CMS

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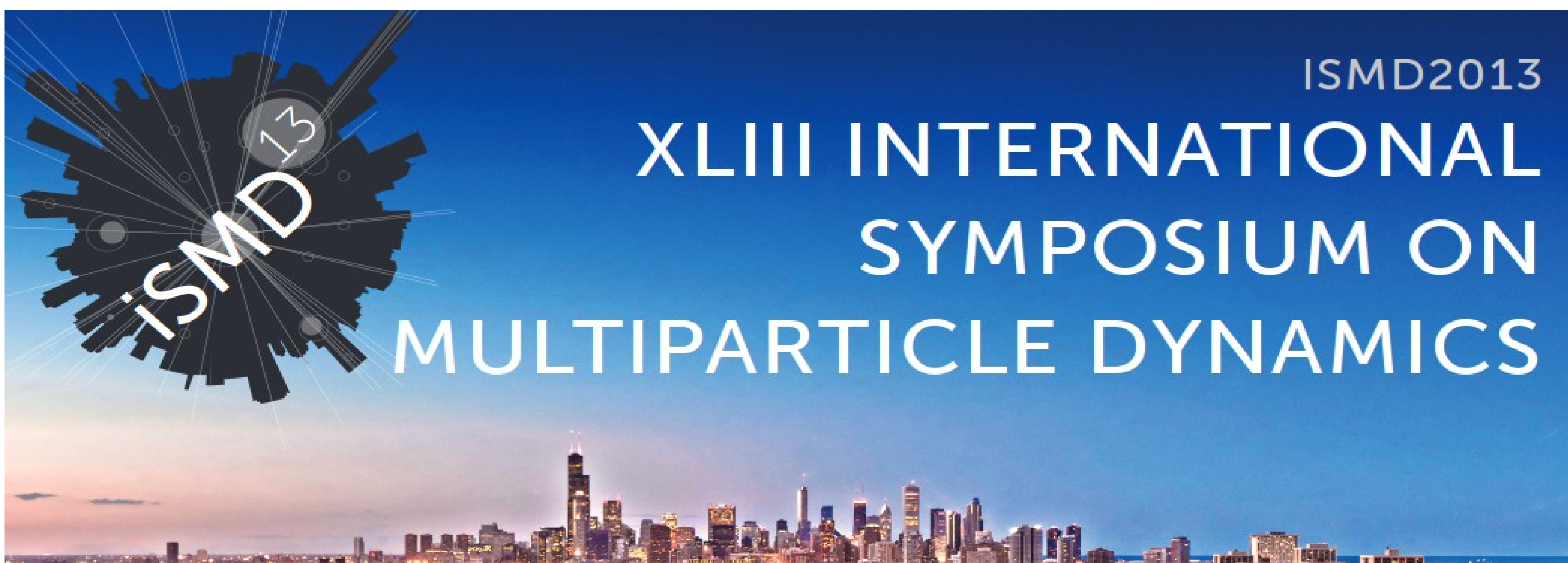
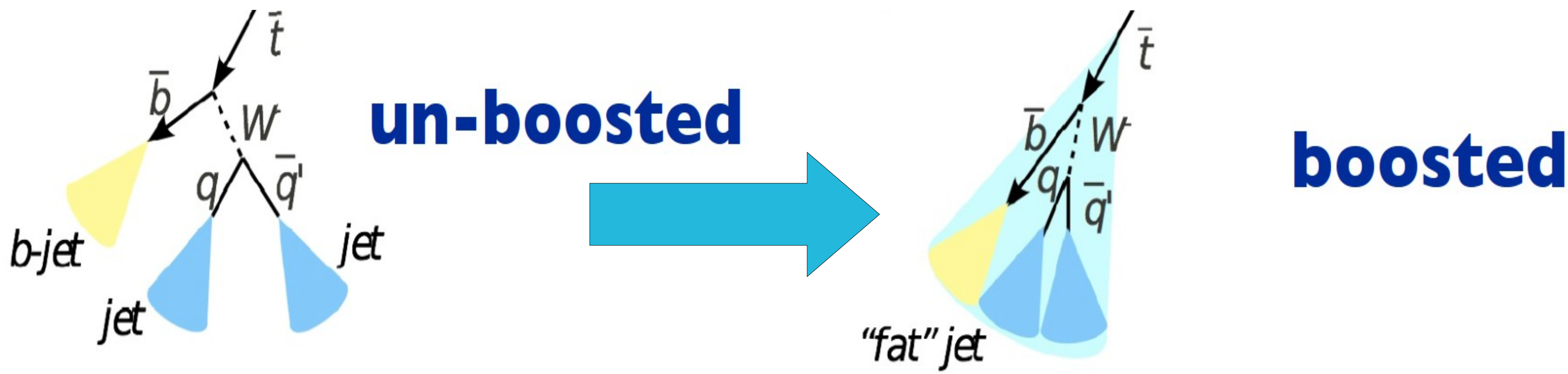
Boosted Heavy Particles and Jet Substructure with the CMS Detector



Ivan Marchesini (Uni. Hamburg), ISMD13, 16 Sep 2013, Chicago

Introduction

Boosted regime: **classical selection methods fail**.



➔multiple, **well separated jets** from W, Higgs or top hadronic decays

➔typical jet collection: **AK5** (anti-k_T, R=0.5)

➔decay products from heavy particles **merged into large fat-jets**

➔jet substructure provides fundamental selection tools (top-tagging, W-tagging...)

➔typically, **larger jet collections**: **CA8** (Cambridge-Aachen, R=0.8) or CA15

Substructure Techniques

W-Tagging
[CMS-PAS-JME-13-006]

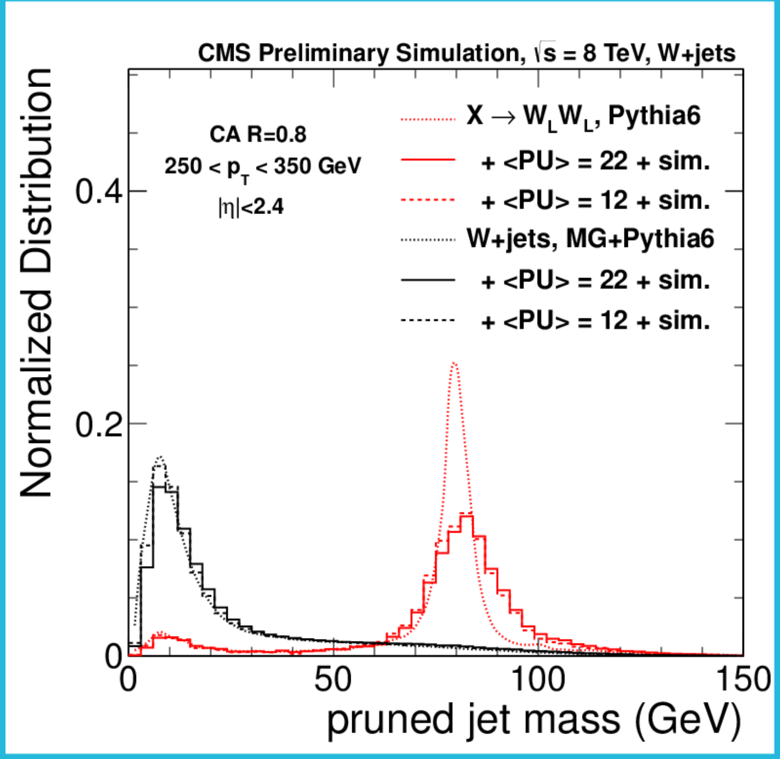
- Based on **jet mass pruning** (*Ellis, Vermillion, Walsh [arXiv:0903.5081], [CMS-PAS-SMP-12-019]*).

- Starting with CA8 jets.

- Re-cluster jet and apply requirements when merging clusters *i* and *j* into cluster *p*. **Veto soft and large angle re-combinations**, removing softer component if:

  - $min(p_T^i, p_T^j)/p_T^p < 0.1$
  - $\Delta R^{ij} > 0.5\, m^{orig}/p_T^{orig}$

W-tagging:
•2 pruned subjets
•pruned jet mass [60,100] GeV



m_{pruned} with/without detector effects, pile-up

signal: resonance (600 GeV) →WW
QCD background

W-Tagging: Additional Observables
[CMS-PAS-JME-13-006]

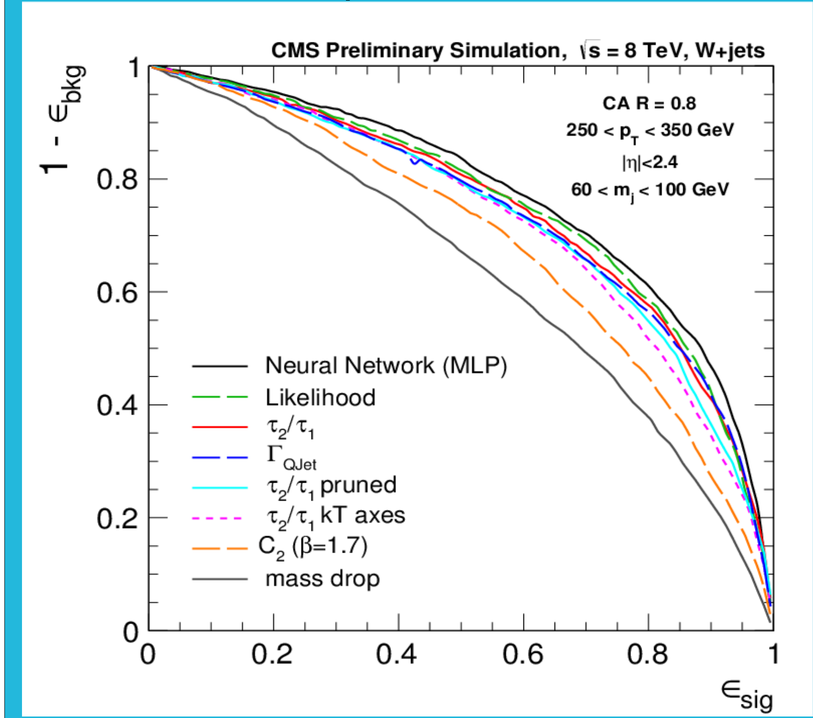
Pruning can be combined with additional observables:

- mass-drop μ
- N-subjettiness τ_N: τ_2/τ_1 used for W-tagging
- also examined: Qjet volatility Γ_{QJet}, generalized energy correlation function C_2^β

N-subjettiness shows the best single discriminating power.

Observables are correlated: moderate improvement with **multivariate combination using TMVA**.

60 GeV < m_{pruned} < 100 GeV



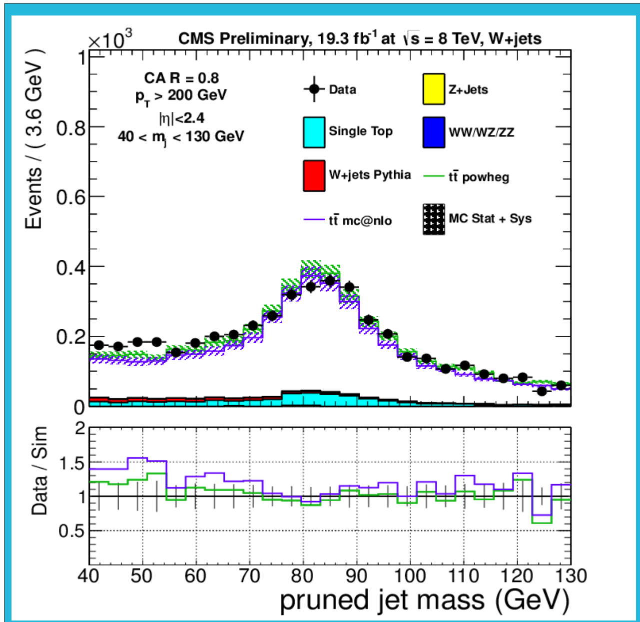
W-tagging ROC curves single substructure observables and their combinations

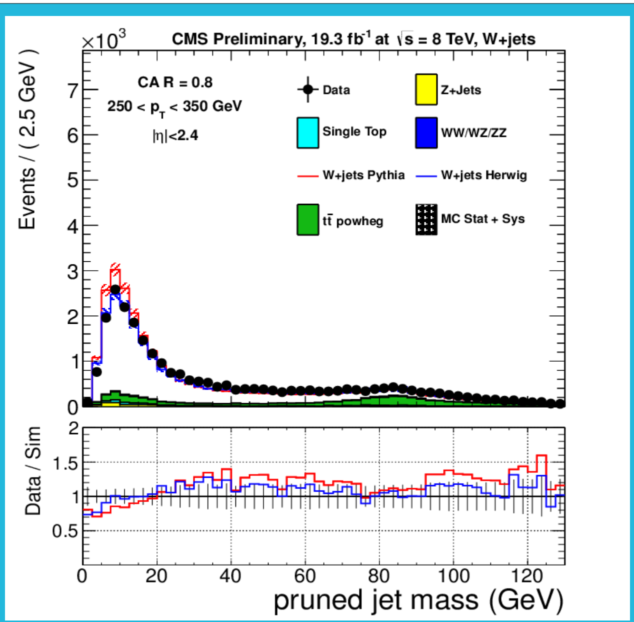
efficiency: H→WW, m_H = 600 GeV

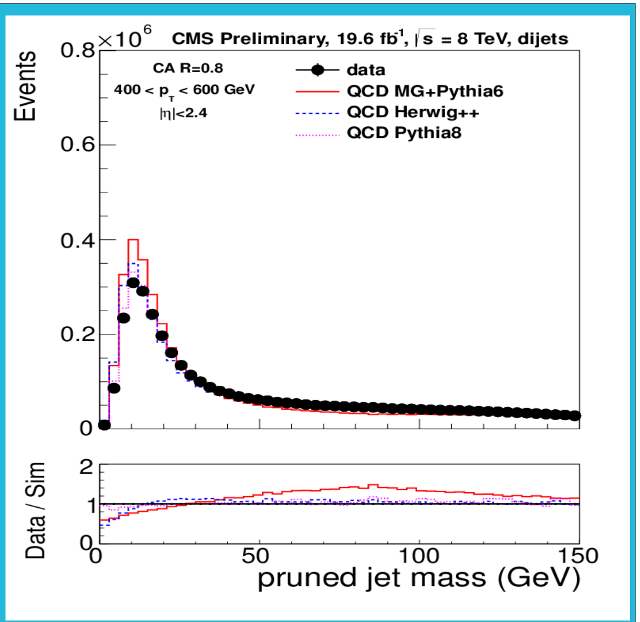
mistag: QCD

W-Tagging: MC vs Data
[CMS-PAS-JME-13-006]

- Detailed **data/MC comparisons** for all substructure observables
- **Different topologies and generators** considered







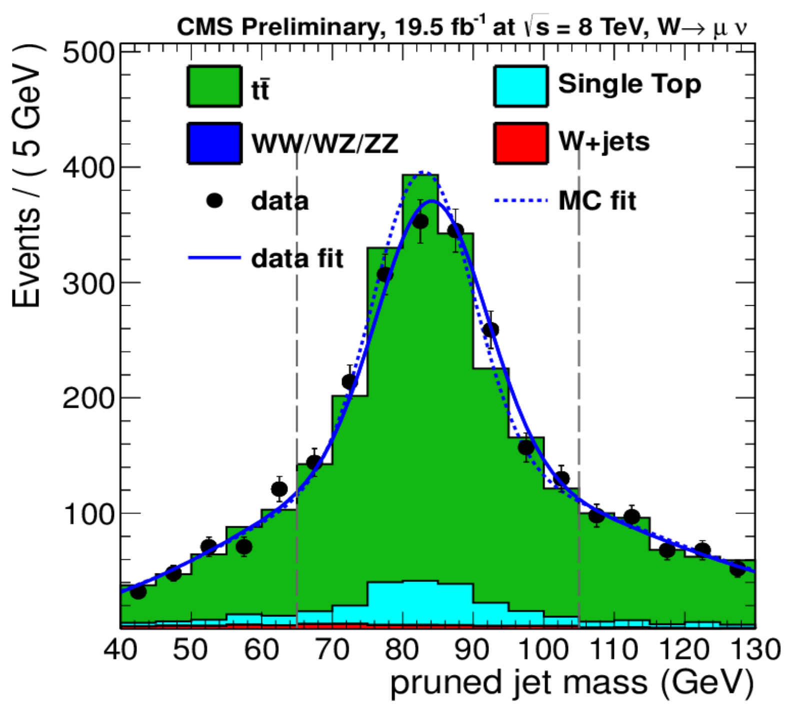
ttbar	leptonic W+jets	di-jets
powheg	Pythia6	MG+Pythia6
mc@nlo	Herwig	Herwig
		Pythia8
sensitive to: efficiency	mistag	mistag
	pT [250, 350] GeV	pT [400, 600] GeV

general good agreement, more observables in the backup

W-Tagging: MC vs Data
[CMS-PAS-JME-13-006]

- **Scale factors** (SF) to correct for residual discrepancies.

μ+jets ttbar



Extract:

→W-jet mass scale (peak position):
•data: 84.5±0.4 GeV
•MC: 83.4±0.4 GeV

→W-jet mass resolution:
•Data: 8.7±0.6 GeV
•MC: 7.5±0.4 GeV

→data/MC correction for W-tagging efficiency (SF):
•0.905 ± 0.08
(operating point: m_{pruned} cut + τ_2/τ_1<0.5)

Top-Tagging
[CMS-PAS-JME-10-013]

▶ Based on **JHU top-tagger** (*Kaplan et al [PRL 101 (2008) 142001]*):

➔ start with **CA8 jets**
➔ **reverse clustering sequence** and examine clusters pairwise
➔ clusters are **split** if:

$$\Delta R > 0.4 - 0.0004\, p_T^C$$

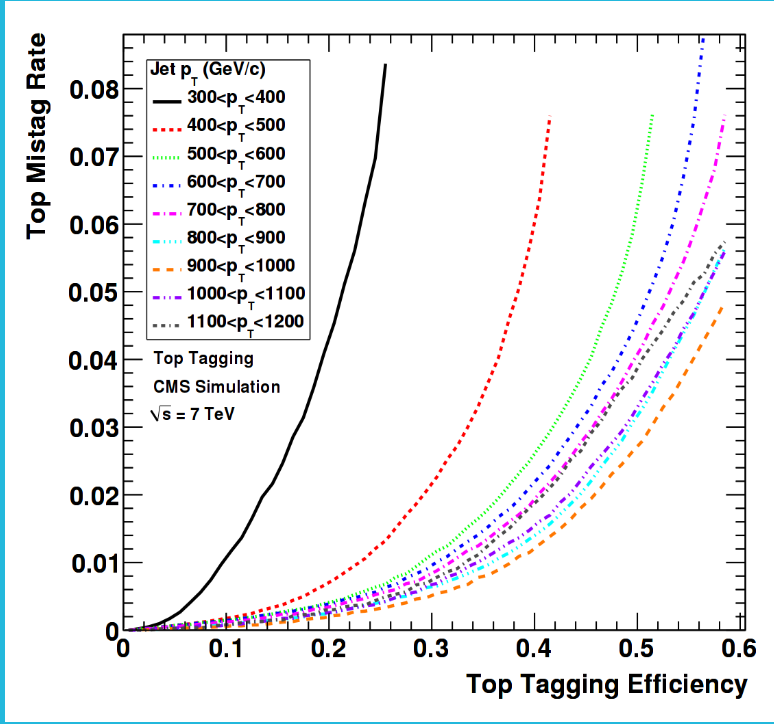
p_T^C is the parent cluster p_T
➔ **low p_T clusters** removed if:

$$p_T < 0.05\, p_T^{jet}$$

Top-tagger requirements:

- **$140 < m_{jet} < 250$ GeV**
- **$N_{subjets} \geq 3$**
- **Min pairwise mass > 50 GeV**

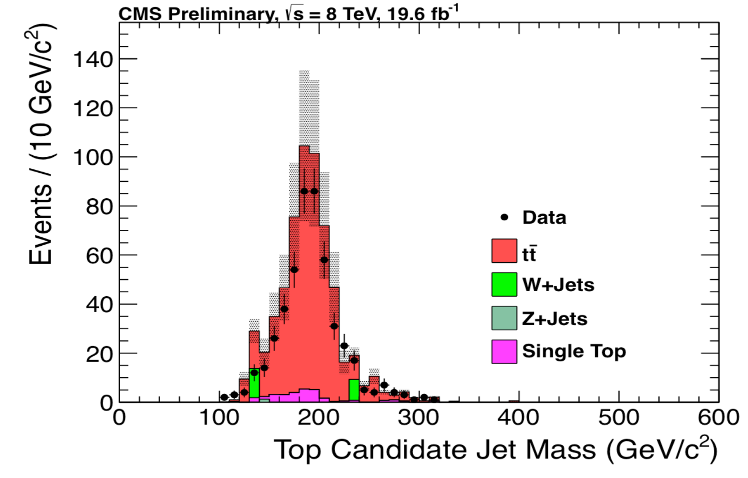
ROC Curves

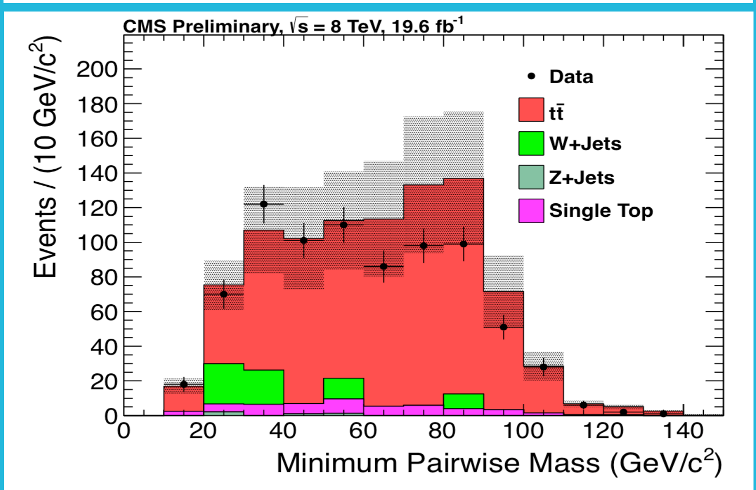


top-mistag (QCD) vs efficiency in simulation

Performance
[CMS-PAS-B2G-12-005]

μ+jets: semileptonic ttbar



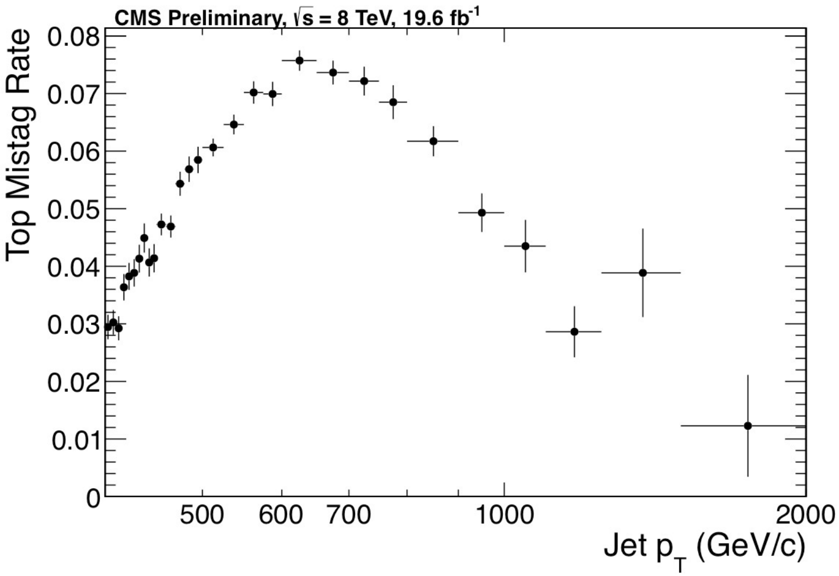


top-tagging data/MC scale factor derived from selection efficiency of hadronic top candidate: 0.93±0.04

QCD

Mistag rate can be measured from data, using **anti-tag method**:

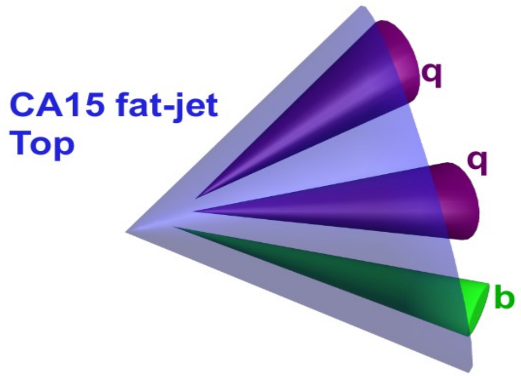
- ➔ two high-p_T jets, p_T >400 GeV
- ➔ anti-tag one jet, inverting min pairwise mass requirement
- ➔ top-tag of other jet is a mistag



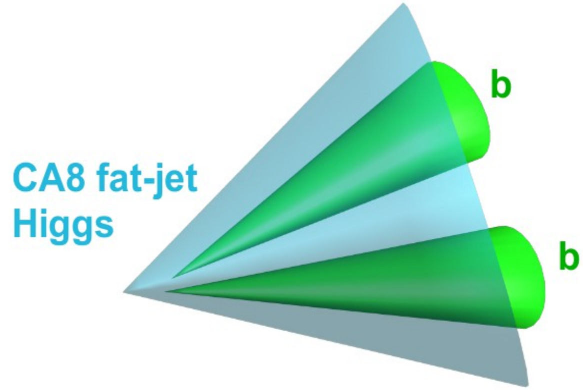
B-Tagging in Boosted Topologies
[CMS-PAS-BTV-13-001]

▶ B-tagging at CMS traditionally developed on **isolated AK5 jets**, mostly suitable for the **non-boosted regime**.

▶ First study at LHC dedicated to b-tagging in the boosted regime. Benchmark topologies:



Boosted top, hadronic decay:
→selected using HEPTopTagger [JHEP 1010 (2010) 078], CA15 jet collection

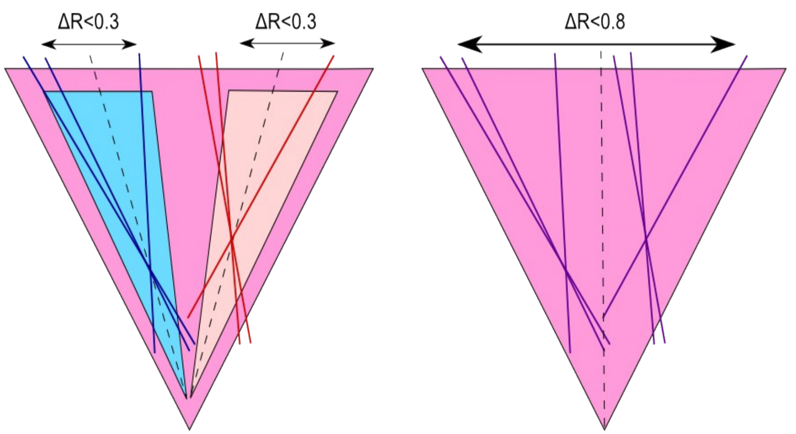


Boosted Higgs→$b\bar{b}$:
→studies based on pruned CA8 jets

▶ Boosted studies based on the **Combined Secondary Vertex CSV** tagger: likelihood ratio combination of **secondary vertex + single track information**.
▶ CSV developed on AK5 jets: currently no dedicated re-training for the boosted regime.

Boosted B-Tagging Scenarios
[CMS-PAS-BTV-13-001]

- Two scenarios considered:
  - **subjet CSV**:
    - CSV b-tagger applied to subjets (**2 b-tags for Higgs-tagging, ≥1 for top-tagging**)
  - **fat-jet CSV**:
    - CSV b-tagger applied to the Higgs/top candidate fat-jet



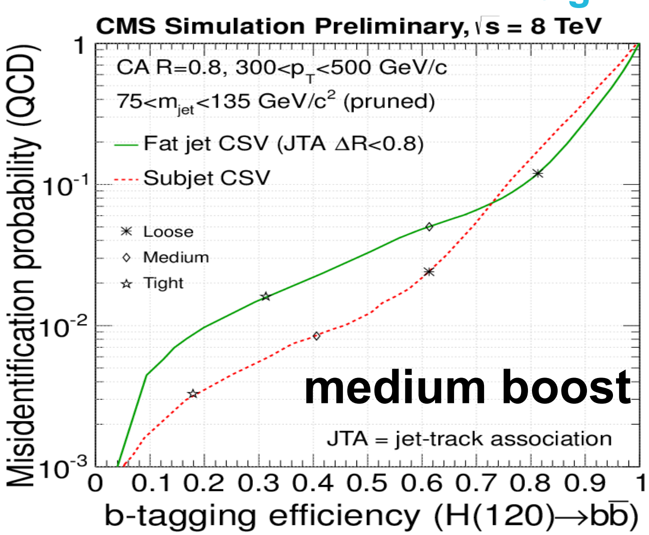
subjet b-tagging: based on subjet tracks

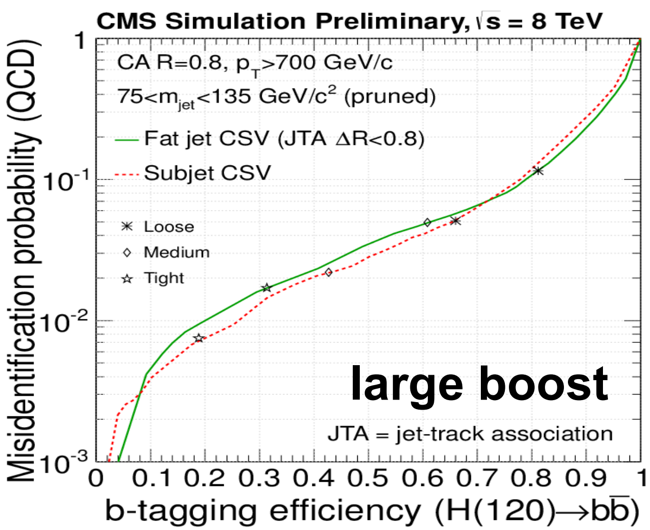
fat-jet b-tagging: based on all fat-jet tracks

Subjet b-tagging generally performs better: chosen as **default technique**

Fat-jet b-tagging suitable at **very high p_T** where subjets start to merge

e.g. Higgs channel





Subjet B-Tagging Validation on Data
[CMS-PAS-BTV-13-001]

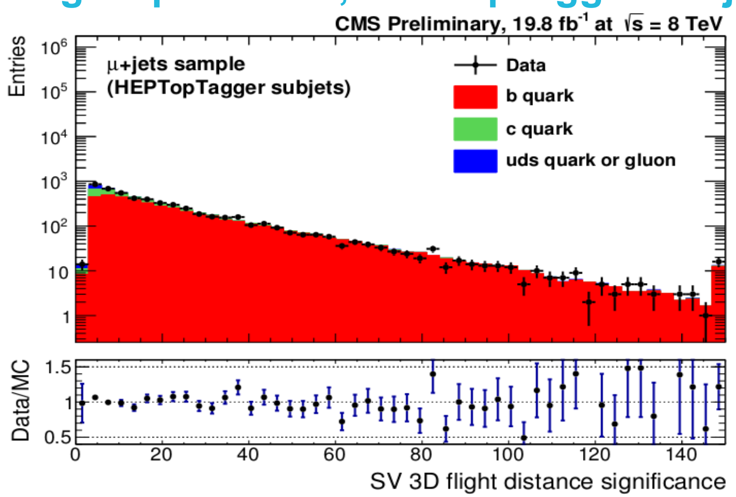
Control samples
Boosted top:

- **μ+jets, semileptonic ttbar**

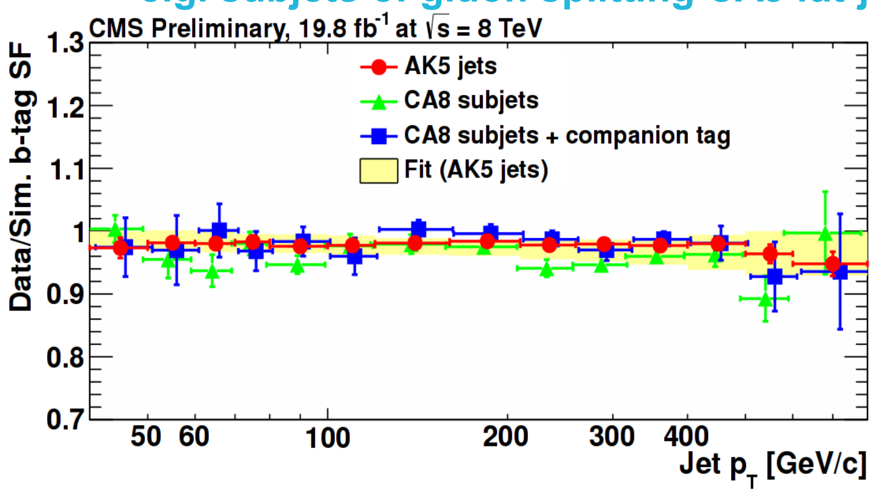
Boosted Higgs: challenging definition of the control sample

- similar topology: **gluon splitting jets**, two closeby b's

e.g. Top channel, HEPTopTagger subjets



e.g. subjets of gluon splitting CA8 fat-jets



standard SF

gluon splitting subjet b-tagging SF

•Good data/MC agreement for b-tagging observables.
•All observables cross-checked (backup).

