Status of LHC Experiments

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Outline

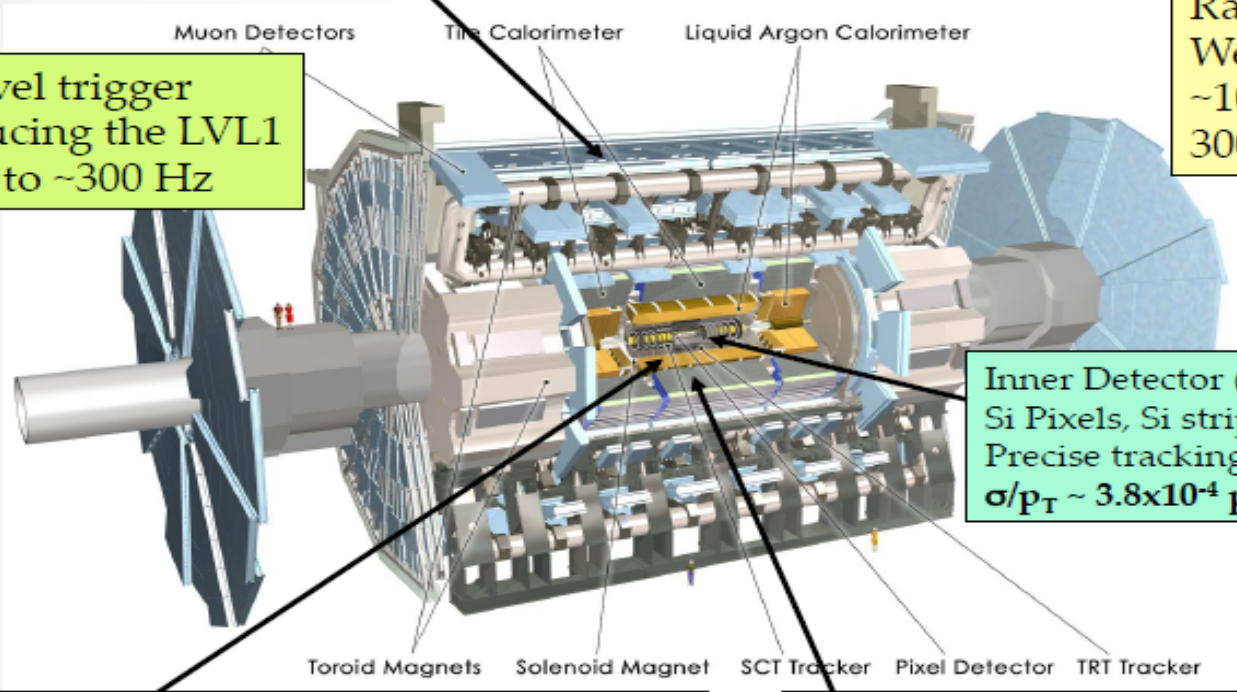
- ATLAS and CMS Detectors
- Performances in 2010 pp data
  - Detector subsystems
  - Object Reconstruction/Identification Tools
- Highlights of 2010 Physics Analyses
  - Electroweak & Top Physics
  - Higgs Searches
  - SUSY & New Physics Searches
  - Very few analyses are chosen here
- Summary & Outlook

A Toroidal LHC ApparatuS

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution **< 10% up to E_μ ~ 1 TeV**

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the LVL1 rate to ~300 Hz

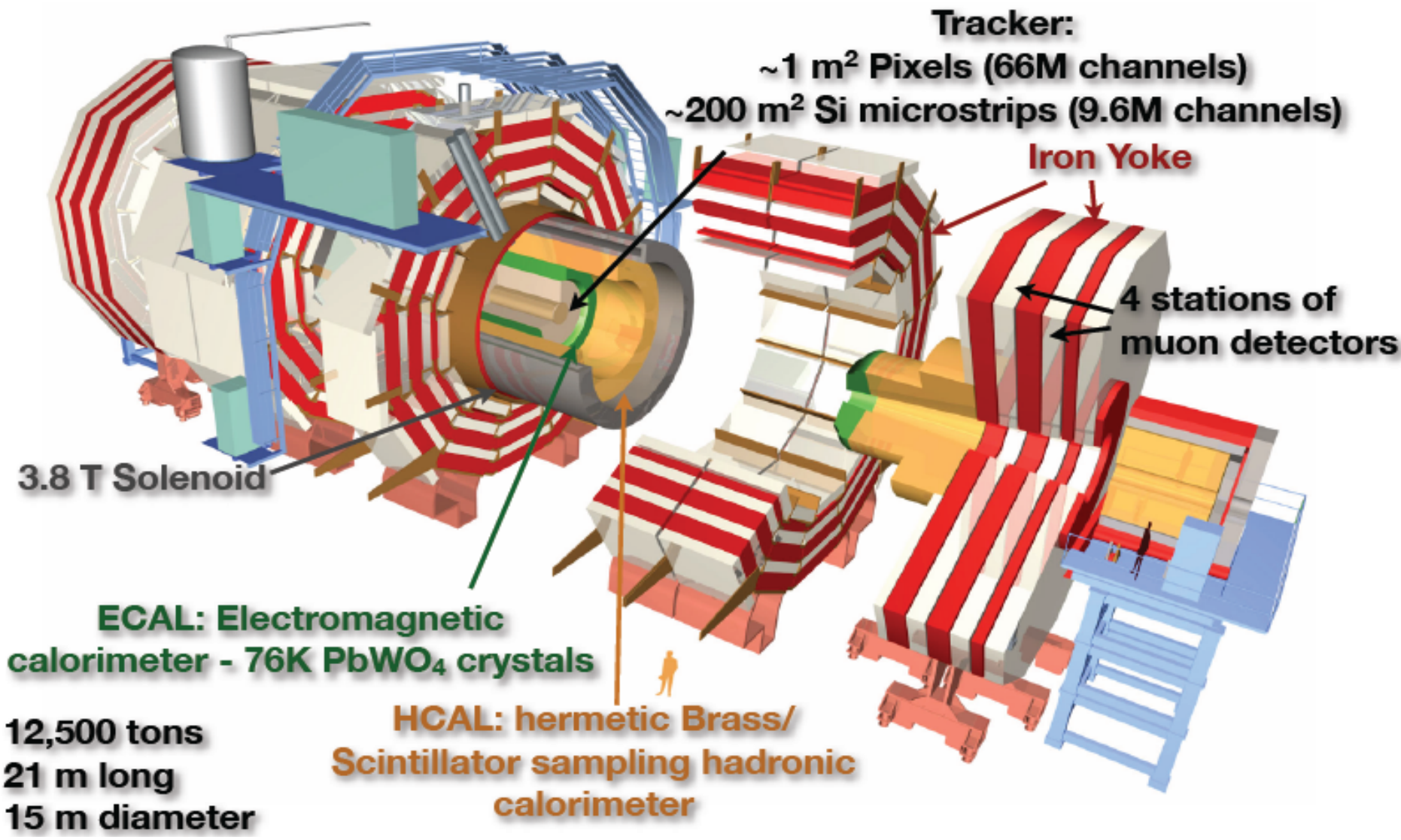


Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, TRT
Precise tracking and vertexing,
$\sigma/p_T \sim 3.8\times10^{-4}\ p_T\,(\mathrm{GeV}) \oplus 0.015$

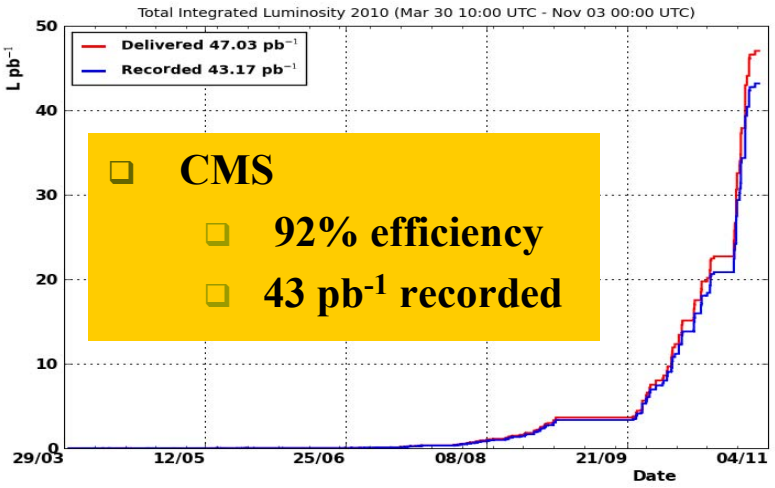
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.007$
High granularity

Hadron calorimetry ($|\eta|<4.9$)
Fe/scintillator Tiles (central), Cu-LAr (endcap)
E-resolution: **$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$**
FWD calorimetry:Cu/W-LAr **$\sigma/E \sim 90\%/\sqrt{E} \oplus 0.07$**

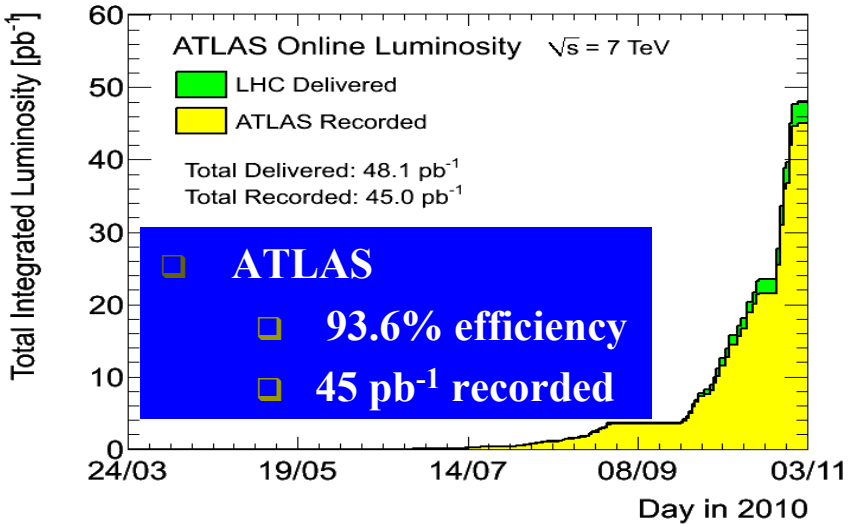
Compact Muon Solenoid



Luminosity for the pp collisions data



- CMS
  - 92% efficiency
  - 43 pb^{-1} recorded

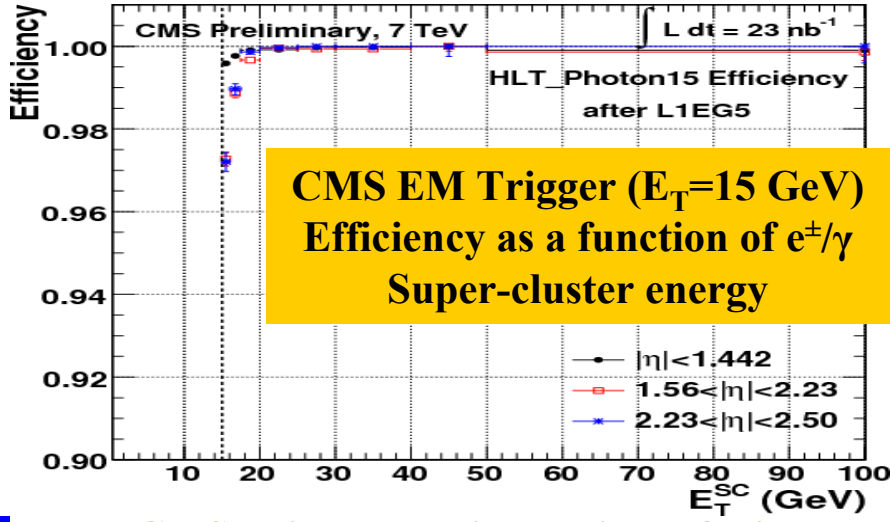


- ATLAS
  - 93.6% efficiency
  - 45 pb^{-1} recorded

2010 has been the most exciting & successful year in the history of LHC so far.

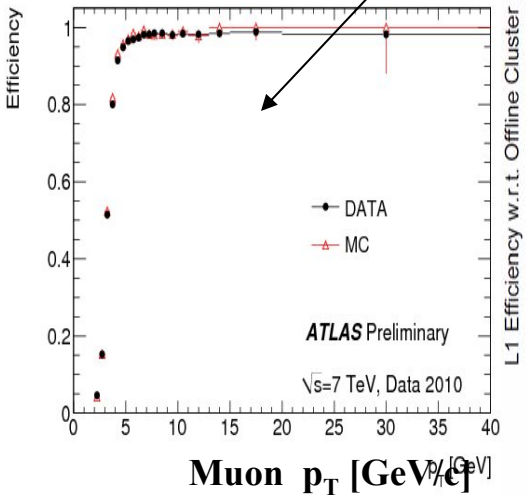
Triggers

- **Tri-level ATLAS Triggers**
  - **L1: Hardware based**
  - **L2 and HLT: Software**
- **Gradual evolution of the Trigger menu with the LHC luminosity increase**
  - **Recorded data @ 300 Hz in 2010**
  - **Performed quite efficiently in 2010**



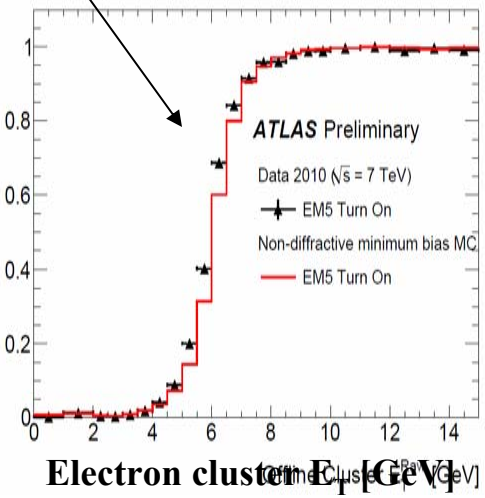
CMS EM Trigger (E_T=15 GeV) Efficiency as a function of $e^{\pm}/\gamma$ Super-cluster energy

ATLAS L2 Muon (4 GeV) Trigger Eff.



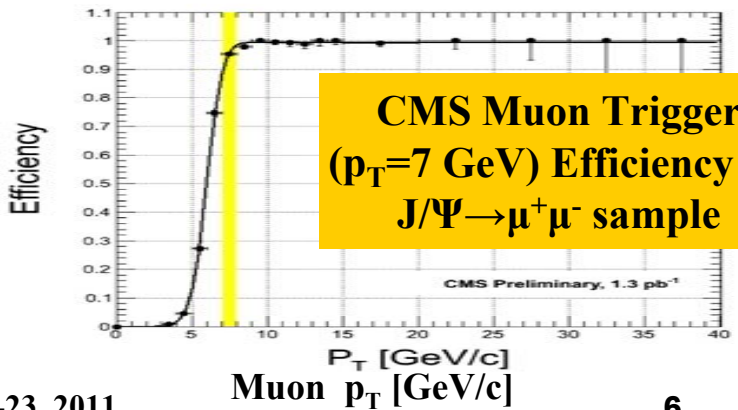
Muon p_T [GeV/c]

ATLAS L1 Electron (5 GeV) Trigger Eff.



