# Search for VBF $H \longrightarrow \tau\tau$ in CMS with 1 $\mathrm{fb}^{-1}$ and commissioning of the particle-flow with data

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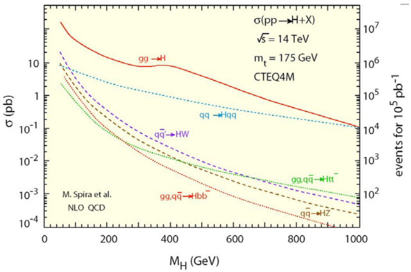
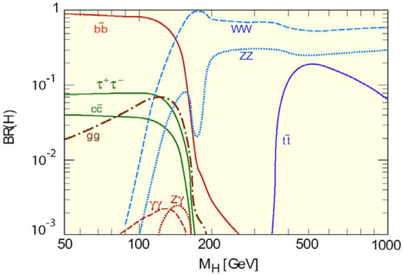
# Outline

1. Search for the Standard Model $H \rightarrow \tau\tau$ in weak boson fusion (VBF) at the LHC.
2. The VBF $H \rightarrow \tau\tau \rightarrow l + \tau_{jet}$ channel in CMS: strategies with 1 $\mathrm{fb}^{-1}$.
3. Commissioning of the particle-flow event reconstruction with the December 2009 data at $\sqrt{s} = 900$ GeV.
4. Conclusions and future plans.

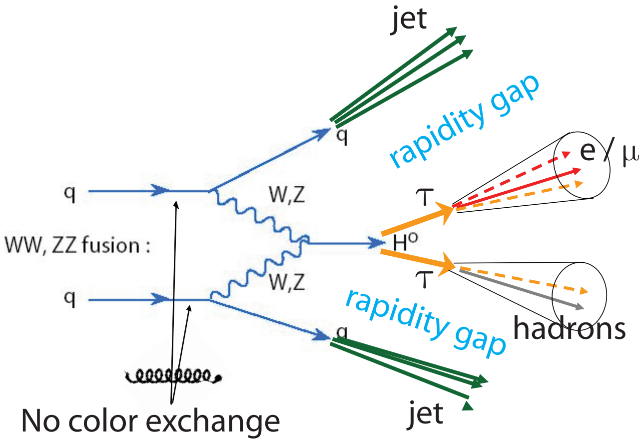
# Why VBF $H \rightarrow \tau\tau \rightarrow l + \tau_{jet}$?





- At the LHC: $\sigma\left(qqH\right) \approx 0.1 \cdot \sigma\left(pp \rightarrow H + X\right)$;
- $3\% < \mathrm{BR}\left(H \rightarrow \tau\tau\right) < 7\%$ for $115 < m_H < 145$ GeV;
- $\mathrm{BR}\left(\tau\tau \rightarrow l + \tau_{jet}\right) \approx 2 \cdot \mathrm{BR}\left(\tau \rightarrow e\right) \mathrm{BR}\left(\tau \rightarrow \text{hadrons}\right) \sim 45\%$;
- $l + \tau_{jet} \Rightarrow$ trigger efficiency;
- $\epsilon\left(\tau\mathrm{ID}\right) > 45\% \rightleftharpoons$ QCD $\tau$ fake-rate $< 2\%$;

# The VBF $H \rightarrow \tau\tau \rightarrow l + \tau_{jet}$ signature



- two forward jets from the interacting quarks, with large $\eta$ separation;
- one lepton plus tau-jet in the central region;
- suppressed central hadron activity due to lack of color exchange between the scattering quarks.

# Search for VBF $H \rightarrow \tau\tau \rightarrow l + \tau_{jet}$ at a hadron collider

- Signal: 1 isolated lepton ($e$ or $\mu$) $+$ 1 tau-jet $+ \geq 2$ jets $+ \vec{E}_T^{miss}$.
- Mass of the tau-pair ($M_{\tau\tau}$) $\Rightarrow$ sensitive to the presence of the Higgs boson.
- Two main sources of SM background:
  - physics background: (QCD+EWK) $Z \rightarrow \tau\tau +$ jets;
  - reducible background: $W +$ jets, QCD multi-jets, $t\bar{t}$, $\gamma +$ jets;
- Use the VBF signature and di-tau constraints as a handle to suppress the background via a cut-based event selection:

at least two jets (e.g. $p_T > 30$ GeV/$c$) in opposite emispheres, with large rapidity separation and invariant mass (e.g. $|\Delta\eta| > 4,\ m_{jj} > 500$ GeV/$c^2$),
veto on extra-jets between the tag jets (e.g. $E_T^{extra\ jet} < 20$ GeV),
physical reconstruction of $M_{\tau\tau}$ (e.g. collinear approximation valid, $m_T\,(l, MET) < 40$ GeV/$c^2$).