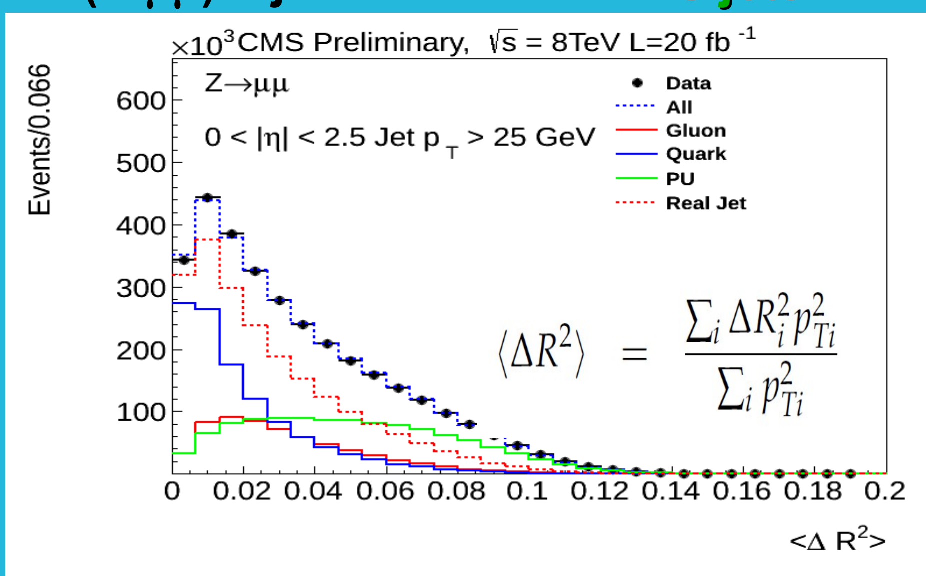
•SF~1, compatibly with SF for standard b-tagging in the non-boosted regime, for both channels.
•Nothing pathological in the boosted regime.

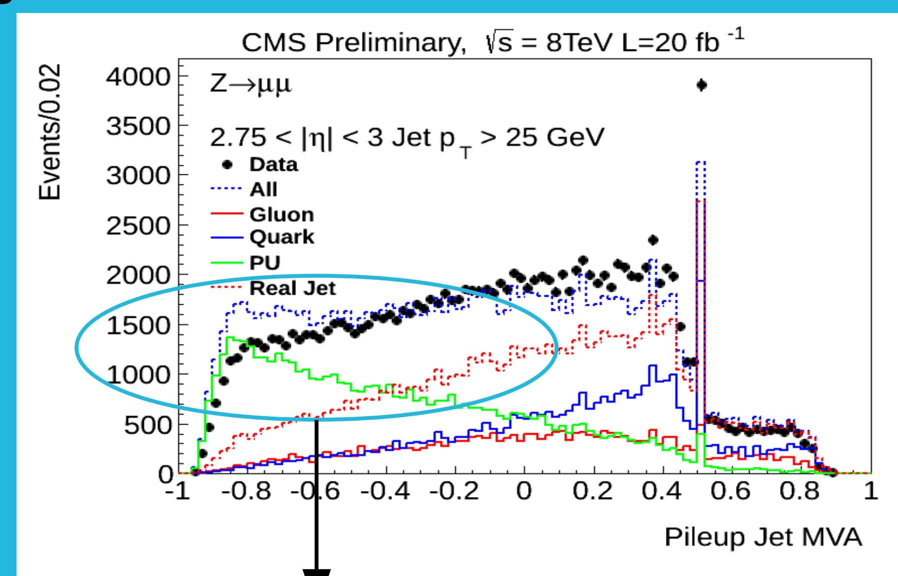
Pile-Up Jet-ID
[CMS-PAS-JME-13-005]

- Traditional PU subtraction: subtract charged particles not pointing to the primary vertex.

- PU Jet-ID:
  - exploit also **non-tracking quantities** (jet shape) to extend PU rejection outside of the tracking acceptance
  - **multivariate discriminant**

Z (→μμ) + jets events **PU jets** **good MVA discrimination outside tracker**



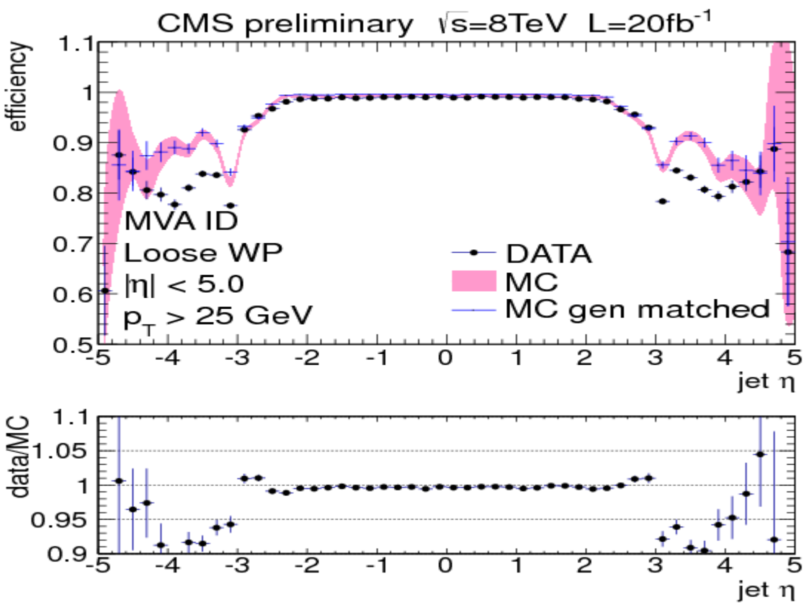


e.g. non-tracking observable: radial distribution of Particle-Flow jet-constituents

known residual discrepancy due to out-of-time pile-up simulation

Pile-Up Jet-ID
[CMS-PAS-JME-13-005]

- Performance:
  - **tag-and-probe method from Z (→μμ) + jets** events, where probe is jet recoiling against Z
  - data/MC agreement within 10%, corrected using SF

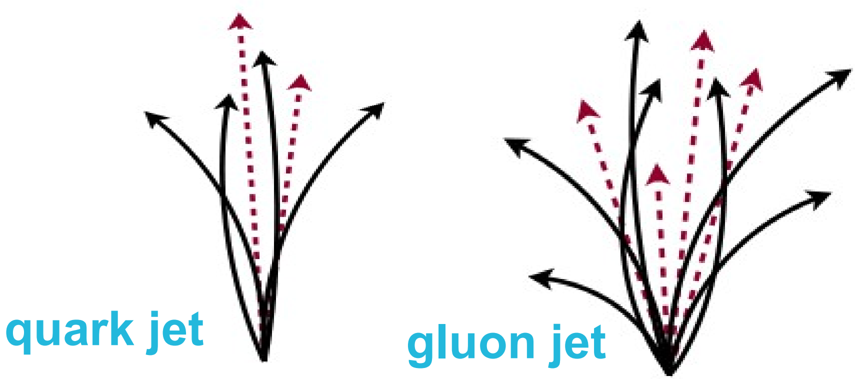


- Several applications:
  - e.g. : **extensions of jet vetos to low p_T** (Higgs searches)

Quark-Gluon Discrimination
[CMS-PAS-JME-13-002]

- Quark/gluon discrimination: similarly to PU Jet-ID, combine discriminating variables in **likelihood**

- Quark and gluon have **different colour interaction**:



+ multiplicity
+ width
more homogeneous energy sharing

Variables:

→**multiplicity:**
charged, neutral, **total**

→**spread:**
$\eta-\phi$ spread
major $\eta-\phi$ matrix axes σ_1
minor $\eta-\phi$ matrix axes σ_2

→**energy sharing:**
hardest candidate off-centering/ energy
$p_T D$:

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

combined in likelihood

Quark-Gluon Discrimination
[CMS-PAS-JME-13-002]

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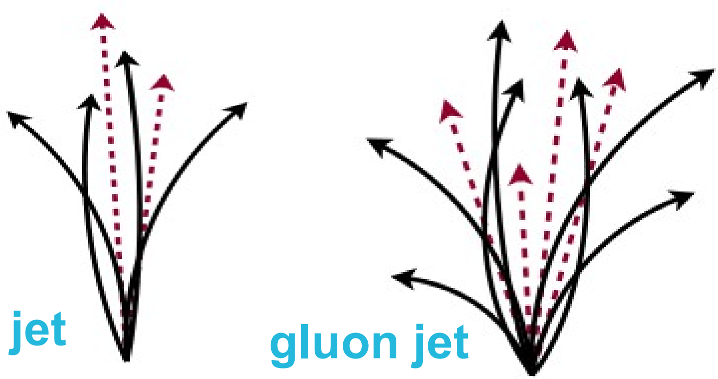

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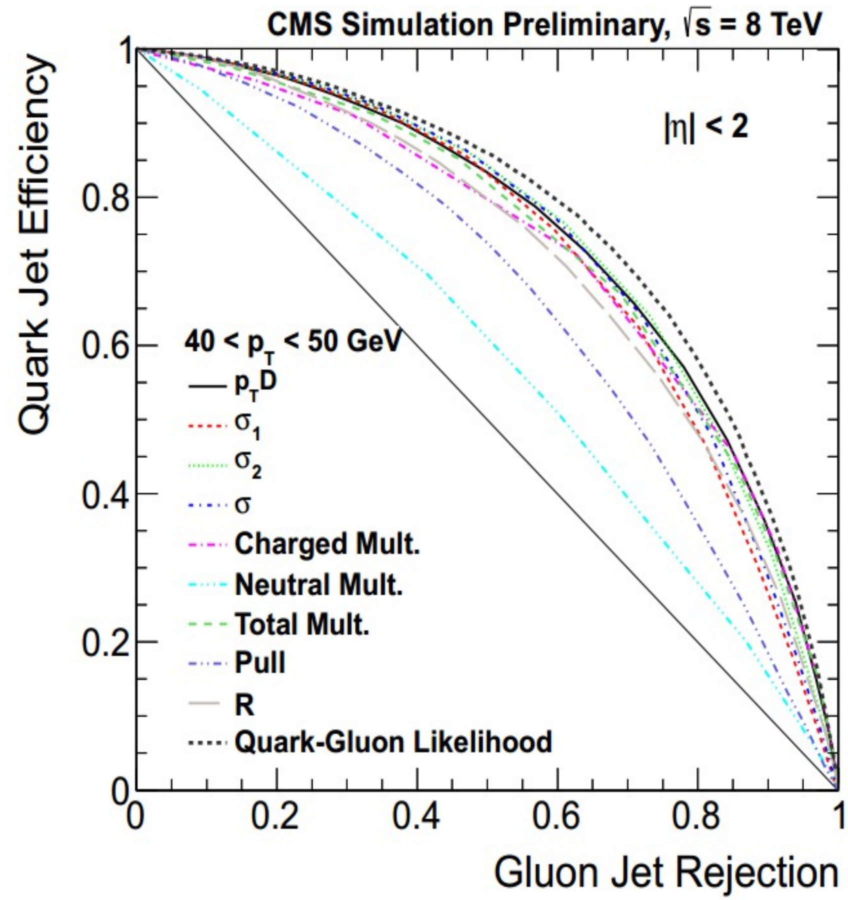


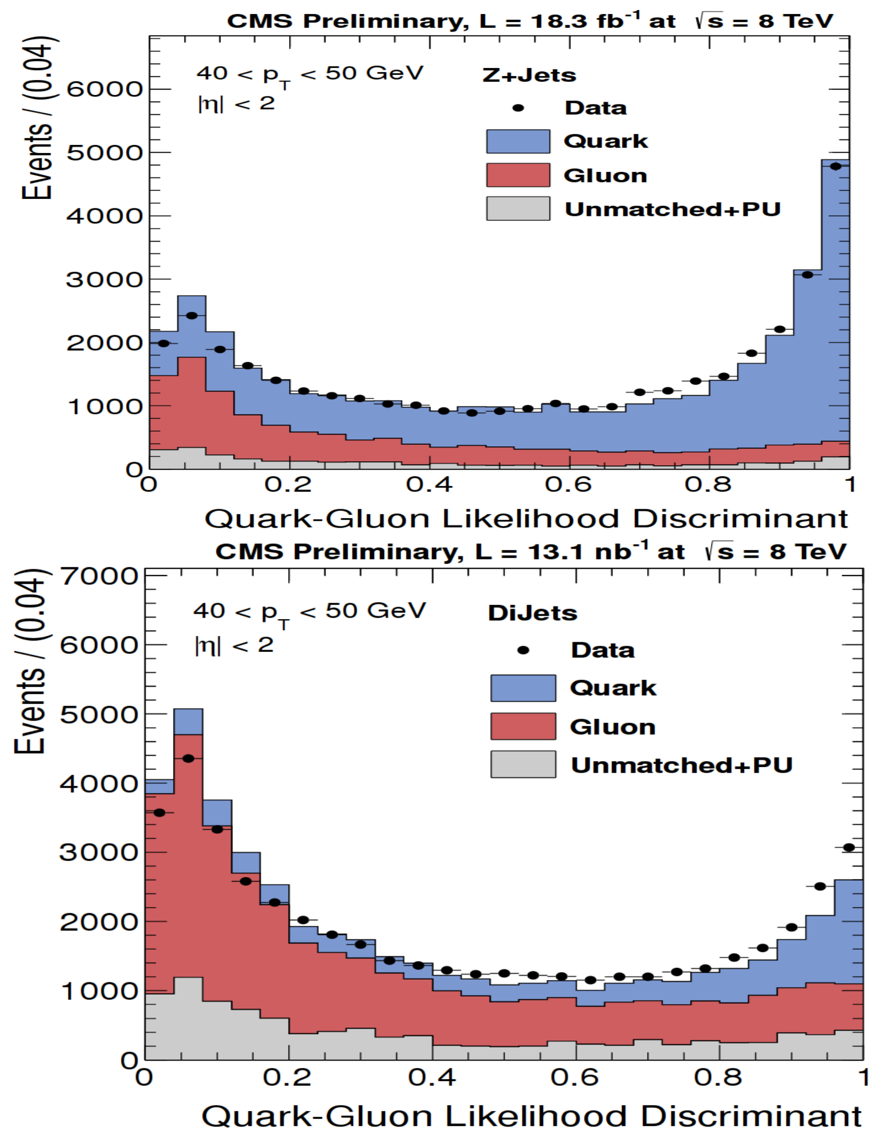
Single-variable and combined likelihood discrimination power

Quark-Gluon Discrimination
[CMS-PAS-JME-13-002]

- Validation in two different samples:
  - **Z+jets**: quark enriched
  - **di-jets**: gluon enriched

- Overall good data/MC agreement. Some discrepancy at low p_T in di-jets, probably due to gluon fragmentation mismodeling. Covered by systematics.

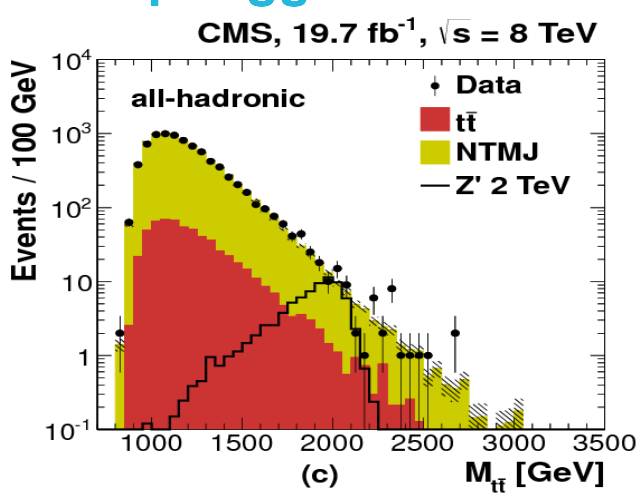
- Useful tool for several searches:
  - many channels with jets are **flavor specific**
  - pioneer analyses at CMS:
    - **Higgs→ZZ→2l2q** [JHEP 04 (2012) 036]
    - **VBF Higgs→bb** [CMS-PAS-HIG-13-011]

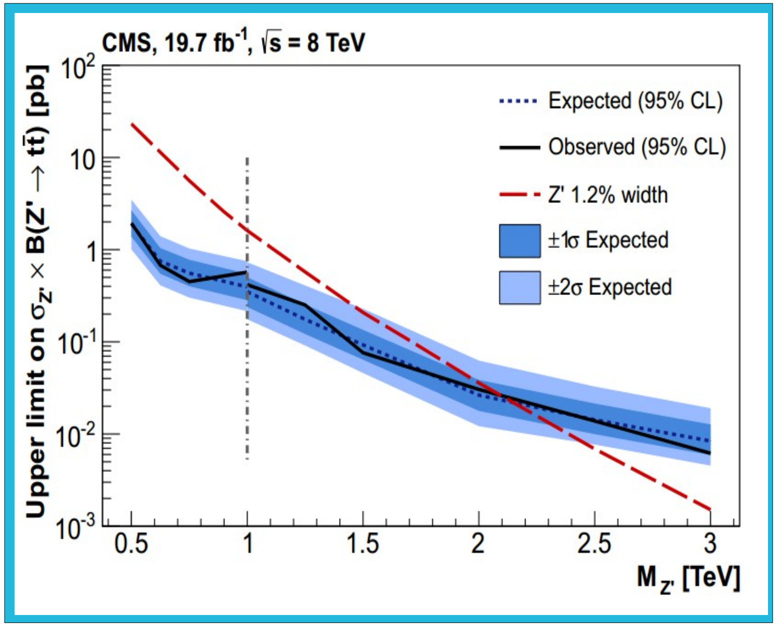


Searches Using Substructure

Resonances→ttbar *All-Hadronic Final State*
[CMS-PAS-B2G-12-005/13-001, arXiv:1309.2030]

- **Flagship** for boosted searches for new physics.
- Sensitive to several models. Considered:
  - extra dimensions, **RS gluon**
  - extended gauge, **Z'**
    narrow $\Gamma/m=0.01$
    broad $\Gamma/m=0.1$
- Selection:
  - 2 back-to-back high p_T jets
  - both **top-tagged**





exclusion limits from combination with semi-leptonic channel exclusion up to 2.7 TeV depending on the channel

High-purity version of the analysis underway: reduce QCD with combination top-tagging+**subjet b-tagging**

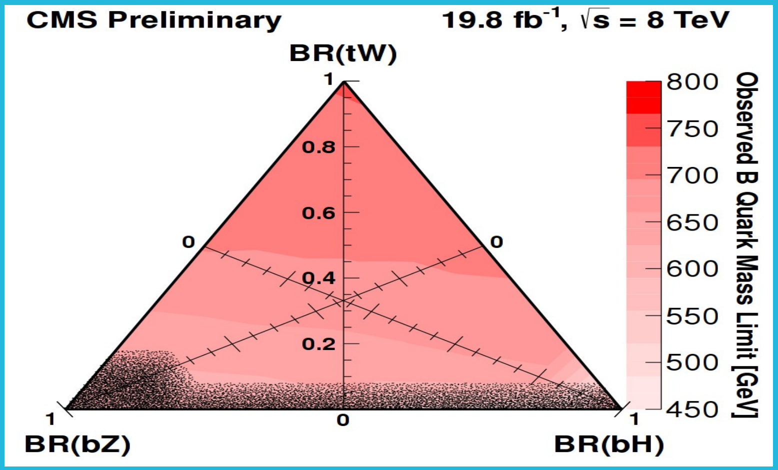
B'-1/3 Bottom Partners
[CMS-PAS-B2G-12-019]

- **Vector-like heavy quarks** predicted by several theories:
  - little/composite Higgs models
  - extra dimenions
- Solution to the **hierarchy problem**.

- Signal:
  - pair-produced **B' with charge -1/3**
  - decay modes: B'→tW, bZ, bH
  - **all branching fractions**

- Selection:
  - **single muon or electron**
  - substructure used in event categories based on number of **V-tags** (V=W/Z/H):

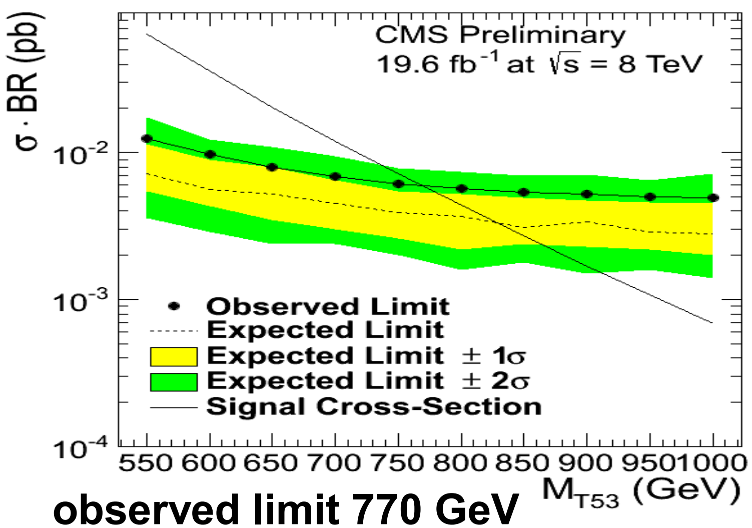
- **CA8 jet, $p_T \geq$ 200 GeV**
- **mass drop μ < 0.4**
- **2 pruned subjets**
- **m_{pruned} [50,150] GeV**



final limit up to 732 GeV

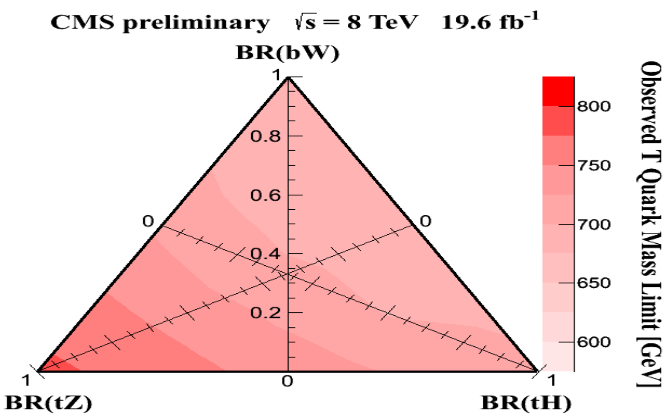
Top Partners
[CMS-PAS-B2G-12-012 and 015]

- [CMS-PAS-B2G-12-012] Signal:
  - pair-produced **T' with charge 5/3**
  - BR 100% **T'→tW**



observed limit 770 GeV

- Selection:
  - two **same sign leptons**
  - **top-tagging**
  - **W-tagging** (m_{pruned} [60,130] GeV)



final combined limit up to 782 GeV

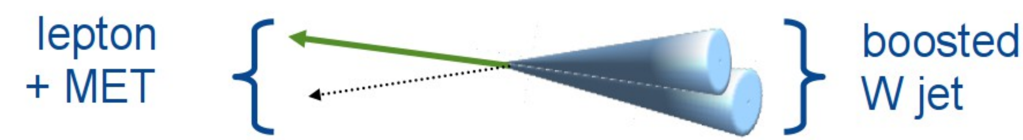
- [CMS-PAS-B2G-12-015] Signal:
  - pair-produced **T' with charge 2/3**
  - decay modes: T'→tH, tZ, bW
  - **all branching fractions**

- Two final states:
  - multilepton: counting experiment, no substructure
  - **single letpon**: **multivariate analysis,** number of **W- and top-tags** enter the BDT discriminant.

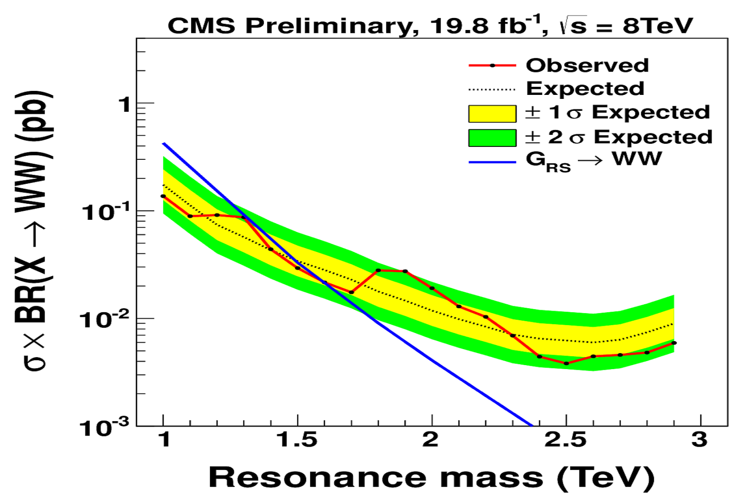
High Mass Dibosons
[CMS-PAS-EXO-12-021/024]

Predicted by several models. Here considered:

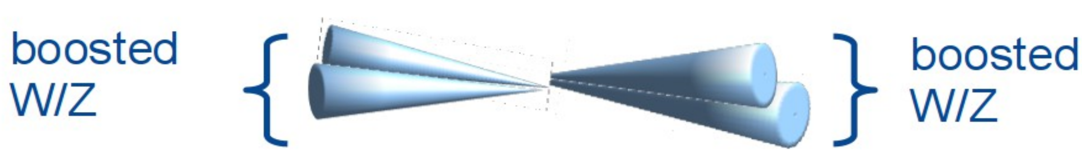
- **bulk graviton** production: $G_{bulk} \rightarrow WW \rightarrow l + jet + MET$



W-tagging:
- m_{pruned} **[65,105]GeV**
- **N-subjettiness:**
  - **high-purity** $\tau_2/\tau_1 < 0.5$
  - **low-purity** $0.5 < \tau_2/\tau_1 < 0.75$



- RS graviton, W heavy partner W'
  $\mathbf{G_{RS} \rightarrow WW/ZZ, W' \rightarrow WZ}$
  all-hadronic decay



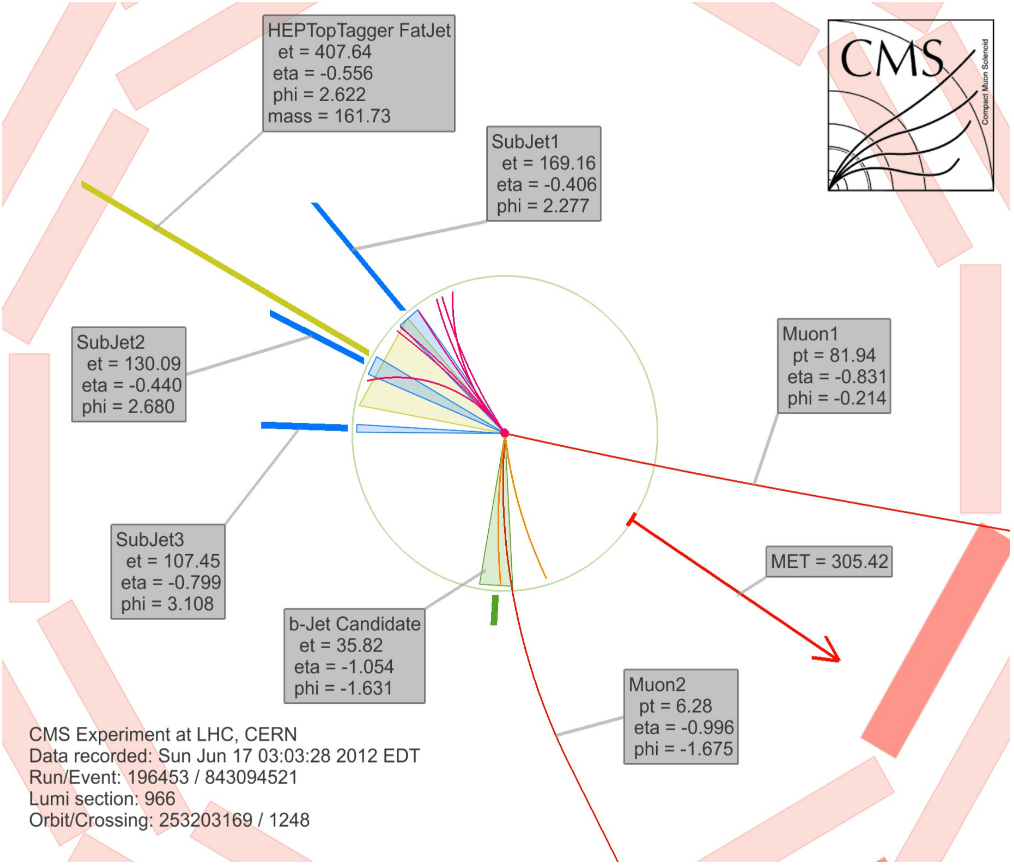
double W/Z-tagging:
m_{pruned} **[70,100] GeV, same** τ_2/τ_1 **cuts as above**

- G_{bulk} σ x BR_{WW} limits between 70fb and 3fb
- $G_{RS} \rightarrow WW$ exclusion: [1.00,1.59] TeV
- $G_{RS} \rightarrow ZZ$ exclusion: [1.00,1.17] TeV
- $W' \rightarrow WZ$ exclusion: up to 1.73 TeV

Outlook

- Substructure techniques
  - major developments recently: subjet b-tagging, W-tagging, pile-up jet-ID, gluon/quark discriminator, …
  - **new results on top-tagging expected soon**
  - extensive data/MC comparisons: generally good agreement
- Searches:
  - increased number of analyses using substructure, beyond typical ttbar resonance searches
  - **searches exploiting powerful new tools** (subjet b-tagging, new top-taggers, ...) **expected before the end of the year**