Electron cluster E_T [GeV]

- **CMS Triggers – wide variety of triggers to support the CMS physics program.**
- **Recorded data @ 300 Hz in 2010 with highly efficient object selection.**



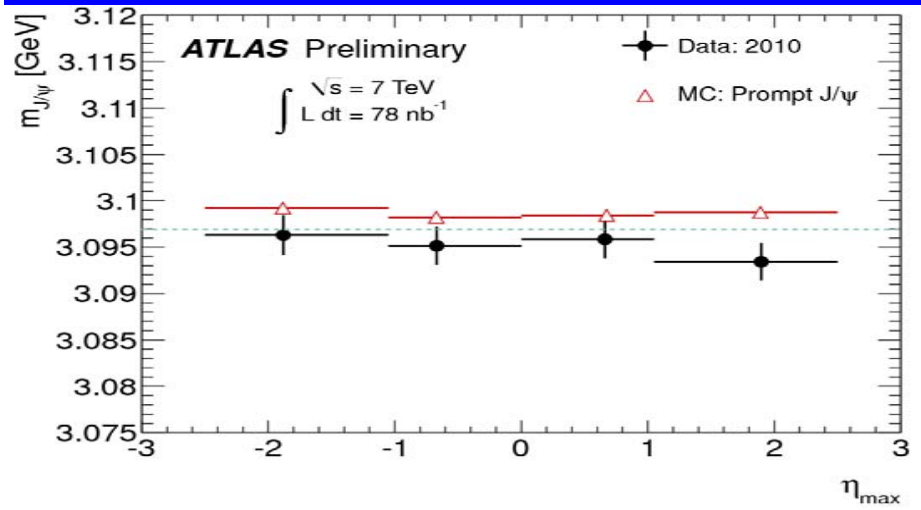
CMS Muon Trigger (p_T=7 GeV) Efficiency on $J/\Psi \rightarrow \mu^+\mu^-$ sample

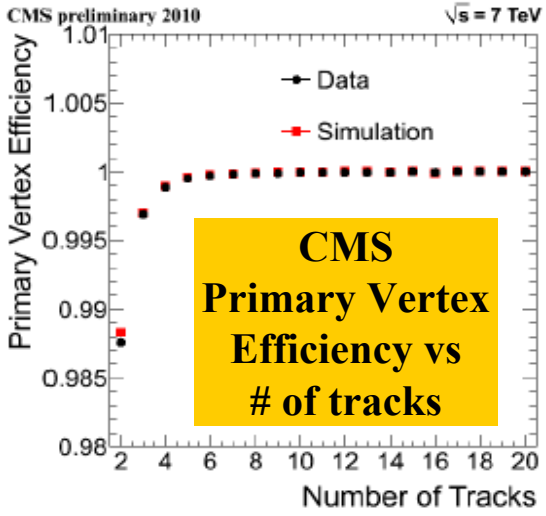
Muon p_T [GeV/c]

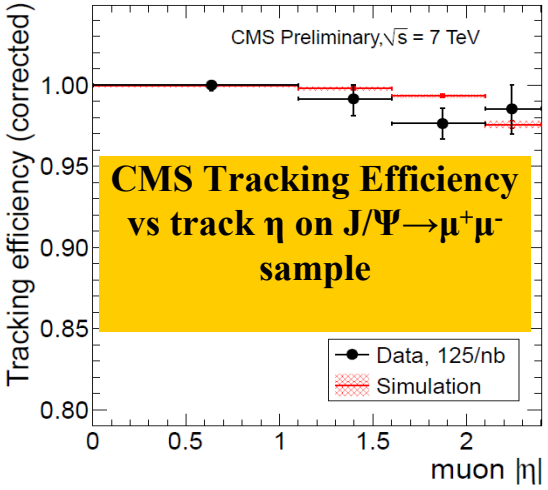
Tracker Performance

- Momentum scale has been tested to per mille level using the classic resonances
  - K_s, K*, φ, Λ, Ω, Ξ, D, D* and J/Ψ
- Good performance of Inner Detectors an tracking/vertexing algorithm
- Material mapping in the Inner Detector volume has been reasonably understood; scope for further improvement.

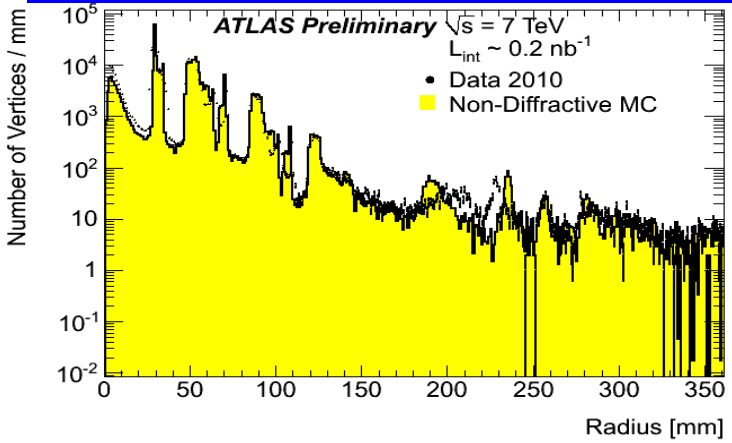
ATLAS J/Ψ→μ⁺μ⁻ Invariant mass vs muon η



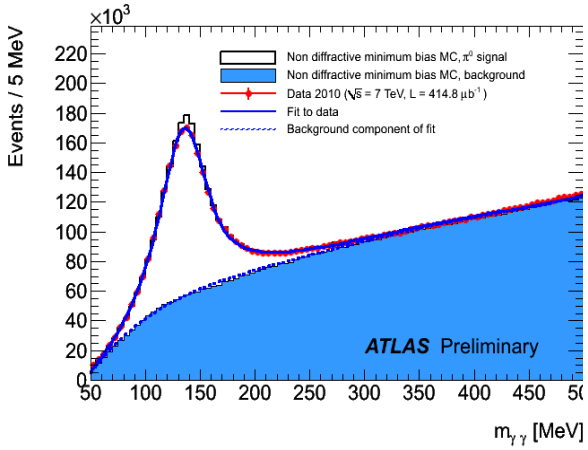


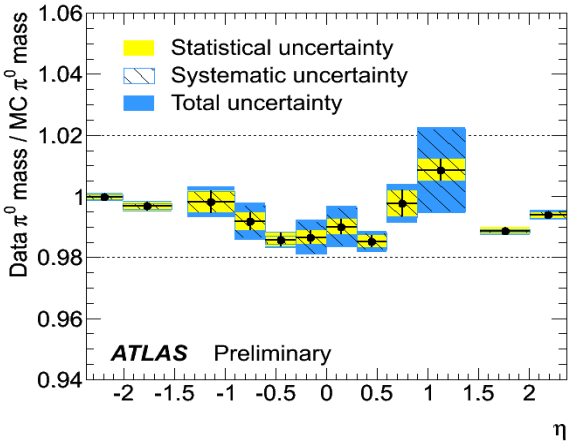


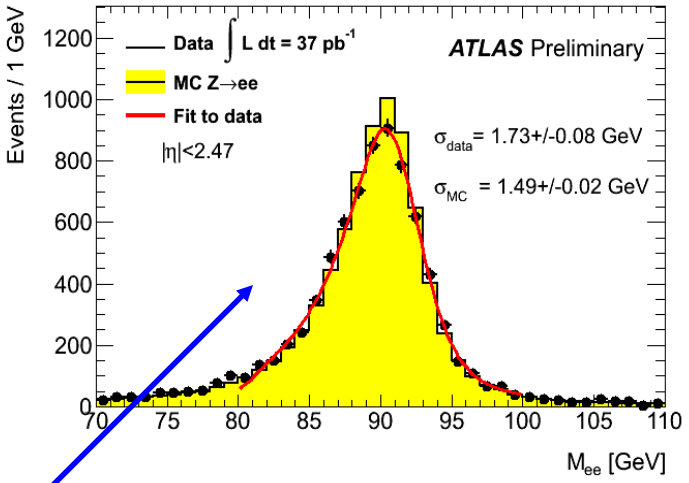
Number of reconstructed vertices in ATLAS Inner Detector volume



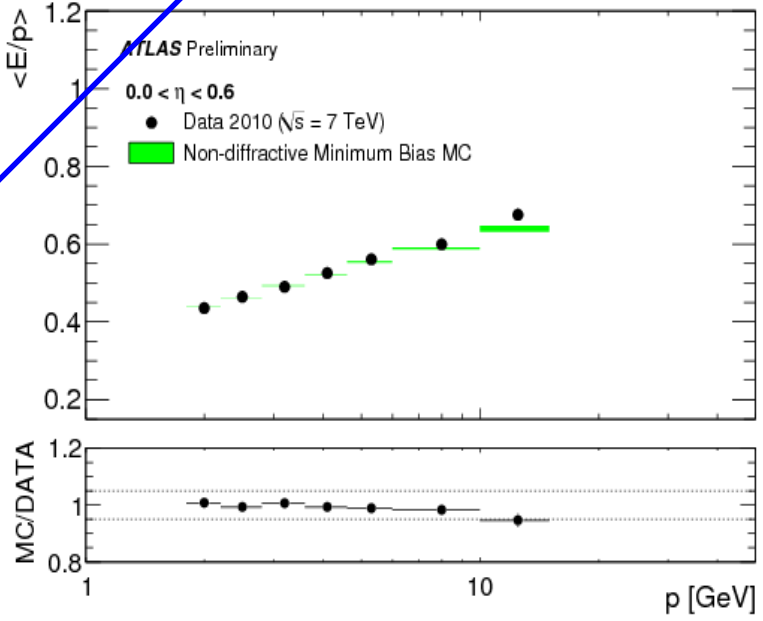
Calorimeter Performance



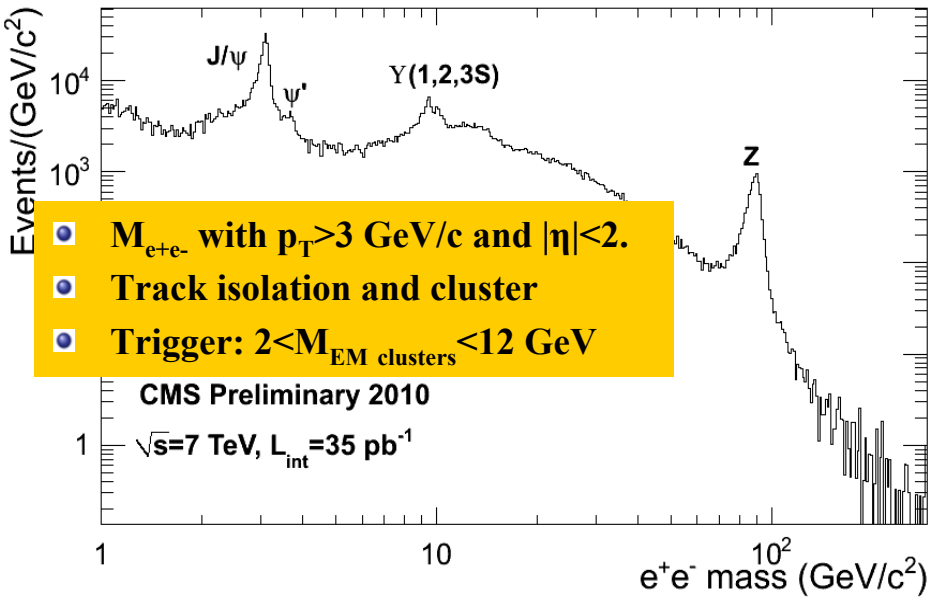




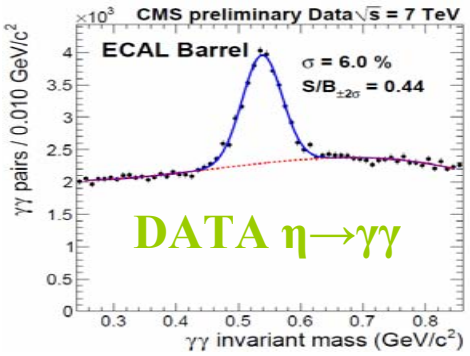
- **Very precise and stable Calibration & Monitoring**
- **Electromagnetic (EM) Energy Scale**
  - **Initial scale from the Test Beam data**
  - **Monitored/checked for uniformity with $\pi^0 \rightarrow \gamma\gamma$ (<0.7% in η and ~2% in φ)**
  - **Rescaled using $Z^0 \rightarrow e^+e^-$ events (1-2%)**
    - **Excellent linearity down to J/Ψ mass**
- **Calorimeter response of the single hadrons has been validated with 2010 collisions data.**

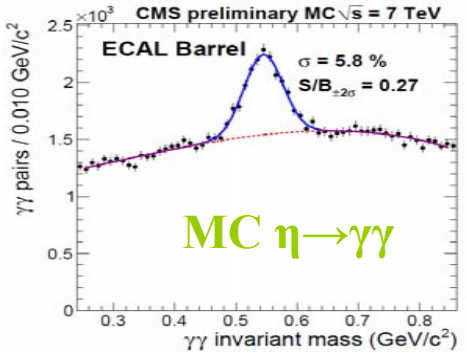


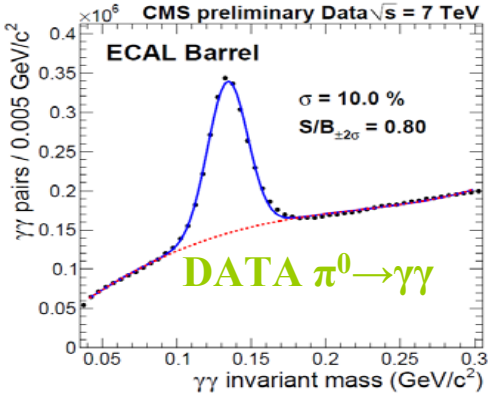
Calorimeter Performance

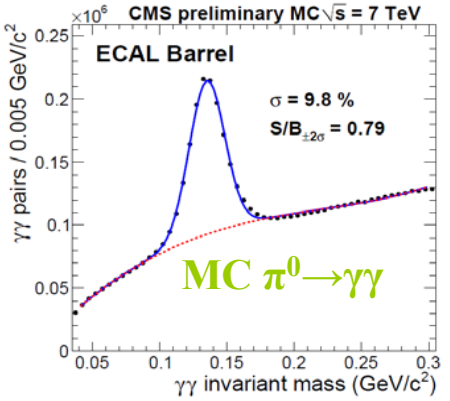


- M_{e+e-} with p_T>3 GeV/c and |η|<2.
- Track isolation and cluster
- Trigger: 2<$M_{EM\ clusters}$<12 GeV

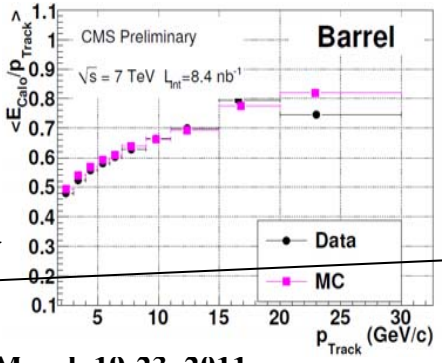


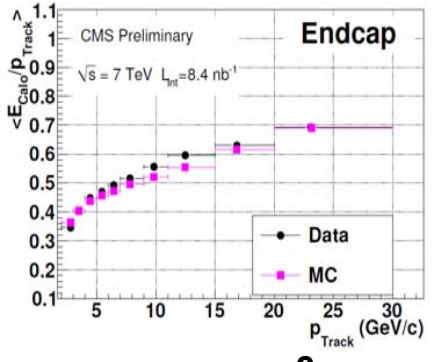






- **EM Energy Scale Strategy**
  - Initially from Test Beam (TB) constants
  - Φ-symmetric inter-calibration using minimum bias (MB) data at √s=7 TeV.
  - In-situ calibration using $\pi^0/\eta\rightarrow\gamma\gamma$ mass peaks
  - Total correction of 1-3% over TB constants
- **Single particle response to the Calorimeter is rechecked using on MB data.**

