Impact of Detector Simulation in Particle Physics Collider Experiments - Highlights

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Motivation

Throughout my career, I received many requests for material showing concrete examples on how detector simulation helps modern particle physics experiments

As a follow-up of one of these requests, John Harvey, former leader of the Software Group (SFT) at CERN, encouraged me to write a note on the topic

The note found its way to Physics Reports where it was recently published as a review paper:

- "Impact of detector simulation in particle physics collider Experiments", Physics Reports 695 (2017) 1–54

This short presentation includes only highlights of the material in the paper

Outline

Detector simulation is of critical importance to the success of HEP experimental programs, a factor for faster delivery of increasingly precise physics results

- Introduction to detector simulation in HEP experiments
  - Some facts and numbers, the simulation software chain
- Applications of detector simulation to collider experiments
  - Simulation in data analysis, detector design and optimization, software & computing design and testing
- Modeling of particle and event properties and kinematics
  - Tagging of heavy quarks, W, Z, and photon event distributions, missing transverse energy distributions
- Simulation and publication turnaround
- Economic impact and cost of simulation in HEP experiments
- The future

Introduction to detector simulation in HEP experiments

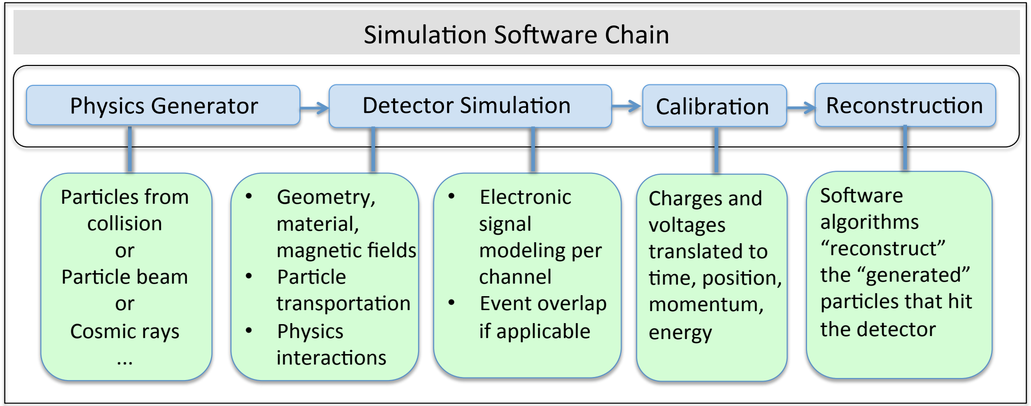
Facts and numbers, the simulation software chain

Simulation facts and numbers

- The role of detailed detector simulation in HEP experiments has increased during the last three decades to become an essential component
- LHC experiments simulate events at a speed and with physics accuracy never seen before
  - ATLAS/CMS: seconds to minutes per event, tens of billions of events since 2010
  - CDF/D0 (early 1990's): hundreds of thousands of poor quality events, in comparison
- Geant4-based simulation has shortened the time between data-taking and journal submission of increasingly precise physics results at the LHC
  - Other factors: detector and computing technology, a wealth of experience from pre-LHC experiments, better calibration and analysis techniques, communication tools, etc.
- In many experiments, detector simulation takes > 1/2 of all computing resources
- Over the next two decades, detector simulation applications need to deliver orders of magnitude more events with increased physics accuracy and within a flat budget

A daunting challenge for detector simulation tools

Simulation software chain in a typical HEP experiment



Simulation Software Chain

Physics Generator → Detector Simulation → Calibration → Reconstruction

Physics Generator: Particles from collision or Particle beam or Cosmic rays …

Detector Simulation:
- Geometry, material, magnetic fields
- Particle transportation
- Physics interactions

- Electronic signal modeling per channel
- Event overlap if applicable

Calibration: Charges and voltages translated to time, position, momentum, energy

Reconstruction: Software algorithms "reconstruct" the "generated" particles that hit the detector

Simulation referred to as "Monte Carlo (MC) simulation"

Simulated events referred to as "Monte Carlo events, data samples"