# Search for VBF $H \to \tau\tau \to l + \tau_{jet}$ in CMS

- Strategies for the VBF $H \to \tau\tau \to l + \tau_{jet}$ channel with 1 $\text{fb}^{-1}$ at $\sqrt{s} = 14$ TeV can be found in **CMS PAS HIG-08-008**.
- Data-driven modeling of the $M_{\tau\tau}$ spectrum:
  - $Z \to \tau\tau$: from real $Z \to \mu\mu$ events with $\tau$ *embedding* (and with only marginal systematics);
  - QCD: from data, using ABCD methods on OS/SS samples;
  - $W$ and $t\bar{t}$: from their leptonic channels with $\tau$ embedding (for real taus), from MC simulation and measured tau fake-rates (otherwise);
  - $\tau$-ID efficiency: from $Z \to \tau\tau$ events with $\sim 5\%$ systematic;
  - $\tau$ fake-rate: from $Z$ + jets ($Z \to \mu\mu$) with 10% systematic;
  - $e$,$\mu$ trigger&offline efficiencies, $e \to \tau$ fake-rate: from $Z \to ee$ with $< 1\%$ systematic using tag-and-probe.
  - Jet veto for $Z \to \tau\tau$: from $Z \to \mu\mu$ events with 5% systematic.
  - JES and MET scale: from $\gamma$+jet and/or QCD di-jets, with $\sim 5\%$ systematic.

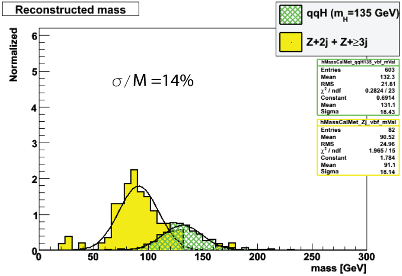
# Search for VBF $H \longrightarrow \tau\tau$ at CMS in the particle-flow language

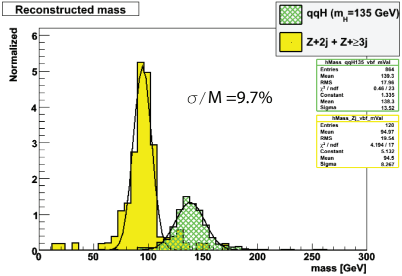
- We have revisited the perspective studies on the VBH channel incorporating a new technique for the global event reconstruction recently developed by the CMS Collaboration: it is known as particle-flow (**PAS PFT-09-001**).
- On top of this new technology:
    1. optimization of the analysis reach (fine-tuning the selection cuts against the background),
    2. improvement on the di-tau reconstruction efficiency (*rescue algorithm* for events failing the collinear approximation).
- You can find all details in **AN-2010/073**.

# Partcle-flow objects Vs calo-objects

- Particle-flow $\Leftrightarrow$ global (*i.e.* unique and complete) event description at the level of the single reconstructed and identified particles exploiting in an optimal way the redundancy of the CMS detectors.
- Better peformances on $\vec{E}_T^{miss} = -\sum_i^{all\ particles} \vec{p}_T^{\,i}$ (in both magnitude and direction), as well as on jets and taus.

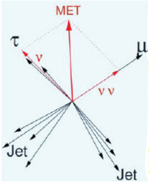
$\Rightarrow$ direct impact on $M_{\tau\tau}$.

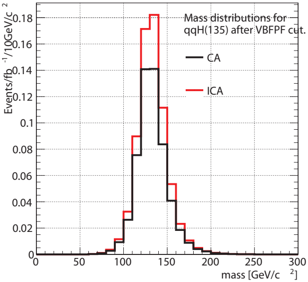




# Improving the collinear approximation

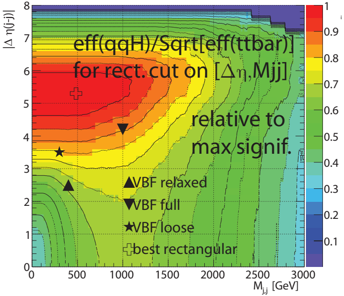
- If $\vec{p}_\nu \propto \vec{p}_\tau$: $p_\mu^{\tau\tau}$ from a parallelogram construction.
- If $\vec{E}_T^{miss}$ lies outside the "parallelogram" $\Rightarrow$ *unphysical* $E_\nu < 0$ solutions.
- For not *back-to-back* taus, this may happen when $E^T_{\nu_\tau} >> (<<) \, E^T_{\nu_\tau + \nu_l}$; we *rescue* the event assuming $E_T^{miss} = E^T_{\nu_\tau} \; (E^T_{\nu_\tau + \nu_l})$.
- Use $Z \rightarrow \tau\tau$ to correct the residual *underestimation*.
- Up to 30% more signal events.

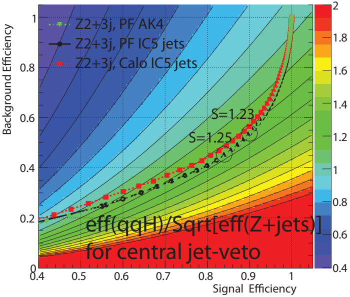




# Fine-tuning of the cut-flow

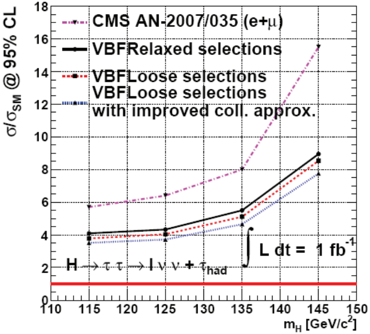
- Need for further requirements to characterize the VBF process;
- Rectangular-cuts on the kinematics of the tag jets are quasi-optimal againts $Z/W+$jets. The central jet-veto can be relaxed to increase the signal efficiency at no price for the significance.