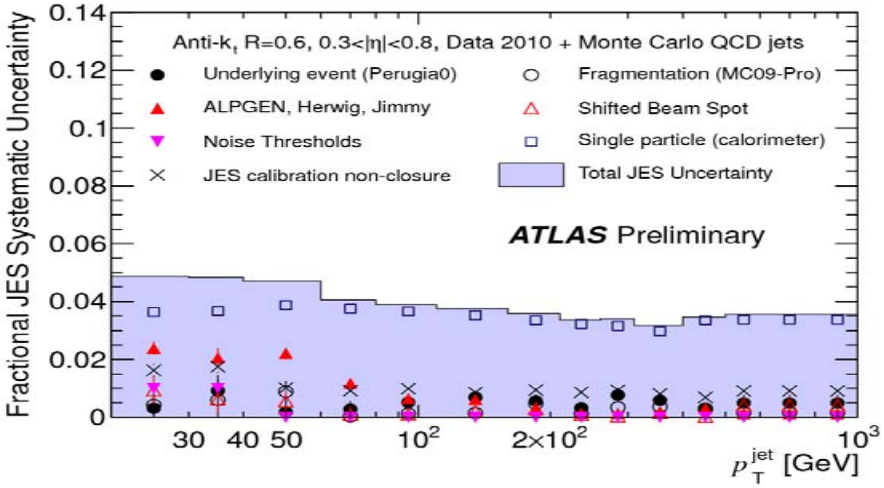




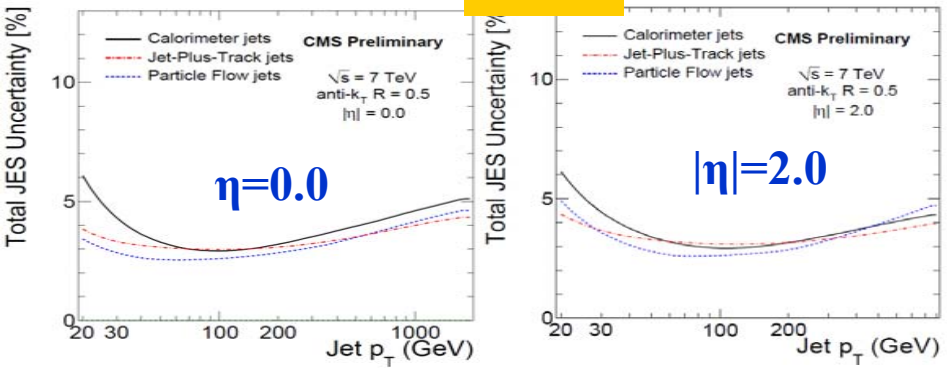
Jet Reconstruction & JES

ATLAS

- Calorimeter based jet reconstruction using energy calibrated topological clusters
- Jet Energy Scale (JES)
  - Initial corrections based on the simulation + Test Beam results.
  - Di-jet & γ+jets events for evaluation of systematic uncertainties
  - Future: In-situ calibration via Z^0-Boson and top events with a goal to reach 1% precision

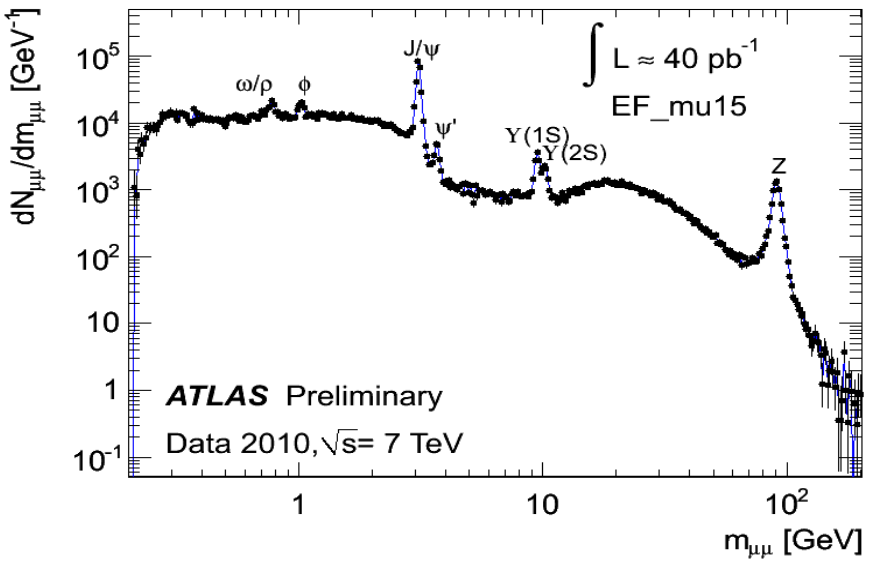


CMS



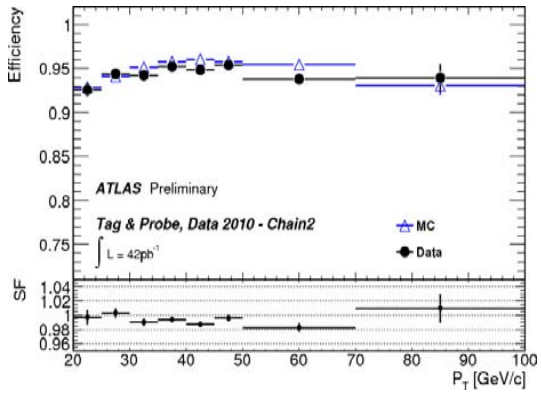
- Three different types for jets
  - Calorimeter only: "Calorimeter" jets
  - Calorimeter + Tracking: "Jet Plus Track" and "Particle-Flow" jets
- Jet Energy Scale with different precision
  - First calibrated using MC (tuned with Test Beam data)
  - "Residual" corrections using collisions data
    - di-jets events with relative η inter-calibration; γ+jets events for absolute energy-scale corrections

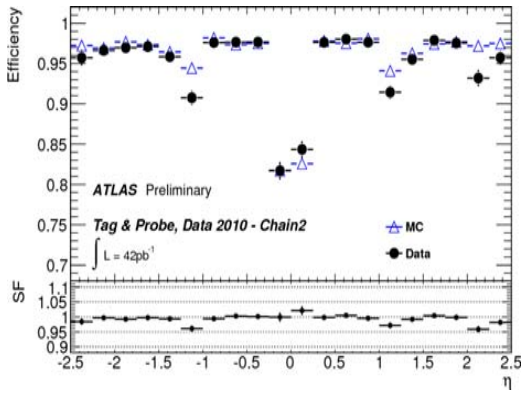
Combined Muon Performance

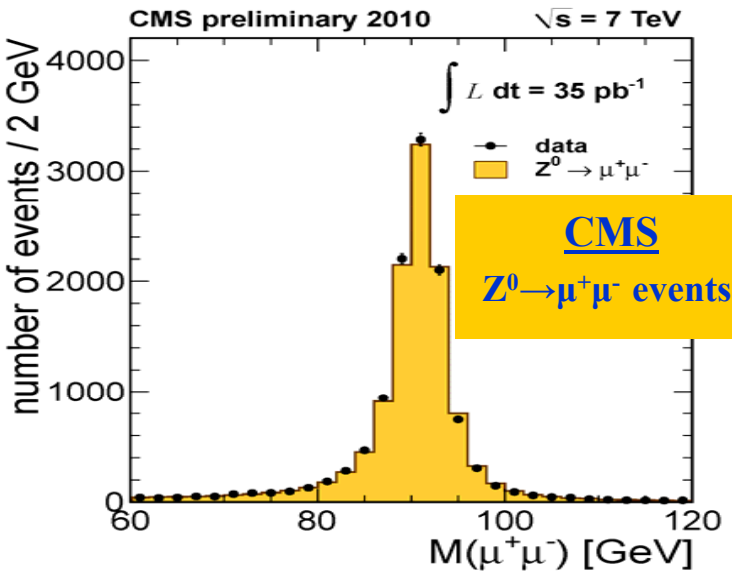


- **Muon Spectrometer (MS) together with the Inner Detectors (ID) are crucial for Muon identification**
  - **Combined muon momentum resolution is dominated by the ID measurements for tracks with p<50 GeV/c.**
  - **For high momenta tracks, ATLAS "MS-only" momentum resolution is compatible with the combined muon momentum resolution.**
  - **Checks for alignment, calibration, magnetic field and material description using $Z^0 \rightarrow \mu^+\mu^-$ events**

ATLAS Muon Identification Efficiency with "tag-and-probe" method in $Z^0 \rightarrow \mu^+\mu^-$ events

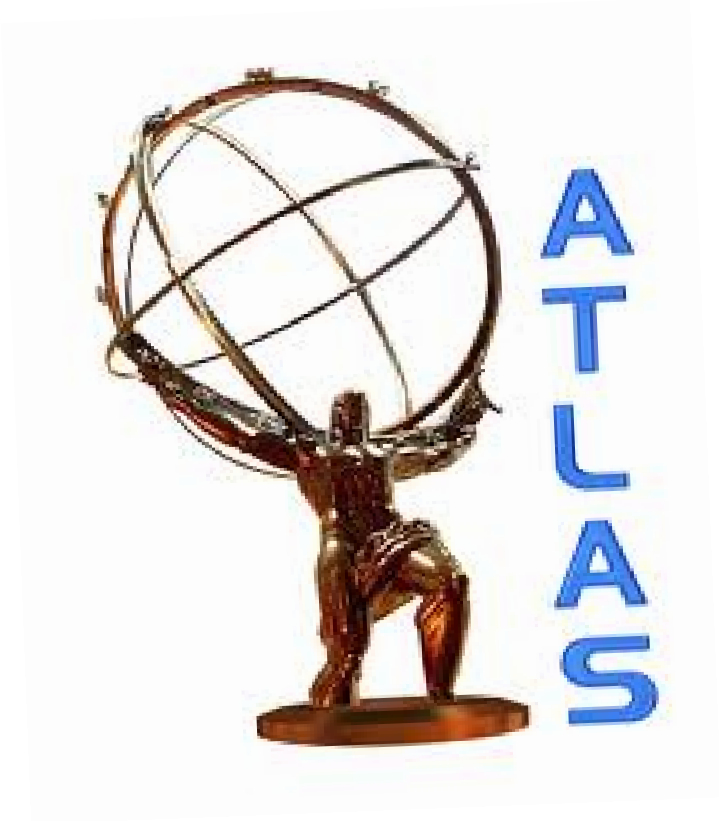


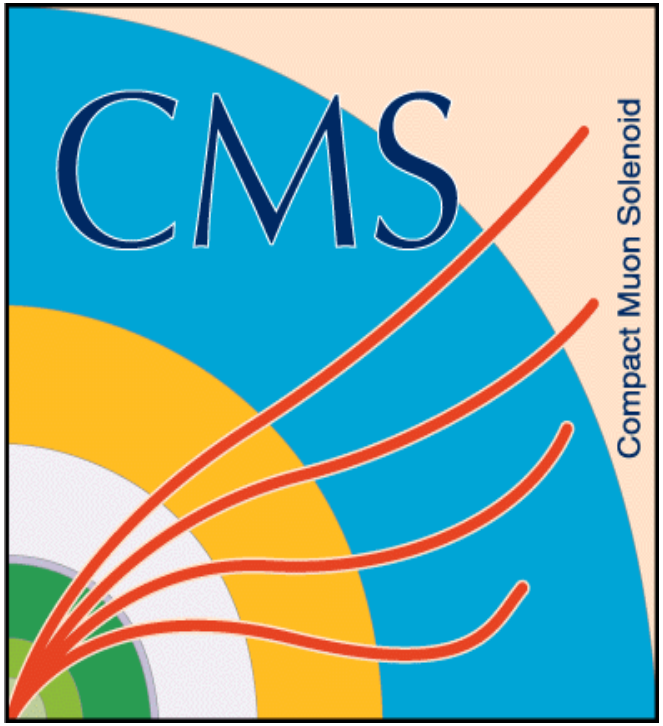




CMS
$Z^0 \rightarrow \mu^+\mu^-$ events

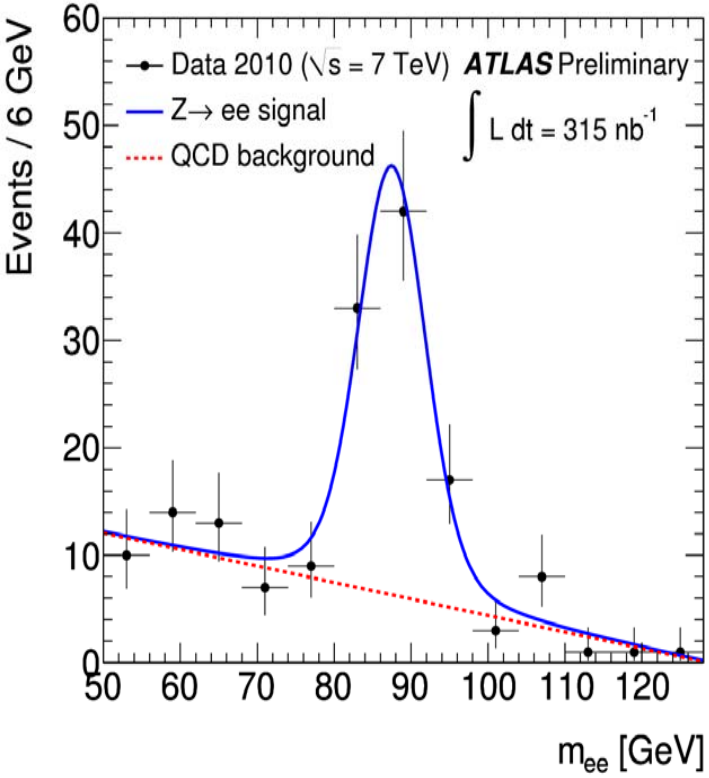
Highlights from ATLAS & CMS Physics Results

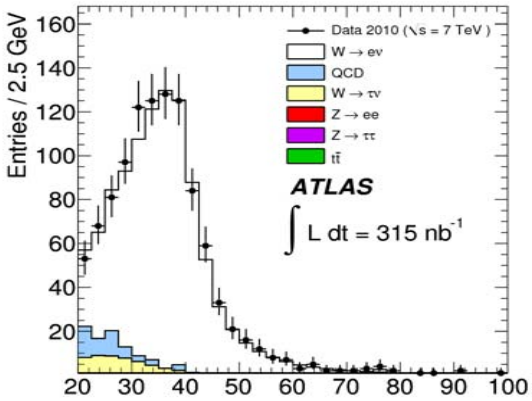




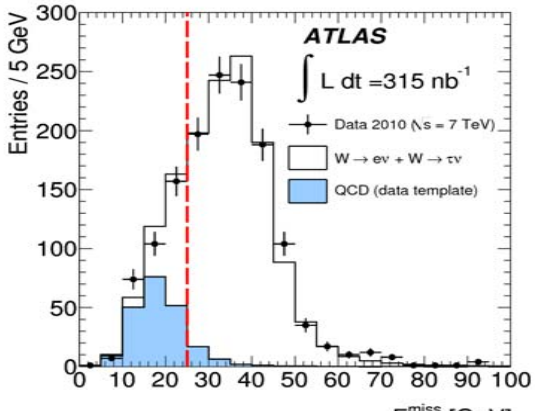
Physics with $W^{\pm}/Z^0$ bosons

- **$W^{\pm}(Z^0)$ observations**
  - **Production cross-sections are measured with 320 nb^{-1} of ATLAS data.**