- Physics generator provides the final states of the physics process of interest (Pythia, Herwig, Madgraph, Alpgen, etc. in colliders; GENIE, etc. for neutrinos)
- Detector simulation [focus of this presentation]
  - First stage: passage of generated particles through detector material and fields (Geant4 application)
  - Second stage: modeling of detector electronics, backgrounds to hard collision (digitization, pileup)
- Calibration from detector quantities to physics quantities
- Event reconstruction algorithms which is typically the same applied to real data

Applications of detector simulation to collider experiments

Data analysis, detector design and optimization, software & computing design, development and testing

Applications of simulation to data analysis

A few examples of applications to data analysis and interpretation:

- Data-driven methods
  - Techniques applied to real collider data to measure ***physics backgrounds, calibration & alignment factors, resolutions, identification & reconstruction efficiencies, fake rates***, etc
  - Based on detector properties, conservation laws, mathematical tools and analysis
    - Applied to detector-level data and detector-level simulated data as if it were real data
- Closure tests
  - Verify data-driven measurements are correct within the quoted uncertainties
    - Comparing detector level MC measurement with MC truth information
      $T = (MC^{\text{reco-level}} - MC^{\text{truth}}) / MC^{\text{truth}} \sim 0$ within the uncertainty of the method
- Modeling of signal samples
  - SM precision measurements (i.e. top, W/Z/Higgs), BSM searches
  - Fast simulation to scan large theory parameter space (i.e. SUSY)

Applications of simulation to data analysis – data-driven methods

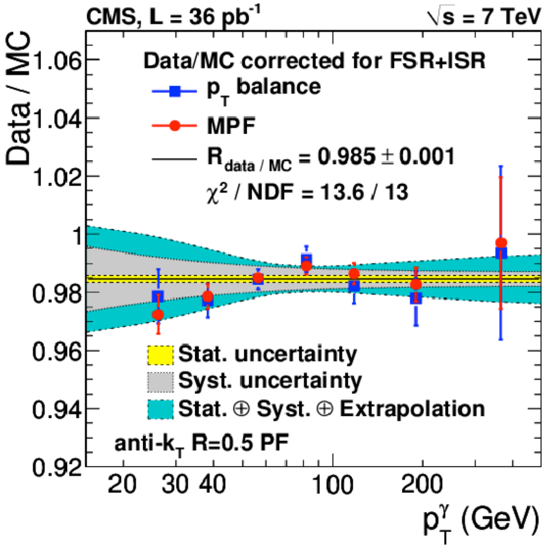
Corrections in data analysis mostly from MC truth with small ”scale factors (SF)”

- SF calculated as ratio of data-driven measurements in detector-level collider data and MC
- The trick is that systematic uncertainties “cancel” in the SF ratio – same method!

- Jet energy response (R_{jet}) or “ jet energy scale” (JES)
  - $R_{jet}^{truth\text{-}MC} = p_T^{jet\ reco\text{-}MC} / p_T^{jet\ particle\text{-}level\text{-}MC}$
  - Data-driven methods use di-object p_T balance: multijet, γ+jets, Z+jets samples (conservation laws)
  - $R_{jet} \sim p_T^{jet}/p_T^{\gamma,Z}$ and $SF = R_{jet}^{reco\text{-}data}/R_{jet}^{reco\text{-}MC}$

JES = $R_{jet}^{truth\text{-}MC}$ x SF, with SF ~ 0.98 +/- 1-2%

- ID & reconstruction efficiencies and fake rates
  - Data-driven methods use tag-and-probe method



Accuracy improves as SF→1 within a small uncertainty – excellent MC modeling of the data

Applications of simulation to data analysis – closure tests

Data-driven methods need to be demonstrated with “closure tests” (T)

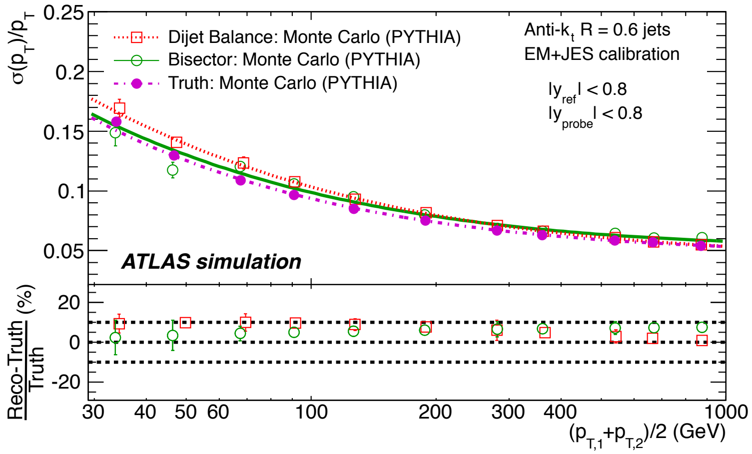
Lack of closure (T≠ 0, outside error band)

Indicates the need to go back to the drawing board and understand biases in the procedure – excellent MC modeling needed!