Semileptonic ttbar



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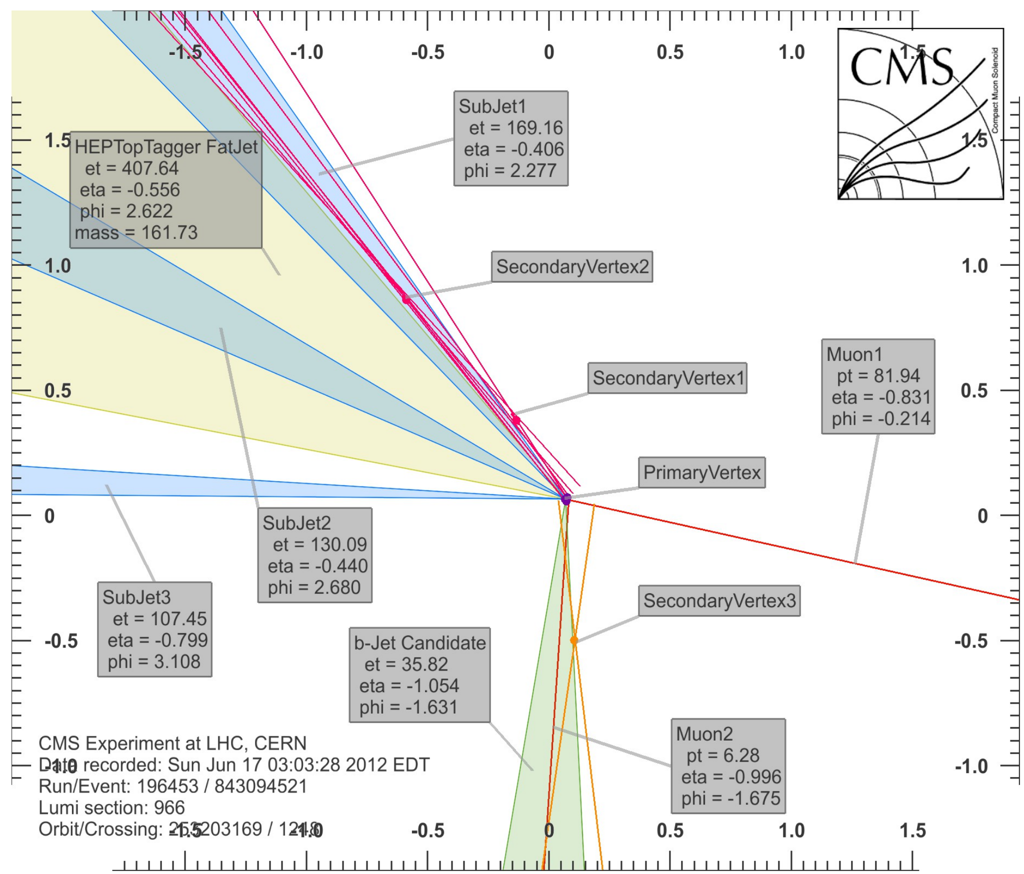

Additional Slides

W-Tagging: Additional Observables

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  - → **mass-drop**

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mass-drop $\mu = m_1/m_{jet}$
m_1 is the highest mass pruned subjet

W-Tagging: Additional Observables

- Pruning can be combined with additional observables:

  - **mass-drop**
  - N-subjettiness τ_N: $\boldsymbol{\tau_2/\tau_1}$ used for W-tagging

probability that jet is composed by N subjets

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

$d_0 = \sum_k p_{T,k} R_0$, and R_0 is the original jet radius

W-Tagging: Additional Observables

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  - also examined: Qjet volatility $\boldsymbol{\Gamma_{QJet}}$, generalized energy correlation function $\mathbf{C_2^{\beta}}$

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  - Qjet volatility $\Gamma_{\mathbf{QJet}}$

RMS (mass jet trees) / m_{jet}
where a jet is interpreted as a distribution of trees based on its clustering sequence

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  - **mass-drop**
  - N-subjettiness τ_N: $\boldsymbol{\tau_2/\tau_1}$ used for W-tagging
  - Qjet volatility $\boldsymbol{\Gamma_{QJet}}$
  - generalized energy correlation function $\mathbf{C_2}^{\beta}$

$$C_2^{\beta} = \frac{\sum_{i,j,k} p_{Ti} p_{Tj} p_{Tk} (R_{ij} R_{ik} R_{jk})^{\beta} \sum_i p_{Ti}}{(\sum_{i,j} p_{Ti} p_{Tj} (R_{ij})^{\beta})^2}$$

based on momentum and pair-wise angles of particles within the jet

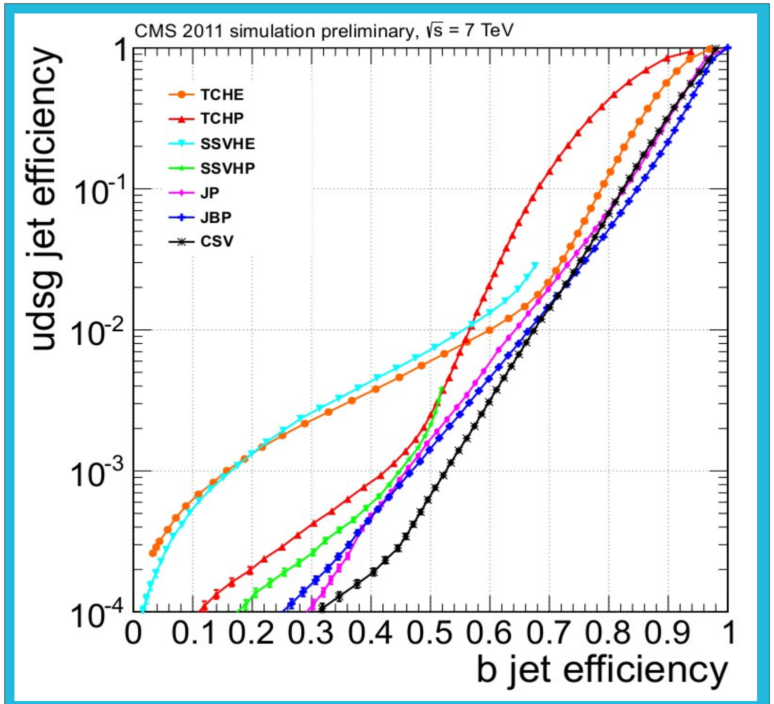
B-Quark Signatures

Life-time b-hadron → jets with:
•secondary vertex
•tracks with large impact parameter

Large mass, ~5 GeV

Fragmentation function:
•high p_T of the b-hadron relatively to jet p_T

B-decay produces often leptons: soft muon or electron within jet



b-tagging algorithms ROC curves [JINST 8 (2013) P04013]

▶ Several taggers implemented at CMS. Boosted studies based on the **Combined Secondary Vertex** **CSV** tagger:

- likelihood ratio combination of **secondary vertex + single track information**;
- currently the best tagger in CMS, improvements ongoing.

B-Tagging at CMS

JTA

→**jet-tracks association**: static **cone** **$\Delta R(tracks,jet) < 0.3$**

OBSERVABLES

→apply tight **selection on tracks**, mainly for pile-up rejection

→determine b-tagging observables

DISCRIMINATORS

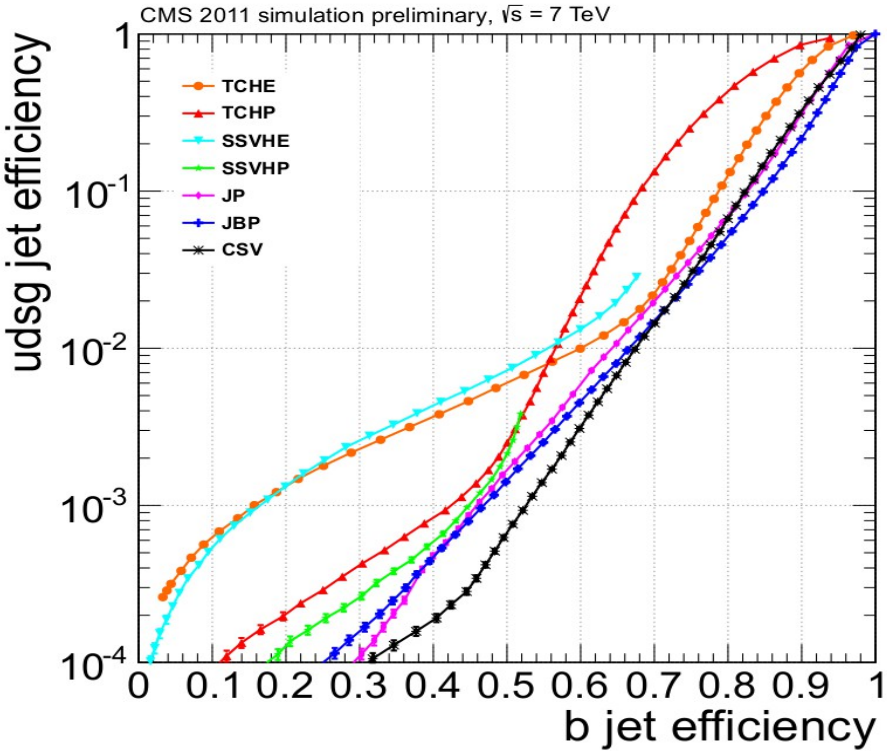
→calculate b-tagging **discriminators**
→several **operating points** defined for taggers, selecting different regions of purity/efficiency:

- loose **L**; 10%
- medium **M**; 1%
- tight **T**; 0.1%

misidentification from light quarks/gluons

B-Tagging Algorithms

- Boosted studies based on the **Combined Secondary Vertex CSV** tagger:
  - likelihood ratio combination of **secondary vertex + single track information**;
  - currently the best tagger in CMS, improvements ongoing.



- For performance measurements used also **Jet-Probability JP** tagger:
  - likelihood estimate of the probability that the jet-tracks come from the PV, based on the IP significance of all jet-tracks;
  - **calibrated on data** from tracks with negative IP.

Higgs Channel

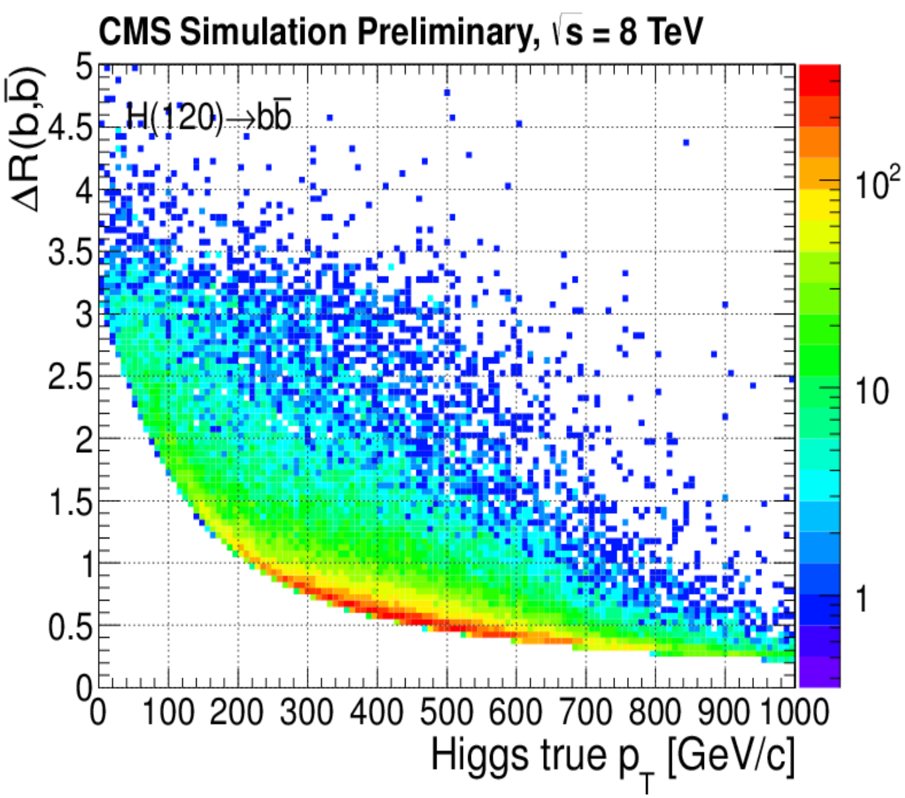
- Based on **CA8 jet collection**: boosted regime for p_T > 300 GeV.

- Signal: **B'→bH** pair production. B-tagging studied on H→bb.

- Inclusive **mistag** from **QCD** and mistags from hadronically-decaying **W/Z/top**.

- Subjet b-tagging based on **pruned subjets**:

➔cut on **pruned jet mass** can be combined with b-tagging requirement (see next slides).



Top Channel

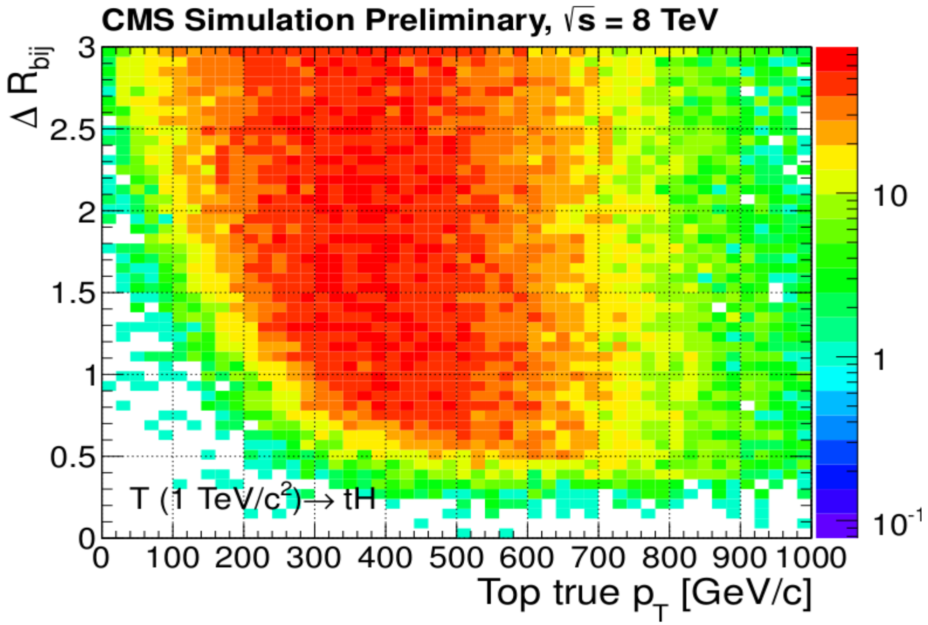
- Based on **CA15** collection, default for **HEPTopTagger**.

- Large cone-size allows to **reach lower p_T's** (~200GeV) without switching from merged-top to un-merged top selection.

- Signal: **T'→tH** pair production. Consistency of the results checked also on SM ttbar production.

- Inclusive **mistag** from **QCD**.

- HEPTopTagger forces **3 filtered subjets**: used for subjet b-tagging.



spread between top decay products (T'→tH)

B-Tagging Performance

Higgs channel

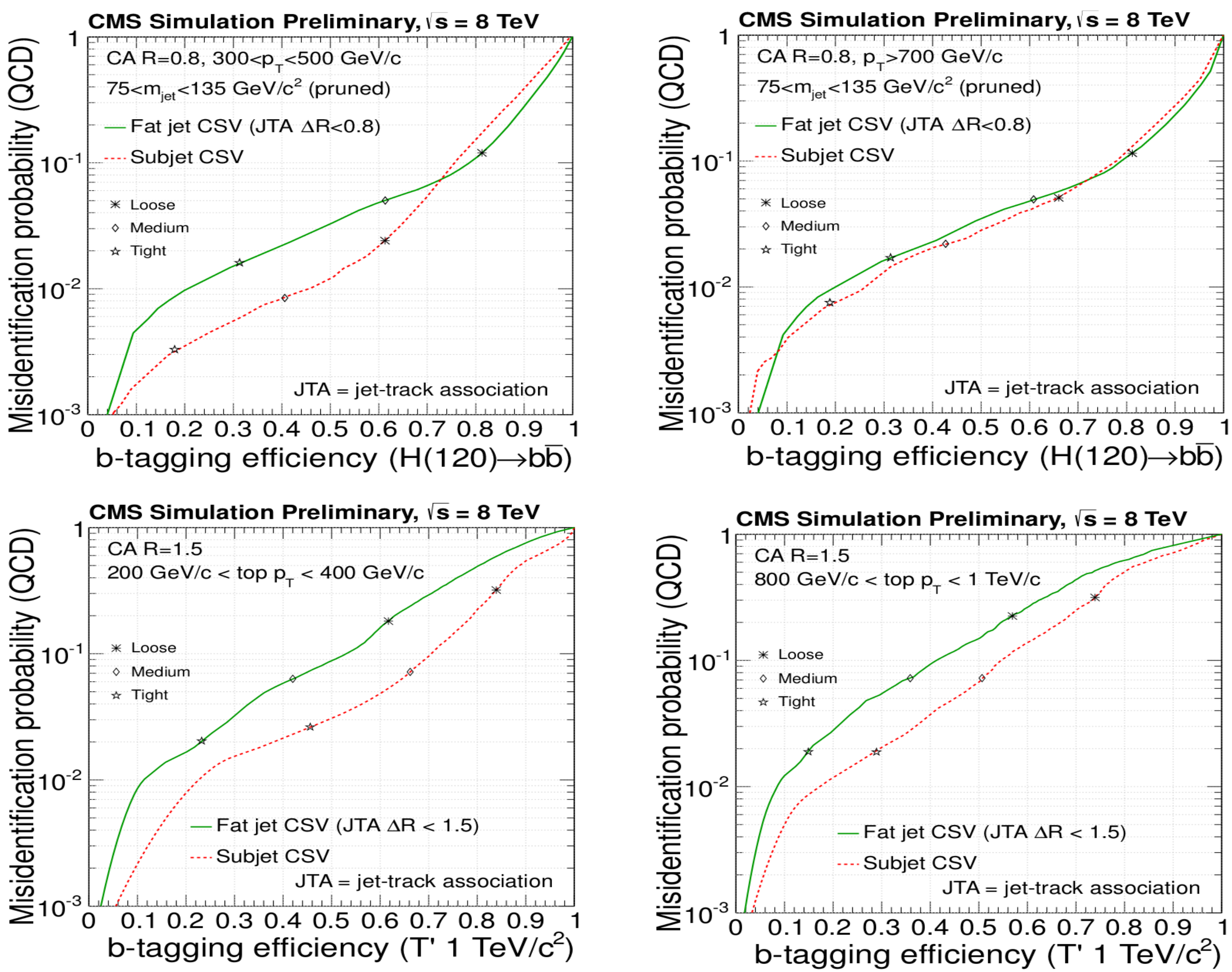
Subjet b-tagging performs better

Fat-jet b-tagging suitable at very high p_T

Top channel

Overall **subjet b-tagging** performs better

medium boost regime **large boost regime**

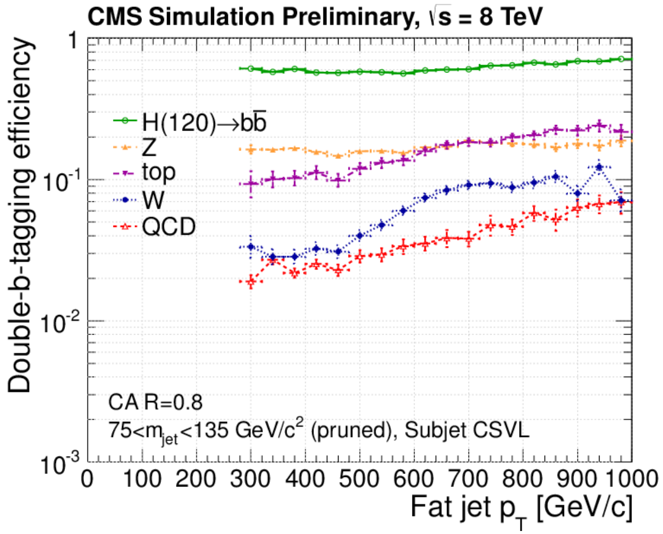


Tagging Performance

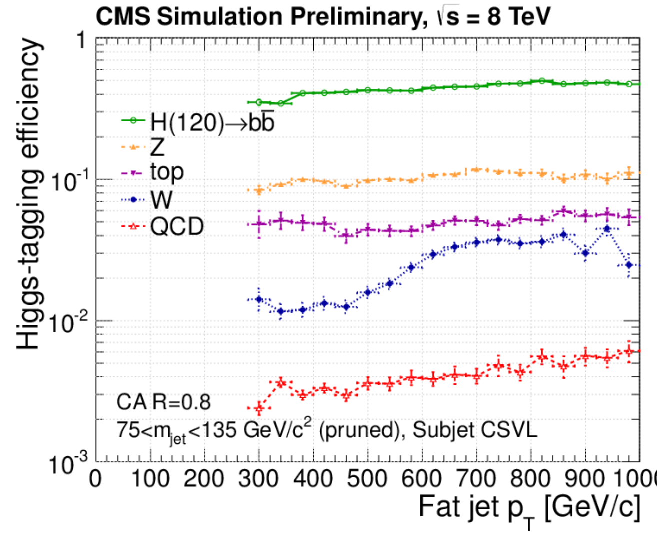
Higgs channel

Higgs-tagging
=
double b-tagging
+
75 < m_{jet} < 135 GeV

double b-tagging

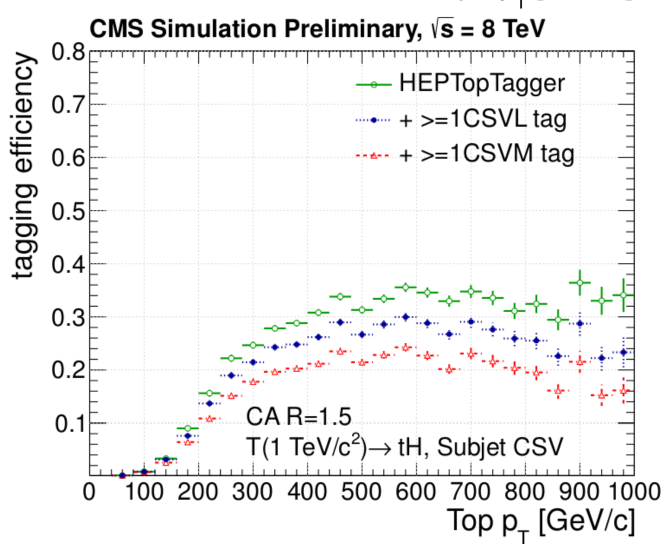


Higgs tagging

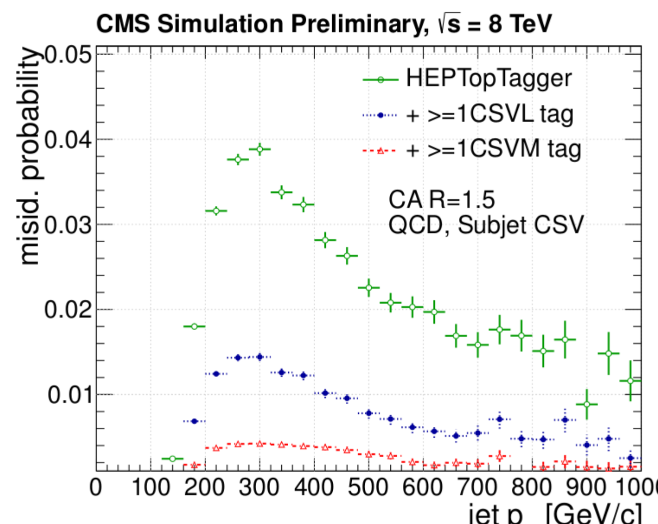


Top channel

QCD mistag rate reduced up to a factor 10 with minor loss of efficiency



tagging efficiency



mistag rate

Validation Sample: Higgs Channel

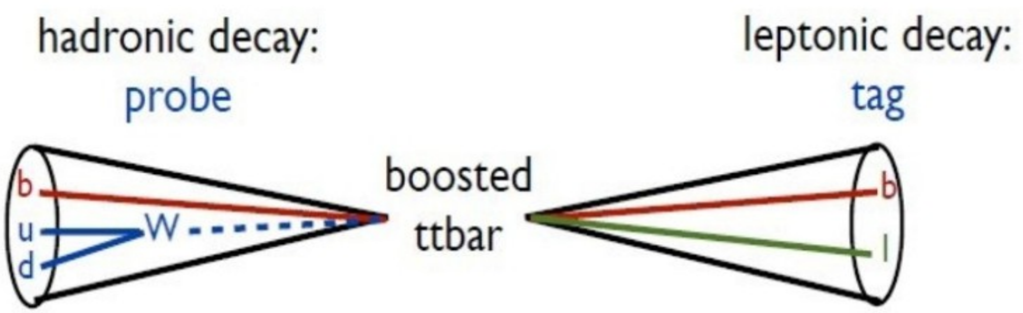
- Challenging definition of the control sample. Similar topology: **gluon splitting jets**, two closeby b's clustered in the same fat-jet.

- Event selection:
  - 1 CA8 jet, p_T>400 GeV, $|\eta|<2.4$;
  - ΔR(subjets)>m_{jet}/p_T: remove infrared unsafe configurations;
  - MC samples: inclusive and muon-enriched QCD, tt, $Z \rightarrow qq$.

- **Muon-tag** to b-enrich subjets sample: require muon with p_T>5GeV within subjet cone.

- Sample of CA8 fat-jets enriched in gluon splitting, requiring **both subjets to be muon-tagged**: **Higgs-like sample**.

Validation Sample: Top Channel



- ttbar semi-leptonic decays.
- Leptonic decay:
  - isolated muon;
  - 1 standard b-tag.
- Hadronic decay selected using HEPTopTagger.
- MC samples: ttbar + all SM backgrounds (single-top, Z/W+jets).

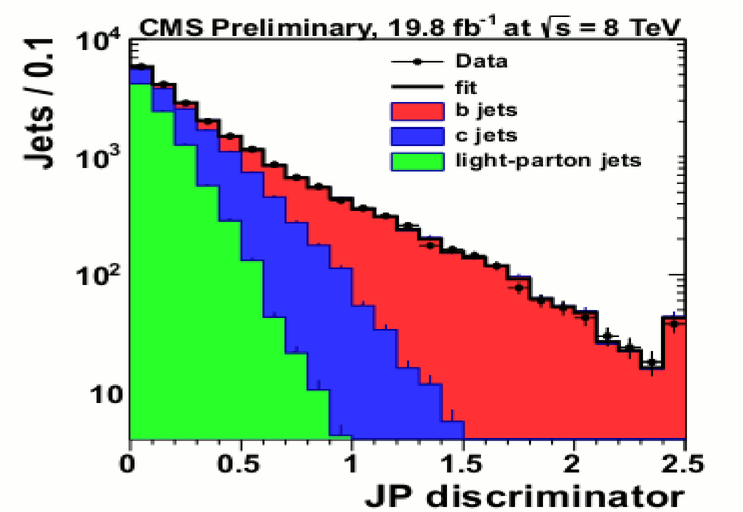
Lifetime Tagger Method

- Method based on **Jet-Probability b-tagger**. Advantage:
  - JP discriminant can be defined for most jets (>90%);
  - calibrated on data.

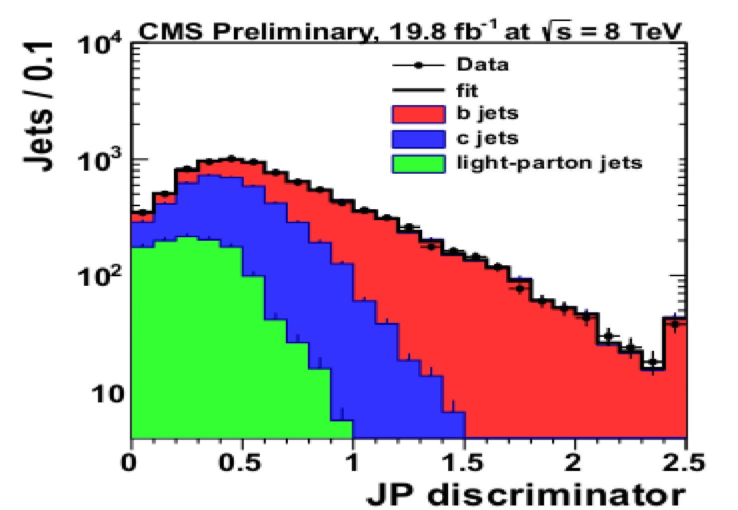
- **Template fit to JP discriminant**, before and after applying CSV. Discriminant shape from MC, while **relative flavor fractions are free parameters**.

- Tagging efficiency in data given by (C_b is fraction of jets for which JP computable):

$$\varepsilon_b^{tag} = \frac{C_b \cdot f_b^{tag} \cdot N_{data}^{tag}}{f_b^{before\ tag} \cdot N_{data}^{before\ tag}}$$



before b-tagging



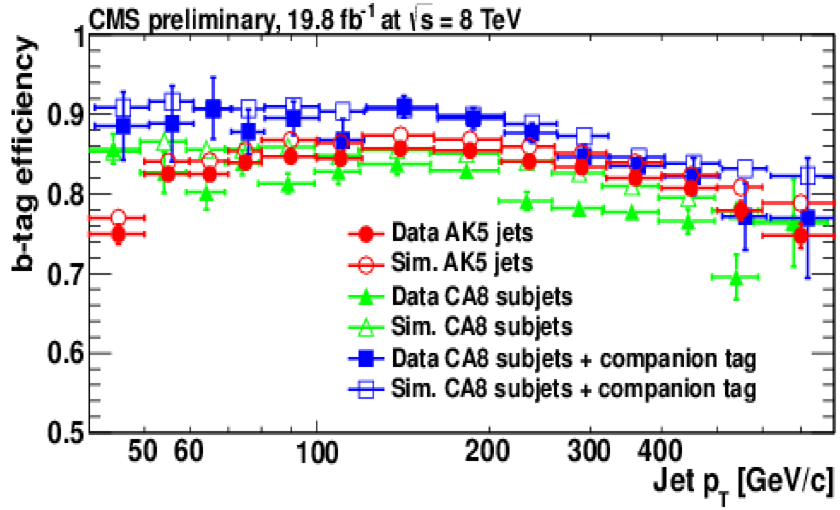
after b-tagging

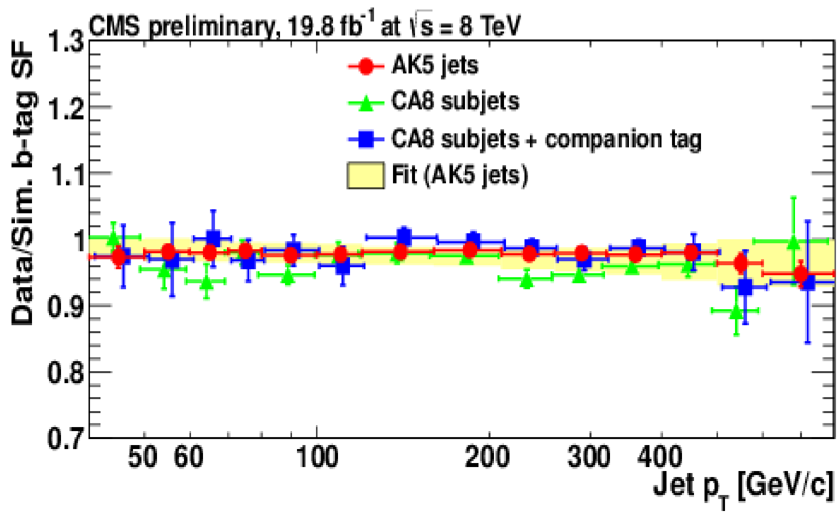
B-tagging Scale Factor

▶LT method applied to individual **muon-tagged subjets of CA8 fat jets** (**w/** and **w/o** the **companion subjet b-tagged**).

▶Very good agreement with the **standard scale factors**.

▶Results for the loose operating point of CSV.