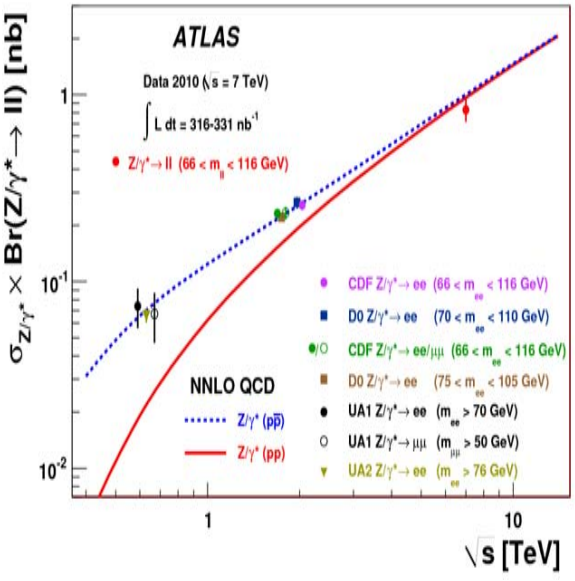


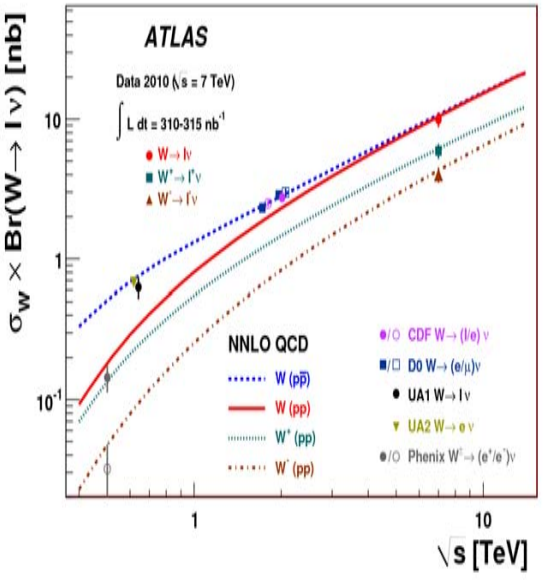


Electron E_T

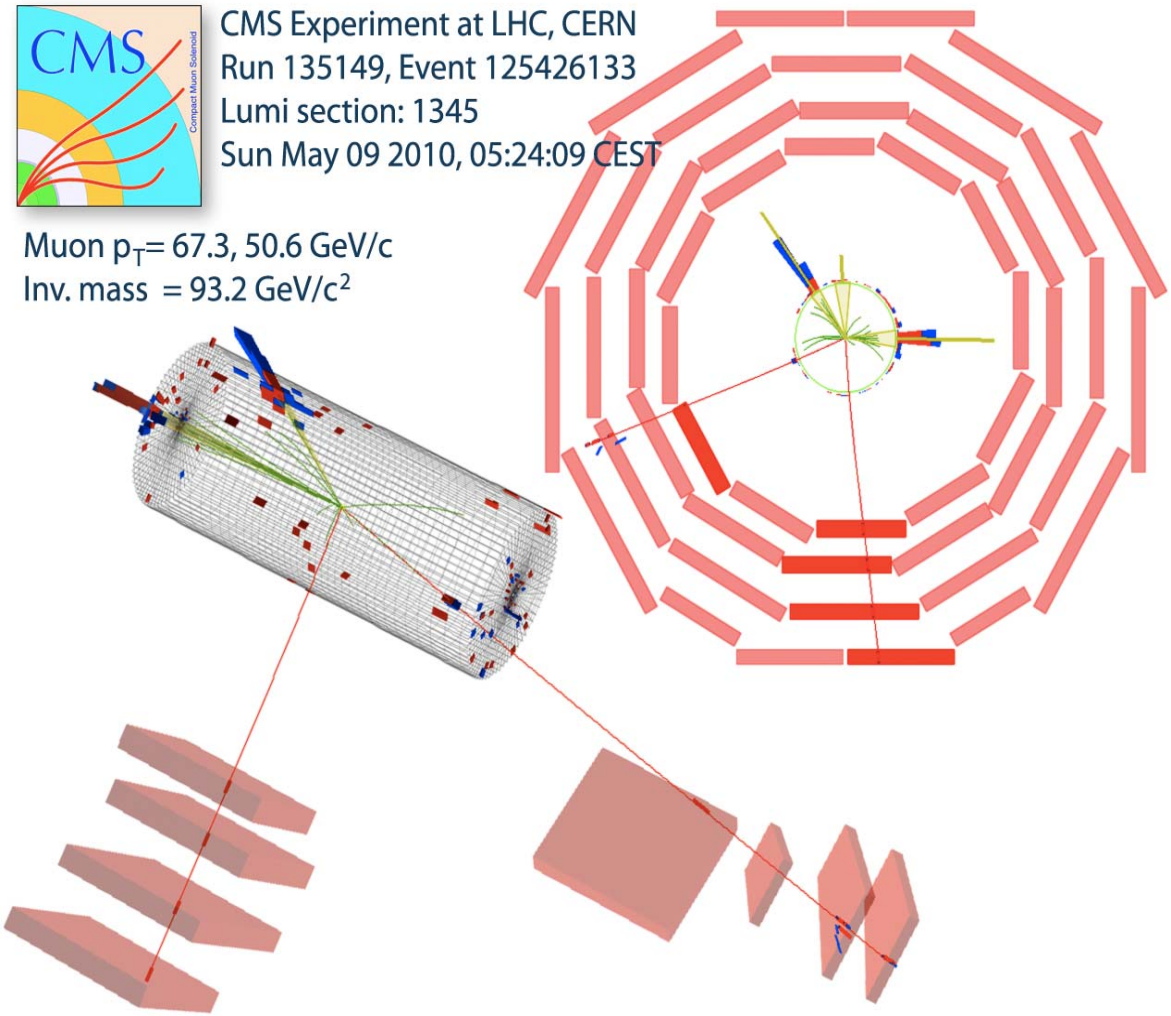


Missing E_T

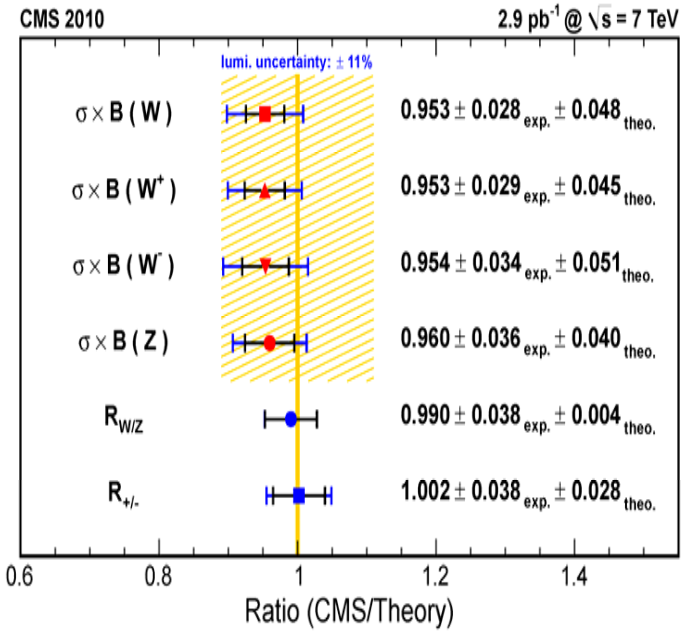




Physics with $W^{\pm}/Z^0$ bosons



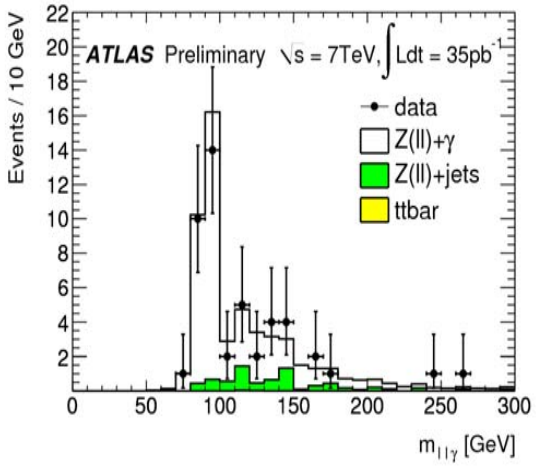
- **Measurement of $W^{\pm}$ (Z^0) production cross-sections by CMS with 198 nb^{-1} data**
  - **In good agreement with ATLAS measurements**

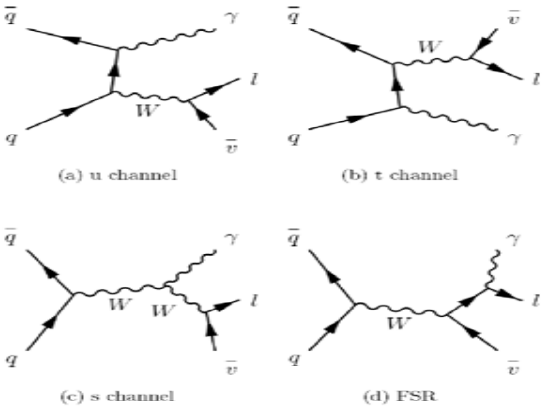


Dibosons –$W^{\pm}/Z^0+\gamma$, W^+W^-

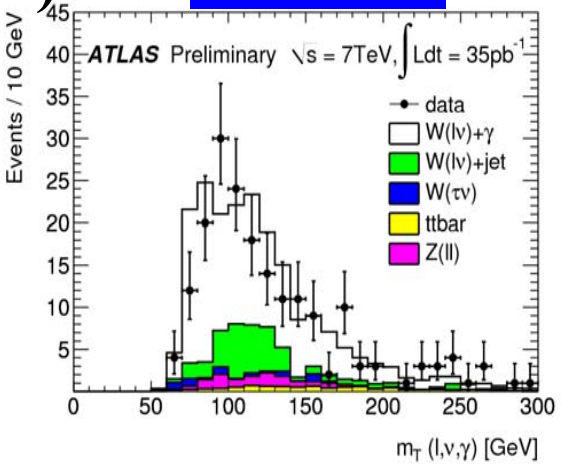
$W^{\pm}(Z^0)+\gamma$ production (35 pb^{-1})

ATLAS



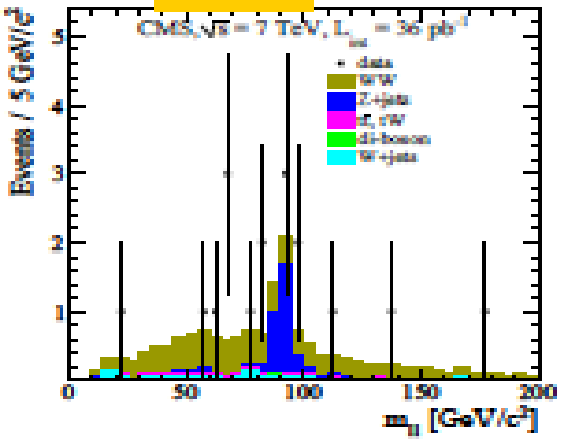


ATLAS

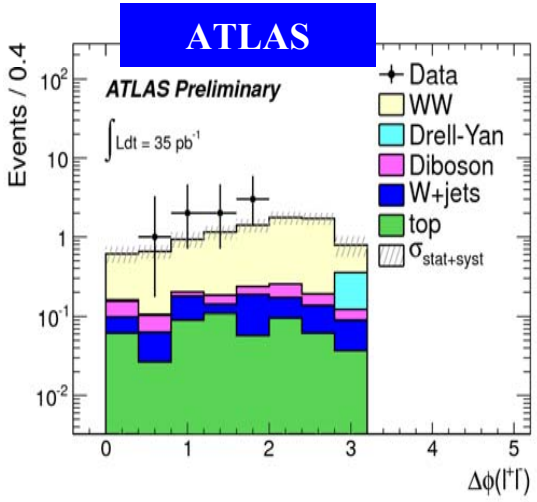


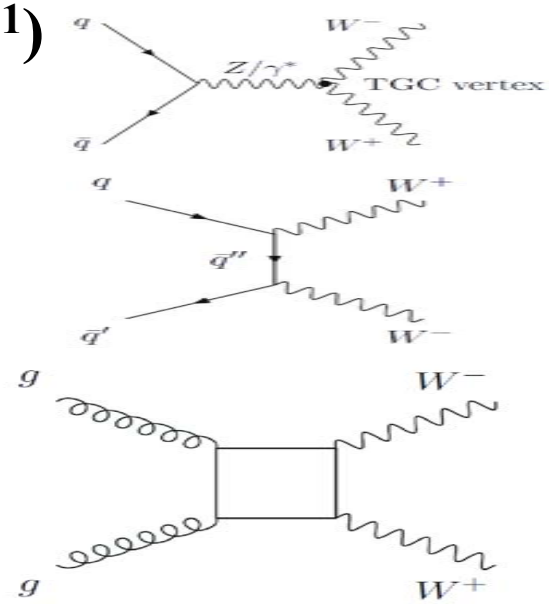
$W+W^-$production (35 pb^{-1})