Limitations of simulation at D0 (early 1990’s)

Geant3: approximate geometry, average material, partial validation of response linearity with data, showers at 95% of total energy deposited (soft contributions, out-of-cone effects missed)

Parametrized “a la CDF” simulation not viable: no central magnetic field until 2001 ⟹ no single particle response measurement for response tuning



ATLAS jet energy resolution closure test

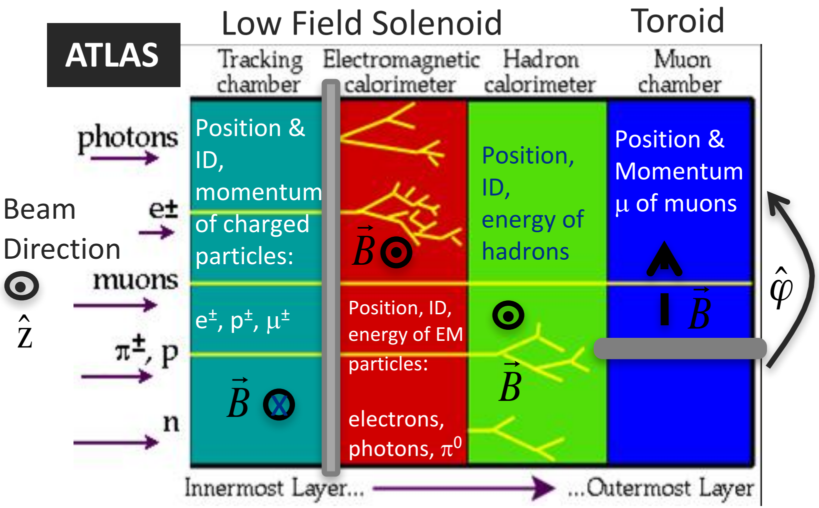
Cause of delay in a number of physics measurements

Jet cross sections and other QCD measurements –delayed 1992 ⇒ 2000 until JES error ≤ 3%

(Lack of large/accurate MC samples to demonstrate data-driven methods and closure for JES)

Simulation in detector design and optimization

To design a HEP detector, different technologies and physical characteristics are modeled and optimized in simulation for best physics performance.



Tracker performance (in Si detector) studied/optimized varying pixel and strip density, number of layers, angular coverage, amount of material a particle traverses

Calorimeter measurements are studied/optimized varying angular coverage and hermeticity, transverse granularity, longitudinal segmentation, and materials

Muon system is studied/optimized varying wire chamber density, number of layers in the radial direction, angular coverage.

More powerful or weaker magnets allow for more compact (CMS) or larger (ATLAS) detector designs

MC campaigns produce millions of events generated with different detector scenarios

- Make the case for a given design, optimize parameters for best physics, impact of de-scoping due to budget

(Interesting: detector configurations also adapt to play to the strengths of the Geant4 simulation toolkit)

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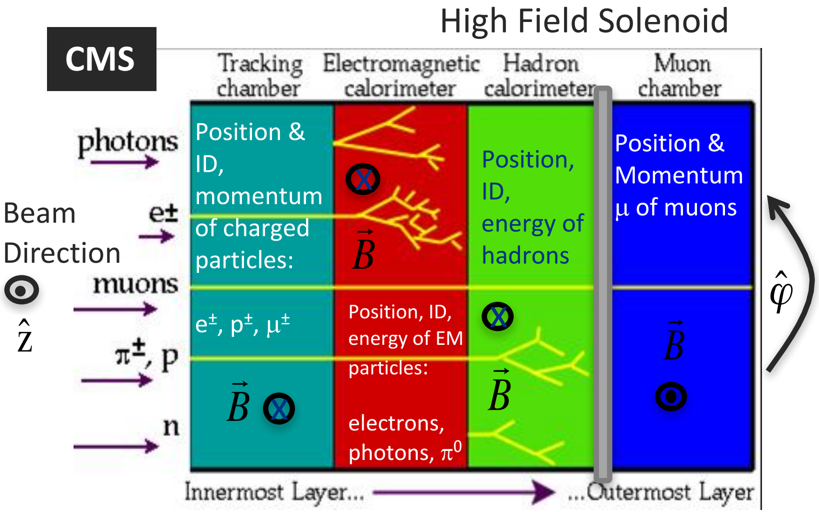

