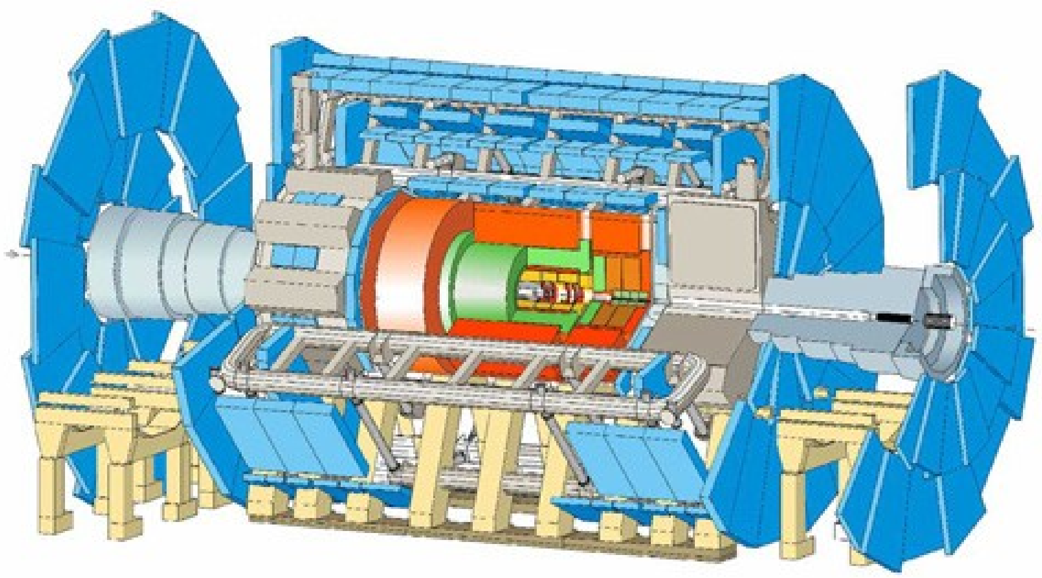
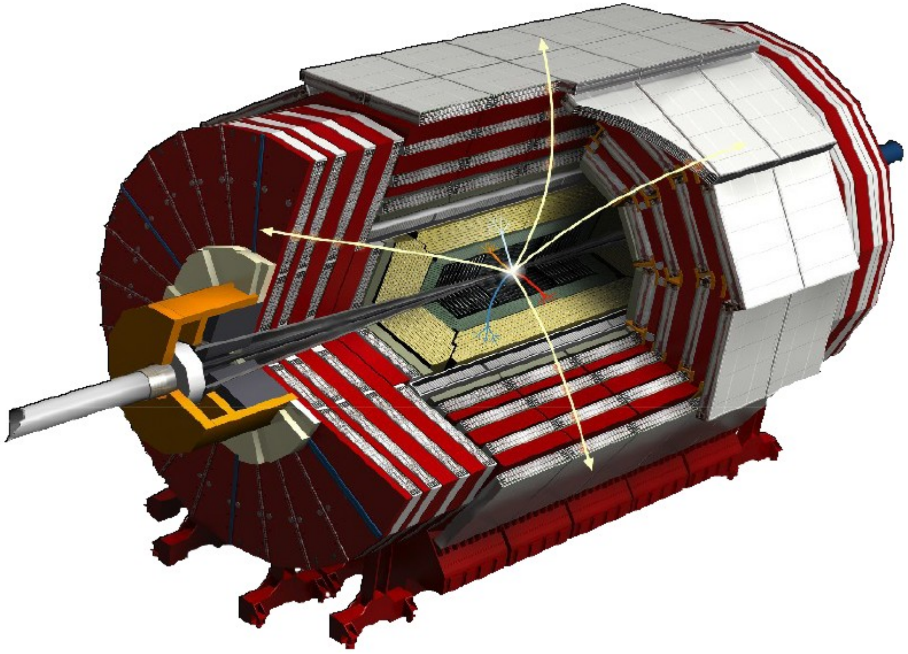
# BOOSTED TOP

# PHYSICS AND RECONSTRUCTION



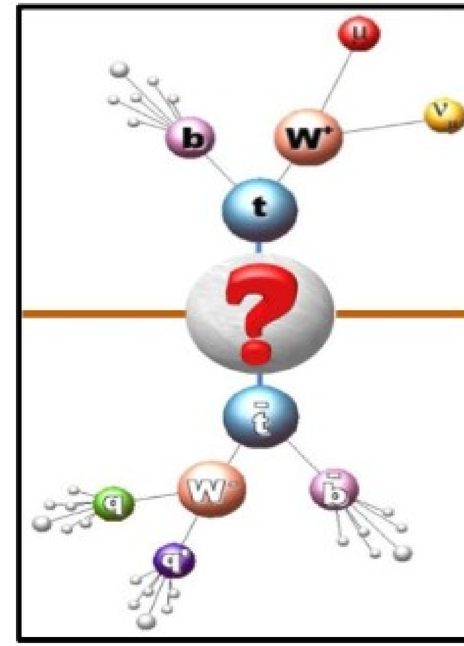


**Jörgen Sjölin on behalf ATLAS collaboration**

**Eric Chabert on behalf CMS collaboration**

# Outline

- The physics motivations
- New reconstruction technique: **top-tagging**[1,5]
- Search for **$t\bar{t}$ resonances** in several channels
- Summary of the sensitivity
- Perspectives



## Channel for $t\bar{t}$ resonances searches:

| | di-leptonic | semi-leptonic | All hadronic |
|---|---|---|---|
| **Low mass** | | CMS[4]/ATLAS[6] | |
| **High mass** | | CMS[3]/ATLAS[7] | CMS[1,2] |

See talk on 'Challenges in new Physics Searches in top-like events'

### Publications:

1. CMS-PAS-JME-09-001
2. CMS-PAS-EXO-09-002
3. CMS-PAS-EXO-09-008
4. CMS-PAS-TOP-09-009
5. ATL-PHYS-CONF-2008-008
6. CERN-OPEN-2008-20
7. ATLAS-PHYS-PUB-2009-081

**Boosted top:** quark top produced with a high boost ($\beta,\gamma$) → high $p_T$

## What can produce boosted top ?

### Standard Model

Hard pp collisions ($gg,q\bar{q}$): 0.5% of the top pair production, $p_T$(top)>500GeV

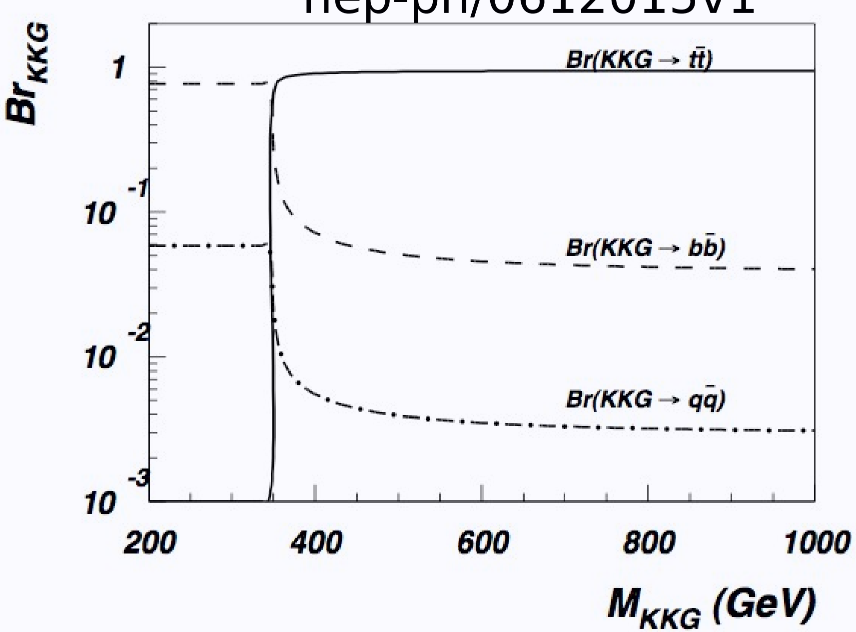
### New physics

**$t\bar{t}$ resonances: heavy particle decaying in tt**

- new scalars, ex: heavy Higgs
- new vectors: Z',W' (ex: Technicolor)
- Colorons (color interaction)
- KK-excitations including gravitons (RS/ADD)
- ...

These resonances can be
- Spin: 0,1,2
- Parity $J^P$: $0^-,0^+,1^-,1^+,2^-,2^+$
- color singlet/octet

hep-ph/0612015v1




**Particles decaying in 1 top+X**

- top partner: stop in SUSY
- fourth generation of quark (b',t')

**Top's boost mainly depends on the mass its mother**

# Physics motivations

$\gamma$ , $p_T$, $M_X$

**Angles between decay products decrease**

## Hadronic decay

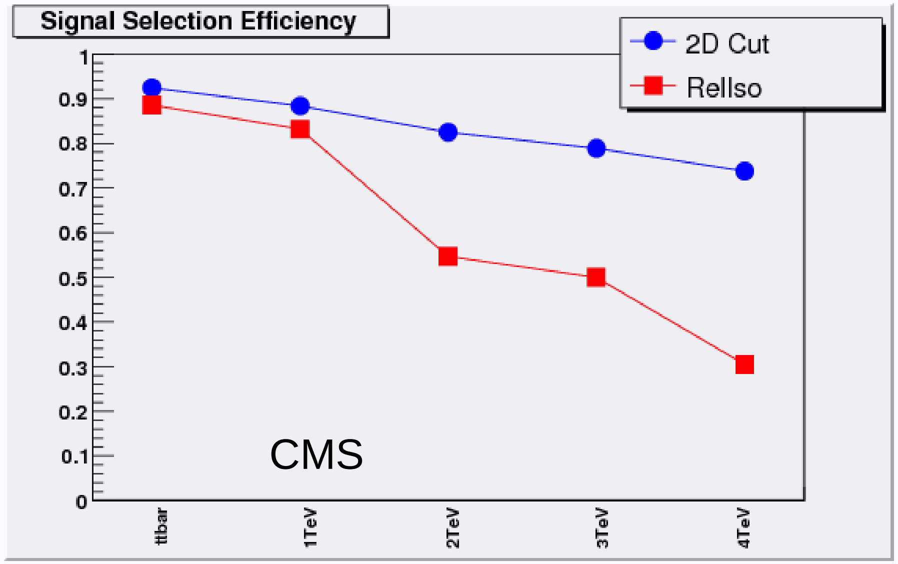
- Jet overlapping
  - Jet merging: 1 or 2 instead of 3
    - A single jet with distinguishable sub-structure **⇉ top-tagging**
      - A single jet, decay product angles below the calorimeter resolution

## Leptonic decay

- Lepton isolation criteria starts to fail
  **⇉ relaxing isolation criteria**
  - Lepton “in” the jet

## $t\bar{t}$ resonances

- tops tend to be more separated
  (back to back)



# Simulations

List of samples/generators used for the results presented in this talk.

| | ATLAS | CMS |
|---|---|---|
| tt generator | MC@NLO | MadGraph |
| Z': generator | Pythia | MadGraph/Pythia |
| width | 1% | 1-10% |
| mass | 500GeV-4TeV | 750 GeV-4 TeV |
| QCD generator | Pythia | Pythia |
| W/Z generator | Alpgen | MadGraph |
| W+bb/cc generator | Alpgen | MadGraph |
| Simulation | GEANT-based | GEANT-based |

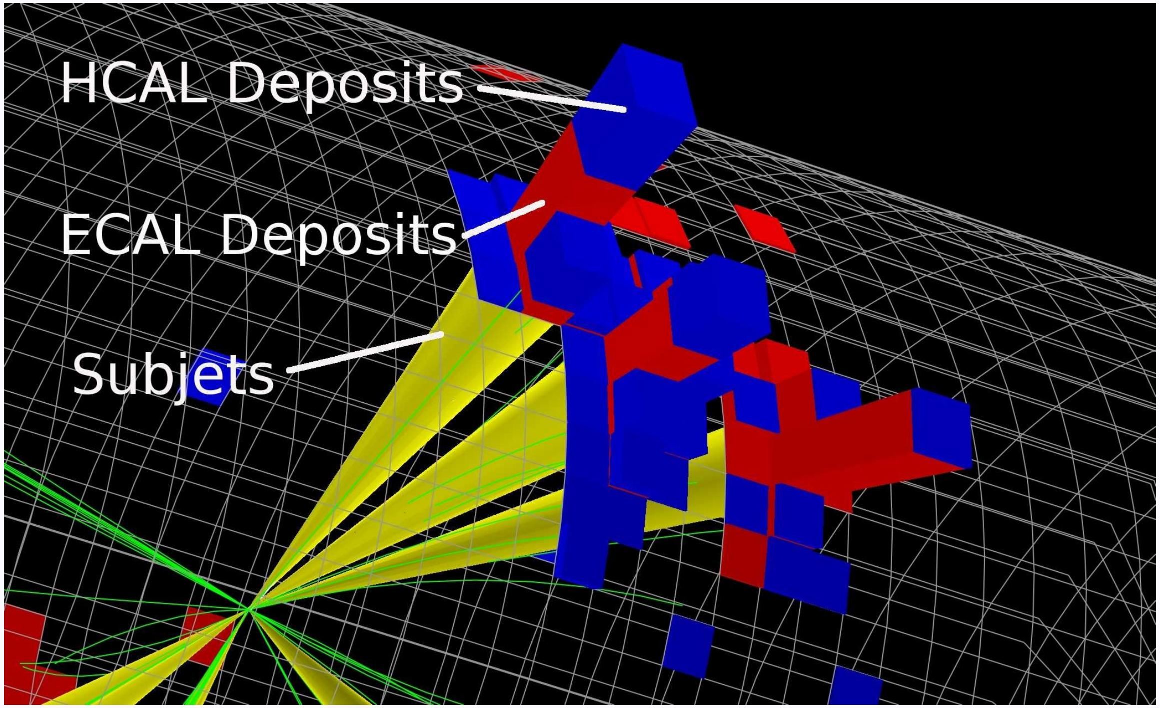
**CMS**: MadGraph interfaced with Pythia with matching (MLM)

# Boosted top-jet tagging

ALGORITHMS | KINEMATIC DISCRIMATORS | PERFORMANCES

**Principle:**

- Develop a algorithm to reconstruct high $p_T$ top as a single jet
- Tag this jet as a top-jet using its sub-structure: sub-jets