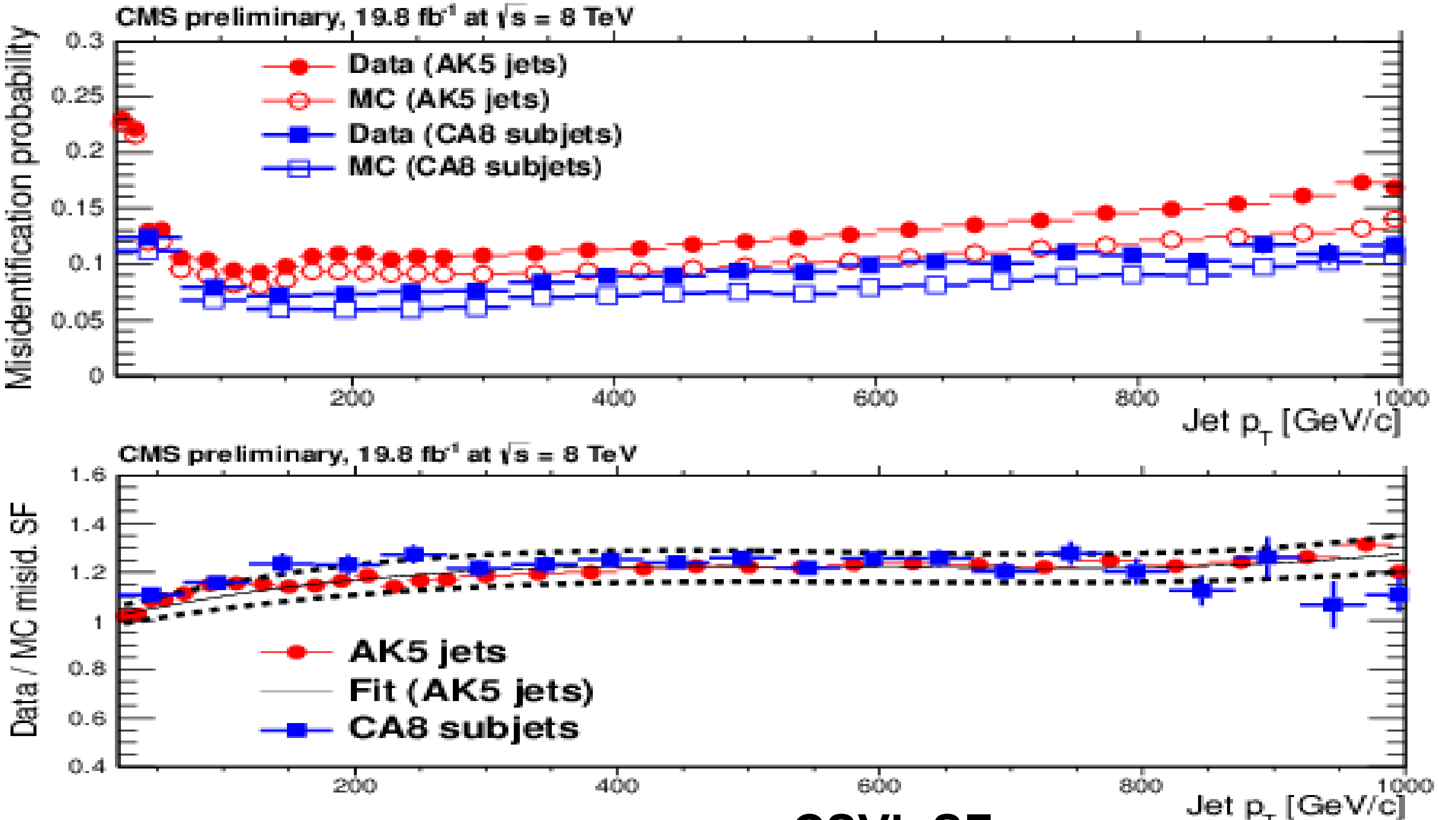




CSVL SF_b

Mistag Scale Factor

- Measurement of **mistag rate SF_{light} for CA8 subjets** based on **negative taggers**, which use tracks with negative impact parameter.
- Very good agreement with the **standard scale factors**.



CSVL SF_{light}

Flavor Tag Consistency Method

- Method based on distribution of **number of b-tags for the 3 subjets of CA15 HEPTopTagged fat-jet**: expected distribution fitted to data, with scale factors as free parameters.

- Expected number *n* of tags for ttbar signal can be expressed as:

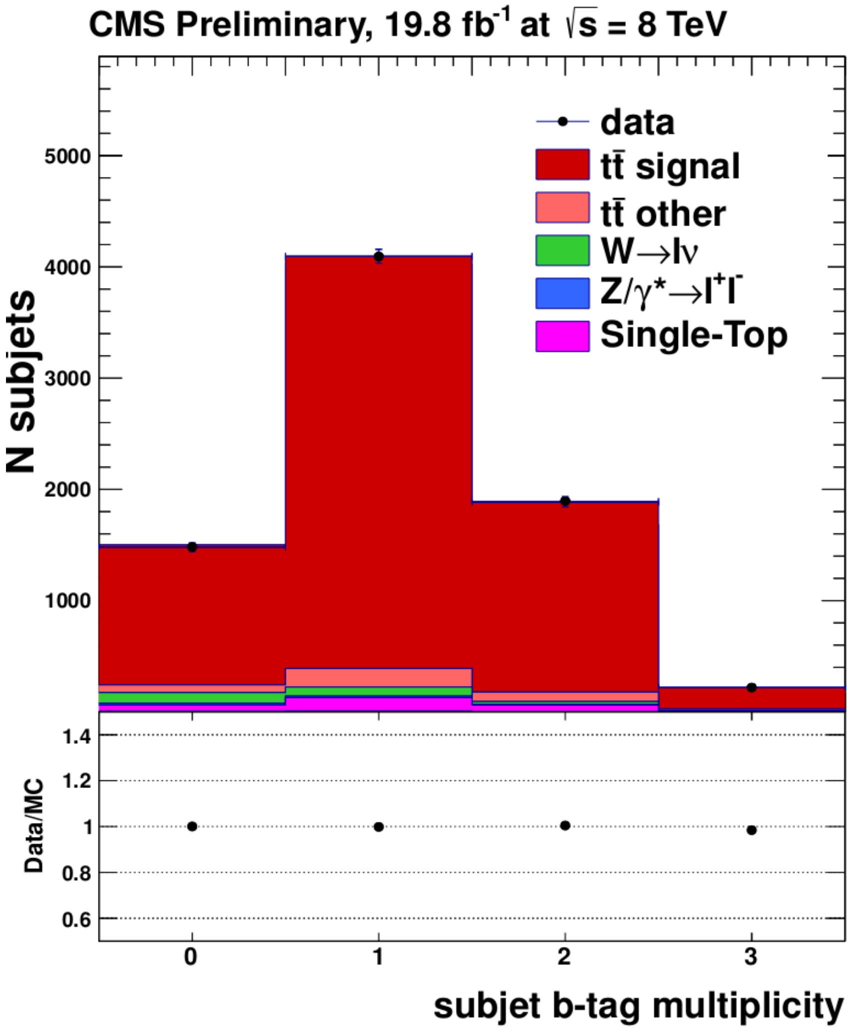
$$\langle N_n \rangle = \mathcal{L} \cdot \sigma_{t\bar{t}} \cdot \varepsilon \cdot \sum_{i,j,k} F_{ijk} \sum_{i'+j'+k'=n}^{i'\leq i, j'\leq j, k'\leq k} [C_i^{i'} \varepsilon_b^{i'} (1-\varepsilon_b)^{(i-i')} C_j^{j'} \varepsilon_c^{j'} (1-\varepsilon_c)^{(j-j')} C_k^{k'} \varepsilon_l^{k'} (1-\varepsilon_l)^{(k-k')}]$$

→ $\boldsymbol{\varepsilon_b}$, $\boldsymbol{\varepsilon_c}$, $\boldsymbol{\varepsilon_l}$ are the tagging efficiencies;
→ $\boldsymbol{C^a_b}$ are the binomial coefficients;
→ ***Fijk*** are the fractions of events with *i* b-subjets, *j* c-subjets and *k* light-subjets: **taken from MC**.
→ **backgrounds included in the fit**.

Fit Modalities

- **2 parameters** fit:
  → σ_{tt}, SF_b are free parameters. Fixed SF_c = SF_b and fixed SF_{light} to SF_{light} for standard b-tagging on AK5 jets.
- **3 parameters** fit:
  → σ_{tt}, SF_b and SF_{light} are free parameters. Fixed SF_c = SF_b.

- Excellent data/MC agreement after fit of subjet b-tag multiplicity.



Post-fit distribution

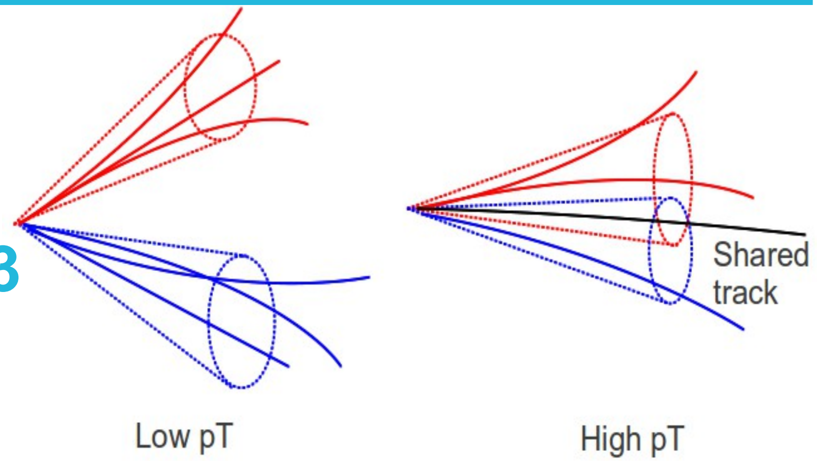
Scale Factors

- Measured SF_b for boosted top subjets are in **agreement with standard SF_b** for AK5 jets.
- **No significant deviation at high top-p_T** of the measured SF_b.
- Mistag SF_{light} are in **agreement with standard SF_{light}** for AK5 jets.

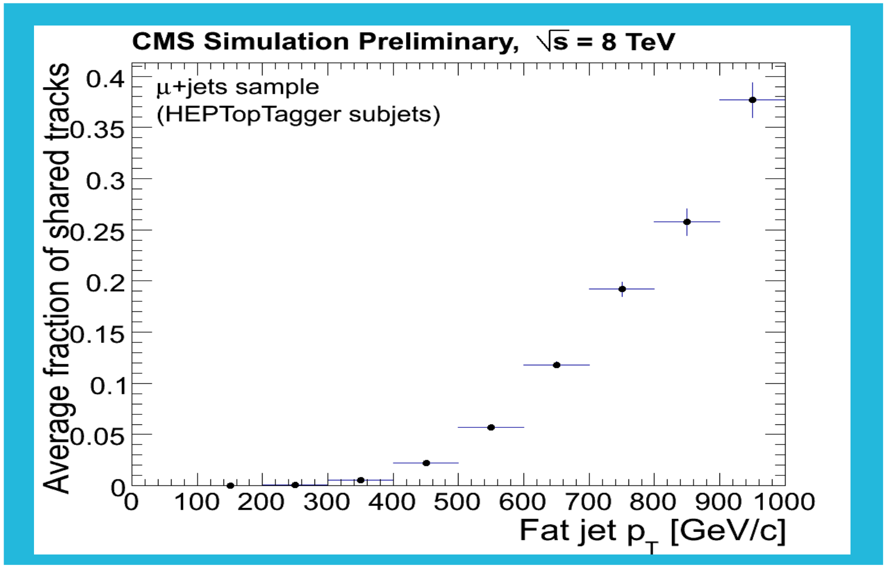
		CSVL	CSVM	CSVT
SF_b	SF_b for non-boosted jets	1.010 ± 0.013	0.970 ± 0.013	0.950 ± 0.015
	SF_b for HEPTopTagger subjets	1.003 ± 0.026	0.979 ± 0.023	0.960 ± 0.036
SF_b pT dependence	$150 \leq p_T < 350$ GeV/c	—	$0.978^{+0.023}_{-0.023}$	—
	$p_T \geq 350$ GeV/c	—	$0.993^{+0.034}_{-0.034}$	—
	$p_T \geq 450$ GeV/c	—	$0.997^{+0.067}_{-0.067}$	—
SF_{light}	SF_{light} for non-boosted jets	$1.080^{+0.063}_{-0.072}$	$1.136^{+0.090}_{-0.110}$	$1.088^{+0.039}_{-0.086}$
	SF_{light} for HEPTopTagger subjets	1.185 ± 0.080	1.580 ± 0.47	—

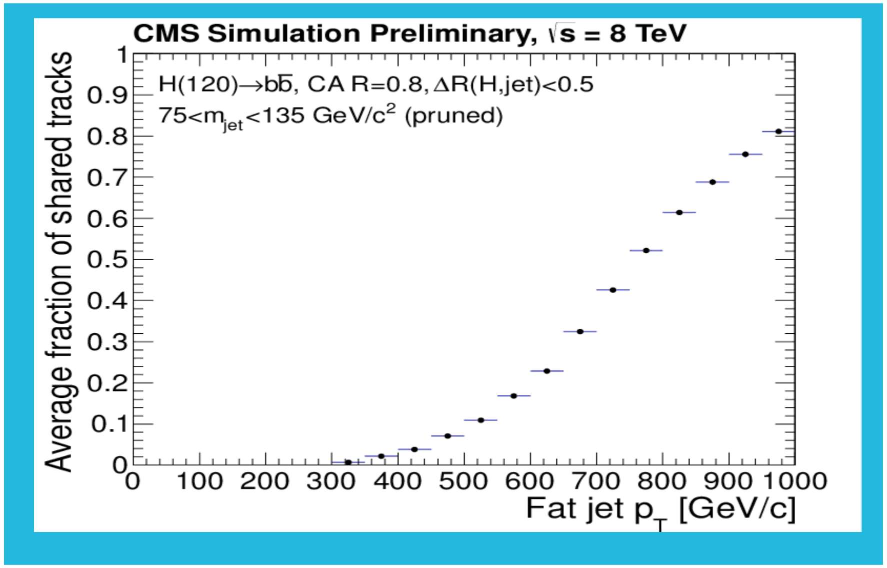
Track Sharing

- Cross-check of **sharing of tracks selected** for b-tagging between subjets.
- Considere tracks in a cone of **ΔR<0.3** around subjet axis (as used by CSV).



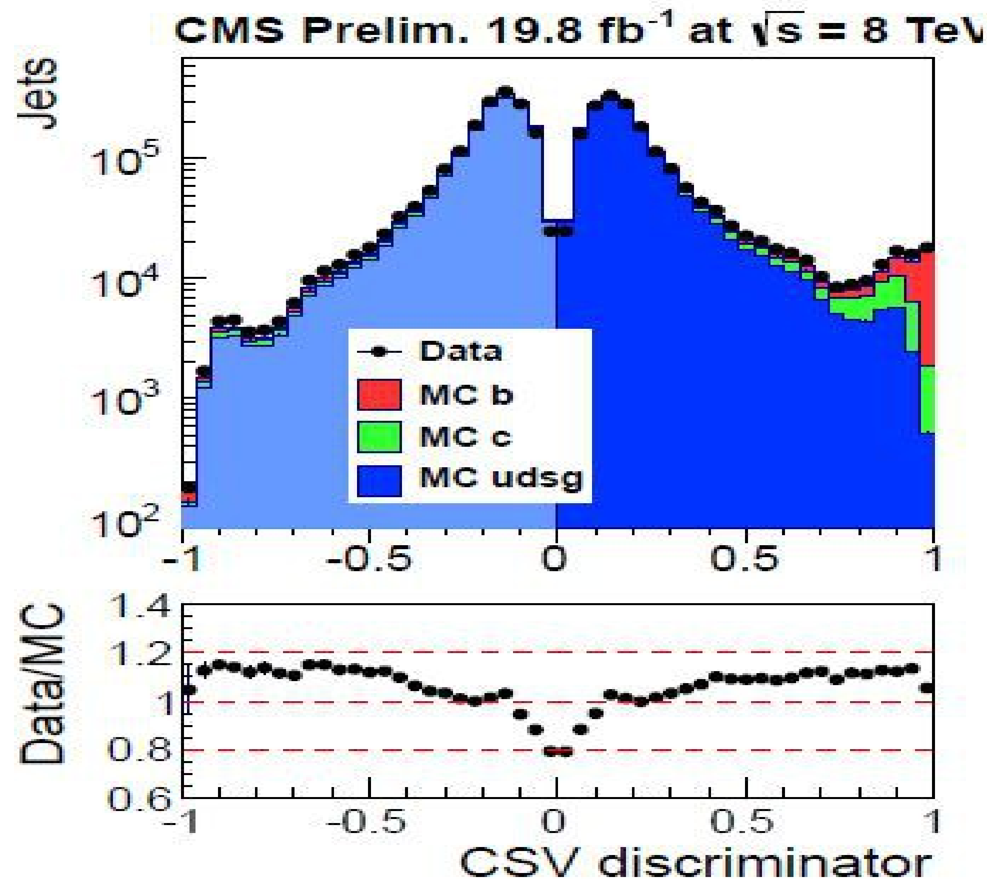
- Track-sharing increases with p_T of the fat-jet. At very high boost, the level of track sharing becomes significantly large. One solution is to switch to fat-jet b tagging.





Mistag SF

- Use tracks with negative IP or SV with negative decay length to define a **negative tagger for each tagger**.
- Scale factor for mistag obtained according to:



given by:

$$\mathbf{SF}_{\mathbf{mistag}} = SF_{neg\ tag} \cdot \frac{R_{light}^{data}}{R_{light}^{MC}}$$

negative tagger

B-tagging Observables

▶ Checking data/Monte Carlo agreement for b-tagging quantities. Presentation ordering:

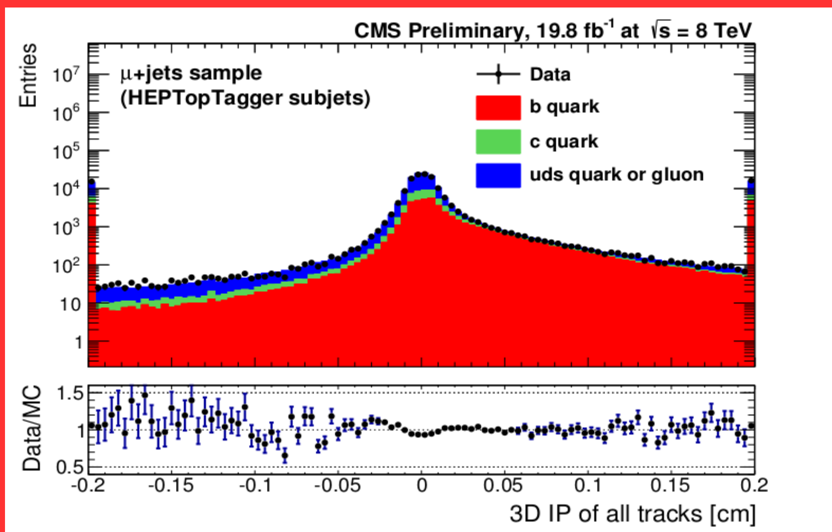
Top channel validation:
HEPTopTagger
Subjets

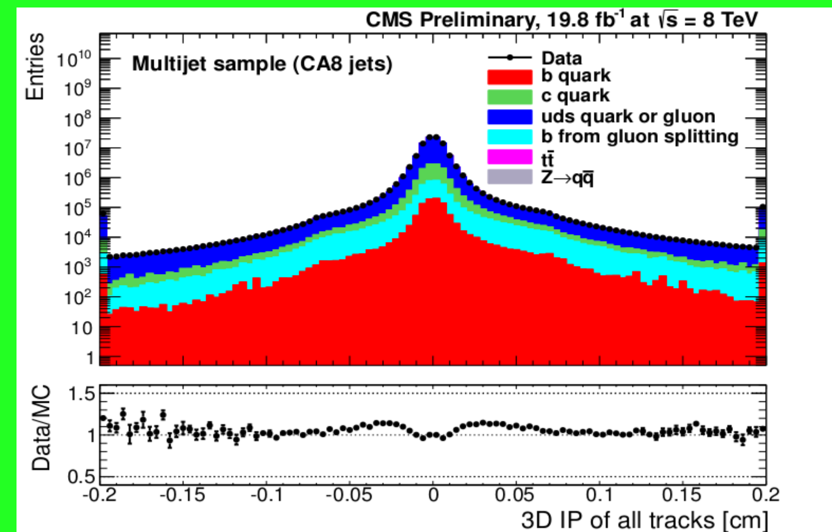
Higgs channel validation:
Multijet sample
(CA8 jets)

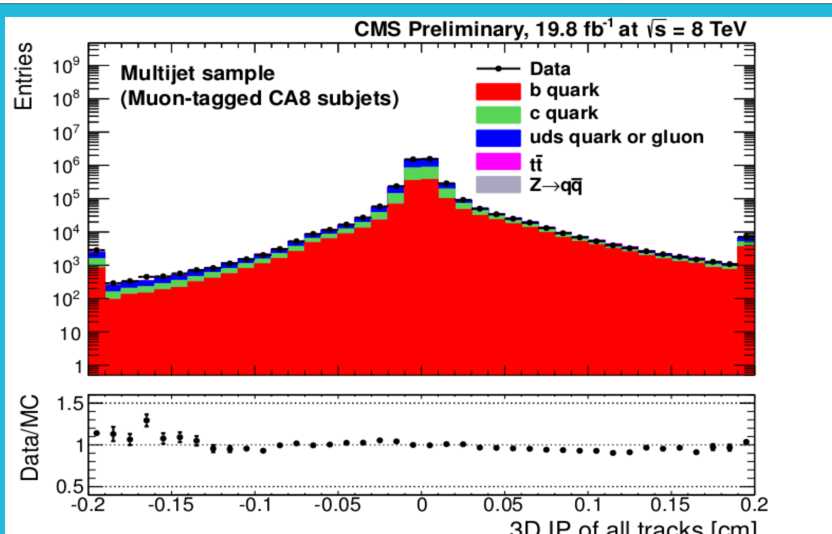
Higgs channel validation:
Multijet sample
(CA8 muon-tagged subjets)

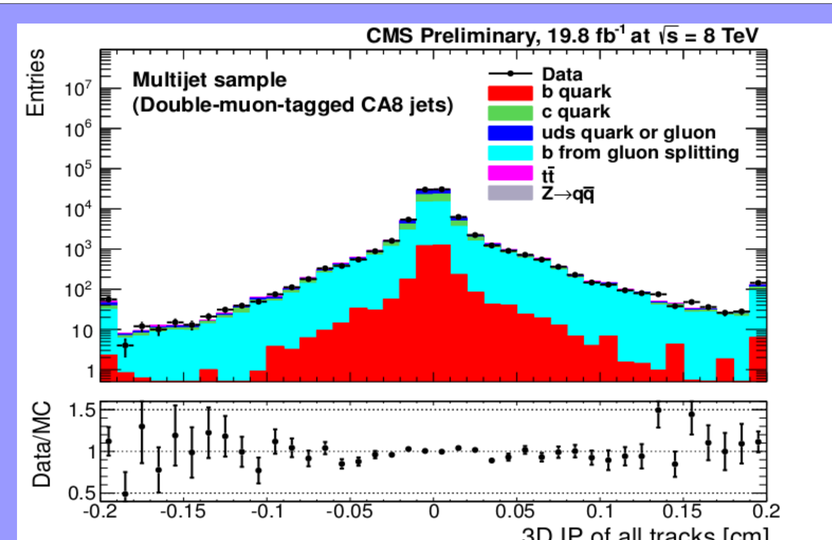
Higgs channel validation:
Multijet sample
(double muon-tagged CA8 jets)