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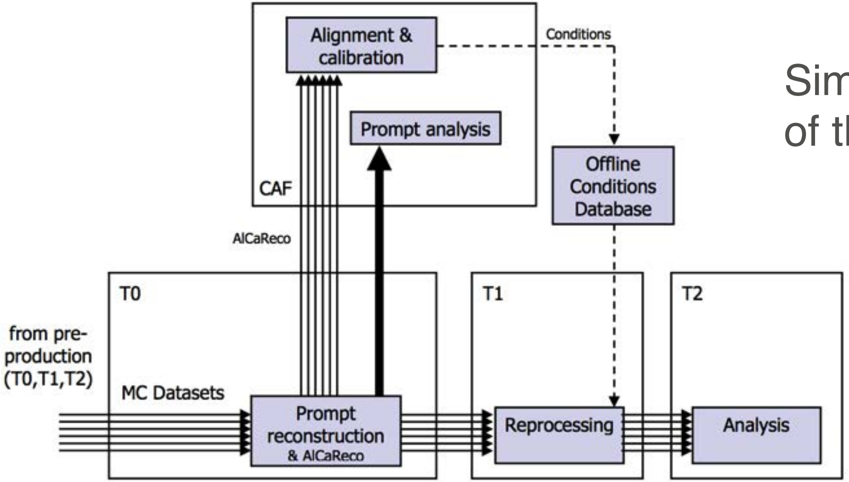
Simulation in software and computing design and testing



Simulation is essential to develop each element of the workflow and data flow for data handling

- Worldwide LHC Computing Grid (WLCG) divided in four tiers: 0, 1, 2, 3
- Each tier performs difference services: acquisition, reconstruction, simulation, storage, data analysis

Combined procedure tested in “Computing, Software, and Analysis challenges” (CSA) in CMS

- Stress testing at 25%, 50%, and 75% capacity in 2006, 2007, and 2008
- 150 million events simulated, trigger rates modeled, data reconstructed, skimmed, calibrated
- Data transfers between centers, event file size, memory and CPU consumption exercised

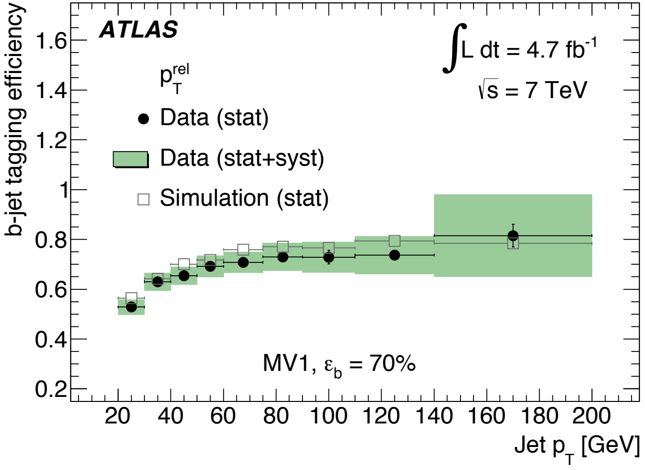
The realism of these tests resulted in computing systems performing as predicted