CMS top tags based on:
Phys.Rev.Lett.101:142001,2008

ATLAS top tags based on:
ATL-PHYS-CONF-2008-008

**Granularity is fine enough to distinguish the sub-structure**

# Boosted top-jet tagging

**ALGORITHMS** | KINEMATIC DISCRIMATORS | PERFORMANCES

**Principle**: using a clustering algorithms with **sequential recombination** with a **large "angle"** (R) to contain all the top decay products

For each four-momentum input (calo-clusters) pairwise (i,j), compute:

Transverse momentum wrt beam axis

Distance in (η,ϕ)

$$d_{ij} = \min(k_{T,i}^{n}, k_{T,j}^{n}) \frac{\Delta R_{ij}^2}{R^2}$$

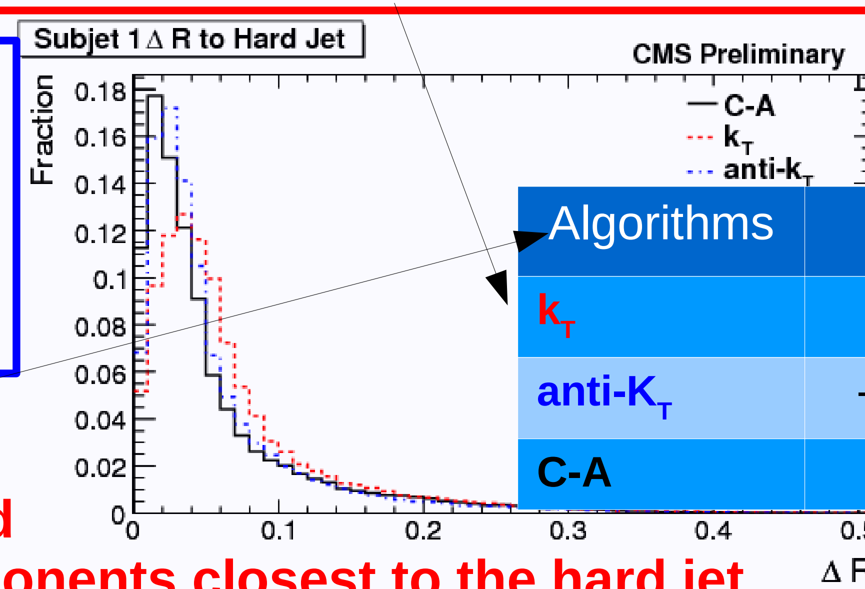
Beam distance $$d_{iB} = k_{T,i}^{n}$$

R is chosen to be (**CMS 0.8, ATLAS 0.6**)

**Clustering**:

- Finding the minimum $d_{min}$
  - If $d_{min} = d_{ij}$ : 2 objects are **merged** (Σp4)
  - If $d_{min} = d_{iB}$ : **final jet**, removed from the list
- Process repeated until there are no objects left

**CMS tested 3 algorithms**




| Algorithms | n |
|---|---|
| $k_T$ | 2 |
| anti-$K_T$ | -2 |
| C-A | 0 |

**Cambridge-Aachen algorithm is retained as it is capable to discern the components closest to the hard jet, well suited for soft/hard subjets discrimination**

## Decomposition of the hard jet

**$p_T$>300 GeV - |η|<2.5**

Run the $k_T$ algorithm backwards to decluster the jet

- The $k_T$ jets are built from topological clusters.
- Identify the splitting scale for the 1 → 2 jet split $\sqrt{(d_{min(1,2)})}$.
- Identify the splitting scale for the 2 → 3 jet split $\sqrt{(d_{min(2,3)})}$.
- Identify the splitting scale for the 3 → 4 jet split $\sqrt{(d_{min(3,4)})}$.

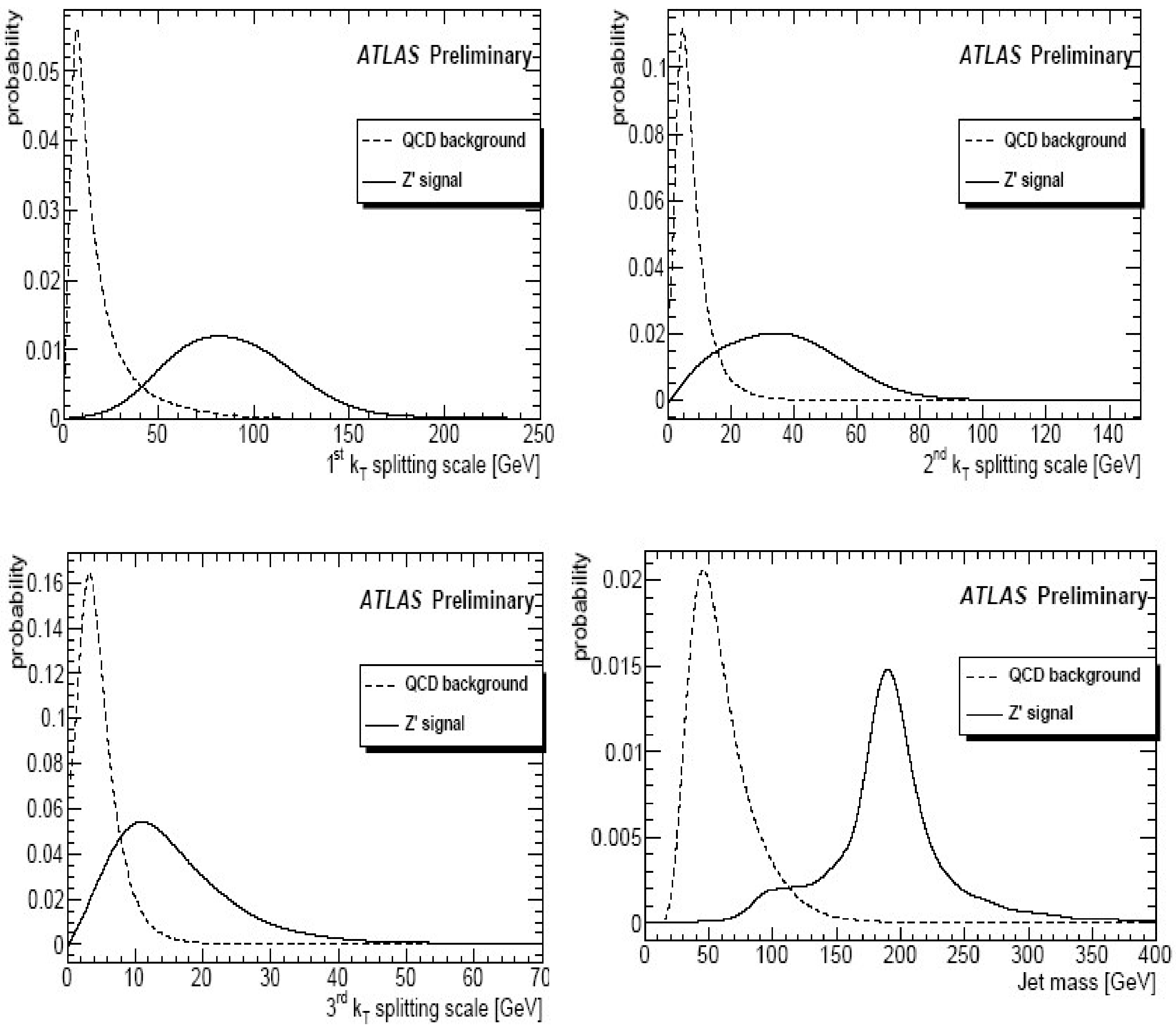
Topological clusters groups cells based on the significance and exploits the fine granularity of ATLAS.

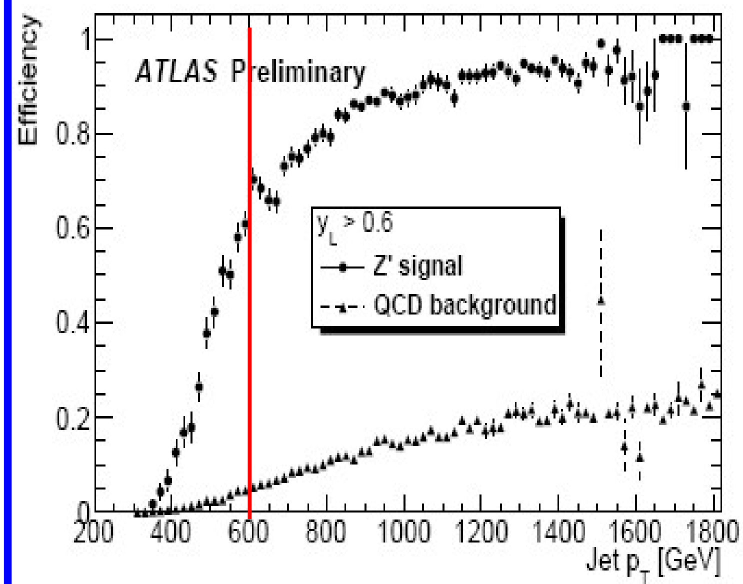
# Boosted top-jet tagging

ALGORITHMS | KINEMATIC DISCRIMATORS | PERFORMANCES

Discriminators: Form a likelihood ratio from the $k_T$ declustering scales and the jet mass

$$y_L = \ln(L_S/L_B)/15$$



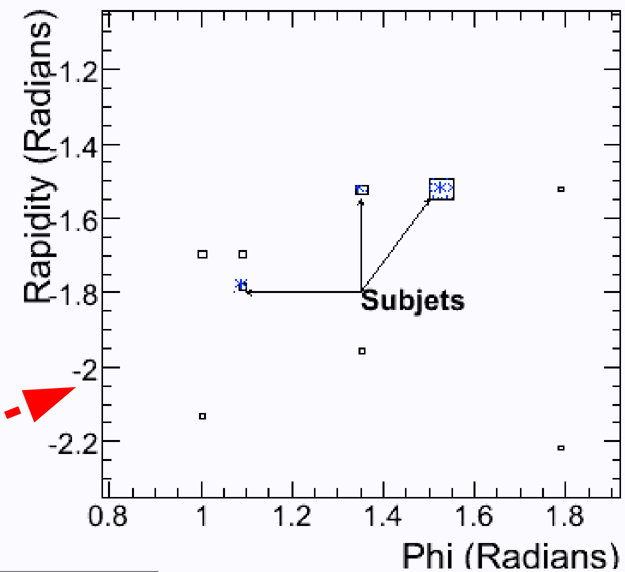
# Boosted top-jet tagging

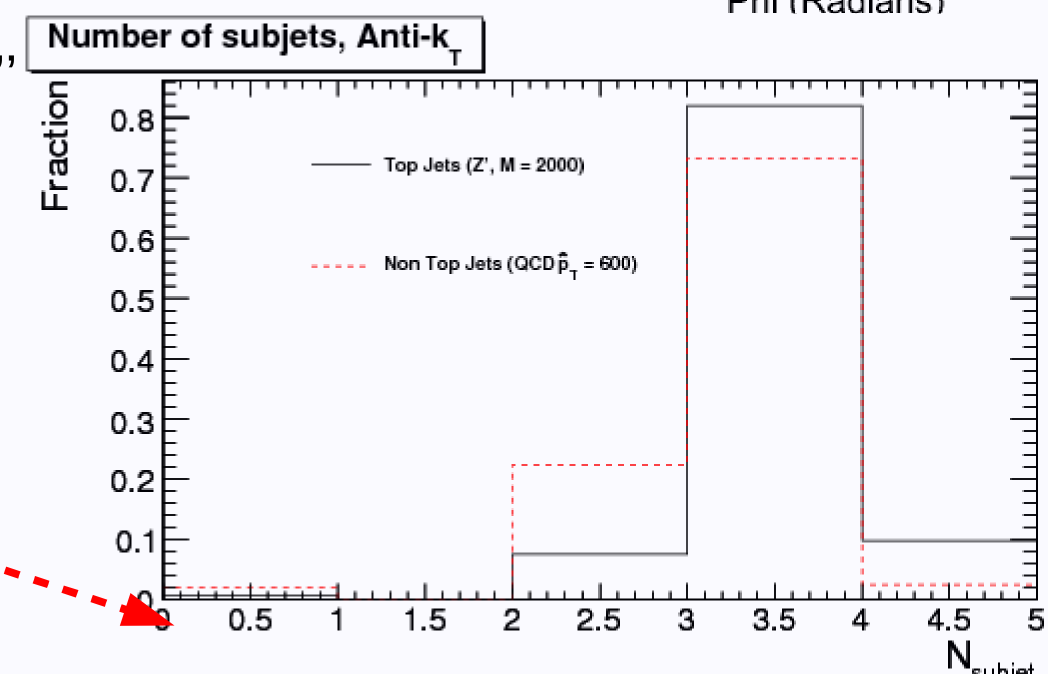
## Decomposition of the hard jet

**$p_T$>250 GeV - |η|<2.5**

Use cluster sequence to decluster hard jets

- Throw out soft clusters
  - Fraction of hard jet pt > 0.05
- Parent clusters A and B
  - Repeat on A and B
- Grandparent clusters A', A'', B', B''
- Require >= 3 clusters
  - A',A'', B
  - A, B', B''
  - A', A'', B', B''
- These are the "subjets"

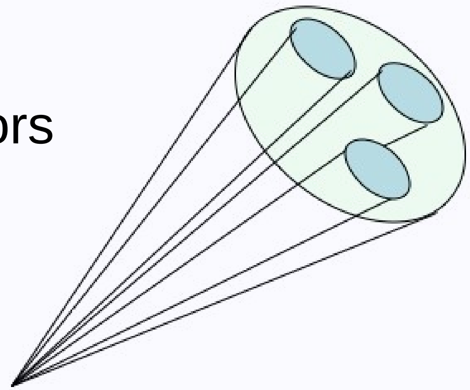


# Boosted top-jet tagging

## Top-tagging

Identification of top-jet based on kinematic discriminators



### For b-jet:

- Track with high impact parameter
- Displaced vertex
- Leptonic decay of b-hadrons: (e/μ)

### For top-jet:

- Mass of the jet (~$m_{top}$)
- 2 body mass (~$m_W$)