3D Impact Parameter

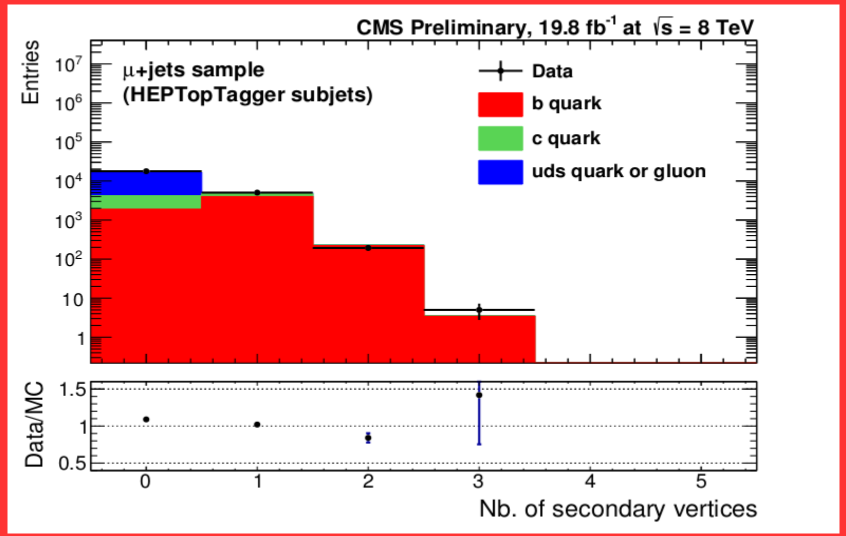


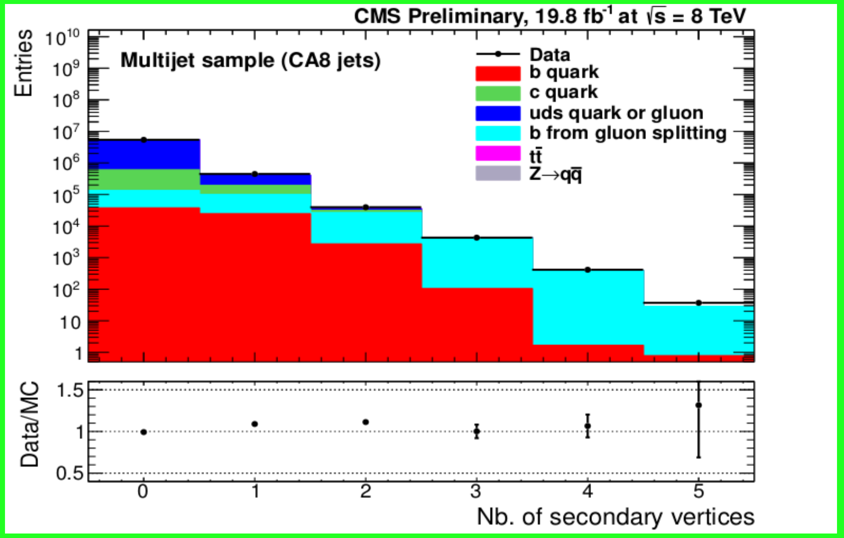


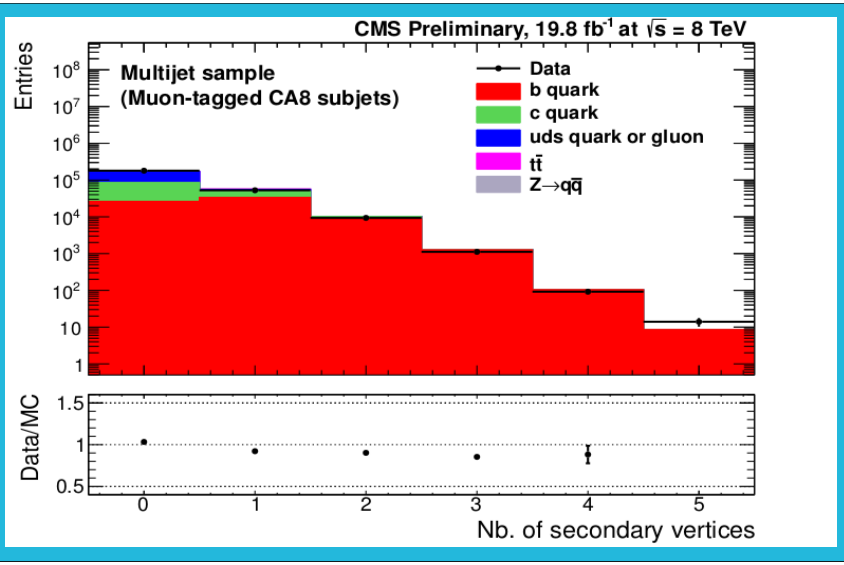


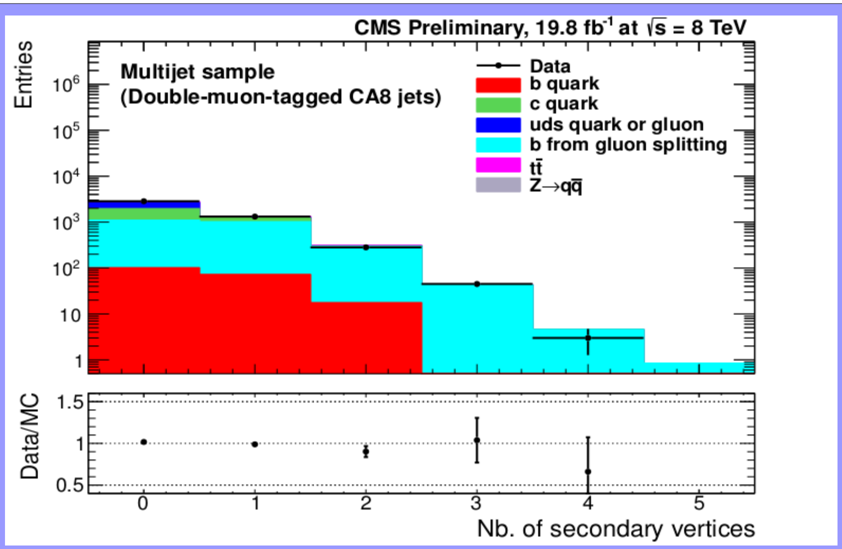


Secondary Vertex Multiplicity

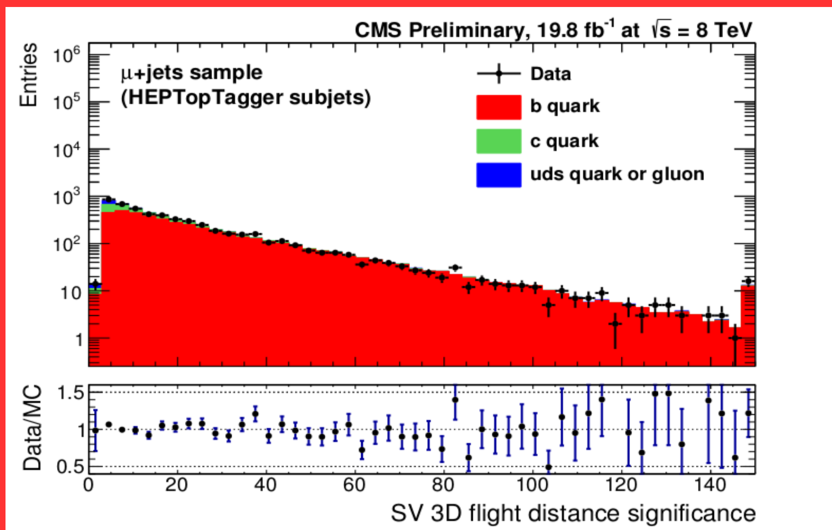


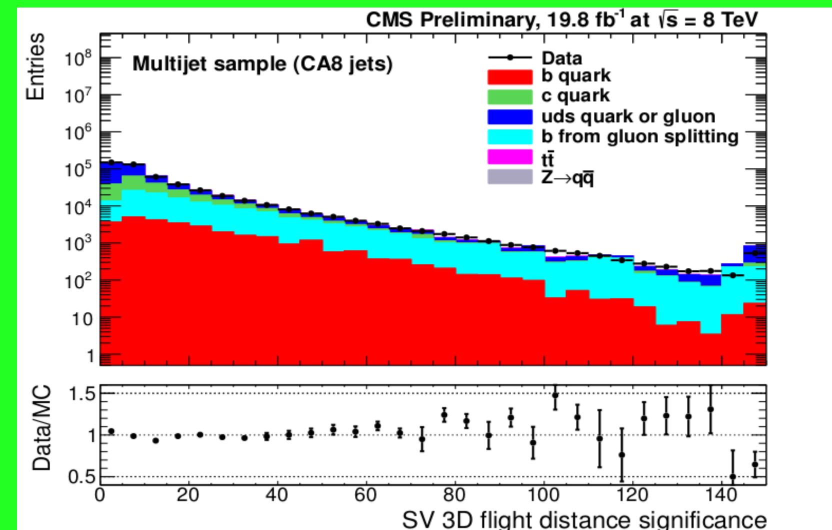


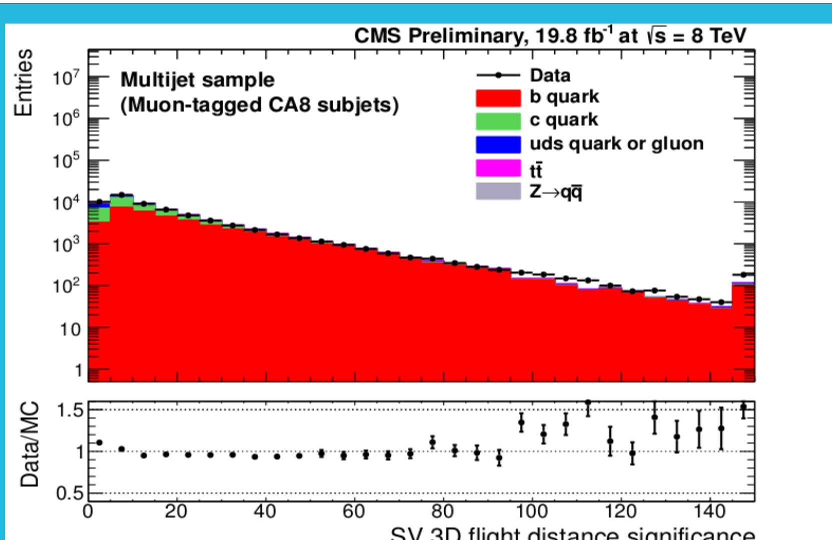


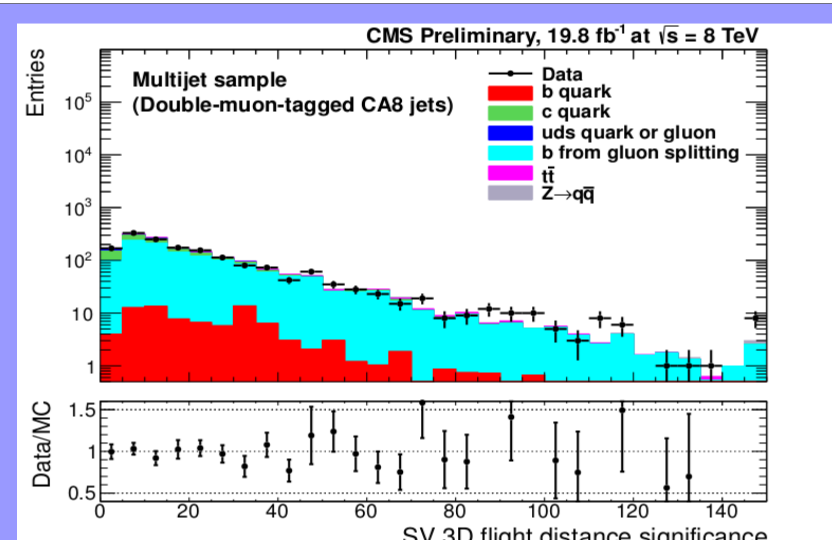


SV Flight Distance Significance

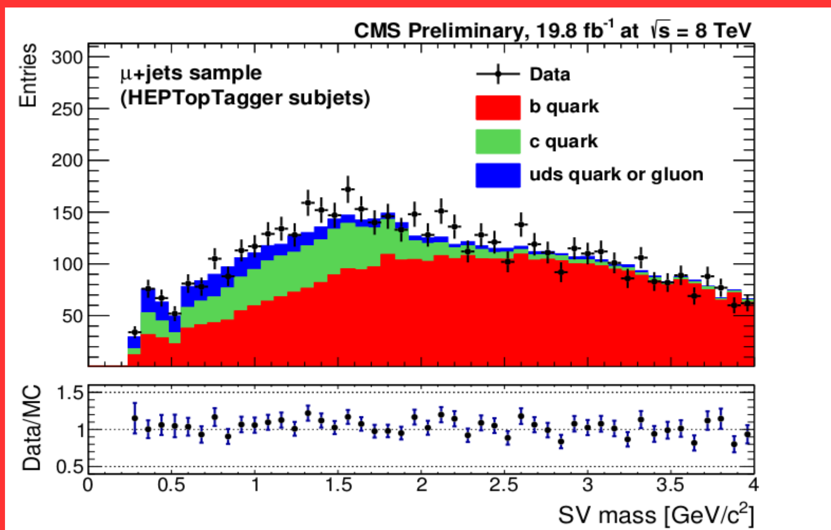


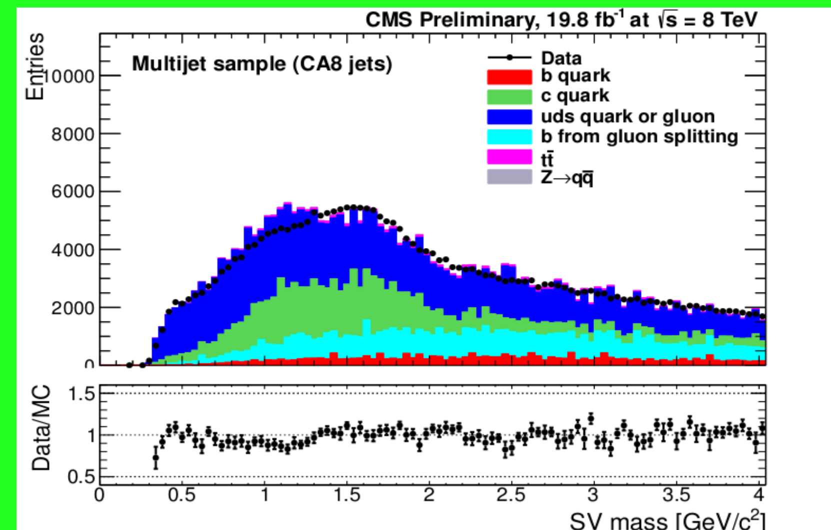


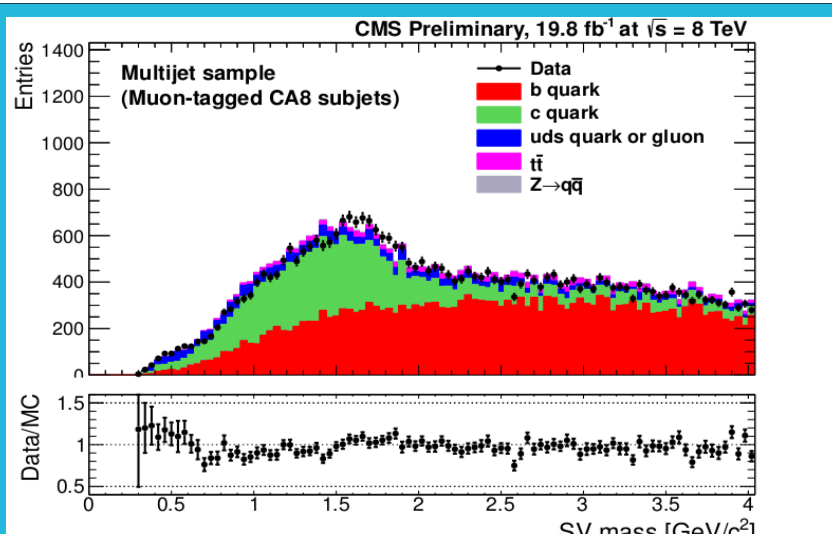


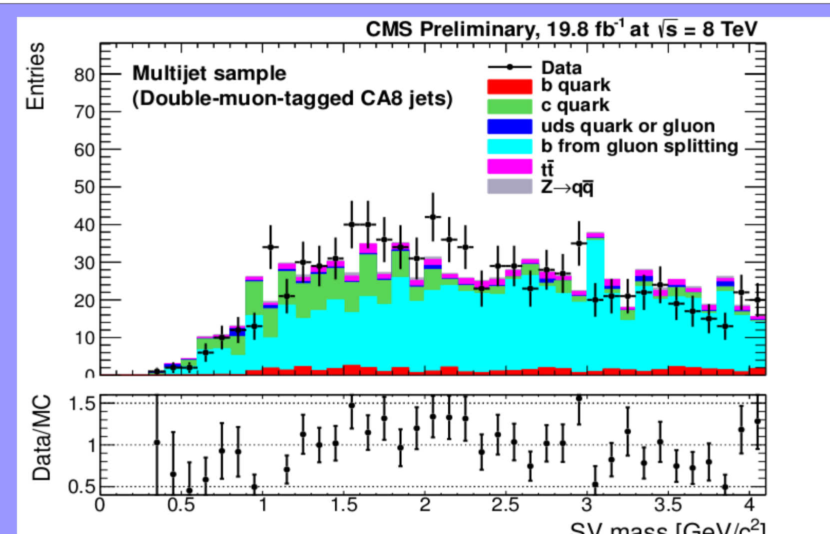


Secondary Vertex Mass

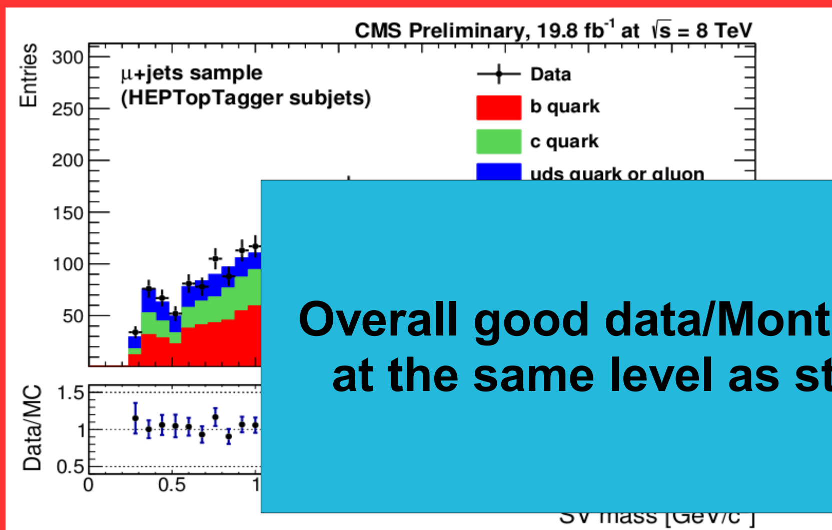


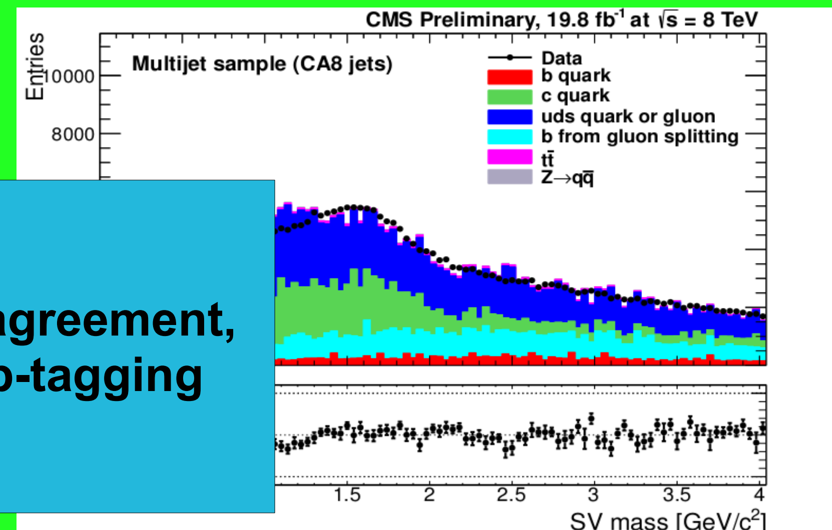




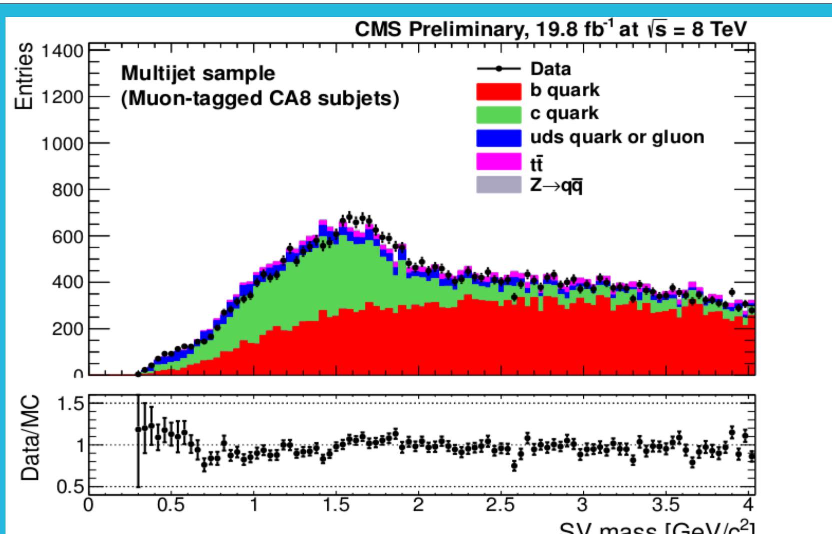


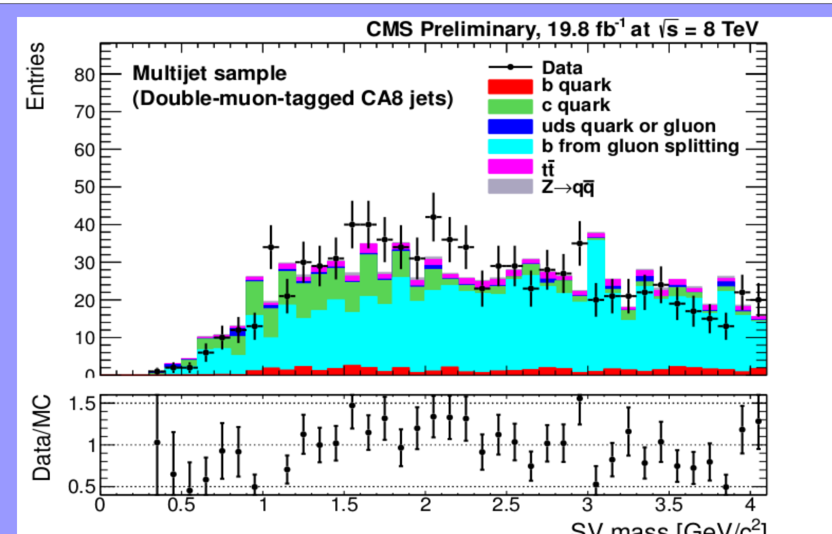
Secondary Vertex Mass





Overall good data/Monte Carlo agreement, at the same level as standard b-tagging





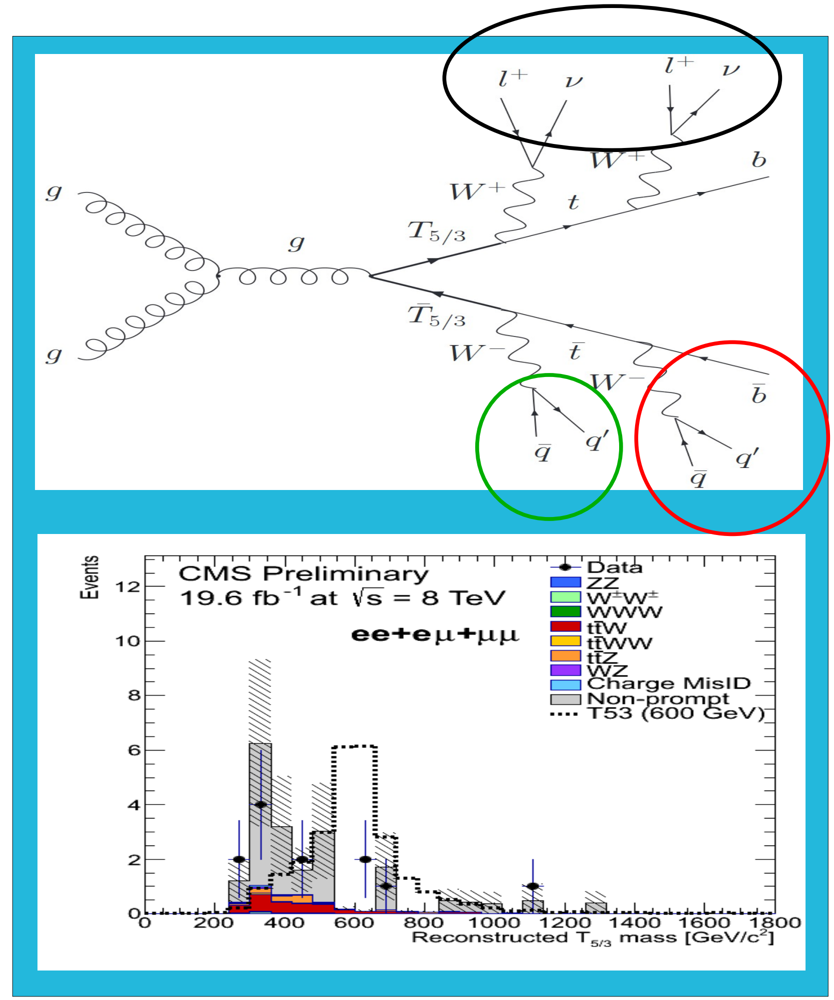
T'5/3 Top Partners [CMS-PAS-B2G-12-012]

- **Vector-like heavy quarks** are part of several theories:
  - little/composite Higgs models
  - extra dimenions
- Solution to the hierarchy problem.

- Signal:
  - pair-produced **T' with charge 5/3**
  - BR 100% **T'→tW**

- Selection:
  - two **same sign leptons**
  - **top-tagging**
  - **W-tagging** (m_{pruned} [60,130] GeV)

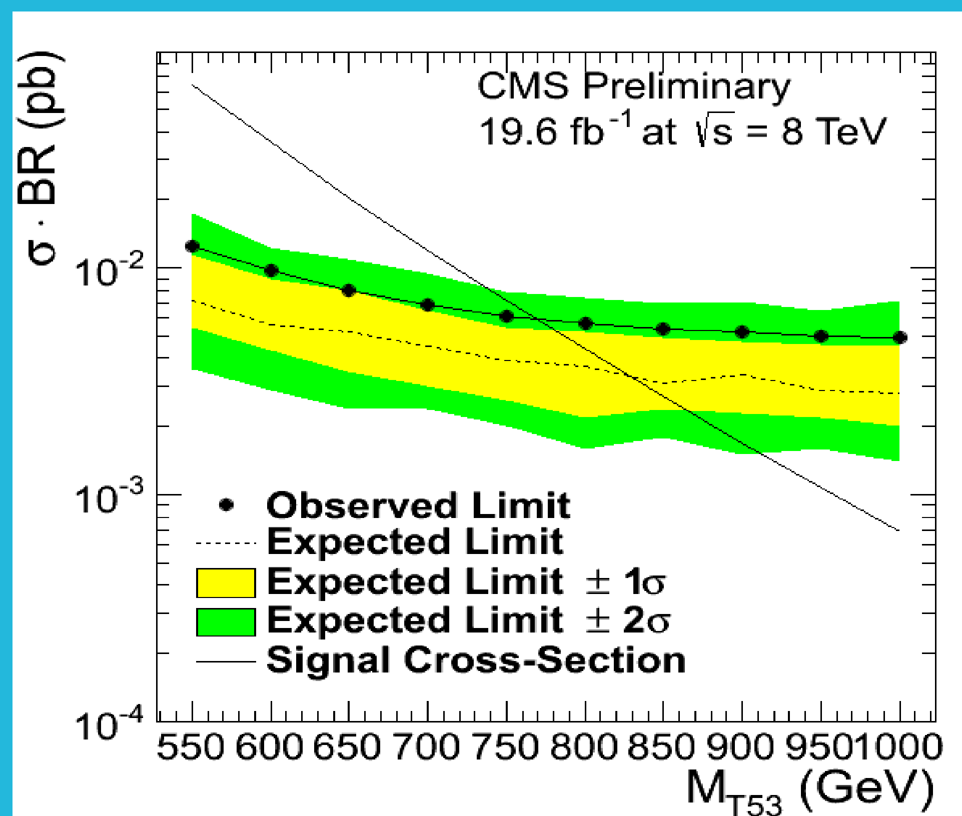
- Limits from event yields.



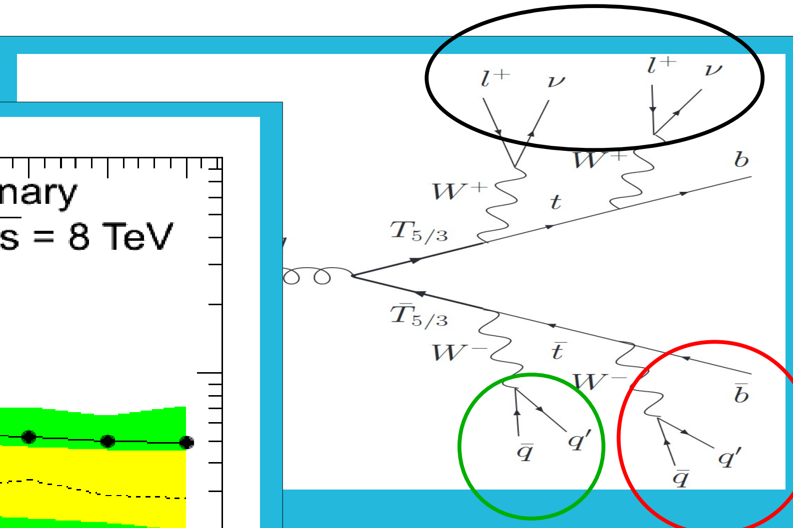
reconstruction of T' mass from all channels

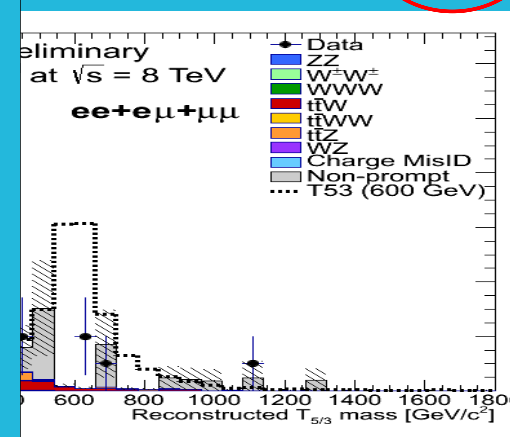
T'5/3 Top Partners [CMS-PAS-B2G-12-012]

- **Vector-like heavy quarks** are part of several theories:
  - little/composite Higgs models
  - extra dimenions
- Solution to
- Signal:
  - pair-produ
  - BR 100%
- Selection:
  - two **same**
  - **top-taggi**
  - **W-taggin**
- Limits from



observed limit 770 GeV





reconstruction of T' mass from all channels

T'2/3 Top Partners [CMS-PAS-B2G-12-015]

Signal:
- pair-produced **T' with charge 2/3**
- decay modes: T'→tH, tZ, bW
- **all possible branching fractions**

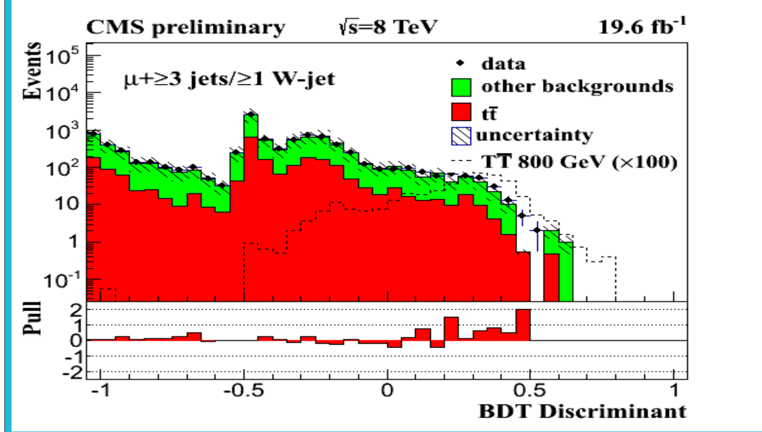
Combination of two analysis strategies:

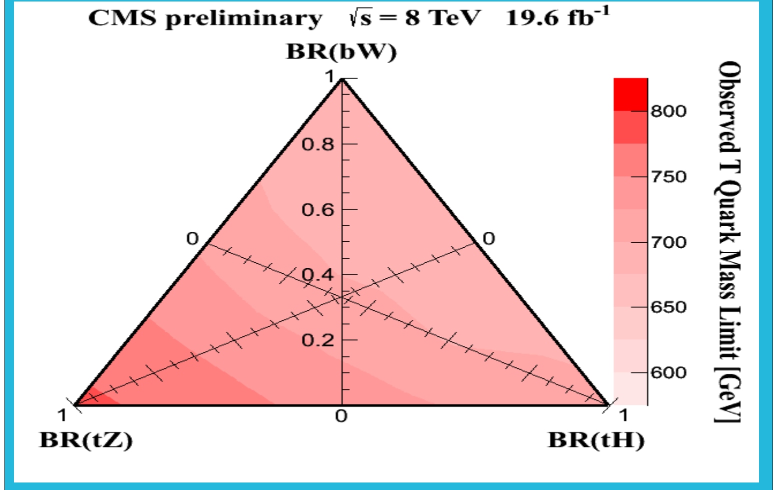
▶ **Multivariate analysis, single lepton**:

- two event categories: with or without **W-tag**
- **top-tagging** applied
- relevant observables combined in BDT:
  - multiplicity/p_T of reconstructed objects (lepton, jets, tagged jets...)
  - N of b-, W- and top-tags

▶ **Counting experiment, multilepton** channel. No substructure.

BDT discriminant, single μ channel





final combined limit up to 782 GeV

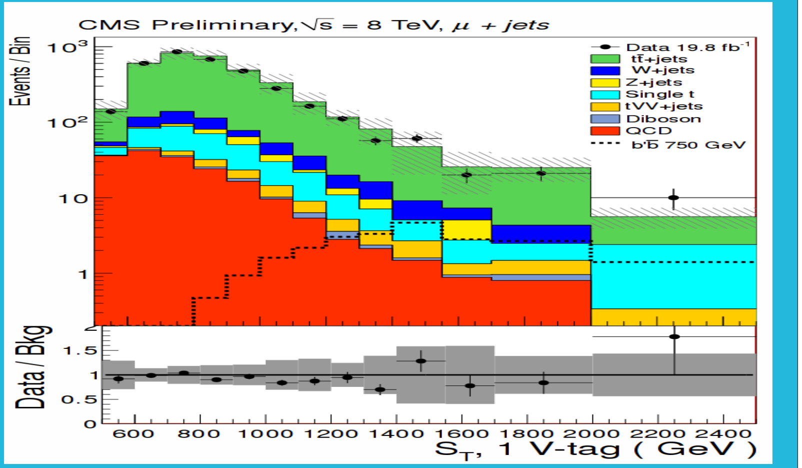
B'-1/3 Bottom Partners
[CMS-PAS-B2G-12-019]

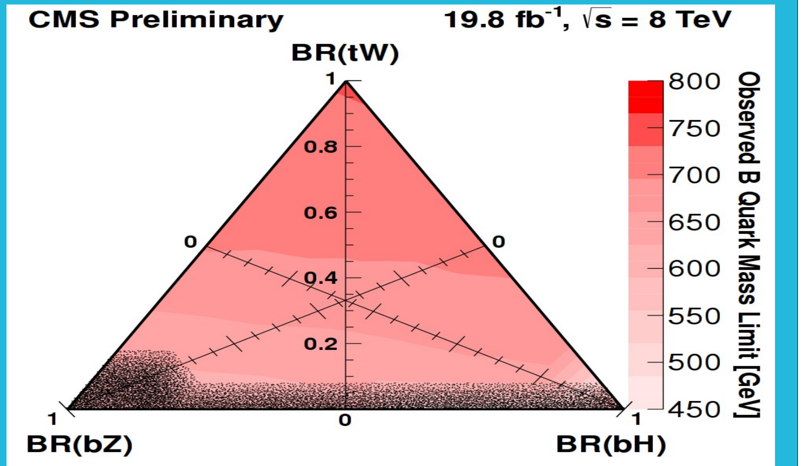
- Signal:
  - pair-produced **B' with charge -1/3**
  - decay modes: B'→tW, bZ, bH
  - all possible branching fractions

- Selection:
  - **single muon or electron**
  - ≥4 AK5 jets, ≥1 **b-tagged**
  - event categories based on number of **V-tags** (V=W/Z/H):

- **CA8 jet, $p_T \geq$ 200 GeV**
- **mass drop μ < 0.4**
- **2 pruned subjets**
- **m_{pruned} [50,150] GeV**

S_T distribution, for 1 V-tag category





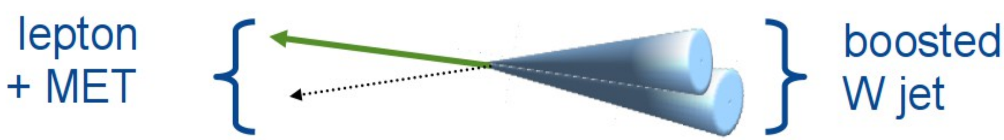
final limit up to 732 GeV

- Limits based on S_T distribution: $S_T = p_T^{lept} + p_T^{miss} + \sum p_T^{jets}$

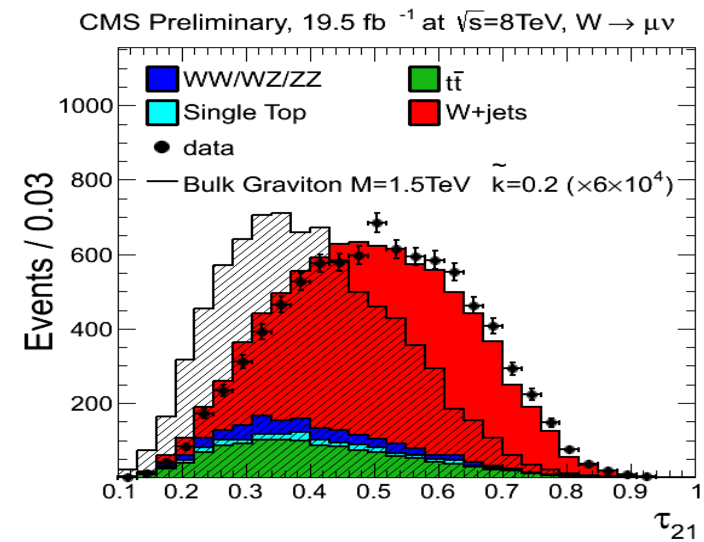
High Mass Dibosons
[CMS-PAS-EXO-12-021/024]

Predicted by several models. Here considered:

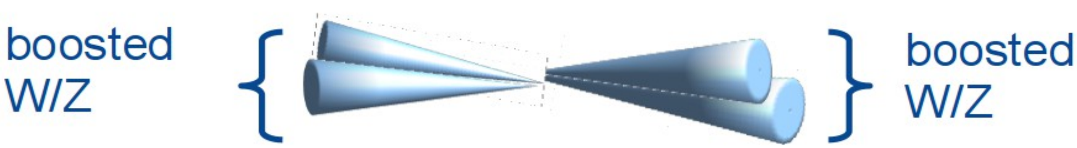
- **bulk graviton** production: $G_{bulk} \rightarrow WW \rightarrow l + jet + MET$

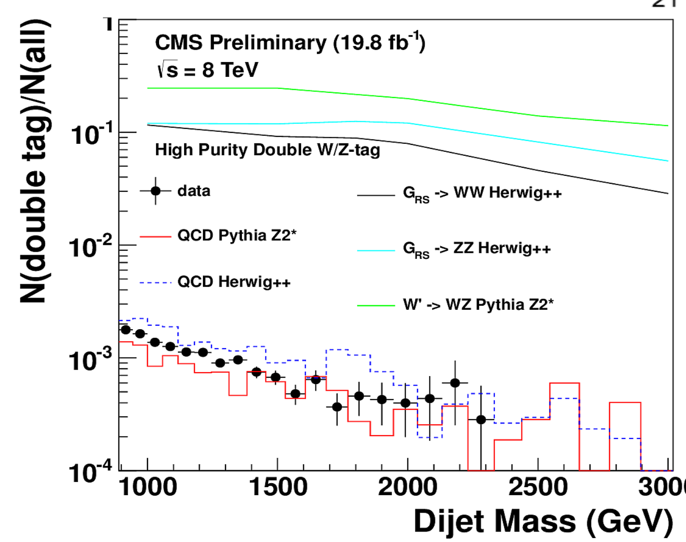


W-tagging:
- m_{pruned} [65,105]GeV
- N-subjettiness:
  - high-purity $\tau_2/\tau_1 < 0.5$
  - low-purity $0.5 < \tau_2/\tau_1 < 0.75$



