Calorimetry at Future Particle Colliders – Technologies & Reconstruction Techniques

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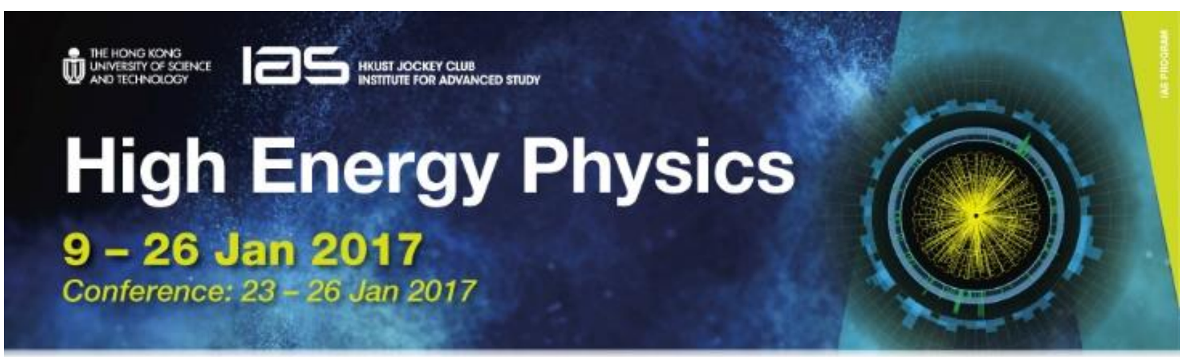

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Preliminaries

This talk …

… is not intended to give a comprehensive review on all possible scenarios for calorimeters at future colliders

… rather, it is intended to highlight the ability of present day and future calorimeters in the high performance reconstruction of physics observables that are important for the physics potential of detector systems at these machines

… has a focus on calorimeters at future proton colliders but will discuss some designs for e^+e^- colliders as well

… is informal!

Please ask questions – if I am not able to answer within the allotted time of this seminar, I am here for another two weeks

Also I am very happy discuss important topics relevant for higher energy/luminosity (hadron) colliders, like …

… jet reconstruction – inputs, algorithms, calibration strategies, performance evaluations

… jet substructure and boosted object analysis

… missing transverse reconstruction

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Roadmap for this Talk

Introduction

General motivation for application of calorimeters @ future colliders

Energy measurements with calorimeters – recalling the basics

Reconstructing physics with calorimeters - segmentation

Calorimeters at future e^+e^- colliders

Expectations for operational environment

Highly segmented imaging calorimeters – CALICE

Calorimeters at future proton colliders

Expectations for operational environment, long term survival

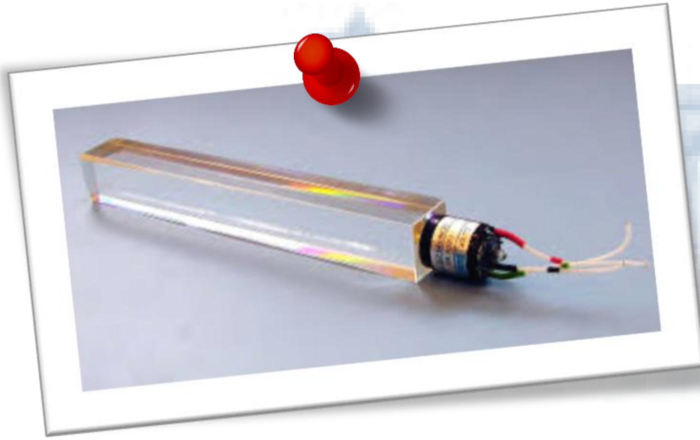
Coverage, acceptance & signal processing

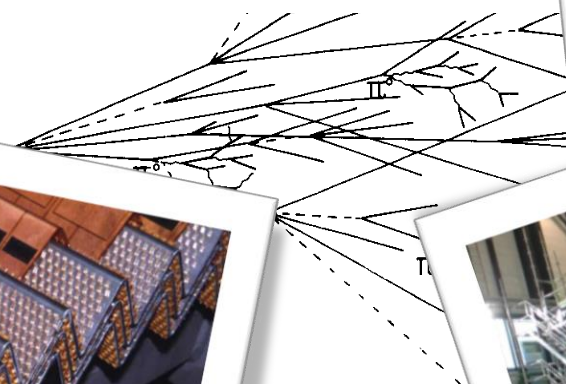
Jet physics aspects

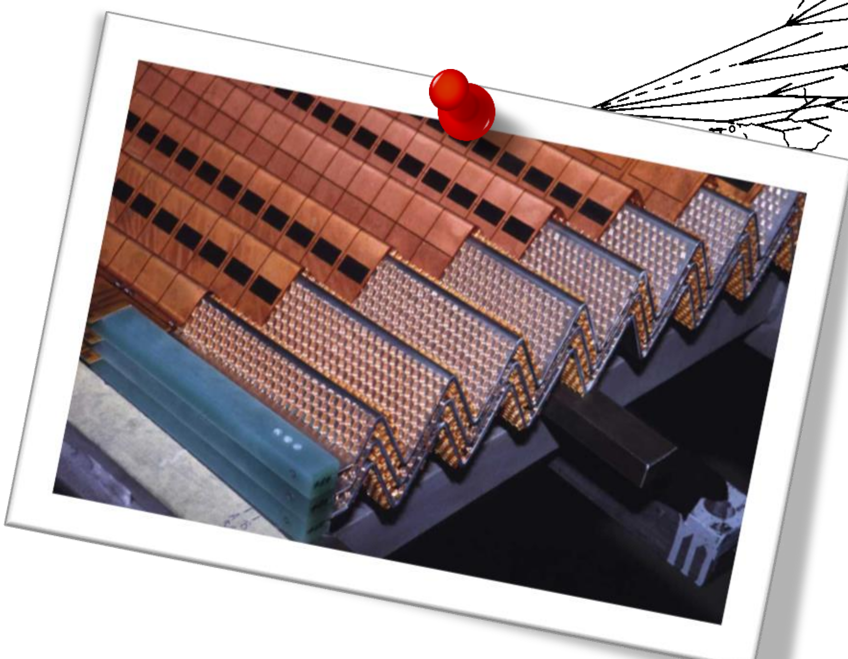
Conclusion

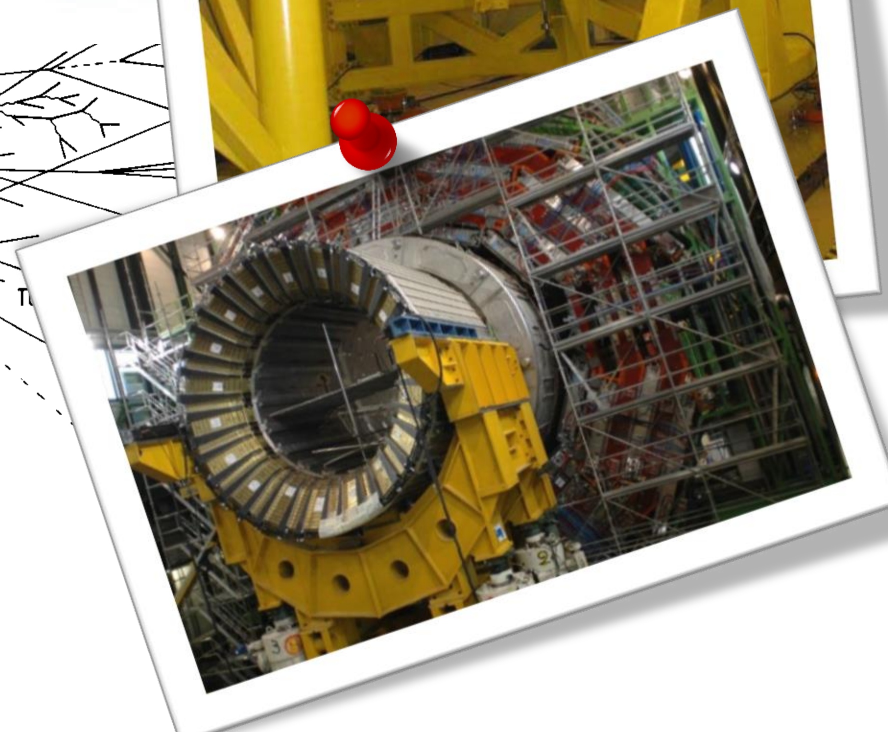
What I would do…

Introduction









Pushing the Energy Frontier

Precision Higgs sector physics explorations

- Predominantly at a future e^+e^- machine
  - See talk by Zhen Liu yesterday – standard model and exotic Higgs features
- Calorimeters used for precision hadronic final state reconstruction
  - Interactions with jets and $E_{\mathrm{T}}^{\mathrm{miss}}$

Discovery physics at highest energies

- Very relevant for hadron (proton) collider(s)
  - BSM particles decaying into SM particles with hadronic final state – high accessible mass scales introduce highly boosted decay products
  - Non-interacting new particles (SUSY, Dark Matter, …) discovery
- Calorimeters essential
  - High precision jet reconstruction
  - High resolution power for internal jet (sub)structure – tagging particle decays and jet flavors
  - Large η-coverage for precision $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction

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Motivation for calorimeters

- Measure energy flow from charged and neutral particles
  - Fully inclusive detector for multi-purpose (collider) experiments
- Relative energy resolution improves with increasing particle energy
  - $\sigma/E = \sqrt{a^2/E + c^2}$ (ignoring noise for now…), with a the stochastic (shower/sampling induced) term and c the constant (intercalibration) term
- Can be designed to provide $\sim 4\pi$ solid angle coverage around the interaction point
  - High acceptance/efficiency for reconstructing the full spectrum of possible final states – and $E_{\mathrm{T}}^{\mathrm{miss}}$
- Provide long term operational stability
  - With the right technology choice for a given collision environment
  - Can often significantly be upgraded without dismantling the detector (electronics, etc.)

Problems with Calorimeters

Limited direction resolution

- High precision reconstruction of jet and particle kinematics need help from tracking detectors
  - At least for e.g. vertex assignments in hadron collisions
- Limited energy flow resolution – separating prongs of energy flow subject to finite spatial resolution
  - Harder (2-3 prong) structures can be resolved for e.g. tagging of jets if jet p_{T} not too high…
  - Intrinsic feature introduced by interaction of particles with matter

Signal source "assignment"

- Calorimeter sensitive to pile-up in hadron colliders
  - No deterministic handle of signal qualification
  - Can be mitigated by shape measurements in case of jets – stochastic jets, q/g tagging… back to spatial resolution limitations!

Principal Detector Features (1)

Calorimeters measure energy

Full absorption detectors convert deposited energy into signals

- Based on particle interaction with matter – electromagnetic and hadronic showers
- Signal generation depends on particle type (usually only particles with $c\tau > 10$ mm in lab frame generate a signal)

Particle	Principal signal source
e^-, p	E_{kin} (add mass to detector)
$e^+, \bar{p}$	$2E_{\mathrm{tot}}$ (annihilation takes mass out of detector)
$\gamma, \pi^\pm, K$	E_{tot} (fully absorbed)
$\mu^\pm$	$\int_{\mathrm{detector\ entrance}}^{\mathrm{detector\ exit}} dE/dx\, dx'$ (ionization energy loss only)

Not too much an issue for high particle energies!

Principal Detector Features (2)

Calorimeters measure energy

- Signals are proportional to the deposited energy
  - Represent the total deposited energy in homogenous calorimeters (e.g. CMS ECAL)
  - Represent a given fraction of the deposited energy in sampling calorimeters (e.g. ATLAS calorimeters, CMS HCAL)

EM energy resolution:

$$\leftarrow \frac{\sigma}{E} \approx \frac{\mathcal{O}(1\%)}{\sqrt{E}} \oplus \mathcal{O}(0\%)$$

$$\leftarrow \frac{\sigma}{E} \approx \frac{\mathcal{O}(10\%)}{\sqrt{E}} \oplus \mathcal{O}(0\%)$$

- Signal proportionality depends on particle type
  - Linear for electrons, photons, and hadrons (ZEUS @ HERA) – compensating calorimeter ($e/h = 1$)
  - Linear for electrons, photons, non-linear (energy dependent) for hadrons (all LHC calorimeters) – non-compensating calorimeters ($e/h > 1$)
  - Muons typically do not generate signal proportional to their energy – signal ~ independent of incoming energy ($e/\mu < 1$)

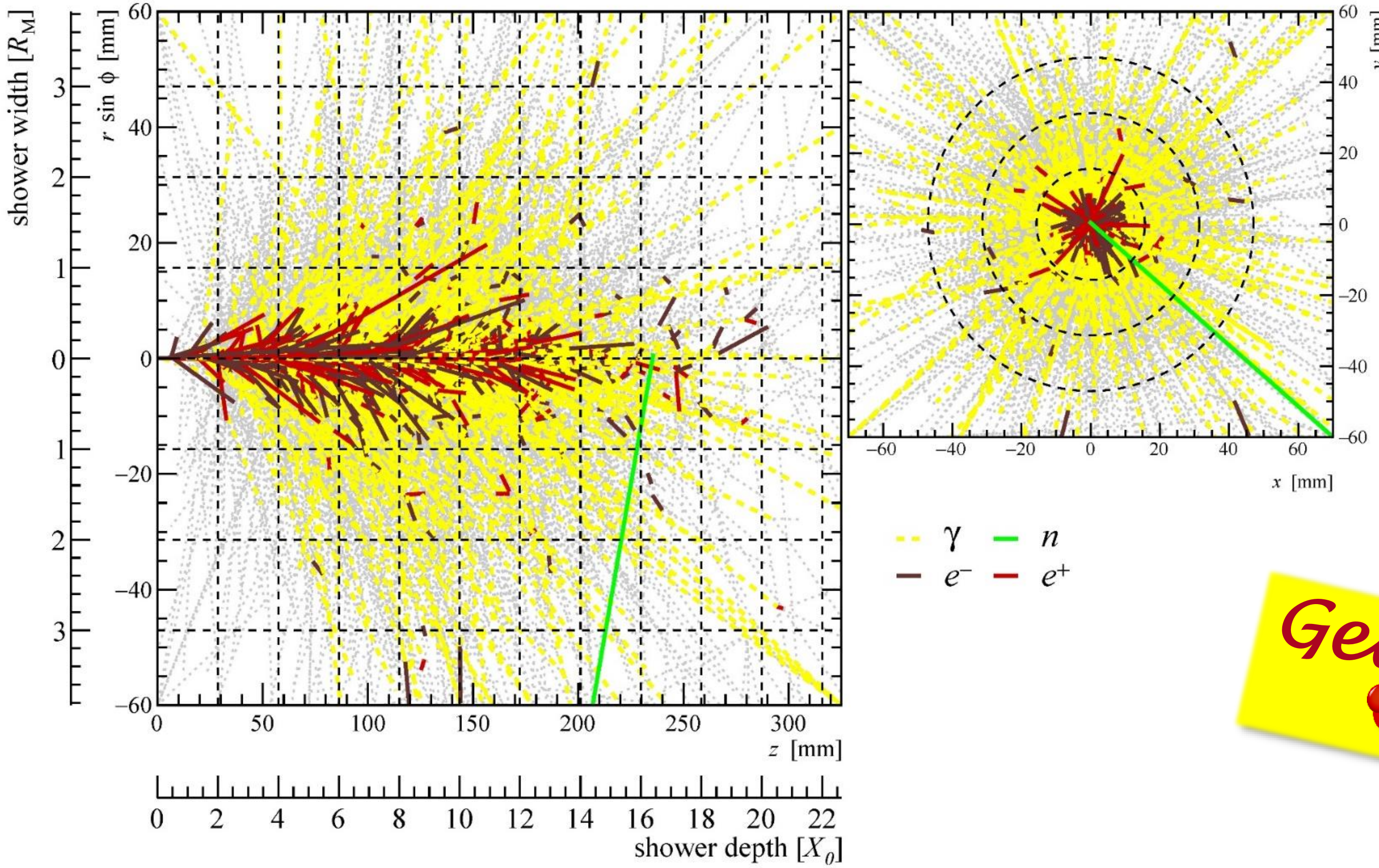
Principal Detector Features (3)

