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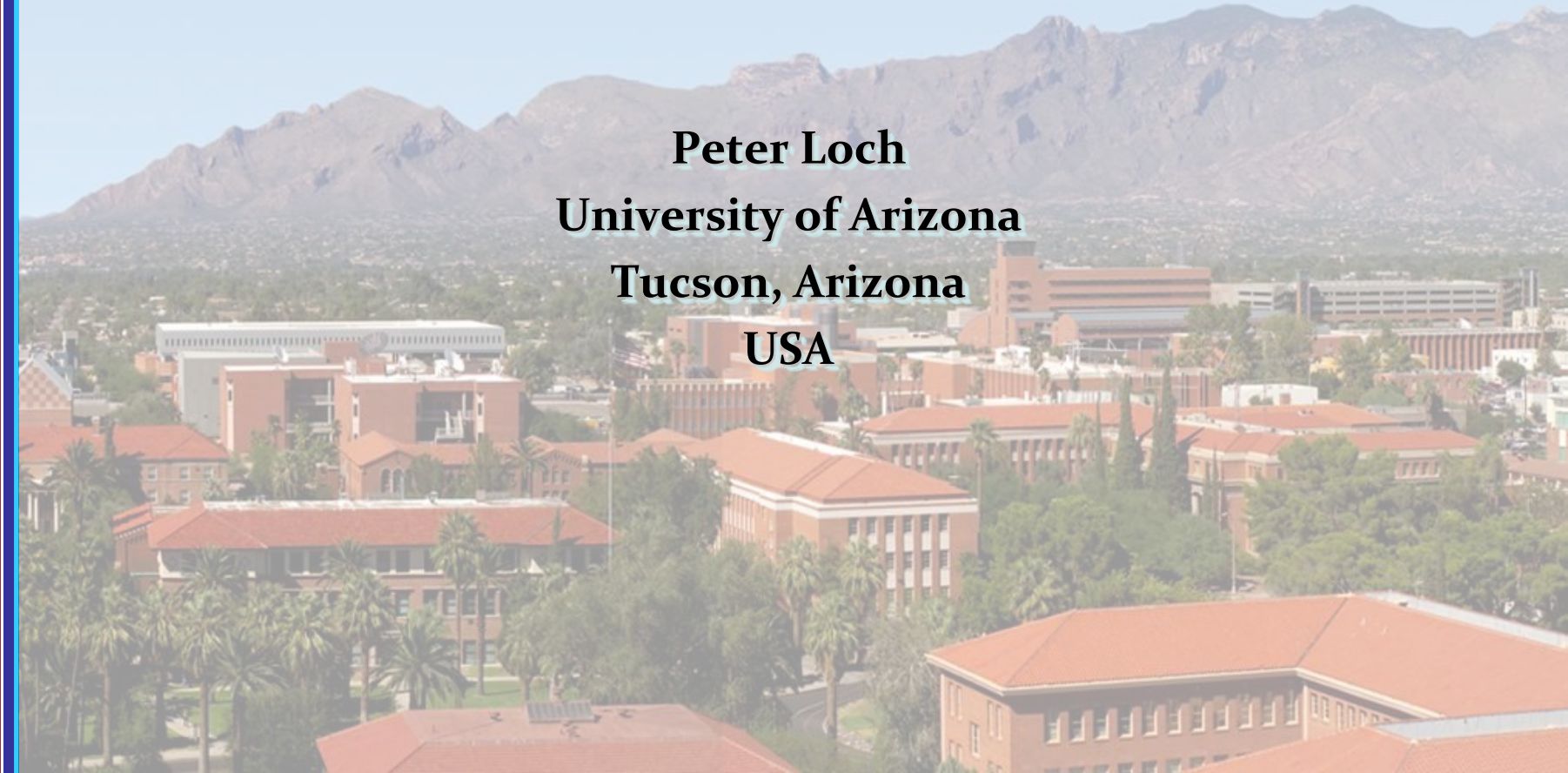
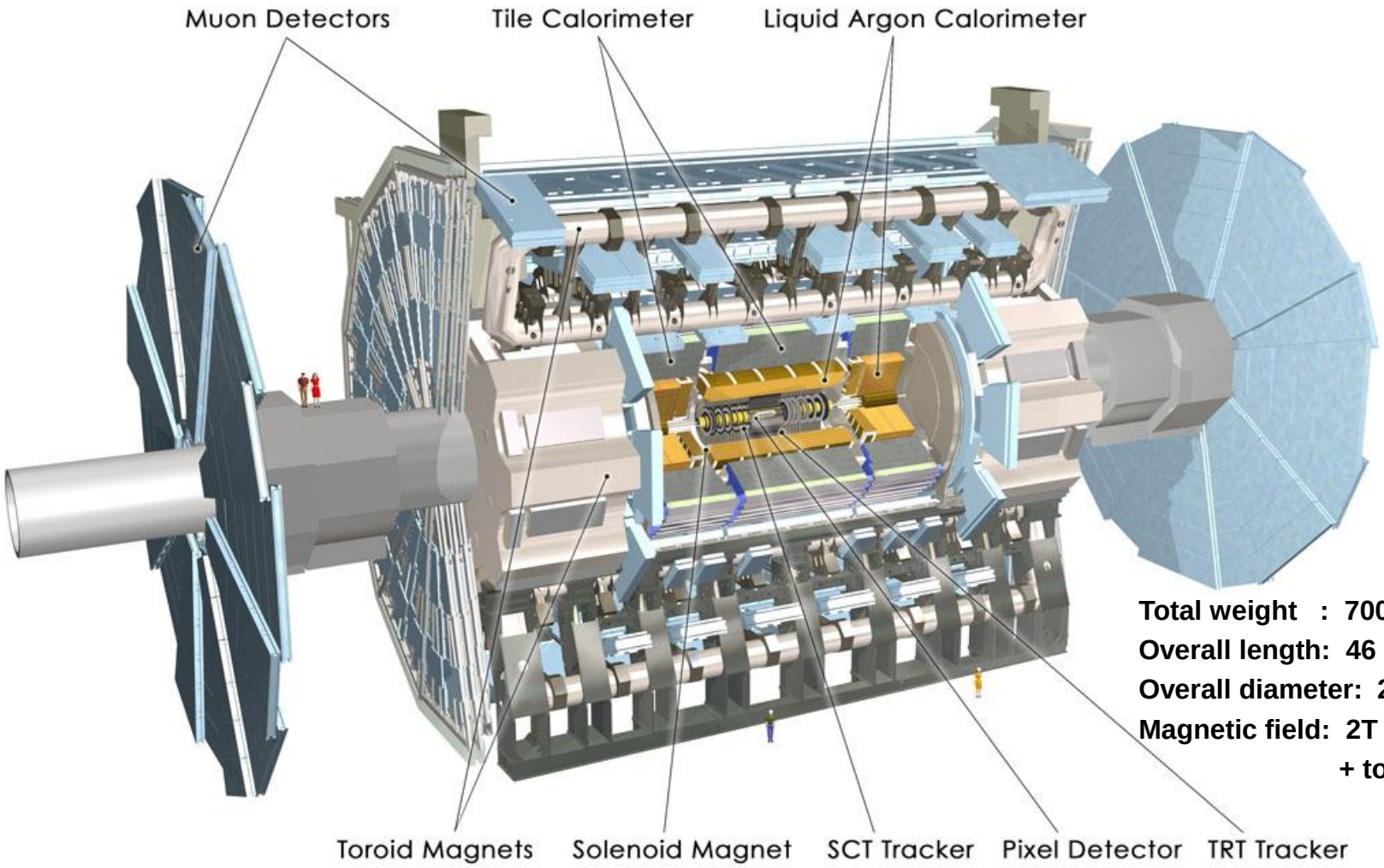
Workshop on Physics at a 100 TeV Collider
April 23-25, 2014, SLAC