CMS

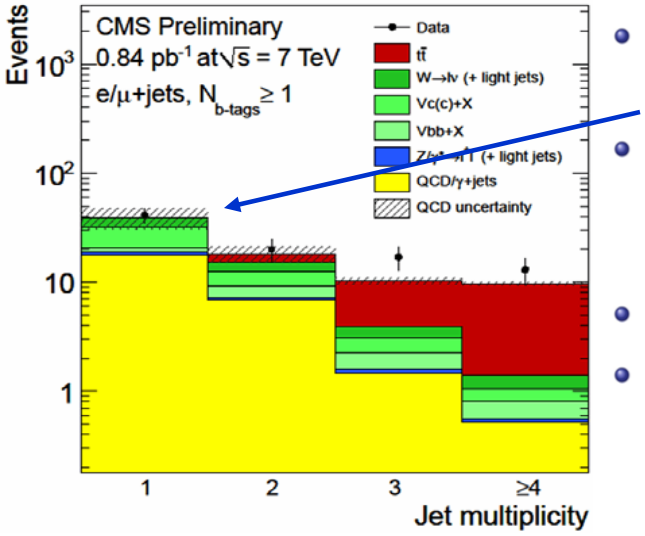


ATLAS

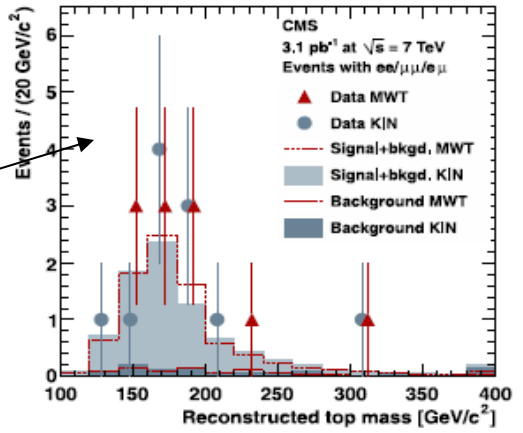




Top Quark

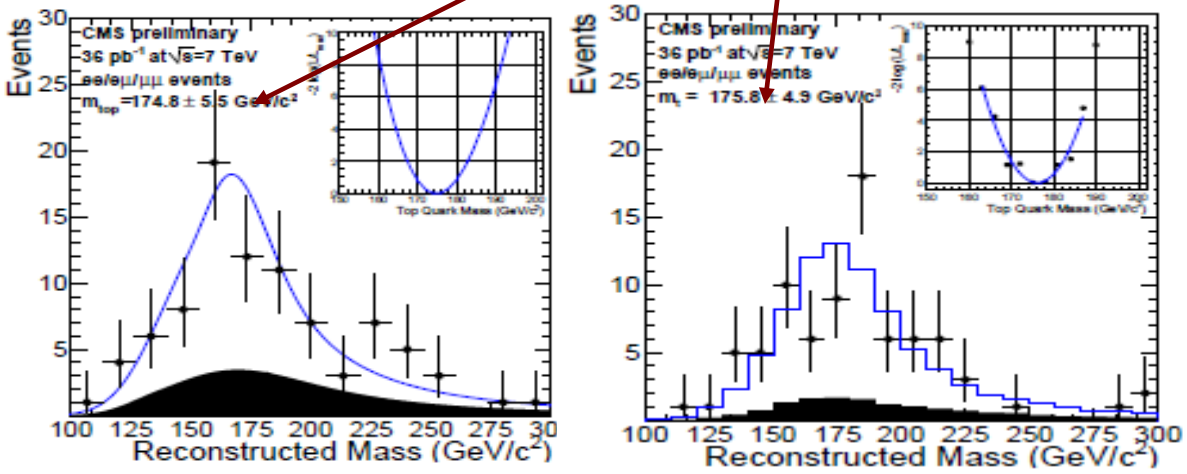


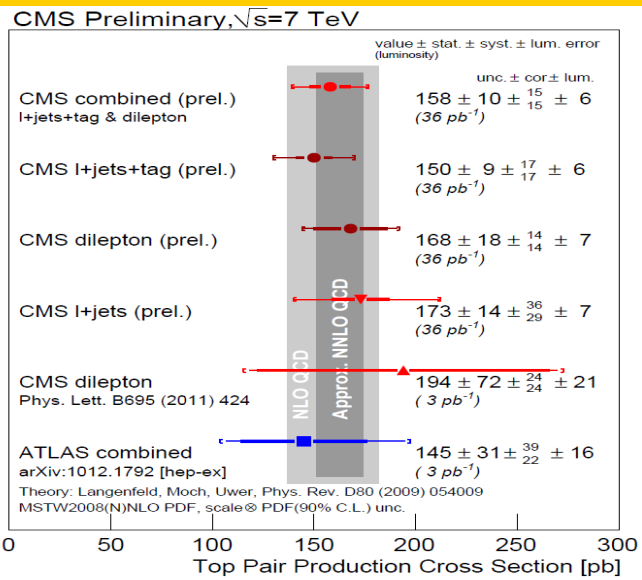
- **Studies of $t\bar{t}\rightarrow e^{\pm}/\mu^{\pm}$+jets events with 78 nb^{-1} data.**
- **Production Cross-section measurement ($\sigma_{t\bar{t}}$) in $t\bar{t}\rightarrow l^{+}l^{-}$ channel (3.1 pb^{-1})**
- **Updated results on $\sigma_{t\bar{t}}$ with 35 pb^{-1}**
- **Top mass measurements in dilepton channel (36 pb^{-1})**



m_{top}= 175.5±4.6(stat)±4.6(syst) GeV/c²

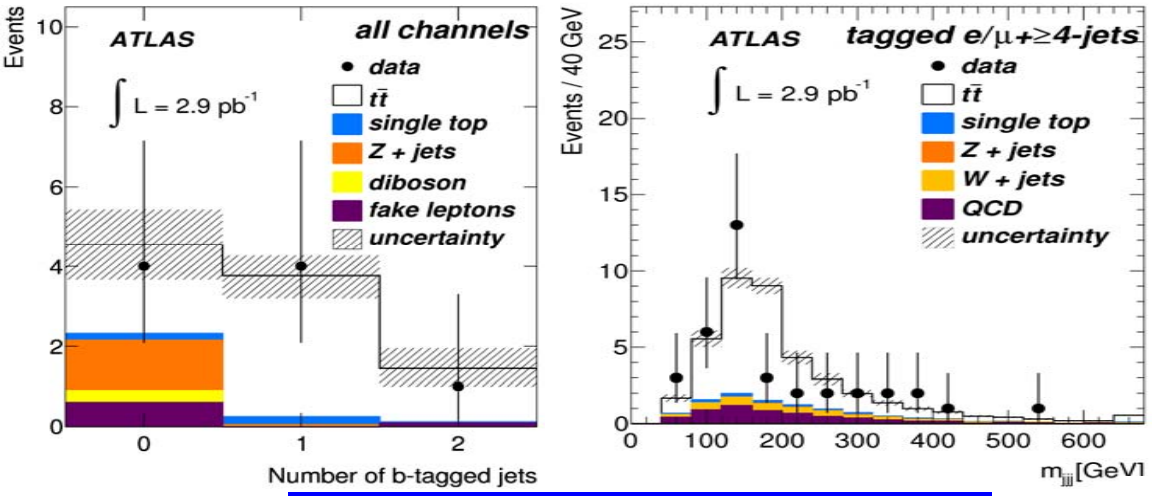
Summary of $\sigma_{t\bar{t}}$ measurements (36 pb^{-1})





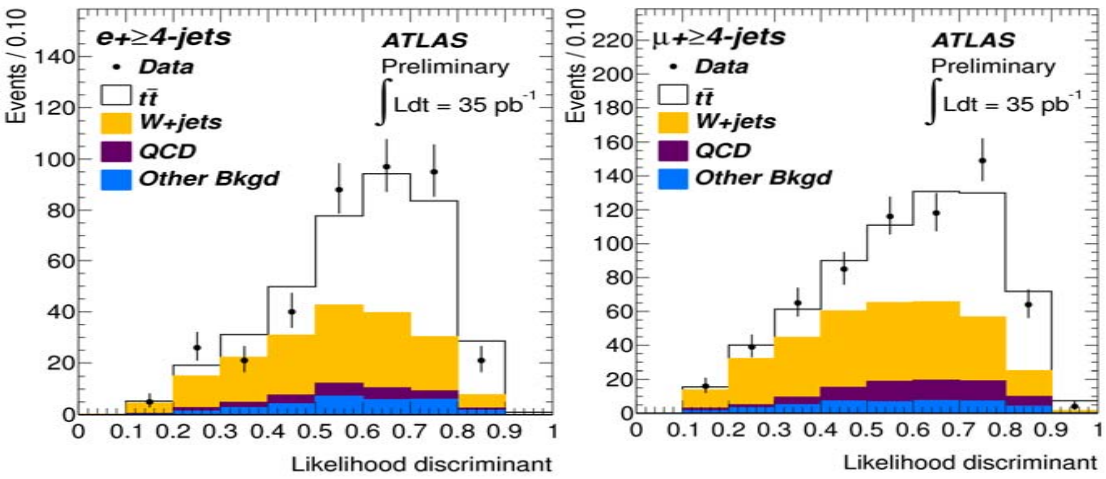
Top Quark

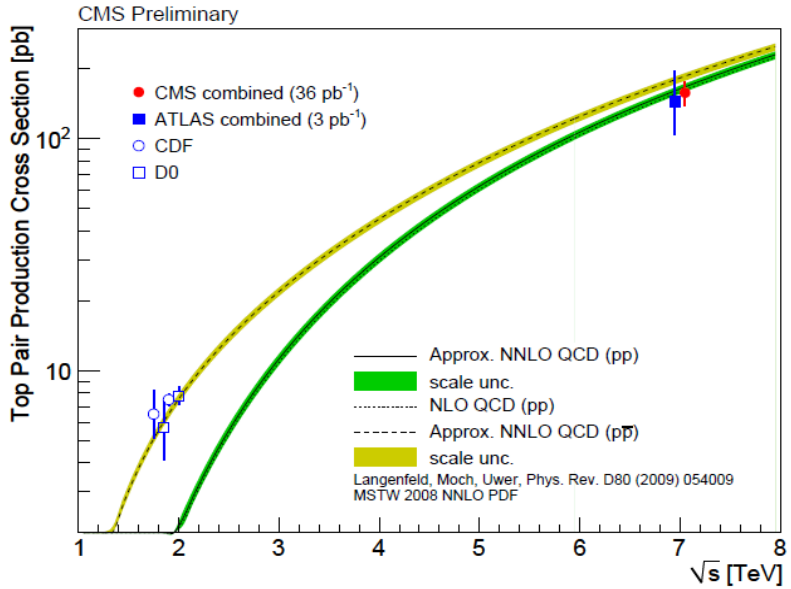
Observation of $t\bar{t}$ (2.9 pb^{-1})



- $t\bar{t}$ production cross-section ($\sigma_{t\bar{t}}$) measurement in lepton+jets and dilepton channel (2.9 pb^{-1})
- Updated $\sigma_{t\bar{t}}$ measurements with 35 pb^{-1} in lepton+jets channel
- Measurement of $\sigma_{t\bar{t}}$ by CMS and ATLAS are in good agreement with the NLO/NNLO theoretical predictions

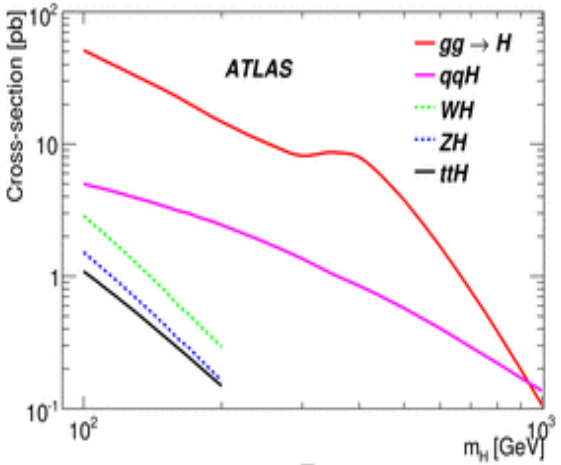
Measurement of $\sigma_{t\bar{t}}$ (35 pb^{-1})

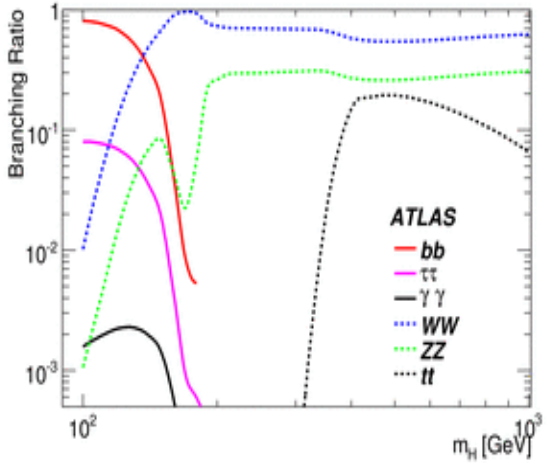


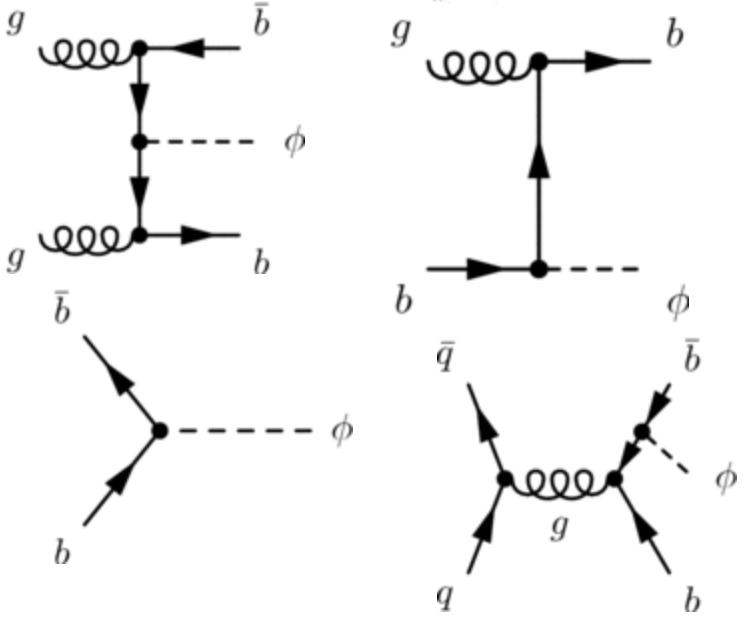


Higgs Searches

SM Higgs Production & Decay modes





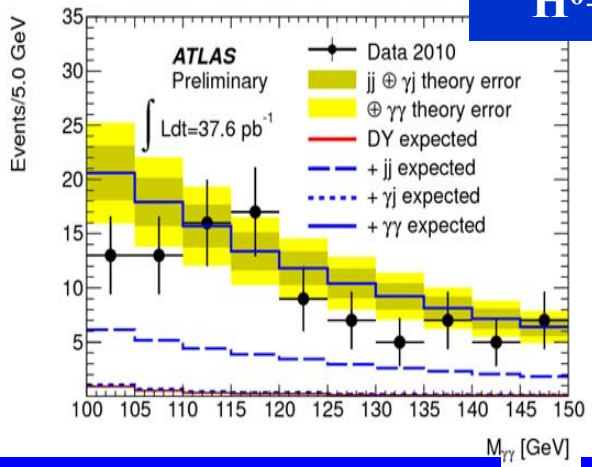


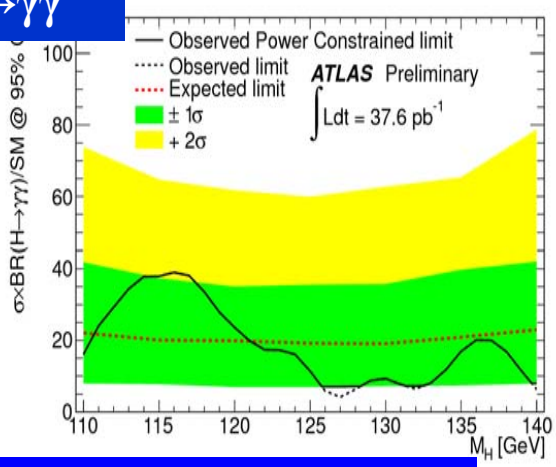
- **Standard Model Higgs Searches**
  - **High mass searches are dominated by $H^0 \to W^+W^-$ and $H^0 \to Z^0Z^0$ searches**
  - **Low mass searches in $H^0 \to \gamma\gamma$**