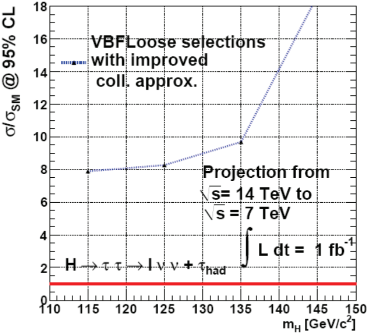




# Exclusion limits and projection for $\sqrt{s} = 7$ TeV

- Exclusion limits at 95% c.l. for the combined $e + \mu$ channel using the CLs method.



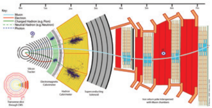


# Commissioning of the particle-flow at $\sqrt{s} = 900$ GeV

- With 1 $\text{fb}^{-1}$ of integrated luminosity, the particle-flow event reconstruction will be fully optimized and commissioned, thus providing powerful analysis tools;
- The first collisions delivered by the LHC at $\sqrt{s} = 900$ GeV, and recorded by CMS in December 2009, already served for a succesful commissioning of the building bricks of the algorithm. In the next months we expect to complete and re-commission the particle-flow at the higher c.o.m energy.

In the following, I will show show some results from the recent commissioning paper of the particle-flow **PAS PFT-10-001** with the purpose of giving a basic idea of the algorithm and to stress the excellent data/simulation agreement.

# The work-flow



calo/tracker/muons hits

clustering/tracking

clusters-tracks linking

Pflow blocks

reconstruction
+
identification

Pflow particles

- isolation deposits
- taus
- MET
- jets
- ....

# Commissionig of the link algorithm

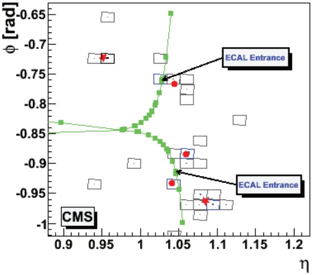


Figure: $\eta - \phi$ view of two charged tracks all their way to ECAL.

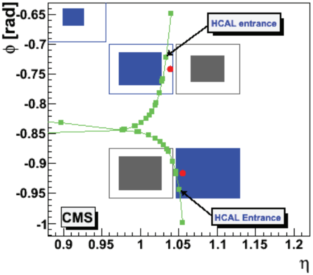


Figure: $\eta - \phi$ view of two charged tracks all their way to HCAL.

$$p_T^{track} = 14.64\ \text{GeV/c} \rightarrow \text{calibrated } E_{ECAL+HCAL} = 14.33\ \text{GeV};$$
$$p_T^{track} = 10.94\ \text{GeV/c} \rightarrow \text{calibrated } E_{ECAL+HCAL} = 9.19\ \text{GeV}.$$

# Energy calibration

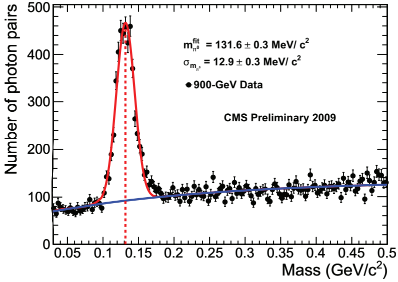


Figure: $\pi^0$ mass plots. All PF photons with $|\eta| < 1$ and $E > 400$ MeV are paired. The mass peak is only $\sim 2\%$ smaller than the world average.

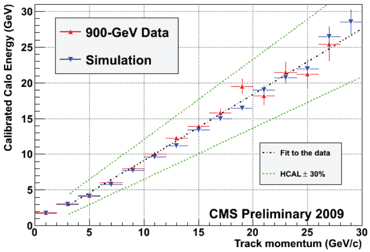


Figure: Average calibrated calorimeter response as a function of the track momentum. Linear fit: $(0.920 \pm 0.037)$

- For the energy-scales probed so far, the calibration is adequate within 2% (5%) for ECAL (HCAL).

# Commissioning of the particle-flow jets

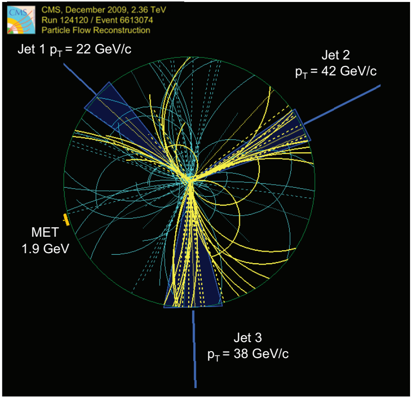


Figure: PF event at $\sqrt{s} = 2.36$ TeV: the small recorded $E_T^{miss}$ (1.9 GeV) validates the PF reconstruction

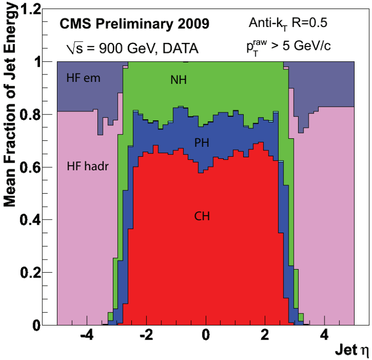


Figure: Fractional components of PF jets measured at $\sqrt{s} = 900$ GeV.

