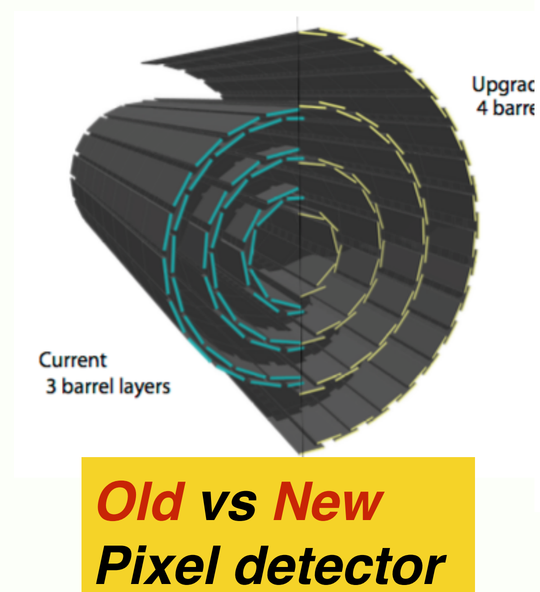
Future prospects

CMS Phase I Pixel upgrade

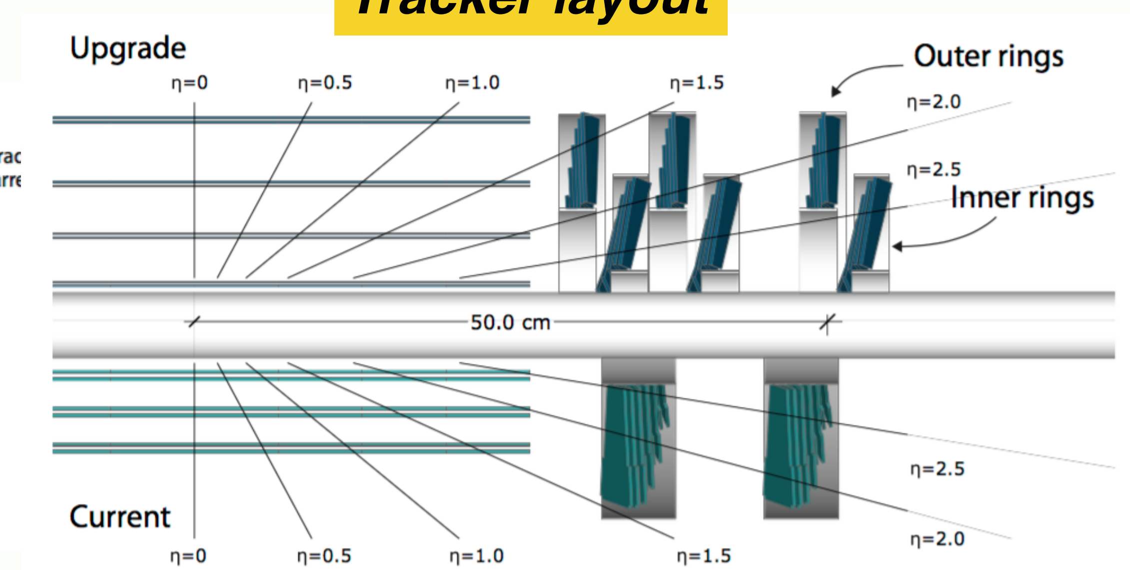
- The **present** pixel detector was designed for a luminosity of **10^{34}** cm^{-2} s^{-1} and pileup of 25 @25ns
- **After LS2**, luminosity to reach **$2x10^{34}$** and will result in the *large data losses in ROCs*
- The ***new beam pipe*** [R_{in} ≈ 22.5 mm] **installed in LS1**, ***full replacement of the pixel detector*** **by the end of** 2016
  - **Significant improvement in b-tagging** due to extra layers, finer granularity, decrease in the amount of material







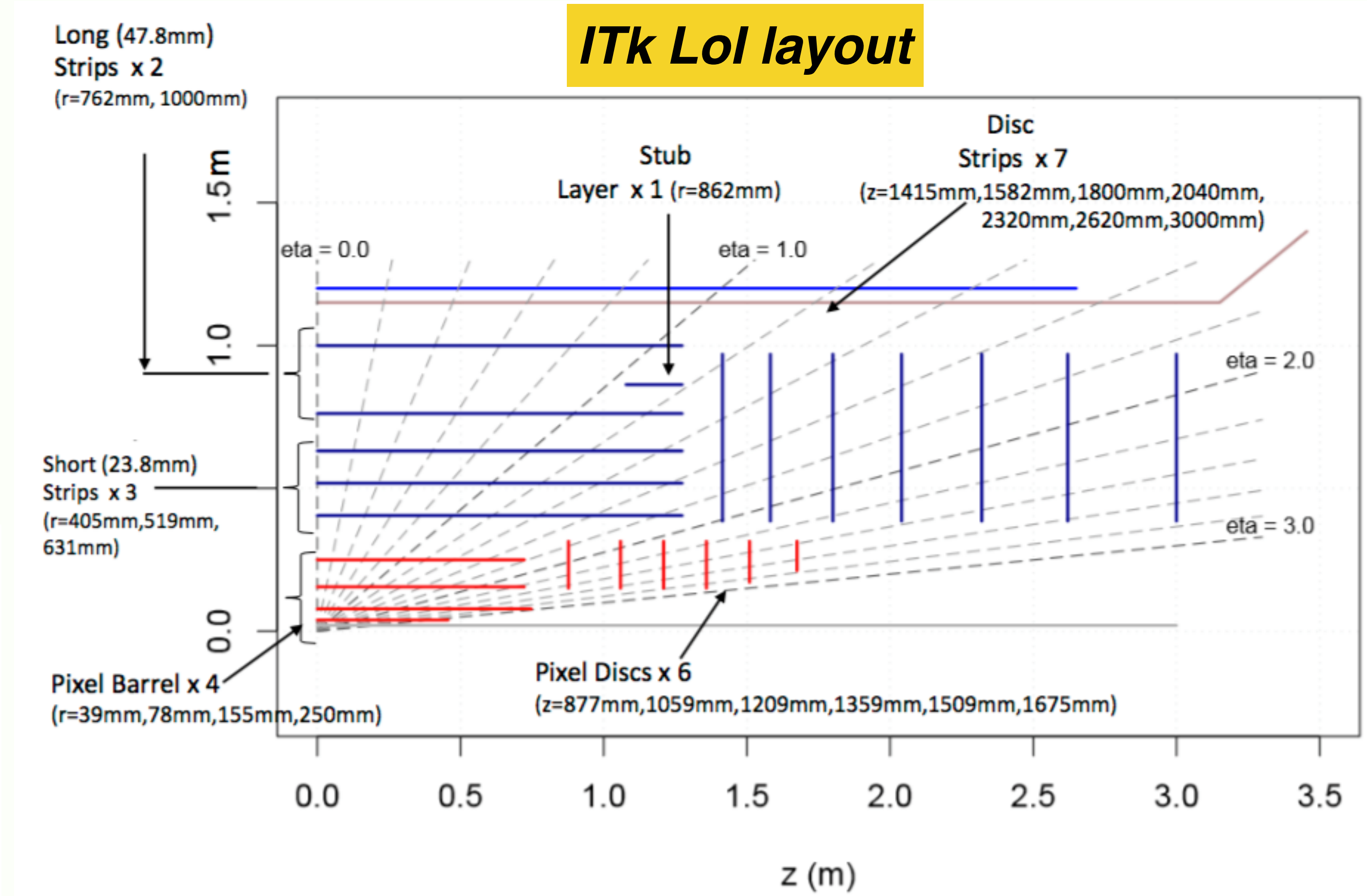
Tracker layout

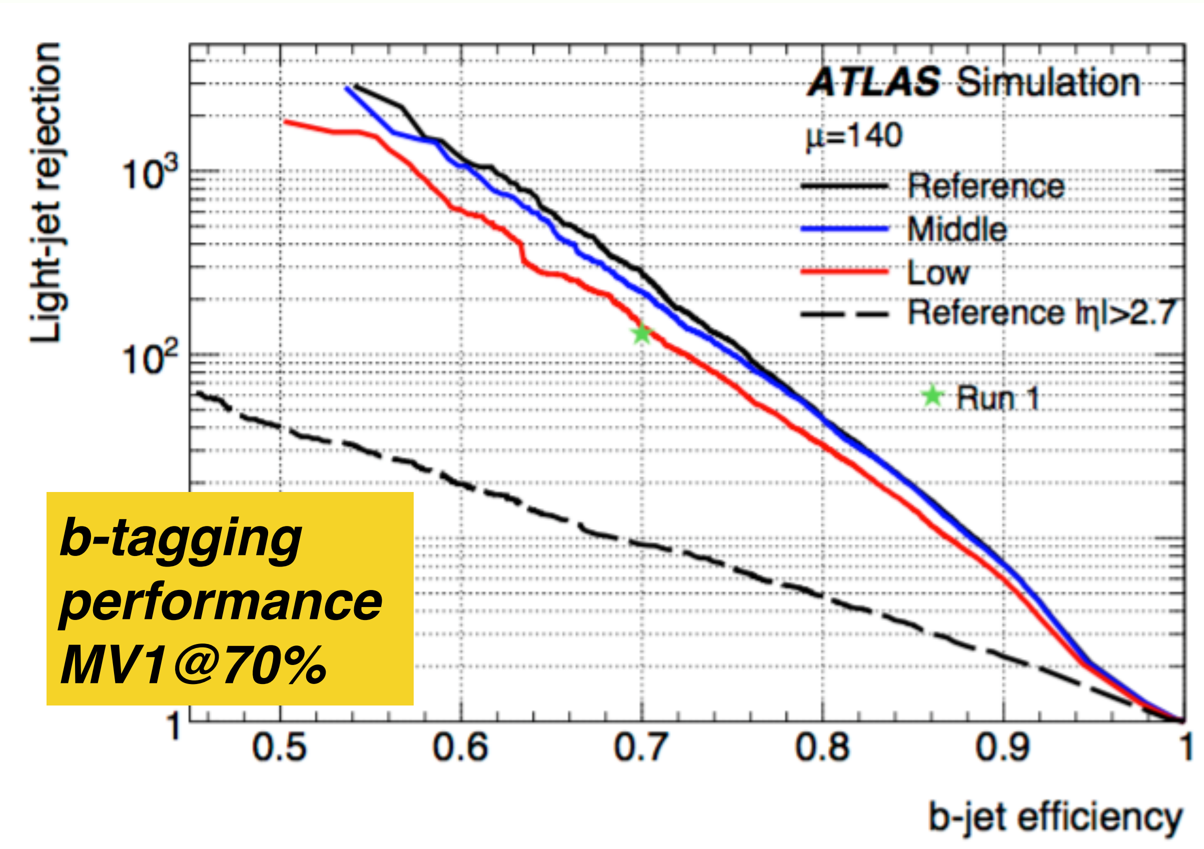


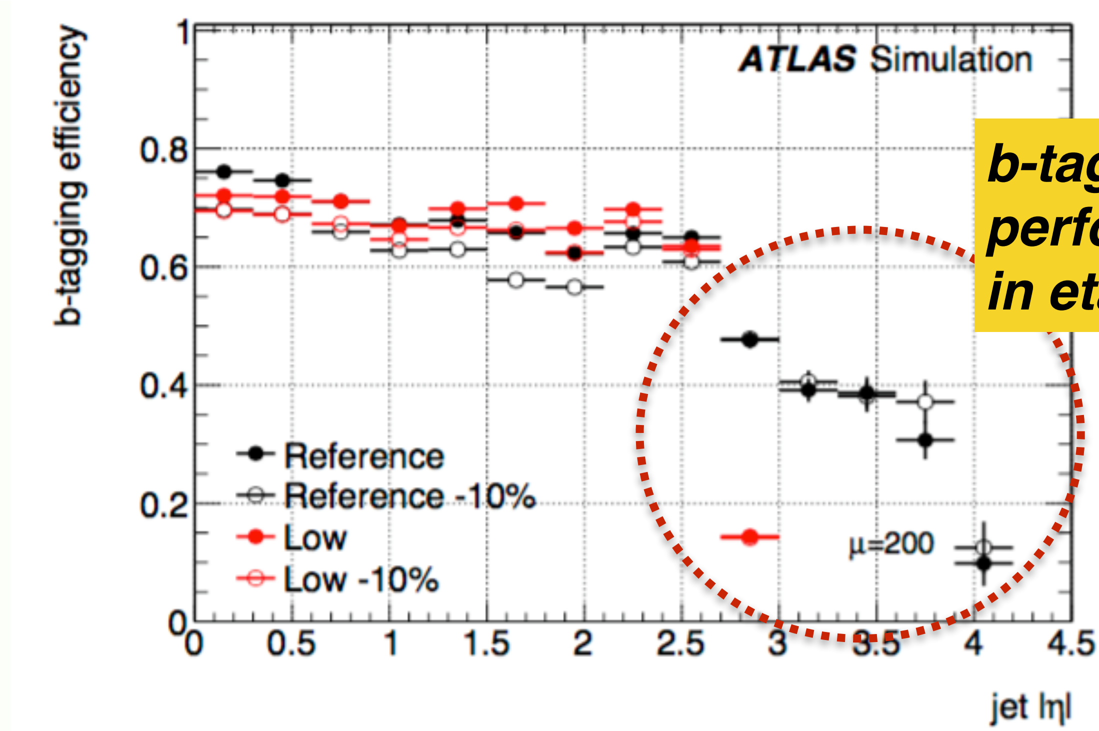
CMS-TDR-011
CERN-LHCC-2011-006

ATLAS Phase II Inner Tracker upgrade

- Several scoping scenarios are planned
  - **New all-silicon tracker (ITk) to replace ID**



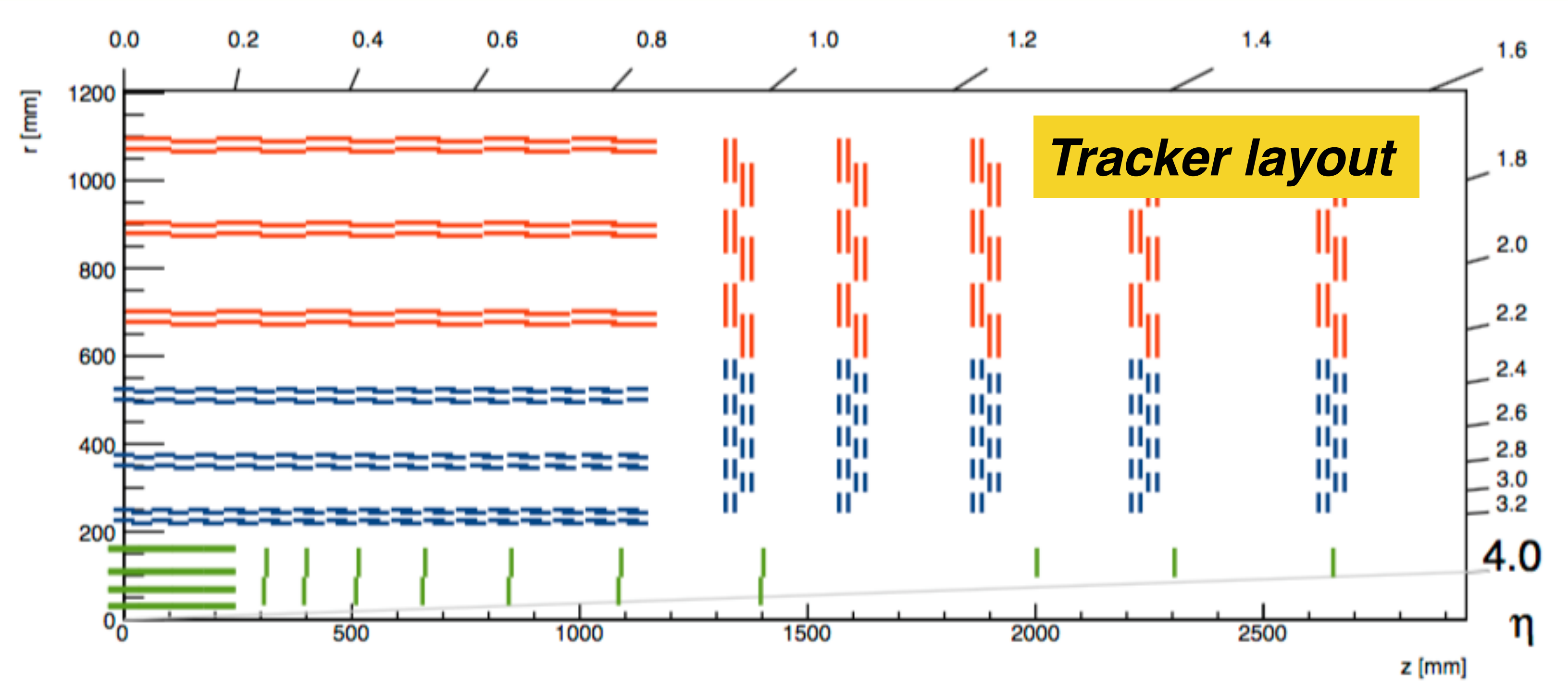




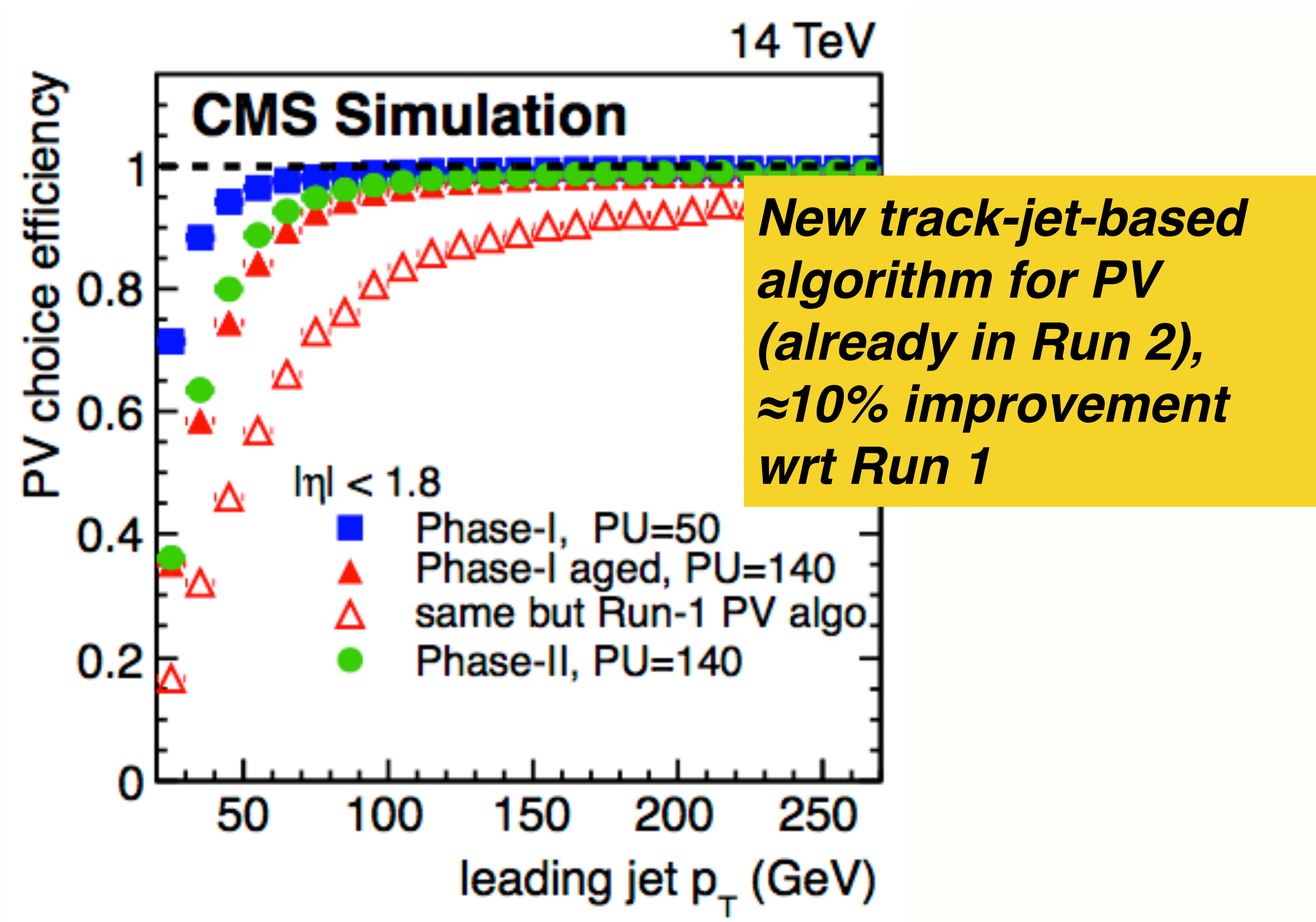
b-tagging performance in eta

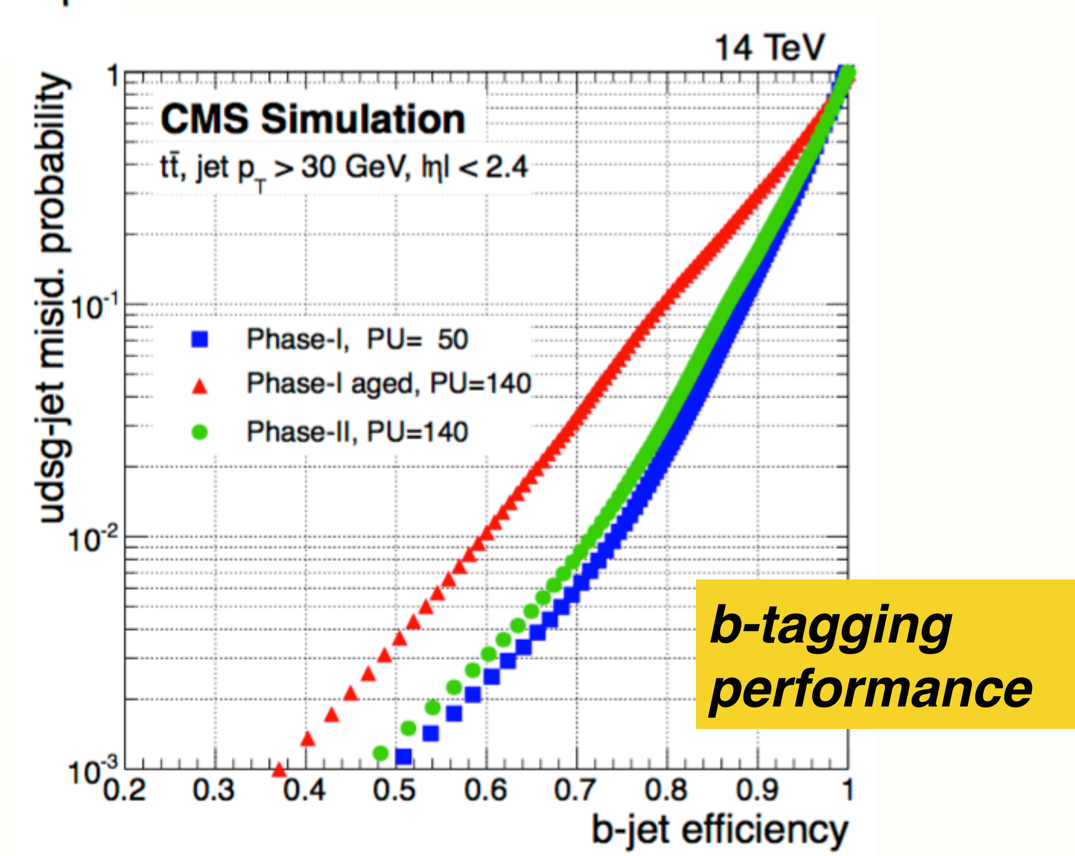
CERN-LHCC-2015-020

CMS Phase II Inner Tracker upgrade



- **Tracker to be completely replaced**
  - Finer granularity [≈4x]
  - L1 track trigger
  - Radiation hardness
  - b-tagging up to |η| = 3





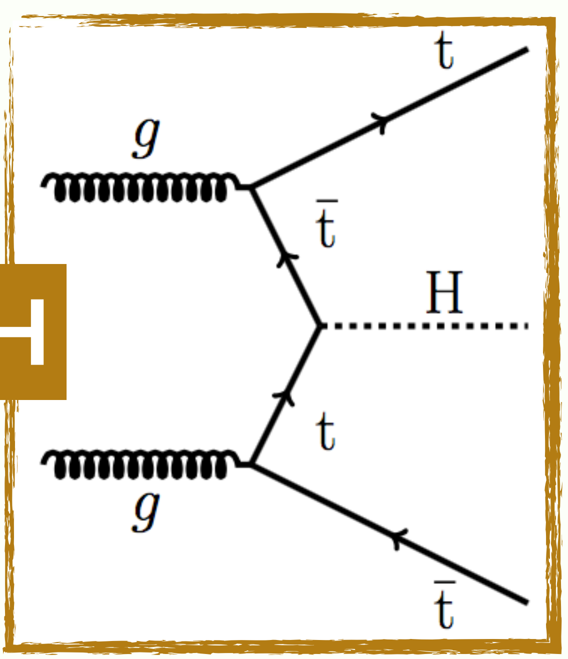
CERN-LHCC-2015-010
CERN-LHCC-2015-019

Higgs associated production with top quarks

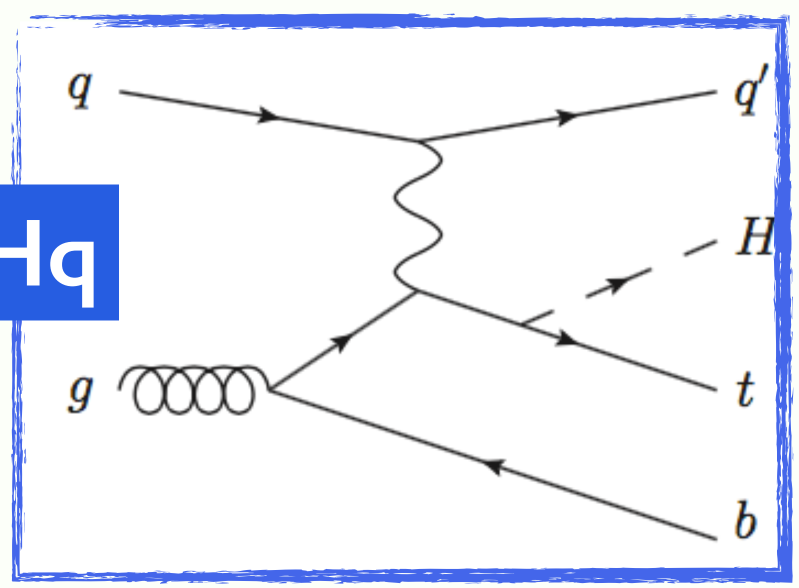
Motivation

- In the SM, a Higgs boson is expected to have a strong coupling to a top quark ($y_t \approx 1$)
- Production of Higgs in association with top quark pair provides a **direct measurement of the top quark Yukawa coupling**
- Associated production of Higgs with a single top quark allows to **measure the sign of the top quark Yukawa coupling**
- **Probe new physics** in the top quark-Higgs sector

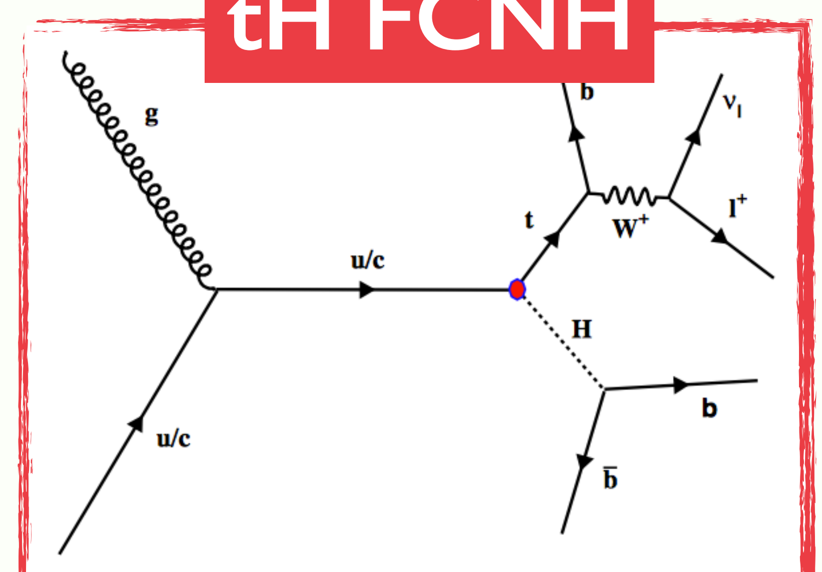
ttH



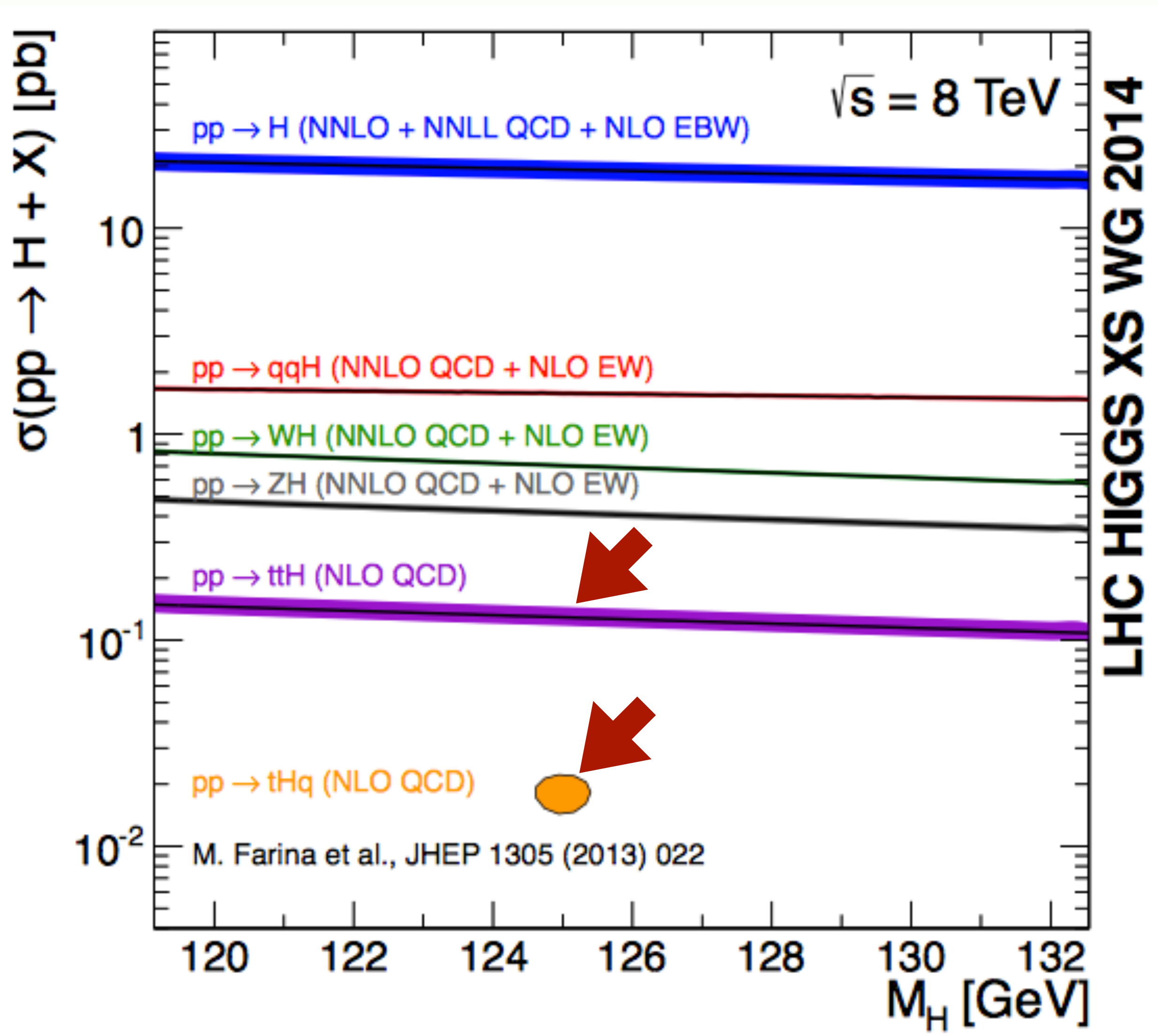
tHq



tH FCNH



Higgs production and decay

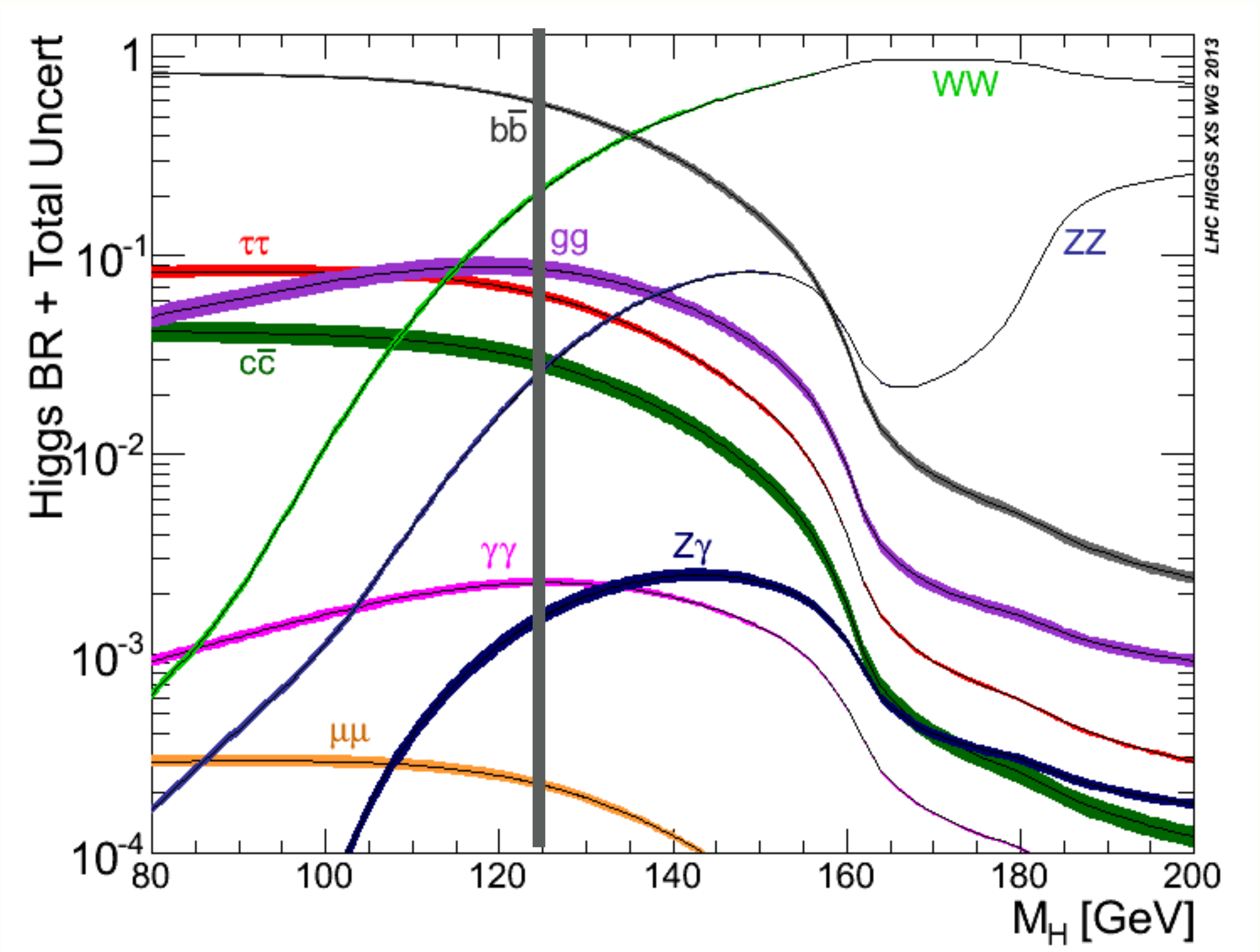


$\sigma(\mathbf{ttH})$ = **129** fb

$\sigma(\mathbf{tHq})$ = **18** fb

LHCHXSWG

$m_H = 125$ GeV



- H→bb channel is dominant [Br ≈ **58**%]
  but overwhelming ttbar background
- H→γγ channel is clean
  but suffers from small Br ≈ 0.2%

ttH

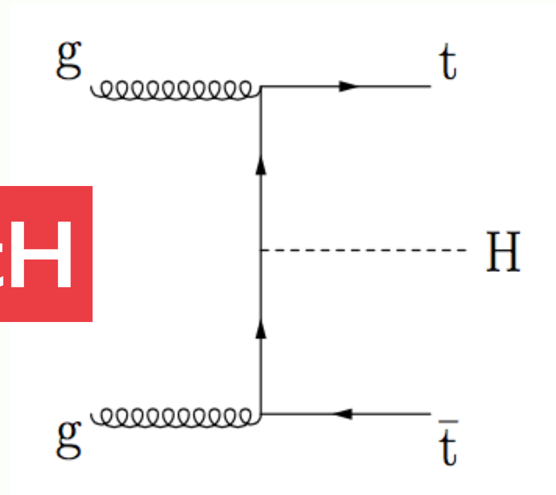
Search for ttH, H→bb with MEM at CMS

Eur. Phys. J. C 75 (2015) 251
CMS, 20 fb^{-1}, 8 TeV

Use MEM to suppress the combinatorial background

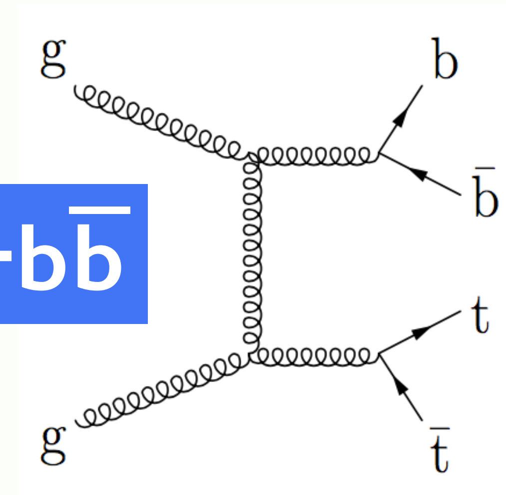
signal hypothesis

ttH



background hypothesis

$t\bar{t}+b\bar{b}$



Event signature:

one (single-lepton=**SL** channel) or two leptons (dilepton=**DL** channel), ≥ 4 jets, ≥ 4 b-jets, missing E_T