- **MSSM Higgs searches – 5 physical Higgs bosons (h, A, H and $H^{\pm}$)**
  - **Neutral Higgs bosons (h/A/H≡Φ)**
    - **At large tanβ, enhancement of the Higgs coupling with the "down"-type quarks (e.g., b-quarks) over the SM; and hence the overall production cross section enhancement.**
    - **$BR(\Phi \to \tau\tau) \approx 10\%$ for large tanβ**
    - **$\Phi \to \tau_{had}\tau_{lep}$ searches have great potential**

SM Higgs Searches

$H^0 \rightarrow \gamma\gamma$

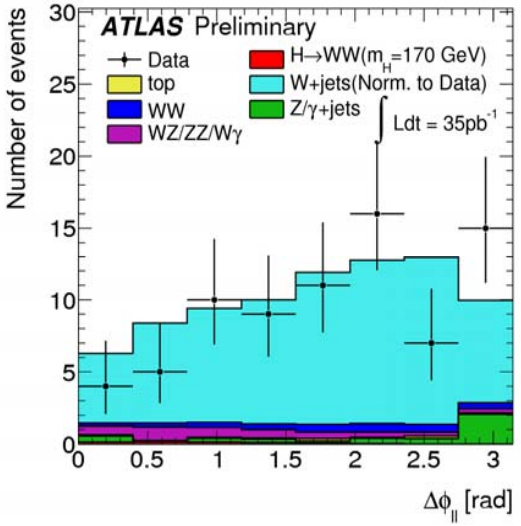




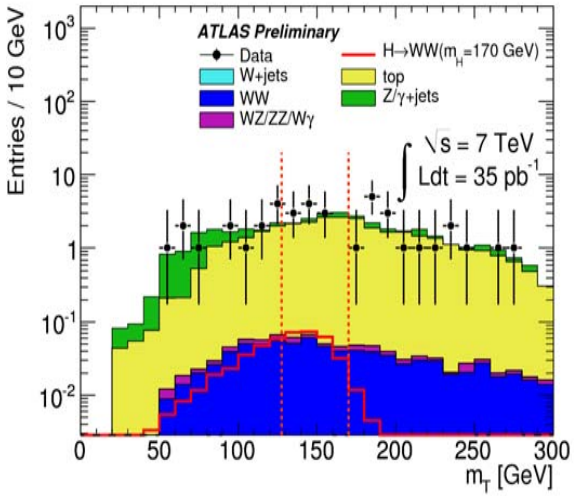
- **Standard Model Higgs Searches**
  - **Low mass searches in $H^0 \rightarrow \gamma\gamma$ (ATLAS 37 pb^{-1}).**
  - **High mass searches are dominated by $H^0 \rightarrow W^+W^-$ and $H^0 \rightarrow Z^0Z^0$ searches**
    - **$H^0 \rightarrow W^+W^- \rightarrow l^+l^+$ only (ATLAS 35 pb^{-1})**

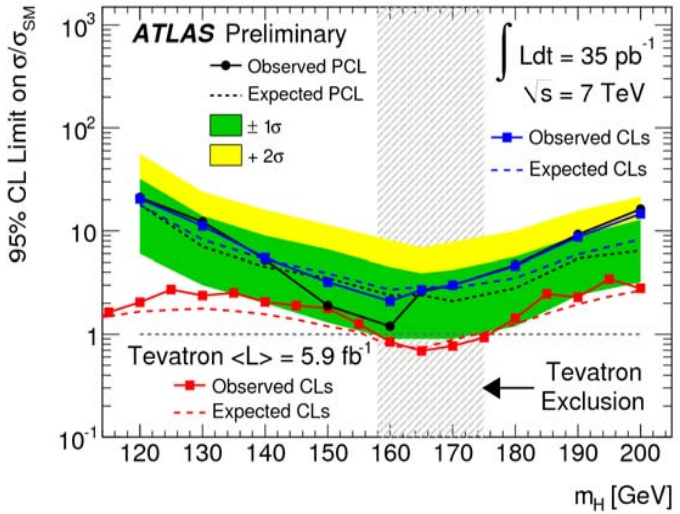
Exclusion limit of 1.2 @ 95% CL for m_H=160 GeV/c^2

$H^0 \rightarrow W^+W^- \rightarrow l^+l^+ + 0j$

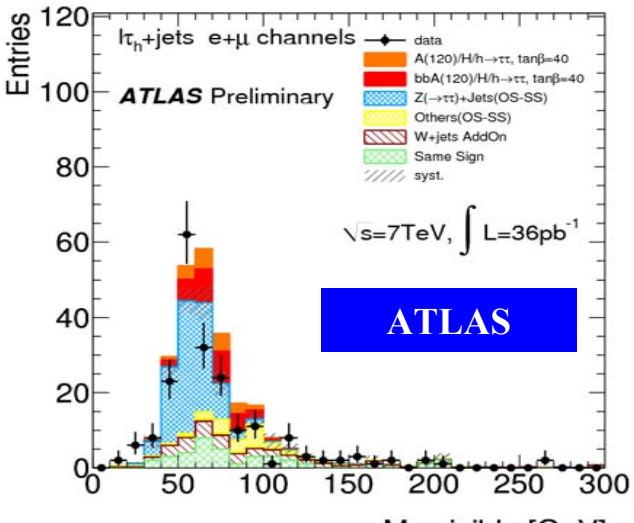


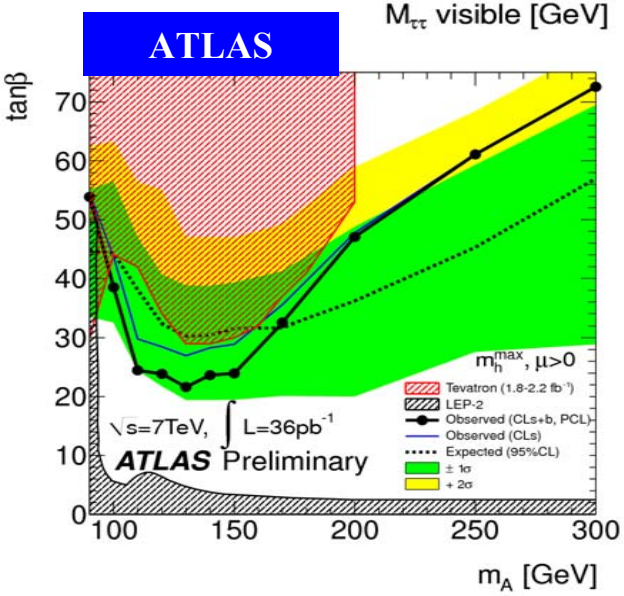
$H^0 \rightarrow W^+W^- \rightarrow l^+l^+ + 2j$



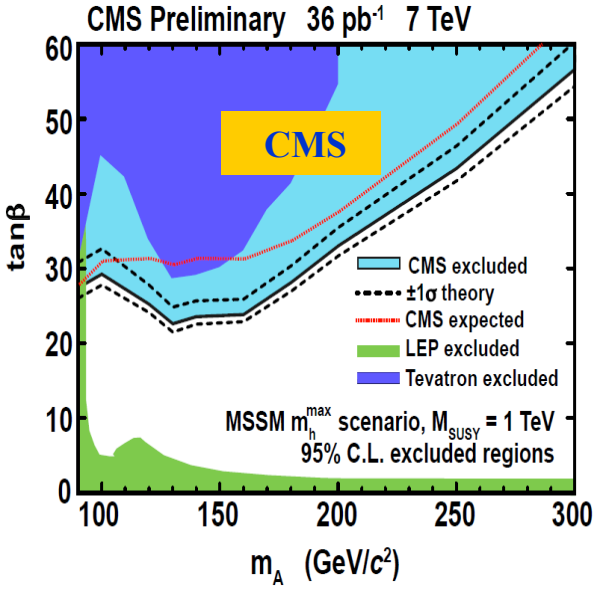


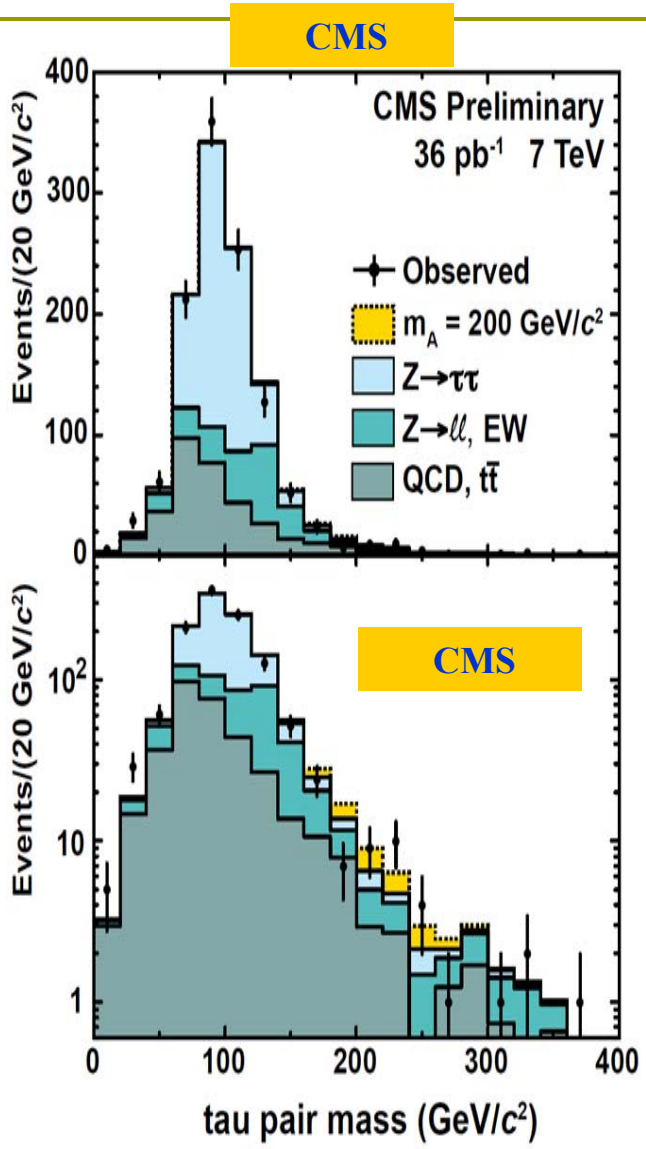
MSSM Higgs Searches





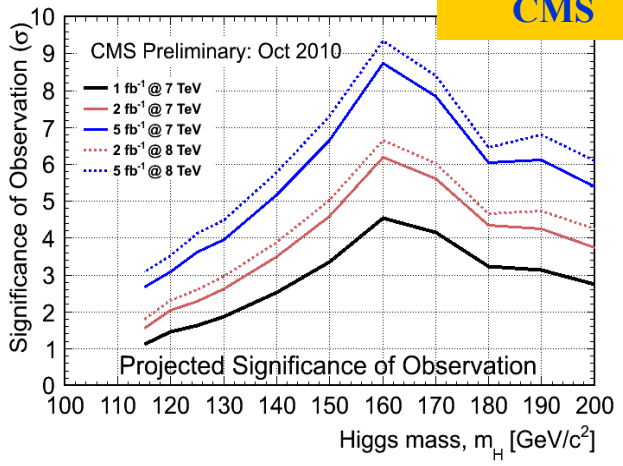
- **MSSM neutral Higgs searches in $\Phi \rightarrow \tau_{had}\tau_{lep}$**
- **ATLAS & CMS have comparable sensitivity in exclusion limits (limit setting procedures are different)**

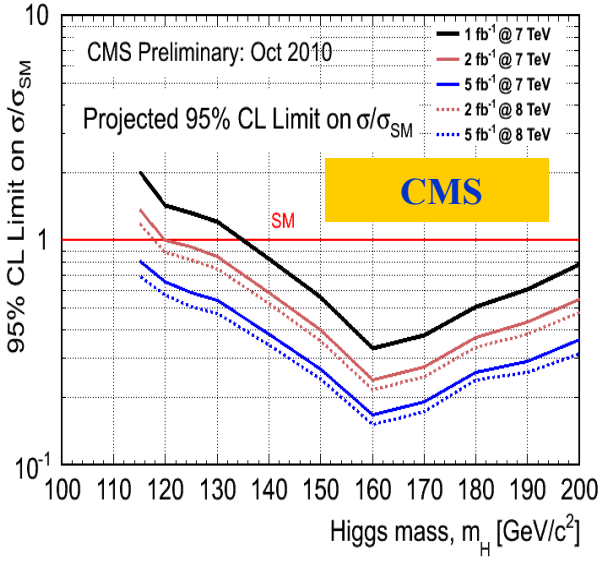




SM Higgs Search Prospects

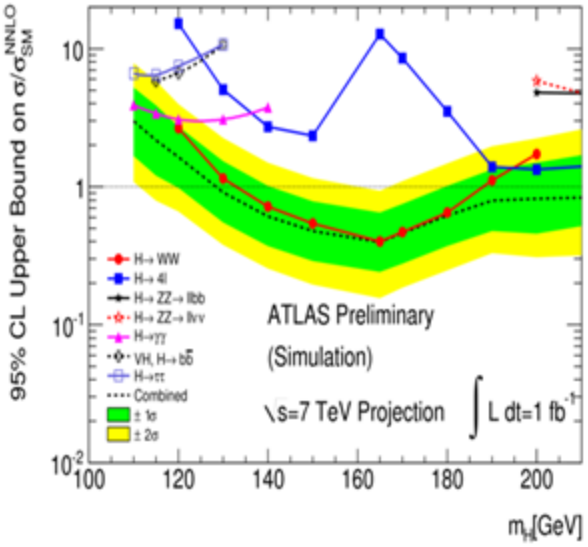
CMS



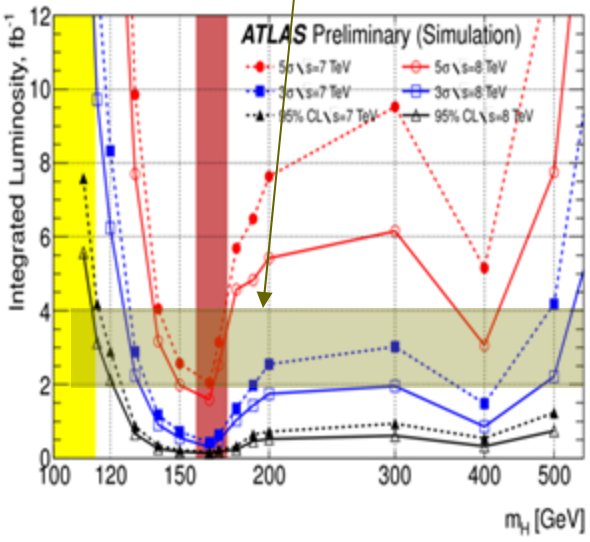


- **2010 MC sensitivity studies for different LHC running scenarios**
- **Additional channels**
  - **Both CMS and ATLAS have great discovery or exclusion potentials for SM Higgs @ 7 TeV**
- **ATLAS & CMS combination would improve the sensitivity further.**

ATLAS



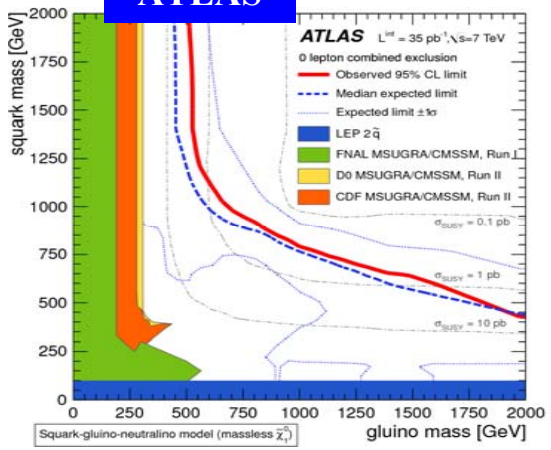
Expected Luminosity (2011)