Calorimeters measure energy

Absorption volume depends on particle type

Dense (compact) showers for electrons/photons

10 GeV e^- entering copper block



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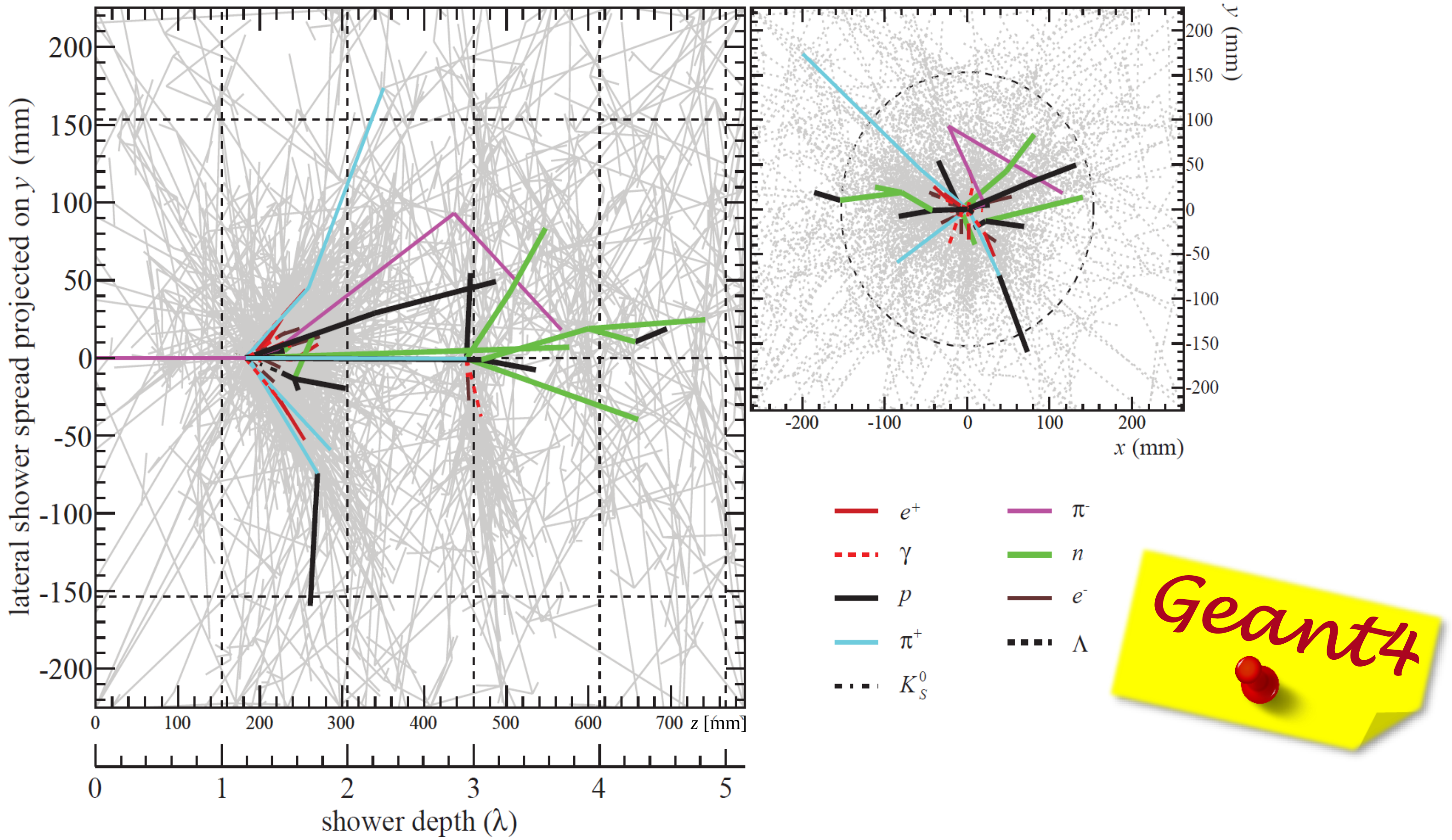
Calorimeters measure energy

Absorption volume depends on particle type

Large (spread) showers for hadrons

10 GeV π^- entering copper block



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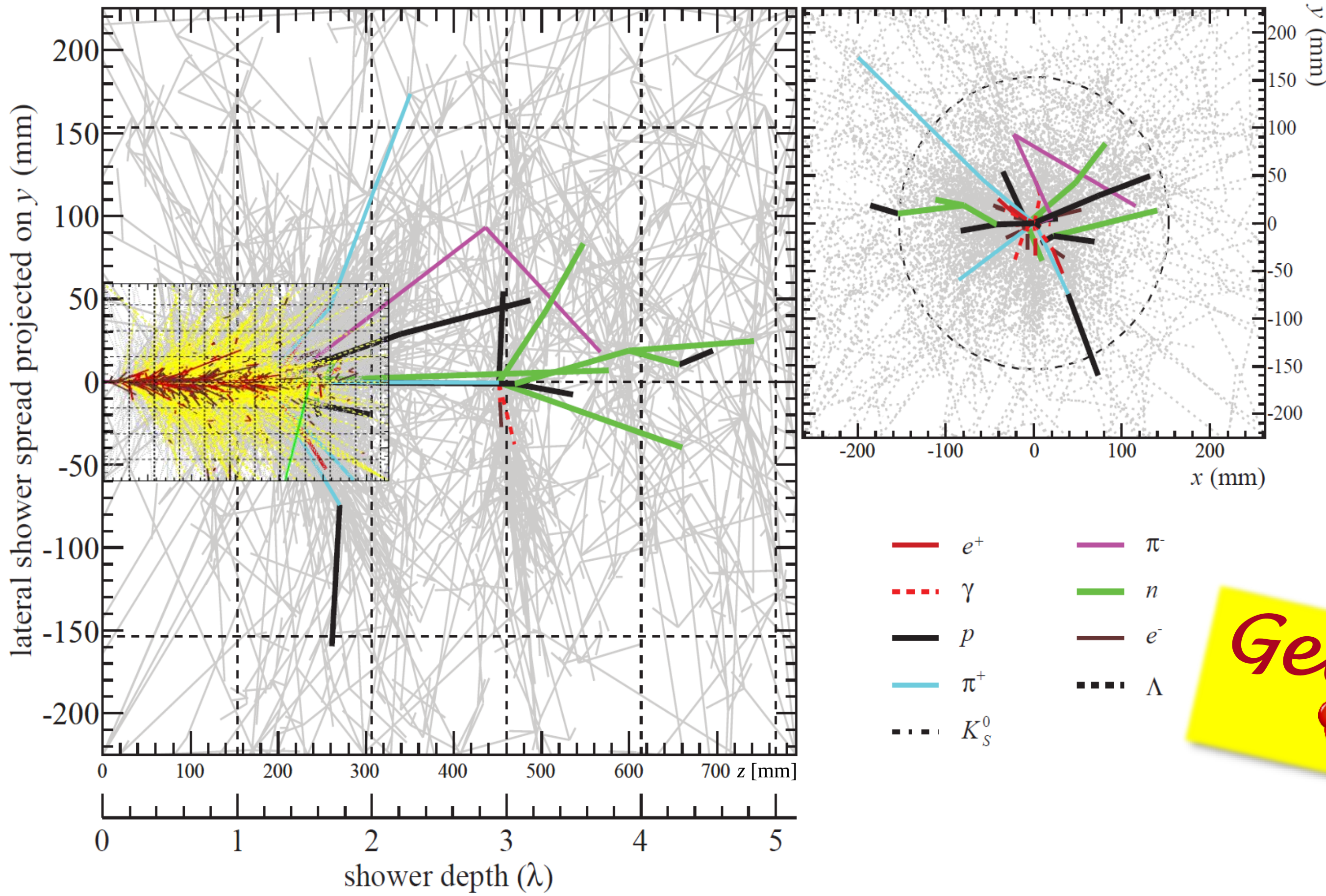

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Segmented readout

Measuring kinematics

Sub-division into independently read out calorimeter cells provides space point for energy deposits – reconstruct

$$E \times (1, \sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta\ )$$

with directions θ (η), φ with respect to a vertex (nominal, or as reconstructed with tracking detectors) and mass assumption (often $m = 0$)

Radial (transverse) segmentation sufficient for vertex-pointing geometries (CMS ECAL)

Particle identification

Longitudinal and radial segmentation helps to separate electrons, photons, and hadrons

Dynamic calibration for hadrons & jets

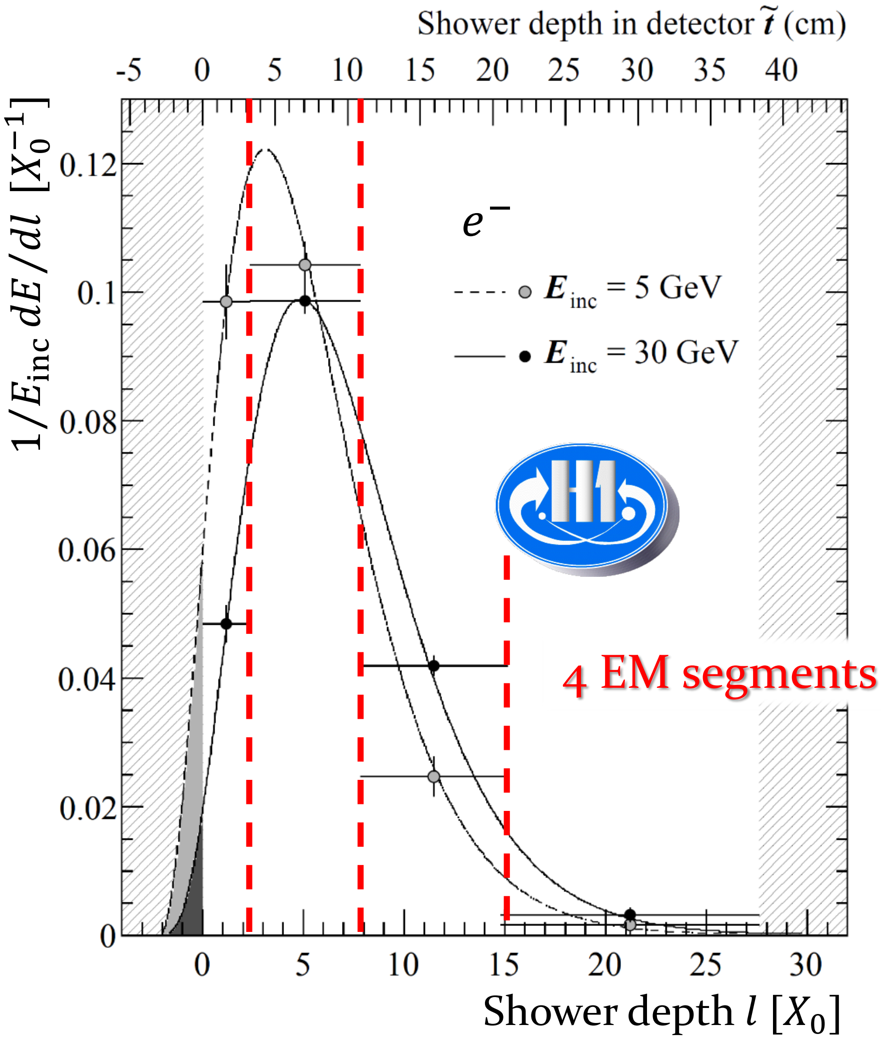
Signal shapes in highly granular readout drive calibration in non-compensating calorimeters – least-biased calorimeter-only signal reconstruction in complex particle flow

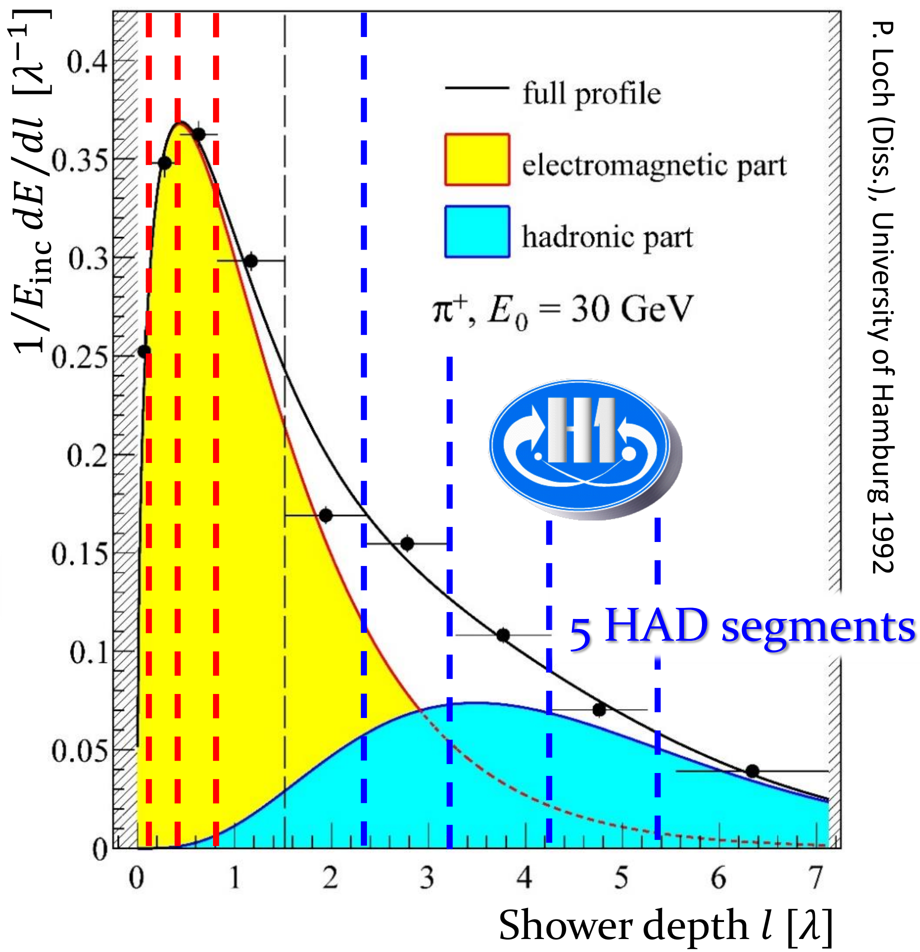
ATLAS topological cell clusters
arXiv:1603.02934 [hep-ex]

Particle Identification & Response (1)

Shower profiles

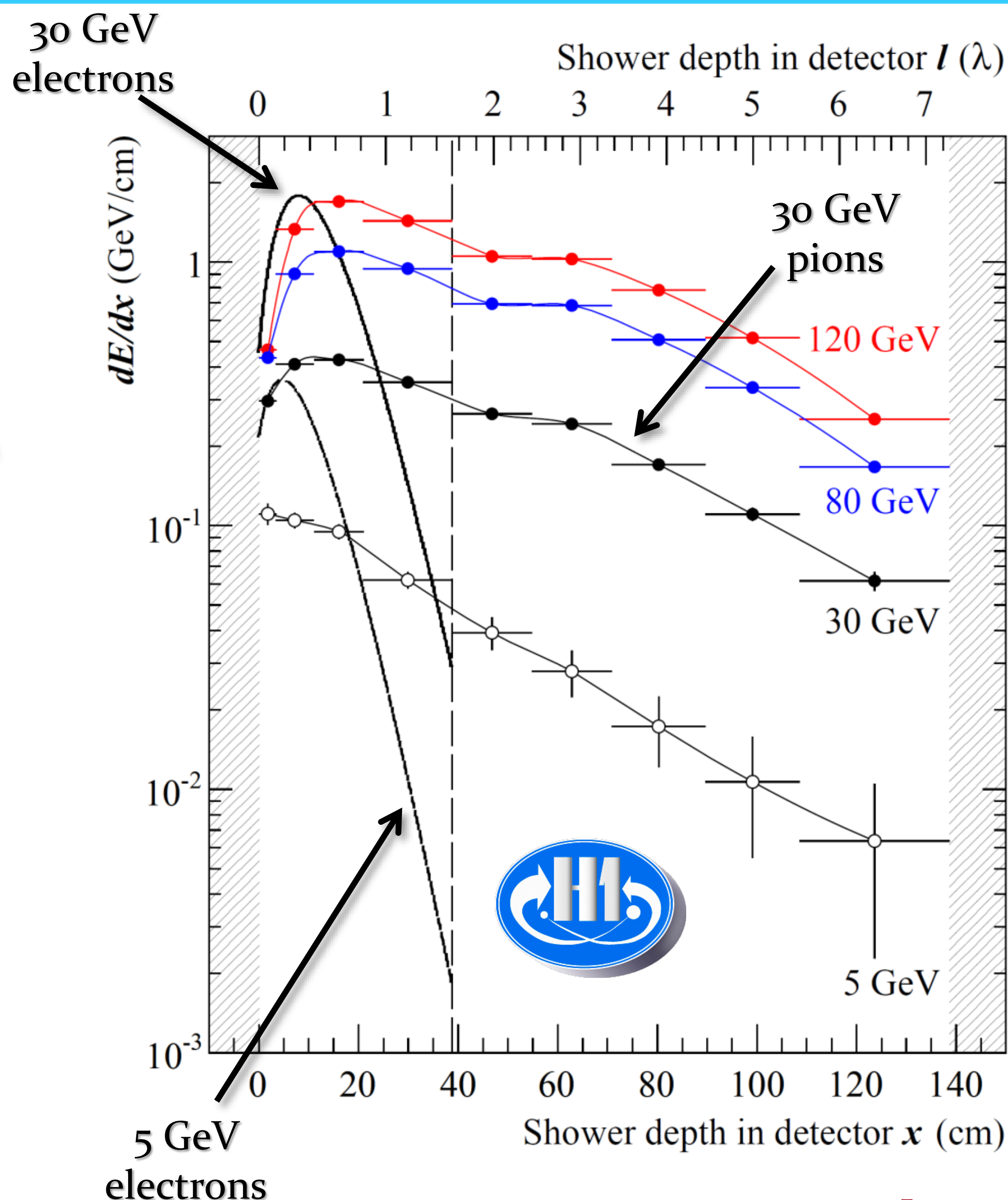
Testbeam data





Particle Identification & Response (2)