$P_{h/l} < 0.5$ $P_{h/l} > 0.5$

Build 2D likelihood ratio:

signal vs background

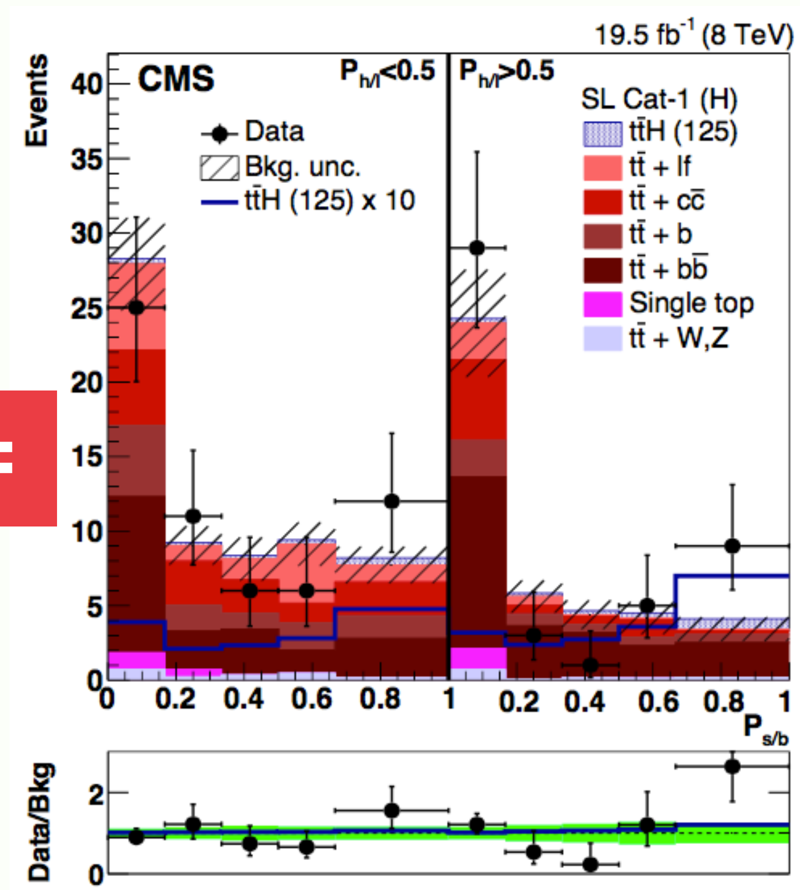
$$P_{s/b} = \frac{w(\vec{y}|t\bar{t}H)}{w(\vec{y}|t\bar{t}H) + k_{s/b} w(\vec{y}|t\bar{t}+b\bar{b})}$$

Heavy vs Light flavour

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

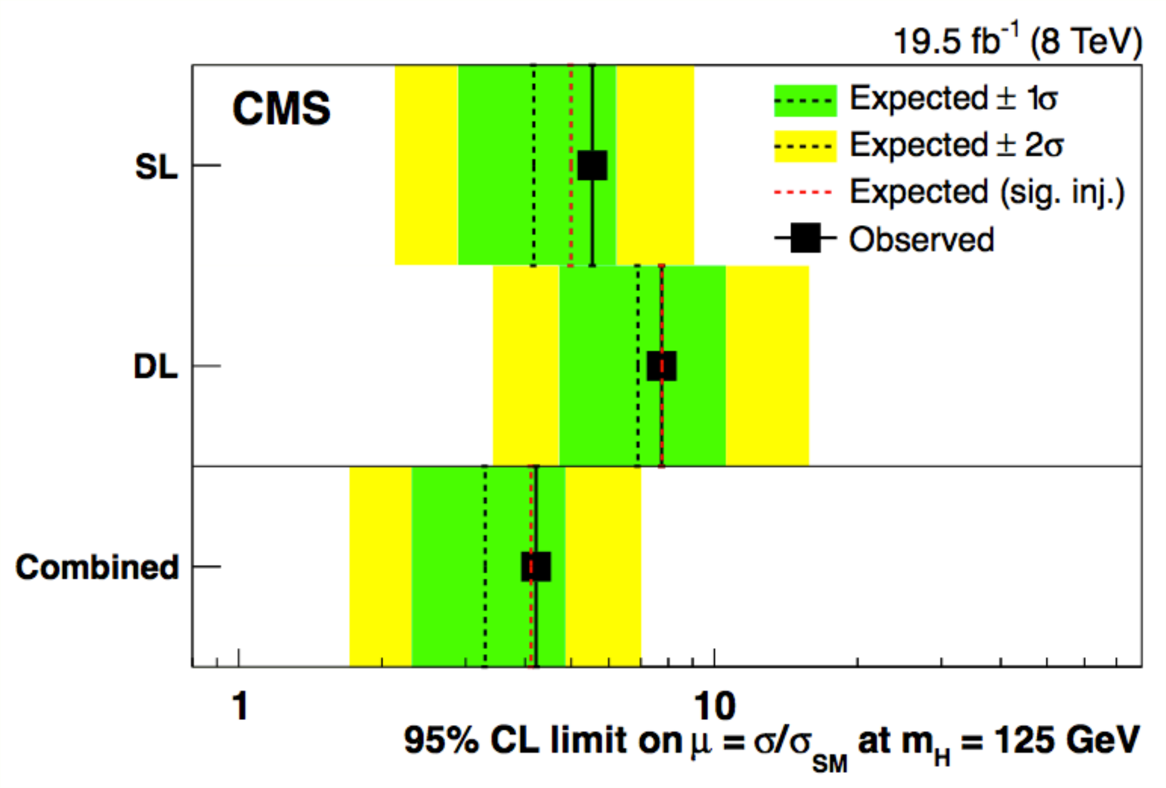
$k_{s/b}$,$k_{h/l}$ - optimization parameters

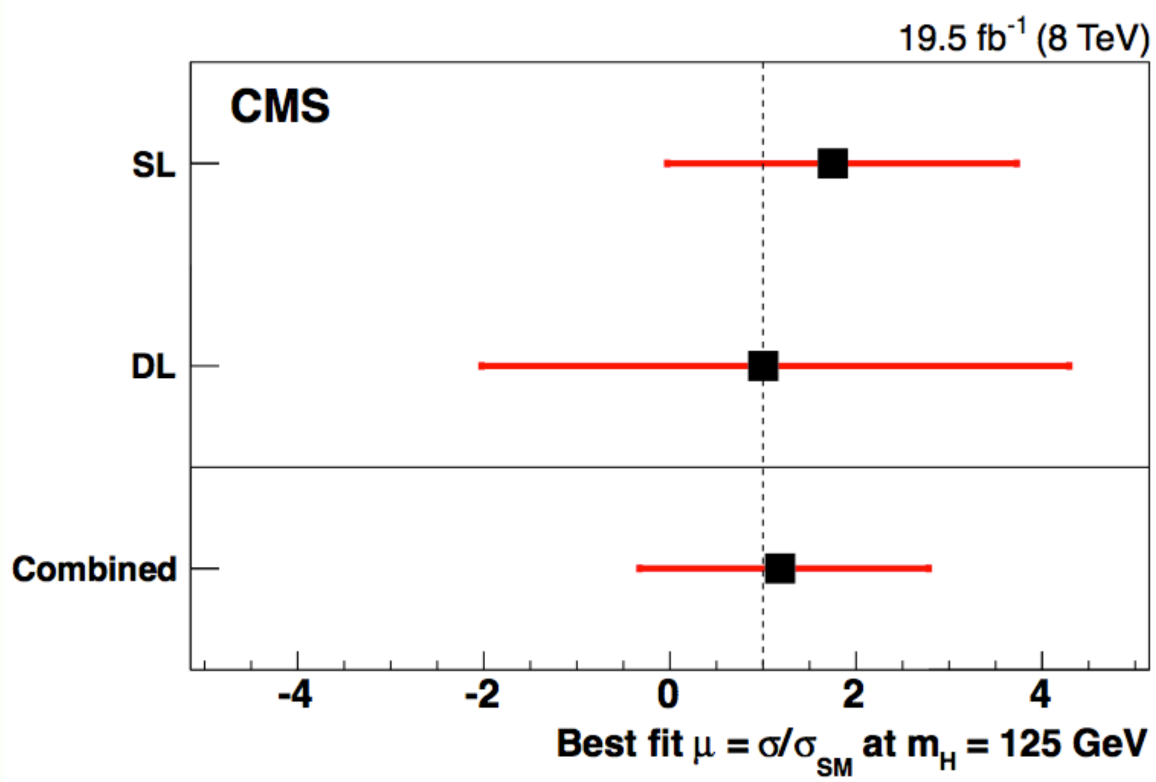
$P_{s/b}$=



Search for ttH, H→bb with MEM at CMS

Eur. Phys. J. C 75 (2015) 251
CMS, 20 fb^{-1}, 8 TeV





Observed (expected) combined limit:

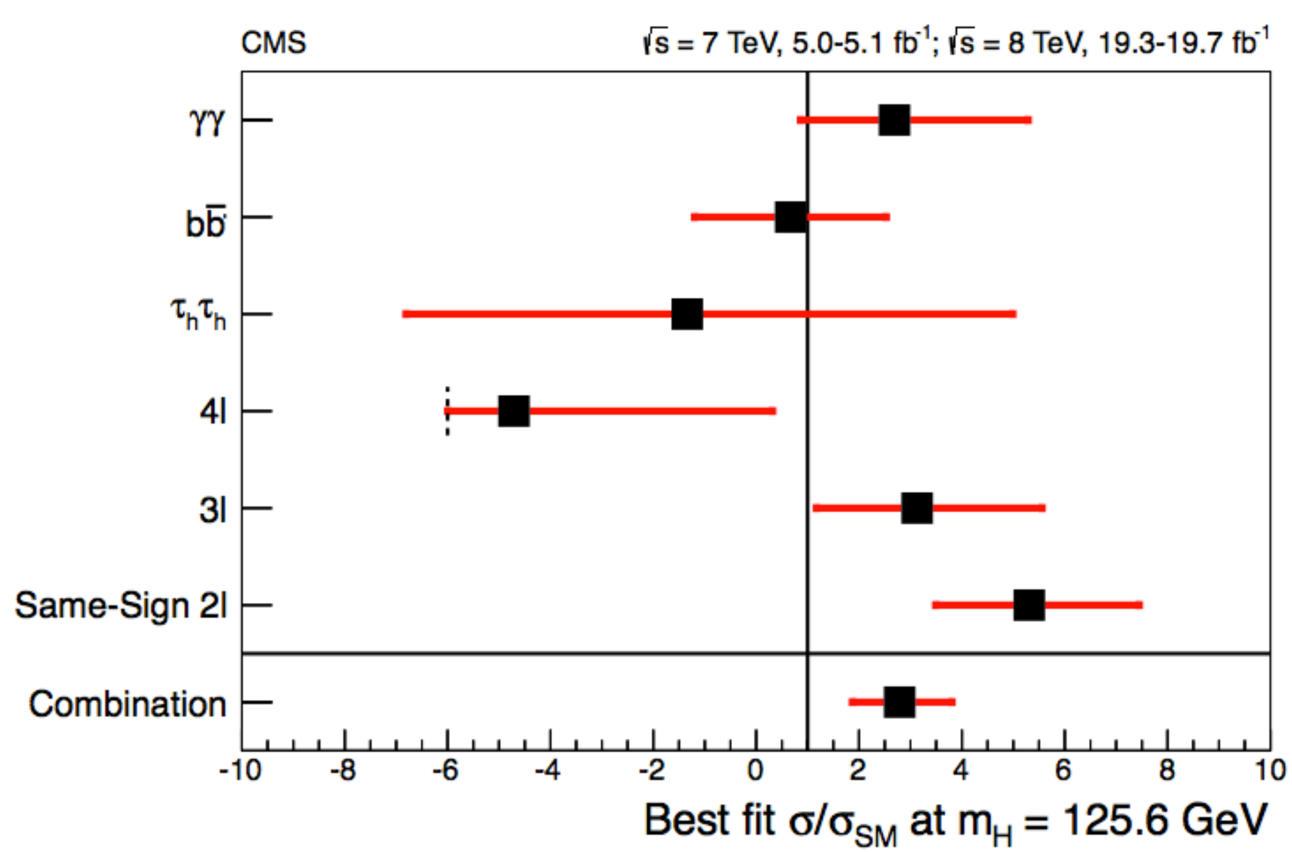
$\mu < 4.2\ (3.3)$

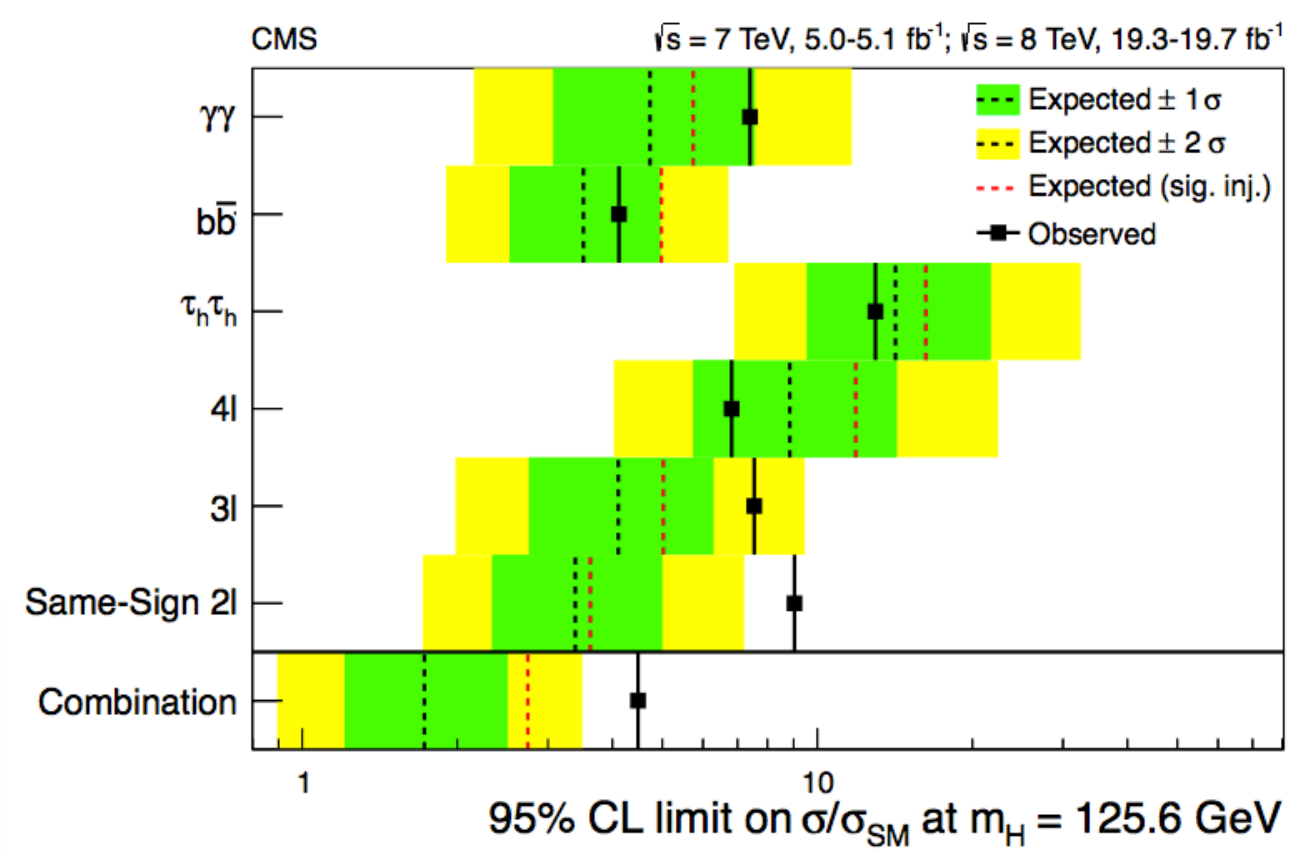
Best fit:

$\mu = 1.2^{+1.6}_{-1.5}$

Search for ttH, H→all channels at CMS

JHEP 1409 (2014) 087
CMS, 5+20 fb^{-1}, 7+8 TeV





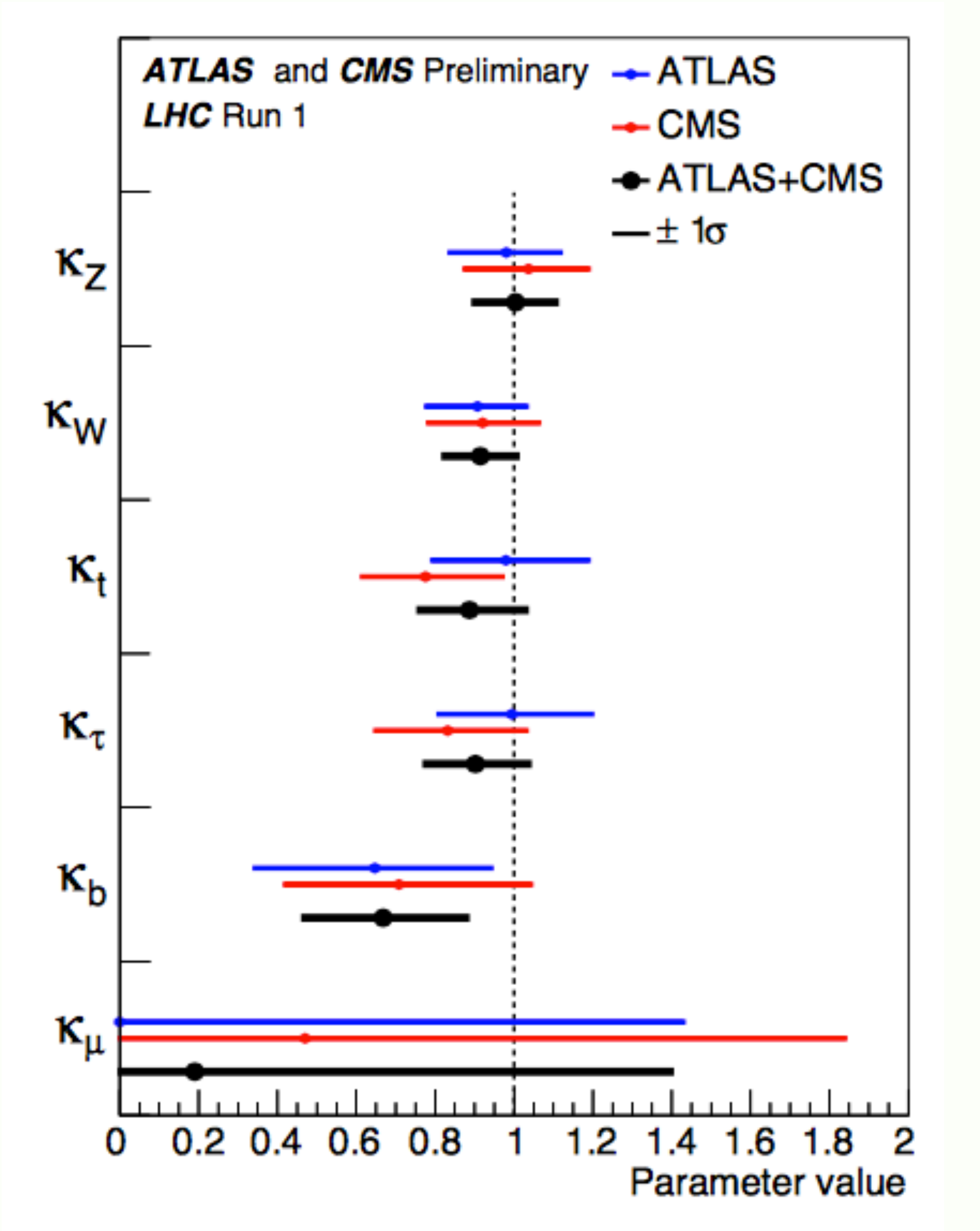
Combination:

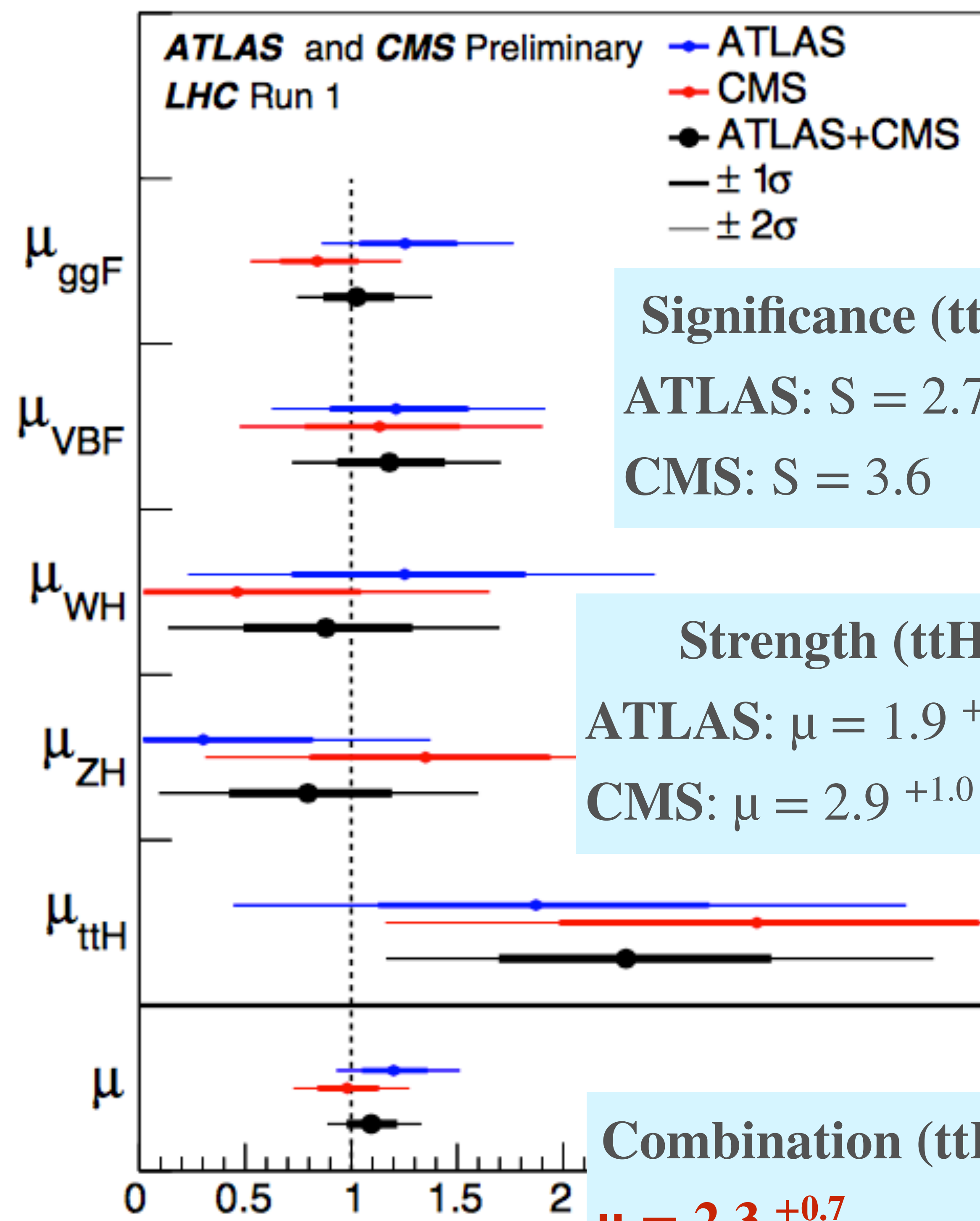
$\mu = 2.8^{+1.0}_{-0.9}$

$S = 3.4$

ATLAS+CMS Run 1 combination for ttH

ATLAS-CONF-2015-044
ATLAS+CMS, 5+20 fb^{-1}, 7+8 TeV





Significance (ttH):

ATLAS: S = 2.7

CMS: S = 3.6

Strength (ttH):

ATLAS: $\mu = 1.9^{+0.8}_{-0.7}$

CMS: $\mu = 2.9^{+1.0}_{-0.9}$

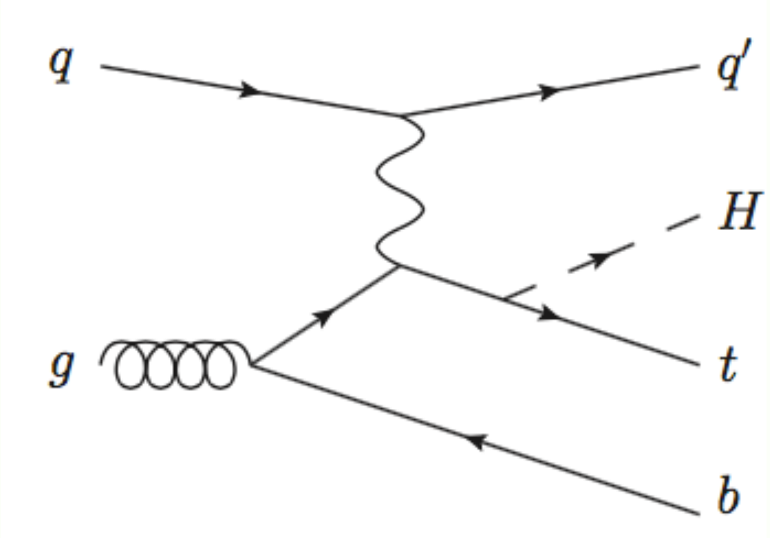
Combination (ttH):

$\mu = 2.3^{+0.7}_{-0.6}$

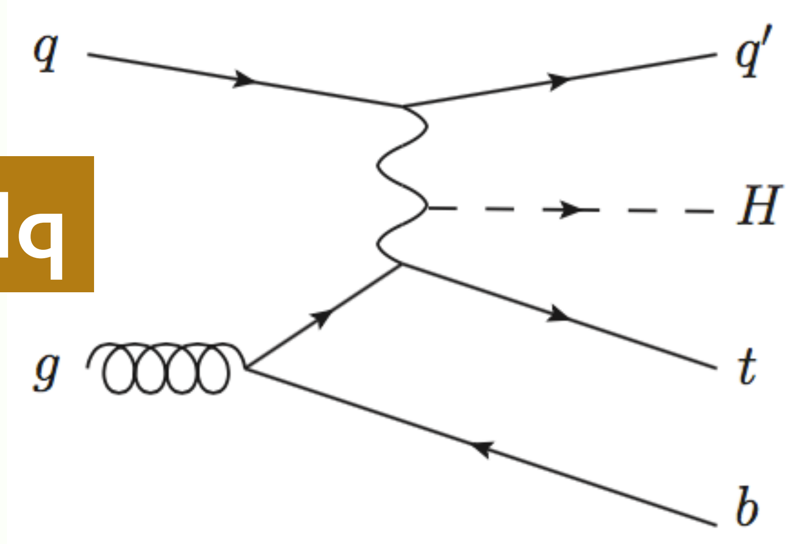
S = 4.4

tHq

Search for tHq

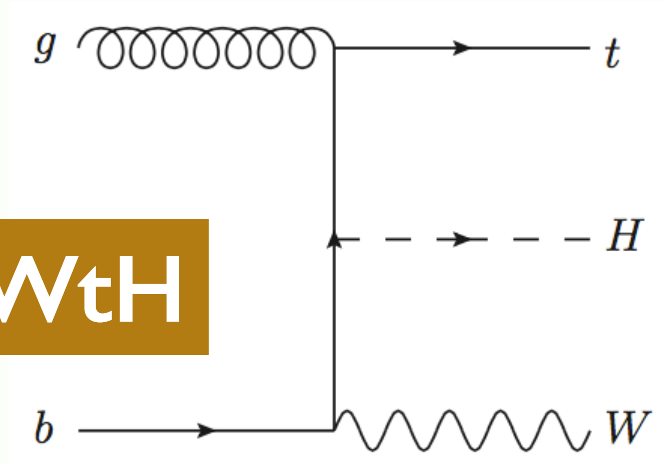


tHq

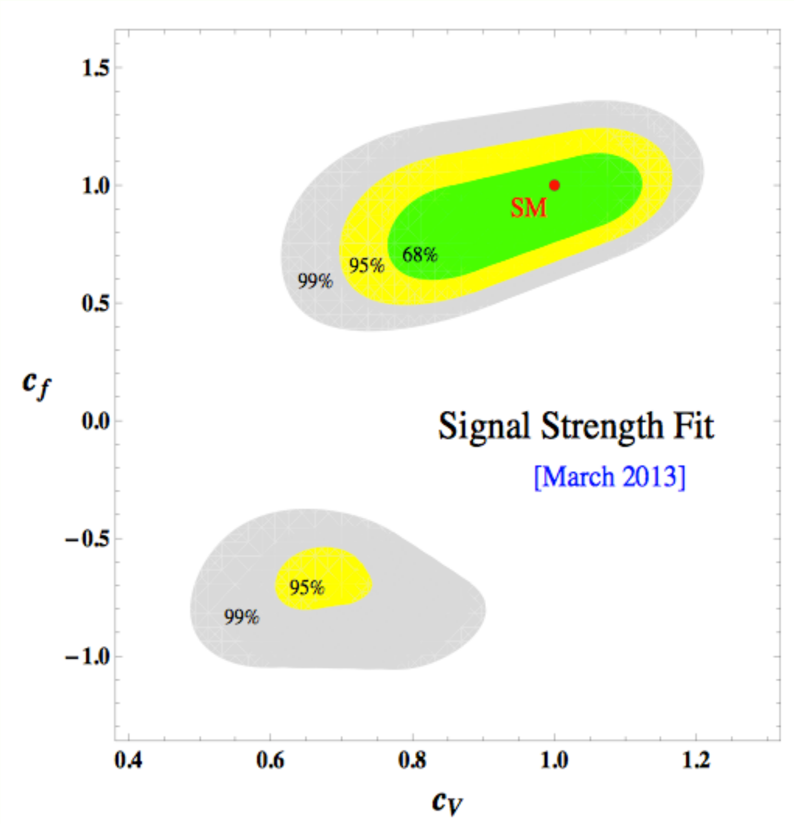


small contribution

WtH

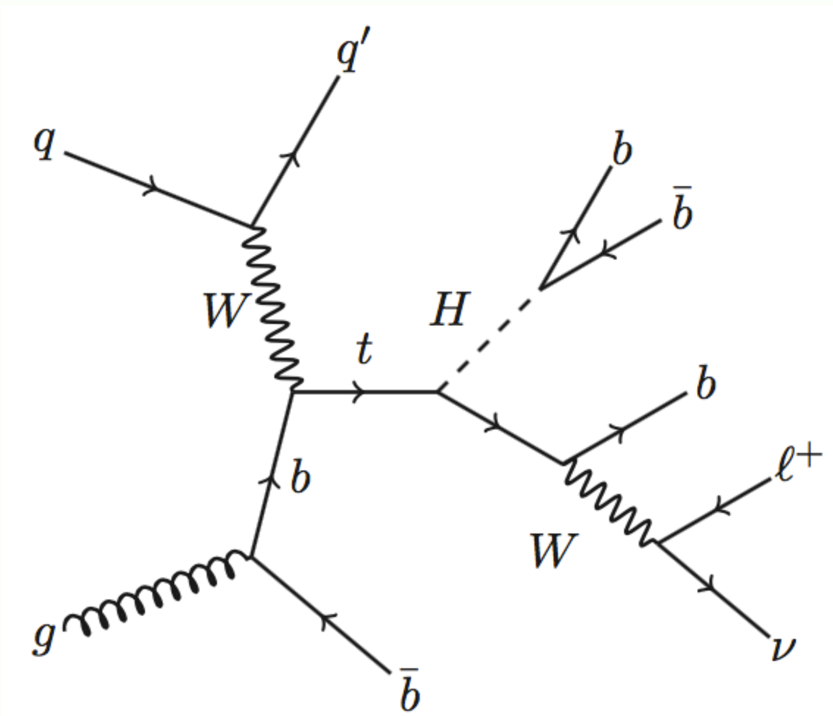


- ***Suppressed*** in the SM by destructive interference: $\mathbf{y_t \cdot y_W < 0}$ **!**
- Single top+Higgs production ***is sensitive to both magnitude and sign of*** y_t
- BSM predictions can be tested by probing negative y_t still allowed from global fits (arXiv:1303.6591)
- For $\mathbf{y_t = -1}$ there is a **15x increase in the cross section**