Considerations for Detectors for a 100 TeV Proton-Proton Collider



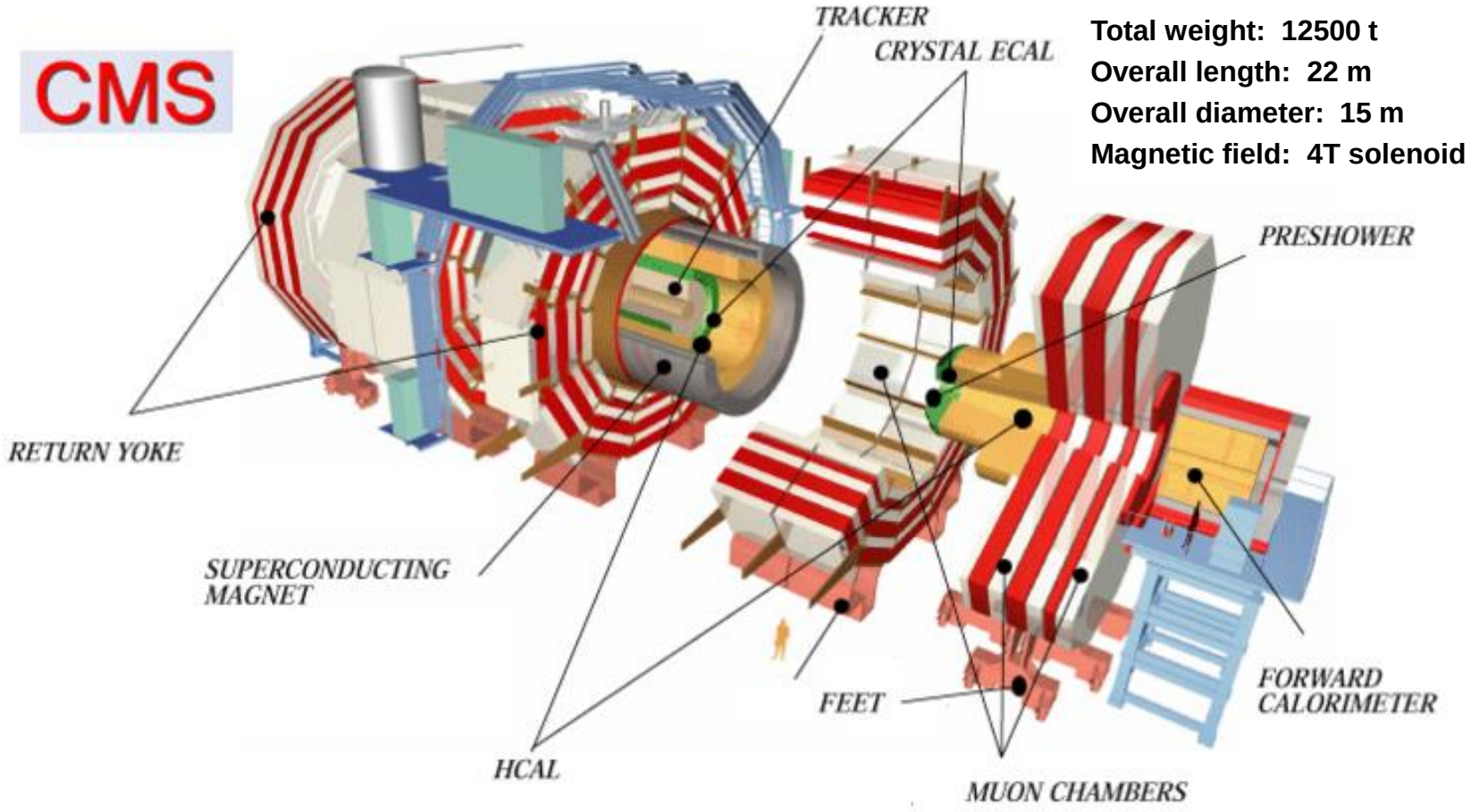
Peter Loch
University of Arizona
Tucson, Arizona
USA

Can we use detectors like ATLAS & CMS at a proton-proton machine at $\sqrt{s}$ = 100 TeV?



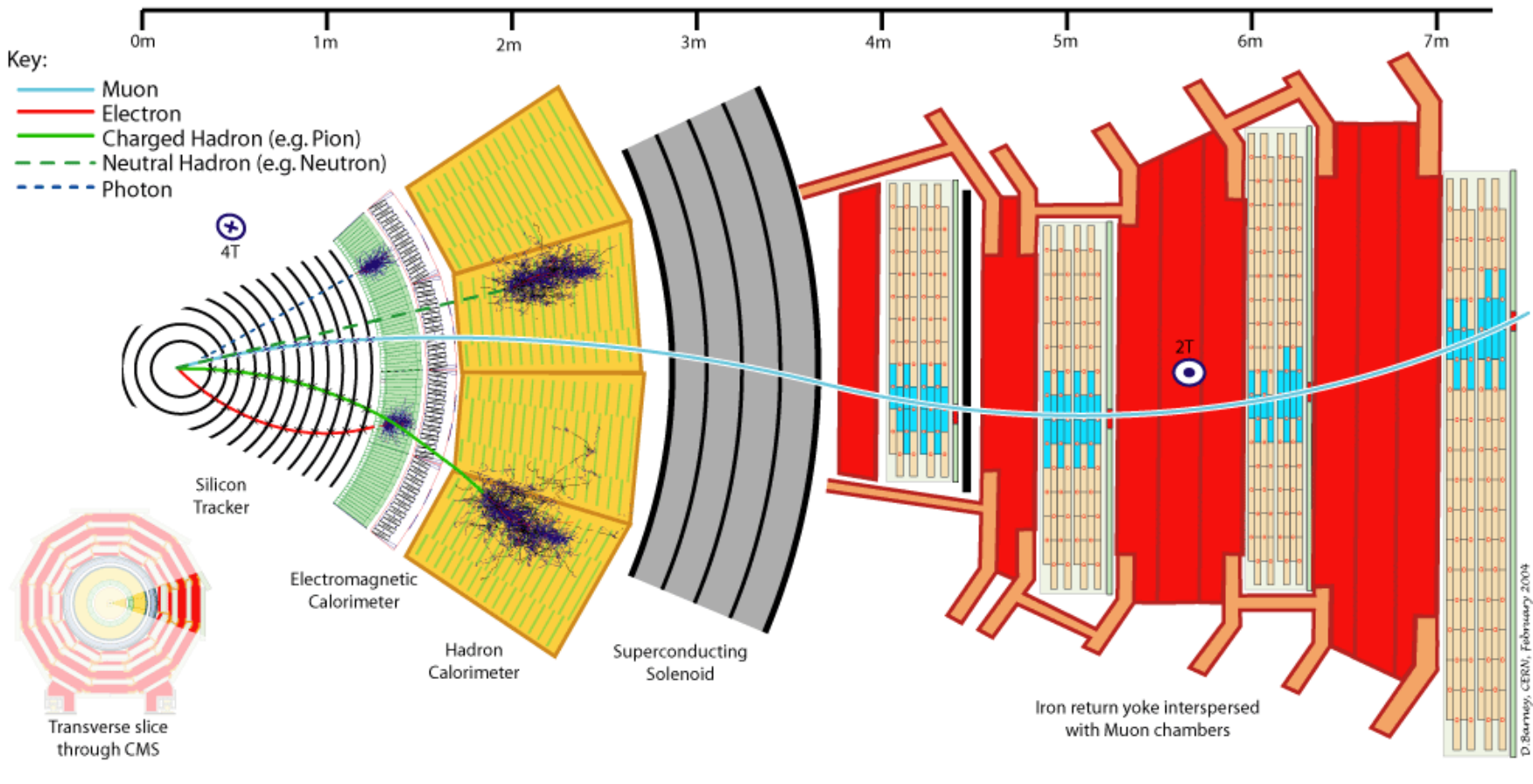
Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid + toroid

Can we use detectors like ATLAS & CMS at a proton-proton machine at $\sqrt{s}$ = 100 TeV?



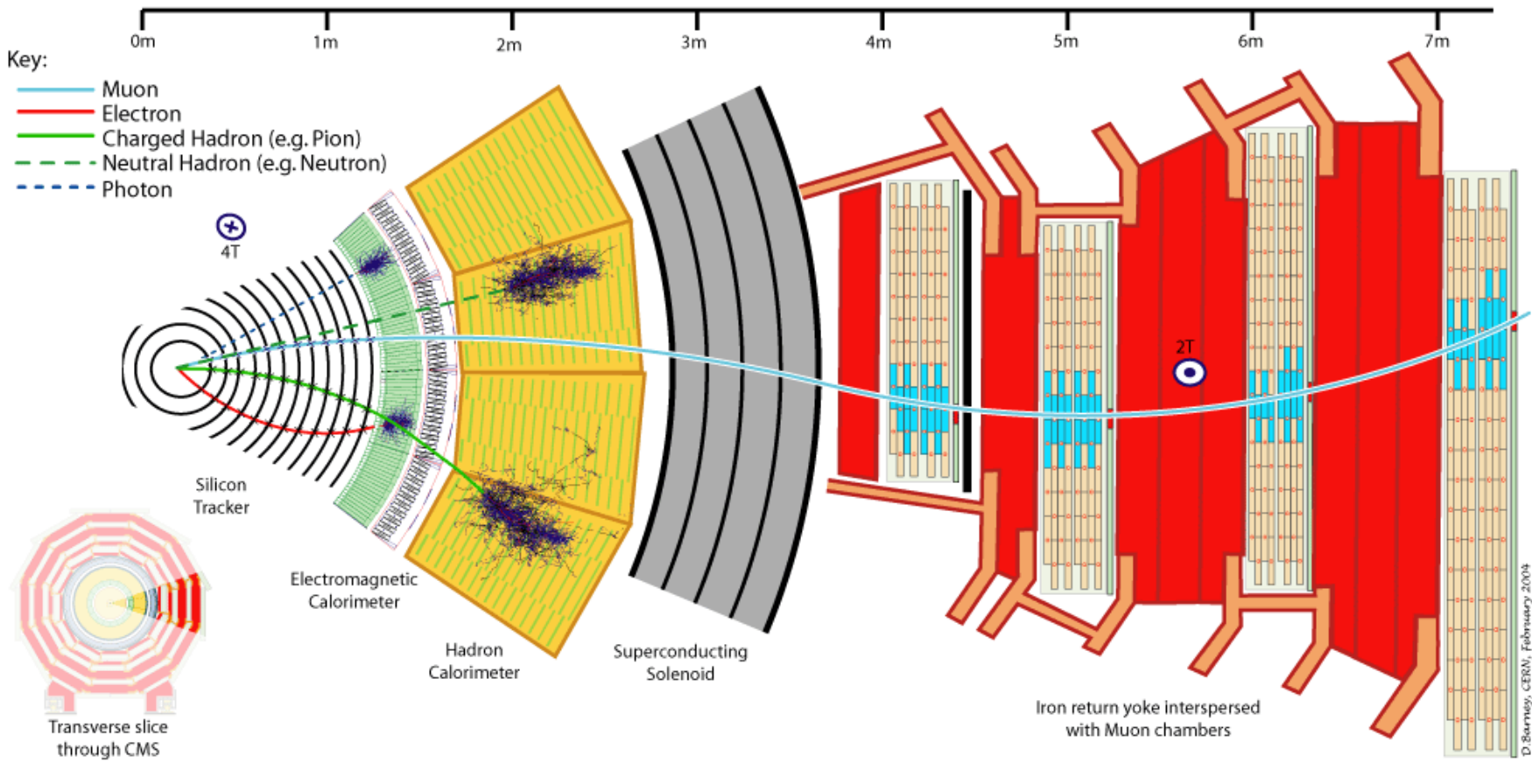
Total weight: 12500 t
Overall length: 22 m
Overall diameter: 15 m
Magnetic field: 4T solenoid

Probably…



… it is always like this, isn't it?