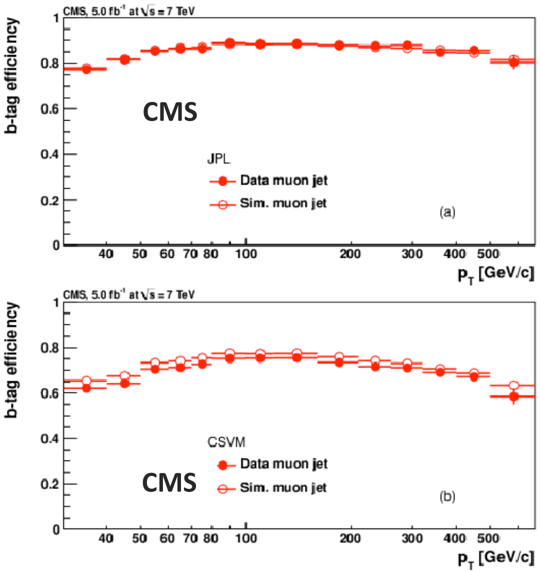
Modeling of particle and event properties and kinematics

Tagging of heavy quarks, W, Z, and photon event distributions, missing transverse energy distributions

Modeling of particles and event properties: b jets

b-tagging efficiencies were derived from data-driven methods using jets with a muon





b-tagging simulation depends on modeling of reconstructed vertices and tracks within jets:

- material budget
- energy loss, ionization
- multiple scattering,
- noise,
- pileup mainly

ATLAS and CMS b-tagging efficiencies for MV1, JPL, and CSVM algorithms

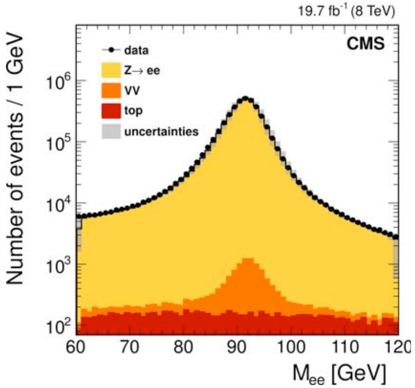
- Simulation models b-tagging efficiency within <5% in both experiments

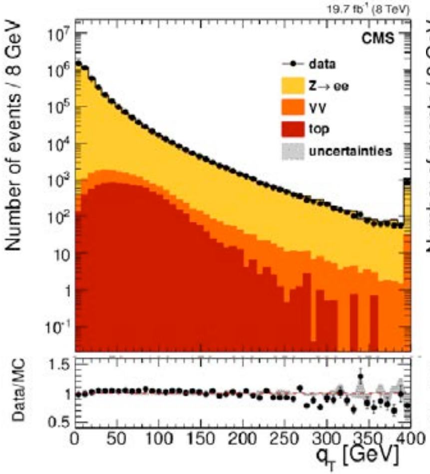
Mis-tag rates (not shown) derived from "negative taggers"

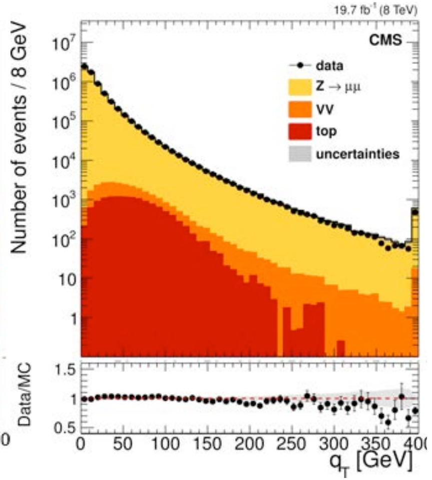
- Modeling of mis-tag rates (light jet passing for a b-jet) is tricky
  CMS: 20% for mis-tag rate in 0.01-0.03 range
  ATLAS: factor 2-3 for mis-tag rate in 0.002-0.005 range

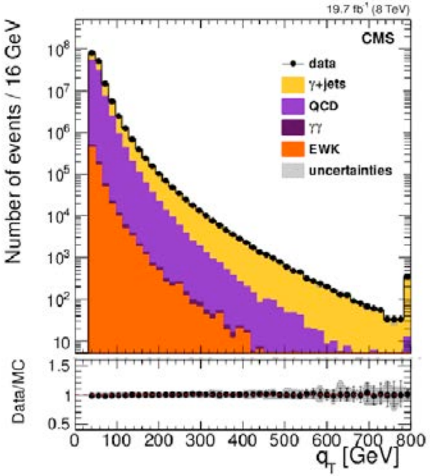
Modeling of particles and event properties: W, Z, photons