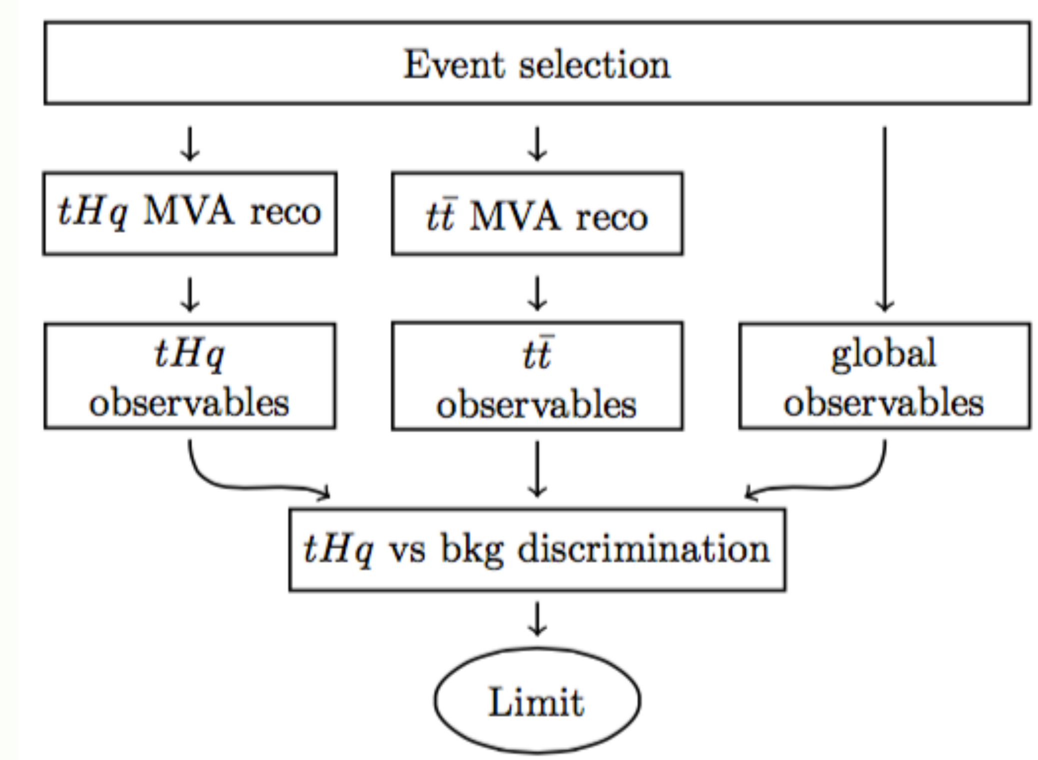
Search for tHq, H→bb at CMS

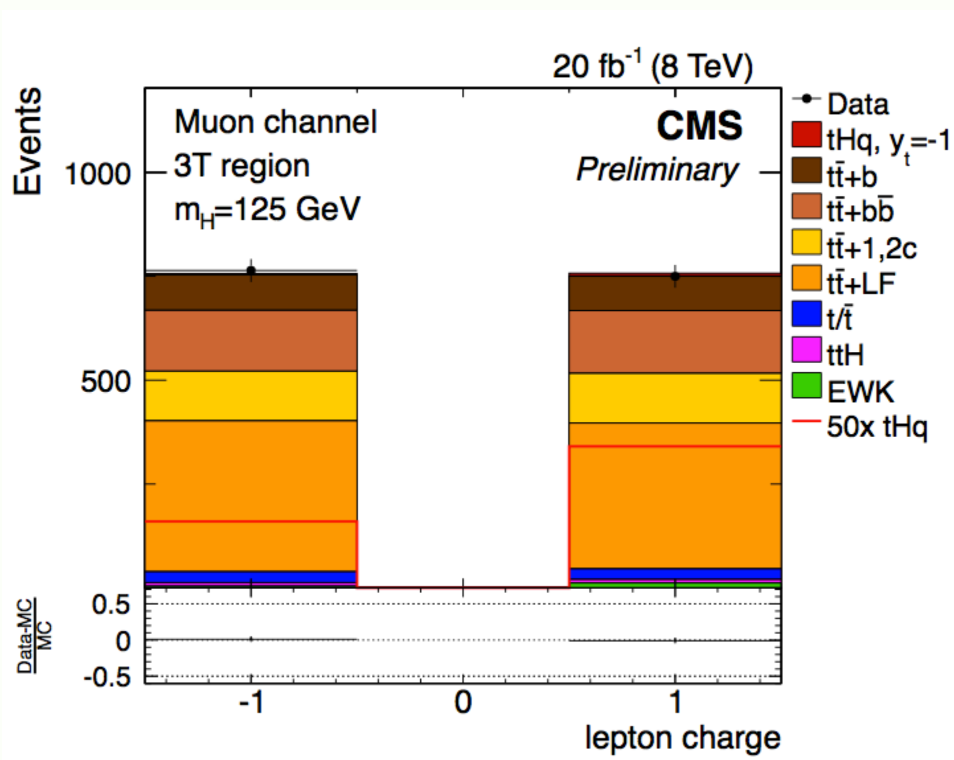
CMS-PAS-HIG-14-015
CMS, 20 fb^{-1}, 8 TeV

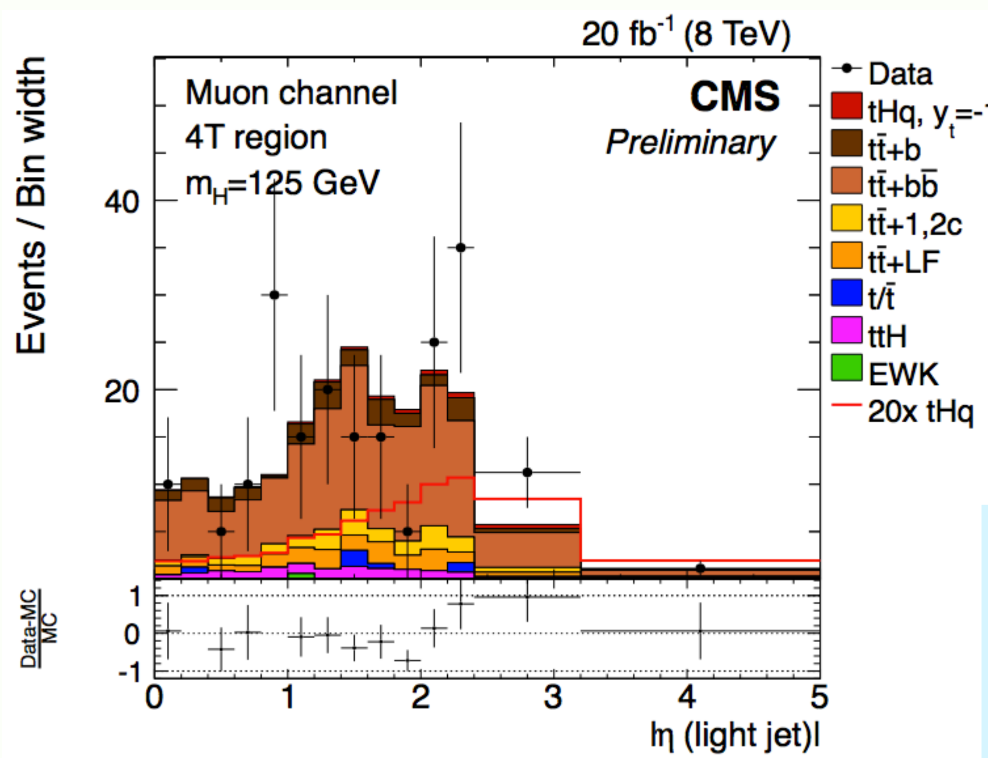


Event signature:
one lepton,
≥ 4 jets,
≥ 3 b-jets,
missing E_T

Efficient b-jet assignment is crucial



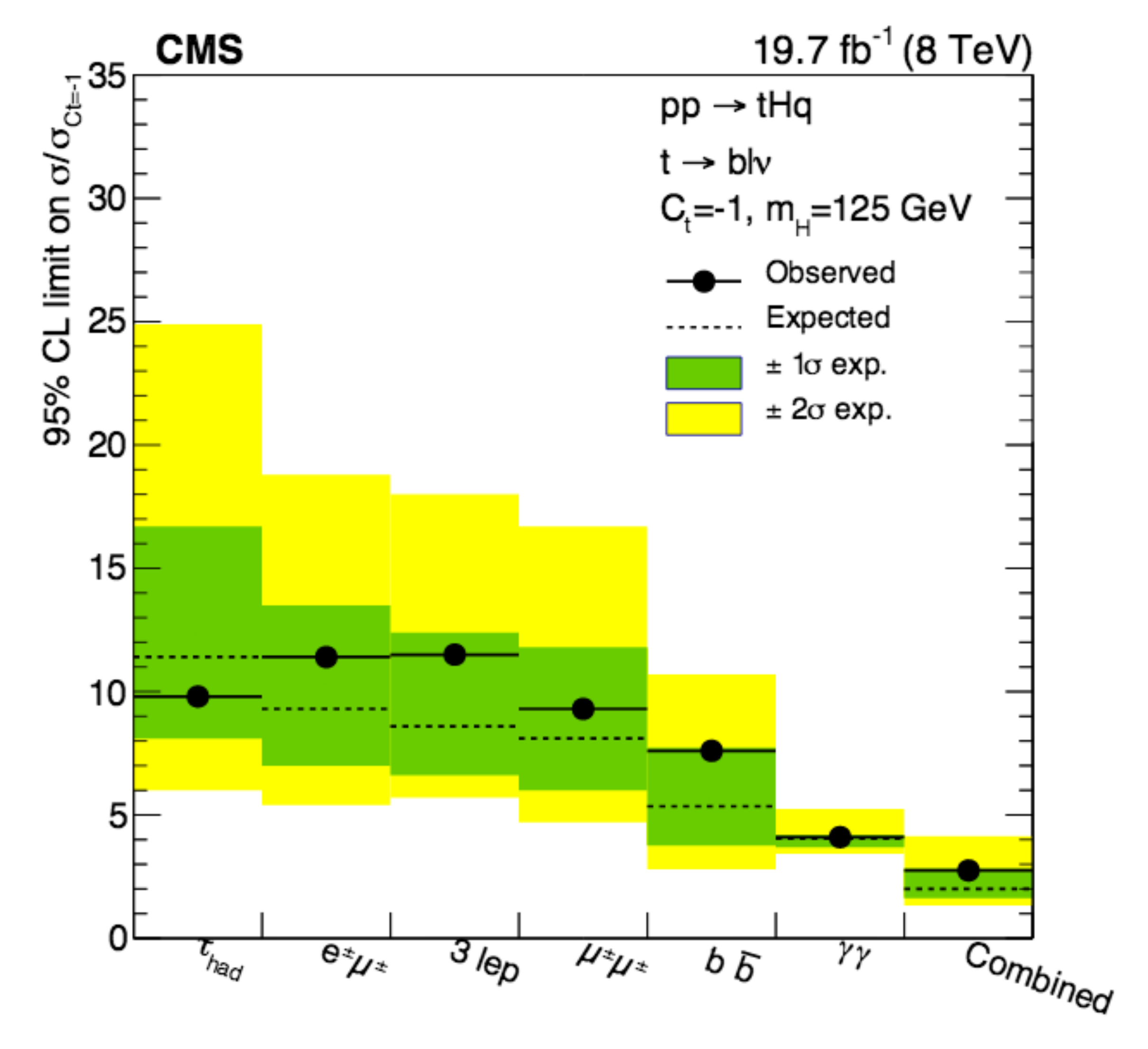


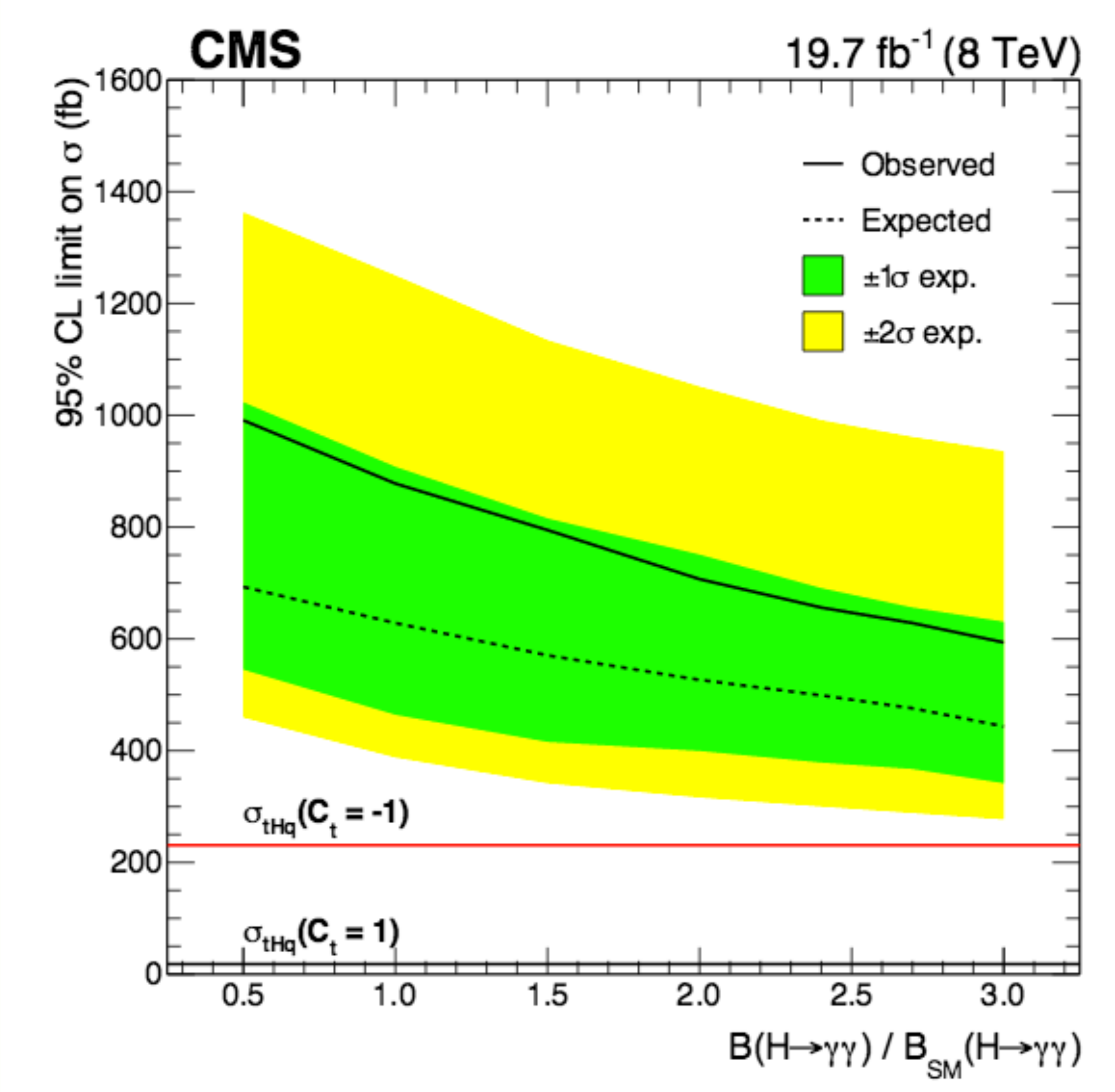


Observed limit (95% CL):
$\sigma/\sigma[y_t=-1] < 7.57$

Search for tHq at CMS (combination)

CMS-HIG-14-027
CMS, 20 fb^{-1}, 8 TeV

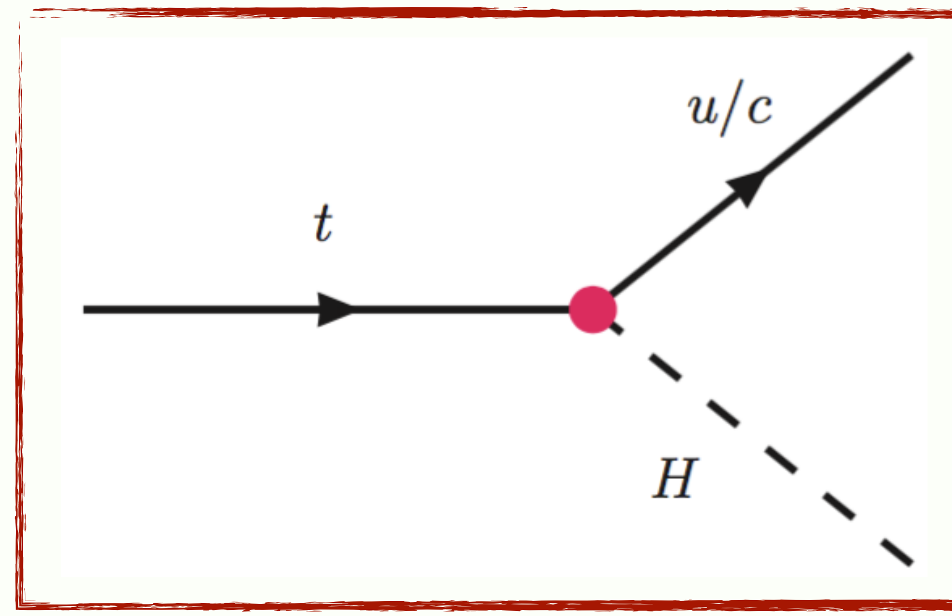




top FCNH

FCNC in tH events

$$
\begin{aligned}
\mathcal{L} = & \sum_{q=u,c} \Big[\sqrt{2}\, g_s \frac{\kappa_{gqt}}{\Lambda}\, \bar{t}\, \sigma^{\mu\nu}\, T_a (f^L_{Gq} P_L + f^R_{Gq} P_R)\, q\, G^a_{\mu\nu} \\
& + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda}\, \bar{t} \sigma^{\mu\nu} (f^L_{Zq} P_L + f^R_{Zq} P_R)\, q\, Z_{\mu\nu} \\
& - e \frac{\kappa_{\gamma qt}}{\Lambda}\, \bar{t}\, \sigma^{\mu\nu} (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R)\, q\, A_{\mu\nu} \\
& + \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} (f^L_{Hq} P_L + f^R_{Hq} P_R)\, q\, H \Big] + \text{h.c.}
\end{aligned}
$$



- **FCNC** = Flavour Changing Neutral Currents
- ***Forbidden in the SM*** by the GIM mechanism, only possible via loop-induced processes (highly suppressed)
- Observation of FCNC events would mean **the new physics**

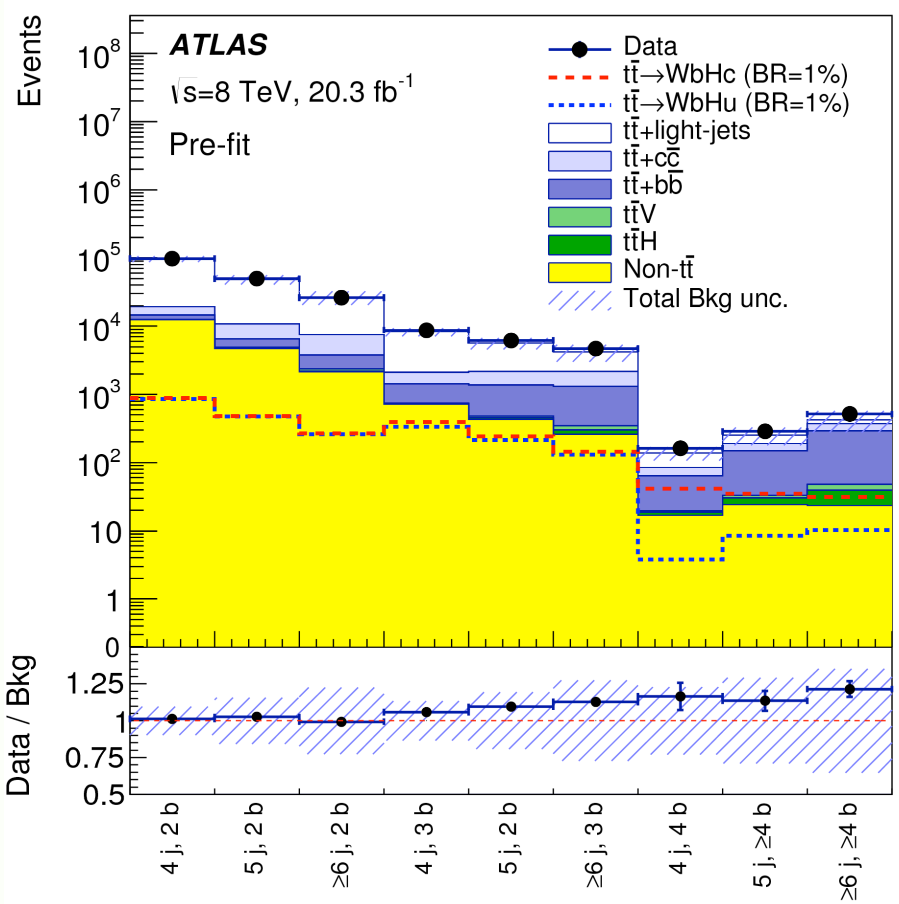
but could be ***highly enhanced in BSM*** scenarios:

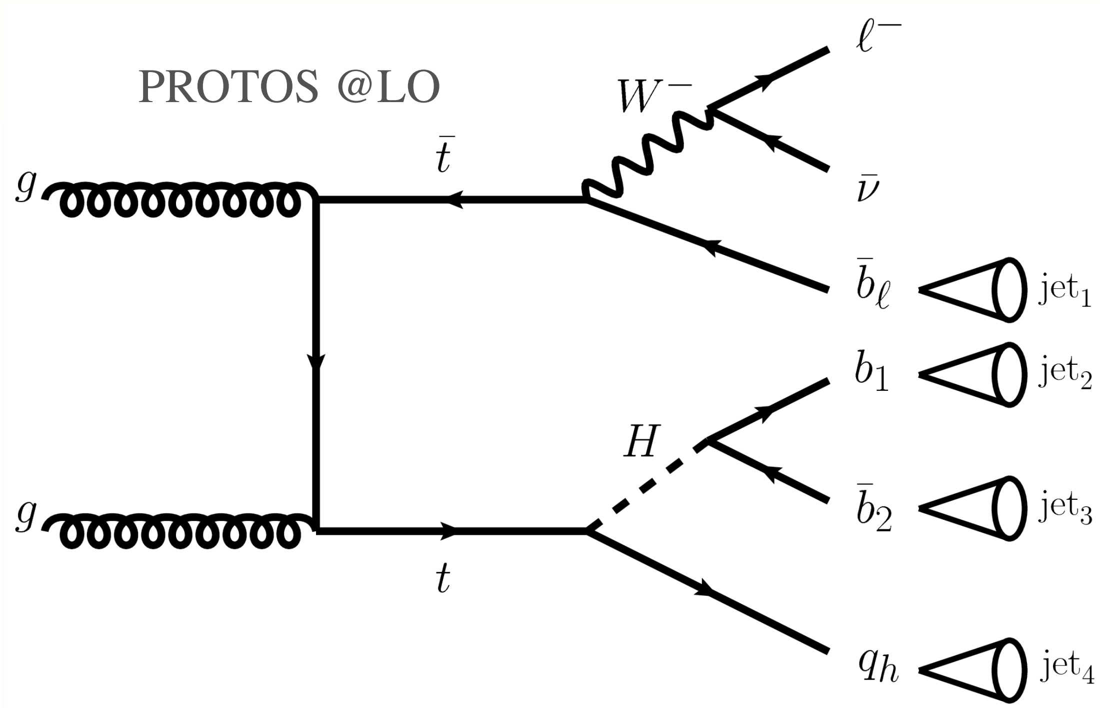
SM: **Br(t→qH) ≈ 10^{-6}**

MSSM: **Br(t→qH) ≈ 10^{-2}**

Search for t→Hq in ttbar events at ATLAS

JHEP 12 (2015) 061
ATLAS, 20 fb^{-1}, 8 TeV





H→bb channel

Event signature: ≥ 4 jets of which ≥ 3 jets are b-jets, one lepton and missing E_T

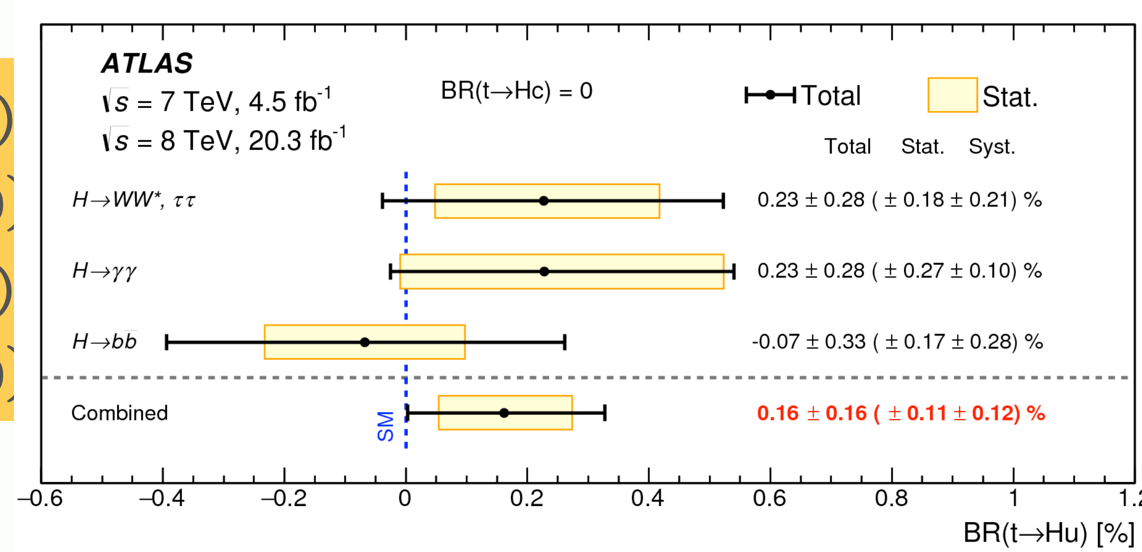
Main background: ttbar+jets

Combination with JHEP 06 (2014) 008 (**H→γγ**) and Phys. Lett. B 749 (2015) 519 (**ttH, H→WW/ττ**)

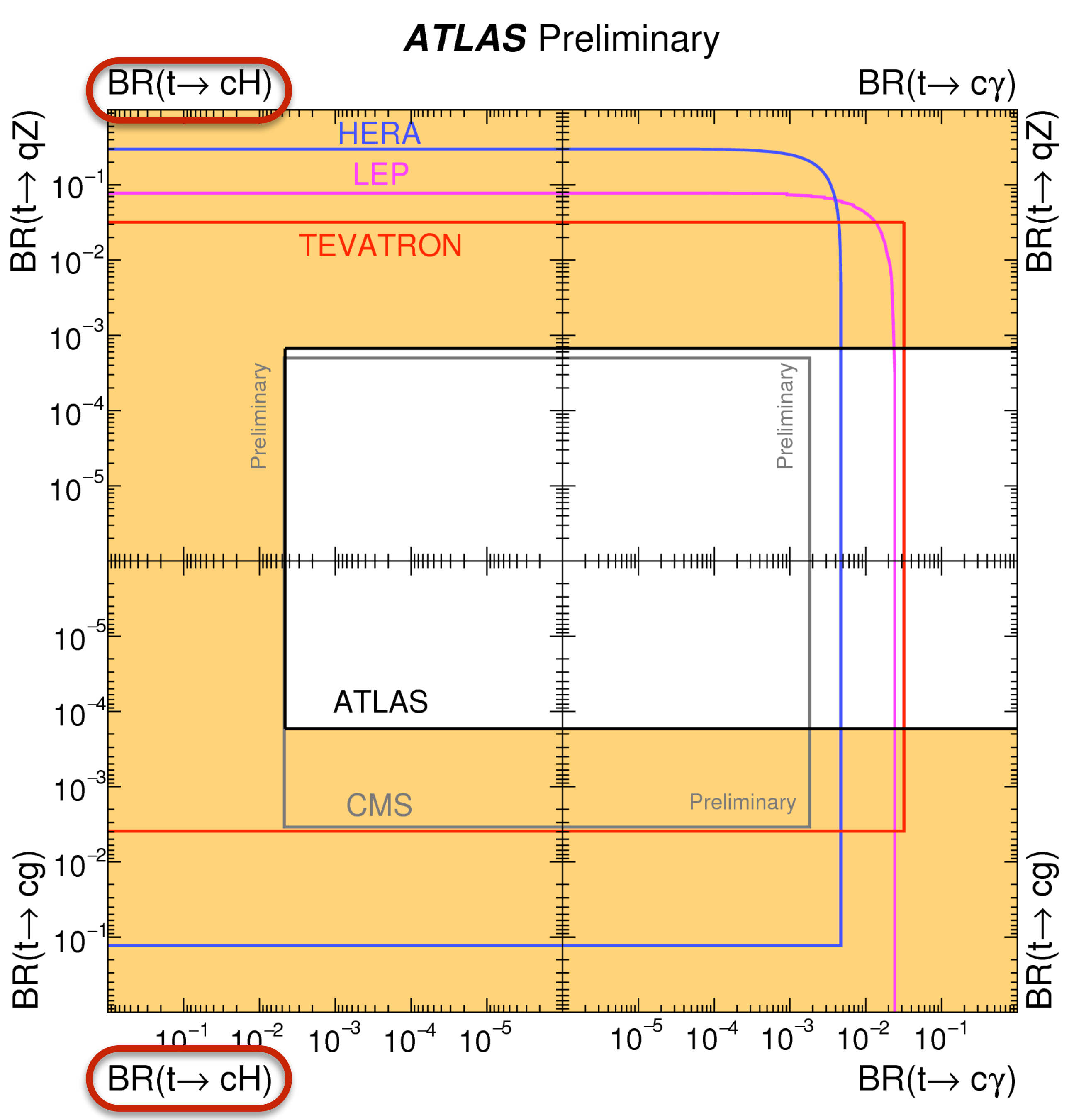
$\kappa_{uHt} < 0.13$, $\kappa_{cHt} < 0.13$

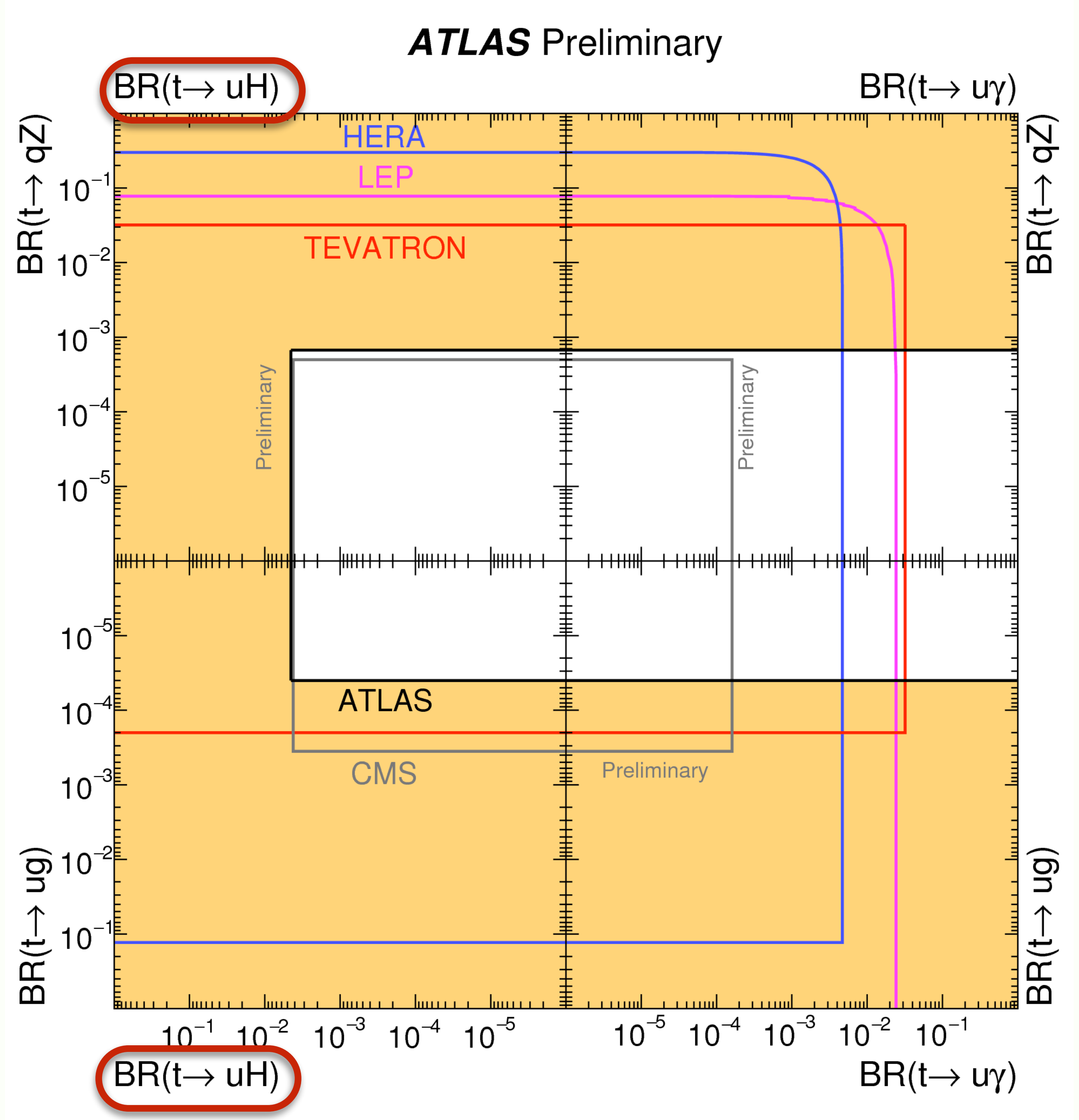
BR(t→u**H**) < 0.45 % (obs)
0.29 % (exp)
BR(t→c**H**) < 0.46 % (obs)
BR(t→c**H**) < 0.25 % (exp)

BR(t→u**H**) < 0.61 % (obs)
0.64 % (exp)
BR(t→c**H**) < 0.56 % (obs)
0.42 % (exp)