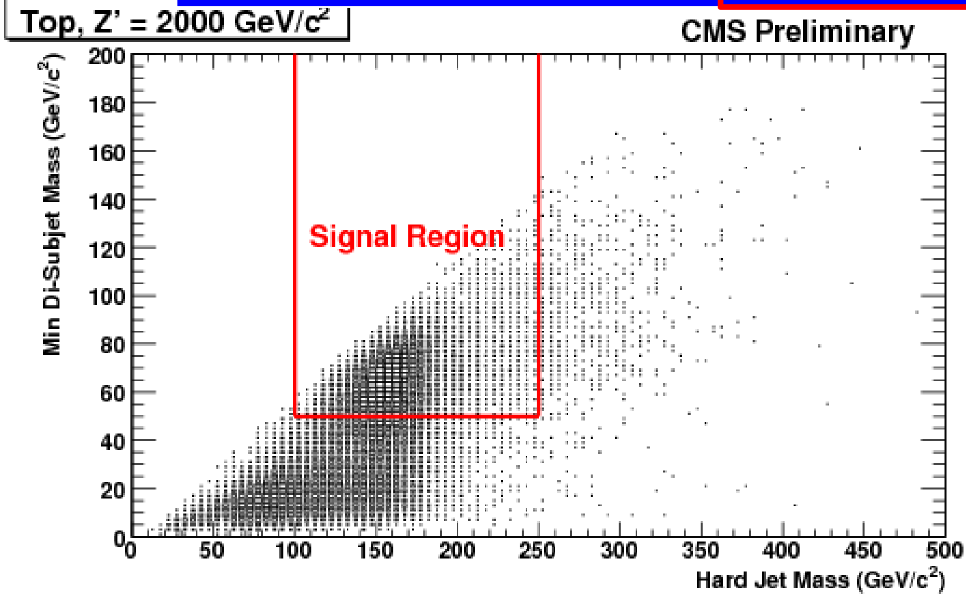
**Signal** = top-jet (from $t\bar{t}$ continuum or resonances)
**Background** = non-top jet (QCD production)
mass of jet scales as ~10% of $p_T$

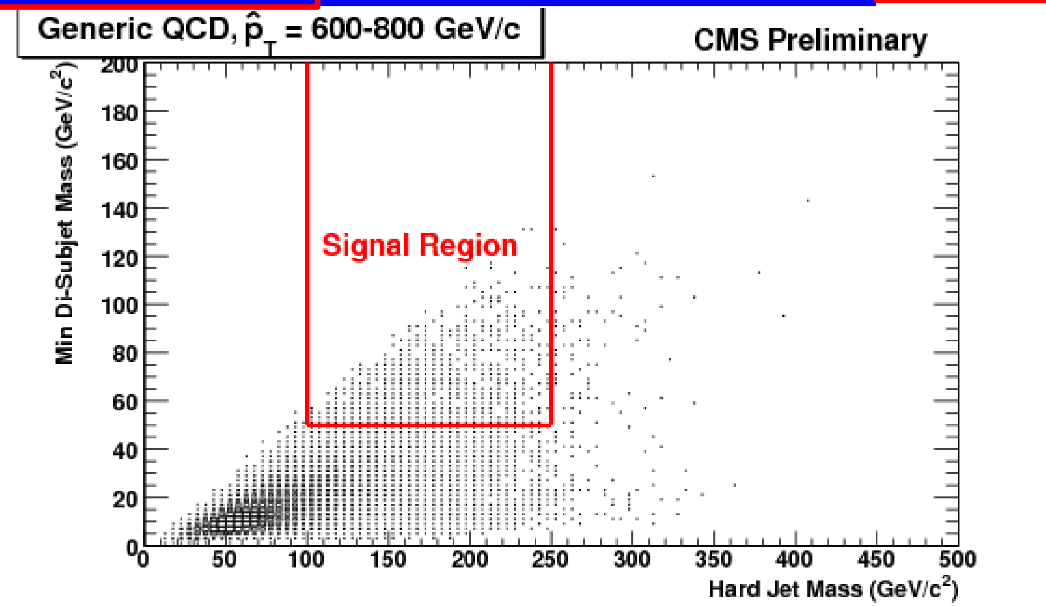
| Kin. discr. | cuts |
|---|---|
| $m_{JET}$ | [100,250] GeV/$c^2$ |
| $M_{min}$ | > 50 GeV/$c^2$ |

| Algorithms | S/√B |
|---|---|
| $K_T$ | 1.6 |
| anti-$K_T$ | 1.3 |
| C-A | 2.4 |

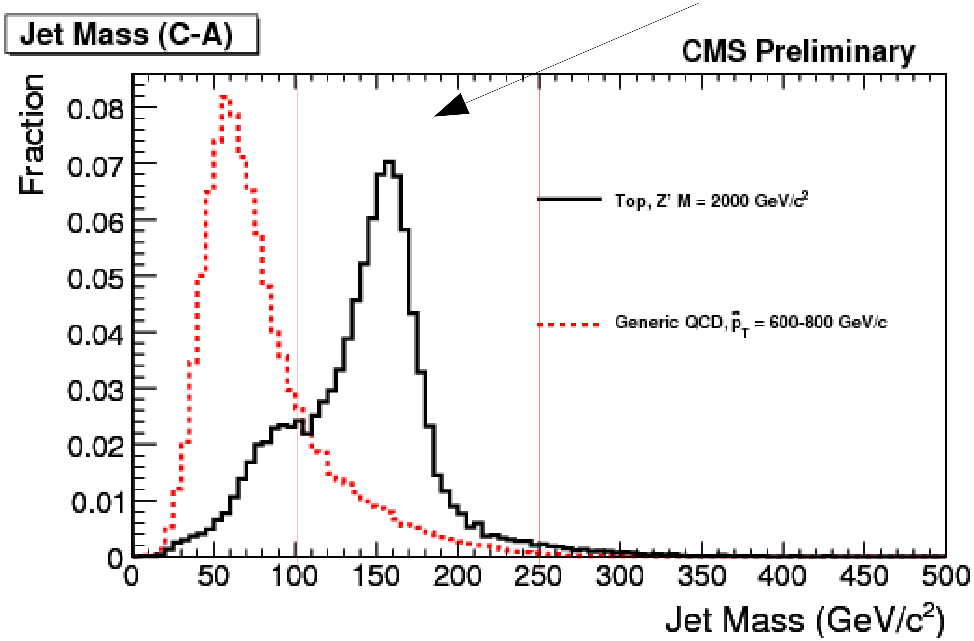
# Boosted top-jet tagging

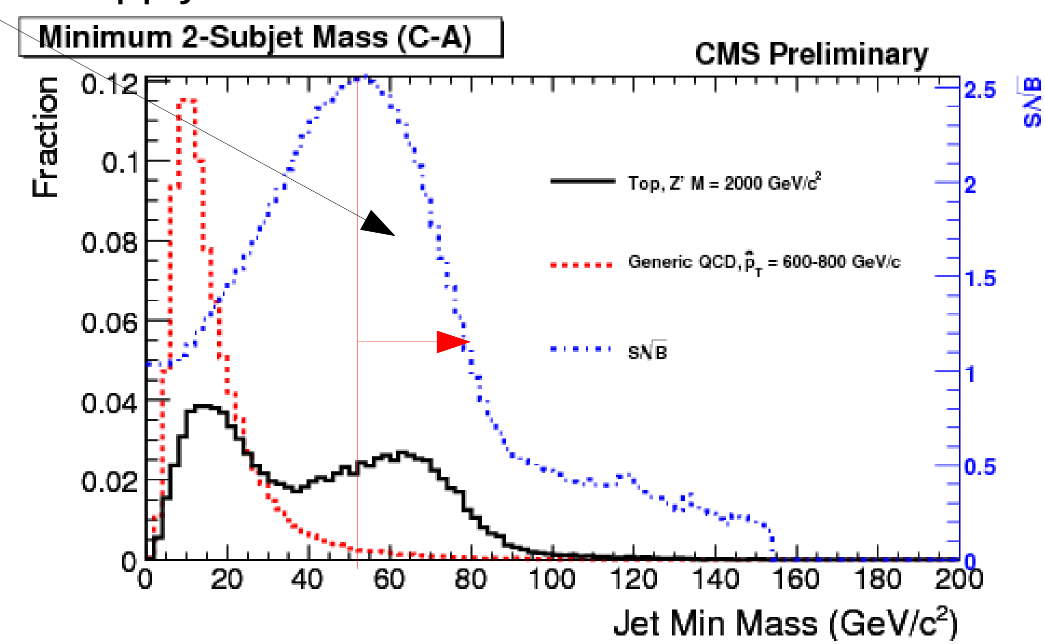
ALGORITHMS | **KINEMATIC DISCRIMINATORS** | PERFORMANCES



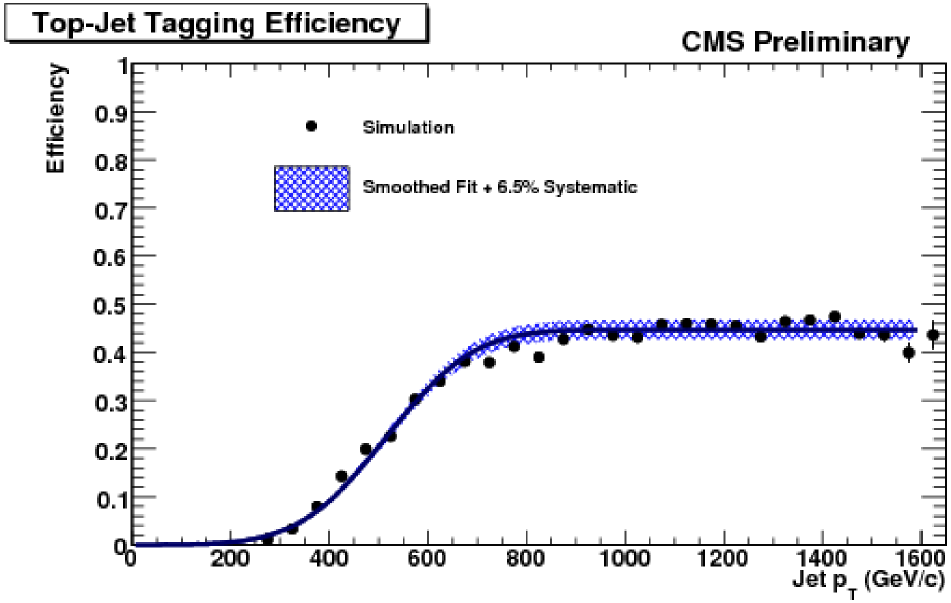

Uncorrelated variables: apply 2 1-D cuts

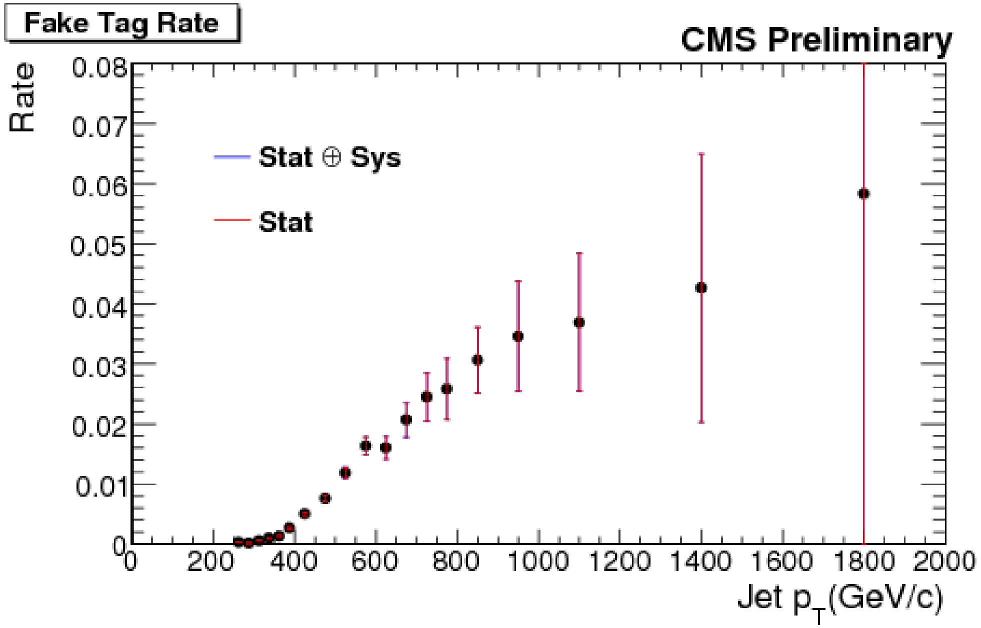


# Boosted top-jet tagging

**jet $p_T$=600 GeV/c: efficiency = 46% & rejection = 98.5%**




## Efficiency from MC (stat limited)

| Effect | Systematic Uncertainty (%) |
|---|---|
| Initial State Radiation | 1 |
| Final State Radiation | 2 |
| Renormalization Scale | 3 |
| Light Quark Fragmentation | < 1 |
| Heavy Quark Fragmentation | < 1 |
| Theoretical Uncertainty | 3.8 |
| Momentum Smearing + 10% | 3.3 |
| Azimuthal Smearing + 50% | 2.9 |
| Rapidity Smearing + 50% | 2.9 |
| Detector-Based Uncertainty | 5.3 |
| Total Systematic Uncertainty | 6.5 |

## Fake rate: data-driven estimation

**Anti-tag & probe method**

**Selection:** Events with 2 jets $p_T$>250 GeV/c & $|\eta|<2.5$

**Anti-tag:** <3 sub-jets or masses outside cut windows

**Probe:** the second jet

Continuum $t\bar{t}$ subtracted from MC expectation

Tag rate is parametrized as function of jet $p_T$

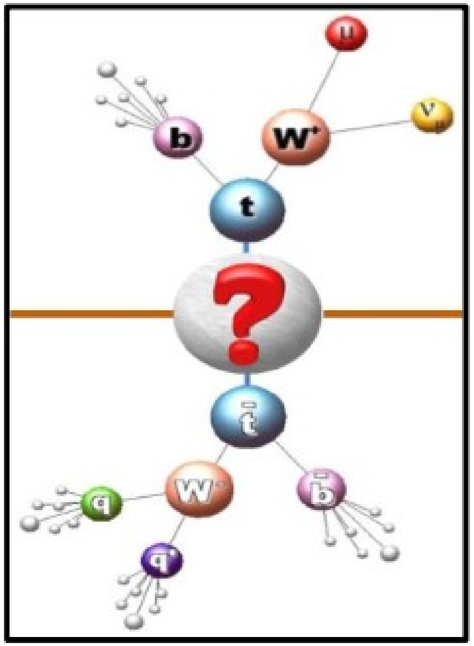
Stat: $10^3$ events for 100 $pb^{-1}$ @ 7 TeV

**Results**: 33% (stat) for jet with $p_T$= 800 GeV

# Search for $t\bar{t}$ resonances

## Channel for $t\bar{t}$ resonances searches:

| | di-leptonic | semi-leptonic | All hadronic |
|---|---|---|---|
| **Low mass** | | CMS[4]/ATLAS[6] | |
| **High mass** | | CMS[3]/ATLAS[7] | CMS[1,2] |