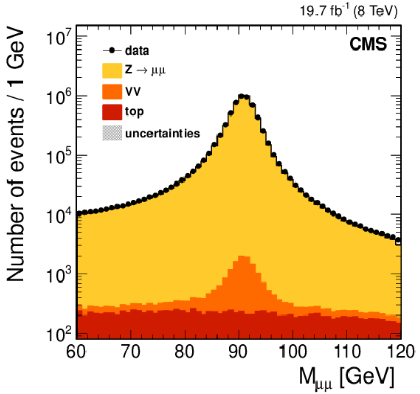
Z mass and p_T distributions were measured from di-lepton p_T‘s: electrons and muons







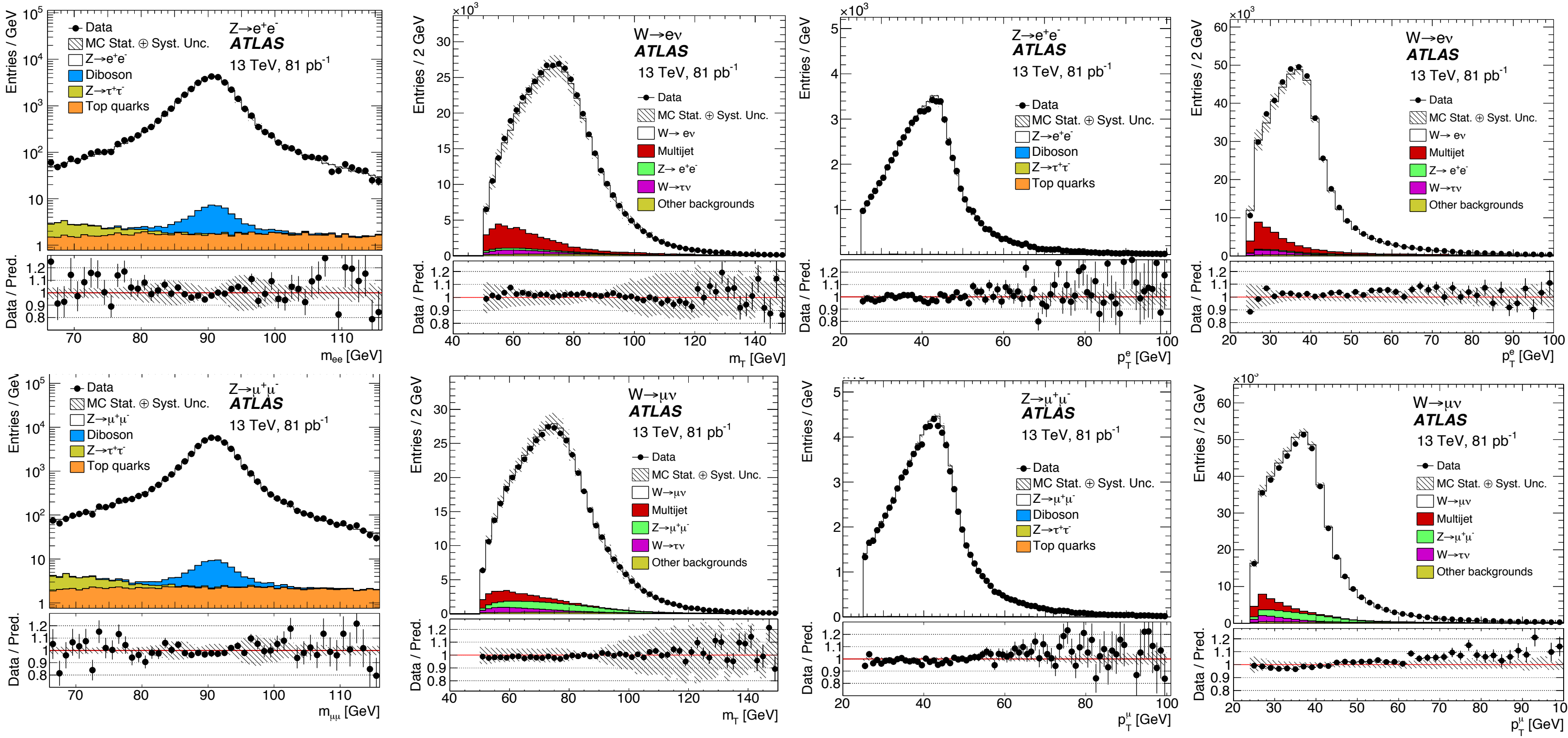




CMS Z mass and Z/γ p_T (q_T in plots) distributions

- ○ Agreement is excellent within statistical and systematic uncertainties
- ○ In the range of $p_T > 200$ GeV for the Z + jets sample, the simulation overestimates the data by a difference that grows linearly with p_T
  - Most probably coming from generator mis-modeling of event topology and kinematics