Shower profiles



P. Loch (Diss.), University of Hamburg 1992

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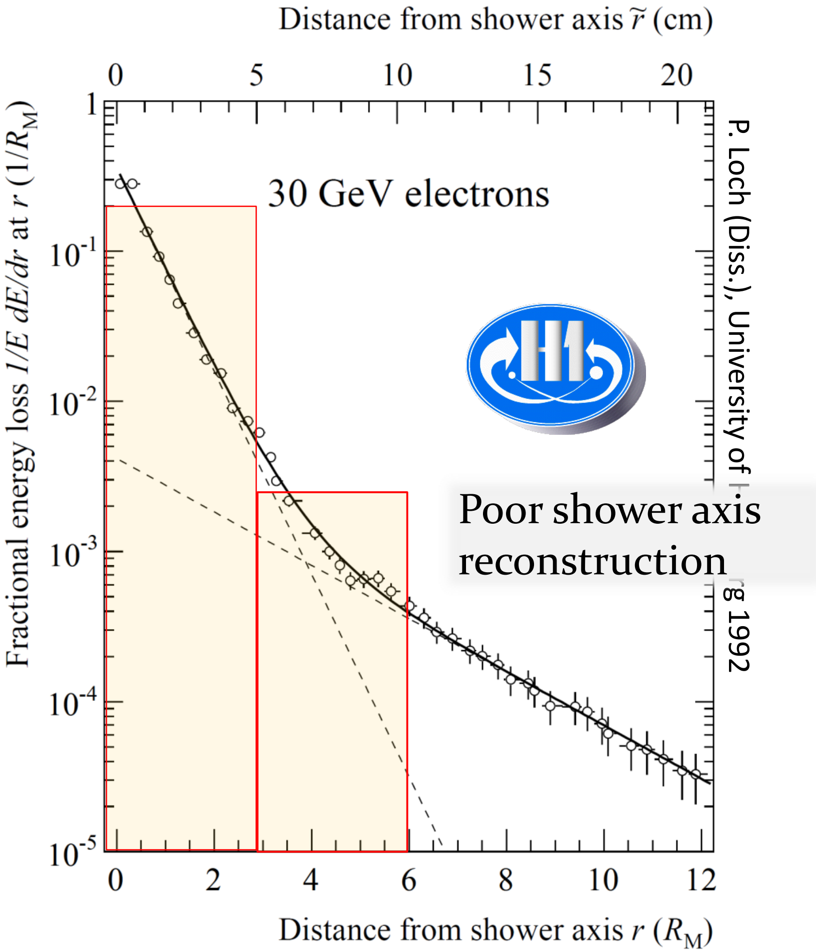
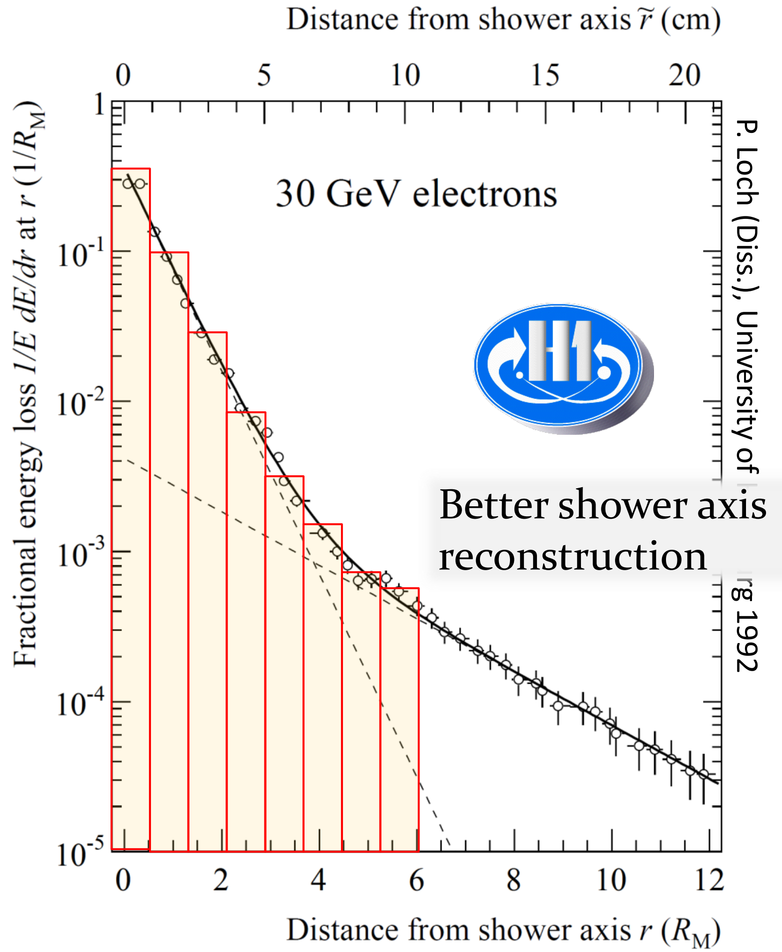
Lateral segmentation

Important for p (p_T) reconstruction – in particular azimuthal resolution

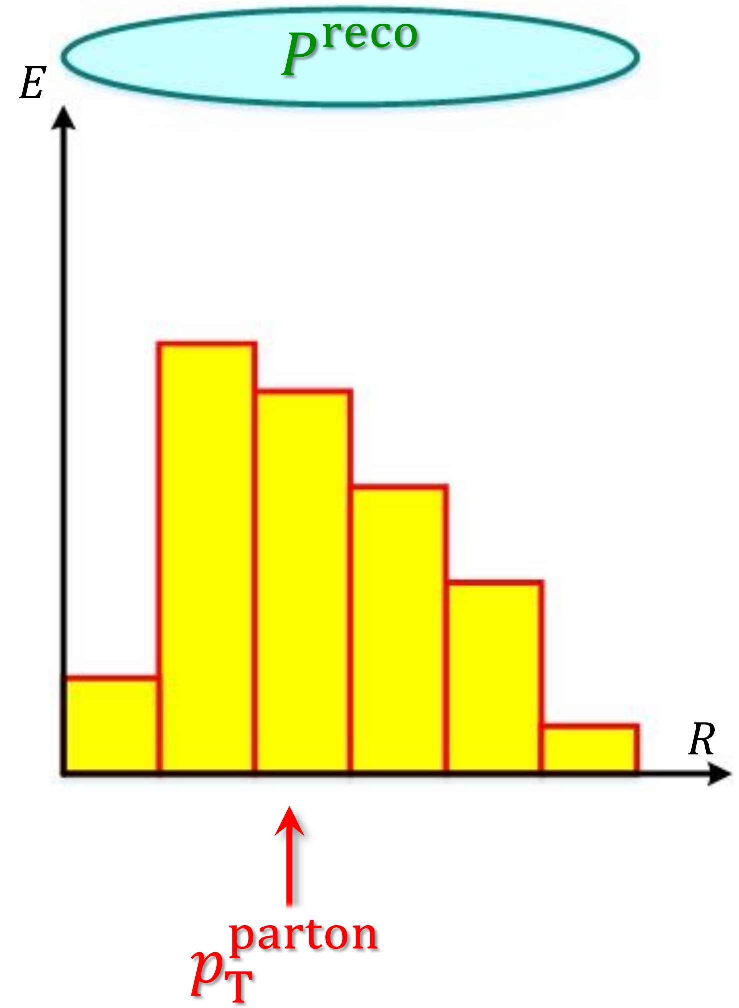




Energy (p_T) Flow Measurement

Lateral segmentation

- Energy/(transverse) momentum flow – (sub)structure resolution
  - Coarse segmentation – limited structural information, limited physics interpretation (single parton/particle)

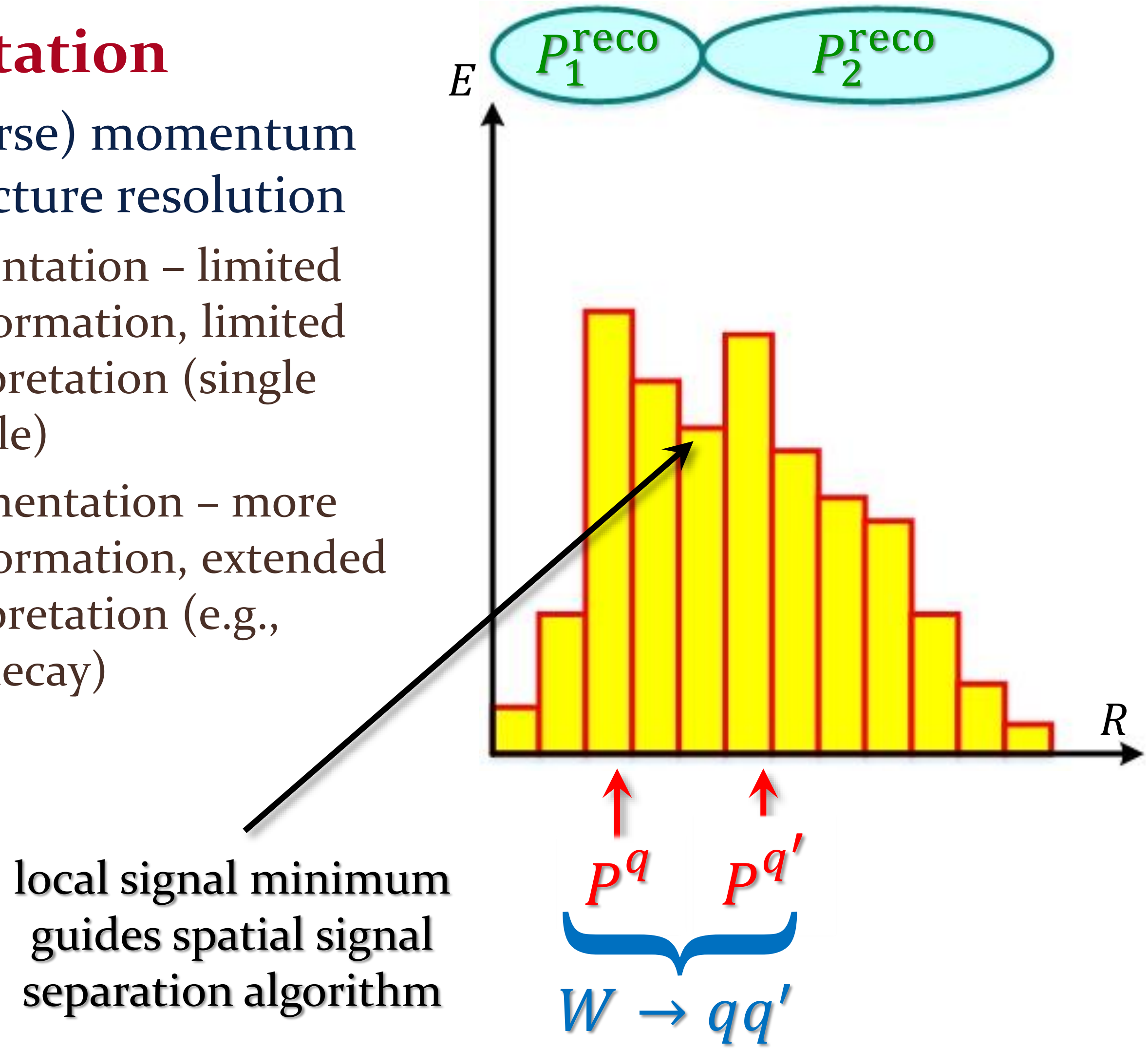


Energy (p_T) Flow Measurement

Lateral segmentation

Energy/(transverse) momentum flow – (sub)structure resolution

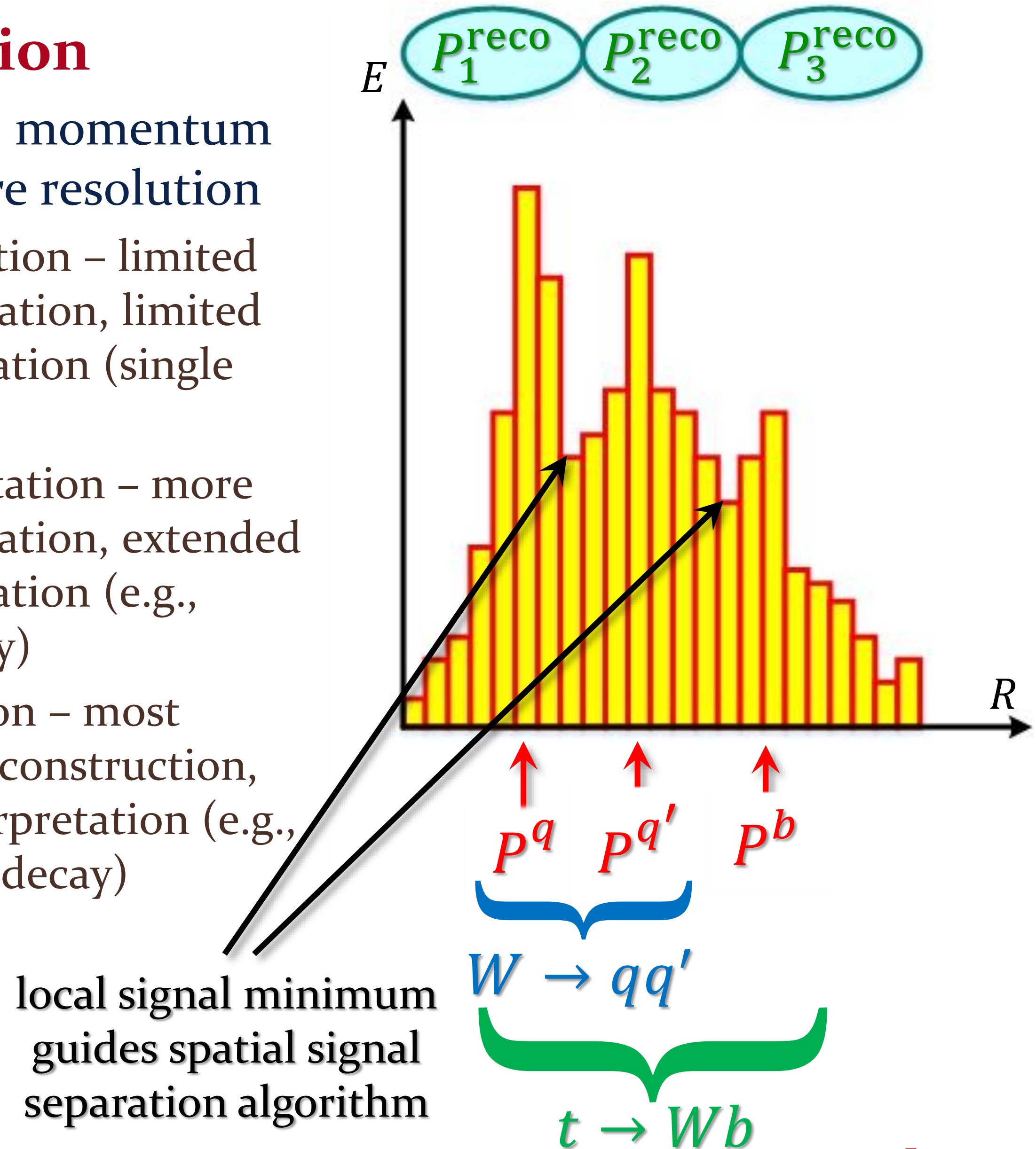
- Coarse segmentation – limited structural information, limited physics interpretation (single parton/particle)
- Medium segmentation – more structural information, extended physics interpretation (e.g., hadronic W decay)



Energy (p_T) Flow Measurement

Lateral segmentation

- Energy/(transverse) momentum flow – (sub)structure resolution
  - Coarse segmentation – limited structural information, limited physics interpretation (single parton/particle)
  - Medium segmentation – more structural information, extended physics interpretation (e.g., hadronic W decay)
  - High segmentation – most structural flow reconstruction, final physics interpretation (e.g., full hadronic top decay)



Energy (p_T) Flow Measurement

Projective readout geometry

- Pointing to (nominal) vertex
  - Hadron collider: projective in (non-linear) flow coordinates (η, φ)
  - e^+e^- collider: projective in (linear) spherical coordinates (θ, φ)

Effect of radial shower spread (*pp* collider)

- Shower size ~ constant
  - Energy containment within cylinder around particle direction of flight (principal shower axis) – radius of cylinder material dependent but about constant (no strong energy dependence)
- Energy sharing between cells in projective read-out geometry
  - Increases with increasing η – e.g. jet size collapses in linear spatial coordinates
  - Direction resolution/flow separation degrades if shower size ≫ projective cell size – largely overlapping showers inside jets, jet size dominated by shower size
  - Particular problem in the very forward direction at e.g. LHC