**With use of top-tagging**

**Publications:**

1. CMS-PAS-JME-09-001
2. CMS-PAS-EXO-09-002
3. CMS-PAS-EXO-09-008
4. CMS-PAS-TOP-09-009
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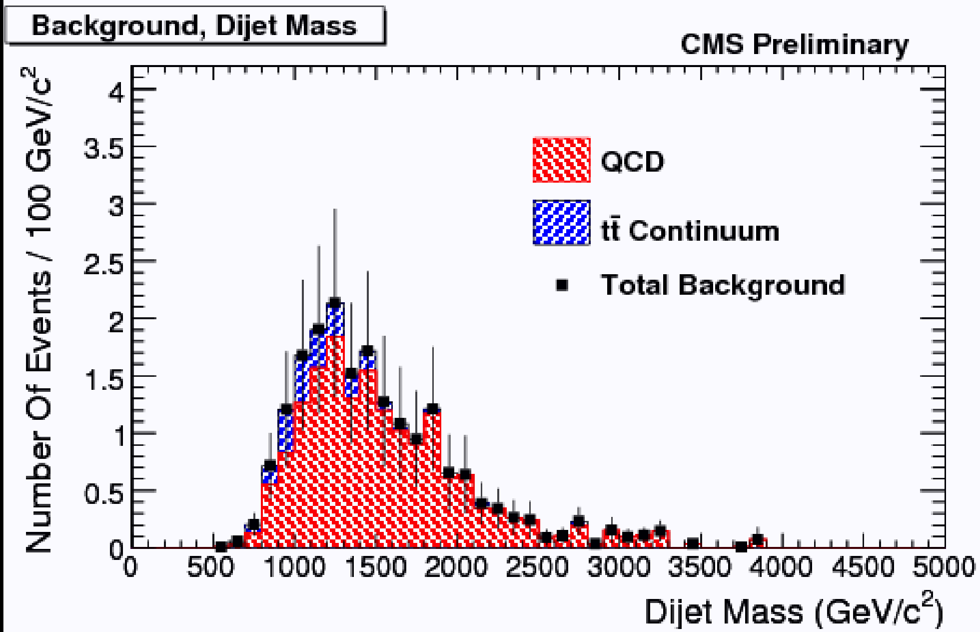
# High-mass resonances: all-hadronic

**SELECTION** SENSITIVITY

**BR = 46 %**

## Event selection

**2 C-A jets with $p_T$>250 GeV/c - |η|<2.5**
**For each jet: 100<$m_{jet}$<250 GeV - 3 or 4 subjets – $m_{min}$>50 GeV/c**



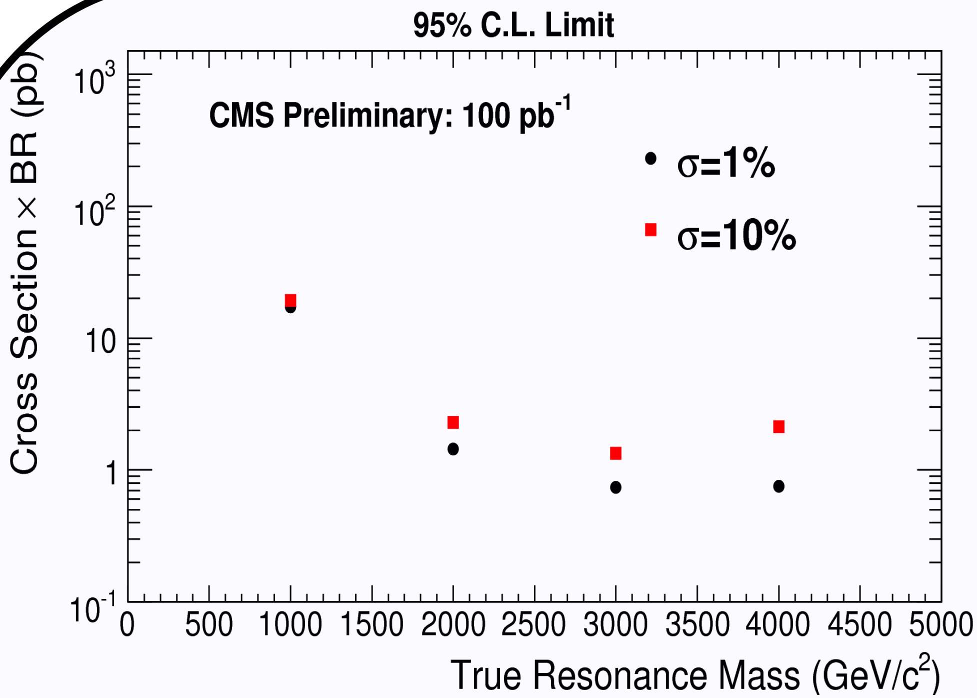

| Backgrounds | | |
|---|---|---|
| W/Z+jets | 2 fakes | negligible |
| single-top | 1 fake/1 hardjet | negligible |
| Continuum tt | 2 hardjets | irreducible |
| di-jets QCD | 2 fakes (high σ) | dominant |

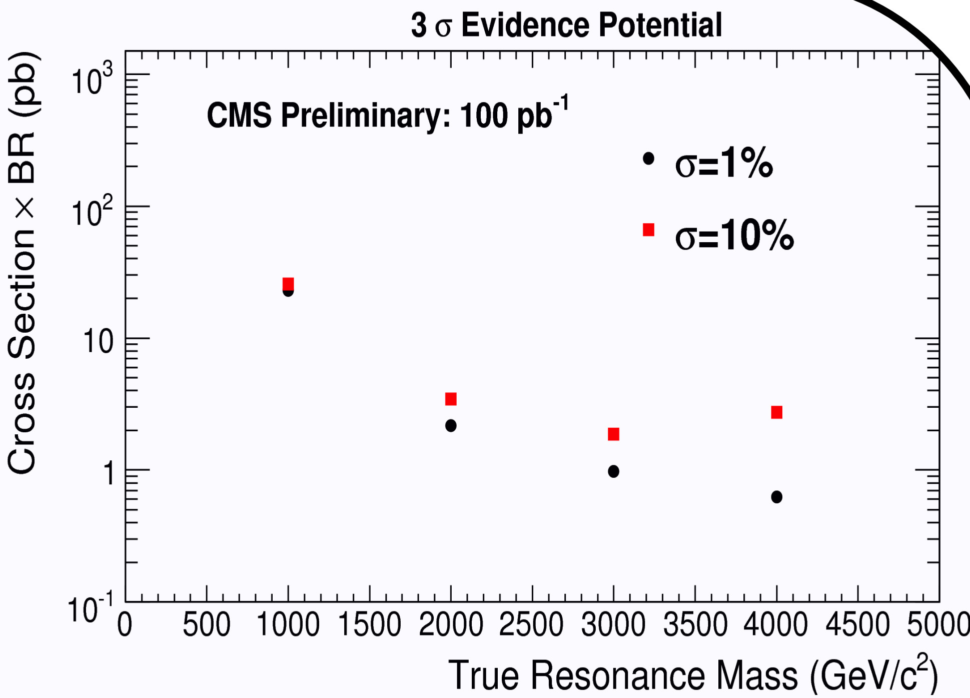
**CMS PAS EXO-09-002**

**$\sqrt{s}$ = 10 TeV / L = 100 $pb^{-1}$**

# High-mass resonances: all-hadronic

SELECTION | **SENSITIVITY**




Results obtained on Z' with a width of 1-10% of the $m_{Z'}$

| Quantity | Relative Uncertainty | Uncertainty on $S$ and $B$ at $m_0 = 2$ TeV/c$^2$ |
|---|---|---|
| Signal Uncertainties | | |
| Top Tagging Efficiency | 6.5% | 13% |
| JES Uncertainty on Acceptance | 5% | 5% |
| Total Signal Uncertainty | | 14% |
| Background Uncertainties | | |
| Statistical uncertainty | 10% | 10% |
| JES Uncertainty on QCD Background | 35% | 33% |
| $t\bar{t}$ Continuum Contribution | 100% | 5% |
| Luminosity | 10% | 10% |
| Total Background Uncertainty | | 36% |

**$\sqrt{s}$ = 10 TeV / L = 100 pb$^{-1}$**

# Search for $t\bar{t}$ resonances

## Channel for $t\bar{t}$ resonances searches:

| | di-leptonic | semi-leptonic | All hadronic |
|---|---|---|---|
| **Low mass** | | **CMS**[4]/ATLAS[6] | |
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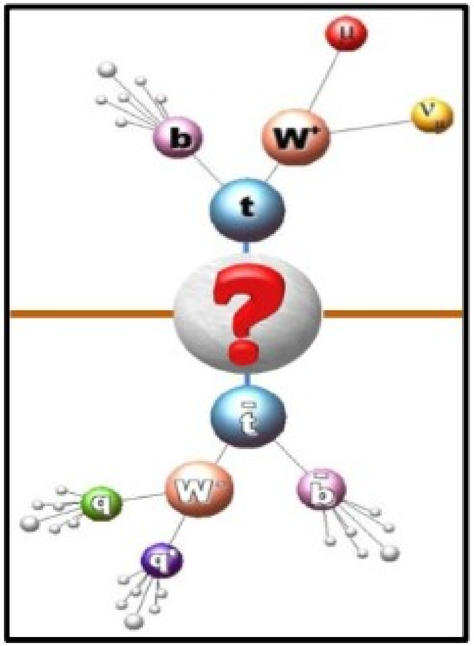


**With a l+4 jets topology**

**Publications:**

1. CMS-PAS-JME-09-001
2. CMS-PAS-EXO-09-002
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7. ATLAS-PHYS-PUB-2009-081

# Low-mass resonances: semi-leptonic

SELECTION | RECONSTRUCTION | SENSITIVITY

**BR = 15 %**

**CMS PAS TOP-09-009**

**Principle**: using standard reconstruction techniques with cuts suited for search of $t\bar{t}$ resonances

## Trigger

**Single muon**

- $p_T$>9 GeV/c
- **No isolation criteria**

ε=80-90% for $M_{Z'}$ 0.5-2 TeV/$c^2$

## At least 4 jets

- SisCone algorithm - ΔR = 0.5
- (η,$p_T$) corrected
- $p_T$> 35 GeV/c - |η|<2.4

## (Calo)Missing $E_T$

- Jets corrections applied
- Muon corrections applied

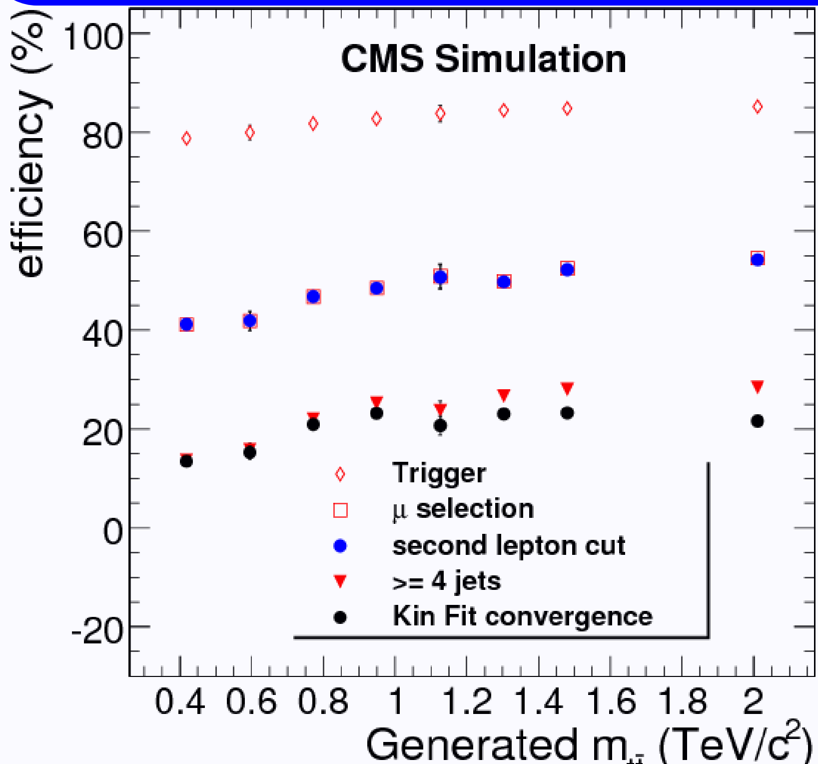
## Veto on 2nd lepton

- Exactly one muon
- No isolated electron,$p_T$>10 GeV/c

## Exactly one muon

- $p_T$>25 GeV/c - |η|<2.1
- **No criteria on calo energy deposit**
- **$\Delta R_{min}$**>0.4
- **$P_T^{rel}$**>35 GeV/c

(the last two criteria, bracketed together:) Closest jet $p_T$>30 GeV/c

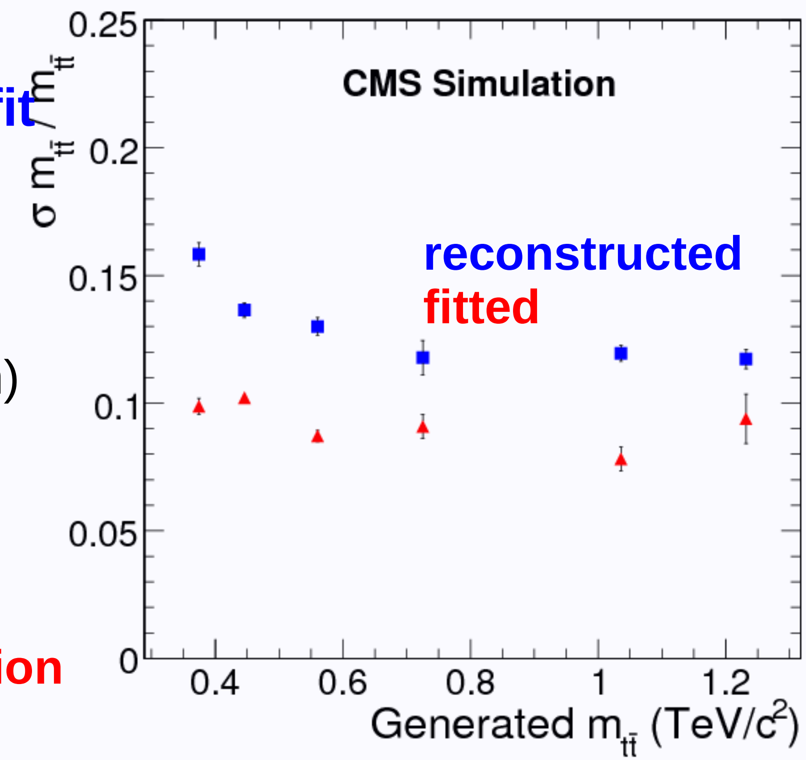


## Selection of 4 jets

- Consider all subset of 4 jets among N jets where 4<=N<=8 with jet $p_T$>20 GeV
- $\binom{N}{N-4}$ subsets with 12 combinations for each.
- Build a $\chi^2$ using hadronic masses (W,top), ΔR(l,b), $m_T$(l,b,MET) and $\Sigma p_T$(jets)
- Parameters and resolution are taken from Monte Carlo
- Select the 4 jets which minimize the $\chi^2$