# Performances on $E_T^{miss}$ and $\sum E_T$

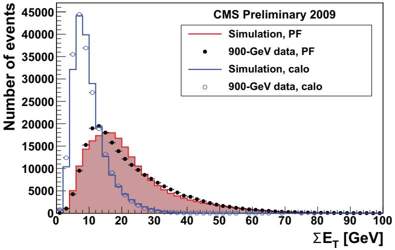


Figure: Distribtion of the particle-based and calo-based $\sum E_T$.

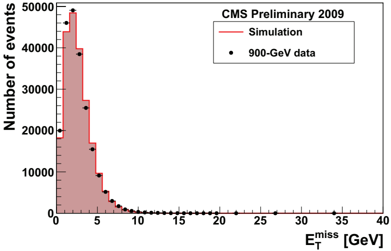


Figure: Distribtion of the particle-based $E_T^{miss}$.

- $\sum E_T$: scalar sum of all particles transverse momenta ⇒ measures the overall energy scale of the event;
- $\vec{E}_T^{miss}$: the missing transverse energy ⇒ expected to be zero in the minimum-bias sample.

# Particle-based isolation and tau fake-rate

- Isolation requirements are often applied in physics analysis as a handle to suppress the QCD background.
- In the PF language: isolation parametrized in terms of "particles": photons, charged, neutral hadrons.
- Throwing *random cones* in the $(\eta, \phi)$ plane to measure isolation efficiency;
- Isolation variables are a key element inside the tau-ID algorithm. PF taus fake-rate in the minimum-bias sample has been measured, and a satisfactory agreement data-simulation is found.

# Particle-based isolation and tau fake-rate

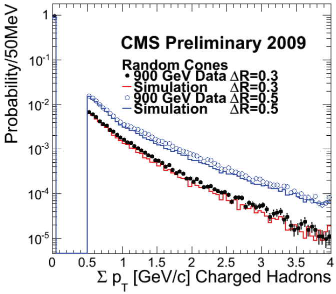


Figure: $\sum p_T$ of charged hadrons inside a cone of radius $\Delta R = 0.3$ (0.5) around random directions.

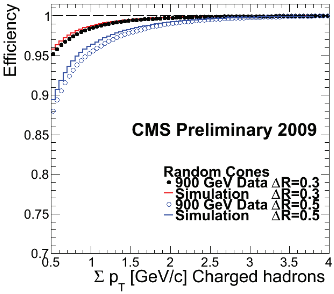


Figure: Isolation efficiency with respect to charged hadrons as a function of the cut on $\sum p_T$.

- Only charged hadrons with $p_T > 500$ MeV/c are considered. The same plots for neutrals and photons show the same level of agreement.

# Particle-based isolation and tau fake-rate

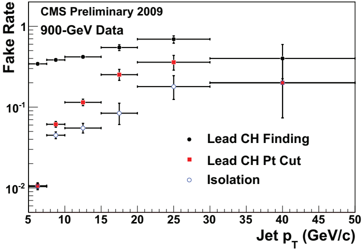


Figure: Cumulative efficiencies for tau selection and identification as a function of the tau jet $p_T$ (data).

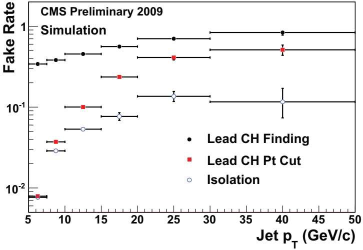


Figure: Cumulative efficiencies for tau selection and identification as a function of the tau jet $p_T$ (simulation).

# Conclusions and future plans

- The search for the SM Higgs boson produced in vector boson fusion and decaying to a tau-pair in the lepton plus tau-jet channel is definitely feasible at the LHC.
- For the Higgs mass in the range $\left(115\ \mathrm{GeV}/c^2, 145\ \mathrm{GeV}/c^2\right)$, $\sim 30\ \mathrm{fb}^{-1}$ are needed for discovery.
- We have discussed search strategies for $1\ \mathrm{fb}^{-1}$ showing that the observability will benefit from both the use of the PF and an optimized selection of the events.

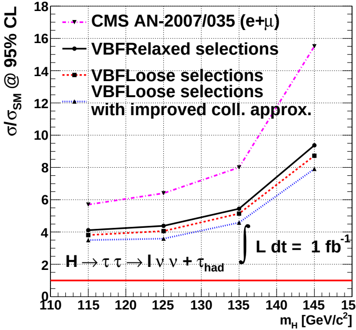
What next?