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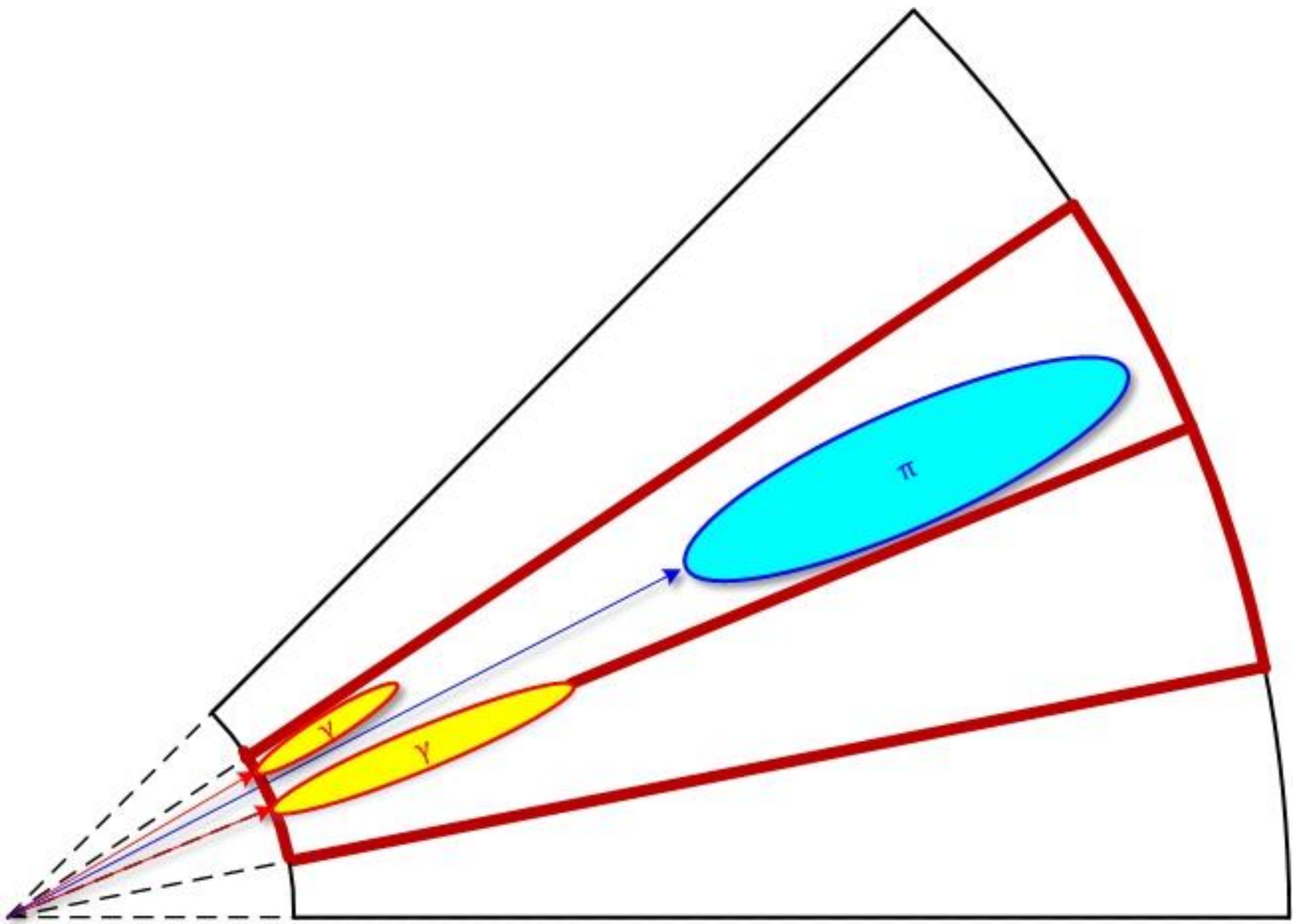
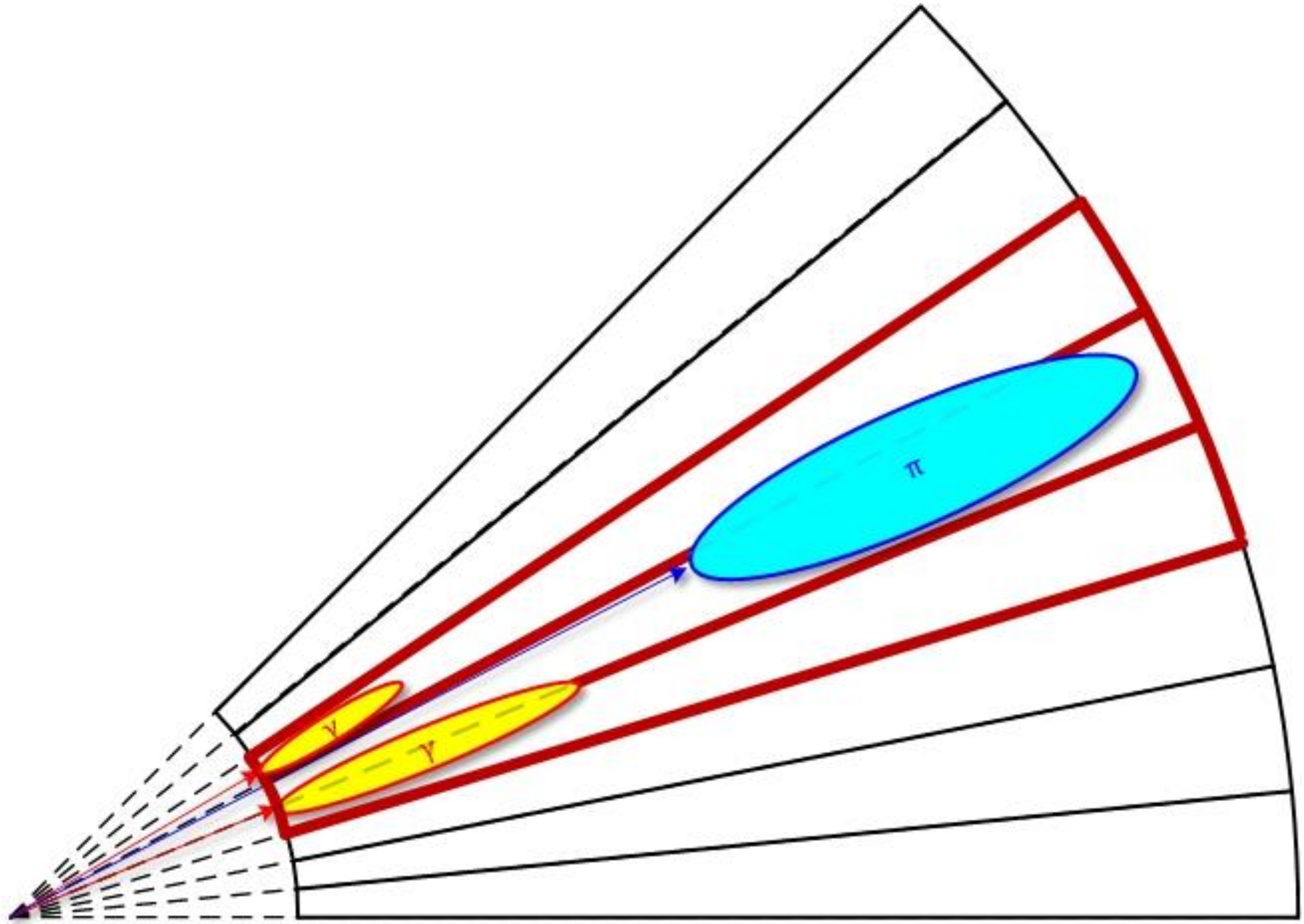
Longitudinal & Radial Segmentation



Longitudinal & Radial Segmentation



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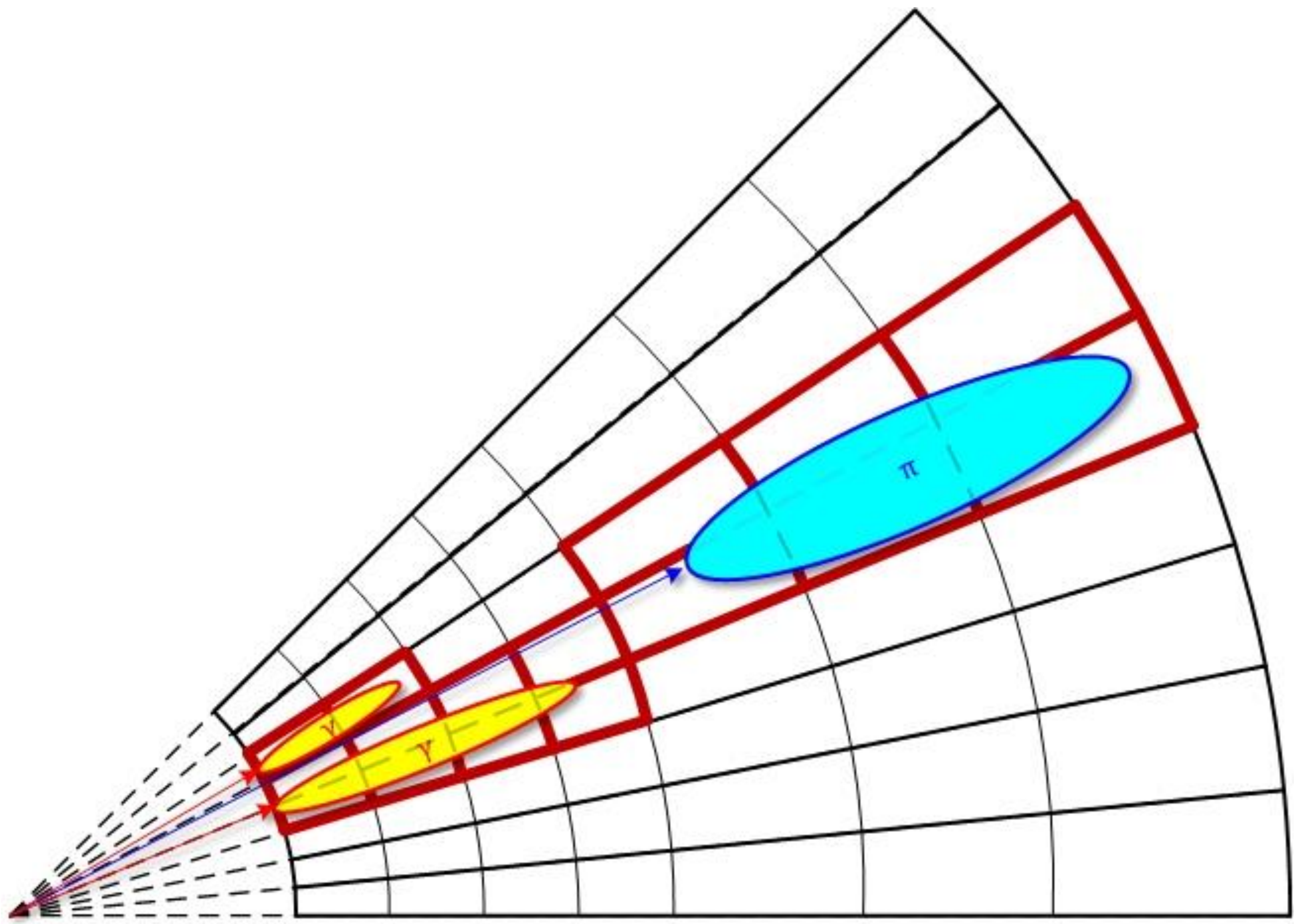
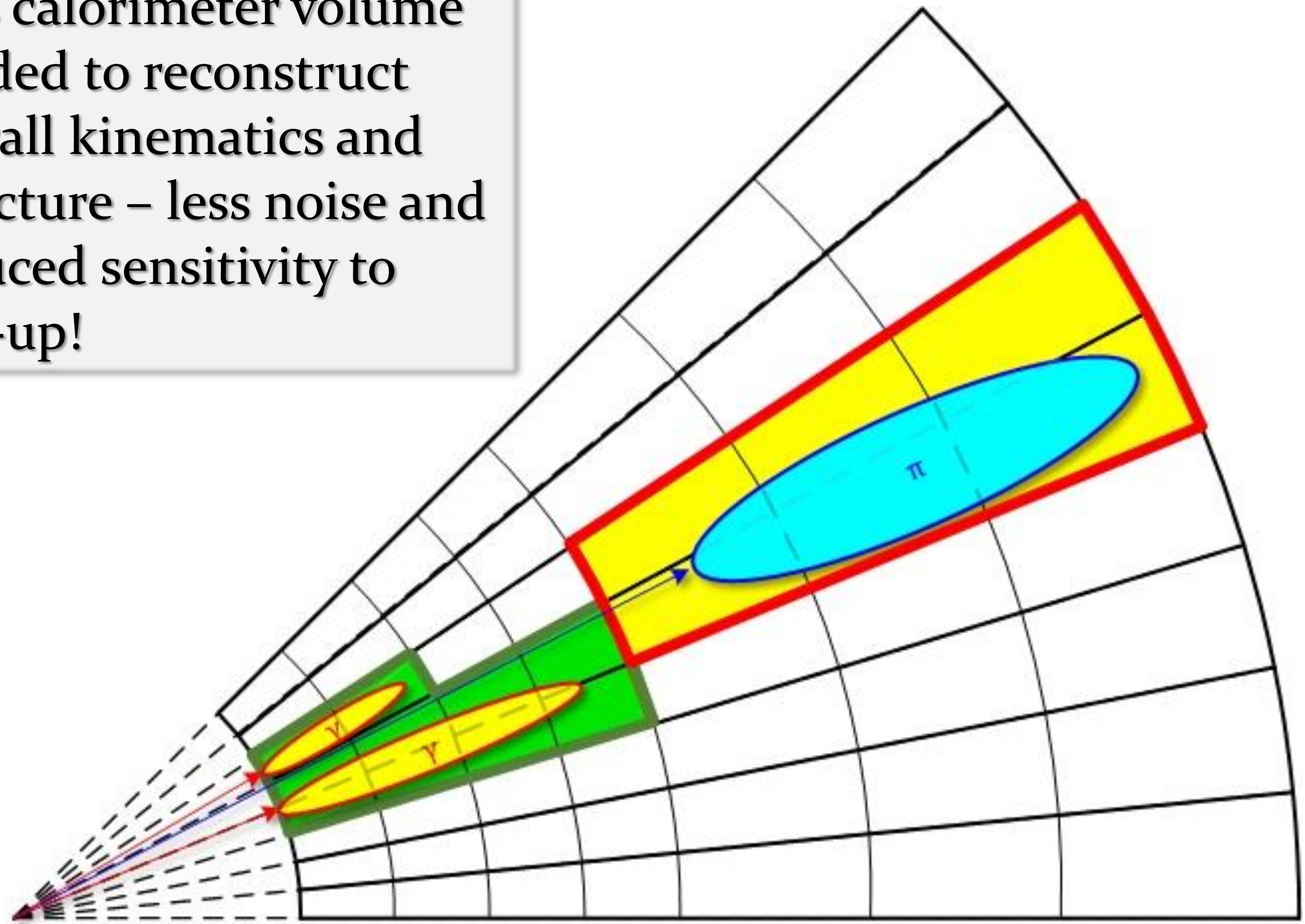
Longitudinal & Radial Segmentation



Longitudinal & Radial Segmentation

Less calorimeter volume needed to reconstruct overall kinematics and structure – less noise and reduced sensitivity to pile-up!



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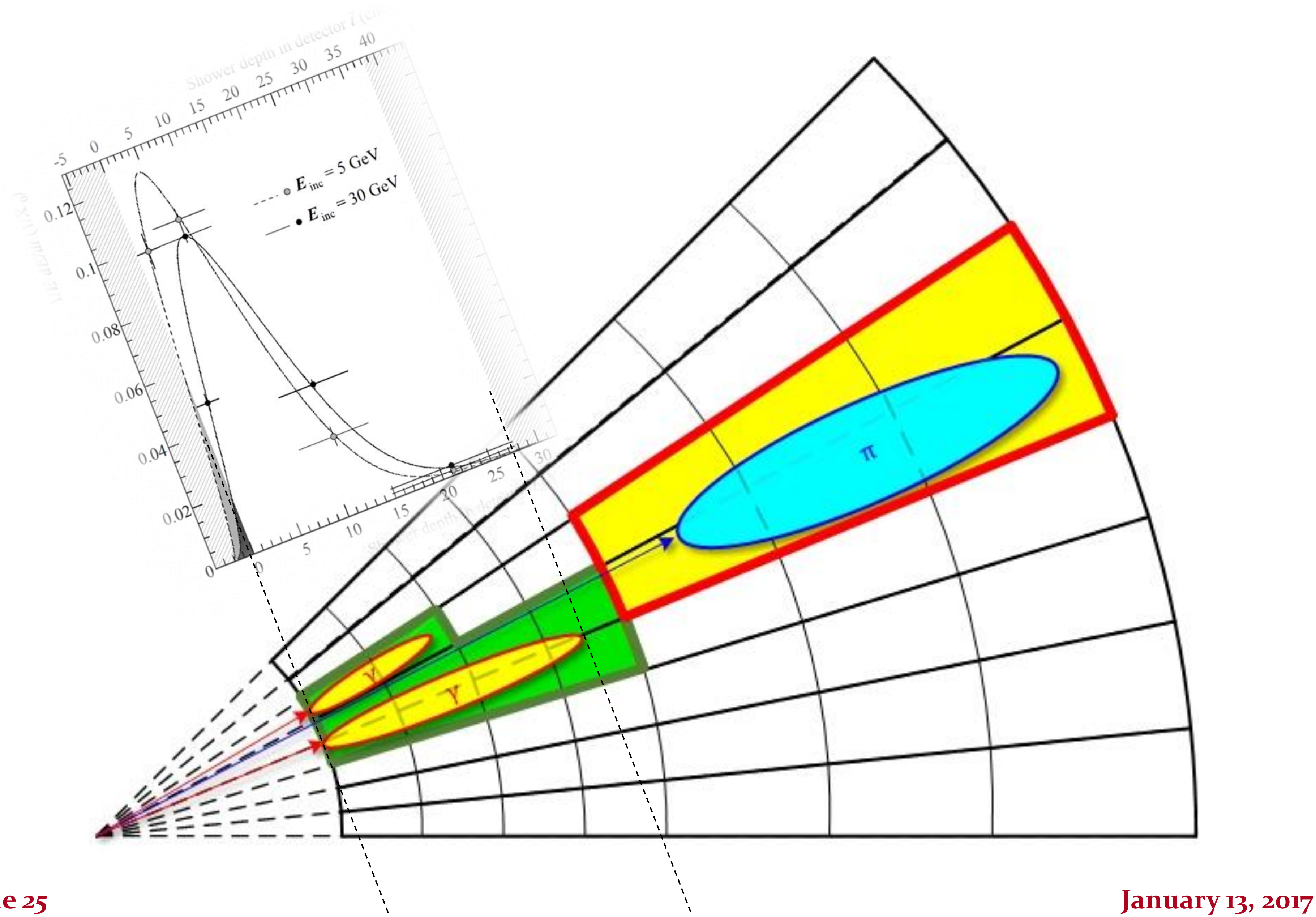
Local Response Corrections