Probably…



… it is always like this, isn't it? *YES – let's go for coffee!*

Does experimental environment require very different detectors?

- Final states – extended phase spaces
  - Higher p_T of signal objects (leptons, photons and jets)
  - Boosted topologies of SM and BSM particle decays
  - Precision physics reconstruction at larger (pseudo)rapidities
- Experimental backgrounds – pile-up
  - Technologies for suppression and correction
  - Signal significance – lowest reliable p_T measurement for physics
  - Long term detector survival in high radiation environment

This talk

- Pile-up
  - Expectations for pile-up at a future high energy/high intensity collider
  - Correction strategies at LHC and their effectiveness
  - High luminosity scenarios at $\sqrt{s}$ = 14 TeV (LHC phase 2 upgrade)
- Detector design considerations
  - Some shopping list from LHC experience
  - Calorimeter design guidelines

Expectations for 100 TeV pp collider

Physics driving pile-up

Inelastic proton-proton cross-section

Collider setup

Beam intensities (= instantaneous luminosity)

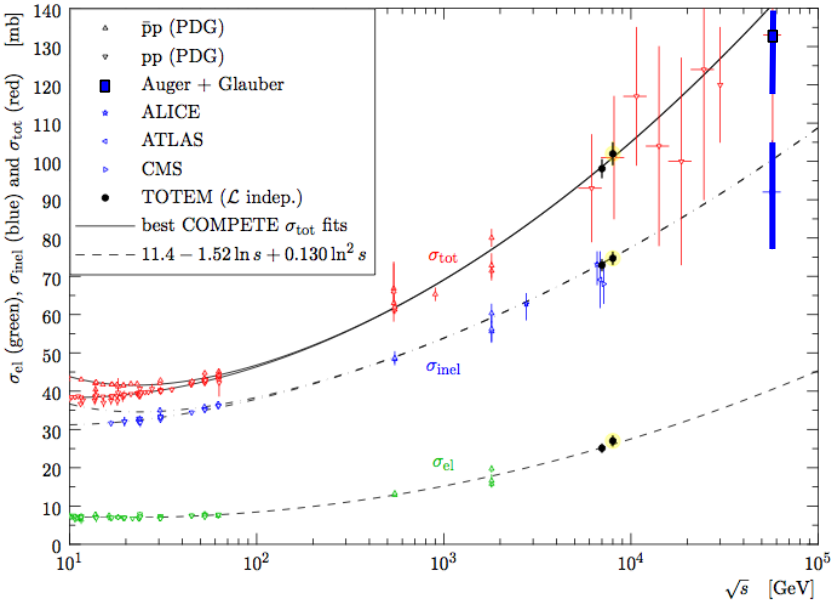
Number of bunches

Frequency

Detector sensitivities

Visibility of pile-up affected by detector acceptance and resolution

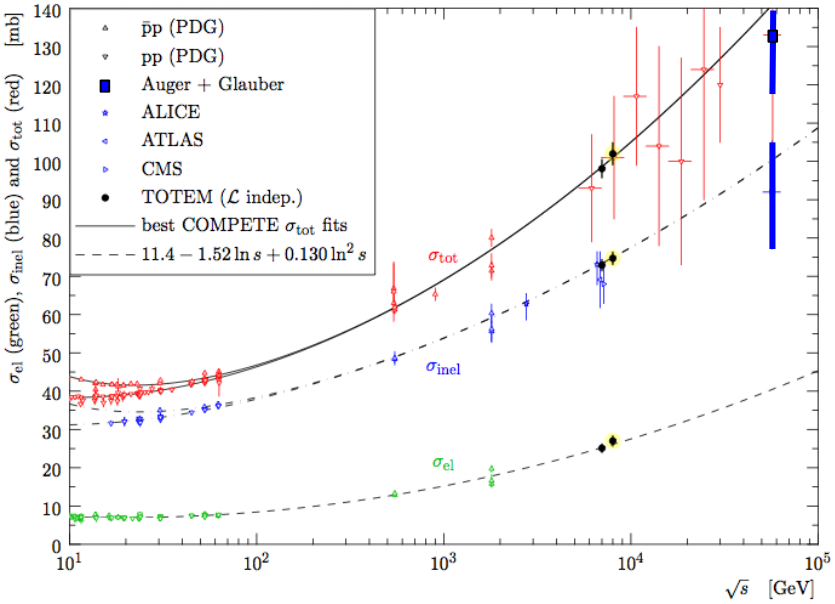
Limits also signal sensitivity



(from talk given by Nicolo Cartiglia, INFN Turin at LISHEP 2013)

Expectations for 100 TeV pp collider

- Physics driving pile-up
  - Inelastic proton-proton cross-section
- Collider setup
  - Beam intensities (= instantaneous luminosity)
  - Number of bunches
  - Frequency
- Detector sensitivities
  - Visibility of pile-up affected by detector acceptance and resolution
  - Limits also signal sensitivity



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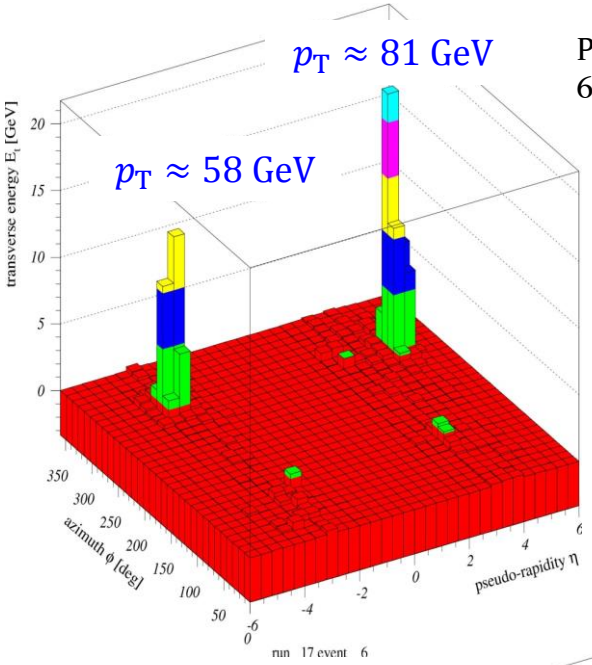
$$\mu = \frac{L \times \sigma_{\text{inel}}}{N_{\text{bunches}} \times f} \Rightarrow$$

$$\mu(100\ \text{TeV}) \approx \frac{110}{70}\mu(8\ \text{TeV}) \approx 1.6\mu(8\ \text{TeV})$$

Assuming a 100 TeV LHC at 2012 intensities and bunch crossing frequencies yields μ up to about 50

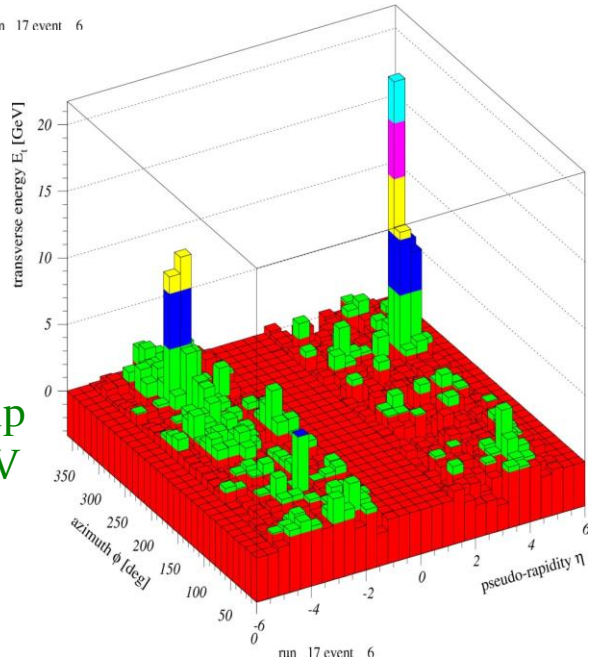
Expectations for 100 TeV pp collider

- Physics driving pile-up
  - Inelastic proton-proton cross-section
- Collider setup
  - Beam intensities (= instantaneous luminosity)
  - Number of bunches
  - Frequency
- Detector sensitivities
  - Visibility of pile-up affected by detector acceptance and resolution
  - Limits also signal sensitivity



Prog.Part.Nucl.Phys. 60:484-551,2008

without pile-up



with pile-up
$\sqrt{s} = 14$ TeV
$\mu = 25$

Features of MB Particle Flow

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U of Arizona
April 23,2014

Pile-up dominated by soft QCD

- Use Pythia8 MB models to generate particle flow
  - Single collision features at particle level
  - Non-perturbative emissions generated by tuned parameterizations of (single and double) diffractive and non-diffractive models

Features important for detector signal reconstruction

- Number density and transverse momentum flow
  - Scales with number of pile-up collisions μ (independent and diffuse emissions)
- Average transverse momentum of particles
  - Independent of pile-up activity – on average same flow pattern for each collision
- Transverse momentum area density
  - Scales with μ – important input for pile-up corrections
- Acceptance limitations
  - ATLAS & CMS typically do not "see" neutral and charged particles with $p_T < 500$ MeV (simplification) – effect on features