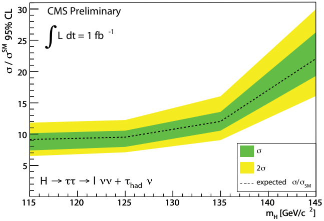
- Commissioning of the PF muons, electrons, jets and $E_T^{miss}$ from EW candles at $\sqrt{s} = 7$ TeV;
- Study the QCD multi-jets events in the VBF-like phase space (most affected by theoretical uncertainties);
- Get involved in the first $Z \to \tau\tau$ CMS paper expected by the end of 2010 (main physics background to the $H \to \tau\tau$ search) which strongly relies on mastering $Z$+jets with $Z \to 2e/2\mu$. .

# Back-up

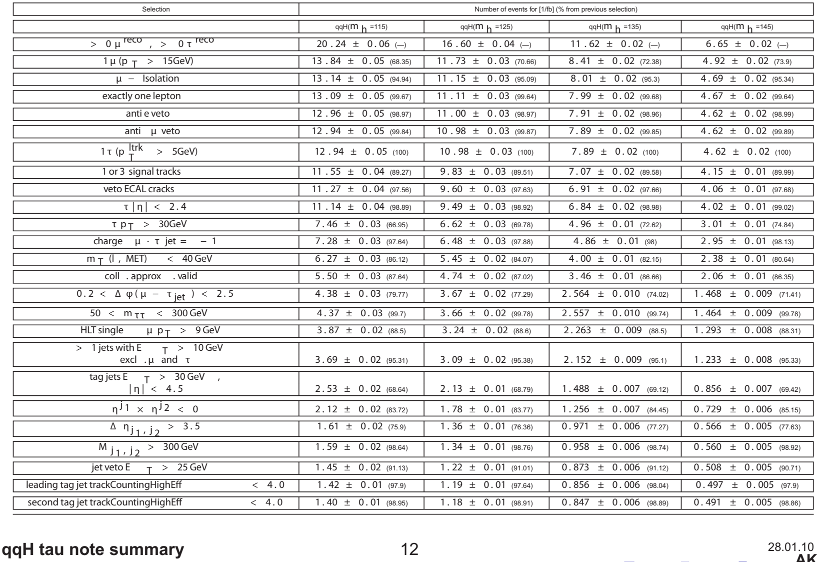
# Exclusions limits

- Exclusion limits at 95% c.l. for the combined $e + \mu$ channel using the CLs method.
- $M_{\tau\tau}$ templates from separate Monte Carlo samples.
- Comparison with the previous analysis, systematics on the right plot.