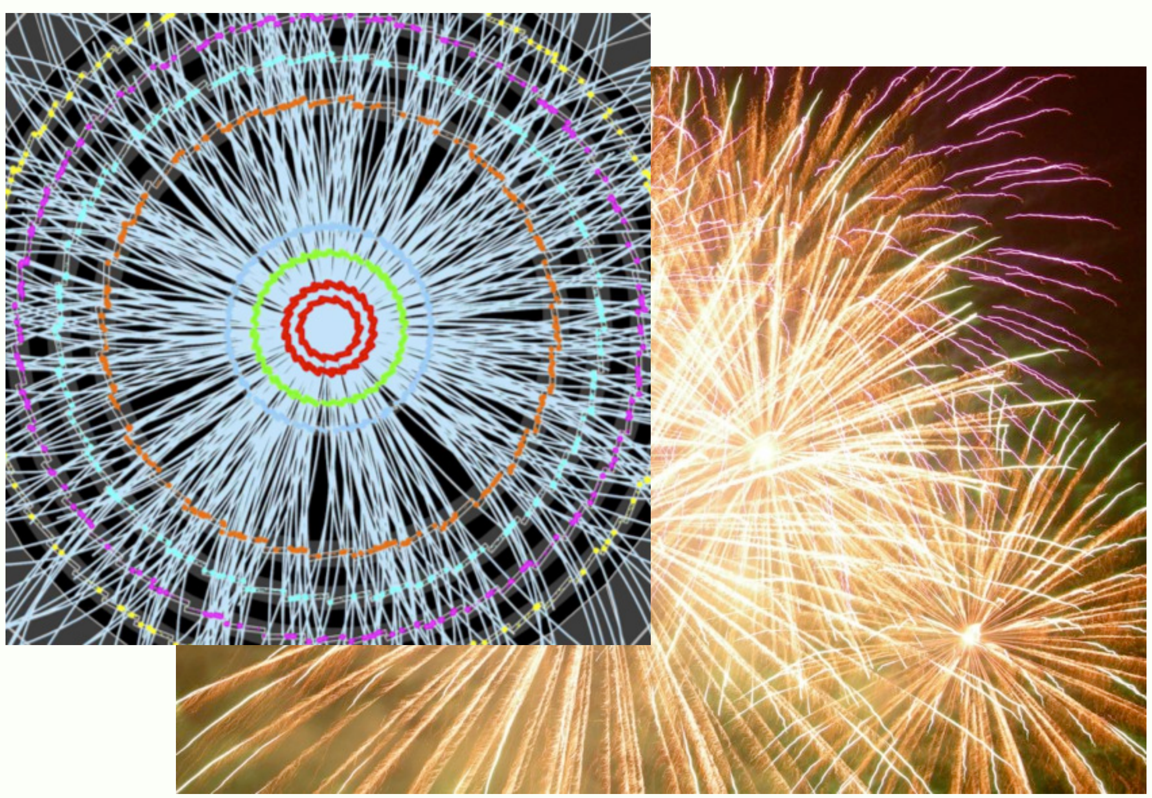
Summary on FCNC limits

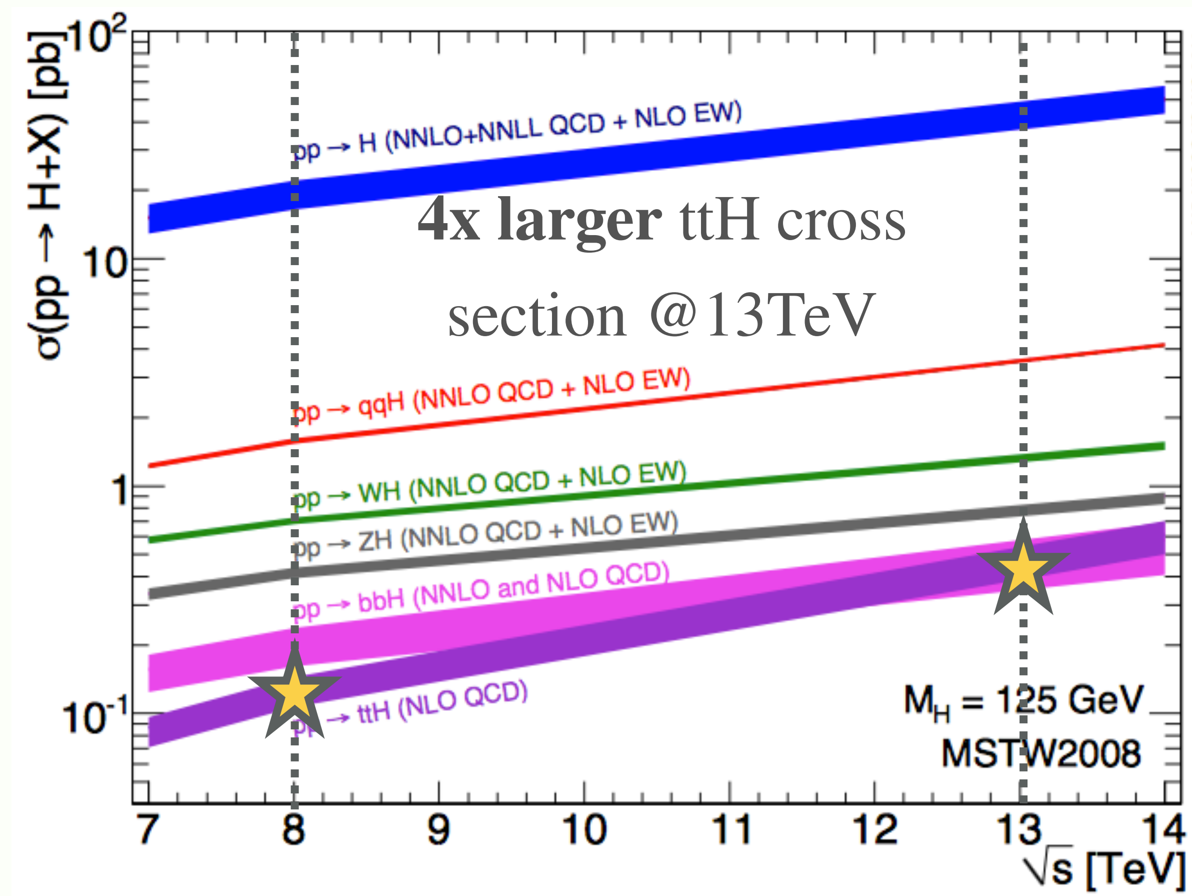




Conclusion

- Study of the ***top+Higgs*** sector is one of the ***hot topics*** at LHC
- A ***good performance of b-tagging is crucial*** for these analyses
- Presented overview of b-tagging activities and the latest top+Higgs results from ATLAS and CMS suggests ***good prospects for Run II***
- A first observation of the ttH process is anticipated at 13 TeV (or, if lucky enough, a non-observation)
- Challenges and excitement ahead !



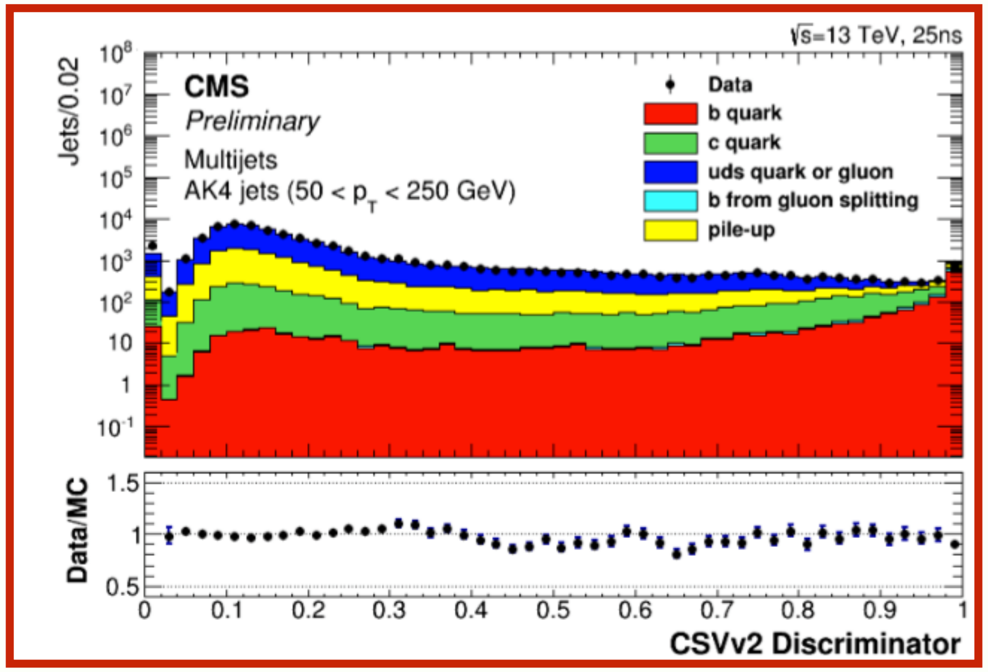


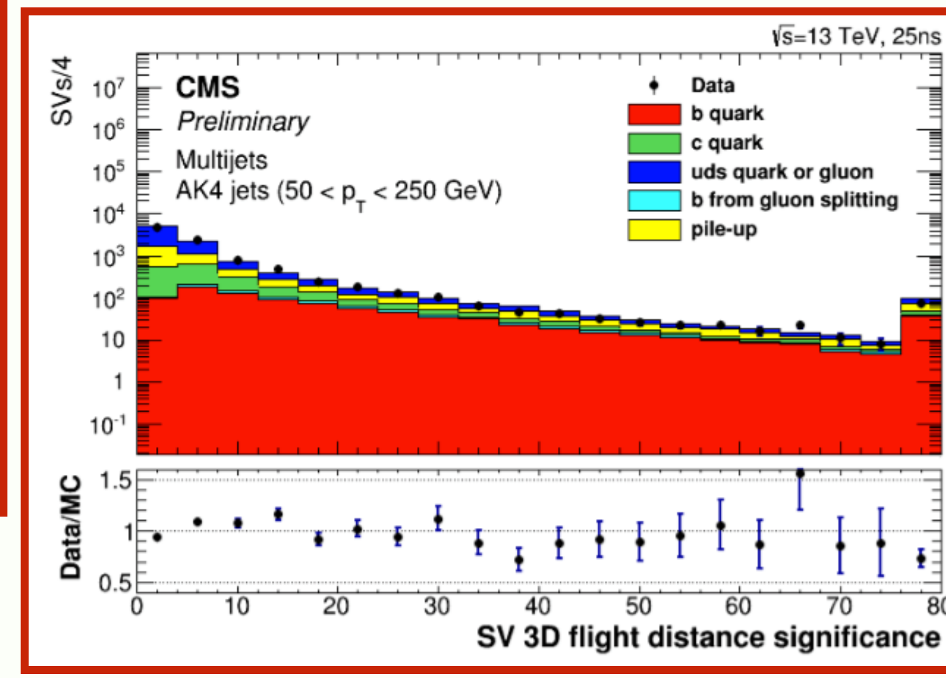
Backup slides

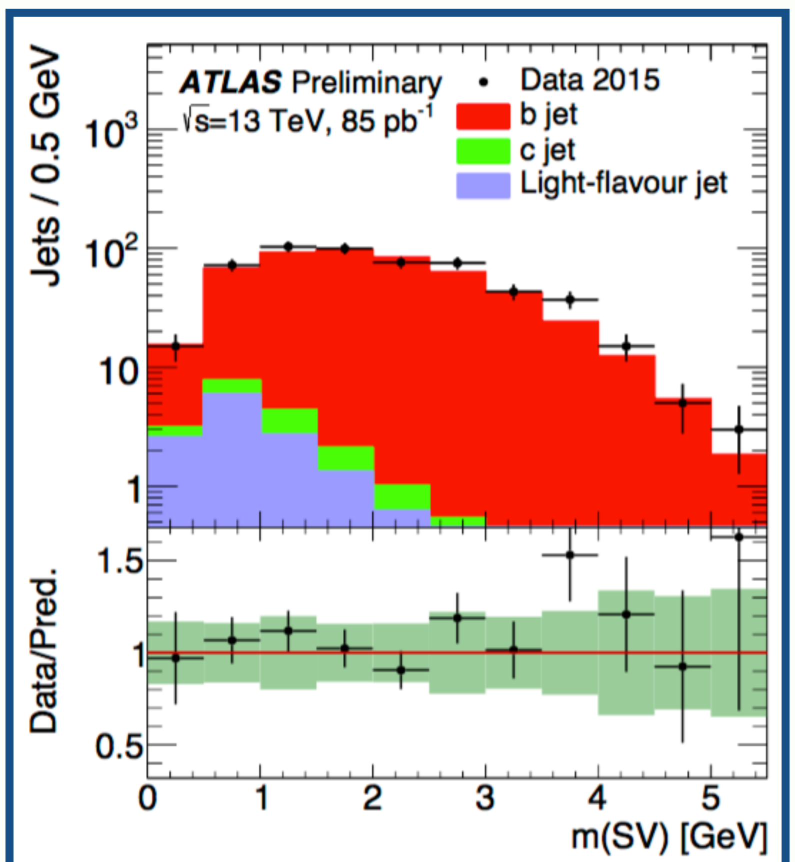
Commissioning of b-tagging variables

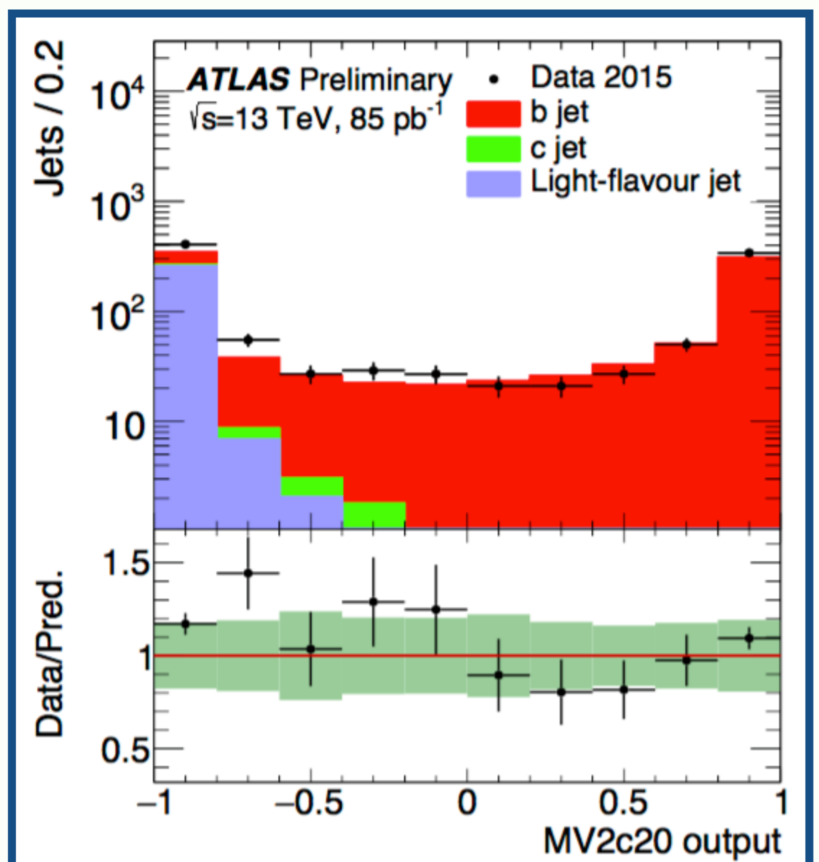
Validate the data/MC agreement for b-tagging variables in

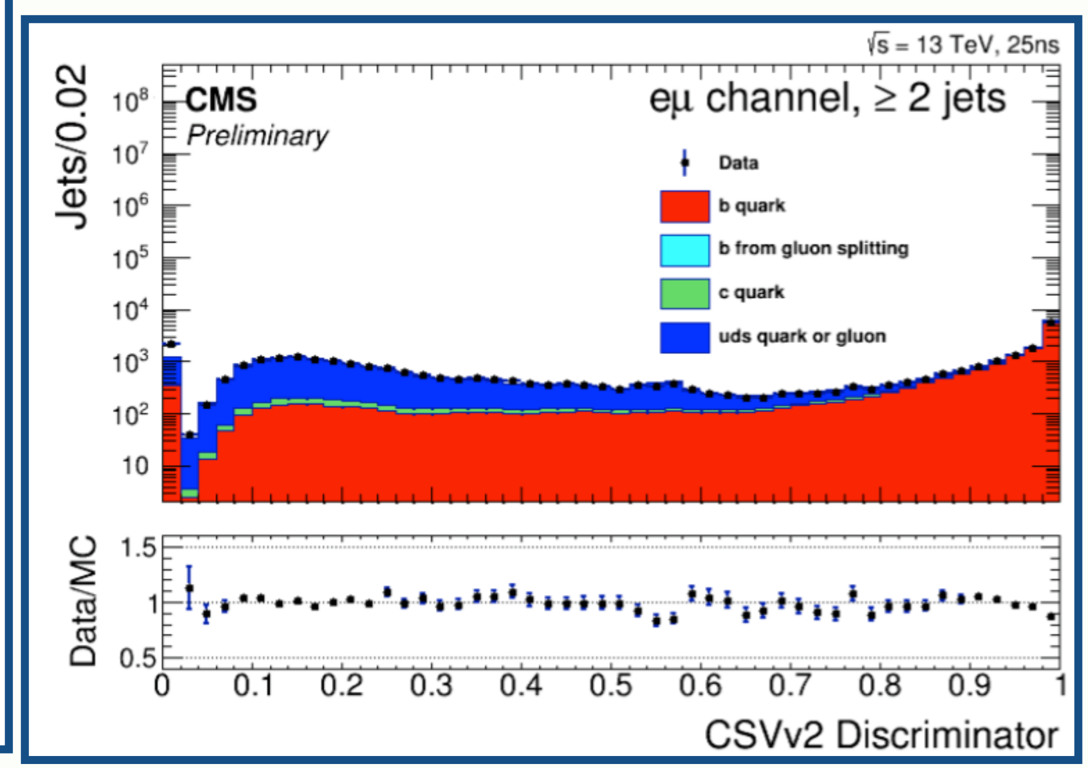
QCD multijet and **ttbar** events









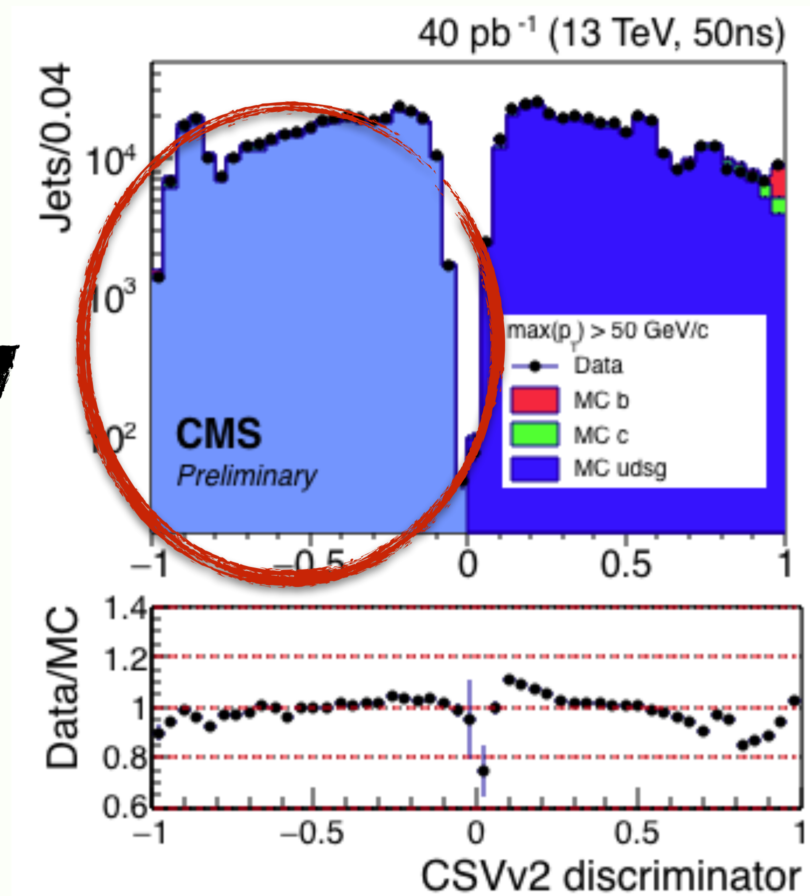


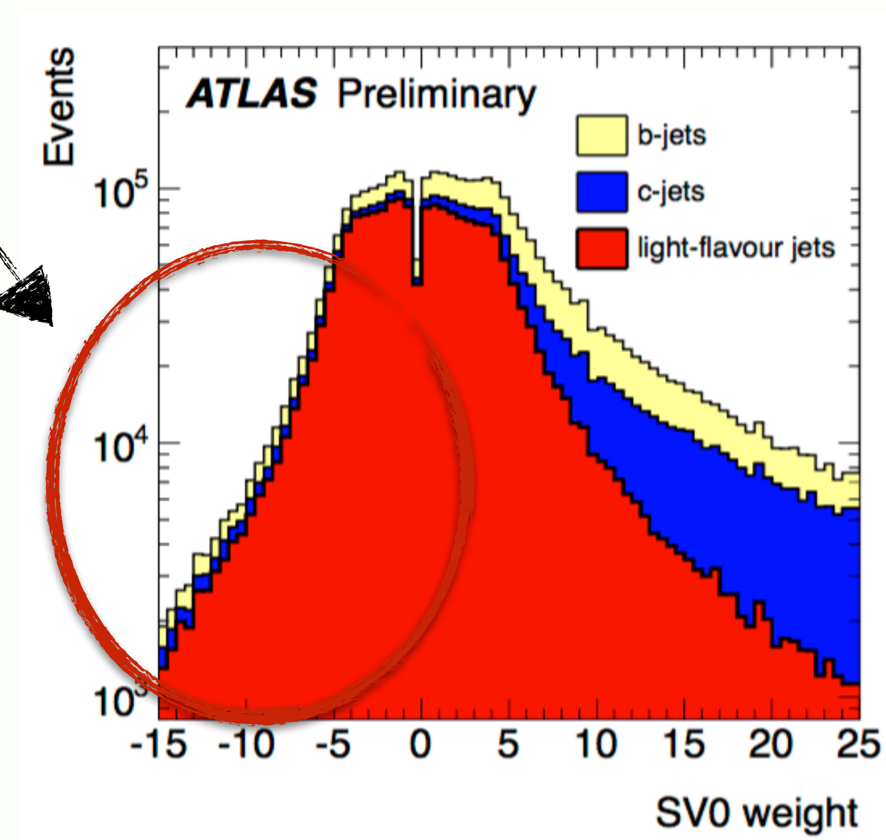
Mis-tag rate measurement

- **Mis-tag rate** ($\epsilon_{\mathrm{inc}}^{\mathrm{neg}}$) - efficiency to tag udsg as b-jets
- Due to finite resolution of the inner detector, displaced vertices from long-lived particles and material interactions
- A ***negative tag method*** - use jets with negative impact parameter tracks (or negative decay length significance)
- Correct for b/c-jet contamination and long-lived particles

$$k_{\mathrm{ll}} = \epsilon_l / \epsilon_l^{\mathrm{neg}} \qquad k_{\mathrm{hf}} = \epsilon_l^{\mathrm{neg}} / \epsilon_{\mathrm{inc}}^{\mathrm{neg}}$$

$$\epsilon_l = \epsilon_{\mathrm{inc}}^{\mathrm{neg}} k_{\mathrm{hf}} k_{\mathrm{ll}}$$





b-tag calibration in QCD events

- **System 8** method is based on extracting b-tagging efficiency from a ***system of 8 non-linear equations***
- Equations constructed from different b-tag samples (n, p, pTrel) defined by the reference and complementary b-tag selections
- Numerical methods are used to find a solution

$$n = n_b + n_{cl}$$
$$p = p_b + p_{cl}$$

b-tagging efficiency

$$n^{tag} = \varepsilon_b^{tag} n_b + \varepsilon_{cl}^{tag} n_{cl}$$
$$p^{tag} = \beta_{12}\varepsilon_b^{tag} p_b + \alpha_{12}\varepsilon_{cl}^{tag} p_{cl}$$

$$n^{pTrel} = \varepsilon_b^{pTrel} n_b + \varepsilon_{cl}^{pTrel} n_{cl}$$
$$p^{pTrel} = \beta_{23}\varepsilon_b^{pTrel} p_b + \alpha_{23}\varepsilon_{cl}^{pTrel} p_{cl}$$

$$n^{tag,pTrel} = \beta_{13}\varepsilon_b^{tag}\varepsilon_b^{pTrel} n_b + \alpha_{13}\varepsilon_{cl}^{tag}\varepsilon_{cl}^{pTrel} n_{cl}$$
$$p^{tag,pTrel} = \beta_{123}\varepsilon_b^{tag}\varepsilon_b^{pTrel} p_b + \alpha_{123}\varepsilon_{cl}^{tag}\varepsilon_{cl}^{pTrel} p_{cl}$$

Unknowns

$$n_b, n_{cl}, p_b, p_{cl}$$
$$\varepsilon_b^{tag}, \varepsilon_{cl}^{tag}, \varepsilon_b^{pTrel}, \varepsilon_{cl}^{pTrel}$$

$$\alpha_{12}, \alpha_{23}, \alpha_{13}, \alpha_{123}$$
$$\beta_{12}, \beta_{23}, \beta_{13}, \beta_{123}$$

Correlation parameters

b-tag calibration in ttbar events

- ***Combinatorial likelihood method*** exploits kinematic correlations between jets in event via unbinned maximum likelihood fit to data
  - PDFs binned in jet flavour, p_T and b-tag weight
  - Done separately for two and three jet cases

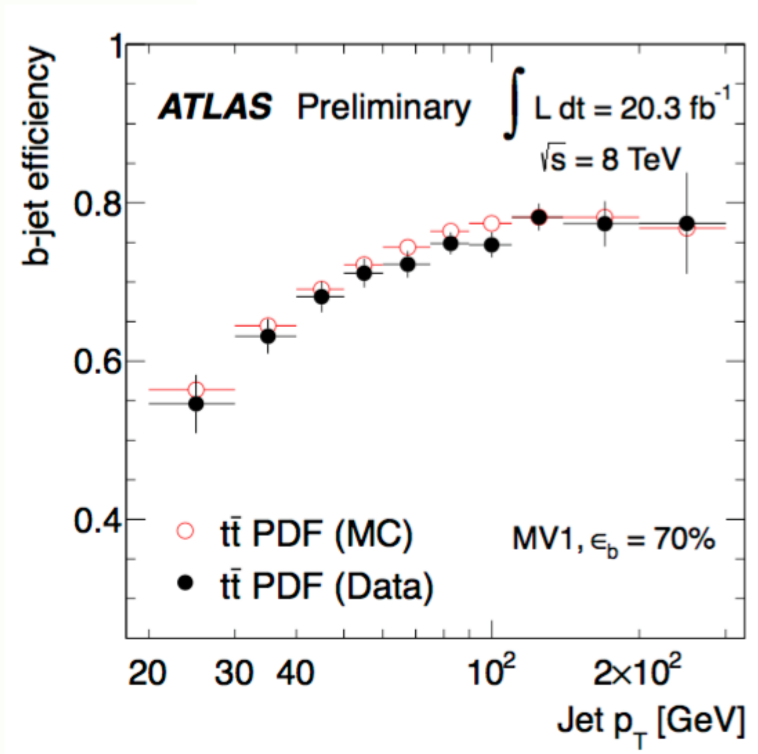
In the two-jet-case:

Jet **flavour fraction**

Jet **b-tag weight PDF** (p_T,flavour)

$$\mathcal{L}(p_{T,1}, p_{T,2}, w_1, w_2) = \frac{1}{2}\sum_{(i,k)} \Big[f_{bb}\mathcal{P}_{bb}(p_{T,i}, p_{T,k})\mathcal{P}_b(w_i|p_{T,i})\mathcal{P}_b(w_k|p_{T,k}) + f_{bj}\mathcal{P}_{bj}(p_{T,i}, p_{T,k})\mathcal{P}_b(w_i|p_{T,i})\mathcal{P}_j(w_k|p_{T,k}) + f_{jj}\mathcal{P}_{jj}(p_{T,i}, p_{T,k})\mathcal{P}_j(w_i|p_{T,i})\mathcal{P}_j(w_k|p_{T,k}) \Big]$$

Jet **2D PDF** (p_T,flavour)



b-jet efficiency →

$$\epsilon_b(p_T) = \int_{w_{cut}}^{\infty} dw' \mathcal{P}_b(w', p_T)$$

ATLAS-CONF-2014-004

b-tag calibration in ttbar events

- ***Tag counting method / Flavour tag consistency method*** is a likelihood fit for the expected number of ***n*** b-tagged jets:

F_{ijk} - fraction of events with ***i*** b, ***j*** c and ***k*** l-jets before b-tagging

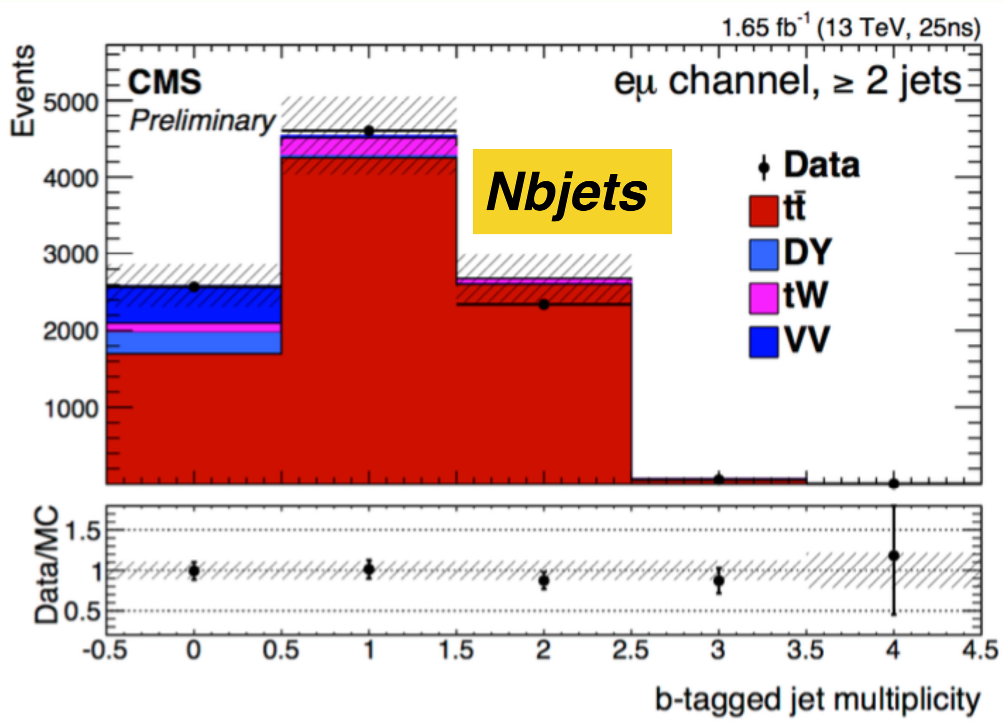
i, ***j***, ***k*** - number of pre-tag jets
i', ***j'***, ***k'*** - number of post-tag jets

$$< N_n > \; = \sum_{i,j,k} \Big\{ (\sigma_{t\bar{t}} \cdot \mathrm{BF} \cdot A_{t\bar{t}} \cdot \mathcal{L} \cdot F^{t\bar{t}}_{ijk} + N_{\mathrm{bkg}} \cdot F^{\mathrm{bkg}}_{ijk}) \times \sum_{i'+j'+k'=n} \binom{i}{i'} \cdot {\varepsilon_b}^{i'} \cdot (1-\varepsilon_b)^{i-i'} \cdot \binom{j}{j'} \cdot {\varepsilon_c}^{j'} \cdot (1-\varepsilon_c)^{j-j'} \cdot \binom{k}{k'} \cdot {\varepsilon_l}^{k'} \cdot (1-\varepsilon_l)^{k-k'} \Big\}$$

  - Rate systematics cancel out as fractions of events are used
  - But relies on flavour composition from MC

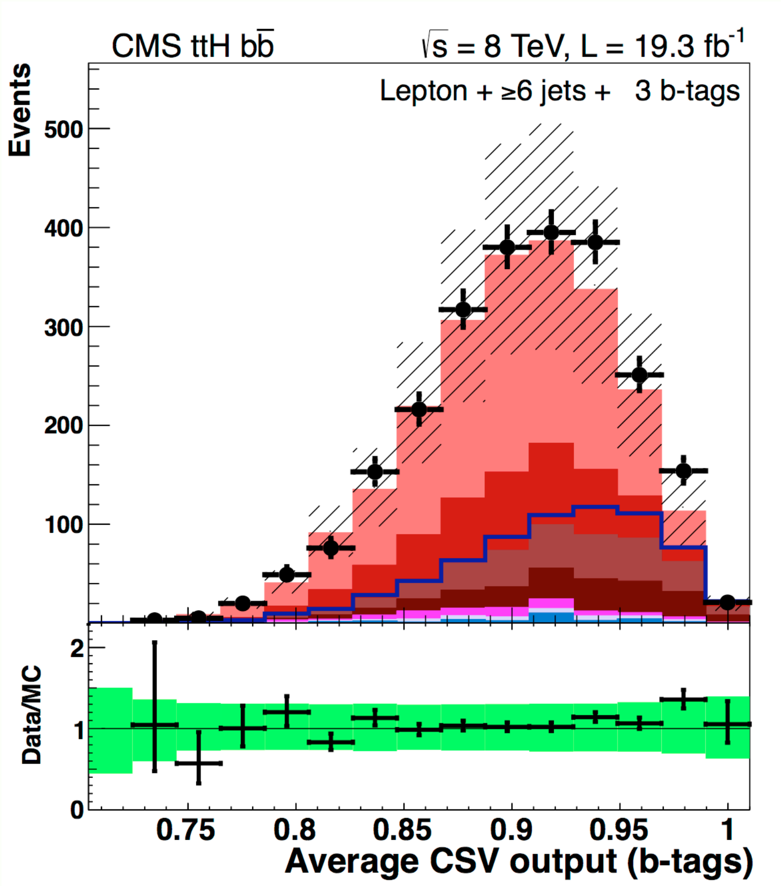
- ***Simplified tag counting method*** is limited to the case of **Njets = 2**
  - No fit, calculate b-tagging efficiency as:

$$\varepsilon_b = \sqrt{\frac{F_{2tag} - F^{truth}_{non2b}}{f_{2b}}}$$



Shape correction for b-tag discriminator

- ***b-tag discriminator shape*** is often used in signal extraction techniques in many analyses
- Efficiency correction is needed over the whole range of discriminator values