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Number Densities in MB

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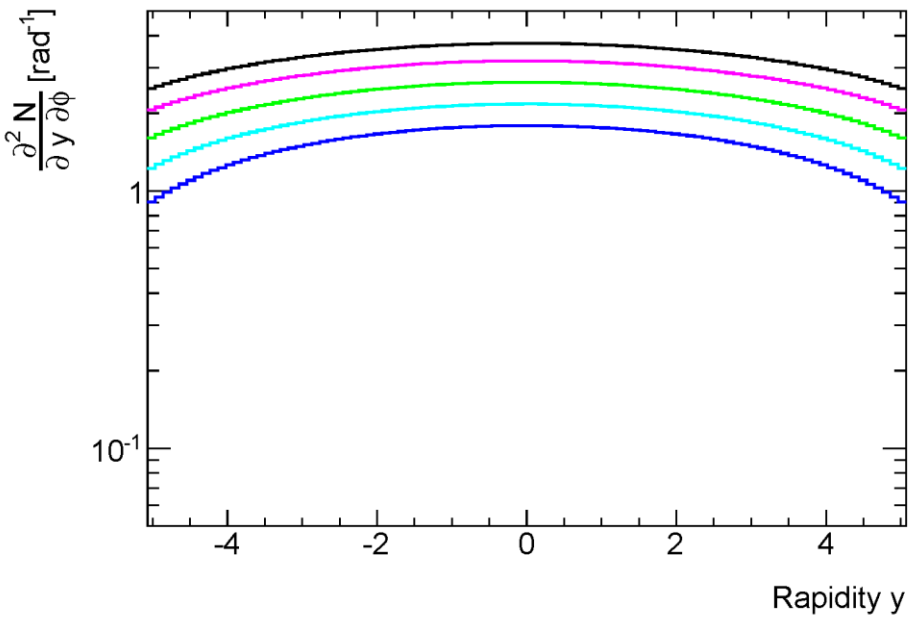


$\sqrt{s}$ = 7 TeV

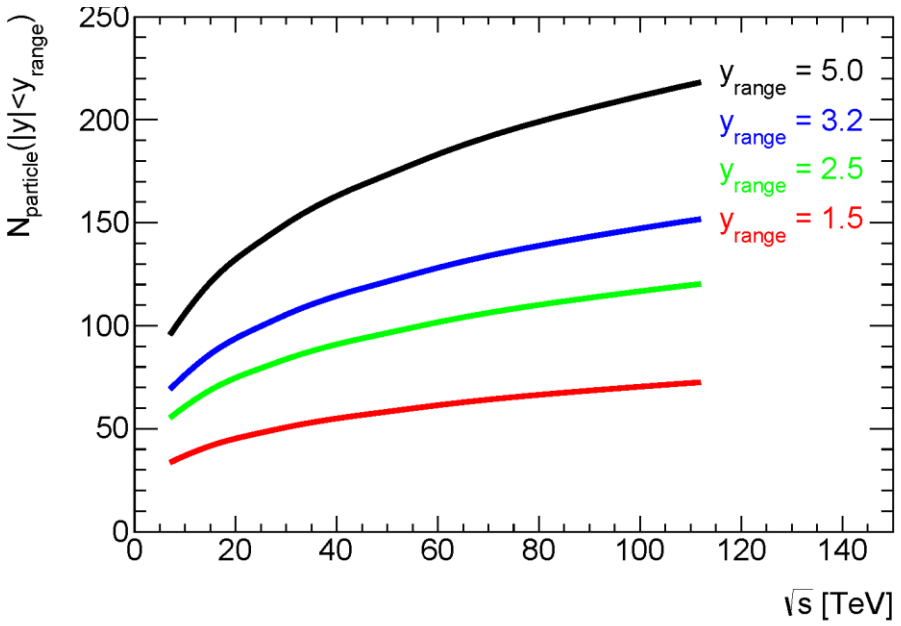
$\sqrt{s}$ = 14 TeV

$\sqrt{s}$ = 28 TeV

$\sqrt{s}$ = 56 TeV

$\sqrt{s}$ = 100 TeV

single MB interactions, all particles!



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Number Densities in MB

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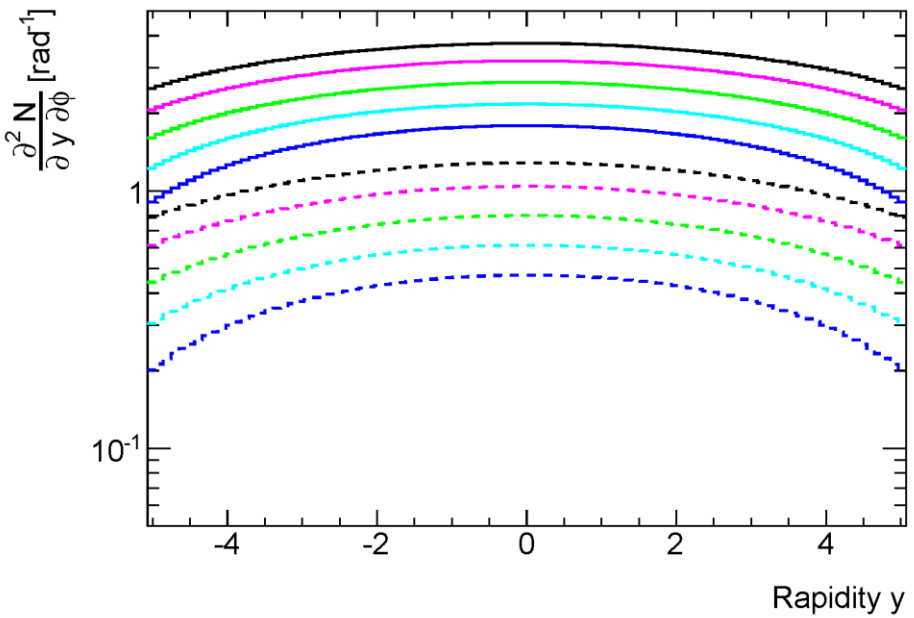

$\sqrt{s}$ = 7 TeV

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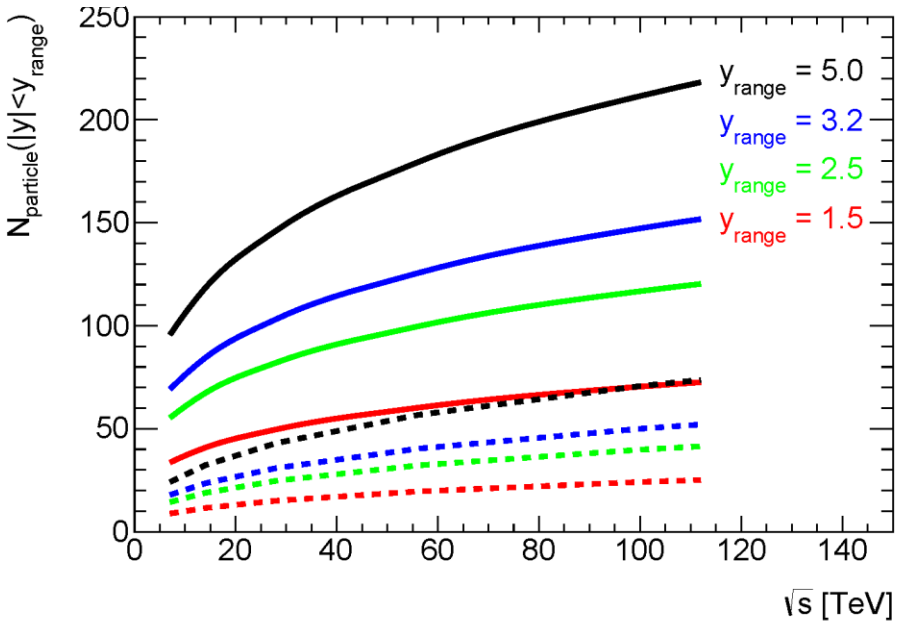
$\sqrt{s}$ = 56 TeV

$\sqrt{s}$ = 100 TeV

single MB interactions, particles with p_T > 500 MeV



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Number Densities in MB

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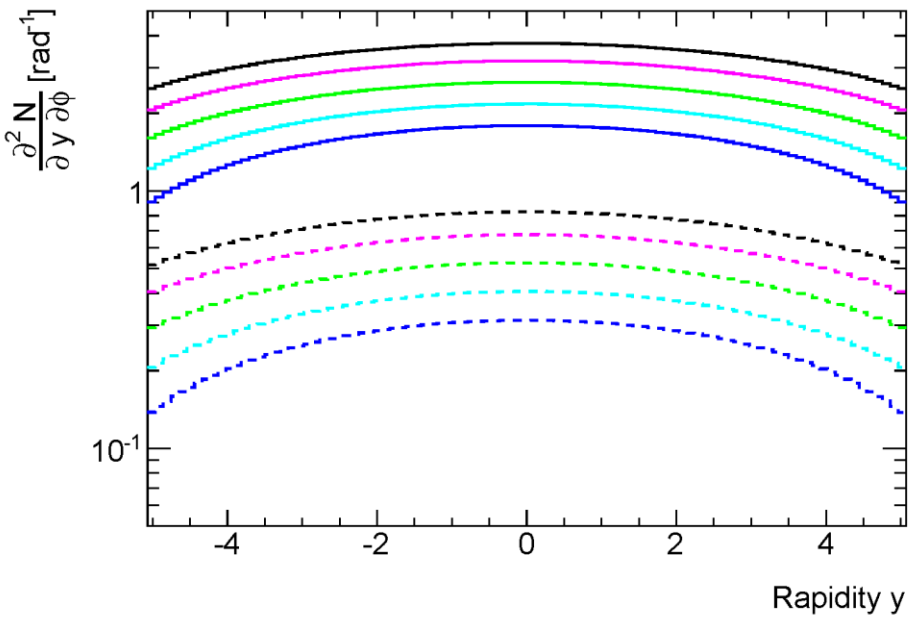