# Yields for *qqH*



| Selection | Number of events for [1/fb] (% from previous selection) | | | |
|---|---|---|---|---|
| | qqH($m_h$=115) | qqH($m_h$=125) | qqH($m_h$=135) | qqH($m_h$=145) |
| $> 0\ \mu^{reco}, > 0\ \tau^{reco}$ | 20.24 ± 0.06 (—) | 16.60 ± 0.04 (—) | 11.62 ± 0.02 (—) | 6.65 ± 0.02 (—) |
| $1\ \mu\ (p_T > 15$GeV) | 13.84 ± 0.05 (68.35) | 11.73 ± 0.03 (70.66) | 8.41 ± 0.02 (72.38) | 4.92 ± 0.02 (73.9) |
| $\mu -$ Isolation | 13.14 ± 0.05 (94.94) | 11.15 ± 0.03 (95.09) | 8.01 ± 0.02 (95.3) | 4.69 ± 0.02 (95.34) |
| exactly one lepton | 13.09 ± 0.05 (99.67) | 11.11 ± 0.03 (99.64) | 7.99 ± 0.02 (99.68) | 4.67 ± 0.02 (99.64) |
| anti e veto | 12.96 ± 0.05 (98.97) | 11.00 ± 0.03 (98.97) | 7.91 ± 0.02 (98.96) | 4.62 ± 0.02 (98.99) |
| anti $\mu$ veto | 12.94 ± 0.05 (99.84) | 10.98 ± 0.03 (99.87) | 7.89 ± 0.02 (99.85) | 4.62 ± 0.02 (99.89) |
| $1\ \tau\ (p_T^{ltrk} > 5$GeV) | 12.94 ± 0.05 (100) | 10.98 ± 0.03 (100) | 7.89 ± 0.02 (100) | 4.62 ± 0.02 (100) |
| 1 or 3 signal tracks | 11.55 ± 0.04 (89.27) | 9.83 ± 0.03 (89.51) | 7.07 ± 0.02 (89.58) | 4.15 ± 0.01 (89.99) |
| veto ECAL cracks | 11.27 ± 0.04 (97.56) | 9.60 ± 0.03 (97.63) | 6.91 ± 0.02 (97.66) | 4.06 ± 0.01 (97.68) |
| $\tau\ \|\eta\| < 2.4$ | 11.14 ± 0.04 (98.89) | 9.49 ± 0.03 (98.92) | 6.84 ± 0.02 (98.98) | 4.02 ± 0.01 (99.02) |
| $\tau\ p_T > 30$GeV | 7.46 ± 0.03 (66.95) | 6.62 ± 0.03 (69.78) | 4.96 ± 0.01 (72.62) | 3.01 ± 0.01 (74.84) |
| charge $\mu \cdot \tau$ jet $= -1$ | 7.28 ± 0.03 (97.64) | 6.48 ± 0.03 (97.88) | 4.86 ± 0.01 (98) | 2.95 ± 0.01 (98.13) |
| $m_T$ (l, MET) $<$ 40 GeV | 6.27 ± 0.03 (86.12) | 5.45 ± 0.02 (84.07) | 4.00 ± 0.01 (82.15) | 2.38 ± 0.01 (80.64) |
| coll. approx. valid | 5.50 ± 0.03 (87.64) | 4.74 ± 0.02 (87.02) | 3.46 ± 0.01 (86.66) | 2.06 ± 0.01 (86.35) |
| $0.2 < \Delta\varphi(\mu - \tau_{jet}) < 2.5$ | 4.38 ± 0.03 (79.77) | 3.67 ± 0.02 (77.29) | 2.564 ± 0.010 (74.02) | 1.468 ± 0.009 (71.41) |
| $50 < m_{\tau\tau} < 300$ GeV | 4.37 ± 0.03 (99.7) | 3.66 ± 0.02 (99.78) | 2.557 ± 0.010 (99.74) | 1.464 ± 0.009 (99.78) |
| HLT single $\mu\ p_T > 9$ GeV | 3.87 ± 0.02 (88.5) | 3.24 ± 0.02 (88.6) | 2.263 ± 0.009 (88.5) | 1.293 ± 0.008 (88.31) |
| $>$ 1 jets with $E_T > 10$ GeV<br>excl. $\mu$ and $\tau$ | 3.69 ± 0.02 (95.31) | 3.09 ± 0.02 (95.38) | 2.152 ± 0.009 (95.1) | 1.233 ± 0.008 (95.33) |
| tag jets $E_T > 30$ GeV,<br>$\|\eta\| < 4.5$ | 2.53 ± 0.02 (68.64) | 2.13 ± 0.01 (68.79) | 1.488 ± 0.007 (69.12) | 0.856 ± 0.007 (69.42) |
| $\eta^{j1} \times \eta^{j2} < 0$ | 2.12 ± 0.02 (83.72) | 1.78 ± 0.01 (83.77) | 1.256 ± 0.007 (84.45) | 0.729 ± 0.006 (85.15) |
| $\Delta\eta_{j_1,j_2} > 3.5$ | 1.61 ± 0.02 (75.9) | 1.36 ± 0.01 (76.36) | 0.971 ± 0.006 (77.27) | 0.566 ± 0.005 (77.63) |
| $M_{j_1,j_2} > 300$ GeV | 1.59 ± 0.02 (98.64) | 1.34 ± 0.01 (98.76) | 0.958 ± 0.006 (98.74) | 0.560 ± 0.005 (98.92) |
| jet veto $E_T > 25$ GeV | 1.45 ± 0.02 (91.13) | 1.22 ± 0.01 (91.01) | 0.873 ± 0.006 (91.12) | 0.508 ± 0.005 (90.71) |
| leading tag jet trackCountingHighEff $< 4.0$ | 1.42 ± 0.01 (97.9) | 1.19 ± 0.01 (97.64) | 0.856 ± 0.006 (98.04) | 0.497 ± 0.005 (97.9) |
| second tag jet trackCountingHighEff $< 4.0$ | 1.40 ± 0.01 (98.95) | 1.18 ± 0.01 (98.91) | 0.847 ± 0.006 (98.89) | 0.491 ± 0.005 (98.86) |