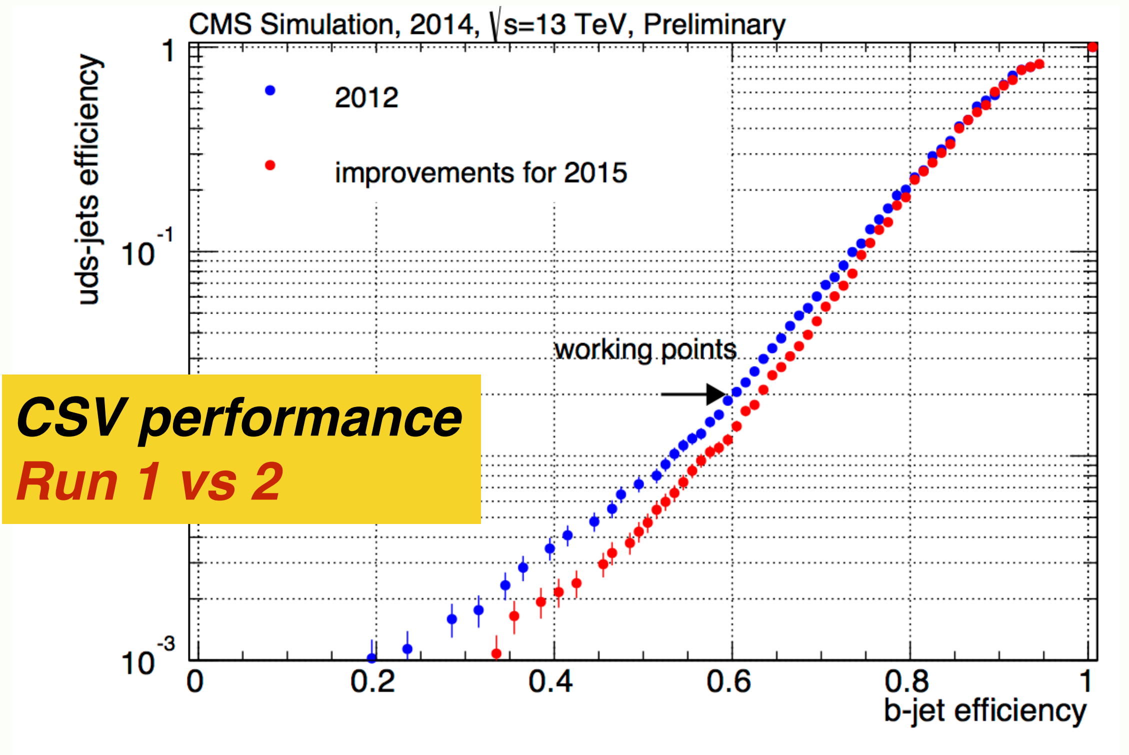


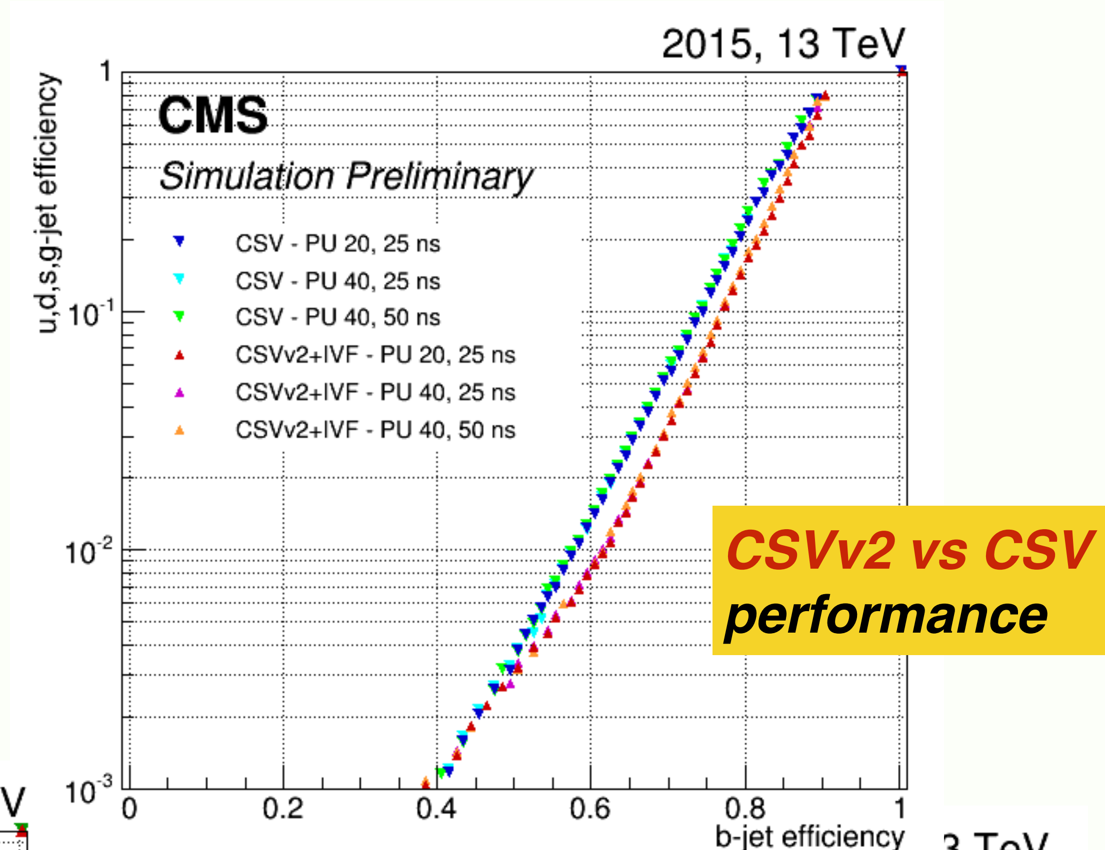
- **ATLAS** does b-tag ***continuous*** (directly from the **Combinatorial Likelihood method**) or ***pseudo-continuous calibration***:

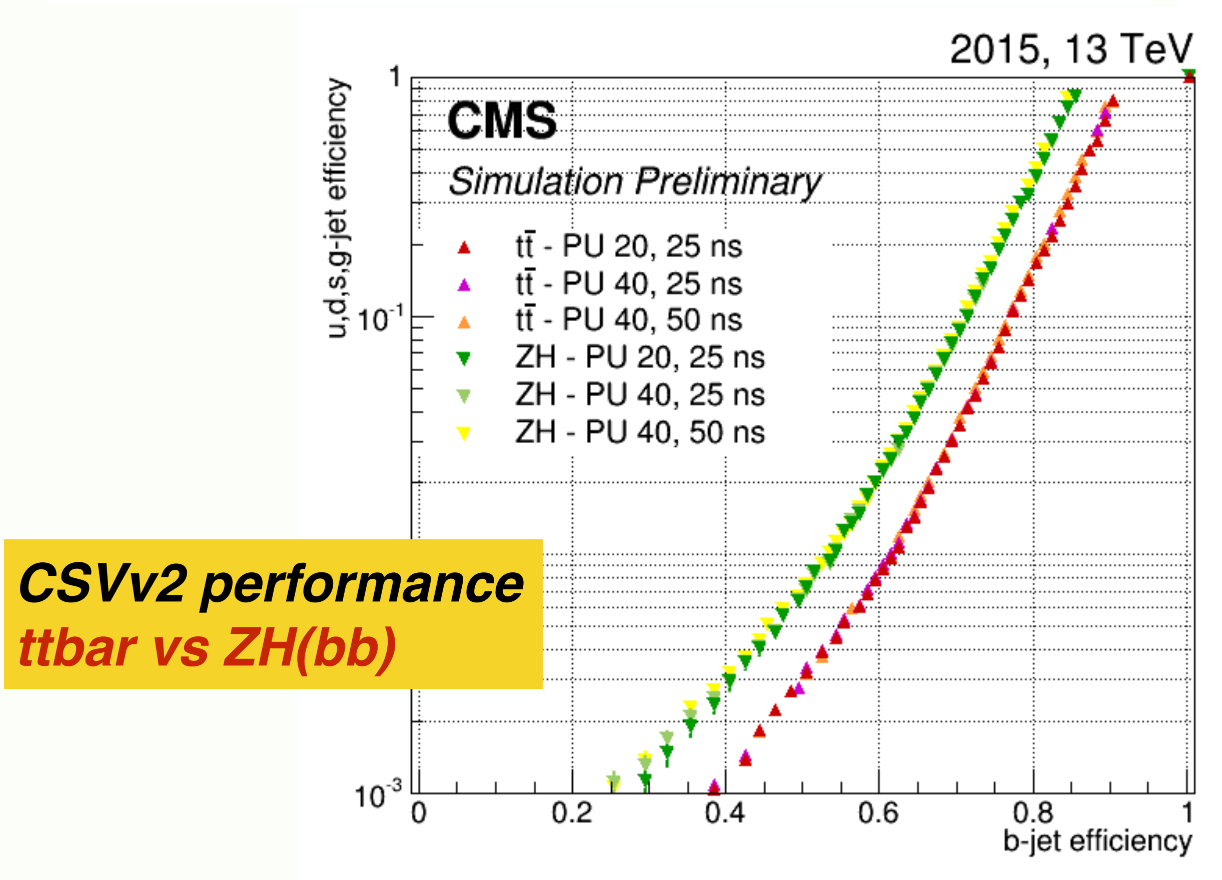
$$\mathrm{SF}_i^{\mathrm{cont}} = \frac{\mathrm{SF}_{i+1}\varepsilon_{i+1}^{\mathrm{MC}} - \mathrm{SF}_i\varepsilon_i^{\mathrm{MC}}}{\varepsilon_{i+1}^{\mathrm{MC}} - \varepsilon_i^{\mathrm{MC}}}$$

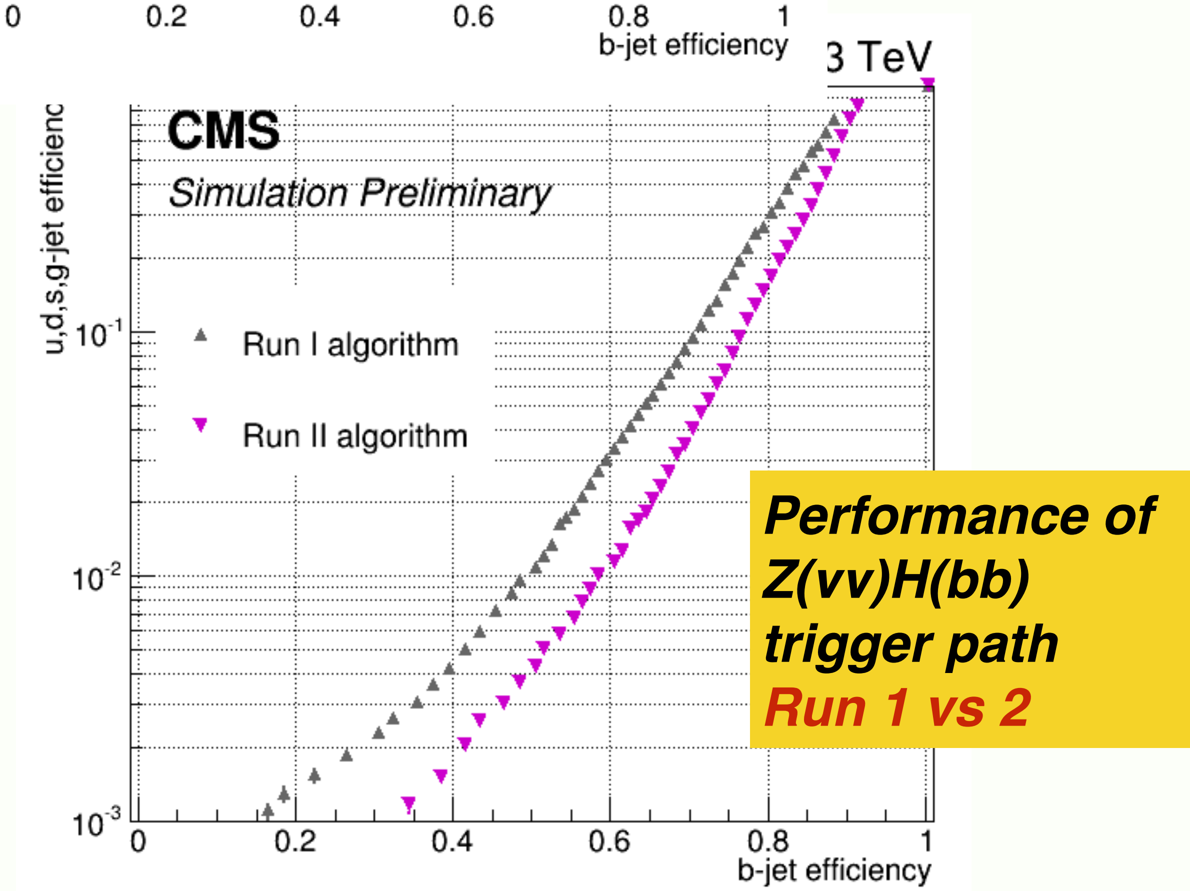
- **CMS** uses ***b-tag re-weighting*** approach with correction factors measured with Tag&Probe method
  - b-jet in ttbar dileptonic events
  - l-jet in Z+jets
- Also a shape correction via interpolation between the measured SFs is used

b-jet trigger performance at CMS

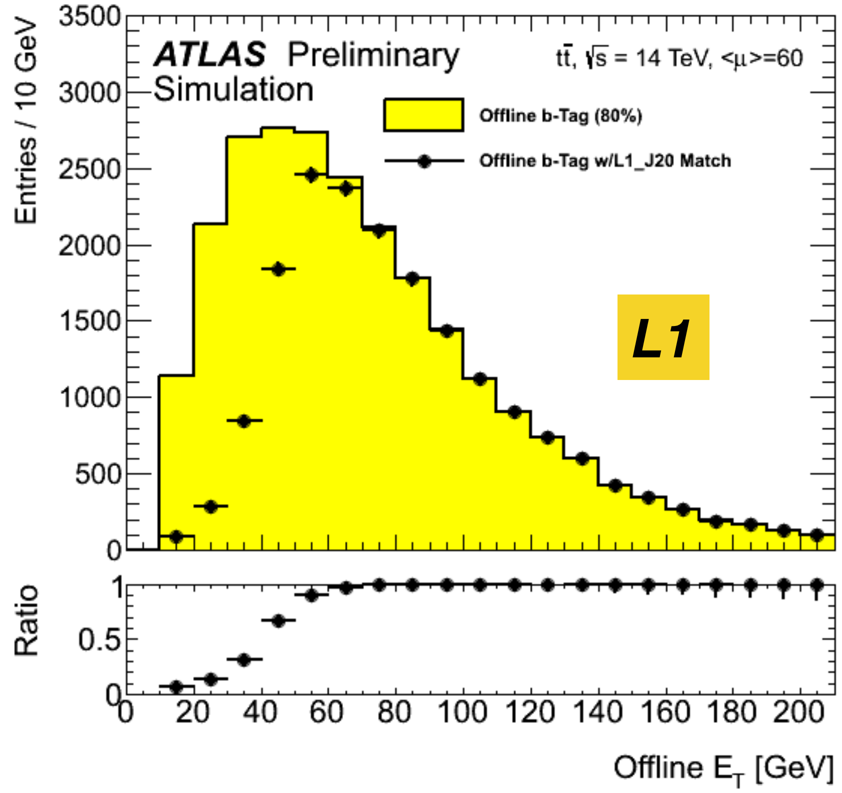


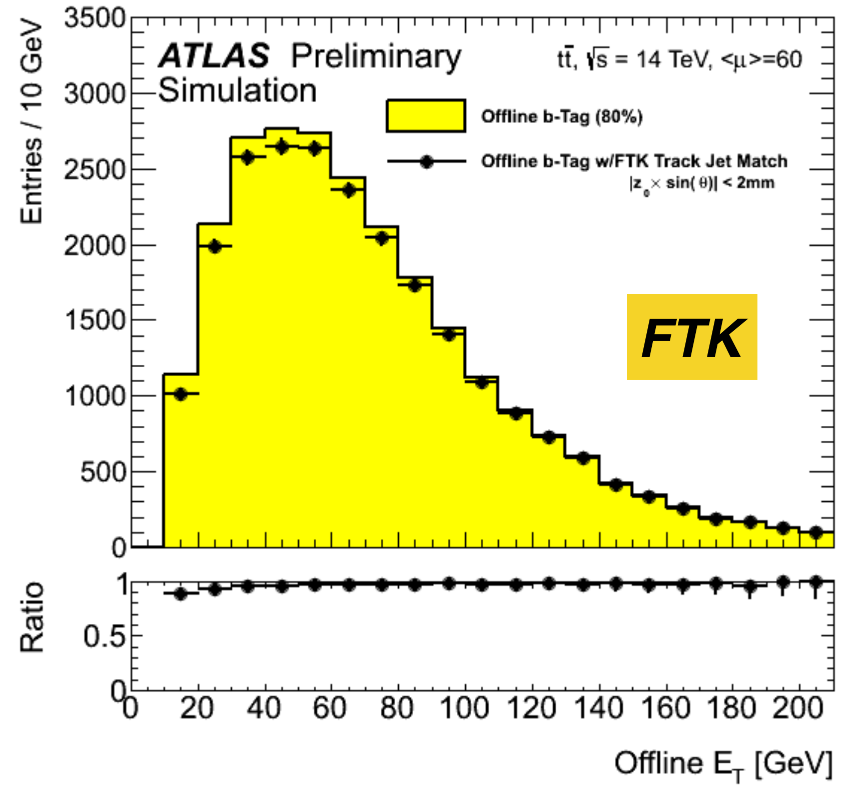






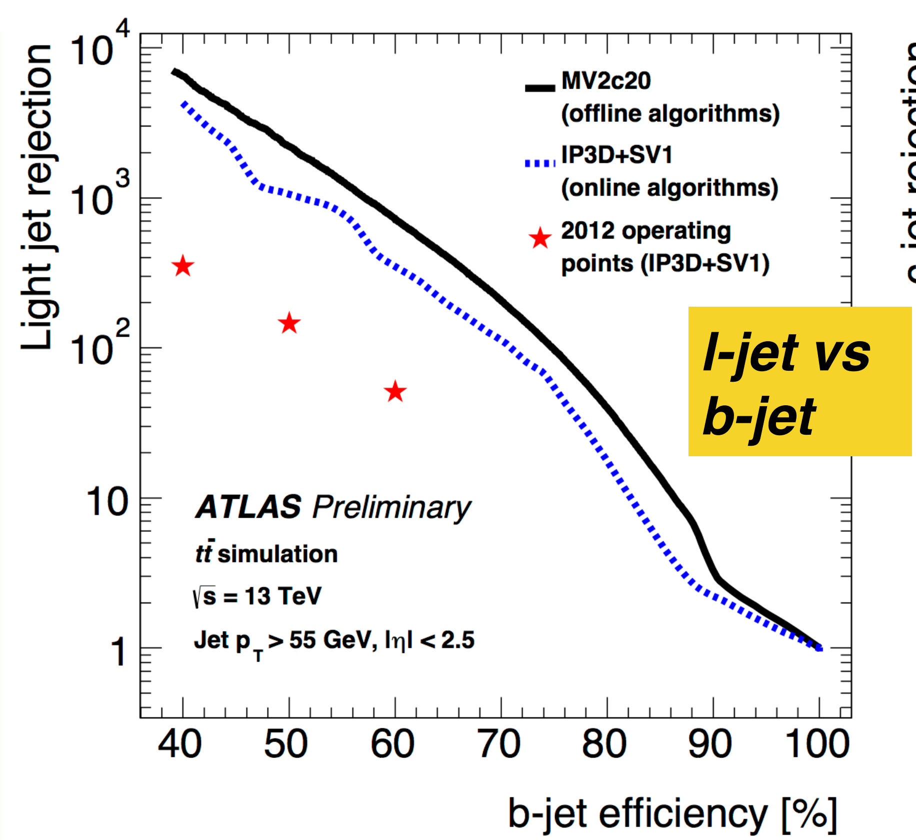
b-jet trigger performance at ATLAS

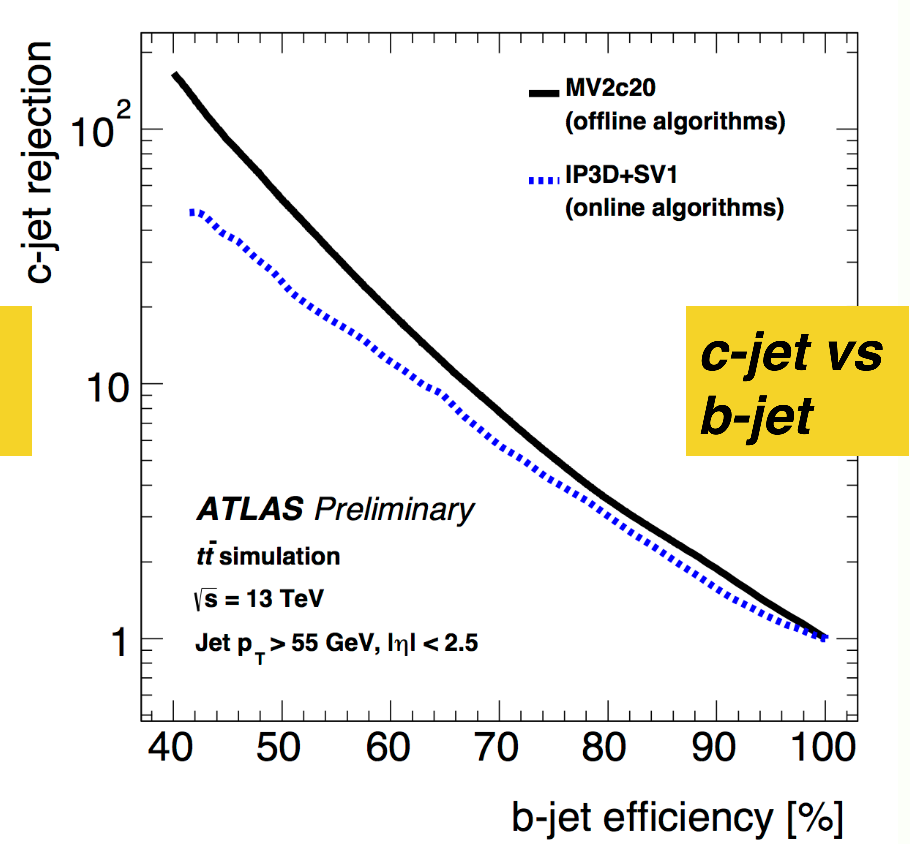




E_T of offline b-tag jets matched to L1 or FTK jets

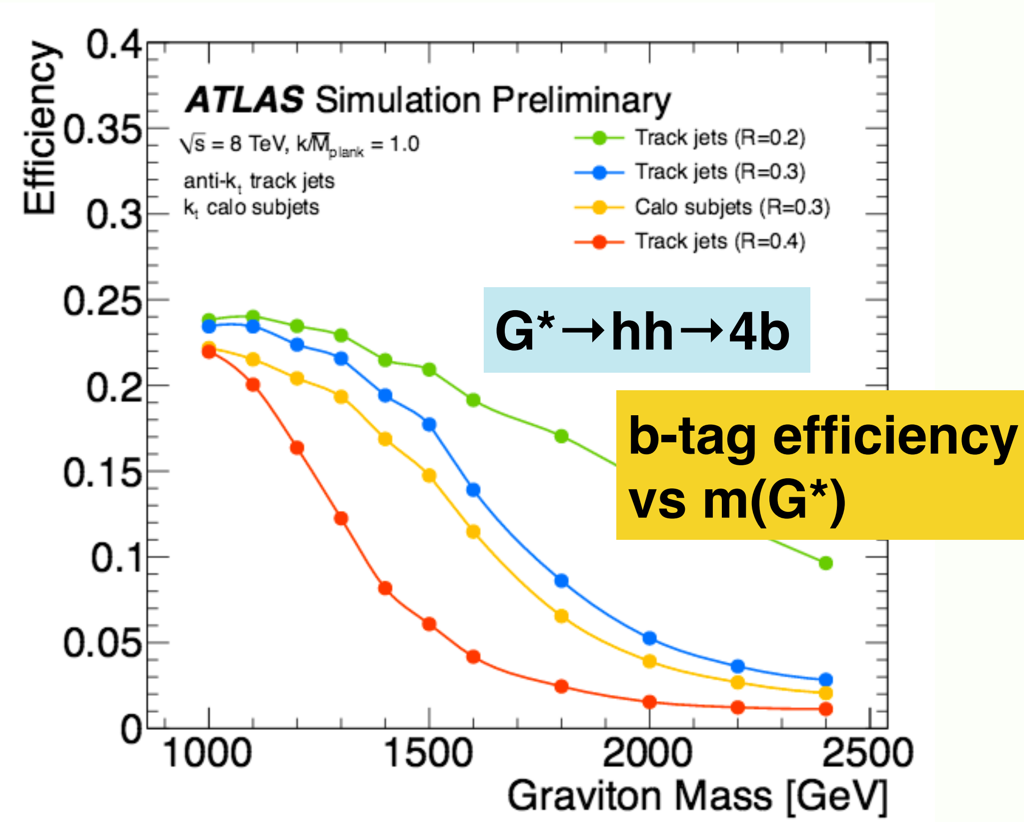
Expected b-tagging performance online vs offline

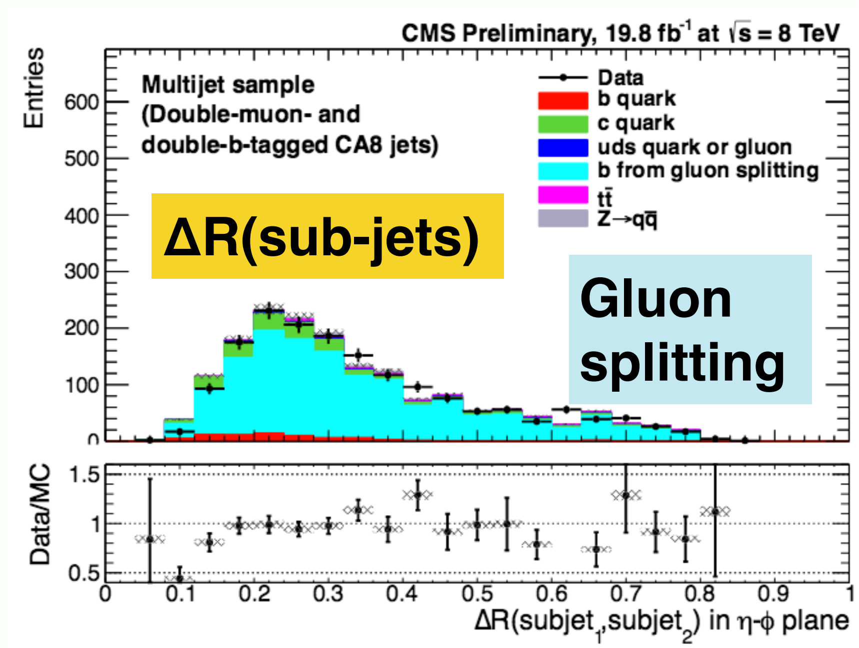


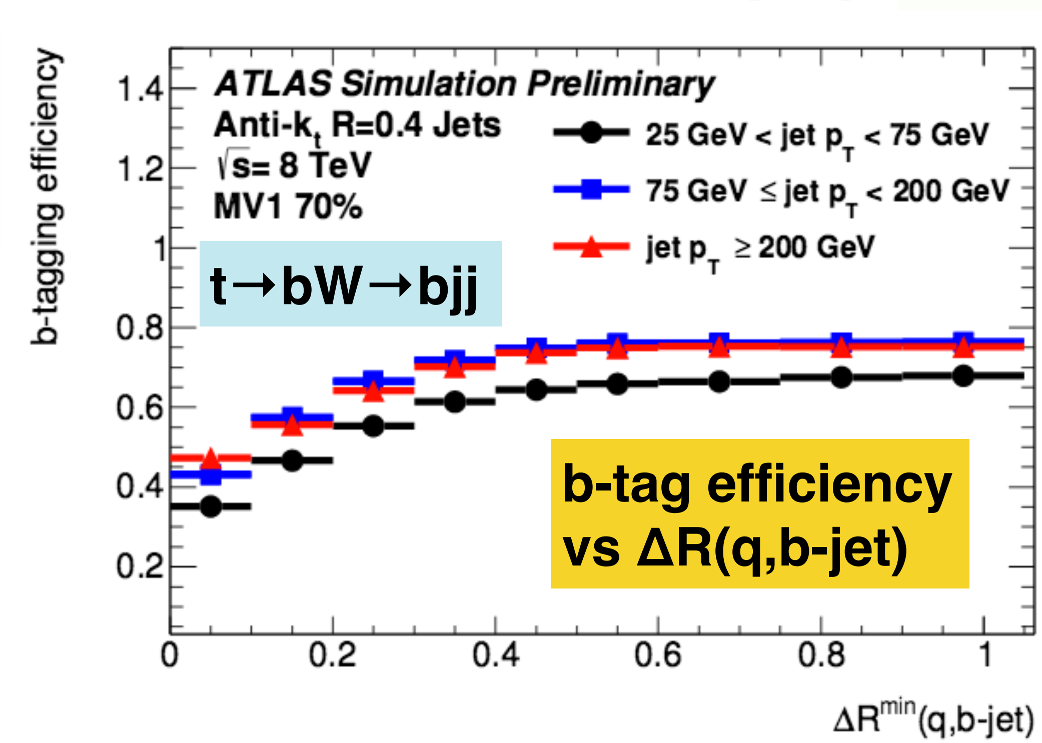


b-tagging in boosted topologies

- **More boosted objects** with the increase of total energy, increased sensitivity to high energy search regions (ttbar resonances, new heavy quark decays)
- b-quarks could be present in decays of boosted particles
- Decay products ***clustered in a single fat (large-R) jet***
- Use ***jet substructure techniques*** to reconstruct sub-jets and apply b-tagging
  - Resolve b-jets from top quark and Higgs decays, gluon splitting
  - Different signatures define several methods:
  - **top-tagging**
  - **Double-b-tagging**







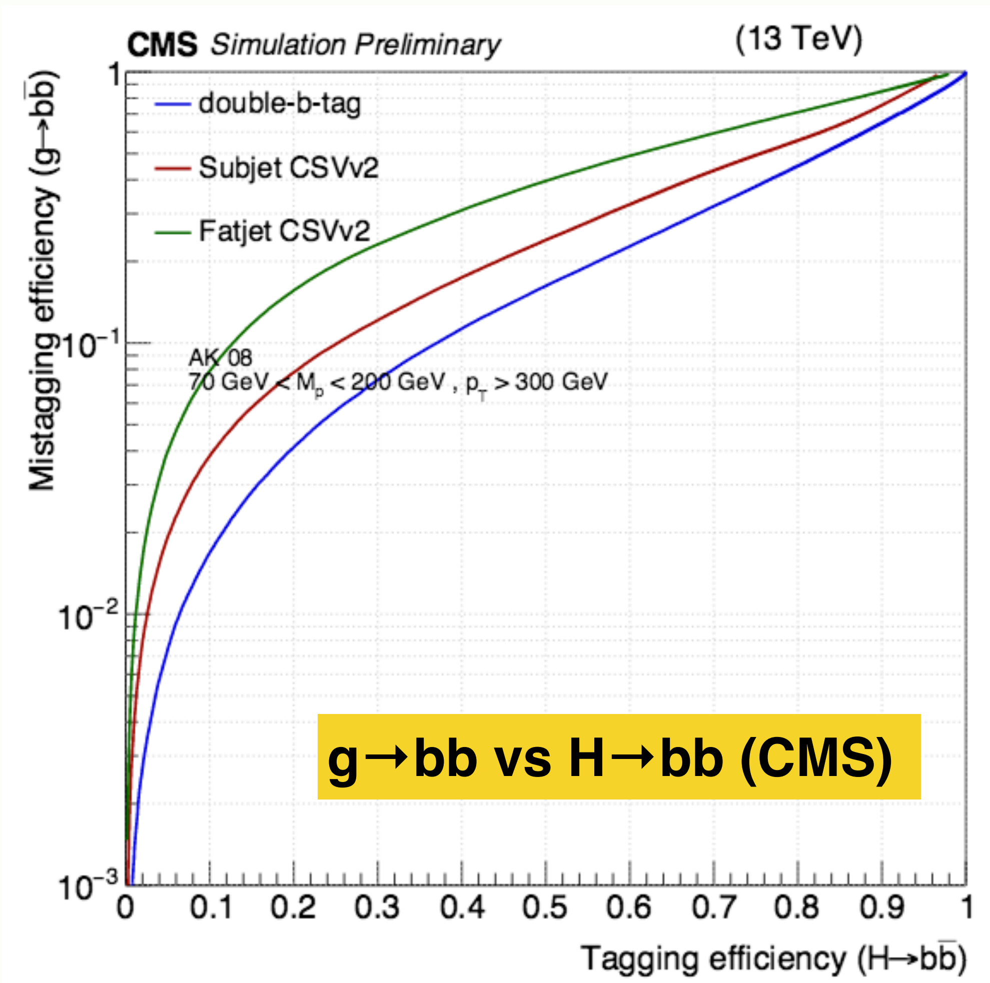
For two-body decay:

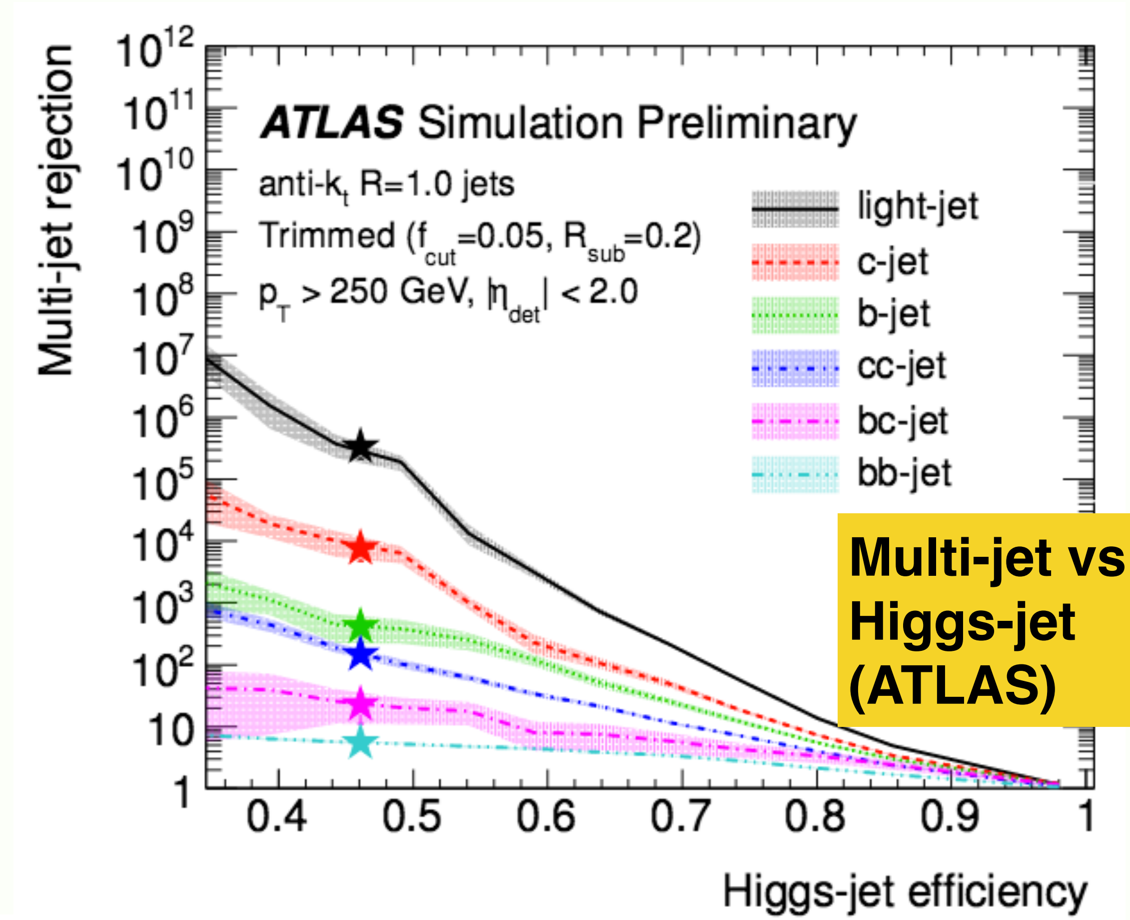
$$\Delta R \approx \frac{2m}{p_T}$$

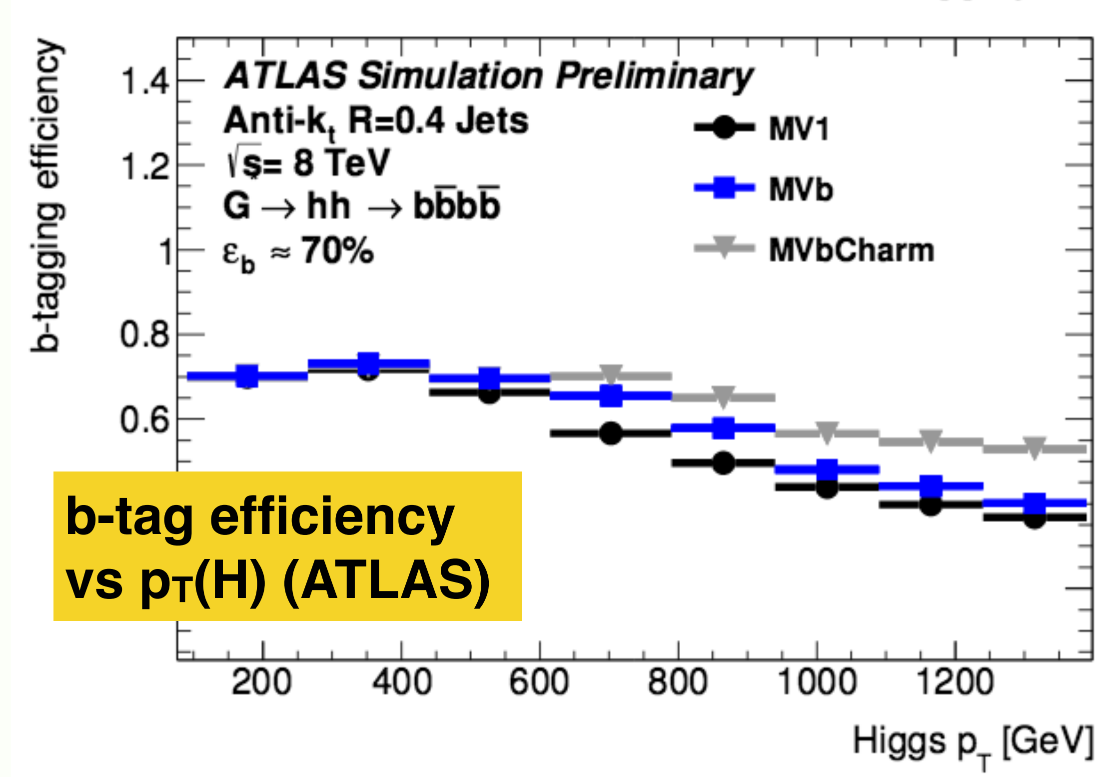
ATL-PHYS-PUB-2014-013
ATL-PHYS-PUB-2014-014
CMS-PAS-BTV-13-001