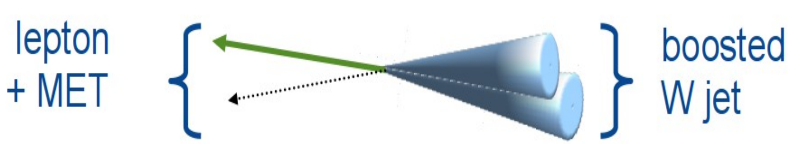
- RS graviton, W heavy partner W'
  $G_{RS} \rightarrow$ WW/ZZ, W' $\rightarrow$ WZ
  all-hadronic decay

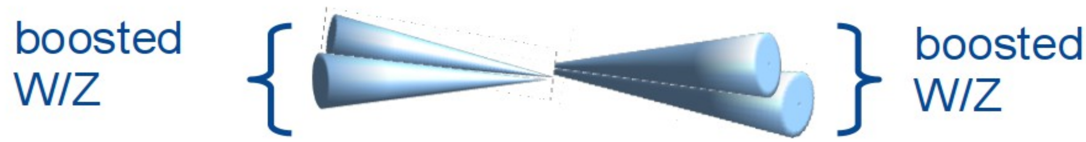


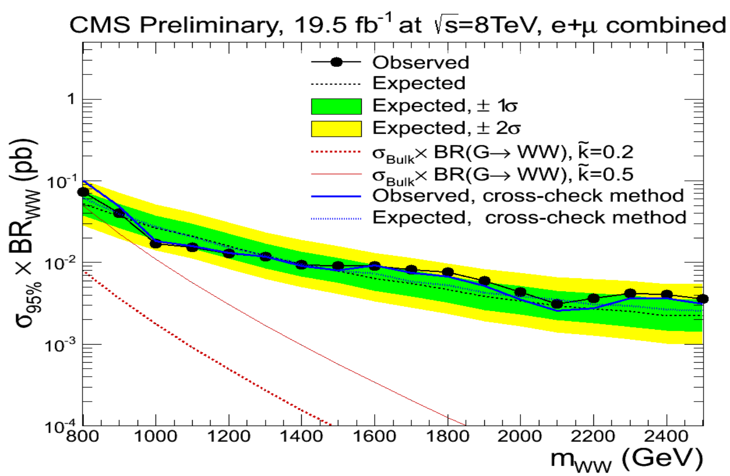


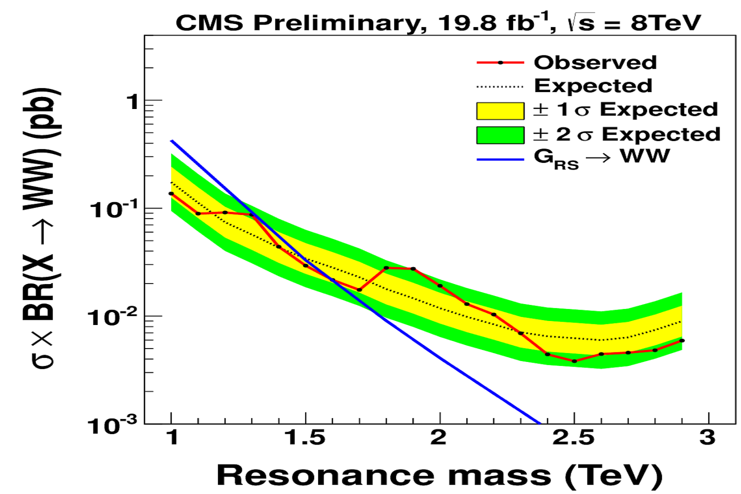
double W/Z-tagging:
m_{pruned} [70,100] GeV, same τ_2/τ_1 cuts as above

High Mass Dibosons
[CMS-PAS-EXO-12-021/024]

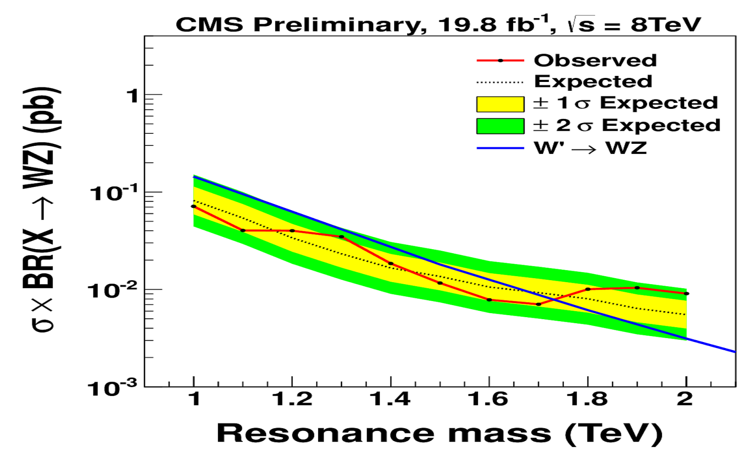






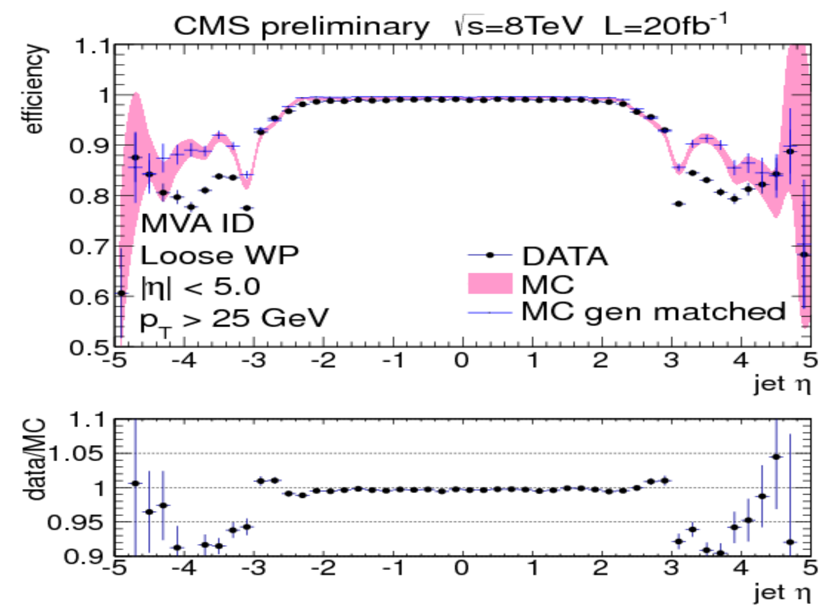


- G_{bulk} σ x BR_{WW} limits between 70fb and 3fb
- G_{RS} → WW excluded between [1.00,1.59] TeV
- G_{RS} → ZZ excluded between [1.00,1.17] TeV
- W' → WZ excluded up to 1.73 TeV



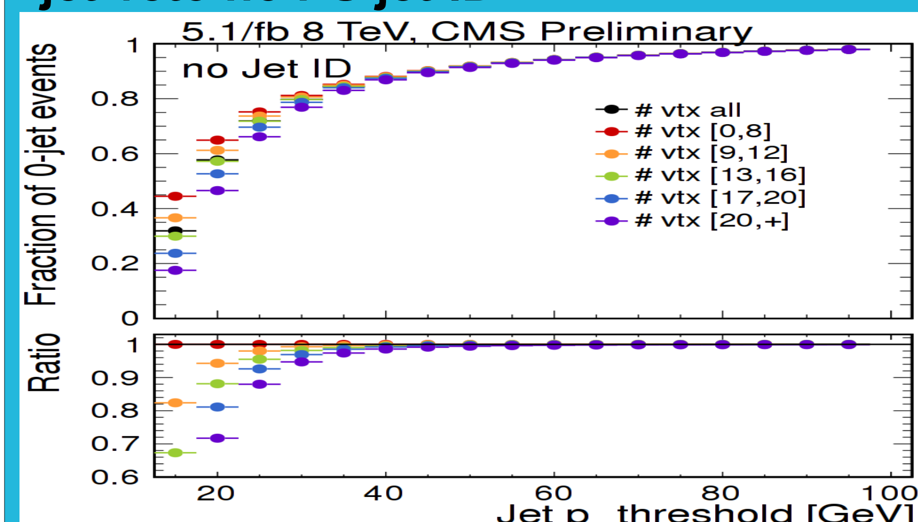
Pile-Up Jet-ID
[CMS-PAS-JME-13-005]

- Performance:
  - **tag-and-probe method from Z (→μμ) + jets** events, where probe is jet recoiling against Z
  - data/MC agreement within 10%, corrected using SF

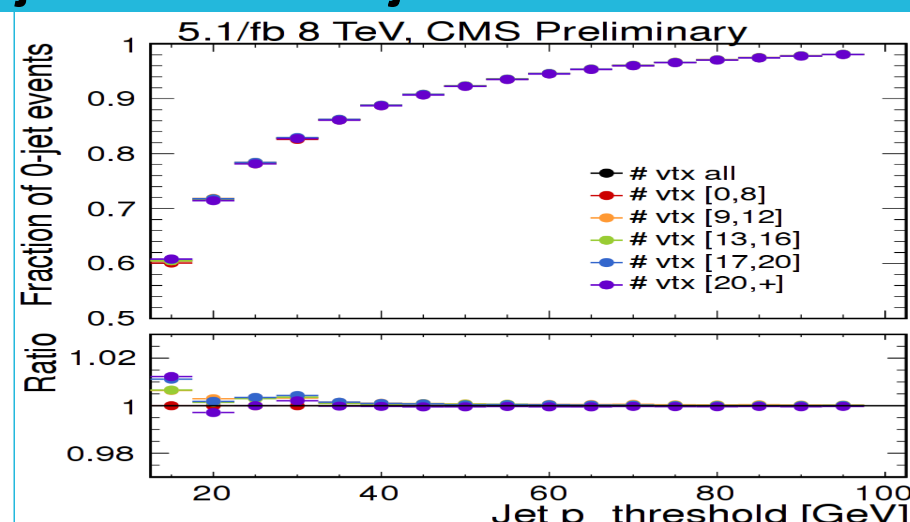


- Several applications:
  - e.g. : **extensions of jet vetos to low p_T** (Higgs searches)

jet-veto no PU jet-ID



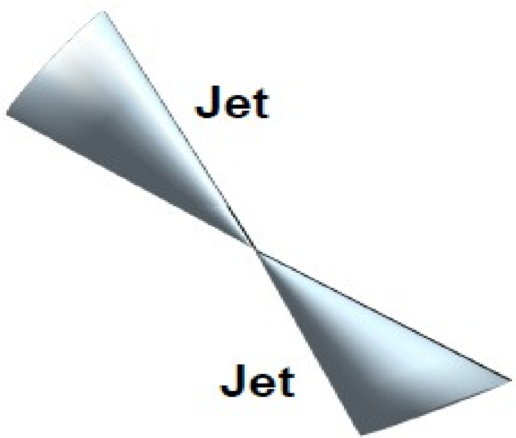
jet-veto with PU jet-ID



W-Tagging
[CMS-PAS-JME-13-006]

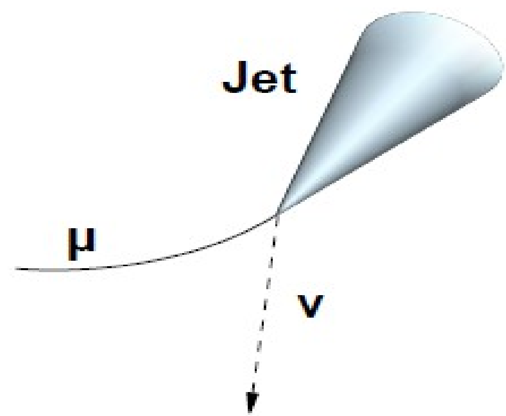
Event topologies considered

Dijet



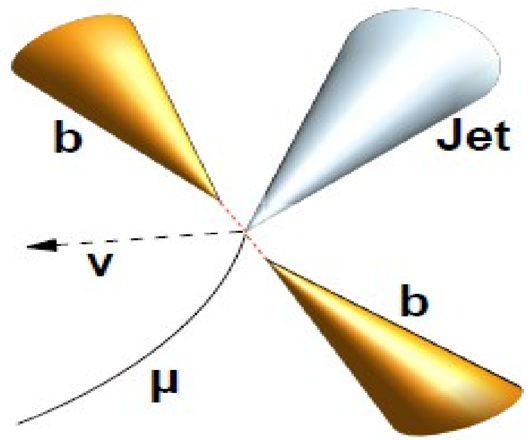
- two hard jets
- p_T = 400-600 GeV
- accesses high p_τ region
- QCD-jet dominated
- used to study fake rate

W+jets



- leptonic W + jet
- p_T = 250-350 GeV
- accesses low p_T region
- QCD-jet dominated
- presence of non-dominant background ($t\bar{t}$, single top)
- used to study fake rate

$t\bar{t}$

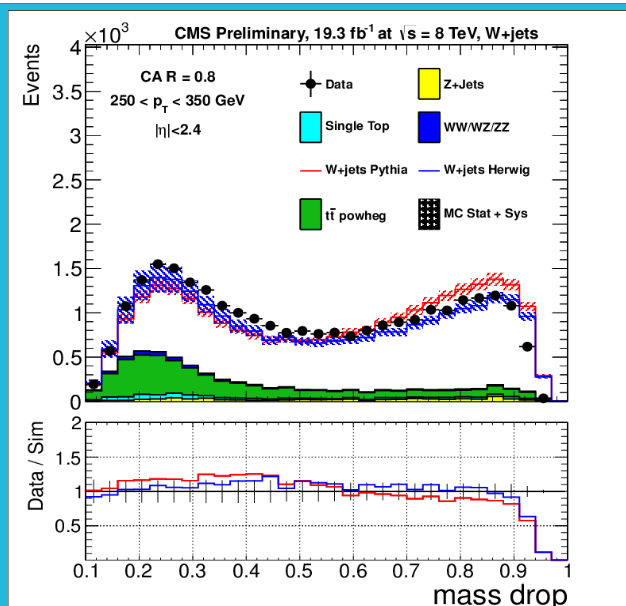


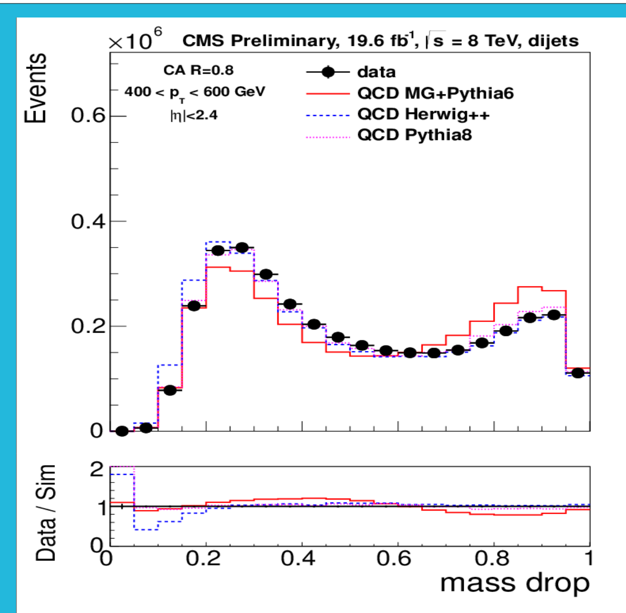
- leptonic top decay + hadronic top
- highly pure sample of W-jets
- used to study efficiency

Benchmark signal: $X \rightarrow W_L W_L$, $M_X = 600\ GeV,\ 1\,TeV$

W-Tagging: MC vs Data
[CMS-PAS-JME-13-006]

- Detailed **data/MC comparisons** for all substructure observables
- **Different topologies and generators** considered





leptonic W+jets
Pythia6
Herwig

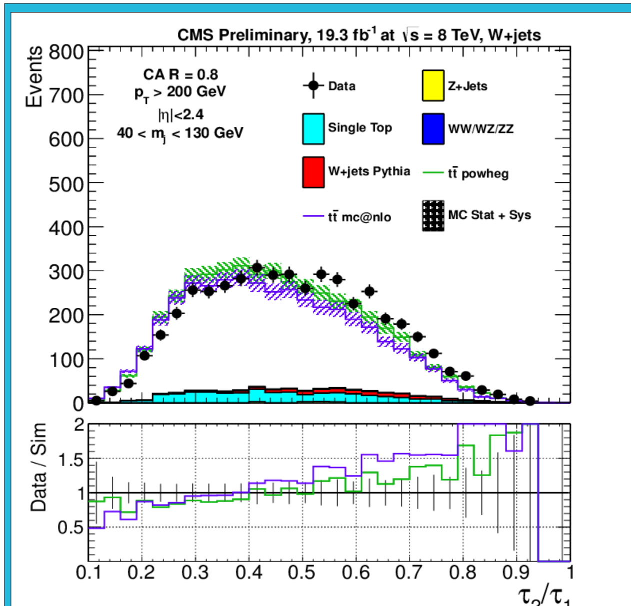
mistag
pT [250, 350] GeV

di-jets
MG+Pythia6
Herwig
Pythia8

mistag
pT [400, 600] GeV

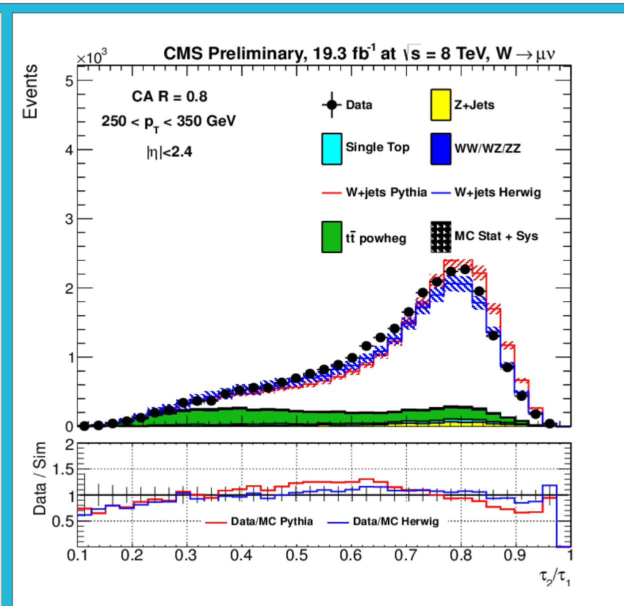
W-Tagging: MC vs Data
[CMS-PAS-JME-13-006]

- Detailed **data/MC comparisons** for all substructure observables
- **Different topologies and generators** considered



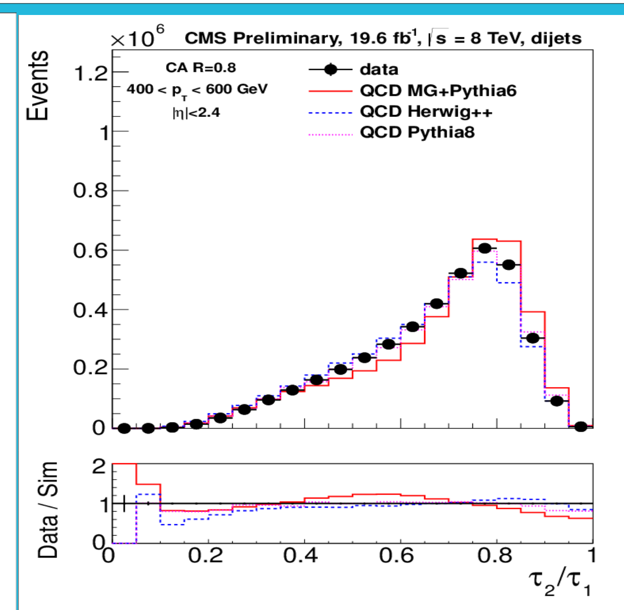
ttbar
powheg
mc@nlo

efficiency



leptonic W+jets
Pythia6
Herwig

mistag
pT [250, 350] GeV

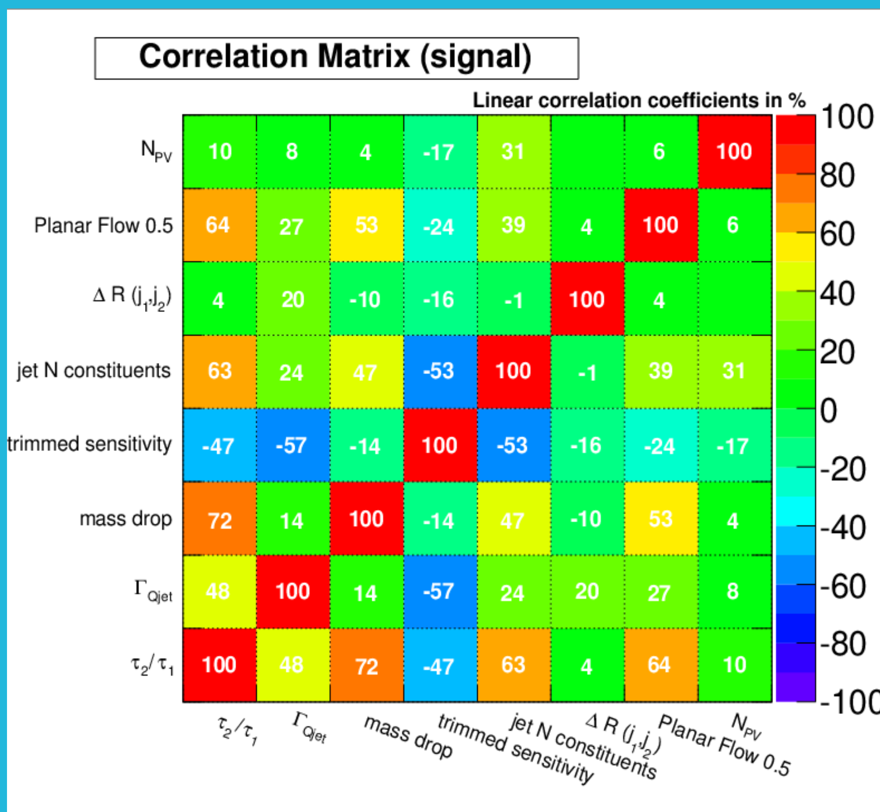


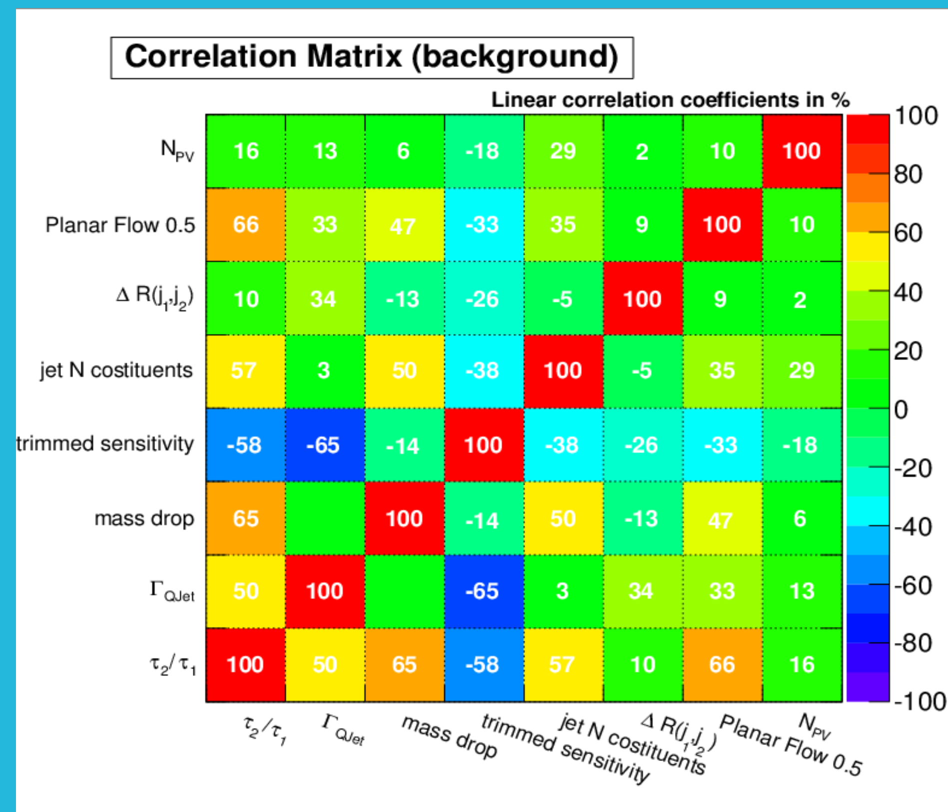
di-jets
MG+Pythia6
Herwig
Pythia8

mistag
pT [400, 600] GeV

W-Tagging
[CMS-PAS-JME-13-006]

- MVA correlations



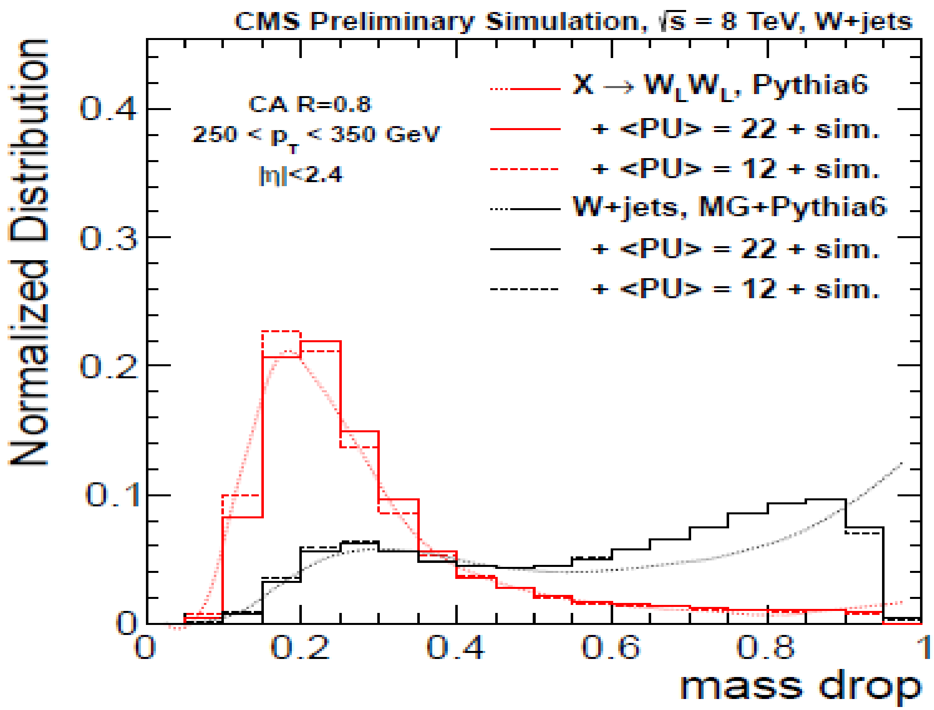


signal **Background (W+jets)**

W-Tagging
[CMS-PAS-JME-13-006]

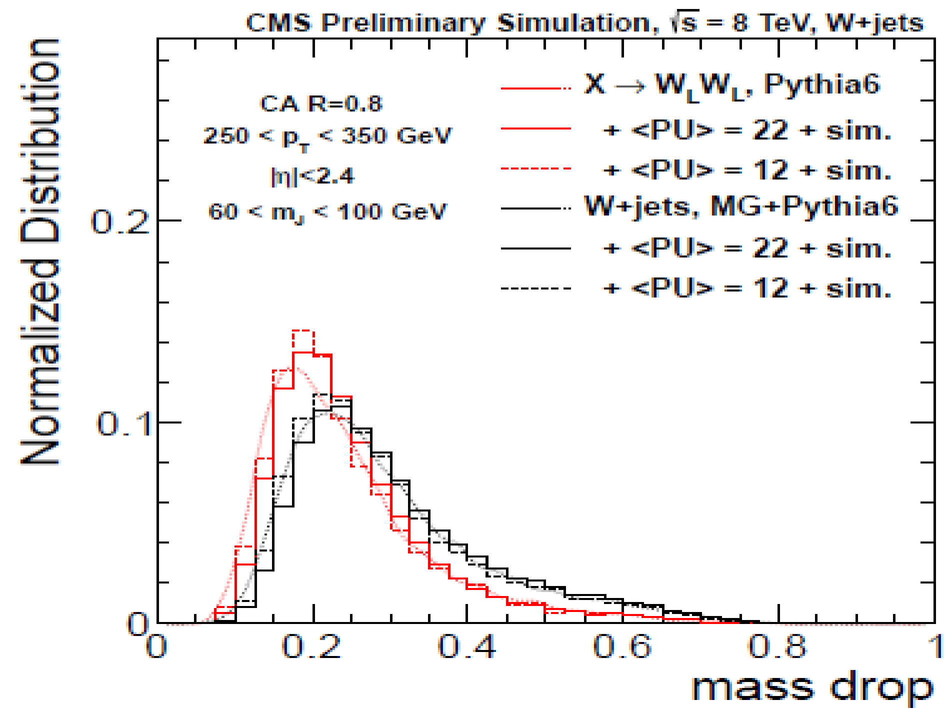
Substructure variables: mass drop, μ

$p_T = 250 - 350$ GeV
(W+jet) - no pruned mass cut



Good discrimination power

$p_T = 250 - 350$ GeV
(W+jet) - pruned mass cut



Discrimination power reduced:
correlation with mass cut

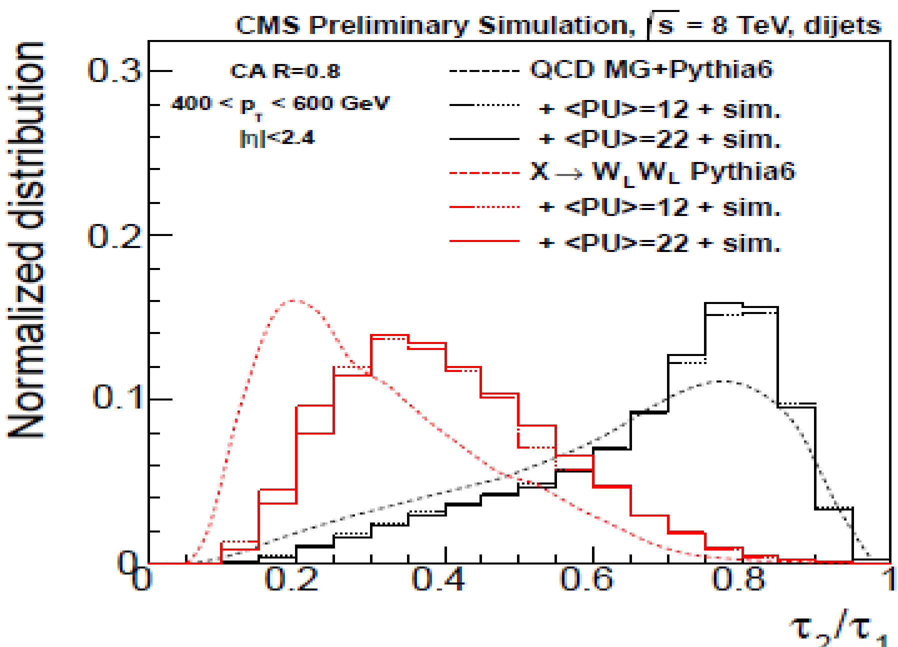
W-Tagging
[CMS-PAS-JME-13-006]

Substructure variables: N-subjettiness

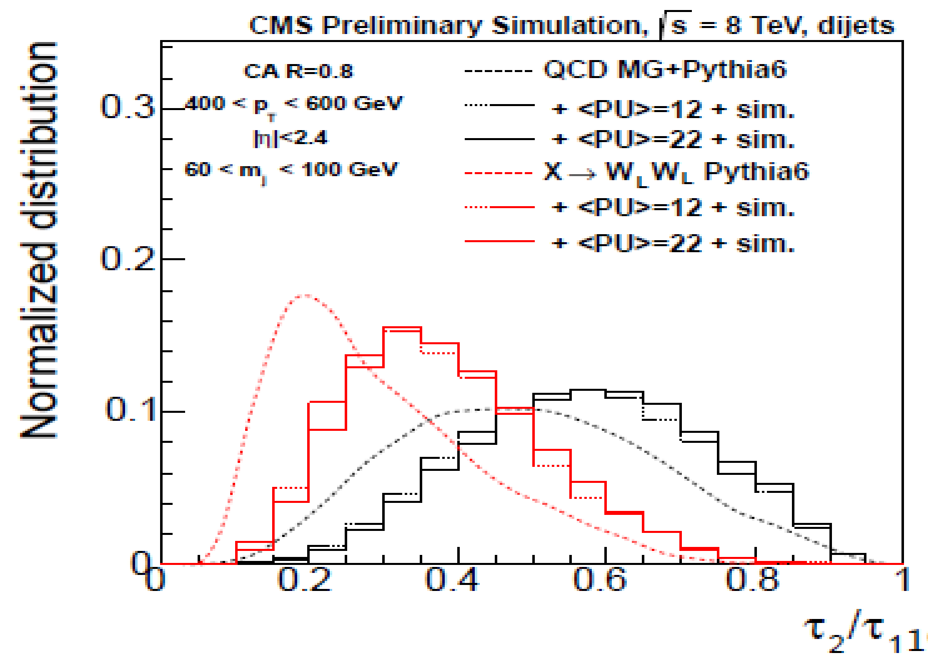
Three variants considered:

- τ_2/τ_1: one step optimization of the k_T subjet axes
- τ_2/τ_1 k_T axes: no optimization
- pruned τ_2/τ_1: uses only pruned constituents + one pass optimization.