$\sqrt{s}$ = 7 TeV

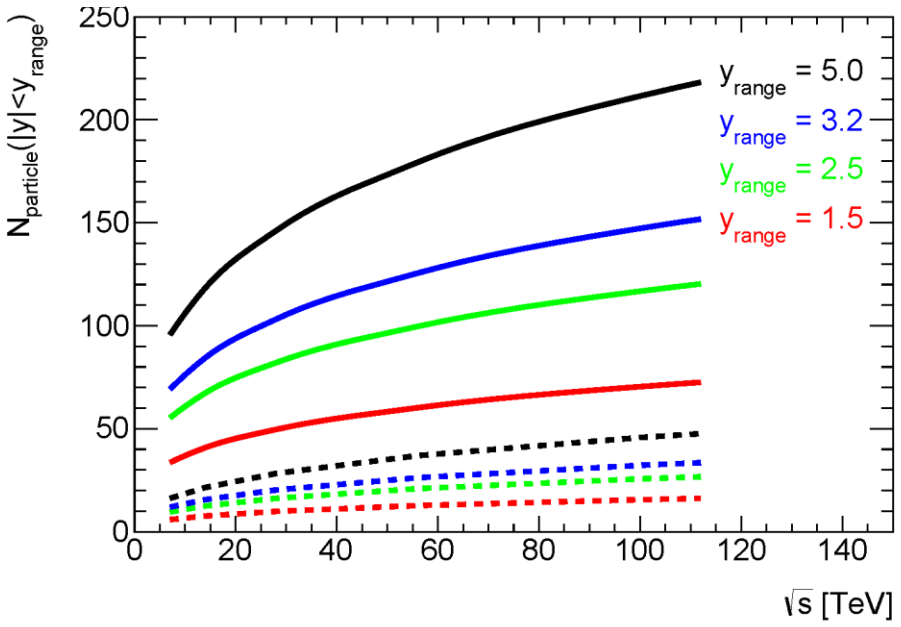
$\sqrt{s}$ = 14 TeV

$\sqrt{s}$ = 28 TeV

$\sqrt{s}$ = 56 TeV

$\sqrt{s}$ = 100 TeV

single MB interactions, charged particles with p_T > 500 MeV



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Transverse Momentum in MB

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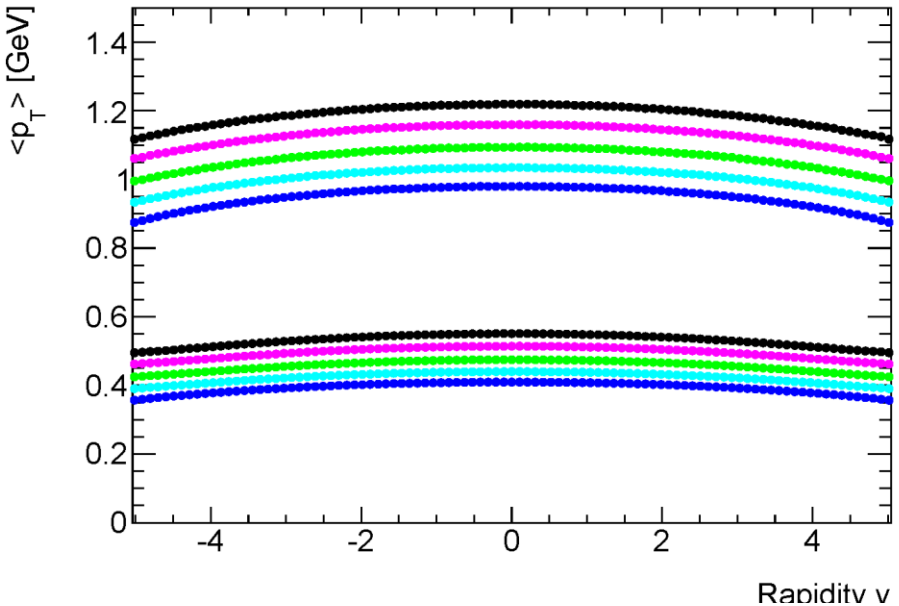