## Reconstruction of the event with a kinematic fit

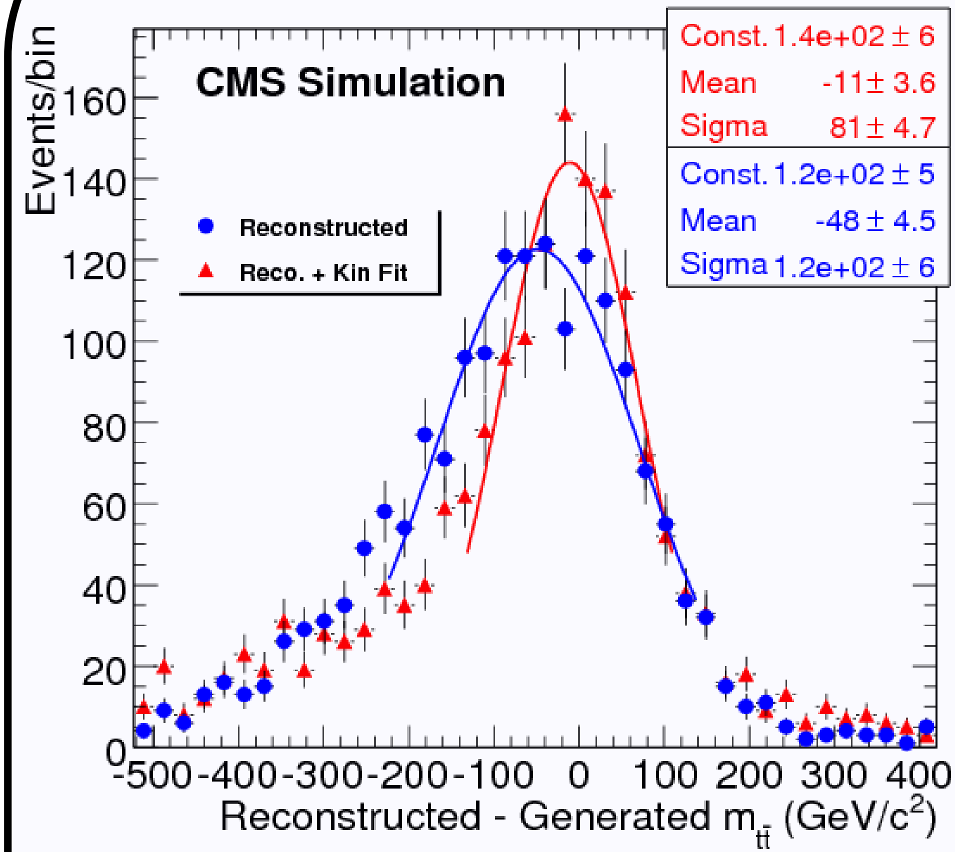
- Build a kinematic fit for the 12 combinations of the 4 previously selected jets
- **Constraints:** W boson, top quark masses
- **16 parameters:** (E,η,Φ) of 4 jets, $P_{x,y,z}$ (ν), E(muon)
- **$P_z$(neutrino) initial**: W mass constraint
- Minimization performed with MINUIT ($\chi^{2'}$)
- Choose the jet combination with minimum $\chi^{2'}$



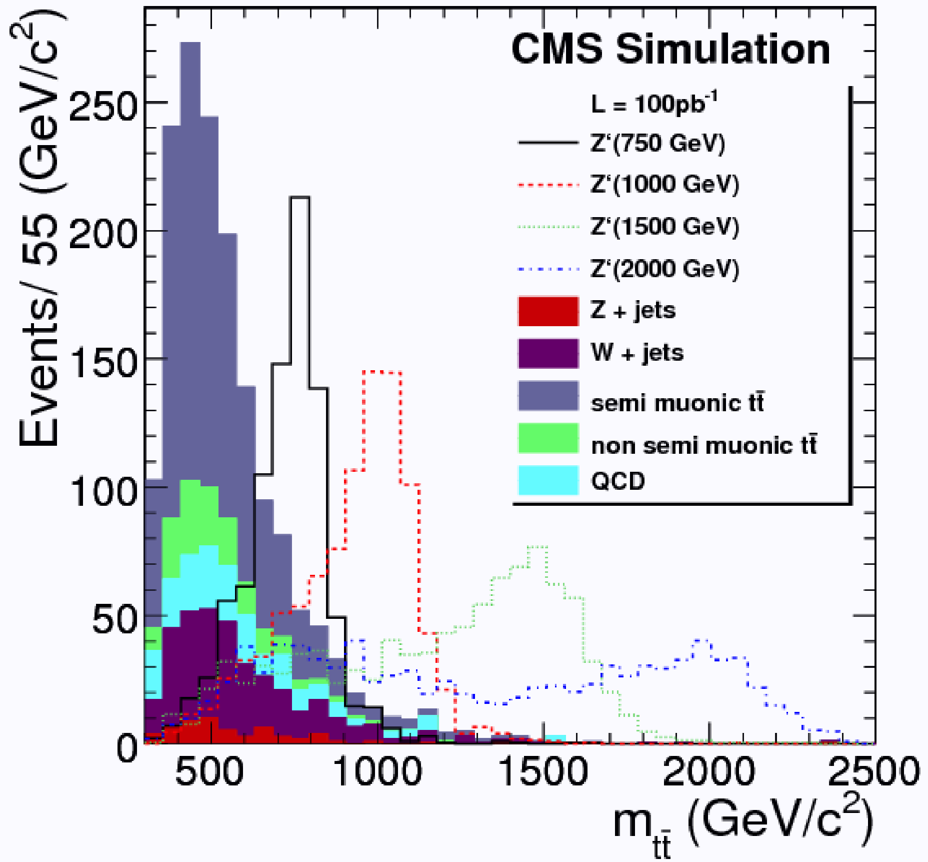

**Kinematic fit improves the linearity and the resolution of the reconstructed top pair invariant mass**

# Low-mass resonances: semi-leptonic

## Invariant mass of a 2 TeV/c² Z'




## Expected Invariant mass for all processes



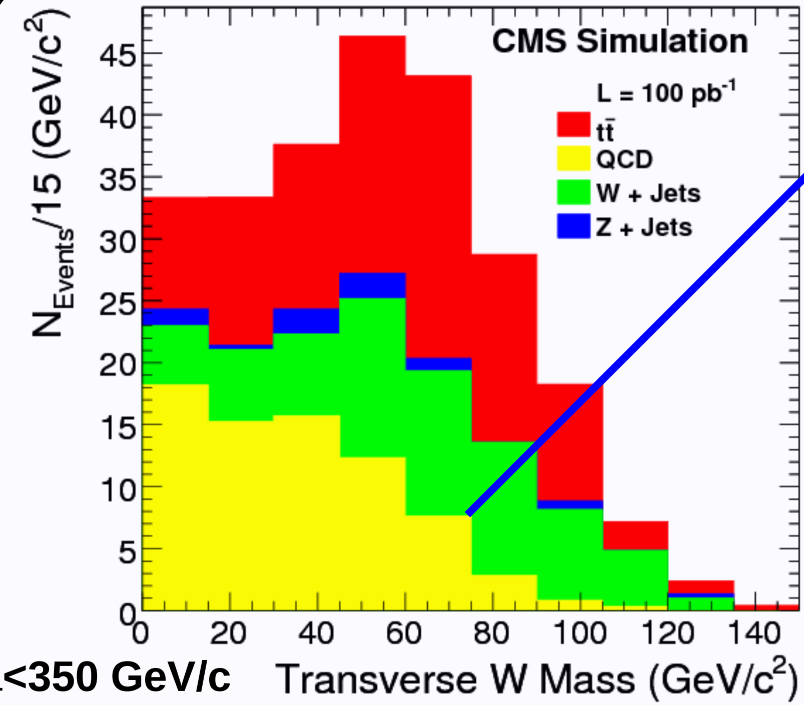

Z' scaled to tt cross-section

**√s = 10 TeV / L = 100 pb$^{-1}$**

# Low-mass resonances: semi-leptonic

SELECTION | RECONSTRUCTION | **SENSITIVITY**

## Data-driven calibration methods:




$H_T$<350 GeV/c

Shape of QCD from data: 0.1 < ΔRmin(μ, jet) < 0.4

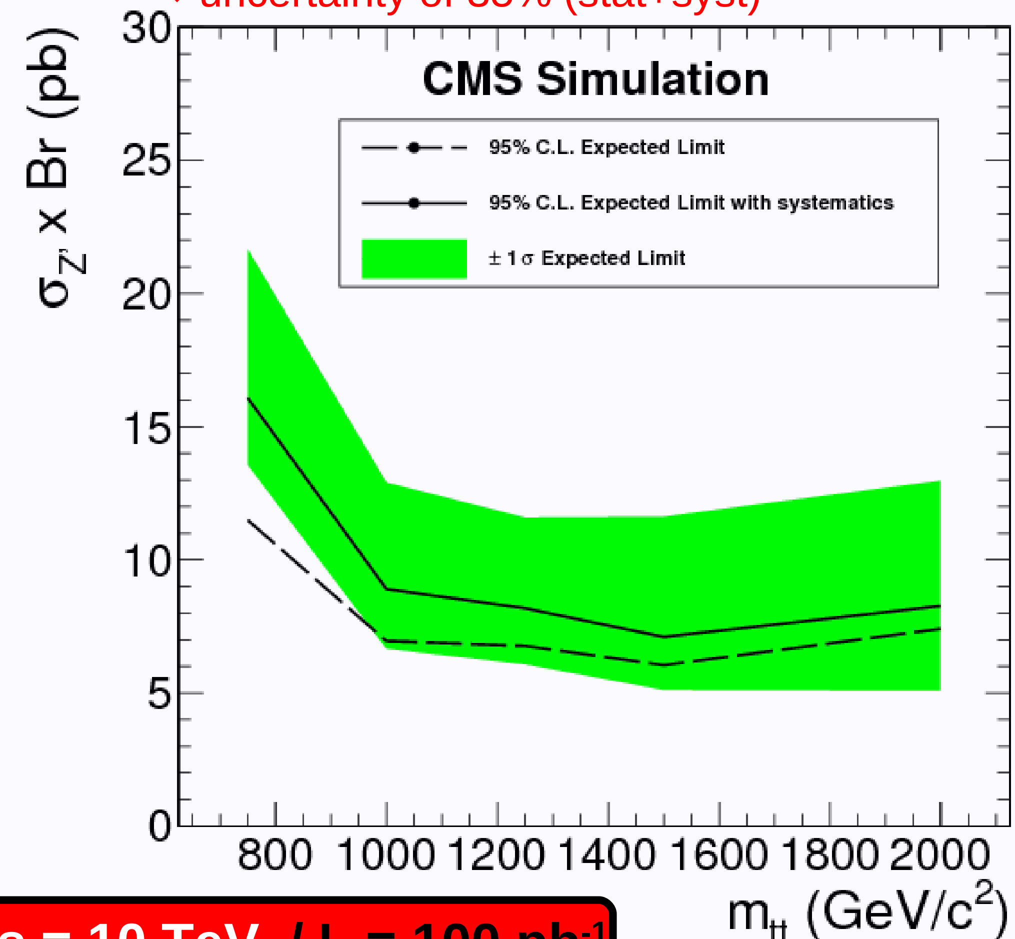
Shape of tt, W/Z from MC:

Level of tt from MC

Level of QCD & W/Z from data

→ extrapolated to the signal region

→ uncertainty of 35% (stat+syst)




## Systematic uncertainties:

- Jet Energy Scale 10%
- Jet Energy Resolution 10%
- Luminosity 10%
- Level of QCD: 50%
- tt: scale & pdf 10%
- W+jets (after selection): 20%
- $\alpha_s$, ISR/FSR: 20% on tt acceptance

**√s = 10 TeV / L = 100 pb$^{-1}$**

# Search for $t\bar{t}$ resonances

## Channel for $t\bar{t}$ resonances searches:

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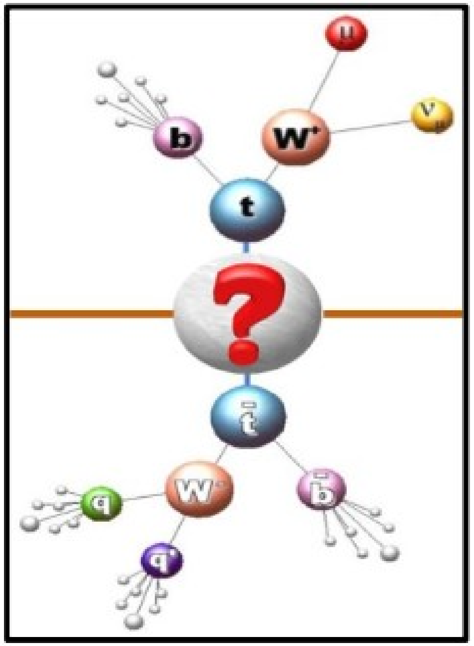

**With a l+4 jets topology**

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# Low-mass resonances: semi-leptonic