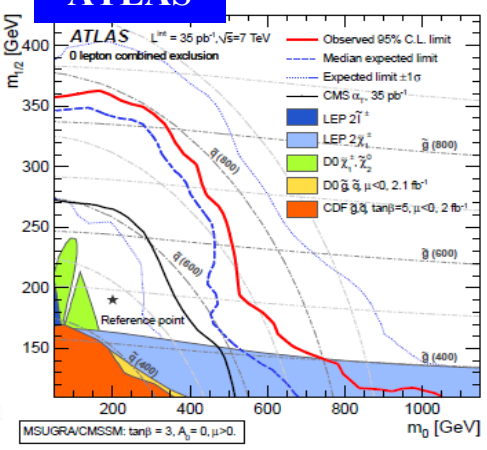
Search for Supersymmetry

No evidence of the SUSY signals in the early data yet

ATLAS

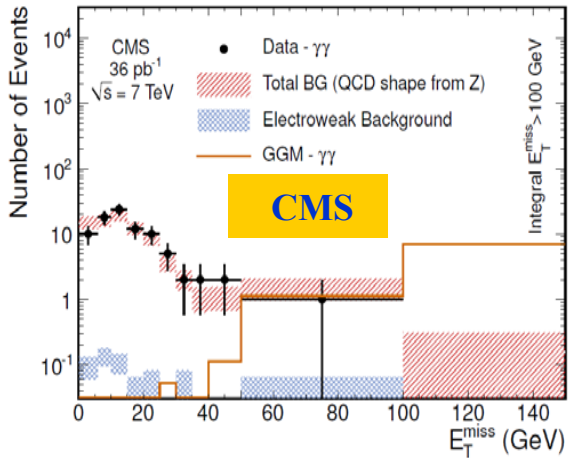


ATLAS

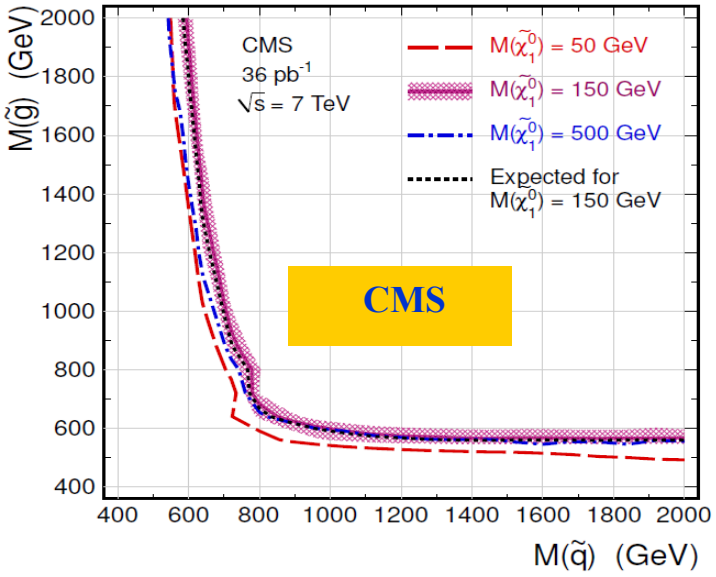


- Rich variety of search strategies to look for the first SUSY signals
  - Clean signatures: jet+E_T^{miss}, $\gamma\gamma$+E_T^{miss}+jet, multileptons, etc.
- Already exceeding the limits on SUSY from the Tevatron experiments

If $m_{squark}=m_{gluino}$, $m_{gluino}<775$ GeV/c^2 (ATLAS) excluded at 95% CL



Limits on the signal cross section for General Gauge-mediated (GGM) Supersymmetry between 0.3 and 1.1 pb at the 95% CL.

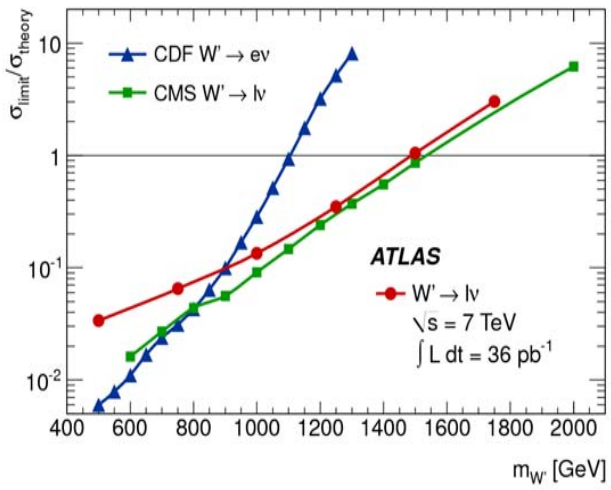


New Physics Searches

- Numerous models to explore
  - W'→lν and Z'/Z_ψ/KK Gravitons→l^+l^-
  - Quark compositeness
  - First Generation leptoquarks
  - 4th Generation quarks
  - …..

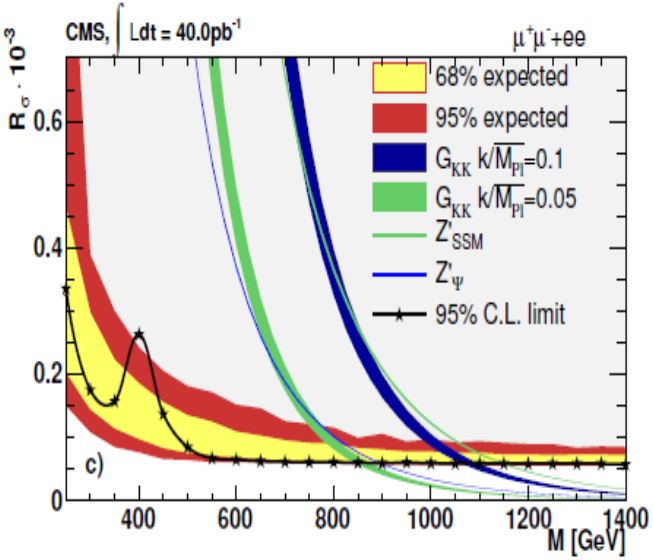
CMS: No evidence for Quark compositeness; di-jet angular distributions ($\chi=e^{|y1-y2|}$) are compatible with pQCD. Lower limit on the contact interaction scale for left-handed quarks Λ=5.6 TeV @ 95% CL

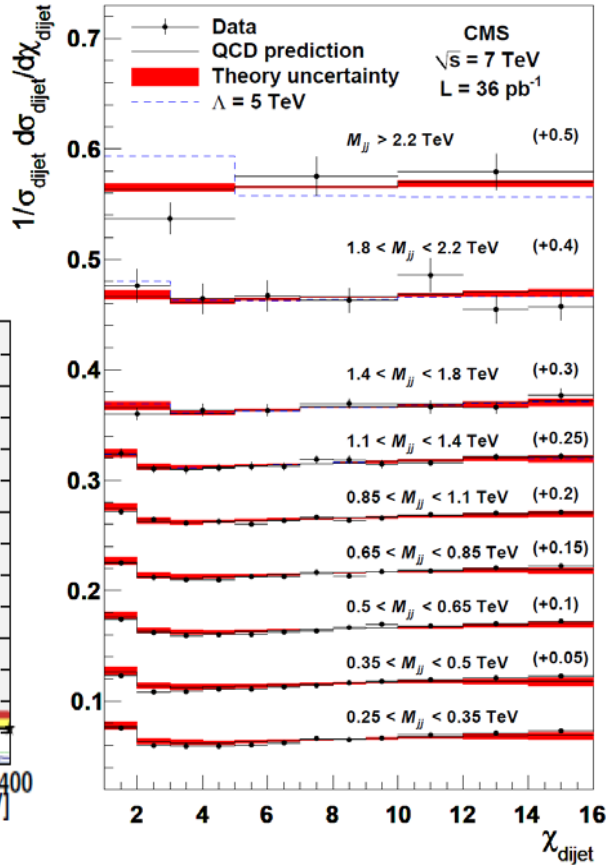
ATLAS: W' Searches: $m_{W'}$<1.49 TeV/c^2 excluded at 95% CL



CMS: $m_{W'}$>158 TeV/c^2 (e+μ)

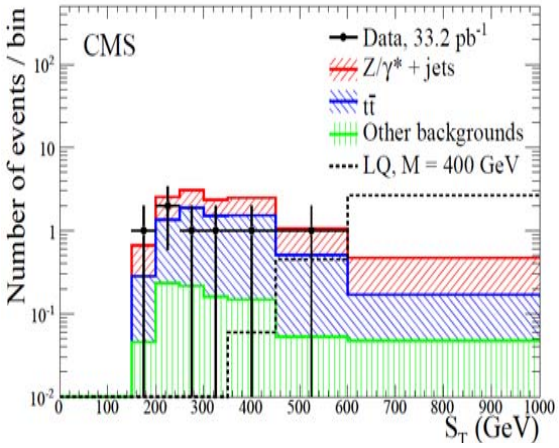
CMS:
Model specific Z'/Z_ψ/KK Graviton Searches

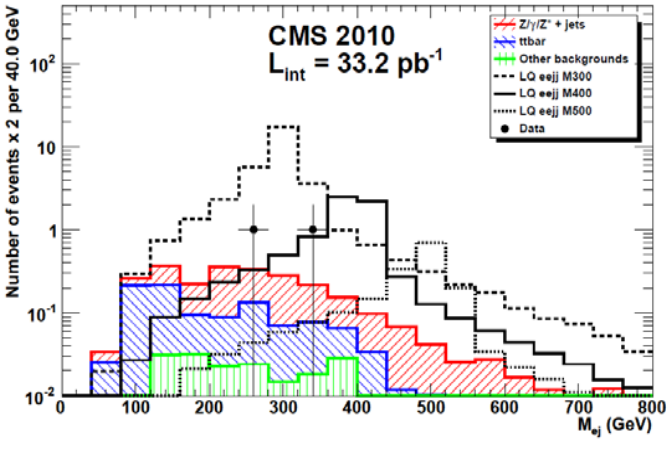


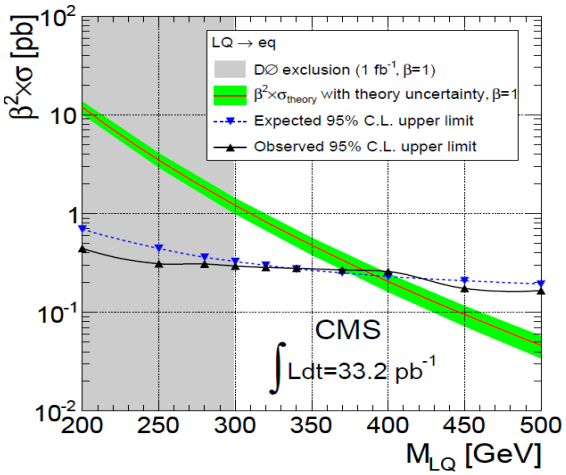


New Physics Searches

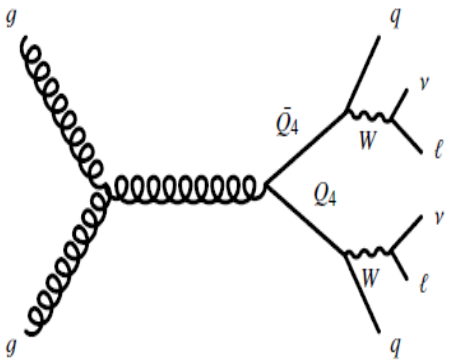
CMS: First Generation Scalar Leptoquark searches (eejj): m_{LQ}<384 GeV/c² excluded at 95% CL for β=1