Calorimeters at future e^+e^- colliders

Physics Environment

Expectations for operations

- Low occupancy due to low cross section
  - Number of hard interactions/bunch crossing approximated by $\mu = \mathcal{L} \times \sigma_{ee\to qq}/(N_{\mathrm{bunches}} \times f_{\mathrm{CEPC}})$
  - For $\sigma_{ee\to qq}(\sqrt{s} = 250\ \mathrm{GeV}) \approx 50\ \mathrm{pb}$, $\mathcal{L} = 1.8 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, $N_{\mathrm{bunches}} = 50$, $f_{\mathrm{CEPC}} = 5591.66\ \mathrm{Hz} \longrightarrow \mu \approx 3 \times 10^{-6}$ (rate is about 0.8 Hz)
  - Typically low multiplicity final states – no (significant) pile-up expected

High resolution spectroscopy

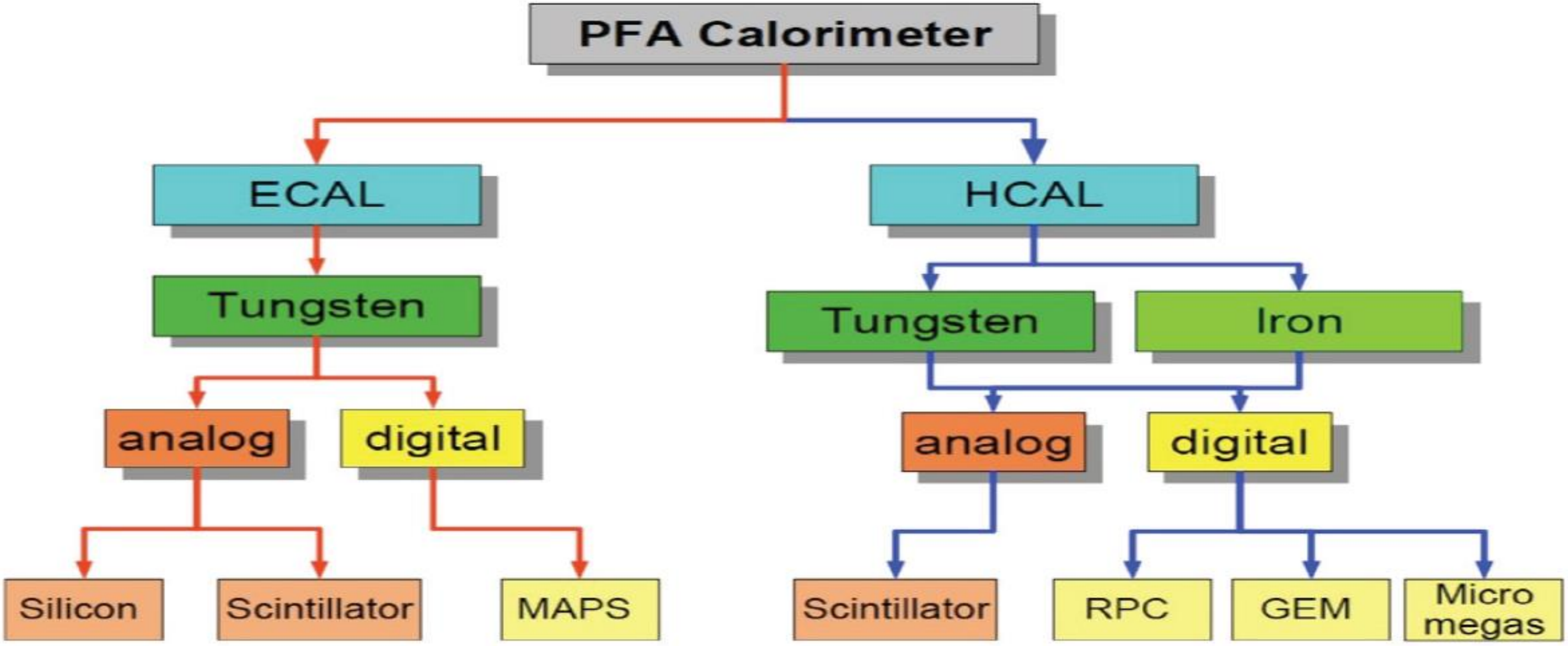
- Best performance expected with particle flow
  - Highly efficient matching of reconstructed track with calorimeter signals – shower by shower
  - High momentum (energy & direction) resolution for neutral particles

Best detector concept: imaging calorimeters

- Pixel-like (small tile) readout granularity
  - High sampling frequency with high density absorber for highest shower separation and containment

Various calorimeter designs under study

Probably a good starting point for circular collider as well



L. Xia, in Proc. of TIPP 2011 - Technology and Instrumentation in Particle Physics 2011, *Physics Procedia 37 (2012) 410 – 420*

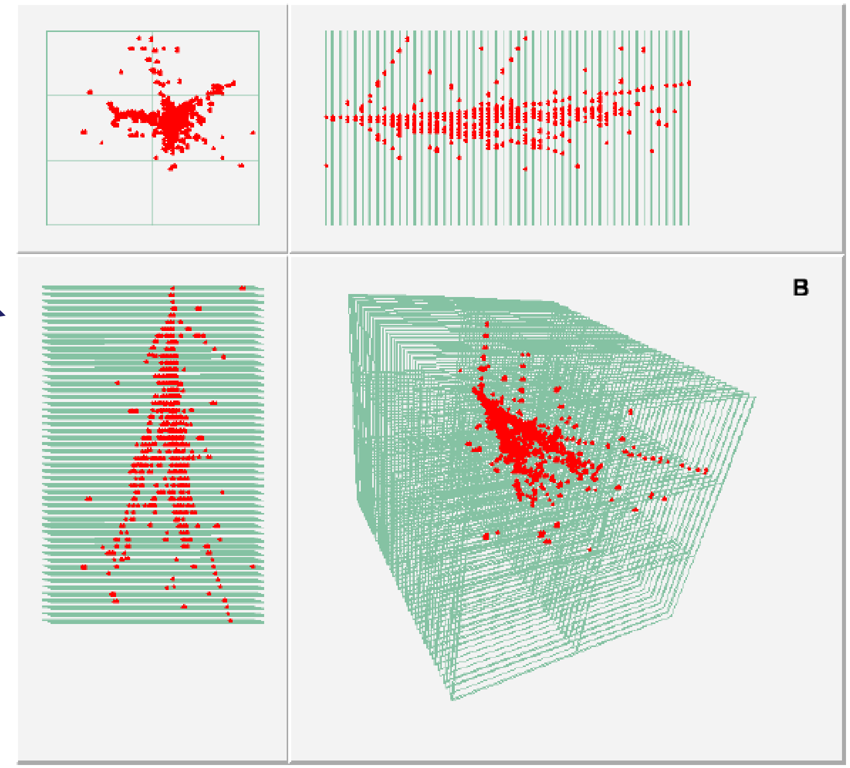
Note – these are all sampling calorimeter options!

CALICE for ILC

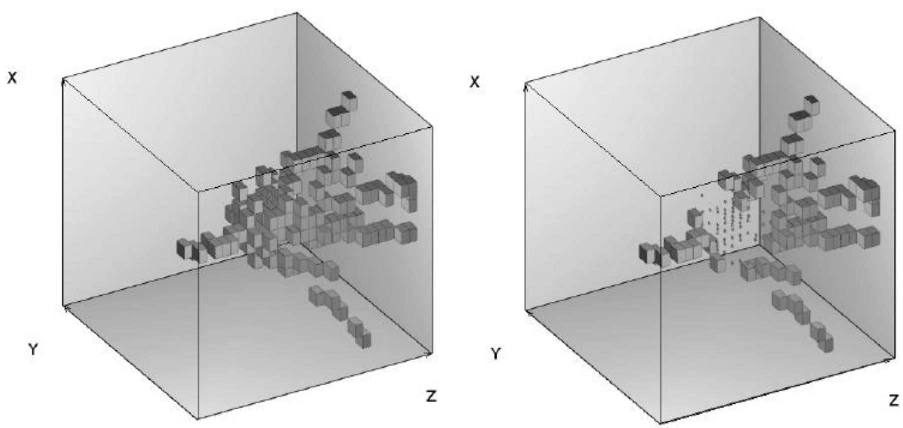
Shower images

16 GeV charged pion

10 GeV charged pion



B. Bilki, J. Repond, L. Xia, arXiv:1308.5929



N. van der Kolk, in Proc. of 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC 2015): San Diego, California, United States

Also helps with hadronic shower tuning in Geant4!

ILC Calorimeters

Reconstruction approaches in CALICE

Particle flow

- Match ("pixelized") electron and charged hadron showers with reconstructed tracks – limitations in boosted scenarios?
- Remove matched showers (pixels) from calorimeter signal

Signal weighting

- W sampling calorimeters are non-compensating – use software signal weighting to correct for $e/h > 1$ locally or globally (c.f. H1, ATLAS…)

Possible degradation of performance

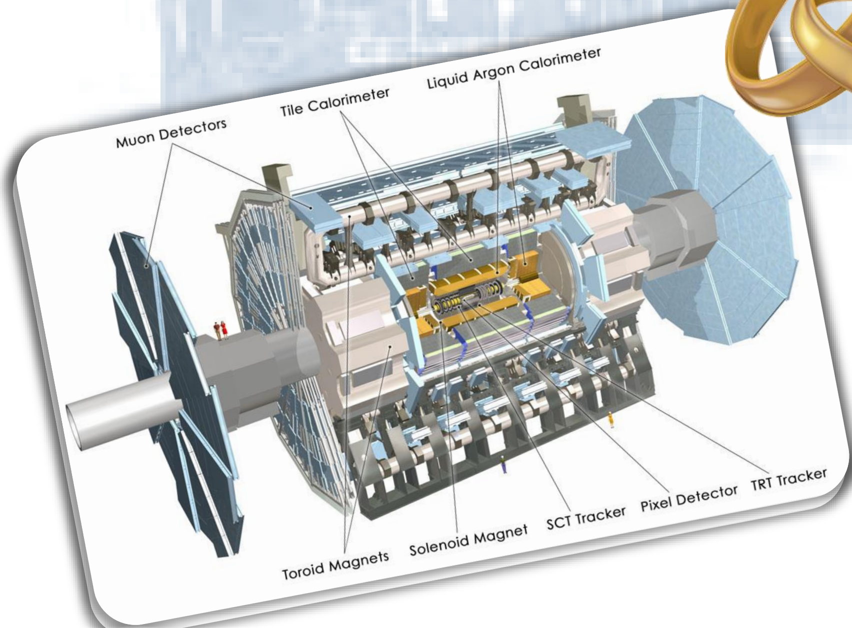
- Boosted decays – confusion term in track/calorimeter matching, tracking resolution,…
- Software weighting techniques may still work for high shower overlaps – but non-optimal resolution and response expected

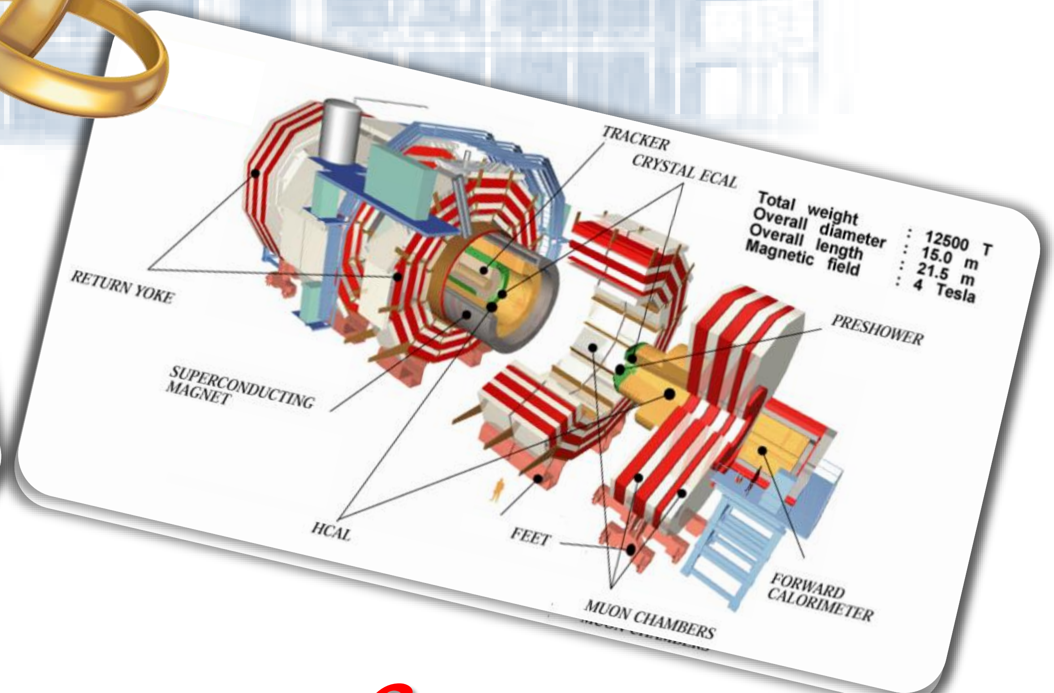
Dual readout calorimeters

Compensating

- Two different signals used for EM and HAD (e.g., Cerenkov and scintillating fiber)
- My concerns: particle flow, possible segmentation, full coverage detector design…

Calorimeters at future *pp* colliders





Who proposes first?

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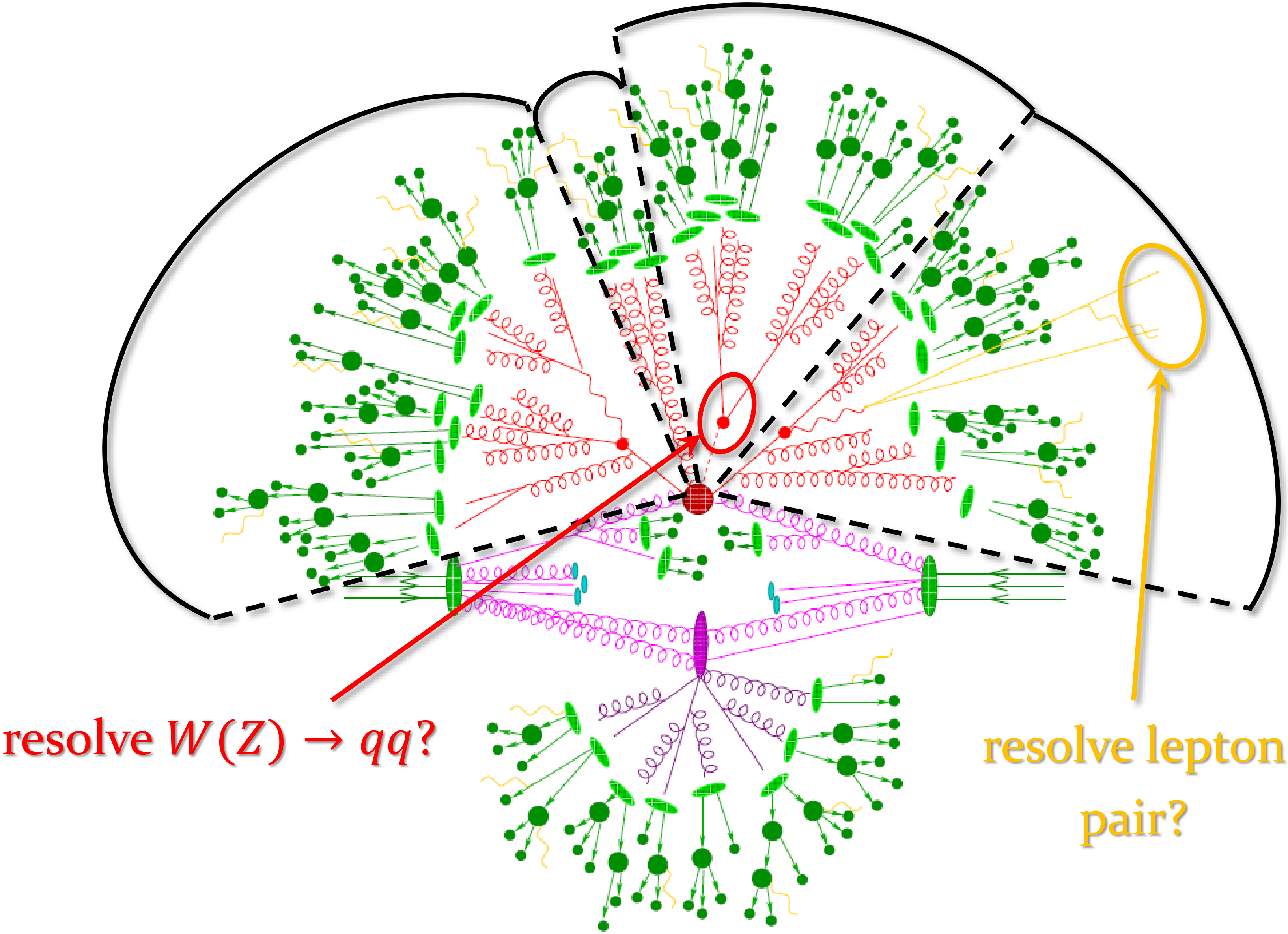
Proton Collisions…



Can we re-use ATLAS & CMS?