Double-b-tagging

- **Dedicated tagger** to ***tag X→bb*** events
  - Improve discrimination against g→bb
  - Trained on G*→hh→4b vs QCD

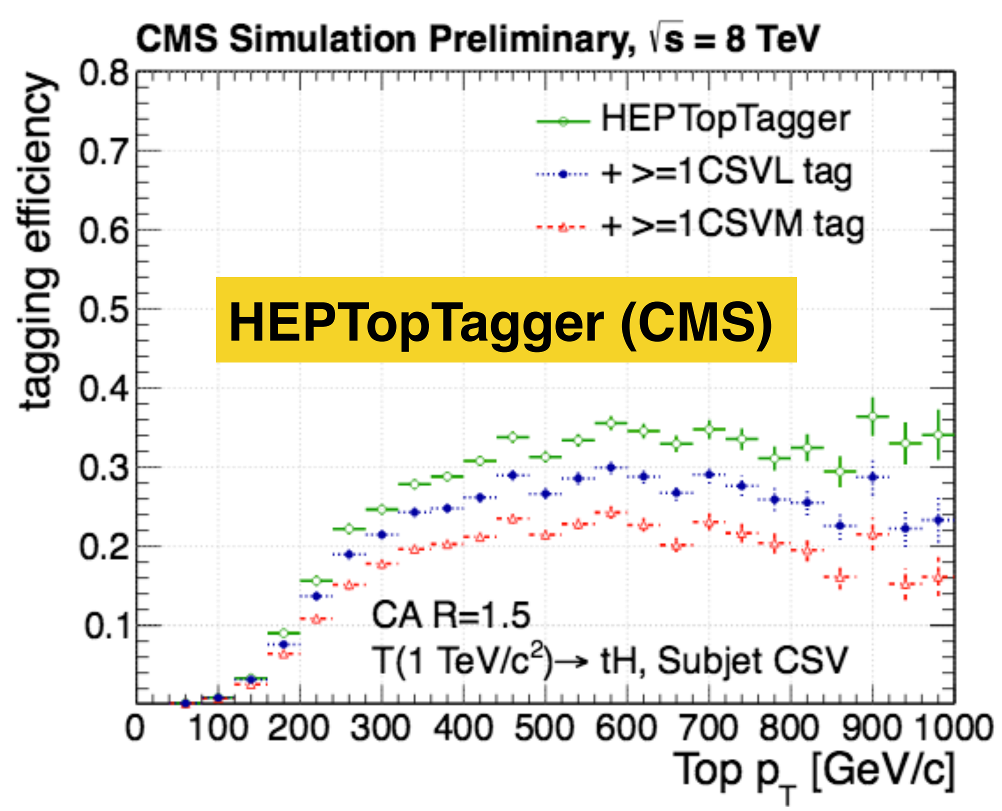




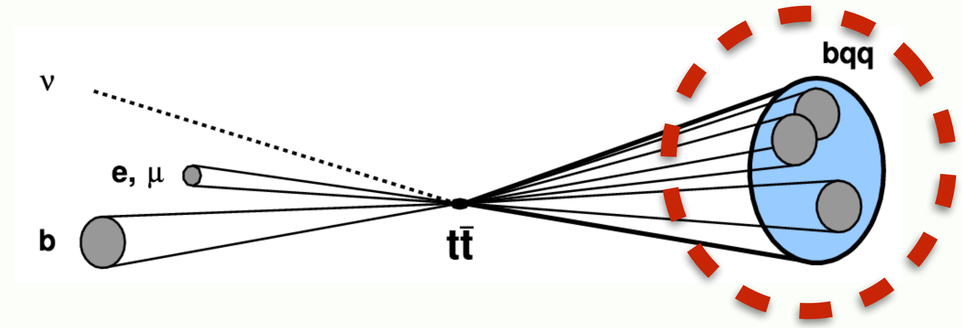


ATL-PHYS-PUB-2015-035
ATL-PHYS-PUB-2014-014
CMS DP-2015/038

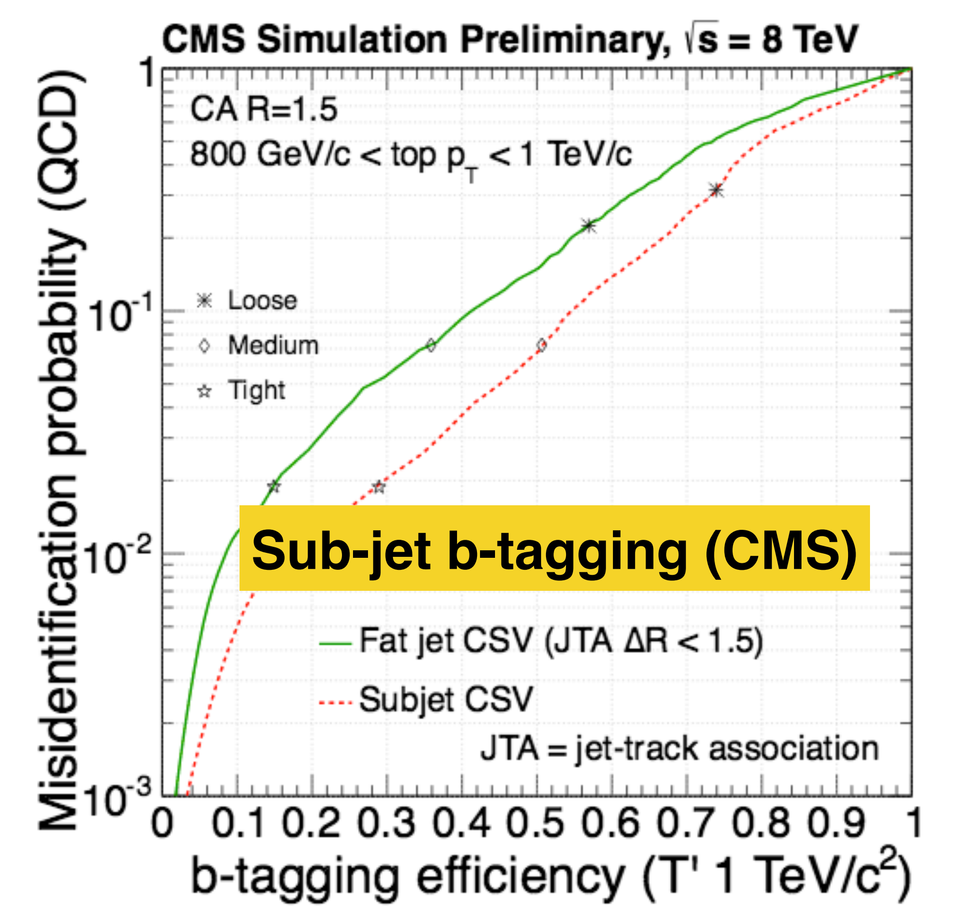
Top-tagging

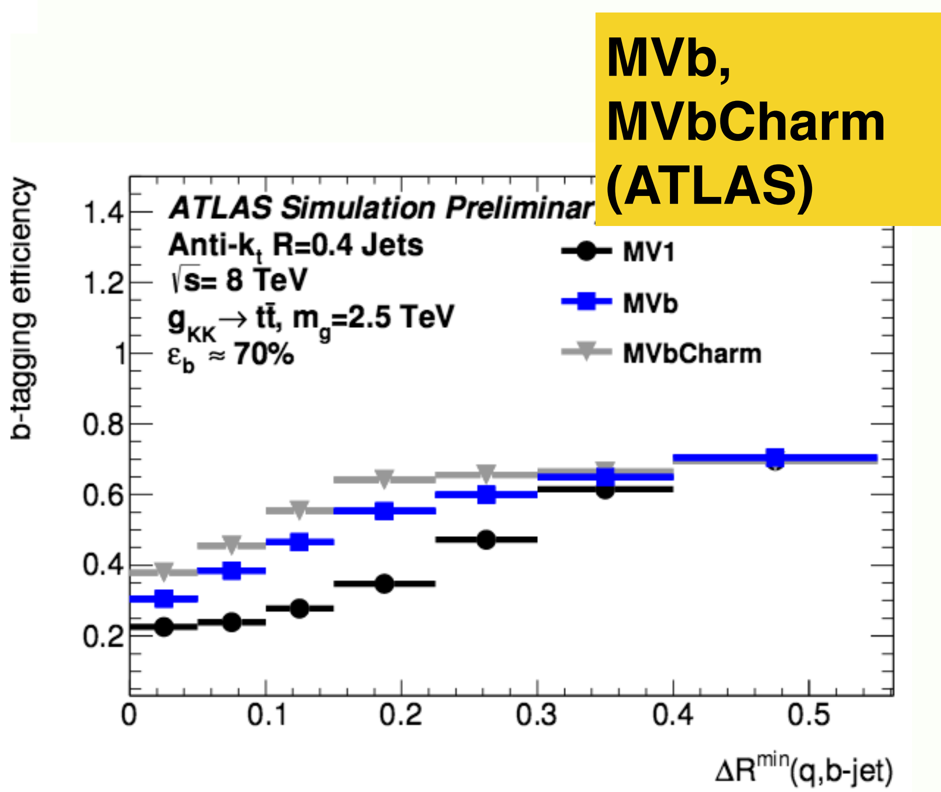


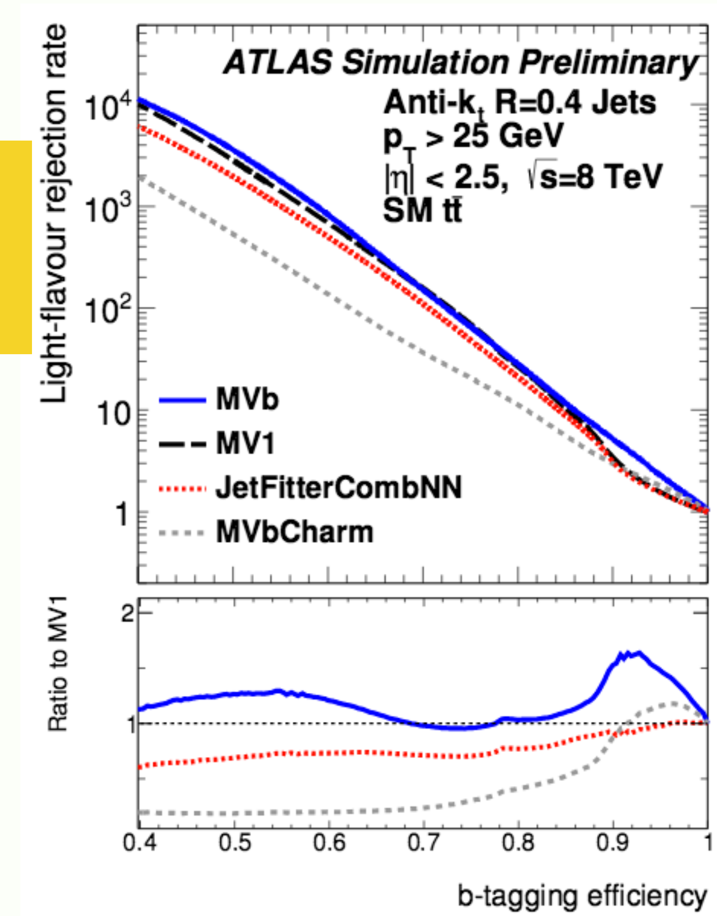
- **CMS**:
  HEPTopTagger,
  CMSTopTagger,
  General sub-jet b-tagging



- **ATLAS**:
  General BDT-based MVb (b vs l),
  MVbCharm (b vs c),
  HEPTopTagger

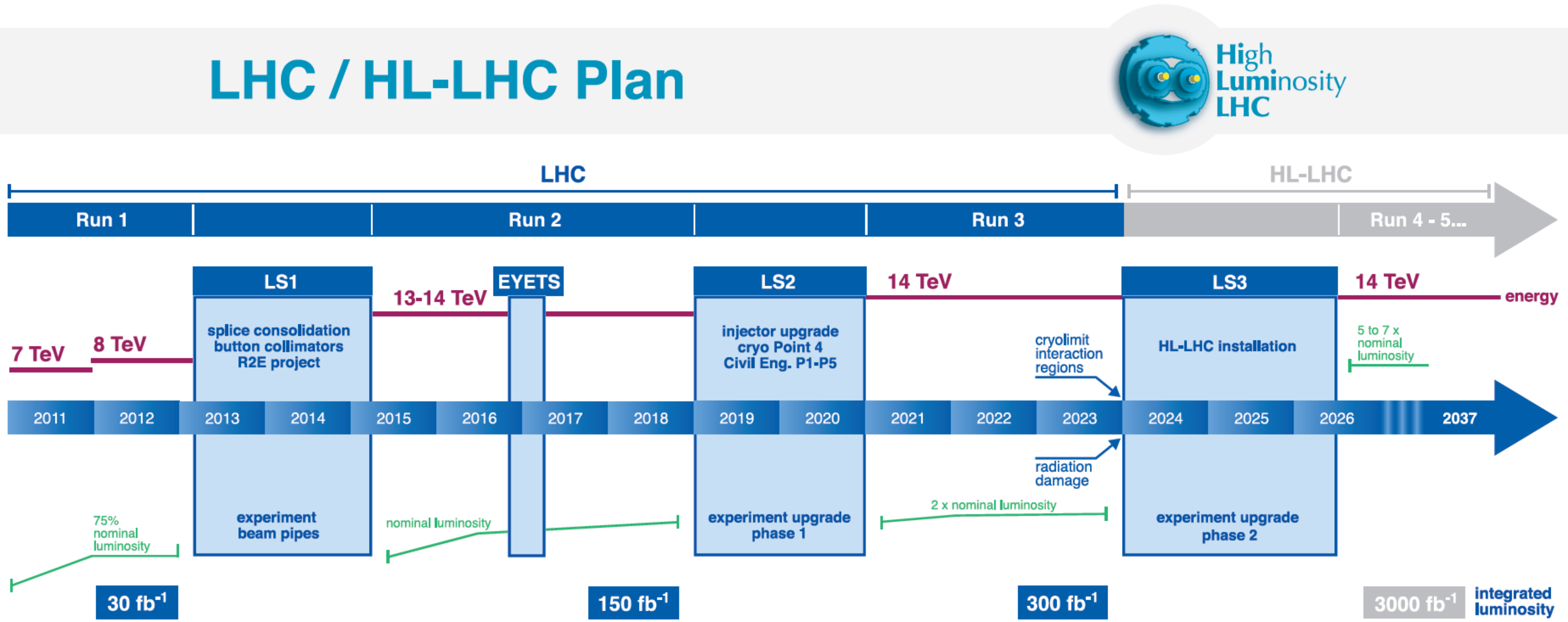






ATL-PHYS-PUB-2014-014
CMS-PAS-BTV-13-001

LHC roadmap



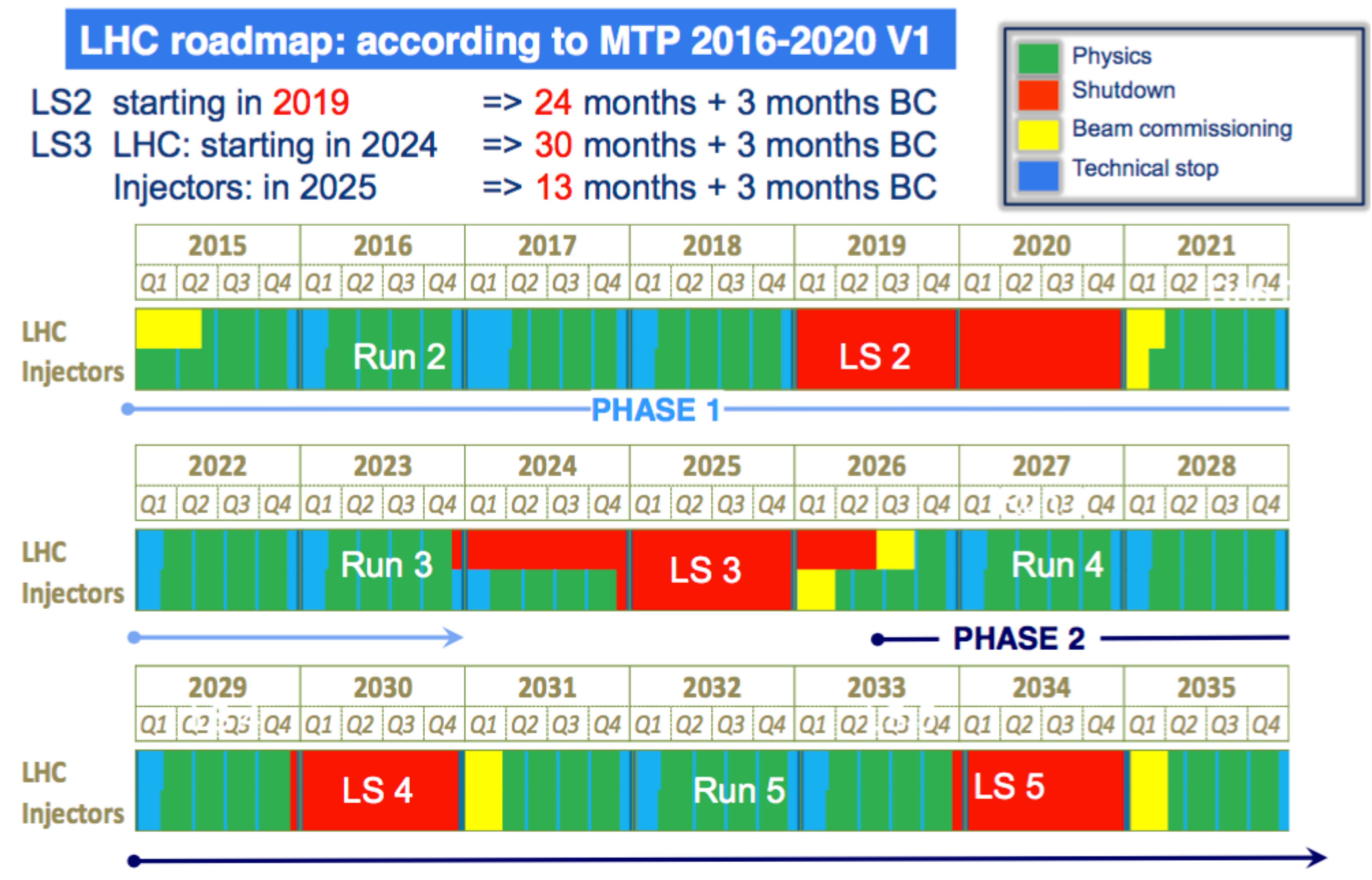
L = 0.75×10^{34}
50ns bunch
pileup ≈ 25

L = 1.5×10^{34}
25ns bunch
pileup ≈ 20-50

L = $1.7\text{-}2.2 \times 10^{34}$
25ns bunch
pileup ≈ 60

http://hilumilhc.web.cern.ch

LHC roadmap



https://lhc-commissioning.web.cern.ch

Systematics in b-tag efficiency measurement

- Several uncertainties affect the measurement of b-tagging efficiency
  - ☑ Gluon splitting
  - ☑ b/c-quark fragmentation
  - ☑ Muon p_T
  - ☑ Away-jet tagger
  - ☑ c/l ratio
  - ☑ Selection on p_TRel
  - ☑ Difference between inclusive and muon jets
  - ☑ Generator uncertainties (PDF, parton shower, ISR/FSR, underlying event, B decay, etc.)
  - ☑ Pileup

source	size at ATLAS	size at CMS
b/c prod.	low pT: 0.1% - 0.2%, high pT for b-prod.: 1.2% - 2.0%	low pT: 0.1% - 0.3%, high pT: 0.5% - 1.3%
mu pT	first pT bin: 2.5%, 0.2% - 0.9% elsewhere	low pT: 0.1% - 1.1%, high pT: 0.1 - 0.9%
c/l ratio	<0.1% - 0.2%	<0.1% - 0.2%
b-frag	0.2% - 2.7%	0.2% - 0.8%
PS	0.1% - 1.5%	0.3% - 0.6%
IFSR	0.3% - 1.4%	0.3% - 0.6%

Treatment of correlations in b-tagging uncertainties between ATLAS and CMS:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/BTaggingSystematics

Current FCNH limits and future

Direct search at the LHC

Process	Br Limit	Search	Data set
$t \to qH$	7.9×10^{-3}	ATLAS $t \to t \to Wb + qH \to \ell\nu b + \gamma\gamma q$	4.7,20 fb^{-1} @ 7,8 TeV
$t \to cH$	5.1×10^{-3}	ATLAS $t \to t \to Wb + qH \to \ell\nu b + \gamma\gamma q$	4.7,20 fb^{-1} @ 7,8 TeV
$t \to cH$	5.6×10^{-3}	CMS $t\bar{t} \to Wb + qH \to \ell\nu b + \ell\ell qX$	19.5 fb^{-1} @ 8 TeV
$t \to qH$	5×10^{-4}	LHC $t\bar{t} \to Wb + qH \to \ell\nu b + \gamma\gamma q$	300 fb^{-1} @ 14 TeV
$t \to qH$	2×10^{-4}	LHC $t\bar{t} \to Wb + qH \to \ell\nu b + \gamma\gamma q$	3000 fb^{-1} @ 14 TeV
$t \to qH$	2×10^{-3}	LHC $t\bar{t} \to Wb + qH \to \ell\nu b + \ell\ell qX$	300 fb^{-1} @ 14 TeV
$t \to qH$	5×10^{-4}	LHC $t\bar{t} \to Wb + qH \to \ell\nu b + \ell\ell qX$	3000 fb^{-1} @ 14 TeV

Measured

Projected

http://arxiv.org/pdf/1508.07579.pdf

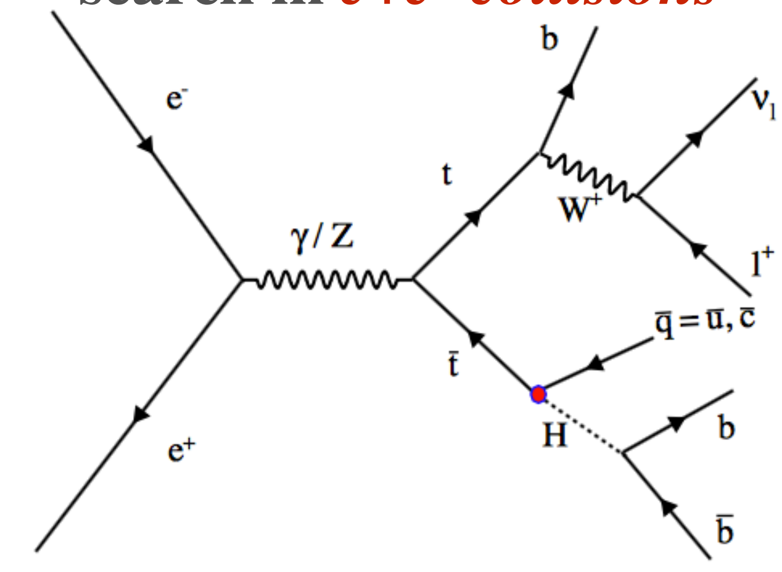
Indirect searches

D^0-$\bar{D}^0$ mixing: Br < **(5.3-7.4) · 10^{-4}**

$Z \to c\bar{c}$: Br < **2.1 · 10^{-3}**

neutron EDM: Br < **6.6 · 10^{-7}**

Projection for direct search in *e+e- collisions*

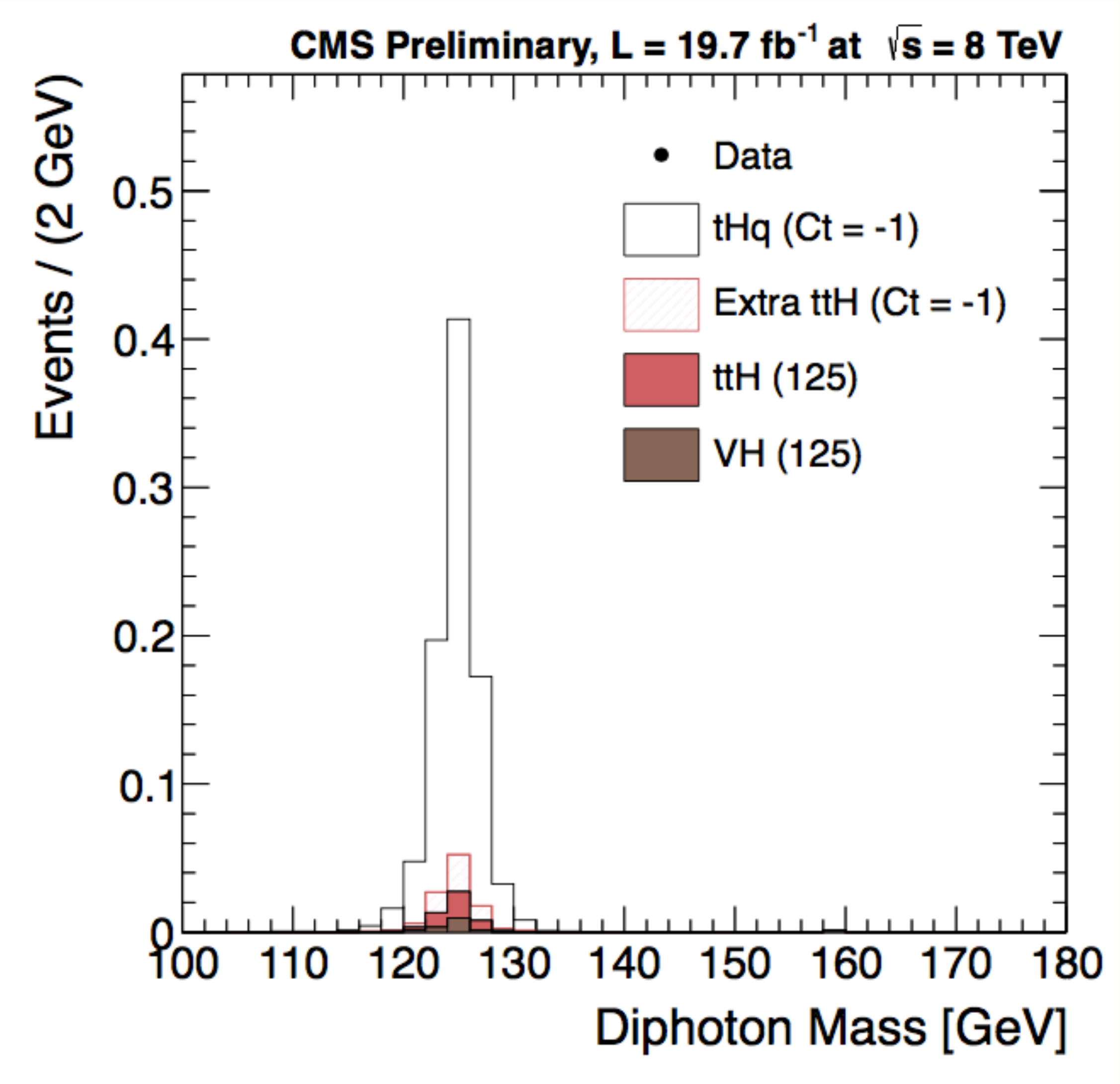


Br < **4 · 10^{-3}** @500 GeV, 300 fb^{-1}

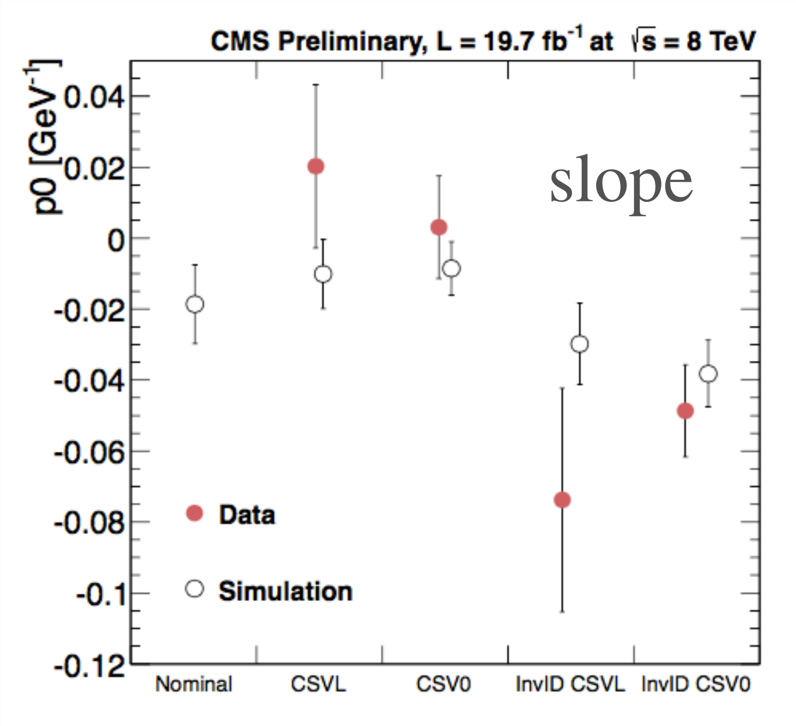
Search for tHq, H→photons at CMS

CMS-PAS-HIG-14-001
CMS, 20 fb^{-1}, 8 TeV

No events observed in data after final selection



Background estimated from the sidebands

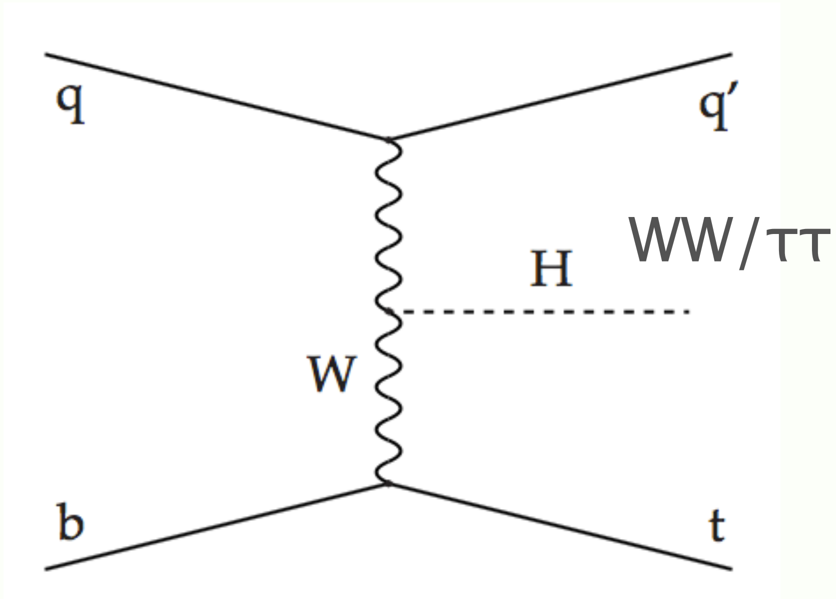


Observed limit (95% CL):