$p_T = 400 - 600$ GeV (dijet) - no pruned mass cut



$p_T = 400 - 600$ GeV (dijet) - pruned mass cut



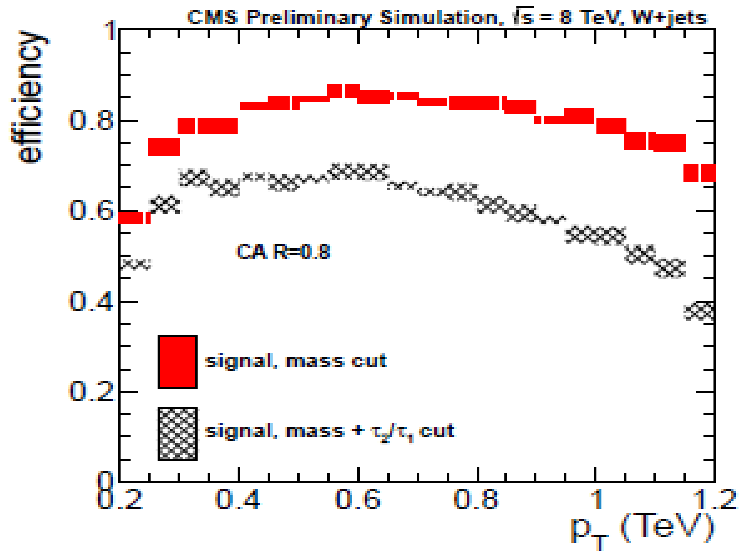
Emanuele Usai BOOST13

W-Tagging
[CMS-PAS-JME-13-006]

Performance in function of p_T

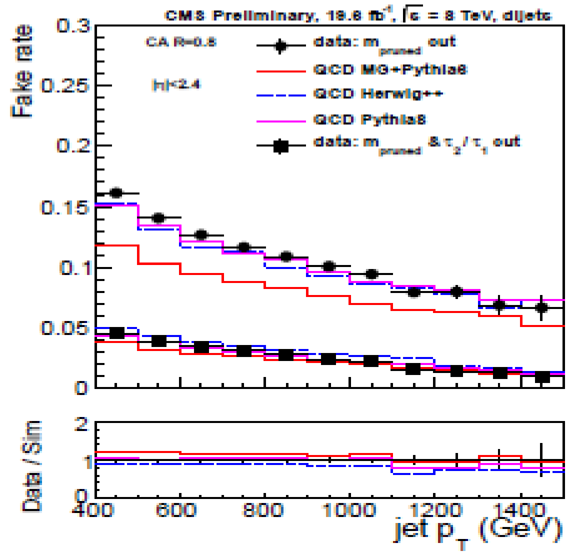
Performance studied for: $60 < m_{jet} < 100$ GeV + $\tau_2/\tau_1 < 0.5$

Efficiency vs p_T (W+jets topology)



- low p_T: W decay products begin to be reconstructed inside CA8 jets
- high p_T: detector resolution for jet substructures degrades, pruning remove too much of the mass of the W

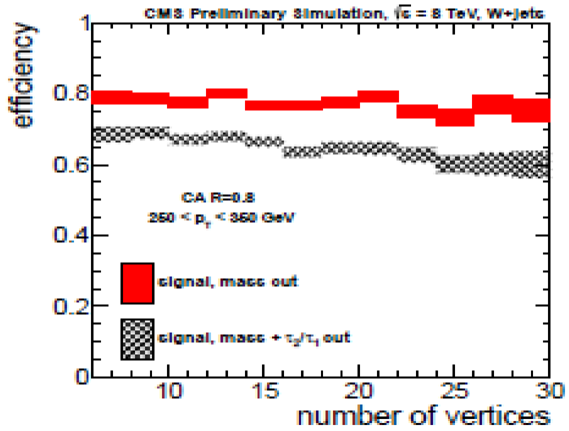
Fake rate vs p_T (dijet topology)

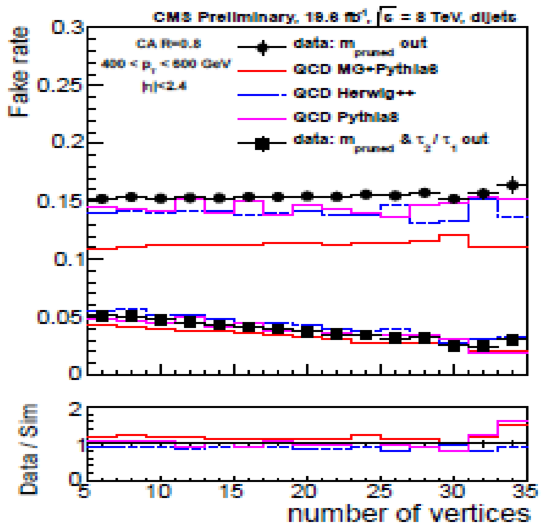


- drops at high p_T similarly to efficiency

W-Tagging
[CMS-PAS-JME-13-006]

Performance in function of number of vertices





Efficiency vs Nvtx (W+jets topology)

- slight degrade of performance
- jet pruning fails to remove all soft contributions

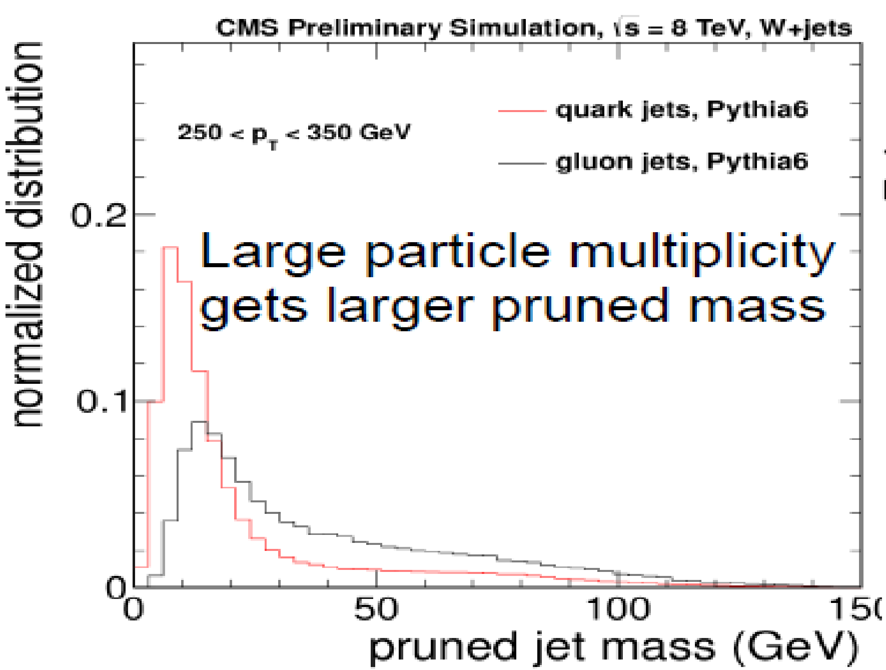
Fake rate vs Nvtx (dijet topology)

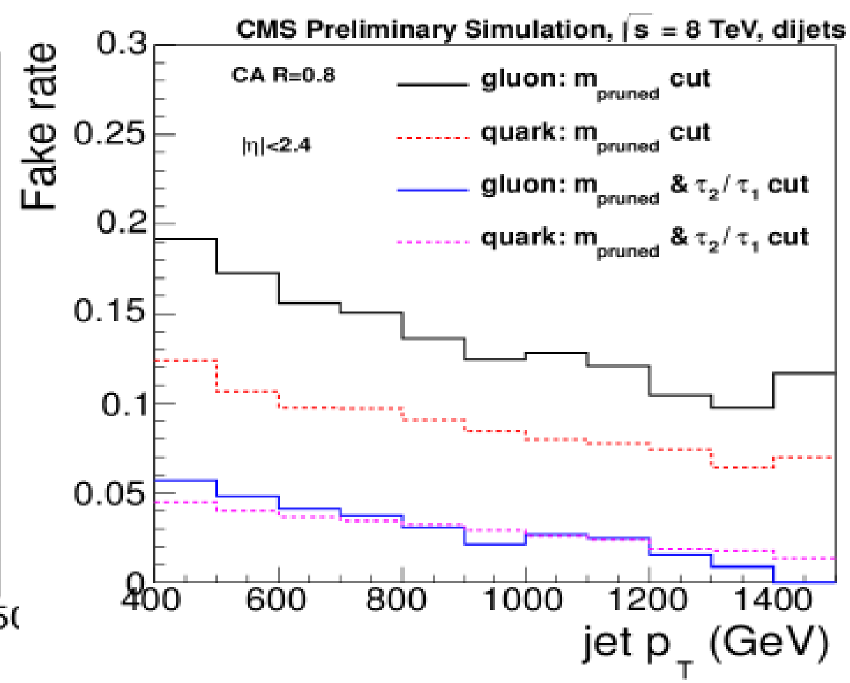
- constant behavior with respect to Nvtx

W-Tagging
[CMS-PAS-JME-13-006]

Quark and Gluons w/Substructure

- Quark/gluon separation vs W same after cuts
  - Mass cut more effective on quark separation
  - N-subjettiness more effective on gluon separation
    - Once mass the cut is applied



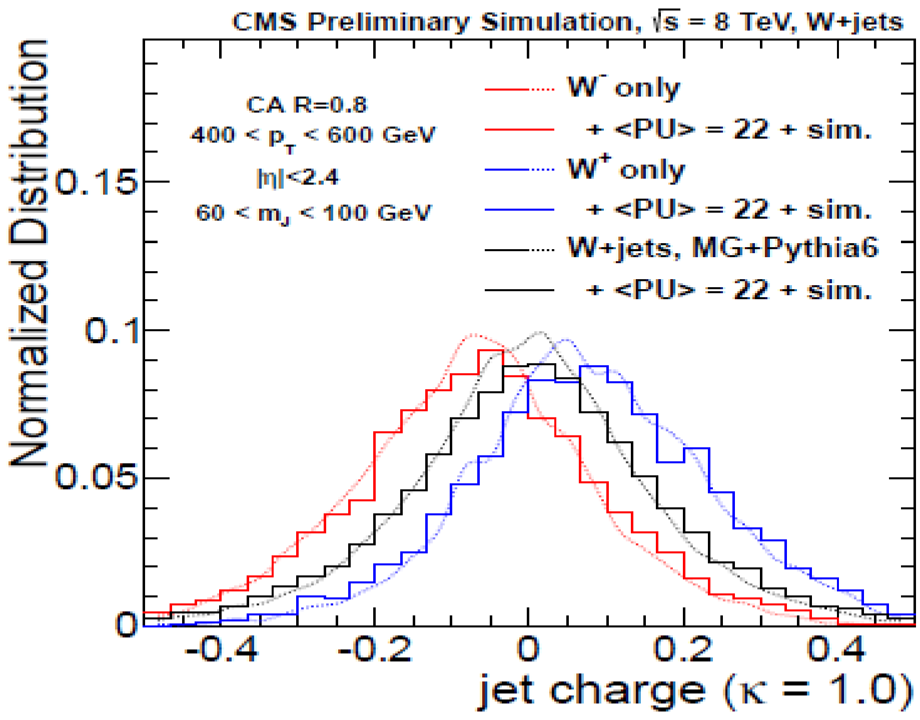


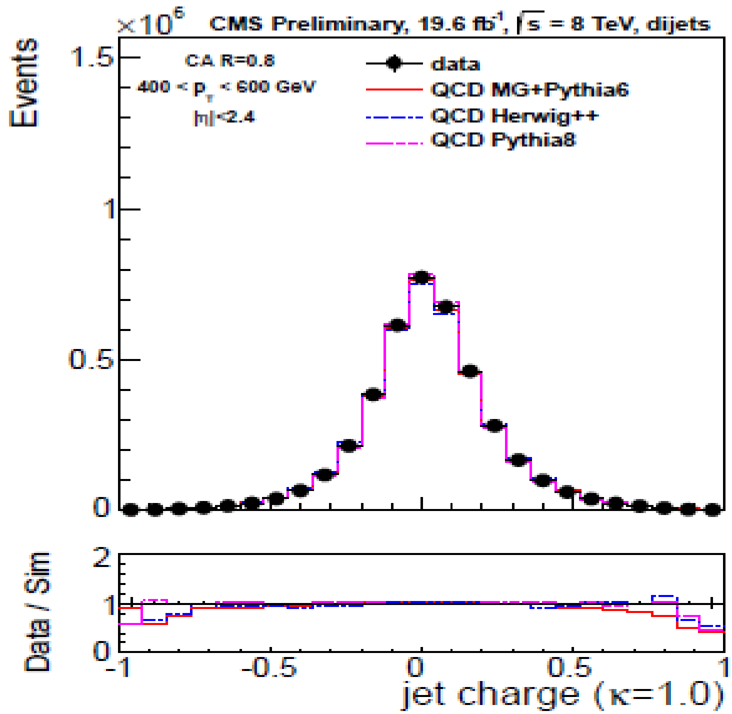
W-Tagging
[CMS-PAS-JME-13-006]

Jet charge, Q^κ

$$Q^\kappa = \frac{\sum_i q_i (p_{Ti})^\kappa}{(\sum_i p_{Ti})^\kappa}$$

Used to discriminate between W+ and W-





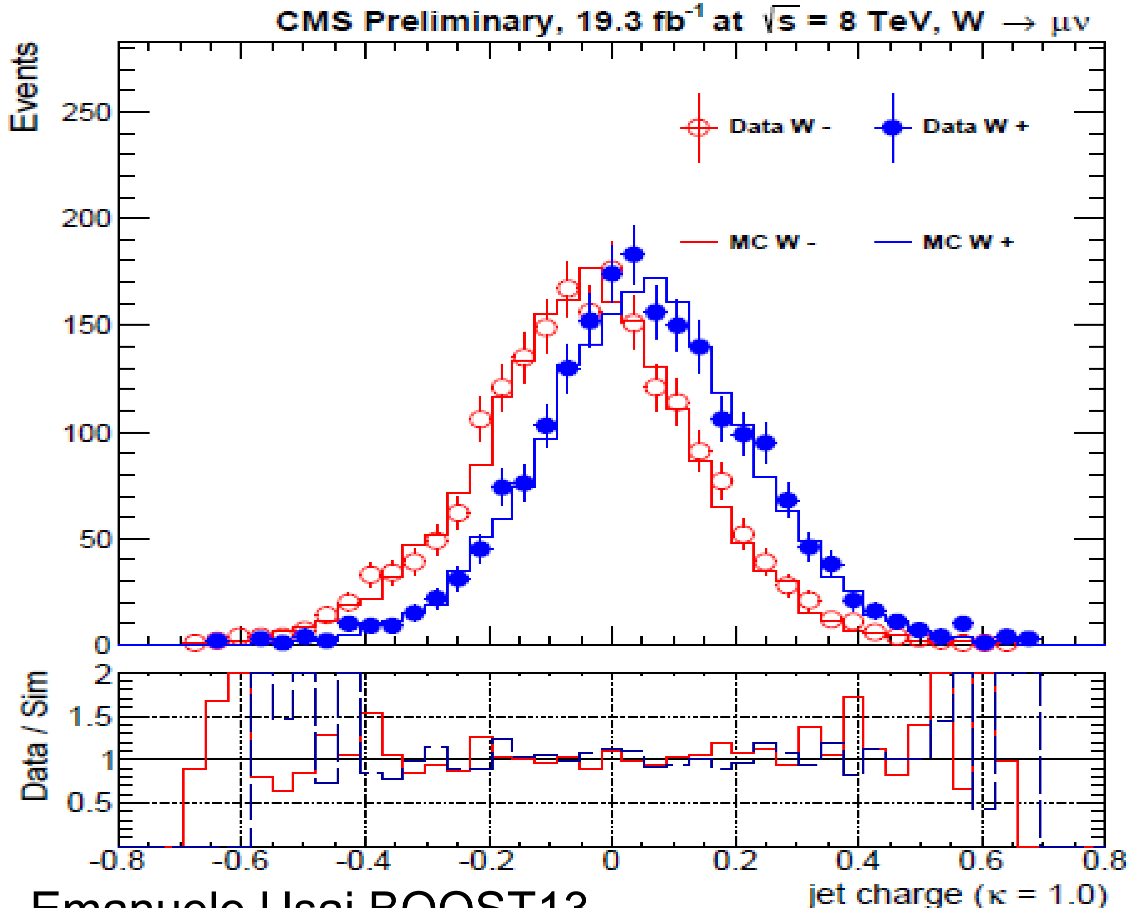
Right plot, note: <**jet charge**> $\neq$ **0**

Emanuele Usai BOOST13

W-Tagging
[CMS-PAS-JME-13-006]

Jet charge distribution

$t\bar{t}$ sample for W^+ and W^- jets in simulation and data.
Simulated distributions are a sum of all processes.

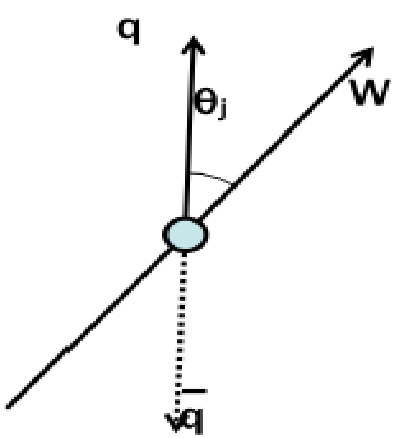


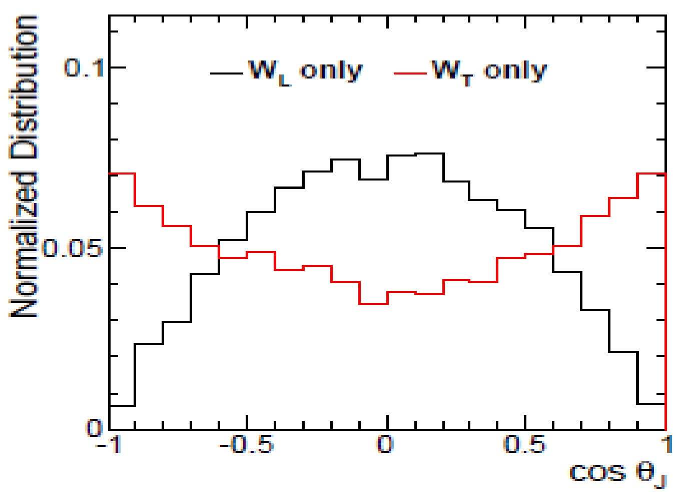
$t\bar{t}$ semileptonic selection
By selecting on the lepton charge, we can isolate W^+ from W^- jets.

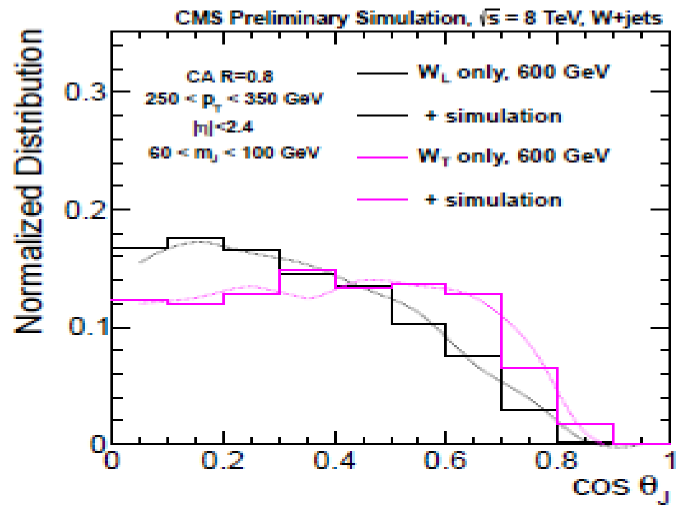
W-Tagging
[CMS-PAS-JME-13-006]

Polarization studies

- Polarization can affect substructure distribution
- Sample used: scalar $X \rightarrow W^L_{lept} W^L_{had}$ and $X \rightarrow W^T_{lept} W^T_{had}$





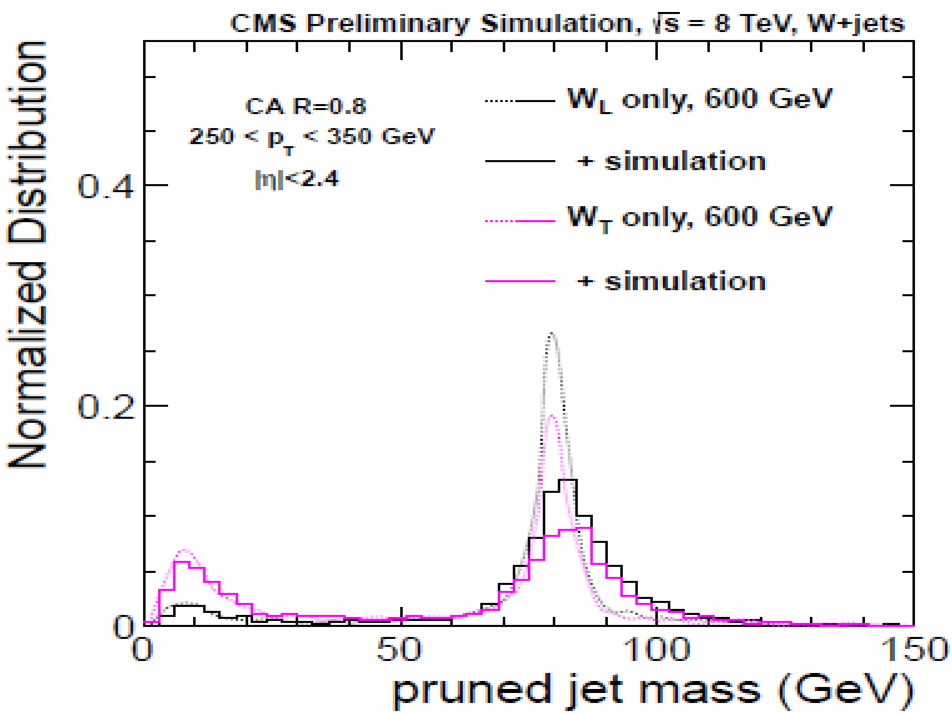


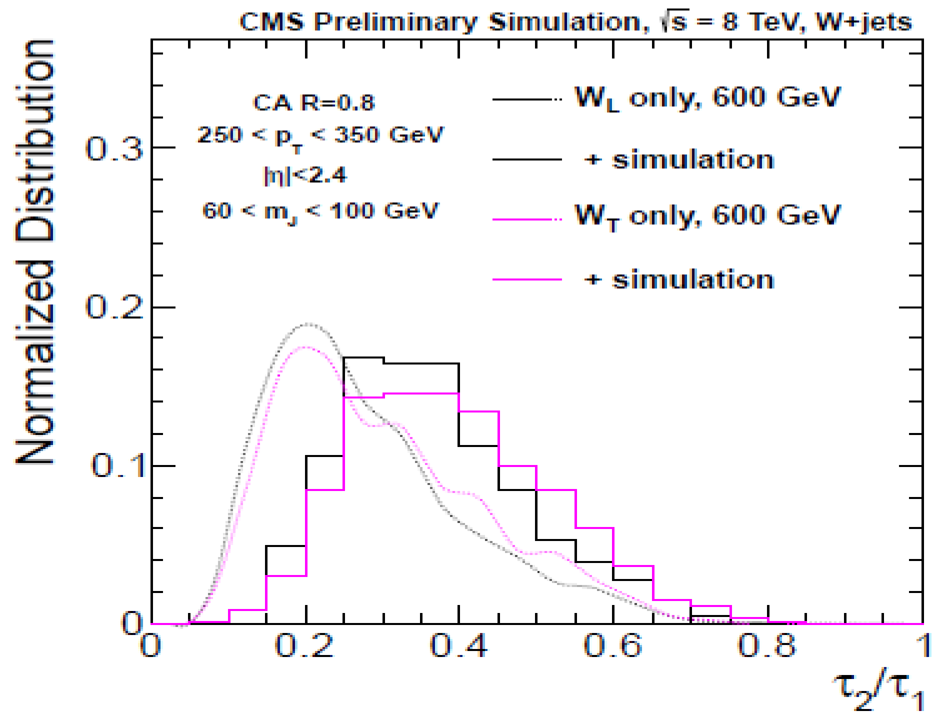
- parton level helicity angle for hadronic W
- observable helicity angle from subjets

Emanuele Usai BOOST13

W-Tagging
[CMS-PAS-JME-13-006]

Polarization studies - τ_2/τ_1





- pruned jet mass acceptance different for W_L and W_T
- ΔR between partons smaller on average for W_L
- W_L more likely to be accepted by CA8 jet
- in W_T topology p_T of the subjets is more asymmetric, thus more QCD-like

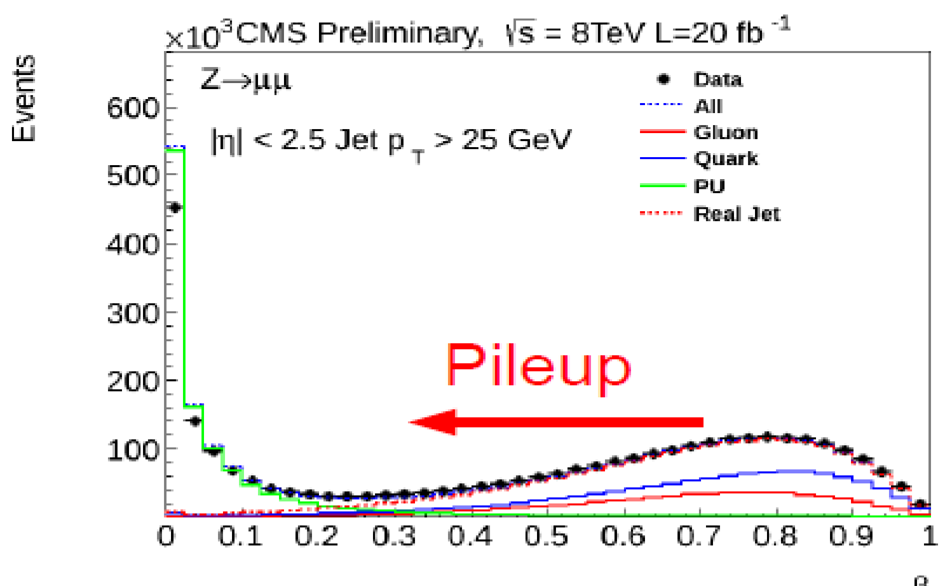
Pile-Up Jet-ID
[CMS-PAS-JME-13-005]

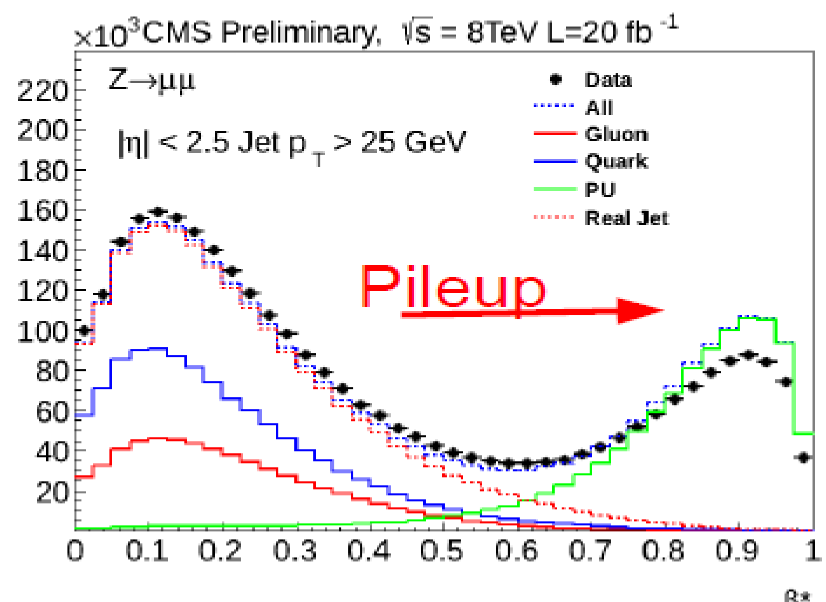
Pileup Jet Id Algorithm:Tracking

- 13 variables for the full discrimination
  - 4 Vertexing related variables (2 most impt shown):

    #vertices, dZ of leading track in jet +

$$\beta = \frac{\sum_{i \in PV} p_{Ti}}{\sum_i p_{Ti}} \qquad \beta^* = \frac{\sum_{i \in otherPV} p_{Ti}}{\sum_i p_{Ti}}$$