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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 – VBF/VBS
- 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

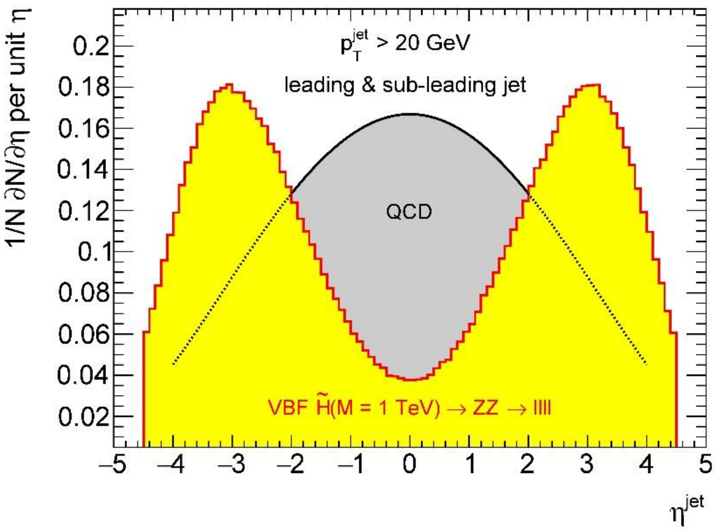
BSM Physics With VBF

Distinctive event topology

Central (new) partial produced in longitudinal WW scattering

Mostly decays into 2-4 W and Z bosons – easy to trigger leptonic final state

But large overlap with continuum di/tri/quad-boson production



Forward going tag (quark) jets

Indicate production mechanism

$\Delta\eta$ gets larger with increasing particle mass and $\sqrt{s}$

Experimental challenge

Significant phase space overlap with pile-up jets

Fake BSM production by enhancing e.g. larger cross section gluon-produced ZZ

Suppression of pile-up jets using calorimeters

Jet shapes – quark/gluon tagging etc.

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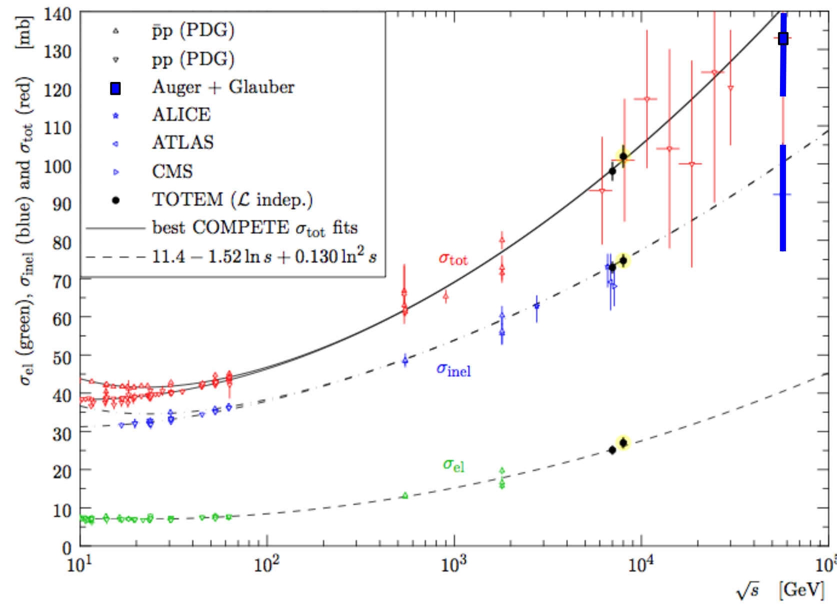
Expectations for 100 TeV pp collider

- 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)

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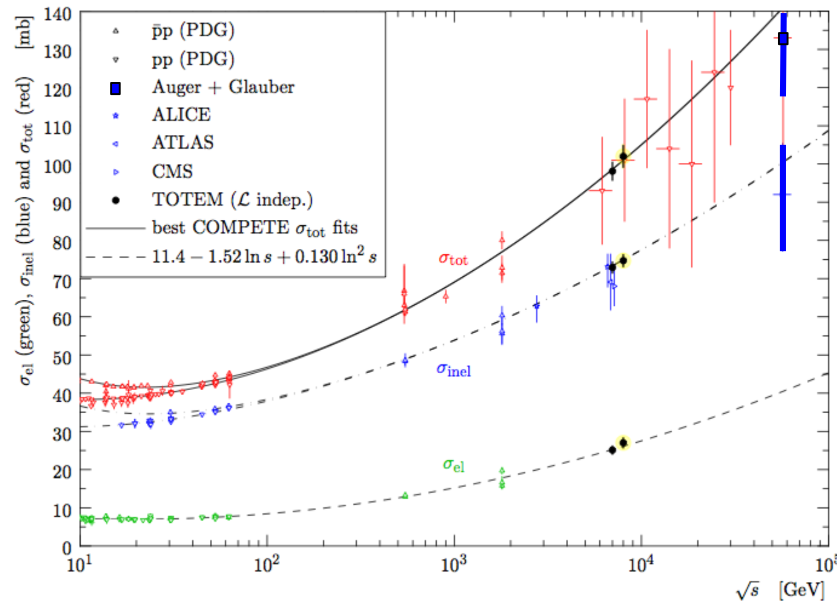

(from talk given by Nicolo Cartiglia, INFN Turin at LISHEP 2013)

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

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

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

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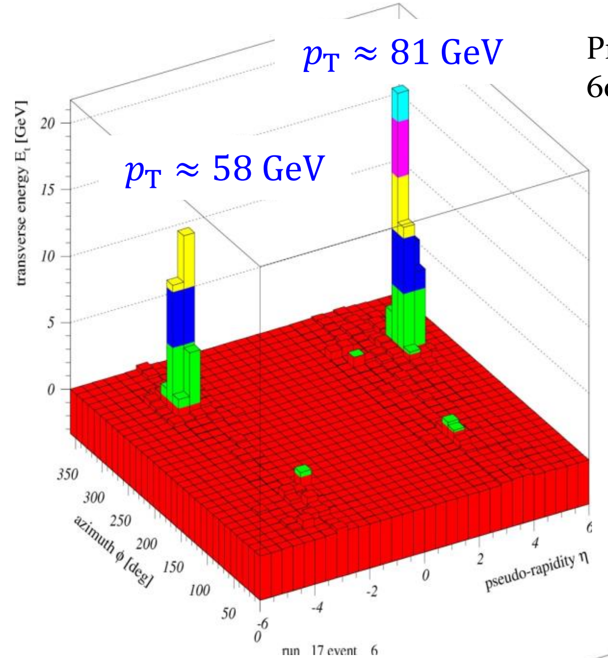
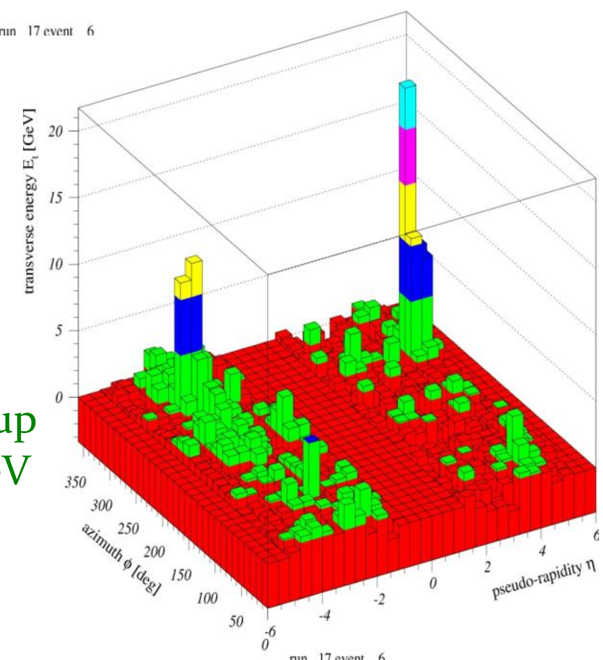
Prog.Part.Nucl.Phys. 60:484-551,2008



without pile-up



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

Features of MB Particle Flow

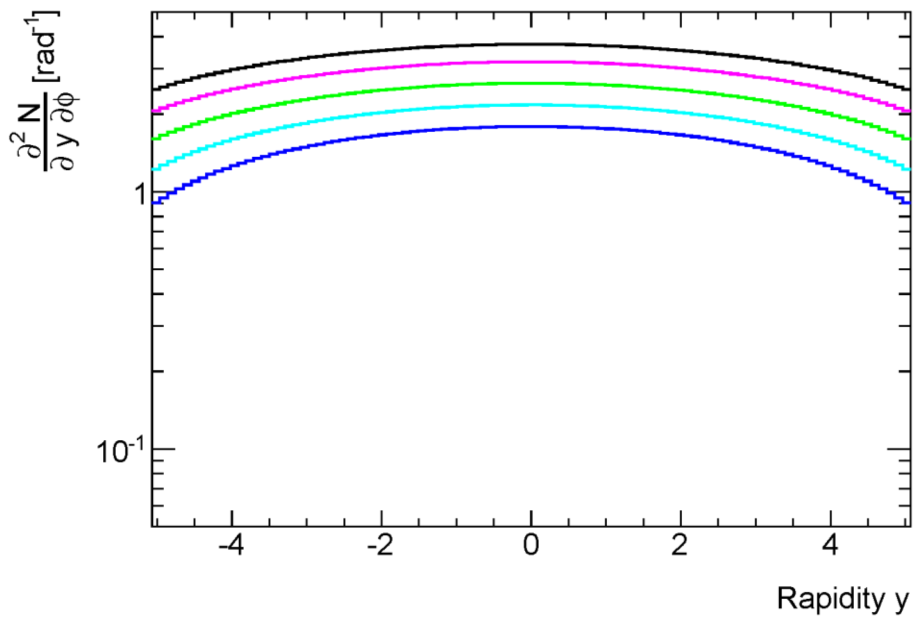
Pile-up dominated by soft QCD

- 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 $p_{\mathrm{T}} < 500$ MeV (simplification) – effect on features

Number Densities in MB



$\sqrt{s}$ = 7 TeV

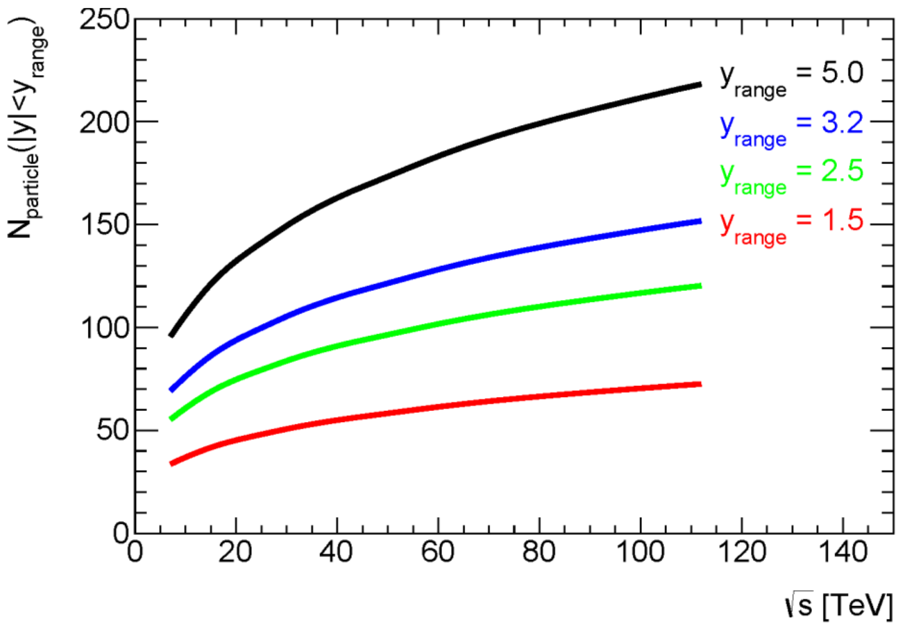
$\sqrt{s}$ = 14 TeV

$\sqrt{s}$ = 28 TeV

$\sqrt{s}$ = 56 TeV

$\sqrt{s}$ = 100 TeV

single MB interactions, all particles!



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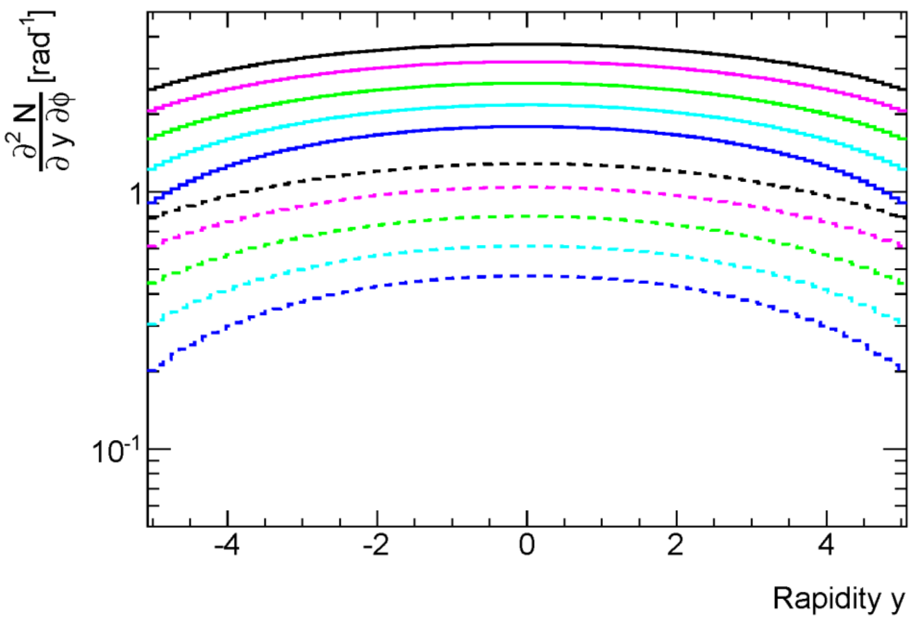
Number Densities in MB



$\sqrt{s}$ = 7 TeV

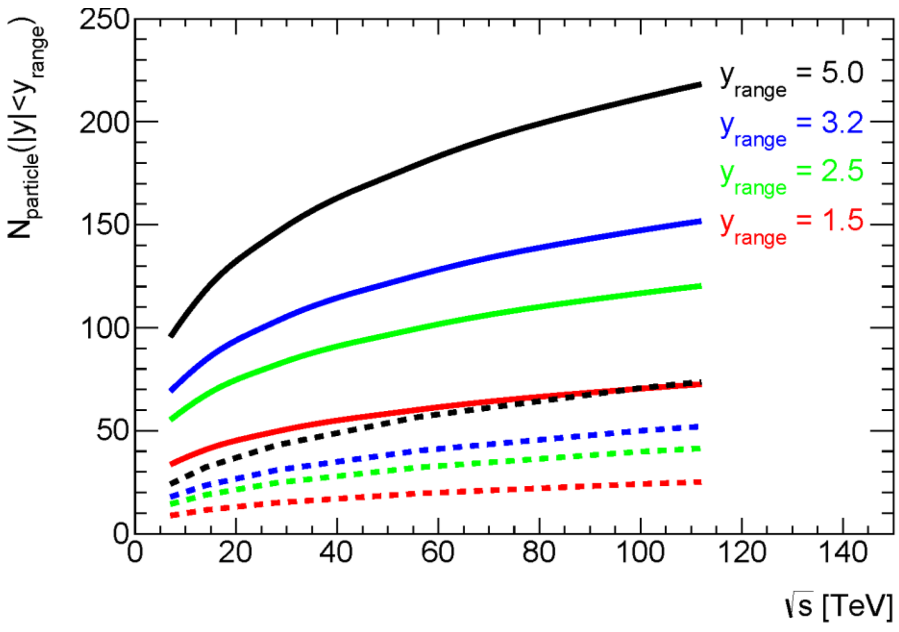
$\sqrt{s}$ = 14 TeV

$\sqrt{s}$ = 28 TeV

$\sqrt{s}$ = 56 TeV

$\sqrt{s}$ = 100 TeV

single MB interactions, particles with p_T > 500 MeV



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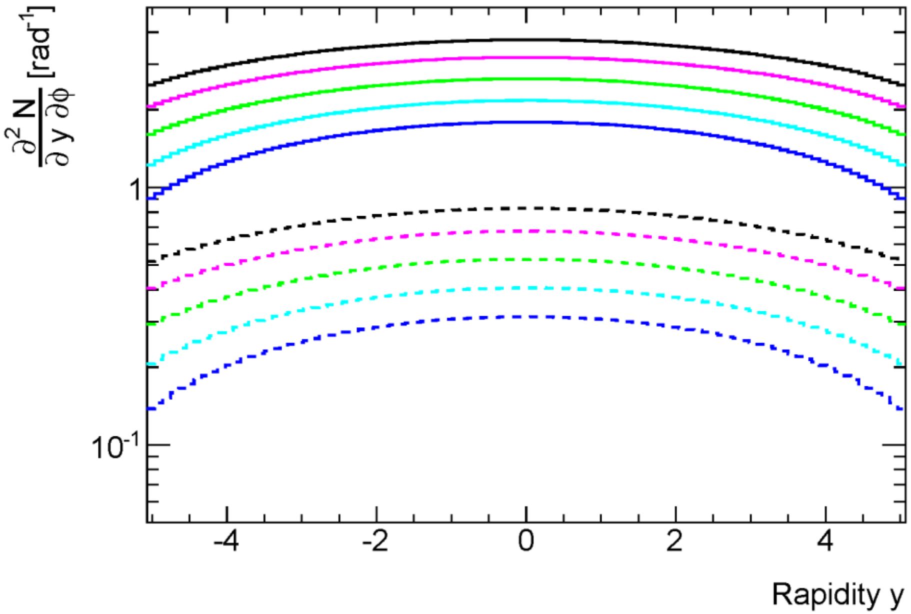
Number Densities in MB