**Principle**: use standard reconstruction techniques

**CERN-OPEN-2008-20**

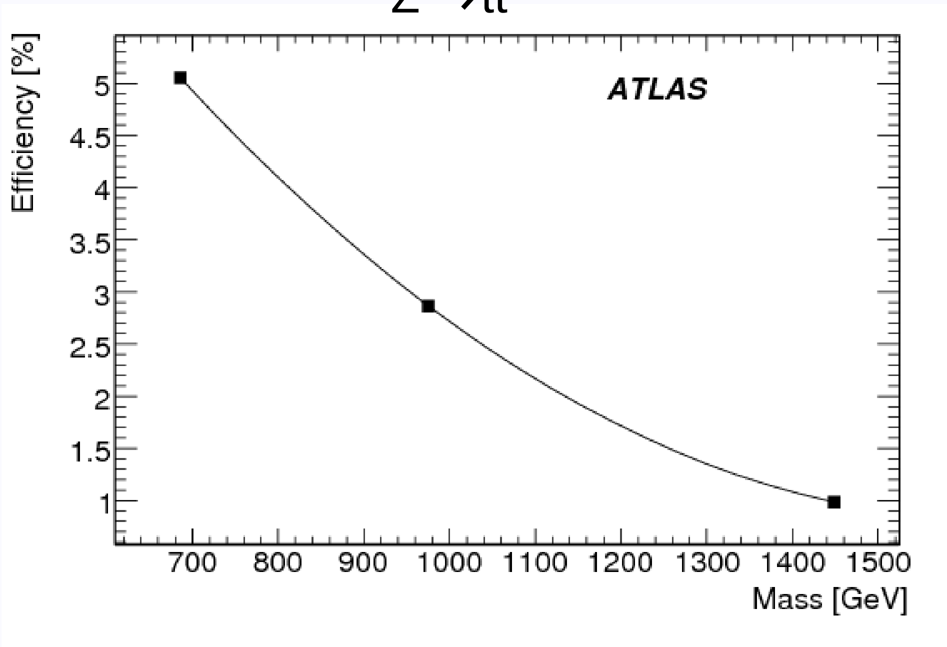
## Trigger
- Single electron(muon)
- $p_T > 22(20)$ GeV/c

## One offline lepton
- $p_T > 25(20)$ GeV/c - $|\eta| < 2.5$
- Calorimeter isolation < 6 GeV

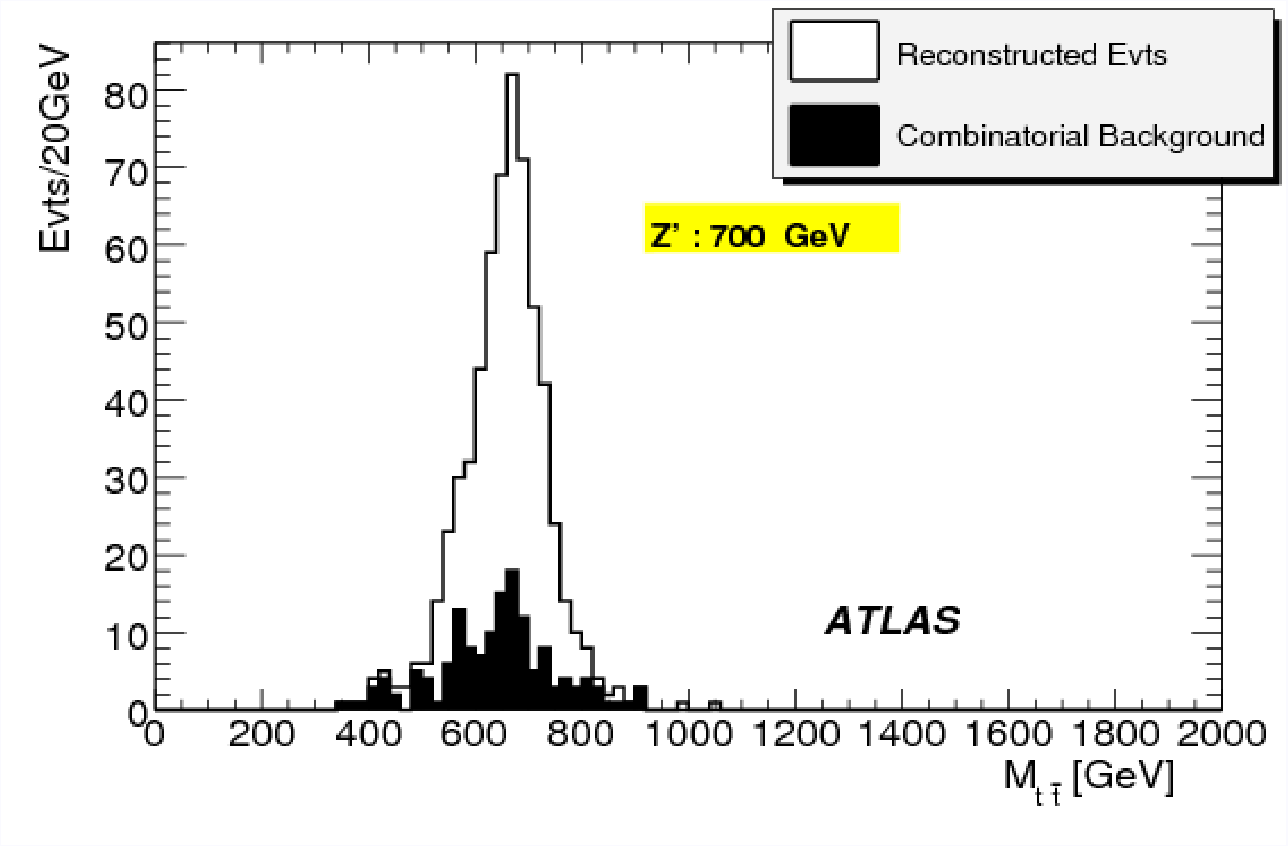
## (Calo)Missing $E_T$
- $E_t^{miss} > 20$ GeV
- Jet corrections applied
- Muon corrections applied

## Jets
- At least 4 jets
- $E_T > 30$ GeV - $|\eta| < 2.5$
- 2 b-jets

Z' →tt

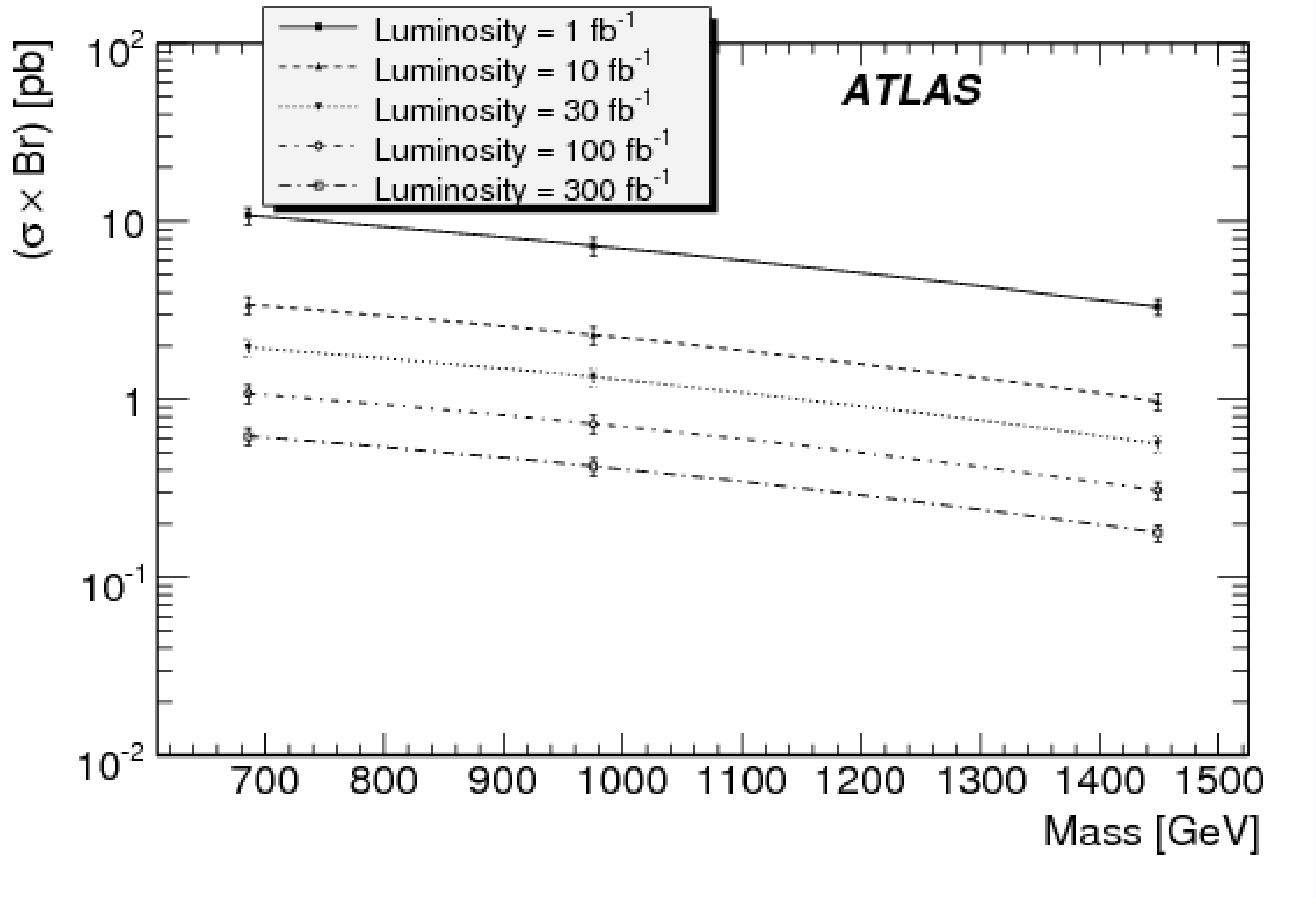


**$P_z$ of the neutrino**: W mass constraint. Use solution closest to top mass.



**√s = 14 TeV**

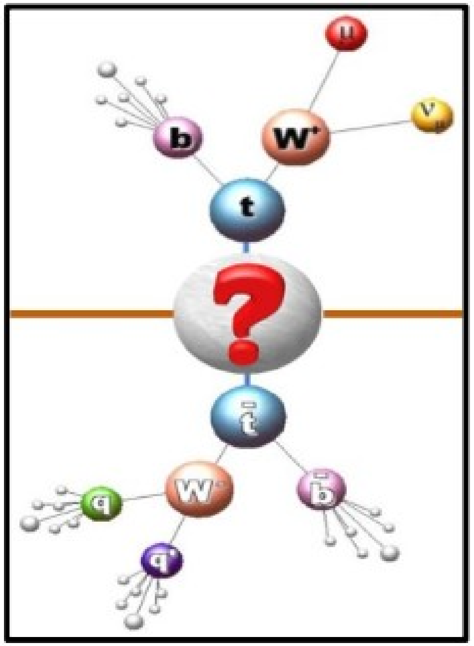
5σ discovery potential, narrow Z'



# Search for $t\bar{t}$ resonances

## Channel for $t\bar{t}$ resonances searches:

| | di-leptonic | semi-leptonic | All hadronic |
|---|---|---|---|
| **Low mass** | | CMS[4]/ATLAS[6] | |
| **High mass** | | CMS[3]/ATLAS[7] | CMS[1,2] |




**With a l+>=2 jets topology**

**Publications:**

1. CMS-PAS-JME-09-001
2. CMS-PAS-EXO-09-002
3. CMS-PAS-EXO-09-008
4. CMS-PAS-TOP-09-009
5. ATL-PHYS-CONF-2008-008
6. CERN-OPEN-2008-20
7. ATLAS-PHYS-PUB-2009-081

# High-mass resonances: semi-leptonic

SELECTION | RECONSTRUCTION | SENSITIVITY

BR = 15 %

CMS PAS EXO-09-008

**Principle**: using standard reconstruction techniques with cuts suited for high-mass resonances

## Trigger

**Single muon**
- $p_T$>15 GeV/c
- **No isolation criteria**

ε=85-90% for $M_{Z'}$ 1-4 TeV/$c^2$

## At least 2 jets

- SisCone algorithm - ΔR = 0.5
- (η,$p_T$) corrected
- |η|<2.4
- $p_T$>**260** - 50 GeV/c
- Leading jet might come from a merged jet

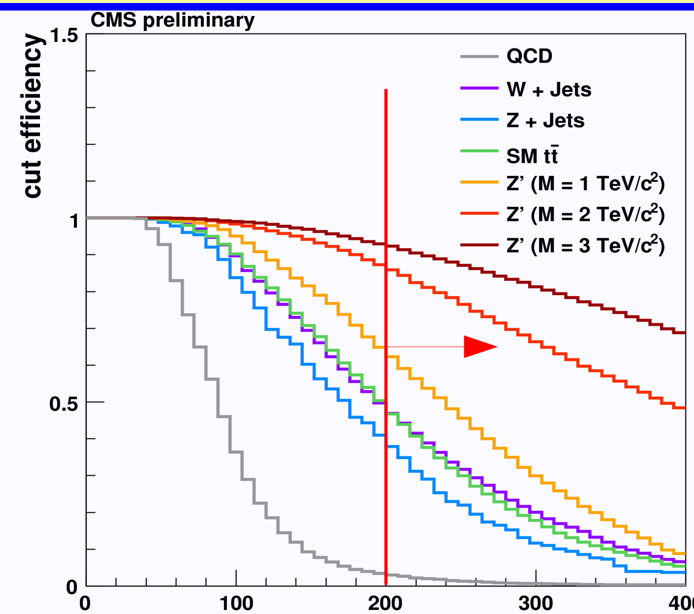
## (Calo)Missing $E_T$

- Jets corrections applied
- Muon corrections applied

## At least one muon

- $p_T$>25 GeV/c - |η|<2.1
- Impact parameter (BS) <0.2 mm
- **No criteria on calo energy deposit**
- **$\Delta R_{min}$**>0.4
- **$P_T^{rel}$**>35 GeV/c

(Closest jet $p_T$>30 GeV/c)




$H_T^{lep} = p_T(\mu) + E_t^{miss}$ >200 GeV/c

# High-mass resonances: semi-leptonic

SELECTION | **RECONSTRUCTION** | SENSITIVITY

**$P_z$ of the neutrino**: W mass constraint. Use real (part) solutions in the following formula

$$\Delta R_{\rm sum} = \Delta R(t_\ell, \mu) + \Delta R(t_\ell, \nu) + \Delta R(t_\ell, b_\ell) - f_1 \Delta R(t_\ell, t_h) - f_2 M_{t_\ell t_h}$$