$\sigma/\sigma[y_t=-1] < 4.1$

Search for tHq, H→leptons at CMS

CMS-PAS-HIG-14-026
CMS, 20 fb^{-1}, 8 TeV



Same-sign dilepton and ***trilepton*** signatures

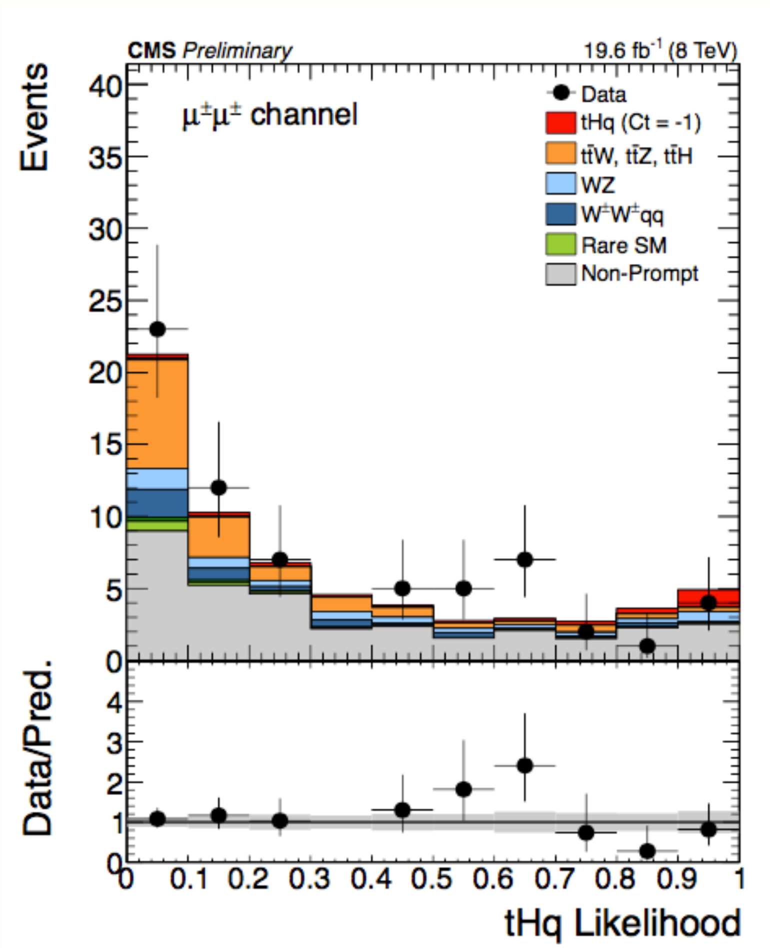
overlap with ttH

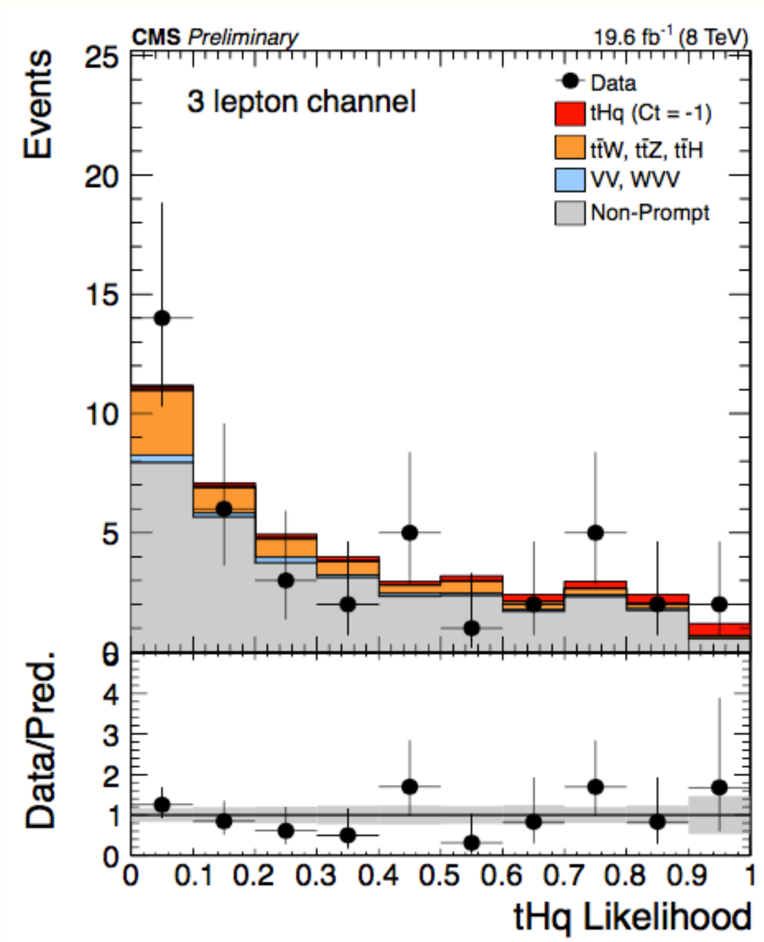
Main background:

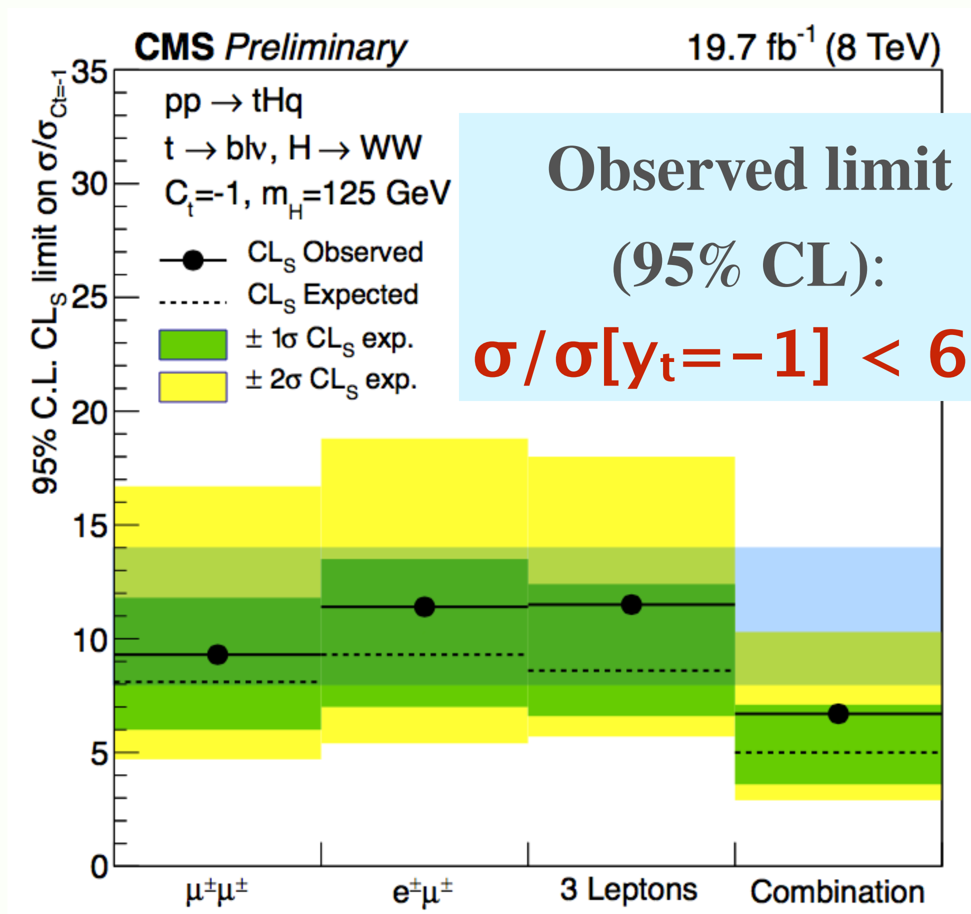
Non-prompt leptons,

ttW/Z

	Total	$\mu\mu$ ($t\bar{t}$H)	$e\mu$ ($t\bar{t}$H)	3ℓ($t\bar{t}$H)
Total		39	51	62
$\mu\mu$ (tHq)	66	19	0	0
$e\mu$ (tHq)	117	0	39	0
3ℓ(tHq)	42	0	0	14





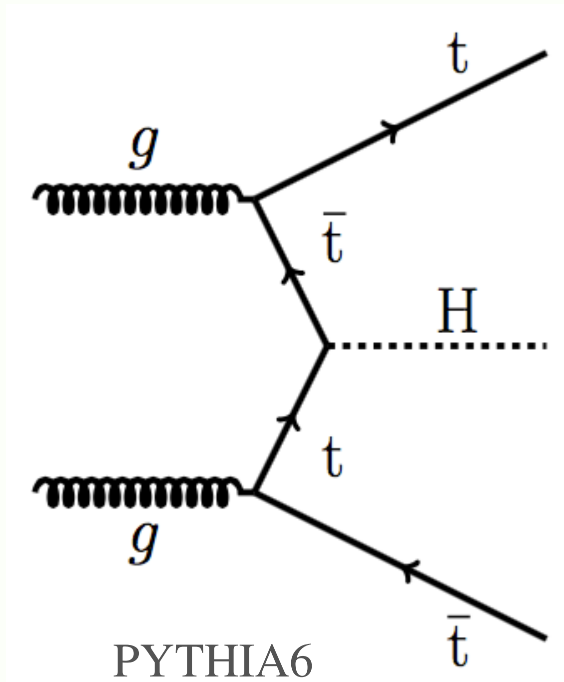


Observed limit (95% CL):

$\sigma/\sigma[y_t=-1] < 6.7$

Search for ttH, H→all channels at CMS

JHEP 1409 (2014) 087
CMS, 5+20 fb^{-1}, 7+8 TeV



- H→**hadrons**
- H→**photons**
- H→**leptons**

H→hadrons

Background: **ttbar+jets**

Signature: **lepton**+jets, **dilepton**+jets

H→photons

Background: **ttbar+jets, photon misID**

Signature: (**hadronic**) diphoton+jets

(**leptonic**) diphoton+lepton+jets

H→leptons

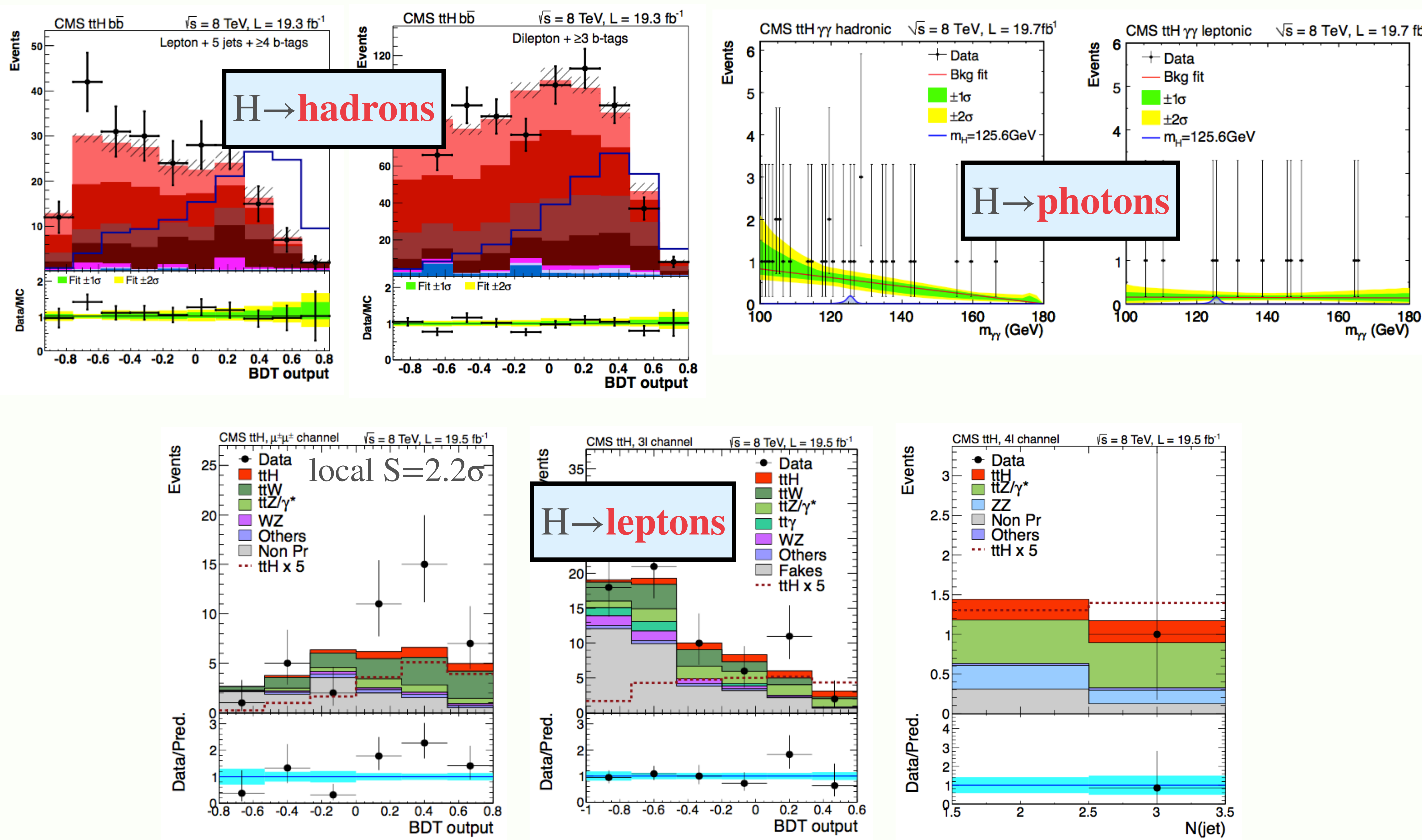
Background: **fake leptons, ttW, ttZ**

Signature: **2SS, 3, 4 leptons+jets**

Final discriminant: BDT

Search for ttH, H→all channels at CMS

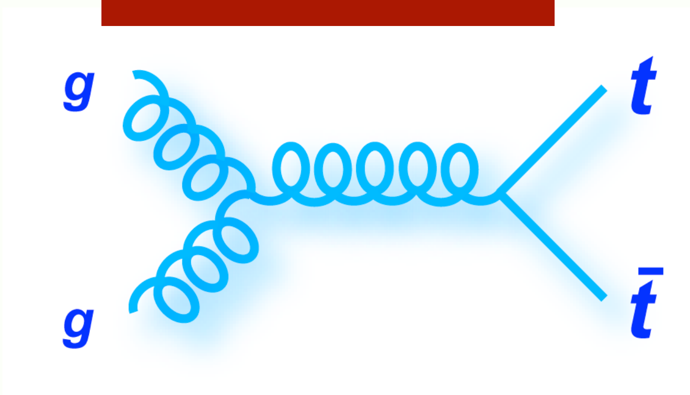
JHEP 1409 (2014) 087
CMS, 5+20 fb^{-1}, 7+8 TeV



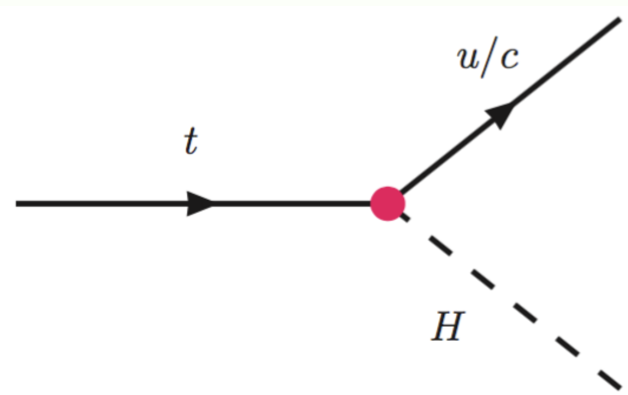
Search for t→Hq in ttbar events at CMS

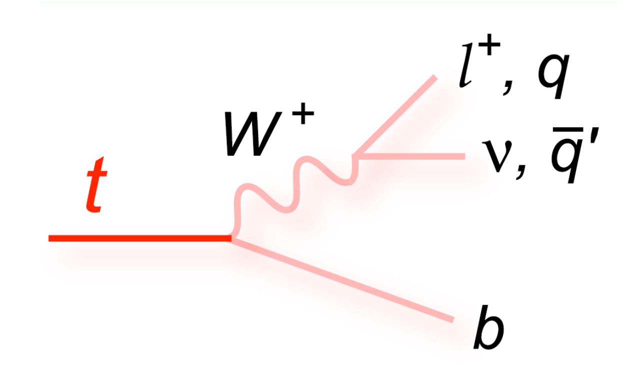
CMS-PAS-TOP-14-019
CMS, 20 fb^{-1}, 8 TeV

H→γγ channel



MadGraph@LO



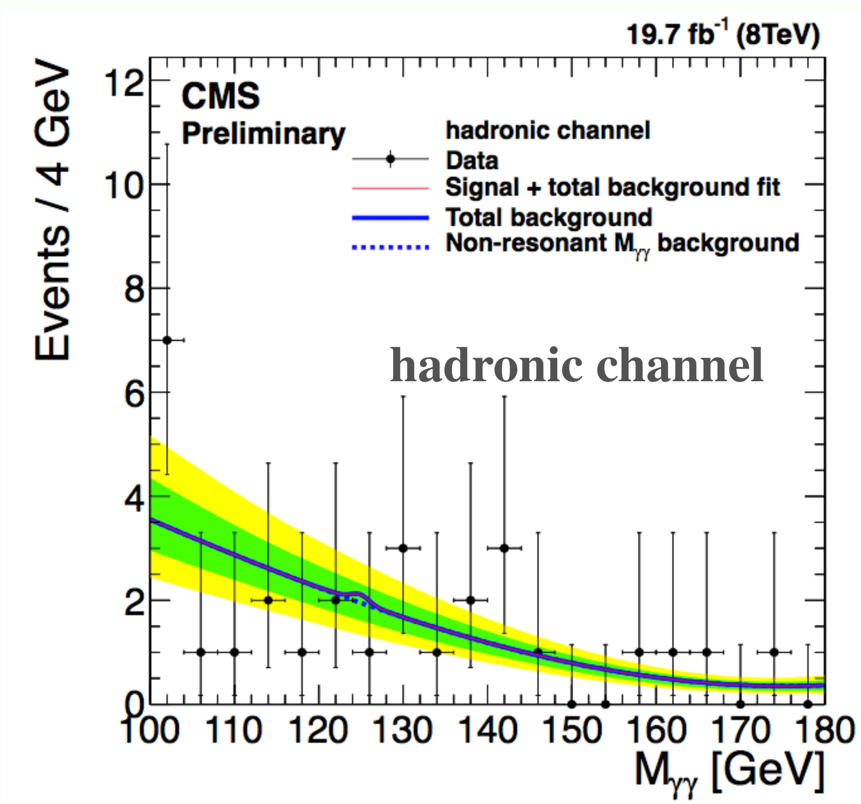


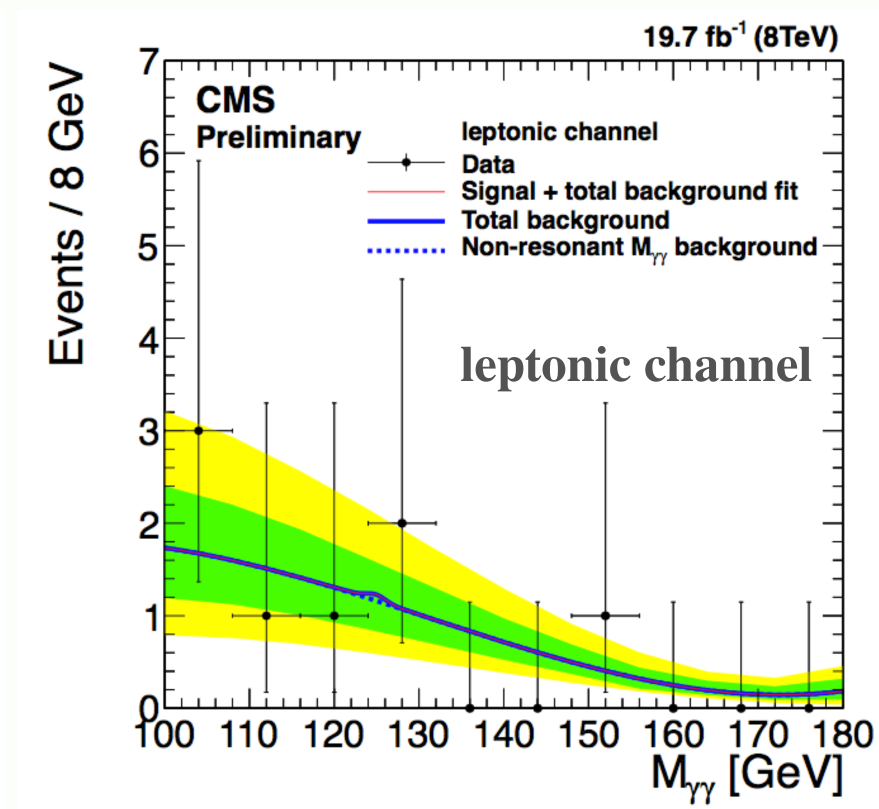
Event signature: two photons, one b-jet, 3 jets (***hadronic*** channel) or one isolated lepton, missing E_T and one b-jet and one additional jet (***leptonic*** channel)

Main background: γγ+jets, W+jets, ttbar

Non-resonant γγ+jets background estimated from the fit to data

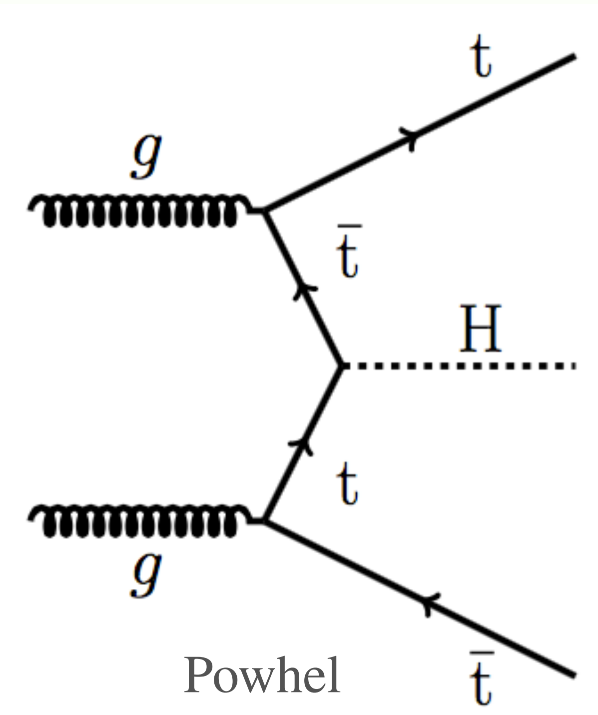
BR(t→u**H**) < 0.42 % (obs)
0.65 % (exp)
BR(t→c**H**) < 0.47 % (obs)
0.71 % (exp)





Search for ttH, H→leptons at ATLAS

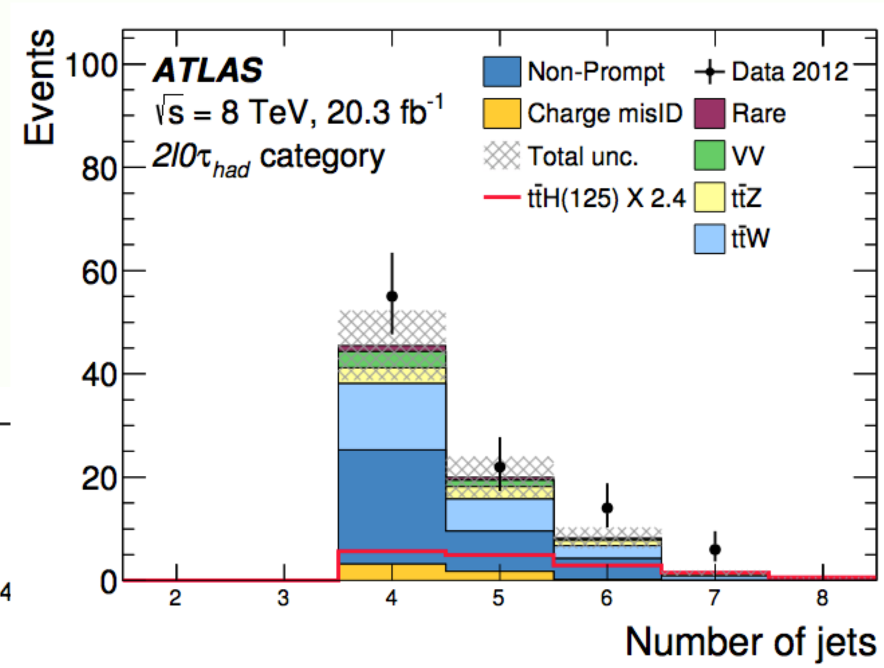
Physics Letters B 749 (2015) 519-541
ATLAS, 20 fb^{-1}, 8 TeV

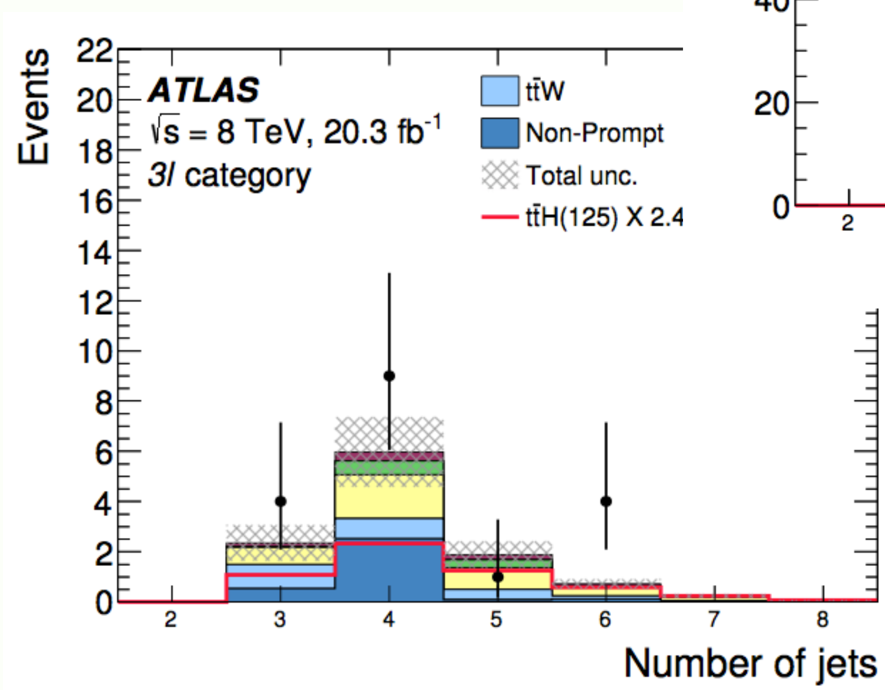


H→**leptons**

Background: **fake leptons, ttW, ttZ**

Signature: **$2l0\tau_{had}$, $2l1\tau_{had}$, $1l2\tau_{had}$, 3l, 4l**

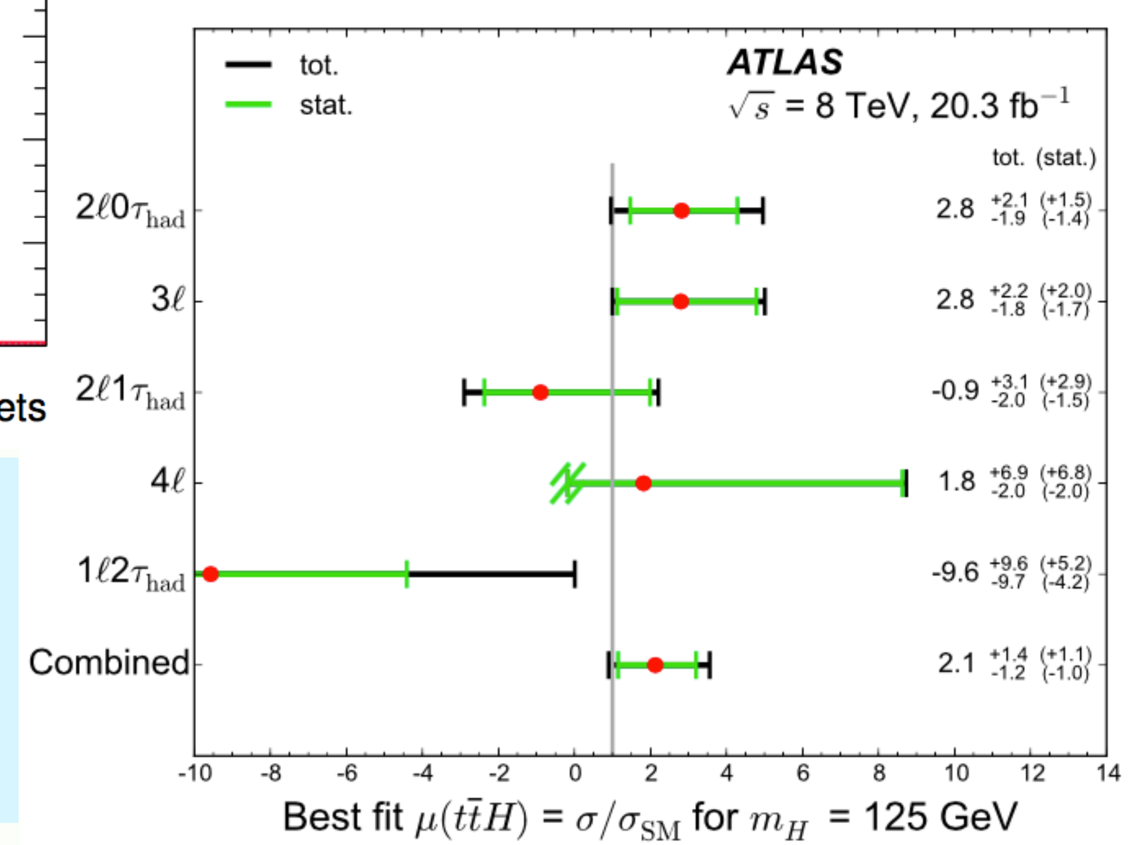




Combination:

$\mu = 2.1^{+1.4}_{-1.2}$

S = 0.9



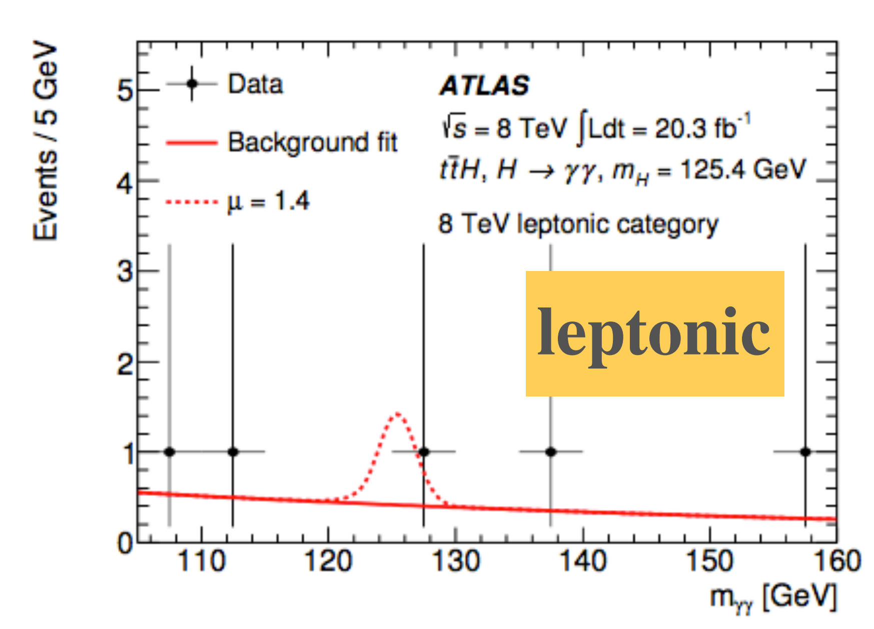
Search for tHq, H→photons at ATLAS

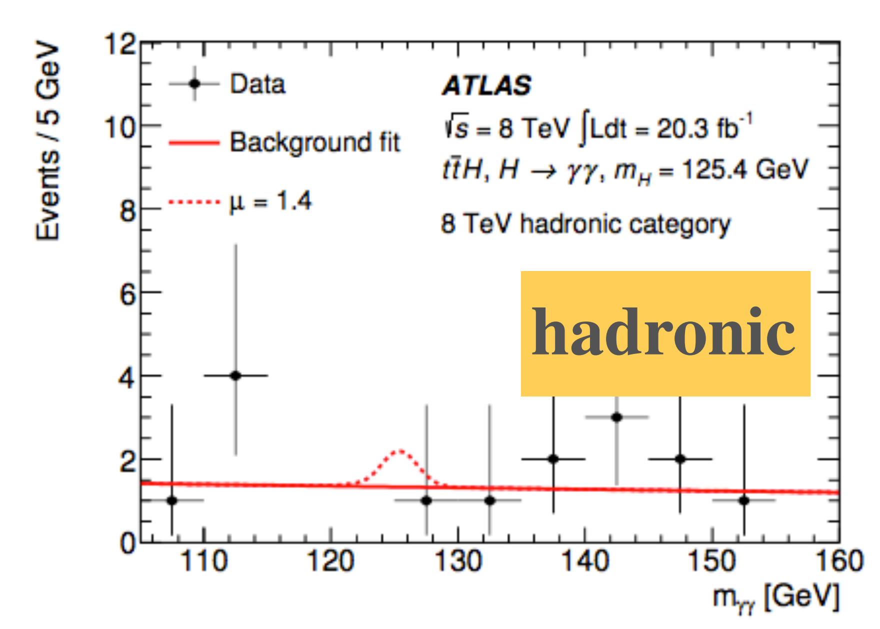
Physics Letters B 740 (2015) 222-242
ATLAS, 5+20 fb^{-1}, 7+8 TeV

Analysis is done in the context of **ttH search**

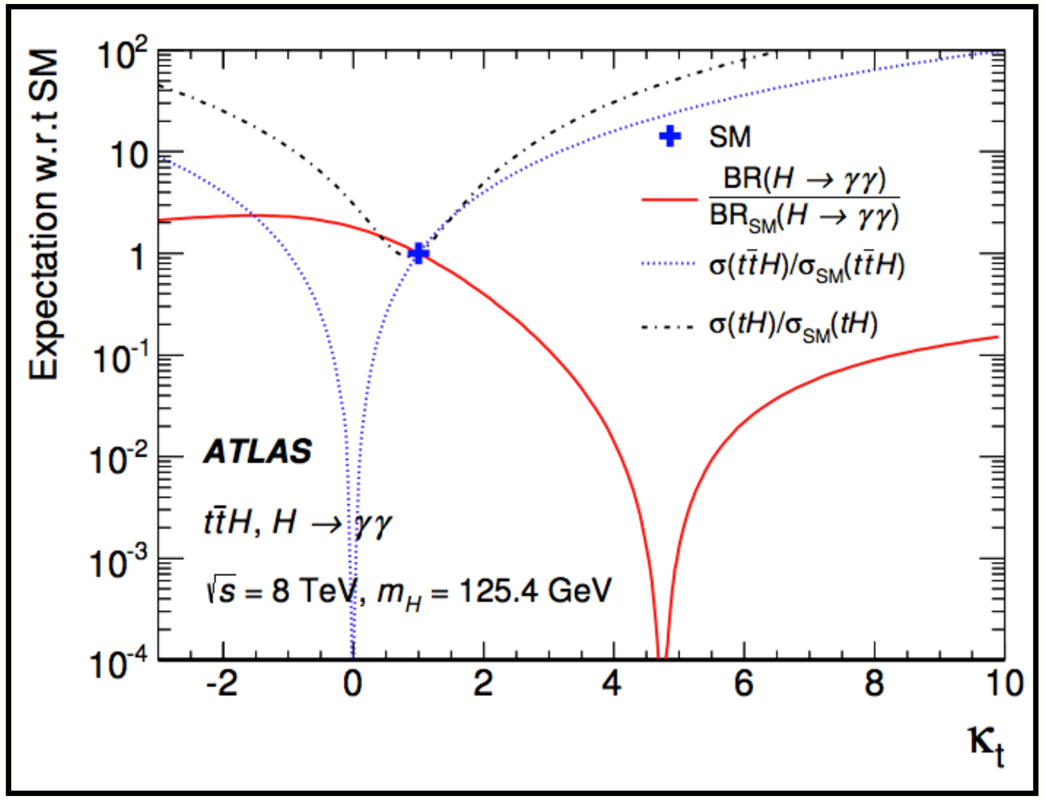
To probe the new physics, measure the scale factor $\kappa_t = y_t / y_t^{SM}$