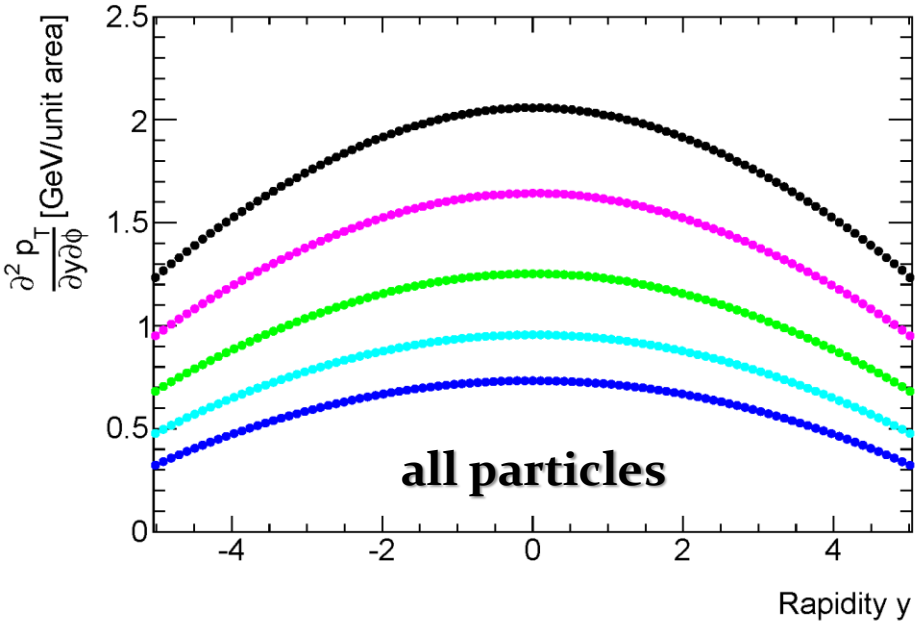
$\sqrt{s}$ = 7 TeV

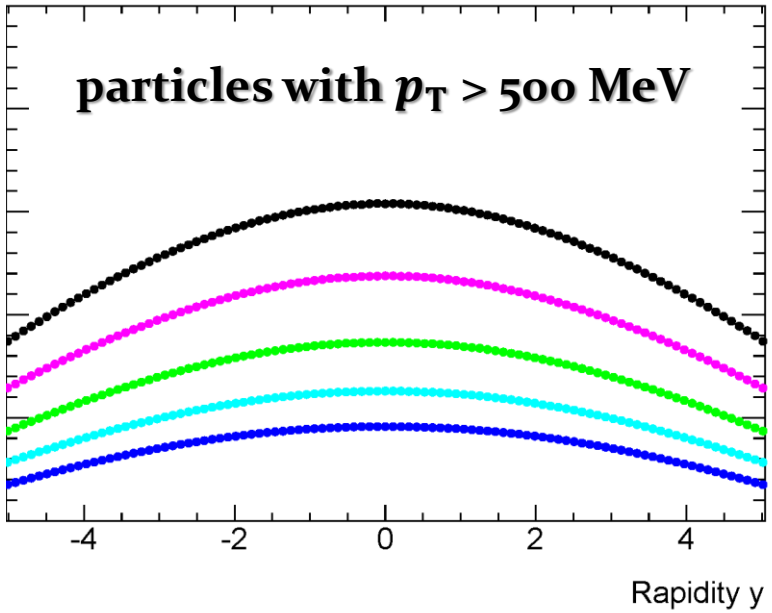
$\sqrt{s}$ = 14 TeV

$\sqrt{s}$ = 28 TeV

$\sqrt{s}$ = 56 TeV

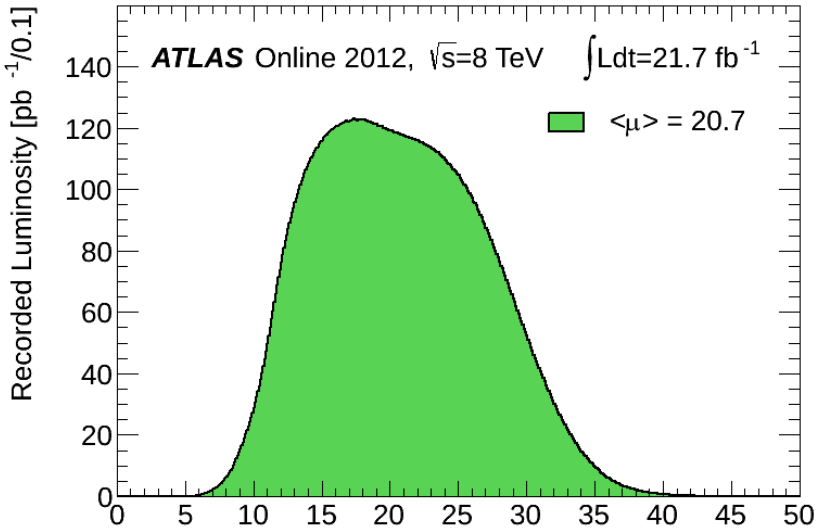
$\sqrt{s}$ = 100 TeV

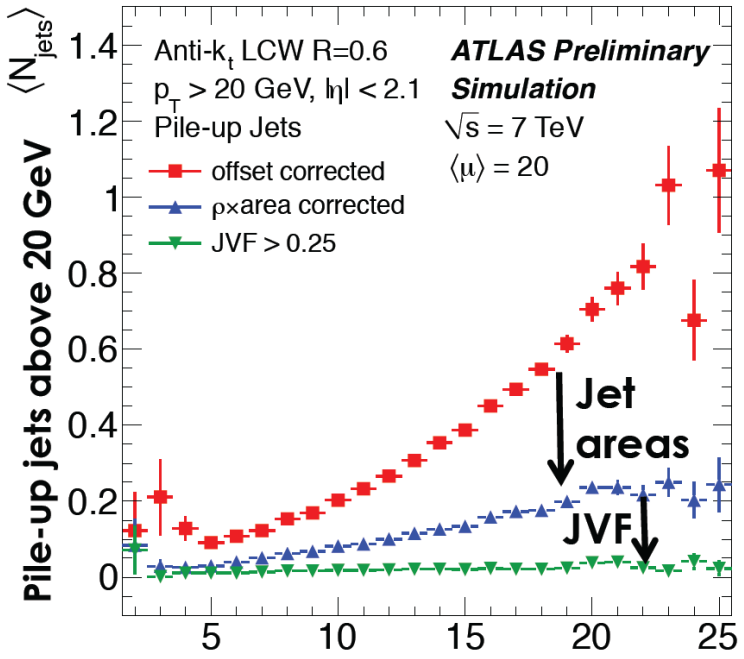




Present experiences in ATLAS & CMS

- Pile-up significant in 2011 and 2012 running
  - Significant effects especially on hadronic object reconstruction performance
- Corrections needed to mitigate effects
  - Jet area based approaches used for calorimeter jets in both ATLAS & CMS
  - Track-based approaches take advantage of hard scatter vertex reconstruction (modified jet vertex fraction in ATLAS, charged hadron subtraction in CMS)





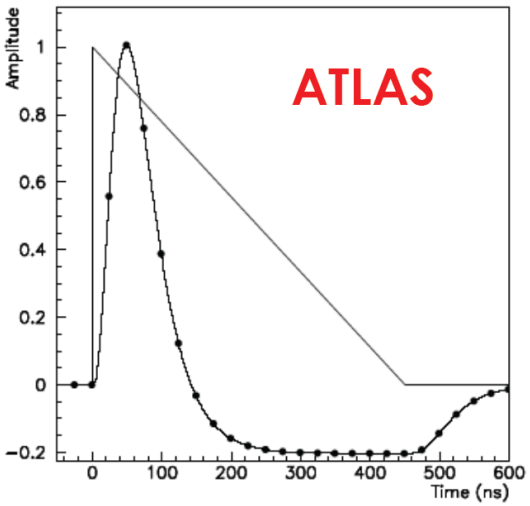
(from talk given by Ariel Schwartzman (SLAC) at BOOST 2013)

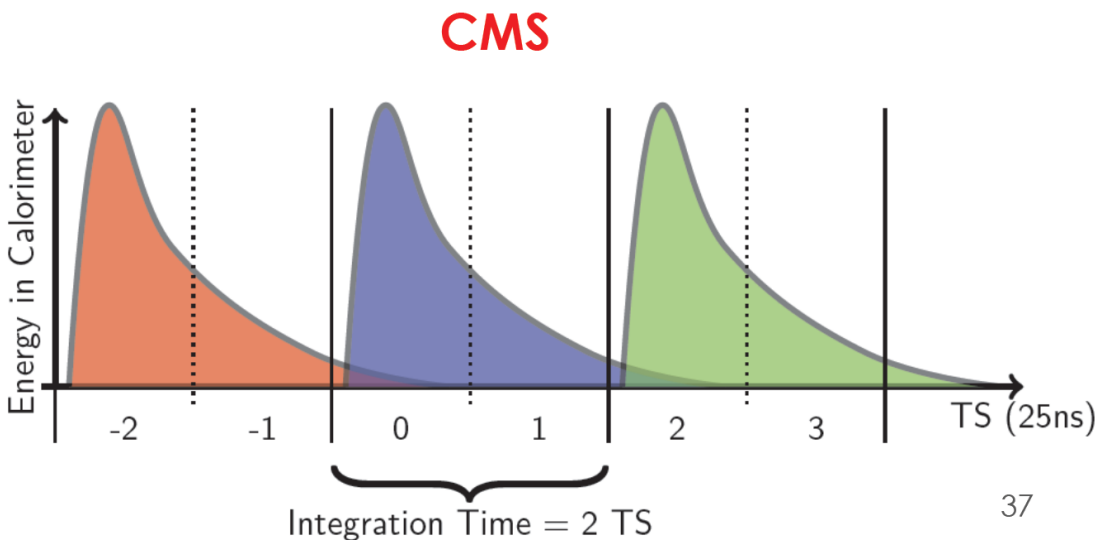
Pile-up signal representation

Depends on detector (mostly calorimeter) technology

CMS – highly granular EM and coarser HAD with (combined) few (2-3) longitudinal segmentation and fast shaped uni-polar readout – little out-of-time pile-up

ATLAS – highly granular EM and coarser HAD with 3-7 longitudinal segments and bi-polar readout with net zero integral – considerable out-of-time pile-up helps with cancellation of in-time pile-up on average

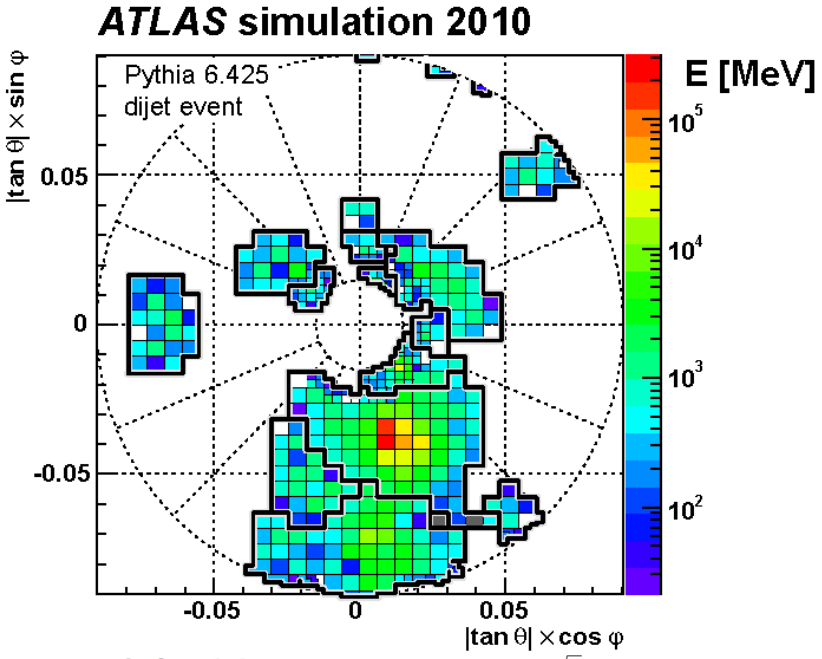


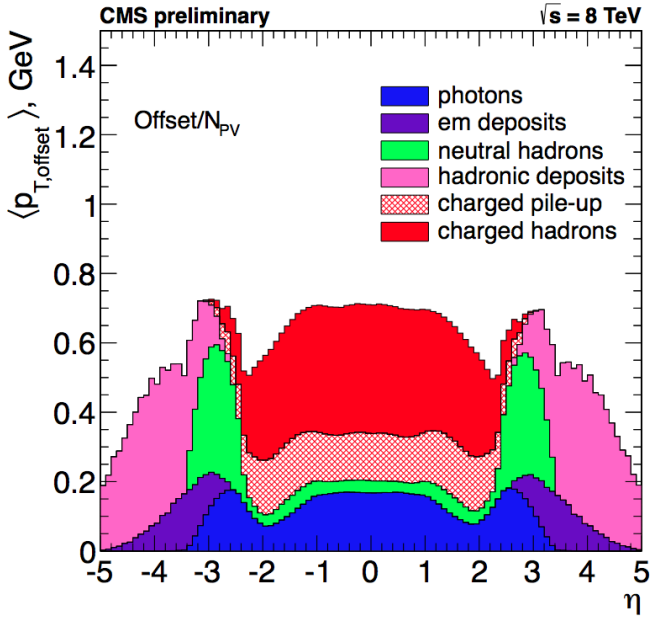


(from talk given by Ariel Schwartzman (SLAC) at BOOST 2013)

Particle flow and topological cell clustering

- Topological cell clustering in ATLAS calorimeter attempts to reconstruct spatial energy flow
  - No straight forward association of clusters with signal or pile-up – better in e.g. jet context
- Particle flow signal in CMS combines tracking and calorimeter signal
  - Use of track-cluster matching provides precise kinematics of charged hadrons in the regime of "good" track momentum resolution – sources of remaining calorimeter signals are estimated from shapes etc.