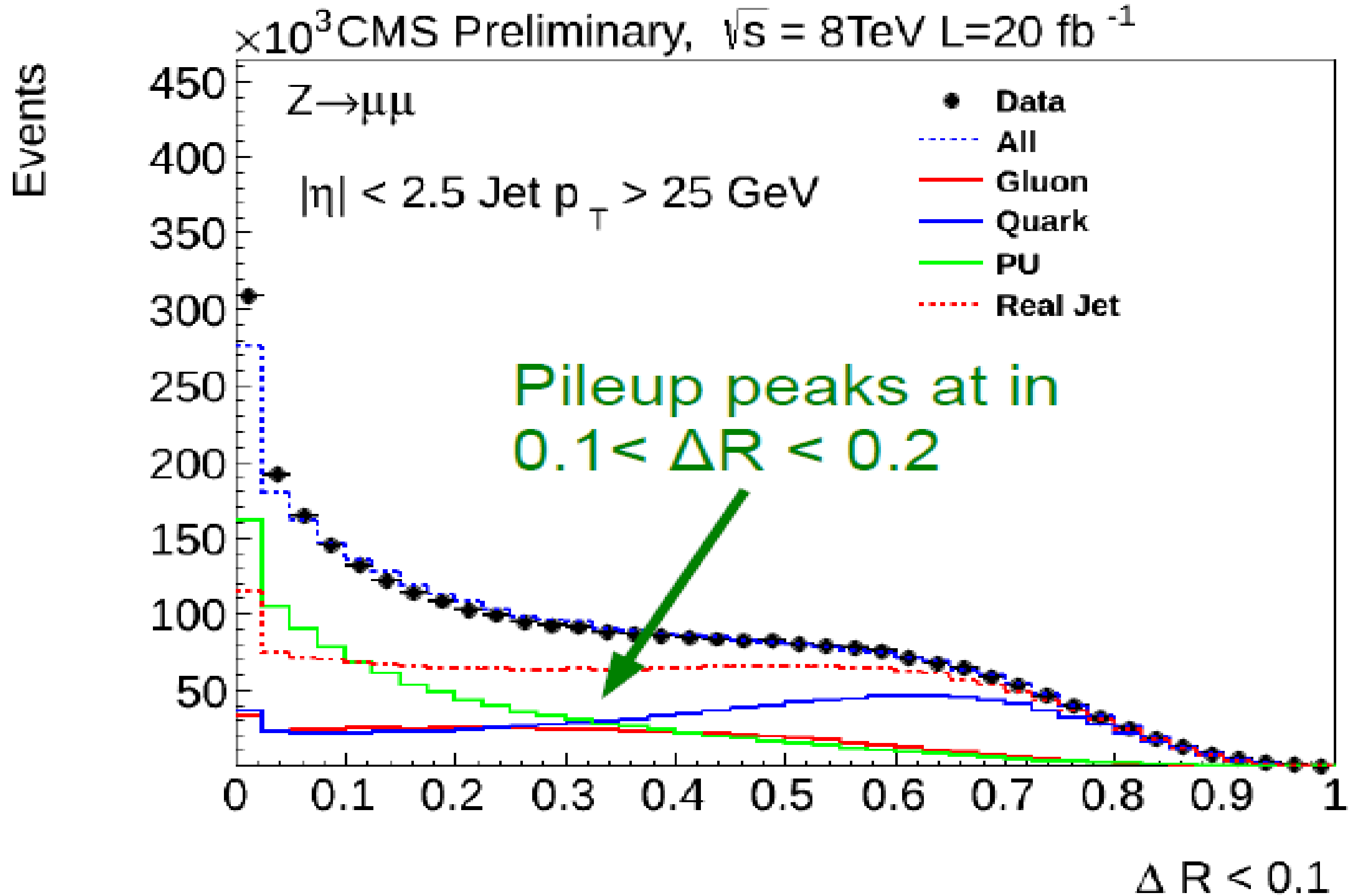


Pileup tends to degrade performance of these variables

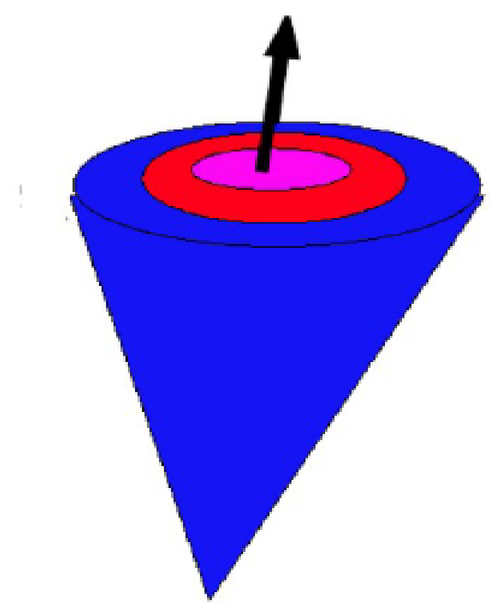
Pile-Up Jet-ID
[CMS-PAS-JME-13-005]

Pileup Jet Id Algorithm:Cones

- Additional shape variables : ΔR annuli



ΔR 0.1=>0.5



Pile-Up Jet-ID
[CMS-PAS-JME-13-005]

Algorithm Construction

- Construct a Boosted decision tree real vs PU Jets
  - Train in four separate regions of η

$|\eta| < 2.5$ tracking Shape variables	$2.5 < |\eta| < 2.75$ Weak tracking (tracking ends at 2.5) Shape variables
$2.75 < |\eta| < 3.0$ Shape variables	$3.0 < |\eta| < 5.0$ Forward HCAL Shape variables

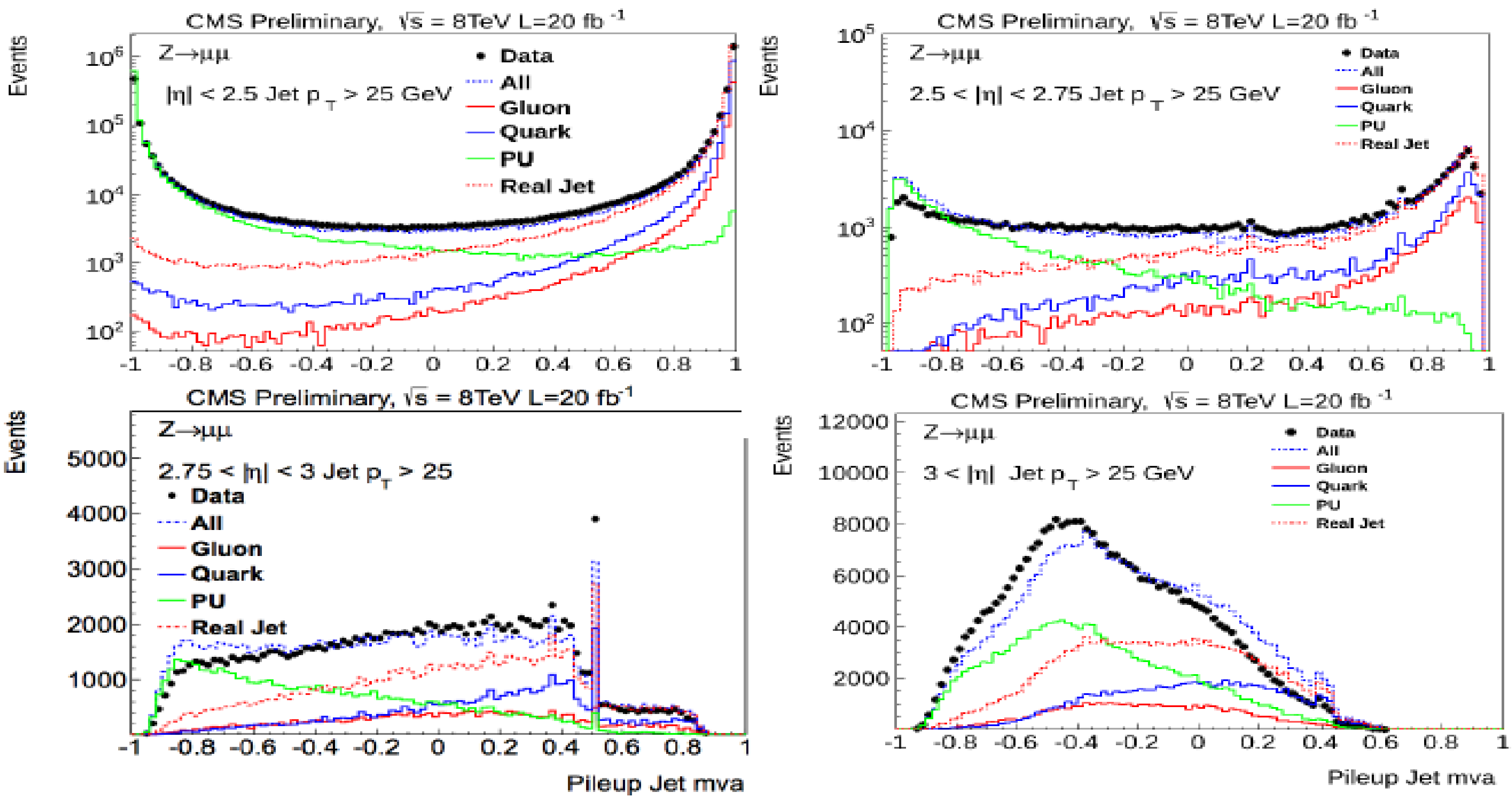
Construct a Boosted decision tree (trained on Z+jets for each)

Pile-Up Jet-ID
[CMS-PAS-JME-13-005]

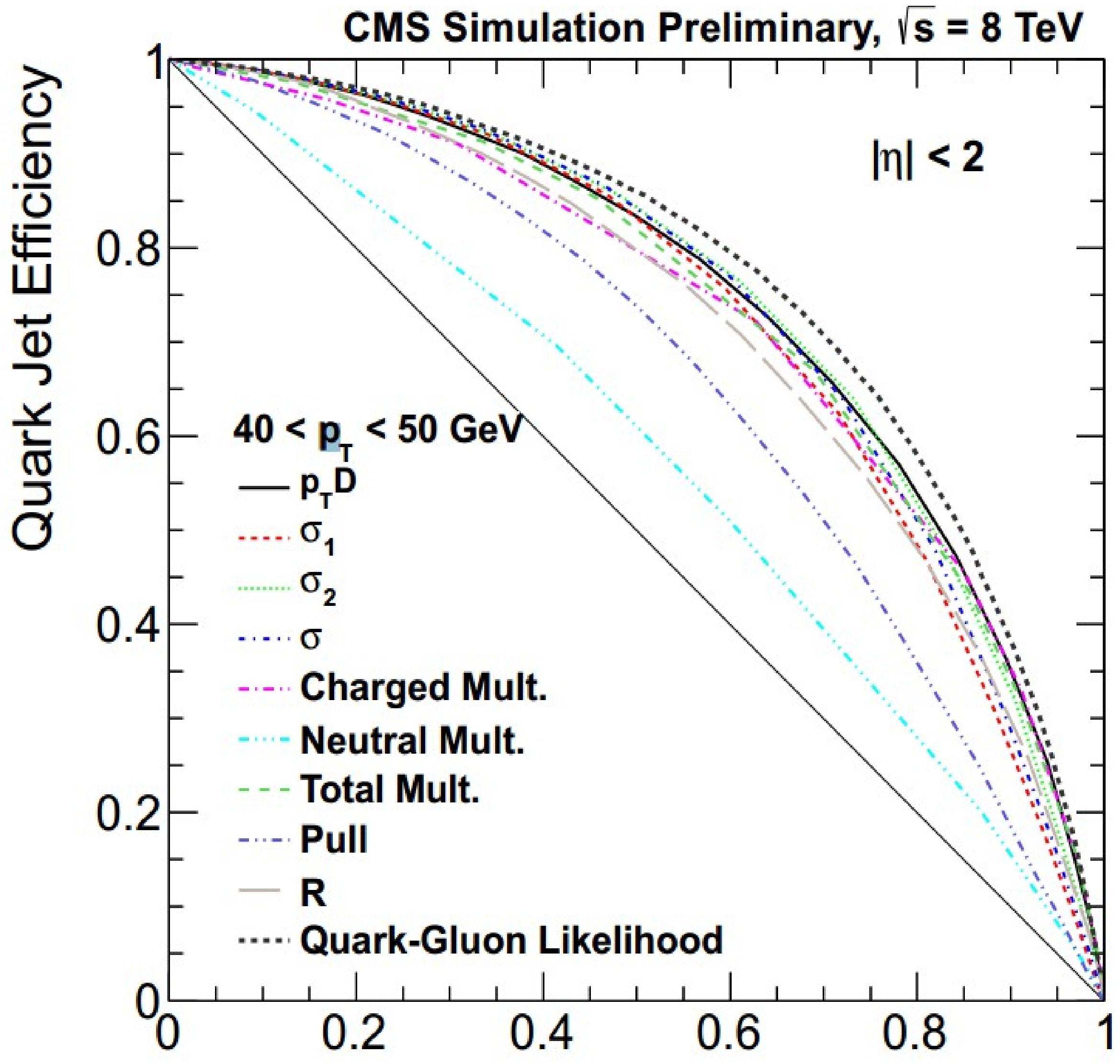
08/13/13 Philip Harris BOOST

Pileup Jet Id in Data

- Fraction of pileup grows with higher |η|

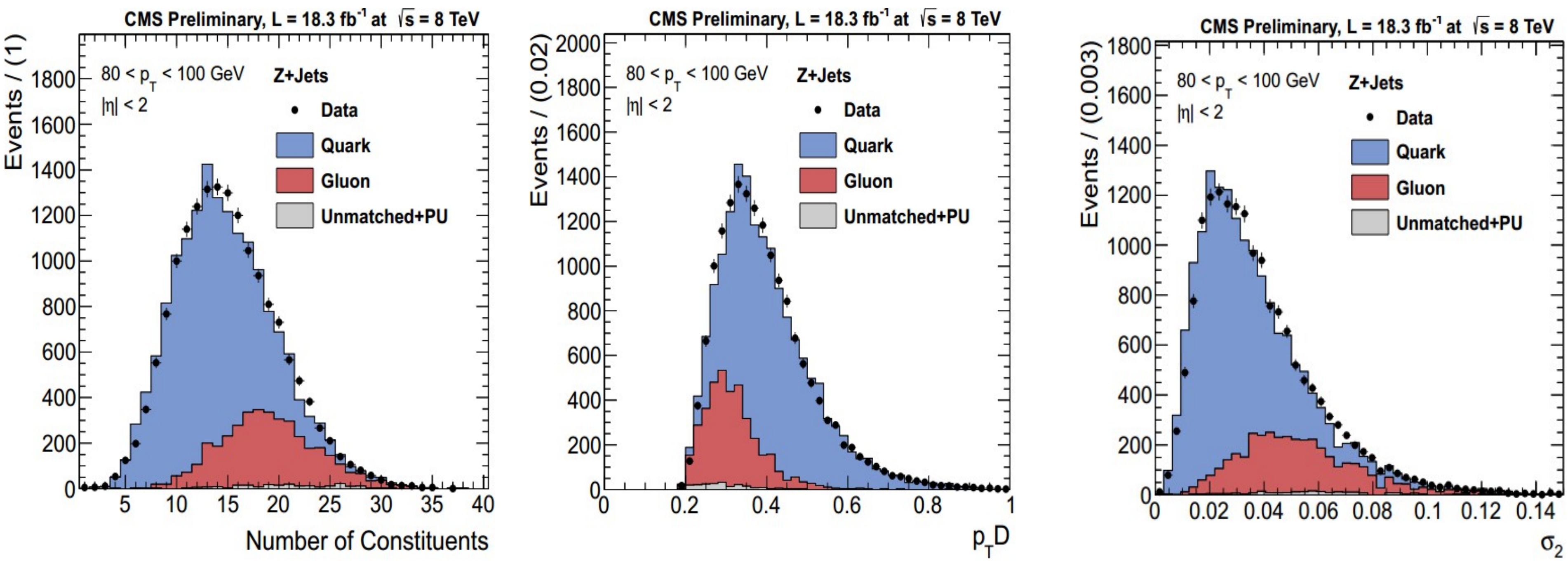


Quark-Gluon Discrimination
[CMS-PAS-JME-13-002]



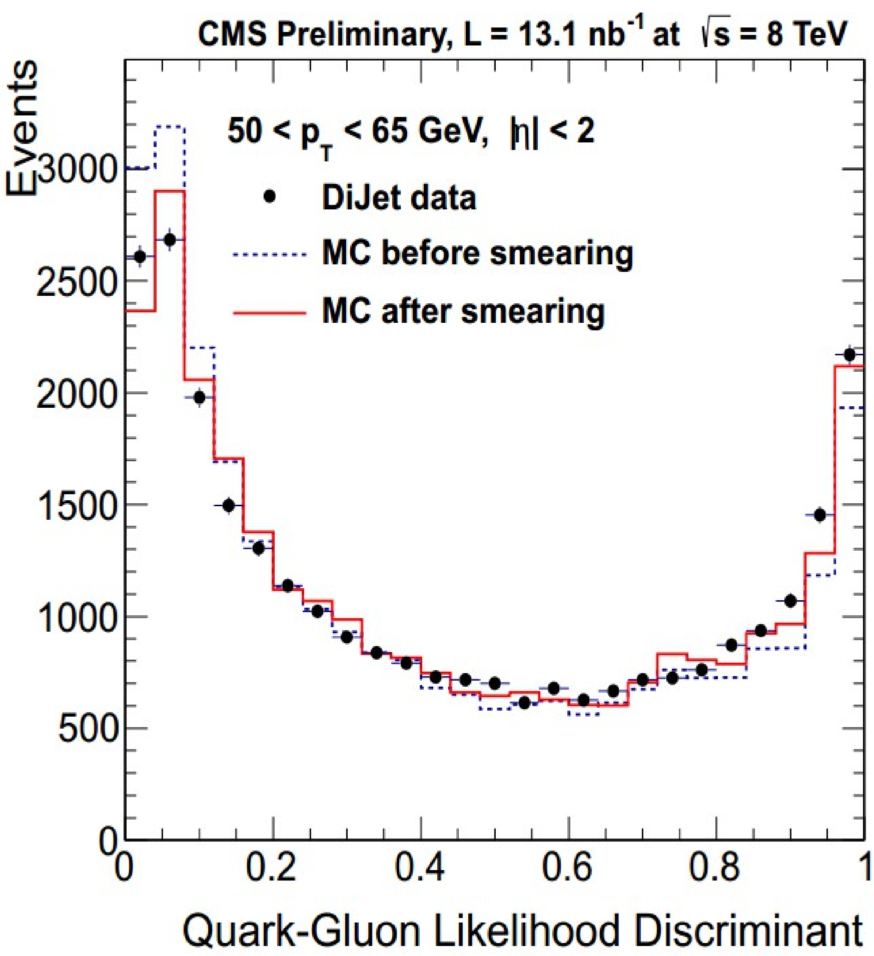
- Single-variable ROCs and likelihood combination

Quark-Gluon Discrimination
[CMS-PAS-JME-13-002]

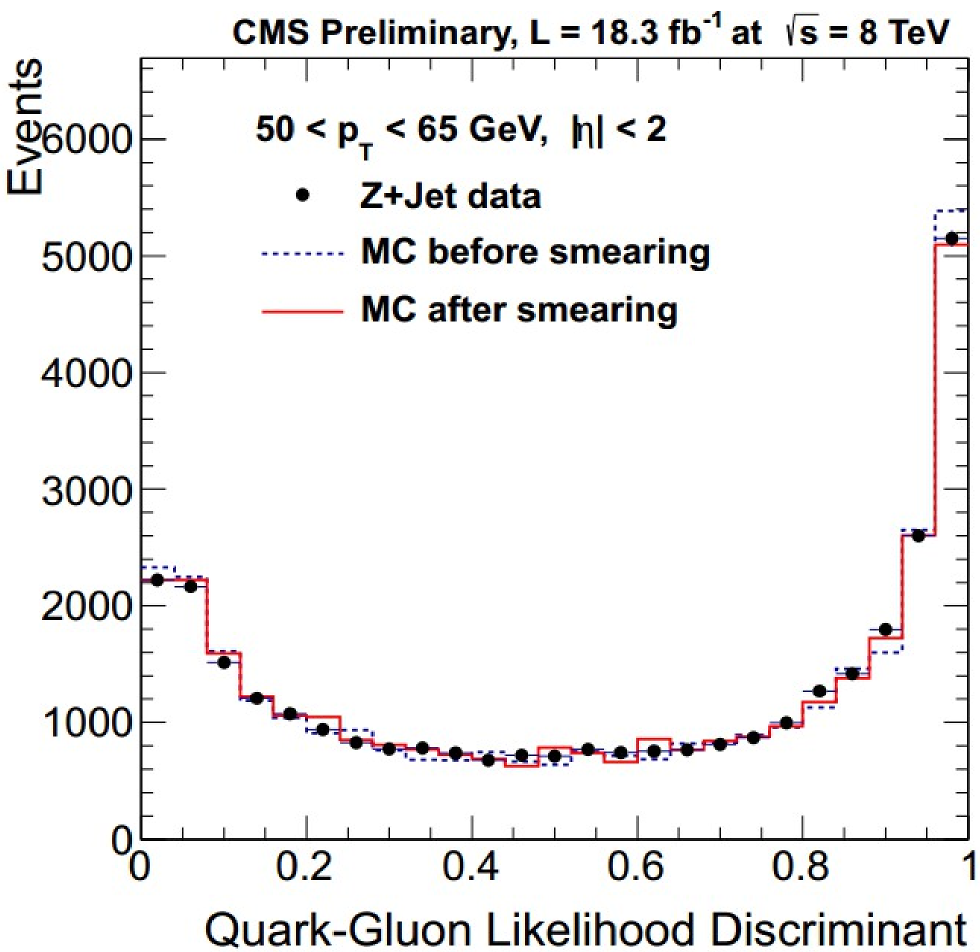


Single variables discrimination power

Quark-Gluon Discrimination
[CMS-PAS-JME-13-002]

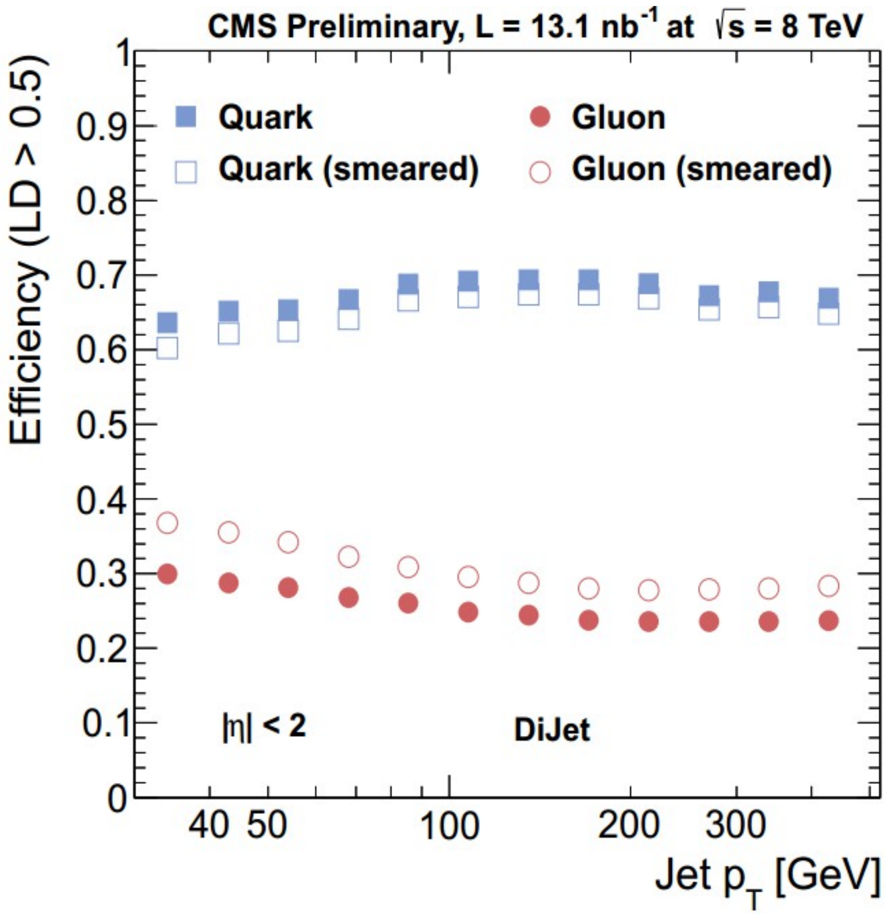


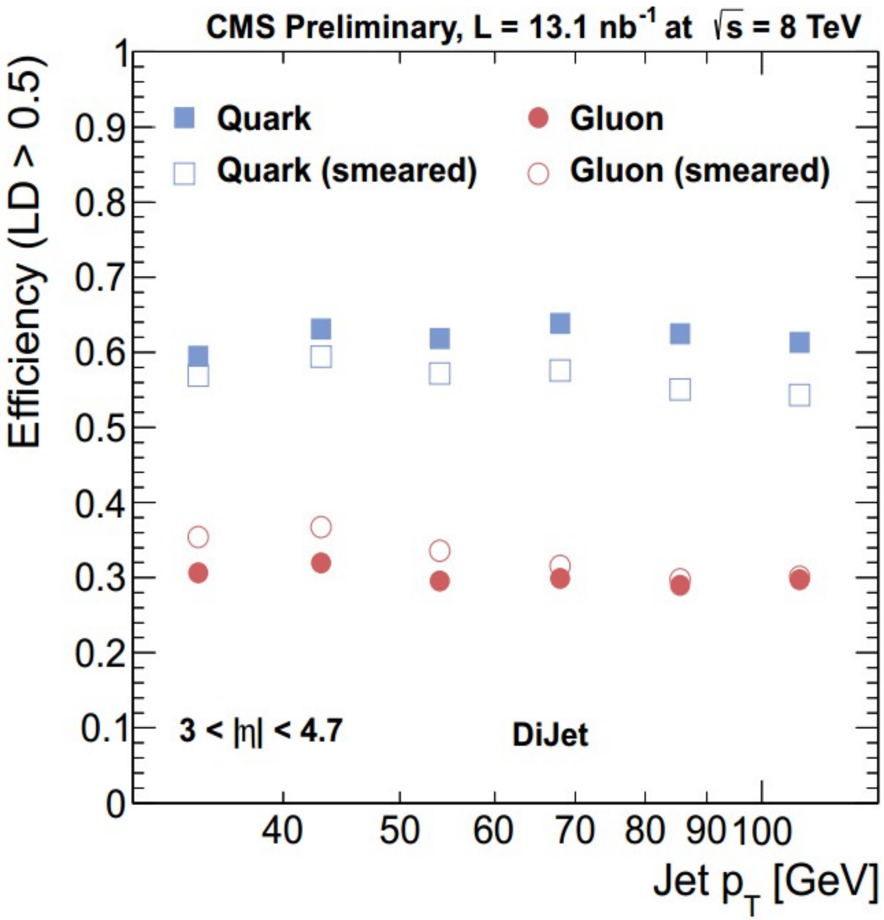
di-jets: derived corrections



Z+jets: applied corrections.
Very good closure

Quark-Gluon Discrimination
[CMS-PAS-JME-13-002]



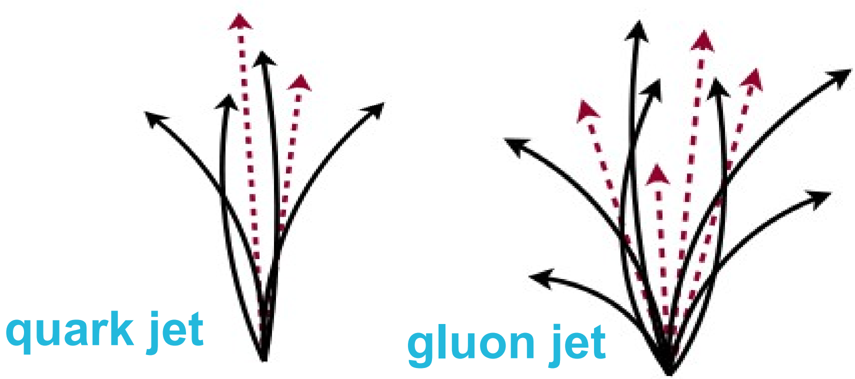


Discrimination power slightly decreases after smearing

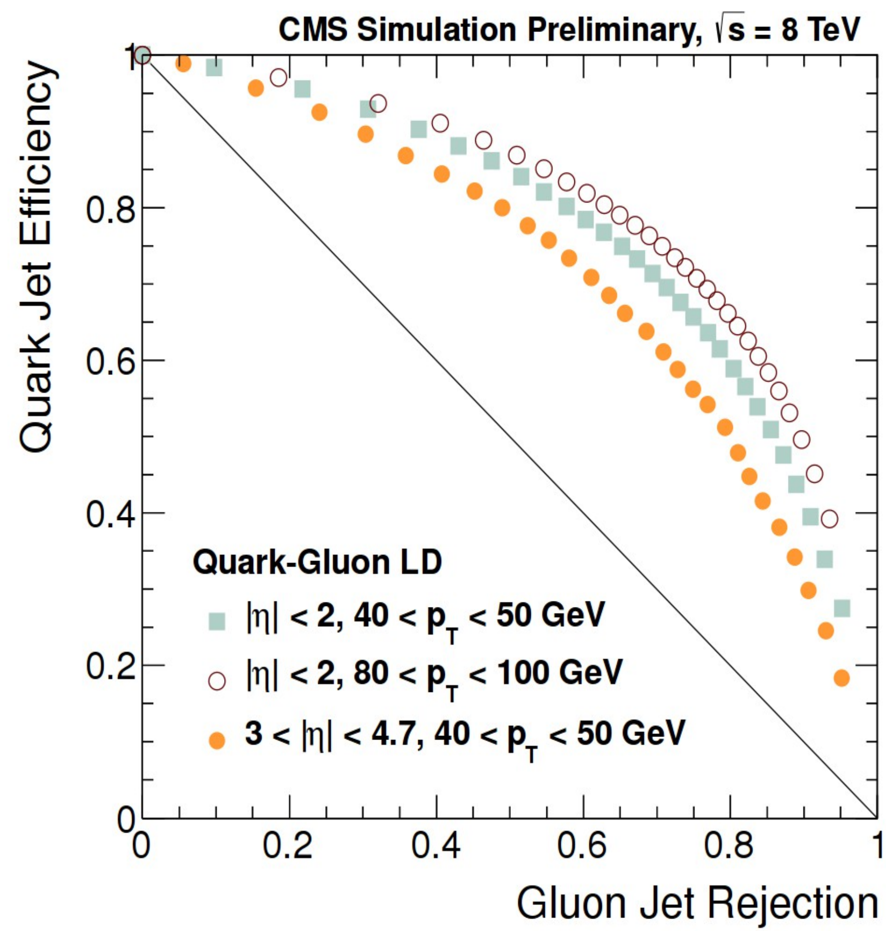
Quark-Gluon Discrimination
[CMS-PAS-JME-13-002]

- Quark/gluon discrimination: similarly to PU Jet-ID, combine discriminating variables in **likelihood**

- Quark and gluon have **different colour interaction**:



+ multiplicity
+ width
more homogeneous energy sharing



good discrimination power in different η, p_T ranges

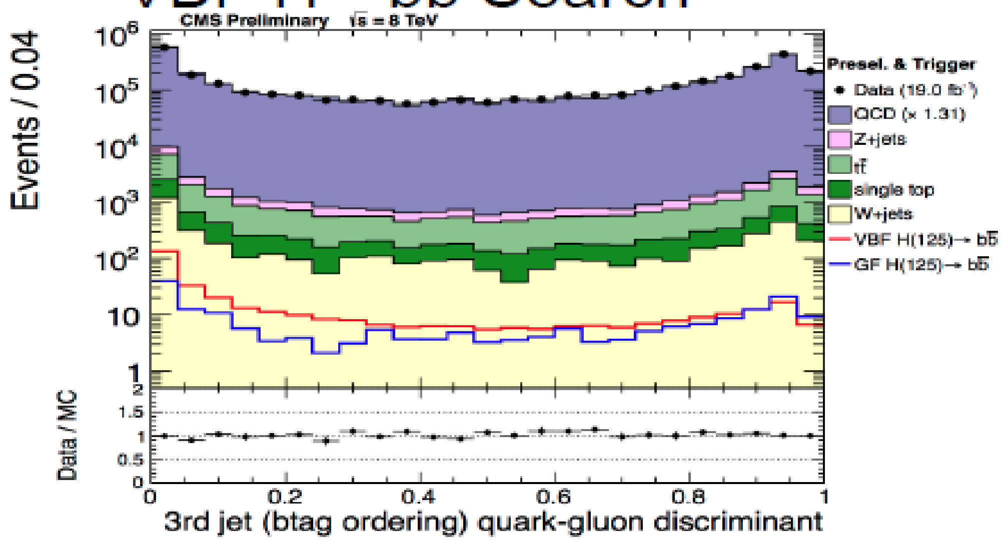
Quark-Gluon Discrimination

08/13/13 Philip Harris BOOST 2(

QG Performance + Usage

- QG discrimination used in VBF selection
  - Reduces the QCD/Pileup bkgs for forward jets
- QG discrimination used in Z boson tagging
- Reduction of 60% gluon for 80% quark eff

VBF H→bb Search



H→ZZ→2l2q Search