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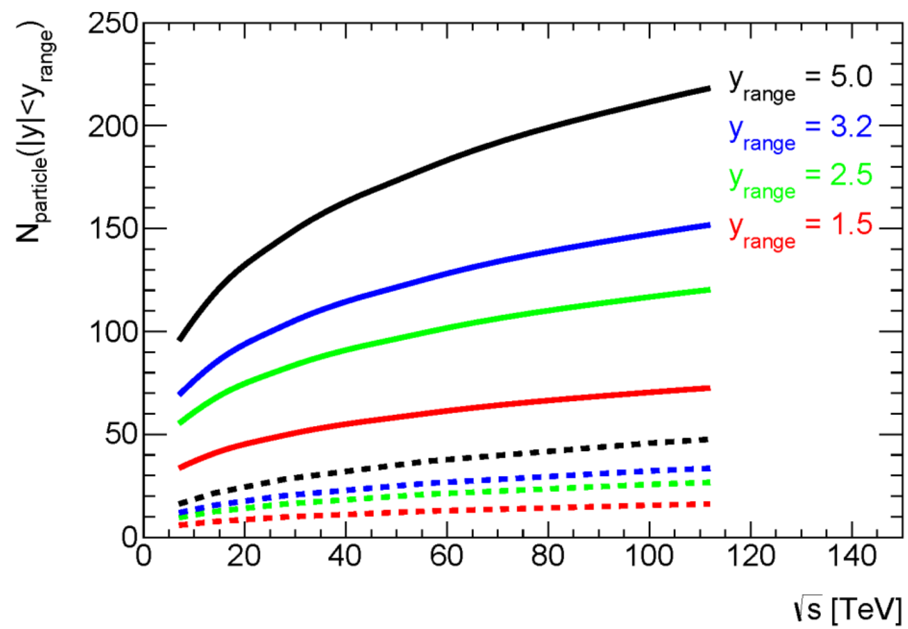
single MB interactions, charged particles with $p_{\mathrm{T}} > 500$ MeV



Transverse Momentum in MB

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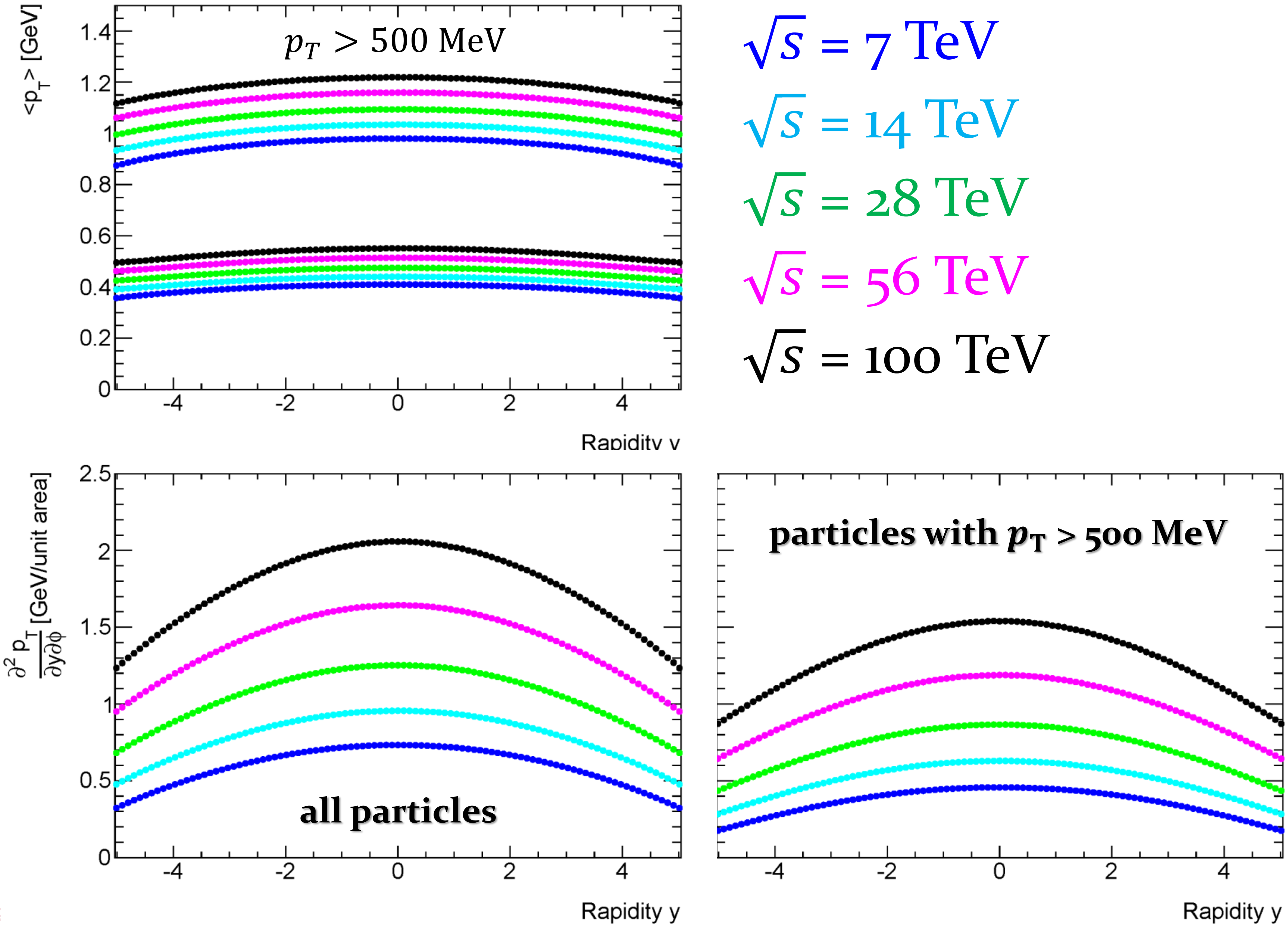
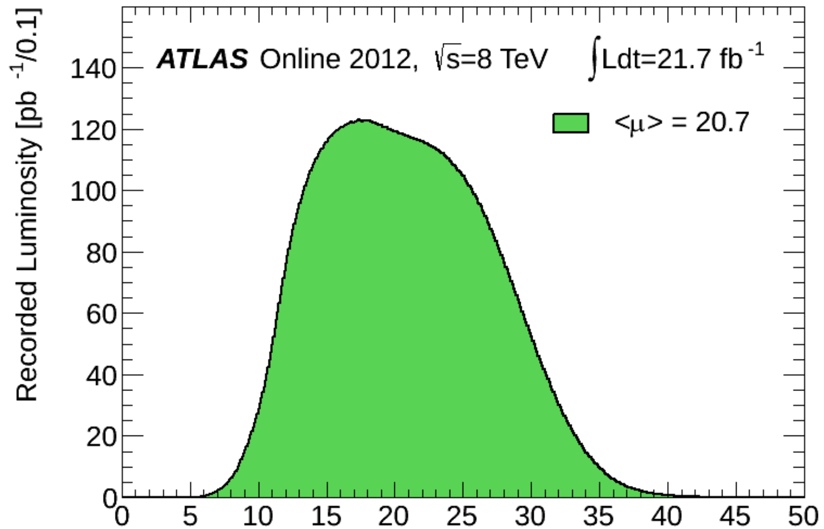
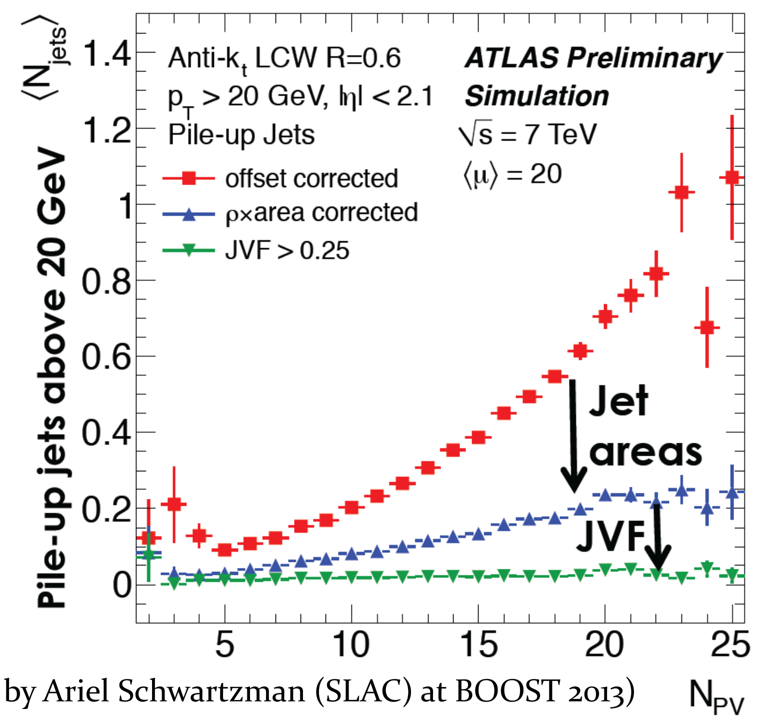


Controlling Pile-up

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)

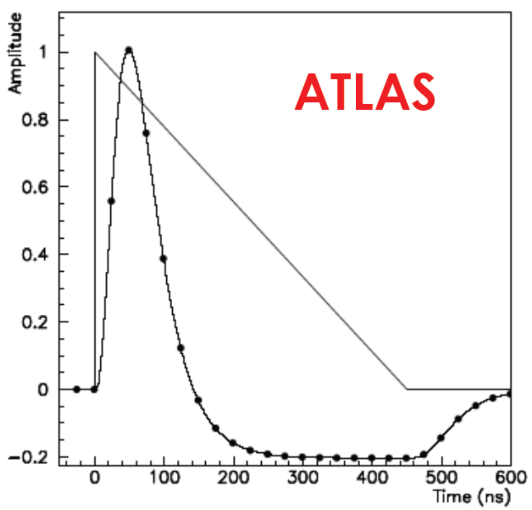
Detector Technology Dependence

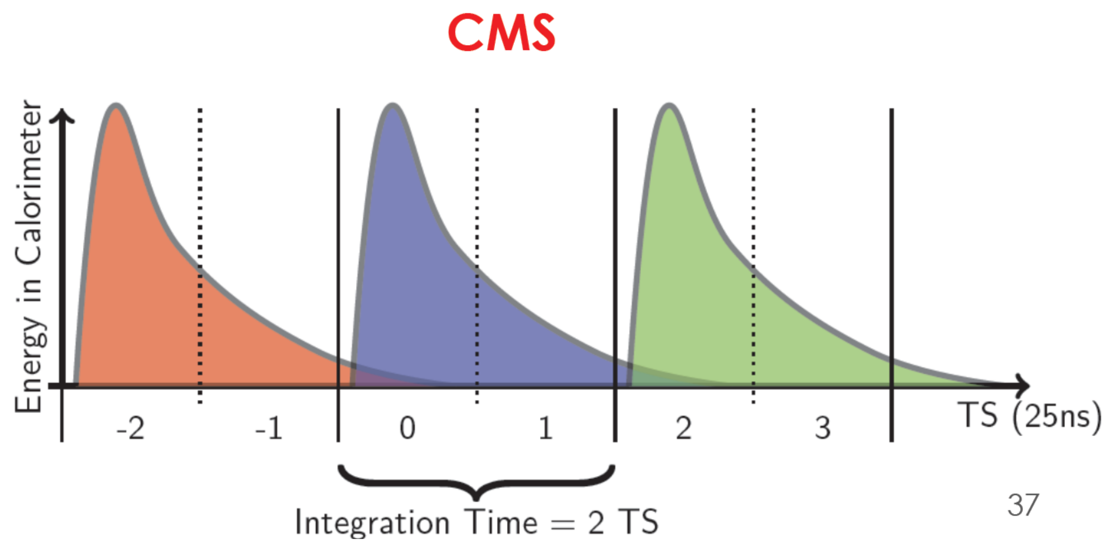
Pile-up signal representation

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)

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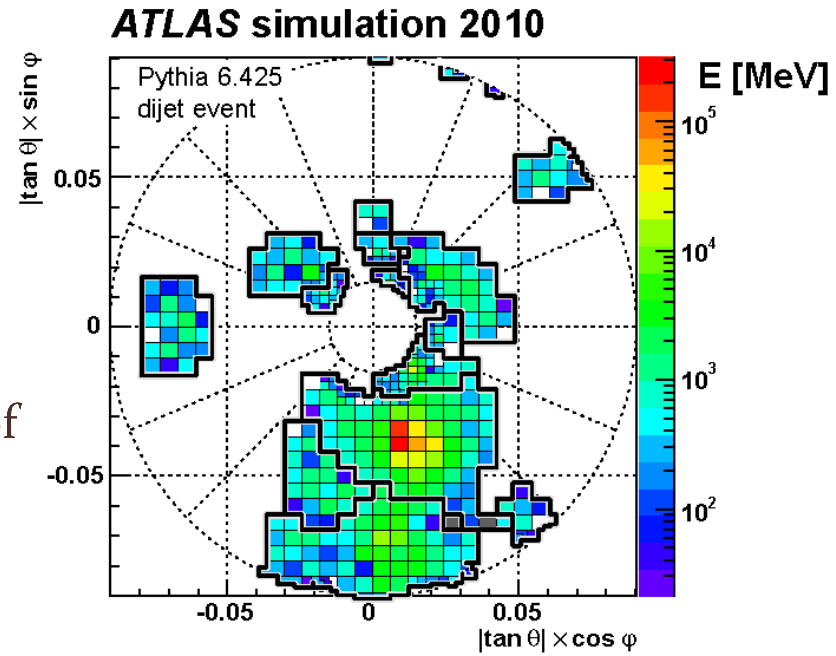
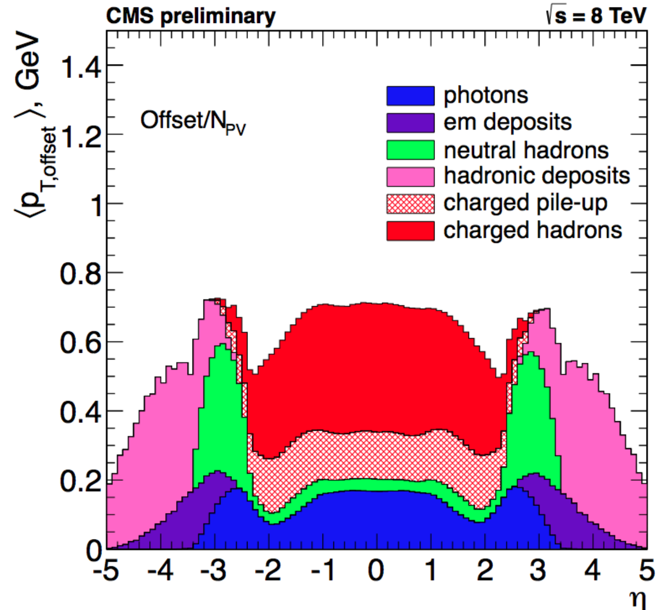
Basic Signal Definition Choices

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.