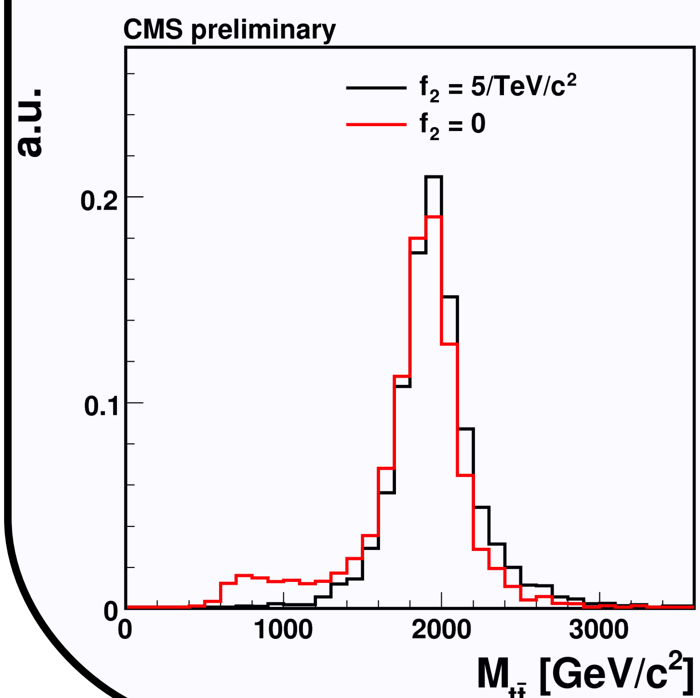
$$\Delta R = \sqrt{((\Delta\phi)^2 + (\Delta\eta)^2)}$$

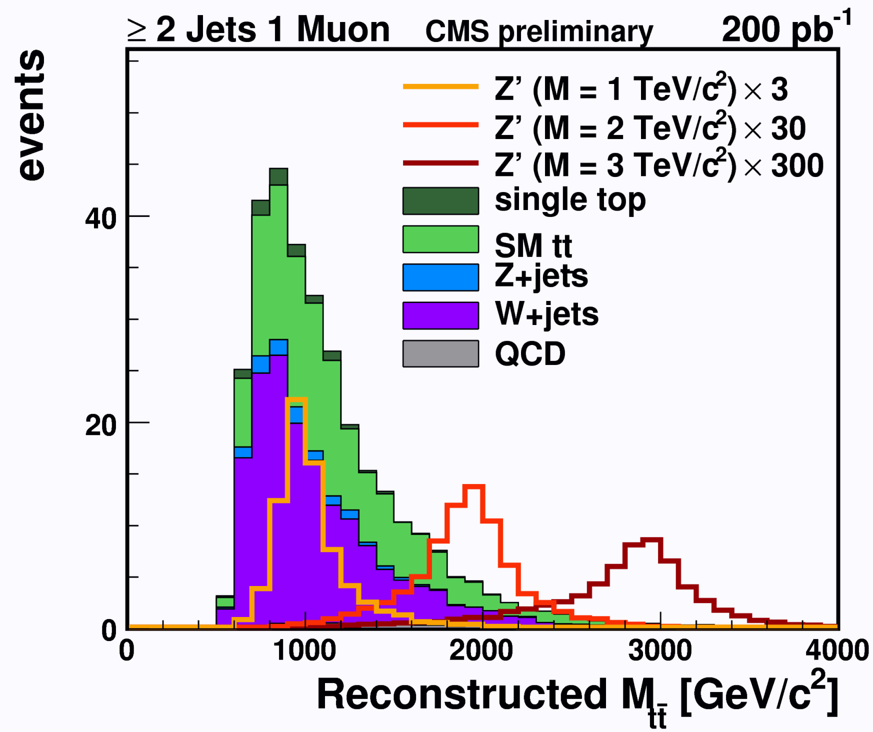
Small separation for decay products

Large separation of the 2 top quarks in a resonant decay

Reduce tail in low top pair mass

**f1** = 0.5
**f2** = (0,1,5)/TeV/$c^2$ for either (2,3,4) jets



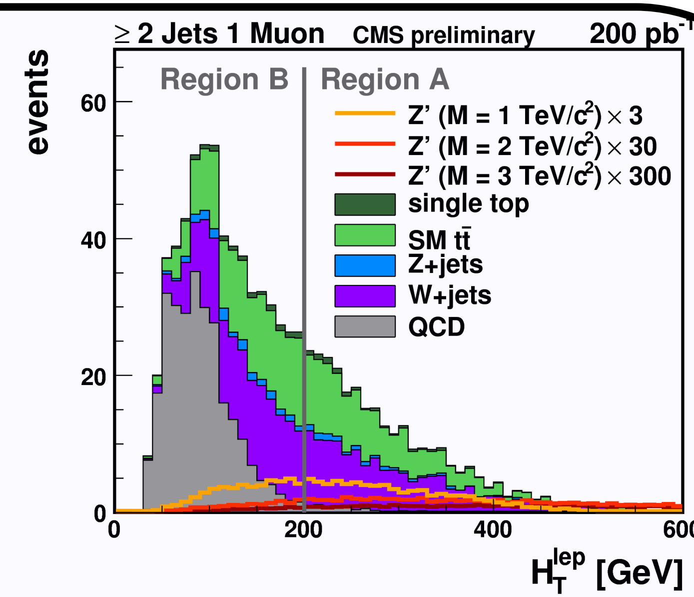



# High-mass resonances: semi-leptonic

SELECTION | RECONSTRUCTION | **SENSITIVITY**

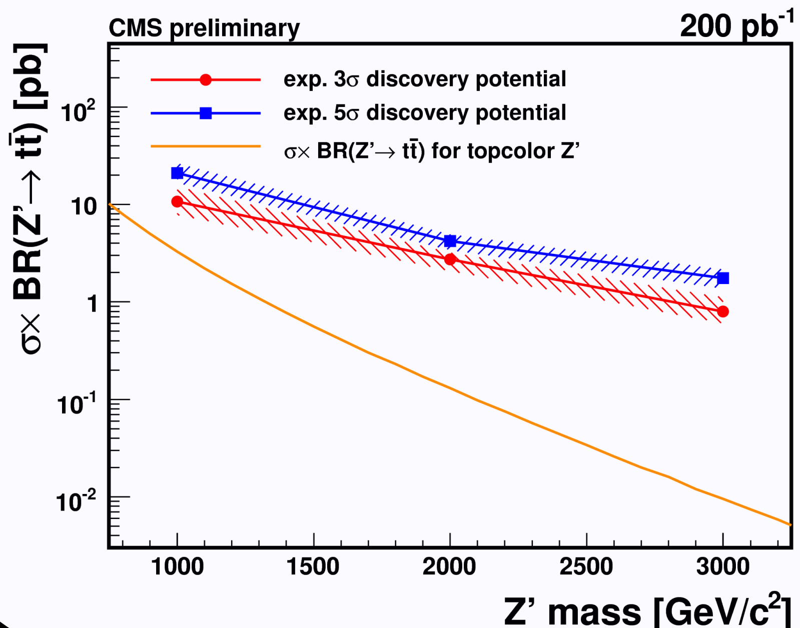
**$\sqrt{s}$ = 10 TeV / L = 200 $pb^{-1}$**

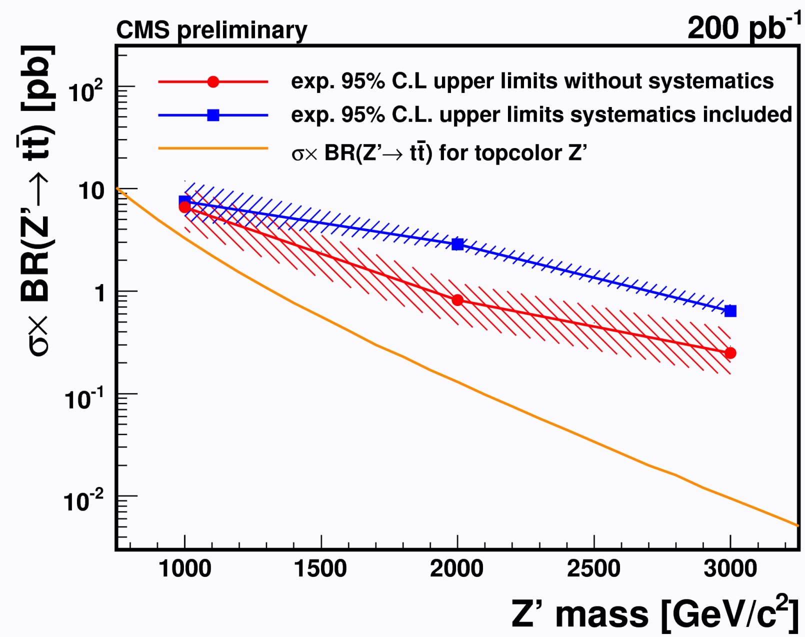
Estimation of the background via a combined fit (cf low-mass analysis)




## Systematic uncertainties

- JES: 10%
- Modeling of W+jets and SM tt: $Q^2$ - ISR/FSR
- Effects on acceptance, $H_T$(lep) & $M_{tt}$ distributions



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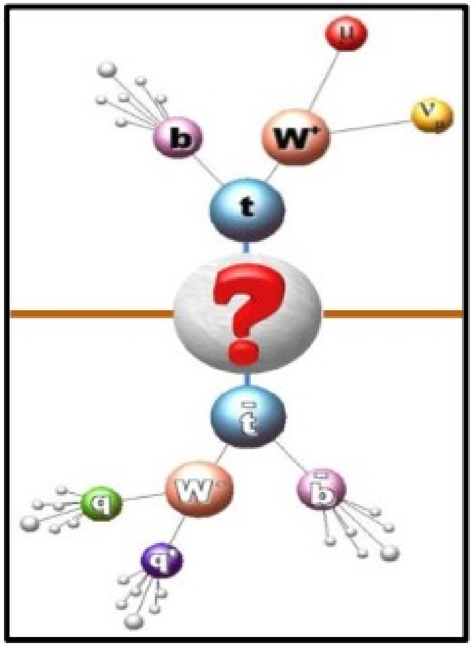


**2 jet topology with a lepton in a jet**

**Publications:**

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# High-mass resonances: semi-leptonic

**Principle**: use top tagged mono jets (Kt algorithm D=0.6)

ATLAS-PHYS-PUB-2009-081

## Trigger/Offline lepton

- Single electron(muon)
- Non isolated
- $p_T > 20$ GeV/c

## (Calo)Missing $E_T$

- $E_t^{miss} > 20$ GeV
- Jet corrections applied
- Muon corrections applied

## Taggable hadronic top jet

- Use highest $P_T$ jet
- $P_T > 300$ GeV
- Not tagged electron/muon jet
- Tag uses splitting scales/mass

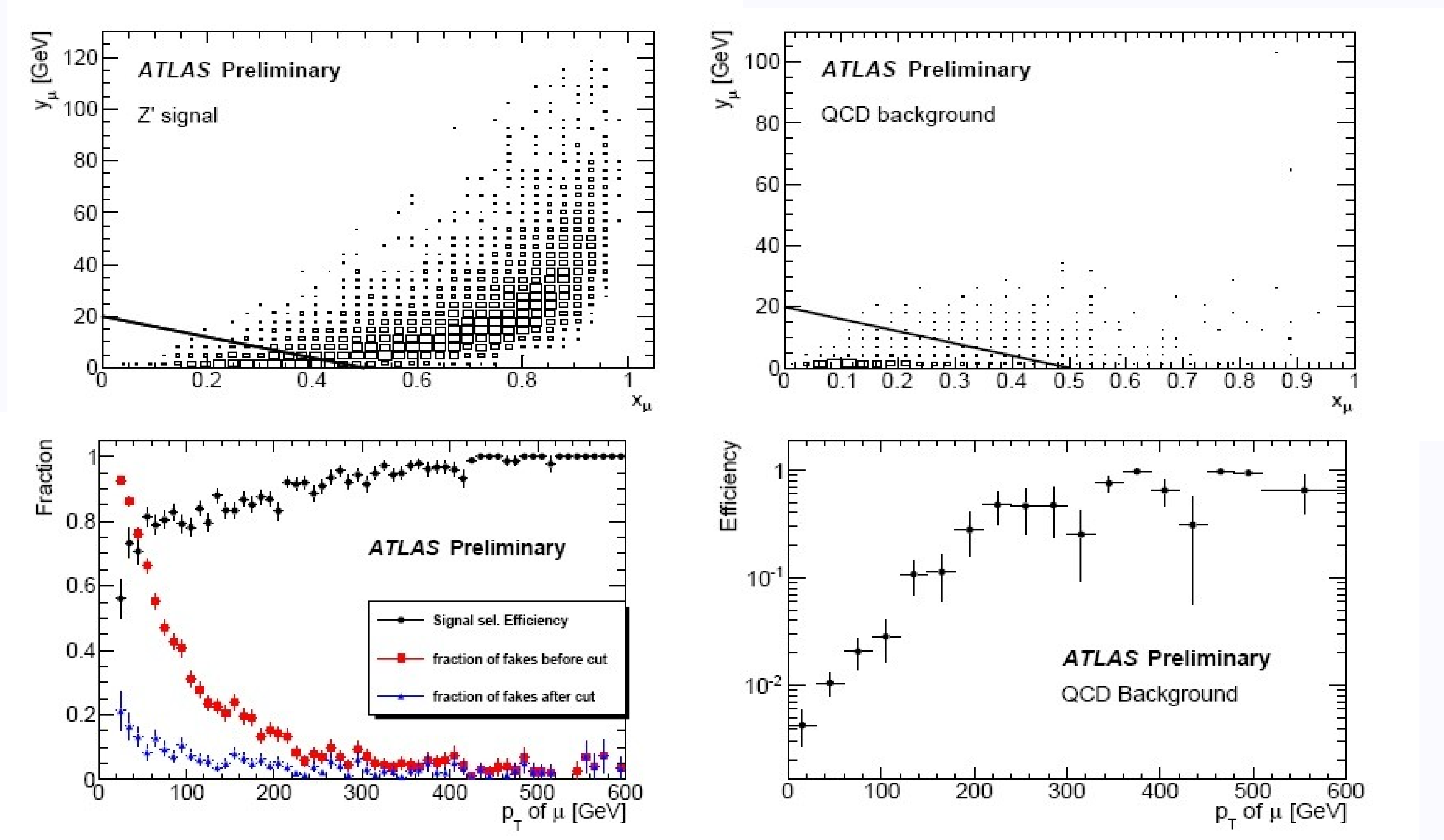
## Taggable muon top jet

- $P_T > 200$ GeV
- $\Delta R$(muon, jet) < 0.6
- Tag uses
  - $y_\mu = p_{\mu\perp b} \cdot \Delta R(\mu, b)$ (muon "$k_T$")
  - $x_\mu = 1 - m_b^2 / m_{visble}^2$ (mass frac.)