Modeling of particles and event properties: W, Z, photons

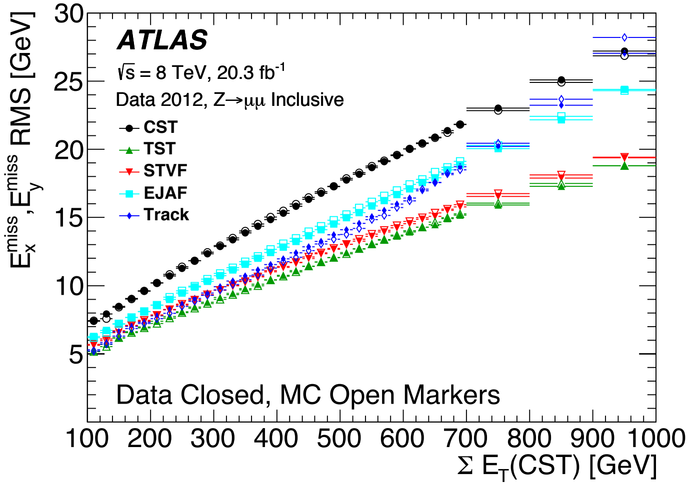


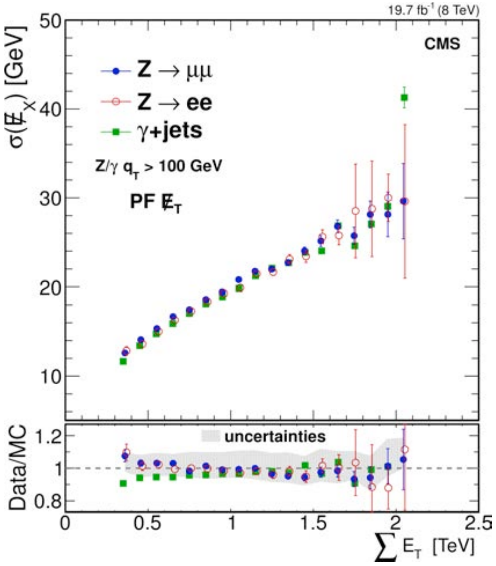
ATLAS W/Z mass and e/μ p_T distributions in the electron and muon W/Z decay channels

- Impressive agreement within <10% in the domain ranges with good statistics

Modeling of particles and event properties: missing E_T

E_T^{miss} measured in $Z(ee/\mu\mu)/\gamma$ + jets samples (E_T scalar sum from the physics objects)





Modeling E_T^{miss} depends on all types of particles, hadronic showers from jets, and un-clustered energy:

- Essential in BSM SUSY, ED, dark matter searches, Higgs characterization
- Critical to calibration of hadronic objects

ATLAS RMS distribution from x and y components of E_T^{miss} vs. scalar sum E_T

- CST, TST, STVF, EJAF refer to different algorithms to reconstruct/calibrate un-clustered energy
- Data-to-MC E_T^{miss} resolution agreement is better than 5%