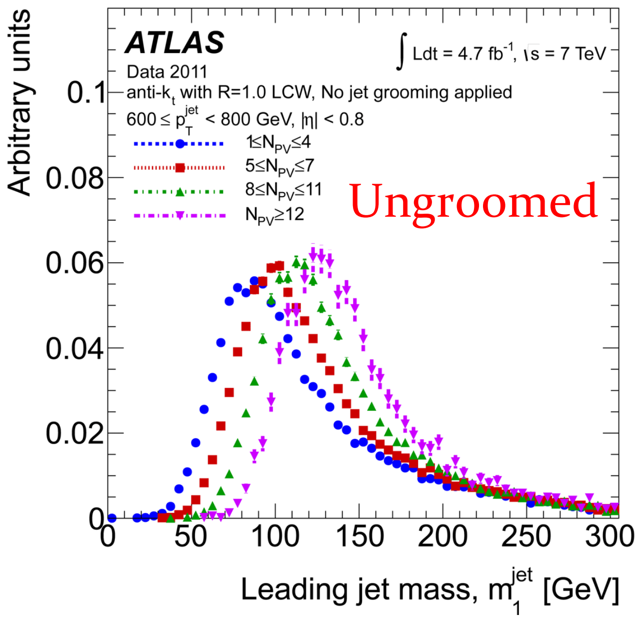
(from talk given by Phil Harris (CERN) at BOOST 2013)

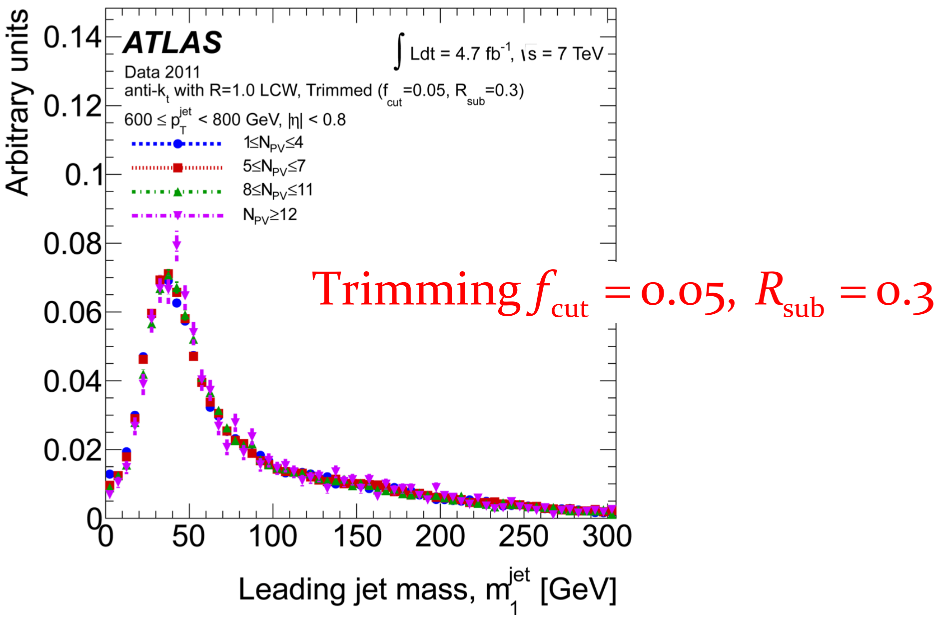
Performance Considerations

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)





Outlook on LHC Run II

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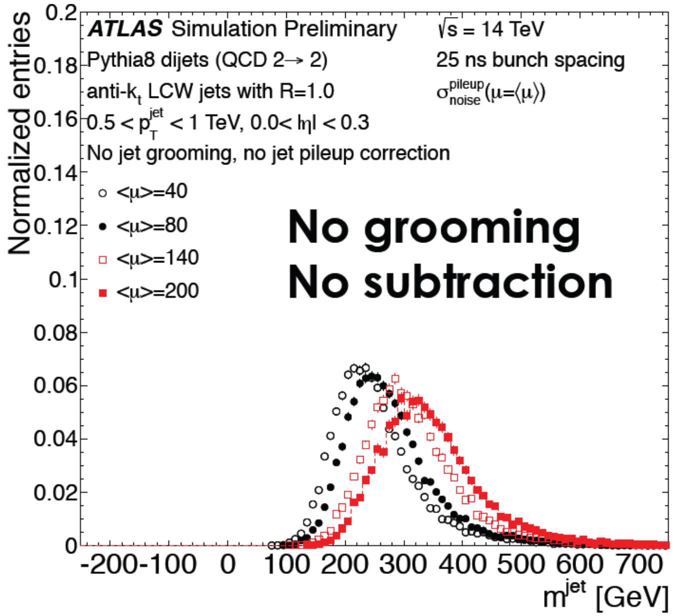
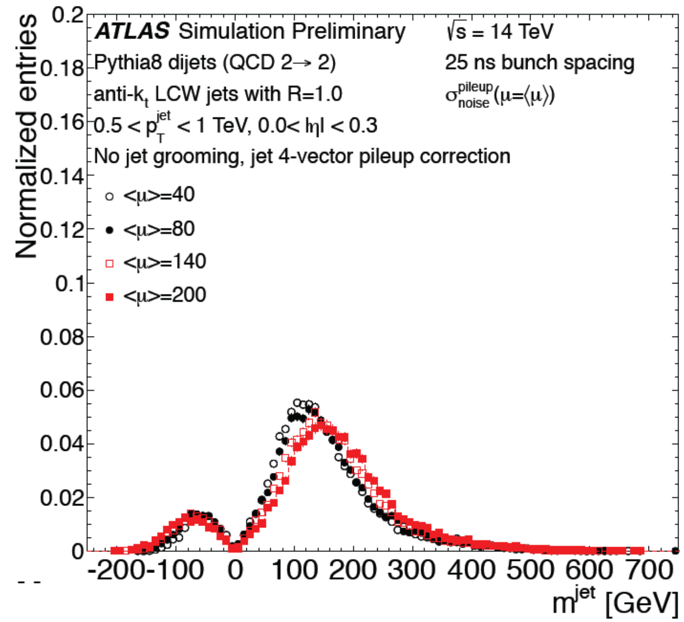


jet 4-vector area based pile-up subtraction

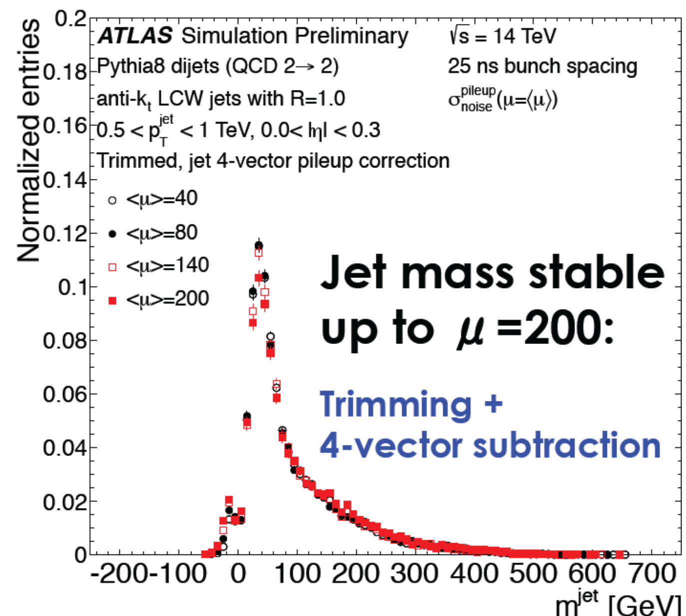
trimming



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



Impressions for a Future Collider

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…

A few more thoughts…

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Calorimeters (1)

Biggest concerns

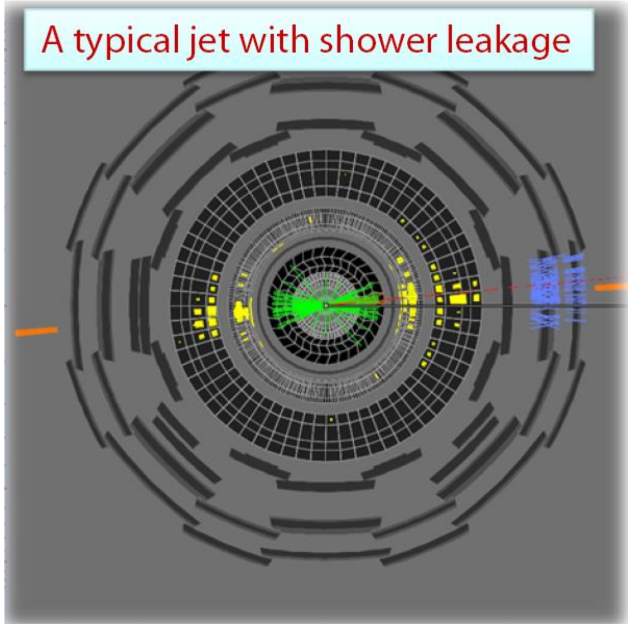
- Need to avoid tails in (jet) response to allow effective searches – avoids fake missing transverse momentum etc.
- Most uniform response across the whole acceptance in pseudorapidity

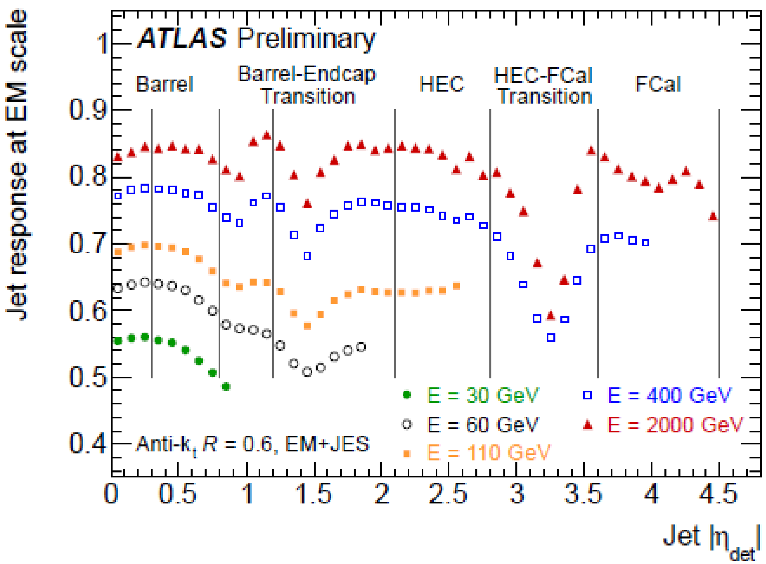
Absorption characteristics

- 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

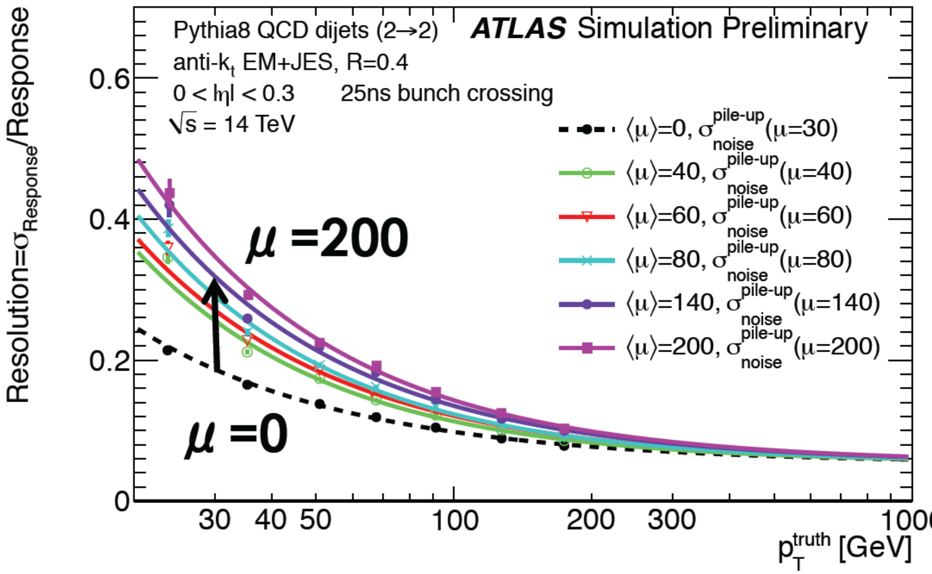
- Highly radiative environment may affect signal yield and proportionality to deposited energy
- Need to focus on technology providing stable signals (within a few %) for decades





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

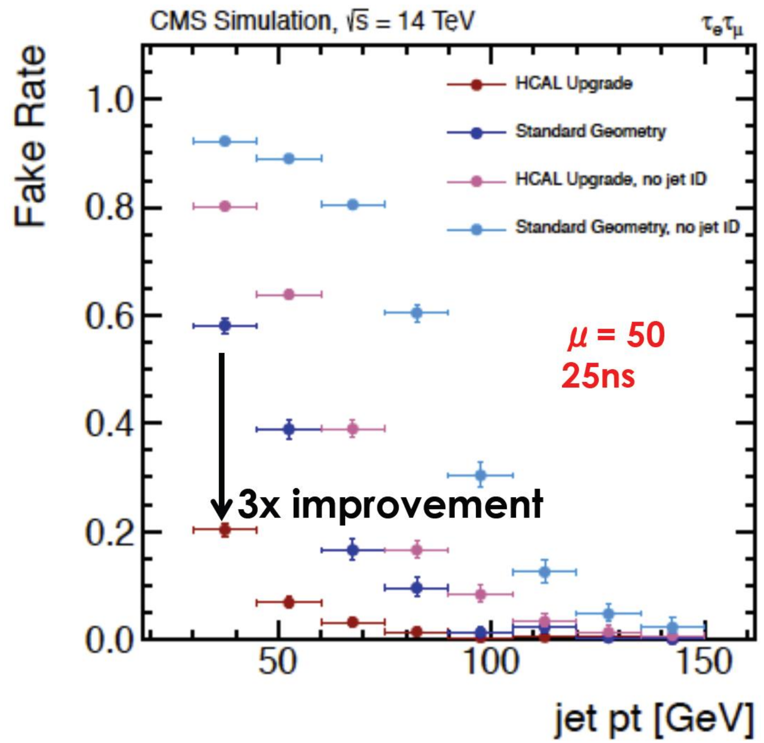


Calorimeter readout structure

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

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

Problem

- Particle flow scales well in (η, φ) space
  - Individual particle showers in calorimeter ~cylinders with $R \approx 15$ cm (Cu/Fe) independent of direction (typical)
  - Best seen so far with W (ATLAS FCal) $R \approx 10$ 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

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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
- …

Suggestions and Conclusions (1)

Developing 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…
- Keep particle flow in mind right away
  - Matching geometries, applicable phase space, …
- Explore tracking in forward region
  - Helps with jet categorization, pile-up suppression, etc. – good physics case outside VBF/VBS based searches?

Suggestions and Conclusions (2)

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First conclusions

Detector design

- ATLAS and CMS seem to be a very good starting point for a 100 TeV collider experiment – but with larger cavities and extended (more forward) tracking
- 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 – less transitions/boundaries introduce by technology choices!
- 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

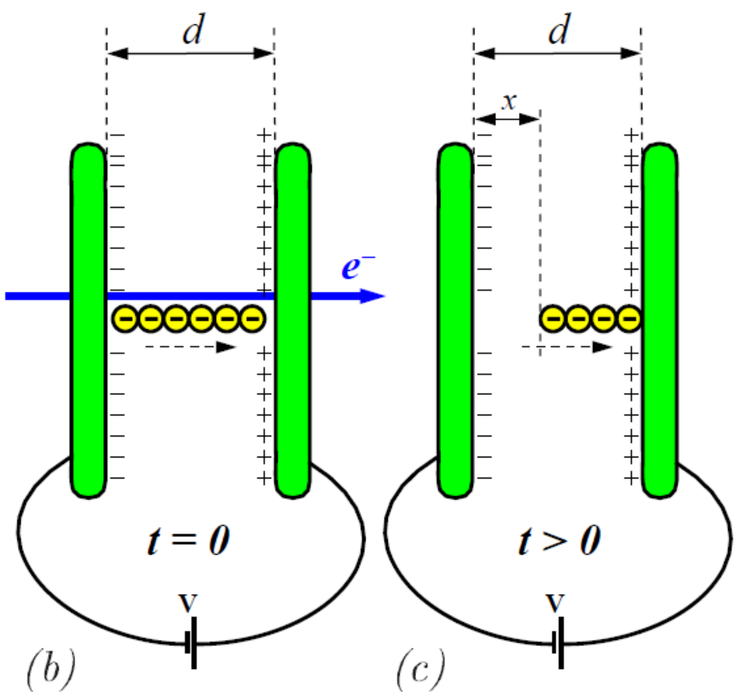
- We learn(ed) a lot from LHC Run 1/2 – significant progress from Tevatron days with respect to jet finding, calibration and feature measurements
- We have good tools for dynamic hadronic calibration, jet refinement and substructure reconstruction – can help to finalize detector requirements (knowing the tools already now helps!)

Technologies (1)

Quick review:

Liquid argon (sampling calorimeter)

- Stable operation – charge efficiency not affected by irradiation, can use radiation hard absorber and other materials
- Liquid argon boiling – highest energy particles in forward direction, may limit absorber choices and require complex cooling systems
- Easy to segment – but once designed segmentation is hard to change (re-opening of large cryostat highly disfavored)
- Slow charge collection – needs appropriate shaping function to reduce pile-up sensitivity
- Positive ion build-up in high ionization environments – thin gaps only in high occupancy (forward) regions



Technologies (2)

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Quick review:

- Crystals (homogeneous calorimeter)
  - Not easy to segment – how small can crystals be? Longitudinal segmentation?
  - Long term stability – radiation damage a concern
  - Fast signal collection – less sensitive to out-of-time pile-up
  - No sampling – high resolution especially for EM particles
  - Can be replaced/changed – readout geometry development supported?

Technologies (3)

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Quick review:

- Scintillator (sampling calorimeter)
  - Simple and stable mechanical design
  - Long term stability – radiation damage a concern
  - Fast signal collection – less sensitive to out-of-time pile-up
  - Good hadronic energy resolution – not so great for EM particles
  - Can be replaced/changed – readout geometry development supported?
- Digital calorimeters (sampling calorimeters)
  - …