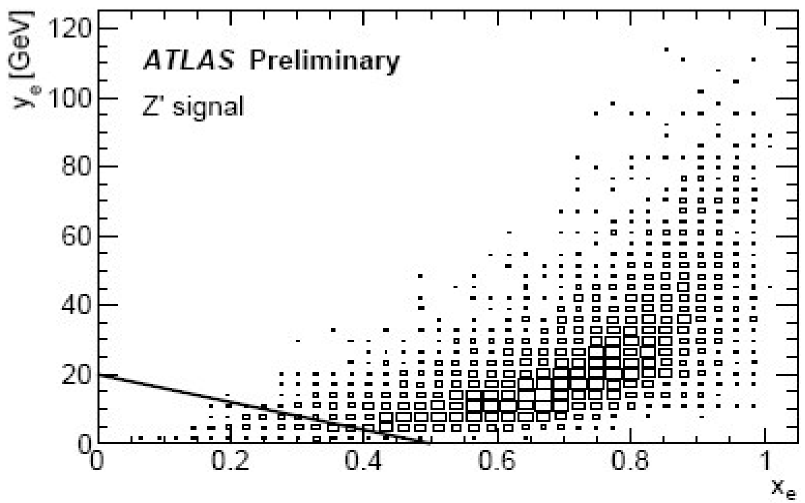
## Taggable electron top jet

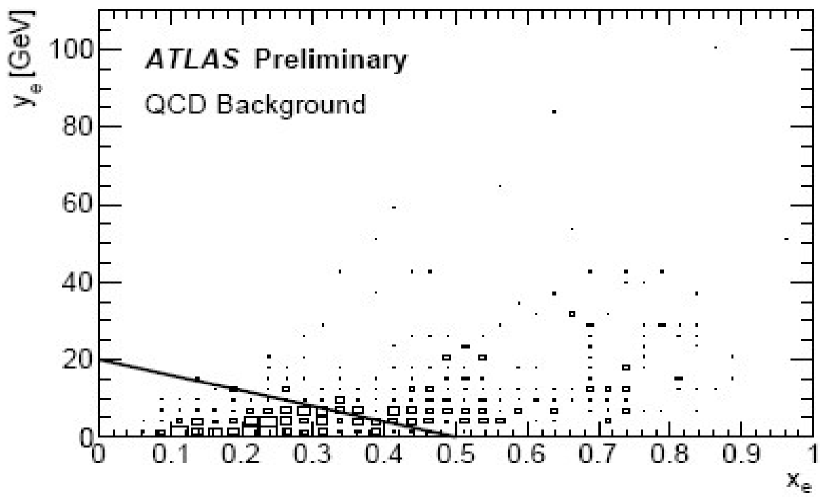
- $P_T > 300$ GeV
- $\Delta R$(electron, jet) < 0.6
- Tag analog to the muon top jet

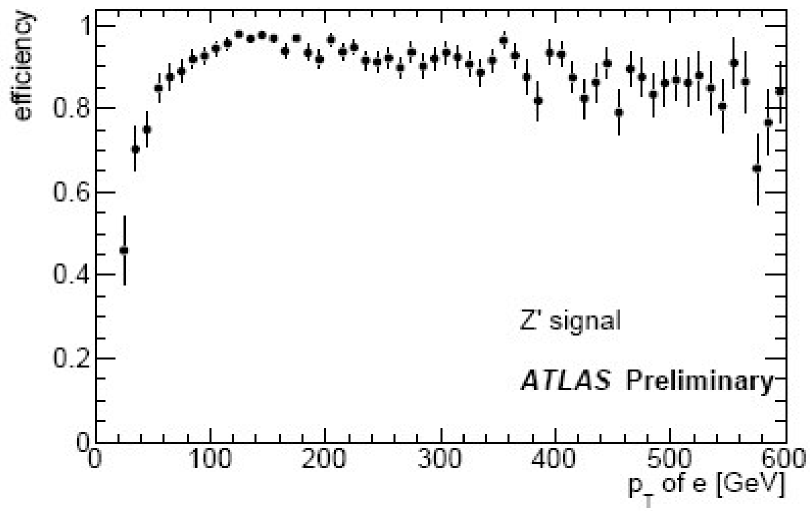
## Tagging of the muon top jet

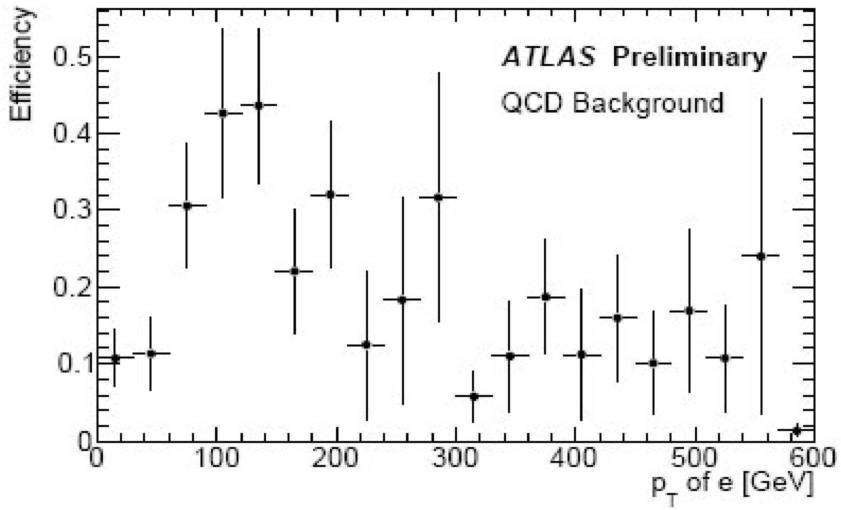


## Tagging of the electron top jet



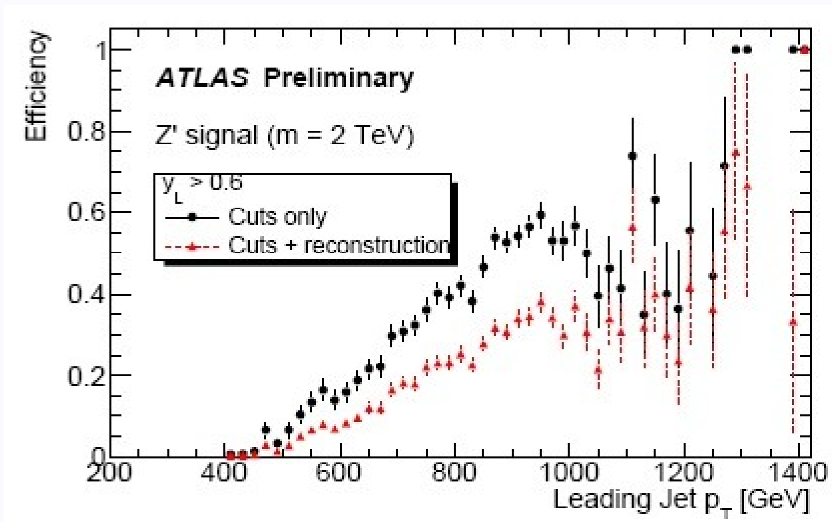



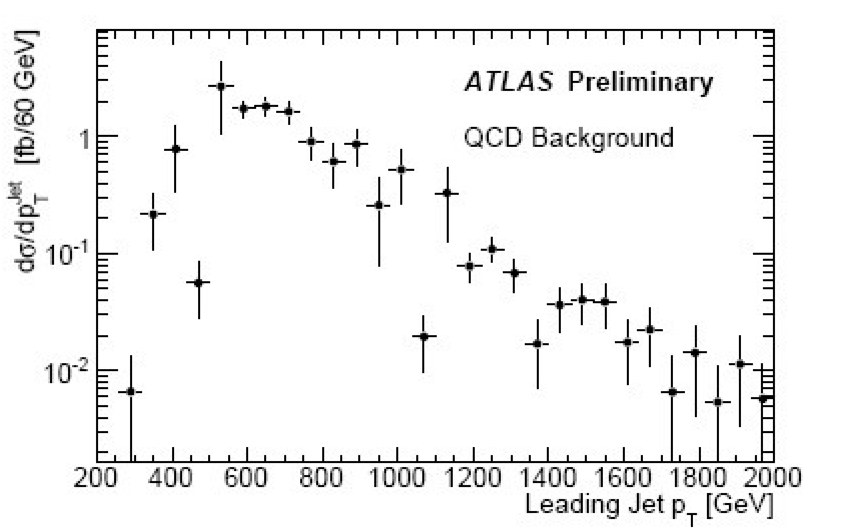



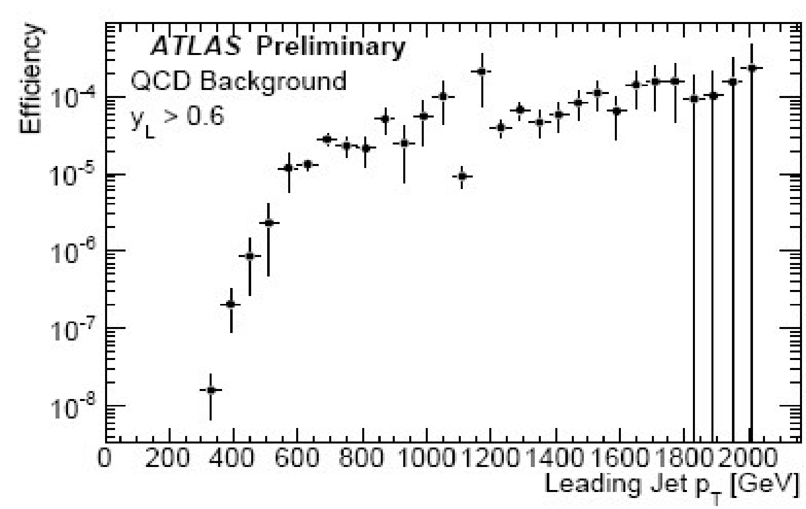
# High-mass resonances: semi-leptonic

**√s = 14 TeV/ L = 100 pb⁻¹**

## Final performance after tagging one hadronic and one leptonic top jet



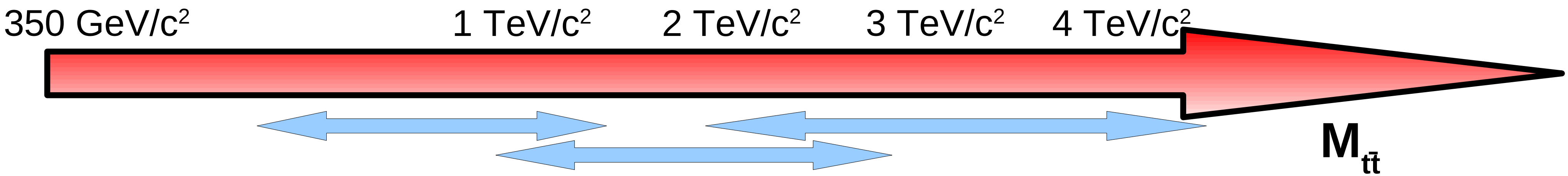




| Model | 95% C.L $\sigma \cdot$ BR (pb) |
|---|---|
| **Z'(2 TeV)** | **0.55** |
| **Z'(3 TeV)** | **0.16** |

# Summary of sensitivity

**Expected limits on σxBR(Z'→$t\bar{t}$)**




| Channels | 0.75 TeV/$c^2$ | 1 TeV/$c^2$ | 2 TeV/$c^2$ | 3 TeV/$c^2$ | 4 TeV/$c^2$ |
|---|---|---|---|---|---|
| Low mass (l+j) | **16.1** | **8.9** | 8.3 | | |
| High mass (l+j)* | | **7.5** | **2.9** | 0.64 | |
| High mass (2 t-jets) | | 17.2 | **1.5** | **0.7** | **0.8** |

*: L=200 $pb^{-1}$

**CMS::Expected limits @ 95% CL - $\sqrt{s}$ = 10 TeV - L = 100 $pb^{-1}$**

| Channels | 0.75 TeV/$c^2$ | 1 TeV/$c^2$ | 2 TeV/$c^2$ | 3 TeV/$c^2$ | 4 TeV/$c^2$ |
|---|---|---|---|---|---|
| High mass (2 t-jets) | | | **0.55** | **0.16** | |

**ATLAS::Expected limits @ 95% CL - $\sqrt{s}$ = 14 TeV - L = 1 $fb^{-1}$**

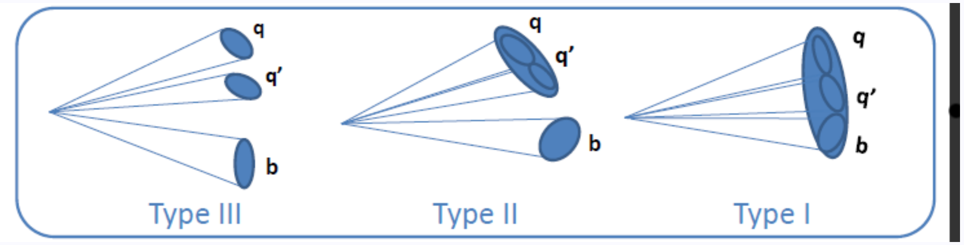
| Channels | 0.70 TeV/$c^2$ | 1 TeV/$c^2$ | 2 TeV/$c^2$ | 3 TeV/$c^2$ | 4 TeV/$c^2$ |
|---|---|---|---|---|---|
| Low mass (l+j) | **10** | **7** | | | |

**ATLAS::5 σ discovery - $\sqrt{s}$ = 14 TeV - L = 1 $fb^{-1}$**

# Perspectives

**Center-of-mass energy:**

Results presented @ 10/14 TeV.
No public results yet @ 7 TeV




**New developments:**

- CMS: Top-tagging: cut windows depending on jet $p_T$
- ATLAS: scanning combinations of known variables for optimal top tagging
- CMS/ATLAS: Handle the transition region between non boosted and boosted

**Activity on data:**

Focus on data-driven estimation of backgrounds, fake rate (top-tagging)

**Coverage of the channels:**

- Semi-leptonic & fully-hadronic channels are covered
- Di-leptonic channel could extend the list
- A combination of the channels within the experiment might be envisaged

**Extension of the searches:**

- Focused on $t\bar{t}$ resonances
- Can be extended to 1 top-tagged + X (higher energy & luminosity)

# Conclusions

- Both ATLAS & CMS experiment prepared a strategy to probe new physics with boosted top
- First approach is to look for resonances in the $m_{tt}$ spectrum
- Several techniques are used to cover the full spectrum
  - From standard jet reconstruction to top-tagging technique
  - From loose isolated lepton to lepton in a jet
- Data-driven methods to estimate backgrounds were developed
- L=1 $fb^{-1}$ @ 7 TeV might already reveals new phenomena
- A increase of energy will then open a new window on new physics where boosted top will play an important role