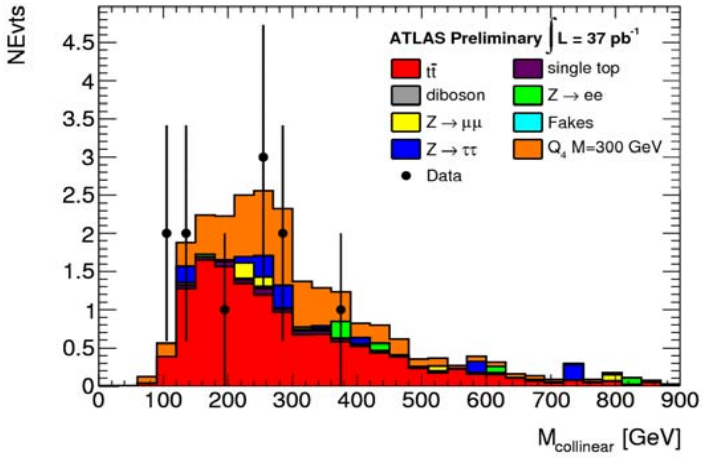


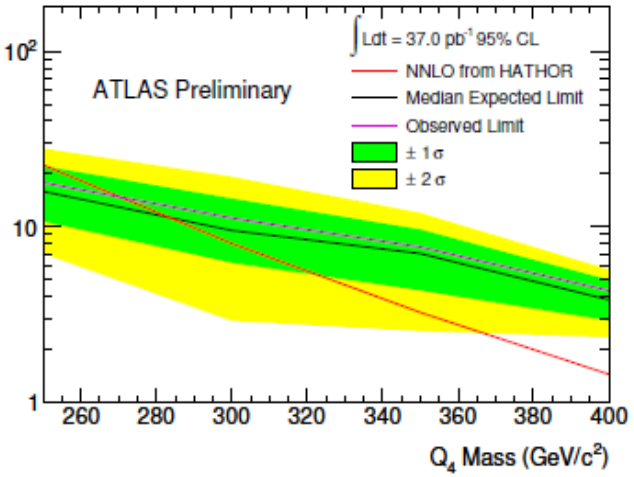




ATLAS: Search for 4th Generation quarks m_{Q4}<270 GeV/c² excluded at 95% CL





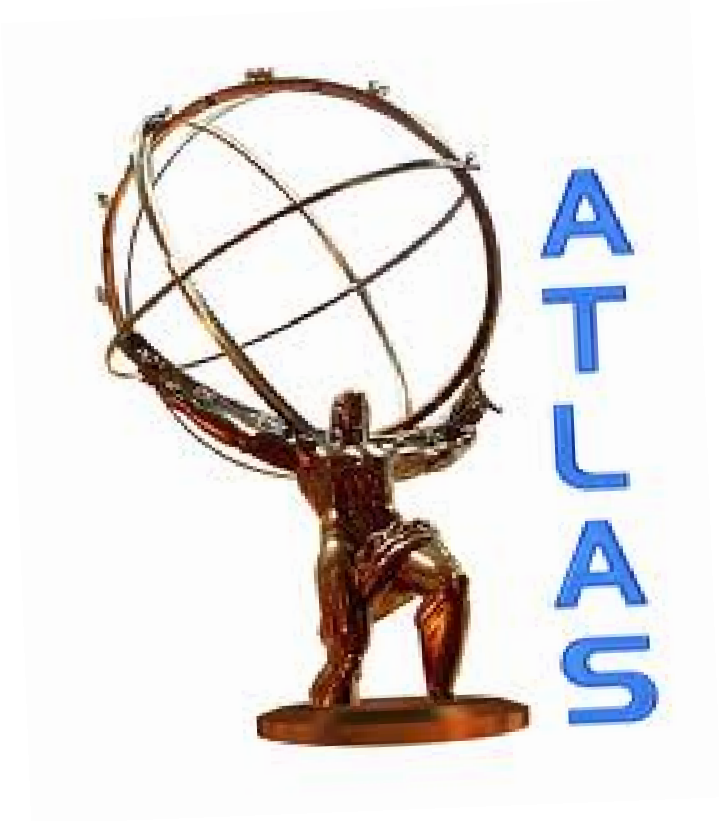


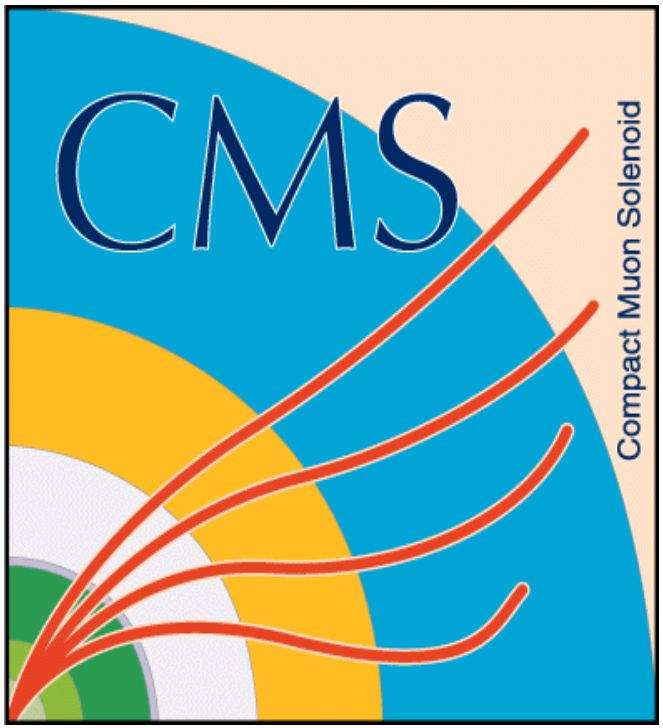
Summary & Outlook

- **ATLAS and CMS experiments have been quite efficiently operational during 2010 LHC running. Detector calibration and performances have been tested and improved through the usage of collisions data.**
- **Both experiments have performed comprehensive set of SM measurements using the pp collisions data at √s=7 TeV.**
  - **Measurements are compatible with SM predictions and within the experiments.**
- **A significantly large number of physics analyses have been devoted to look for the new physics beyond the Standard Model (BSM), including Higgs bosons (both SM and BSM) and SUSY searches.**
  - **No evidence for new physics or Higgs bosons found in 2010 data. Exclusion limits have been set in various areas, already exceeding the current Tevatron limits.**
- **Further details about ATLAS/CMS physics analysis:**
  - **ATLAS:** https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - **CMS:** https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- **Prospects for the Higgs, SUSY and BSM searches seem to be quite promising with 2011-12 LHC running. 2011 LHC running would accumulate at least 50 times larger dataset.**

LHC has resumed its first pp collisions in 2011. Stay Tuned!

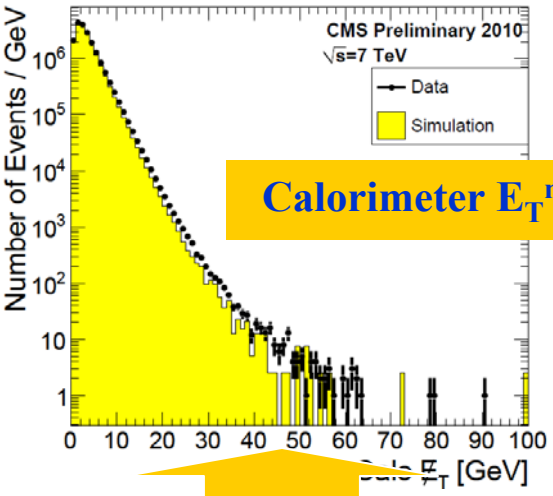
Extras





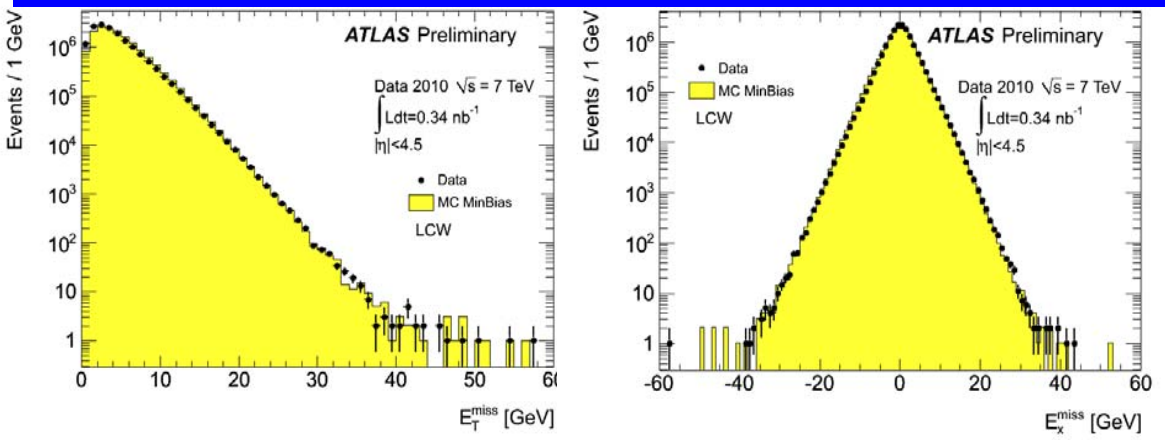
Missing Transverse Energy

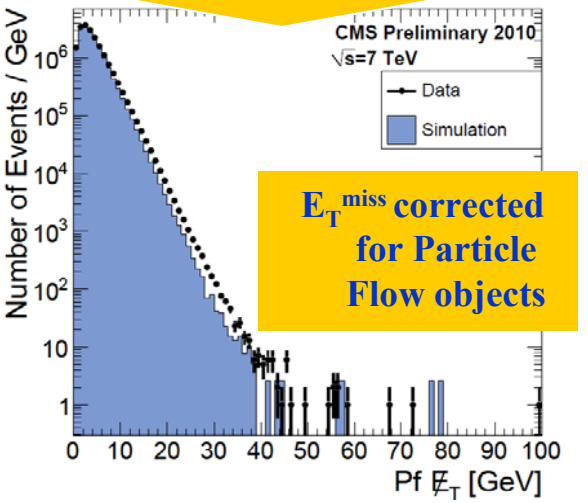
- Many new physics signatures are characterized by the Missing Transverse Energies (E_T^{miss})
  - Calorimeter plays the crucial role for such reconstruction (sensitive to noise sources, dead cells etc.)
- ATLAS E_T^{Miss} (<300 GeV) calibration using a large statistics (15.2 million) of Minimum Bias (MB) events from pp collisions at √s= 7 TeV.
- ATLAS/CMS performance checks of E_T^{Miss} on MB and/or di-jet events from pp collisions at √s= 7 TeV.



CMS E_T^{miss} in di-jet events at √s=7 TeV

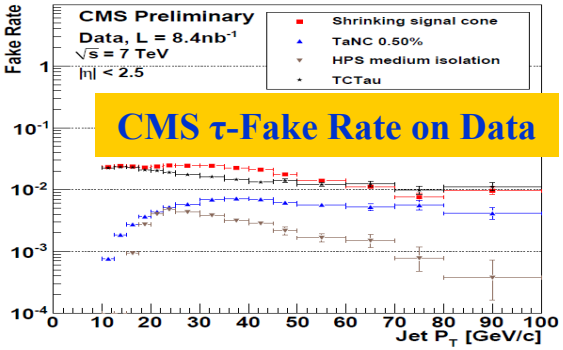
ATLAS E_T^{miss}/E_x^{miss} on Minimum Bias events @√s=7 TeV



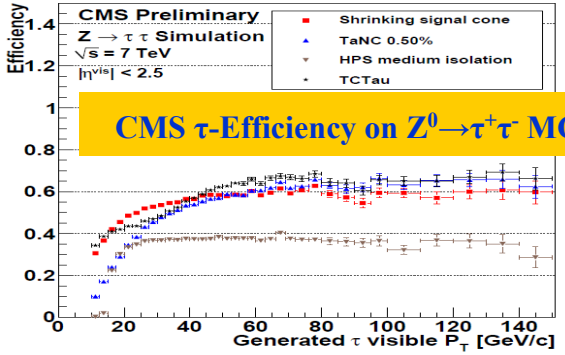


Reconstruction of hadronic τ-decay

- The hadronic decay of τ-lepton is characterized by a narrow calorimeter cluster in association with a track or set of tracks
- Identification is based on cluster shapes and the matching variables between the tracks and the cluster
- Discrimination/Separation from QCD jets
  - ATLAS: cut based or multivariate methods (Maximum Likelihood, Boosted Decision Tree)
  - CMS has 4 different techniques : based on Particle Flow algorithms/multivariate techniques and cut based.

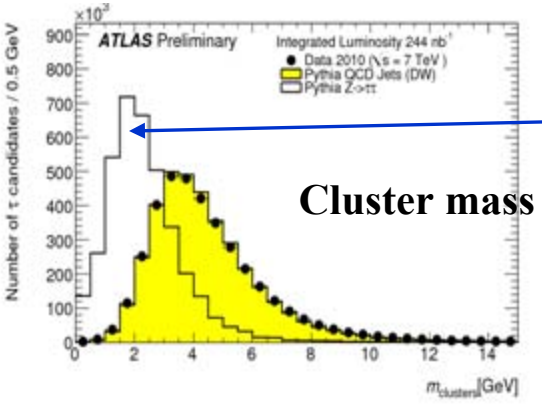


CMS τ-Fake Rate on Data

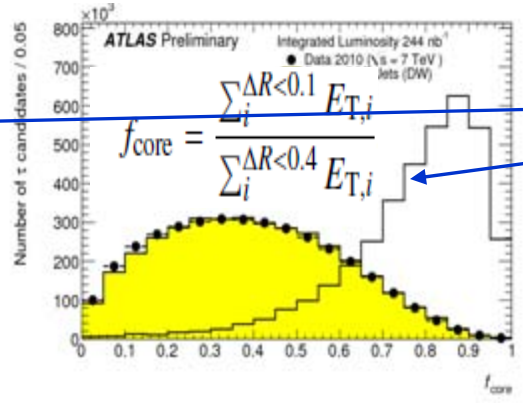


CMS τ-Efficiency on $Z^0 \rightarrow \tau^+\tau^-$ MC

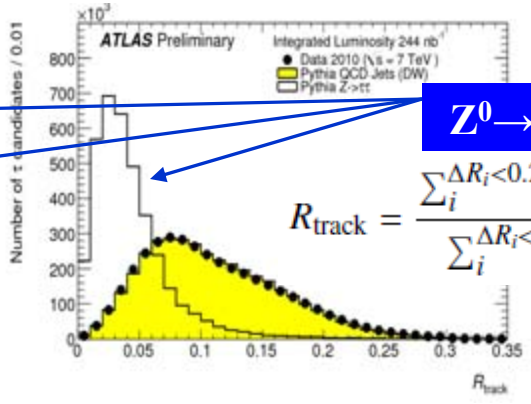
ATLAS discriminating variables for τ-identification



Cluster mass



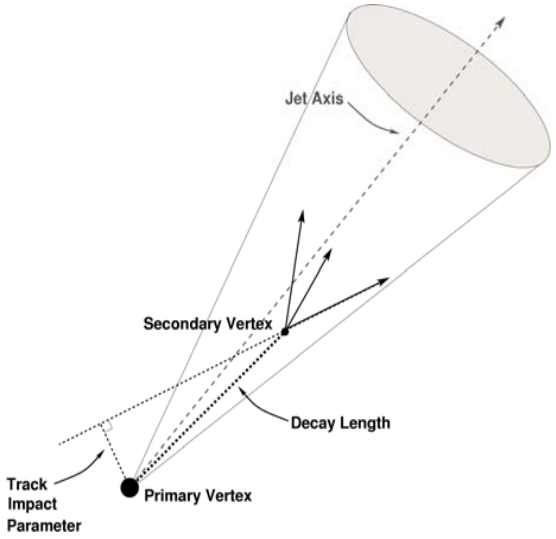
$$f_{\text{core}} = \frac{\sum_i^{\Delta R<0.1} E_{T,i}}{\sum_i^{\Delta R<0.4} E_{T,i}}$$



$$R_{\text{track}} = \frac{\sum_i^{\Delta R_i<0.2} p_{T,i}\Delta R_i}{\sum_i^{\Delta R_i<0.2} p_{T,i}}$$

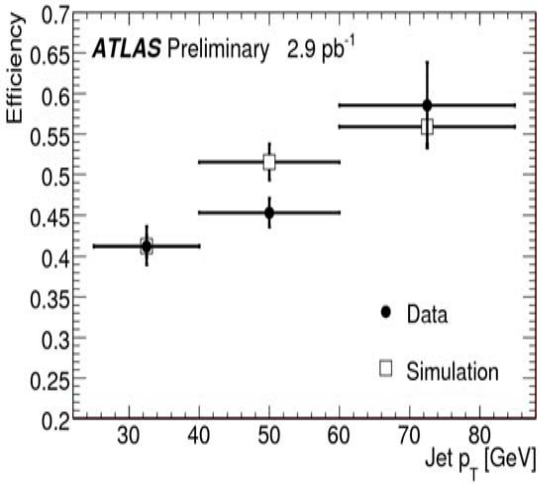
$Z^0 \rightarrow \tau^+\tau^-$ MC

Flavor tagging

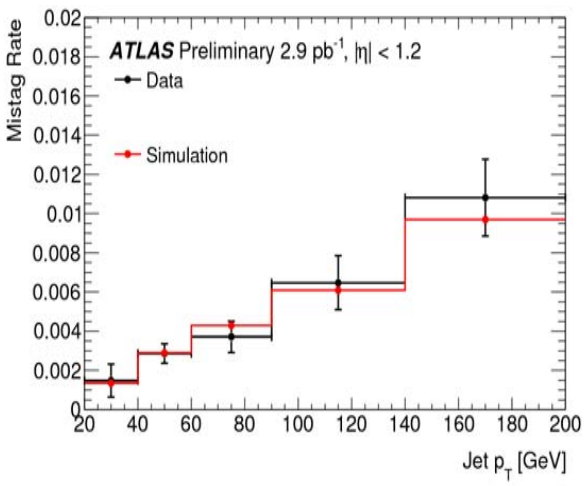


- **b-jet identification is an essential tool for Higgs searches, including many BSM searches**
- **Three methods based on Secondary Vertex (SV)**
  - **SV0 - Signed decay length significance (L/σ_L)**
  - **TrackCount: Counting number of tracks with significant IP**
  - **JetProb: Probability of all tracks originated from PV**

ATLAS "SV0" efficiency



ATLAS "SV0" mis-tag rate



CMS: Reconstructed SV Mass for >=3 tracks