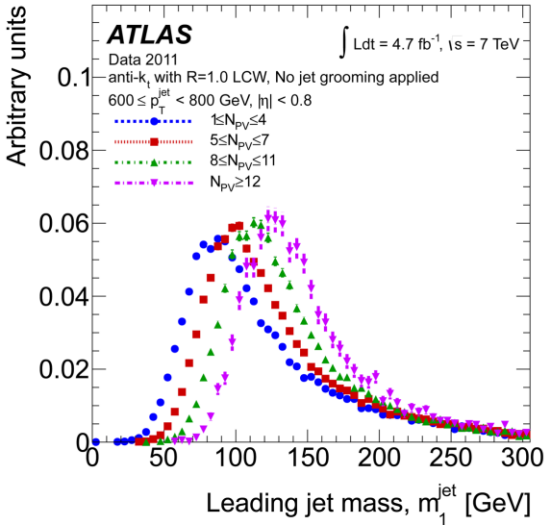
(from talk given by Phil Harris (CERN) at BOOST 2013)

Jet substructure

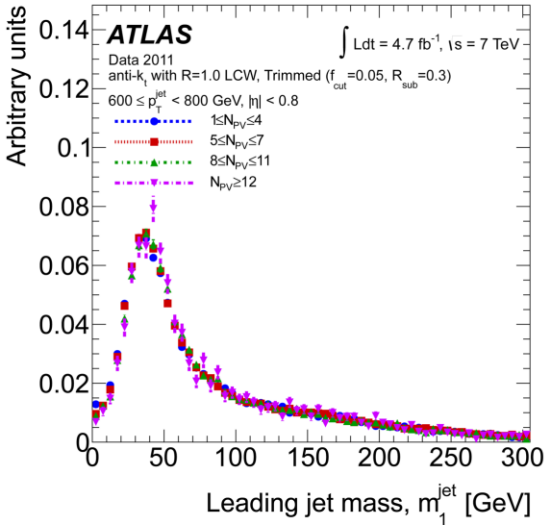
- Highly granular calorimeters allow substructure analysis at small scales
  - Application of all recent jet grooming techniques is now part of many standard analyses
- Pile-up is controlled
  - Modelled well enough & focus on observables little affected anyway
  - But details of pile-up are often not modeled well especially outside of jets (like for missing transverse momentum)

(ATLAS Coll., JHEP 1309 (2013) 076)

Ungroomed



Trimming $f_{\text{cut}} = 0.05,\ R_{\text{sub}} = 0.3$



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Outlook on LHC Run II

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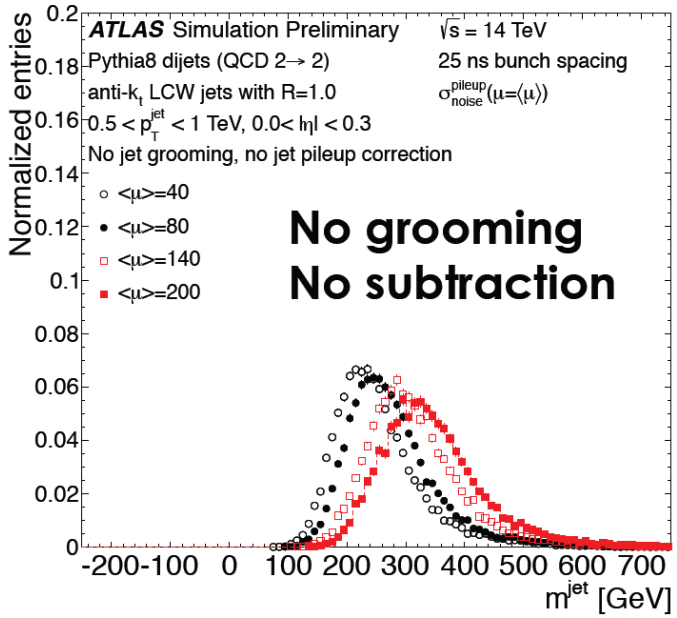
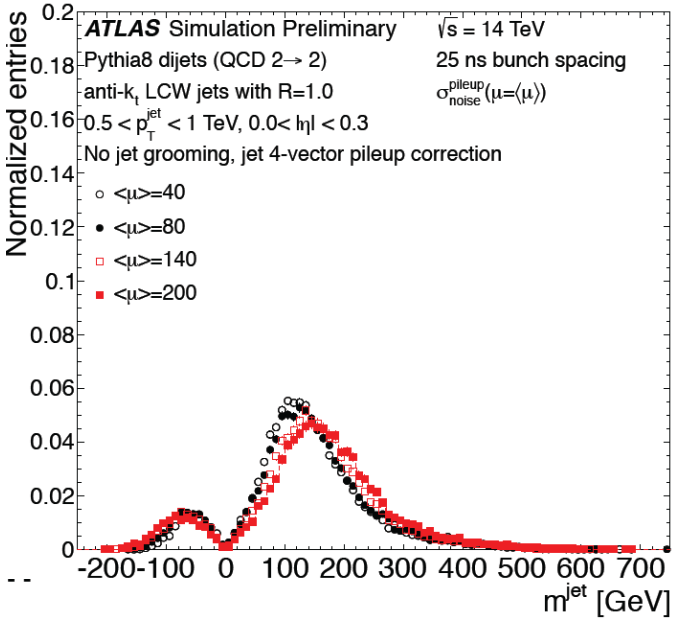
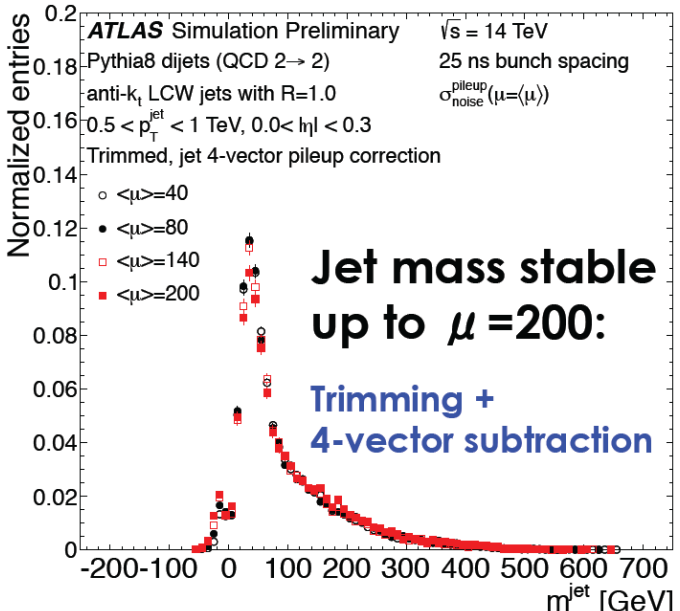
April 23,2014



jet 4-vector area based pile-up subtraction →



trimming ↓



Higher energy and intensities

- Detailed studies with a well-known detector useful for preparation for even higher energy scenarios
  - Understand effectiveness of signal definitions and jet grooming techniques

Not too concerned about pile-up

ATLAS & CMS like detectors

- Studies with pile-up scenarios approaching 200 pp interactions per bunch crossing indicate both topological clusters and particle flow will work well
- Small objects like electrons, photons, and muons are likely not much affected by pile-up even in a future high intensity environment – some attention needs to be paid to isolation for EM objects…

Mitigation techniques well advanced

- Global corrections for large objects like jets well understood – substructure techniques developed and refined
- Will need dedicated adjustments to detector specifics but so far deliver promising performance even in most intense pile-up at LHC

Loss of sensitivity to substructure

- Focus on substructure observables not too affected by pile-up in terms of the structural analysis – kinematics still under study but techniques applied for resolved jets seem to be promising…

Tracking

Resolution requirements can be stringent

- Spatial resolution of O(10 μm) to efficiently separate O(10-100?) pile-up vertices – depending on "beam crossing diamond" size…
- Good (transverse) momentum resolution beyond up to several 100 GeV – highly boosted jets may be too compact for calorimeter but may have stiff prongs (or core) to be resolved
- Tracking is essential for refinement of kinematics (particle flow, leptons), in-situ calibration reference, vertex associations, pile-up suppression, …

Operational concerns

- Mostly radiation hardness of today's silicon pixel based trackers (best spatial resolution!) in environments with significantly higher particle fluxes

Physics performance

- Extend tracking to more forward regimes – today only 50% of the full detector coverage is instrumented with tracking (physics case: VBF/VBS signatures in high pile-up…)

Calorimeters (1)

Biggest concerns

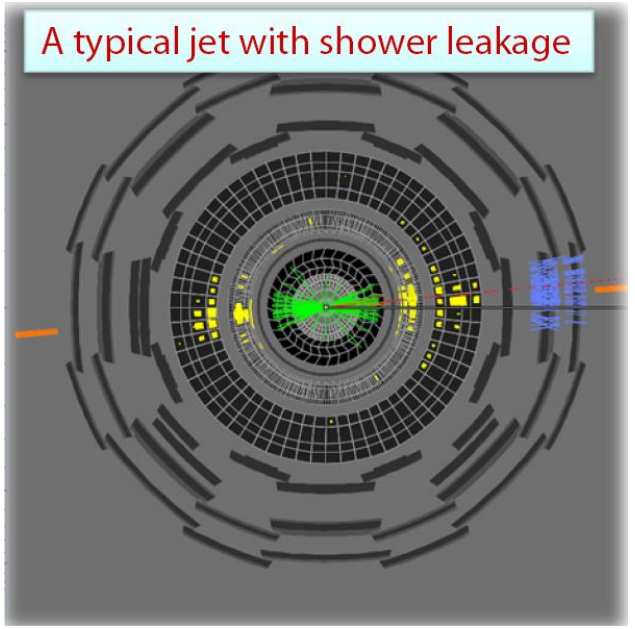
- Need to avoid tails in (jet) response to allow effective searches – avoids fake missing transverse momentum etc.
- Most uniform response across the whole acceptance in pseudorapidity