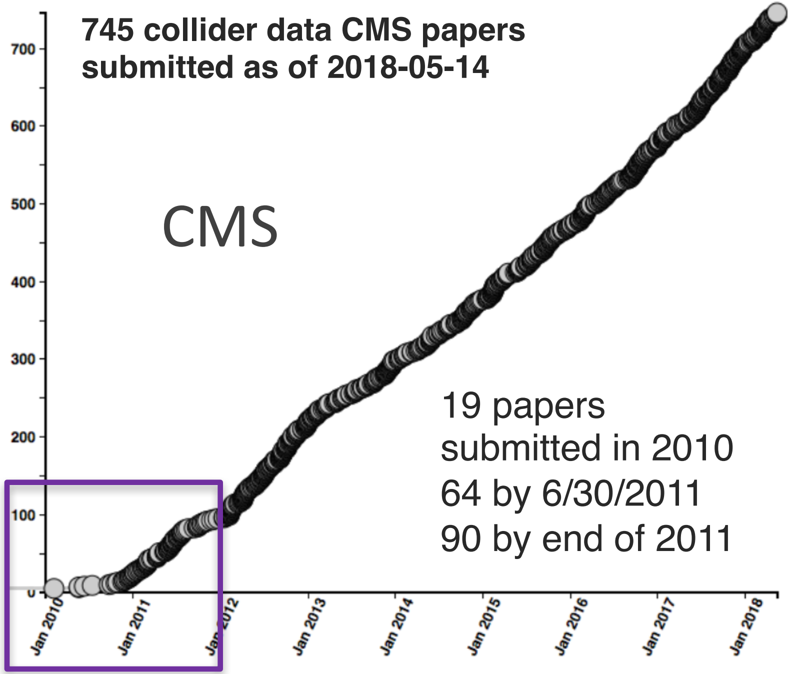
CMS RMS E_T^{miss} projections along x and y vs. scalar sum E_T

- Photons and leptons not in the scalar sum
- E_T^{miss} resolutions are described by simulation within a ~10% accuracy

Simulation and publication turnaround

The ATLAS and CMS examples as compared to the Tevatron experiments

Simulation and publication turnaround



Simulation shortened significantly the detector and physics commissioning time

- Computing model and software worked basically as in designed specifications
- Reconstruction software, calibration and analysis data-driven methods performed out-of-the-box

Examples of papers submitted the first year CMS & ATLAS:

- **CMS:** Dijet cross sections, top pair production, W/Z cross sections, J/ψ and direct photon production, BSM searches for gluinos and leptoquarks
- **ATLAS:** Inclusive jets and dijet cross sections, W/Z cross sections, J/ψ and direct photon production, top pair cross sections, jet shapes measurement

Factors for LHC faster than Tevatron: thousands vs. hundreds of members, technology.

Simulation had a direct impact through the effect on calibration, corrections, analysis methods

Economic impact and cost of simulation in HEP collider experiments

The CMS case

Economic impact/cost of simulation in HEP collider experiments

We define “simulation chain” physics generation, interaction with matter (G4), readout modeling, reconstruction, analysis

- Took 85% of CPU resources used by CMS, while G4 module took 40% of total (Run 1, 2)
- ATLAS’s Geant4 module was 8-9 times slower than CMS’s and the experiment uses significantly more resources than CMS in physics generation
- Rest of resources used in reconstruction and analysis of real collider data

CMS in more detail taken from (analysis of 2012, and May 2015-May 2016 periods)

- 540k/860k core months corresponding to 45/70k CPU cores at full capacity (half in G4)
- Purchasing cost is 5/8 million dollars
- Cost of physical hardware including life-cycle, operation, maintenance
  - 0.9 cents/core hour (FNAL), or 1.4 cents/core hour (what FNAL paid industry in 2017)
- Annual cost of simulation in CMS: 3.5-6.2/5.5-10 million dollars
- Improvements of 1%, 10%, 35% in G4 time performance would render 50-80k, 500-800k, 1.8-2.8M dollars savings to CMS

Computing needs of HL-LHC program are 10-100 times higher depending on simulation and reconstruction solutions implemented – reconstruction will take a larger fraction (pileup)

The future

Better physics accuracy and increased speed in modern computing architectures

The future

Next generation HEP experiments will require orders of magnitude more simulated events with improved physics accuracy

- The effort to improve the physics and computing performance of simulation tools (and reconstruction algorithms) requires immediate attention
- Transistor density growth is more or less keeping with Moore's law but clock speed has been flat since 2003
  - Leverage core count growth in multicore machines, use new generation coprocessors, re-engineer code using fine grained parallelization for accelerators and HPC systems
  - Use of machine learning techniques to replace the detector simulation step

The simulation community is working hard on improved physics models and software & computing R&D to meet the challenges:

A Roadmap for HEP Software and Computing R&D for the 2020s
(https://arxiv.org/abs/1712.06982)
HEP Software Foundation Community White Paper Working Group - Detector Simulation
(https://arxiv.org/abs/1803.04165)

Thank you!

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