**qqH tau note summary** 12 28.01.10

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# Yields for $Z$+jets

| Selection | Number of events for [1/fb] (% from previous selection) | | |
|---|---|---|---|
| | Z1j | Z2j | Z3j |
| $> 0\ \mu^{reco}$, $> 0\ \tau^{reco}$ | 8796 ± 10 (—) | 2627.8 ± 3.6 (—) | 1018.6 ± 1.4 (—) |
| 1 $\mu$ ($p_T > 15$GeV) | 4618.5 ± 7.5 (52.51) | 1447.6 ± 2.7 (55.09) | 603.8 ± 1.1 (59.27) |
| $\mu -$ Isolation | 4342.4 ± 7.3 (94.02) | 1352.9 ± 2.6 (93.46) | 561.2 ± 1.0 (92.95) |
| exactly one lepton | 4335.7 ± 7.3 (99.85) | 1349.5 ± 2.6 (99.75) | 559.1 ± 1.0 (99.63) |
| anti e veto | 4295.5 ± 7.3 (99.07) | 1337.0 ± 2.6 (99.07) | 553.3 ± 1.0 (98.96) |
| anti $\mu$ veto | 4288.6 ± 7.3 (99.84) | 1334.2 ± 2.6 (99.79) | 552.0 ± 1.0 (99.75) |
| 1 $\tau$ ($p_T^{ltrk} > 5$GeV) | 4288.6 ± 7.3 (100) | 1334.2 ± 2.6 (100) | 552.0 ± 1.0 (100) |
| 1 or 3 signal tracks | 3817.5 ± 6.8 (89.01) | 1163.2 ± 2.4 (87.18) | 473.2 ± 0.9 (85.73) |
| veto ECAL cracks | 3710.8 ± 6.7 (97.21) | 1131.6 ± 2.4 (97.28) | 459.9 ± 0.9 (97.18) |
| $\tau\ \|\eta\| < 2.4$ | 3685.2 ± 6.7 (99.31) | 1120.3 ± 2.4 (99.01) | 454.1 ± 0.9 (98.75) |
| $\tau\ p_T > 30$GeV | 1624.2 ± 4.5 (44.07) | 545.8 ± 1.7 (48.71) | 248.3 ± 0.7 (54.68) |
| charge $\mu \cdot \tau$ jet $= -1$ | 1579.3 ± 4.4 (97.24) | 523.3 ± 1.6 (95.88) | 236.1 ± 0.7 (95.08) |
| $m_T$ (l, MET) $< 40$ GeV | 1468.3 ± 4.2 (92.97) | 477.8 ± 1.5 (91.31) | 211.9 ± 0.6 (89.73) |
| coll. approx. valid | 1130.9 ± 3.7 (77.02) | 381.9 ± 1.4 (79.93) | 177.1 ± 0.6 (83.6) |
| $0.2 < \Delta\varphi(\mu - \tau_{jet}) < 2.5$ | 663.5 ± 2.9 (58.67) | 288.1 ± 1.2 (75.43) | 147.1 ± 0.5 (83.06) |
| $50 < m_{\tau\tau} < 300$ GeV | 657.8 ± 2.8 (99.14) | 283.6 ± 1.2 (98.45) | 144.2 ± 0.5 (98.04) |
| HLT single $\mu$ $p_T > 9$ GeV | 565.8 ± 2.6 (86.02) | 244.6 ± 1.1 (86.24) | 125.0 ± 0.5 (86.64) |
| $> 1$ jets with $E_T > 10$ GeV excl. $\mu$ and $\tau$ | 311.1 ± 2.0 (54.99) | 239.3 ± 1.1 (97.83) | 124.9 ± 0.5 (99.94) |
| tag jets $E_T > 30$ GeV, $\|\eta\| < 4.5$ | 6.2 ± 0.3 (2.003) | 134.8 ± 0.8 (56.34) | 109.7 ± 0.5 (87.8) |
| $\eta^{j1} \times \eta^{j2} < 0$ | 3.1 ± 0.2 (49.8) | 50.9 ± 0.5 (37.76) | 44.8 ± 0.3 (40.87) |
| $\Delta\eta_{j_1,j_2} > 3.5$ | 0.52 ± 0.08 (16.6) | 5.9 ± 0.2 (11.55) | 6.4 ± 0.1 (14.28) |
| $M_{j_1,j_2} > 300$ GeV | 0.38 ± 0.07 (73.81) | 5.1 ± 0.2 (86.79) | 6.0 ± 0.1 (93.72) |
| jet veto $E_T > 25$ GeV | 0.27 ± 0.06 (70.97) | 4.8 ± 0.2 (94.5) | 2.38 ± 0.07 (39.62) |
| leading tag jet trackCountingHighEff $< 4.0$ | 0.26 ± 0.06 (95.45) | 4.7 ± 0.2 (98.13) | 2.35 ± 0.07 (98.72) |
| second tag jet trackCountingHighEff $< 4.0$ | 0.26 ± 0.06 (100) | 4.7 ± 0.2 (98.62) | 2.32 ± 0.07 (98.71) |

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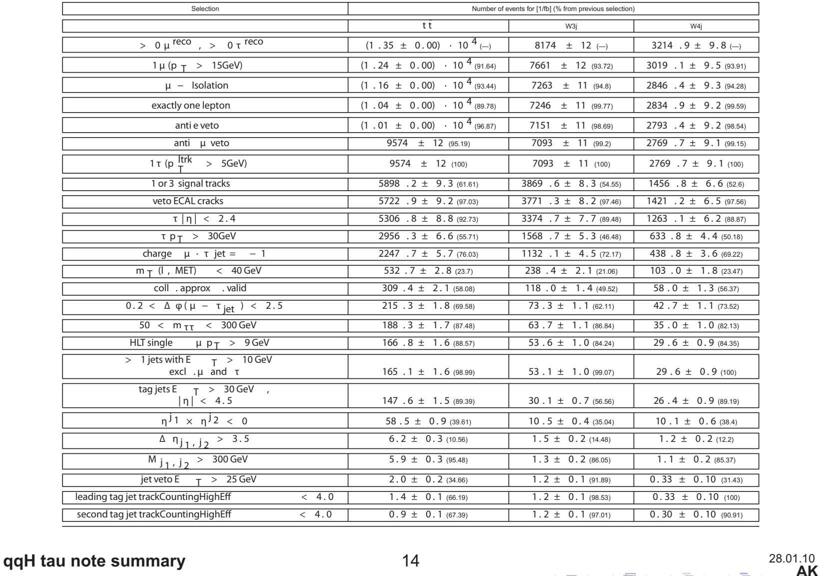
# Yields for $W$+jets and $t\bar{t}$