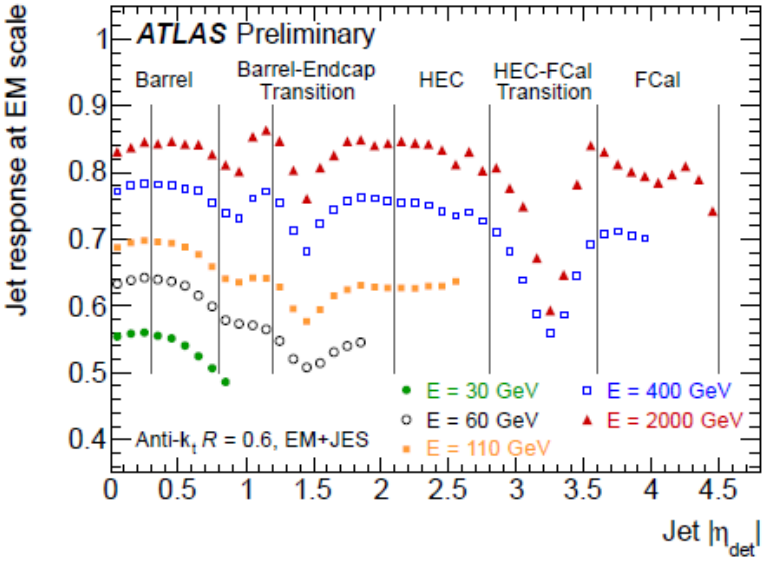
Absorption characteristics

- Depth for hadrons needs to accommodate O(10) TeV jets (energy)
- High energetic EM particles should be stopped in EM calorimetry – present day calorimeters may be a bit shallow…

Signal stability

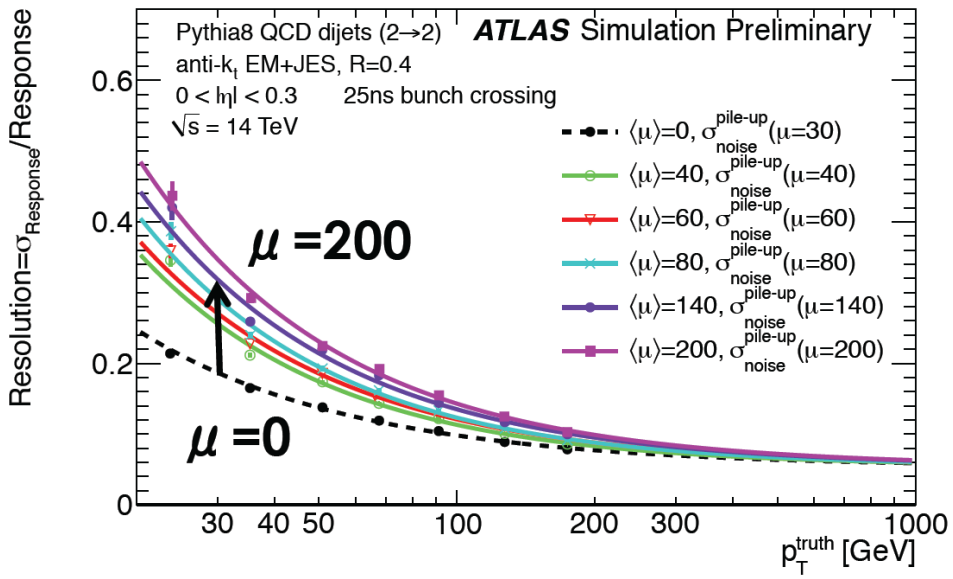
- Highly radiative environment may affect signal yield and proportionality to deposited energy
- Need to focus on technology providing stable signals (within a few %) for decades





Calorimeters (2)

- Electron/photon energy response
  - Excellent signal linearity and resolution possible even in the most hostile environments
  - High energy resolution limit comparable to zero
- Jet energy resolution
  - Lower energies strongly affected by pile-up
  - High energy limit affected by hadronic calibration – but few % (≪10%) possible



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Calorimeter readout structure

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U of Arizona
April 23,2014

High granularity

Lateral and longitudinal

Particle identification, jet substructure, pile-up suppression – c.f. CMS Phase-I upgrade of HCAL

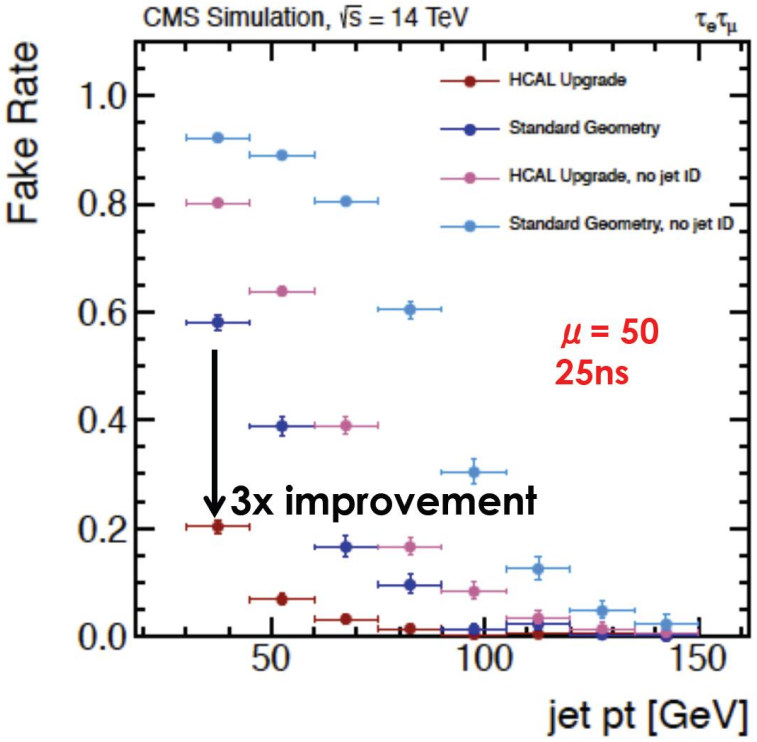
Optimization of shower size versus (η,ϕ) projective readout – better resolution of intrinsic energy flow in jets

Absorption and signal formation

Ultra-fine readout

Resolve individual shower structures - supports precise shower/track matching in particle flow techniques

Typically expensive (tungsten absorbers, silicon pixel readout in large volumes) – cheaper with scintillator mini-tiles (CALICE)…



Calorimeter Signal Formation

P. Loch
U of Arizona
April 23,2014

Shower size control

- Small (lateral) shower extensions suppress coherent component of pile-up noise
  - Limited correlation range
- Means very dense absorbers
  - Small sampling fraction – loss of energy resolution
  - Trade sampling fraction for sampling frequency to maintain resolution – digital calorimetry (e.g. for ILC) – lots of (thin) active layers instead of few (thick) ones

Compensation

- Equalizing EM and HAD response is desirable…
  - C.f. ZEUS calorimeter reached intrinsic limit in hadronic energy resolution
- …but relies on catching slow shower components…
  - Long signal integration times cannot be afforded in high pile-up conditions
- …or suggests homogeneous calorimetry
  - Expensive in large scale applications (like BGO)
- Not a big issue
  - We know how to dynamically calibrate hadronic signals – particle flow, local hadronic calibration of topological clusters

Shower Sizes

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U of Arizona
April 23,2014

Problem

- Particle flow scales well in (η,ϕ) space
  - Individual particle showers in calorimeter ~cylinders with R ~ 15 cm (Cu/Fe) independent of direction (typical)
  - Best seen so far with W (ATLAS FCal) R ~ 10 cm – not too impressive, jet size at high pseudorapidity still smaller…

Solution?

- Digital readout with dense absorber in forward region
  - Radiation concerns (W/Si) and (W/Scint)
  - Electron response (important?) highly suppressed
- Low sampling fraction/high frequency
  - ATLAS FCal < 1% but high sampling frequency (O(10k) elecrodes in cylinder with 45 cm radius)
  - Very good high energy resolution
  - Stochastic fluctuations irrelevant (?)
  - But spatial resolution still not better than 0.2 x 0.2 to 0.4 x 0.4

Requirements for detector research

P. Loch
U of Arizona

Physics use cases

- Need to collect a catalogue of physics final states to be studied with respect to detector performance
  - Not too limiting – need to be able to discover the "unknown unknown" together with the "known unknown"
- Dynamic range of detector
  - Upper limit from kinematic limit – but what is the lowest energy object of interest?
  - Spatial resolution requirements for tracking and calorimetry

Experimental conditions

- Suggestions for beam configurations
  - Beam energies, bunch spacing, instantaneous luminosities, pile-up, beam crossing angle, …
  - Determines pile-up, radiation environment, detector survival requirements, …
- Radiation and survival
  - Predictions for radiation levels at various locations in the detector
- …

Detector design guidelines

- Consider using ATLAS/CMS full simulation to study 100 TeV collisions
  - DELPHES etc. is nice, but has limited messages which may be severely misleading concerning detector performance and capabilities – both optimistic and pessimistic…
  - Needs significant help (and resources?) from the experiments – not easy with upcoming LHC Run II and upgrades
  - Maybe a exploratory study is possible – pile-up + lepton final state signal?
- Simplify (homogenize) technologies
  - Avoid complex transition regions in calorimetry as much as possible – in particular between EM and HAD
  - Finer readout at higher pseudorapidity – only useful if shower size can be reduced…
- Explore tracking in forward region
  - Helps with jet categorization, pile-up suppression, etc. – good physics case outside VBF/VBS based searches?

First conclusions

Detector design

Detectors similar to ATLAS and CMS seem to be a very good starting point for a 100 TeV collider experiment

Simplification and homogenization should be paramount design guideline – "have calorimeter design will travel" was nice in the pioneering days of SSC and LHC but we should come up with detectors with easier to calibrate response characteristics – seems doable!

Details of trigger and readout need to be hammered out of course – no "region of interest" triggers are probably non-optimal

Missing transverse momentum reconstruction requires no azimuthal discontinuities and largest possible pseudorapidity coverage

Performance

We learned a lot from LHC Run I – significant progress from Tevatron days with respect to jet finding, calibration and feature measurements

We have good tools for dynamic hadronic calibration, jet refinement and substructure reconstruction – can help to finalize detector requirements (knowing the tools already now helps!)