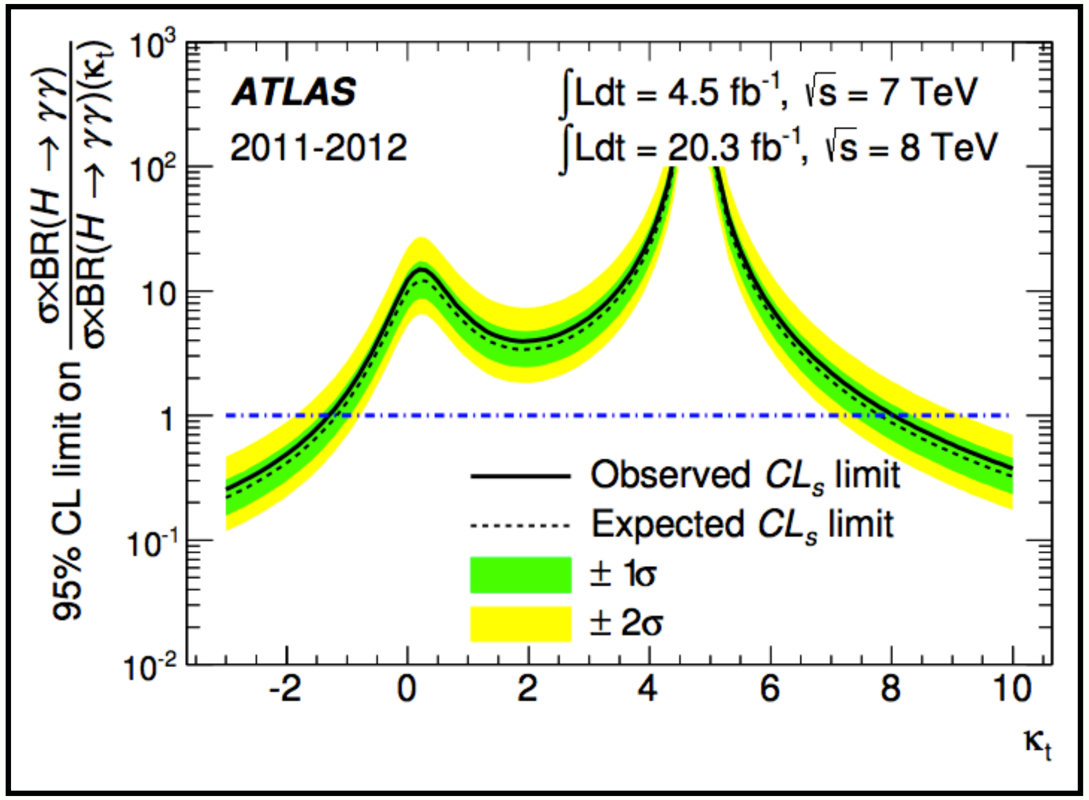
Look for ***m(γγ) resonance***





σ/σ^{SM}





Matrix Element Method (MEM)

MEM feasibility pheno studies in Phys. Rev. Lett. 111 (2013) 091802

First used to precisely measure the top quark mass at Tevatron

Integration over phase-space

Leading-order matrix element = parton level probability

Event weight

$$P(\boldsymbol{x}|\boldsymbol{\alpha}) = \frac{1}{\sigma_\alpha}\int d\Phi(\boldsymbol{y})|M_\alpha|^2(\boldsymbol{y})W(\boldsymbol{x},\boldsymbol{y})$$

experimental event

hypothesis

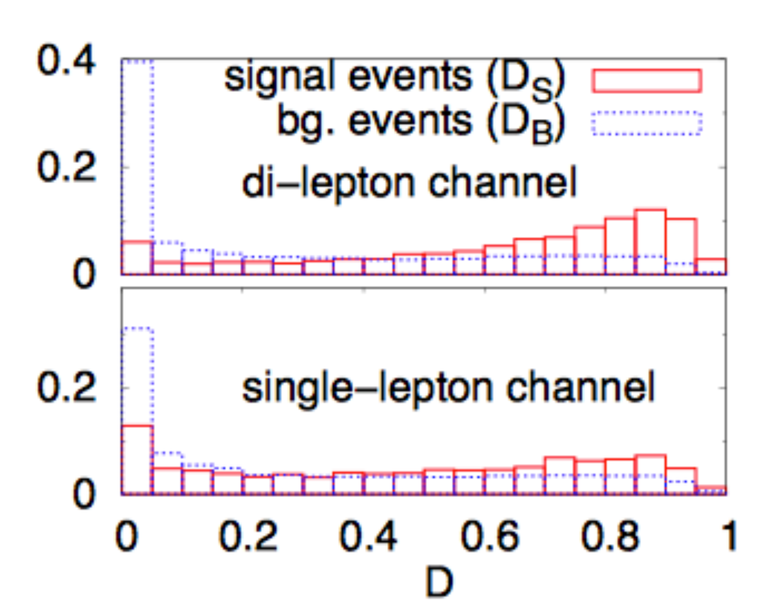
cross section

Transfer function

Likelihood is constructed **directly from the theory** prediction

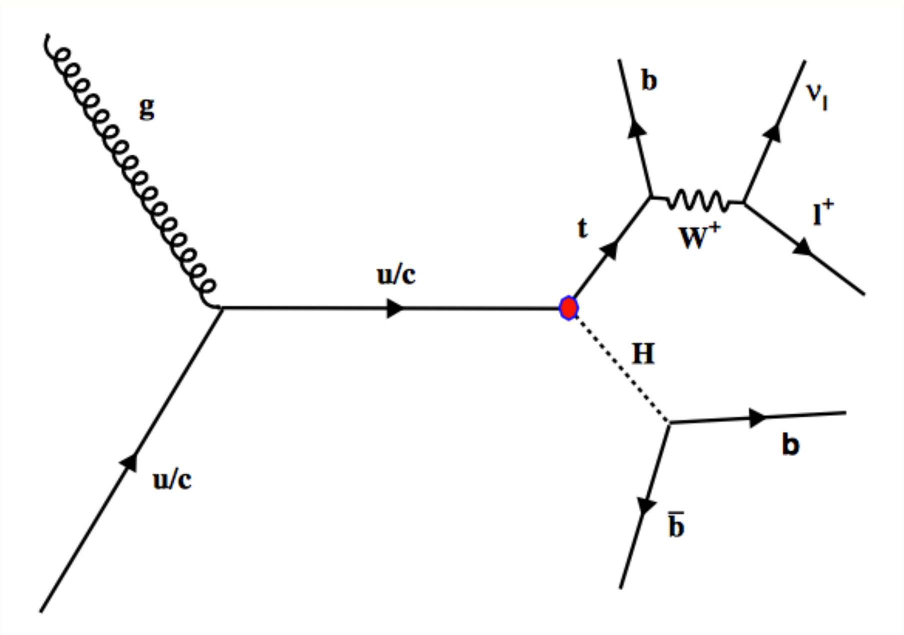
MEM-based observable

$$D_i = \frac{P(\boldsymbol{x}_i|S)}{P(\boldsymbol{x}_i|S) + P(\boldsymbol{x}_i|B)}$$



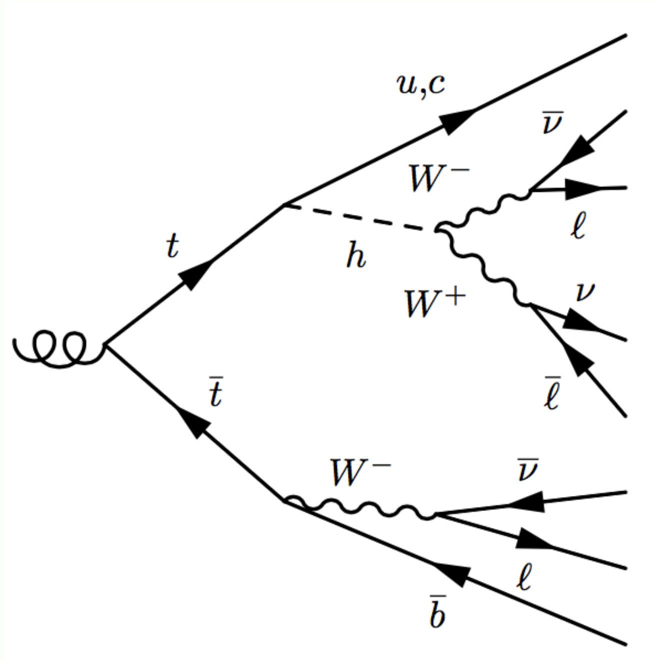
Search for FCNH

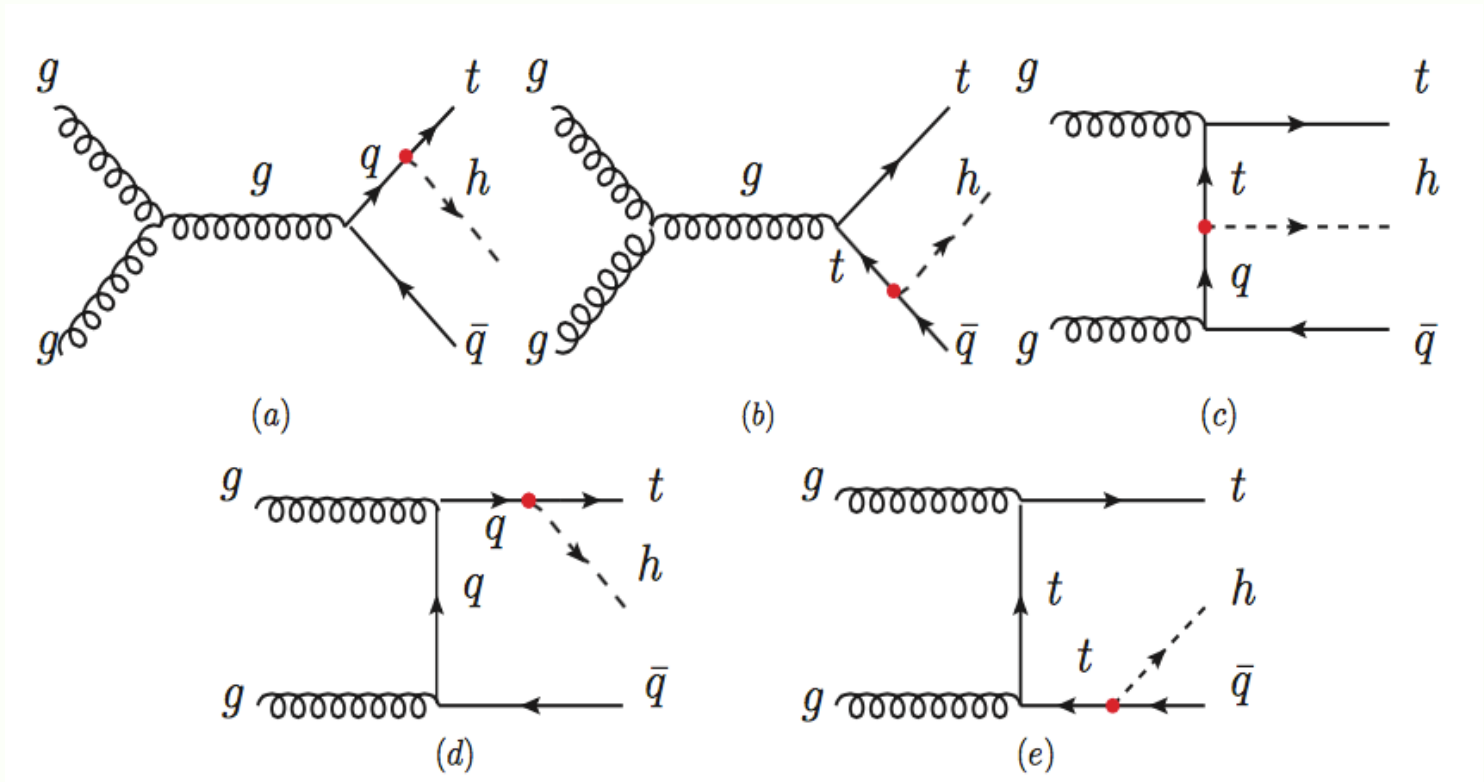
single top FCNH production



+

top FCNH decay in **ttbar** events



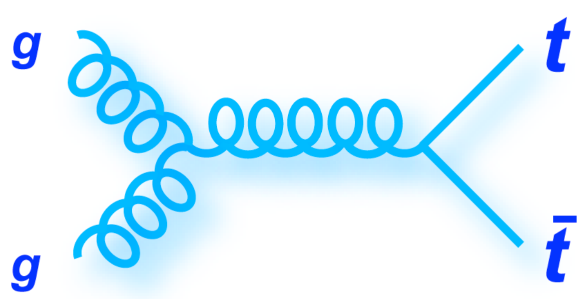


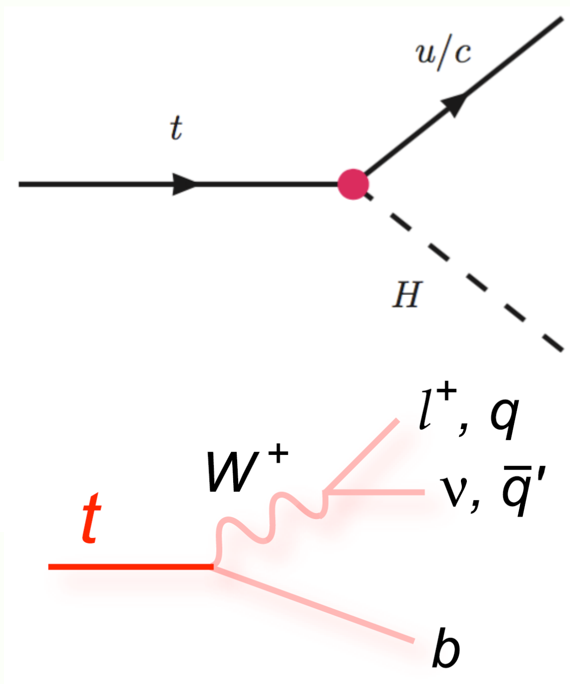
Interference with SM tHq production in higher orders (tH+jets FCNH)

Search for t→Hq in ttbar events at ATLAS

JHEP 1406 (2014) 008
ATLAS, 5+20 fb^{-1}, 7+8 TeV

H→γγ channel



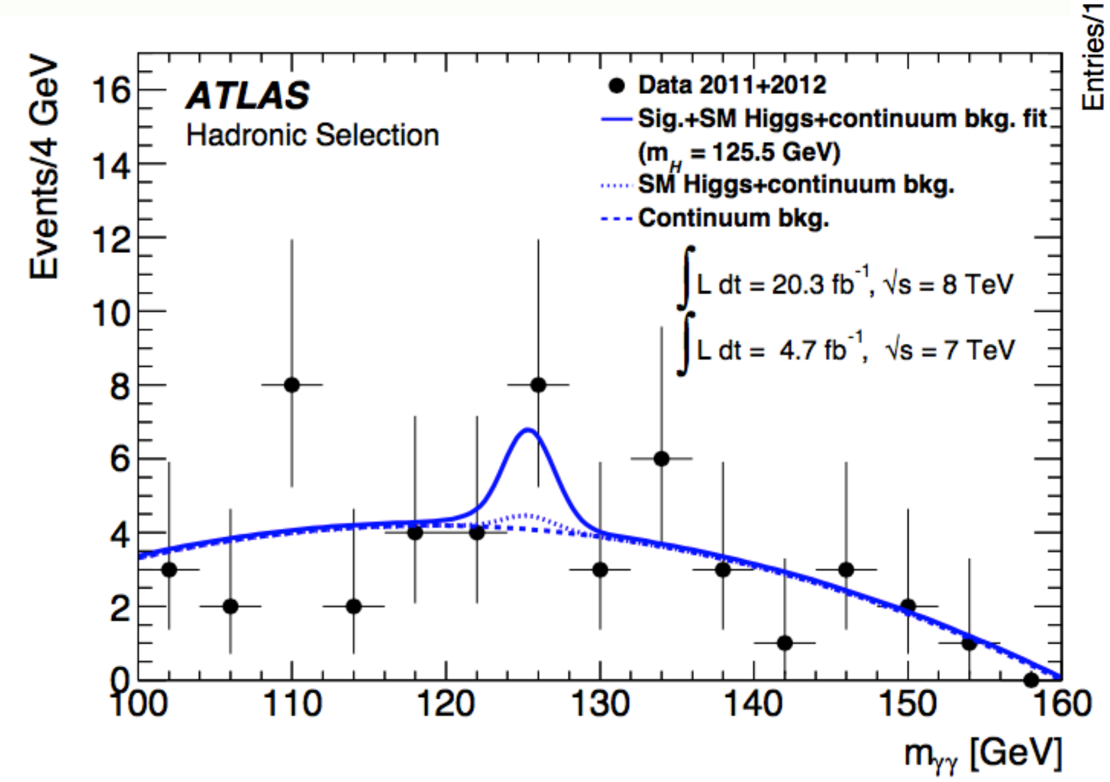


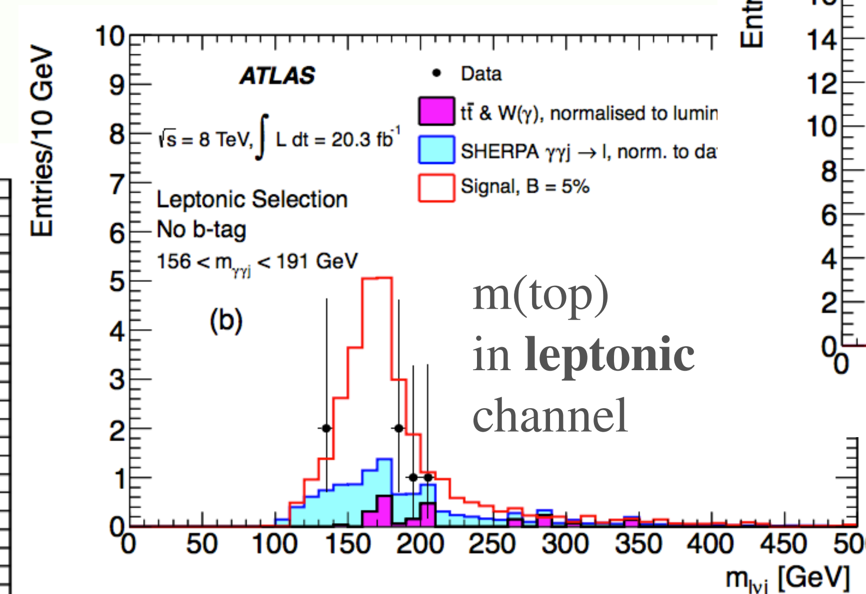
PROTOS @LO

Event signature: two photons, one b-jet, 3 jets (***hadronic*** channel) or one isolated lepton, missing E_T and one jet (***leptonic*** channel)

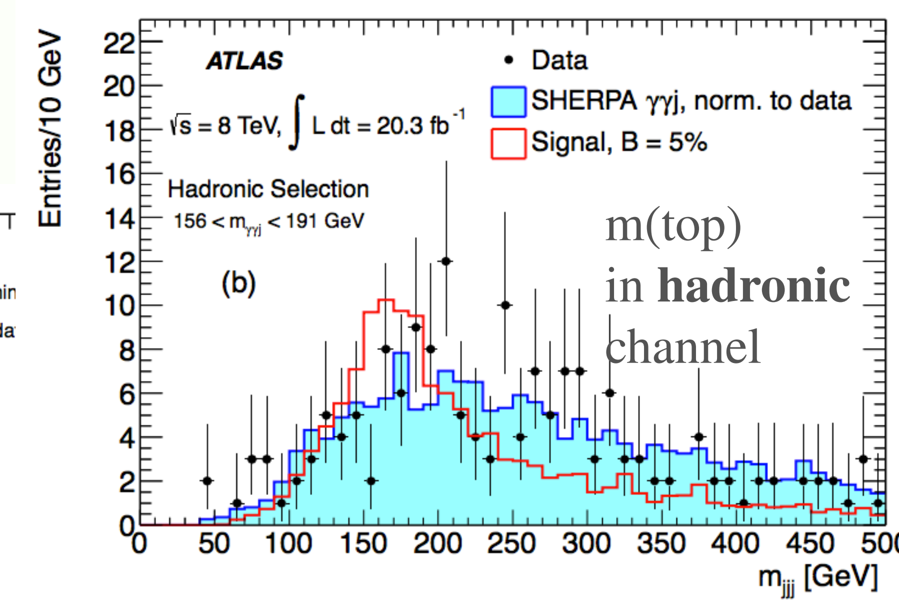
Background for **hadronic** channel estimated from γγj data sample, and from γγ(j→l) sample for **leptonic** channel

Main background: γγ+jets, W+jets, ttbar





m(top) in **leptonic** channel



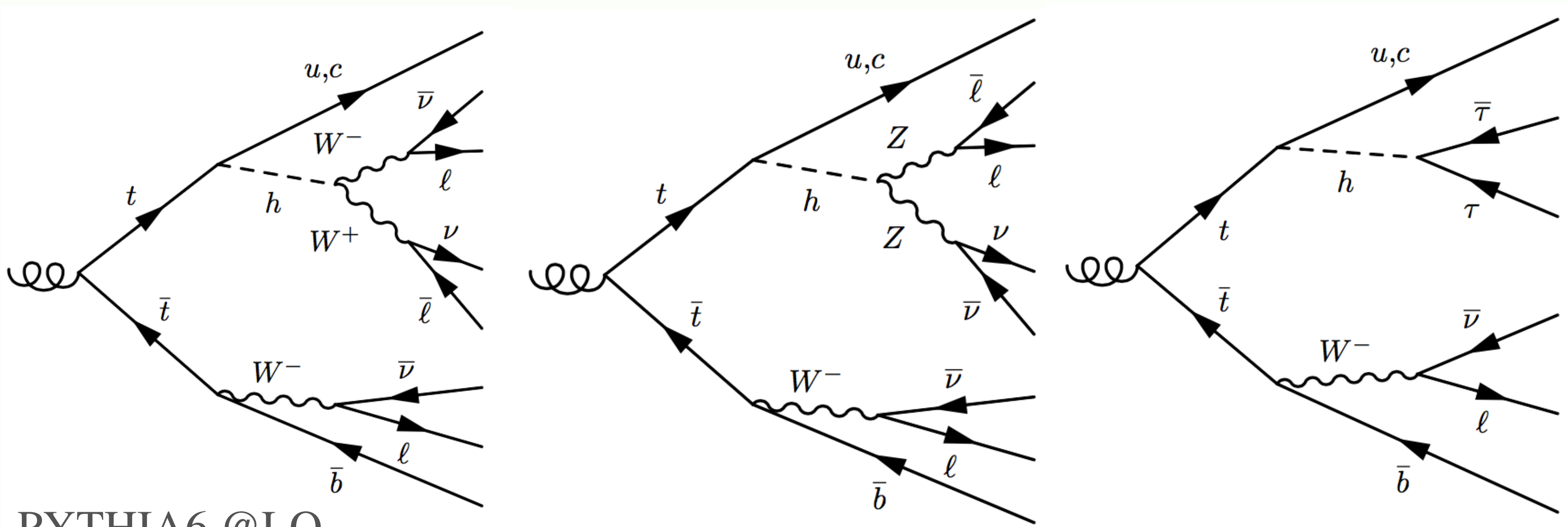
m(top) in **hadronic** channel

$\kappa_{qHt} < 0.17$

BR(t→q**H**) < 0.79 % (obs)
0.51 % (exp)

Search for t→Hq in ttbar events at CMS

CMS-PAS-TOP-13-017
CMS, 20 fb^{-1}, 8 TeV



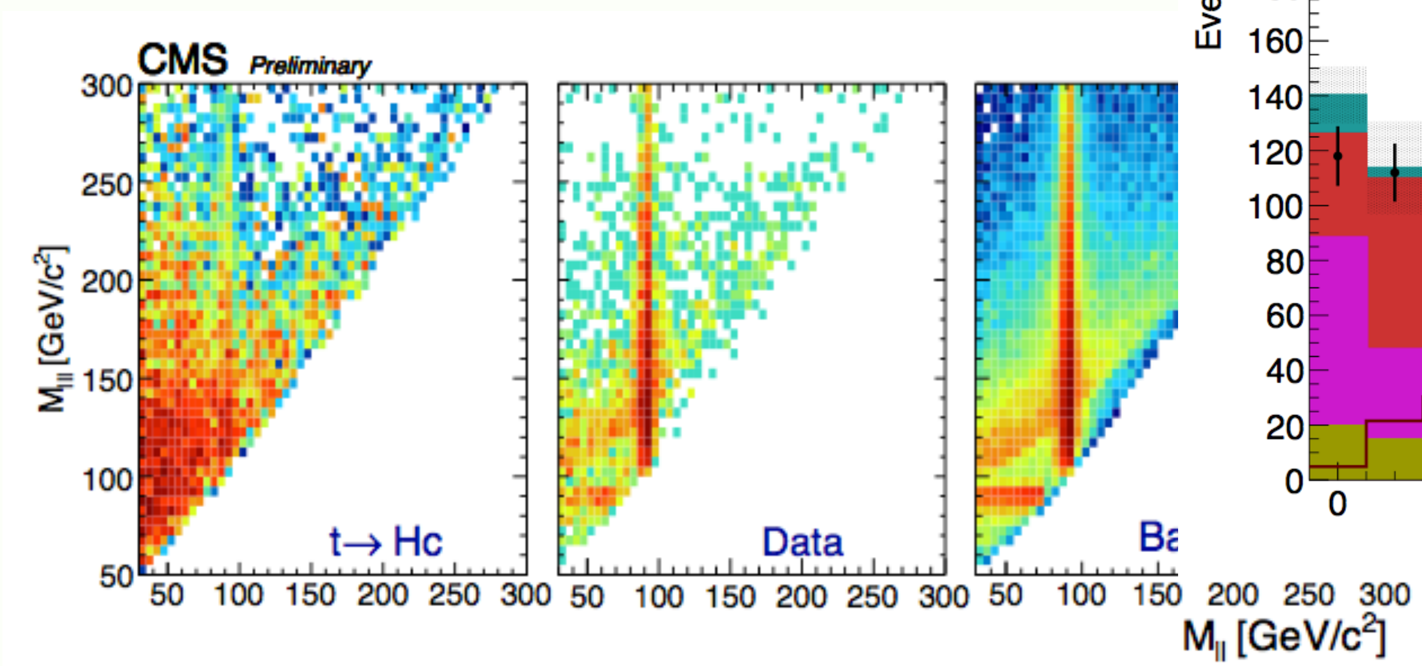
PYTHIA6 @LO

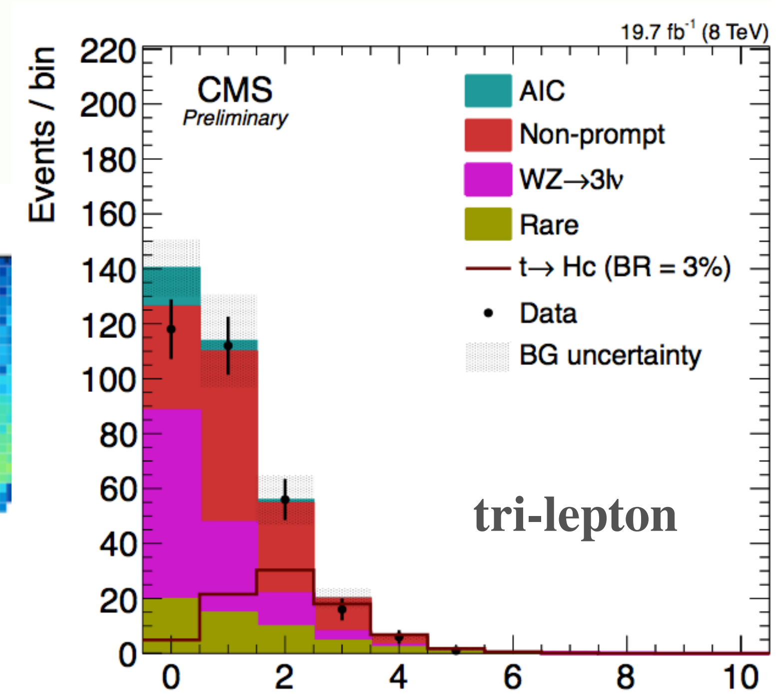
H→WW/ZZ/ττ channel

Event signature: **three** or **two** **same-sign** leptons, one b-jet, missing E_T, $\geq$ 2 jets

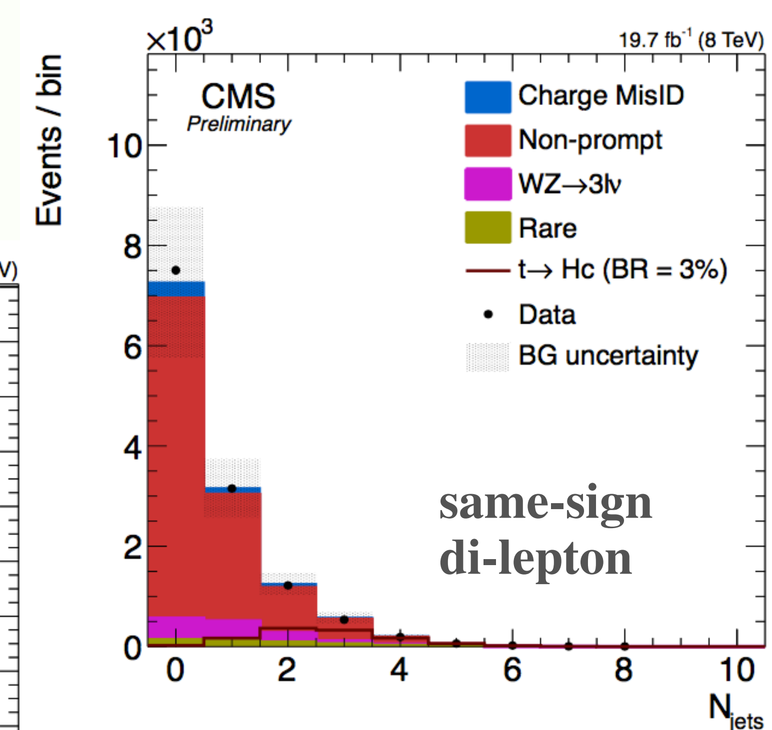
Main background: WZ+jets, ttbar+V (**tri-lepton**), fake leptons, charge mis-ID (**same-sign dilepton**)

Fake and **charge misID** lepton backgrounds estimated from data





AIC=WW/ZZ/Z+jets



$\kappa_{qHt} < 0.18$

BR(t→qH) < 0.93 % (obs)
0.89 % (exp)

Search for t→Hq in ttbar events at CMS

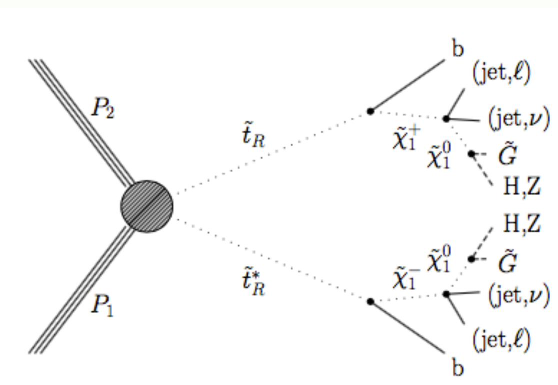
CMS-PAS-HIG-13-034
CMS, 20 fb^{-1}, 8 TeV

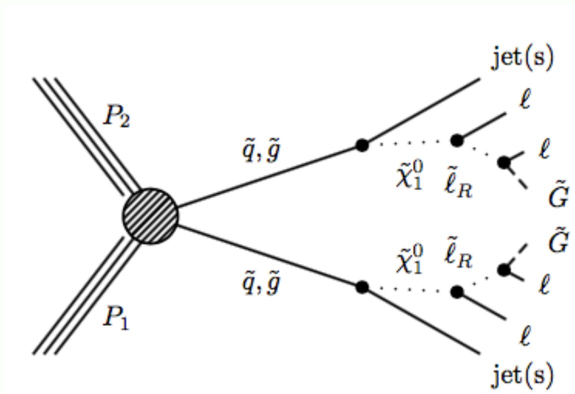
Based on a combination of two analyses performed in multilepton ($H\to WW/ZZ/\tau\tau$) and $H\to\gamma\gamma$ channels

Phys. Rev. D 90 032006 (2014)
CMS, 20 fb^{-1}, 8 TeV

CMS-PAS-HIG-13-025
CMS, 20 fb^{-1}, 8 TeV

Multi-lepton analysis is done in the framework of the SUSY search for natural Higgsino, slepton, etc.





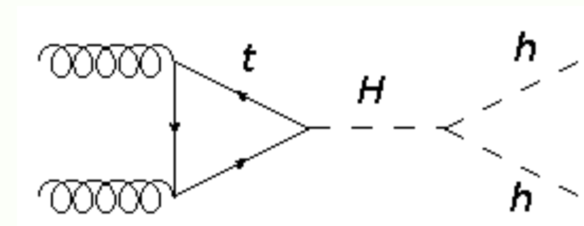
Several SUSY scenarios are probed, also possible to **set limits on FCNH** in this inclusive search:

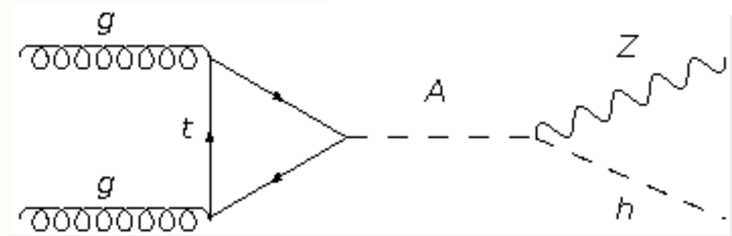
Higgs boson decay mode	Upper limits on $\mathcal{B}(t\to cH)$ Obs.	Exp.	1σ range
$\mathcal{B}(H\to WW^*) = 23.1\%$	1.6 %	1.6%	(1.0–2.2)%
$\mathcal{B}(H\to\tau\tau) = 6.2\%$	7.01%	5.0 %	(3.5–7.7)%
$\mathcal{B}(H\to ZZ^*) = 2.9\%$	5.3%	4.11%	(2.9–6.5)%
Combined	1.3%	1.2%	(0.9–1.7)%

$\kappa_{qHt} < 0.21$
BR($t\to qH$) < 1.28 %

MadGraph @LO is used for FCNH generation

Di-photon analysis developed for the search for 2HDM $H\to H_{SM}H_{SM}$ and $A\to ZH_{SM}$





Higgs Decay Mode	observed	expected	1σ range
$H\to WW^*$ ($\mathcal{B}=23.1\,\%$)	1.58 %	1.57 %	(1.02–2.22) %
$H\to\tau\tau$ ($\mathcal{B}=6.15\,\%$)	7.01 %	4.99 %	(3.53–7.74) %
$H\to ZZ^*$ ($\mathcal{B}=2.89\,\%$)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)	1.28 %	1.17 %	(0.85–1.73) %
$H\to\gamma\gamma$ ($\mathcal{B}=0.23\,\%$)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons	0.56 %	0.65 %	(0.46–0.94) %

Combination of results

$\kappa_{qHt} < 0.14$
BR($t\to qH$) < 0.56 %