| Selection | Number of events for [1/fb] (% from previous selection) | | |
|---|---|---|---|
| | $t\bar{t}$ | W3j | W4j |
| $> 0\ \mu^{reco}$, $> 0\ \tau^{reco}$ | $(1.35 \pm 0.00) \cdot 10^4$ (—) | $8174 \pm 12$ (—) | $3214.9 \pm 9.8$ (—) |
| 1 μ ($p_T > 15$GeV) | $(1.24 \pm 0.00) \cdot 10^4$ (91.64) | $7661 \pm 12$ (93.72) | $3019.1 \pm 9.5$ (93.91) |
| μ − Isolation | $(1.16 \pm 0.00) \cdot 10^4$ (93.44) | $7263 \pm 11$ (94.8) | $2846.4 \pm 9.3$ (94.28) |
| exactly one lepton | $(1.04 \pm 0.00) \cdot 10^4$ (89.78) | $7246 \pm 11$ (99.77) | $2834.9 \pm 9.2$ (99.59) |
| anti e veto | $(1.01 \pm 0.00) \cdot 10^4$ (96.87) | $7151 \pm 11$ (98.69) | $2793.4 \pm 9.2$ (98.54) |
| anti μ veto | $9574 \pm 12$ (95.19) | $7093 \pm 11$ (99.2) | $2769.7 \pm 9.1$ (99.15) |
| 1 τ ($p_T^{ltrk} > 5$GeV) | $9574 \pm 12$ (100) | $7093 \pm 11$ (100) | $2769.7 \pm 9.1$ (100) |
| 1 or 3 signal tracks | $5898.2 \pm 9.3$ (61.61) | $3869.6 \pm 8.3$ (54.55) | $1456.8 \pm 6.6$ (52.6) |
| veto ECAL cracks | $5722.9 \pm 9.2$ (97.03) | $3771.3 \pm 8.2$ (97.46) | $1421.2 \pm 6.5$ (97.56) |
| τ $\lvert\eta\rvert < 2.4$ | $5306.8 \pm 8.8$ (92.73) | $3374.7 \pm 7.7$ (89.48) | $1263.1 \pm 6.2$ (88.87) |
| τ $p_T > 30$GeV | $2956.3 \pm 6.6$ (55.71) | $1568.7 \pm 5.3$ (46.48) | $633.8 \pm 4.4$ (50.18) |
| charge μ · τ jet = − 1 | $2247.7 \pm 5.7$ (76.03) | $1132.1 \pm 4.5$ (72.17) | $438.8 \pm 3.6$ (69.22) |
| $m_T$ (l, MET) < 40 GeV | $532.7 \pm 2.8$ (23.7) | $238.4 \pm 2.1$ (21.06) | $103.0 \pm 1.8$ (23.47) |
| coll. approx. valid | $309.4 \pm 2.1$ (58.08) | $118.0 \pm 1.4$ (49.52) | $58.0 \pm 1.3$ (56.37) |
| $0.2 < \Delta\varphi(\mu - \tau_{jet}) < 2.5$ | $215.3 \pm 1.8$ (69.58) | $73.3 \pm 1.1$ (62.11) | $42.7 \pm 1.1$ (73.52) |
| $50 < m_{\tau\tau} < 300$ GeV | $188.3 \pm 1.7$ (87.48) | $63.7 \pm 1.1$ (86.84) | $35.0 \pm 1.0$ (82.13) |
| HLT single μ $p_T > 9$ GeV | $166.8 \pm 1.6$ (88.57) | $53.6 \pm 1.0$ (84.24) | $29.6 \pm 0.9$ (84.35) |
| > 1 jets with $E_T > 10$ GeV excl. μ and τ | $165.1 \pm 1.6$ (98.99) | $53.1 \pm 1.0$ (99.07) | $29.6 \pm 0.9$ (100) |
| tag jets $E_T > 30$ GeV, $\lvert\eta\rvert < 4.5$ | $147.6 \pm 1.5$ (89.39) | $30.1 \pm 0.7$ (56.56) | $26.4 \pm 0.9$ (89.19) |
| $\eta^{j1} \times \eta^{j2} < 0$ | $58.5 \pm 0.9$ (39.61) | $10.5 \pm 0.4$ (35.04) | $10.1 \pm 0.6$ (38.4) |
| $\Delta\eta_{j1,j2} > 3.5$ | $6.2 \pm 0.3$ (10.56) | $1.5 \pm 0.2$ (14.48) | $1.2 \pm 0.2$ (12.2) |
| $M_{j1,j2} > 300$ GeV | $5.9 \pm 0.3$ (95.48) | $1.3 \pm 0.2$ (86.05) | $1.1 \pm 0.2$ (85.37) |
| jet veto $E_T > 25$ GeV | $2.0 \pm 0.2$ (34.66) | $1.2 \pm 0.1$ (91.89) | $0.33 \pm 0.10$ (31.43) |
| leading tag jet trackCountingHighEff < 4.0 | $1.4 \pm 0.1$ (66.19) | $1.2 \pm 0.1$ (98.53) | $0.33 \pm 0.10$ (100) |
| second tag jet trackCountingHighEff < 4.0 | $0.9 \pm 0.1$ (67.39) | $1.2 \pm 0.1$ (97.01) | $0.30 \pm 0.10$ (90.91) |

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